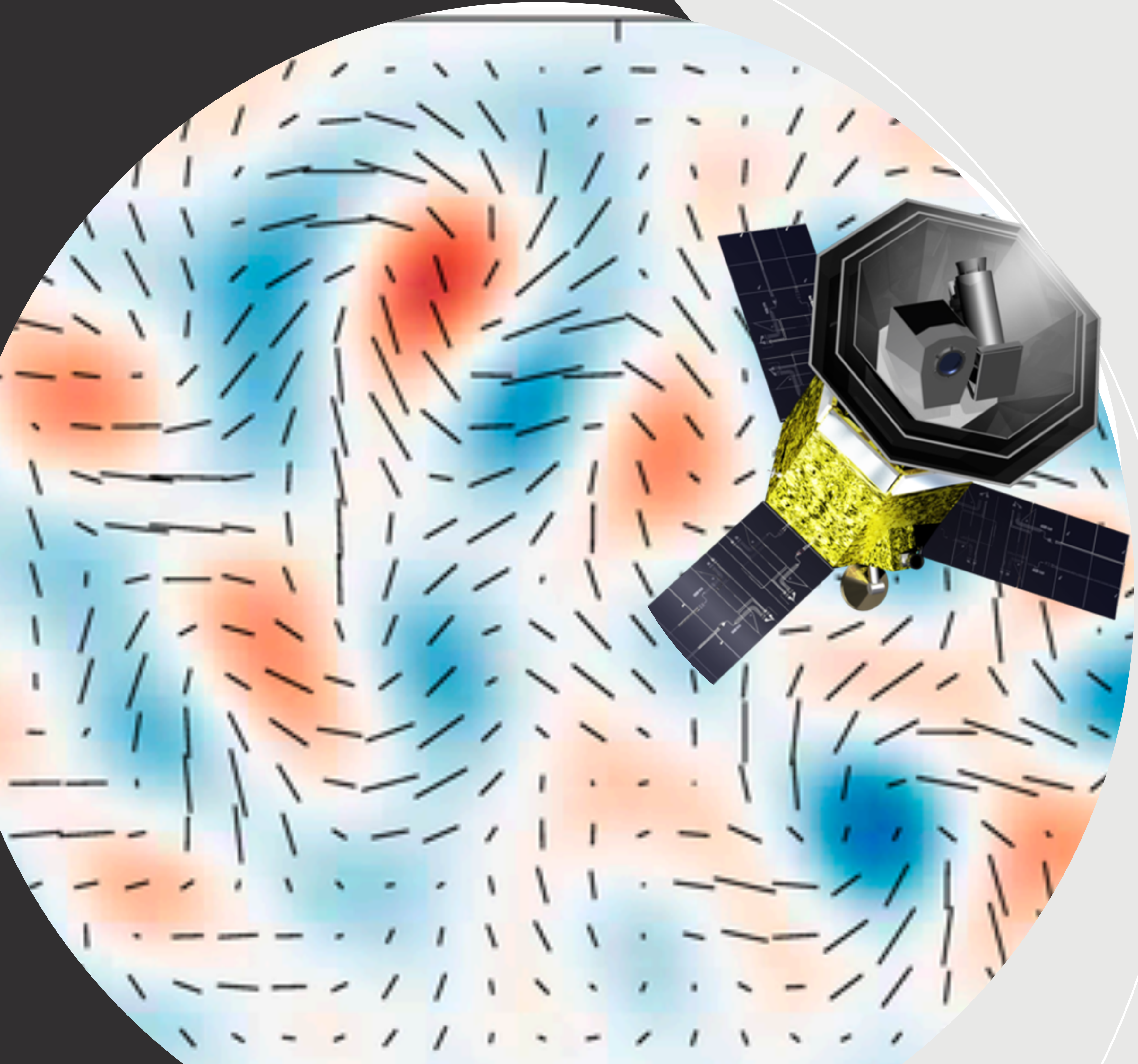
DUNLAP INSTITUTE
for ASTRONOMY & ASTROPHYSICS



The space of B-modes

Renée Hložek

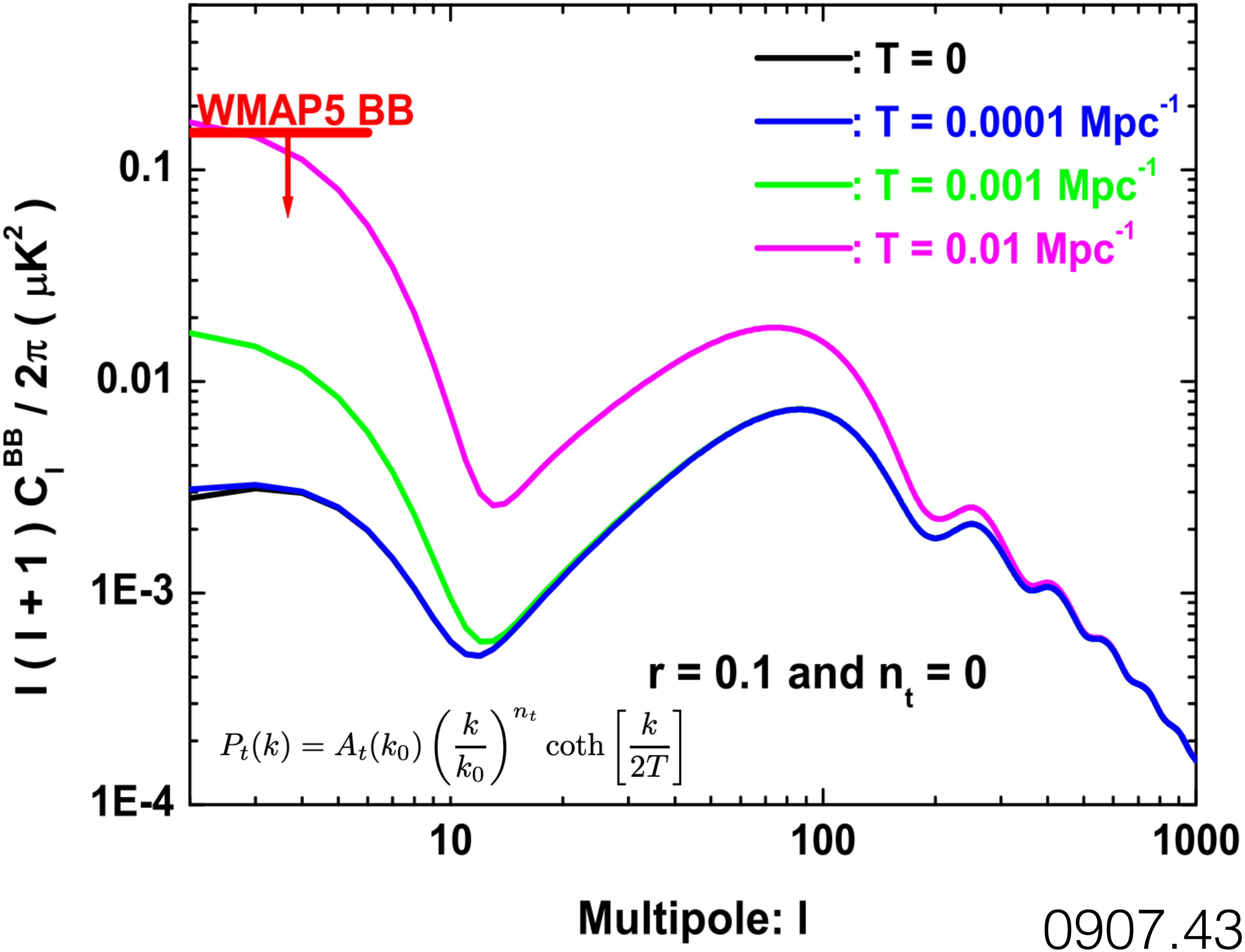
@reneehlozek

Dunlap Institute for
Astronomy & Astrophysics
UNIVERSITY OF TORONTO

What did we expect 10 years ago?

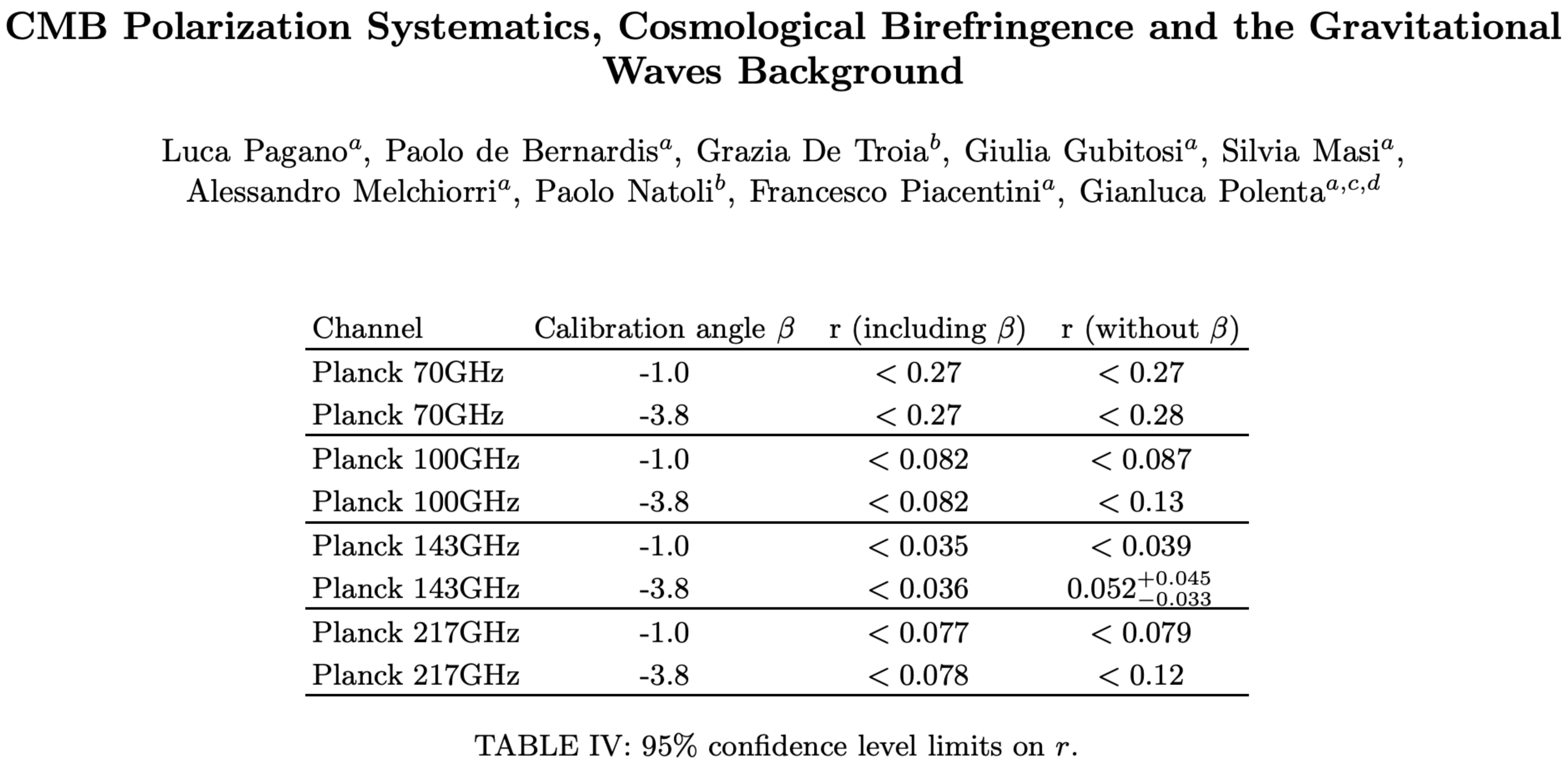
May 2009

ESA-CNES-ARIANESPACE / Optique Vidéo du CSG - P BAUDON



0907.4303

Dunlap Institute for
Astronomy & Astrophysics
UNIVERSITY OF TORONTO



CMB Polarization Systematics, Cosmological Birefringence and the Gravitational Waves Background

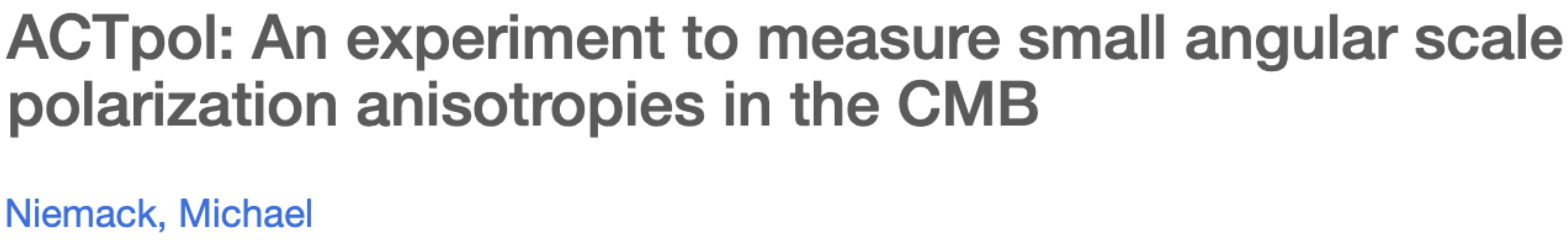
Luca Pagano[a], Paolo de Bernardis[a], Grazia De Troia[b], Giulia Gubitosi[a], Silvia Masi[a],
Alessandro Melchiorri[a], Paolo Natoli[b], Francesco Piacentini[a], Gianluca Polenta[a,c,d]

Channel	Calibration angle β	r (including β)	r (without β)
Planck 70GHz	-1.0	< 0.27	< 0.27
Planck 70GHz	-3.8	< 0.27	< 0.28
Planck 100GHz	-1.0	< 0.082	< 0.087
Planck 100GHz	-3.8	< 0.082	< 0.13
Planck 143GHz	-1.0	< 0.035	< 0.039
Planck 143GHz	-3.8	< 0.036	$0.052^{+0.045}_{-0.033}$
Planck 217GHz	-1.0	< 0.077	< 0.079
Planck 217GHz	-3.8	< 0.078	< 0.12

TABLE IV: 95% confidence level limits on r.

0905.1651

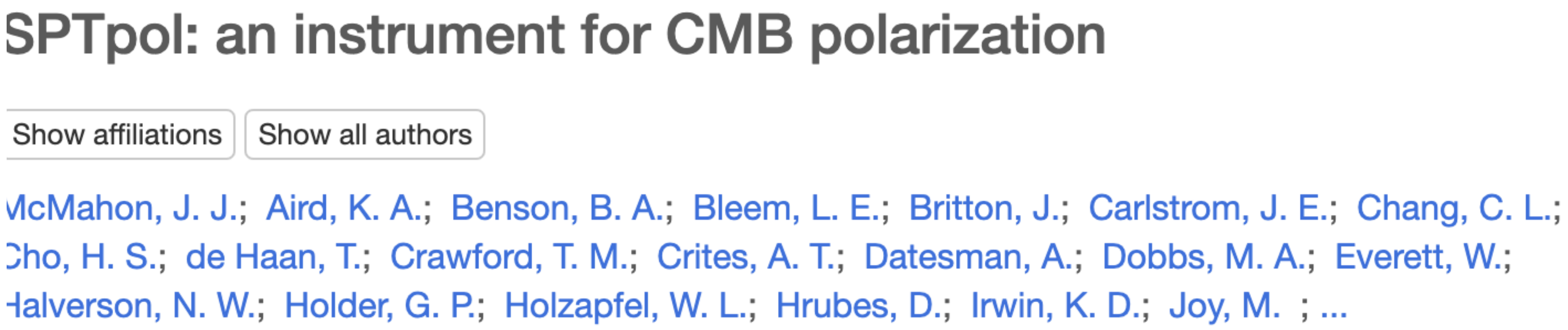
The systematics work was already in full force



ACTpol: An experiment to measure small angular scale polarization anisotropies in the CMB

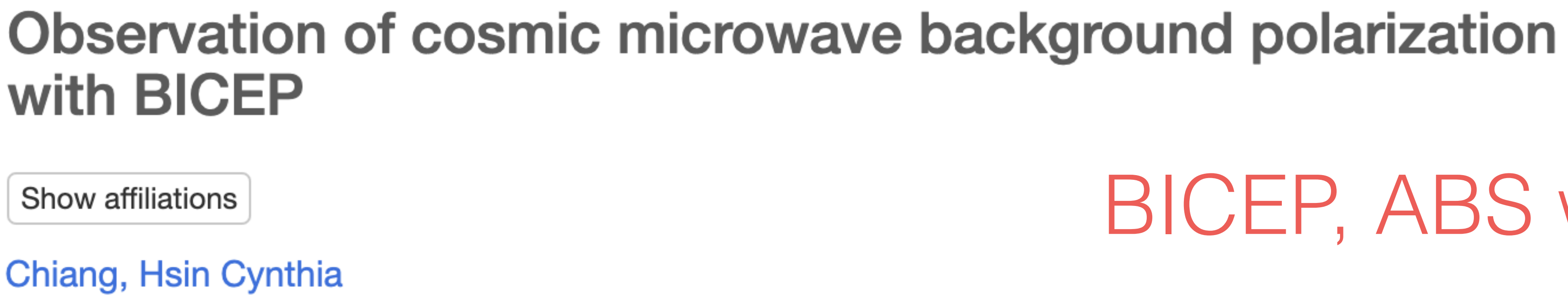
Niemack, Michael

ACT, SPT already developing polarization experiments



SPTpol: an instrument for CMB polarization

McMahon, J. J.; Aird, K. A.; Benson, B. A.; Bleem, L. E.; Britton, J.; Carlstrom, J. E.; Chang, C. L.; Cho, H. S.; de Haan, T.; Crawford, T. M.; Crites, A. T.; Datesman, A.; Dobbs, M. A.; Everett, W.; Halverson, N. W.; Holder, G. P.; Holzapfel, W. L.; Hrubes, D.; Irwin, K. D.; Joy, M. ; ...



Observation of cosmic microwave background polarization with BICEP

Chiang, Hsin Cynthia

BICEP, ABS were taking data

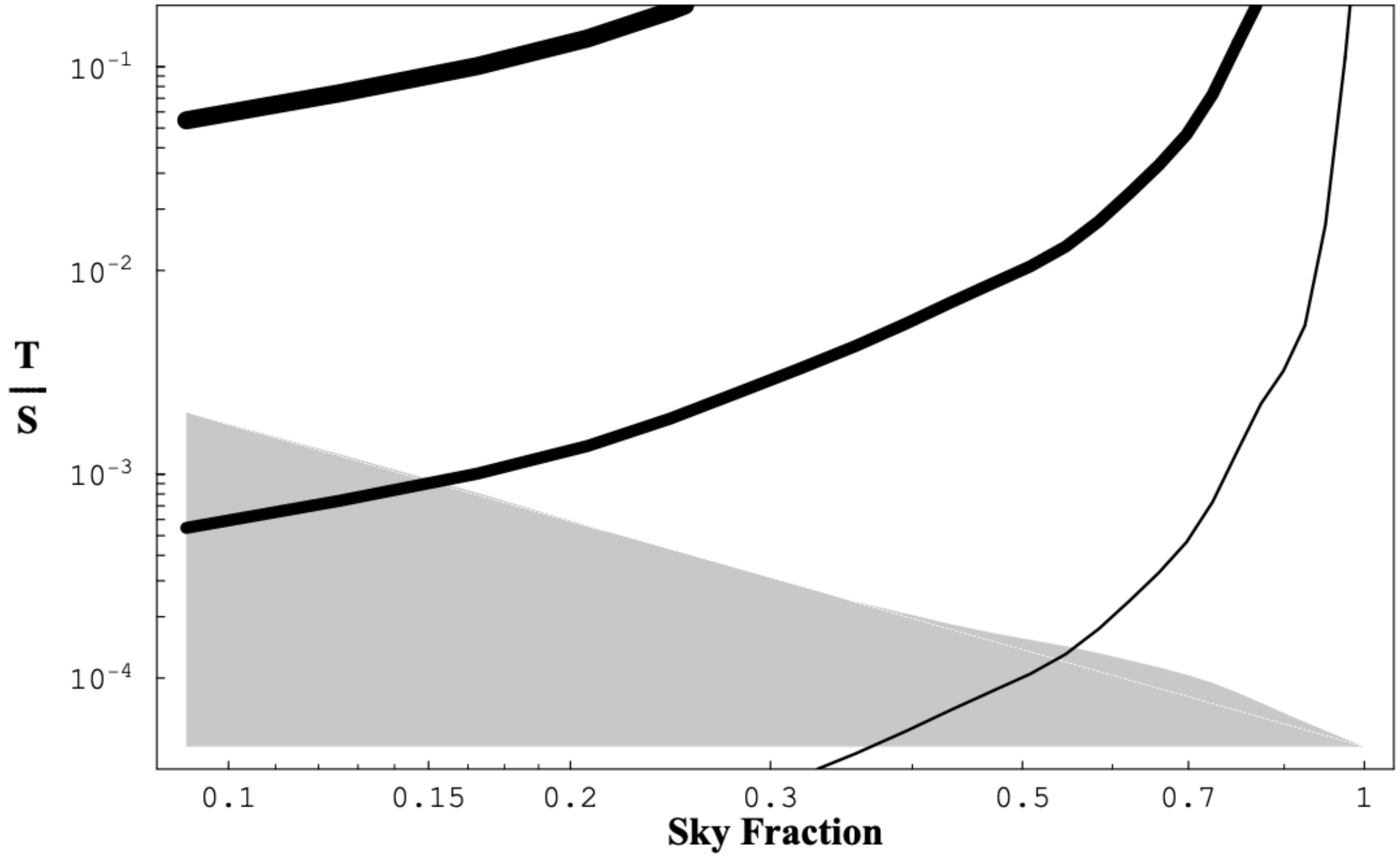
The Atacama B-mode Search: An Experiment to Probe Inflation by Measuring the Cosmic Microwave Background Polarization

Niemack, Michael; Appel, J.; Cho, H. M.; Essinger-Hileman, T.; Fowler, J.; Halpern, M.; Irwin, K. D.; Marriage, T. A.; Page, L.; Parker, L. P.; Pufu, S.; Staggs, S. T.; Visnjic, K.; Yoon, K. W.; Zhao, Y.

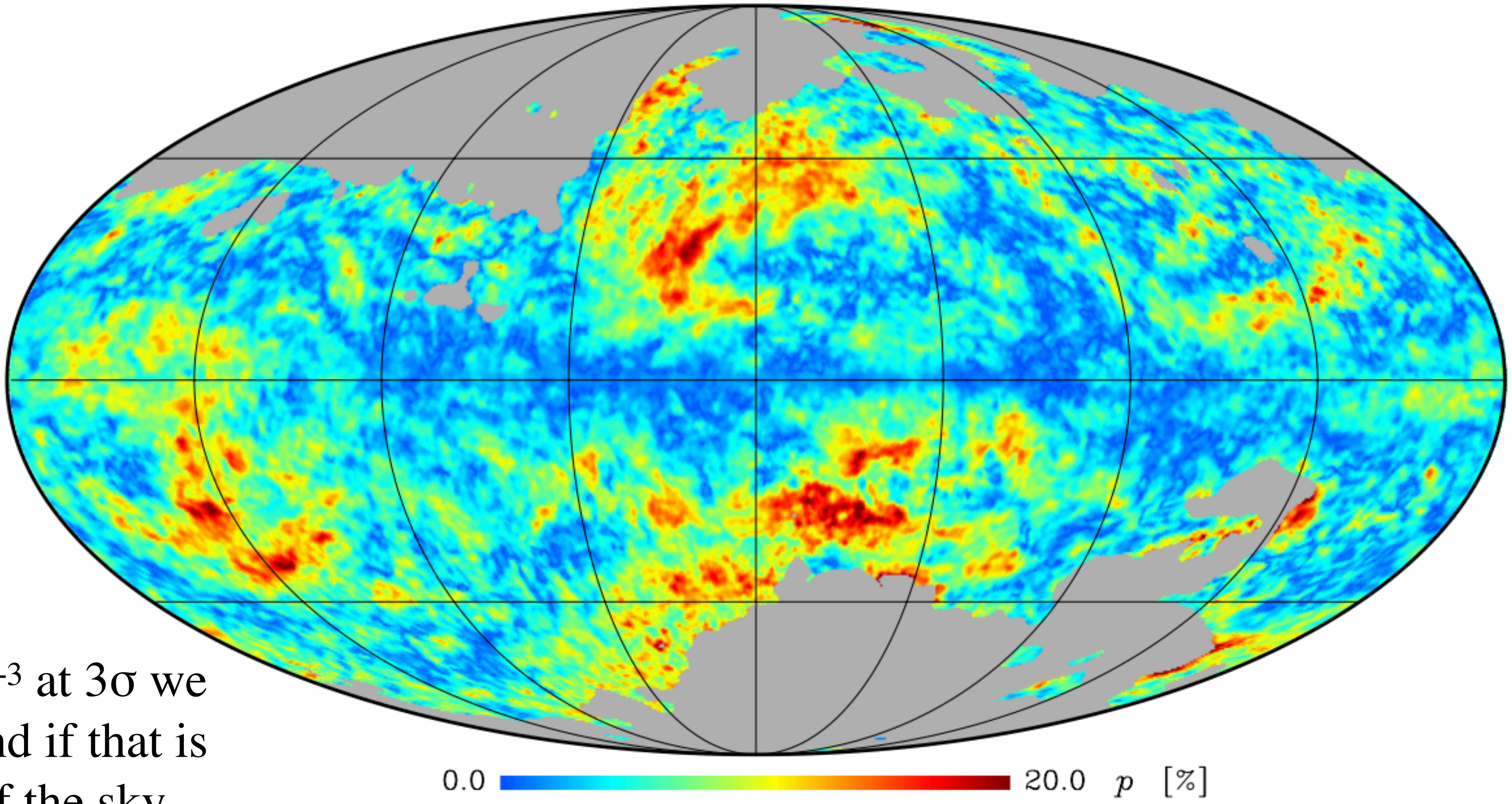
Ok, so what about in 2005?

astro-ph/0508293

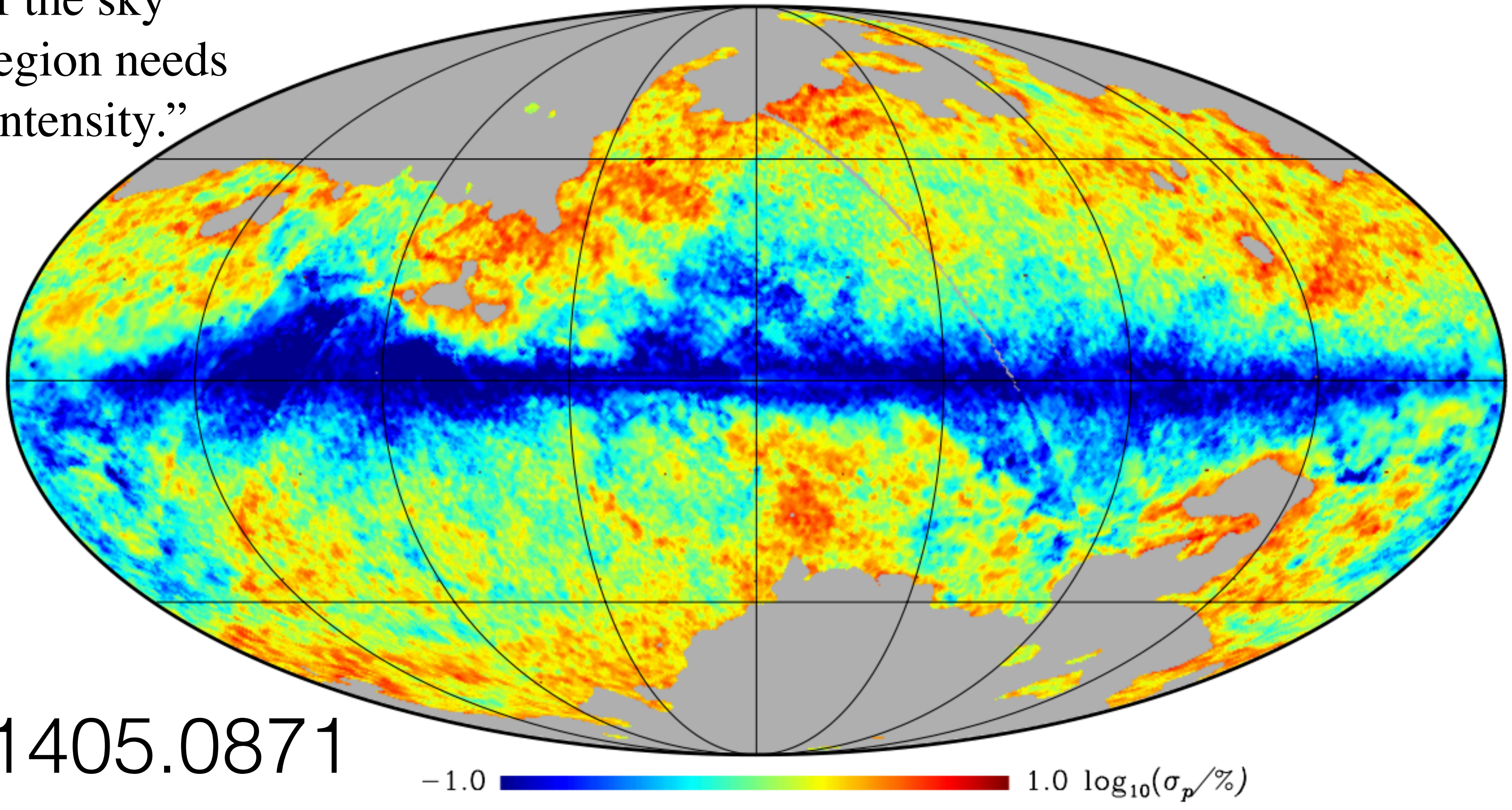
Perhaps slightly more optimism about delensing and foregrounds



"For example, to detect T /S = 10^{-3} at 3σ we need to observe 15% of the sky and if that is chosen to be the cleanest region of the sky then the dust polarization in this region needs to be cleaned at 0.1% level of its intensity."



