Cosmic Near Infrared Background

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Astro Seminar, CMU, November 16, 2011

in collaboration with

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This talk is based on...

- "*Cosmic Near Infrared Background: Remnant Light from Early Stars*," Fernandez & Komatsu, ApJ, 646, 703 (2006)
- "*Cosmic Near Infrared Background II: Fluctuations*," Fernandez, Komatsu, Iliev & Shapiro, ApJ, 710, 1089 (2010)
- "*Cosmic Near Infrared Background III: Effects of Minimum Mass and Self-regulation*," Fernandez, Iliev, Komatsu & Shapiro, close to being submitted to ApJ.

Motivation

- SDSS showed that reionization of the universe nearly completed at **$z \sim 6$**. (Neutral fraction is non-zero: $>10^{-4}$)
- WMAP showed that the bulk of reionization took place at **$z \sim 10$**. (Probably the universe was half neutral then.)
- UV light emitted at those redshifts will be seen at near infrared bands.
  - For example, Lyman-α photons emitted at those redshifts will be seen at **$\lambda \sim 0.9$–$1.2\mu m$**.

Go Near Infrared!

High-z Universe

- A number of galaxies have been detected at $z>6$.
  - Mostly via Lyman-α emission lines.
- JWST (if it ever flies) would find more of them at even higher redshifts.

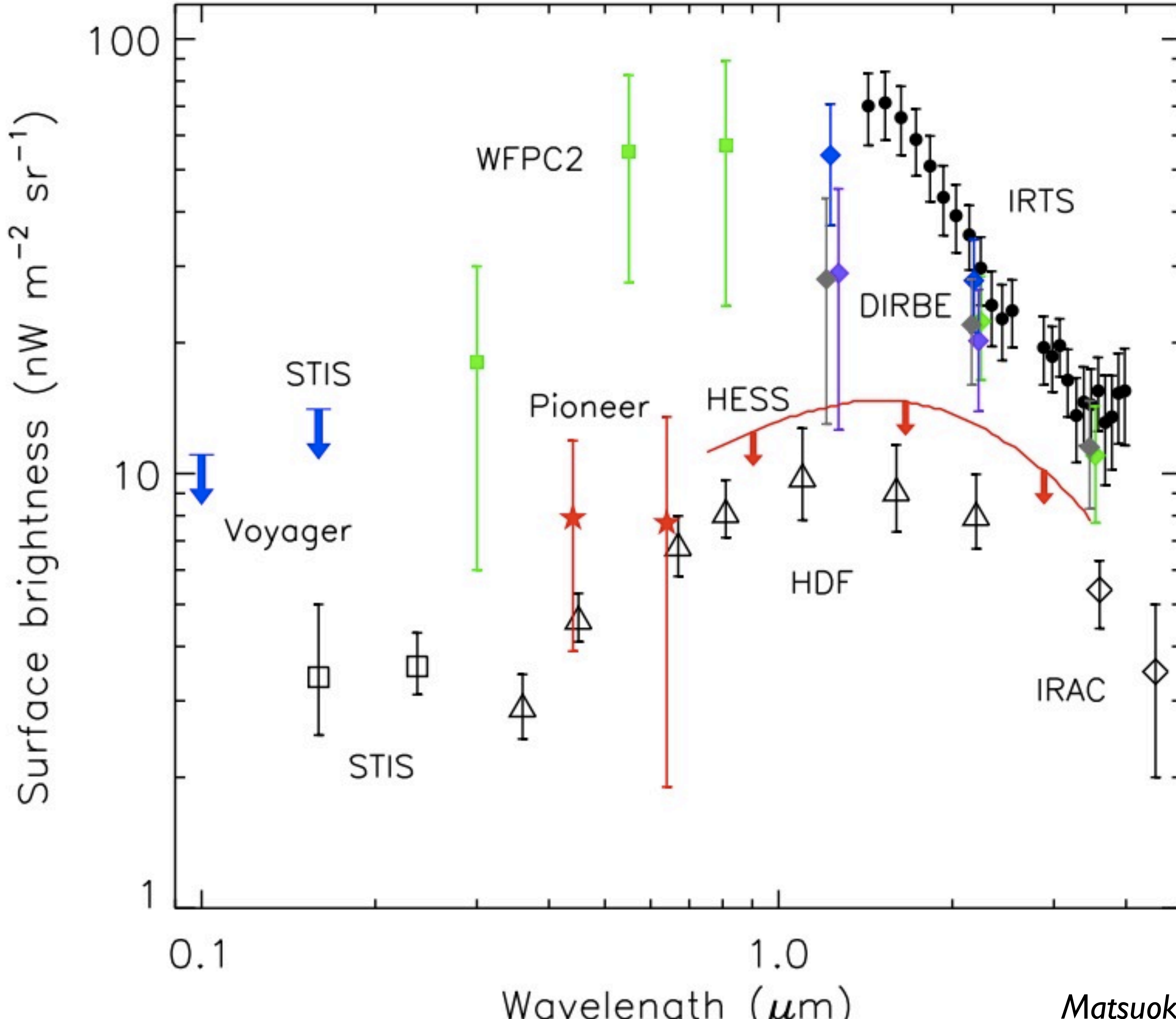
- *Can we do anything interesting before JWST flies?*

Near Infrared Background (NIRB)

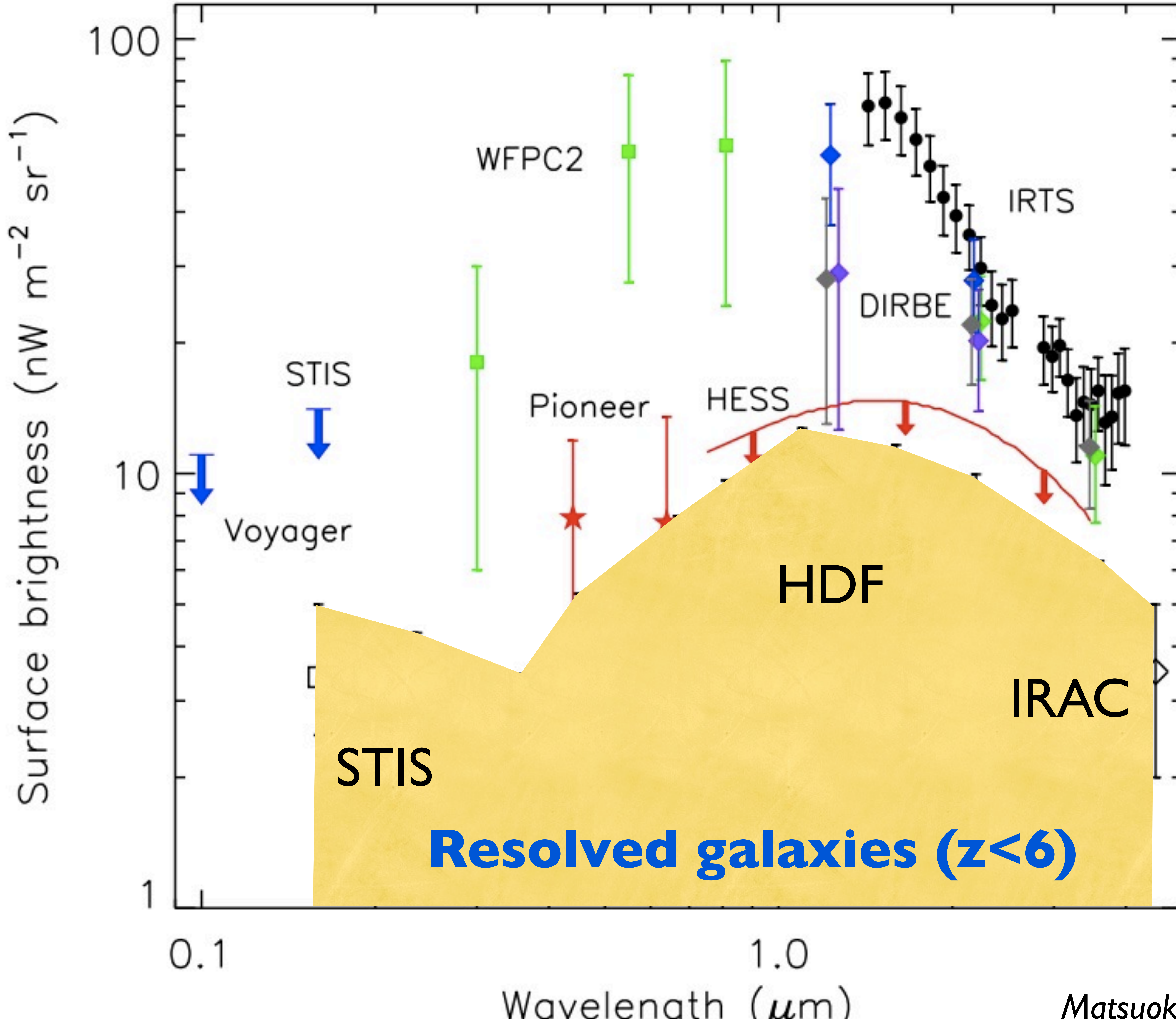
- Instead of focusing on detecting individual objects, focus on detecting unresolved, high-z objects using the diffuse background light in the near infrared bands.
- We can use both the mean intensity and fluctuations.
- There are data for both already, and more data are coming!
  - Most people may not know this, but it is actually an exciting field (and there aren't too many papers written yet).

Let me emphasize...

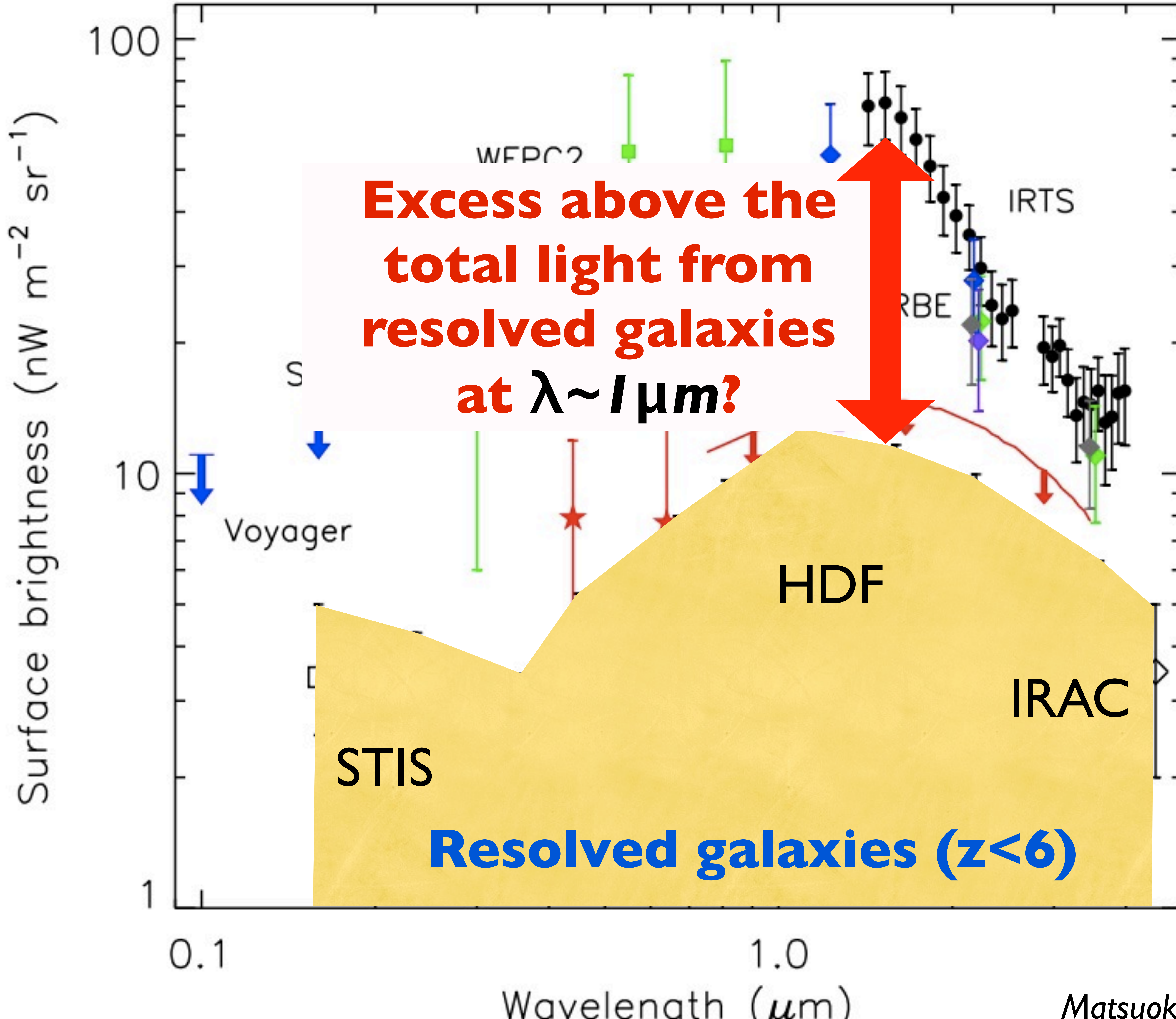
- We know that the universe was reionized at z~10.
- Most likely, stars played the dominant role in reionizing the universe.
- Stars had to produce UV photons to reionize.
- Then, the redshifted light MUST be with us.
- *We oughta look for it!*



Matsuoka et al. (2011)



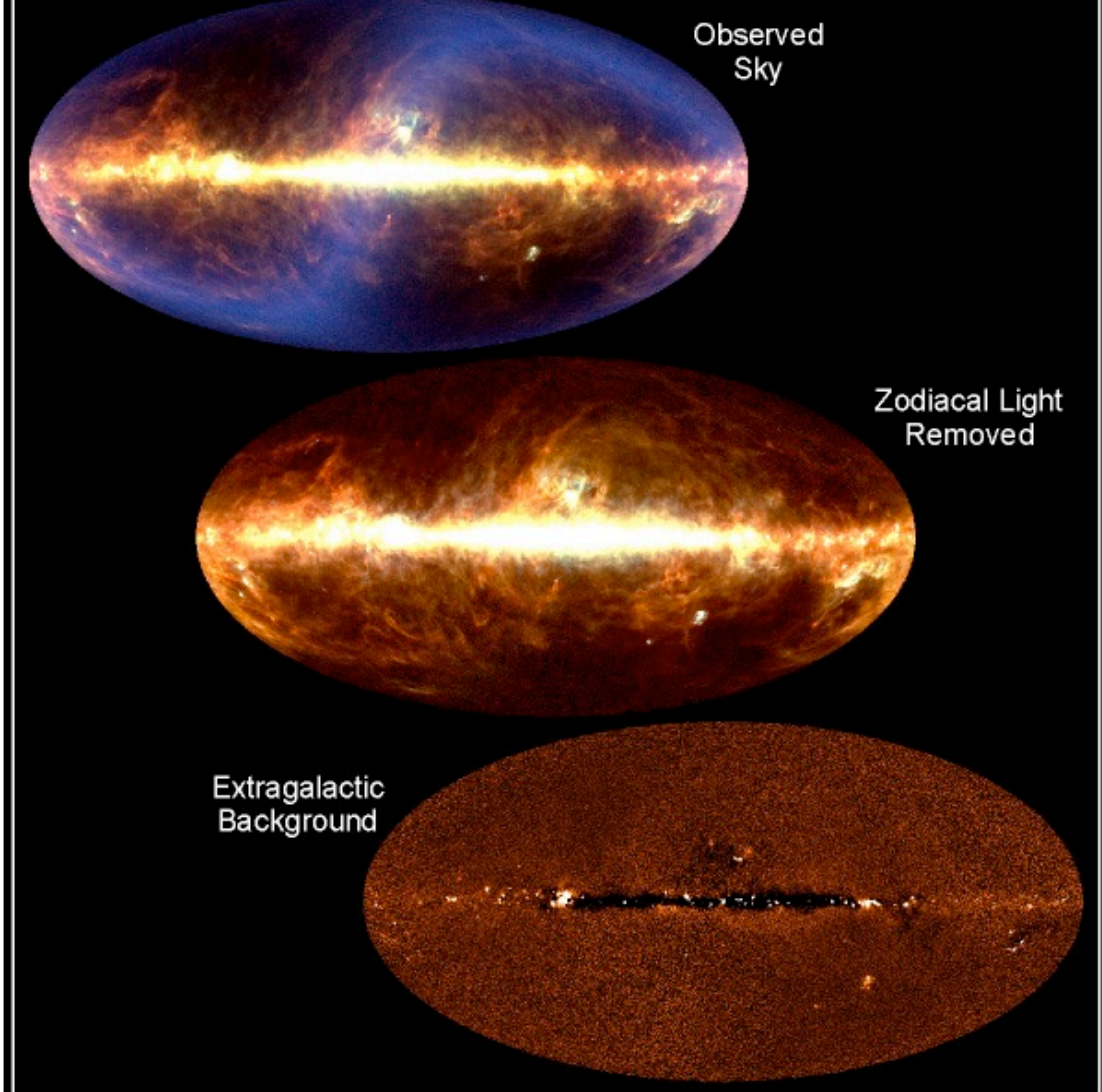
Matsuoka et al. (2011)



