CMB secondary anisotropies and synergies with LSS probes

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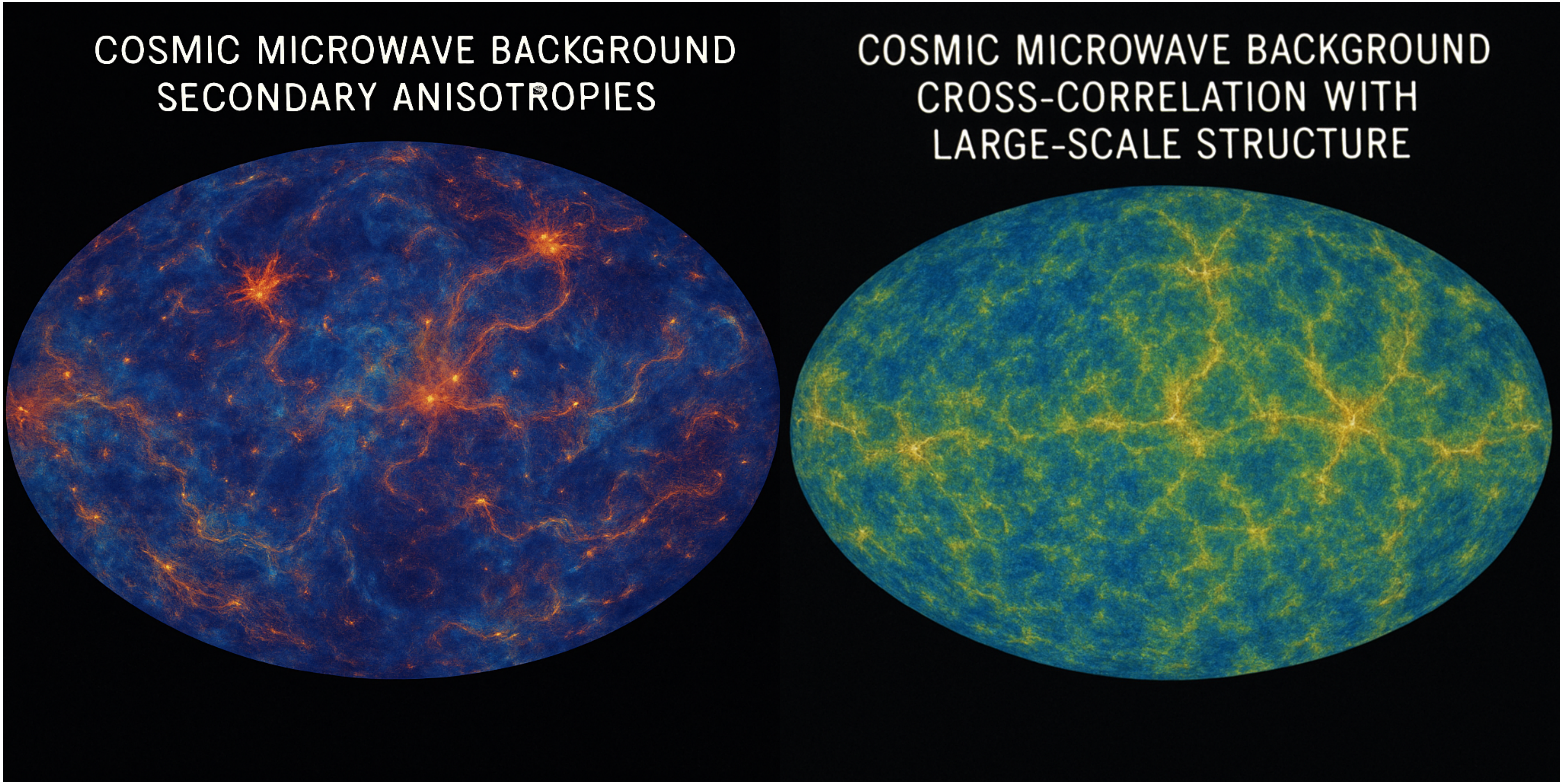
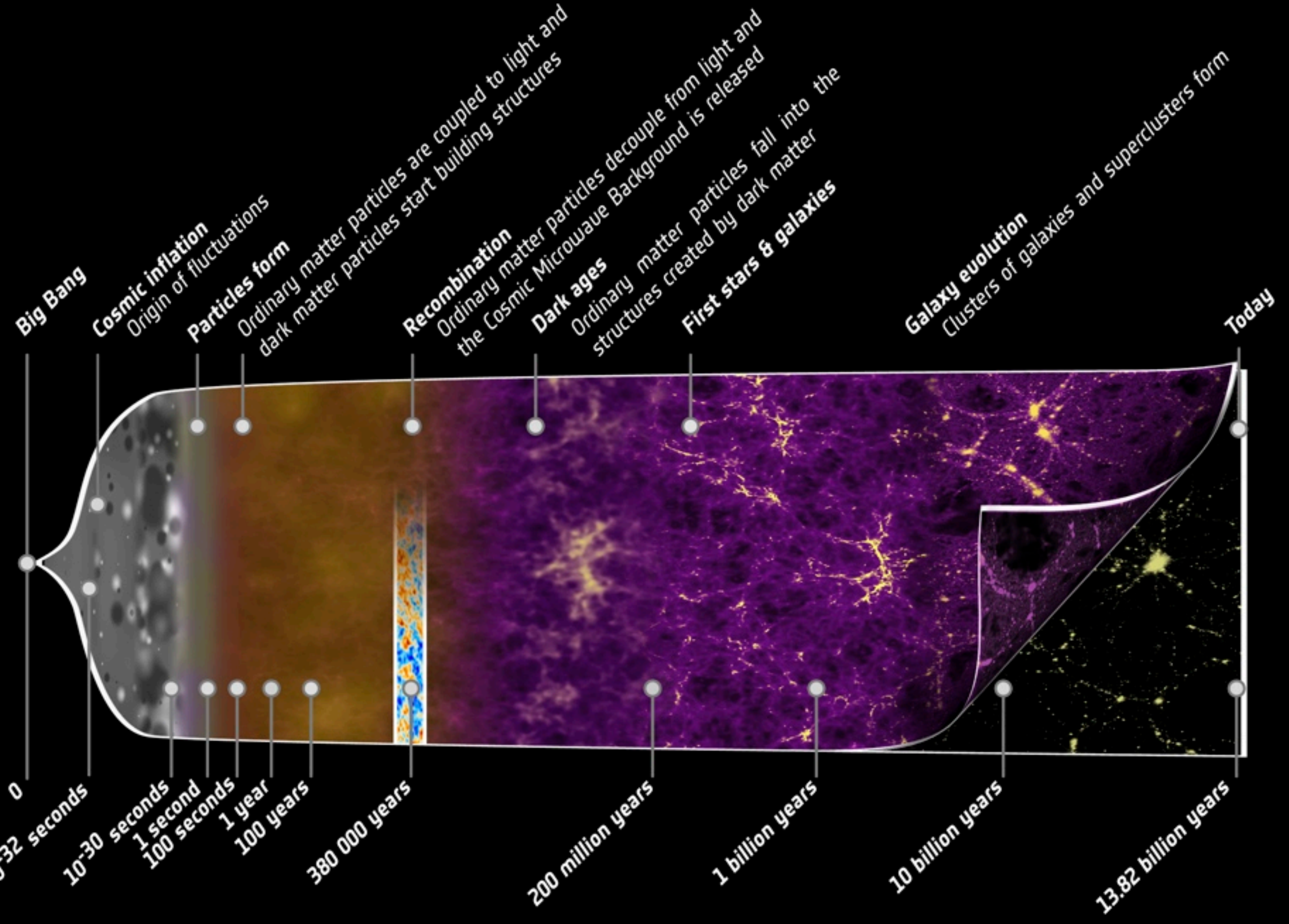
Outline (by ChatGPT)



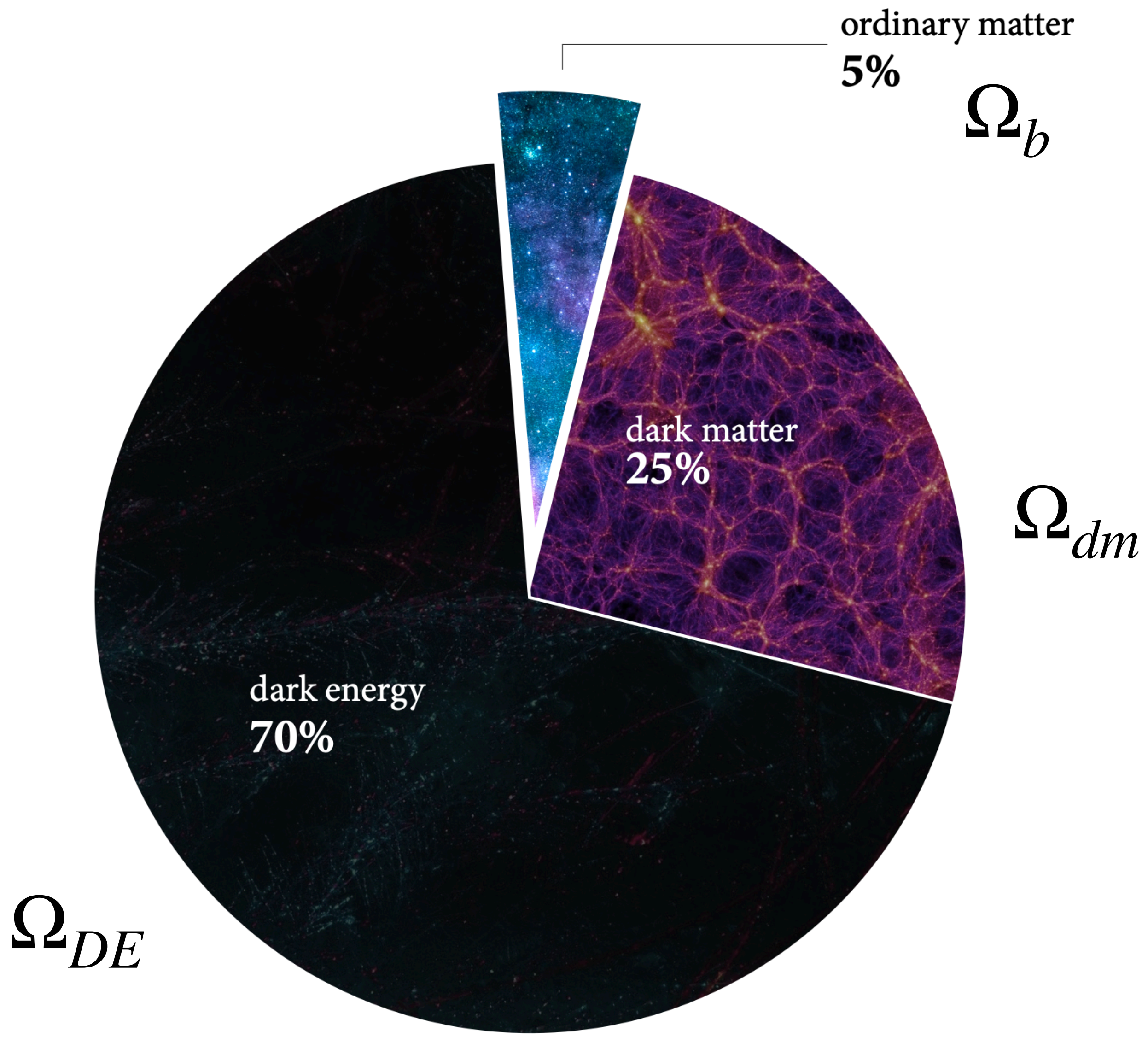
Outline (optimistic)

- Few practical concepts on experimental CMB.
- Secondary anisotropies
  - Deep dive on CMB lensing…
    - Quadratic estimators…
    - Cross-correlation with large-scale structure
    - Delensing: synergies between LSS, CMB and primordial universe.
  - Thermal and kinetic Sunyaev Zeldovich
  - Integrated Sachs-Wolfe and CIB if time

The Universe as we know it

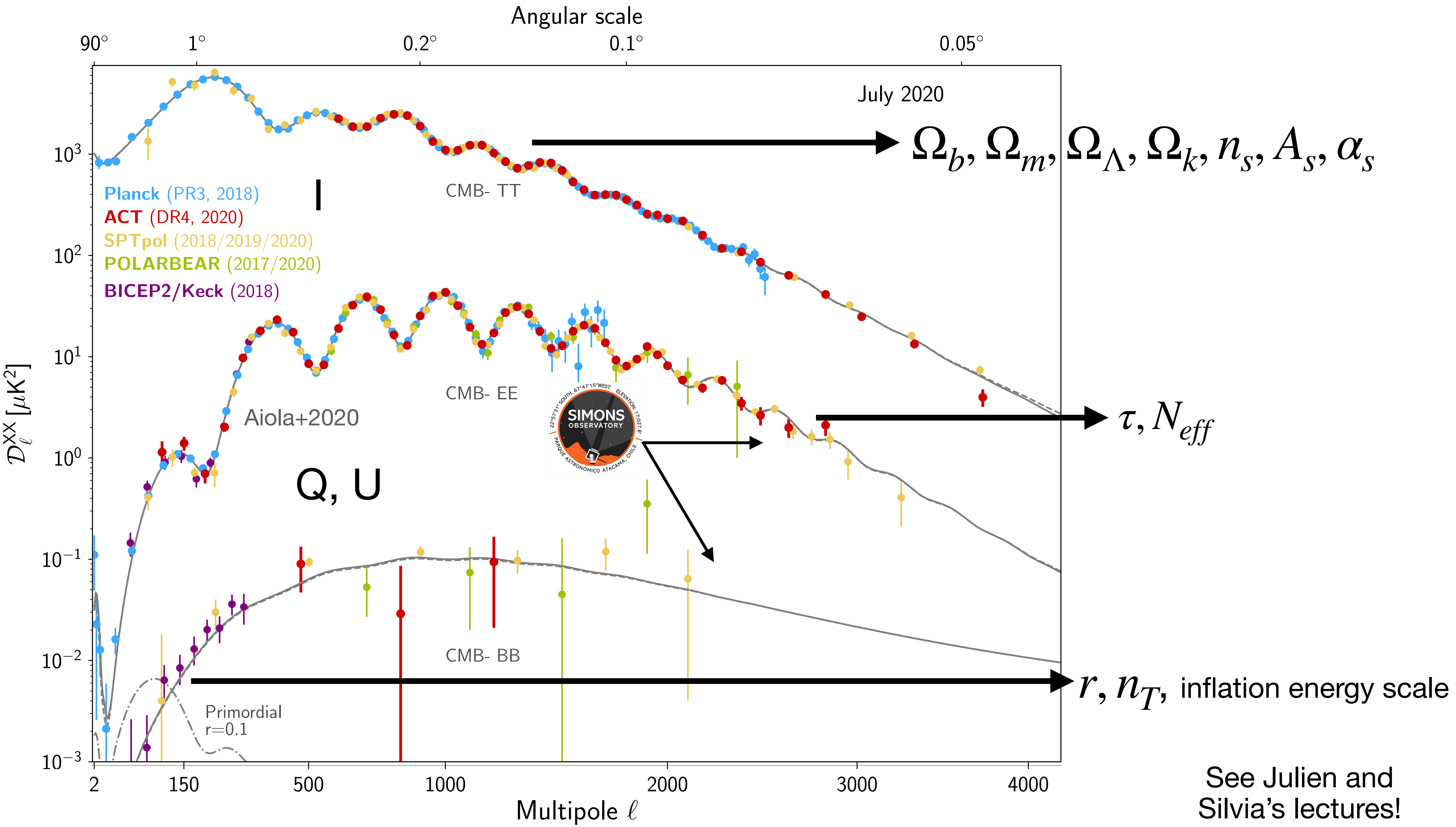


Open questions in cosmology as of 2025



- What is dark matter? Do **massive neutrinos** contribute?
- What is the nature of **dark energy**? Is General Relativity correct?
- Which mechanism drove primordial **inflation**?

Cosmological probes: CMB

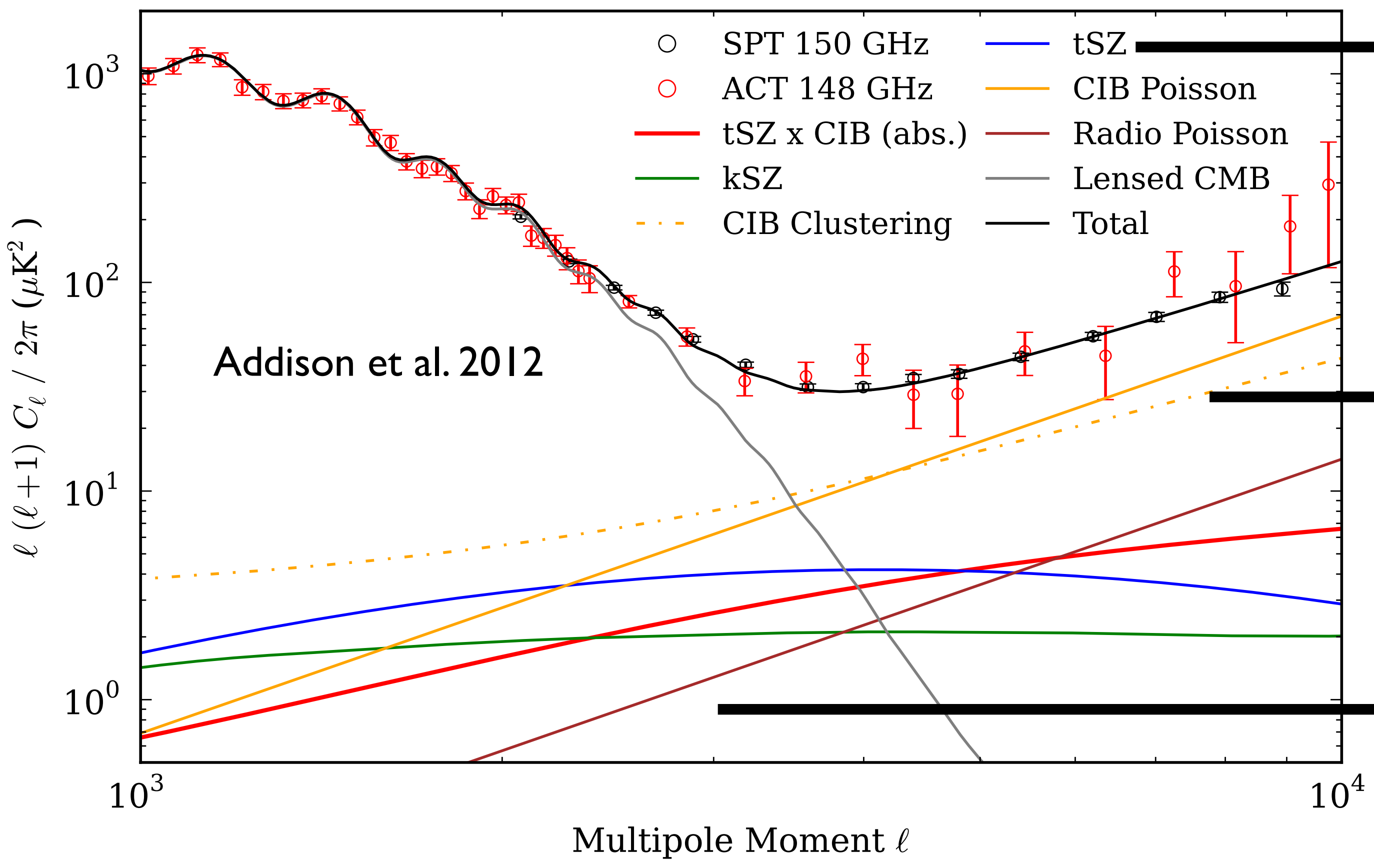


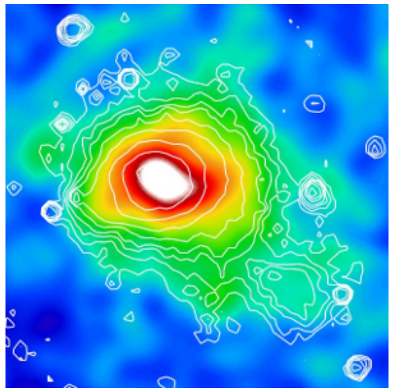
See Julien and Silvia's lectures!

- Also improvements on $\sum m_\nu$ and others from new polarization measurements.

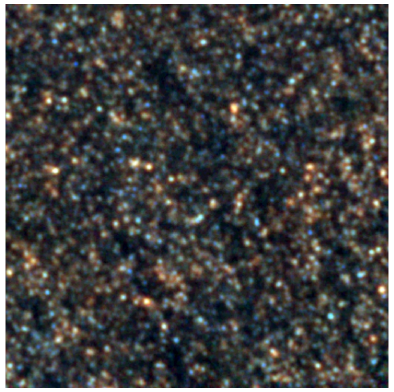
Is CMB “the” CMB?

- CMB is a snapshot of the universe at z ~1100.... plus lots of other things!
  - Imprint of astrophysical emissions (galactic / extragalactic…)
  - Late time physics (e.g. Integrated Sachs-Wolfe effect, **weak lensing**)

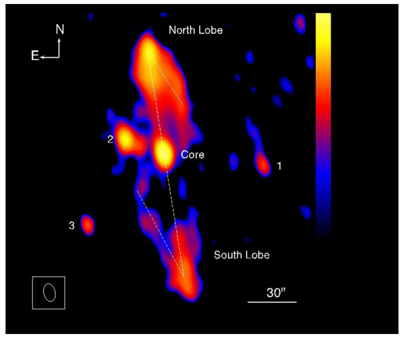




- ICM (g)astrophysics, cosmology (**SZ**)

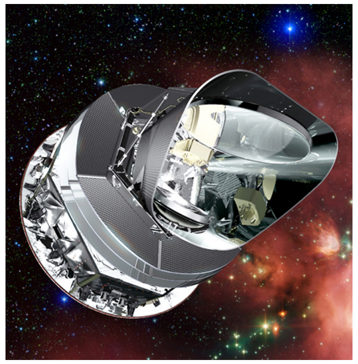


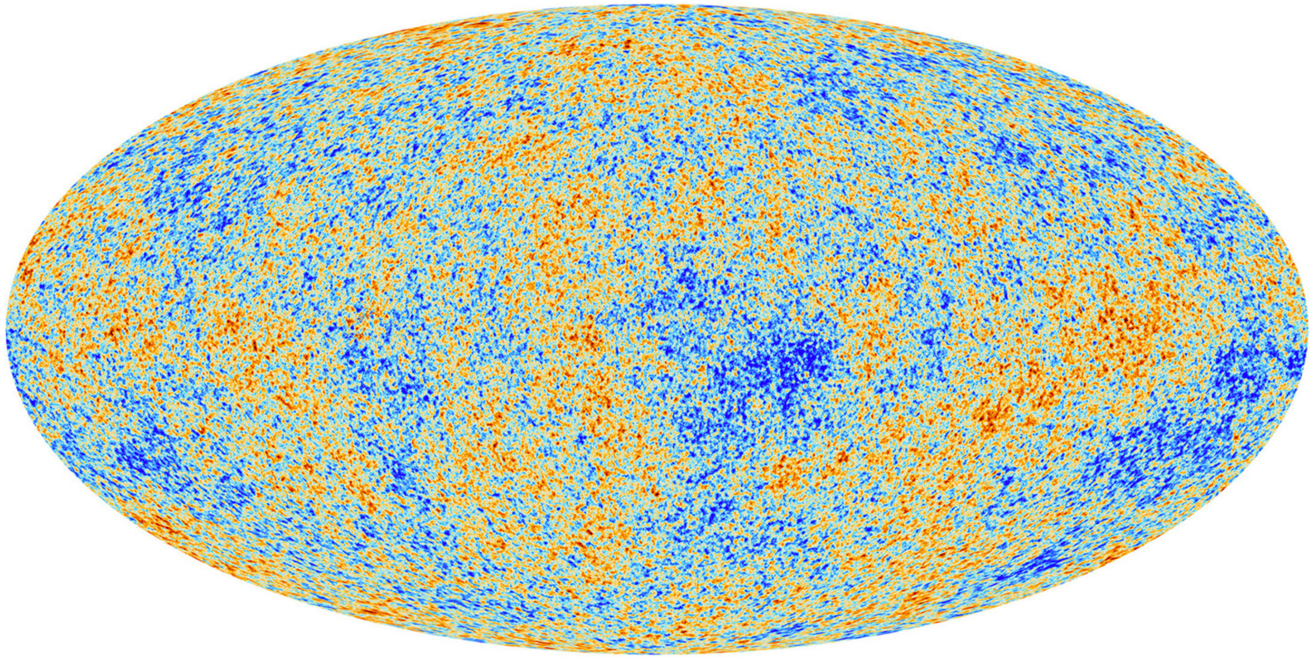
- Star formation, cosmology (CIB)

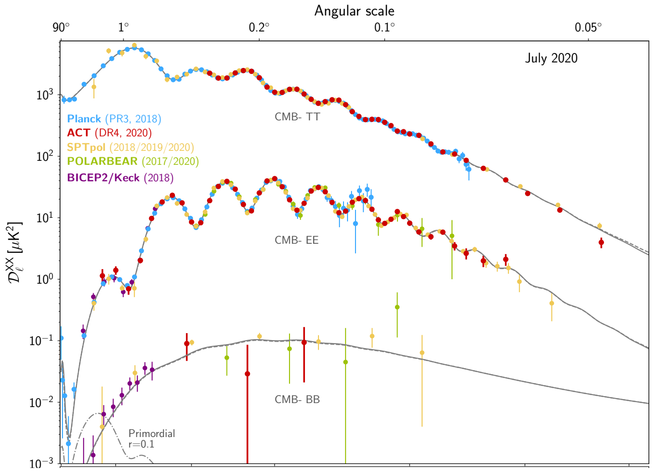


- Extragalactic astronomy, Galaxy evolution

CMB analysis chain

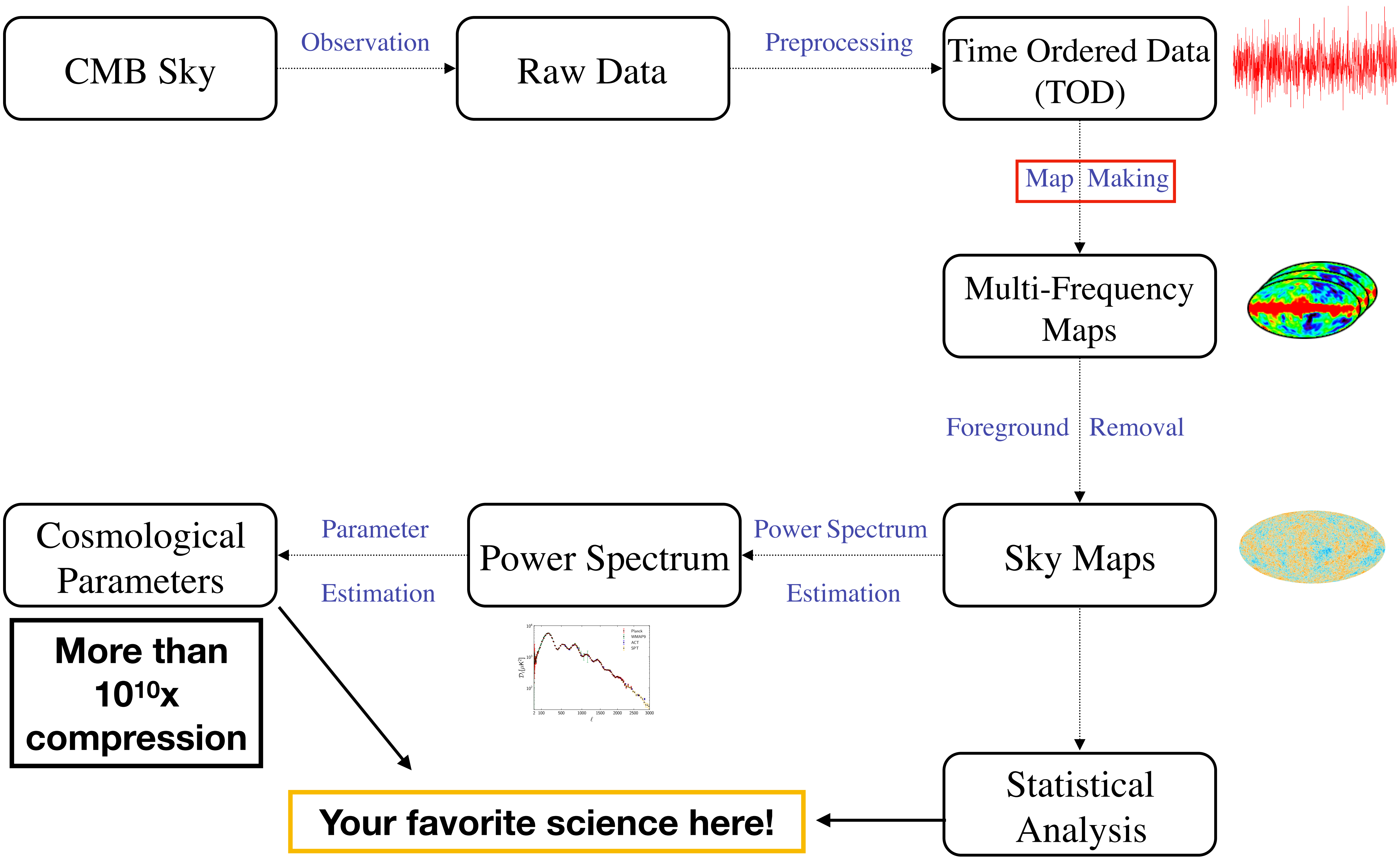




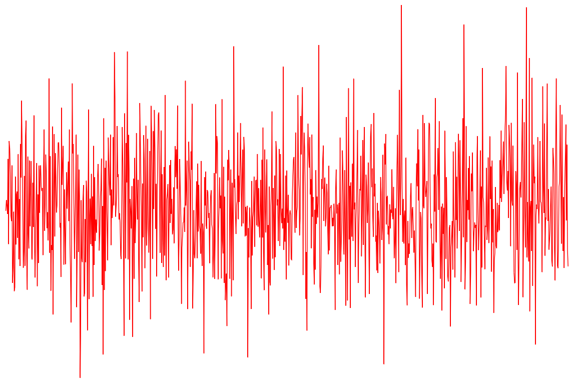
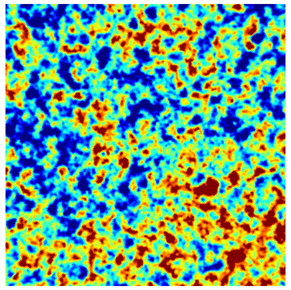
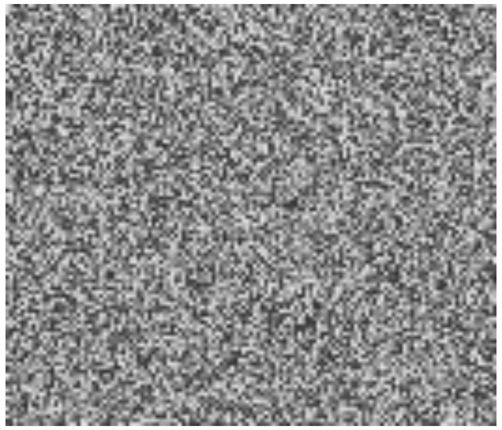


$$\Omega_b, \Omega_{cdm}, \Omega_\Lambda, \Omega_k, n_s, \sigma_8, \tau, \sum m_\nu, w, h, N_{eff} \ldots$$

CMB analysis chain: a radical compression



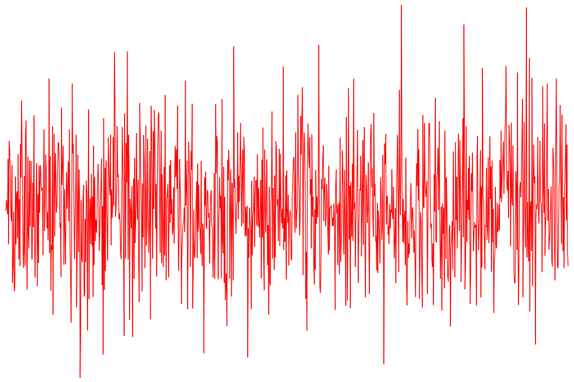
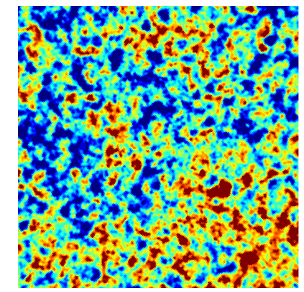
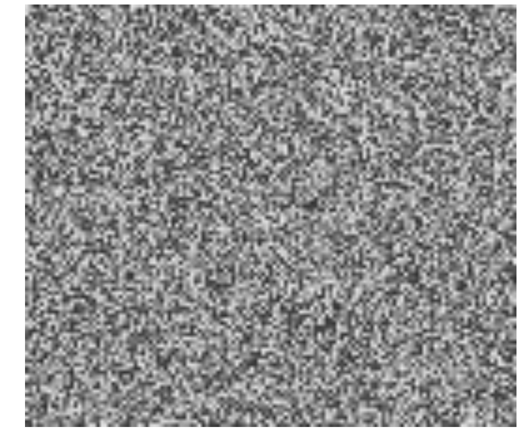
Mapmaking: the most challenging inverse problem

 =  () + 

$$d_t = I_{p_t} + \cos(2\varphi_t) Q_{p_t} + \sin(2\varphi_t) U_{p_t} + n_t$$

- n_t ← Noise contribution
- d_t: Samples of the TOD recorded at time *t*
- I_{p_t}, Q_{p_t}, U_{p_t}: Pixelized maps of the Stokes parameters
- φ_t: Orientation of the detector projected on the sky
- p_t: Sky pixel observed

Mapmaking: the most challenging inverse problem

 =  () + 

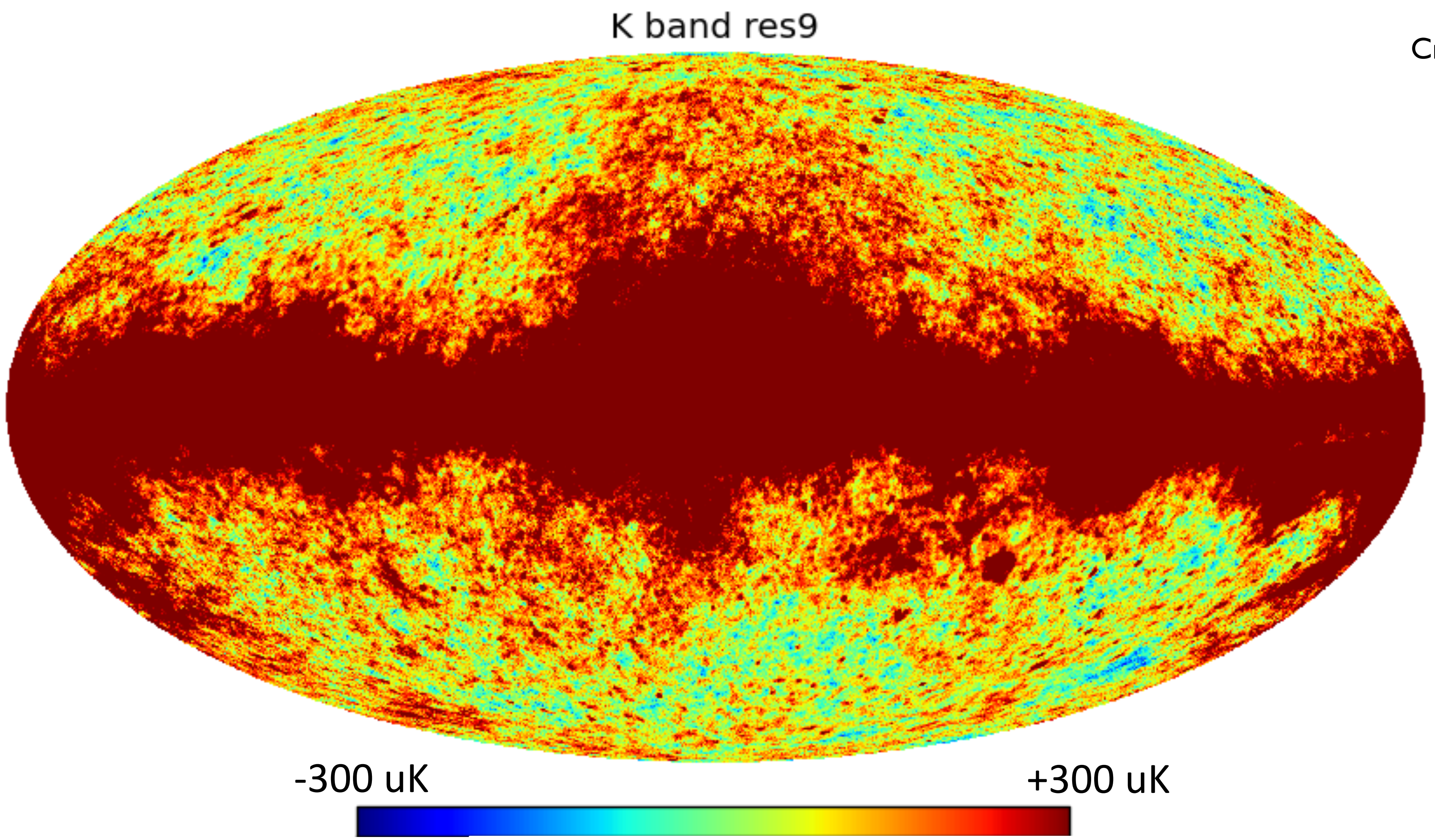
$$\mathbf{d} = \mathbf{A} \cdot \mathbf{s} + \mathbf{n}$$

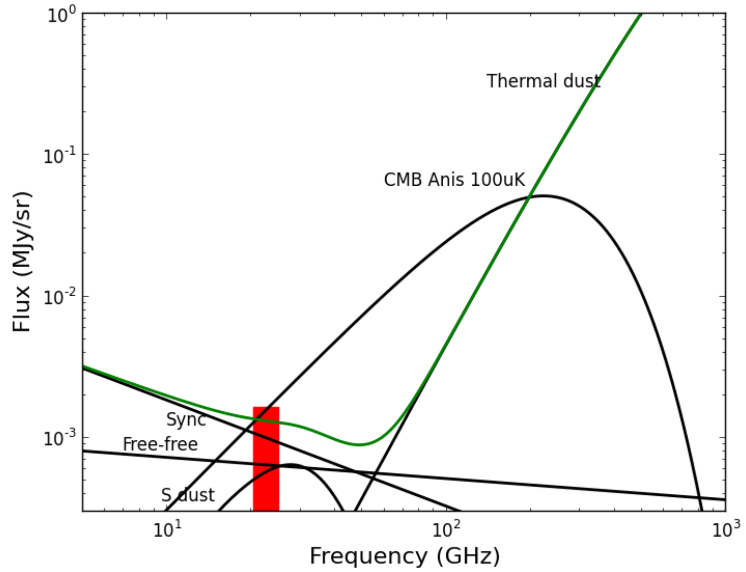
- Unbiased GLS solution $\hat{\mathbf{s}} = (\mathbf{A}^{\mathsf{T}}\mathbf{N}^{-1}\mathbf{A})^{-1}\mathbf{A}^{\mathsf{T}}\mathbf{N}^{-1}\mathbf{d}$ $\quad \mathbf{N} \equiv \langle \mathbf{n}^{\mathsf{T}}\mathbf{n} \rangle$
- Challenging, advanced algebraic techniques mandatory $\mathcal{N}_p = 10^6 \quad \mathcal{N}_t = 10^{12}$

$$\hat{\mathbf{s}} = \boxed{\mathcal{N}_p \times \mathcal{N}_p} \bullet \boxed{\mathcal{N}_p \times \mathcal{N}_t} \bullet \boxed{\mathcal{N}_t \times \mathcal{N}_t} \bullet \boxed{\mathcal{N}_t}$$

The microwave sky

Credits: Lyman Page





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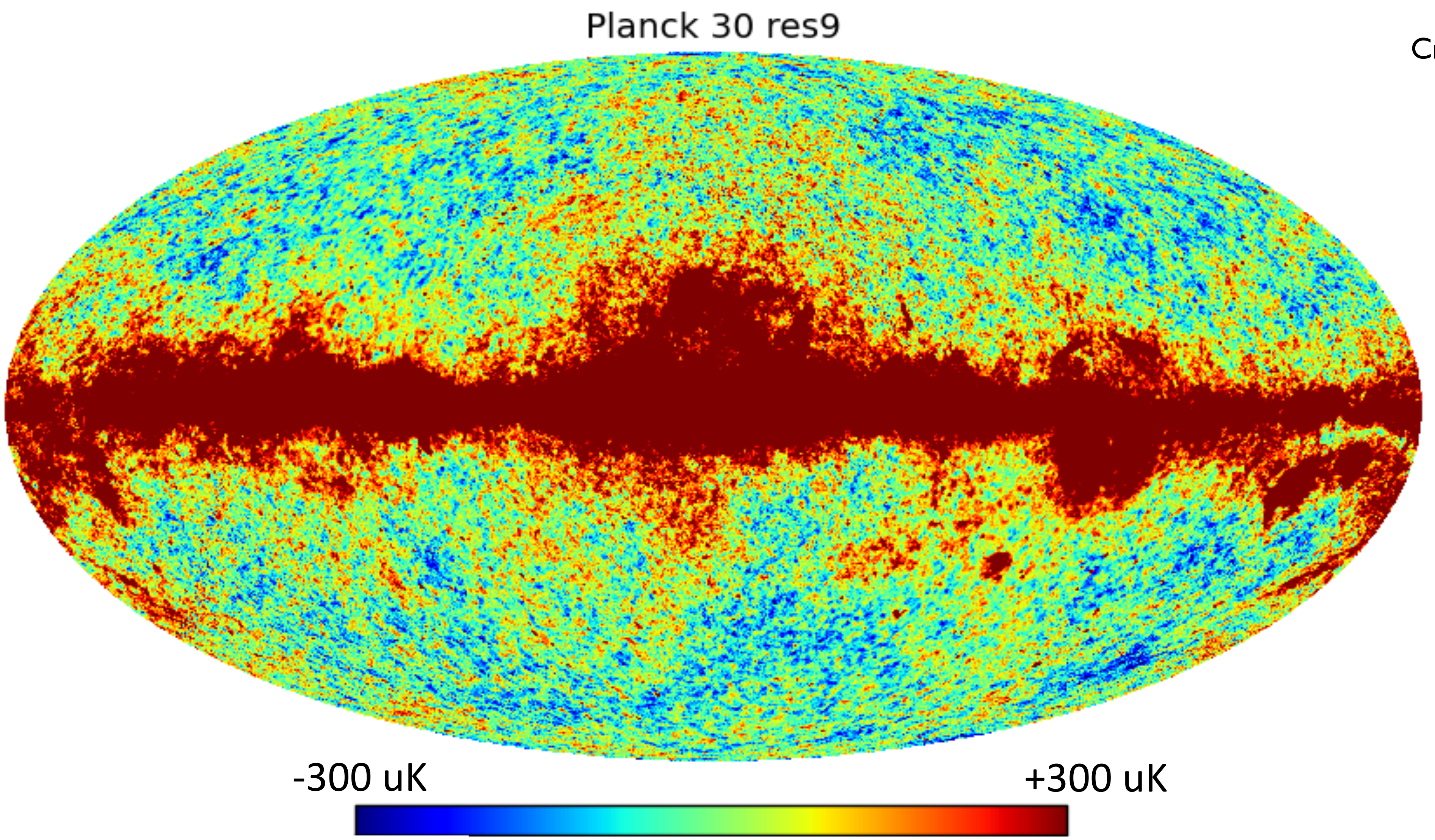

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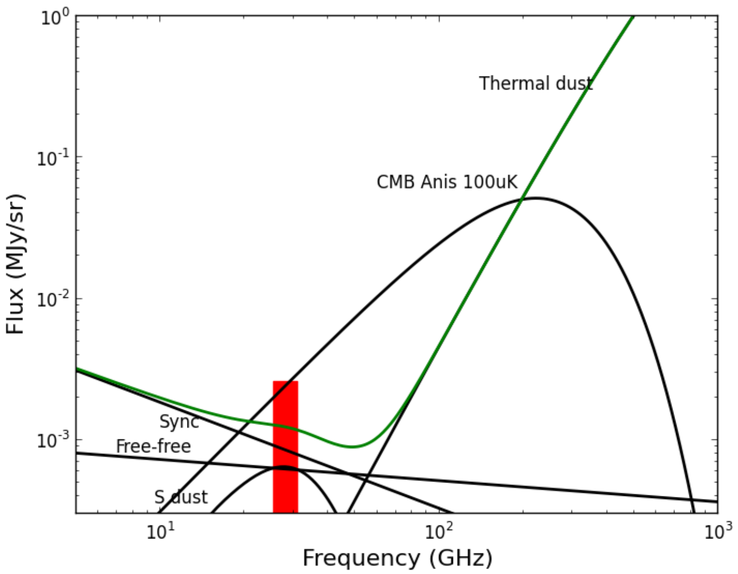

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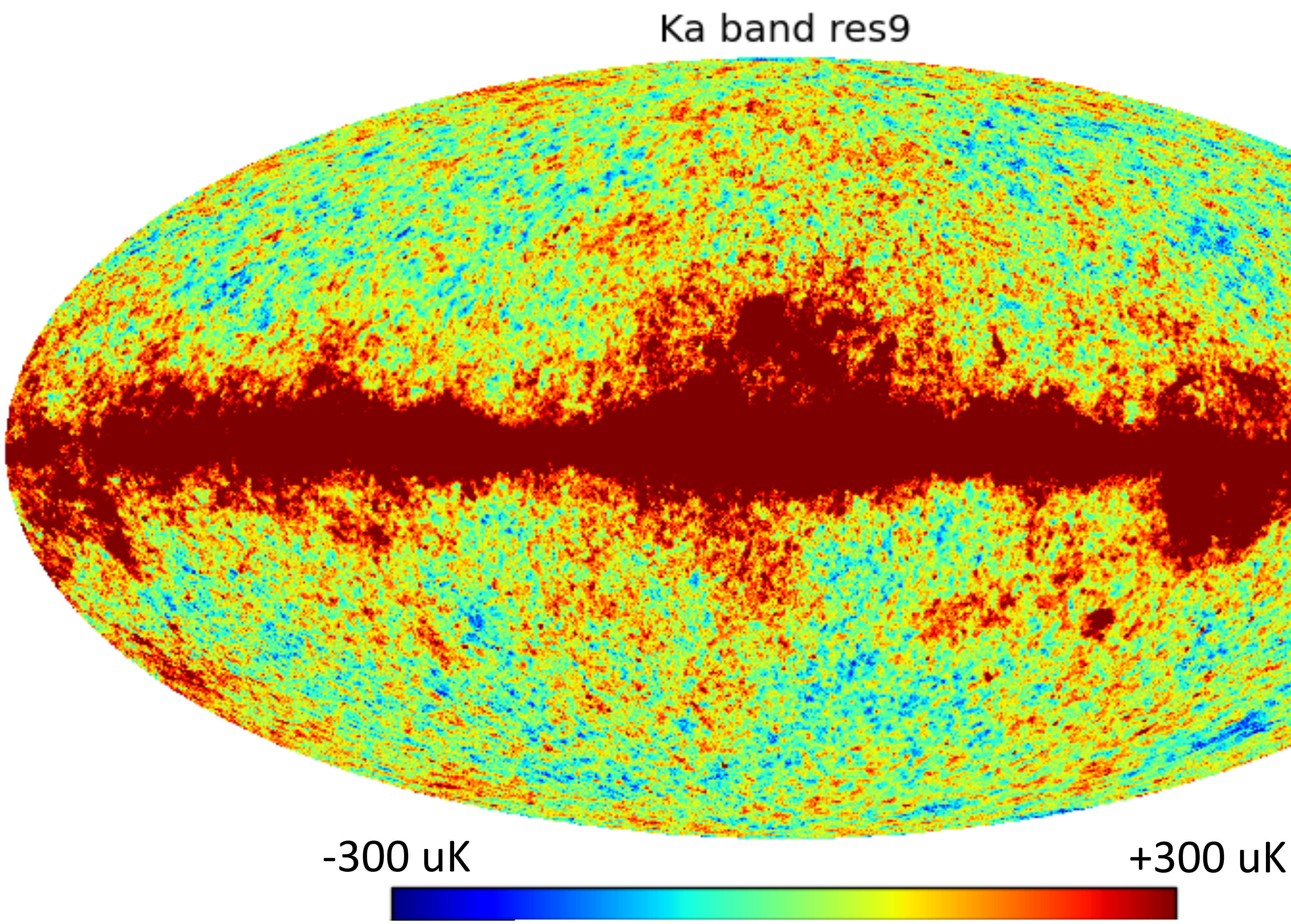

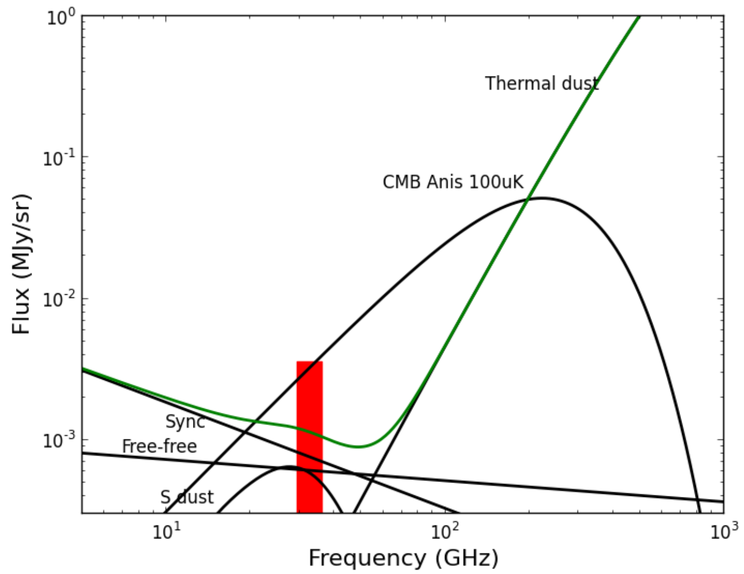

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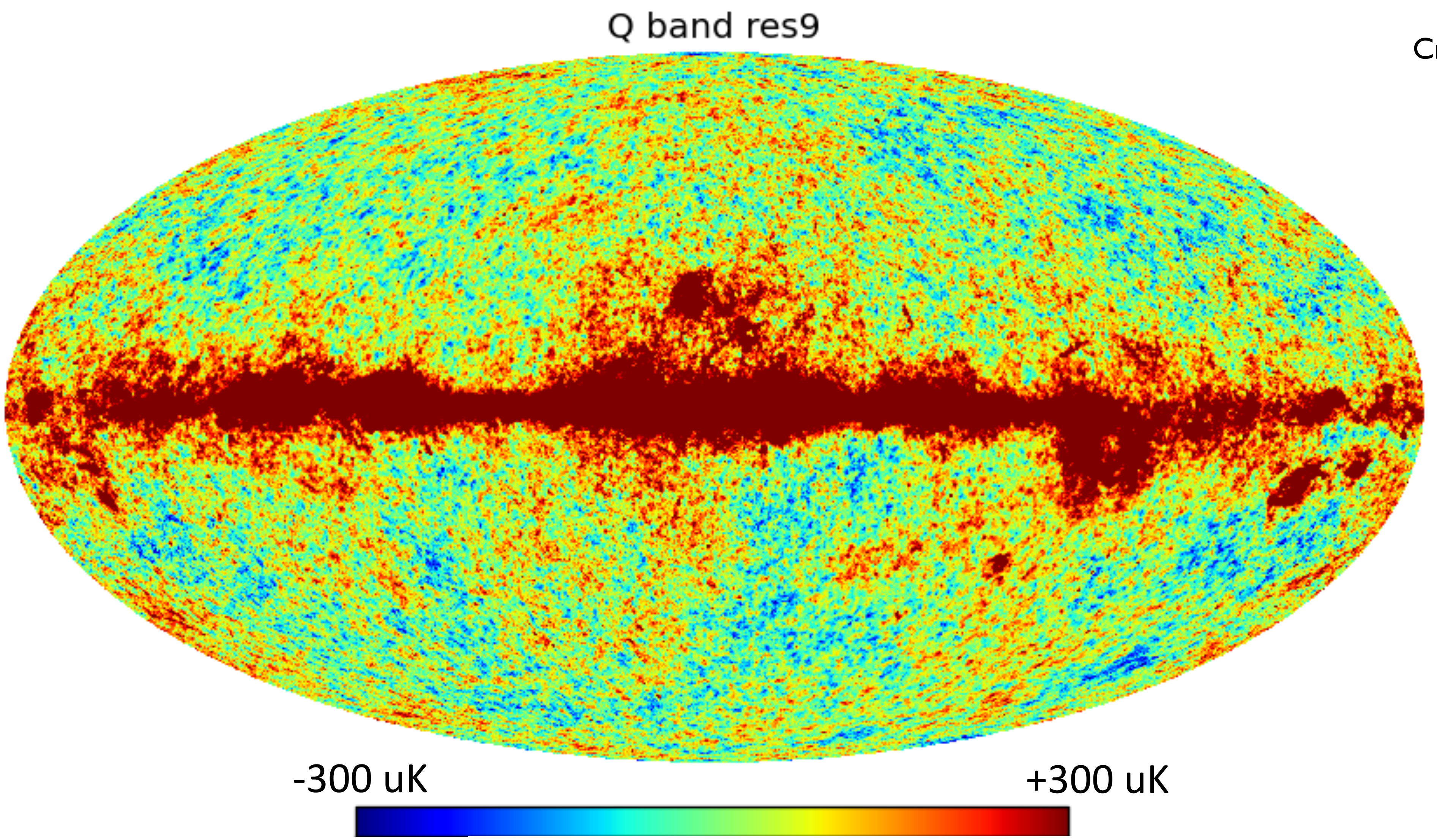

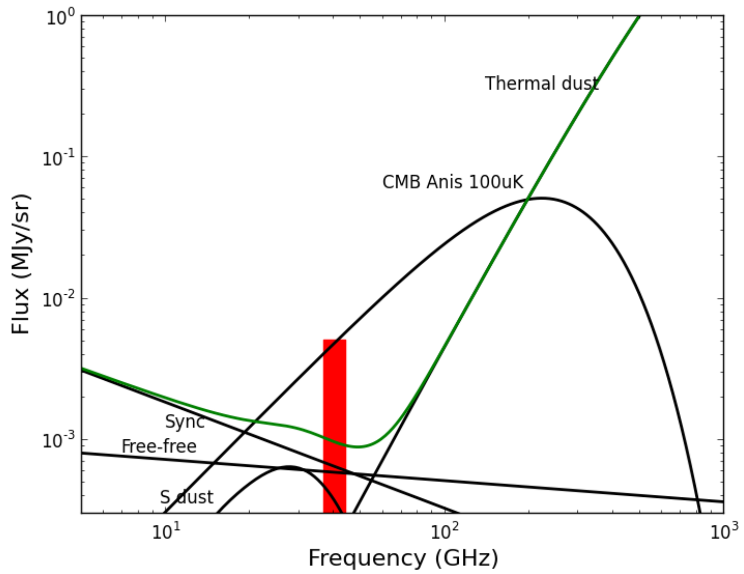

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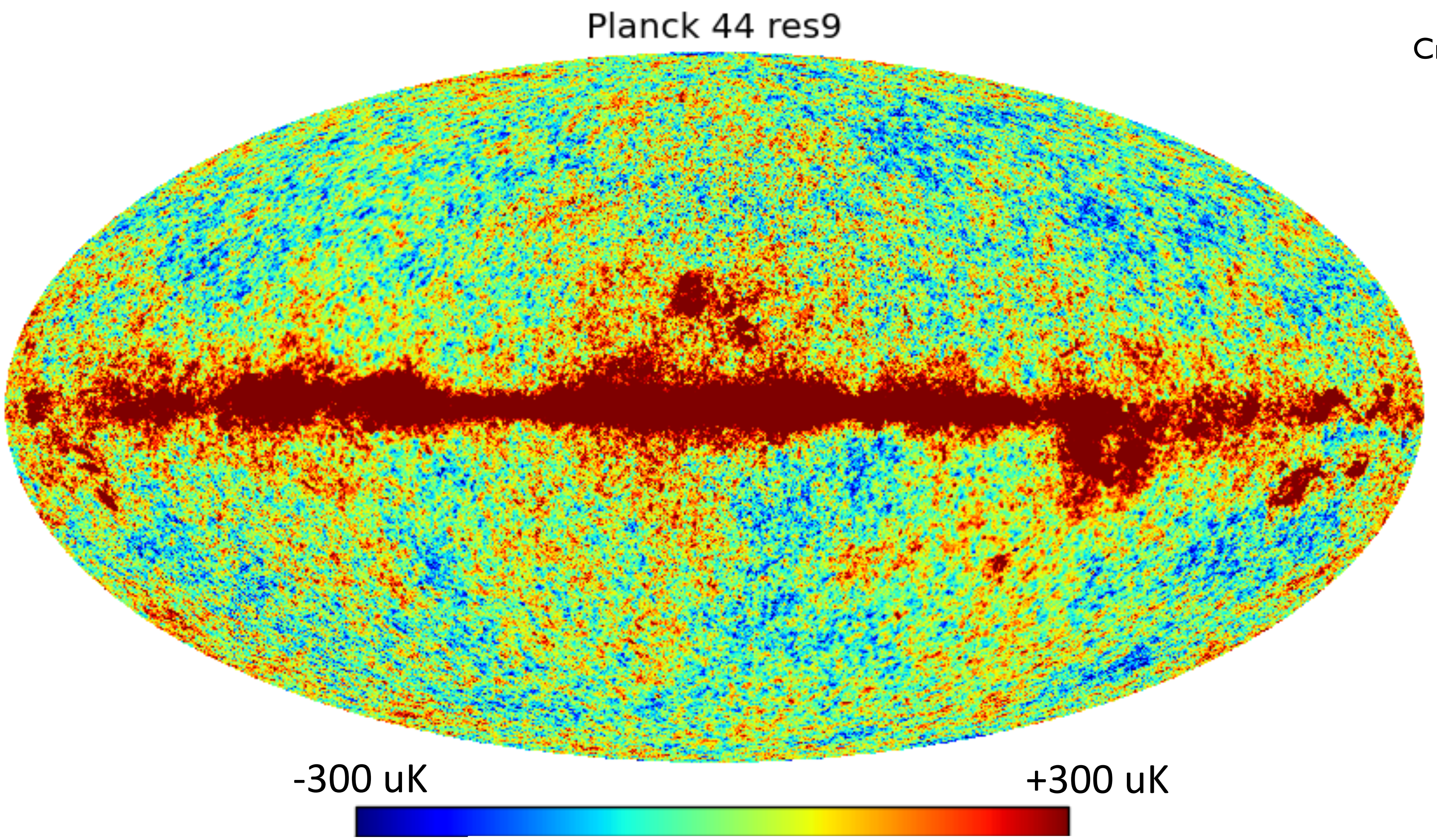

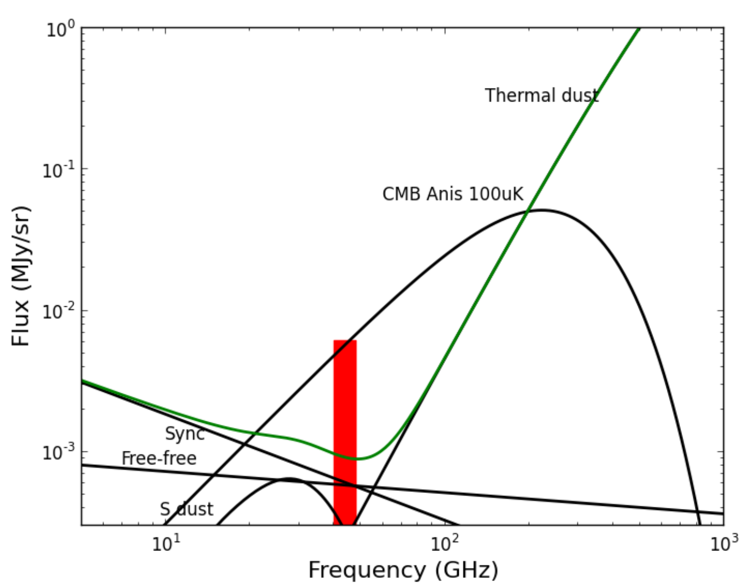

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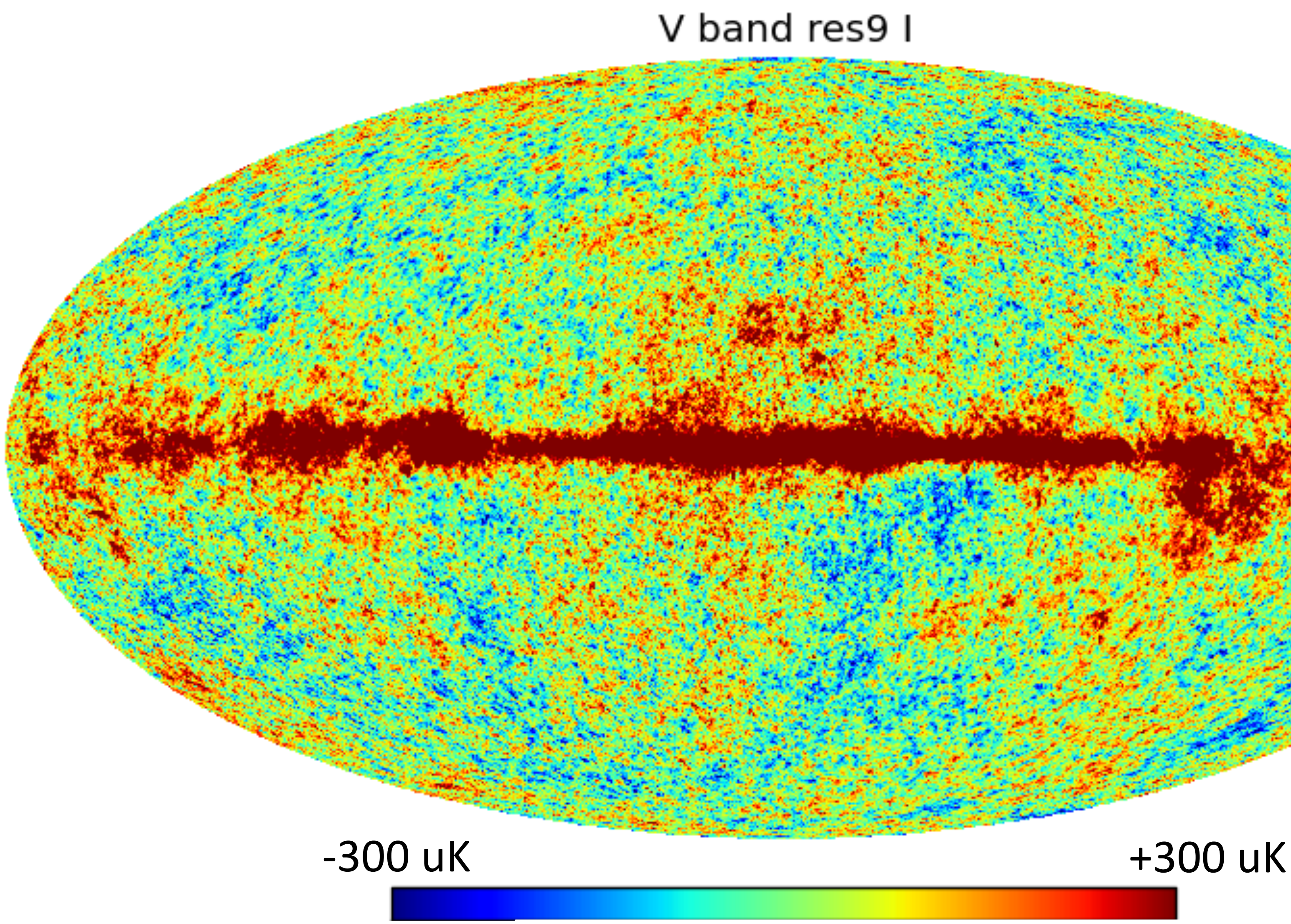

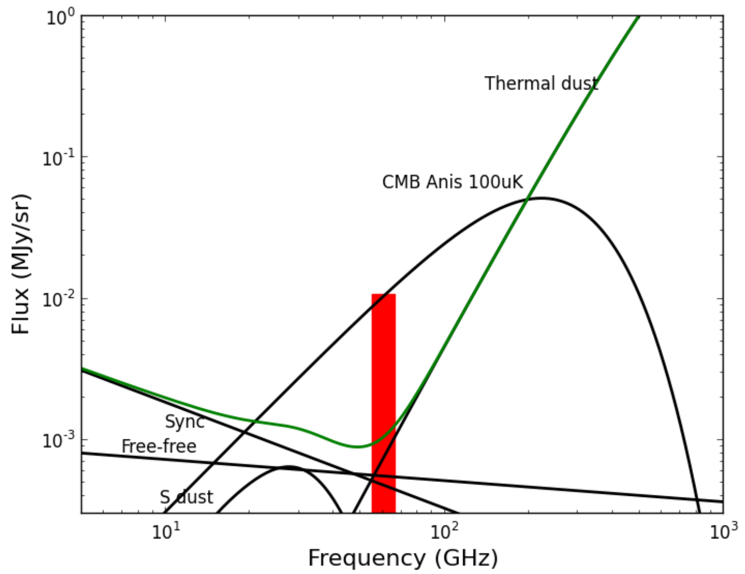

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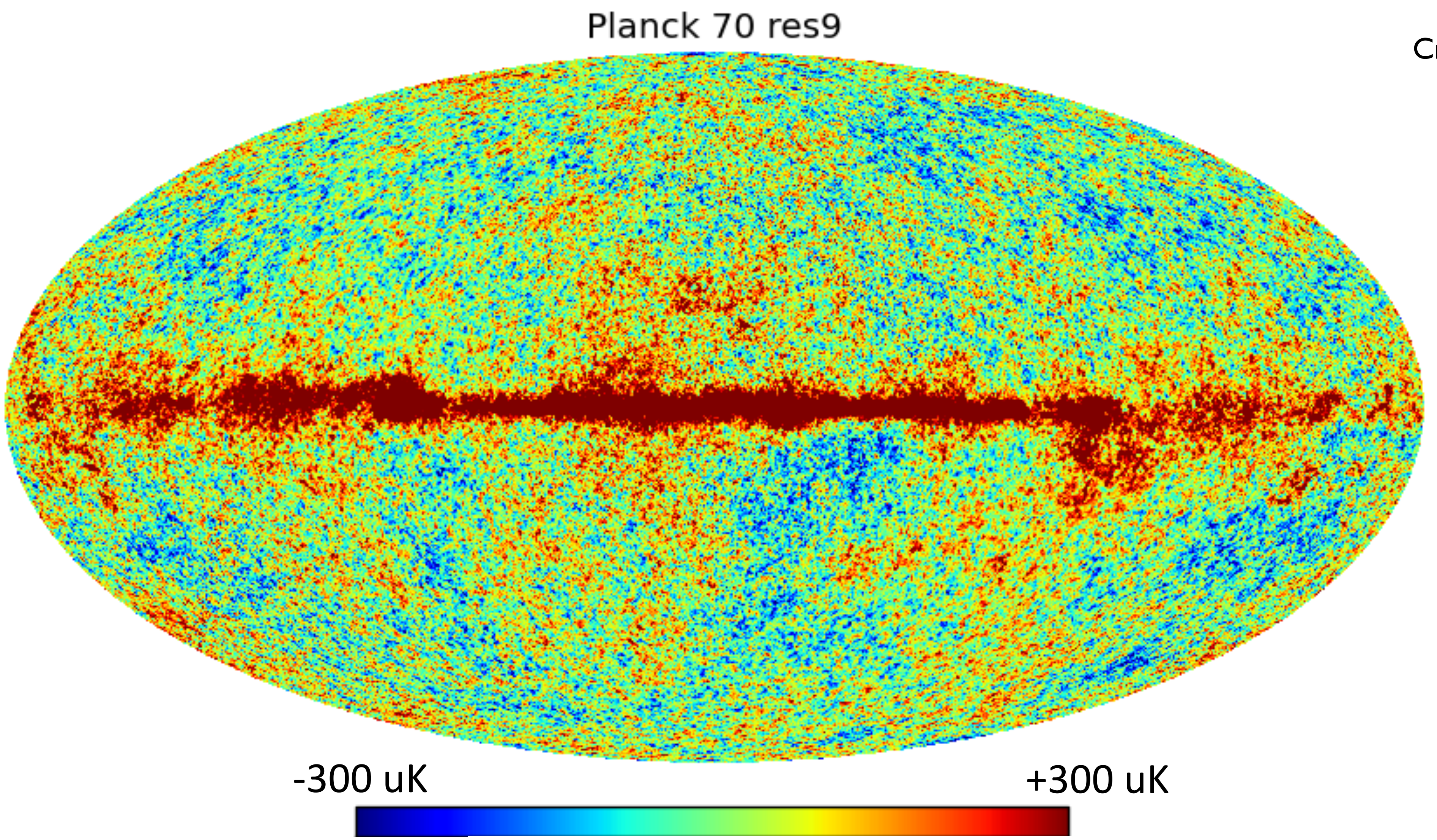

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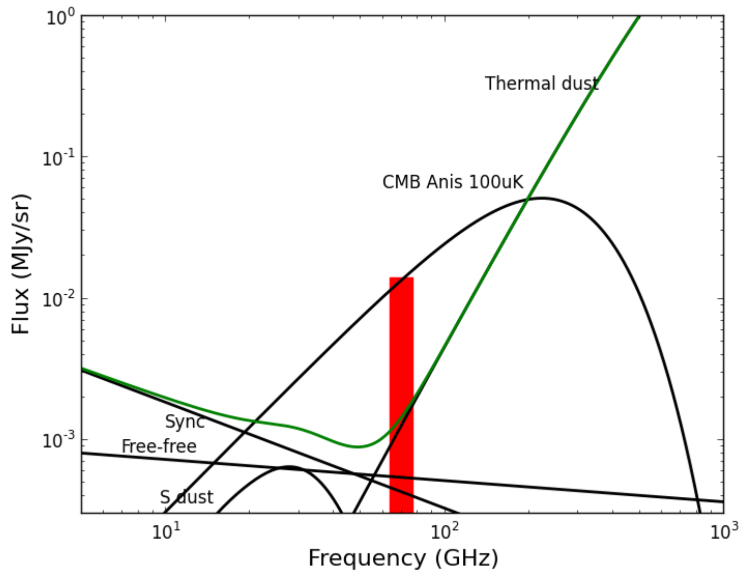

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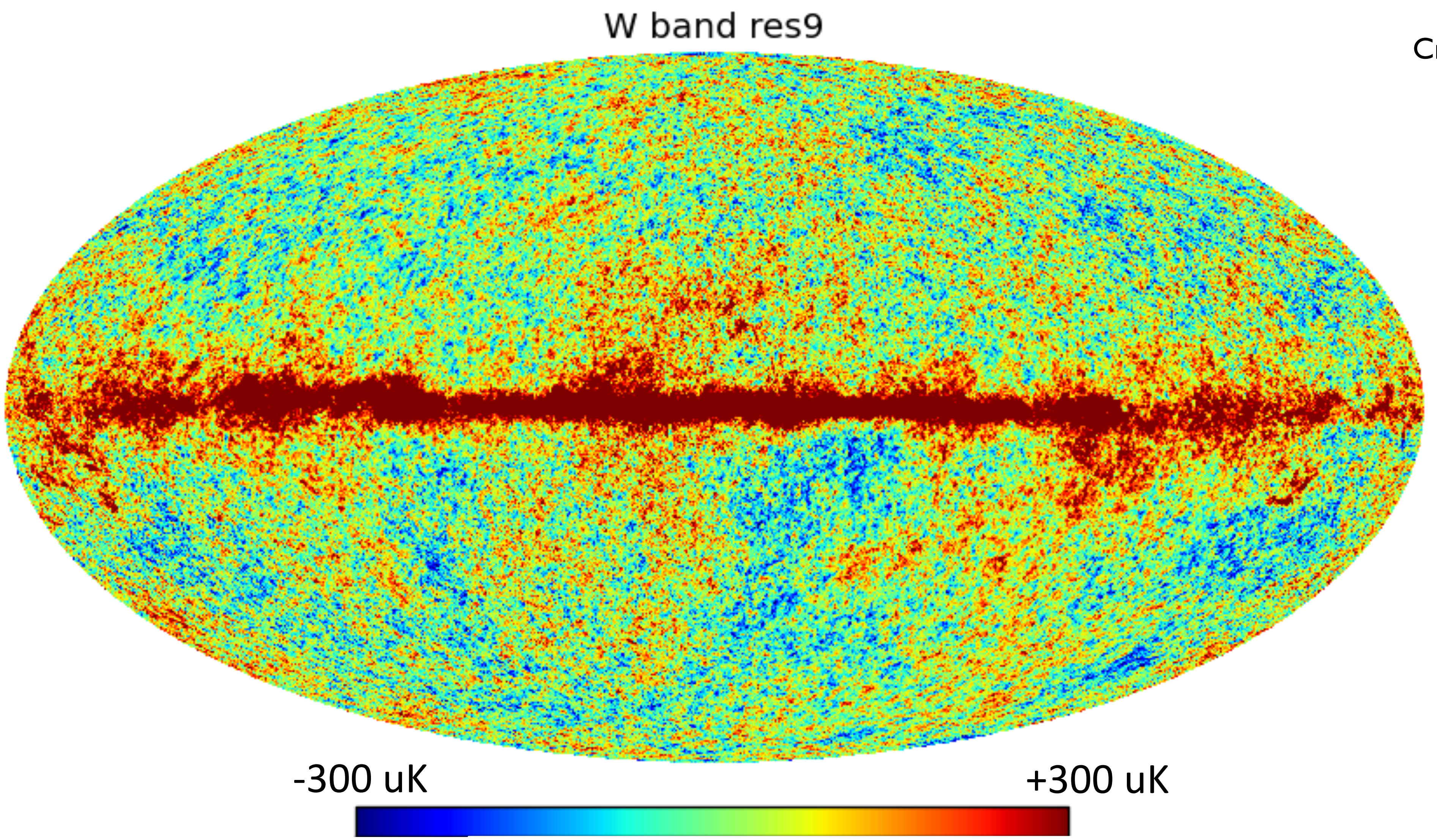

