Spectral distortion science and measurement challenges

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From Planck to the Future of CMB

2-6 May 2022

Plan for the talk :

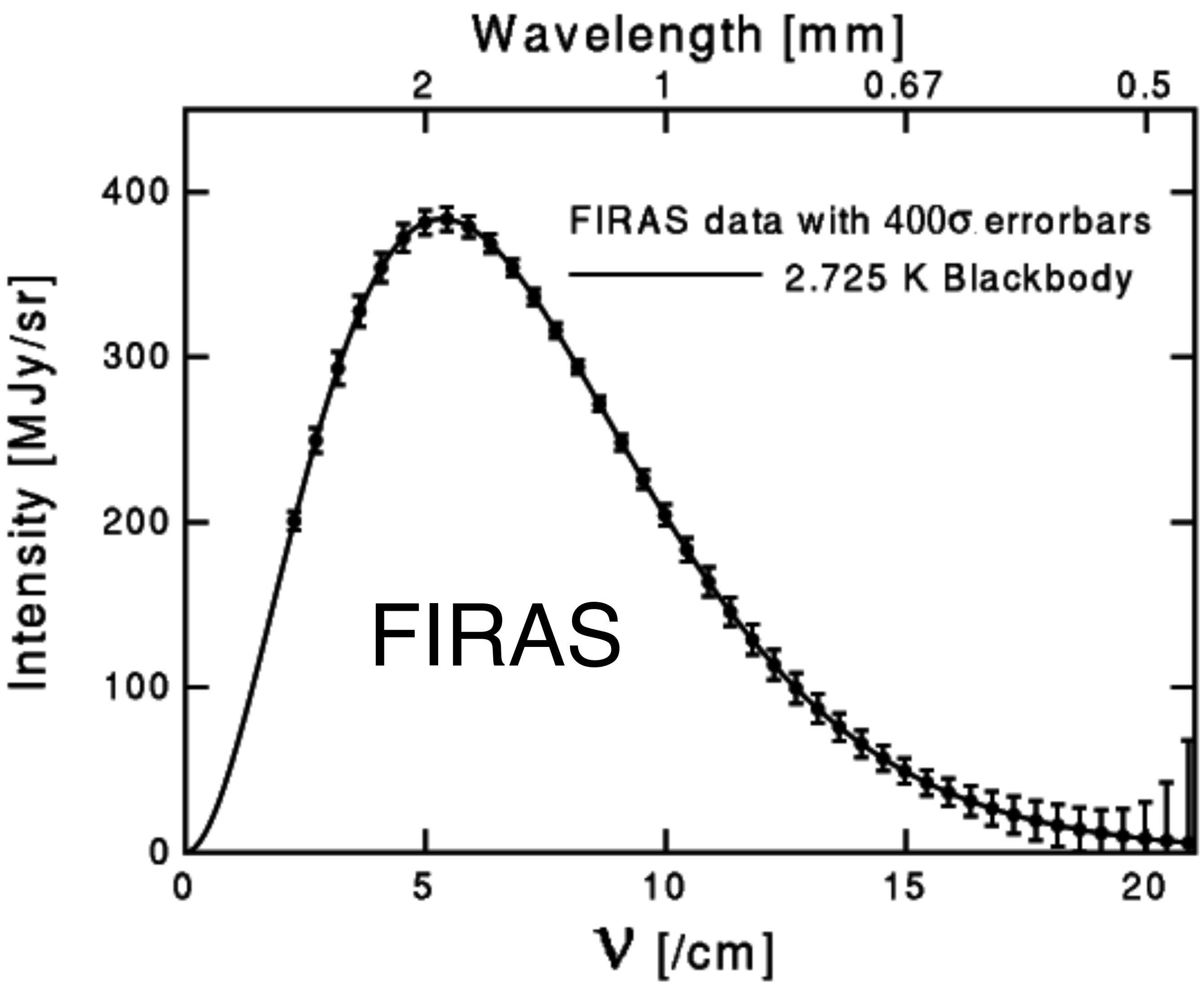
1. The monopole spectral distortions
   - Key science goals and what we hope to uncover

2. The foregrounds challenge
   - Where we stand right now and where we are heading

3. Anisotropic spectral distortions
   - Probing primordial non-Gaussianity with spectral distortions

COBE / FIRAS (**F**ar **I**nfra**R**ed **A**bsolute **S**pectrophotometer)

First exquisite measurement of the CMB spectrum in the early 90's



Nobel Prize in Physics 2006!

Mather et al., 1994, ApJ, 420, 439

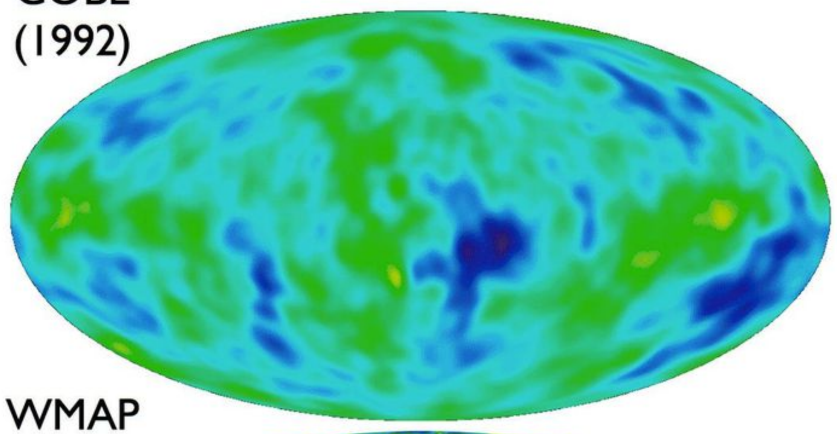
Fixsen et al., 1996, ApJ, 473, 576

Fixsen et al., 2003, ApJ, 594, 67

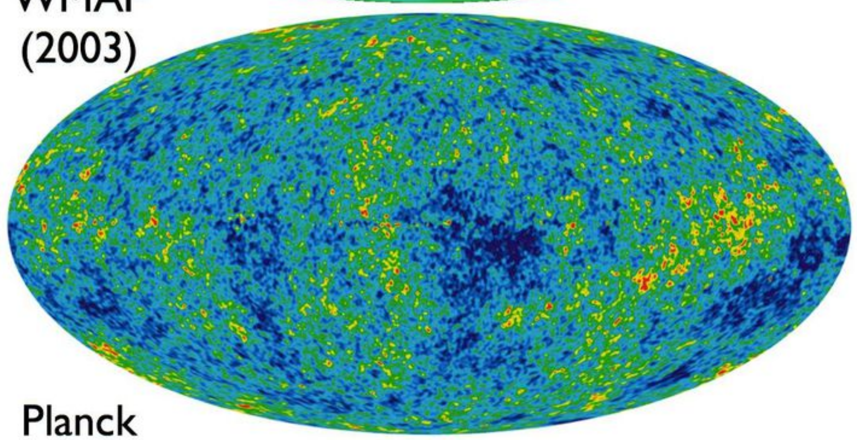
Anisotropy measurements have made huge strides

PROGRESS

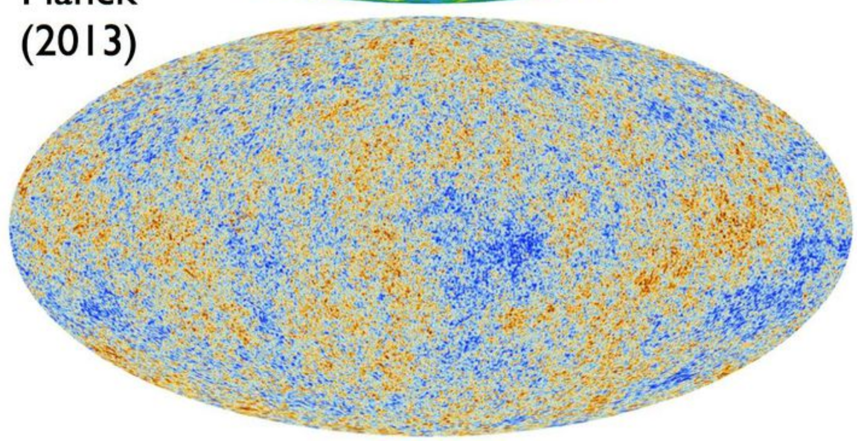
COBE (1992)

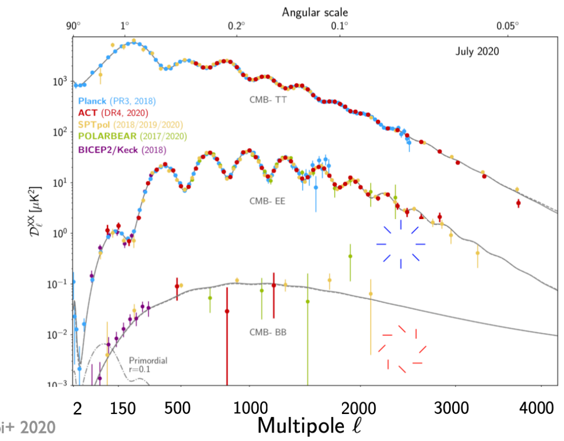


WMAP (2003)

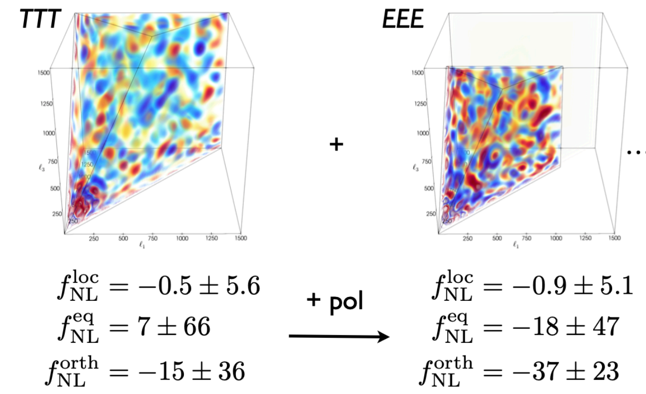


Planck (2013)

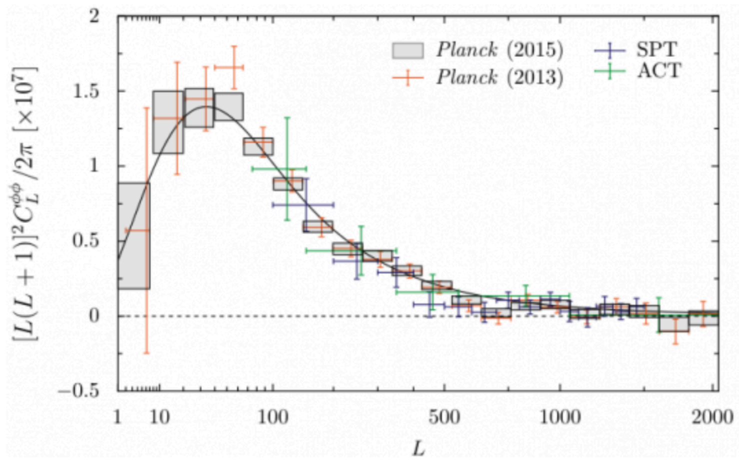


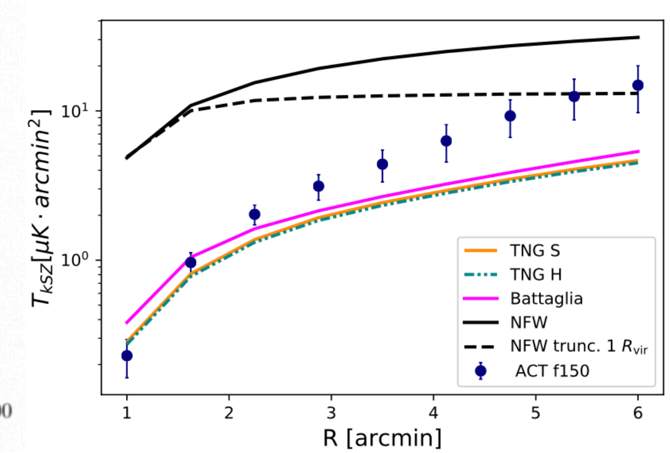


Choi+ 2020

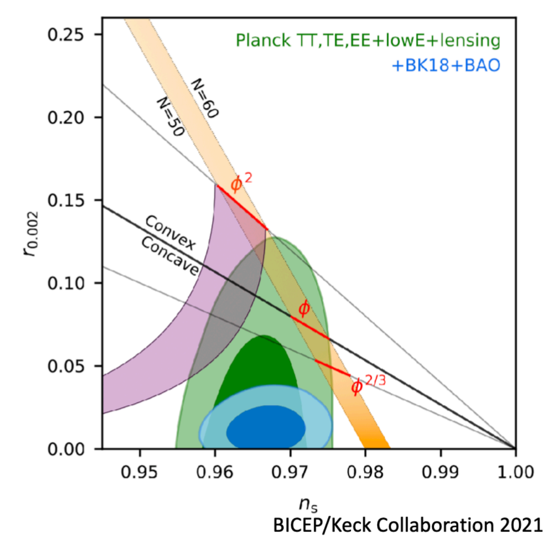


Planck Collaboration 2019

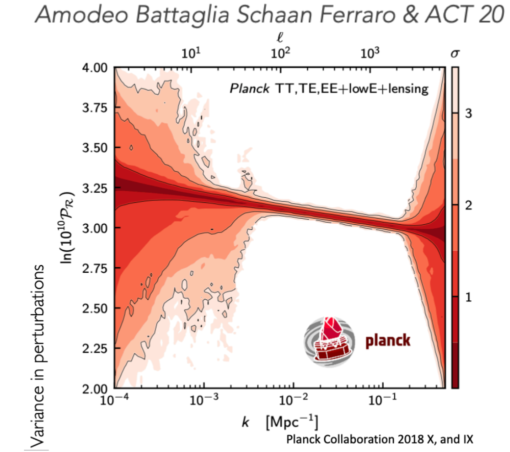




Amodeo Battaglia Schaan Ferraro & ACT 20



BICEP/Keck Collaboration 2021



Planck Collaboration 2018 X, and IX

FUTURE

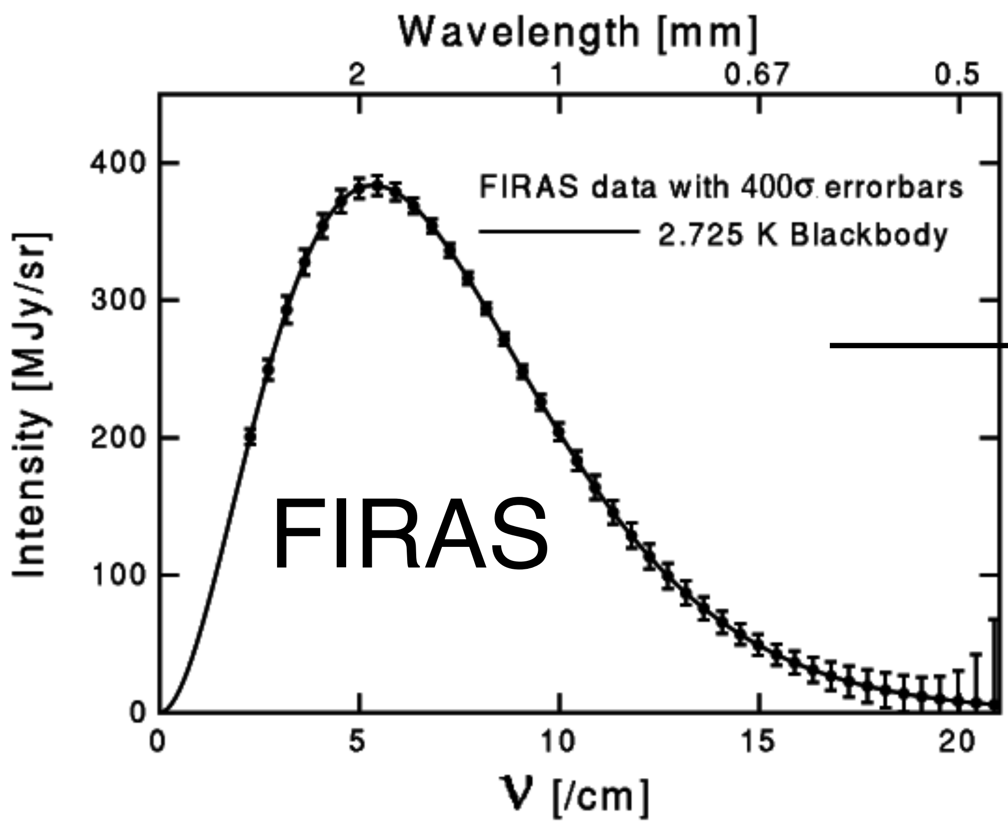
+ ACT, SPT, BICEP, SPIDER, CLASS, QUIJOTE, CBASS ...

B-modes, lensing, tSZ, kSZ etc…

LiteBird, AdvAct, SPT-3G, SO, etc…….

Summary talks by Jo Dunkley & Anthony Challinor on Day-1

FIRAS already puts very stringent constraints on SD



$$|\mu| \leq 9 \times 10^{-5}$$
$$|y| \leq 1.5 \times 10^{-5}$$

Only very small distortions of CMB spectrum are still allowed!

?

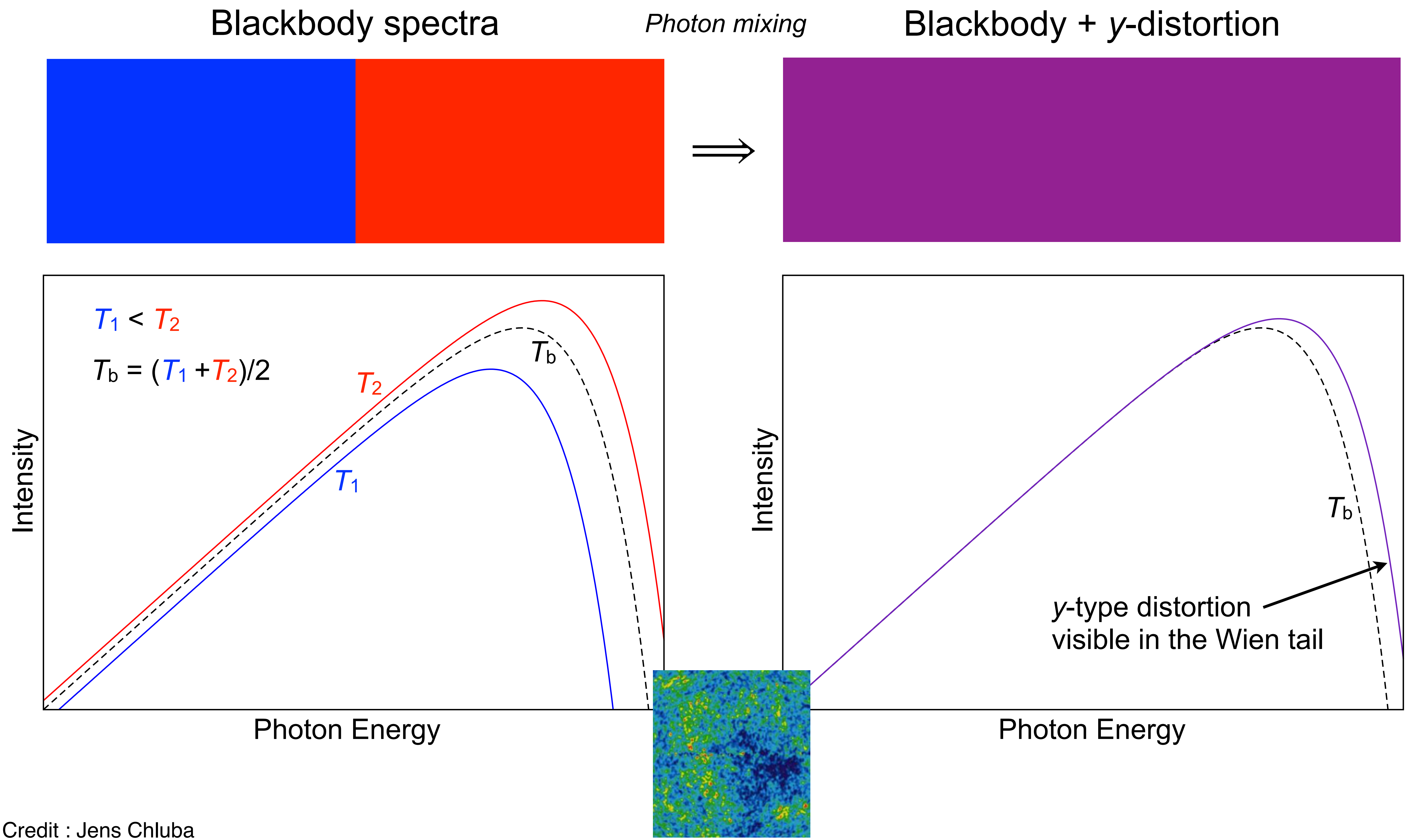
but…

There exist many **definitive signals** providing unique insights into the early universe, motivating more refined measurements

Progress has stalled

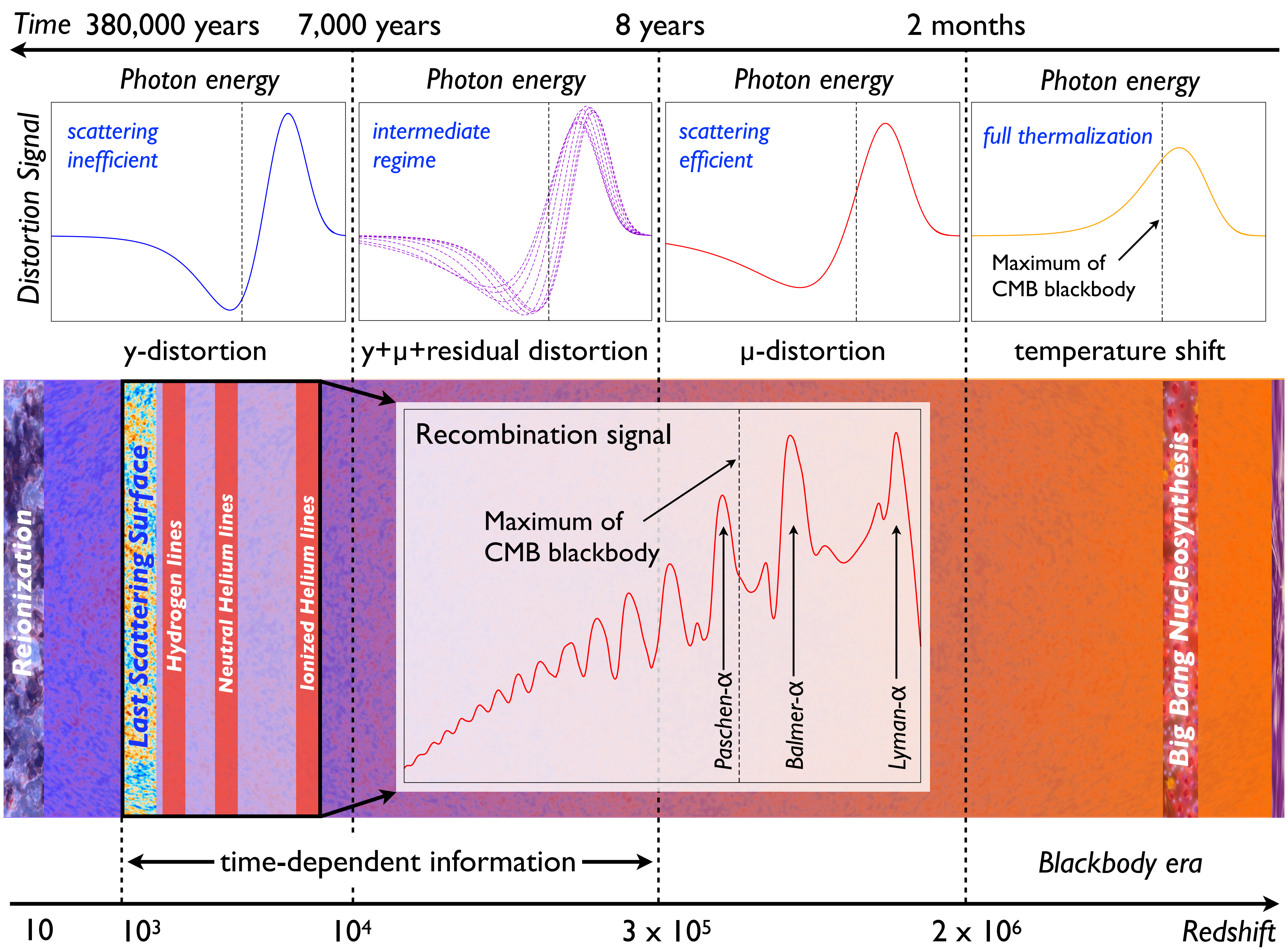
See talk by Jens Chluba on Day-5

How do you generate distortions to the Planck spectrum?