Matsuoka et al. (2011)

It's not so easy

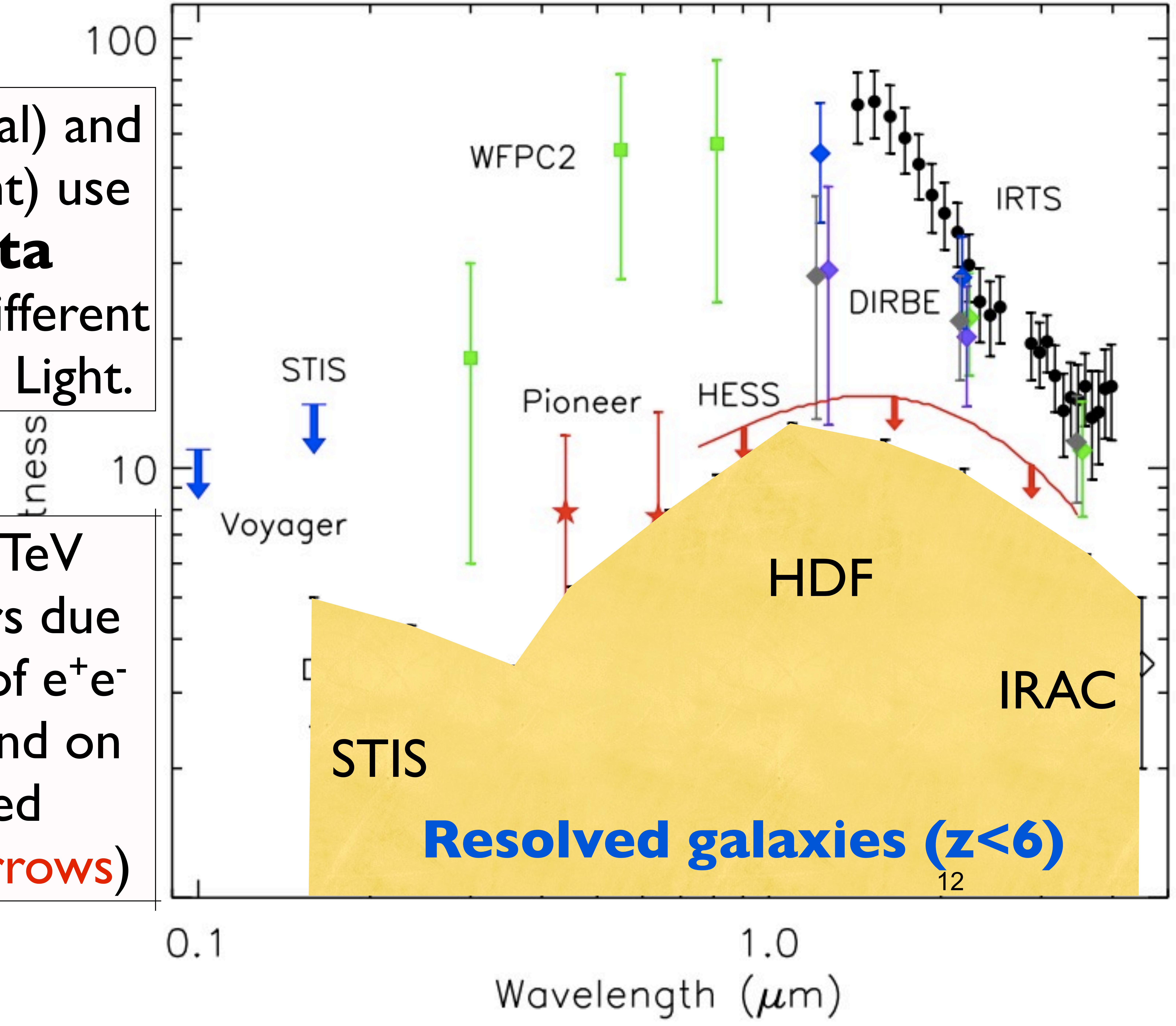
- However, the measurement of NIRB is complicated by the existence of Zodiacal Light.



Observed
Sky
Zodiacal Light
Removed
Extragalactic
Background

Blue (Cambresy et al) and purple/grey (Wright) use **the same data** (DIRBE), but with different models of Zodiacal Light.

Attenuation of a TeV spectrum of blazars due to a pair creation of e^+e^- puts an upper bound on the near infrared background (red arrows)



There is a hope

- One can do a model-independent subtraction of Zodiacal Light by measuring Fraunhofer lines in the Zodiacal Light!
  - This is precisely what is being/will be done by the CIBER experiment (ISAS–JPL).
- We can use fluctuations (anisotropies), which would be much less susceptible to a smooth Zodiacal Light (more later).
  - Then low-z galaxies become the biggest contaminant.

My Attitude

- If it is scientifically important, we will eventually get there. Our job is to explore the scientific potential, and make concrete predictions (so that we learn something by measuring something).
- In the future, ultimately, one can fly a satellite that goes above the plane of Solar System, or goes far enough (several AUs!) on the plane such that Zodiacal Light would be much reduced (ISAS is working on the concept: EXZIT)
  - Our calculations would help justify this proposal.

Previous Study

- Very massive (1000 M_{sun}!), metal-free stars may explain the excess signal (Santos, Bromm & Kamionkowski 2002; Salvaterra & Ferrara 2003)
- Mini quasars? (Cooray & Yoshida 2004) It would overproduce the soft X-ray background (Madau & Silk 2005)

Fernandez & Komatsu (2006)

Our Finding (2006)

- We need neither very massive, nor metal-free, stars to explain this!
    - Metal-poor (like 1/50 solar) with a Salpeter mass function is enough. Why? Energy conservation.
    - Don't be so quick to jump into the conclusion that the evidence for first stars is seen in NIRB (Kashlinsky et al.). In fact, this interpretation is almost certainly wrong.
- This is a good news: we don't expect metal-free stars to be around at z~6–10 anyway.

Simple, but robust

What we measure

$$I_\upsilon = \frac{c}{4\pi}\int \frac{p([1+z]\upsilon, z)dz}{H(z)(1+z)}$$

volume emissivity
(luminosity per volume)

$$p(\upsilon, z)$$

$$= (M_* c^2)/\mathrm{Time} \times \mathrm{Efficiency}$$

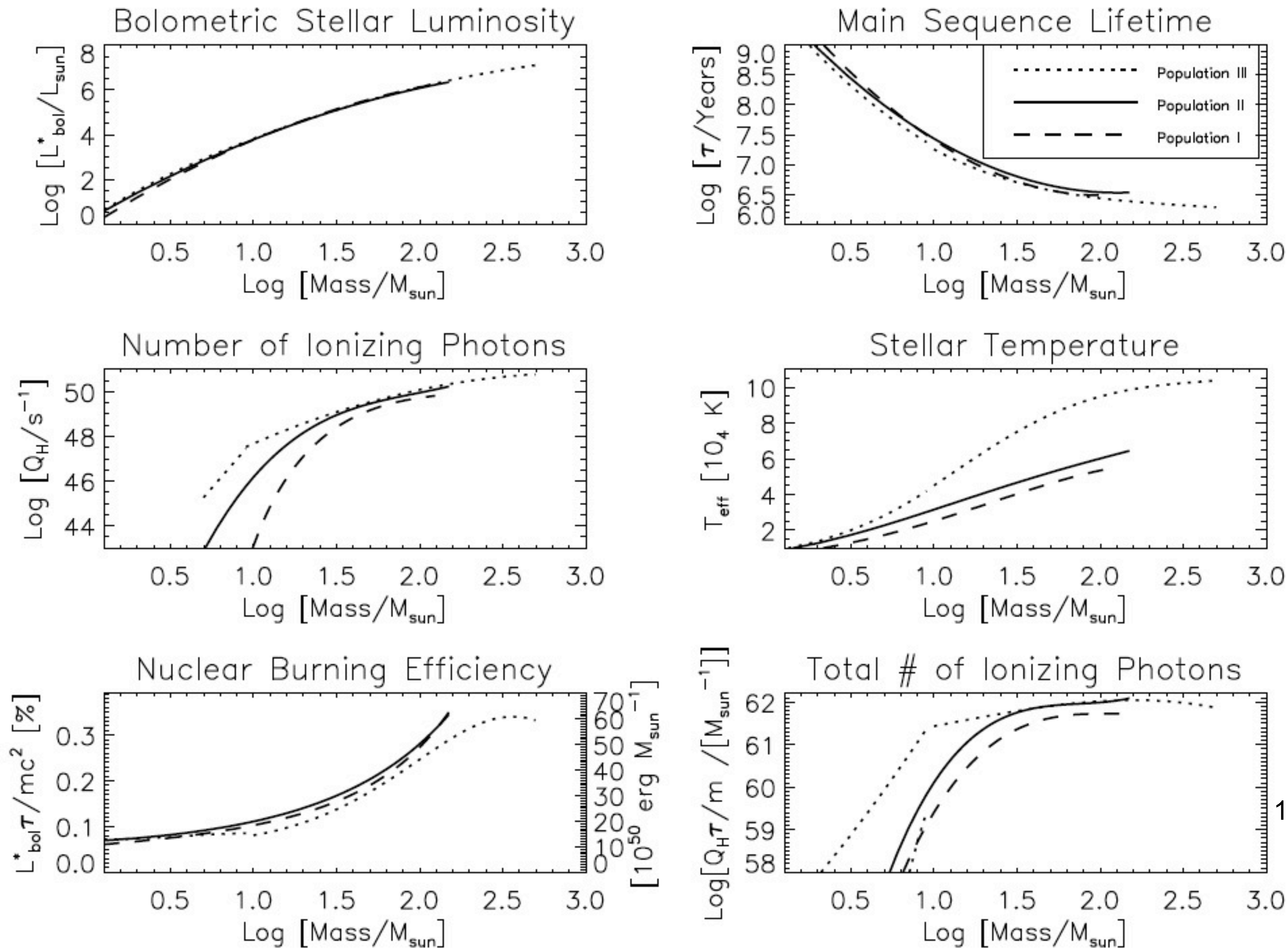
$$= \underbrace{\dot{\rho}_*(z)}_{\text{Unknown}} c^2 \sum_\alpha \underbrace{\langle e_\upsilon^\alpha \rangle}_{\text{Can be calculated}}$$

Simple argument:
Luminosity per volume
= (Stellar mass energy)
x(Radiation efficiency)
/(Time during which radiation is emitted)

"Radiation Efficiency" $\langle e_\upsilon^\alpha \rangle \equiv \frac{1}{m_*}\int dm\, mf(m)\left[\frac{\overline{L}_\upsilon^\alpha(m)\tau(m)}{mc^2}\right]$

Stellar Data

Schaller et al. (1992); Schaerer et al. (2002)



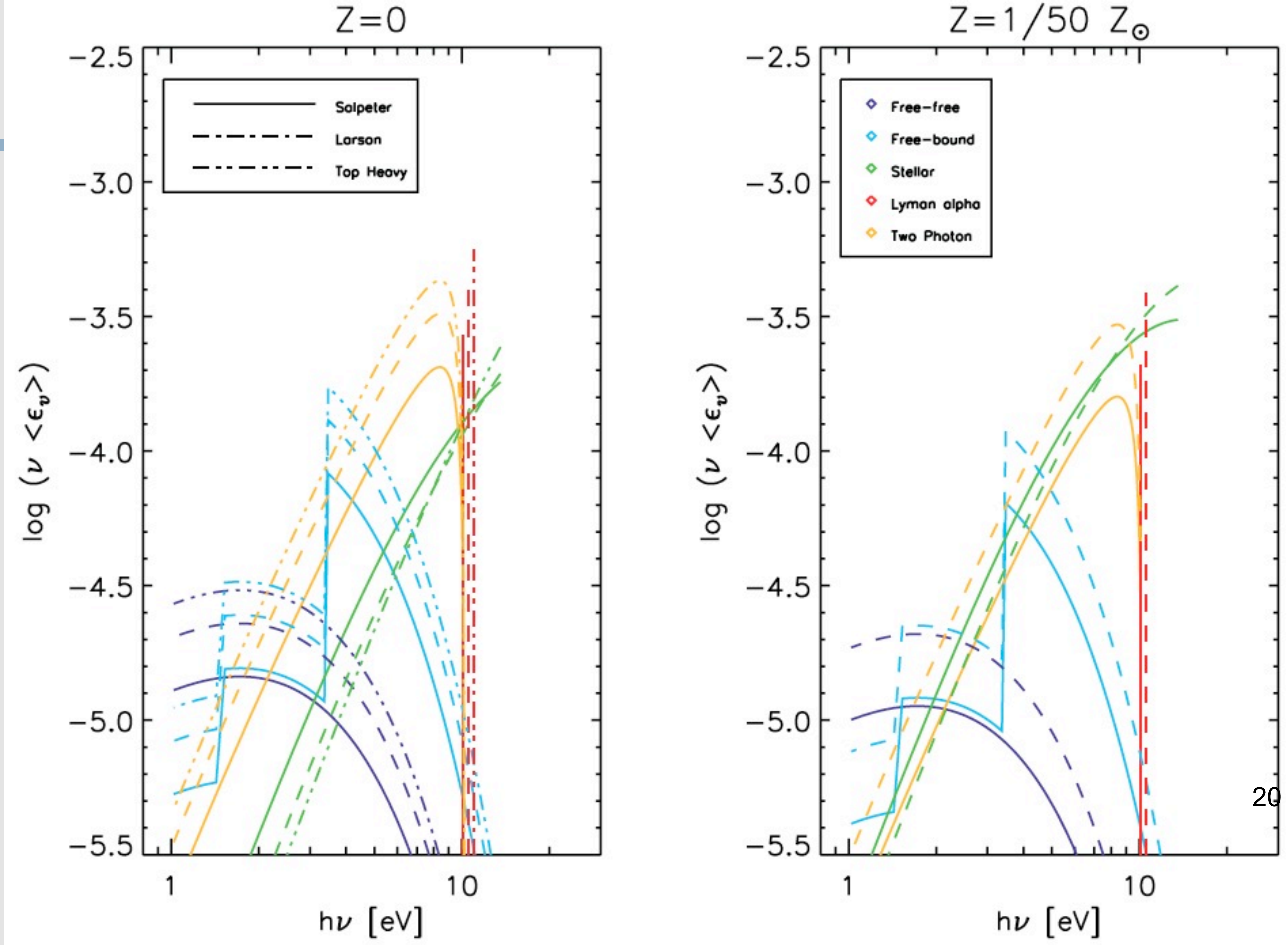
Sample Initial Mass Functions of Stars

Salpeter: $$f(m) \propto m^{-2.35}$$

Larson: $$f(m) \propto m^{-1}\left(1+\frac{m}{m_c}\right)^{-1.35}$$ $m_c (= 50\ M_\odot)$

