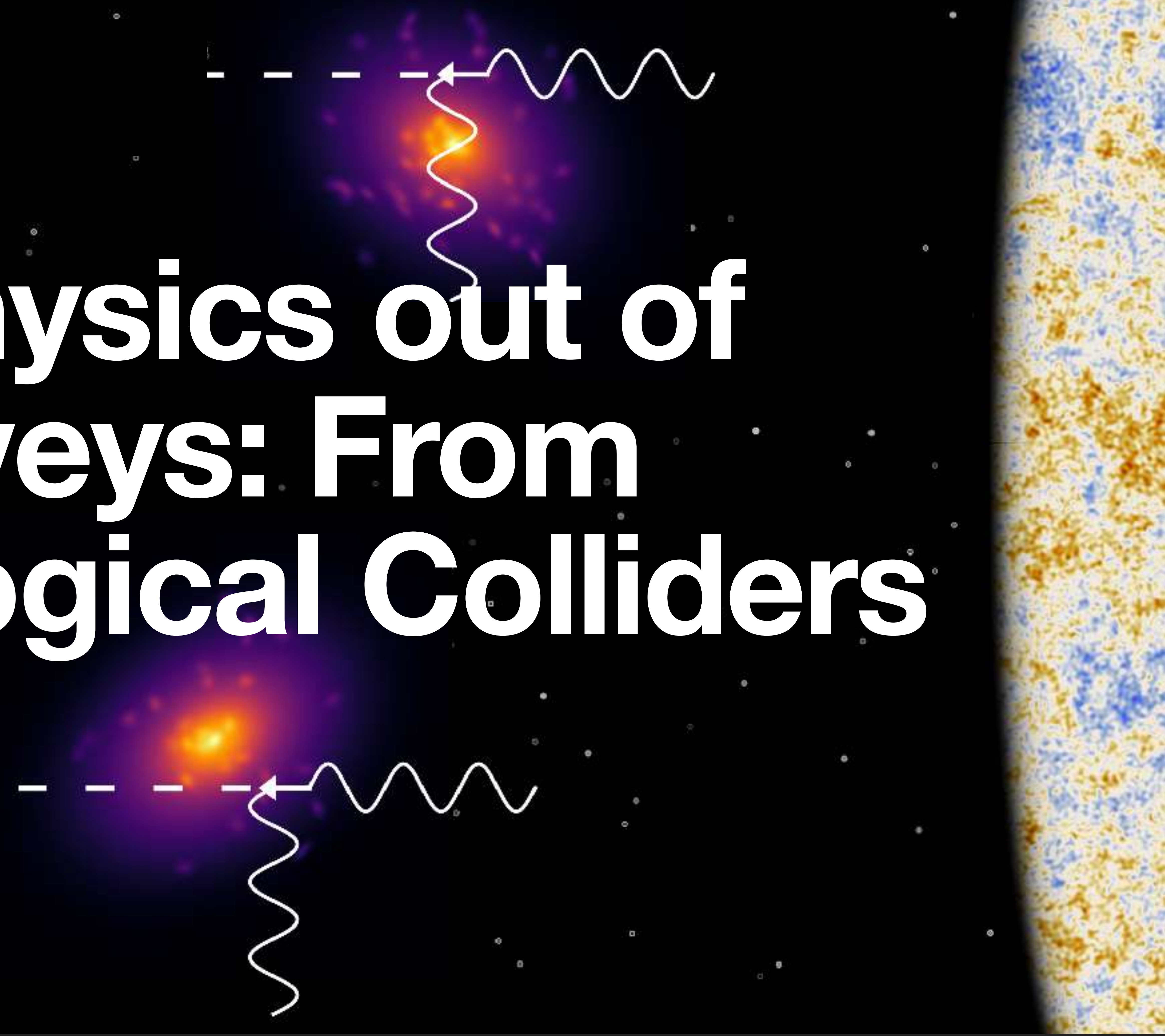
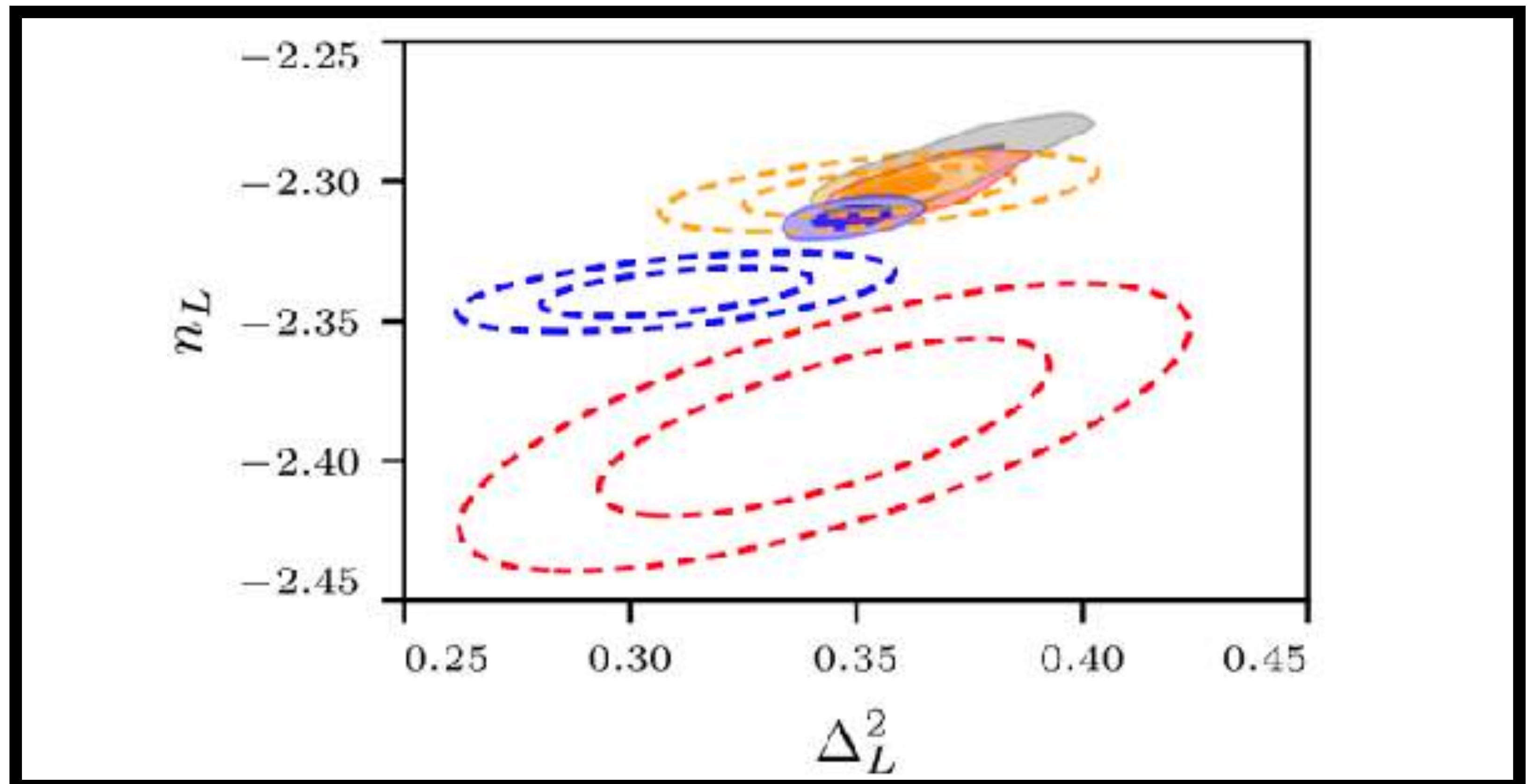
Squeezing New Physics out of Cosmological Surveys: From Axions to Cosmological Colliders



Sam Goldstein

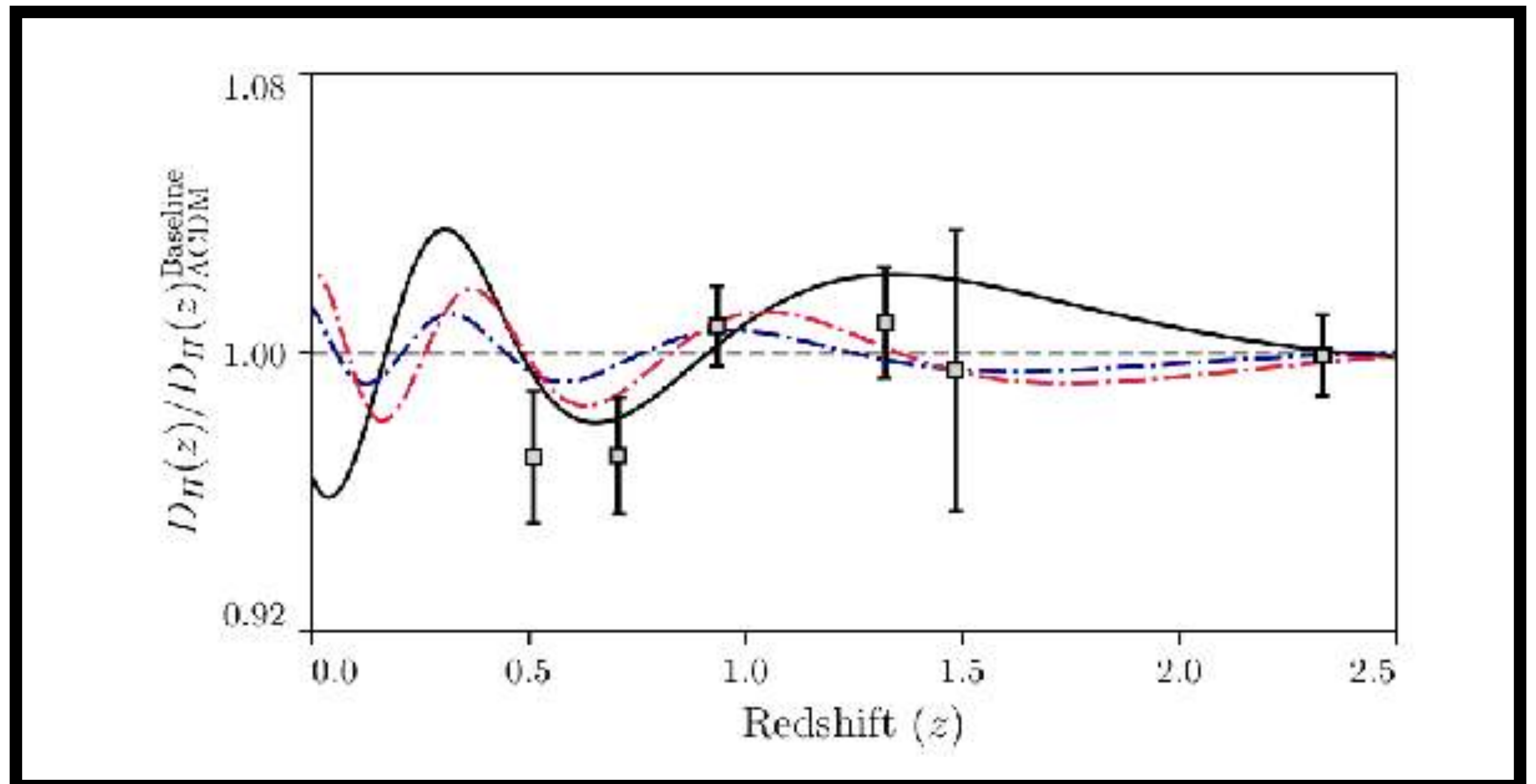
Columbia University

Things I won't talk about today, but I am around for the next 6 weeks!



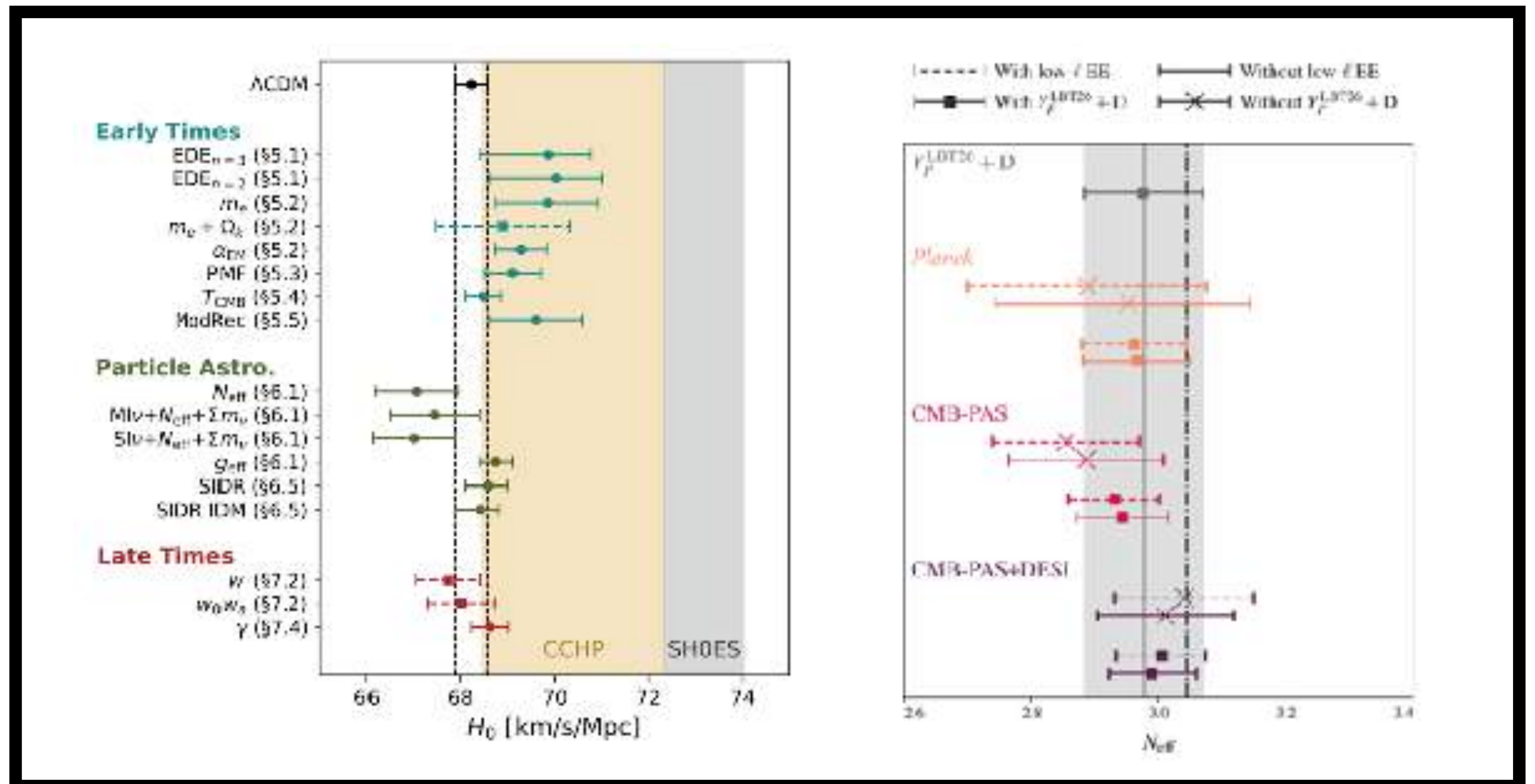
Early dark energy and Ly-α forest

SG++ 2303.00746 **(PRL)**, ***Editors' Suggestion***



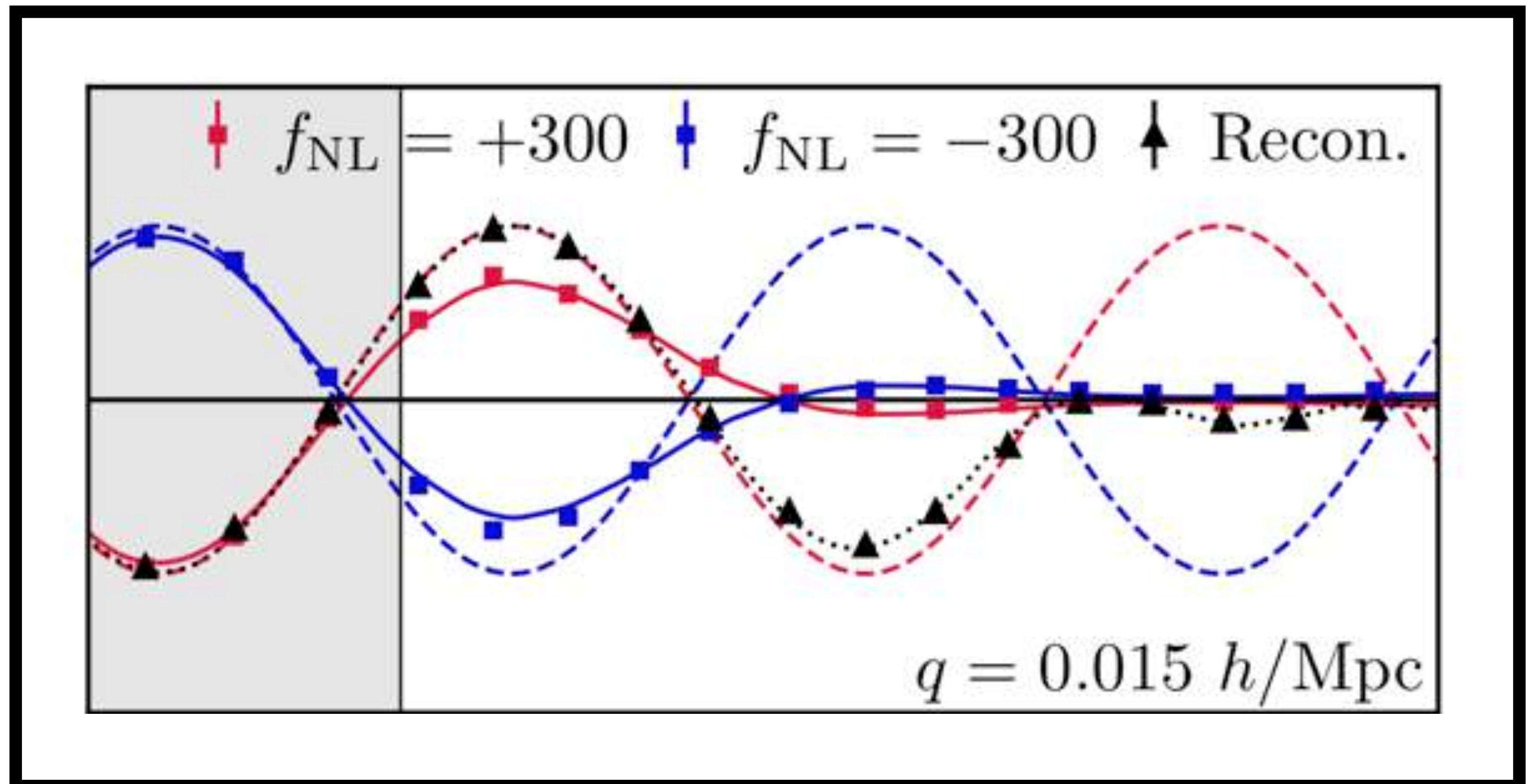
(Over?)fitting wiggles in DESI BAO

SG++ 2507.16970 (**PRD**)



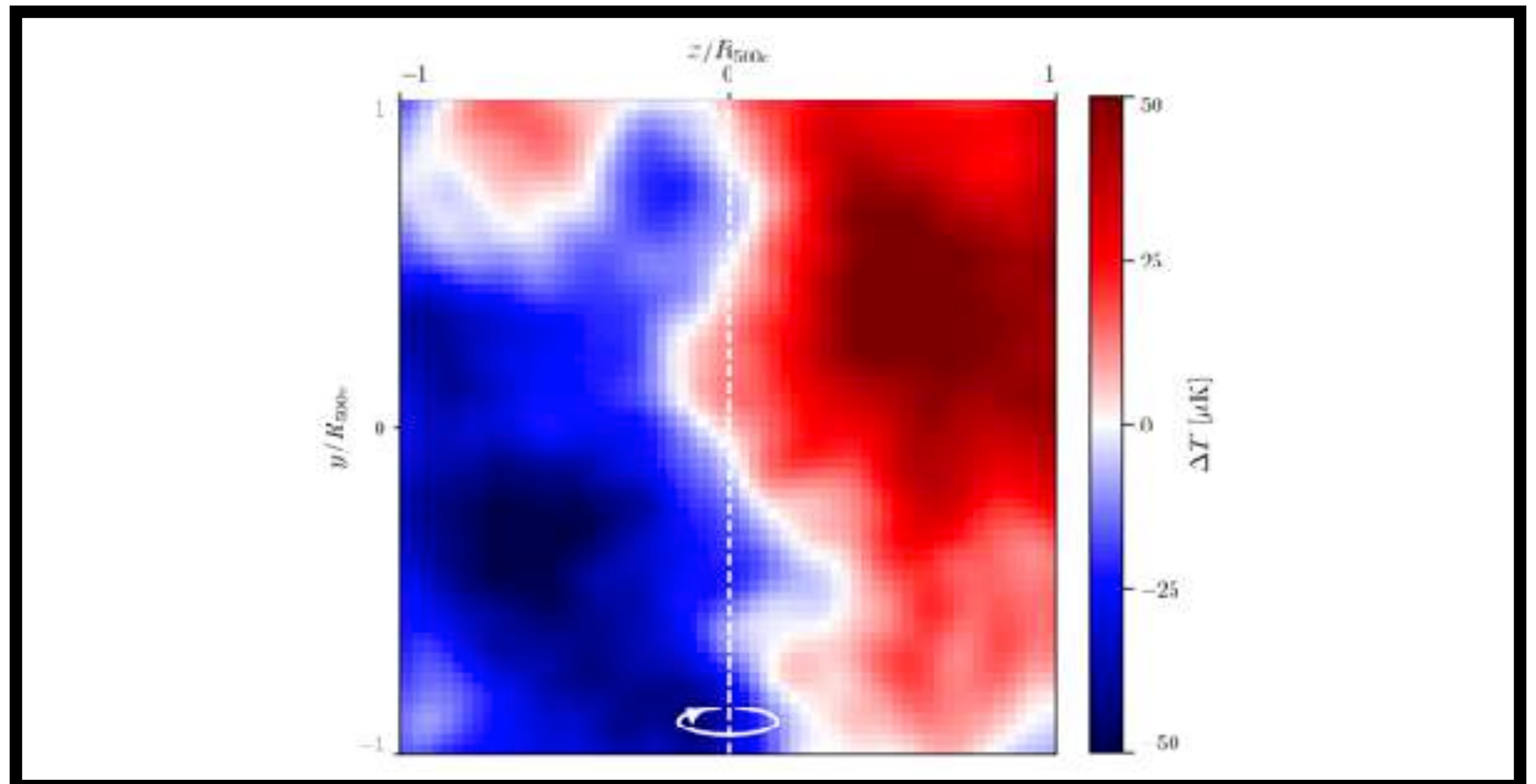
Cosmology from the primary CMB

ACT DR6 2503.14454 (**JCAP**) **SG++**2603.13226 (**PRD**)



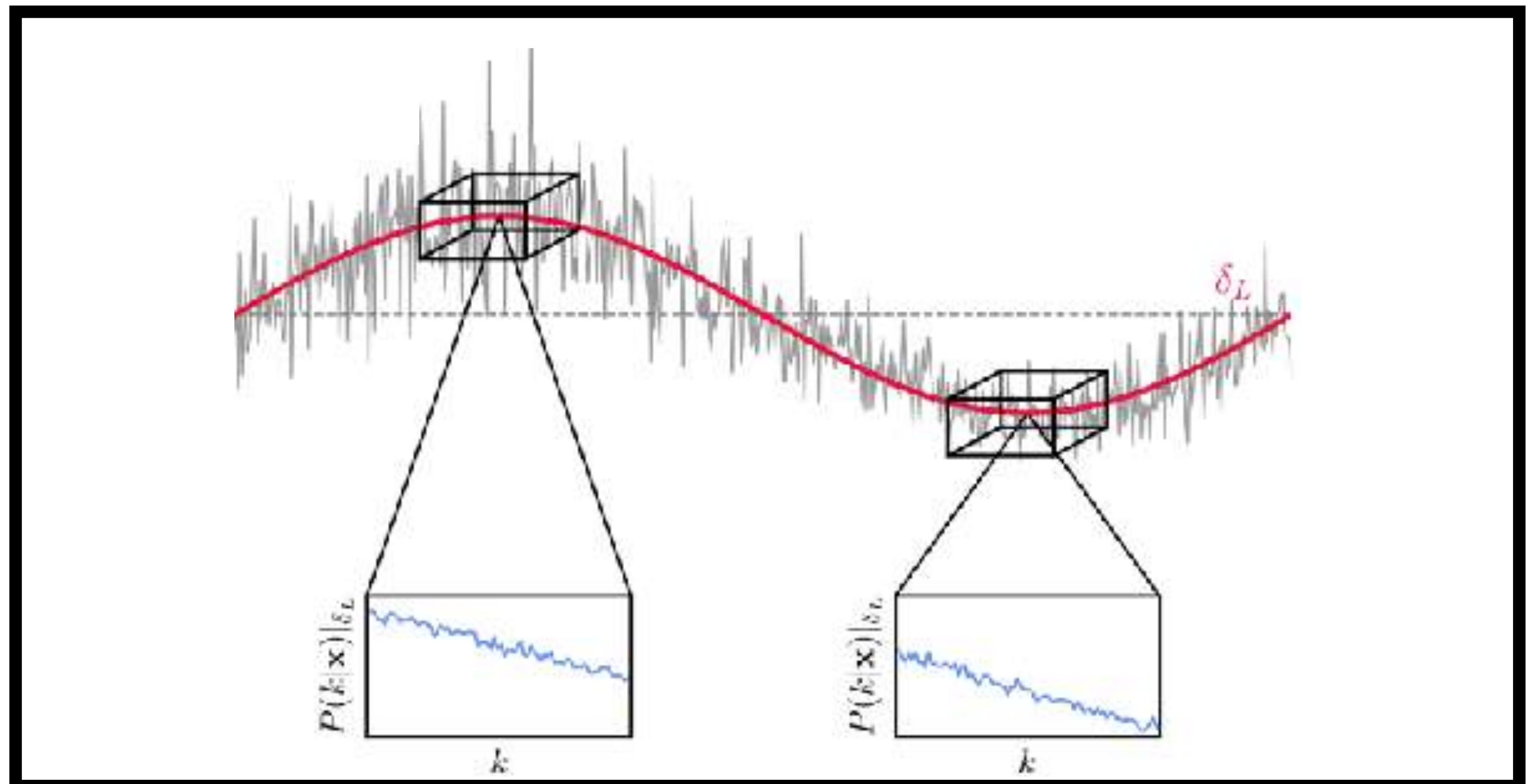
Simulating the cosmological collider

SG++2407.08731 (**PRD**) **SG++**2505.13443 (**PRD**)



Rotational kSZ effect

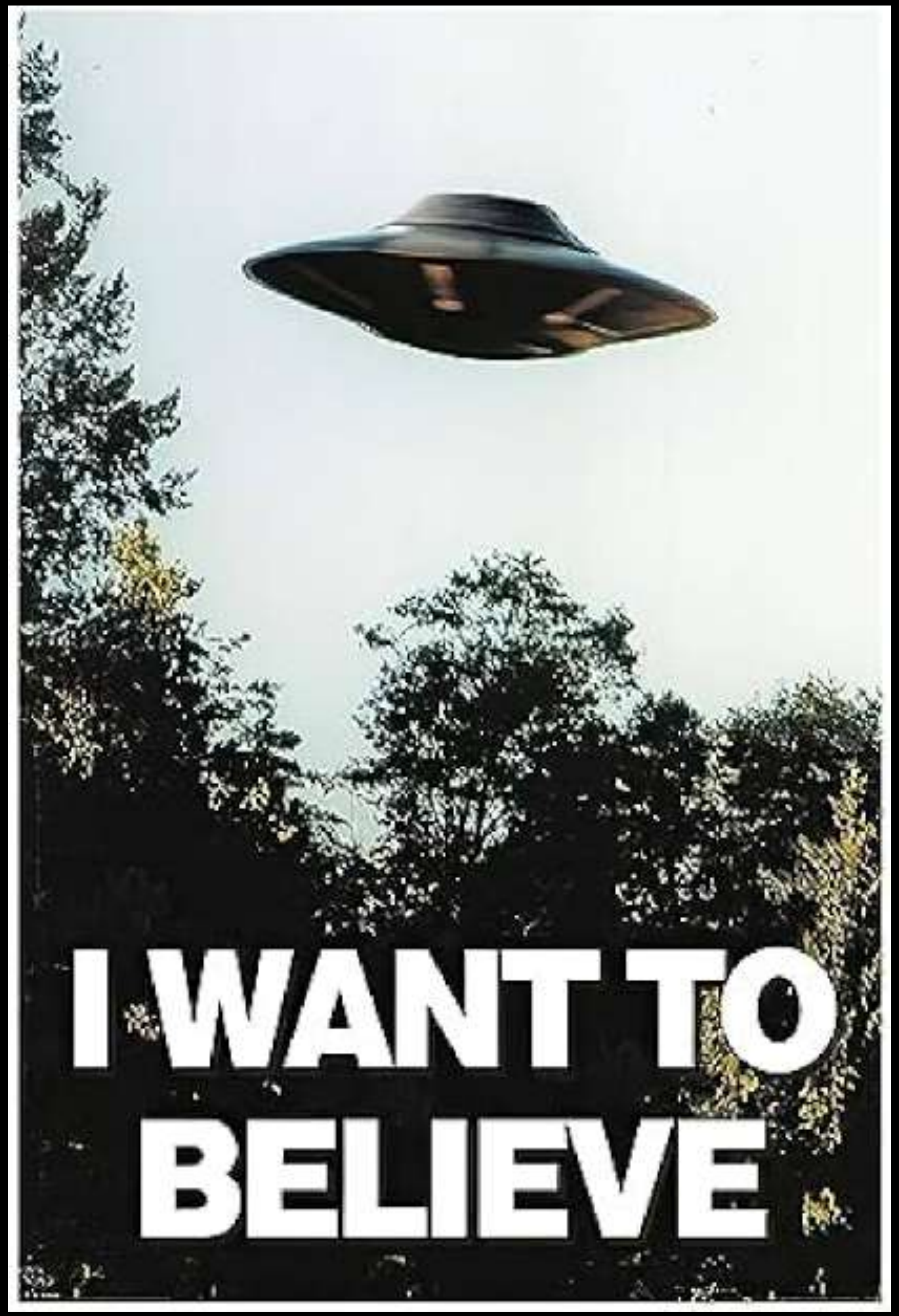
SG++ (**PRL** in press), ***Editors' Suggestion***



Power spectrum covariance estimation

SG++ 2604.18581 (**PRD** under review)

Why search for new physics?



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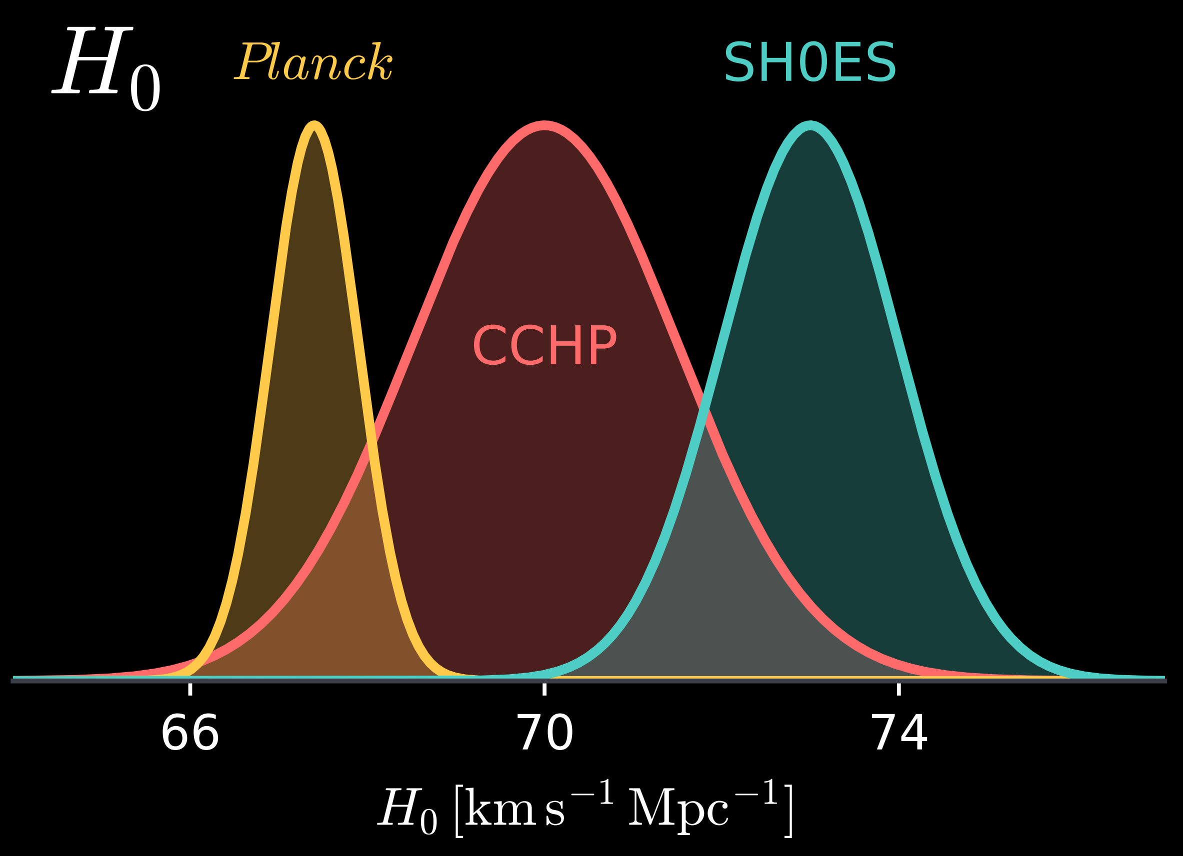