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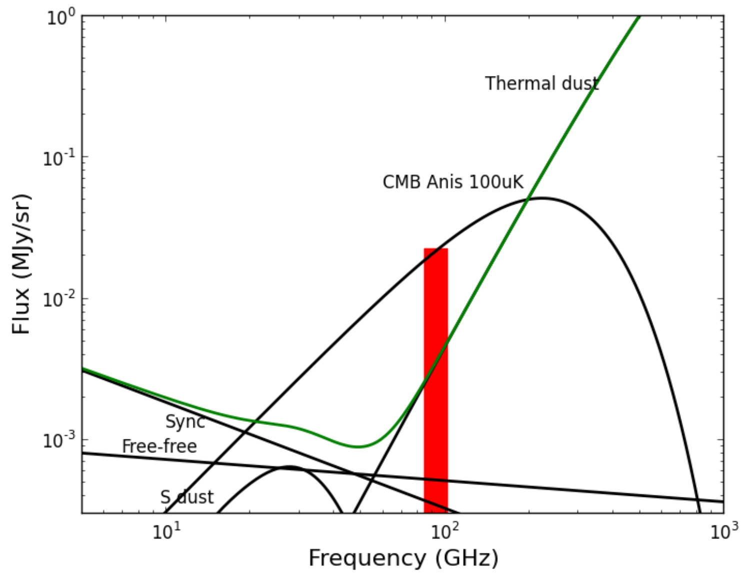

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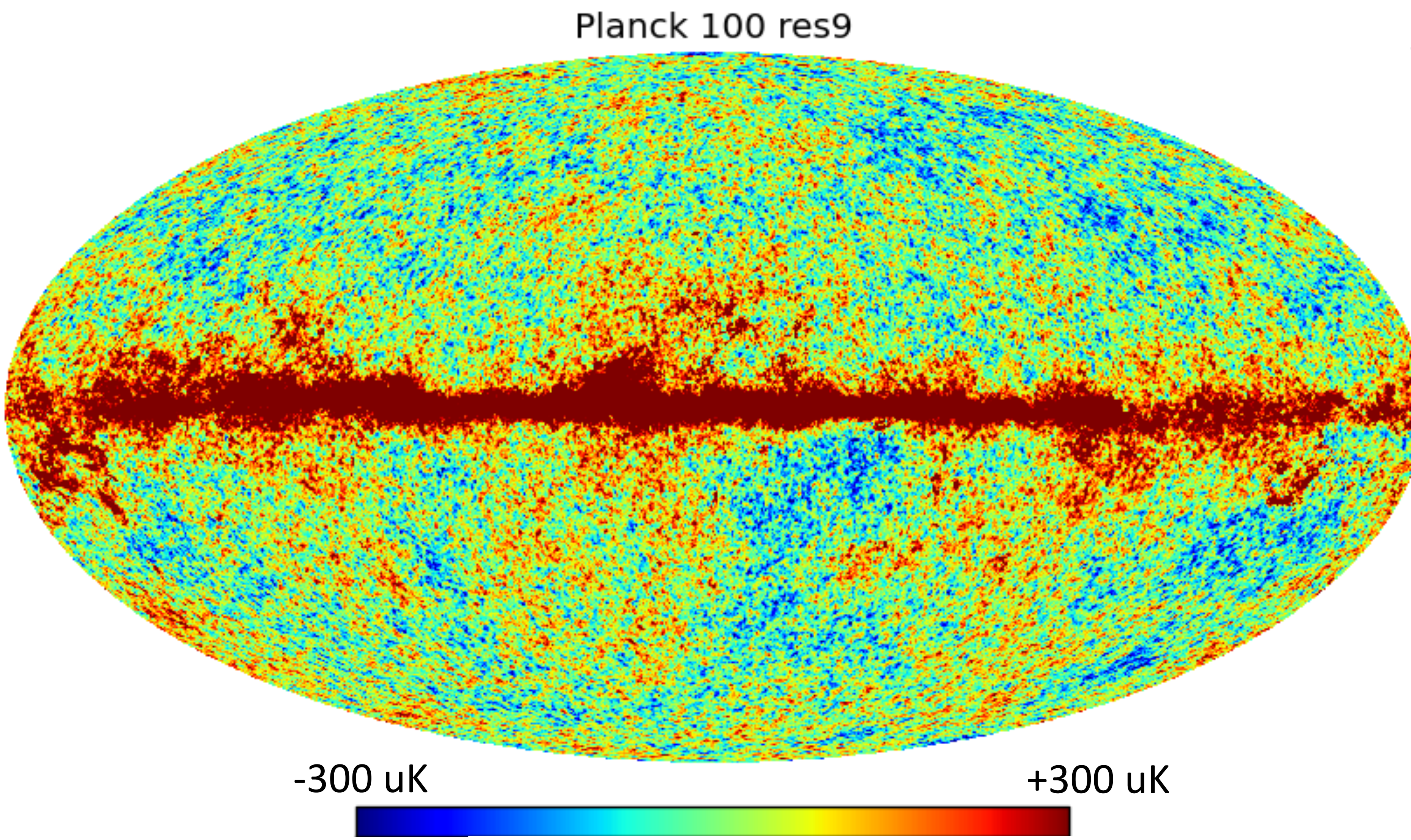

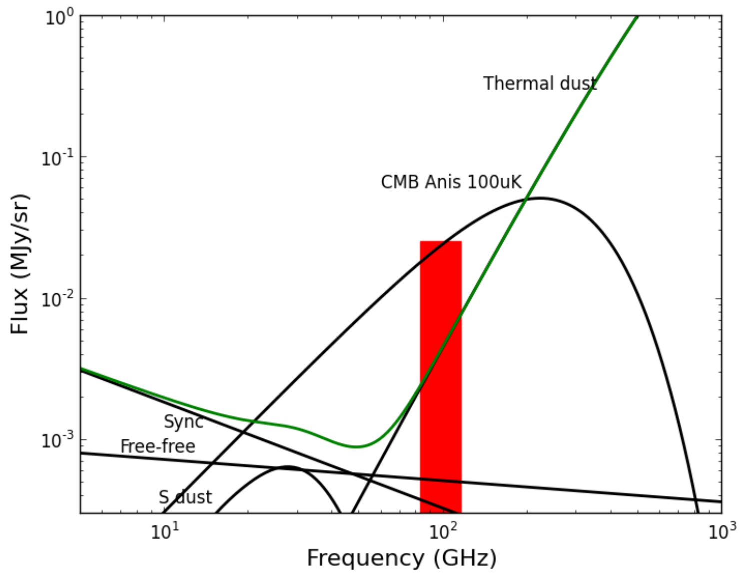

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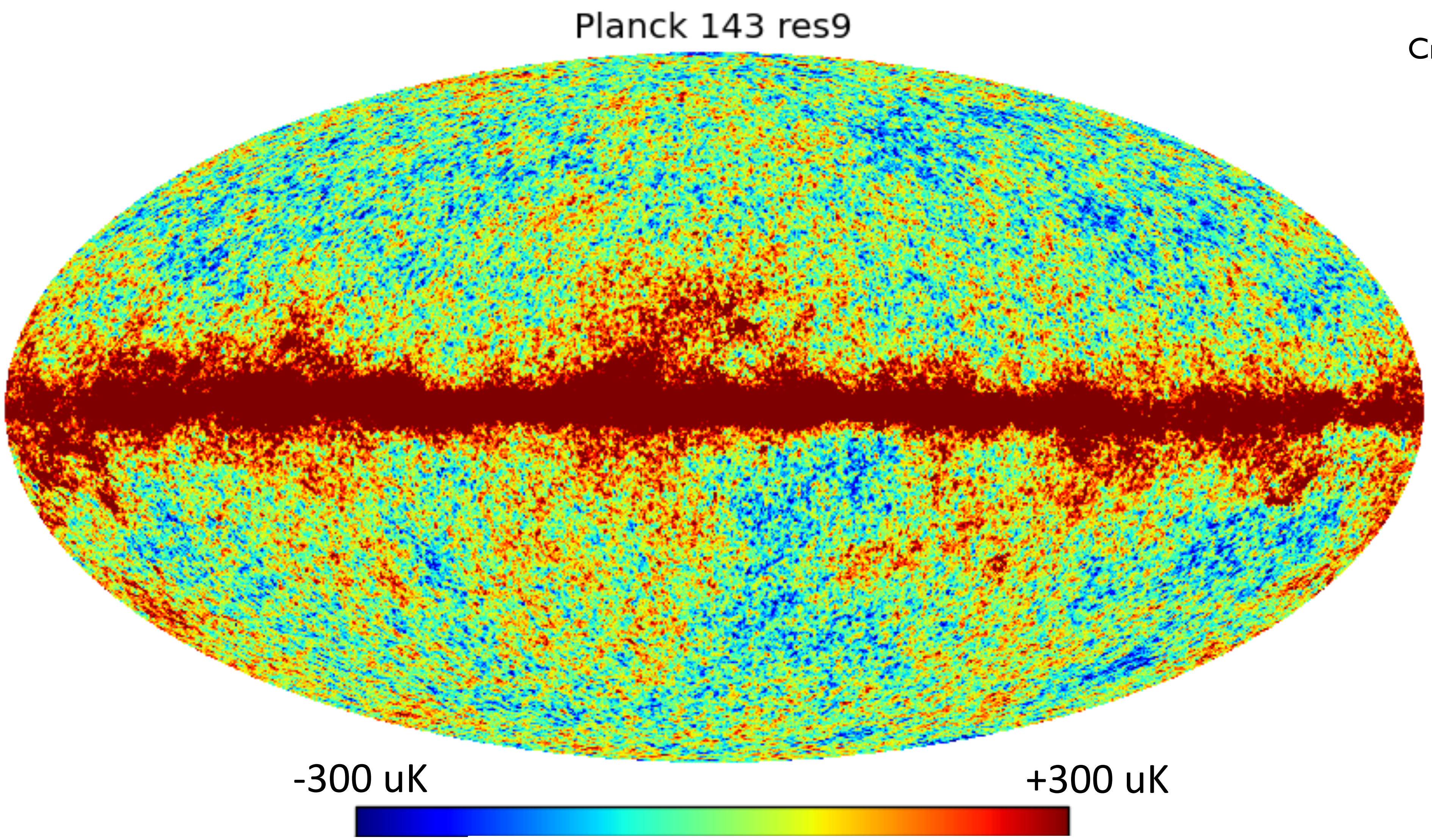

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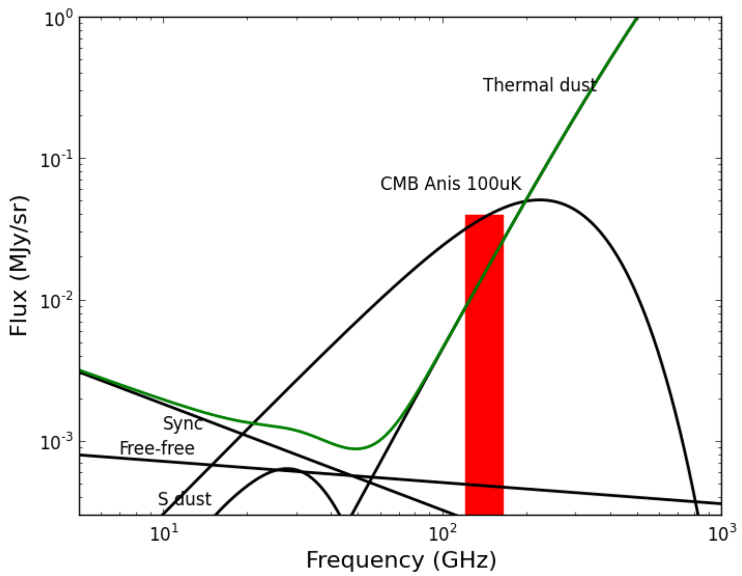

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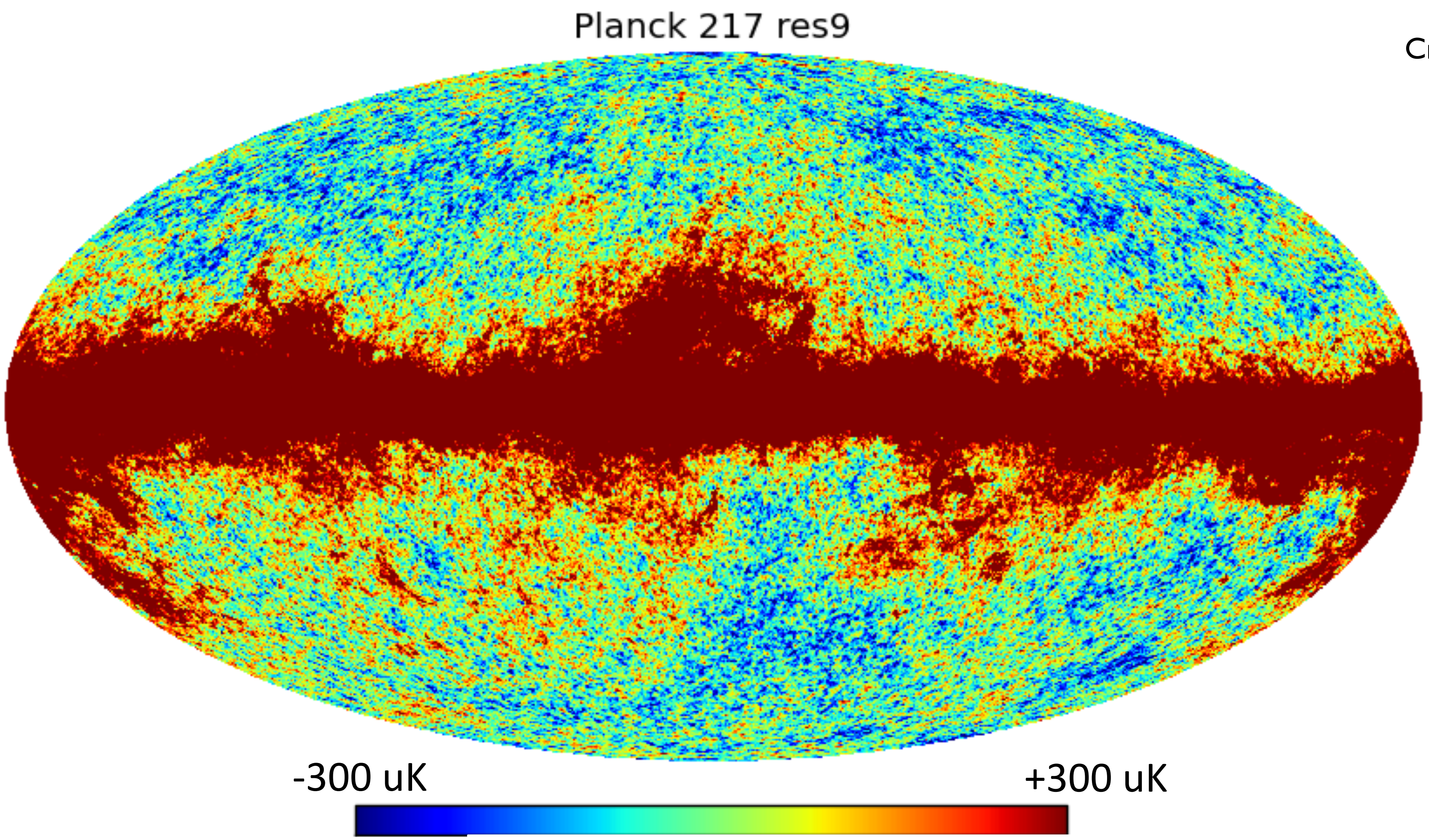

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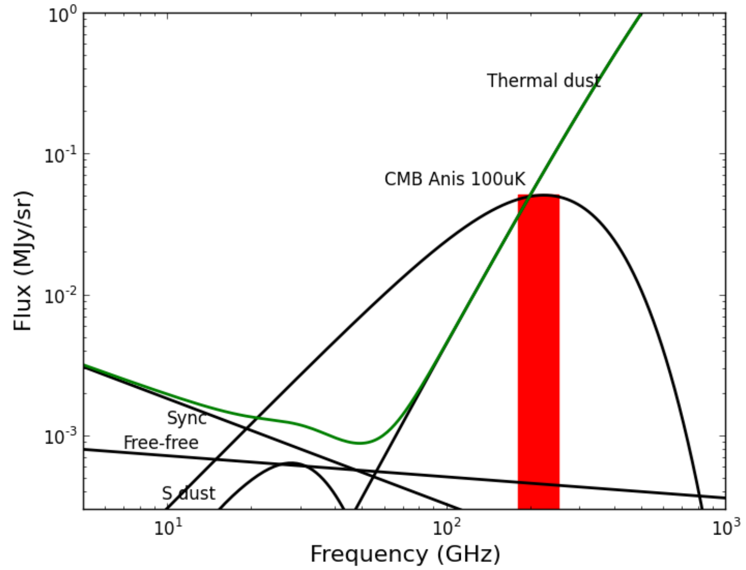

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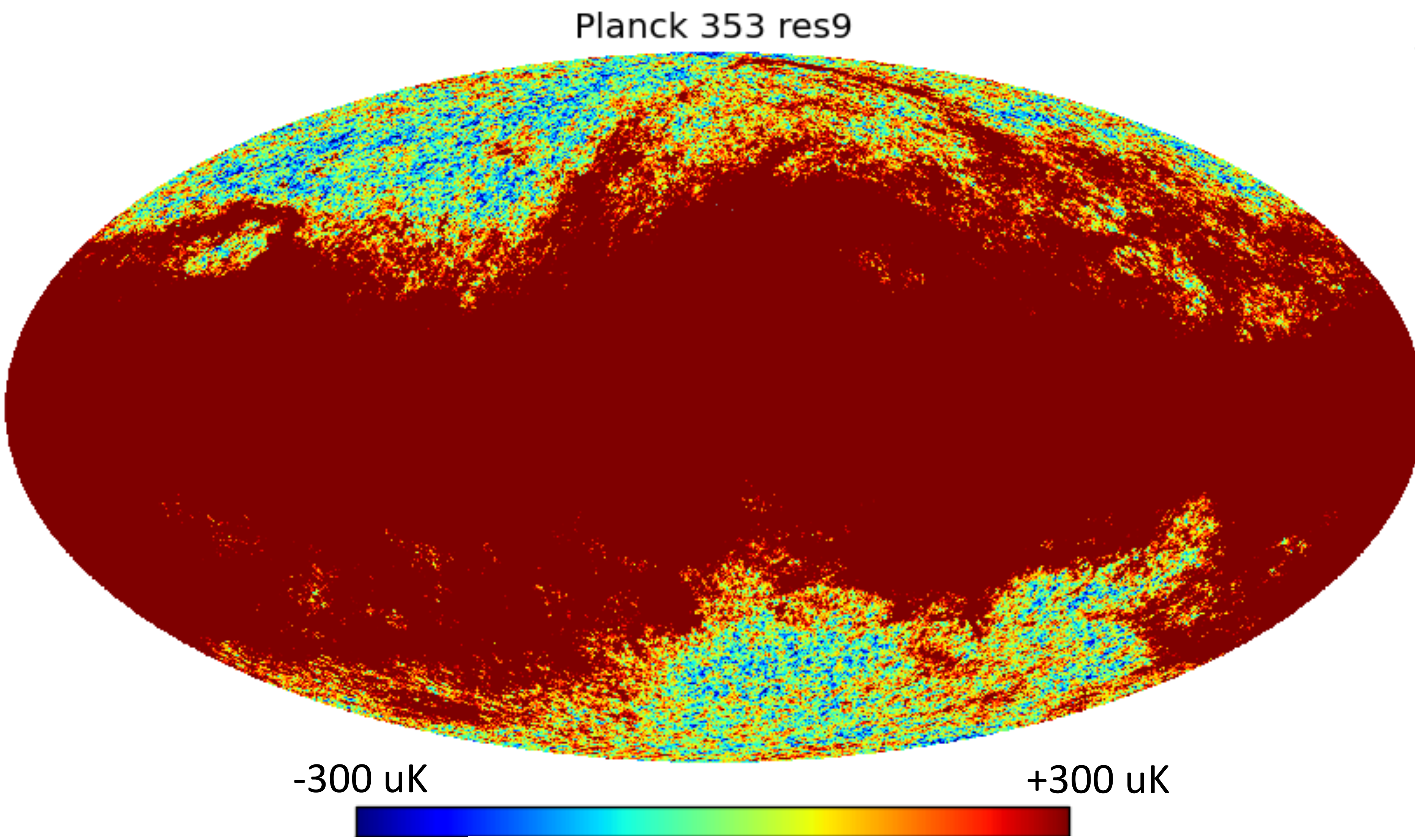

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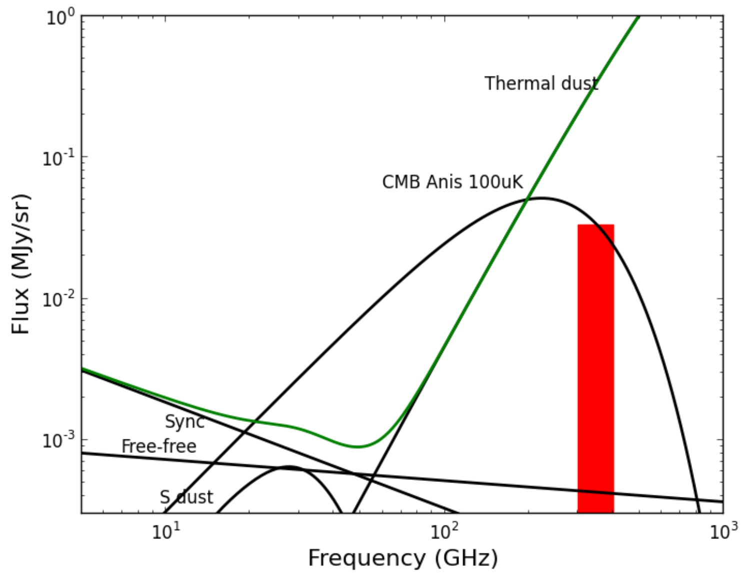
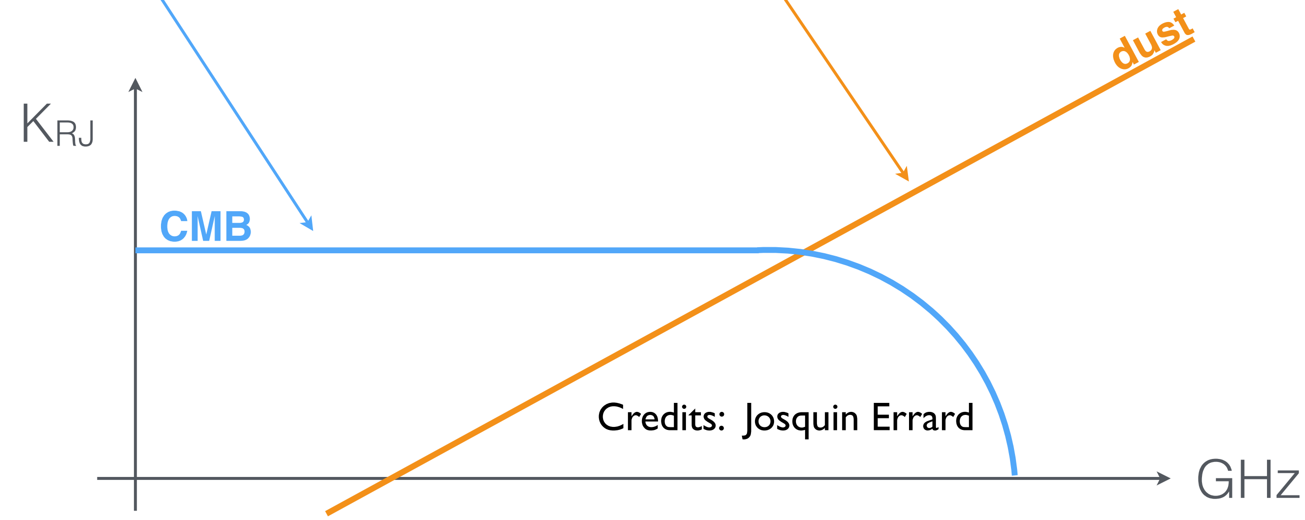


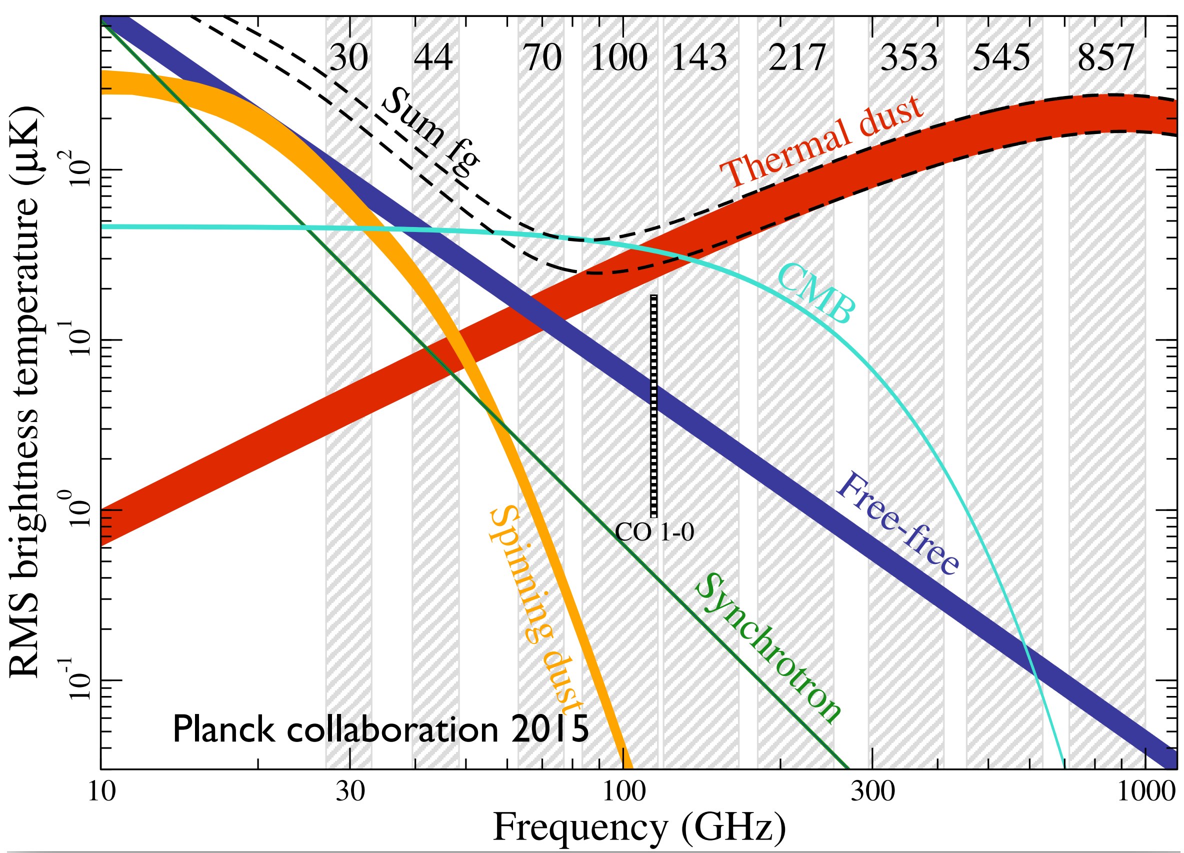
Component separation principle

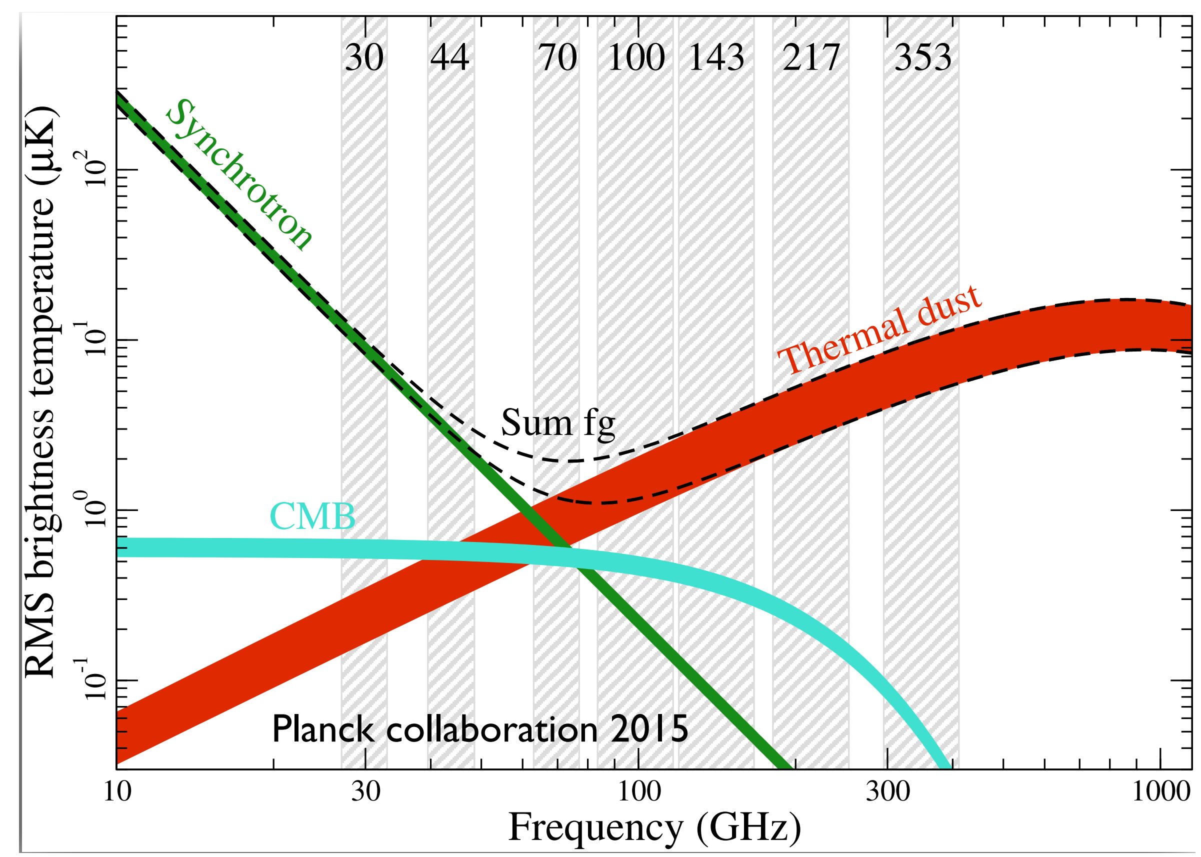
- How to disentangle CMB and foregrounds?
- Different emission laws, different scaling with frequency
- Multifrequency observations

$$a_{cmb} = \frac{(\nu/k_BT)^2 \exp(\nu/k_BT)}{(\exp(\nu/k_BT)-1)^2}$$

$$a_{dust}\,(\nu,\nu_{ref}) = \left(\frac{\nu}{\nu_{ref}}\right)^{\beta_d+1} \frac{\exp\frac{h\nu_{ref}}{kT_d}-1}{\exp\frac{h\nu}{kT_d}-1}$$







Component separation: a concrete example

1- Component separation generalities

a map at a given frequency is a sum of cmb, dust and noise

(1) $$map(\nu) = a_{cmb}(\nu)s_{cmb} + a_{dust}(\nu)s_{dust} + n(\nu)$$

$$s \equiv \begin{bmatrix} Q \\ U \end{bmatrix}$$

for three frequency channels, using matrix form

(2) $$\begin{bmatrix} map(\nu_1) \\ map(\nu_2) \\ map(\nu_3) \end{bmatrix} = \mathbf{A}(\nu_1, \nu_2, \nu_3) \begin{bmatrix} s_{cmb} \\ s_{dust} \end{bmatrix} + \begin{bmatrix} n(\nu_1) \\ n(\nu_2) \\ n(\nu_3) \end{bmatrix}$$

it's like map-making!

Component separation is performed in two steps:
1- Estimation of the mixing matrix **A** — method specific
2- Solving the linear system (2), with **A** estimated above — general to any method

GLS solution

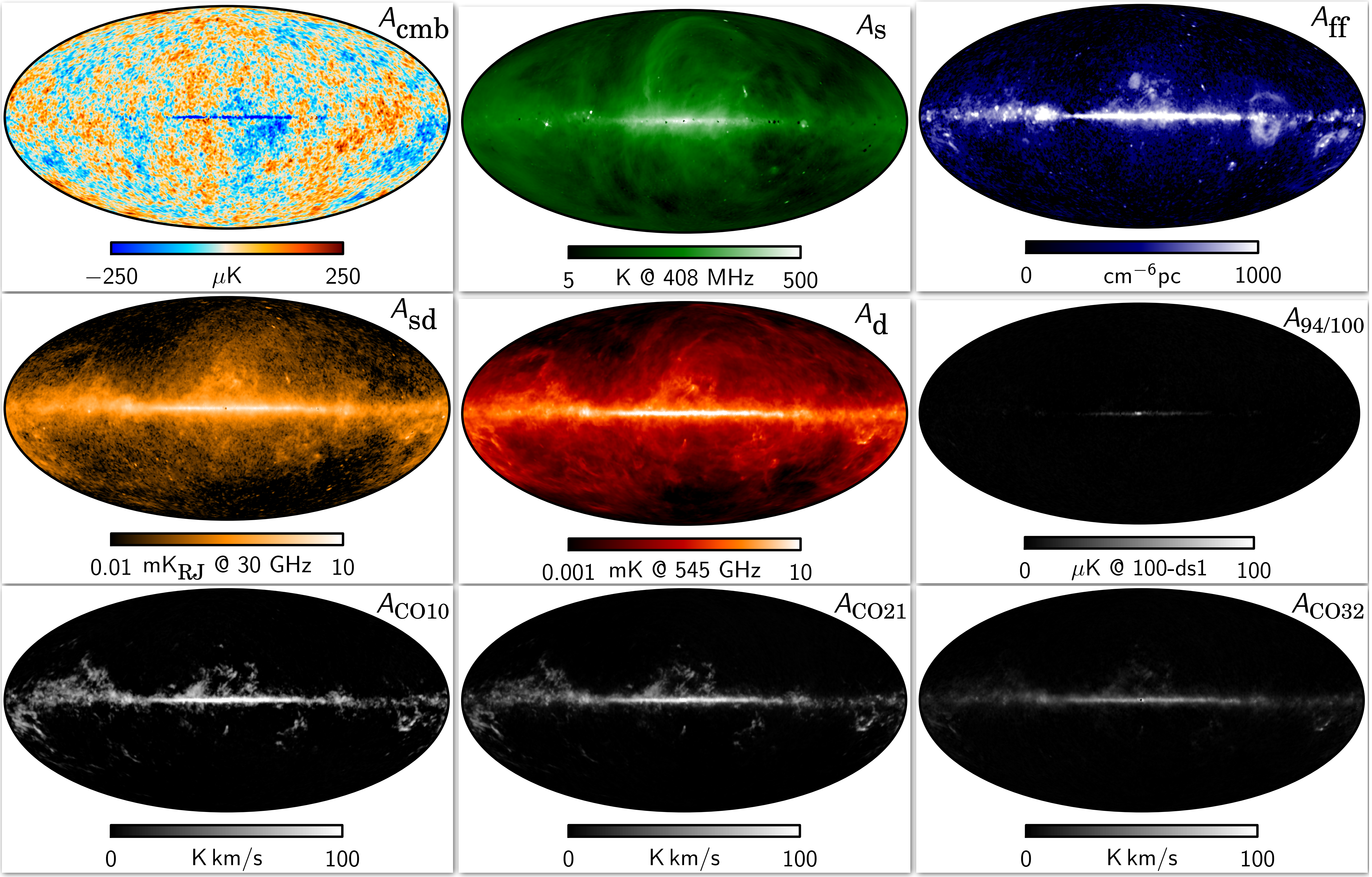
(3) $$\begin{bmatrix} s_{cmb} \\ s_{dust} \end{bmatrix} = \left(\mathbf{A}^T\mathbf{N}^{-1}\mathbf{A}\right)^{-1}\mathbf{A}^T\mathbf{N}^{-1} \begin{bmatrix} map(\nu_1) \\ map(\nu_2) \\ map(\nu_3) \end{bmatrix}$$

$\tilde{\mathbf{N}}$

Planck collaboration 2015

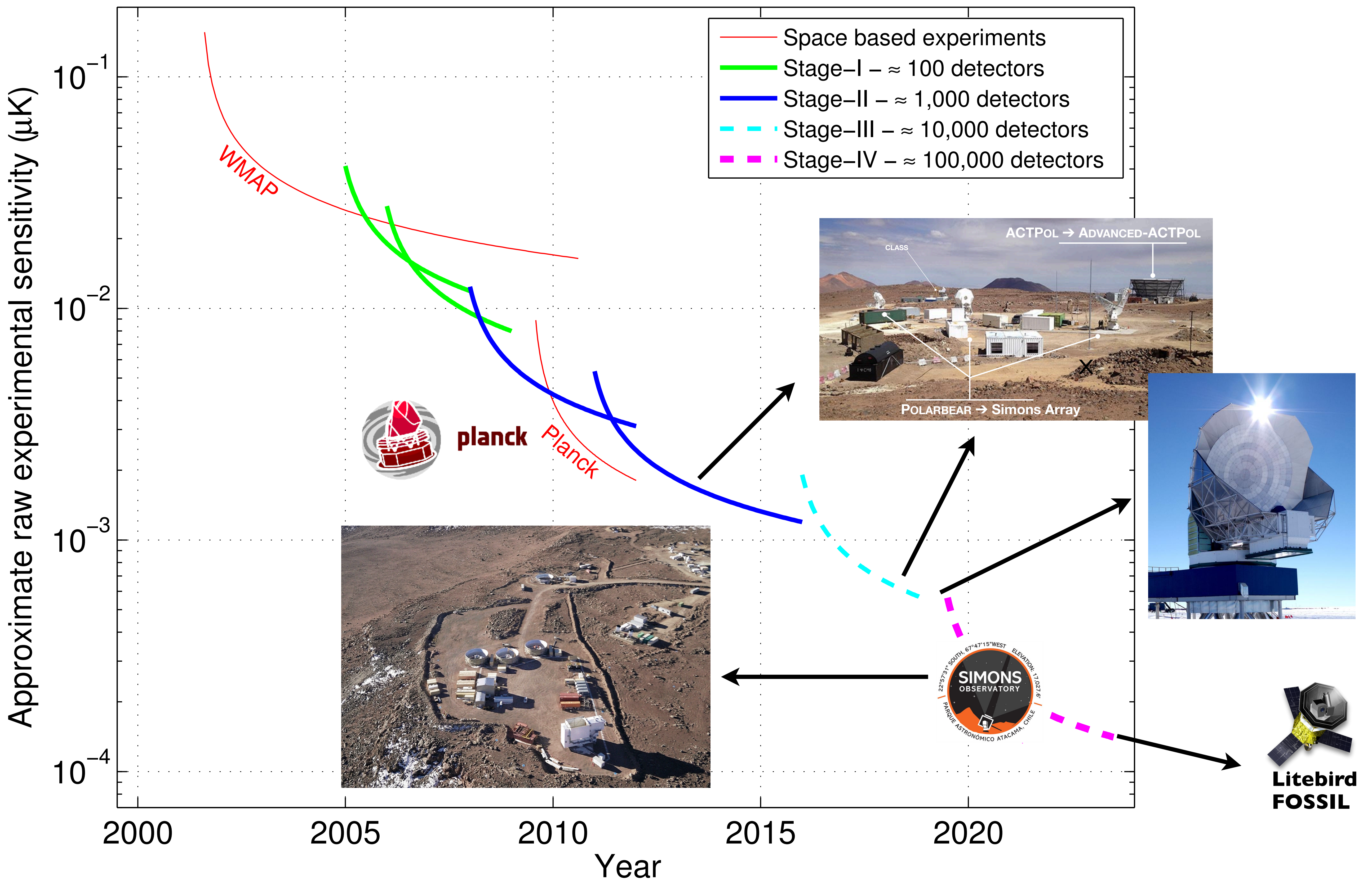
Credits: J. Errard

Component separation: results



Planck collaboration 2015

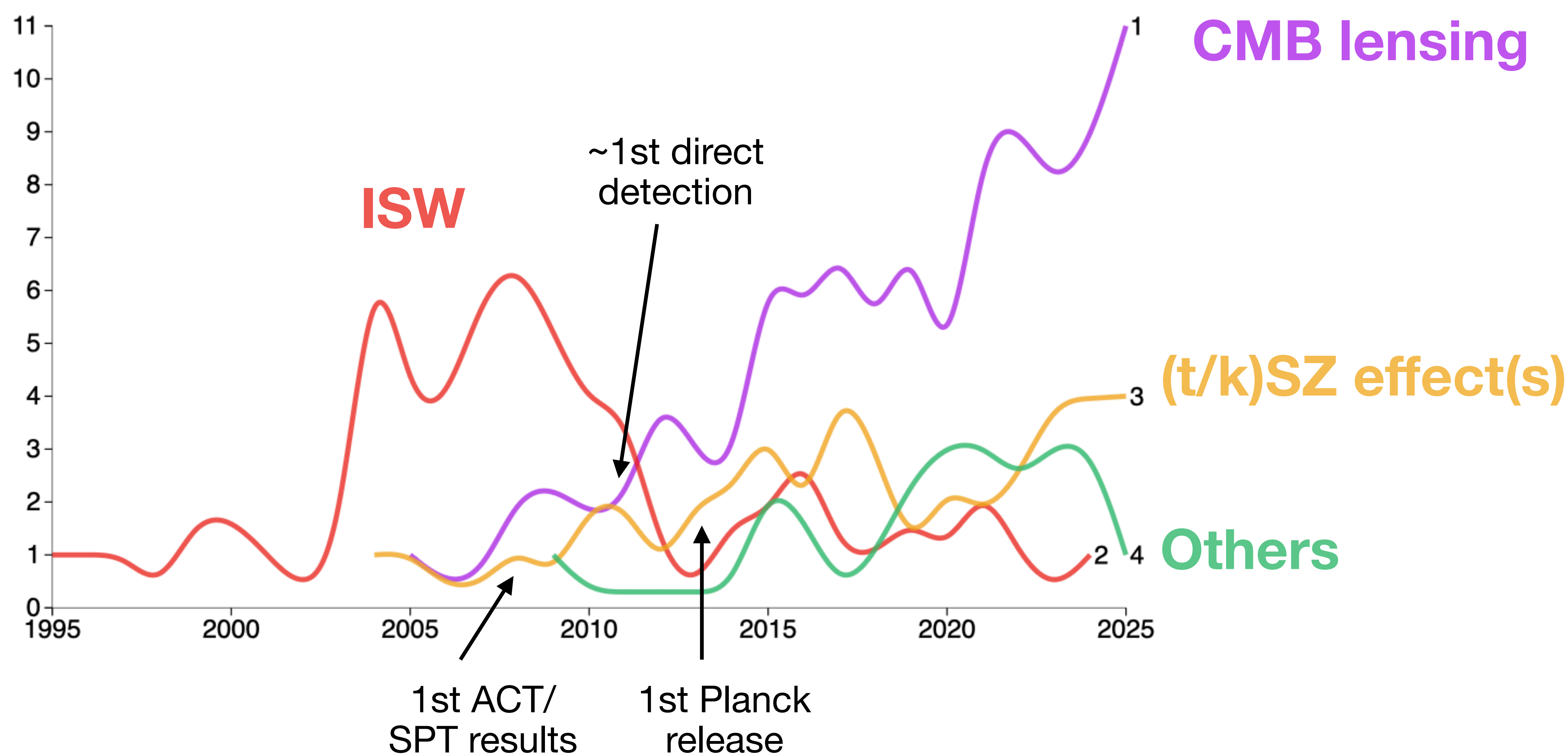
Experimental CMB landscape



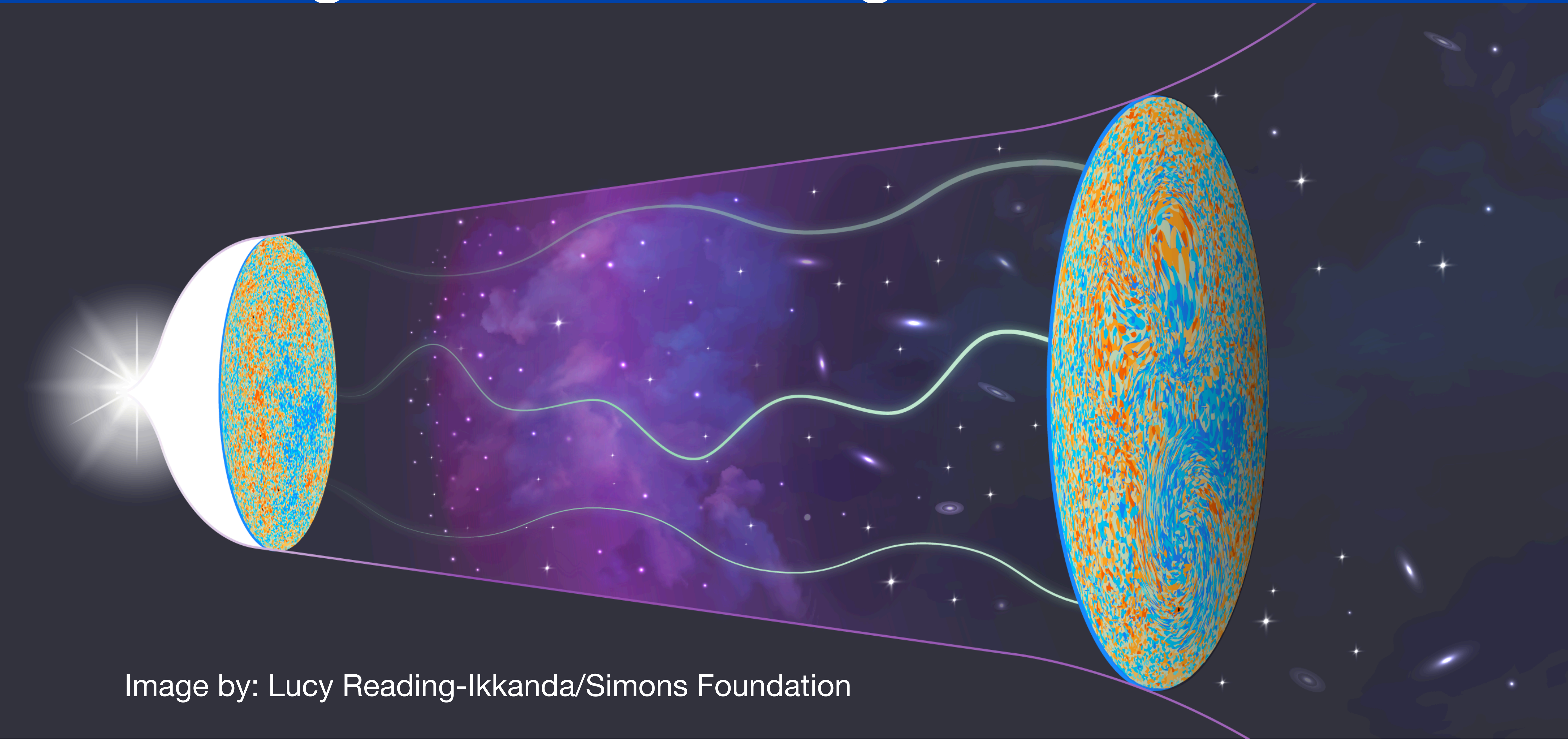
State of the art of the CMB secondaries

- ISW "oldest" probe, becoming less competitive because of limited achievable precision (cosmic variance…)
- CMB lensing hints in early 2000s, first detections 2010, now booming!
- SZ picking up after first Planck data release….

Ignore units

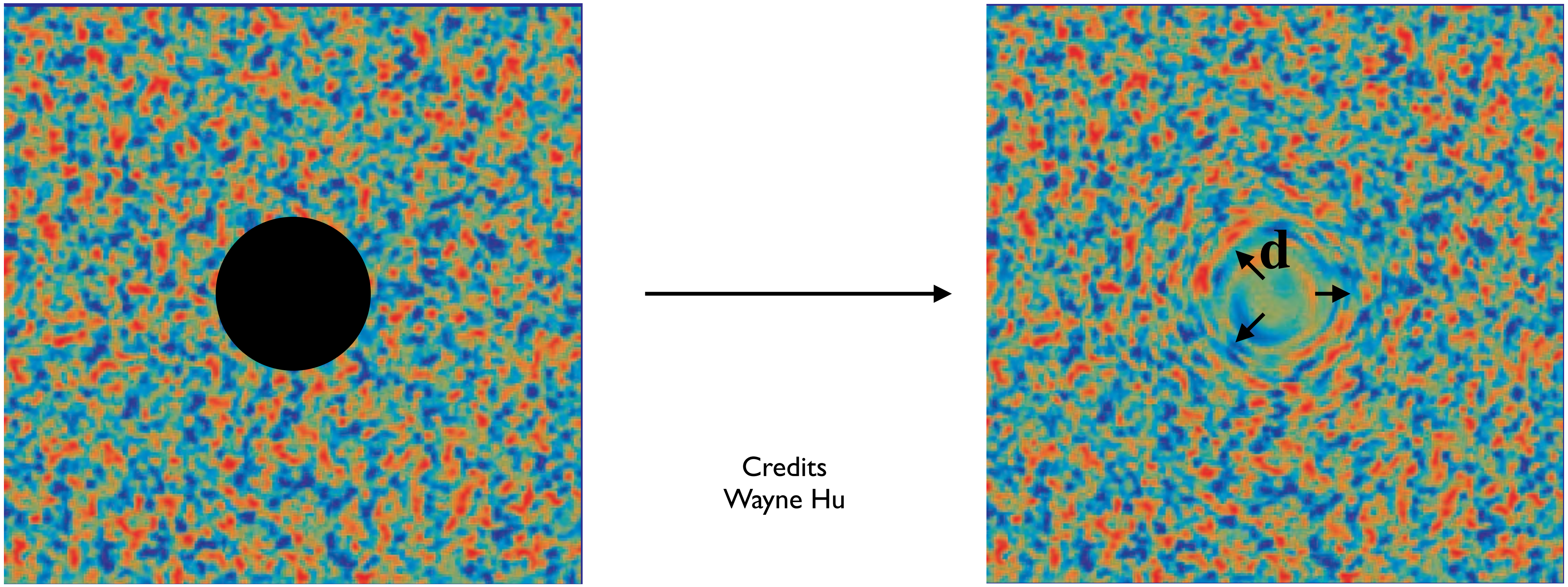


CMB and gravitational lensing



- CMB is the most distant and oldest source of radiations: photons cross potential wells of LSS as they form.
- Preserves surface brightness: no effect if CMB is fully homogeneous.

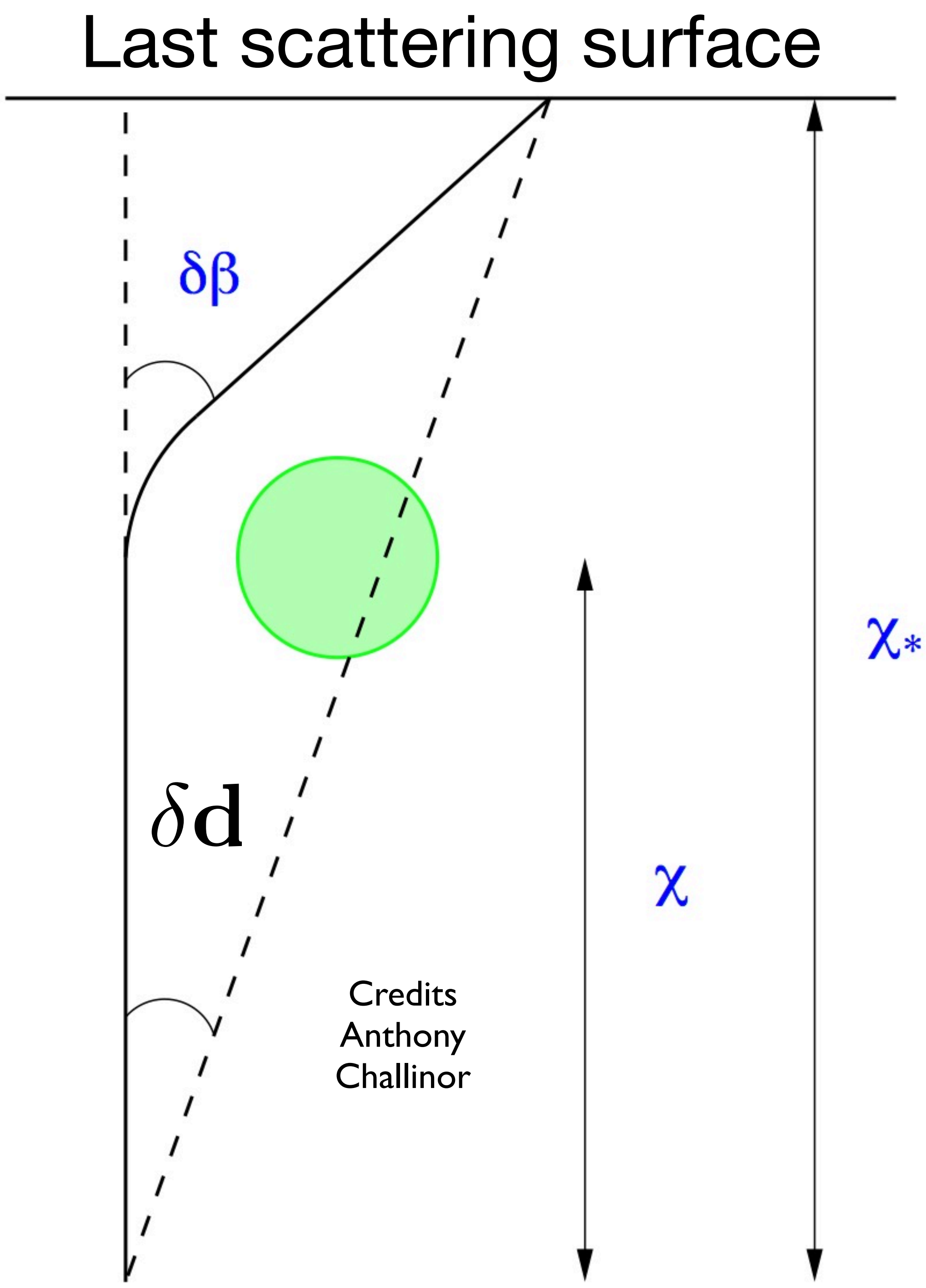
Lensing cartoon



$T(\hat{\mathbf{n}})$ $\qquad$ $T(\hat{\mathbf{n}} + \mathbf{d}(\hat{\mathbf{n}}))$

- WARNING: exaggerated cartoon
- Dark matter introduces features in the CMB anisotropies pattern causing shearing and magnification
- The properties of lensing are encoded in the deflection field: can we estimate this?

The lensing geometry



- According to GR photon obey the geodesic equation

$$\frac{dp^\mu}{d\lambda} + \Gamma^\mu_{\nu\rho} p^\nu p^\rho = 0$$

- Exercise: $\delta\beta = -2\delta\chi\nabla_\perp\Phi$

- By pure geometric considerations then

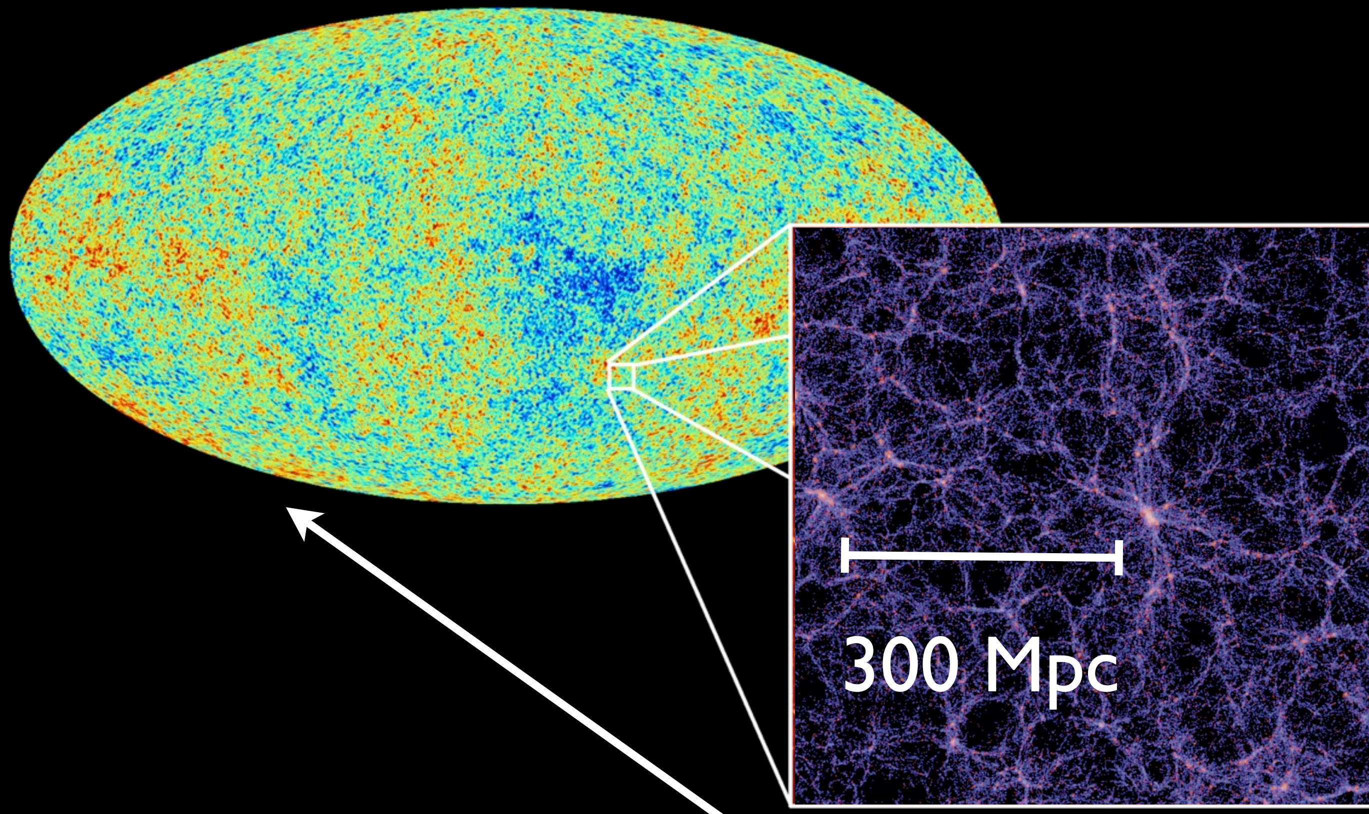
$$\delta\mathbf{d} = -2\frac{\chi_* - \chi}{\chi_*}\delta\chi\nabla_\perp\Phi$$

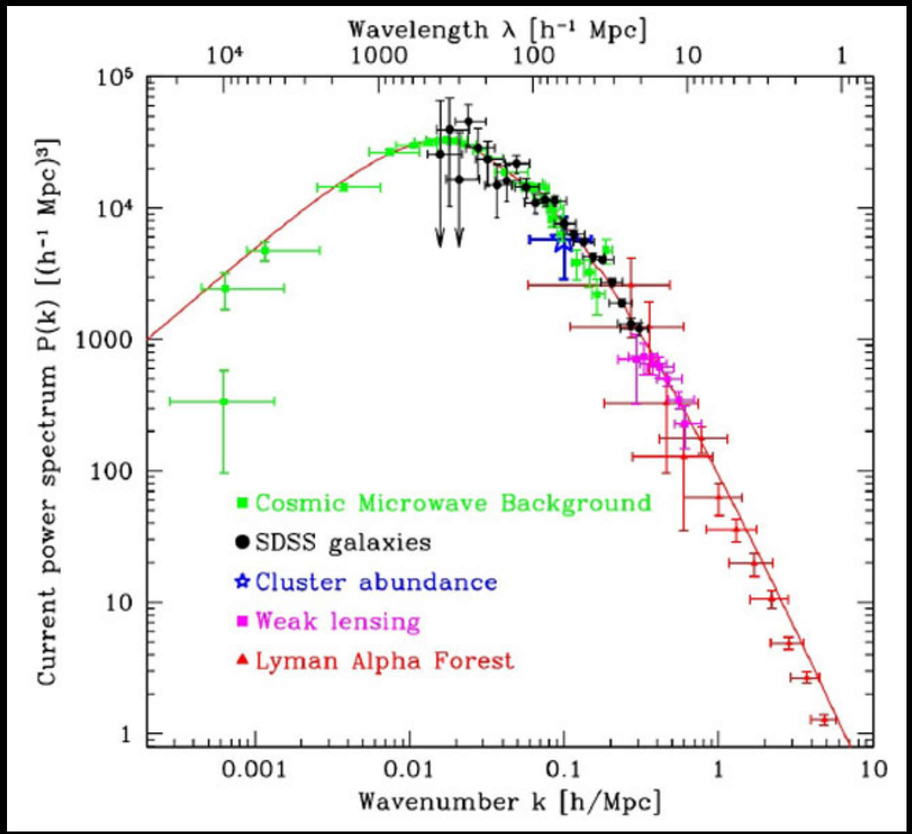
- Total effect then given by

$$\mathbf{d}(\hat{\mathbf{n}}) = -\int_0^{\chi_*} 2d\chi\frac{\chi_* - \chi}{\chi_*}\delta\chi\nabla_\perp\Phi(\chi\hat{\mathbf{n}}, \eta_0 - \chi)$$

ÉCOLE DE PHYSIQUE DES HOUCHES

0-th order calculation





~7000 Mpc

~14000 Mpc

$$\Psi(R) \approx 2 \cdot 10^{-5}$$

$$\delta\beta \approx \frac{2\Psi(R)}{c^2} \approx 10^{-4}$$

$$N_{dev} \simeq 50$$

$$\Delta\theta \approx \sqrt{N_{dev}} \times \delta\beta \approx 7 \times 10^{-4} = 2 \ arcmin$$

$$\Delta\theta_{coherence} \simeq \frac{300}{7000} \approx 2^\circ$$

The CMB lensing potential

- Unbiased tracers of the whole integrated matter distribution along the line of sight.

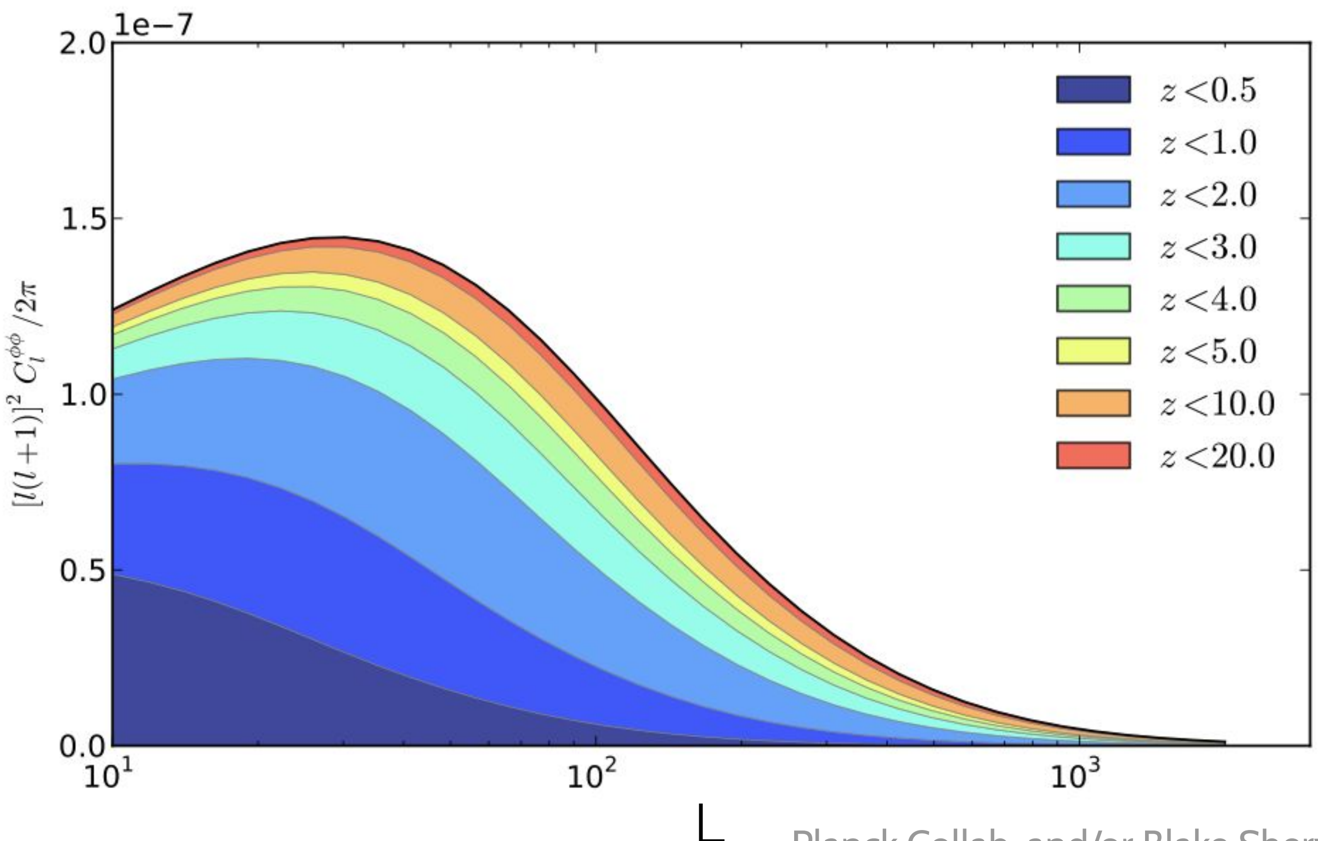
$$\phi(\boldsymbol{\theta}) = -2\int_0^{\chi_s} \frac{D_A(\chi_s-\chi')}{D_A(\chi_s)D_A(\chi')}\Psi\left(\boldsymbol{\theta},\chi'\right)\mathrm{d}\chi'$$

$$\mathbf{d} = \nabla\phi$$

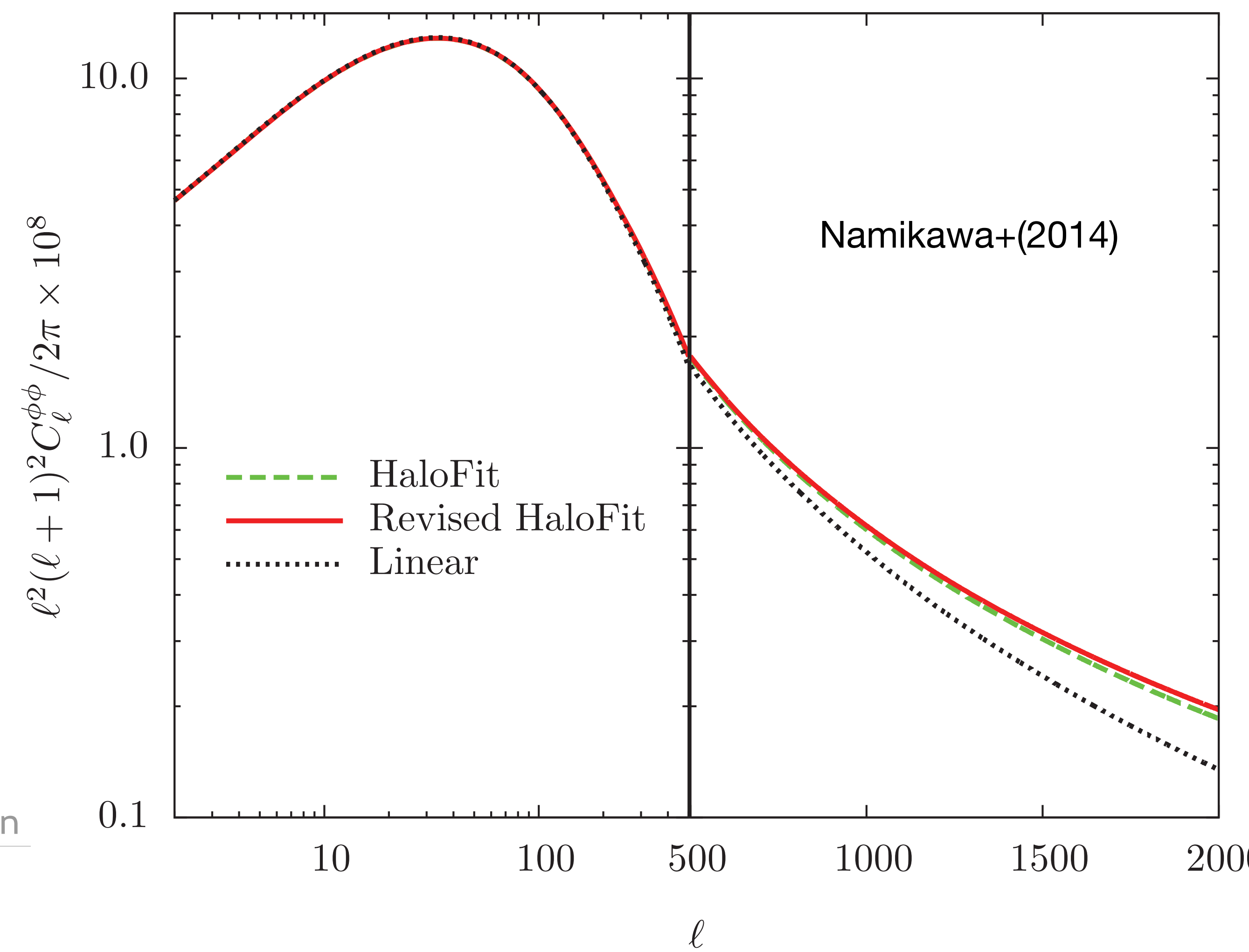
$$\kappa \propto -\nabla^2\phi \rightarrow \delta$$

Notation Warning!

- Sensitive to total matter distribution $\sigma_8\Omega_m^{0.25}$ at z~0.6-5 on mildly non-linear scales.

