Sloan Digital Sky Survey 3 and primordial non-gaussianities

Shirley Ho
Carnegie Mellon University
+
Sloan Digital Sky Survey III Collaboration

Critical Test of Inflation Using Non-Gaussianity
MPA, Nov 5-8,2012

Rolling the credits

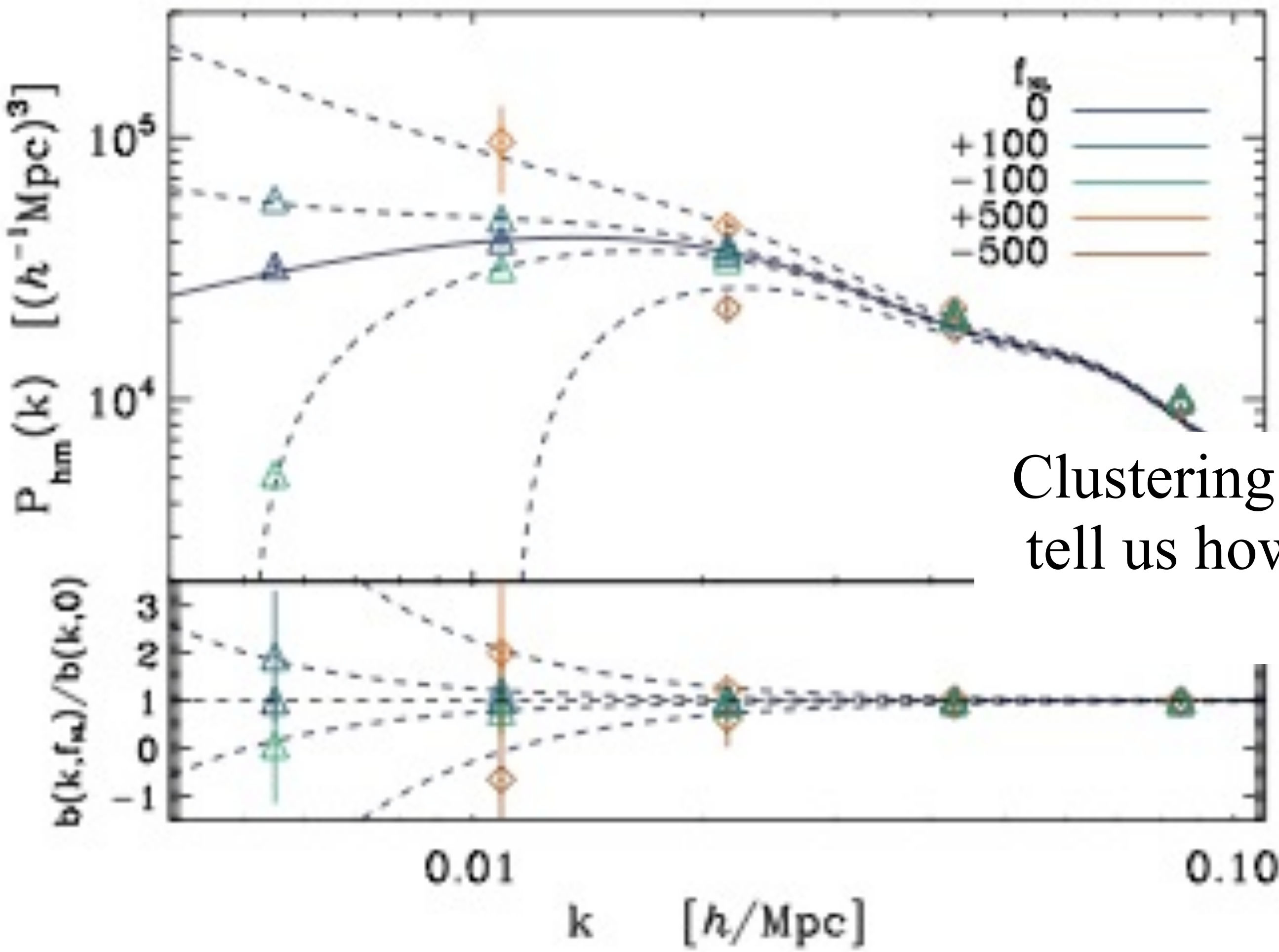
SDSS III collaboration, and especially the following folks:
Nishant Agarwal, Michael Blanton, Jo Bovy, Antonio Cuesta, Roland DePutter, Daniel Eisenstein, Eric Huff, Mario Juric, Adam Myers, Rich O'Connel, Nikhil Padmanabhan, Will Percival , Connie Rockosi, Ashley Ross, Eddie Schlafly, David Schlegel, Uros Seljak, Hee-Jong Seo, Sarah Shandera, Anze Slosar, Licia Verde, Martin White

Outline

- **Motivations**
- **Using the largest multicolor image of the Universe to learn about it? How?**
  - **Early Universe (with large scale clustering)**
- **Angular clustering**
  - **With Luminous Galaxies and Quasars**

Using Large scale structure to learn about the beginning of the Universe

Power spectrum of dark matter halos



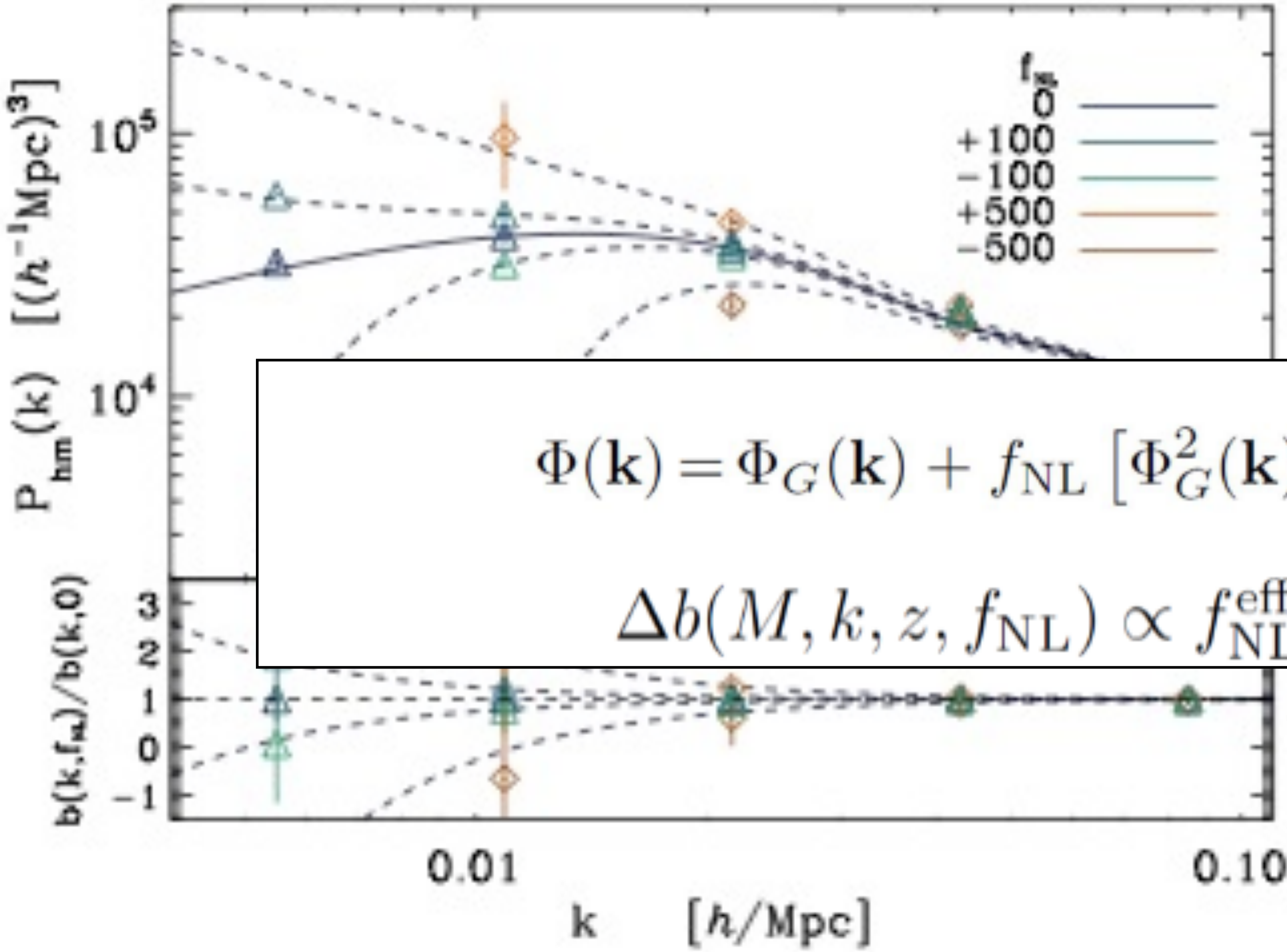
Clustering of dark matter halos can tell us how non-gaussian the early Universe is

Dalal, Dore, Huterer, Shirokov 2008

Using Large scale structure to learn about the beginning of the Universe

Power spectrum of dark matter halos

$$\delta_{tracer} = b\delta_m$$

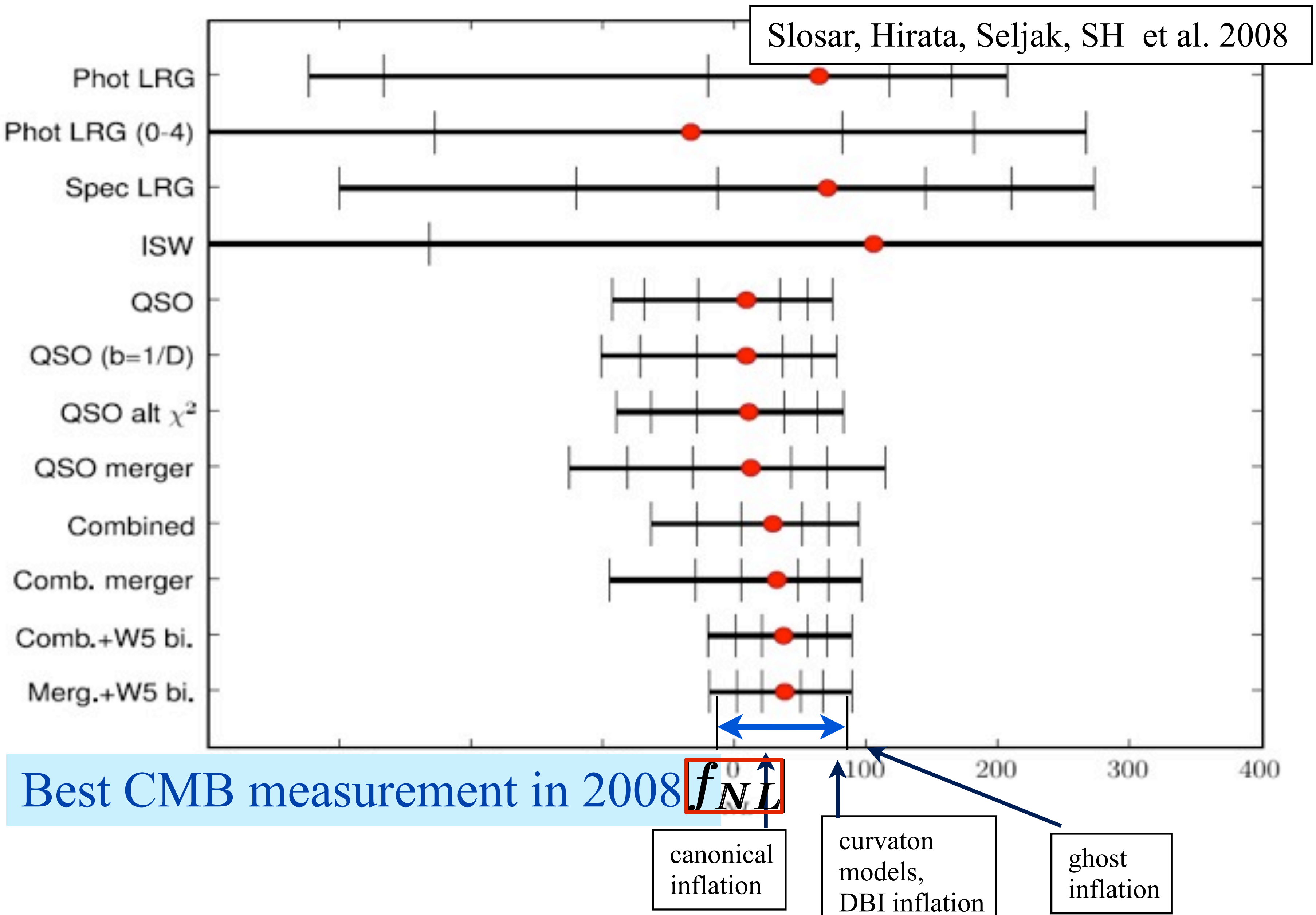


$$\Phi(\mathbf{k}) = \Phi_G(\mathbf{k}) + f_{\rm NL}\left[\Phi_G^2(\mathbf{k}) - \langle\Phi_G^2(\mathbf{k})\rangle\right]$$

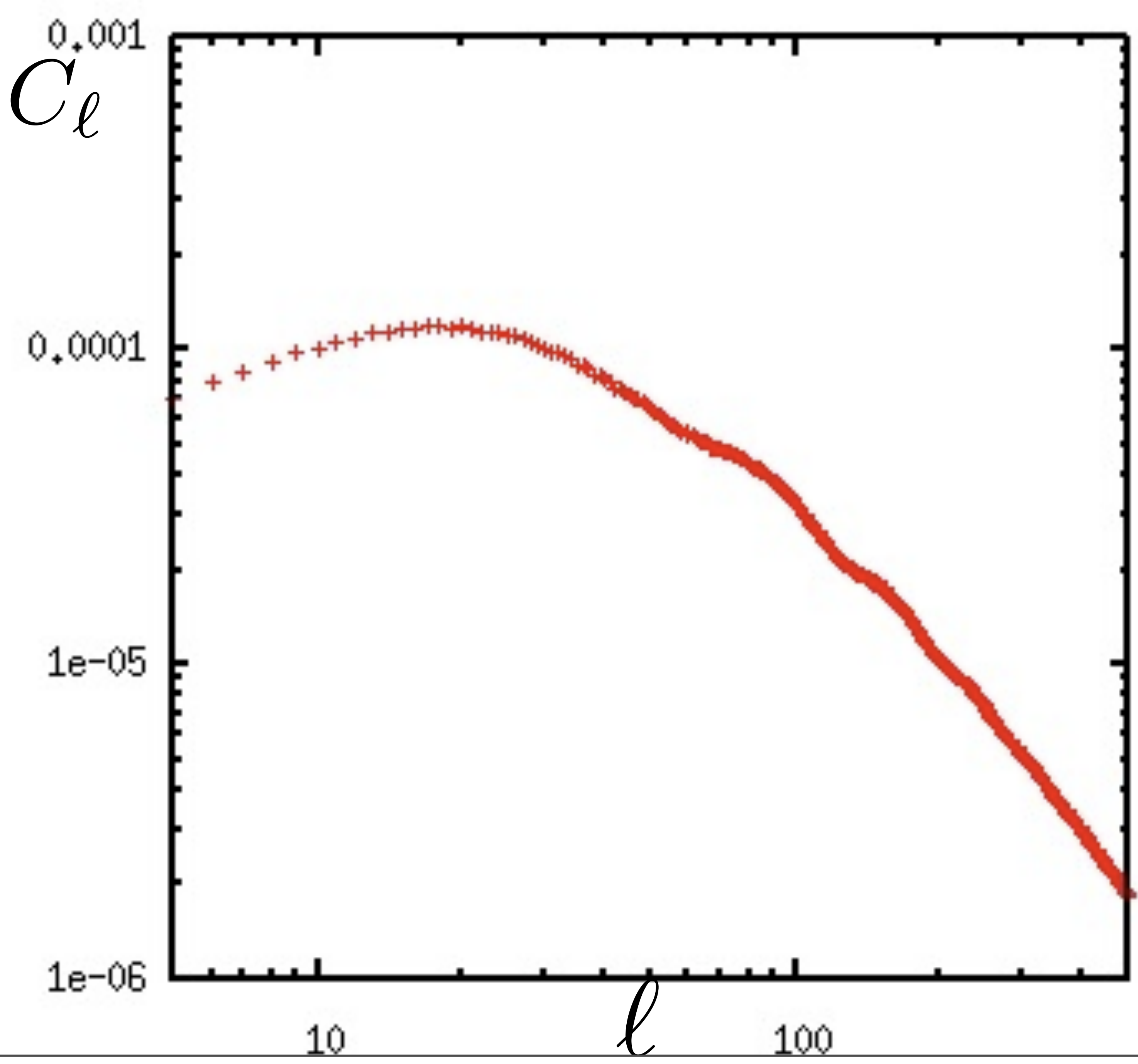
$$\Delta b(M,k,z,f_{\rm NL}) \propto f_{\rm NL}^{\rm eff}(M)/k^{\alpha}$$

Dalal, Dore, Huterer, Shirokov 2008

Using Large scale structure to learn about the beginning of the Universe



Instead of looking at the 3D clustering, we look a 2D clustering!
We can calculate the Angular Clustering/Power-spectrum.



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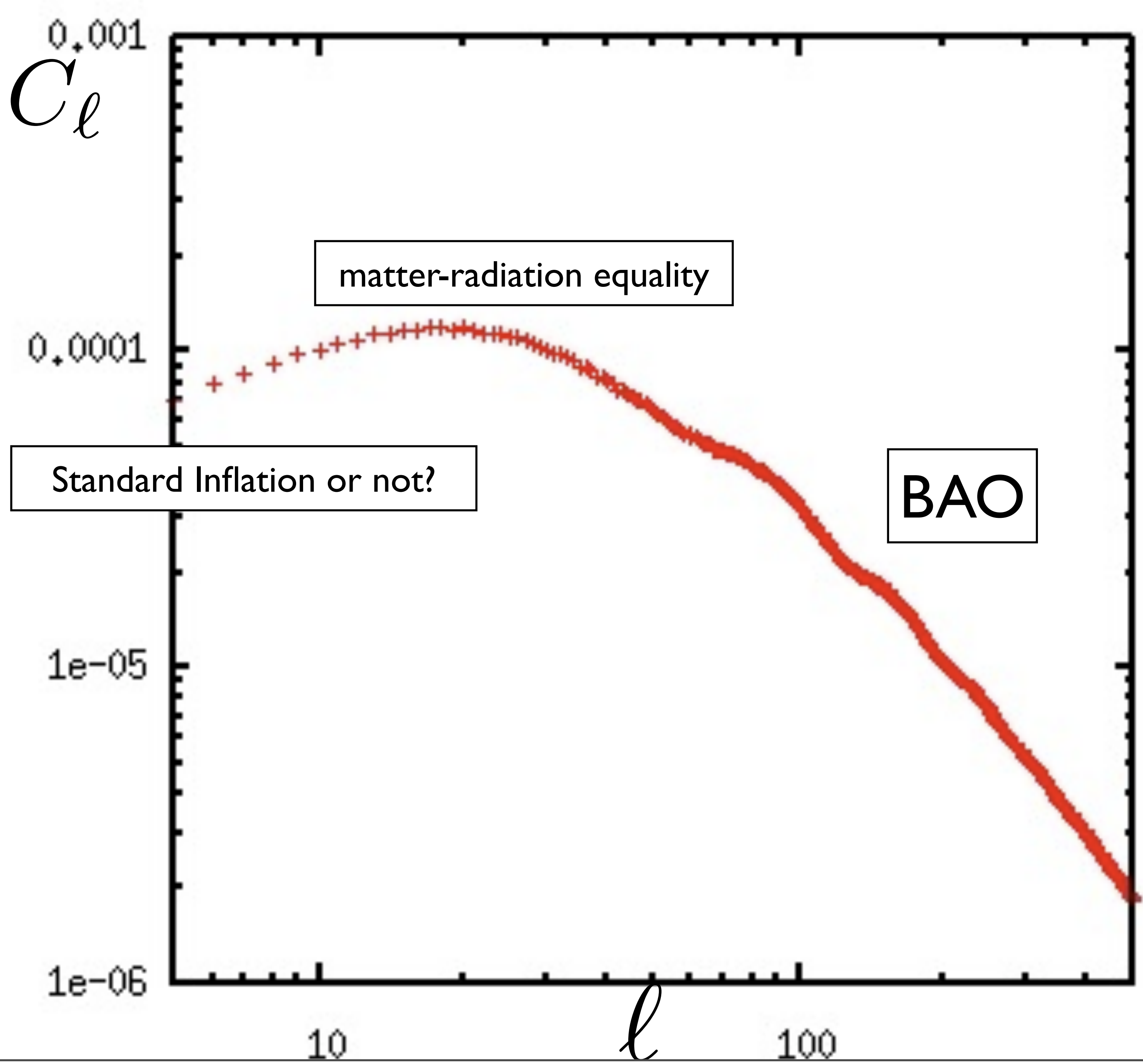

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Physics of Angular Clustering

BERKELEY LAB

$b = \frac{\delta g}{\delta \rho}$ describe how galaxies are related to cold dark matter

$\frac{dN}{dz}$ describe how many galaxies are there at each dz bin

$D(z)$ describe how matter grows

$P(\frac{l+\frac{1}{2}}{\chi})$ describe how matter cluster (matter powerspectrum, describes the rms fluctuations)

Galaxy angular power-spectrum

$$C_\ell^{gg} = \int dz \frac{d\chi}{dz} \frac{1}{\chi^2(z)} b^2(z) N^2(\chi) P(k,z)$$

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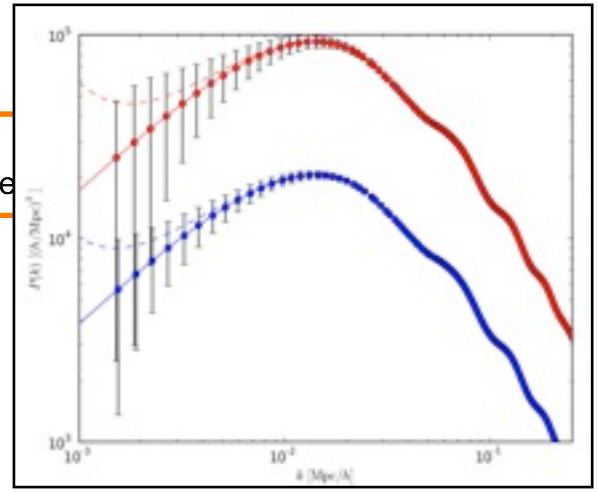

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Angular power-spectrum contains a wealth of cosmological information ranging from

a) What is **dark energy**? to

b) What happened at the very early Universe? Inflation? What kind?

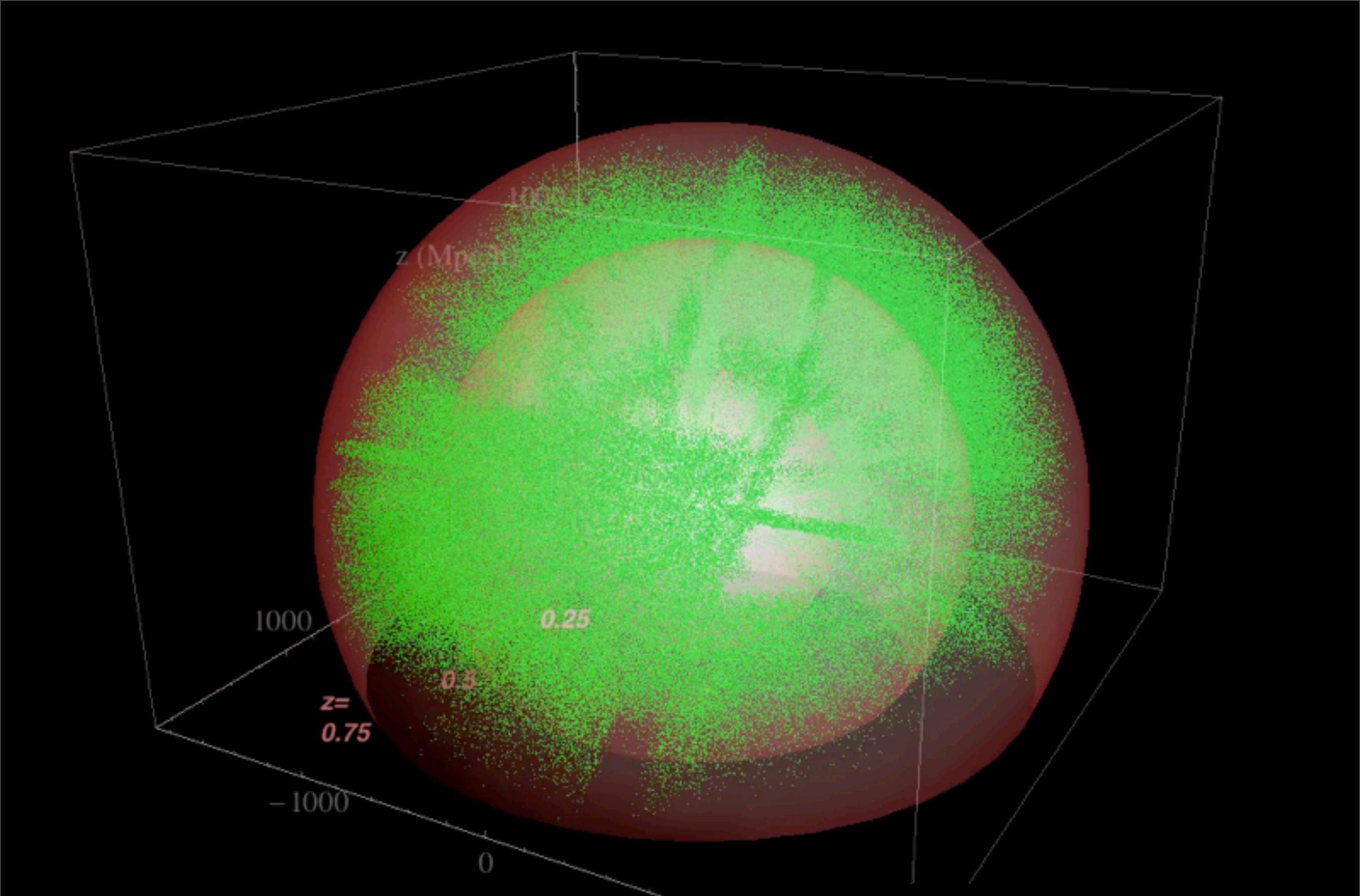

Image: David Kirkby / Jan 2012
http://darkmatter.ps.uci.edu/lrg-sdss (movie)

SDSS III

SLOAN DIGITAL SKY SURVEY III

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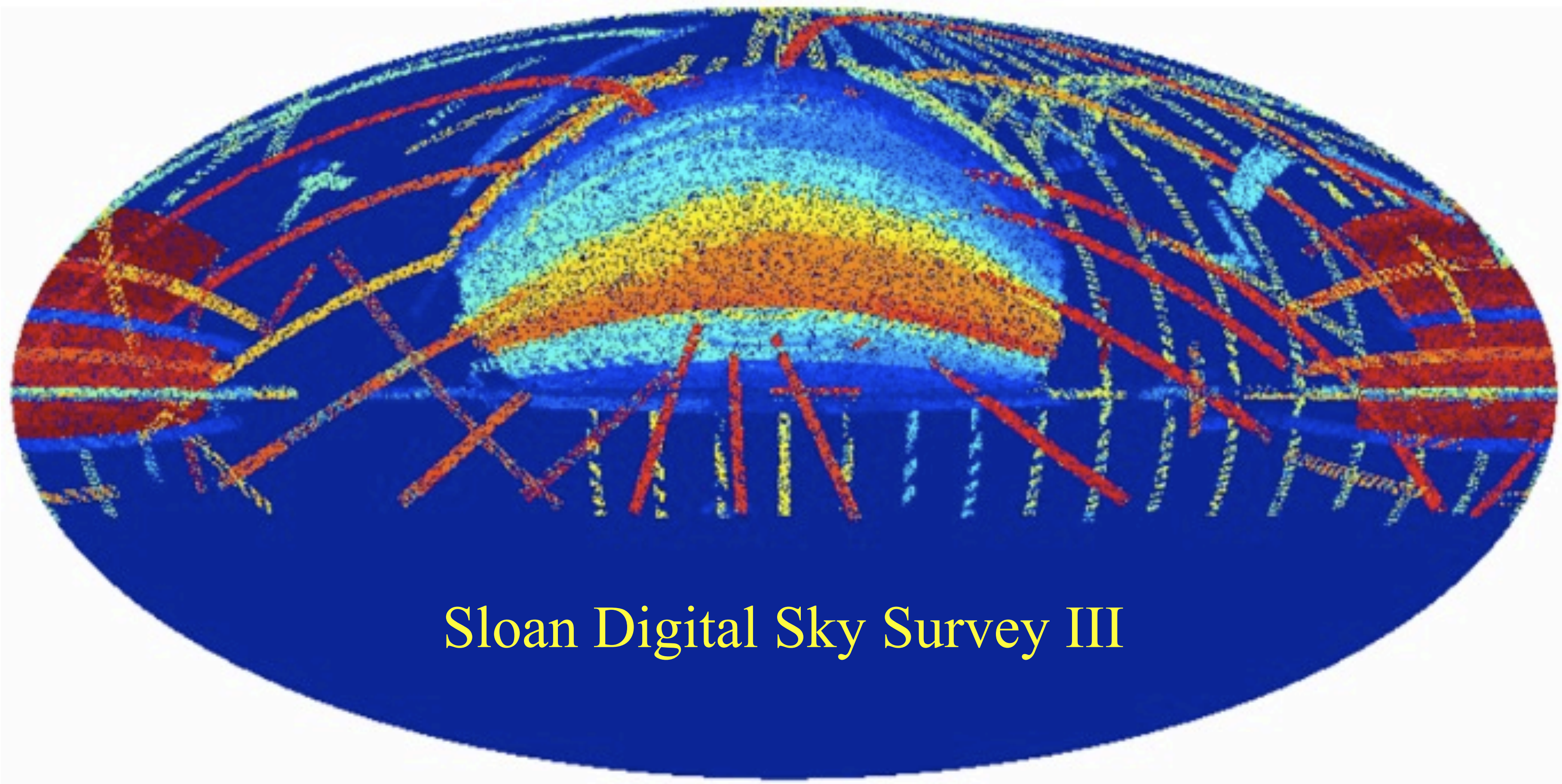
Angular Clustering
The Data

Total Area: 14,555 sq deg

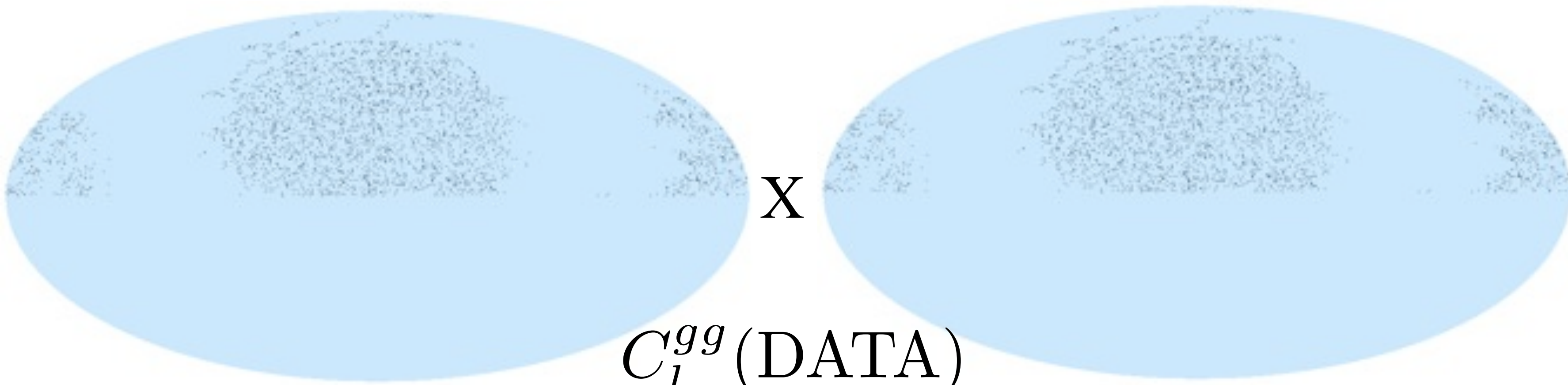
1.5 million LRGs: 0.4<z<0.7



note: Colors only indicates the when a certain area of the sky is surveyed.

Angular Clustering
How to do this?

- For each of the redshift bin, we cross-correlates the Luminous Red Galaxies with themselves, and we get the angular power-spectra of the galaxies.



$$C_l^{gg}(\mathrm{DATA})$$

- We want the best measurement of the angular power-spectra possible, from the stand point of not only statistical error, but also systematic errors.
- To get the best statistical errorbar, we apply “Quadratic Estimator”, which are proven to provide:
  - Unbiased Minimum variance measurement of the parameters that are being estimated if the field is gaussian.
  - Many people have worked on this Quadratic Estimators: Hamilton, Tegmark, Bond, Jaffe and Knox, White, Padmanabhan, Hirata, Blake, et al.

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- We want the best measurement of the angular power-spectra possible, from the stand point of not only statistical error, but also systematic errors.
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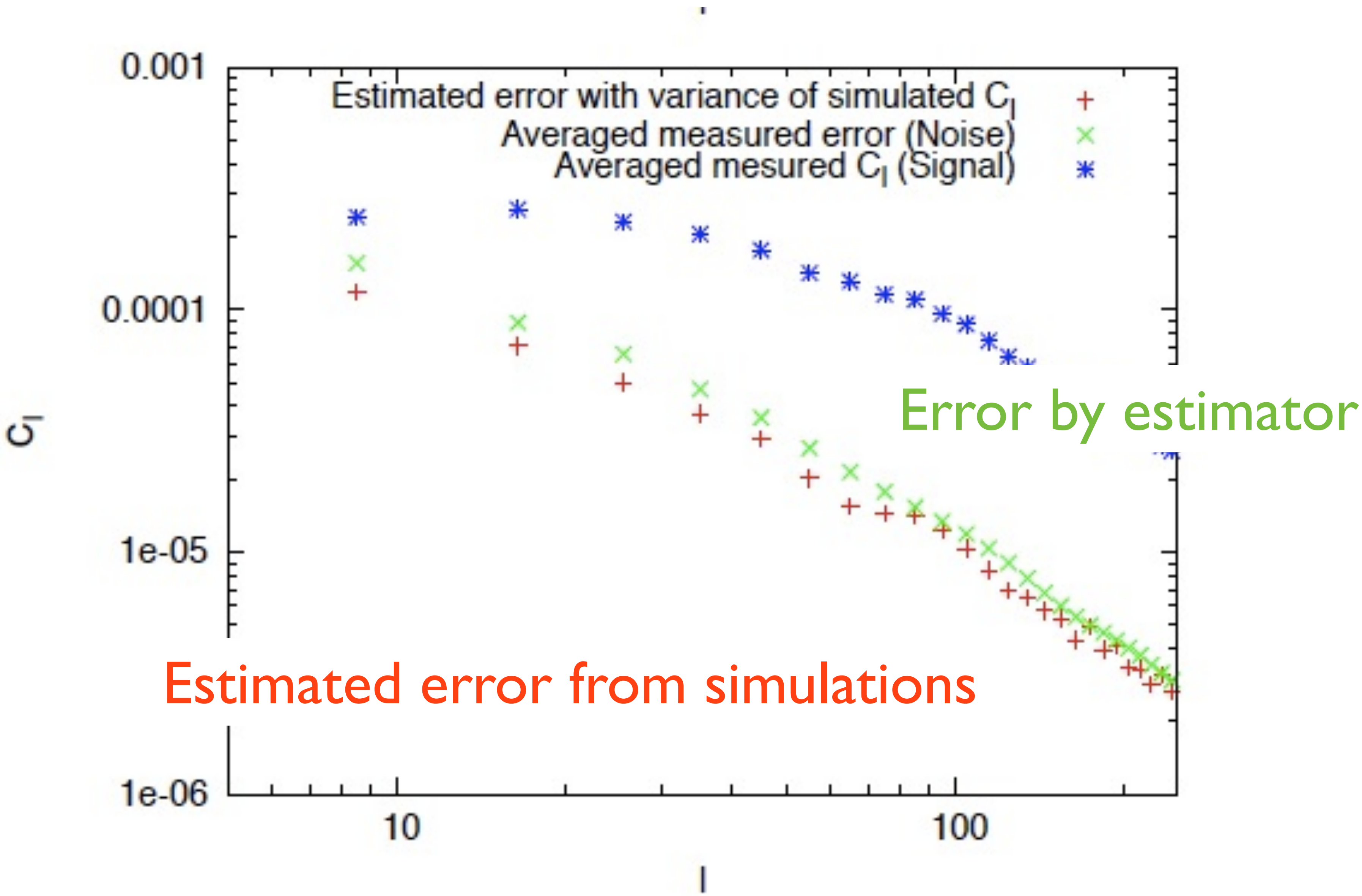
  — ***Unbiased* Minimum variance** measurement of the parameters that are being estimated if the field is gaussian.
  — Many people have worked on Quadratic Estimators: Hamilton, Tegmark, Bond, Jaffe and Knox, White, Padmanabhan, Hirata, Blake, et al.
  — Had been mostly adopted by CMB community, and but had only been used in Tegmark et al. 2004, 2006; Padmanabhan et al. 2006; Hirata et al. 2008, Ho et al. 2008.

How good is the estimator?



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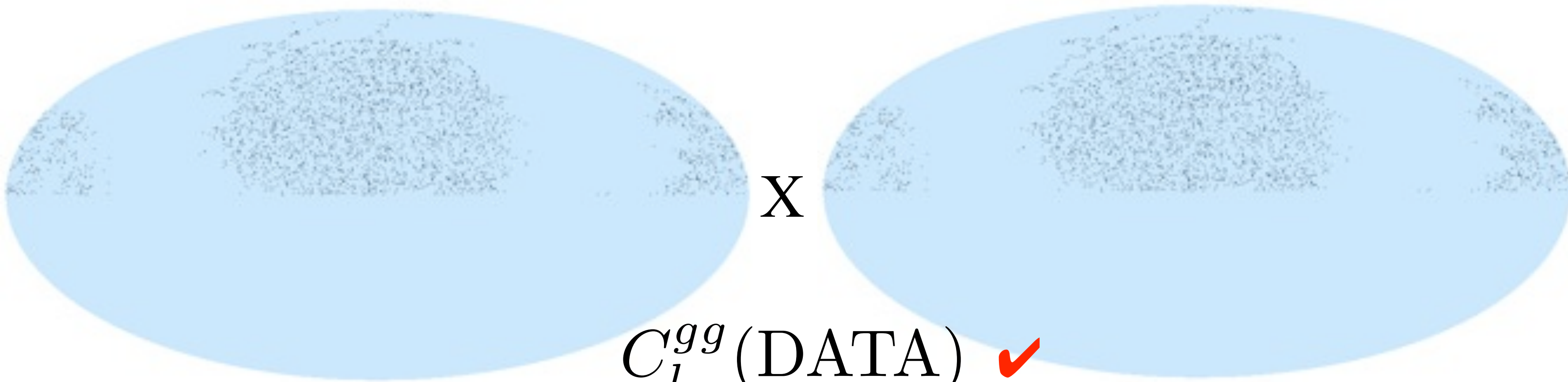
Angular Clustering
How to do this?

- For each of the redshift bin, we cross-correlates the tracers with themselves, and we get the angular power-spectra of the galaxies.



$$C_l^{gg}(\mathrm{DATA})$$ ✔

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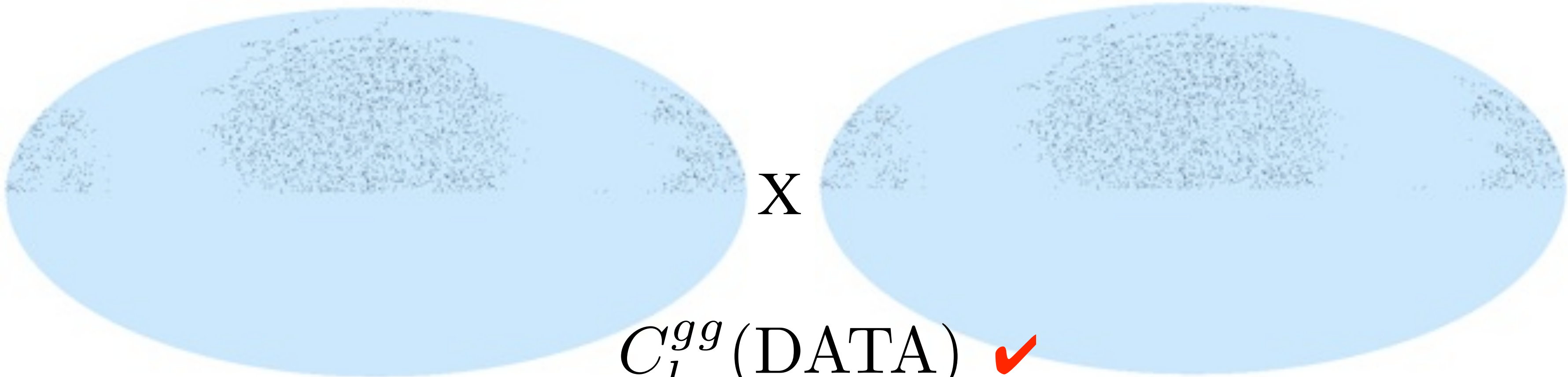

C_l^{gg}(DATA) ✔

- But in order to derive cosmological constraints, we need to be able to predict the angular power-spectra given any cosmological models.
- That's why: we need the **theory**:

$$C_\ell^{gg} = \int dz \frac{d\chi}{dz} \frac{1}{\chi^2(z)} b^2(z) N^2(\chi) P(k, z)$$

- Given a cosmological model, we can predict the theory, except we need two inputs: bias b(z) and redshift distribution dN/dz.

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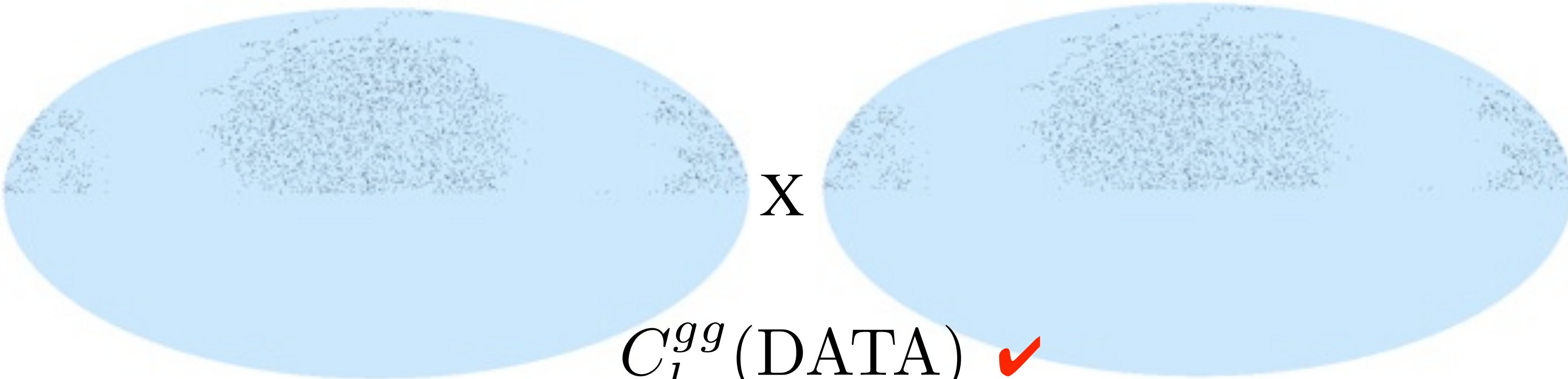

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Angular Clustering
The Redshift Distribution

SDSS III has been taking spectra of all of these photometric LRGs, therefore, we have an unbiased spectroscopic confirmation of the photometric redshifts for ~10% of the sample, therefore, we have very good understanding of the redshift distribution of the sample.

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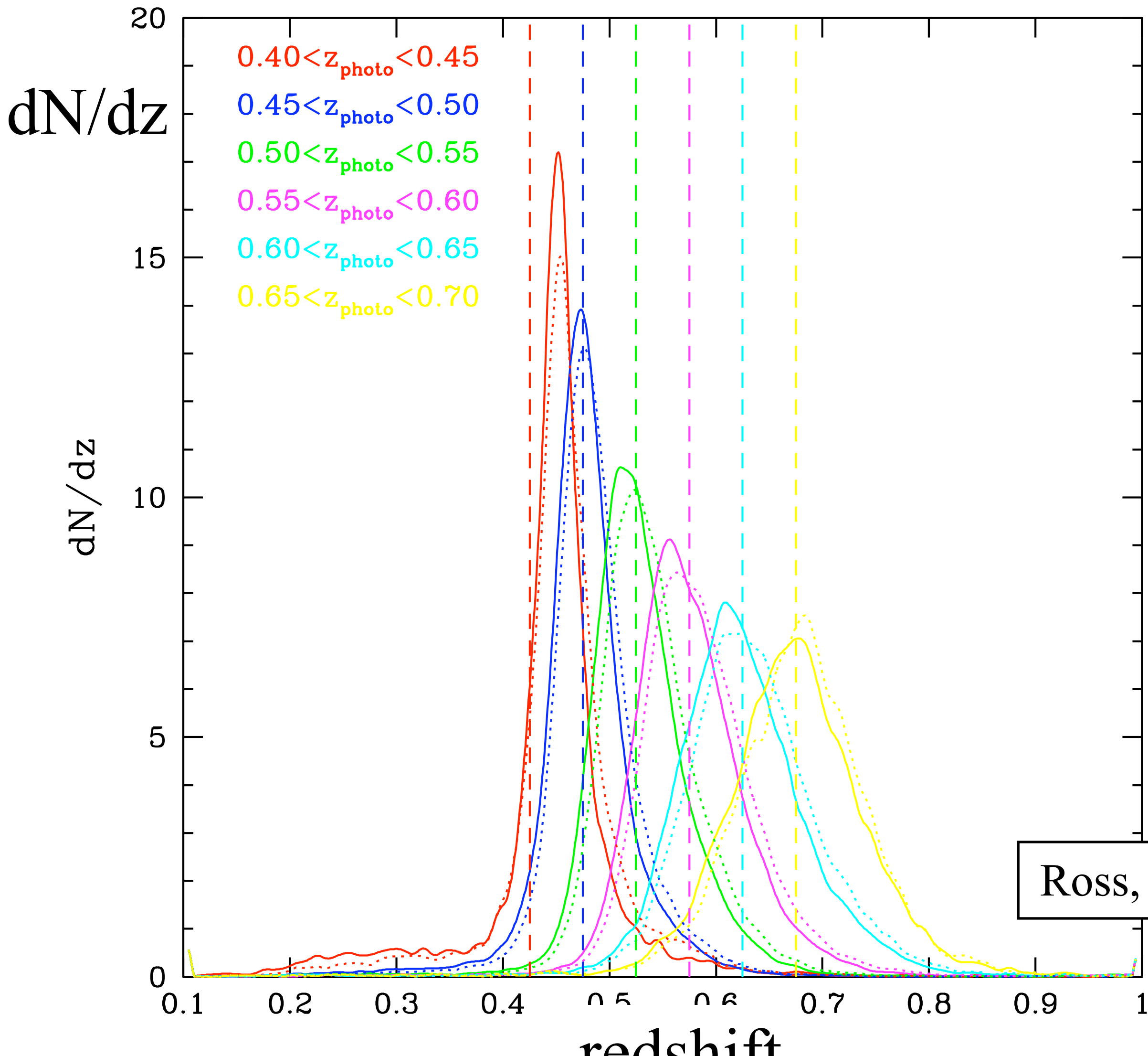

Ross, SH, Percival et al. (2011)

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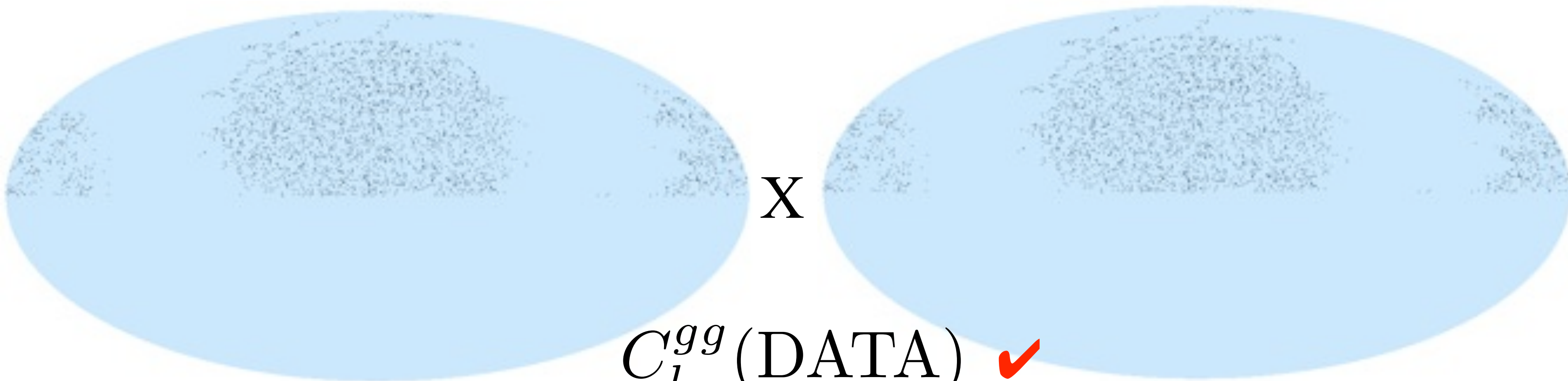

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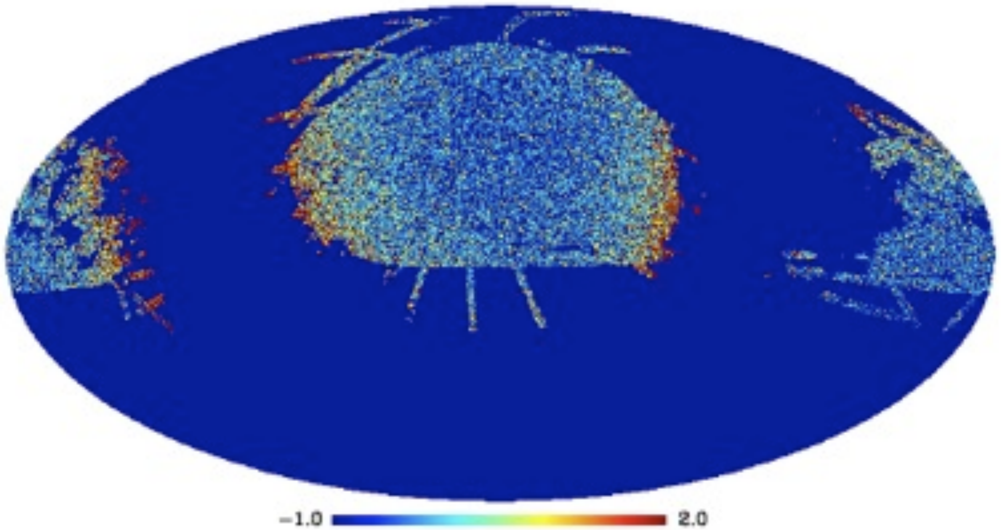
- We then only need to know bias, but since it only changes the overall amplitude of the angular power-spectrum.
- We fit for overall bias (when it is only BAO), and in the case of fnl, we fit for an overall bias and a fnl induced additional bias.

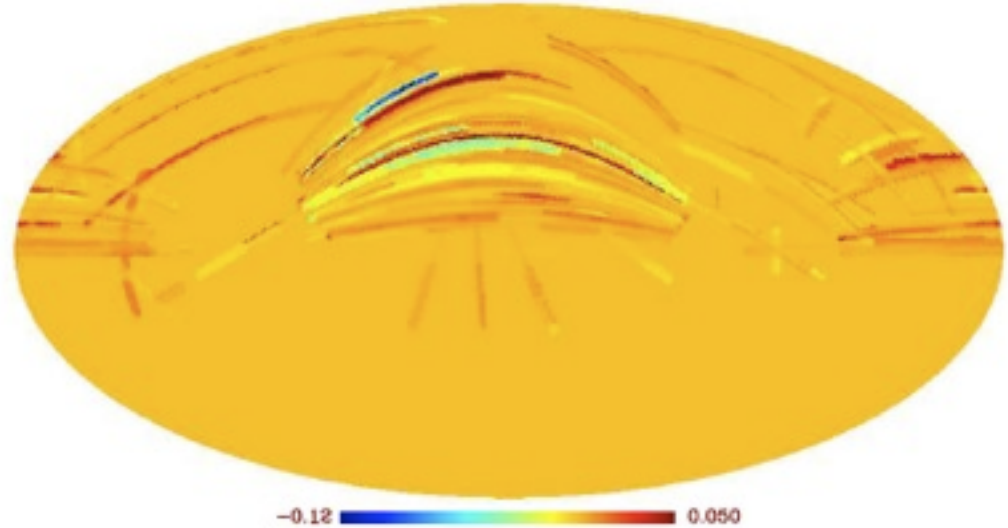
Now we have
a)Theory predictions
b) Optimally estimated observables

What should we be worried about?
Systematics...

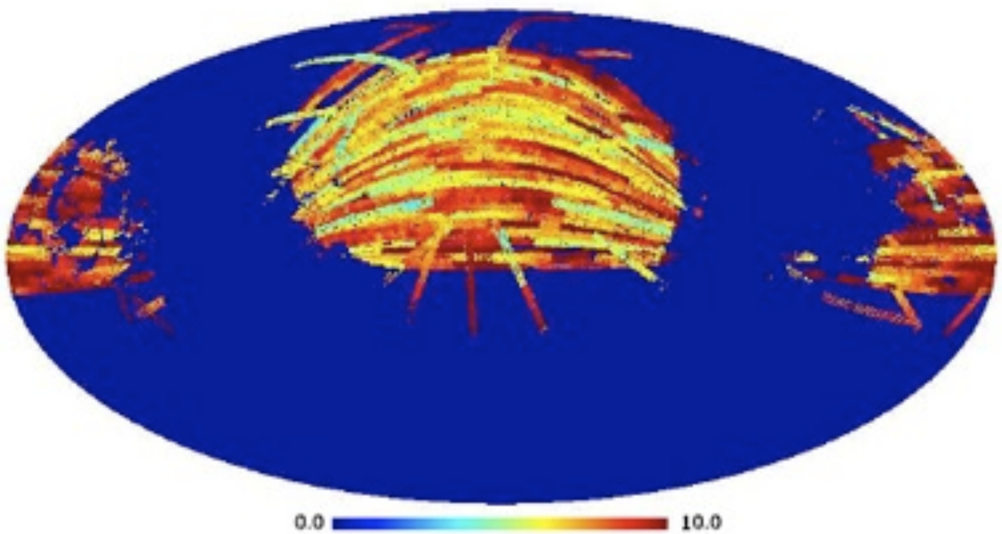
Stars !



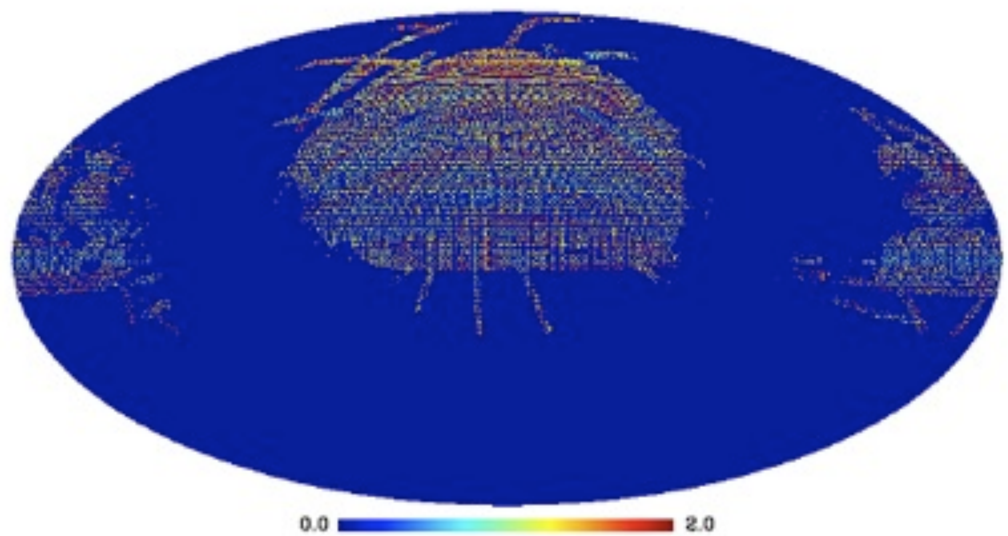
Color offsets from Schlafly et al. 2011



Sky Brightness



Seeing



SH, Cuesta, Seo, Ross, DePutter et al. (2012)

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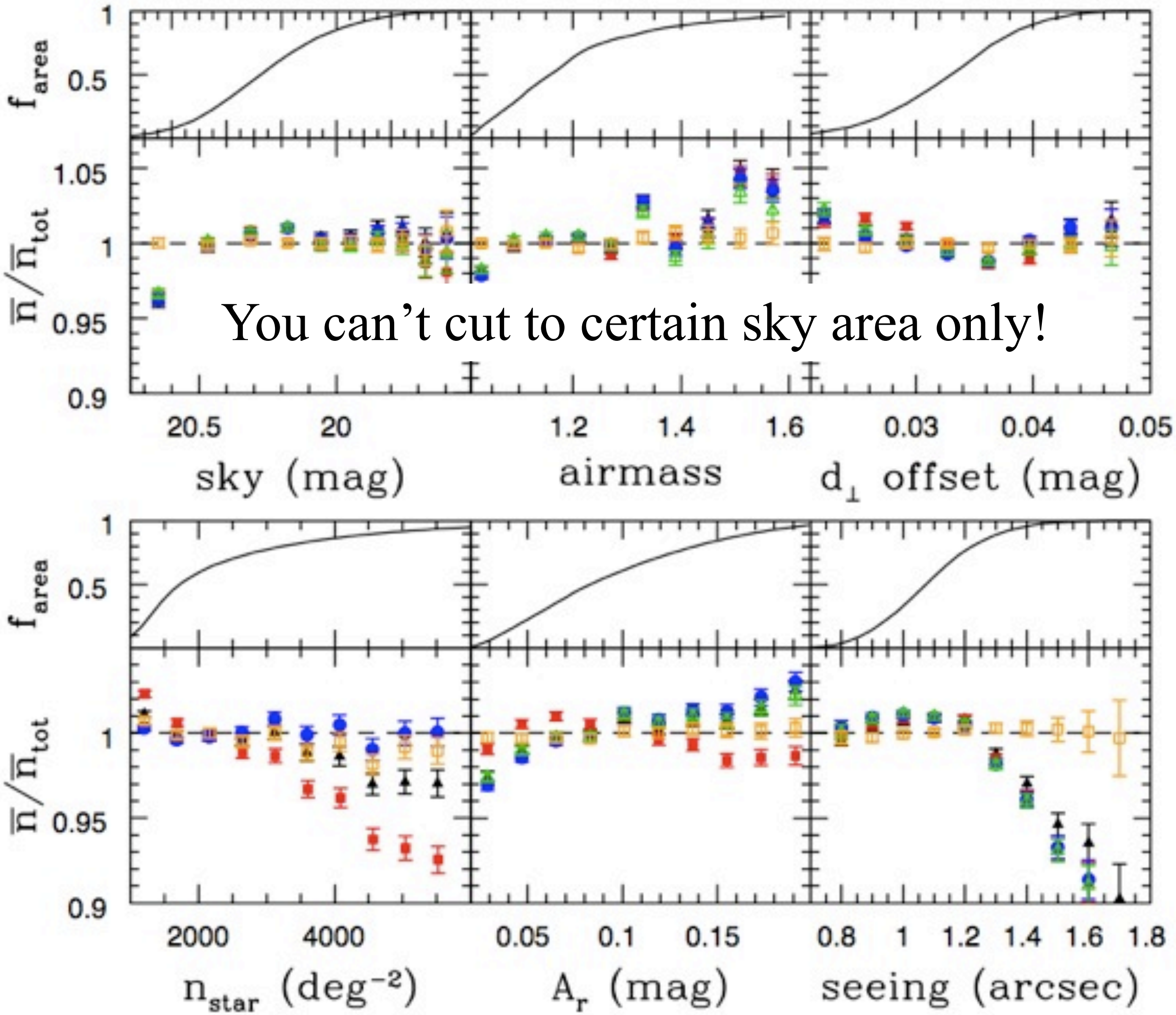
Short summary:



Ross, SH, Cuesta et al. (2011)

Systematics: Taking them out of the equation

True galaxy overdensity

Observed galaxy overdensity

$$\delta_g^o = \delta_g^t + \sum_{i=0}^{N} \epsilon_i \delta_{s_i}$$

Various systematics

For example, if i=2 only:

$$< \delta_g^o \delta_{s_1} >=< \delta_g^t \delta_g^t > +\epsilon_1 < \delta_{s_1} \delta_{s_1} > +\epsilon_2 < \delta_{s_2} \delta_{s_1} >$$

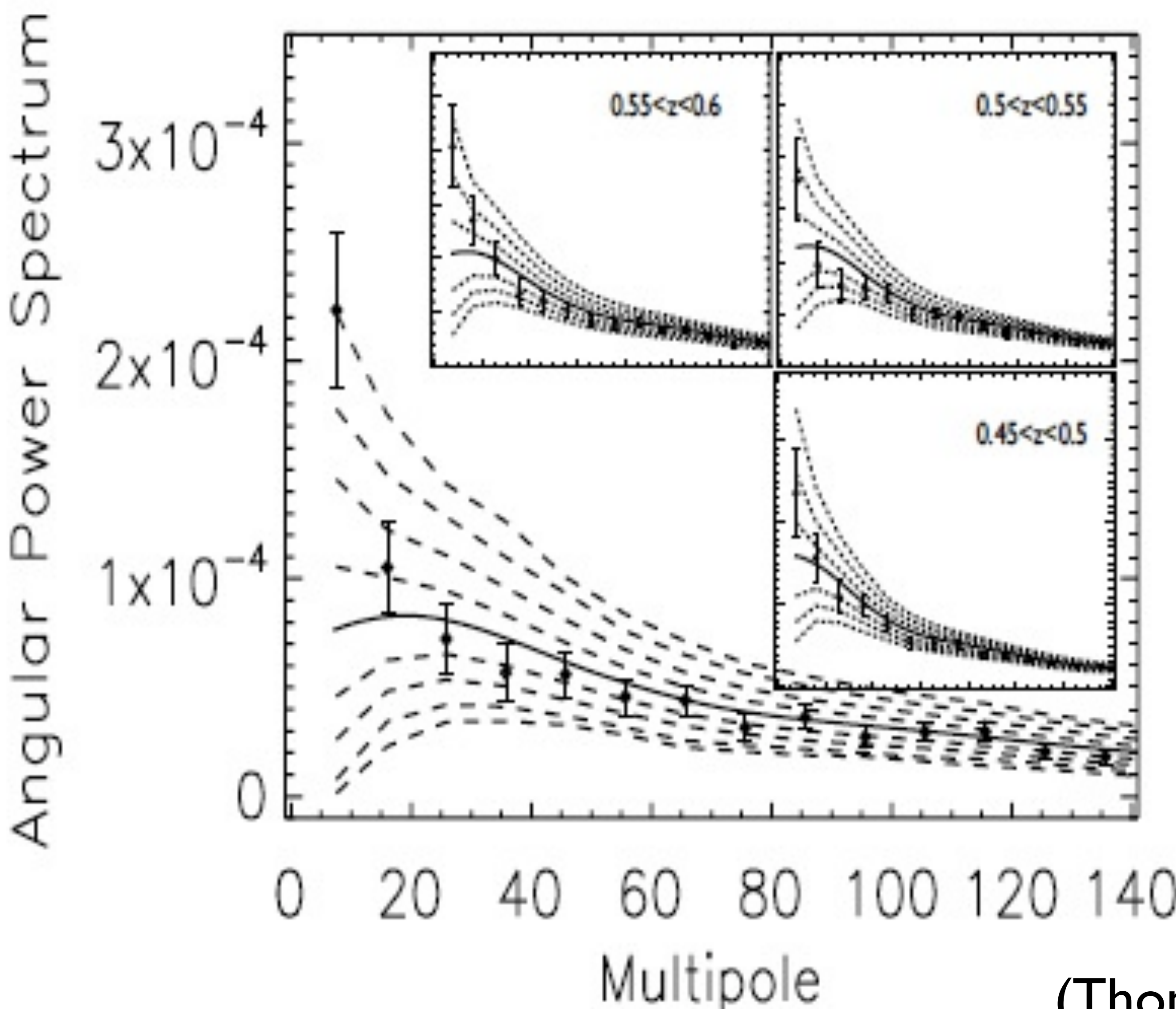
$$< \delta_g^o \delta_{s_2} >=< \delta_g^t \delta_g^t > +\epsilon_1 < \delta_{s_1} \delta_{s_2} > +\epsilon_2 < \delta_{s_2} \delta_{s_2} >$$

$$< \delta_g^o \delta_g^o >=< \delta_g^t \delta_g^t > +\epsilon_1^2 < \delta_{s_1} \delta_{s_1} > +2\epsilon_1\epsilon_2 < \delta_{s_2} \delta_{s_1} > +\epsilon_2^2 < \delta_{s_2} \delta_{s_2} >$$

We also need to take into account of all the covariances between systematics and across different band power, and this only works if the systematics contributes linearly (ask me how we test this later).

SH, Cuesta, Seo, Ross, DePutter et al. (2012)

Recall multiple previous analyses which have seen large excess in large scale clustering



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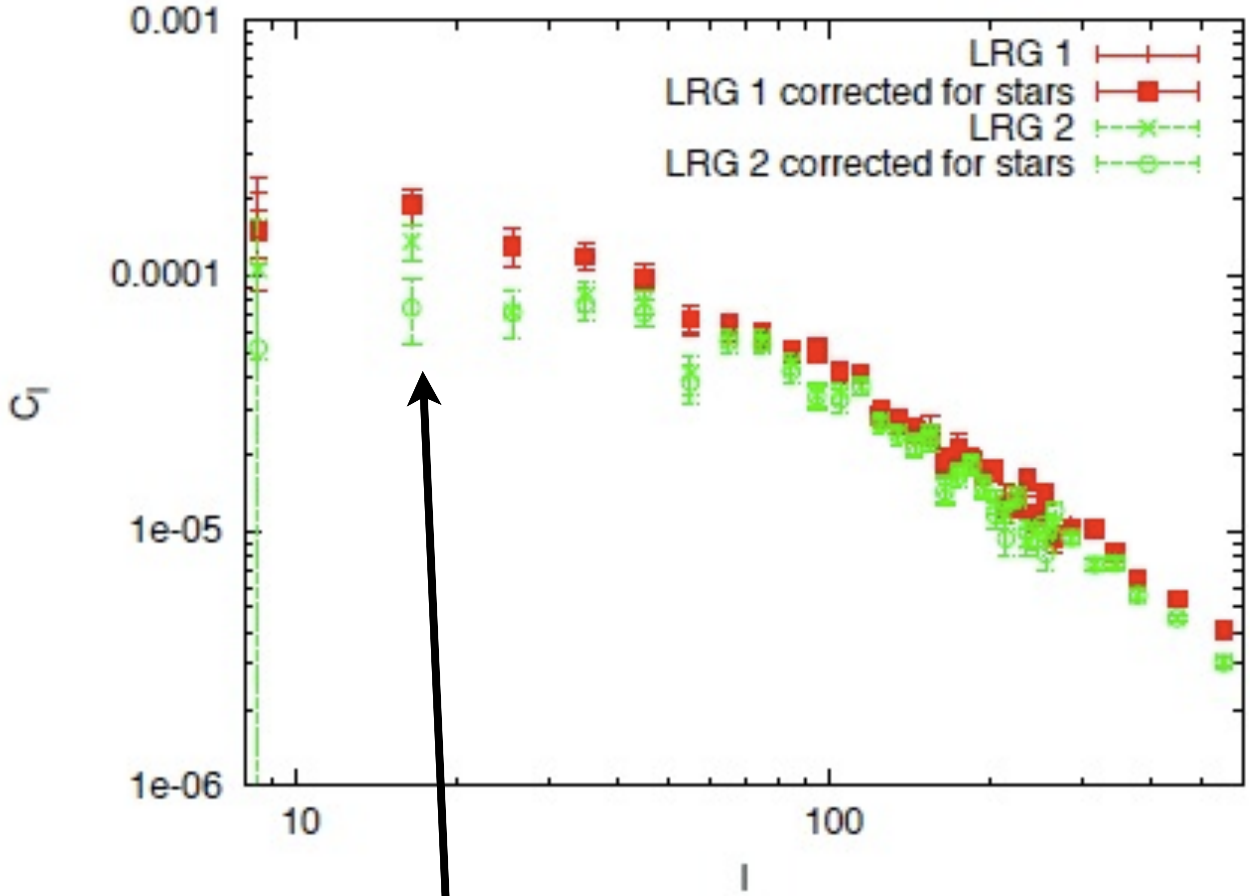
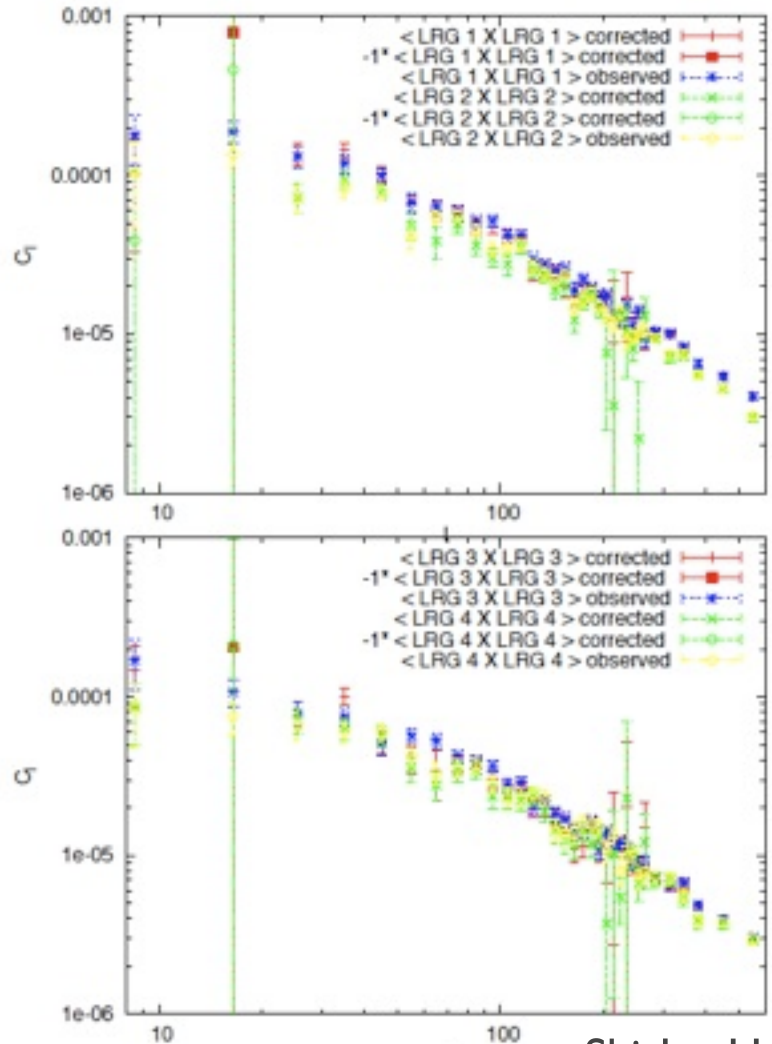
(Thomas et al. 2011)

We can correct the power-spectra for systematics!





We see no large excess in large scale, and can even see the matter- radiation equality turnover!

SH, Cuesta, Seo, Ross, DePutter et al. (2012)

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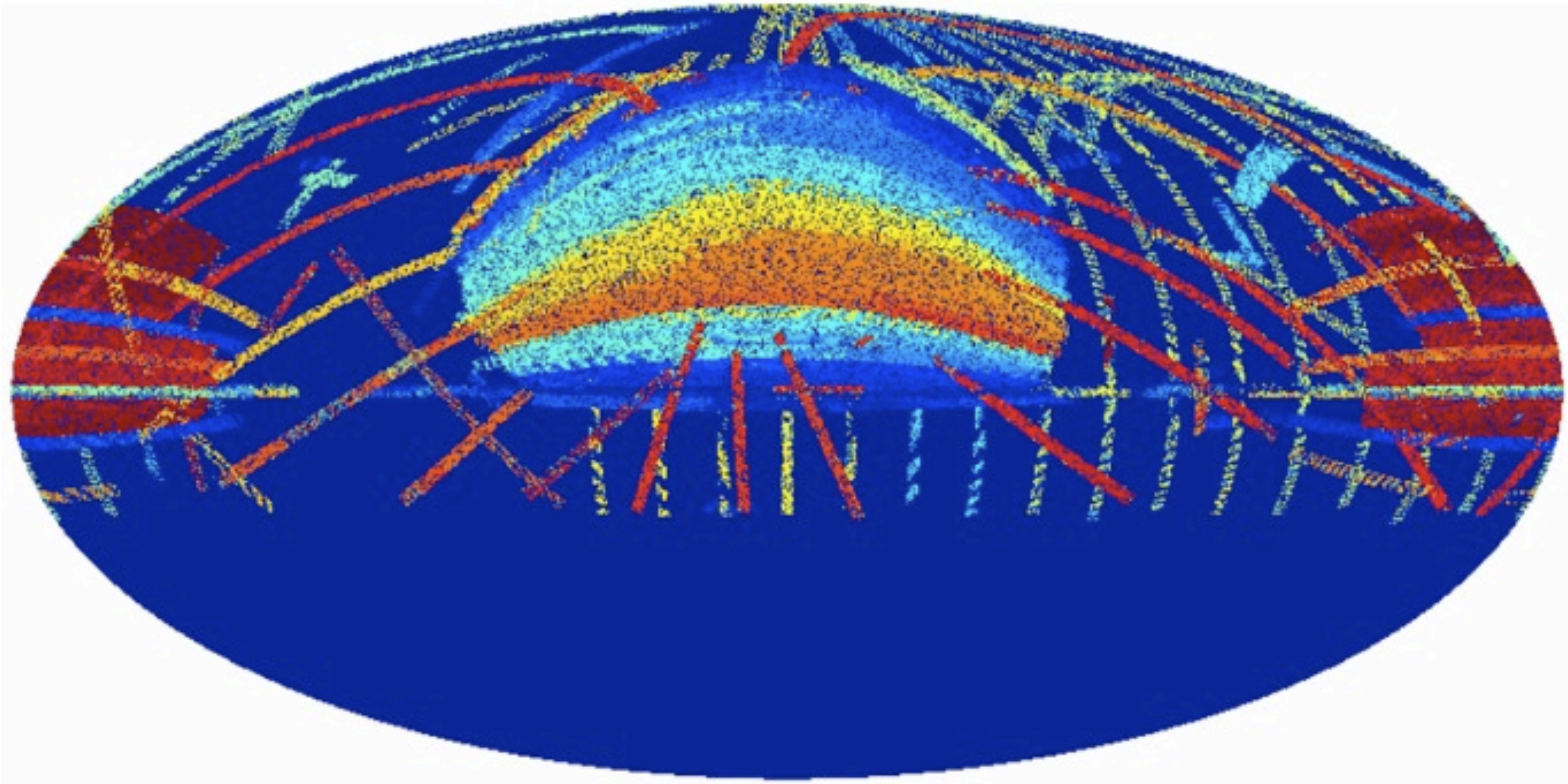
Angular Clustering of Quasars

14,555 square degrees



Two different photometric quasar samples:

a) 1.6 million quasars 0.5<z<2.5 (Bovy+Myers et al. 2012)

b) 1.2 million quasars 0.5<z<2.2 (extension of Ho, Hirata et al. 2008)

Recall: What we do

Optimal quadratic Estimation

$$C_{QQ,DATA}(l)$$

↓

Systematic Corrections

↓

Theory about the Universe

↑

$$C_l^{QQ} = \int d\chi \frac{H_0}{c} b^2(z)(dN/d\chi)^2 D^2(z) P(k = \frac{l+1/2}{\chi})$$

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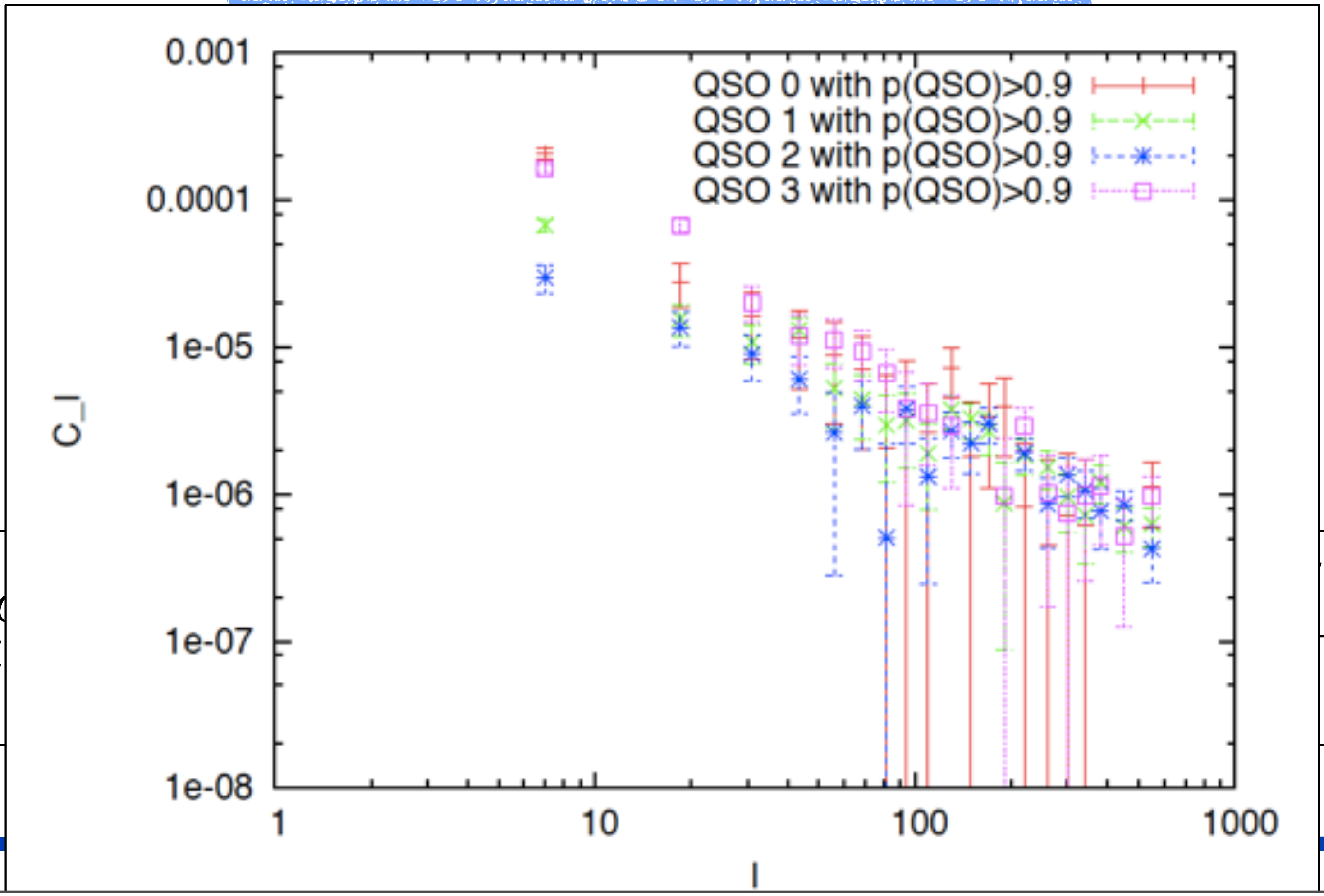

C_l^{Q} … 2)

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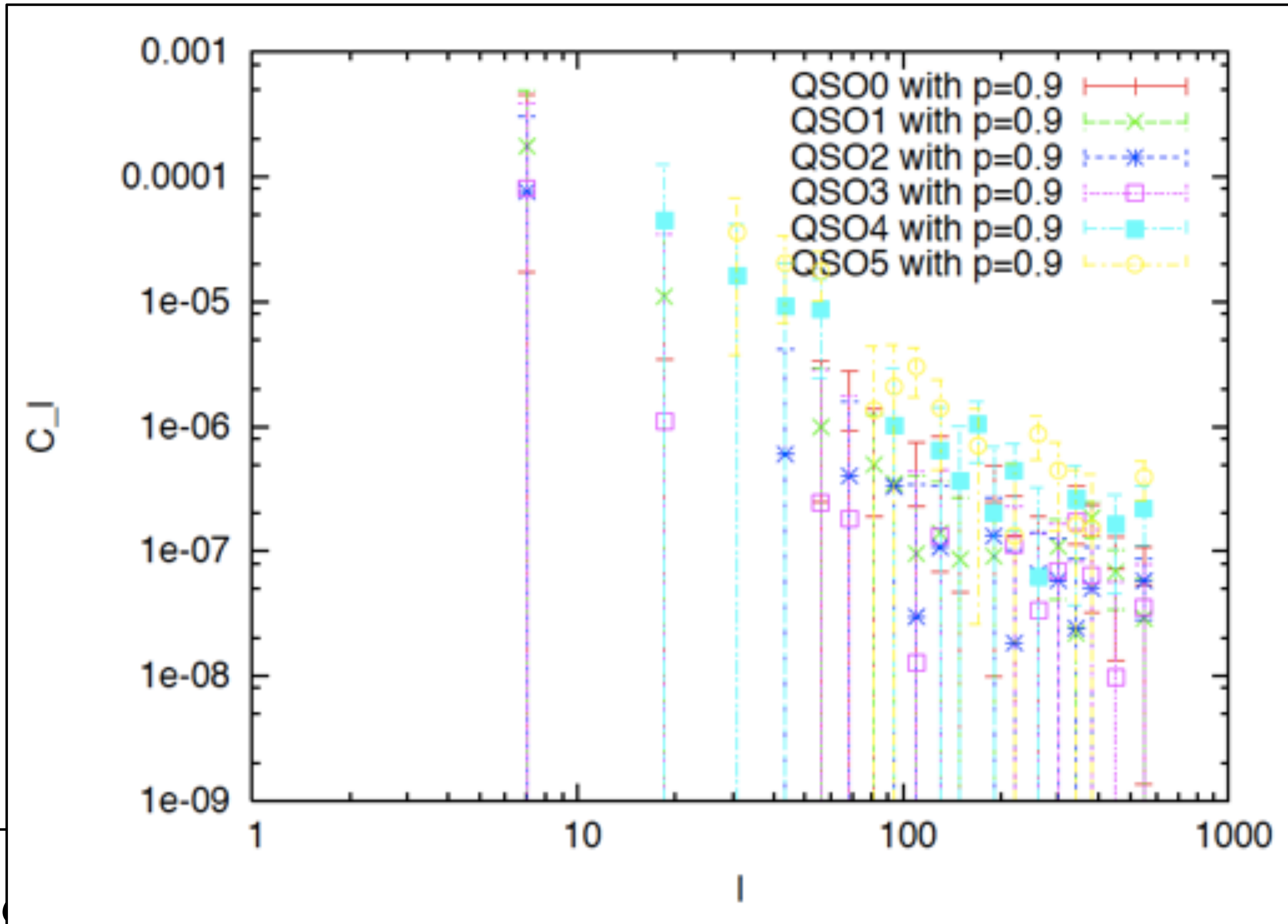
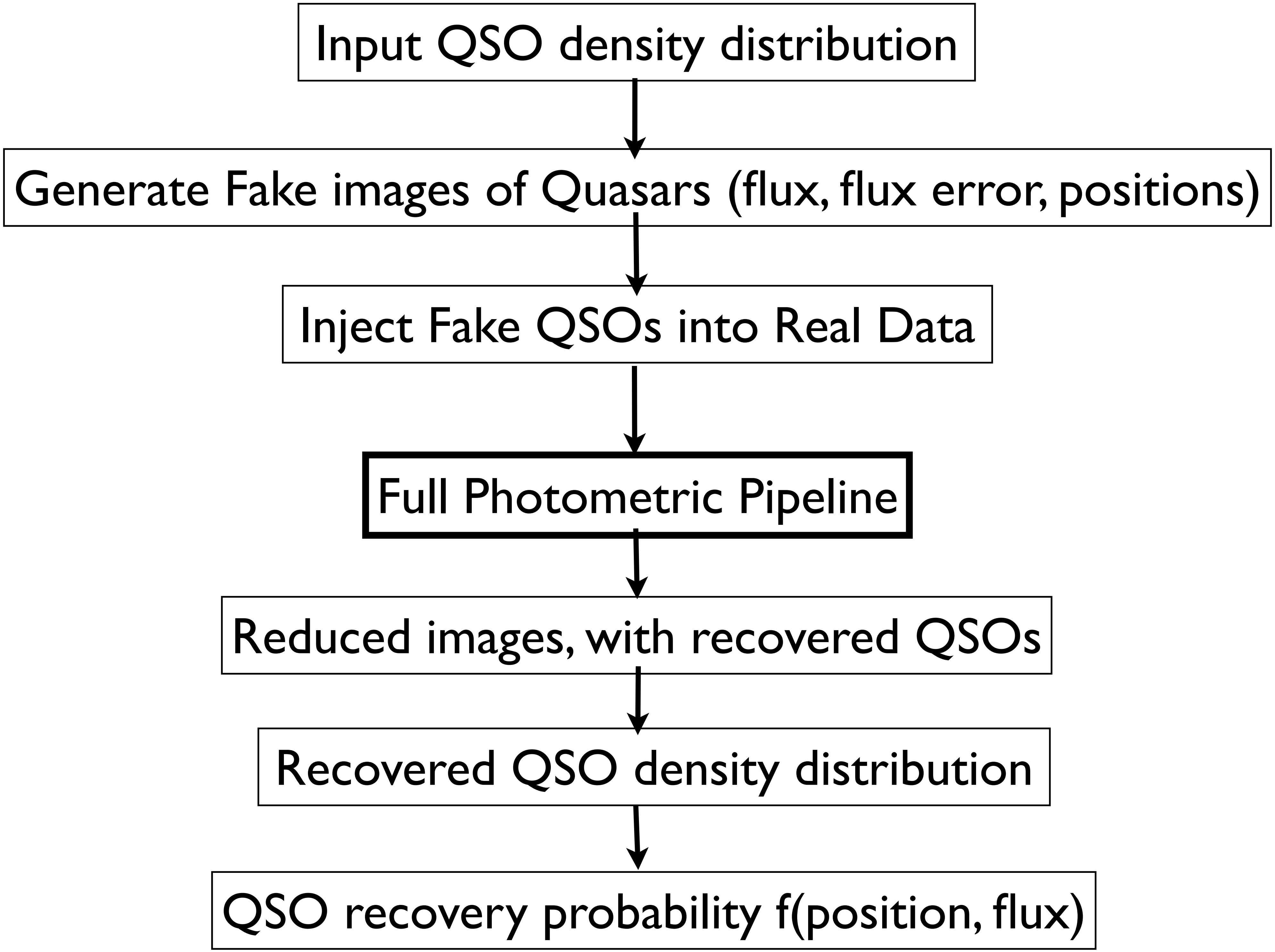
Recall: What we do

Star X QSO



$$C_l^{Q\cdots} = \int d\chi \frac{\cdots}{c} b\cdots(z)(dN/d\chi)\cdots D\cdots(z)P(k = \frac{\cdots 1/2}{\chi})$$


Input QSO density distribution
Generate Fake images of Quasars (flux, flux error, positions)
Inject Fake QSOs into Real Data
Full Photometric Pipeline
Reduced images, with recovered QSOs
Recovered QSO density distribution
QSO recovery probability f(position, flux)

Input QSO density distribution

↓

Generate Fake images of Quasars (flux, flux error, positions)

↓

Inject Fake QSOs into Real Data

Full Pipeline Reconstruction to achieve the correct intrinsic number densities of objects.