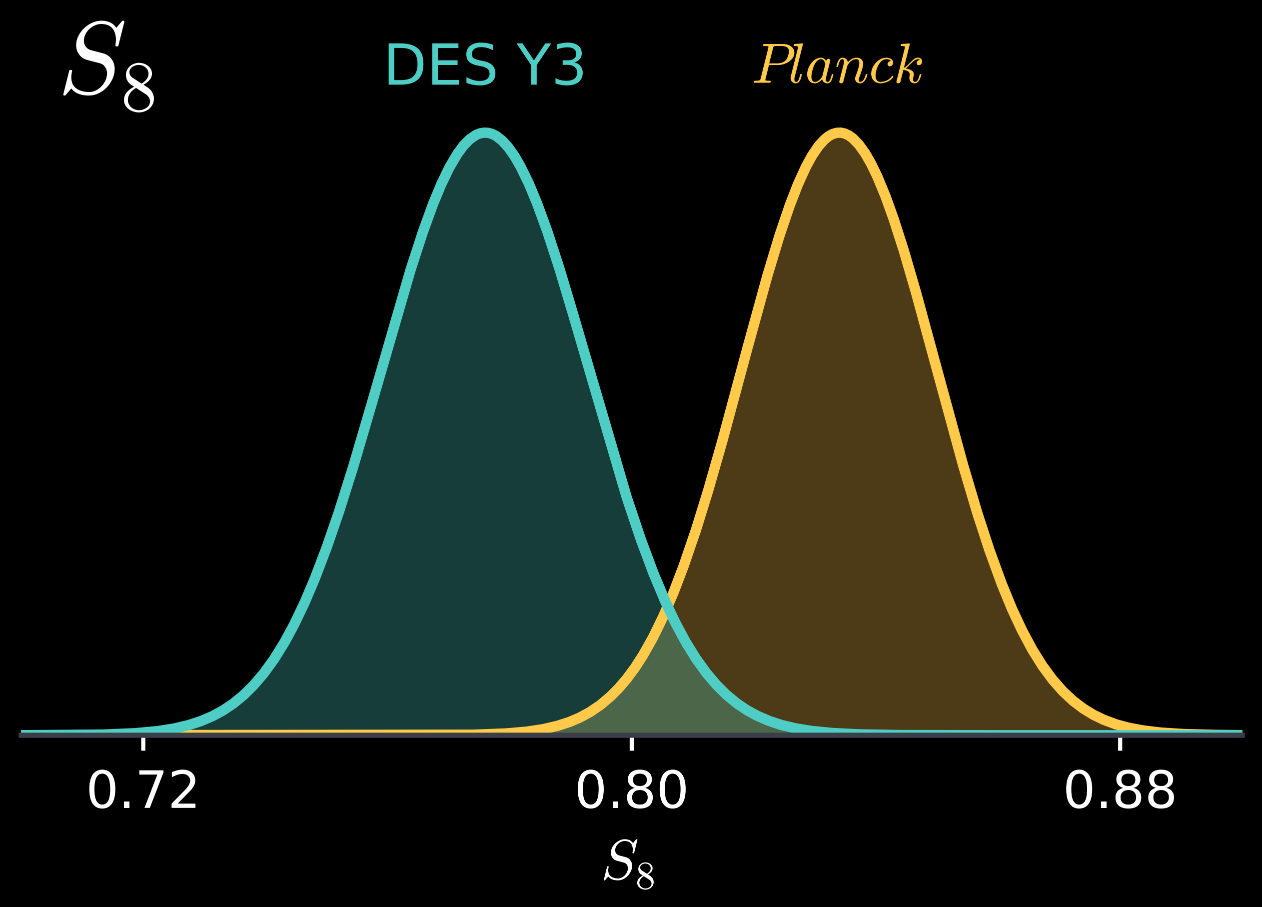

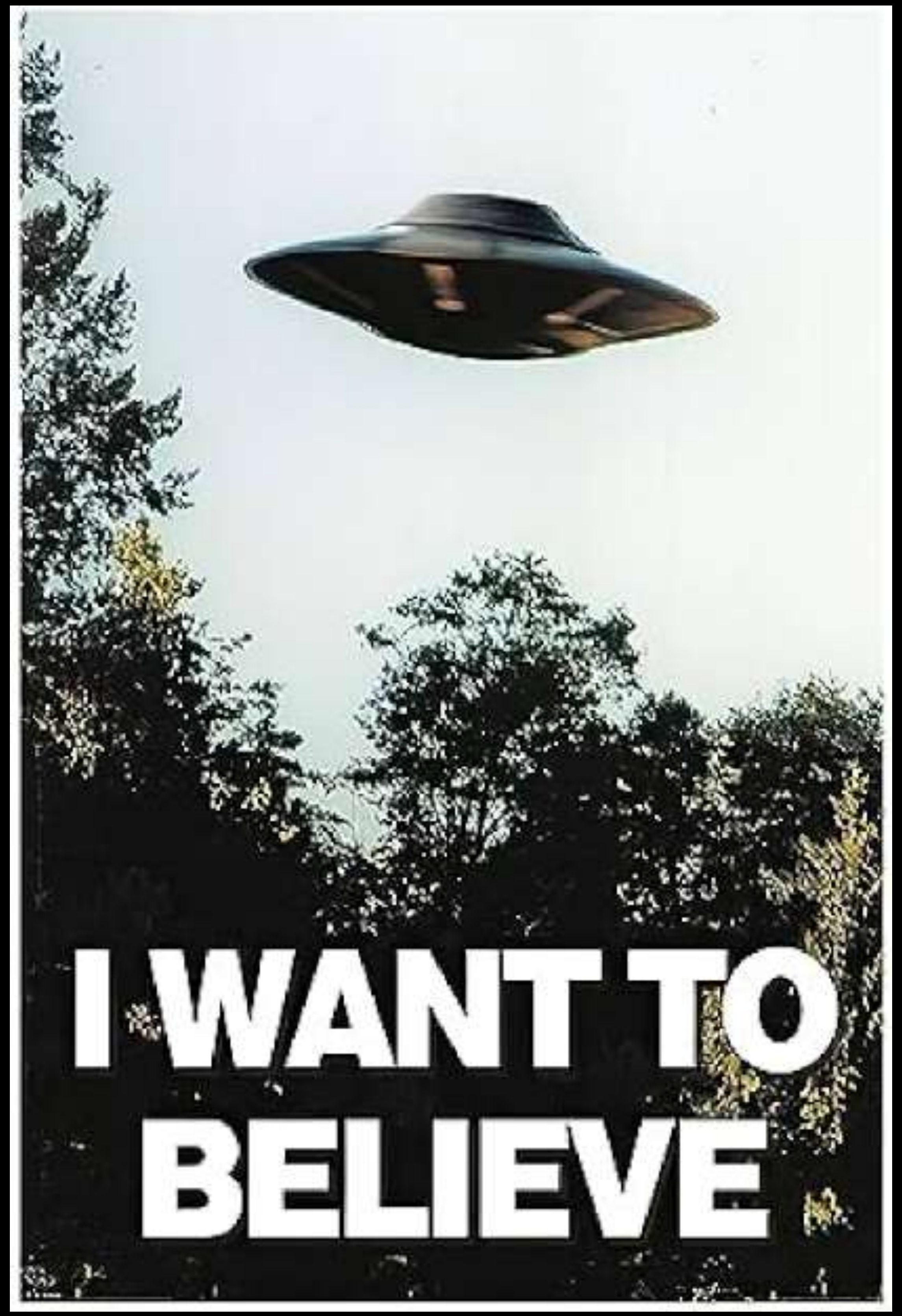

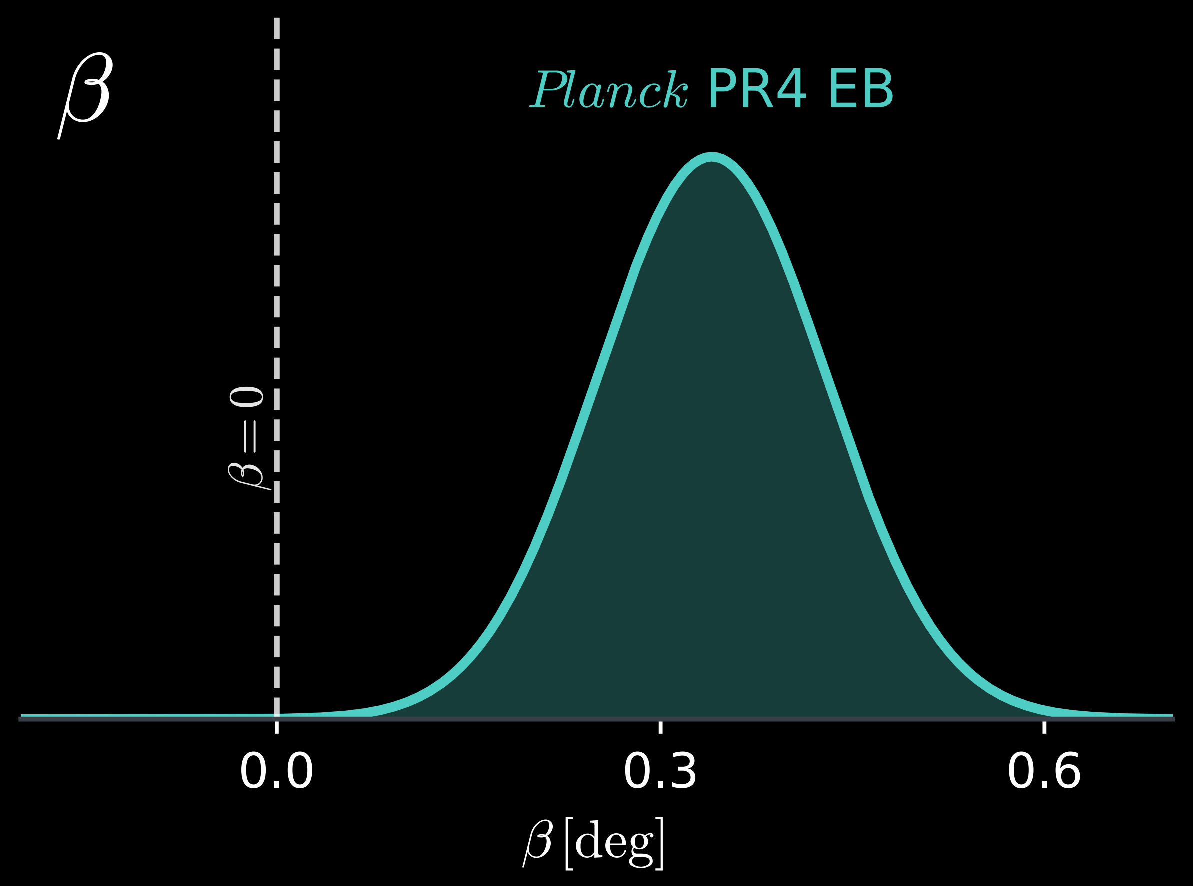

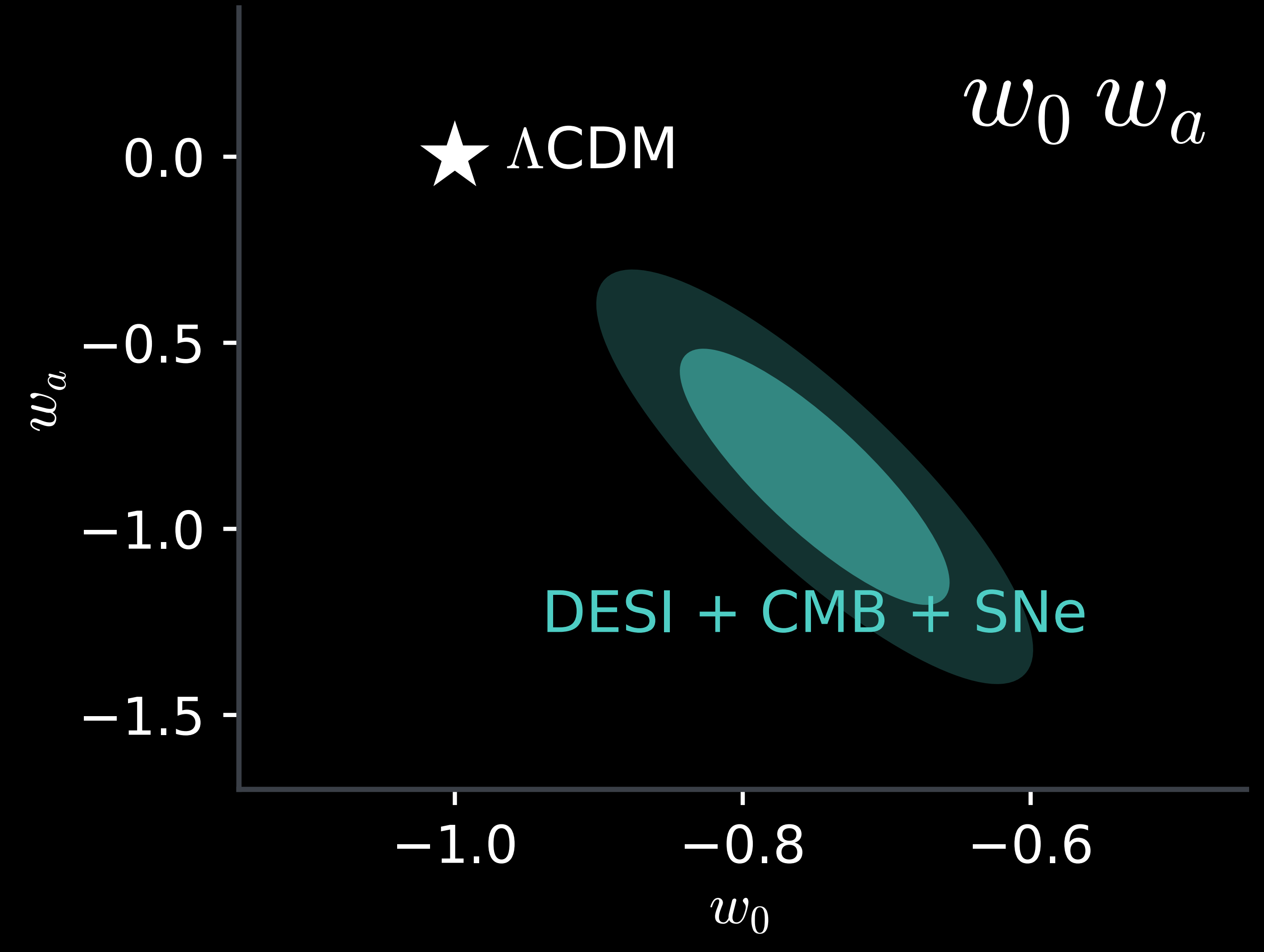

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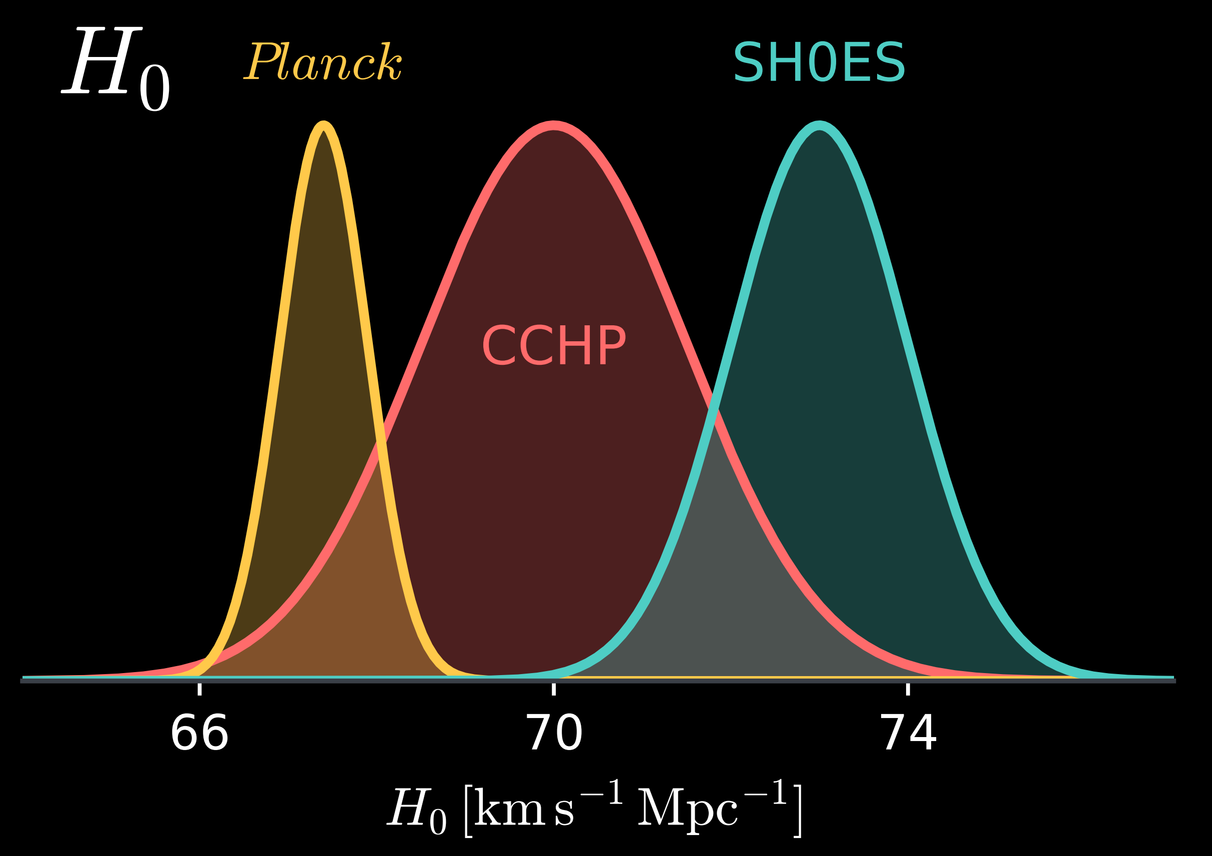
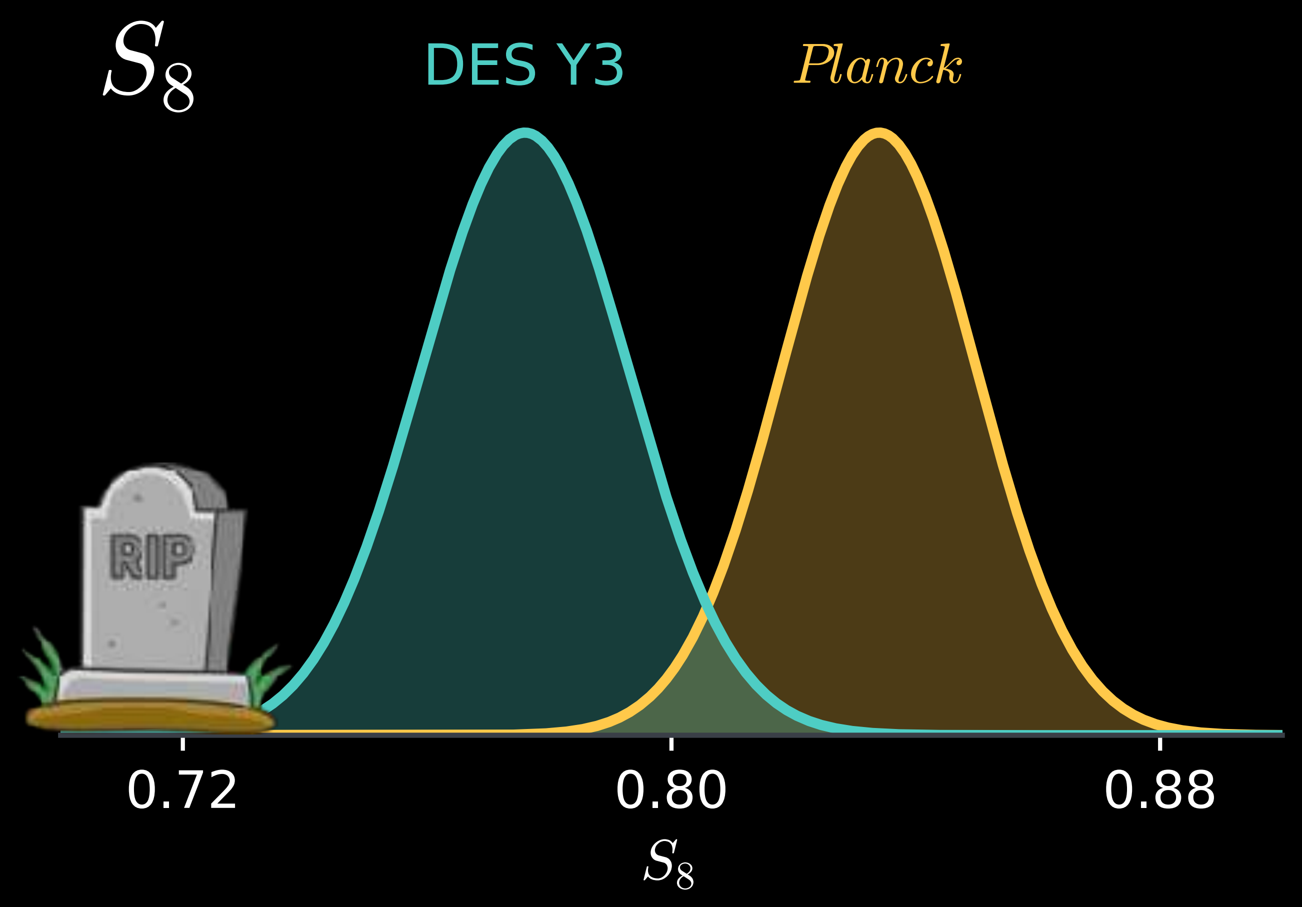
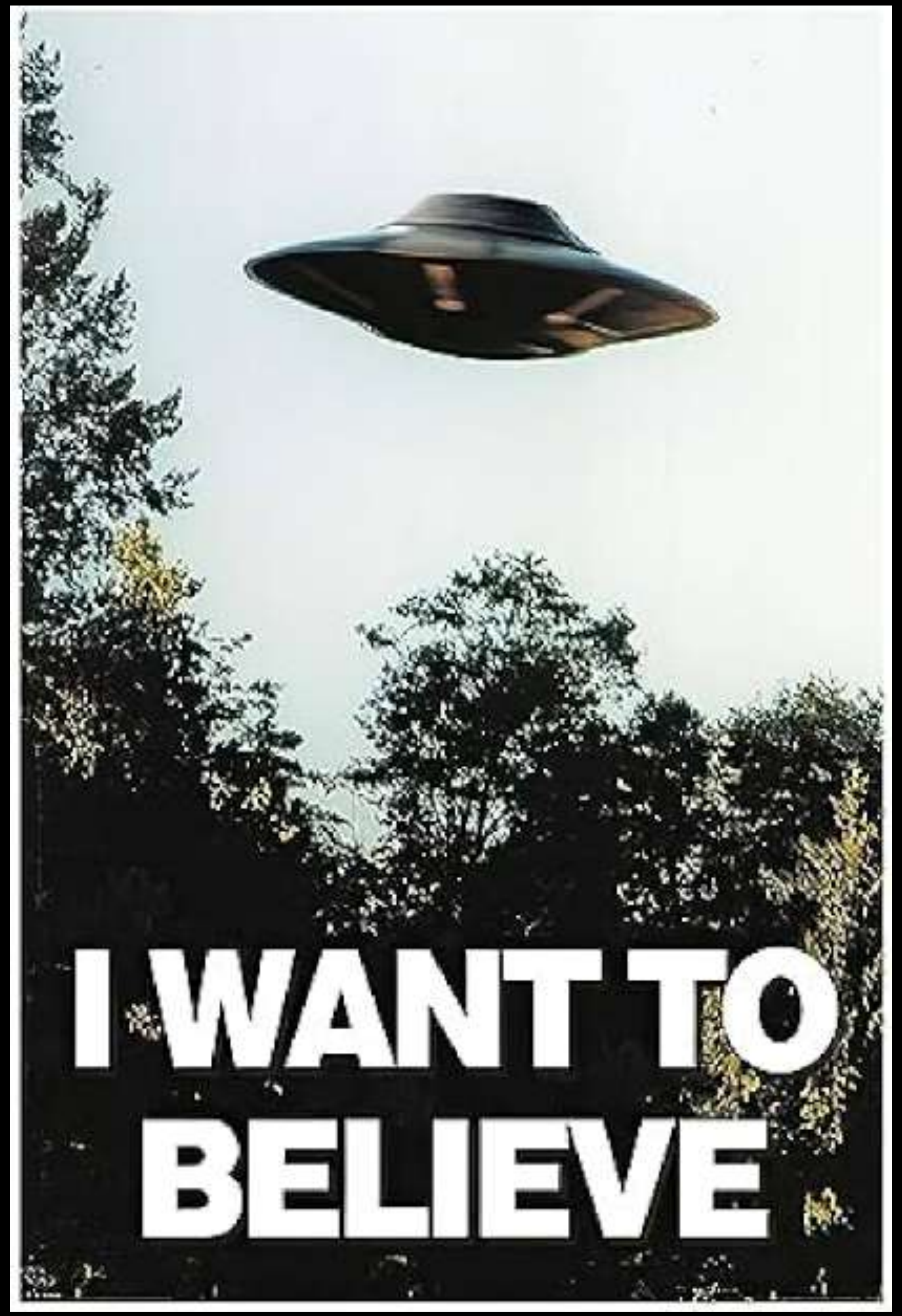
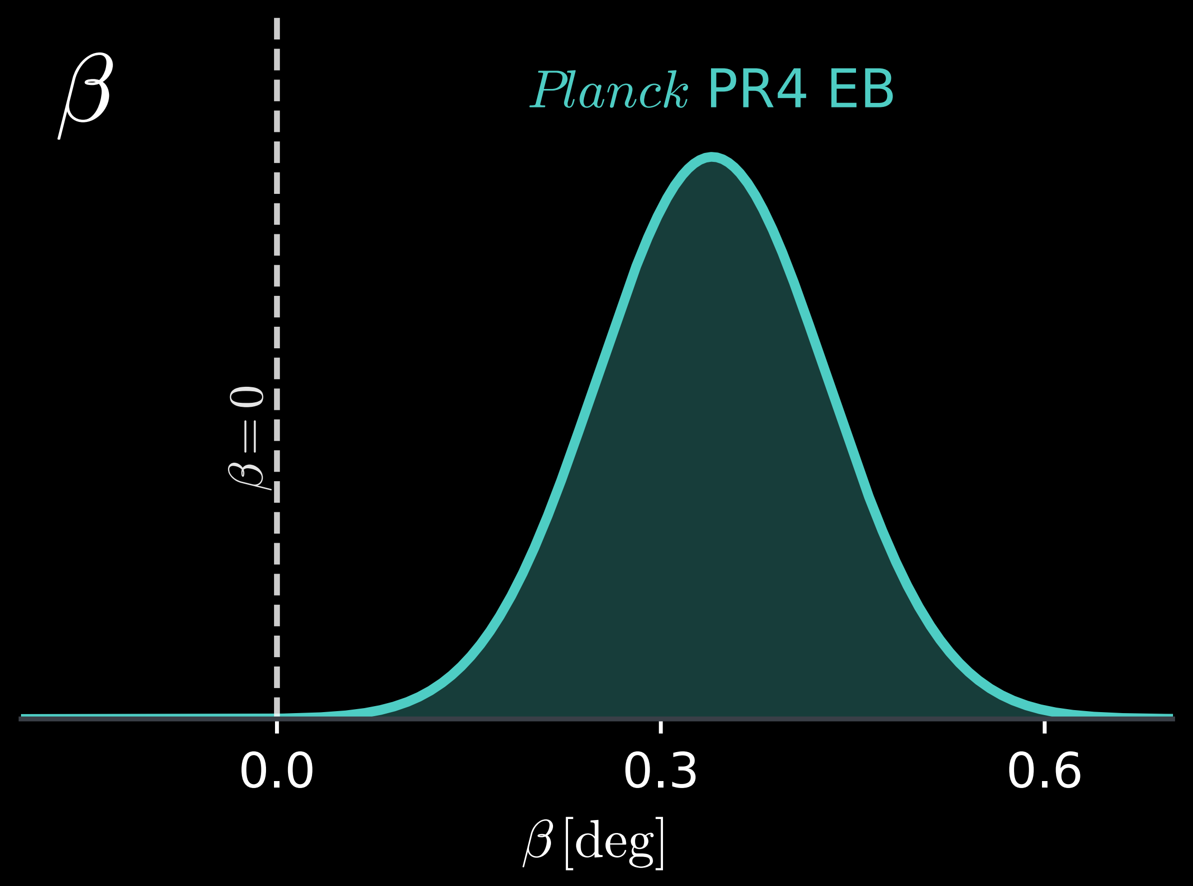
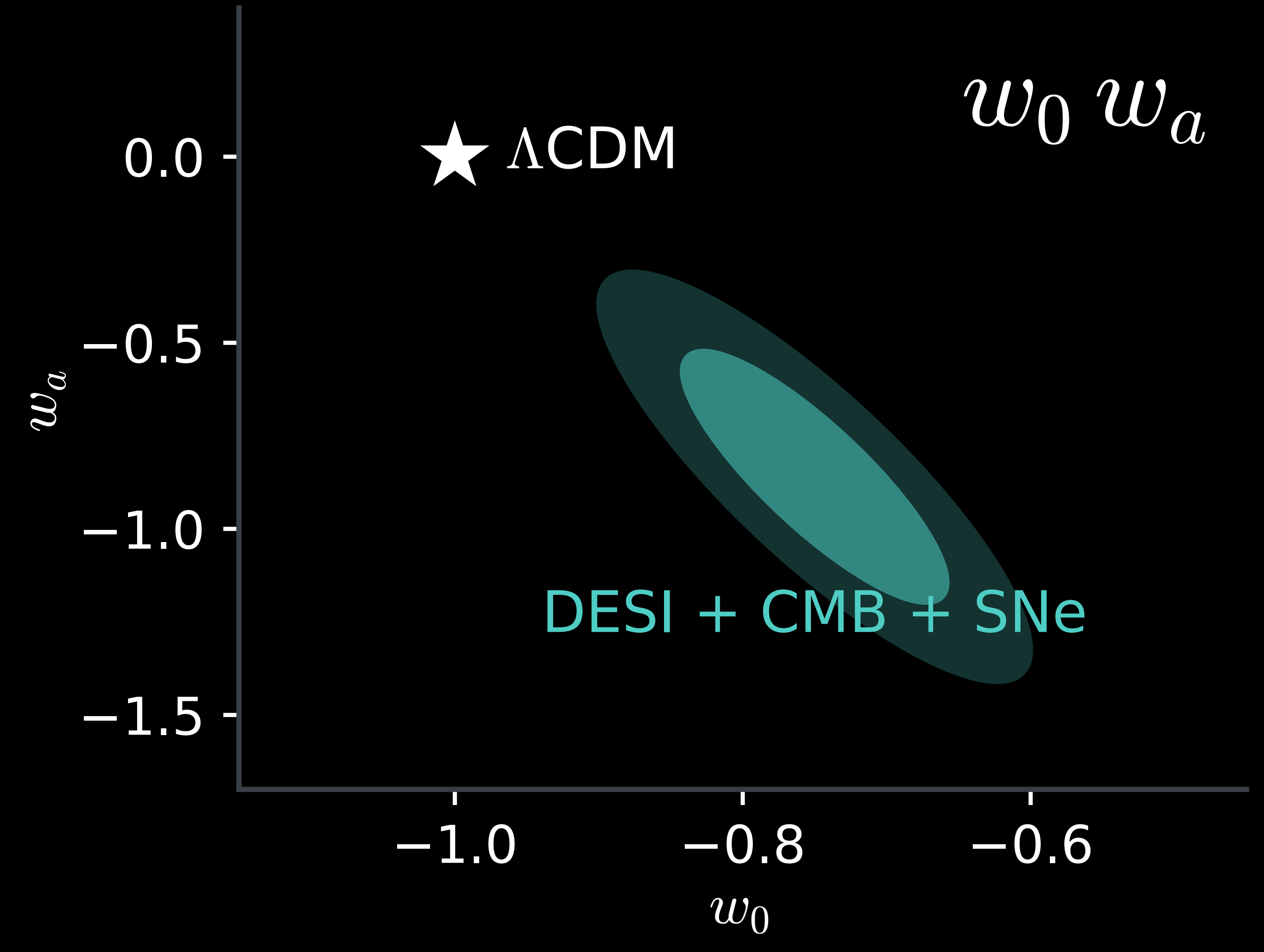






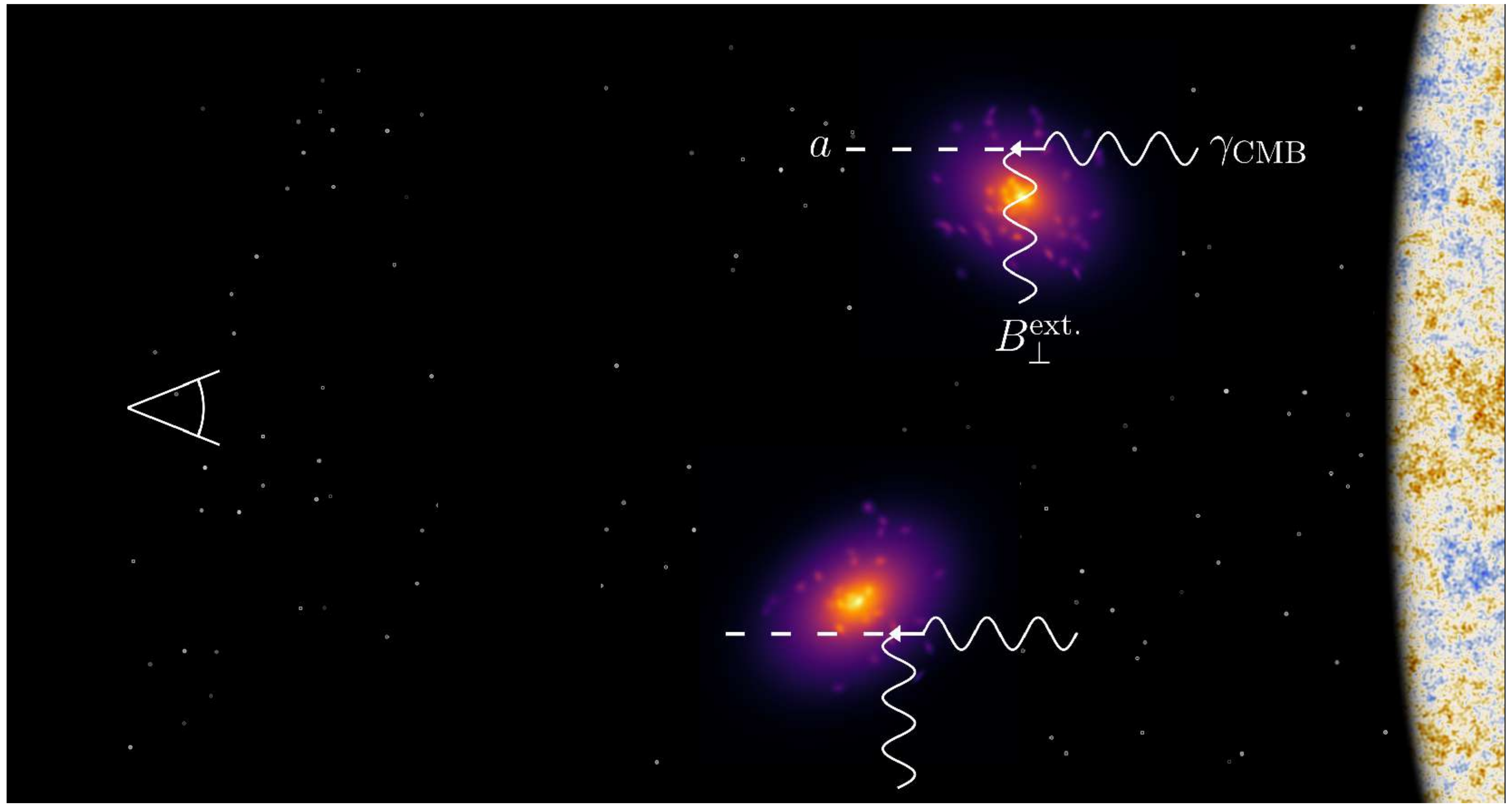




hints of new physics
come and go

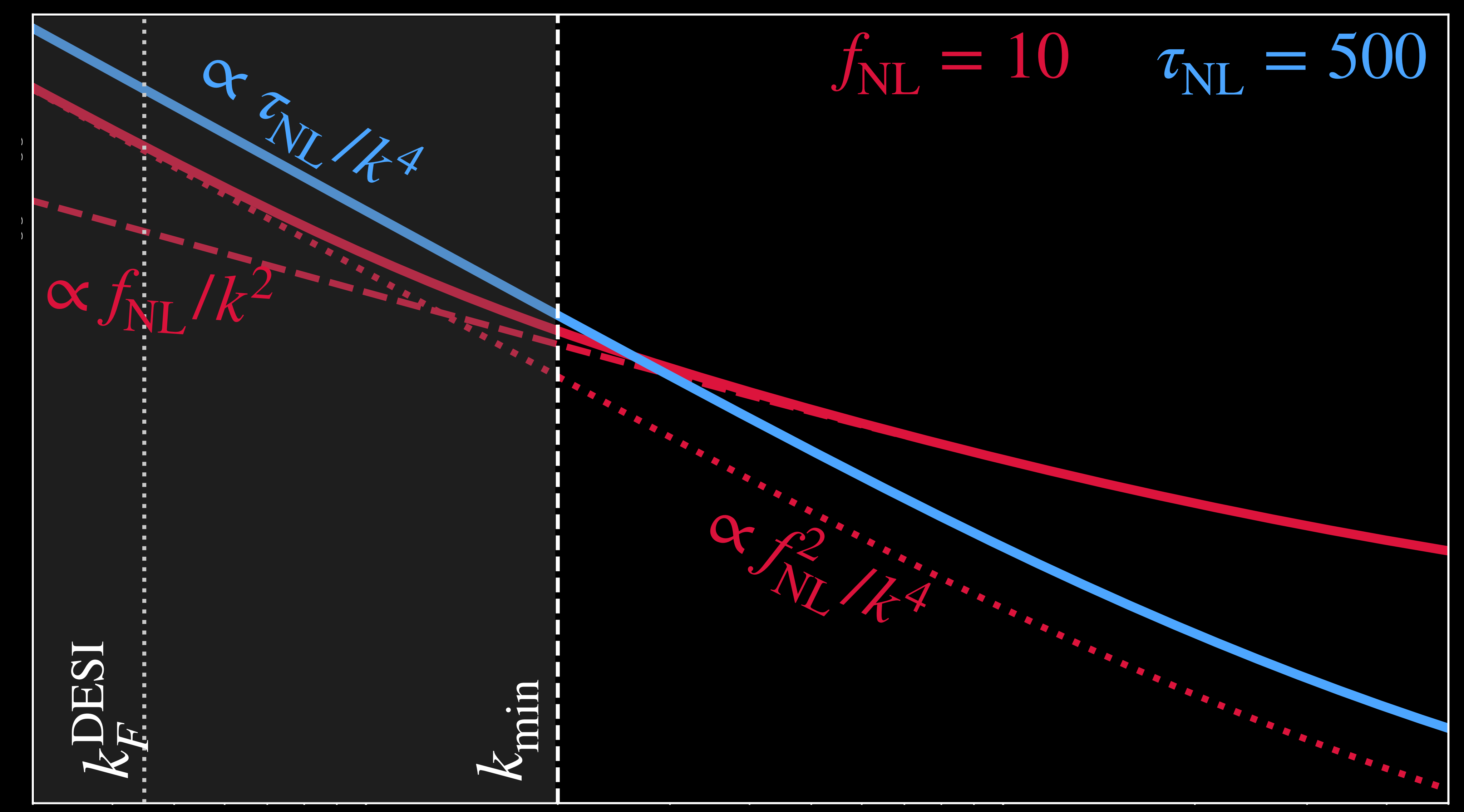
but the ~~friends~~ *pipelines*
we made along the way
are forever

Outline



Part 1: Searching for axions with CMB × LSS

- *Background*: axion-induced screening of the CMB
- *Challenge*: foregrounds and analyzing high-resolution CMB data
- *Results*: axion constraints and a first look at Simons Observatory LAT data



Part 2: Testing inflation with galaxy surveys

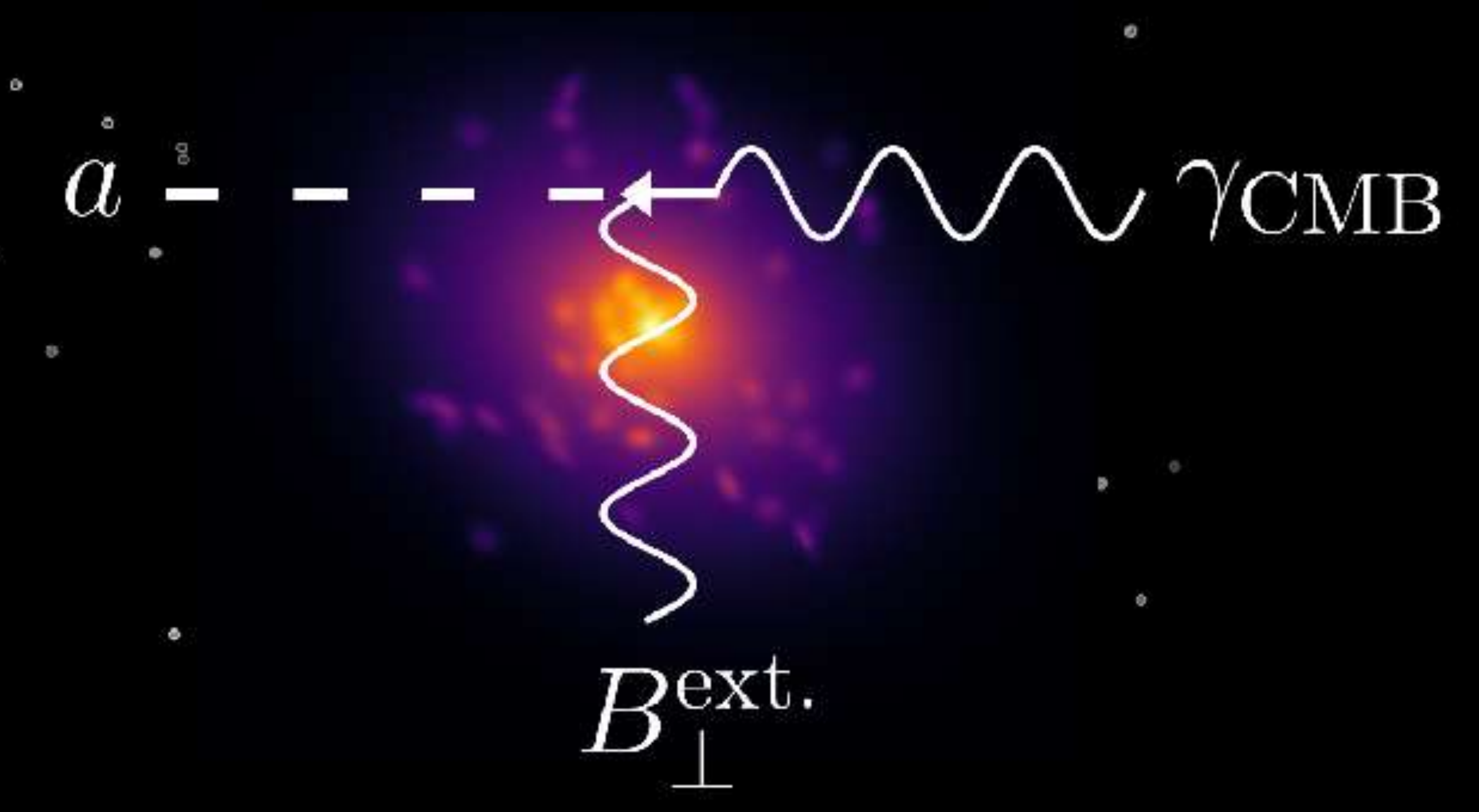
- *Background*: galaxy bias as a probe of inflation
- *Challenge*: galaxy clustering on ultra-large scales
- *Results*: first LSS constraint on $\tau_{\rm NL}$ with DESI, plus a pipeline for its largest scales

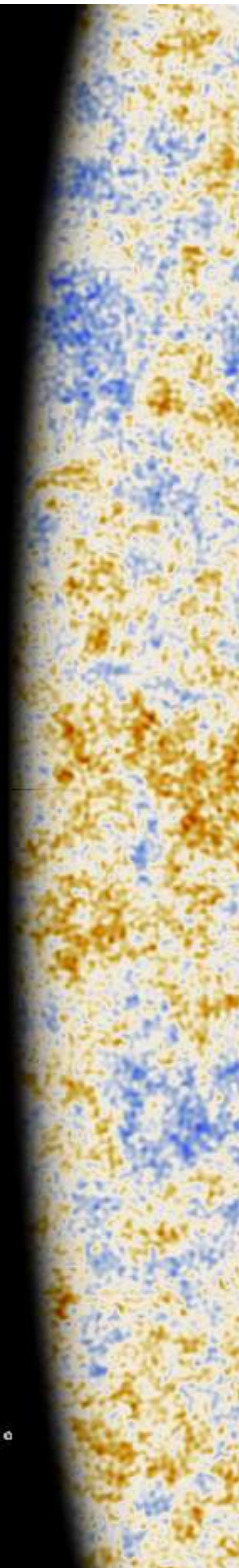
Axion-induced screening of the CMB

Central questions:

1. *Can CMB photons convert into axions as they travel to us?*

2. *If so, how do we search for this?*





References

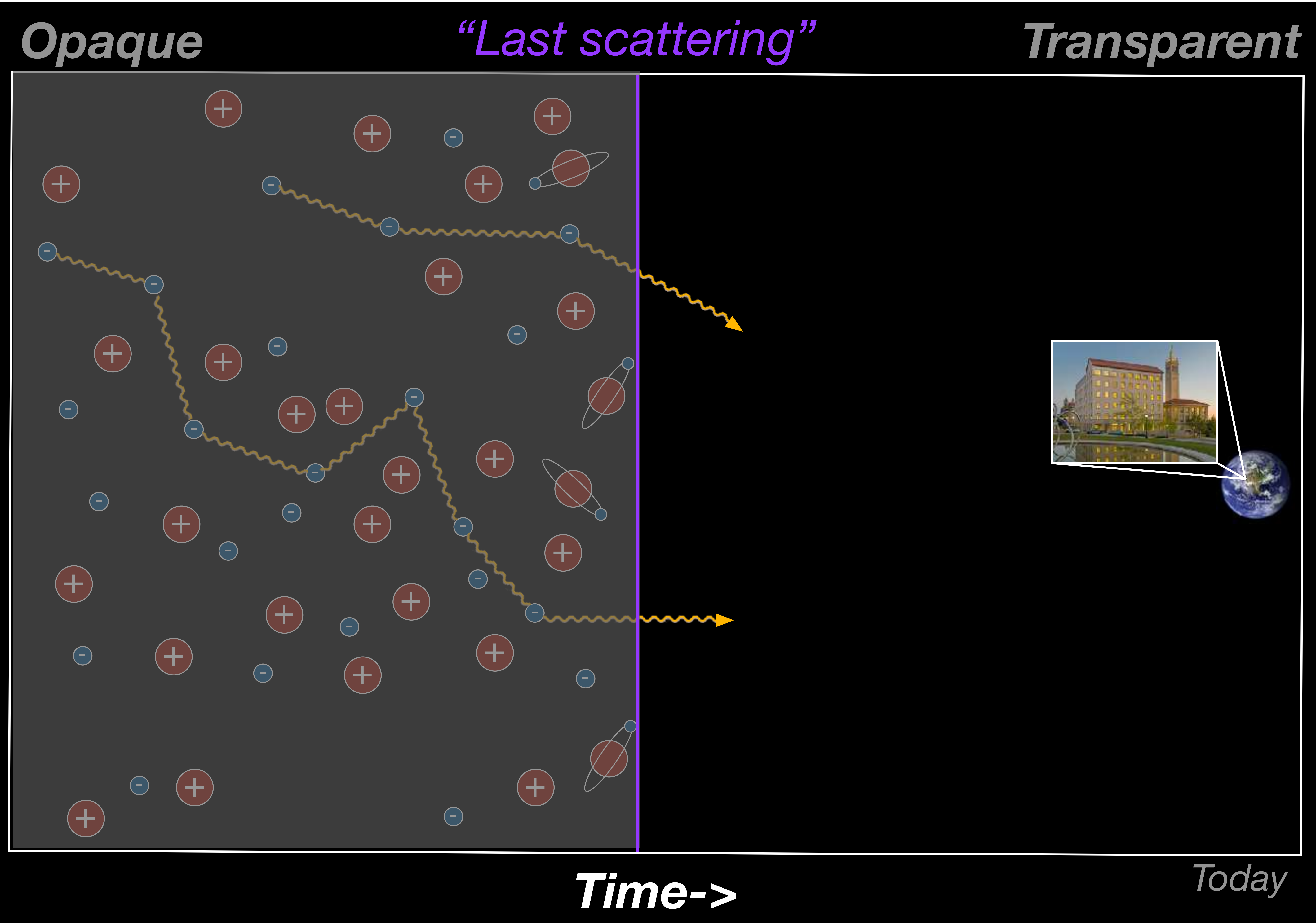
SG, McCarthy, Mondino, Hill, Huang, Johnson (*PRL*, *2409.10514*)

SG++ (Atacama Cosmology Telescope) in prep.

SG++ (Simons Observatory) in prep.

with J. Colin Hill, Junwu Huang, Matthew Johnson, Fiona McCarthy, Cristina Mondino

Cosmic microwave background background (CMB^2)



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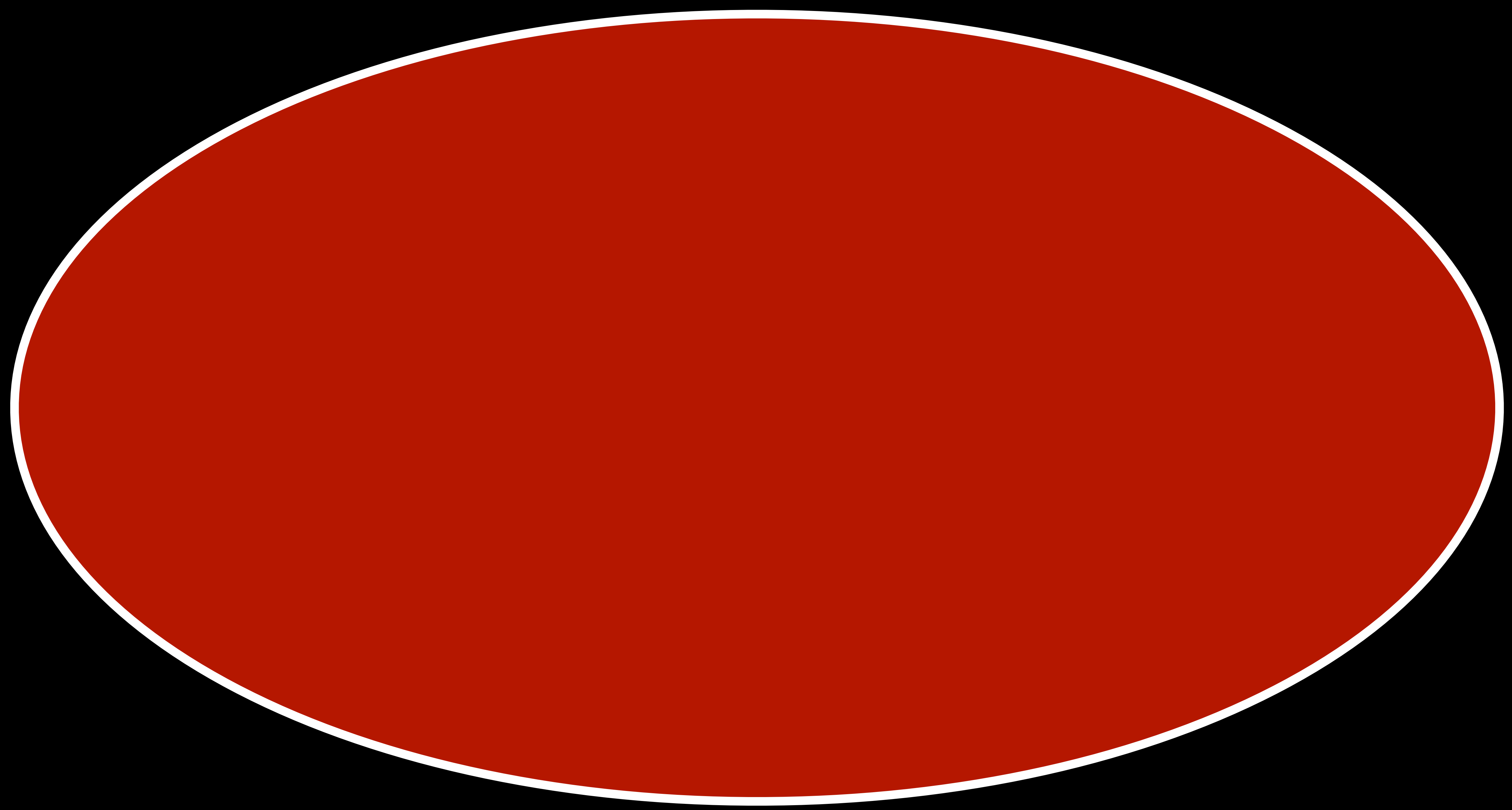
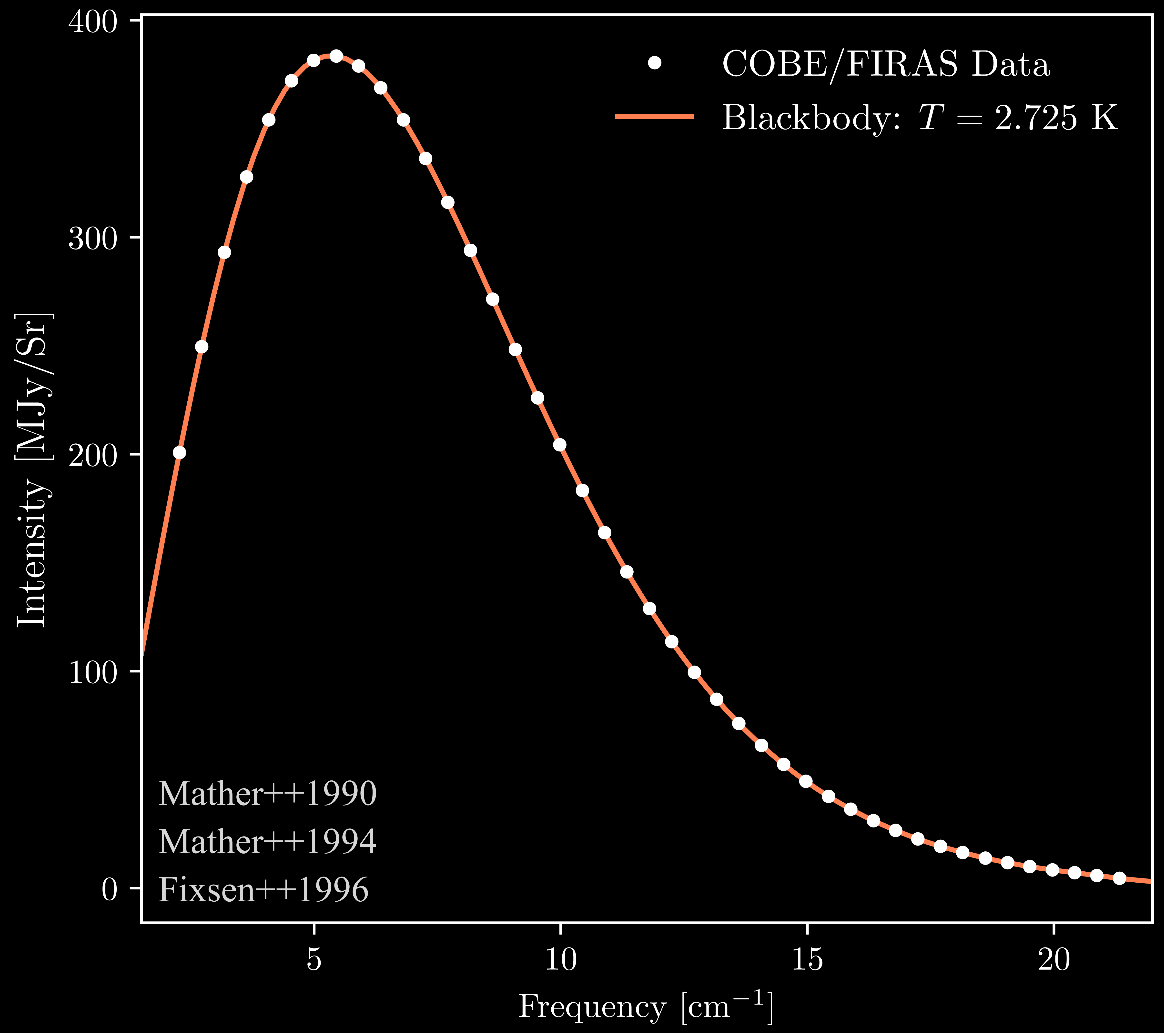
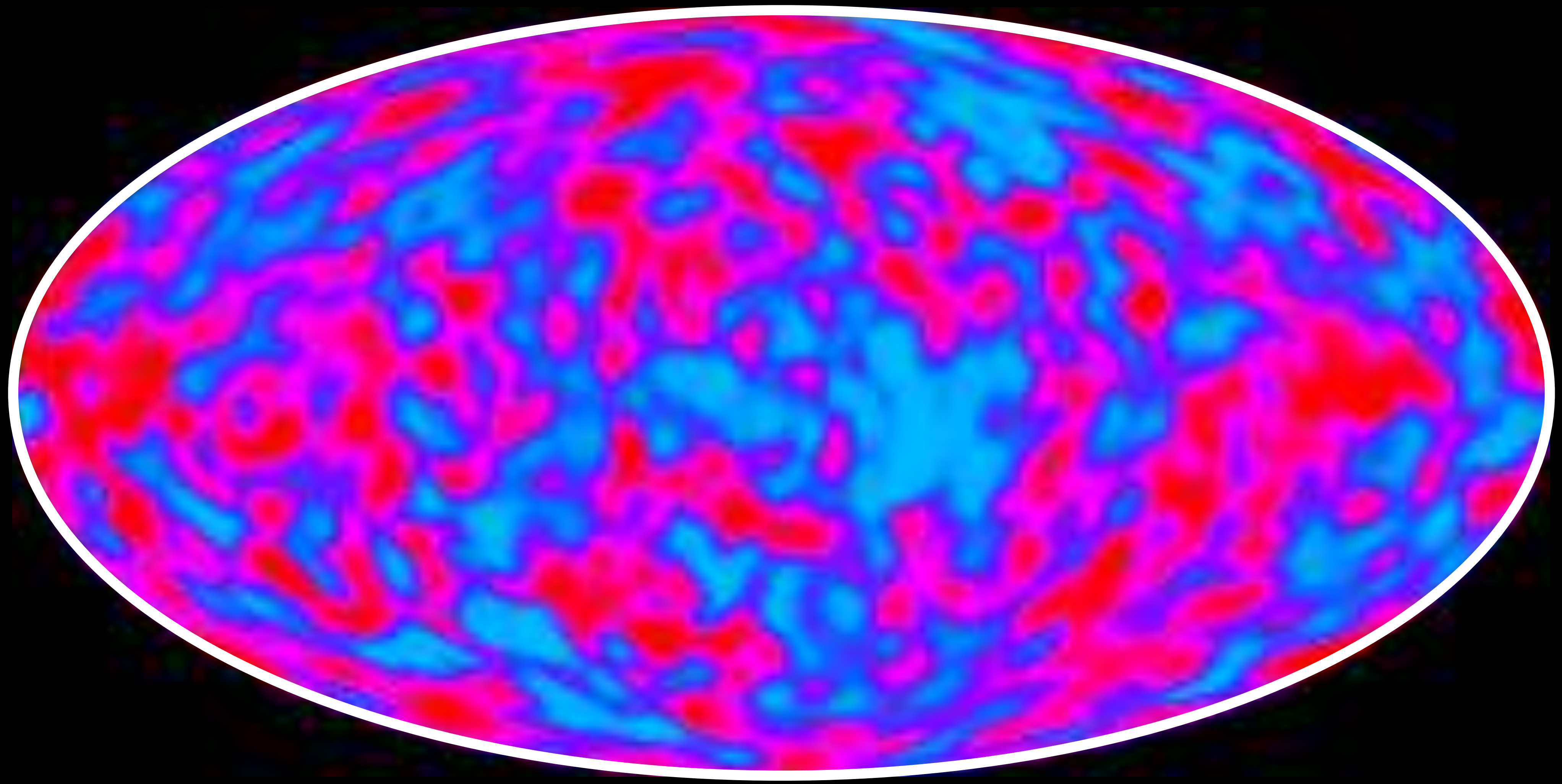