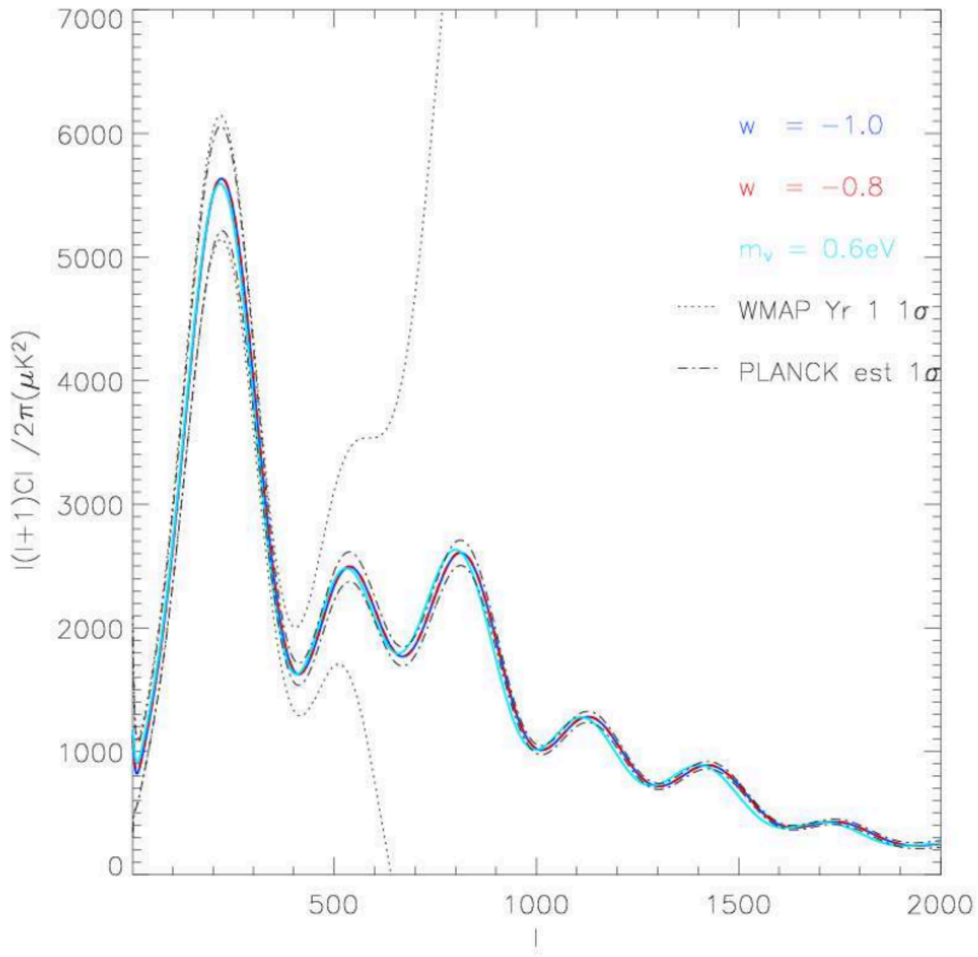
“For example, to detect T /S = 10^{-3} at 3σ we need to observe 15% of the sky and if that is chosen to be the cleanest region of the sky then the dust polarization in this region needs to be cleaned at 0.1% level of its intensity.”

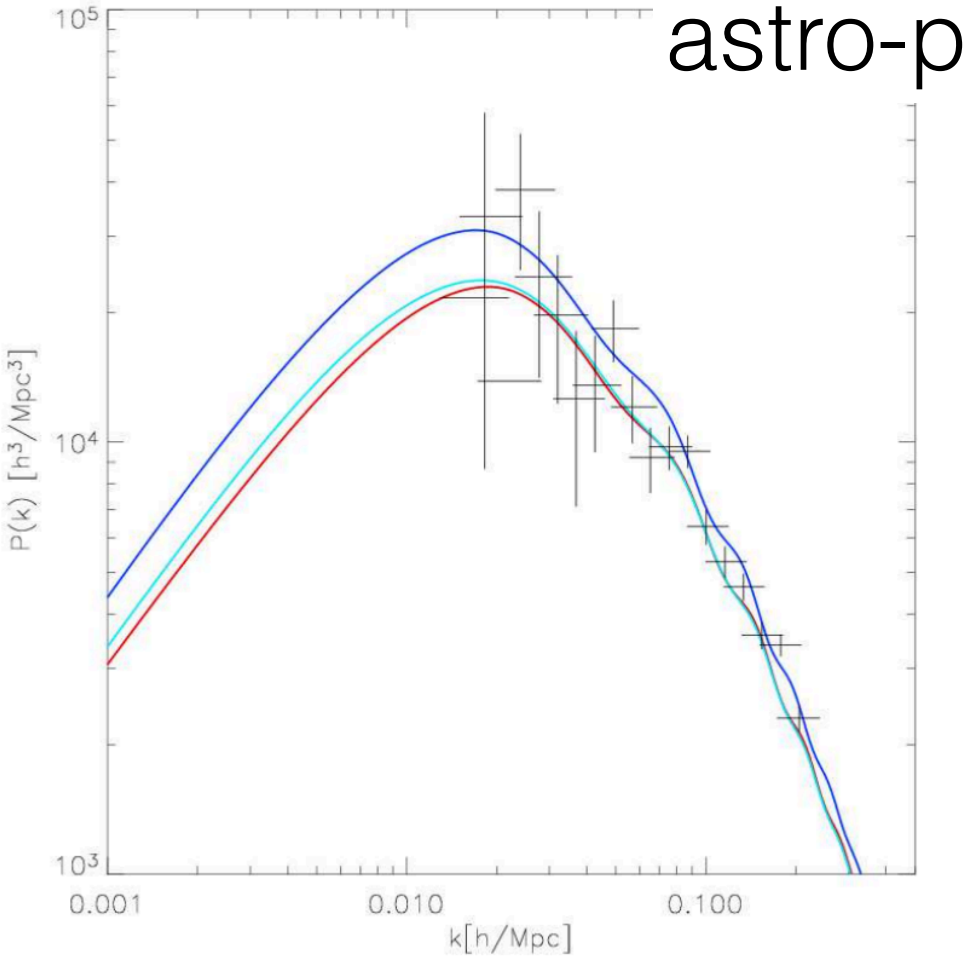


DUNLAP INSTITUTE
for **ASTRONOMY & ASTROPHYSICS**

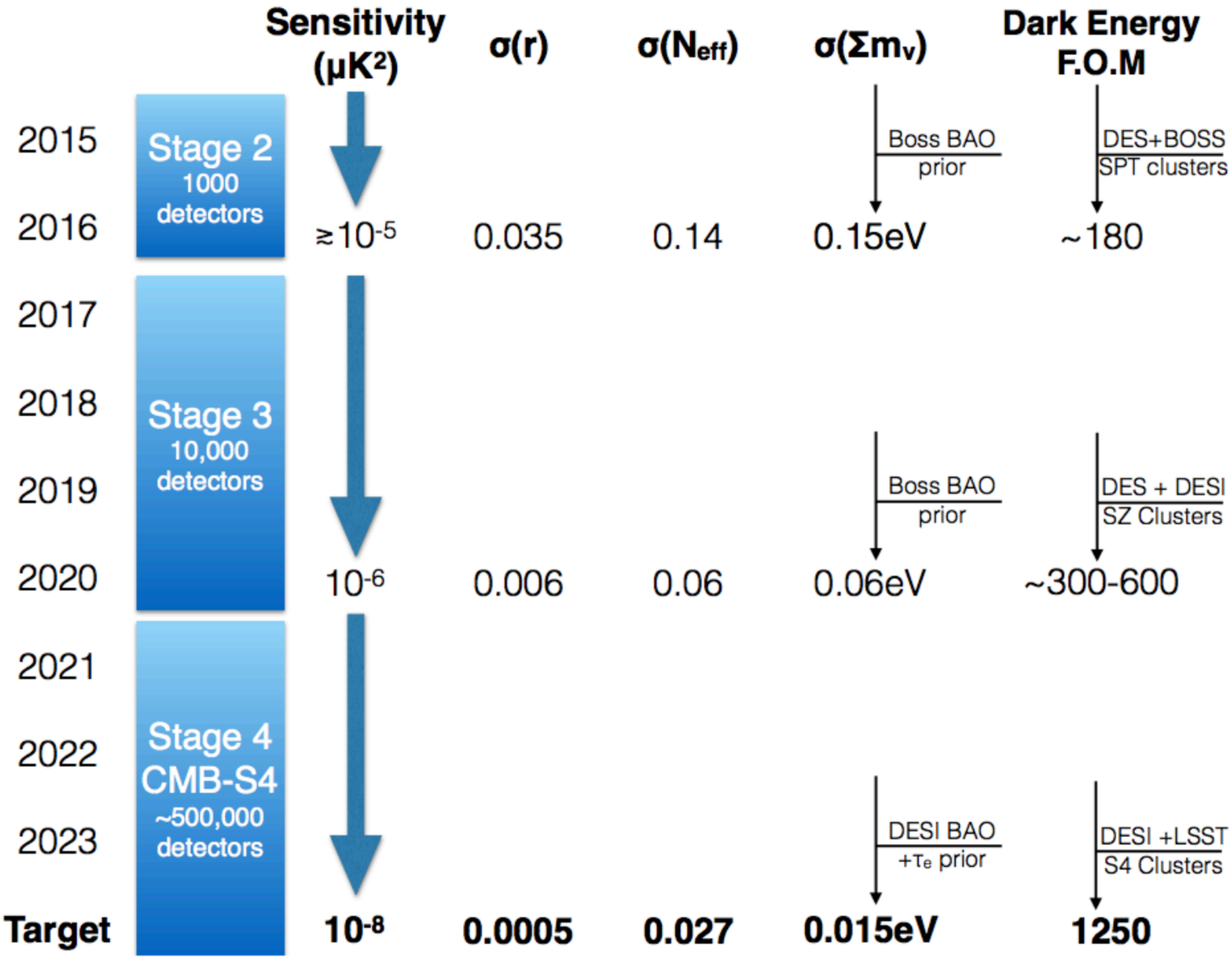
1405.0871

astro-ph/0511161





		h	Ω_b	Ω_{CDM}	$\sum m_\nu$ (eV)	Ω_m	w	σ_8
Model B $\sim$ 2248 clusters	0%	$0.64^{+0.03}_{-0.02}$	$0.060^{+0.004}_{-0.004}$	$0.30^{+0.02}_{-0.02}$	0.0	$0.36^{+0.02}_{-0.03}$	$-0.80^{+0.06}_{-0.09}$	$0.88^{+0.03}_{-0.02}$
	10%	0.63	0.062	0.32		0.38	-0.77	0.89
	20%	0.62	0.062	0.32		0.38	-0.77	0.92
Model C $\sim$ 1601 clusters	0%	$0.65^{+0.01}_{-0.01}$	$0.056^{+0.001}_{-0.002}$	$0.32^{+0.01}_{-0.01}$	$0.60^{+0.07}_{-0.13}$	$0.38^{+0.02}_{-0.01}$	-1.00	$0.84^{+0.01}_{-0.02}$
	10%	0.65	0.056	0.33	0.50	0.39		0.90
	20%	0.64	0.056	0.33	0.50	0.40		0.92



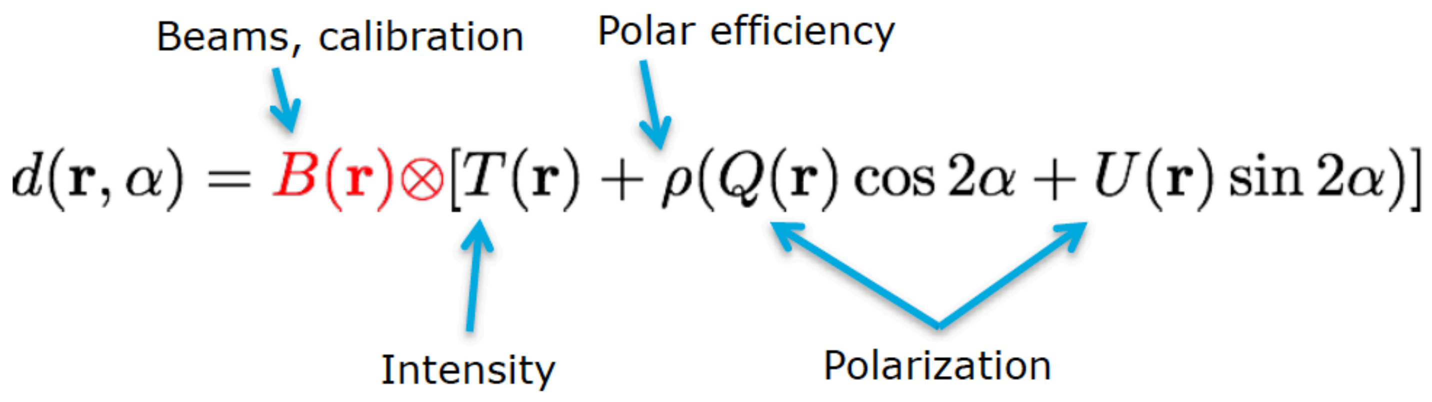
		Sensitivity (μK^2)	$\sigma(r)$	$\sigma(N_{eff})$	$\sigma(\Sigma m_\nu)$	Dark Energy F.O.M
2015 2016	Stage 2 1000 detectors	$\gtrsim 10^{-5}$	0.035	0.14	Boss BAO prior 0.15eV	DES+BOSS SPT clusters ~180
2017 2018 2019 2020	Stage 3 10,000 detectors	10^{-6}	0.006	0.06	Boss BAO prior 0.06eV	DES + DESI SZ Clusters ~300-600
2021 2022 2023 **Target**	Stage 4 CMB-S4 ~500,000 detectors	**10^{-8}**	**0.0005**	**0.027**	DESI BAO +T_e prior **0.015eV**	DESI +LSST S4 Clusters **1250**

From Adrian Lee's talk

What did ~~we~~ I learn from 10 years ago?

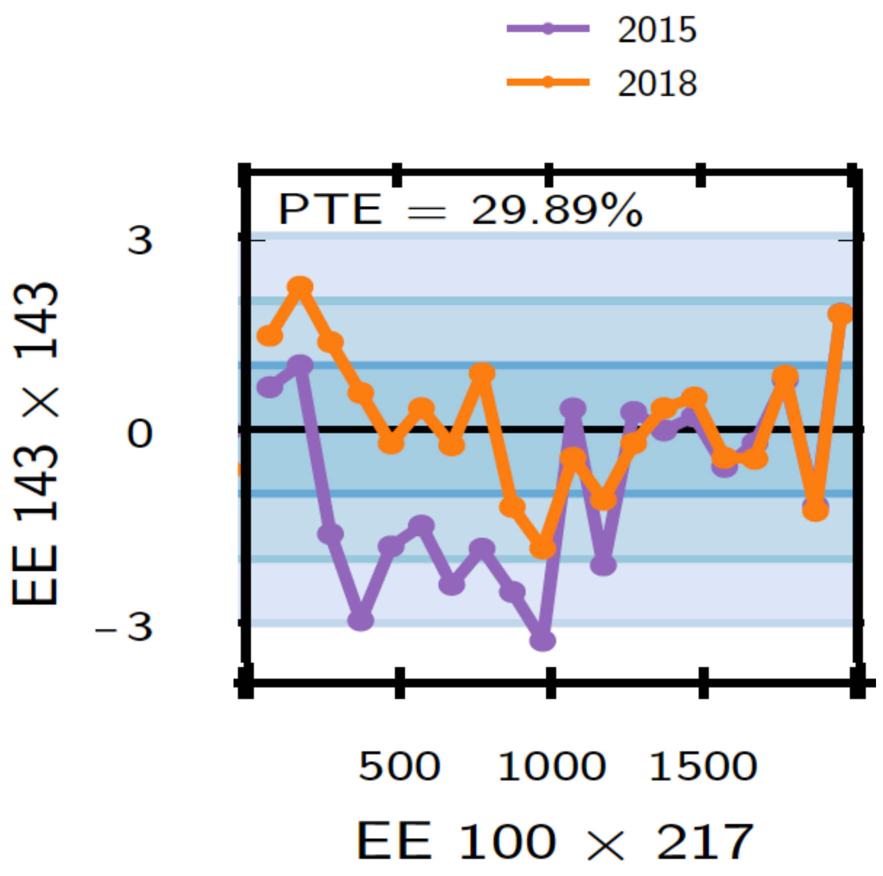
1. Polarization is hard

- **Correction of systematics** in polarization (large scales: map-making and sims. Small scales: beam leakage (improved TE by $\Delta\chi^2=37$) and polarization efficiency corrections (improved TE by $\Delta\chi^2=50$). Changes of $< 1\sigma$ on parameters.



$$d(\mathbf{r},\alpha) = B(\mathbf{r})\otimes[T(\mathbf{r}) + \rho(Q(\mathbf{r})\cos 2\alpha + U(\mathbf{r})\sin 2\alpha)]$$

- Cleaning for these systematics dramatically improved the interfrequency agreement and χ^2. →



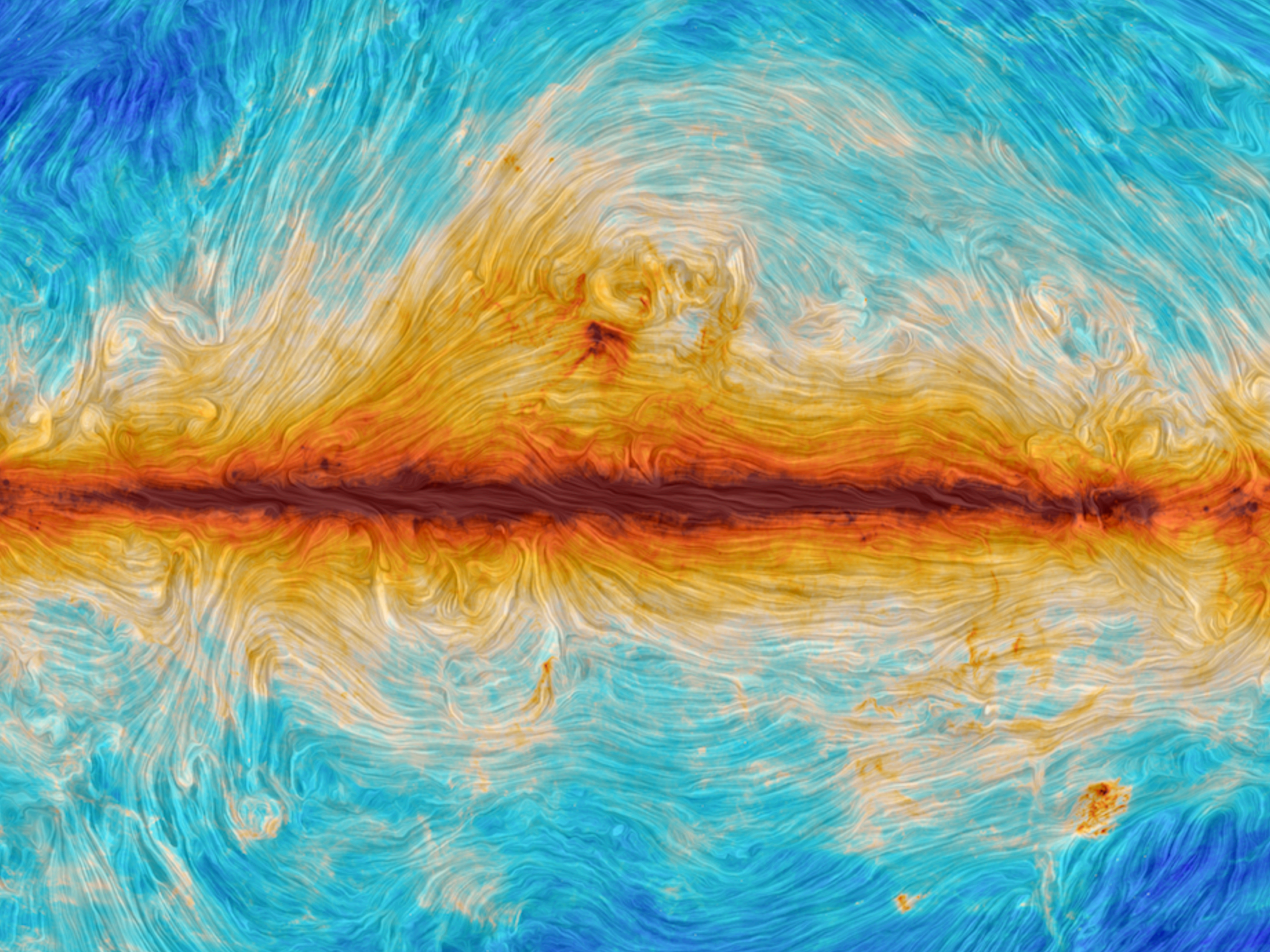
Planck **2018** results. V. Legacy Power Spectra and Likelihoods

- **Limitations** small remaining uncertainties of systematics in polarization (~0.5s on cosmo. parameters) (quantified with alternative likelihood(CAMspec) at high-l which uses different choices than baseline (Plik)).

Slide from Silvia Galli

What did ~~we~~ I learn from 10 years ago?

1. Polarization is hard
2. Planck released amazing maps, spectra and parameters

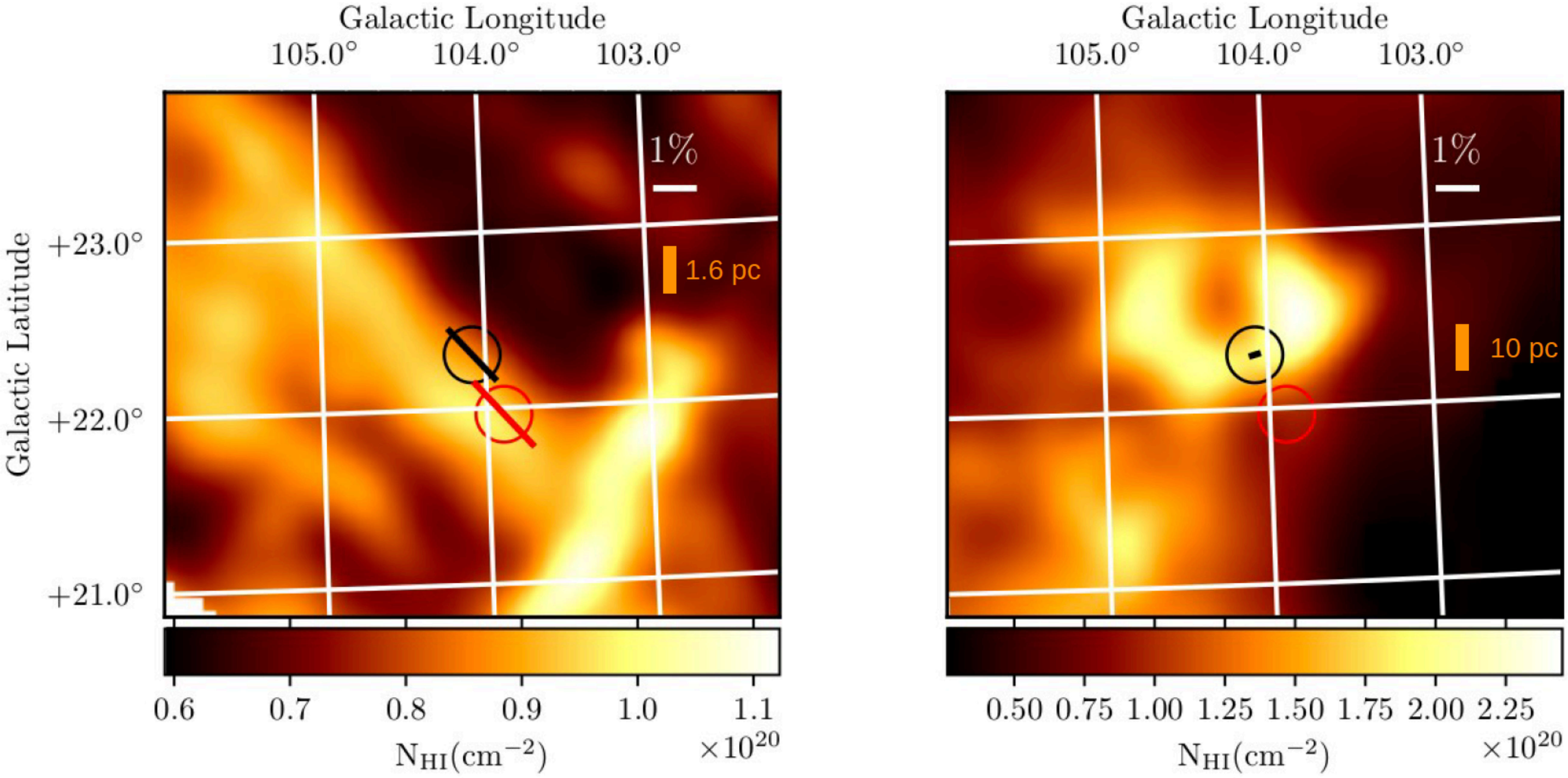


What did ~~we~~ I learn from 10 years ago?

