Title: CMB Foregrounds: Problems, Parameterizations, and Progress

Date: May 23, 2018 10:00 AM

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Abstract: <p>The next frontiers in cosmic microwave background (CMB) science include a detailed mapping of the CMB polarization anisotropy, with goals of detecting the inflationary B-mode signal and reconstructing high-fidelity maps of the matter distribution via CMB lensing, as well as a first detection of CMB spectral distortions. At this level of precision (~nK), Galactic and extragalactic foregrounds may be the ultimate limiting factor in deriving cosmological constraints. I will discuss biases due to foregrounds in CMB lensing measurements, including the first calculation of the lensing bias due to the kinematic Sunyaev-Zelâ€™dovich effect, as well as recent progress in developing novel foreground-free CMB lensing estimators. I will then present methods to extend CMB foreground parameterizations in a systematic, flexible way, with applications to both polarization and spectral distortion measurements. Using this framework, I will discuss spectral distortion forecasts for CMB spectrometer mission concepts, showing that high-significance measurements of the Compton-y and relativistic thermal Sunyaev-Zelâ€™dovich signals can be expected, as well as a potential detection of the primordial mu-type distortion due to Silk damping of small-scale acoustic modes.</p>

CMB Foregrounds:

Problems, Parameterizations, and Progress

Colin Hill

Institute for Advanced Study

Flatiron Institute - Center for Computational Astrophysics

ACTPOL

SIMONSOBSERVATORY

CMB-S4
Next Generation CMB Experiment

1608.03169
1705.02332
1705.06751
1711.10524

Perimeter Institute
22 May 2018

1508.07005
1512.06834
1701.00274
1802.08230

1

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Cosmic Microwave Background

What have we learned?

- Precise constraints on cosmological parameters: matter density, baryon density, age, spatial curvature
- Properties of initial fluctuations: near-scale invariant, Gaussian, adiabatic, super-horizon

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Cosmic Microwave Background

What have we learned?

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What questions remain?

- How did structure grow?

  Neutrinos, dark energy, modified gravity
- How did galaxies form? Where are baryons today?

  Astrophysical feedback
- What seeded the initial fluctuations?

  Inflation

4

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Cosmic Microwave Background

What have we learned?

- Precise constraints on cosmological parameters: matter density, baryon density, age, spatial curvature
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What questions remain?

- How did structure grow? → *CMB Lensing*
  Neutrinos, dark energy, modified gravity
- How did galaxies form? Where are baryons today?
  Astrophysical feedback
- What seeded the initial fluctuations?
  Inflation → *CMB Polarization*
  CMB Spectral Distortions

7

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Cosmic Microwave ~~Background~~ Backlight

Cosmic Microwave Backlight

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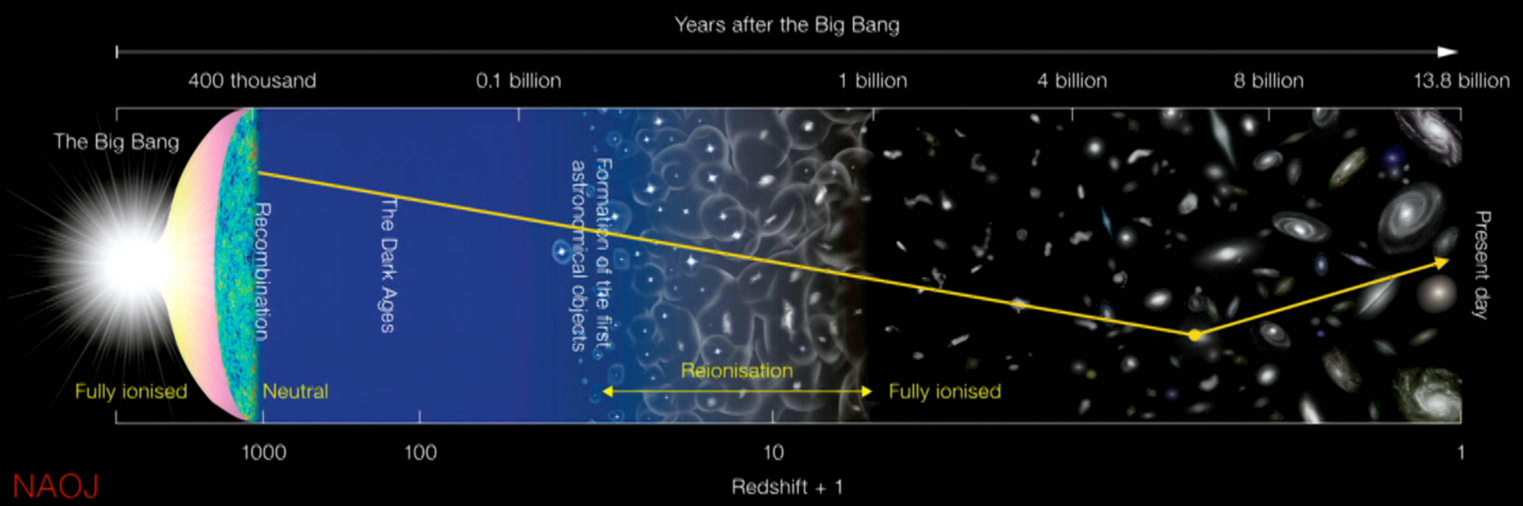
Secondary Anisotropies



Gravitational Lensing of the CMB

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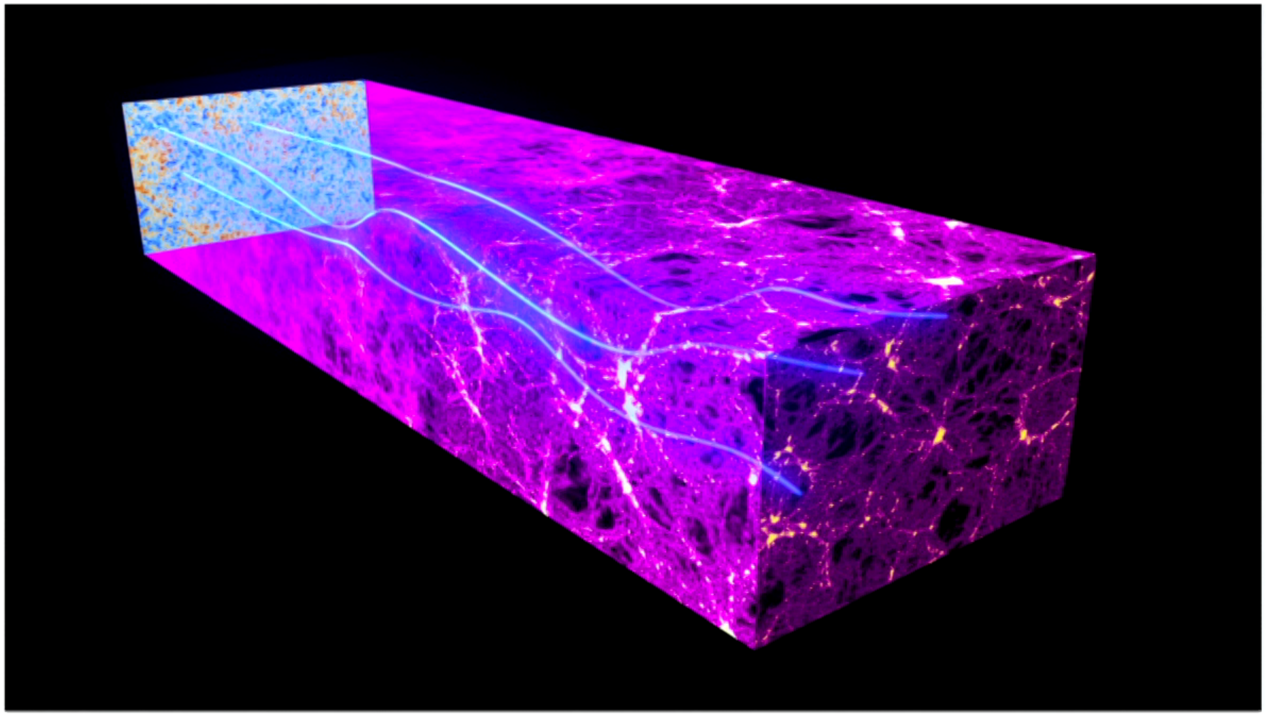
The paths of CMB photons are bent by the gravity of intervening matter (e.g., clusters of galaxies) along the way

sensitive to *total* matter density — including dark matter



CMB Lensing

→ Integrated Total Mass

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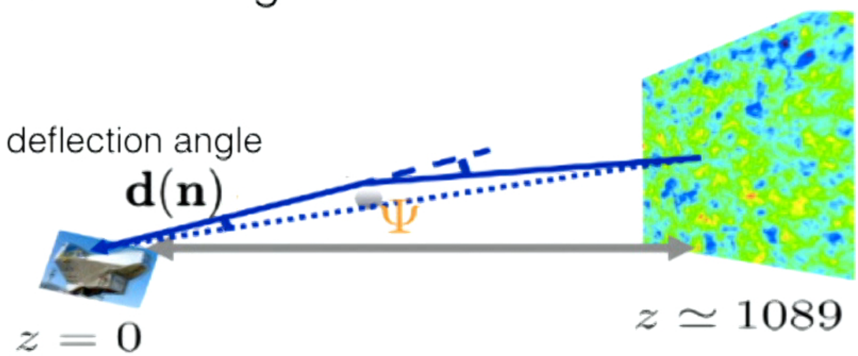
Re-mapping of CMB fluctuations (preserves blackbody form)

Many (~50) small random deflections lead to a net deflection (~2-3 arcmin), coherent on ~deg scales



$$T(\hat{\mathbf{n}})_{\text{lensed}} = T(\hat{\mathbf{n}} + \mathbf{d}(\hat{\mathbf{n}}))_{\text{unlensed}}$$

CMB Lensing

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→ Integrated Total Mass

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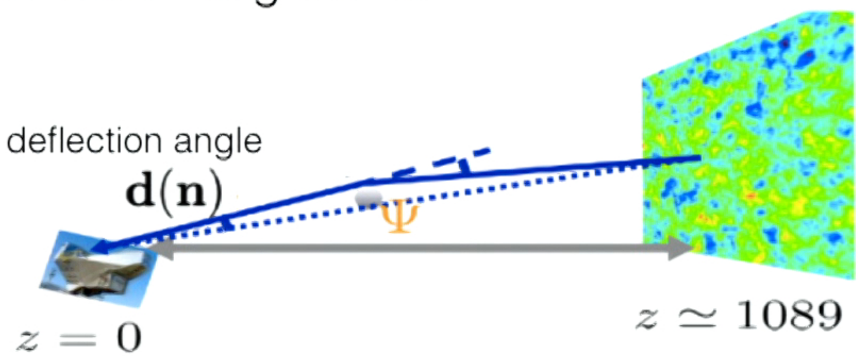

$$T(\hat{\mathbf{n}})_{\mathbf{lensed}} = T(\hat{\mathbf{n}} + \mathbf{d}(\hat{\mathbf{n}}))_{\mathbf{unlensed}}$$

Quadratic reconstruction: $\phi(\vec{\mathbf{L}}) \sim T(\vec{\ell})T(\vec{\mathbf{L}} - \vec{\ell})$ $\vec{\mathbf{d}} = \nabla\phi$

lensing potential

13

CMB Lensing

→ **Integrated Total Mass**

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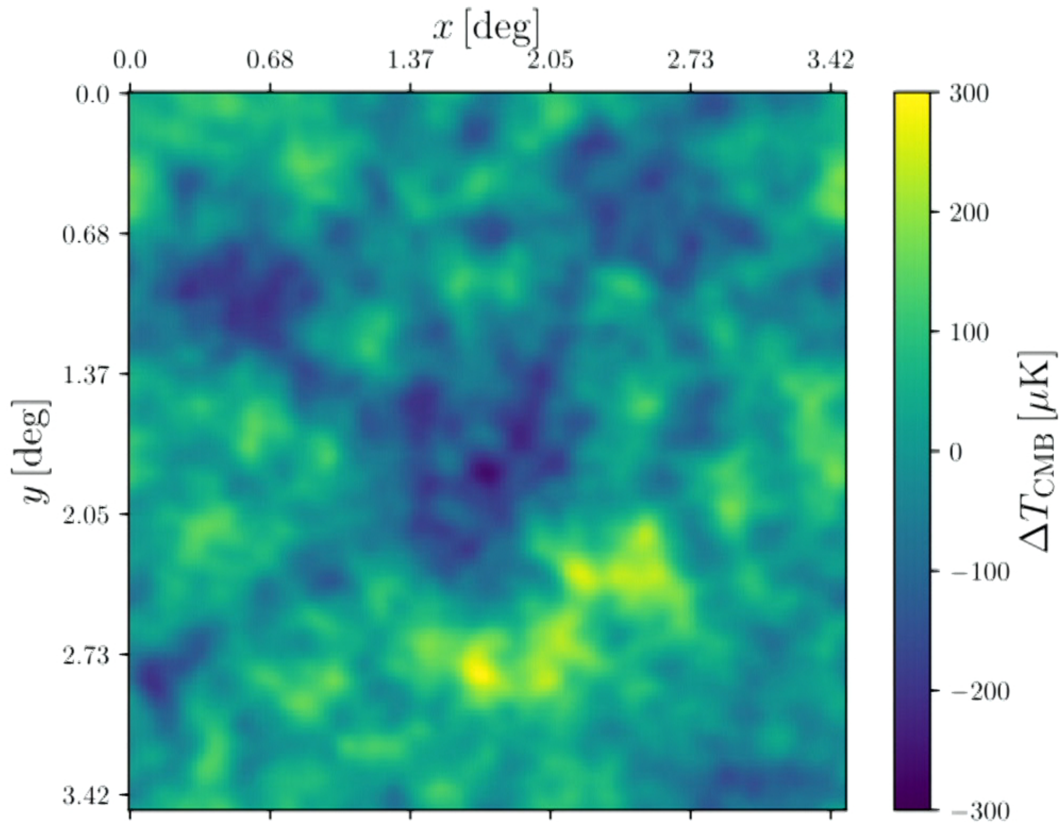

unlensed

15

CMB Lensing

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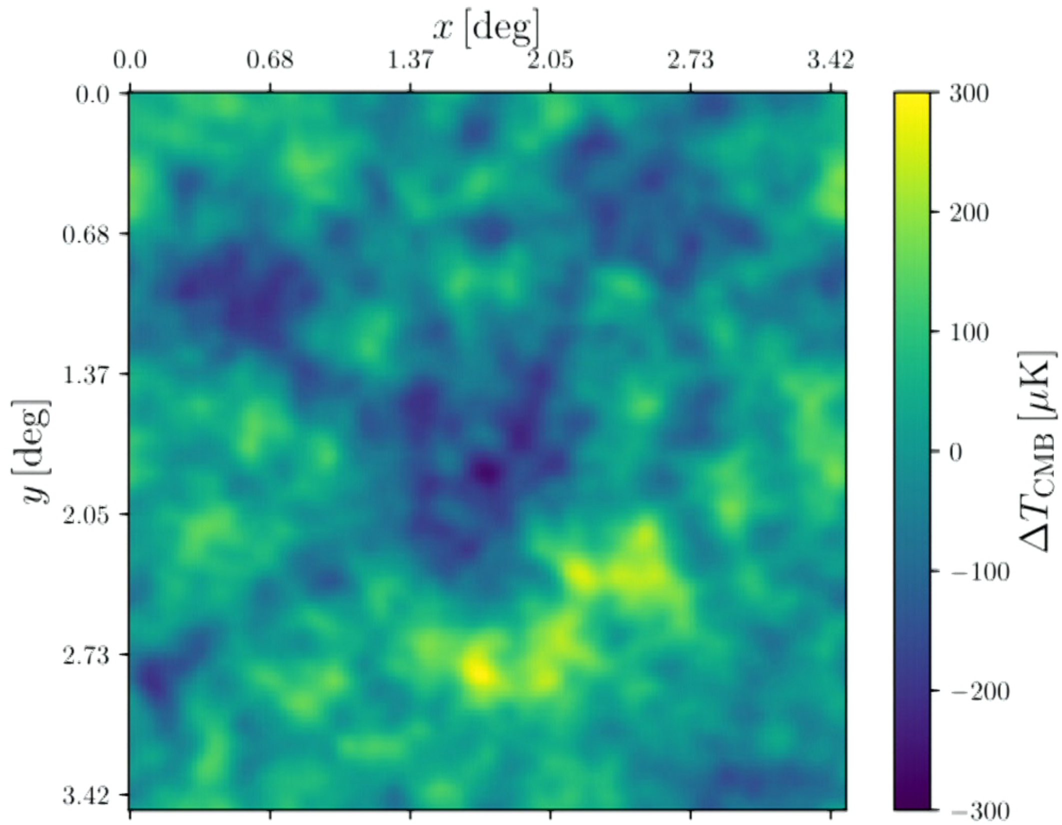
→ **Integrated Total Mass**



unlensed

15

CMB Lensing

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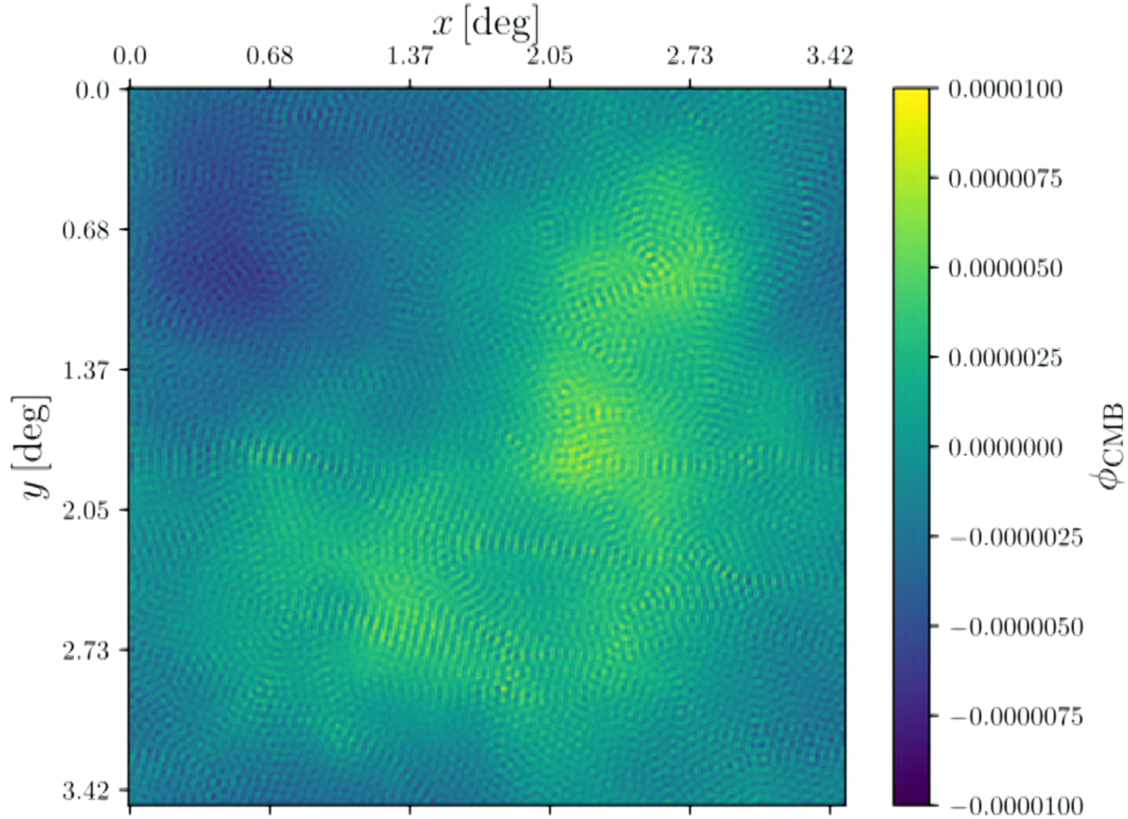
→ **Integrated Total Mass**



reconstructed lensing potential
(TT-only)