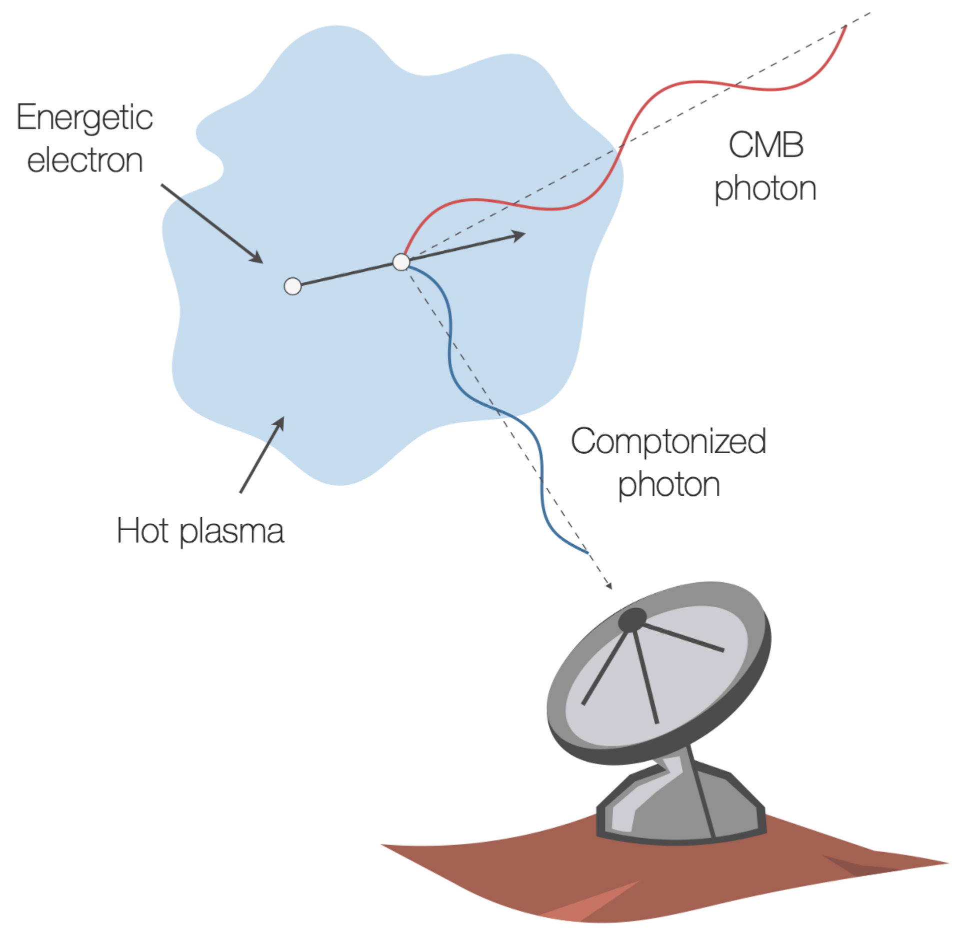
Credit : Jens Chluba

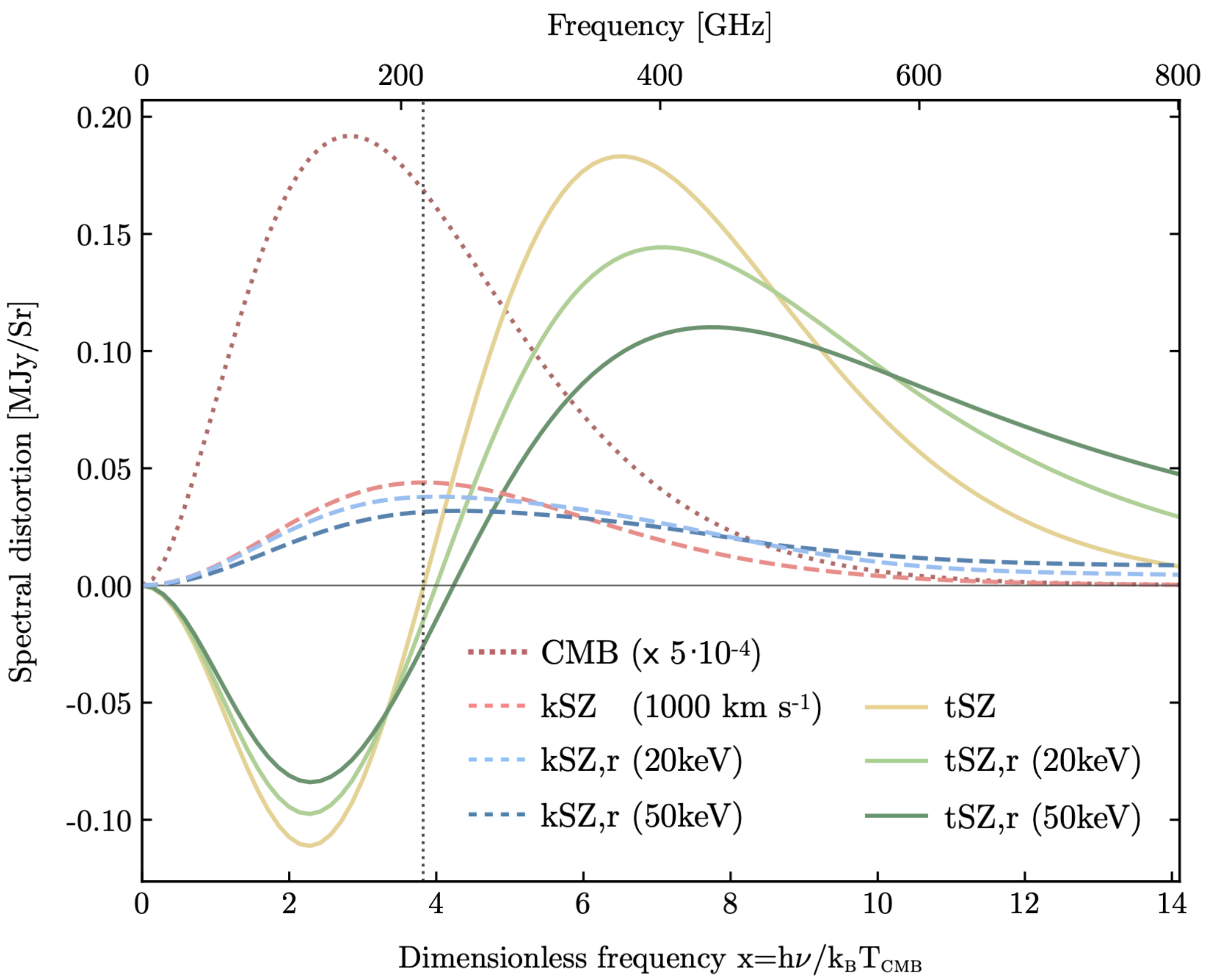
SD offer a unique probe of the low as well as high z universe



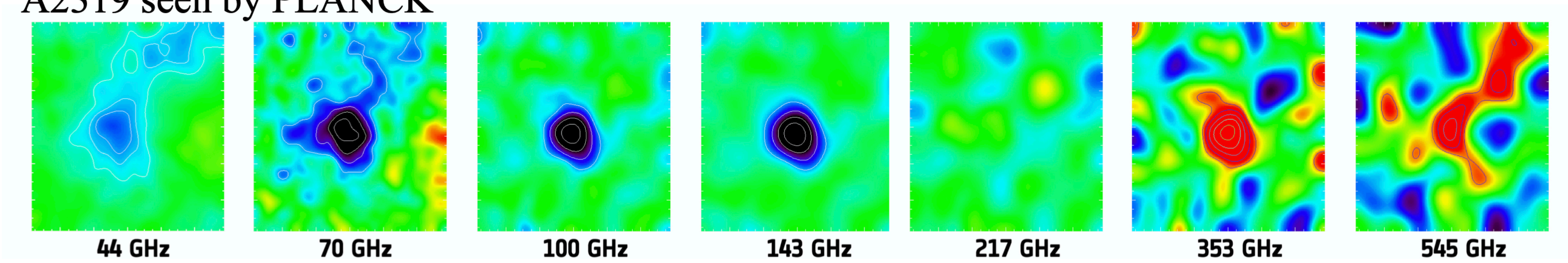
Voyage 2050 white paper: arXiv:1909.01593

The y-distortion spectrum and the relativistic corrections to it



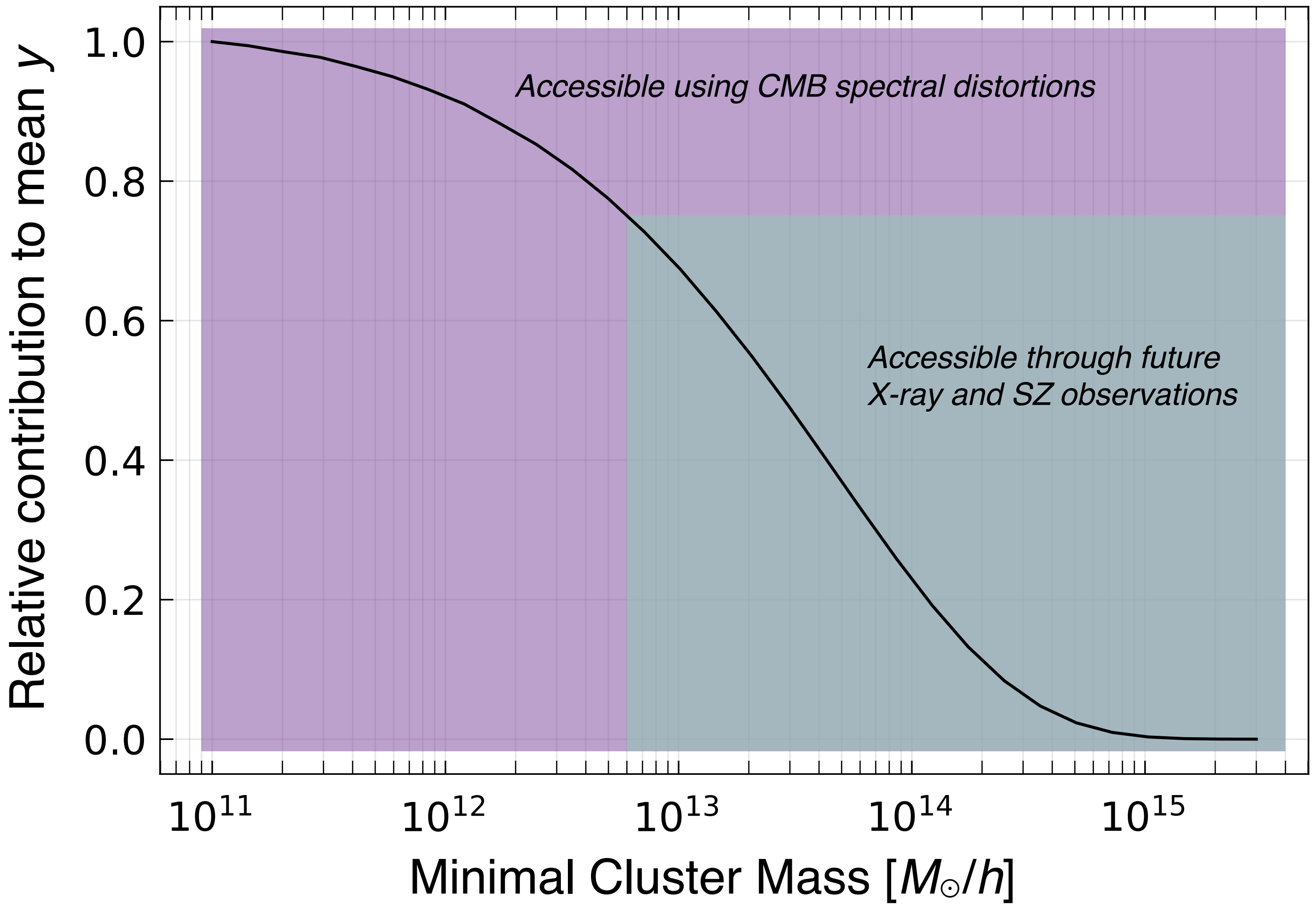


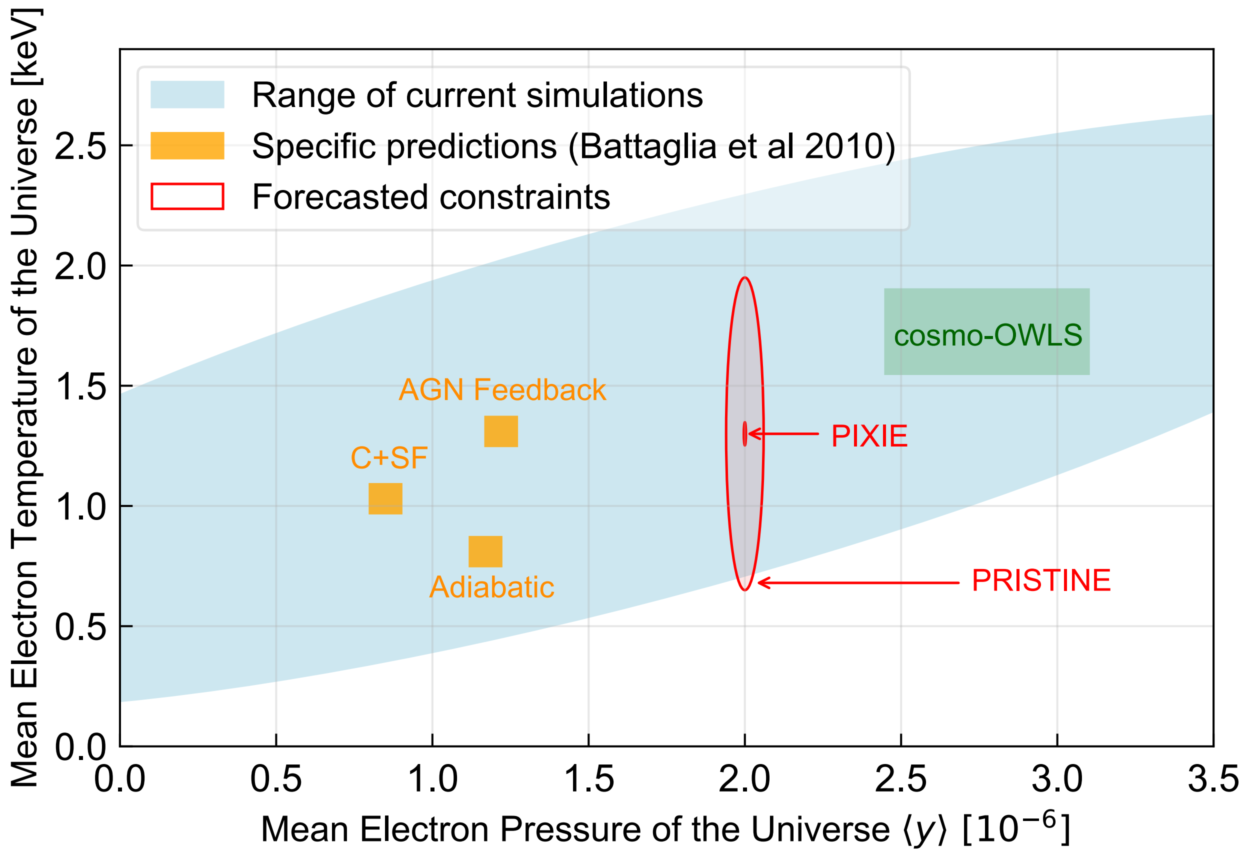
A2319 seen by PLANCK



Sunyaev & Zeldovich, 1980
Rephaeli, 1995
Birkinshaw, 1999
Carlstrom, Holder & Reese, 2002
Mroczkowski et al, 2019

What we seek to measure are the monopole y and rSZ distortion





Sky averaged signals :

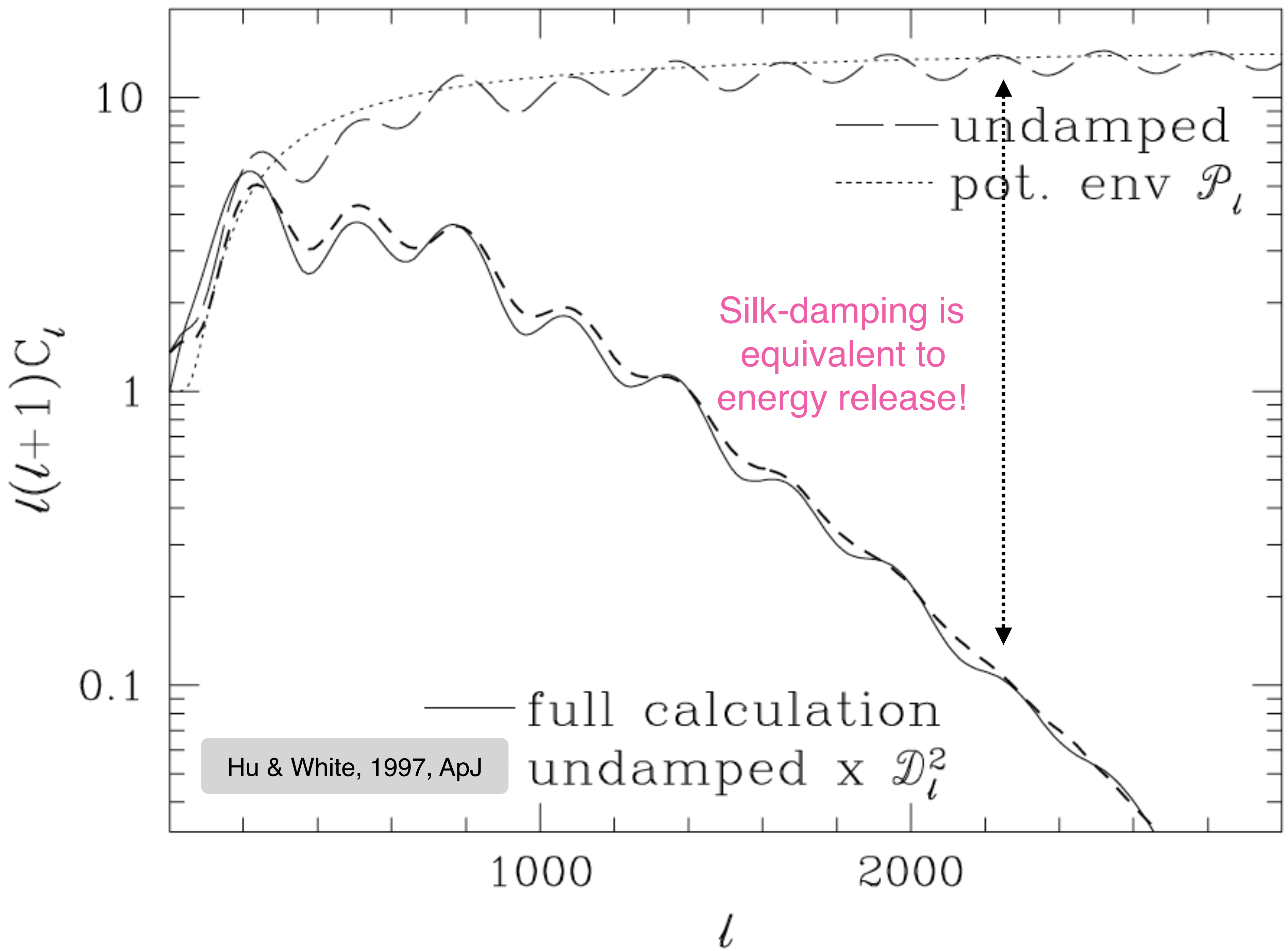
$$\langle y \rangle \sim \text{few} \times 10^{-6}$$

$$\langle kT_e \rangle = 1 - 3 \text{ keV}$$

- Models highly uncertain
- Tight constraints from spectral distortions
- Census of all the hot gas in the Universe from y parameter

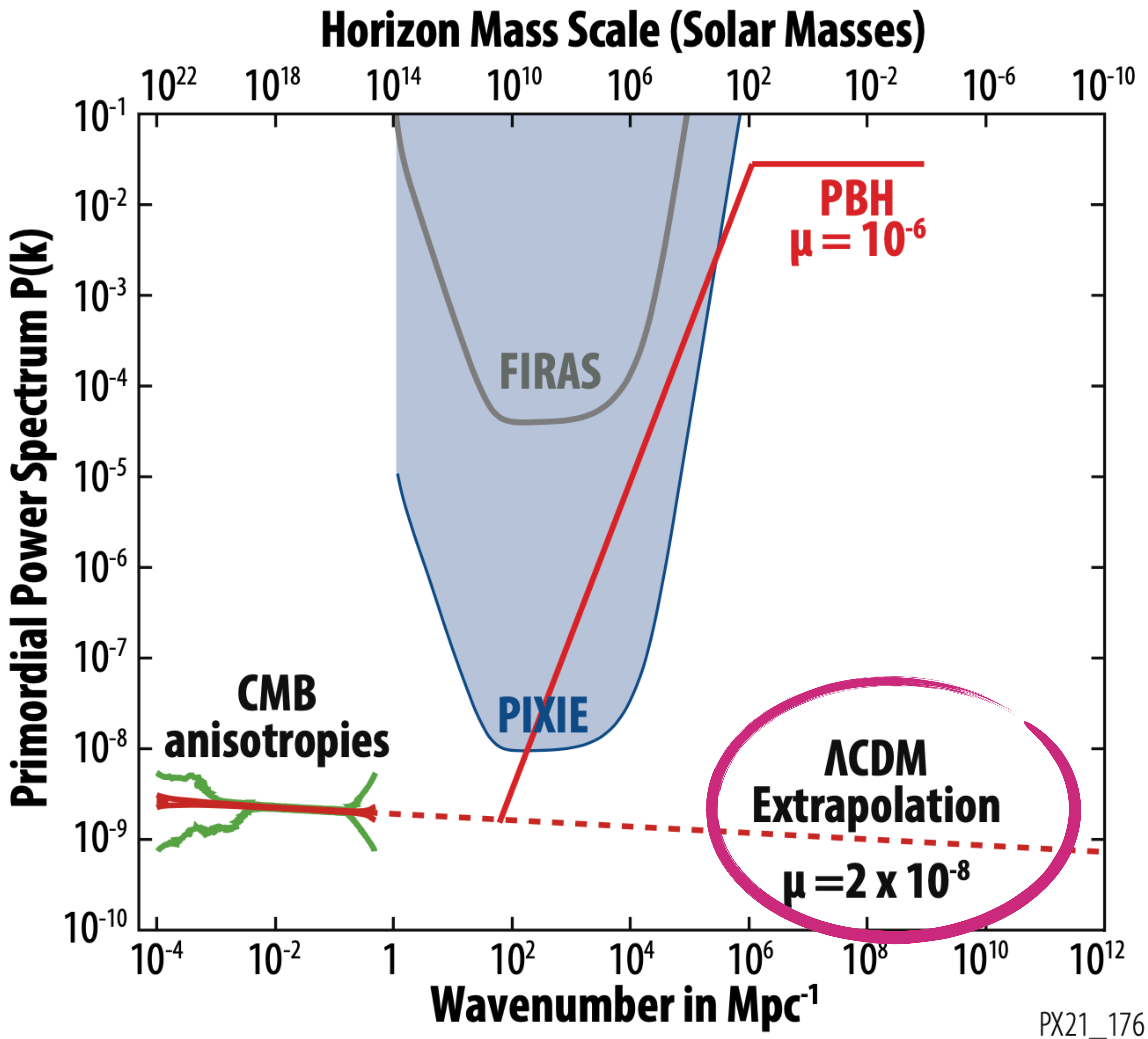
Voyage 2050 white paper: arXiv:1909.01593

Dissipation of small-scale acoustic modes sources distortions in the early universe

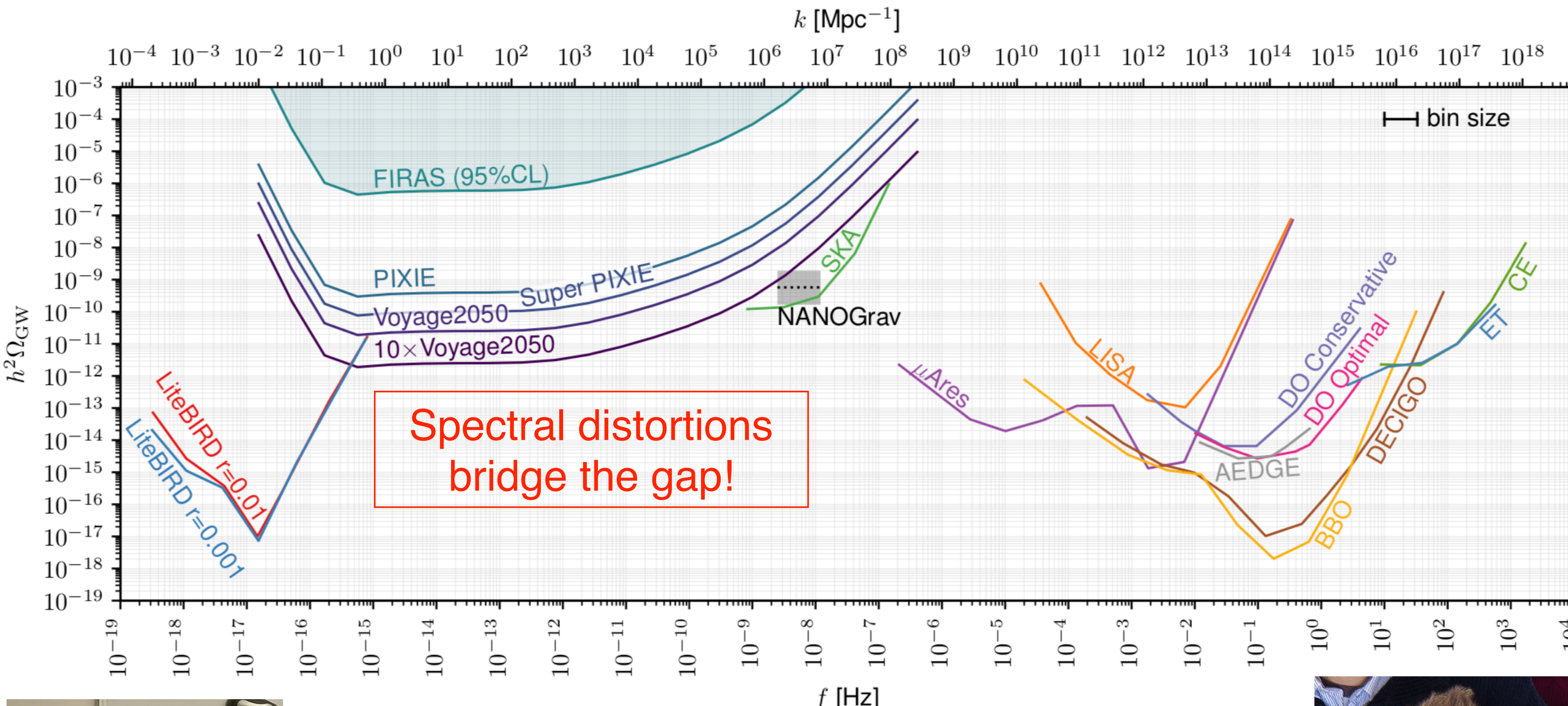


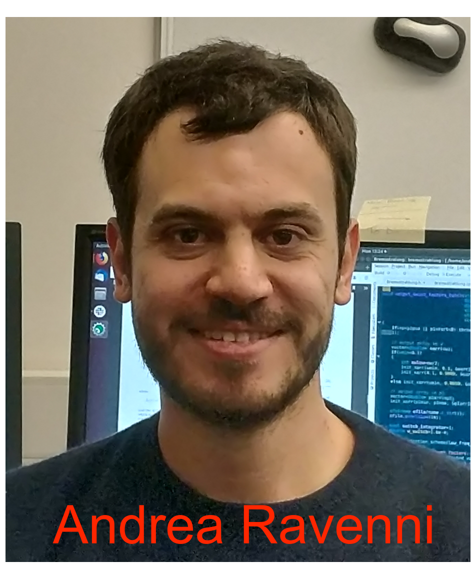
Details of how much SDs are produced, naturally depend on the A_s, n_s, k_D etc….