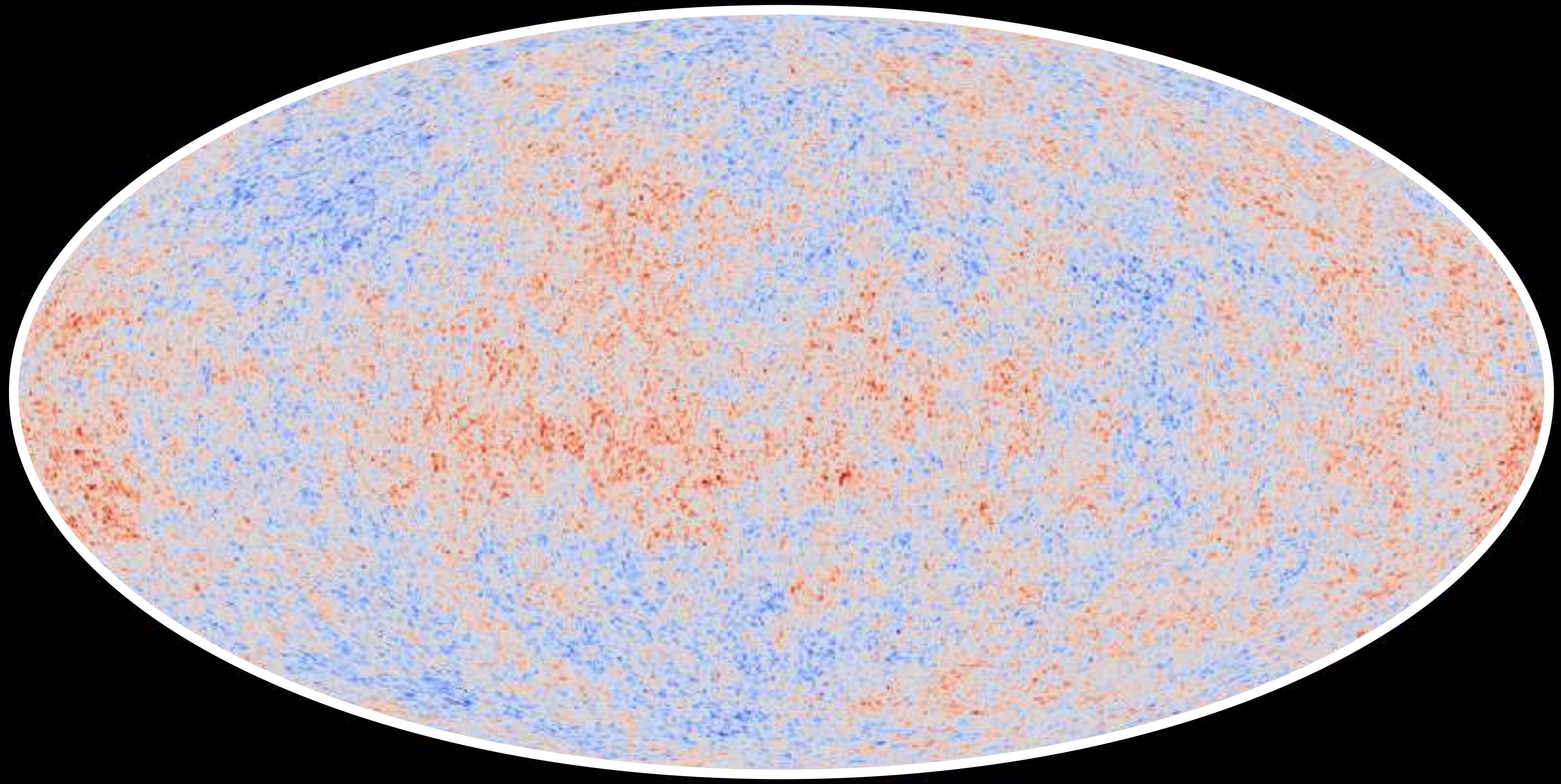


Sky-averaged (monopole) CMB is a ***near***-perfect **blackbody**

CMB primary anisotropies



COBE

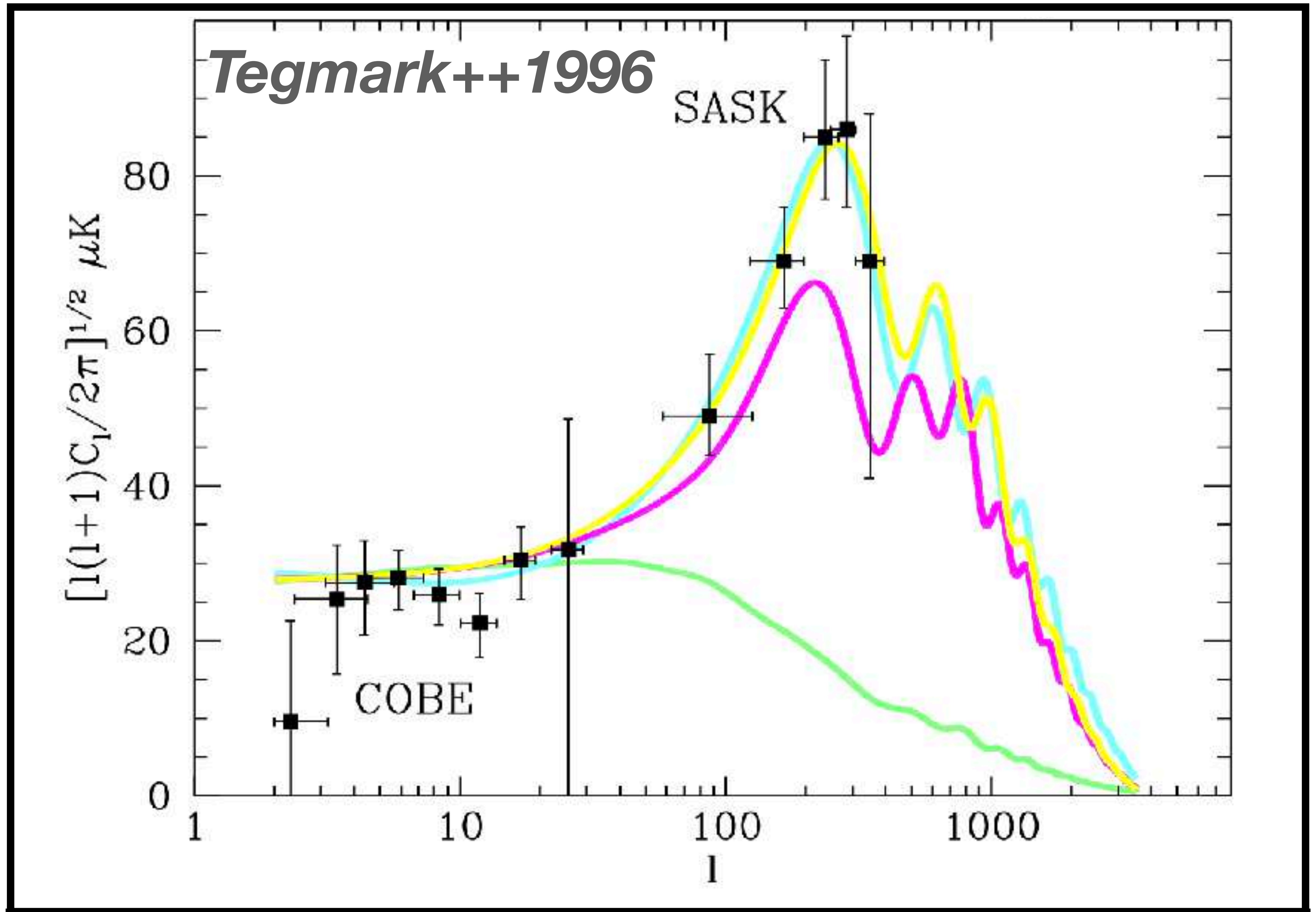


Planck

Smoot++1992, Bennett++1996

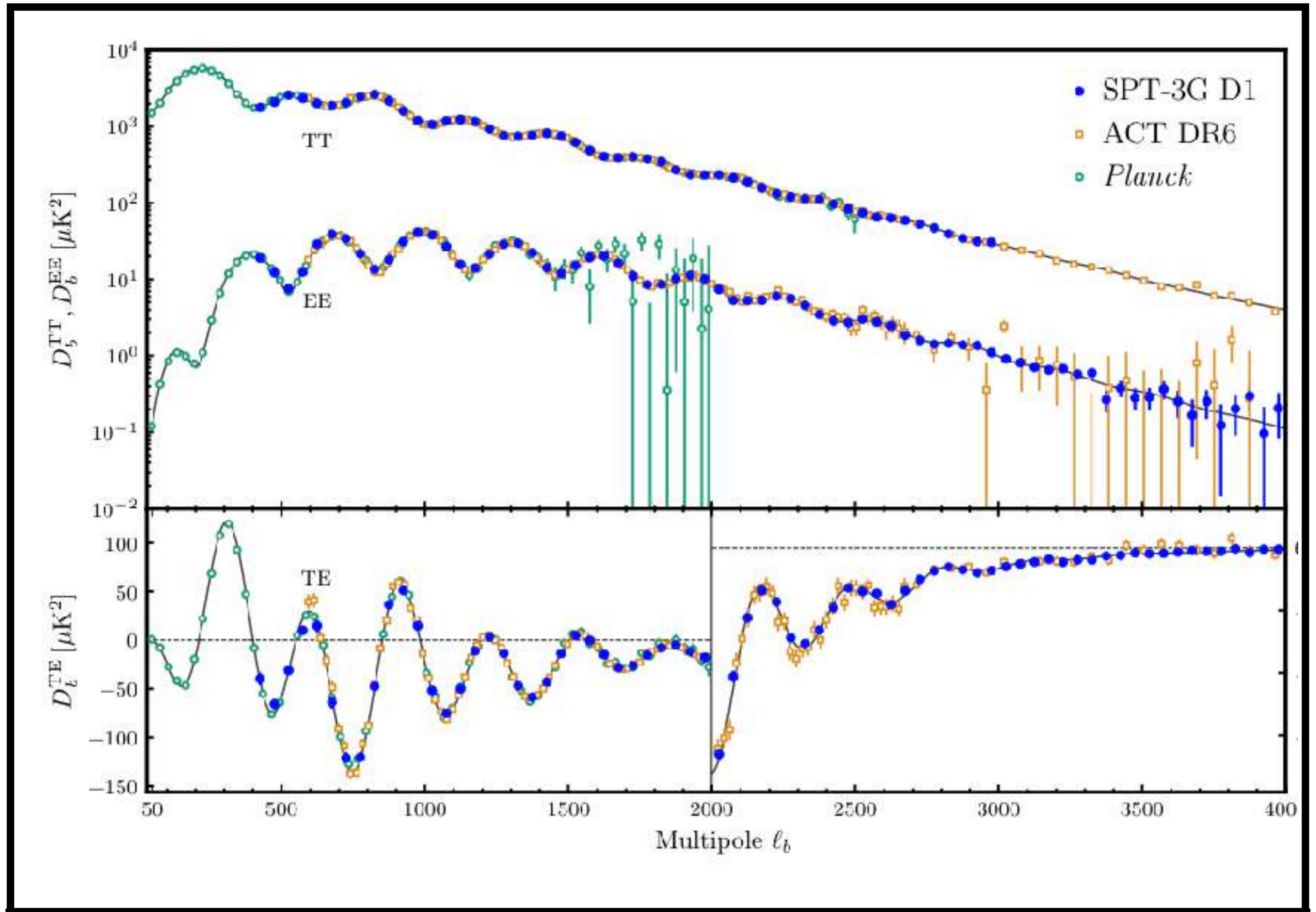
Planck Collaboration 2018, IV

Evolution of CMB power spectrum measurements



COBE
[Smoot++1992](#)

SASK
[Netterfield++1996](#)



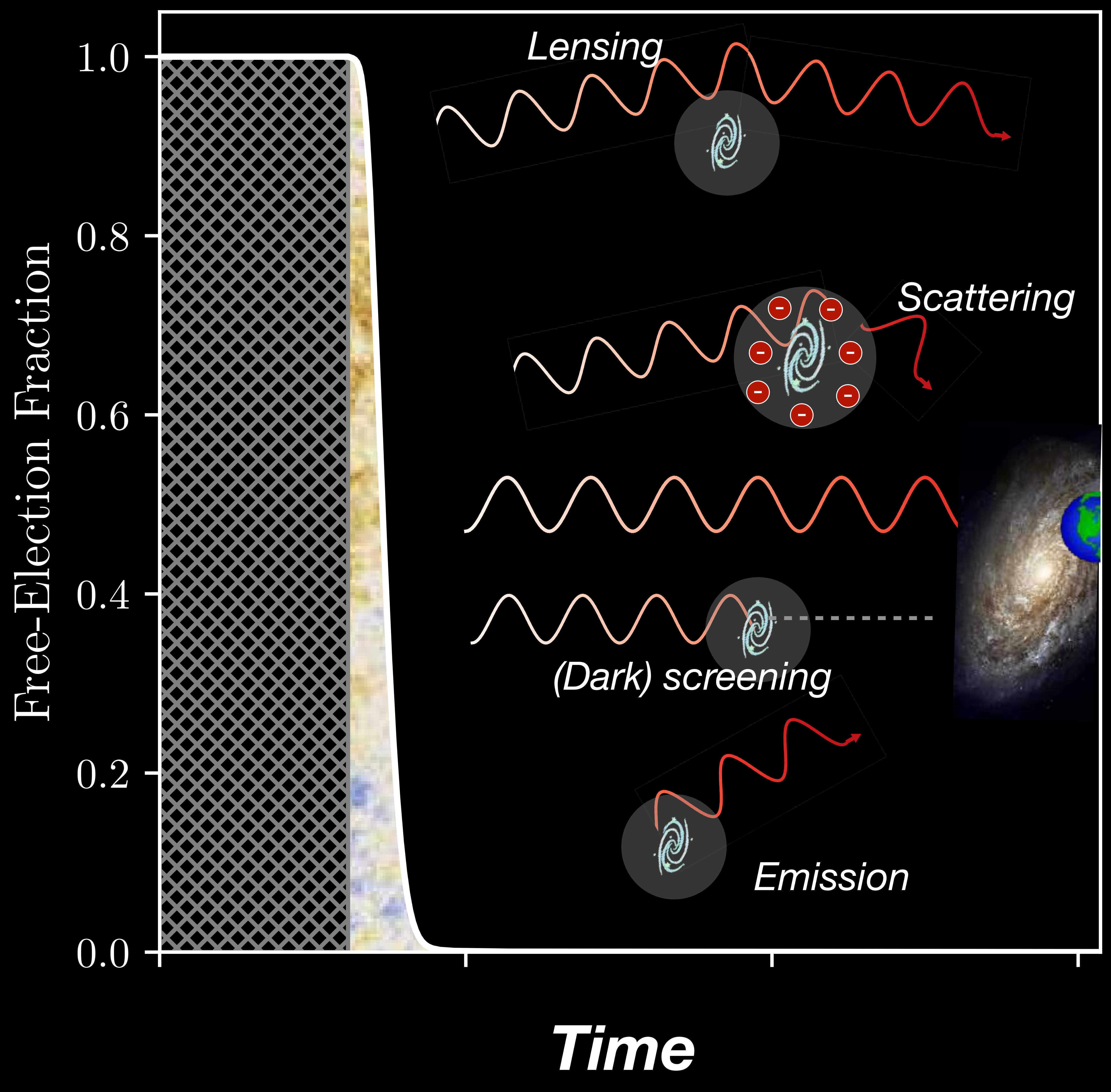
ACT DR6:
[Naess++2025](#)
[Louis++2025](#)
[Calabrese++2025](#)

SPT 3G:
[Camphuis++2025](#)

CMB Secondary Anisotropies

- *Secondary anisotropies:* modifications as photons propagate after last scattering

- **Powerful*:*** contain valuable information
  - **Cosmology**: new large-scale structure (LSS) tracers
  - **Astrophysics**: unique sensitivity to baryons
- **Challenging*:*** difficult to isolate/separate



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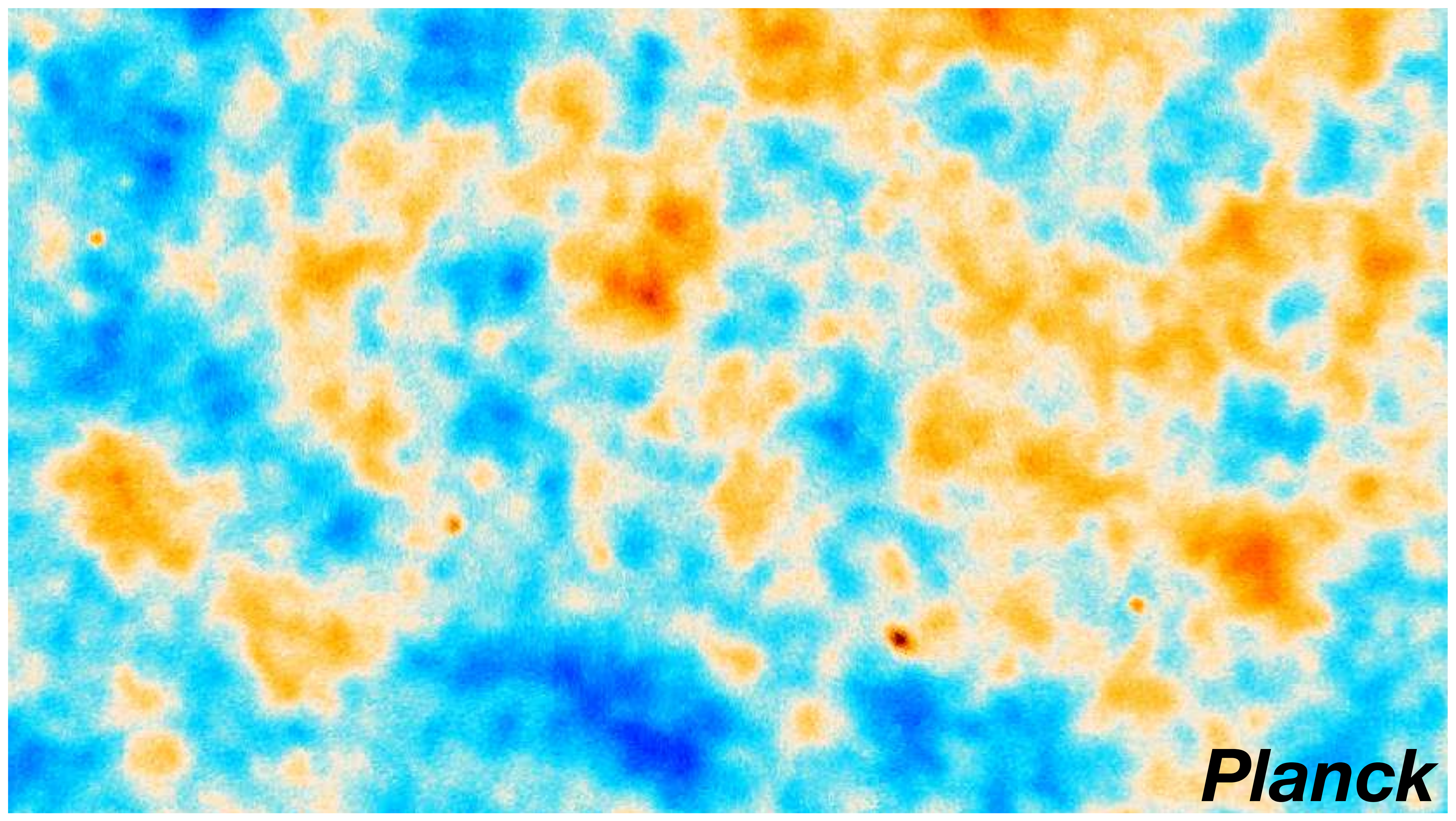
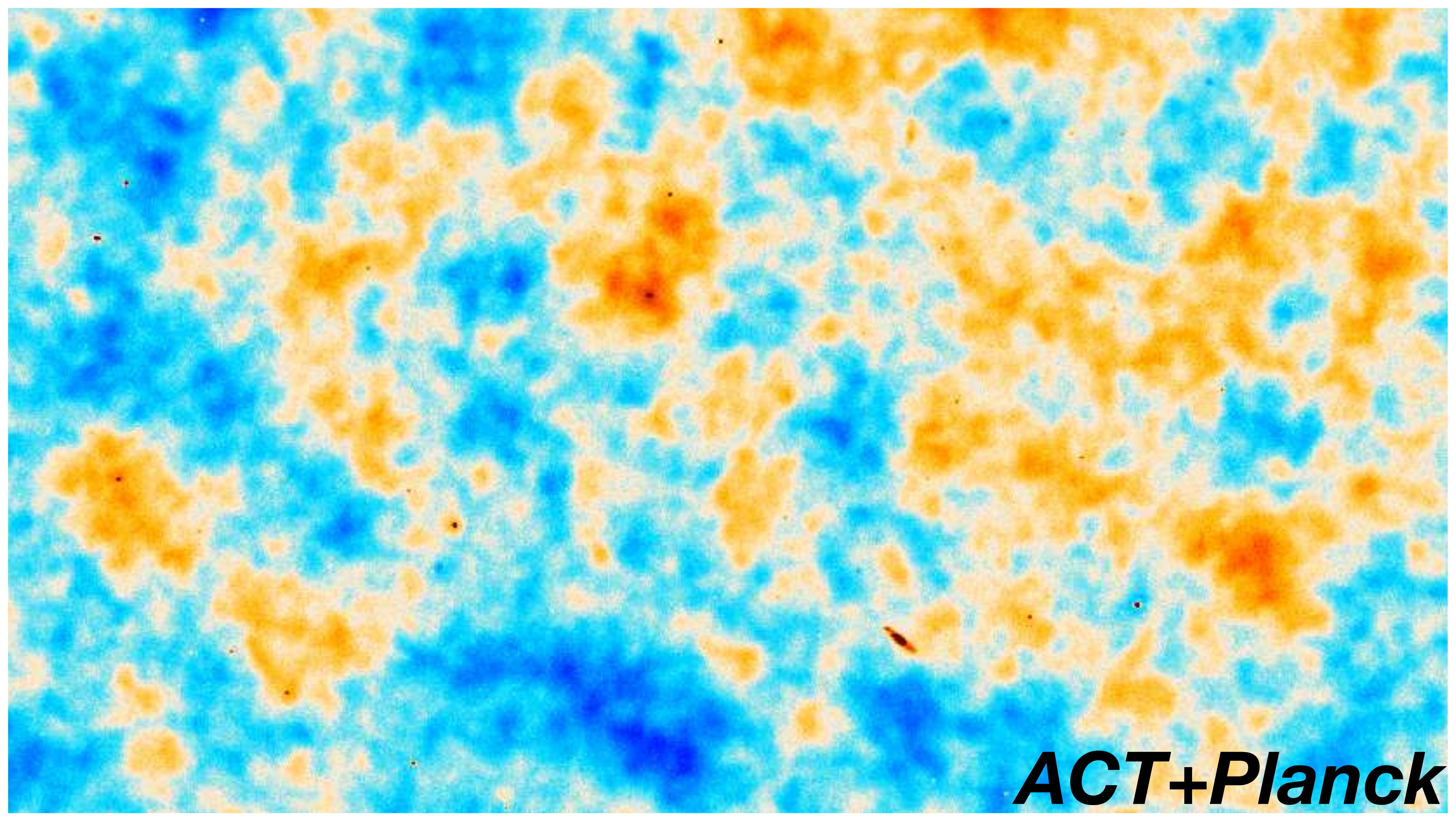
We are entering an exciting era for CMB secondaries with ACT, SPT, SO!





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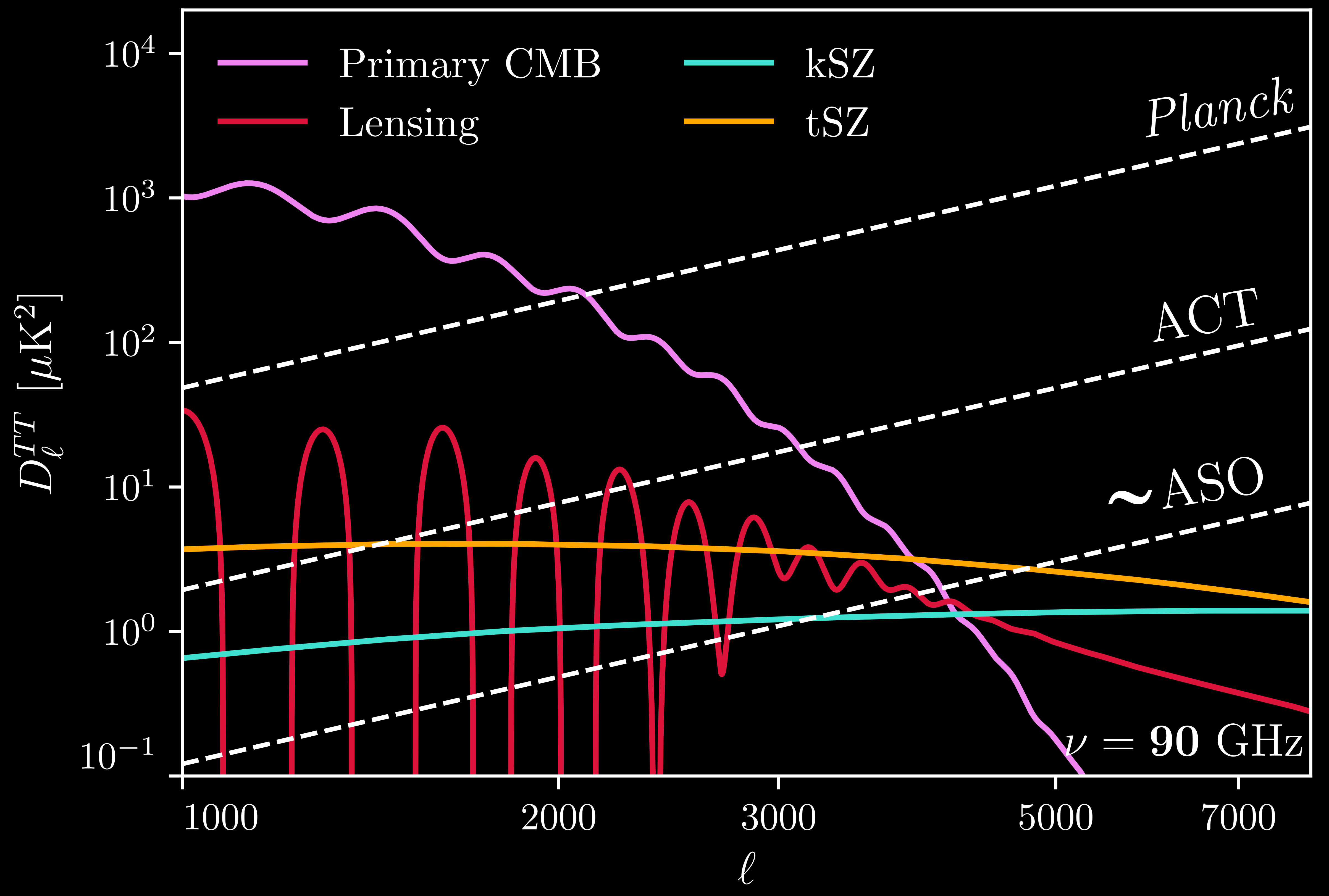


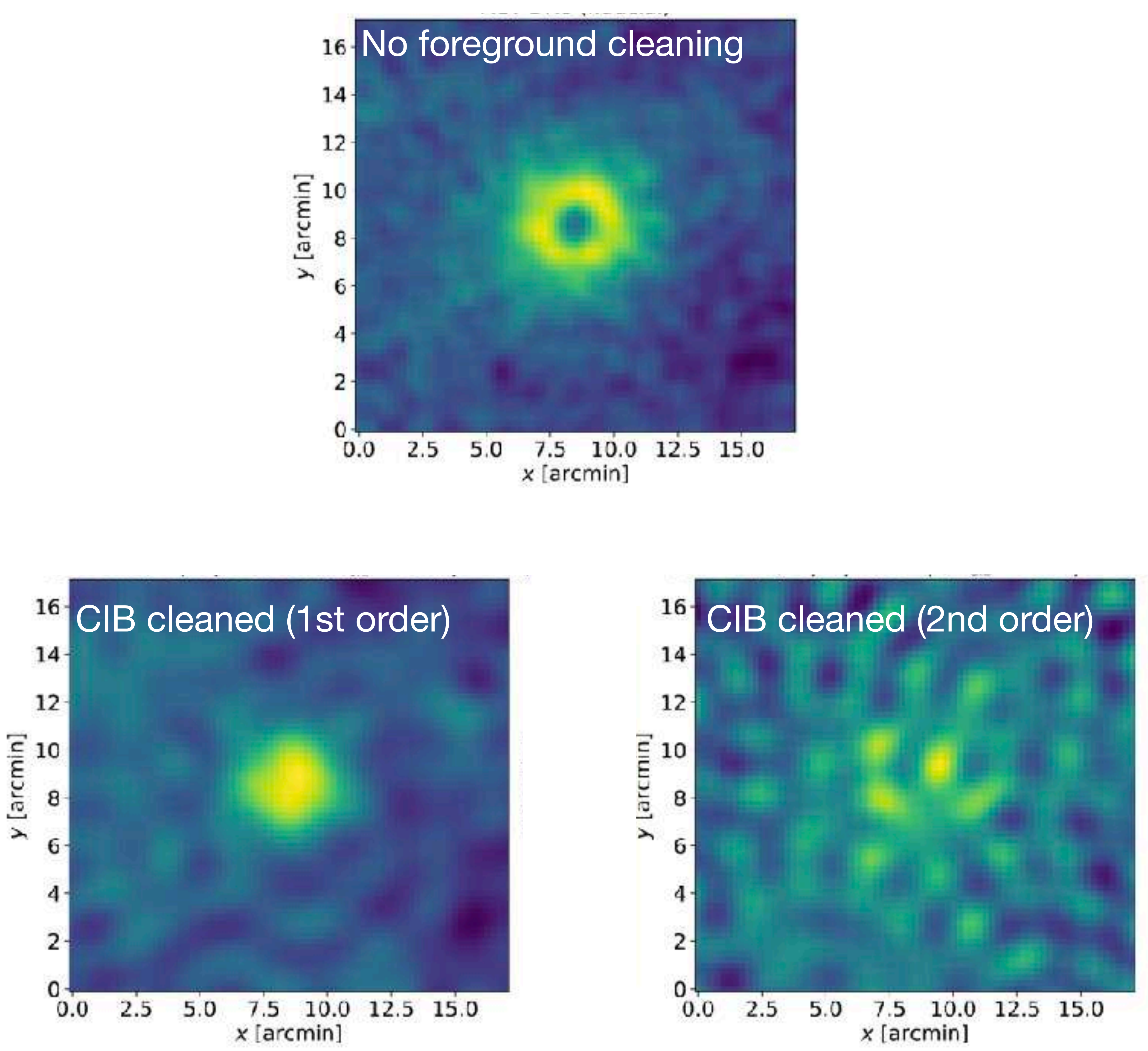
Qualitative illustration of near-term sensitivity to CMB secondaries.

A familar example: the thermal Sunyaev—Zel'dovich (tSZ) effect

- ***tSZ:*** *CMB photons inverse-Compton scatter off hot electrons*

$$y(\hat{\mathbf{n}}) = \frac{\sigma_T}{m_e c^2} \int dl\, P_e(l)$$

- ***In theory:*** *powerful probe*
  - *Cosmology:* cluster abundance/σ_8
  - *Baryons:* gas thermodynamics/feedback
- ***In practice:*** *challenging*
  - *Measurements*: foregrounds, esp. cosmic infrared background (CIB)
  - *Modeling*: uncertain galaxy-halo connection

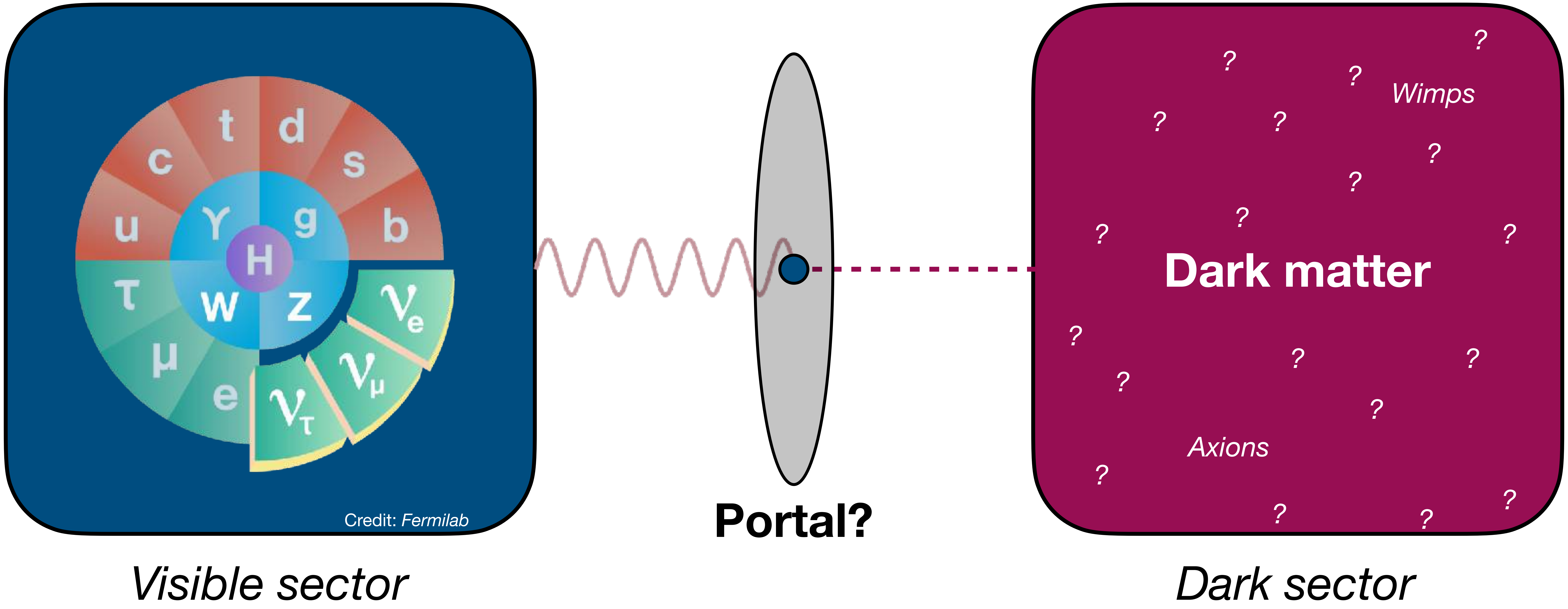


Stacking Planck+ACT on DESI galaxies: *CIB biases the tSZ signal. Removing it degrades S/N (from Liu++2025)*

A new secondary? Patchy dark screening

The dark sector

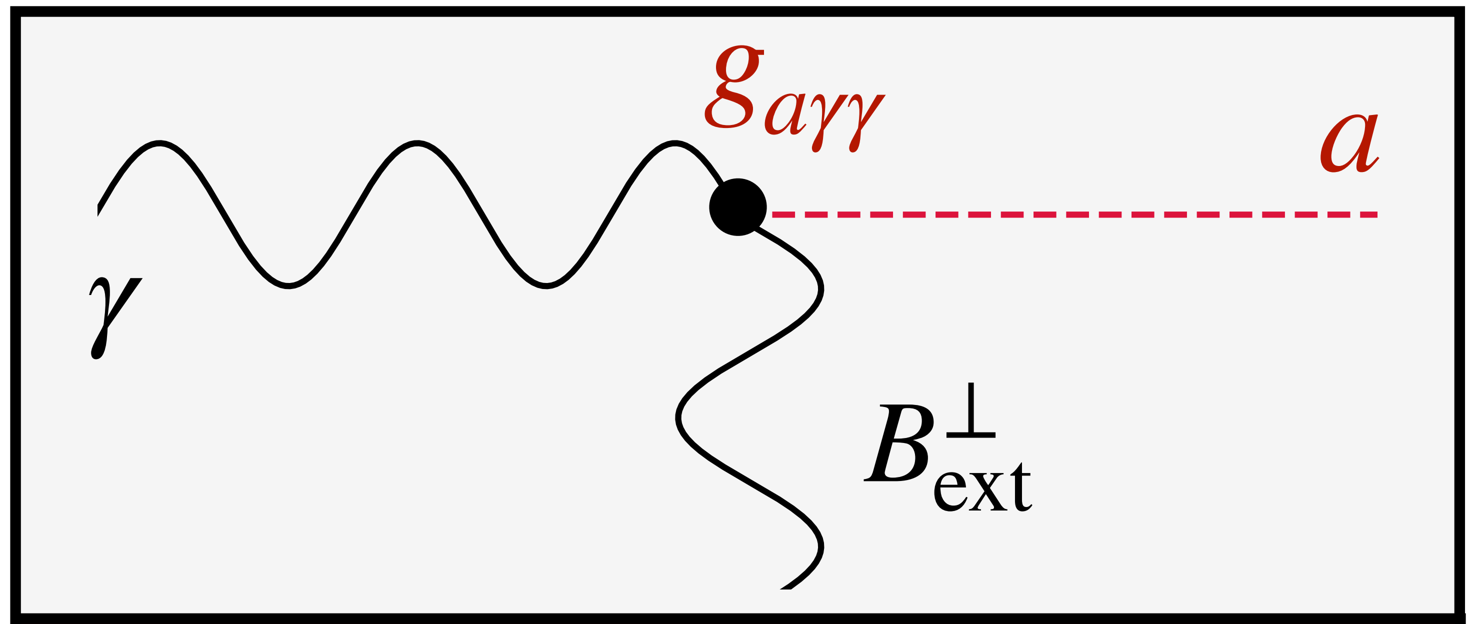
- **Dark matter** and dark energy provide significant motivation to search for beyond standard model (BSM) fields



The dark sector

- What can the CMB photons interact with?
  - *(Pseudo)-scalar portal:* **axion***(-like particles)*

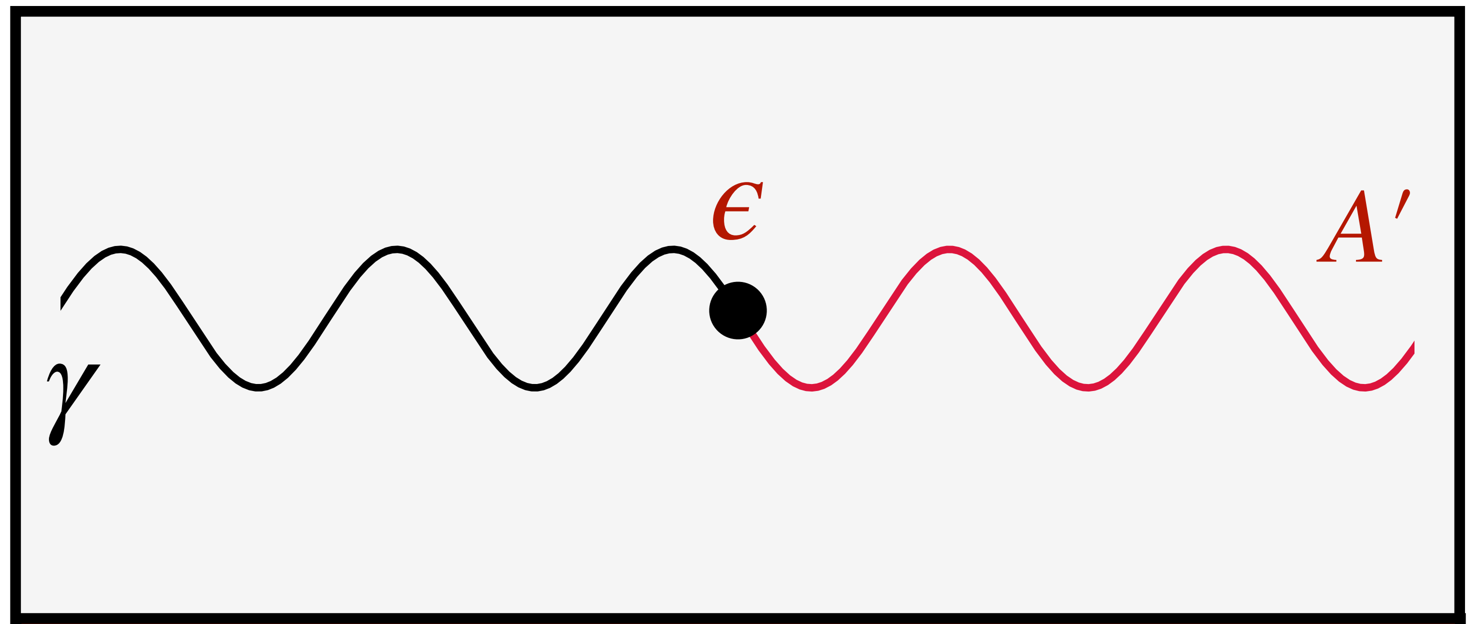
$$\mathscr{L} \supset -\frac{1}{2}\partial_\mu a\, \partial^\mu a - \frac{1}{2}{m_a}^2\, a^2 - \frac{1}{4} g_{a\gamma\gamma} a F_{\mu\nu}\tilde{F}^{\mu\nu} \longrightarrow$$



Photon-axion oscillations

  - *Vector portal:* **dark photons**

$$\mathscr{L} \supset -\frac{1}{4}F'_{\mu\nu}F'^{\mu\nu} - \frac{1}{2}{m_{\rm DP}}^2 A'_\mu A'^\mu - \frac{\epsilon}{2}F_{\mu\nu}F'^{\mu\nu} \longrightarrow$$