18

AdvACT-like experiment:
FWHM=1.4' + 6 μK' noise

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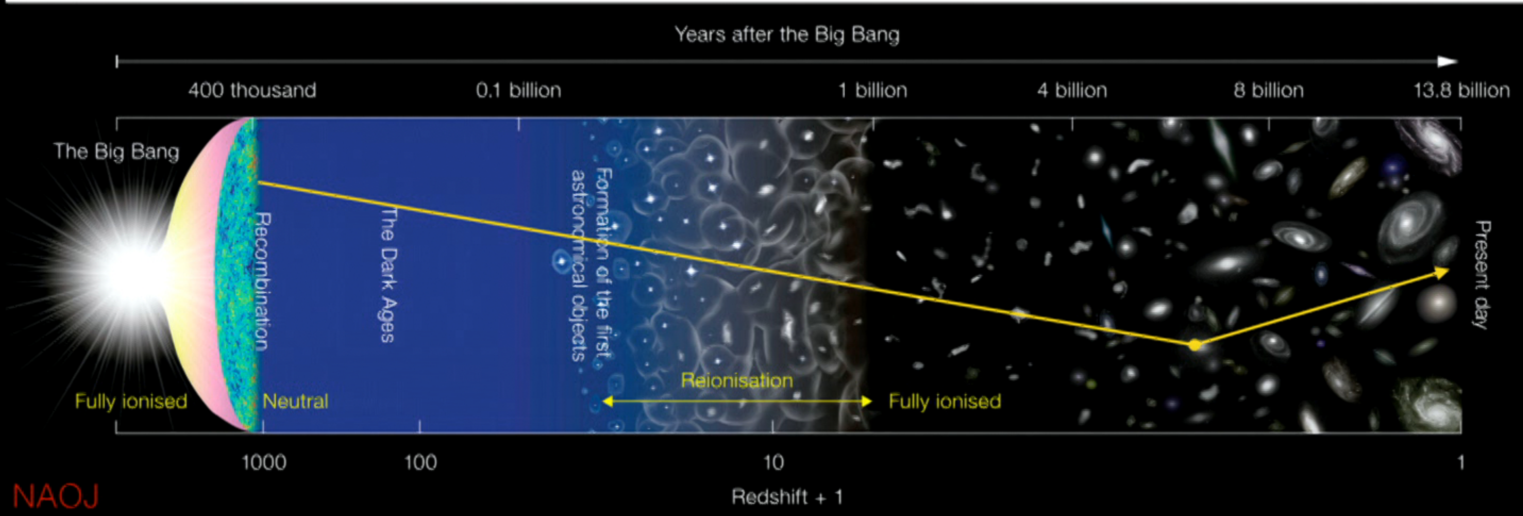
Cosmic Microwave Backlight

Secondary Anisotropies



- Deflection: gravitational lensing
- Scattering: thermal / kinematic Sunyaev-Zel'dovich effect

redshift-independent

Kinematic SZ Effect

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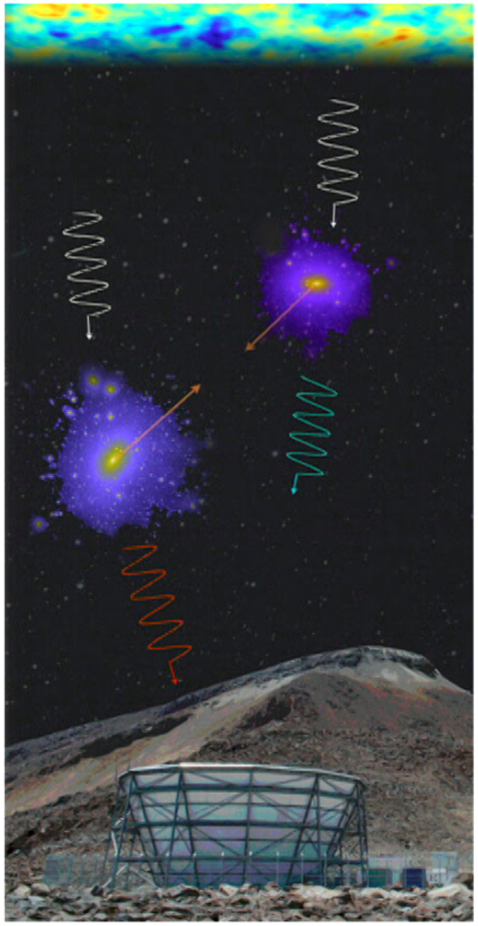
→ Integrated Electron Momentum



Sudeep Das/ACT

Kinematic Sunyaev-Zel'dovich Effect:
Doppler boosting of CMB photons
Compton-scattering off free electrons
with non-zero line-of-sight velocity

20

Kinematic SZ Effect

→ Integrated Electron Momentum

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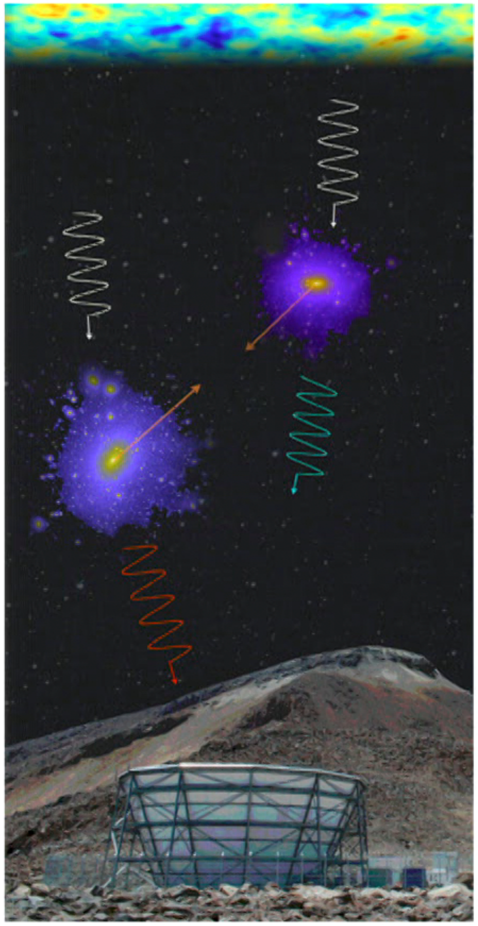
Sudeep Das/ACT

Kinematic Sunyaev-Zel'dovich Effect:
Doppler boosting of CMB photons
Compton-scattering off free electrons
with non-zero line-of-sight velocity

- Preserves blackbody CMB spectrum
- Probe of electron momentum field

$$\frac{\Delta T_{\rm kSZ}(\hat{\mathbf{n}})}{T_{\rm CMB}} = -\frac{1}{c}\int_0^{\eta_{\rm re}} d\eta \, g(\eta) \, \mathbf{p}_e \cdot \hat{\mathbf{n}}$$

visibility function

- Unbiased tracer of free electrons — a precise tool to measure gas distribution (e.g., find "missing baryons")

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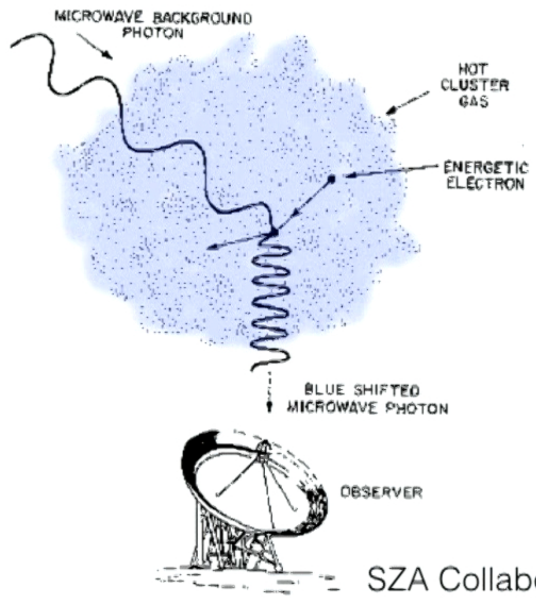
Thermal SZ Effect

→ Integrated Electron Pressure

Thermal SZ Effect:
Change in temperature of CMB photons due to inverse Compton scattering off hot electrons, most of which are in the intracluster medium (ICM) of galaxy clusters



SZA Collaboration

Compton-y

$$\frac{\Delta T_{\rm tSZ}}{T_{\rm CMB}} = g_\nu \frac{\sigma_T}{m_e c^2} \int P_e(\chi) d\chi$$

tSZ spectral function — electron pressure — line-of-sight integral

Thermal SZ Effect

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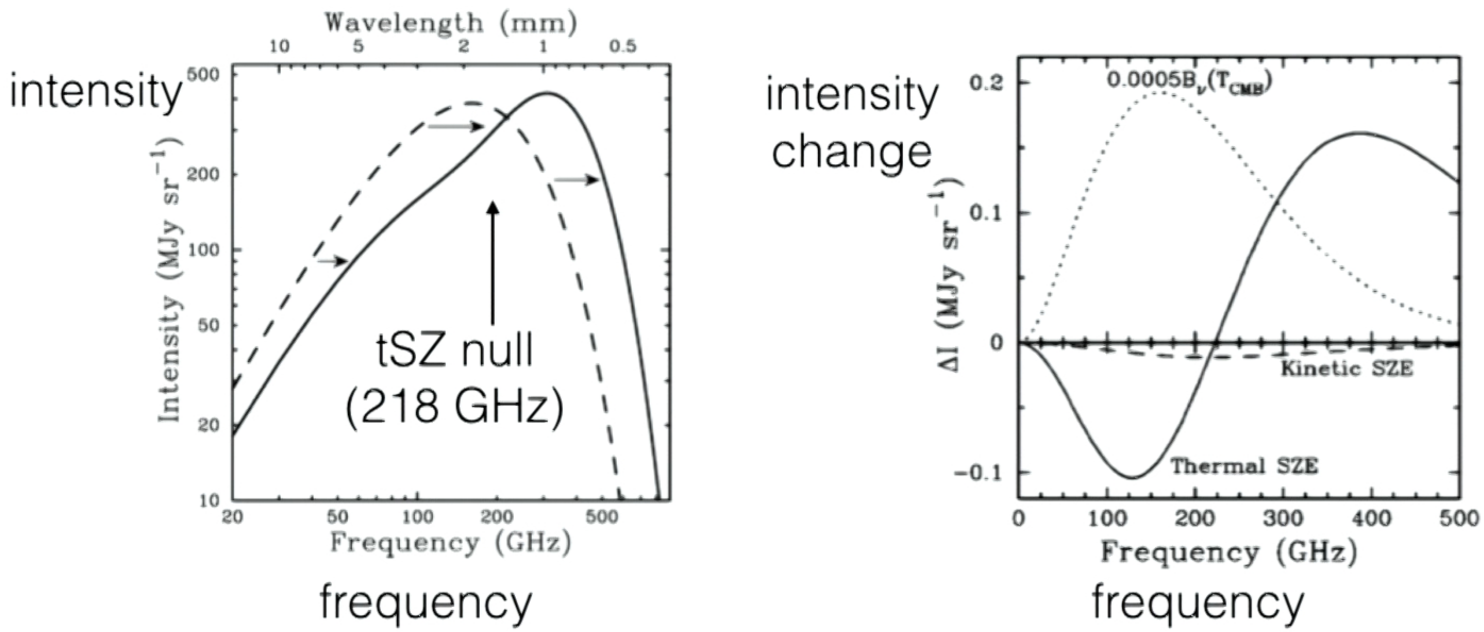
→ Integrated Electron Pressure

Unique spectral signature



Figures: Carlstrom+ (2002)

Thermal SZ Effect

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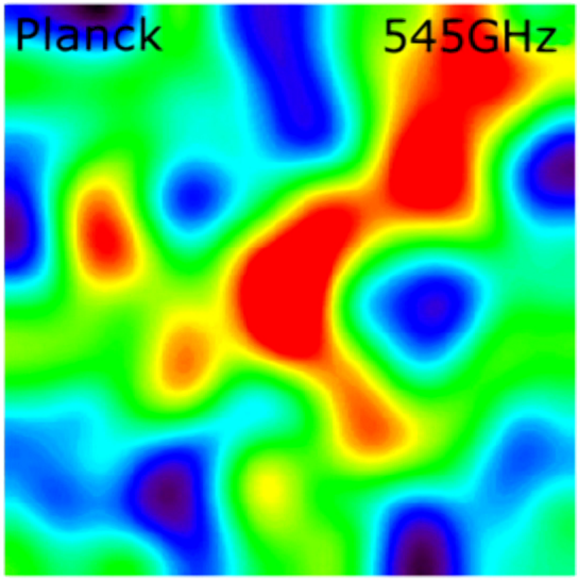
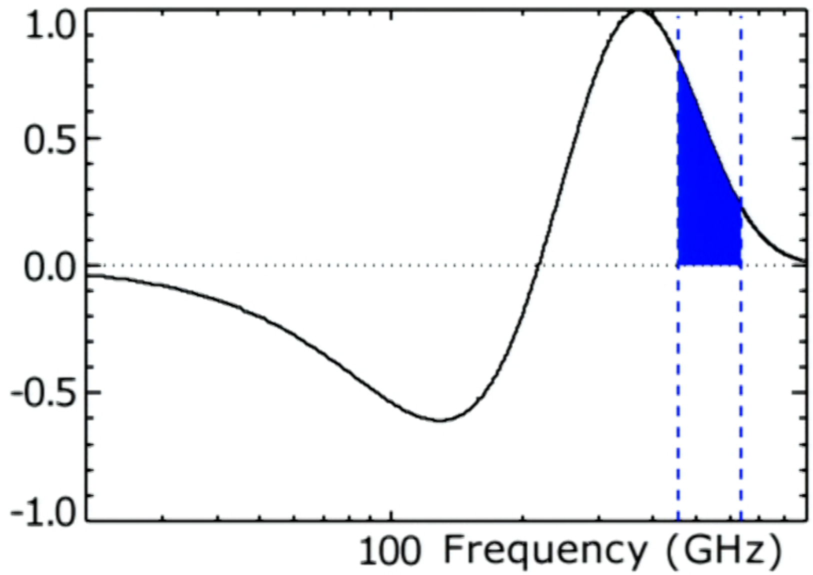
→ Integrated Electron Pressure

Unique spectral signature



simulation



Credit: ESA/Planck Collaboration

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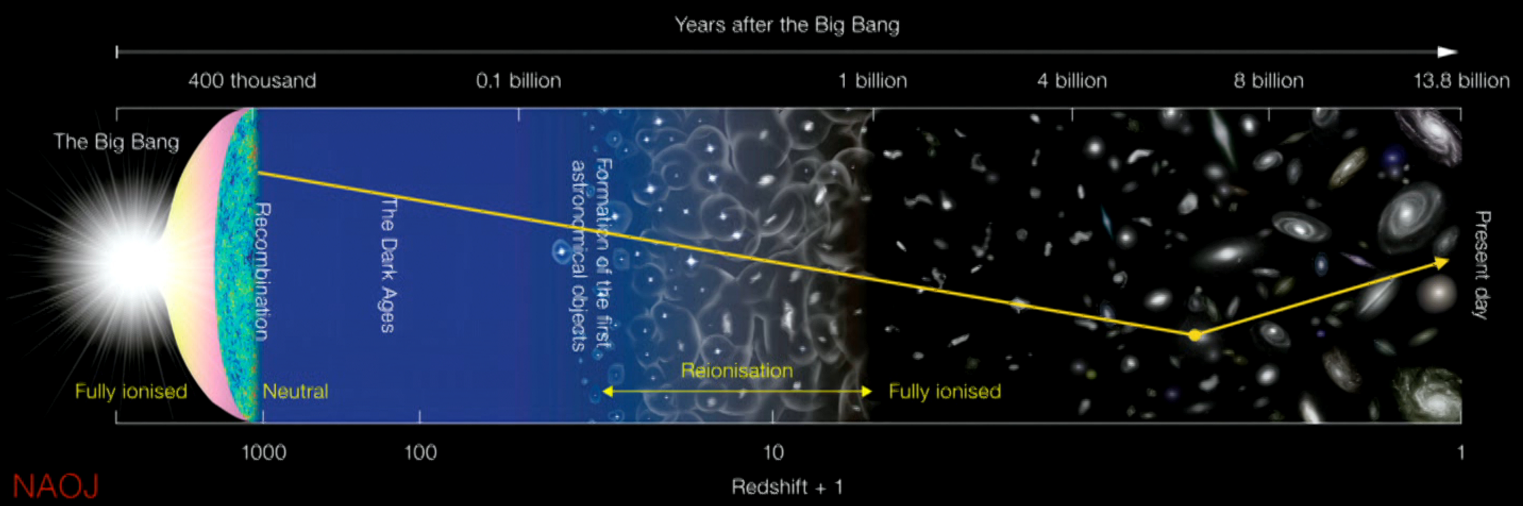
Cosmic Microwave Backlight

Secondary Anisotropies



- Deflection: gravitational lensing
- Scattering: thermal / kinematic Sunyaev-Zel'dovich effect
- Evolving potentials: integrated Sachs-Wolfe, Rees-Sciama

spectral reconstruction

quadratic reconstruction

cross-correlation analysis

26

CMB Lensing

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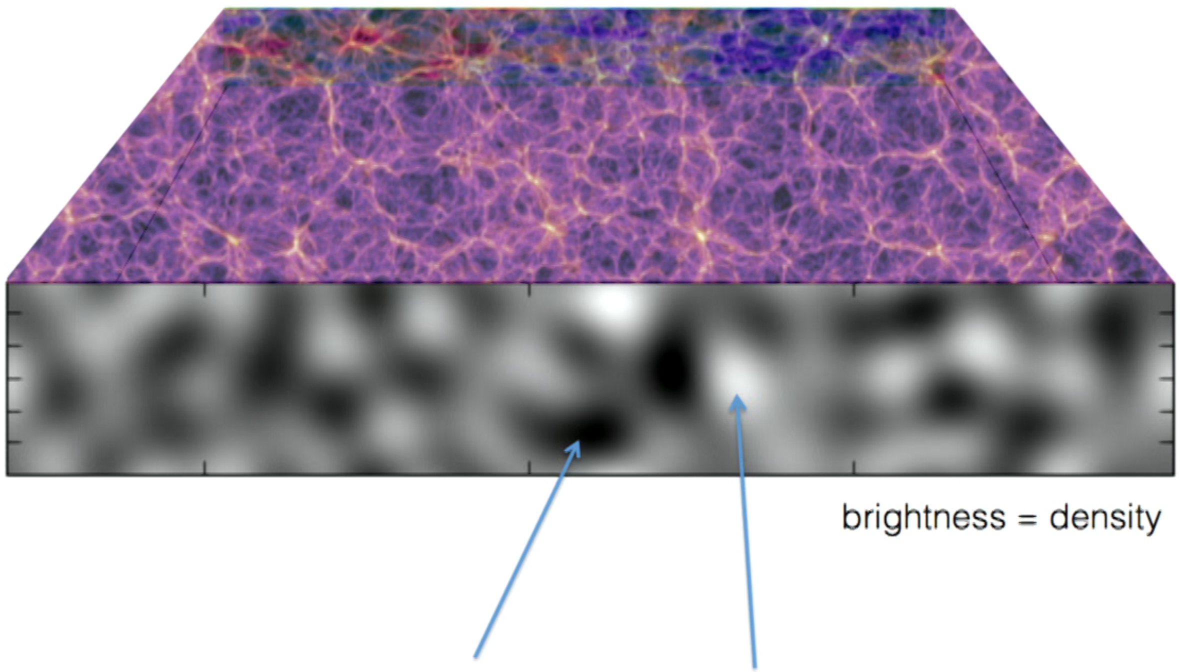
This has been measured!