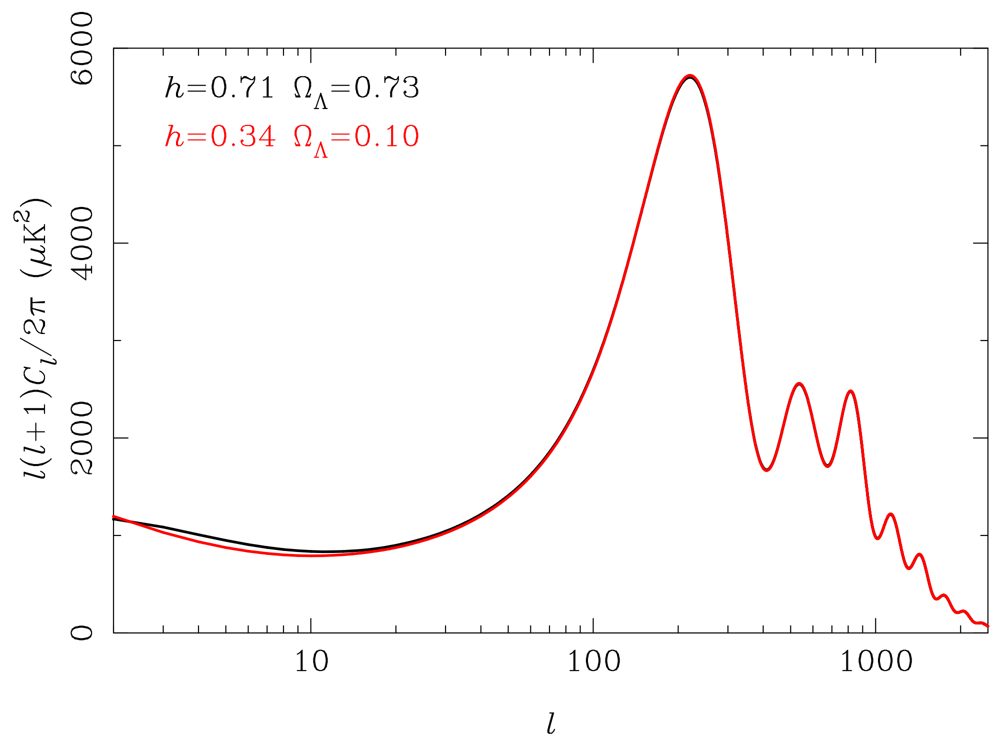


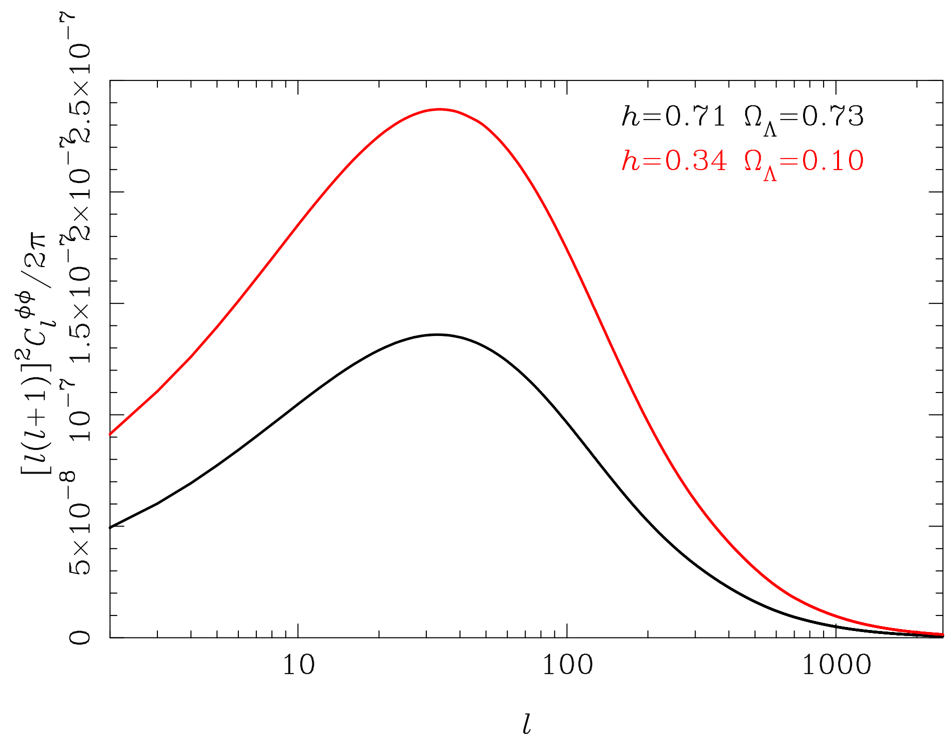
Planck Collab. and/or Blake Sherwin



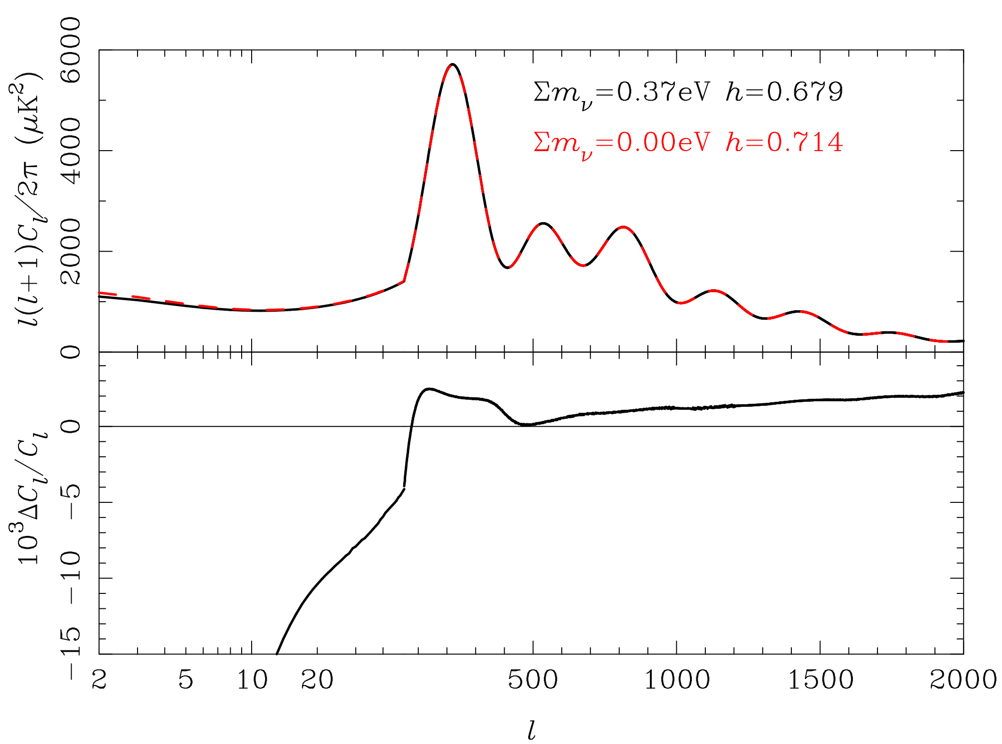
Breaking degeneracies with CMB lensing

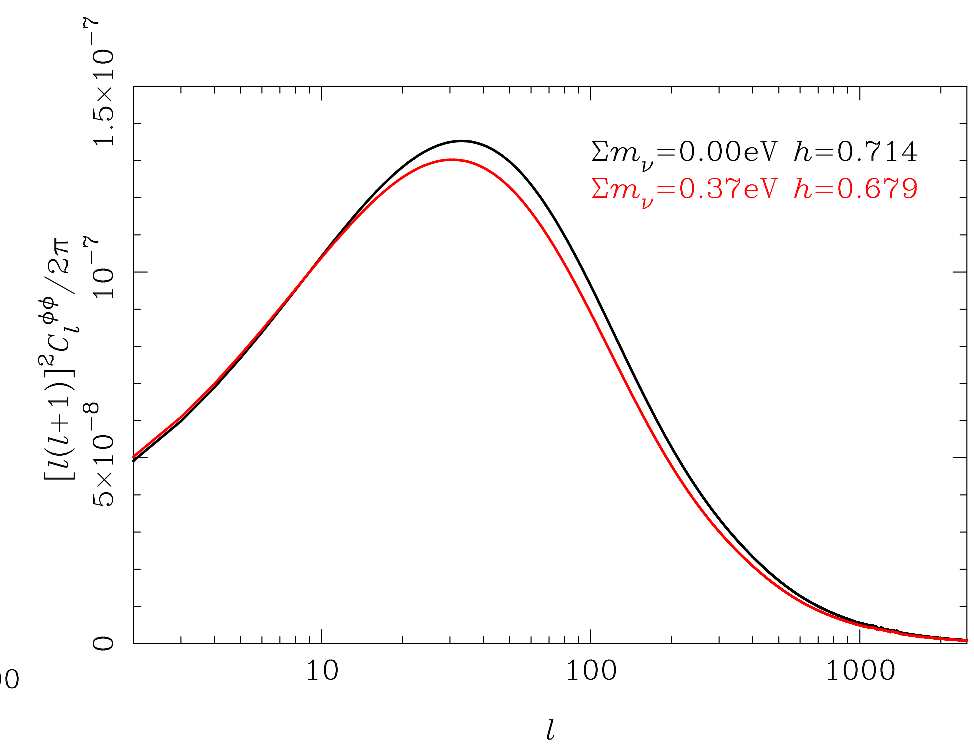
- Lensing sensitive to geometry and late-time growth of structure: curvature





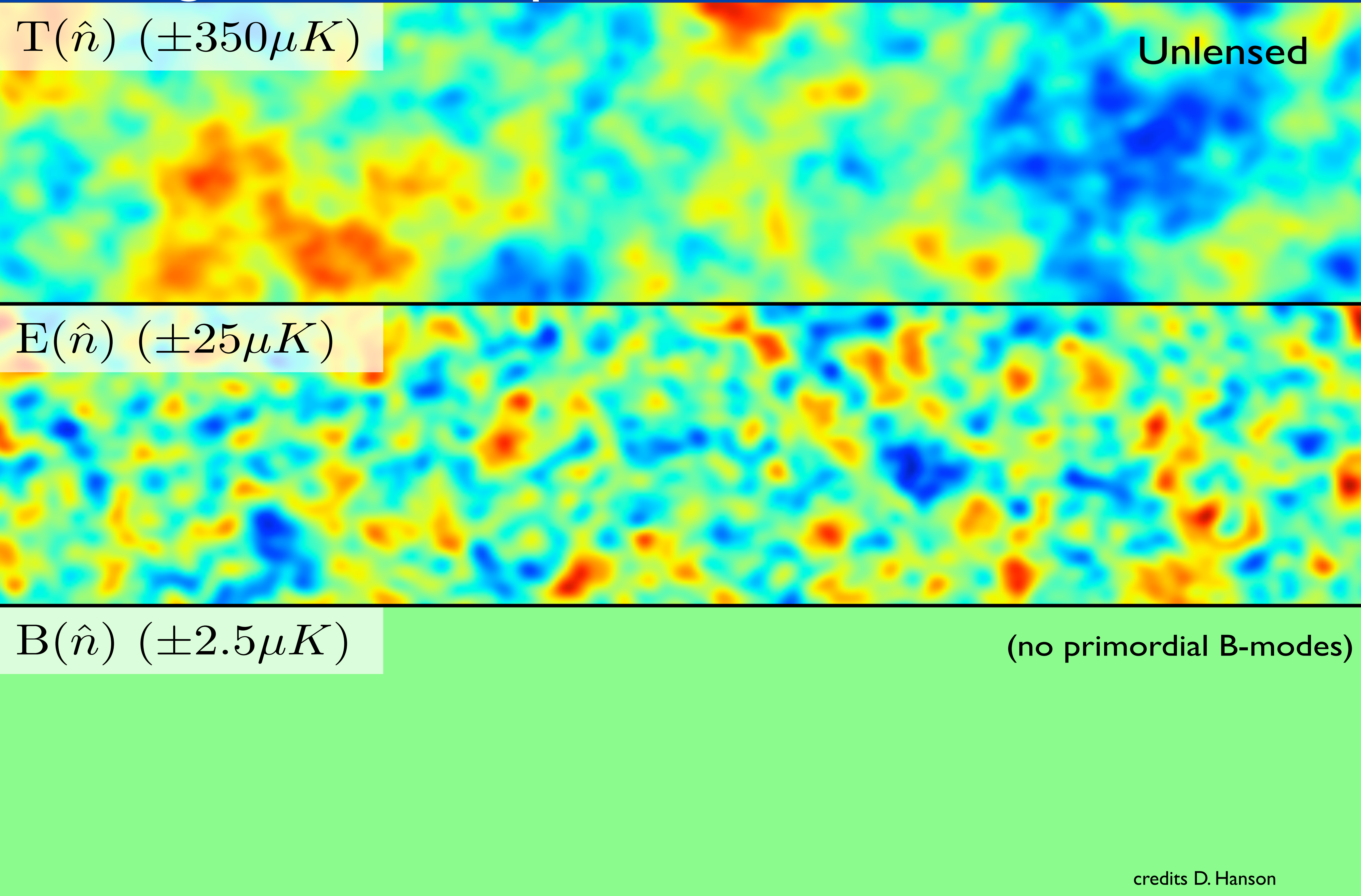
- Neutrino masses:



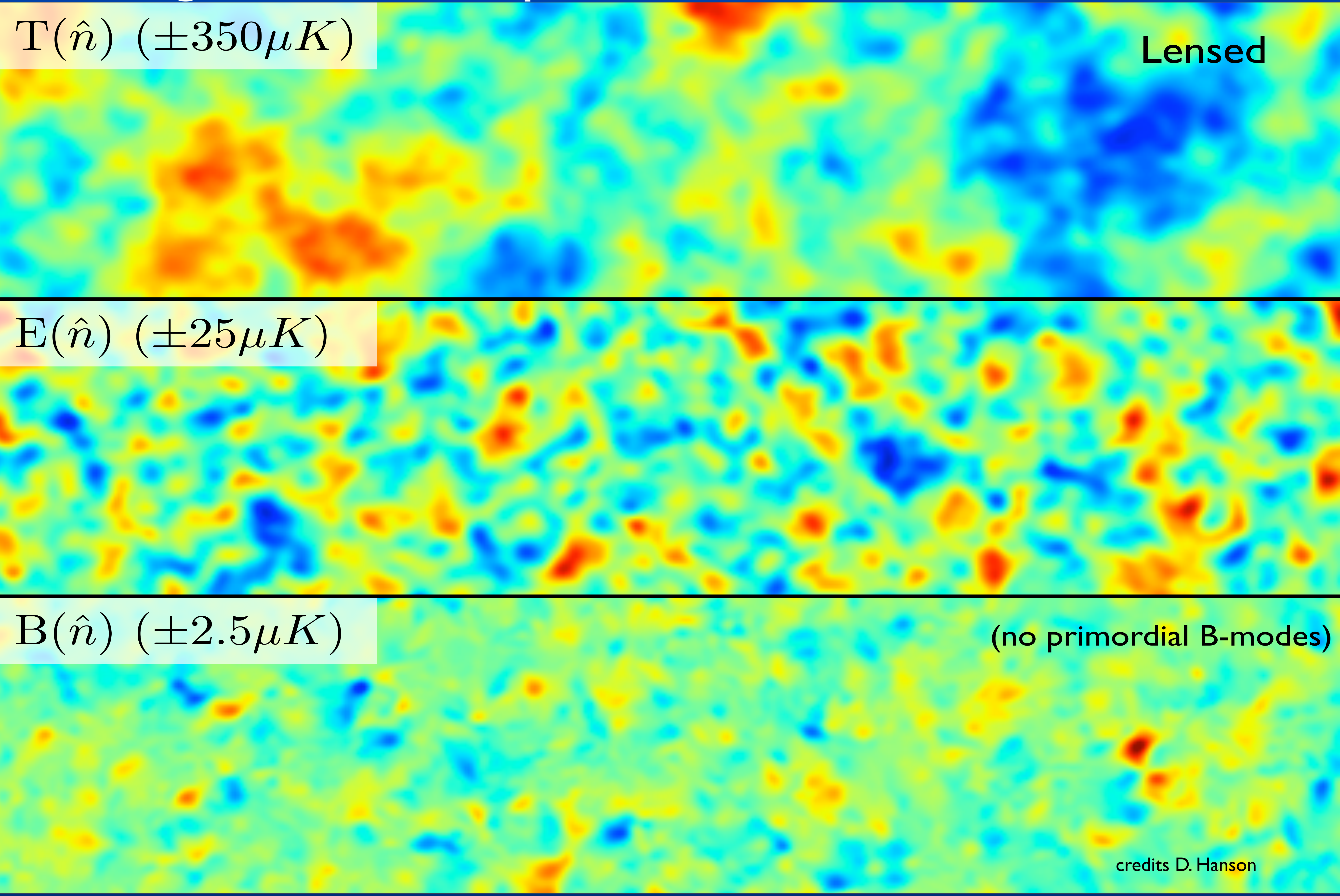


Credits
Anthony
Challinor

Lensing on CMB maps



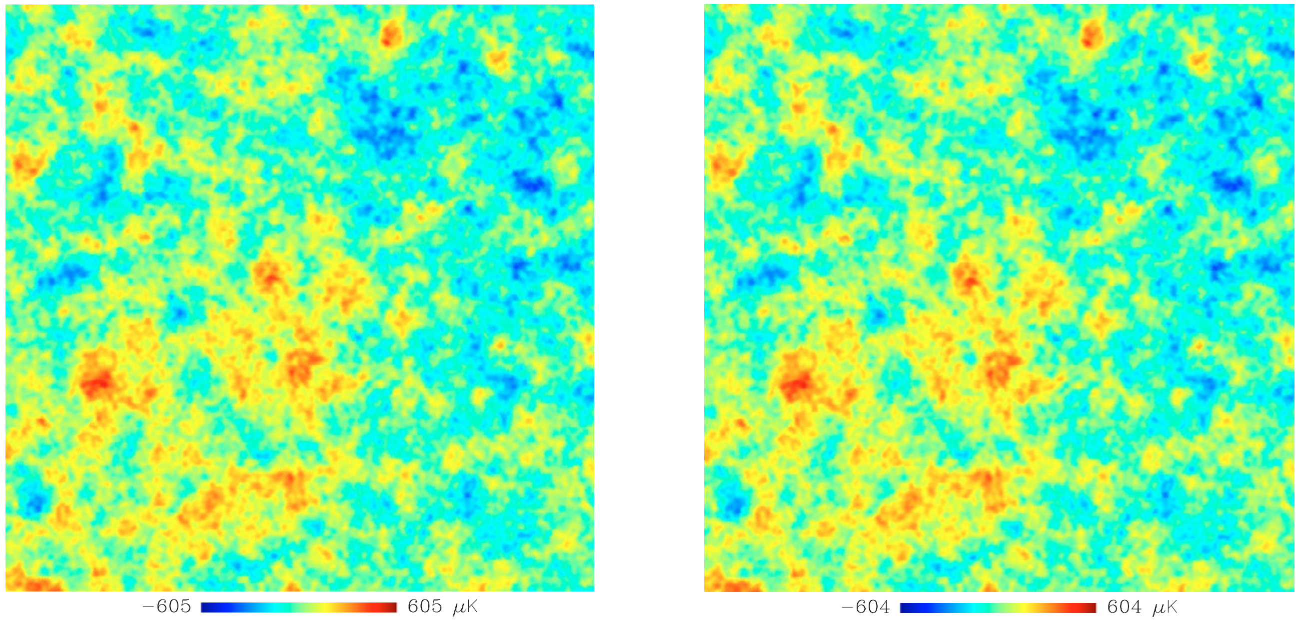
Lensing on CMB maps



Effects on maps

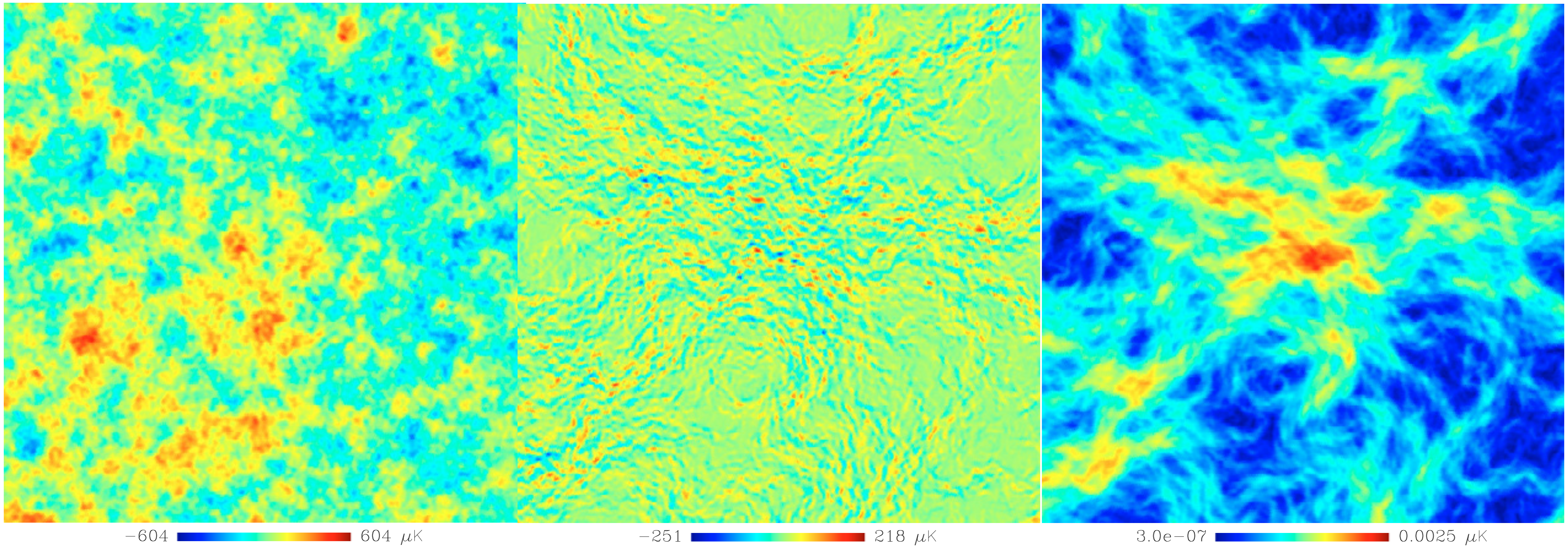
- Lensed and unlensed maps are practically indistinguishable by eye

Lensed



Unlensed

- Their difference shows a pattern similar to the LSS which lensed the signal



Basak+ (2009)

A sketch of the effect of lensing

- Expanding in 2D Fourier modes

$$\Theta(\mathbf{x}) = \int \frac{d^2 l}{(2\pi)^2} \Theta(\mathbf{l}) e^{i\mathbf{l}\cdot\mathbf{x}}$$

Hu+(2000)
Lewis & Challinor (2006)

- Expanding in Taylor series and Fourier transforming

$$\tilde{\Theta}(\mathbf{x}) = \Theta(\mathbf{x} + \mathbf{d}) = \Theta(\mathbf{x}) + \nabla\phi \cdot \nabla\Theta + \cdots$$
$$\tilde{\Theta}(\mathbf{l}) = \Theta(\mathbf{l}) + \int \frac{d^2 L}{(2\pi)^2} [\mathbf{L}\phi(\mathbf{L})] \cdot [(\mathbf{l} - \mathbf{L})\Theta(\mathbf{l} - \mathbf{L})] + \cdots$$

- The power spectrum reads

$$\langle \Theta(\mathbf{l}) \Theta^*(\mathbf{l}') \rangle = (2\pi)^2 C_{\mathbf{l}} \delta(\mathbf{l} - \mathbf{l}')$$

$$\langle \tilde{\Theta}(\mathbf{l}) \tilde{\Theta}^*(\mathbf{l}') \rangle = (2\pi)^2 C_{\mathbf{l}} \delta(\mathbf{l} - \mathbf{l}') + \langle \delta^{(1)}\Theta(\mathbf{l}) \delta^{(1)}\Theta(\mathbf{l}') \rangle + \langle \Theta(\mathbf{l}) \delta^{(2)}\Theta(\mathbf{l}') \rangle + \langle \Theta(\mathbf{l}') \delta^{(2)}\Theta(\mathbf{l}) \rangle + \cdots$$

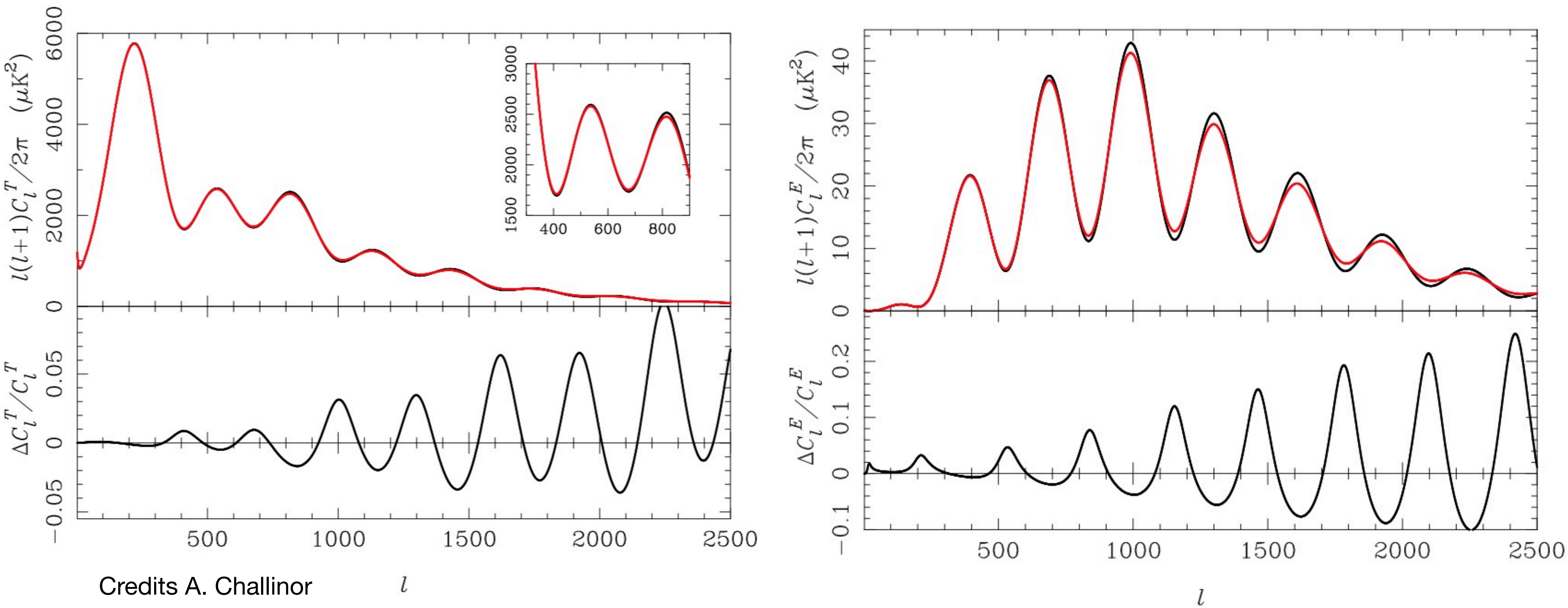
Effect of CMB angular power spectra

- Effective smoothing of peaks measured at 1% error and routinely accounted for

$$\tilde{C}_{\mathbf{l}} = \left[1 - \frac{1}{2} l^2 \langle d^2 \rangle \right] C_{\mathbf{l}} + \int \frac{d^2 L}{(2\pi)^2} C_{|\mathbf{l}-\mathbf{L}|} C^{\phi}_{\mathbf{L}} [\mathbf{L} \cdot (\mathbf{l} - \mathbf{L})]^2$$

Hu (2000), Lewis & Challinor (2000)

- Smoothing = power redistribution. More accurate formulas available…



Credits A. Challinor

Visualizing the lensing convolution

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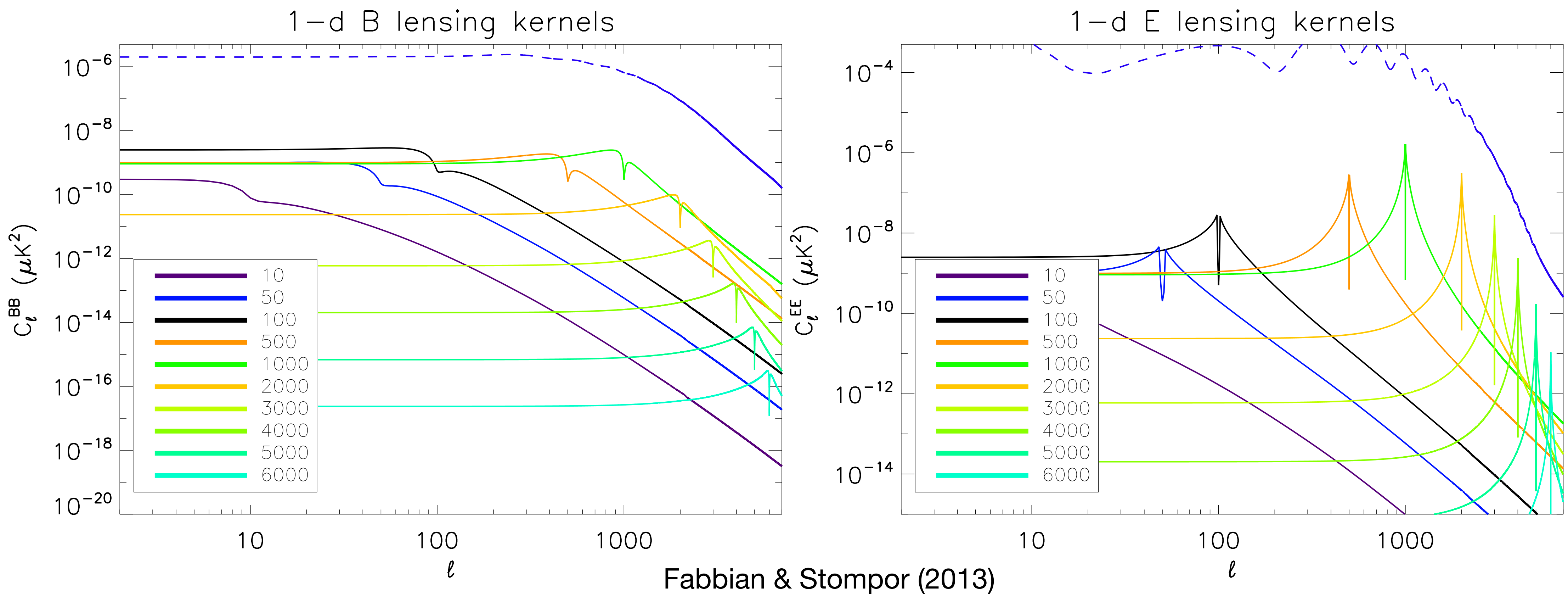
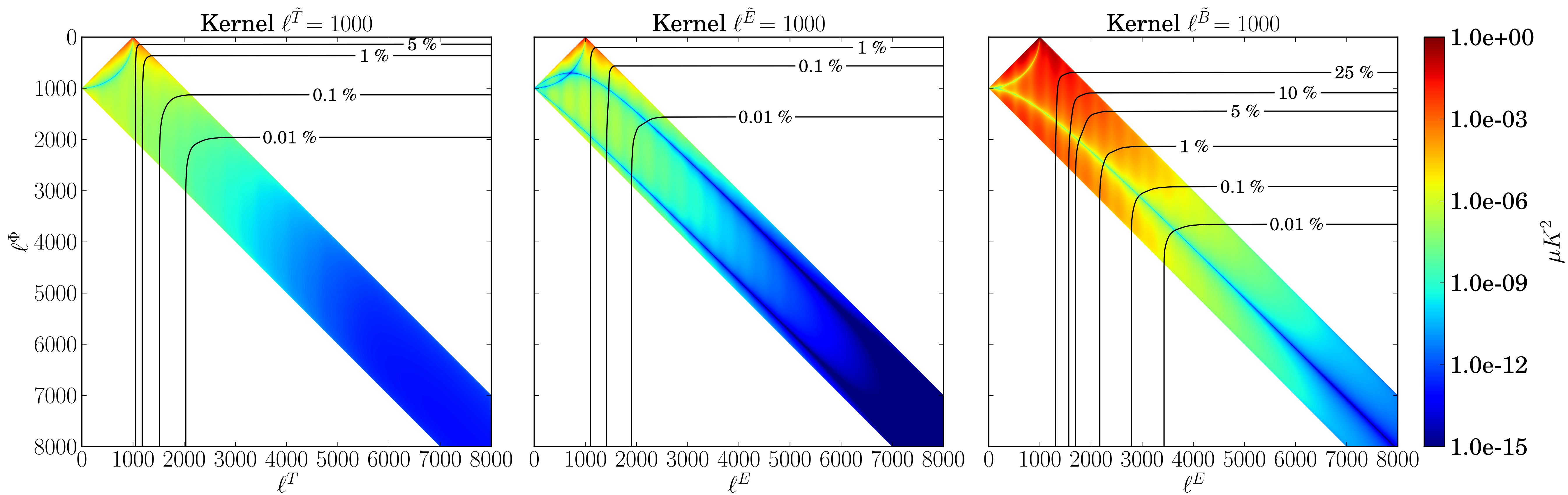
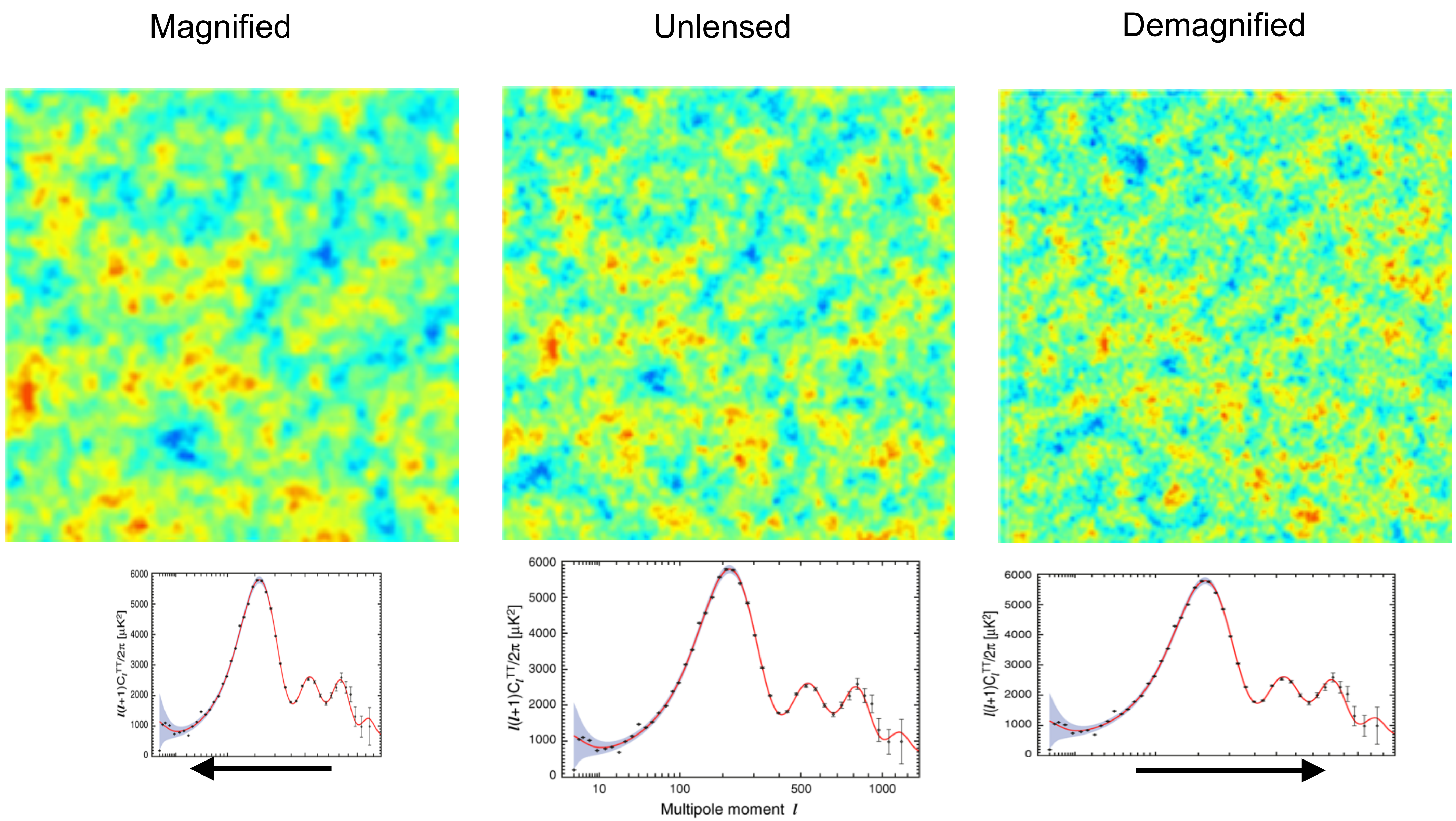


Fabbian & Stompor (2013)



CMB lensing reconstruction fundamentals



Courtesy Antony Lewis

- Modulation of the statistical properties as a function of the position of the sky, i.e. a field (CMB) modulated by an intervening one (lensing): break of translational invariance

$$\langle \Theta(\mathbf{l})\Theta^*(\mathbf{L}-\mathbf{l})\rangle = 0 \longrightarrow \langle \tilde{\Theta}(\mathbf{l})\tilde{\Theta}^*(\mathbf{L}-\mathbf{l})\rangle \sim \phi(\mathbf{L})$$

- Similar techniques for other quantities in CMB: $\tau(\hat{\mathbf{n}})$, $\alpha(\hat{\mathbf{n}})$ ….

More in details…

- A general quadratic estimator uses a combination of 2 Fourier modes of the data

$$\hat{\phi}(\mathbf{L}) = A_L \int_{\mathbf{l}} f(\mathbf{l}, \mathbf{L}) \tilde{\Theta}_{expt}(\mathbf{l}) \tilde{\Theta}_{expt}(\mathbf{L} - \mathbf{l})$$

Hu & Okamoto (2001)
Lewis (2011)
Fabbian, Lewis, Beck (2019)

- One has to pick the g and A to make the estimator unbiased and optimal

$$\phi(\mathbf{L}) = \left\langle \hat{\phi}(\mathbf{L}) \right\rangle_{\text{CMB}} \longrightarrow \langle \tilde{\Theta}(\mathbf{l}) \tilde{\Theta}(\mathbf{L} - \mathbf{l}) \rangle_{\text{CMB}} = \left[(\mathbf{L} - \mathbf{l}) \cdot \mathbf{L} \, \tilde{C}_{\mathbf{l}-\mathbf{L}} + \mathbf{l} \cdot \mathbf{L} \, \tilde{C}_l \right] \phi(\mathbf{L}) \equiv K(\mathbf{l}, \mathbf{L}) \phi(\mathbf{L})$$

$$\left\langle \hat{\phi}^*(\mathbf{L}) \hat{\phi}(\mathbf{L}') \right\rangle_{\text{CMB}} - \phi^*(\mathbf{L}) \phi(\mathbf{L}') = (2\pi)^2 \, V[f](\mathbf{L}) \, \delta(\mathbf{L} - \mathbf{L}')$$

- Once you have that you can compute your power spectrum (with some complications)

$$\boxed{\hat{\phi}(\mathbf{L}) = N(\mathbf{L}) \mathbf{L} \cdot \int \frac{d^2 l}{(2\pi)^2} \frac{\mathbf{l} C_l}{C_l^{noisy}} \Theta(\mathbf{l}) \frac{C_{|L-l|}}{C_{|L-l|}^{noisy}} \overset{*}{\Theta}(\mathbf{l} - \mathbf{L})}$$

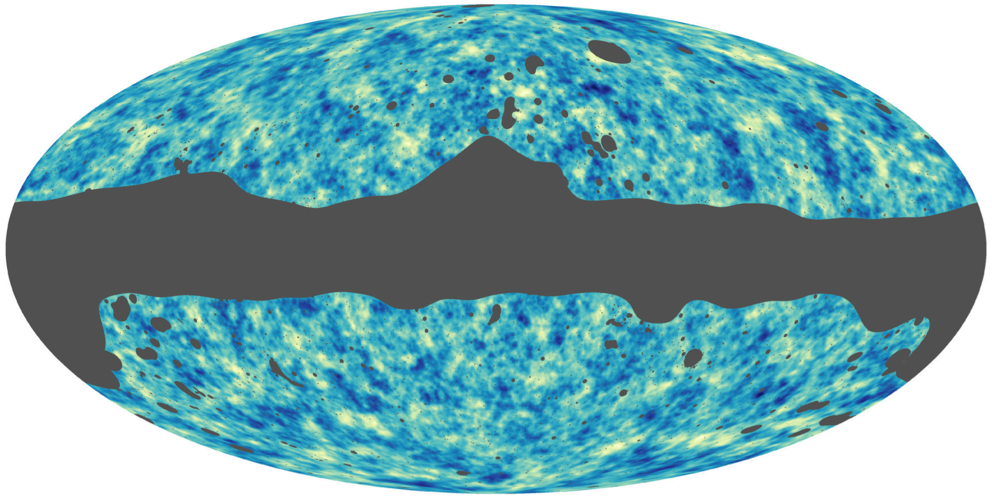
$$C_L^{\hat{\phi}\hat{\phi}} \sim \langle \tilde{\Theta}\tilde{\Theta}\tilde{\Theta}\tilde{\Theta} \rangle \rightarrow \langle \tilde{\Theta}\tilde{\Theta}\tilde{\Theta}\tilde{\Theta} \rangle - \langle \tilde{\Theta}\tilde{\Theta} \rangle \langle \tilde{\Theta}\tilde{\Theta} \rangle + \ldots = C_L^{\phi\phi} + N_0 + N_1 \ldots$$

- Similar estimators can be derived for polarization or temperature plus polarization.

- Better estimator can be derived to minimize spurious contaminations (e.g. foregrounds…)

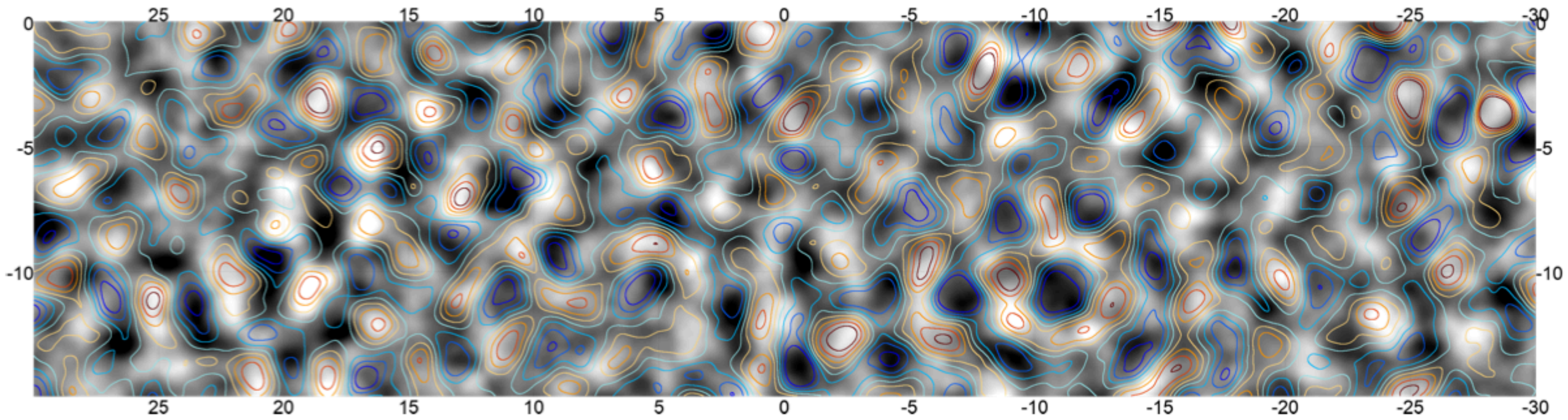
CMB lensing state of the art

Planck DR4 $|\mathbf{d}| = |\nabla\phi|$



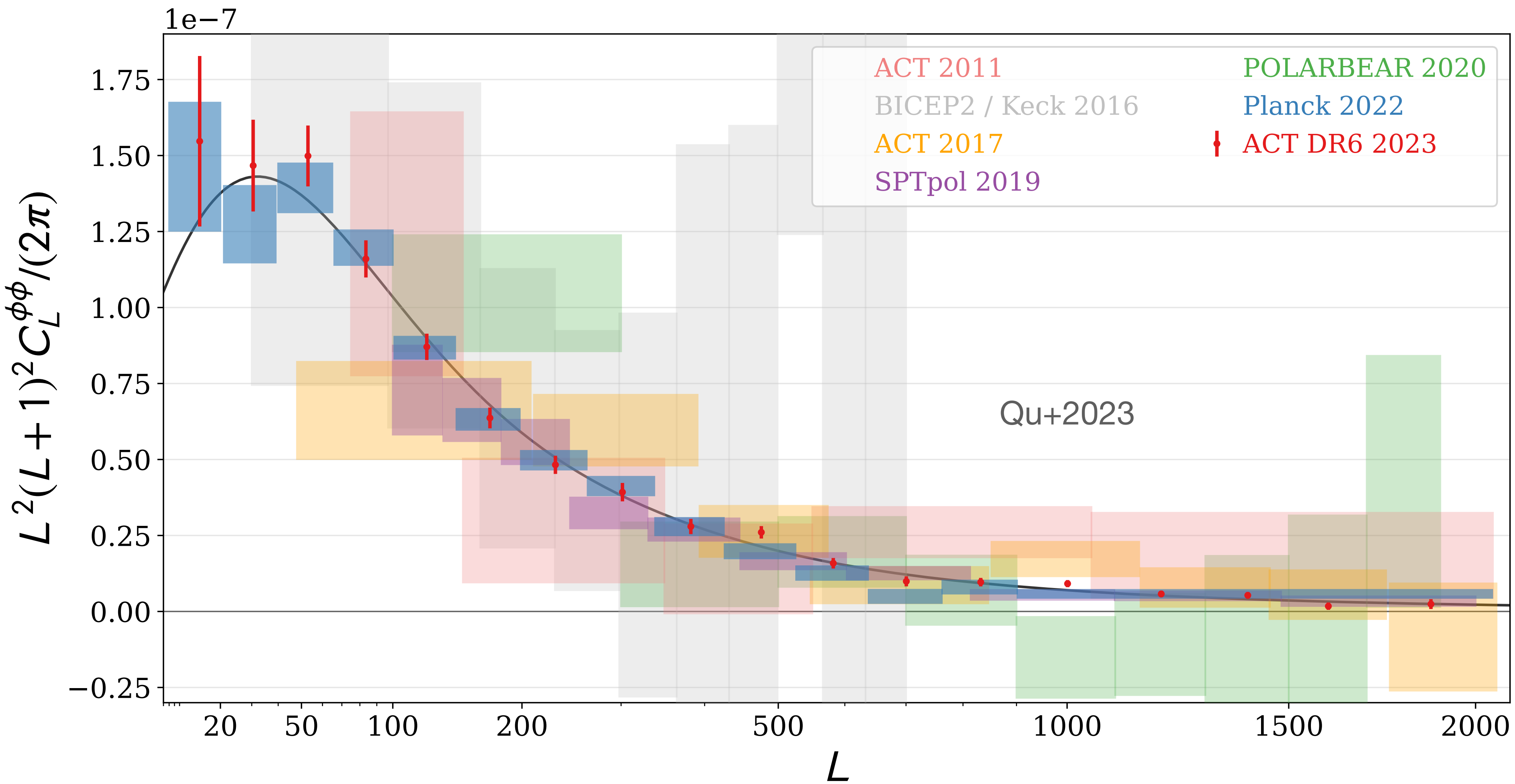
Planck (2018), Carron+(2022)

ACT (~40% sky, $\kappa \propto \nabla^2\phi$)



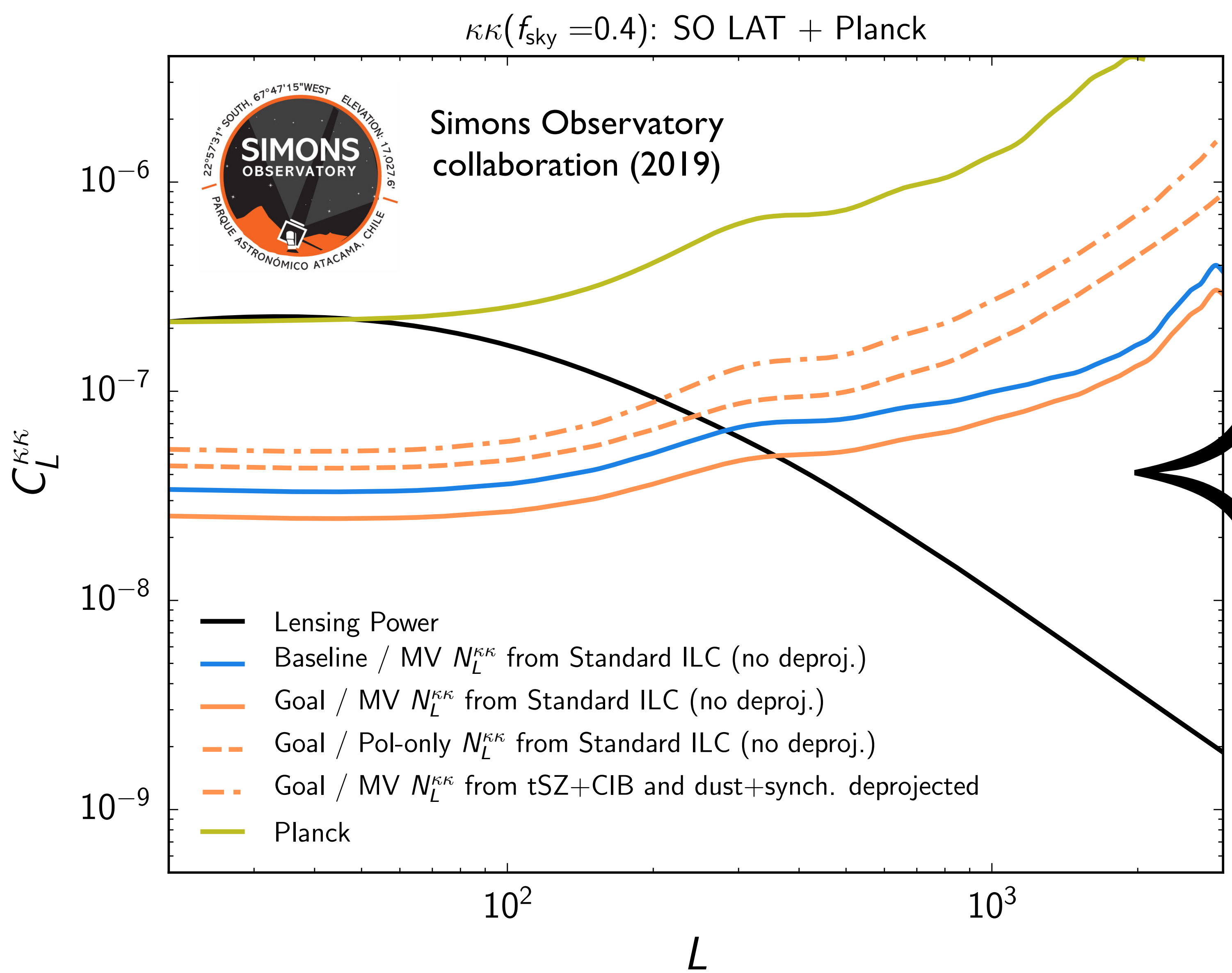
Madhavacheril+(2024), Qu+(2023).
See also Fe, Millea+(2024) for SPT on 1500deg2

40σ detection



What we expect in the coming years

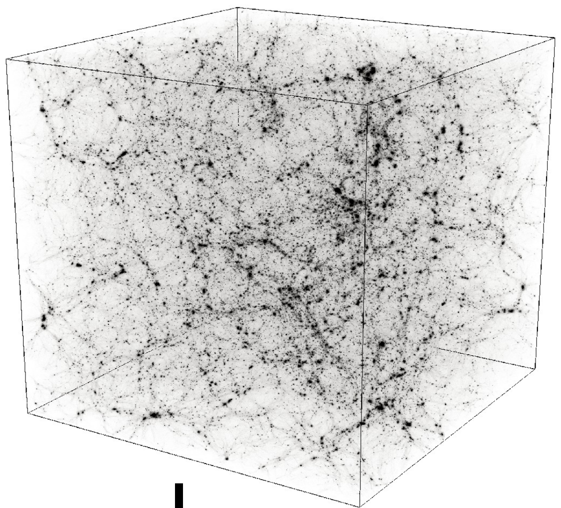
- First detection at 30% precision in ~2011, rapid progress but this is just the beginning.
- SO will measure CMB lensing potential at >100σ significance, even higher precision for S4.
- CMB lensing will soon start imaging non-linear structures on large sky fractions



- Instrumental effects.
- Analysis systematics / new estimators
- Theoretical systematics
- Galactic and extragalactic foregrounds.

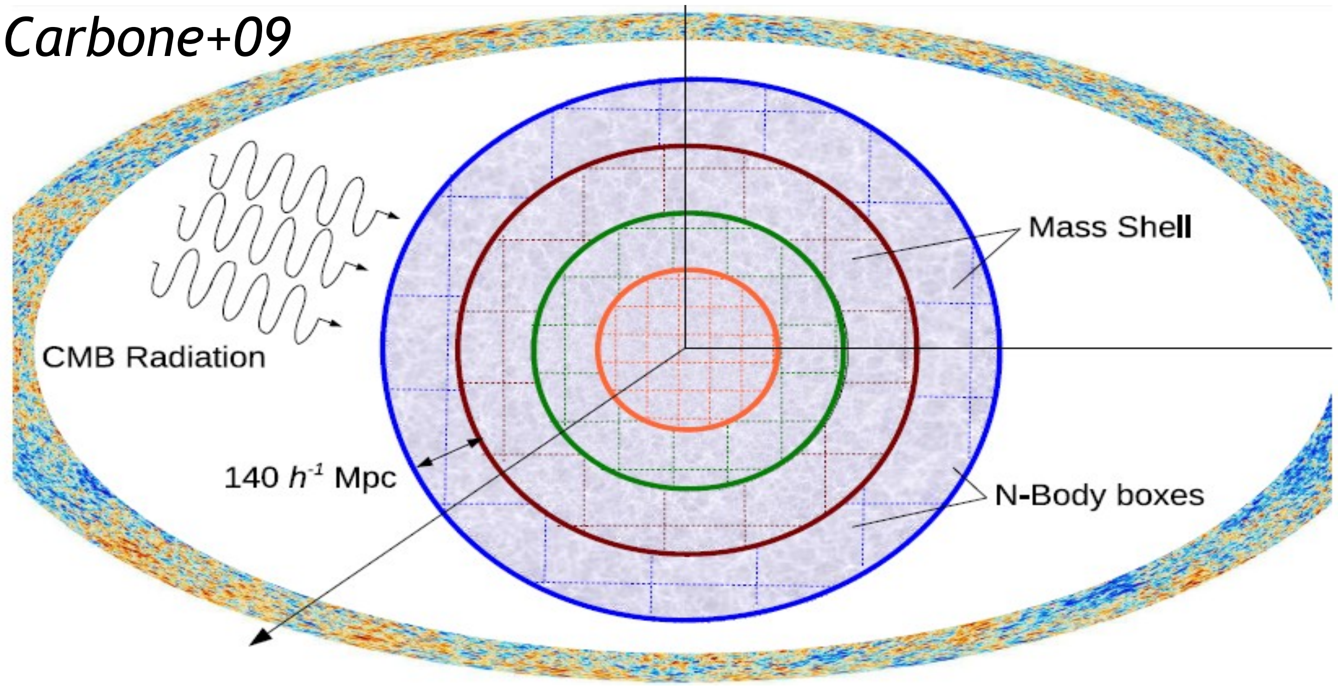
Towards a coherent modeling of lensing

- Lensing depends on matter and we know matter is not a Gaussian random field…



+

Carbone+09



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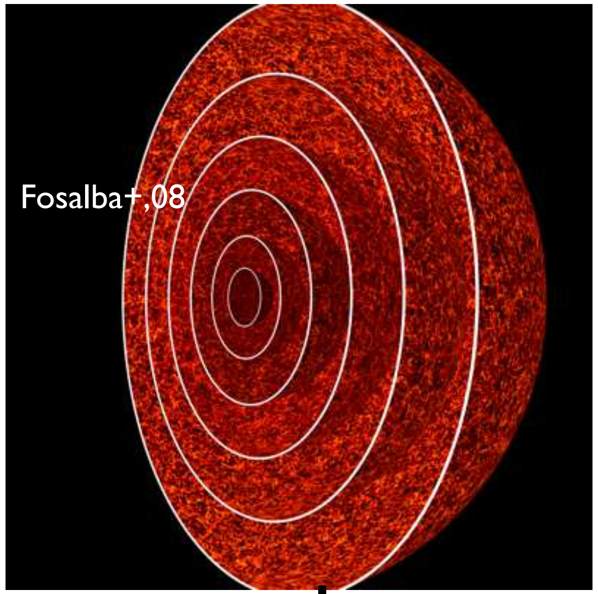
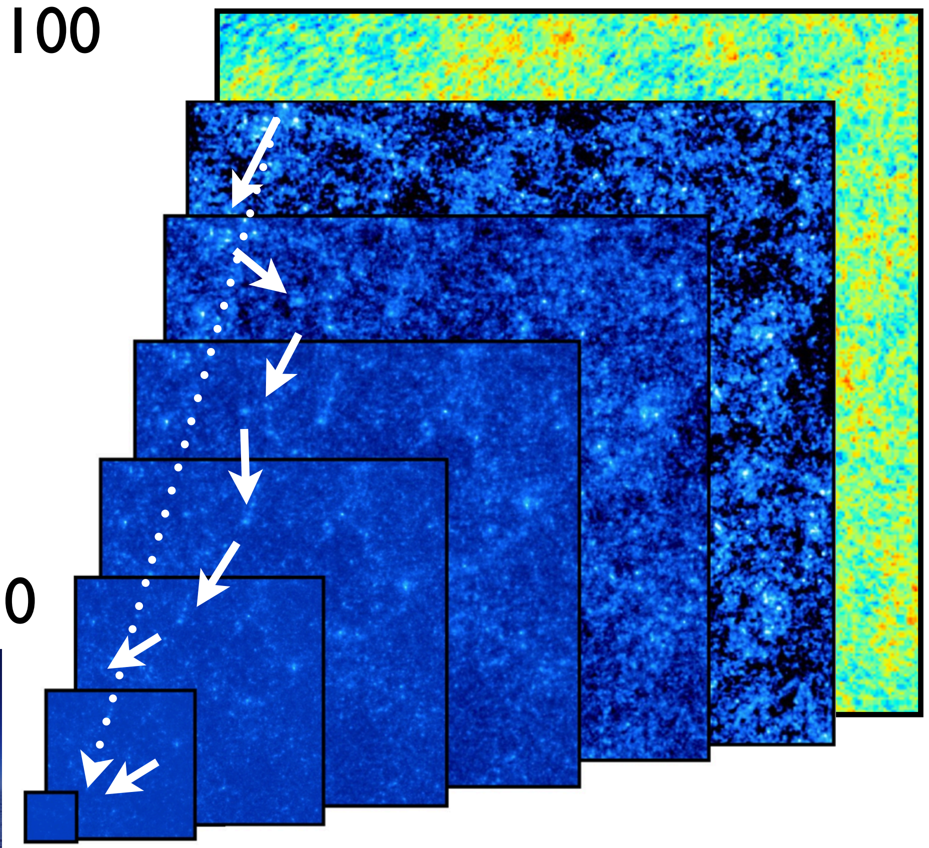


z = 1100



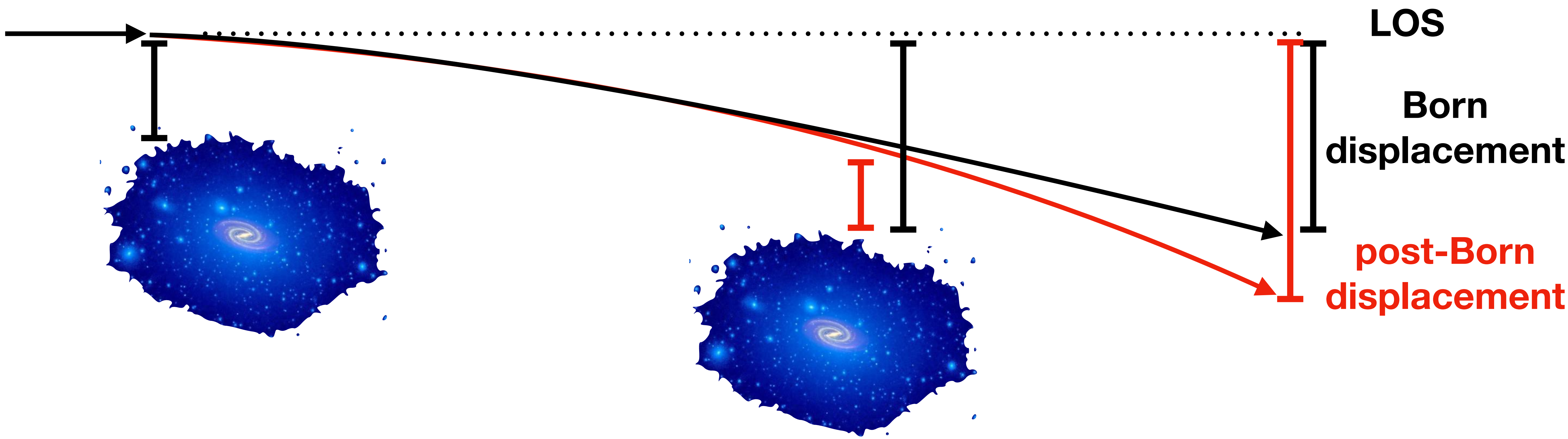
z = 0

- Non-linearities fully accounted

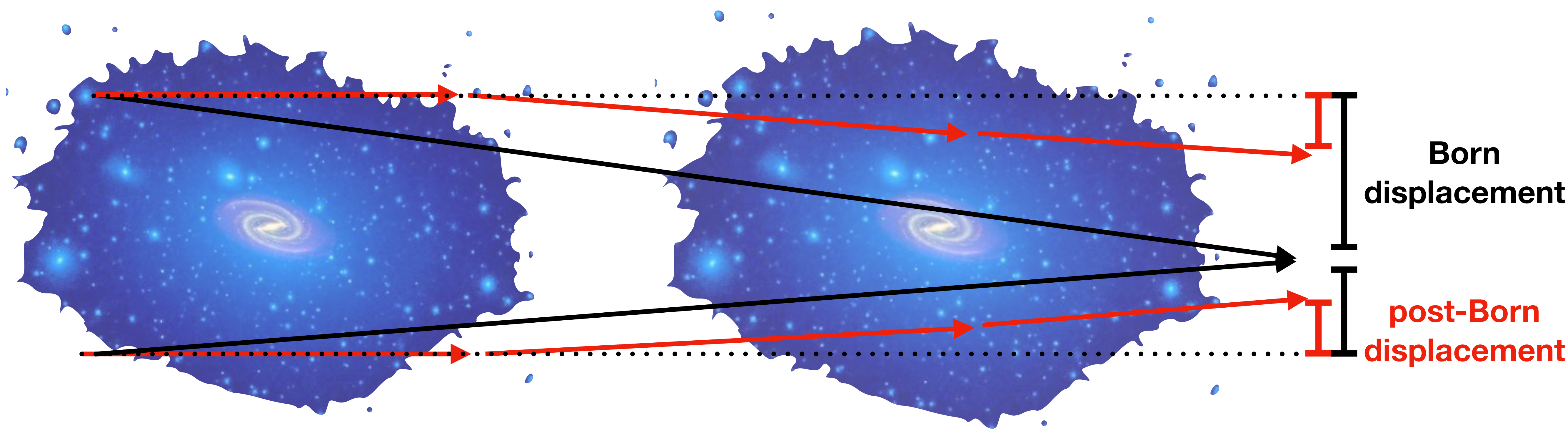
- Realistic photon diffusion propagation

Carbone+(2009)
Calabrese+(2015)
Lewis+(2016,2017)
Pratten+(2017)
Fanizza+(2016)
Fabbian+(2018)

Post-Born corrections: what are they?