Dark photon kinetic mixing

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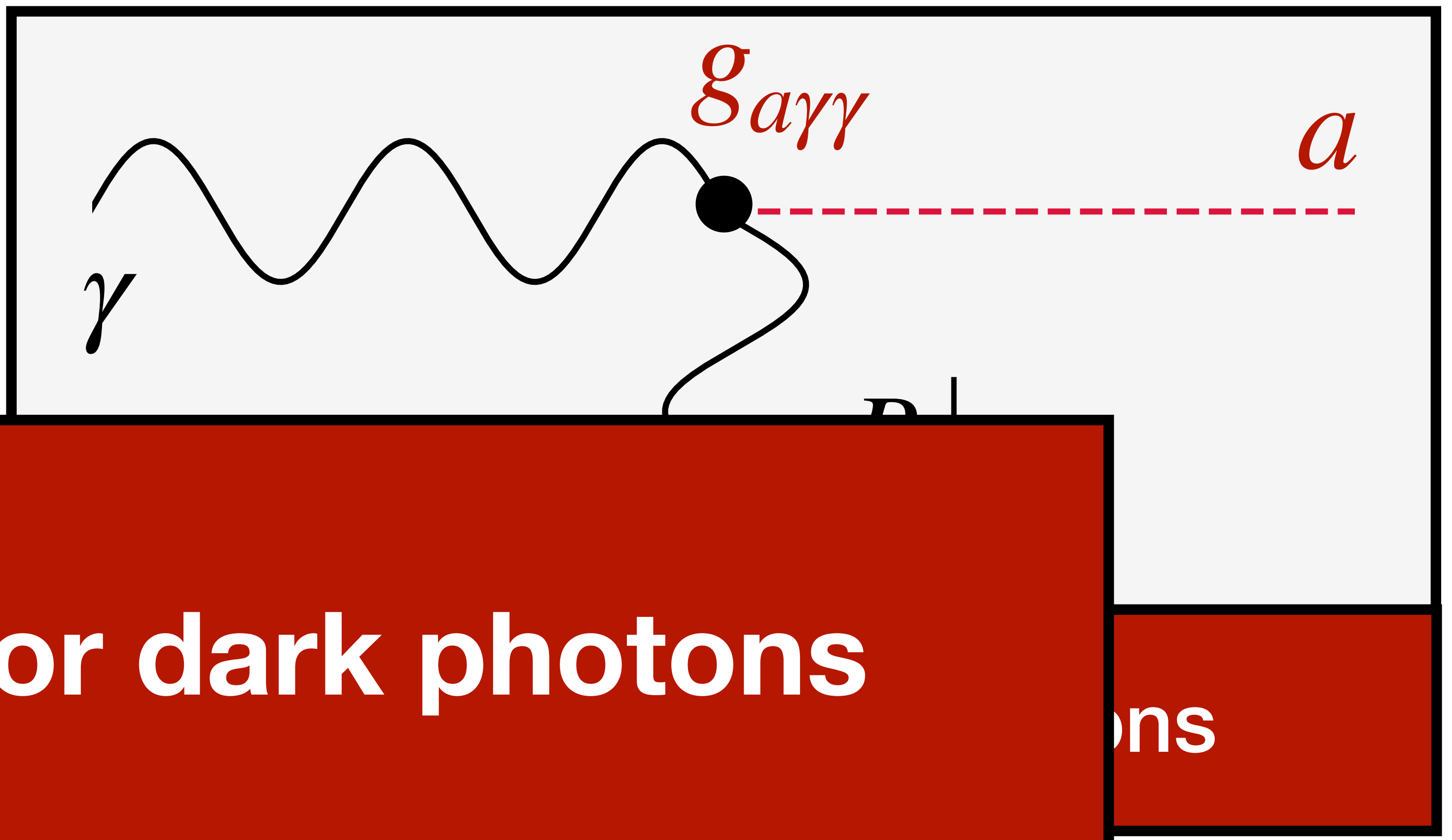

I will mostly focus on axions, but story is similar for dark photons

  - *Vector portal:* **dark photons**

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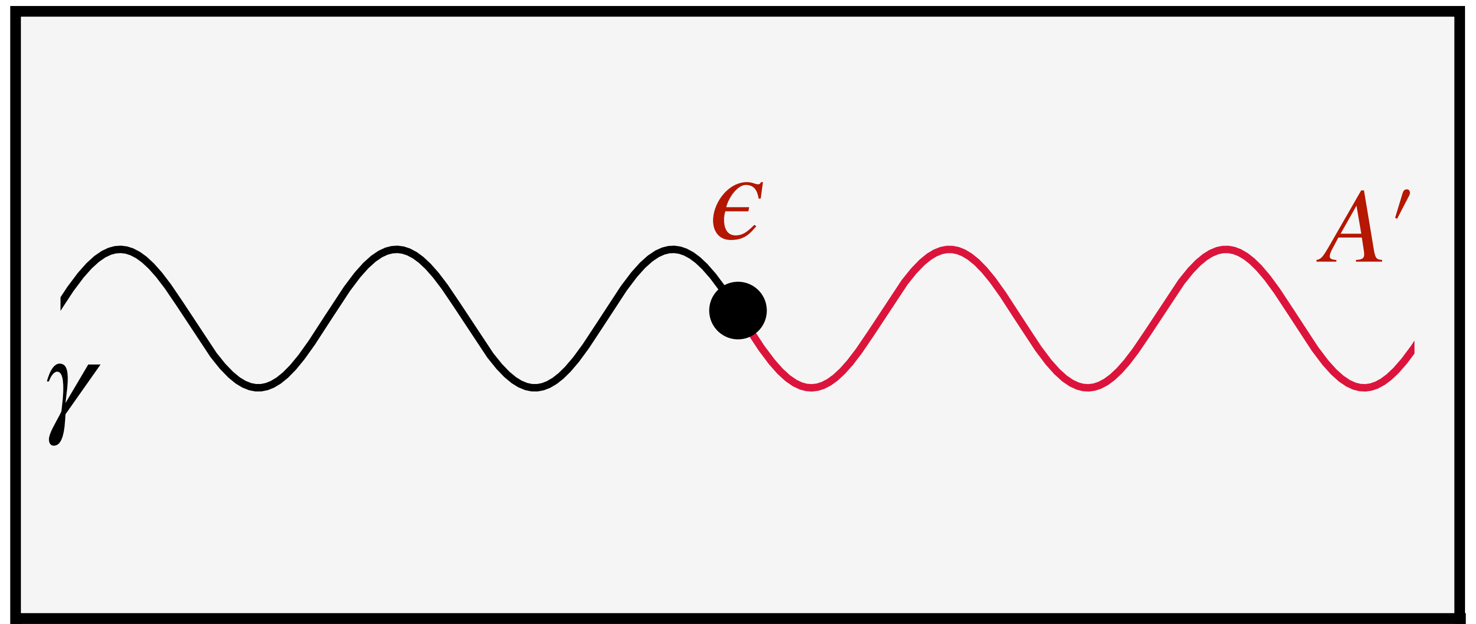
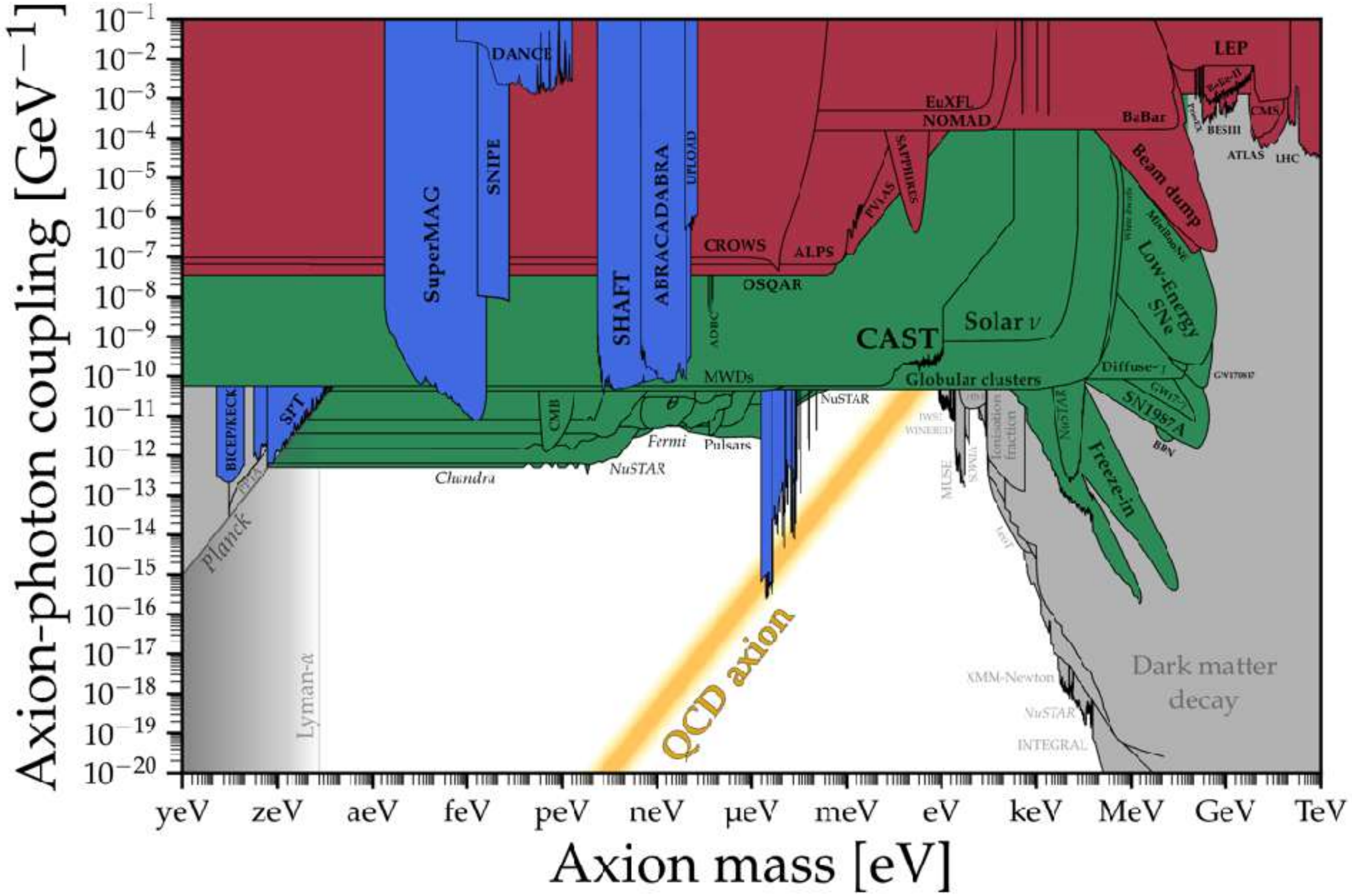


Dark photon kinetic mixing

Substantial effort devoted to axion/dark photon searches

$g_{a\gamma\gamma}$



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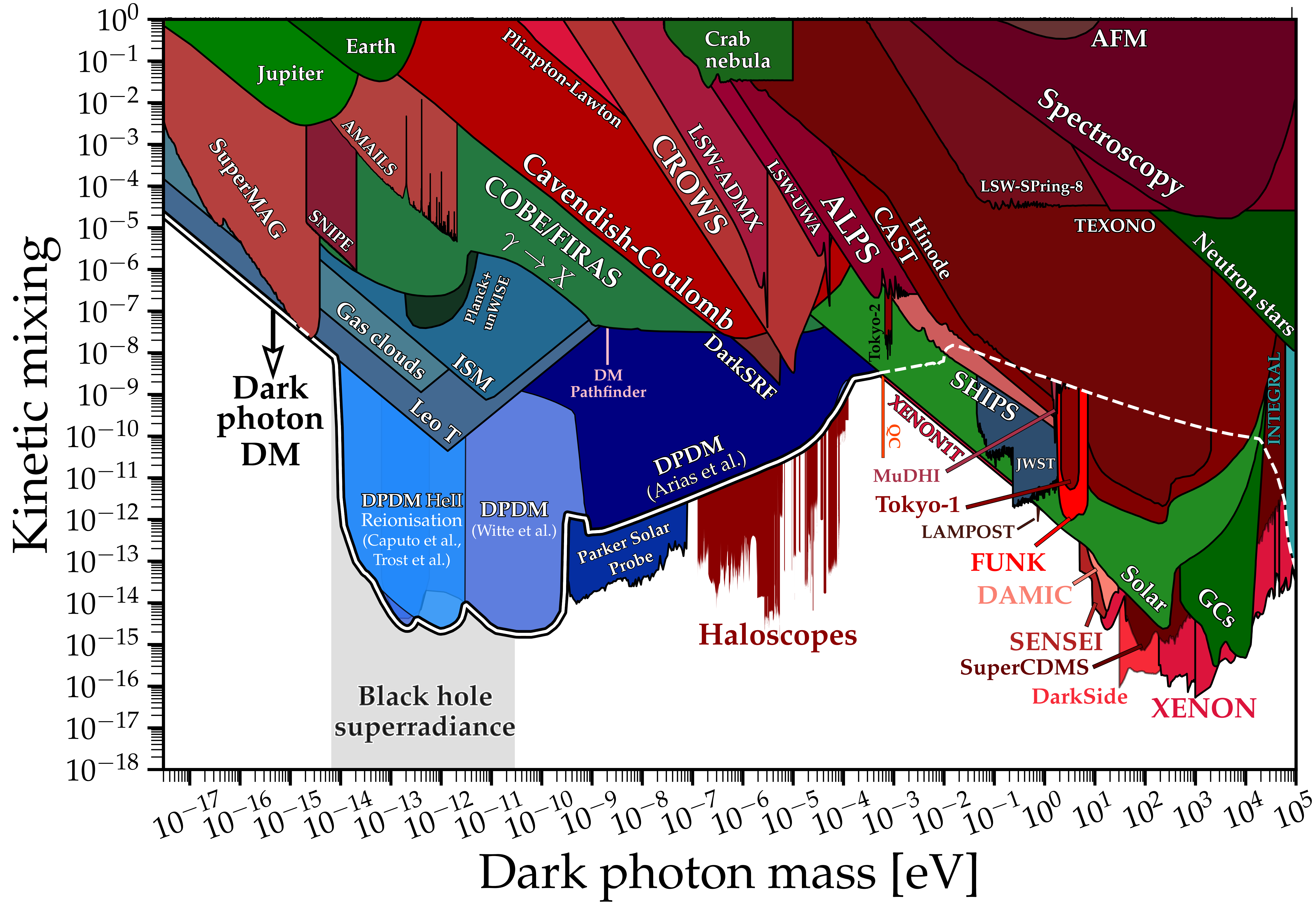


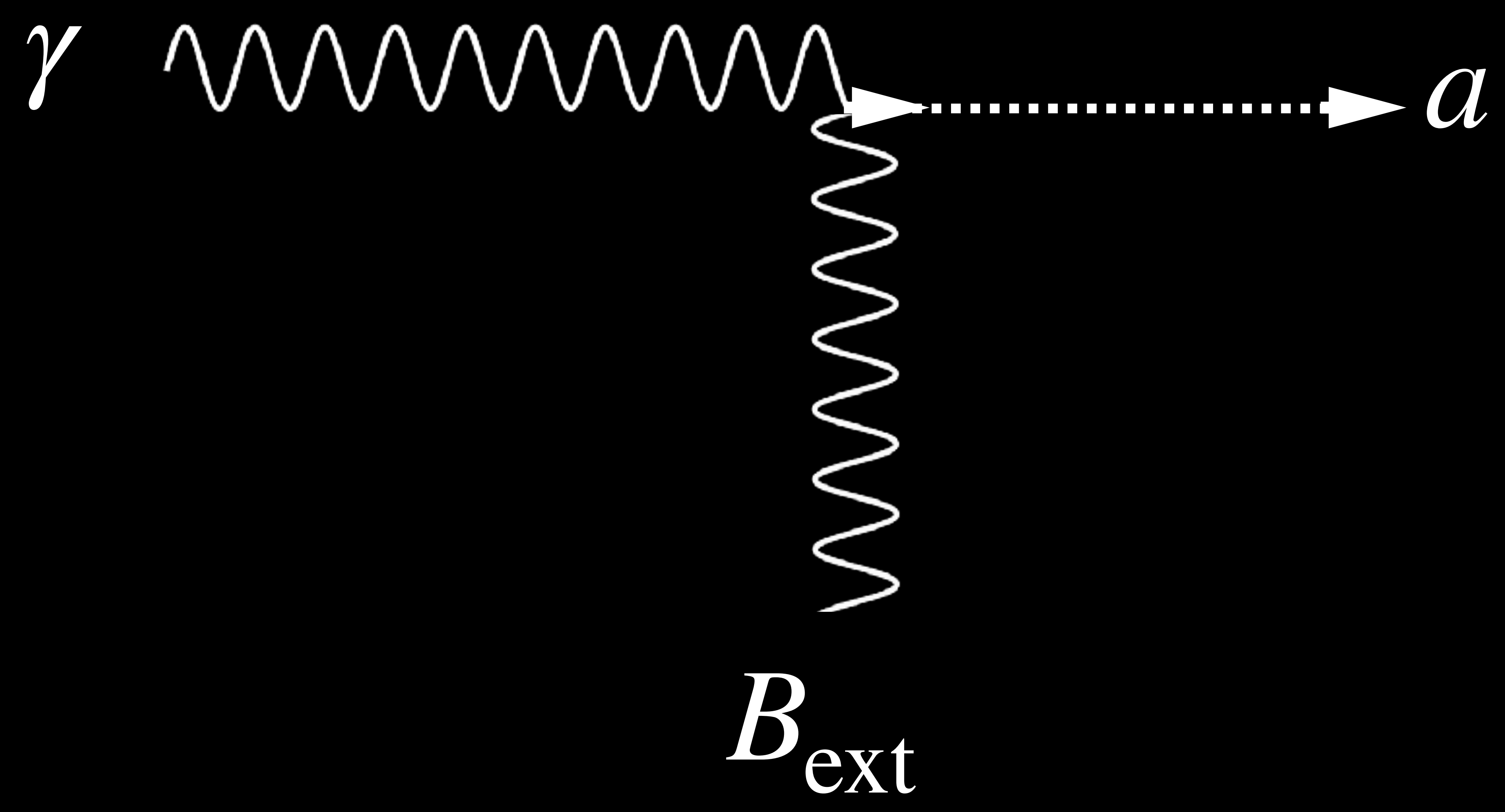
Existing constraints span wide range of masses (https://cajohare.github.io/AxionLimits/)

How to find an axion?

- Axions **modify Maxwell's equations**

$$\mathscr{L} \supset g_{a\gamma\gamma}\, a\, \mathbf{E}\cdot\mathbf{B} \implies \begin{cases} \nabla\cdot\mathbf{E} = \rho_0 + g_{a\gamma\gamma}(\nabla a)\cdot\mathbf{B} \\ \nabla\times\mathbf{B} = \partial_t\mathbf{E} + \mathbf{J} + g_{a\gamma\gamma}\left(\mathbf{B}\,\partial_t a - \mathbf{E}\times\nabla a\right) \\ \nabla\cdot\mathbf{B} = 0 \\ \nabla\times\mathbf{E} = -\,\partial_t\mathbf{B} \end{cases}$$

- Photons can convert to axions in a magnetic field



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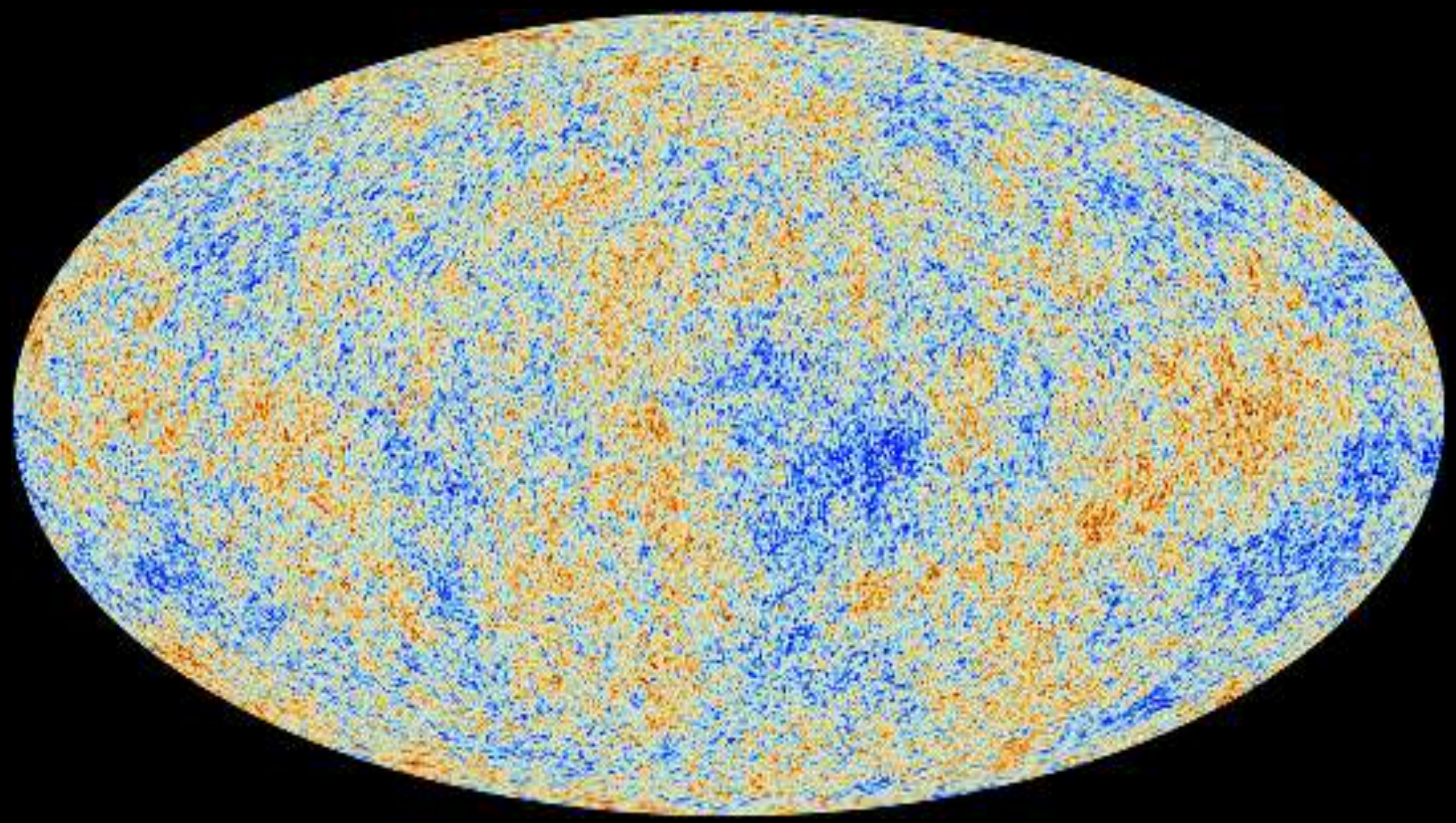
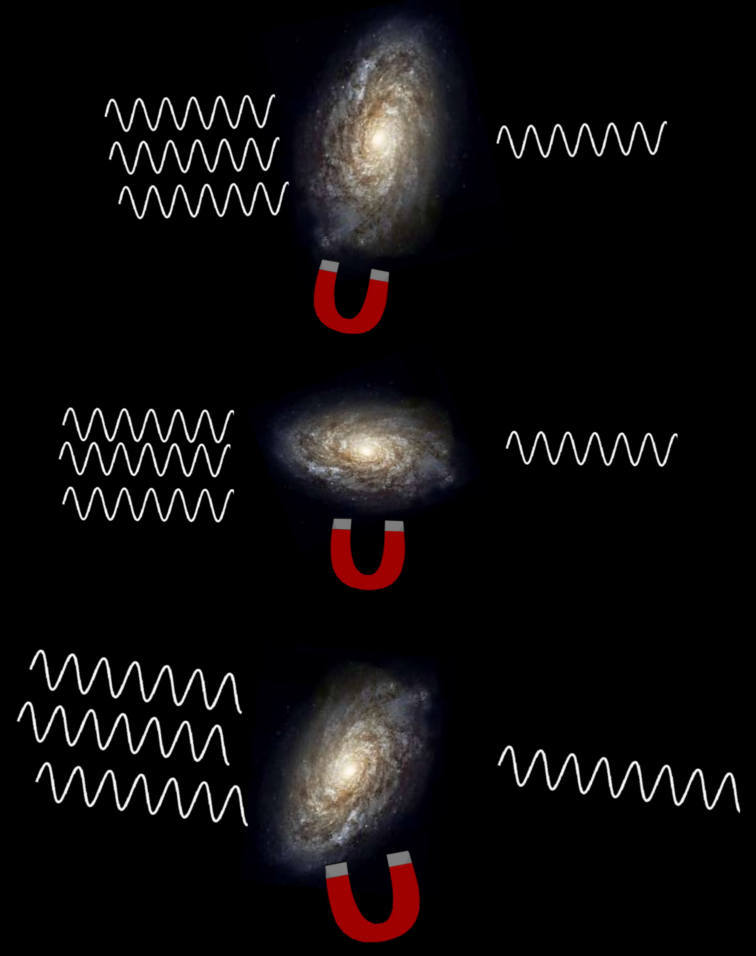
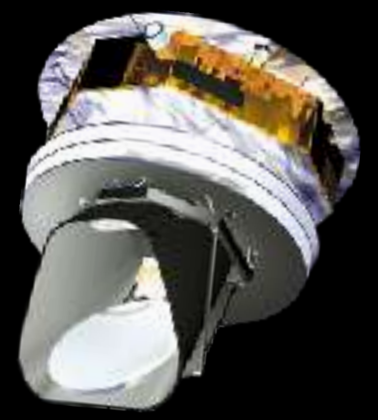


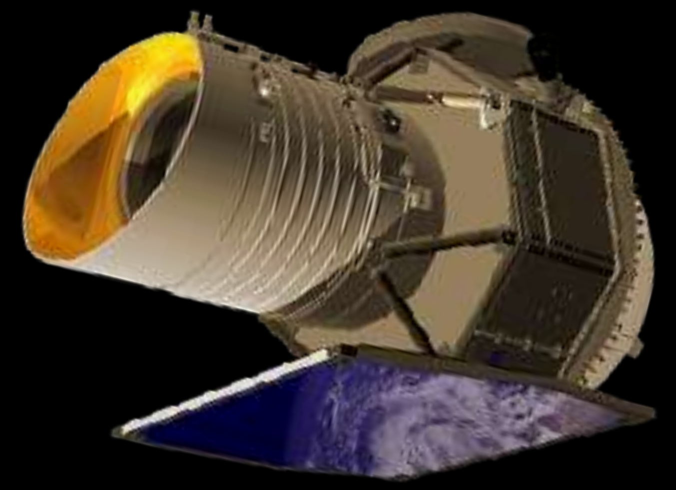
Photon source=CMB



B-field=30 million galaxies

Planck

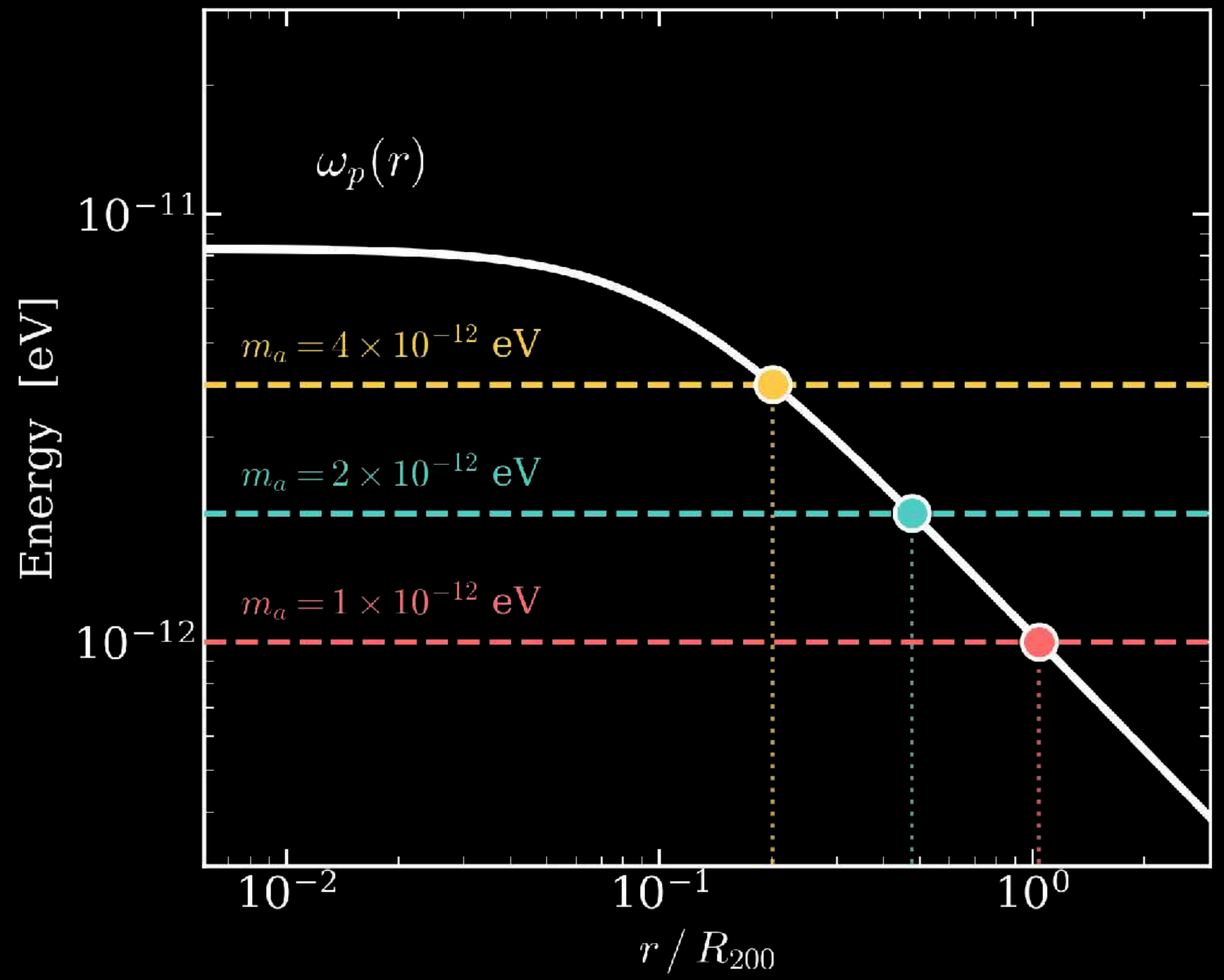


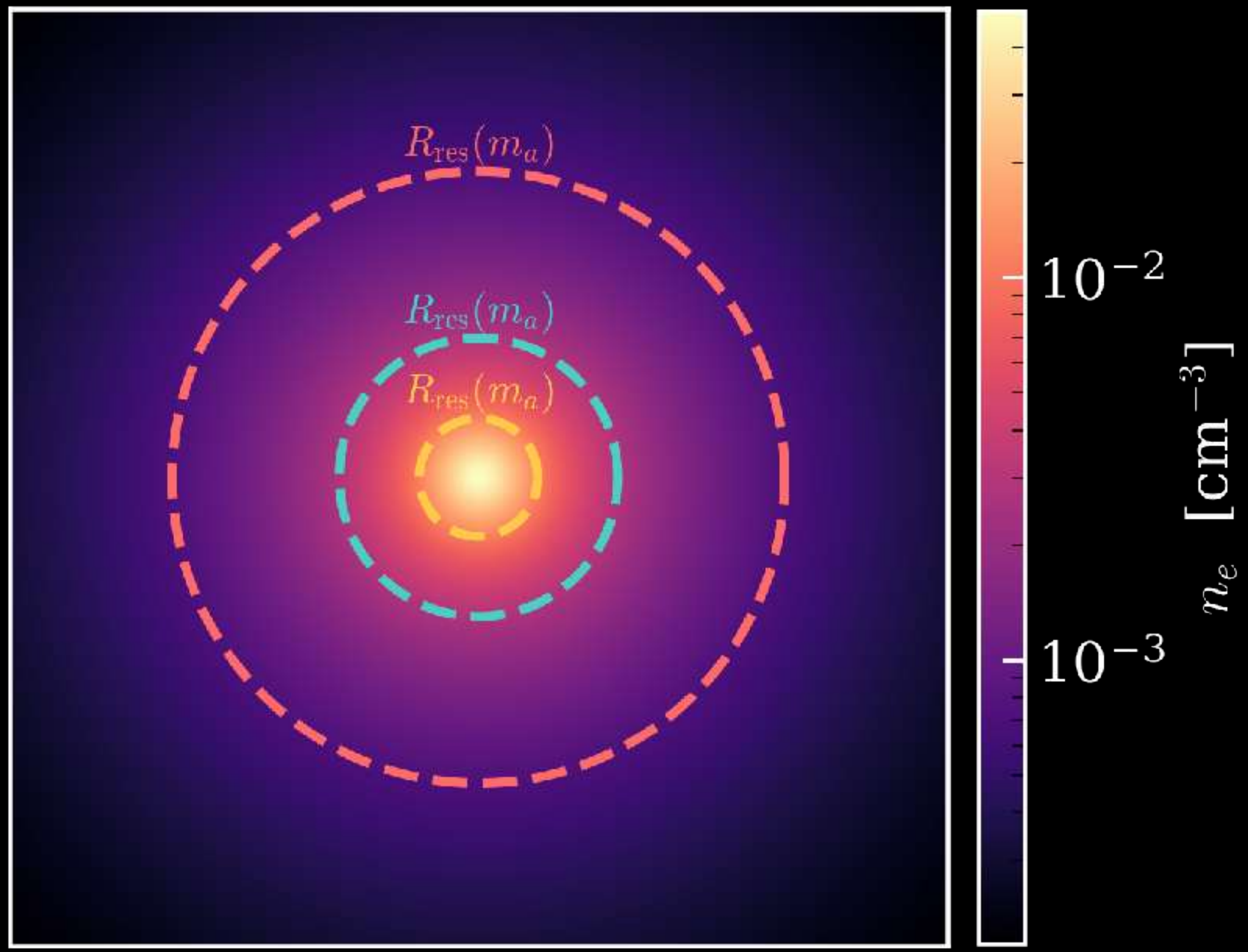


WISE

Note: we do not assume axions are dark matter

Resonant photon-axion conversion in halos





$$P^{\rm res}_{\gamma\to a}(R_{\rm res}, \nu) \propto \frac{\nu g^2_{a\gamma\gamma} |\mathbf{B}^{\rm res}_\perp|^2}{m_a^2} \left| \frac{d \ln n_e}{dr} \right|^{-1}_{R_{\rm res}}$$

Conversion prob. given by Landau-Zener

Parke++1986 , Mirizzi++2009, Tashiro++2013, Pîrvu++2023, Mondino++2024

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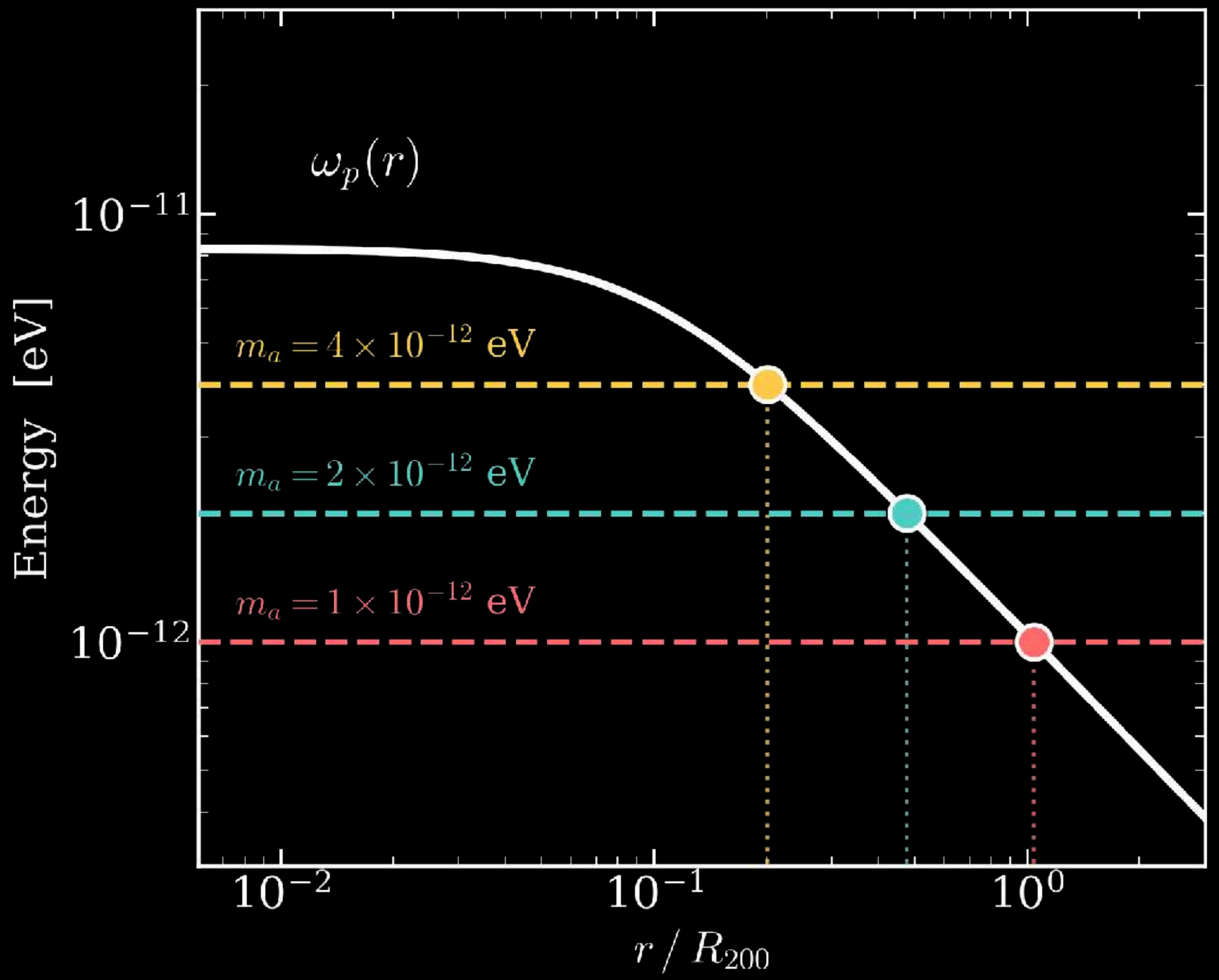

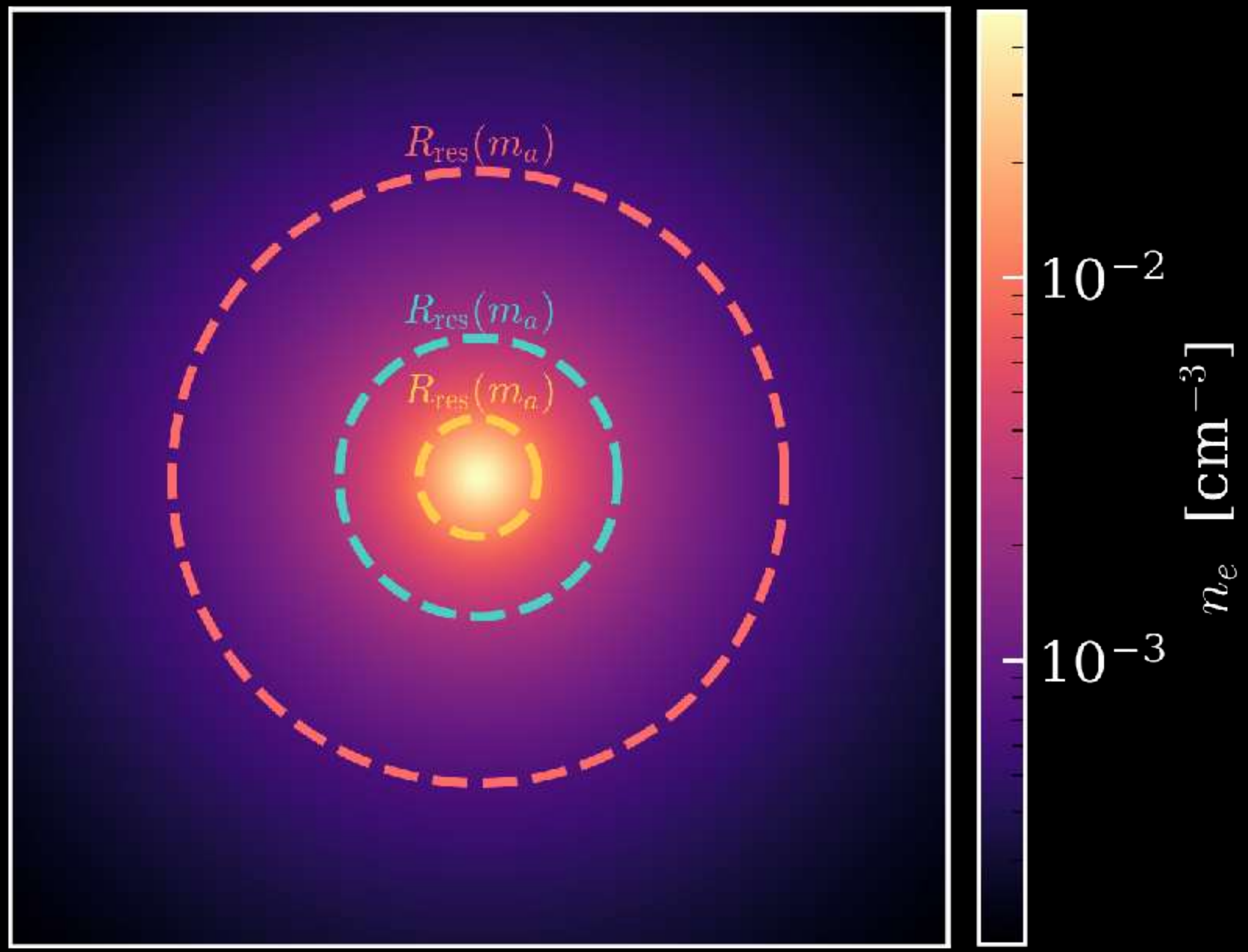

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The dark-screening optical depth

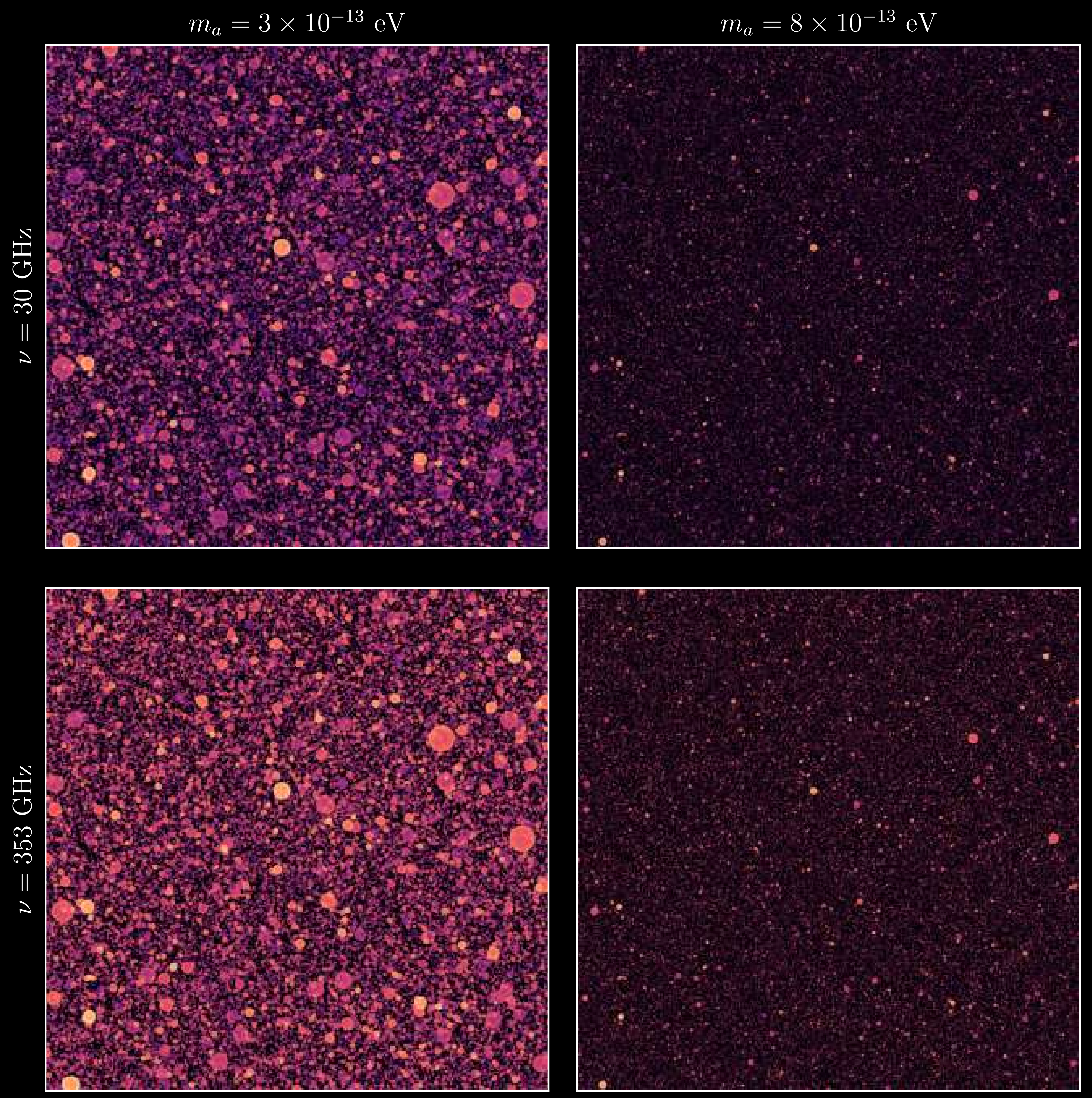
- CMB is “screened” by dark sector conversions -> described by optical depth

$$\frac{\Delta T}{T_{\rm CMB}}(\hat{\mathbf{n}},\nu) \equiv -\tau_a(\hat{\mathbf{n}},\nu) \propto \sum_{\text{halos along } \hat{\mathbf{n}}} P^{\rm res}_{\gamma\to a}(\hat{\mathbf{n}},\nu)$$