ACT: Das, Sherwin+ (2011): first detection

28

CMB Lensing

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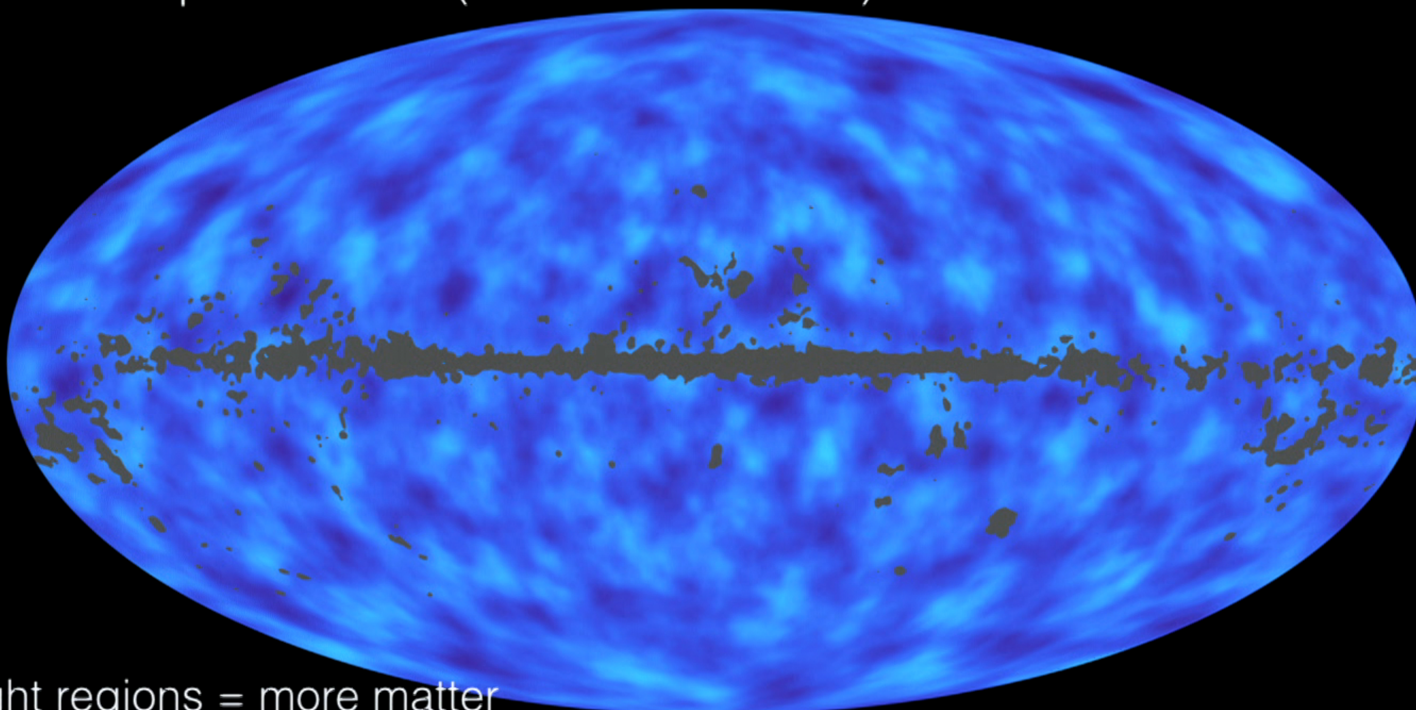
This has been measured!

A map of matter (dark + luminous) in the entire universe*



light regions = more matter
dark regions = less matter

*(almost)

Planck Collaboration (2016)

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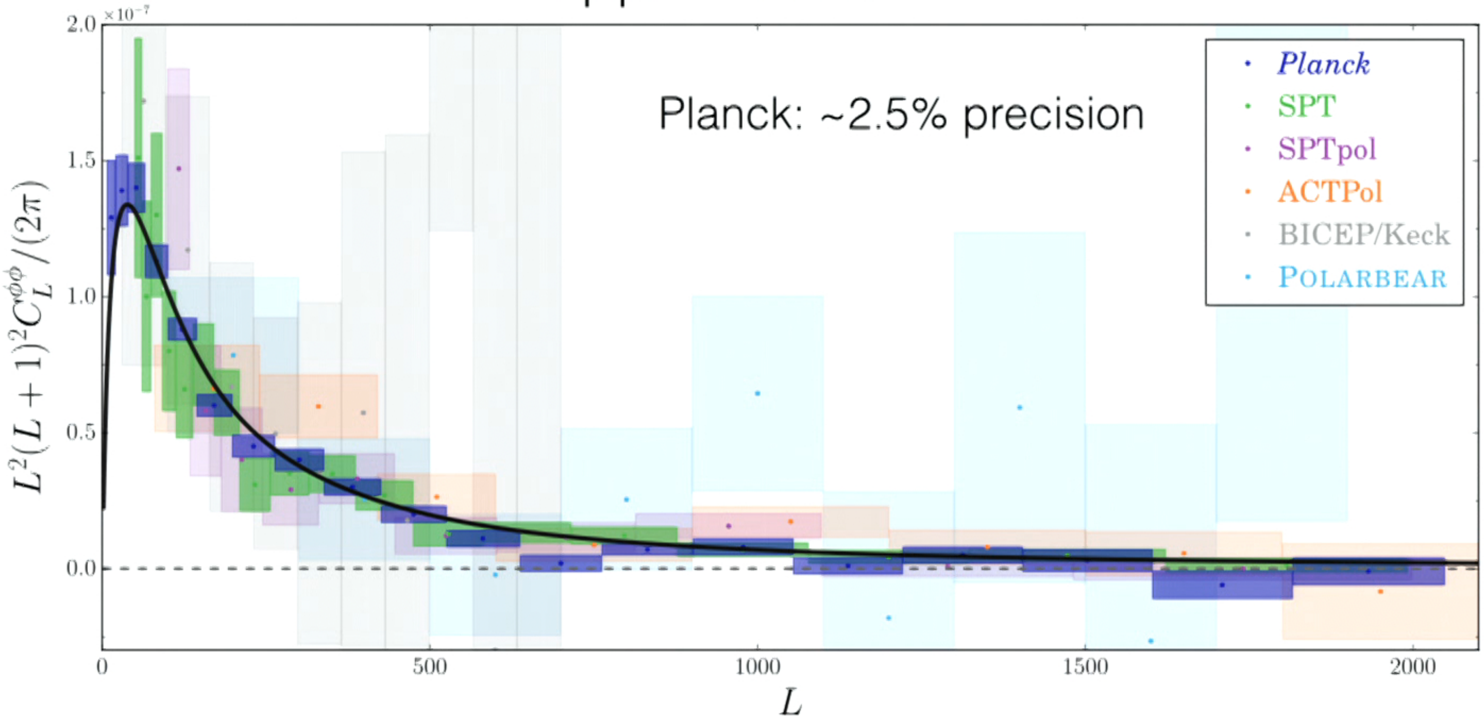
CMB Lensing Power Spectrum

Current status of the field

<ϕϕ>~<TTTT>



compilation by A. van Engelen

30

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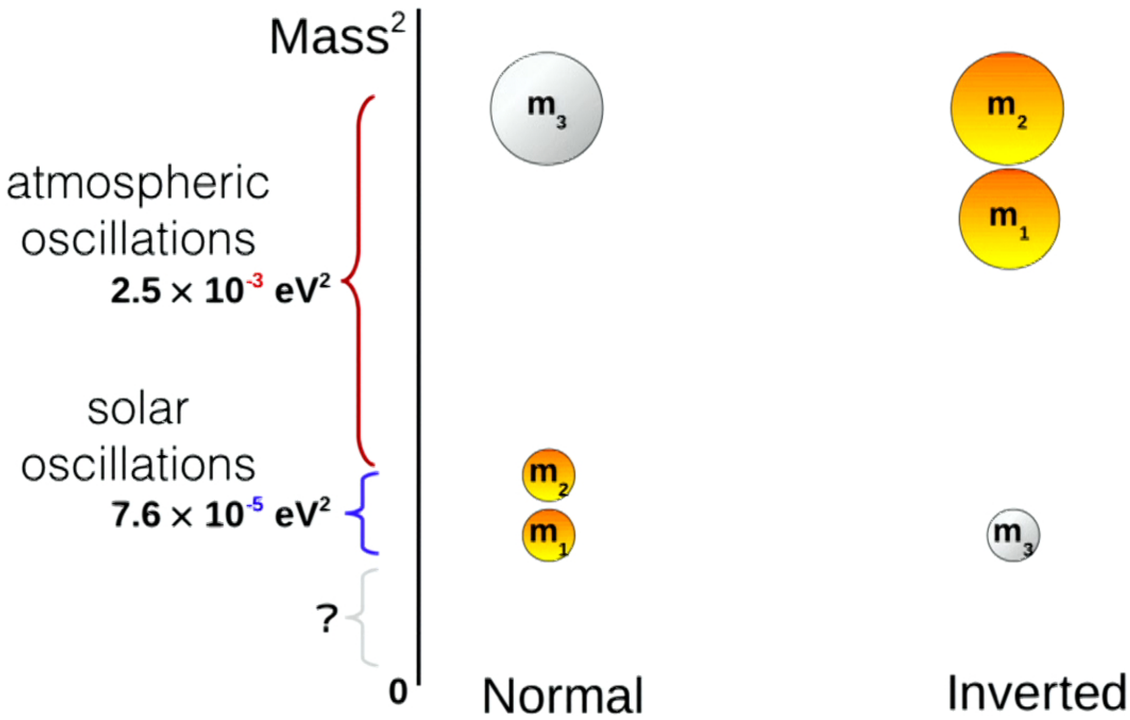
Neutrino Mass Hierarchy

Fundamental physics from CMB lensing

What new physics is responsible for neutrino masses?



Minimum total mass: ~60 meV ~100 meV

Credit: Hyper-Kamiokande

Neutrinos in Cosmology

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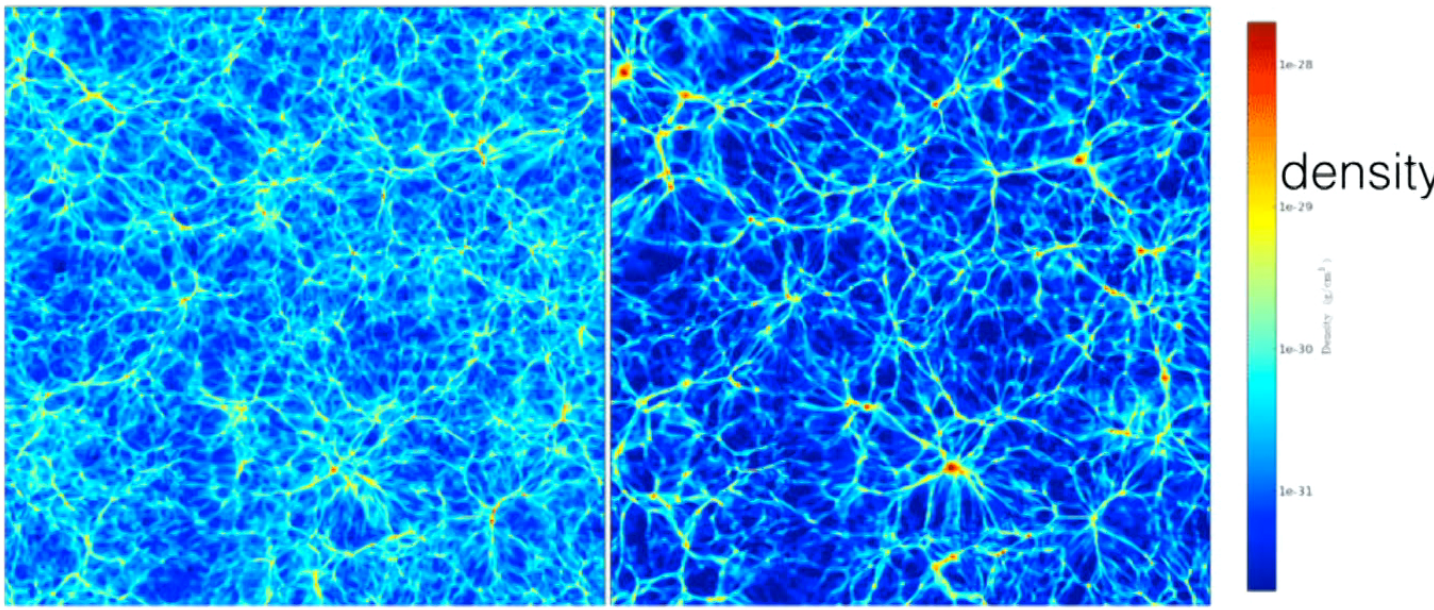
Massive neutrinos affect how cosmic structure grows: fast-moving neutrinos do not cluster!



with massive neutrinos   without massive neutrinos

Agarwal & Feldman (2011)

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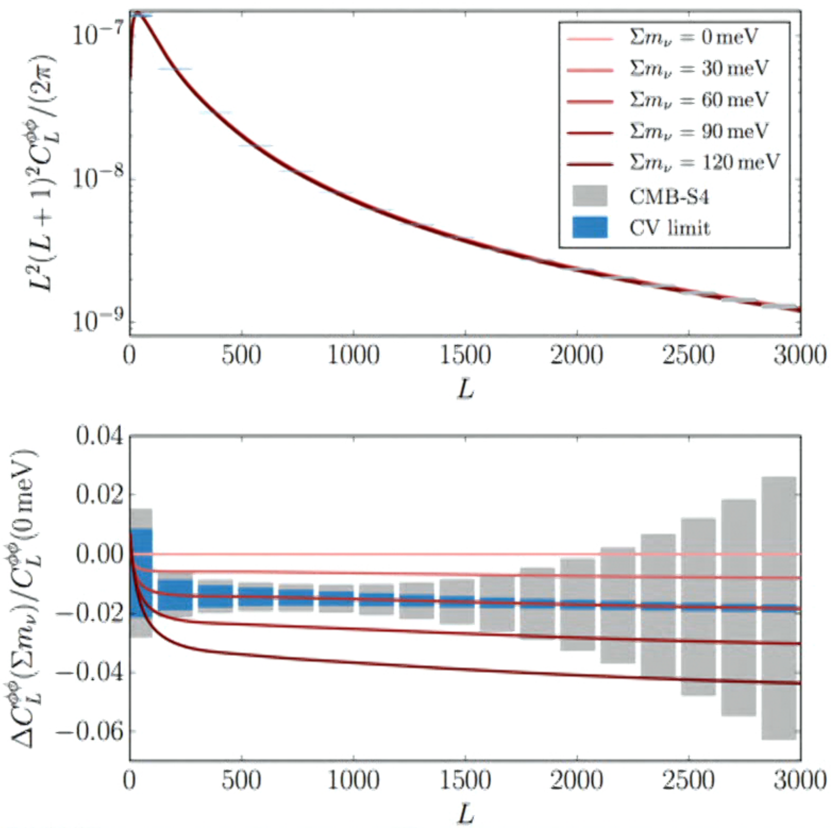
Neutrino Masses from CMB Lensing

Massive neutrinos suppress the lensing power spectrum



upcoming experiments will be sensitive to minimum allowed mass from oscillation experiments

CMB-S4 Science Book (2016)

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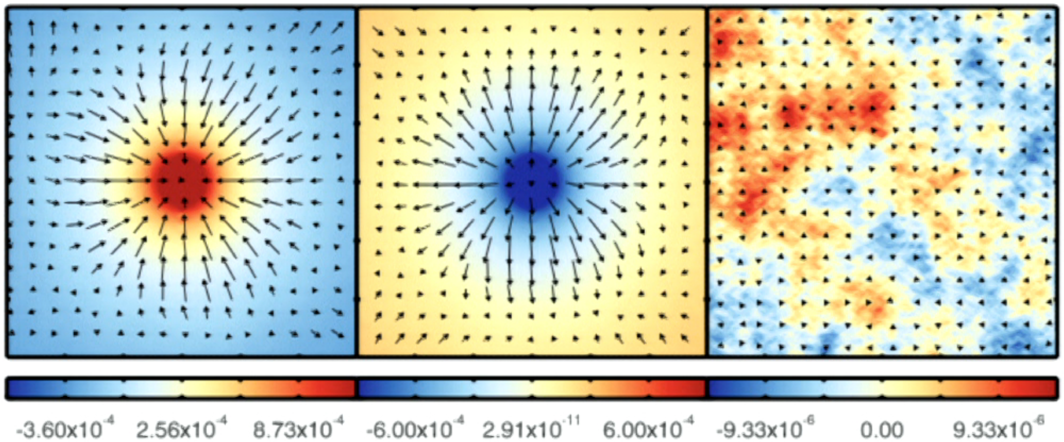
Cosmic Infrared Background

cumulative emission of dusty, star-forming galaxies over cosmic time

strongly correlated with CMB lensing

545 GHz



arrows = lensing deflection
color = CIB intensity

Planck XVIII (2013)

Foreground Challenges

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- Temperature lensing reconstruction
  - Cosmic infrared background
  - Thermal SZ
  - Kinematic SZ
  - Point sources

→ correlated w/ lensing field!