↓

Reduced images, with recovered QSOs

↓

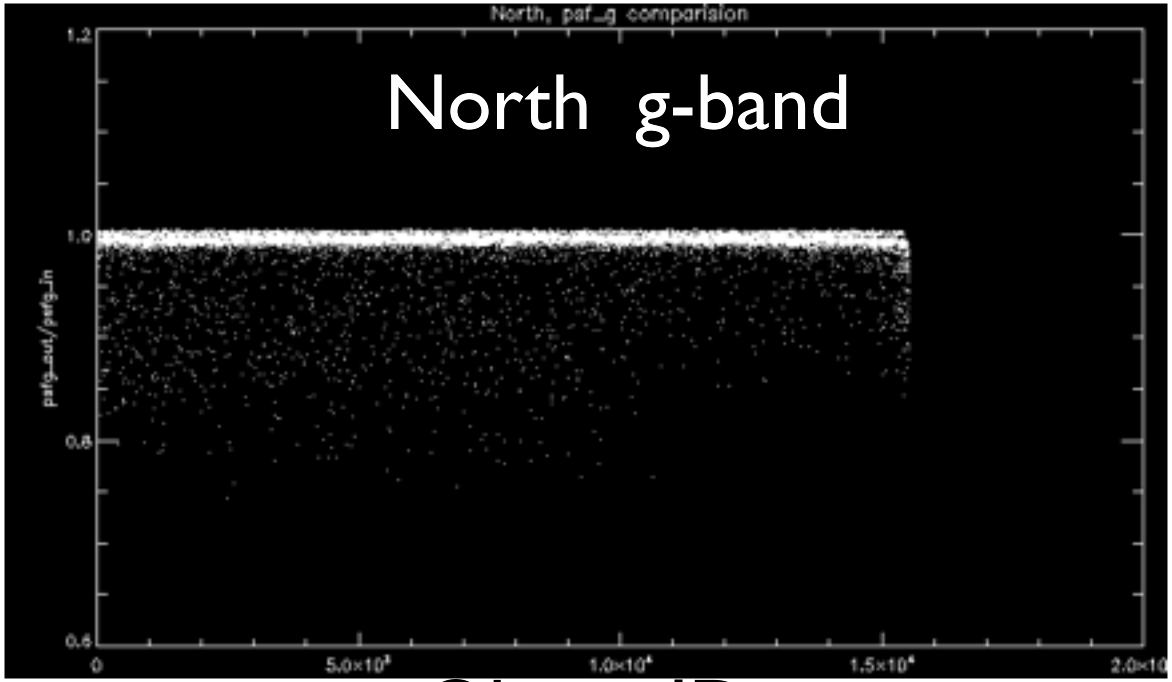
Recovered QSO density distribution

↓

QSO recovery probability f(position, flux)

Comparing the input and output magnitudes

g_out/g_in



Object ID

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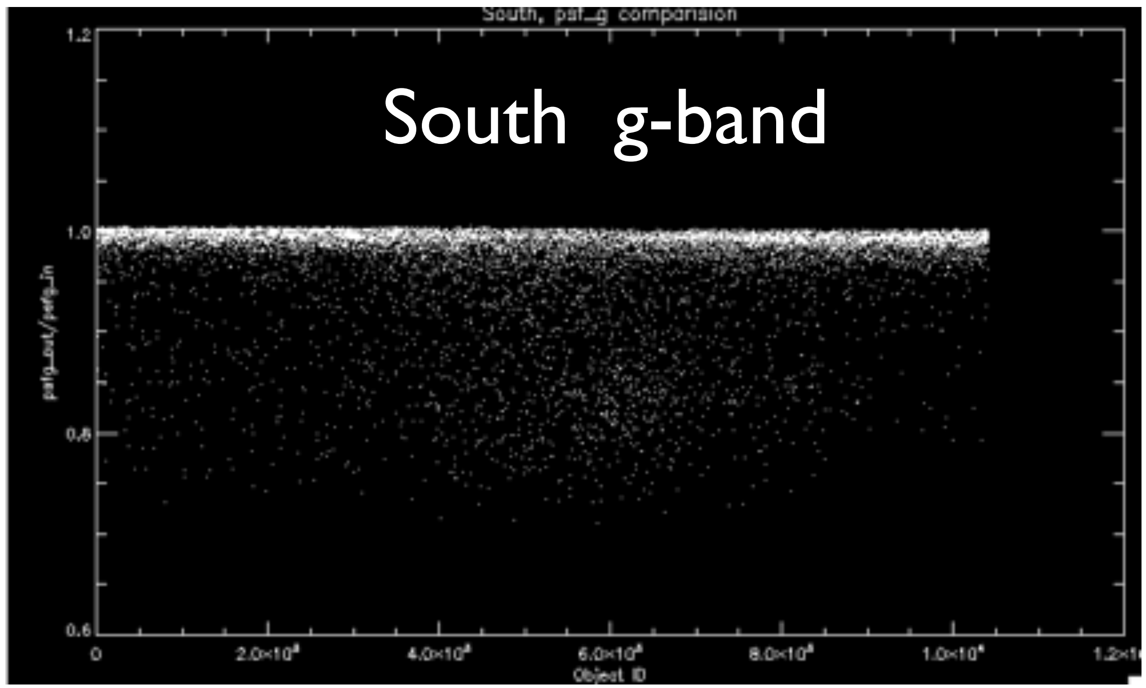
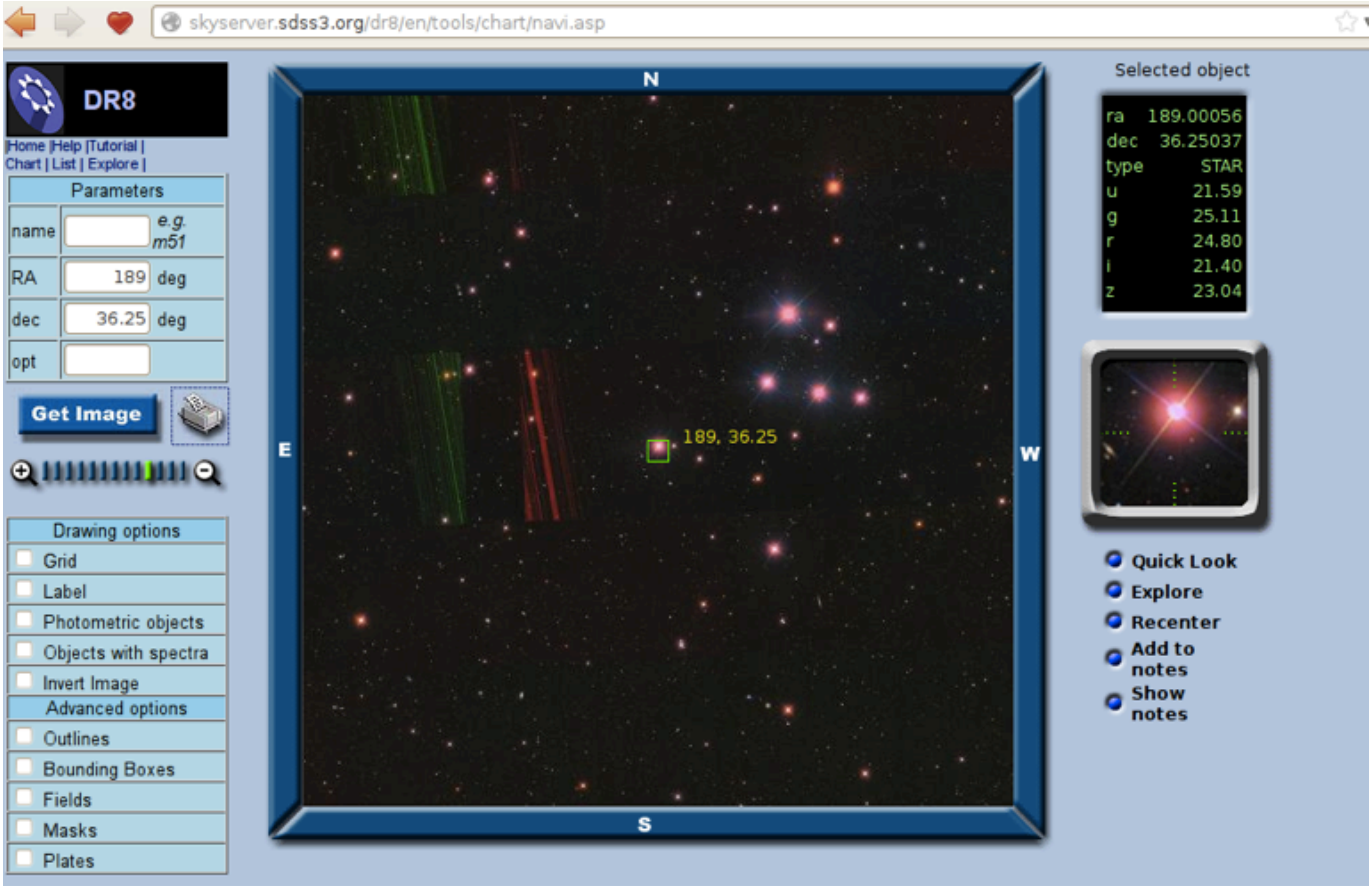


Simulations from Eric Huff,
help from David Schlegel

Other interesting things we found along the way



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Recall: What we do

Berkeley Lab

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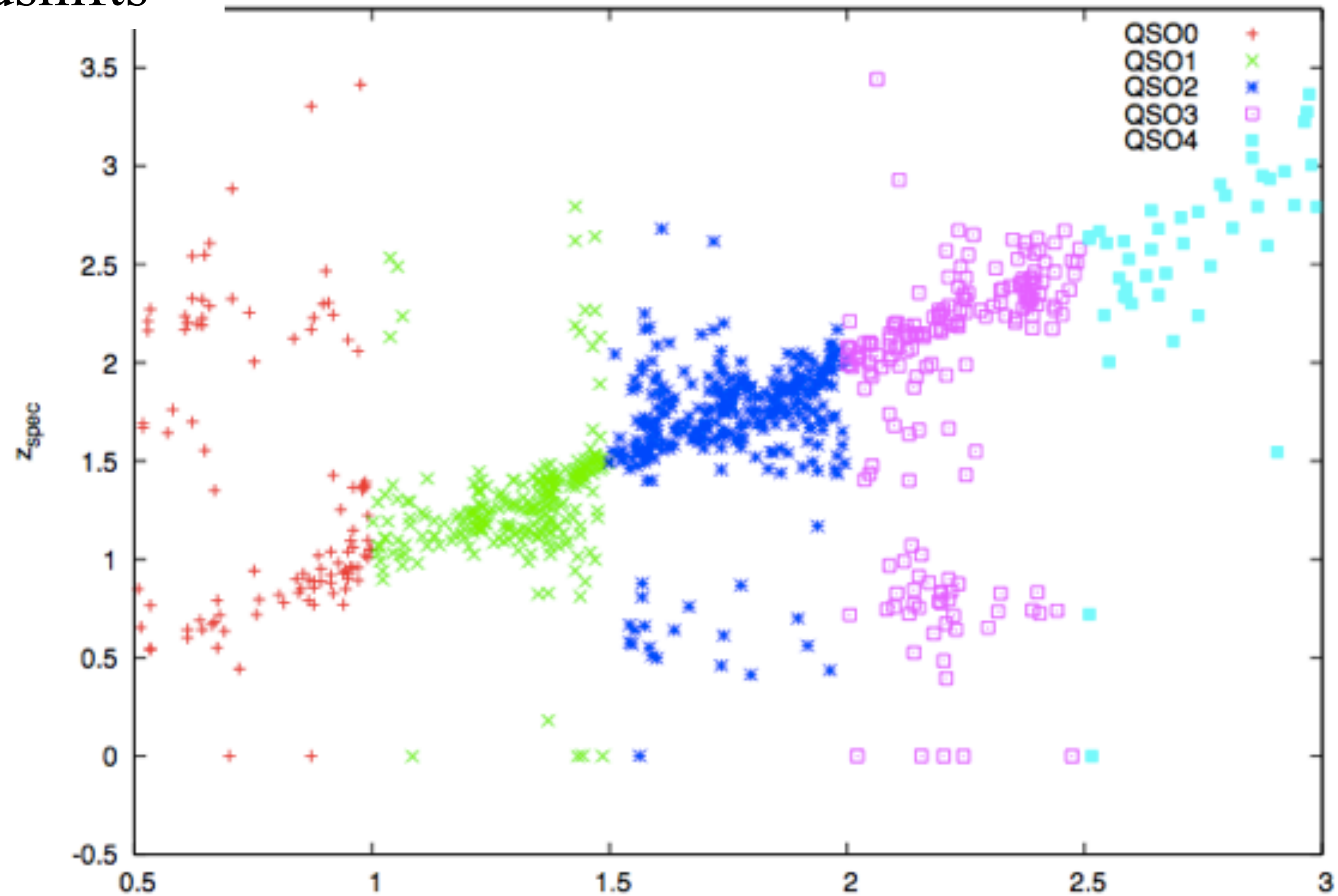
Recall: What we do

Spectroscopic Redshifts

Redshift distributions



Photometric Redshifts

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Systematic Corrections

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Science from Large scale structure samples

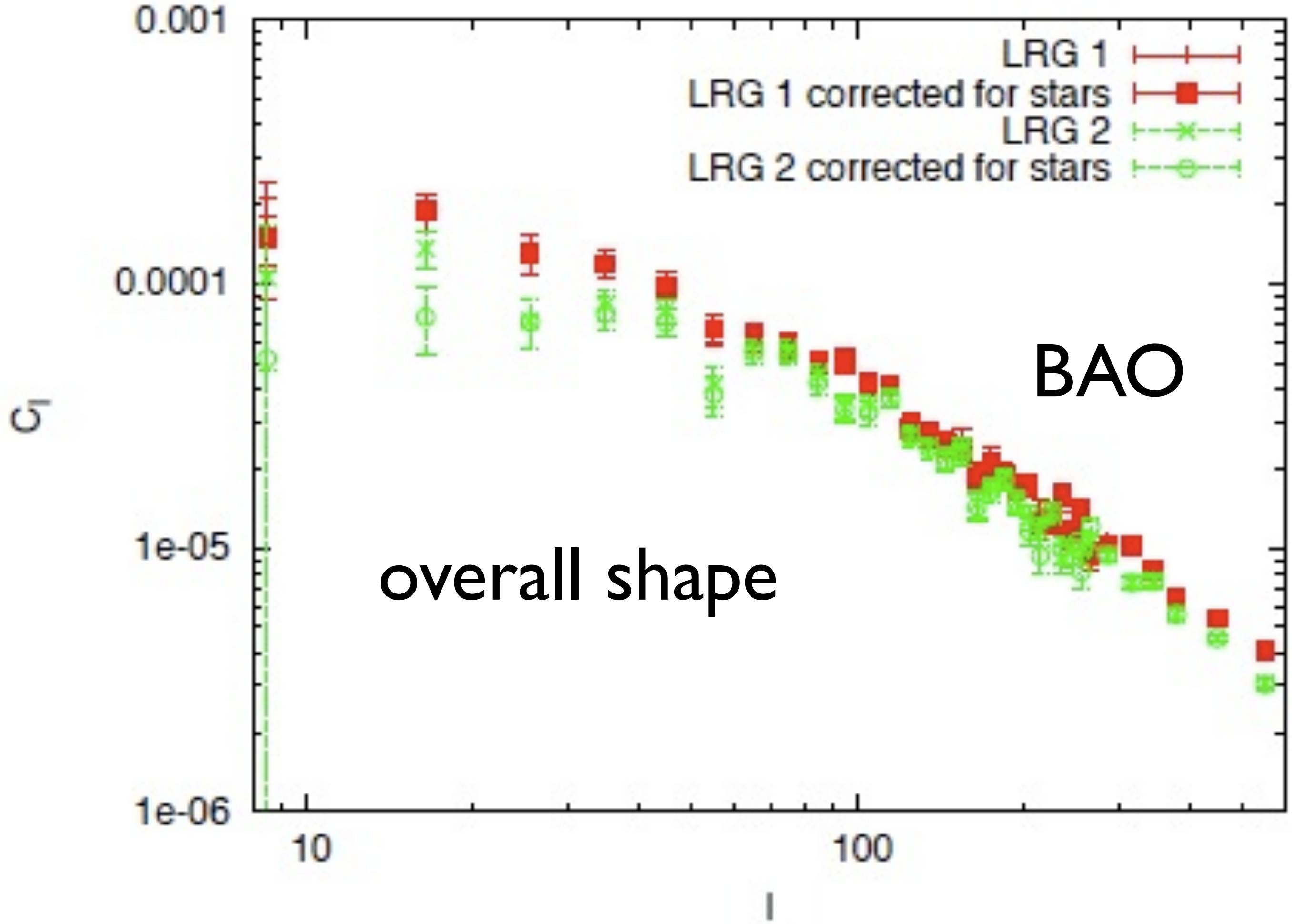
Shirley Ho

Science from Large Scale Structure Galaxy Sample

Learning about contents of Universe from 2D clustering

C_ℓ

Observed 2D clustering vs theory



ℓ

SH, Cuesta, Seo, Ross, DePutter et al. (2012)

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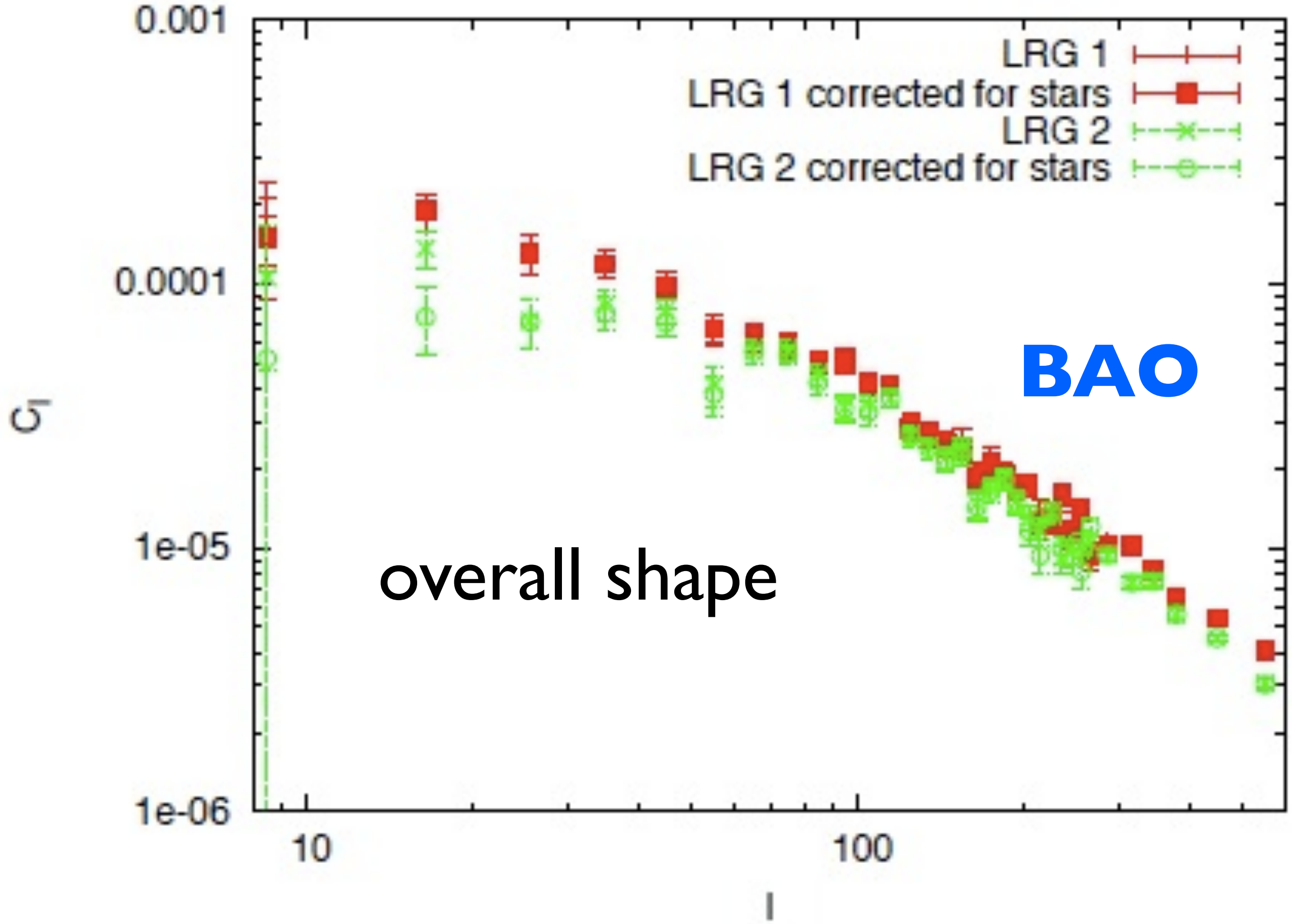
Science from Large Scale Structure Galaxy Sample

Learning about contents of Universe from 2D clustering

C_ℓ

Observed 2D clustering vs theory



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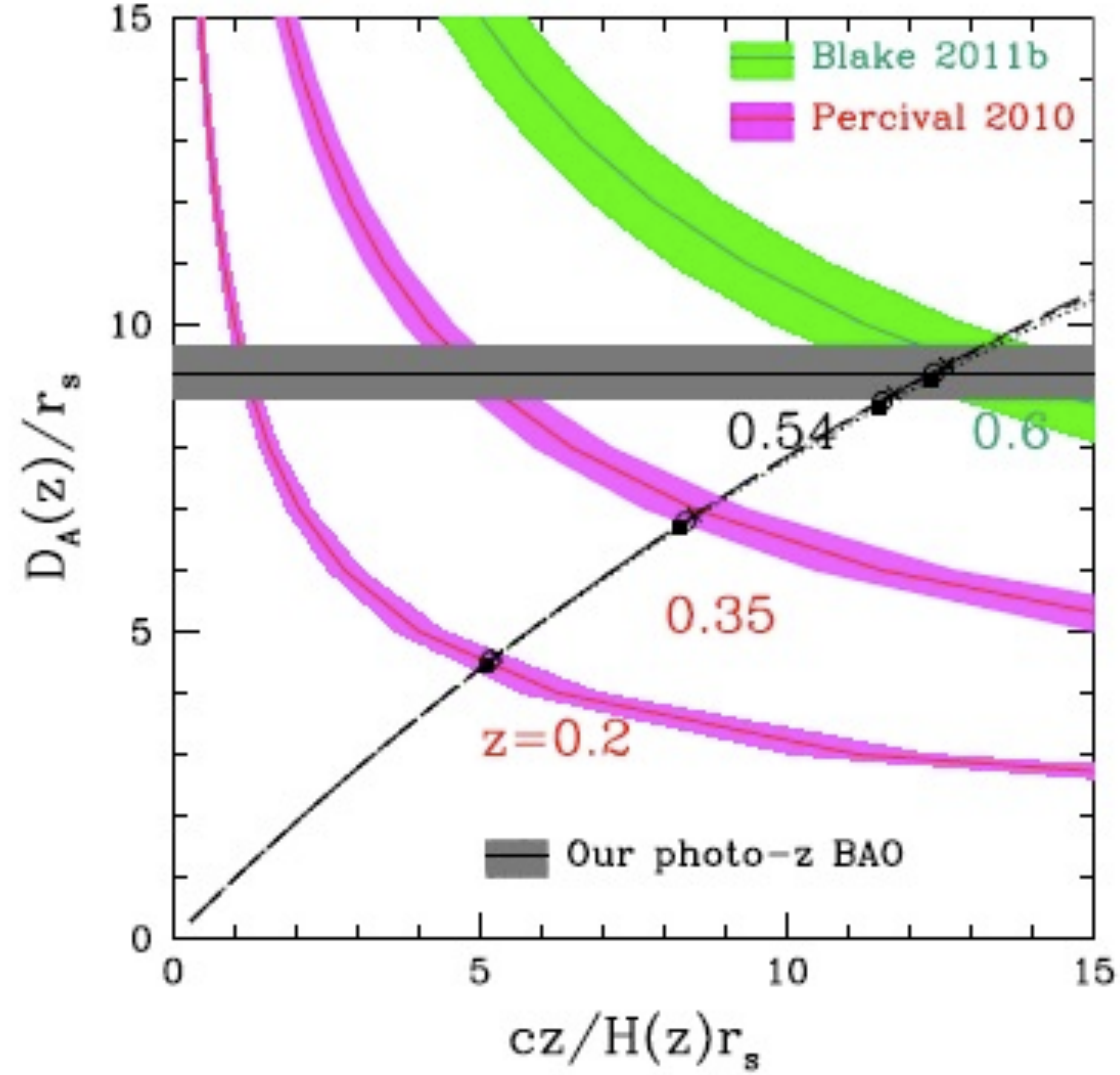
Shirley Ho



Seo, SH, White et al. (2012)

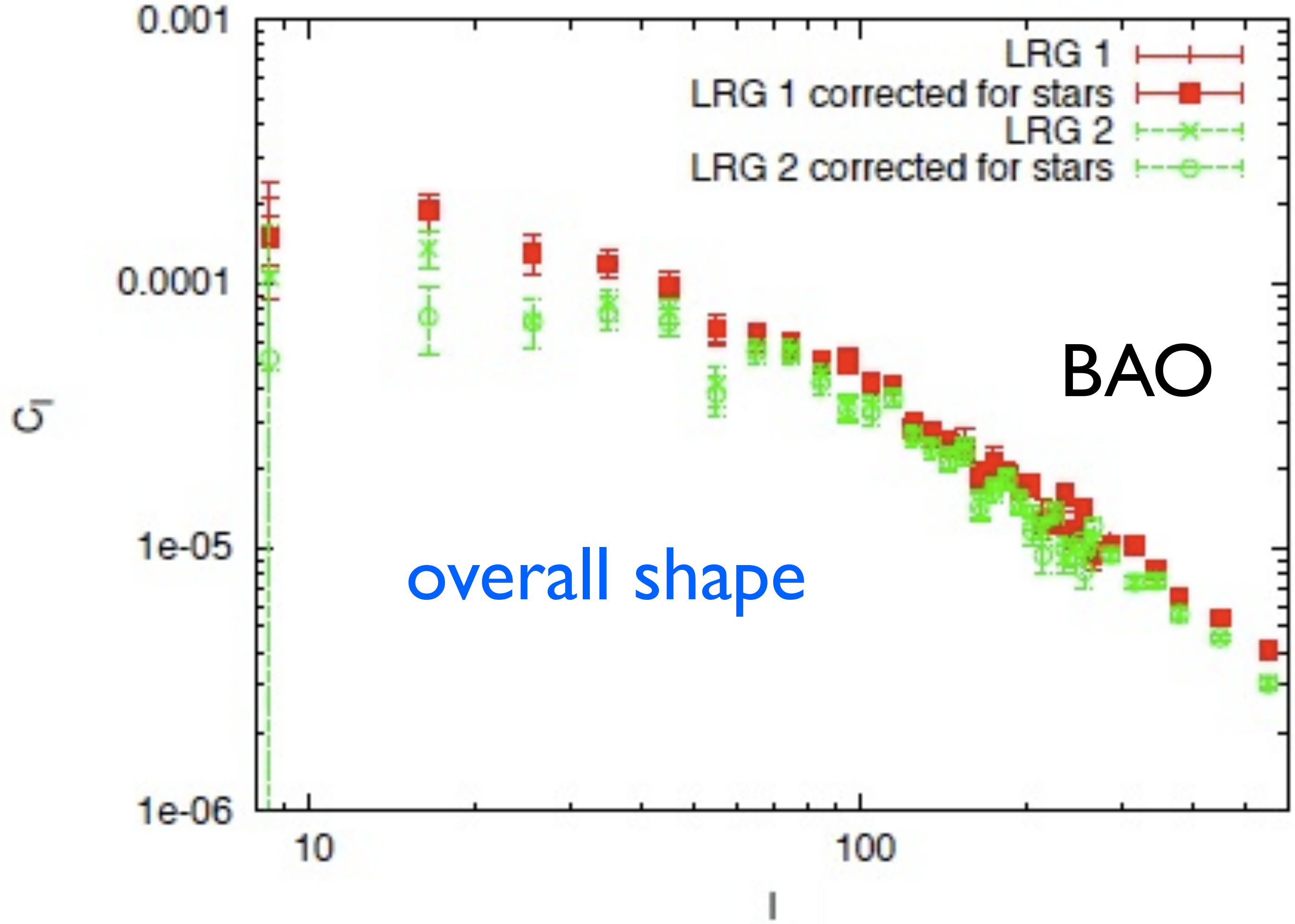
Shirley Ho

Science from Large Scale Structure Galaxy Sample

Learning about contents of Universe from 2D clustering

C_ℓ

Observed 2D clustering vs theory

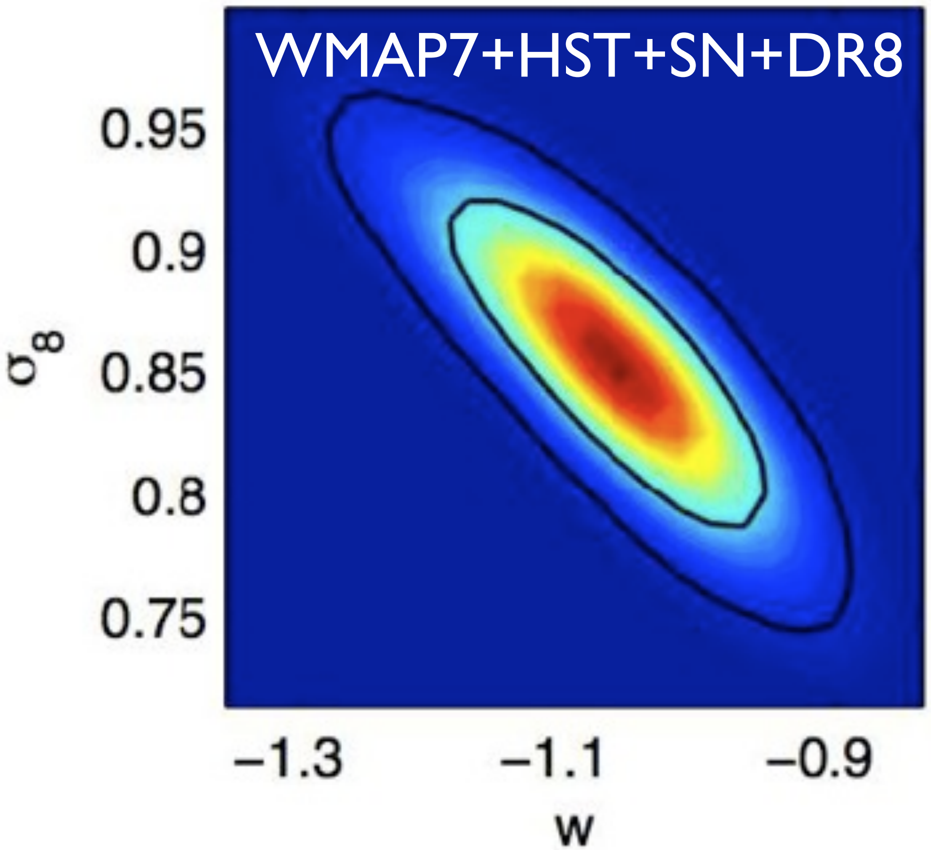


ℓ

SH, Cuesta, Seo, Ross, DePutter et al. (2012)

Shirley Ho

Cosmological Constraints from the overall shape



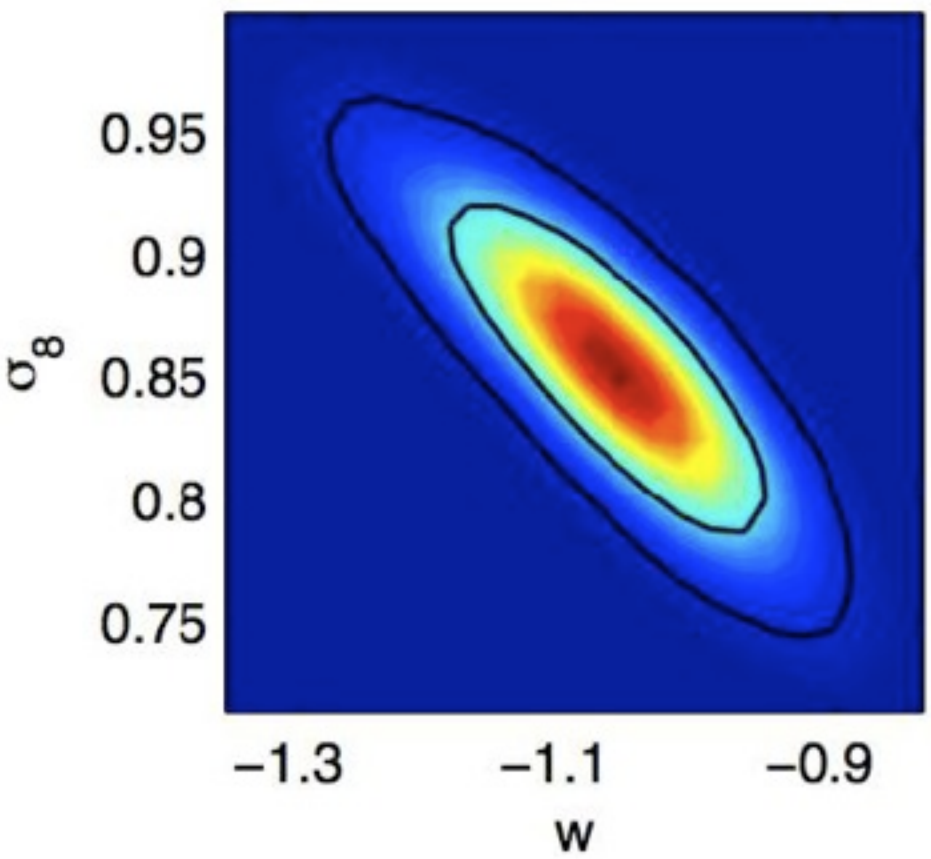
Combining with WMAP7+SN+HST, Dark Energy equation of state is constrained to 7% (1-sigma), which is competitive to the latest large scale structure measurement such as WiggleZ (when it is combined with the same datasets).

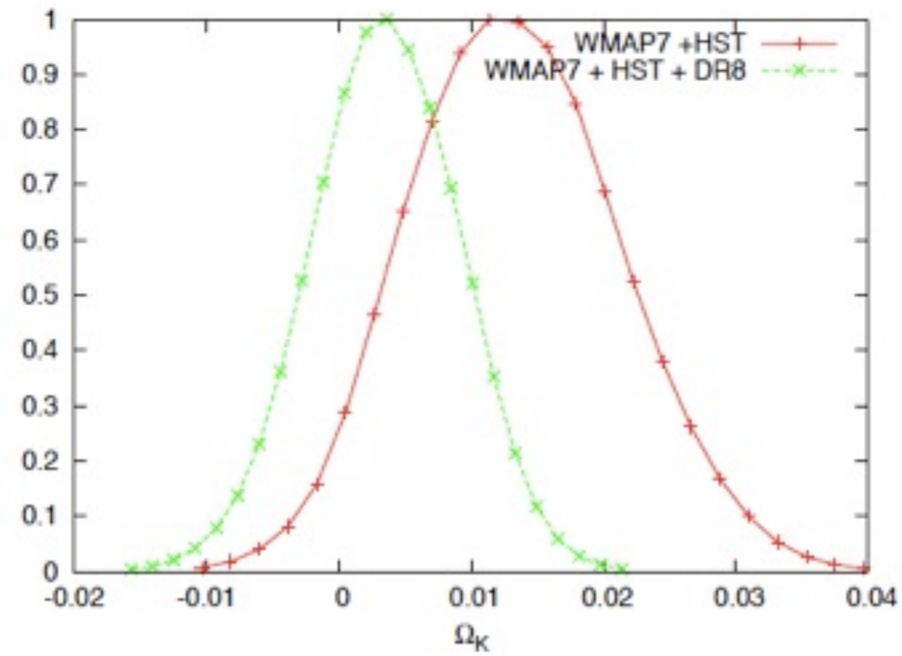
SH, Cuesta, Seo, Ross, DePutter et al. (2012)

SDSS III

Shirley Ho

Cosmological Constraints from the overall shape





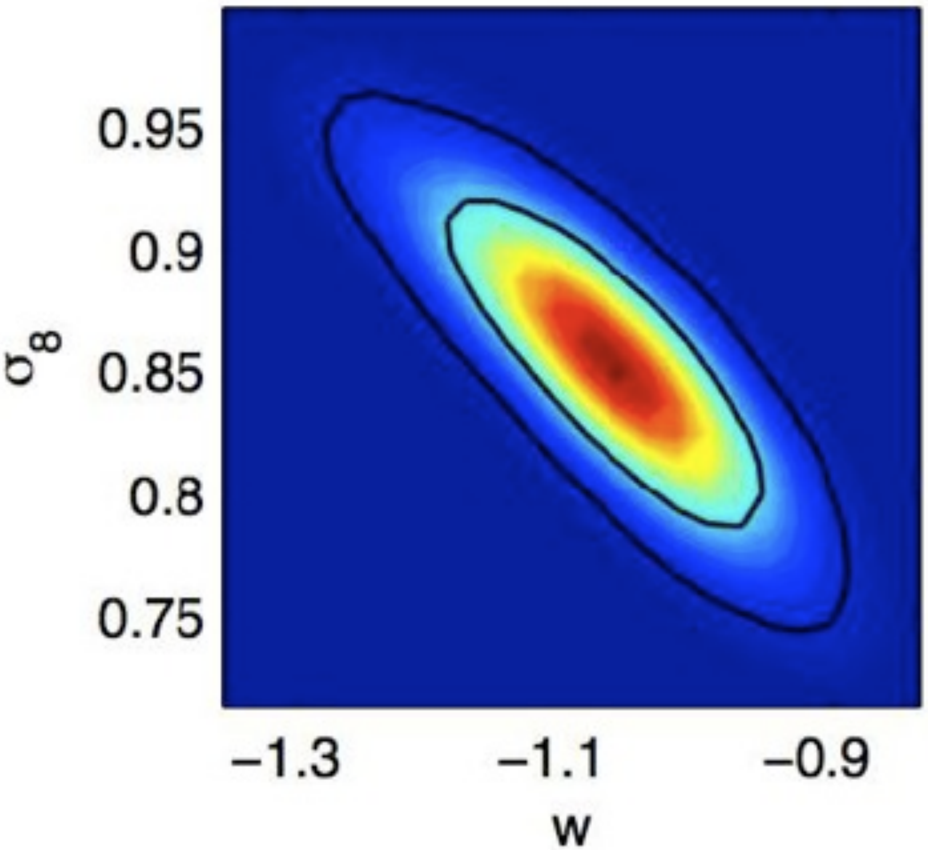
By including DR8 angular clustering (+WMAP+HST), we improve the constraint on flatness of the Universe by 40% over WMAP7+HST

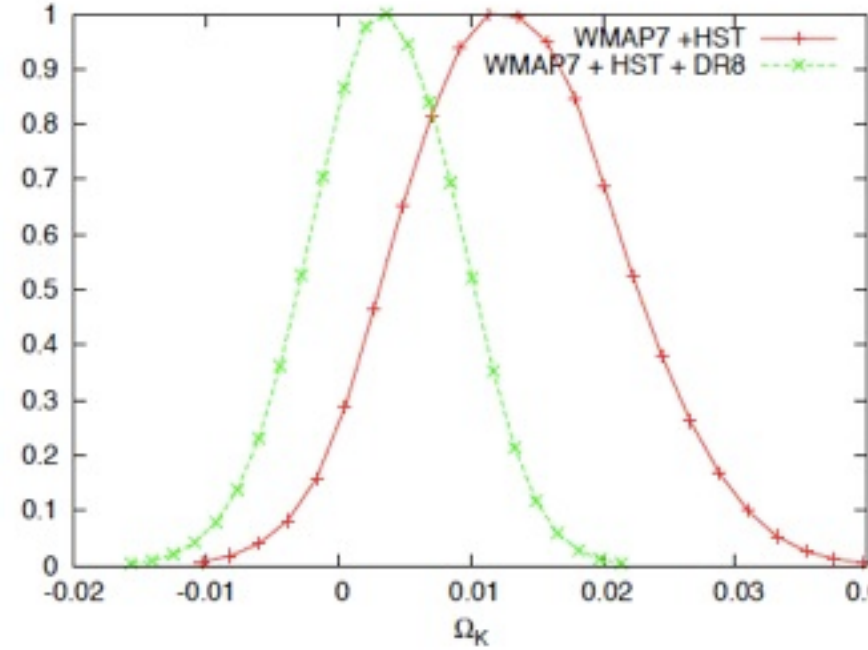
SH, Cuesta, Seo, Ross, DePutter et al. (2012)

SDSS III

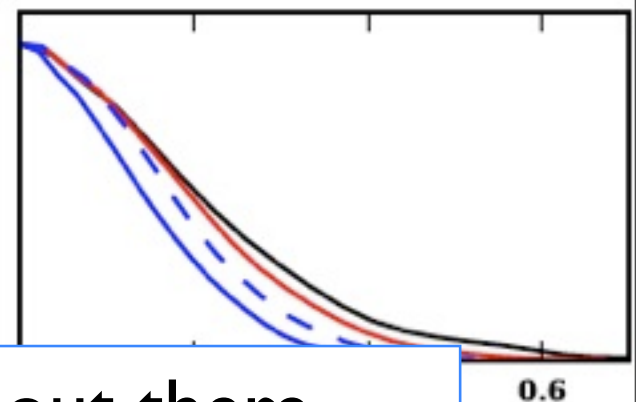
Shirley Ho

Cosmological Constraints from the overall shape





The sum of neutrino masses is constrained to less than 0.26eV



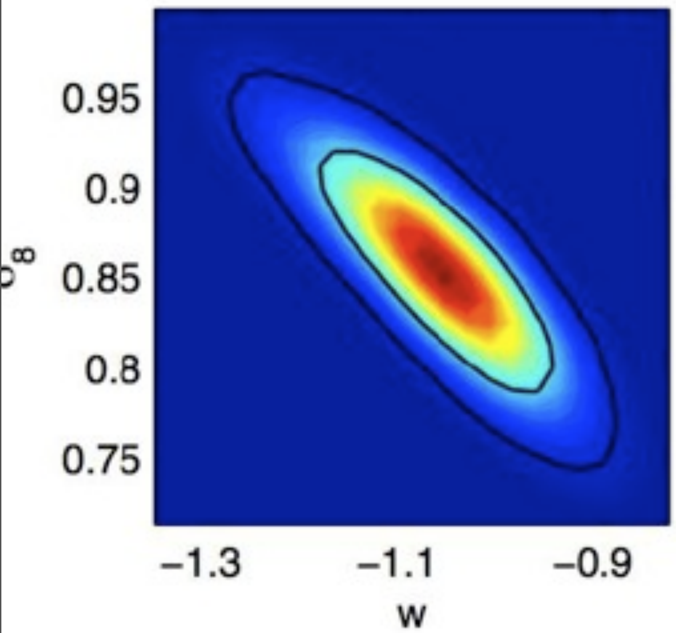
Most Stringent Neutrino mass constraint out there

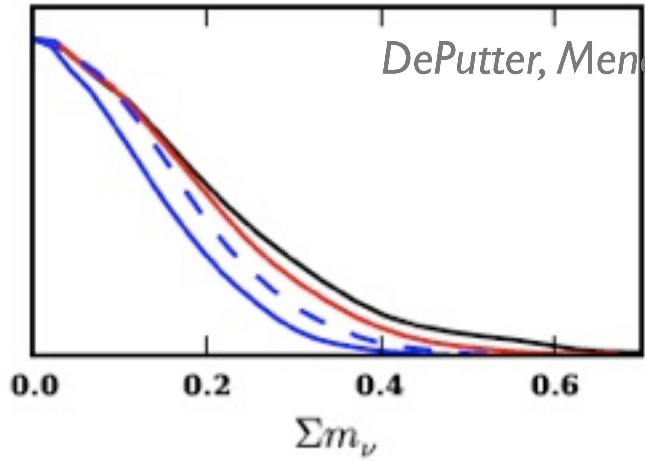
SDSS III

DePutter, Mena, Guisarma, SH, Seo et al. (2012)
SH, Cuesta, Seo, Ross, DePutter et al. (2012)

Shirley Ho

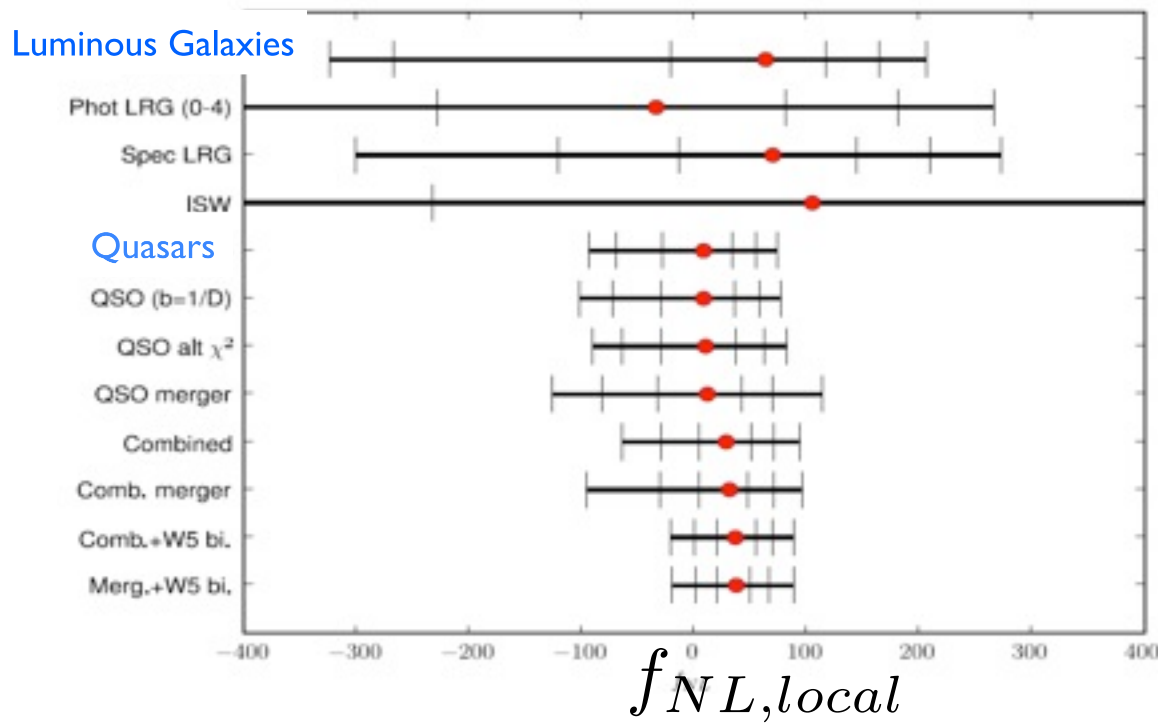
Cosmological Constraints from the overall shape

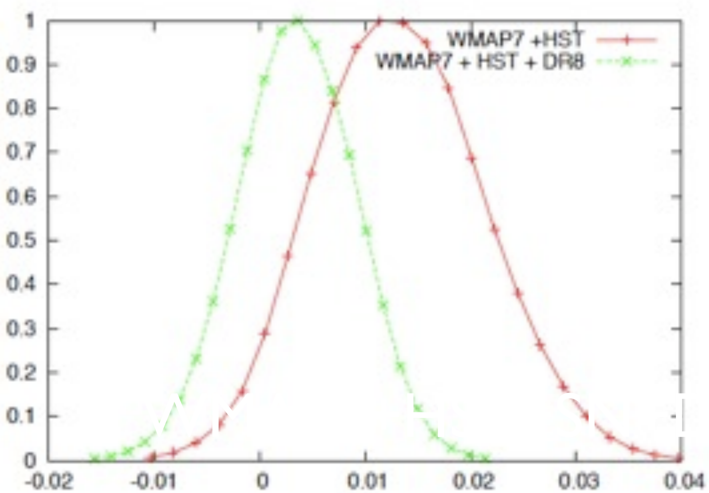




DePutter, Mena, Guisarma, SH, Seo et al. (2012)

New preliminary constraints (3-sigma) Constraints on early Universe via primordial non-gaussianities





SDSSIII

SH, Myers, Slosar et al. (in prep)

SH, Cuesta, Seo, Ross, DePutter et al. (2012)

Shirley Ho

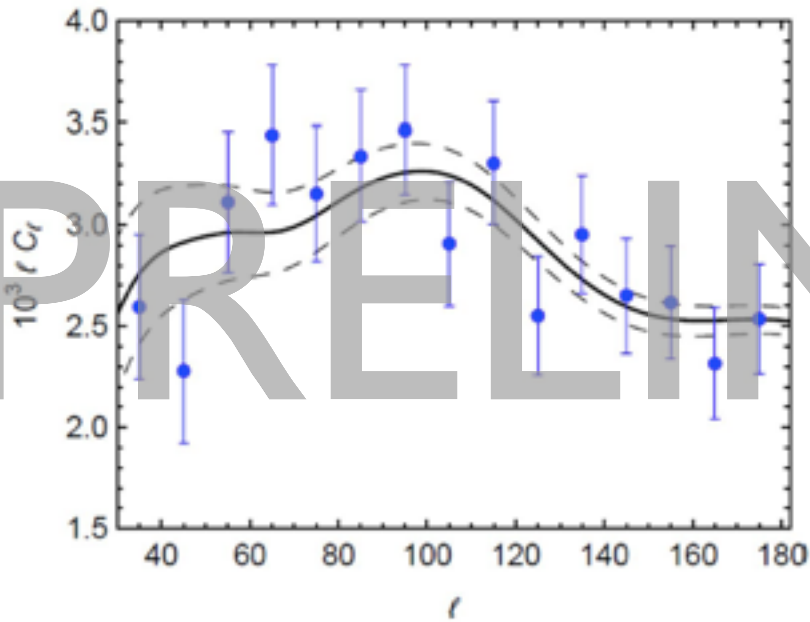
PRELIMINARY results from 1 LRG sample + 2 QSO samples (*Before* full pipeline corrections)

$$\Phi(\mathbf{k}) = \Phi_G(\mathbf{k}) + f_{\rm NL}\left[\Phi_G^2(\mathbf{k}) - \langle\Phi_G^2(\mathbf{k})\rangle\right]$$

$$\Delta b(M,k,z,f_{\rm NL}) \propto f_{\rm NL}^{\rm eff}(M)/k^{\alpha}$$

LRGs

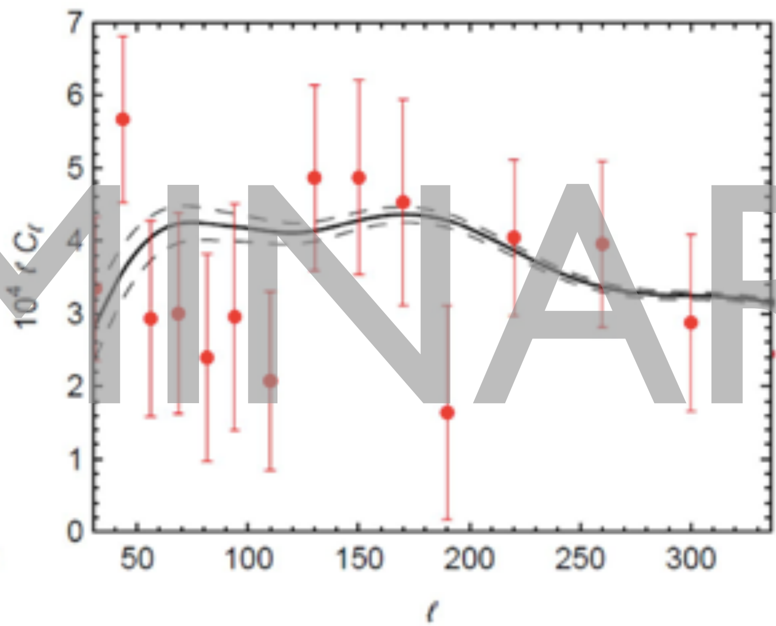
$0.55 < z < 0.60$



$-155 < f_{NL,local} < 94$

(Uncorrected) QSOs

$1.0 < z < 1.5$



$10 < f_{NL,local} < 70$

$-1 < f_{NL,local} < 61$

95% CL

PRELIMINARY

SDSS III

SH, Myers, Slosar et al. (in prep)

Agarwal, SH, Shandera et al. (in prep)

Shirley Ho

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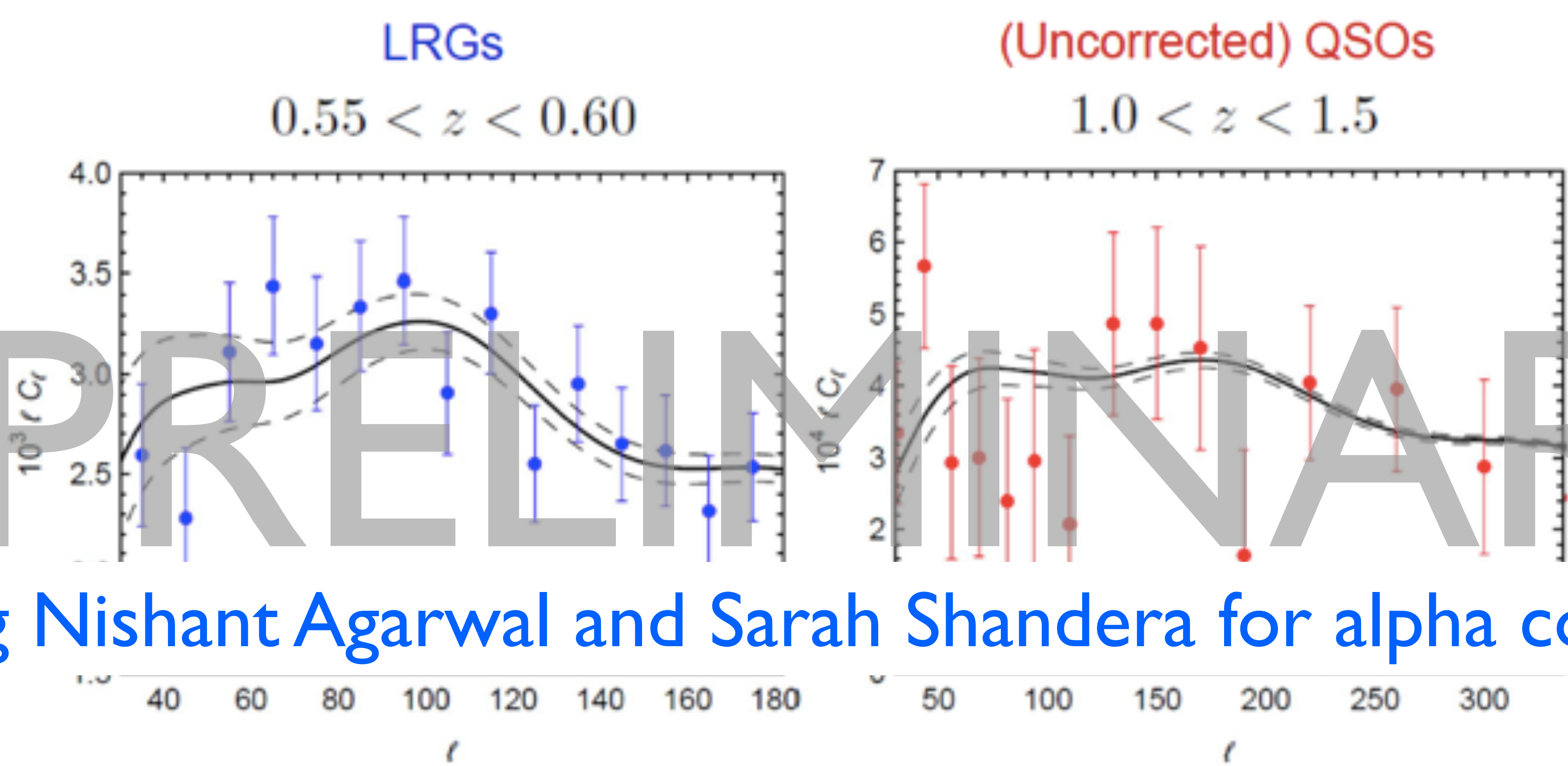

Bug Nishant Agarwal and Sarah Shandera for alpha constraints!

$$-155 < f_{NL,local} < 94$$

$$10 < f_{NL,local} < 70$$

$$-1 < f_{NL,local} < 61$$

95% CL

SH, Myers, Slosar et al. (in prep) *Agarwal, SH, Shandera et al. (in prep)*

SDSS III

Shirley Ho

But we don’t stop here!

- Other datasets we are working on:
    - Cross-correlating QSO and Lyman Alpha Forest!
        - Large volume, relatively high signal, large overlap between the two tracers’ redshift ranges.
    - Lya X Lya in BOSS
        - smaller signal, but opposite signal (than usual)
    - Different color selections on photometric QSOs to see if the extra power is still there: bluer vs redder QSOs.

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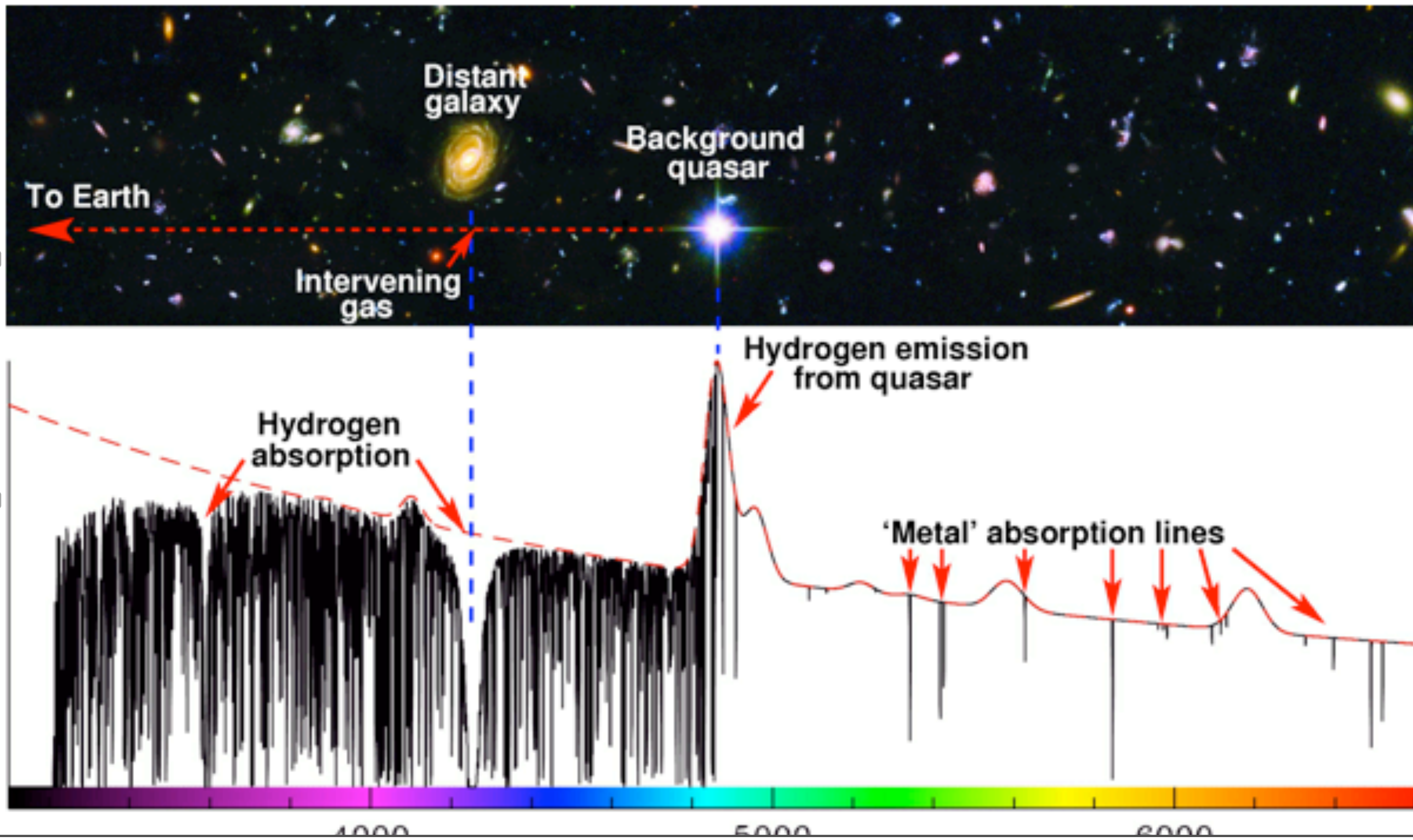
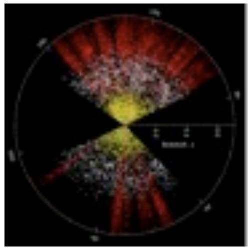


SDSS III - BOSS
Baryon Oscillation Spectroscopic Survey

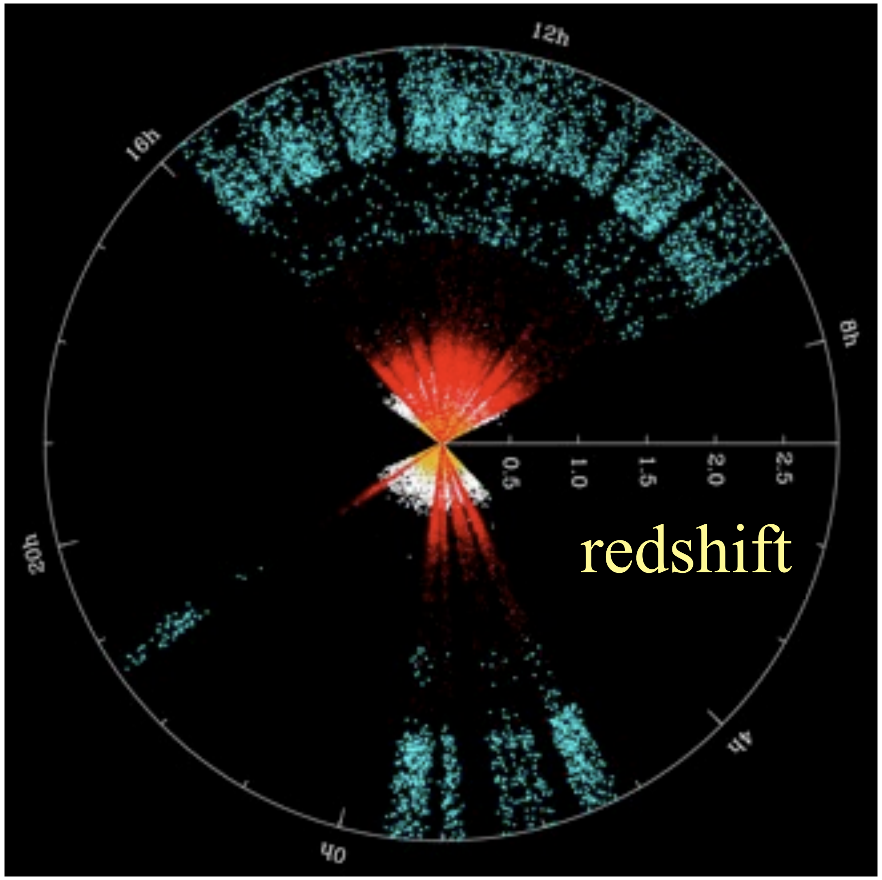
Volume of the Universe probed by SDSS I-II spectroscopy



SDSS DR7 Main Galaxies

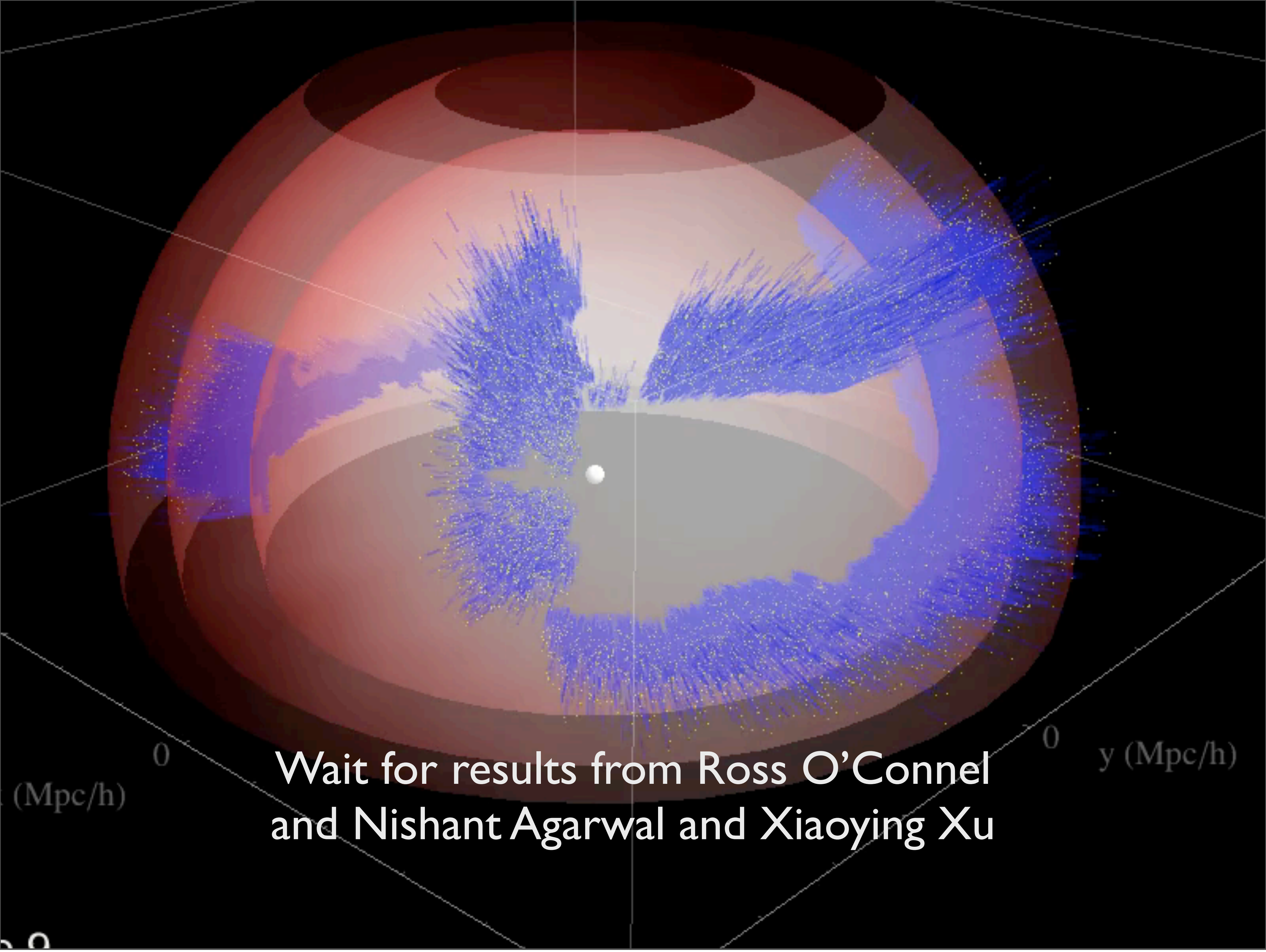
SDSS DR7-LRGs

Volume of the Universe probed by BOSS



BOSS CMASS (LRG)

BOSS QSOs



Wait for results from Ross O'Connel
and Nishant Agarwal and Xiaoying Xu

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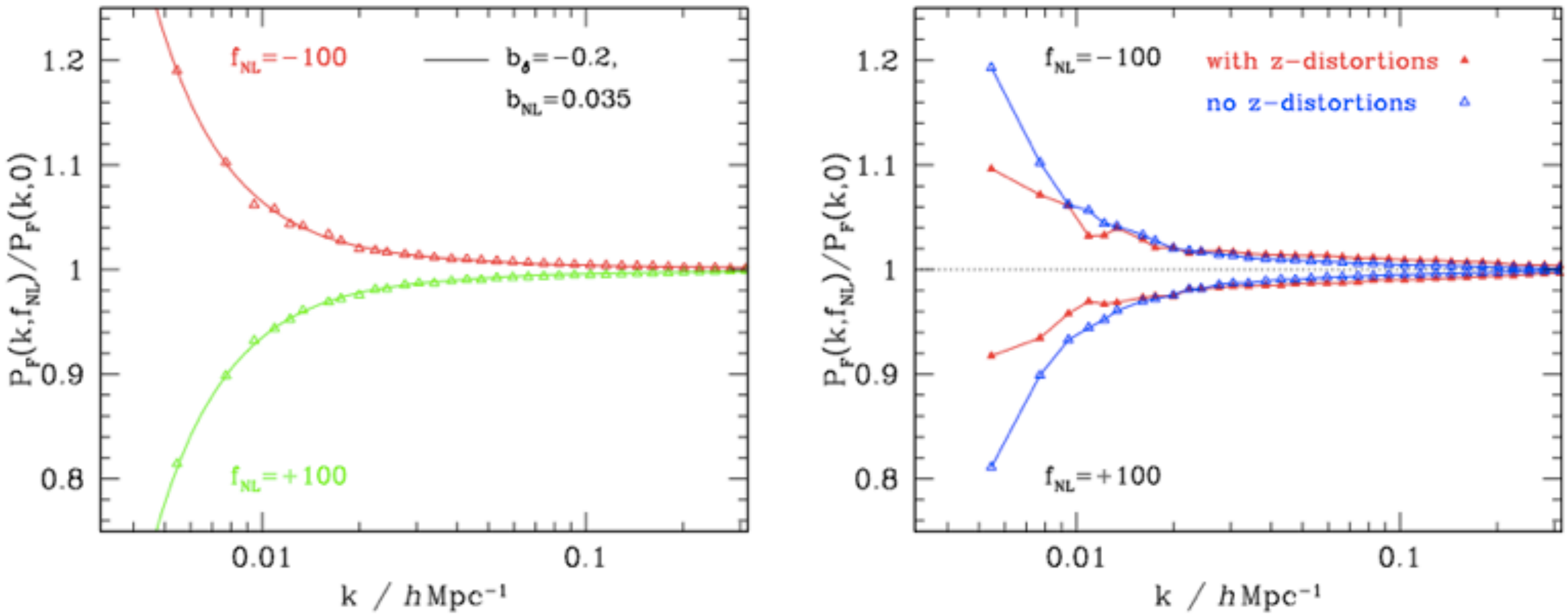


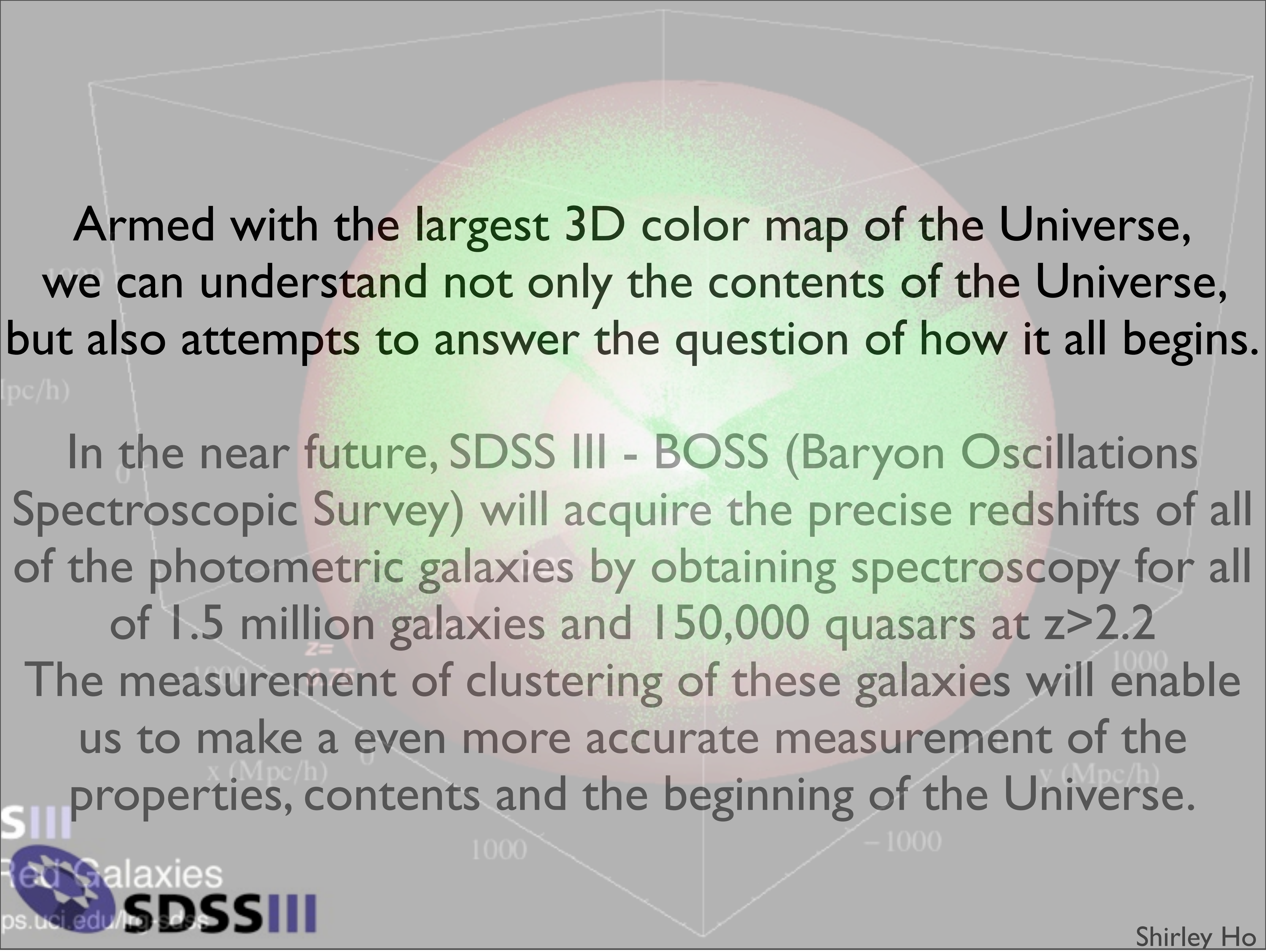
QSOs.

Ho, Desjacques, Seljak (in prep)

Armed with the largest 3D color map of the Universe,
we can understand not only the contents of the Universe,
but also attempts to answer the question of how it all begins.

In the near future, SDSS III - BOSS (Baryon Oscillations Spectroscopic Survey) will acquire the precise redshifts of all of the photometric galaxies by obtaining spectroscopy for all of 1.5 million galaxies and 150,000 quasars at z>2.2

The measurement of clustering of these galaxies will enable us to make a even more accurate measurement of the properties, contents and the beginning of the Universe.



Shirley Ho

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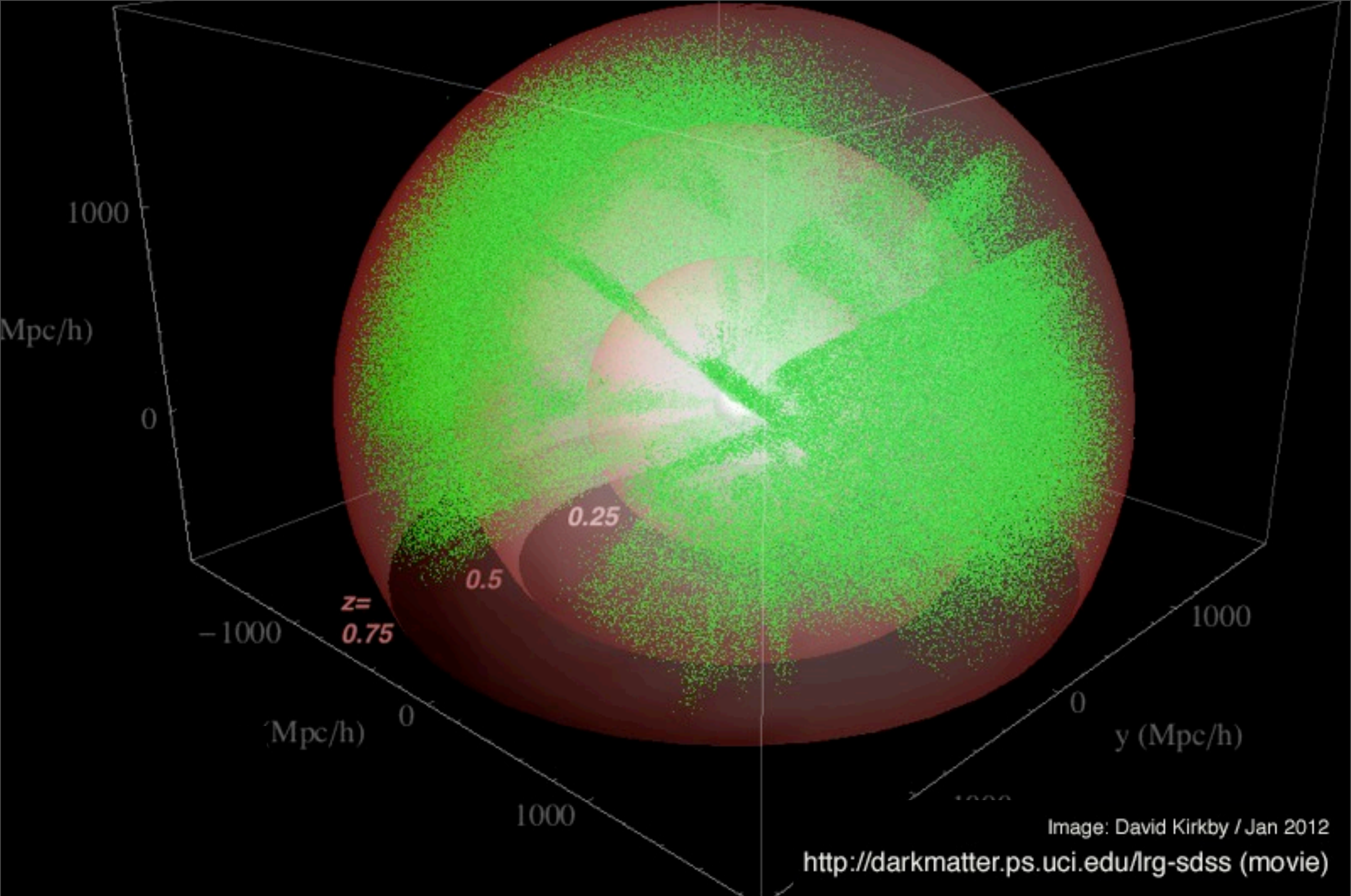
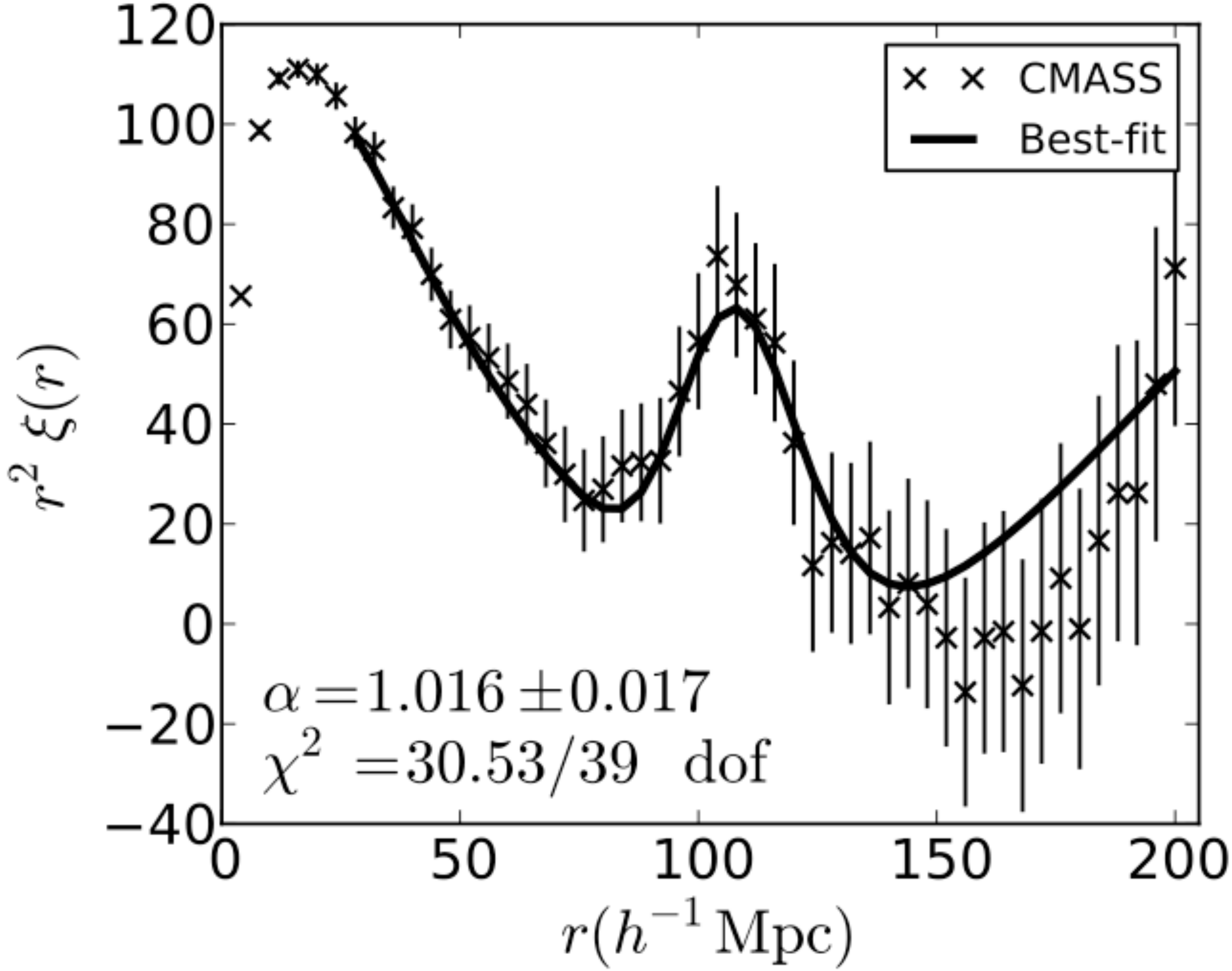
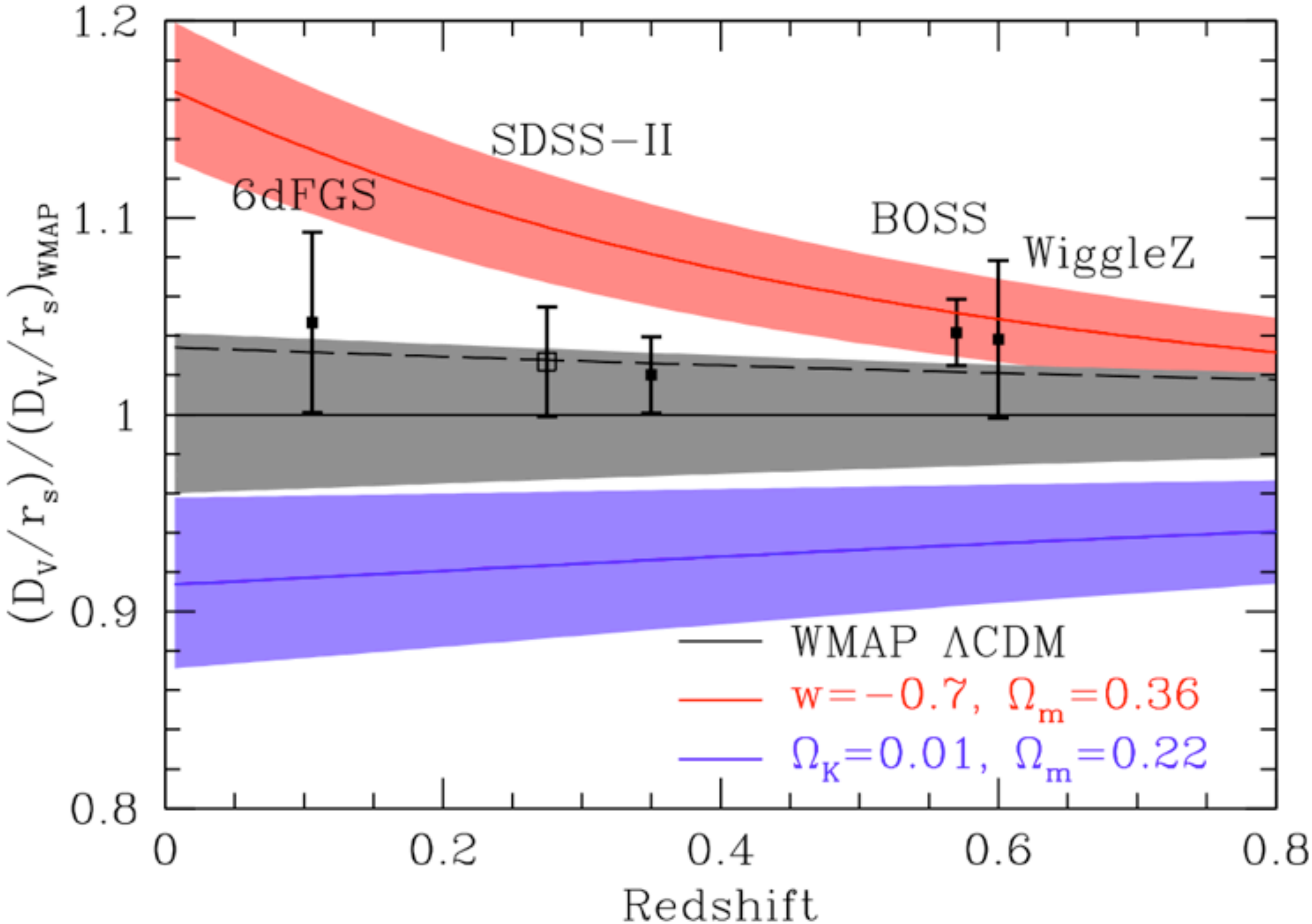


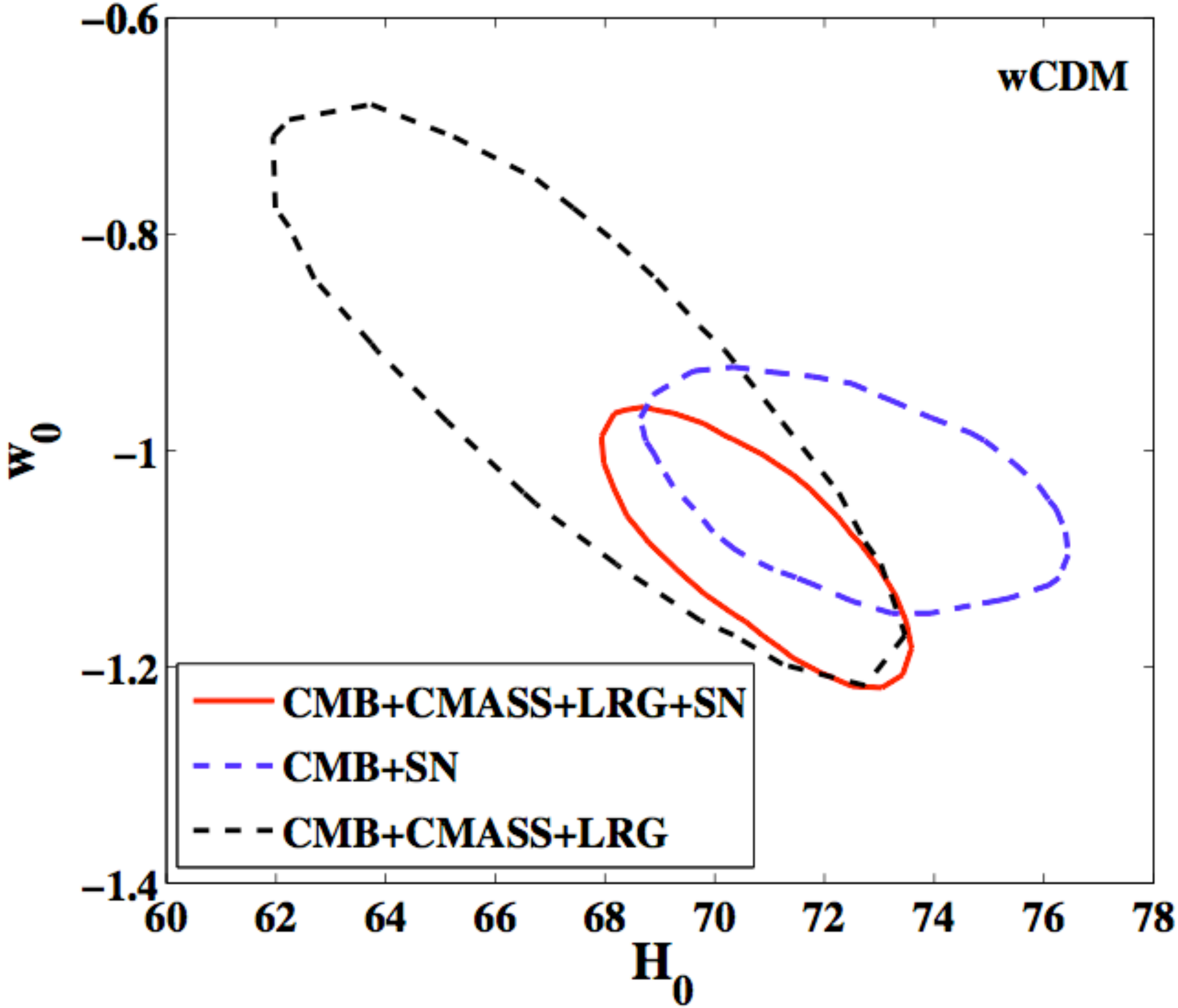
Thursday, November 8, 12

With only 1/3 of spectroscopic data from SDSS III:





1.2
1.1
1
0.9
0.8
0
0.2
0.4
0.6
0.8
Redshift
$(D_V/r_s)/(D_V/r_s)_{WMAP}$
SDSS−II
6dFGS
BOSS
WiggleZ
WMAP ΛCDM
$w=-0.7,\ \Omega_m=0.36$
$\Omega_K=0.01,\ \Omega_m=0.22$


wCDM
−0.6
−0.8
−1
−1.2
−1.4
60
62
64
66
68
70
72
74
76
78
w_0
H_0
CMB+CMASS+LRG+SN
CMB+SN
CMB+CMASS+LRG

Wait... what about
the beginning of the Universe?

Non-Gaussianities in early Universe

parameterize how much non-linear corrections are there to the potential

$$\Phi = \phi + f_{NL}\phi^2$$

Primordial potential (assumed to be gaussian random field)

Non-Gaussianity from Inflation

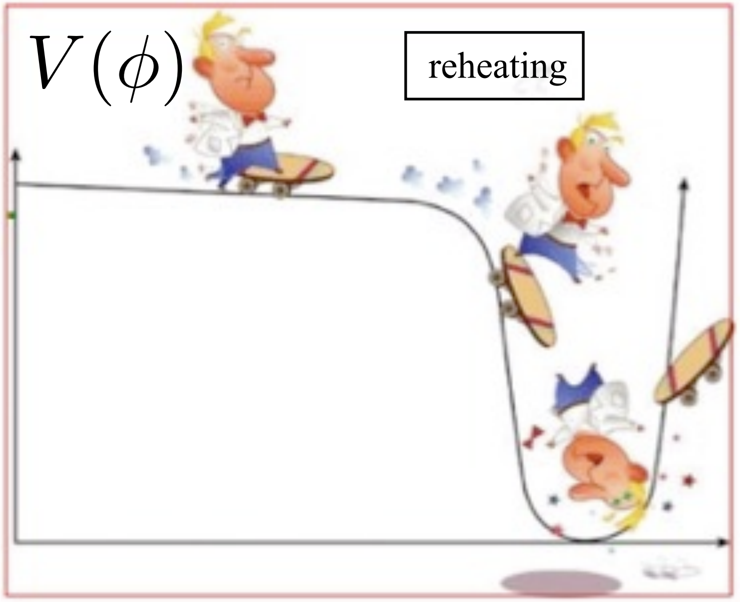
f_{NL} ~ 0.05 canonical inflation (single field, couple of derivatives) (Maldacena 2003, Acquaviva etal 2003)

f_{NL} ~ 0.1--100 higher order derivatives

- DBI inflation (Alishahiha, Silverstein and Tong 2004)
- UV cutoff (Craminelli 2003)

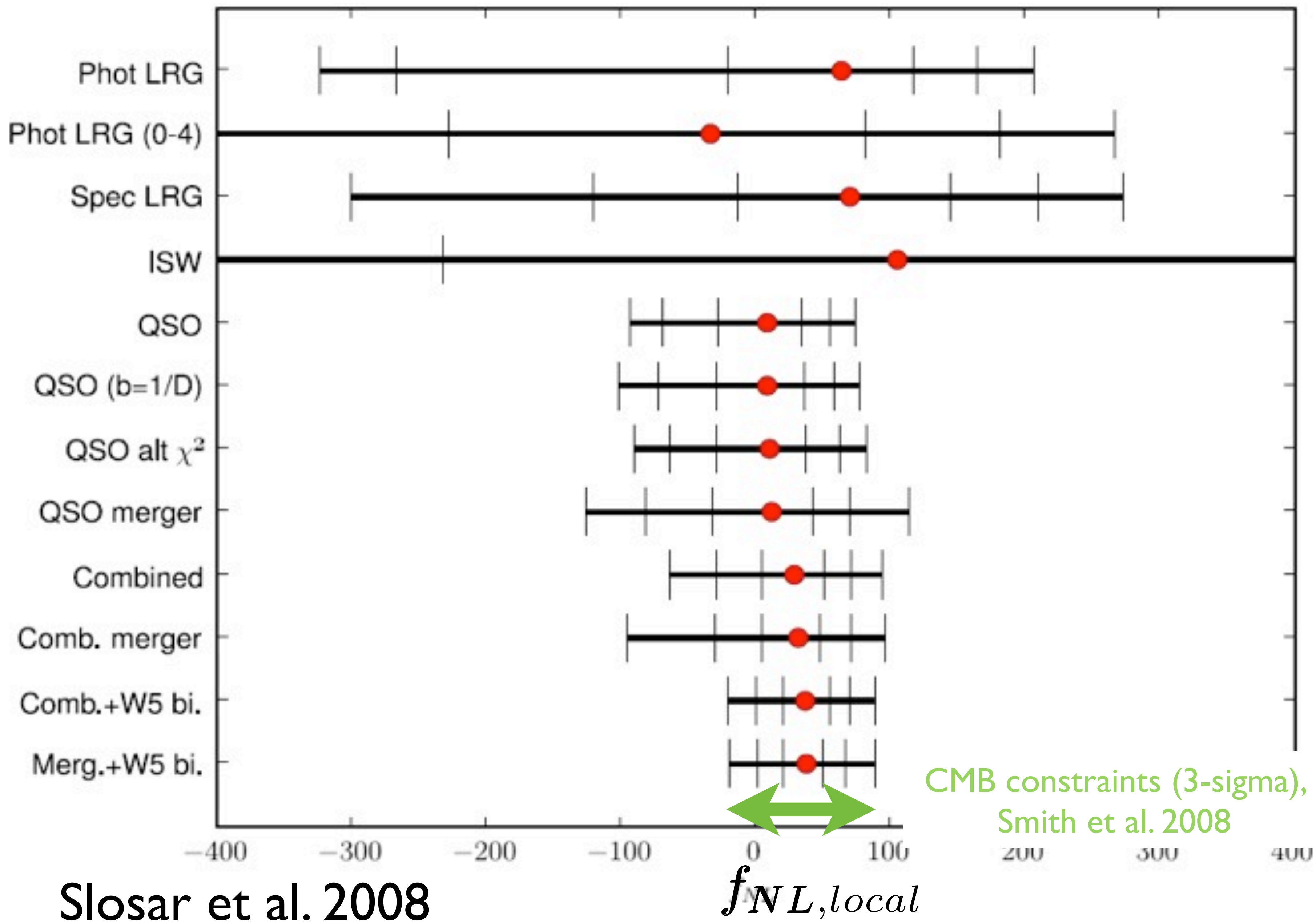
f_{NL} >10 curvaton models (Lyth, Ungarelli and Wands, 2003)

f_{NL} ~100 ghost inflation (Arkani-Hamed et al., 2004)



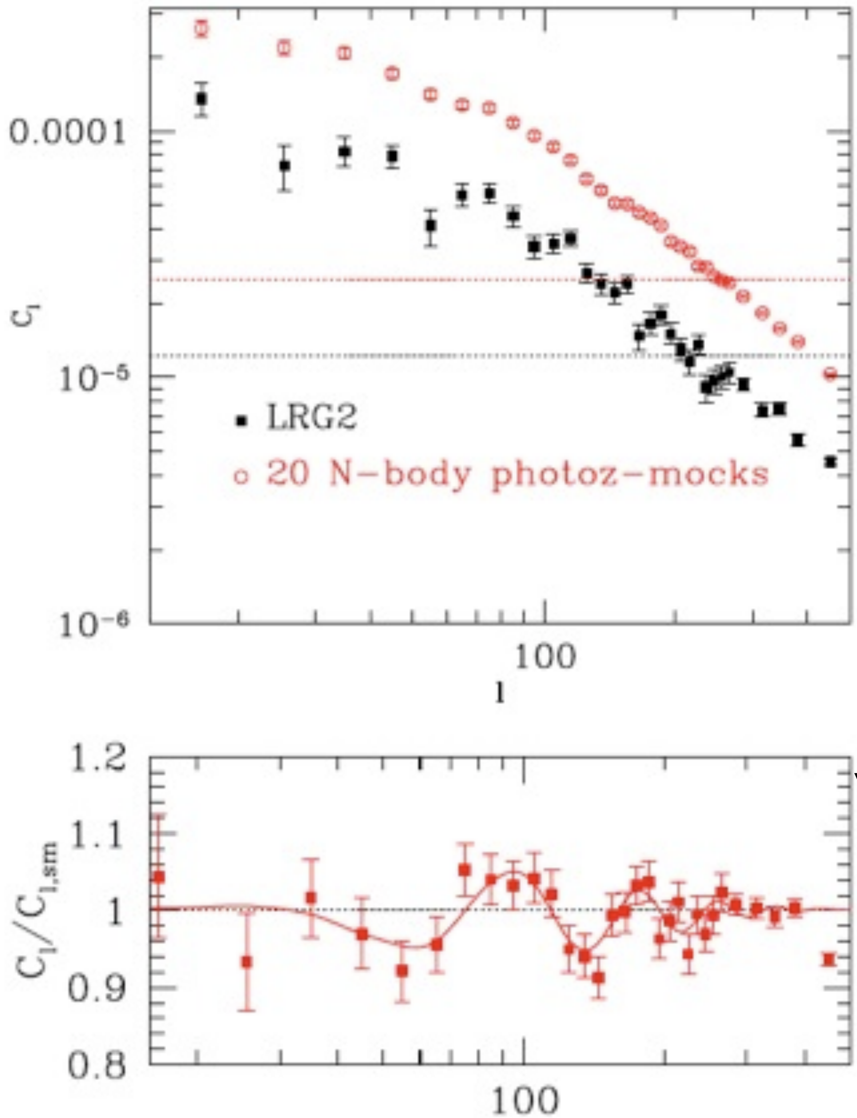
← Inflation →

Preliminary Results: Primordial Non-gaussianities
3 years ago...



Slosar et al. 2008

Baryon Acoustic Oscillations !
What? in imaging?



We ask the question:
What is the best we can do?

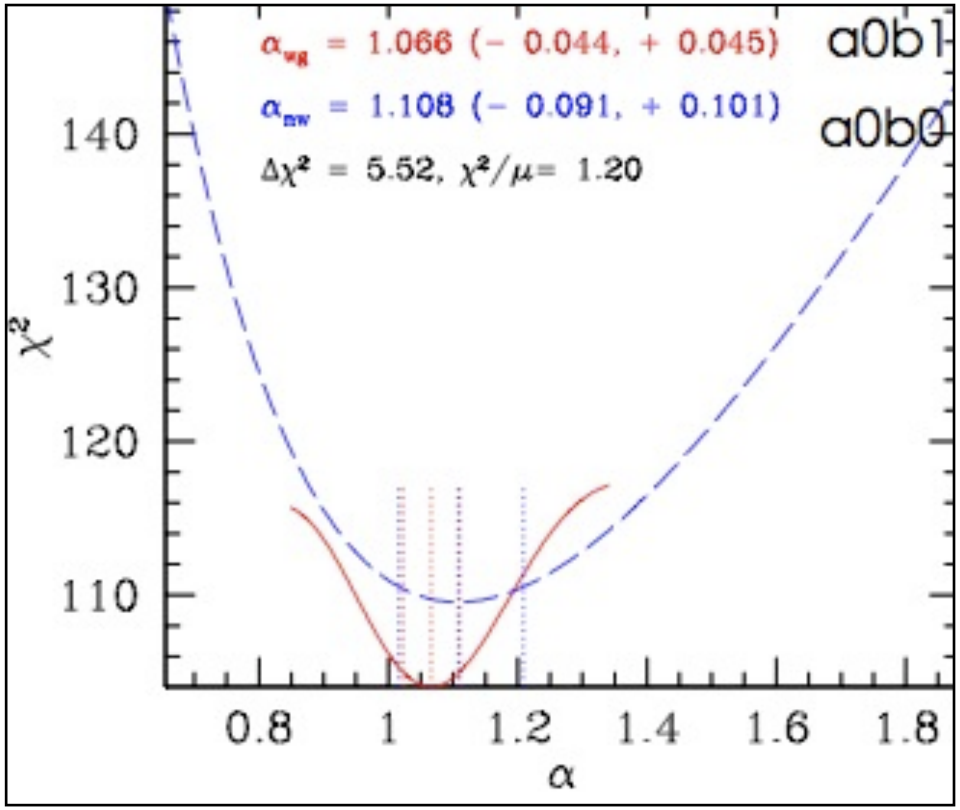
With ~4 times more data, that's what we expect, so this is what we can do with either the same SDSS depth for ful sky, or 4 times more volume (by going deeper)

Seo, SH, White et al. (2012)

Shirley Ho

Science from Large Scale Structure Galaxy Sample

Learning about Dark Energy from Baryon Acoustic Oscillations



$$\alpha = \frac{(D_A/r_s)_{obs}}{(D_A/r_s)_{fid}}$$

$\alpha = 1$ fiducial cosmology

$\alpha > 1$ when observed acoustic scale is larger than fiducial

$\alpha < 1$ when observed acoustic scale is smaller than fiducial

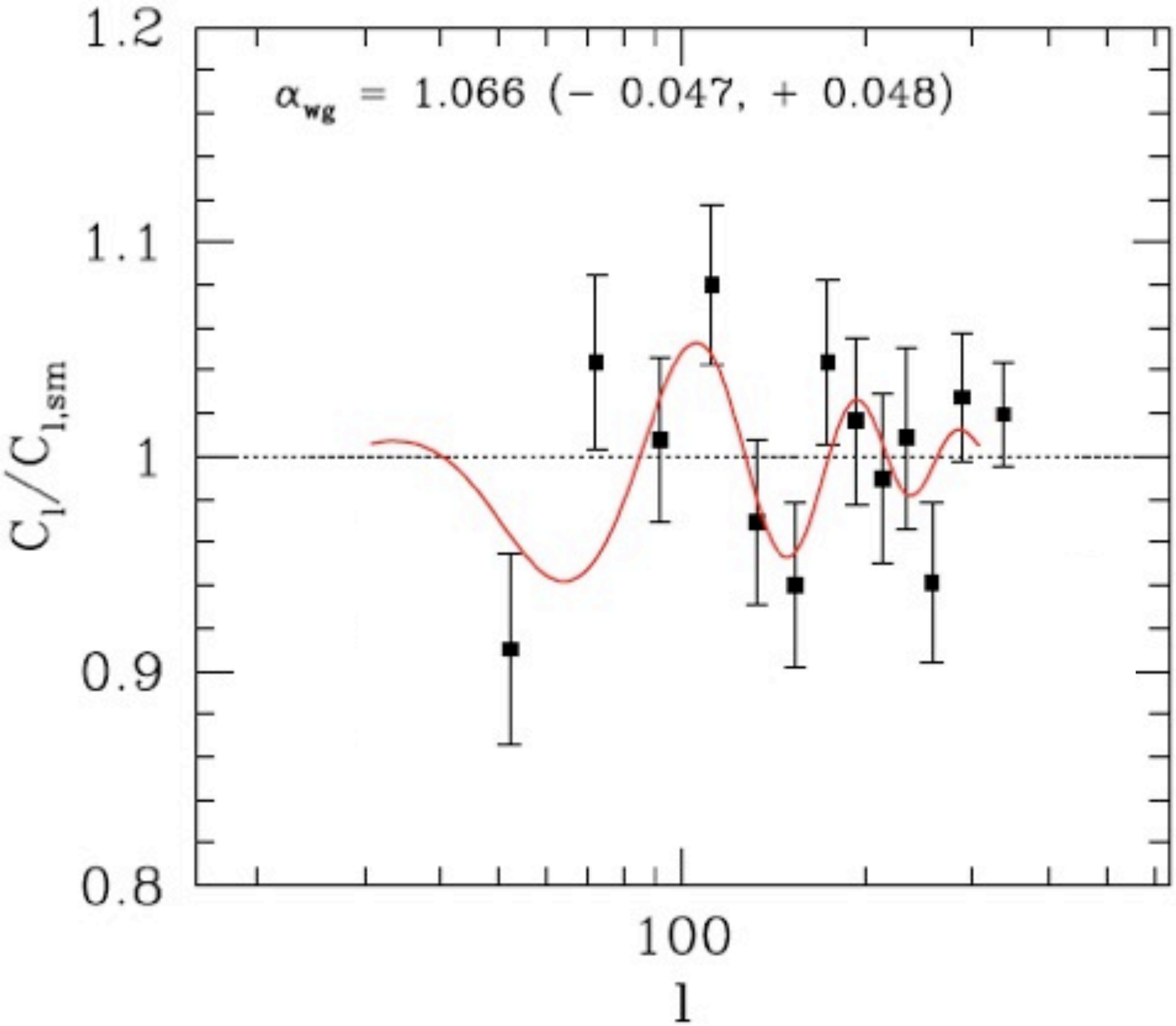
$$\chi^2/dof = 1.20$$

$$\alpha - 1 = 0.066 \pm 0.045$$

Seo, SH, White et al. (2012)

Shirley Ho

Combining all redshift slices



SH, Cuesta, Seo, Ross, DePutter et al. (2012)

Shirley Ho

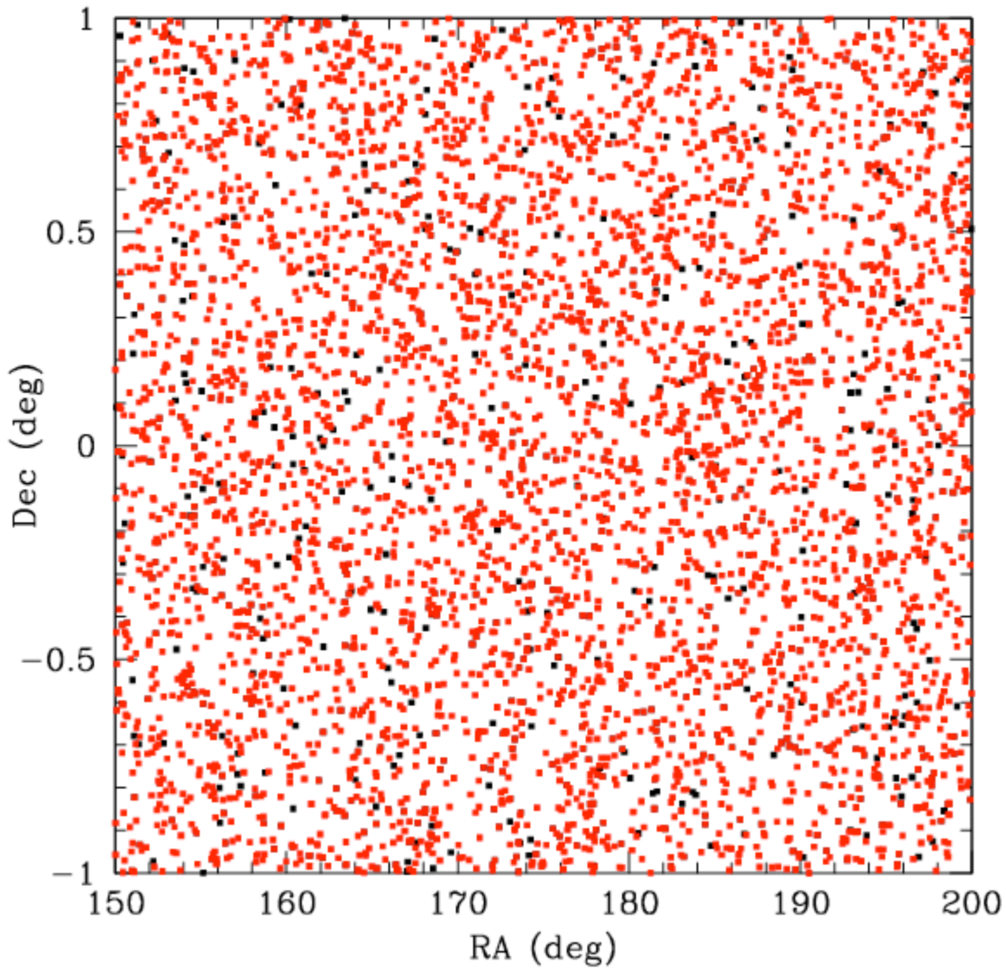
Outline

- Motivations
- Using the largest multicolor image of the Universe to learn about it? How?
  - — Early Universe (with large scale clustering)
  - — Dark Energy (with Baryon Acoustic Oscillations)
- Angular clustering
  - — With Luminous Galaxies and Quasars
  - — With Stars?

The Making of a Large Scale Structure Sample or two ...

Photometric Quasar sample too!