1. Polarization is hard
2. Planck released amazing maps, spectra and parameters
3. Foreground science made possible by Planck

The magnetic field orientation in each cloud

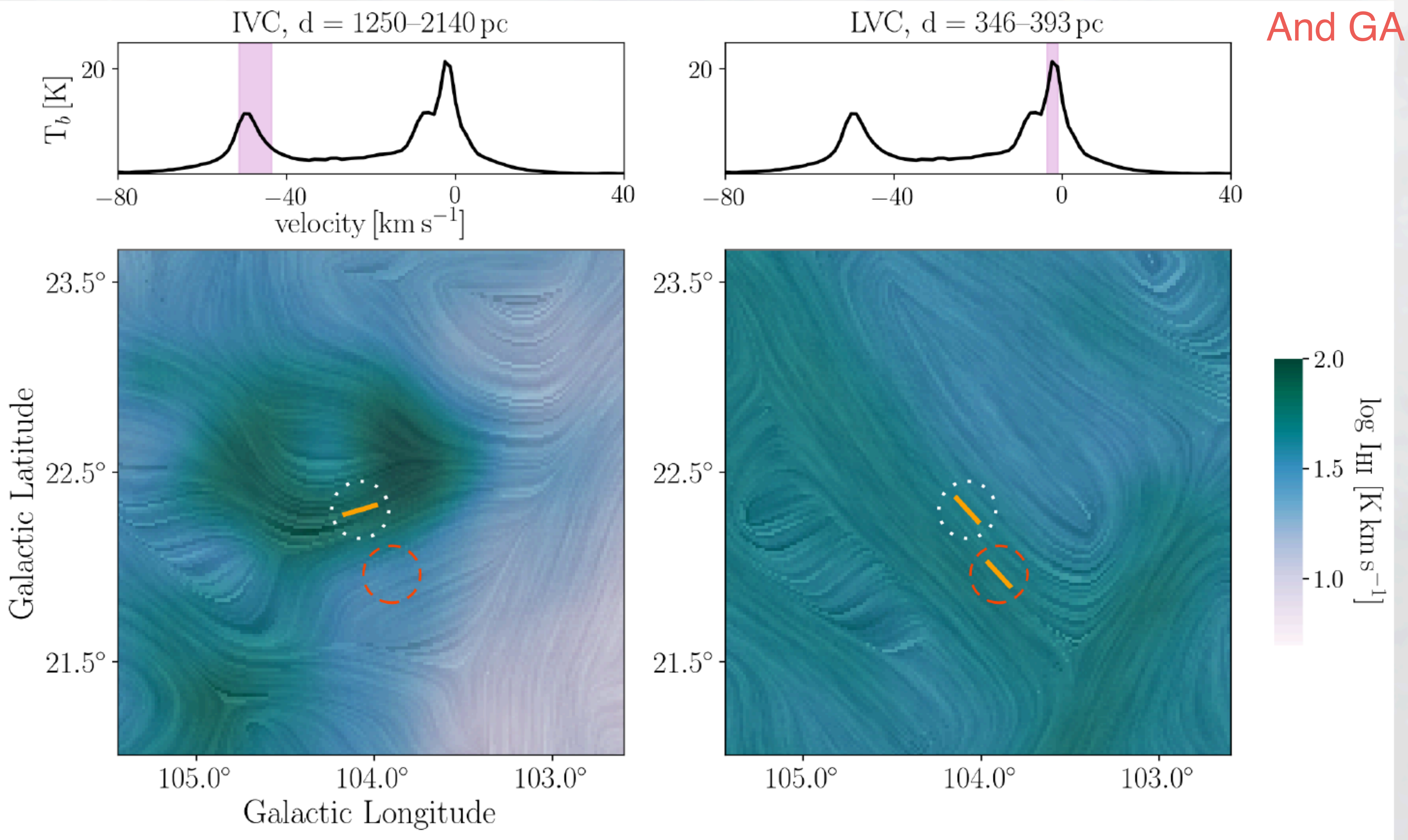
New studies of magnetic fields with starlight polarization
Effelsberg-Bonn HI Survey



Slide from Gina Panopalou

Panopoulou+2019a

Our maps provide a local estimate of the magnetic field orientation as a function of velocity.



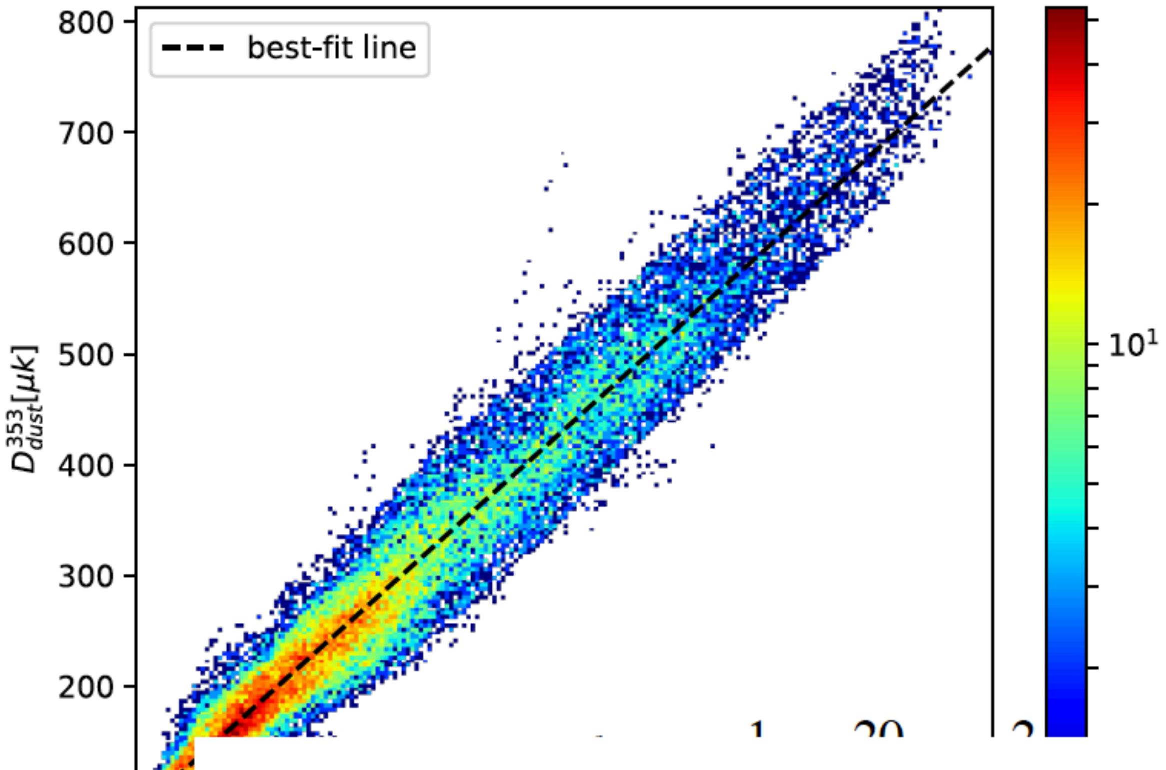
And GALFA-HI

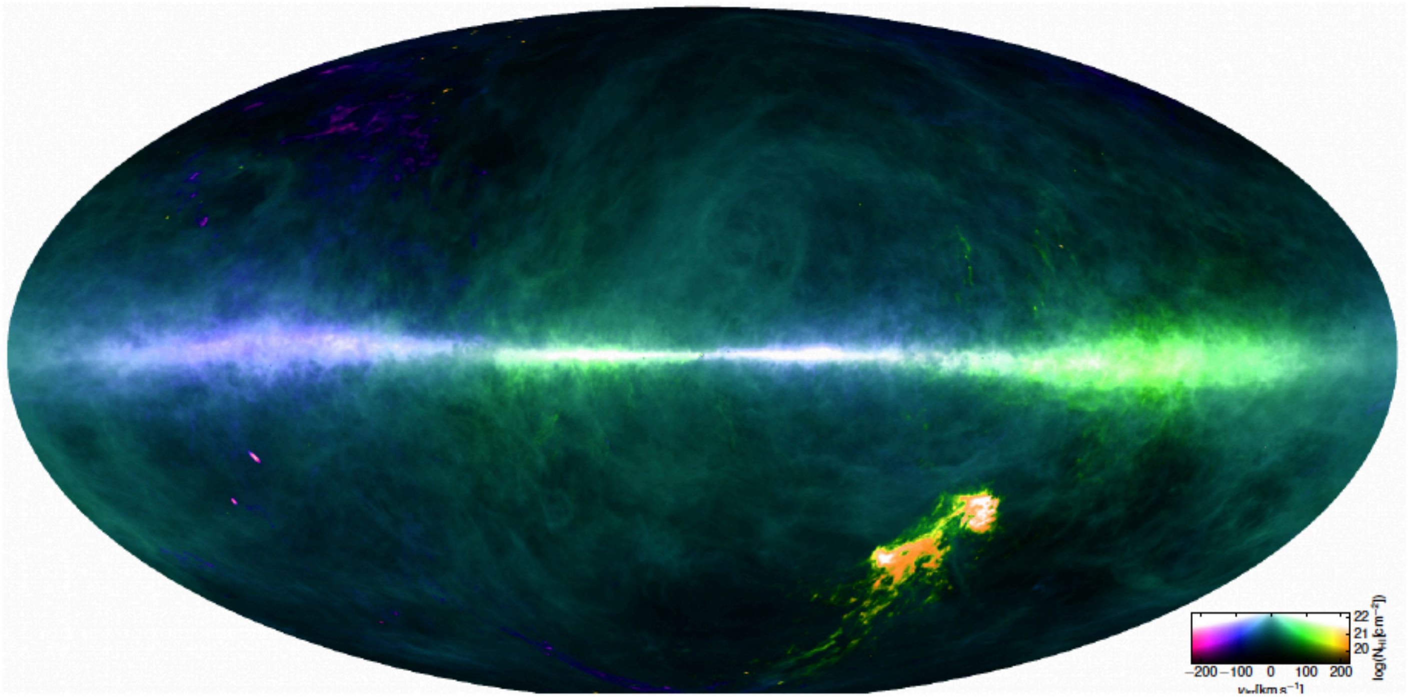
Orientations: Panopoulou+ 2019

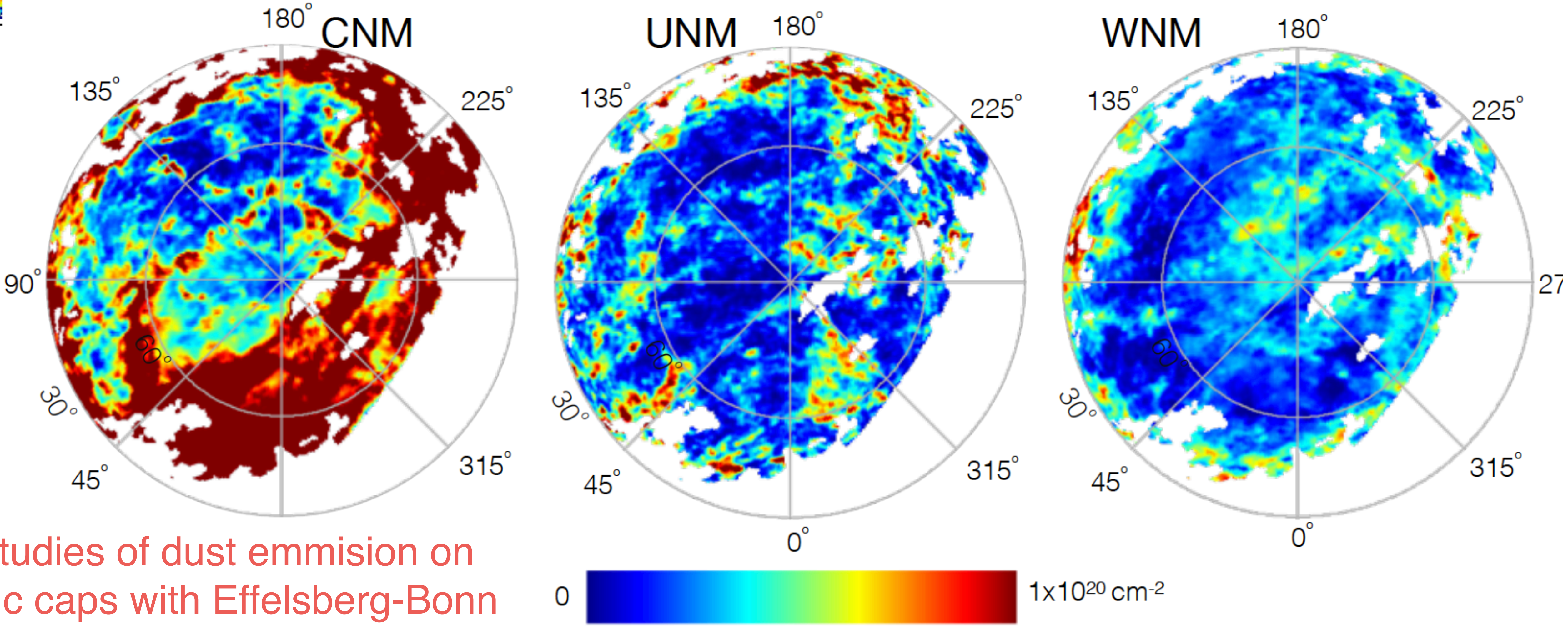
Background: Clark & Hensley

Slide from Susan Clark

Slide from Debabrata Adak

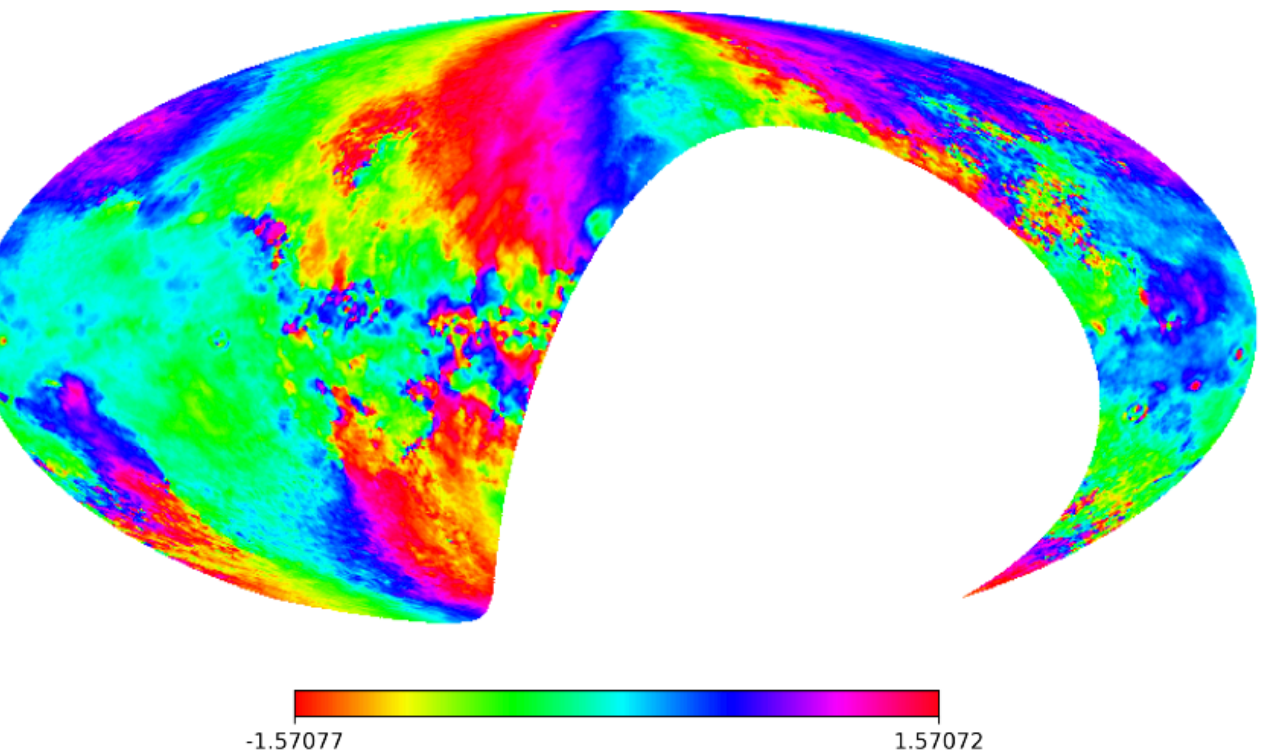


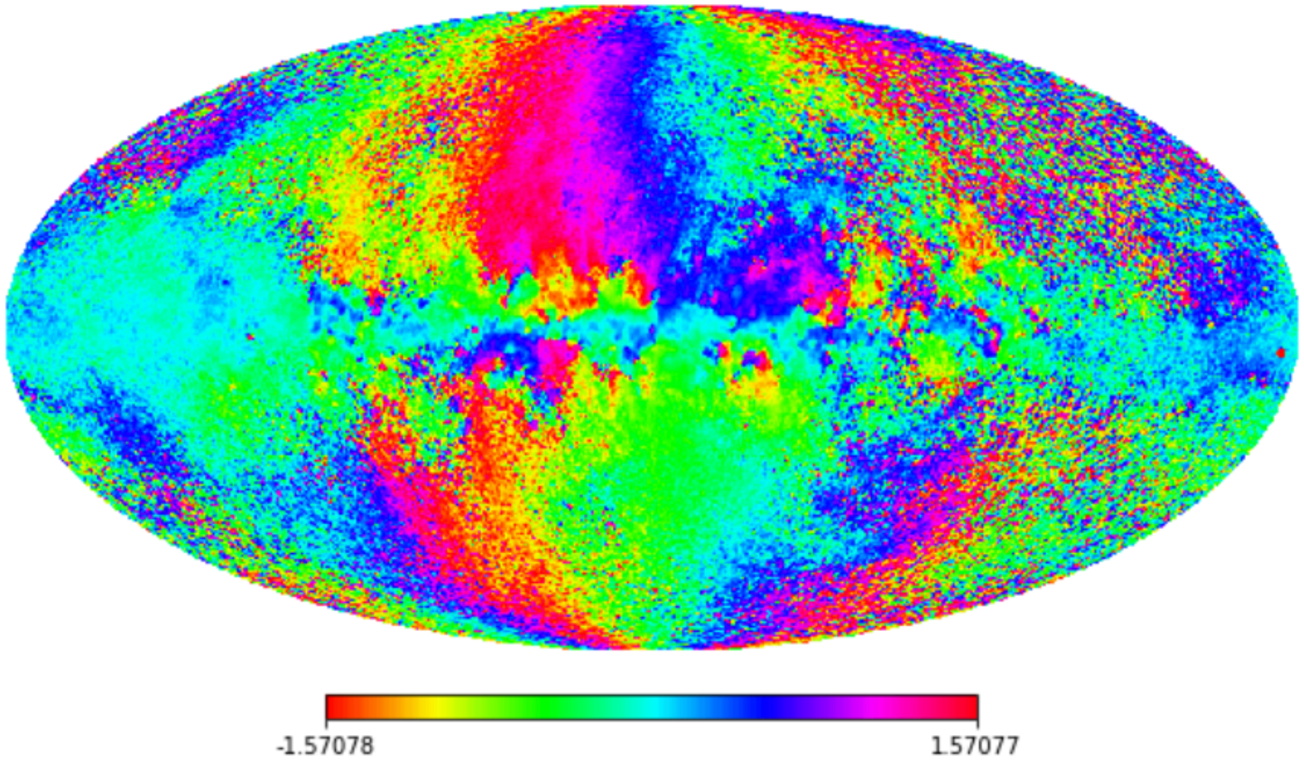


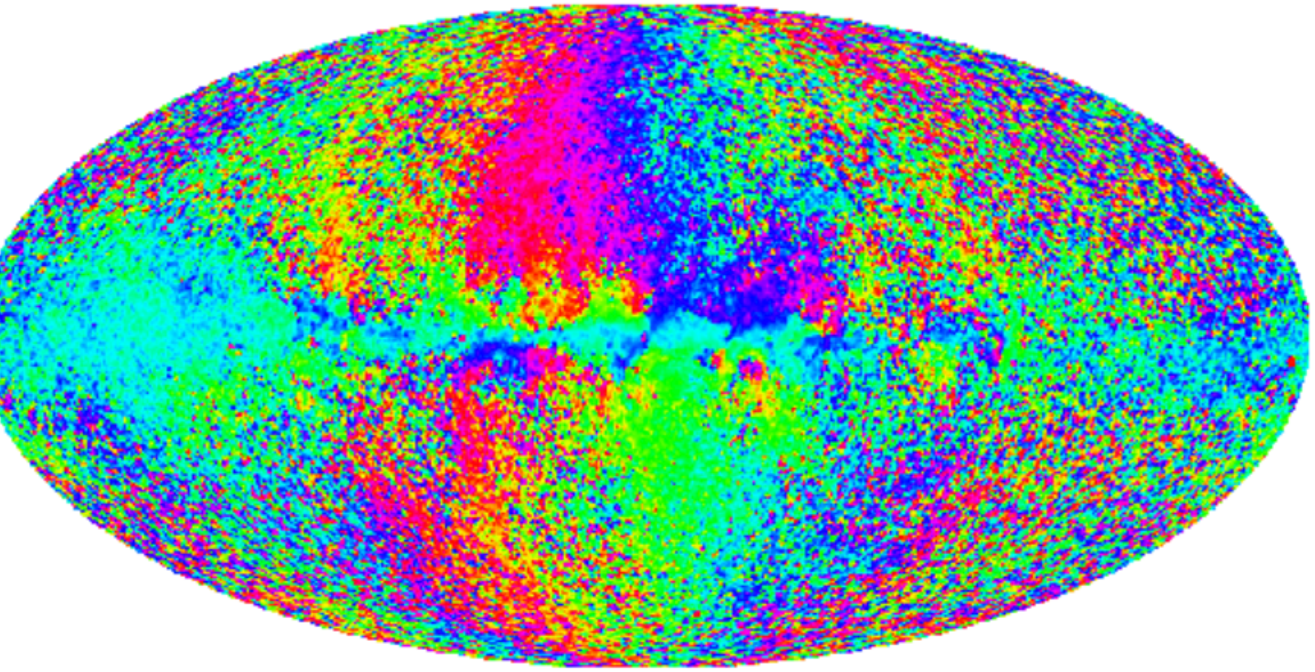


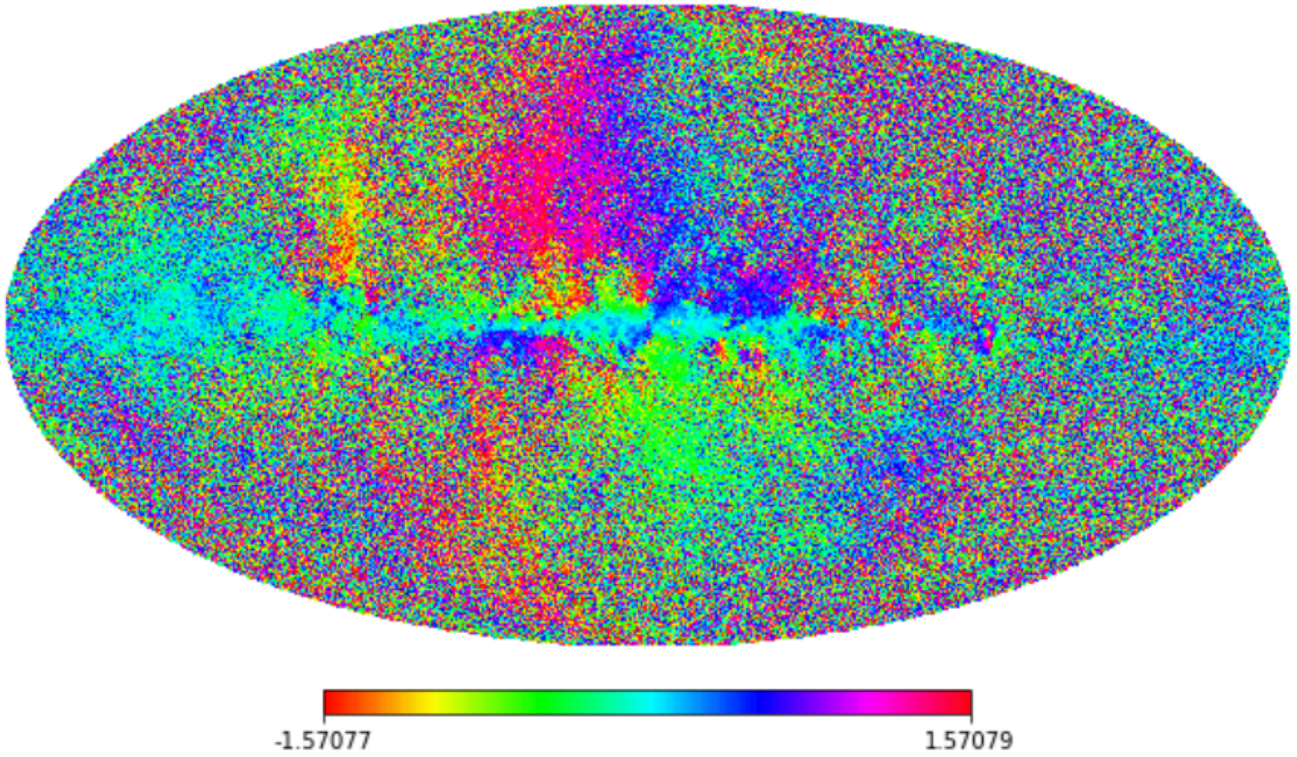
New studies of dust emmision on galactic caps with Effelsberg-Bonn HI Survey

Slide from Mike Jones


CBASS Pol Angle


WMAP K Pol Angle


WMAP Ka Pol Angle

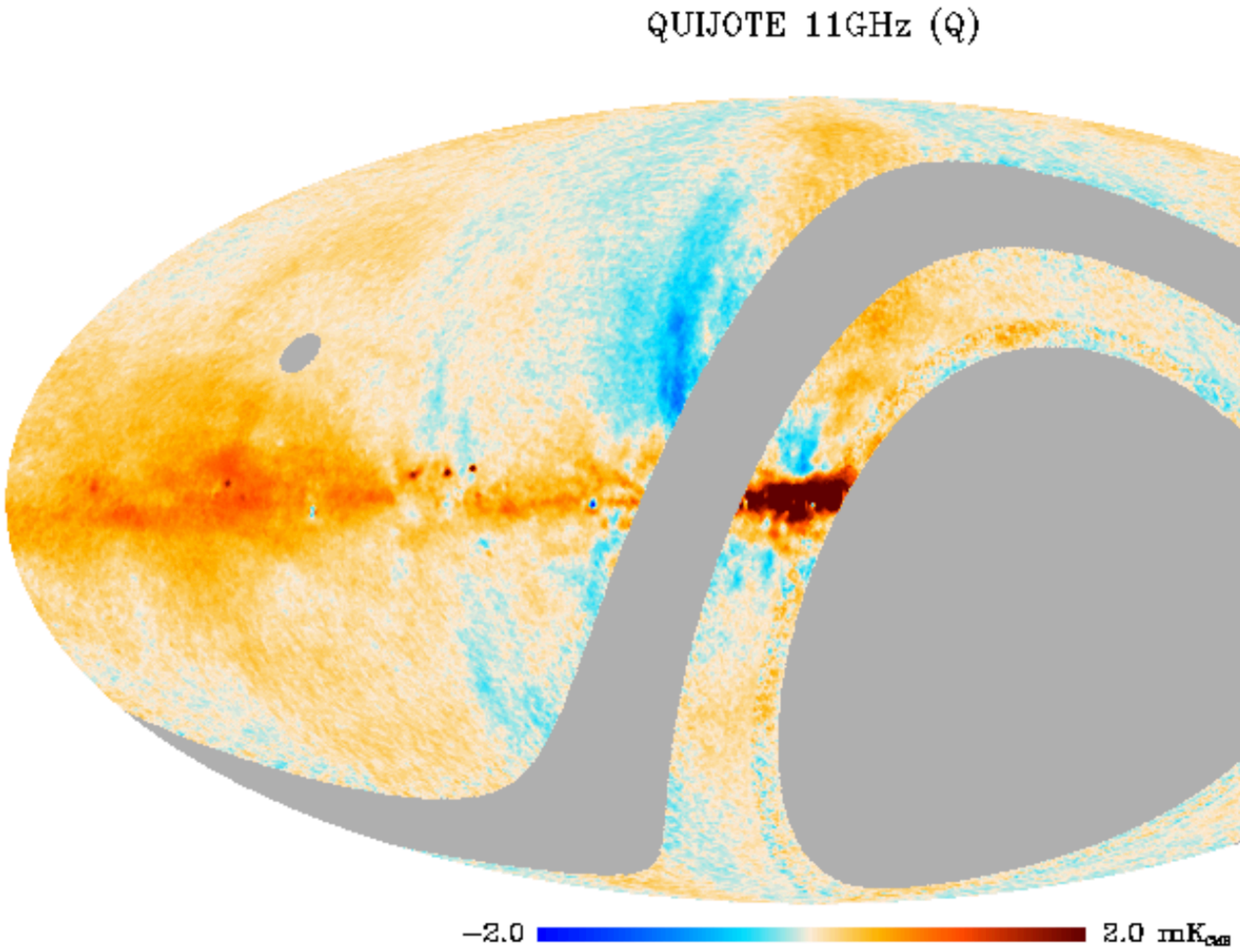

Planck 30 Pol Angle

C-BASS provides low-frequency anchor on foreground emission - high S/N detection of polarization angle distribution