- Two keys for isolating this signal

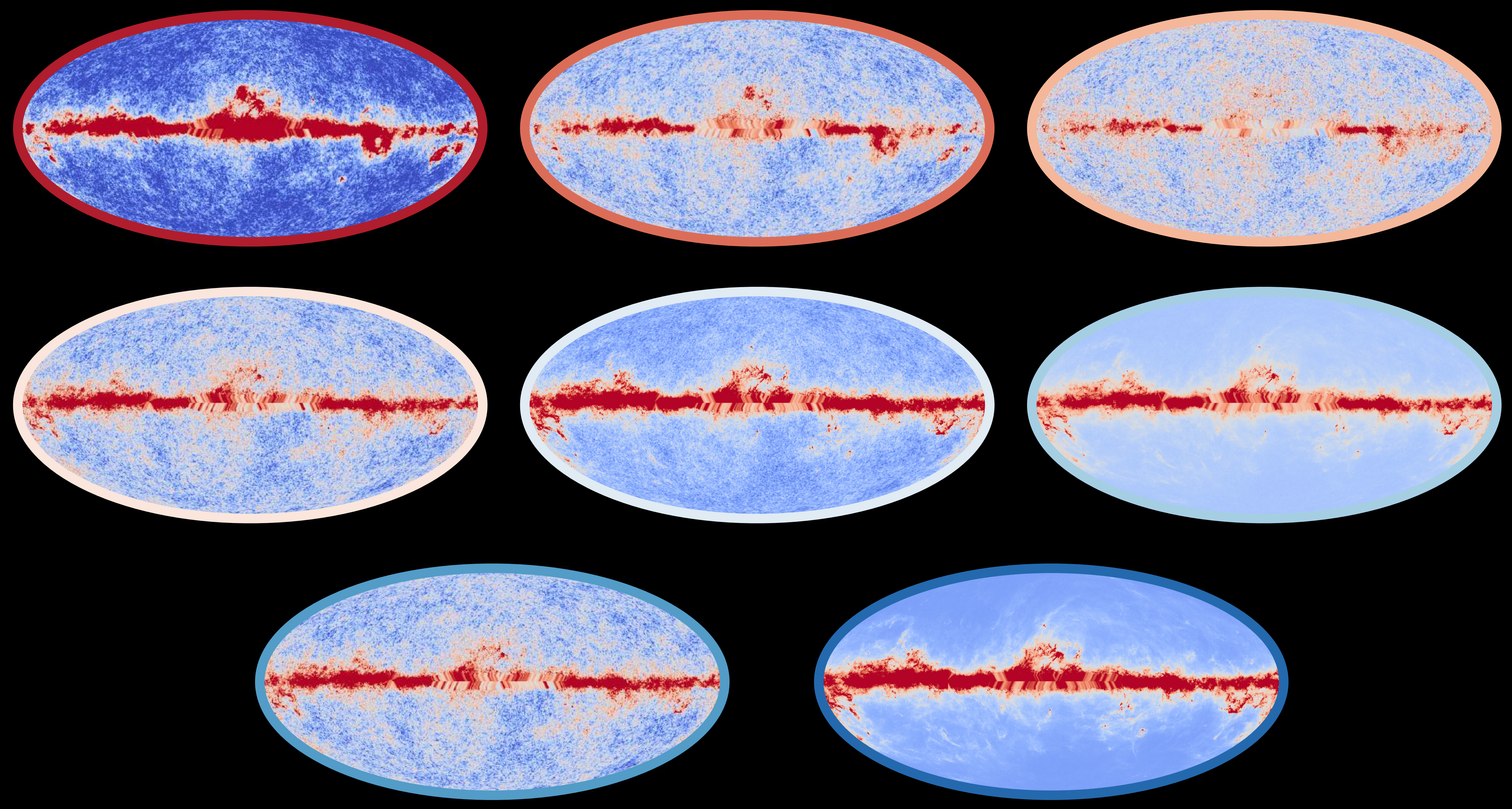
  1. ***Spectral info:*** screening has non-thermal frequency dependence

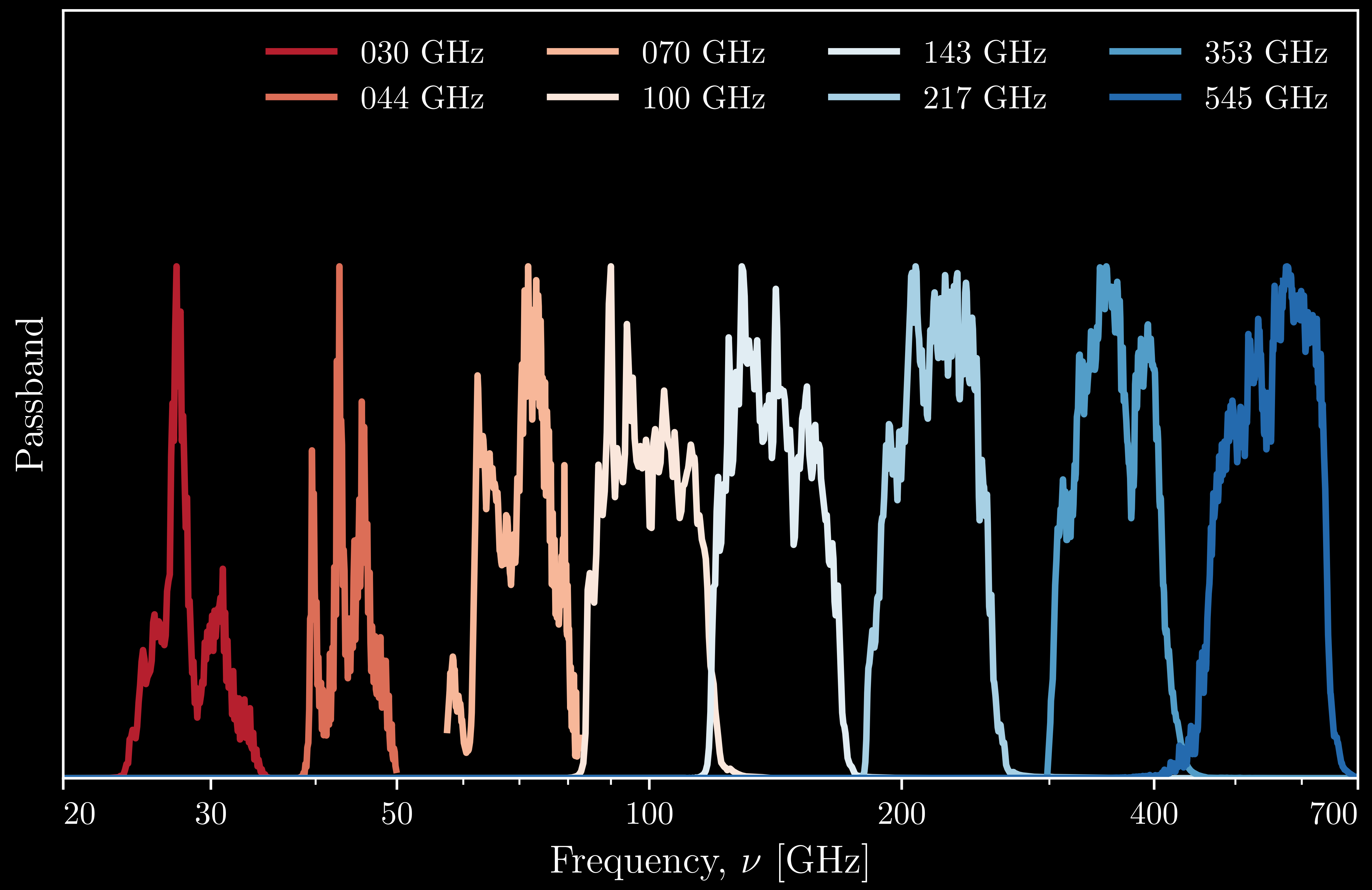
  2. ***Spatial info:*** screening traces large-scale structure



Qualitative illustration of dark screening

Isolating CMB secondaries with multi-frequency data

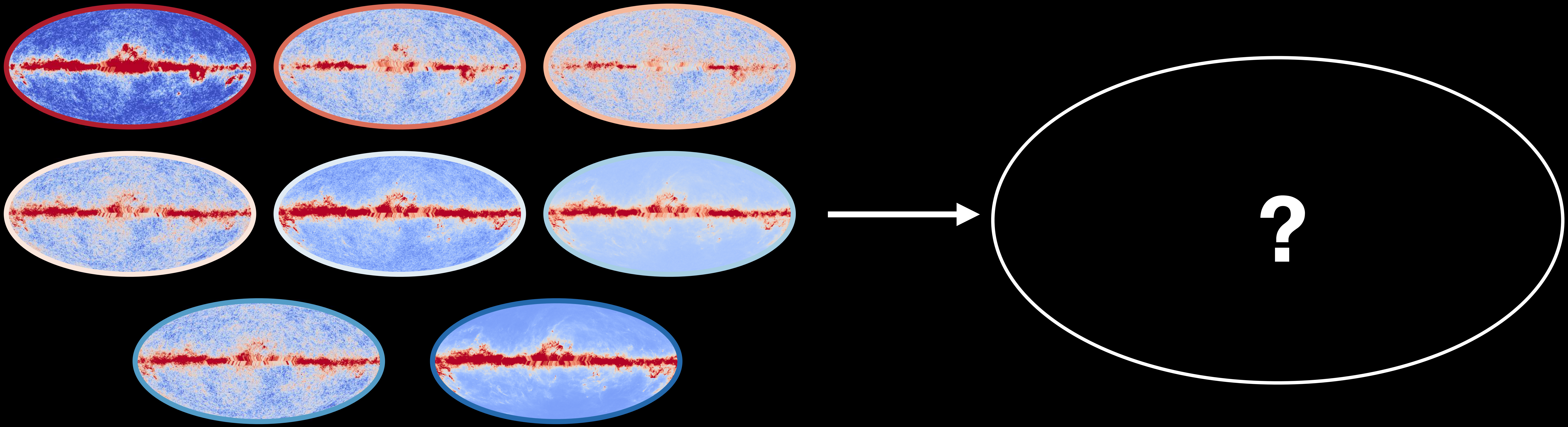




Can we combine multi-frequency “CMB” maps into a single map containing the CMB secondary of interest (axions) and suppressing other contributions?

Planck PR4 NPIPE maps ([Planck Collaboration, 2020])

Isolating CMB secondaries with multi-frequency data



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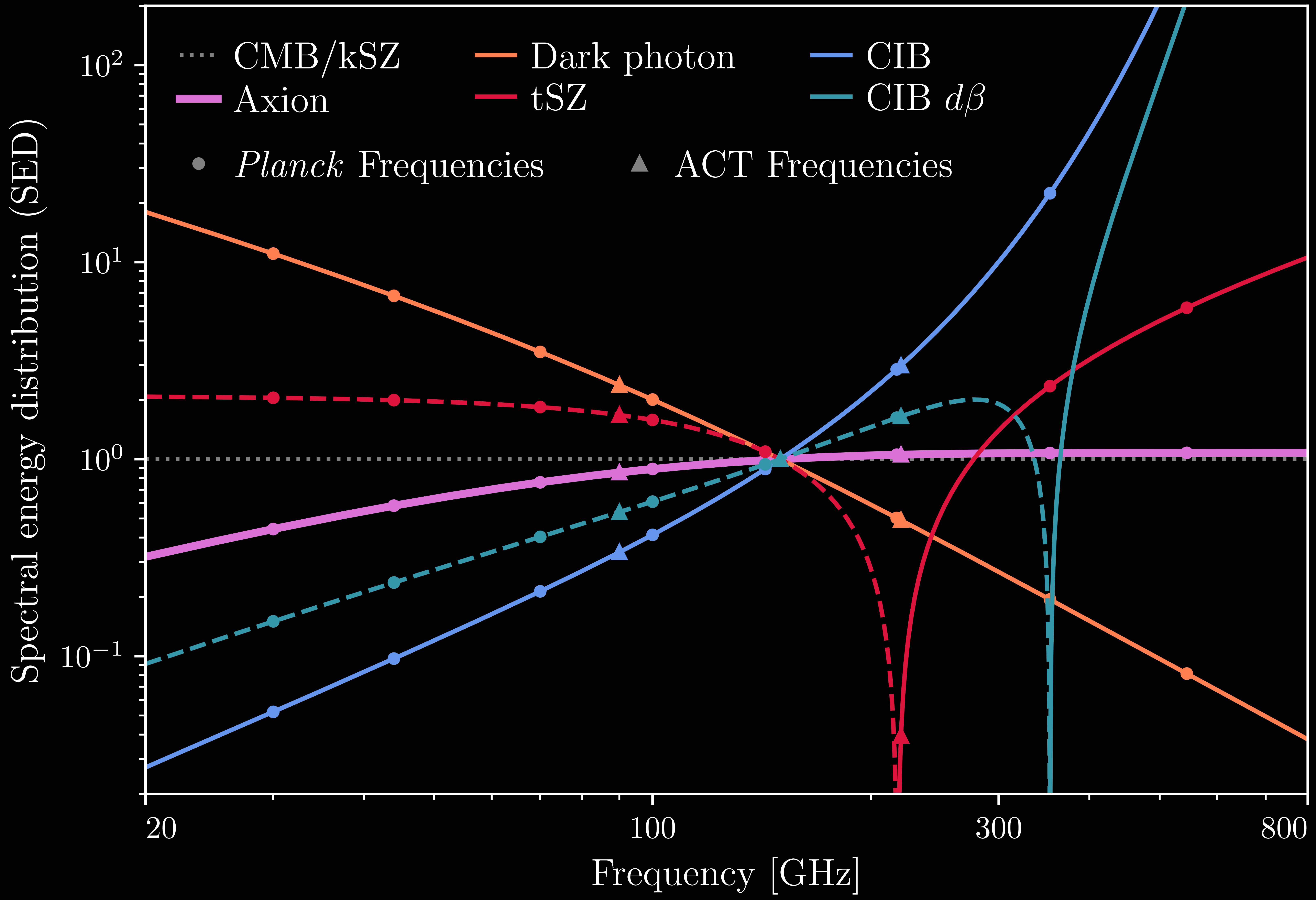
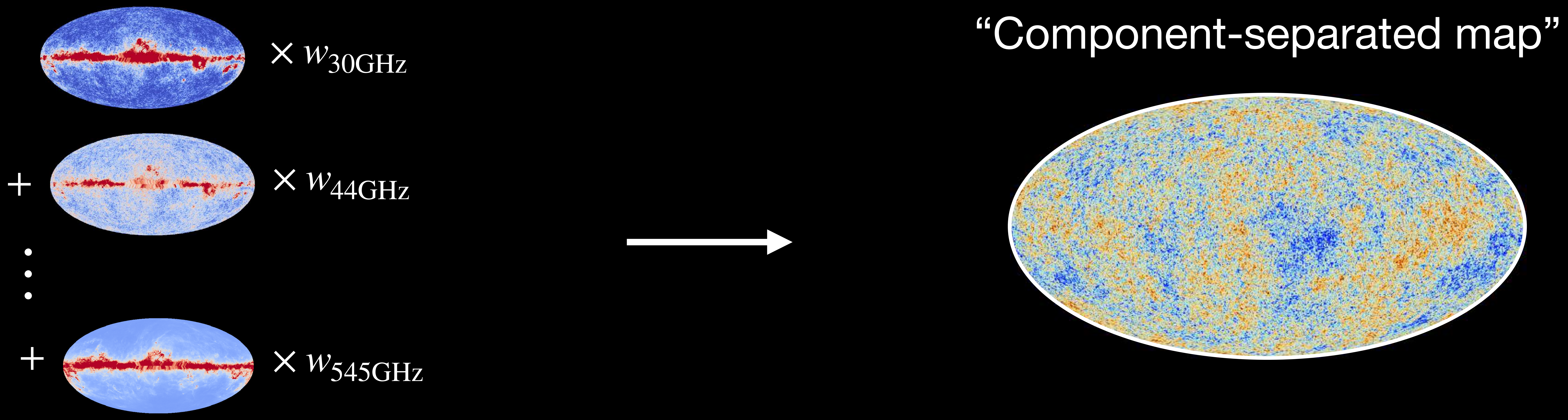
Planck PR4 NPIPE maps (Planck Collaboration, 2020)



Yes, because the axion signal has a characteristic frequency dependence!

Internal linear combination (ILC) approach

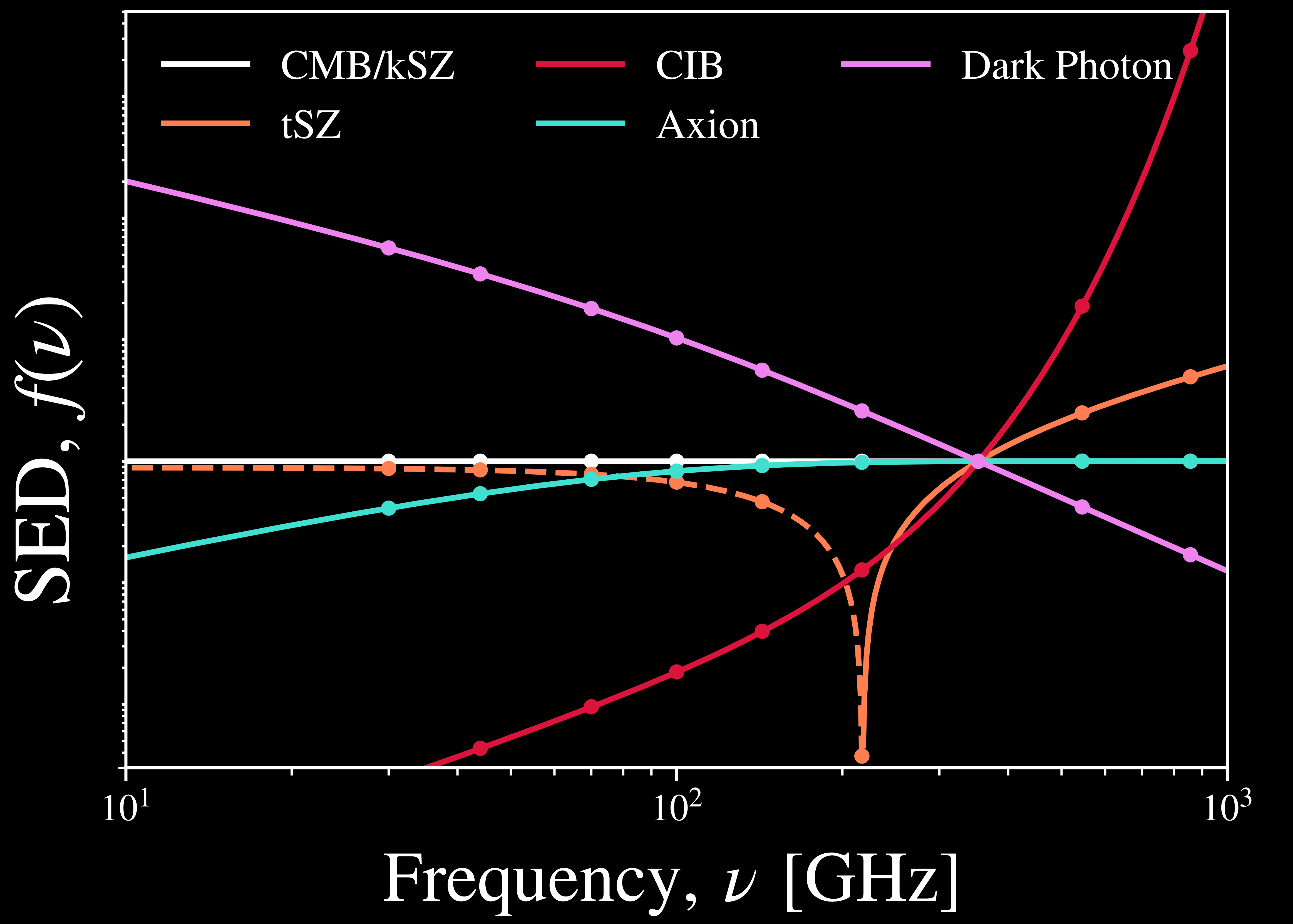


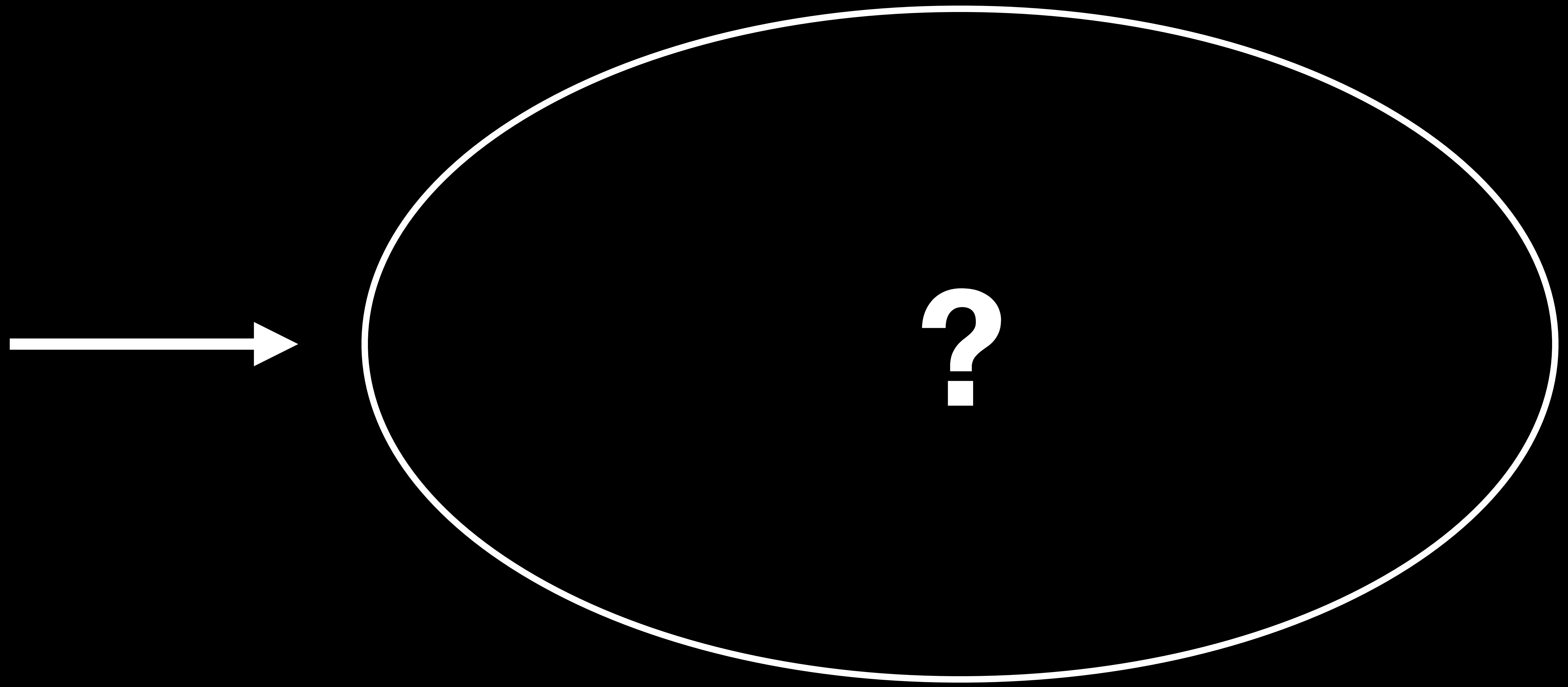
- *Minimum-variance linear combination, subject to unit response to the SED of interest*

$$\text{Minimize } \; w^T \boldsymbol{C} w \text{ s.t. } \; w^T a = 1 \implies w = \boldsymbol{C}^{-1} a / (a^T \boldsymbol{C}^{-1} a)$$ ***Bennett++03***

- ***Blind:*** *need only SED you want, not a foreground model*
- ***Internal:*** *covariance estimated from data*
- ***Needlets:*** *weights vary with position and multipole (**Delabrouille++08**)*

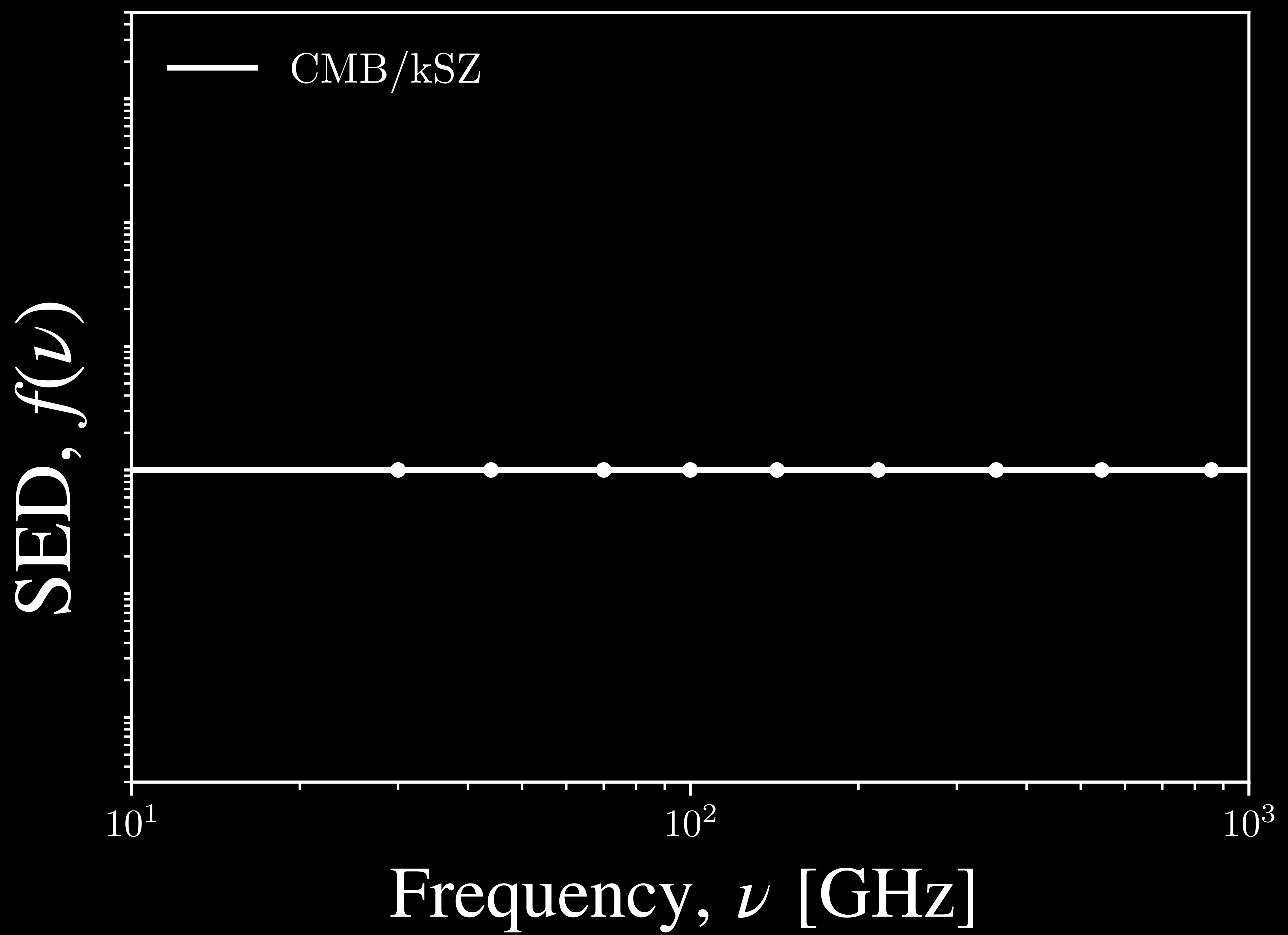
Some example ILC maps

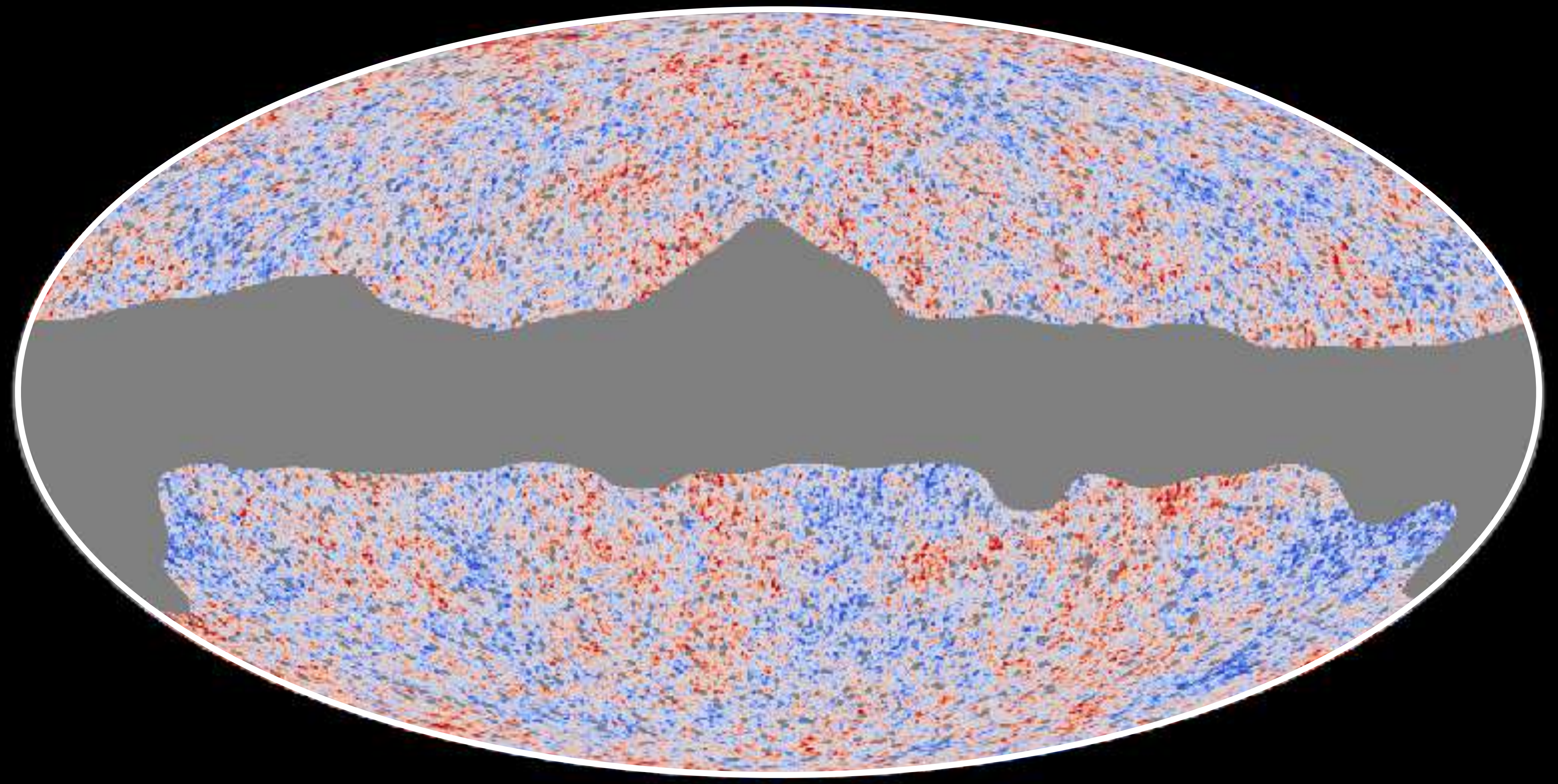




*For the *Planck* analysis, *we use pyilc* implementation (McCarthy & Hill, 2023)

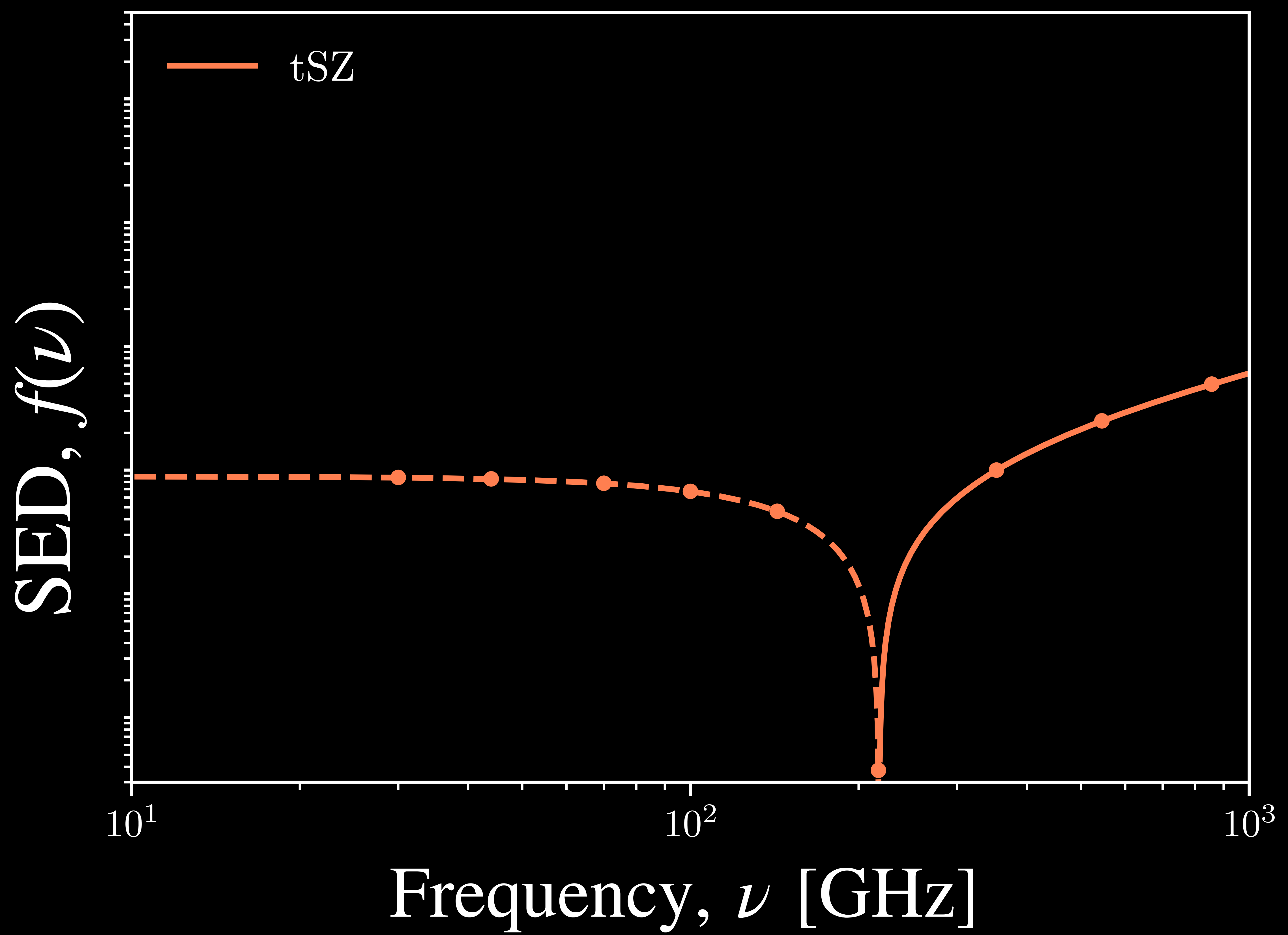
Some example ILC maps

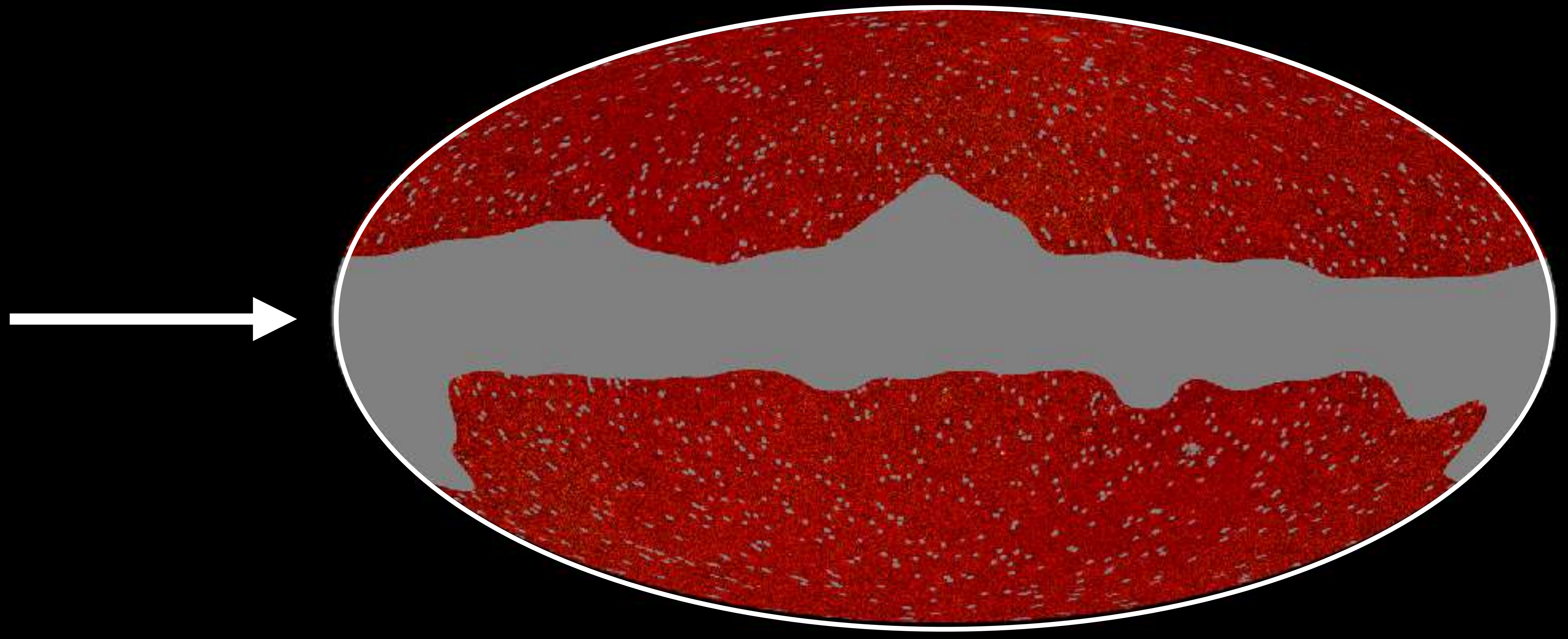




Blackbody T: CMB+kSZ

Some example ILC maps

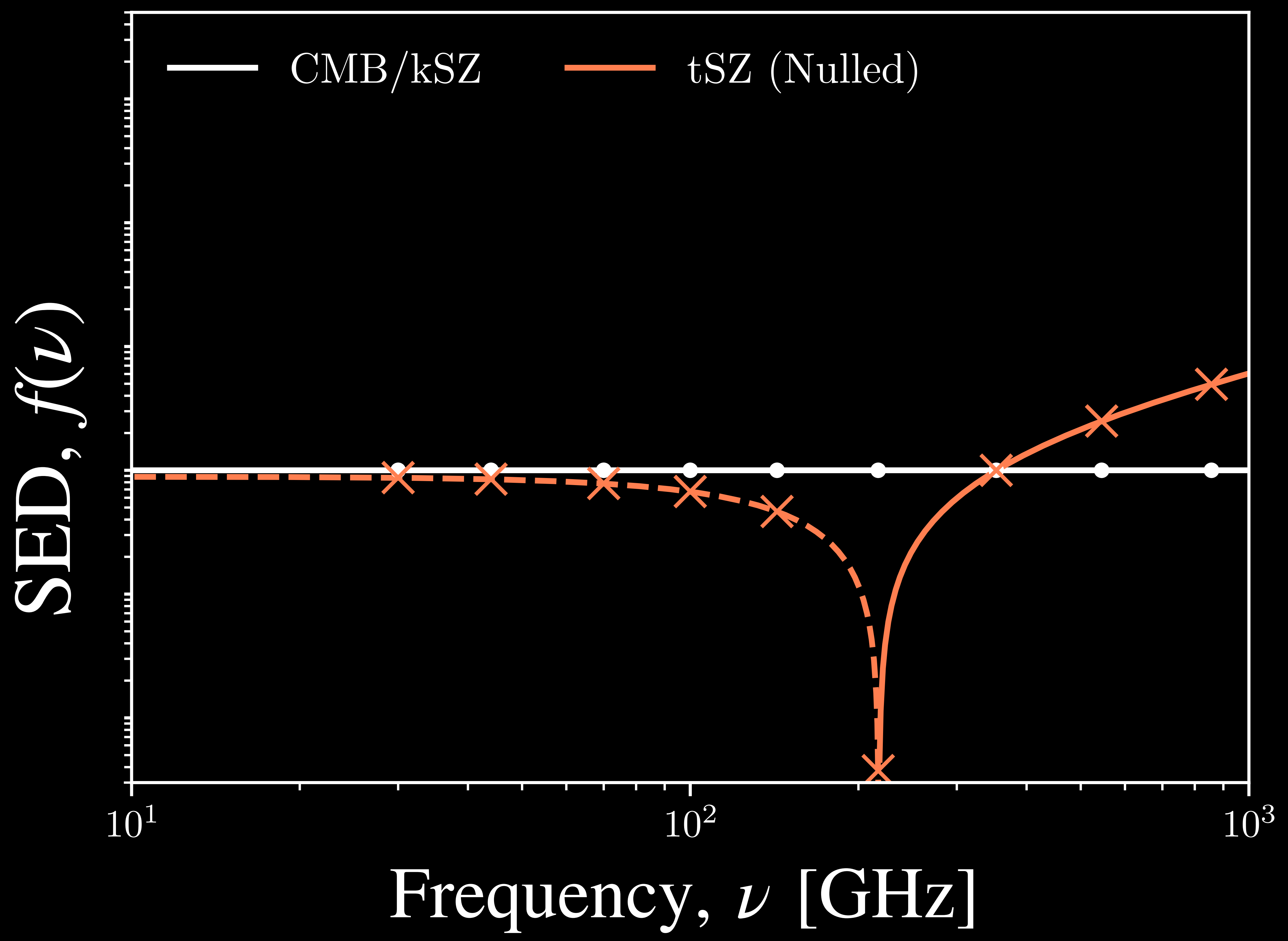


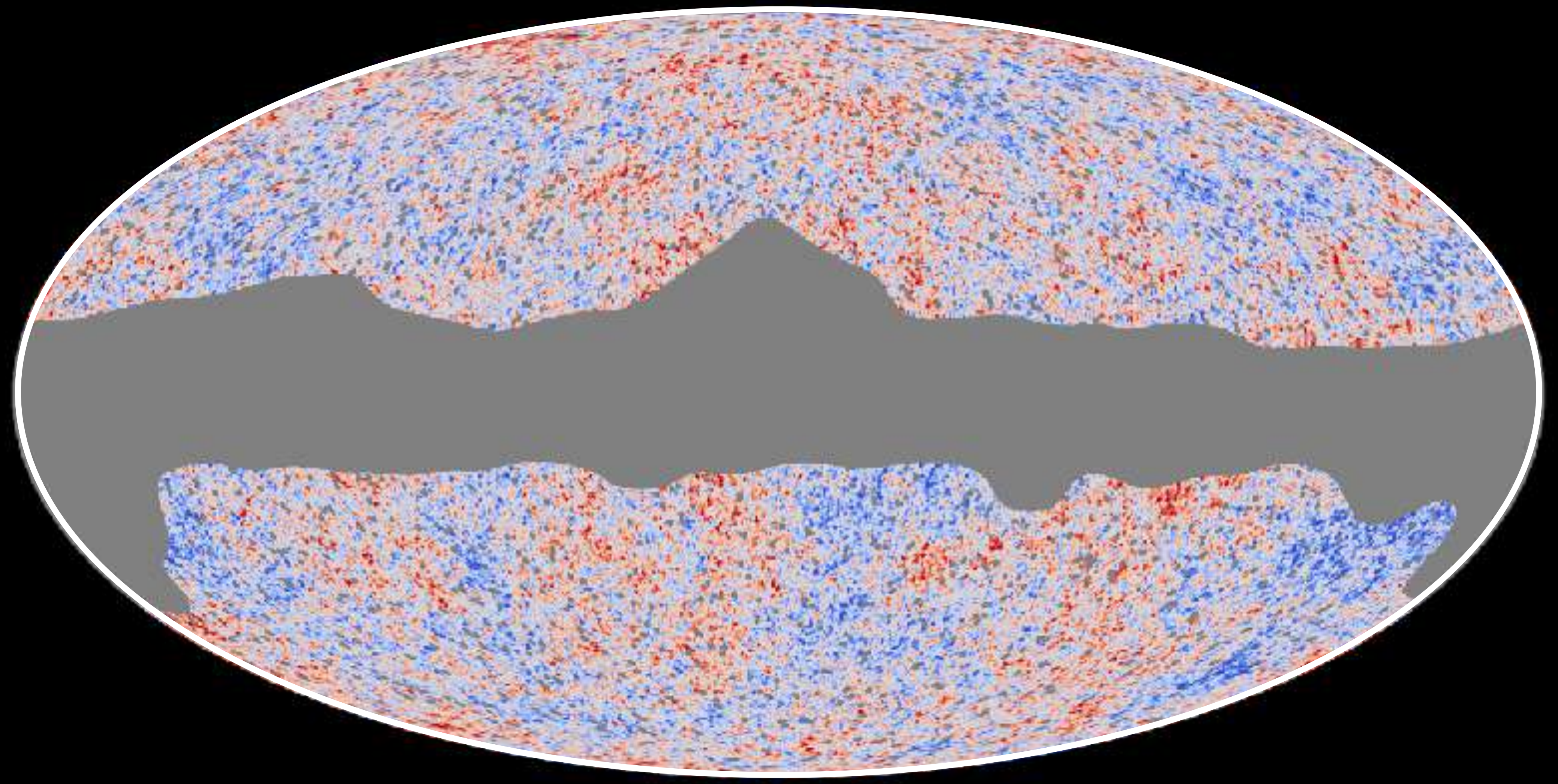


Compton-y (tSZ)