37

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Foreground Challenges

- Temperature lensing reconstruction
  - Cosmic infrared background
  - Thermal SZ
  - Kinematic SZ
  - Point sources
  - Galactic dust
  - Other Galactic foregrounds

→ correlated w/ lensing field!

- Polarization lensing reconstruction (dominates S/N for CMB-S4)
  - Polarized Galactic dust
  - Polarized Galactic synchrotron
  - Point sources

?

CMB Lensing: Foregrounds

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quadratic estimator susceptible to biases from other non-Gaussian signals in the microwave sky (e.g., tSZ, dust, etc.)

$$\phi(\vec{\mathbf{L}}) \sim T(\vec{\ell})T(\vec{\mathbf{L}} - \vec{\ell})$$

van Engelen+ (2014); Osborne+ (2014)

CMB Lensing: Foregrounds

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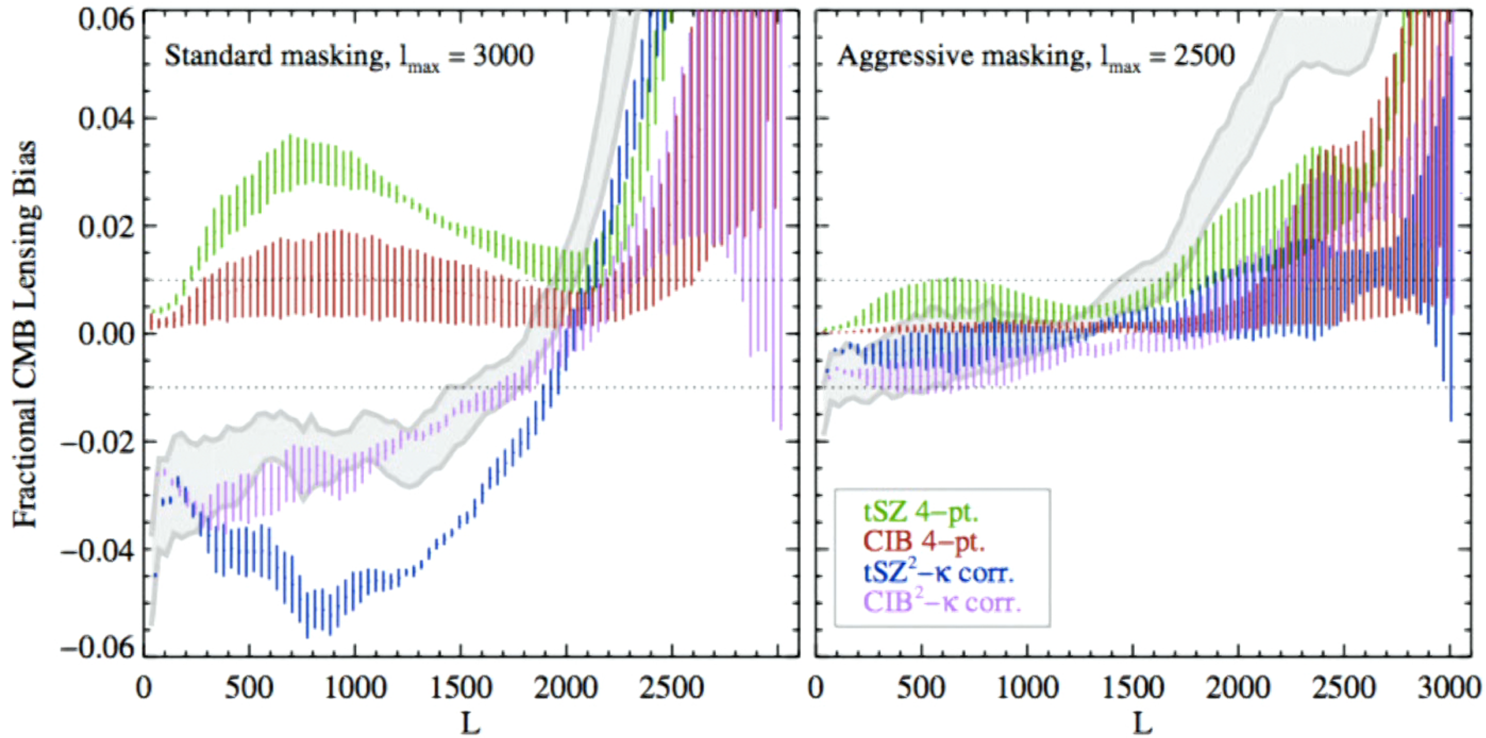

van Engelen+ (2014); Osborne+ (2014)

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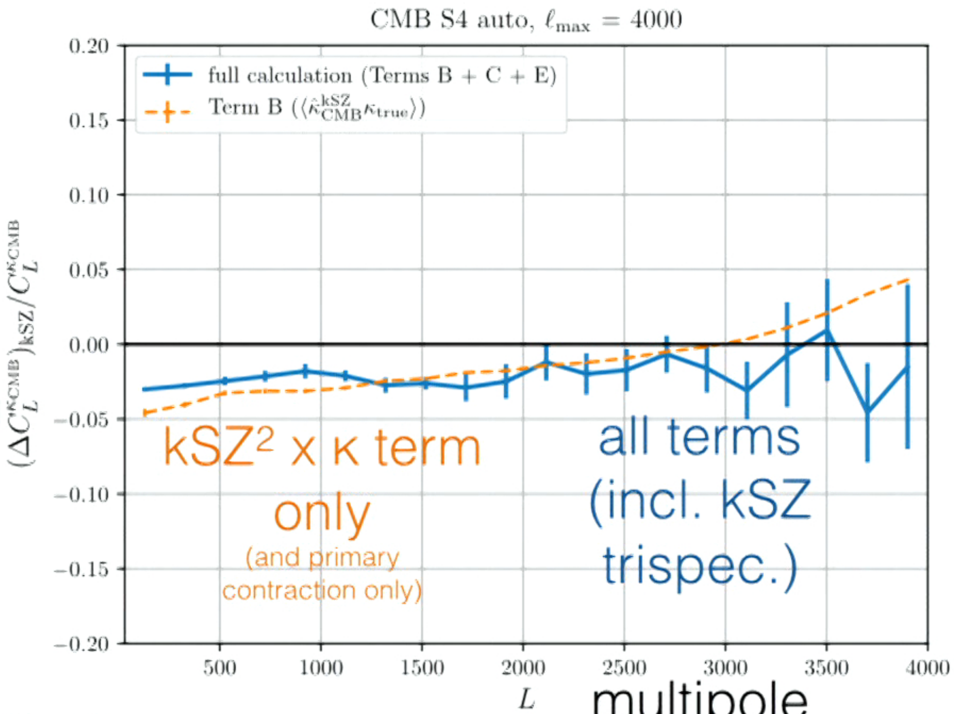
CMB Lensing: Foregrounds

in principle, all biases can be removed via multi-frequency component separation — **except kinematic SZ**

biases **κ auto-spectrum** and LSS cross-correlations



would lead to non-negligible bias on neutrino mass

Ferraro & **JCH** (2018)

42

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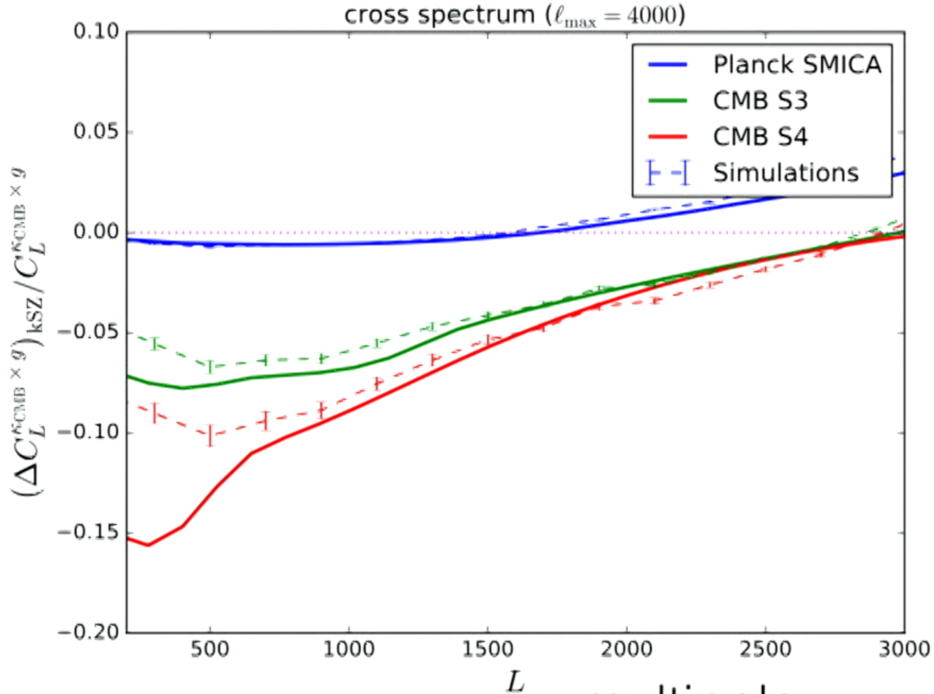
CMB Lensing: Foregrounds

in principle, all biases can be removed via multi-frequency component separation — **except kinematic SZ**

biases κ auto-spectrum and **LSS cross-correlations**

fractional bias to κ-galaxy cross-correlation



multipole

would lead to non-negligible bias on neutrino mass

Ferraro & **JCH** (2018)

CMB Lensing: Foregrounds

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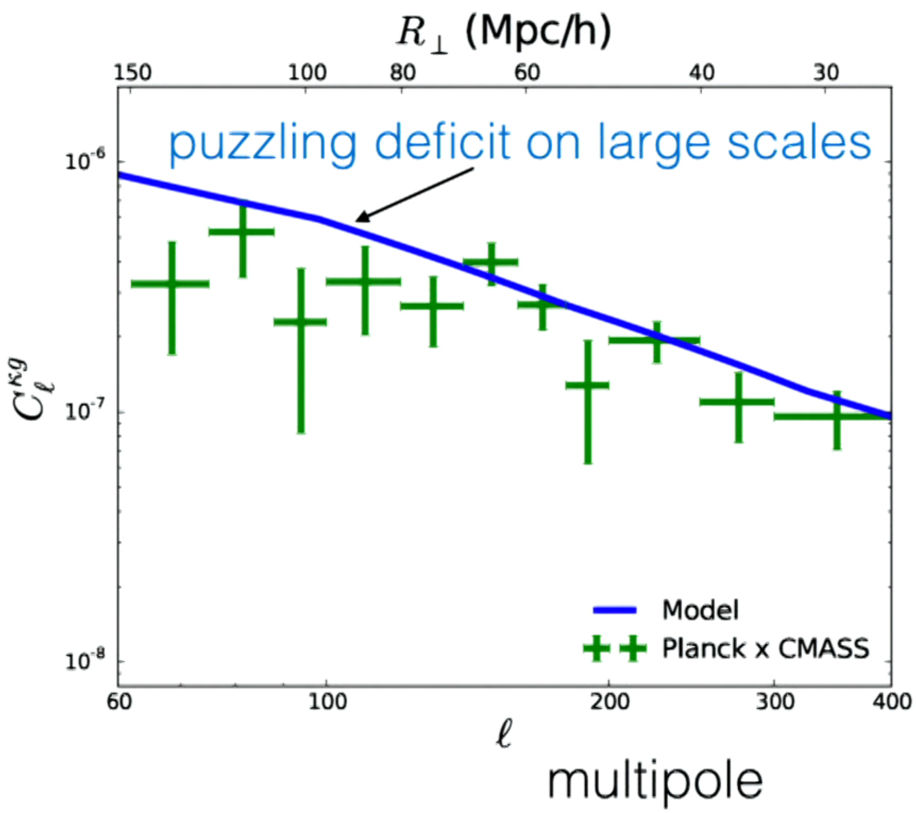
perhaps already signs of such biases in current measurements?

Planck κ cross-correlation w/ BOSS CMASS galaxy catalog



Pullen+ (2016); similar low-L deficit seen in WISE-κ cross-correlation **JCH**+ (2016)

CMB Lensing: Foregrounds

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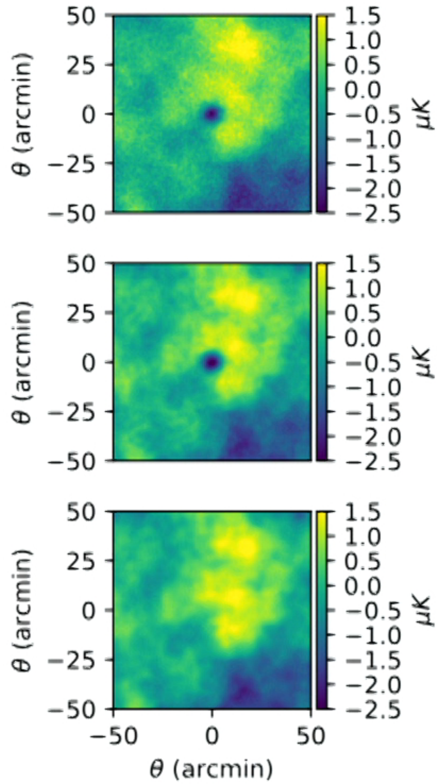
N.B. SMICA map used in Planck lensing reconstruction has significant tSZ residuals

stack on SDSS DR8 redMaPPer clusters



Planck 143 GHz

Planck SMICA CMB

LGMCA CMB (tSZ deprojected)

Madhavacheril & **JCH** (2018)

Asymmetric Lensing Recon.

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Observation 1:

$$\kappa^{XY}(\boldsymbol{\theta}) = -\mathcal{F}^{-1}\left\{A^{XY}(\boldsymbol{L})\mathcal{F}\left\{\mathrm{Re}\left[\nabla \cdot \left[\boldsymbol{\nabla} X_f(\boldsymbol{\theta}) Y_f(\boldsymbol{\theta})^*\right]\right]\right\}\right\}$$

T gradient saturates by ell~2000

Madhavacheril & **JCH** (2018)

Asymmetric Lensing Recon.

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T gradient saturates by ell~2000

Observation 2:

$$\begin{aligned}\langle\tilde{\kappa}(\boldsymbol{\theta})\rangle &= \left\langle\nabla\cdot\left[[\boldsymbol{\nabla}T^o(\boldsymbol{\theta})]_f T^o_f(\boldsymbol{\theta})\right]\right\rangle & (3)\\ &= \langle\nabla\cdot[[\boldsymbol{\nabla}T_f(\boldsymbol{\theta})+\boldsymbol{\nabla}F_f(\boldsymbol{\theta})][T_f(\boldsymbol{\theta})+F_f(\boldsymbol{\theta})]]\rangle & (4)\\ &= \langle\nabla\cdot[[\boldsymbol{\nabla}T_f(\boldsymbol{\theta})]T_f(\boldsymbol{\theta}))]\rangle + \langle\nabla\cdot[[\boldsymbol{\nabla}F_f(\boldsymbol{\theta})]F_f(\boldsymbol{\theta})]\rangle & (5)\end{aligned}$$

only need to clean one leg to remove bias

Madhavacheril & **JCH** (2018)

Cause for Optimism

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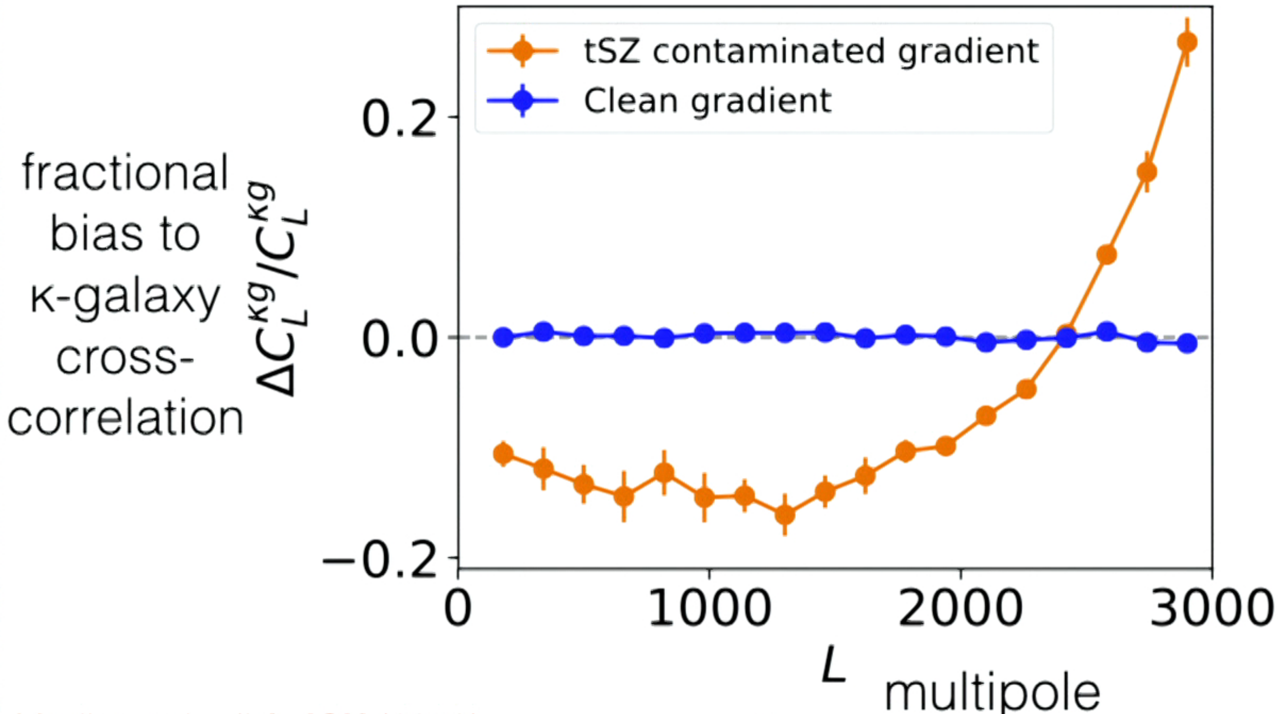
foreground cleaning requirements may be less stringent than originally thought: we only need to foreground-clean one "leg" of the quadratic estimator ("asymmetric" lensing recon.)