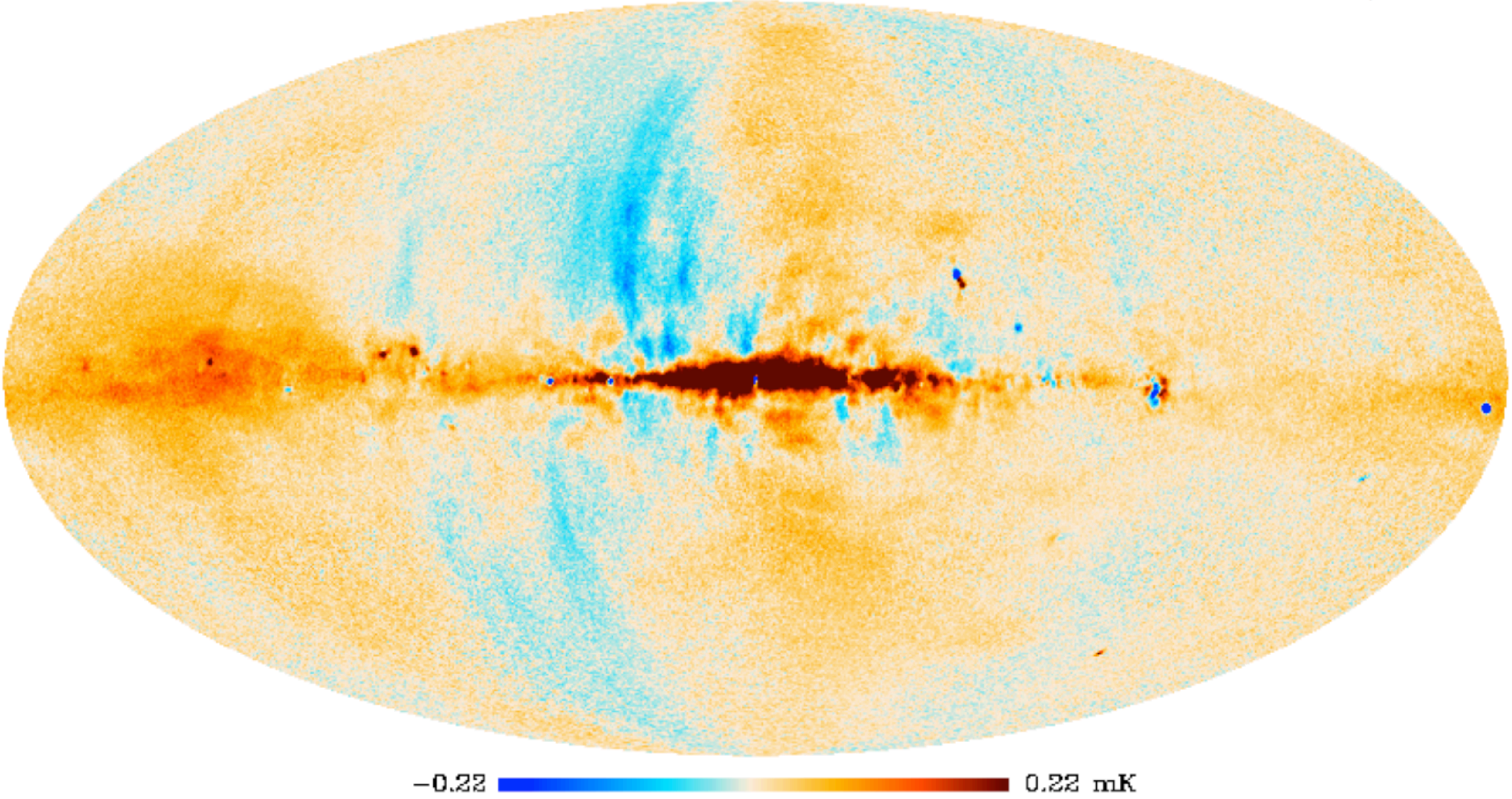
Wide survey with the QUIJOTE MFI (10-20 GHz)

Preliminary maps

(Smoothed to 1º)



Wide survey with the QUIJOTE MFI (10-20 GHz)

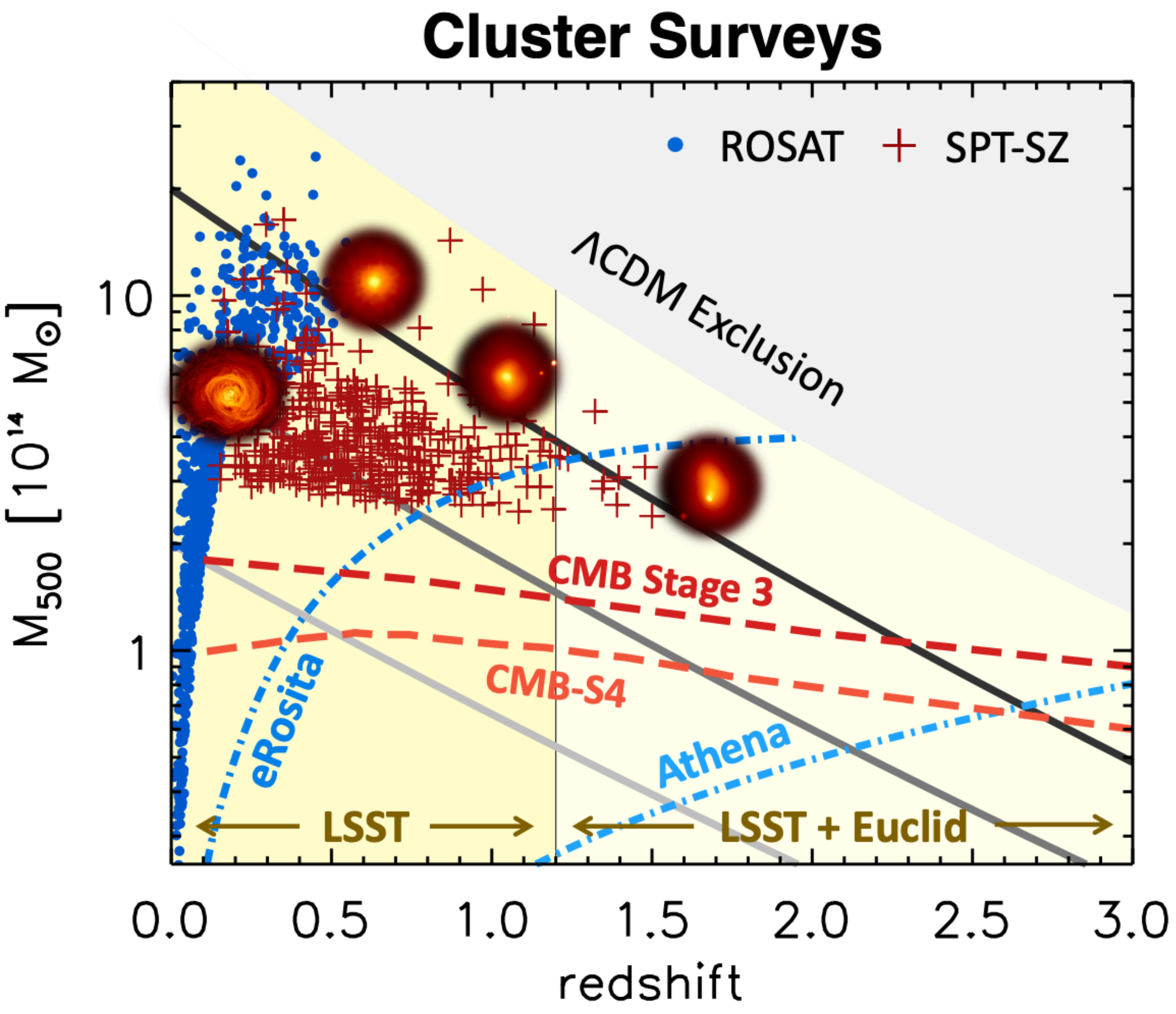

WMAP 23GHz (Q)

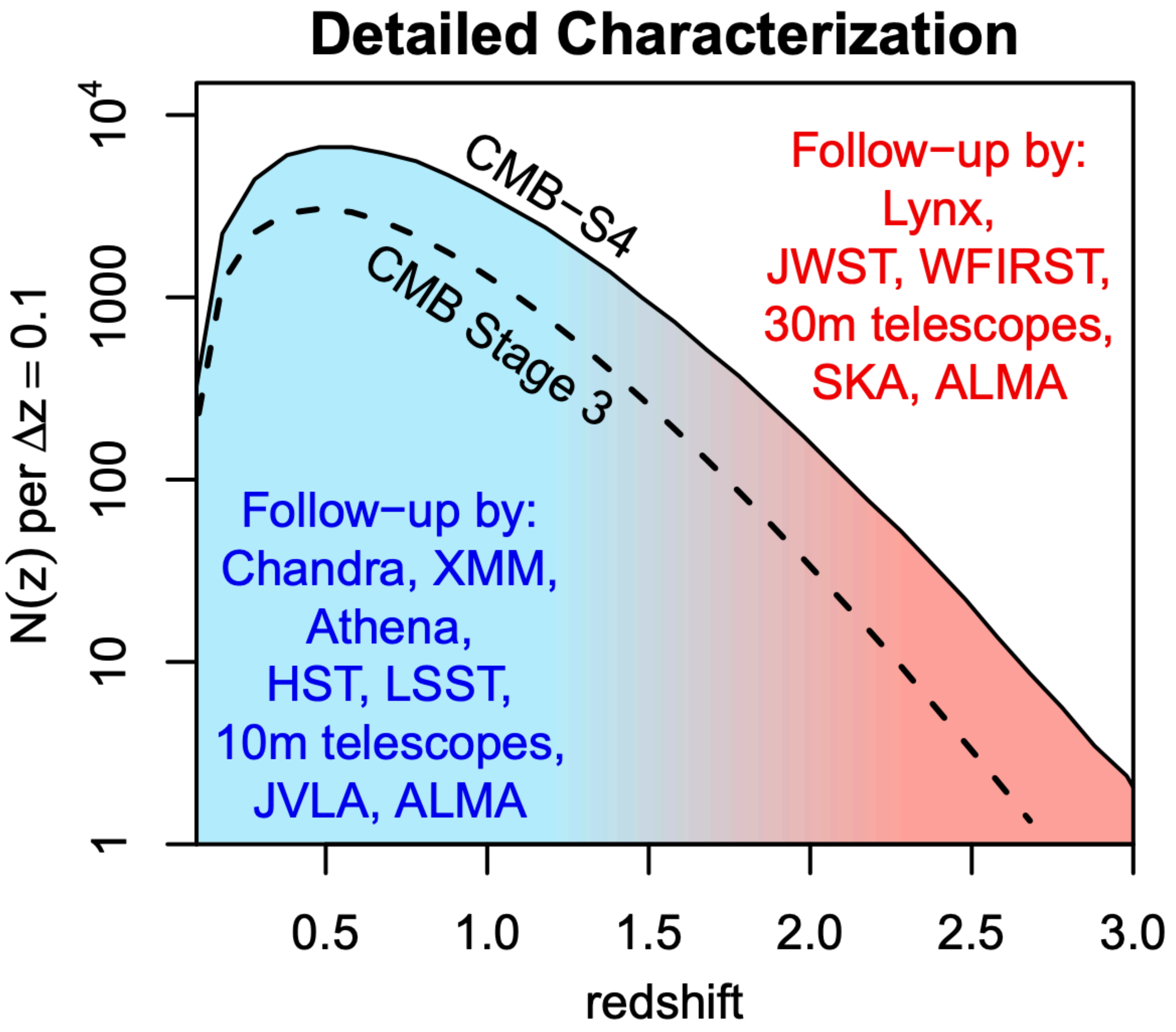
(scaled to preserve the same color
for a signal with β=-3, and
smoothed to 1º)

Slide from Jose Alberto Rubino-Martin

What did ~~we~~ I learn from 10 years ago?

1. Polarization is hard
2. Planck released amazing maps, spectra and parameters
3. Foreground science made possible by Planck
4. lower sigma8 made science with clusters harder



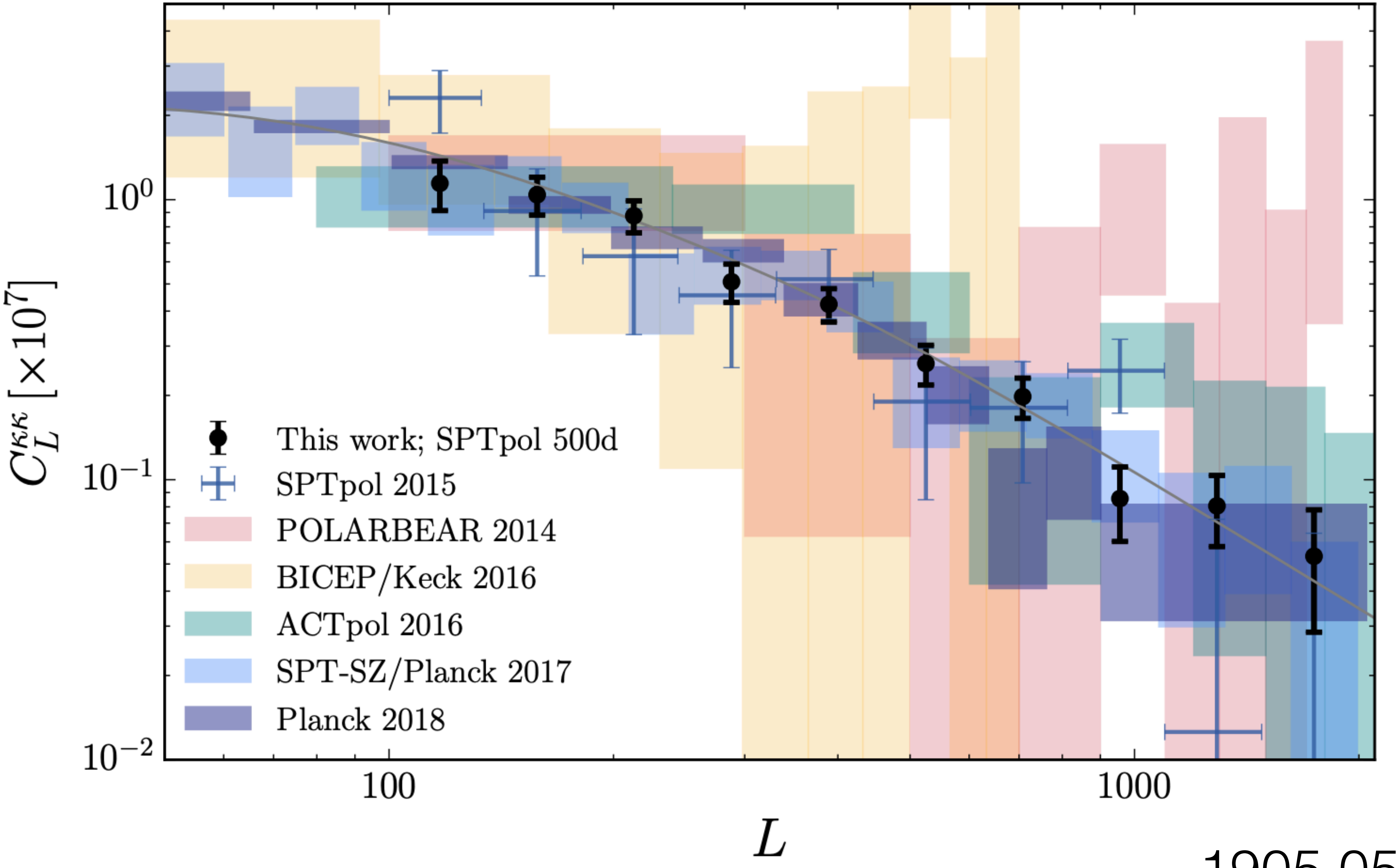


See Sunyaev's talk - this plot from Mantz et al. 2019 Cluster white paper

DUNLAP INSTITUTE
for ASTRONOMY & ASTROPHYSICS

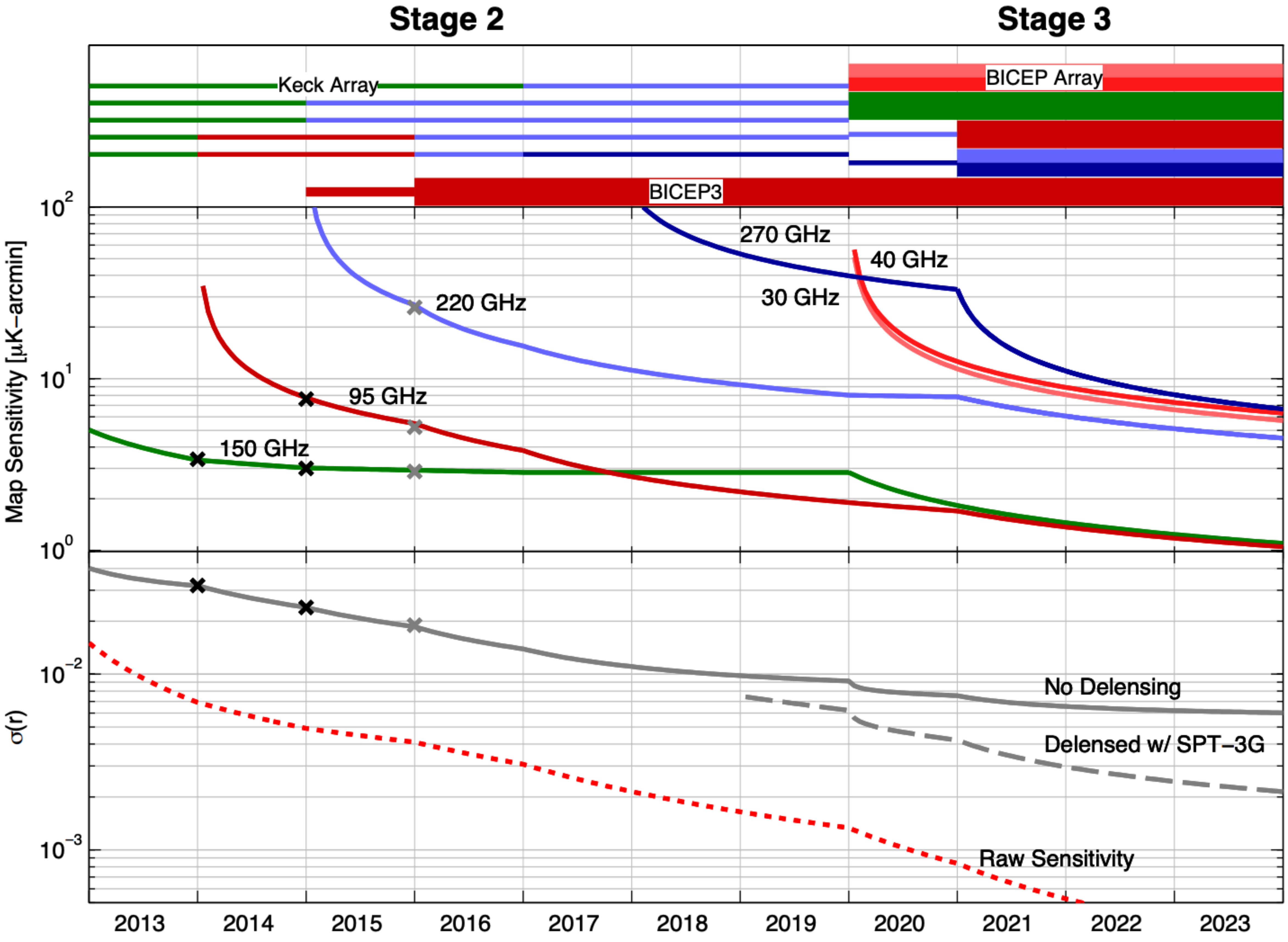
What did ~~we~~ I learn from 10 years ago?

1. Polarization is hard
2. Planck released amazing maps, spectra and parameters
3. Foreground science made possible by Planck
4. lower sigma8 made science with clusters harder
5. Ground-based experiments performed really well



1905.05777

Lots of cool science from ground based experiments - e.g. lensing (see Kimmy Wu's talk)

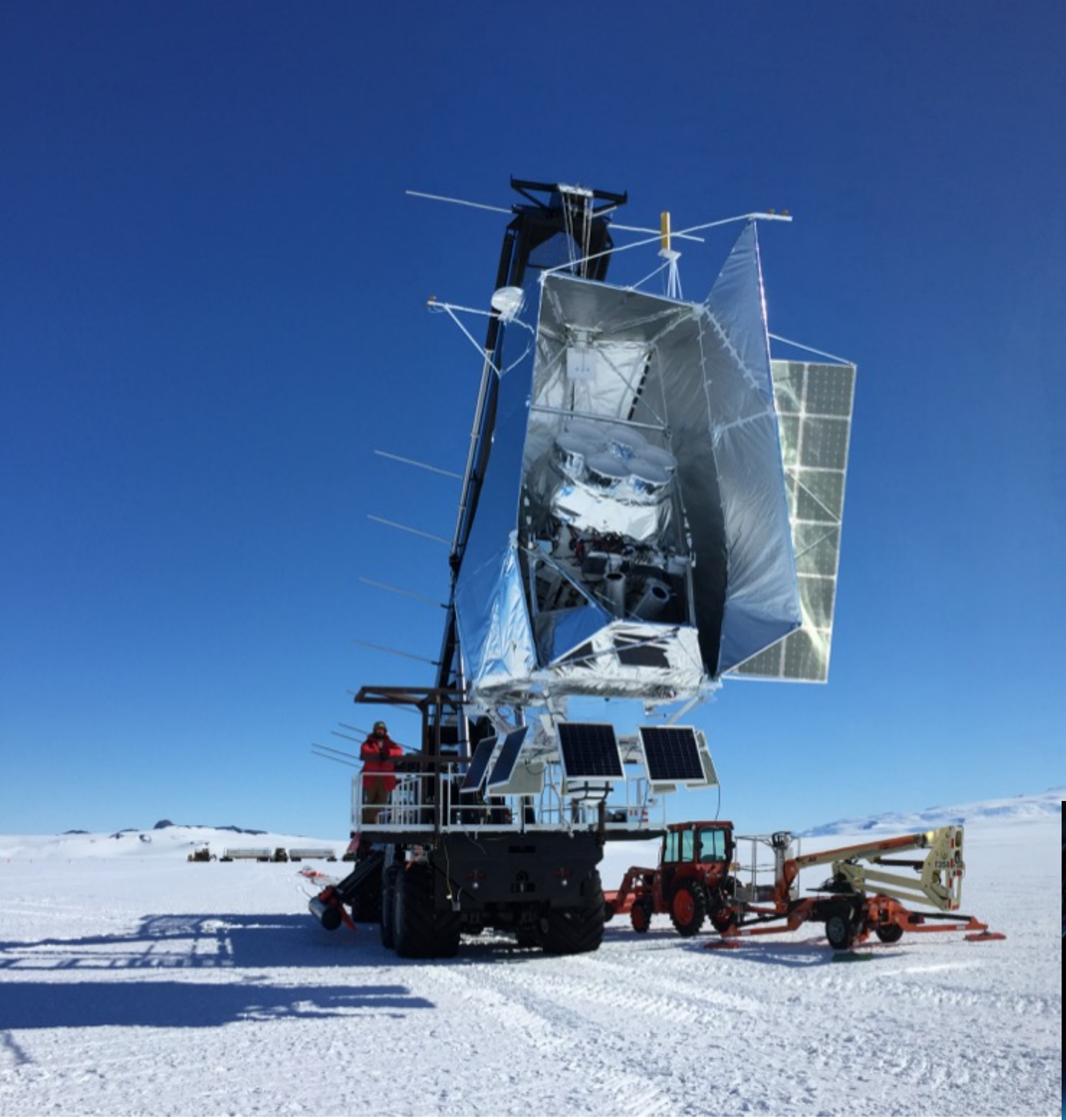


See Ben Racine's talk

Dunlap Institute for
Astronomy & Astrophysics
UNIVERSITY OF TORONTO

What did ~~we~~ I learn from 10 years ago?

1. Polarization is hard
2. Planck released amazing maps, spectra and parameters
3. Foreground science made possible by Planck
4. lower sigma8 made science with clusters harder
5. Ground-based experiments performed really well
6. Lots of innovation from balloons

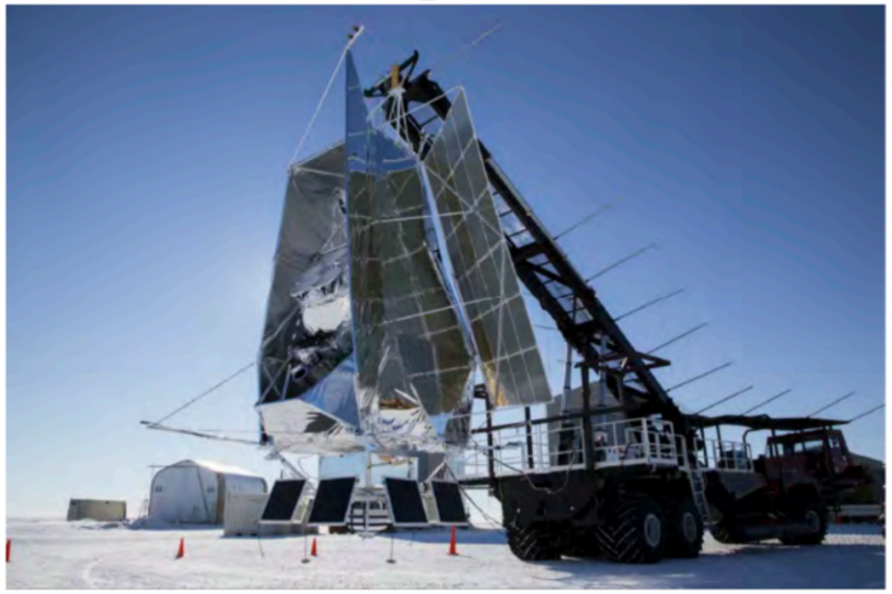


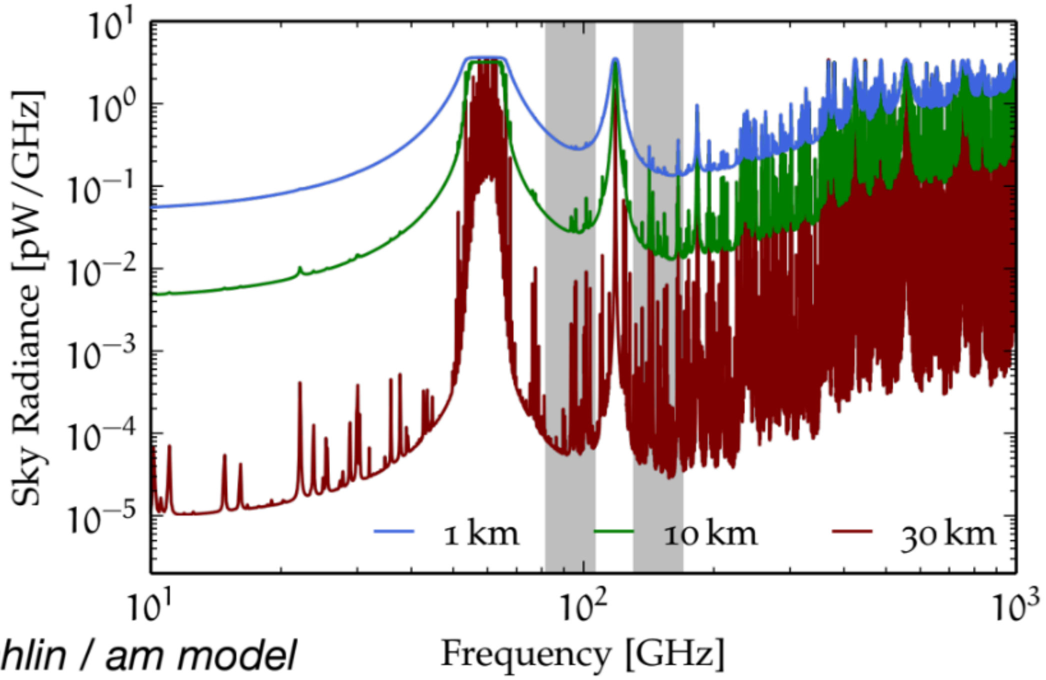
See Jeff Filippini’s talk

Antarctic Ballooning

The Good

- **High sensitivity** to approach CMB photon noise limit
- Access to **higher frequencies** obscured from the ground
- Retain **larger angular scales** due to reduced atmospheric fluctuations (*less aggressive filtering*)
- **Technology pathfinder** for orbital missions





A.S. Rahlin / am model

The Bad

- Limited **integration time** (~weeks)
- Stringent **mass**, **power** constraints
- Very limited bandwidth demands ***nearly autonomous operations***
- Elevated cosmic ray flux

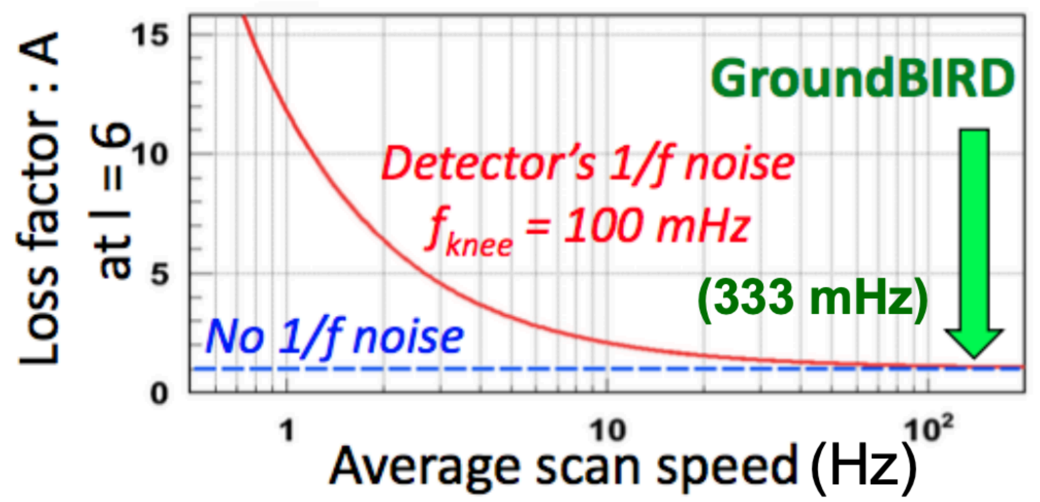
Excellent proxy for space operations!