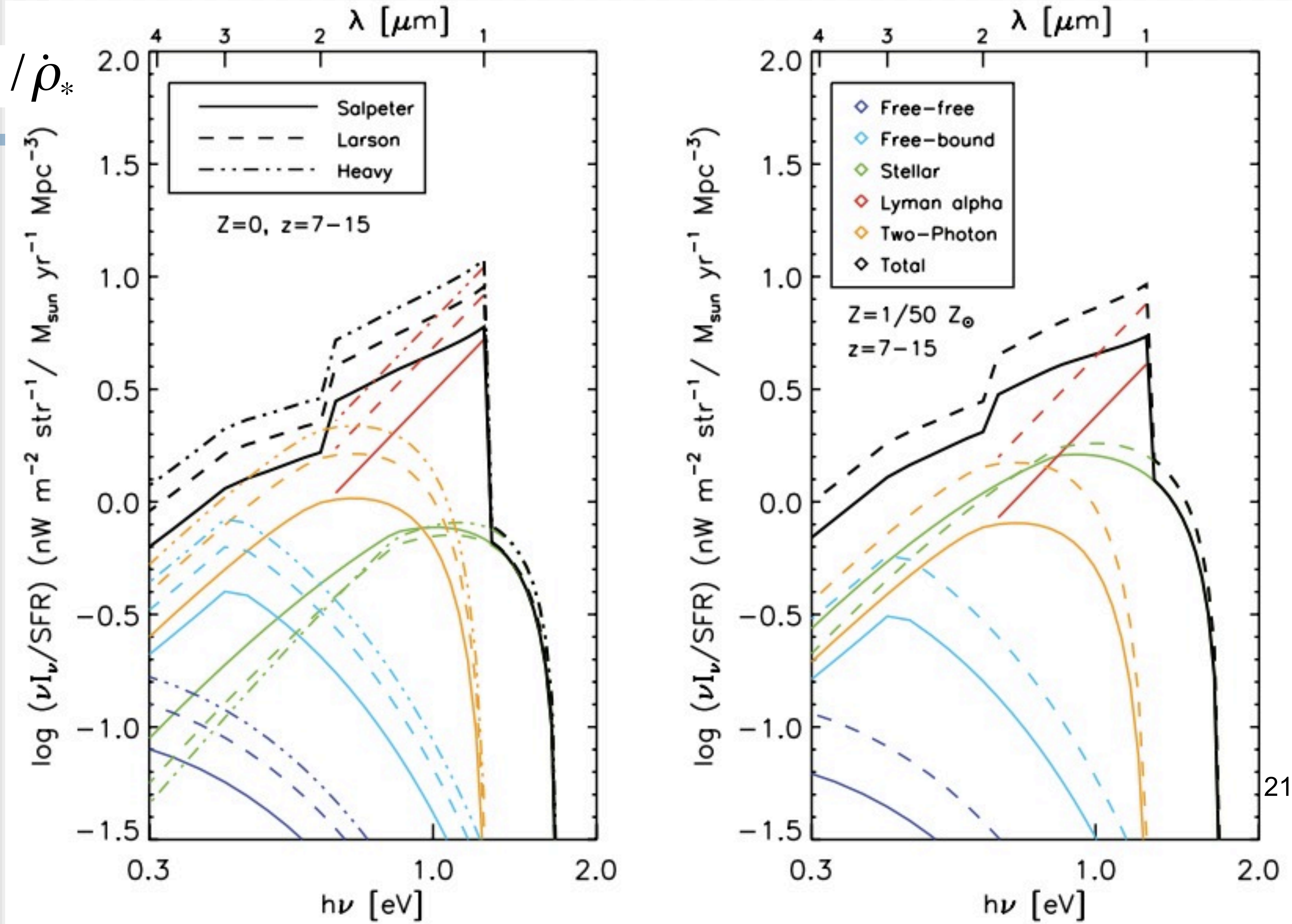
Top-heavy: $$f(m) \propto \begin{cases} m^{-1}, & 100\ M_\odot < m < 500\ M_\odot \\ 0, & \text{otherwise,} \end{cases}$$

Rest-frame Spectrum of <ε_ν>



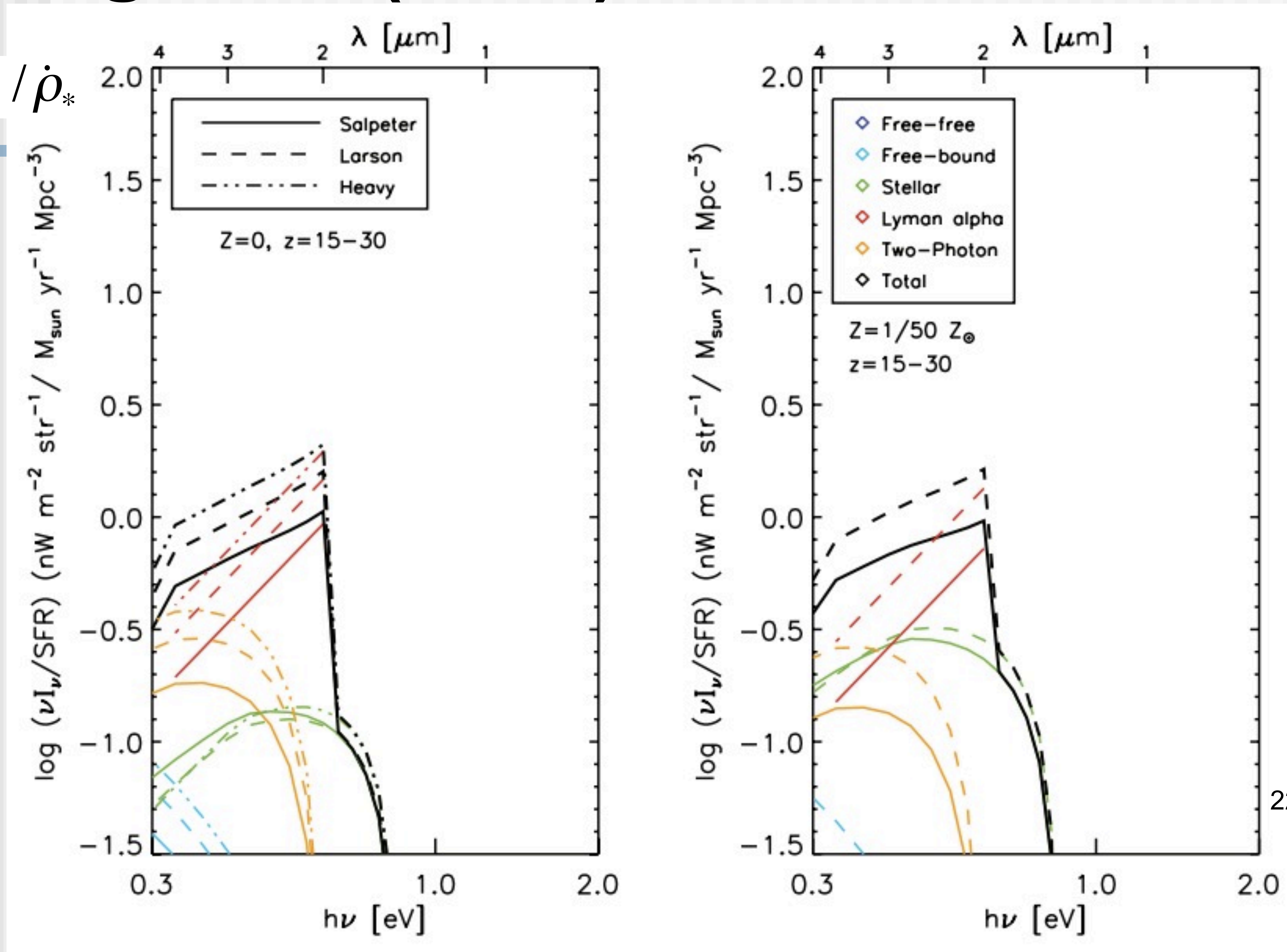
NIRB Spectrum per unit SFR

$\upsilon I_\upsilon / \dot{\rho}_*$

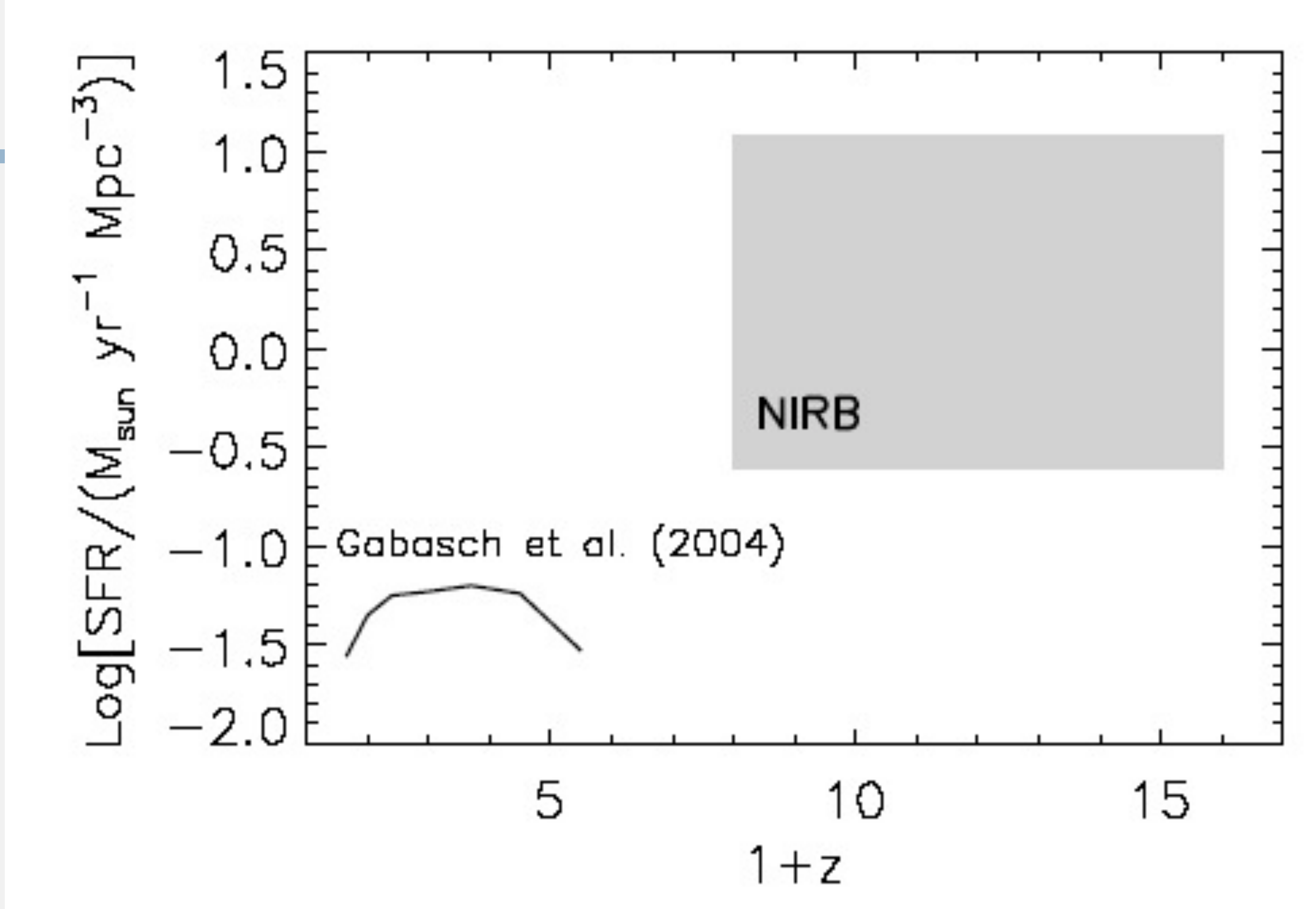


Higher z (z>15) won't contribute

$\upsilon I_\upsilon / \dot{\rho}_*$



The “Madau Plot” at z>7

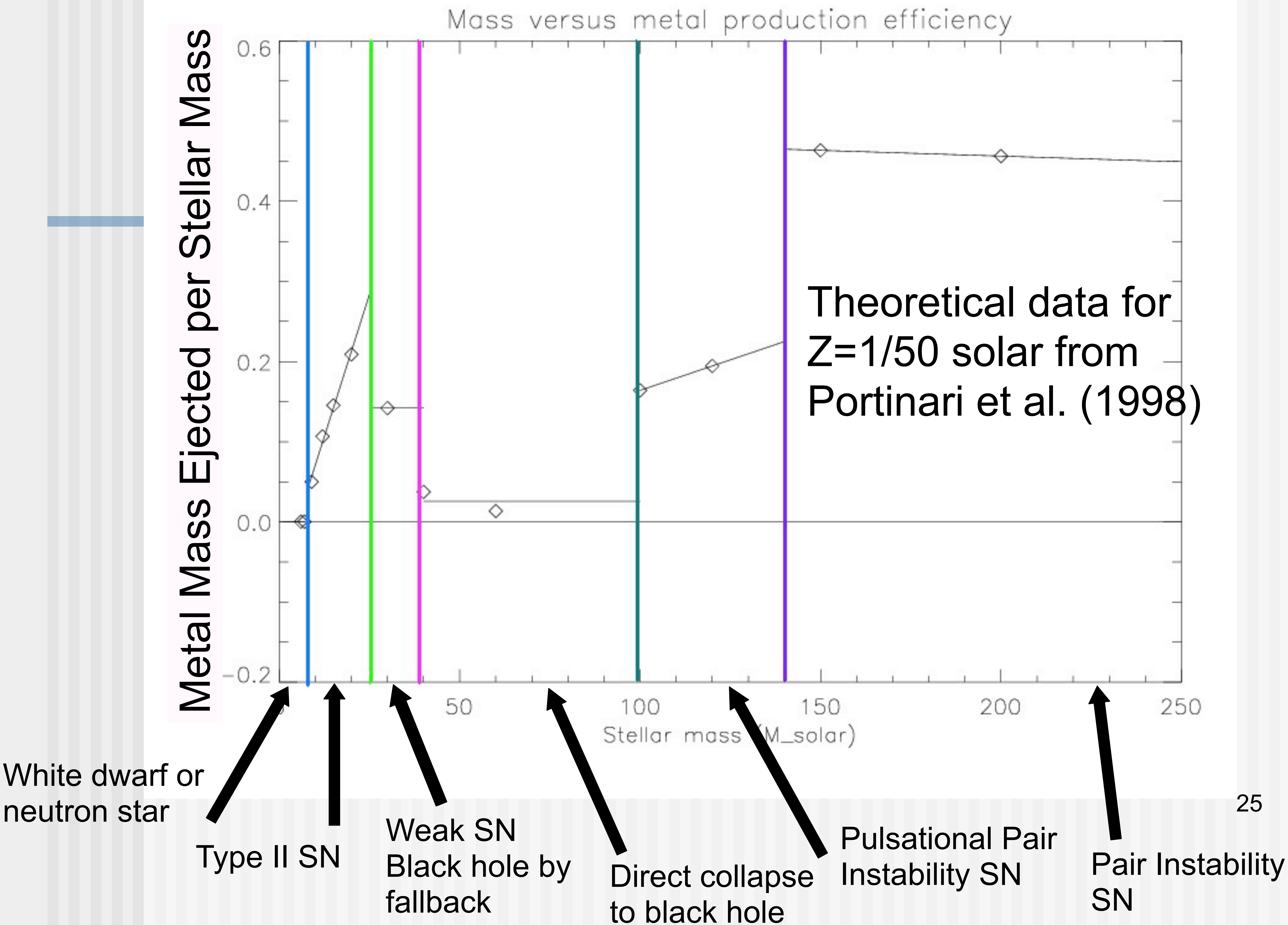


You don’t have to take this seriously for now. We need better measurements!

How About Metal Production?

- Is the inferred star formation rate at z>7 consistent with the metal abundance in the universe?
  - Did these early stars that are responsible for the near infrared background over-enrich the metals in the universe too early?

$$\rho_{metals} = \frac{\rho_*}{m_*} \int_{m_1}^{m_2} f(m) M_{metals,ej}(m) dm$$


Mass versus metal production efficiency
Metal Mass Ejected per Stellar Mass
0.6
0.4
0.2
0.0
-0.2
50
100
150
200
250
Stellar mass (M_solar)
Theoretical data for Z=1/50 solar from Portinari et al. (1998)
White dwarf or neutron star
Type II SN
Weak SN
Black hole by fallback
Direct collapse to black hole
Pulsational Pair Instability SN
Pair Instability SN

Metal Production (Z=1/50 solar)

IMF	$\dot{\rho}_*$	$\rho_{metals}\ M_\odot Mpc^{-3}$
Salpeter	0.48	9.59×10^5
	12	2.40×10^7
Larson	0.30	1.61×10^7
	7.6	4.09×10^8

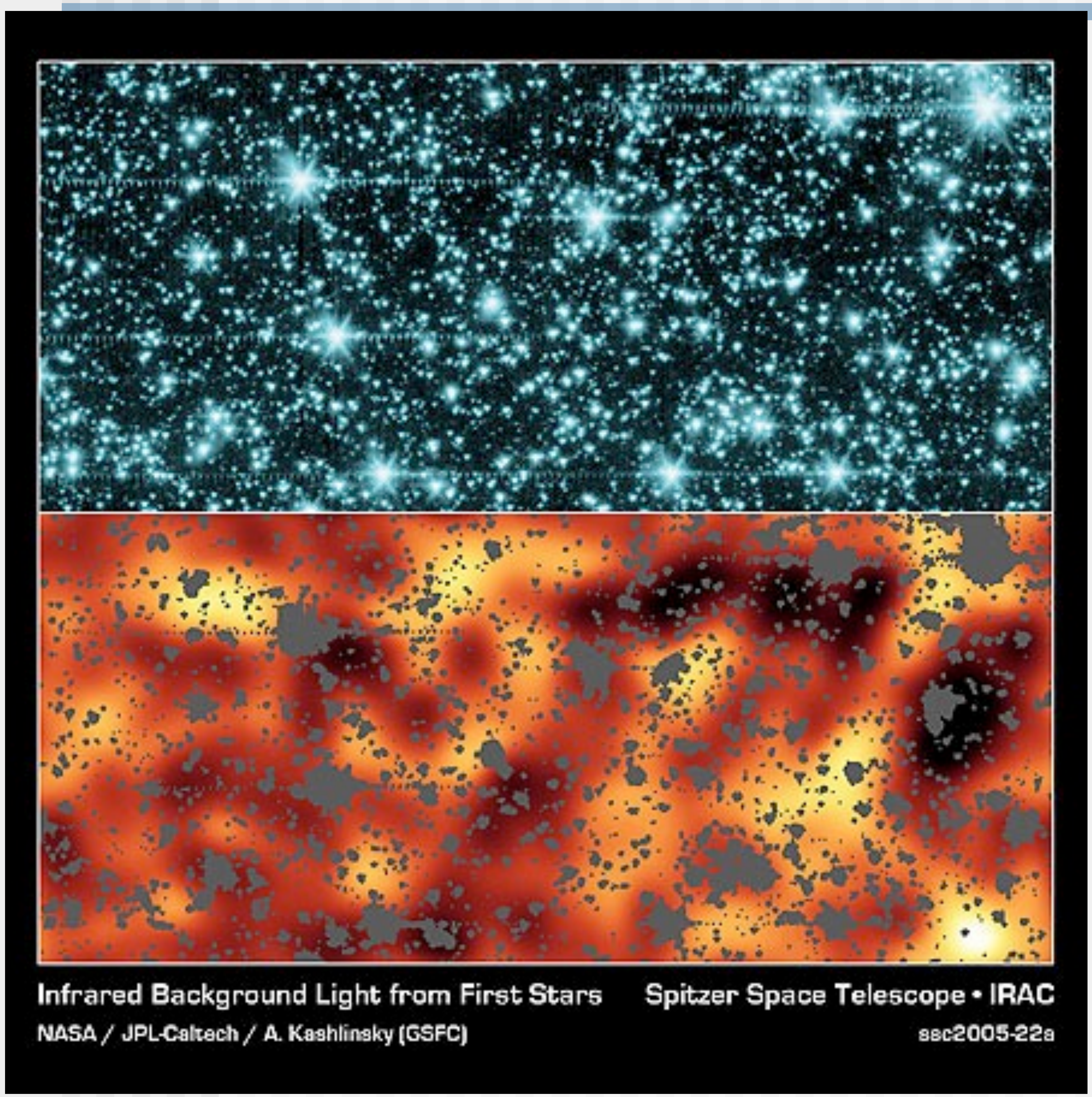
The metal density now is $1.2 \times 10^8\ M_\odot\ Mpc^{-3}$

-> The upper limit from the near infrared background for a larson IMF is excluded, but most of the parameter space survives the metallicity constraint.