Testing ΛCDM in unchartered territory



Gravitational Wave Constraints with Distortions





Spectral distortions allow probing:

- Phase transitions
- Axion inflation models
- Cosmic bubble collisions

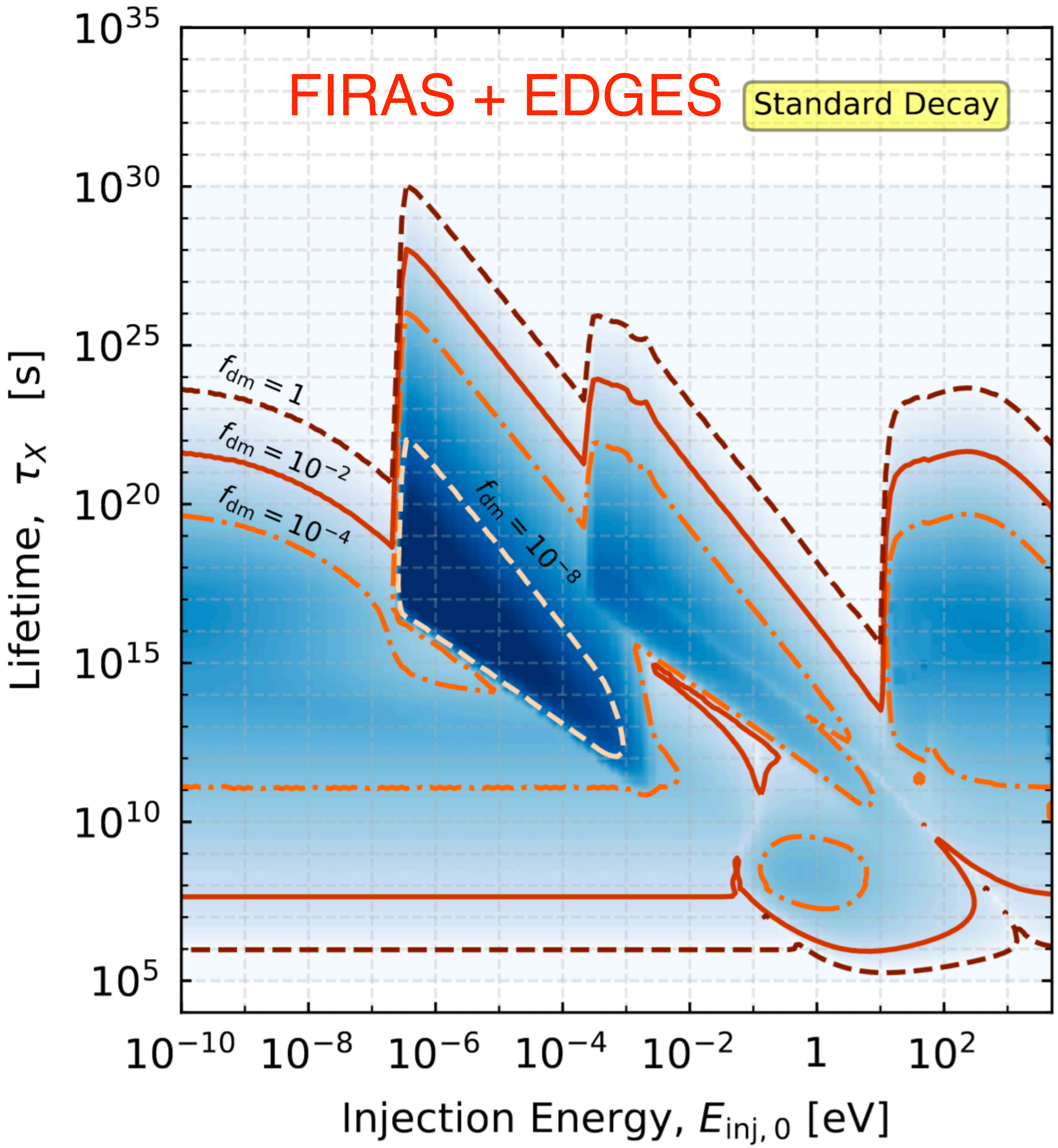
Kite, Ravenni, Patil & Chluba, 2020, arXiv:2010.00040

ΛCDM works with the dark matter hypothesis

- A priori no specific particle in mind
- But: we do not know what dark matter is and where it really came from!
- Was dark matter thermally produced or as a decay product of some heavy particle?
- is dark matter structureless or does it have internal (excited) states?
- sterile neutrinos? Axions? PBH? Some other relic (sub-dominant) particle?
- From the theoretical point of view really no shortage of particles to play with...

CMB spectral distortions offer a new independent way to constrain these kind of models

Photon injection distortions from particle decays

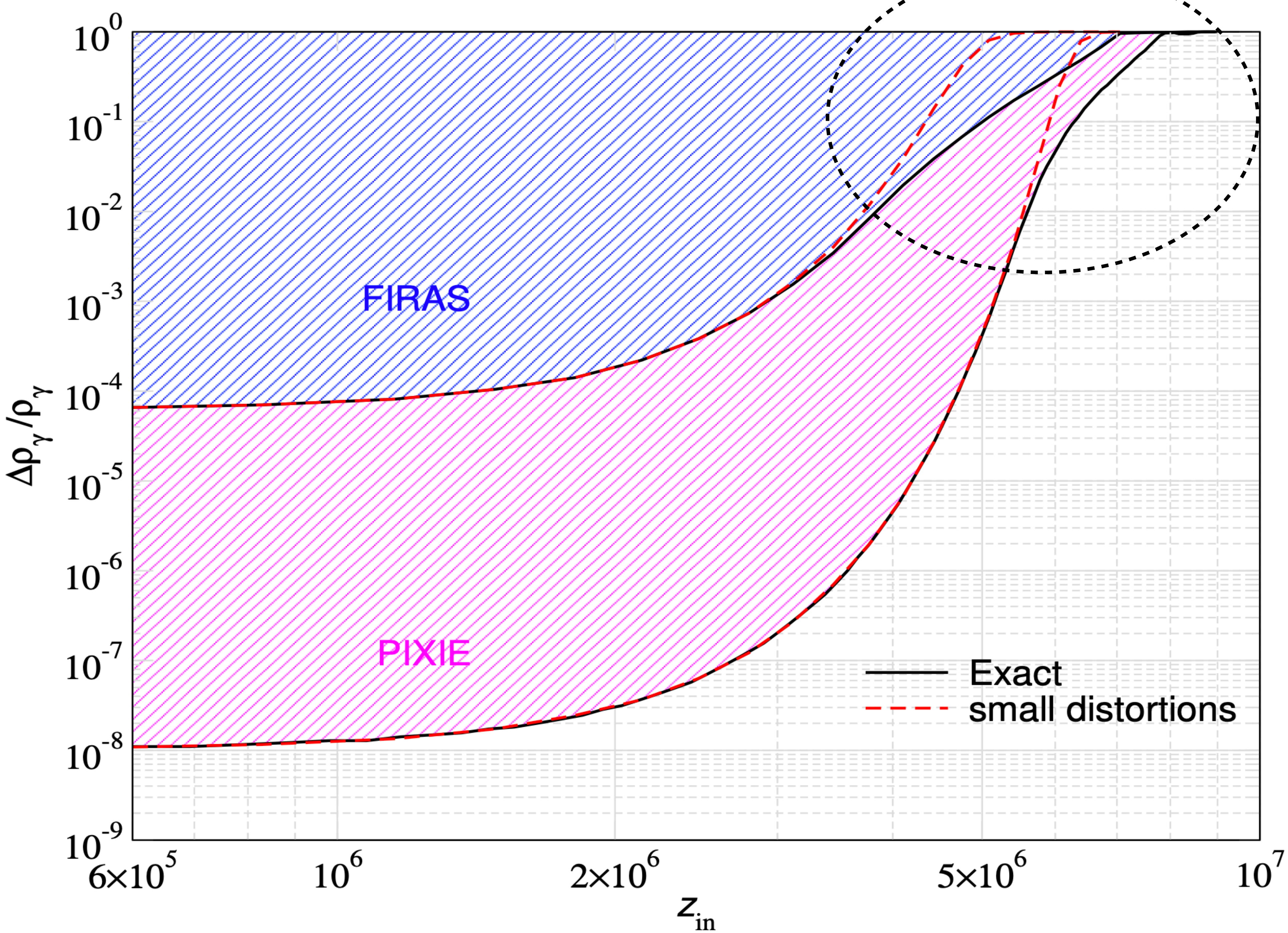


- New way to constrain particle decays/ excited states of DM
- Application to axions
- Possible link to ARCADE *excess* and EDGES?

See poster by Boris Bolliet

Bolliet, JC & Battye, 2020, arXiv:2012.07292

Updated constraints on high energy release from SD

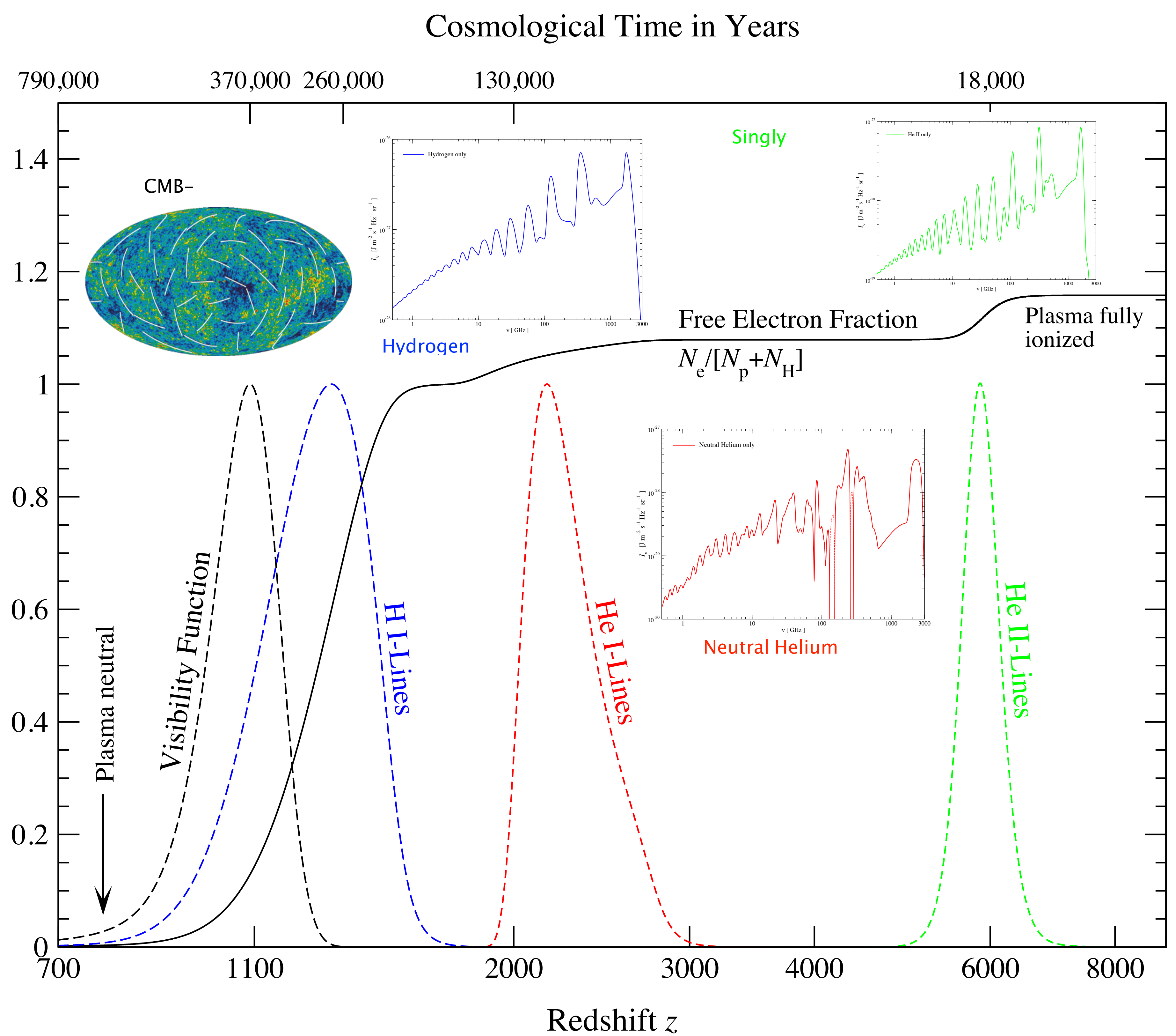


See poster by Sandeep Acharya

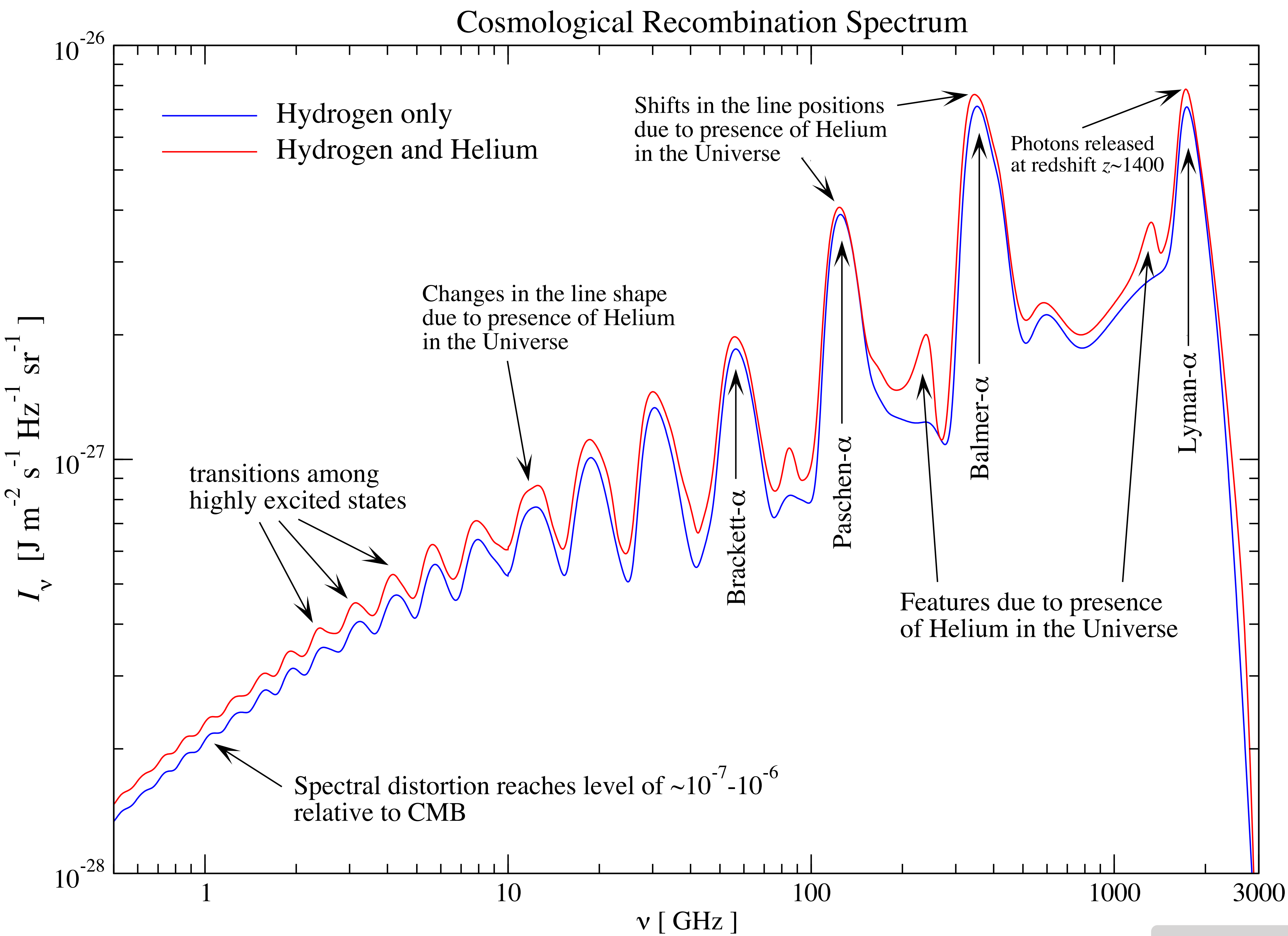
- Requires solving the non-linear Kompaneets eq.

Acharya & Chluba, 2021, arxiv:2112.06699

The Cosmological Recombination Radiation

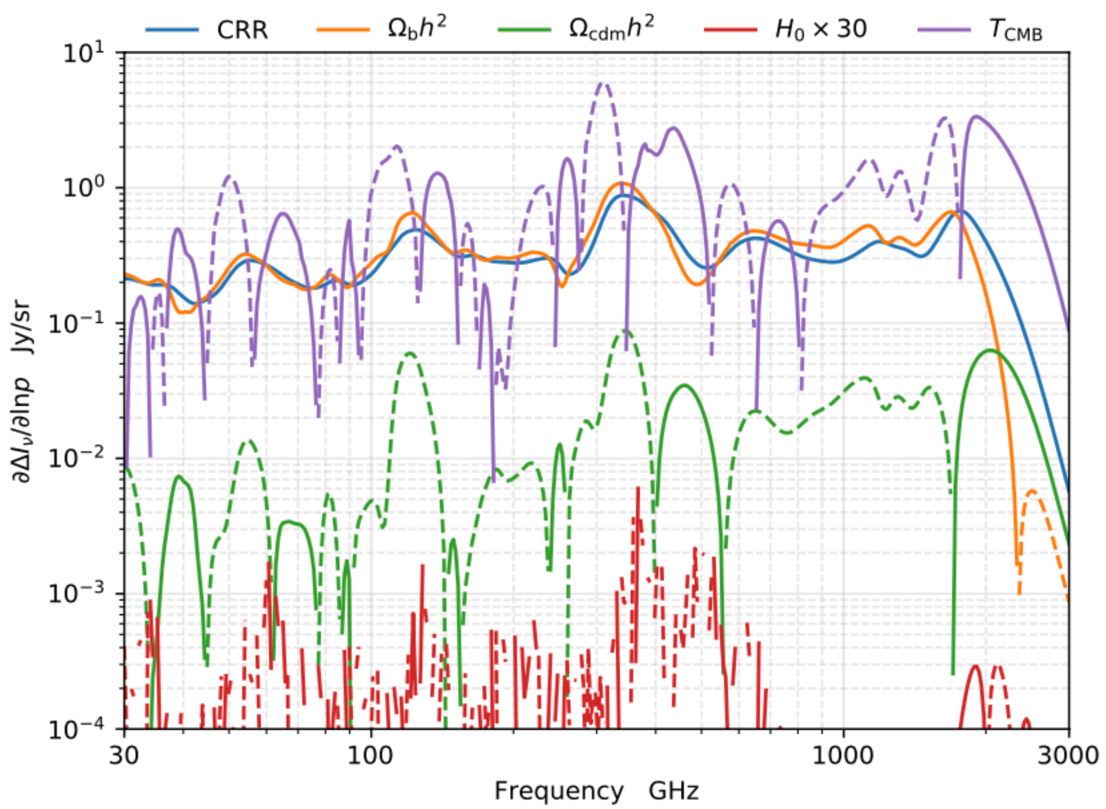


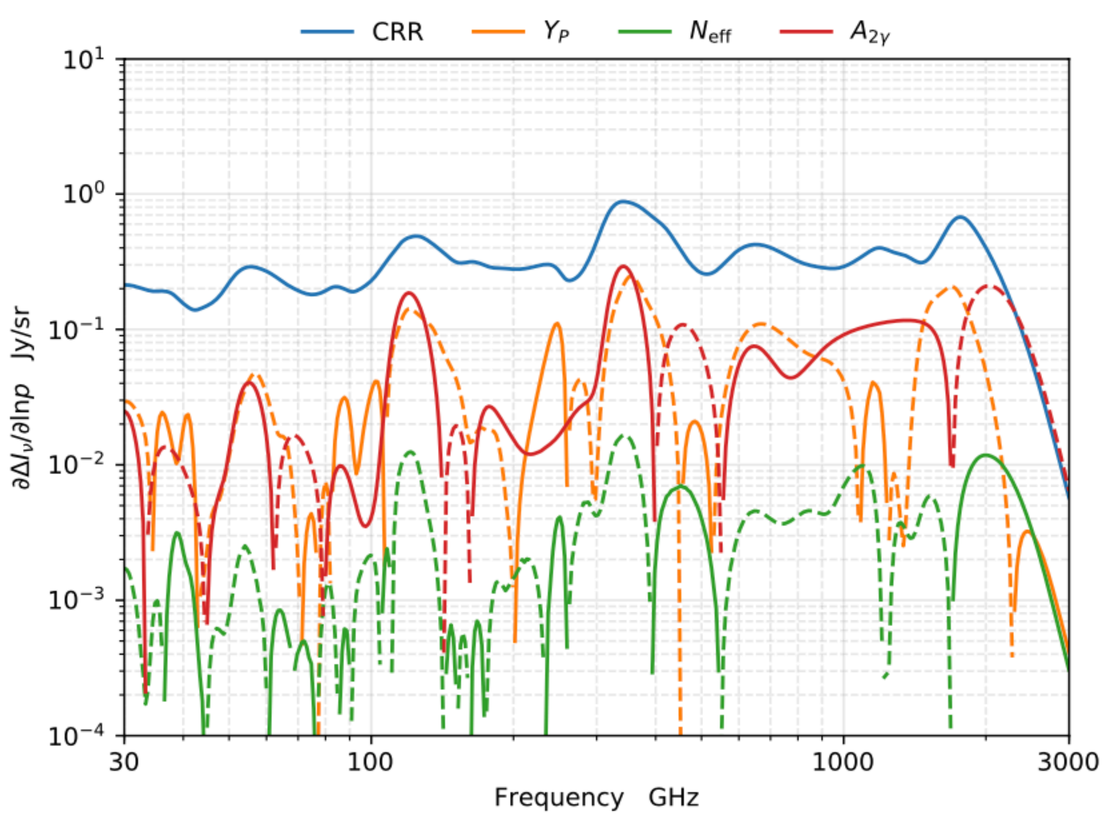
The Cosmological Recombination Radiation

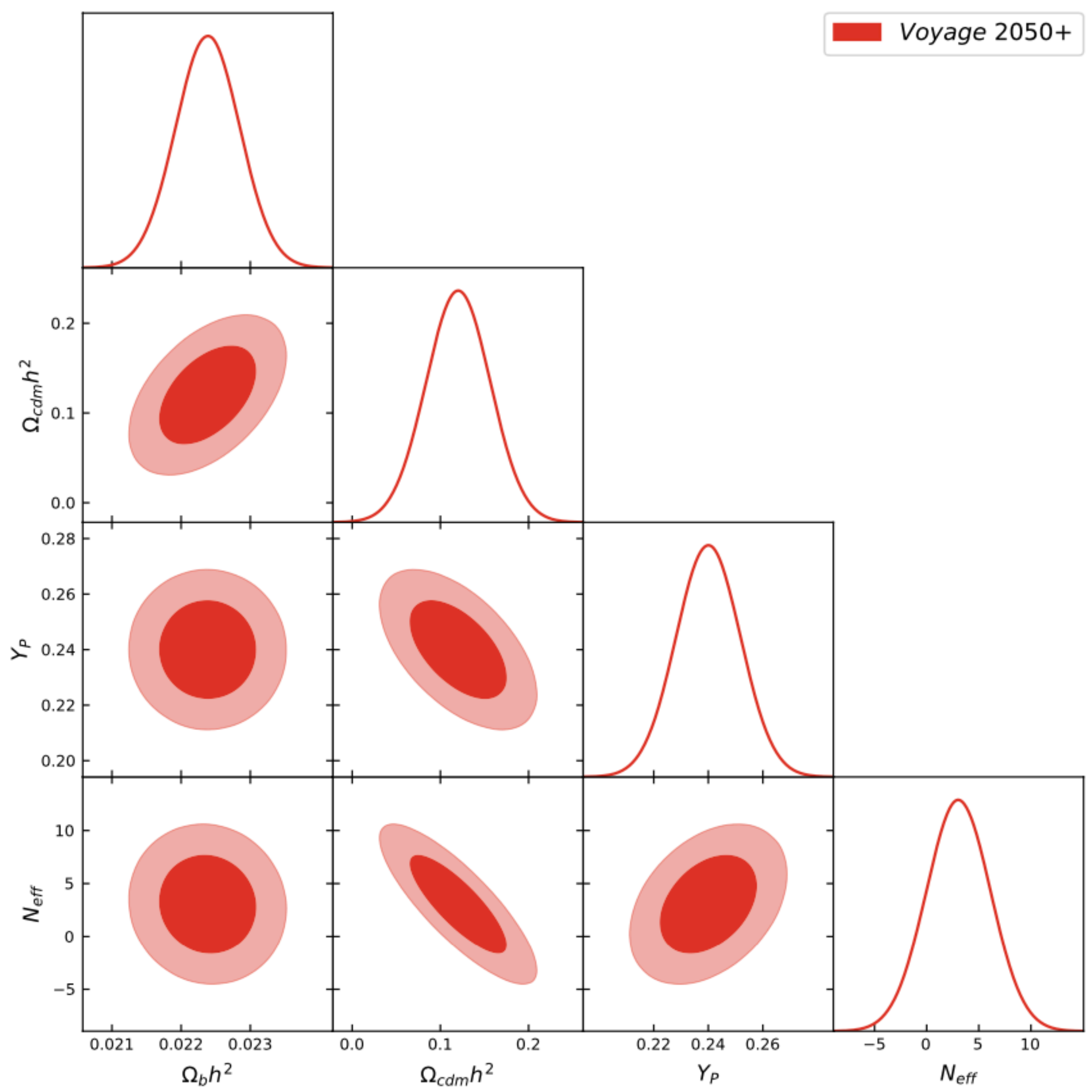


Rubino-Martin et al. 2006, 2008
Sunyaev & Chluba, 2009

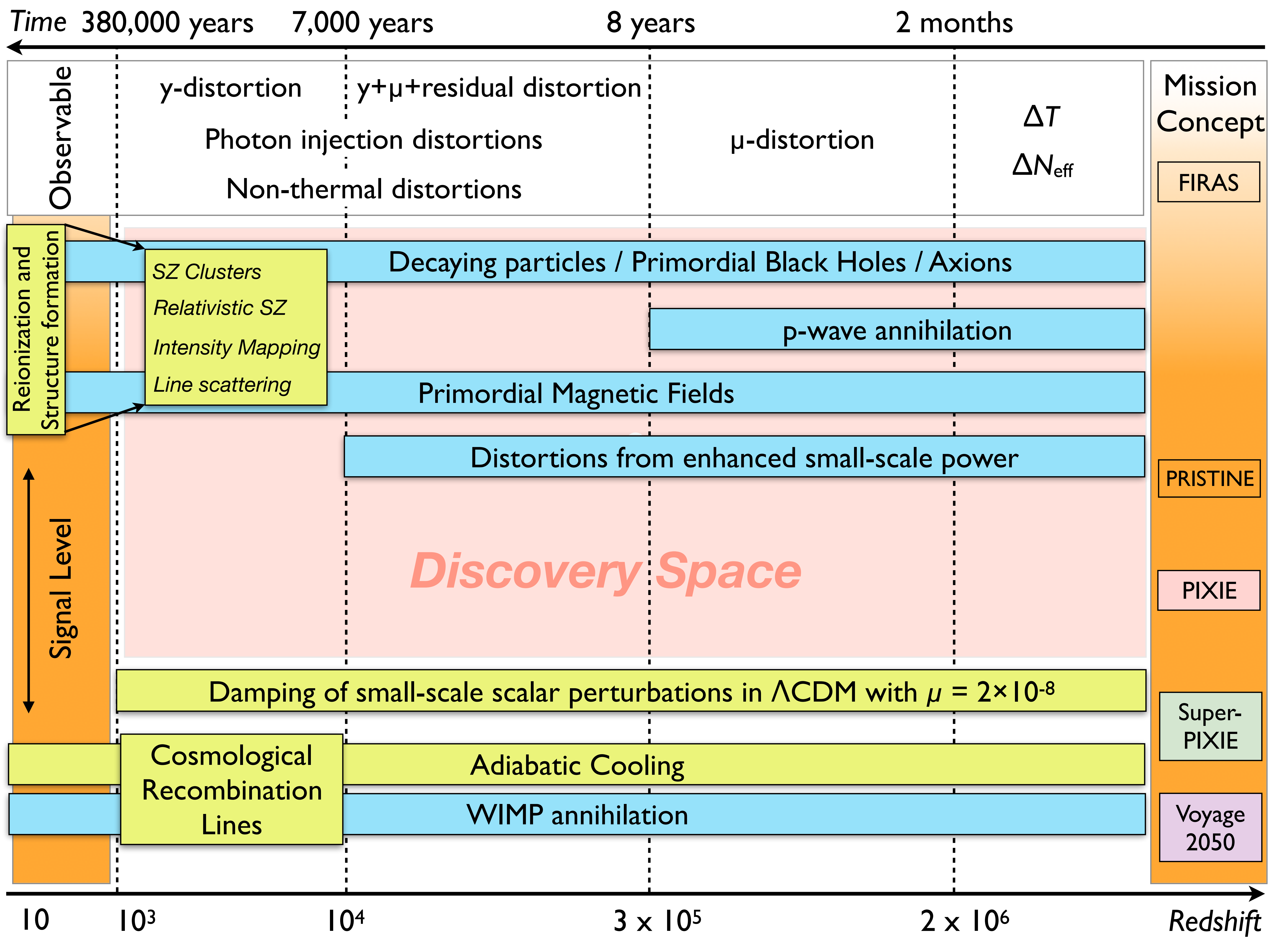
Cosmology with the feature rich CRR spectrum