Huge Quasar Samples Classified From Imaging Only



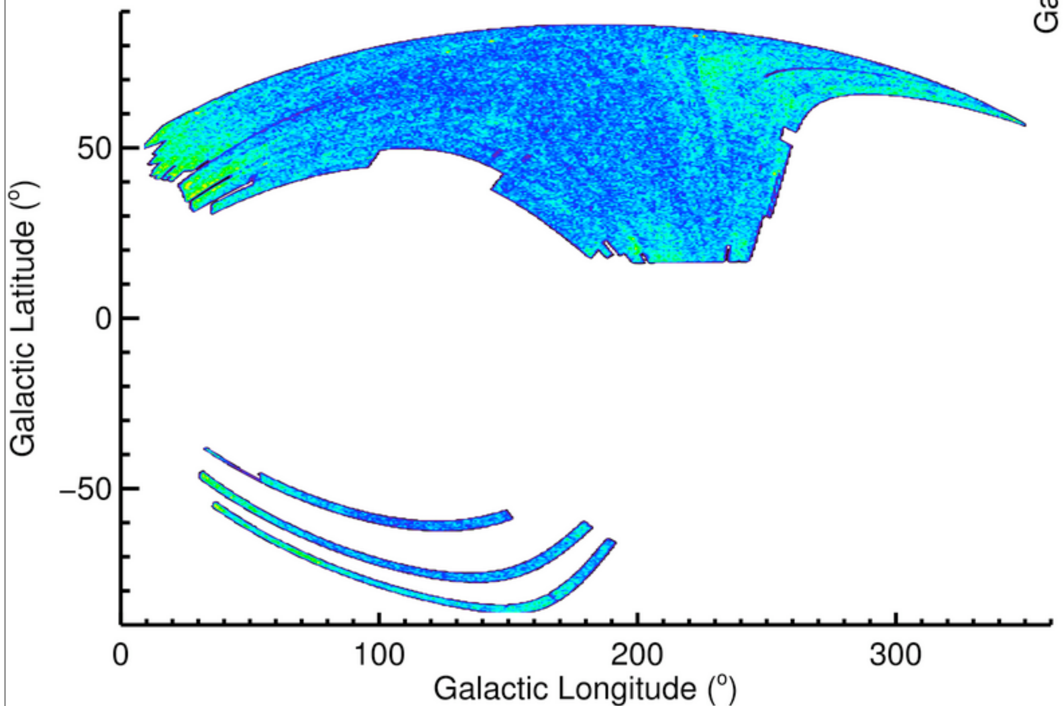
SDSS I spectroscopic quasar sample

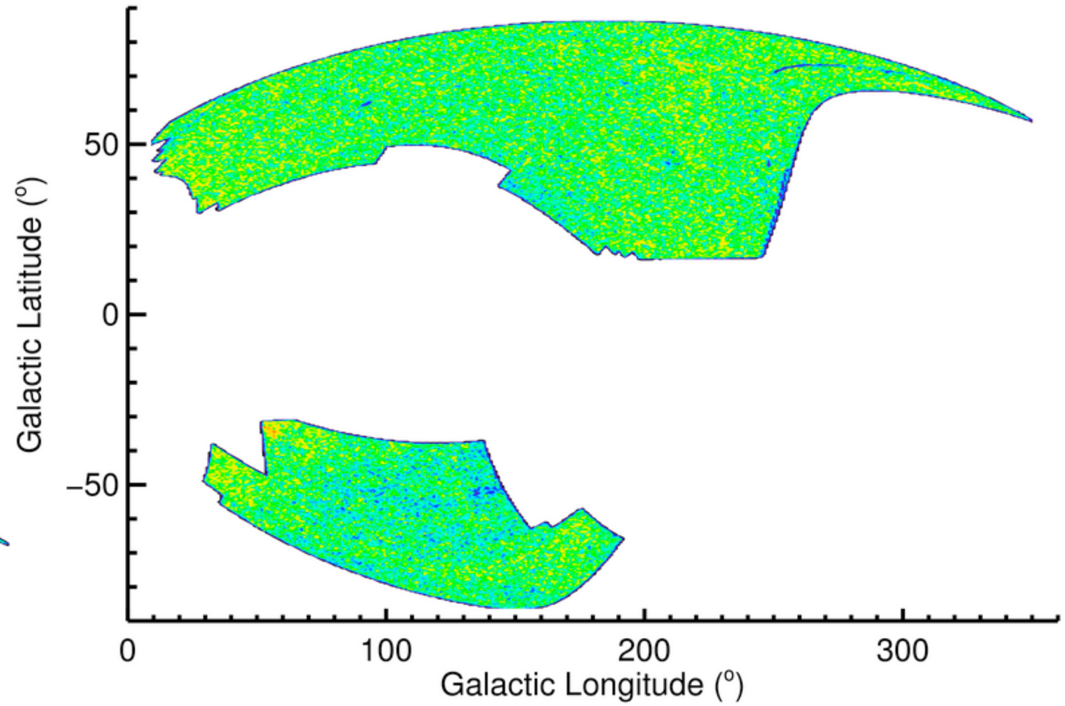
SDSS I photometric quasar sample (Kernel Density Estimation, Richards et al. 2004, 2009)

Courtesy Adam Myers

Photometric Quasar Catalogs

KDE DR6 Richards et al. (2009) ~600,000 z < 2.5 quasars over 8400 deg^2



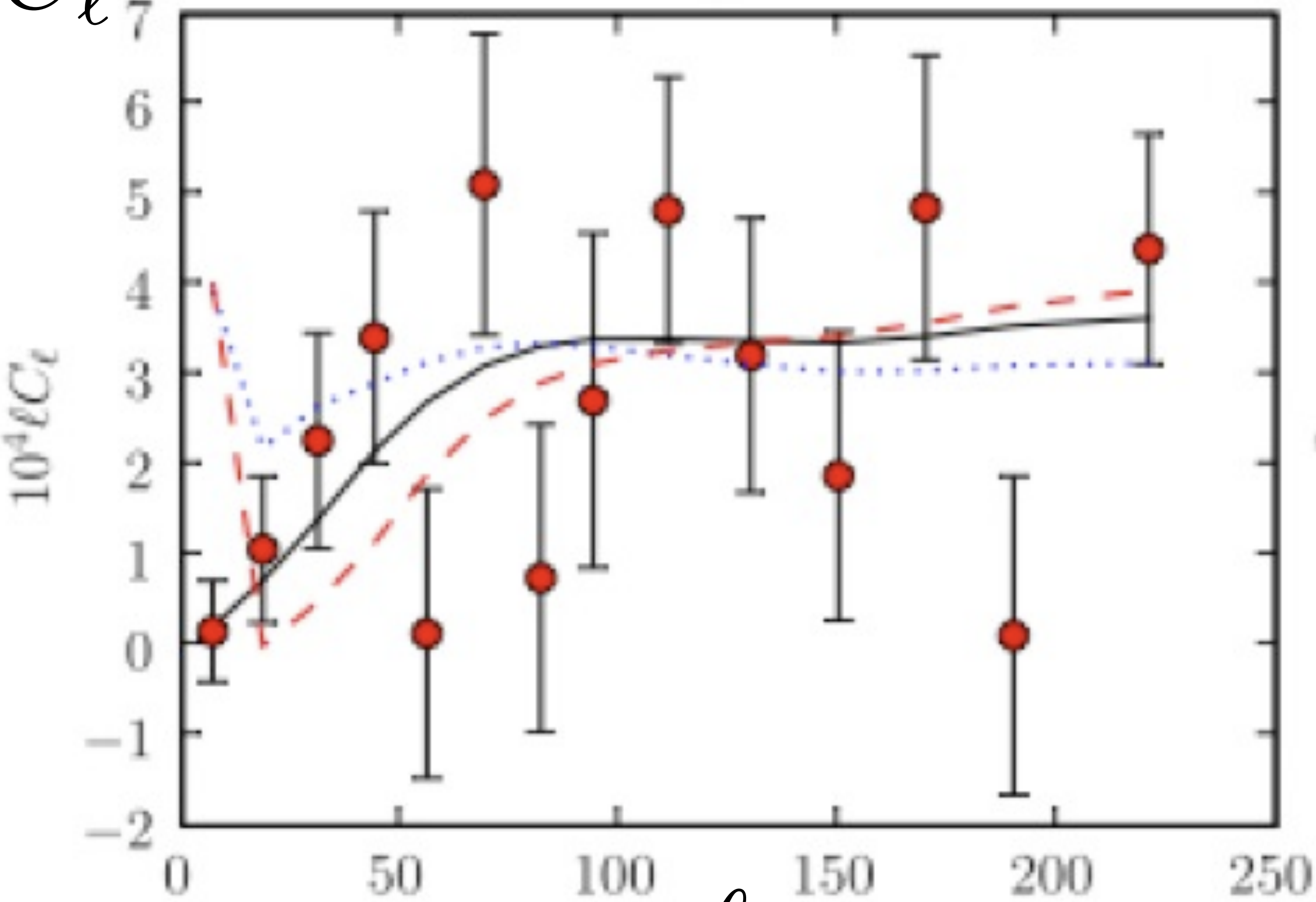


Bovy et al. (2011) DR8, ~800,000 z < 2.5 quasars over 10800 deg^2 ($P_{QSO} > 0.9$)

Courtesy Adam Myers

Back to QSOs (3 years ago)

$10^4 \ell C_\ell$



ℓ

Slosar et al. 2008, SH et al. 2008

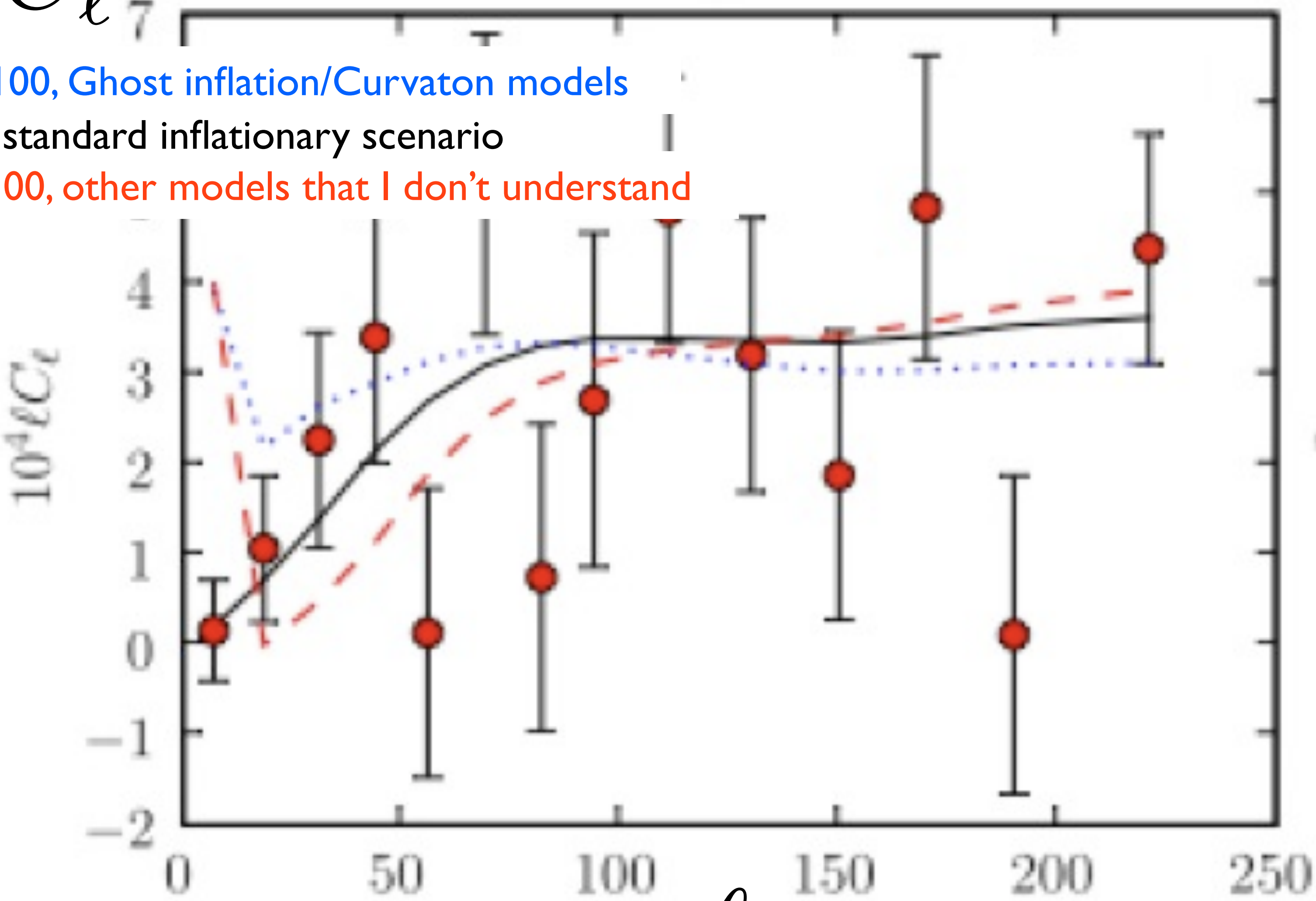
Back to QSOs... (3 years ago)

$10^4 \ell C_\ell$

$f_{NL,local}$ =+100, Ghost inflation/Curvaton models

=0, standard inflationary scenario

=-100, other models that I don't understand



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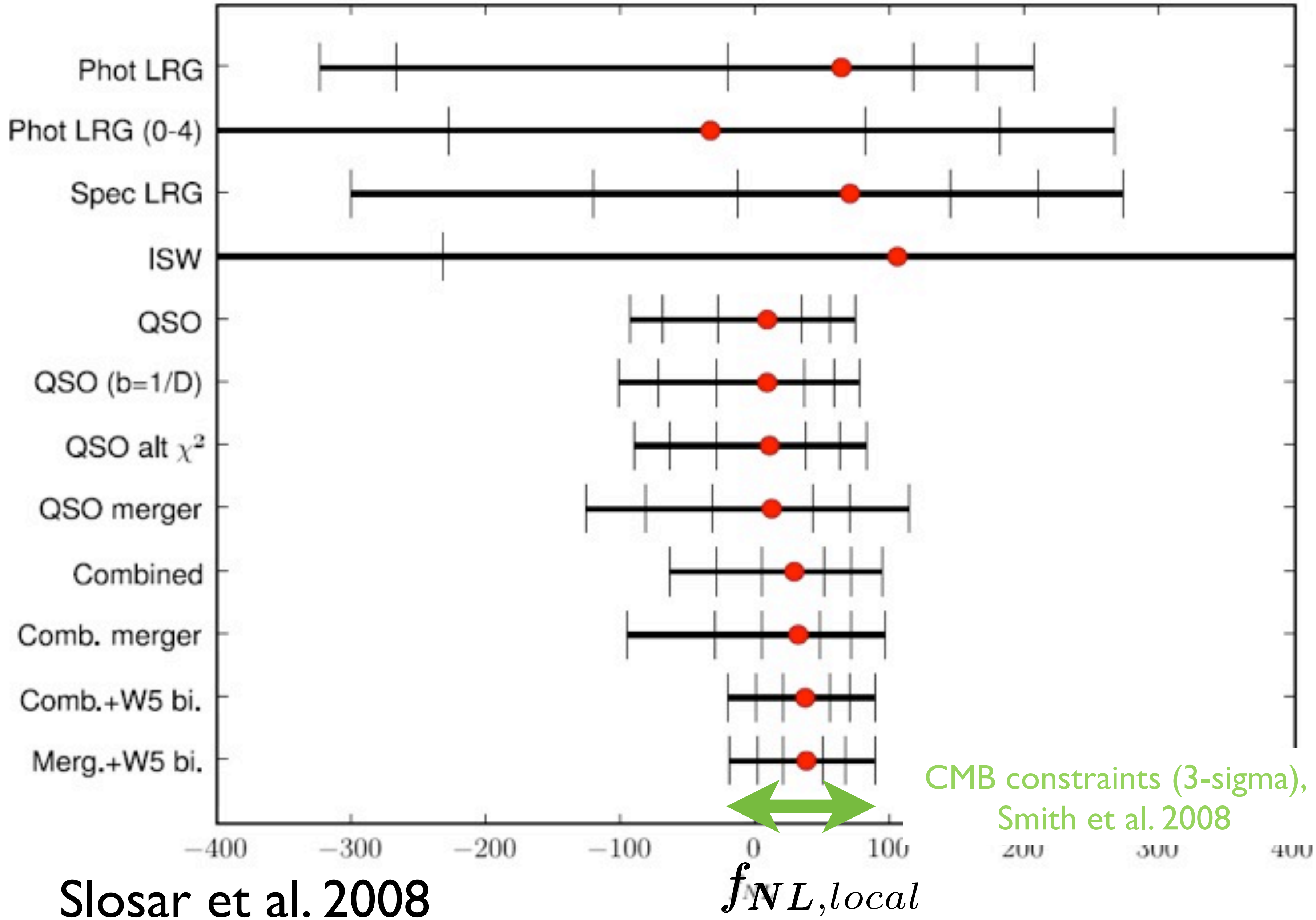
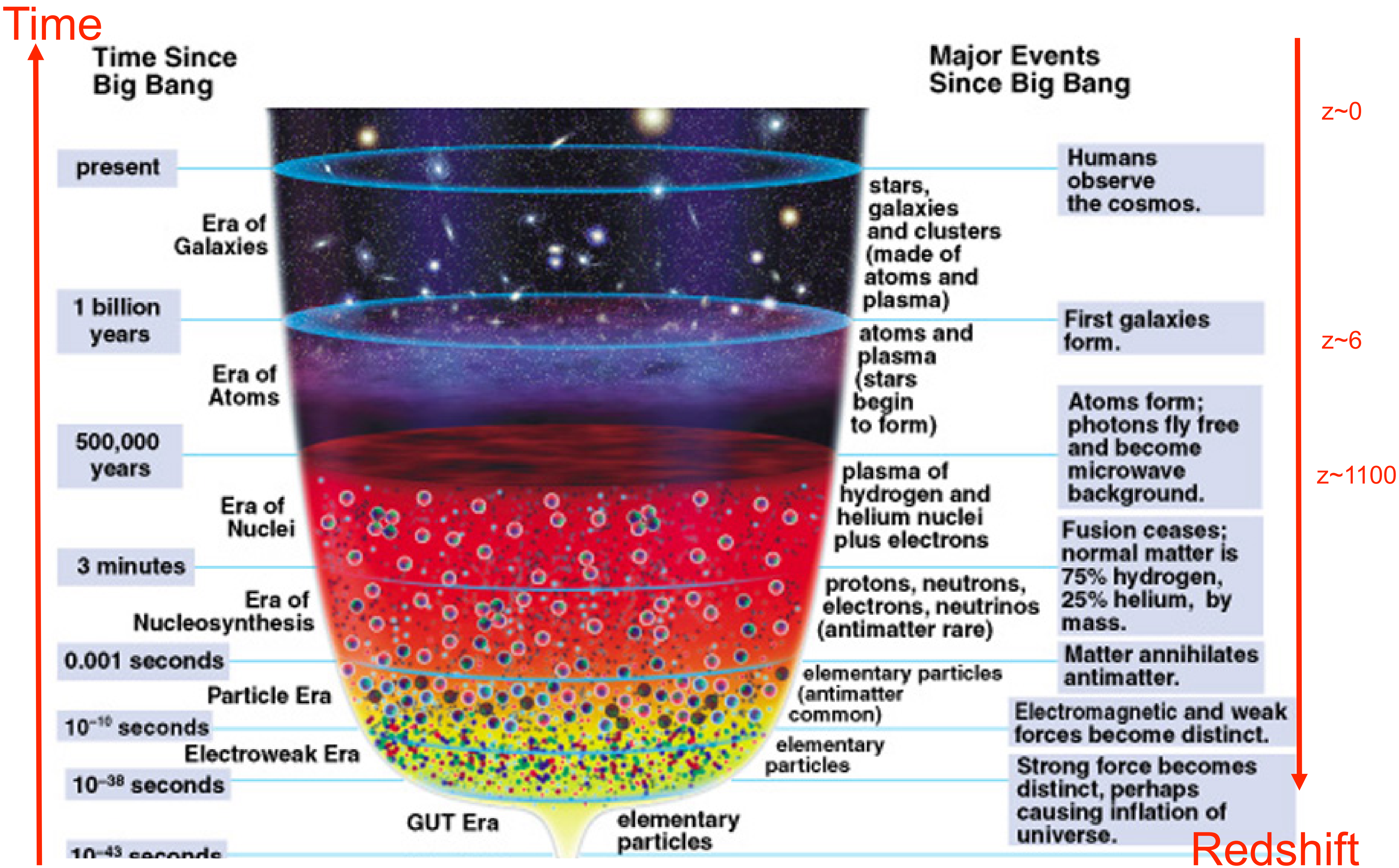
Slosar et al. 2008, SH et al. 2008

Preliminary Results: Primordial Non-gaussianities
3 years ago...



Slosar et al. 2008

Motivations

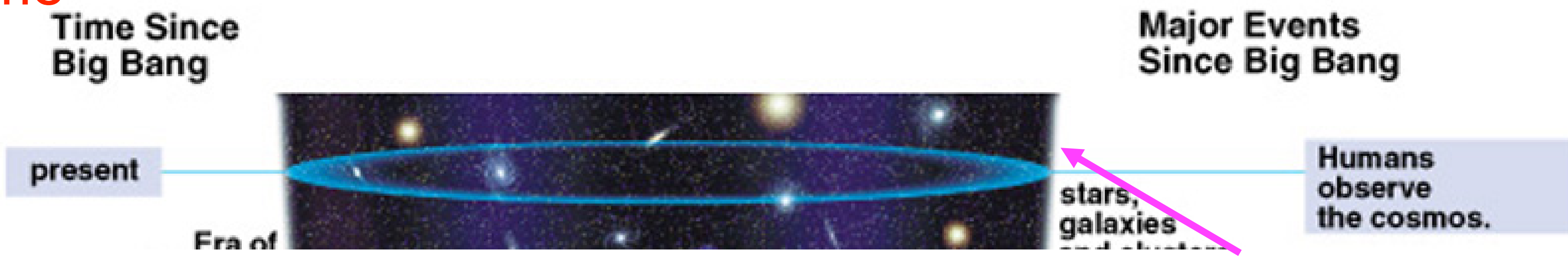


Carnegie Mellon University

Motivations

BERKELEY LAB

Time



z~0

z~6

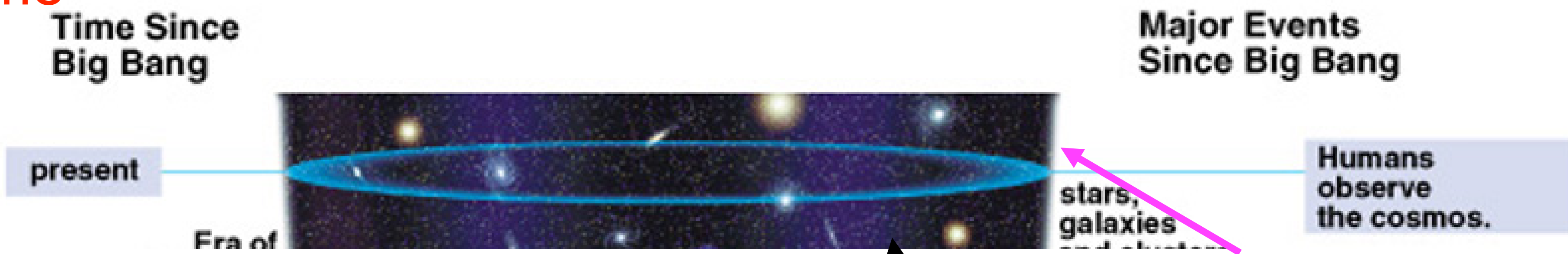
z~1100

Gravity +
observing movement of
local galaxies ->
"Dark Matter"

Redshift

Motivations

Time



z~0

Gravity +
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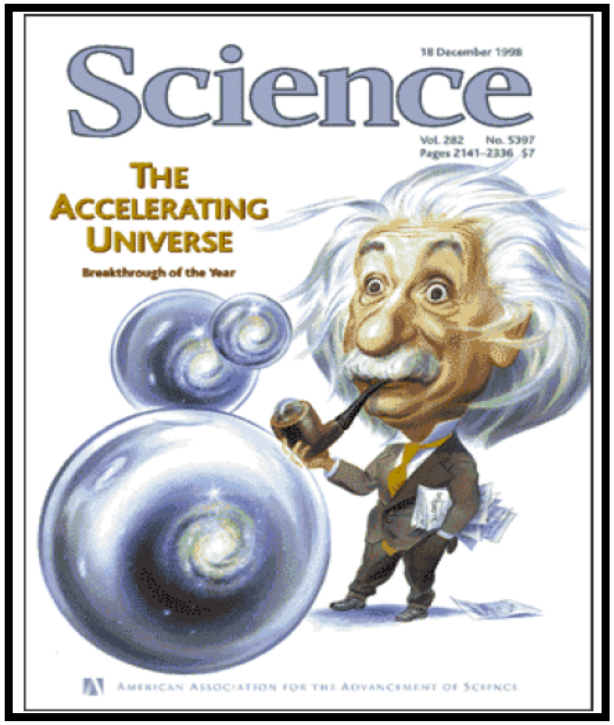
"Dark Matter"

z~6



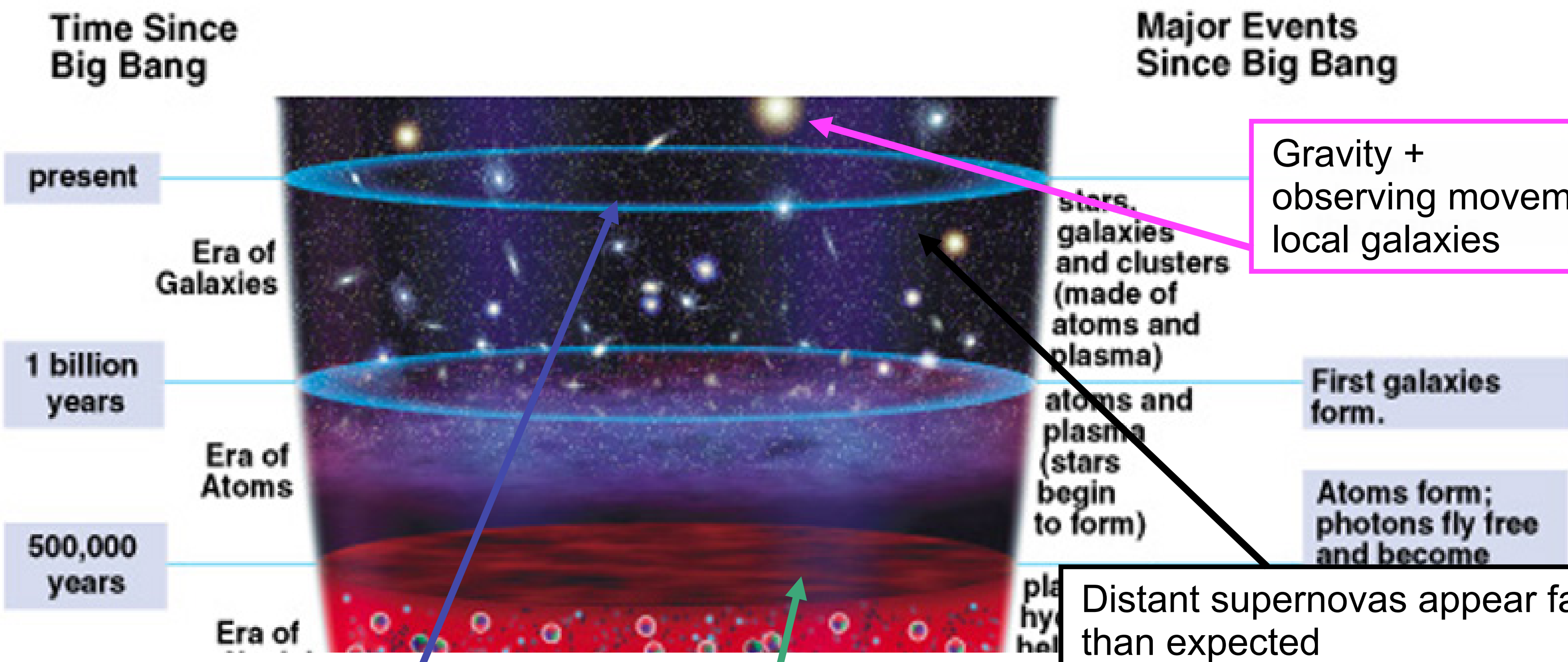
Distant supernovas appear fainter
than expected (1998)->
Universe is accelerating ->
Cosmological Constant?
Dark Energy?

z~1100

Redshift

Motivations

Time

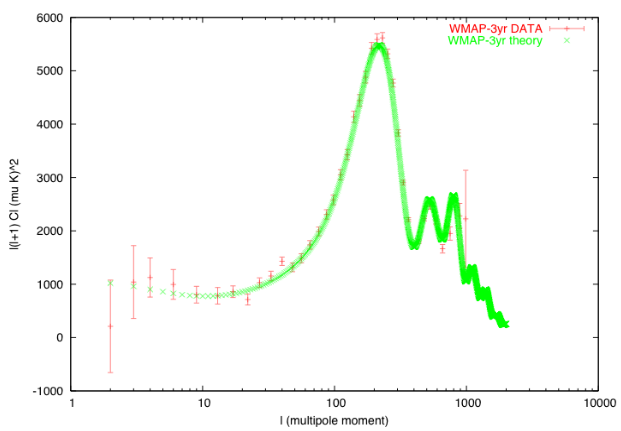


Gravity + observing movement of local galaxies

Distant supernovas appear fainter than expected

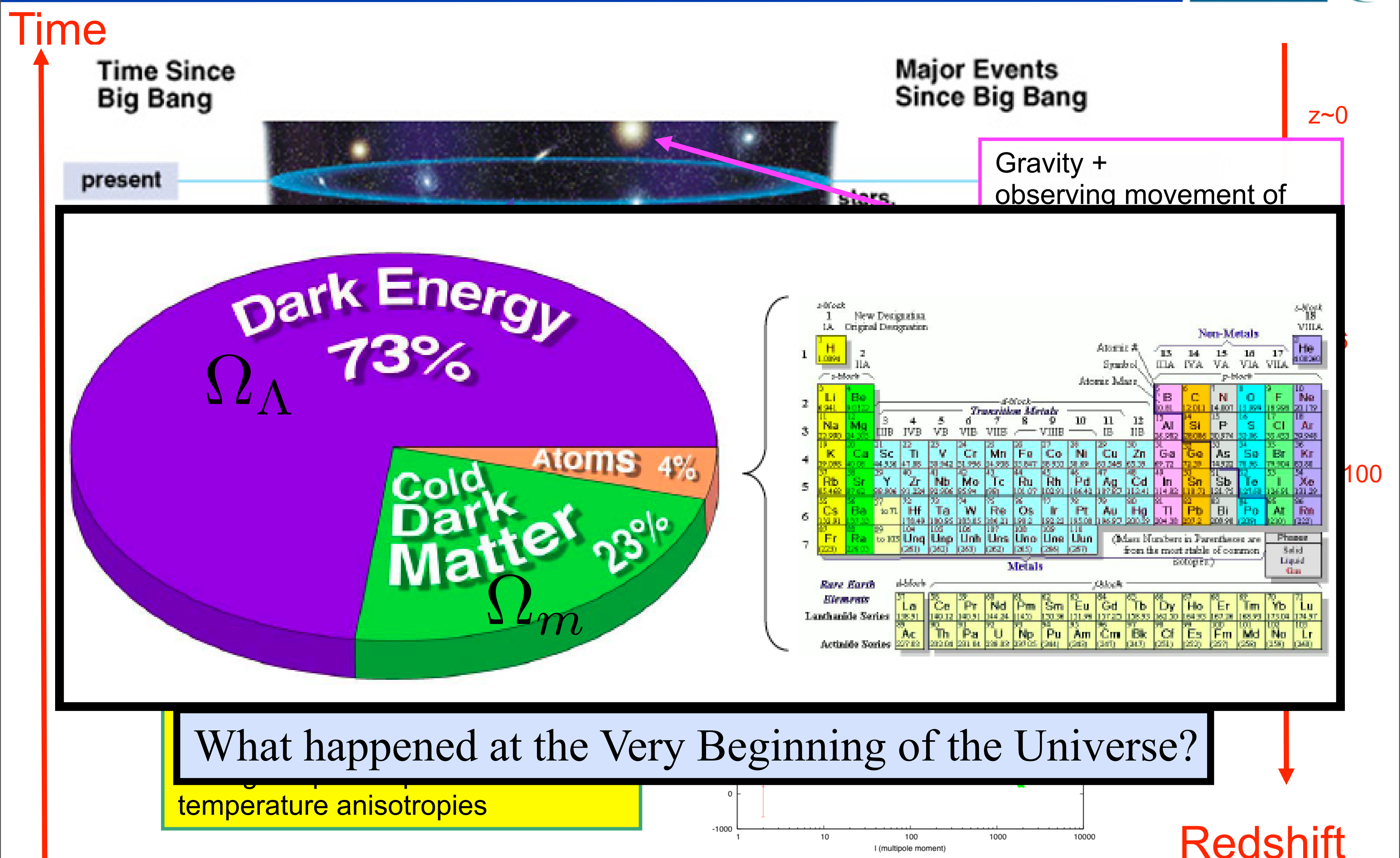
Observations of how galaxies cluster

Observations of Cosmic Microwave Background (CMB) -> angular powerspectrum of temperature anisotropies

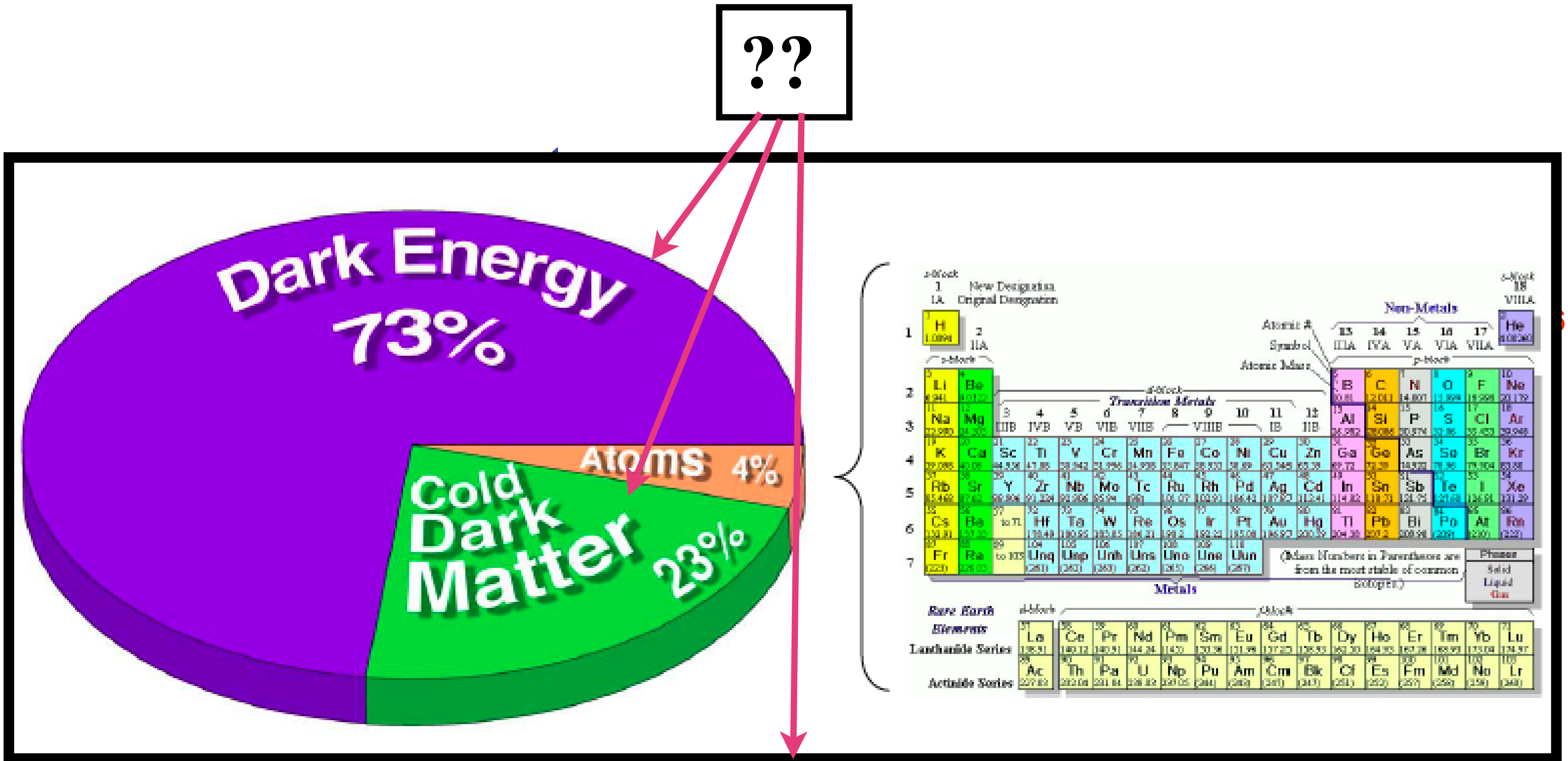


Redshift

Motivations

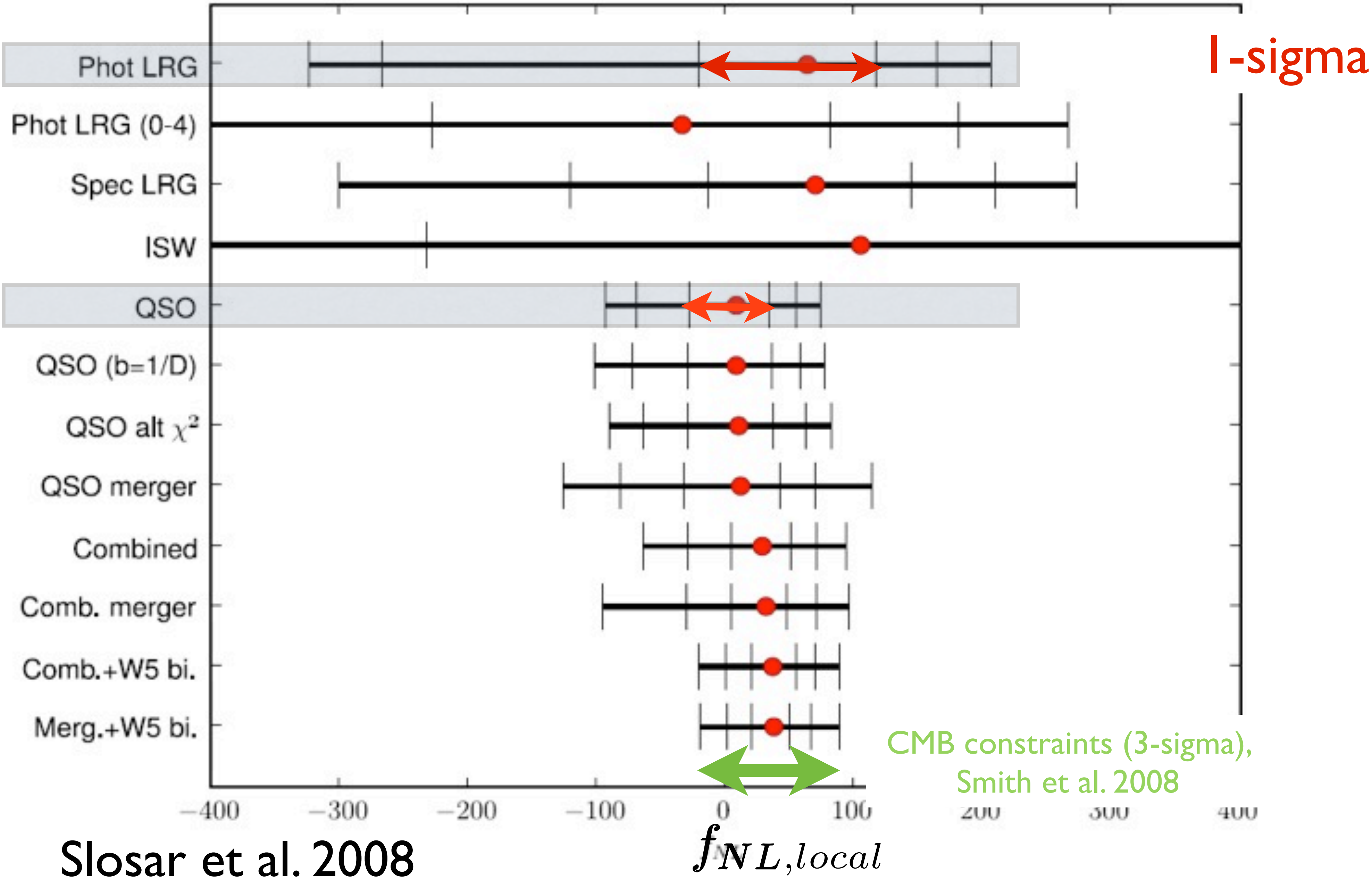


Motivations



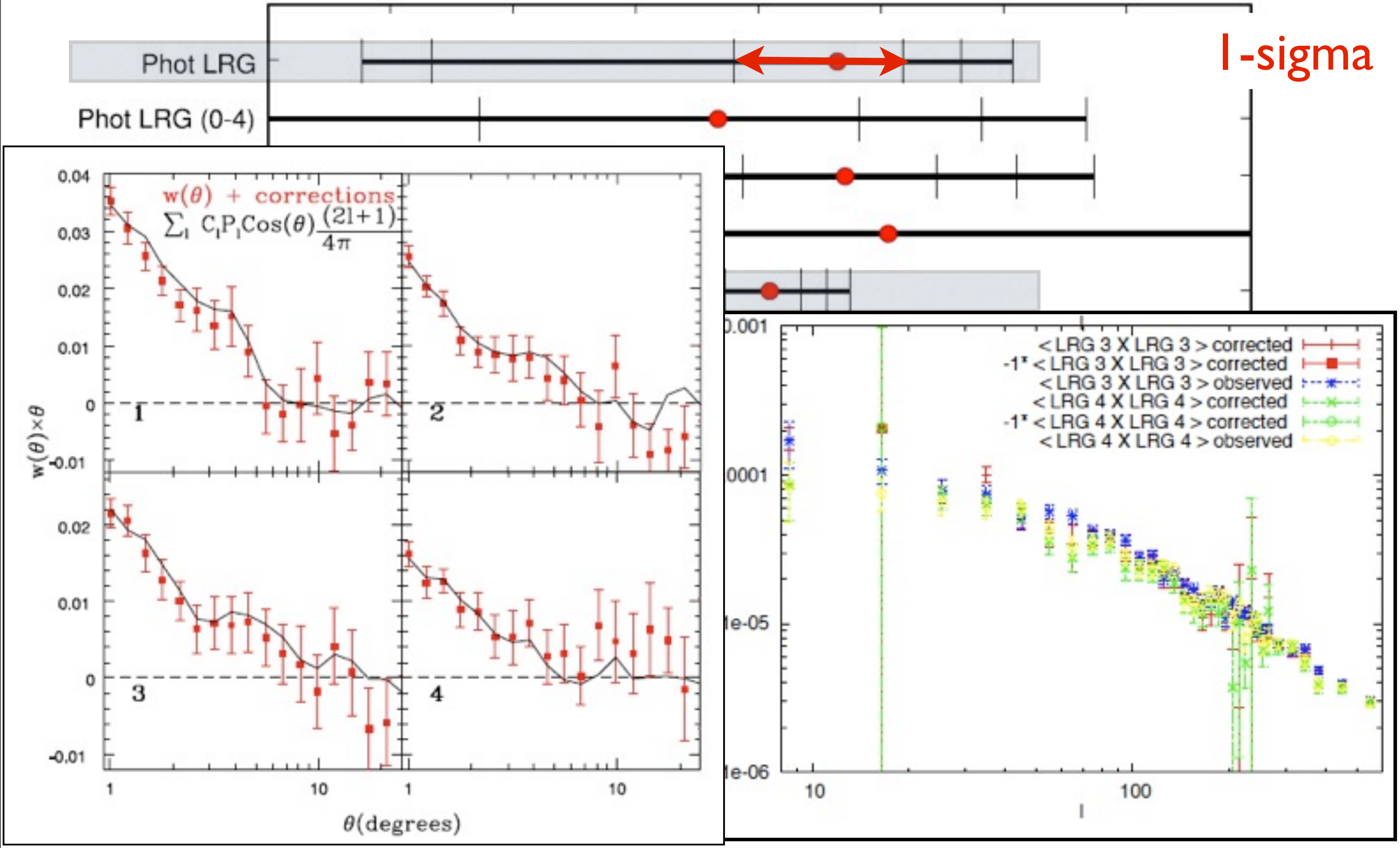
What happened at the Very Beginning of the Universe?

Preliminary Results: Primordial Non-gaussianities
3 years ago...



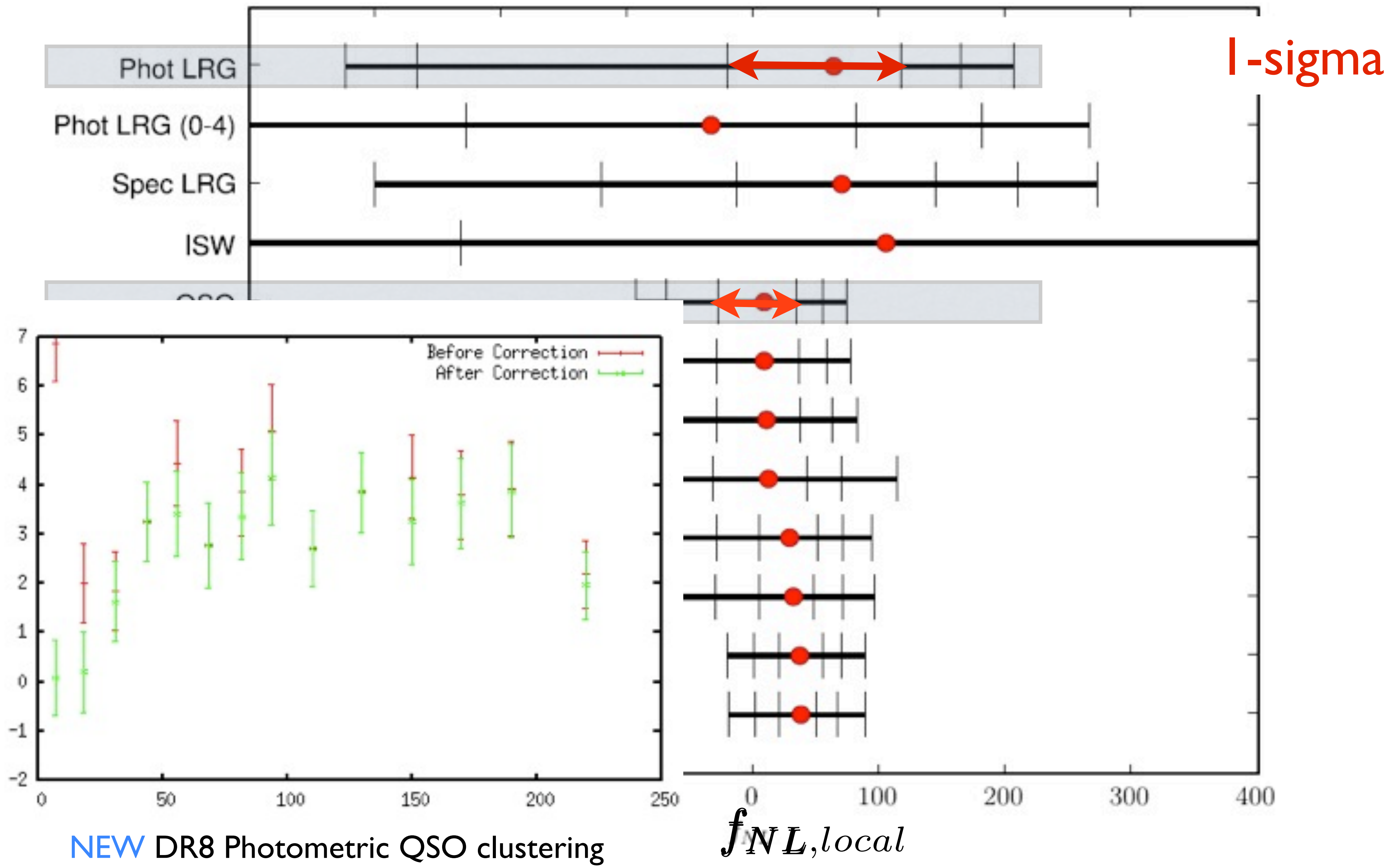
Slosar et al. 2008

Preliminary Results:
Primordial Non-gaussianities from Luminous Galaxies



We now go through nearly the same process (data construction, redshift distribution determination, optimal estimation of power-spectra, systematics, cosmological interpretation) with the Quasars as we did with the Luminous Galaxies

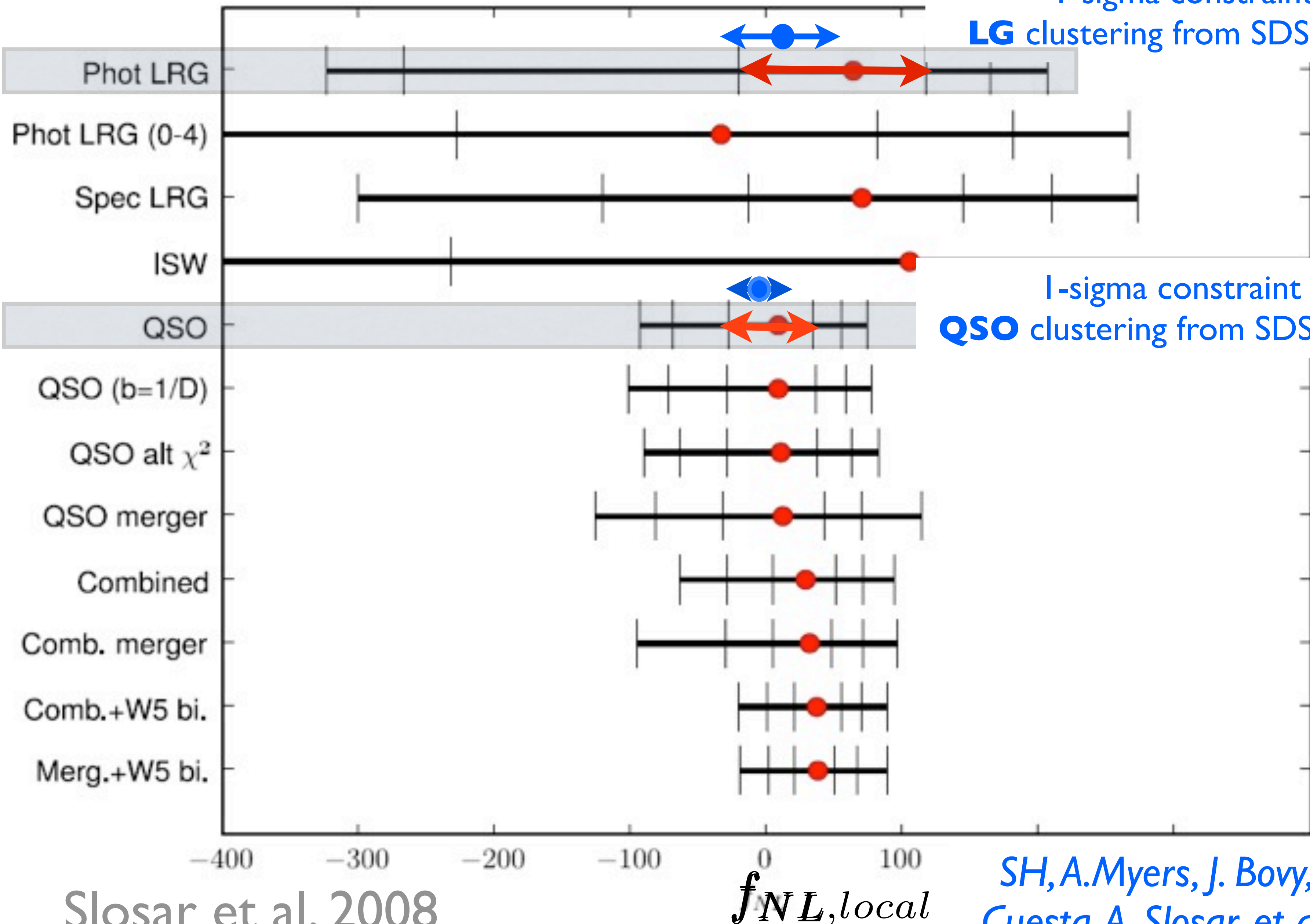
Preliminary Results:
Primordial Non-gaussianities with Quasars



NEW DR8 Photometric QSO clustering

Preliminary Results on Non-gaussianities
NOW

1-sigma constraint from **LG** clustering from SDSS III imaging

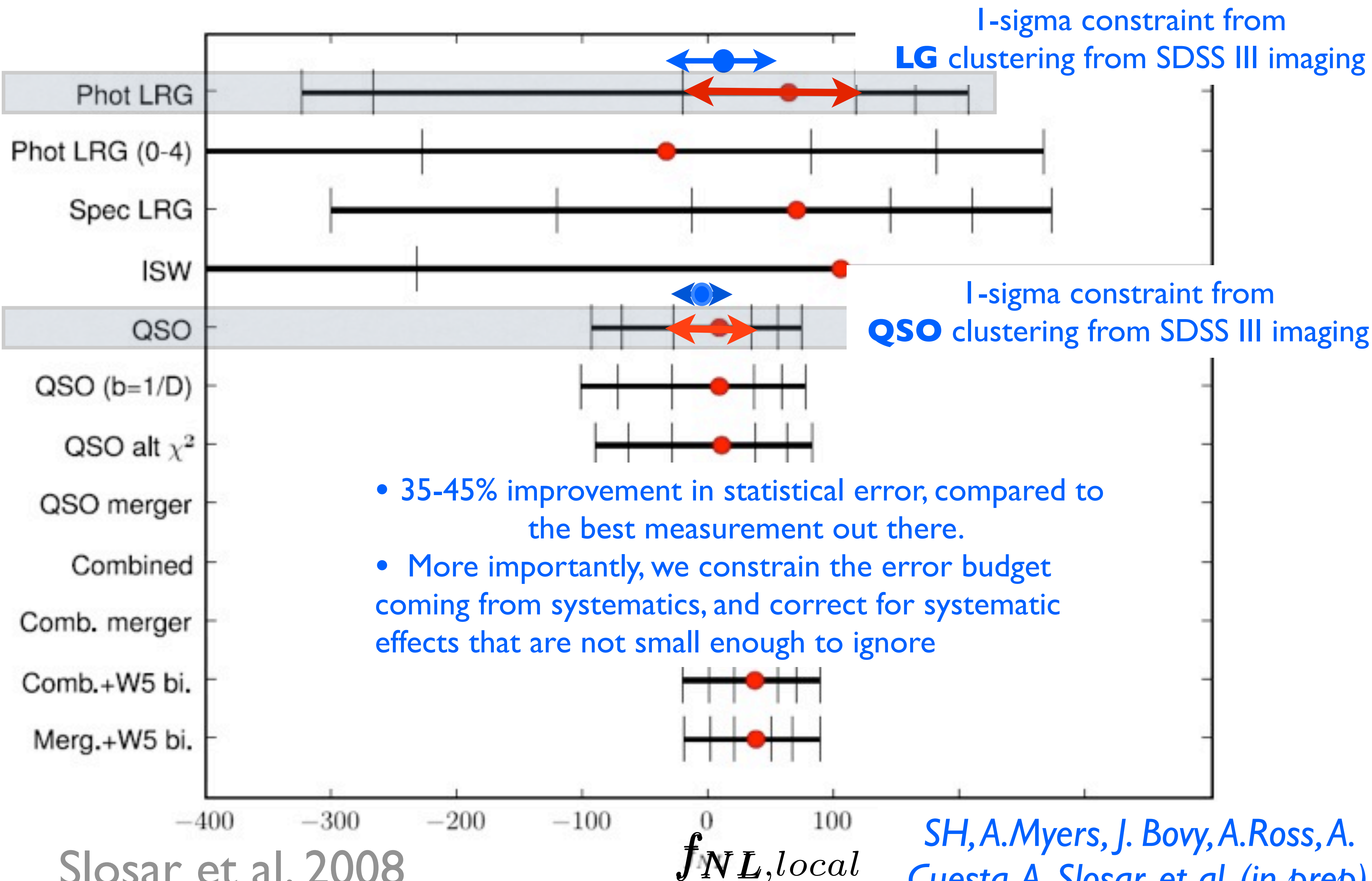


1-sigma constraint from **QSO** clustering from SDSS III imaging

Slosar et al. 2008

SH, A. Myers, J. Bovy, A. Ross, A. Cuesta, A. Slosar, et al. (in prep)

Preliminary Results: Primordial Non-gaussianities NOW



- 35-45% improvement in statistical error, compared to the best measurement out there.
- More importantly, we constrain the error budget coming from systematics, and correct for systematic effects that are not small enough to ignore

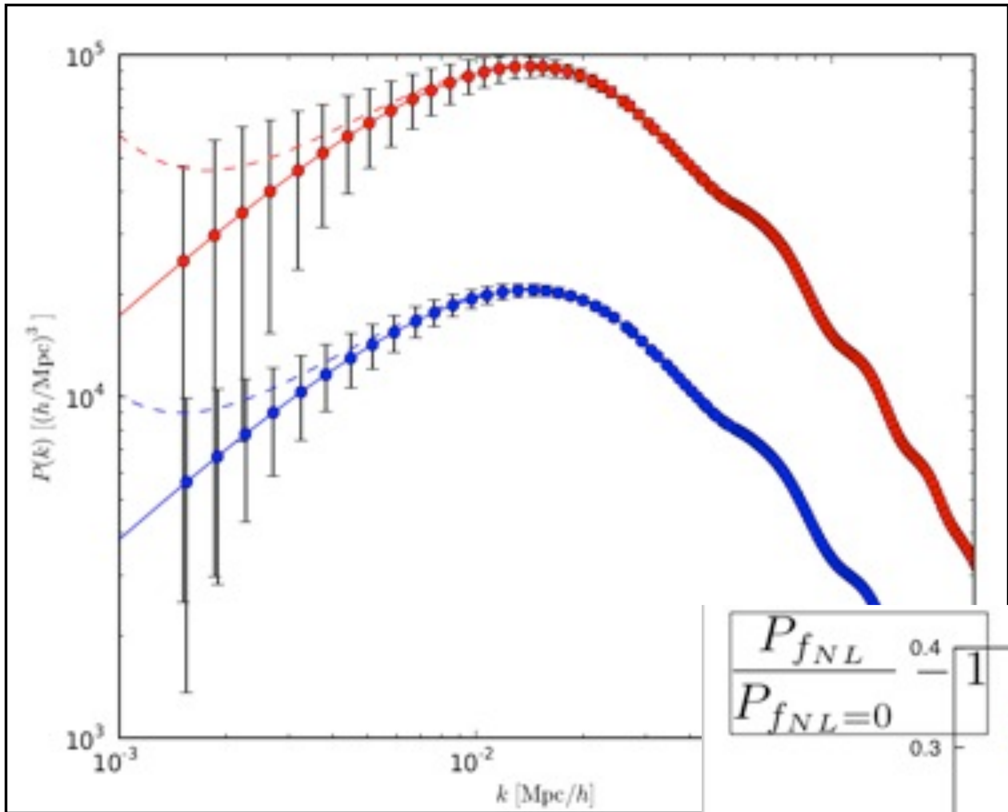
Slosar et al. 2008

SH, A.Myers, J. Bovy, A.Ross, A. Cuesta, A. Slosar, et al. (in prep)

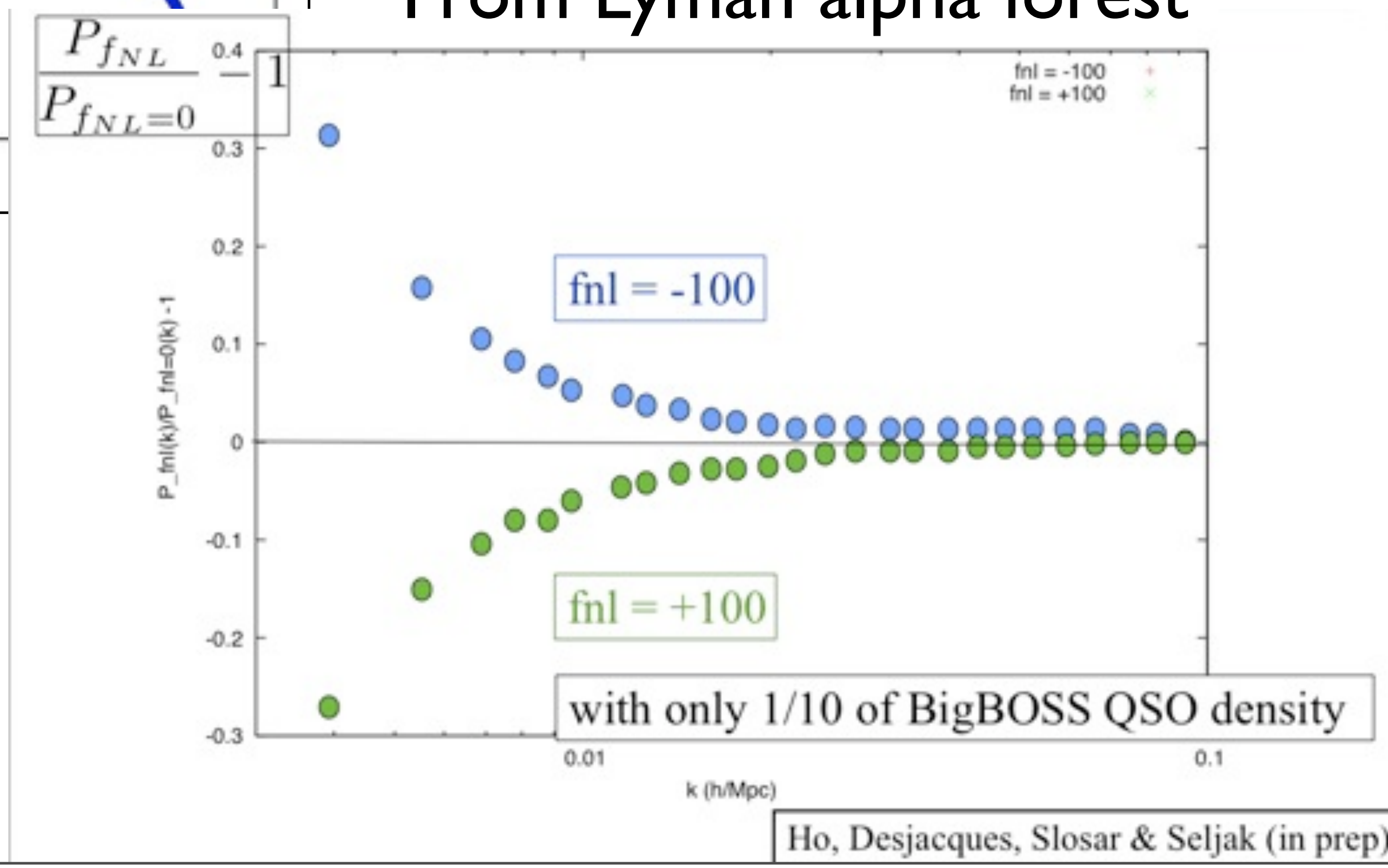
What happens when we have millions of spectra?

- What I showed earlier is what you can already do with only imaging data, with spectroscopic data set such as BOSS or BigBOSS, you can do better in terms of the following:
  - confirmed galaxy/quasar identities
  - reduction (hopefully) in systematics
  - nearly independent constraint (from high-z QSOs)
  - possible constraint from Lyman alpha forest.

From Galaxies/ Quasars



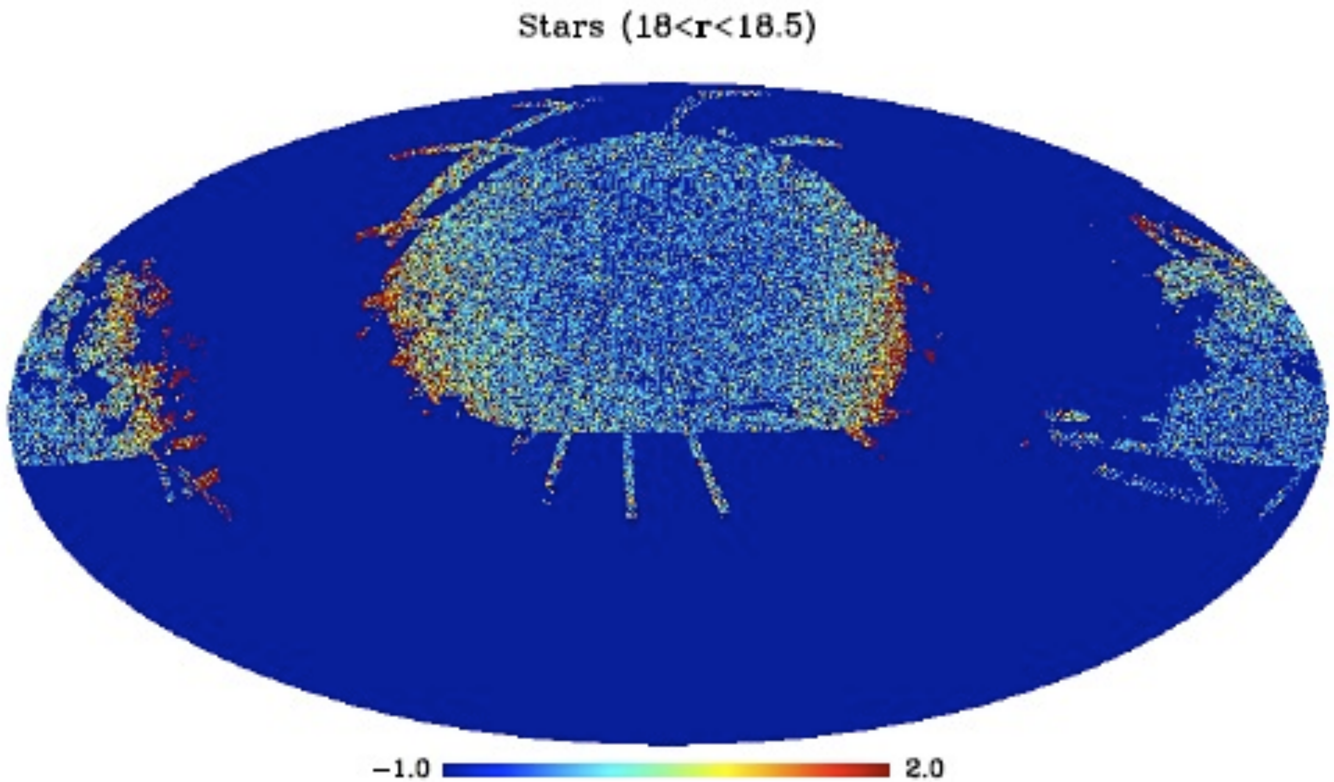
From Lyman alpha forest



Outline

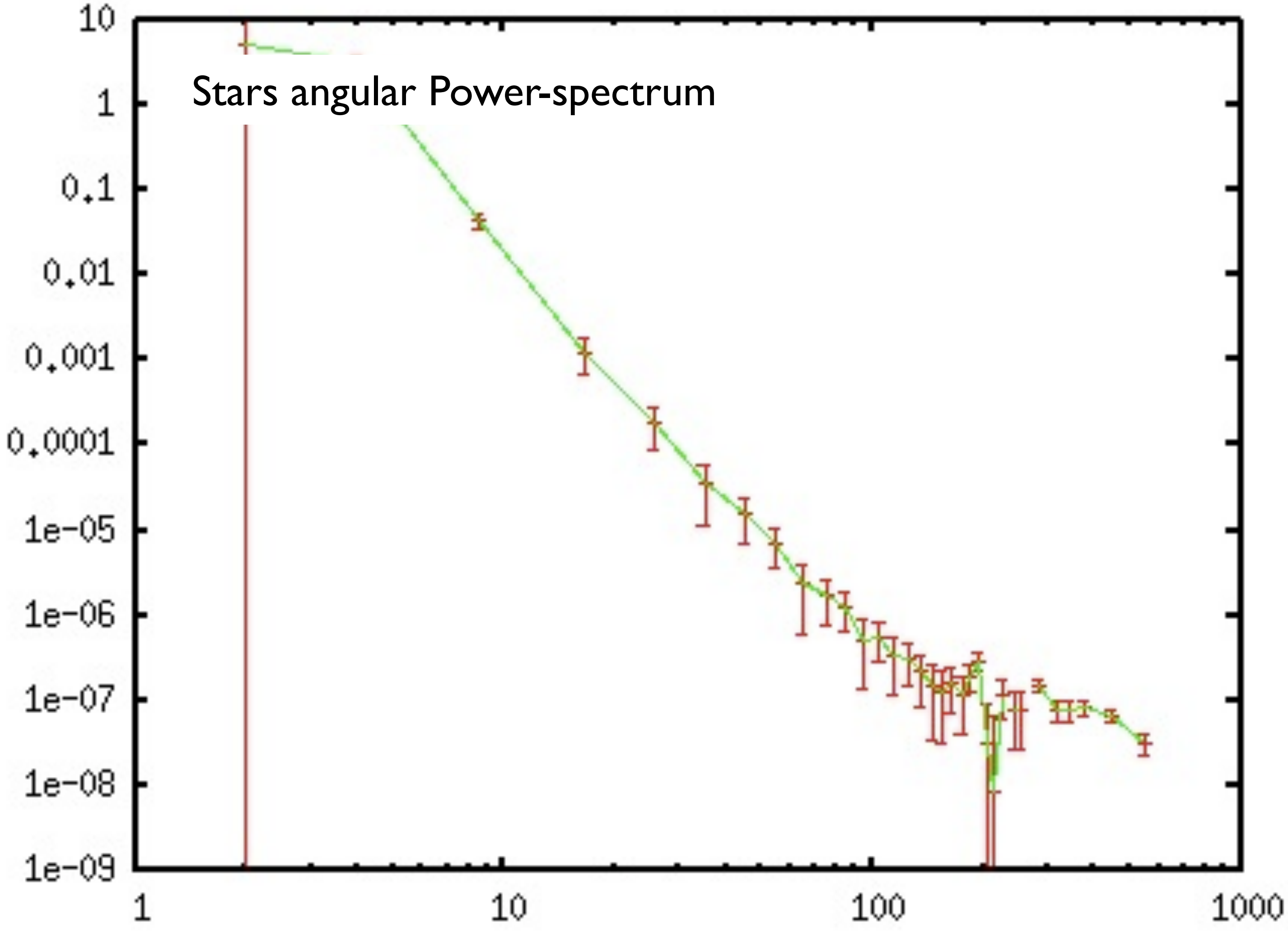
- Motivations
- Using the largest multicolor image of the Universe to learn about it? How?
  - Early Universe (with large scale clustering)
  - Dark Energy (with Baryon Acoustic Oscillations)
- Angular clustering
  - With Luminous Galaxies and Quasars
  - With Stars?

Stars?!



Angular clustering of stars

C_ℓ stars selected from imaging with 18<r<18.5



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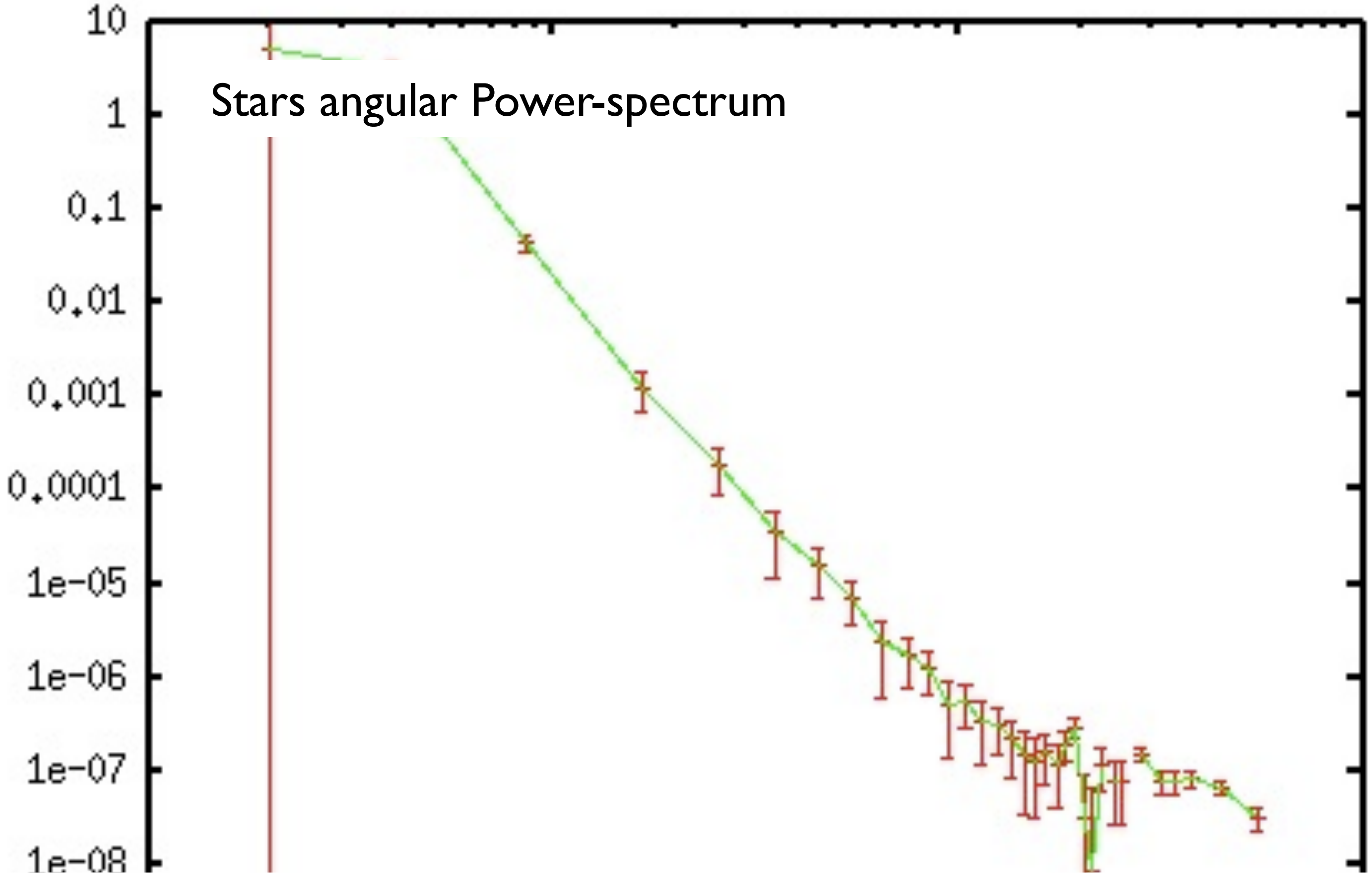

How does the angular clustering of stars at different magnitude range (different distance) compared to simulations such as VL2 and Aquarius?

Angular clustering of stars

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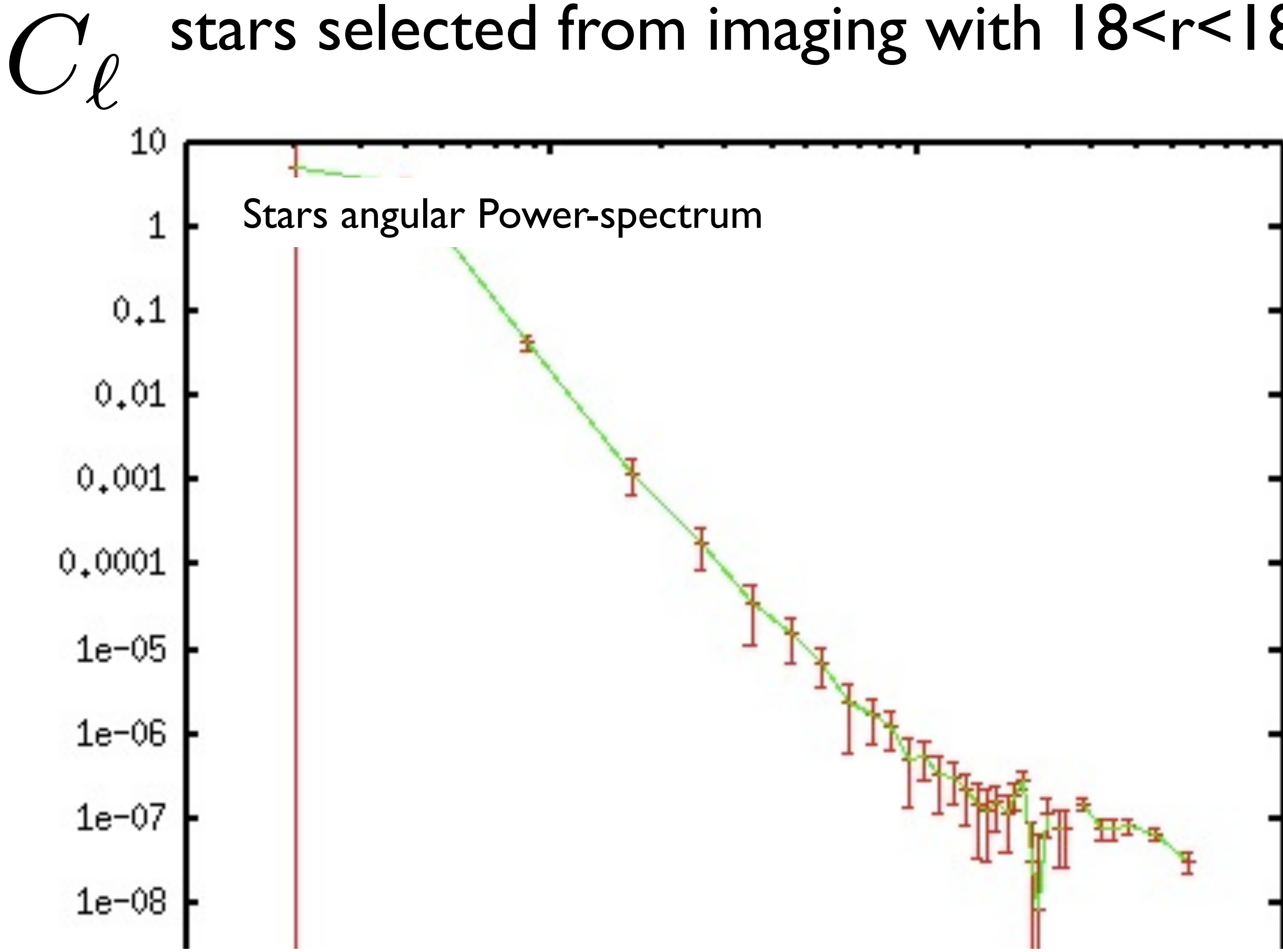


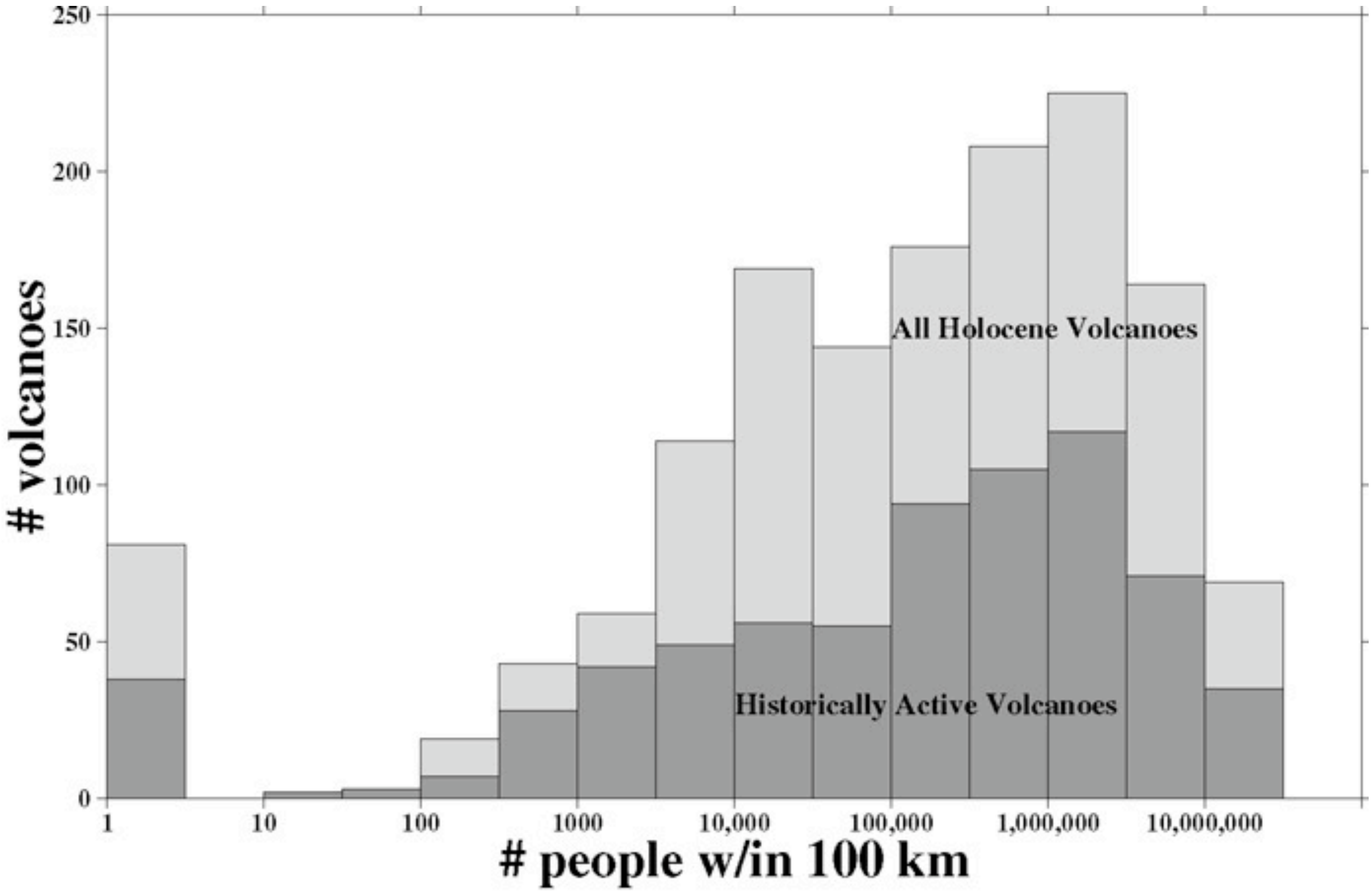
How much of it is from systematics?

how much of it is from actual clustering of stars in our galaxy?

Conclusion *and Advertisement*

- There are lots of good science in SDSS III imaging, and it also paves the way for understanding the spectroscopic sample
    - Optimally estimated Angular power-spectra of the Luminous Galaxies and Quasars with the minimum systematics: useful for Dark Energy, Flatness of the Universe, Neutrino masses, What happened at the beginning of the Universe...
- Useful resources available online:
    - DR8 Luminous Galaxy sample: http://portal.nersc.gov/project/boss/galaxy/photoz
    - DR8 Quasar sample: http://cosmo.nyu.edu/~jb2777/qsocat/xdqsoz_pqso0.5_imag21.5-nobadu.fits.gz
    - Systematics maps of the final SDSS (DR8) imaging (latest color offset maps Schlafly et al. (2011), seeing, sky, stars; email me for more info): http://lymanalpha.lbl.gov/~shirley/systematics
- Carnegie Mellon University has become the latest institutional member of SDSS III
- Participating faculty includes: Rupert Croft, Tiziana Di Matteo, Rachel Mandelbaumn, Jeff Peterson, Hy Trac, many more and me. We are offering >~5 postdoc fellowships in our group this fall to work on various different aspects of cosmology, galaxy and quasars.

The End



250
200
150
100
50
0
volcanoes
All Holocene Volcanoes
Historically Active Volcanoes
1
10
100
1000
10,000
100,000
1,000,000
10,000,000
people w/in 100 km

There is a lot more ...

- Cluster finding using maxBCG method [Sheldon et al. , previous work using SDSS data: Rozo et al. 2008, 2009]
- Cluster lensing [Sheldon et al., Leathaud et al.]
- Weak Lensing in CMB [SDSS III-imaging X Planck, ACT]
- Integrated Sachs Wolfe Effect in CMB [SDSS III imaging X Planck]
- Cluster mass-SZ (Sunyaev Zeldovich) scaling [SDSS III imaging X ACT, Planck, SPT]

Full disclosure:

The results I showed earlier on primordial non-Gaussianities are highly preliminary because of the following, thus the list of future work:

- There are few assumptions/hand-waving that went into:
  - The error on the correction terms due to systematics
  - The translation between the Lagrangian bias and the Eulerian bias for QSOs are assumed to be b-1.6, which can be better modeled/improved
  - We currently throw out a significant number of QSO candidates, so that we have low stellar contamination in the high-z QSO sample. We choose a high QSO probability threshold to do this, this needs to be tested.

BAO: with Luminous Red Galaxies
What is new?

- Data: **Largest volume** ever used for galaxy clustering: 14,000 sq deg up to z=0.7, this is equivalent to $15\mathrm{Gpc}^3$

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BERKELEY LAB

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  - **Un** with various sys
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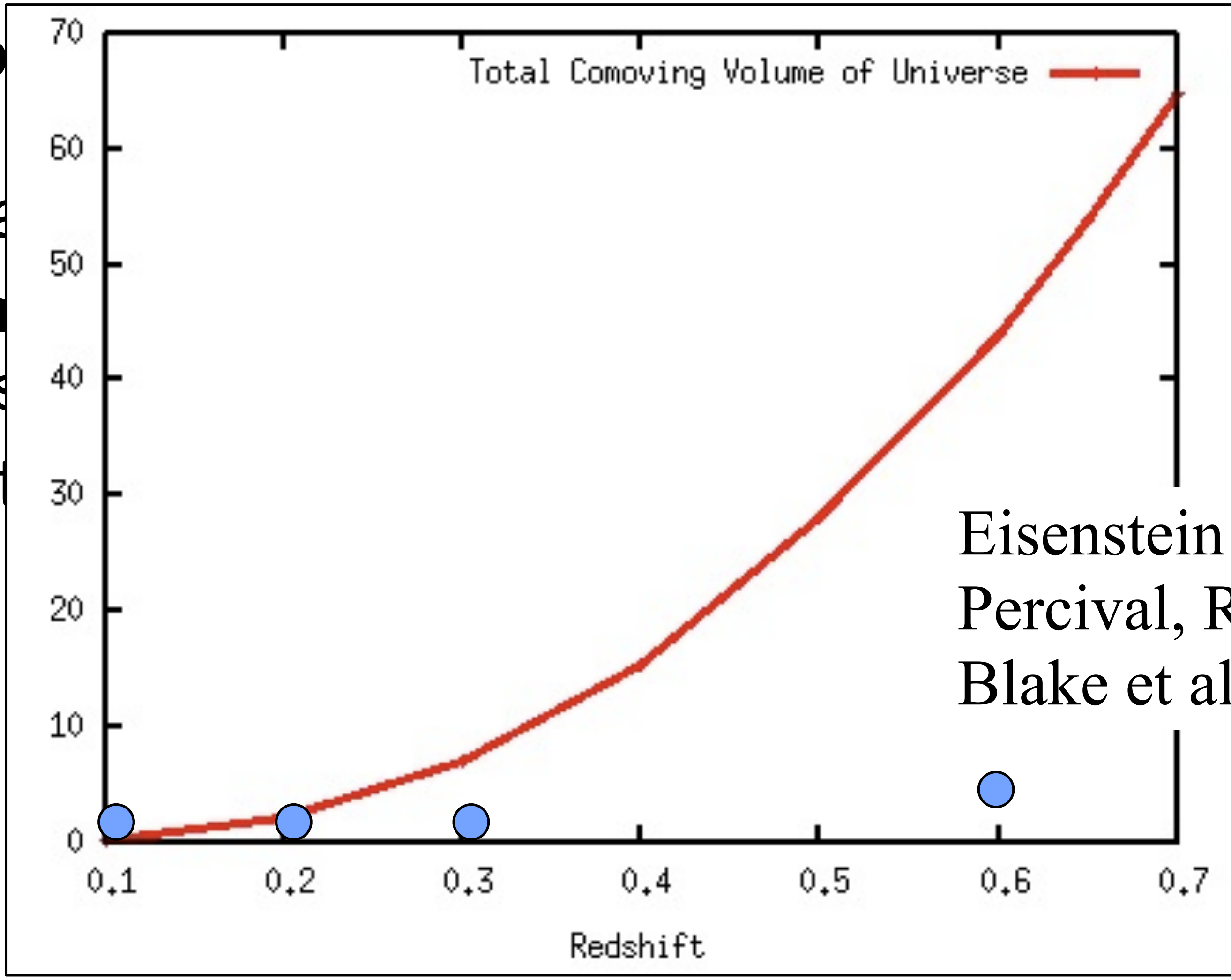

Eisenstein et al. 2005
Percival, Reid et al. 2008
Blake et al. 2011

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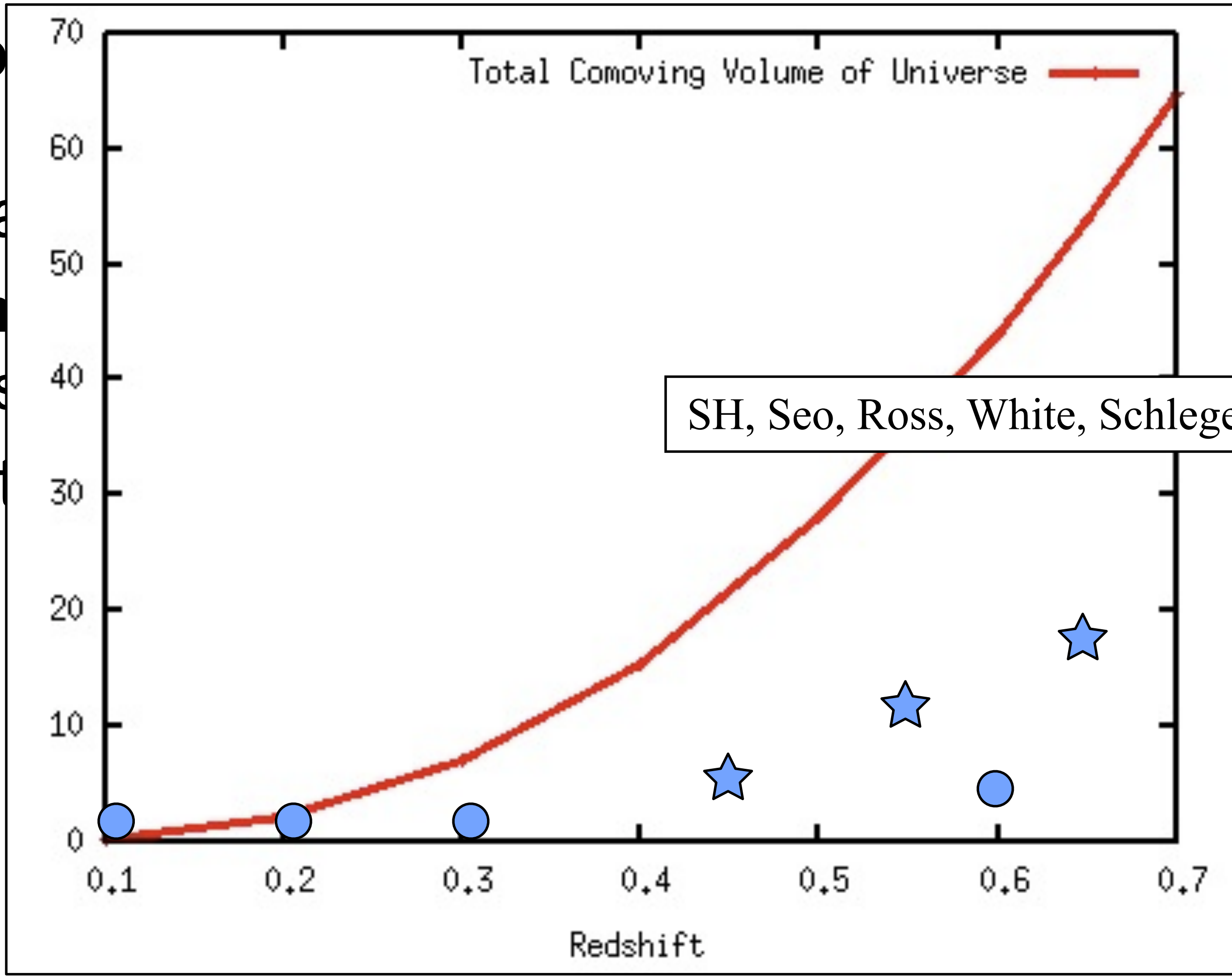

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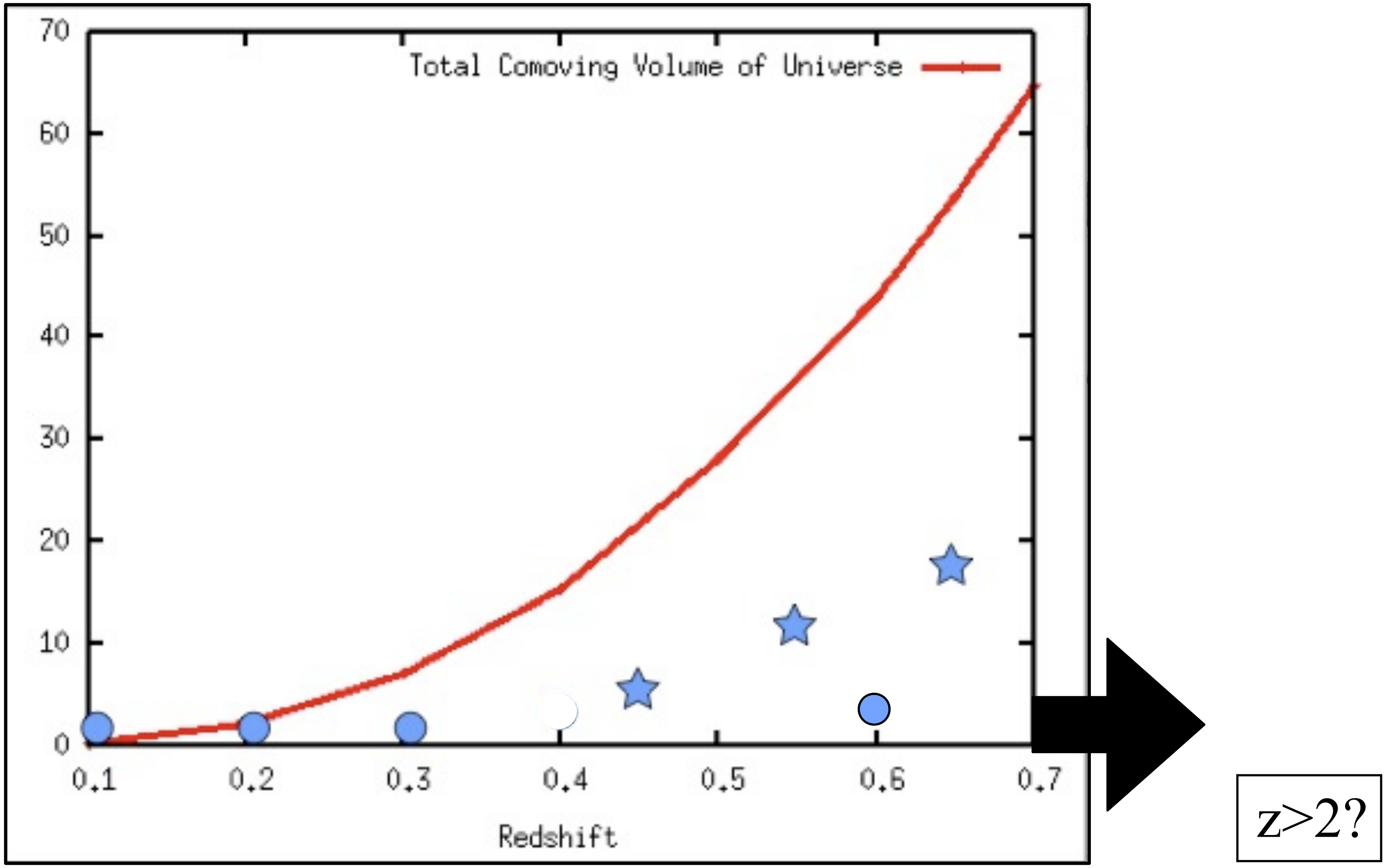
- Detection:
  - This work: Significant Detections at **high redshift** range: $0.45<z<0.65$ (competitive to constraints from spectroscopic survey WiggleZ [Blake et al. 2011])

BAO: with Luminous Red Galaxies
Looking forward

- Cosmological Constraints from BAO will be coming soon.
- More detailed systematic tests have to be carried out.
- Photometric LRGs can be used for BAO in upcoming surveys such as DES, PanStarrs and LSST.
- A variant of the Quadratic Estimator can be applied to any Spectroscopic LRGs (in SDSS III-BOSS, BigBOSS, SuMire-PFS, WFIRST...) will provide < 10% constraint on equation of state of Dark Energy.

BAO: Beyond Galaxies

- How can we learn about cosmology at much higher redshift ?



Next lecture ...