Summary (Part 1)

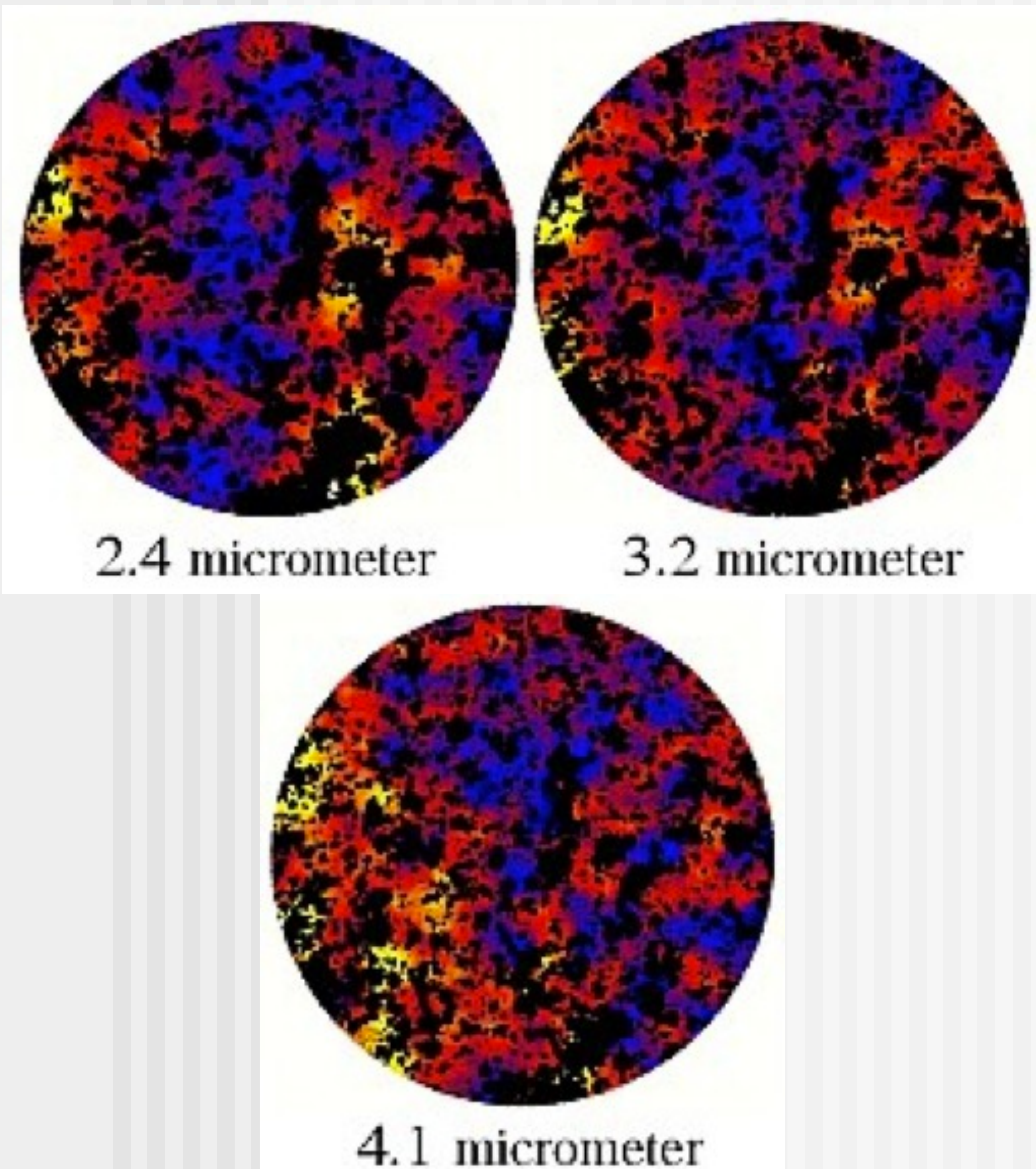
- Population II stars ($Z \sim 1/50$ solar) obeying a Salpeter mass function can produce the observed excess near infrared background, if the star formation rate was elevated at $z>7$.
- Most of the parameter space satisfies the metallicity constraint.
- It is perfectly reasonable to think that NIRB offers a window into the high-z ($z>6$) star formation!
  - So, it is worth going beyond the mean intensity (and writing more papers)

“Smoking-gun”: Anisotropy



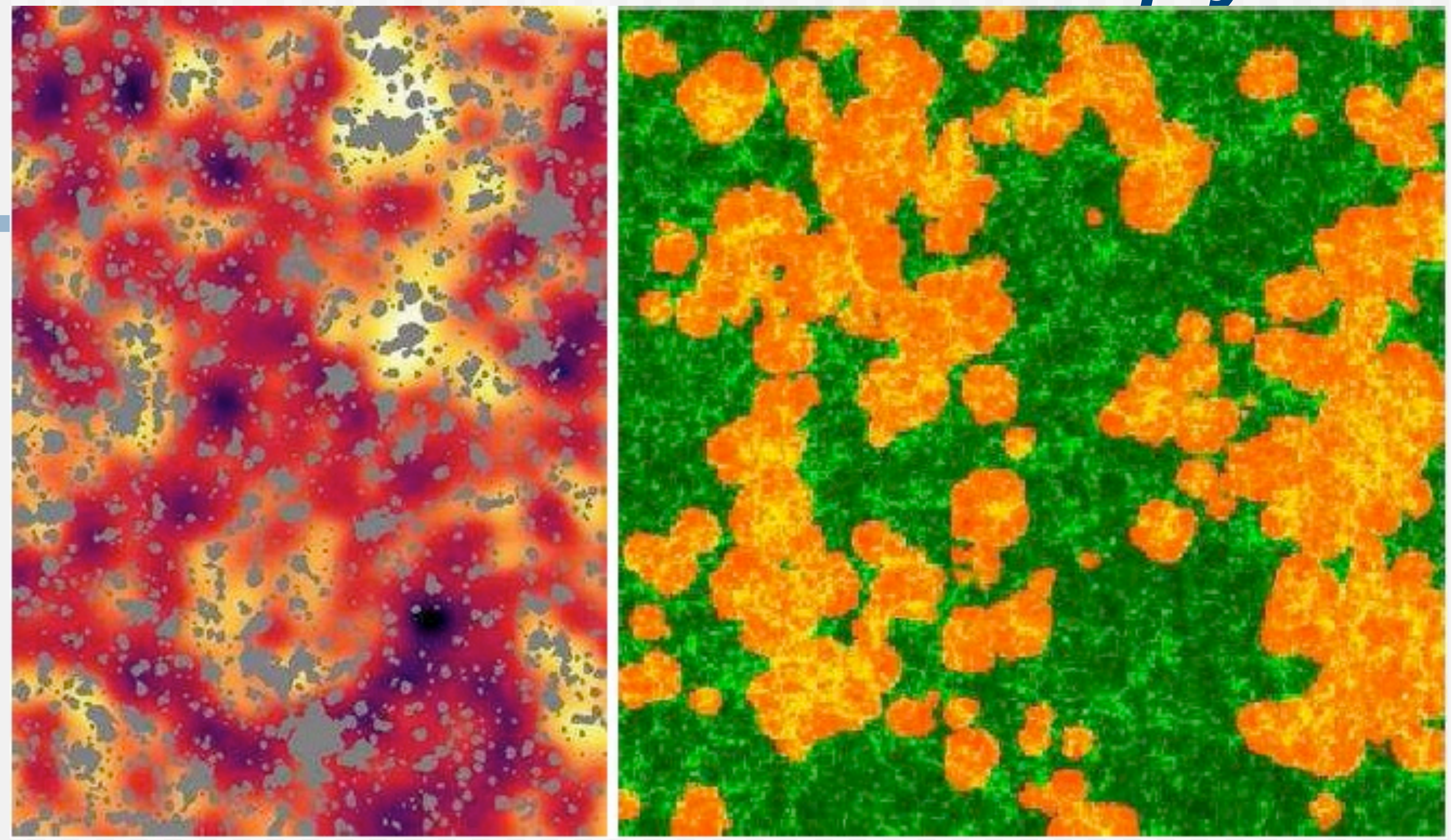
- Press-release from **Kashlinsky et al.**:
  - Detection of significant anisotropy in the **Spitzer IRAC** data
  - They claim that the detected anisotropy originates from the first stars.
- But, as we have seen already, we cannot say that these come from the first stars (in fact, most likely, they do *not* come from the first stars)
- We need better data from CIBER, which is designed to measure anisotropy over 4 deg^2
  - The **Spitzer** image (left) is over **12’x6’**.
  - CIBER has flown twice already!

"Smoking-gun": Anisotropy



- Press-release from **Matsumoto et al.**:
  - Detection of significant anisotropy in the **AKARI** data
  - They also claim that the detected anisotropy originates from the first stars.
- But, as we have seen already, we cannot say that these come from the first stars (in fact, most likely, they do *not* come from the first stars)
- We need better data from CIBER, which is designed to measure anisotropy over 4 deg^2
  - The **AKARI** image (left) is over **10' diameter**.
  - CIBER has flown twice already!

The Future is in *Anisotropy*



- Previous model (Kashlinsky et al. 2005; Cooray et al. 2006) used simplified analytical models, which may not be adequate.
  - We will show why.
- We used the reionization simulation (Iliev et al. 2006) to make the first calculation of NIRB anisotropy from simulation.

Power Spectrum, C_l

$$I_\upsilon = \frac{c}{4\pi}\int \frac{p([1+z]\upsilon, z)dz}{H(z)(1+z)}$$

$I_\nu(n)=\sum_{lm} a_{lm} Y_{lm}(n)$

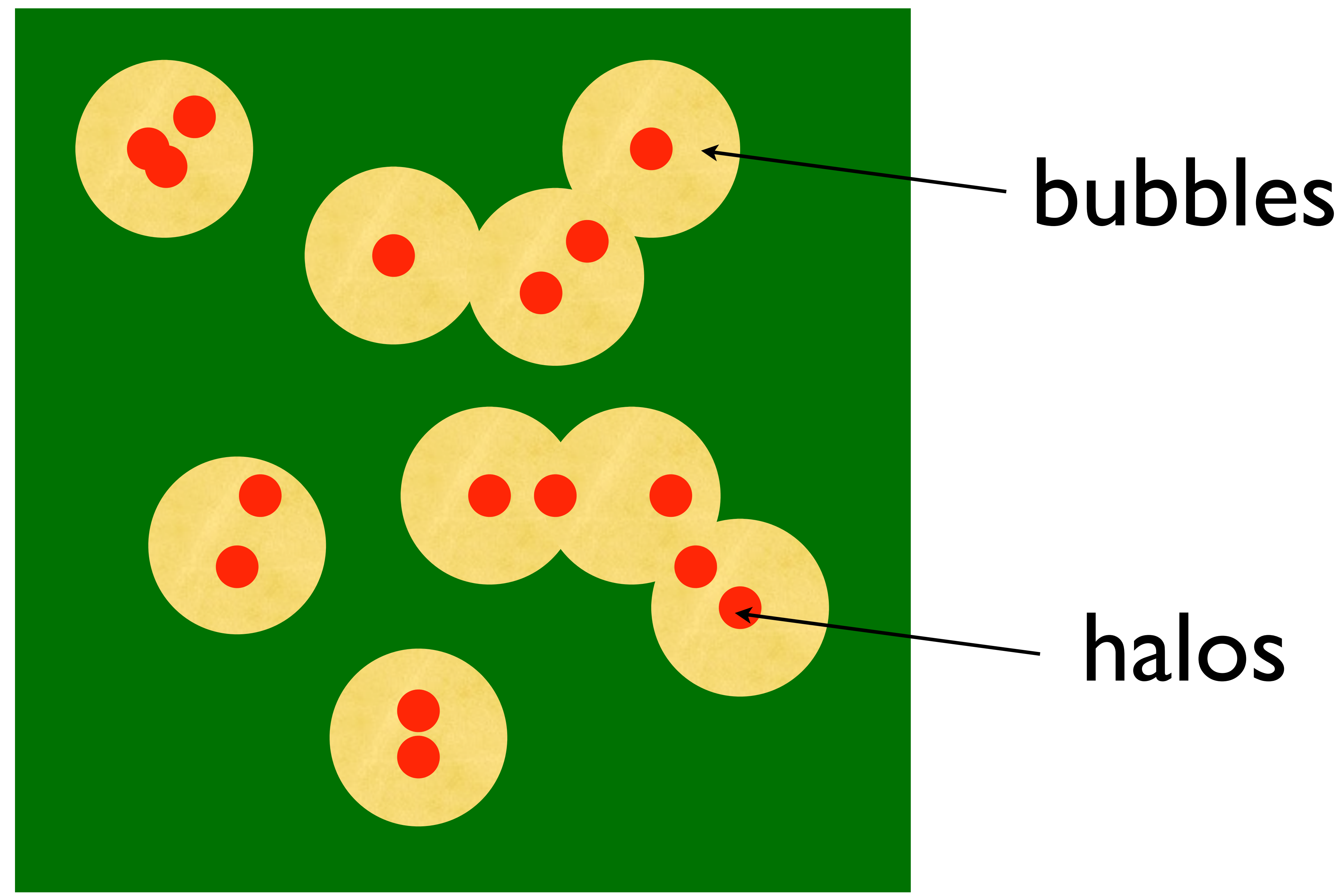
$C_l = \langle a_{lm} a_{lm}^* \rangle$

$$C_l = \frac{c}{(4\pi)^2}\int \frac{dz}{H(z)r^2(z)(1+z)^4} \underline{P_L\left(k=\frac{l}{r(z)}, z\right)}$$

3d power spectrum
of the volume emissivity, p

Halos vs Bubbles

- Two contributions to the intensity: halos and bubbles.



- It turns out that, in most cases, the halo contribution totally dominates the power spectrum (the density is too low). So, we will ignore the bubble contribution from now.