Some example ILC maps

Constrained ILC (*Remazeilles++10*)





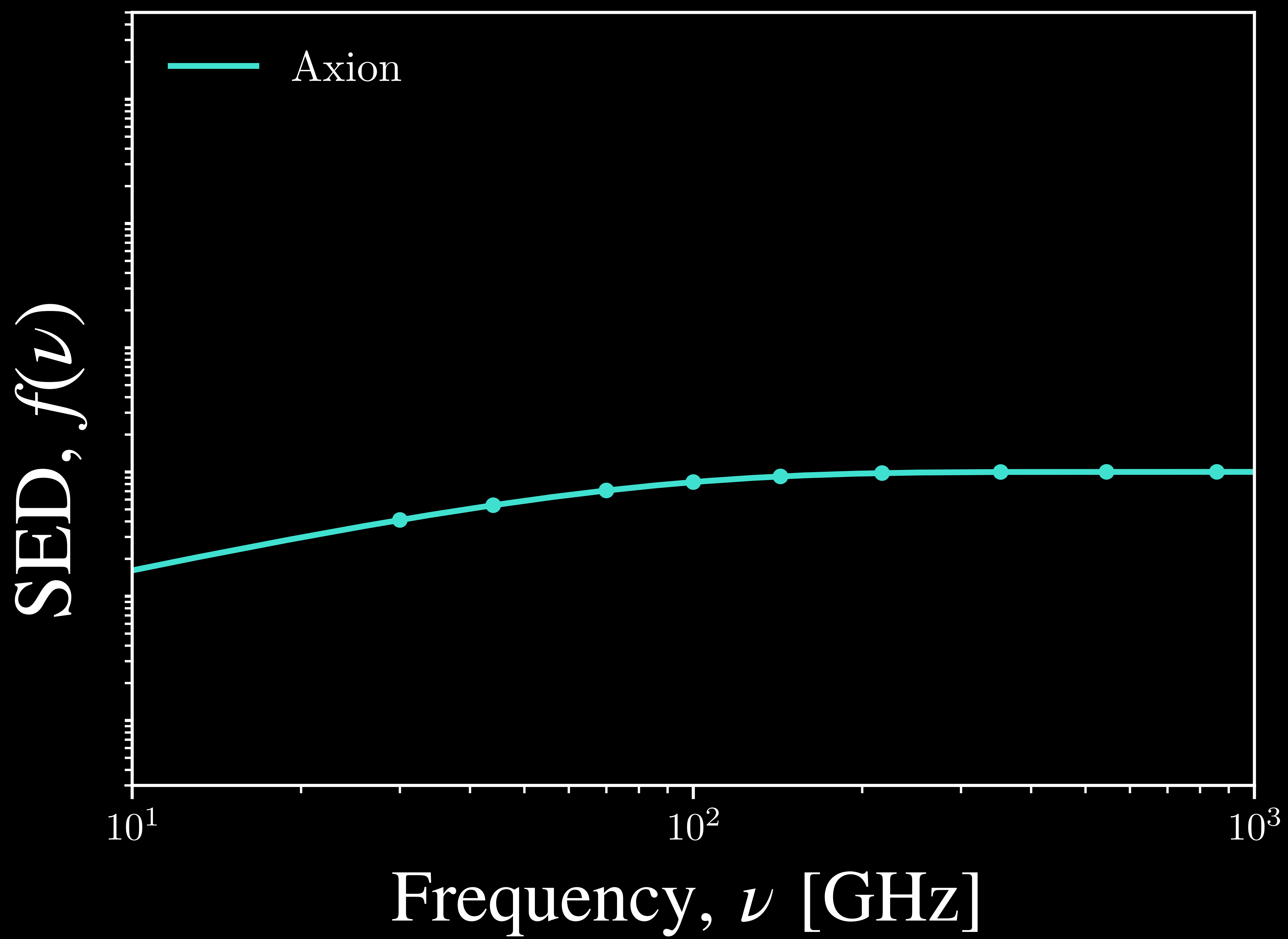
Blackbody T with tSZ deprojected

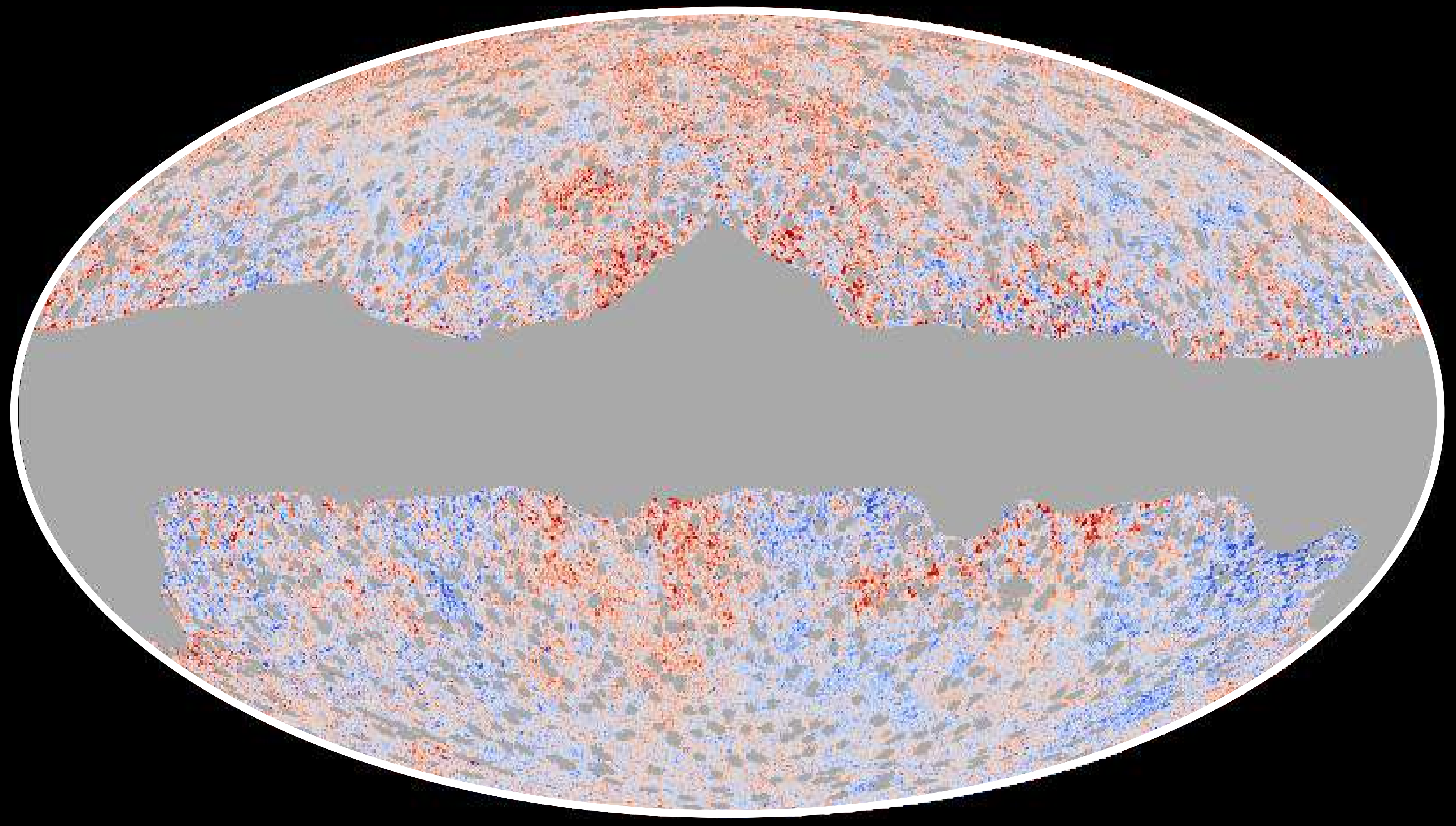
Stacking NILC maps on 60 X-ray selected clusters

Stacking NILC maps on 60 X-ray selected clusters

NILC is a powerful tool for studying CMB secondaries. Let's use it to search for axions

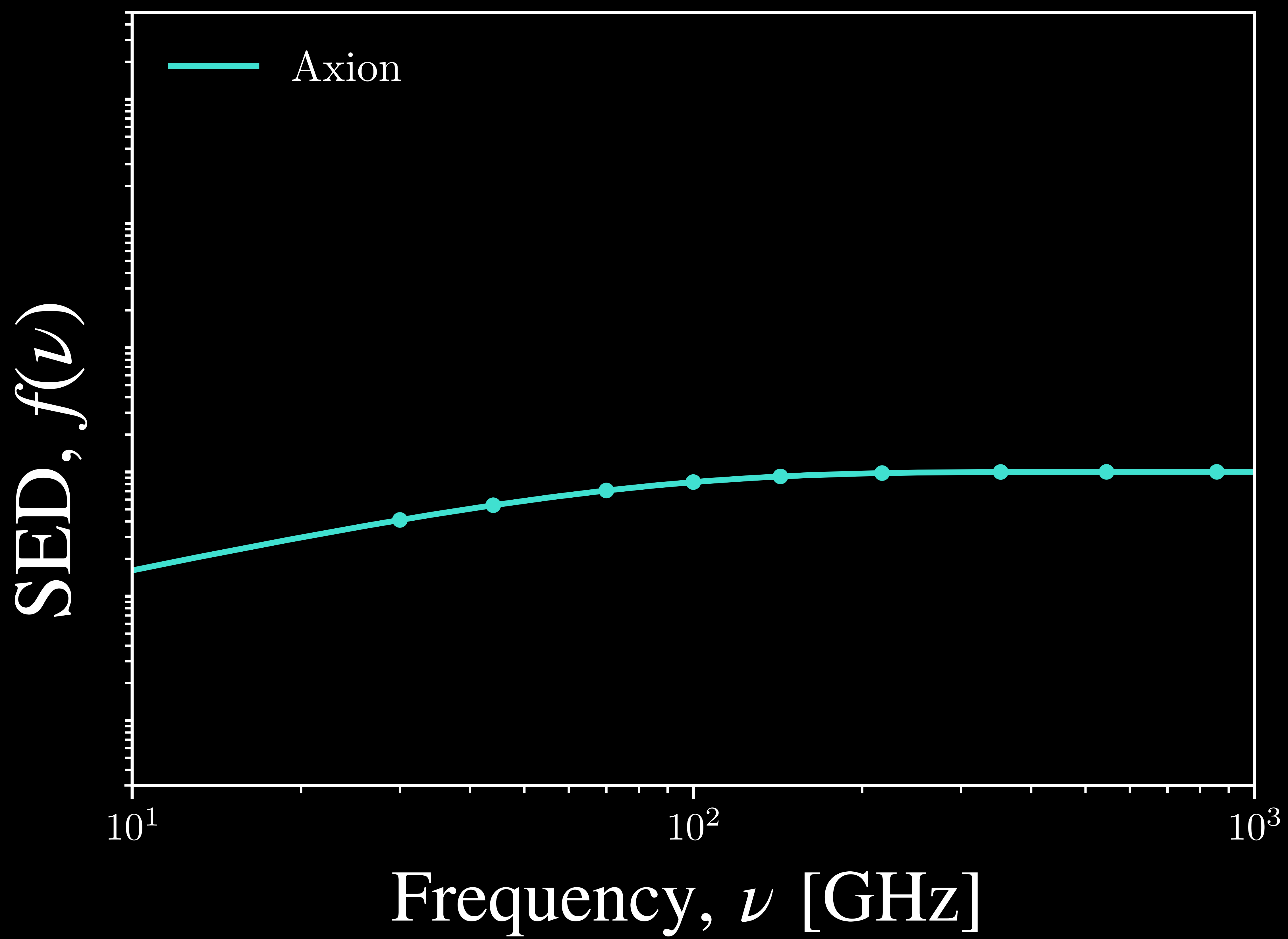
Axion-induced screening map

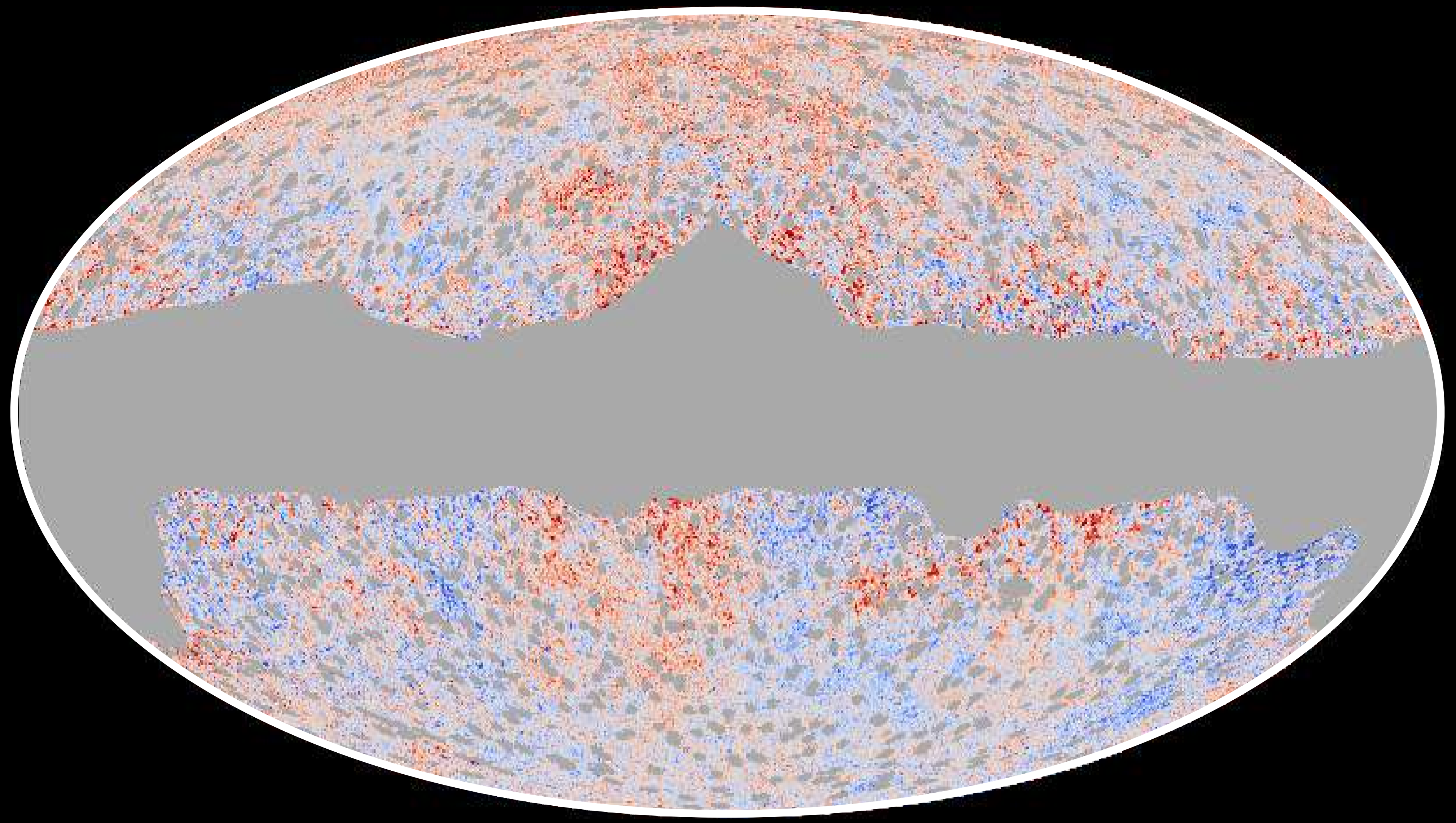




Map = axion signal + “noise”

Axion-induced screening map



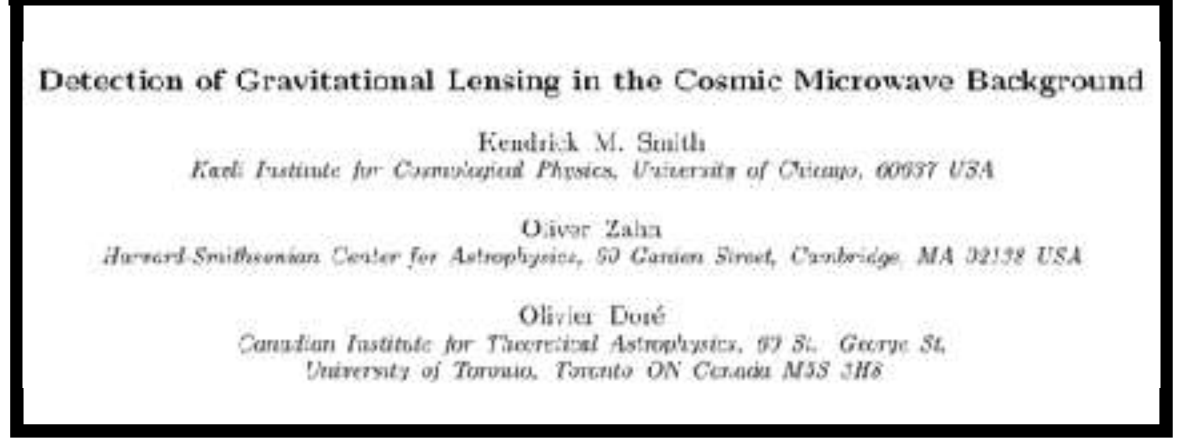


Cool… but what can we do with it?

Option a). Auto-Power Spectrum

- ***Extremely* difficult to interpret**
  - NILC map = signal+complicated mix of foregrounds and instrumental noise
  - Difficult to make a “detection”
- **Sub-optimal**
  - Signal is correlated with LSS and we have great LSS data
  - Historic example: detection of CMB lensing

WMAPx*NRAO *(2007)



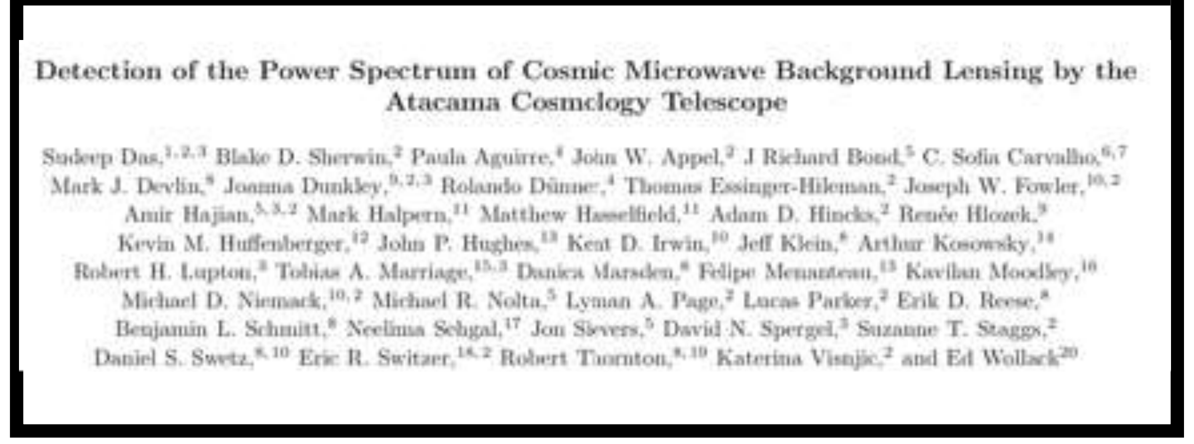
Detection of Gravitational Lensing in the Cosmic Microwave Background

Kendrick M. Smith
Kavli Institute for Cosmological Physics, University of Chicago, 60637 USA

Oliver Zahn
Harvard-Smithsonian Center for Astrophysics, 60 Garden Street, Cambridge, MA 02138 USA

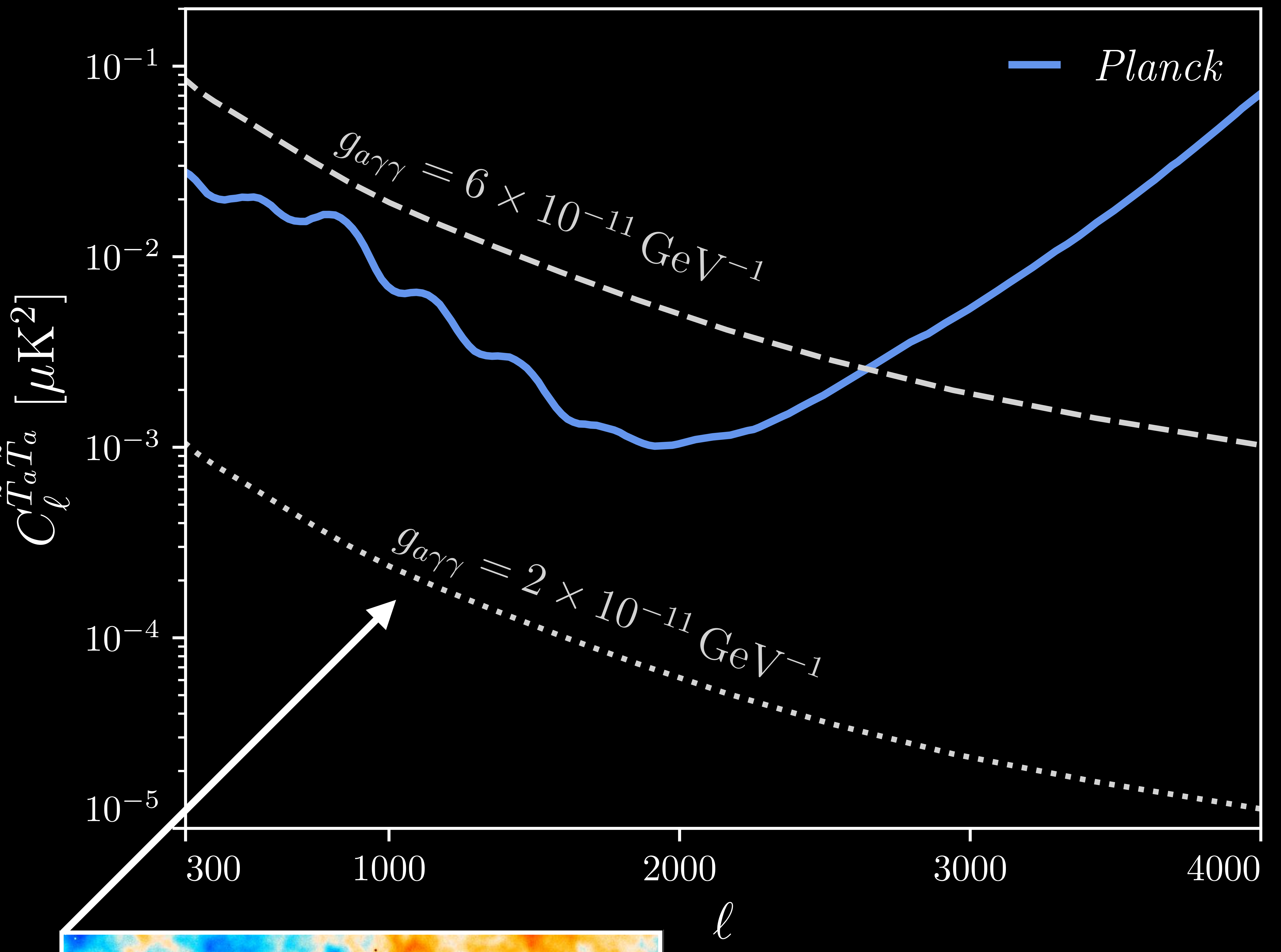
Olivier Doré
Canadian Institute for Theoretical Astrophysics, 60 St. George St, University of Toronto, Toronto ON Canada M5S 3H8

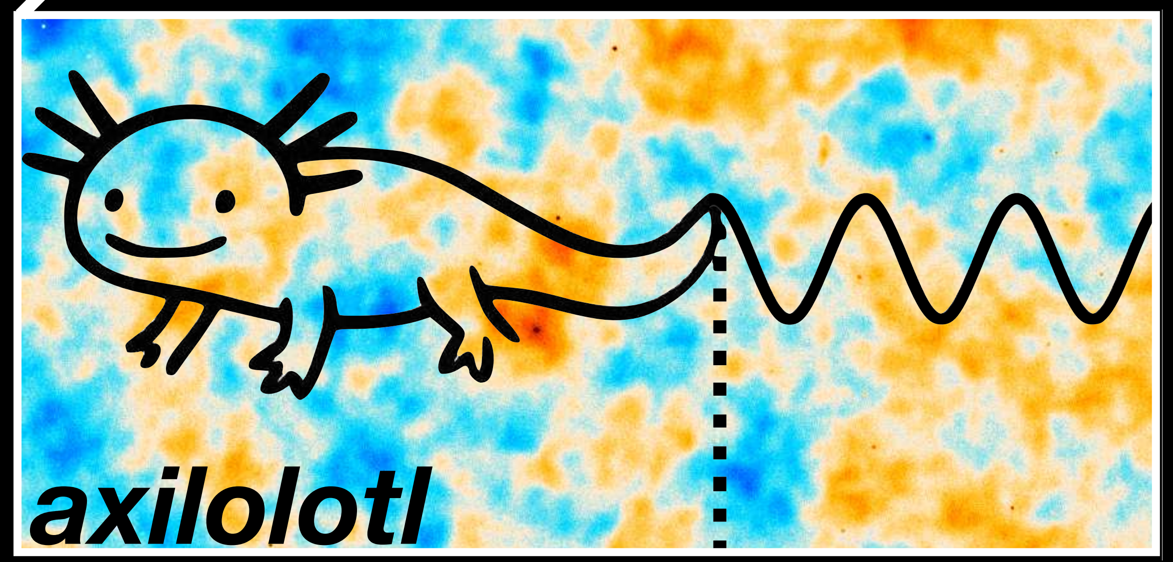
ACT (2011)



Detection of the Power Spectrum of Cosmic Microwave Background Lensing by the Atacama Cosmology Telescope

Sudeep Das,[1,2,3] Blake D. Sherwin,[2] Paula Aguirre,[4] John W. Appel,[2] J Richard Bond,[5] C. Sofia Carvalho,[6,7] Mark J. Devlin,[8] Joanna Dunkley,[9,2,3] Rolando Dünner,[4] Thomas Essinger-Hileman,[2] Joseph W. Fowler,[10,2] Amir Hajian,[5,3,2] Mark Halpern,[11] Matthew Hasselfield,[11] Adam D. Hincks,[2] Renée Hlozek,[9] Kevin M. Huffenberger,[12] John P. Hughes,[13] Kent D. Irwin,[10] Jeff Klein,[8] Arthur Kosowsky,[14] Robert H. Lupton,[3] Tobias A. Marriage,[15,3] Danica Marsden,[8] Felipe Menanteau,[13] Kavilan Moodley,[16] Michael D. Niemack,[10,2] Michael R. Nolta,[5] Lyman A. Page,[2] Lucas Parker,[2] Erik D. Reese,[8] Benjamin L. Schmitt,[8] Neelima Sehgal,[17] Jon Sievers,[5] David N. Spergel,[3] Suzanne T. Staggs,[2] Daniel S. Swetz,[8,10] Eric R. Switzer,[18,2] Robert Thornton,[8,19] Katerina Visnjic,[2] and Ed Wollack[20]





Halo model code for dark screening

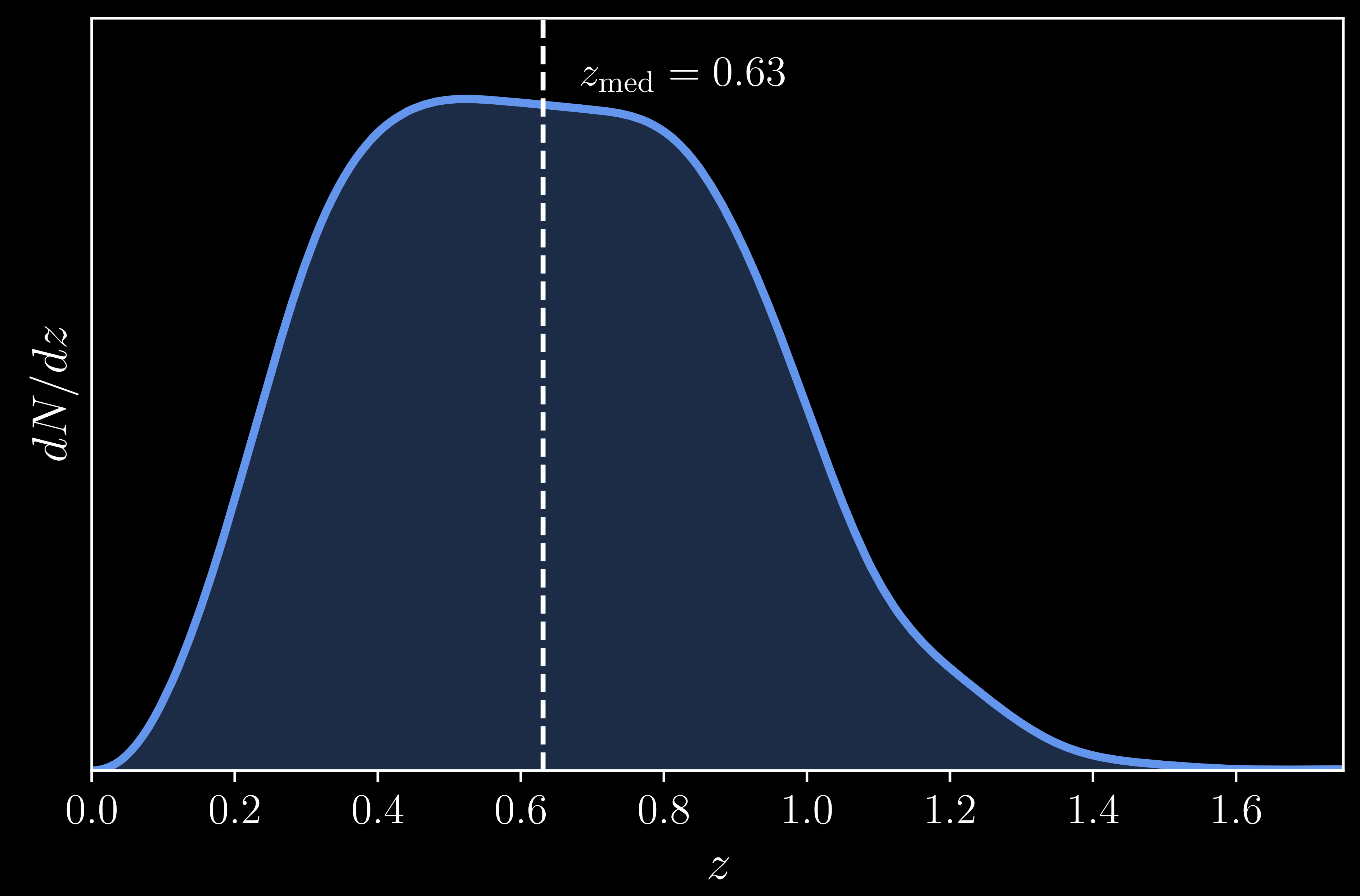
Intermission: spot the snow leopard (auto-correlation edition)

Intermission: spot the snow leopard (cross-correlation edition)

What should we correlate with?

- *unWISE catalog (**Schlafly++19**)*
  - Based on WISE and NEOWISE
  - Full sky with >500 million galaxies

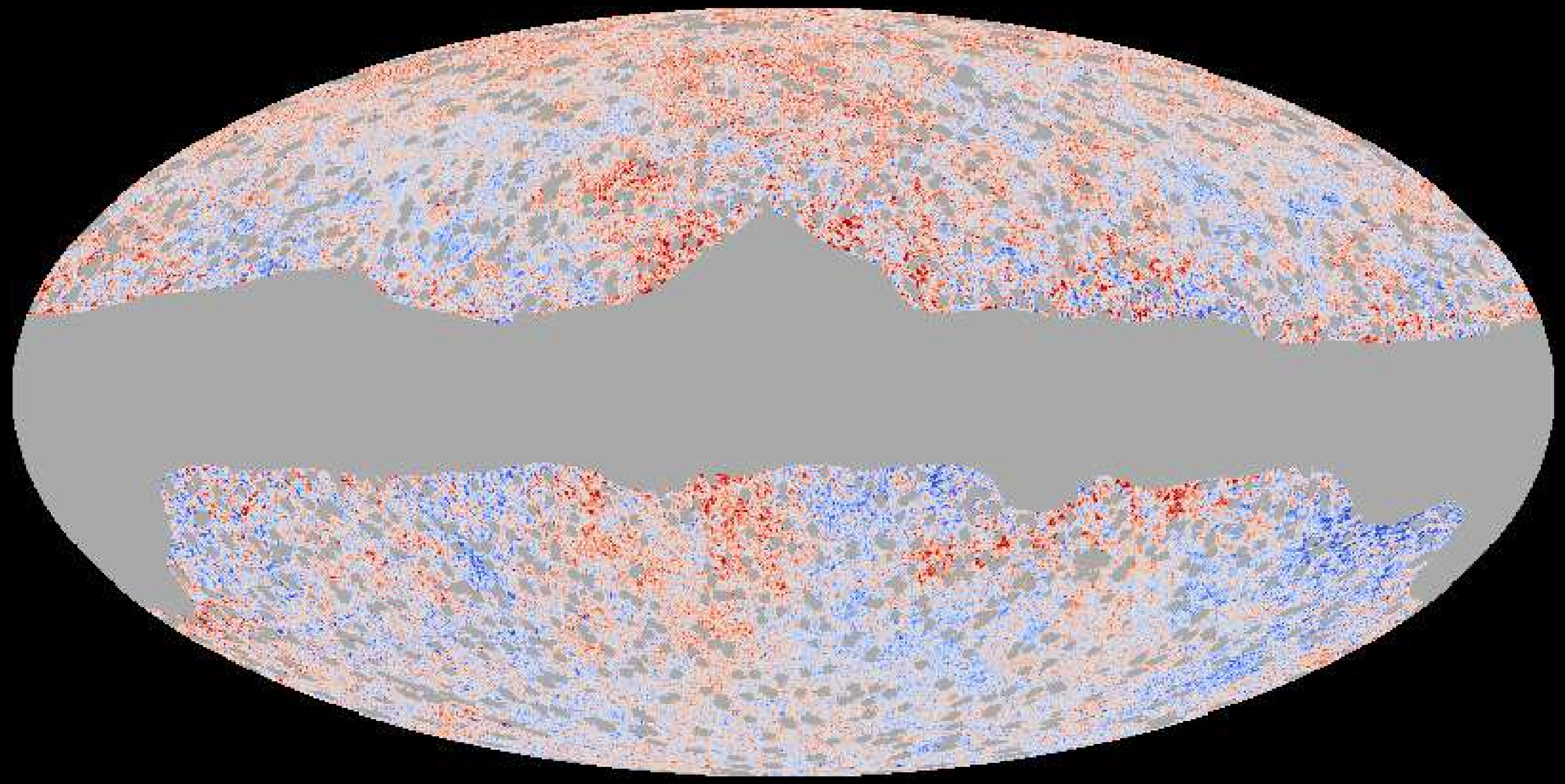
- Great for cross-correlations
  - CMB lensing/S_8 (***Krolewski++19***, ***Farren++23***)
  - Characterized HOD (***Kusiak++22***)



We use the "Blue" subsample

Cross-correlating with unWISE galaxies

Axion Map



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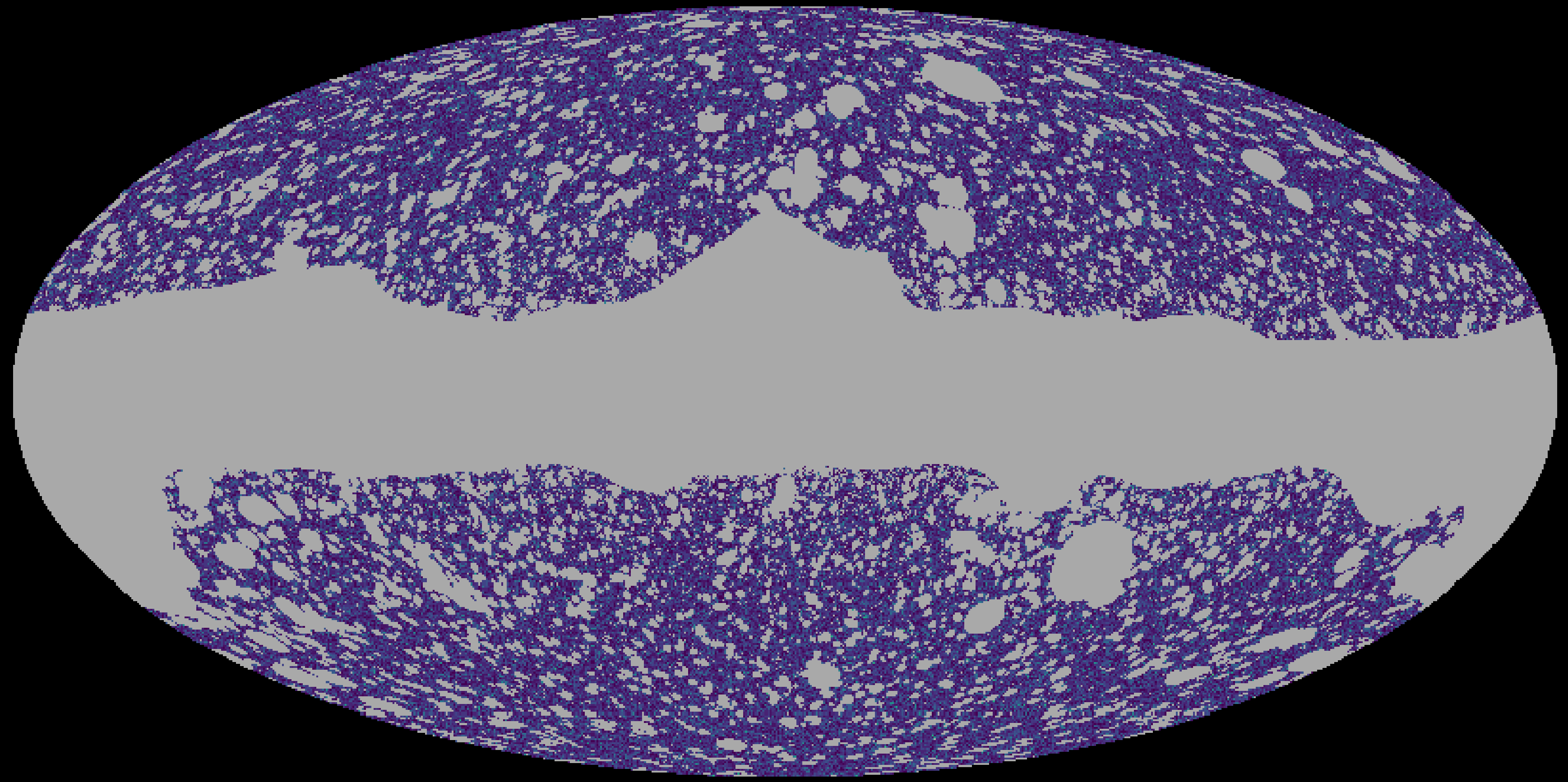
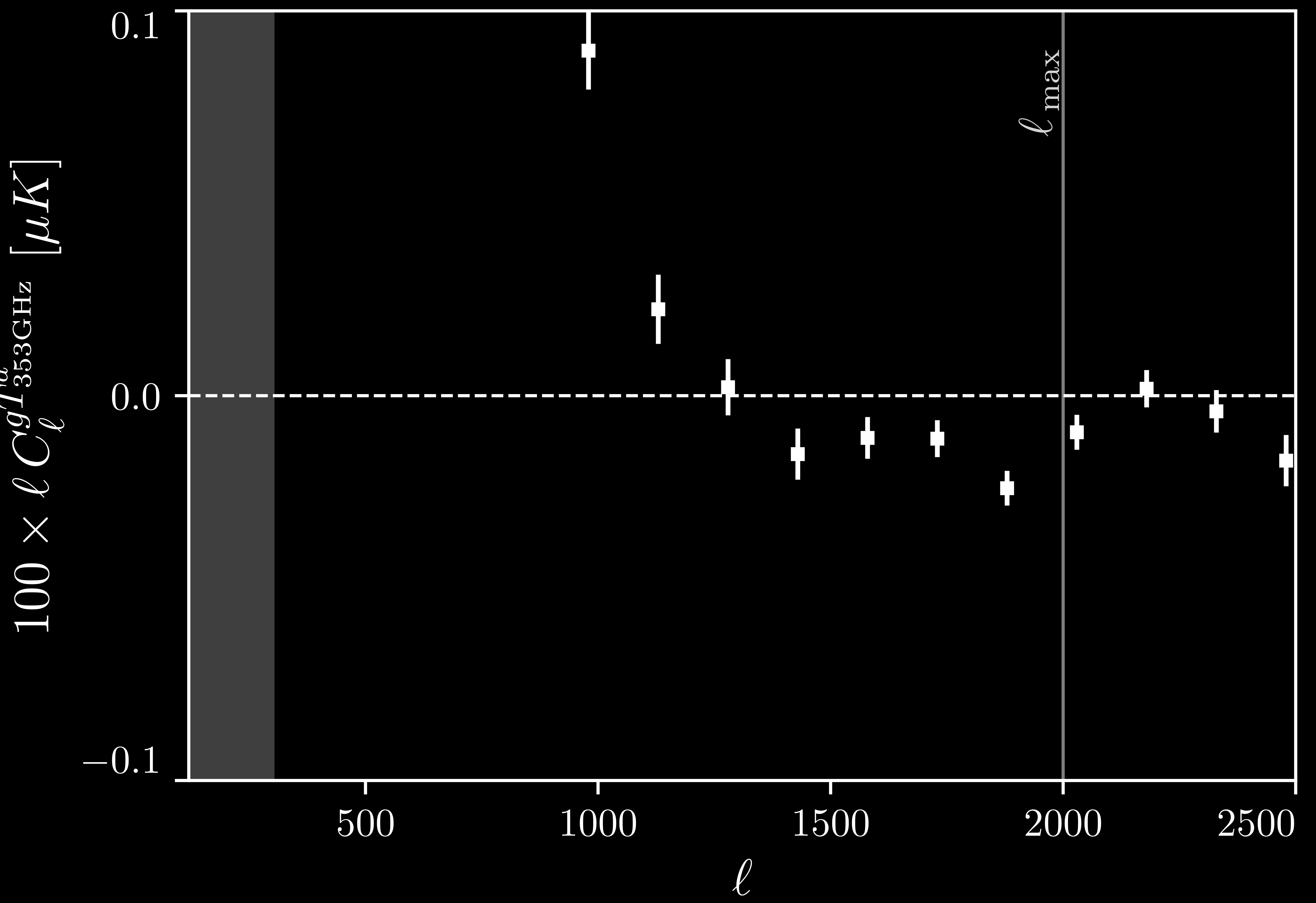
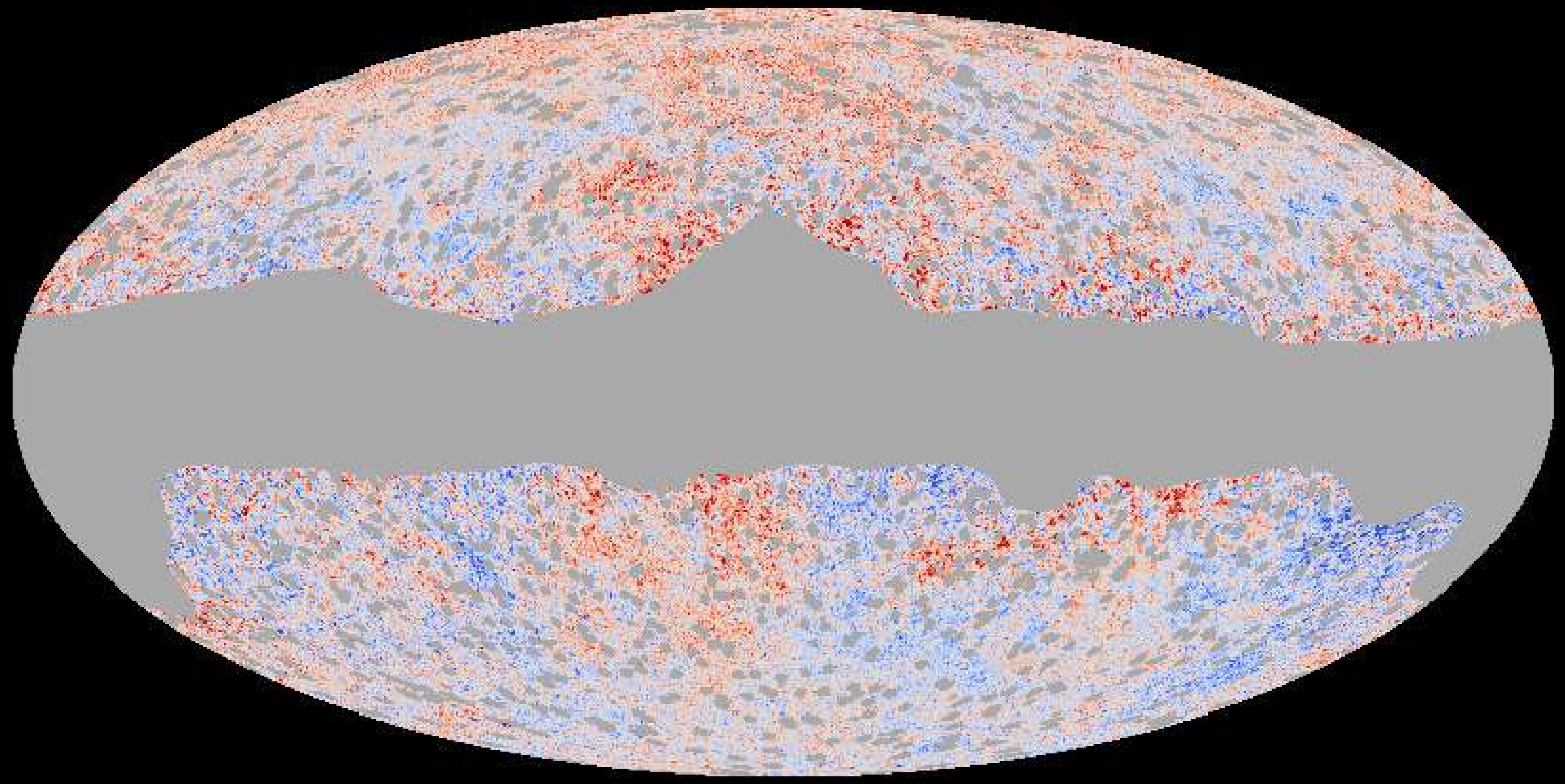