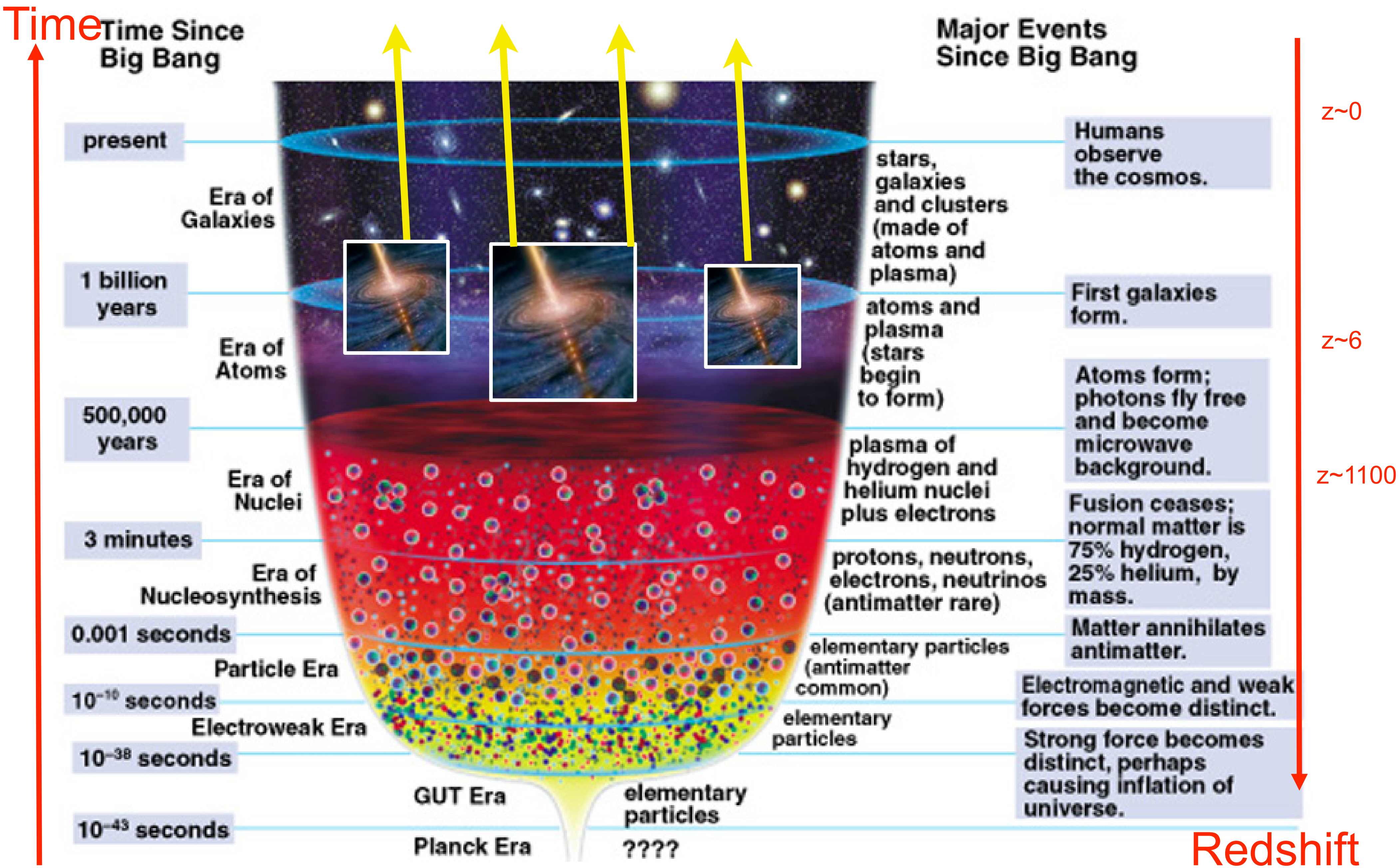
3 Lectures

- Dark Energy, Baryon Acoustic Oscillations and more
- Observational Cosmology in Action
- A new large scale structure tracer:
  - Lyman alpha forest

End of slides

Beyond: With Lyman Alpha Forest

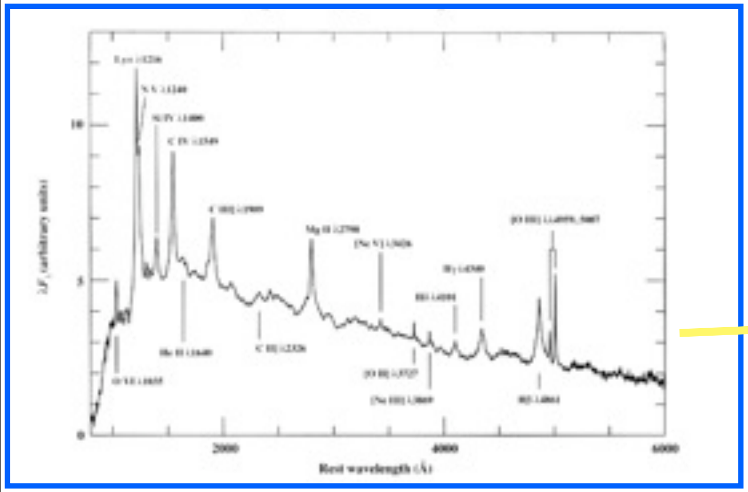
What is it?

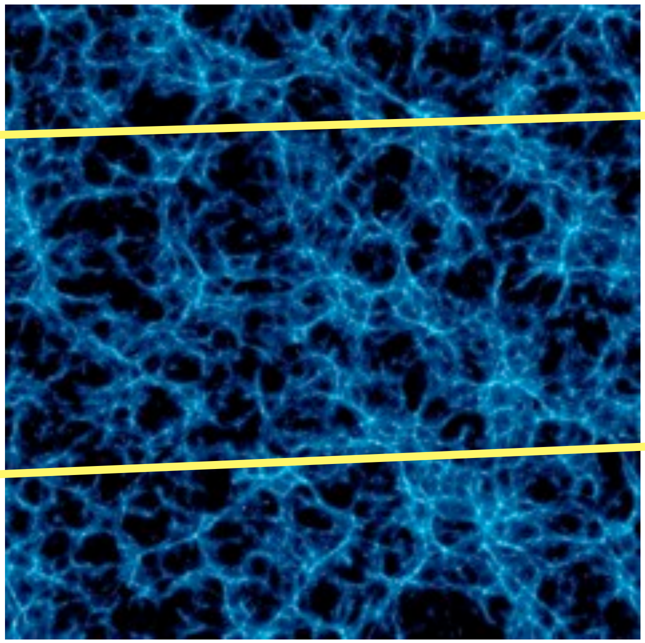


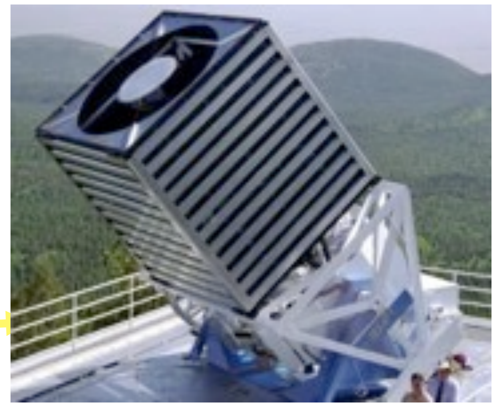
Beyond: With Lyman Alpha Forest

What is it?

Quasar Spectra





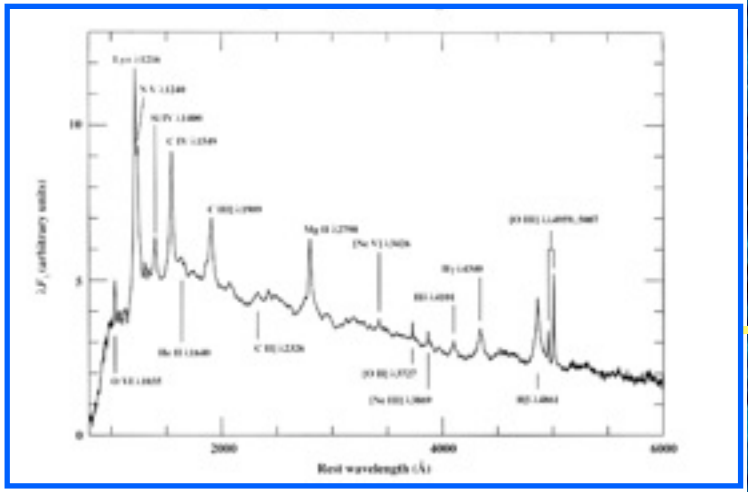


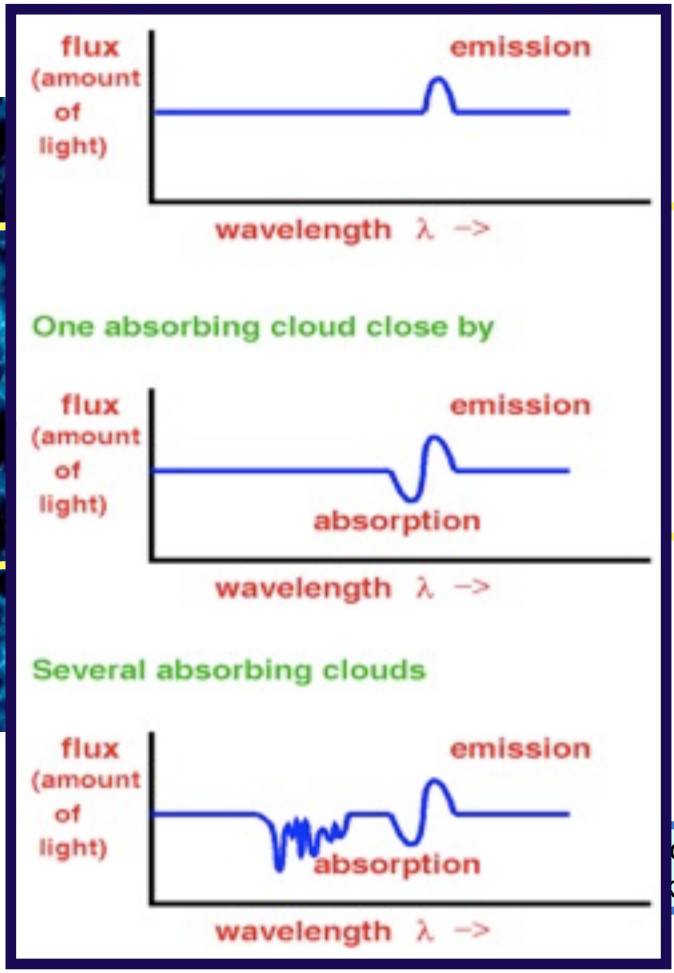
Courtesy simulation of gas from Renyue Cen and Jerry Ostriker

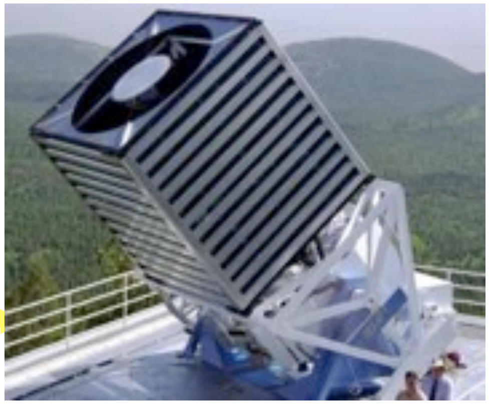
Beyond: With Lyman Alpha Forest

What is it?

Quasar Spectra





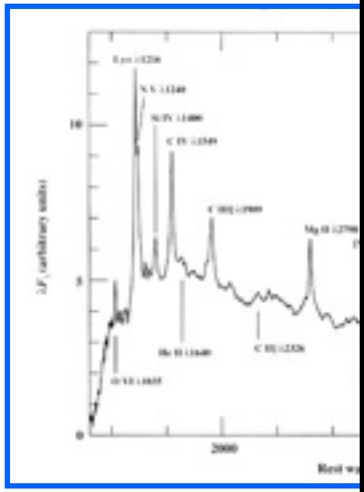


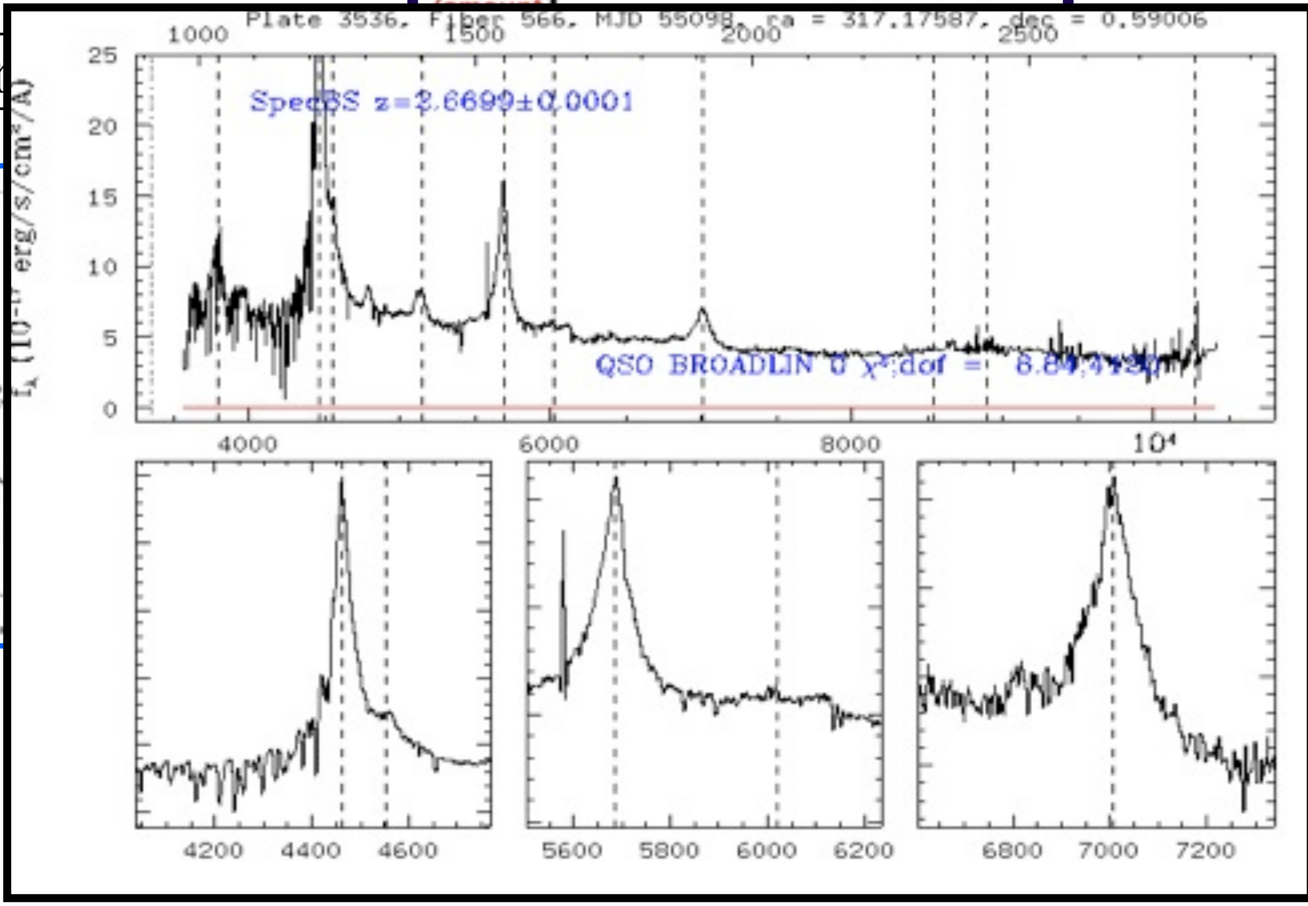
From Joanne Cohn's website

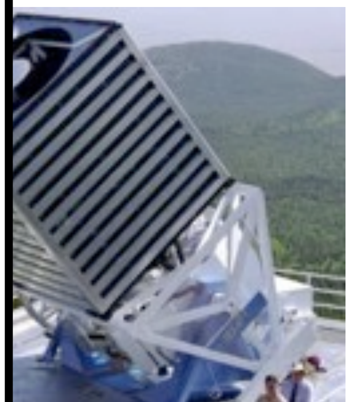
Beyond: With Lyman Alpha Forest
What is it?

Locates the Neutral Hydrogen of the Universe, thus tracing overdensities of the Universe

Quasar







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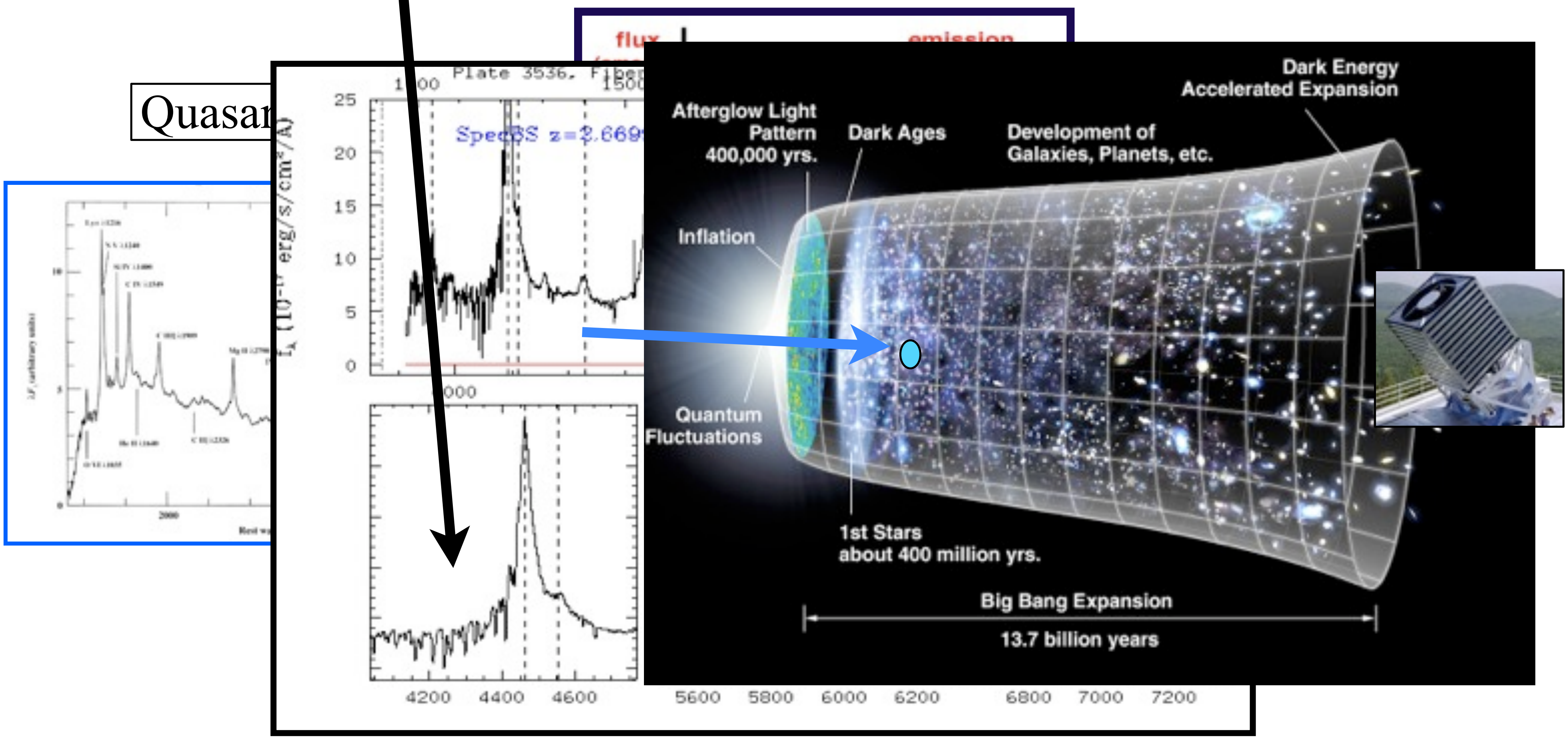

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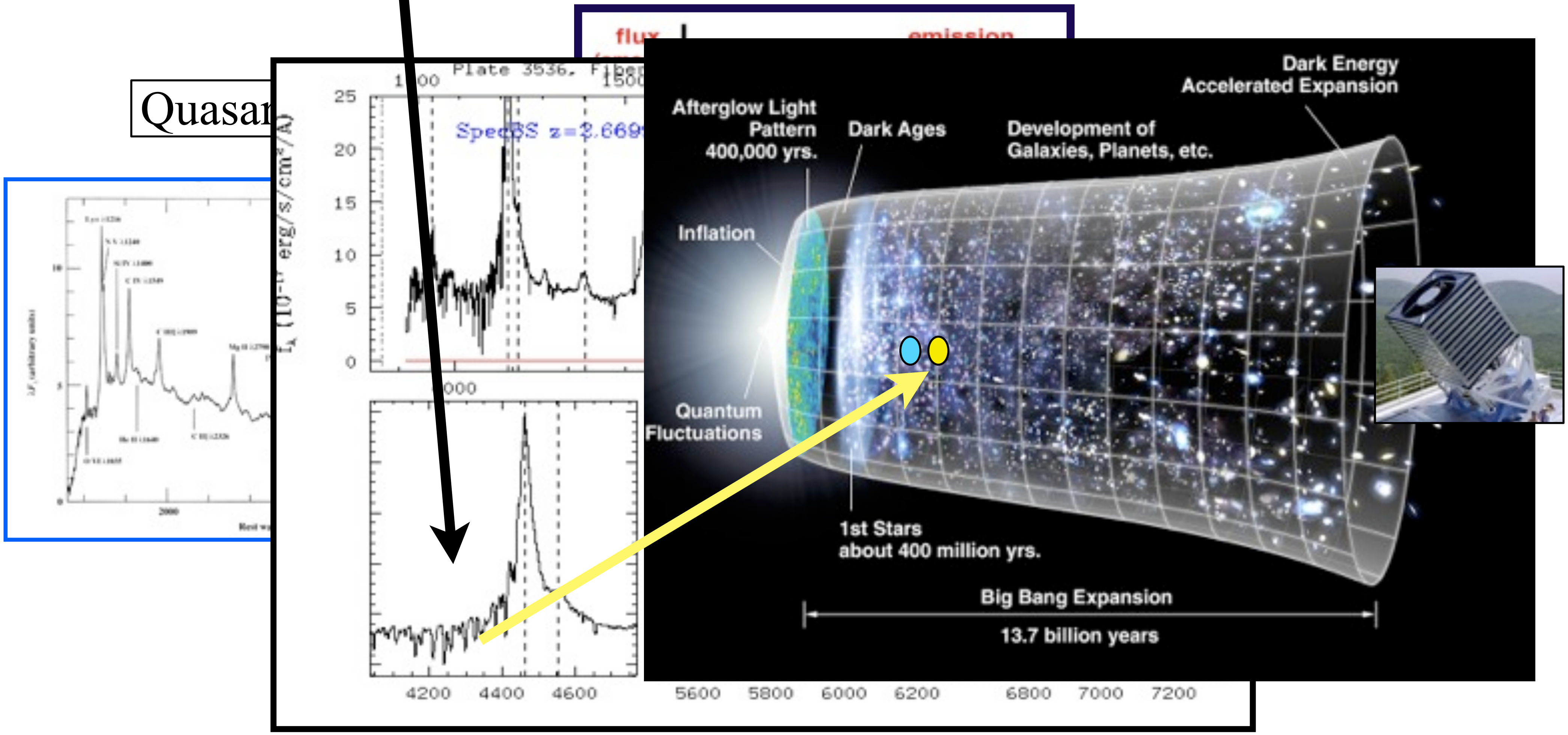

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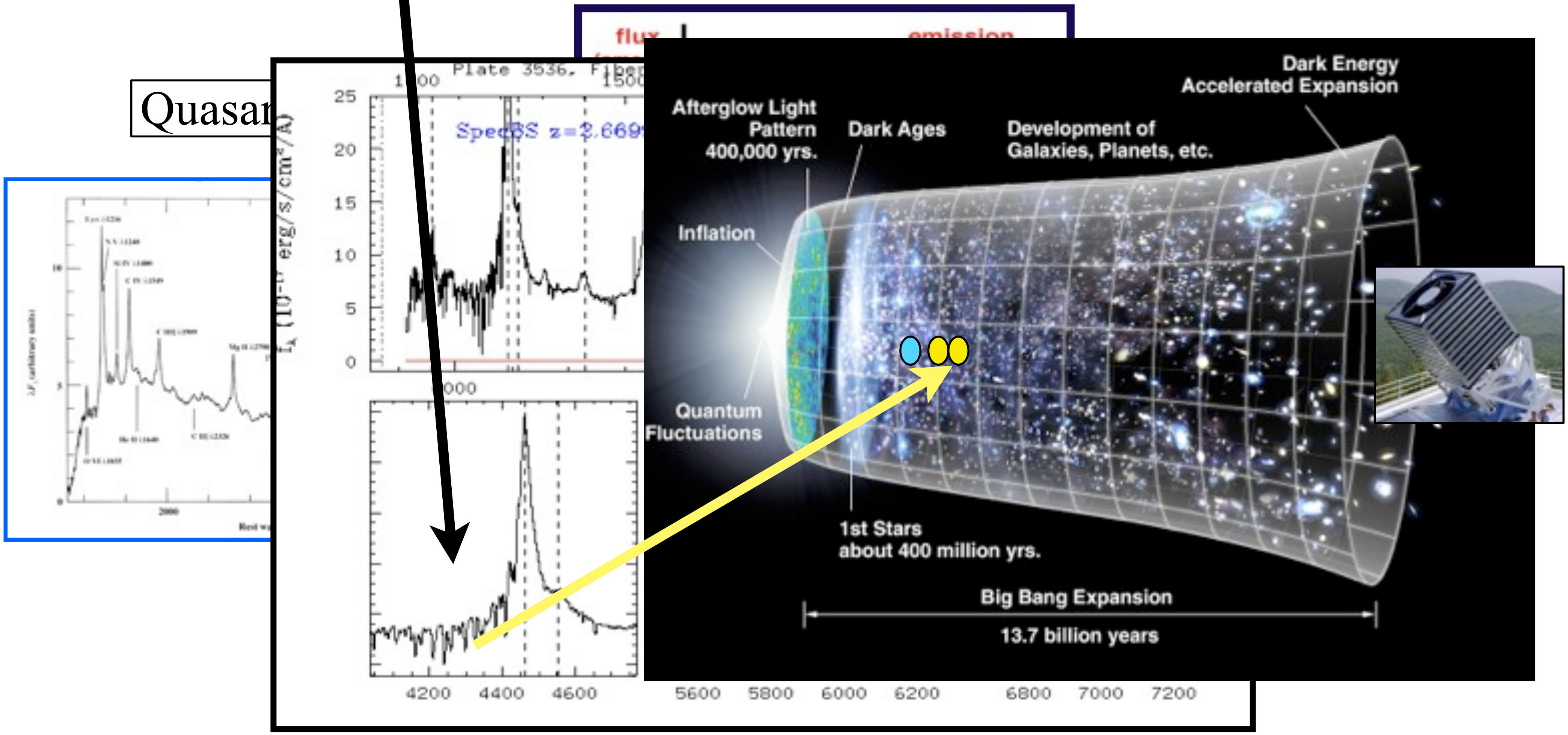

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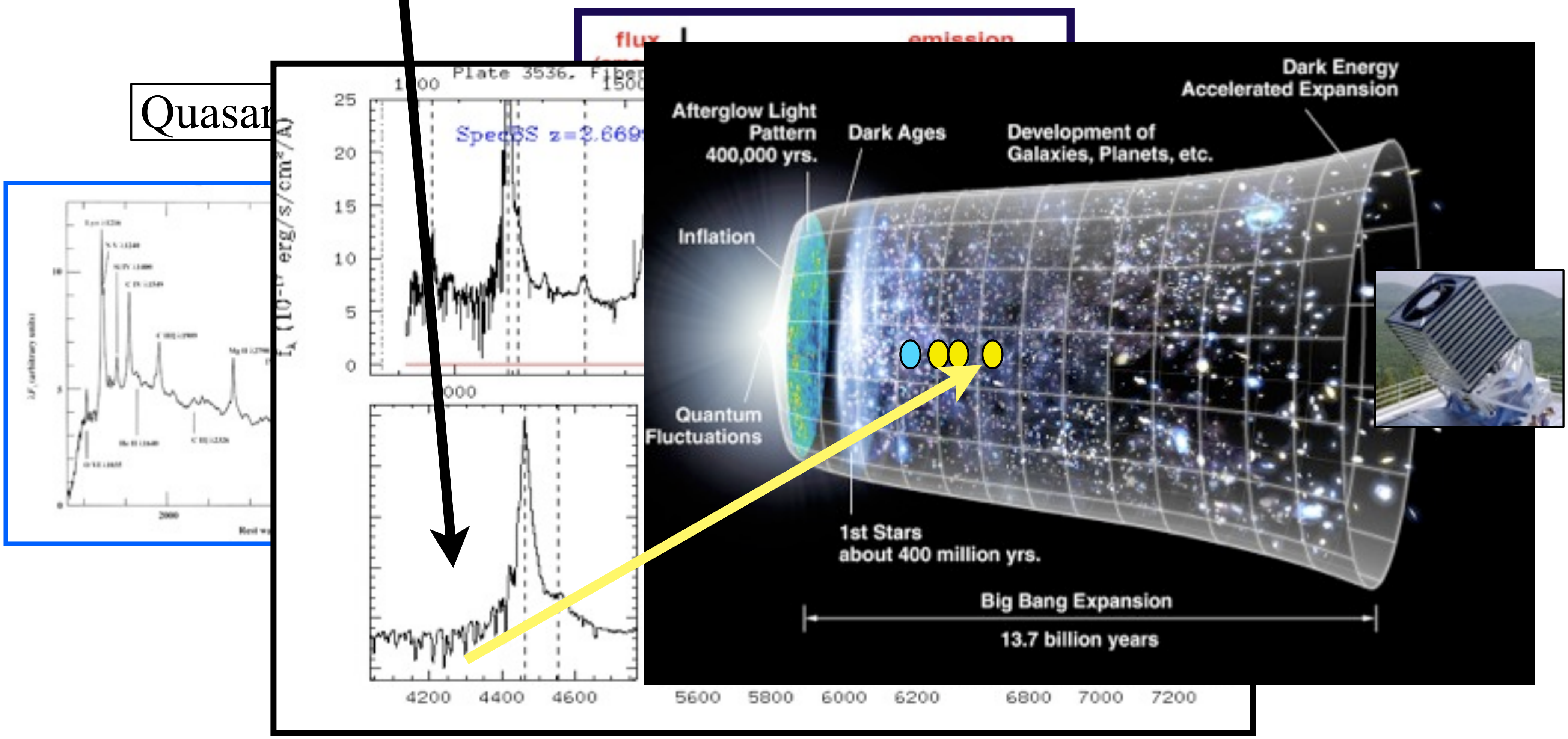

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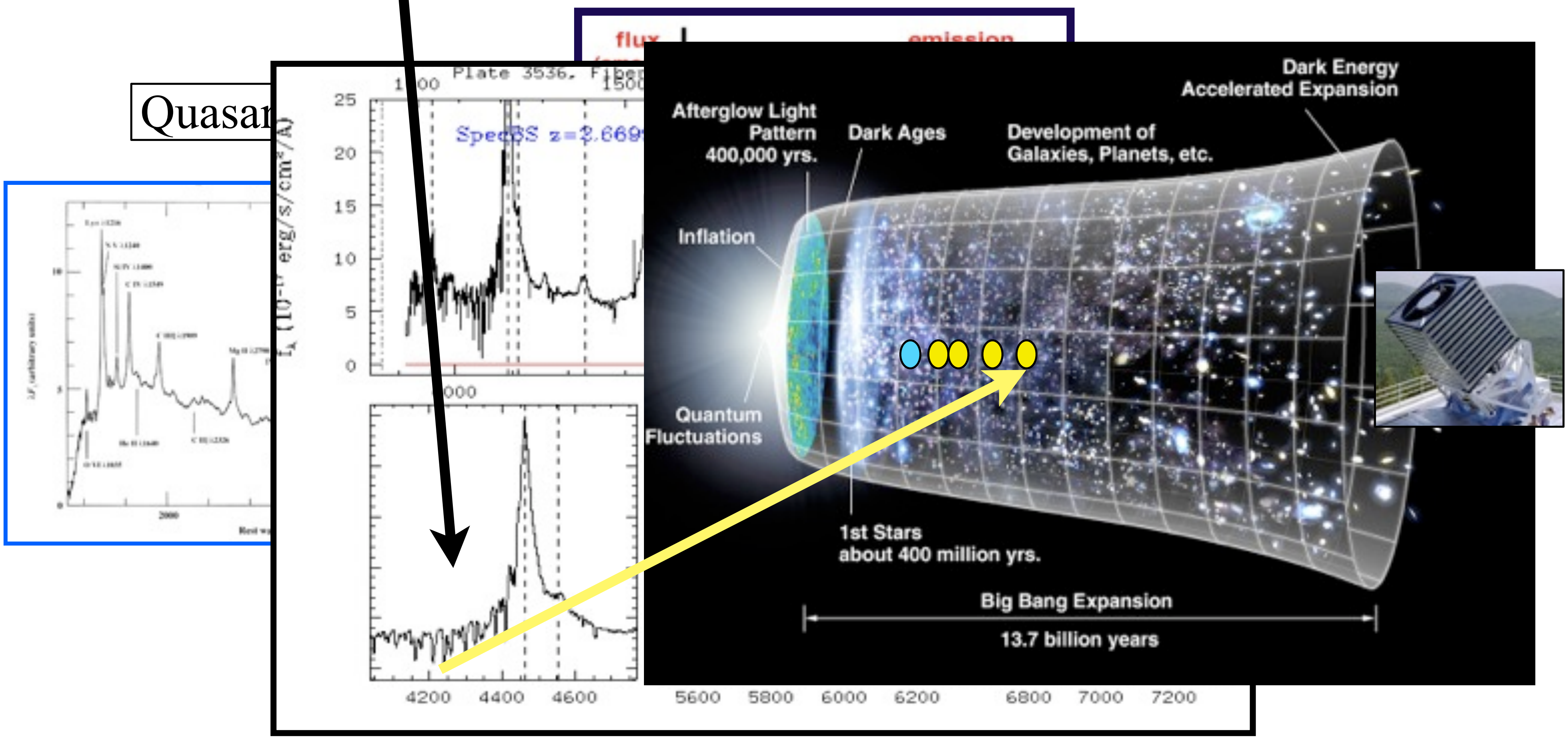

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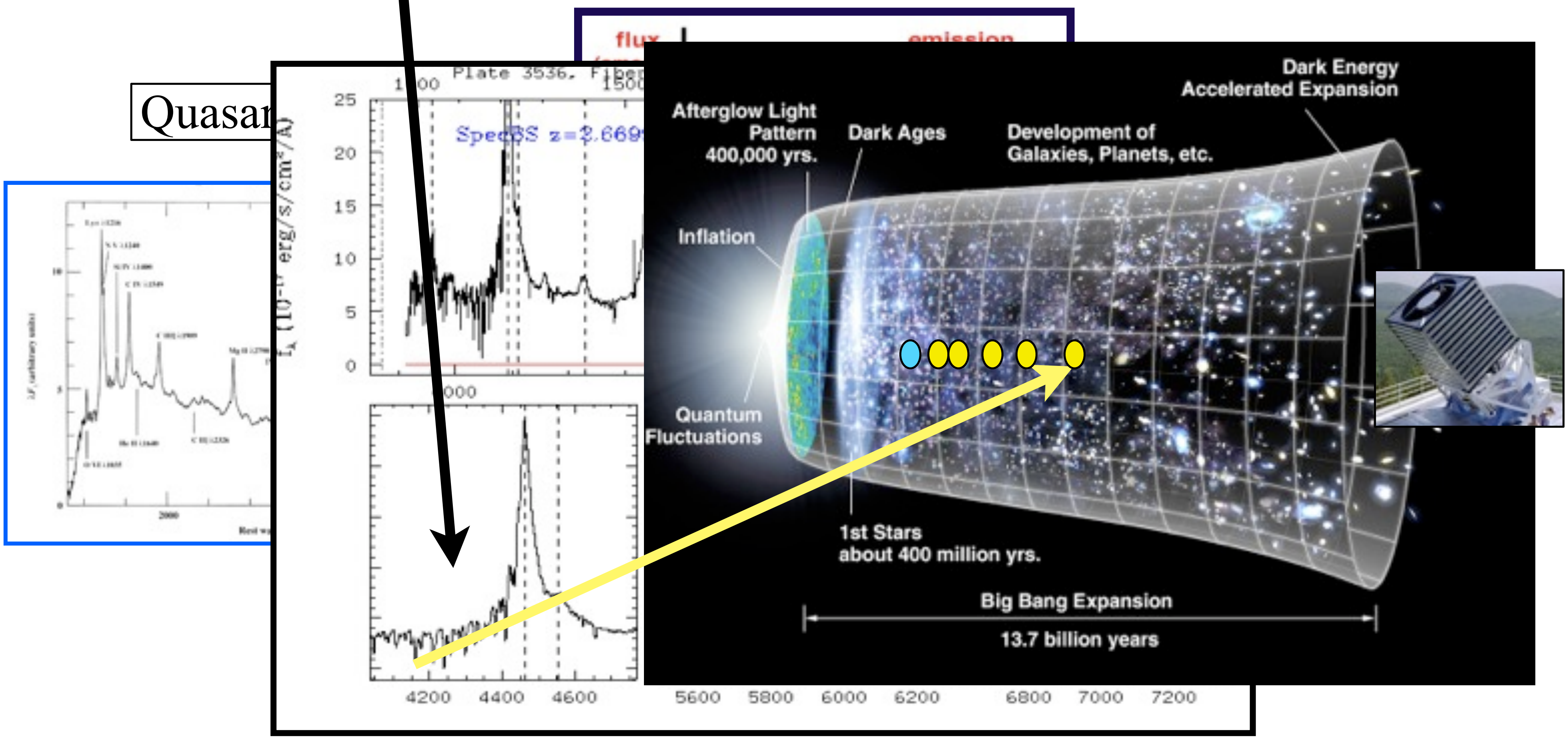

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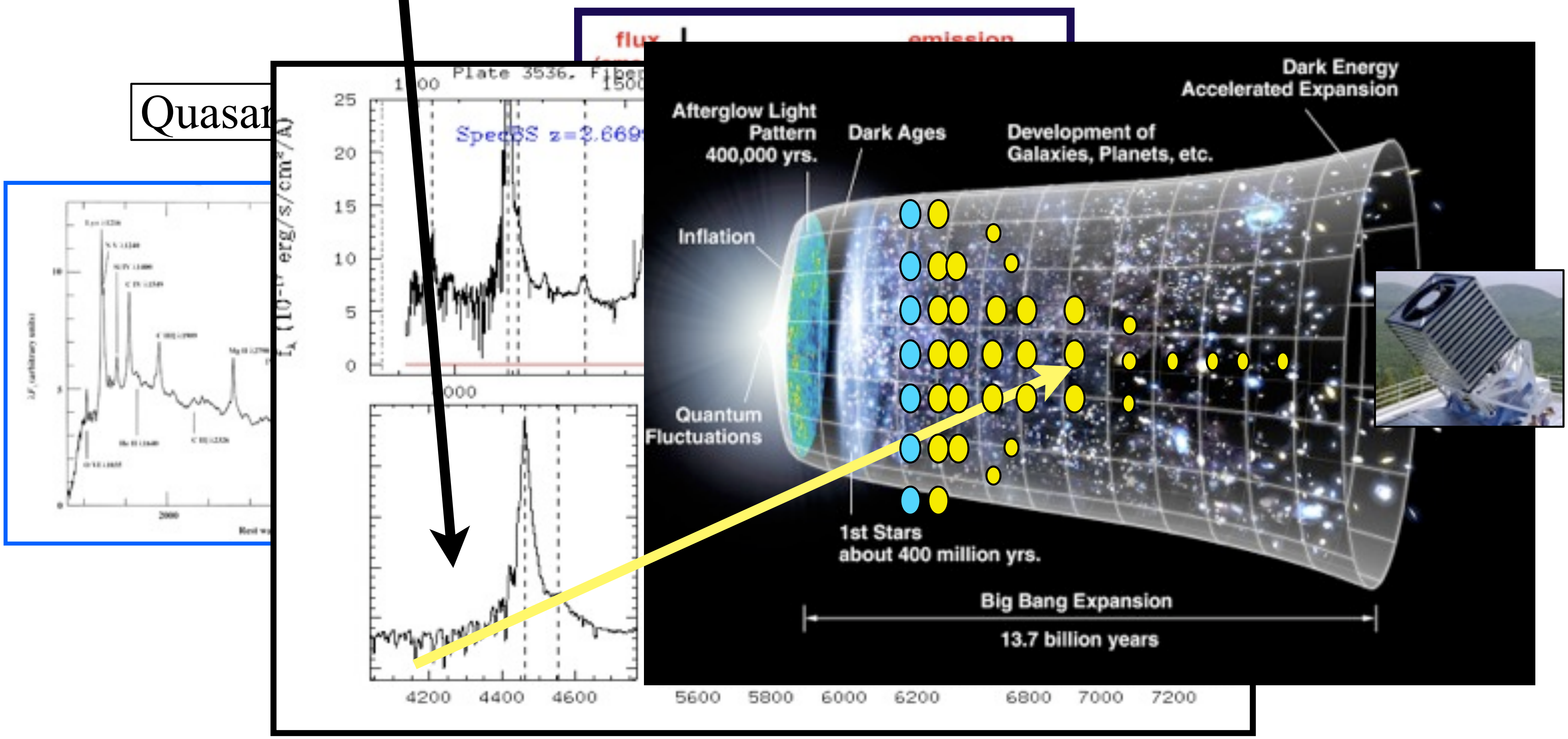

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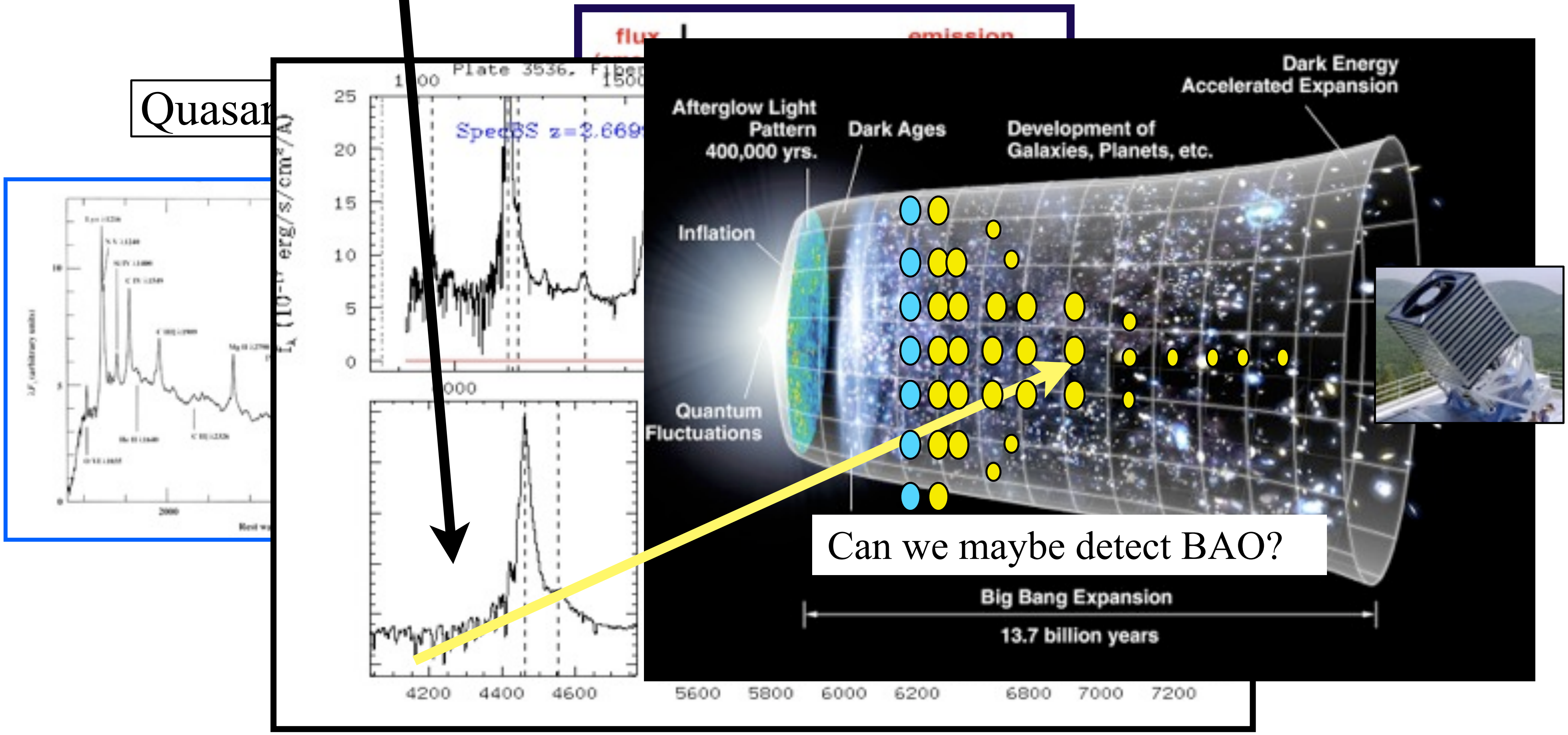
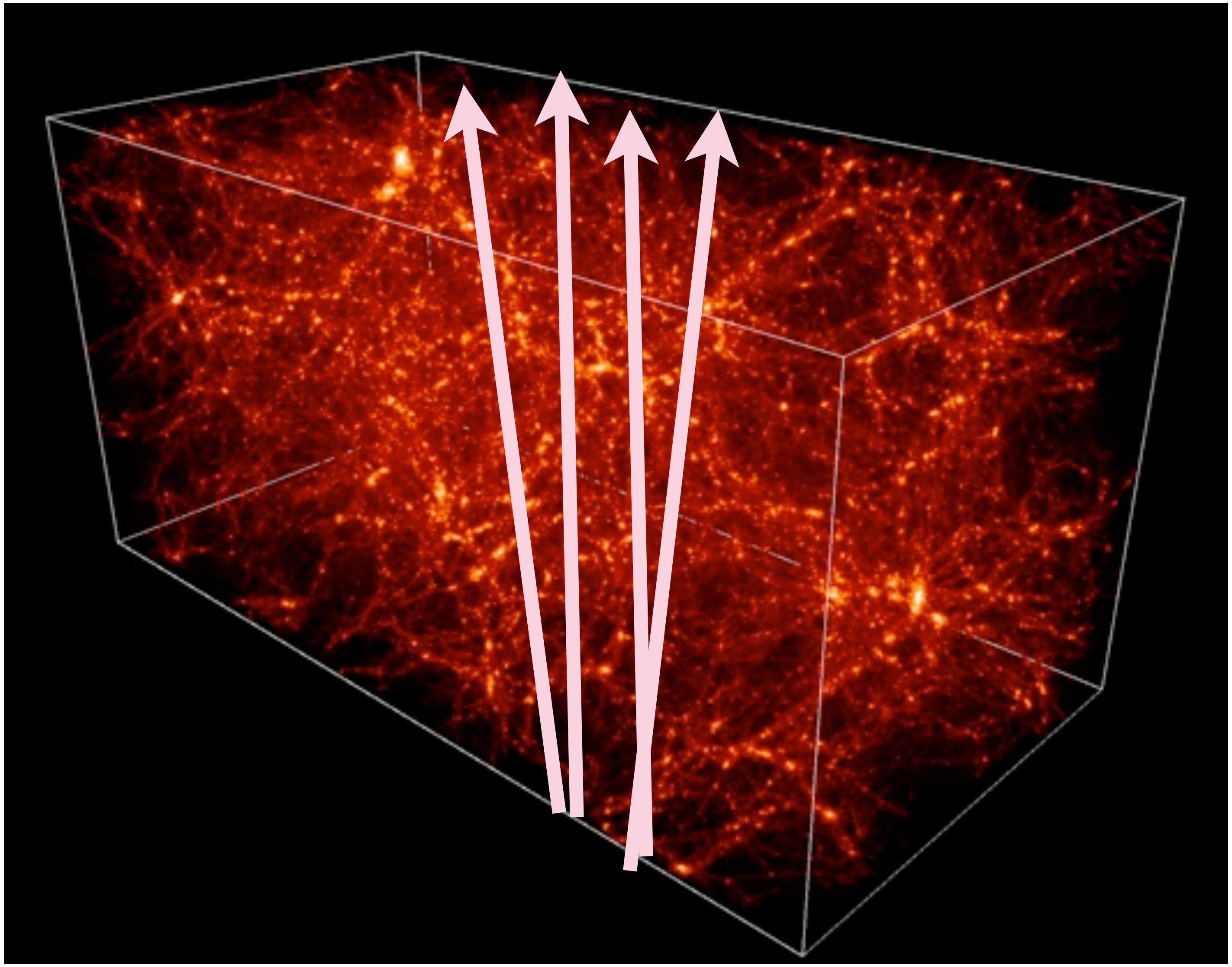


Beyond: With Lyman Alpha Forest
Simulations



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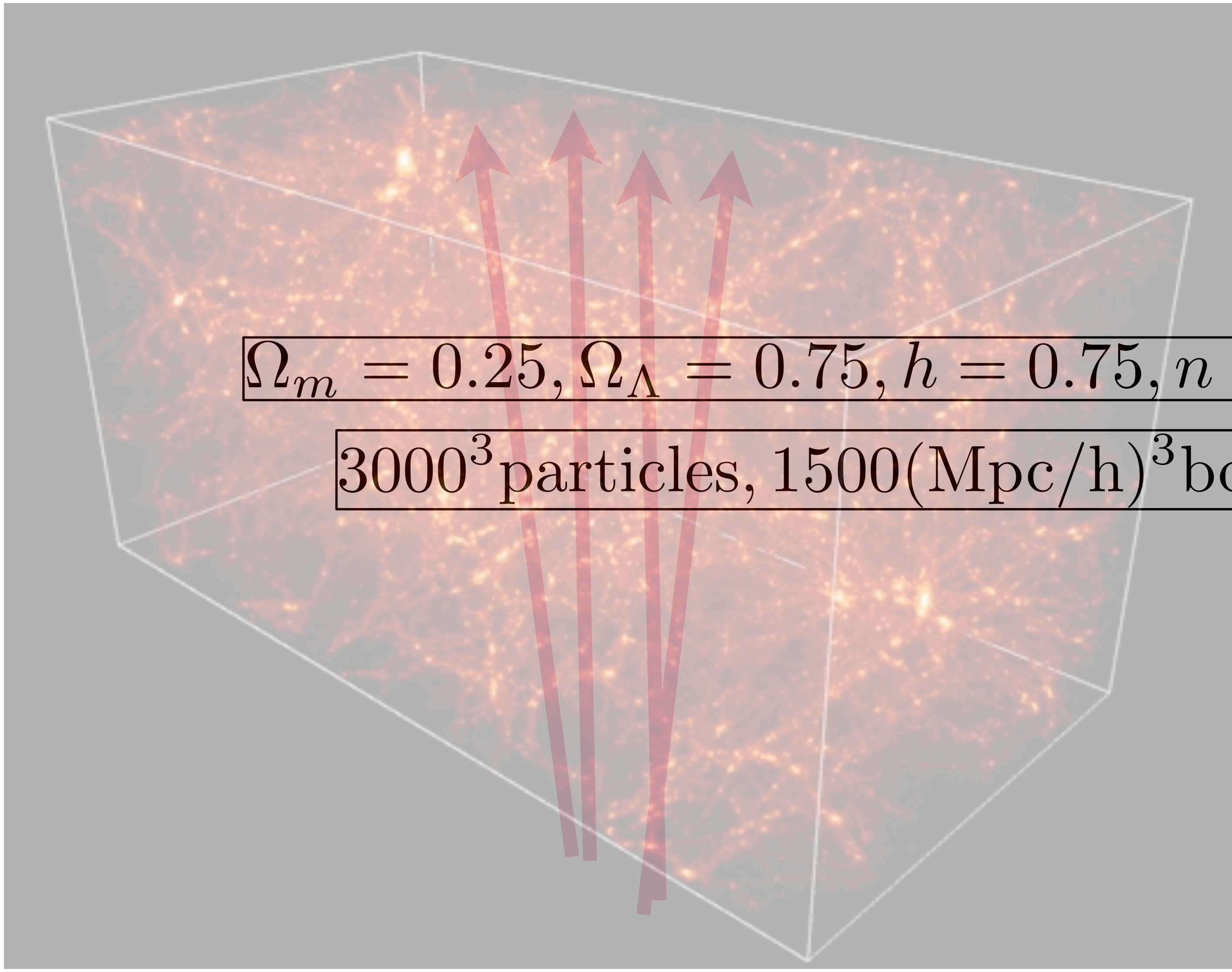
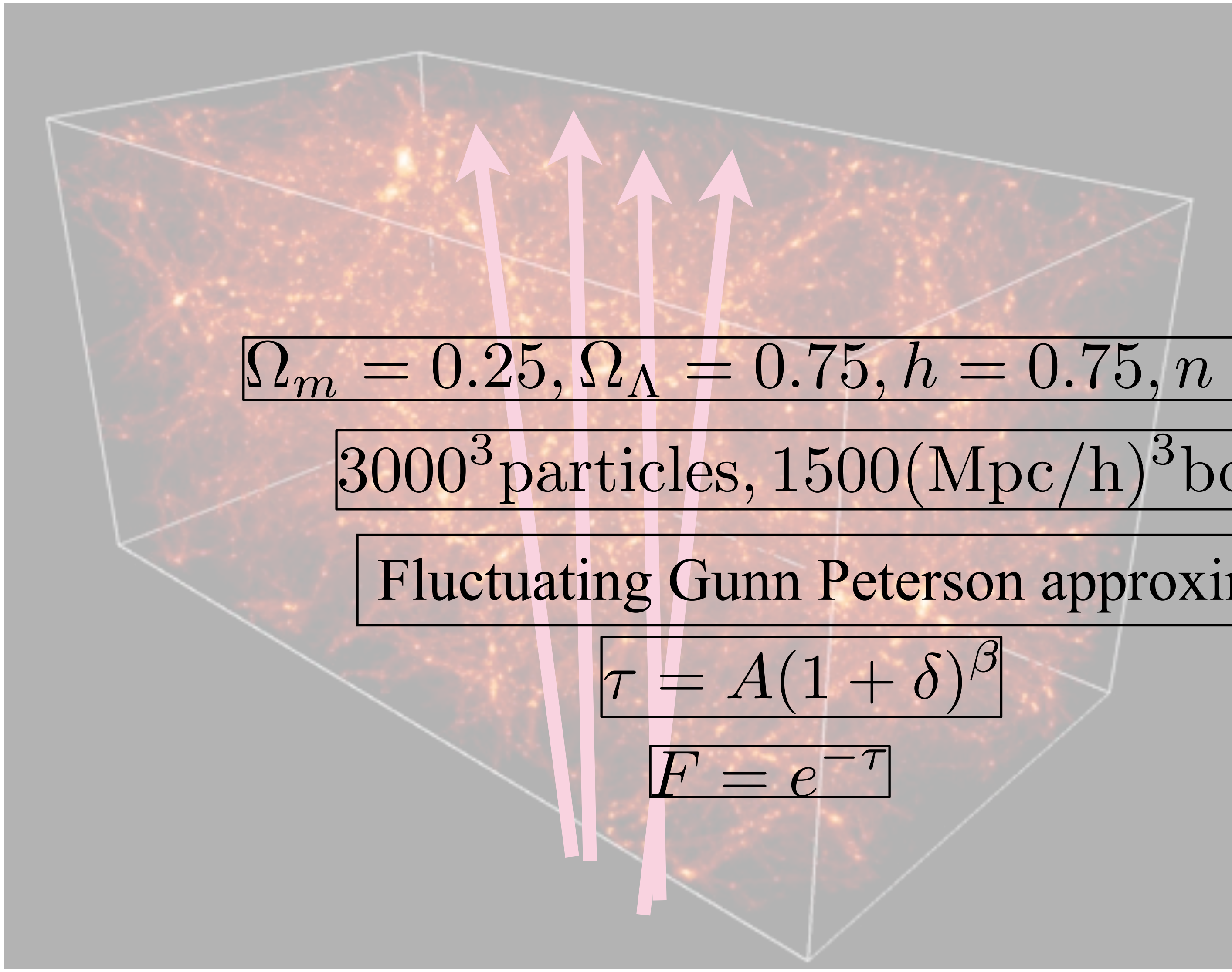


$$\Omega_m = 0.25, \Omega_\Lambda = 0.75, h = 0.75, n = 0.97, \sigma_8 = 0.8$$

$$3000^3 \text{particles}, 1500(\text{Mpc/h})^3 \text{box}, 3000^3 \text{grid}$$

Beyond: With Lyman Alpha Forest
Simulations



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Fluctuating Gunn Peterson approximation

$$\tau = A(1+\delta)^\beta$$

$$F = e^{-\tau}$$

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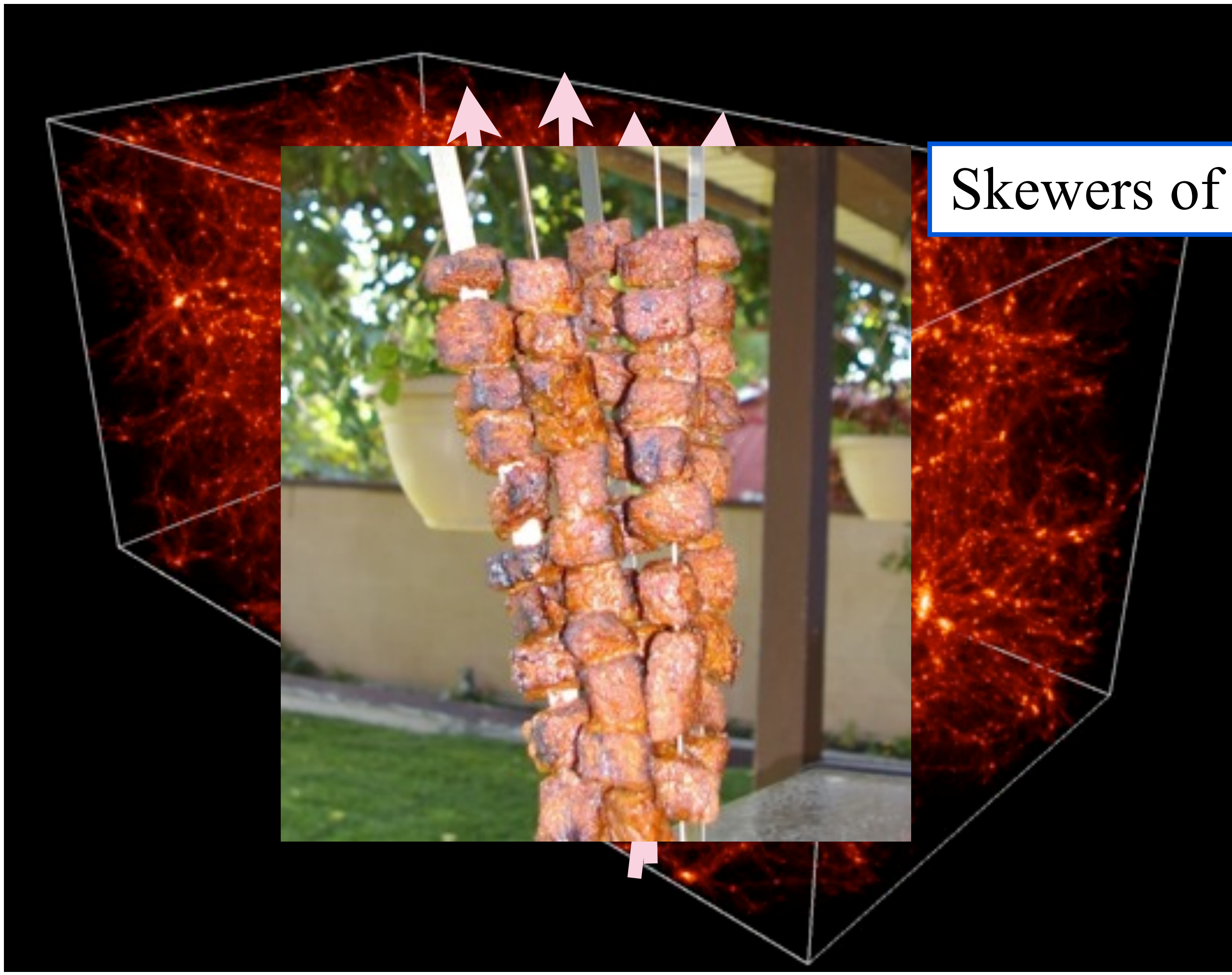
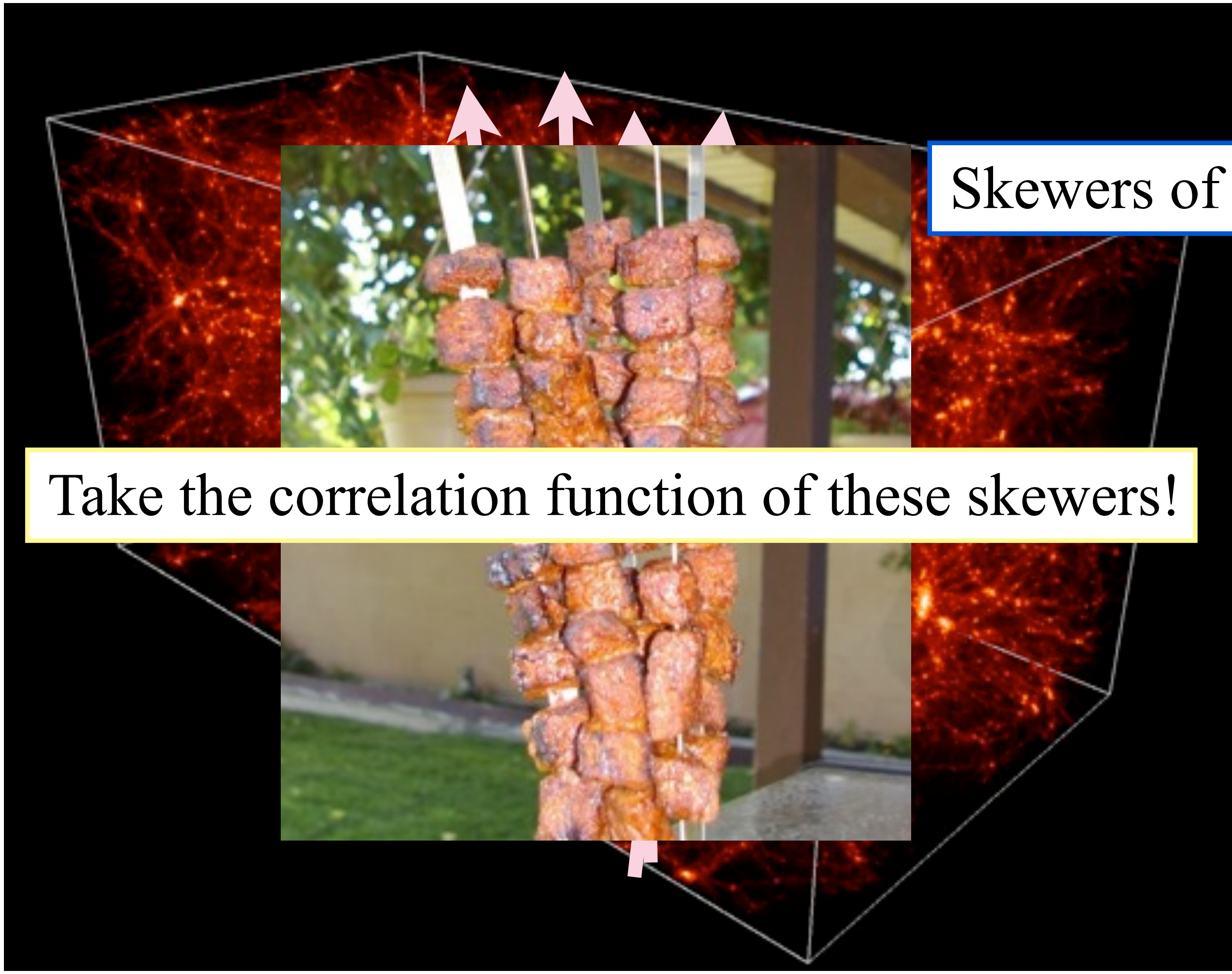
Simulations



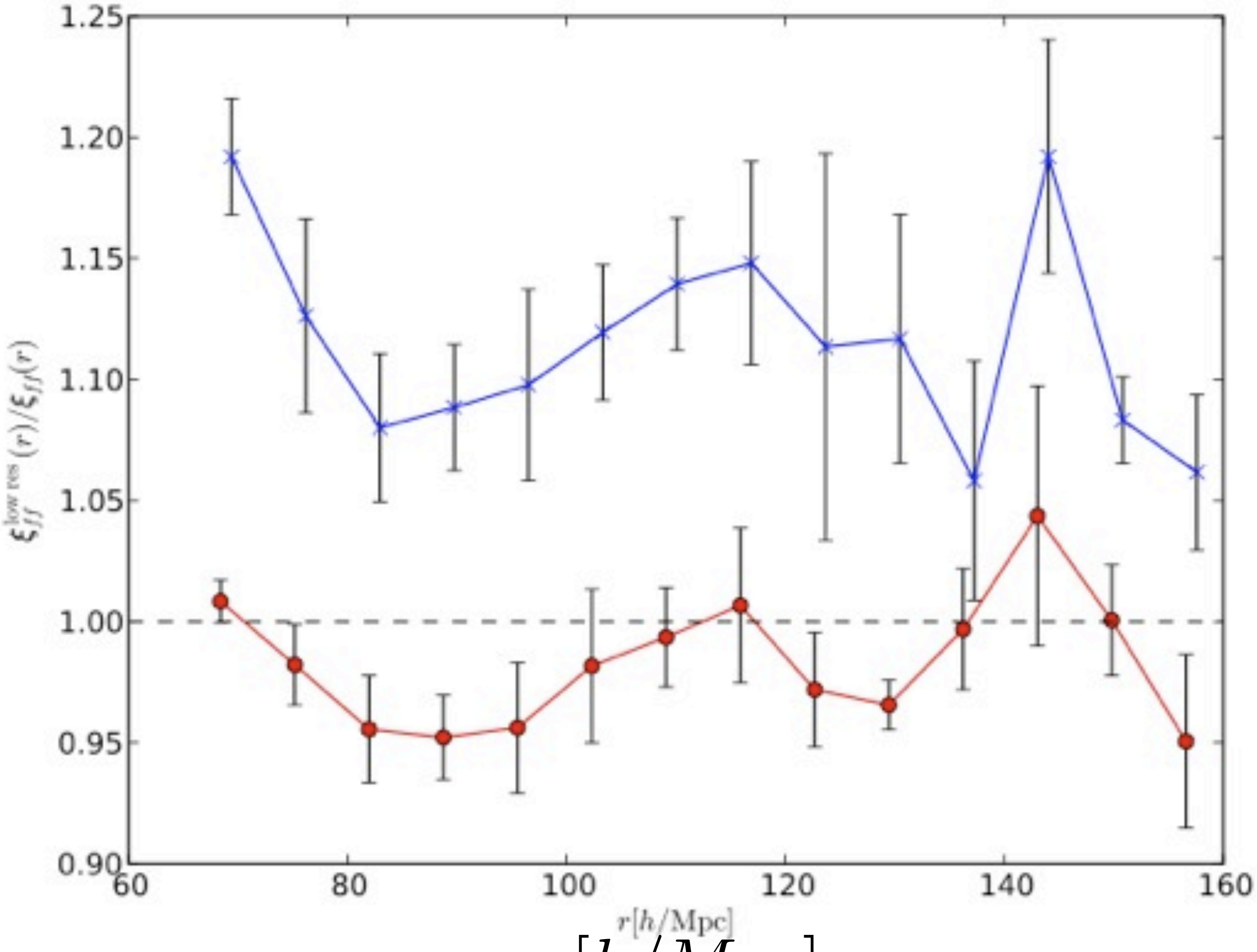
Skewers of Neutral Hydrogen

Beyond: With Lyman Alpha Forest
Simulations



Beyond: With Lyman Alpha Forest
Simulations: Resolution Effects?

$$\xi_{ff}^{\mathrm{lowres}}(r)/\xi_{ff}(r)$$



resolution 4X worse

resolution 2X worse

$r[h/Mpc]$

Slosar, SH, White & Louis (2009)

Beyond: With Lyman Alpha Forest
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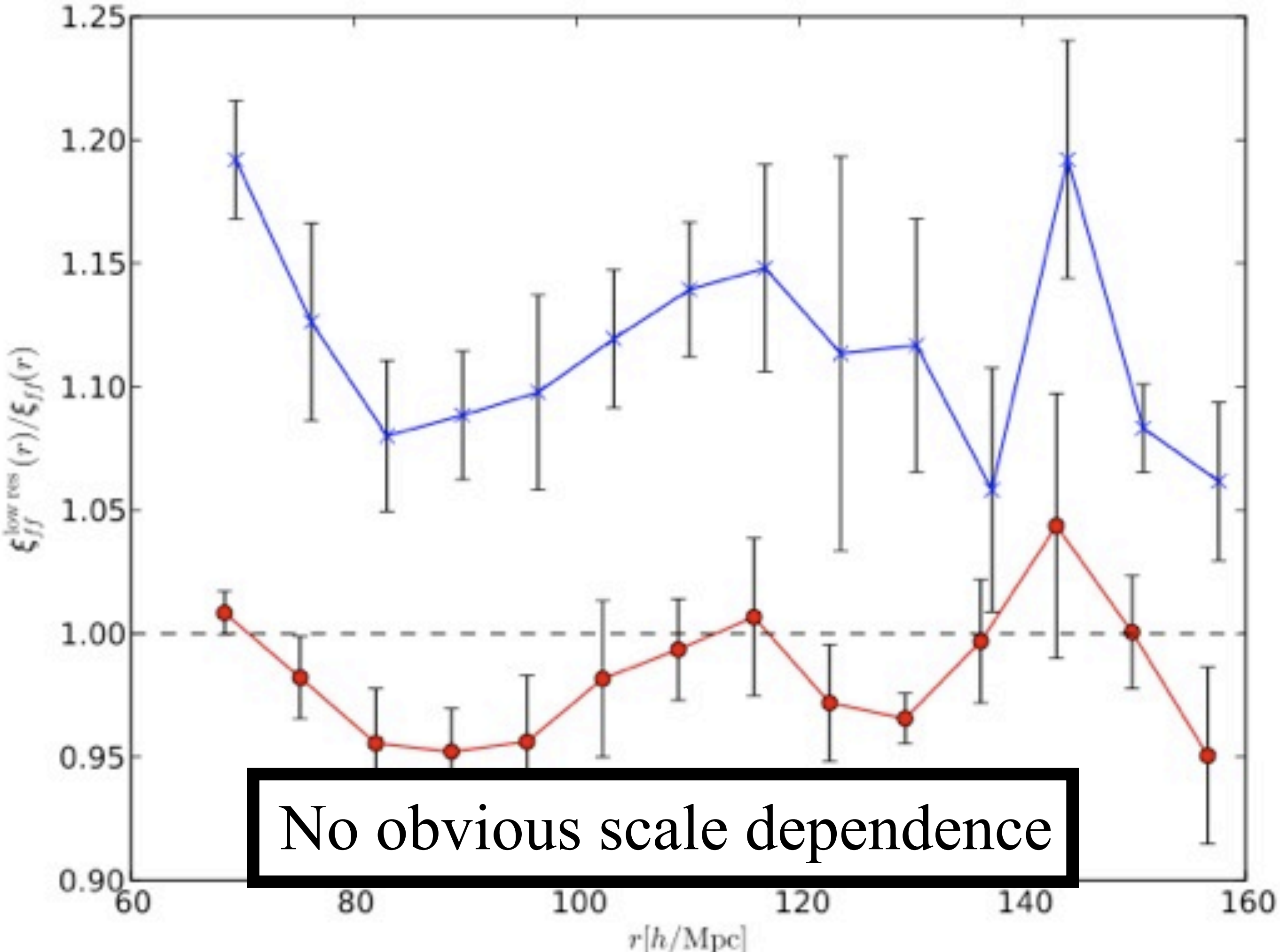
$\xi_{ff}^{\text{lowres}}(r)/\xi_{ff}(r)$



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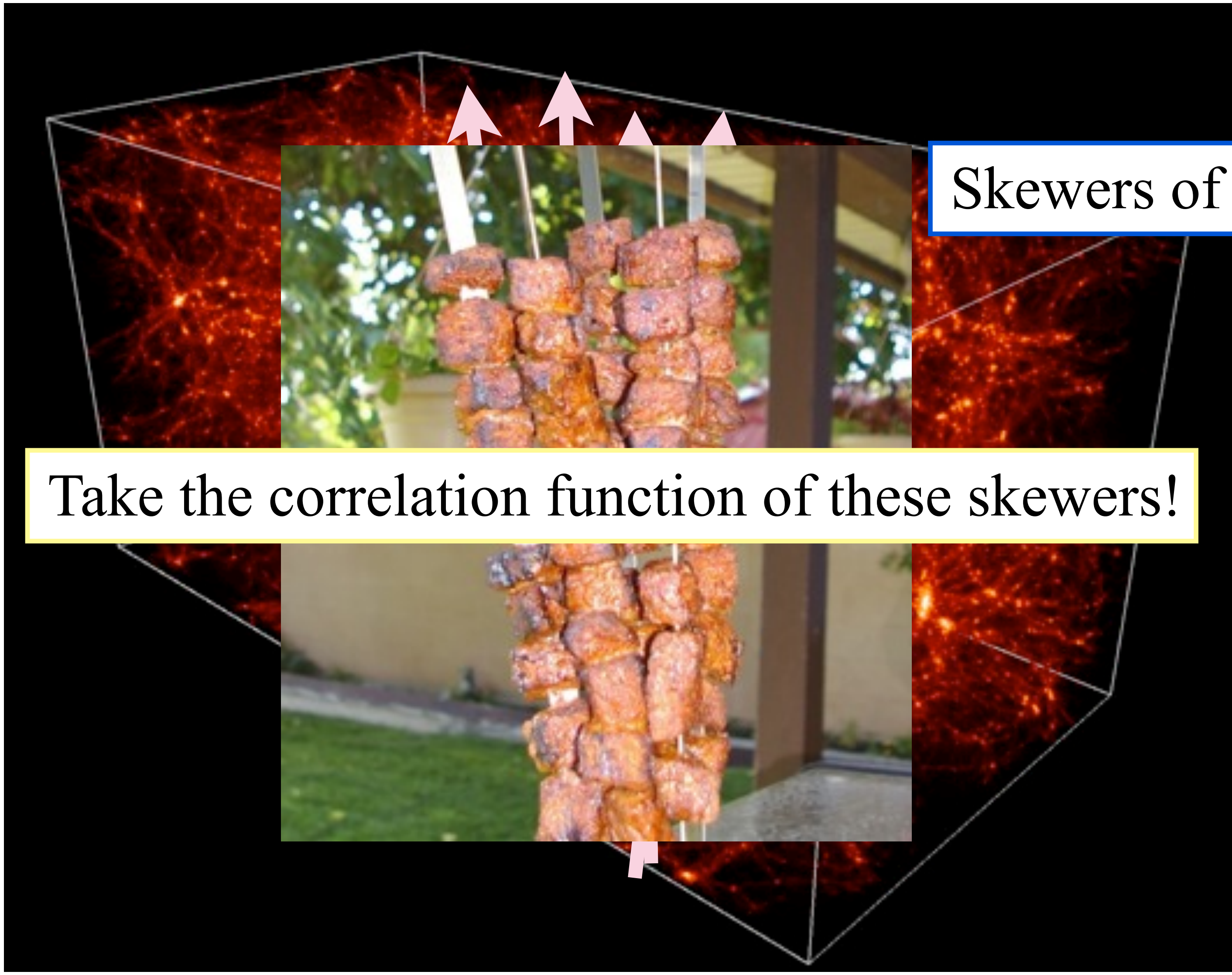


Beyond: With Lyman Alpha Forest
Correlation function (in configuration space)

$$\xi_f(r) =< \delta_f(\hat{x})\delta_f(\hat{x}+\hat{r}) >$$

BAO: with Luminous Red Galaxies
Systematics

- The Reason why BAO become so popular is that it is one of the cleanest probe of cosmology, since there are not that many systematics that can cause a shift in BAO scale (~100 Mpc)
- Therefore, the systematics I am going through here are mostly for getting a clean angular power-spectrum which contains other information such as the shape of matter power-spectrum, scale dependent bias that can be caused by non-gaussianities at the early Universe.

Color offsets: We compute cross-correlations between all of the photometric offsets (from Schlafly et al. 2010)

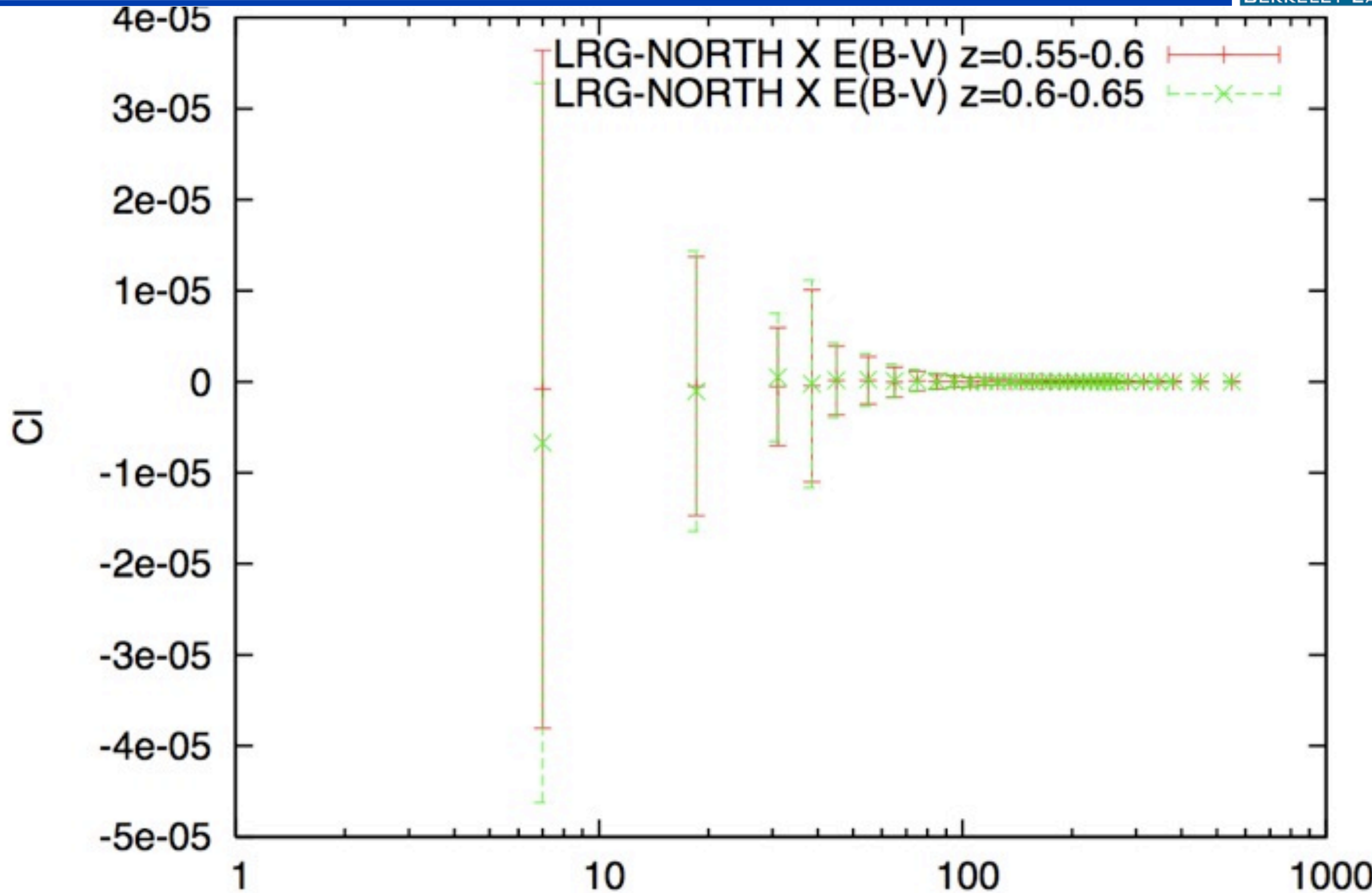
$$C_l^{gg}(\mathrm{DATA}) = \mathrm{b}^2 \mathrm{C}_\mathrm{l}^{\delta_\mathrm{m}\delta_\mathrm{m}} + \mathrm{C}_\mathrm{l}^{\mathrm{d,d}} + \mathrm{C}_\mathrm{l}^{\mathrm{s,s}} + \mathrm{C}_\mathrm{l}^{\mathrm{g(z),g(z')}} + \ldots$$

Dust Extinction: We cross-correlate the extinction map (SFD) with the galaxies to see if there is any correlations.

Stellar Contamination: We cross-correlate the stellar density maps (generated from SDSS) with the galaxies.

Galaxies from next photometric slice: We compute all the correlations between different redshift slices, and take into account of the covariances and correlations between different slices.

The effect of dust extinction



Ho, Seo, Ross, White, Schlegel et al. (in prep)

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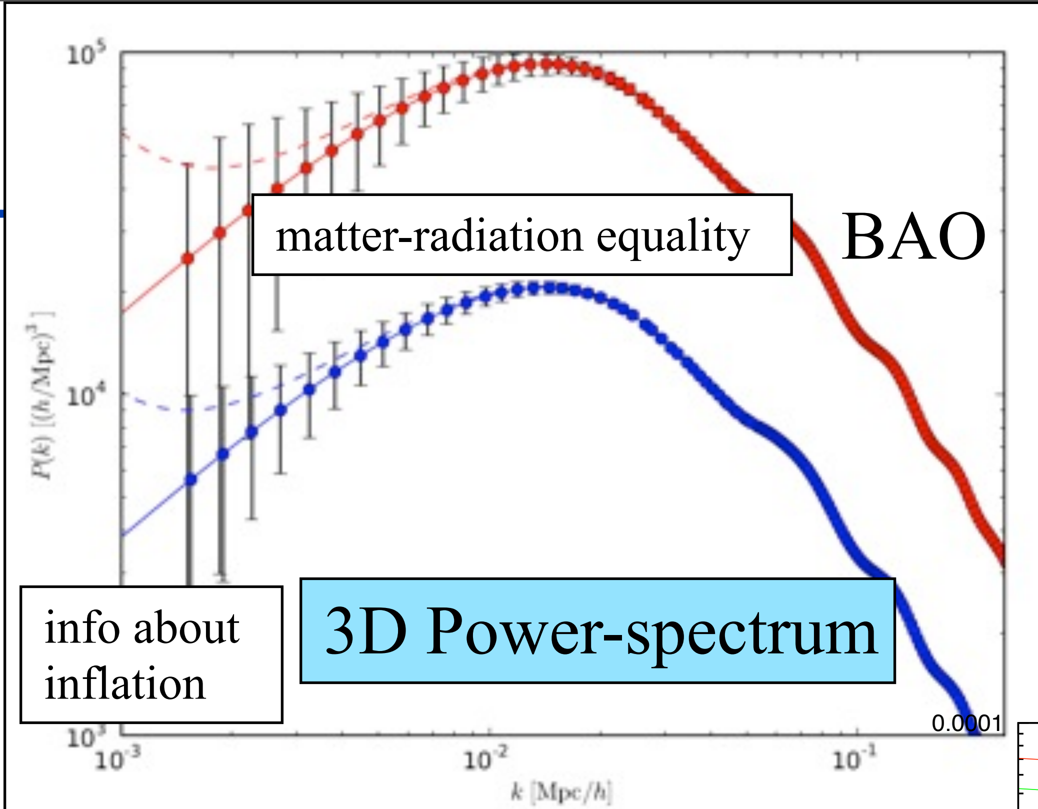
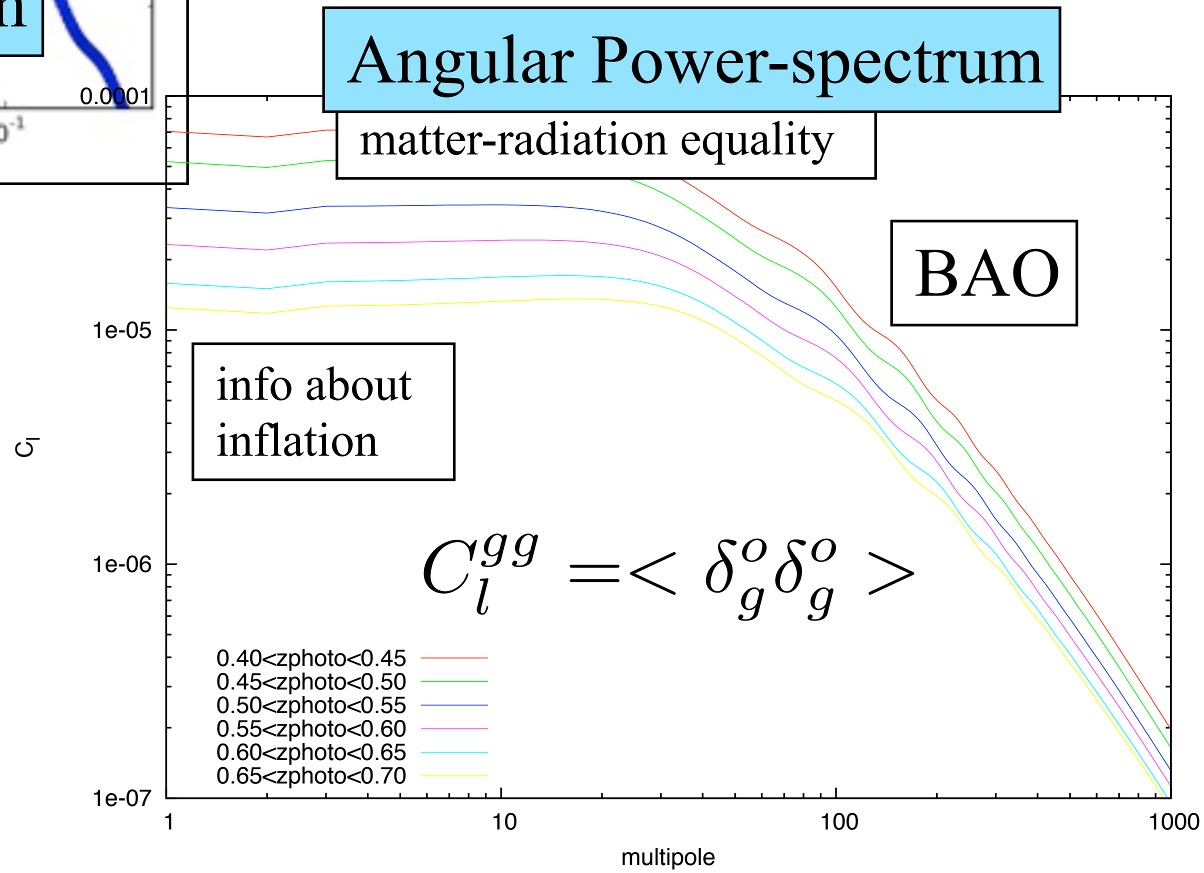
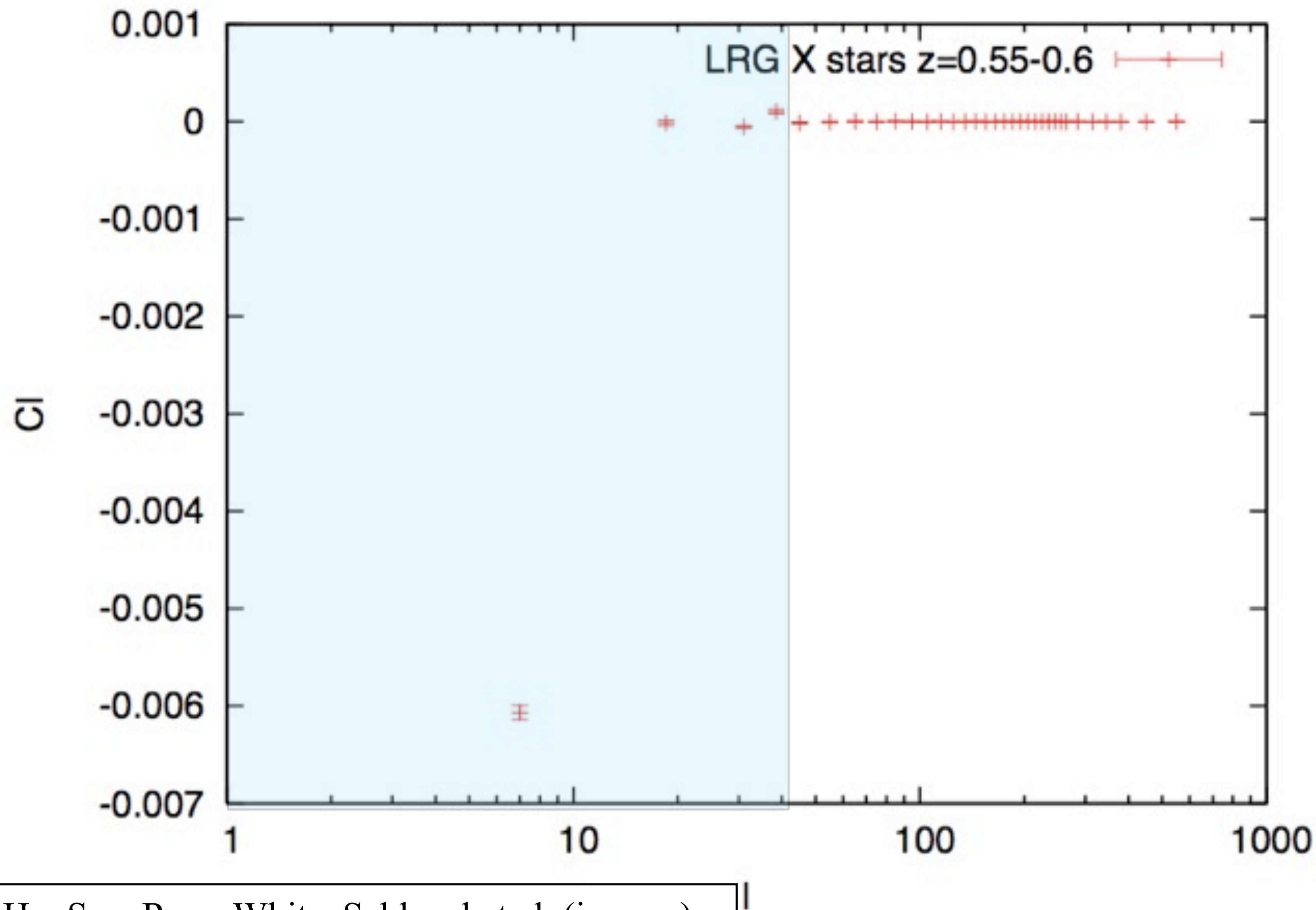


plot borrowed from Anze Slosar

Recall: Eisenstein et al.(2005), Percival & Reid et al. (2010), Blake et al (2011)



The effect of stars



Ho, Seo, Ross, White, Schlegel et al. (in prep)

BAO: with Luminous Red Galaxies
Systematics

- The Reason why BAO become so popular is that it is one of the cleanest probe of cosmology, since there are not that many systematics that can cause a shift in BAO scale (~100 Mpc)
- Therefore, the systematics I am going through here are mostly for getting a clean angular power-spectrum which contains other information such as the shape of matter power-spectrum, scale dependent bias that can be caused by non-gaussianities at the early Universe.

Color offsets: We compute cross-correlations between all of the photometric offsets (from Schlafly et al. 2010)

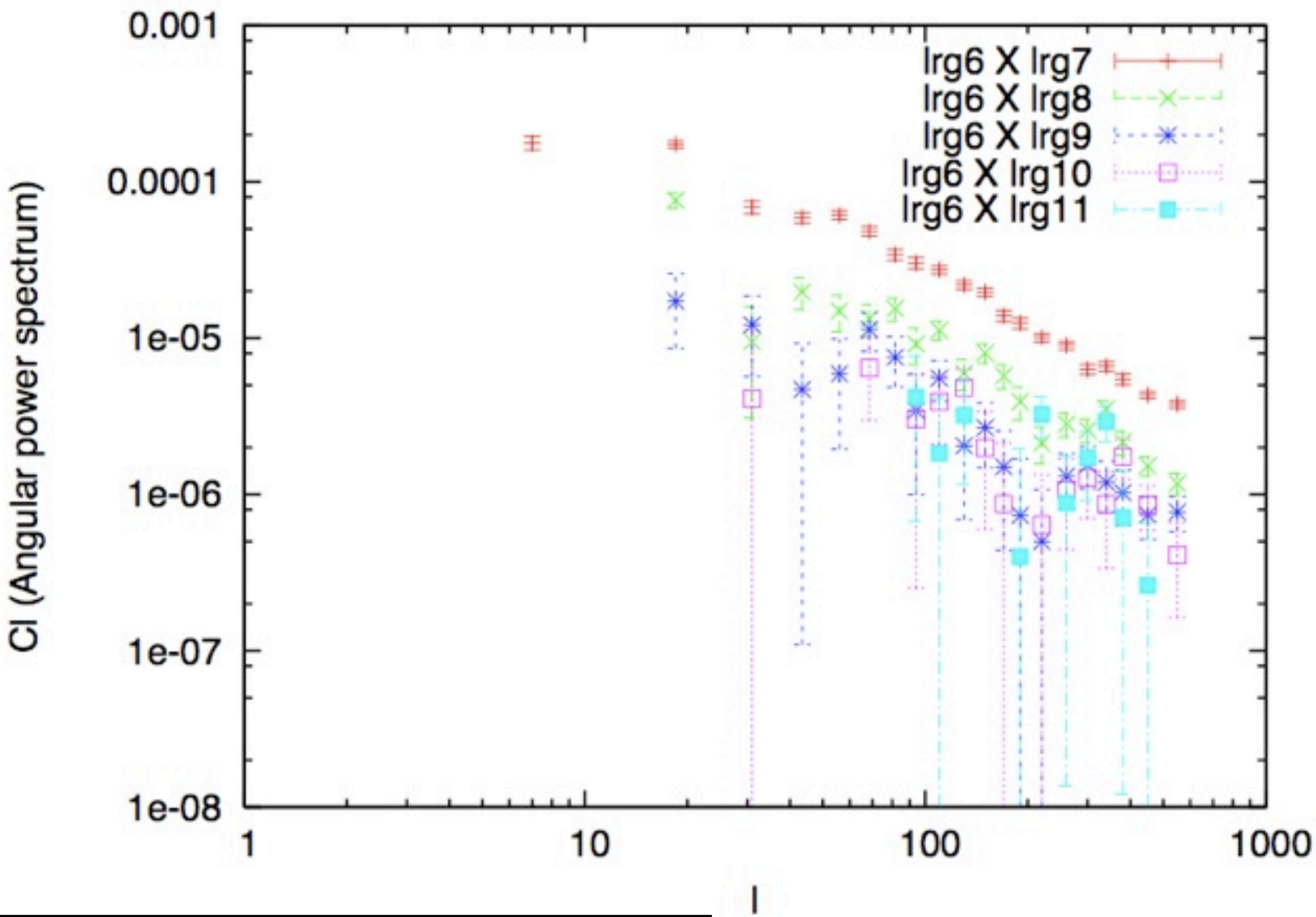
$$C_l^{gg}(\mathrm{DATA}) = \mathrm{b}^2\mathrm{C}_\mathrm{l}^{\delta_\mathrm{m}\delta_\mathrm{m}} + \mathrm{C}_\mathrm{l}^{\mathrm{d,d}} + \mathrm{C}_\mathrm{l}^{\mathrm{s,s}} + \mathrm{C}_\mathrm{l}^{\mathrm{g(z),g(z')}} + \ldots$$

Dust Extinction: We cross-correlate the extinction map (SFD) with the galaxies to see if there is any correlations.

Stellar Contamination: We cross-correlate the stellar density maps (generated from SDSS) with the galaxies.

Galaxies from next photometric slice: We compute all the correlations between different redshift slices, and take into account of the covariances and correlations between different slices.

Overlap of the redshift bins



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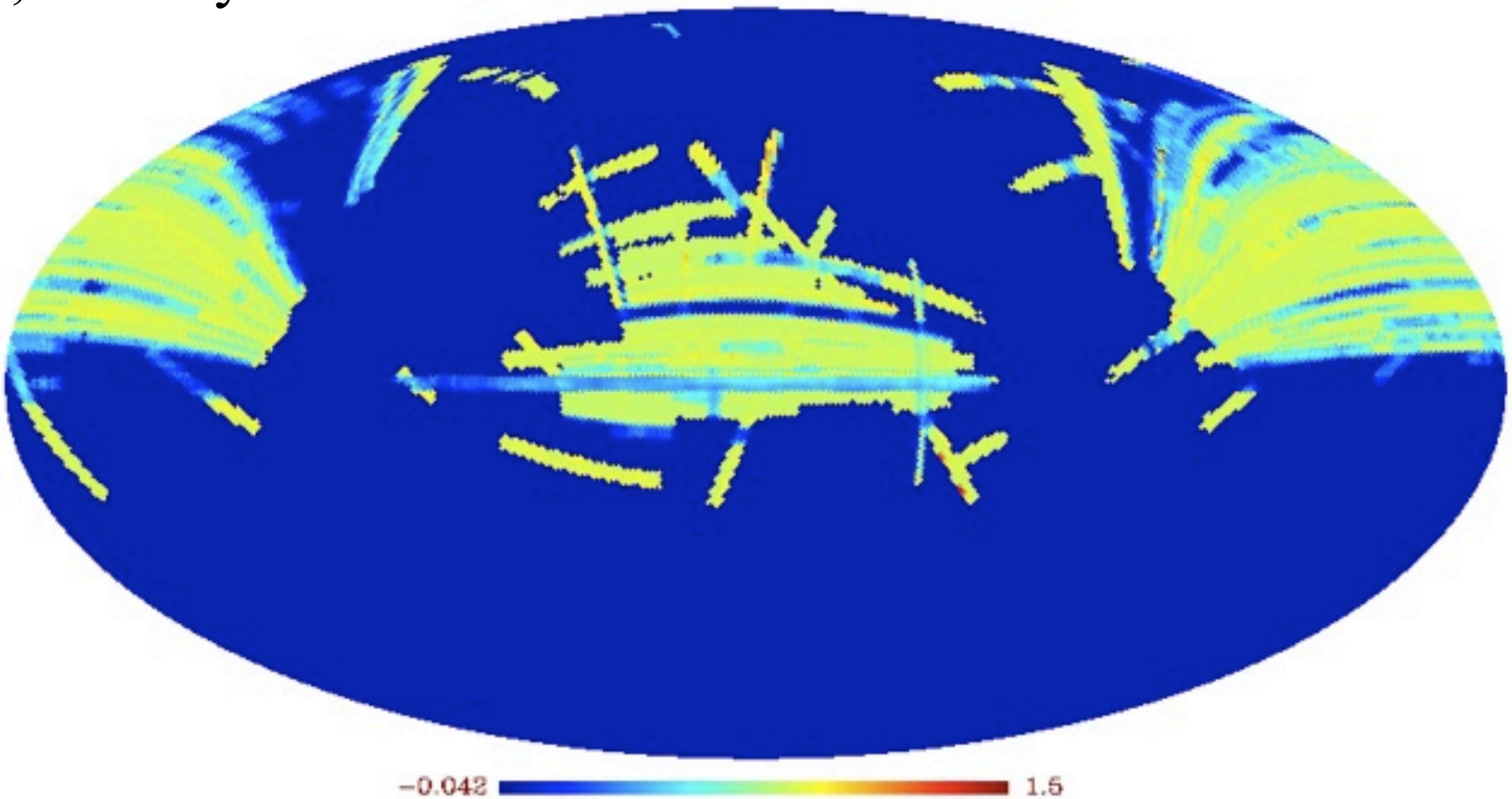
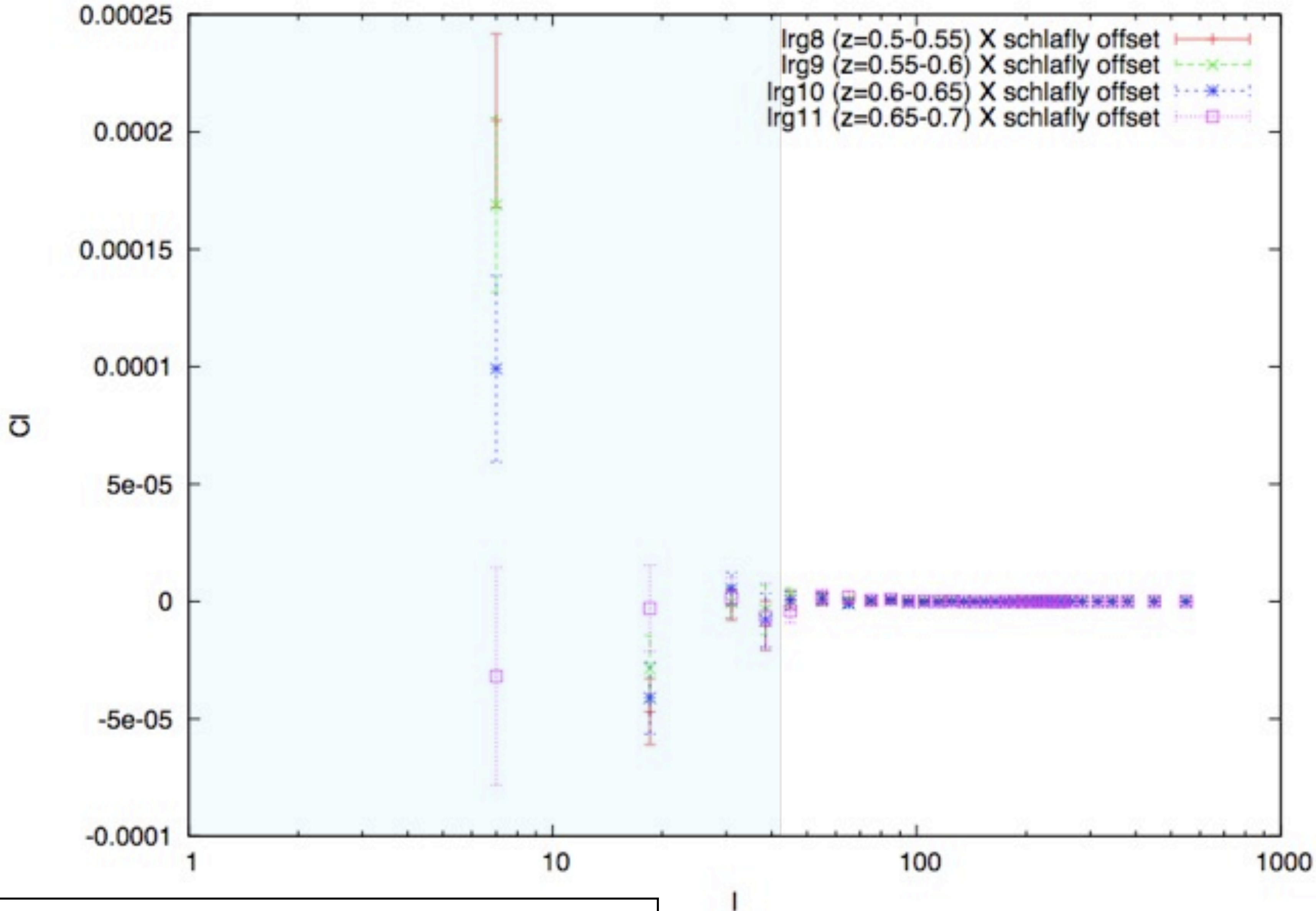
What are the photometric offsets?