Halo Power Spectrum

- In the limit that the luminosity power spectrum, $P_L(k)$, is dominated by the halo power spectrum, one can relate $P_L(k)$ to the halo mass power spectrum, $P_M(k)$, which is familiar to cosmologists.

$$\delta\rho_L^{\rm halo}(\mathbf{x}) = (L_h/M_h)\delta\rho_M^{\rm halo}(\mathbf{x})$$

$$\Downarrow$$

$$P_L^{\rm halo}(k) = \underline{\left(\frac{L_h}{M_h}\right)}^2 P_M^{\rm halo}(k)$$

Luminosity per halo mass= $$\frac{L_h(z)}{M_h} = f_* \frac{\Omega_b}{\Omega_m}\{\bar{l}^*(z) + (1 - f_{\rm esc})[\bar{l}^{ff}(z) + \bar{l}^{fb}(z) + \bar{l}^{2\gamma}(z) + \bar{l}^{\rm Ly\alpha}(z)]\},$$

Halo Power Spectrum

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$$\delta\rho_L^{\text{halo}}(\mathbf{x}) = (L_h/M_h)\delta\rho_M^{\text{halo}}(\mathbf{x})$$

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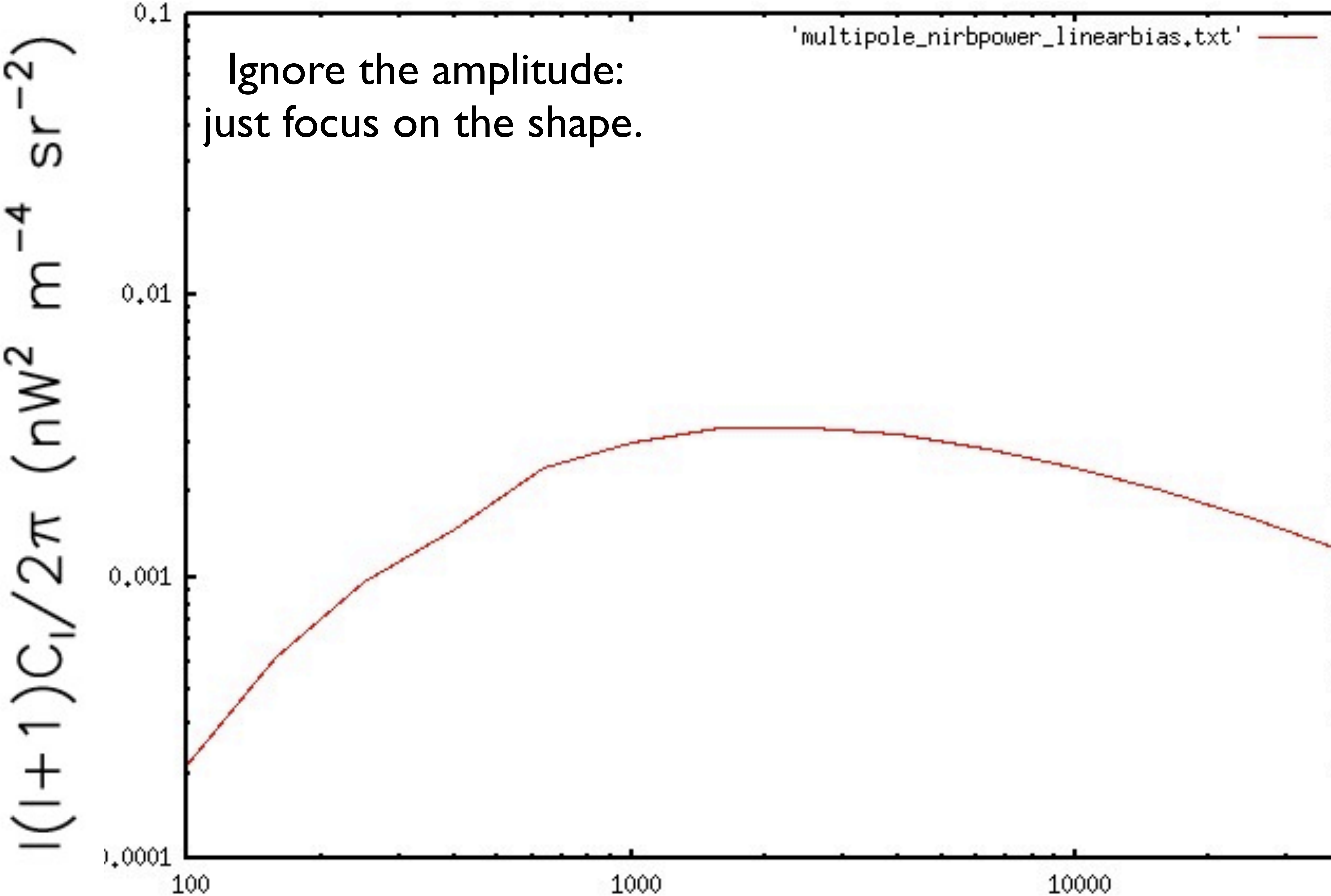
Luminosity per halo mass= $\dfrac{L_h(z)}{M_h} = f_* \dfrac{\Omega_b}{\Omega_m}\{\bar{l}^*(z) + \underline{(1 - f_{\text{esc}})}[\bar{l}^{ff}(z) + \bar{l}^{fb}(z) + \bar{l}^{2\gamma}(z) + \bar{l}^{\text{Ly}\alpha}(z)]\},$

Before Simulation...

- Let's try out a "linear model," where it is assumed that the halo power spectrum is simply proportional to the underlying matter power spectrum.

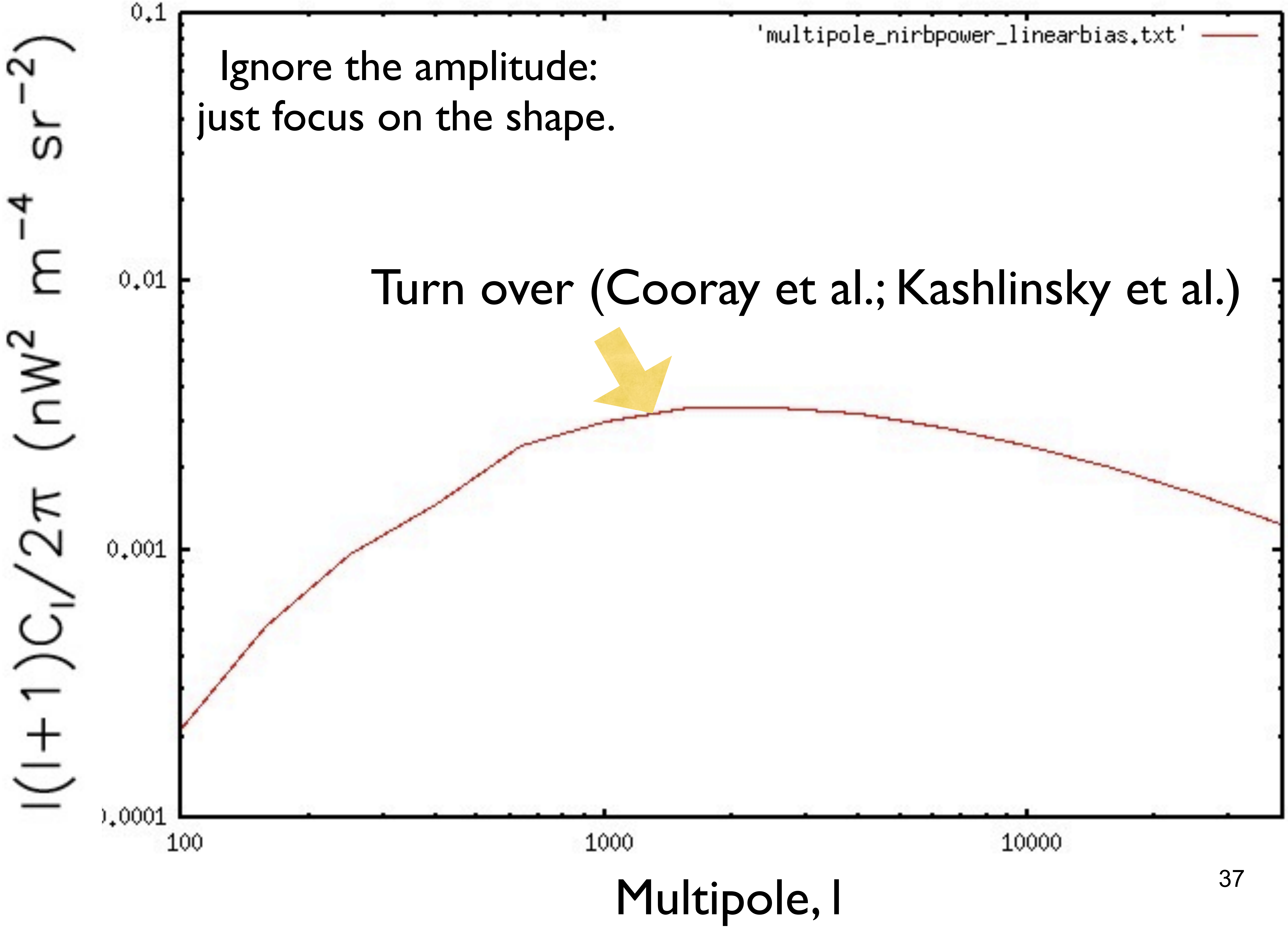
$$P_L^{\rm halo}(k) = \left(\frac{\bar{\rho}_M^{\rm halo} L_h}{M_h}\right)^2 b_{\rm eff}^2 \times P_{\rm lin}(k)$$

Then, look at the **shape** of the angular power spectrum, C_l

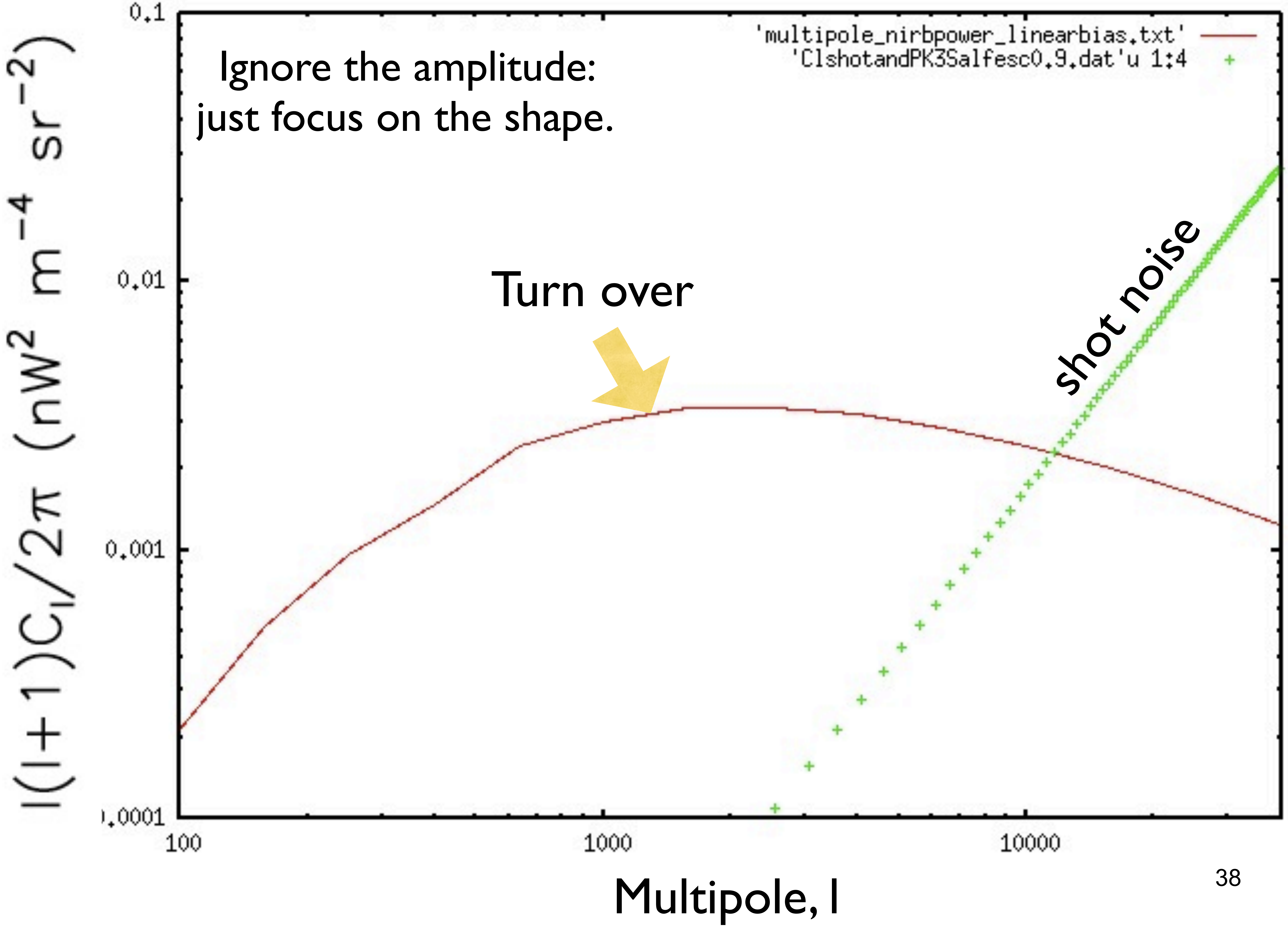


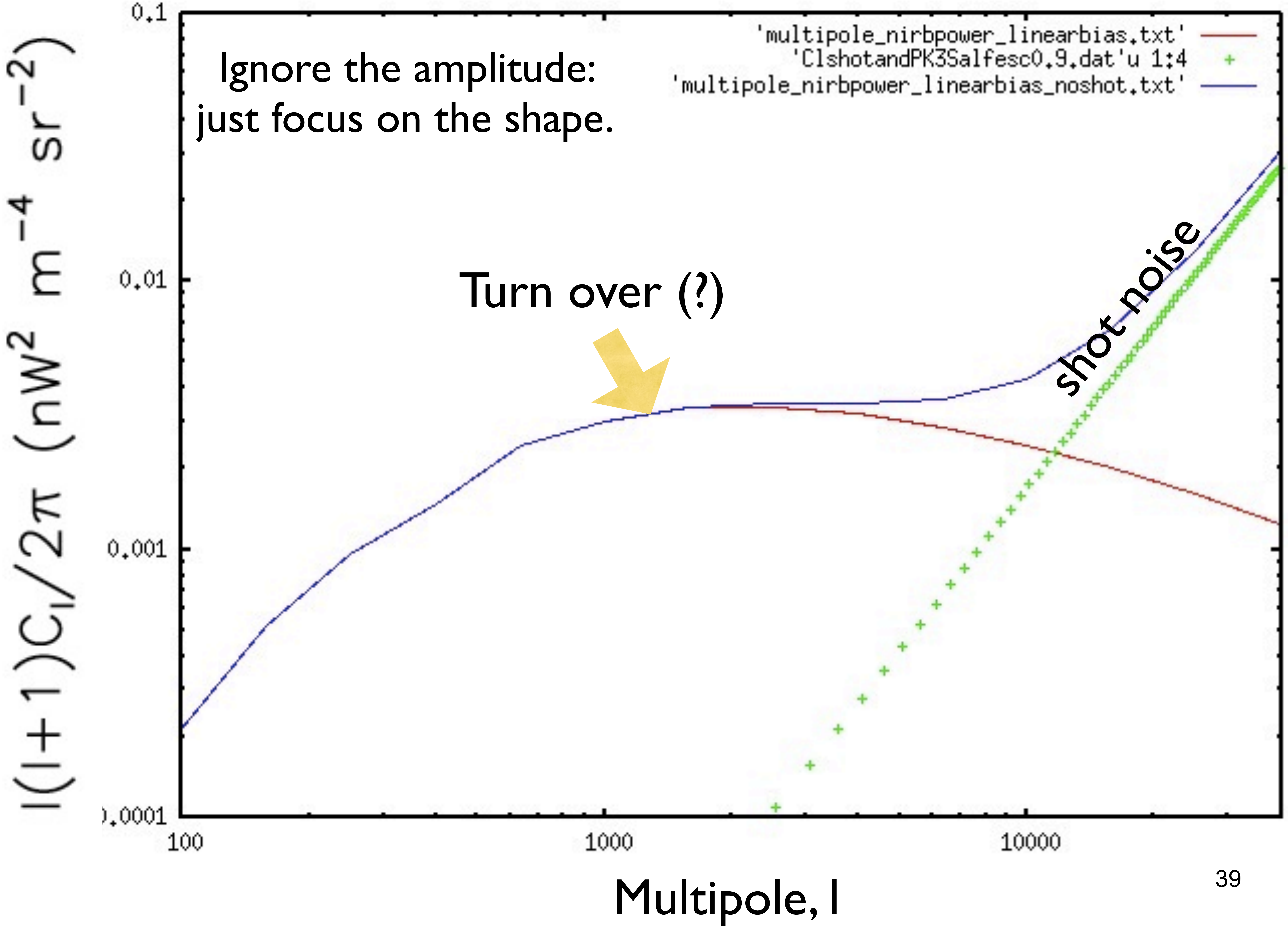
Ignore the amplitude:
just focus on the shape.