Lensing changes location of later lensing events

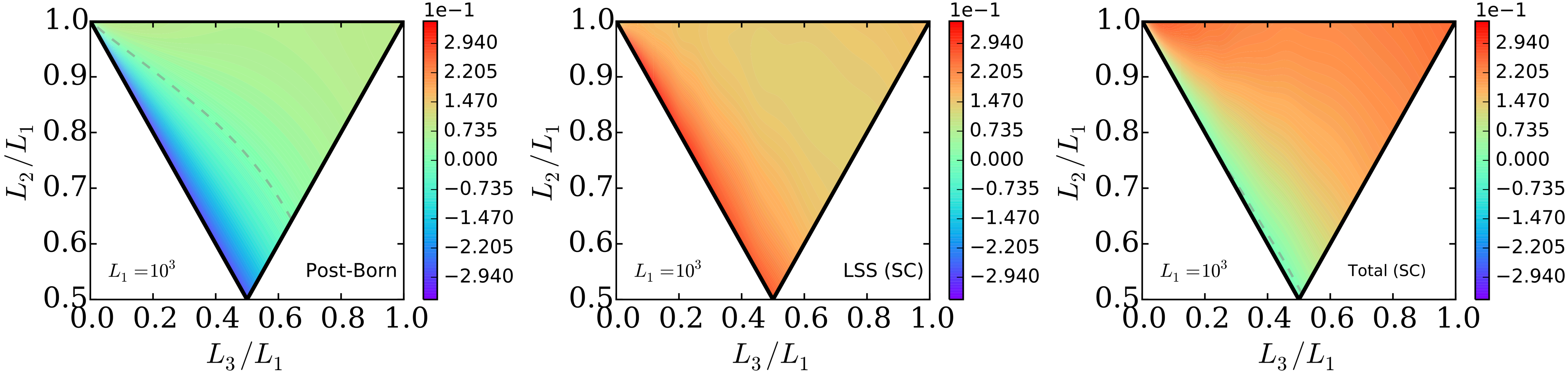


Size and shape of image affected by first lensing event

Higher-order biases in CMB lensing estimation

Pratten & Lewis (2016)
Fabbian+(2018)

$$(L_2 L_3)^{1/2}\, b^{\kappa\kappa\kappa}_{L_1 L_2 L_3} / (C^{\kappa\kappa}_{L_1} C^{\kappa\kappa}_{L_2} C^{\kappa\kappa}_{L_3})^{1/2}$$



$$\hat{\phi}(\mathbf{L}) = A_L \int_{\mathbf{l}} g(\mathbf{l},\mathbf{L}) \tilde{T}_{\rm expt}(\mathbf{l}) \tilde{T}_{\rm expt}(\mathbf{L}-\mathbf{l})$$

$$\tilde{T}(\mathbf{l}) = T(\mathbf{l}) + \delta T(\mathbf{l}) + \delta^2 T(\mathbf{l}) + \mathcal{O}(\phi^3) \qquad \delta T(\mathbf{l}) = -\int_{\mathbf{l}'} \mathbf{l}' \cdot (\mathbf{l}-\mathbf{l}') T(\mathbf{l}') \phi(\mathbf{l}-\mathbf{l}')$$

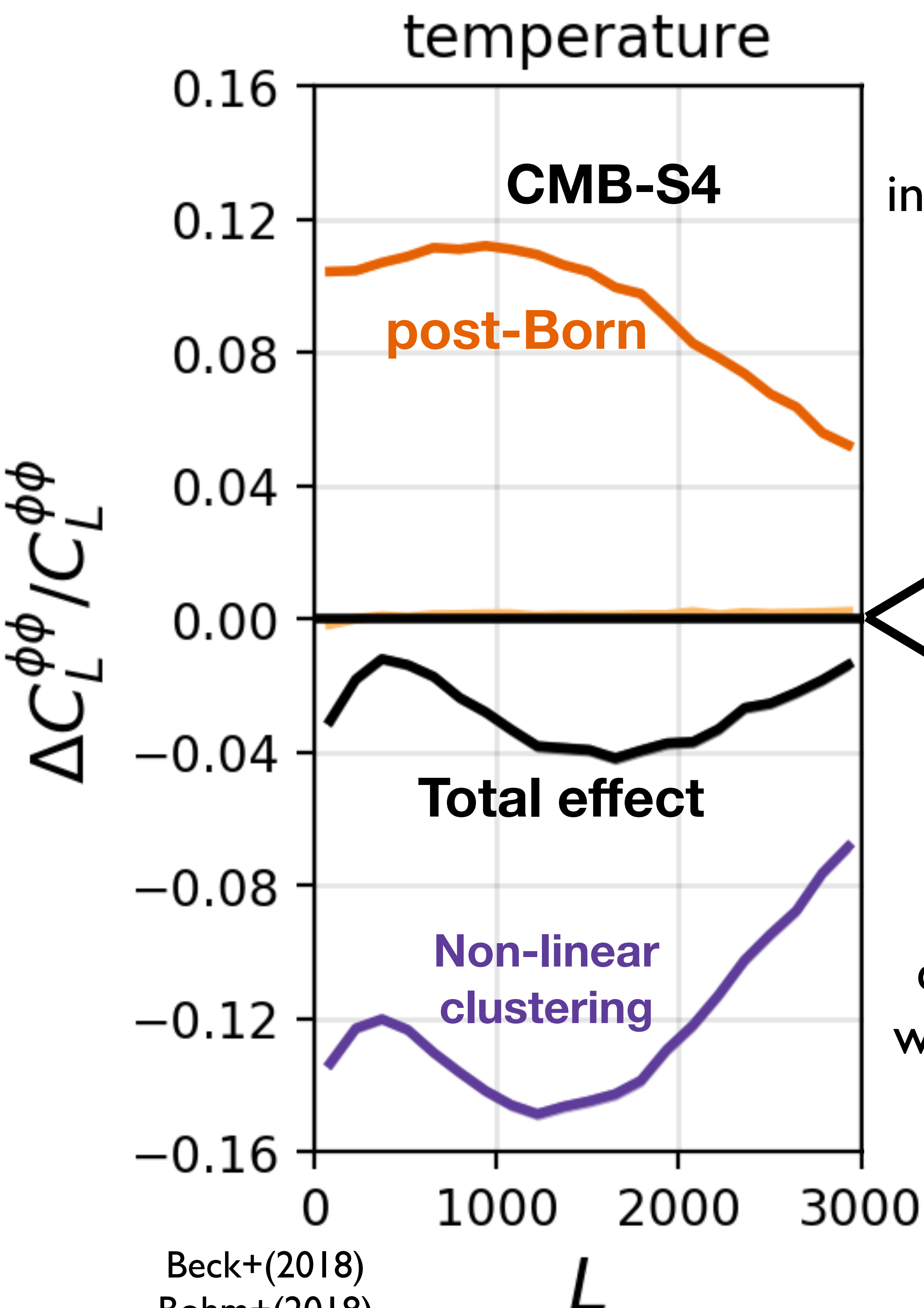
$$\langle \tilde{T}\tilde{T}\tilde{T}\tilde{T} \rangle = \langle \delta T \delta T \delta T T \rangle + \cdots = \langle T_{,i}\phi_{,i} T_{,j}\phi_{,j} T_{,k}\phi_{,k} T \rangle + \cdots$$

Böhm+(2016)

$$C^{TT}_l B_\phi(\mathbf{l}_1 - \mathbf{l}, \mathbf{l}_2 + \mathbf{l}, -\mathbf{l}_1 - \mathbf{l}_2)$$

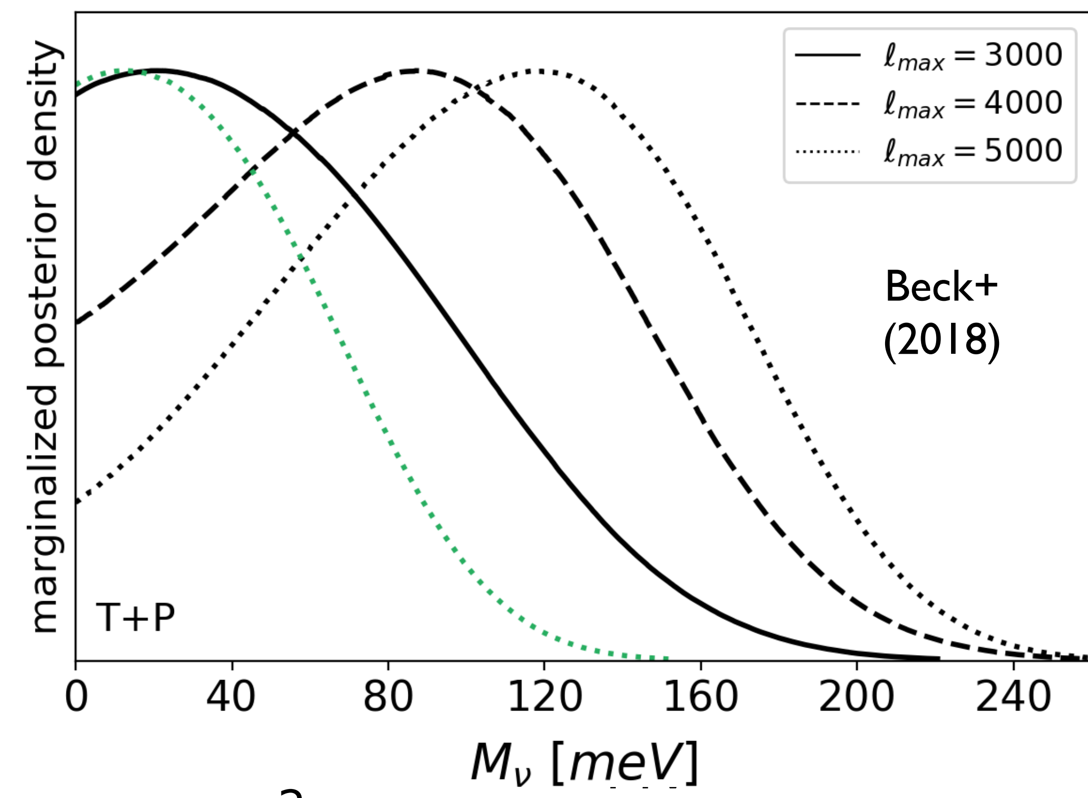
Non-Gaussian effects in reconstructed $\phi(N^{3/2})$

$$C_L^{\hat{\phi}\hat{\phi}} \sim C_L^{\phi\phi} + N_L^0 + N_L^1 + N_L^{3/2}$$



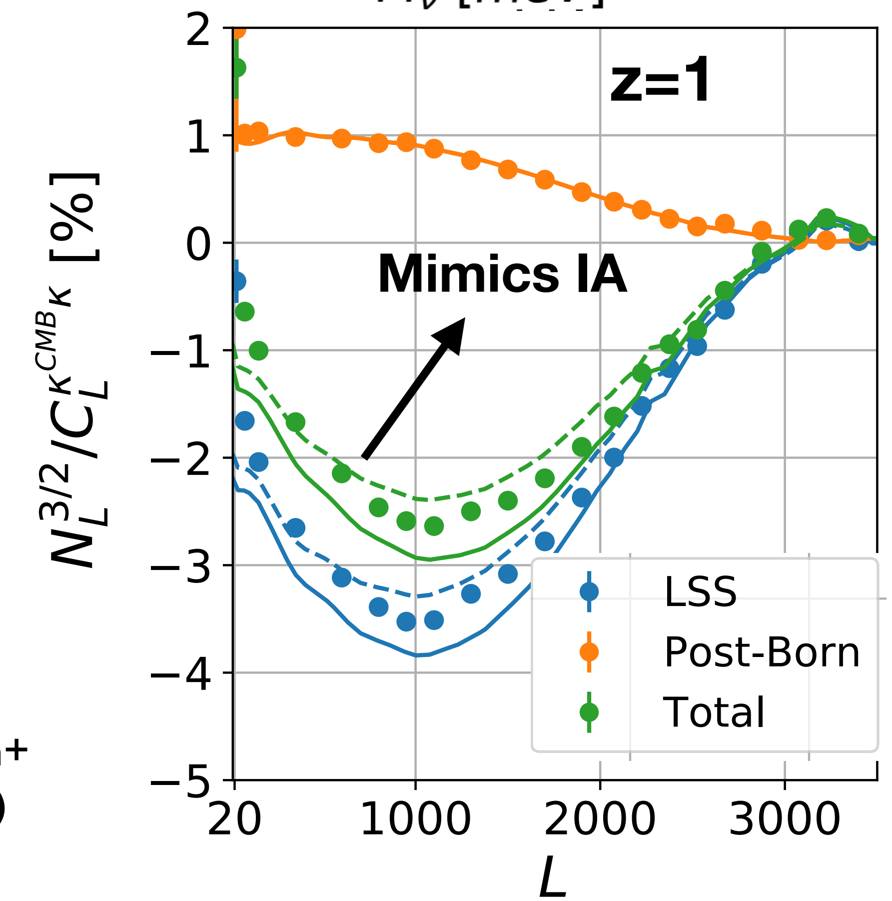
Beck+(2018)
Bohm+(2018)

Biases or inconsistencies in cosmological parameters



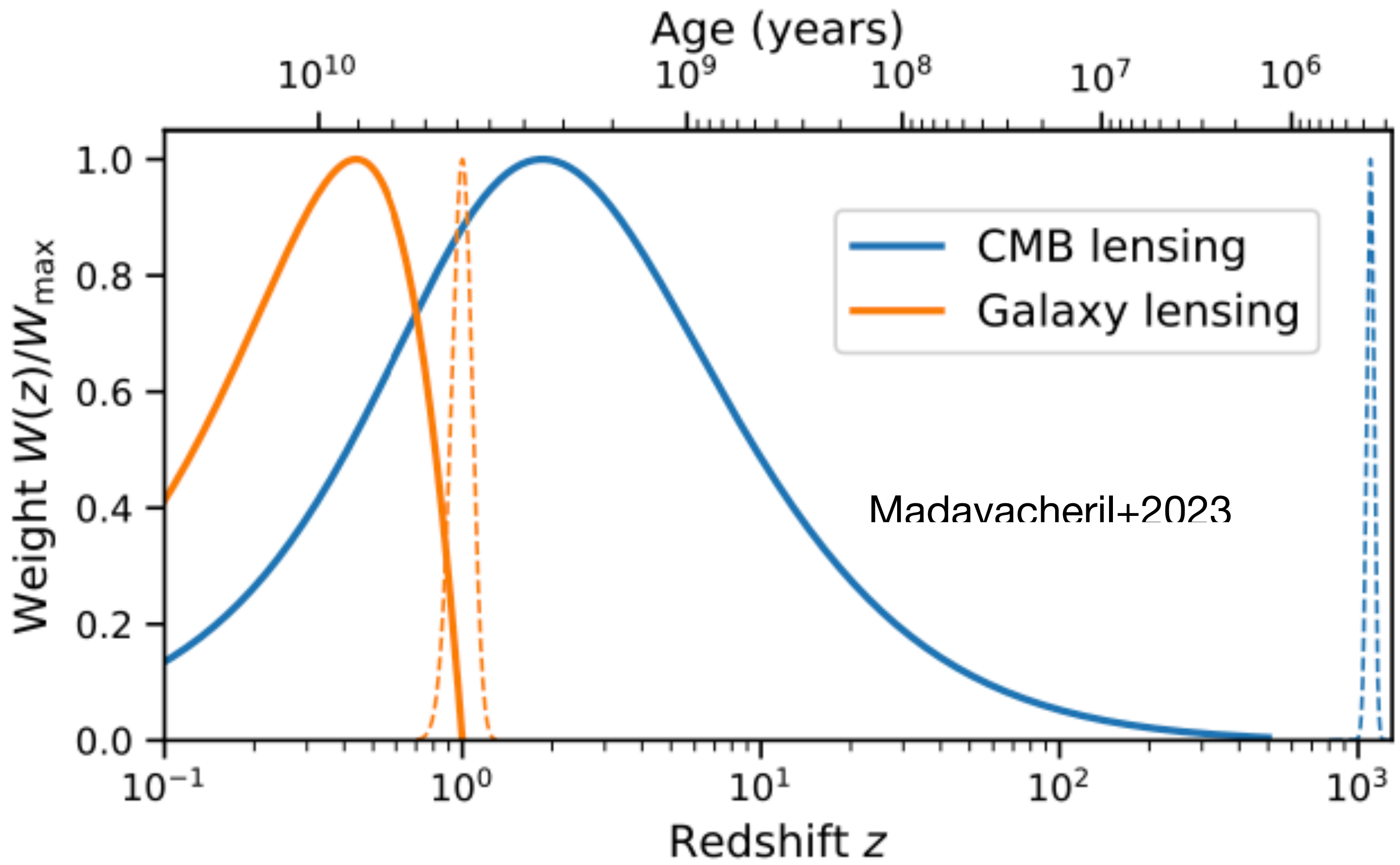
Nasty effects in cross-correlation with galaxy surveys

Fabbian+ (2019)



CMB probes and cross-correlation

- CMB lensing: integrated, 2D projected, unbiased probe of matter.
- Integrated = overlaps with all the matter in the universe.
- Synergies with any other probe of matter e.g. LSS surveys.
- Reduces systematics



$$\kappa_{gal,obs} = \kappa_{gal} + s_{gal} \qquad \kappa_{CMB,obs} = \kappa_{CMB} + s_{CMB}$$

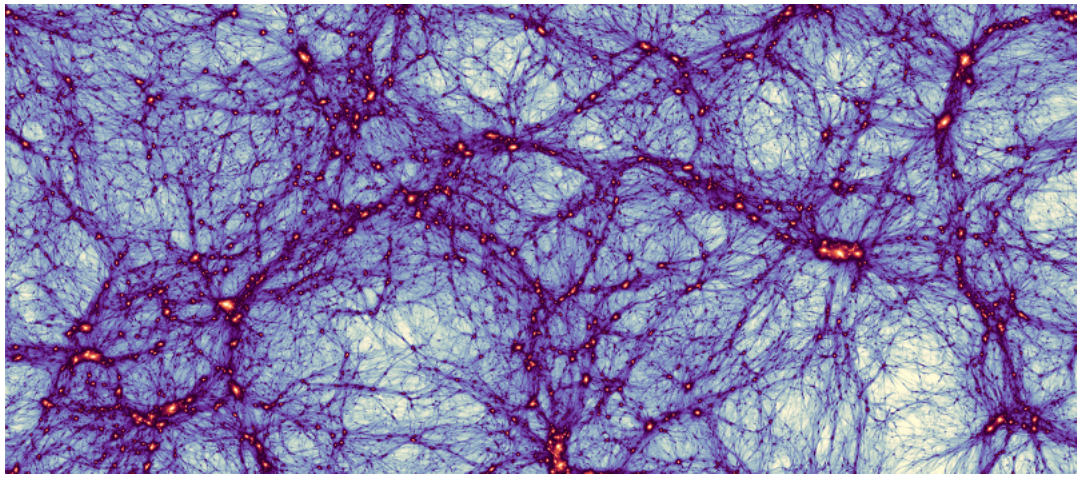
$$\langle \kappa_{gal,obs} \kappa_{gal,obs} \rangle = \langle \kappa_{gal} \kappa_{gal} \rangle + \langle s_{gal} s_{gal} \rangle + \langle \kappa_{gal} s_{gal} \rangle$$

$$\langle \kappa_{CMB,obs} \kappa_{CMB,obs} \rangle = \langle \kappa_{CMB} \kappa_{CMB} \rangle + \langle s_{CMB} s_{CMB} \rangle + \langle \kappa_{CMB} s_{CMB} \rangle$$

$$\langle \kappa_{CMB,obs} \kappa_{gal,obs} \rangle = \langle \kappa_{CMB} \kappa_{gal} \rangle + \cancel{\langle s_{CMB} s_{gal} \rangle} + \cancel{\langle \kappa_{CMB} s_{gal} \rangle} + \cancel{\langle \kappa_{gal} s_{CMB} \rangle}$$

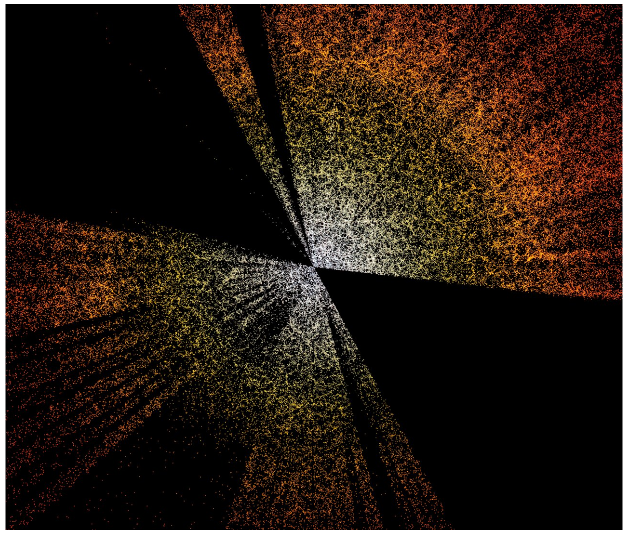
Beyond CMB observations

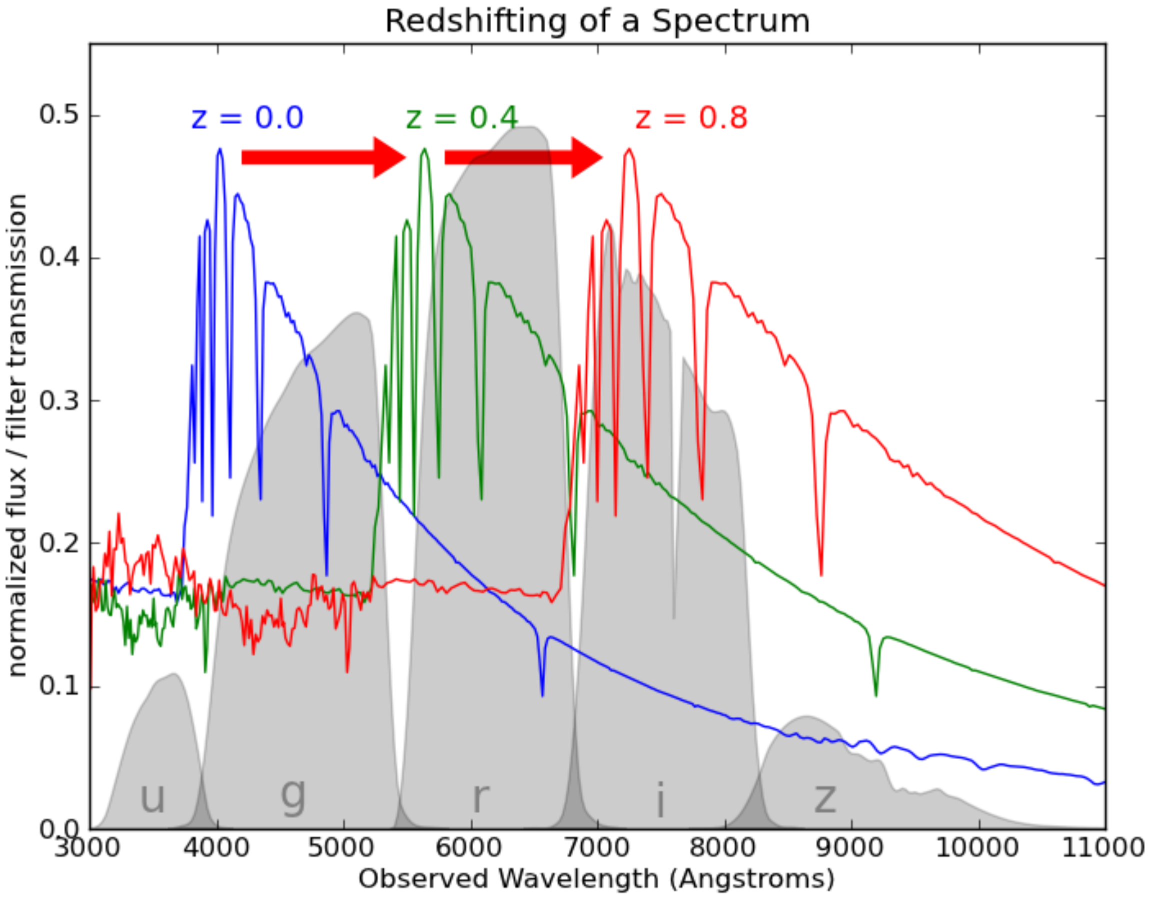
- Observing matter distributions as it grows: we need "tracers"



$f[\delta_m]$ →

- Spectroscopic surveys (e.g. DESI, Euclid)

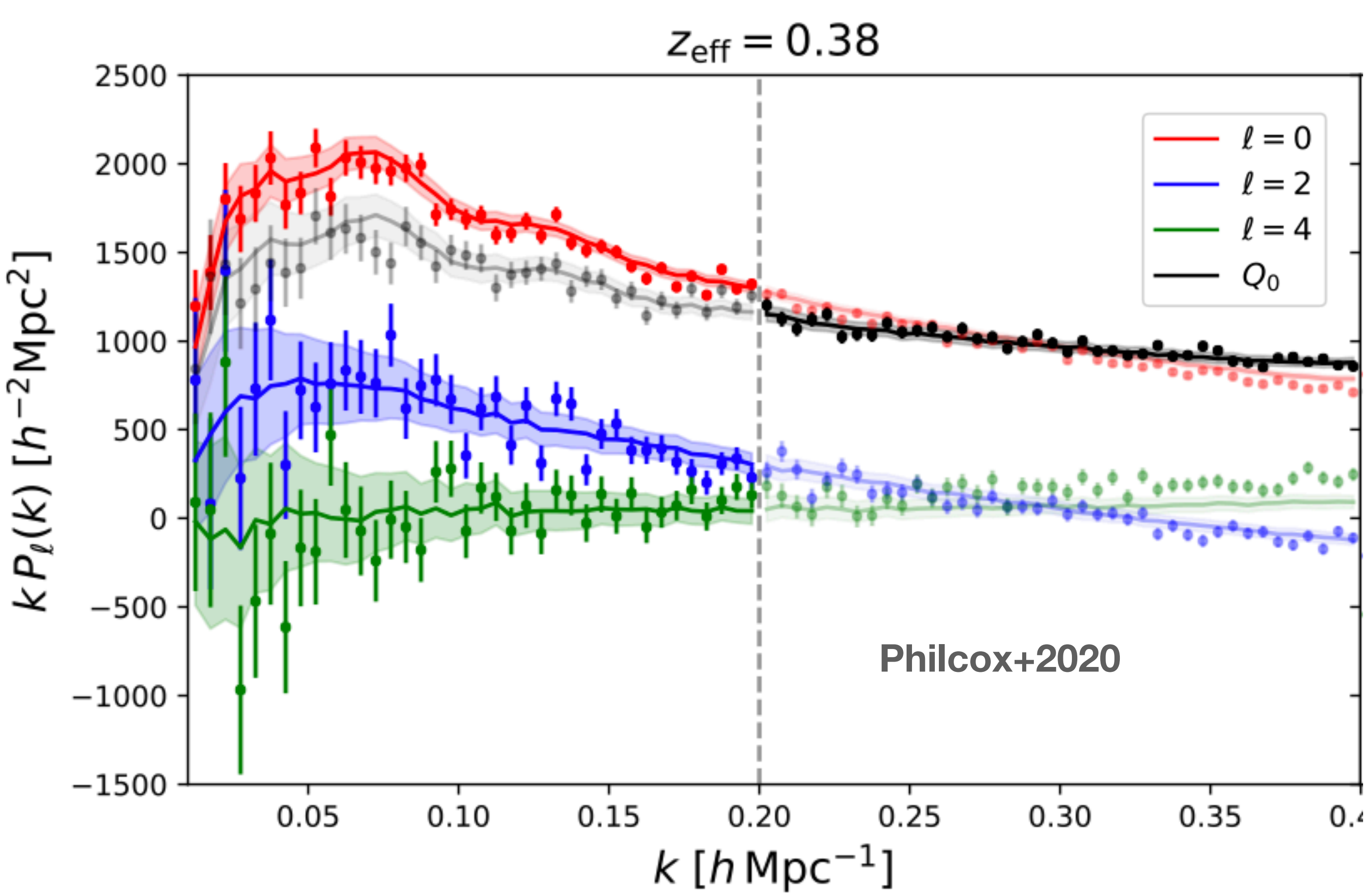


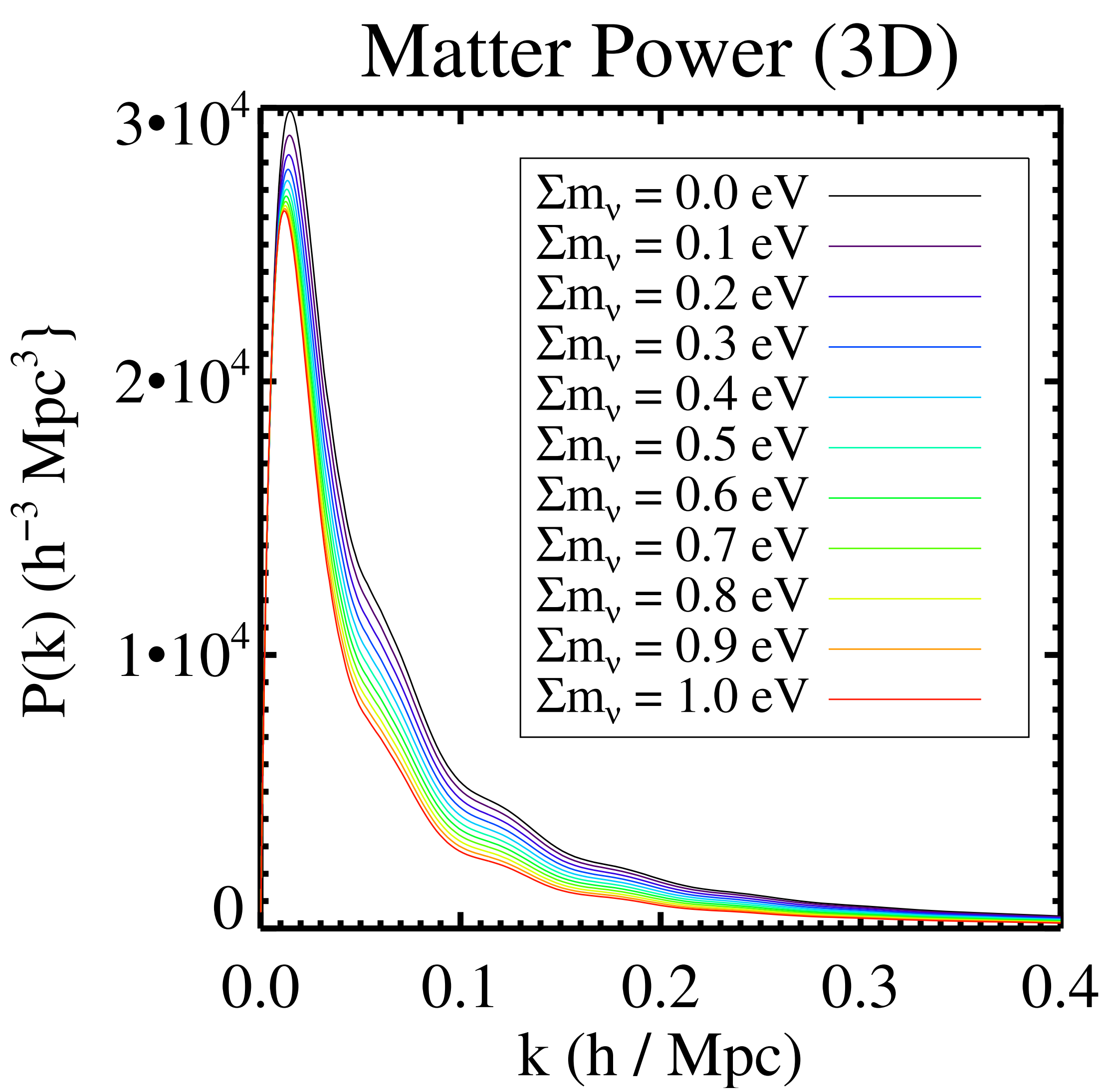


- Photometric surveys (e.g. Rubin, Euclid)

Cosmological probes: galaxy clustering

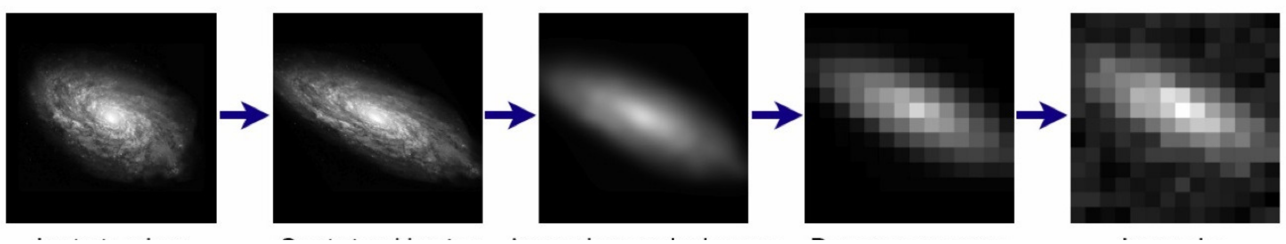
- CMB alone is weakly sensitive to the details of recent growth rate of LSS
- To test LCDM model large scale structures offer invaluable tomographic help!
- Galaxy clustering: P(k), BAO, RSD, voids are more sensitive but are local, biased, non-linear tracers…

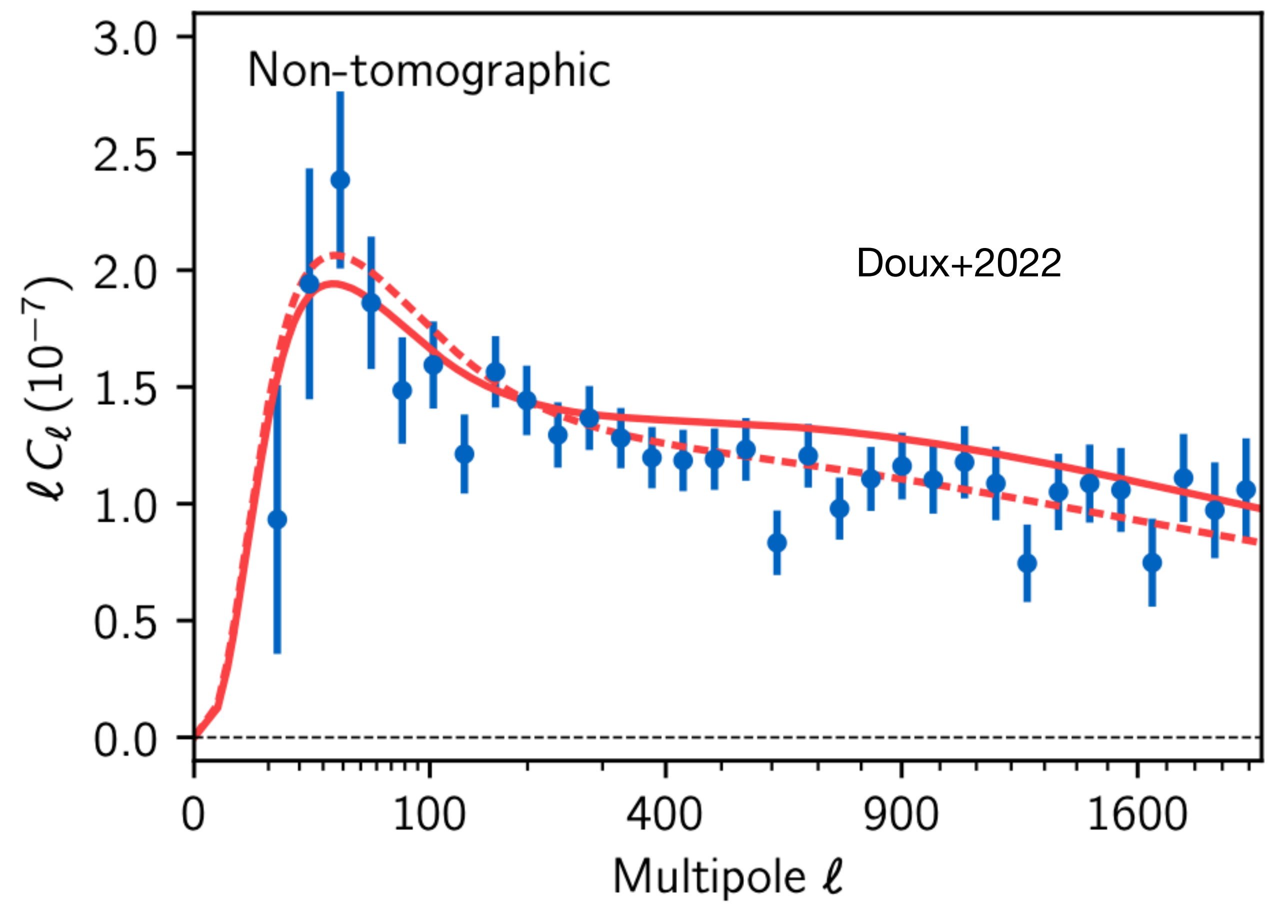




Cosmological probes: weak lensing

- Galaxy ellipticity: correlated by the presence of dark matter through lensing.
- $$C^{\gamma}_{ij}(\ell) = \frac{2}{\pi}\, t^2(\ell,2)\, \mathcal{A}^2 \int_0^\infty \frac{\mathrm{d}\chi}{\chi} \frac{q_i(\chi)}{a(\chi)} \int_0^\infty \frac{\mathrm{d}\chi'}{\chi'} \frac{q_j(\chi')}{a(\chi')} \int_0^\infty \frac{\mathrm{d}k}{k^2} P_{\mathrm{m}}(k,\chi,\chi')\, \mathrm{j}_\ell(k\chi)\, \mathrm{j}_\ell(k\chi')$$

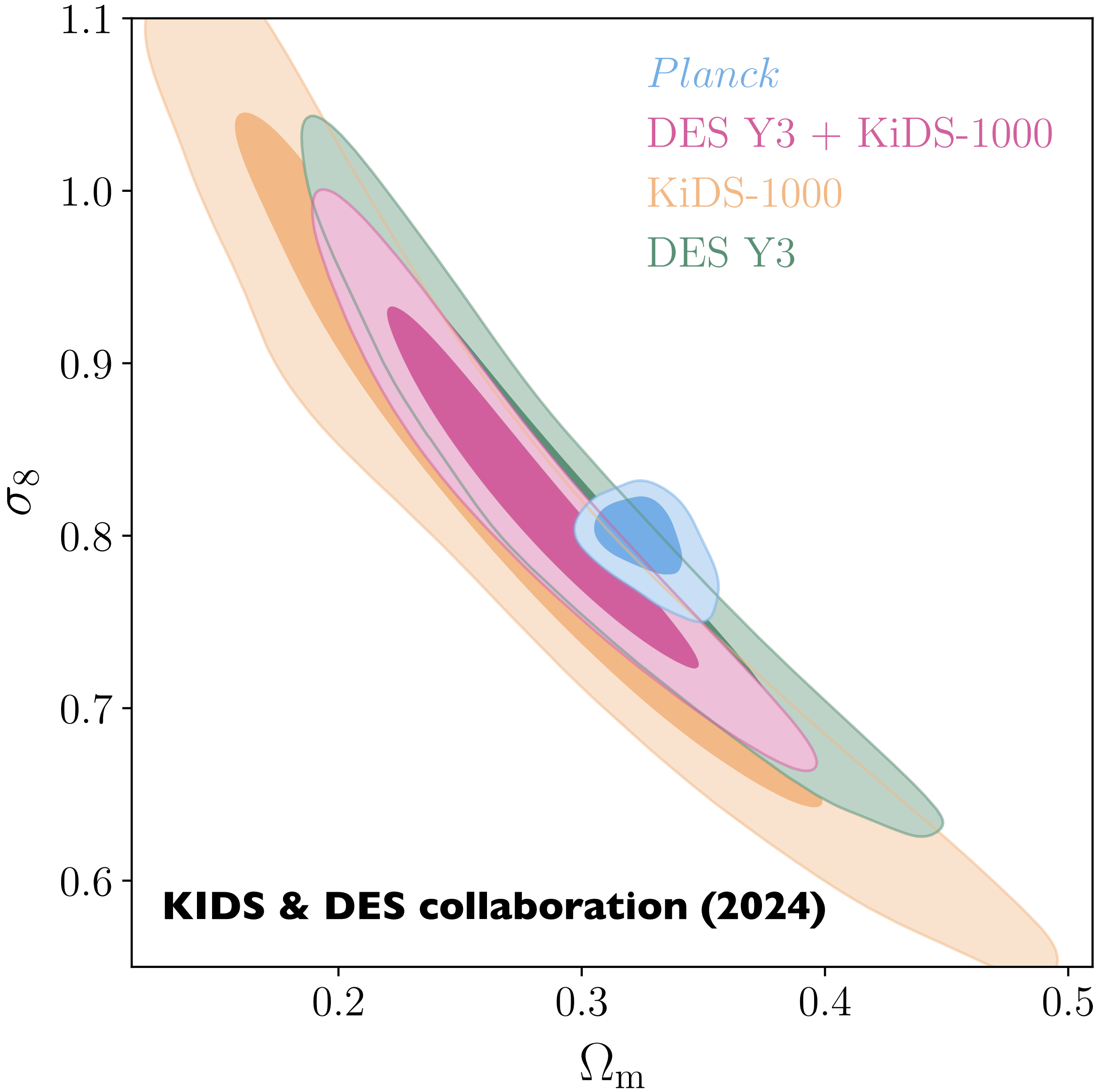


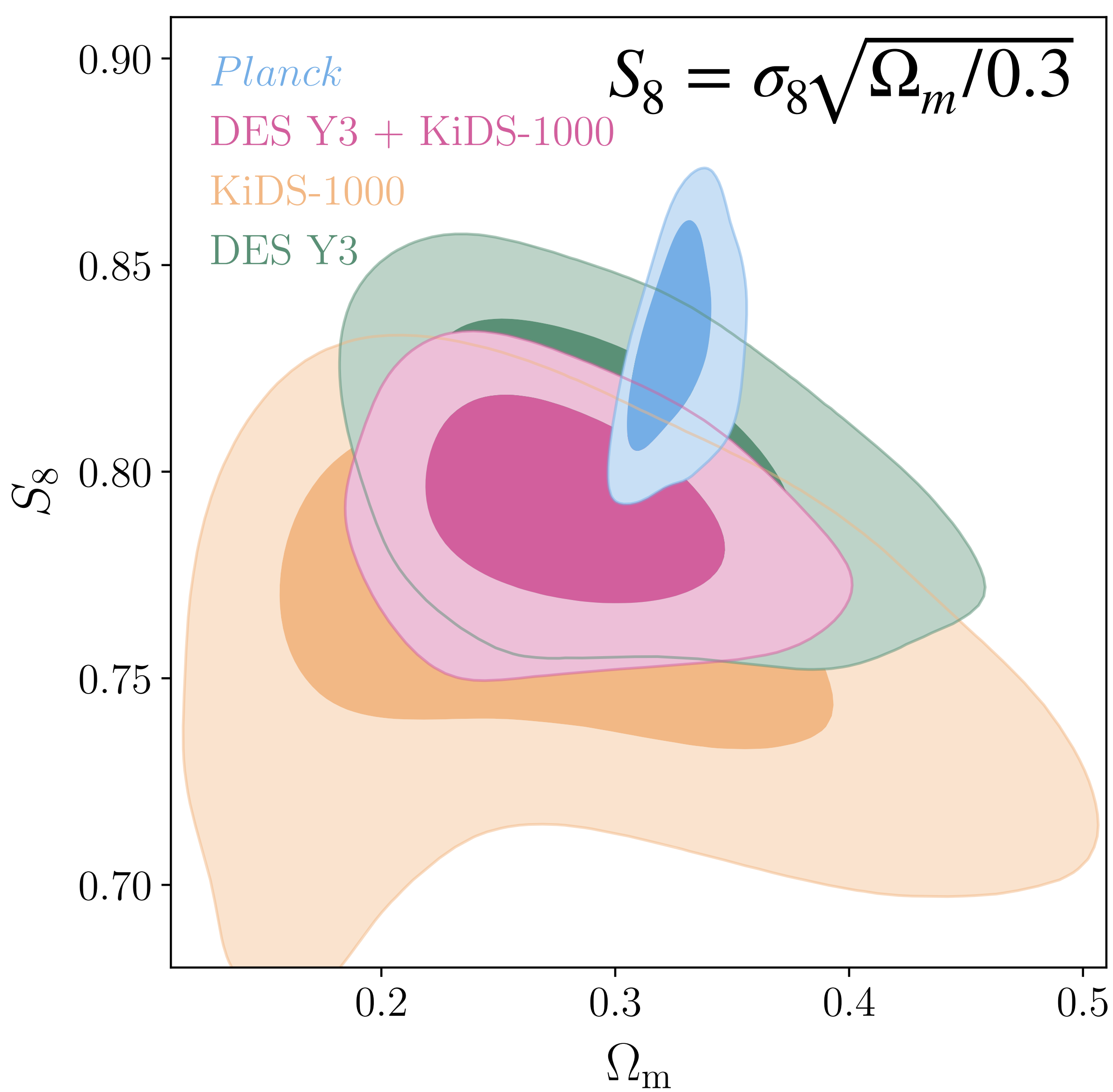


- Galaxy intrinsic alignment: $\langle \hat{\gamma}\hat{\gamma} \rangle = \langle \gamma\gamma \rangle + \langle \epsilon^s \epsilon^s \rangle + \langle \gamma \epsilon^s \rangle$
- PSF, noise and lensed galaxies' distribution: $\hat{\gamma} = (1+m)\gamma + \mathbf{n}$

3x2pt in large-scale structure surveys

- Galaxy clustering: local, growth rate $C_\ell^{gg} \propto b_g^2 \sigma_8^2$
- Weak lensing /shear: LOS integrated, sensitive to amplitude of fluctuations S_8.
- Shear + galaxy-shear: sensitive to $\partial C_\ell / \partial P(k)$, $C_\ell^{g\gamma} \propto b_g \sigma_8^2$





Cross-correlation basis and examples

CMB lensing

$$C_L^{AB} \approx \int \frac{d\chi}{\chi^2} W_A(\chi) W_B(\chi) P_\delta \left(k = \frac{L+1/2}{\chi}, z(\chi)\right)$$

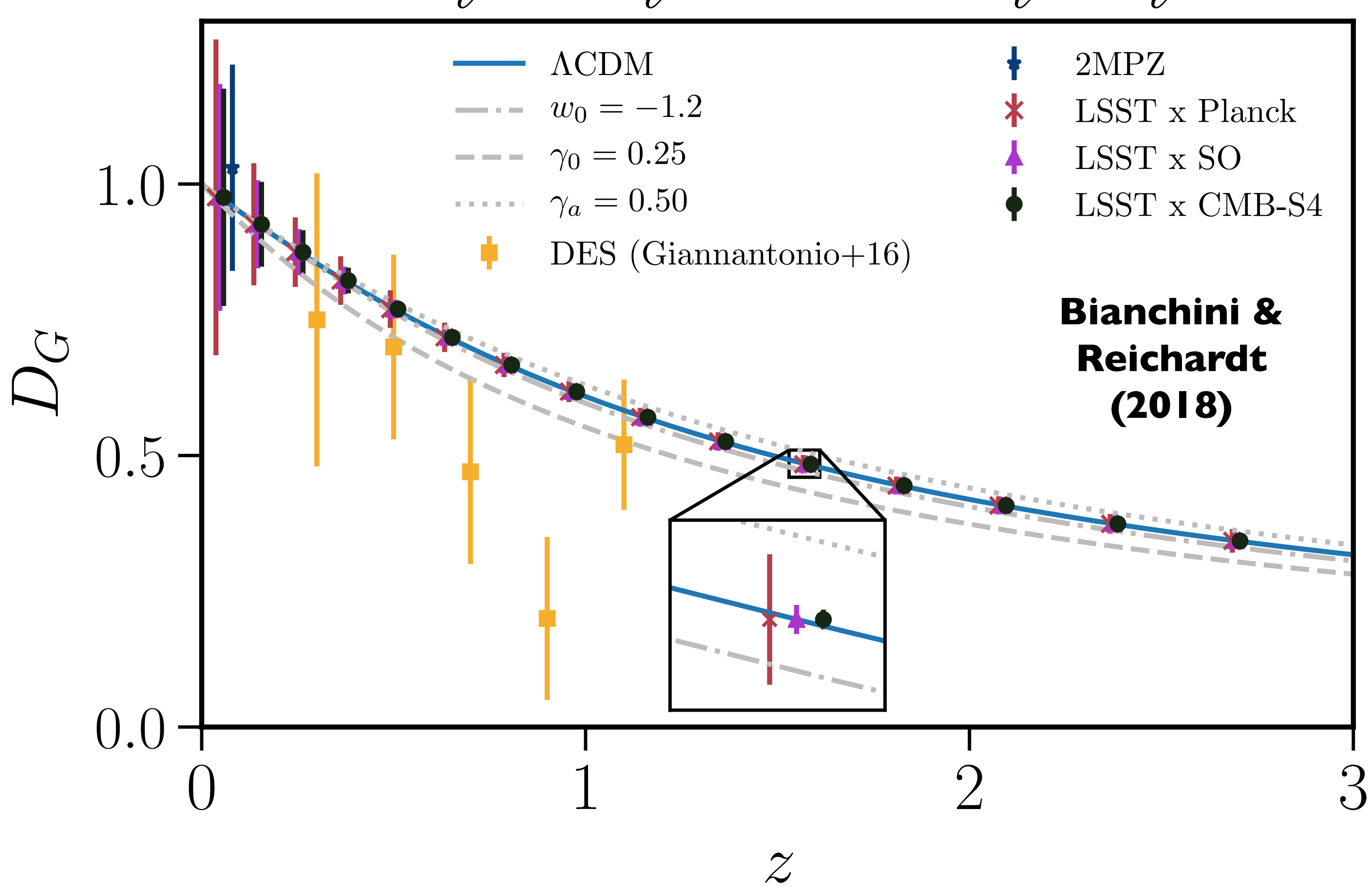
Galaxy clustering

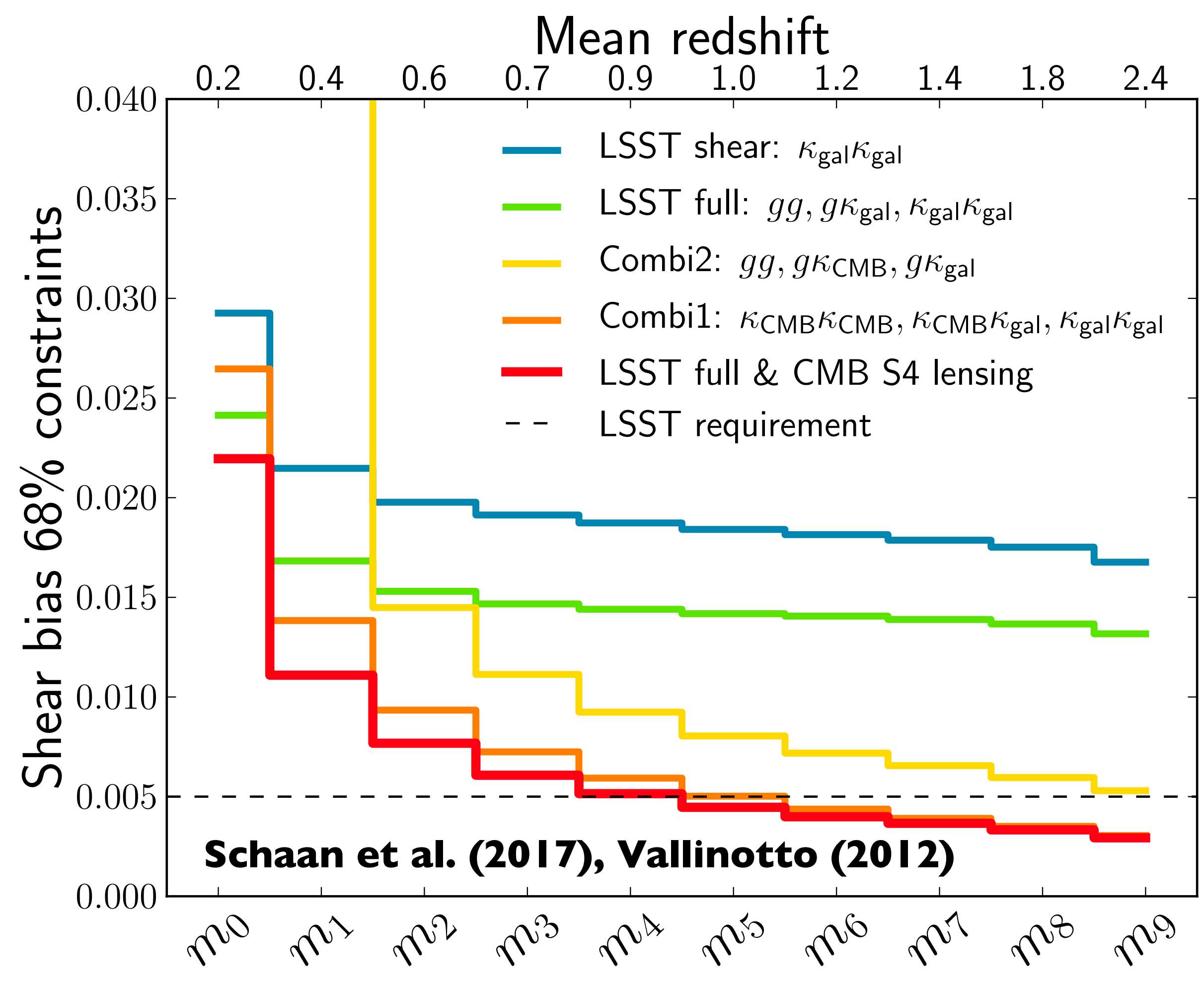
$$W_g(\chi) = b_g(z) \frac{1}{n}\frac{dn}{dz}\frac{dz}{d\chi}$$

Galaxy lensing

$$W_\kappa(\chi, \chi_s) = \gamma(\chi)\chi^2 \left(\frac{1}{\chi} - \frac{1}{\chi_s}\right) \Theta(\chi_s - \chi)$$

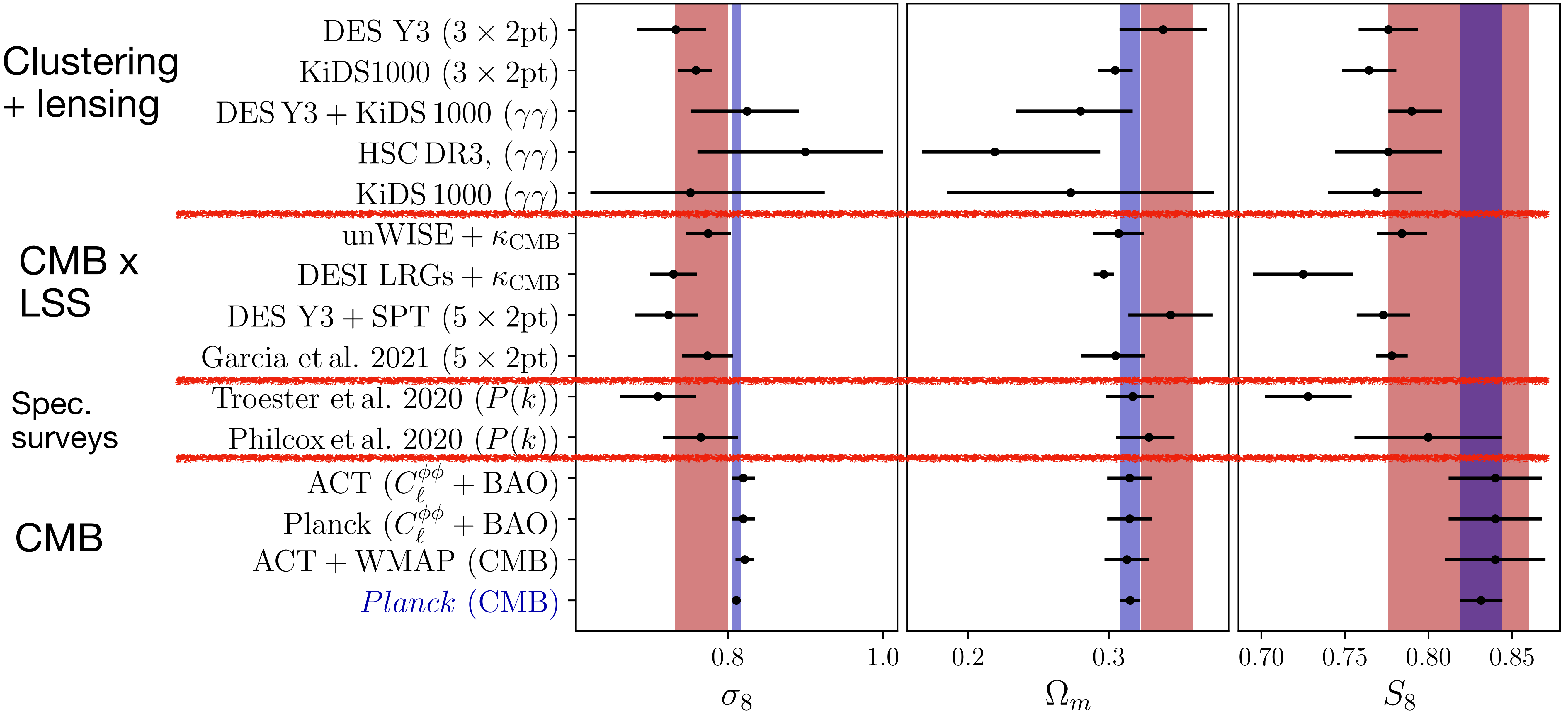
$$D_G \approx (C_\ell^{\kappa g})^2 / C_\ell^{gg} \approx \hat{\boldsymbol{\theta}} \in \{C_\ell^{\kappa g}, C_\ell^{gg}\}$$





State of the art on tensions (neglecting H0)

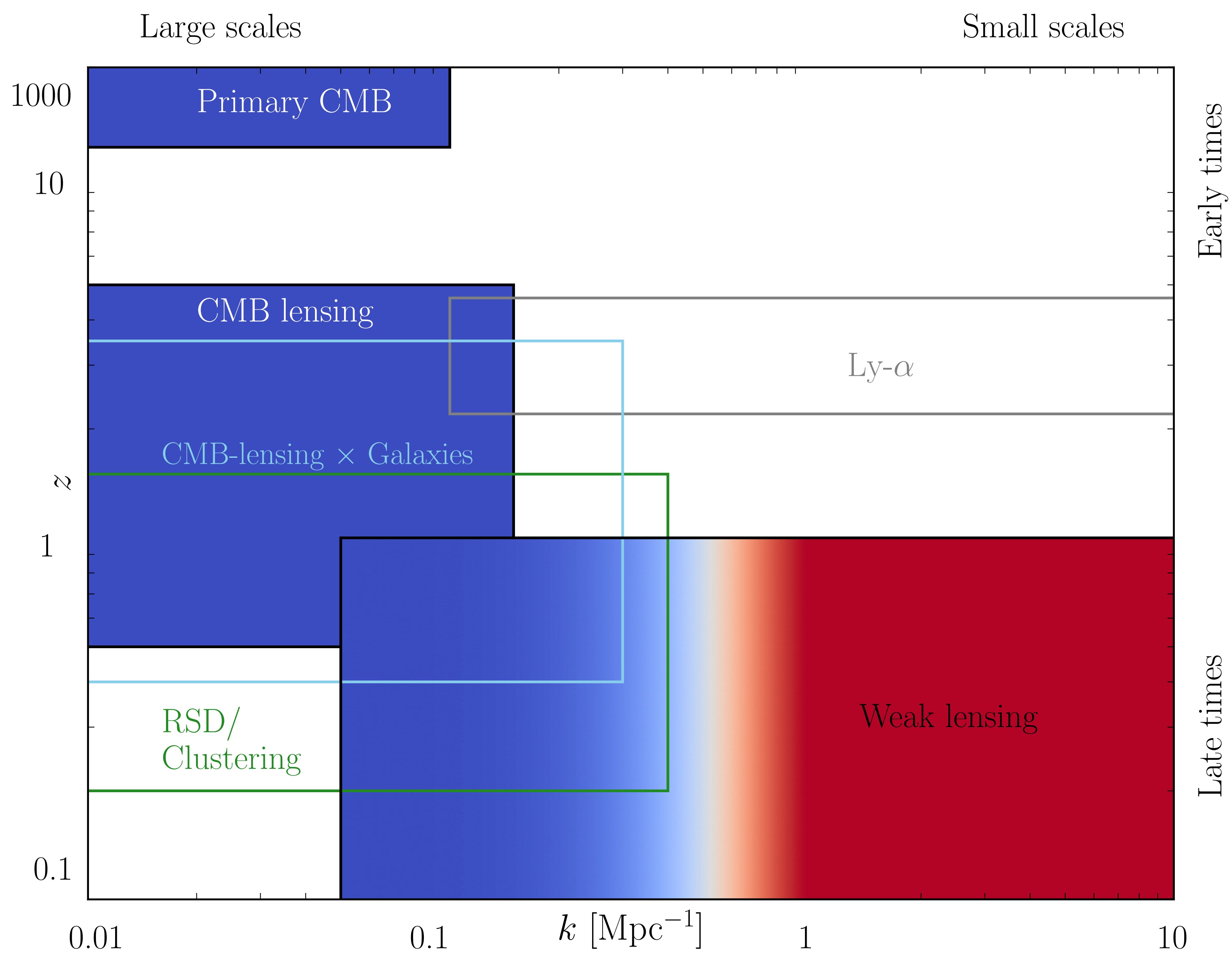
- Lots of inconsistencies and agreement across data sets
- Is inconsistency between probes a consequence of new physics?



Alonso, Fabbian, Storey-Fisher+(2023)

Ways forward

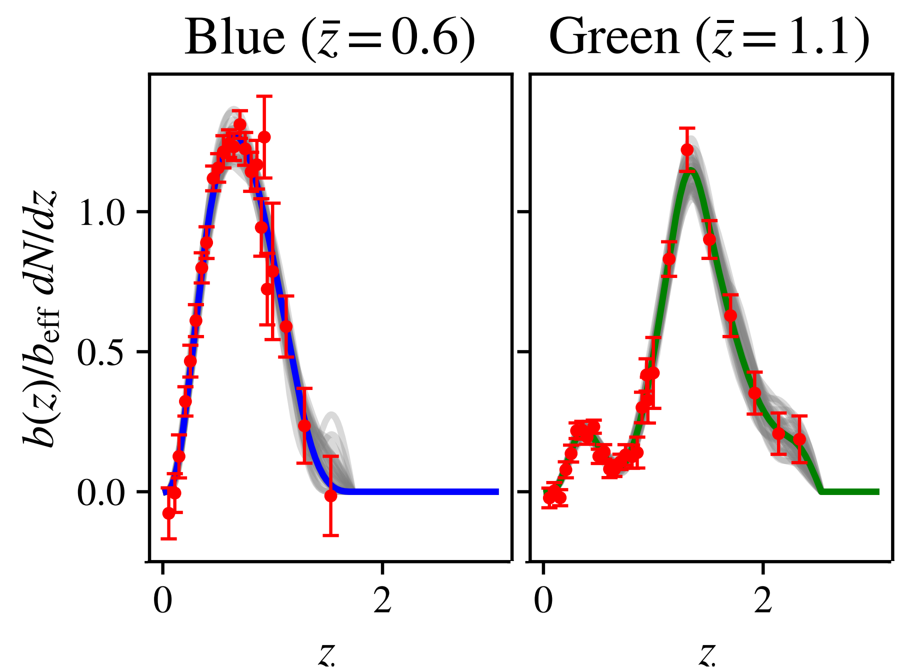
- Different probes means different scales at different redshift…
- Need to assess if this is real or effects of non-linear physics.

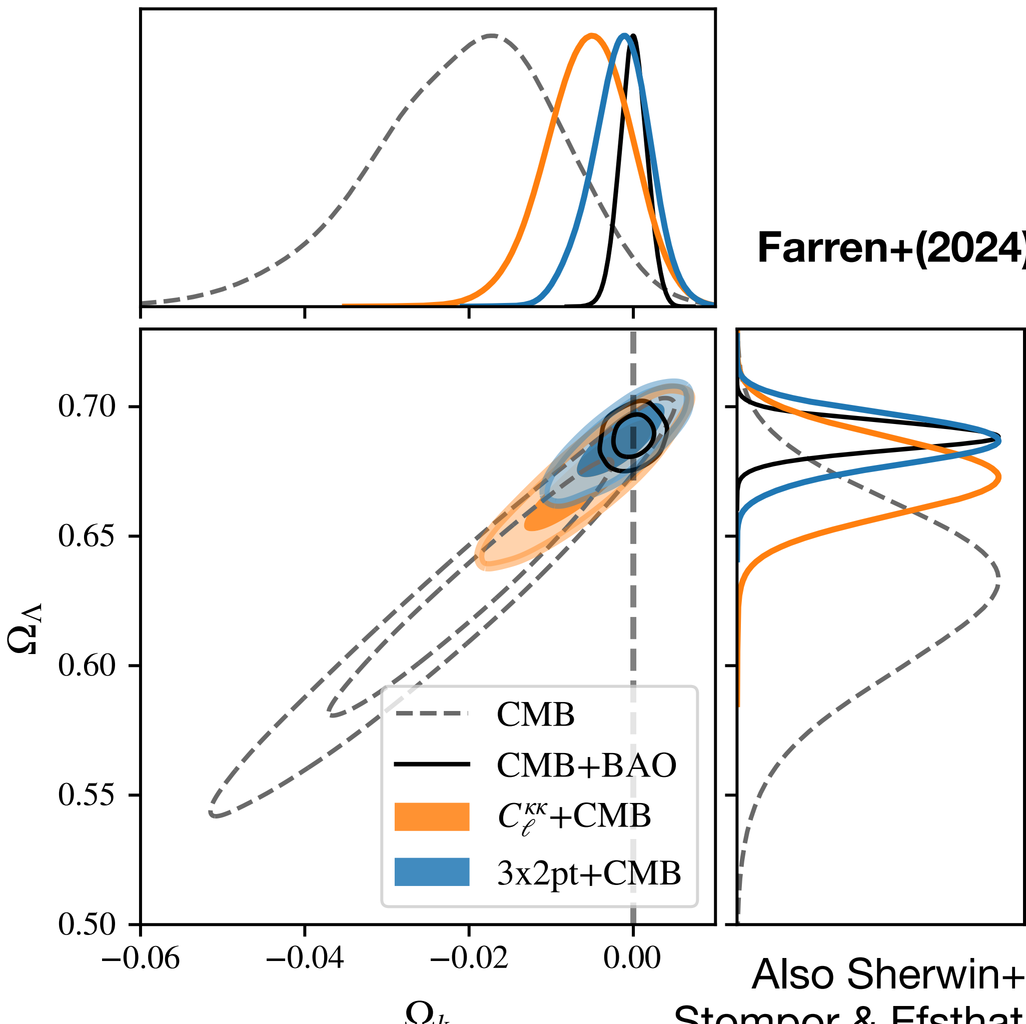


Preston, Amon, Efsthathiou (2023)

CMB lensing x galaxies: state of the art 1

- 6xp2t w/ UNWISE x ACT DR6 & Planck PR4: in agreement with CMB primary
- UNWISe Green / blue galaxies at z~0.6 / 1.1
- Tensions limited to $k \gtrsim 0.3\ h/\mathrm{Mpc}$ in $0.2 \leq z \leq 1.6$ (from 2x2pt)

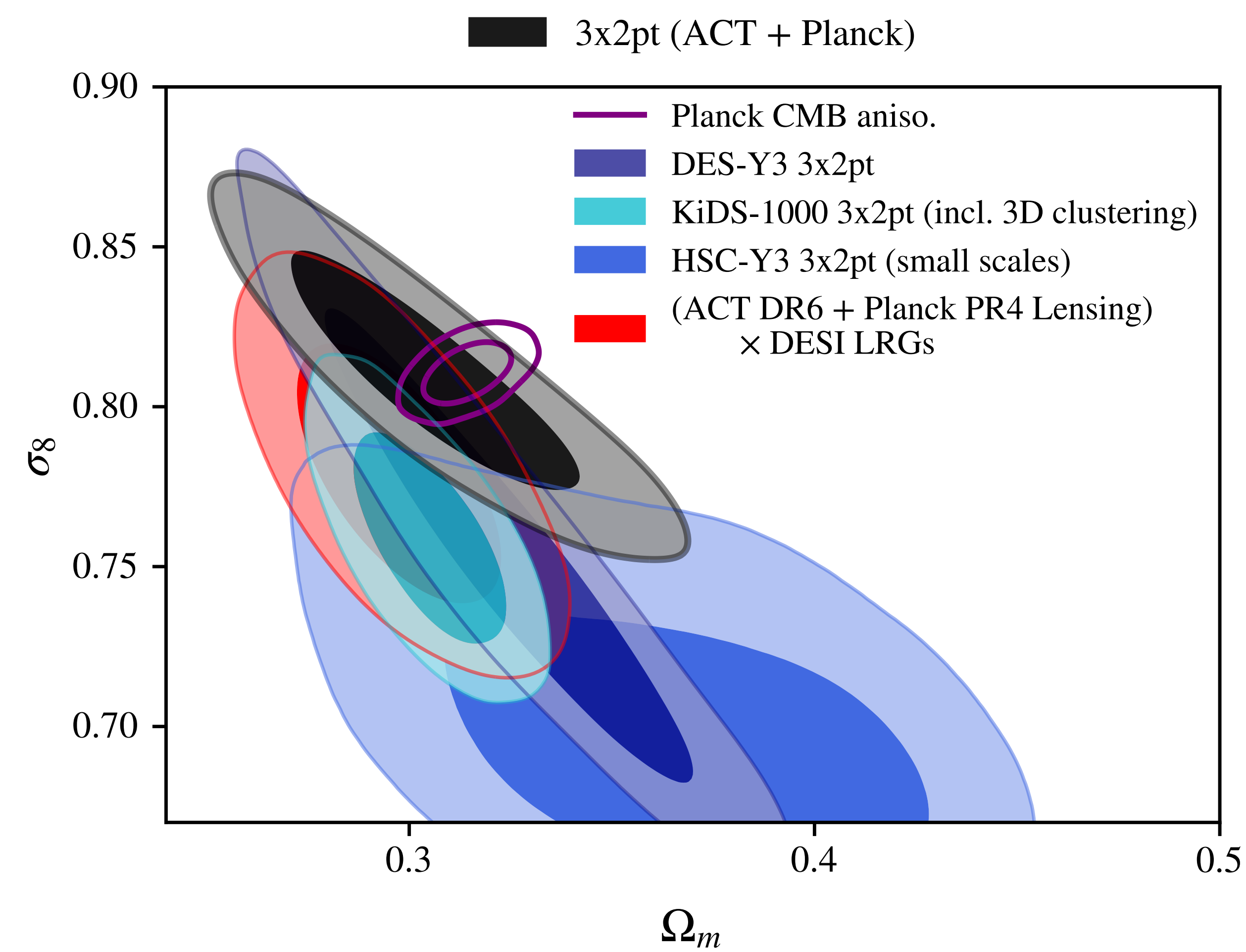




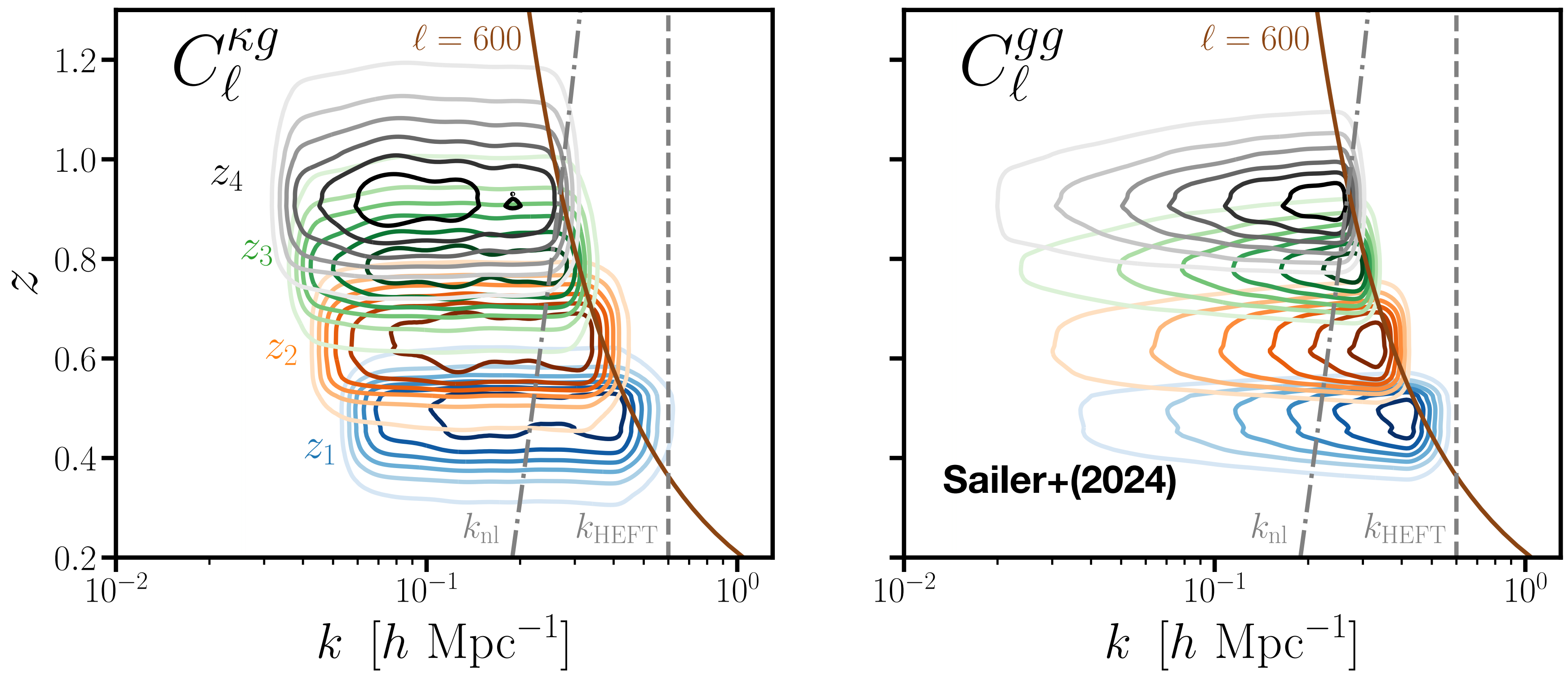
Farren+(2024)

Also Sherwin+(2011), Stompor & Efsthathiou (1997)

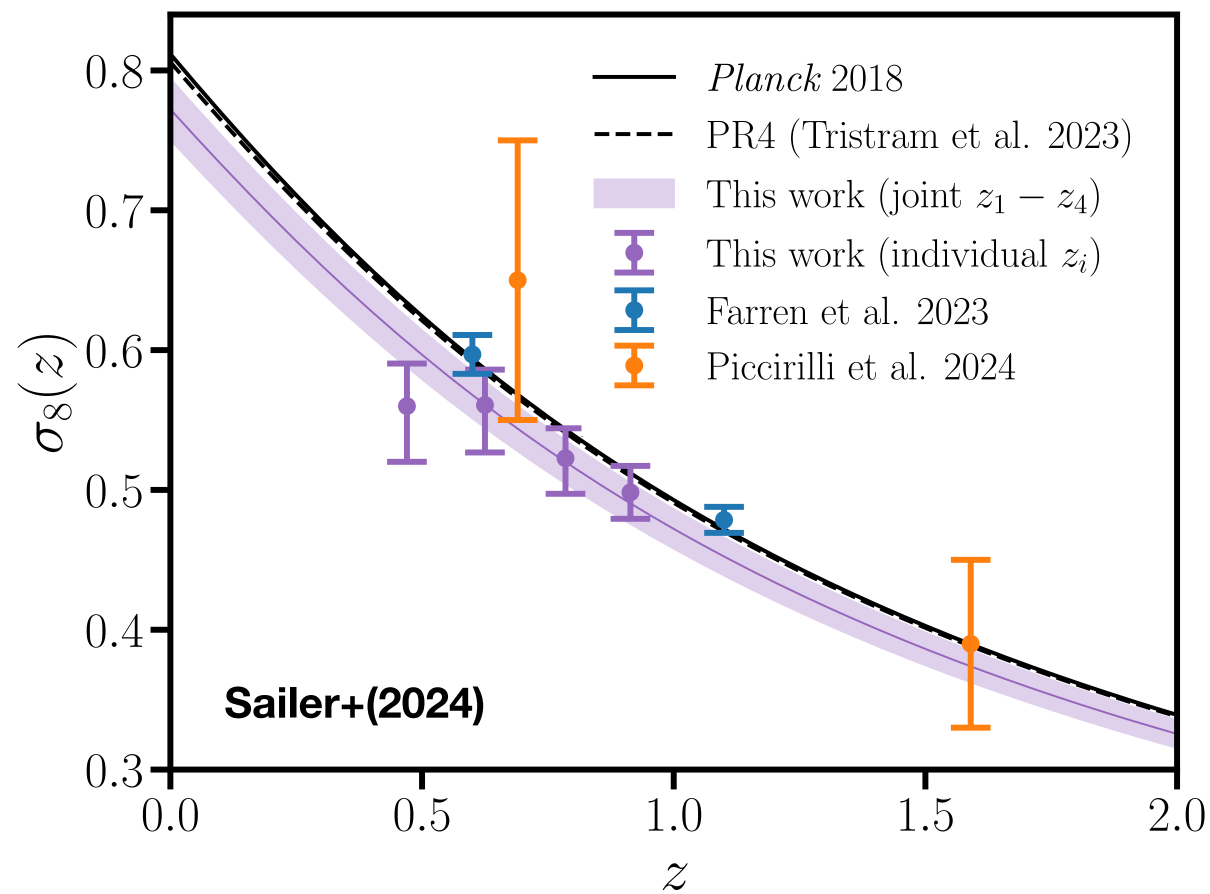
$S_8 = 0.816 \pm 0.015 \qquad \sigma_8 = 0.815 \pm 0.012$



CMB lensing x galaxies: state of the art 2

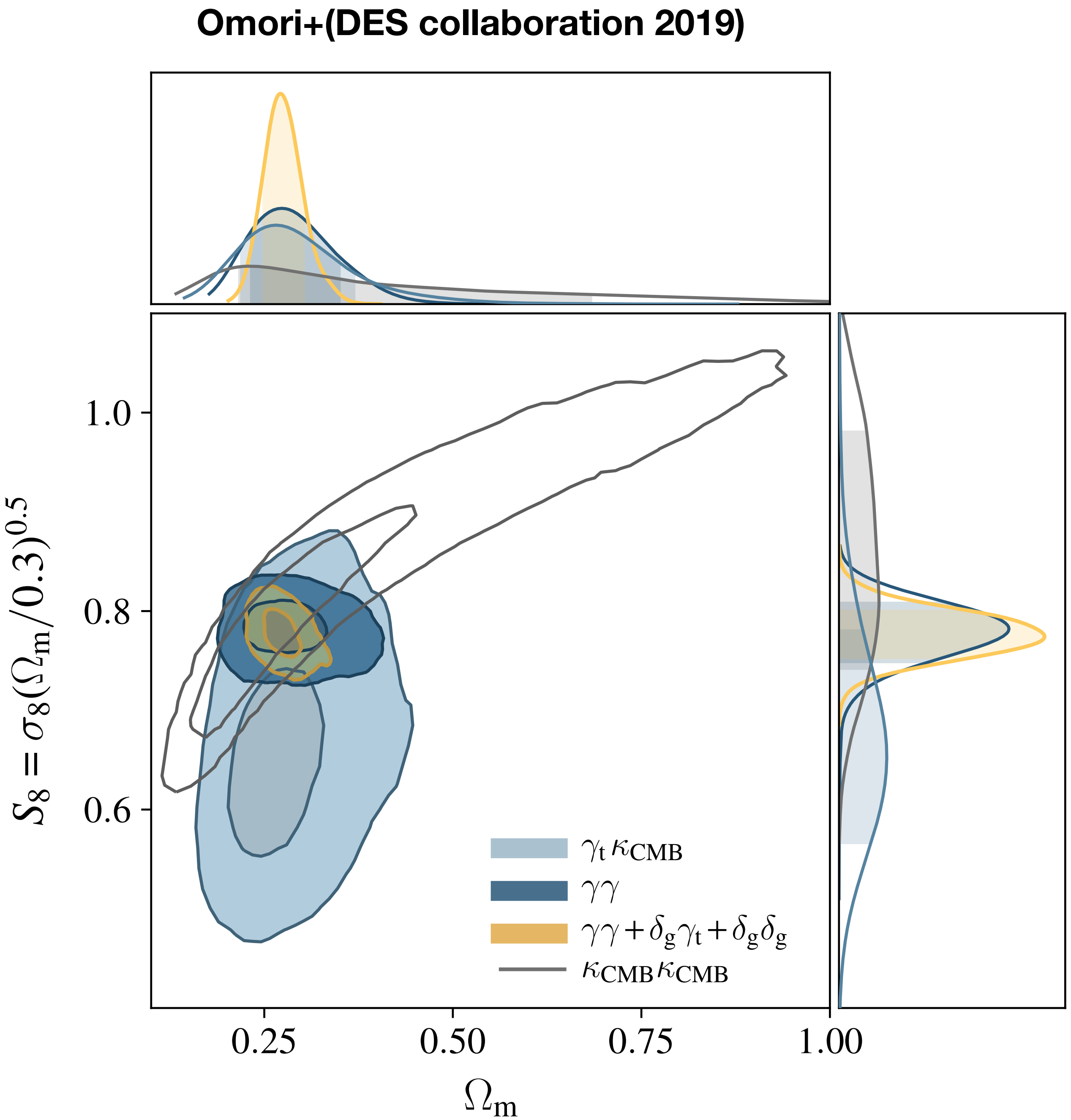


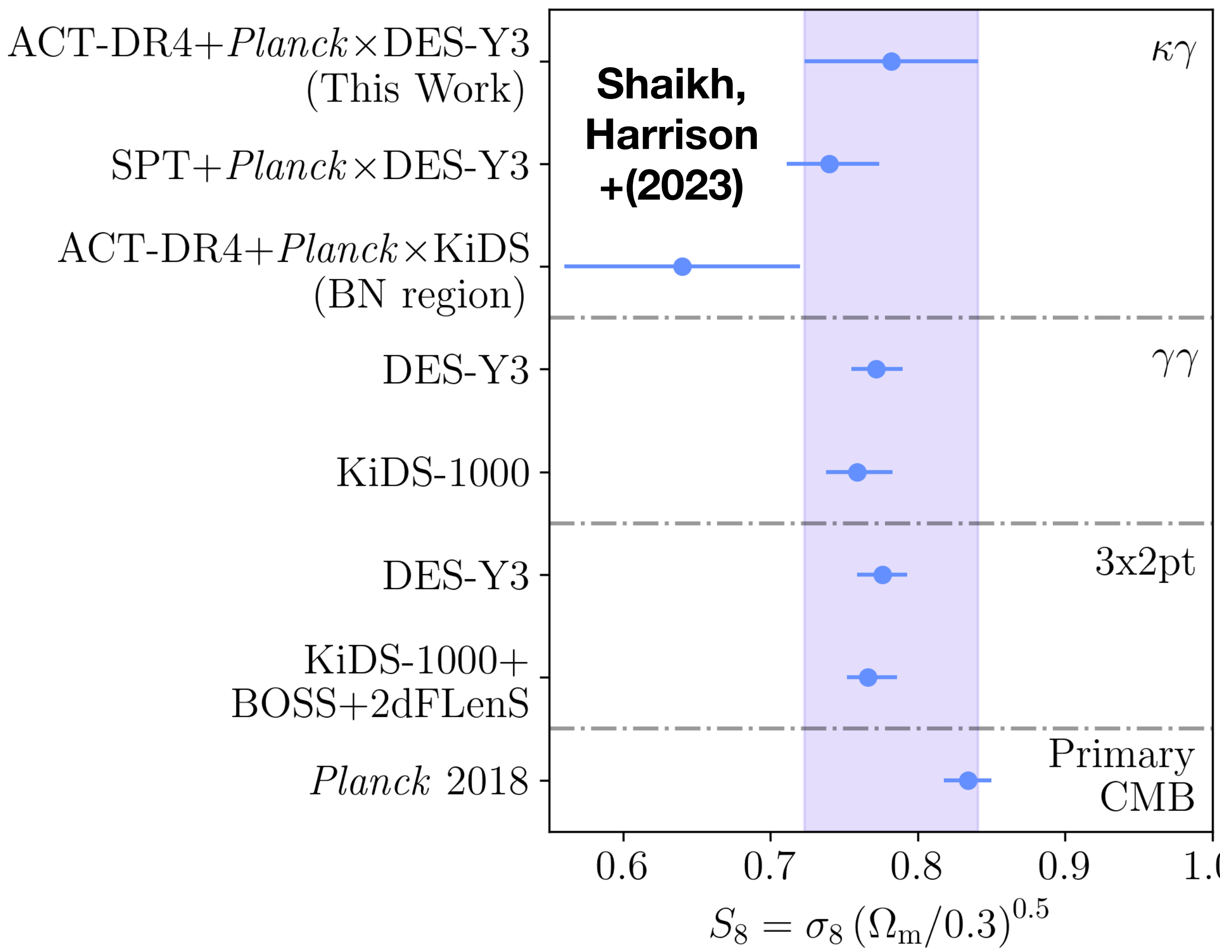
- DESI Legacy LRGs calibrated with spectroscopy data x ACT DR6
- Complementary scales wrt UNWISE.
- Highly tested for bias expansion
- Consistent results with CMB, other analysis ongoing…

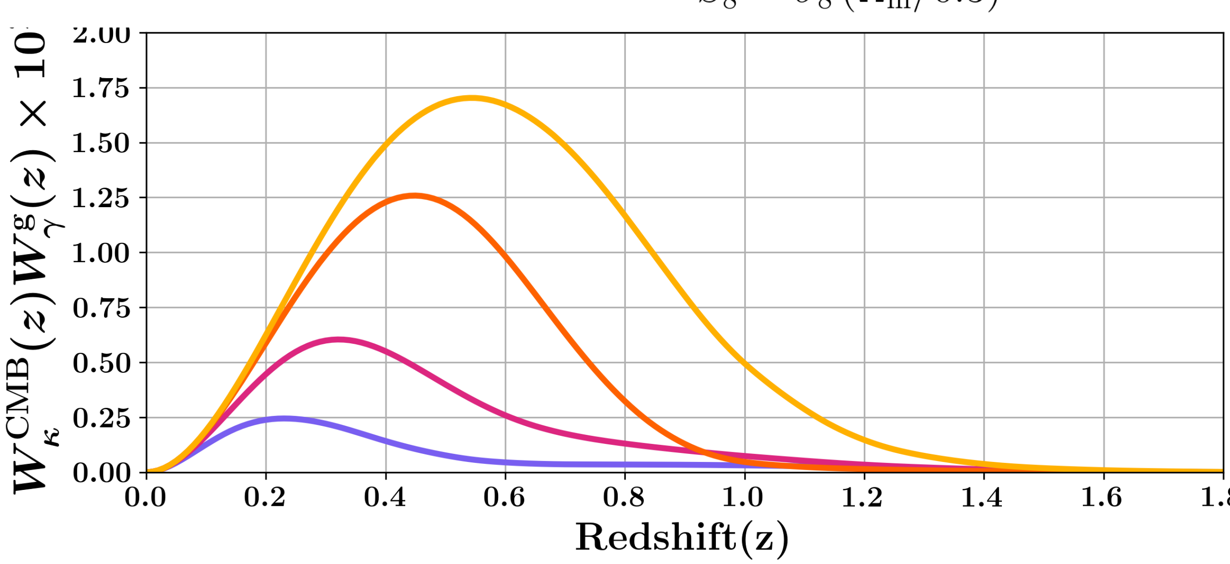


ACT DR4 & SPT X DES cosmic shear

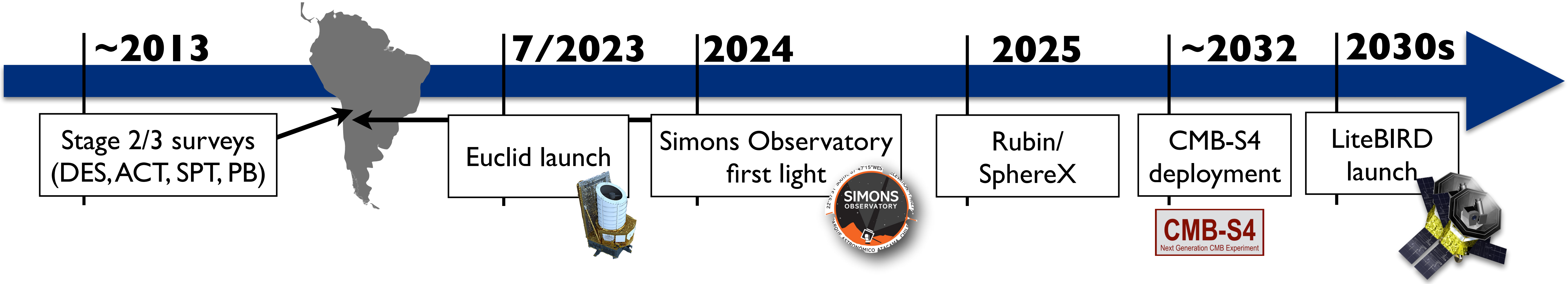
- Tightens systematics but large uncertainties new analyses on the way.