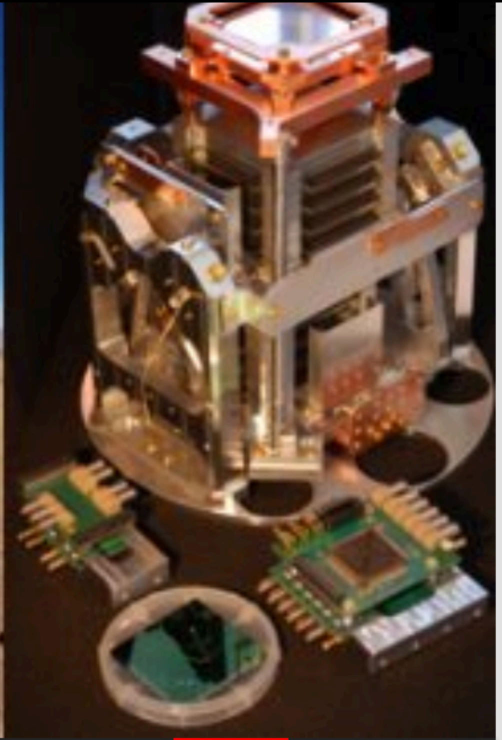
From Jeff Filippini's talk

What did ~~we~~ I learn from 10 years ago?

1. Polarization is hard
2. Planck released amazing maps, spectra and parameters
3. Foreground science made possible by Planck
4. lower sigma8 made science with clusters harder
5. Ground-based experiments performed really well
6. Lots of innovation from balloons
7. There are lots more experiments about to start taking data!

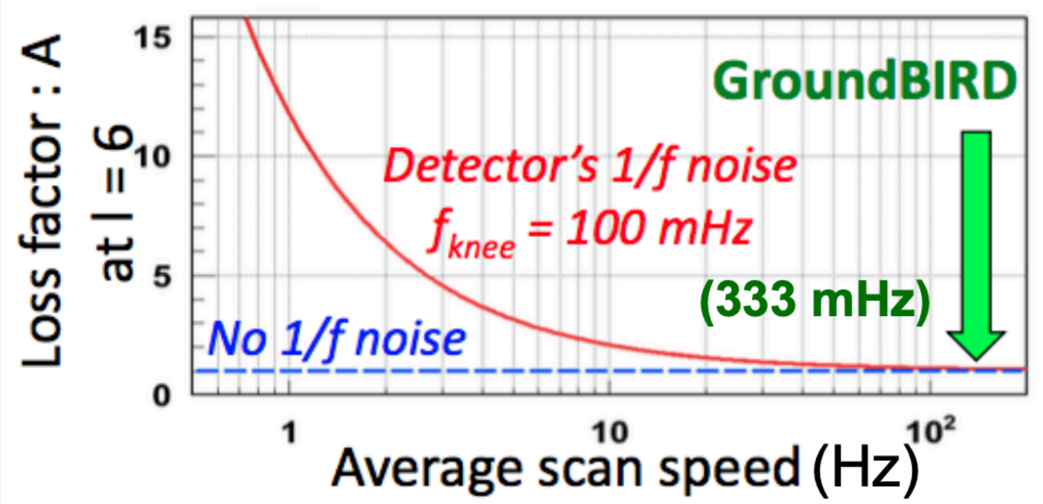
LSPE : the Large-Scale Polarization Explorer

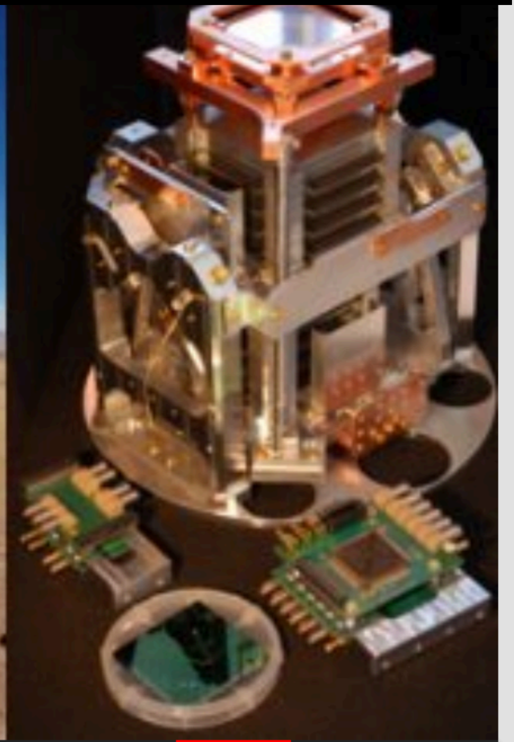




LSPE : the Large-Scale Polarization Explorer

Logos please!



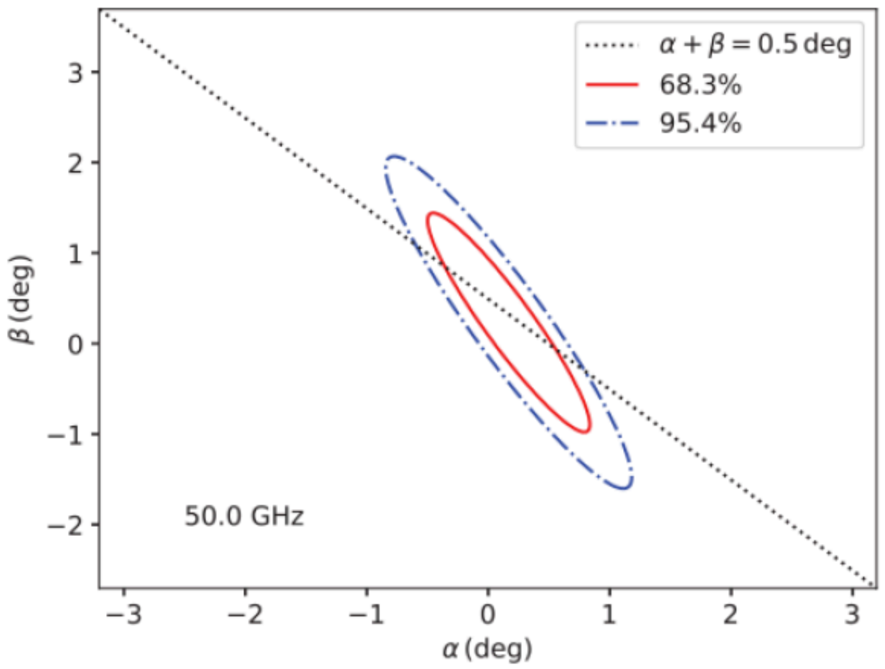


What did ~~we~~ I learn from 10 years ago?

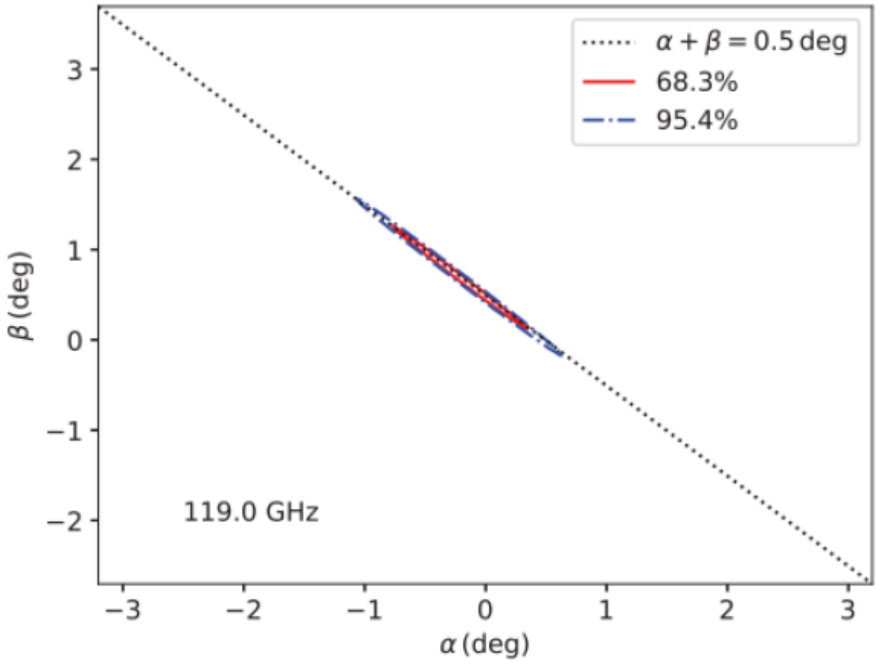
1. Polarization is hard
2. Planck released amazing maps, spectra and parameters
3. Foreground science made possible by Planck
4. lower sigma8 made science with clusters harder
5. Ground-based experiments performed really well
6. Lots of innovation from balloons
7. There are lots more experiments about to start taking data!
8. People are excited about new physics beyond SM

Correlation between α and β

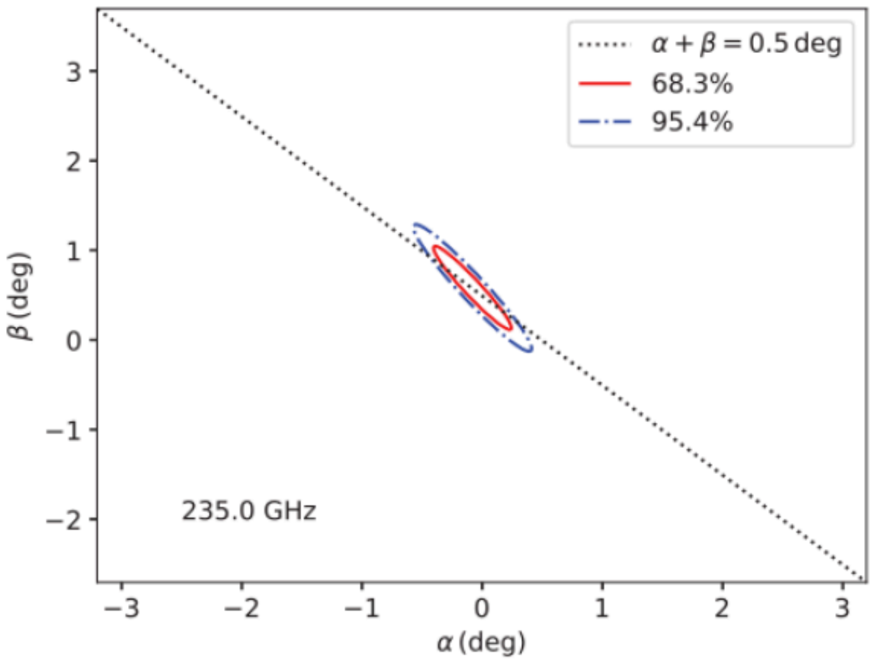
$$E^{\mathrm{o}}_{\ell,m} = E^{\mathrm{fg}}_{\ell,m}\cos(2\alpha) - B^{\mathrm{fg}}_{\ell,m}\sin(2\alpha) + E^{\mathrm{CMB}}_{\ell,m}\cos(2\alpha+2\beta) - B^{\mathrm{CMB}}_{\ell,m}\sin(2\alpha+2\beta)$$



Synchrotron channel
(50 GHz)



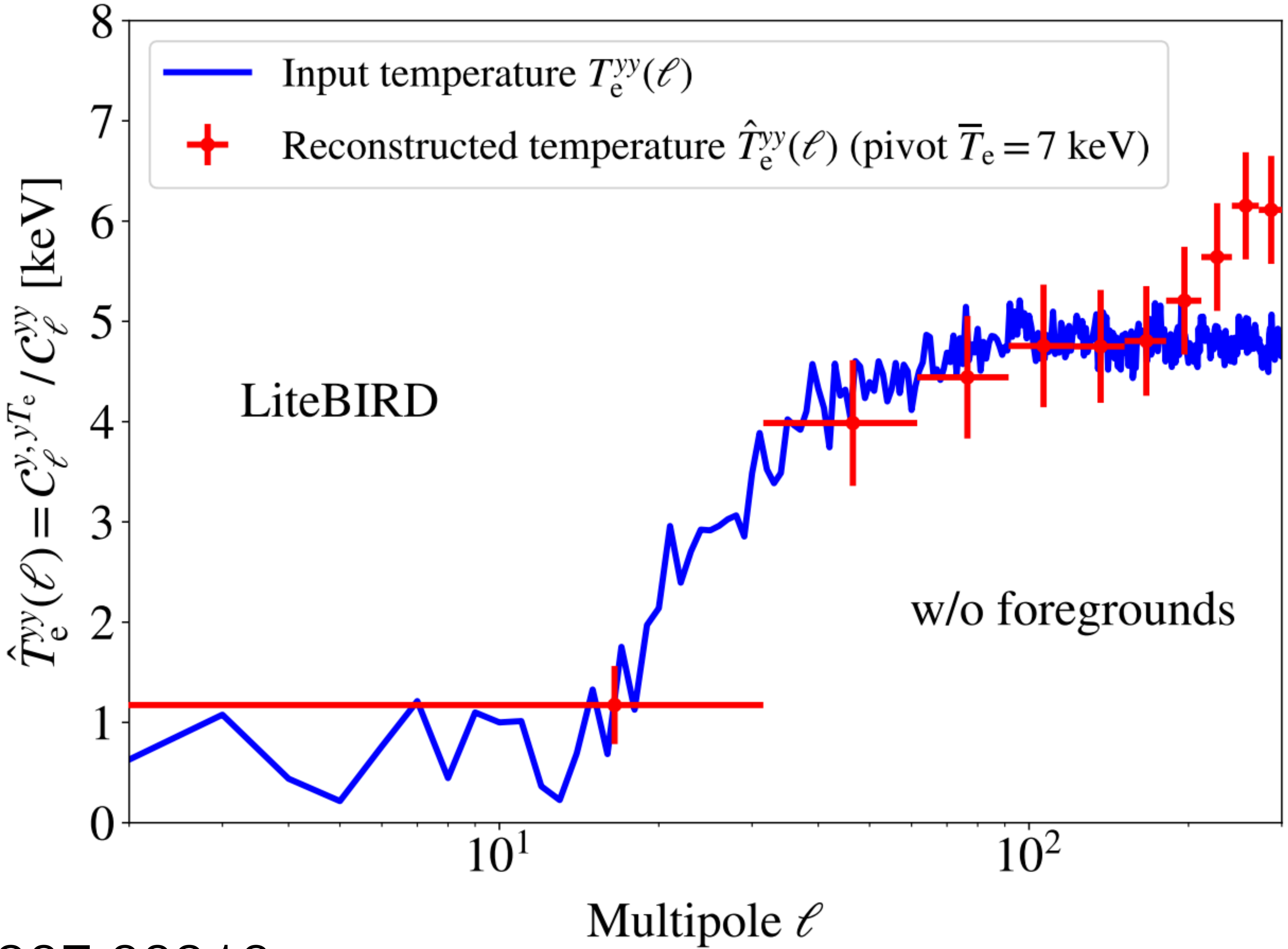
CMB channel
(119 GHz)



Dust channel
(235 GHz)

- CMB has a power to determine α+β
- FG has a power to determine α

Slide from Yuto Minimani



1907.00916

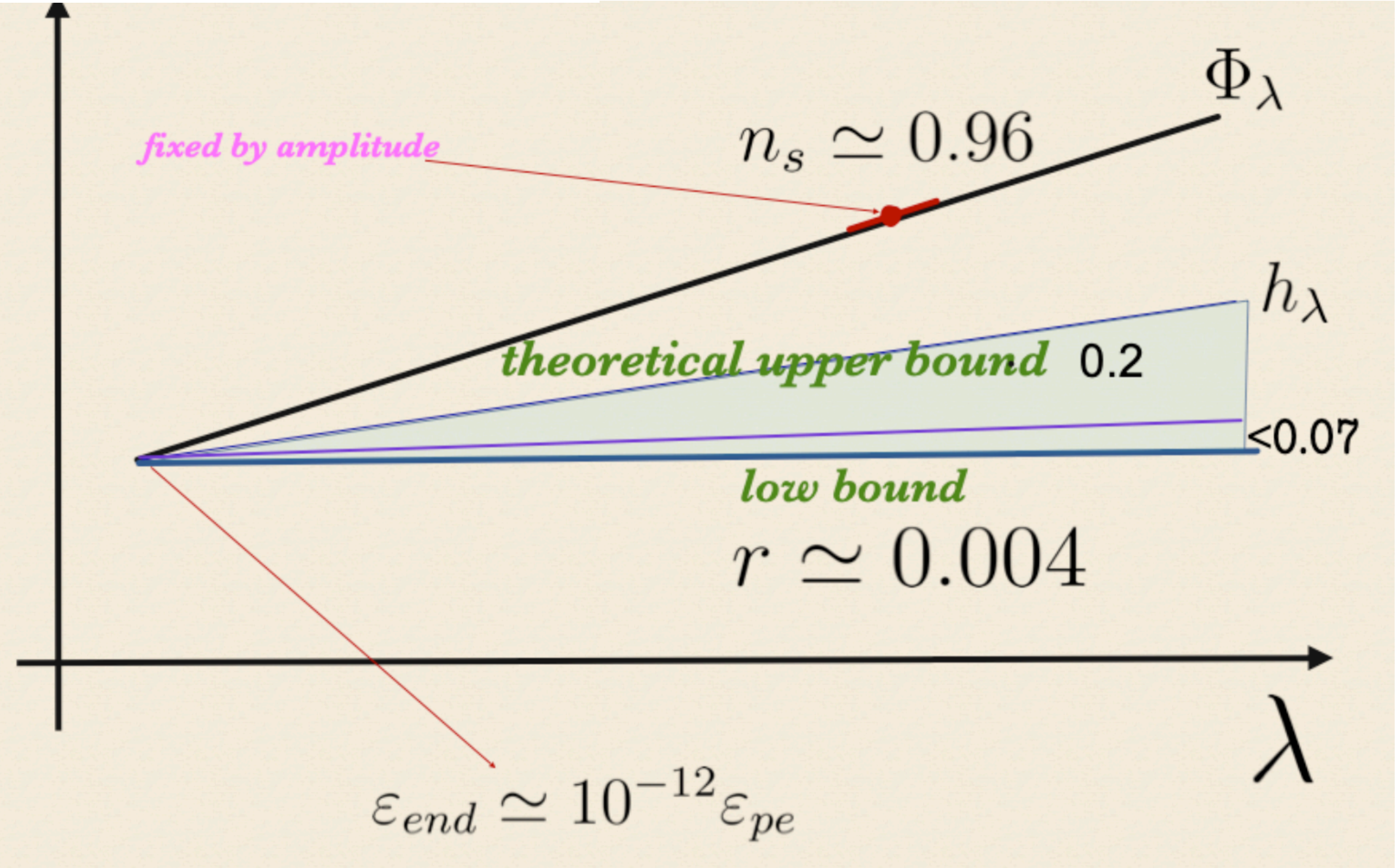
$$\Delta I^{\rm tSZ}(\nu,\boldsymbol{\theta},T_e) \simeq f\left(\nu,\overline{T}_e\right) y(\boldsymbol{\theta}) + \frac{\partial f\left(\nu,\overline{T}_e\right)}{\partial \overline{T}} y(\boldsymbol{\theta}) \left(T_e(\boldsymbol{\theta}) - \overline{T}_e\right)$$

DUNLAP INSTITUTE
for ASTRONOMY & ASTROPHYSI

Slide from Mathieu Remazeilles

What are the inflation targets?

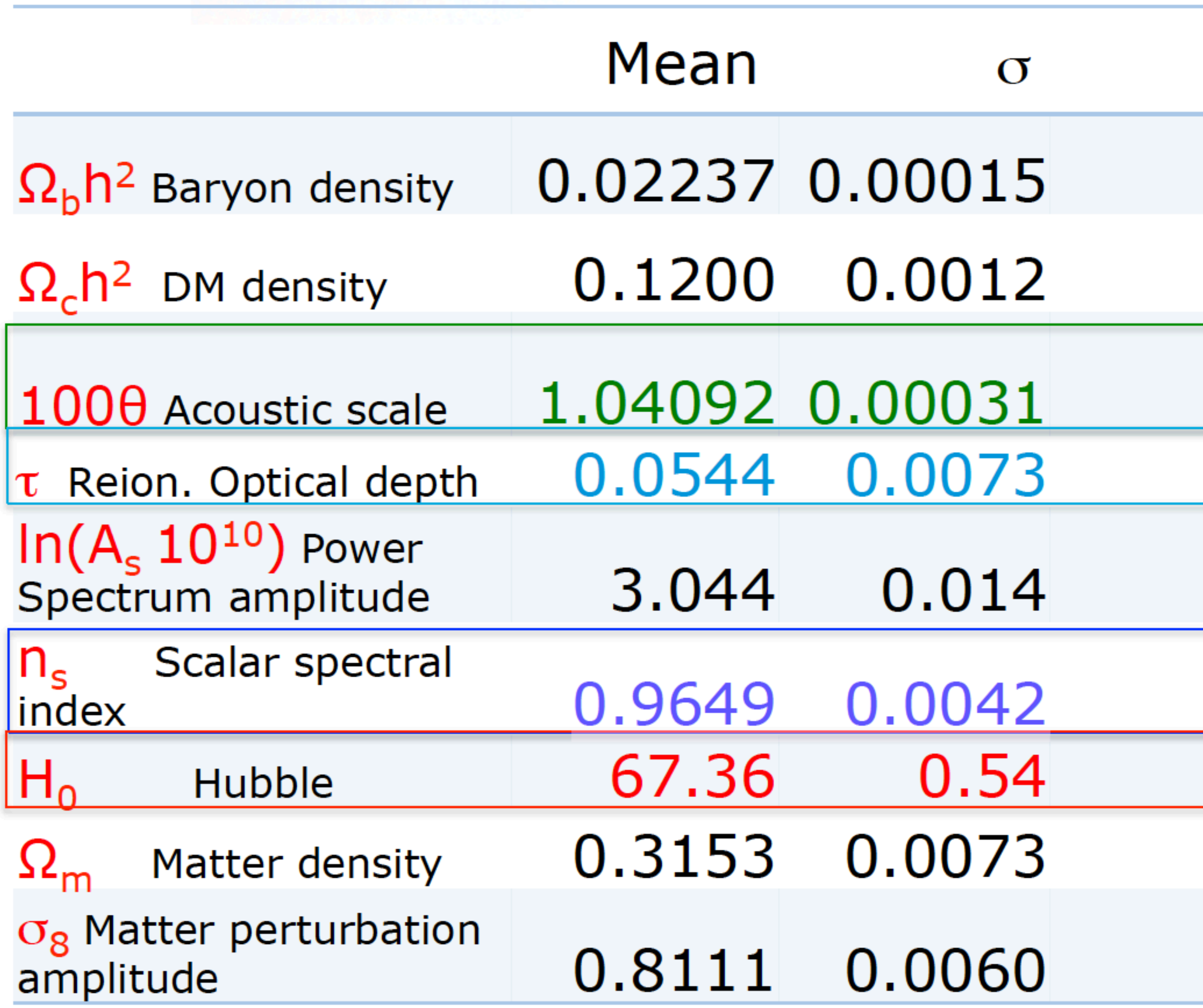
$$r \equiv \frac{T}{S} = 24 \cdot (1 + p/\varepsilon) = \frac{24\beta}{N^\alpha} \qquad 1 - n_S = 3(1+w) - \frac{d\ln(1+w)}{dN} = \frac{3\beta}{N^\alpha} + \frac{\alpha}{N}$$



huh?

What are the inflation targets?

$$\begin{aligned}
1 - n_s &= \frac{\beta}{N^\alpha} + \frac{\alpha}{N} \\
r &= 24\frac{\beta}{N^\alpha} \\
50 < N &< 60 \\
\beta &\simeq 1 \\
\alpha &= 1 \rightarrow (\lambda\phi)^n \\
&= \boxed{2 \rightarrow \text{ Starobinsky}} \\
&= 3 \rightarrow \text{ new inflation}
\end{aligned}$$



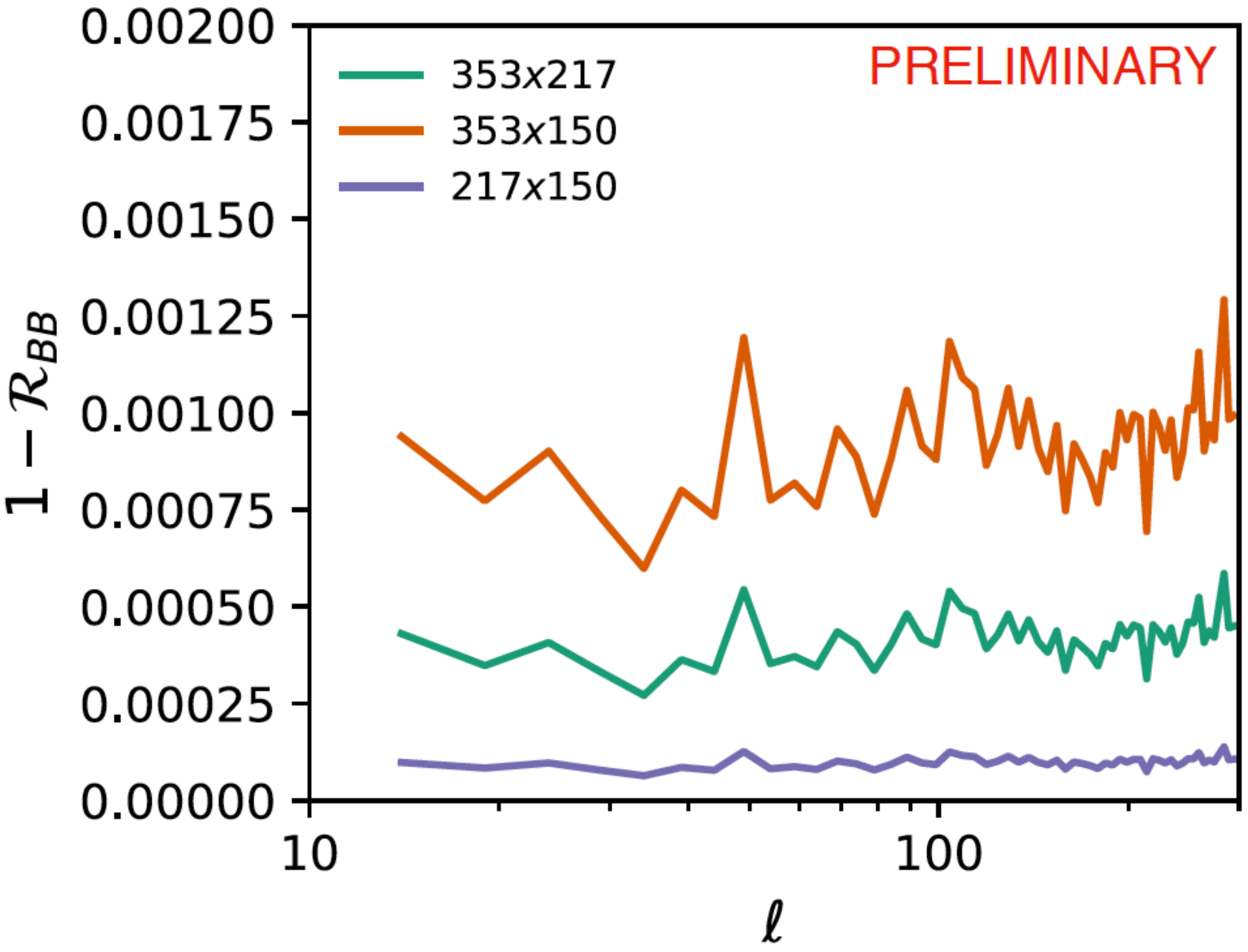
	Mean	σ
$\Omega_b h^2$ Baryon density	0.02237	0.00015
$\Omega_c h^2$ DM density	0.1200	0.0012
100θ Acoustic scale	1.04092	0.00031
τ Reion. Optical depth	0.0544	0.0073
$\ln(A_s 10^{10})$ Power Spectrum amplitude	3.044	0.014
n_s Scalar spectral index	0.9649	0.0042
H_0 Hubble	67.36	0.54
Ω_m Matter density	0.3153	0.0073
σ_8 Matter perturbation amplitude	0.8111	0.0060

$$\alpha = 2: \quad \rightarrow \quad n_s = 1 - \frac{1+2N}{N^2}\,;\, r = \frac{24}{N^2}$$

$$\begin{aligned}
N &= \frac{\sqrt{(2-n_s)/(n_s-1)^2 n_s} - \sqrt{(2-n_s)/(n_s-1)}}{n_s - 1} \\
n_s(low) &= 0.9646 - 3 \times 0.0042 \\
N(n_s \text{ low}) &= 42 \\
&\boxed{r(n_s \text{ low}) = 0.01} \\
n_s(\text{high}) &= 0.9646 + 3 \times 0.0042 \\
N(n_s \text{ high}) &= 89 \\
&\boxed{r(n_s \text{ high}) = 0.003}
\end{aligned}$$

What do we think we have got under control?