Madhavacheril & **JCH** (2018)

48

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CMB Lensing Outlook

on the road to M_ν

- tSZ and CIB biases can be mitigated with minimal loss in S/N (~ < 10%)
- The same trick appears to work for CMB lensing auto-power spectrum as well — need to verify with simulations
- Similar arguments expected to work in polarization
- To-do:
  - End-to-end tests of lensing reconstruction with full component separation in T (this has never been done! even by Planck…)
  - Continued analysis of polarized foreground biases in simulations + data (including end-to-end tests)
  - New methods for kSZ bias (in the era until we have ~few μK-arcmin maps over large sky areas, i.e., the next 5-10 years)

→ promising development: shear-only reconstruction

Prince+ (2018); Schaan & Ferraro (2018)

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CMB Lensing Outlook

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Prince+ (2018); Schaan & Ferraro (2018)

Foregrounds

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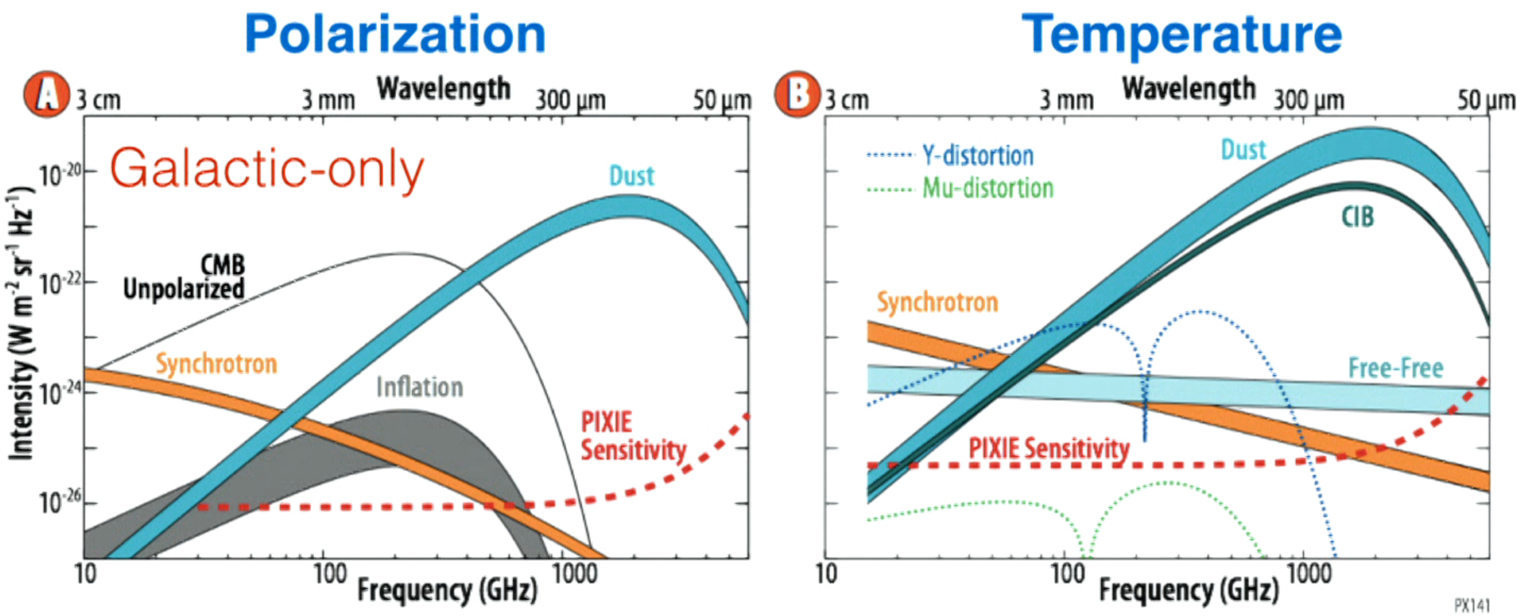

- Anomalous microwave emission
- CO line emission
- Radio sources
- Atmosphere

N.B. foregrounds can cross-talk w/ other systematics: e.g., CMB polarimeter self-calibration [Abitbol, **JCH**+ (2016)]

Kogut+ (2016)

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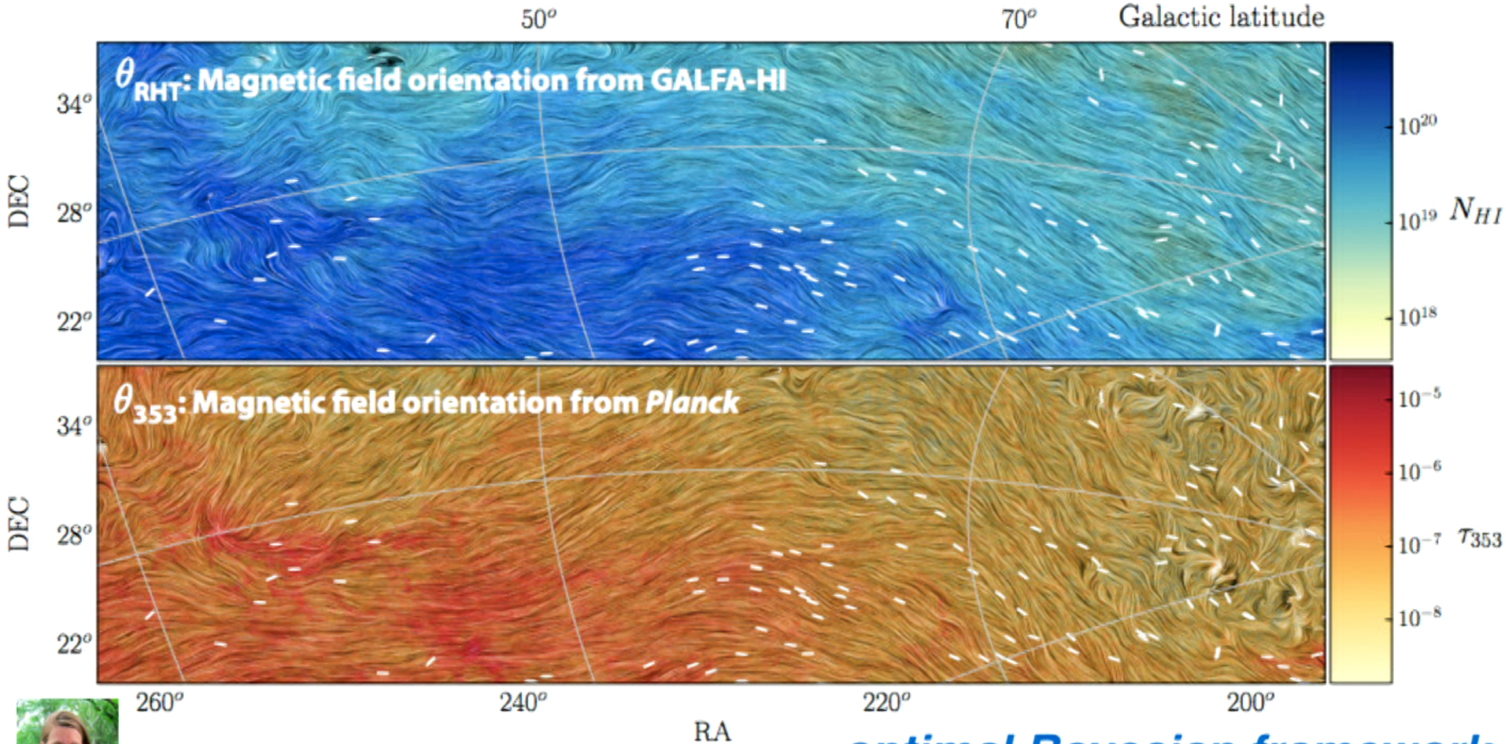
Future: Sweep Away the Dust

For example: by using other types of Galactic data (e.g., HI)



Clark, **JCH**+ (PRL 2015)

optimal Bayesian framework to combine these data sets currently in progress

Foreground Cleaning

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beam and line-of-sight averages are *inevitable*

→ superposition of spectral shapes, leading to new behavior

Chluba, **JCH**, and Abitbol (2017)

Why Not Go Fully Parametric?

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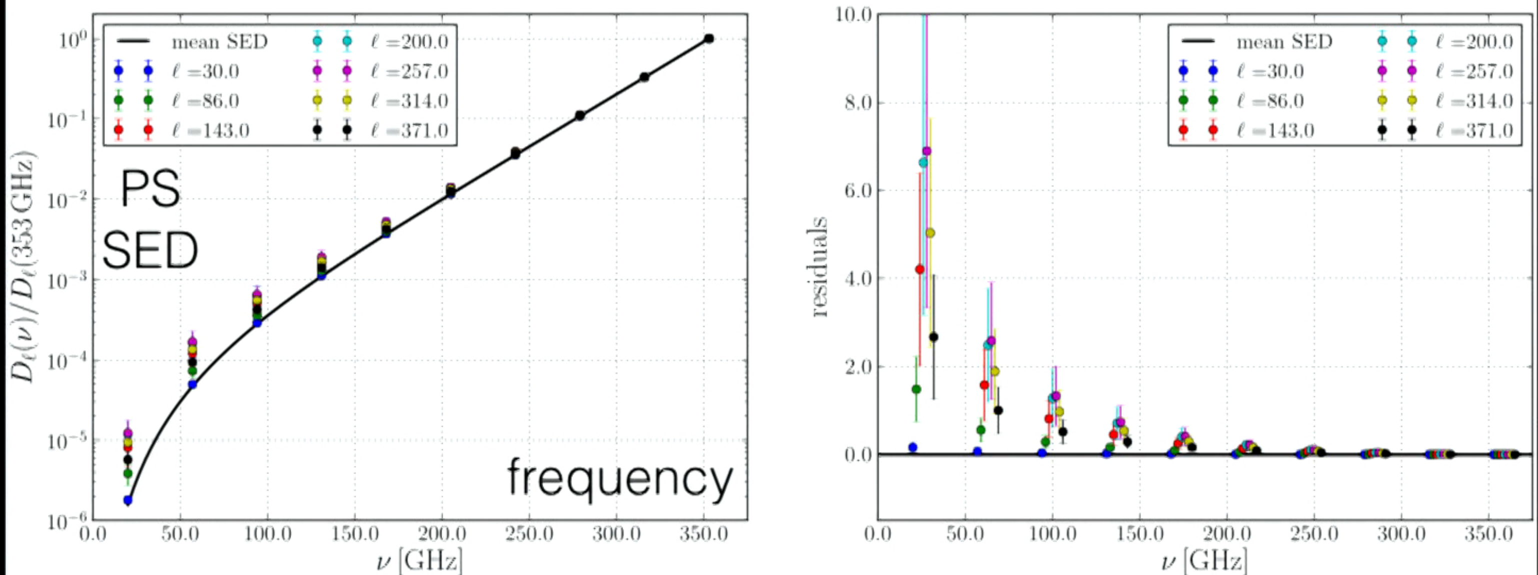
beam and line-of-sight averages are *inevitable*

➜ superposition of spectral shapes, leading to new behavior

e.g.: suppose dust SED is a modified blackbody everywhere, but spectral index varies on degree scales: α ~ N(1.6,0.1)



simple assumptions can lead to highly inaccurate results

Chluba, **JCH**, and Abitbol (2017)

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Internal Linear Combination (ILC)

relatively agnostic approach, flexible choice of domain

$$\Delta T_i(p) = a_i y(p) + n_i(p)$$

i ⟷ frequency

observed temperature fluctuation — component of interest — noise+ contaminants

minimum variance estimator with unit response to desired component:

$$\hat{y}(p) = w_i \Delta T_i(p) \qquad w_j = \frac{a_i (\hat{R}^{-1})_{ij}}{a_k (\hat{R}^{-1})_{kl} a_l}$$

$$\hat{R}_{ij} = N_{\rm pix}^{-1} \sum_p \Delta T_i(p) \Delta T_j(p)$$

flexibility = choice of domain on which to compute covariance

e.g. Eriksen+ (2004)

Constrained ILC

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extension: explicitly remove ("deproject") other component(s) as well

$$\Delta T_i(p) = a_i y(p) + b_i s(p) + n_i(p)$$

observed temperature fluctuation | component of interest | component to remove | noise + other contaminants

minimum variance estimator with unit response to desired component and zero response to undesired component:

$$w_j = \frac{\left(b_k(\hat{R}^{-1})_{kl}b_l\right) a_i(\hat{R}^{-1})_{ij} - \left(a_k(\hat{R}^{-1})_{kl}b_l\right) b_i(\hat{R}^{-1})_{ij}}{\left(a_k(\hat{R}^{-1})_{kl}a_l\right)\left(b_m(\hat{R}^{-1})_{mn}b_n\right) - \left(a_k(\hat{R}^{-1})_{kl}b_l\right)^2}$$

- can be extended to explicitly remove N components
- advantage: can remove contaminants that could bias some analysis
- disadvantage: variance in final ILC map is larger

e.g. Remazeilles+ (2011), **JCH** (to appear)

Hybrid Solution

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"Multiply Constrained Monte Carlo ILC" = $(MC)^2$ILC

idea: remove components via additional spectral constraint(s); marginalize over SED models to deal with spectral uncertainties

$$\Delta T_i(p) = a_i y(p) + b_i s(p) + c_i d(p) + n_i(p)$$

observed temperature fluctuation	component of interest	component to remove	component to remove	noise + other contaminants

- instead of marginalizing, can further minimize variance by optimizing on dust SED model
- idea: use HI maps as a tracer of Galactic dust, and minimize cross-correlation of the cleaned CMB map with this
- another idea: minimize higher-order, non-Gaussian statistics such as $\langle T_{353} B_{ILC} B_{ILC} \rangle$ (foregrounds are non-Gaussian, while CMB should be Gaussian) — may be more effective than <BB>

JCH (to appear)

Colin Hill
IAS/CCA

Hybrid Solution

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JCH (to appear)

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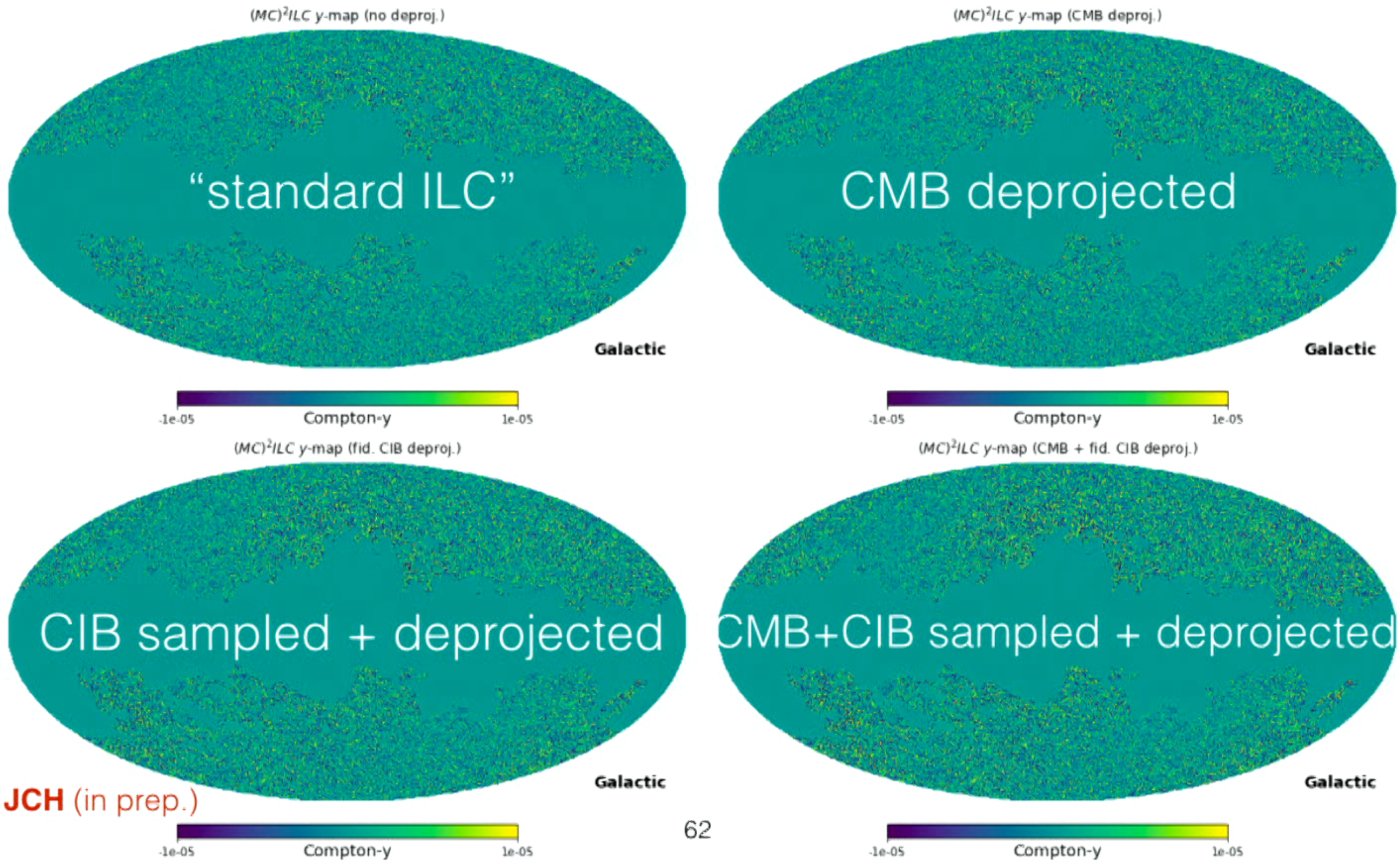
A Quick Look