These are the "zero points" of colors (difference in magnitudes) of the survey, but they are not zero!



Color offsets as discussed in Schlafly et al. 2010

The effect of the photometric offsets



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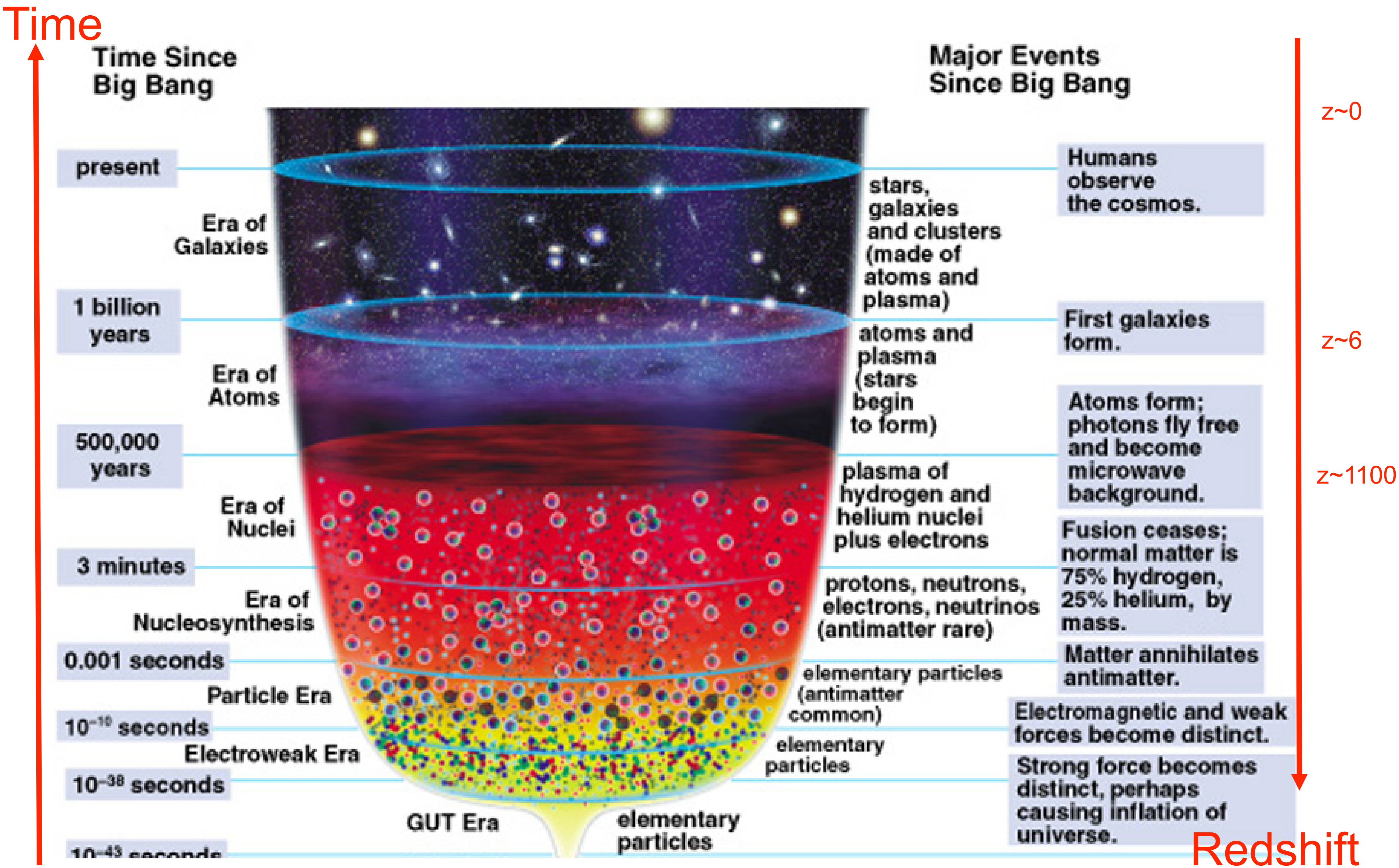
Motivations

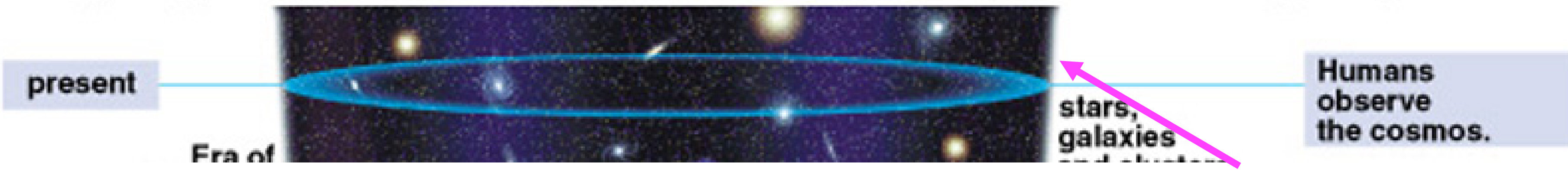


Motivations

Time

Time Since
Big Bang

Major Events
Since Big Bang



Gravity +
observing movement of
local galaxies ->
"Dark Matter"

z~0

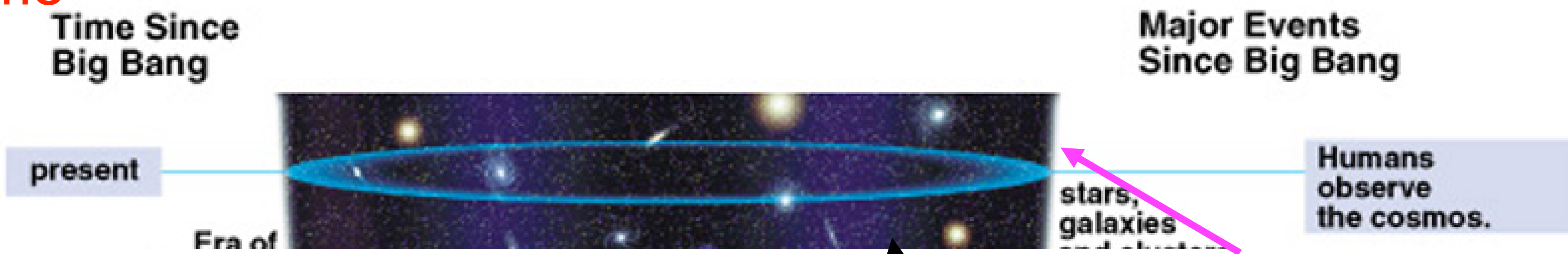
z~6

z~1100

Redshift

Motivations

Time



z~0

Gravity +
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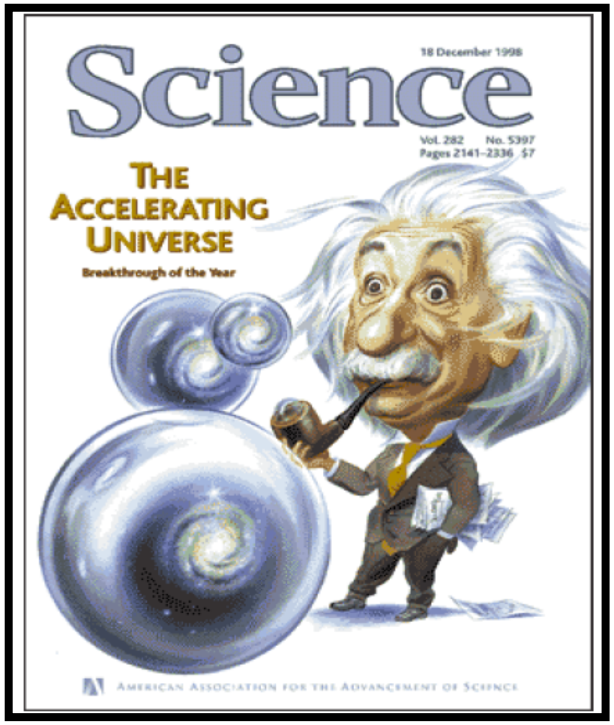

Distant supernovas appear fainter than expected (1998)->
Universe is accelerating ->
Cosmological Constant?
Dark Energy?

z~1100

Redshift

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Dust Extinction

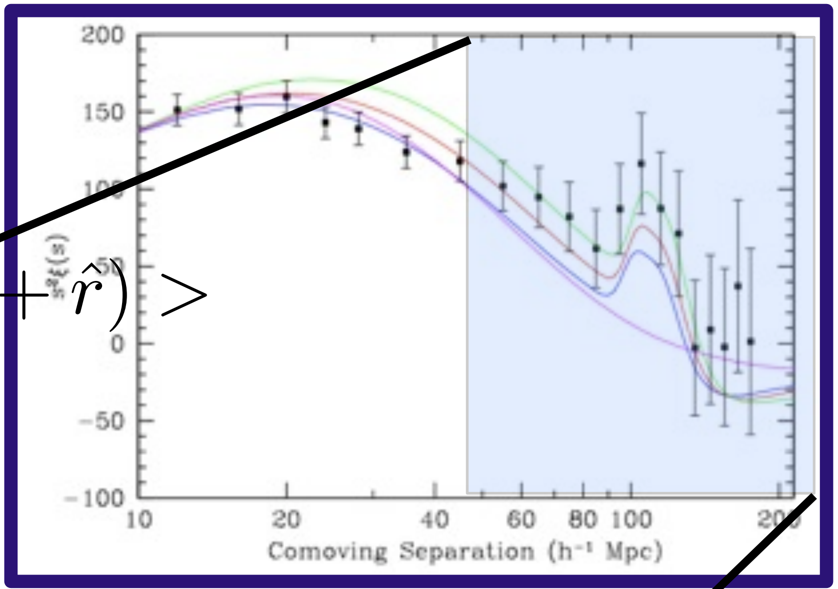
Stellar Contamination

Galaxies from next photometric slice

If we don't take out the systematics, we won't be able to trust the power-spectra until at least **l> 40**

Beyond: With Lyman Alpha Forest
Correlation function (in configuration space)

$$\xi_f(r) =< \delta_f(\hat{x})\delta_f(\hat{x}+\hat{r}) >$$



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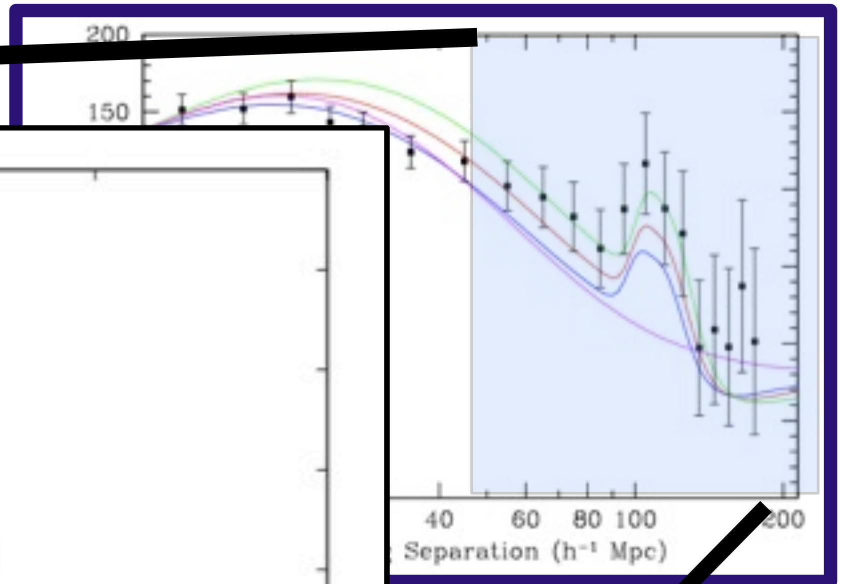
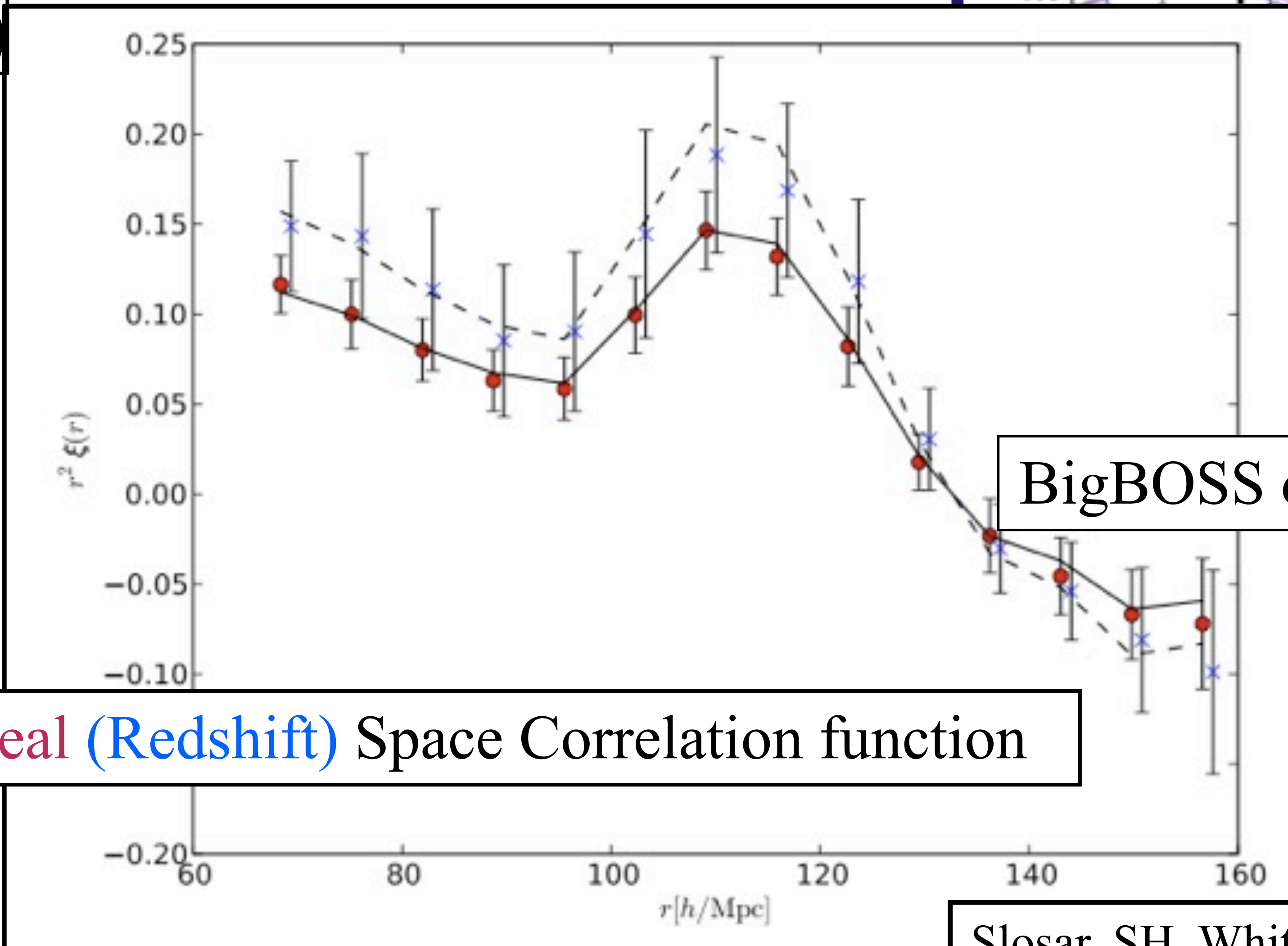


BigBOSS density of QSO

$r^2\xi(r)$



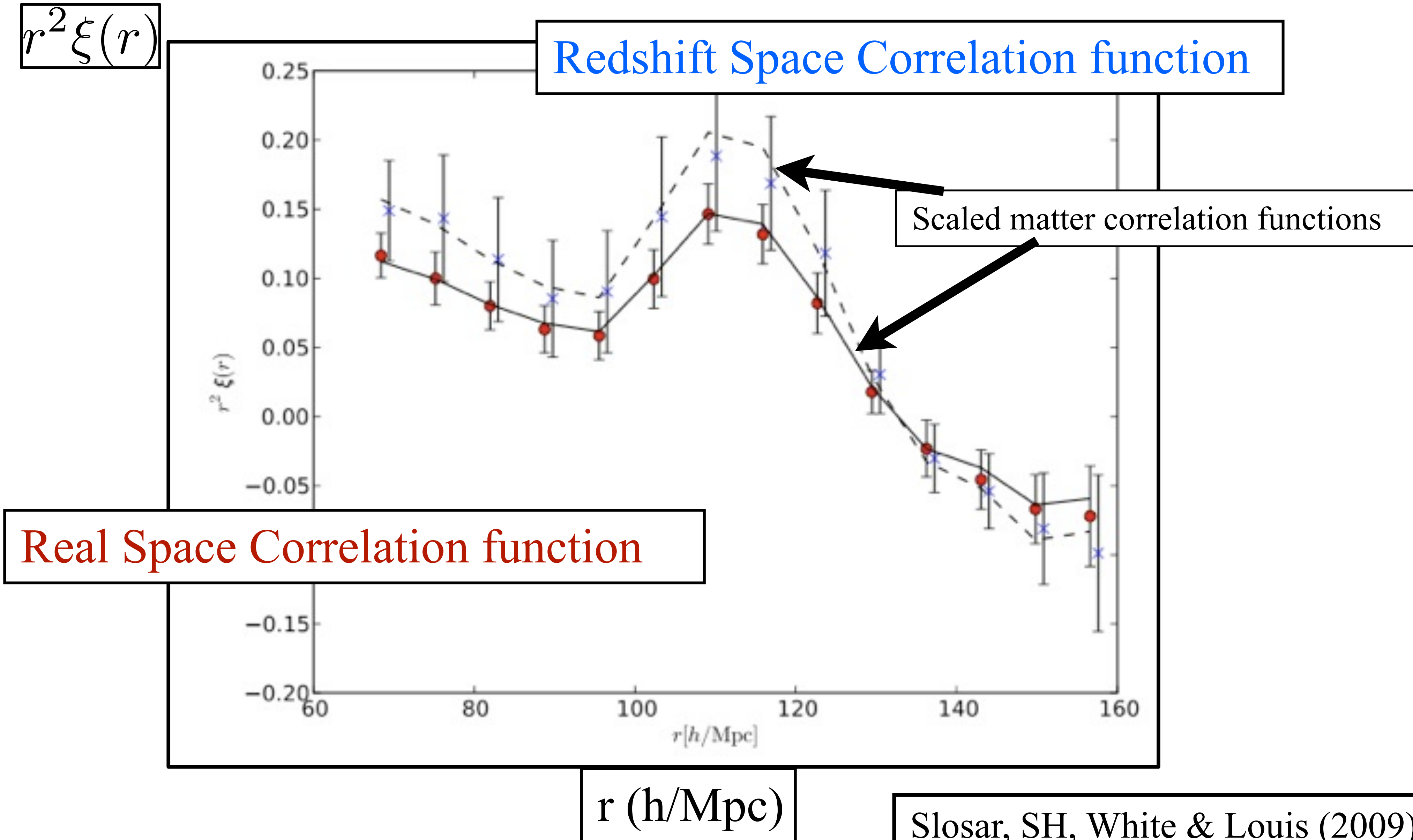
Flux Real (Redshift) Space Correlation function

r (h/Mpc)

Slosar, SH, White & Louis (2009)

Beyond: With Lyman Alpha Forest

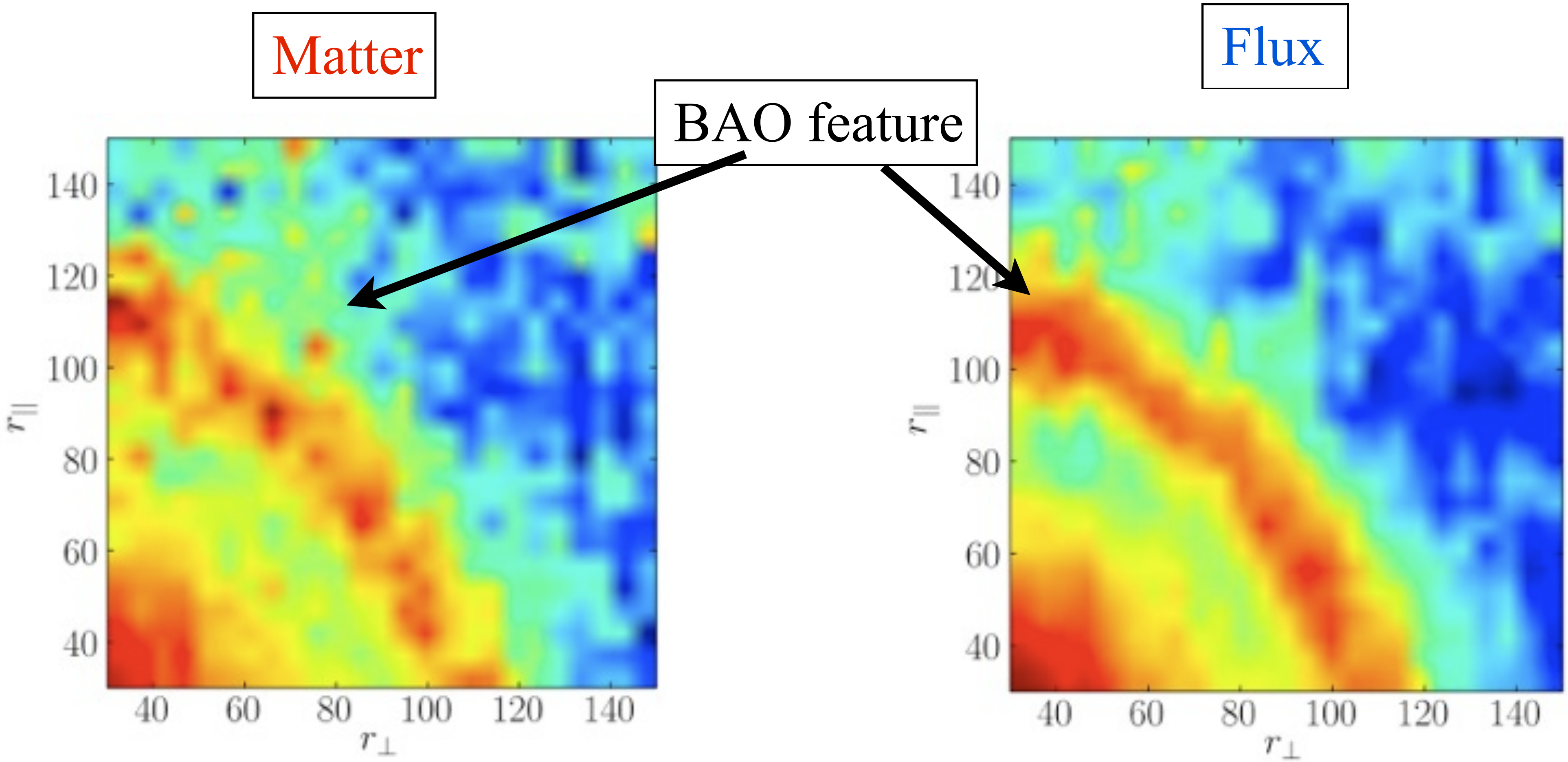
Correlation function (in configuration space)



Slosar, SH, White & Louis (2009)

Beyond: With Lyman Alpha Forest
Correlation function (in configuration space)

Real Space Correlation function



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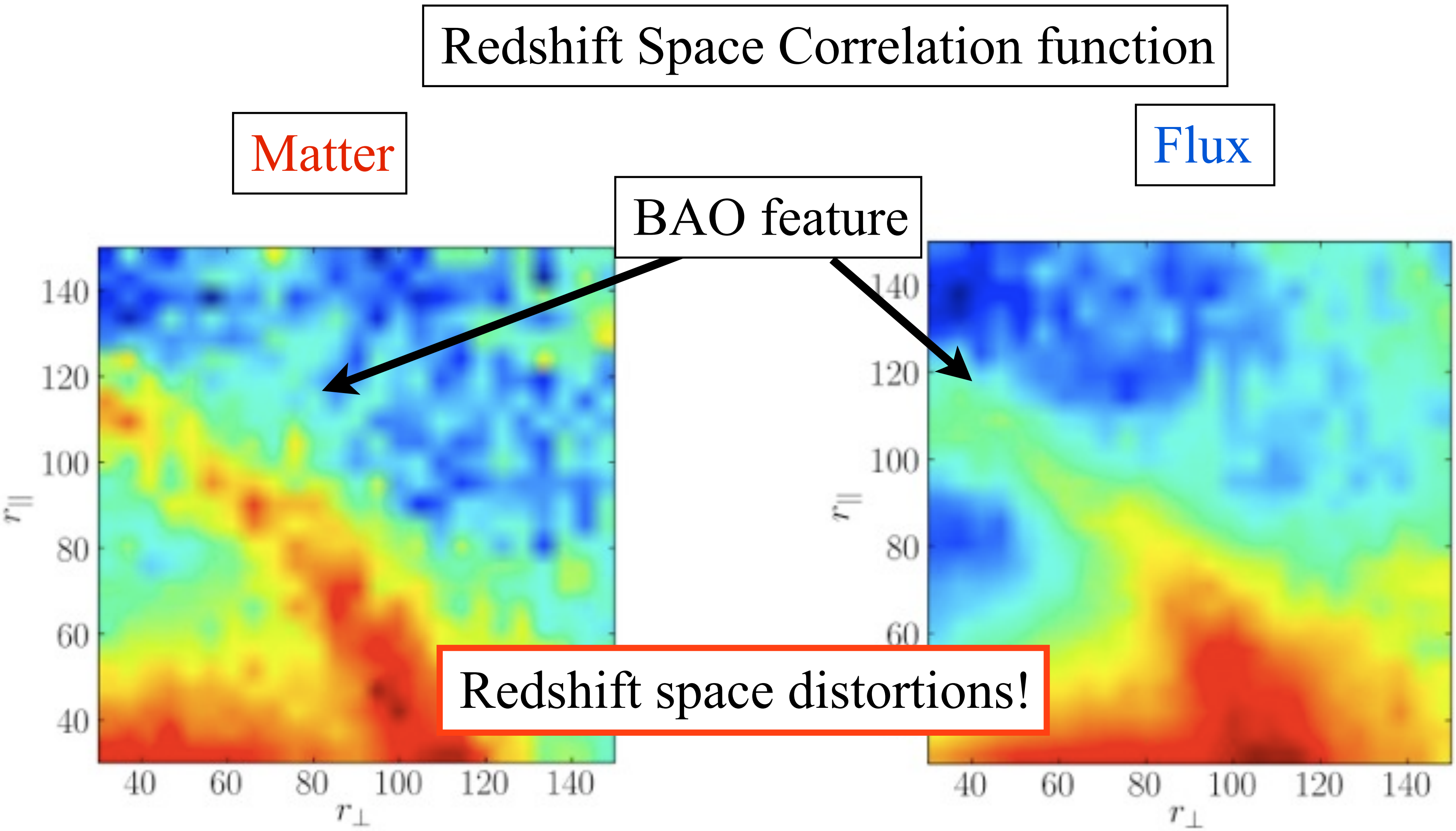

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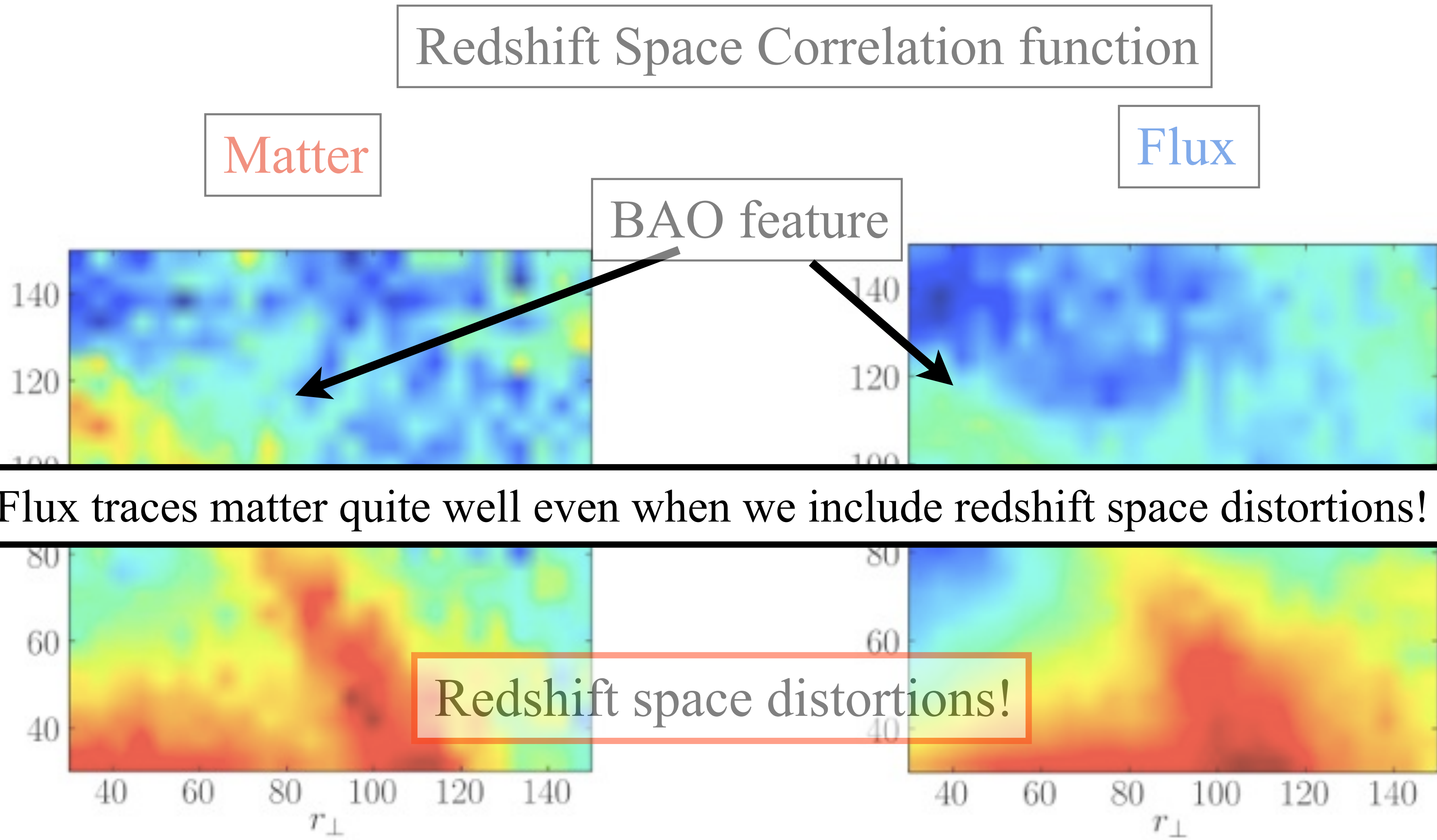


Flux traces matter quite well even when we include redshift space distortions!

Slosar, SH, White & Louis (2009)

Beyond: With Lyman Alpha Forest
Correlation function (in configuration space)

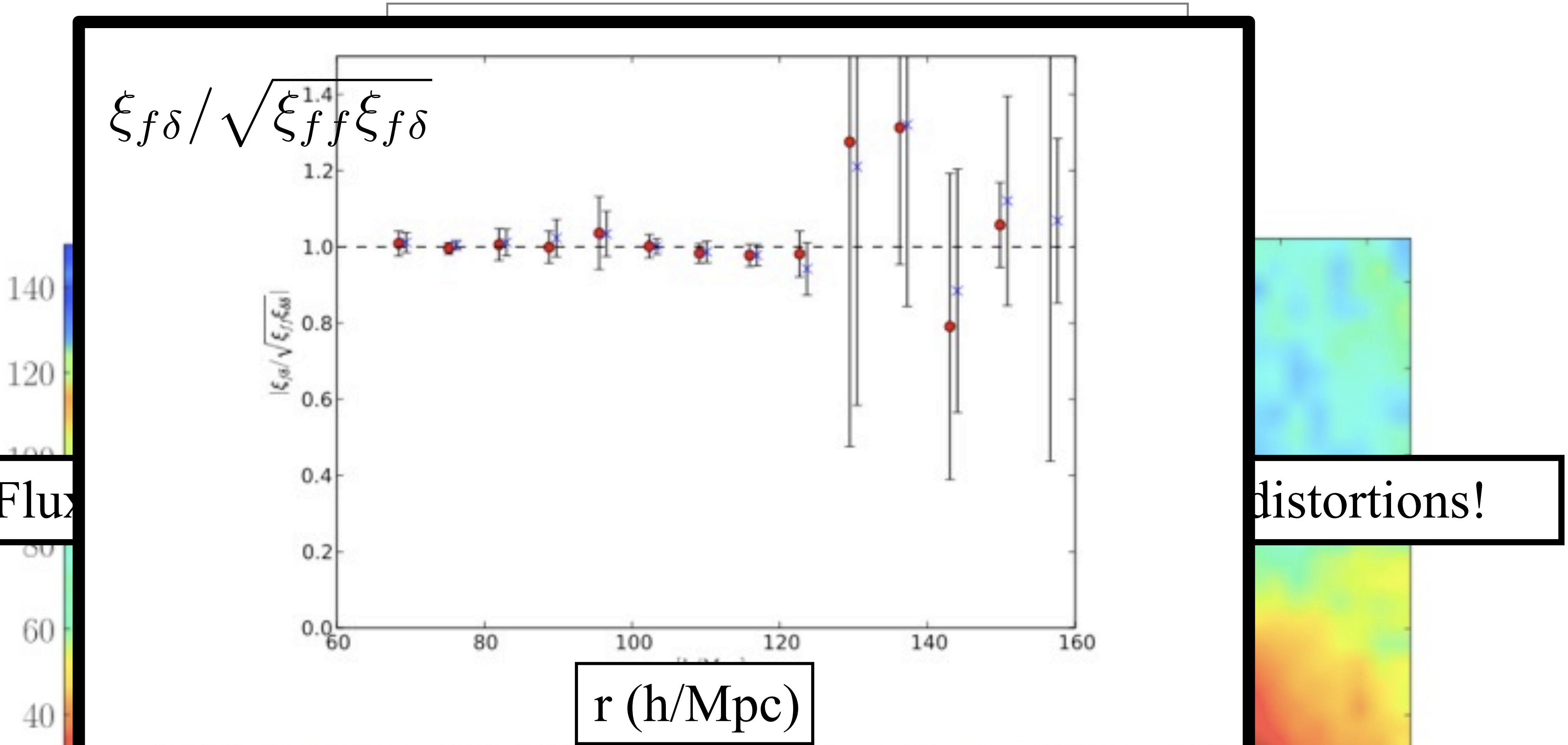


FIG. 7: The cross-correlation coefficient between flux and matter over-density in real (red) and redshift (blue) space.

Slosar, SH, White & Louis (2009)

Beyond: With Lyman Alpha Forest
Redshift space distortions

Redshift Space Correlation function

Matter

Flux

BAO feature

But what how should we deal with this redshift space distortion ?

Flux traces matter quite well even when we redshift space distortions!

Redshift space distortions!

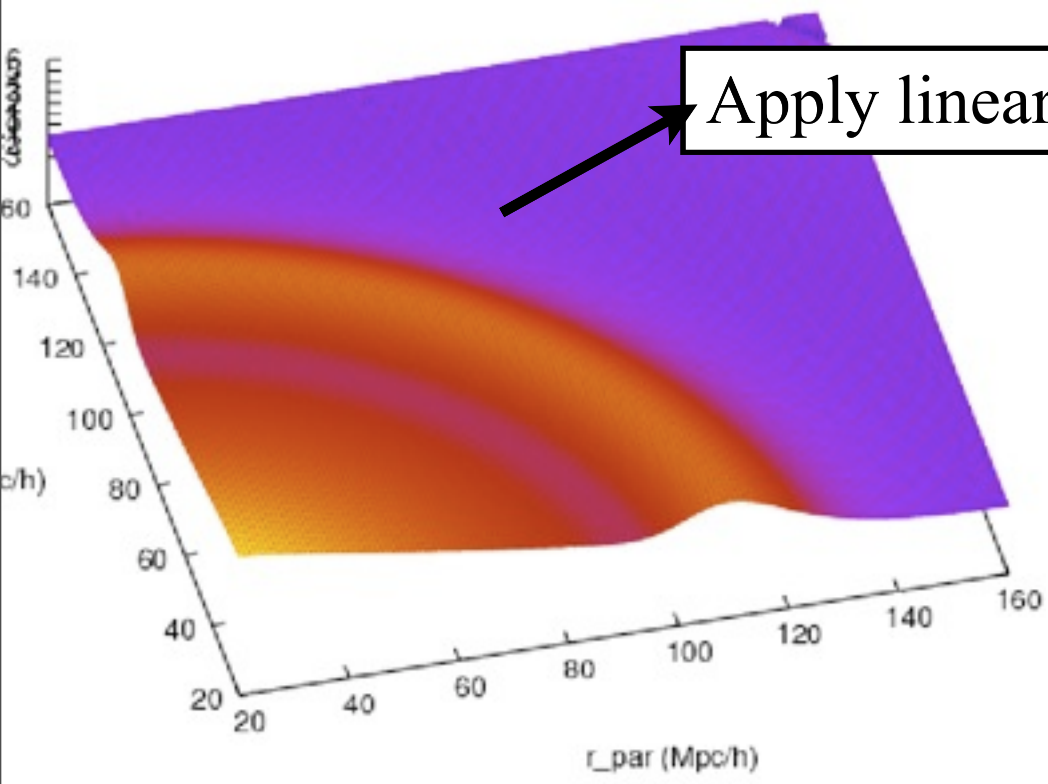
Beyond: With Lyman Alpha Forest
Redshift space distortions

Berkeley Lab

No z-space distortion

z-space distortions

Apply linear Kaiser formula



$$\xi(r,\mu) = \sum_{\ell=0,2,4} L_\ell(\mu)\xi_l(r),$$

$$\xi_0(r) = C_0\xi_R(r),$$

$$\xi_2(r) = C_2\left(\xi_R(r) - \bar{\xi}(r)\right),$$

$$\xi_4(r) = C_4\left(\xi_R(r) + 2.5\bar{\xi}(r) - 3.5\bar{\bar{\xi}}(r)\right),$$

$$\mu = r_{par}/|\vec{r}|$$

$$C_i = f_i(\beta)$$

$$\beta = dln\delta/dlna = \Omega_m^{0.6}$$

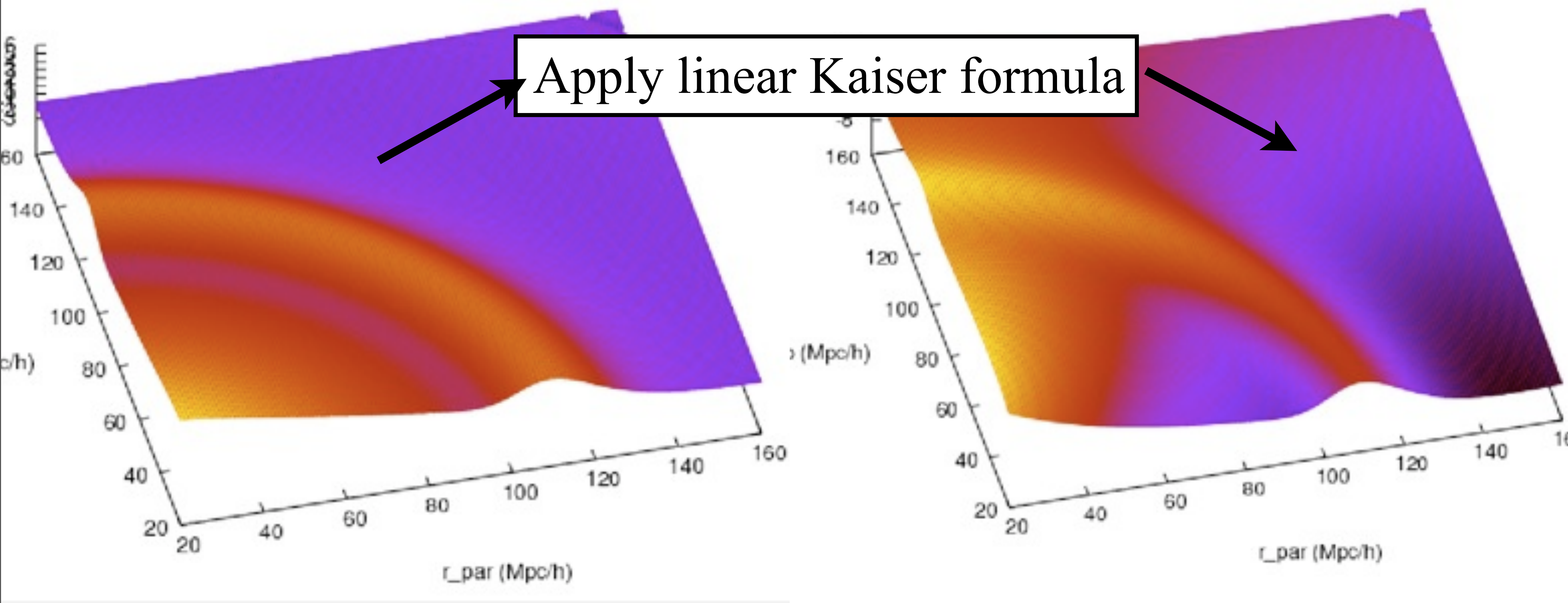
Beyond: With Lyman Alpha Forest

Redshift space distortions

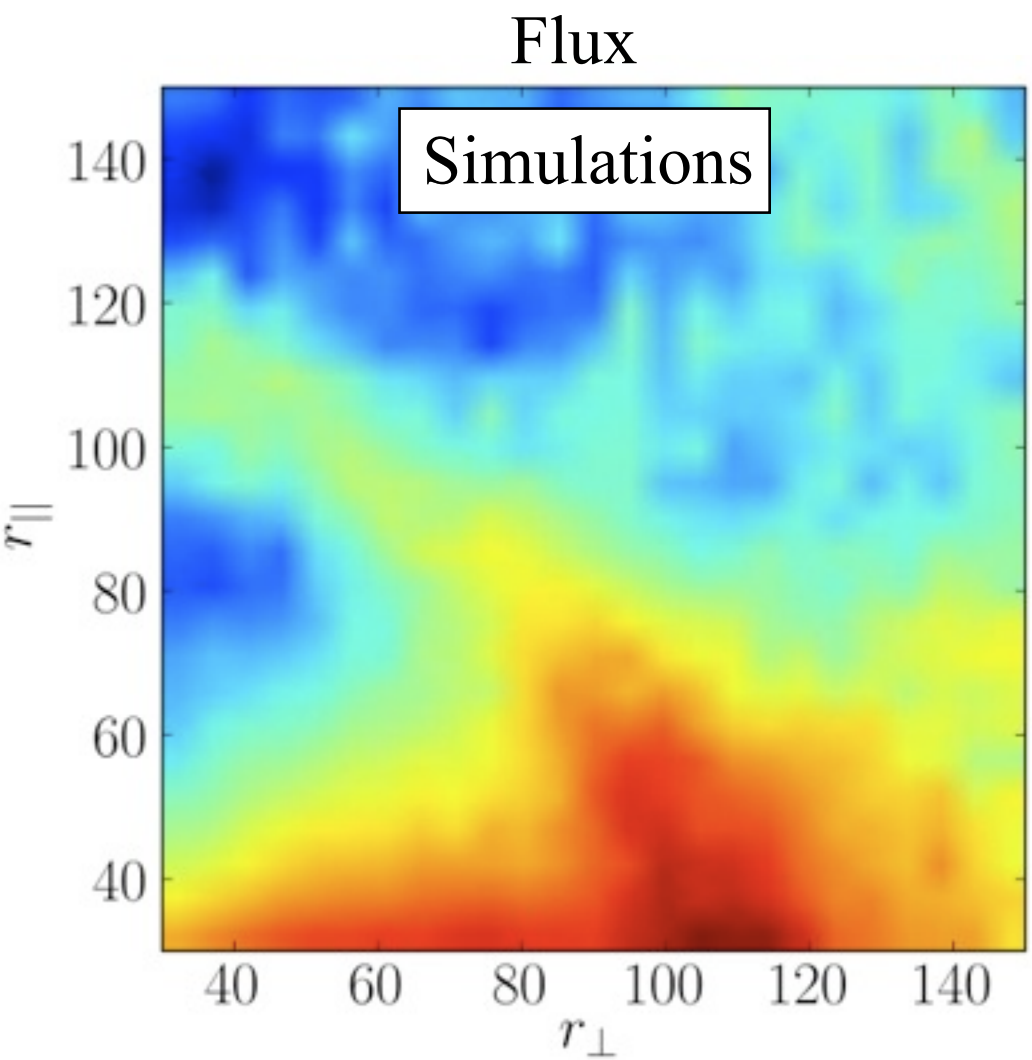
No z-space distortion

z-space distortions

Apply linear Kaiser formula

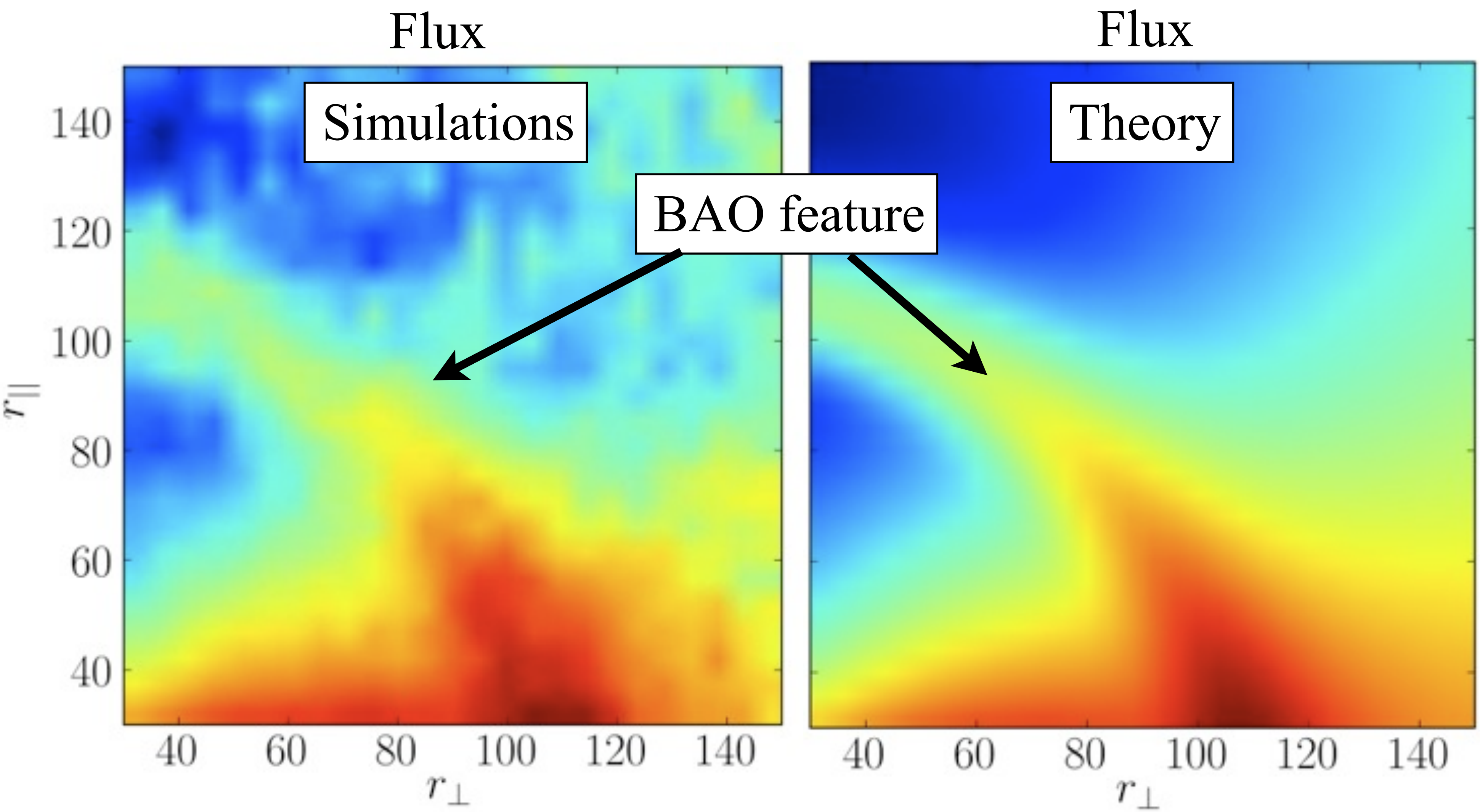


Beyond: With Lyman Alpha Forest
Redshift space distortions

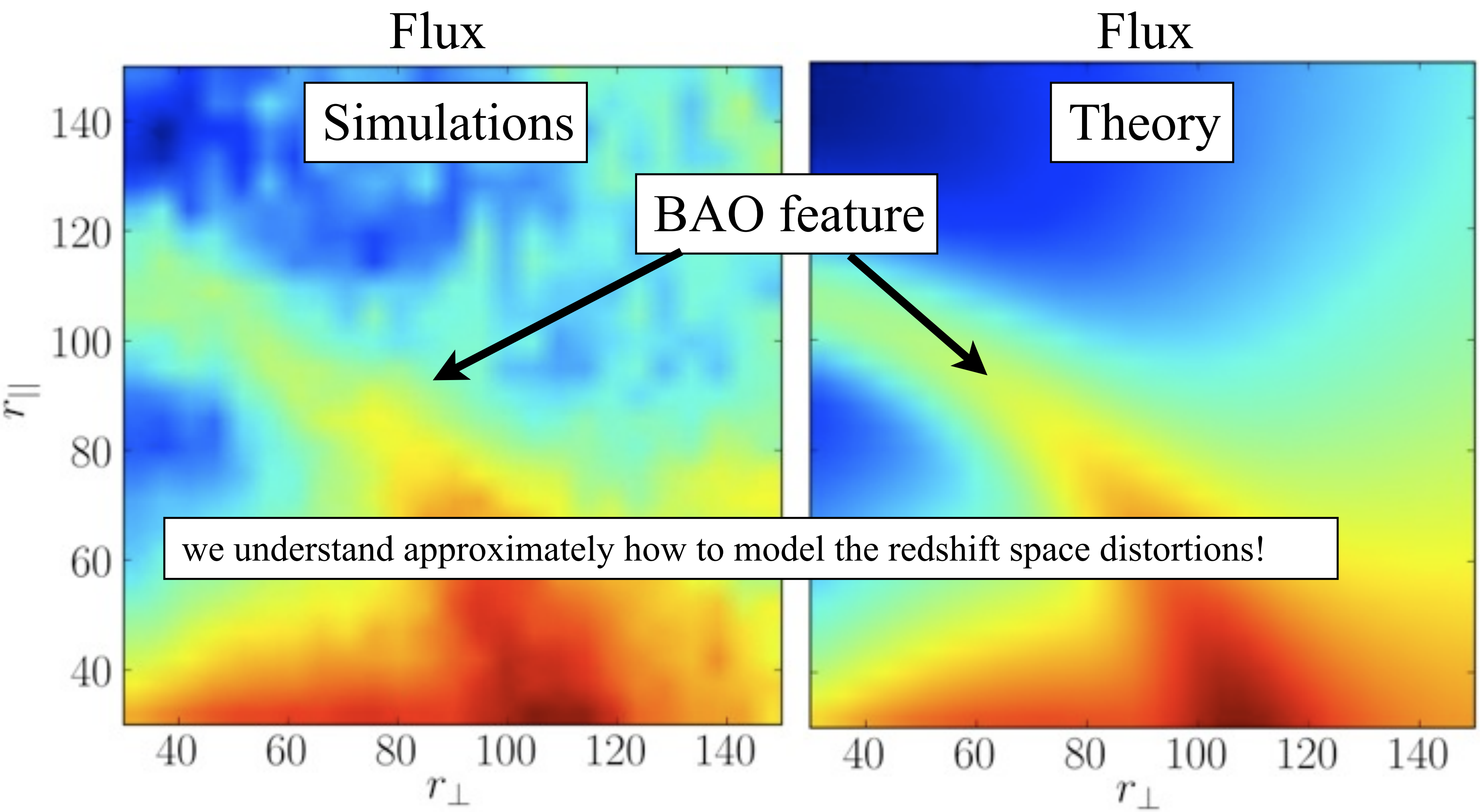


Beyond: With Lyman Alpha Forest

Redshift space distortions



Beyond: With Lyman Alpha Forest
Redshift space distortions

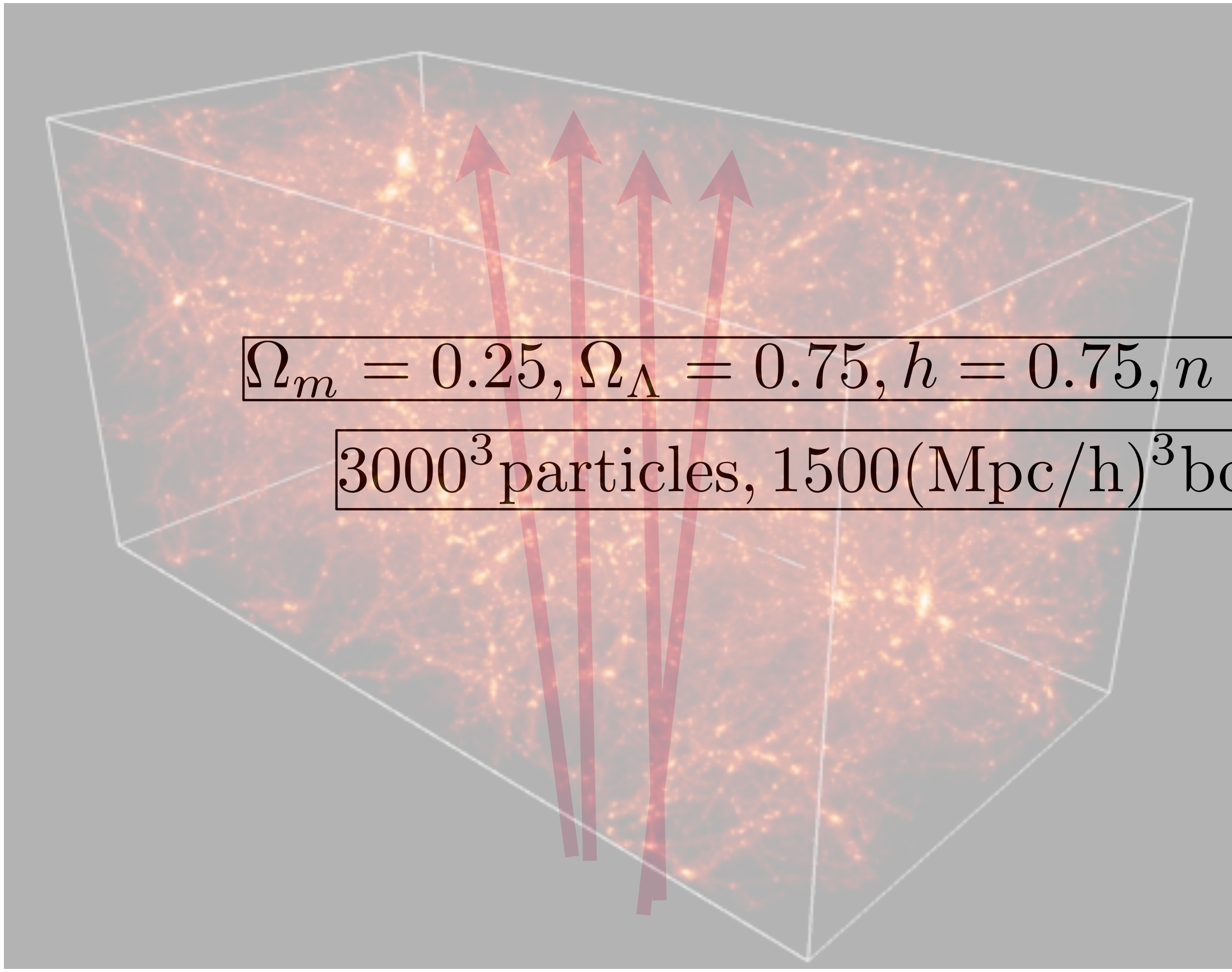


Slosar, SH, White & Louis (2009)

Beyond: With Lyman Alpha Forest
Possible systematics

- UV background fluctuations
- Metal Line contaminations
- Continuum fitting errors
- Damped Lyman alpha systems
- Broad Absorption Line systems

Lyman Alpha Forest: what can it do?

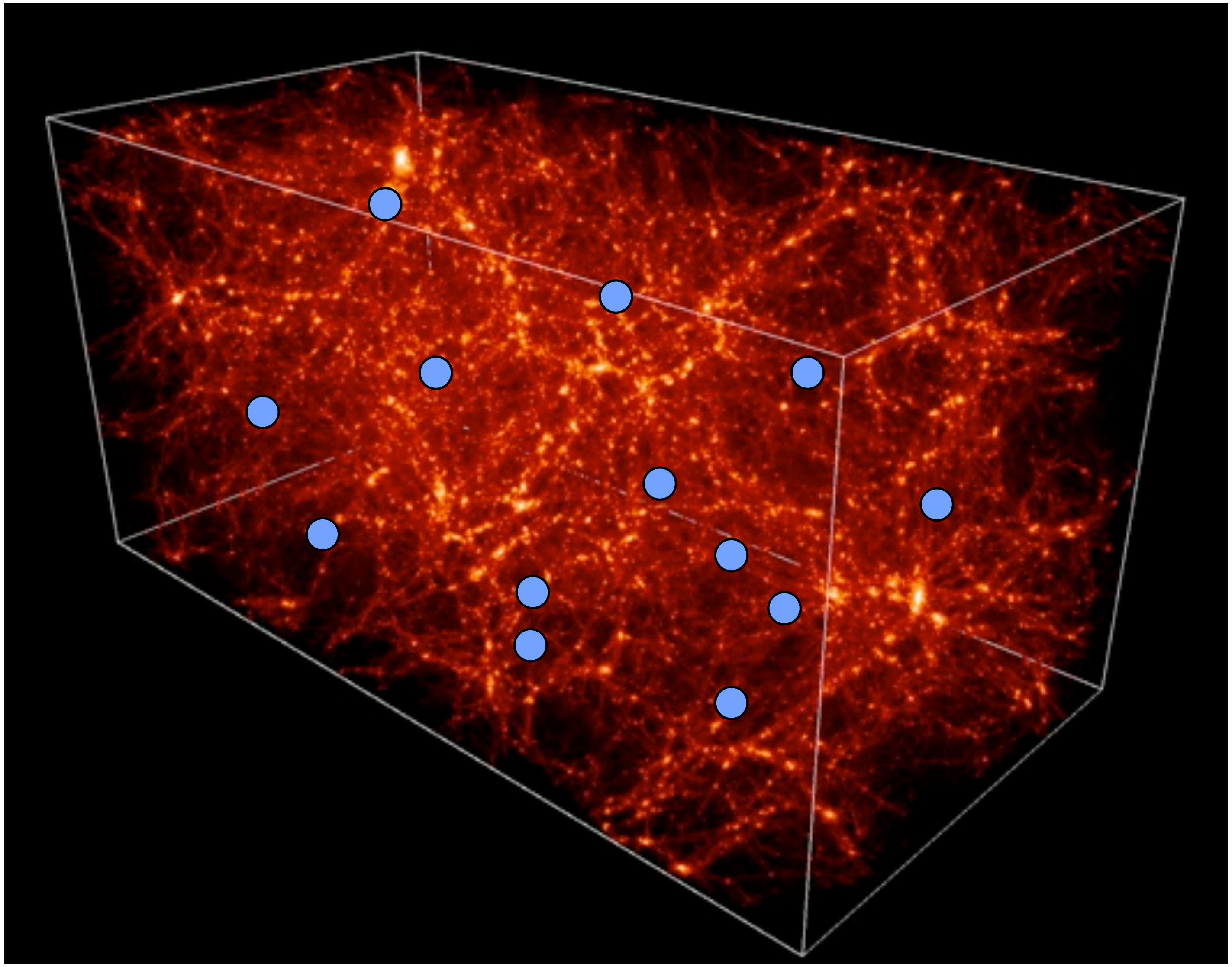


$$\Omega_m = 0.25, \Omega_\Lambda = 0.75, h = 0.75, n = 0.97, \sigma_8 = 0.8$$

$$3000^3 \text{particles}, 1500(\text{Mpc/h})^3 \text{box}, 3000^3 \text{grid}$$

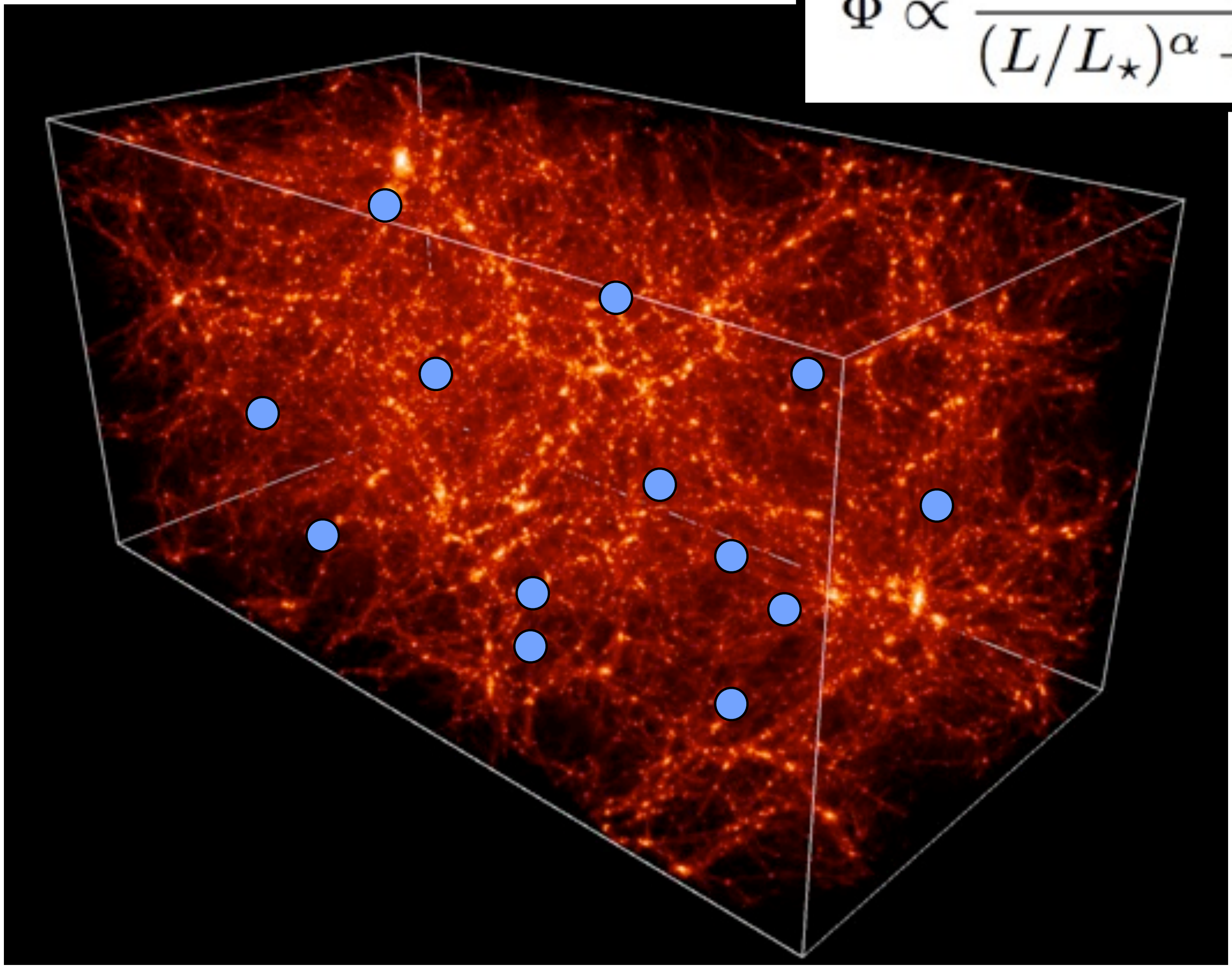
Beyond: With Lyman Alpha Forest

Possible systematics: UV background fluctuations



Beyond: With Lyman Alpha Forest
Possible systematics: UV background fluctuations

$$\Phi \propto \frac{1}{(L/L_\star)^\alpha + (L/L_\star)^\beta}$$



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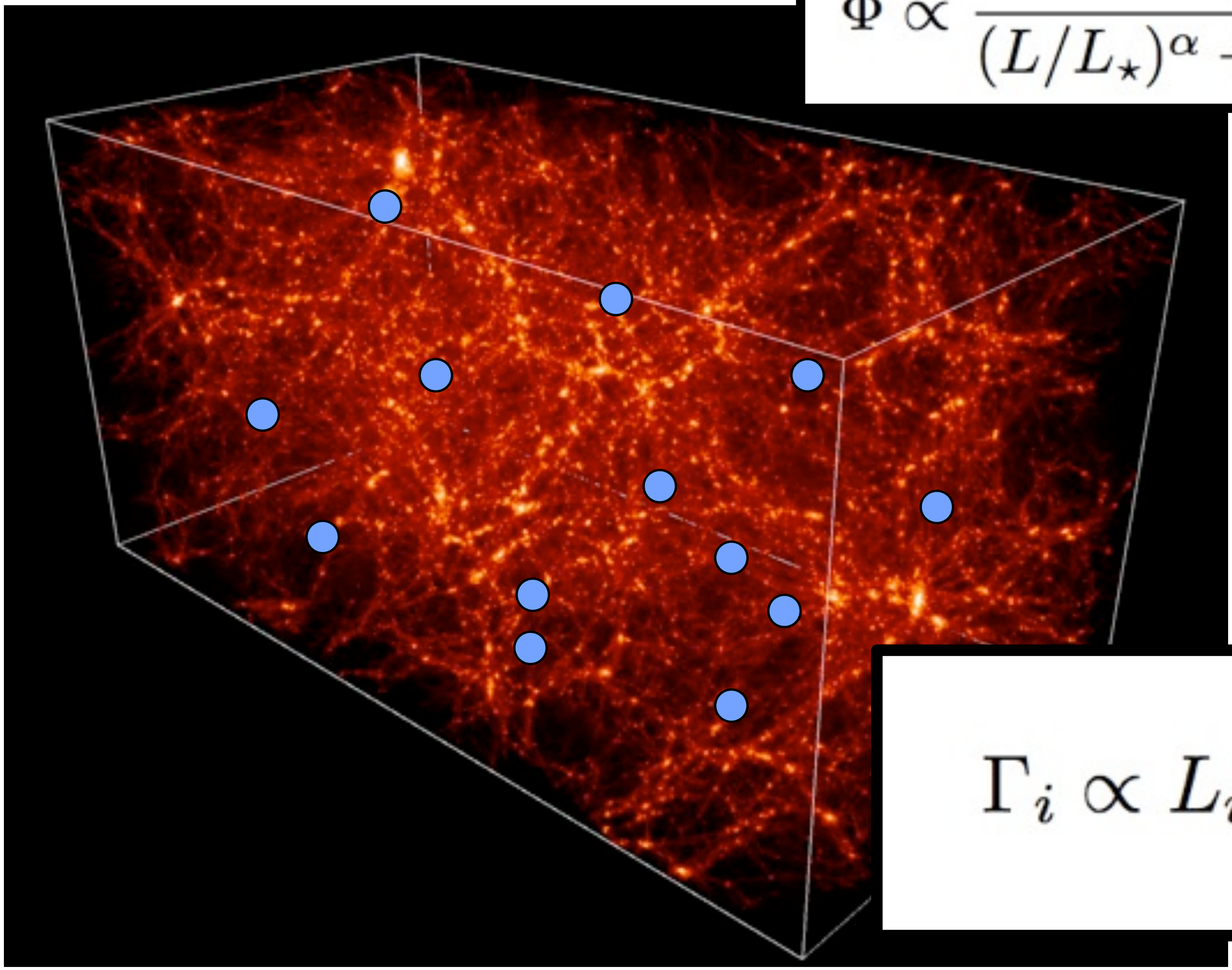
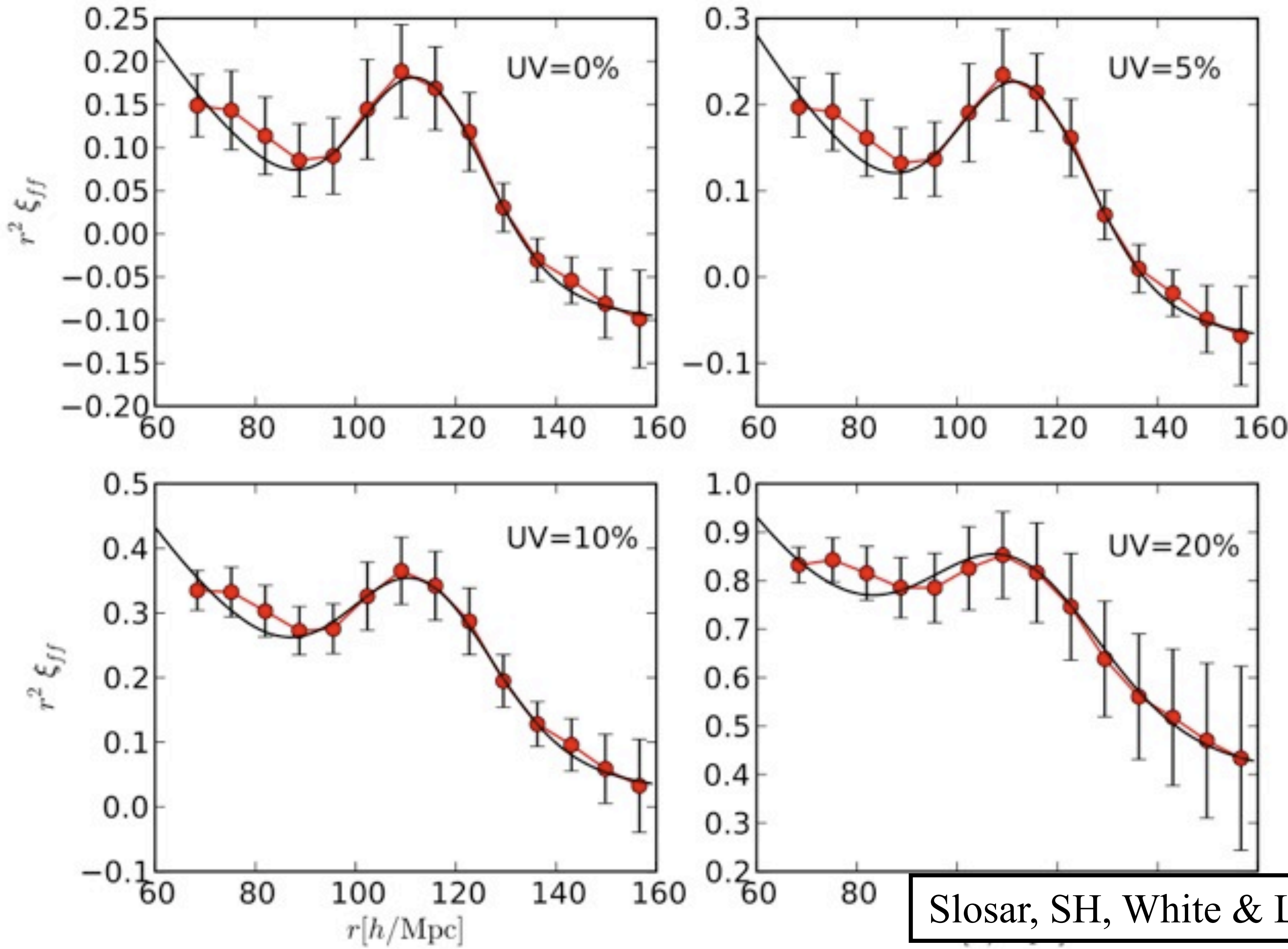


$$\Phi \propto \frac{1}{(L/L_\star)^\alpha + (L/L_\star)^\beta}$$

$$\Gamma_i \propto L_i \, \frac{e^{-r_i/r_0}}{4\pi r_i^2}$$

Beyond: With Lyman Alpha Forest
Possible systematics: UV background fluctuations



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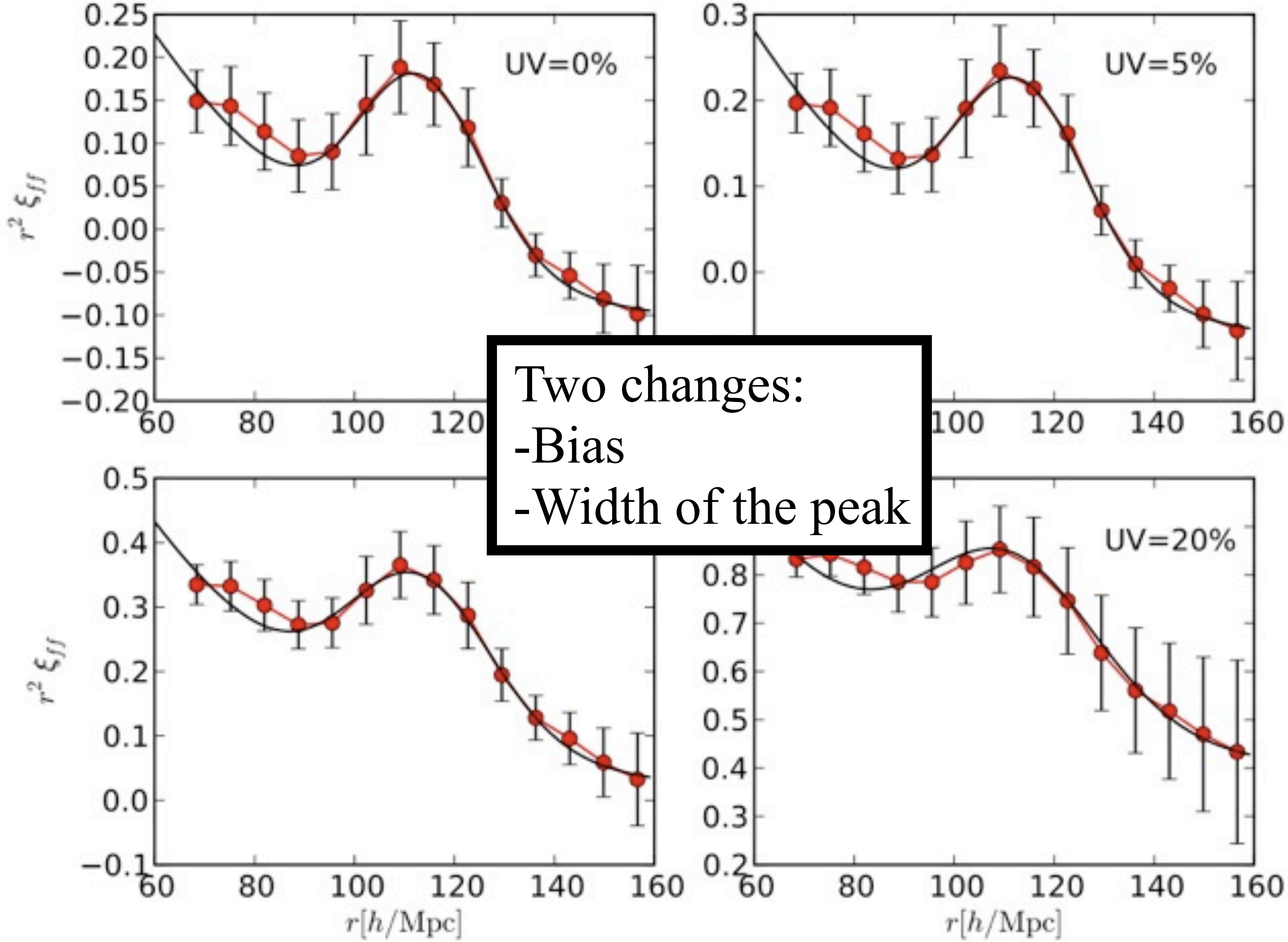
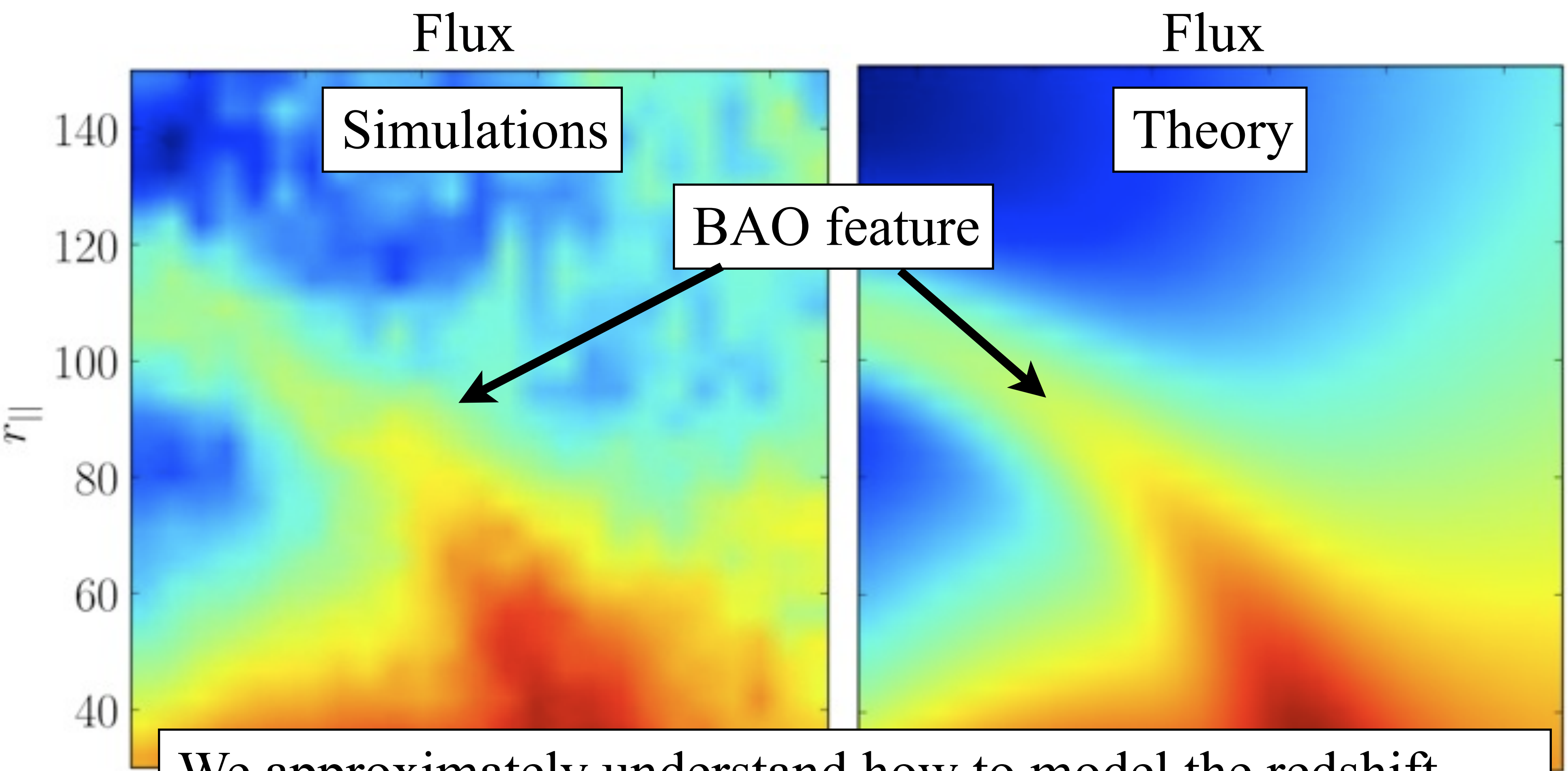


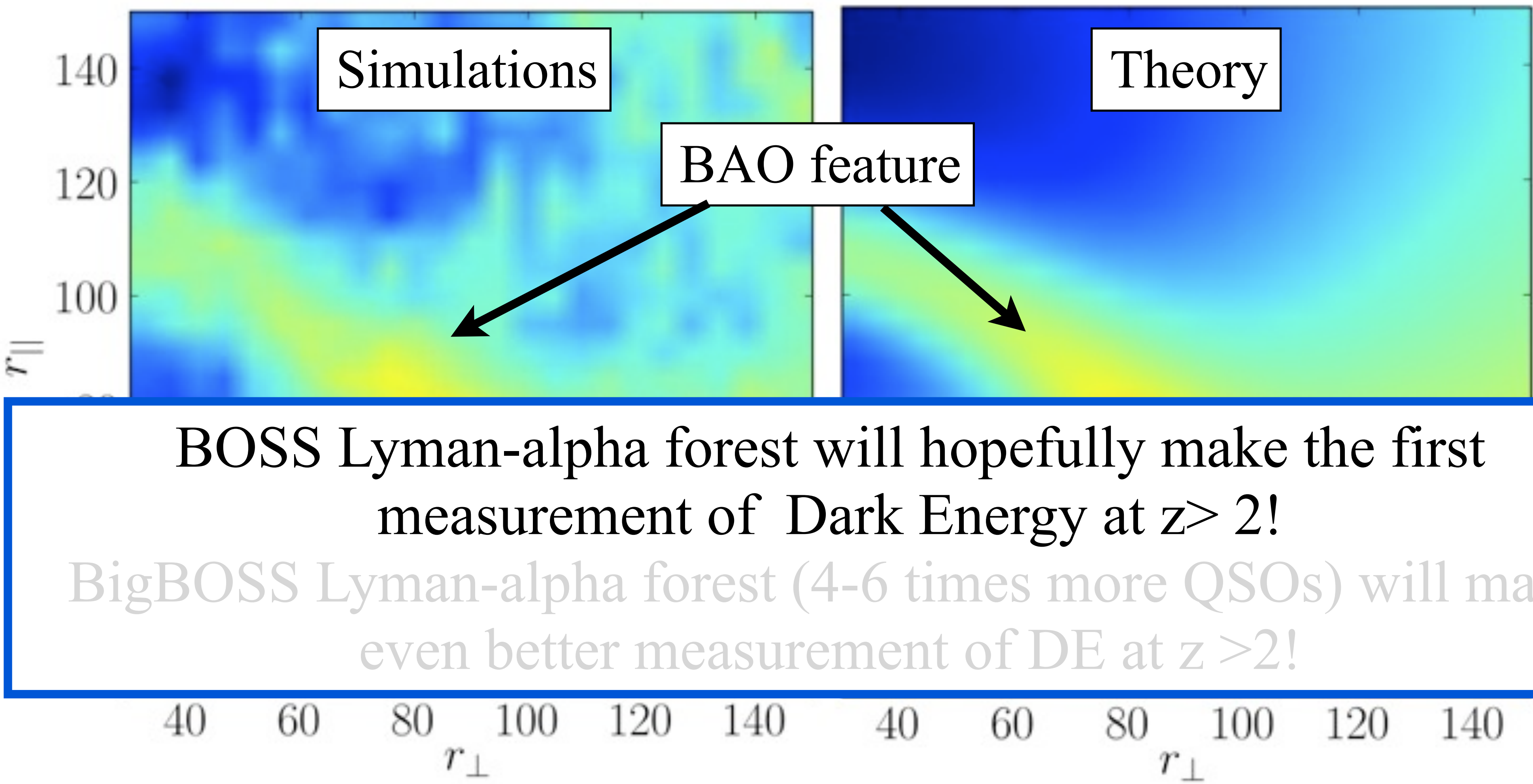
Two changes:
-Bias
-Width of the peak

Beyond: With Lyman Alpha Forest
Mini Conclusion



We approximately understand how to model the redshift space distortions, and what happens when we include systematics such as UV background fluctuations.

Beyond: With Lyman Alpha Forest
Mini Conclusion



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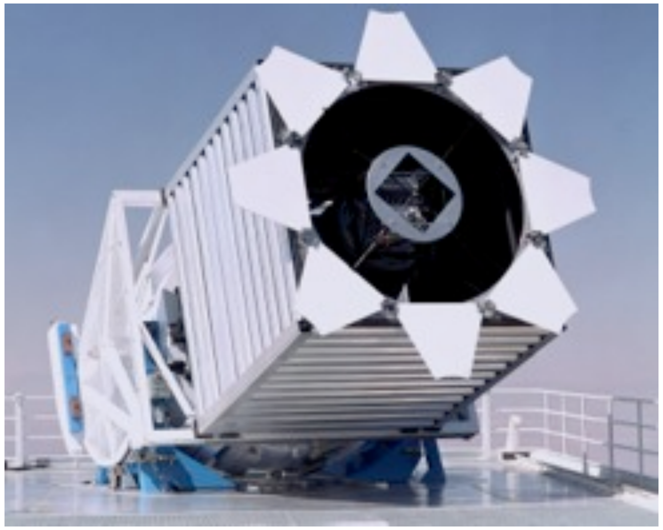
BigBOSS Lyman-alpha forest (4-6 times more QSOs) will make even better measurement of DE at z >2!

SDSS III - BOSS
Baryon Oscillation Spectroscopic Survey

- New program for the SDSS telescope for 2008–2014 (already working and providing data!).
- Definitive study of the low-redshift acoustic oscillations. 10,000 deg^2 of new spectroscopy from SDSS imaging.
  - 1.5 million LRGs to z=0.8, including 4x more density at z<0.5.
  - 7-fold improvement on large-scale structure data from entire SDSS survey; measure the distance scale to 1% at z=0.35 and z=0.6.
  - Easy extension of current program.
- Simultaneous project to discover the BAO in the Lyman α forest.
  - 160,000 quasars. 20% of fibers.
  - 1.5% measurement of distance to z=2.3.
  - Higher risk but opportunity to open the high-redshift distance scale.



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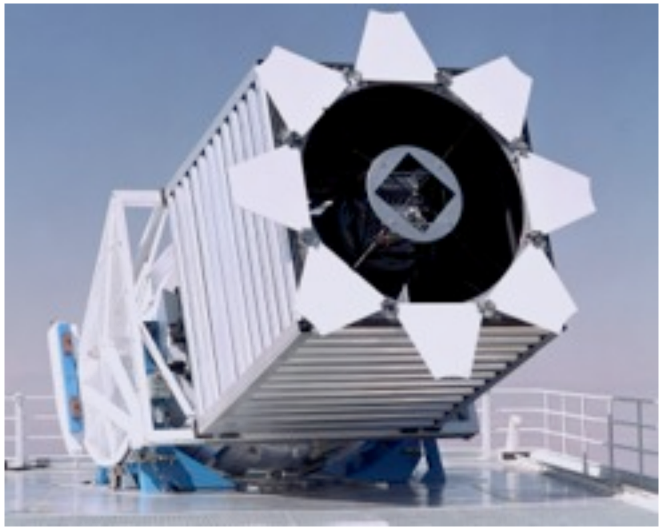

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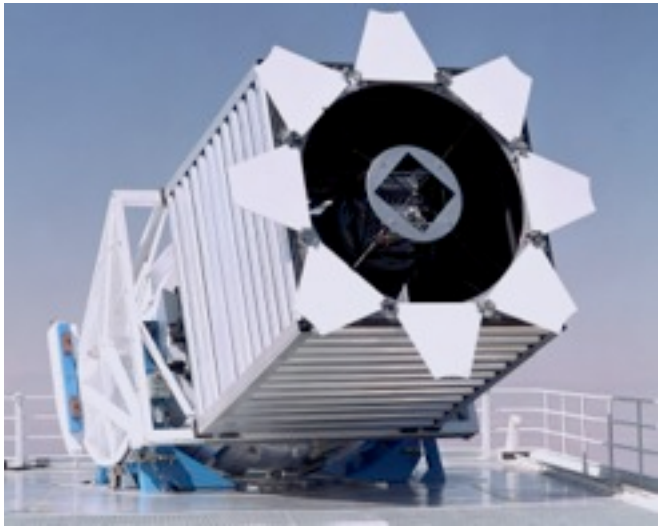
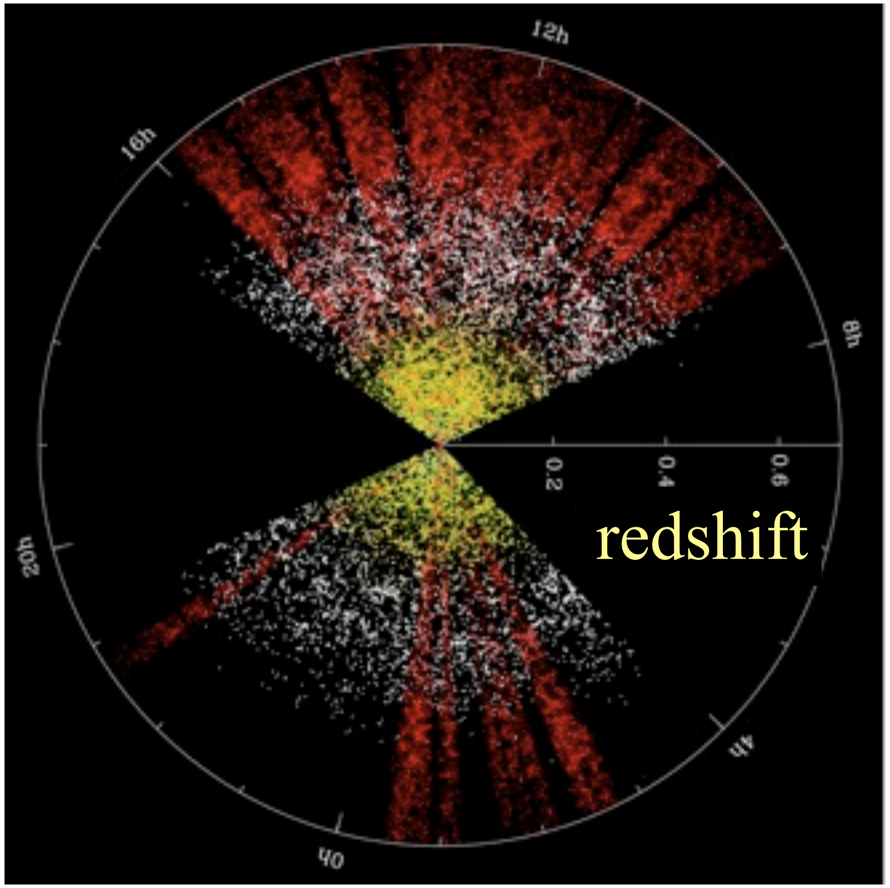


SDSS III - BOSS
Baryon Oscillation Spectroscopic Survey

Volume of the Universe probed by SDSS

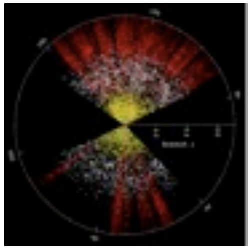


Courtesy plots from Michael Blanton

SDSS III - BOSS
Baryon Oscillation Spectroscopic Survey

Volume of the Universe probed by SDSS

Volume of the Universe probed by BOSS



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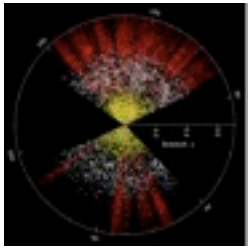

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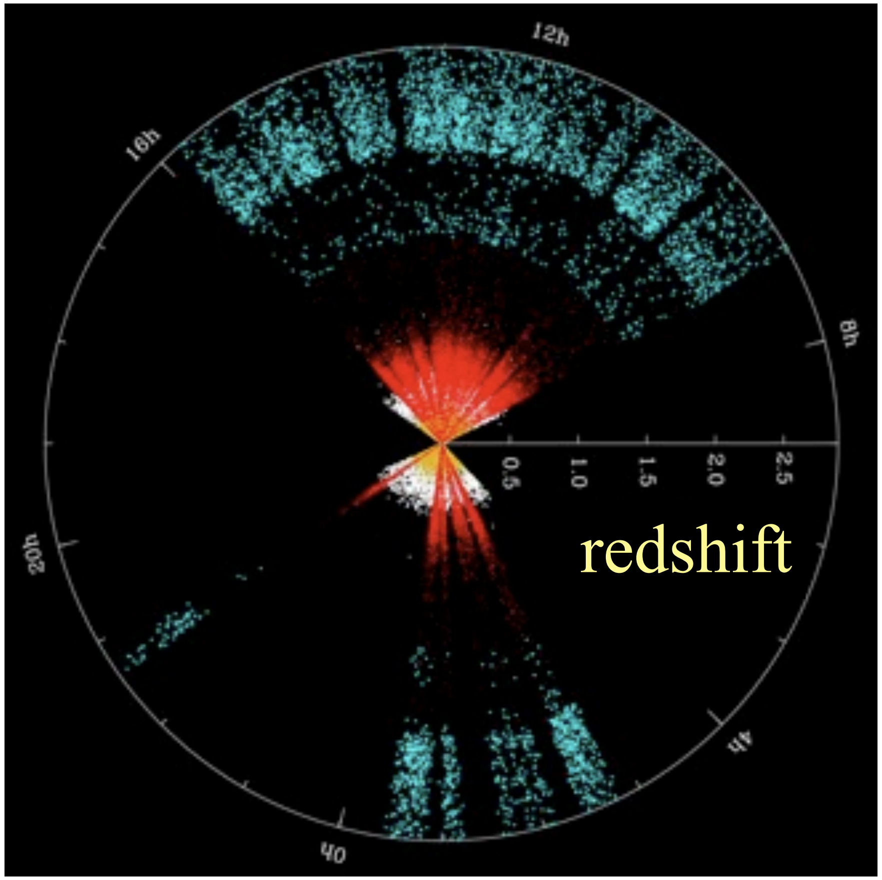

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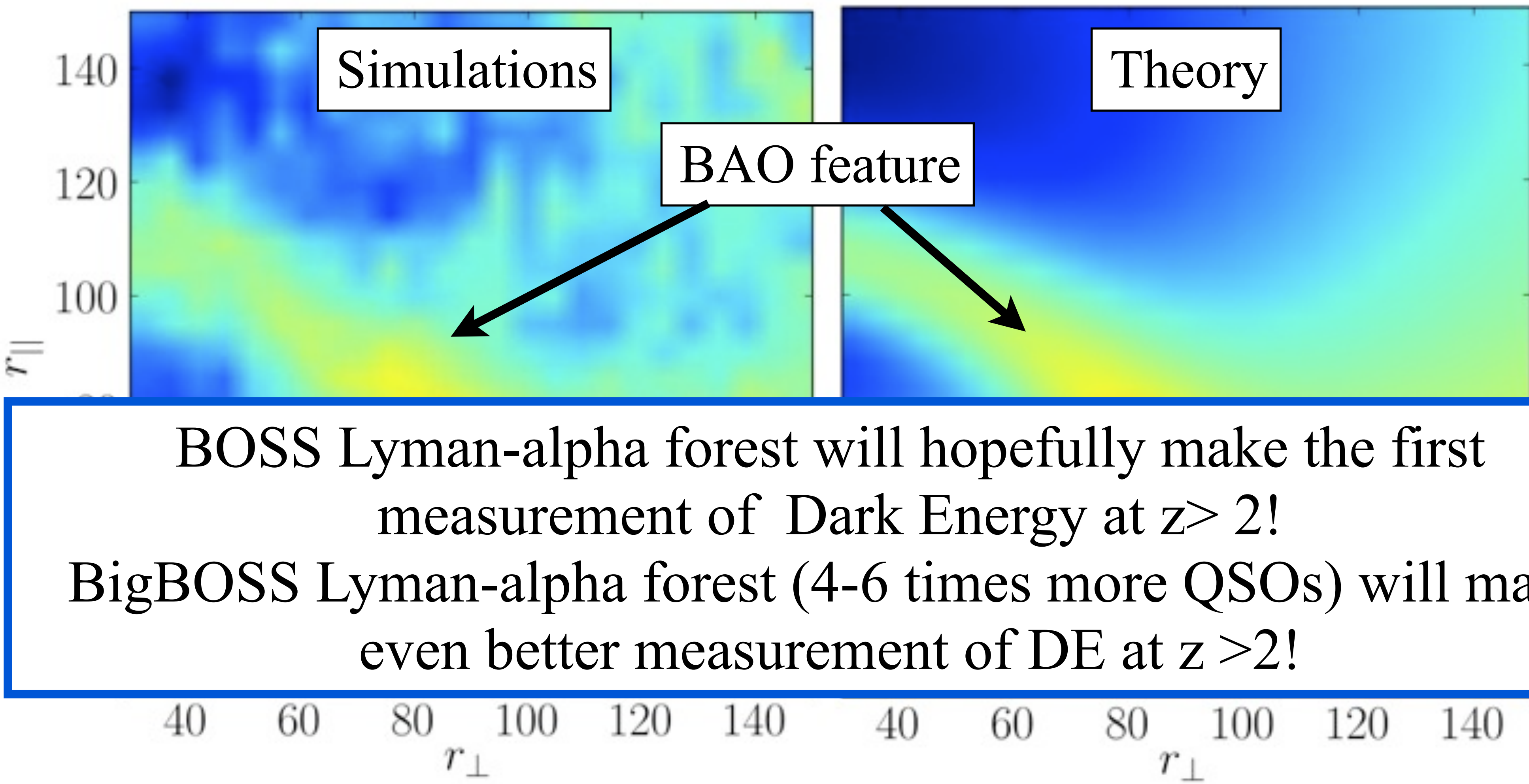
Beyond: With Lyman Alpha Forest
Mini Conclusion



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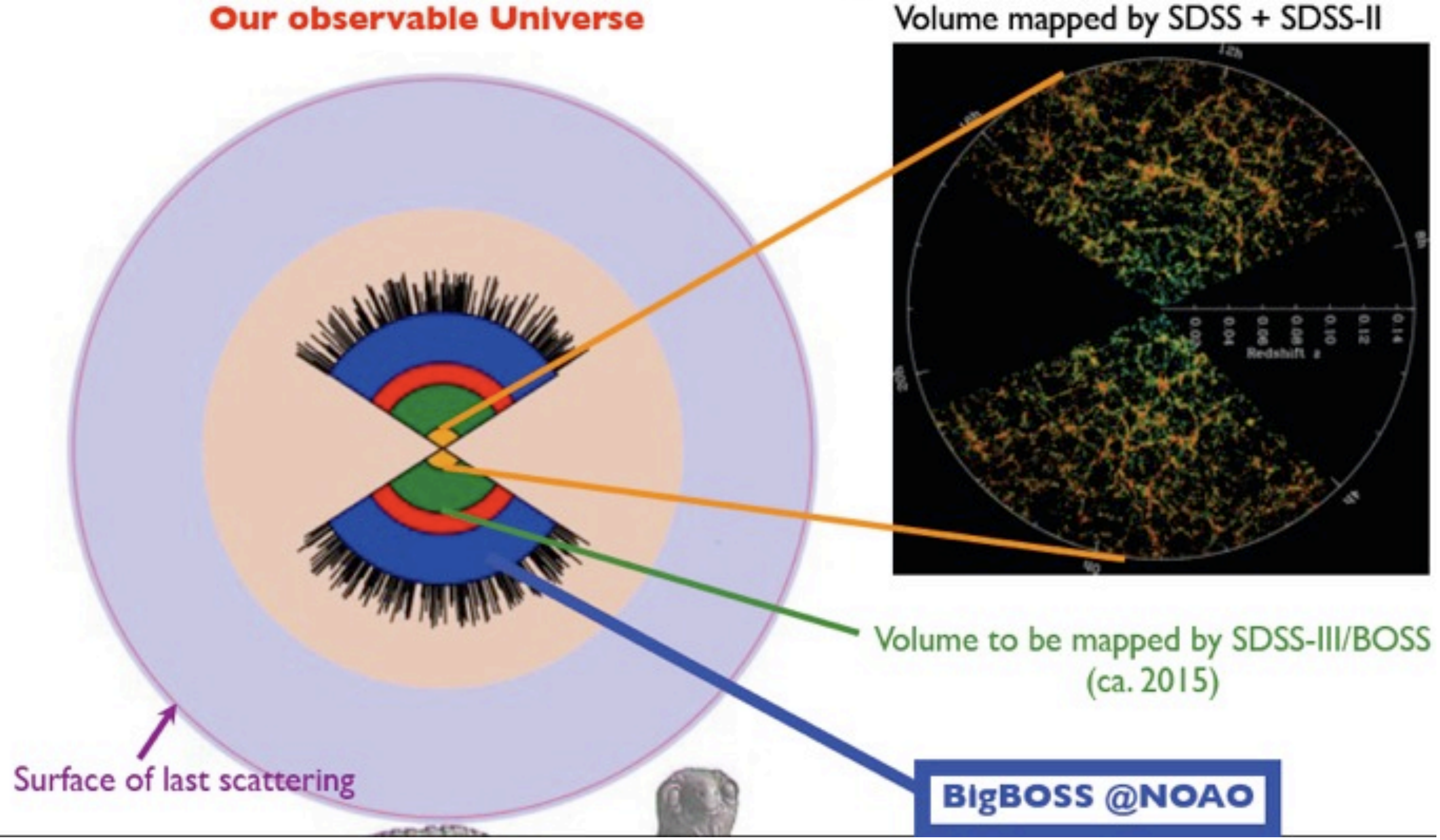
Science Goals: 50 million redshifts

Sensitivity to new physics scales as volume surveys -- # of modes



Courtesy Slide from David Schlegel

Outline

- Motivations
- Introduction
  - What are Baryon Acoustic Oscillations?
- Baryon Acoustic Oscillations: Now and Beyond
  - Now: With Luminous Red Galaxies
  - Beyond: With Lyman Alpha Forest
- **Conclusions**

Conclusions

- Baryon Acoustic Oscillations is one of the cleanest probes of **Dark Energy**
- We made the **minimum variance measurement** of galaxy clustering for **largest volume** of galaxies ever used for clustering
- Allowing us to make **significant detection of BAO at z=0.45-0.65**, the **highest redshift** range BAO is ever detected significantly.
- Looking forward, we can apply the same optimal method to both photometric and spectroscopic surveys such as DES, LSST, BOSS and BigBOSS
- We can also push measurement of BAO to higher redshift via Lyman alpha forest.
- Our results of **first simulation** of Lya forest BAO signals indicate that Lyman alpha flux provides **a good tracer of the underlying dark matter field** on large scales, therefore making Lyman alpha forest a well-suited candidate for BAO measurement.