Decorrelation

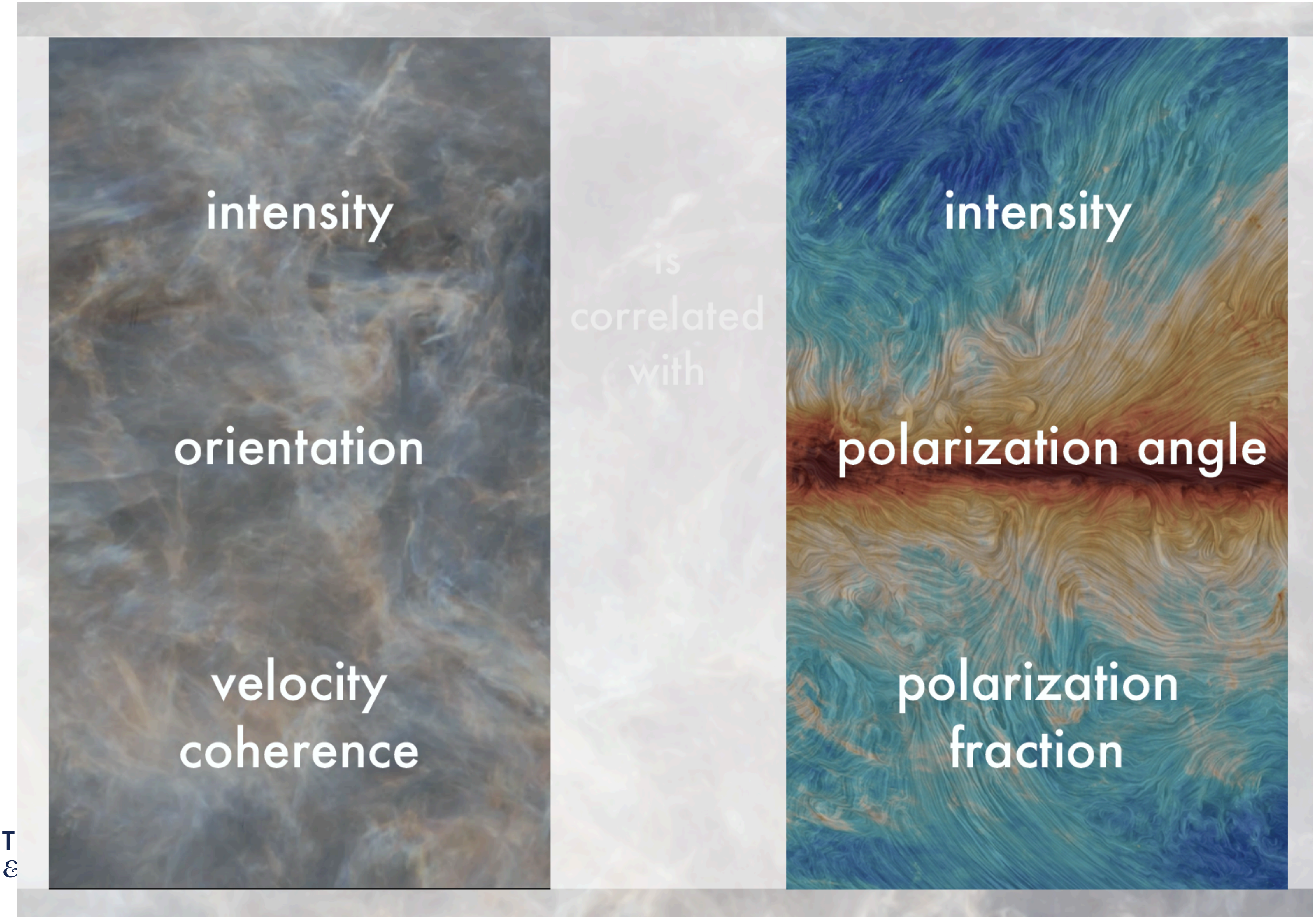


From Brandon Hensley’s talk

What do we think we have got under control?

Dust from the ISM

From Susan Clark's talk



intensity

orientation

velocity coherence

is correlated with

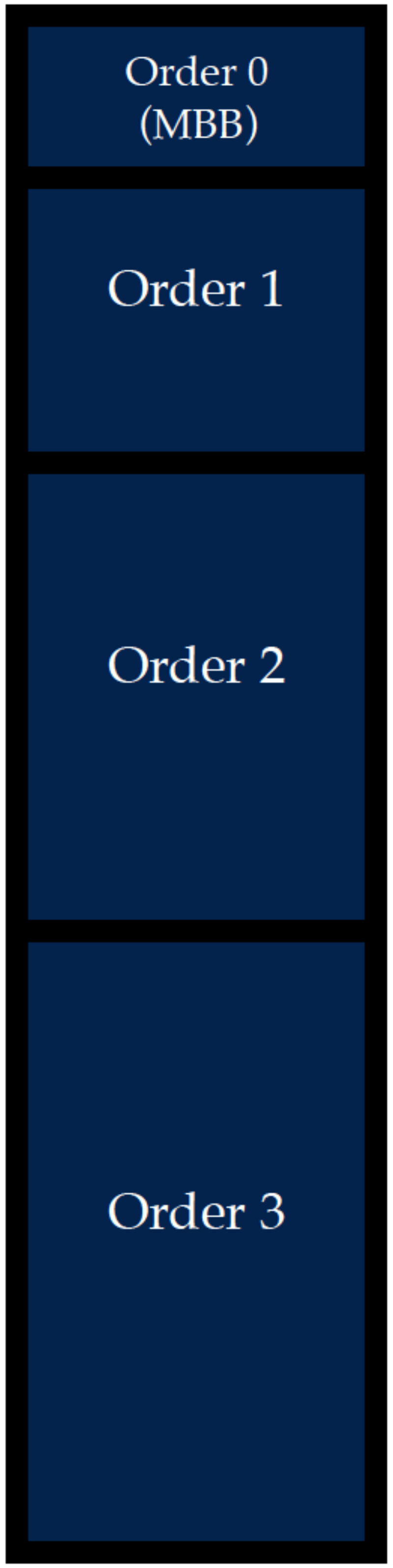
intensity

polarization angle

polarization fraction

X-SPECTRA MOMENT EXPANSION — Formalism

POWER SPECTRUM DOMAIN


Order 0
(MBB)

Order 1

Order 2

Order 3

$$
\begin{aligned}
\mathcal{D}_\ell(\nu_1\times\nu_2) = \frac{I_{\nu_1}(T_0,\beta_0(\ell))I_{\nu_2}(T_0,\beta_0(\ell))}{I_{\nu_0}(T_0,\beta_0(\ell))^2}\Bigg\{ & \mathcal{D}_\ell^{A_\mathrm{D}A_\mathrm{D}} \\
& + \left[\ln\frac{\nu_1}{\nu_0}+\ln\frac{\nu_2}{\nu_0}\right]\mathcal{D}_\ell^{A_\mathrm{D}\omega_1} \\
& + \left[\ln\frac{\nu_1}{\nu_0}\ln\frac{\nu_2}{\nu_0}\right]\mathcal{D}_\ell^{\omega_1\omega_1} \\
& + \frac{1}{2}\left[\ln^2\frac{\nu_1}{\nu_0}+\ln^2\frac{\nu_2}{\nu_0}\right]\mathcal{D}_\ell^{A_\mathrm{D}\omega_2} \\
& + \frac{1}{2}\left[\ln\frac{\nu_1}{\nu_0}\ln^2\frac{\nu_2}{\nu_0}+\ln\frac{\nu_2}{\nu_0}\ln^2\frac{\nu_1}{\nu_0}\right]\mathcal{D}_\ell^{\omega_1\omega_2} \\
& + \frac{1}{4}\left[\ln^2\frac{\nu_1}{\nu_0}\ln^2\frac{\nu_2}{\nu_0}\right]\mathcal{D}_\ell^{\omega_2\omega_2} \\
& + \frac{1}{6}\left[\ln^3\frac{\nu_1}{\nu_0}+\ln^3\frac{\nu_2}{\nu_0}\right]\mathcal{D}_\ell^{A_\mathrm{D}\omega_3} \\
& + \frac{1}{6}\left[\ln\frac{\nu_1}{\nu_0}\ln^3\frac{\nu_2}{\nu_0}+\ln\frac{\nu_2}{\nu_0}\ln^3\frac{\nu_1}{\nu_0}\right]\mathcal{D}_\ell^{\omega_1\omega_3} \\
& + \frac{1}{12}\left[\ln^2\frac{\nu_1}{\nu_0}\ln^3\frac{\nu_2}{\nu_0}+\ln^2\frac{\nu_2}{\nu_0}\ln^3\frac{\nu_1}{\nu_0}\right]\mathcal{D}_\ell^{\omega_2\omega_3} \\
& + \frac{1}{36}\left[\ln^3\frac{\nu_1}{\nu_0}\ln^3\frac{\nu_2}{\nu_0}\right]\mathcal{D}_\ell^{\omega_3\omega_3} \\
& + \dots\Bigg\}
\end{aligned}
$$

Leading order term ~ bias on , $\beta_0(\ell)$ in the limit of many moments

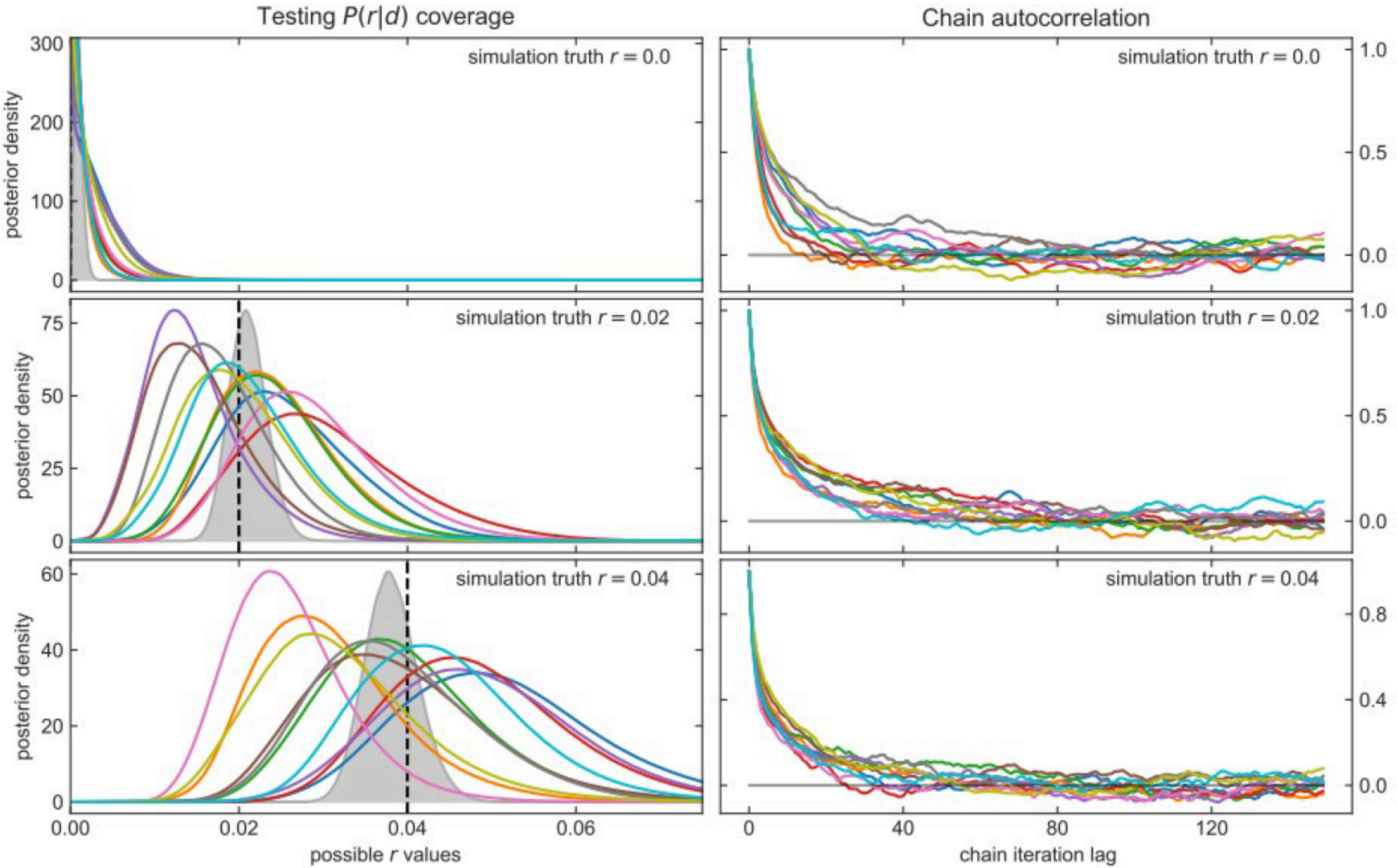
[Mangilli et al., 2019, to be submitted]

Slide from Jonathan Aumont

What do we think we have got under control?

Delensing

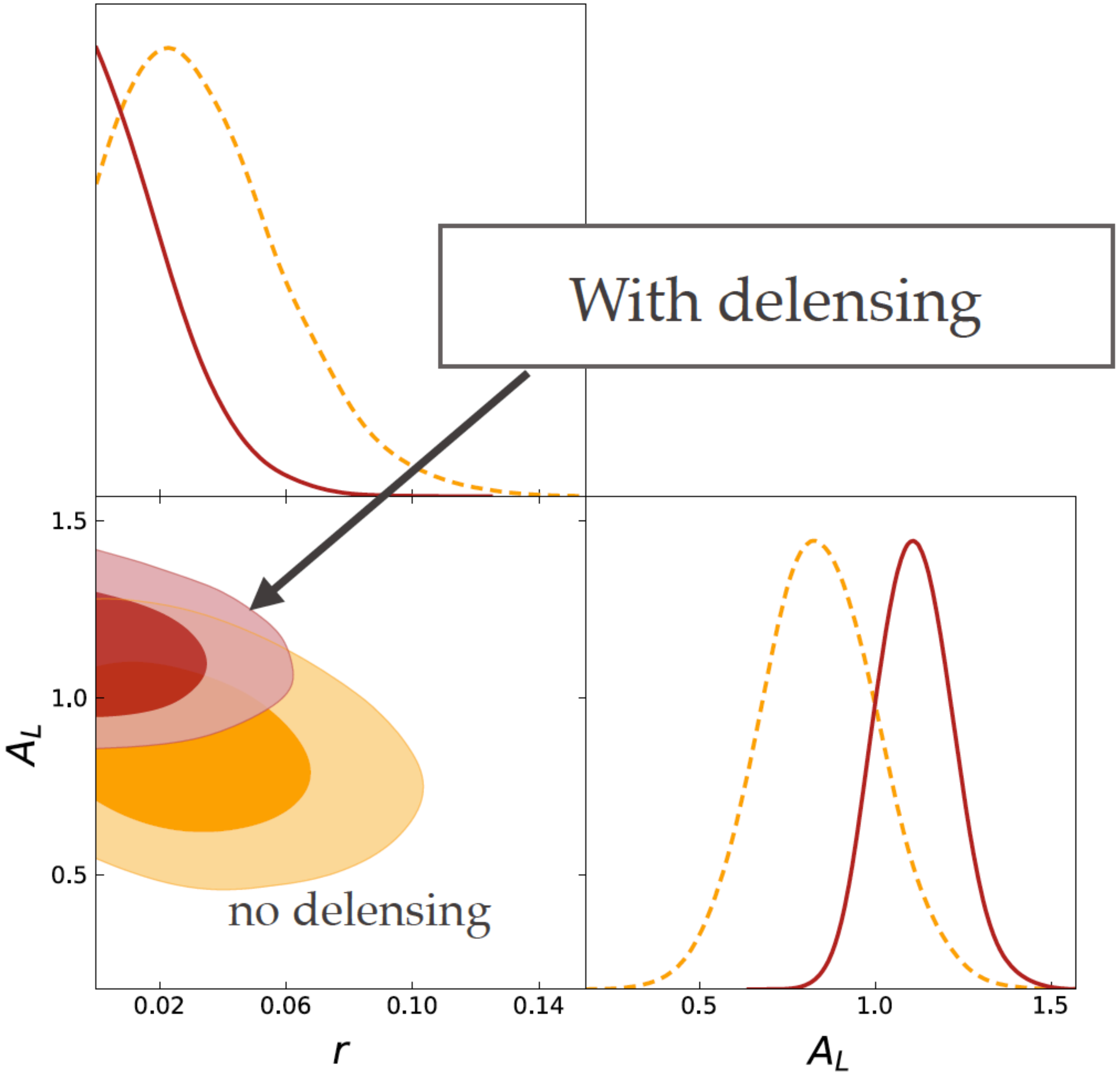
From Marius Millea’s talk



What do we think we have got under control?

Delensing

From Kimmy Wu's talk



What do we think will keep us up at night?

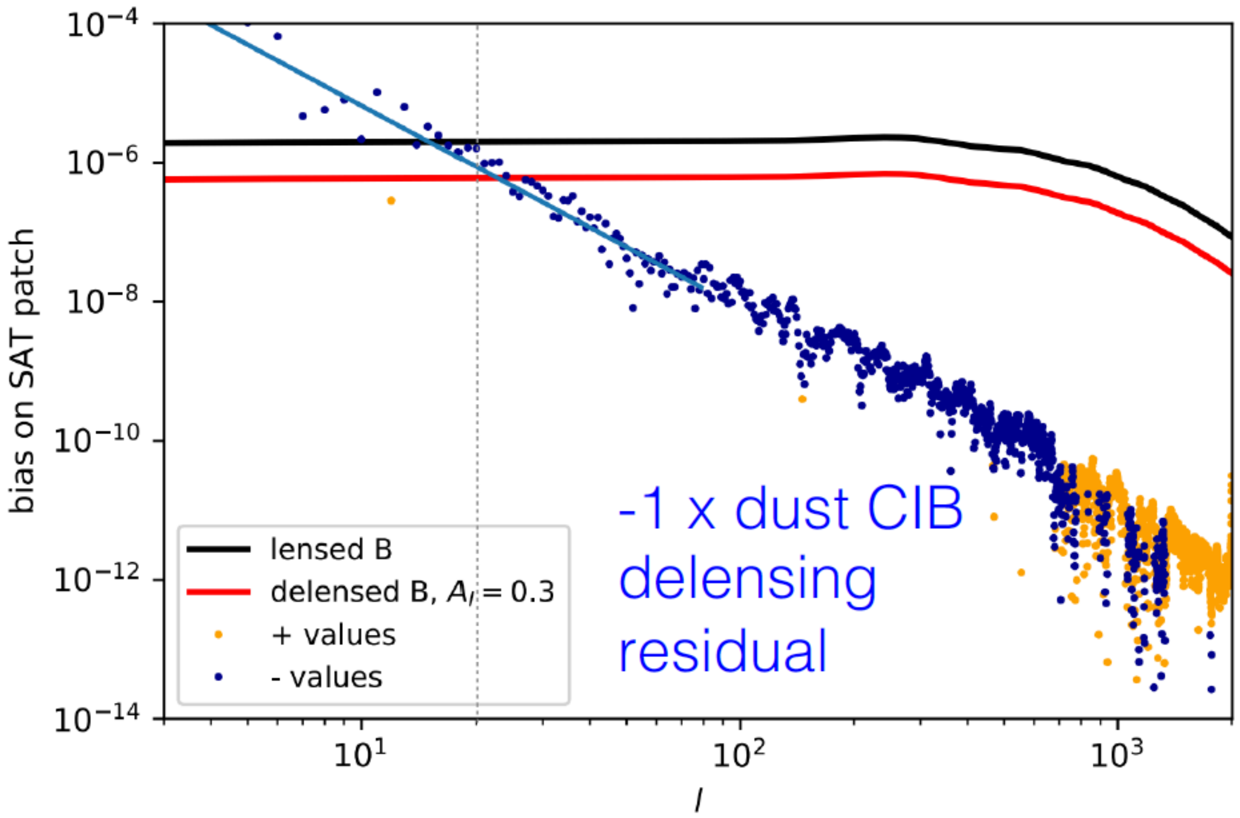
Delensing

Why this might not work:
Correlated foreground propagation,…

- Lensing foregrounds correlated with B foregrounds can give biases, e.g., <(B-Ed) x (B-Ed)>, cross terms involving <BEd>

fgs.??? fgs.??? fgs.???

From Blake Sherwin's talk



-1 x dust CIB delensing residual

CIB delensing dust residuals appear small for SO/S4, but non-negligible at large scales

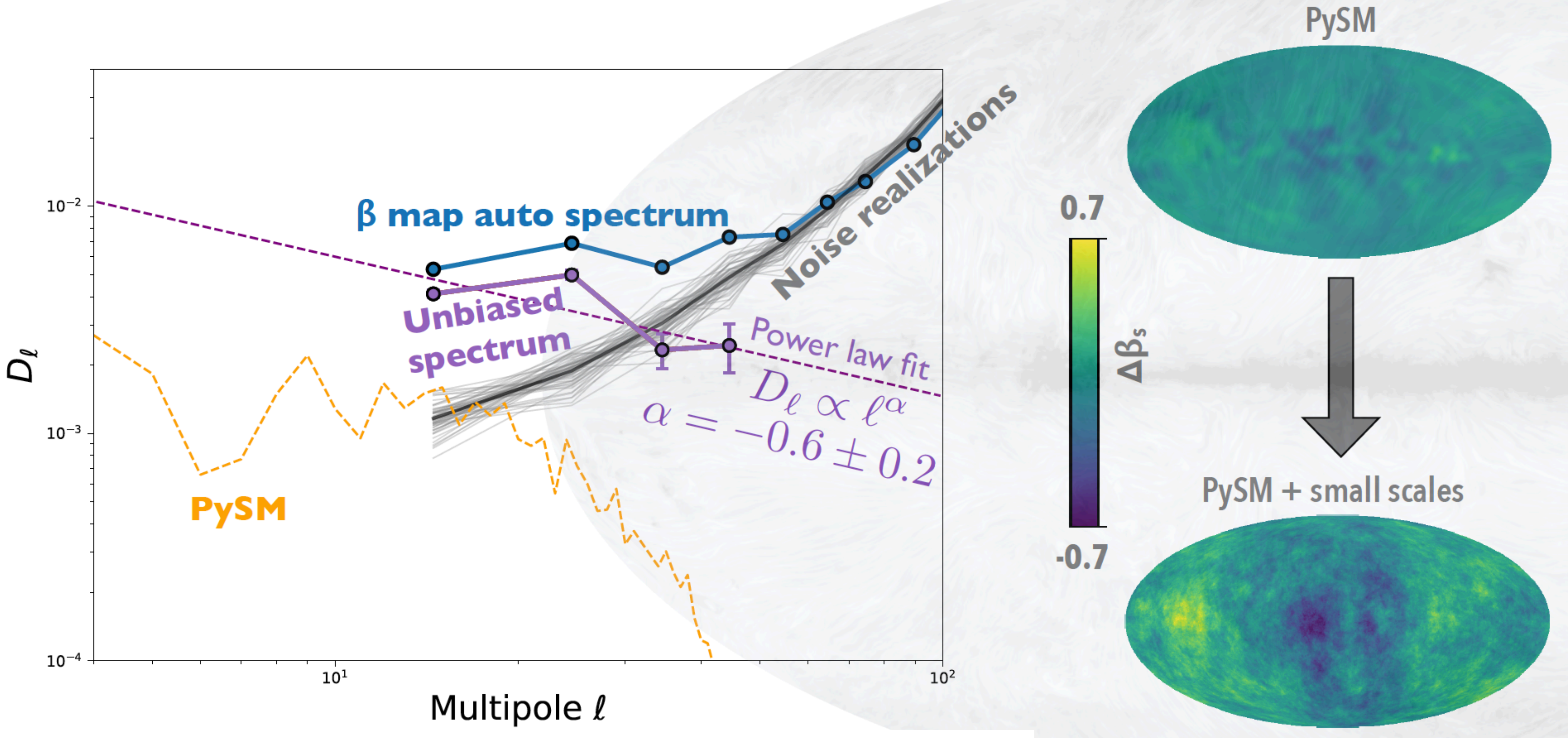
[Baleato, Challinor, Sherwin, Namikawa prep.]

- Other challenges: likelihood and integration with foreground cleaning,…

What do we think will keep us up at night?