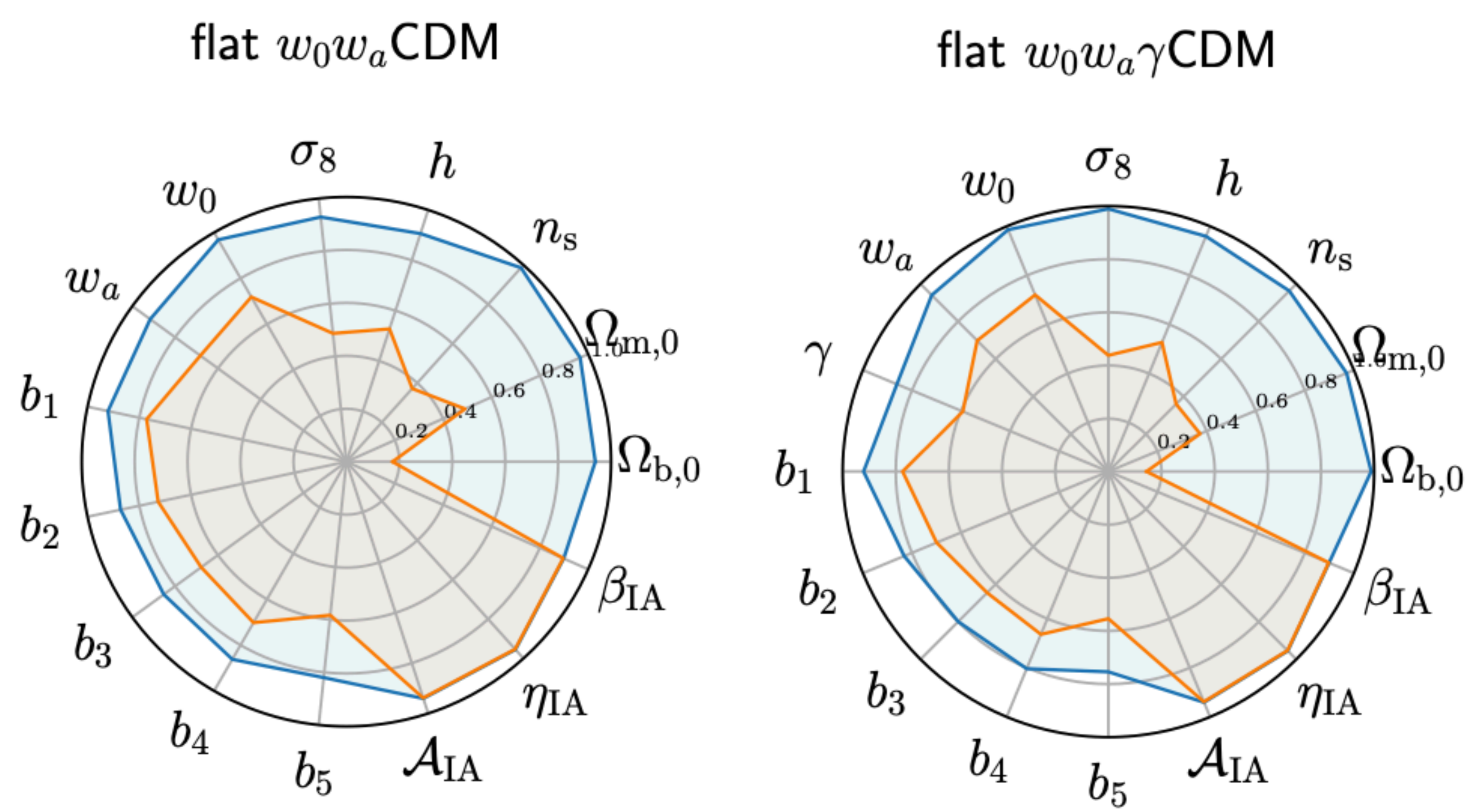




Data combination perspectives…



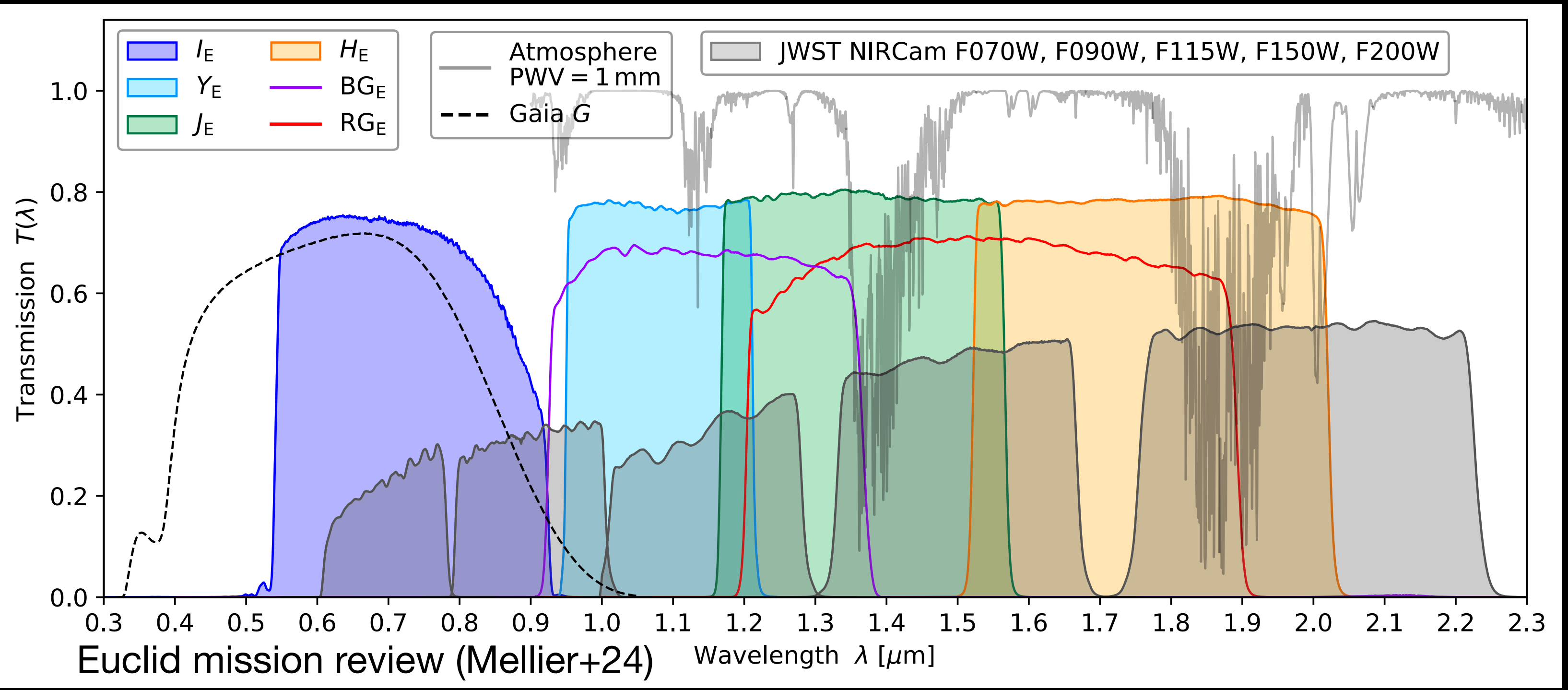
- Current data: marginalizing over systematics at limited cost, no additional power!
- Euclid: ~3x improvement on non-standard /extended models

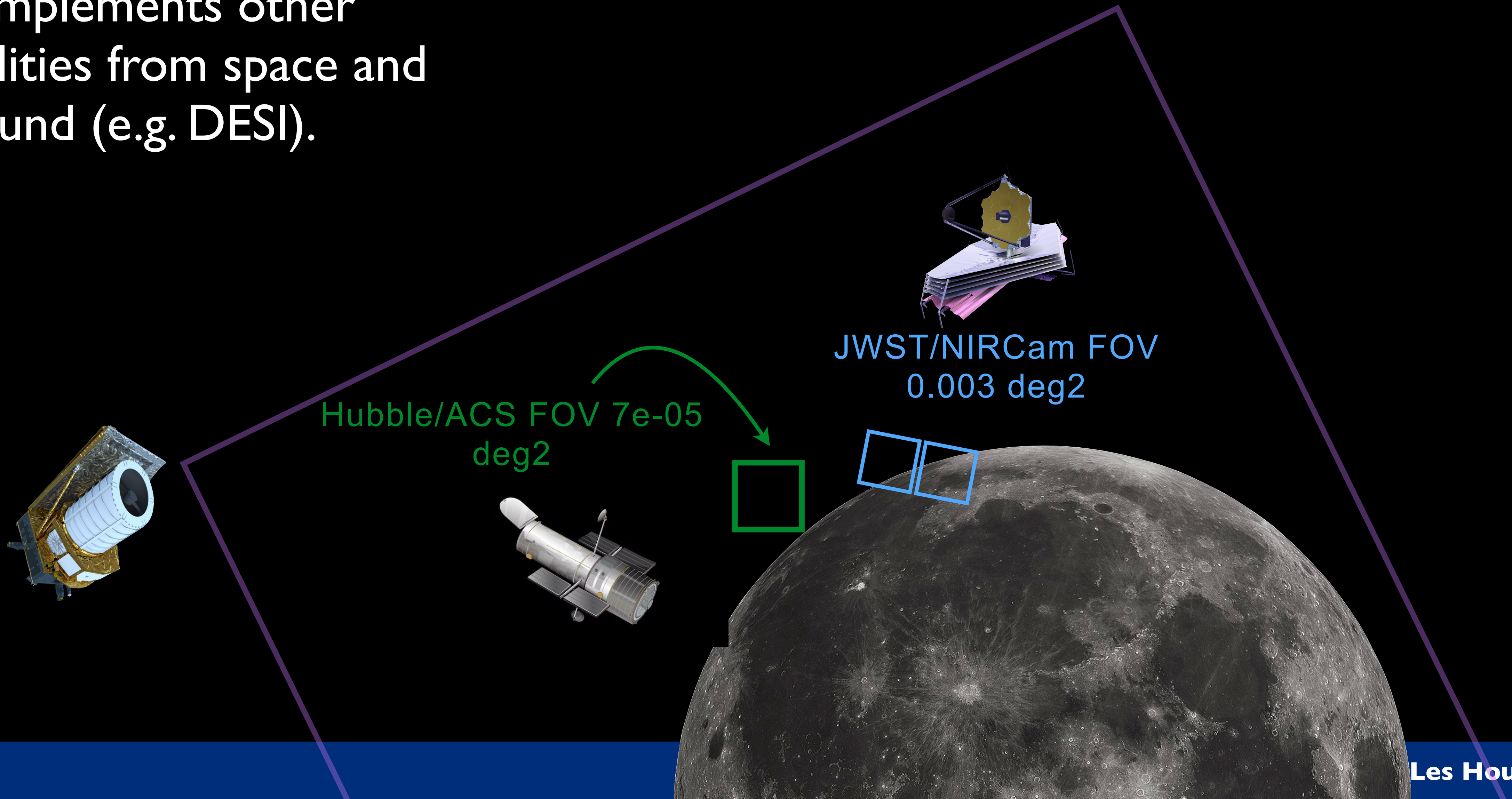


Euclid consortium: Ilic+(w/ GF 2022)

Euclid preview

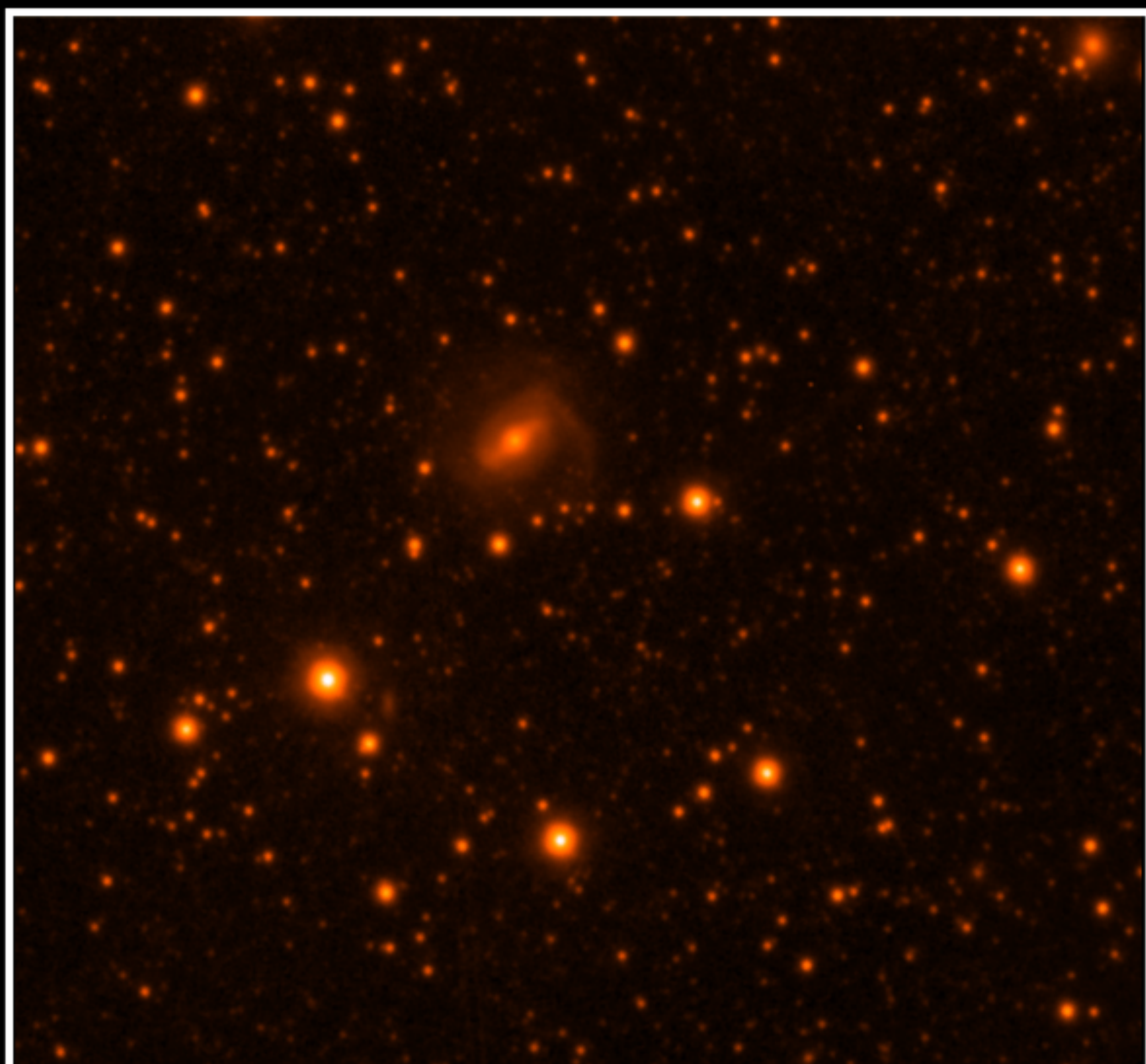
- Euclid will cover 30 years of Hubble operation every ~5 days
- Euclid FOV ~ 3x the moon size
- Complements other facilities from space and ground (e.g. DESI).



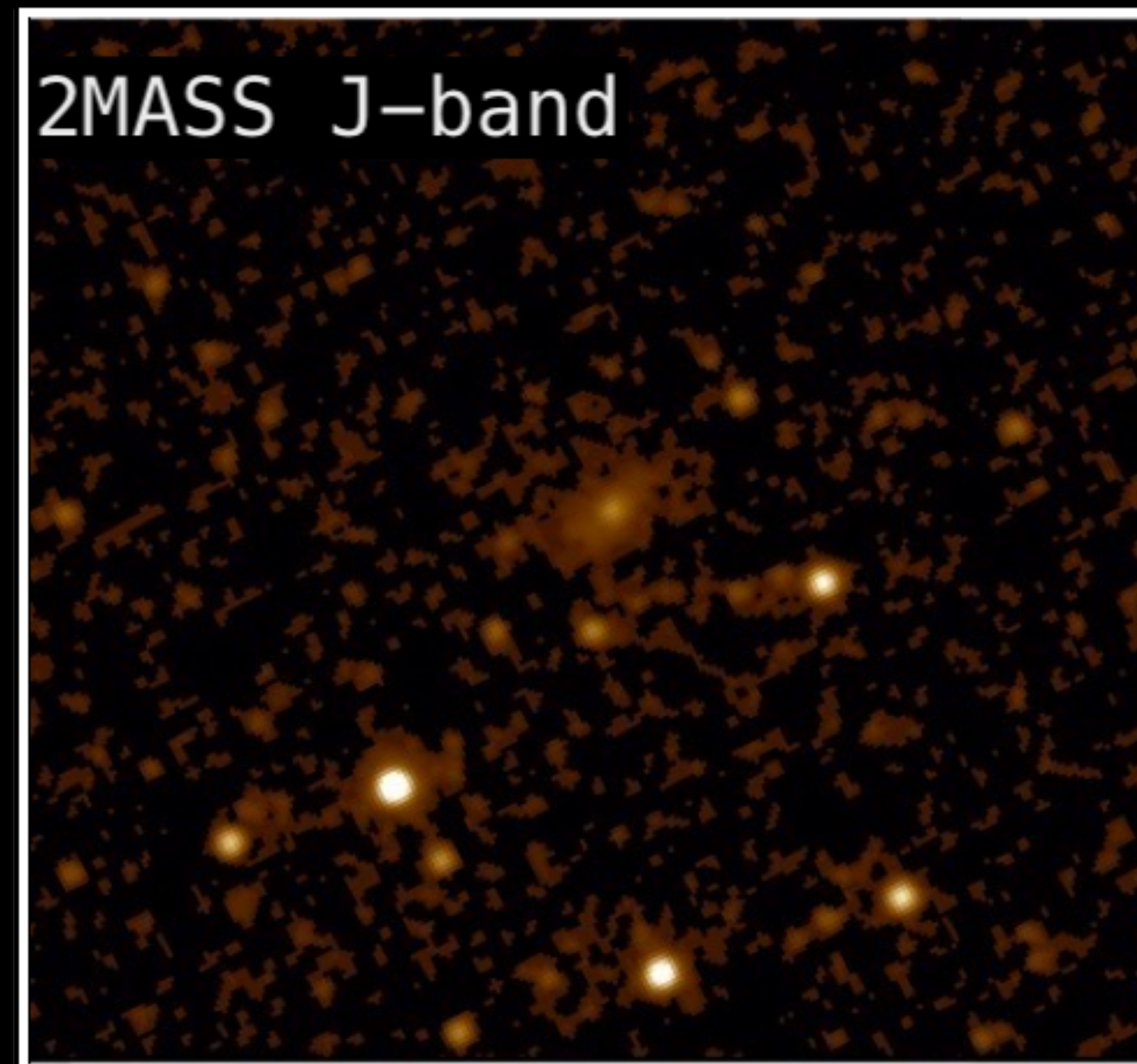


EUCLID

RESULTS SO FAR



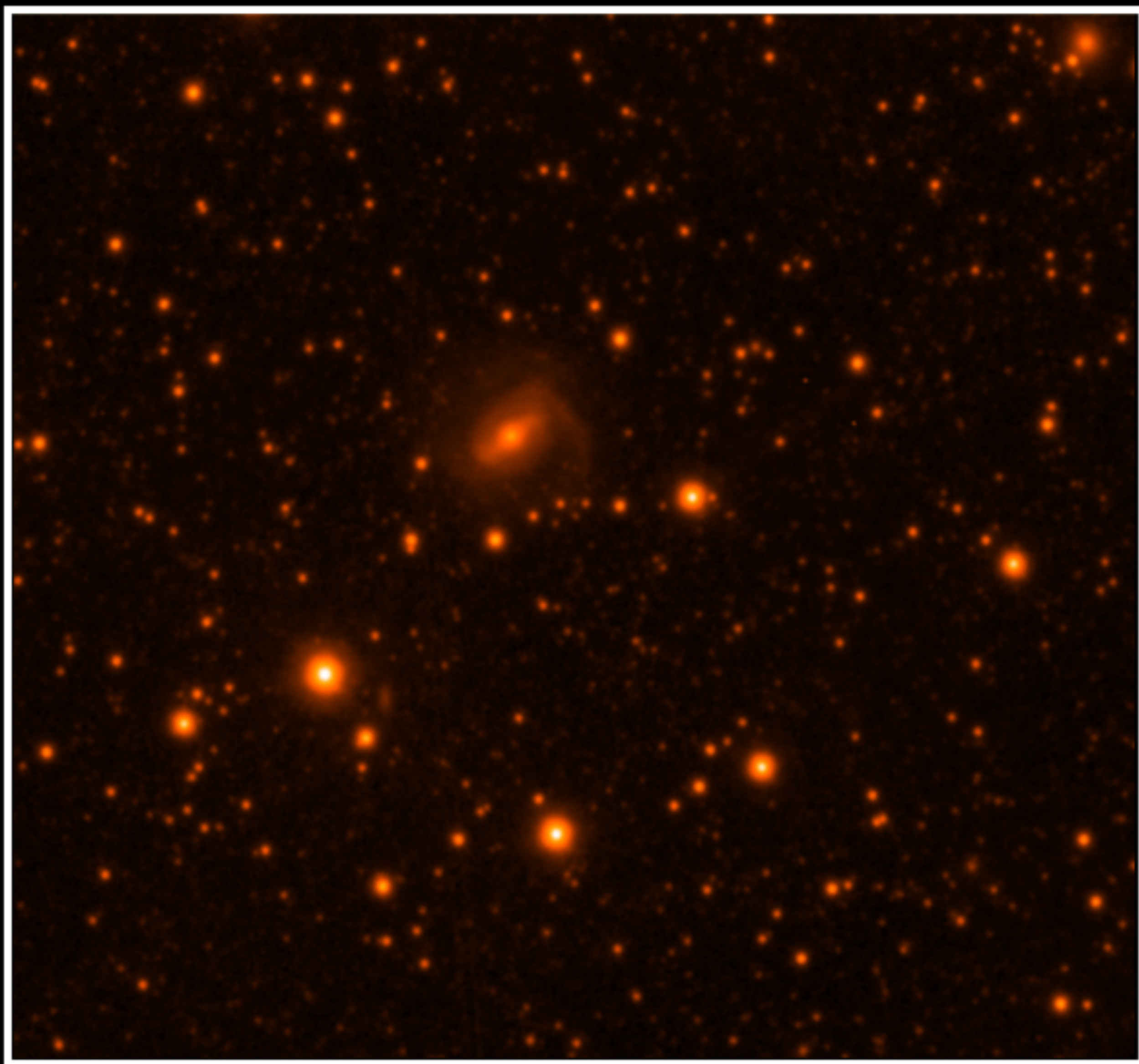
VISTA VMC J–band



Credit: Ralf Bender & Ross Collins using public data from Euclid and VISTA

EUCLID

RESULTS SO FAR



VISTA VMC J–band

Euclid NISP Test Image

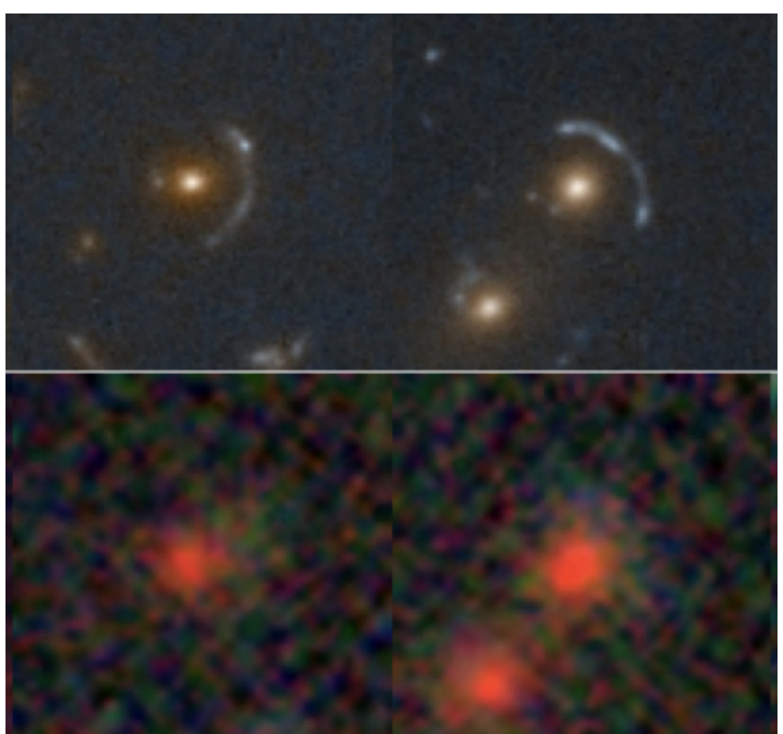
Credit: Ralf Bender & Ross Collins using public data from Euclid and VISTA

What to expect: synergies between surveys.

Euclid Early Release Observation image

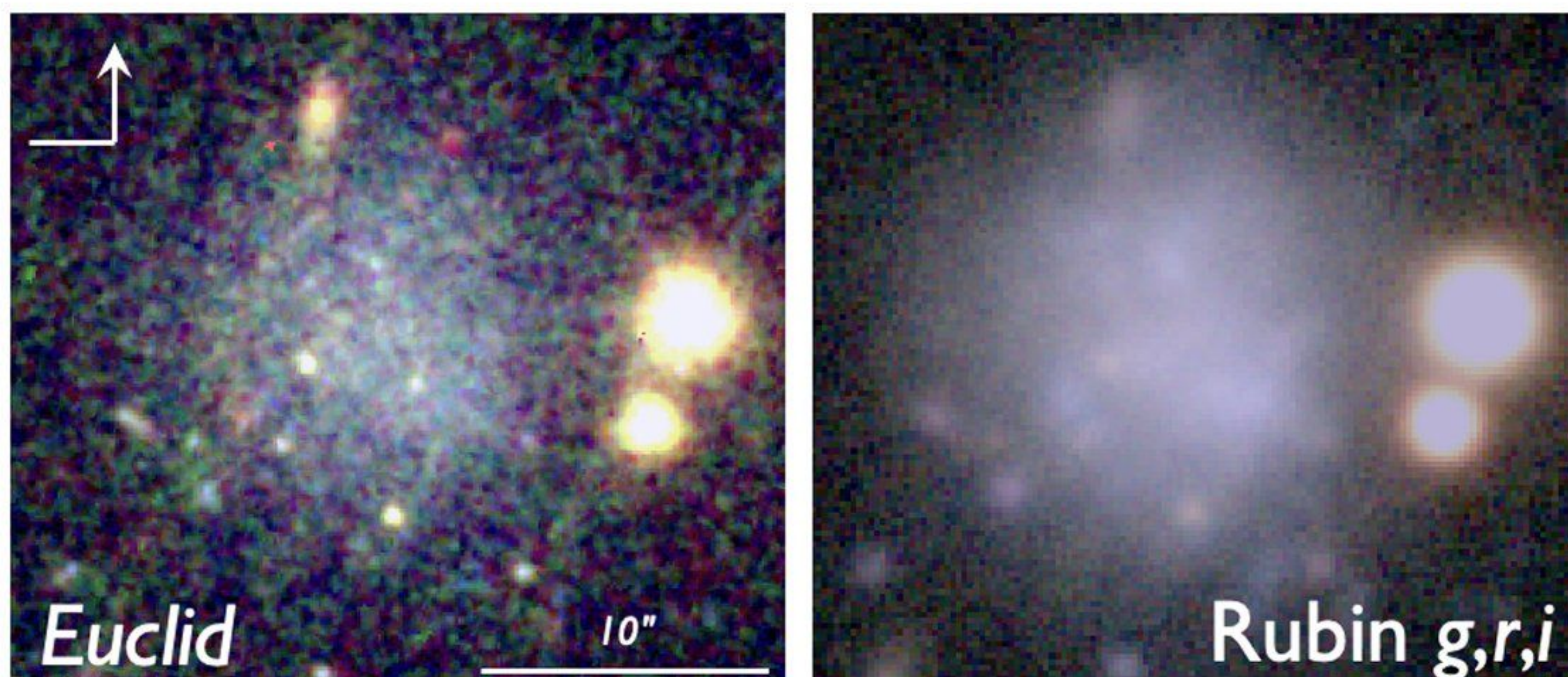
Rubin 1st wide image

Euclid Q1 release



DESI Legacy Imaging Survey

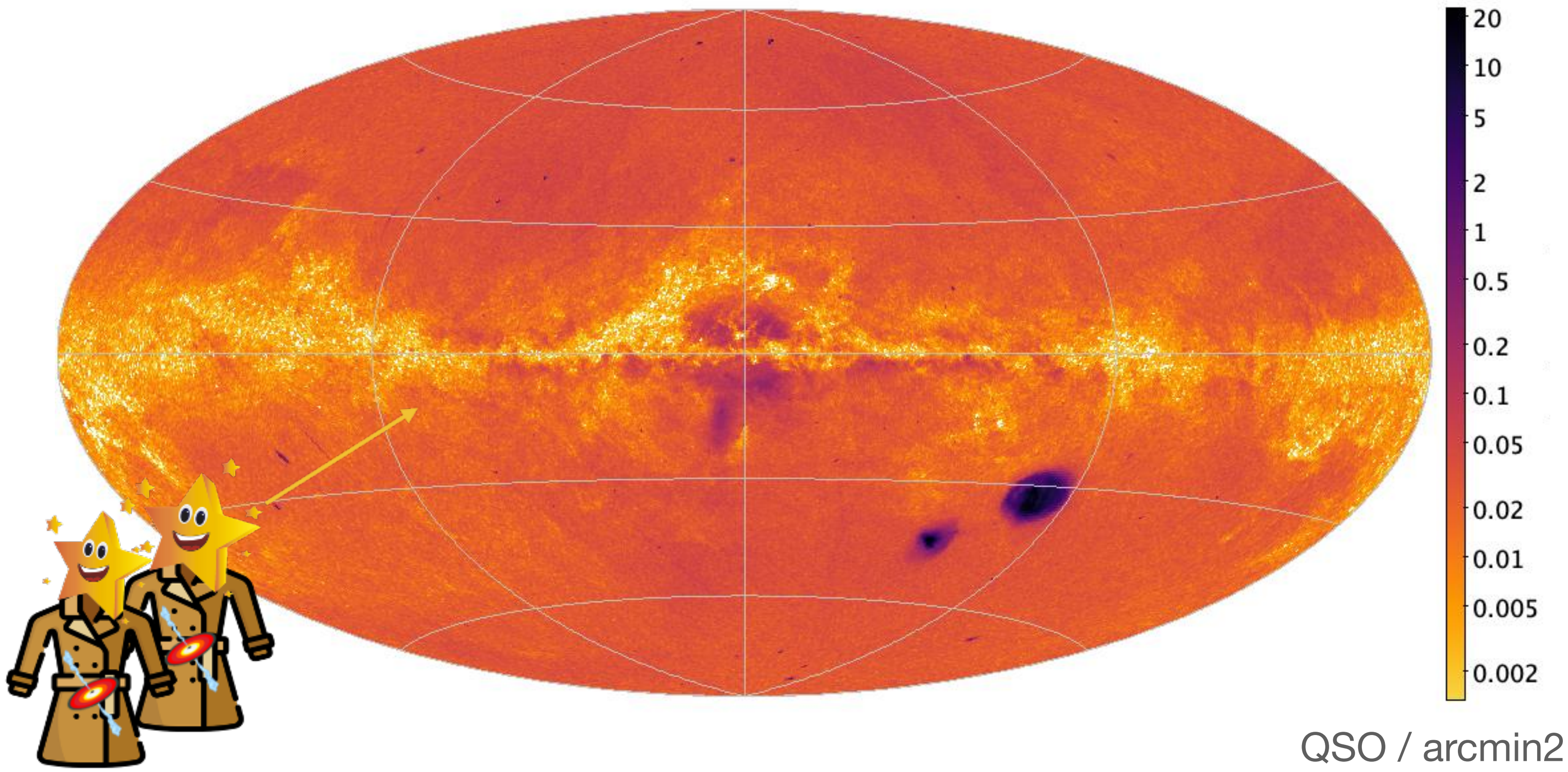
Romanowsky+(2025)



In the meantime… Gaia!

- Photometry, astrometry, slitless spectroscopy with $30 \leq \lambda/\Delta\lambda \leq 100$ resolution

- DR3 released 6.6 million quasar candidates!

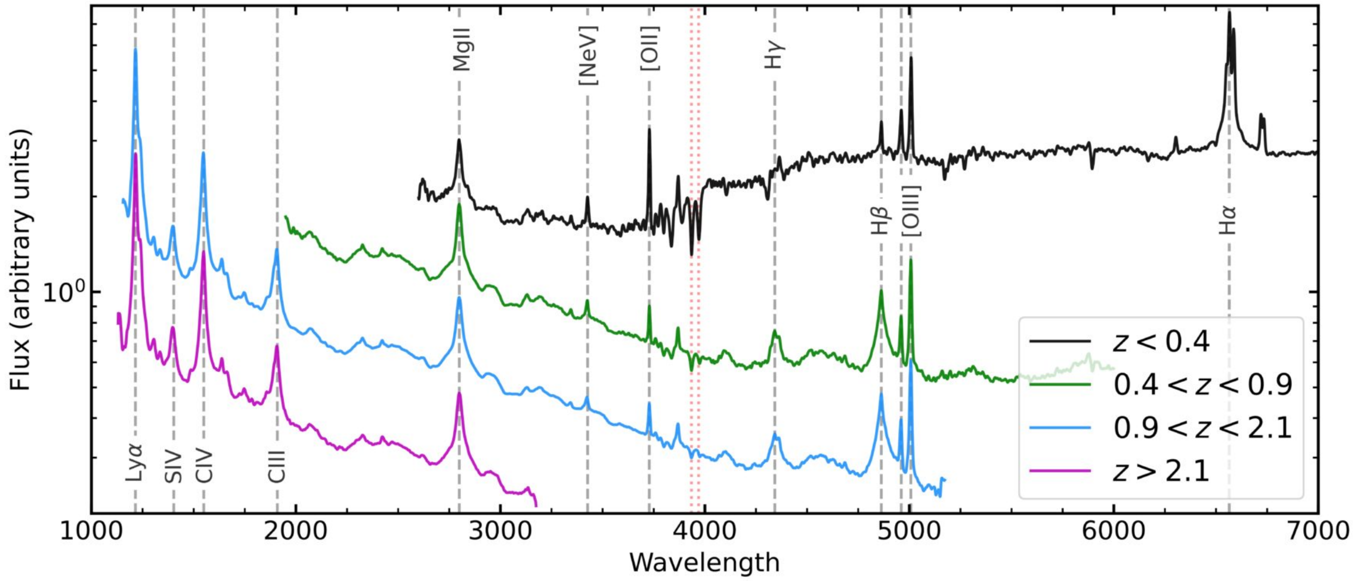


Bailer-Jones+2022

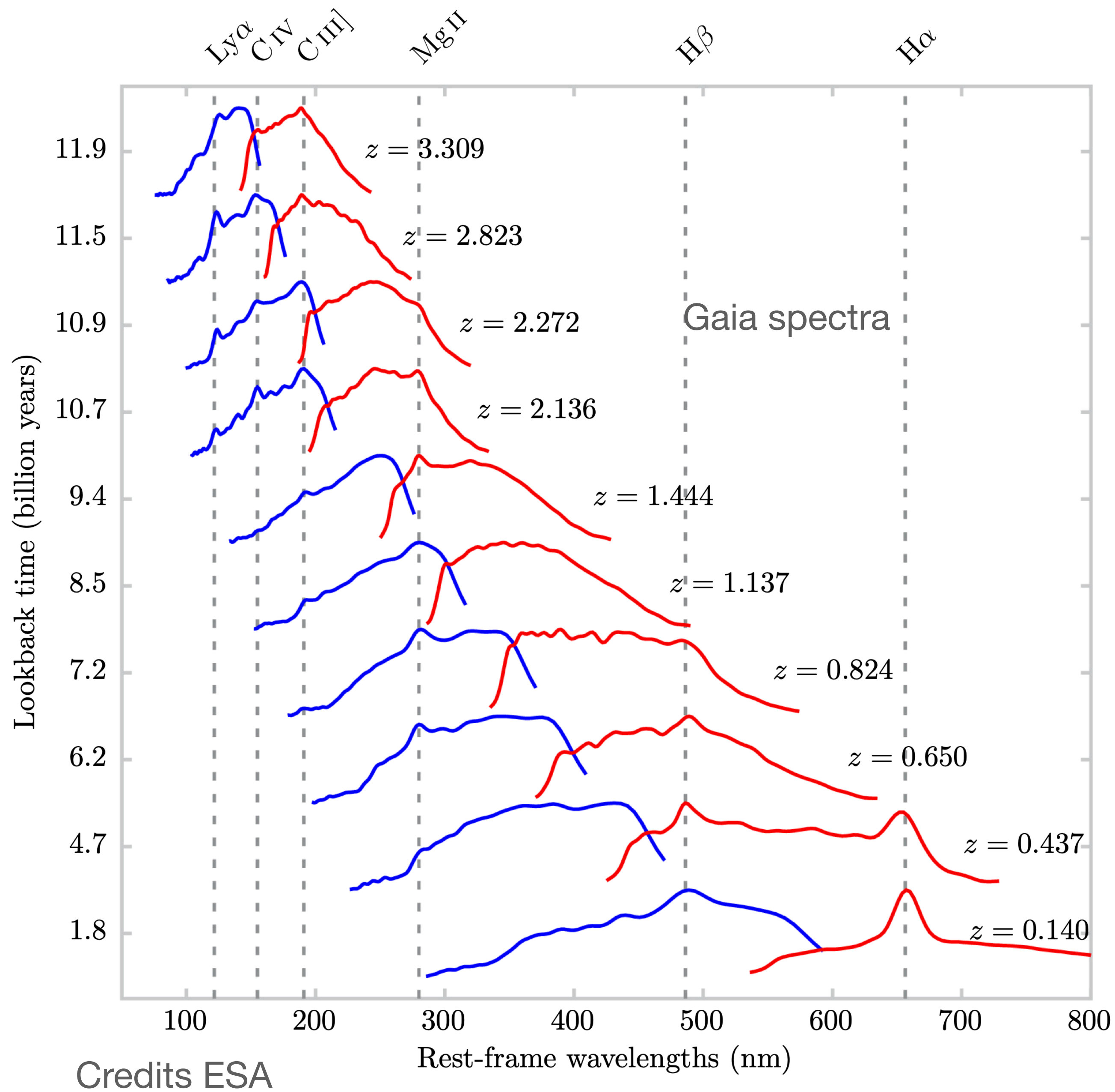
- Complete, low purity, as many are stars masquerading as QSO :/ but… we can improve it

Gaia: more than astrometry

- Space-quality data means e.g. no seeing, airmass, stable observing conditions…
  - larger volume, cleaner selection function than any existing sample (full sky).
  - Synergies with external data allowed to clean this sample further: Quaia



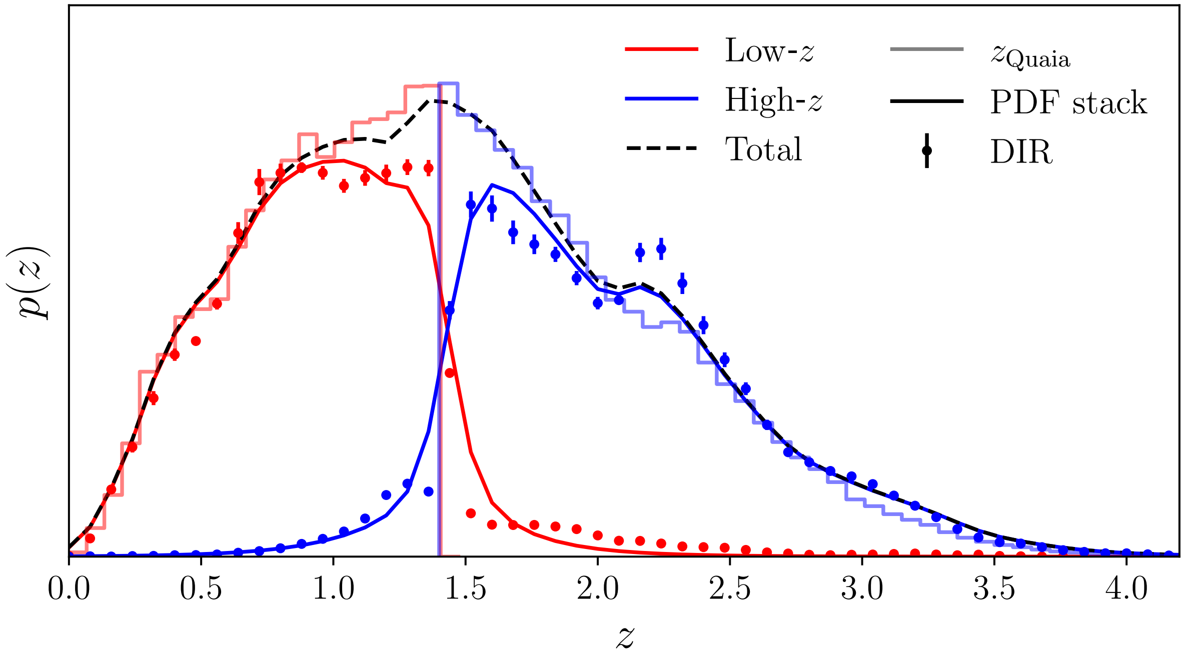
DESI spectra

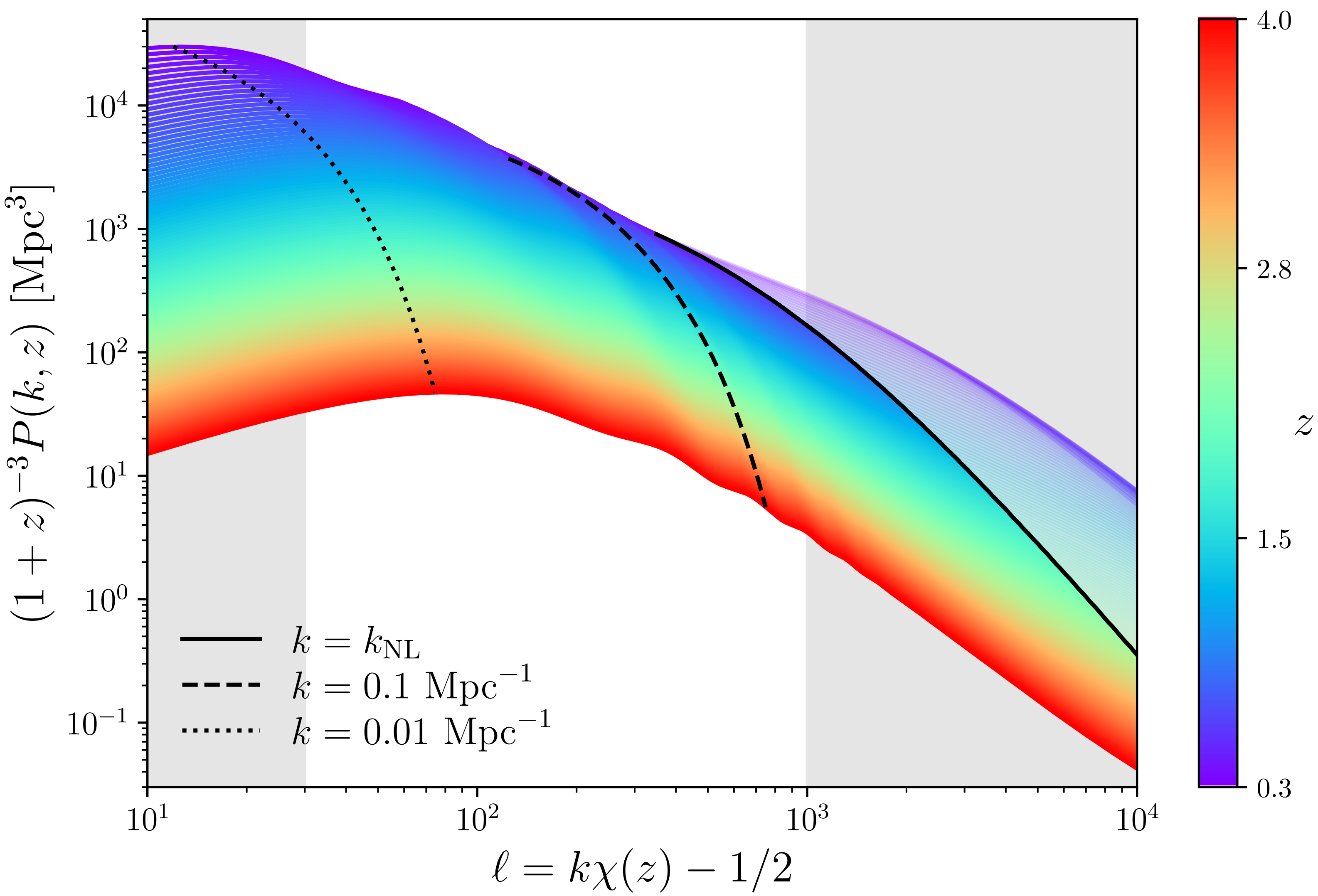


Credits ESA

What Quaia can do for cosmology?

- High redshift
- Linear or quasi-linear scales.



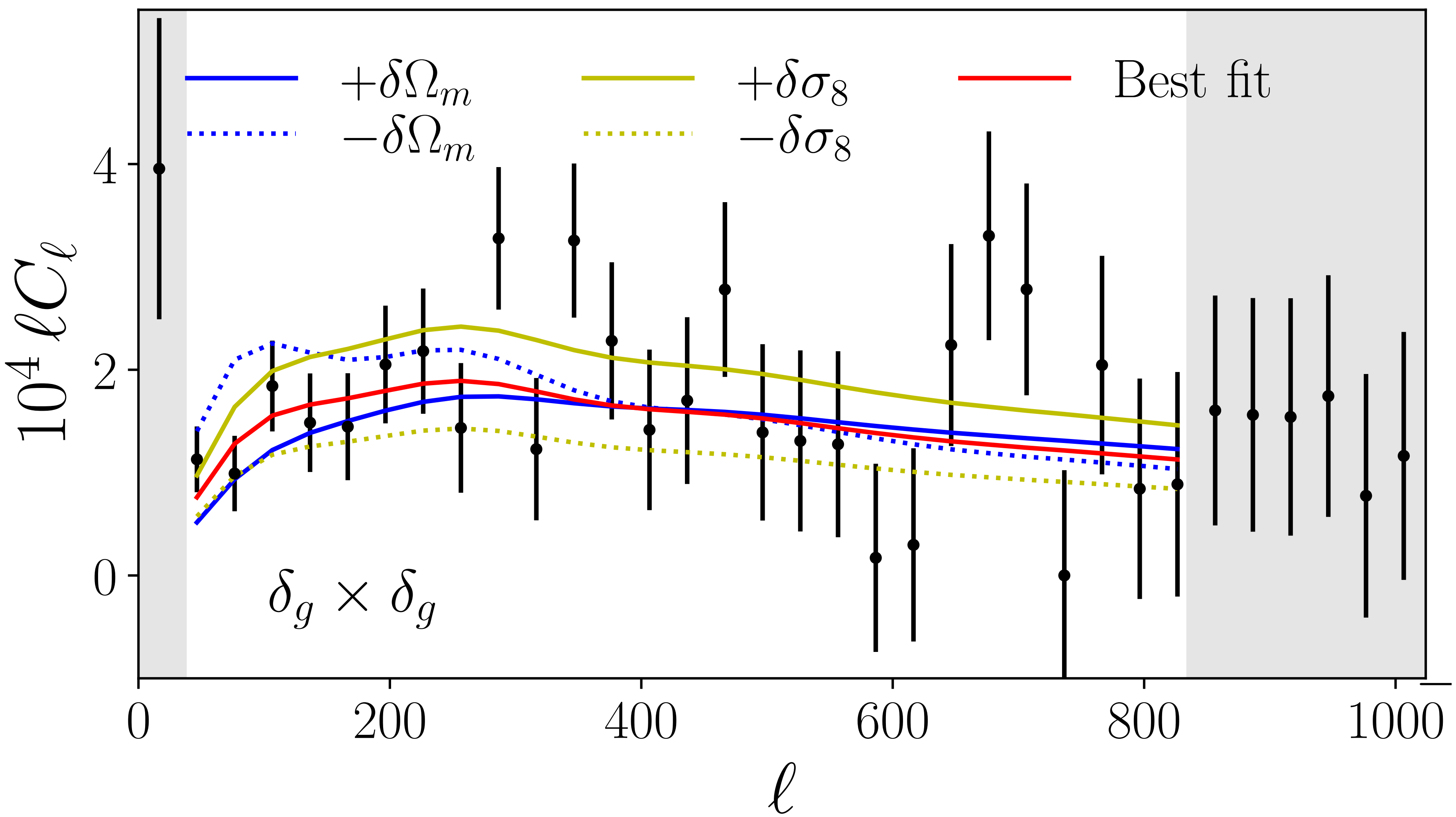


Storey-Fisher+ (w/ GF, 2023)

Alonso, GF, Storey-Fisher+(2023)

What Quaia can do for cosmology?

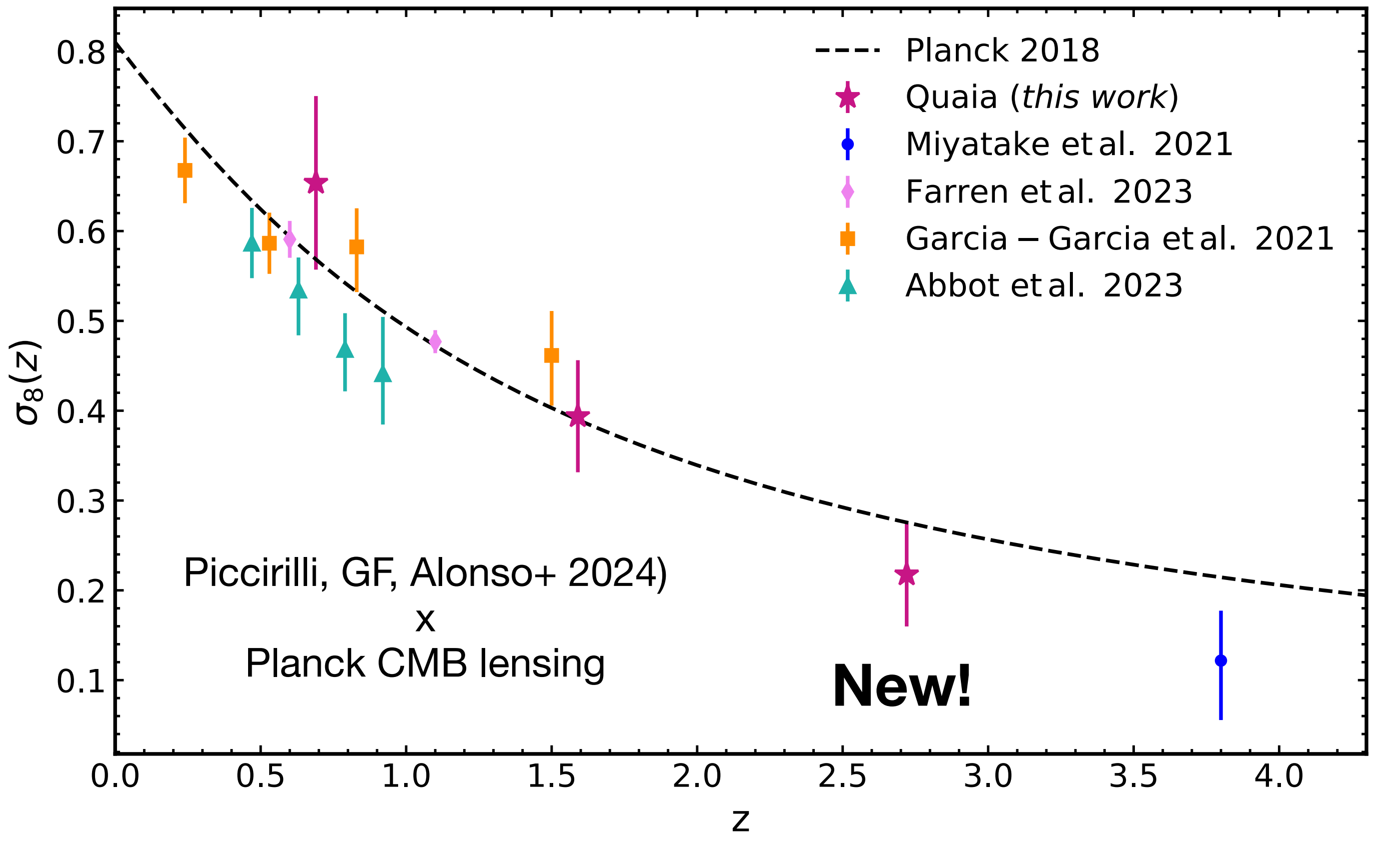
- Large sky coverage means capability to measure large angular scales.
- Towards non-degenerate σ_8, Ω_m measurements



Alonso, GF, Storey-Fisher+(2023)

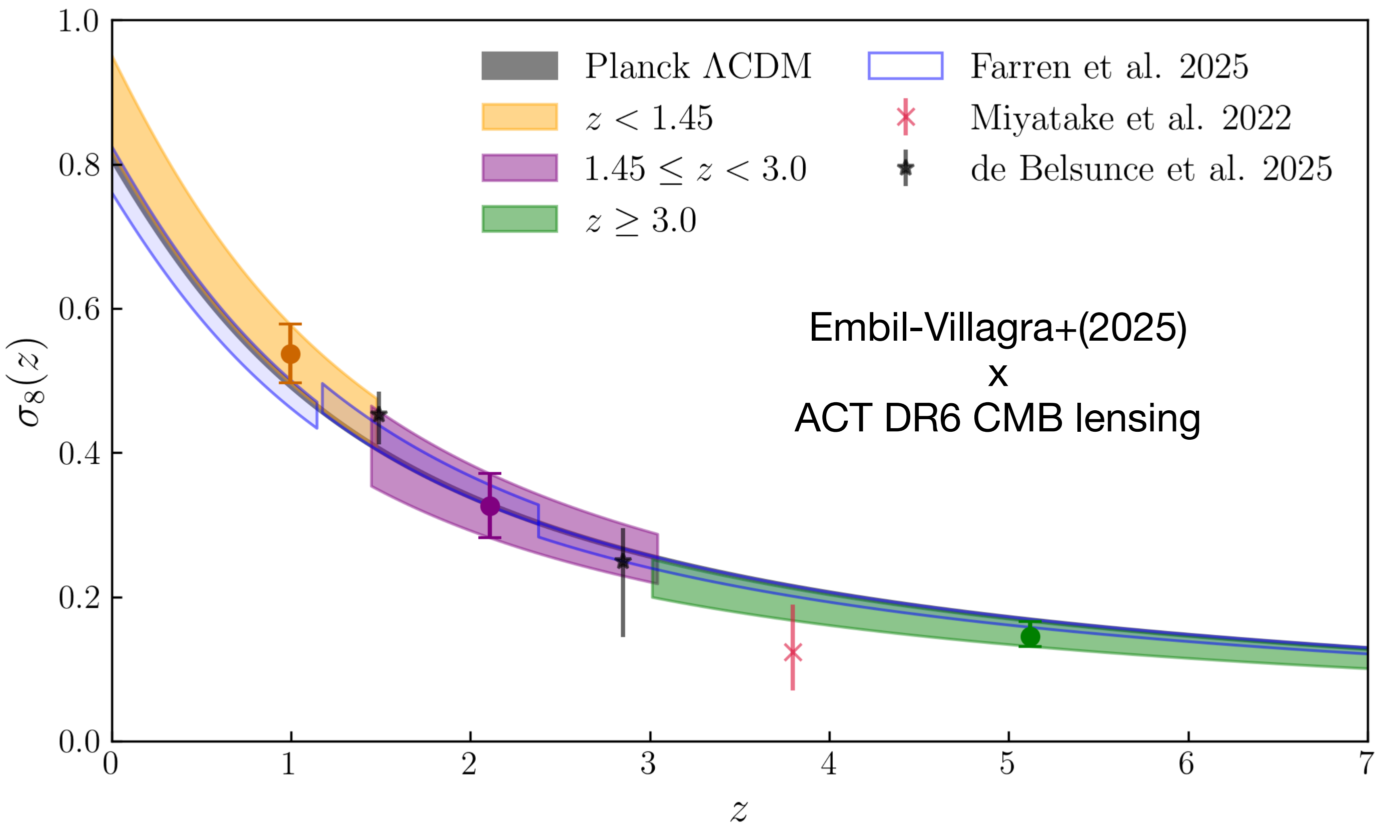
Cosmology from Quaia x CMB lensing

- Tomographic $C_\ell^{gg}, C_\ell^{\kappa g}$ with Planck lensing
  - New high-z σ_8 constraints
  - Results competitive with current LSS surveys with fewer objects and/or worse redshifts.