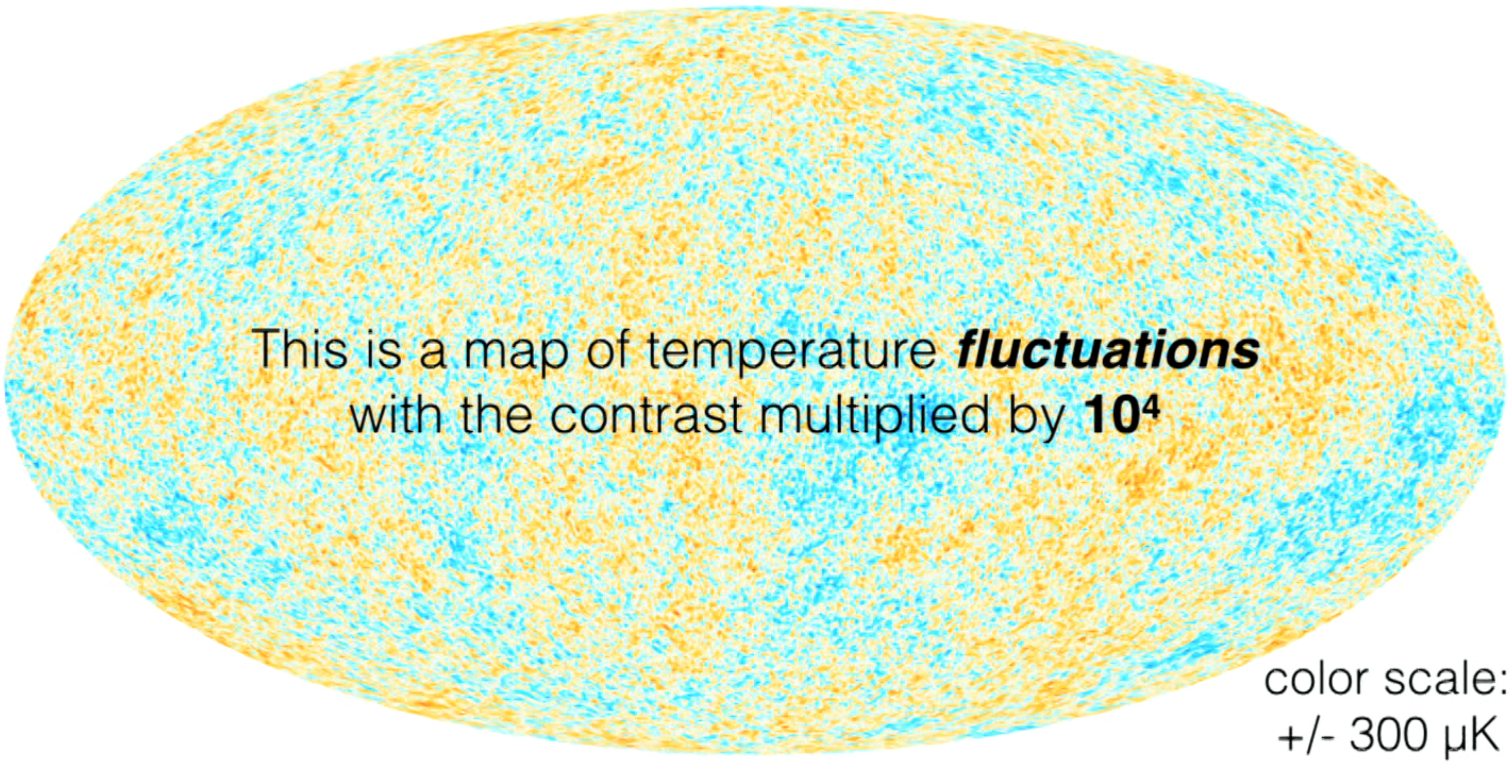
New tSZ map pipeline: (MC)²ILC (here applied to Planck data)



JCH (in prep.)

62

Cosmic Microwave Background



This is a map of temperature ***fluctuations*** with the contrast multiplied by $\mathbf{10^4}$

color scale:
+/- 300 μK

Planck Collaboration (2016)

64

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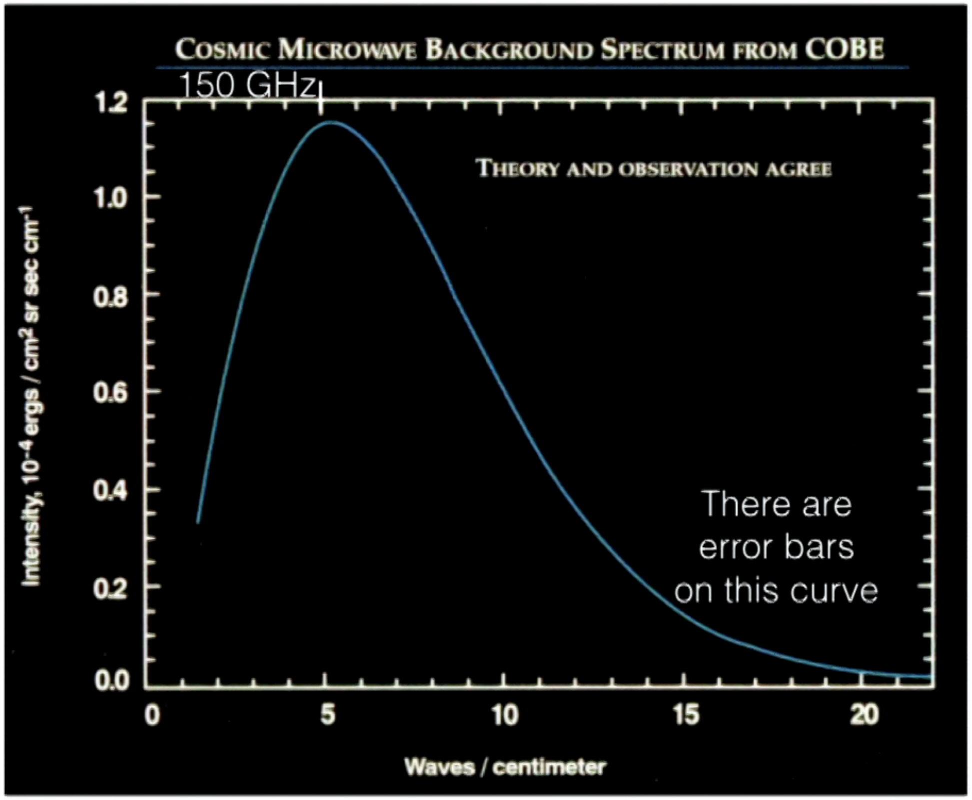
COBE-FIRAS

CMB is blackbody to 50 ppm precision (most precise known in nature)
T_{CMB} = 2.726 +/- 0.001 K

Nobel Prize in Physics (2006): J. Mather/ G. Smoot



Direct evidence of the hot Big Bang

Fixsen+ (1996); Fixsen (2009)

66

Is That All? No

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CMB Spectral Distortions: not a perfect blackbody!

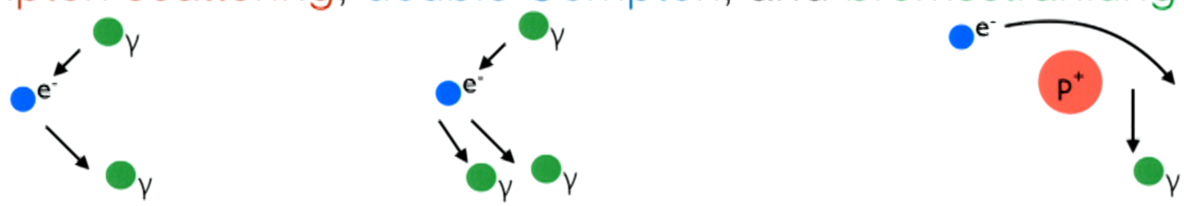
- At very early times ($z >> 10^6$), baryon-photon fluid is in full thermodynamic equilibrium:
  - Photons possess pure blackbody spectrum at all times
  - Fully characterized by $T_{CMB} \sim 2.726\,(1+z)$ K

- Perturb this equilibrium:
  - Energy injection
  - Entropy injection (production of energetic photons/particles)

→ Photon spectrum deviates from blackbody

Thermalization process partially (or fully) erases distortions

(Compton scattering, double Compton, and bremsstrahlung emission)



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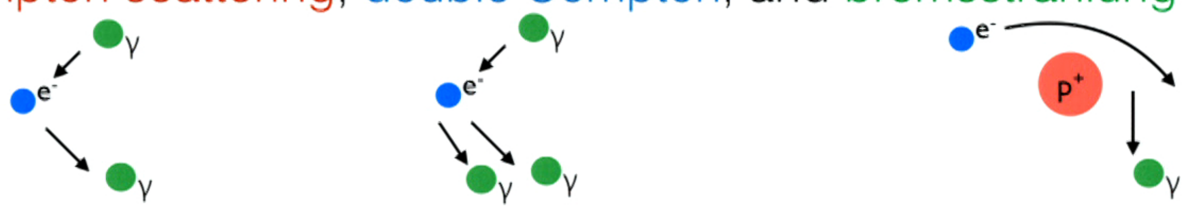

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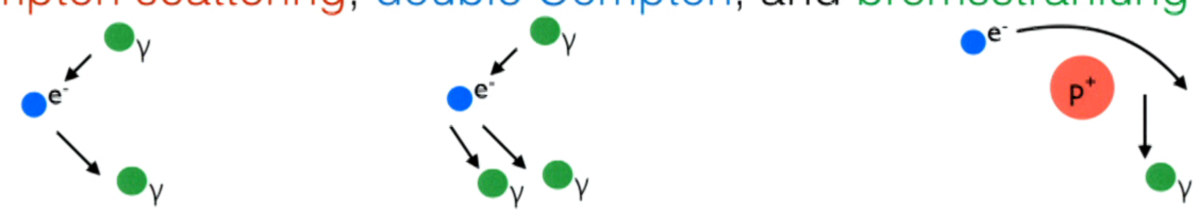

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Theory of Spectral Distortions

What processes can inject (or remove) energy?

- Electron-positron annihilation ($z \sim 10^8$ - 10^9): too early

- Adiabatically cooling ordinary matter
  - non-relativistic matter redshifts as $T_e \sim (1+z)^2$
  - since $T_{CMB} \sim (1+z)$, electrons "Compton cool" CMB until z~150
  - due to large heat capacity of CMB, small effect: **$\mu \sim -2 \times 10^{-9}$**

- Heating by decaying/annihilating particles + exotic sources

Sunyaev, Zel'dovich, Danese, de Zotti, Hu, Silk, Chluba, Daly, many others

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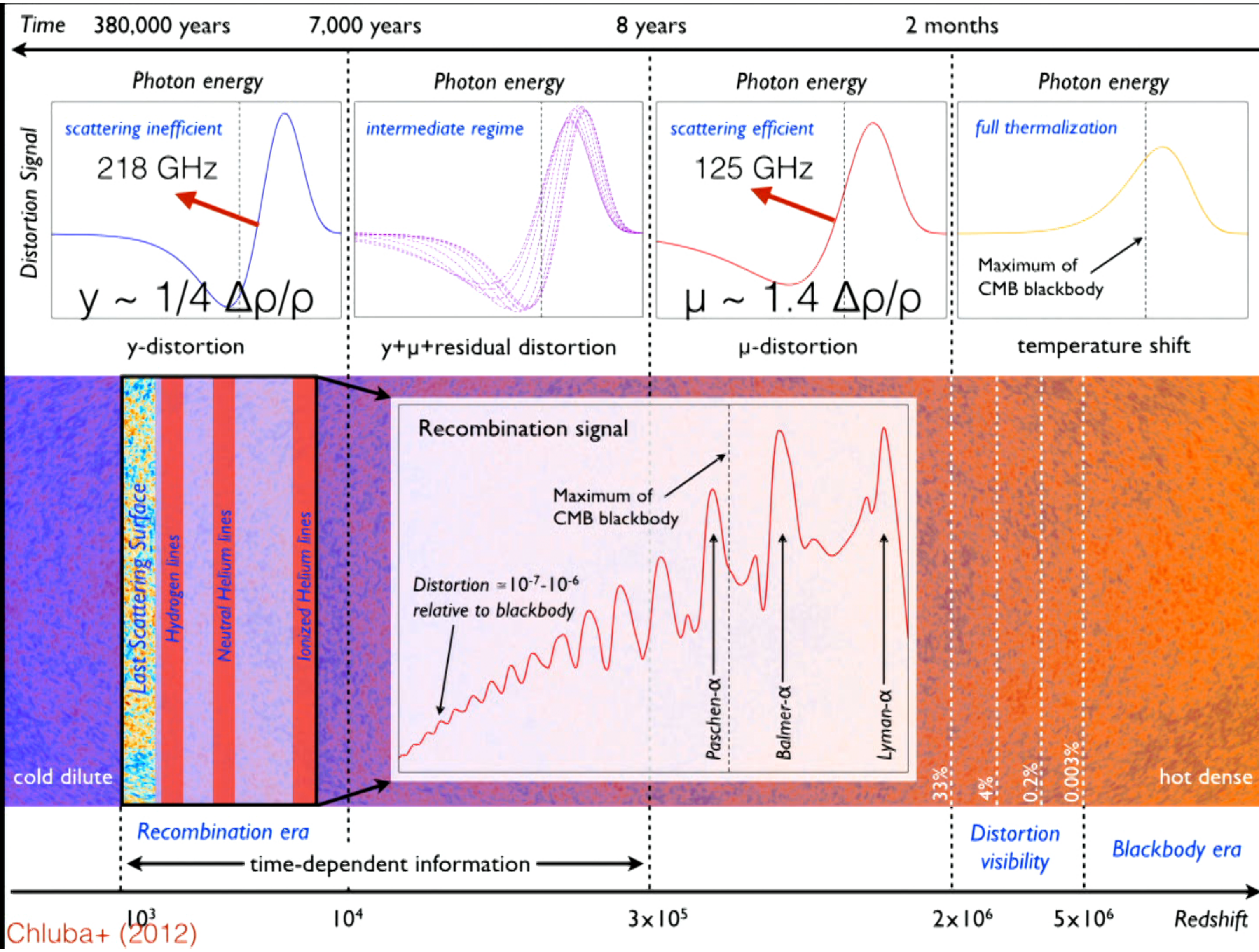

Time
380,000 years
7,000 years
8 years
2 months
Photon energy
Distortion Signal
scattering inefficient
218 GHz
y ~ 1/4 Δρ/ρ
intermediate regime
scattering efficient
125 GHz
μ ~ 1.4 Δρ/ρ
full thermalization
Maximum of CMB blackbody
y-distortion
y+μ+residual distortion
μ-distortion
temperature shift
Last Scattering Surface
Hydrogen lines
Neutral Helium lines
Ionized Helium lines
Recombination signal
Maximum of CMB blackbody
Distortion ≈ 10⁻⁷-10⁻⁶ relative to blackbody
Paschen-α
Balmer-α
Lyman-α
cold dilute
hot dense
33%
4%
0.2%
0.003%
Recombination era
time-dependent information
Distortion visibility
Blackbody era
10³
10⁴
3x10⁵
2x10⁶
5x10⁶
Redshift
Chluba+ (2012)

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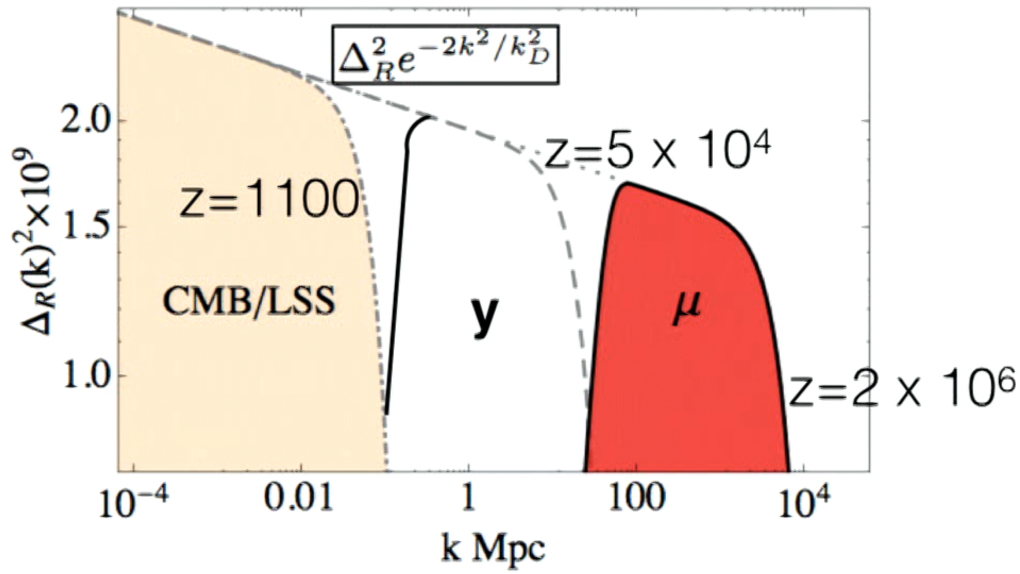
Dissipation of Small-Scale Modes



$$\langle \mu \rangle \approx \int d\log k\, \Delta_{\mathcal{R}}^2(k) W_\mu(k) \qquad \langle y \rangle \approx \int d\log k\, \Delta_{\mathcal{R}}^2(k) W_y(k)$$

Probe of primordial power on extremely small scales
($50\ h$/Mpc $< k < 10^4\ h$/Mpc)

Pajer & Zaldarriaga (2012); Chluba+ (2012)