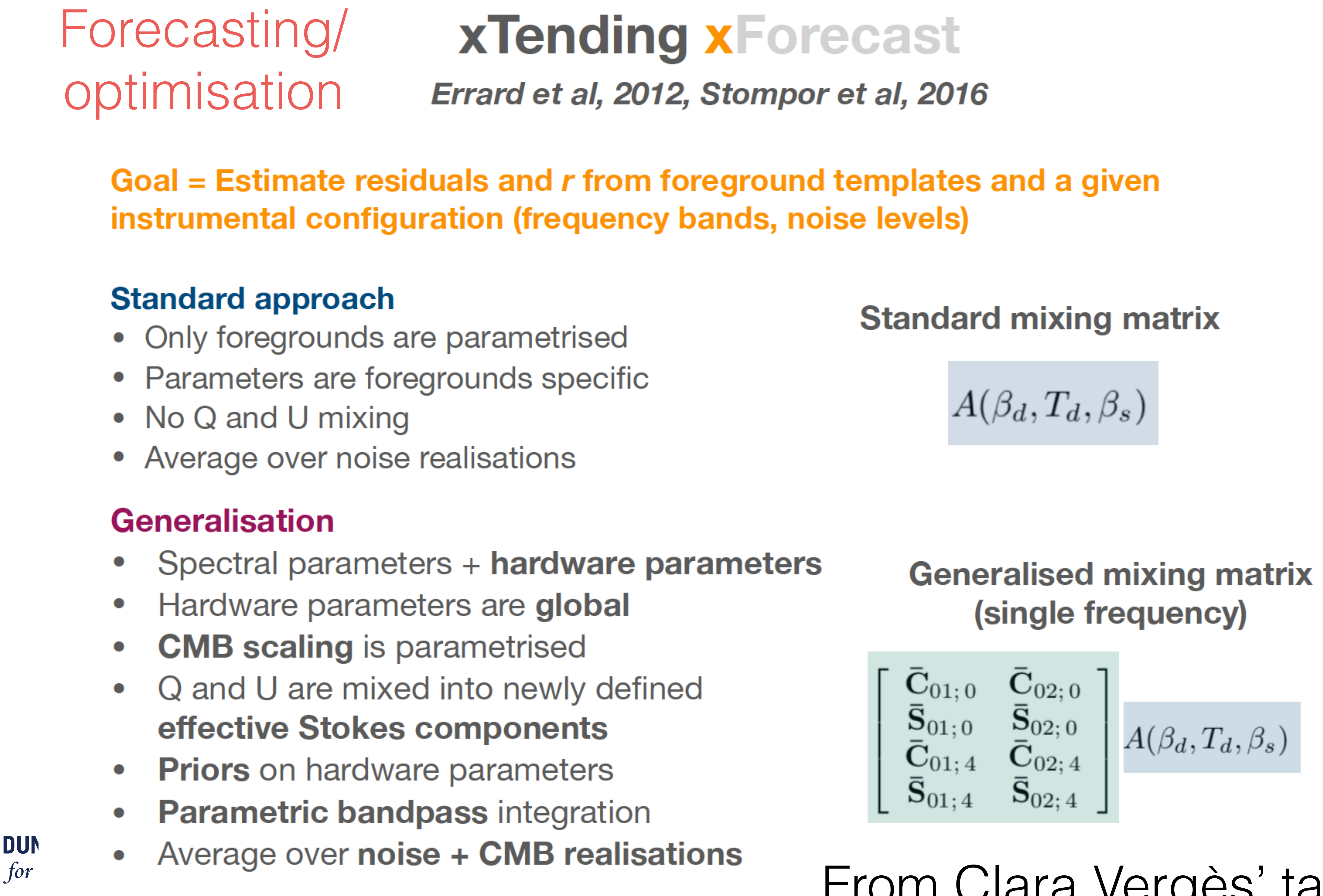
Foreground cleaning

i. **Large scale** signal amplitude and morphology
ii. **Small scale** signal amplitude and statistics
iii. **Global SED** model
iv. **SED** spatial **variation**



From Nicoletta Krachmalnicoff's talk

What do we think will keep us up at night?



Forecasting/ optimisation

xTending xForecast

Errard et al, 2012, Stompor et al, 2016

Goal = Estimate residuals and *r* from foreground templates and a given instrumental configuration (frequency bands, noise levels)

Standard approach

- Only foregrounds are parametrised
- Parameters are foregrounds specific
- No Q and U mixing
- Average over noise realisations

Standard mixing matrix

$$A(\beta_d, T_d, \beta_s)$$

Generalisation

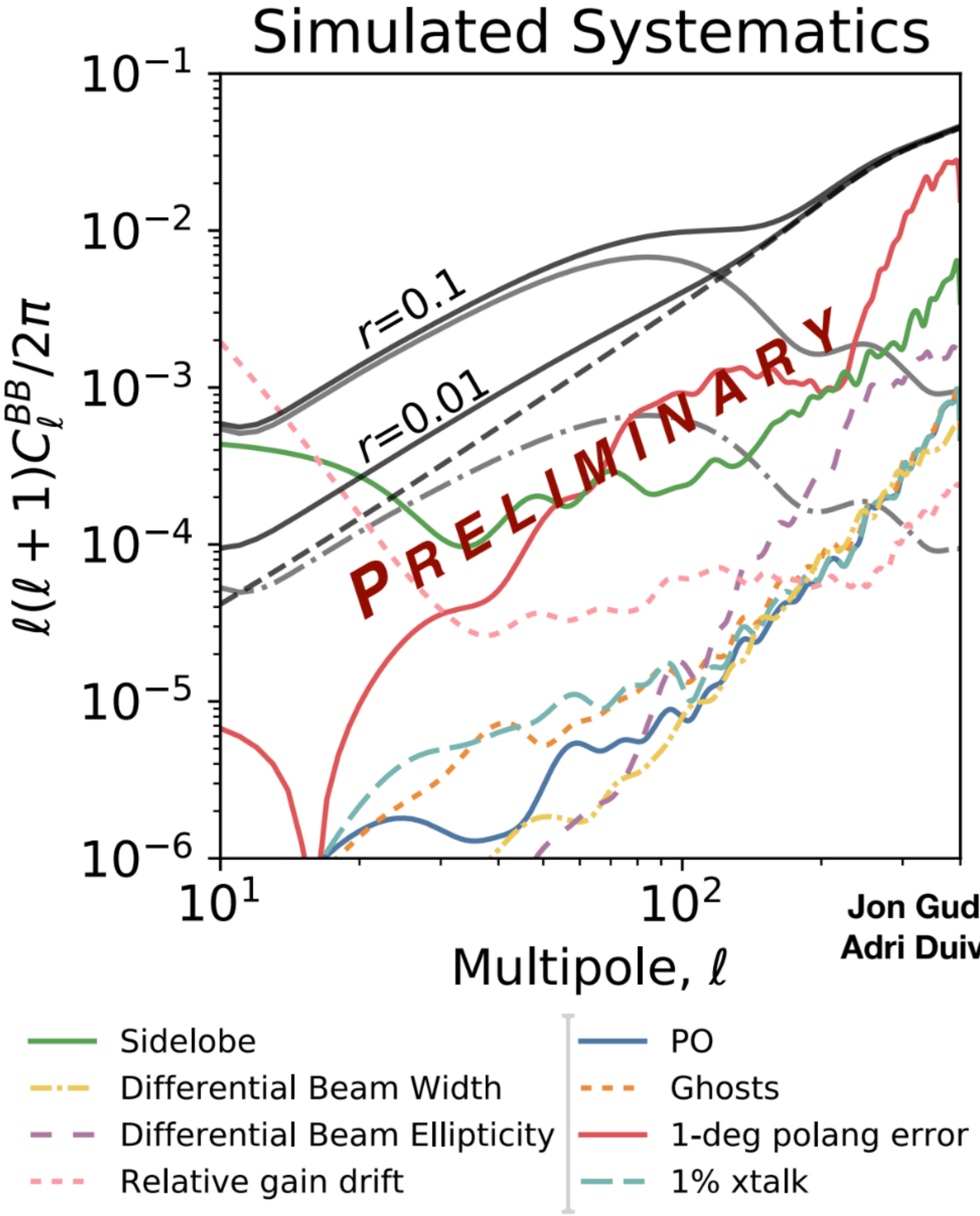
- Spectral parameters + **hardware parameters**
- Hardware parameters are **global**
- **CMB scaling** is parametrised
- Q and U are mixed into newly defined **effective Stokes components**
- **Priors** on hardware parameters
- **Parametric bandpass** integration
- Average over **noise + CMB realisations**

Generalised mixing matrix (single frequency)

$$\begin{bmatrix} \bar{\mathrm{C}}_{01;\,0} & \bar{\mathrm{C}}_{02;\,0} \\ \bar{\mathrm{S}}_{01;\,0} & \bar{\mathrm{S}}_{02;\,0} \\ \bar{\mathrm{C}}_{01;\,4} & \bar{\mathrm{C}}_{02;\,4} \\ \bar{\mathrm{S}}_{01;\,4} & \bar{\mathrm{S}}_{02;\,4} \end{bmatrix} A(\beta_d, T_d, \beta_s)$$

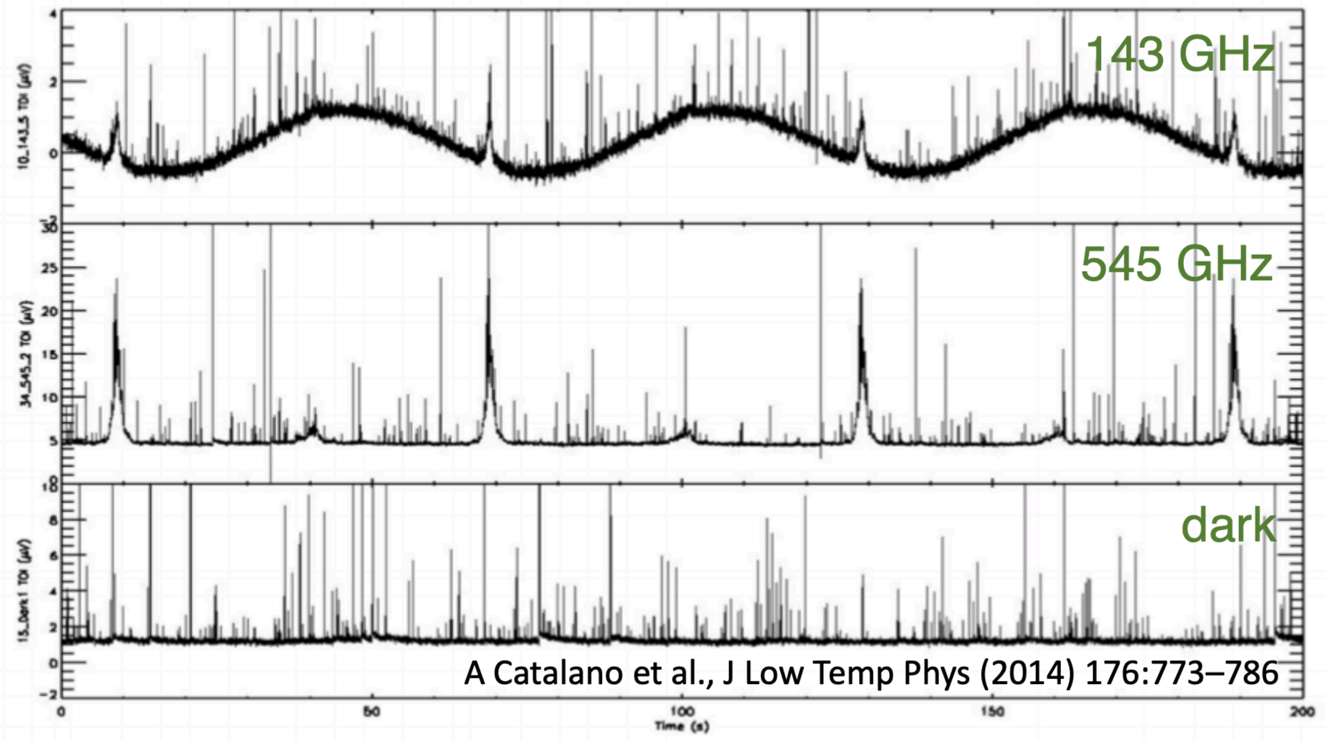
From Clara Vergès' talk

Systematics

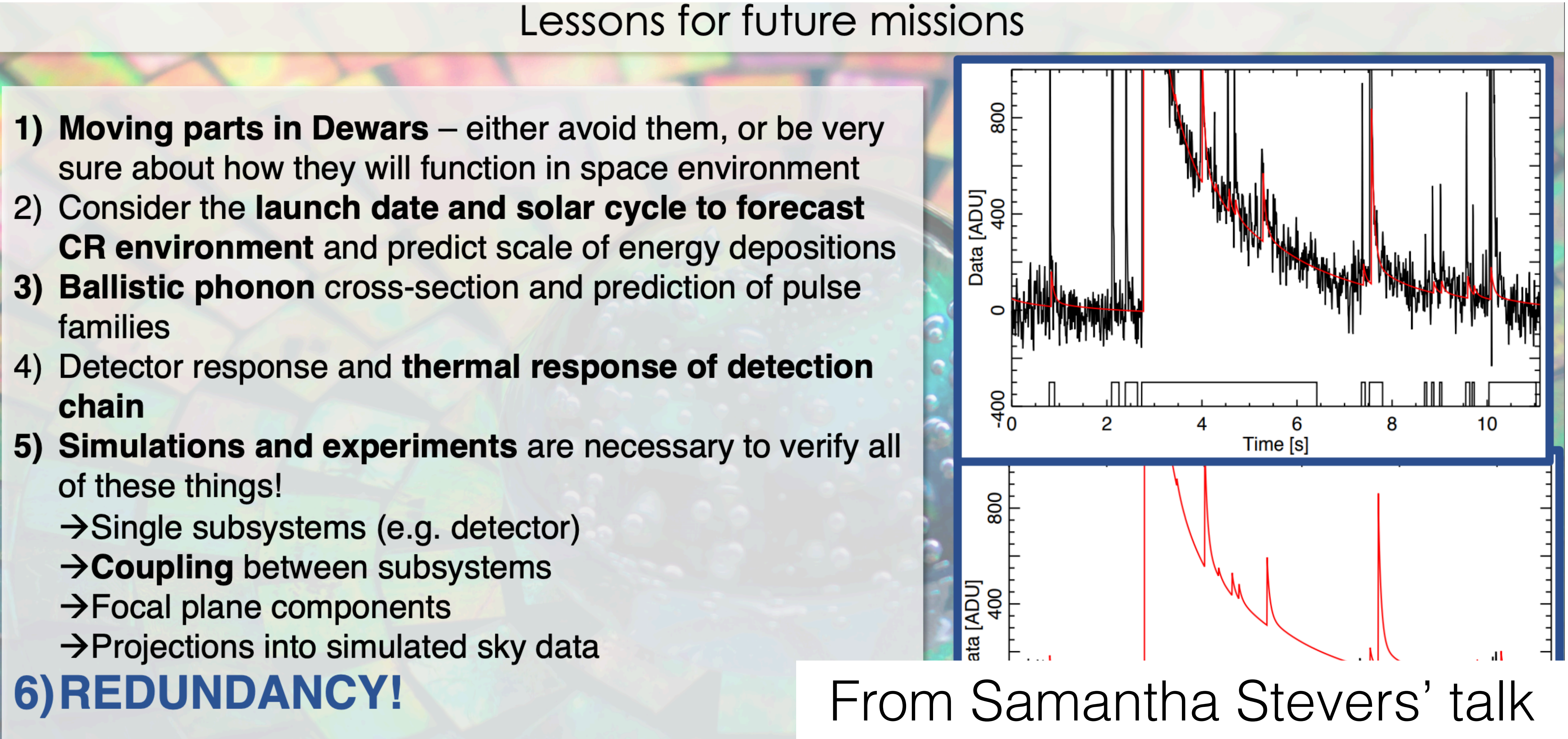


Jon Gudmundsson
Adri Duivenvoorden

Cosmic rays



A Catalano et al., J Low Temp Phys (2014) 176:773–786



Lessons for future missions

1) **Moving parts in Dewars** – either avoid them, or be very sure about how they will function in space environment
2) Consider the **launch date and solar cycle to forecast CR environment** and predict scale of energy depositions
3) **Ballistic phonon** cross-section and prediction of pulse families
4) Detector response and **thermal response of detection chain**
5) **Simulations and experiments** are necessary to verify all of these things!
   - →Single subsystems (e.g. detector)
   - →**Coupling** between subsystems
   - →Focal plane components
   - →Projections into simulated sky data
6) **REDUNDANCY!**

From Samantha Stevers’ talk

What keeps you up at night?

Are we looking at the right (deep, clean) part of the sky?

Are we looking at enough sky?

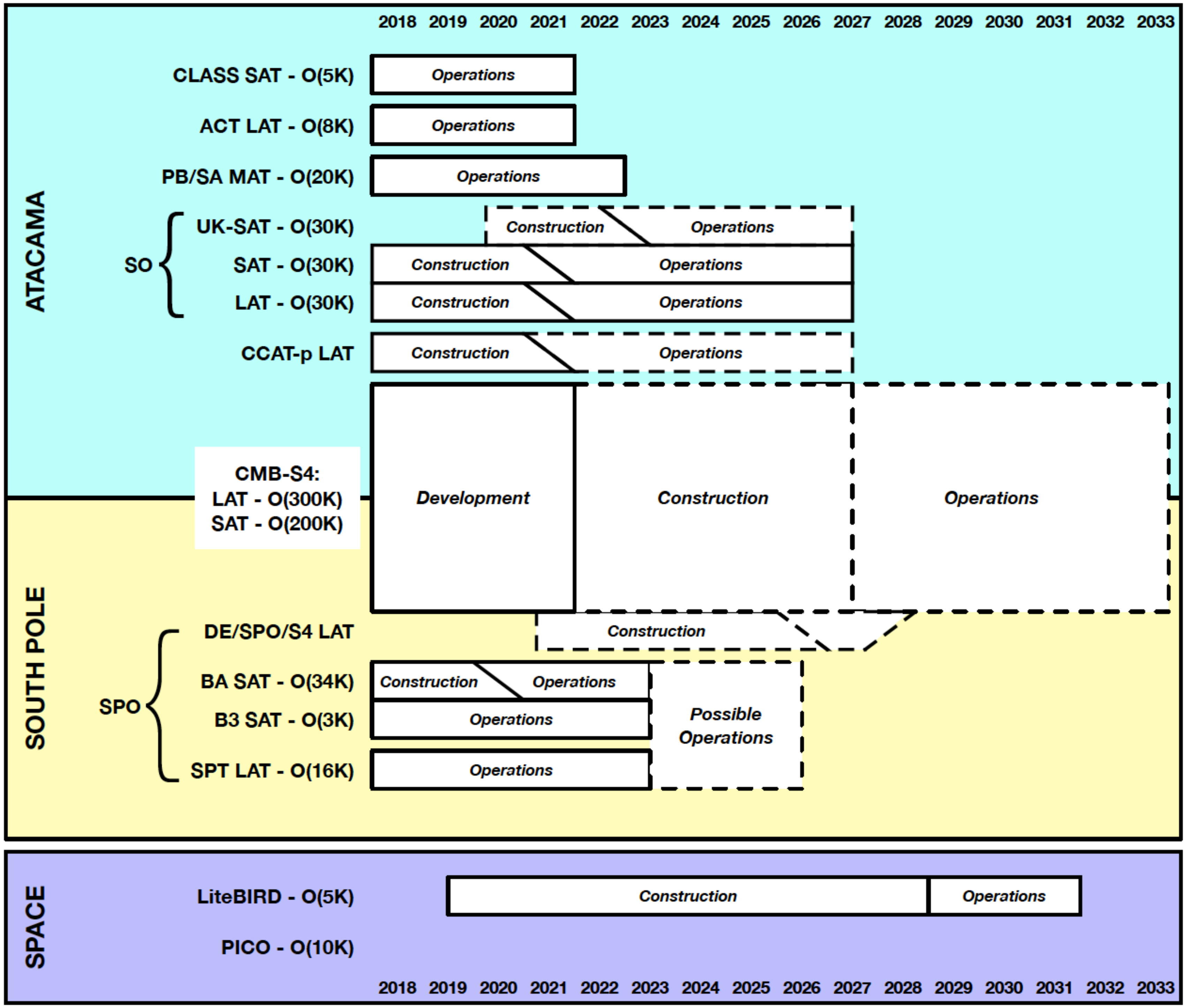
Will we believe r when we see it?

Will our instruments surprise us (to HWP or not?)

(How fast groundbird is spinning)

What keeps you up at night?

The Next Next Generation



From Adrian Lee's talk

Dunlap Institute for
Astronomy & Astrophysics
UNIVERSITY OF TORONTO

What science in 2035+ ?

Primordial B-modes?

2035

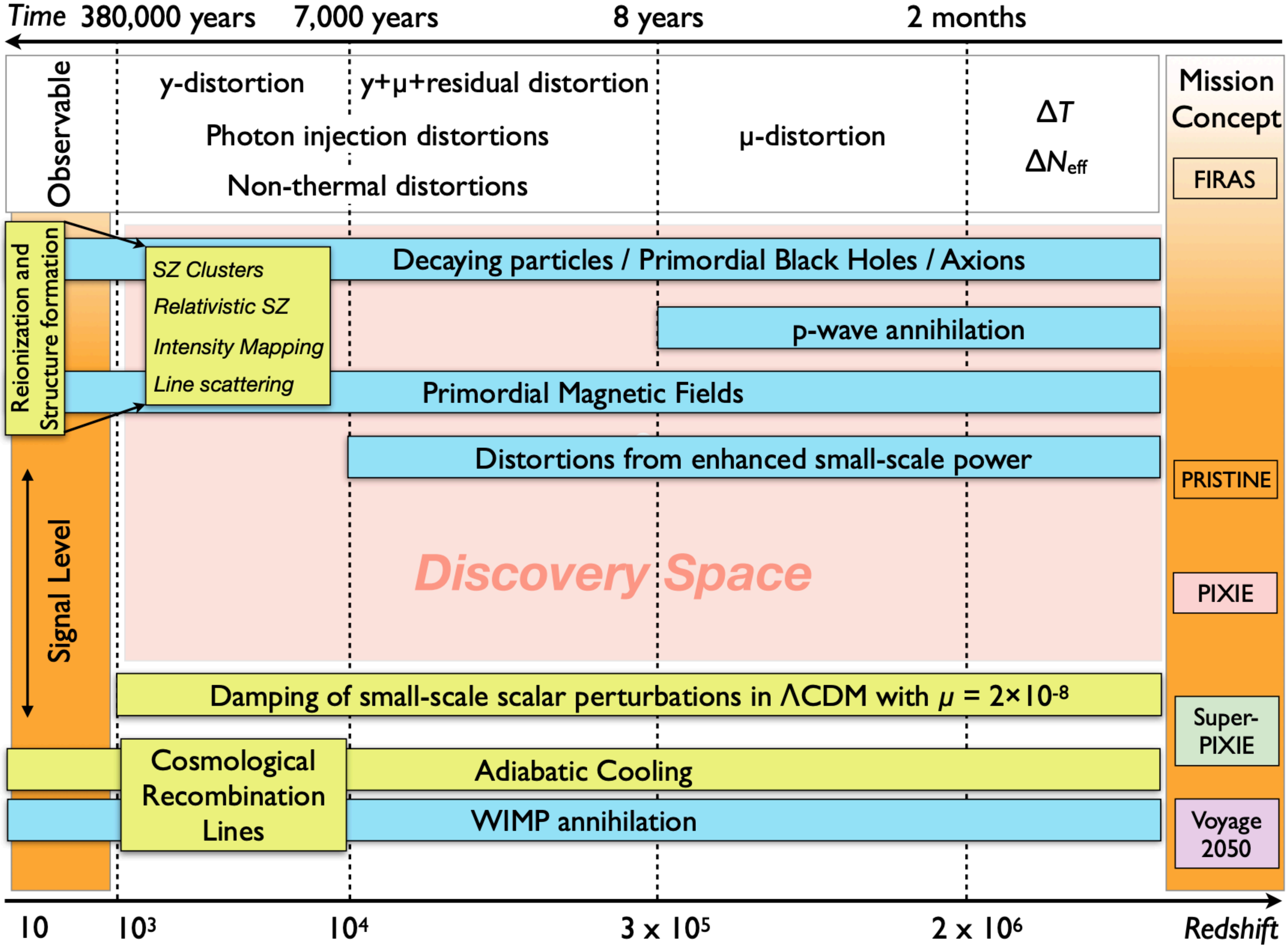
r	LiteBIRD / S4	PICO ?	Next ?
r > 0.005	detection	detection	map B-modes
0.001 < r < 0.005	hint?	detection	confirm
0.0001 < r < 0.001	-	hint?	push down?

Or perhaps we hit a wall of foregrounds and lensing residuals?

- many more channels for full foreground understanding !
- much better delensing capability with CMB and with structures (CIB+LIM)

From Jacques Delabrouille’s talk

From Jens Chluba's talk



Time 380,000 years 7,000 years 8 years 2 months

Observable

y-distortion

y+μ+residual distortion

Photon injection distortions

Non-thermal distortions

μ-distortion

ΔT

ΔN_{eff}

Mission Concept

FIRAS

PRISTINE

PIXIE

Super-PIXIE

Voyage 2050

Reionization and Structure formation

SZ Clusters

Relativistic SZ

Intensity Mapping

Line scattering

Decaying particles / Primordial Black Holes / Axions

p-wave annihilation

Primordial Magnetic Fields

Distortions from enhanced small-scale power

Signal Level

Discovery Space

Damping of small-scale scalar perturbations in ΛCDM with $\mu = 2\times10^{-8}$

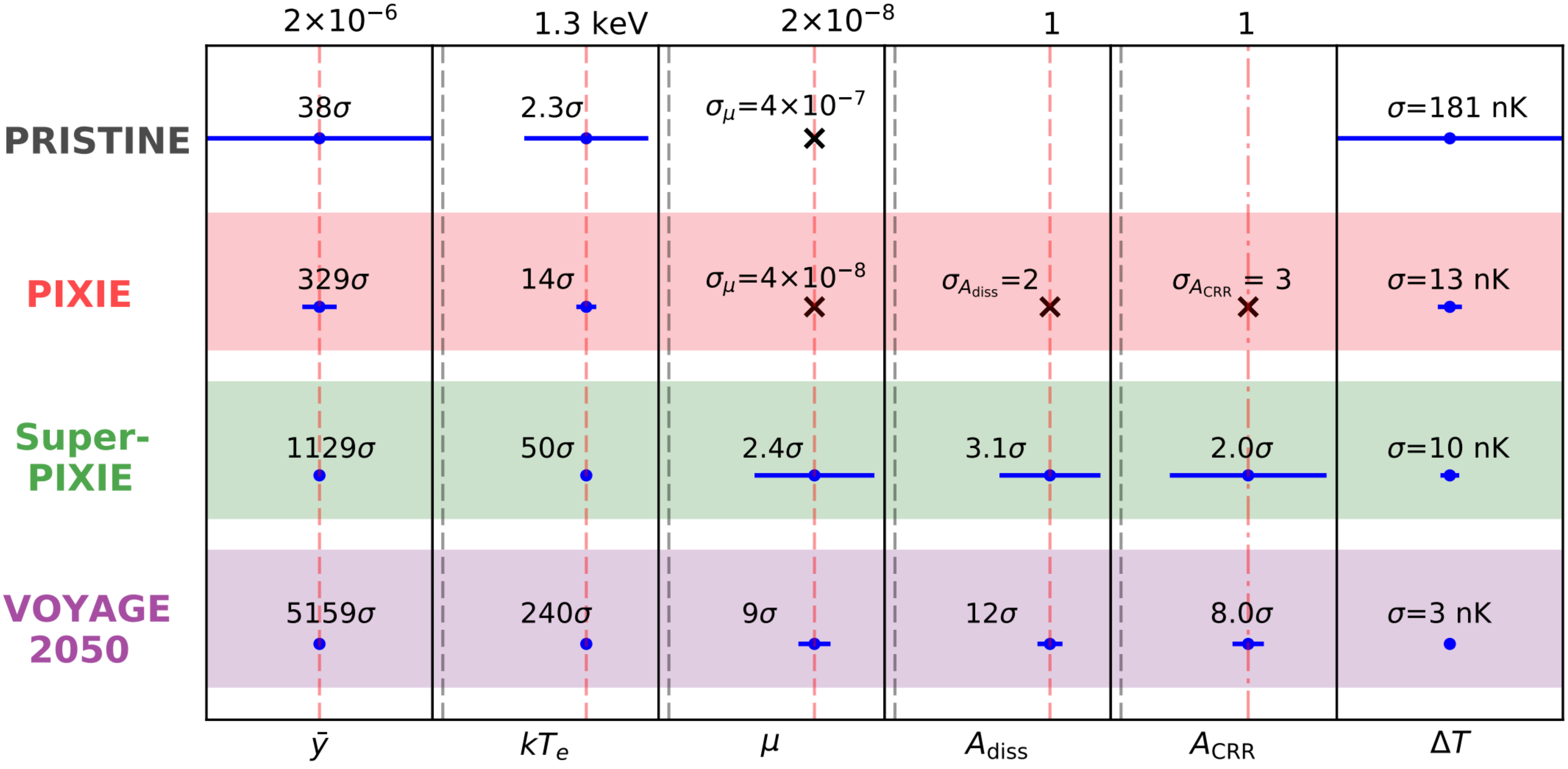
Cosmological Recombination Lines

Adiabatic Cooling

WIMP annihilation

10 10^3 10^4 3×10^5 2×10^6 *Redshift*

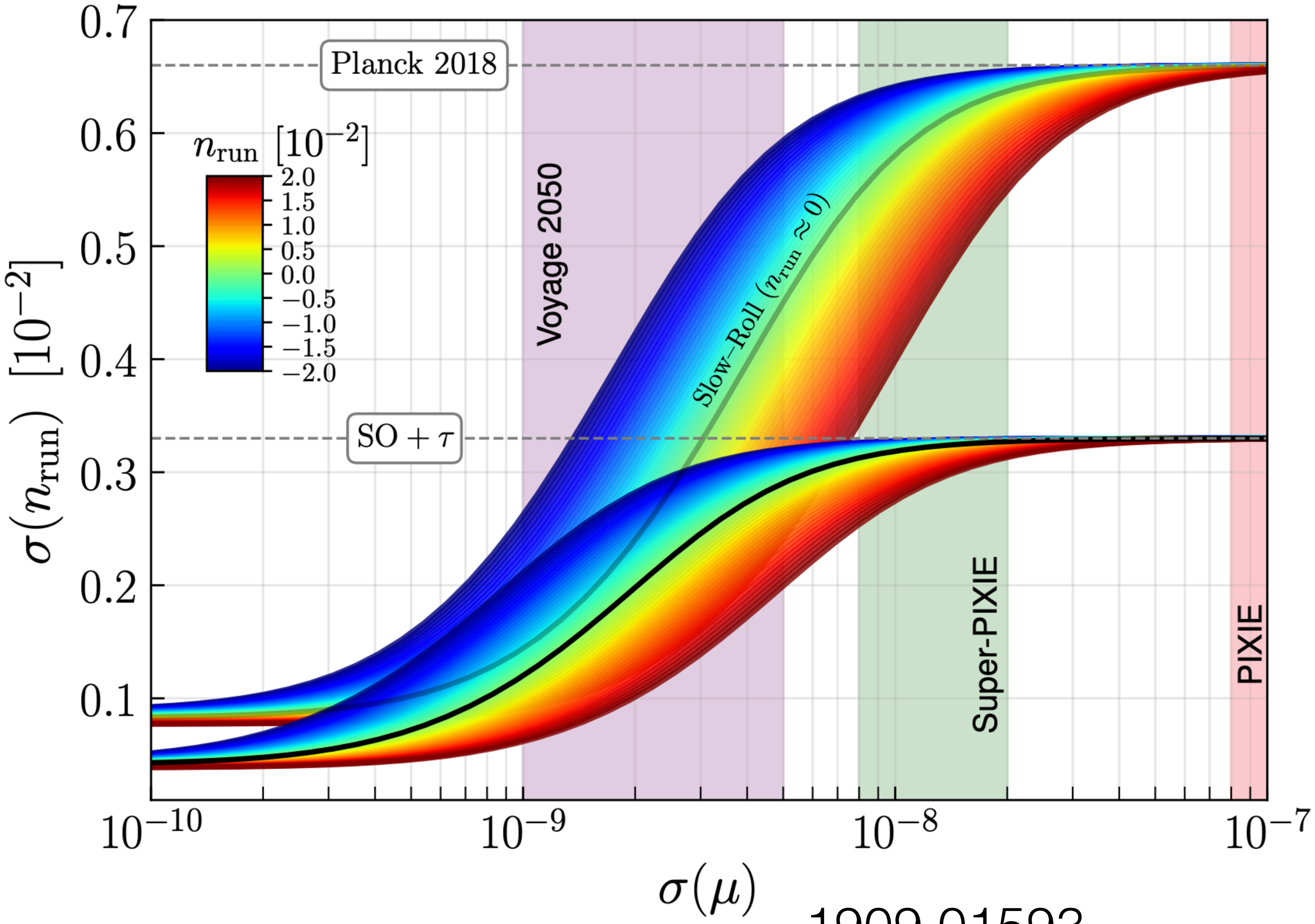
From Jens Chluba's talk (also Aditya Rotti)