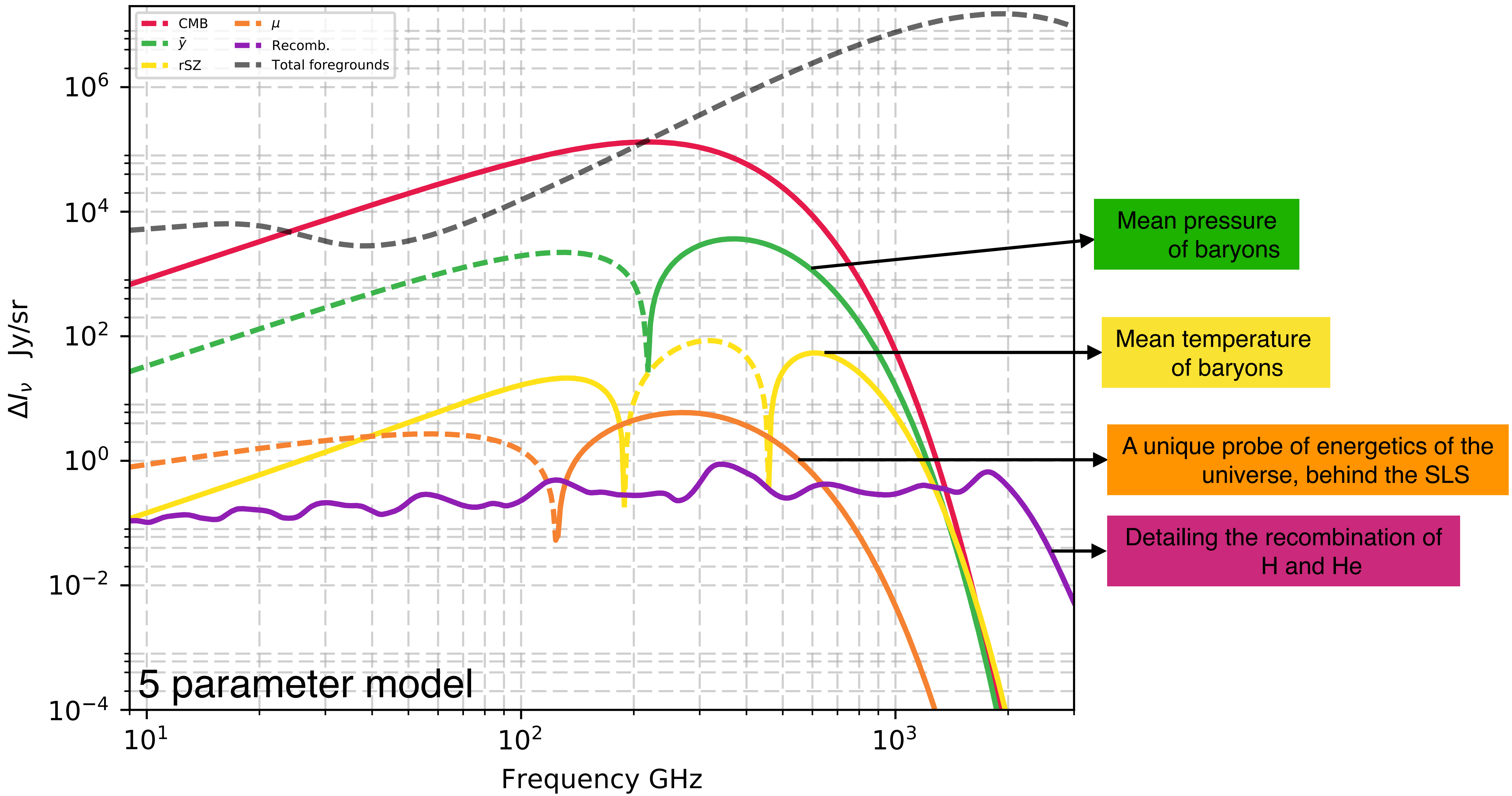


Hart, Rotti & Chluba, 2020, arXiv:2006.04826v1



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
Discovery Space
Signal Level
Damping of small-scale scalar perturbations in ΛCDM with μ = 2×10^-8
Cosmological Recombination Lines
Adiabatic Cooling
WIMP annihilation
10
10^3
10^4
3 x 10^5
2 x 10^6
Redshift

Prominent spectral distortion signals



- Definitive signals that we expect to see in ΛCDM
- Not shown - residual distortion (in standard cosmology this is small, but could be amplified in non standard scenarios - think discovery space!)

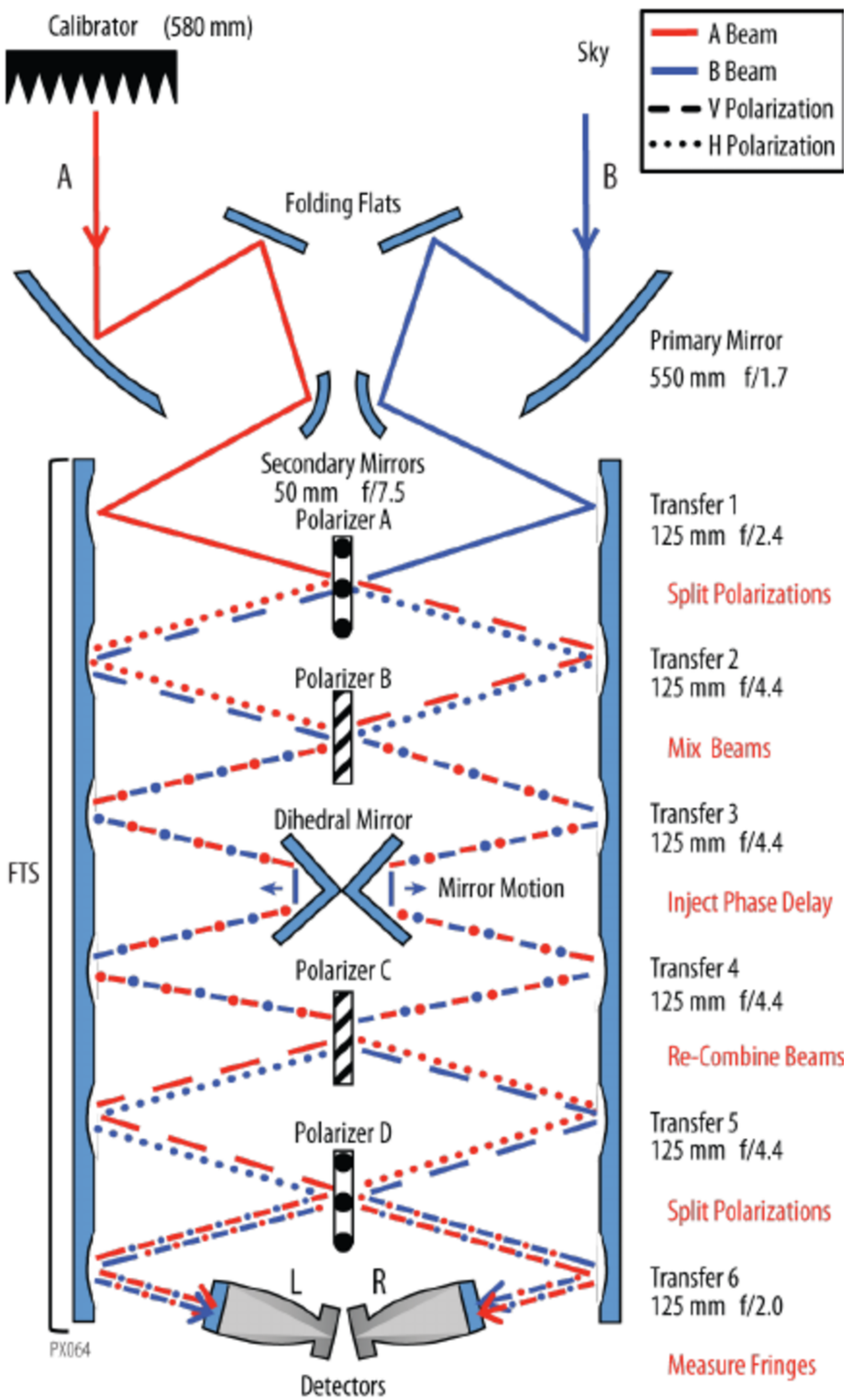
Requirements for measuring spectral distortions

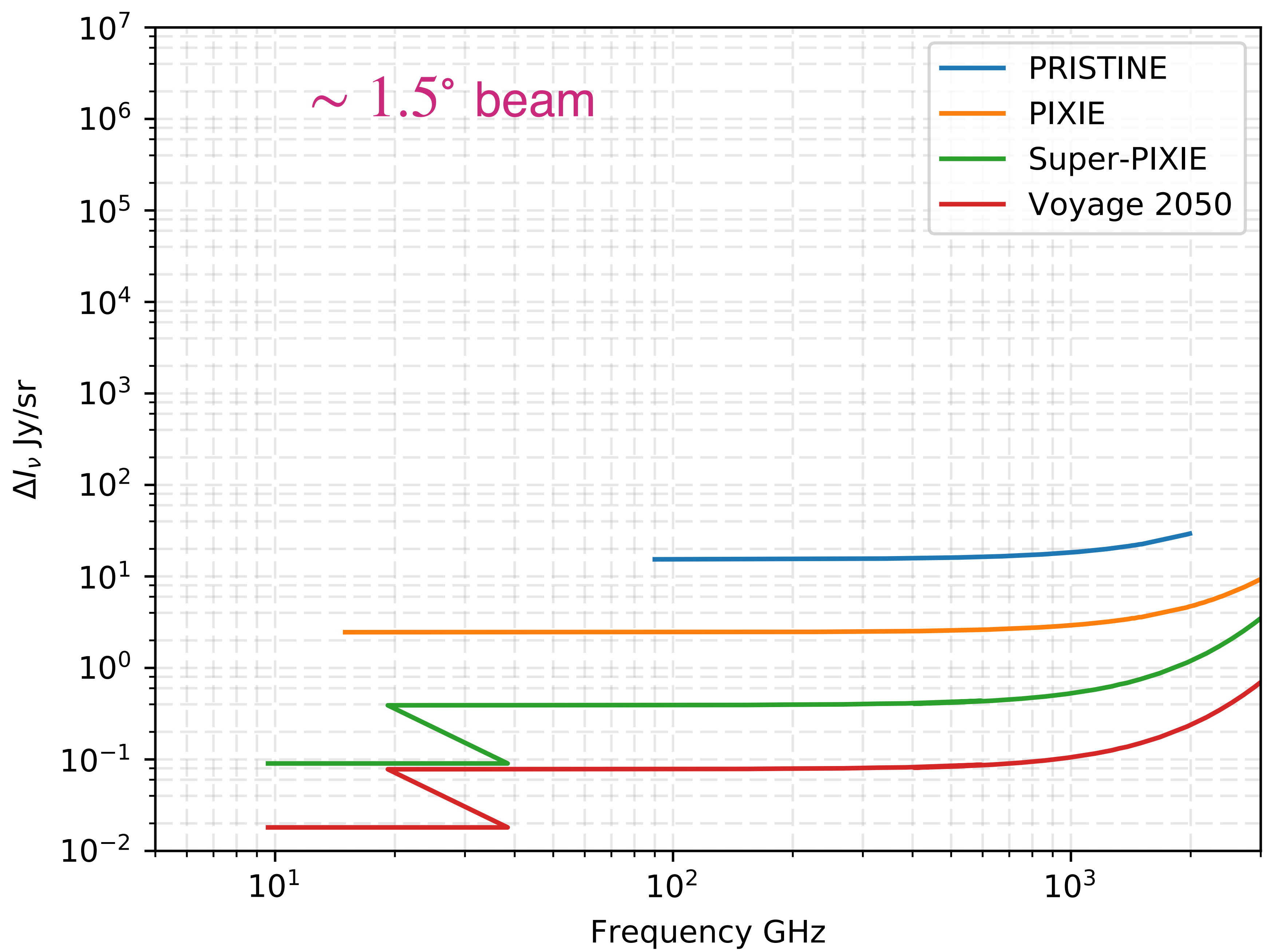
- Signals are small!
- Many many foregrounds (+ ones we have not seen yet !!)
- Variation in signals are small.
- In principle, single pixel measurement is enough. But, sky coverage and resolution might help with mitigating the foregrounds challenge + provide visual clues!

- Sensitivity (~ 0.1 Jy/sr)
- Many many channels with good frequency coverage
- Good cross channel calibration
- Sky coverage
- Resolution ? (there is always a sensitivity - resolution bargain)

We seek to measure the monopole signal

FTS concepts targeting spectral distortion measurements





The foregrounds challenge for SD

Require foreground cleaned sensitivity of $\lesssim 10$ nK to measure μ and CRR signals

This is the same as the requirements for measuring primordial B-modes @ $r \sim 10^{-3}$

but…

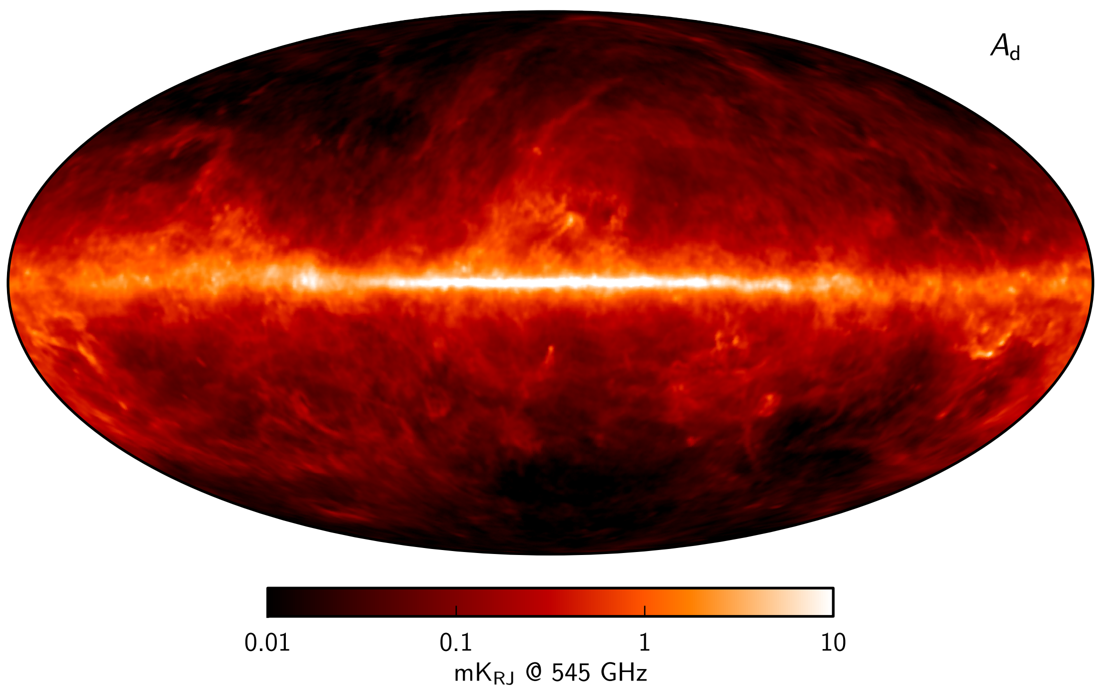
for SD the dominant signal that we seek to measure is in the **monopole** and we dont have the multipole leverage that we have with measurements of C_ℓ^{BB}

+

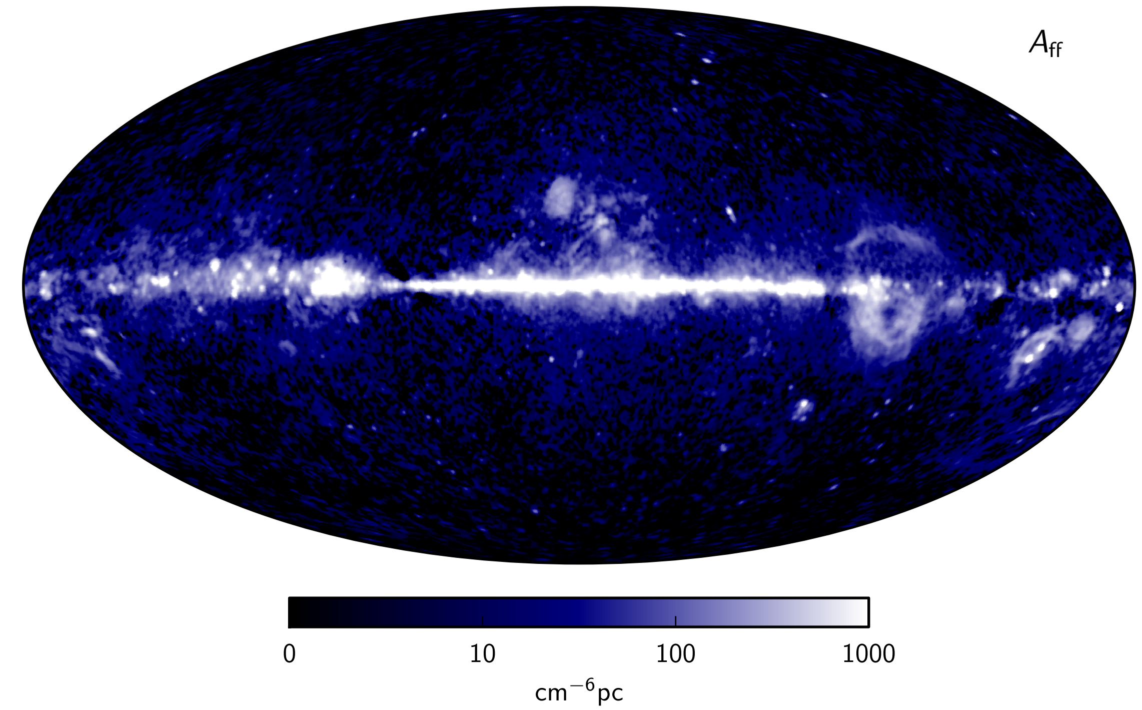
we have to deal with intensity foregrounds as opposed to the “fewer” polarized foregrounds for B-modes