Dissipation of Small-Scale Modes

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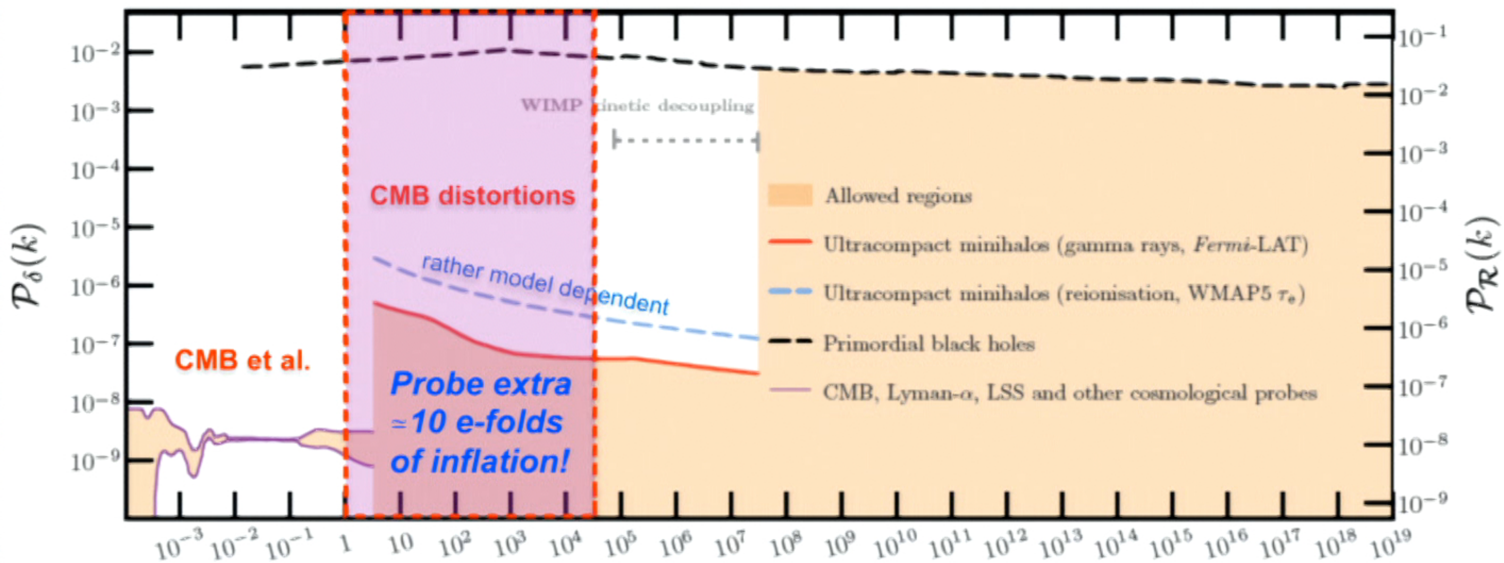

Bringmann, Scott & Akrami, 2011, ArXiv:1110.2484

Physical Scale

Increase from ~7 to ~17 in number of inflationary e-foldings probed by cosmologists

Probe *primordial* power spectrum at M_{sun} scales

Colin Hill
IAS/CCA

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- Heating by decaying/annihilating particles + exotic sources

- Dissipation of small-scale primordial perturbations: **prediction of standard model (positive μ and y distortions): $\mu \sim 2 \times 10^{-8}$**

- Compton-scattering of CMB photons in galaxy groups and clusters, intergalactic medium, reionization: **prediction of standard model (positive y distortion): $y \sim 1.8 \times 10^{-6}$** [**JCH**+ 2015 (PRL)]

Sunyaev, Zel'dovich, Danese, de Zotti, Hu, Silk, 74 Chluba, Daly, many others proposed to NASA Dec. 2016

PIXIE Concept

Primordial Inflation Explorer

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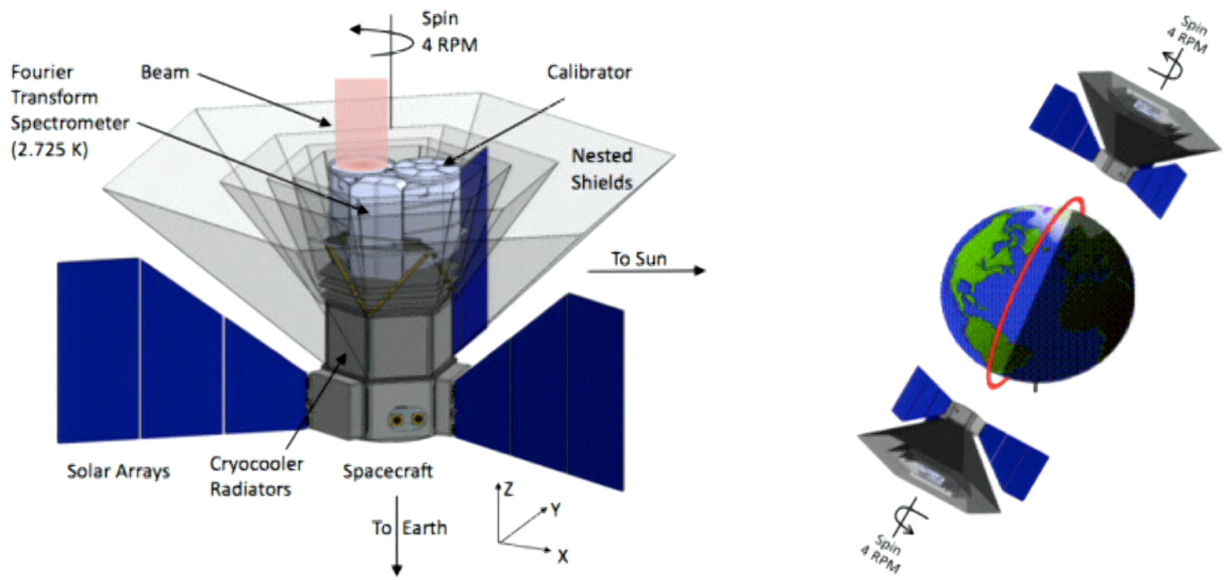

~3 order of magnitude improvement over COBE-FIRAS

Kogut+ (2011)

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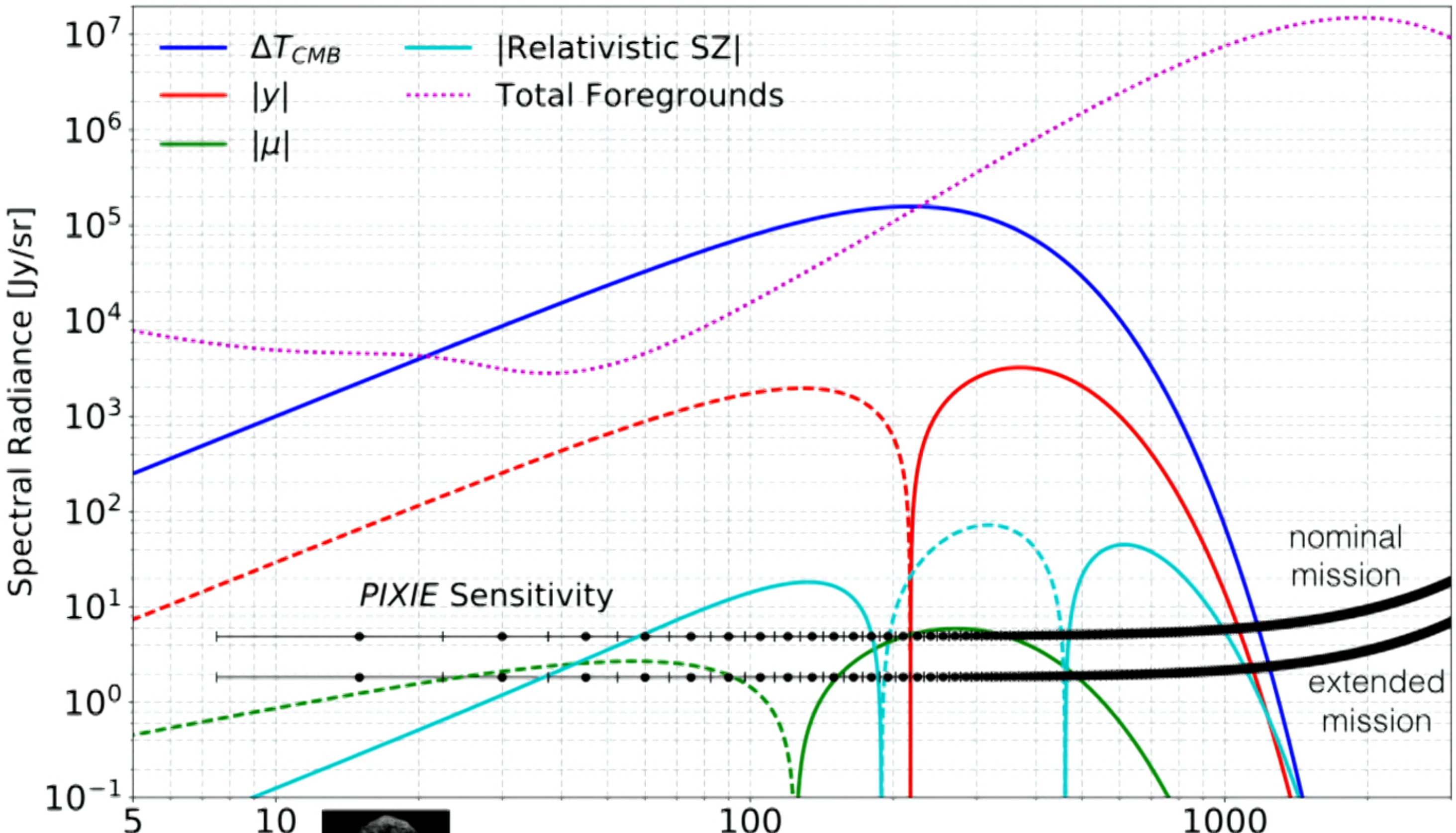
PIXIE: signals

specific intensity



frequency

Abitbol, Chluba, **JCH**, and Johnson (2017)

76

PIXIE: forecasts

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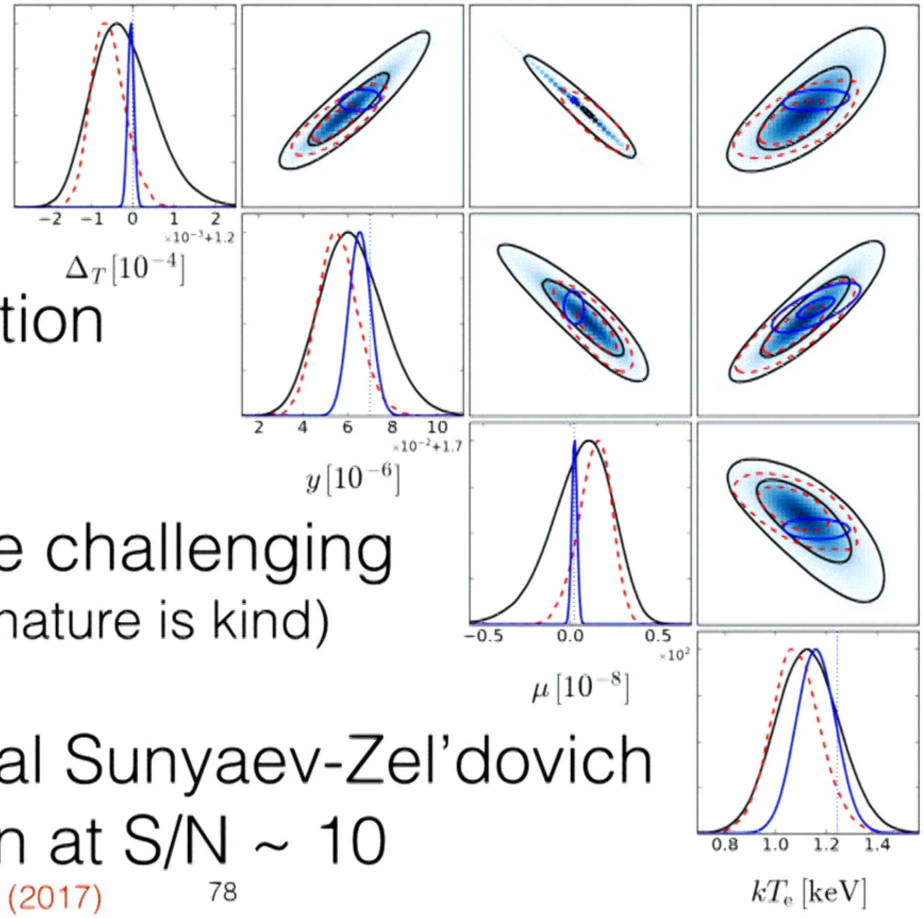
First spectral distortion forecast w/ all foregrounds included

$\sigma(T_{CMB})$ ~ 100 nK
(S/N ~ 1.3 x 10^7)

Compton-y detection
at S/N >100

μ detection will be challenging
(S/N ~ 0.1, unless nature is kind)

Relativistic thermal Sunyaev-Zel'dovich
detection at S/N ~ 10



Abitbol, Chluba, **JCH**, and Johnson (2017)

Beyond PIXIE: A μ Hope

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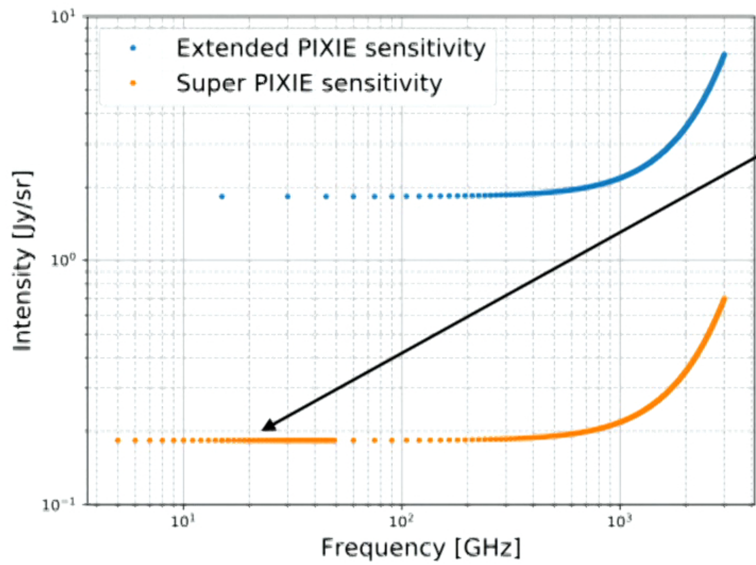
IAS/CCA

Can we modify the mission concept to get to ΛCDM Silk μ?



- Improve sensitivity 10x
- Add low-freq. spectrometer

preliminary!

5σ detection of μ

Can also get there w/ only 5x sensitivity improvement and different binning choice

Abitbol, **JCH**, + (in prep.)

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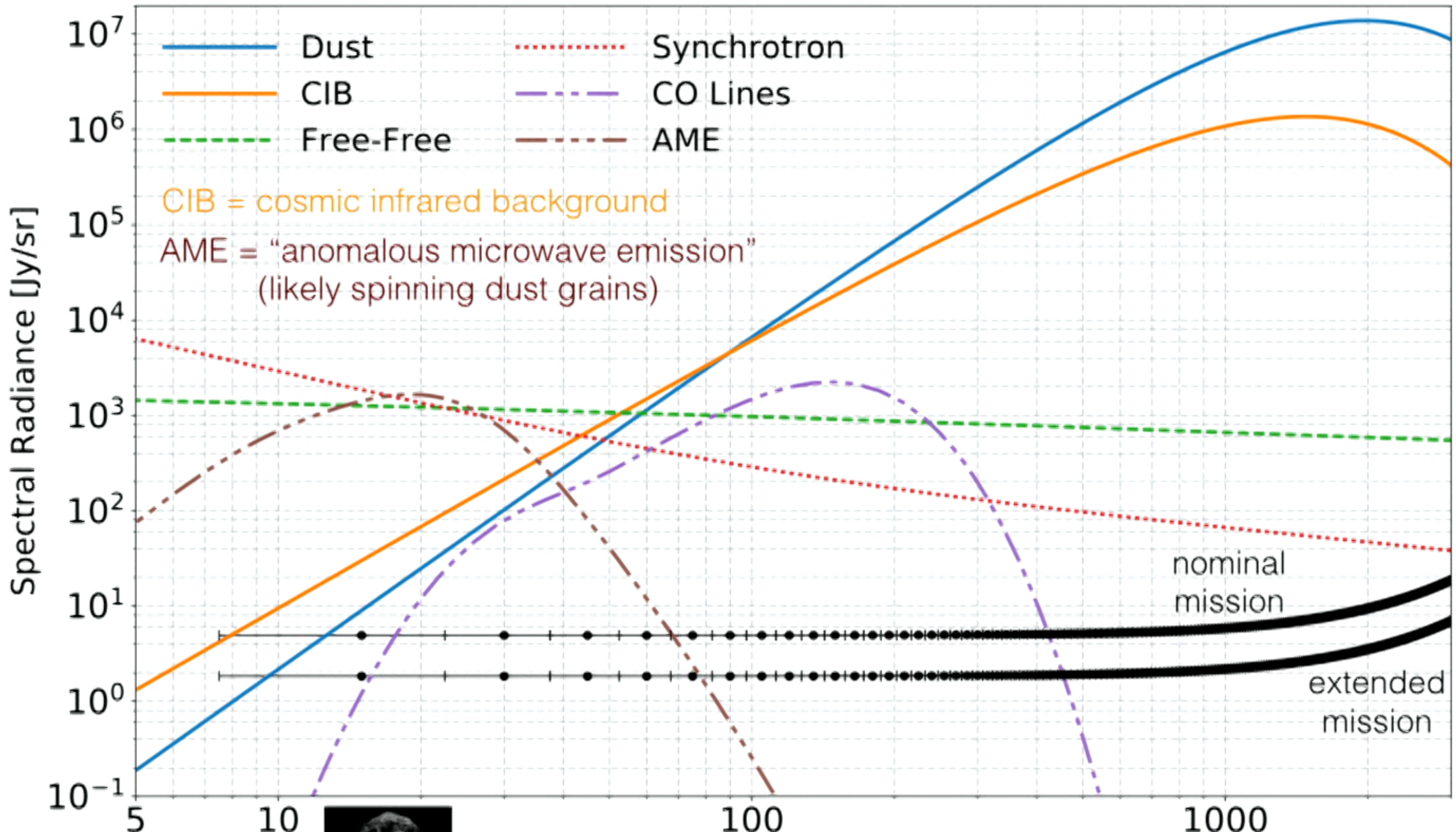
specific intensity

PIXIE: foregrounds



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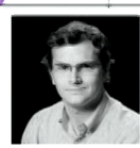
Abitbol, Chluba, **JCH**, and Johnson (2017)