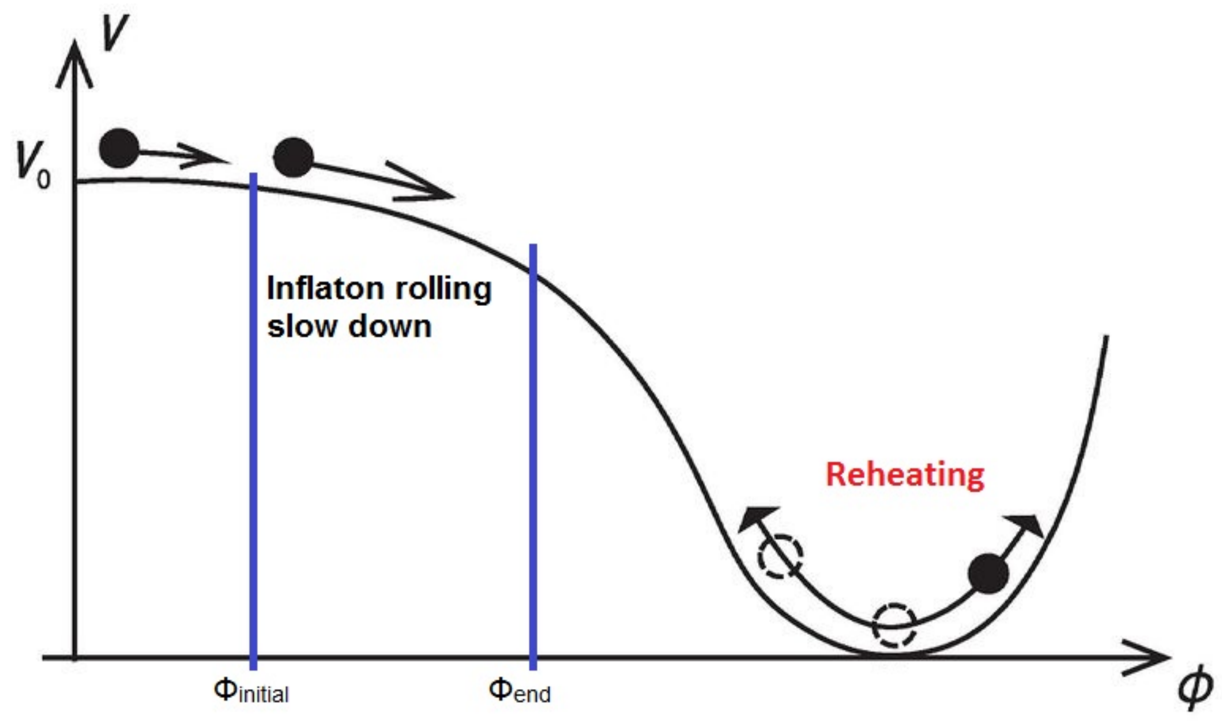


- Tomographic 3x2pt $C_\ell^{gg}, C_\ell^{\kappa g}, C_\ell^{\kappa\kappa}$ with ACT CMB lensing
  - Constraints on $\sigma_8(z = 5.1)$

$$
\begin{aligned}
P_{\rm lin}^{\rm new}(k,z) =& P_{\rm lin}^{\rm input}(k,z)A(z) \\
=& P_{\rm lin}^{\rm input}(k,z)\begin{cases} A_0 & 0 \le z < z_1 \\ A_1 & z_1 \le z < z_2 \\ A_2 & z_2 \le z \end{cases} .
\end{aligned}
$$



(Beyond) Inflation in a nutshell



- Energy density dominated by potential energy of a scalar field that fills the universe
- Small level of acceleration drive the exponential expansion

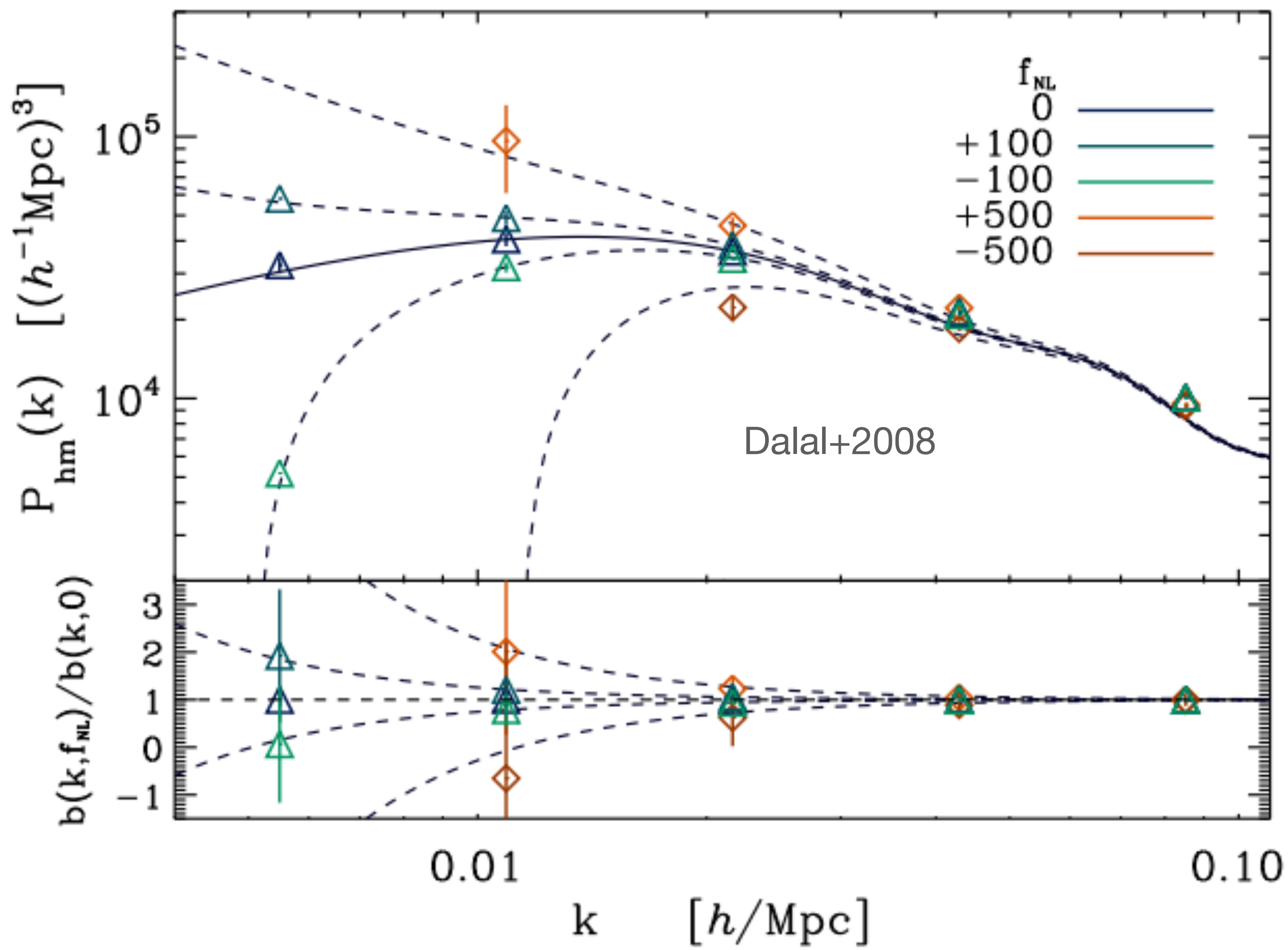
$$n_s, \alpha_s, A_s \longrightarrow dV/d\phi, d^2V/d\phi^2$$

- Non-Gaussianity offers a new window beyond slow-roll / single-field models

$$\Phi(\mathbf{x})_{\rm NG} = \Phi(\mathbf{x}) + f_{\rm NL}\left(\Phi^2(\mathbf{x}) - \langle\Phi^2\rangle\right)$$

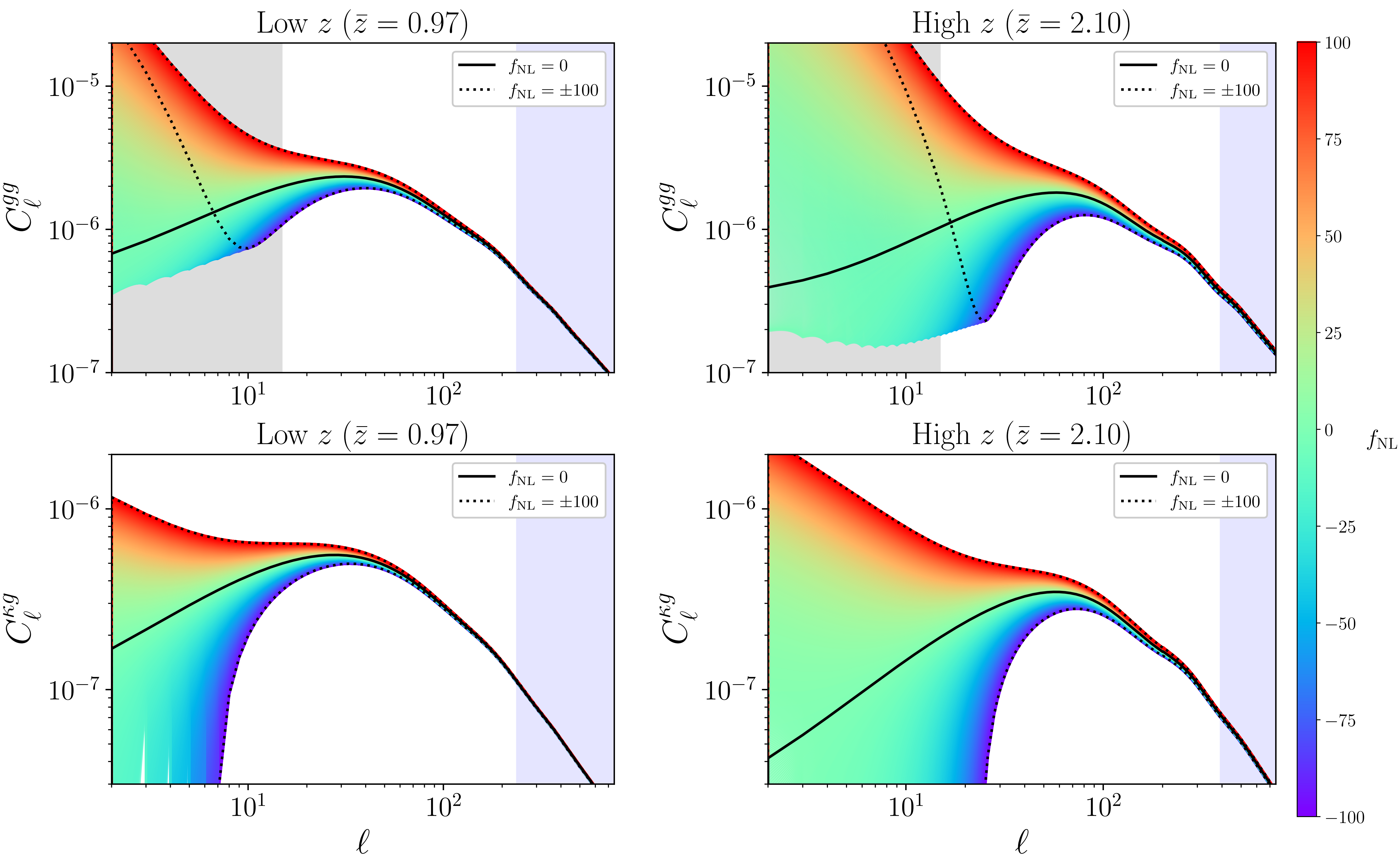
Non-Gaussianities and scale dependent bias

$$\Delta b_1 \propto \frac{f_{\rm NL} b_1 b_\phi}{k^2 T(k)}$$



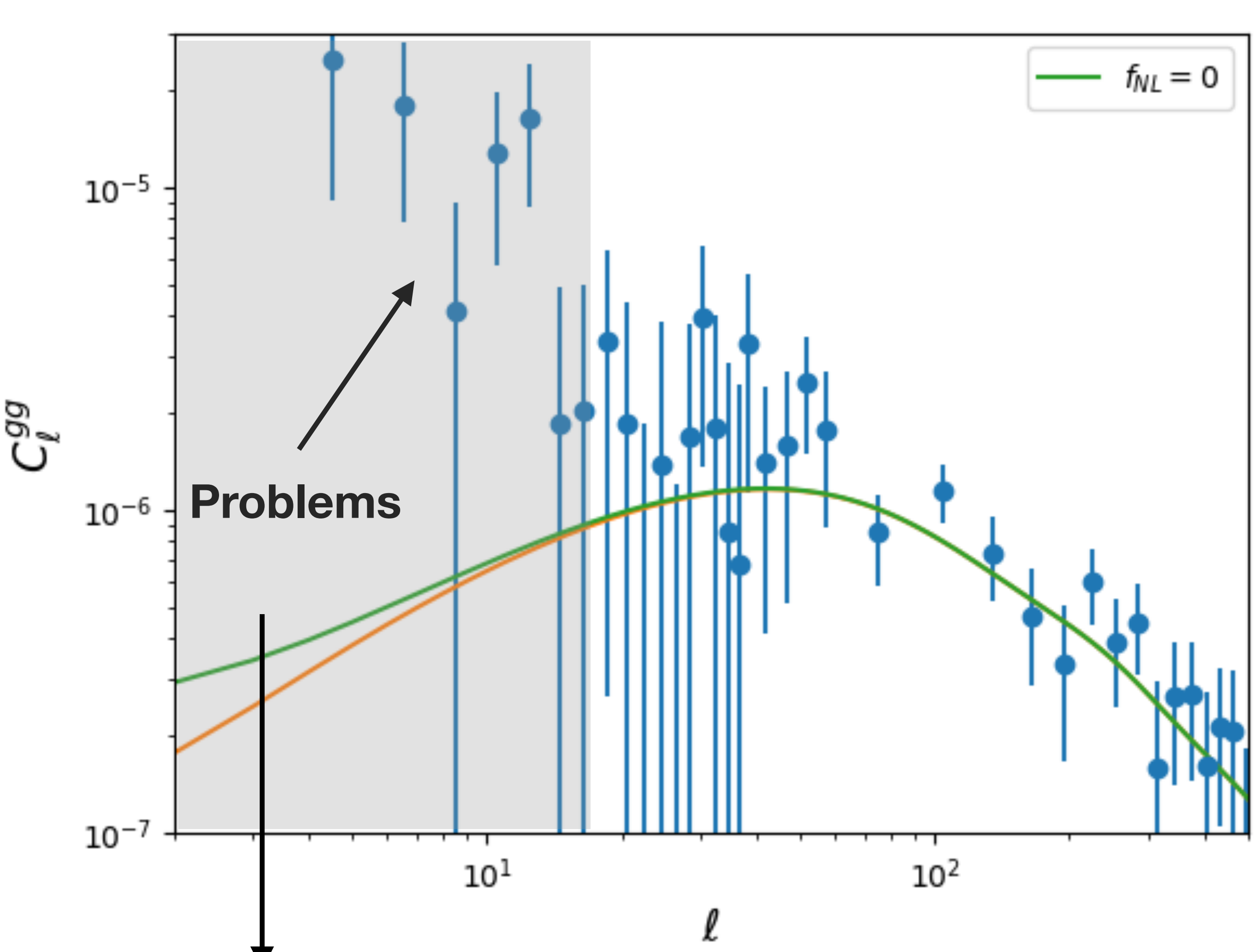
- Huge volume and high bias tracers is required to enhance detection.
- Quasars: detectable at high z thanks to bright AGNs, ~linear scales, ideal for f_{NL} studies.
- Galactic extinction, stellar contamination, seeing, survey depth inhomogeneity cause large scale variations / power excess in clustering measurements…

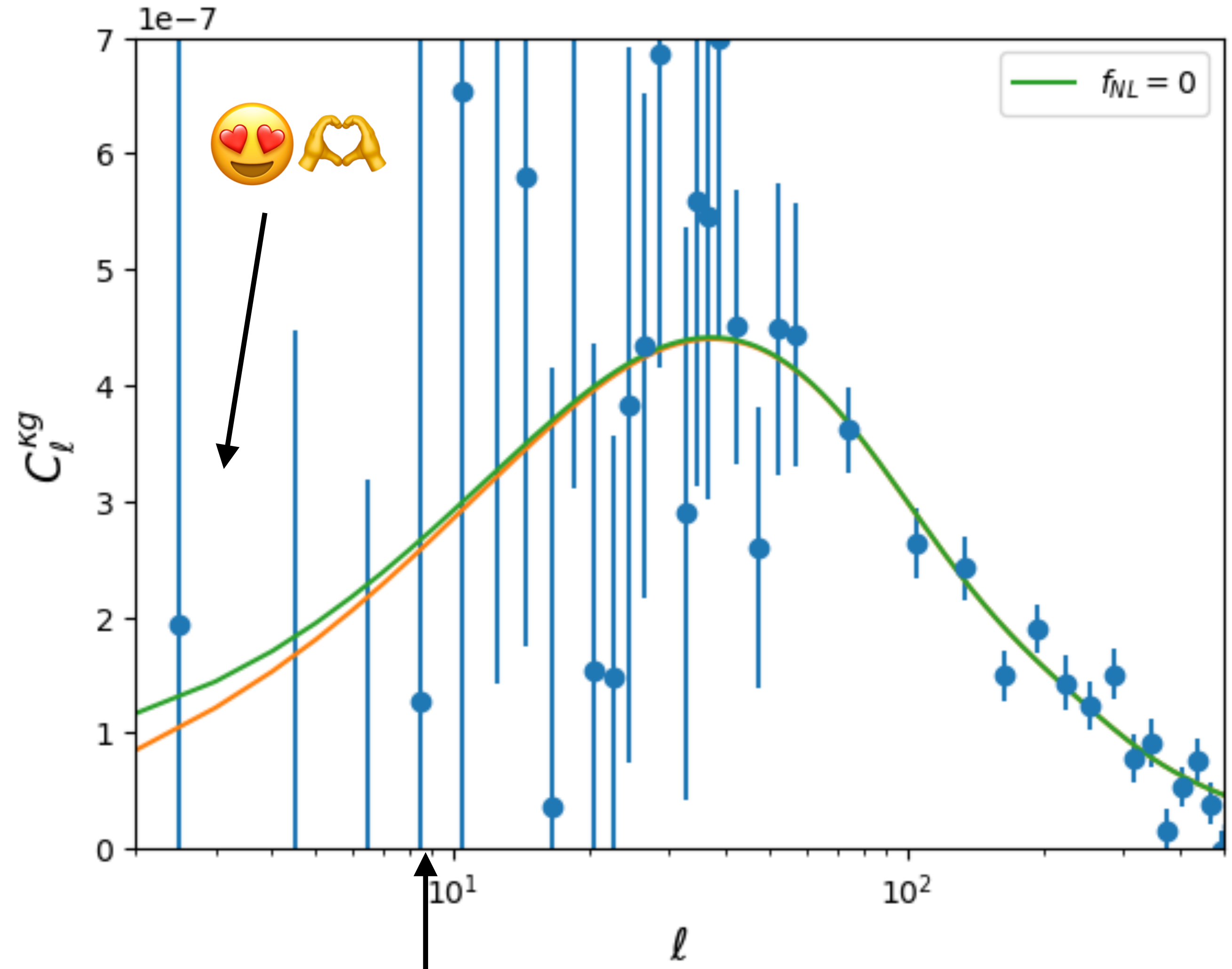
Signature of f_{NL} for projected statistics



Fabbian, Alonso, Storey-Fisher (2025)

Constraints on f_{NL}



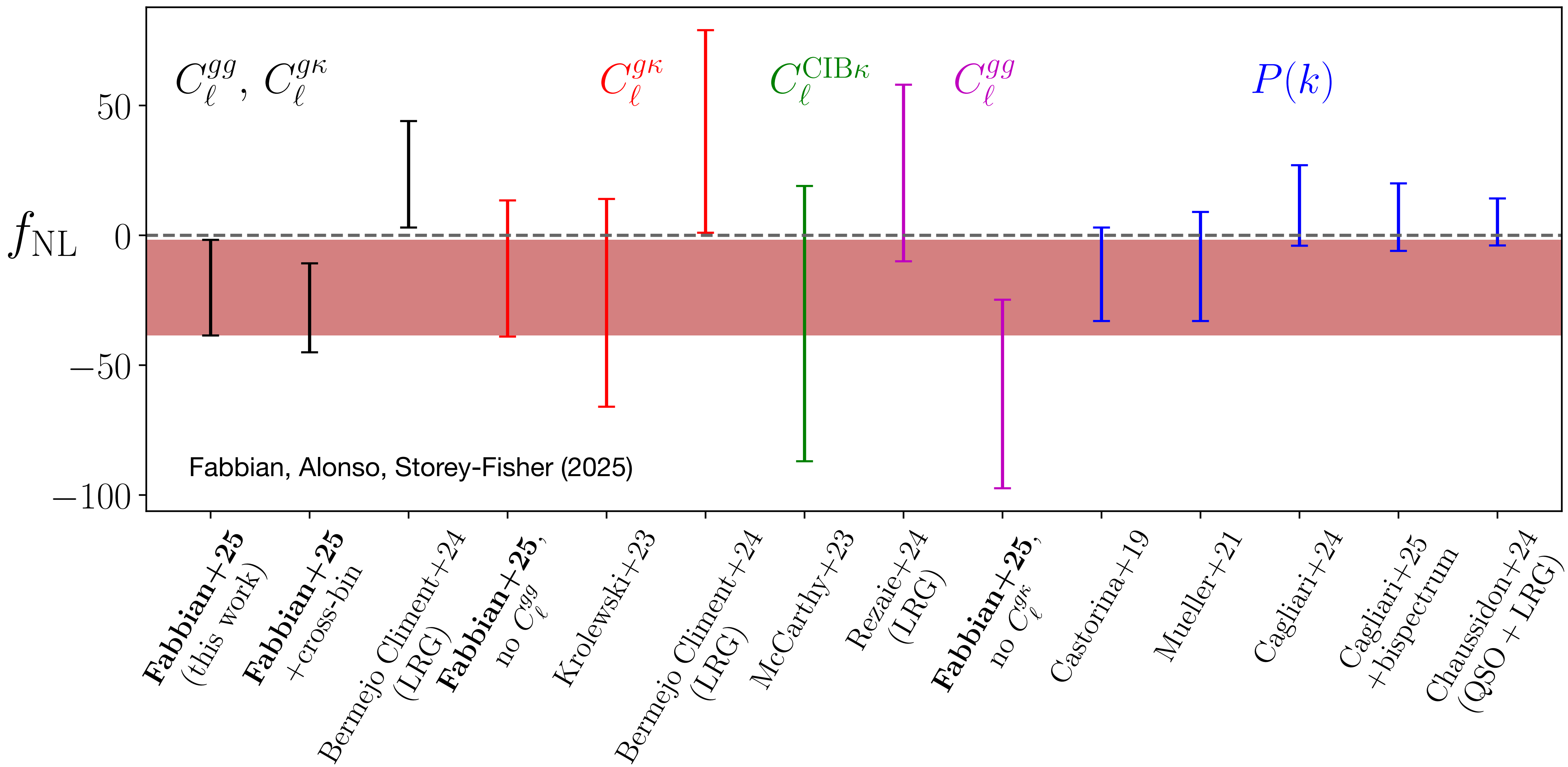


Aggressive systematics subtraction needs: ~3x degradation of results (Rezeie+2025)

Scale cuts from ground-based surveys (Krolewski+2023)

- Cross-correlation can reach the largest scales!
- $\sigma(f_{\rm NL})$: worse than expectations due to residual systematics $\Delta C_\ell^{\kappa g} \propto \sqrt{C_\ell^{\kappa\kappa} C_\ell^{gg}}$

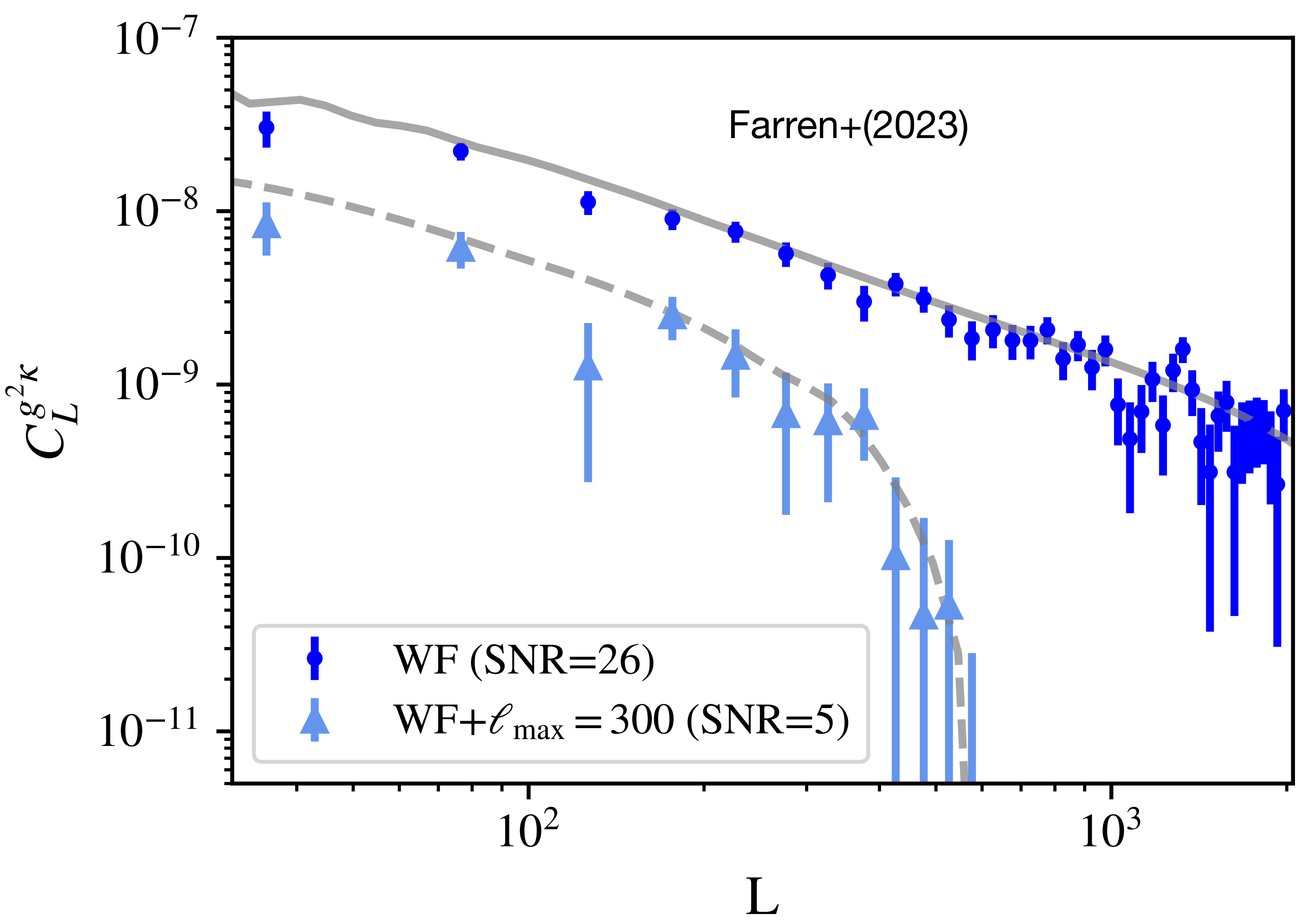
Robustness tests and perspectives

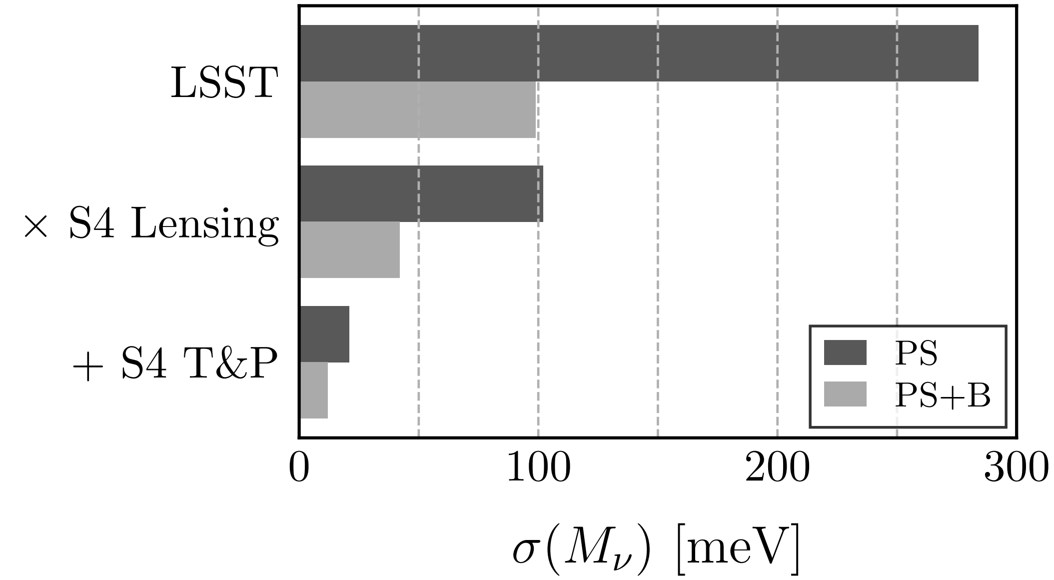


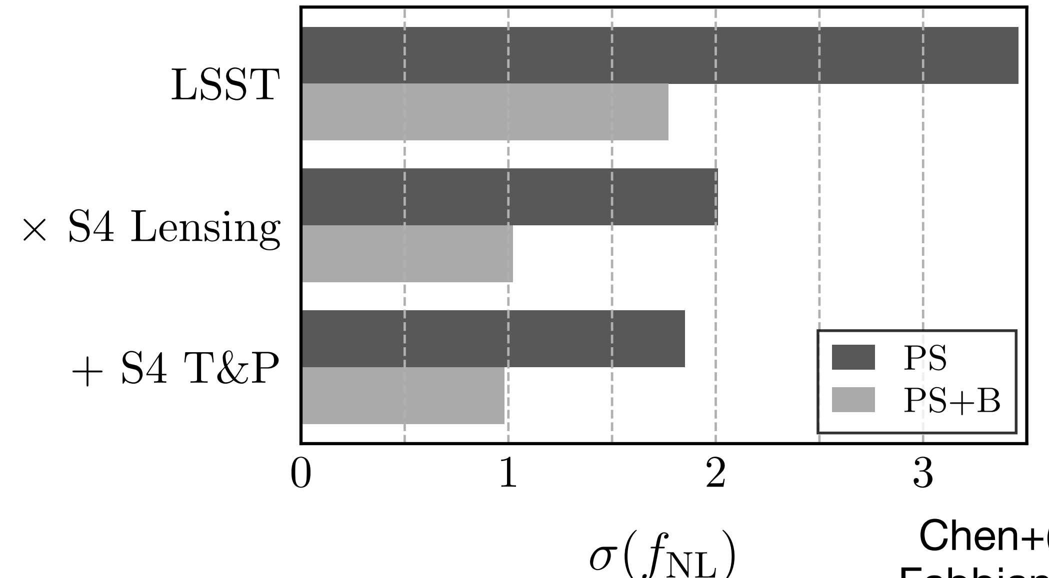
- Sensitivity comparable to spectroscopic galaxy surveys in 3D
- Limited by systematics on auto correlation on large scales but highly robust to systematics.
- Newer data releases from Gaia could improve this results (more sources, different source separation).

Higher-order cross-correlation

- Why limit to 2-point correlation functions….
- $\langle \kappa\kappa g \rangle, \langle \kappa g g \rangle$: great tools to reduce errors due to galaxy bias uncertainties.
- High-significant detections appeared very recently, hard to model…







Chen+(2023), Fabbian+(2019)

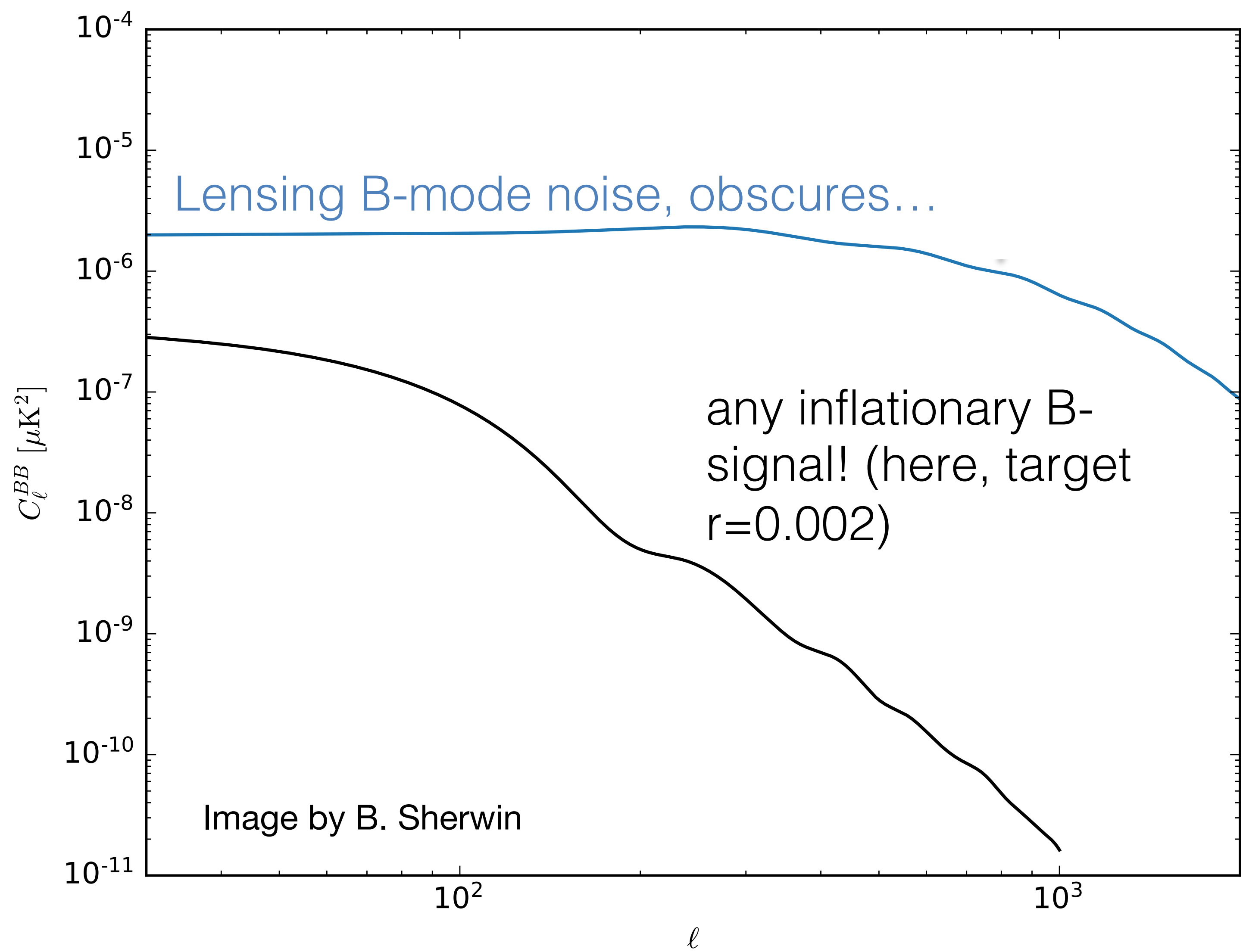
Lensing and CMB B-modes polarization

- E to B-modes conversion can hide primordial signal

$$B^{lens}(\mathbf{l}) \sim \int d\mathbf{l}'\ W(\mathbf{l},\mathbf{l}')E(\mathbf{l}')\phi(\mathbf{l}-\mathbf{l}')$$

- $\sigma(r) \propto N_\ell^{BB} + C_\ell^{BB,lens}$

- Limiting factor to constrain inflation from deep data (10x degradation for CMB-S4)



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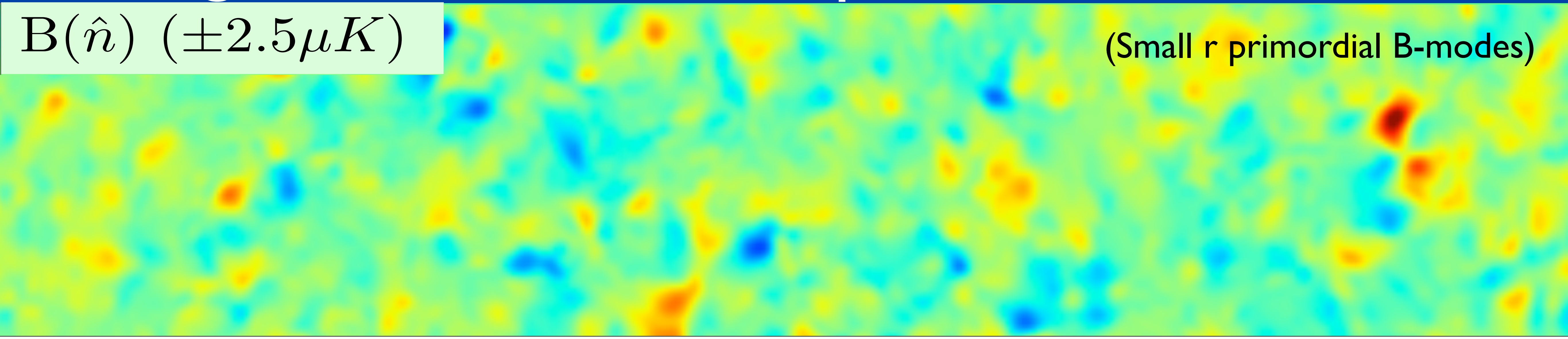

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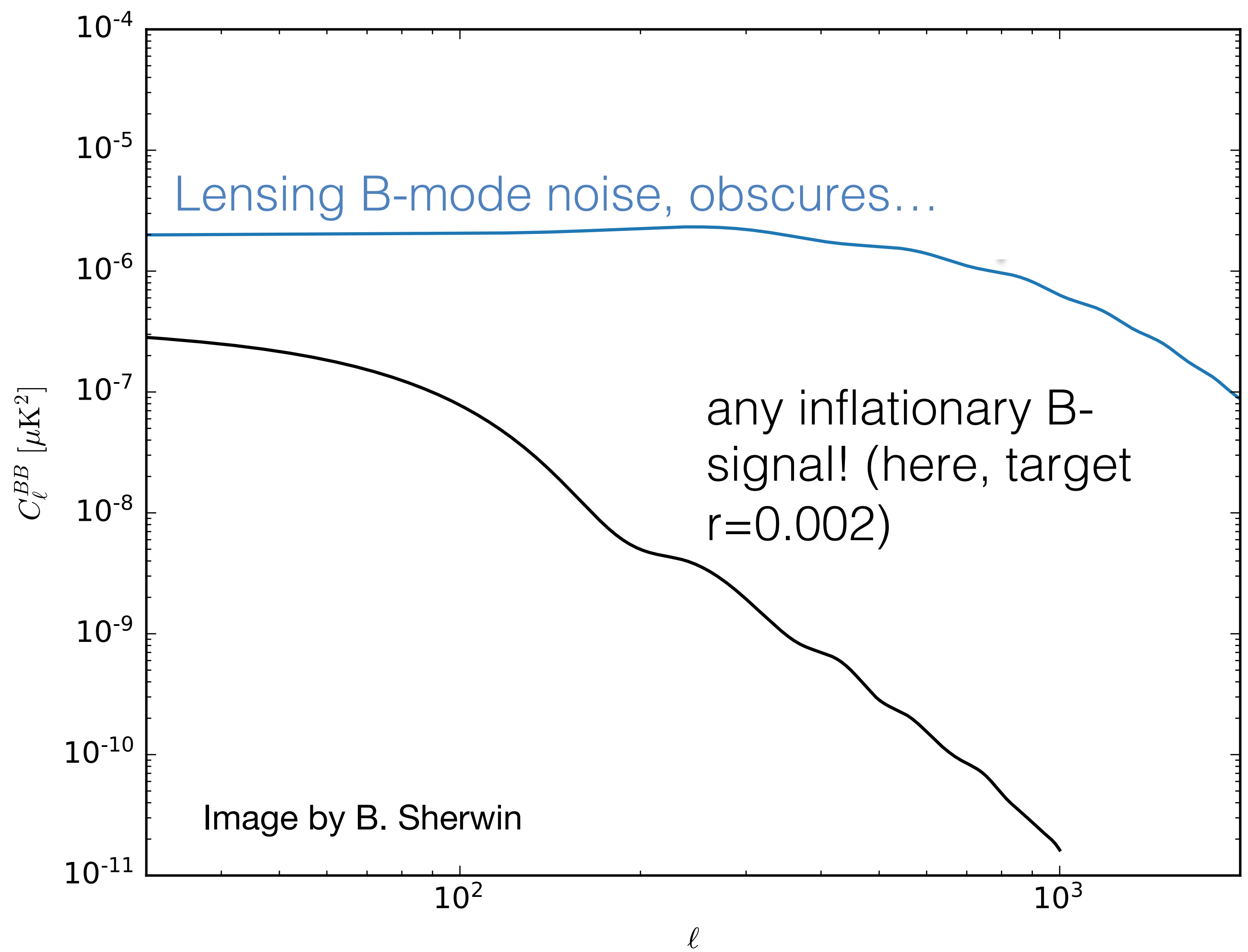
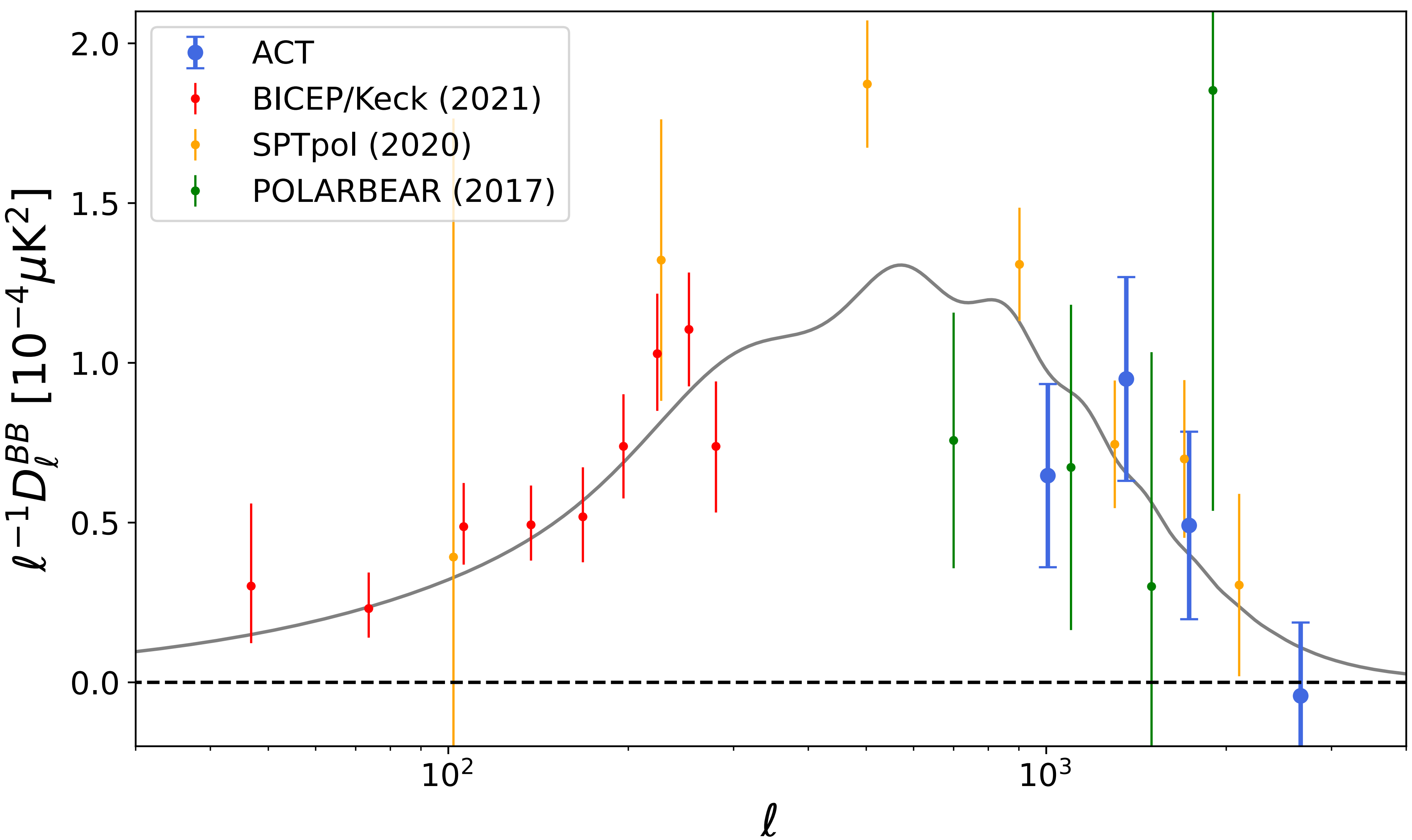


CMB B-modes status

- First direct measurement in 2014 by POLARBEAR ($\sim 3\sigma$, $f_{sky} < 0.1\,\%$)
- Highest SNR by SPT and BICEP on large sky fractions.
- Inflationary part not detected, signal consistent with lensing only.

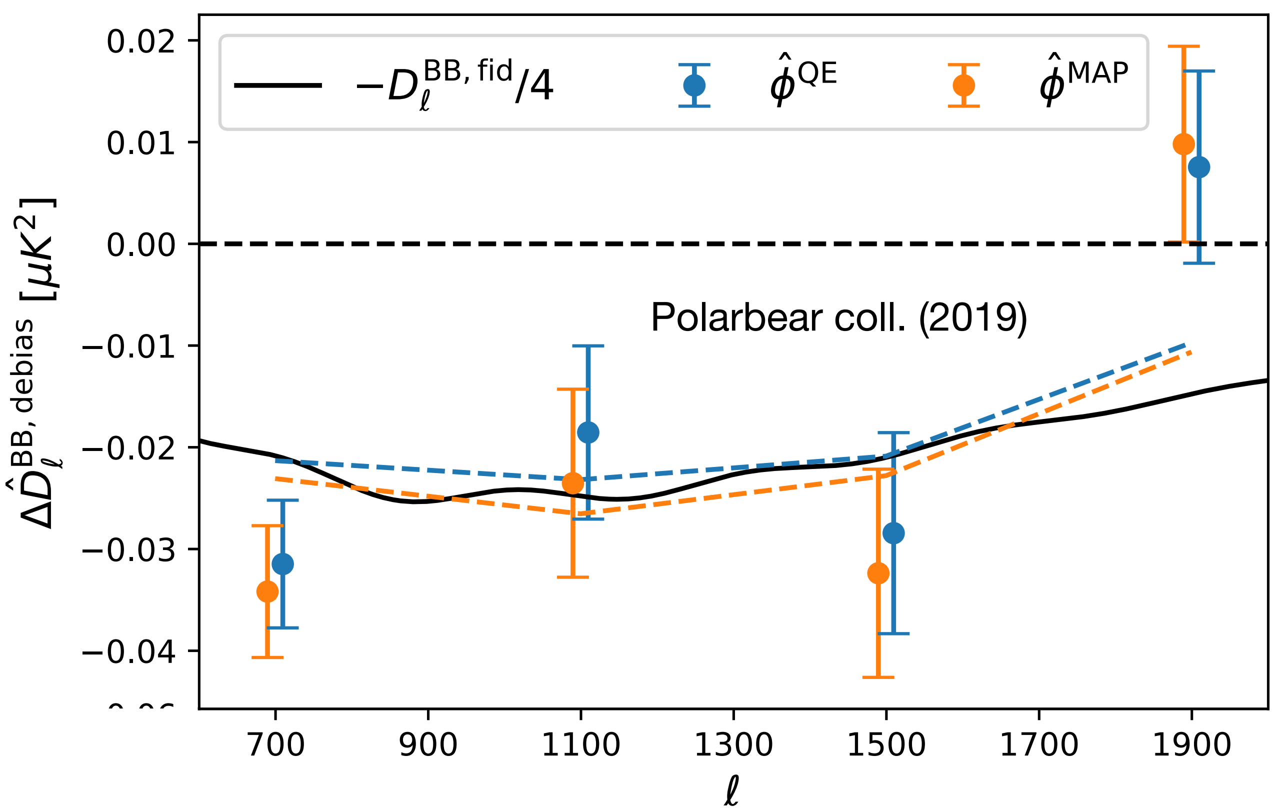


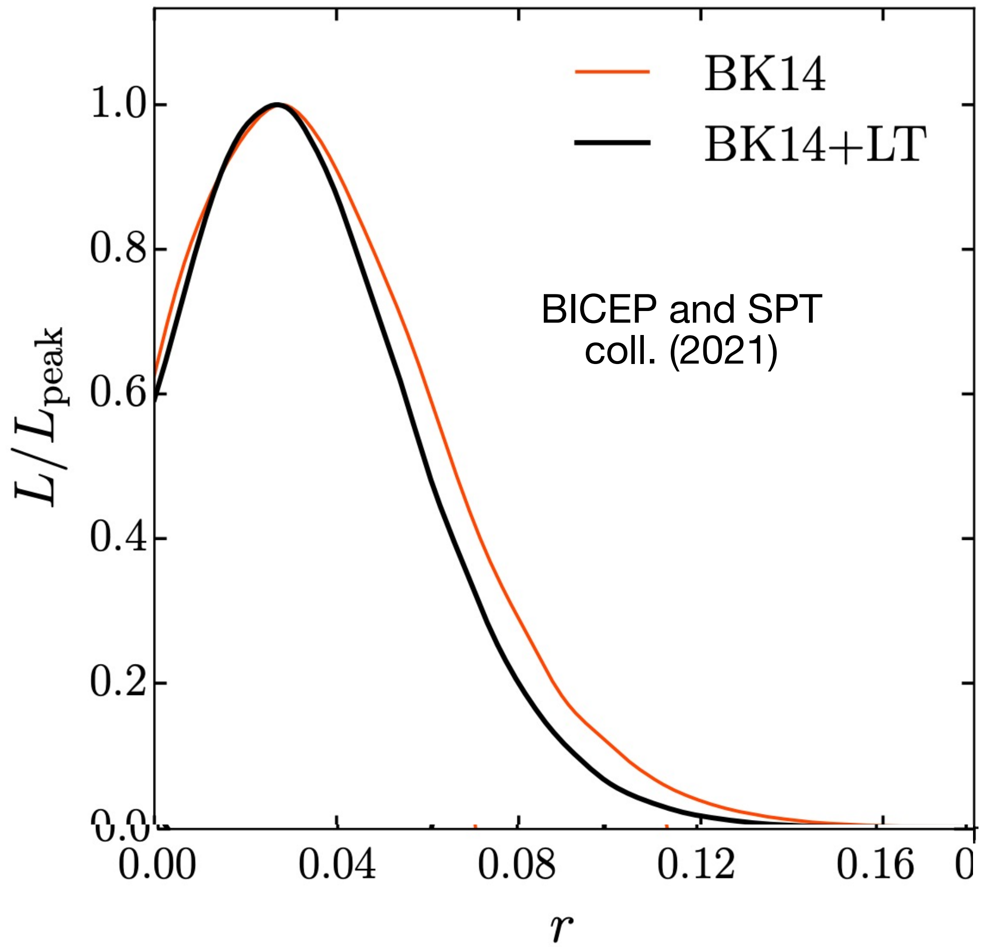
Delensing CMB polarization

- Subtract a template of the lensing B-modes to reduce signal and variance

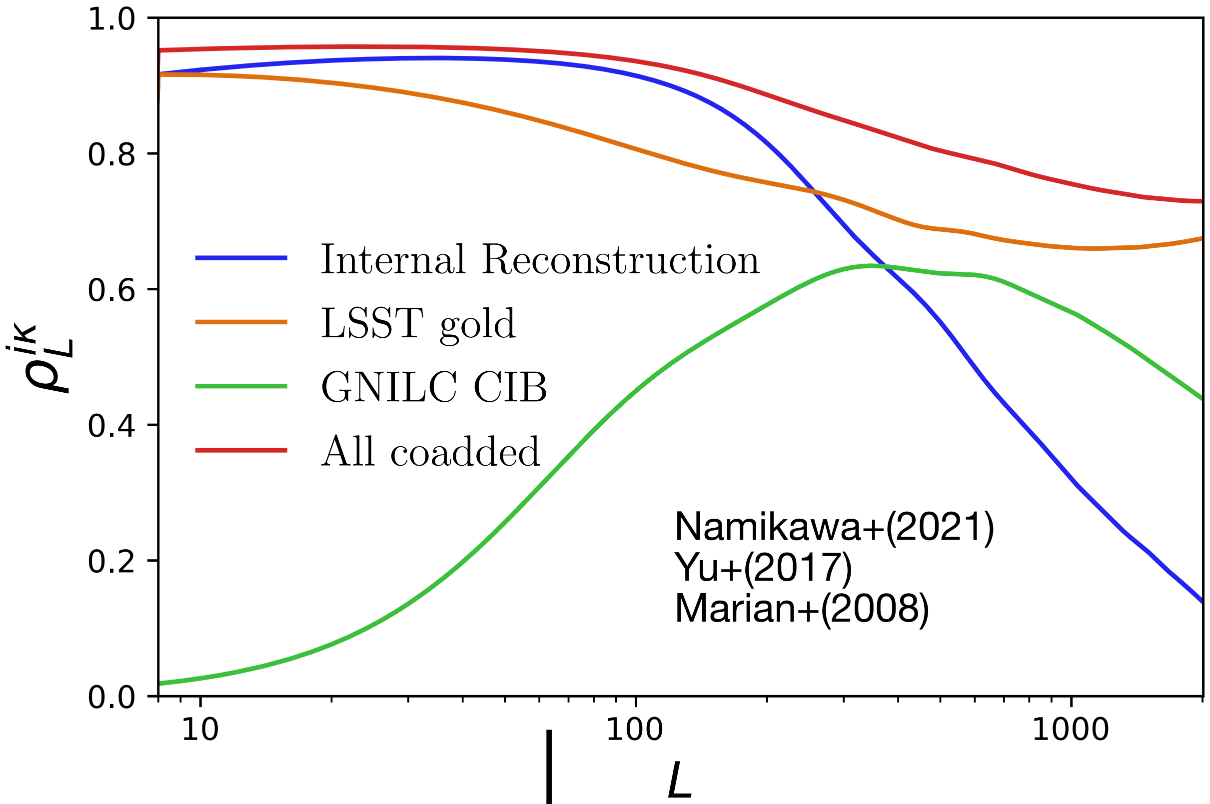
$$B^{data} - \hat{B}^{lens} \sim B^{data} - \int d\mathbf{l}' W(\mathbf{l}, \mathbf{l}') E(\mathbf{l}') \phi(\mathbf{l} - \mathbf{l}')$$

- I need low noise high resolution E-mode polarization (e.g. ACT, SPT…)
- and an estimate of the matter distribution that lensed the CMB, i.e. a good estimate of ϕ

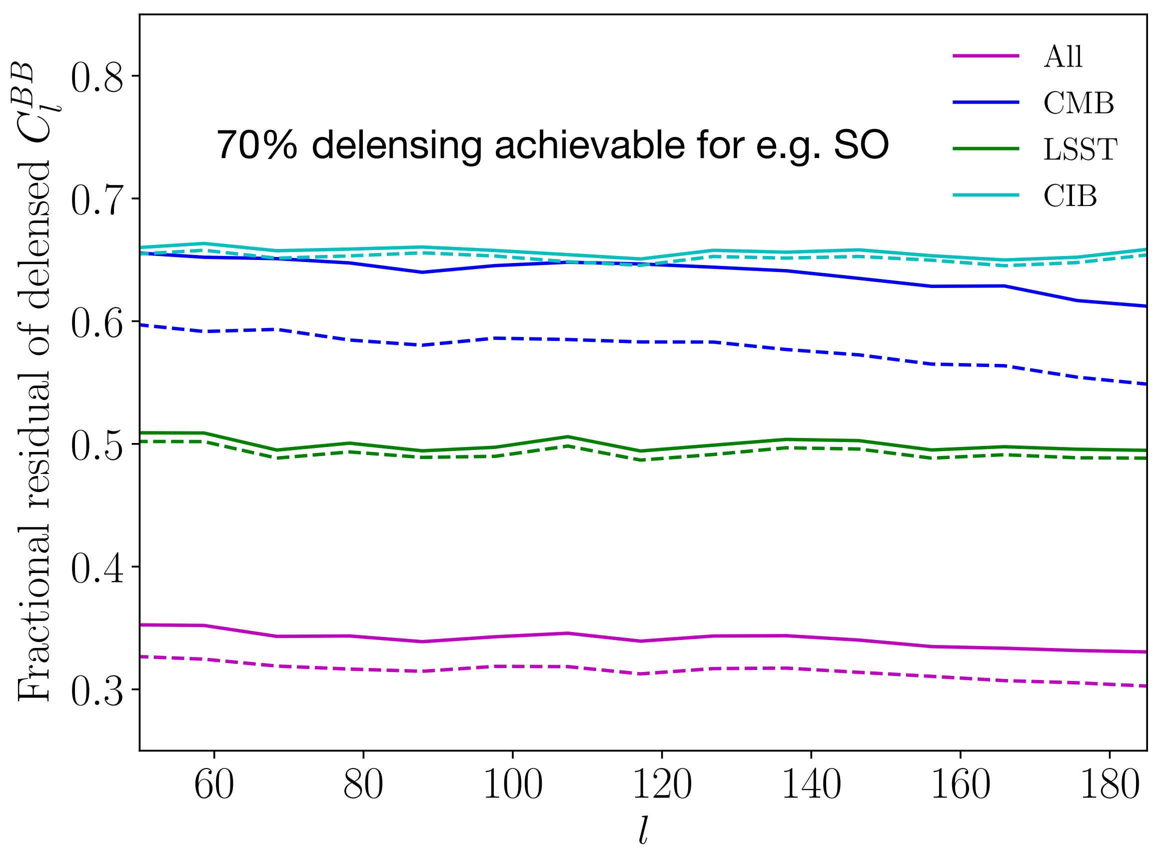




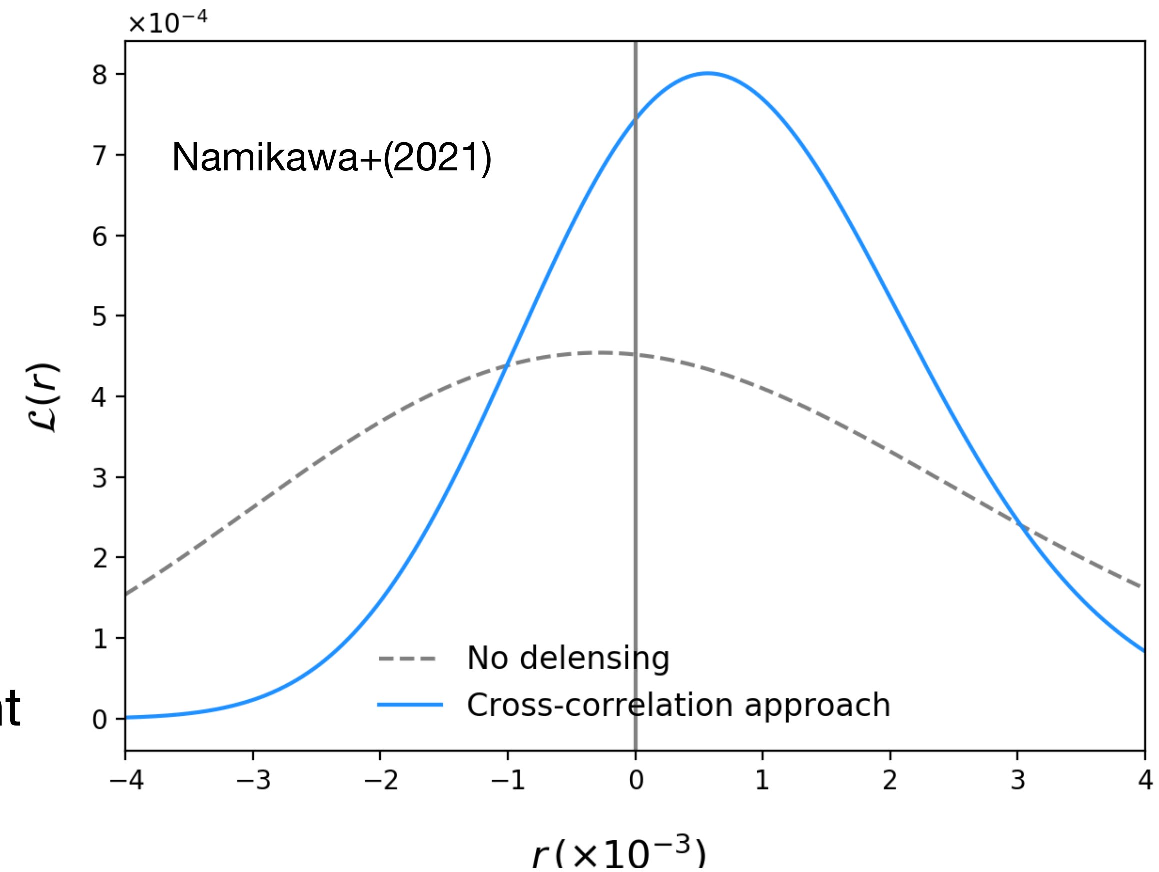
Delensing with galaxy surveys



- Accuracy of CMB lensing reconstruction is limited by noise.
  - Combine external galaxy tracers to improve SNR using cross-correlation.
  - Crucial improvements for low-resolution experiments (Litebird…)

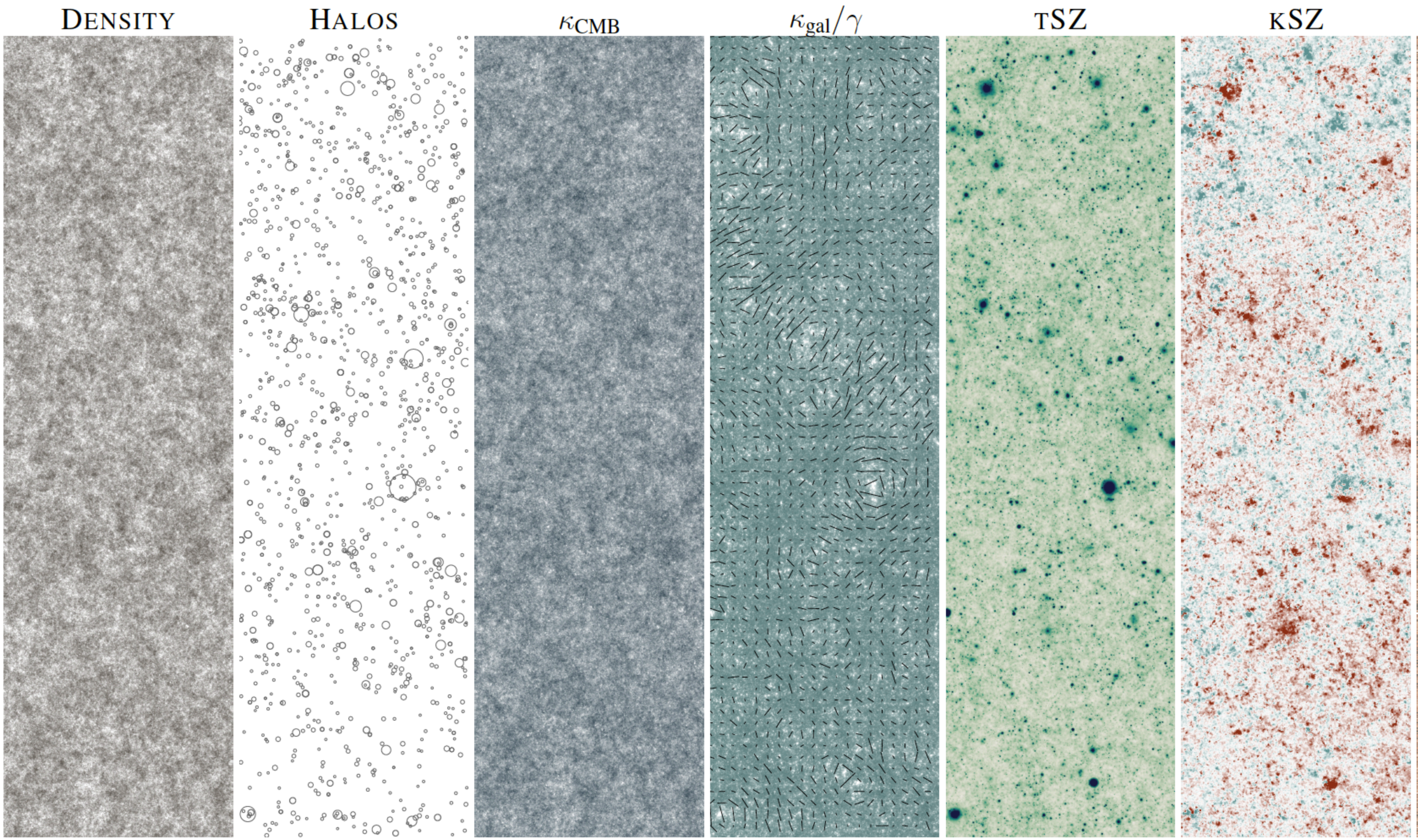


2x inflation constraints improvement



Switching gears to SZ

- Questions? Comments? Remarks? Complaints?



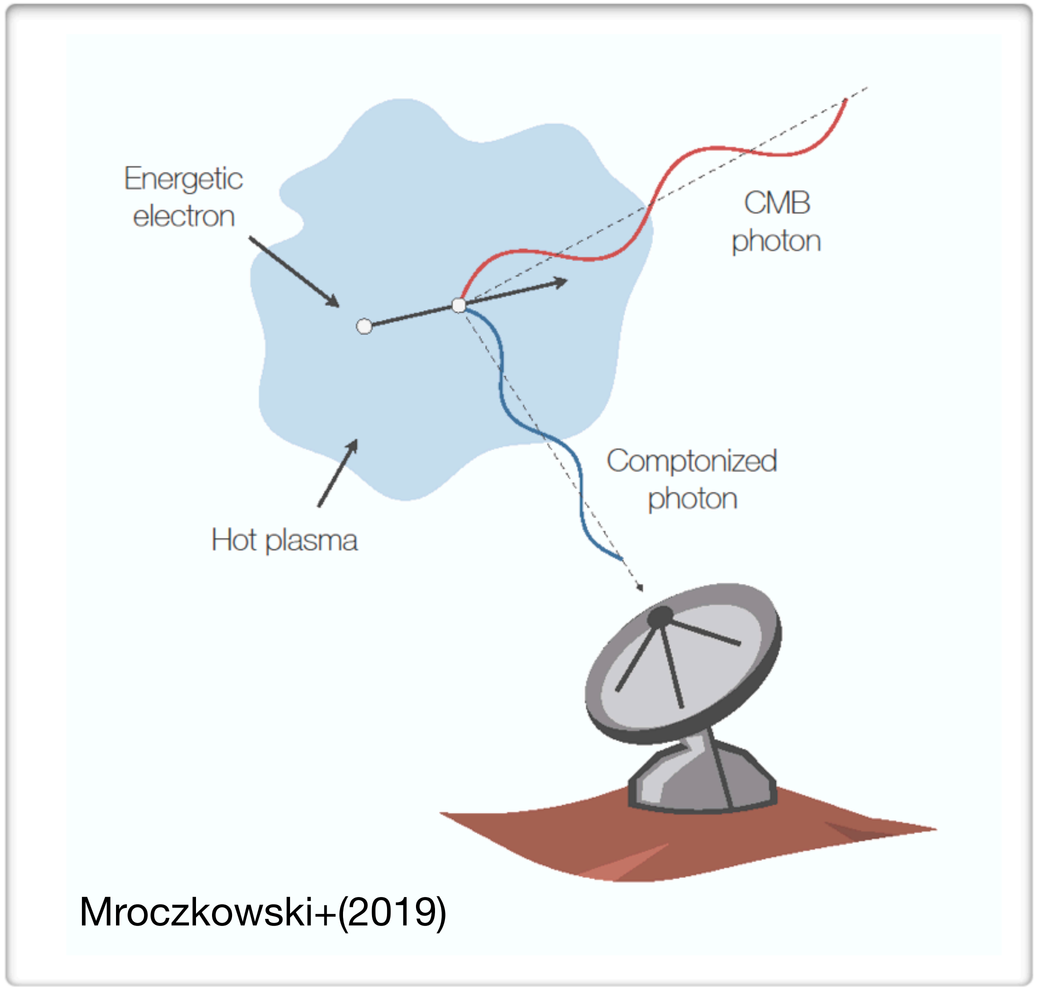
Omori (2023)

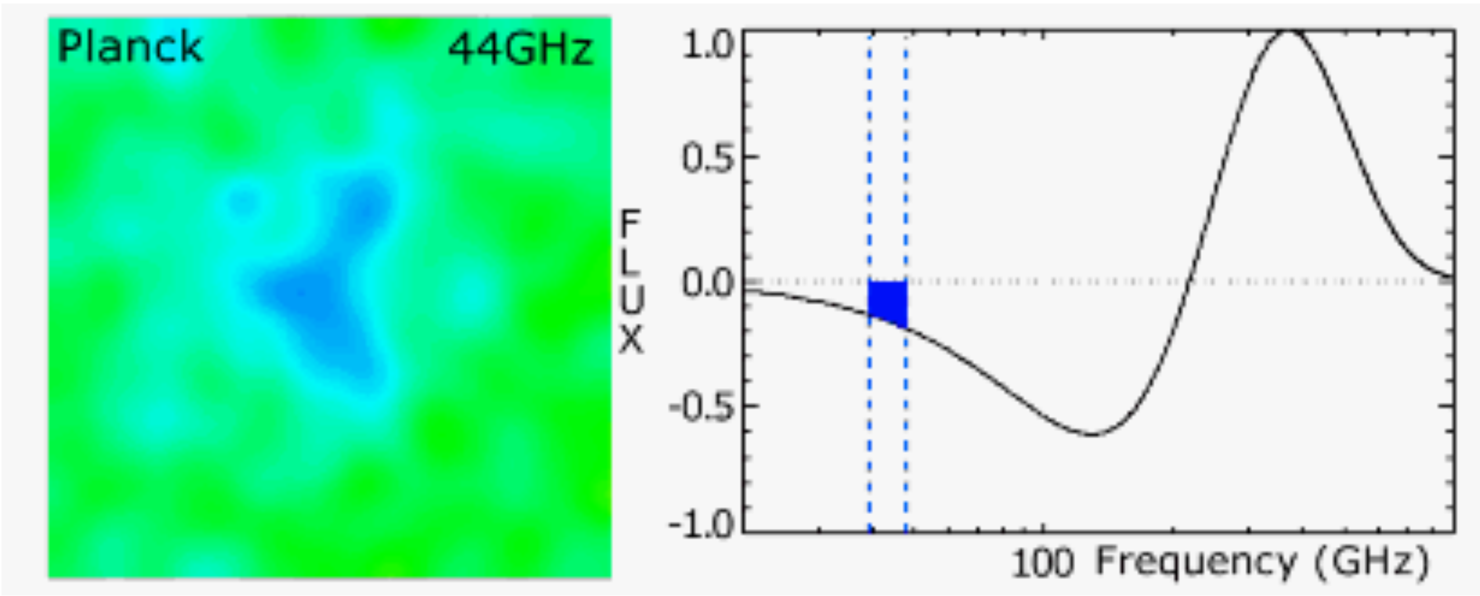
tSZ primer

- Inverse Compton scattering off hot electrons in ICM/CGM changes CMB T locally.
  - Direct probe of **gas pressure**
  - Interface between astrophysics and cosmology.

$$y(\hat{\mathbf{n}}) = \int n_e \frac{k_B T_e}{m_e c^2} \sigma_T \, ds$$

- Can be disentangled through accurate multi-frequency observations.





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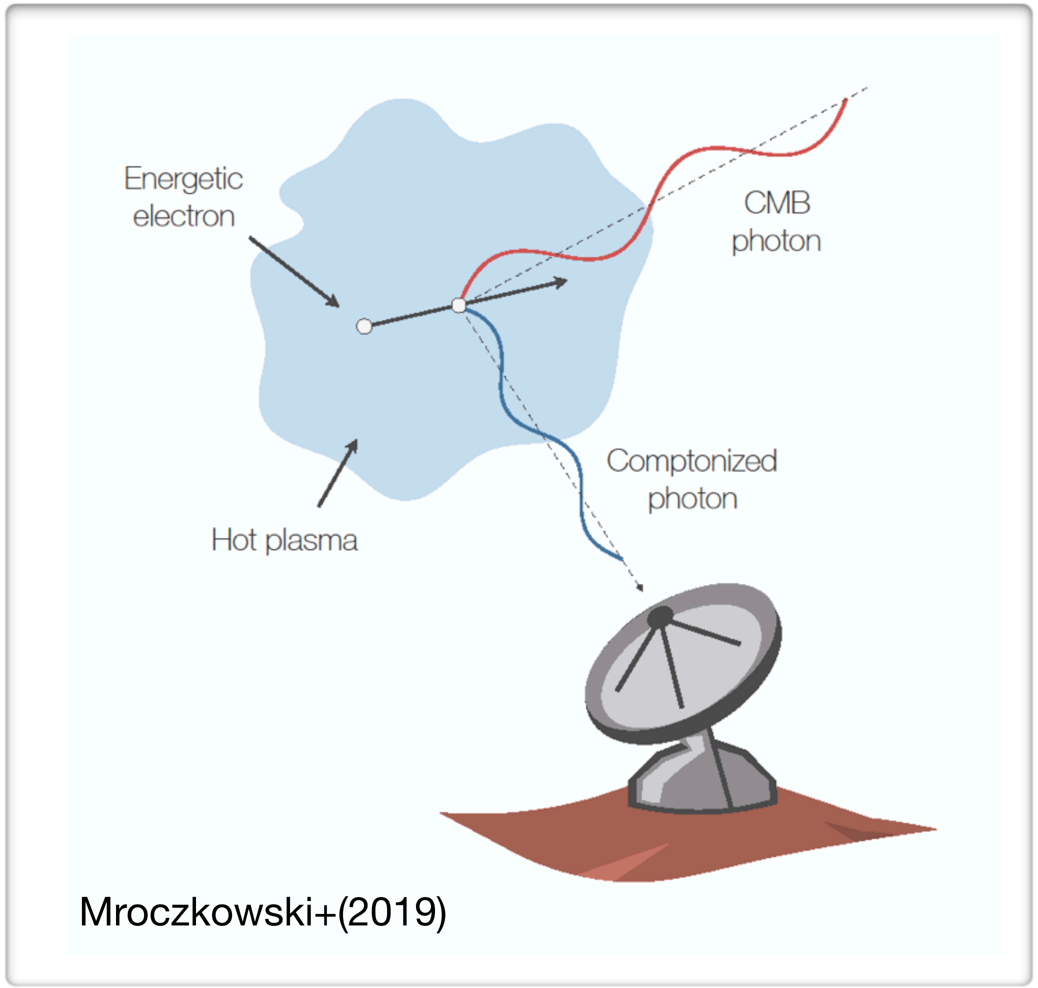
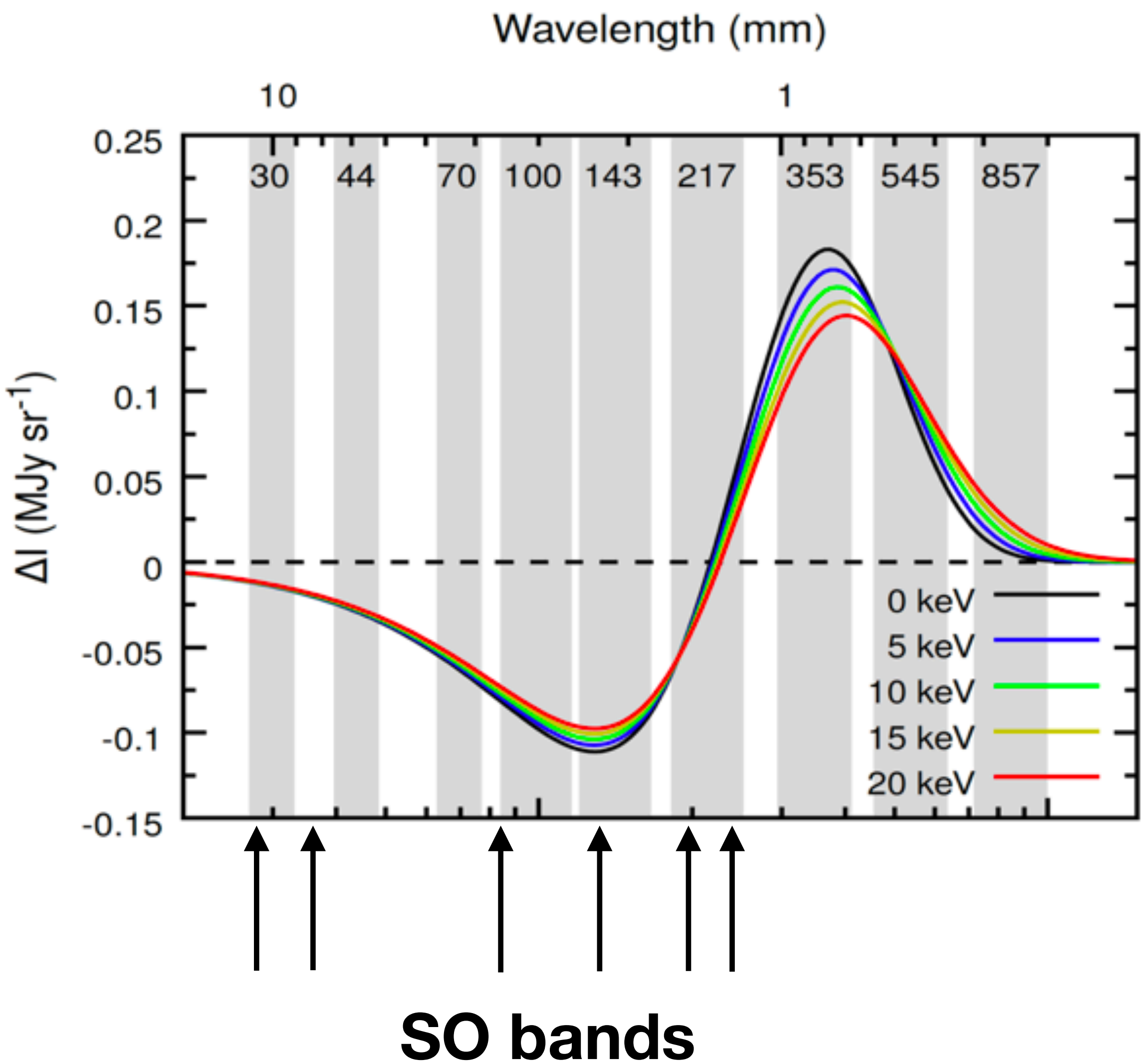
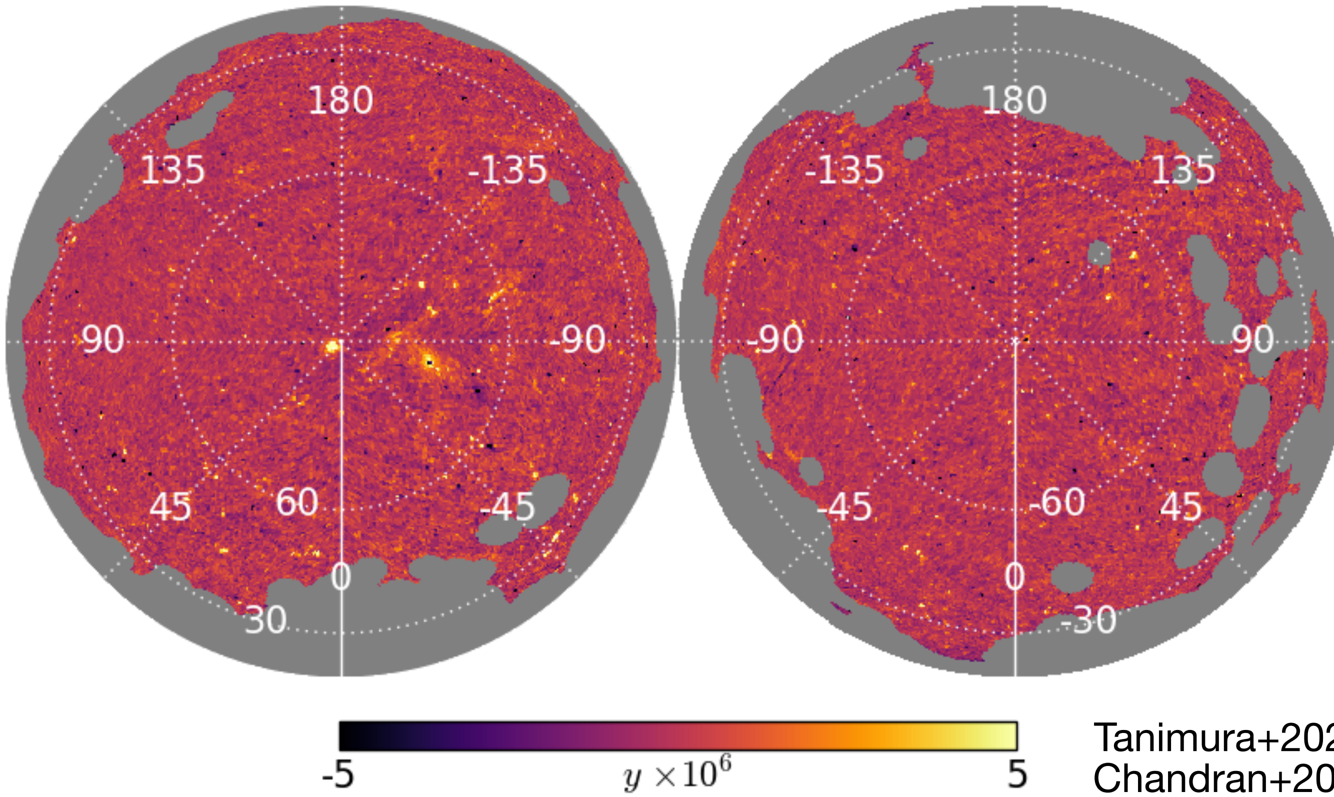




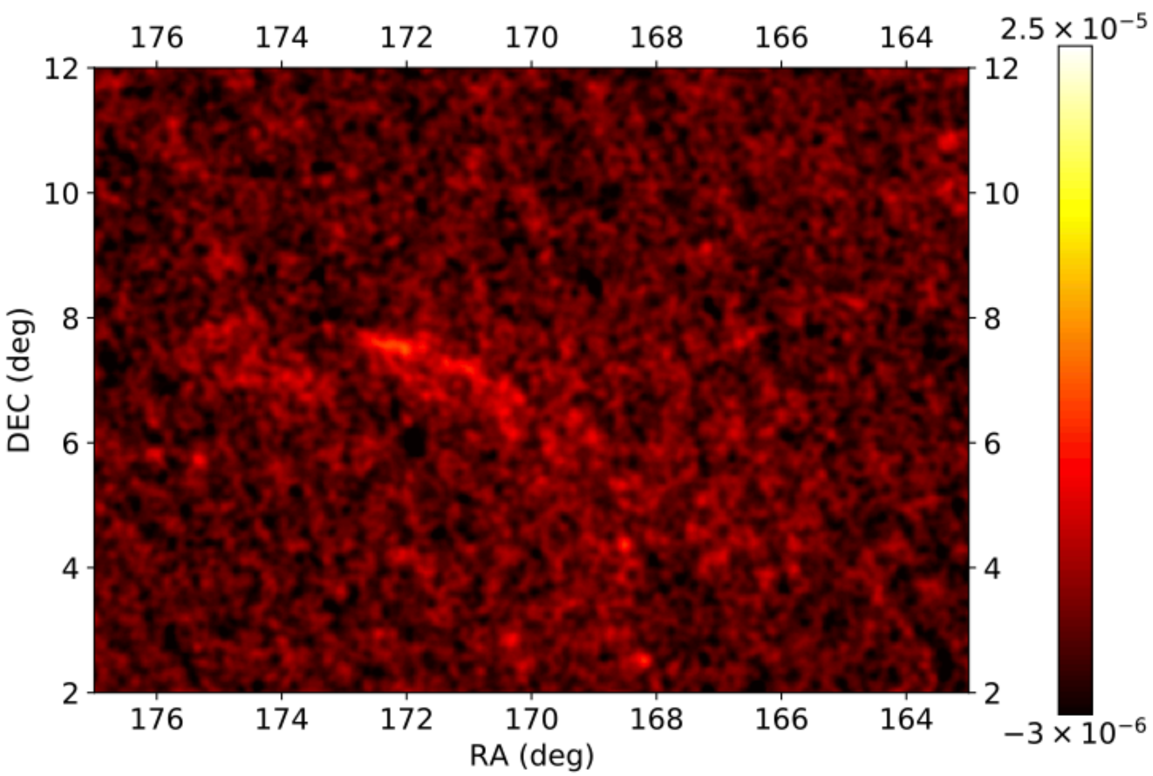
tSZ maps state of the art

- New analysis on Planck DR4 w/ different foreground cleaning methods.
- ACT DR6 used Planck additional channel and different cleaning method for higher-resolution map.