Some of the foregrounds and their spatial variation

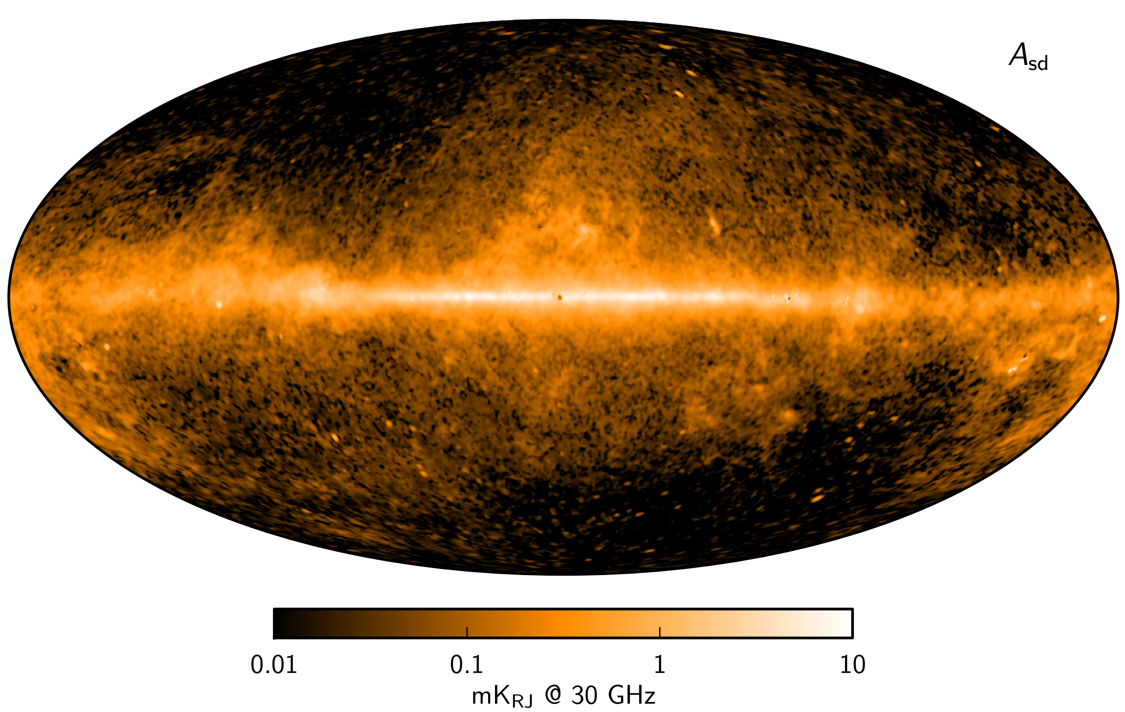
Thermal dust



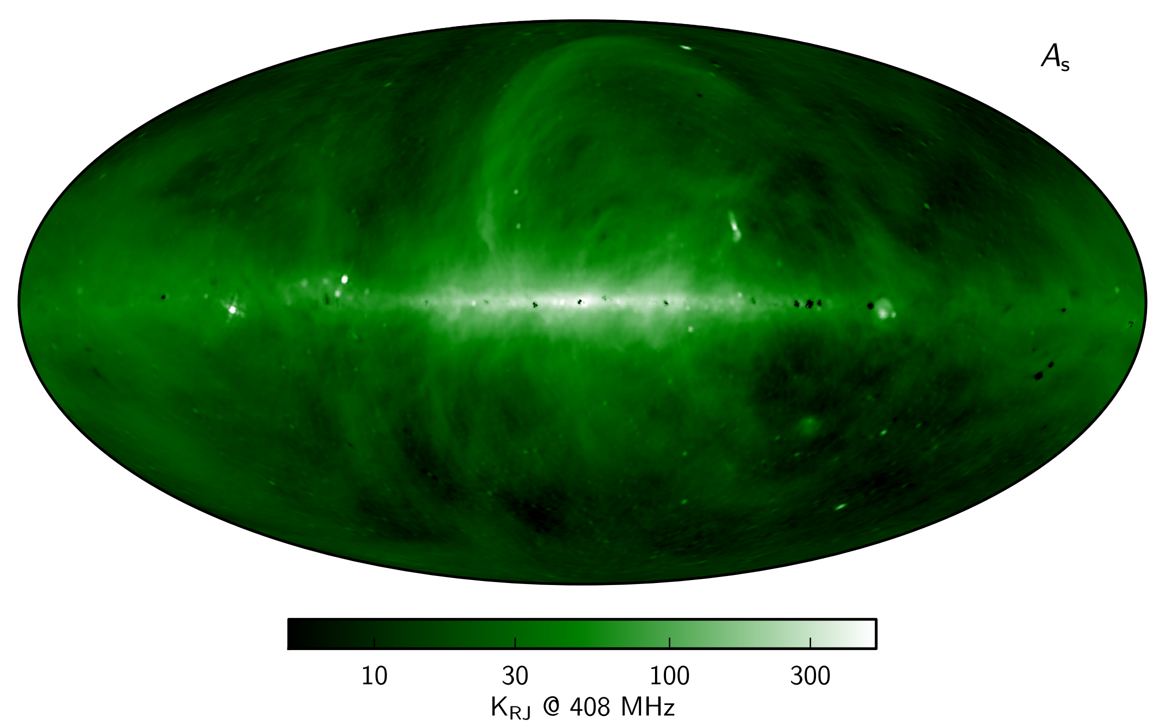
free-free emission



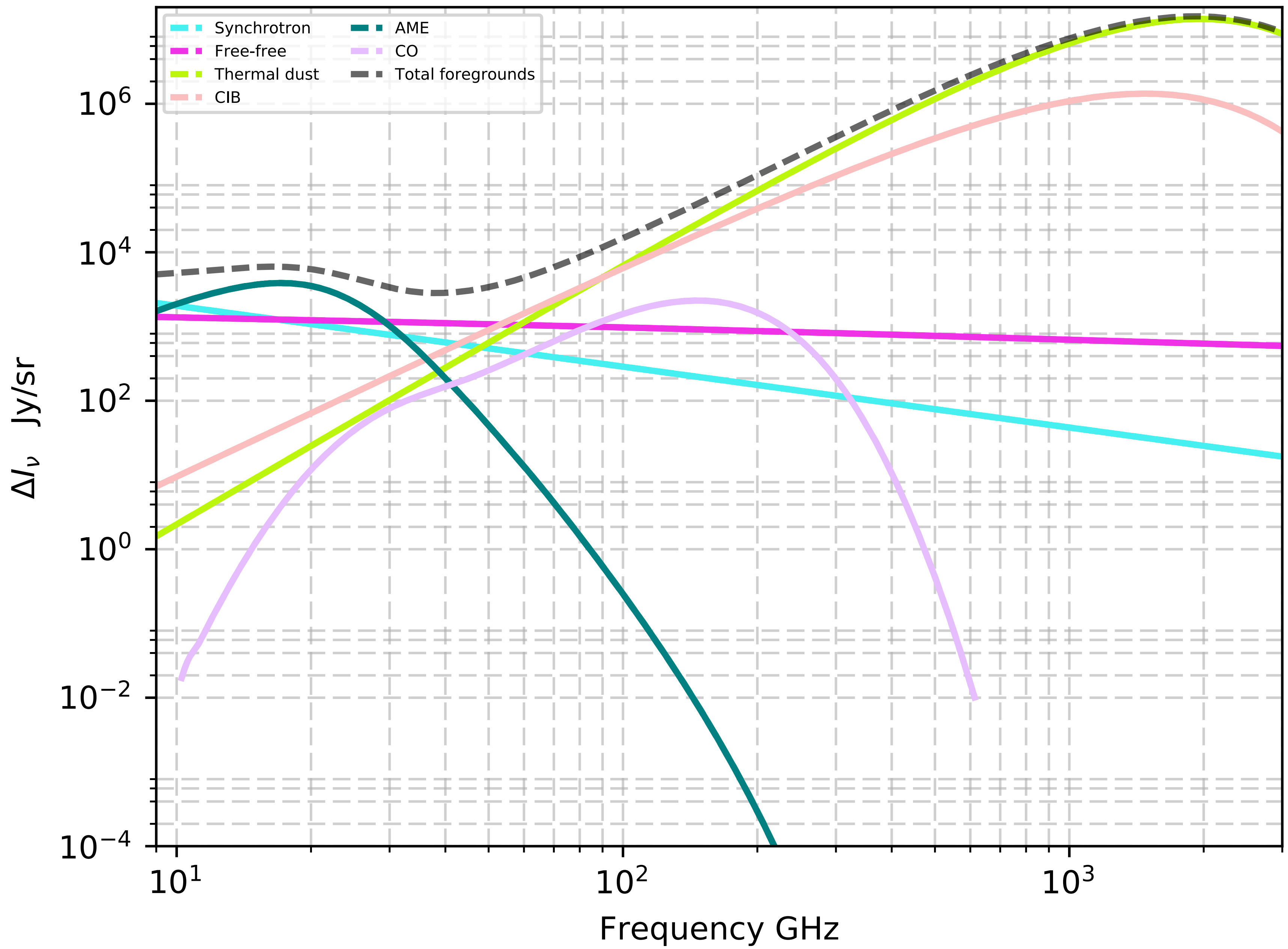
Spinning dust



Synchrotron

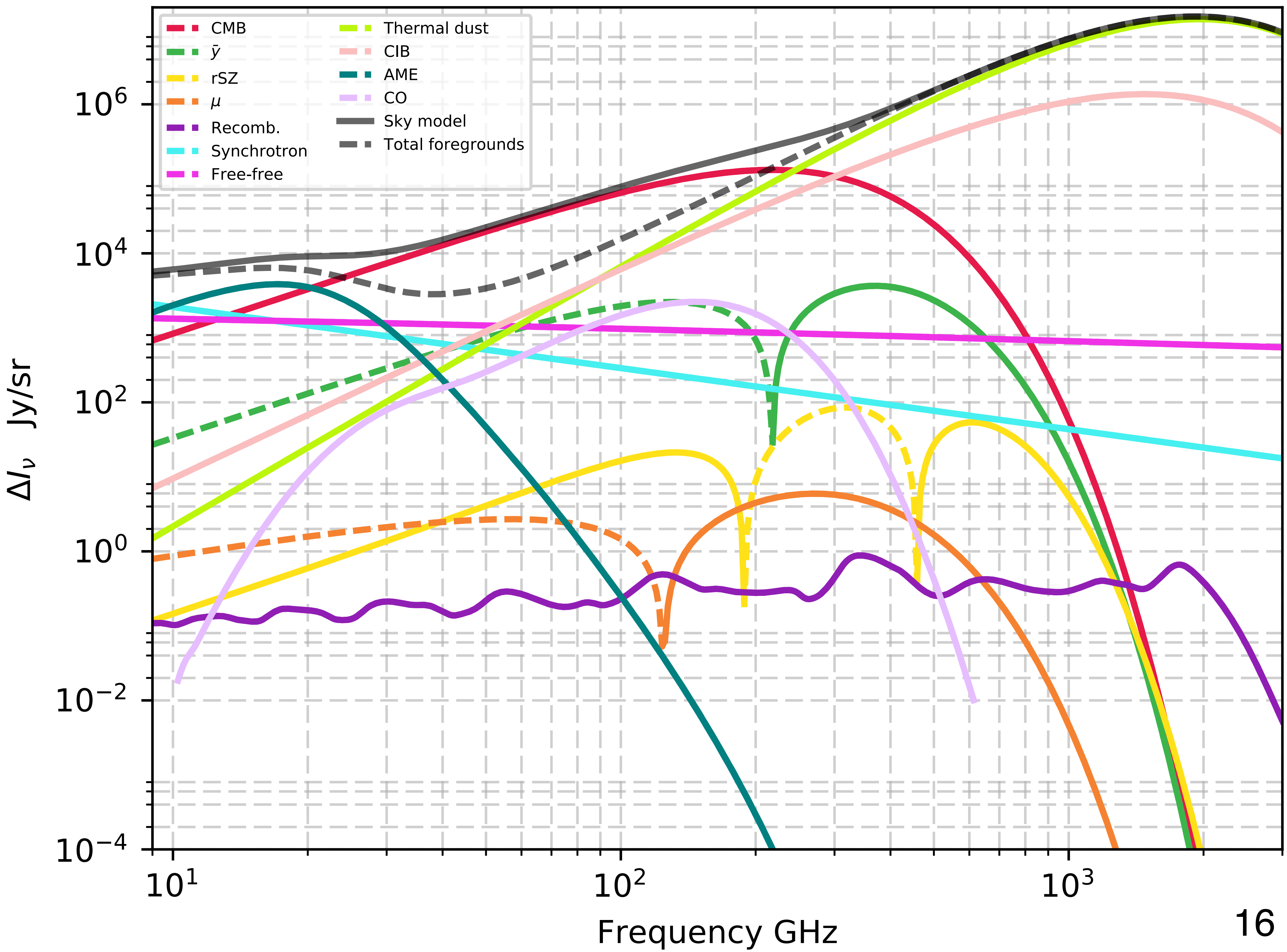


The foregrounds landscape



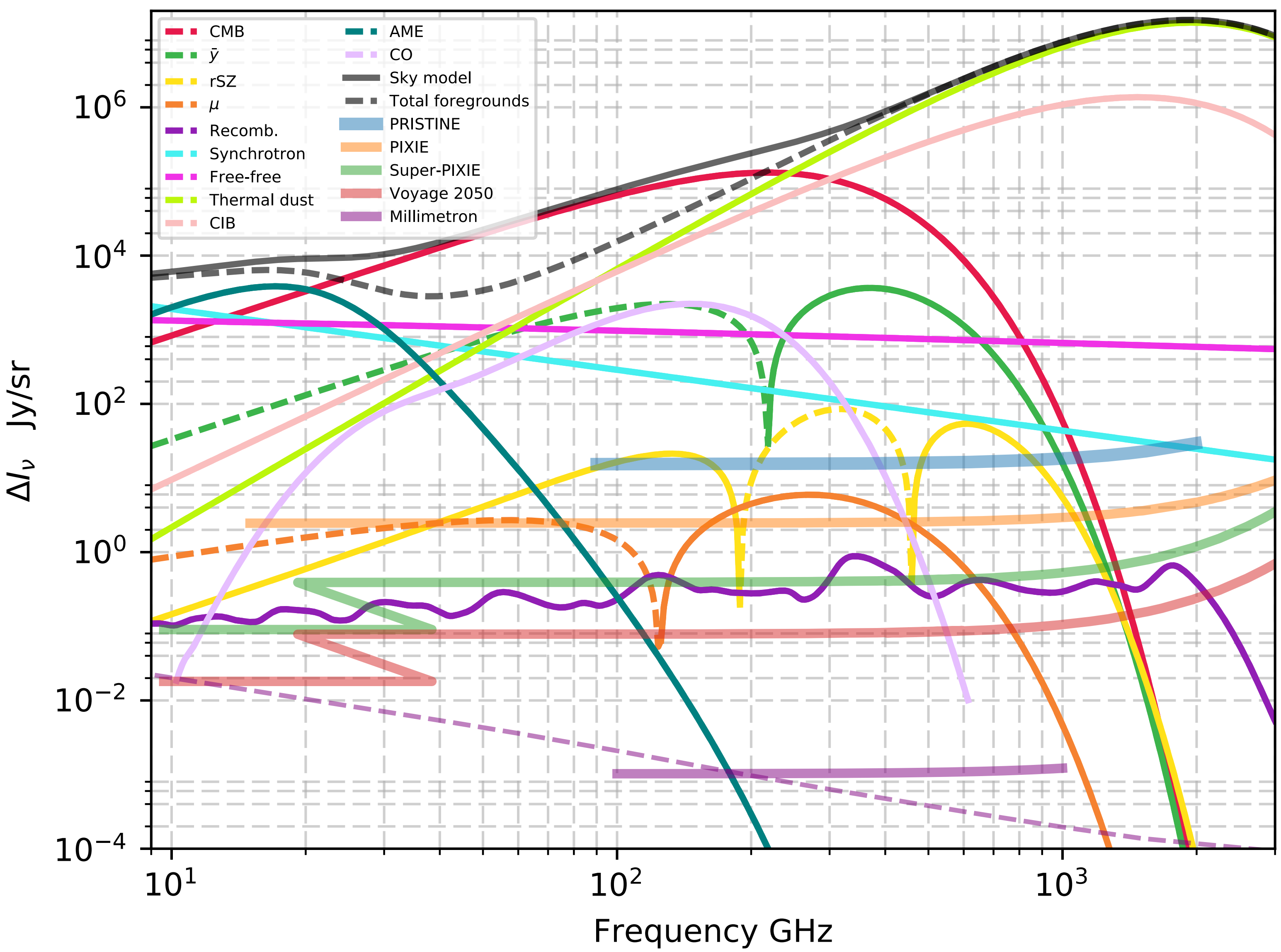
- Assuming the fiducial functional forms (ν^α : synchrotron, $\nu^\beta B_\nu(T_d)$: dust, cib) for these foregrounds, in the simplest case this is characterized by **11 parameters**
- Then there are the unknown unknowns ….but ….we will learn lot about these via upcoming anisotropy experiments that will measure the sky with comparable sensitivity.

A BASIC model for our sky



16 parameters

Fisher forecasting procedure



Non-linear optimization problem

$$d_\nu = \sum_c A_c S^c_\nu(\vec{\alpha}) + n_\nu$$

↓

Linearize

↓

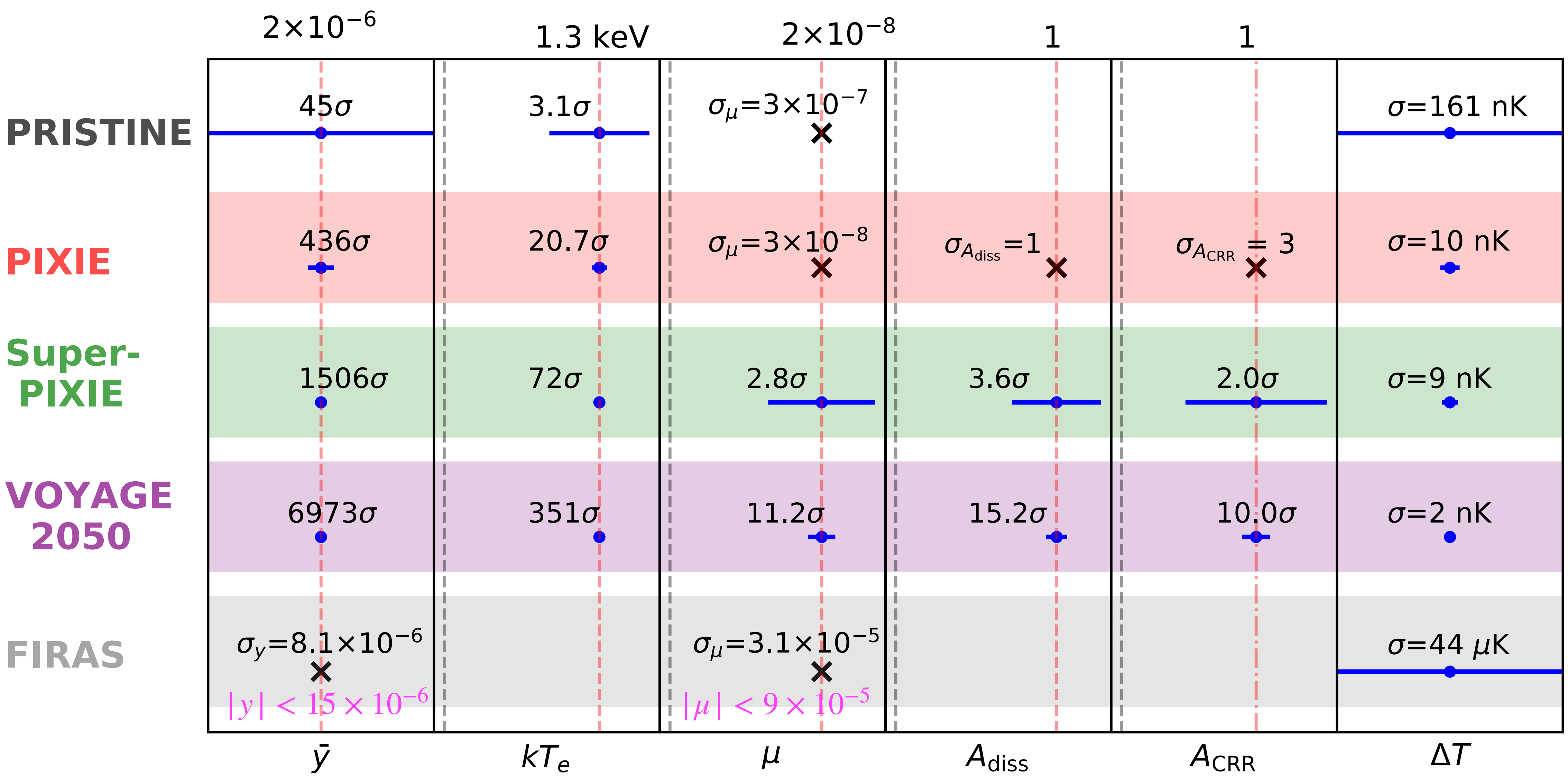
Fisher analysis

↓

SNR forecasts

M. Abitbol, J. Chluba, J. C. Hill and B. R. Johnson et. al. MNRAS (2017) 471 (1): 1126–1140

Forecasts for SD measurements



This is a good first step! But we need a more careful assessment

Assumption : Foreground characterized by the simple SED form on the monopole spectrum

Voyage 2050 white paper: arXiv:1909.01593

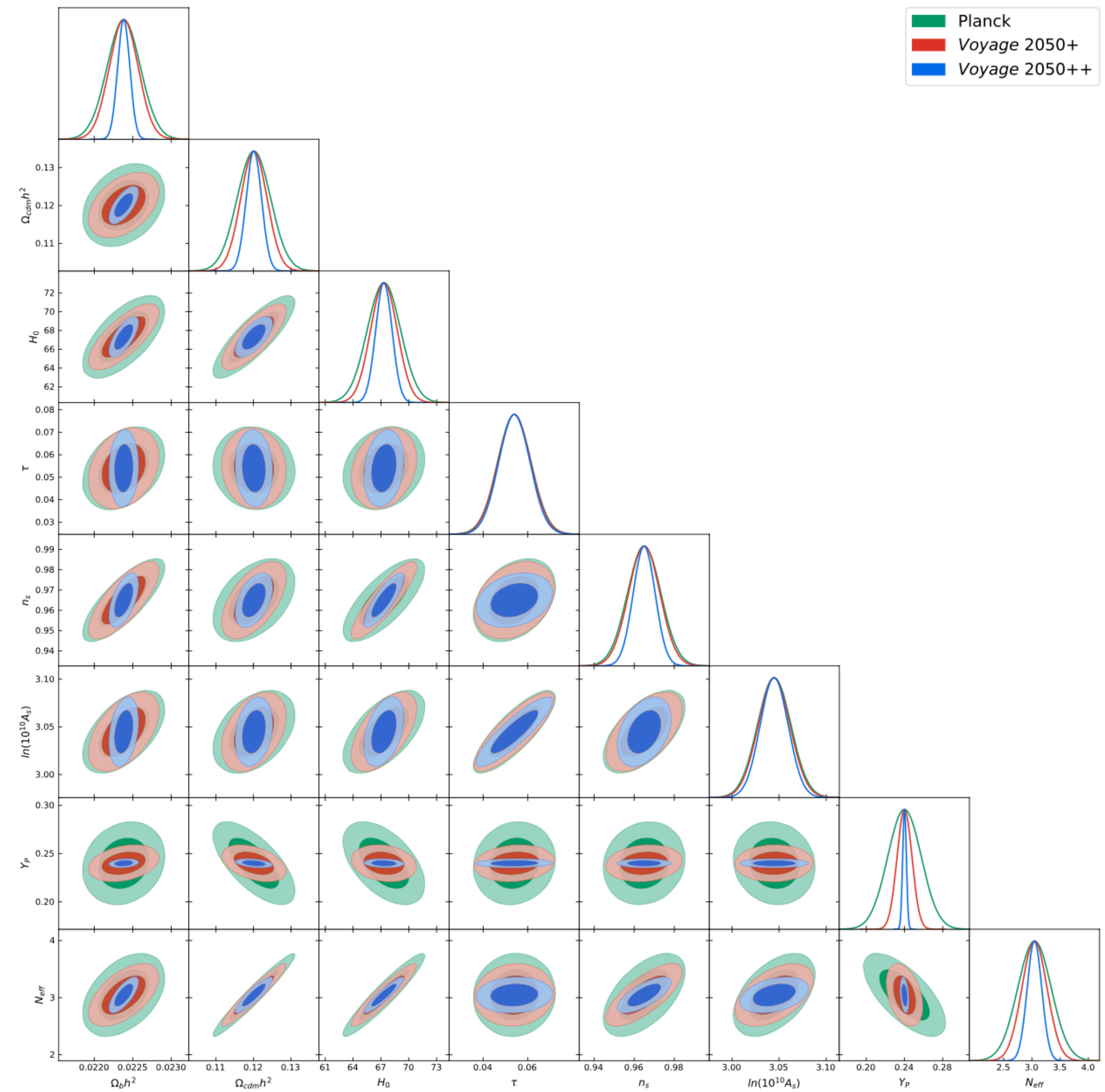
With Fisher we can already forecast cosmology constraints from CRR measurements, accounting for the foreground degradation

SNR recomb

Analysis	*PIXIE*	*SuperPIXIE*	*Voyage 2050*	*Voyage 2050+*
No Frgs.	1.6	9.5	47.7	476.5
Dist. Frgs.	1.1	3.6	17.8	178.5
Astr. Frgs.	0.5	2.4	12.2	122.3
All Frgs.	0.3	1.5	7.7	77.2

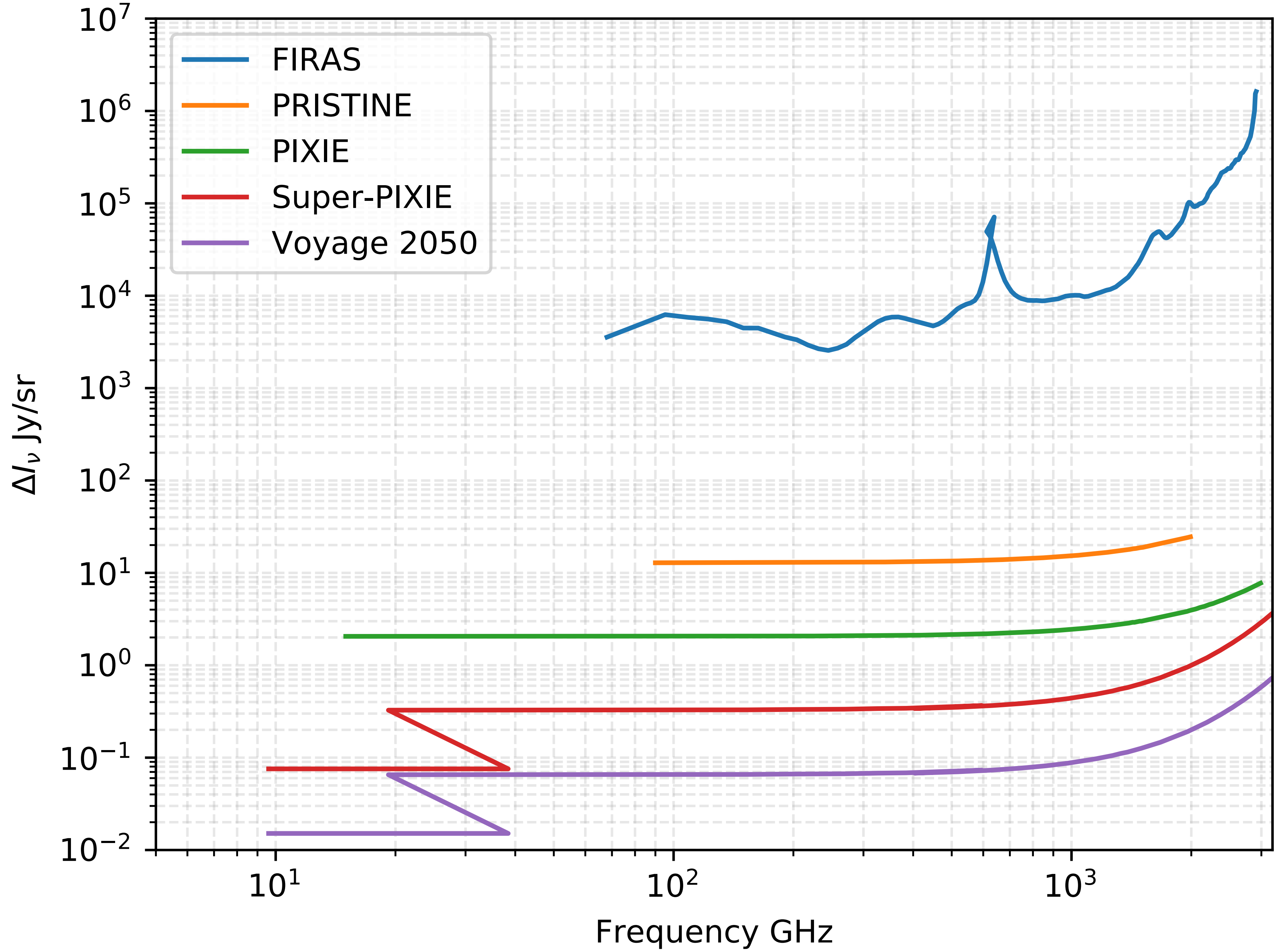
Spectrometer only standard params + $N_{\rm eff}$ + $Y_{\rm He}$

Expt.	Analysis	$\Omega_b h^2$	$\Omega_{\rm CDM} h^2$	H_0	Y_P	$N_{\rm eff}$
Voyage 2050	No Frgs.	35.81	0.55	0.00	4.77	0.12
	Dist. Frgs.	11.57	0.50	0.00	3.88	0.11
	Astr. Frgs.	6.29	0.39	0.00	2.54	0.10
	All Frgs.	4.81	0.33	0.00	2.03	0.10
Voyage 2050+	No Frgs.	360.97	5.50	0.02	47.65	1.18
	Dist. Frgs.	115.69	4.99	0.02	38.79	1.13
	Astr. Frgs.	62.66	3.93	0.01	25.15	1.01
	All Frgs.	48.13	3.30	0.01	20.21	0.99



Hart L., Rotti A. & Chluba J. MNRAS 497, 4, 2020

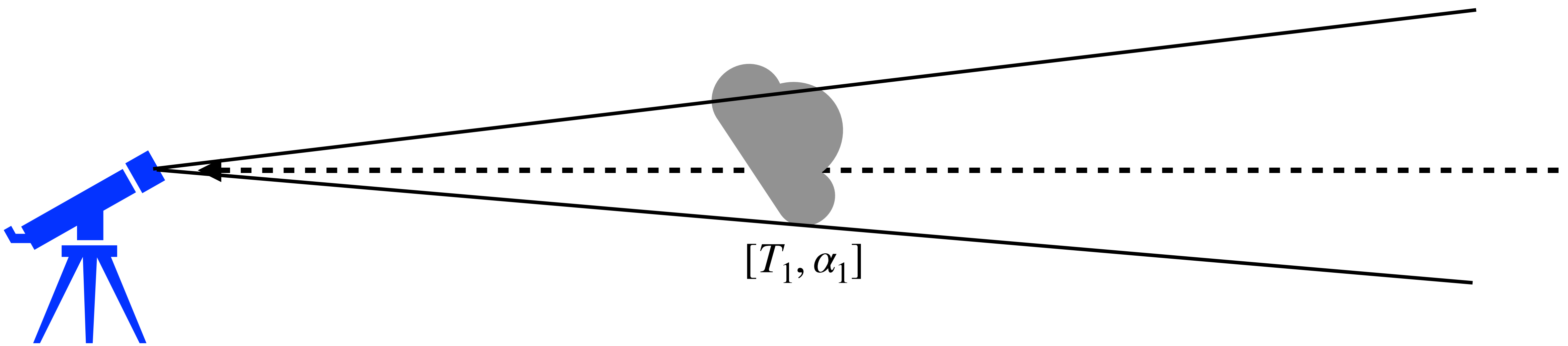
Given the order of magnitude jump in sensitivity we cannot assume the simple SED models to accurately describe foregrounds!

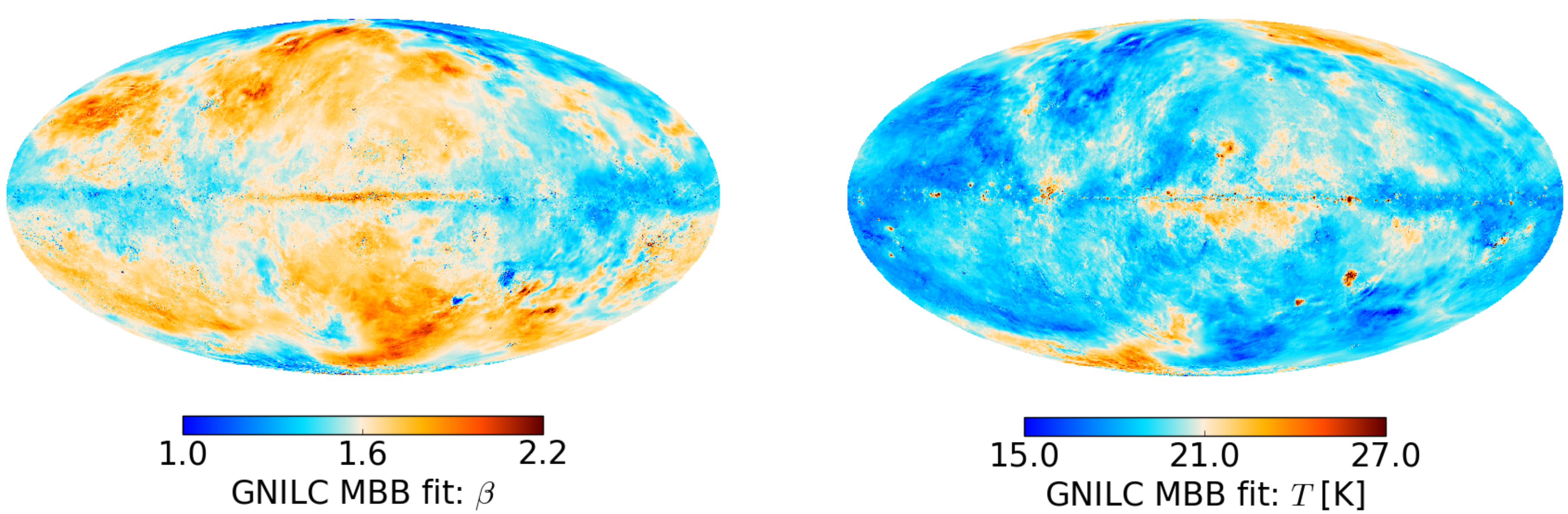


Observer assumption

Each cloud emits a modified black body spectrum.

$$B_\nu(\alpha, T) = A\frac{2h\nu^3}{c^2}\left(\frac{\nu}{\nu_0}\right)^\alpha \frac{1}{e^{\frac{h\nu}{kT}} - 1}$$

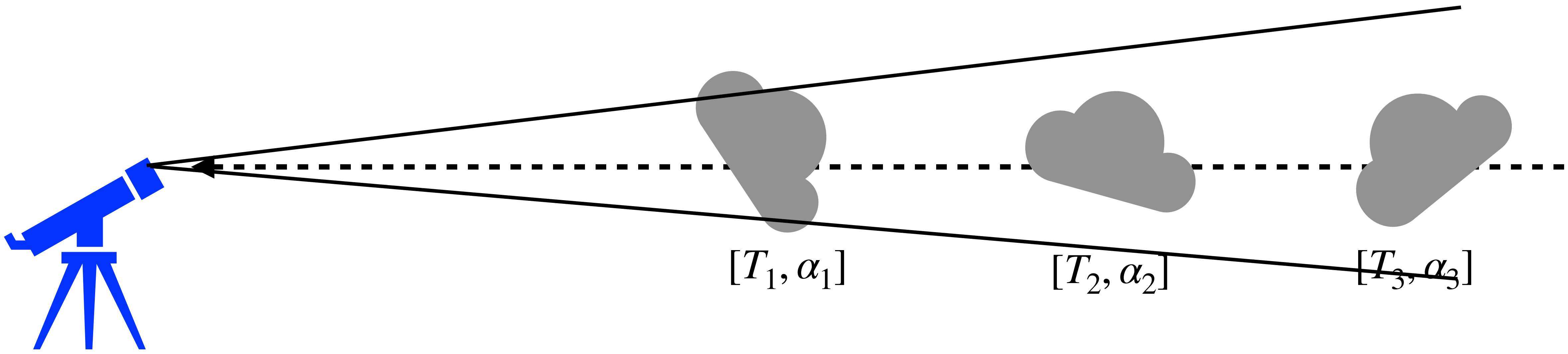




Reality in nature

Each cloud emits a modified black body spectrum.

$$B_\nu(\alpha, T) = \frac{2h\nu^3}{c^2}\left(\frac{\nu}{\nu_0}\right)^\alpha \frac{1}{e^{\frac{h\nu}{kT}} - 1}$$



$$S_\nu = \int \frac{dI}{ds} ds \neq B_\nu(\alpha', T')$$

What are moments?