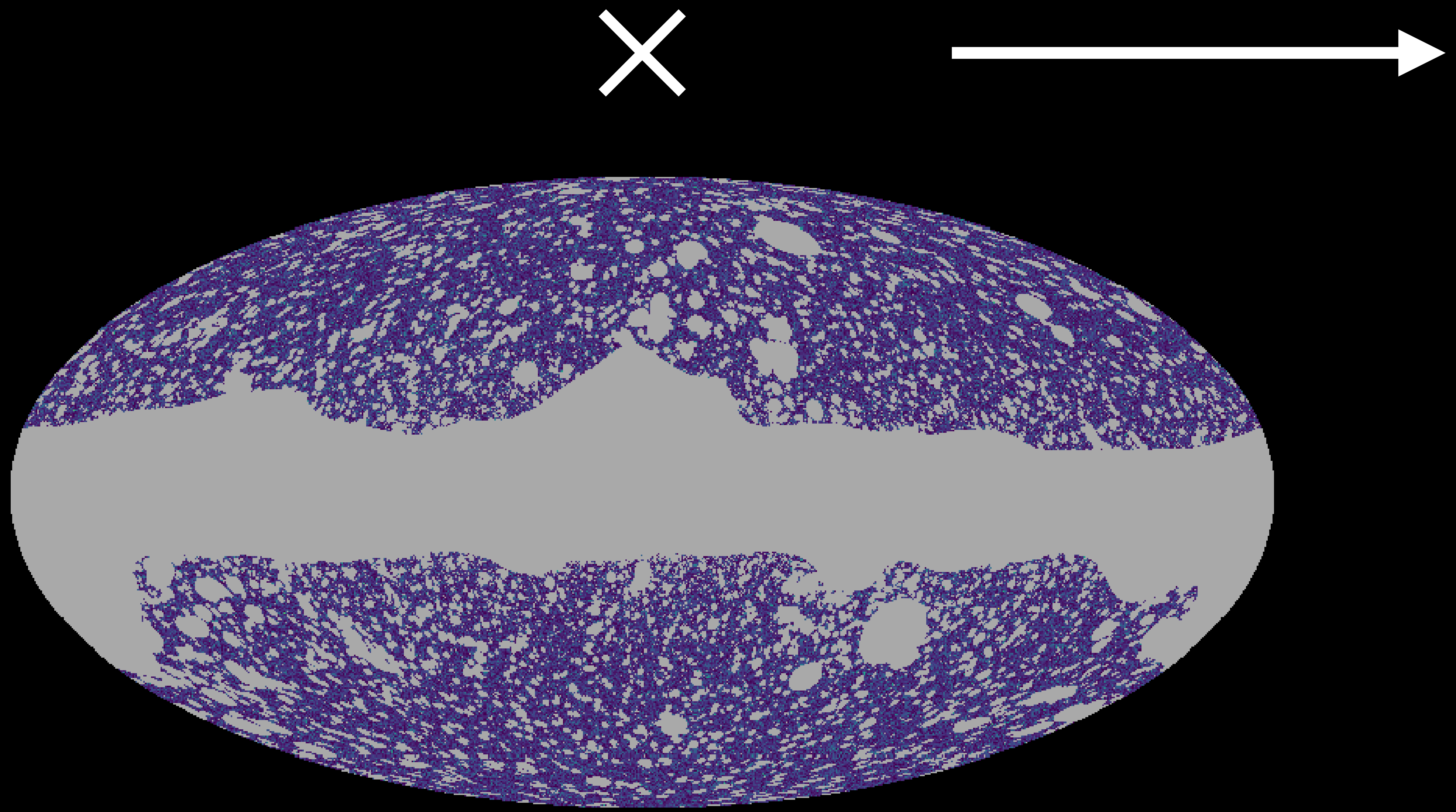
unWISE "Blue" Galaxies

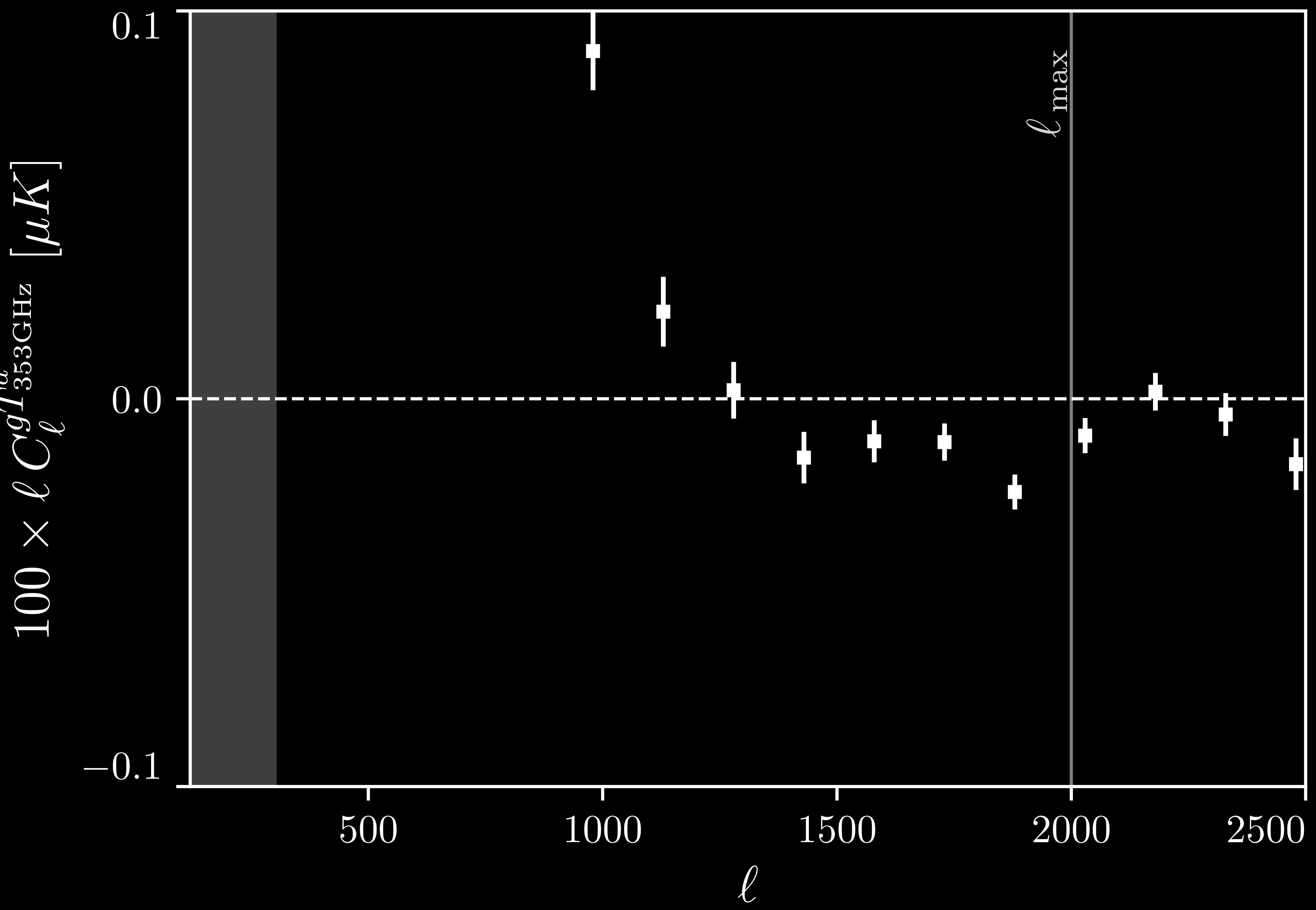


Cross-correlating with unWISE galaxies

Axion Map





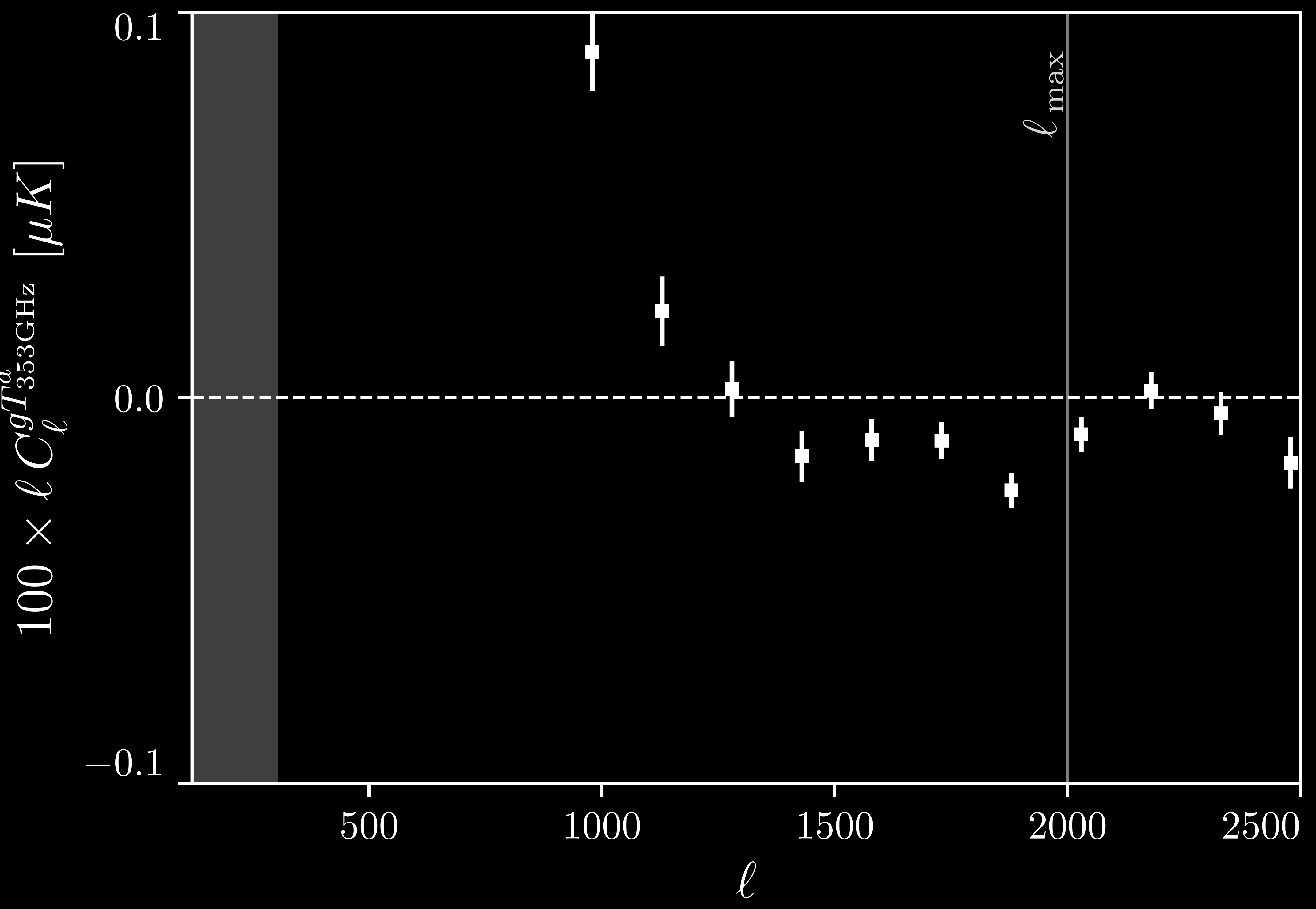


unWISE "Blue" Galaxies

Non-zero -> did we detect axions?

Foreground contamination

- Measurement is sensitive to any residual foregrounds that correlate with unWISE galaxies

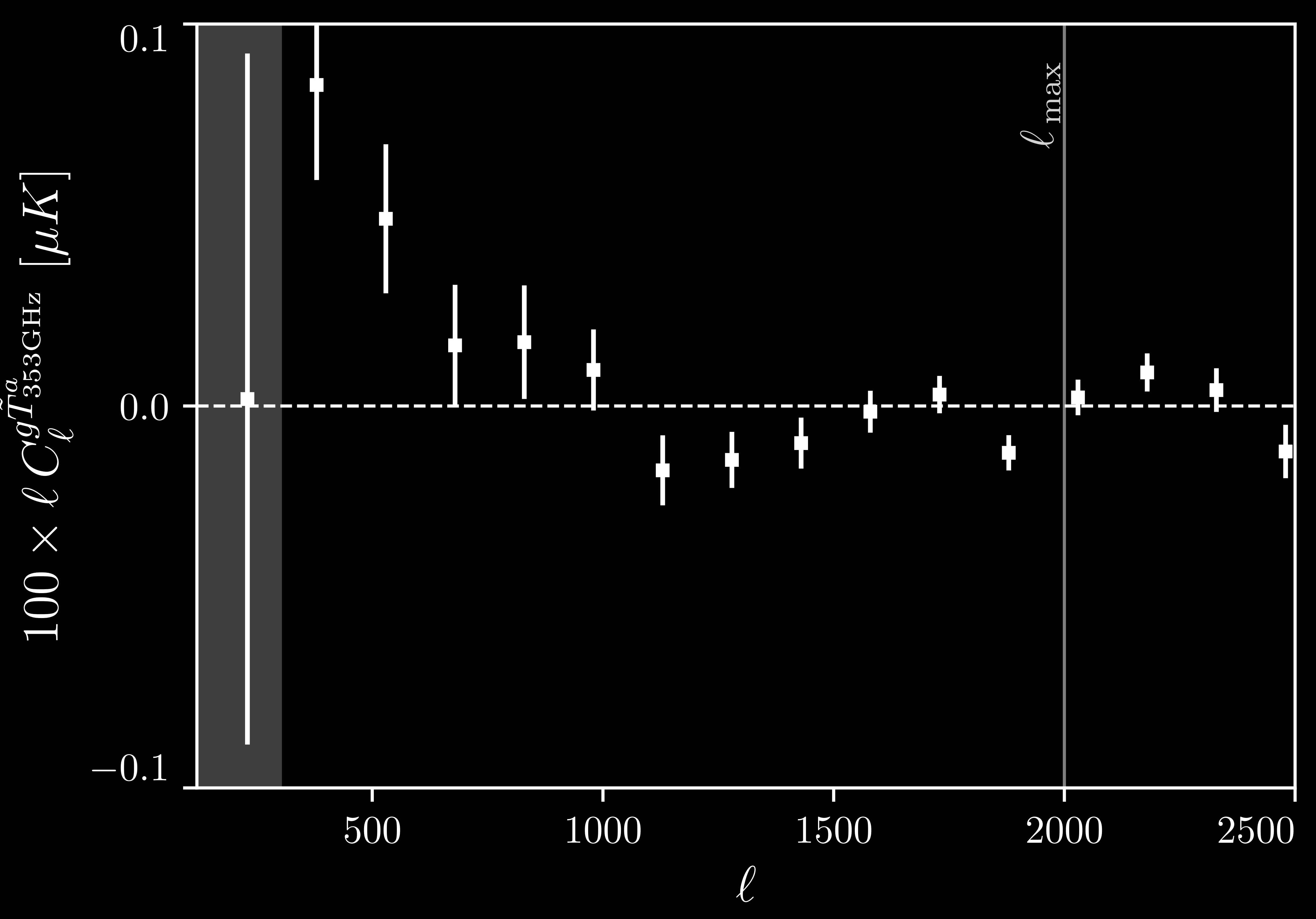


Without foreground deprojection.

Foreground contamination

- Measurement is sensitive to any residual foregrounds that correlate with unWISE galaxies

  1. **tSZ:** significant correlation, but SED is known



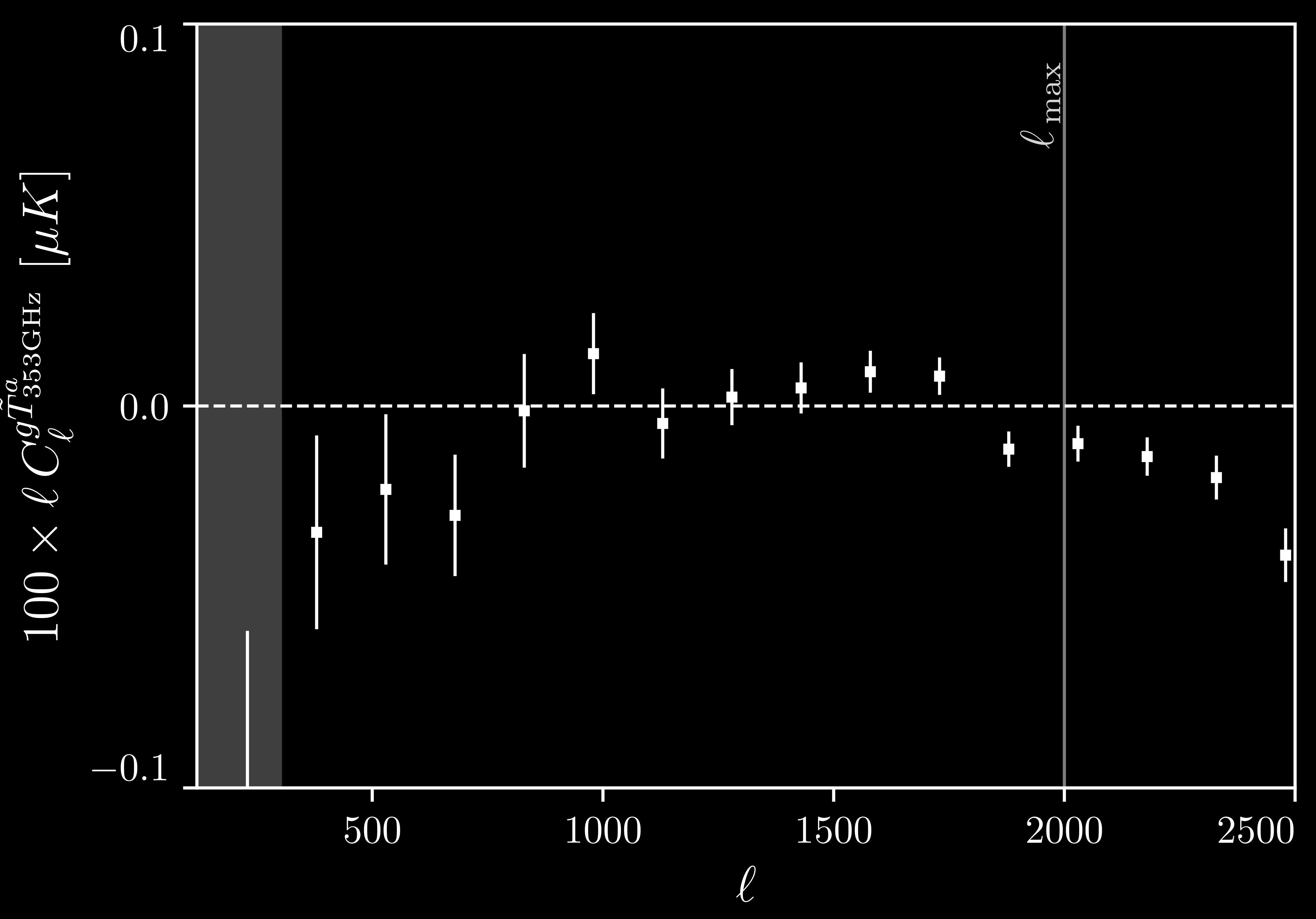
Deproject tSZ

Foreground contamination

- Measurement is sensitive to any residual foregrounds that correlate with unWISE galaxies

1. **tSZ:** significant correlation, but SED is known
2. **CIB:** significant correlation (Yan++2023), uncertainty in SED
   - Model as modified blackbody (MBB)

$$\Theta_{\rm CIB}(\nu\,|\,T^{\rm eff}_{\rm CIB}, \beta^{\rm eff}_{\rm CIB}) = \nu^{\beta^{\rm eff}_{\rm CIB}}\, B(\nu\,|\,T^{\rm eff}_{\rm CIB})$$



Deproject tSZ+CIB MBB

$$(T^{\rm eff}_{\rm CIB}, \beta^{\rm eff}_{\rm CIB}) = (20.0\ {\rm K},\ 1.6)$$

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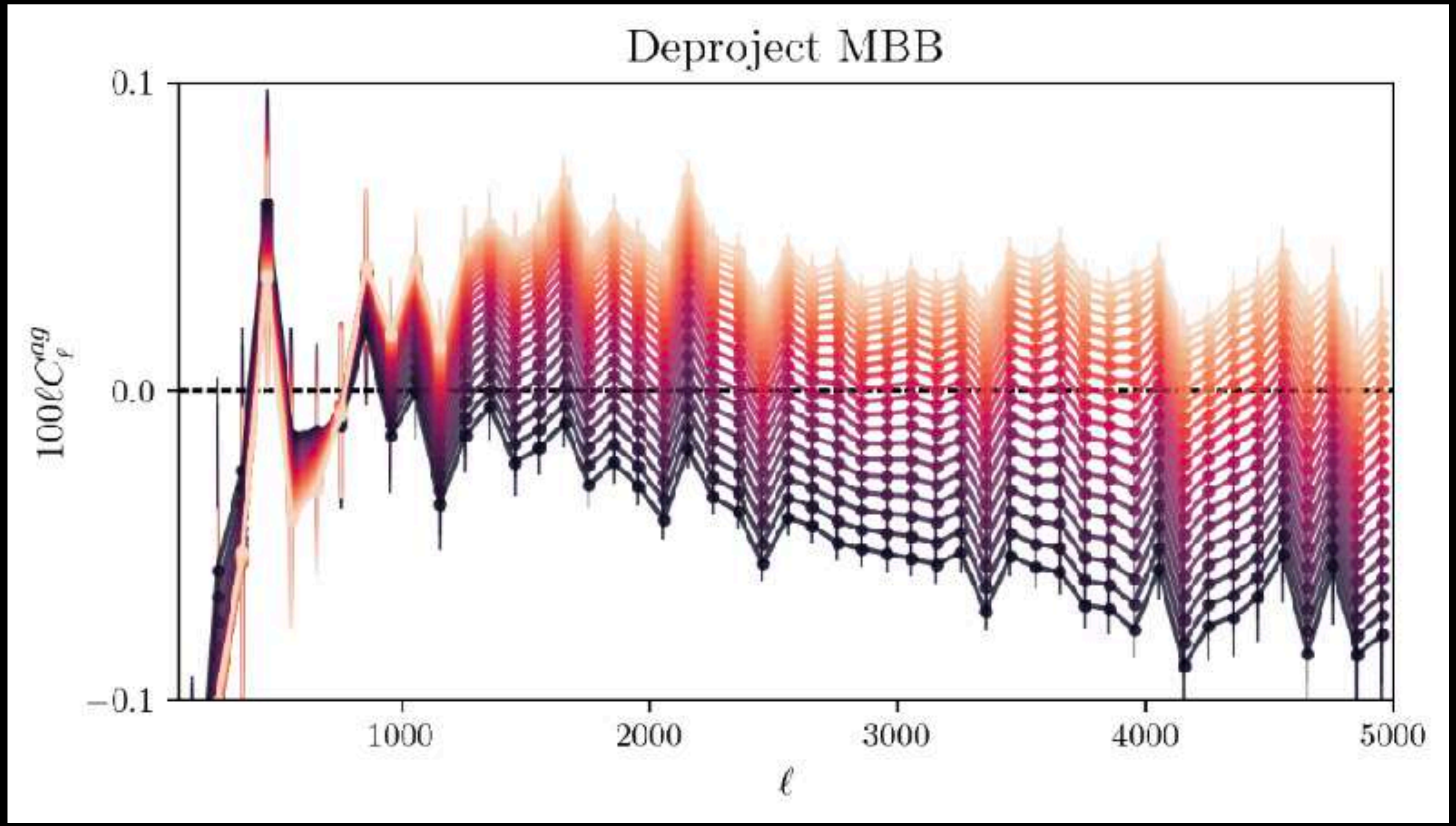
Very sensitive to CIB SED parameters!



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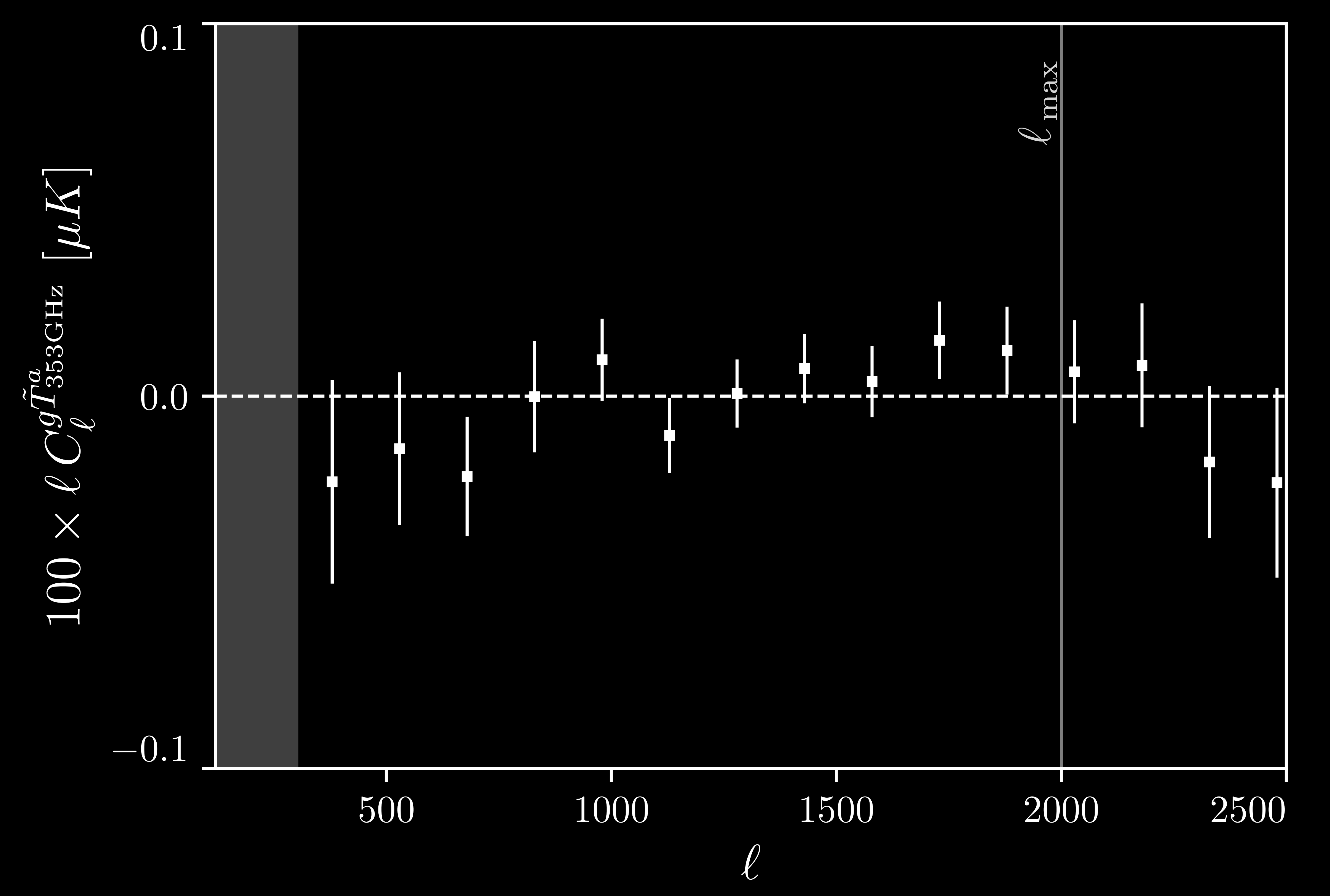
    - Deproject first moment of MBB (Chluba++2017)



Deproject tSZ+CIB MBB+$d\beta_{\rm CIB}$

Foreground contamination

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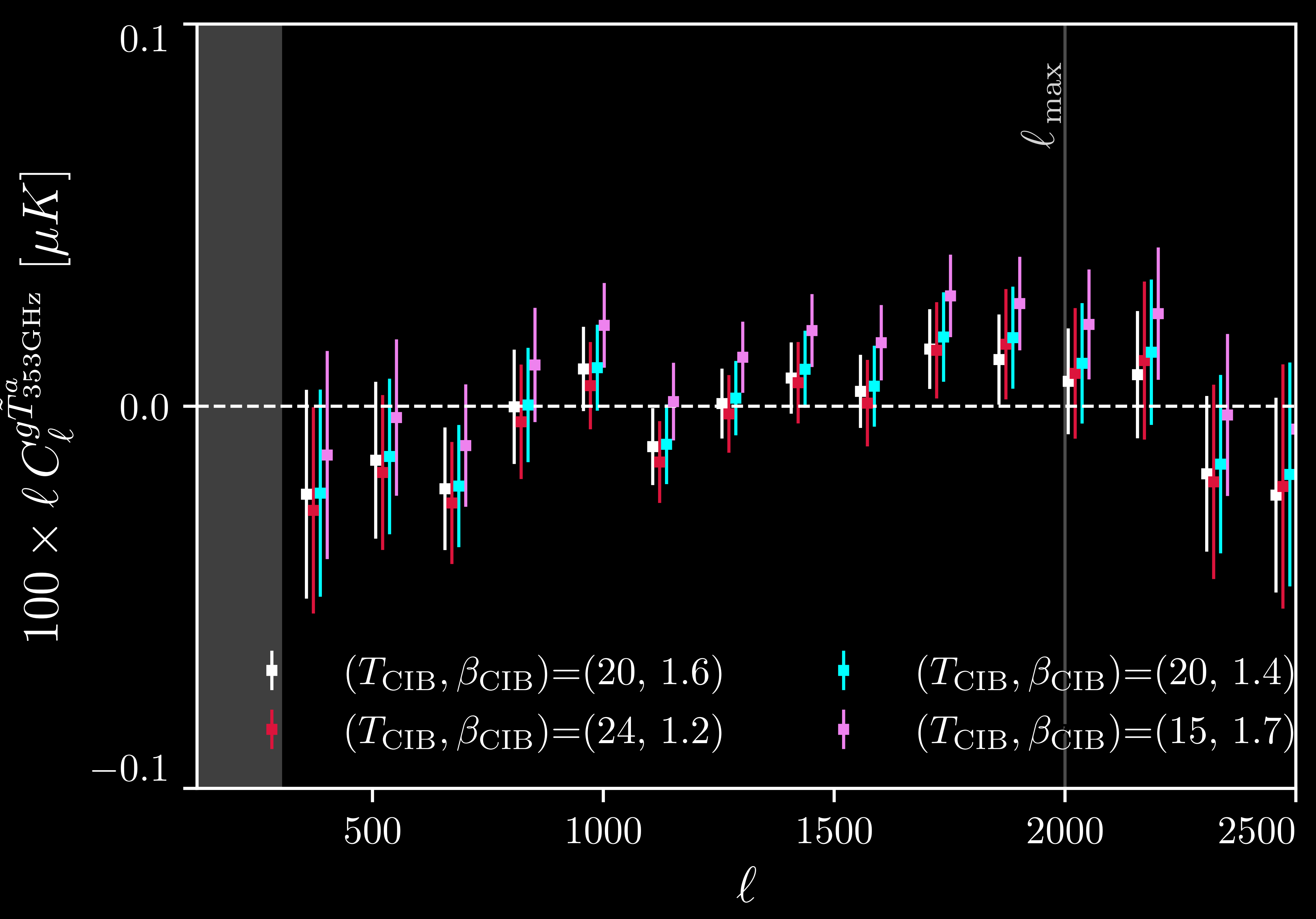
   - Deproject first moment of MBB (Chluba++2017)

Reduce bias, but increase variance



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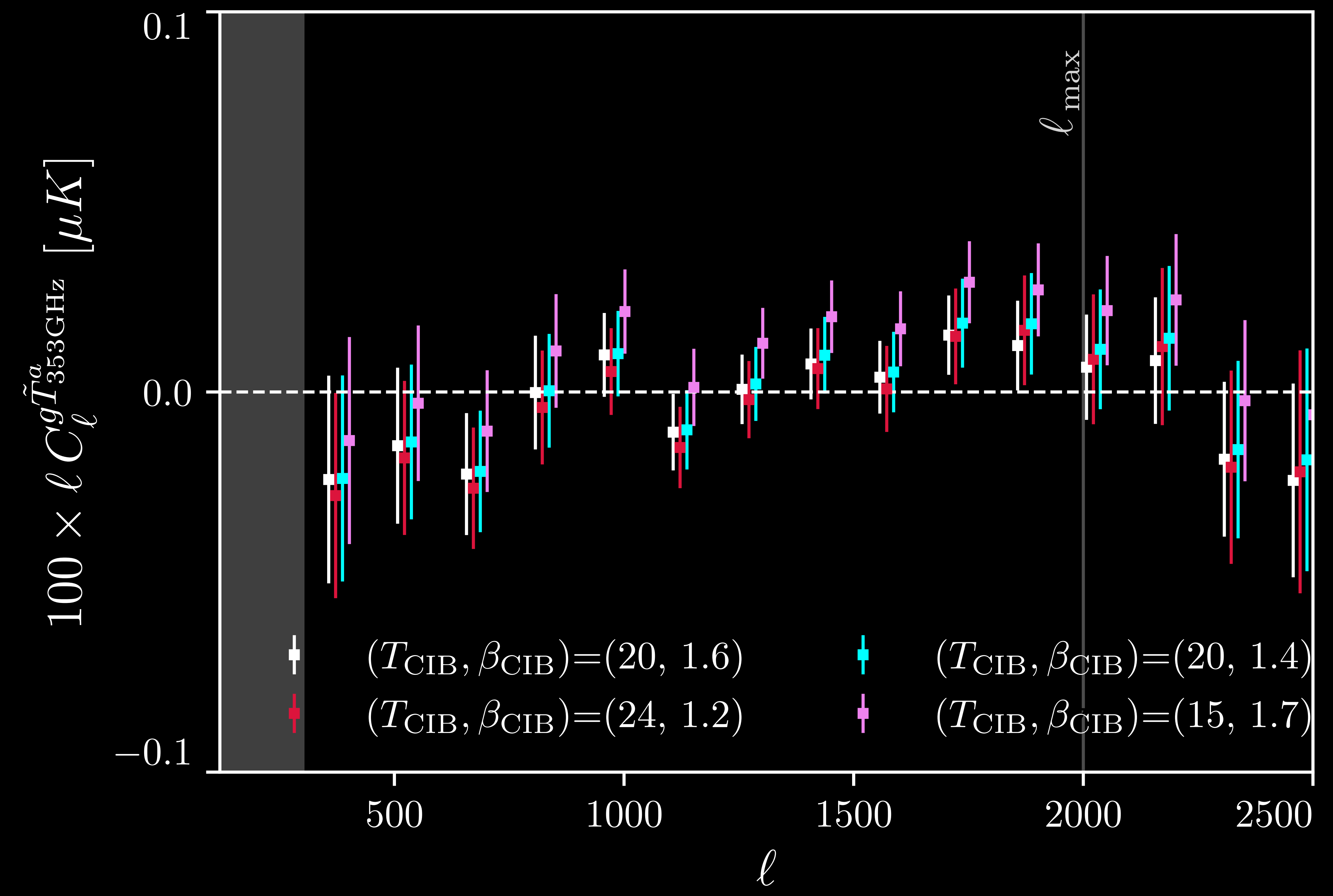
   - Deproject first moment of MBB (Chluba++2017)

We find no evidence for axion-induced spectral distortions in *Planck*xunWISE!



Deproject tSZ+CIB MBB+$d\beta_{\rm CIB}$

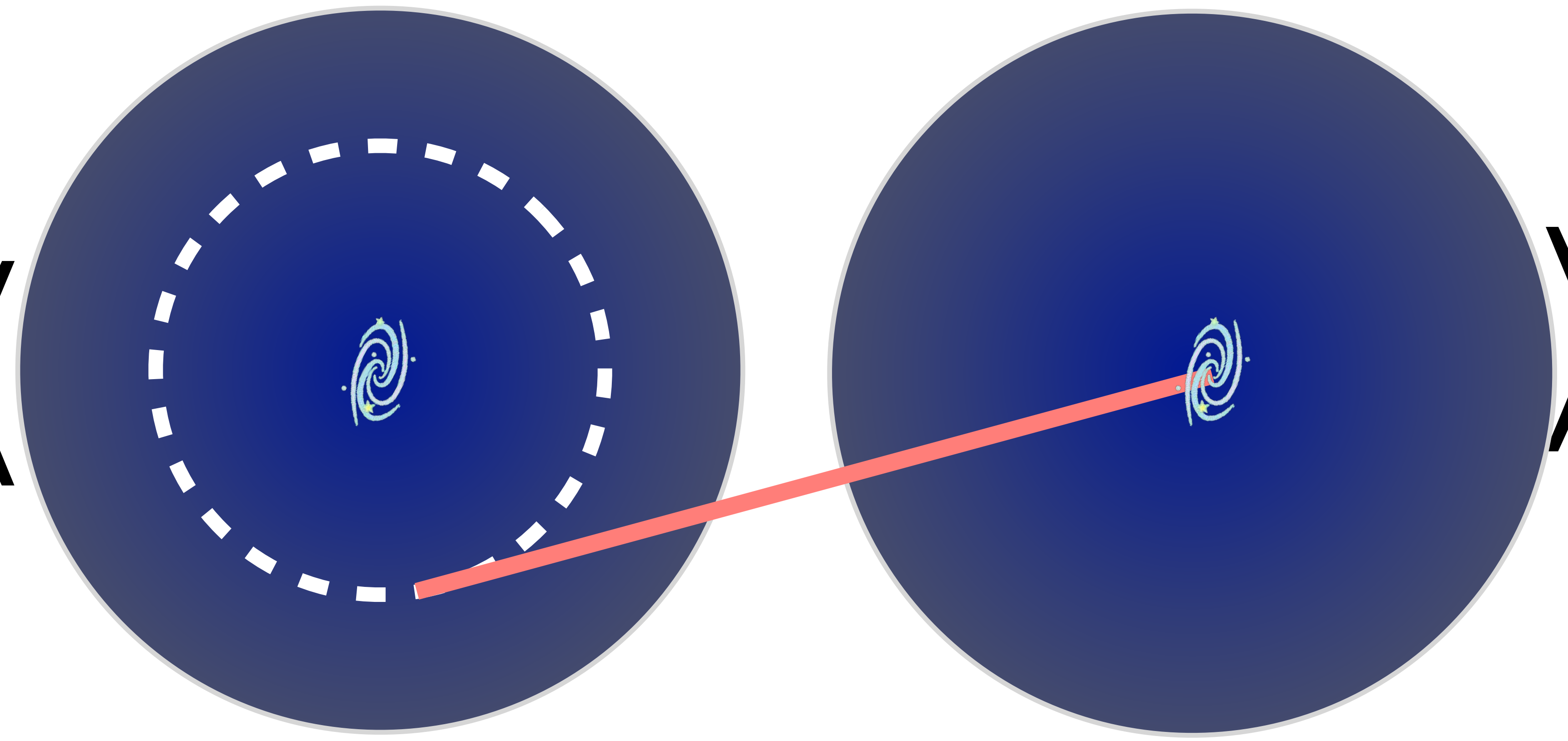
Converting non-detection into constraints

- Theoretical predictions are computed using halo model

$$\langle \tilde{T}_a g \rangle = C_\ell^{\tilde{T}_a g;\ 1\ \mathrm{halo}} + C_\ell^{\tilde{T}_a g;\ 2\ \mathrm{halo}}$$

$\sim \langle$

$\rangle + \langle$



$\rangle$

$$\int dz\, \frac{\chi(z)^2}{H(z)} \int dM\, n(z,M)\, \tilde{T}_\ell^a(z,M)\, u_\ell^g(z,M)$$

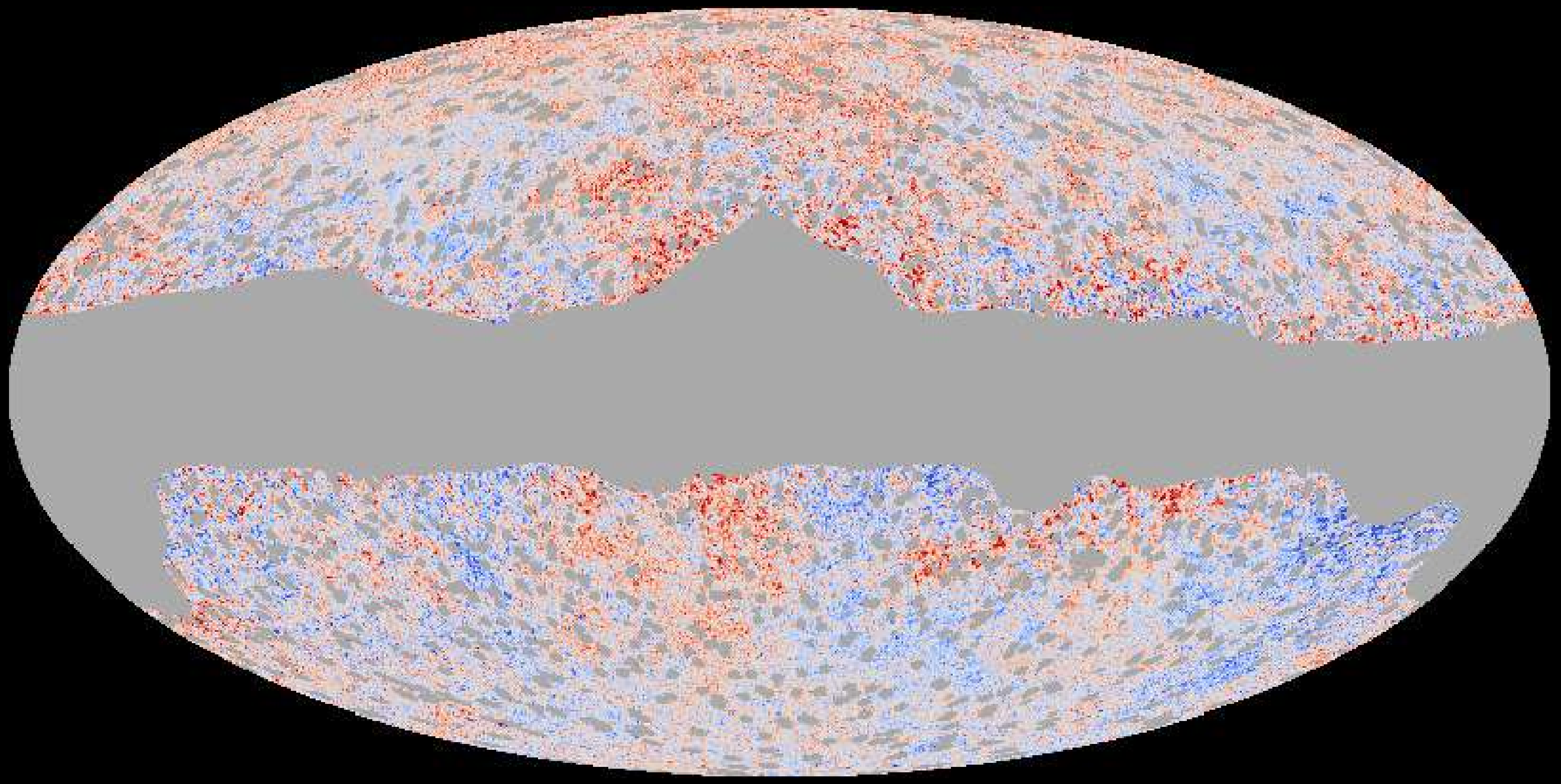
$$\int dz\, \frac{\chi(z)^2}{H(z)} \left[\prod_{i=1,2} \int dM_i\, n(z,M_i)\, b(z,M_i) \right] u_\ell^g(z,M_1) \tilde{T}_\ell^a(z,M_2) P_{mm}^{\mathrm{lin}} \left(\frac{\ell+1/2}{\chi(z)}, z \right),$$

Additional ingredients

- Halo occupation distribution (HOD) from Kusiak++22
- Electron number density profile from Battaglia++ 2011
- Magnetic field profiles from IllustrisTNG