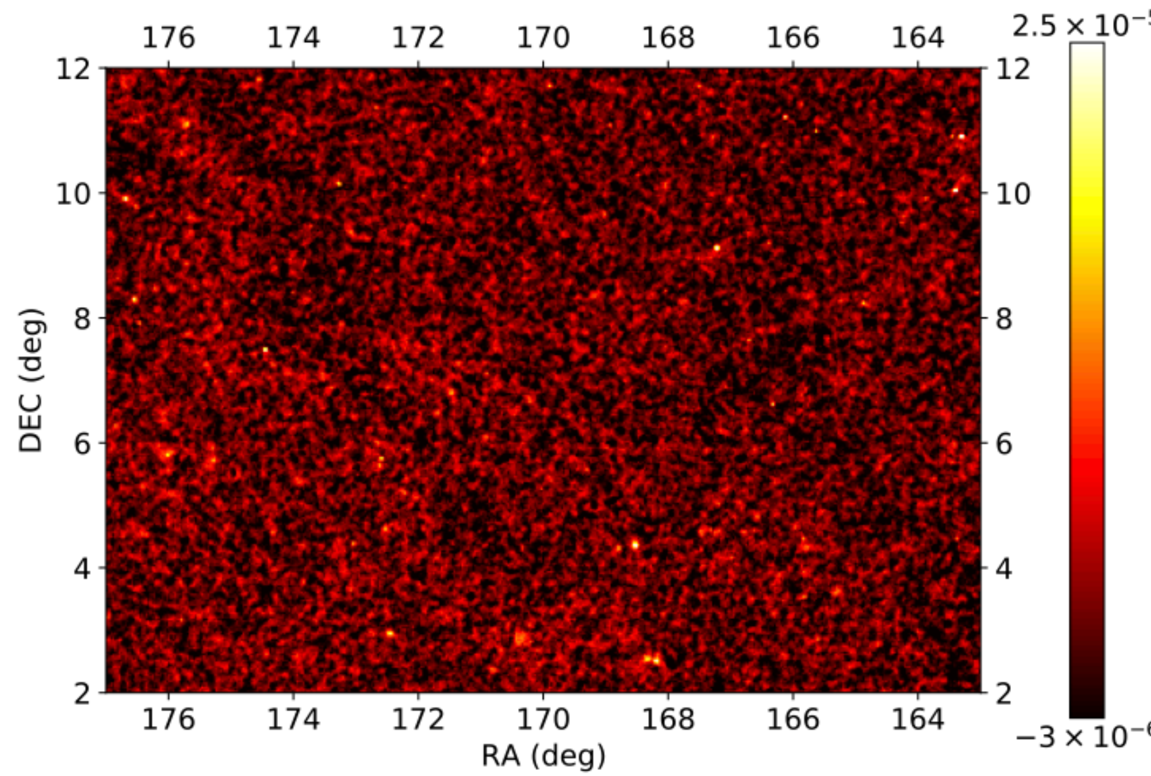
tSZ map 2020



Tanimura+2021, Chandran+2024



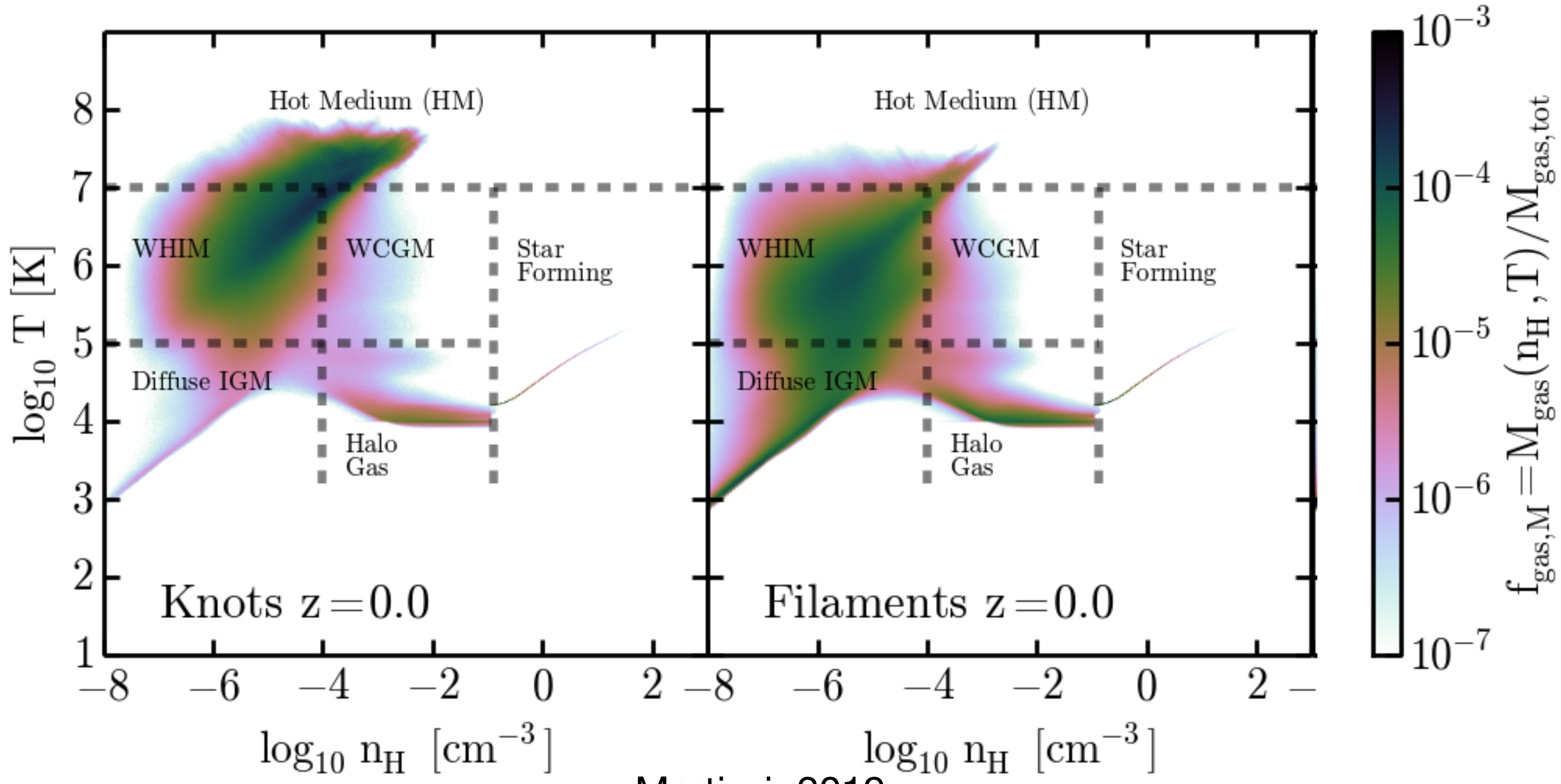
Planck 2015 MILCA



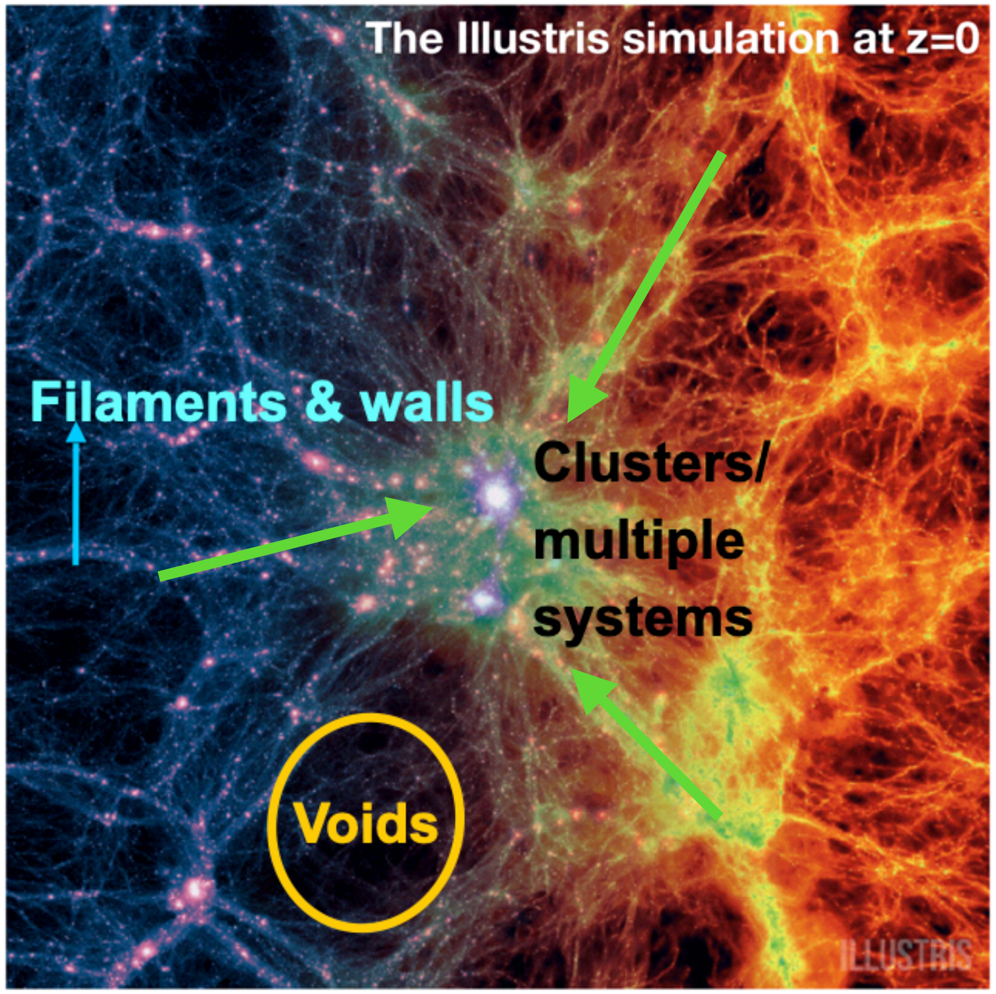
Coulton+ 2024

ACT+Planck

Where is the tSZ?



Martizzi+2019

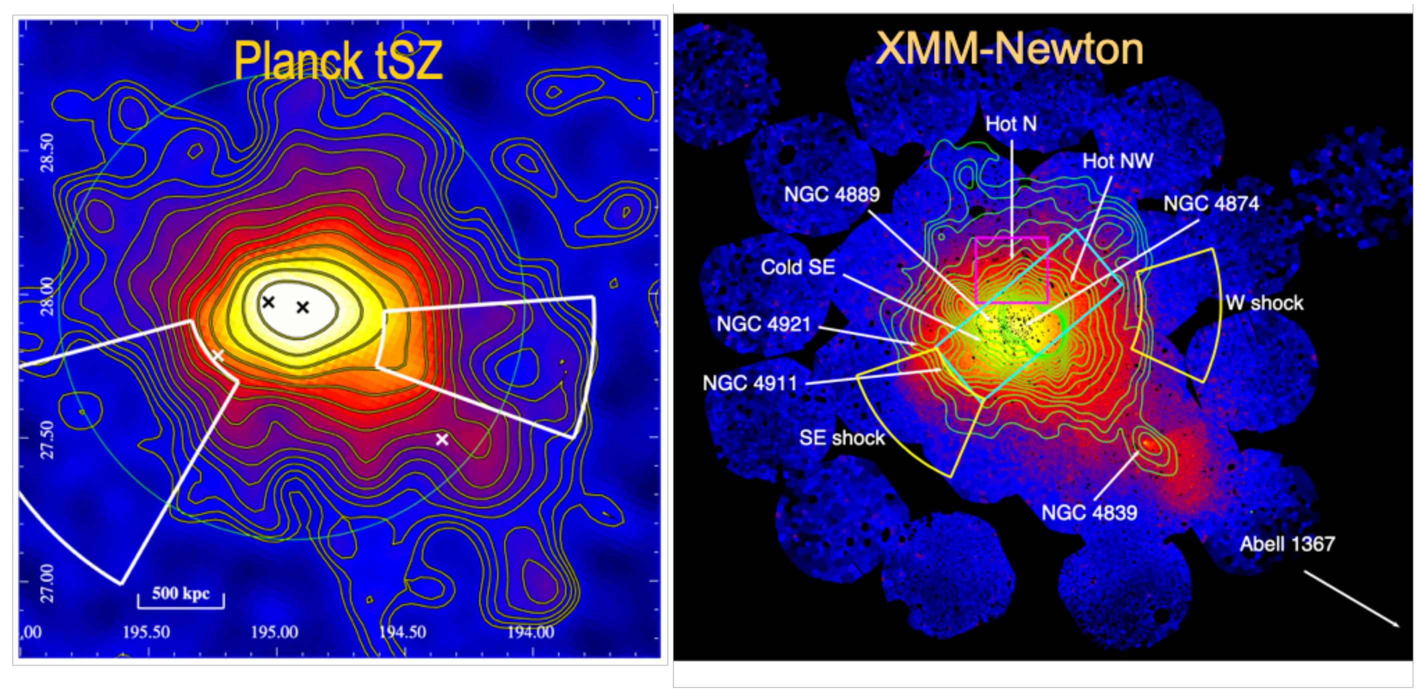


Courtesy N.Battaglia, N. Aghanim

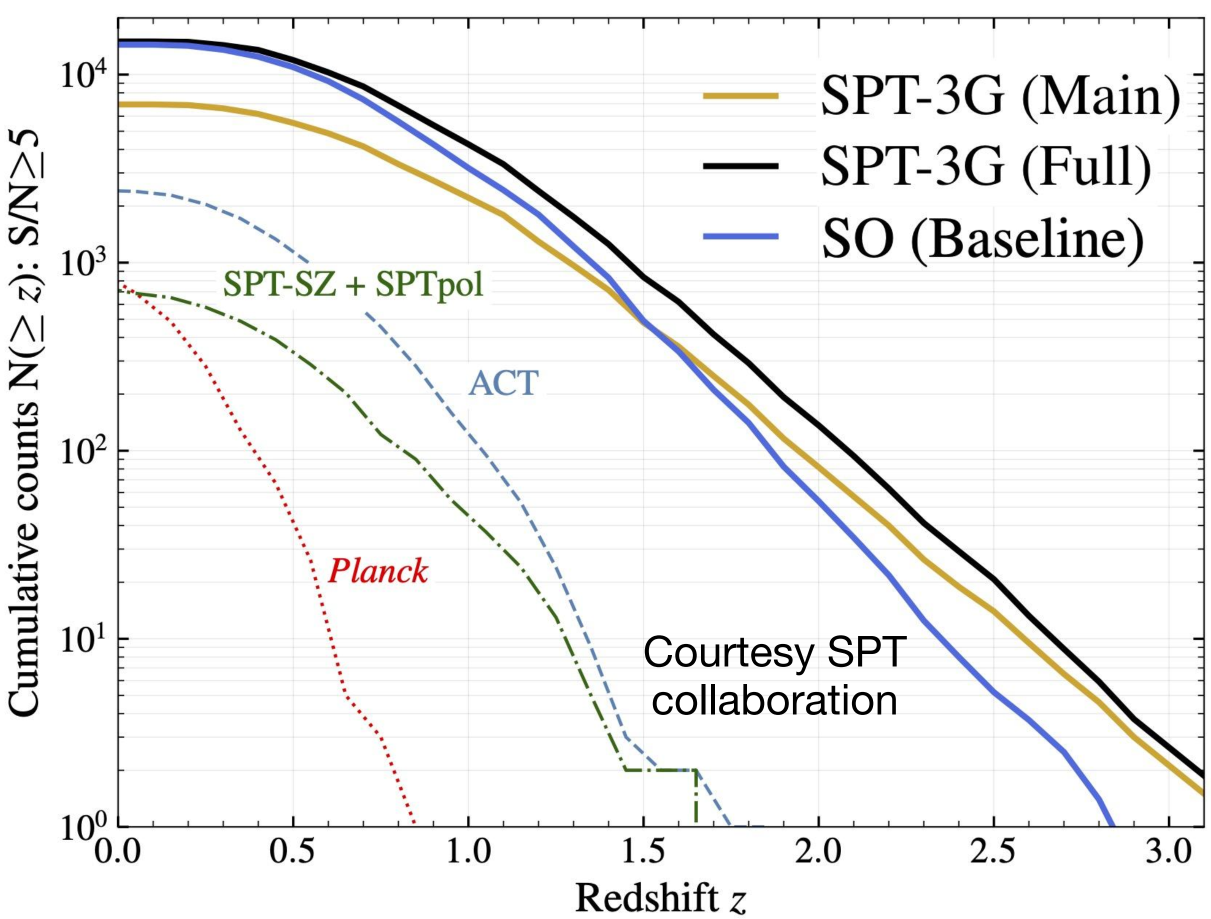
- Ionized hot and warm gas is ubiquitous and can generate tSZ:
  - Direct probe of gas across environments (filaments, voids, clusters)
  - Useful probe of accretion of matter through filaments as well as feedback processes.

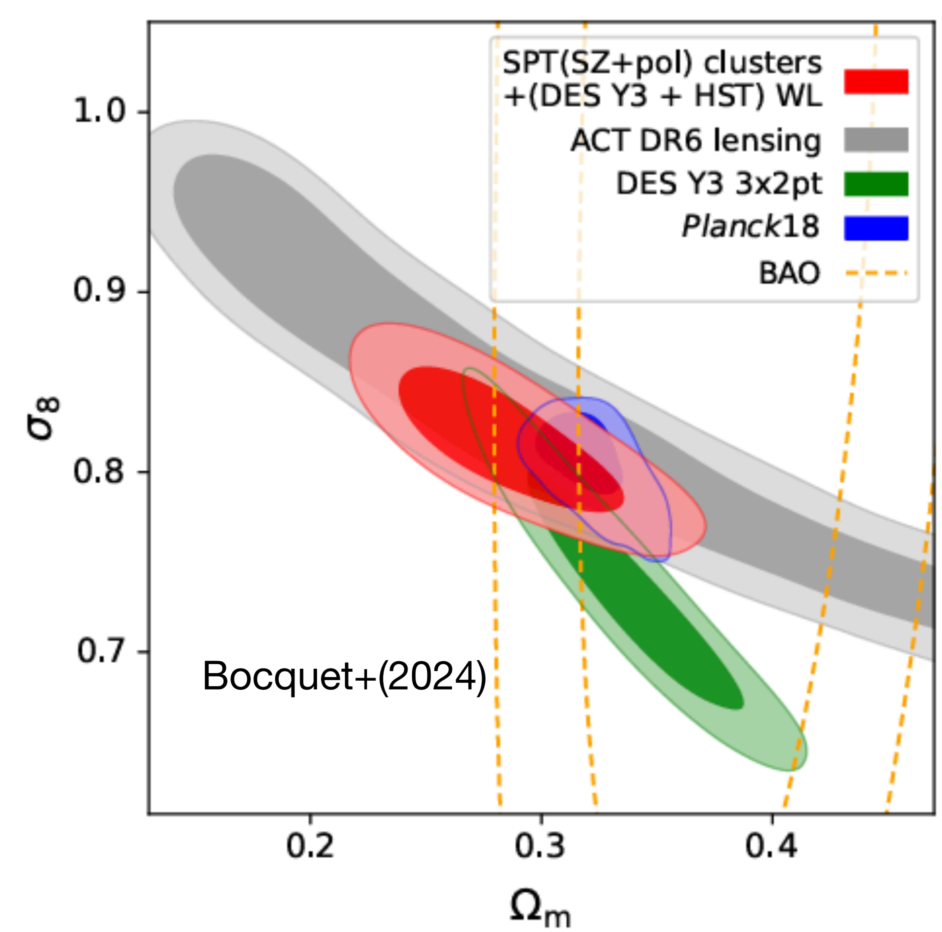
Cluster cosmology

- Number counts sensitive to dark energy (now ~1000s)
    - tSZ flux limit ~ mass limit!
    - Complementarity / synergies with X-ray and lensing surveys



Coma cluster (Planck coll. 2015, Mirakhor+2020)





tSZ power spectrum

- Strong cosmological dependency on e.g. dark energy and neutrinos…

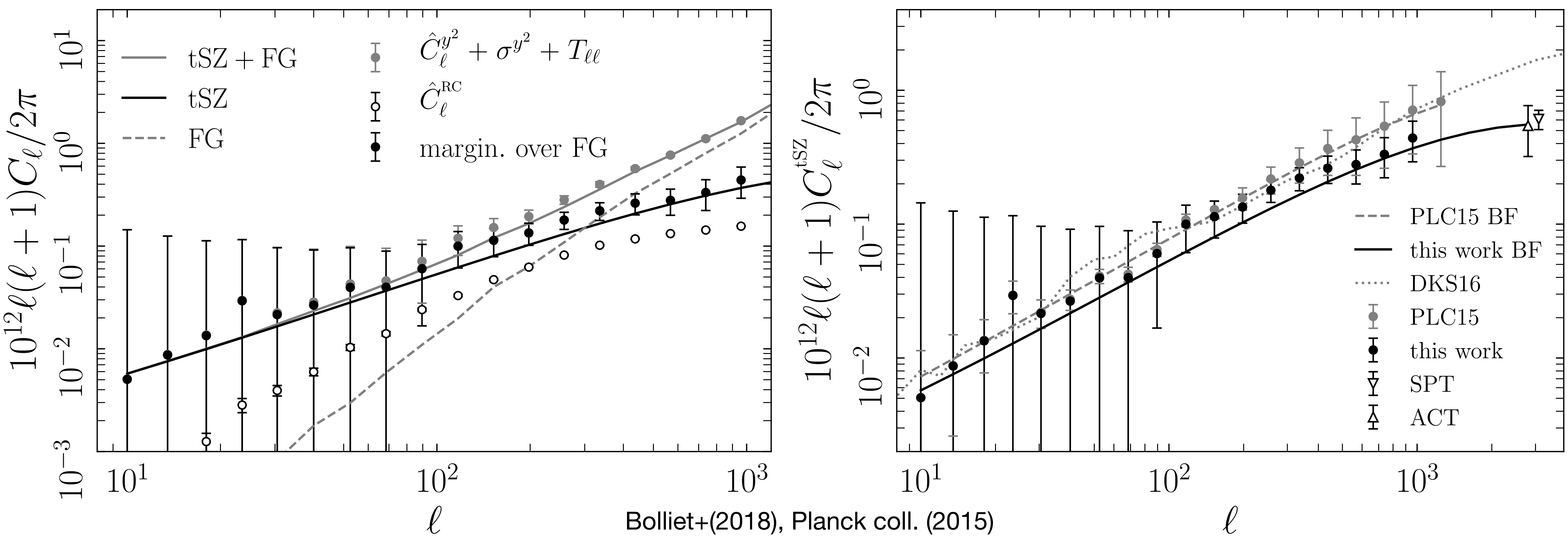
$$C_\ell^{yy} \propto \sigma_8^{8.1}\Omega_m^{3.2}B^{-3.2}h^{-1.7}$$

  - Same applies to higher order statistics (e.g. 1-p PDF, bispectra…)

- Very sensitive to astrophysical modeling and extragalactic foreground subtraction.

- Work in progress for joint modeling with upcoming lensing surveys

See also Elizabeth's lecture!



Bolliet+(2018), Planck coll. (2015)

tSZ cross-correlations with LSS surveys

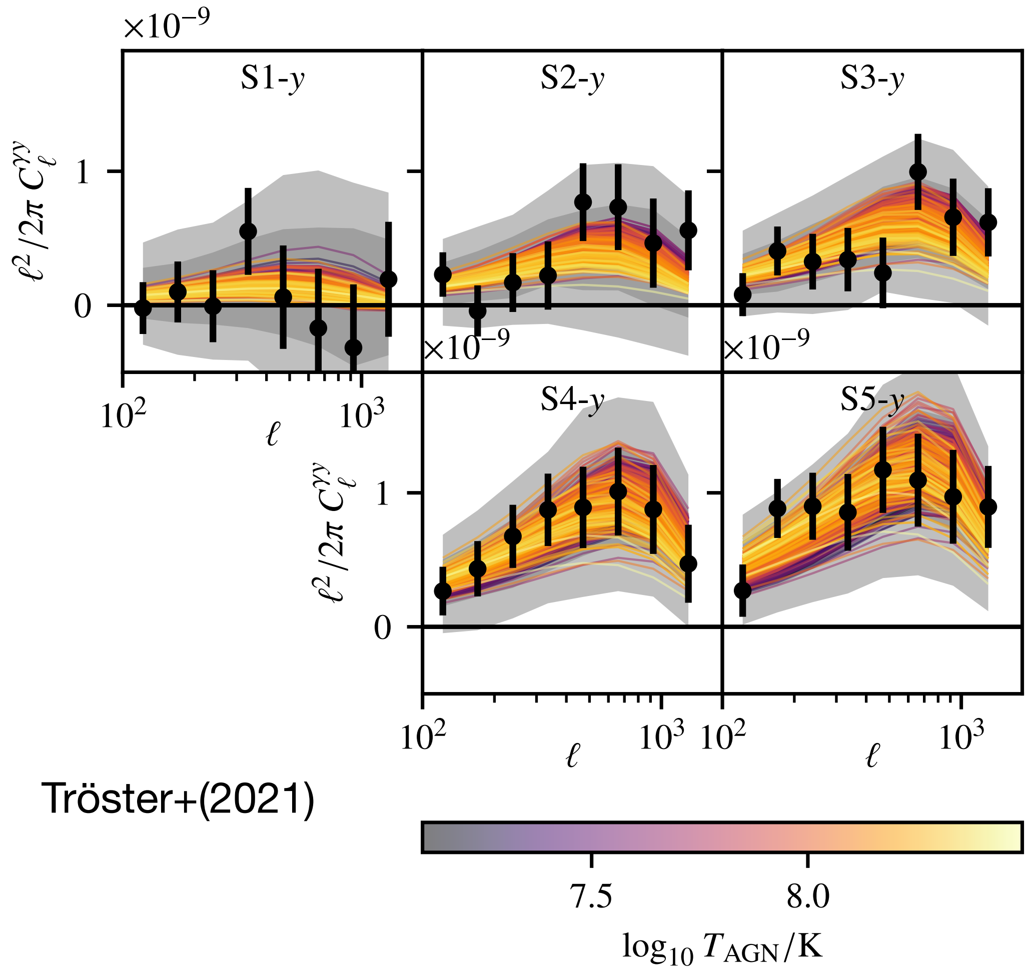
$$C_l^{\mathrm{AB,1h}} = \int_{z_{\min}}^{z_{\max}} \mathrm{d}z \frac{\mathrm{d}V}{\mathrm{d}z\mathrm{d}\Omega} \int_{M_{\min}}^{M_{\max}} \mathrm{d}M \frac{\mathrm{d}n}{\mathrm{d}M} \tilde{u}_l^{\mathrm{A}}(M,z)\tilde{u}_l^{\mathrm{B}}(M,z)$$

Makiya & Komatsu (2018)

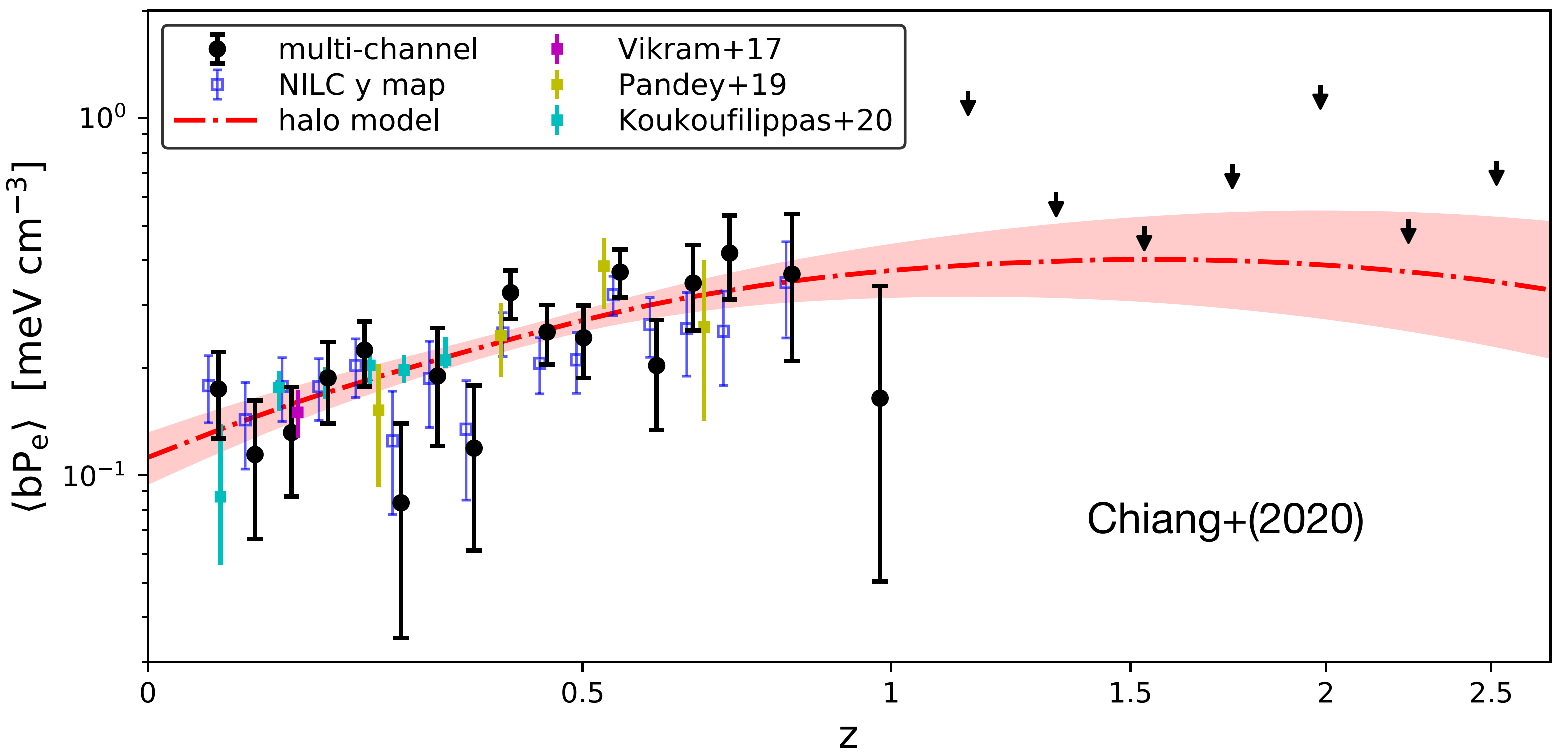
$$\tilde{u}_l^y(M,z) = \frac{4\pi r_{500c}}{l_{500c}^2} \int_{x_{\min}}^{x_{\max}} \mathrm{d}x x^2 \boxed{y_{3D}(x)} \frac{\sin(lx/l_{500c})}{lx/l_{500c}} \longrightarrow$$

$$P_e(x) = 1.65(h/0.7)^2 \ \mathrm{eV\ cm^{-3}} \times E^{8/3}(z) \left[\frac{M_{500c}}{3\times 10^{14}(0.7/h)M_\odot}\right]^{2/3+\alpha_P} p(x)$$

- Statistical measurements of pressure in the LSS, probe of thermal history
- Can inform analysis of weak-lensing data to account for baryonic effects.



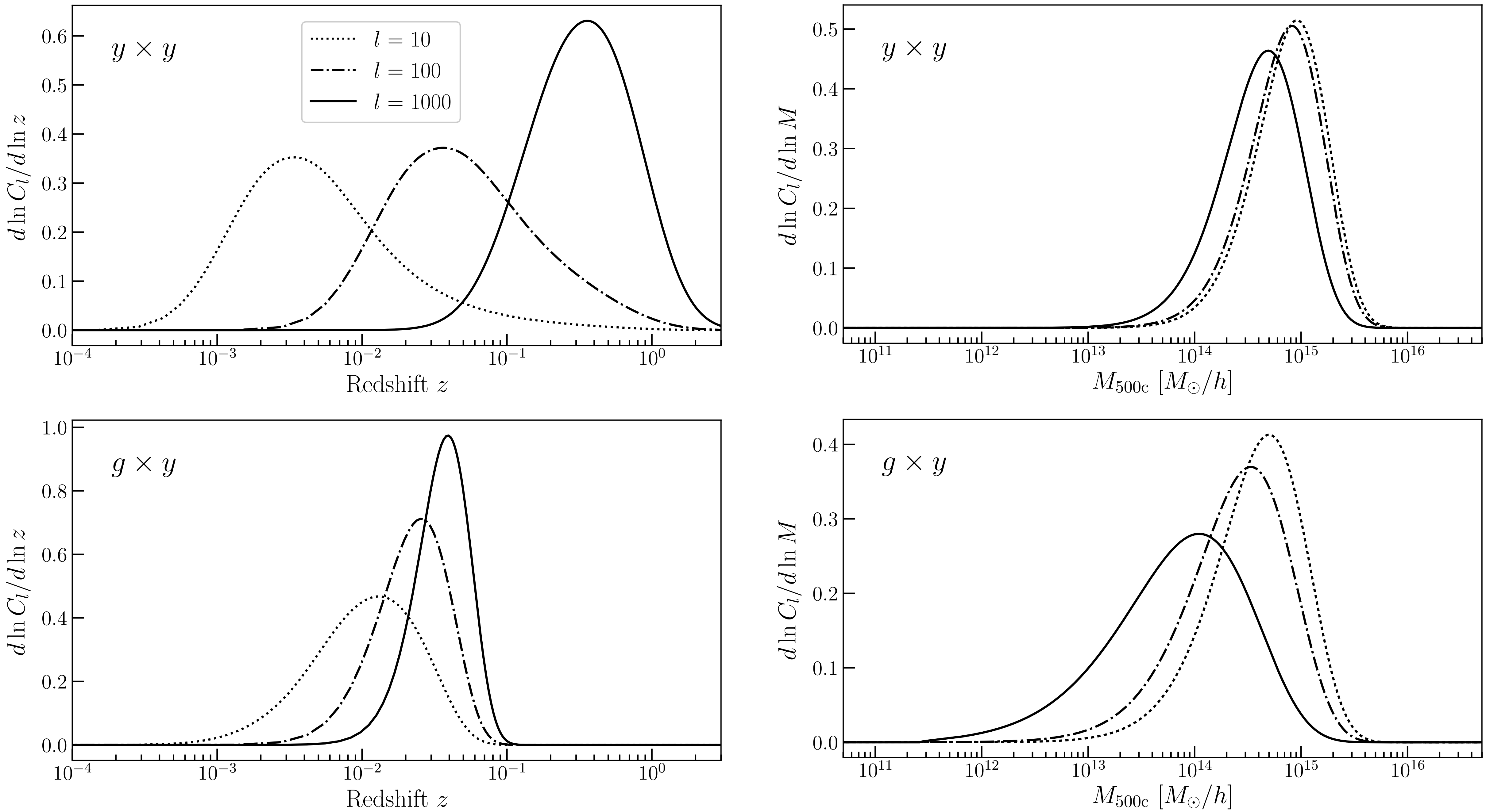
Tröster+(2021)



Chiang+(2020)

tSZ cross-correlations with LSS surveys

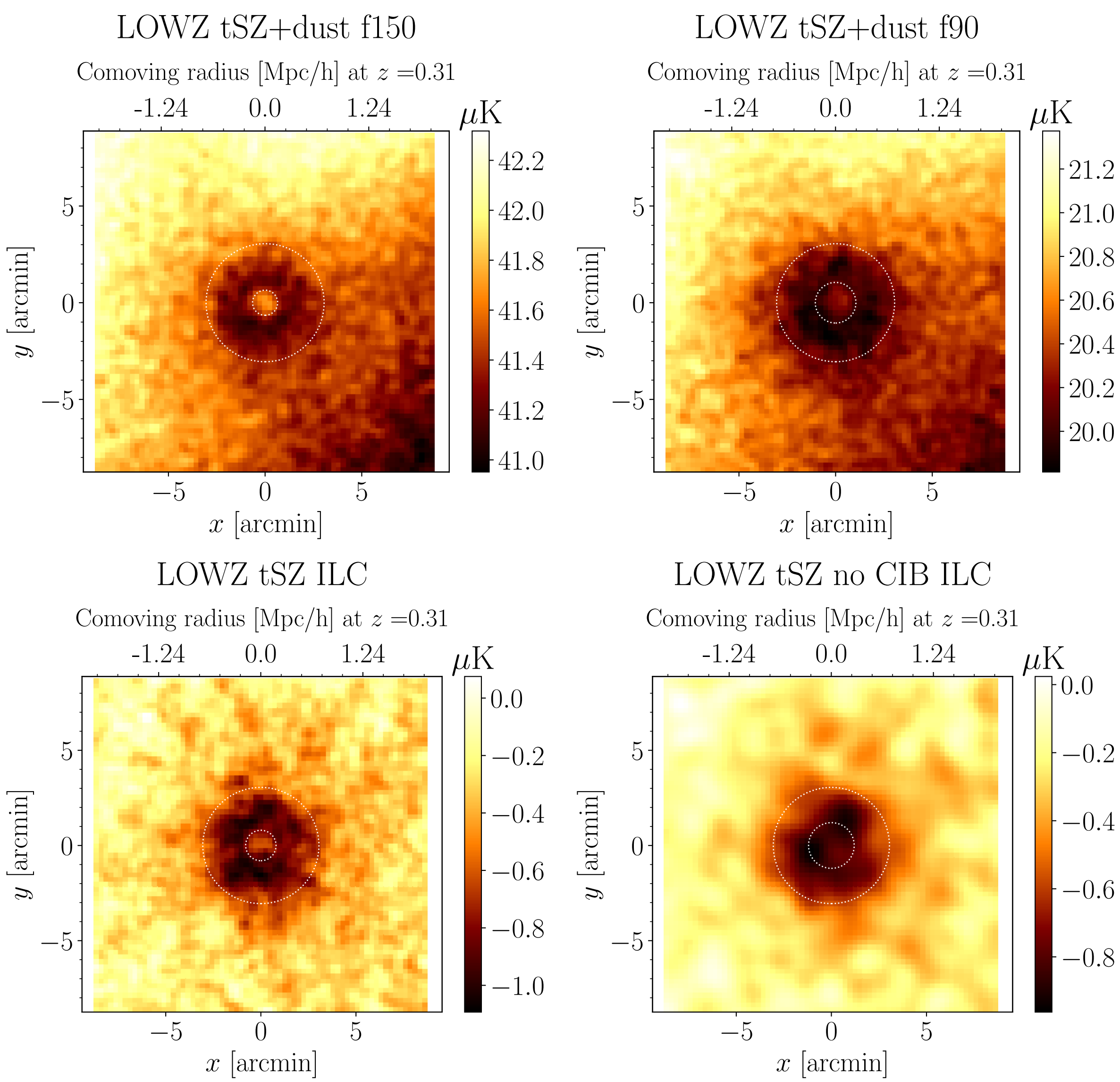
- Dissect the physics of the hot gas in baryons tomographically (similar to CMB lensing cross-correlation)

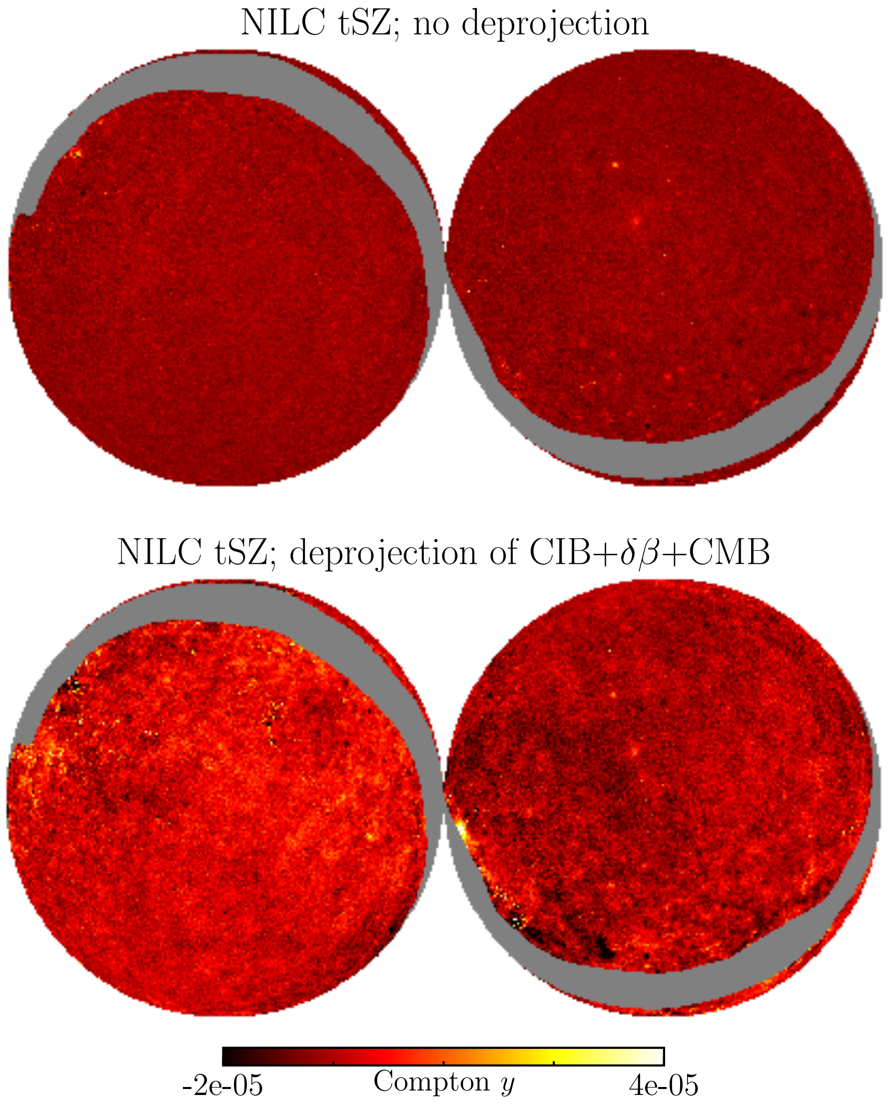


Makyia & Komatsu (2019)

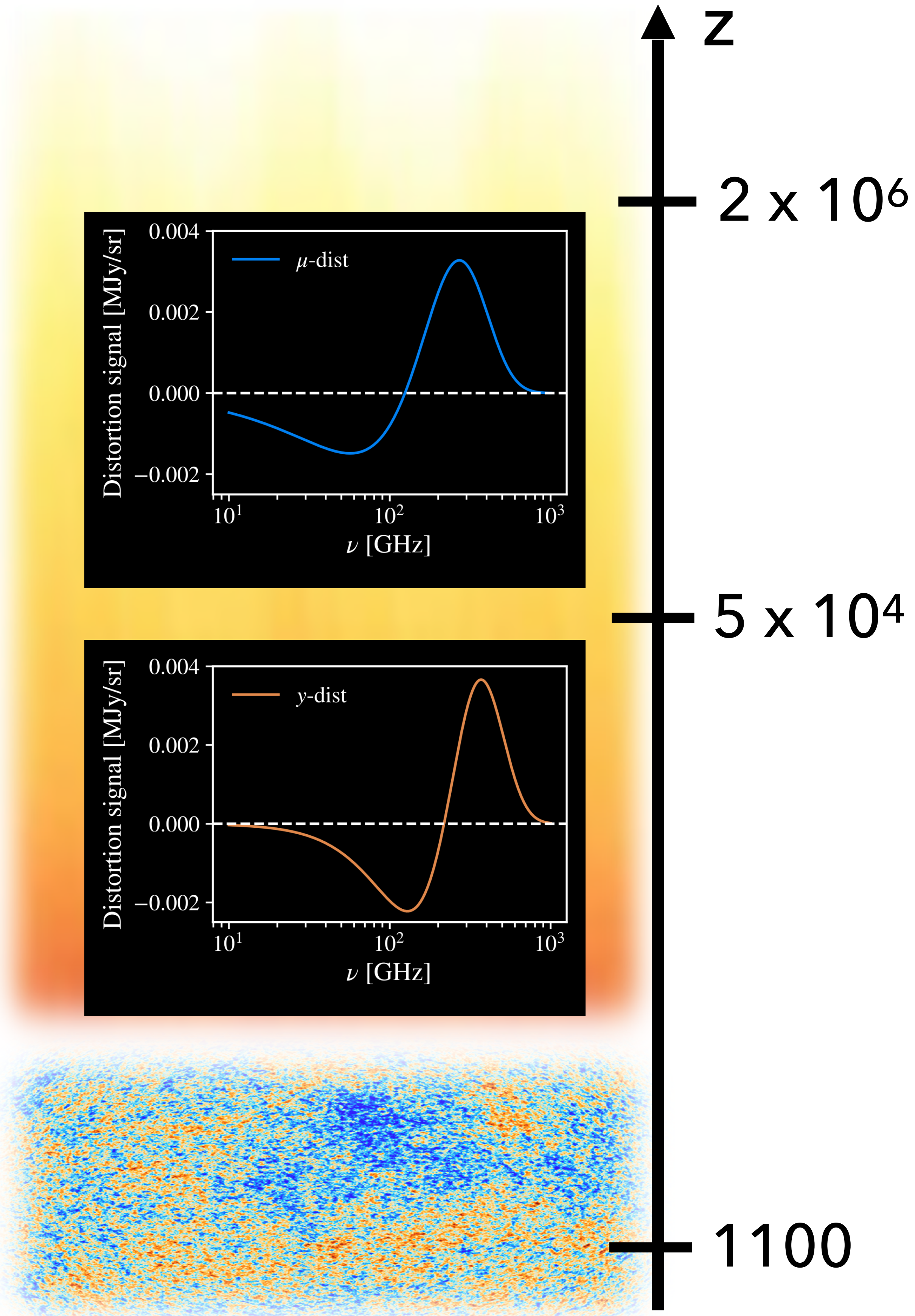
The CIB challenge

- The Cosmic Infrared Background is the most important, critical tSZ contaminant.
  - Highly correlated greybody $\propto \nu^{\beta} B(\nu, T_{CIB})$ with large SED uncertainties.
  - More important effects as the noise goes down…





A brief thermal history of the universe



- $z >> 10^6$ Compton scattering and brehmsstralung establish thermal equilibrium and perfect BB spectrum.
- After $z \sim 10^6$ energy injection in the plasma will not thermalize anymore and leave imprint in the CMB spectrum.
- μ distortions monopole will constraint energy releases, particle decays and small scale perturbations in the early universe.
- y distortions will probe reionization and structure formation from e.g. SZ power spectra.

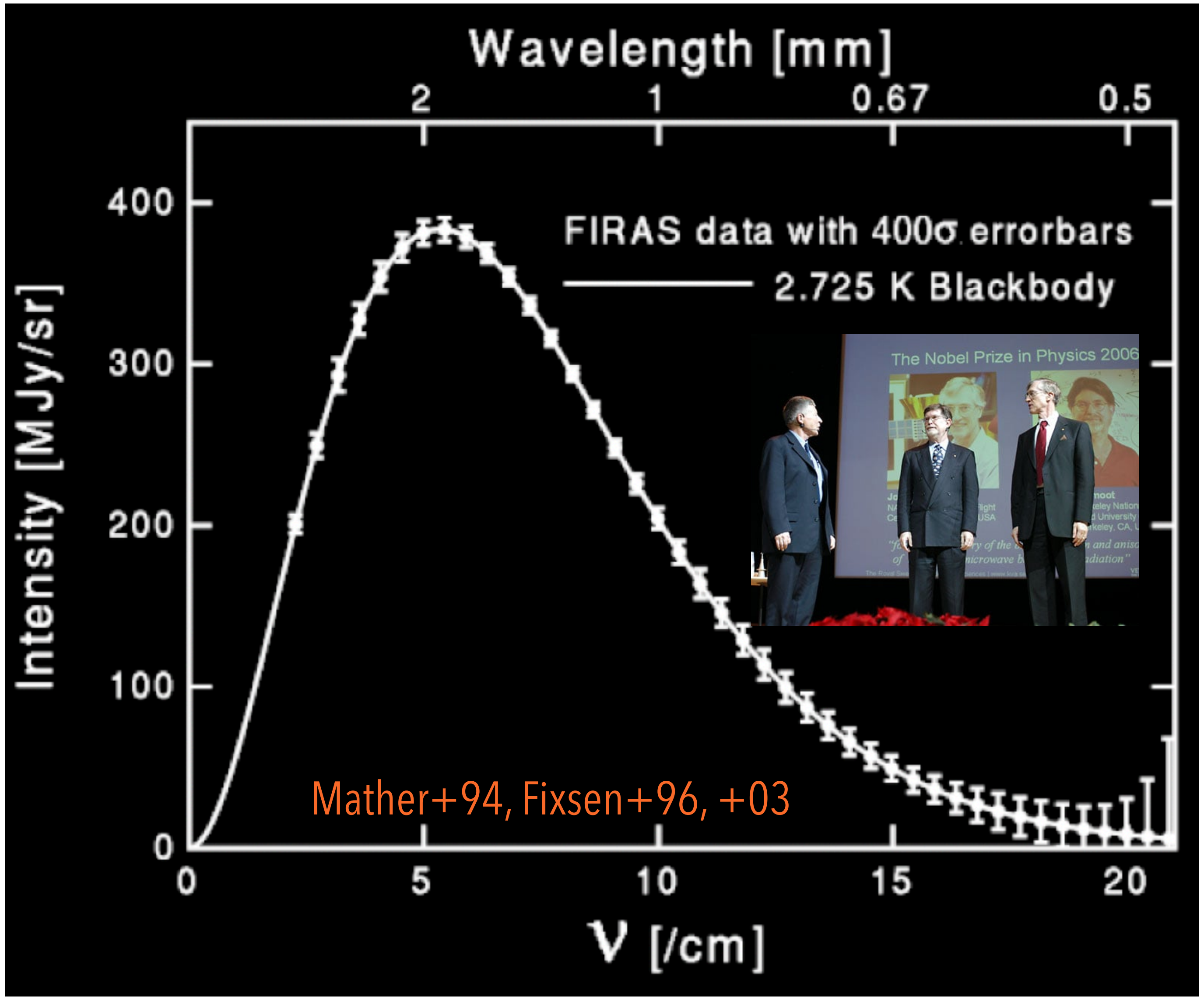
Constraints on spectral distortions

- Limited improvements after FIRAS (~1996)

$$|\langle\mu\rangle| \lesssim 90\times10^{-6}$$

$$|\langle y\rangle| \lesssim 15\times10^{-6} \rightarrow (-1\pm6\times10^{-6}\ \text{stat.})\times10^{-6}$$

- ARCADE, TRIS: improved at ν < 10 GHz, questions on foreground/systematics remain.

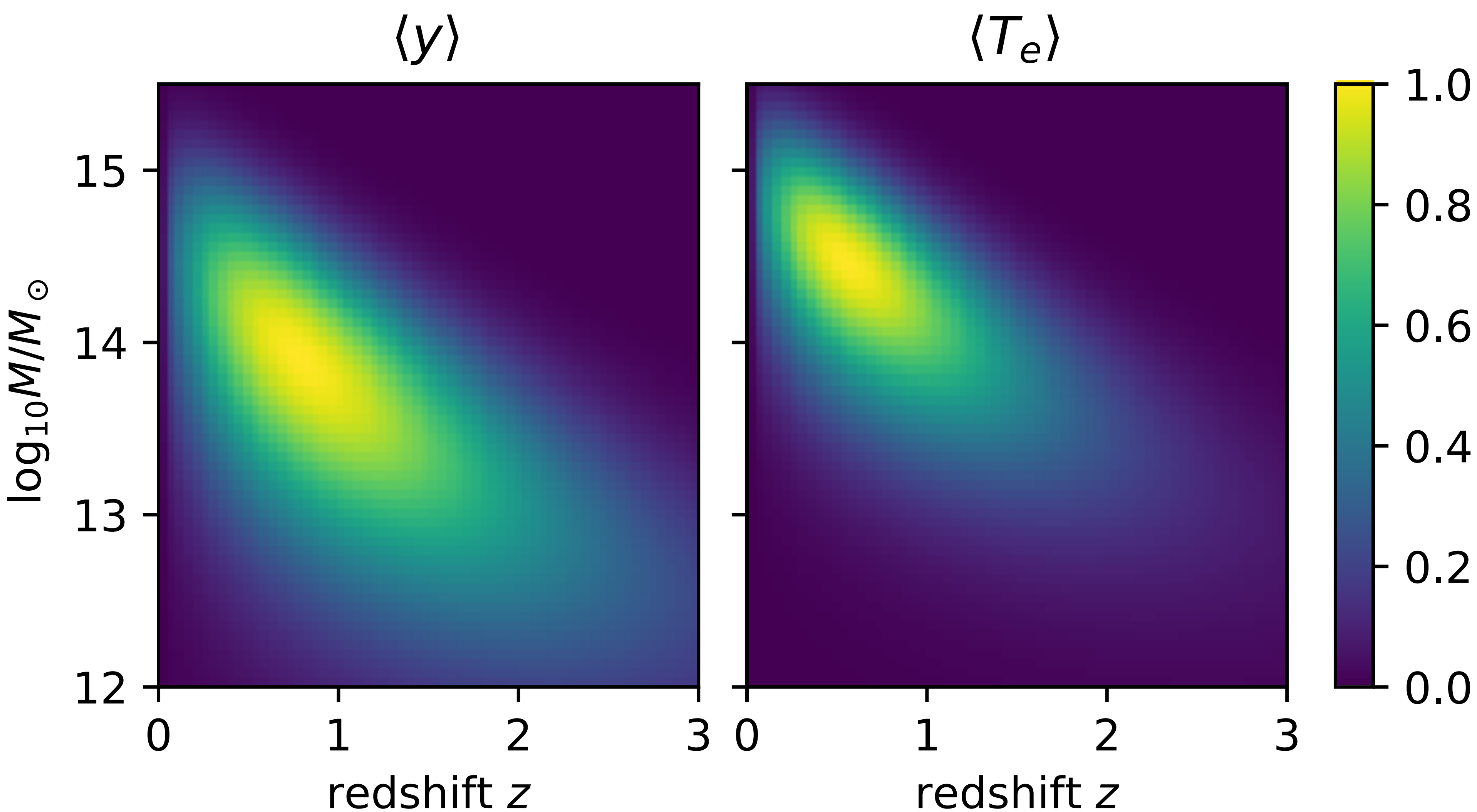


Why do we care?

- y distortions are dominated by late time gas physics: unique probe of feedback.

$$\langle y \rangle \equiv \langle y(\hat{\mathbf{n}}) \rangle_{\hat{\mathbf{n}}} = \int \frac{d\hat{n}}{4\pi} \frac{\sigma_T}{m_e} \int P_e(\hat{\mathbf{n}}, l) dl$$

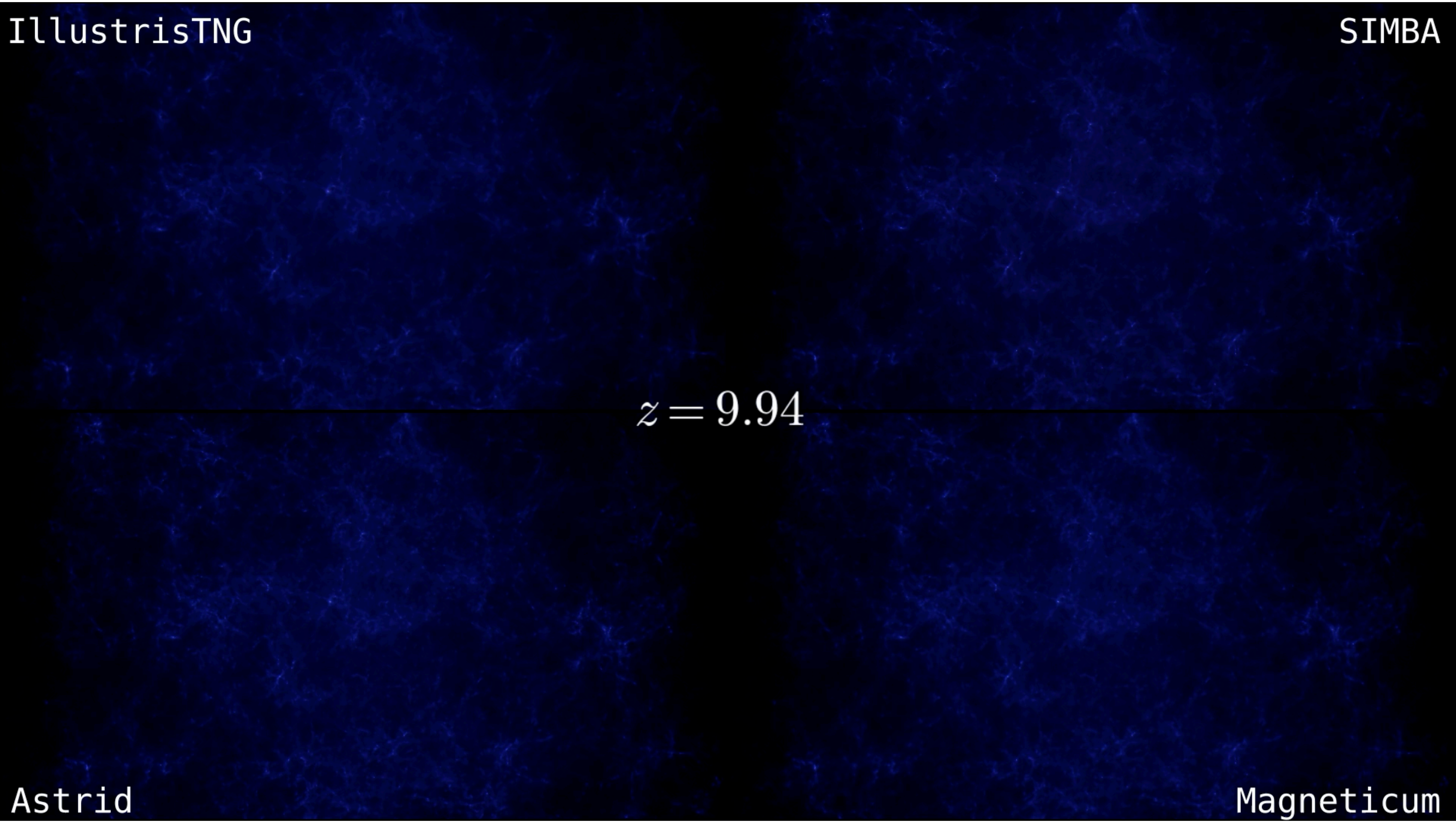
$$\langle T_e \rangle \equiv \langle T_e(\hat{\mathbf{n}}) \rangle_{\hat{\mathbf{n}}} = \langle y \rangle^{-1} \int \frac{d\hat{n}}{4\pi} \frac{\sigma_T}{m_e} \int \left[T_e P_e \right](\hat{\mathbf{n}}, l) dl$$



Thiele+ (2022)

- … and also reionization (subdominant) or primordial P(k) k ~ 1-10 h/Mpc.

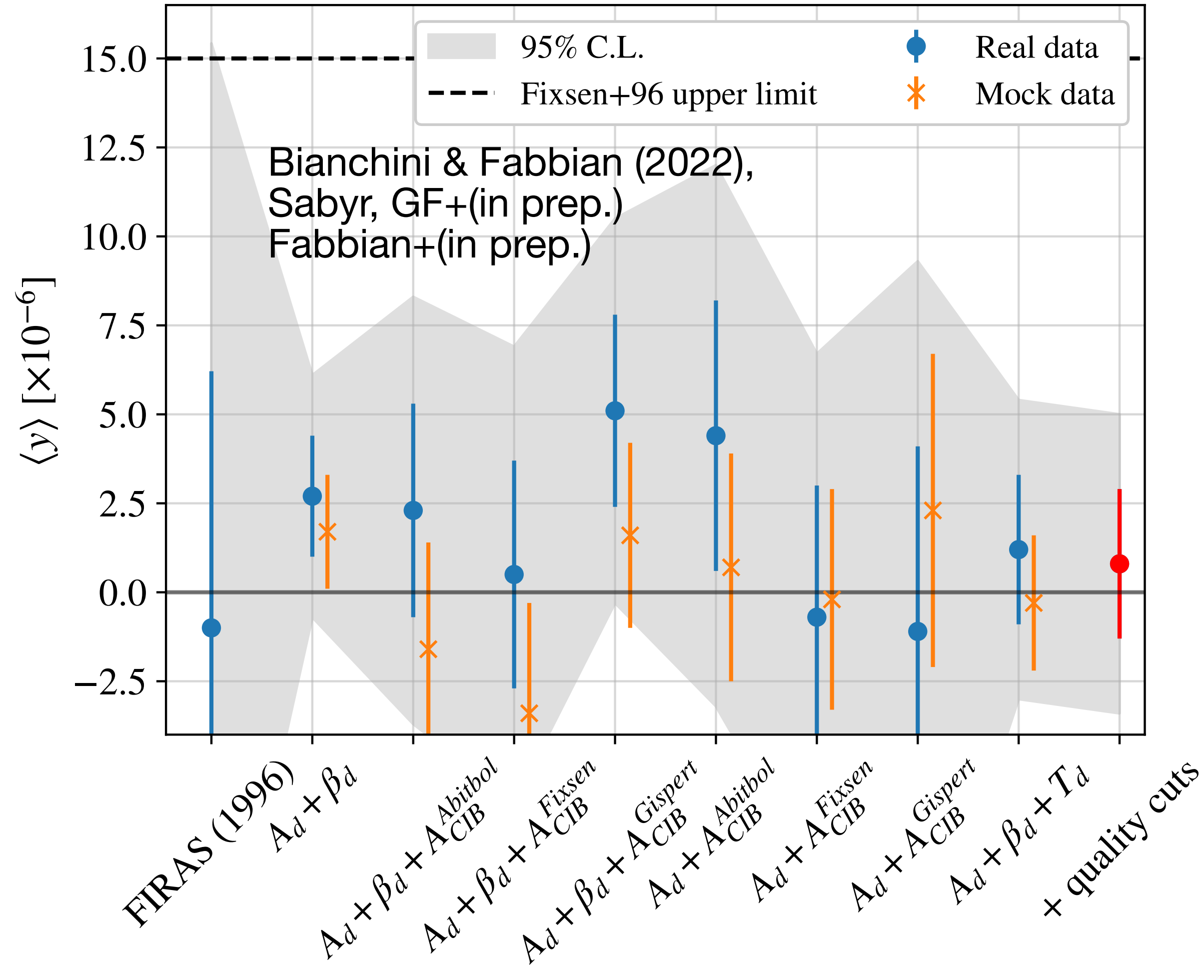
Richness of feedback models

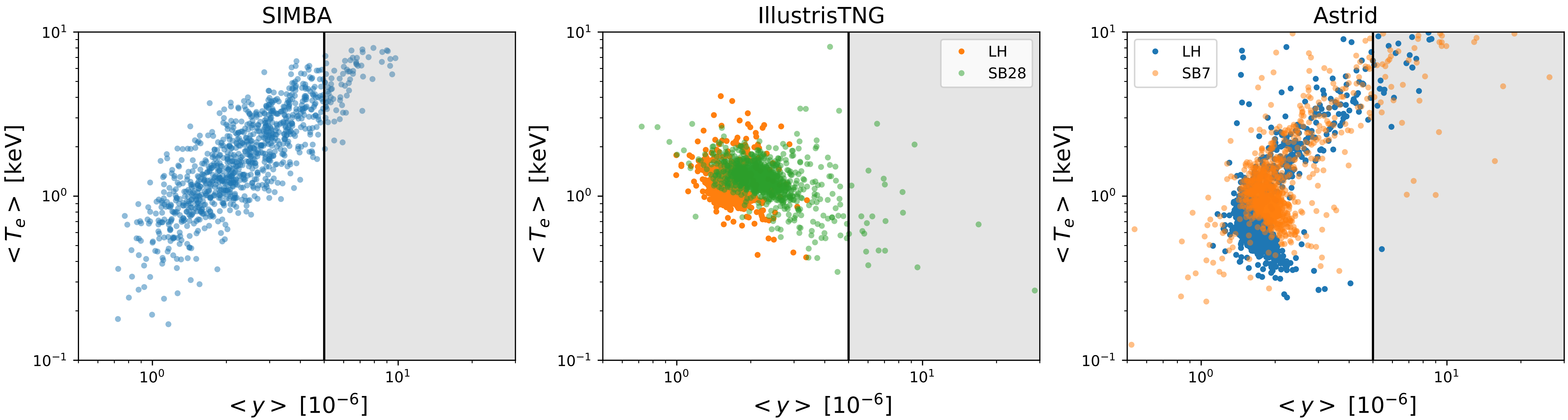


Courtesy F. Villaescusa Navarro

Constraining galaxy formation models

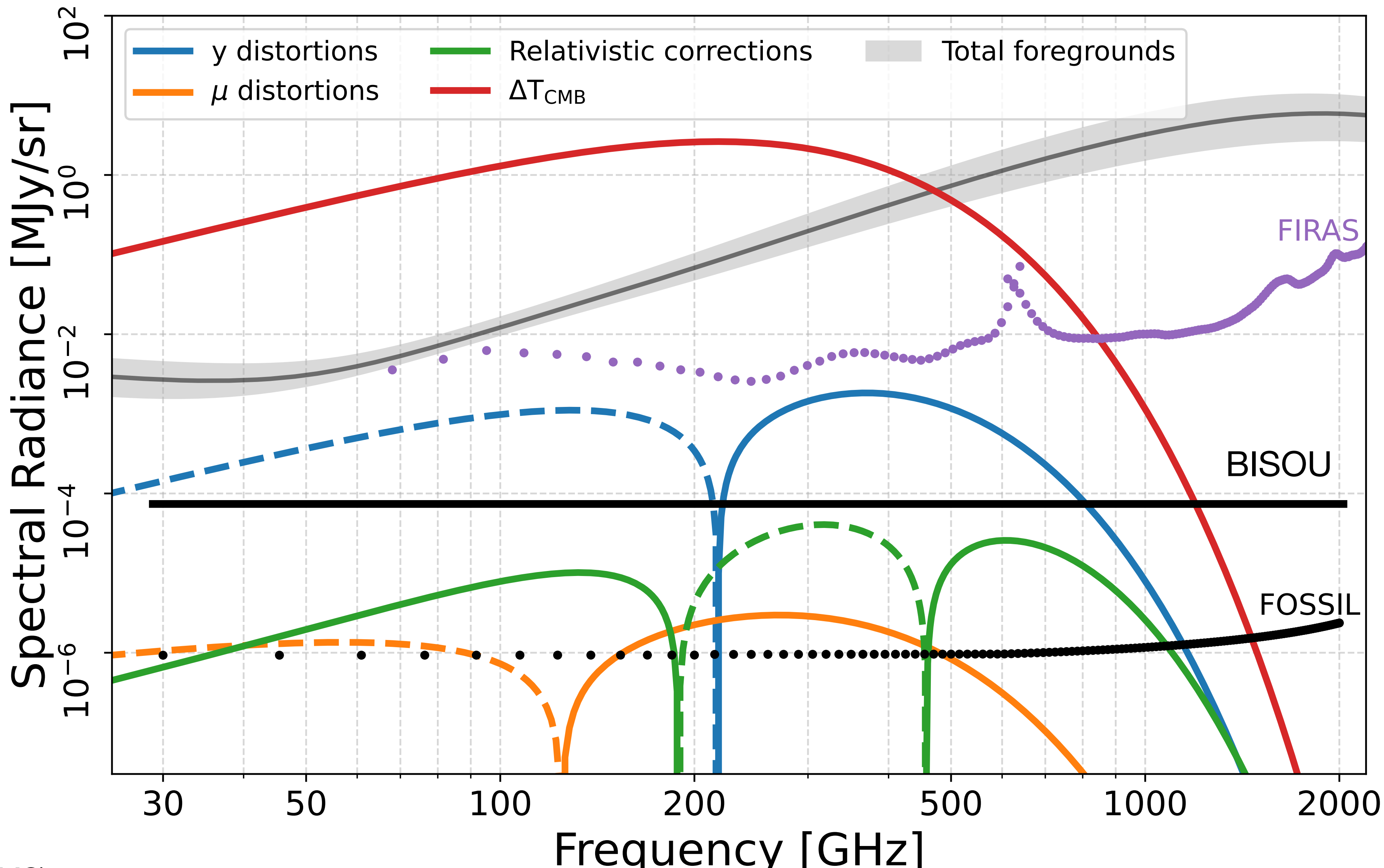
- Reanalysis of archival data with modern component separation techniques brought improvements after ~30 years.
- 2-3x better upper limit
- Feedback models from hydro simulations can be ruled out, too soon for constraints.