Multipole, l



'multipole_nirbpower_linearbias.txt'
Ignore the amplitude:
just focus on the shape.
Turn over (Cooray et al.; Kashlinsky et al.)
0.1
0.01
0.001
0.0001
100
1000
10000
$l(l+1)C_l/2\pi$ (nW^2 m^{-4} sr^{-2})
Multipole, l

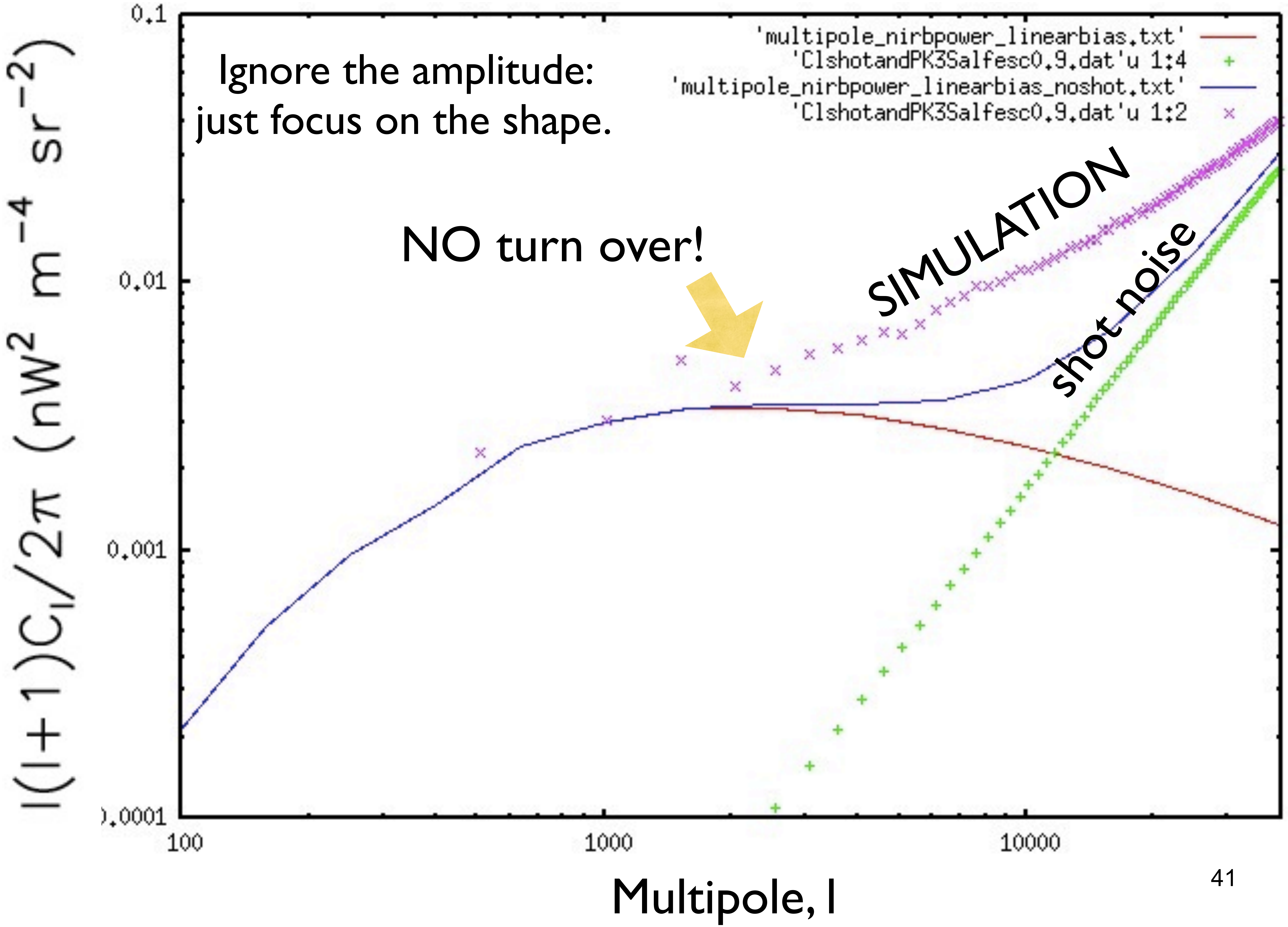

Ignore the amplitude: just focus on the shape.
'multipole_nirbpower_linearbias.txt'
'ClshotandPK3Salfesc0.9.dat'u 1:4
Turn over
shot noise
0.1
0.01
0.001
0.0001
100
1000
10000
l(l+1)C_l/2π (nW^2 m^-4 sr^-2)
Multipole, l



Ignore the amplitude:
just focus on the shape.
'multipole_nirbpower_linearbias.txt'
'ClshotandPK3Salfesc0.9.dat'u 1:4
'multipole_nirbpower_linearbias_noshot.txt'
Turn over (?)
shot noise
0.1
0.01
0.001
0.0001
100
1000
10000
$l(l+1)C_l/2\pi$ (nW^2 m^{-4} sr^{-2})
Multipole, l

Simulation (Iliev et al. 2006)

- N-body simulation (Particle-Mesh)
  - 100 h^{-1} Mpc; 1624^3 particles
  - Minimum halo mass resolved = **2.2×10^9** Msun
  - The luminosity of halos is chosen such that it can reproduce WMAP's measurement of the optical depth.


Ignore the amplitude:
just focus on the shape.
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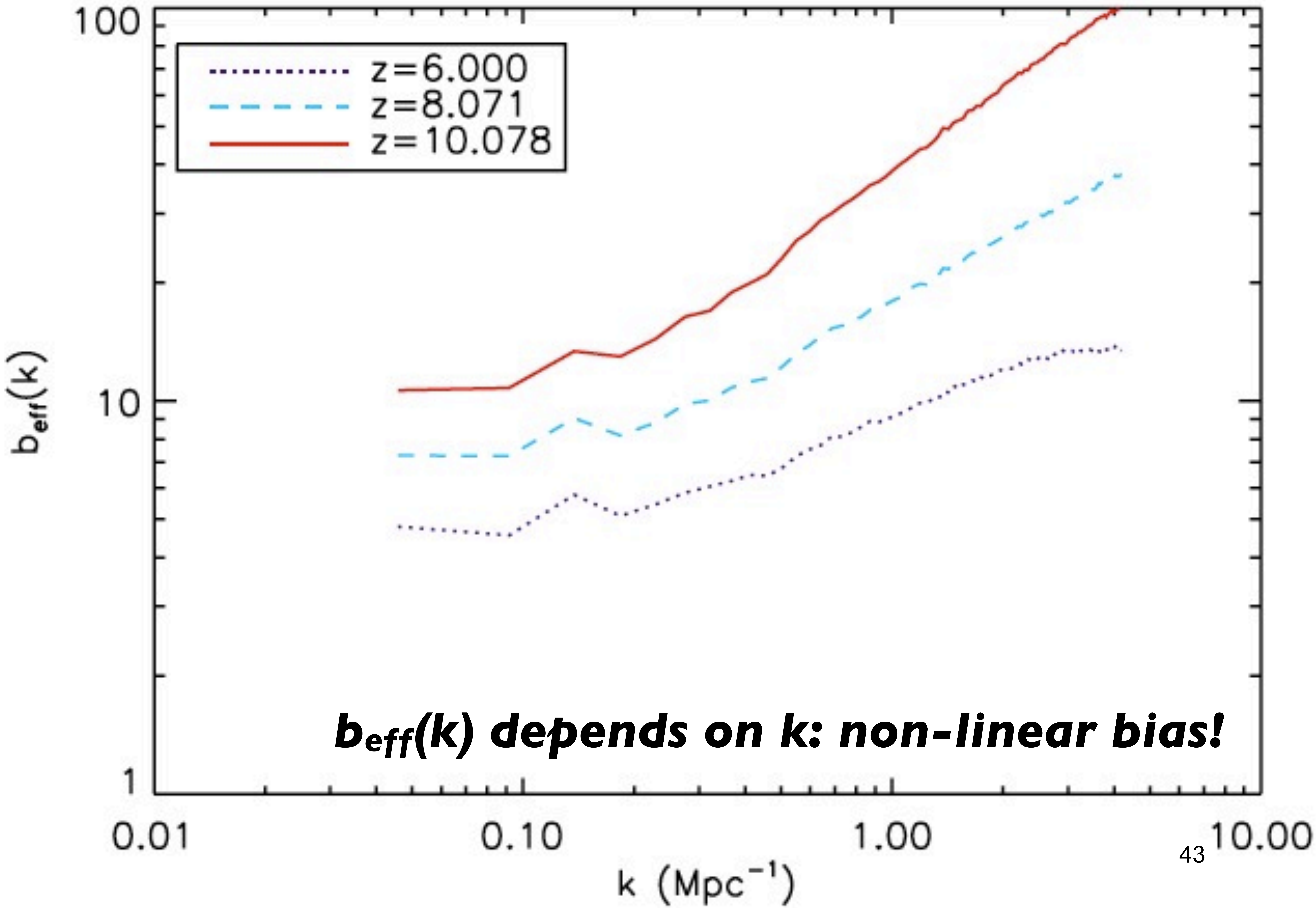
'ClshotandPK3Salfesc0.9.dat'u 1:4
'multipole_nirbpower_linearbias_noshot.txt'
'ClshotandPK3Salfesc0.9.dat'u 1:2
NO turn over!
SIMULATION
shot noise
0.1
0.01
0.001
0.0001
100
1000
10000
$l(l+1)C_l/2\pi$ (nW^2 m^{-4} sr^{-2})
Multipole, l

Non-linear Bias

- Why are we seeing the excess power on small scales?
- It is known that halos trace the underlying matter distribution in a *non-linear* (scale-dependent) manner:

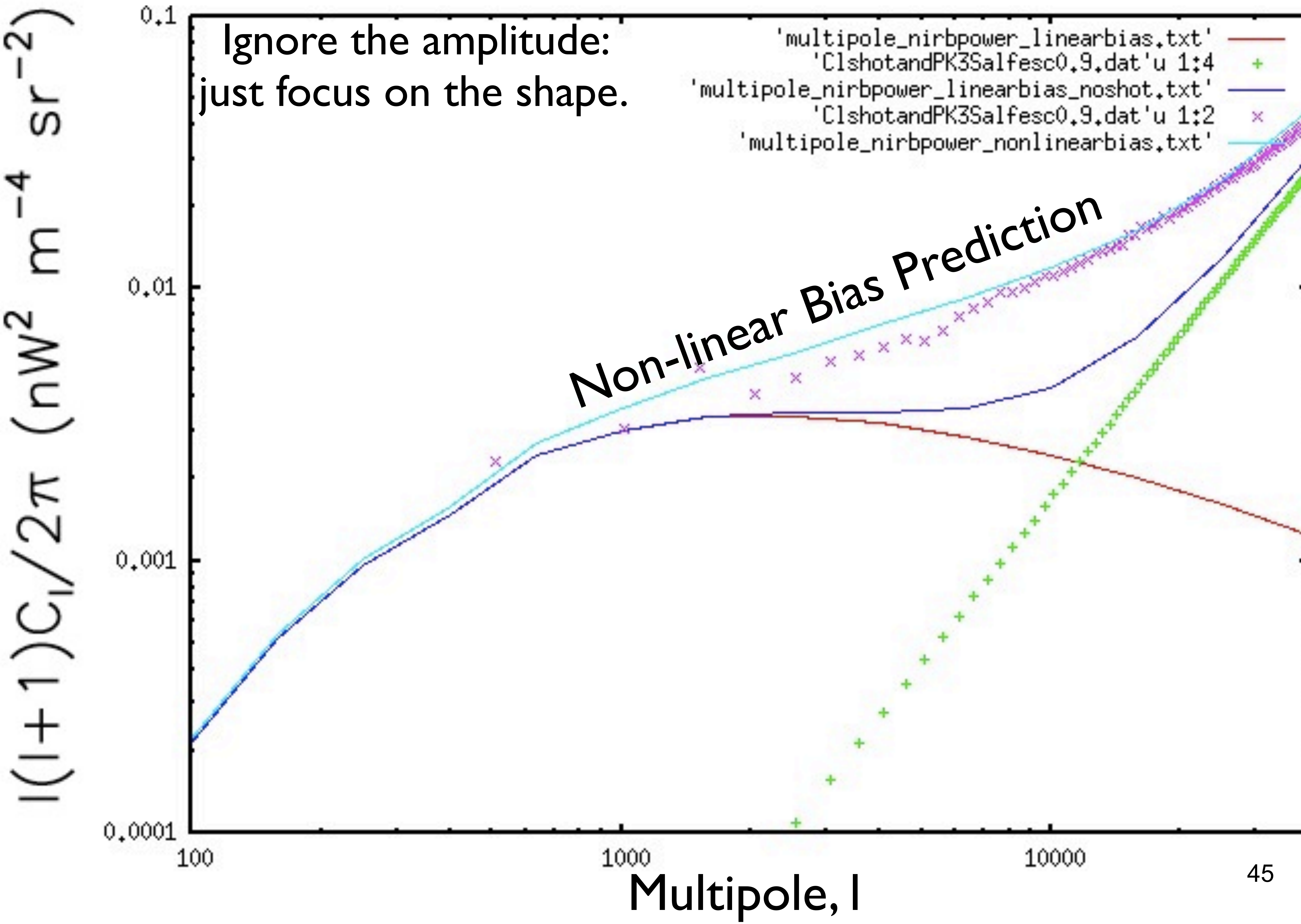
$$P_L^{\mathrm{halo}}(k) = \left(\frac{\bar{\rho}_M^{\mathrm{halo}} L_h}{M_h} \right)^2 b_{\mathrm{eff}}^2 \boxed{(k)} P_{\mathrm{lin}}(k)$$



$b_{eff}(k)$ depends on k: non-linear bias!

Improved Analytics

- Using a spherical collapse model (a la Press-Schechter) or an improved version (a la Sheth-Tormen), one can calculate the non-linear bias analytically.
- The required input is the minimum mass above which galaxies would be formed.
  - Set M_{min}=2.2x10^9 M_{sun}, in accordance with the simulation.

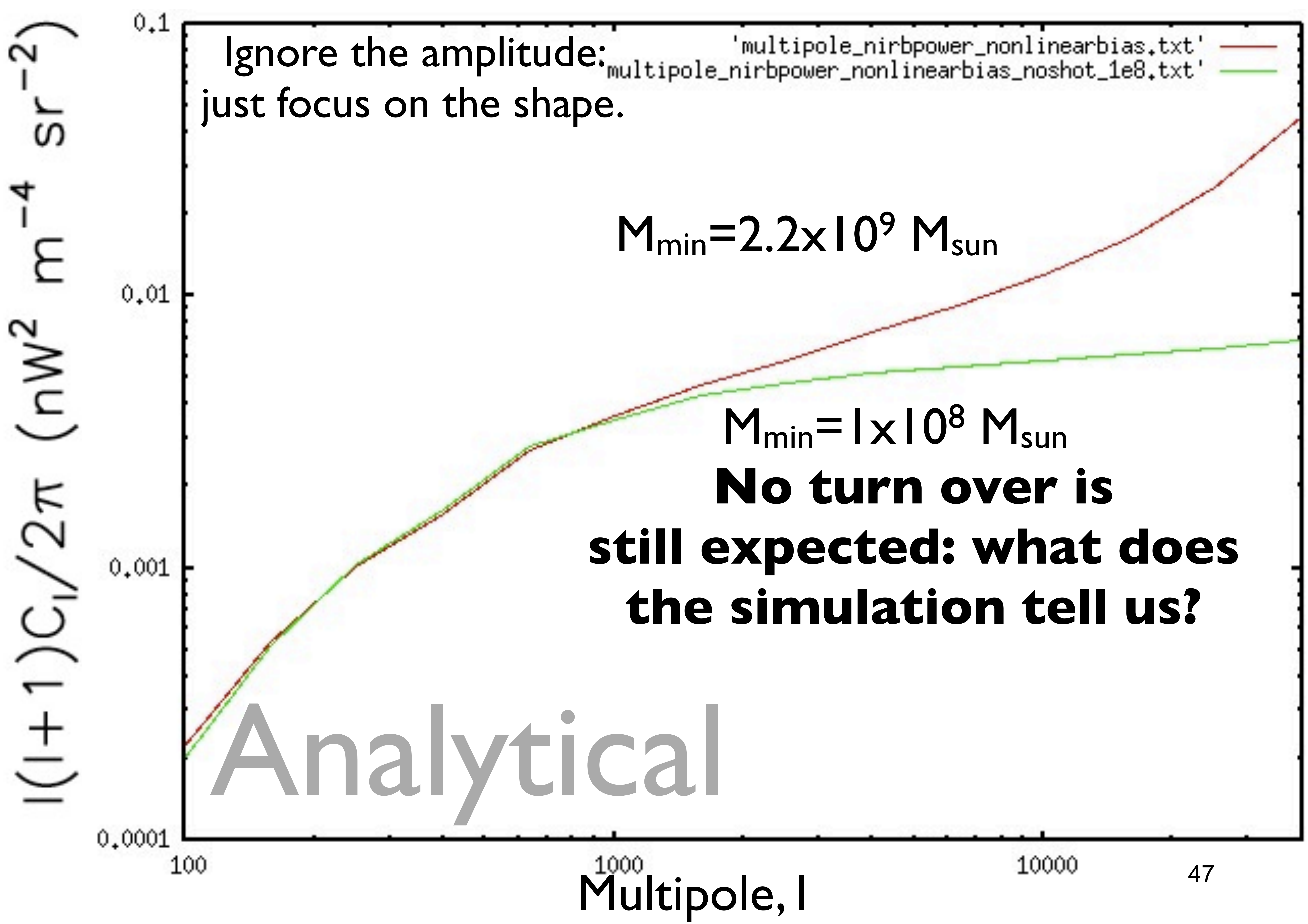


Ignore the amplitude:
just focus on the shape.
'multipole_nirbpower_linearbias.txt'
'ClshotandPK3Salfesc0.9.dat'u 1:4
'multipole_nirbpower_linearbias_noshot.txt'
'ClshotandPK3Salfesc0.9.dat'u 1:2
'multipole_nirbpower_nonlinearbias.txt'
Non-linear Bias Prediction
0.1
0.01
0.001
0.0001
100
1000
10000
l(l+1)C_l/2π (nW^2 m^-4 sr^-2)
Multipole, l