Describing SED resulting from sum of modified black bodies:

$$S_\nu = \int \frac{dI}{ds} ds = \int B_\nu(\alpha, T) P(\alpha, T) d\alpha dT$$

g on top of the simple parametrization:

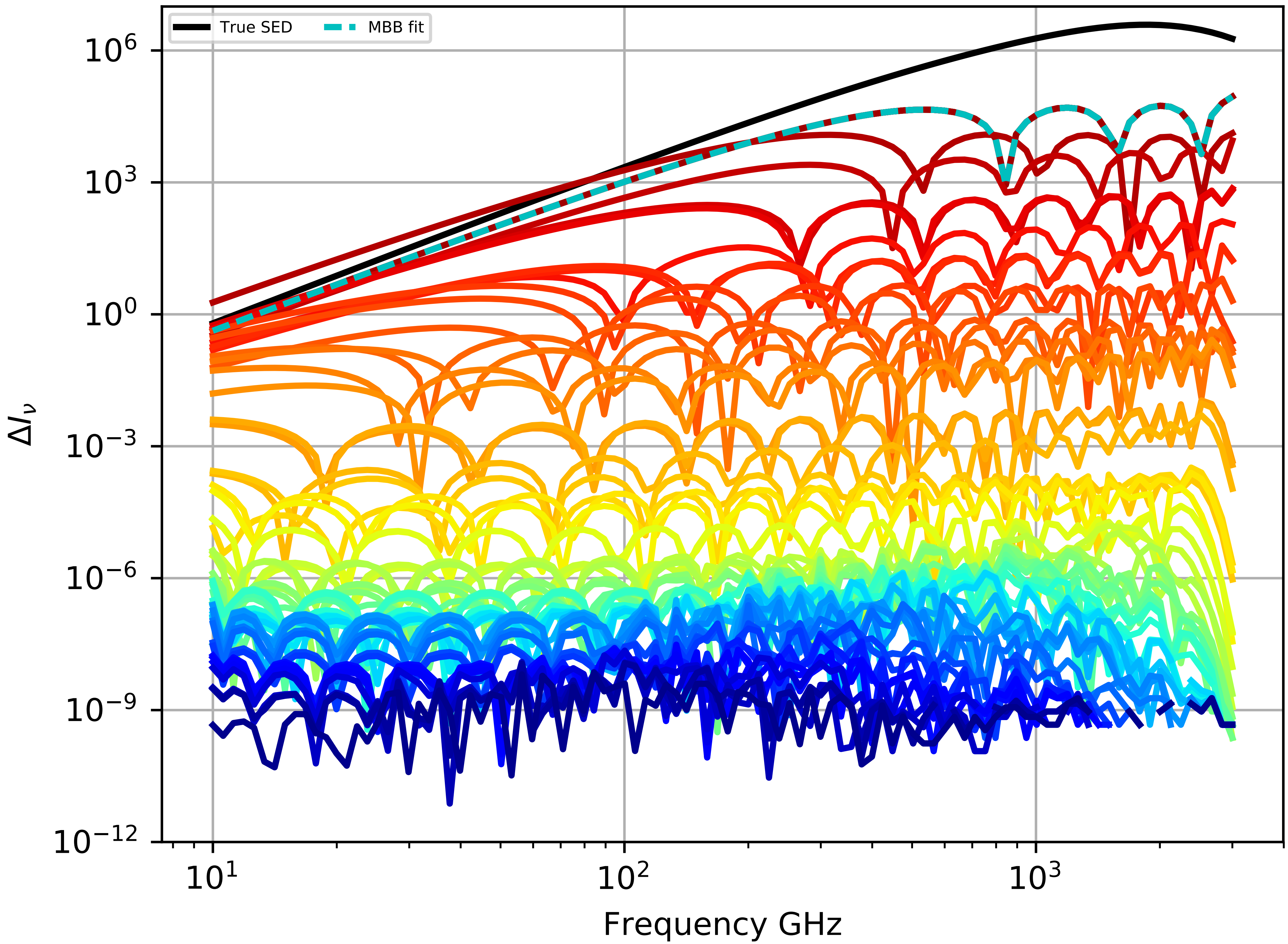
$$S_\nu = \sum_{m,n} \partial_\alpha^m \partial_T^n B_\nu(\alpha_0, T_0) \int (\alpha - \alpha_0)^m (T - T_0)^n P(\alpha, T) d\alpha dT$$

Moments of the distribution function

$$S_\nu(\alpha_0, T_0, A, p_\alpha, p_T, p_{\alpha\alpha}, p_{\alpha T}, p_{TT}, \cdots) \simeq AB_\nu(\alpha_0, T_0)$$
$$+ p_\alpha \partial_\alpha B_\nu(\alpha_0, T_0) + p_T \partial_T B_\nu(\alpha_0, T_0)$$
$$+ p_{\alpha\alpha} \partial_\alpha^2 B(\alpha_0, T_0) + p_{\alpha T} \partial_\alpha \partial_T B(\alpha_0, T_0) + p_{TT} \partial_T^2 B(\alpha_0, T_0) + \cdots$$

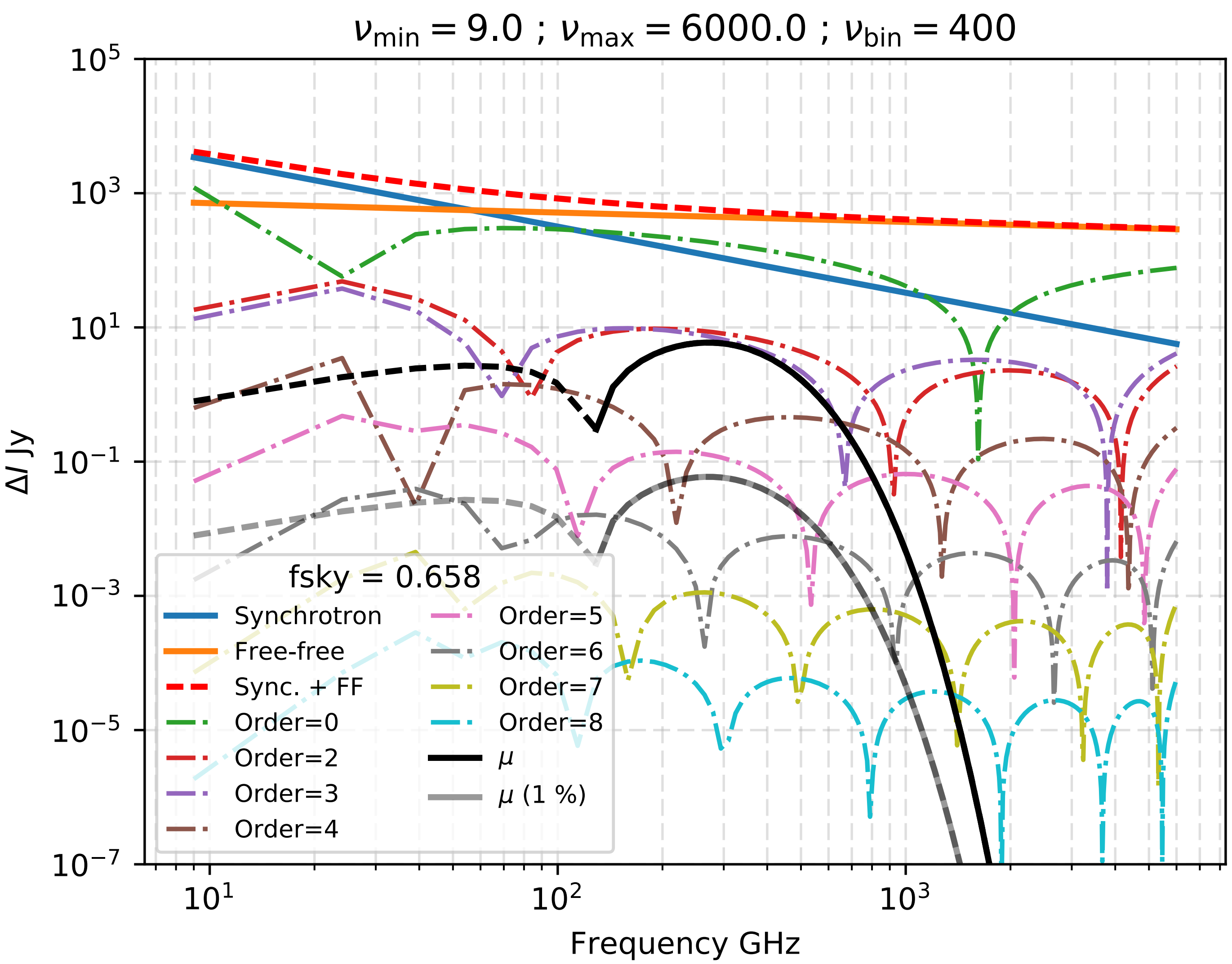
J. Chluba, J. C. Hill & M. H. Abitbol, MNRAS, Vol. 472, Iss. 1, 1195-1213
A. Rotti & J. Chluba arXiv:2006.02458

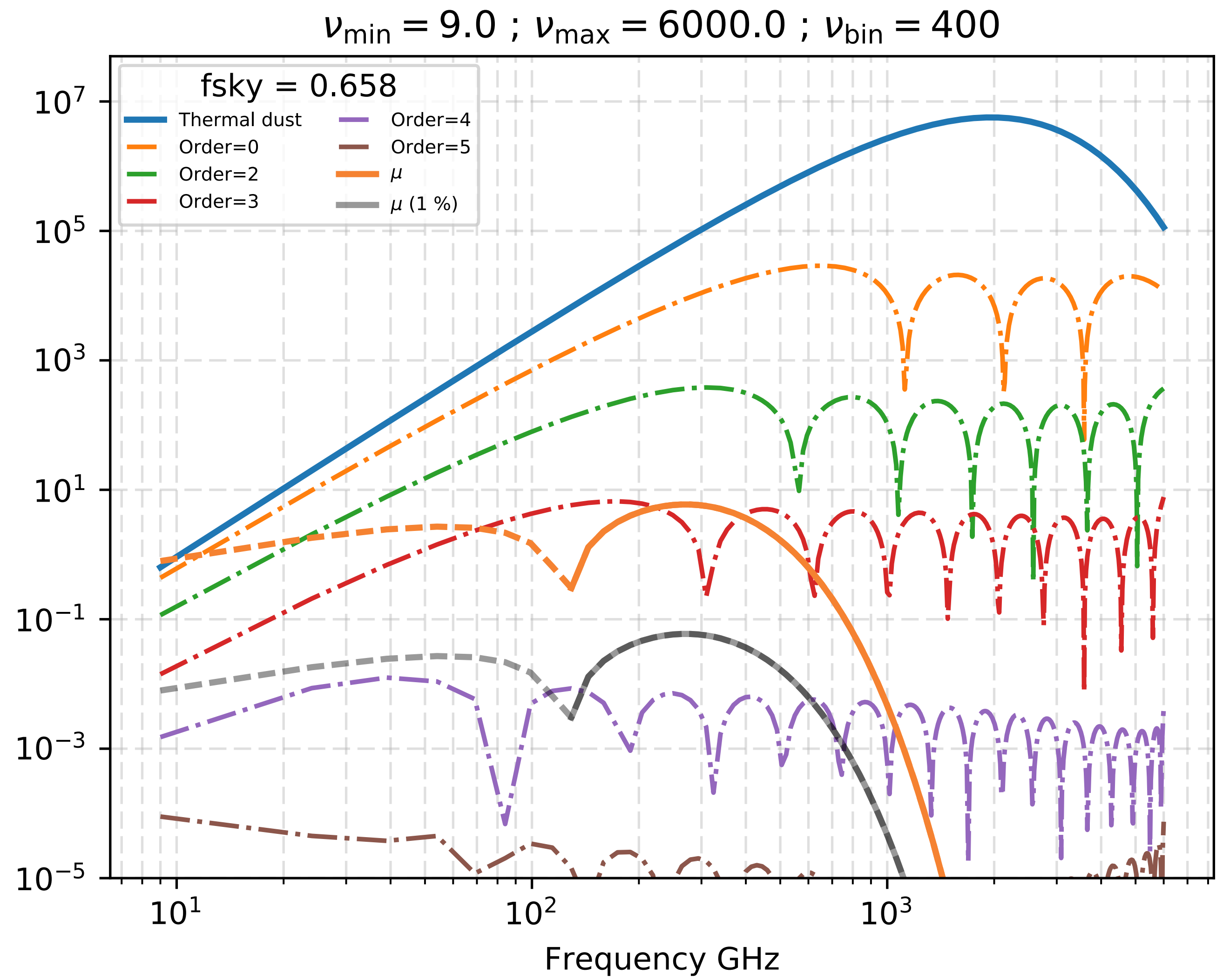
Moments work really well



Two component MBB: [9.75 K, 1.63] + [15.7,2.82]

How many moments to model foregrounds to desired accuracy for the Planck sky?





SKY AVERAGED – SINGLE PIXEL

- SED evaluated from sky sims. generated using Python Sky Model (fsky=0.66)
- These moments are generated from spatial averaging.
- One expects similar order of magnitude moments arising from line of sight averaging

Do we need to fit all the spectral degrees of freedom - a single pixel experiment would mandate that!

Could we circumvent this by exploiting the fact that foregrounds are spatially varying — ILC motivated semi-blind methods ?

Moment ILC - A semi-blind component separation approach

Goal : Minimize bias at the least noise cost

$$V = [S_\nu^{\rm CMB}, S_\nu^{\rm tSZ}, S_\nu^{\mu}, \cdots]$$

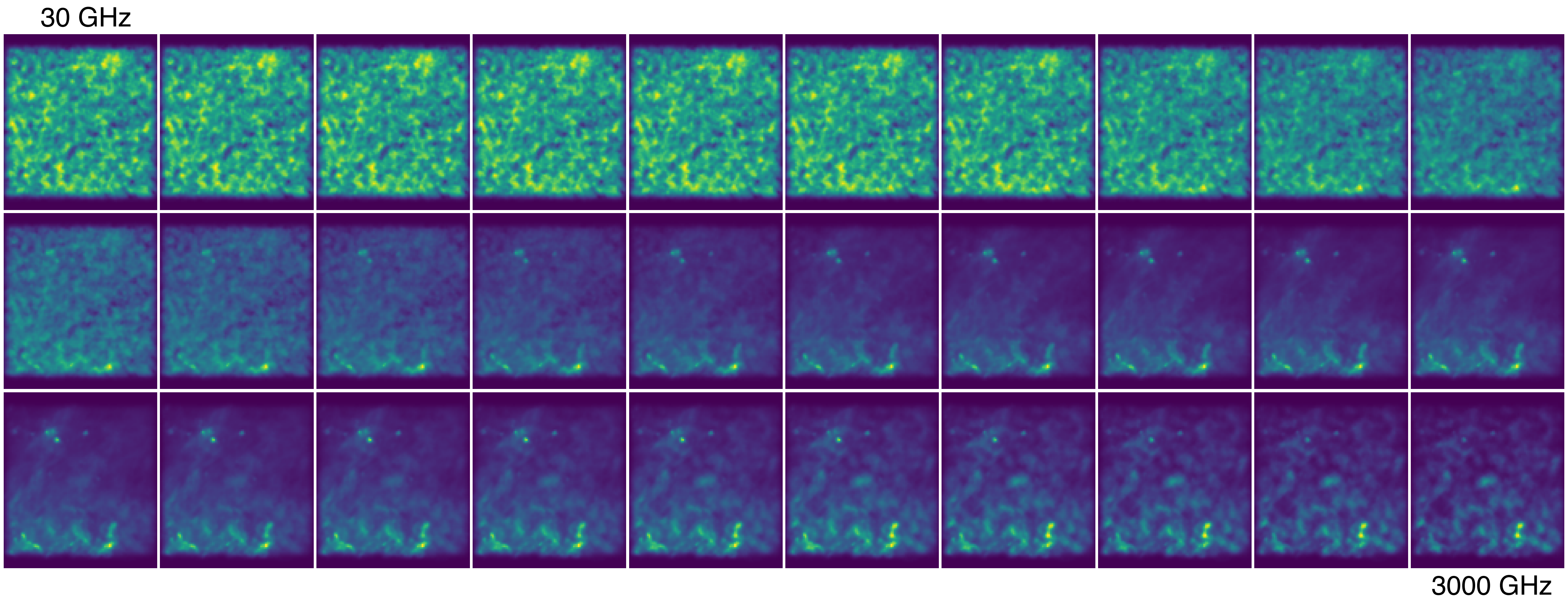
+ frg. moments

$$\overrightarrow{\hat{m}} = [V^T \mathscr{C}_{\nu\nu'}^{-1} V]^{-1} [V^T \mathscr{C}_{\nu\nu'}^{-1} d_{\nu'}]$$

If **V spans all spectral degrees of freedom**, then this is equivalent to parametric fitting.

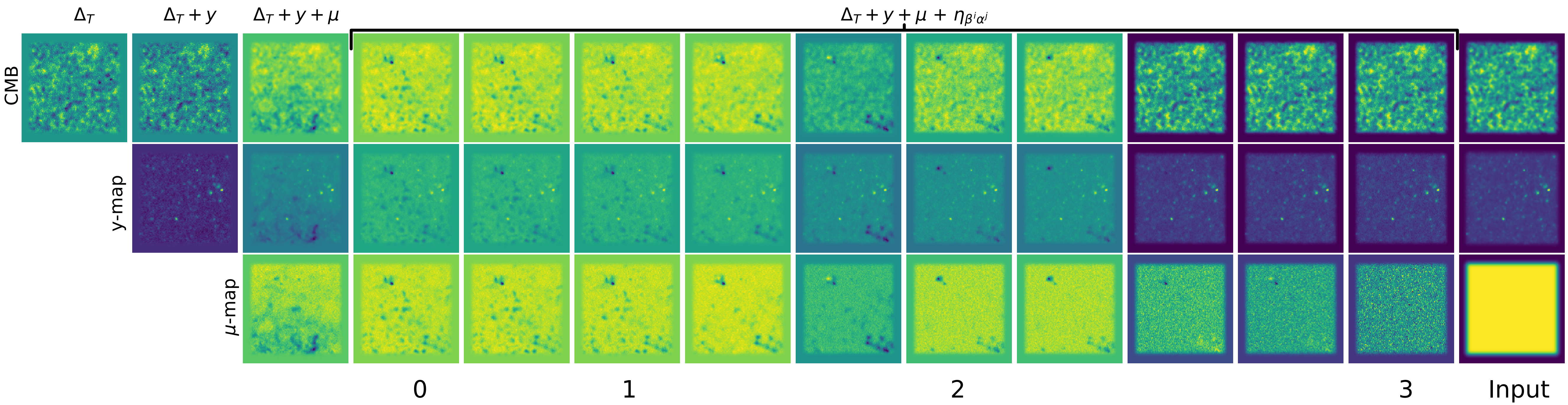
Remazeilles M., Delabrouille J., & Cardoso J. F. arXiv:1006.5599 (2010)
A. Rotti & J. Chluba arXiv:2006.02458 (2020)
Remazeilles M., Rotti A., & Chluba J : arXiv:2006.08628 (2020)

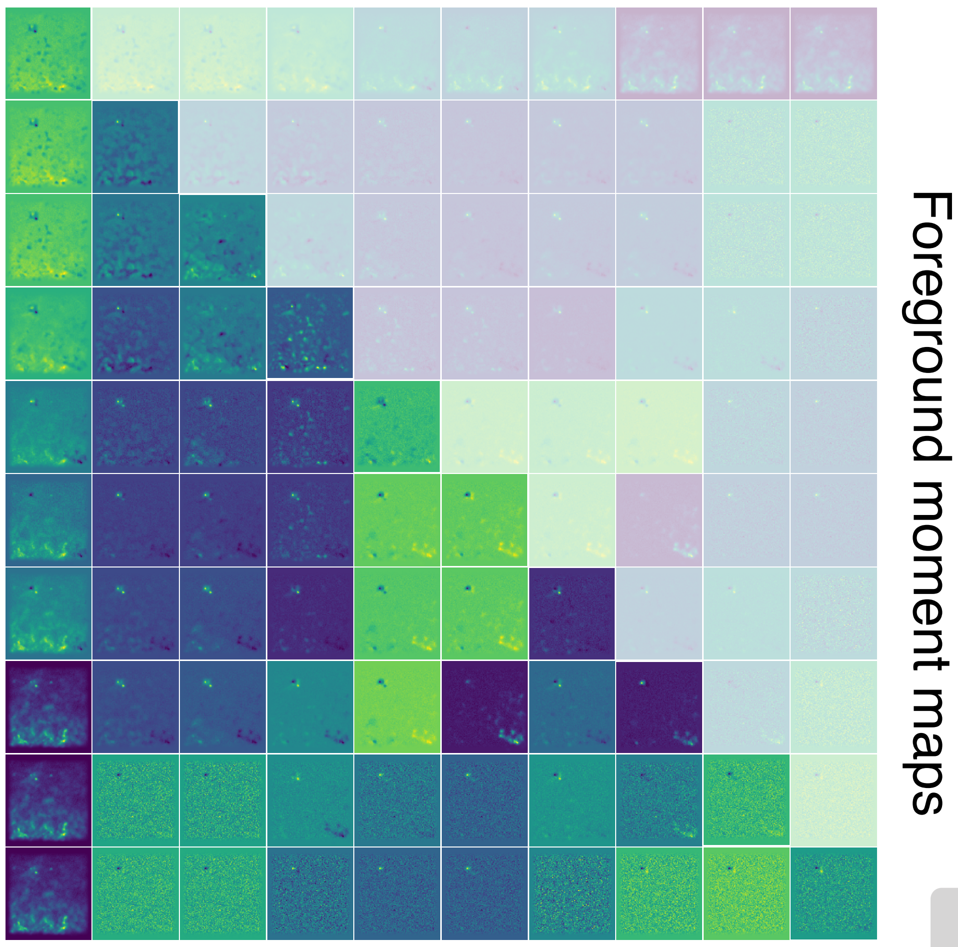
Simulations



- 4 different sensitivities
- 30 channels from 30-3000 GHz
- 30 arc minute Gaussian beam
- Only dust frg. D2 model from PySM
- μ distortion amplitude ~100 smaller than FIRAS

Solutions from moment ILC

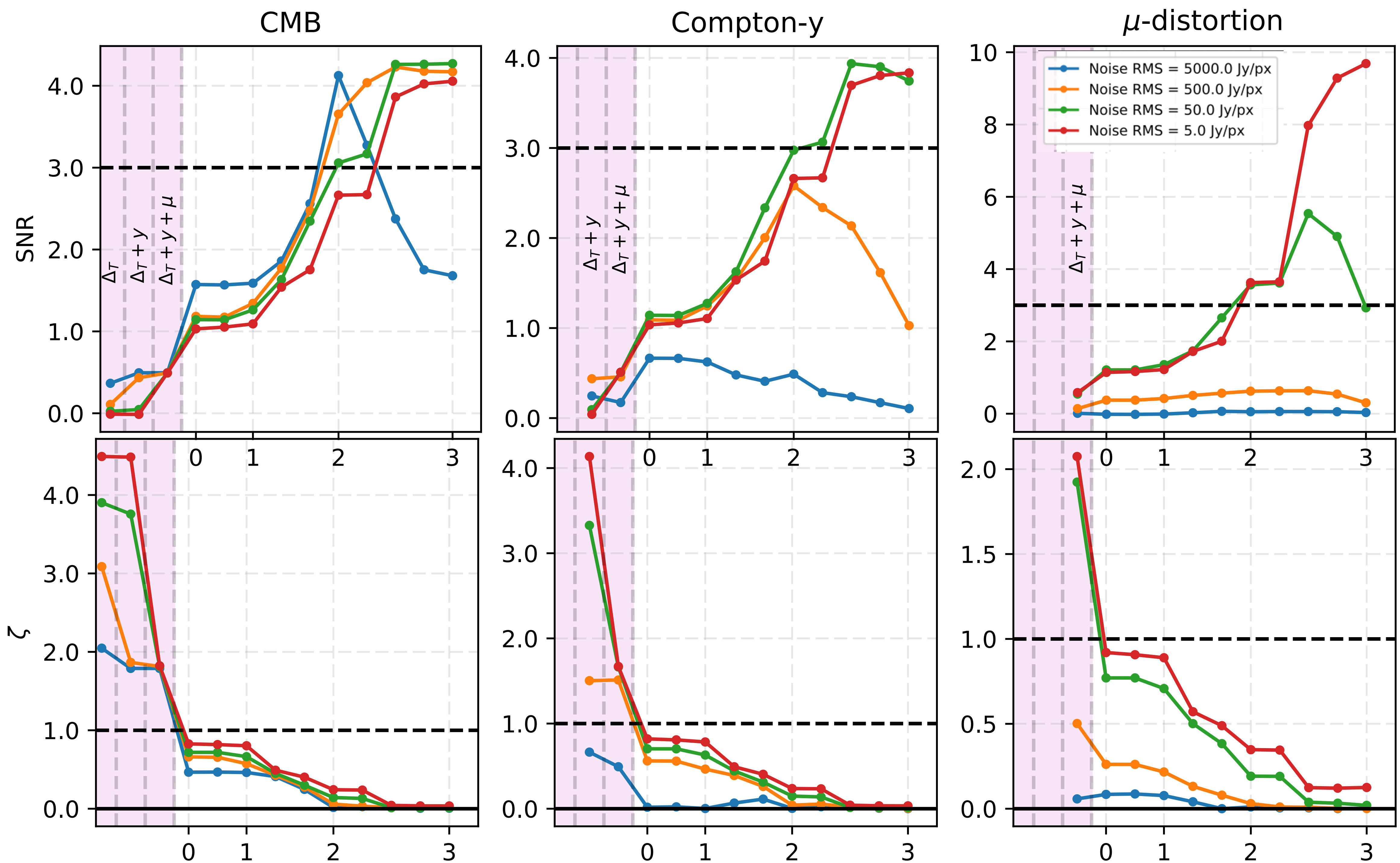




Noise RMS : 50 Jy/px

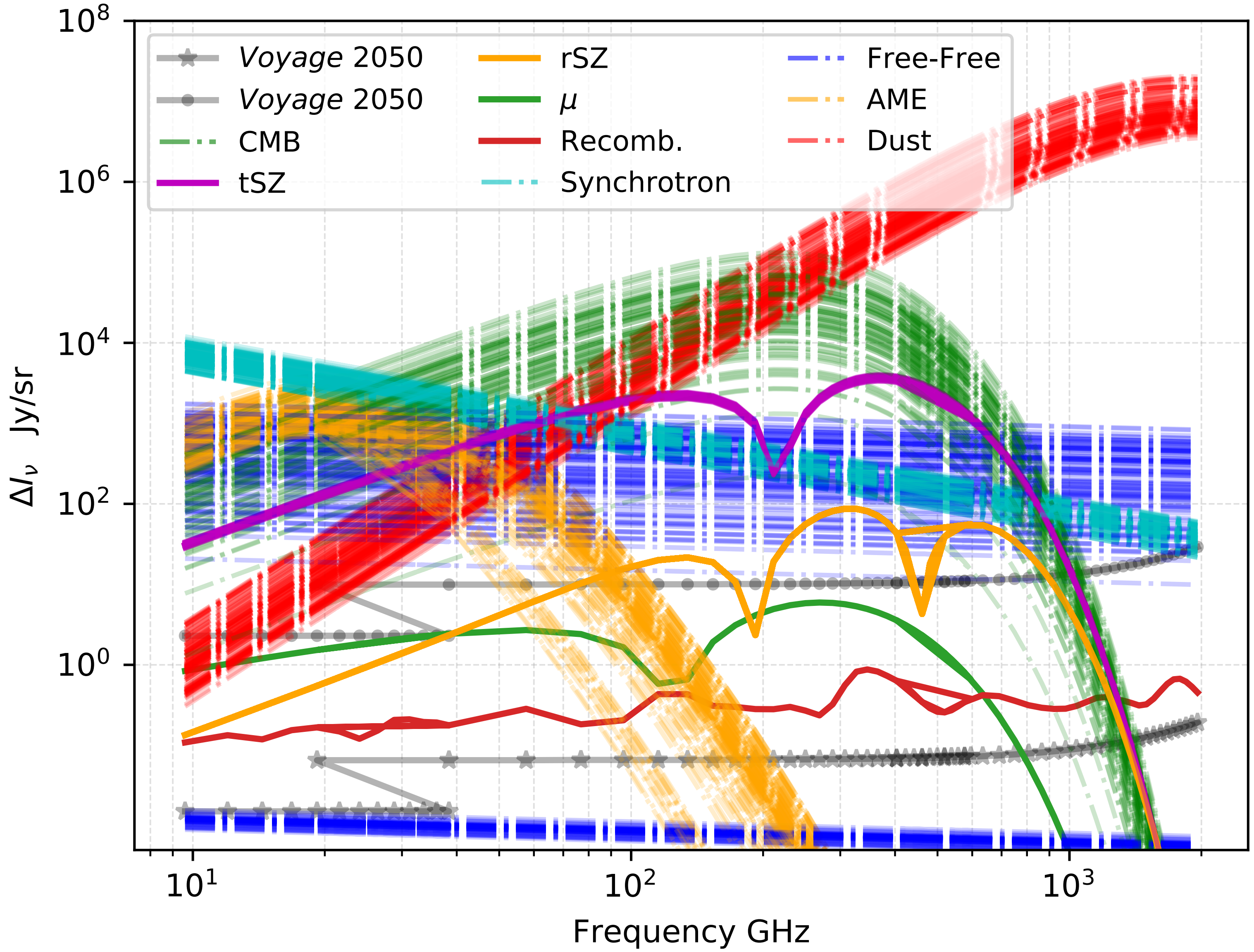
A. Rotti & J. Chluba arXiv:2006.02458 (2020)