1909.01593

DUNLAP INSTITUTE *for* ASTRONOMY & ASTROPHYSICS

Dunlap Institute for Astronomy & Astrophysics UNIVERSITY OF TORONTO

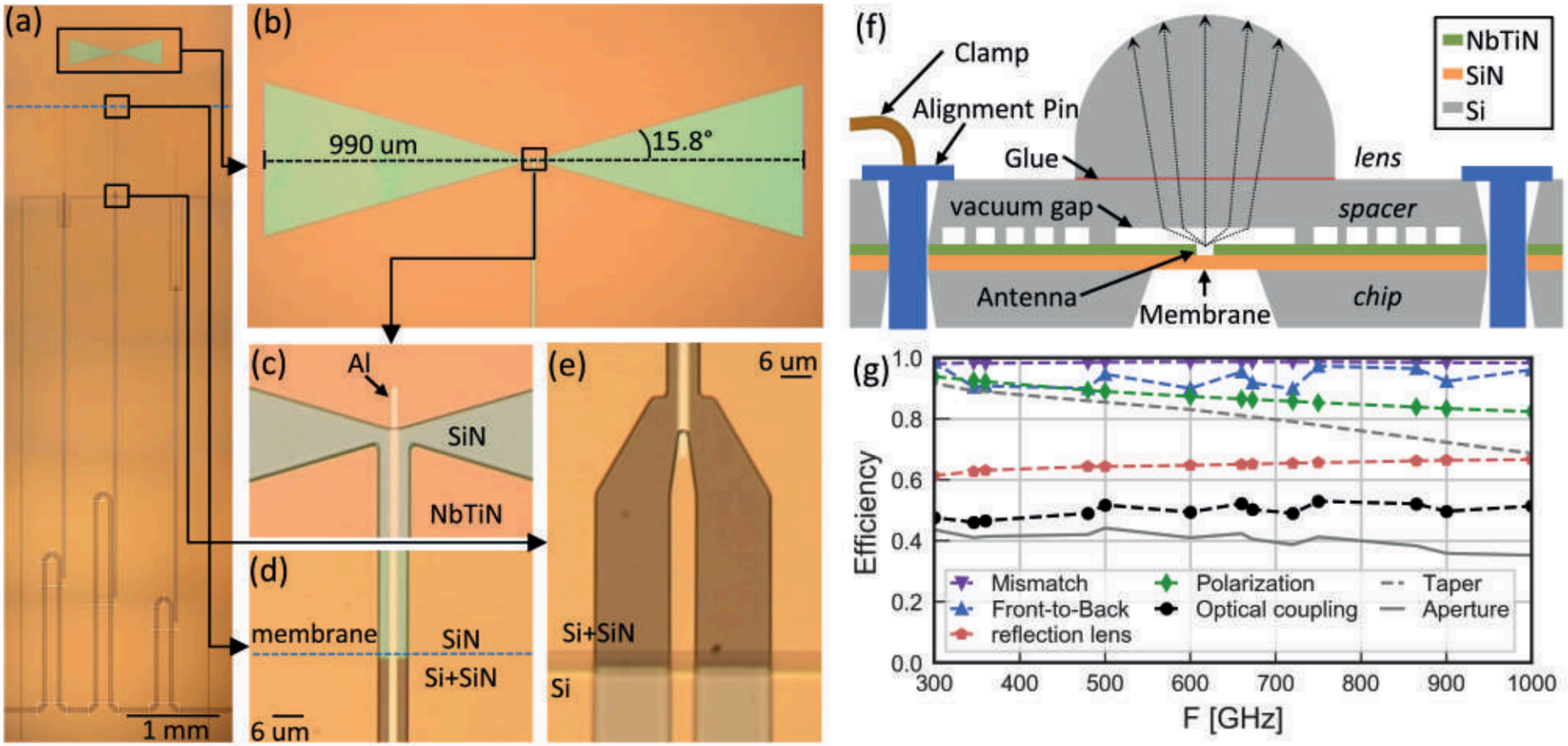


1909.01593

DUNLAP INSTITUTE
for **ASTRONOMY & ASTROPHYSICS**

Dunlap Institute for
Astronomy & Astrophysics
UNIVERSITY OF TORONTO

Broad band on chip imaging spectrometers —> ready for space

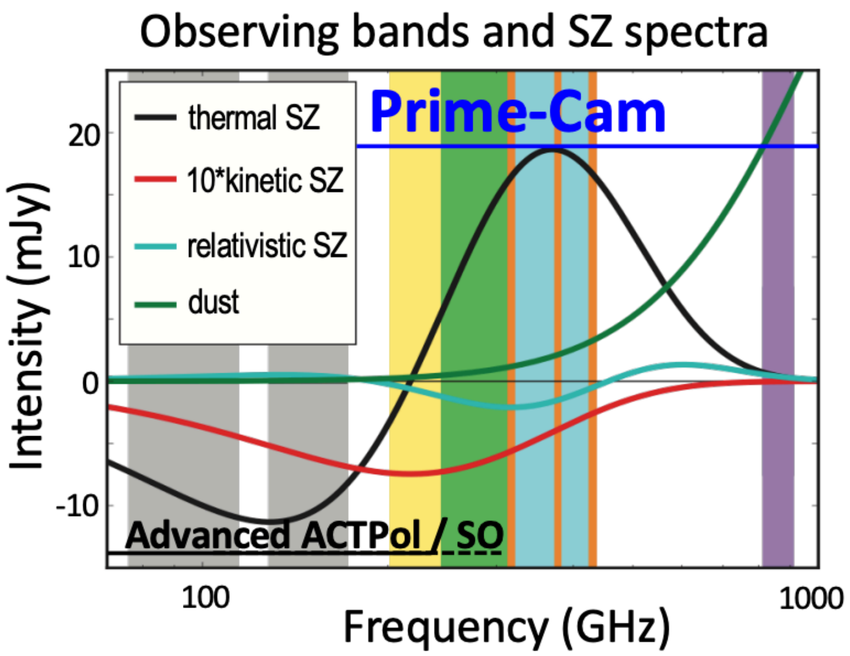


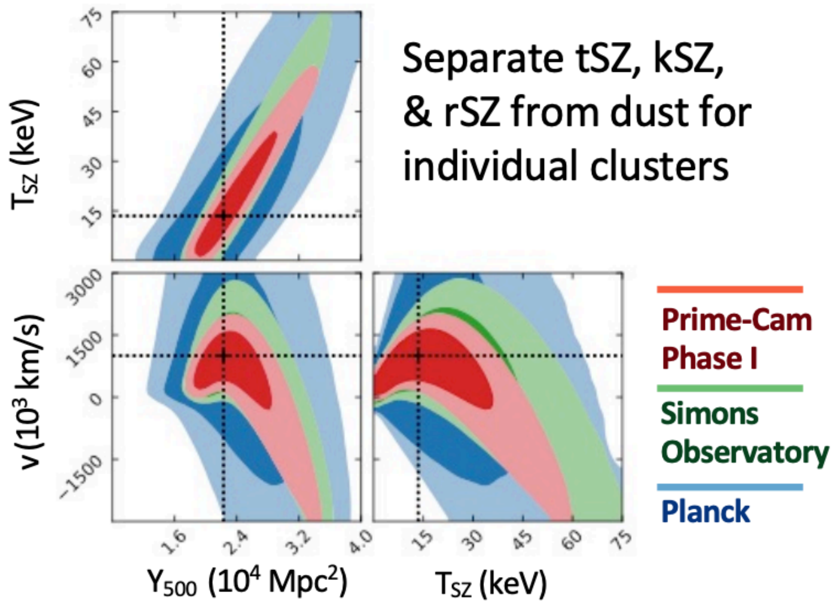
See Jochem Baselmans' talk

1912.07428

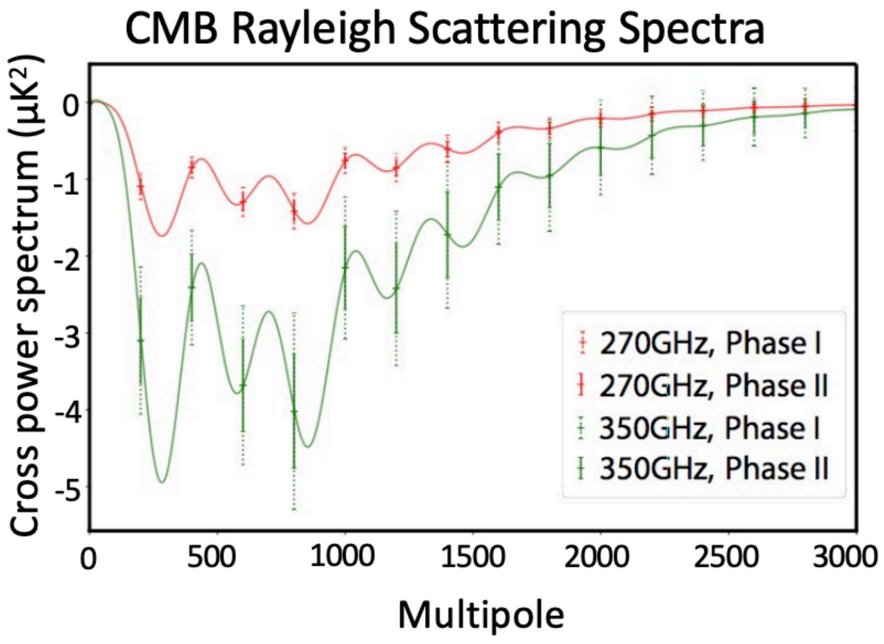
DUNLAP INSTITUTE
for **ASTRONOMY & ASTROPHYSICS**

Dunlap Institute for
Astronomy & Astrophysics
UNIVERSITY OF TORONTO



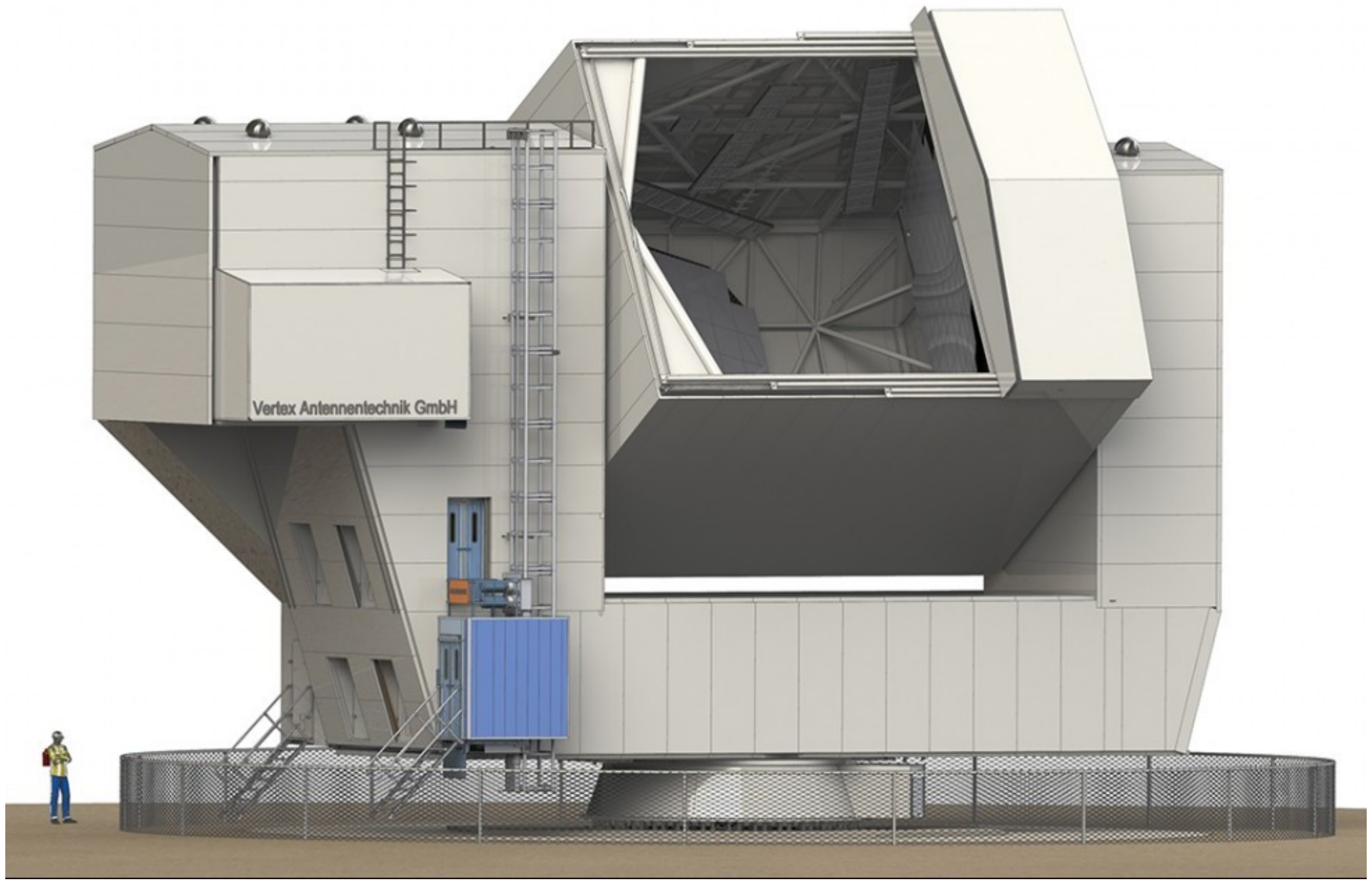


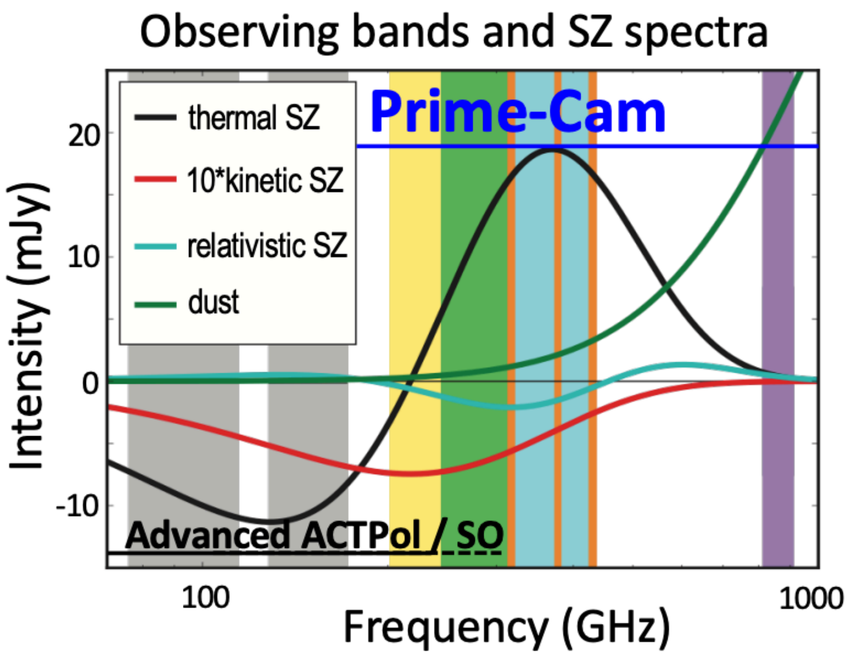
Separate tSZ, kSZ, & rSZ from dust for individual clusters

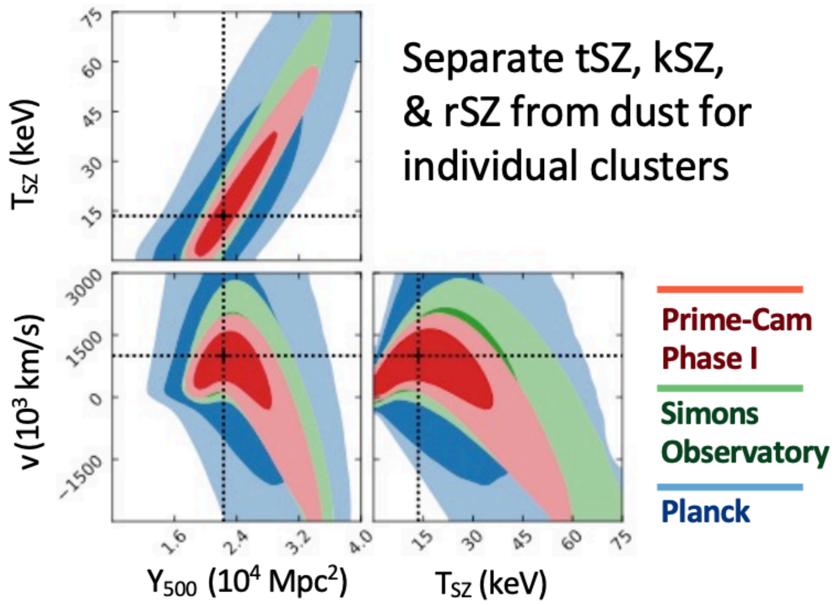


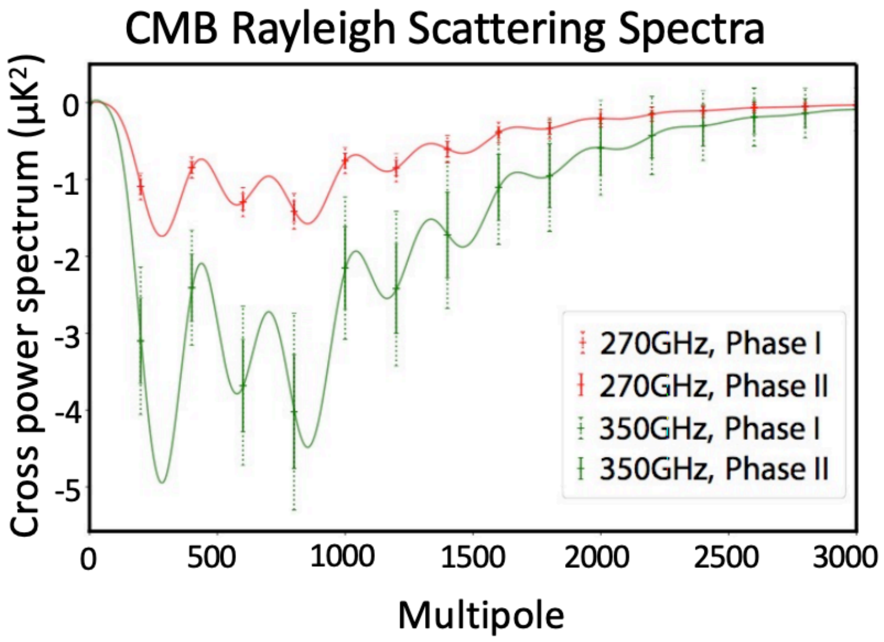
CCATp

See Kaustav Basu's talk



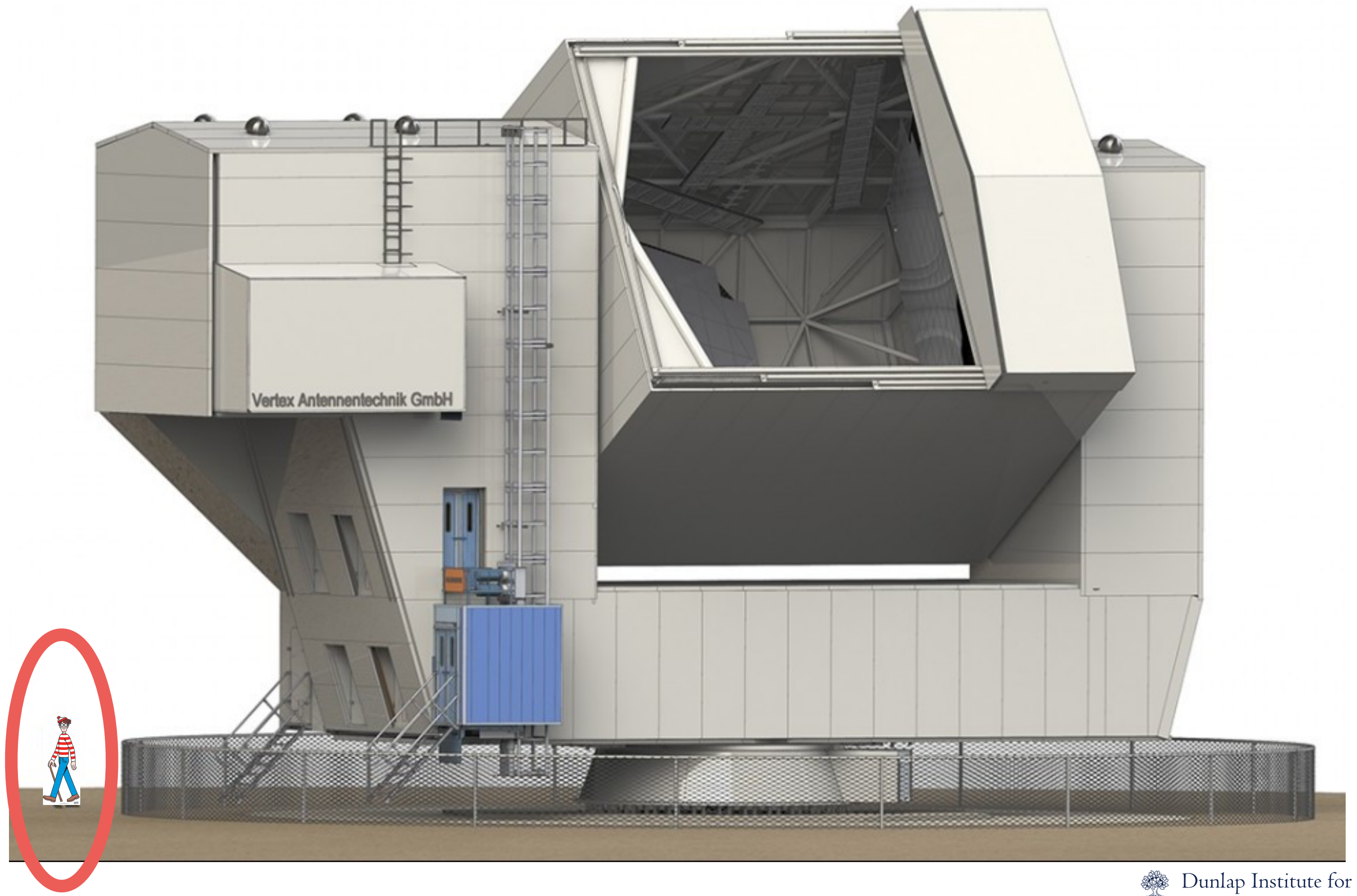

Observing bands and SZ spectra


Separate tSZ, kSZ, & rSZ from dust for individual clusters


CMB Rayleigh Scattering Spectra

CCATp

See Kaustav Basu's talk



Final thoughts

Does 2035+ signal significant departure from ‘standard’ cosmology for distortions, higher order effects + astrophysics?

Final thoughts

Does 2035+ signal significant departure from ‘standard’ cosmology for distortions, higher order effects + astrophysics?

How does that change the funding/proposal landascape?

Final thoughts

Does 2035+ signal significant departure from ‘standard’ cosmology for distortions, higher order effects + astrophysics?
How does that change the funding/proposal landascape?

What are the biggest things that could hamper us?

Final thoughts

Does 2035+ signal significant departure from ‘standard’ cosmology for distortions, higher order effects + astrophysics?
How does that change the funding/proposal landascape?

What are the biggest things that could hamper us?
e.g. systematics, instrument performance, theoretical modelling uncertainties?

Final thoughts

Has focus on B-modes ‘distracted’ from e.g. spectral studies?

Final thoughts

Has focus on B-modes ‘distracted’ from e.g. spectral studies?

Or are B-modes the low(er)-hanging fruit that we have to go after?

Final thoughts

Has focus on B-modes ‘distracted’ from e.g. spectral studies?
Or are B-modes the low(er)-hanging fruit that we have to go after?

Are there too many proposed projects?
How to balance competition with collaboration and ground vs space?

Final thoughts

Has focus on B-modes ‘distracted’ from e.g. spectral studies?
Or are B-modes the low(er)-hanging fruit that we have to go after?

Are there too many proposed projects?
How to balance competition with collaboration and ground vs space?
Does it matter, given decoupled agency funding?

Final thoughts

What are the lessons we will share with our students in ten years?

Final thoughts

What are the lessons we will share with our students in ten years?
Can we learn them now?