Fernandez et al. (2010)

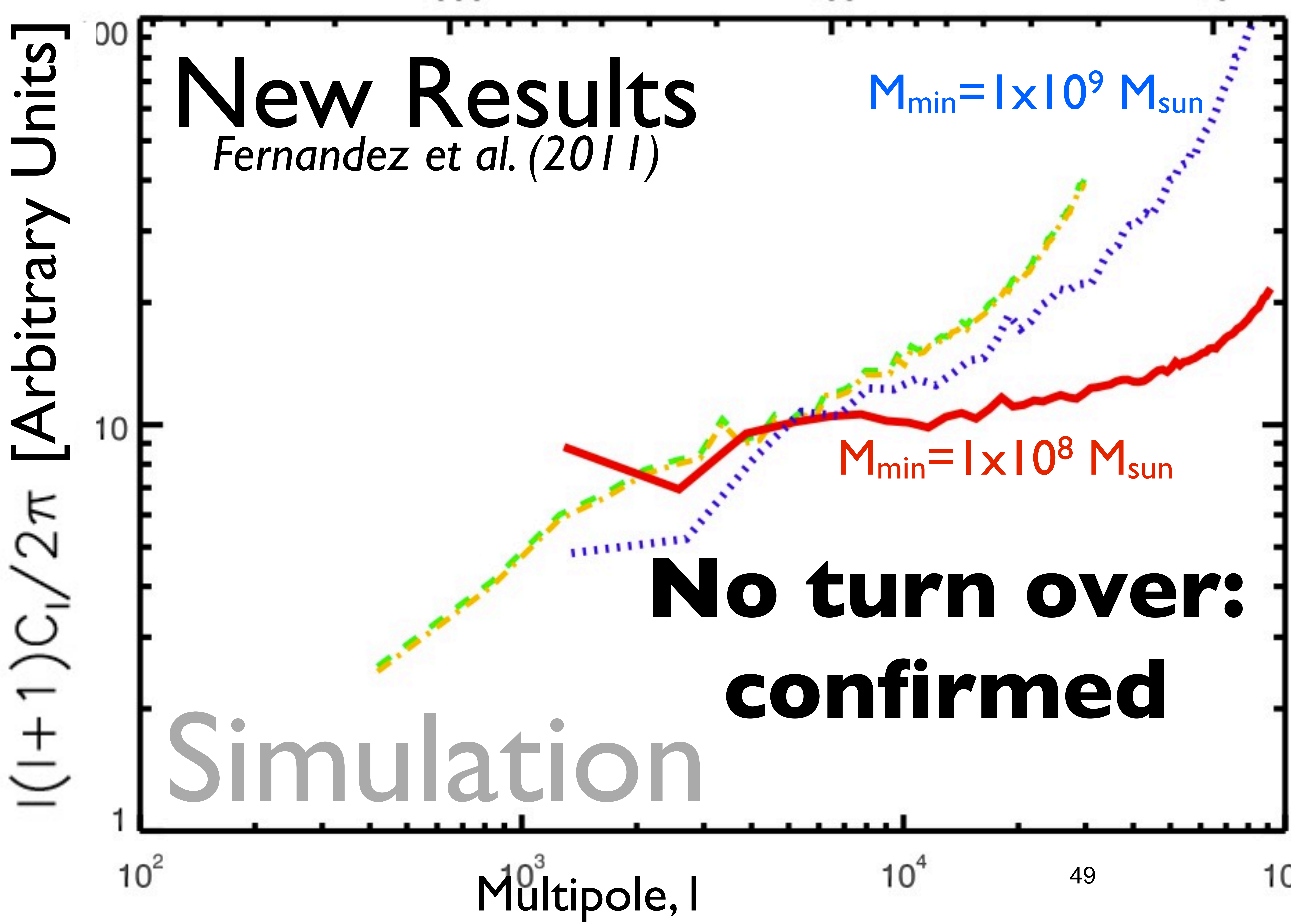
Important Message

- We will soon see the results from the CIBER experiment as well as from AKARI on large angular scales.
- Do not expect a turn over - the theory of the large-scale structure formation predicts that non-linear bias makes C_l continue to rise.
  - However, our calculation was limited to $M_{min}=2.2\times10^9$ M_{sun}. What if we lower the minimum mass?
  - The lower the mass, the lower the bias, hence lower the non-linearity.

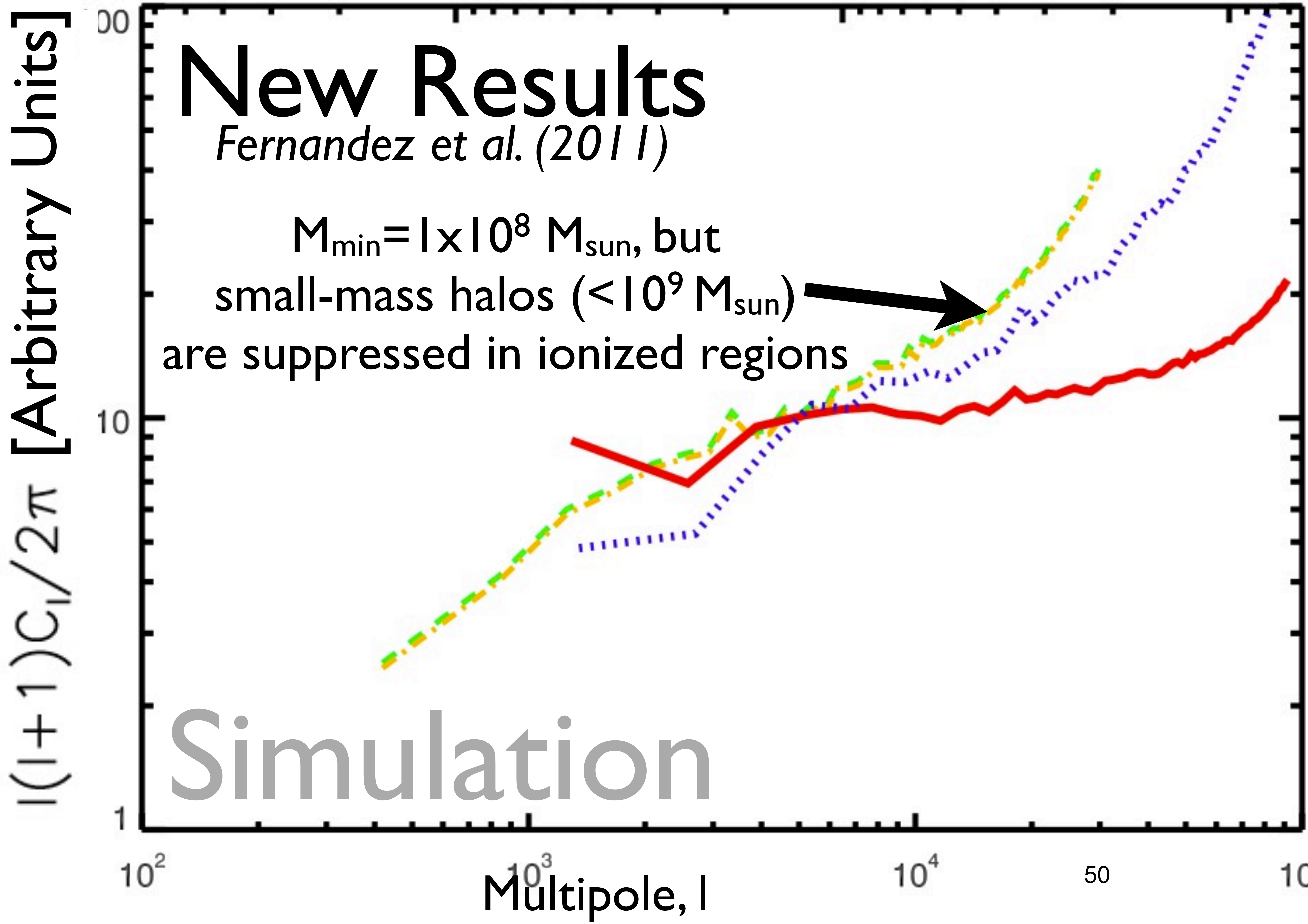

Ignore the amplitude:
just focus on the shape.
'multipole_nirbpower_nonlinearbias.txt'
'multipole_nirbpower_nonlinearbias_noshot_1e8.txt'
M_{min}=2.2x10^9 M_{sun}
M_{min}=1x10^8 M_{sun}
No turn over is still expected: what does the simulation tell us?
Analytical
l(l+1)C_l/2π (nW^2 m^{-4} sr^{-2})
0.1
0.01
0.001
0.0001
100
1000
10000
Multipole, l

New Simulation (Iliev et al. 2011)

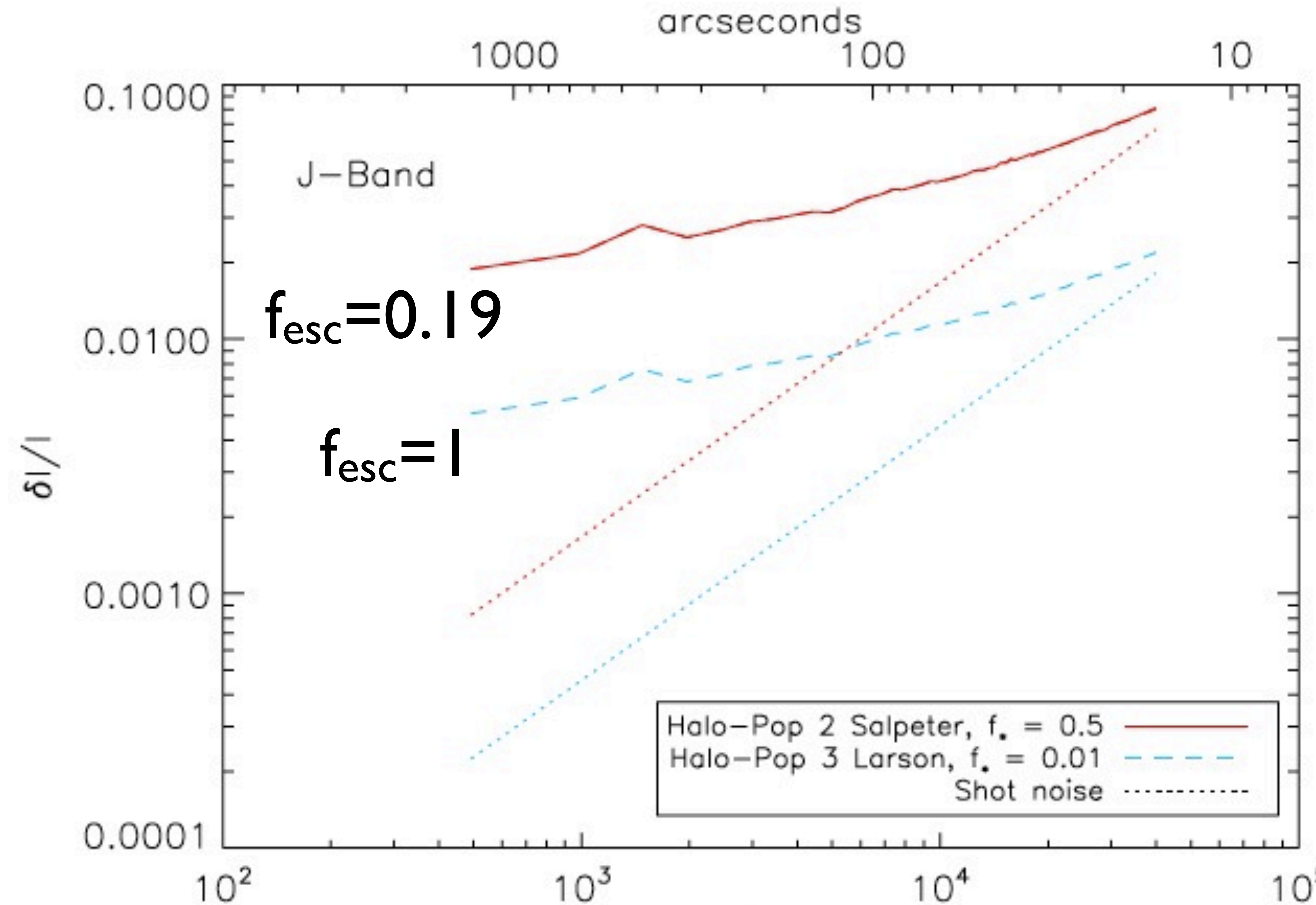
- N-body simulation (Particle-Particle-Particle-Mesh)
  - 114 h^{-1} Mpc; 3072^3 particles & 37 h^{-1} Mpc; 1024^3 particles
  - Minimum halo mass resolved = **1×10^8** Msun
  - The luminosity of halos is chosen such that it can reproduce WMAP's measurement of the optical depth.



New Results
Fernandez et al. (2011)
Mmin=1x10^9 Msun
Mmin=1x10^8 Msun
No turn over:
confirmed
Simulation
l(l+1)Cl/2π [Arbitrary Units]
Multipole, l
100
10
1
10^2
10^3
10^4


New Results
Fernandez et al. (2011)
M_{min}=1x10^8 M_{sun}, but
small-mass halos (<10^9 M_{sun})
are suppressed in ionized regions
Simulation
l(l+1)C$_l$/2π [Arbitrary Units]
Multipole, l
100
10
1
10^2
10^3
10^4

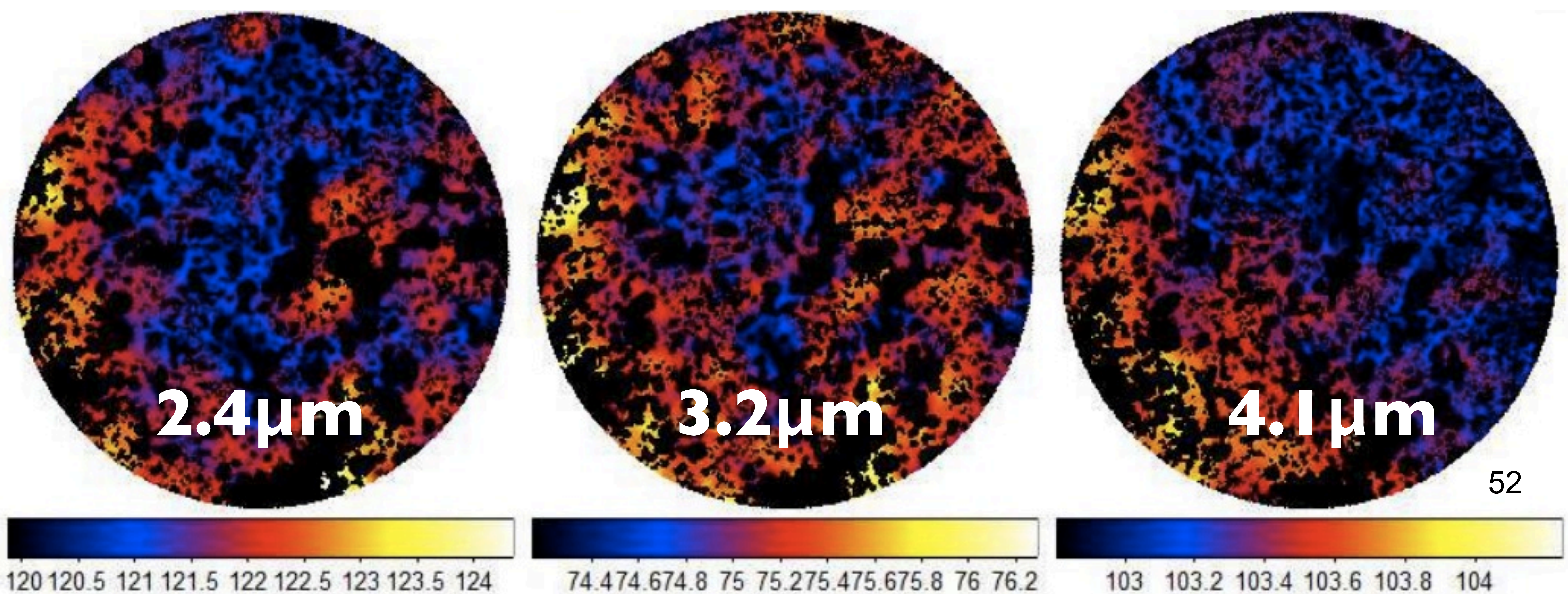
Fractional Anisotropy



- A useful quantity to calculate is the fluctuation divided by the mean intensity. It's of order 1% to 10%.