Moment ILC can successfully recover the SD monopole signals



A. Rotti & J. Chluba arXiv:2006.02458 (2020)

Next target : Get realistic forecasts for SD monopole measurements using PySM simulated skies



Comps.	Signal	Mean	Std. dev.	SNR	Bias
CMB	**CMB** ($\times 10^4$)	1.42	0.0027	527	0.01
CMB+tSZ	**CMB** ($\times 10^4$)	1.72	0.0027	630	0.19
	tSZ ($\times 10^6$)	1.97	0.0004	4,629	0.01
CMB+tSZ+rSZ	**CMB** ($\times 10^4$)	1.90	0.0027	700	0.32
	tSZ ($\times 10^6$)	2.05	0.0004	4,842	0.03
	rSZ ($\times 10^6$)	2.80	0.0035	788	0.08
CMB+tSZ+rSZ+μ	**CMB** ($\times 10^4$)	1.87	0.0028	679	0.30
	tSZ ($\times 10^6$)	2.03	0.0005	4,206	0.02
	rSZ ($\times 10^6$)	2.63	0.0041	649	0.01
	μ ($\times 10^8$)	26.01	0.3023	86	12.01
CMB+tSZ+rSZ+μ+Recomb.	**CMB** ($\times 10^4$)	1.86	0.0028	672	0.29
	tSZ ($\times 10^6$)	2.03	0.0005	4,156	0.02
	rSZ ($\times 10^6$)	2.71	0.0042	640	0.04
	μ ($\times 10^8$)	33.94	0.3306	103	15.97
	Recomb.	7.71	0.1266	61	6.71

Work in progress

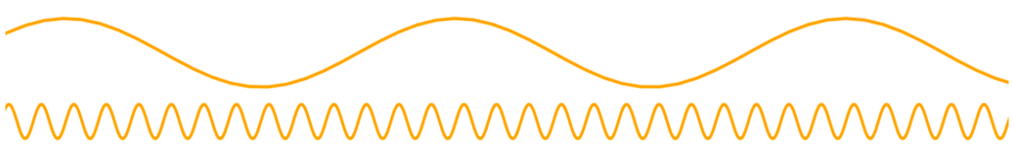
Anisotropic spectral distortions

Primordial NG can generate anisotropic distortions

$$\langle \zeta(\mathbf{k_1})\zeta^*(\mathbf{k_2})\rangle = (2\pi)^3\delta^{(3)}(\mathbf{k_1}-\mathbf{k_2})P(k_1)$$

$$\langle \zeta(\mathbf{k_1})\zeta(\mathbf{k_2})\zeta(\mathbf{k_3})\rangle = (2\pi)^6\delta^{(3)}(\Sigma_i\mathbf{k_i})B(k_1,k_2,k_3)$$

Gaussian universe: uncorrelated modes.



Non-Gaussianity correlates modes.

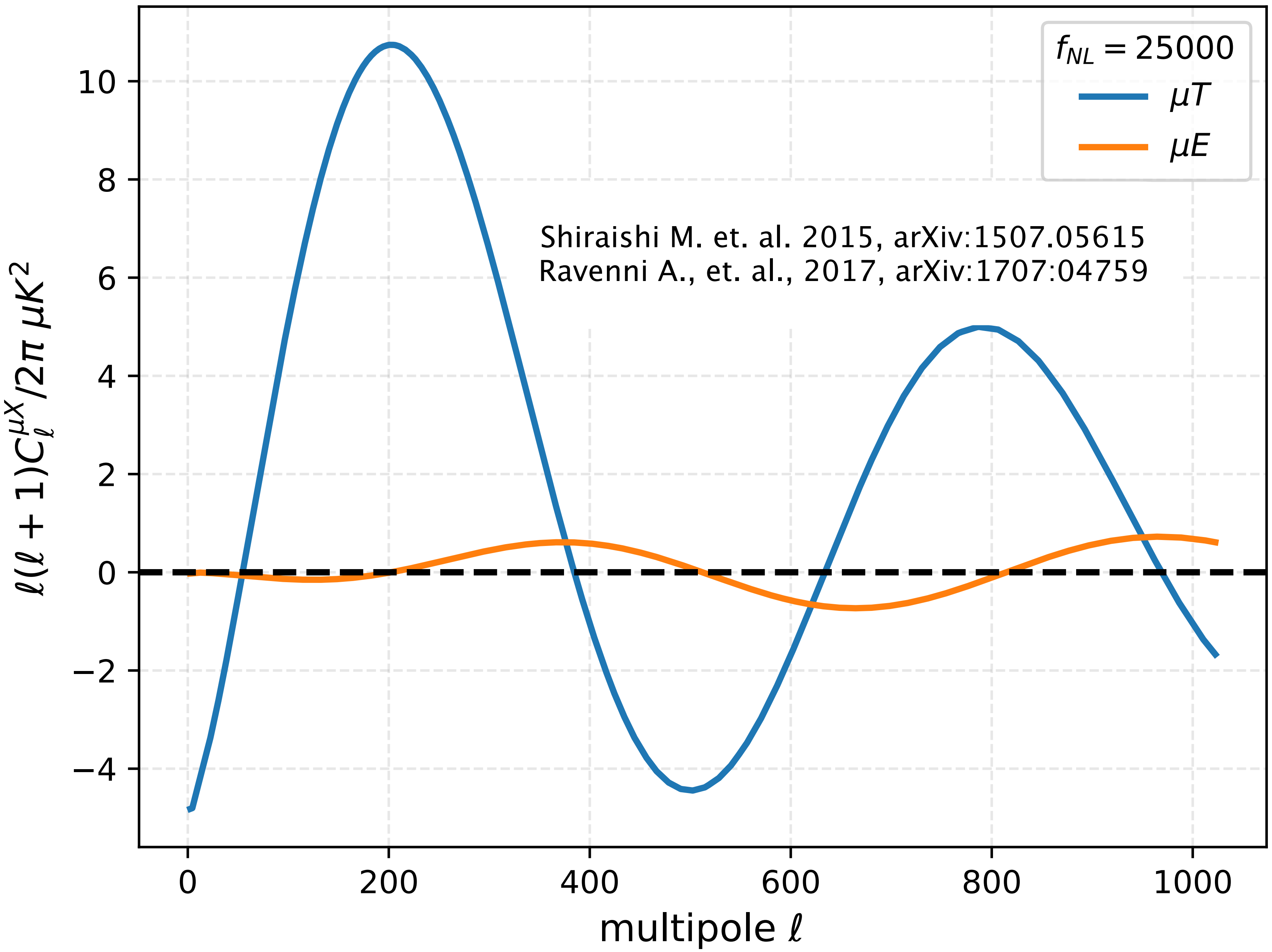
ΔT μ

$$\langle \zeta(\mathbf{k_1})\zeta(\mathbf{k_2})\zeta(\mathbf{k_3})\rangle \approx \frac{12}{5} f_{\rm NL} P(k_L)P(k_s)$$

$$C_\ell^{\mu X} \approx \frac{12}{5} f_{\rm NL}\langle\mu\rangle \int {\rm d}k\, k^2\, \frac{2}{\pi} j_\ell(kr_{\rm ls})\mathcal{T}_\ell^{X/\zeta}(k)P_\zeta(k)$$

Pajer E. & Zaldarriaga M., 2012, arXiv:1201.5375
Ganc J. & Komatsu E., 2012, arXiv:1204.4241v2

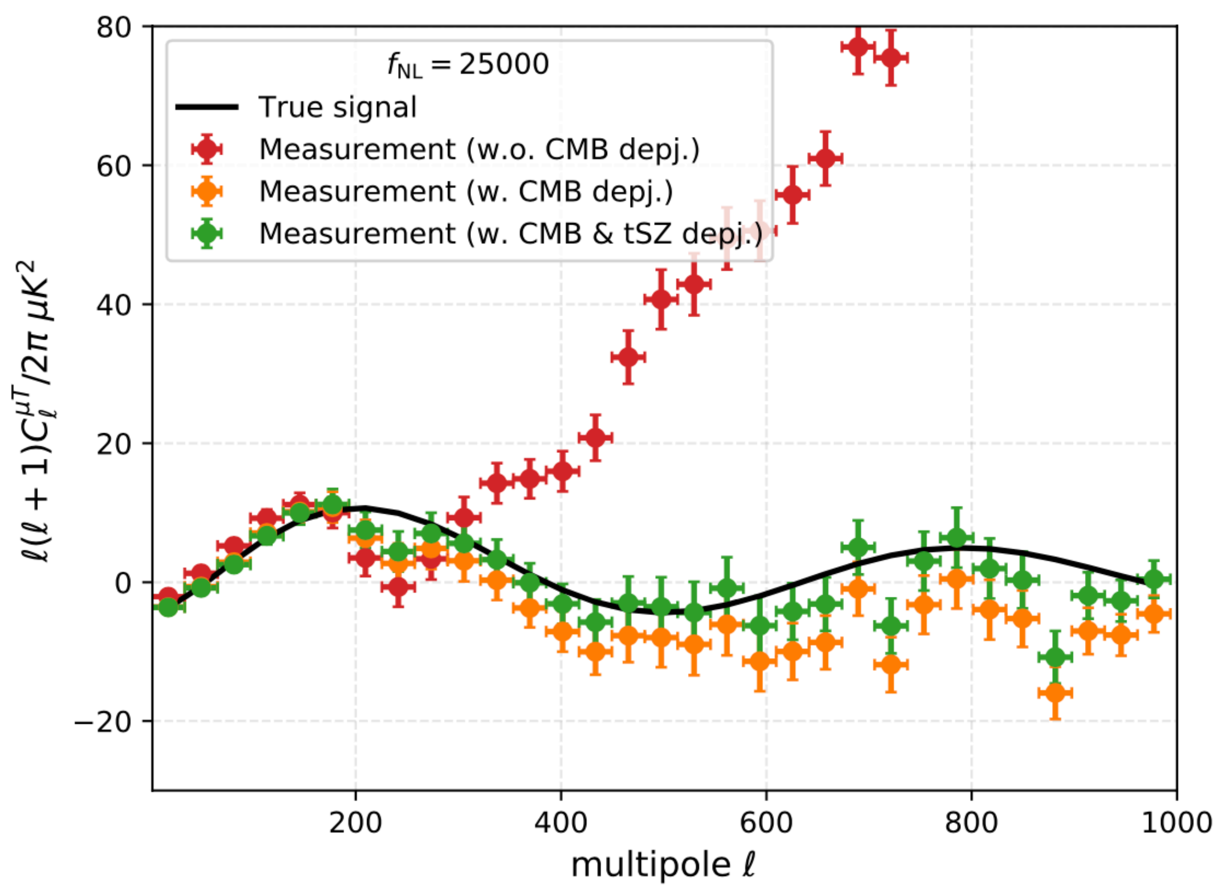
The predicted signal $\propto f_{NL}$



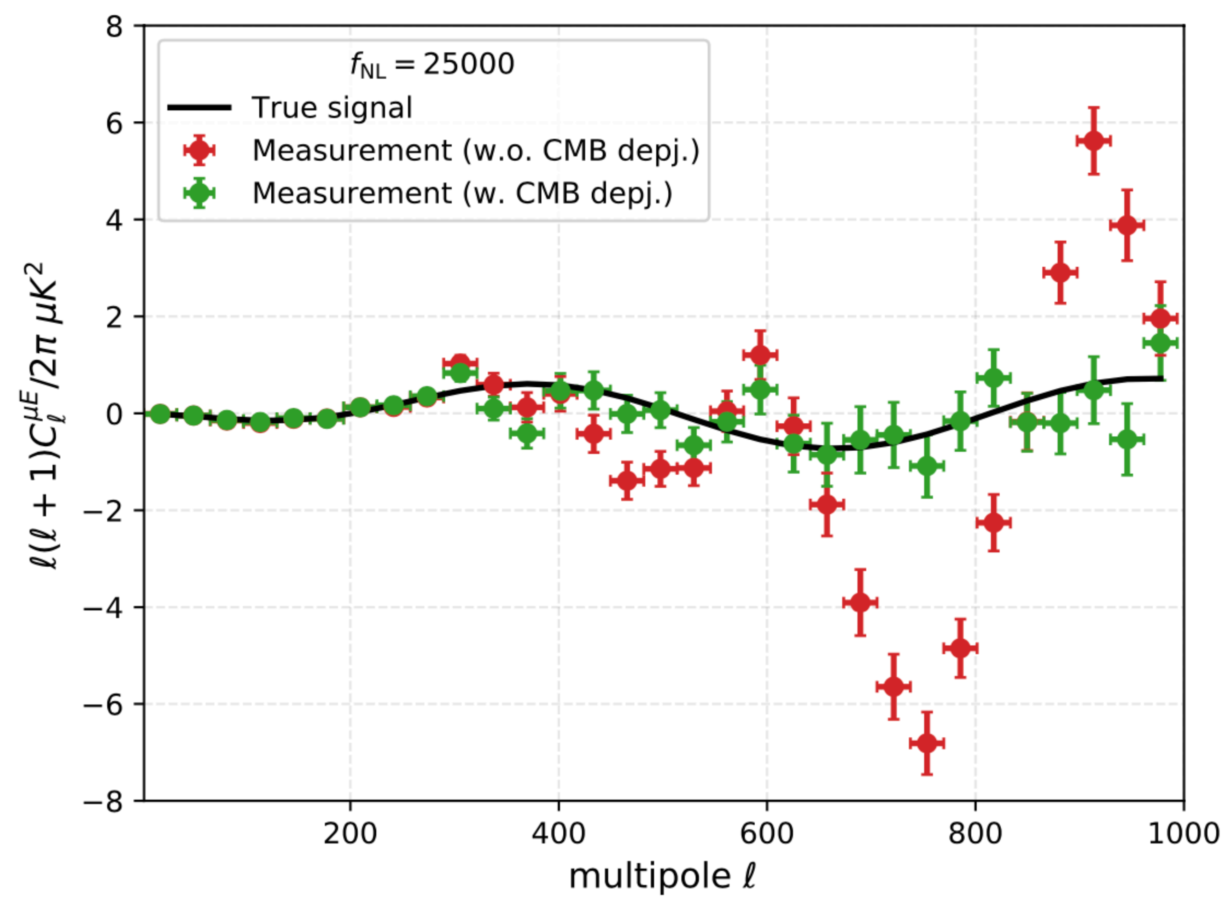
- μE signal is an order of magnitude smaller, it gains from having to deal with fewer foregrounds
- Also less susceptible to biases sourced by SZ and CIB

How to make unbiased measurements of μ

Simple simulations : CMB + tSZ. + μ + Planck Noise



(a) μ-T

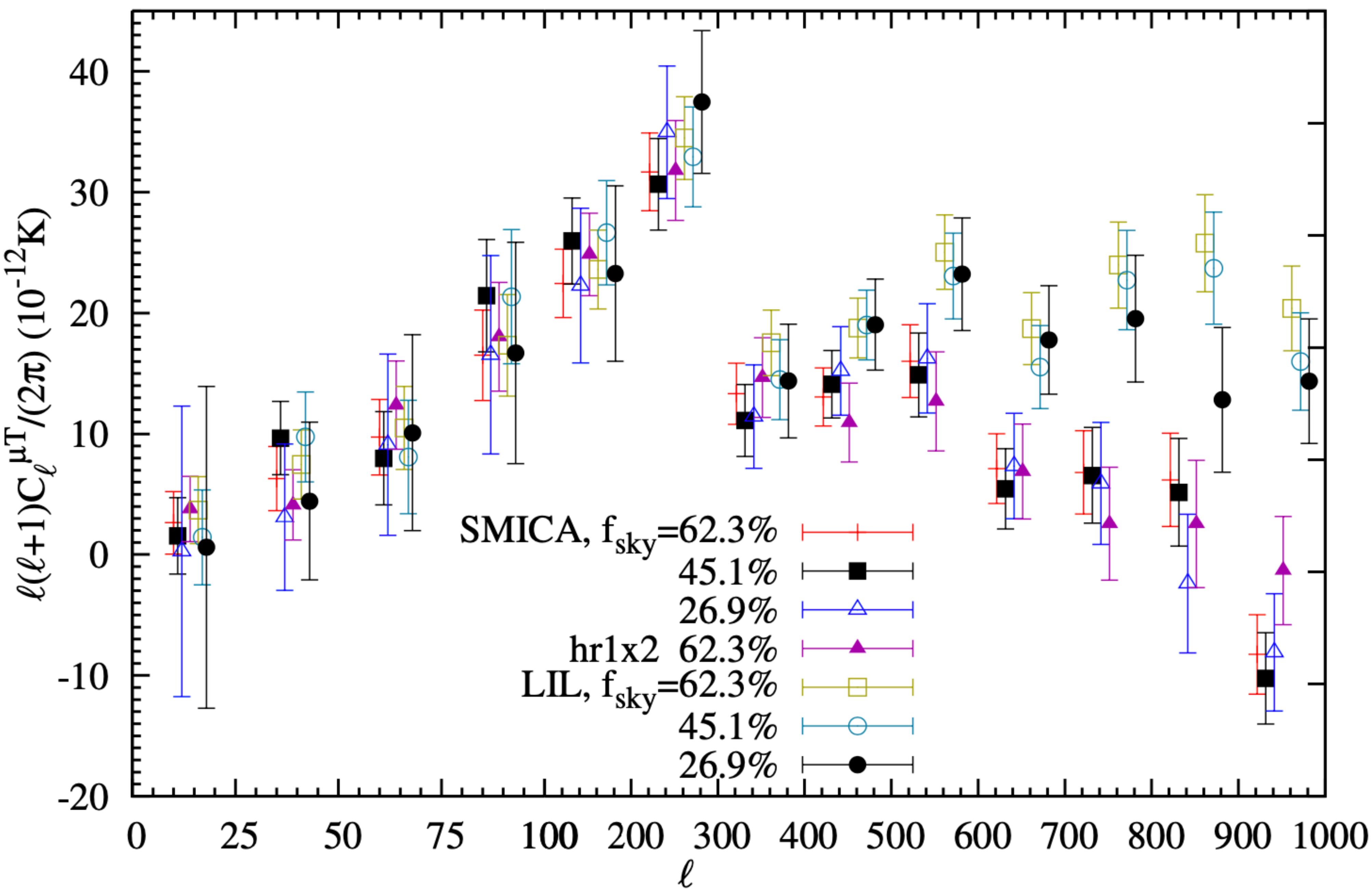


(b) μ-E

- Deprojection CMB when reconstructing μ is critical for both μT and μE measurements.
- tSZ deprojection important for μT measurement.

Remazeilles M. & Chluba J. 2018 arXiv:1802.10101
Rotti A., Ravenni A. & Chluba J, in prep.

Previous work has attempted the μT measurement

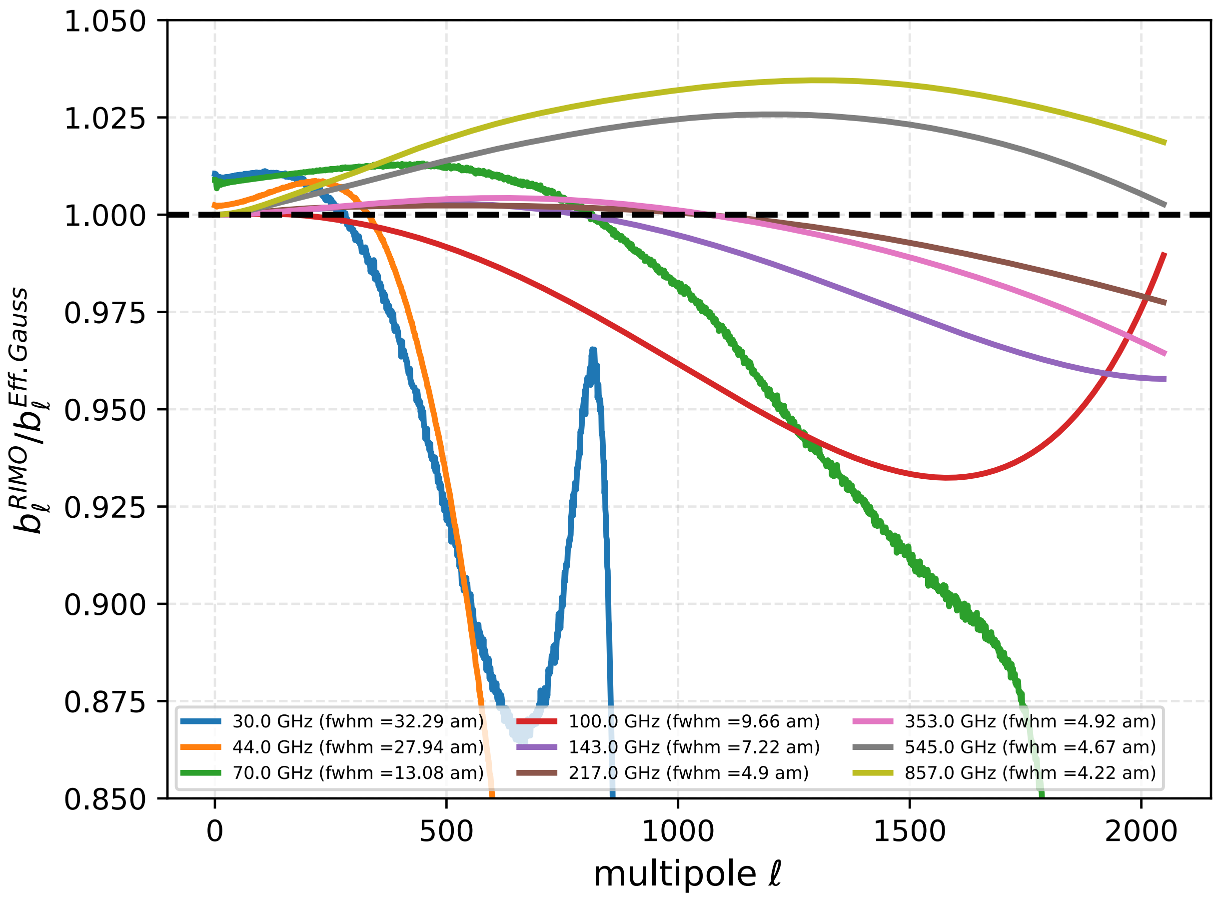


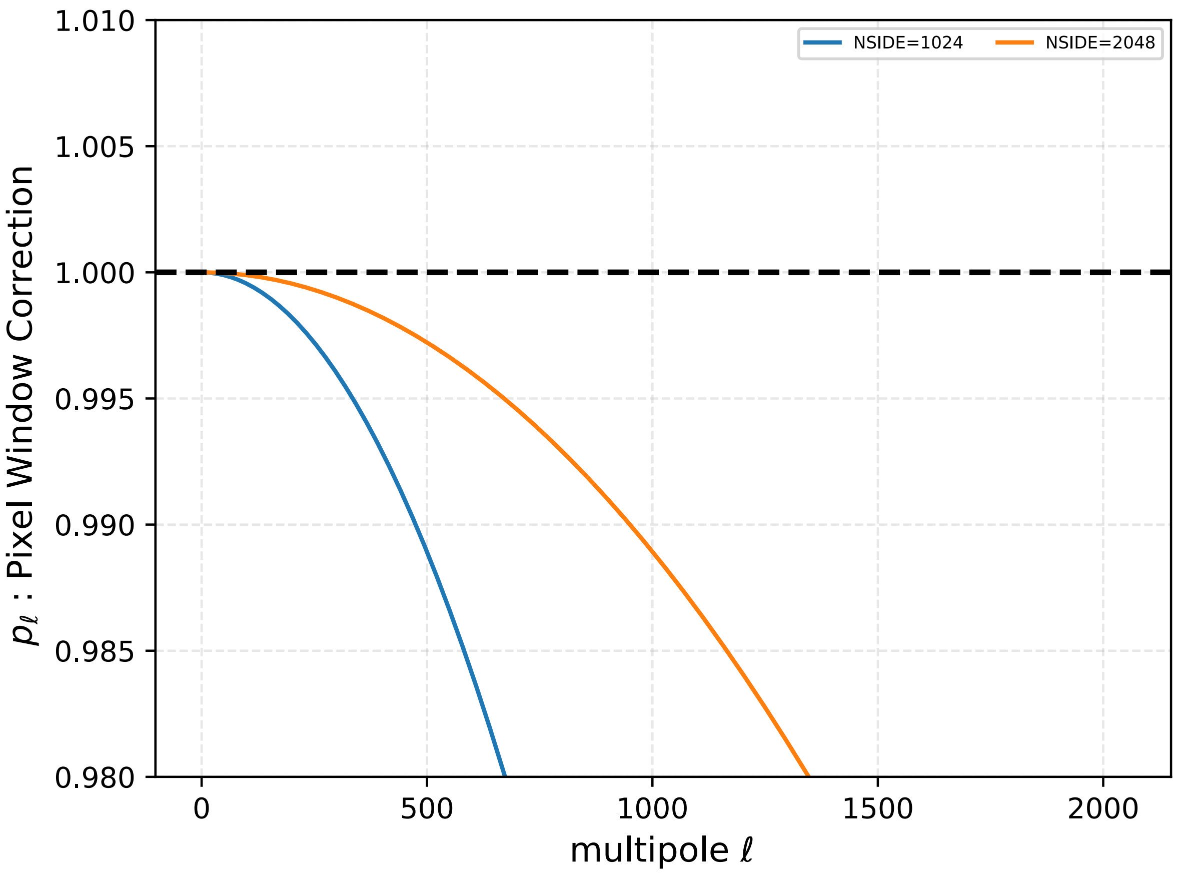
$$f_{NL} = \frac{\ell(\ell+1)}{2\pi} \frac{C_\ell^{\mu T}}{2.4 \times 10^{-17}}$$
$$< 10^5$$