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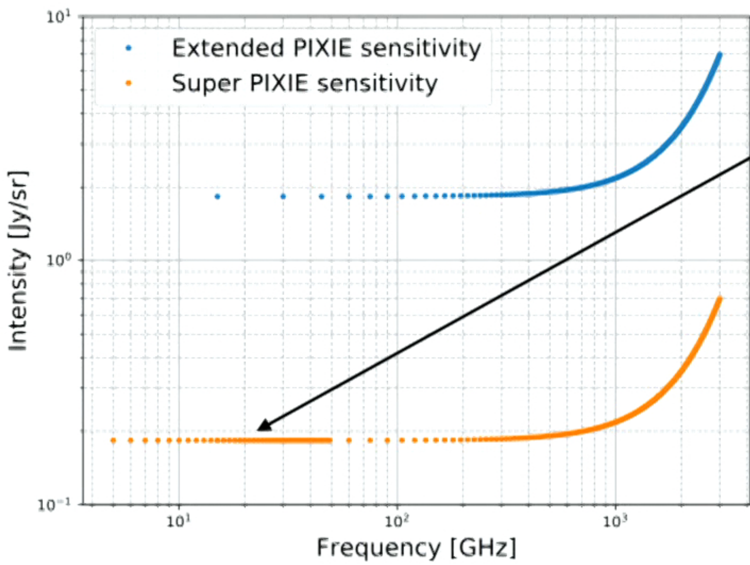

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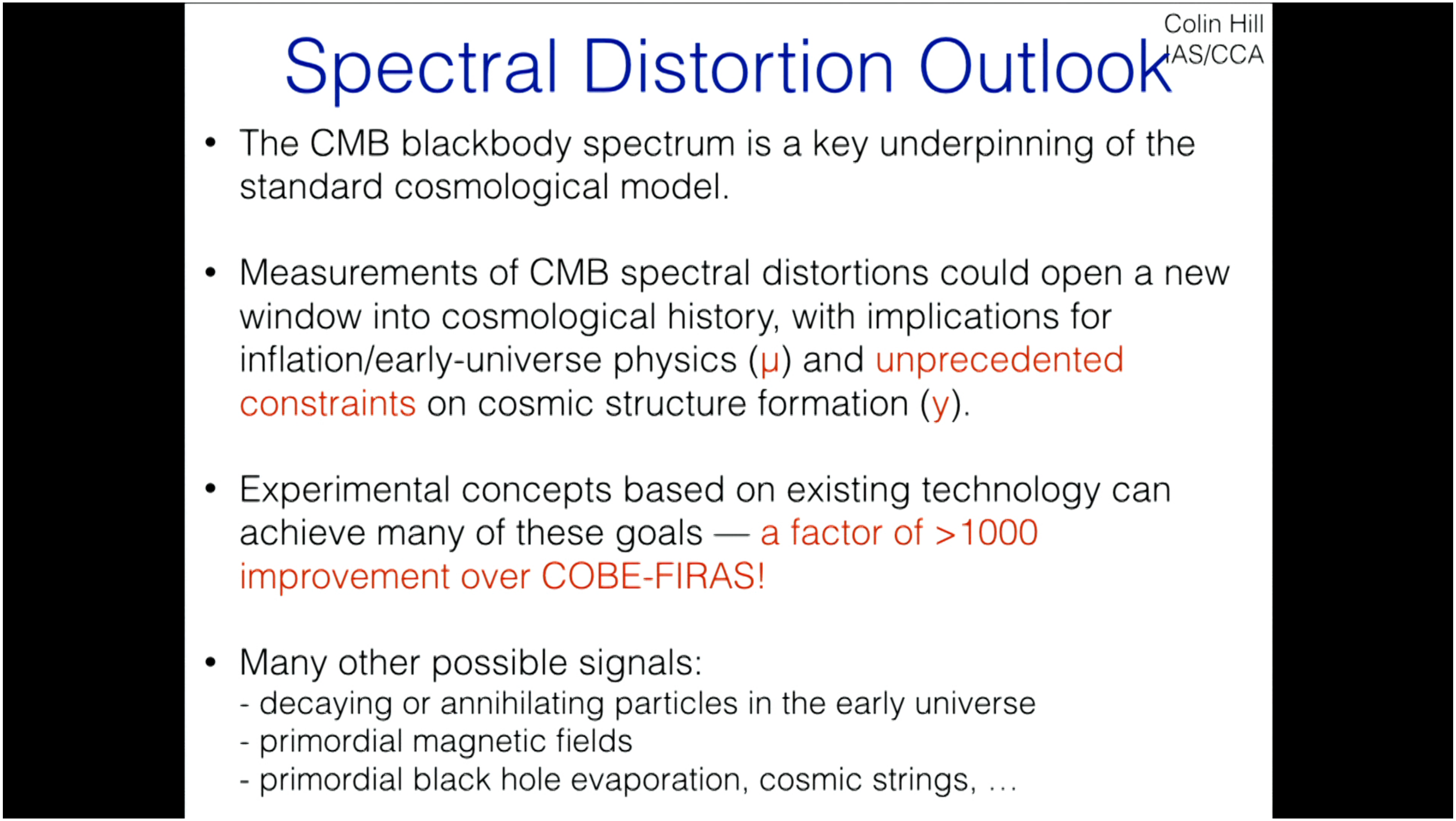
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Spectral Distortion Outlook
• The CMB blackbody spectrum is a key underpinning of the standard cosmological model.
• Measurements of CMB spectral distortions could open a new window into cosmological history, with implications for inflation/early-universe physics (μ) and unprecedented constraints on cosmic structure formation (y).
• Experimental concepts based on existing technology can achieve many of these goals — a factor of >1000 improvement over COBE-FIRAS!
• Many other possible signals:
- decaying or annihilating particles in the early universe
- primordial magnetic fields
- primordial black hole evaporation, cosmic strings, …

Dissipation of Small-Scale Modes

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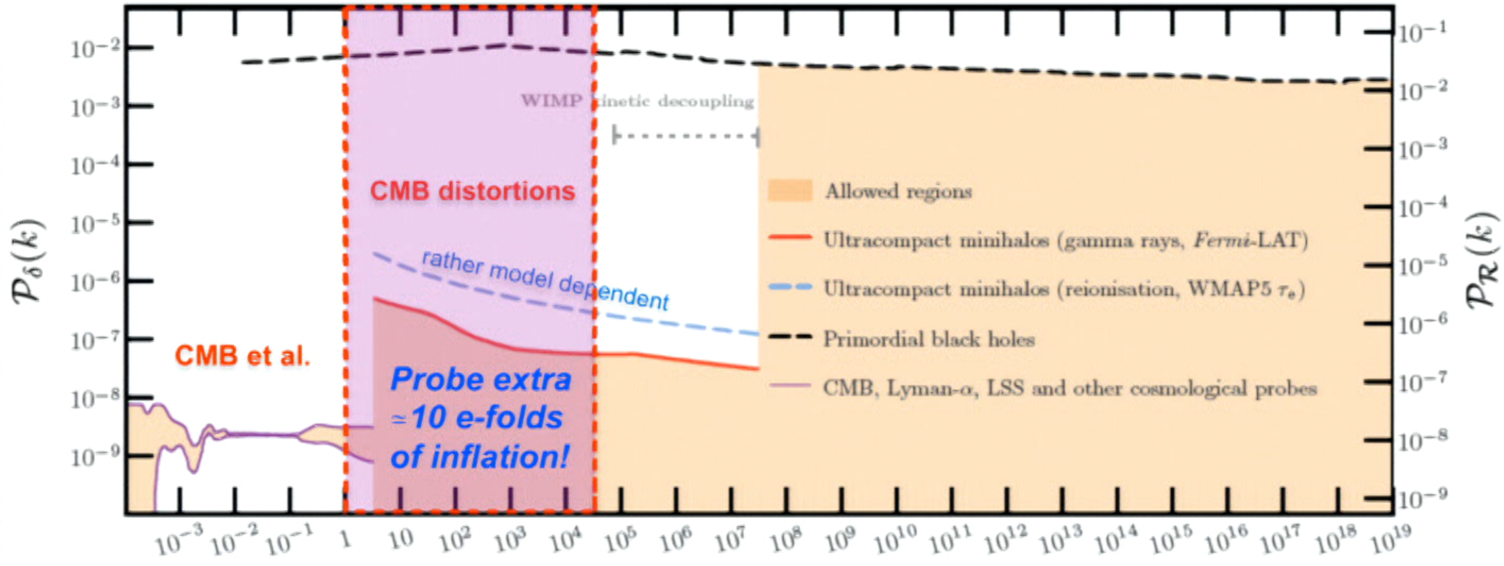

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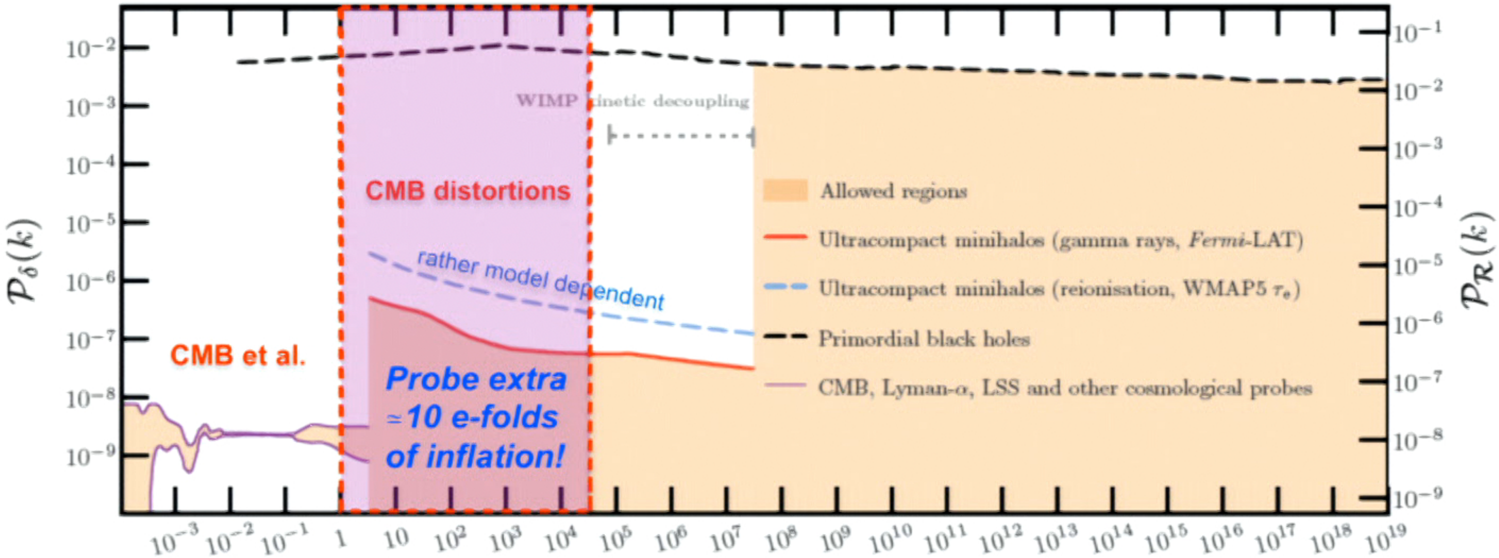

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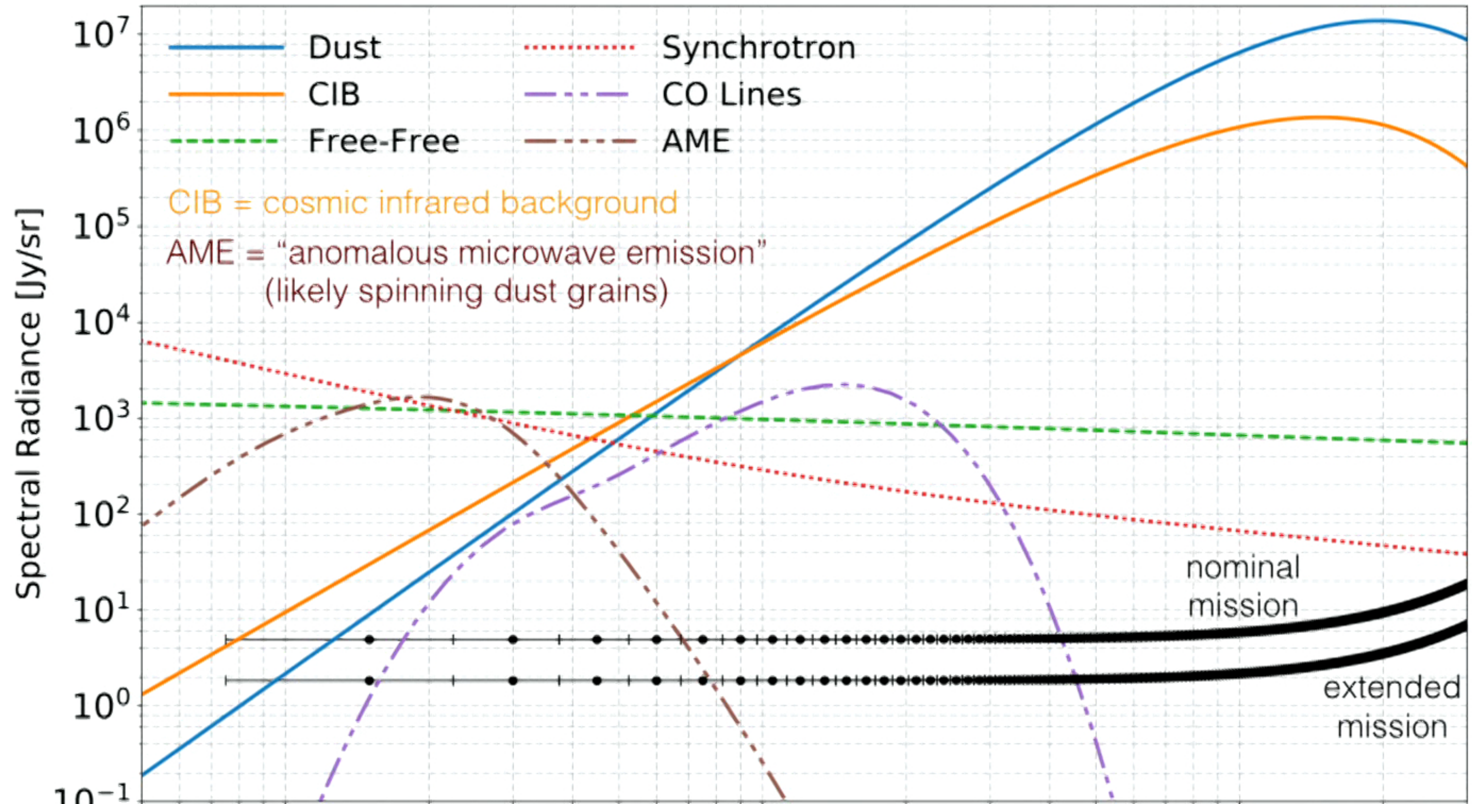
PIXIE: foregrounds



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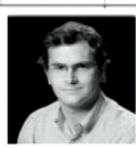

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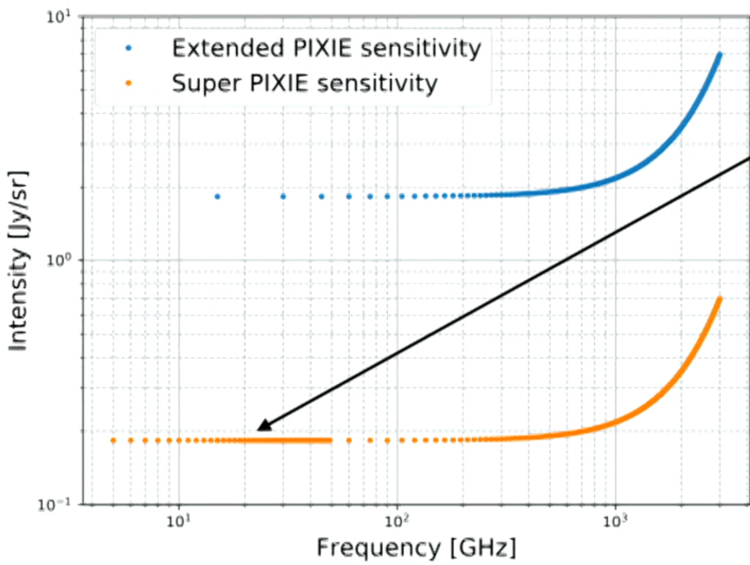

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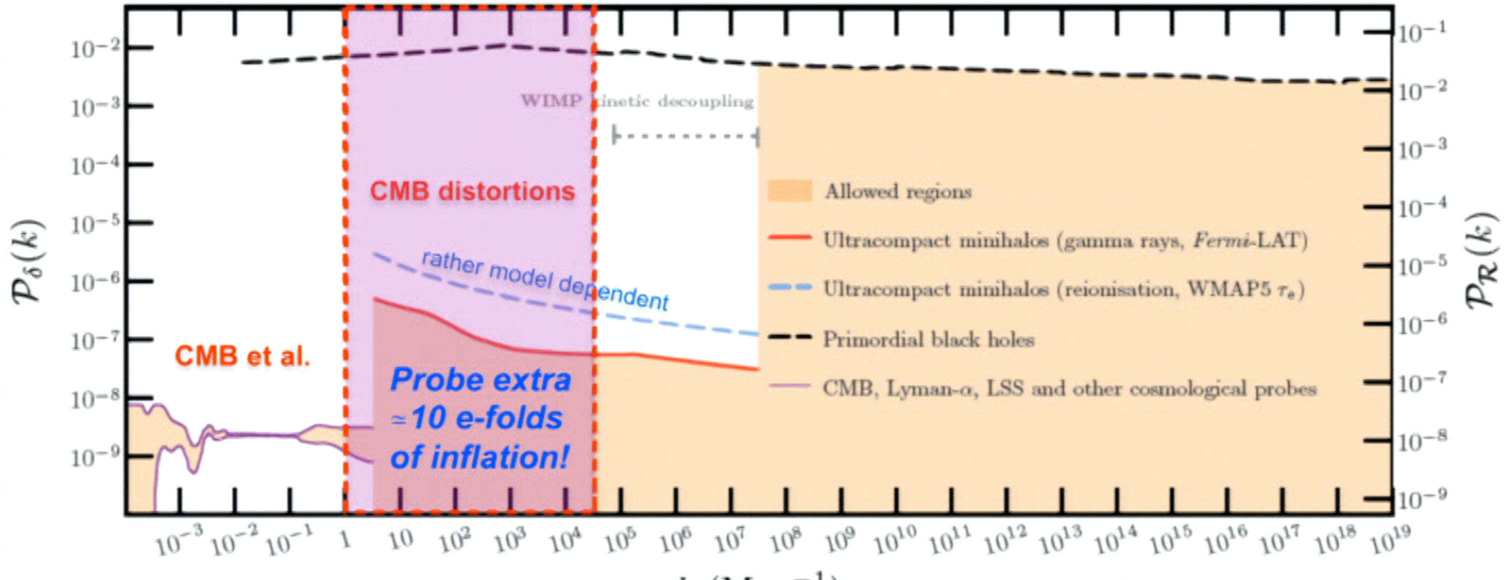

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