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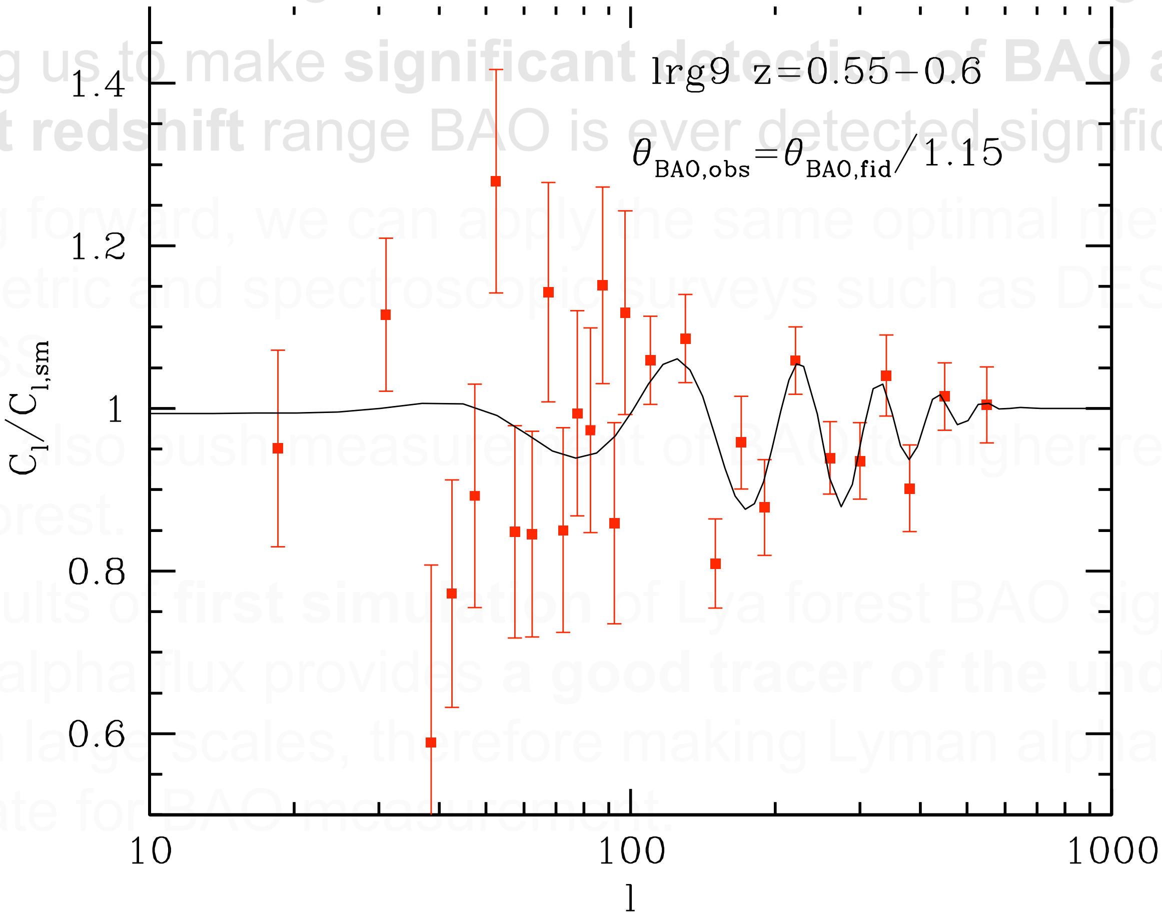

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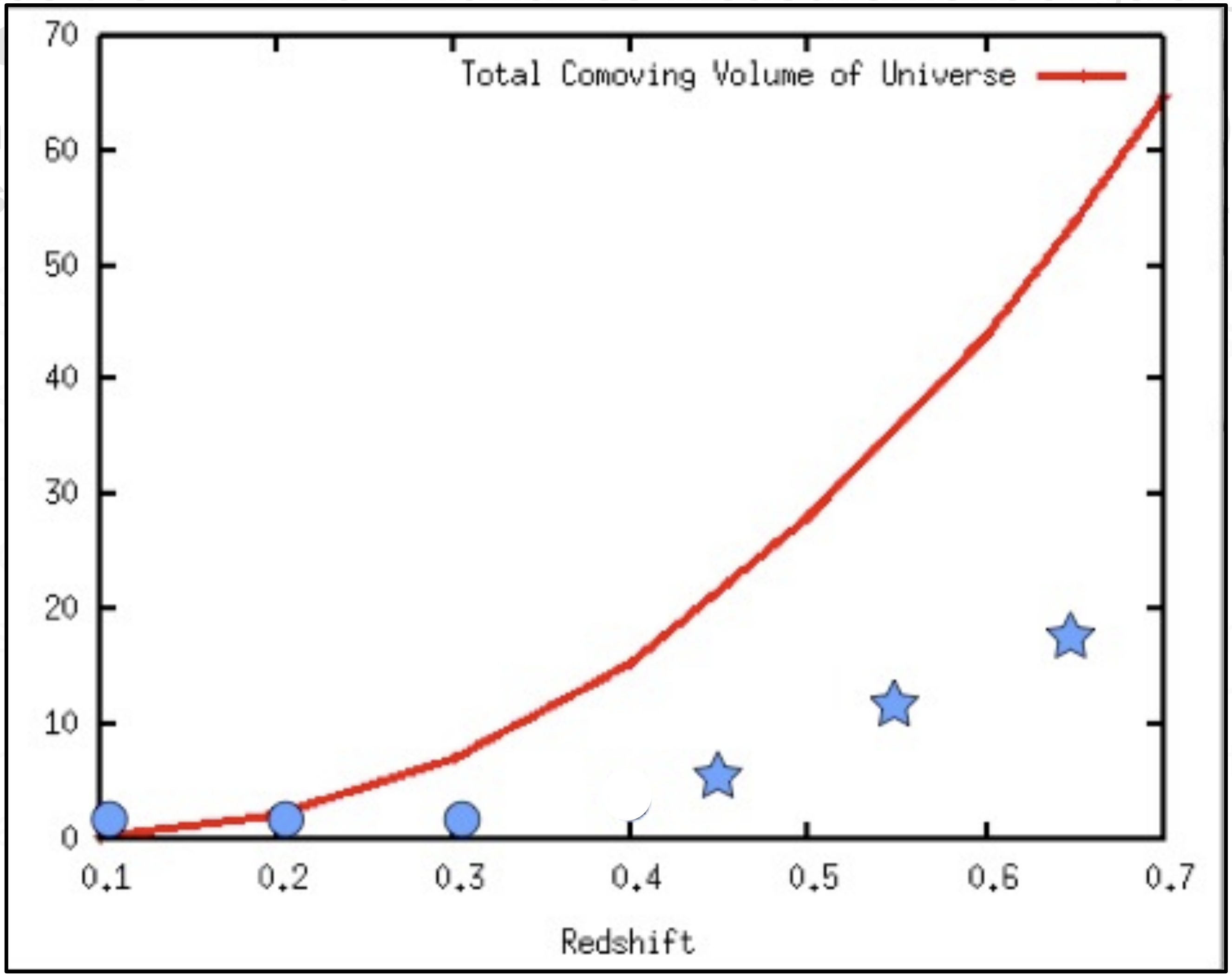

Conclusions

- Baryon Acoustic Oscillations is one of the cleanest probes of **Dark Energy**
- We made the **minimum variance measurement** of galaxy clustering for **largest volume** of galaxies ever used for clustering
- Allowing us to make **significant detection of BAO at z=0.45-0.65**, the **highest redshift** range BAO is ever detected significantly.
- Looking forward, we can apply the same optimal method to both photometric and spectroscopic surveys such as DES, LSST, BOSS and BigBOSS
- We can also push measurement of BAO to higher redshift via Lyman alpha forest.
- Our results of **first simulation** of Lya forest BAO signals indicate that Lyman alpha flux provides **a good tracer of the underlying dark matter field** on large scales, therefore making Lyman alpha forest a well-suited candidate for BAO measurement.

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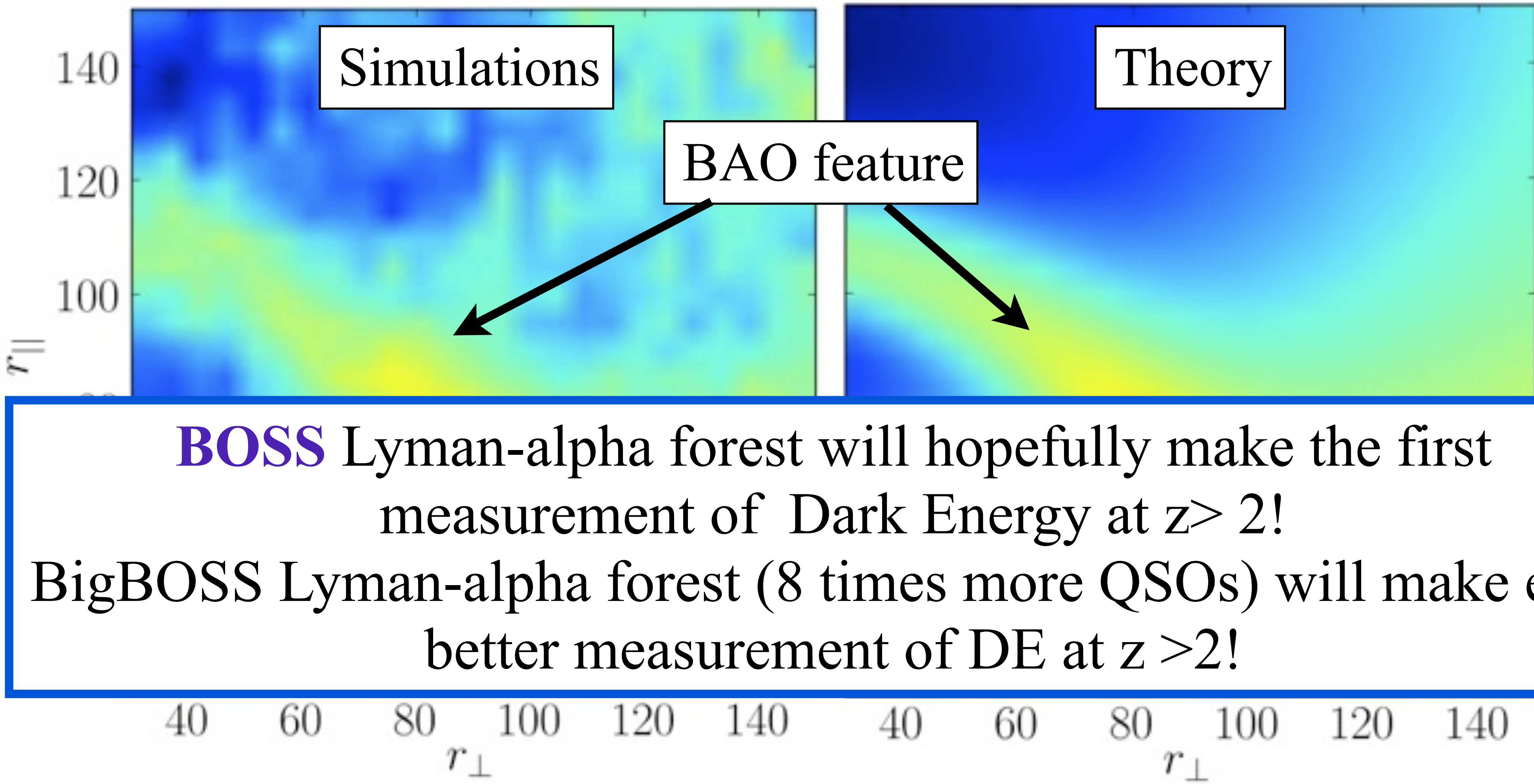
The End

Beyond: With Lyman Alpha Forest

Mini Conclusion

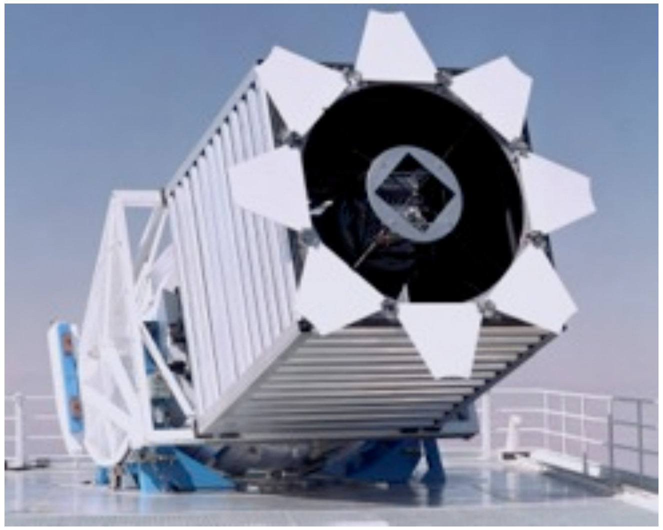


BOSS Lyman-alpha forest will hopefully make the first measurement of Dark Energy at z> 2!

BigBOSS Lyman-alpha forest (8 times more QSOs) will make even better measurement of DE at z >2!

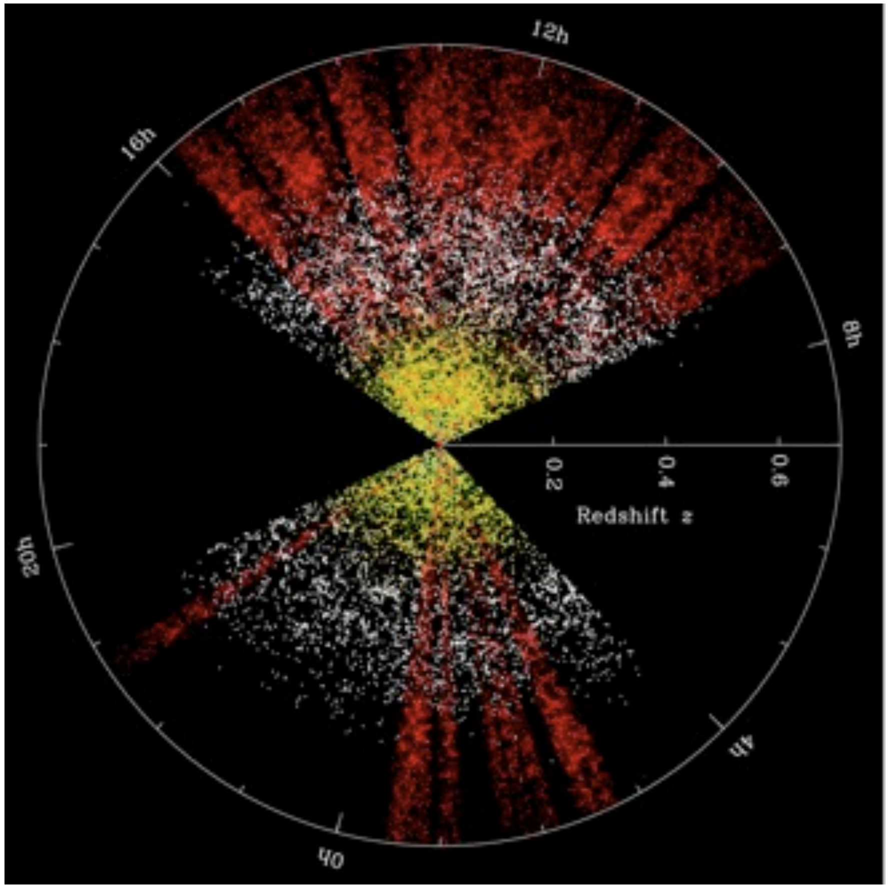
What is BOSS?
Baryon Oscillation Spectroscopic Survey

- New program for the SDSS telescope for 2008–2014 (already working and providing data!).
- Definitive study of the low-redshift acoustic oscillations. 10,000 deg^2 of new spectroscopy from SDSS imaging.
  - 1.5 million LRGs to z=0.8, including 4x more density at z<0.5.
  - 7-fold improvement on large-scale structure data from entire SDSS survey; measure the distance scale to 1% at z=0.35 and z=0.6.
  - Easy extension of current program.
- Simultaneous project to discover the BAO in the Lyman α forest.
  - 160,000 quasars. 20% of fibers.
  - 1.5% measurement of distance to z=2.3.
  - Higher risk but opportunity to open the high-redshift distance scale.

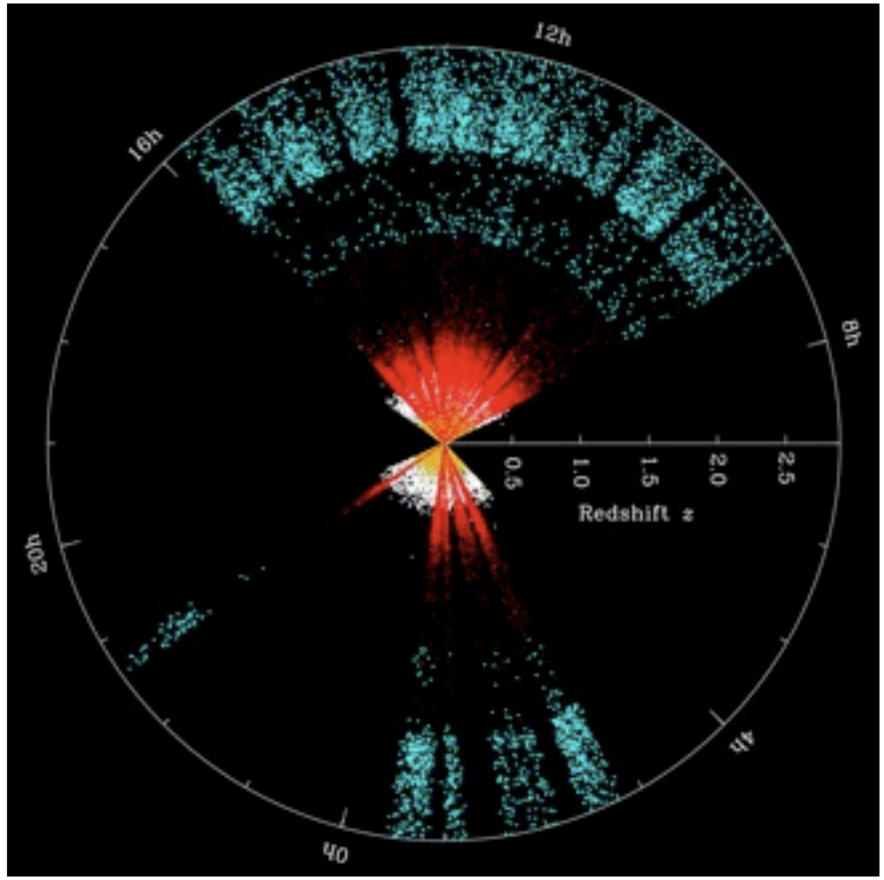


BOSS

Volume of the Universe probed by SDSS

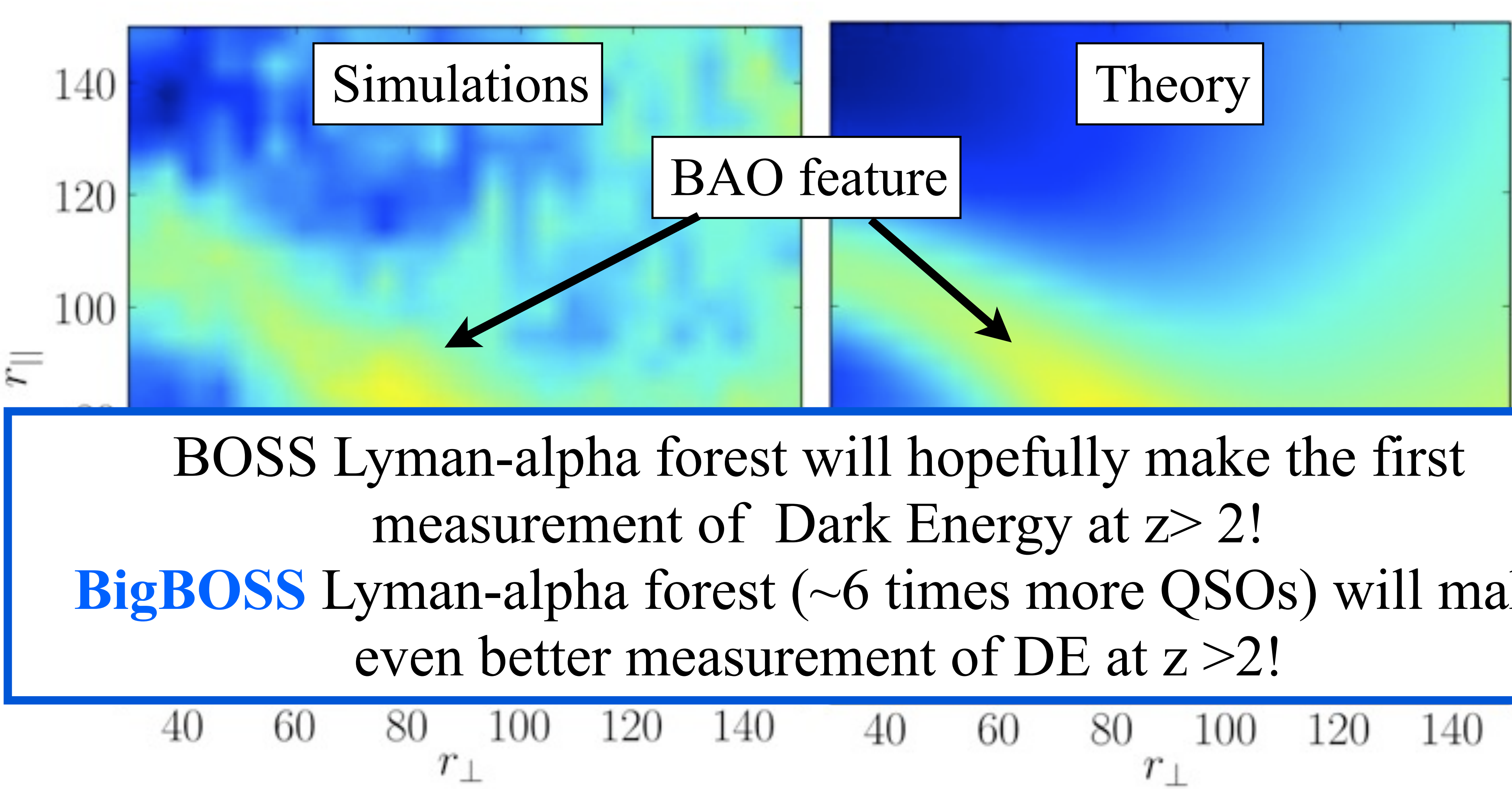


Volume of the Universe probed by BOSS



Courtesy plots from Michael Blanton

- **Dark Energy via Baryon Acoustic Oscillations**

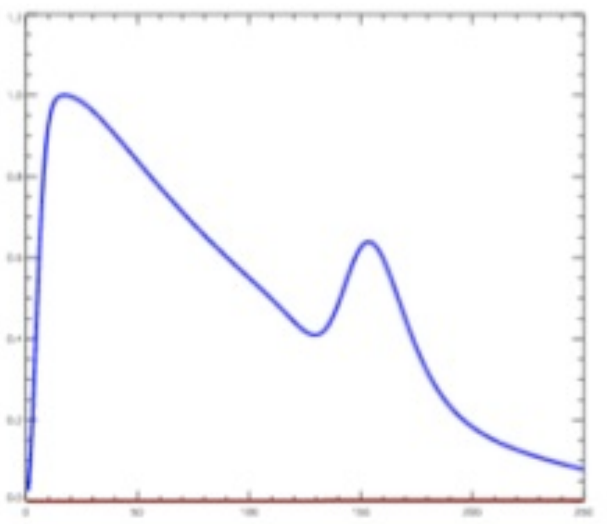


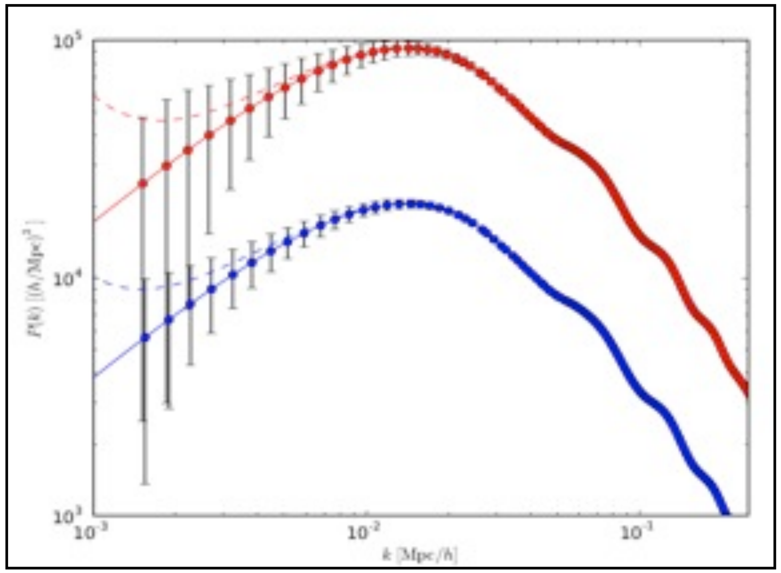
BOSS Lyman-alpha forest will hopefully make the first measurement of Dark Energy at z> 2!

BigBOSS Lyman-alpha forest (~6 times more QSOs) will make even better measurement of DE at z >2!

How do you go about measuring BAO?

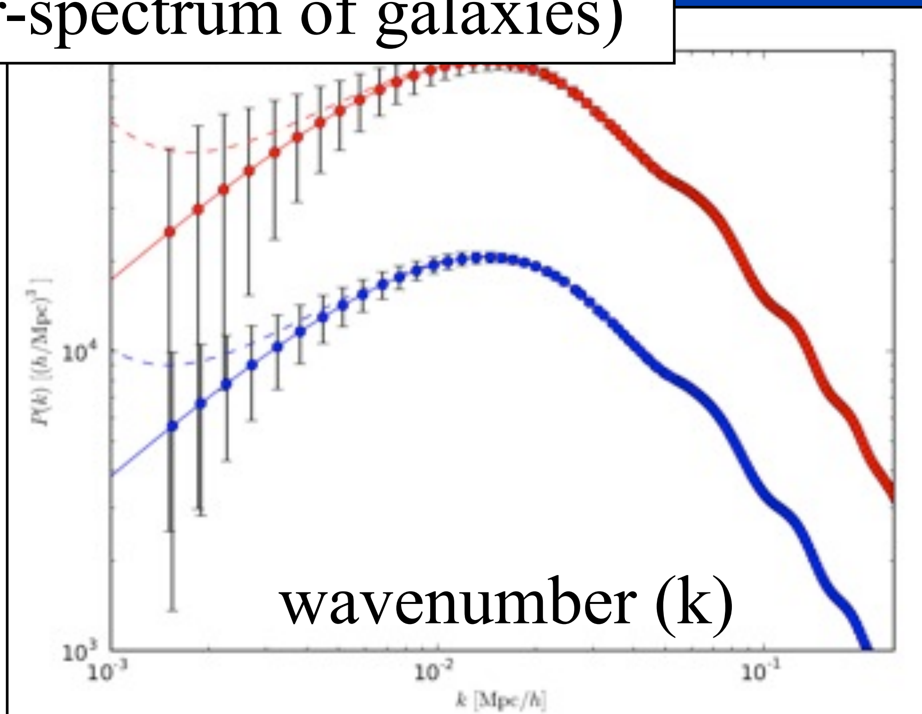
- Since there are many ripples, how do we actually measure the BAO?
- We measure the correlation function or its Fourier transform, called the power-spectrum.





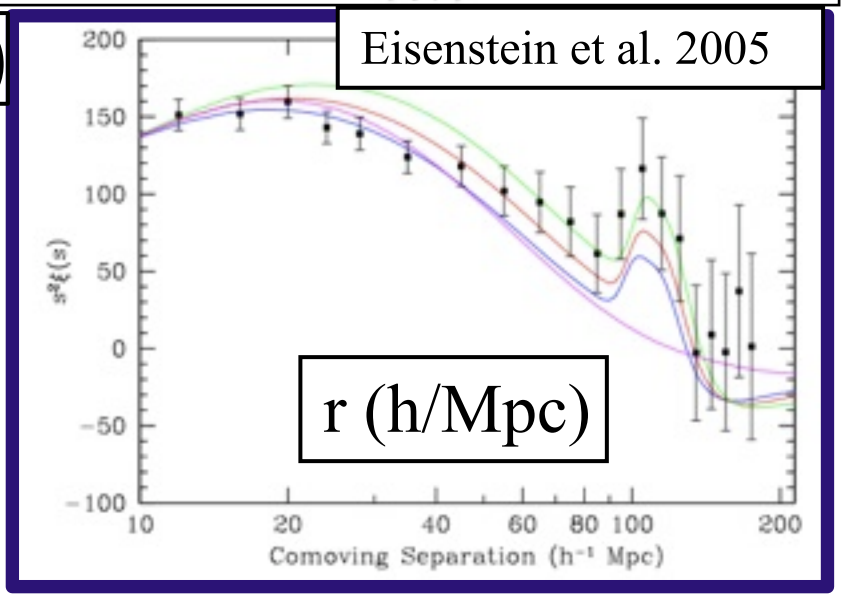
Predicted signals of BAO

P(k) (power-spectrum of galaxies)



Fourier space

$r^2\xi(r)$



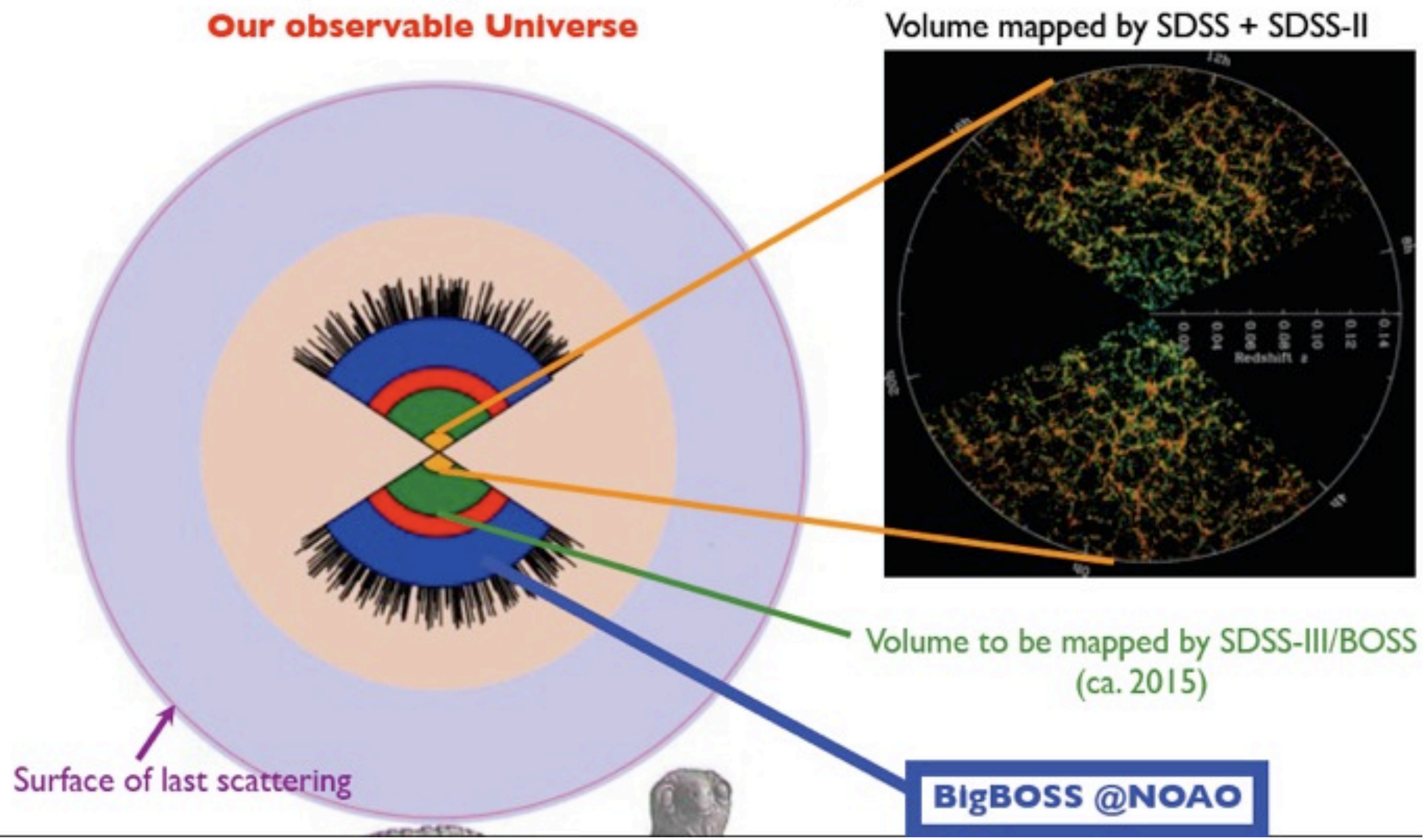
Configuration space

The Ground-Based Stage IV BAO Experiment
BigBOSS

Science Goals: 50 million redshifts

BERKELEY LAB

Sensitivity to new physics scales as volume surveys -- # of modes



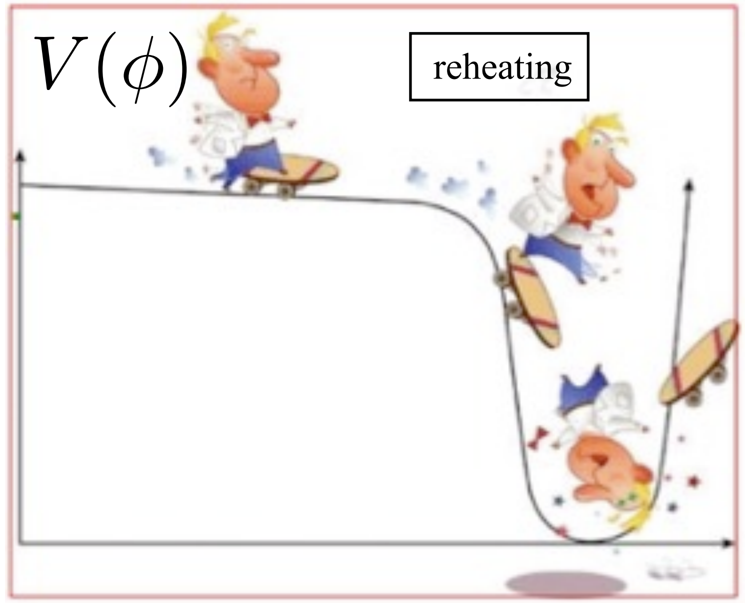
Courtesy Slide from David Schlegel

Lyman Alpha Forest: what can it do?
— Non-gaussianities in Early Universe

parameterize how much non-linear corrections are there to the potential

$$\Phi = \phi + f_{NL}\phi^2$$

Primordial potential (assumed to be gaussian random field)



Inflation

Lyman Alpha Forest: what can it do?
— Non-gaussianities in Early Universe

parameterize how much non-linear corrections are there to the potential

$$\Phi = \phi + f_{NL}\phi^2$$

Primordial potential (assumed to be gaussian random field)

Non-Gaussianity from Inflation

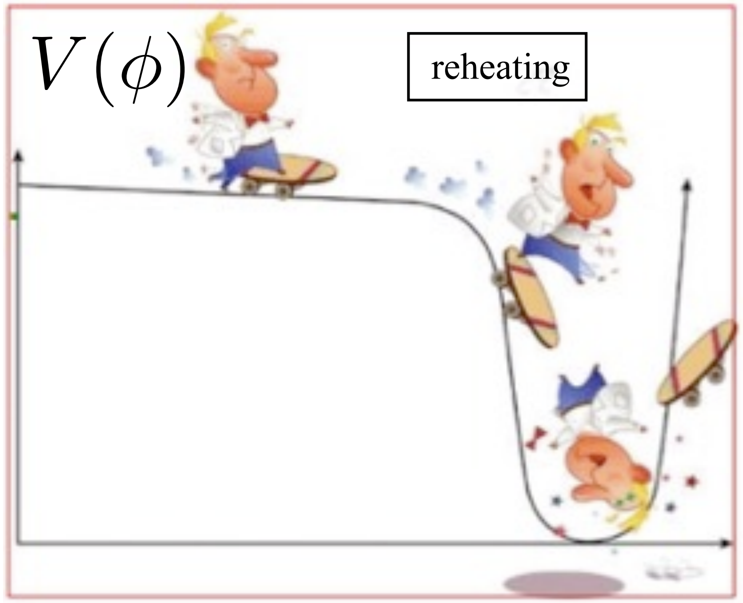
f_{NL} ~ 0.05 canonical inflation (single field, couple of derivatives) (Maldacena 2003, Acquaviva etal 2003)

f_{NL} ~ 0.1--100 higher order derivatives

- DBI inflation (Alishahiha, Silverstein and Tong 2004)
- UV cutoff (Craminelli 2003)

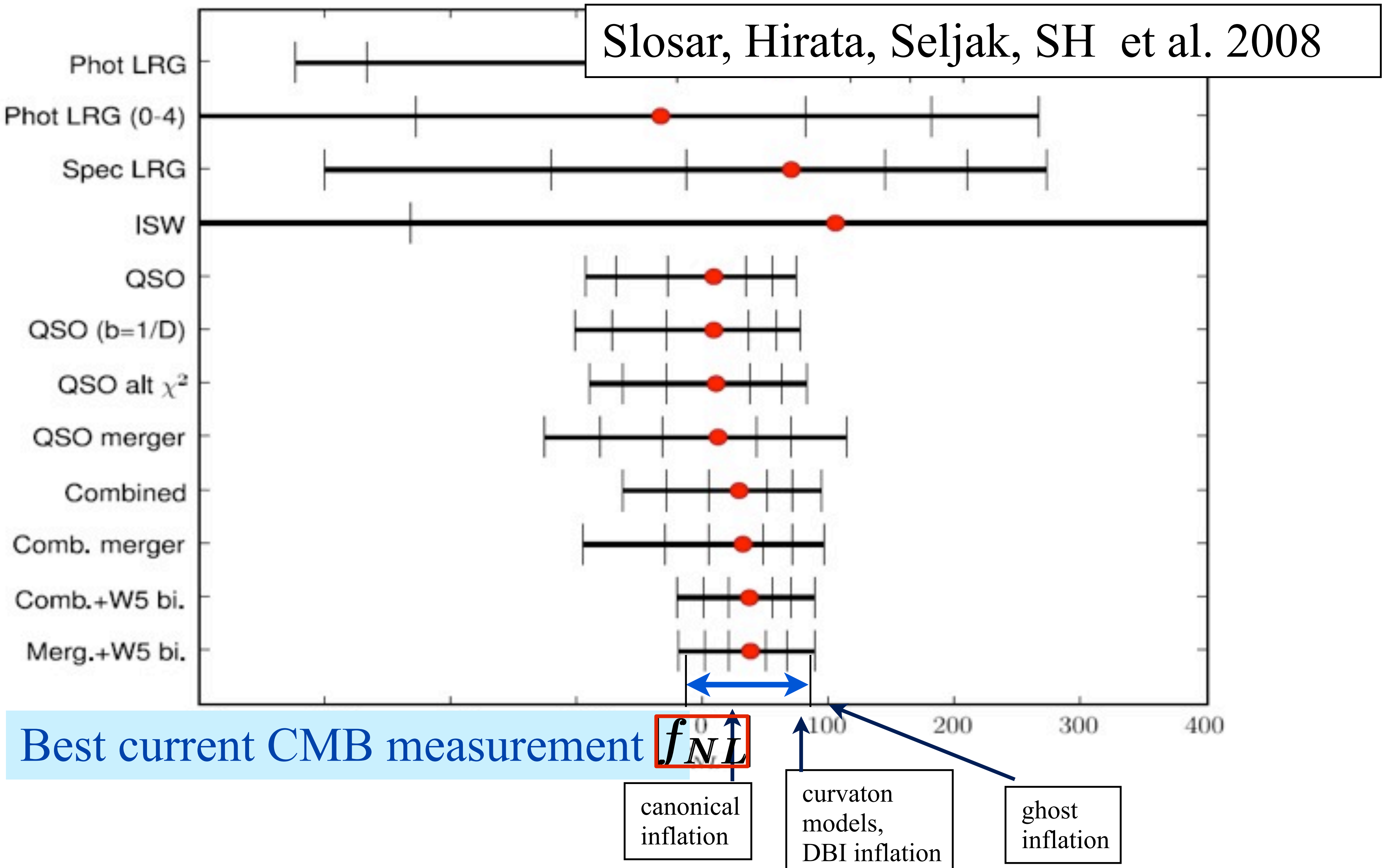
f_{NL} >10 curvaton models (Lyth, Ungarelli and Wands, 2003)

f_{NL} ~100 ghost inflation (Arkani-Hamed et al., 2004)

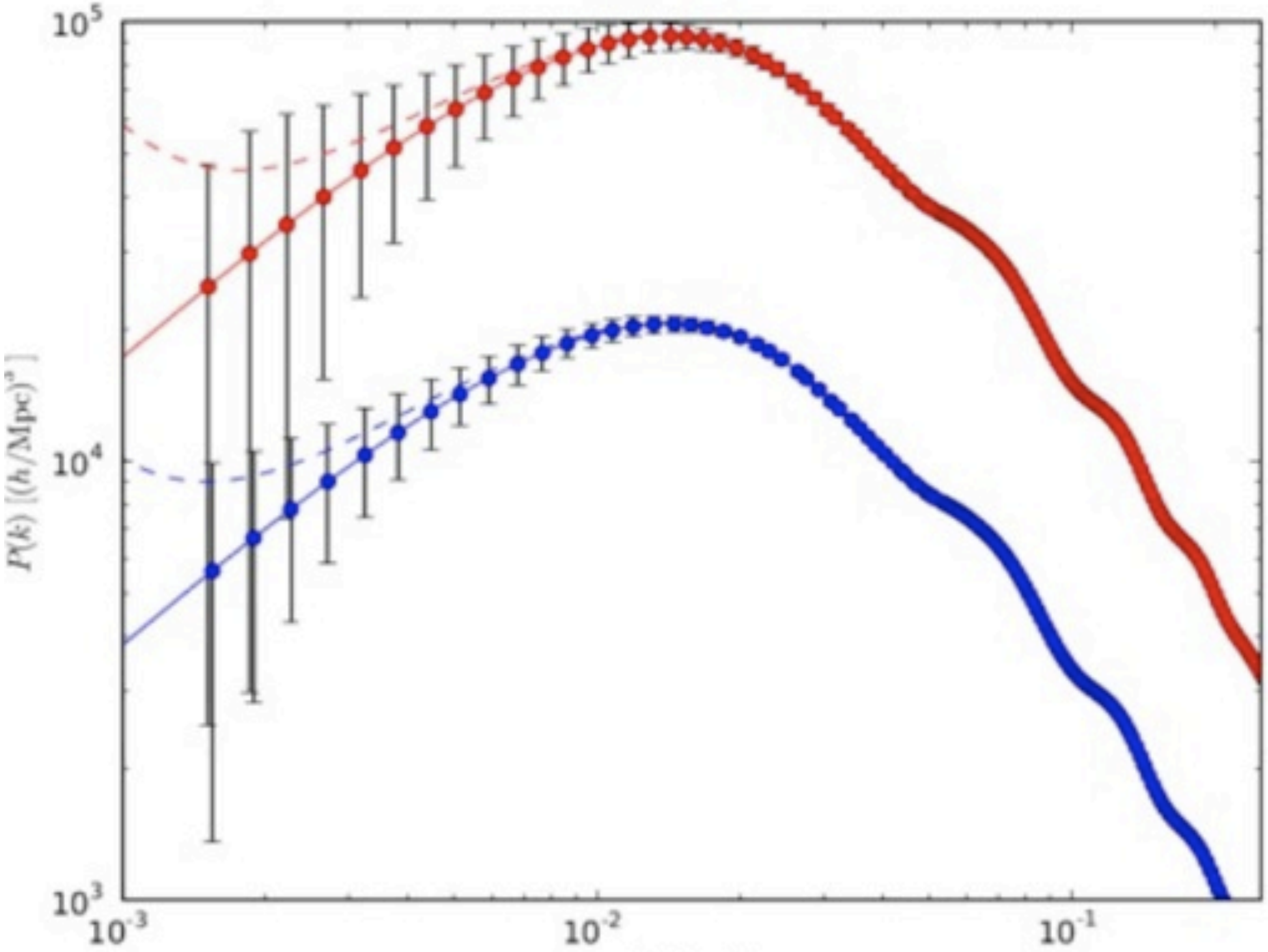


← Inflation →

Lyman Alpha Forest: what can it do?
— Non-gaussianities in Early Universe

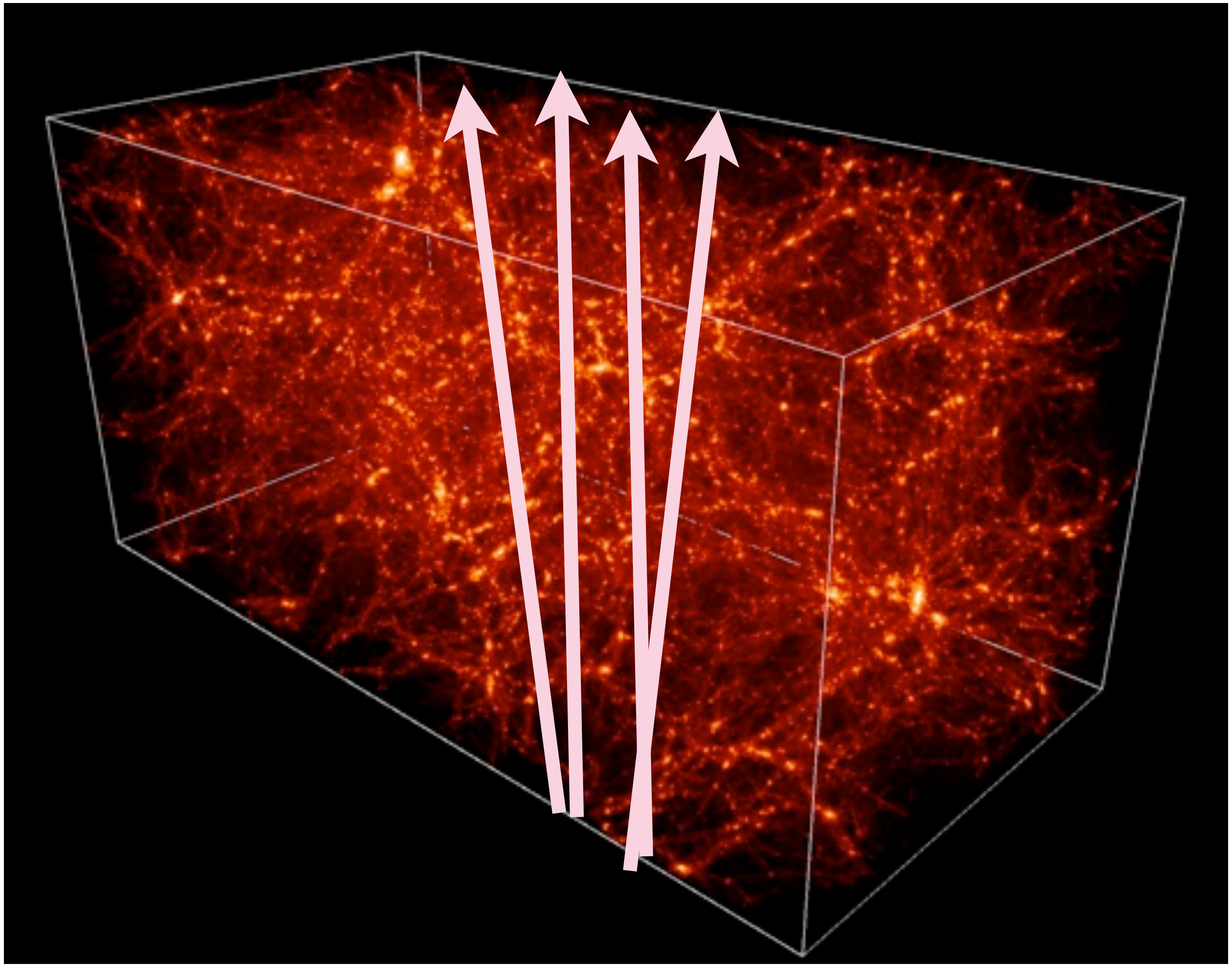


P(k) (Mpc/h)^3



k (h/Mpc)

Lyman Alpha Forest: what can it do?



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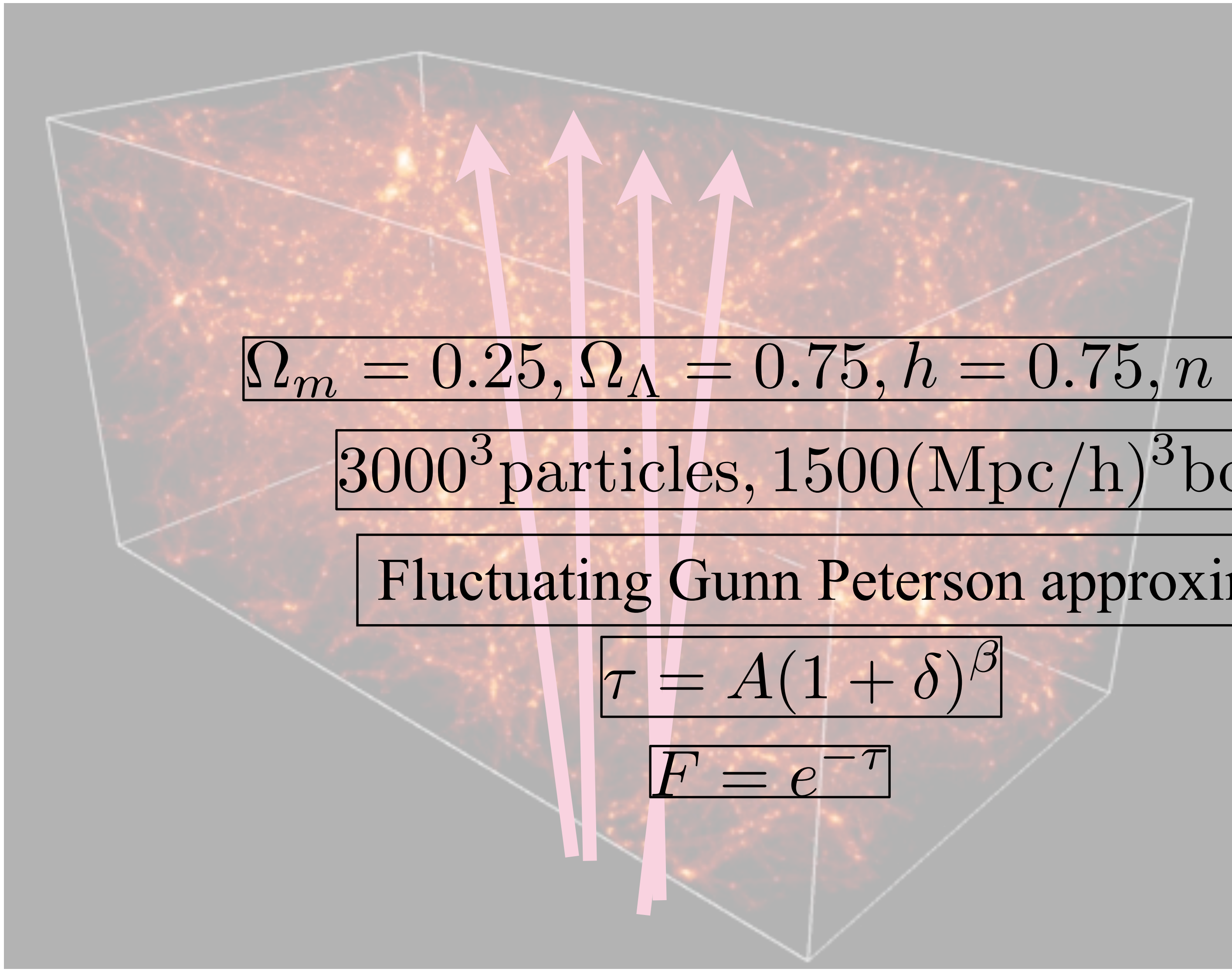


$$\Omega_m = 0.25, \Omega_\Lambda = 0.75, h = 0.75, n = 0.97, \sigma_8 = 0.8$$

3000^3 particles, $1500(\mathrm{Mpc/h})^3$ box, 3000^3 grid

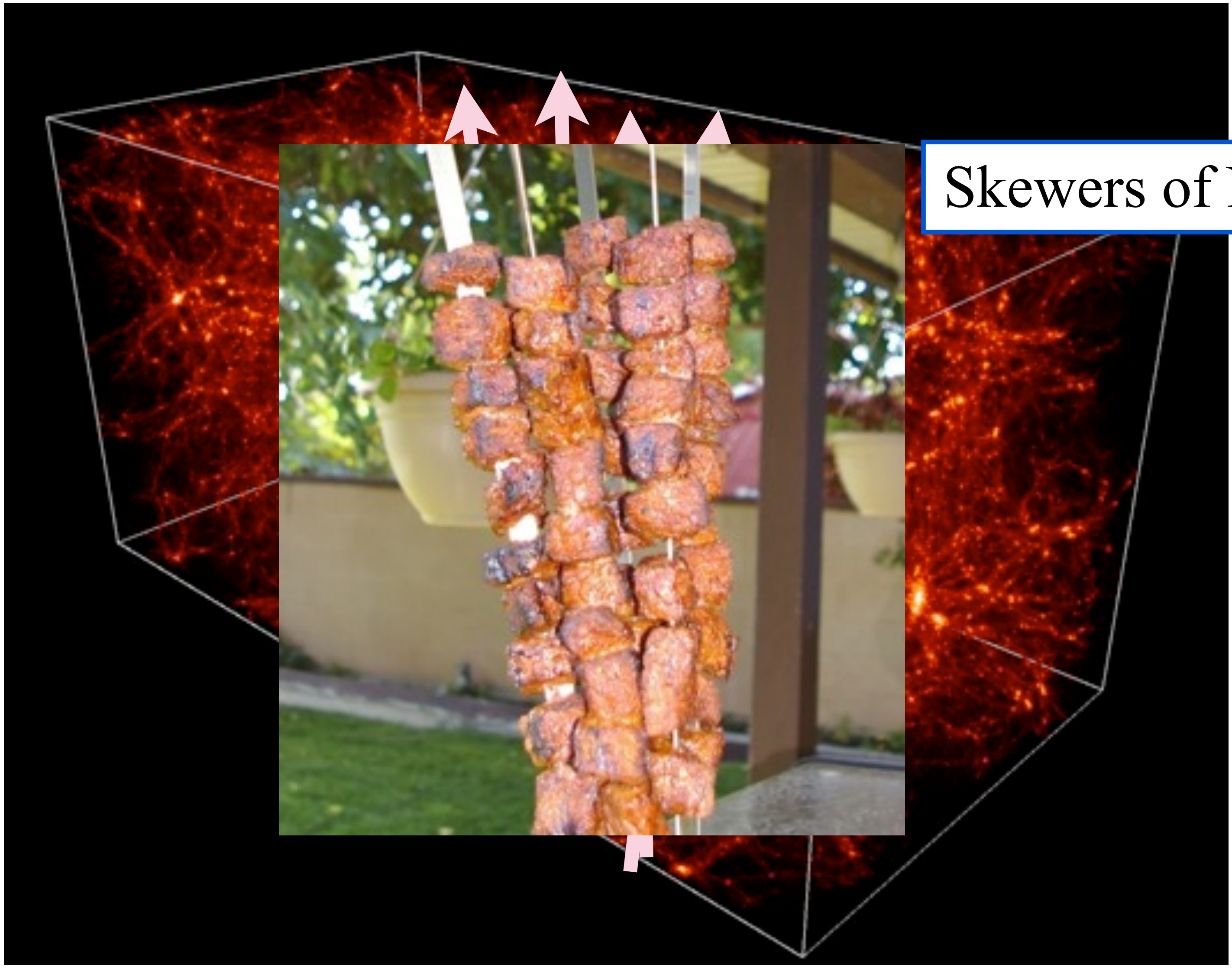
Fluctuating Gunn Peterson approximation

$$\tau = A(1+\delta)^\beta$$

$$F = e^{-\tau}$$

Lyman Alpha Forest: what can it do?

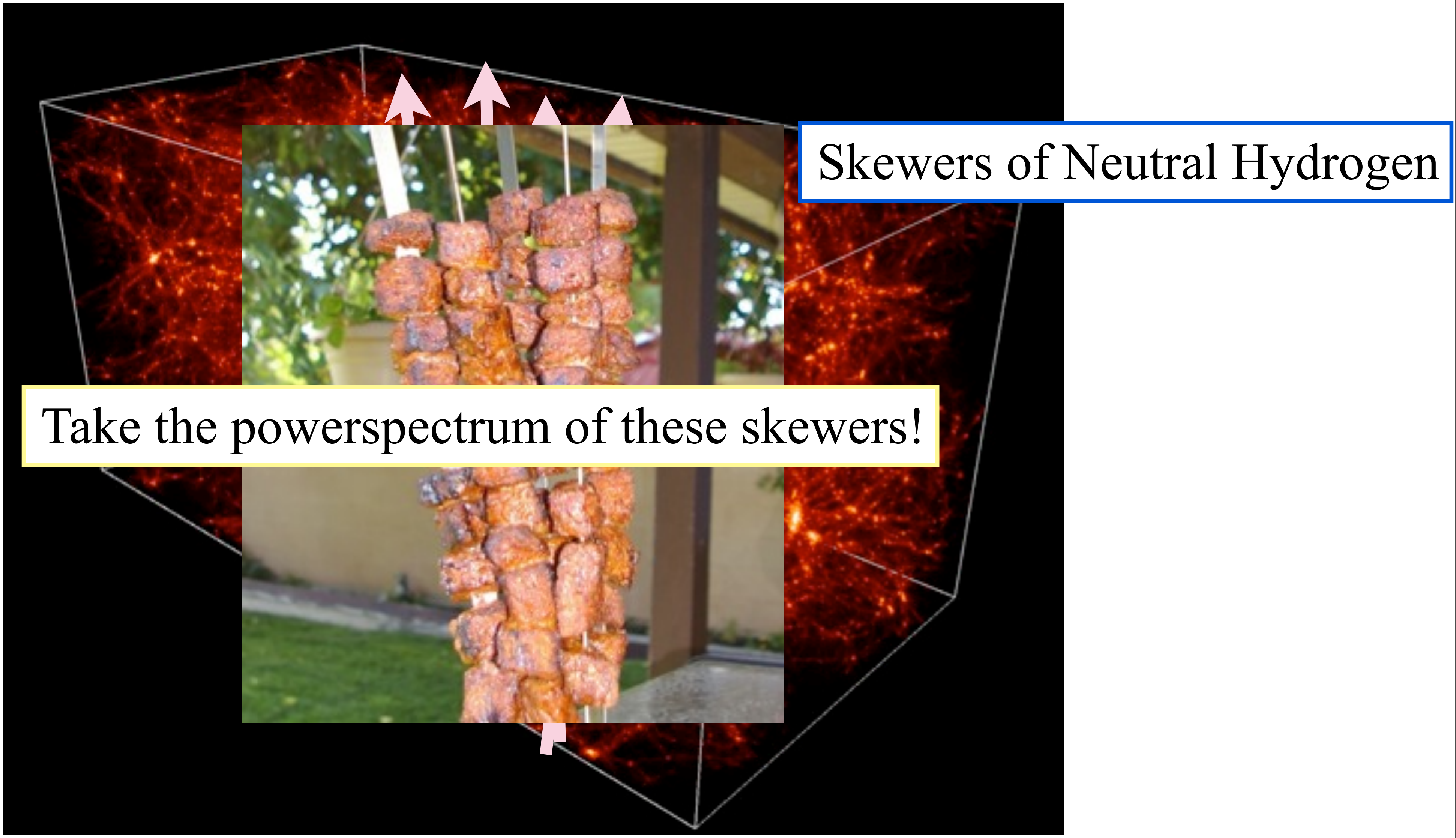
- **Dark Energy via Baryon Acoustic Oscillations**



Skewers of Neutral Hydrogen

Lyman Alpha Forest: what can it do?

- **Dark Energy via Baryon Acoustic Oscillations**



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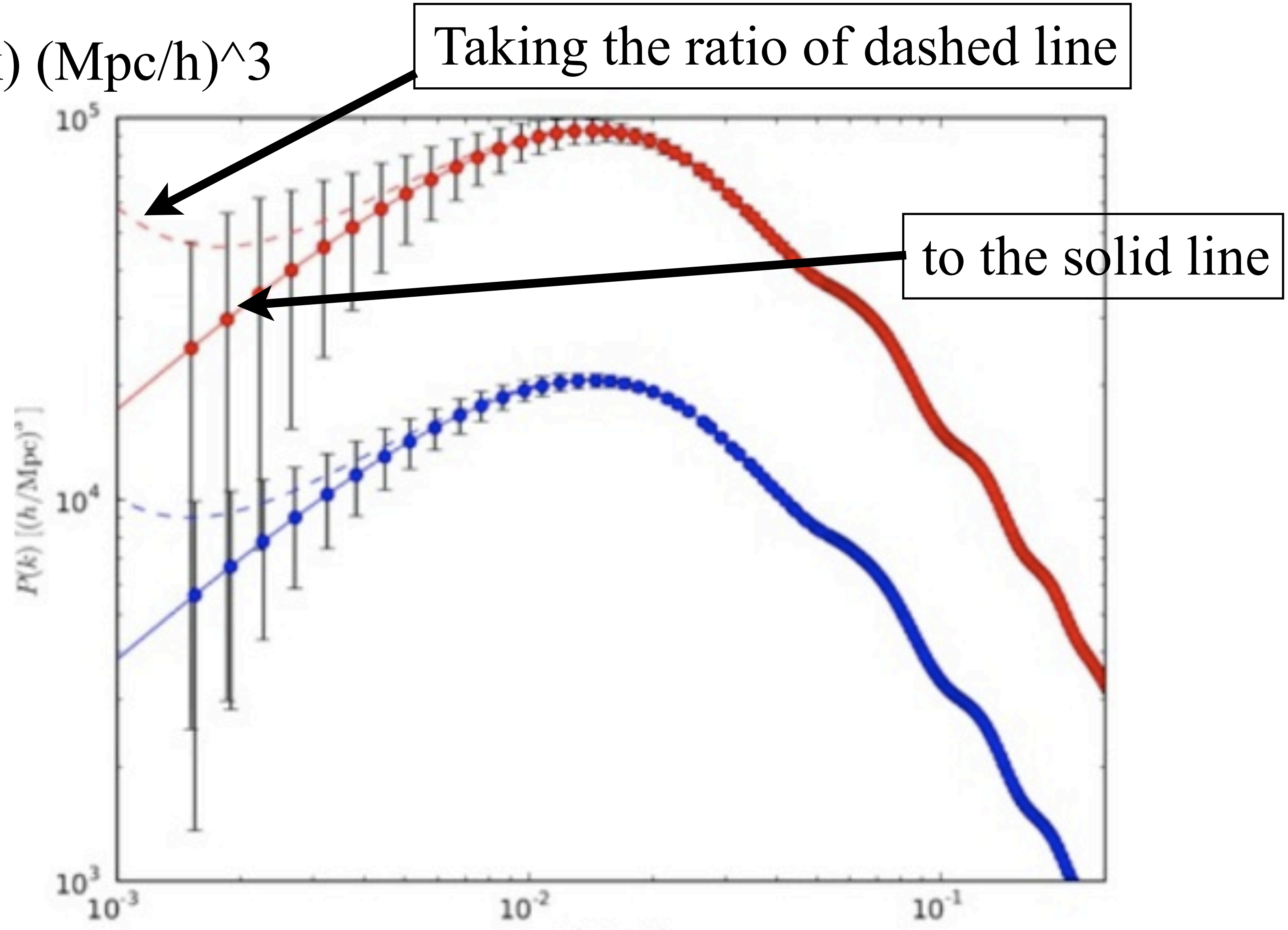
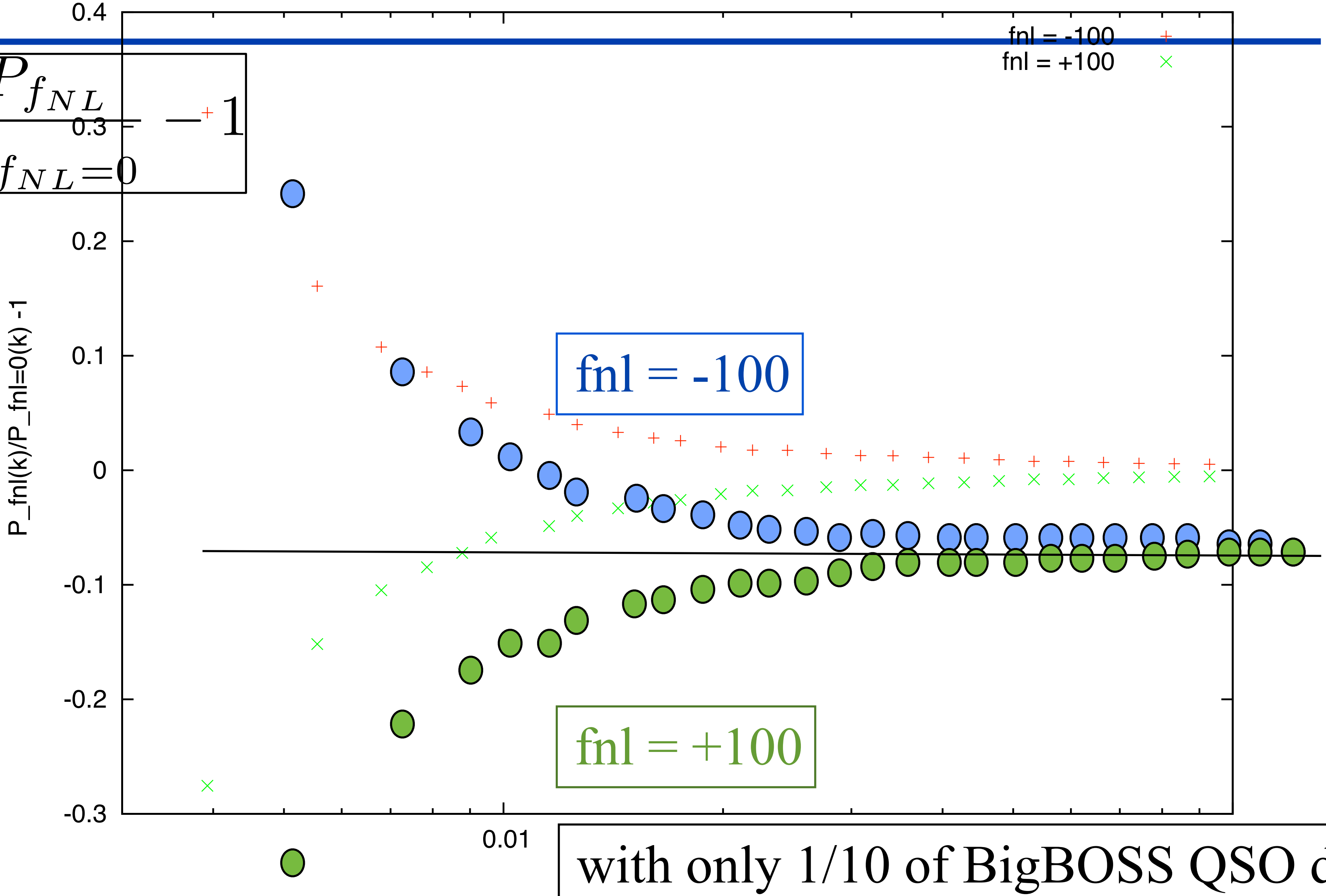


k (h/Mpc)

What can we do with Lya and fnl?



$$\frac{P_{f_{NL}}}{P_{f_{NL}=0}} - 1$$

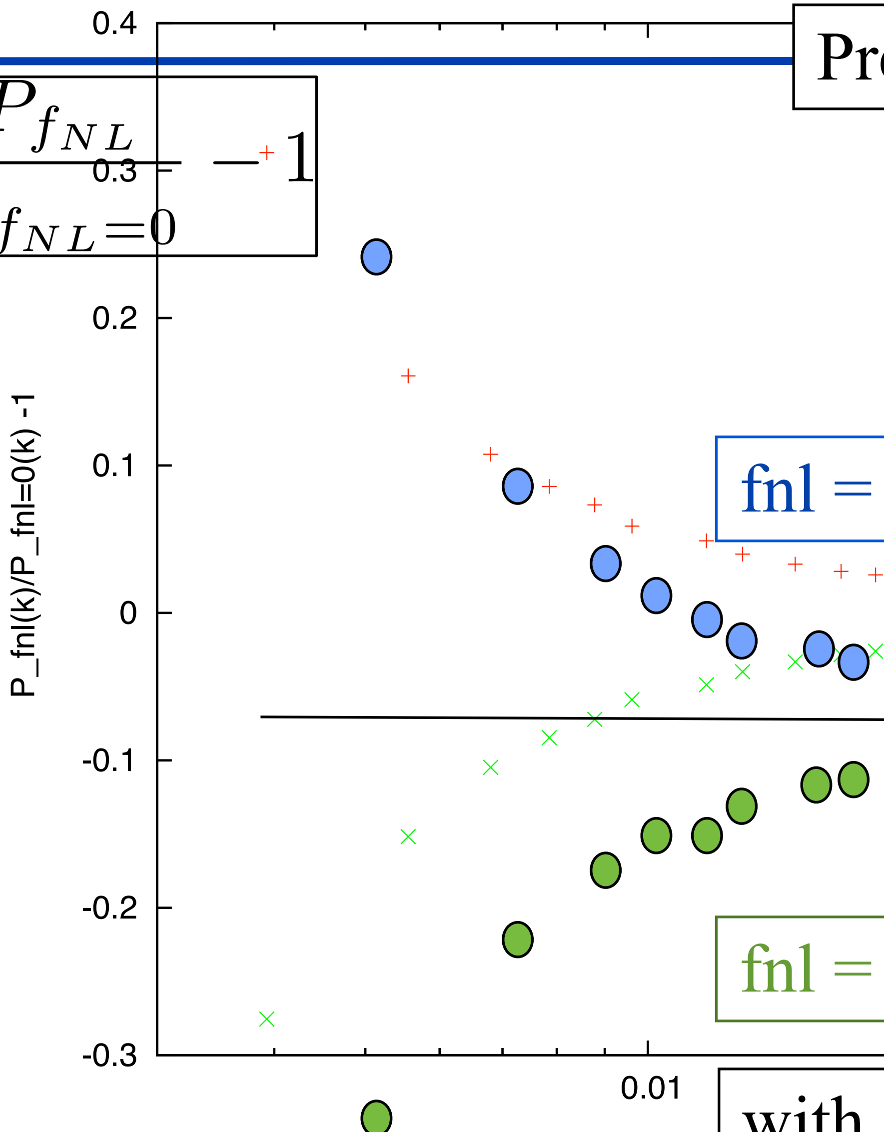
with only 1/10 of BigBOSS QSO density

Ho, Desjacques, Slosar & Seljak (in prep)

What can we do with Lya and fnl?

Preliminary theory predictions

$$\frac{P_{f_{NL}}}{P_{f_{NL}=0}} - 1$$



fnl =

fnl = +100

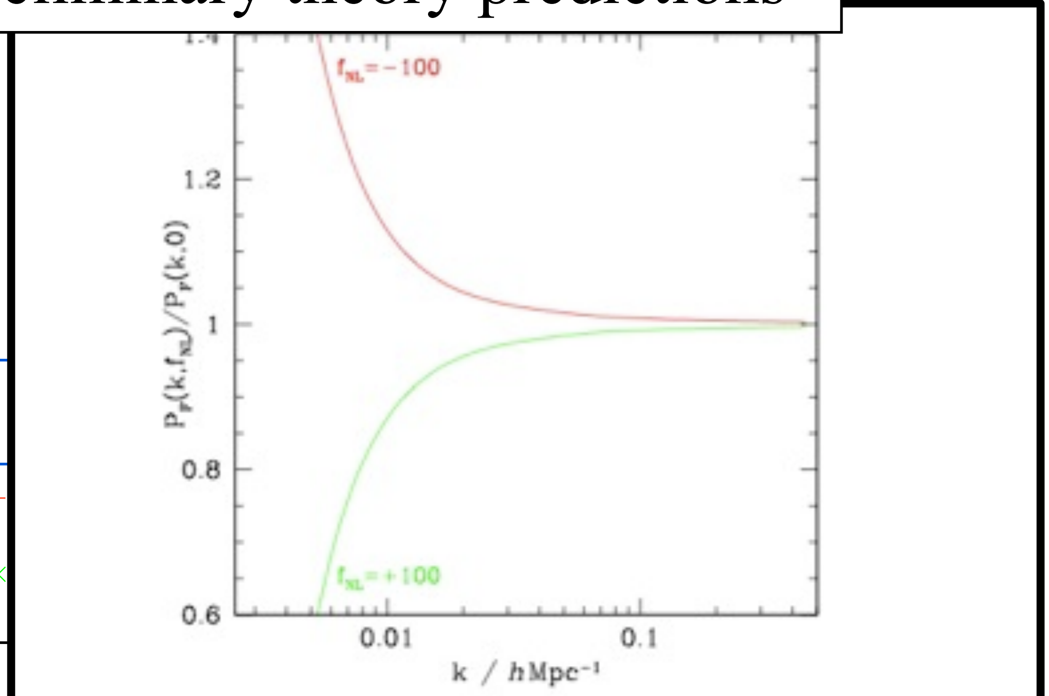
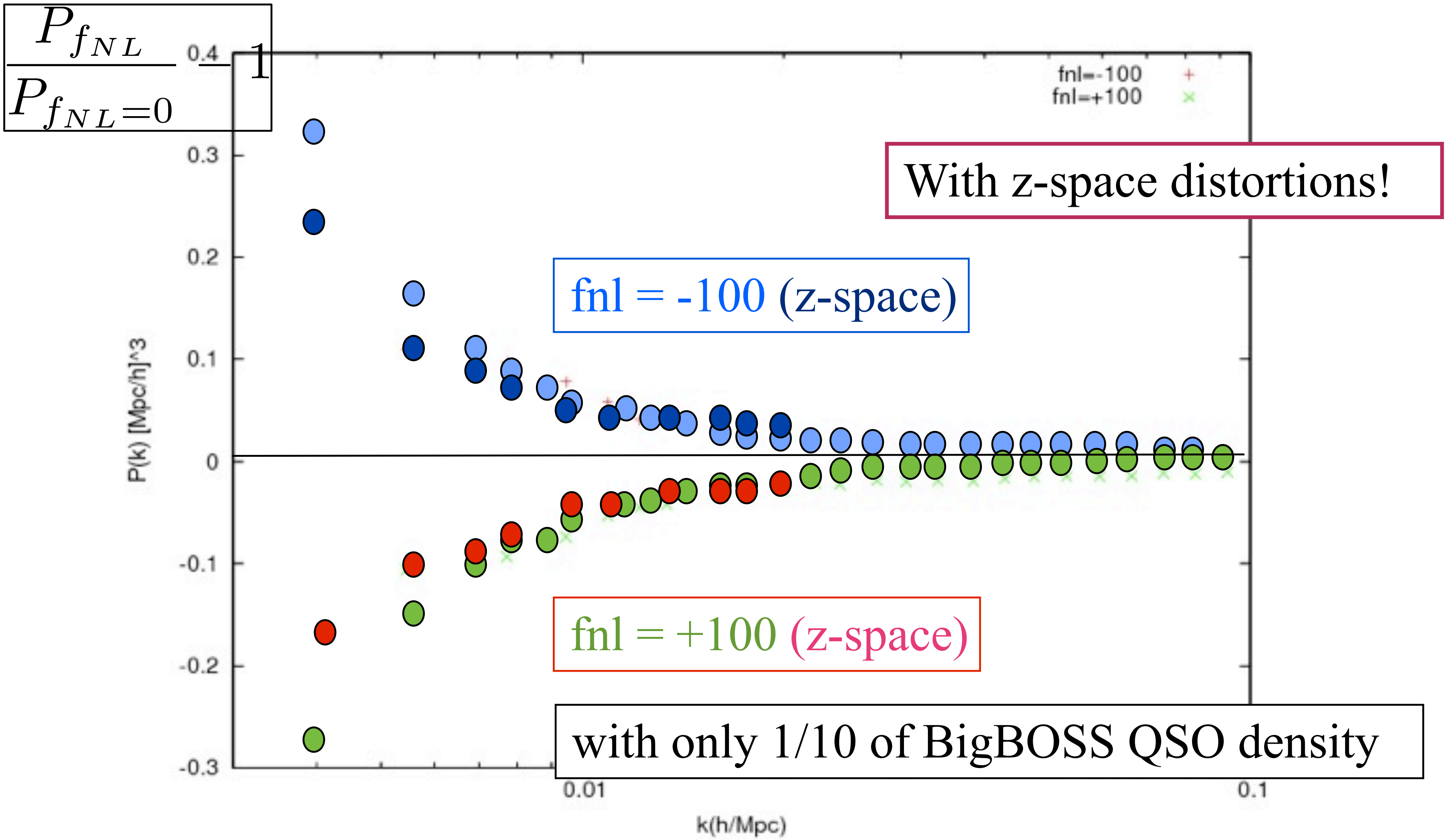


FIGURE 1. Fractional deviation from the Gaussian Lyα flux power spectrum at $z = 2$.

with only 1/10 of BigBOSS QSO density

Ho, Desjacques, Slosar & Seljak (in prep)

What can we do with Lya and fnl?



Ho, Desjacques, Slosar & Seljak (in prep)

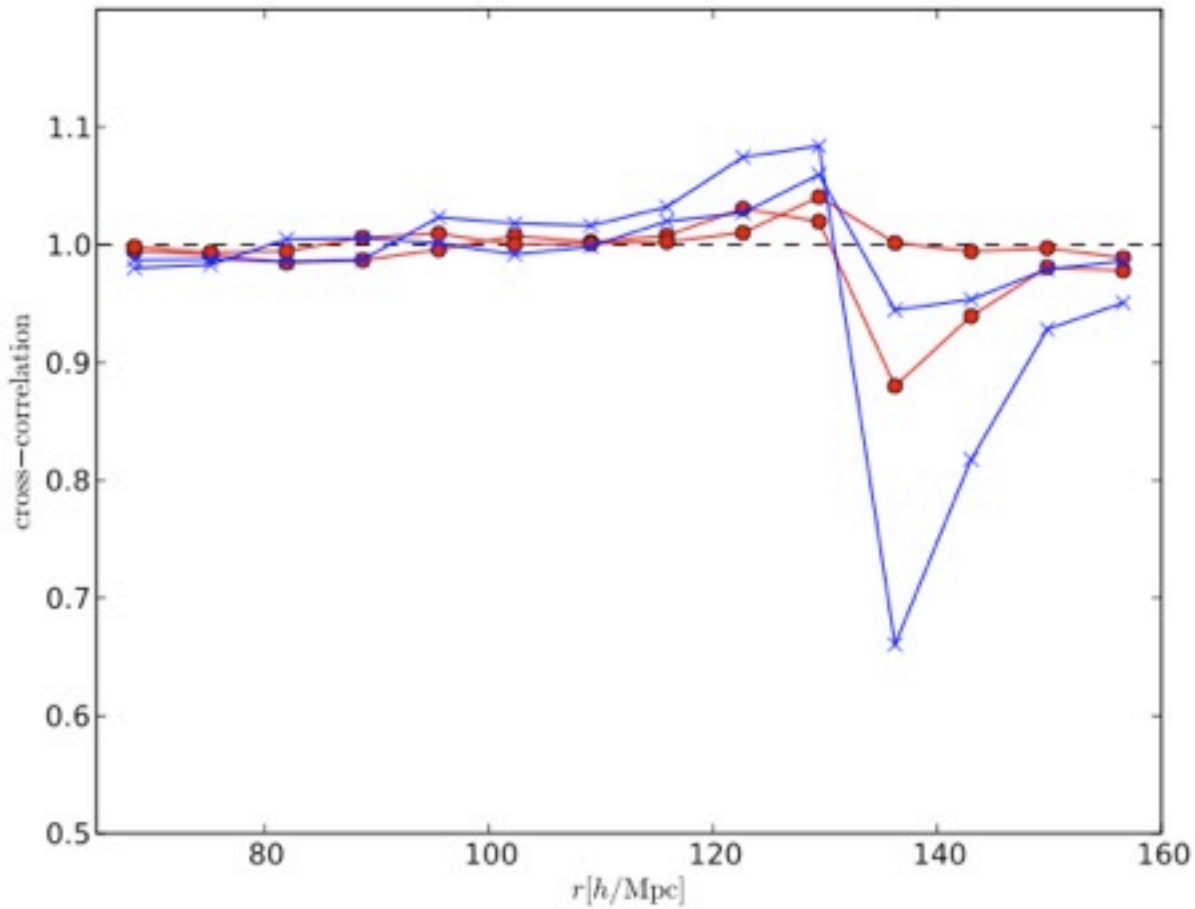
Things I can talk about, but won't...

- Redshift space distortions' effect
- Effects of DLAs (Damped Lya systems), BALs (Broad Absorption line systems), Metals
- Effect of incomplete continuum subtractions
- The other systematic error that will be coming from the experiment/analysis.

Conclusion

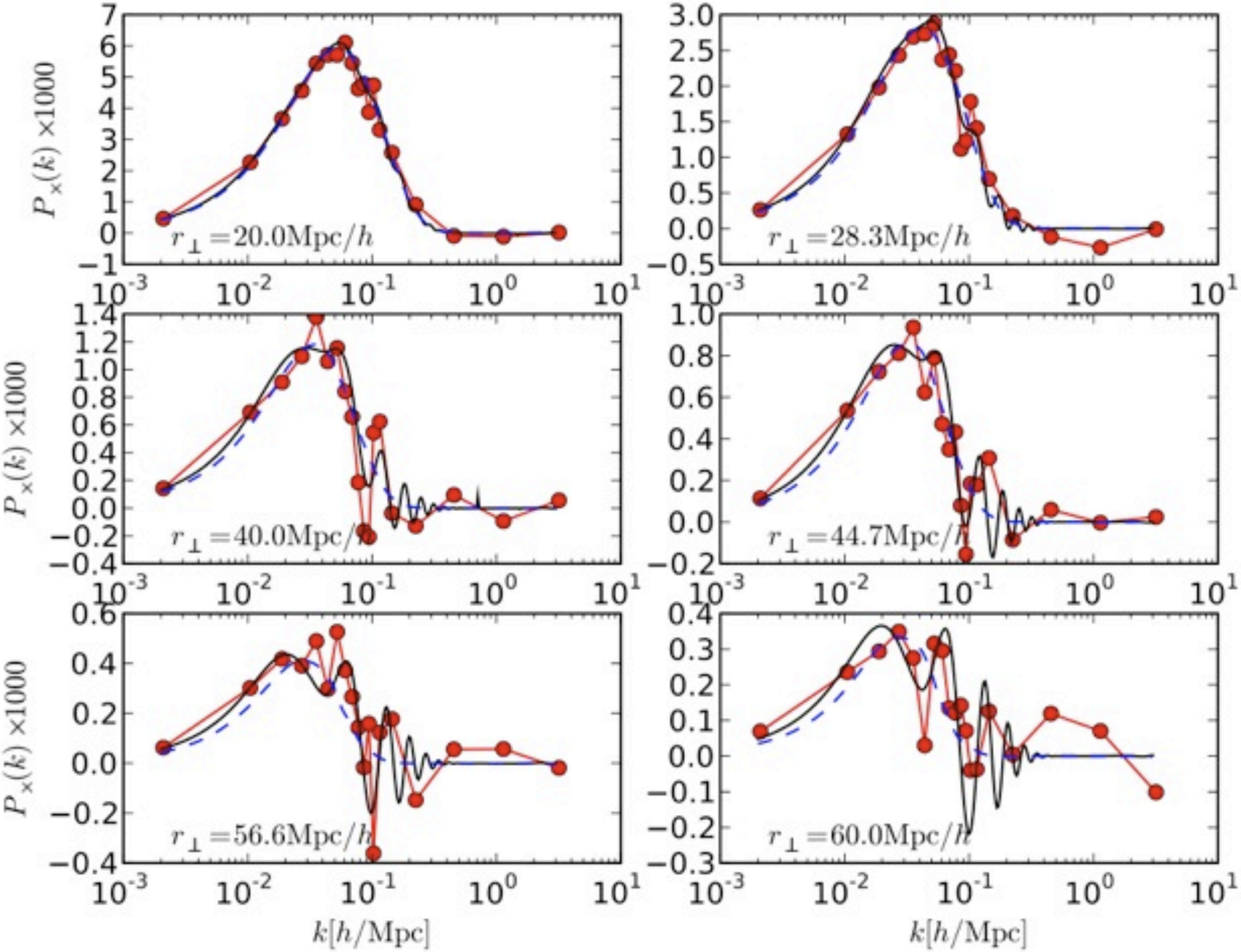
- **Lyman-alpha forest in BOSS and BigBOSS will (hopefully) do the following:**
  - — **Lya BAO to measure Dark Energy at z>2**
  - — **Lya probes non-gaussianity of the Early Universe**
  - — **Other applications:**
    - **Lya P(k) tighten the cosmological constraints**
    - **temperature density relation in the IGM**
    - **finding missing baryons at higher z**

$$\sqrt{\xi_{lh}^2/\xi_{ll}\xi_{hh}}$$



$$r[h/Mpc]$$

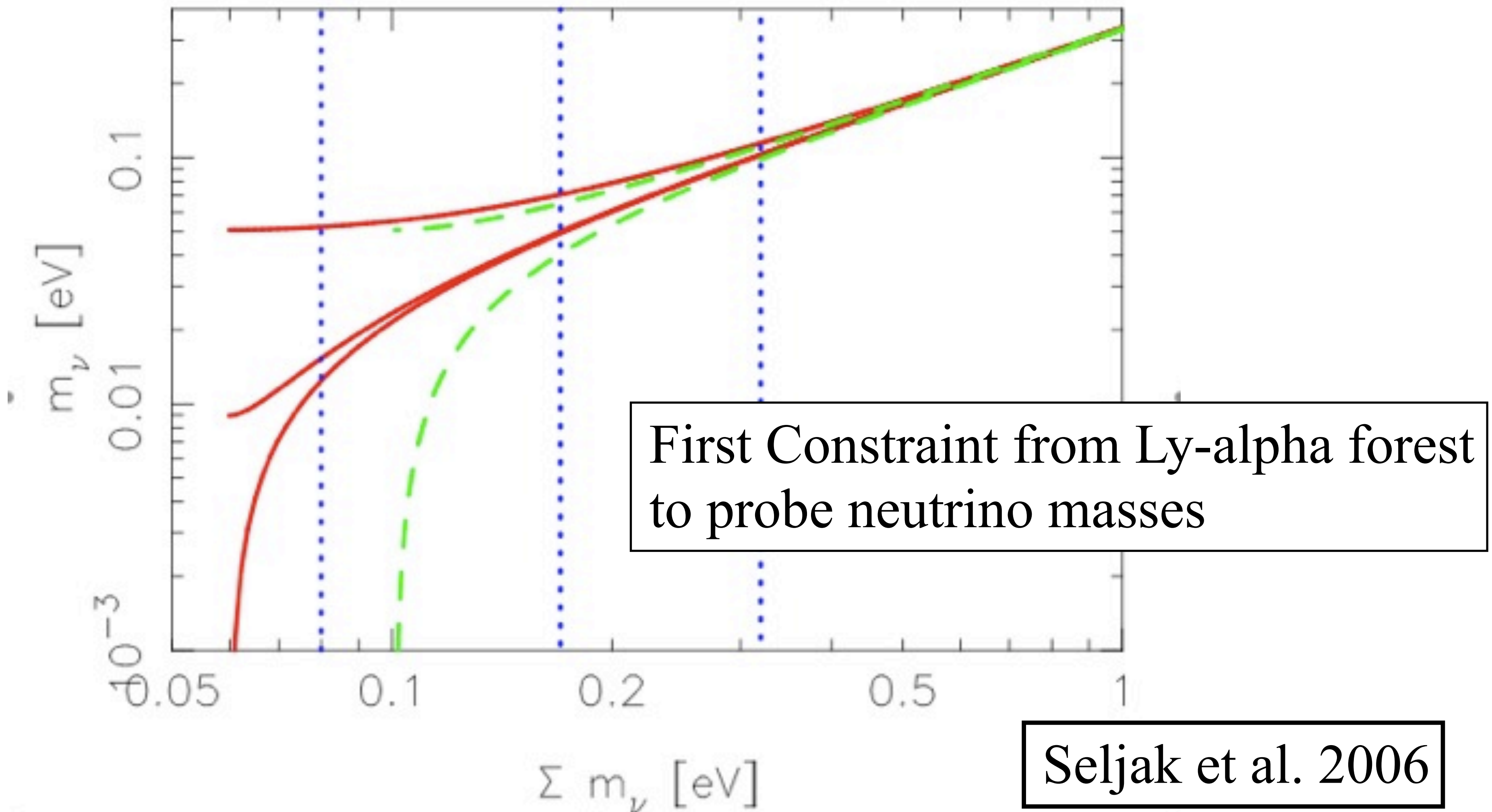
FIG. 2: The cross-correlation coefficient between the flux in our low and high resolution boxes, $\sqrt{\xi_{lh}^2/\xi_{ll}\xi_{hh}}$. Red points show the result for the two low resolution boxes having twice the smoothing length of the high resolution box, blue is the same for 4× smoothing length.



$r_\perp = 20.0\mathrm{Mpc}/h$
$r_\perp = 28.3\mathrm{Mpc}/h$
$r_\perp = 40.0\mathrm{Mpc}/h$
$r_\perp = 44.7\mathrm{Mpc}/h$
$r_\perp = 56.6\mathrm{Mpc}/h$
$r_\perp = 60.0\mathrm{Mpc}/h$
$P_\times(k) \times 1000$
$k[h/\mathrm{Mpc}]$

Lyman Alpha Forest: what can it do?

- **Cosmological Constraints from Lyman-alpha power spectrum**



Seljak et al. 2006

Lyman Alpha Forest: what can it do?

- **Cosmological constraints from Lyman-alpha power spectrum (with no BAO)**

	Planck	Planck + BigBOSS Lya	Planck + BigBOSS Lya + Galaxies
$\sigma(\sum m_\nu)$	0.307	0.048	0.006
$\sigma(\Omega_K)$	0.011	0.0041	0.00038
$\sigma(n_s)$	0.0034	0.0023	0.001
$\sigma(dn_s/dln(k))$	0.003	0.0028	0.0005

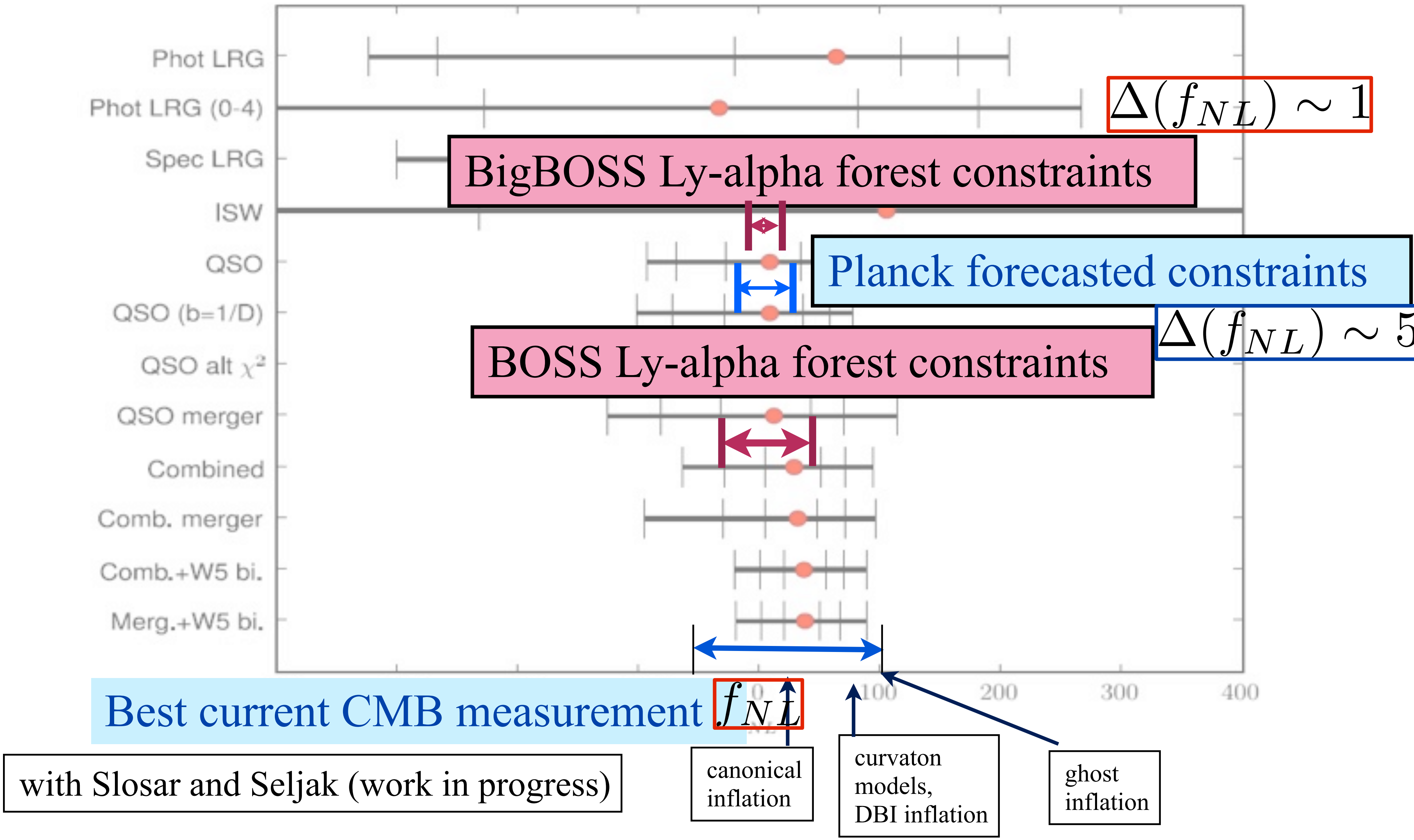
Courtesy from Anze Slosar

Outline

- Motivations
- Introduction (What is Lyman-alpha forest?)
- What can you do with Lyman-alpha forest?
  - — Baryon Acoustic Oscillations -> Dark Energy
  - — Lyman-alpha power spectrum
  - — Non-gaussianities in Early Universe

- Conclusion

Lyman Alpha Forest: what can it do?
— Non-gaussianities in Early Universe



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Lyman Alpha Forest: what can it do?