- LFI not used
- No CMB deprojection

Khatri & Sunyaev, 2015, arXiv:1507.05615

The analysis is sensitive to very subtle details

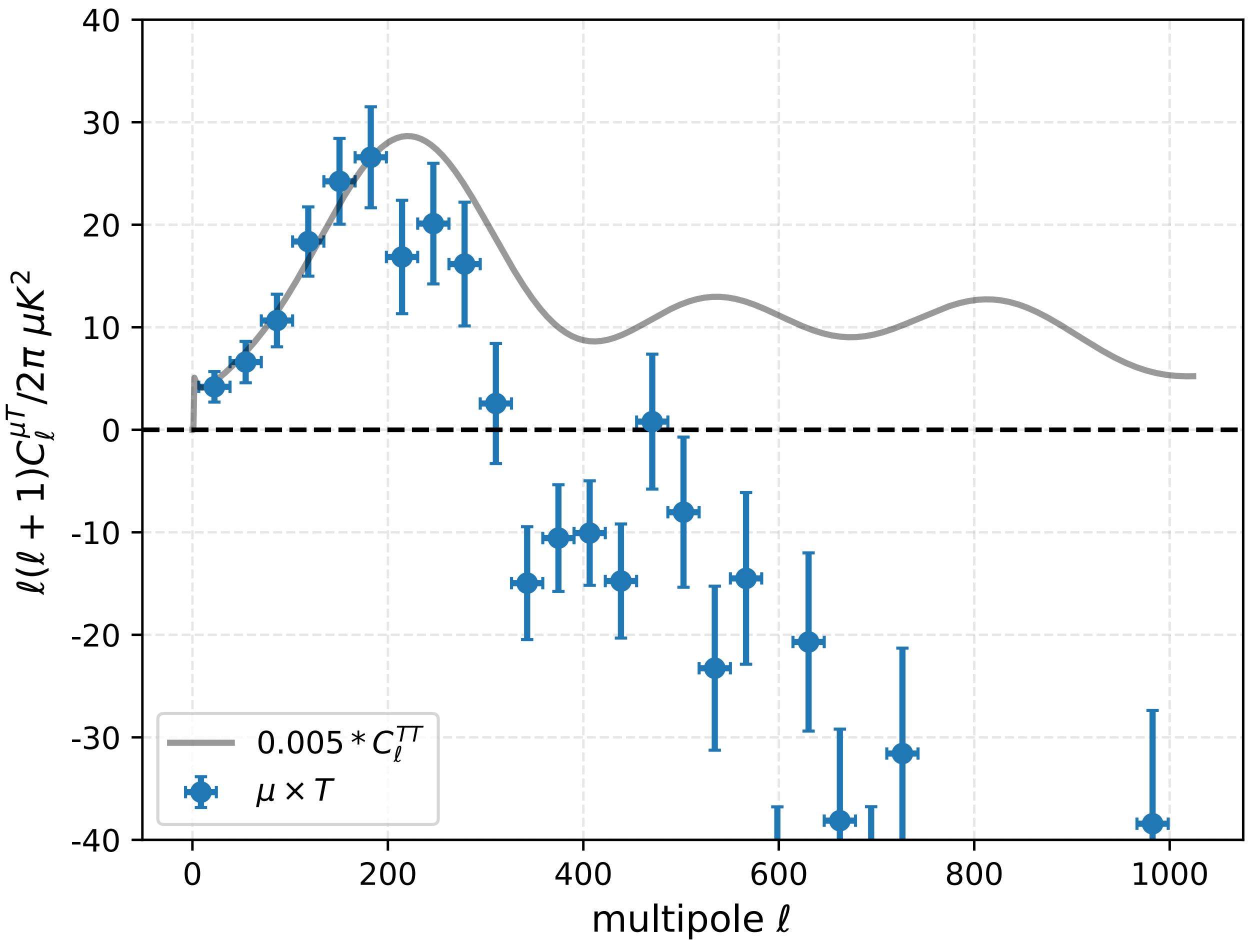


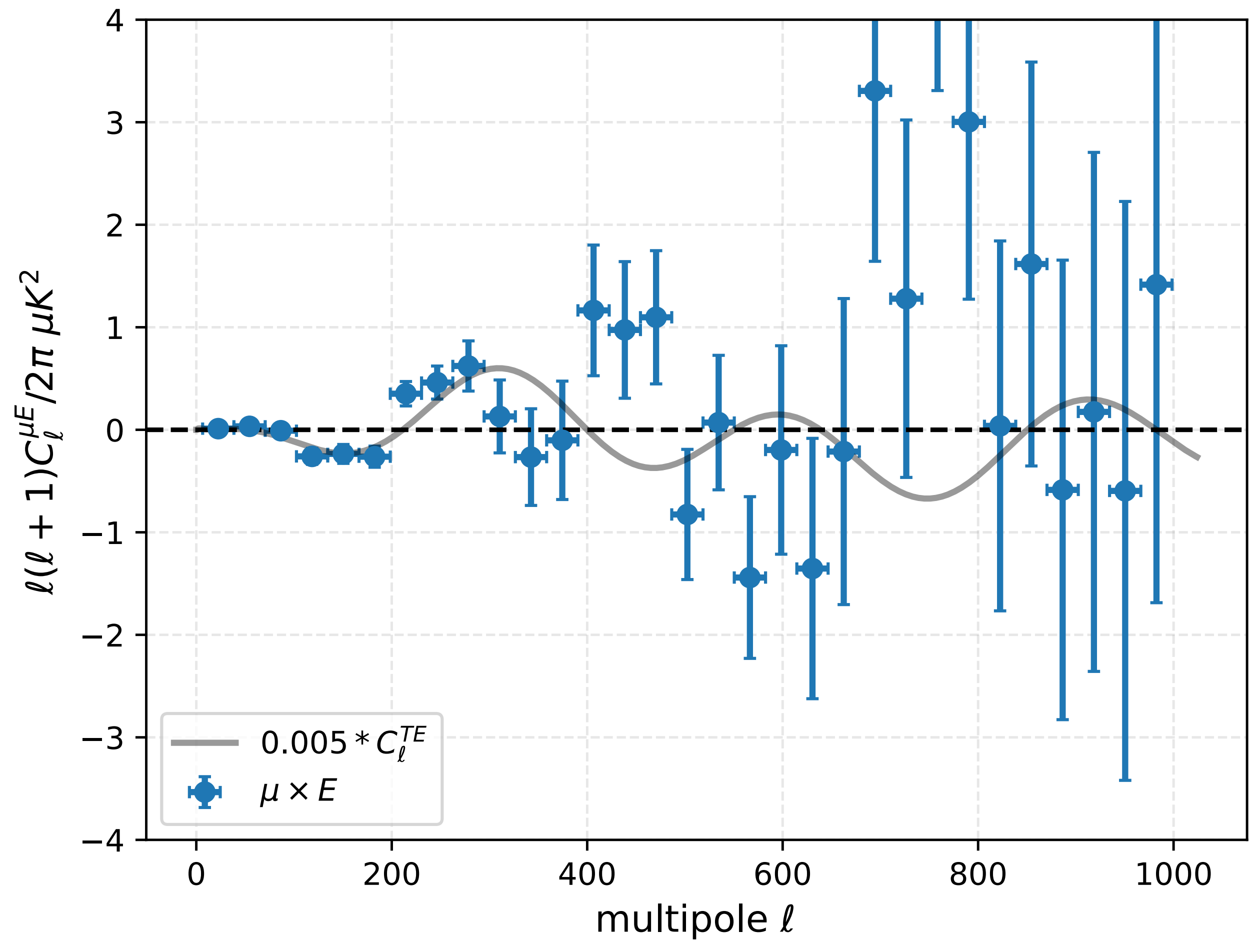


- At multipole of interest $\ell \lesssim 500$, RIMO and effective Gaussian beams differ by < 1%, but this is important.
- Same is true for the pixel window correction.

Rotti A., Ravenni A. & Chluba J, in prep.

If these subtle details are not accounted for…



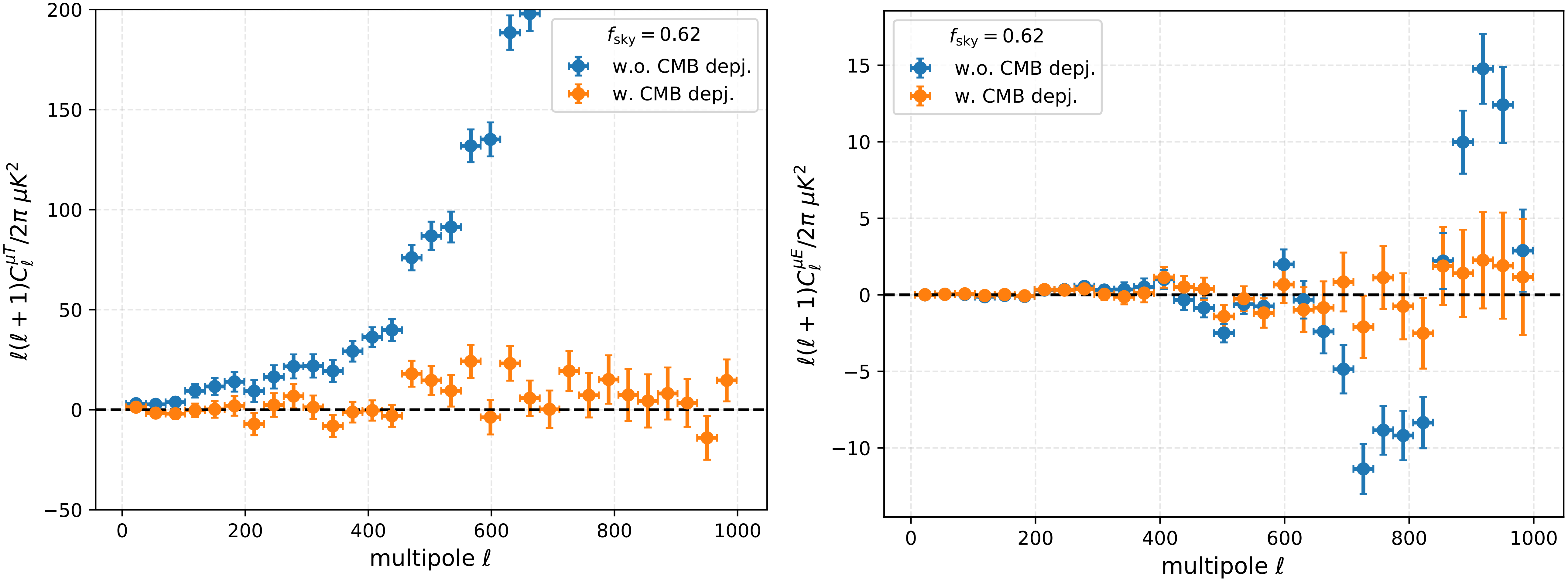


…one would claim a detection of primordial non-Gaussianity

Not using the accurate beam model, can be thought of introducing a multipole dependent miscalibration causing a T to μ leakage (low multipole measurements well explained by 0.5% leakage).

Rotti A., Ravenni A. & Chluba J, in prep.

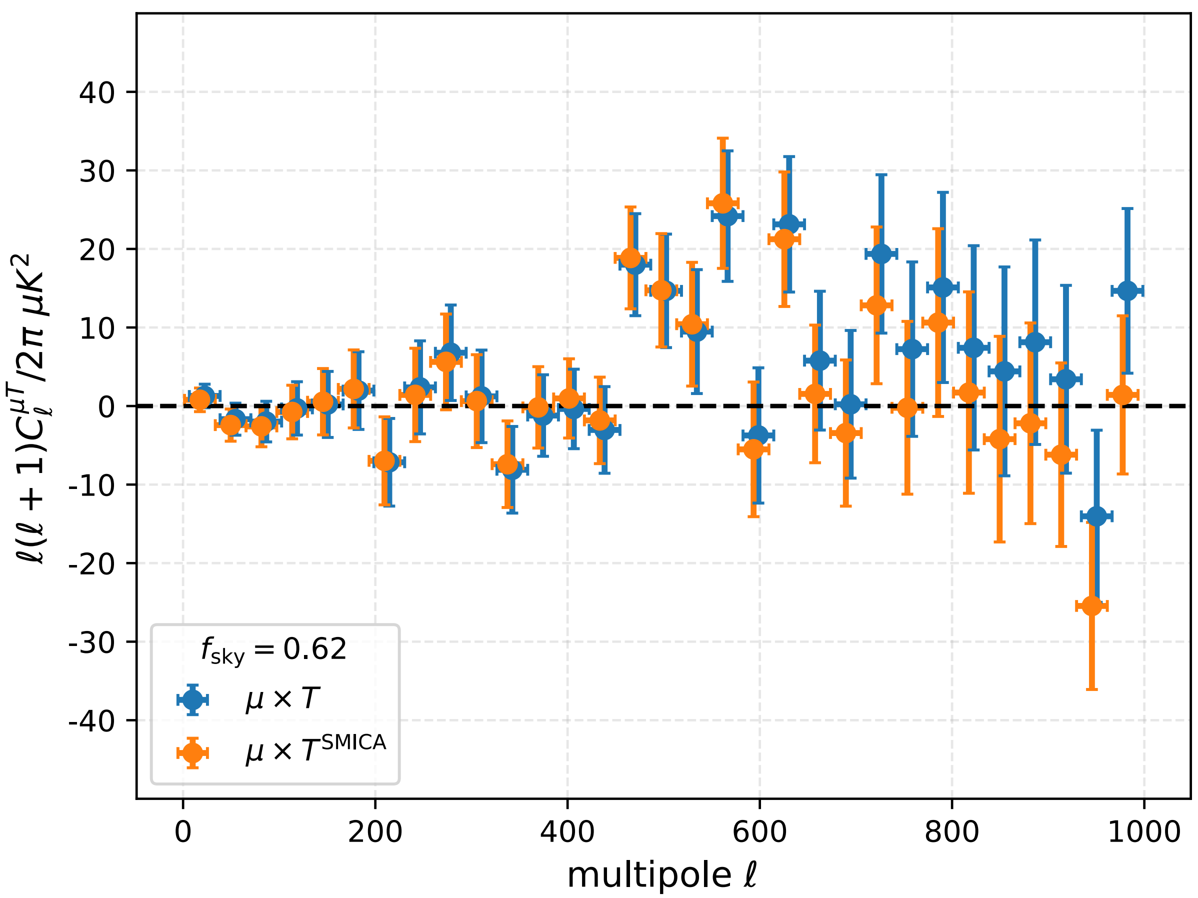
The μT & μE measurements from Planck data

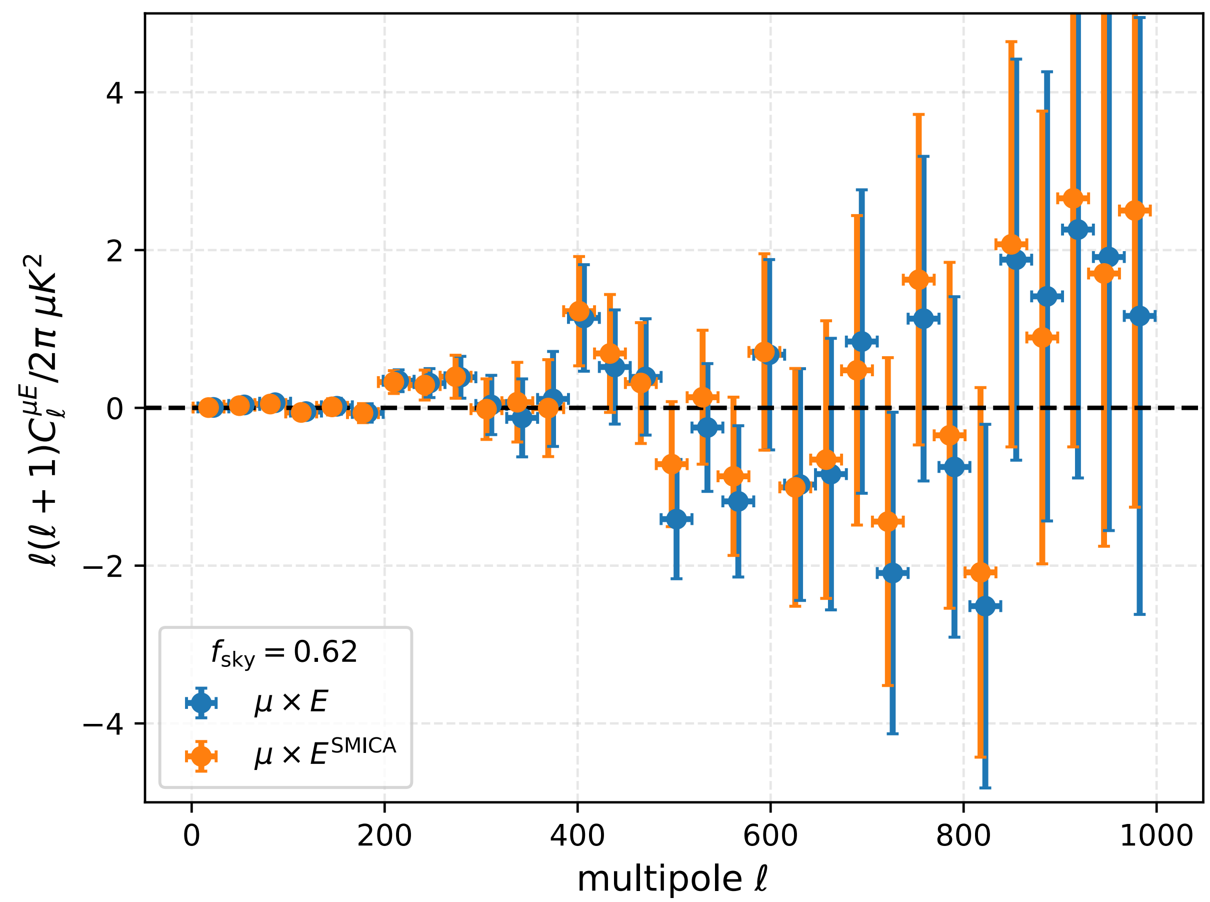


Note the importance of CMB deprojection

Rotti A., Ravenni A. & Chluba J, in prep.

Very consistent μT & μE measurements when using Planck SMICA maps

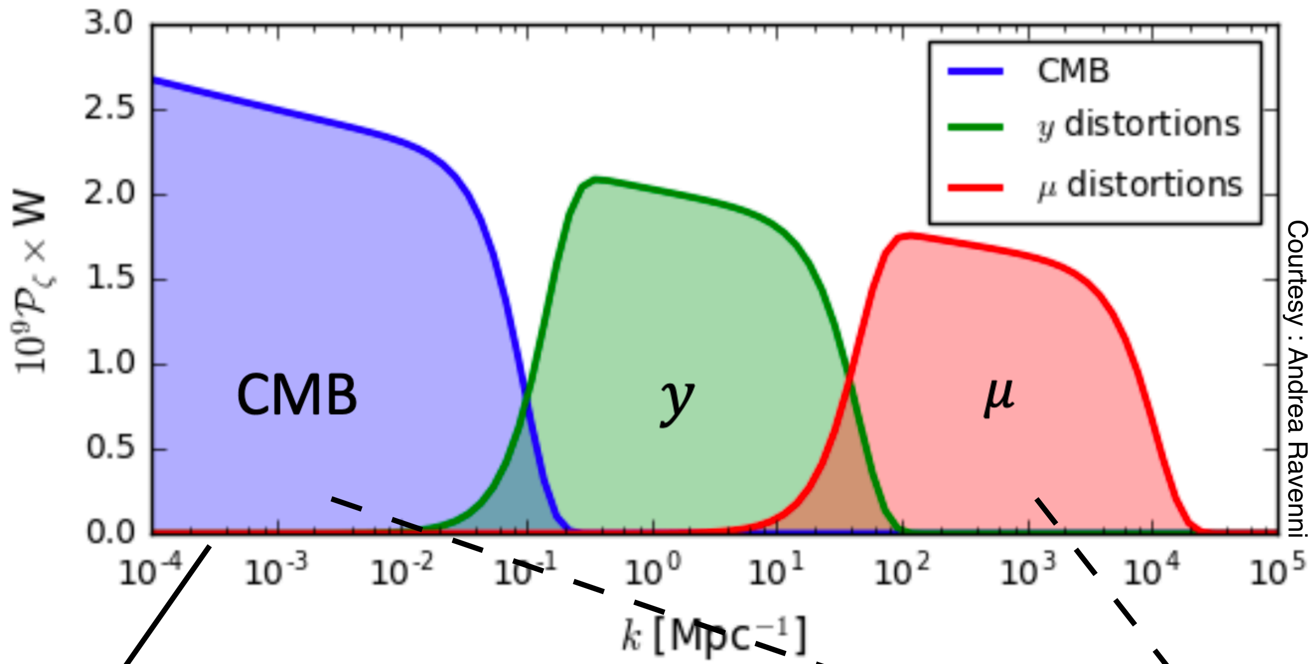




Data	$f_{\rm NL}$	$\sigma_{f_{\rm NL}}$	SNR
T	-4273	4382	-0.98
SMICA T	-5670	4395	-1.29
E	3937	4719	0.83
SMICA E	5409	4733	1.14
T+E	-812	3398	-0.24
SMICA T+E	-840	3410	-0.25

Rotti A., Ravenni A. & Chluba J, in prep.

Interpretation of these f_{NL} constraints



$$f_{NL}^{loc} = -0.9 \pm 5.1$$

$$f_{NL}^{eq} = -18 \pm 47$$

$$f_{NL}^{orth} = -37 \pm 23$$

Planck Collaboration 2019

Data	f_{NL}	$\sigma_{f_{NL}}$	SNR
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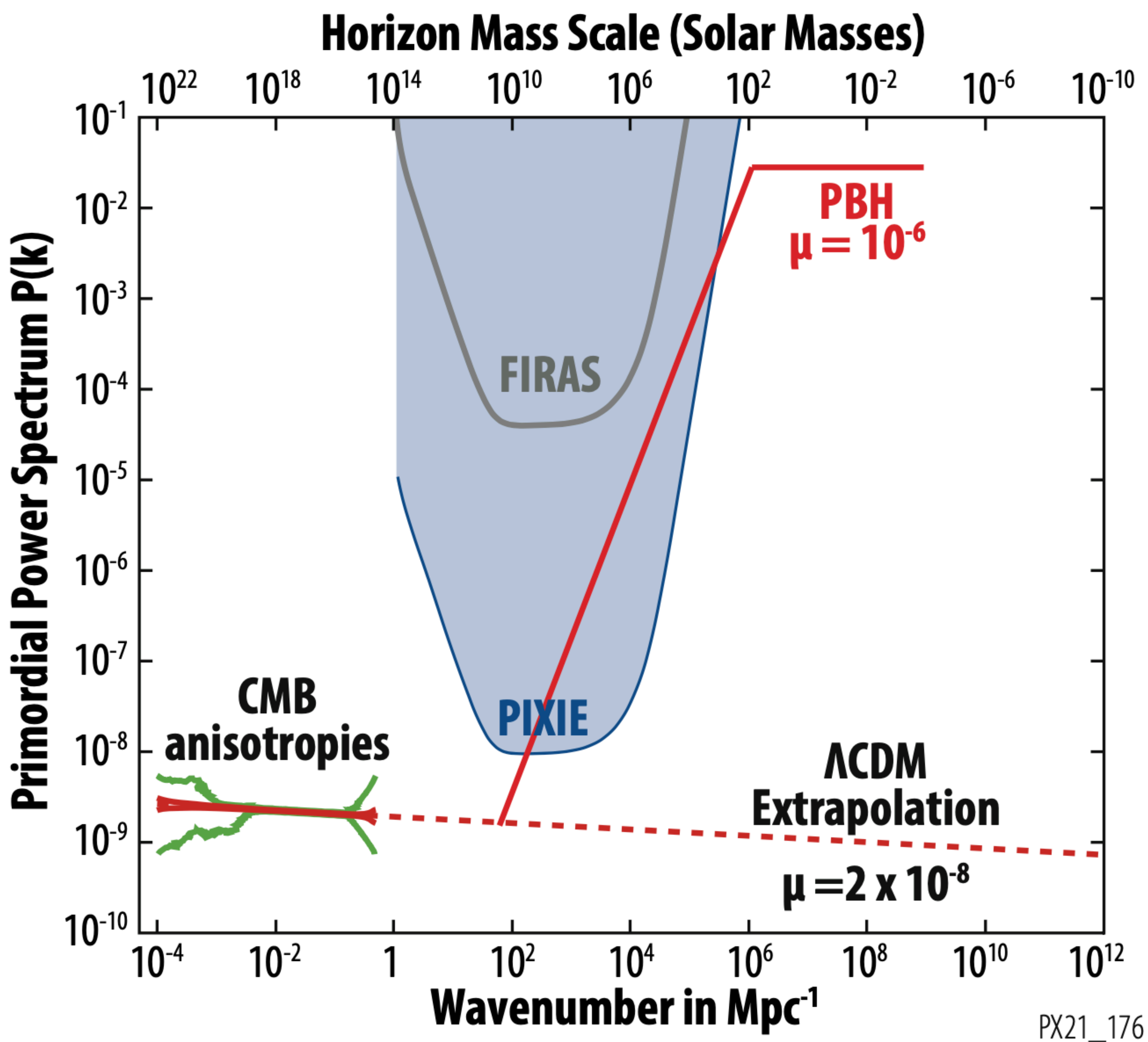
μT & μE measurements only constrain the highly squeezed configuration in

These $f_{\rm NL}$ constraints assume $< \mu >$ is known!

μT & $\mu E \propto f_{\rm NL} < \mu >$

Translating μT & μE measurements to limits on $f_{\rm NL}$, necessarily assumes a huge extrapolation of ΛCDM into untested territory.



To make these $f_{\rm NL}$ model independent, we need to complement these measurements with those of $< \mu >$ —> that needs a spectrometer

Outlook

- Spectral distortions are a direct probe into epochs not directly accessible via any other measurement. Measurements will test ΛCDM in new ways
- These measurements allow you to probe the universe at very high wave numbers ($k \sim 10^4\ \mathrm{Mpc}^{-1}$), though relying on fully linear physics
- ΛCDM extrapolated predictions are tiny and driving current instrument design, but SD measurements will open up a huge discovery space.
- Foregrounds will be challenging, but we will have fewer unknown unknowns in the near future owing to measurements by anisotropy experiments.
- SD foreground cleaning methods will benefit a lot from those developed for anisotropy analyses and vice versa (e.g. moments).
- Finally anisotropic spectral distortions will be probed by anisotropy experiments, but a model independent interpretation of these will necessarily need spectrometer measurements.