Data are coming!

- Matsumoto et al., arXiv:1010.0491 (ApJ in press)
  - Analysis of 10 arcmin circular patches on the north ecliptic pole, taken by AKARI.



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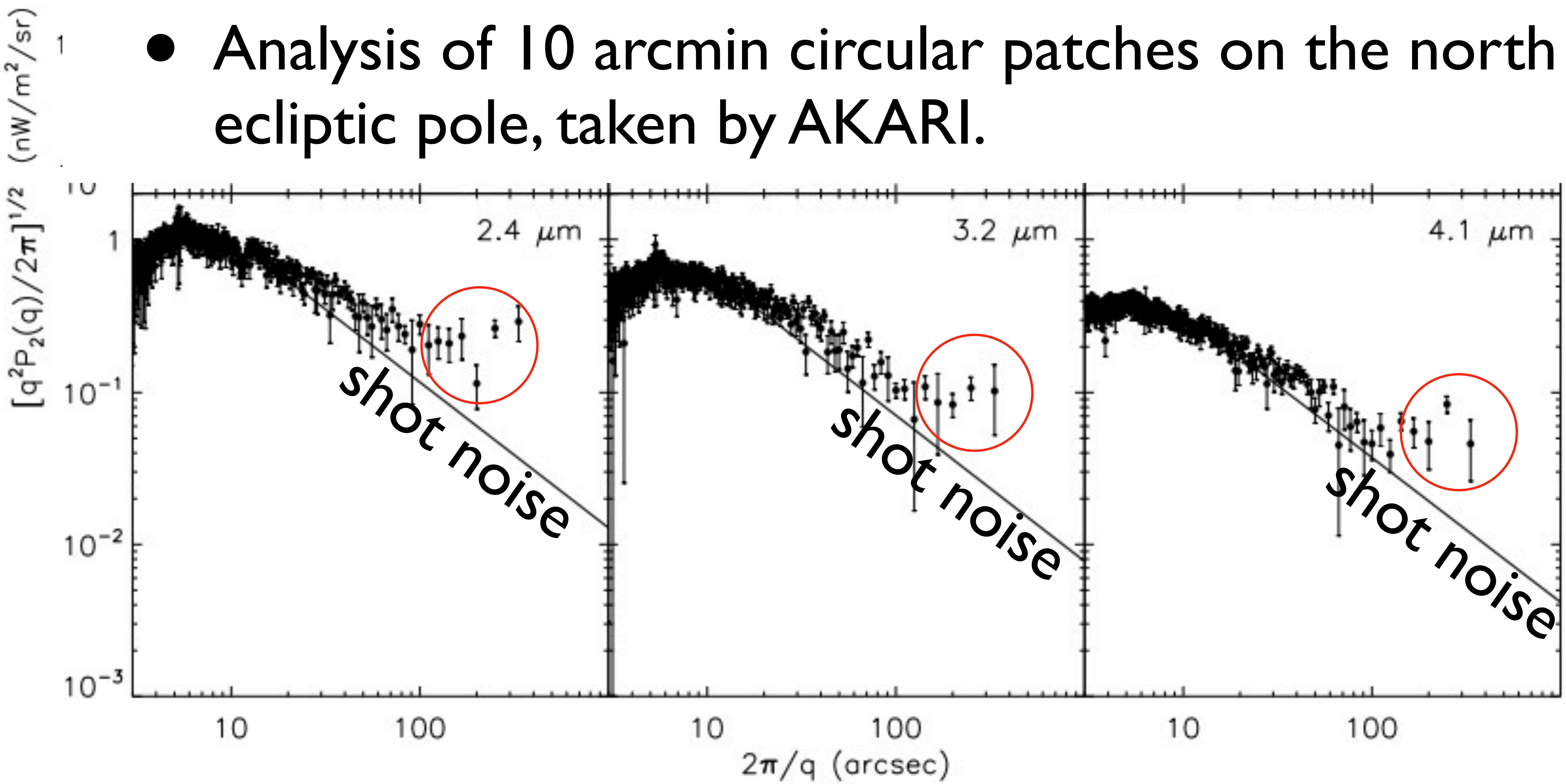

Data are coming!

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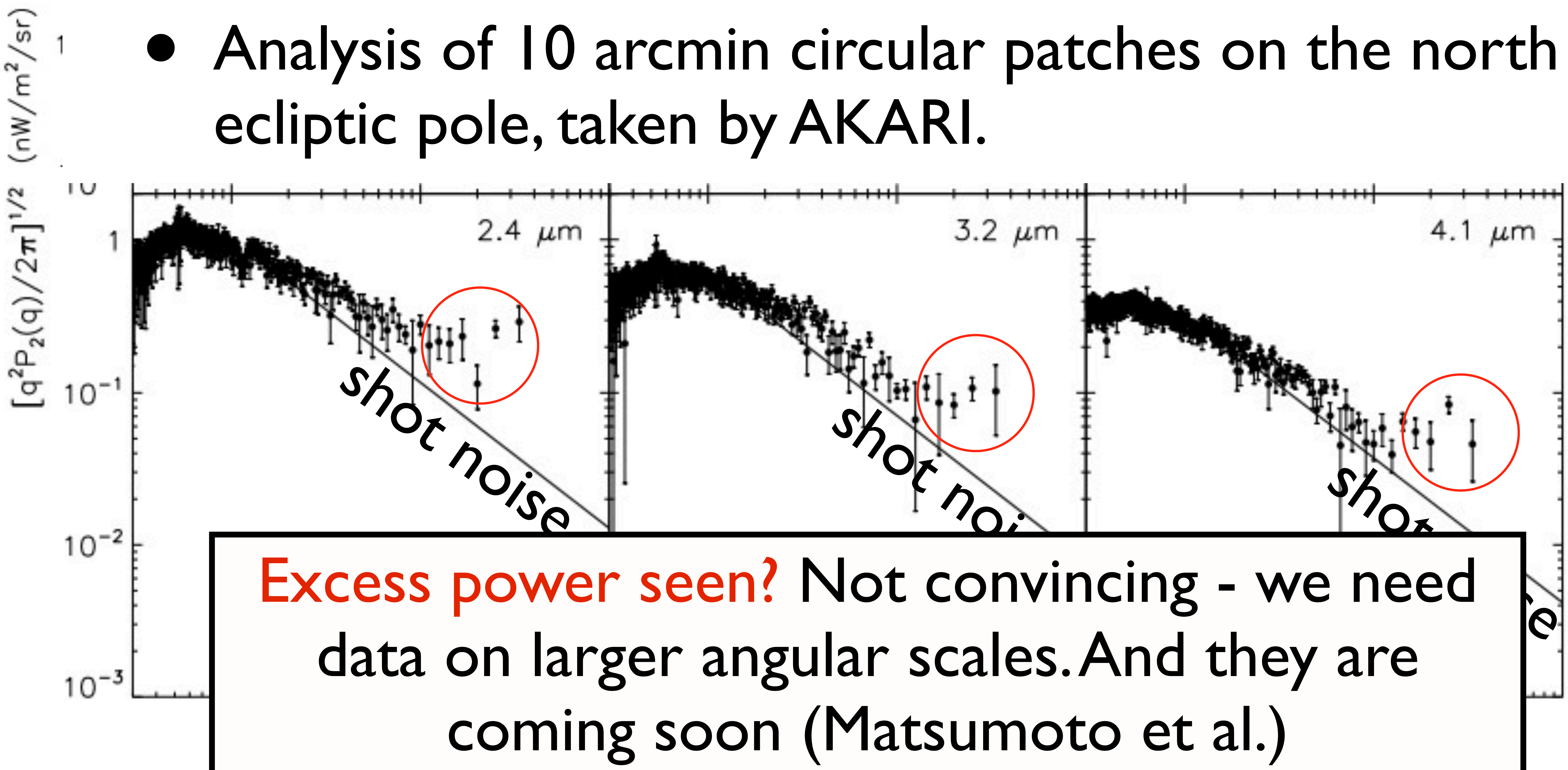
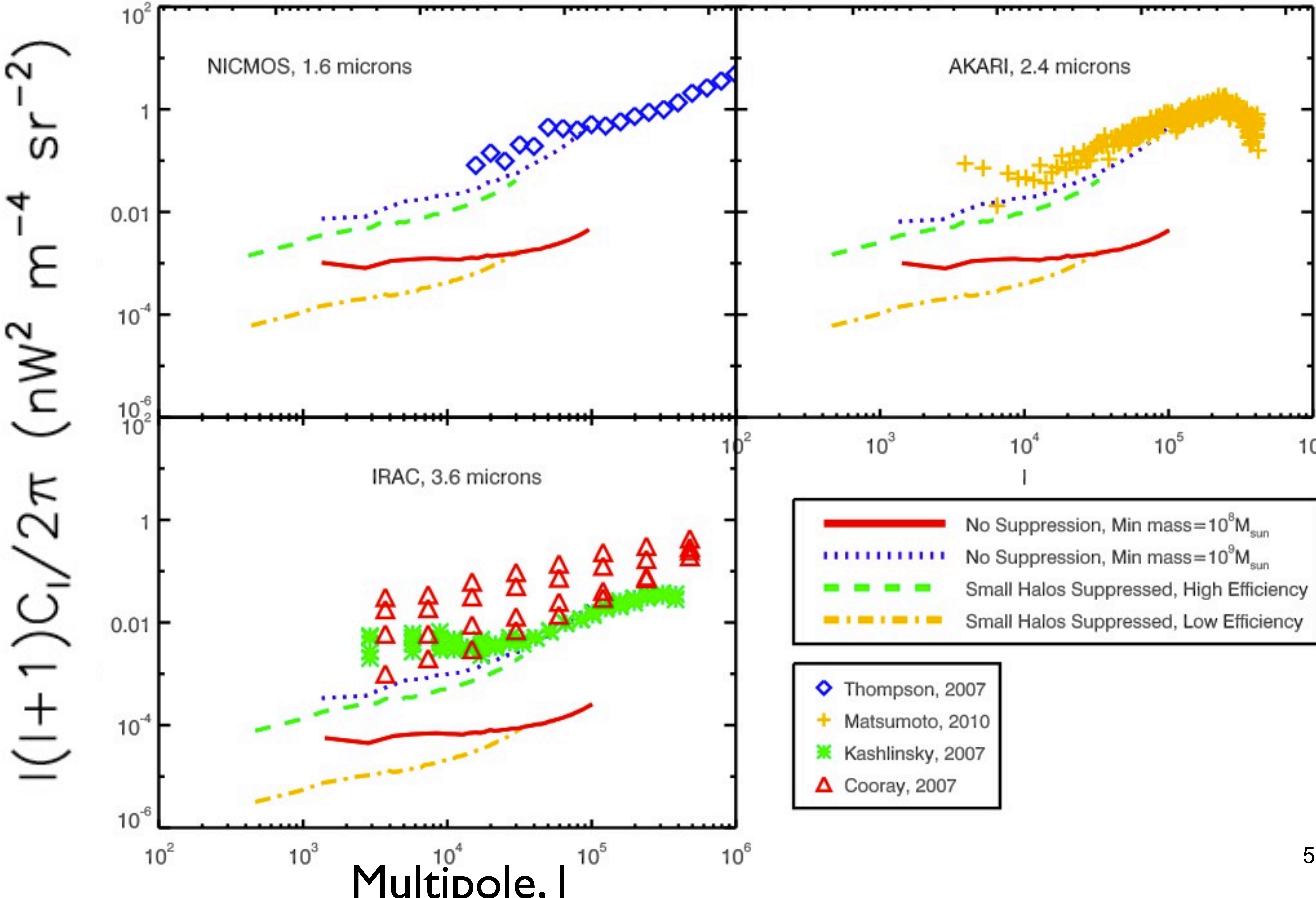
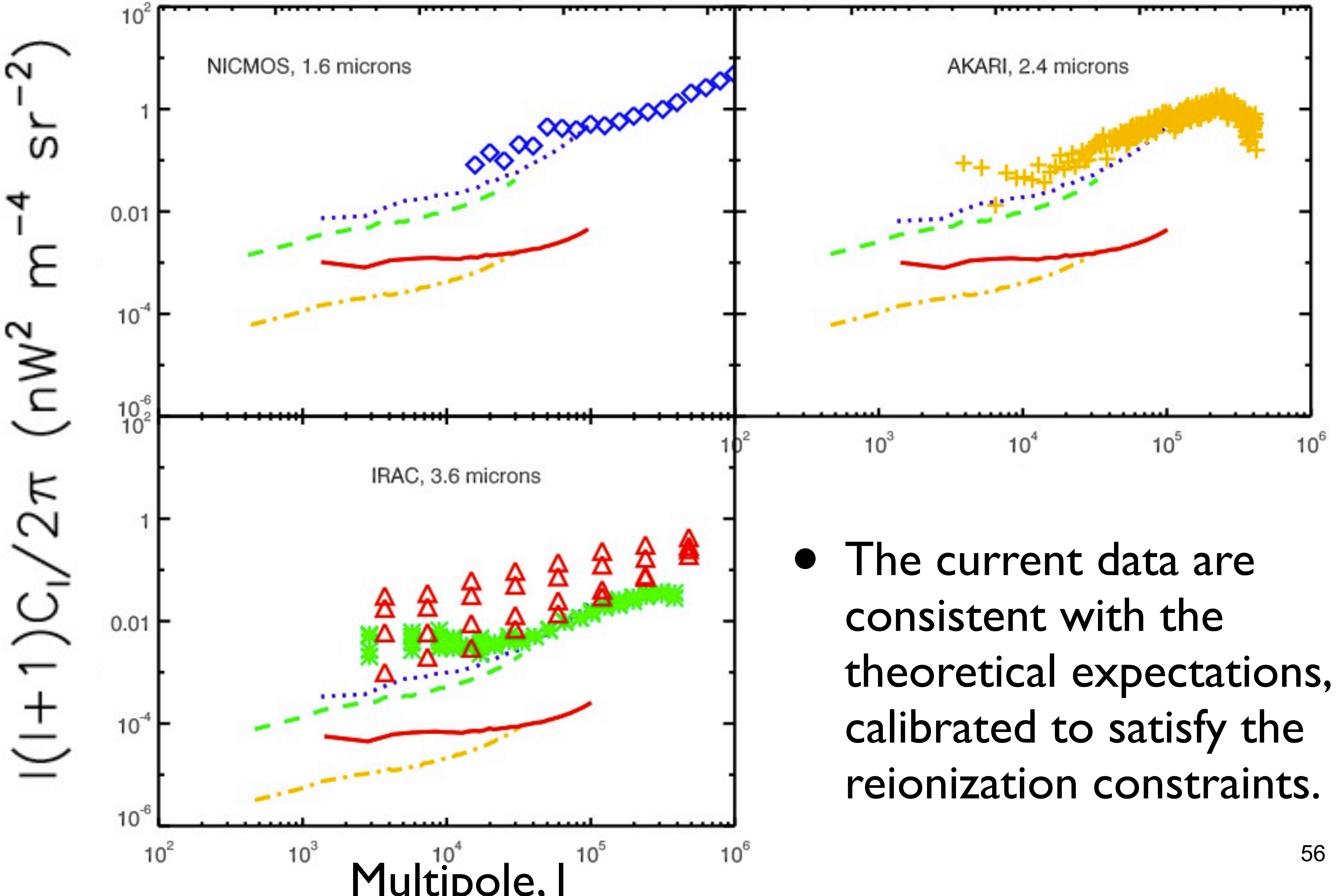
  - Analysis of 10 arcmin circular patches on the north ecliptic pole, taken by AKARI.



Excess power seen? Not convincing - we need data on larger angular scales. And they are coming soon (Matsumoto et al.)



NICMOS, 1.6 microns
AKARI, 2.4 microns
IRAC, 3.6 microns
l(l+1)C_l/2π (nW² m⁻⁴ sr⁻²)
Multipole, l
l
No Suppression, Min mass=10⁸M_sun
No Suppression, Min mass=10⁹M_sun
Small Halos Suppressed, High Efficiency
Small Halos Suppressed, Low Efficiency
Thompson, 2007
Matsumoto, 2010
Kashlinsky, 2007
Cooray, 2007



- The current data are consistent with the theoretical expectations, calibrated to satisfy the reionization constraints.

More data are coming!

- CIBER (=Cosmic Infrared Background Experiment)
  - ISAS-JPL experiment (rocket-borne); see, e.g., Zemcov et al., arXiv:1101.1560
  - Flown twice already. Being upgraded to CIBER-2.
- They can subtract the Zodiacal Light using the Fraunhofer lines.
- The fluctuation analysis is under way.
  - The results will be announced next year (May?)

Summary (Part 2)

- We used both numerical and analytical methods to calculate the power spectrum NIRB. The results make sense.
  - Qualitatively new result - no turnover! This has an important implication for the interpretation of the coming data.
- AKARI and CIBER are expected to yield the data that are sufficiently sensitive, so that we can test our understanding of early (z>6) structure/star formation in the universe, before JWST!