- **Simulation boxes of Dark matter**
- 3000^3 particles

  3000^3 mesh

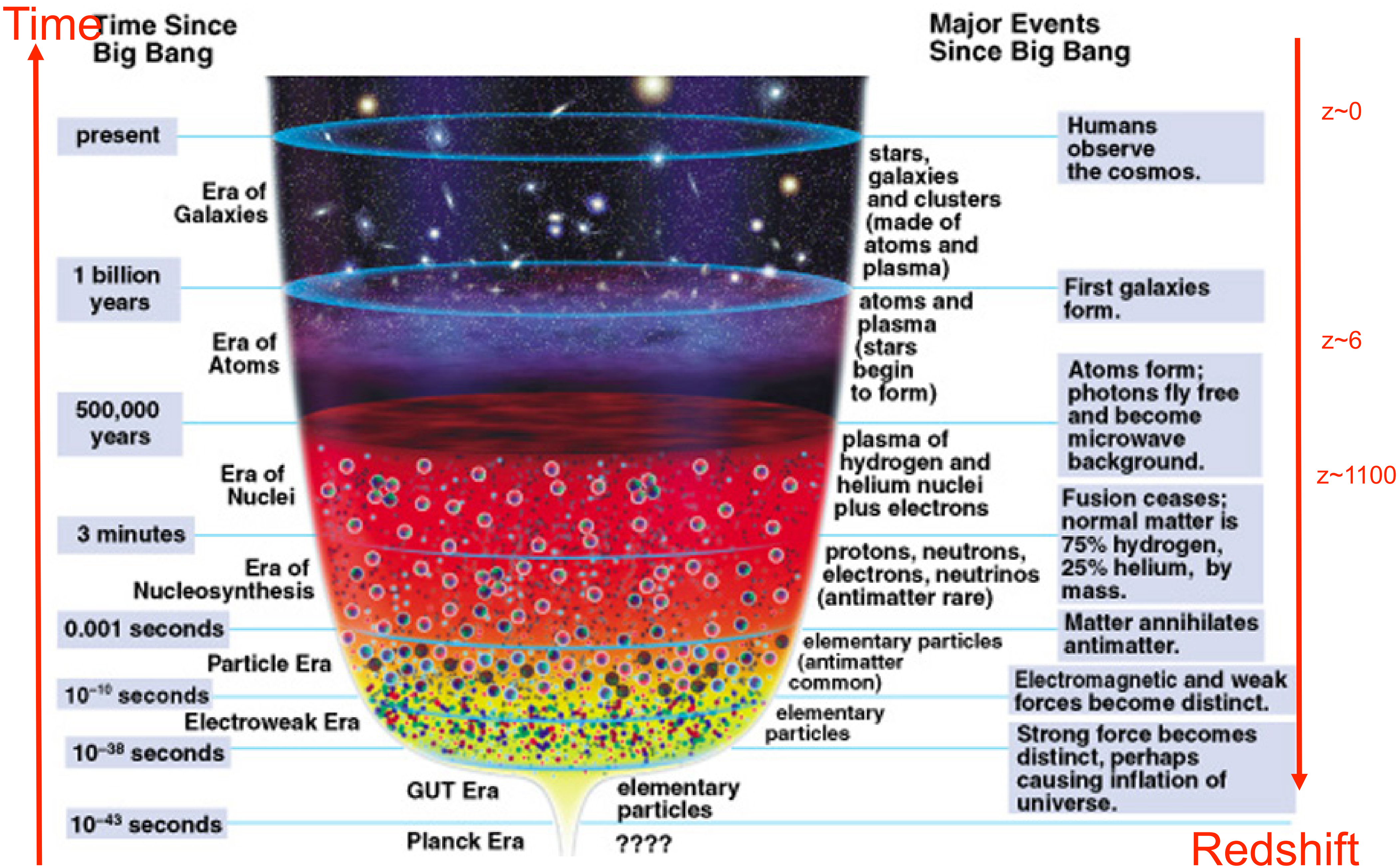
  $1500\ (h^{-1}Mpc)^3$ on the side

  $\Omega_m = 0.25$, $\Omega_\Lambda = 0.75$, h = 0.75, n = 0.97, $\sigma_8 = 0.8$

  Fluctuating Gunn Peterson approximation

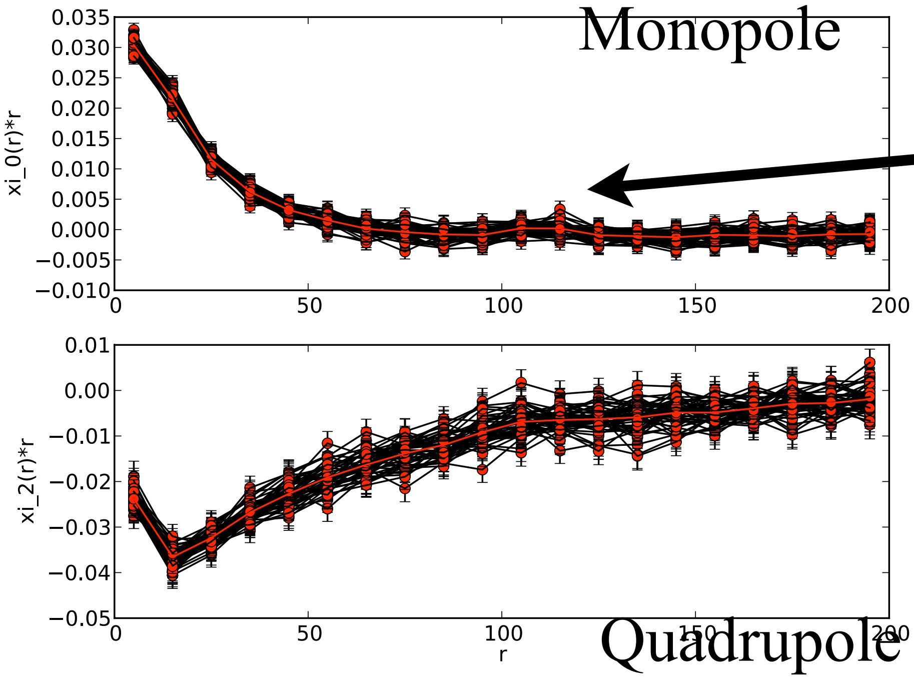
  Peculiar velocities included

Motivations



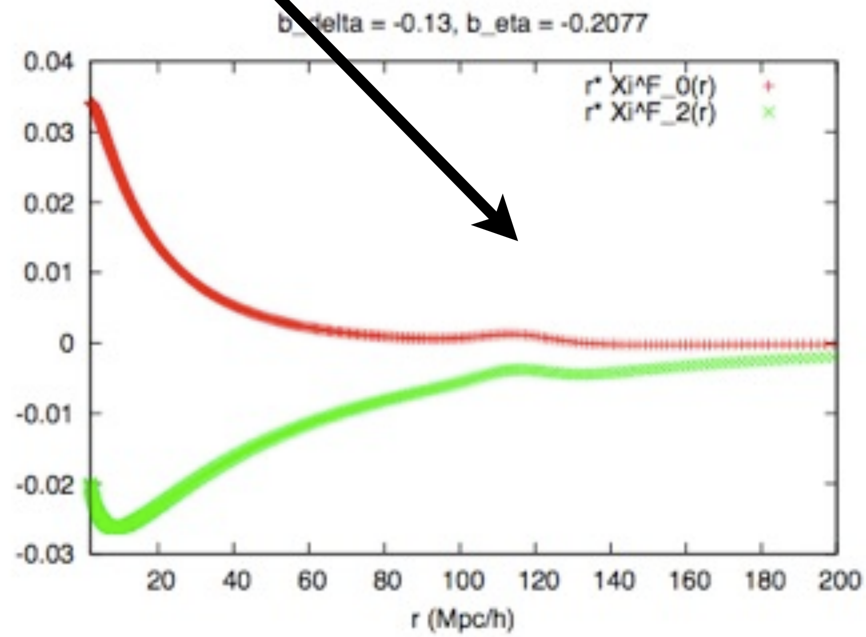
Recall? Modeling z-space distortions

Simulations



Recall that we are looking for an enhancement of power at ~110 Mpc/h?

Predictions

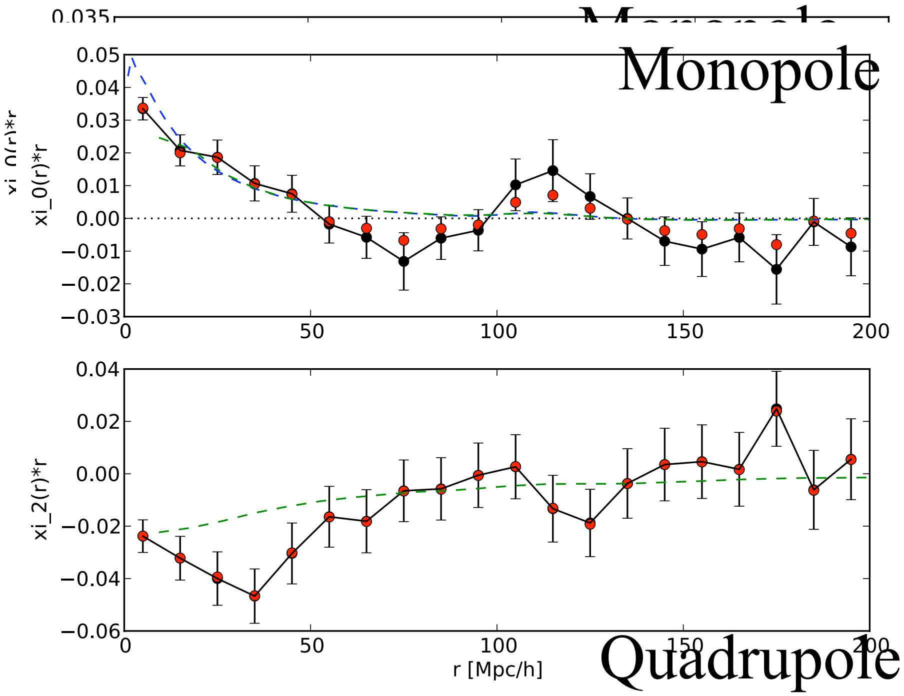


The large scale correlation functions from simulations of Lyman alpha forest

SH, Slosar & White (in prep)

Recall? Modeling z-space distortions

DATA



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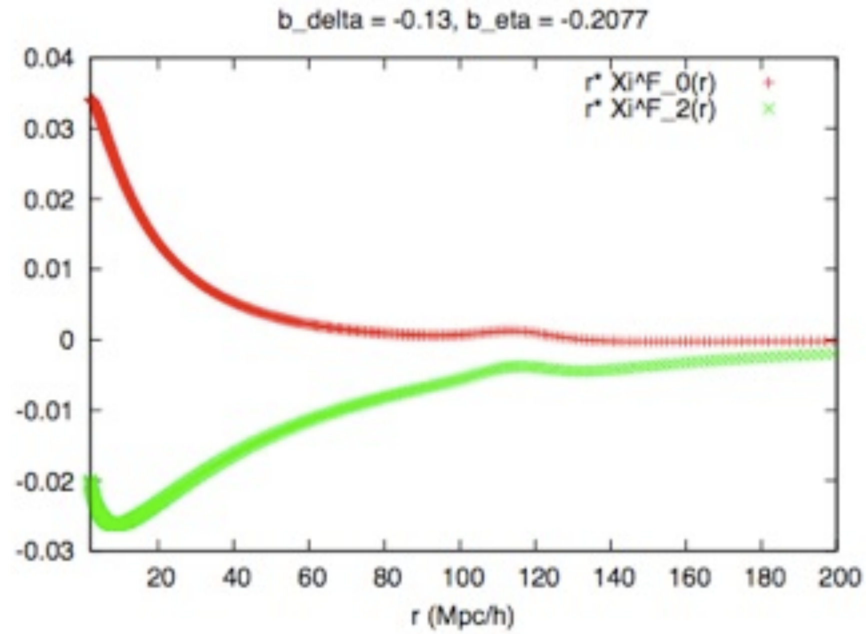
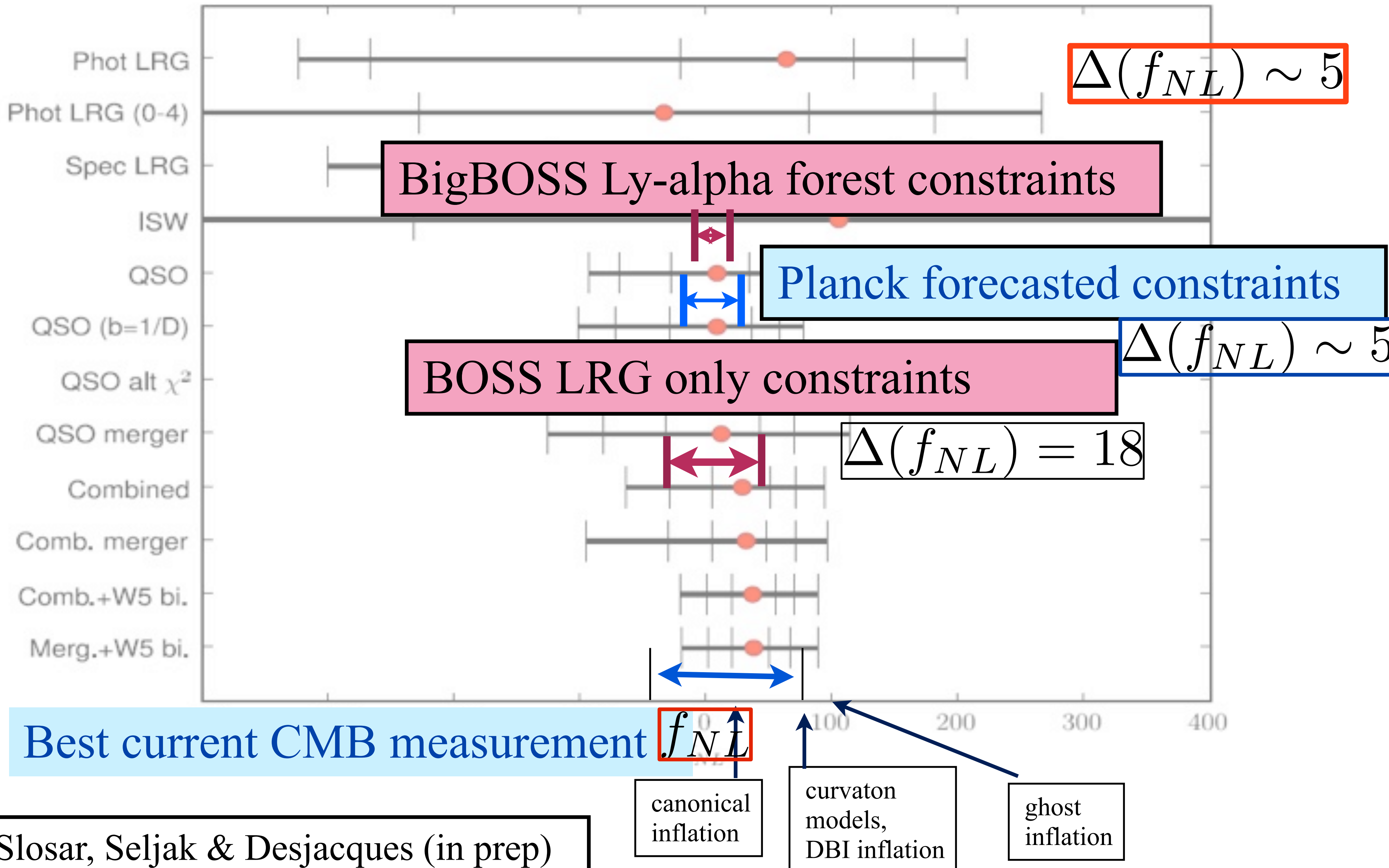


The large scale correlation functions from 5% of Lyman alpha forest in BOSS

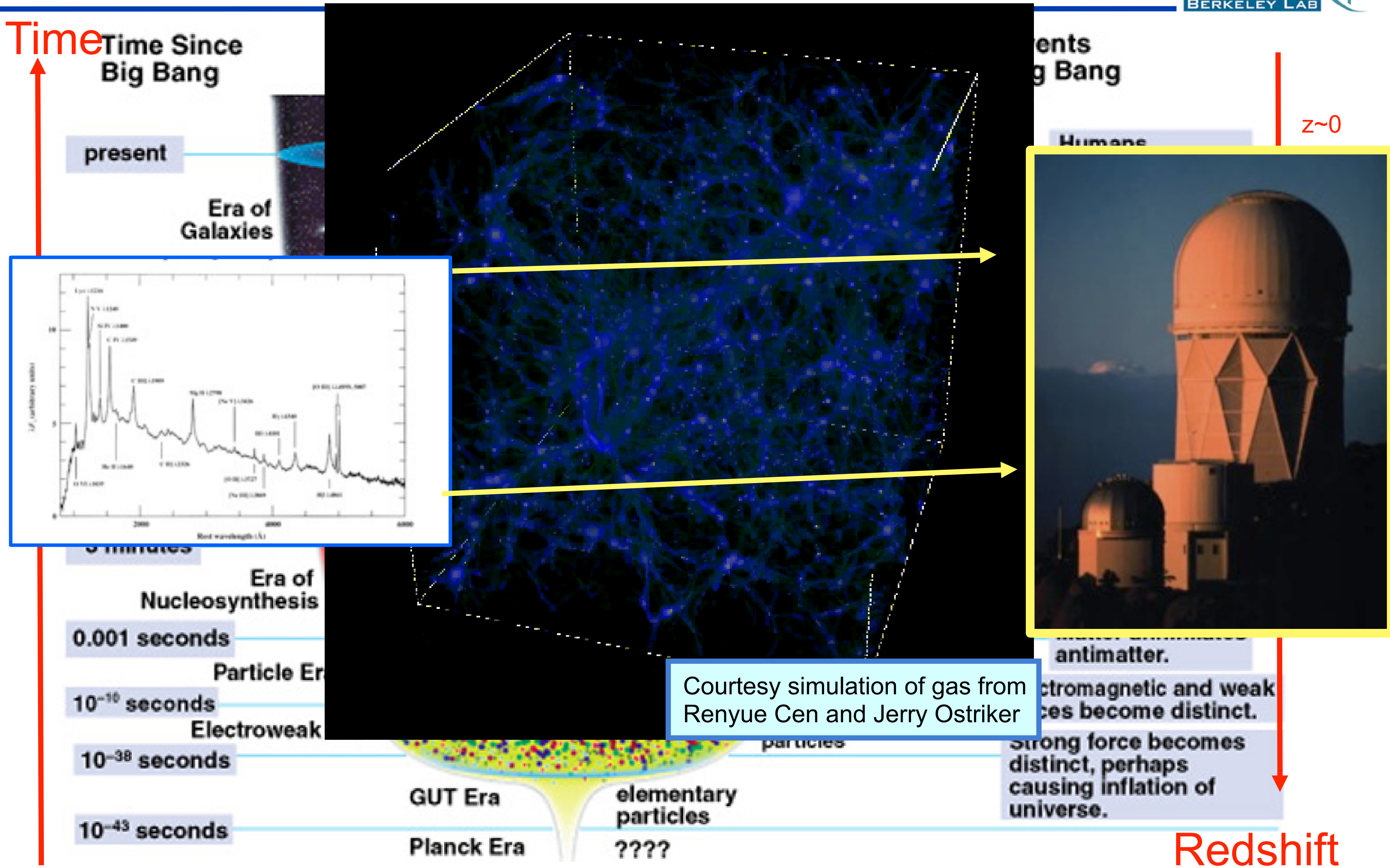
SH, Slosar & White (in prep)

What can we do with Lya and fnl?
— Non-gaussianities in Early Universe



Ho, Slosar, Seljak & Desjacques (in prep)

Lyman Alpha Forest: what is it?



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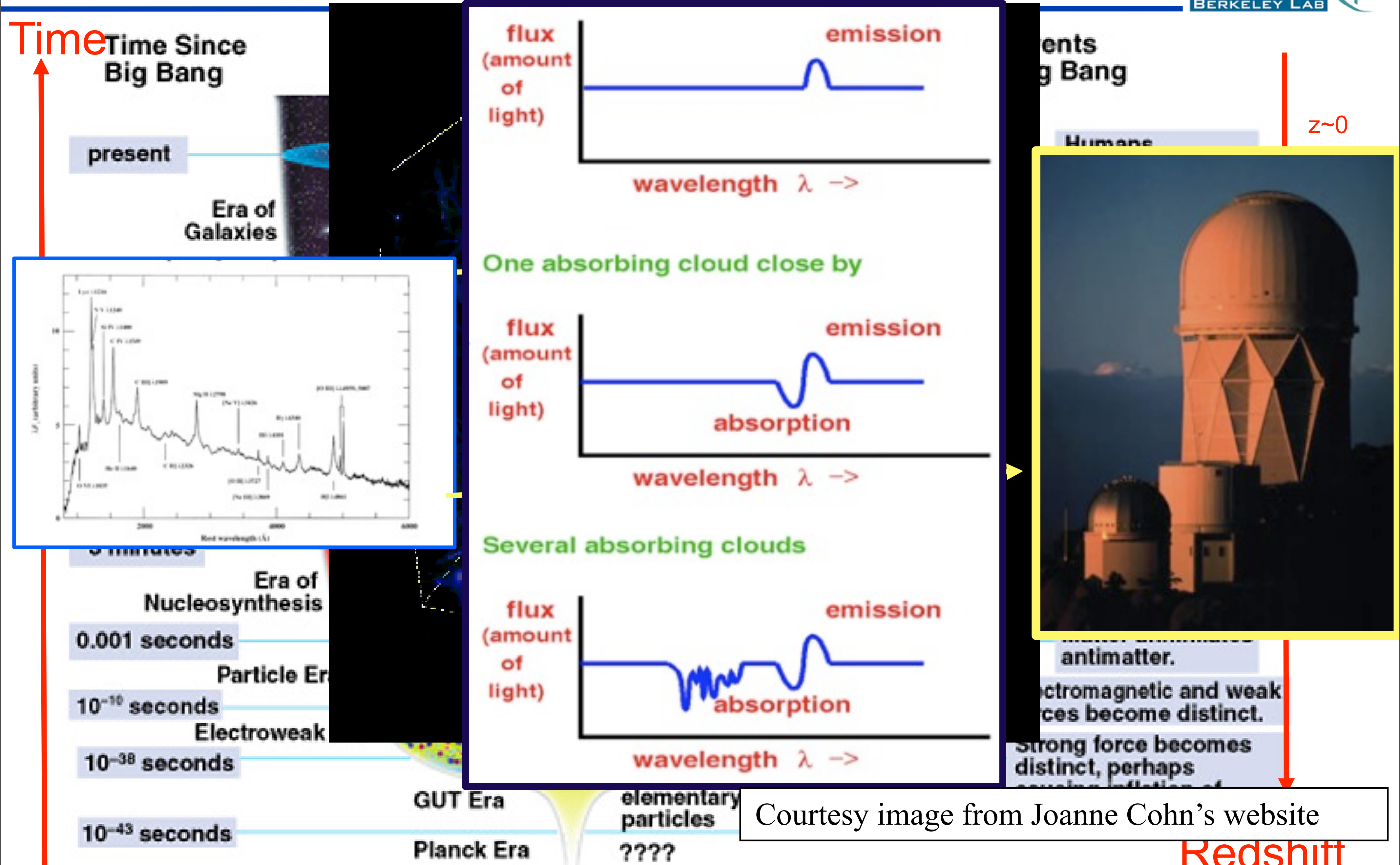
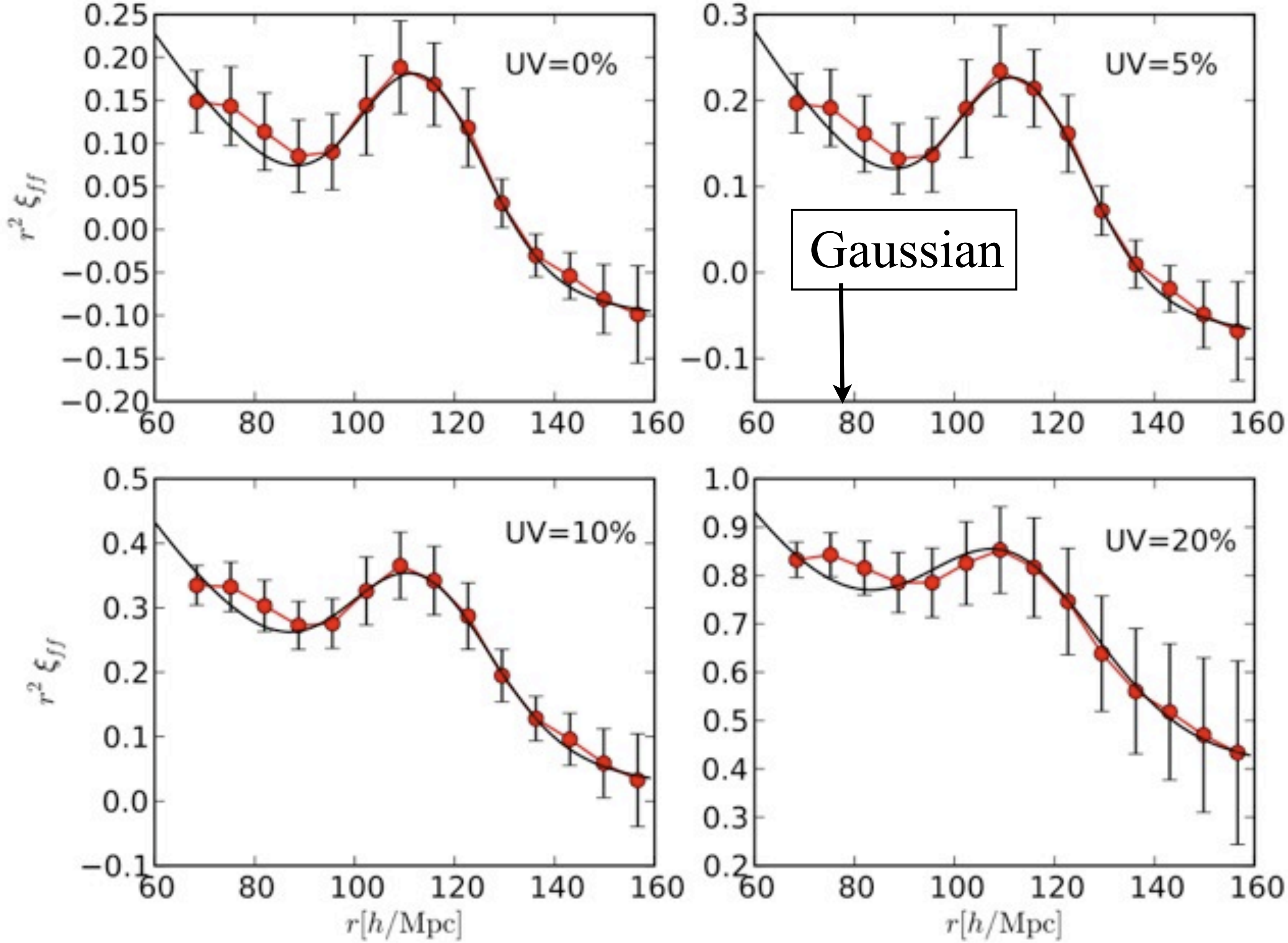


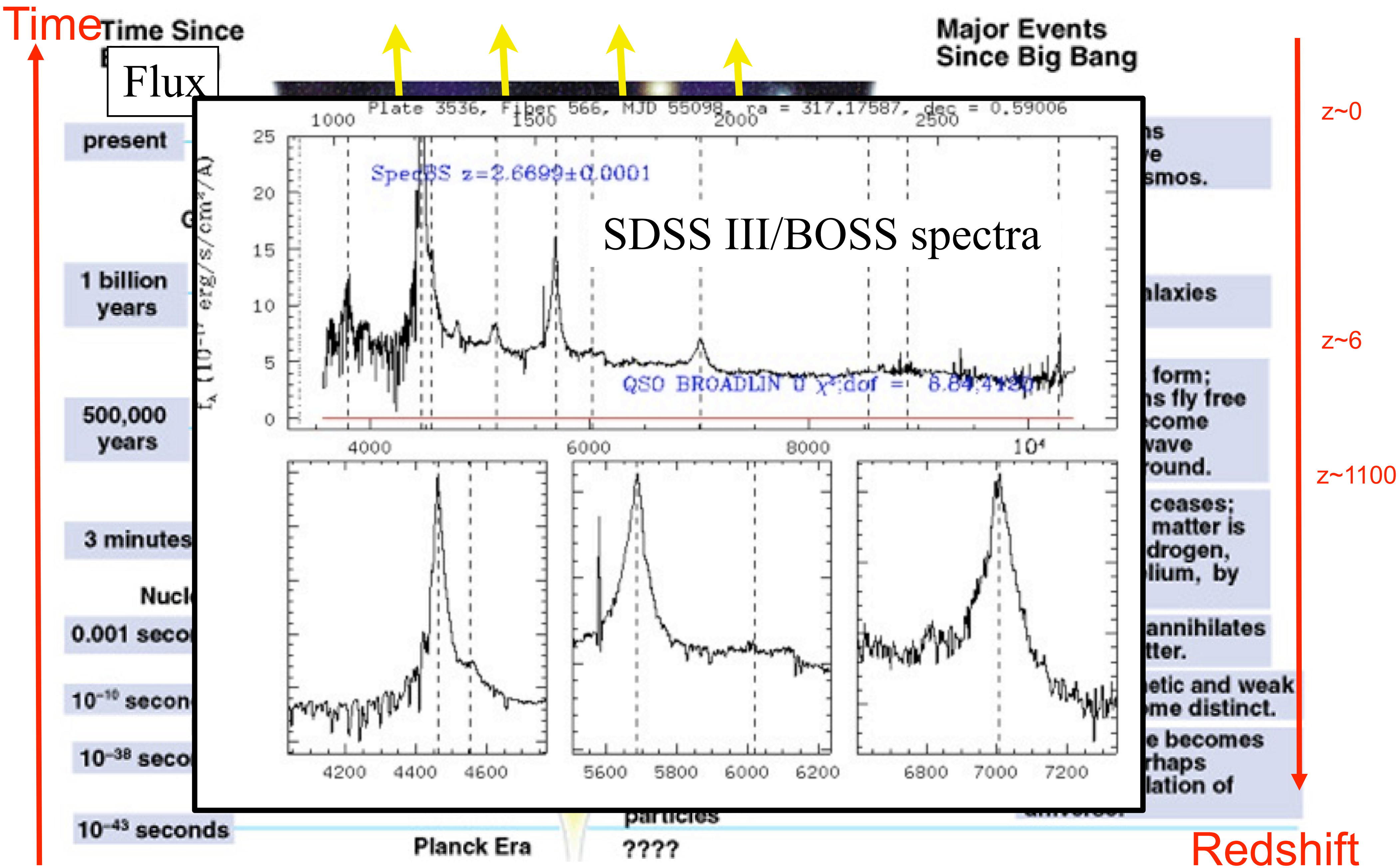
Courtesy image from Joanne Cohn's website

Beyond: With Lyman Alpha Forest

Possible systematics: UV background fluctuations

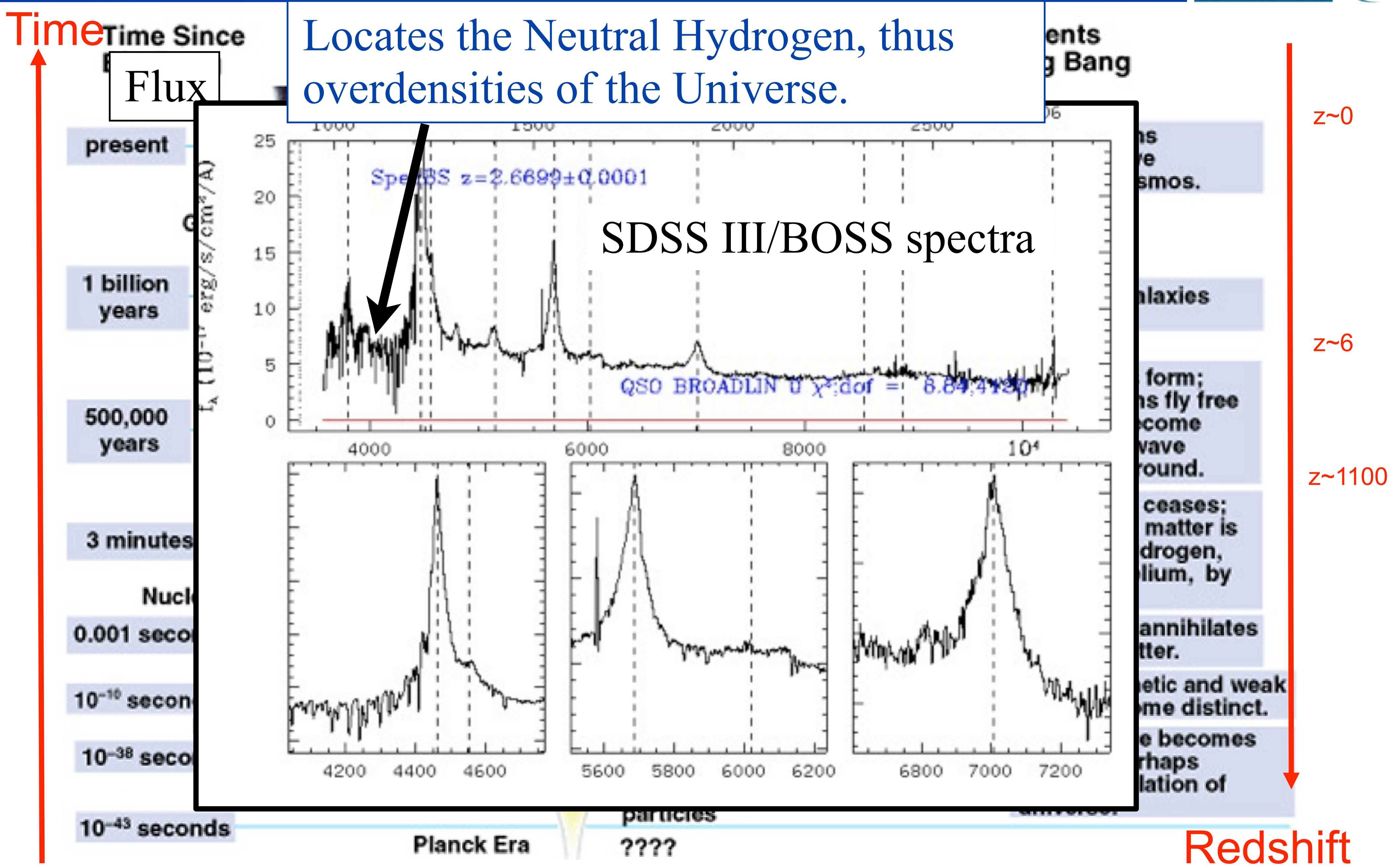


Lyman Alpha Forest: what is it?



Lyman Alpha Forest: what is it?

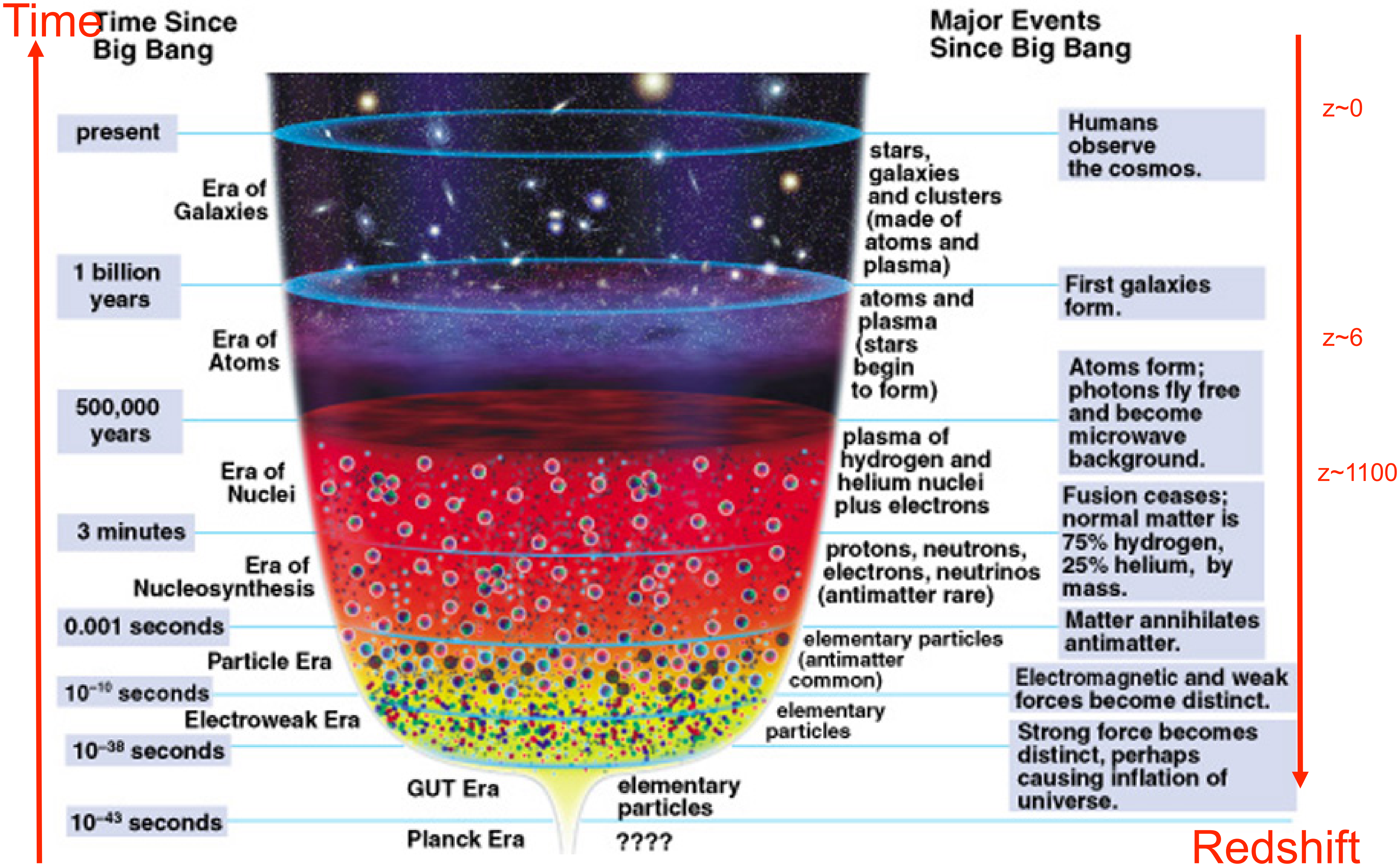
Locates the Neutral Hydrogen, thus overdensities of the Universe.



Outline

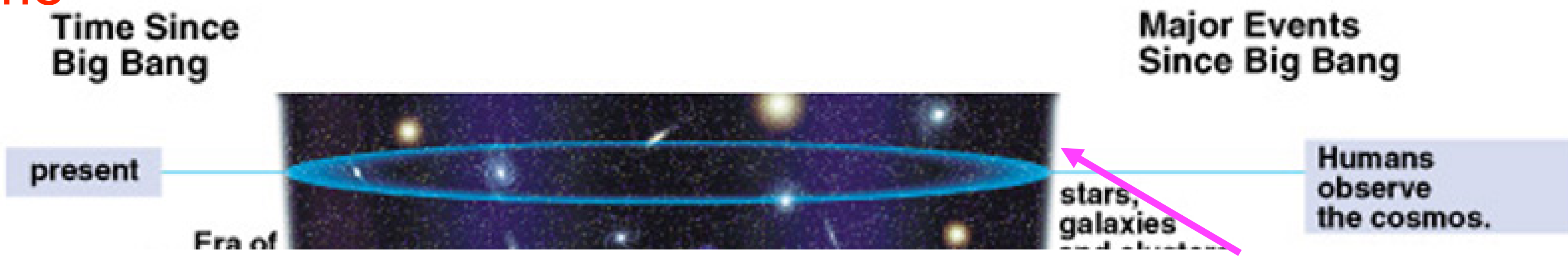
- Motivations
- Introduction (What is Lyman-alpha forest?)
- What can you do with Lyman-alpha forest?
  - — Baryon Acoustic Oscillations
    - Dark Energy
  - — Scale Dependent Bias
    - Primordial Non-gaussianities (f_nl)
- Conclusion

Motivations



Motivations

Time



Gravity +
observing movement of
local galaxies ->
"Dark Matter"

z~0

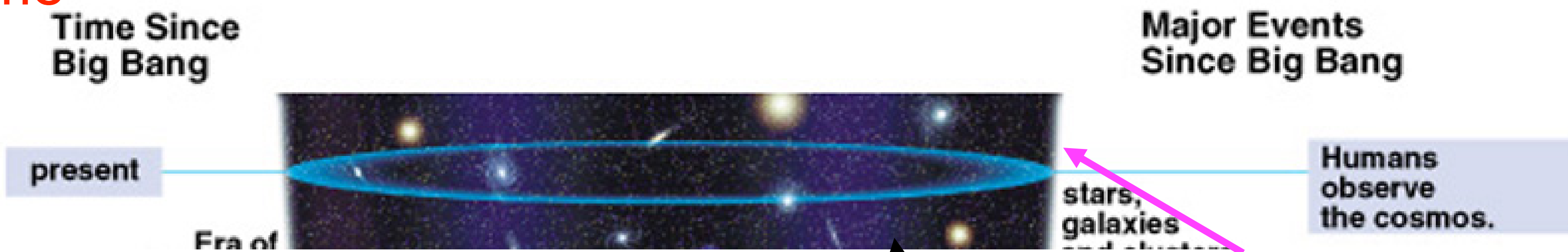
z~6

z~1100

Redshift

Motivations

Time

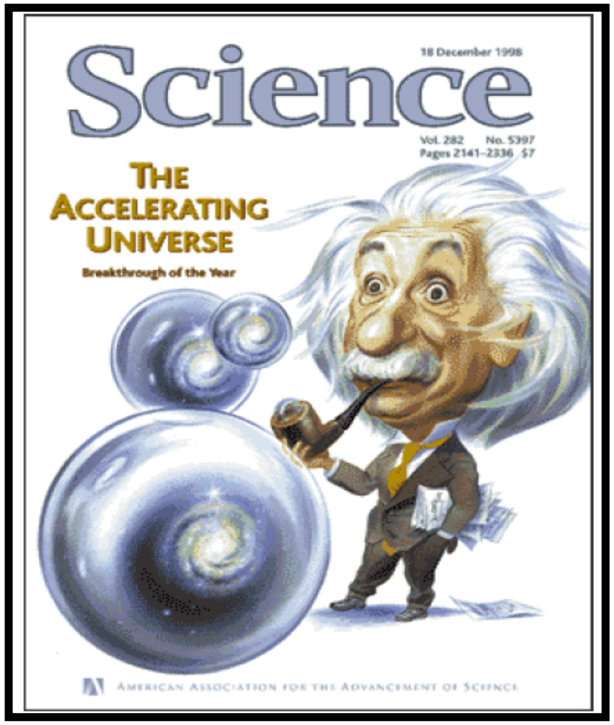


z~0

z~6

z~1100

Gravity +
observing movement of local galaxies ->
"Dark Matter"

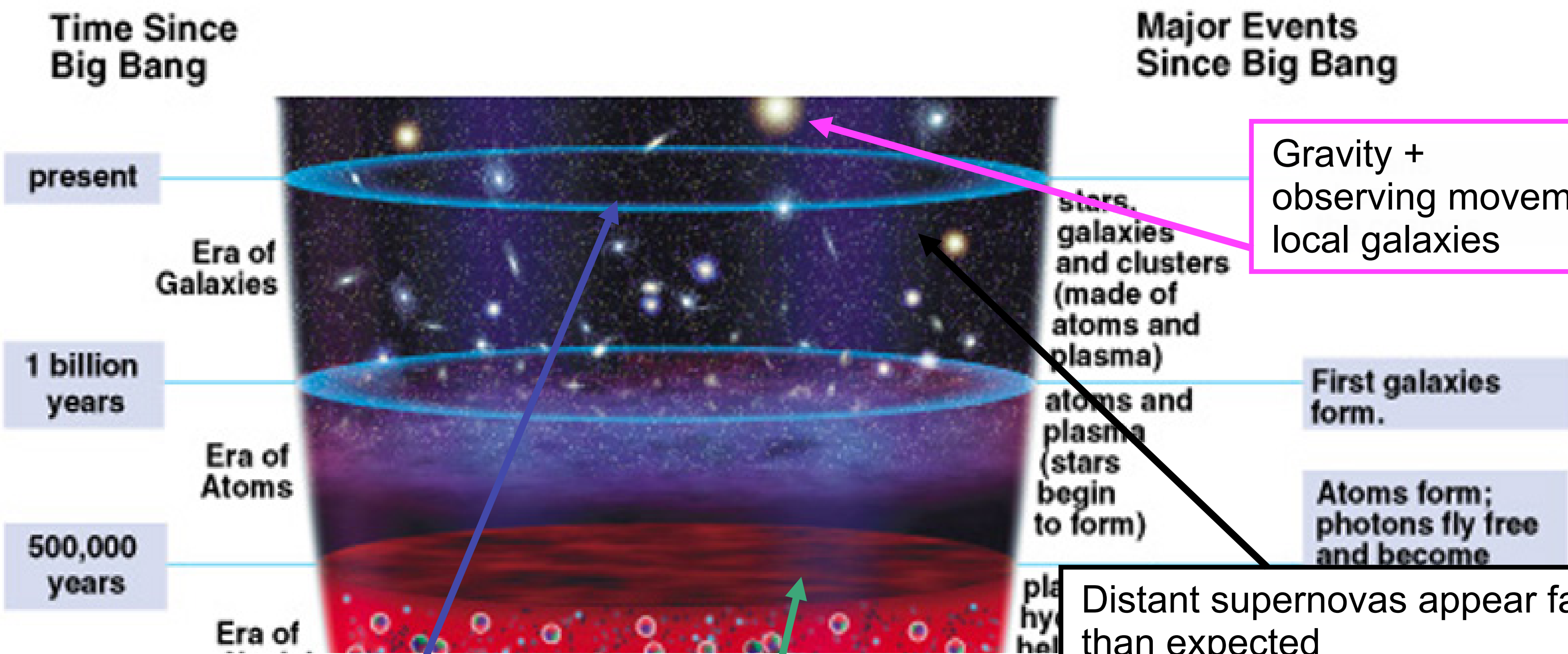


Distant supernovas appear fainter than expected (1998)->
Universe is accelerating ->
Cosmological Constant?
Dark Energy?

Redshift

Motivations

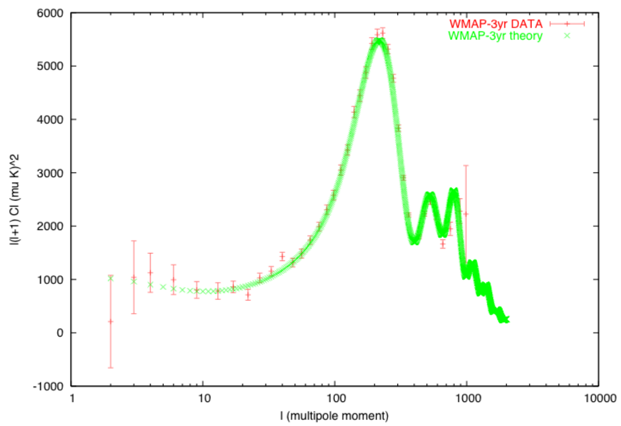
Time



Gravity + observing movement of local galaxies

Distant supernovas appear fainter than expected

Observations of how galaxies cluster



Observations of
Cosmic Microwave Background (CMB)
-> angular powerspectrum of temperature anisotropies

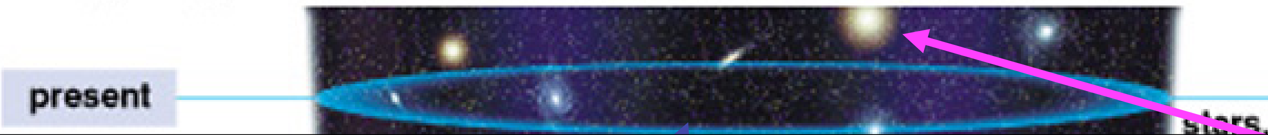
Redshift

Motivations

Time

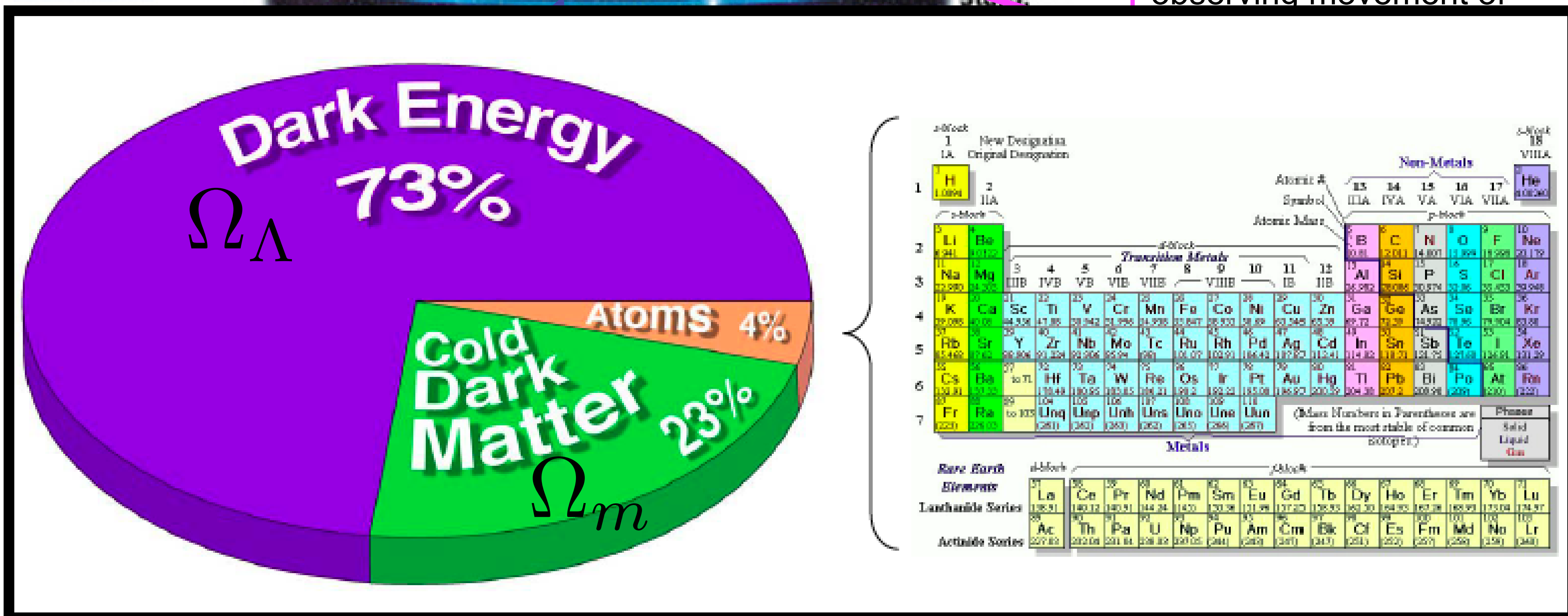
Time Since Big Bang

Major Events Since Big Bang



z~0

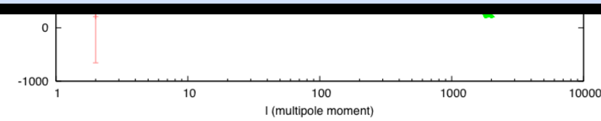
Gravity +
observing movement of



100

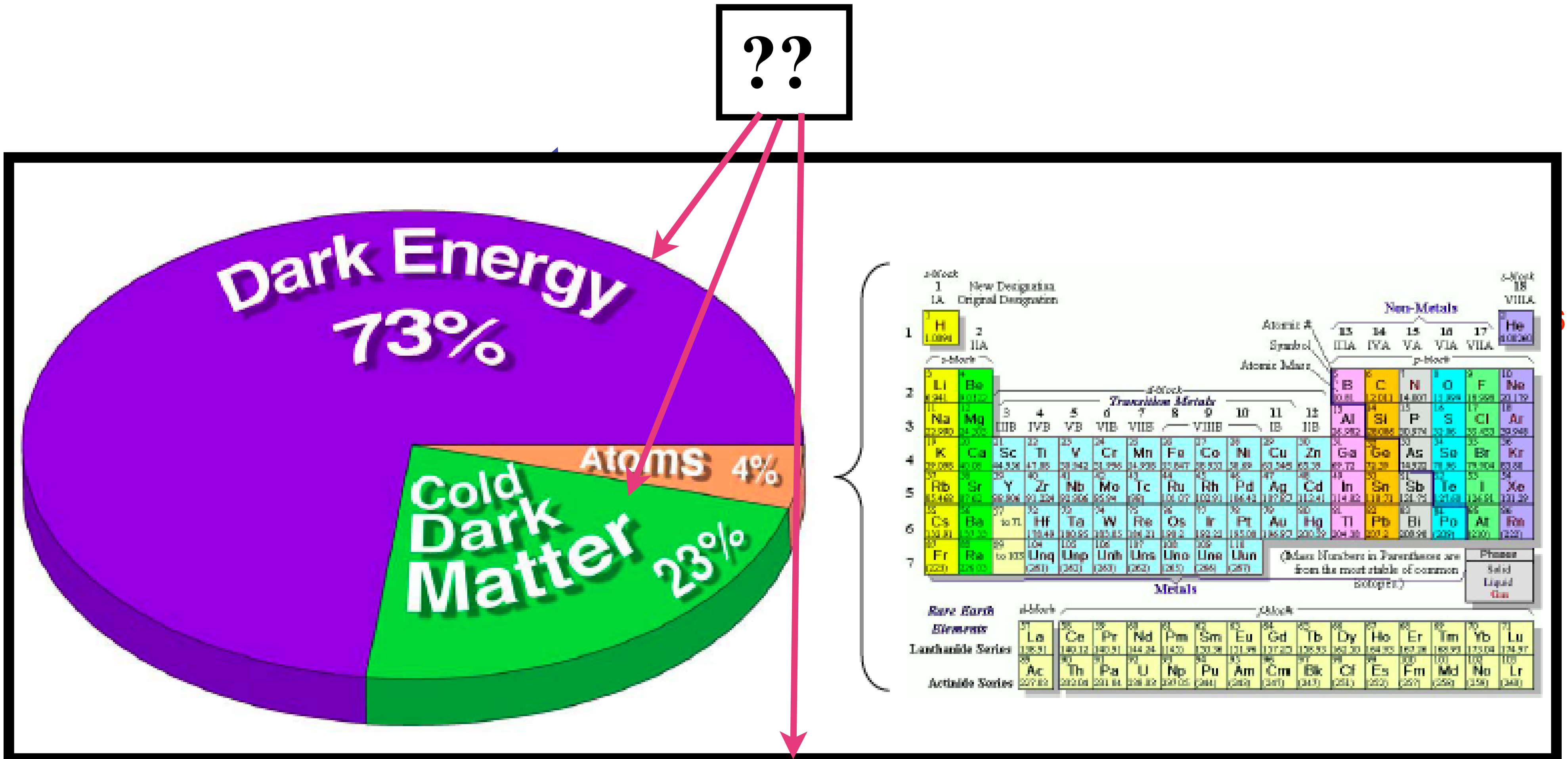
What happened at the Beginning of the Universe?

temperature anisotropies



Redshift

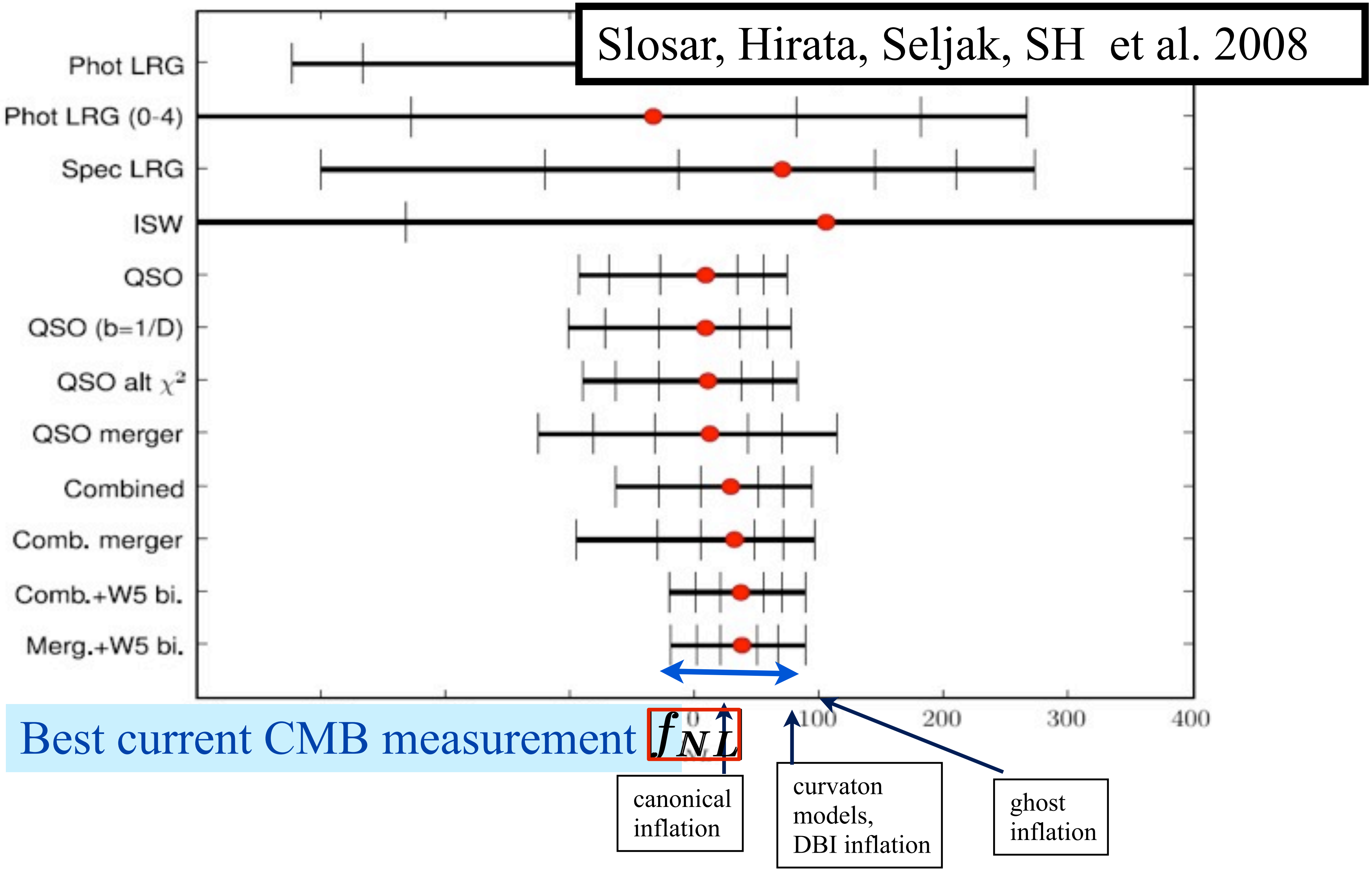
Motivations



What happened at the Beginning of the Universe?

Lyman Alpha Forest: what can it do?
— Non-gaussianities in Early Universe

BERKELEY LAB

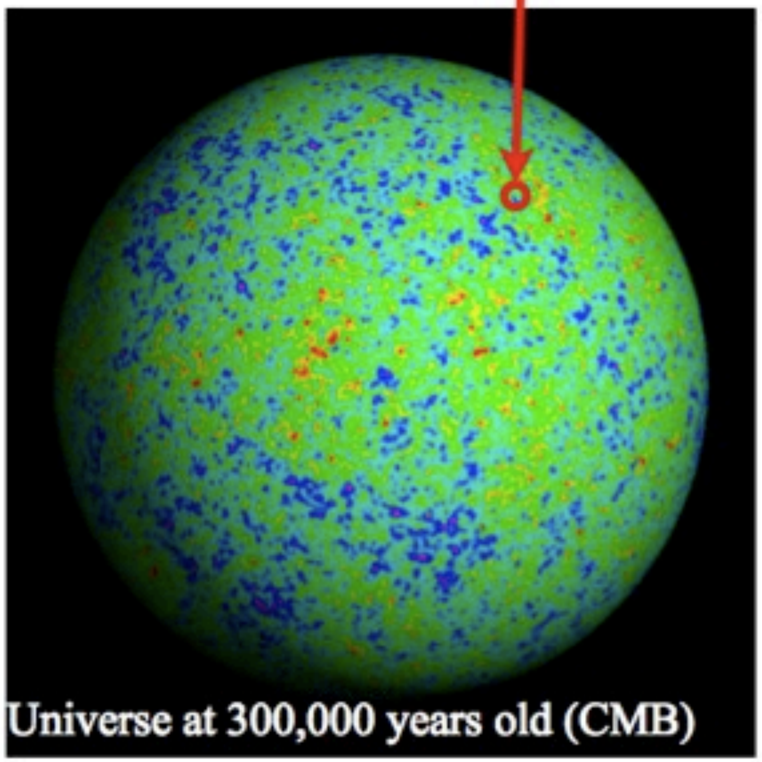


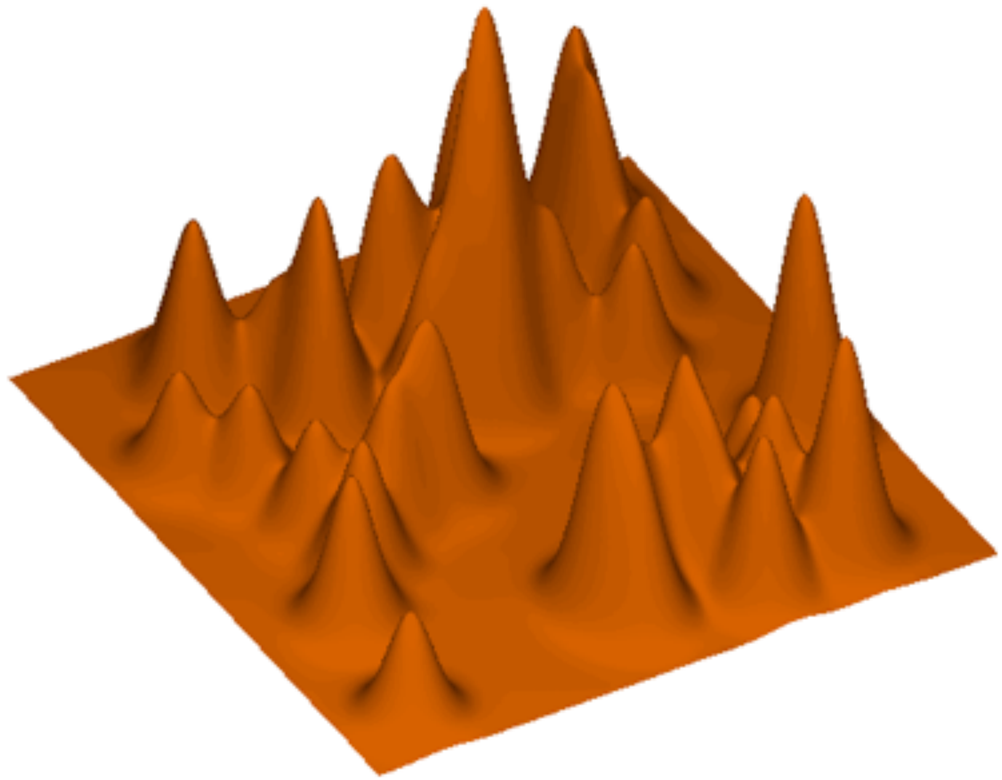
What are the Baryon Acoustic Oscillations?

What are baryon acoustic oscillations (BAO)?

These fluctuations of 1 part in 10^5 gravitationally grow into...

...these ~unity fluctuations today





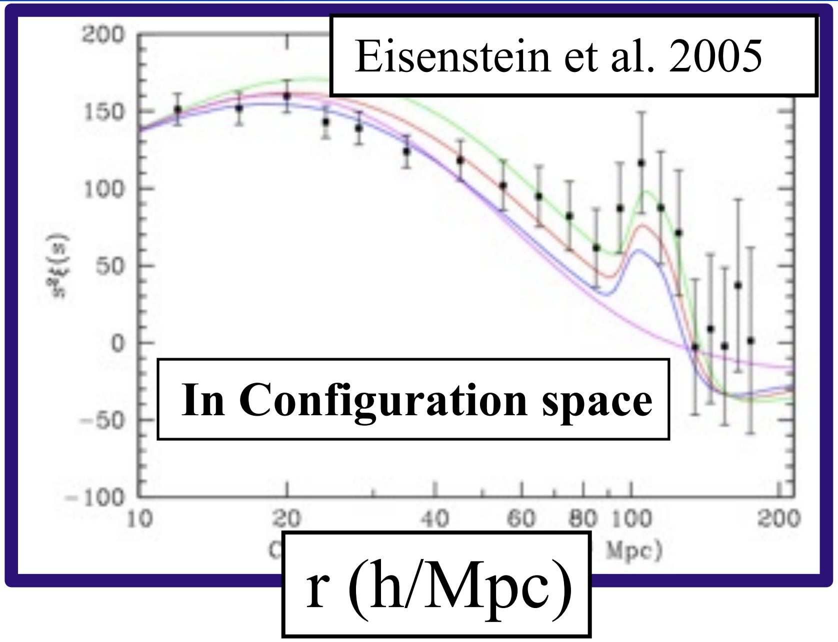
This sound wave can be used as a "standard ruler"

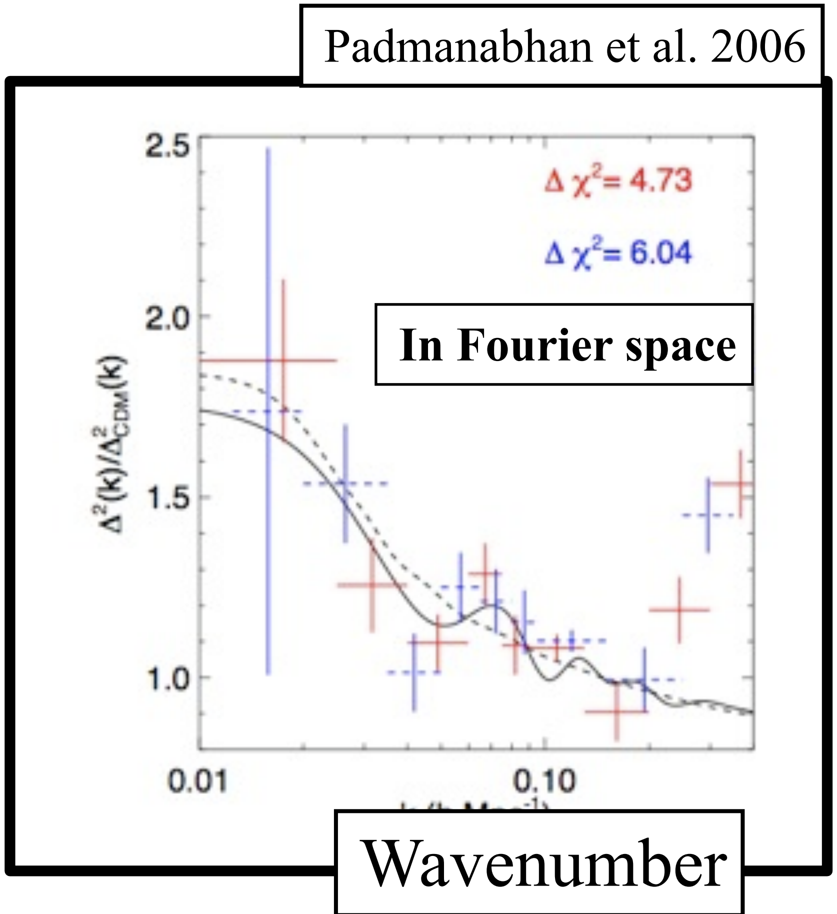
Dark energy changes this apparent ruler size

Courtesy slide from David Schlegel and animation from Daniel Eisenstein

First detections of BAO

$r^2\xi(r)$



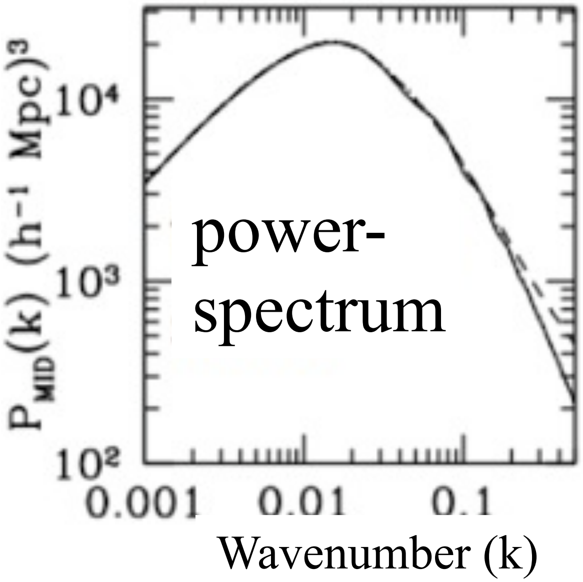


Outline

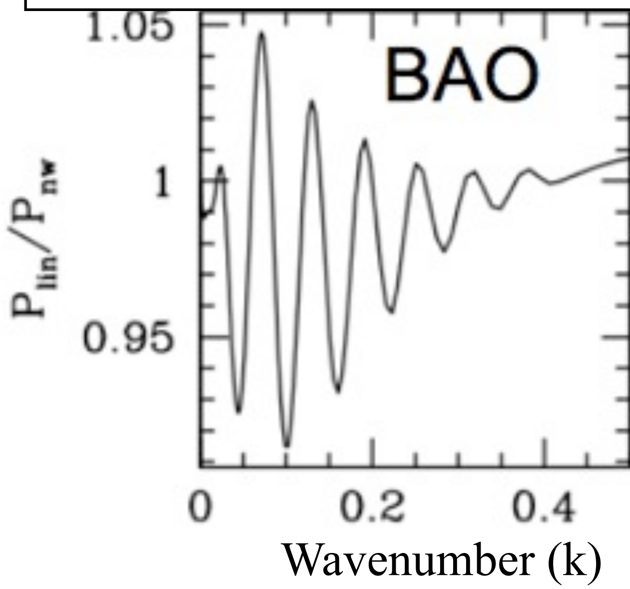
- Motivations
- Introduction (What is Lyman-alpha forest?)
- What can you do with Lyman-alpha forest?
  - Baryon Acoustic Oscillations -> Dark Energy
  - Lyman-alpha power spectrum
  - Non-gaussianities in Early Universe

- Conclusion

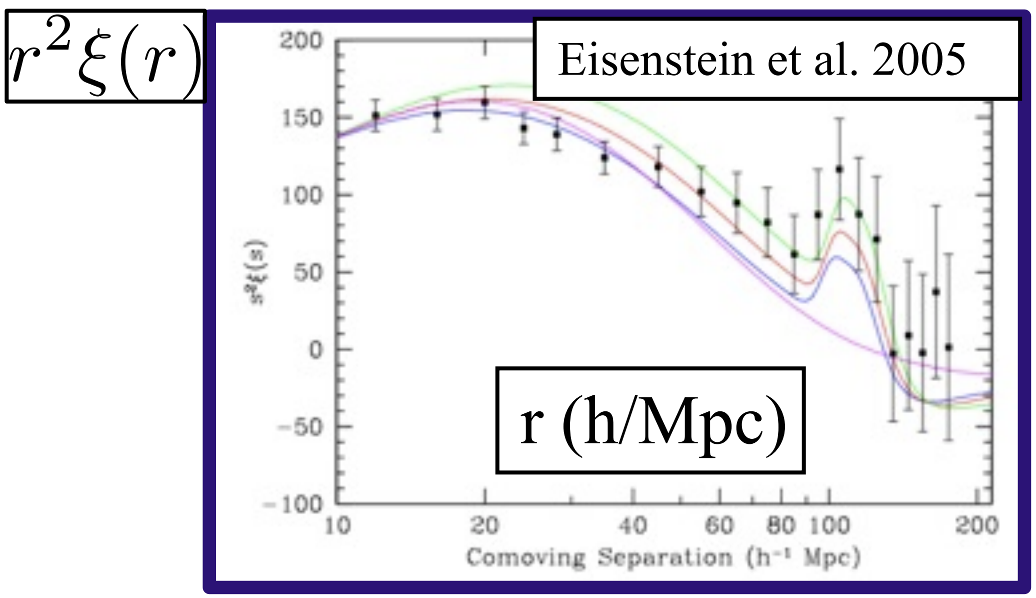
Predicted signals of BAO



power-spectrum with smoothed part divided out



Fourier space



Configuration space

BAO: with Luminous Red Galaxies
Systematics: Dust

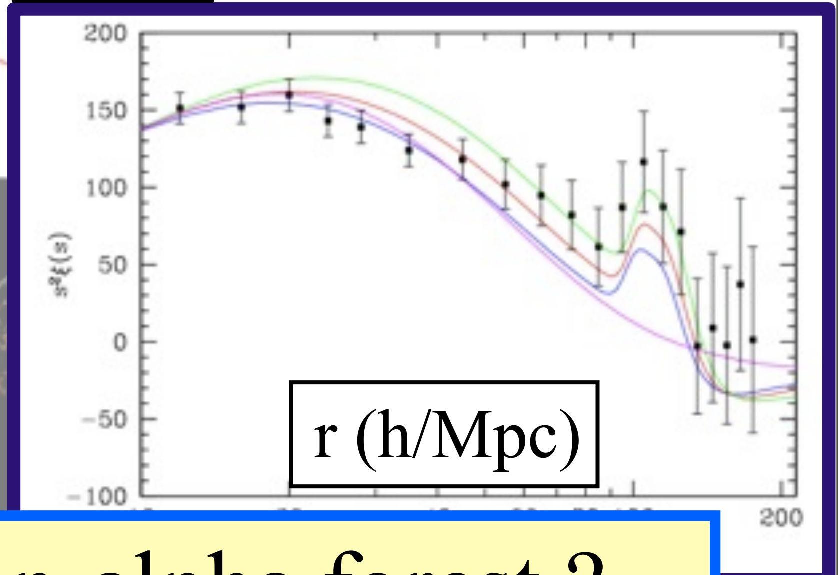
- As pointed out by Schlafly, Finkbeiner et al (2010), there is a normalization difference in galactic north and south of ~15%. There is also reddening factor overestimates by factor ~1.4.
- These all possibly contribute to extra power in galaxy power-spectra

Lyman Alpha Forest: what can it do?

What are baryon acoustic oscillations (BAO)?

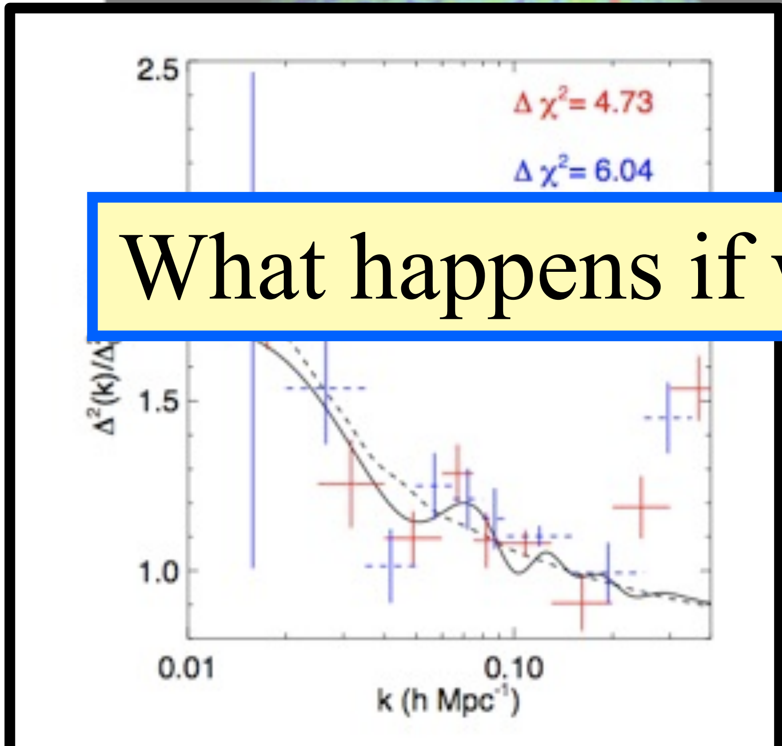
These fluctuations of 1 part in 10^5 gravitationally grow into...

...these ~



Eisenstein et al. 2005

What happens if we use Lyman-alpha forest ?



Padmanabhan et al. 2006

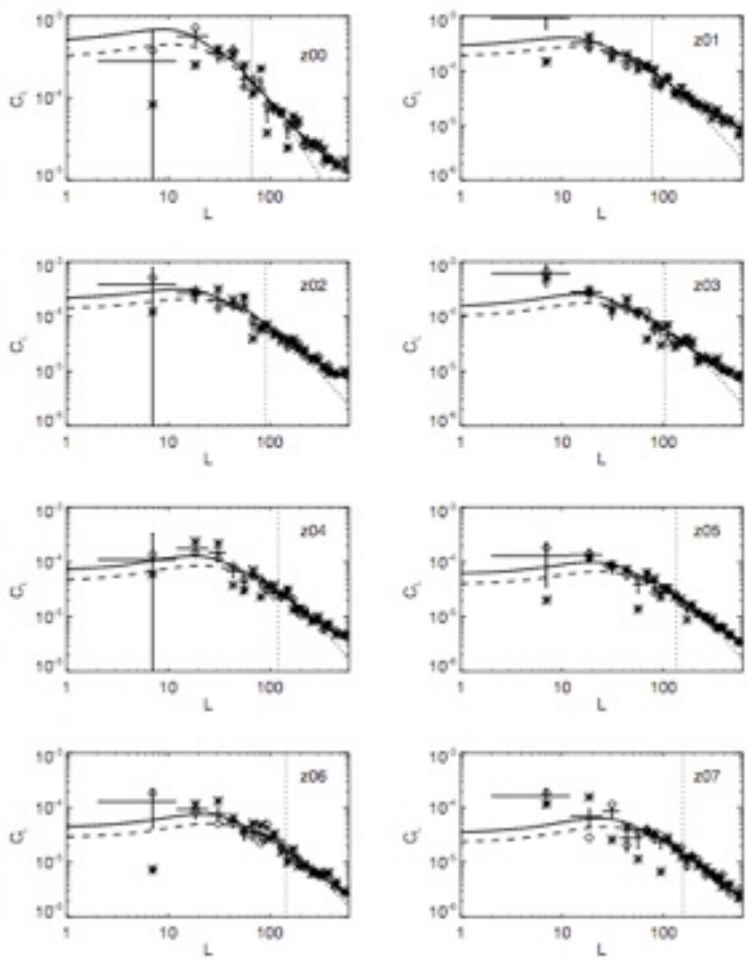
...ed as a “standard ruler”

...apparent ruler size

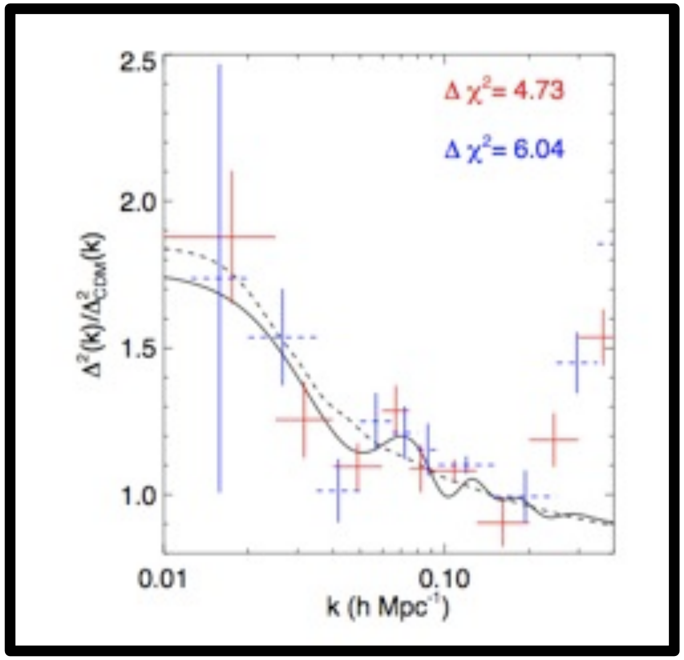
Courtesy slide from David Schlegel

How do you detect BAO with photometric data?

Angular power-spectrum
with 3500 sq deg of SDSS I/II imaging



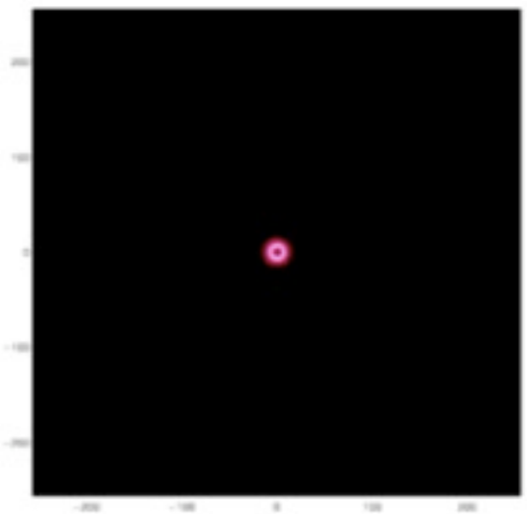
Reconstructed Galaxy power-spectrum
with ~2.6 sigma 'detection' of BAO



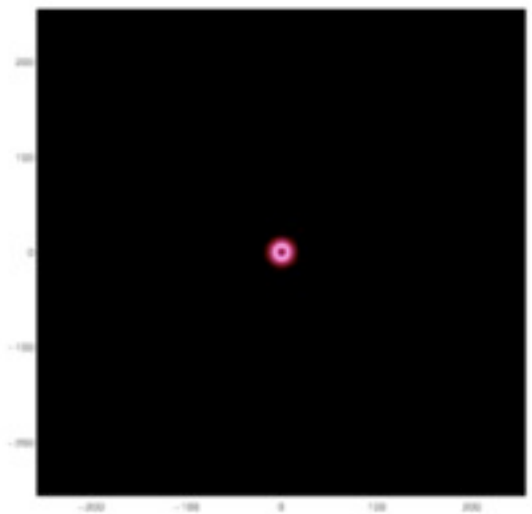
Padmanabhan et al. 2006

What are the Baryon Acoustic Oscillations?

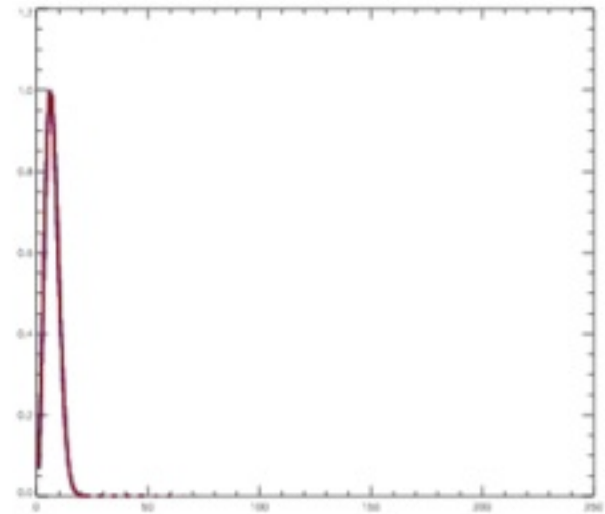
- We start with single perturbation and the plasma is totally uniform except for an excess of matter at the origin
- High pressure drives the gas+photon fluid outwards approaching speed of light.



Baryons



Photons

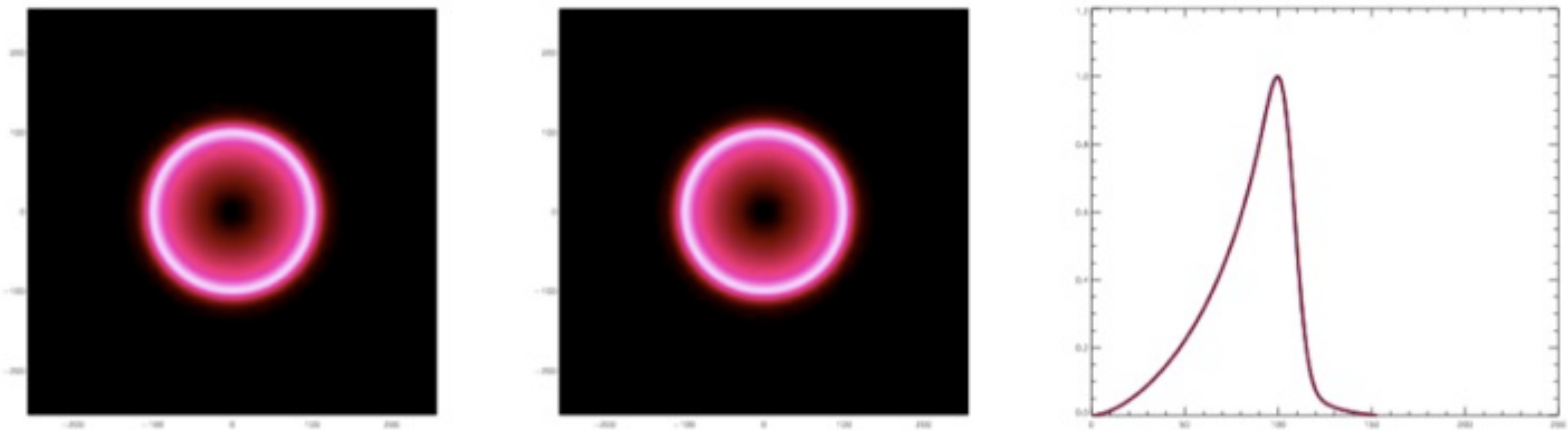


Mass profile

Eisenstein, Seo and White (2006)

What are the Baryon Acoustic Oscillations?

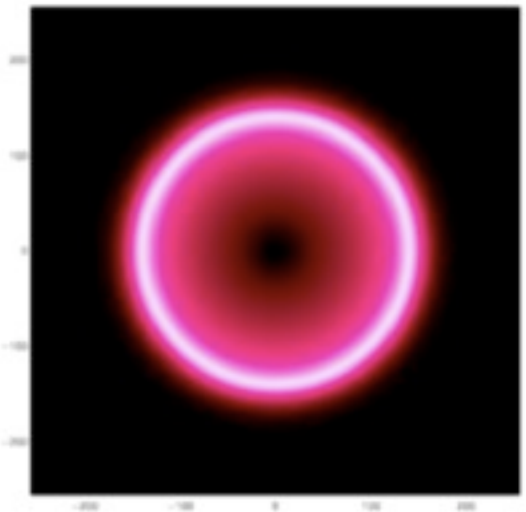
- **This expansion continues for 100,000 years.**

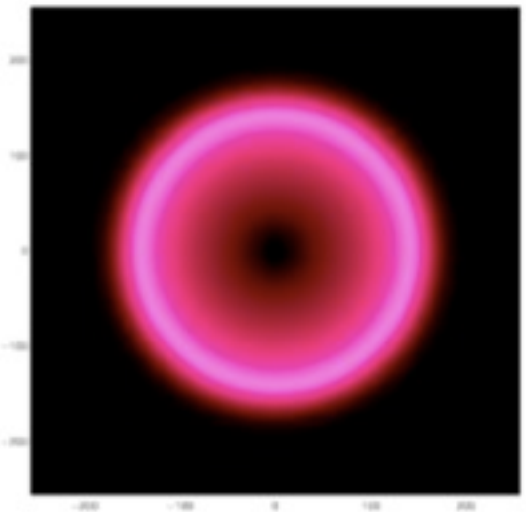


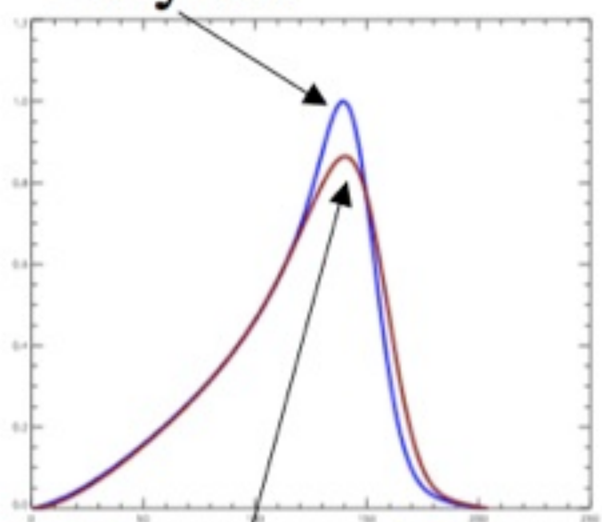
Eisenstein, Seo and White (2006)

What are the Baryon Acoustic Oscillations?

- After 100,000 years, the Universe is cool enough that protons capture electrons to form neutral hydrogen
- This decouples the photons from the baryons. The photons quickly streamed away, leaving baryon peak stalled.



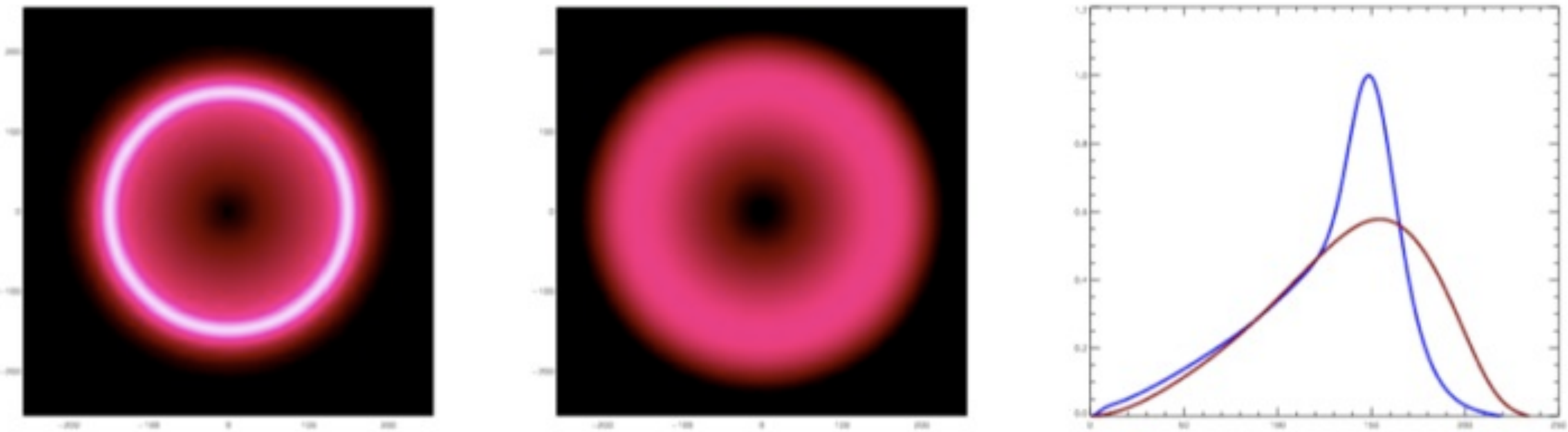




Eisenstein, Seo and White (2006)

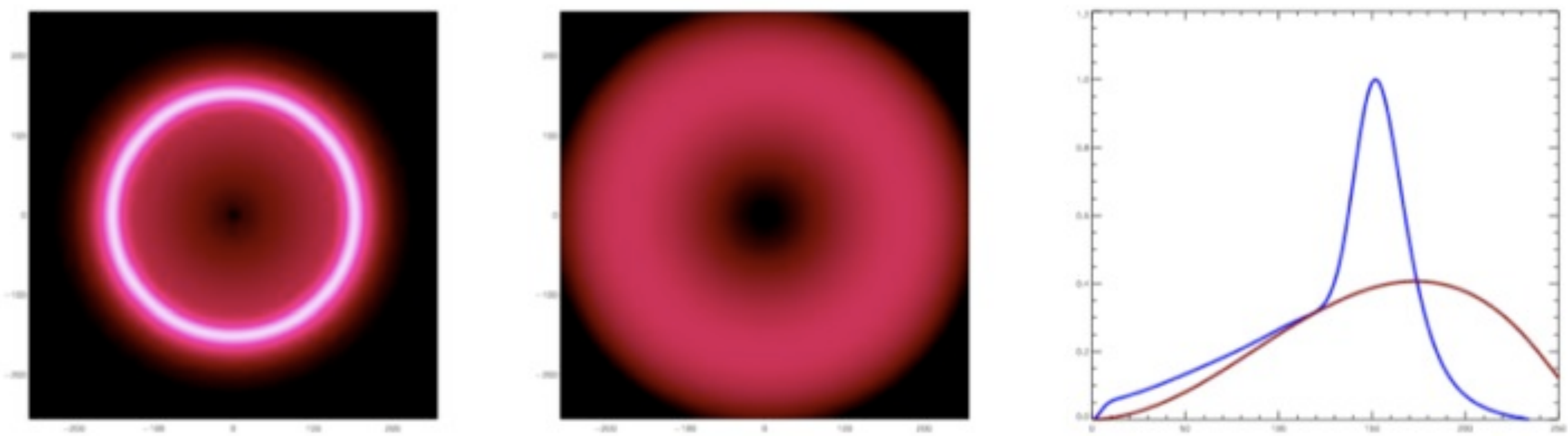
What are the Baryon Acoustic Oscillations?

- **The photons continue to stream away, while baryons, having lost the motive pressure, remain in place.**



Eisenstein, Seo and White (2006)

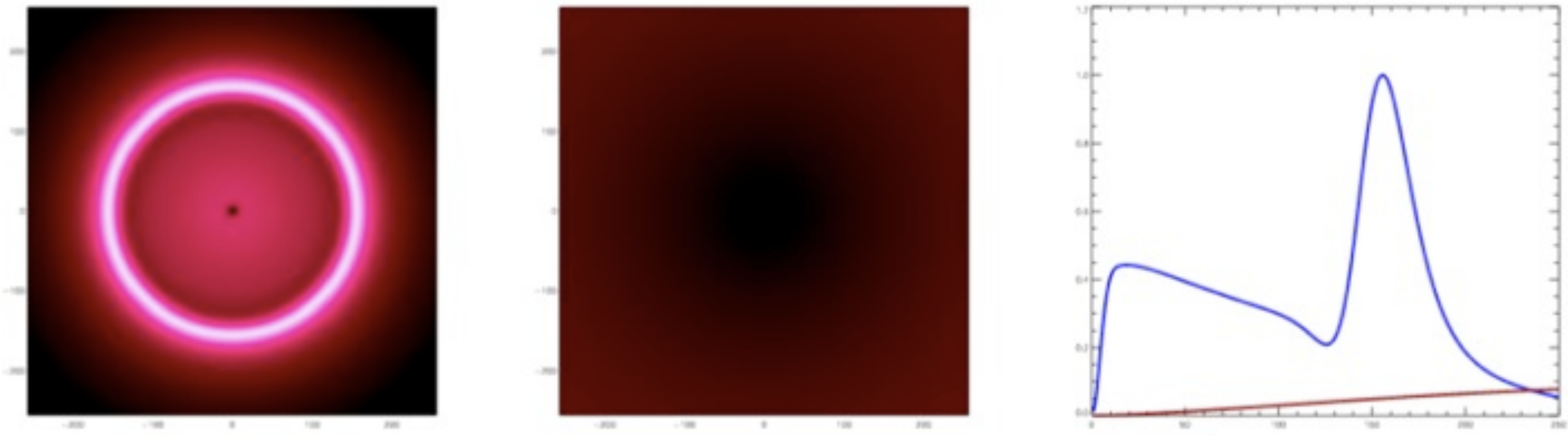
What are the Baryon Acoustic Oscillations?



Eisenstein, Seo and White (2006)

What are the Baryon Acoustic Oscillations?

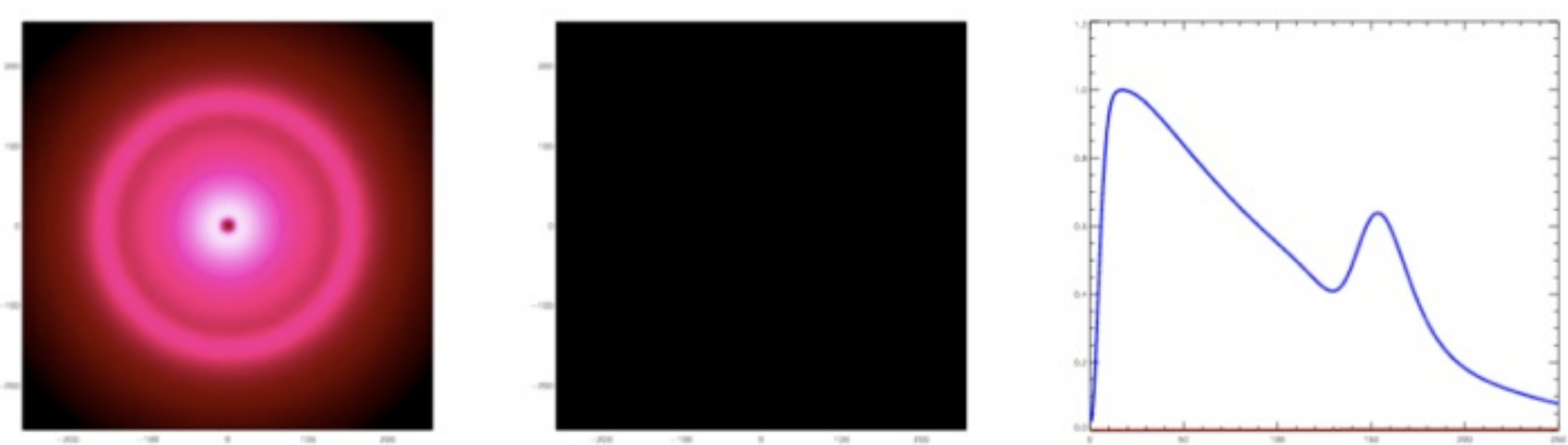
- **The photons are nearly completely uniform now, but the baryons remain overdense in a shell of ~100 Mpc in radius**
- **In addition, the large gravitational potential well which we started with starts to draw the material back to it.**



Eisenstein, Seo and White (2006)

What are the Baryon Acoustic Oscillations?