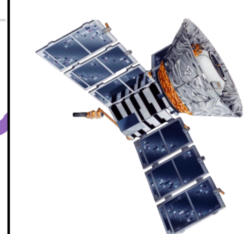




Experimental prospects

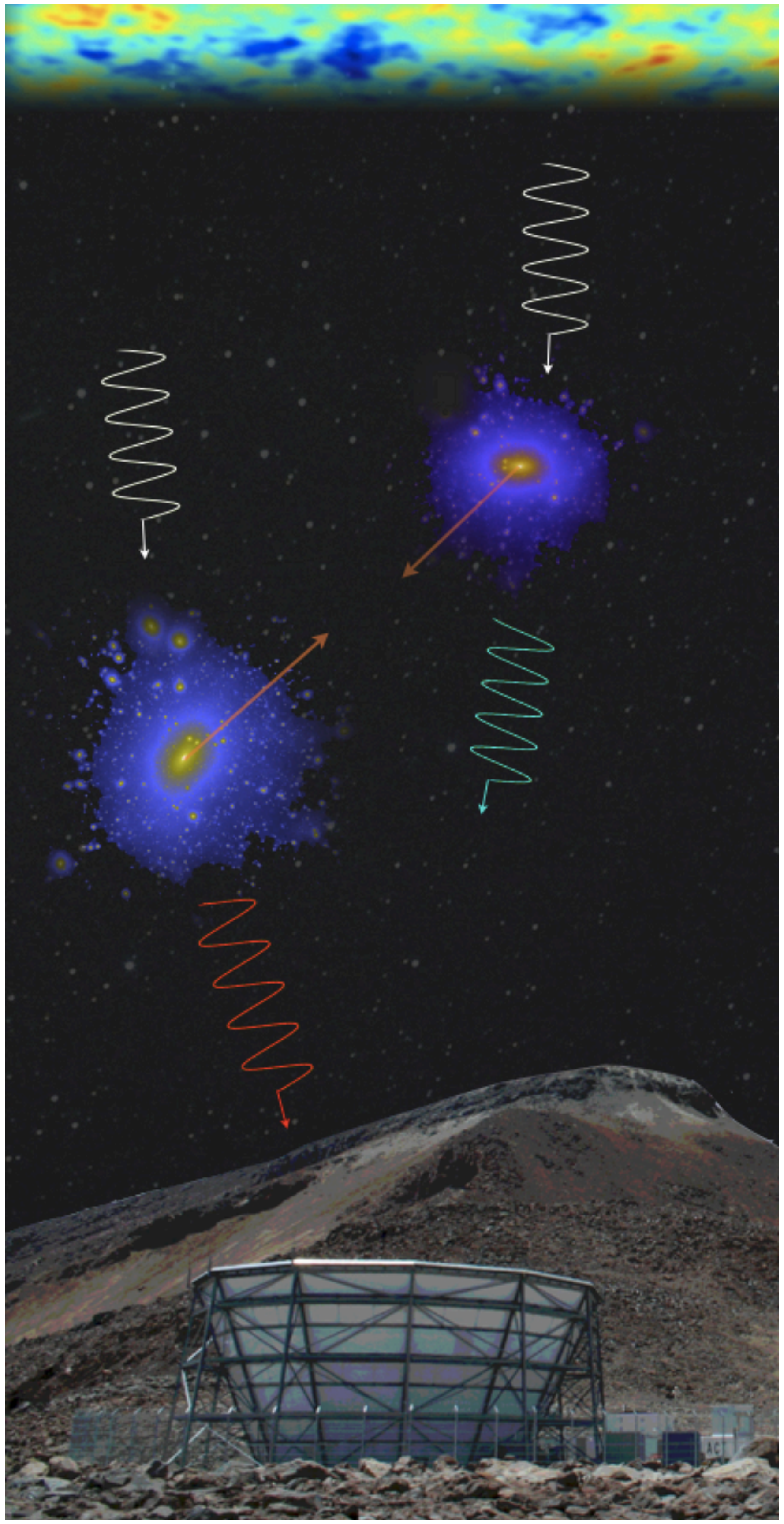
- Several instruments are being built, deployed or in phase A: transformational potential!
- **FOSSIL: ESA M8 mission proposal** (PI N. Aghanim, B. Maffei+), get in touch!



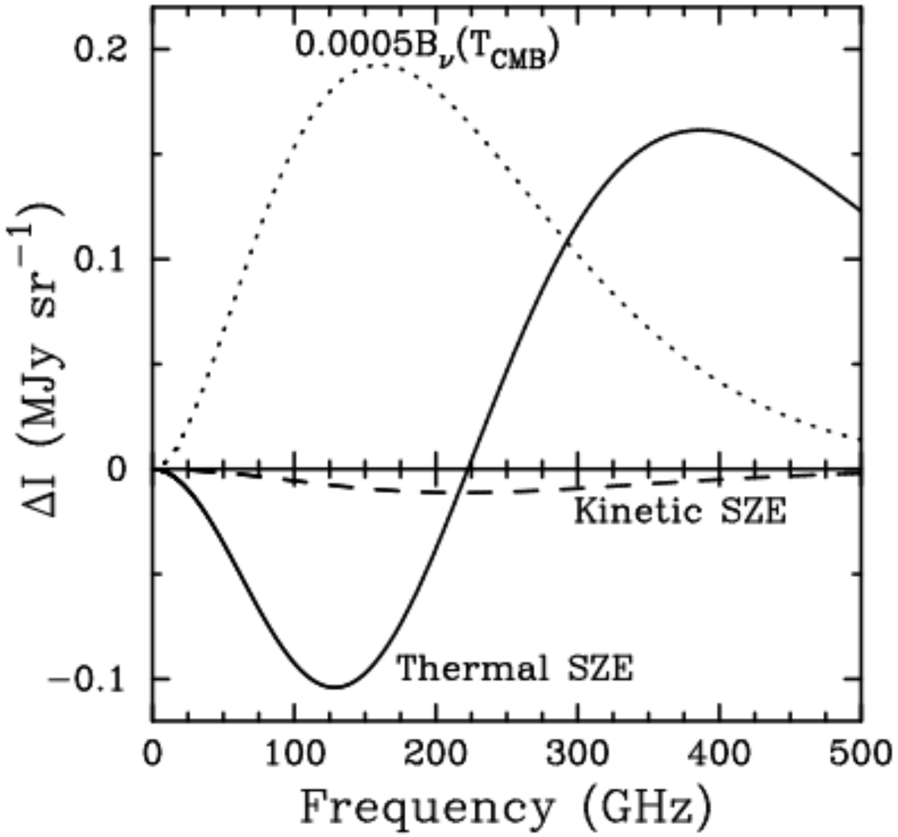


Maffei+ (2021, BISOU),
Aghanim+ (FOSSIL),
Masi+(2021, COSMO),
Rubiño-Martin+(2020, TMS)
Sabyr+(2024)

What is this



- Compton-scattering of CMB photons off free electrons with non-zero line-of-sight bulk velocity.
- Direct probe of **gas momentum and gas abundance!**
- Cosmological information through velocity field, gas properties through optical depth.



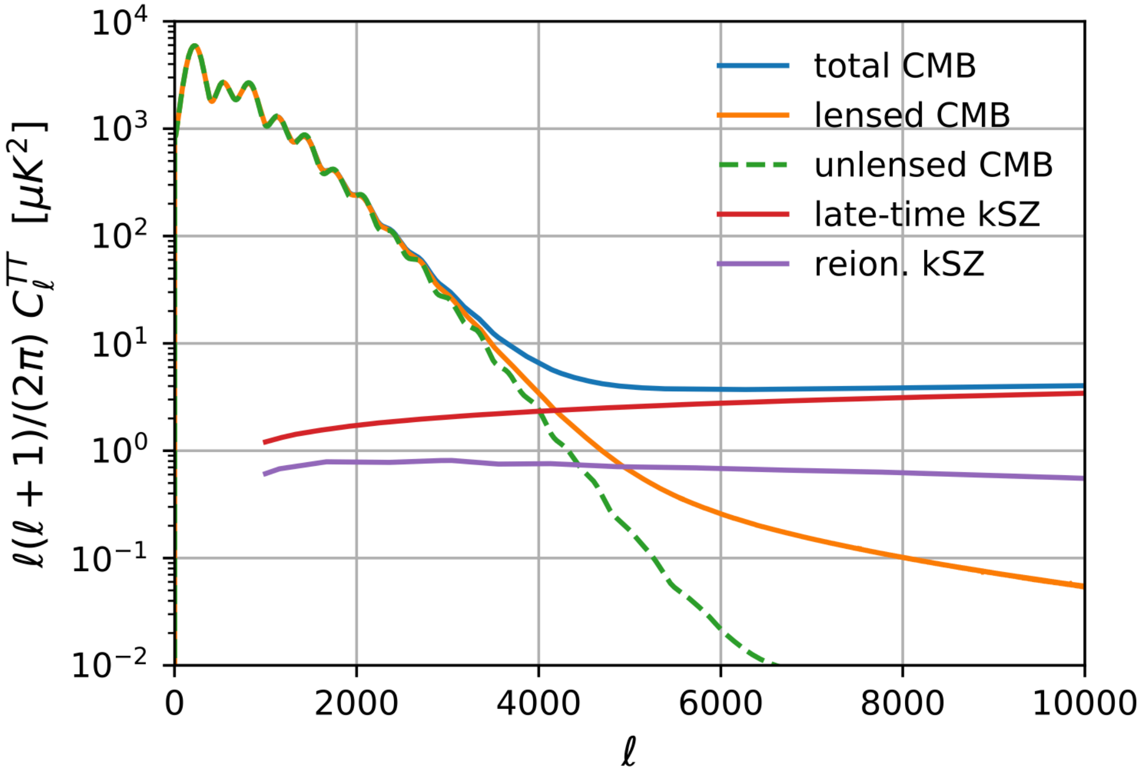
$$\Delta T_{kSZ} \sim -\tau_e \frac{v_{los}}{c}$$

$$\tau_e = \int dl n_e \sigma_T$$

What is kSZ used for and how can we measure it?

- You cannot make a map but you can see it in
  - Internally in CMB data
    - kSZ contribution to CMB

See Marian's lecture



  - In combination with LSS catalogues!
    - Direct detection in galaxy clusters (hard, needs very high-resolution data).
    - Pairwise-velocity estimators (hard, needs very good redshift measurements).
    - Projected field estimators.
    - Stacking estimators.
    - kSZ velocity reconstruction.

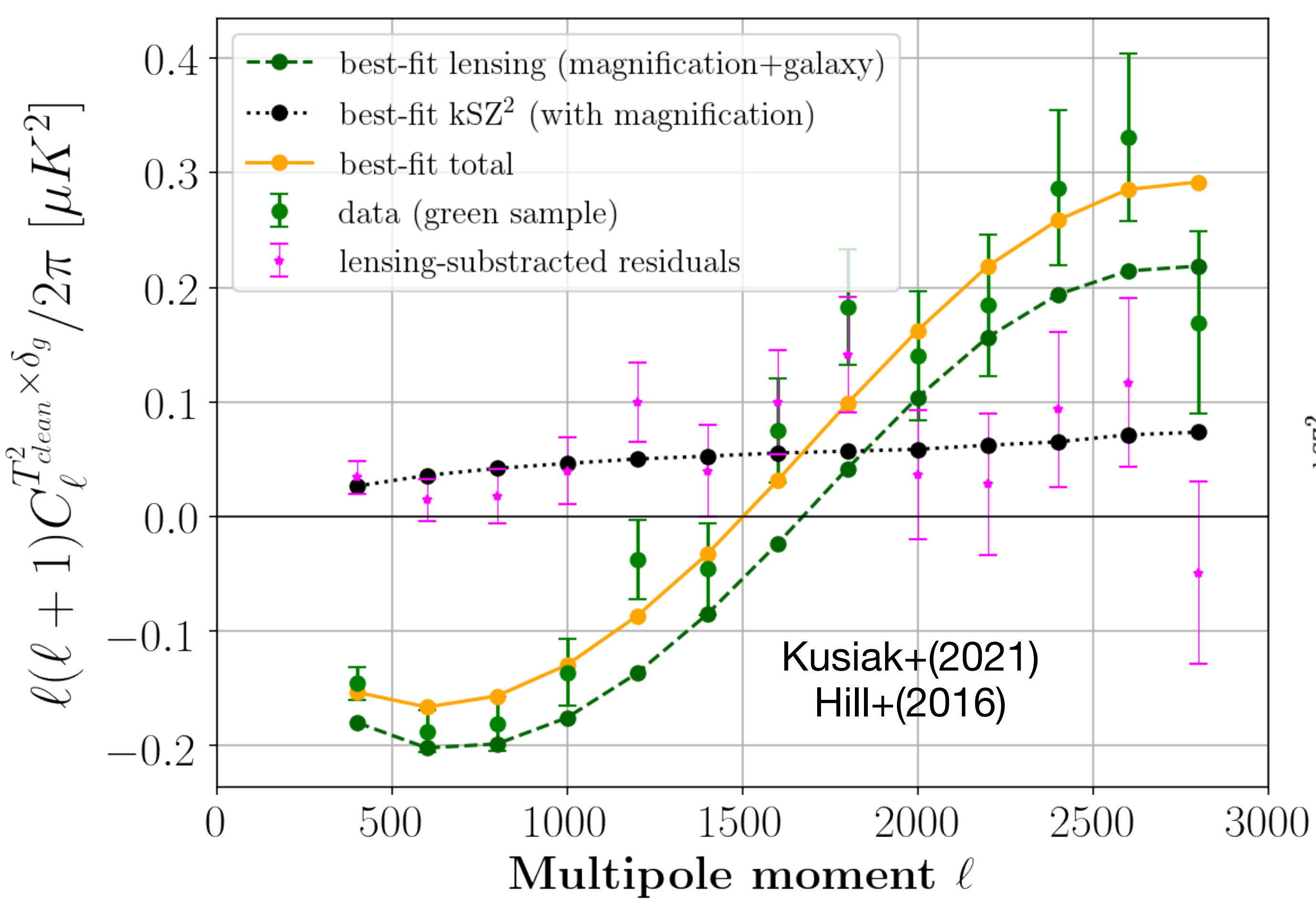
Projected field kSZ

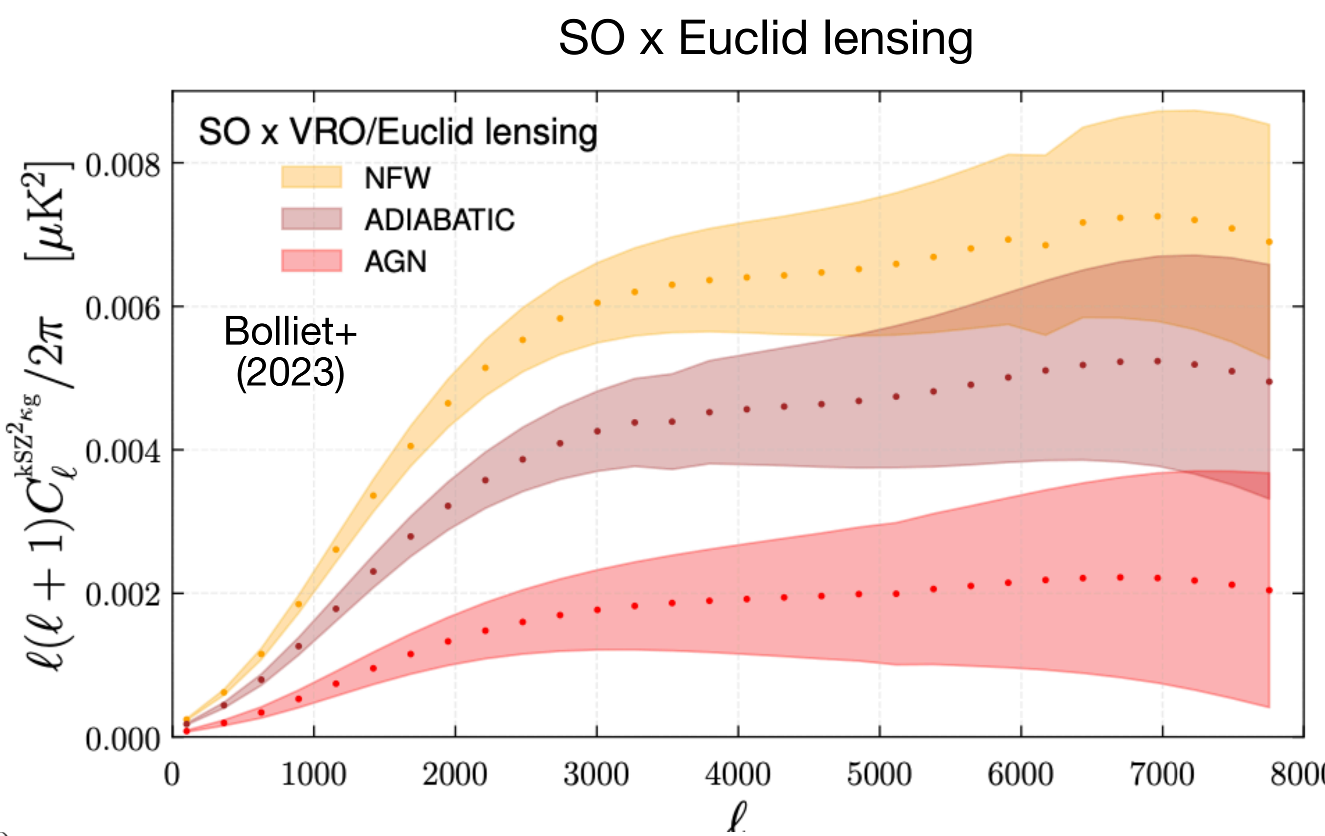
- Doesn't need accurate redshifts, avoids v_{los} cancellation but requires modeling of bispectrum

Doré+(2004)
Ferraro+(2016)

$$C_\ell^{\mathrm{kSZ}^2\times\delta_g} = \int_0^{\eta_{\max}} \frac{d\eta}{\eta^2} W^g(\eta) g^2(\eta) \mathcal{T}\left(j = \frac{\ell}{\eta}, \eta\right) \quad \mathcal{T}(j,\eta) = \int \frac{d^2\mathbf{q}}{(2\pi)^2} f(q\eta) f(|\mathbf{j}+\mathbf{q}|\eta) B_{p_{\hat{\mathbf{n}}}p_{\hat{\mathbf{n}}}\delta}(\mathbf{q}, -\mathbf{j}-\mathbf{q}, \mathbf{j}).$$

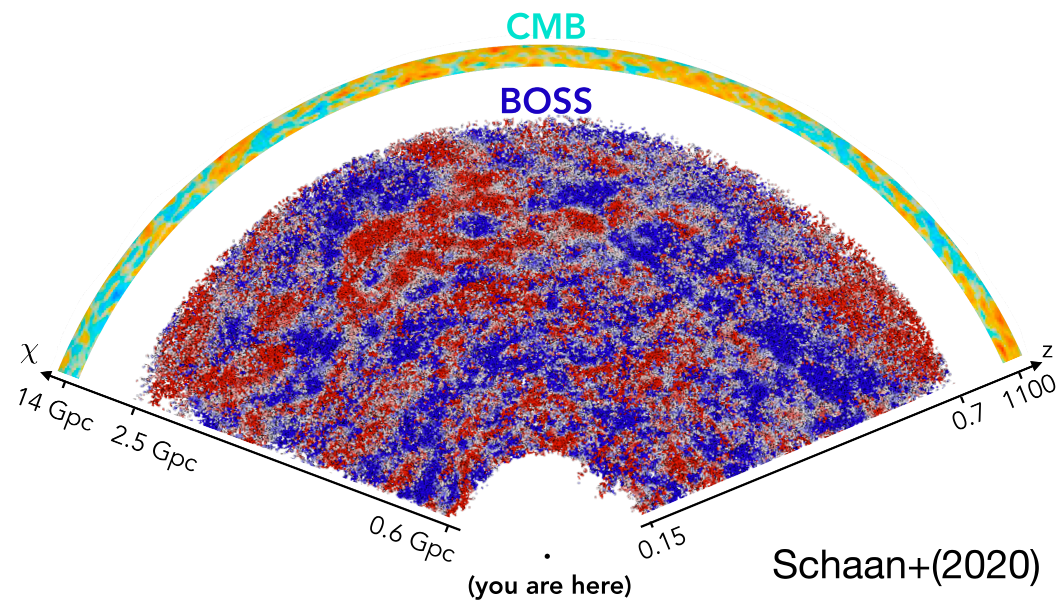
- $\sim 5\sigma$ detection, can accurate probe gas with future CMB and LSS measurements.





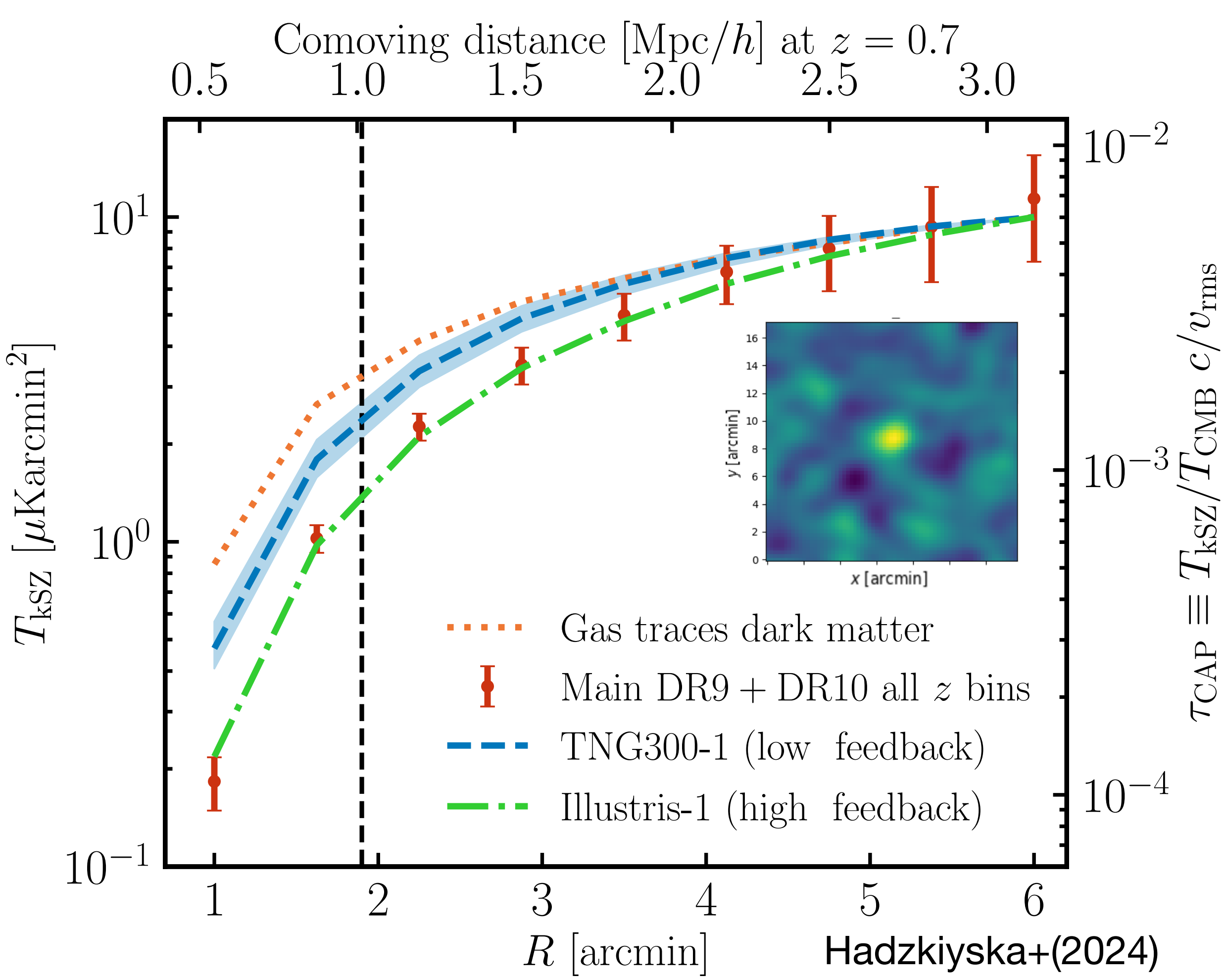
Velocity-weighted stacking

- Stack at position of dark matter halos to accounting for large scale velocity.
- Evidence for feedback pushing the gas out of halos.
- Can be combined with tSZ and CMB lensing stack to solve halo thermodynamics.

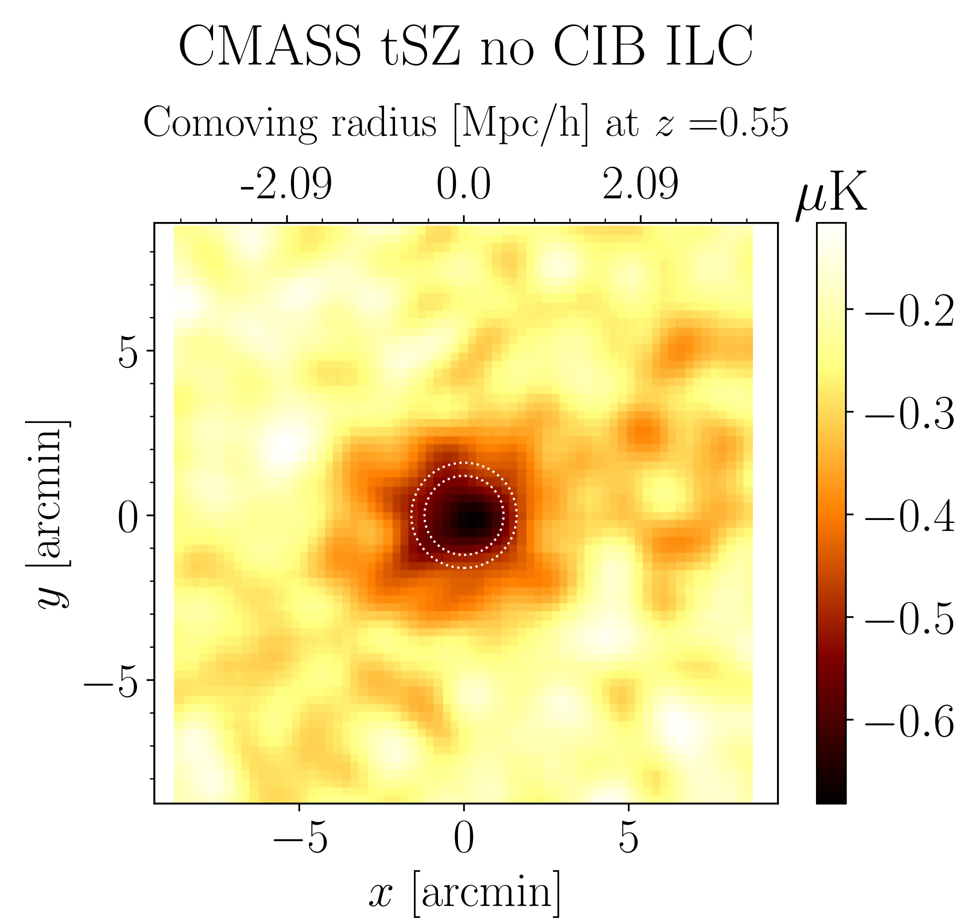


Schaan+(2020)

$$\mathbf{v}(\mathbf{k}) = i\frac{faH\delta(\mathbf{k})}{k}\hat{\mathbf{k}}$$



Hadzkiyska+(2024)

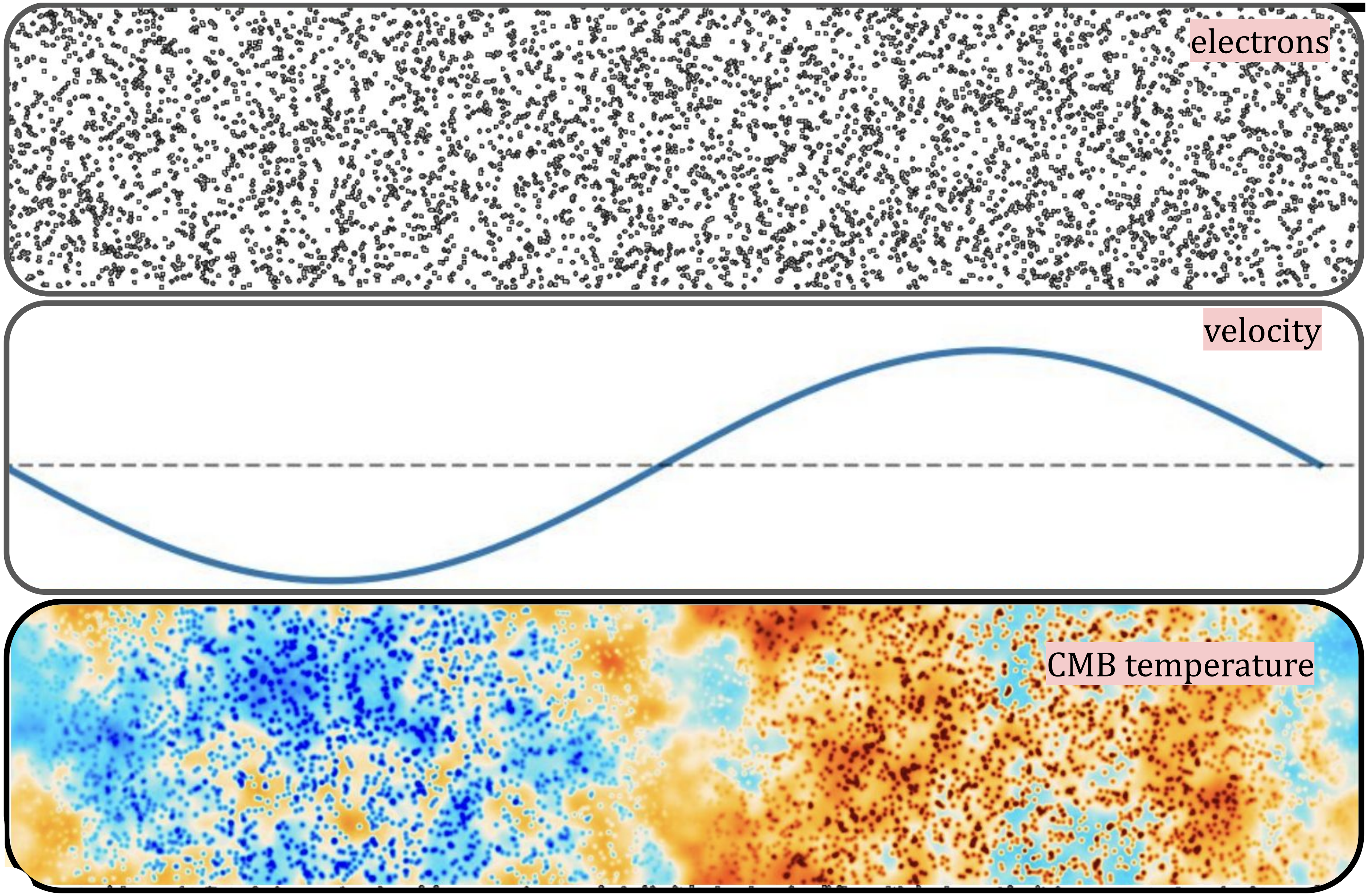


Velocity reconstruction cartoon

Consider distribution of **free electrons**

...and a cosmological velocity fluctuation

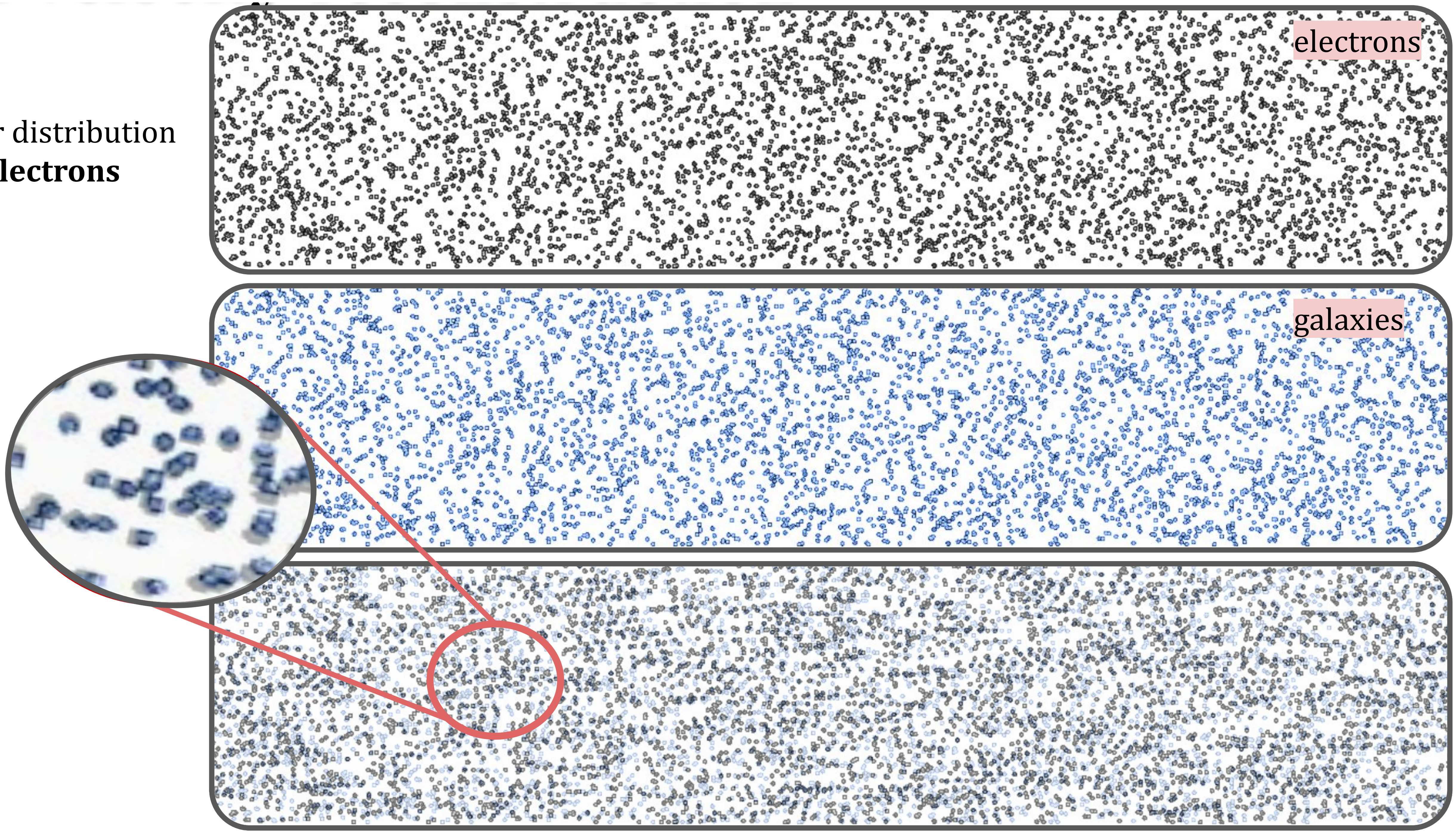
Primary CMB + kSZ



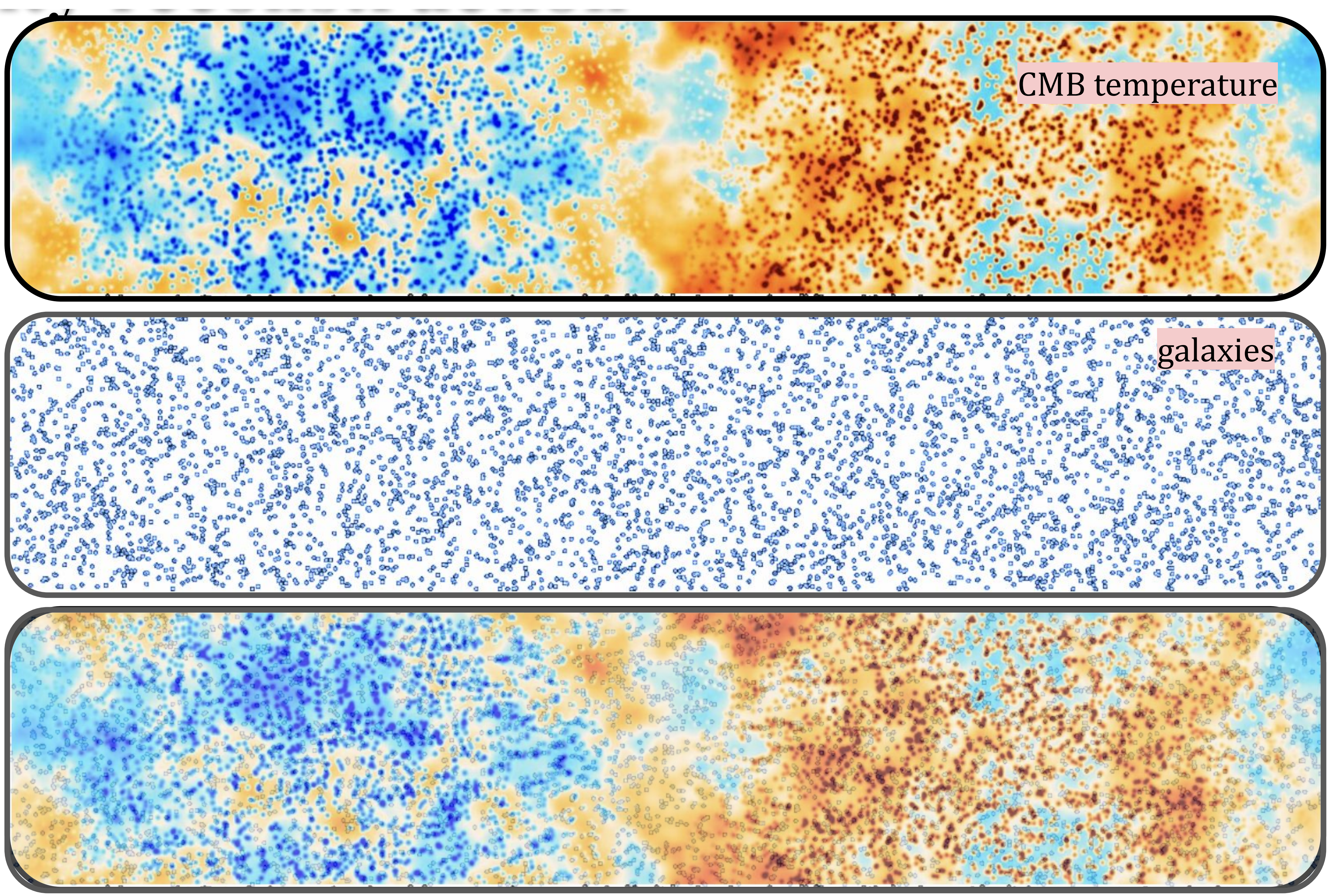
Figures by M. Madhavacheril, A. Lague

Velocity reconstruction

Consider distribution of **free electrons**



Velocity reconstruction



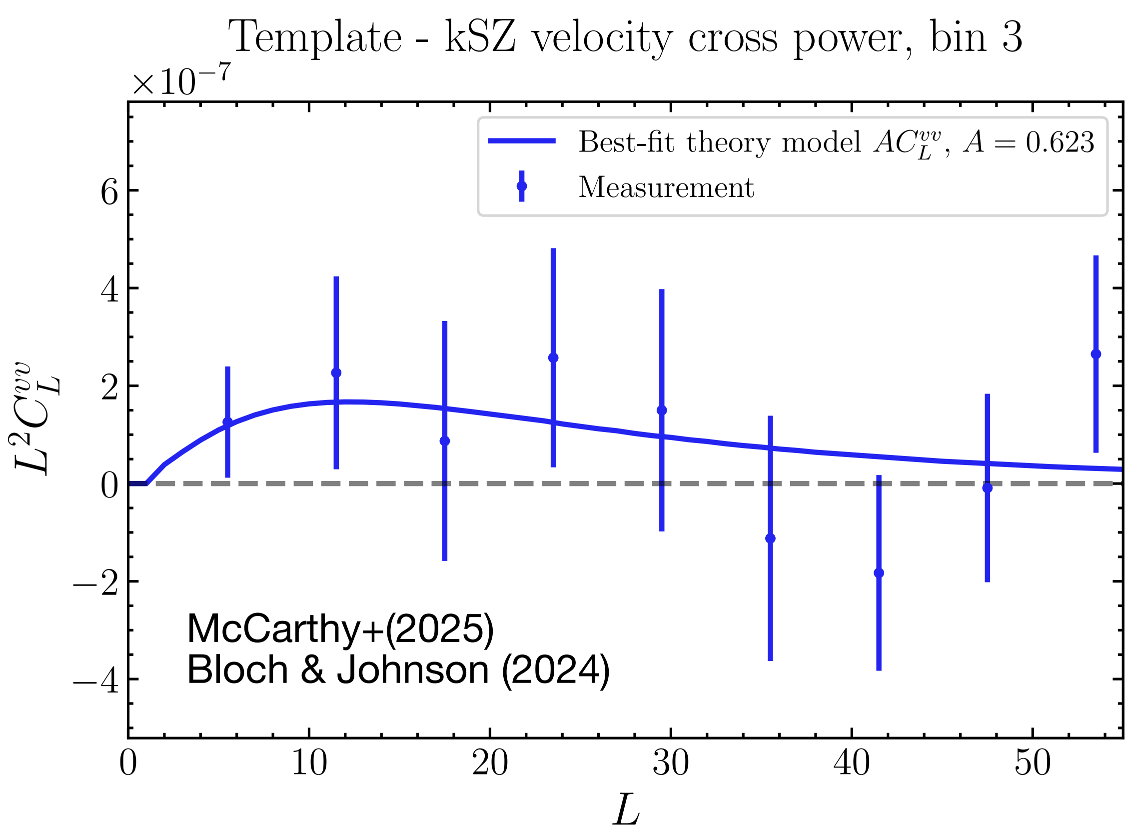
Velocity reconstruction as a quadratic estimator

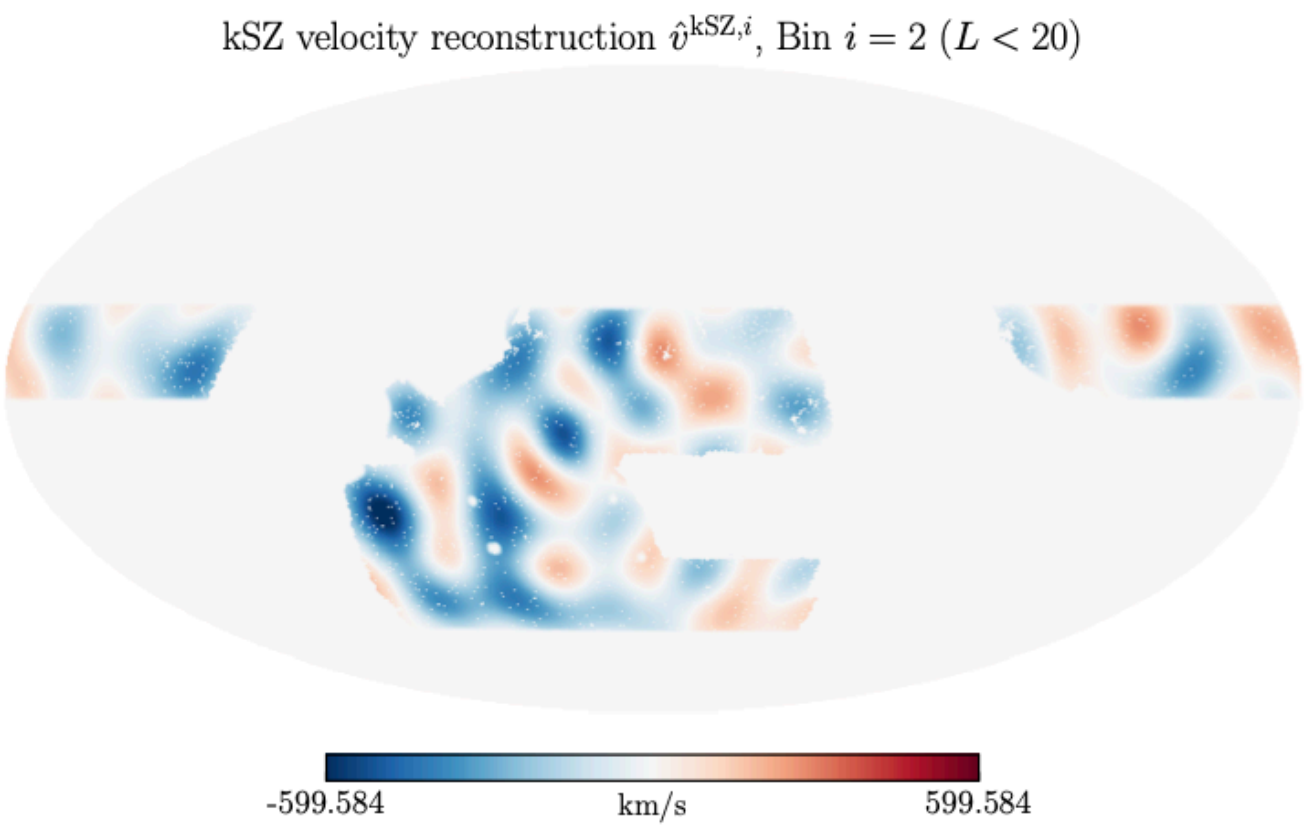
- Cross-correlating CMB T and galaxy surveys as a squeezed bispectrum estimator

$$\Delta T_{kSZ}(\hat{\mathbf{n}}) = -\int d\chi \dot{\tau}(\hat{\mathbf{n}},\chi)\frac{v_{los}}{c}(\hat{\mathbf{n}},\chi) \qquad \langle \delta_g \Delta T_{kSZ} \rangle \sim \int d\chi \langle \delta_g \dot{\tau} v \rangle \sim \int d\chi \langle \delta_g \dot{\tau} \rangle v$$

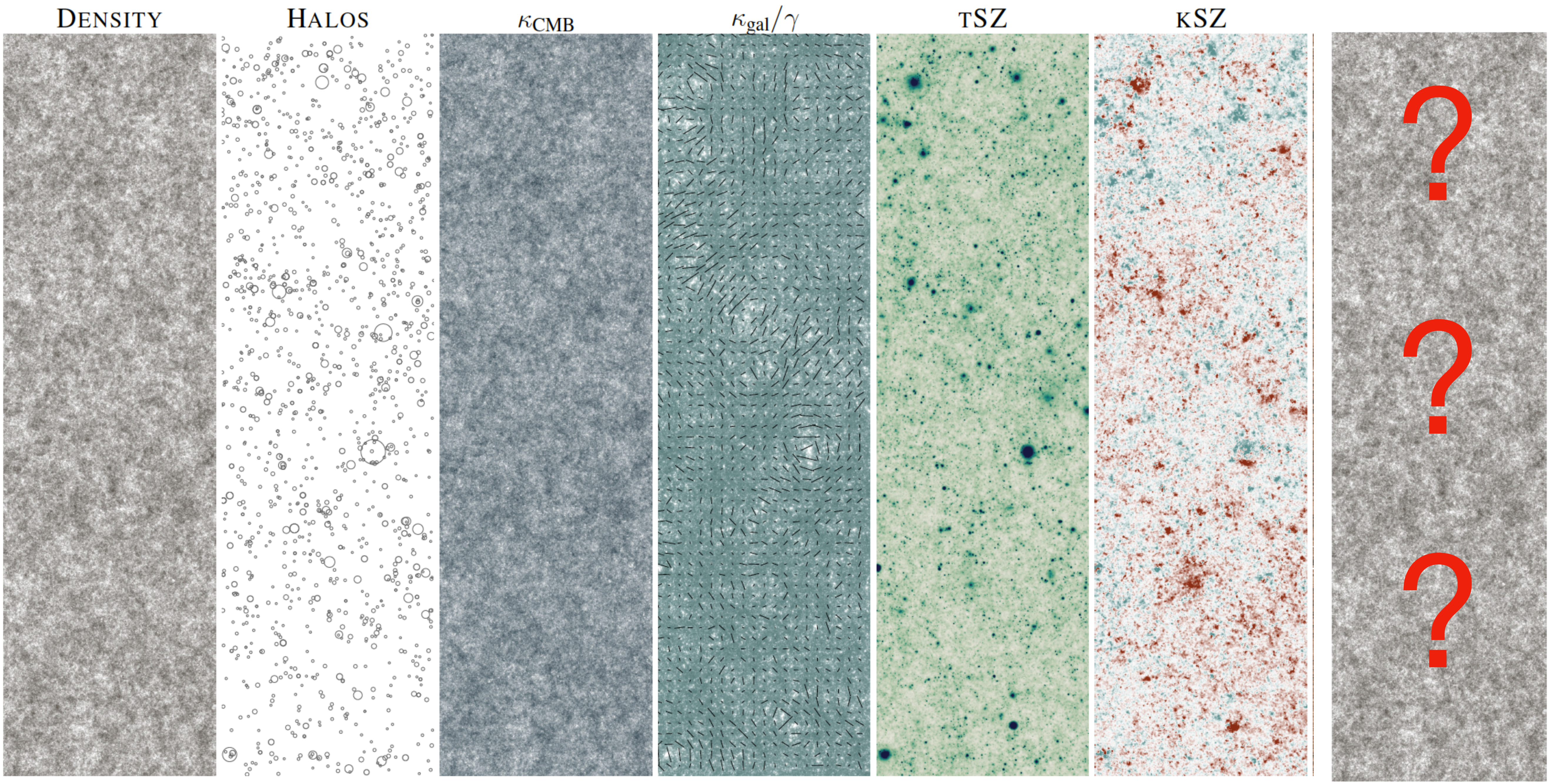
- If you can model $\langle \delta_g \dot{\tau} \rangle \ldots$ $\quad \hat{v} \sim \dfrac{\delta_g \Delta T_{kSZ}}{\int d\chi \langle \delta_g \dot{\tau} \rangle}$ (also in 3D) Lague+(2025)

- $3\sigma - 7\sigma$ detection in auto and cross-correlation, new large-scale cosmology !





Anything else?



Omori (2023)

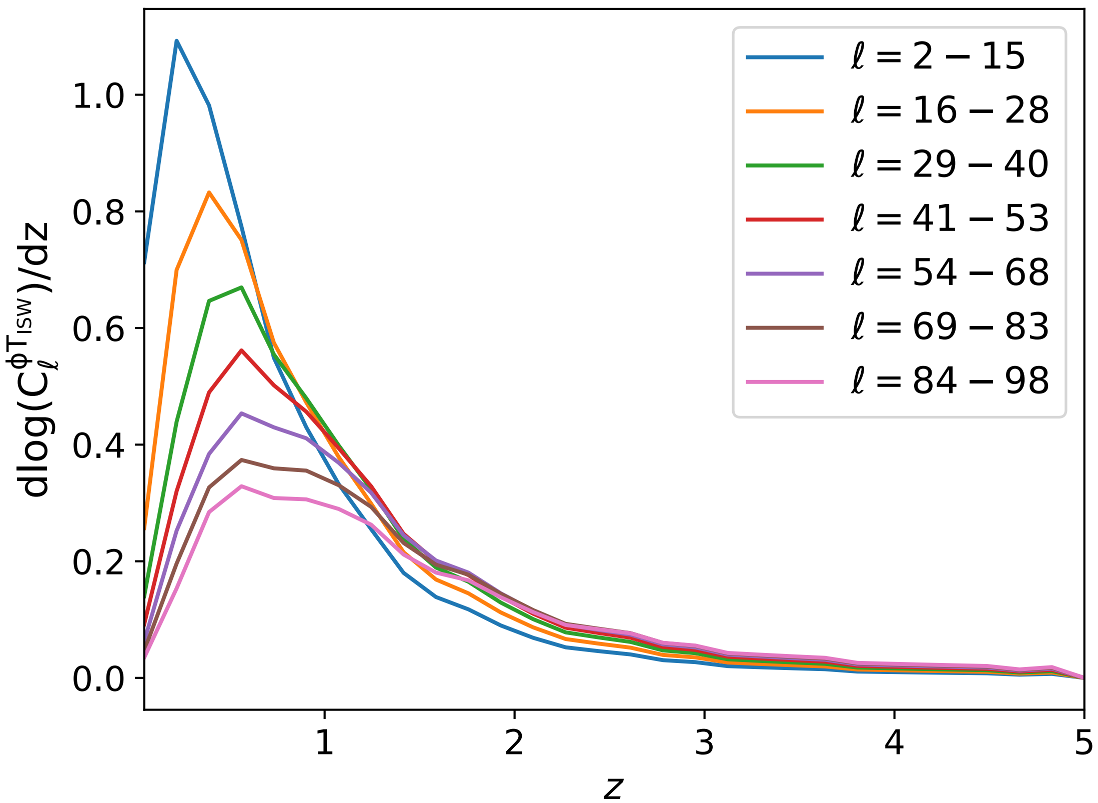
ISW effect

- Photons pick up a net blue or redshift while propagating through time-varying potentials

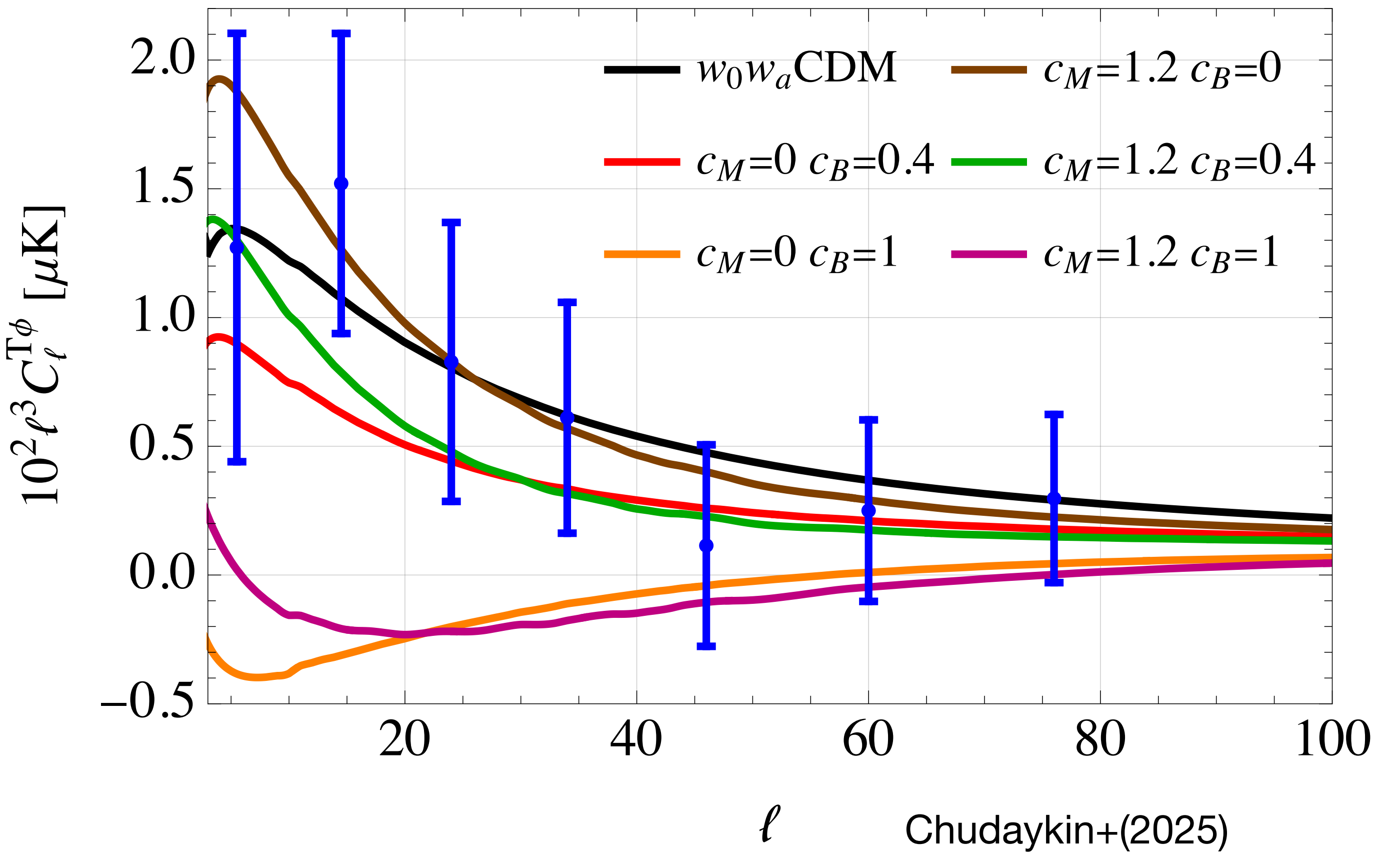
$$\Delta T(\hat{\boldsymbol{n}})_{\rm ISW} \approx 2\int_0^{\chi_*} {\rm d}\chi\,\dot{\Psi}(\chi\hat{\boldsymbol{n}},\eta_0-\chi)$$

- Effect dominated by onset of dark energy at late time but same potential cause lensing…

  - Limited precision (large scale cosmic variance) but unique constraints on e.g. generalized EFT of dark energy.



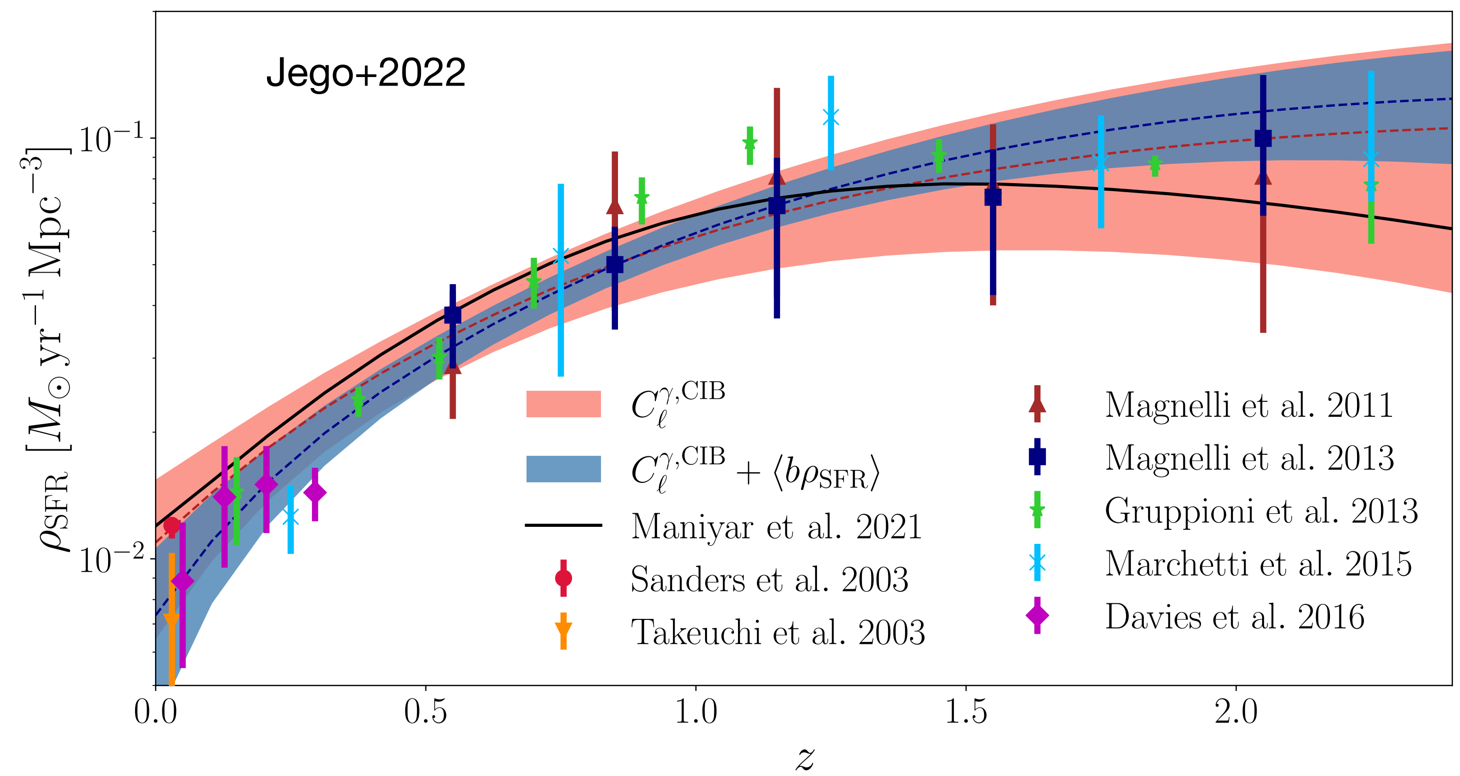
Carron, GF, Lewis (2022)

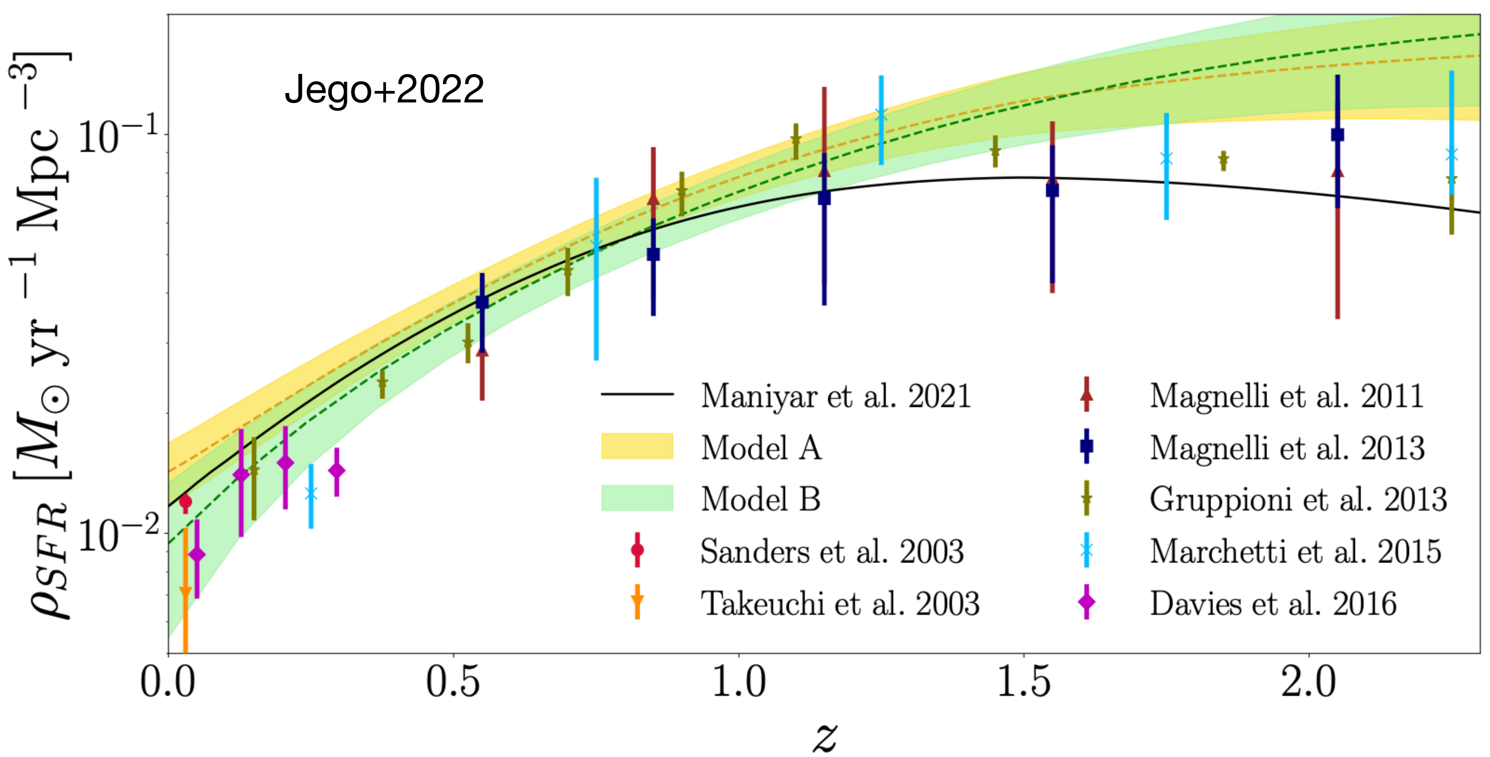


Chudaykin+(2025)

CIB cross-correlations

- CIB: sourced by dusty star-forming galaxies since the epoch of reionisation
- Maps can be extracted from CMB frequencies through component separation
    - also IR bands from e.g. Euclid or others…
- Cross-correlation allows to link SFR and matter distribution





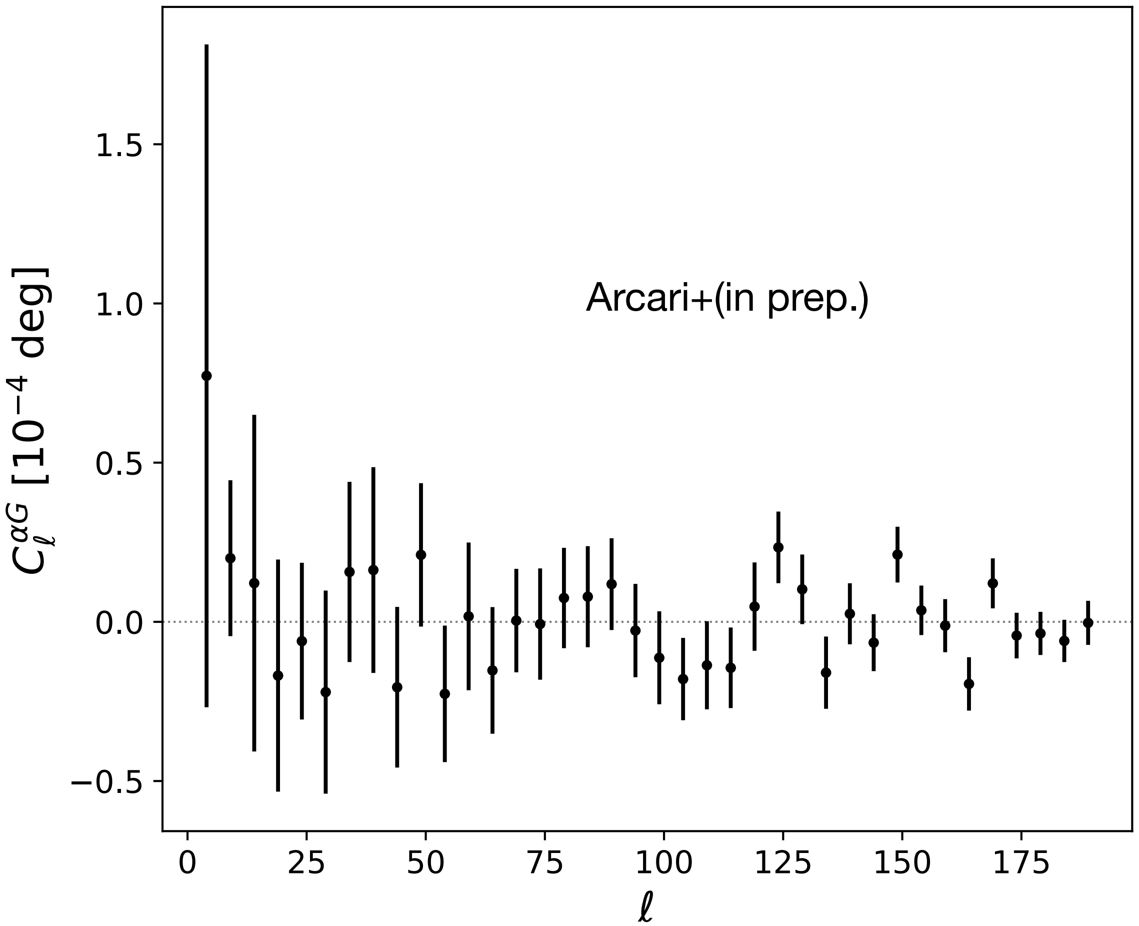
Cross-correlation with cosmic birefringence

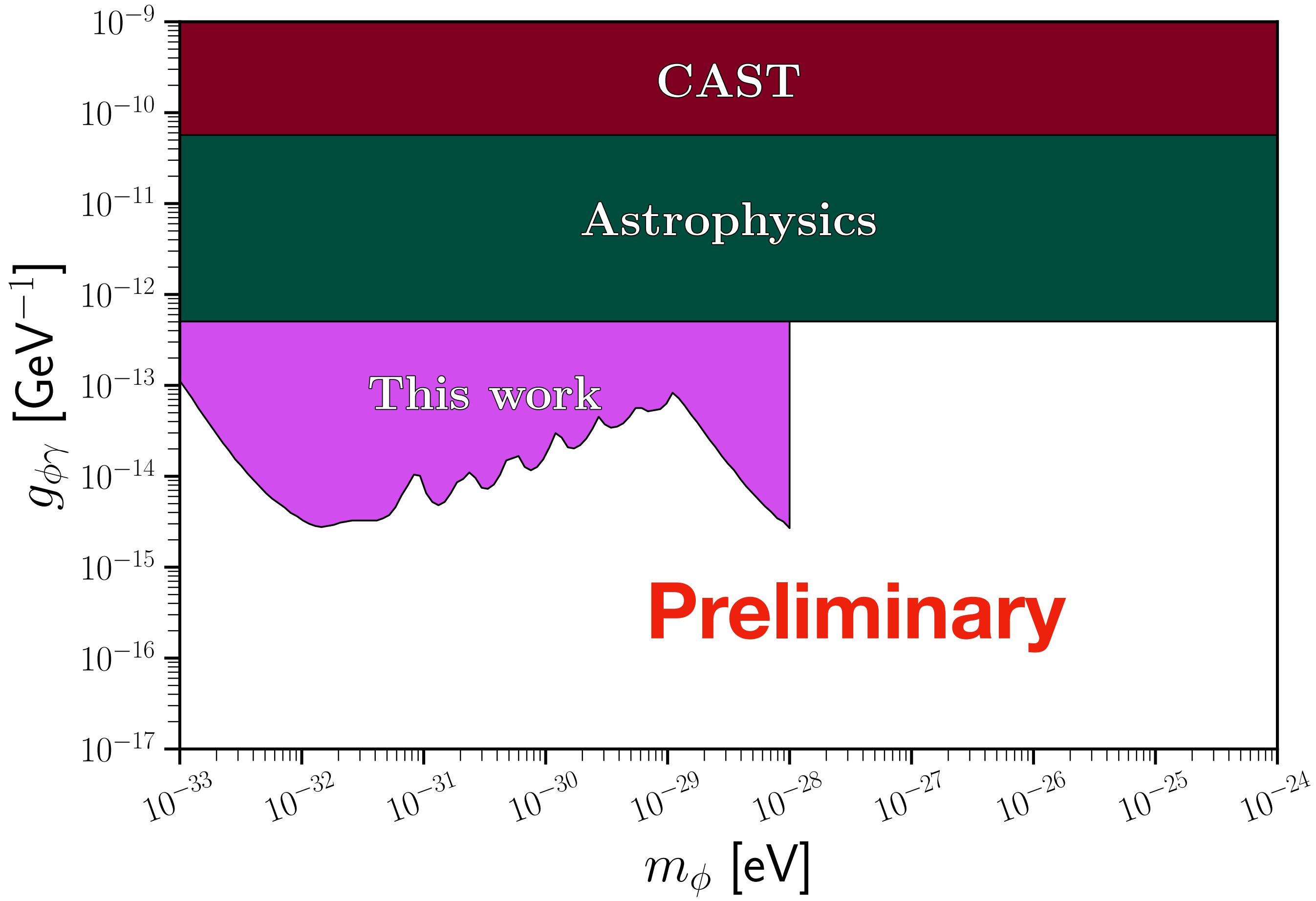
- Presence of axion like coupling can generate cosmic birefringence

$$\mathscr{L} \supset -\frac{1}{2} g^{\mu\nu}\partial_\mu\phi\,\partial_\nu\phi - V(\phi) - \frac{1}{4} g_{\phi\gamma}\,\phi\,F_{\mu\nu}\tilde{F}^{\mu\nu} \quad \longrightarrow \quad Q \pm iU \to e^{\mp 2i\alpha(\hat{\mathbf{n}})}(Q \pm iU)$$

- $\alpha(\hat{\mathbf{n}})$ can be reconstructed with quadratic estimators and correlated with matter tracers.

$$\delta\phi'' + 2\mathscr{H}\,\delta\phi' + \left(k^2 + a^2\frac{d^2V}{d\bar{\phi}^2}\right)\delta\phi = -\frac{1}{2}h'\bar{\phi}' \quad \Delta^\alpha_\ell(k) = g_{\phi\gamma}\int_0^{\tau_0} \mathrm{d}\tau\; g(\tau) T_{\delta\phi}(\tau,k) j_\ell\left[k(\tau_0-\tau)\right]$$





Conclusions

- **Exciting times ahead with CMB experiments and LSS surveys**
  - More than the sum of the two.
- **CMB - LSS cross-correlations are booming!**
  - CMB lensing will be the new high precision/high accuracy cosmological probe.
  - More precise and robust cosmology / fundamental physics and astrophysics.
- **Your new ideas and input here…**
  - Probe combination / CMB secondaries require cross-disciplinary expertise.
  - Have fun with data!
  - Think about new theory probes and applications out of the box (rotation, bispectra, birefringence, spectral distortions…)