- As the perturbation grows, the baryons and dark matter reach equilibrium densities in the ratio of global baryon-to-dark matter ratio.
- The final configuration is our original peak at the center and an ‘echo’ in a shell roughly 100 Mpc in radius with width ~10%



Eisenstein, Seo and White (2006)

What are the Baryon Acoustic Oscillations?

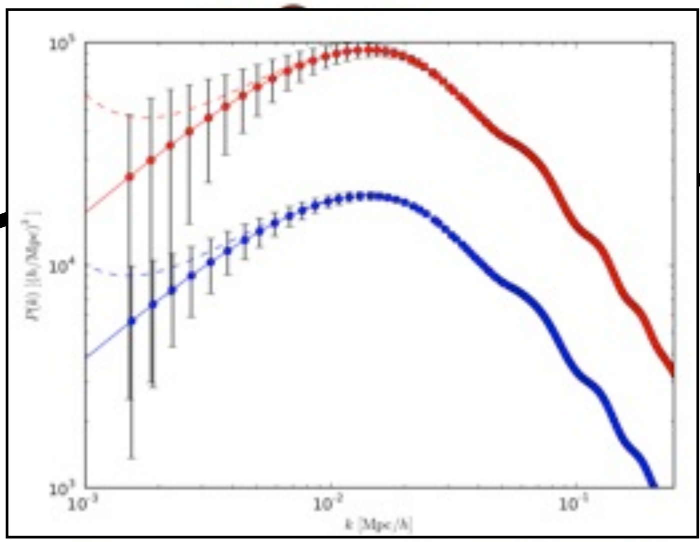
How do we detect Baryon Acoustic Oscillations?
We calculate the correlation functions or its Fourier Transform: power-spectrum

What is the correlation function ?

$$\xi_f(r) = < \delta_f(\hat{x})\delta_f(\hat{x}+\hat{r}) >$$

Fourier Transform: correlation function-> **power-spectrum**

100 Mpc



There will be wiggles

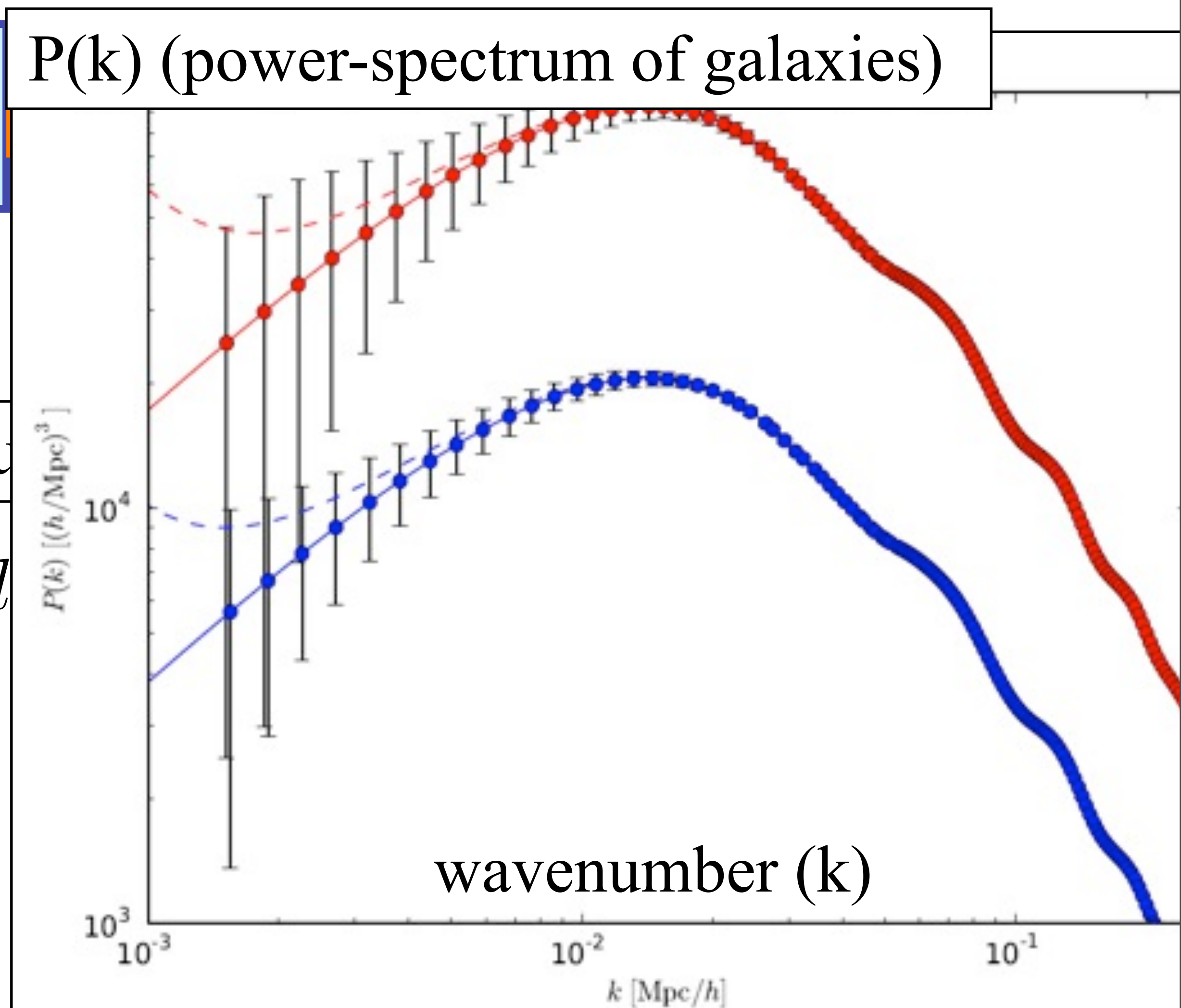
BAO: with Luminous Red Galaxies
Physics of Angular Clustering

$b = \frac{\delta g}{\delta \rho}$ describe how galaxies are related to cold dark matter

$\frac{dN}{dz}$ describe how many galaxies are there at each dz bin

$D(z)$ describe how matter grows

$P(\frac{l+\frac{1}{2}}{\chi})$



Galaxy angular power-spectru

$$C_l^{gg} = \int dz \frac{H_0}{c} b^2(z)(d$$

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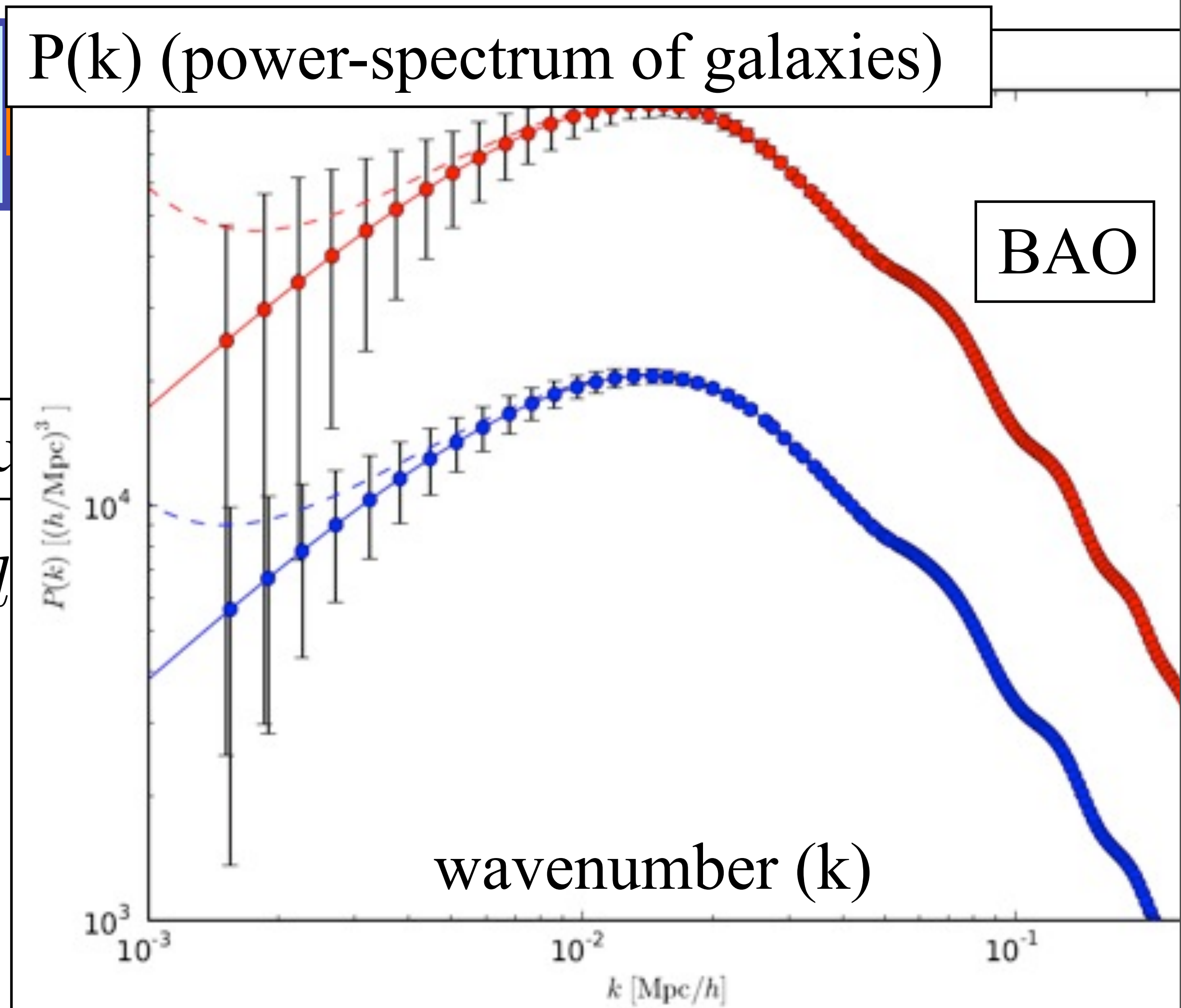

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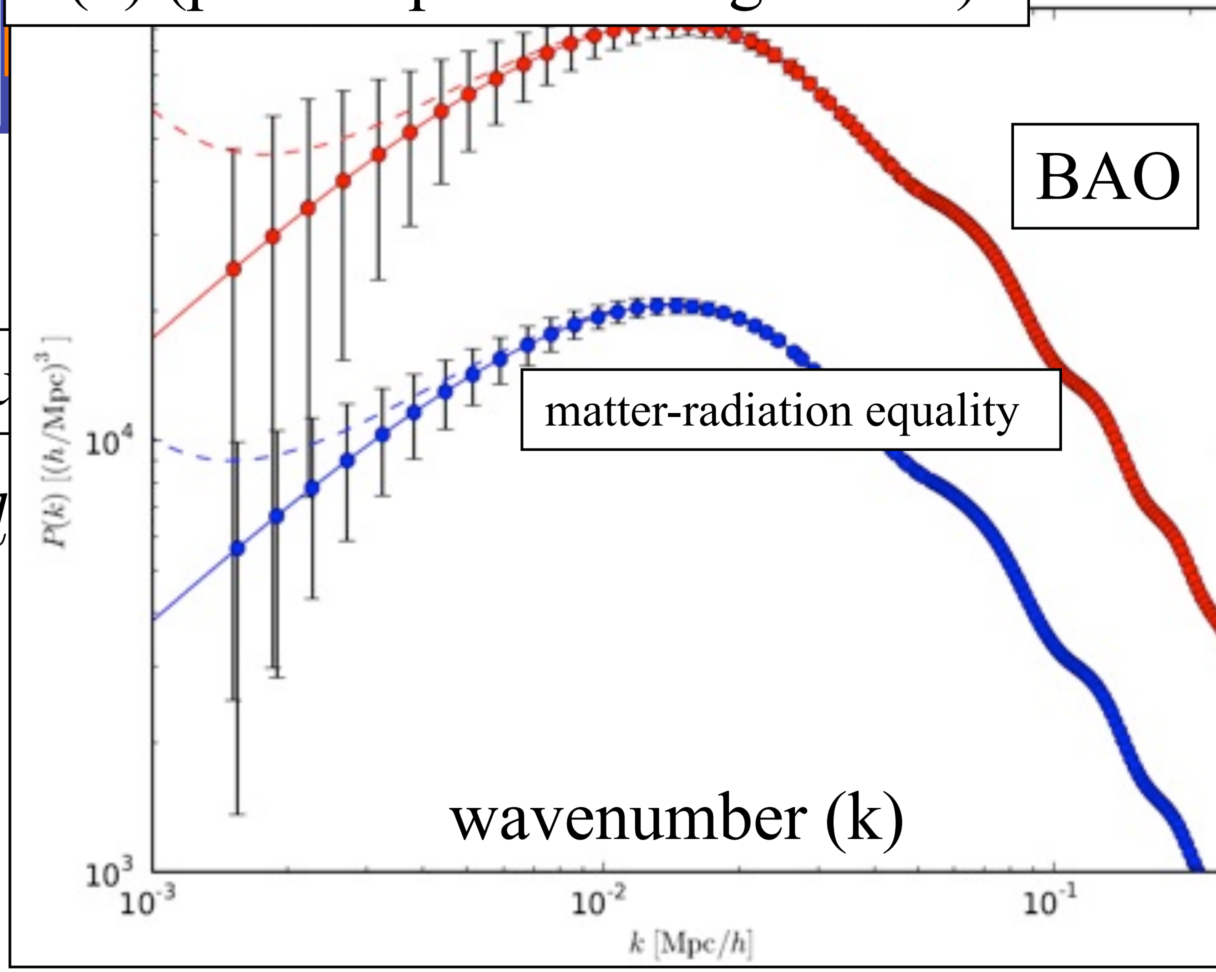
P(k) (power-spectrum of galaxies)



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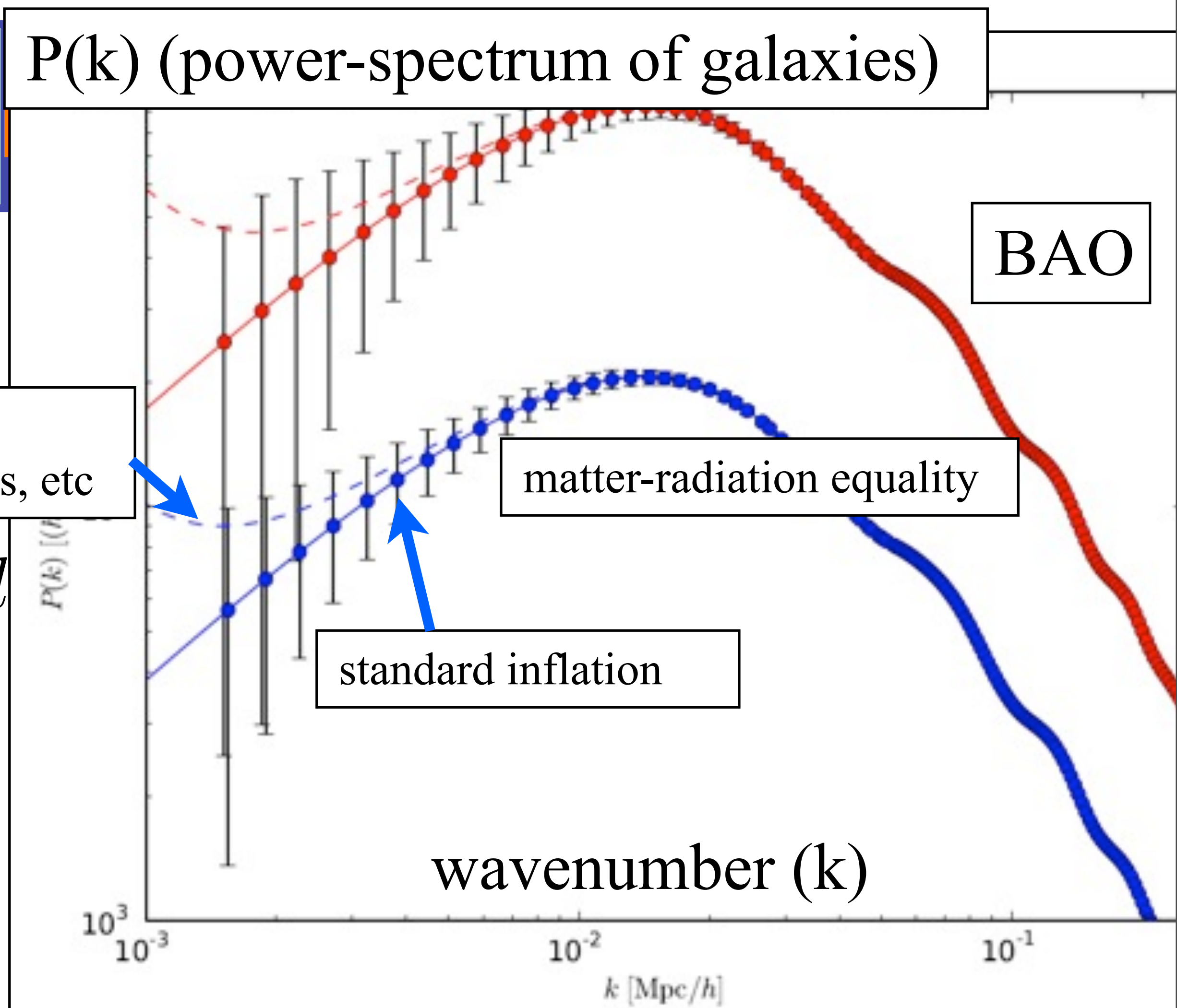
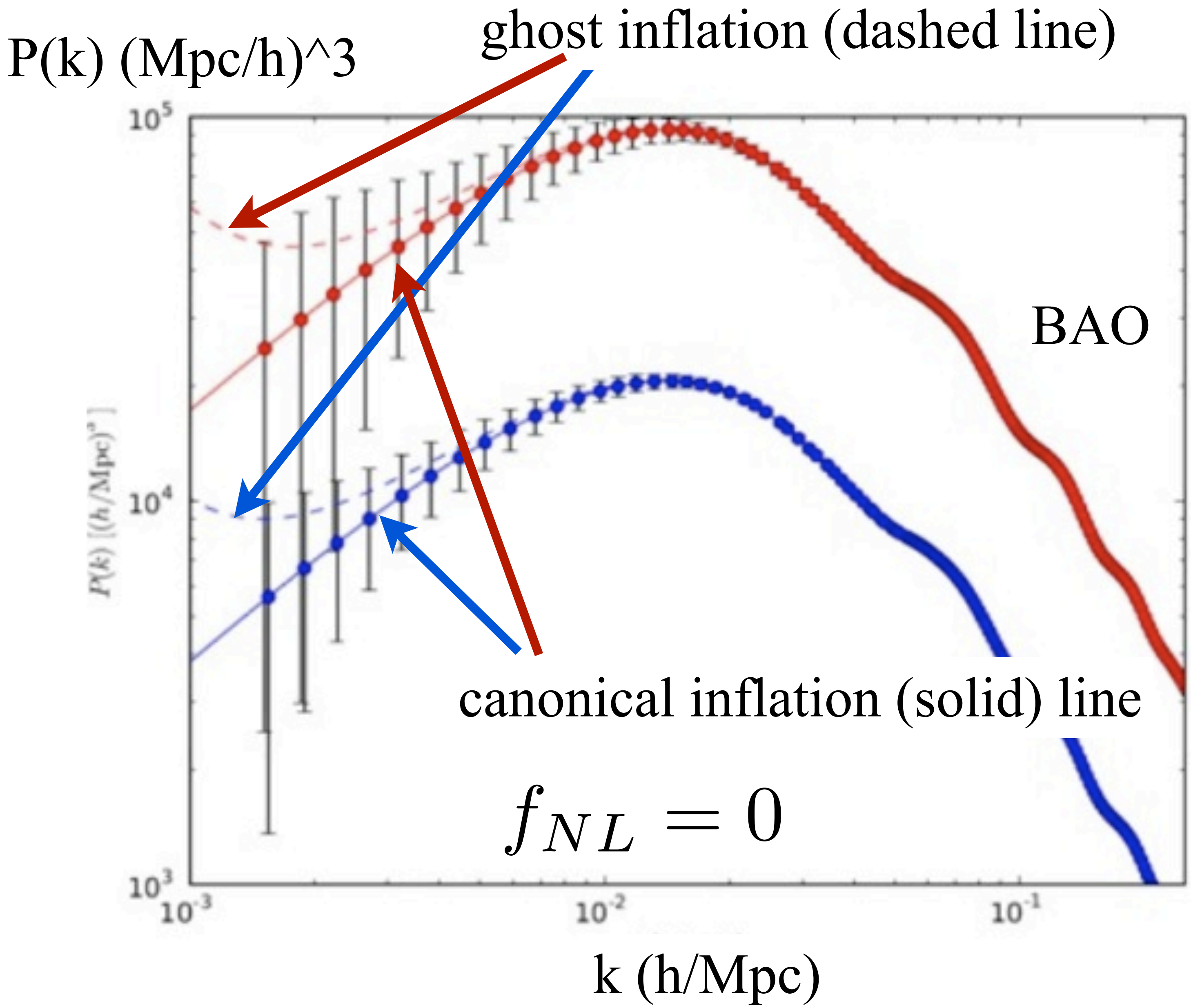


Galaxy angular po

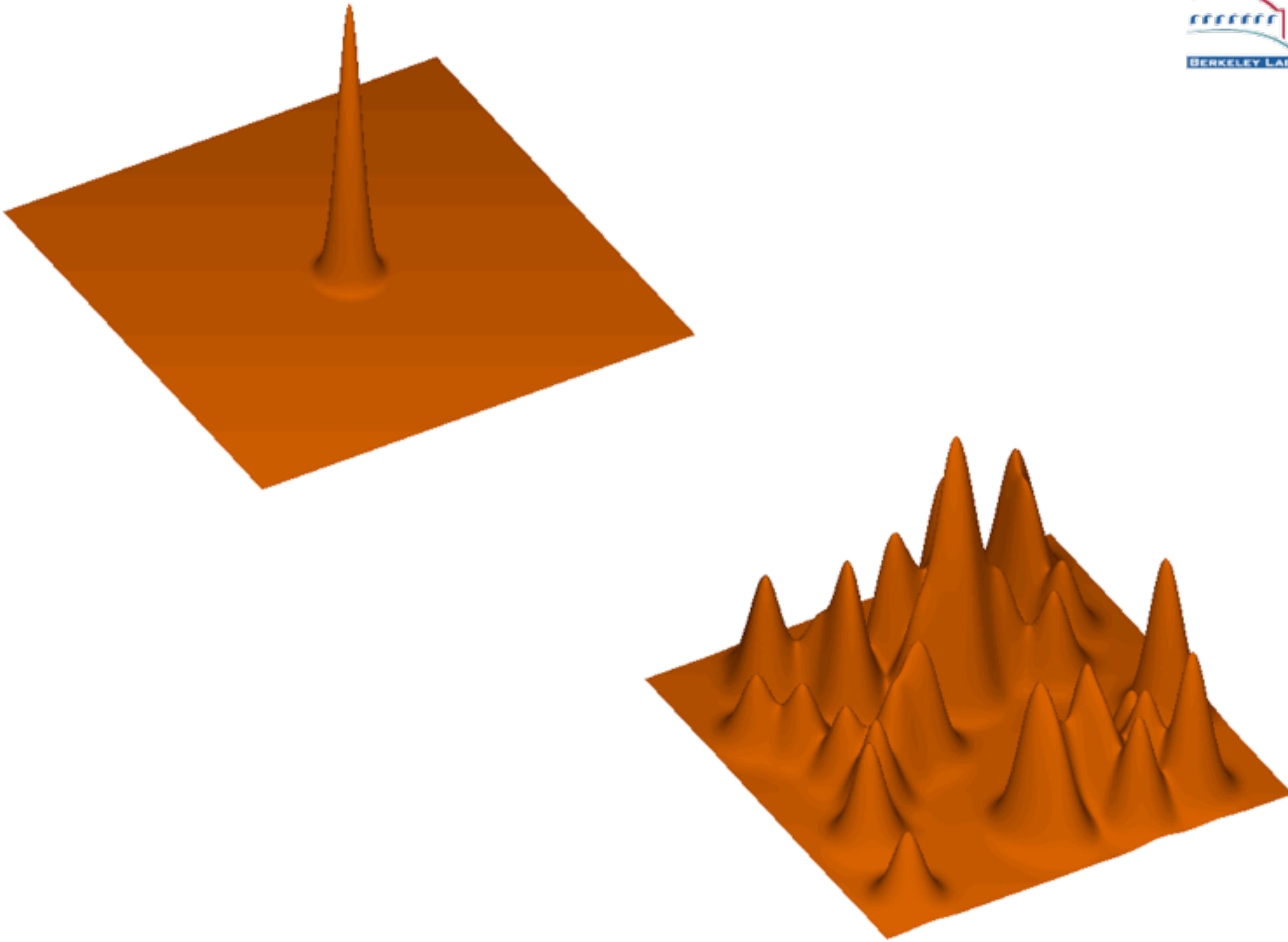
$$C_l^{gg} = \int dz \frac{H_0}{c} b^2(z)(d$$

$f_{NL} = 100$

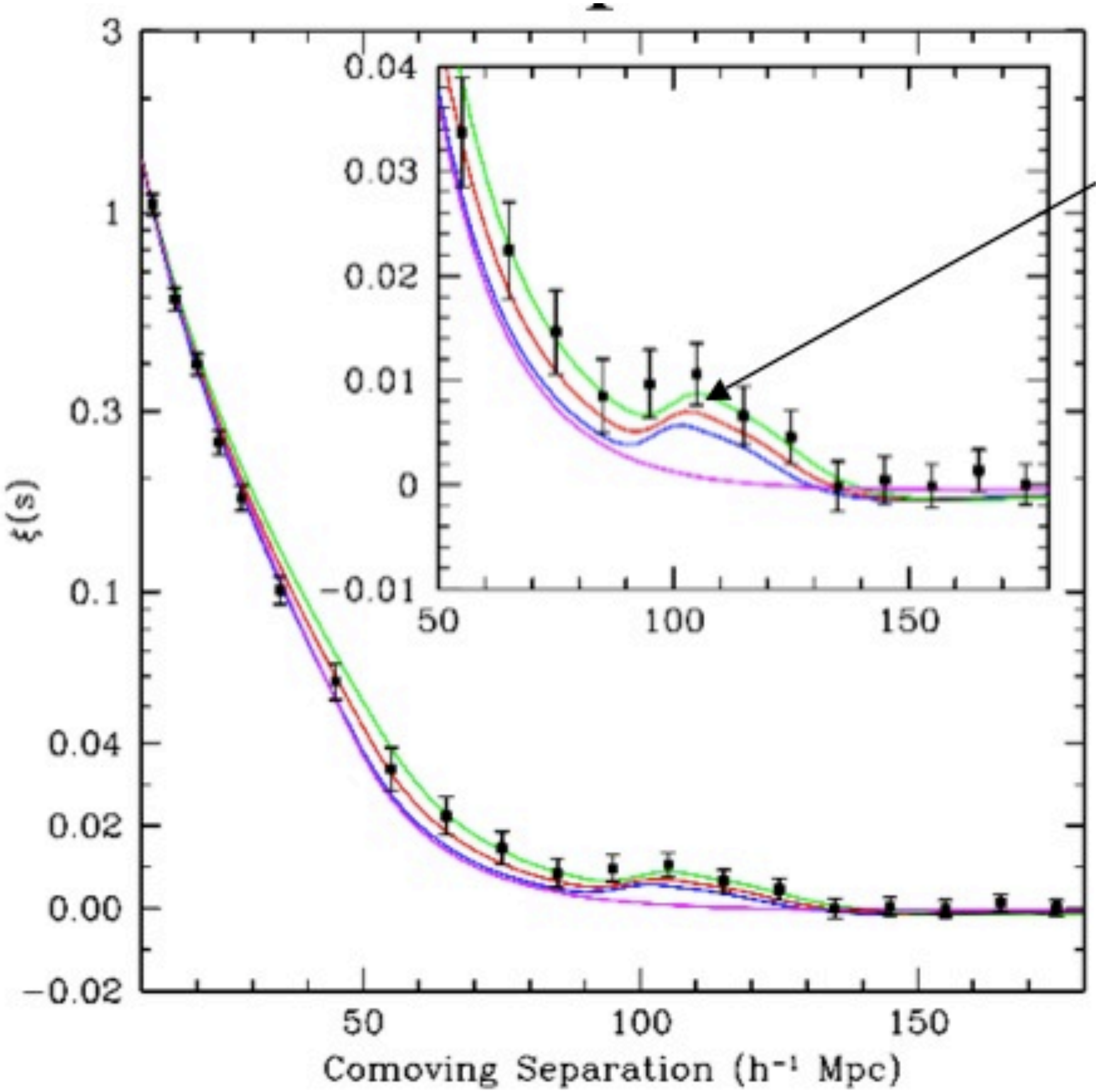


P(k) (Mpc/h)^3
ghost inflation (dashed line)
BAO
canonical inflation (solid) line
$f_{NL} = 0$
k (h/Mpc)
$P(k)$ [$(h/\mathrm{Mpc})^3$]
10^5
10^4
10^3
10^{-3}
10^{-2}
10^{-1}


Large scale structure exists in our real universe.
There are voids, clusters, web-like features.

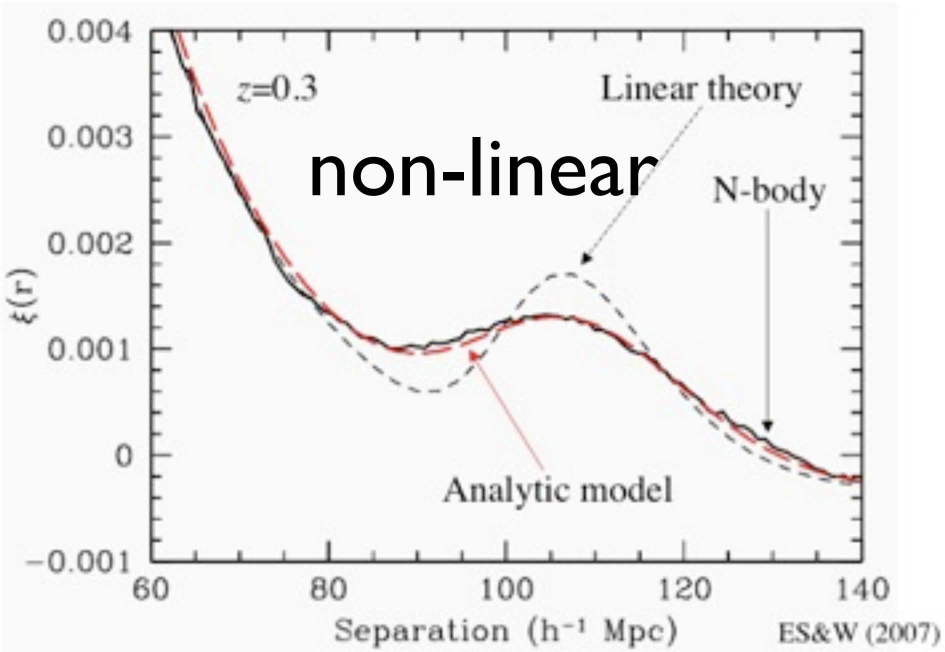


First Detection of this standard ruler: Baryon Acoustic Oscillations



Eisenstein et al. 2005

We measure non-linear galaxy power-spectrum in redshift space instead of linear dark matter power-spectrum in real space



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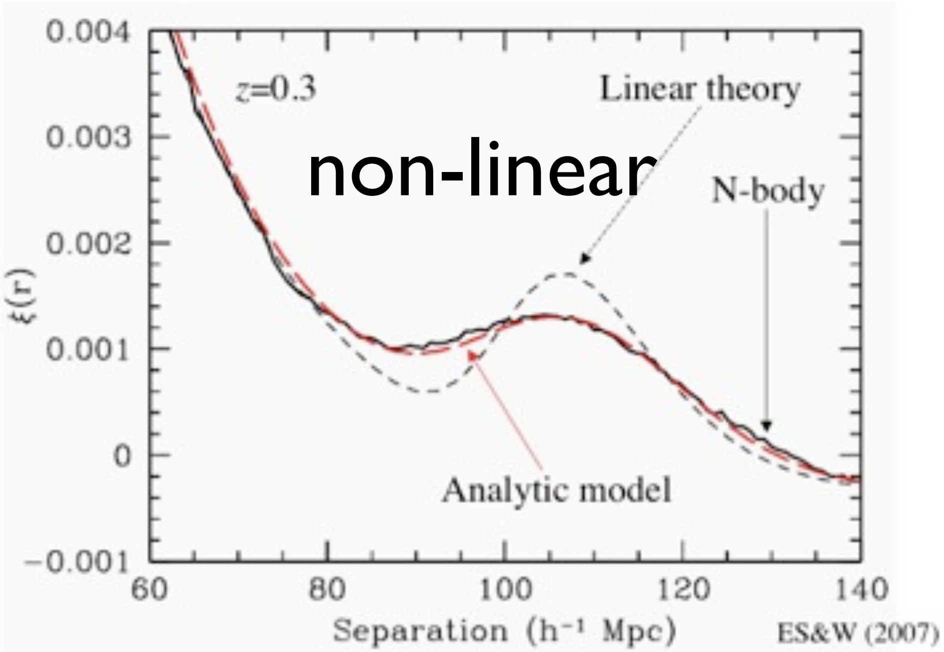
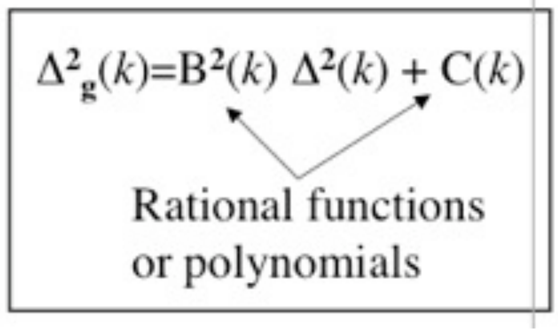


Galaxy power-spectrum



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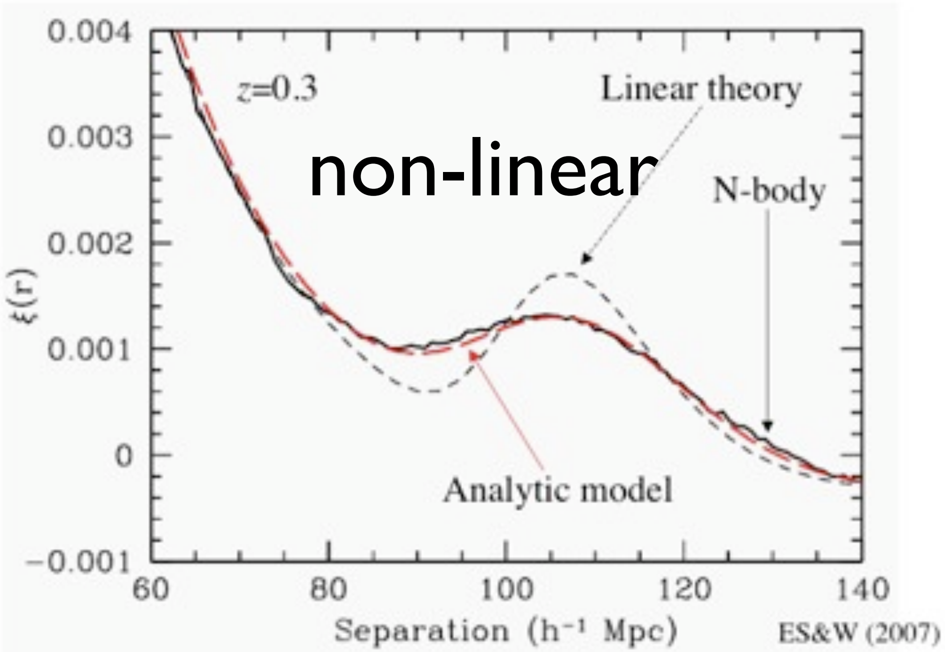
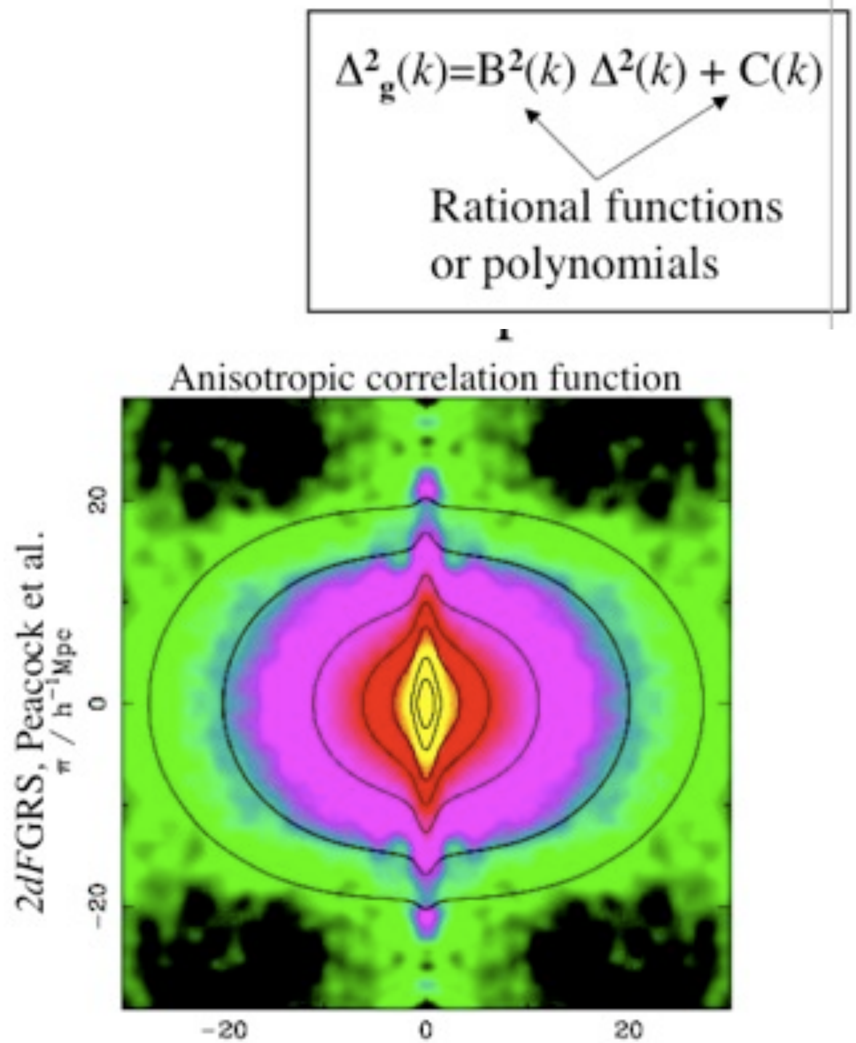


Galaxy power-spectrum



Redshift space

Systematics

- Therefore, the systematics I am going through here are mostly for getting a clean angular power-spectrum which contains information such as the shape of matter power-spectrum, scale dependent bias that can be caused by non-gaussianities at the early Universe.

Can we restrict ourselves to certain l-modes?

$$C_l^{gg}(Data) = C_l^{g_{real}g_{real}} + \epsilon_1 C_l^{stars,stars} + \epsilon_2 C_l^{sky,sky} + \epsilon_3 C_l^{c,c} + \ldots$$

Real Galaxy Power | Stars | Sky Brightness | Color Offset

Systematics

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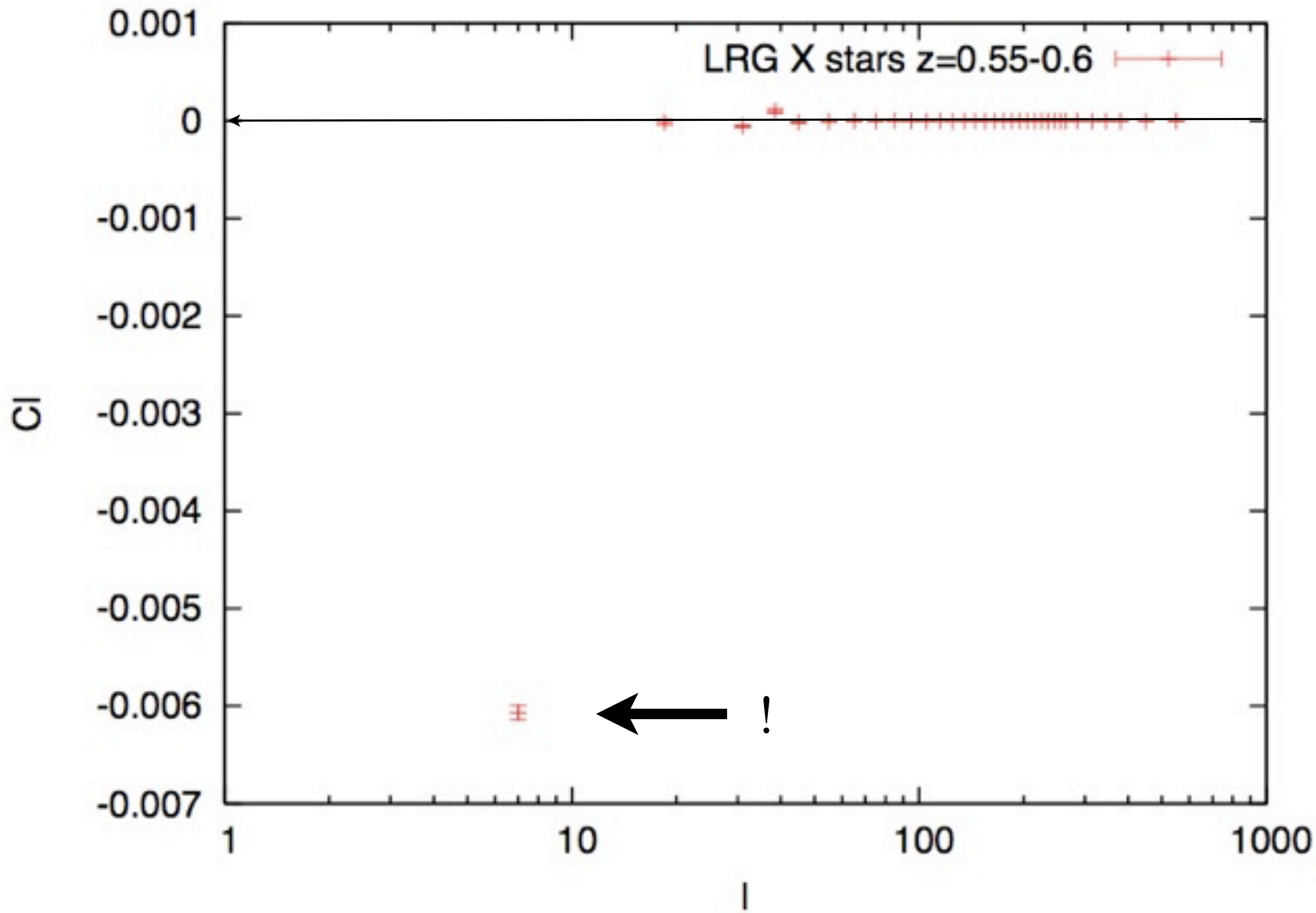
Real Galaxy Power Stars Sky Brightness Color Offset

Effect of stars



SH, Ross, Cuesta, Seo, White, Schlegel et al. (in prep)

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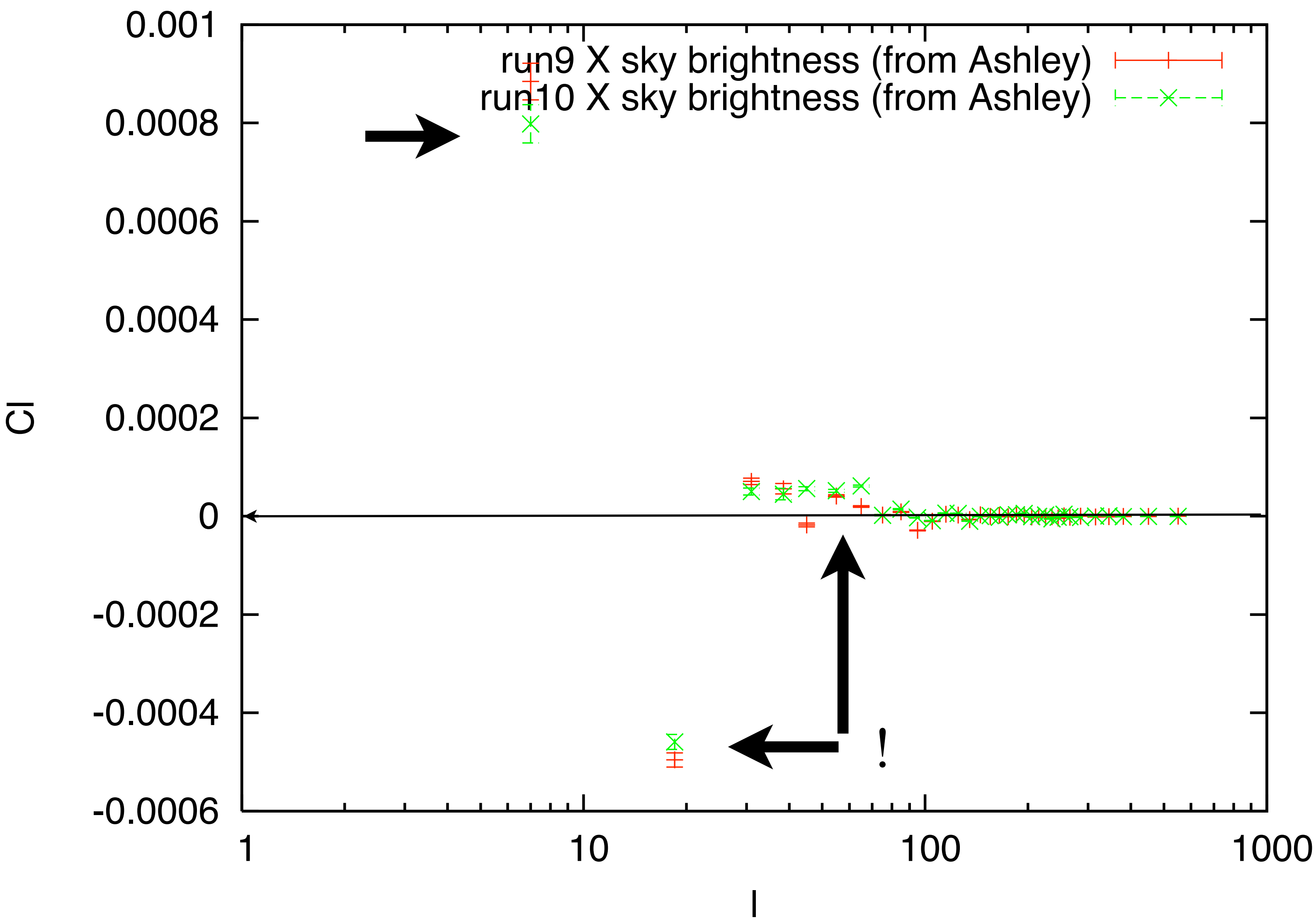
Real Galaxy Power   Stars   Sky Brightness   Color Offset

The effect of sky brightness



LAWRENCE

SH, Ross, Cuesta, Seo, White, Schlegel et al. (in prep)

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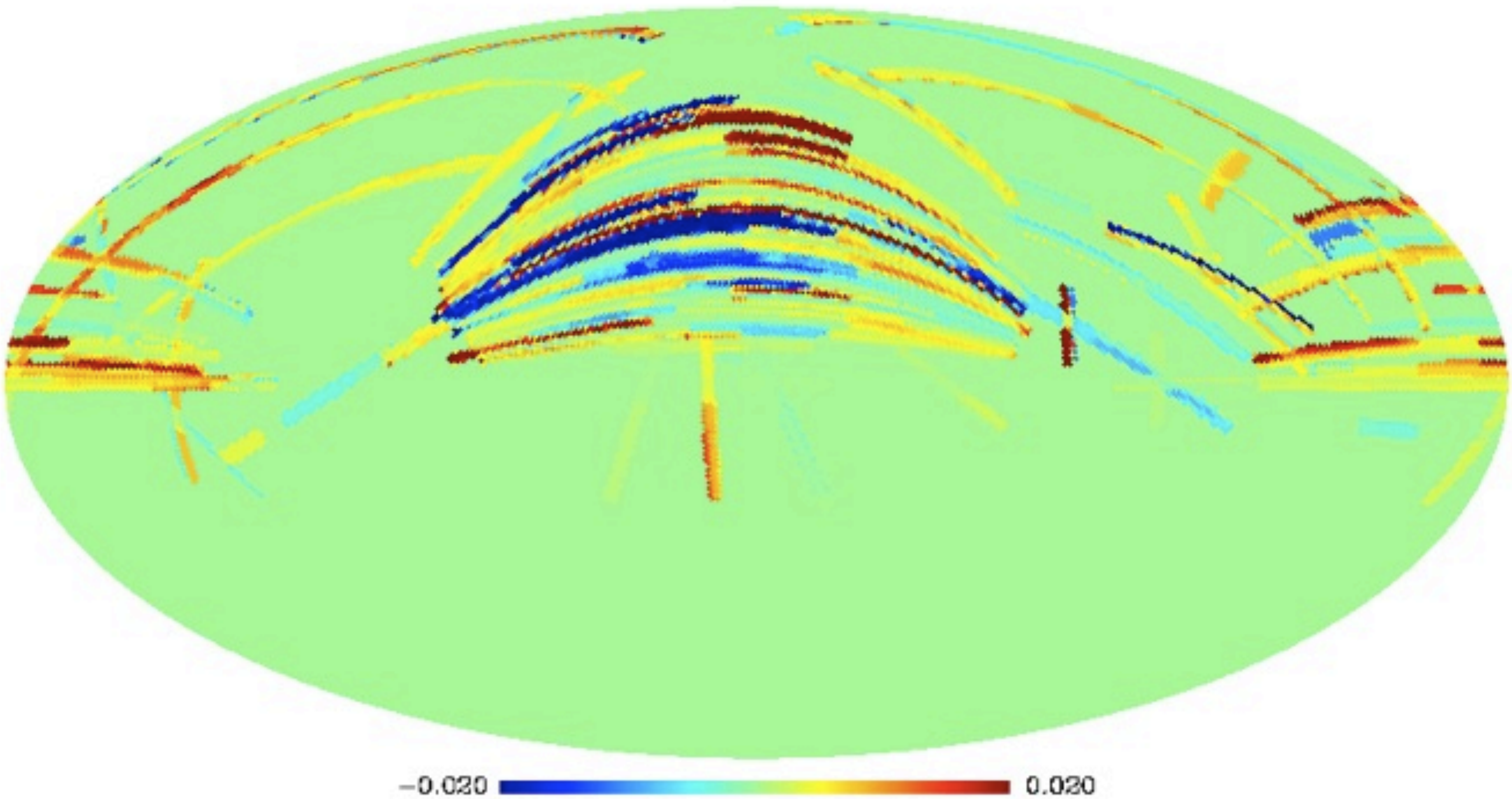
Real Galaxy Power — Stars — Sky Brightness — Color Offset

Color offsets

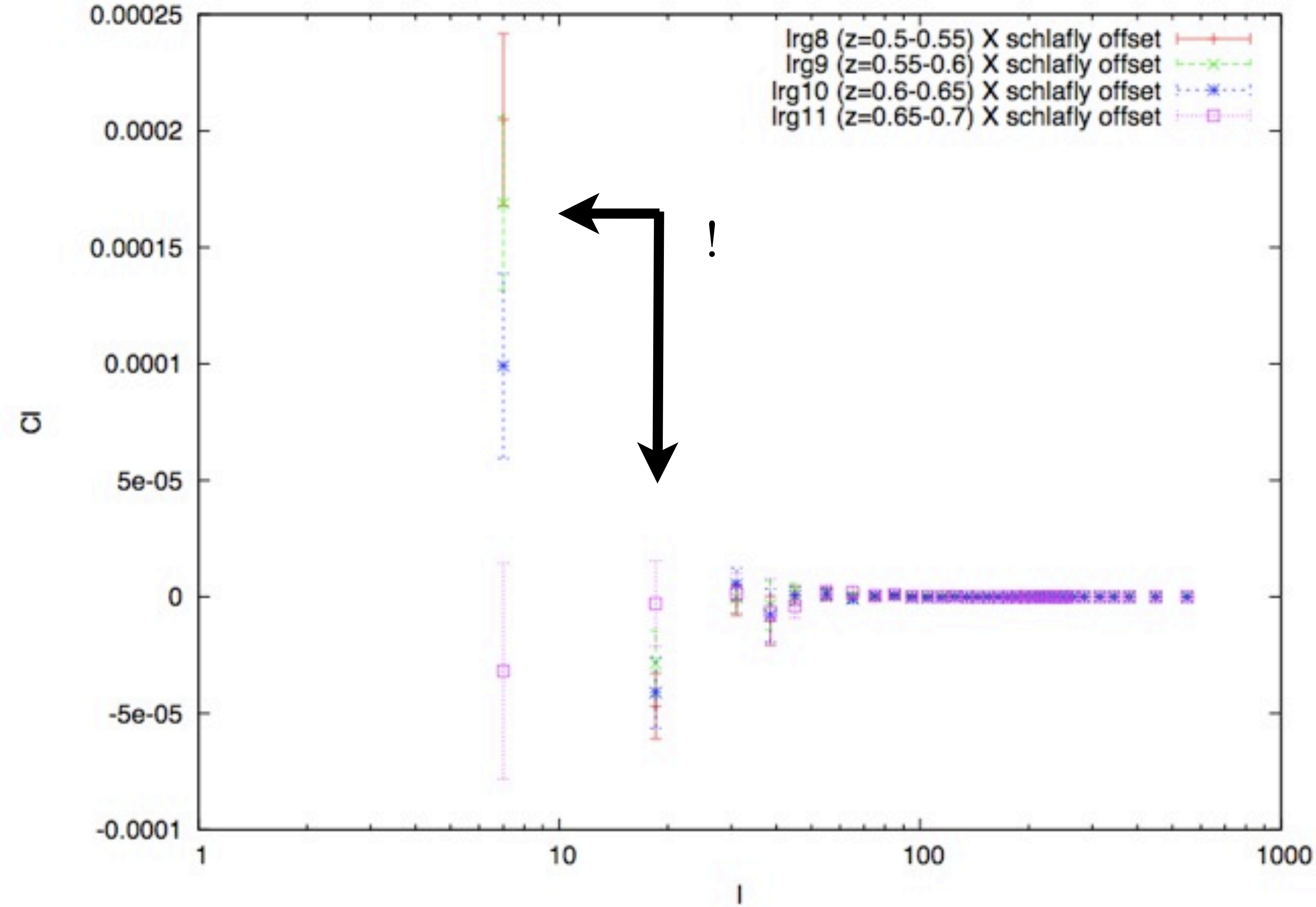
DR8 Color offsets in g-r



These are color (difference in magnitudes) zero points of SDSS

Color offsets as discussed in Schlafly et al. 2010

The effect of the color offsets



SH, Ross, Cuesta, Seo, White, Schlegel et al. (in prep)

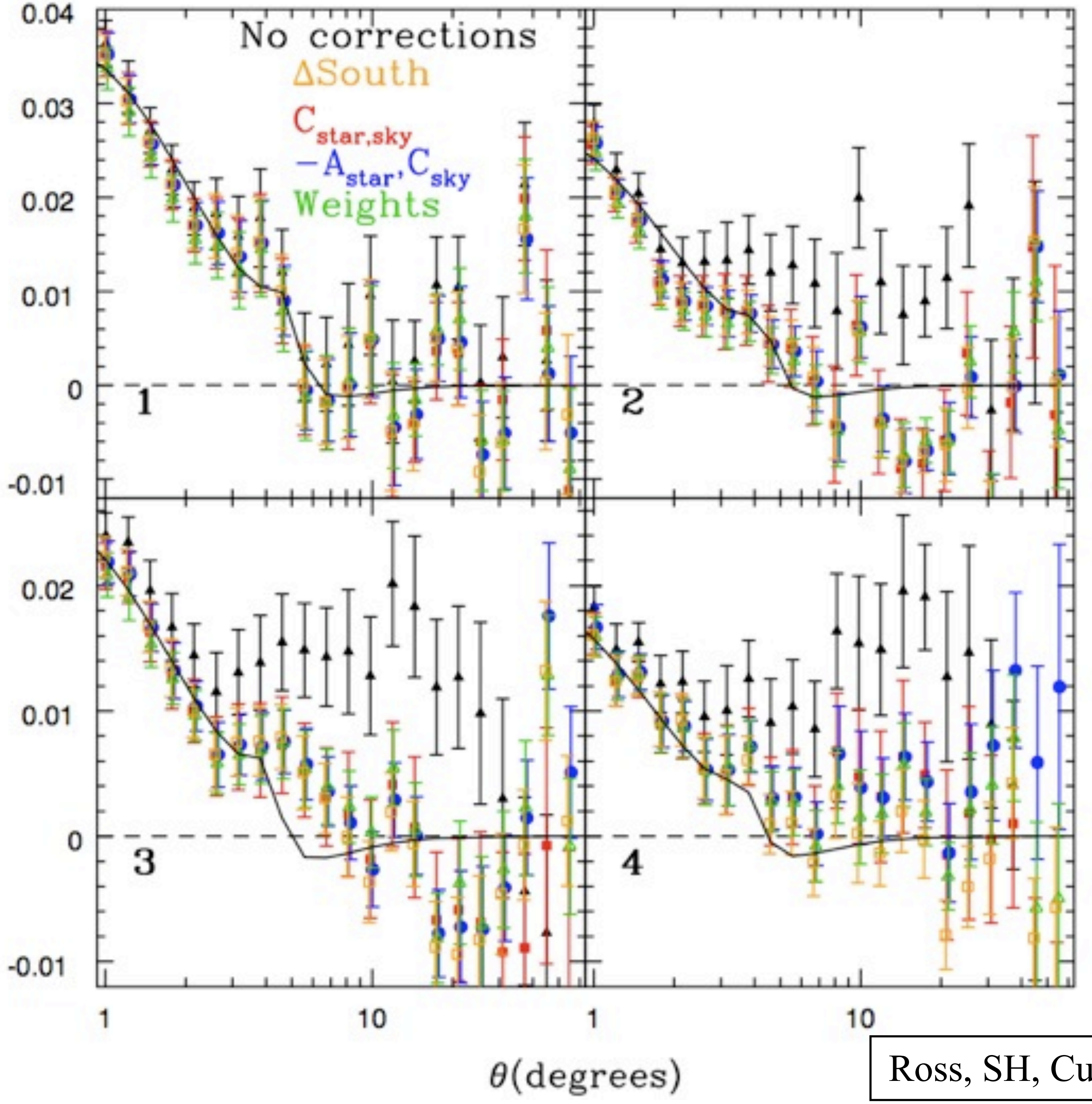
Systematics

What can we do when we can't/ don't want to cut to a certain l-range?

3 Lectures

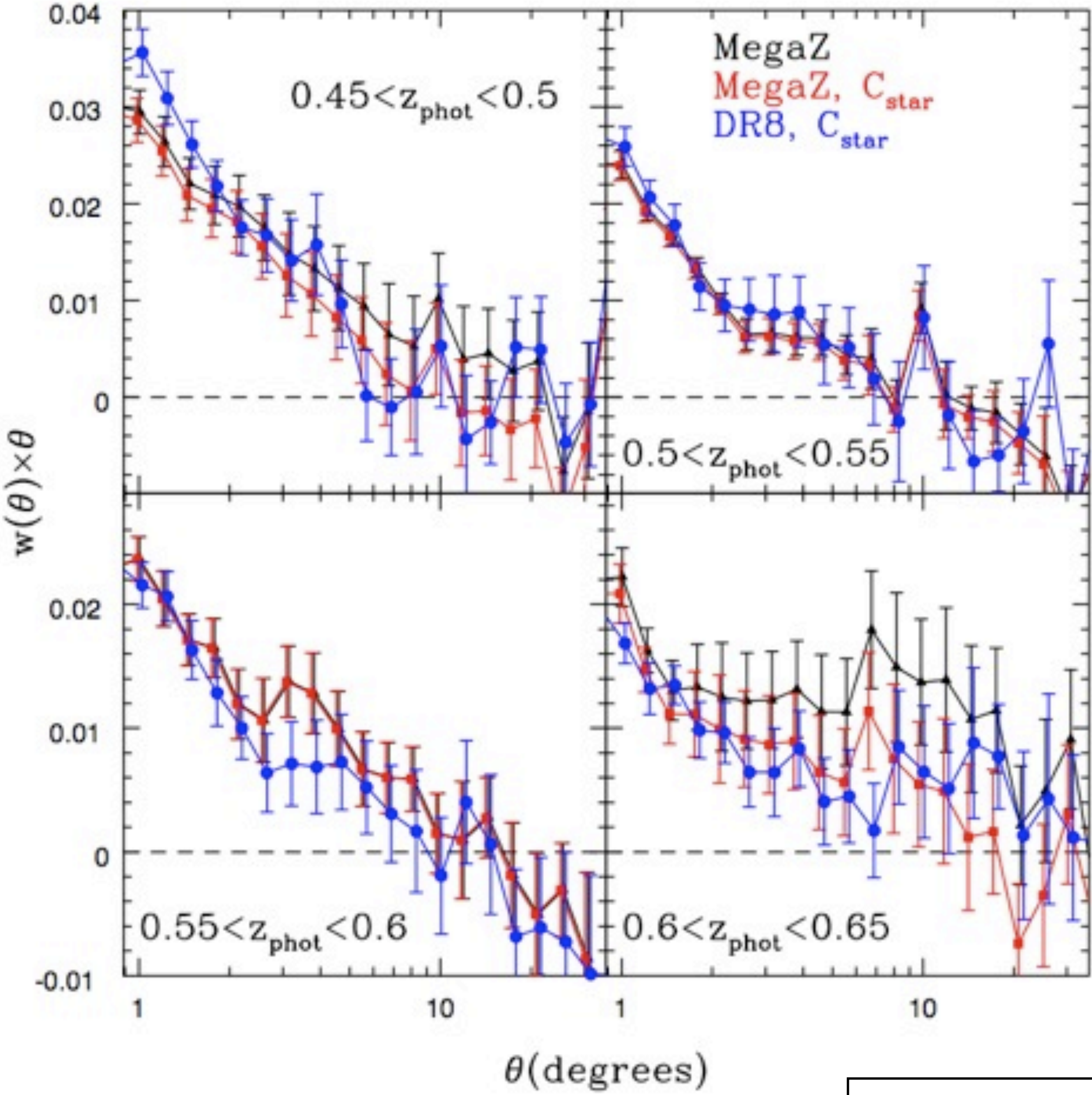
- Dark Energy, Baryon Acoustic Oscillations and more
- Observational Cosmology in Action
- A new large scale structure tracer:
    - Lyman alpha forest

In configuration space: Auto-correlation functions



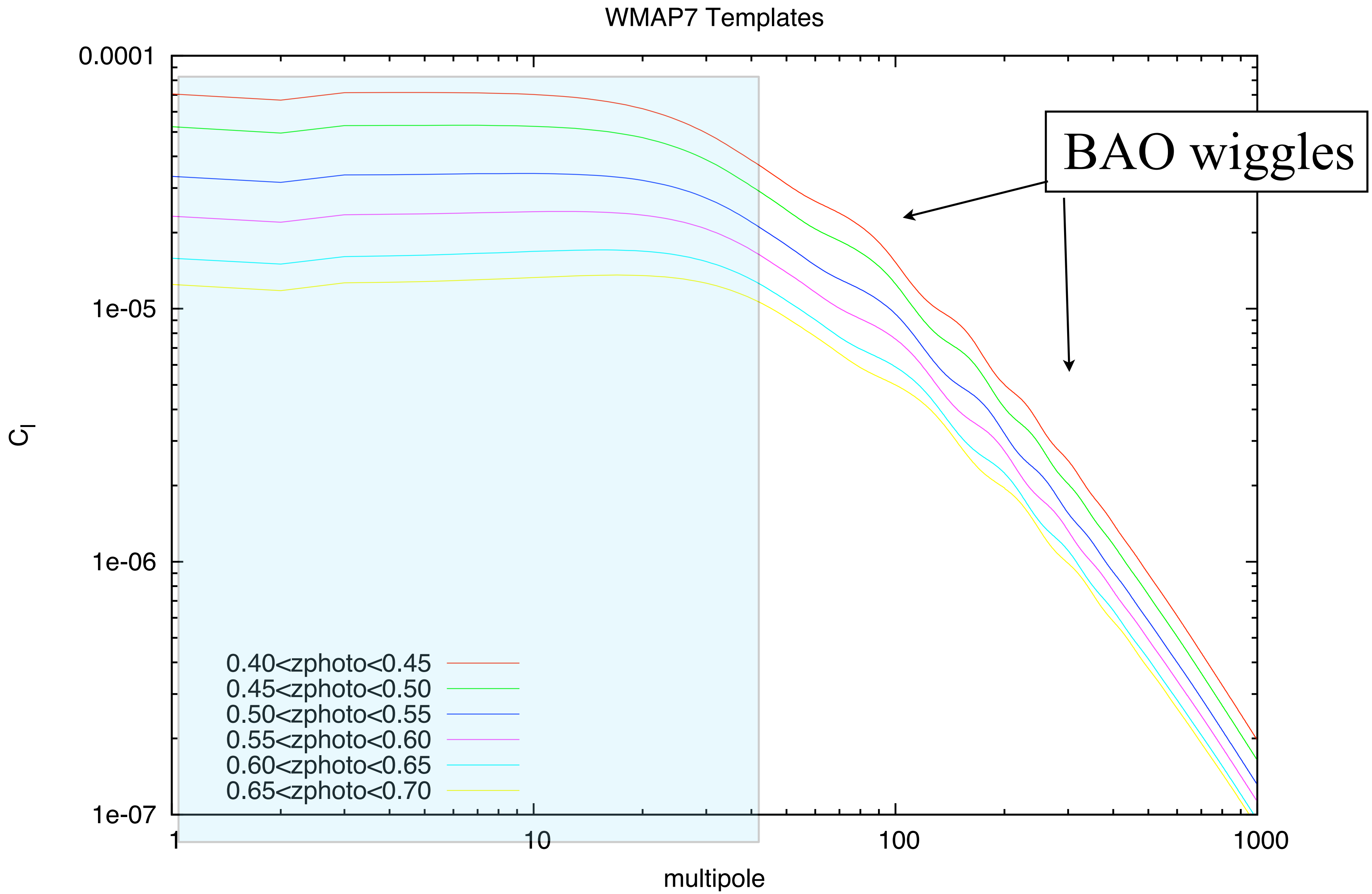
Ross, SH, Cuesta et al. (2011)

People has made claims on extra power in large scales and that it points to primordial non-gaussianities, but it can be explained away by systematics we just talked about



Ross, SH, Cuesta et al. (2011)

Remember? What we expect to see

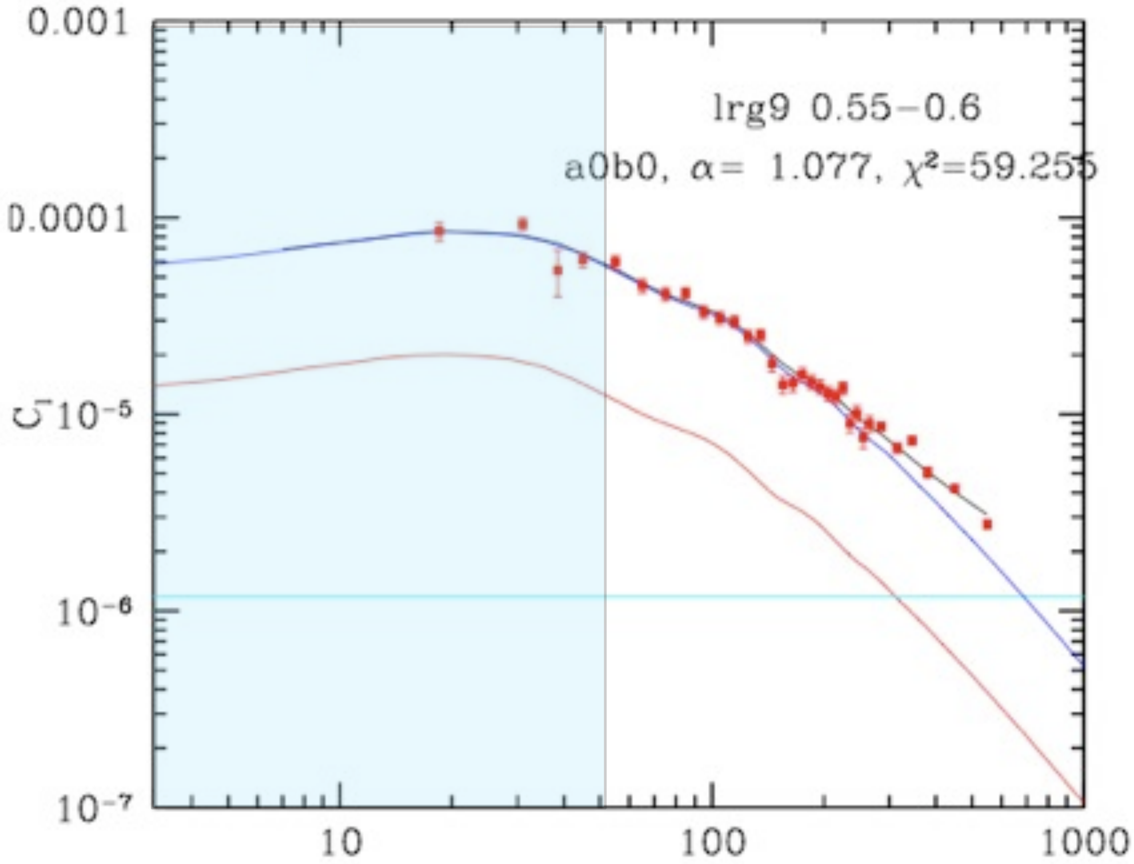


BAO: with Luminous Red Galaxies

Preliminary Results before taking out systematics

Angular Power-spectrum

z=0.55-0.6



l (as in spherical harmonics)

It is really hard to see the BAO feature, but one can divide out the smooth part of the spectrum

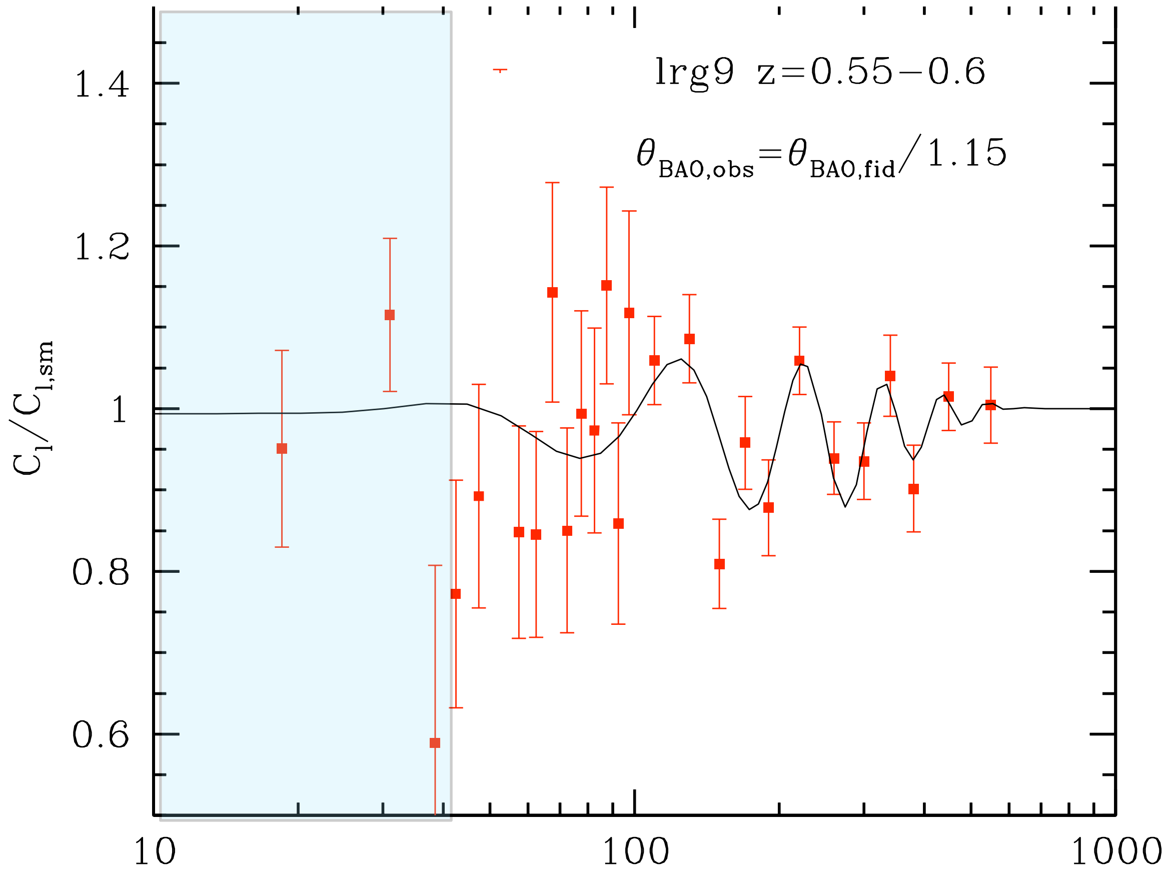
SH, Seo, Ross, White, Schlegel et al. (in prep)

BAO: with Luminous Red Galaxies

Preliminary BAO before taking out systematics

$$C_l/C^{smoothed}(l)$$

z=0.55-0.6



l (as in spherical harmonics)

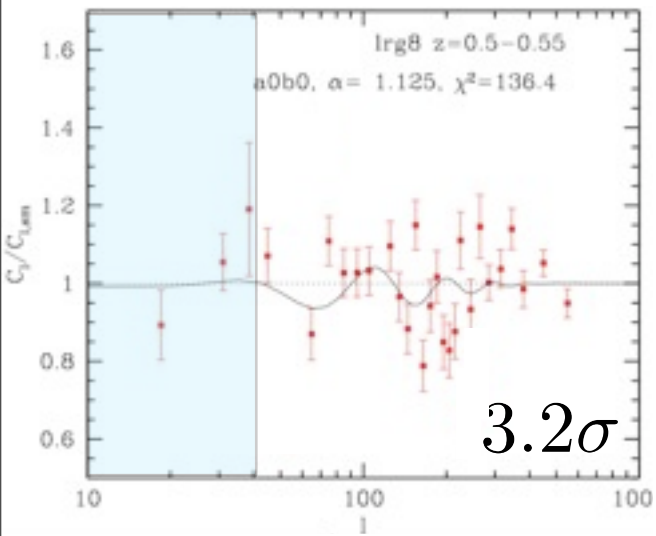
SH, Seo, Ross, White, Schlegel et al. (in prep)

BAO: with Luminous Red Galaxies

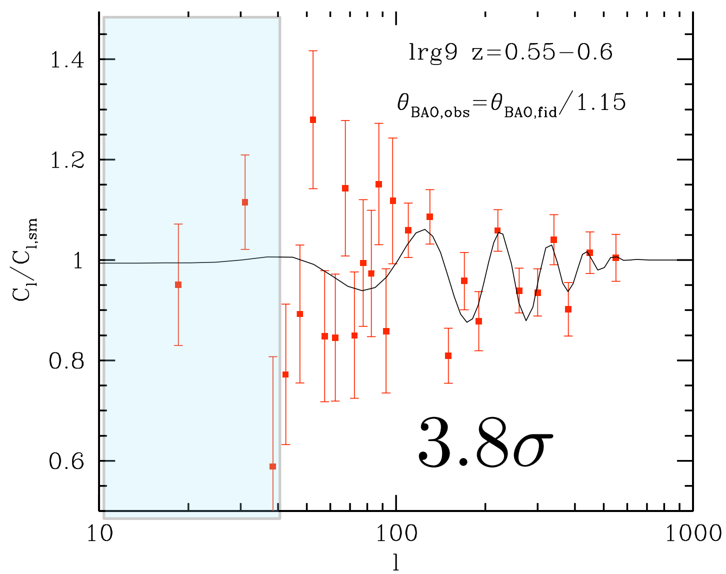
Preliminary BAO before taking out systematics

SH, Seo, Ross, White, Schlegel et al. (in prep)

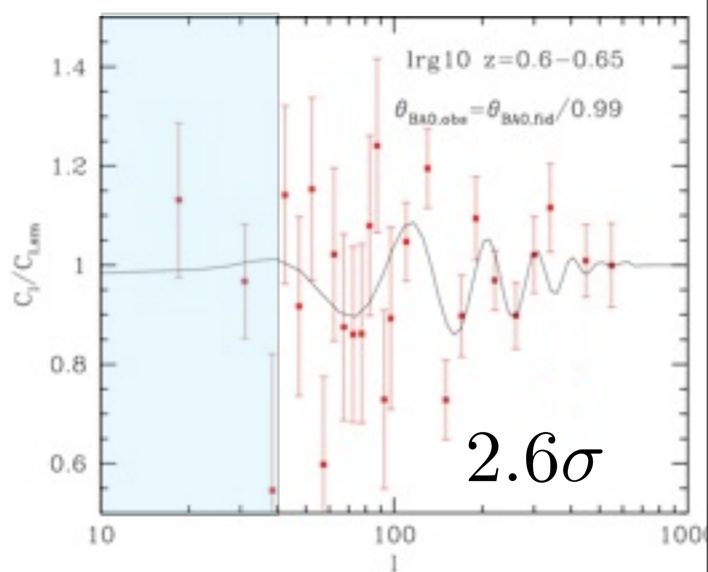
z=0.5-0.55



z=0.55-0.6



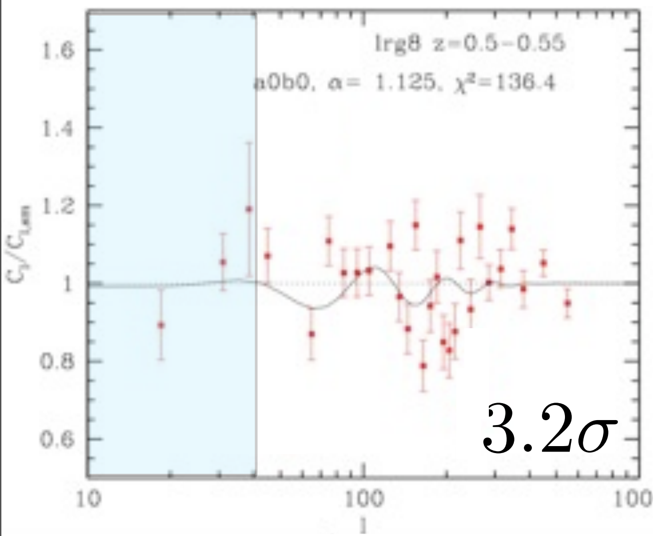
z=0.6-0.65



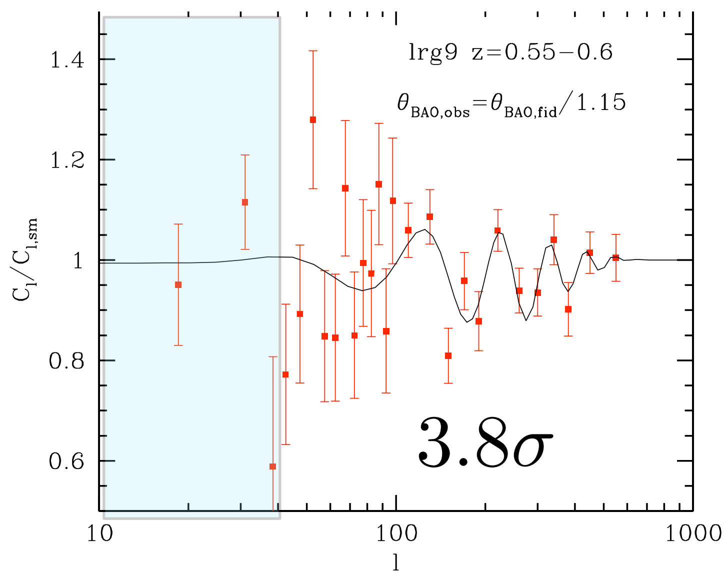
BAO: with Luminous Red Galaxies
Preliminary BAO before taking out systematics

SH, Seo, Ross, White, Schlegel et al. (in prep)

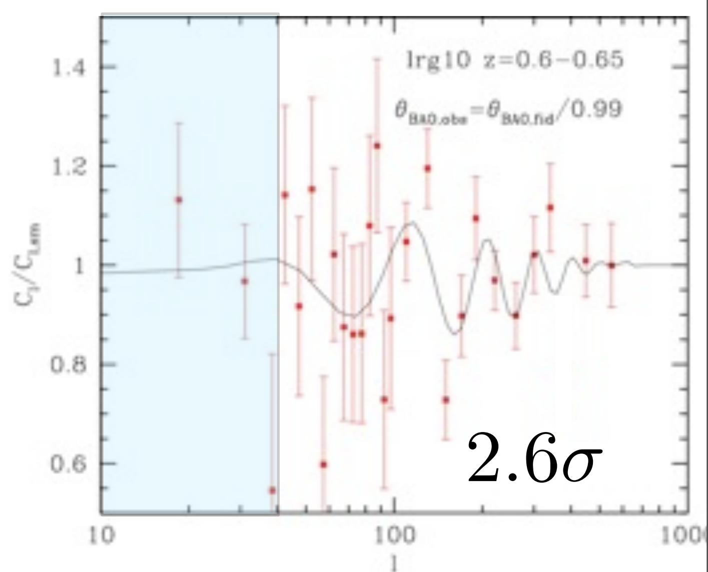
z=0.5-0.55



z=0.55-0.6



z=0.6-0.65



However, there may still be small remaining systematics in higher l...

BAO: with Luminous Red Galaxies
Systematics: Taking them out of the equation

True galaxy overdensity

Observed galaxy overdensity

$$\delta_g^o = \delta_g^t + \sum_{i=0}^{N} \epsilon_i \delta_{s_i}$$

Various systematics

For example, if i=2 only:

$$< \delta_g^o \delta_{s_1} >=< \delta_g^t \delta_g^t > + \epsilon_1 < \delta_{s_1} \delta_{s_1} > + \epsilon_2 < \delta_{s_2} \delta_{s_1} >$$

$$< \delta_g^o \delta_{s_2} >=< \delta_g^t \delta_g^t > + \epsilon_1 < \delta_{s_1} \delta_{s_2} > + \epsilon_2 < \delta_{s_2} \delta_{s_2} >$$

$$< \delta_g^o \delta_g^o >=< \delta_g^t \delta_g^t > + \epsilon_1^2 < \delta_{s_1} \delta_{s_1} > + 2\epsilon_1 \epsilon_2 < \delta_{s_2} \delta_{s_1} > + \epsilon_2^2 < \delta_{s_2} \delta_{s_2} >$$

We also need to take into account of all the covariances between systematics and across different band power

Awaiting for the new answers ...

SH, Seo, Ross, White, Schlegel et al. (in prep)

Preliminary results
without taking out all of the systematics

(if you really want to know)

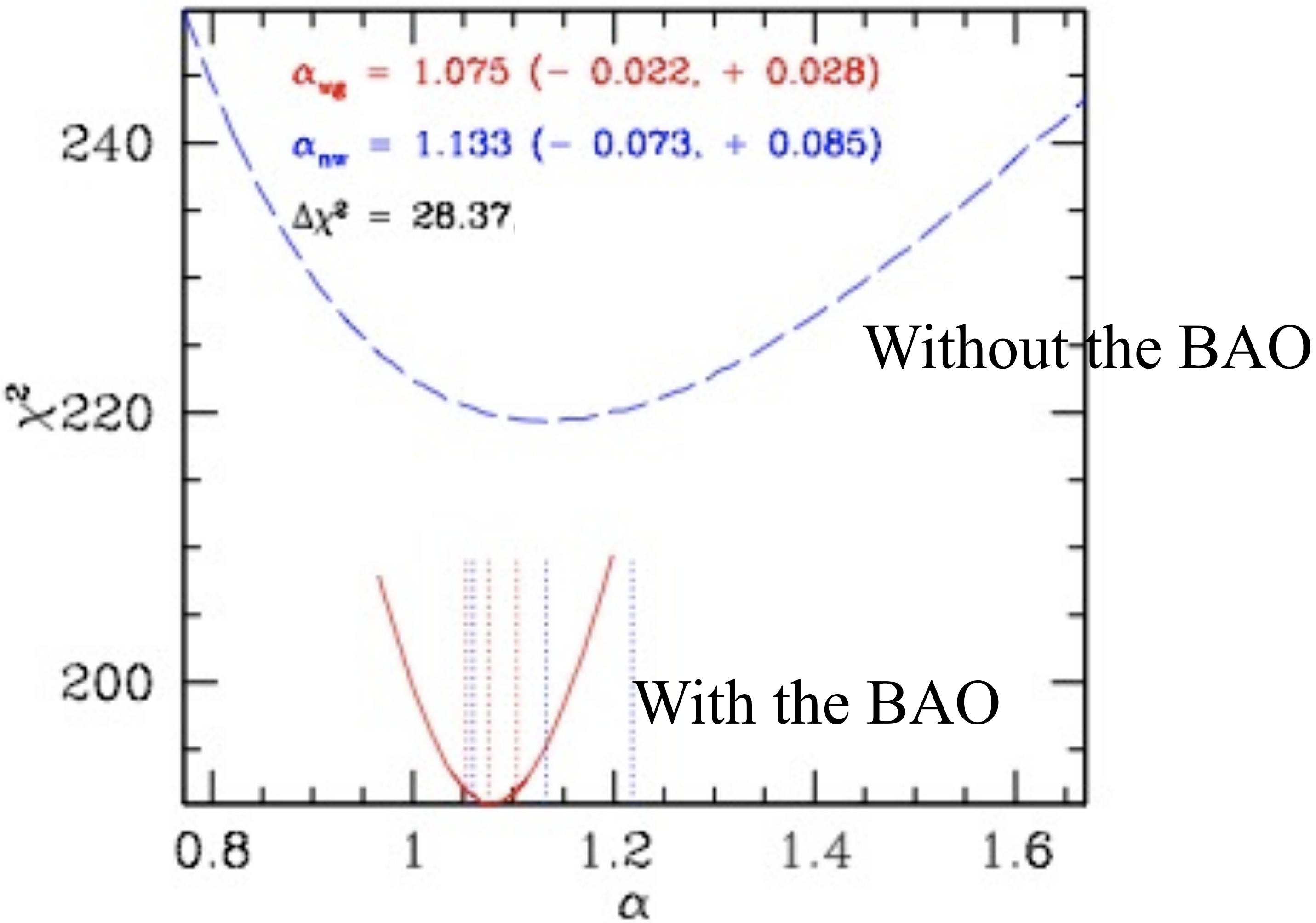
The following results are derived:

by taking into account of angular power-spectra from l >40 from z=0.45-0.65.

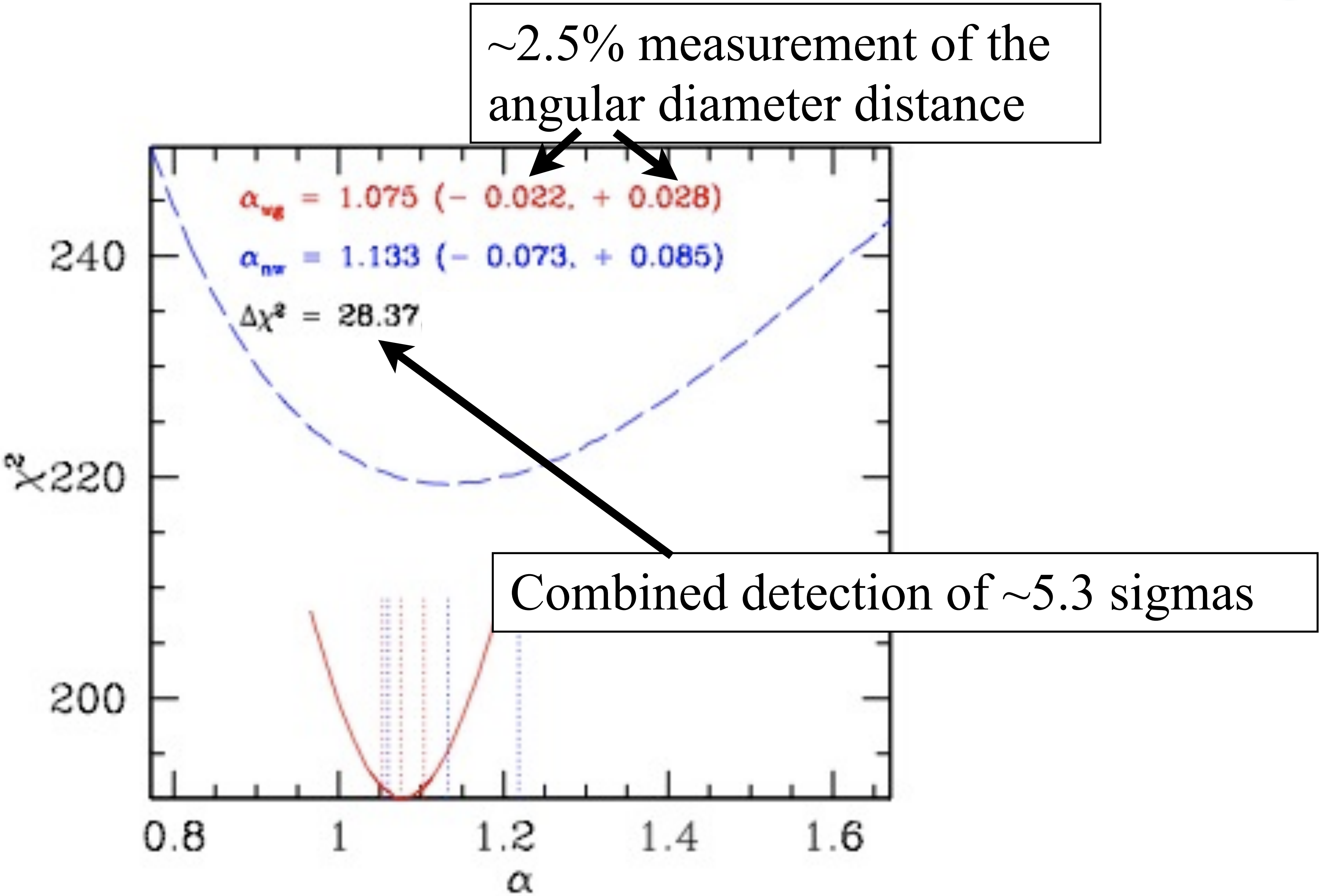
It should be quite clean of systematics, but there are probably some residuals which we are going to take out with our new method.

Preliminary results
without taking out all of the systematics

We look at the difference in chi-square for BAO and no-BAO models

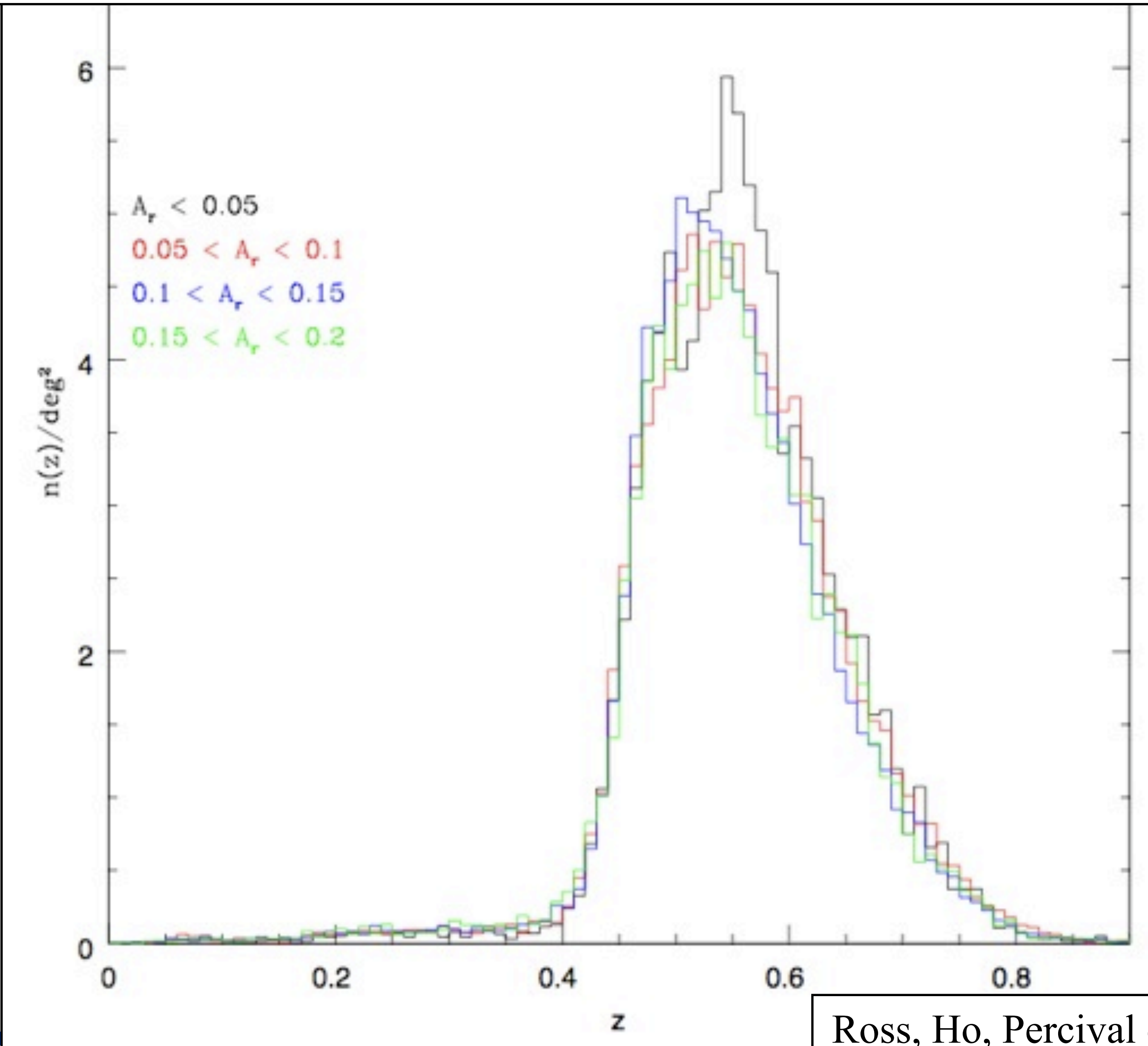


Preliminary results
without taking out all of the systematics

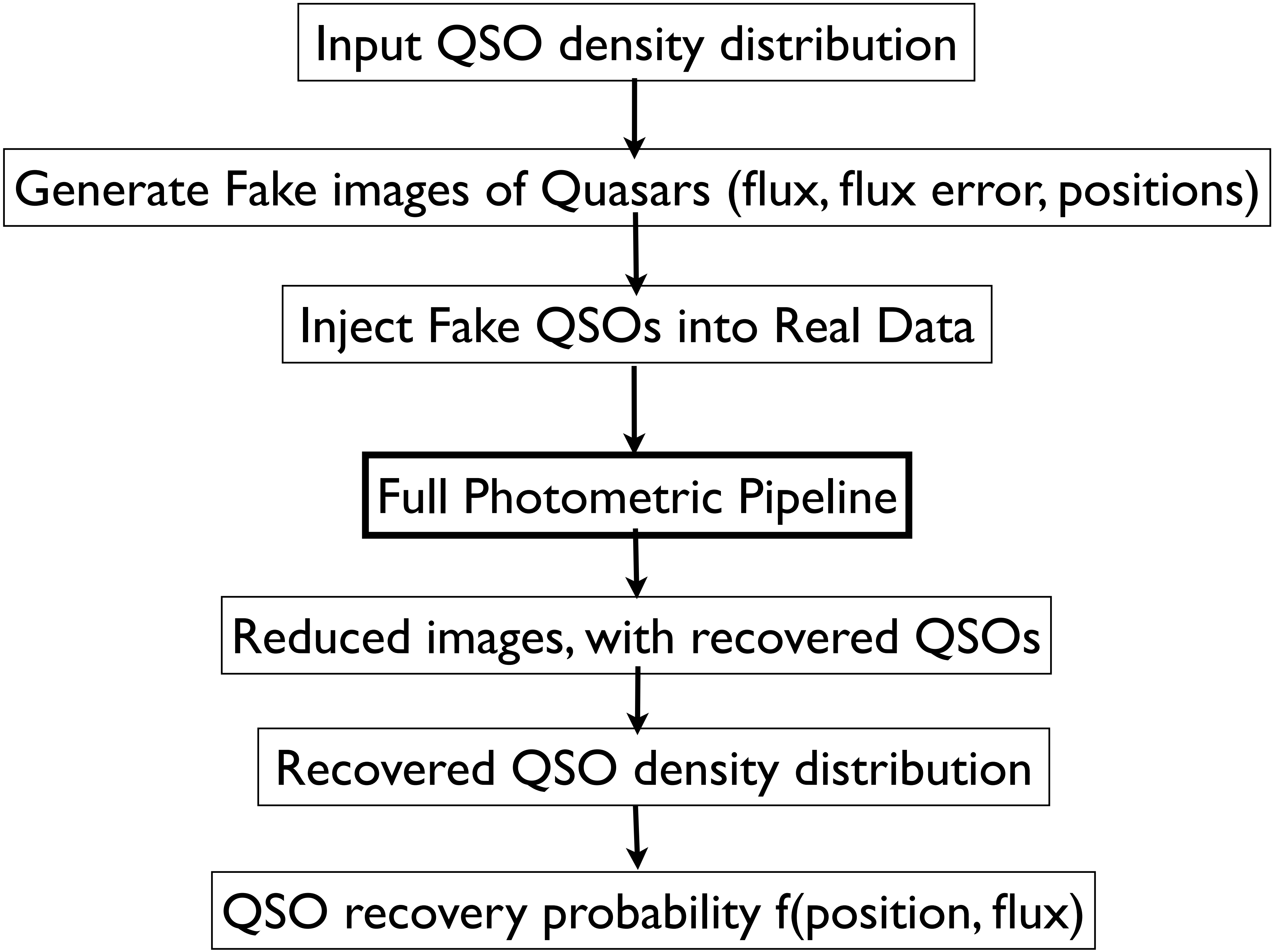


BAO: with Luminous Red Galaxies
Systematics: Dust

Dust extinction affects redshift distribution of the galaxies



Ross, Ho, Percival et al. (in prep)


Input QSO density distribution
Generate Fake images of Quasars (flux, flux error, positions)
Inject Fake QSOs into Real Data
Full Photometric Pipeline
Reduced images, with recovered QSOs
Recovered QSO density distribution
QSO recovery probability f(position, flux)