From measurements to constraints

Axion Map



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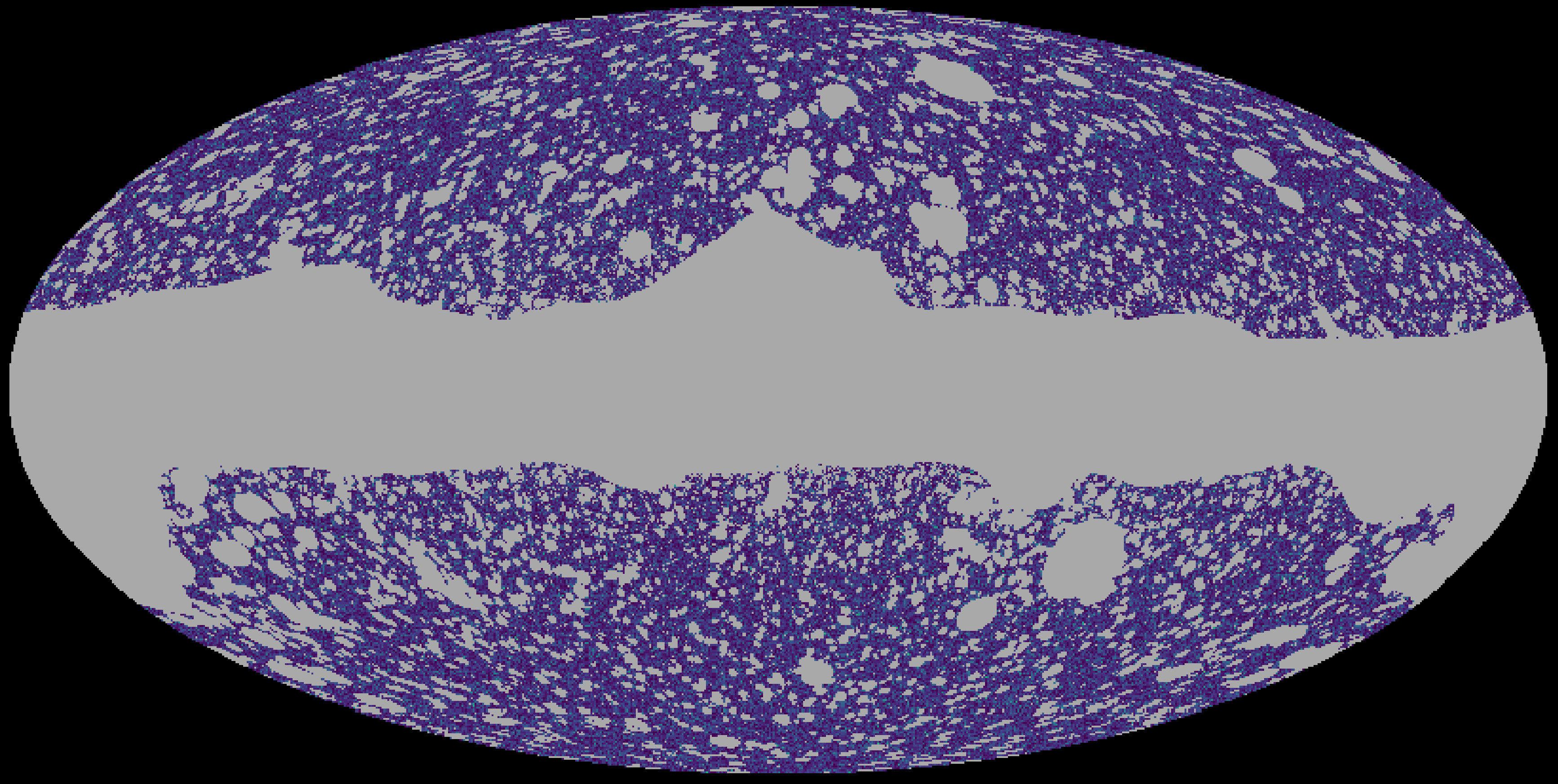
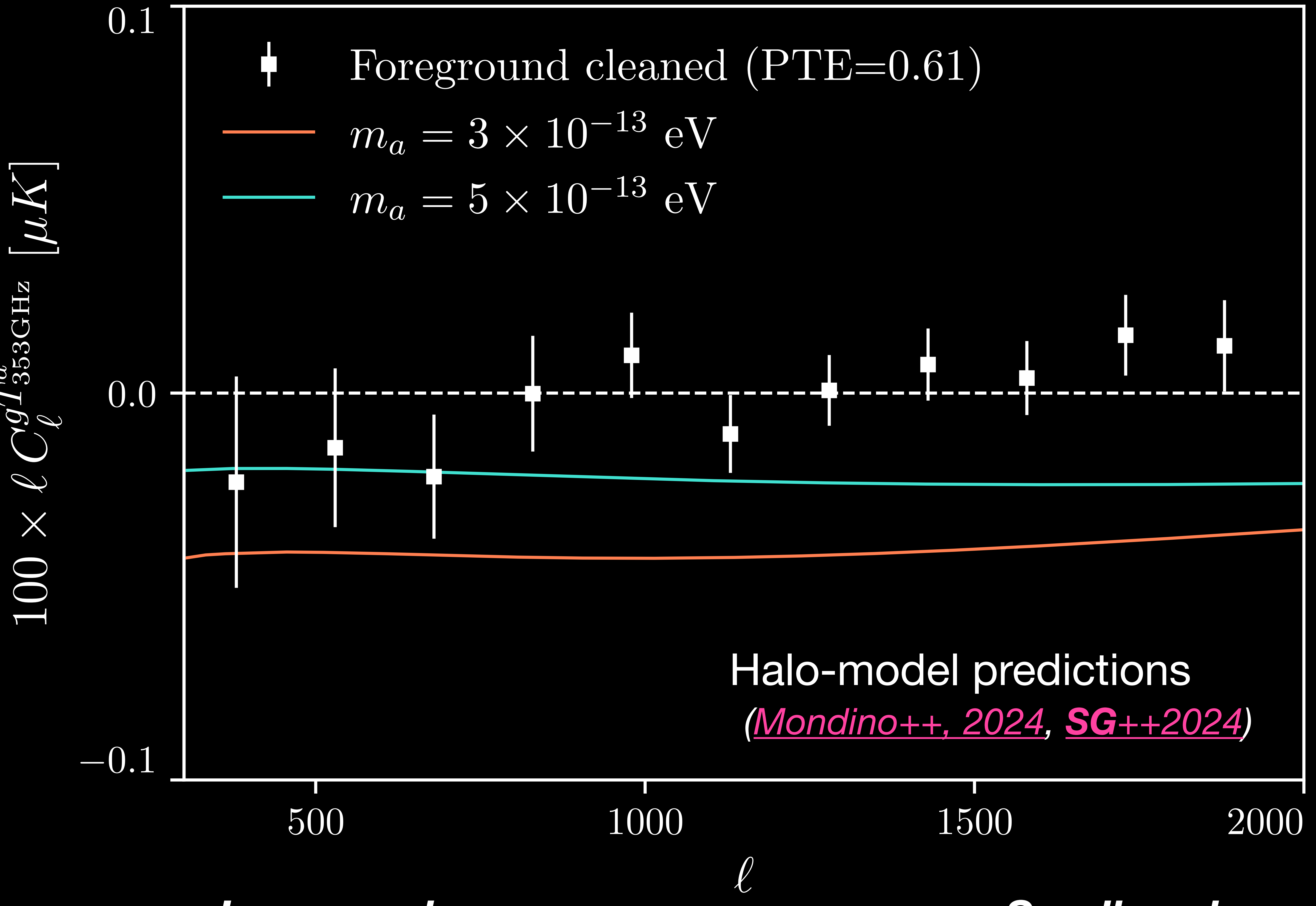


unWISE Galaxies

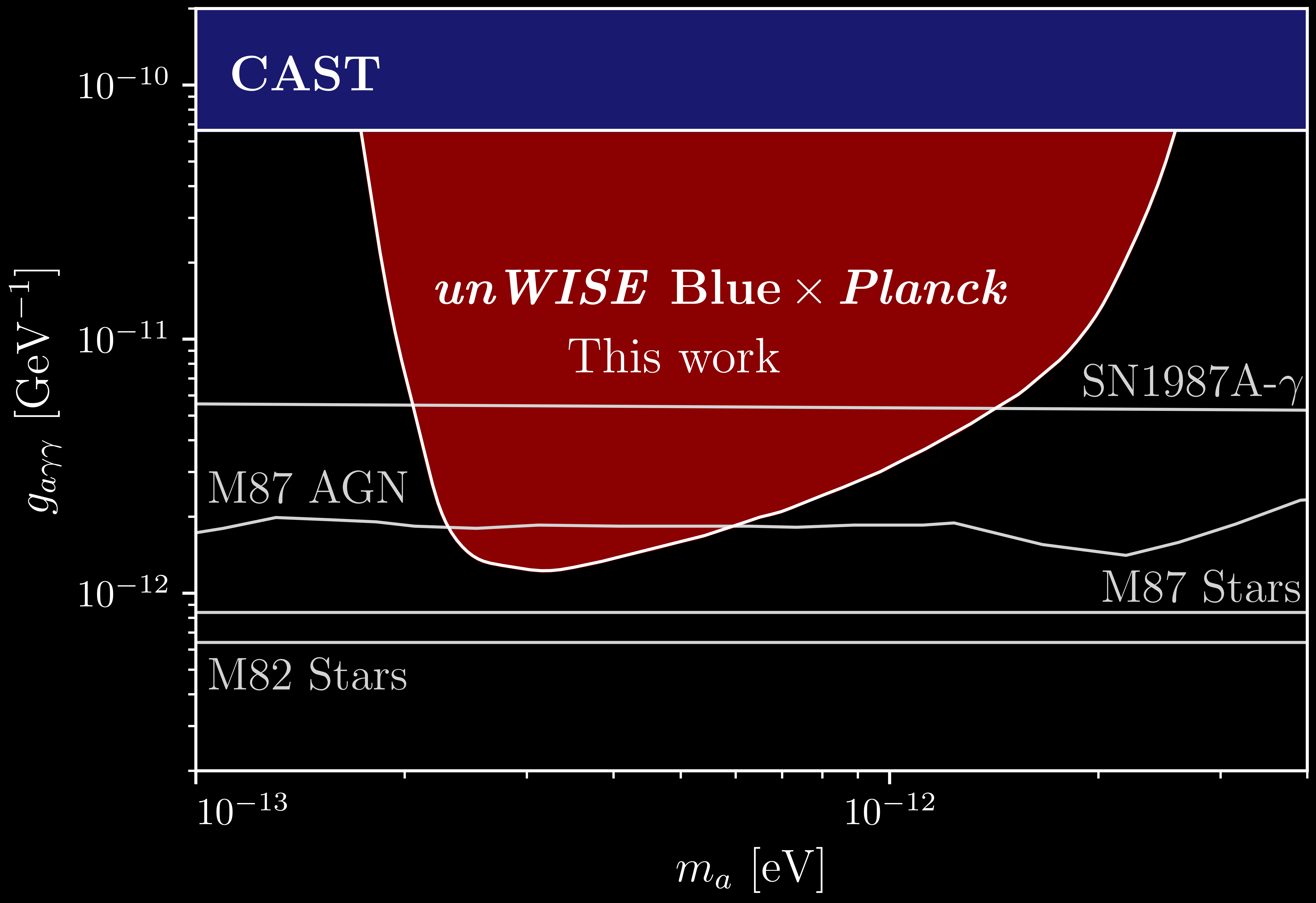


Large scales ***Small scales***

Constraints on axion-photon coupling

- We obtain some of the tightest constraints on $g_{a\gamma\gamma}$ for $m_a \approx 5 \times 10^{-13}$ eV axions
- Highly complementary to existing bounds
  - Existing bounds: **single astrophysical object**
  - Our bounds: ensemble average over **30 million objects**

Goldstein++, *PRL 134.081001*



95% confidence interval on $g_{a\gamma\gamma}$

(https://cajohare.github.io/AxionLimits/)

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- Highly complementary to existing bounds
  - Existing bounds: **single astrophysical object**
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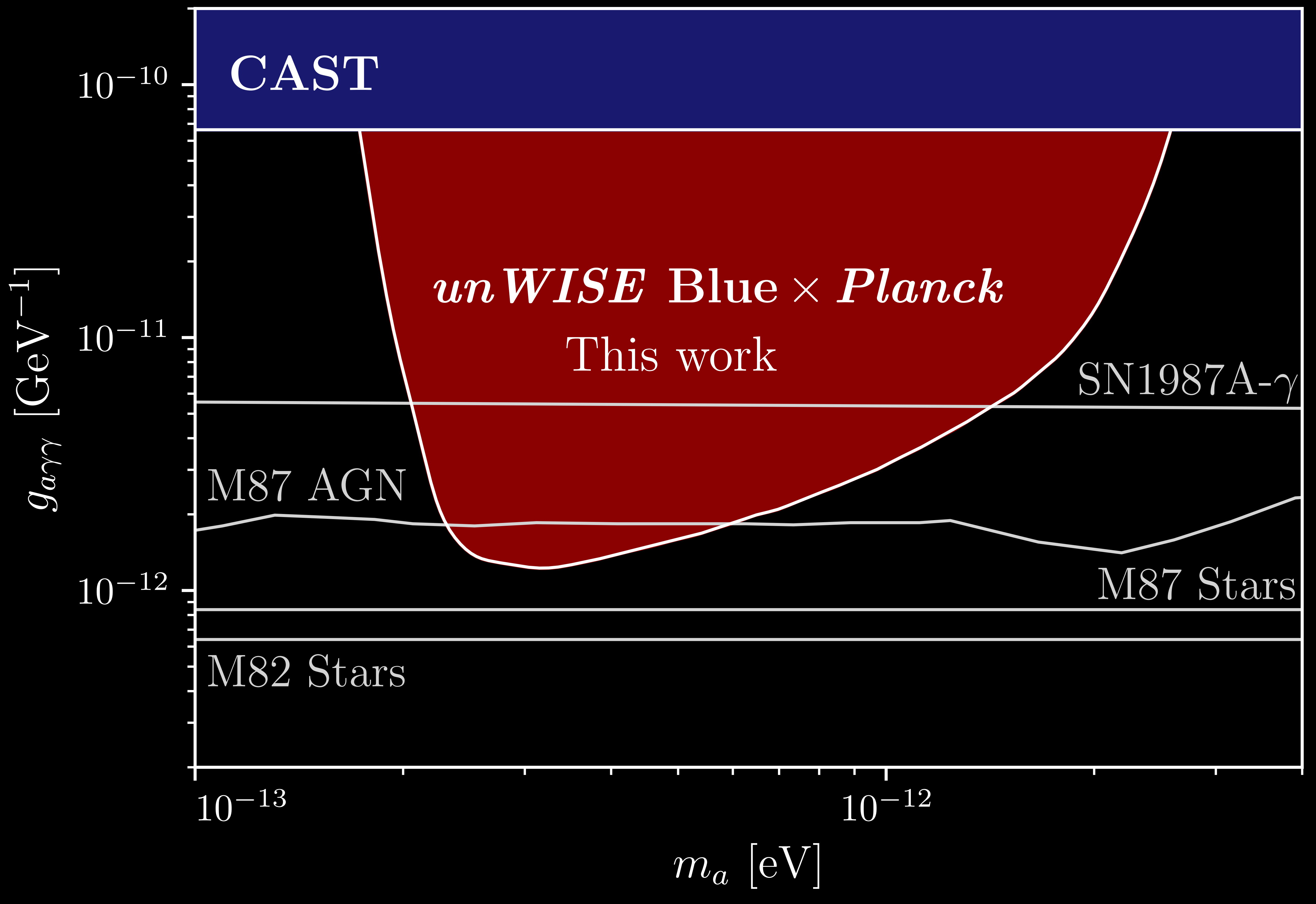
We can do better with new ACT DR6 data!

Goldstein++, *PRL 134.081001*



95% confidence interval on $g_{a\gamma\gamma}$

(https://cajohare.github.io/AxionLimits/)

Adding in ACT data

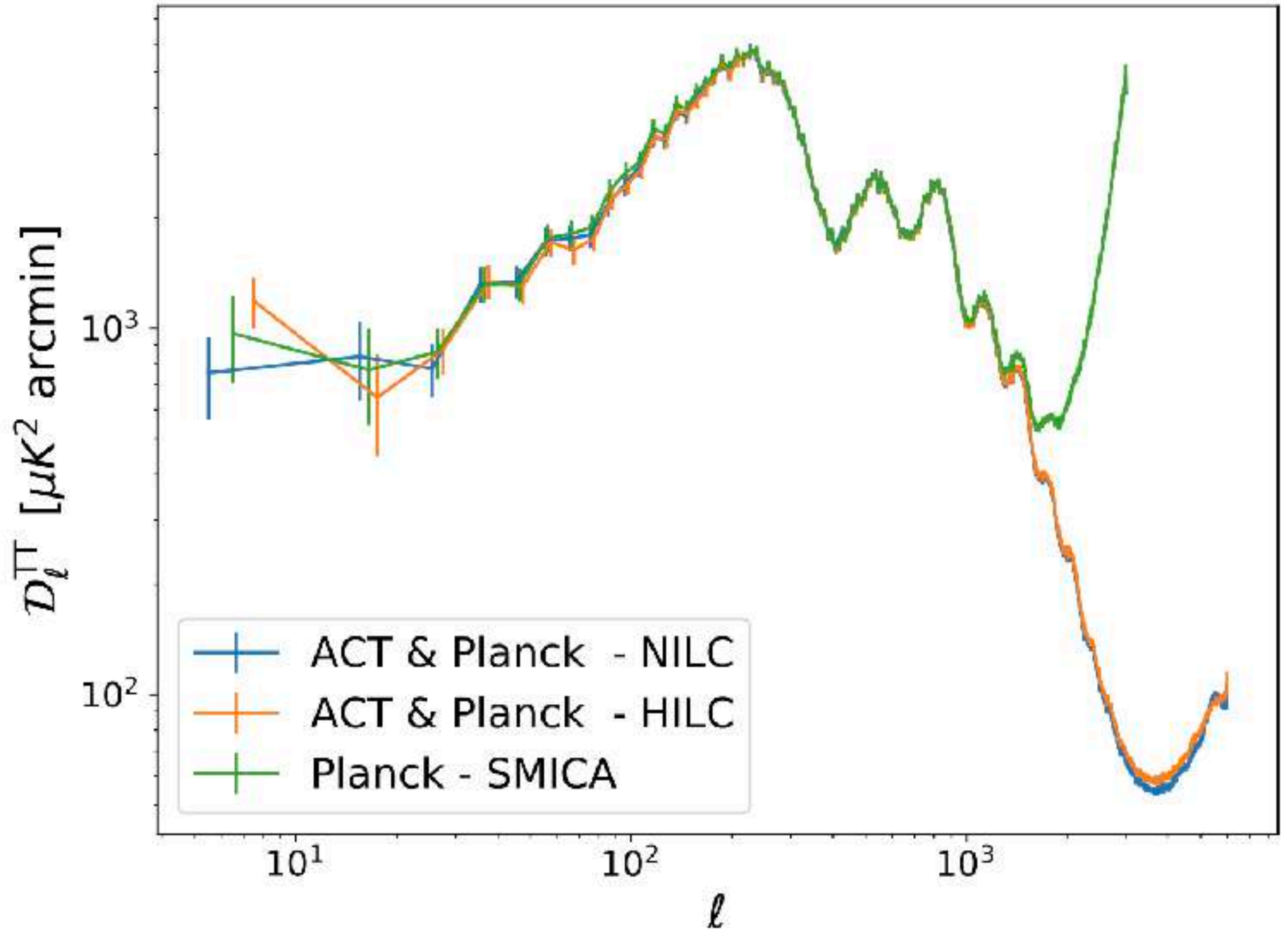
- Screening happens inside halos -> additional info at small scales

- ACT has high-resolution 90, 150, and 220 GHz maps

- ***Challenges***:

  - More maps + higher resolution -> need a faster NILC pipeline

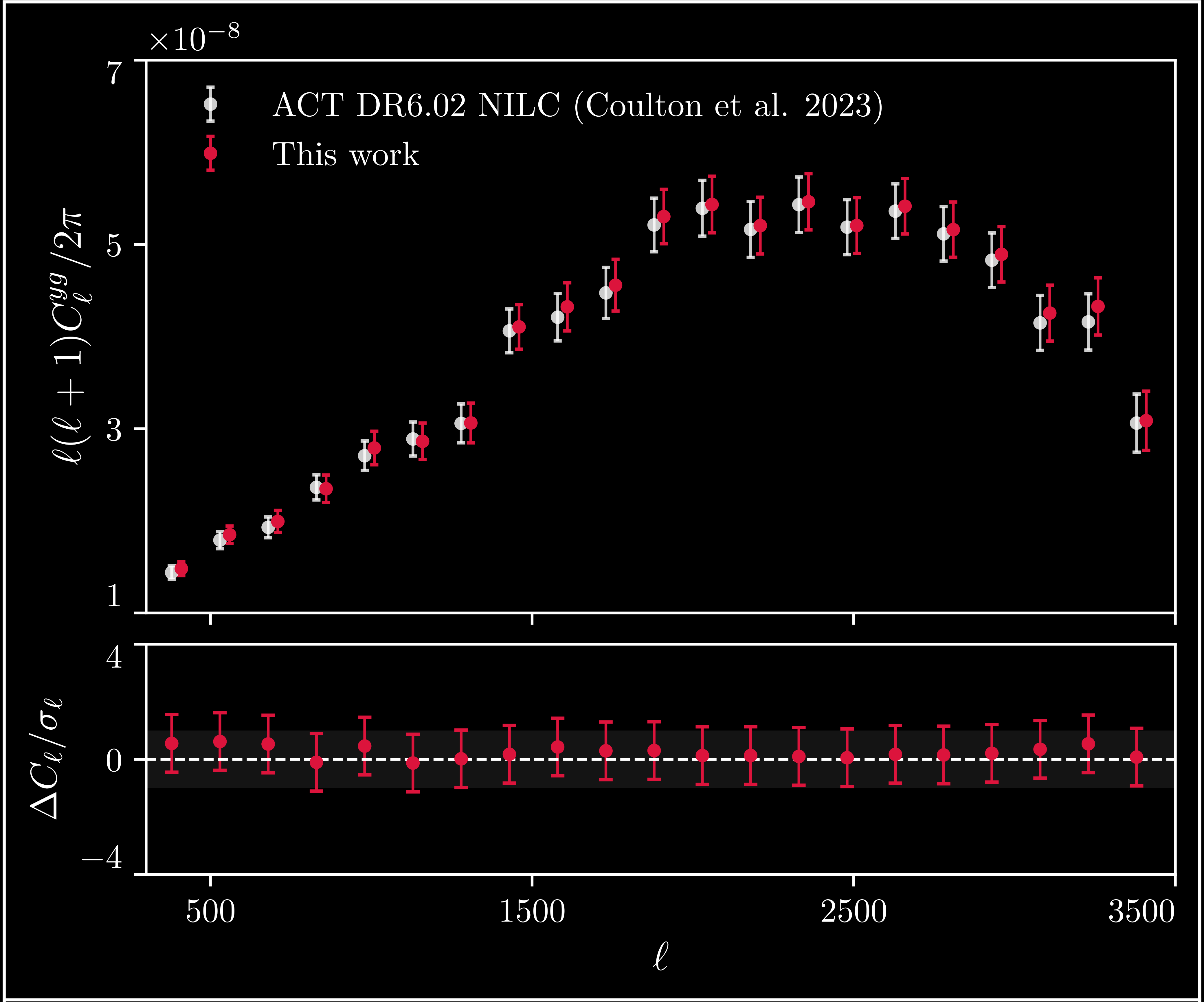
  - More sensitive data requires better foreground model and improved treatment of systematic uncertainties



*Example of statistical gains in NILC maps after adding ACT data (**Coulton++23**)*

A new NILC pipeline: Coberus

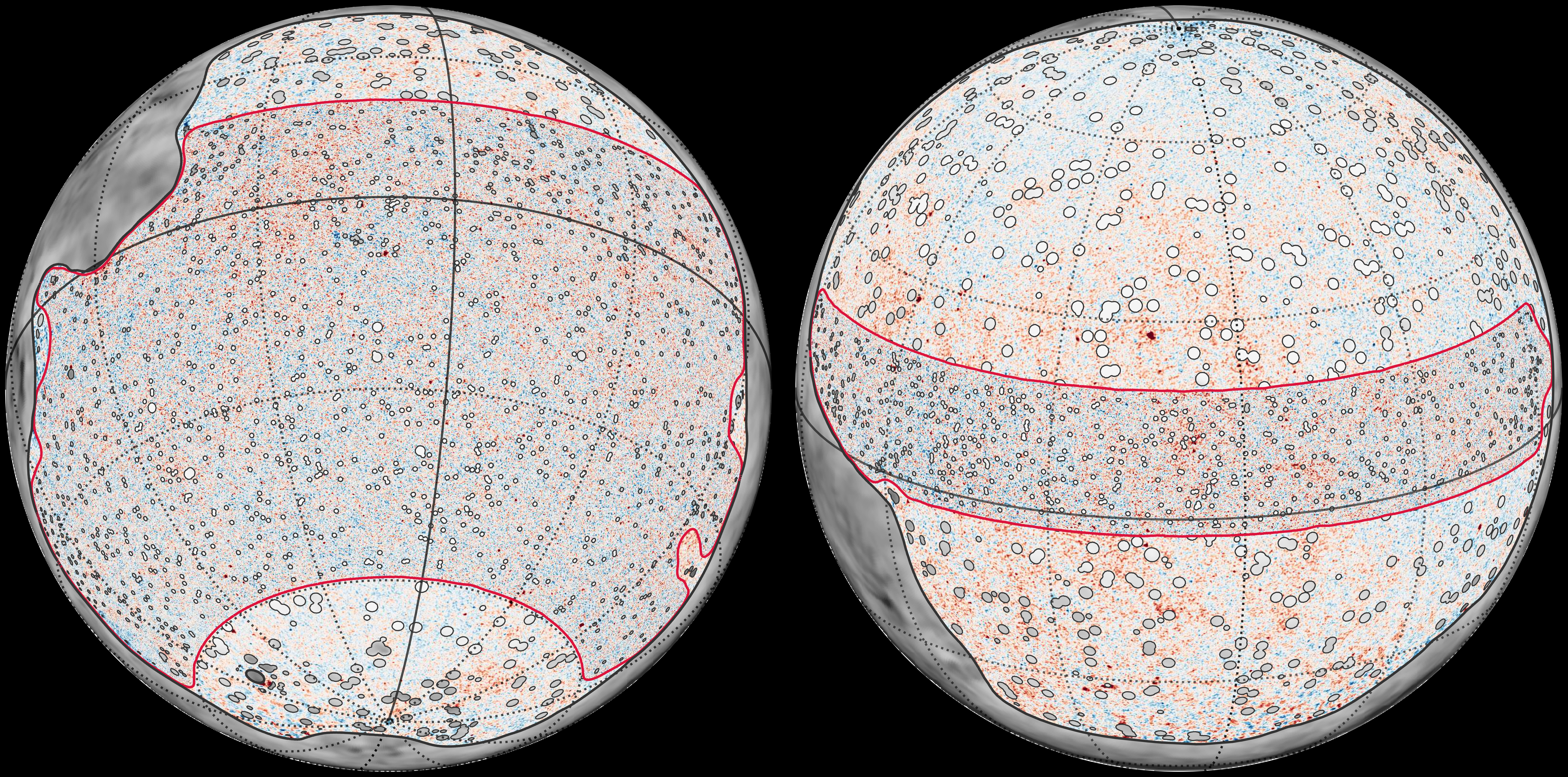
- **Coberus*** dask-based NILC code developed for SO)
  - Combine ACT+Planck up to $\ell_{\max} \sim 10{,}000$ in ~5 minutes on a single node
  - Full sky component separation
- Can now marginalize over calibration, passband, and beam uncertainties



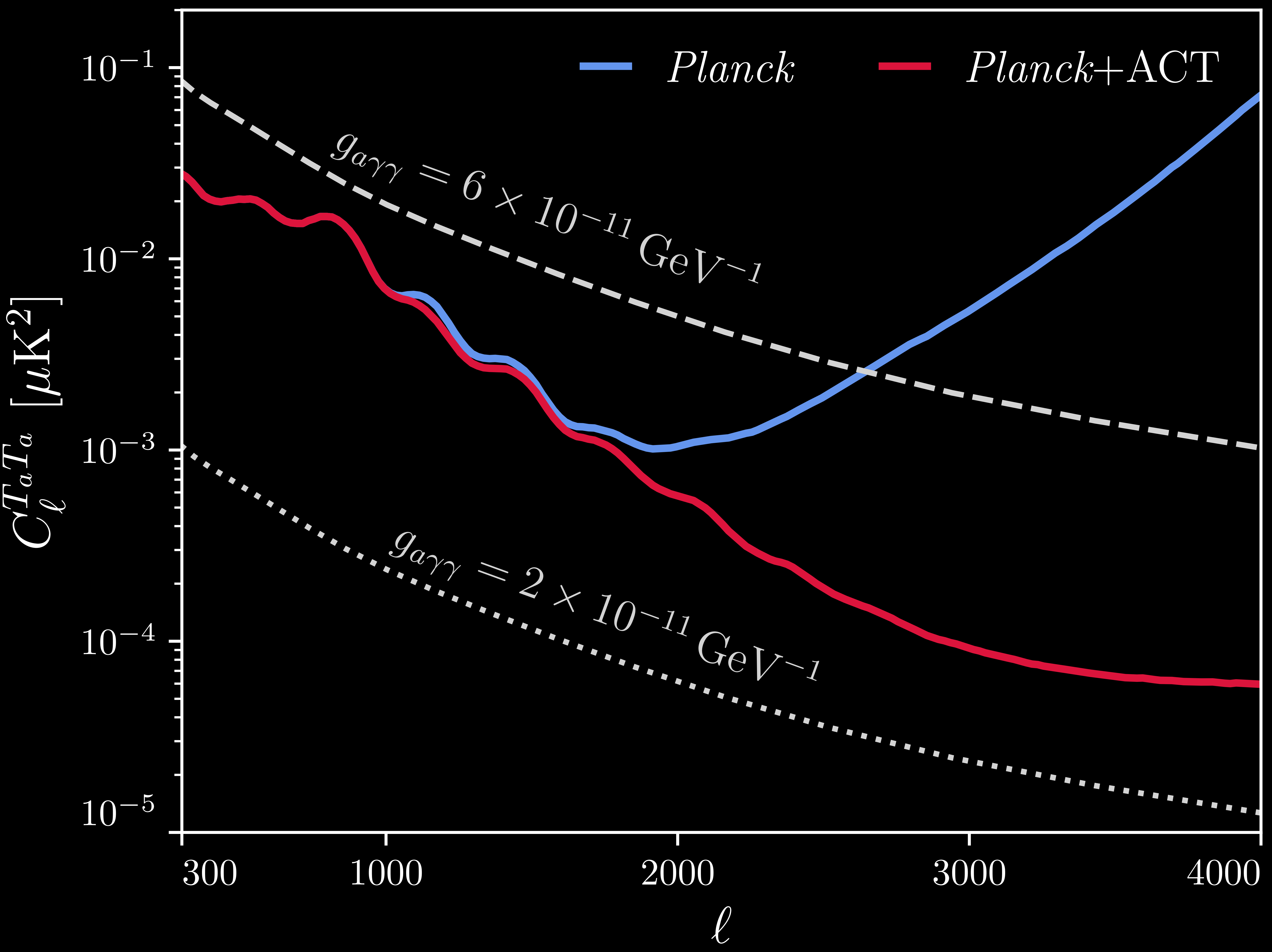
Key result: publicly available pipeline for *Planck*+ACT NILC maps.

*https://github.com/simonsobs/coberus/ (with Josh Borrow, Joshua Kim, and Mathew Madhavacheril)

Planck+ACT Axion-induced screening NILC map: no deprojections

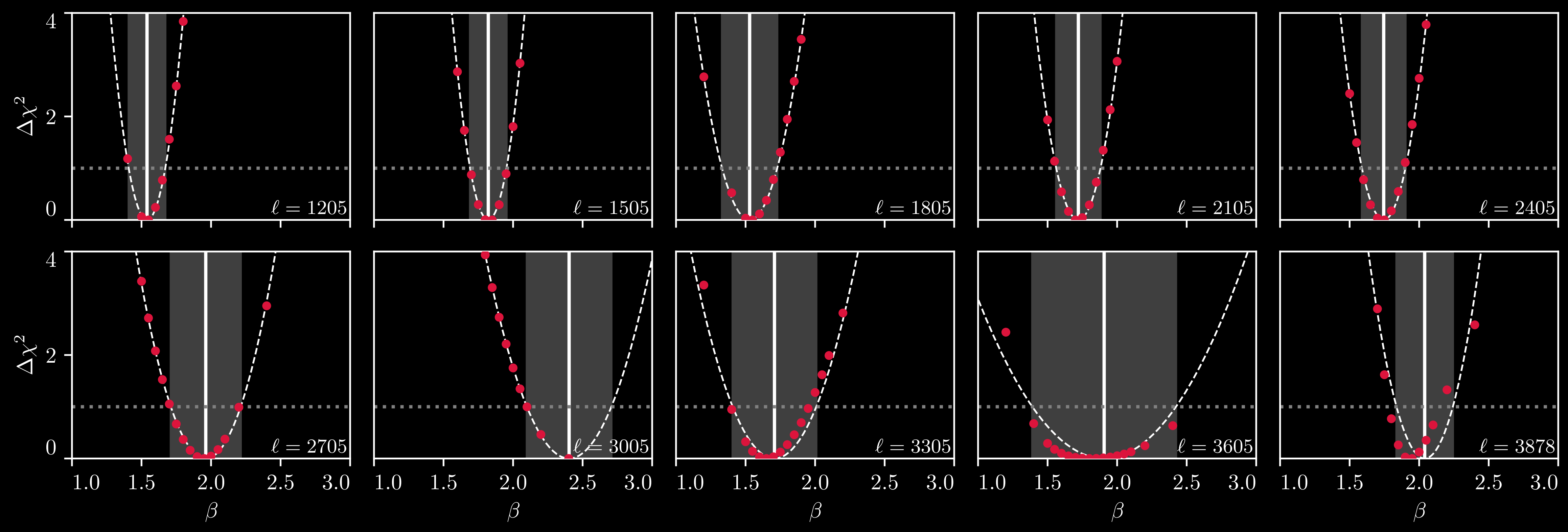


Improvement 1: Adding in ACT data

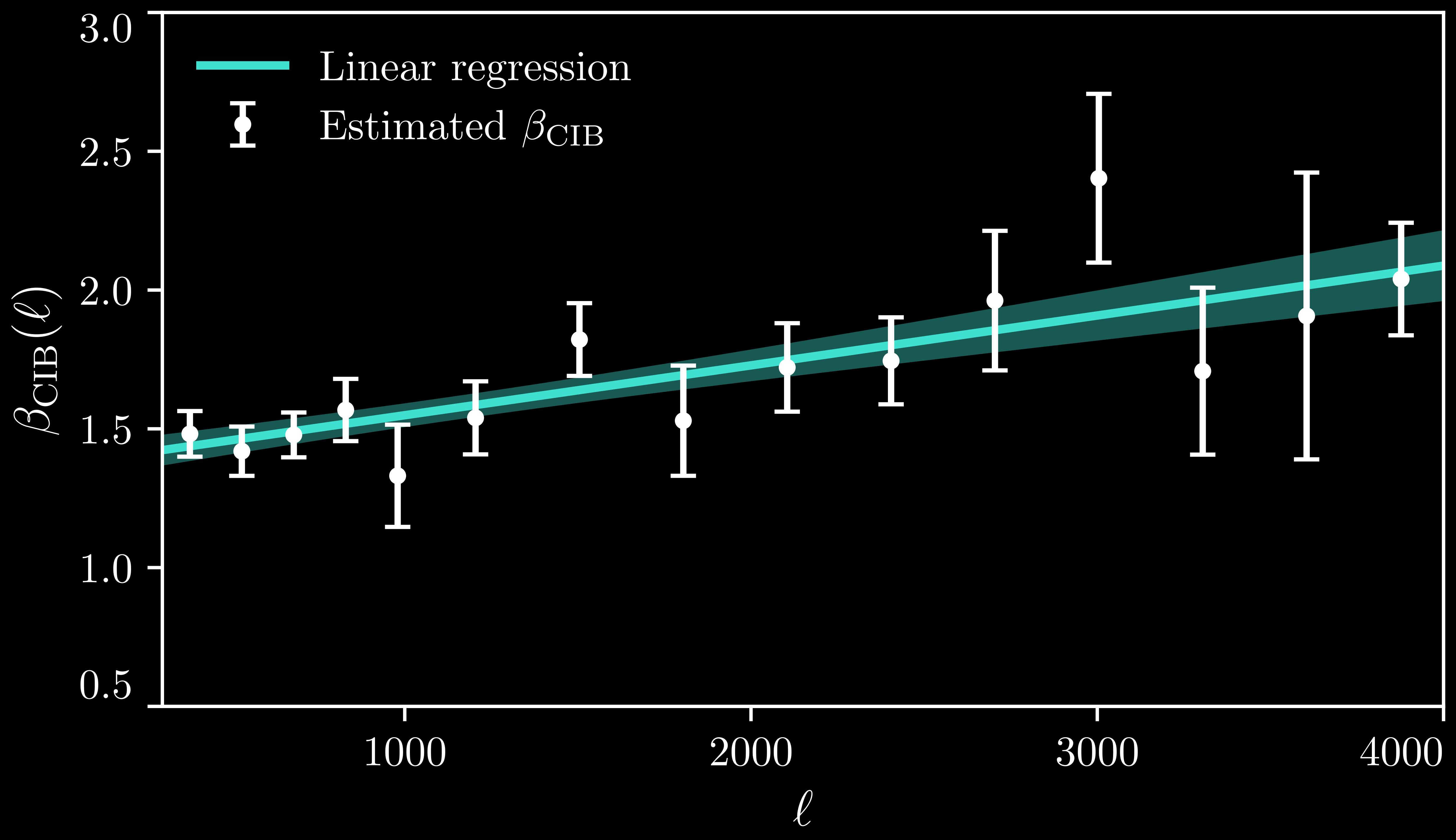


Improvement 2: Better treatment of the CIB SED

- First application of a new technique for mitigating CIB proposed in ***Surrao++25***
  - Data-driven approach to estimate $\beta_{\rm CIB}$ for a particular LSS tracer

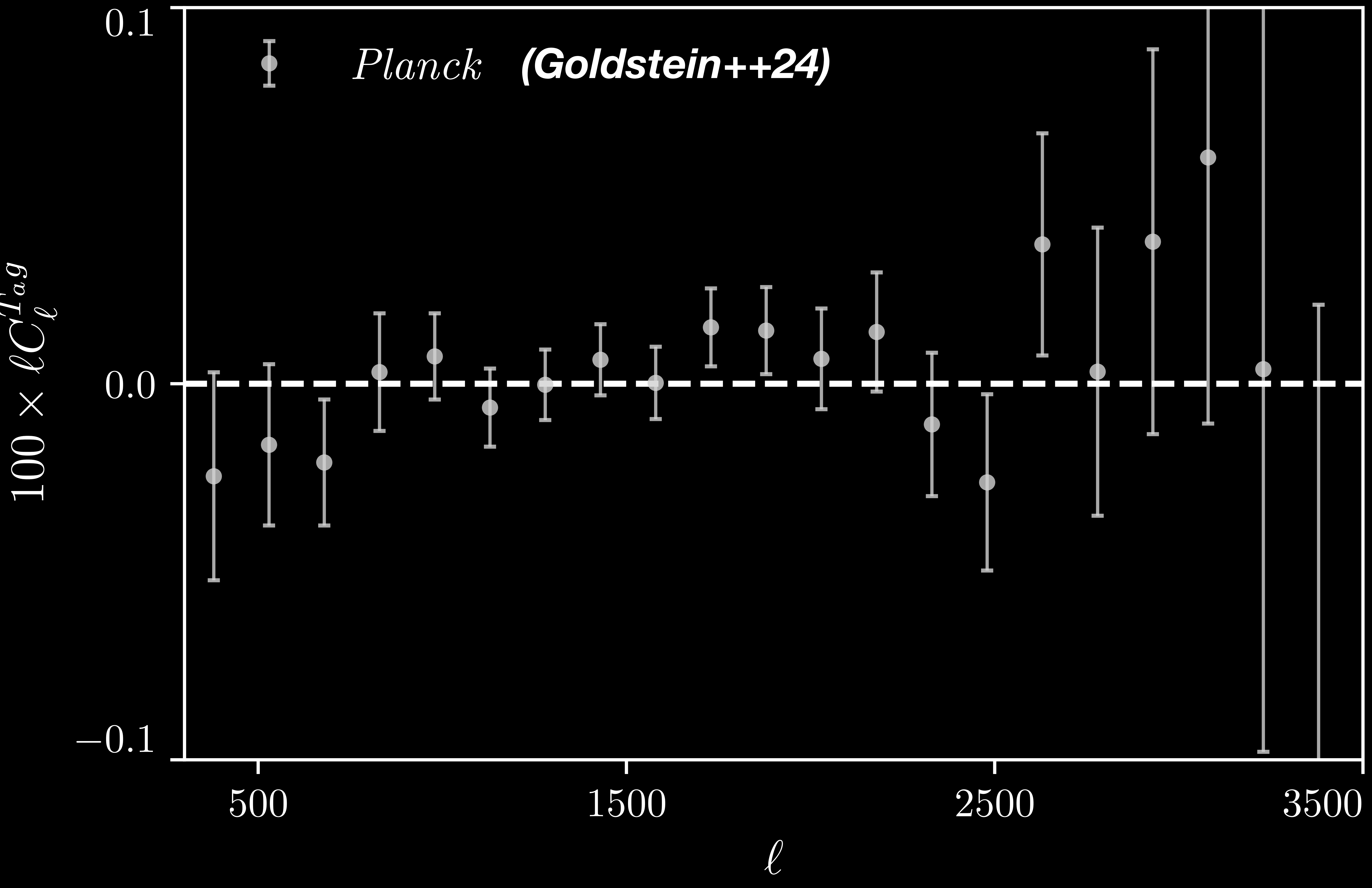


- ***Advantage:*** no moment deprojection -> lower noise in NILC map

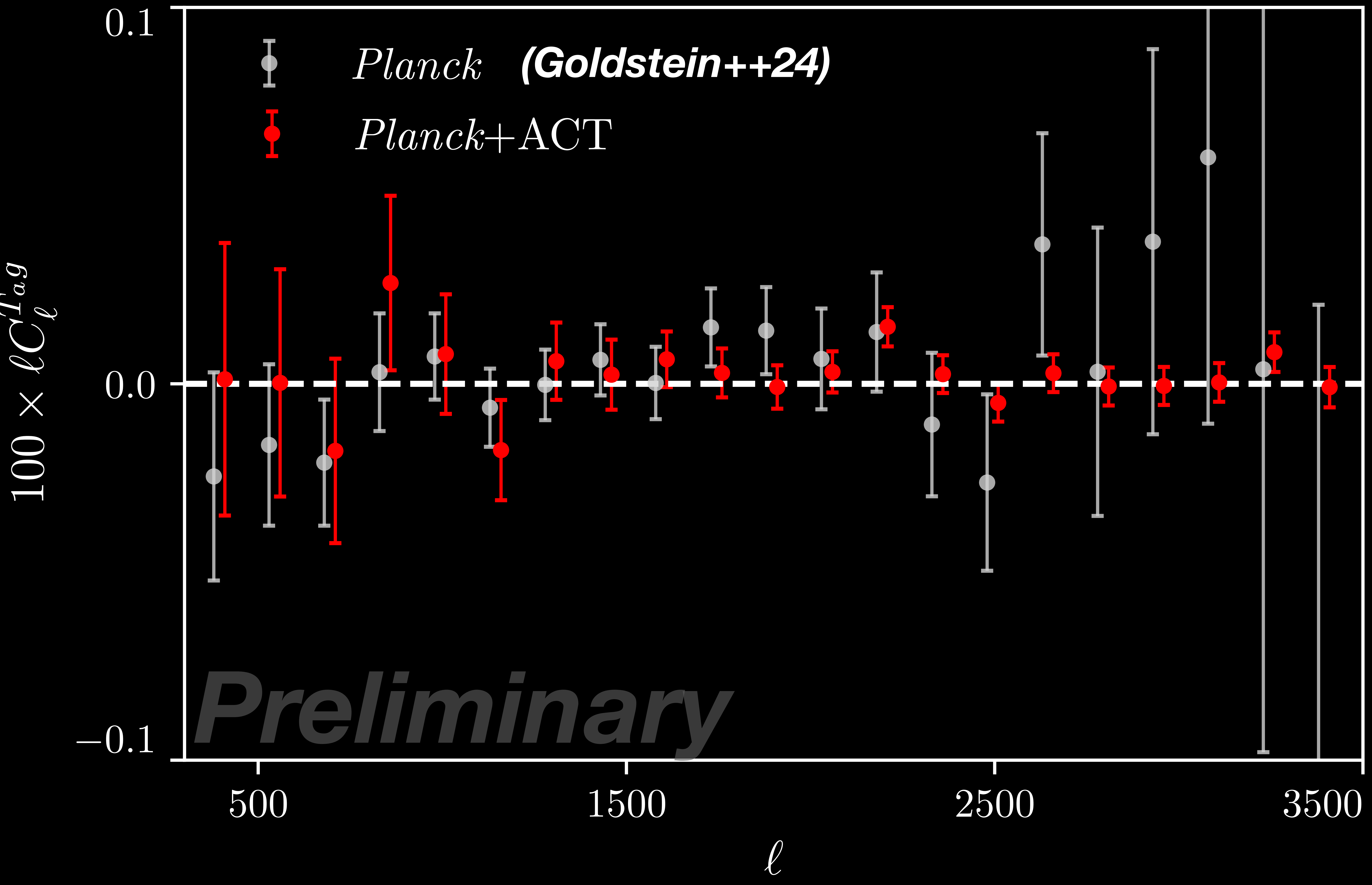


- ***Challenge:*** requires running 100-1000 NILCs **without reuising covariances**
  - Infeasible without Coberus

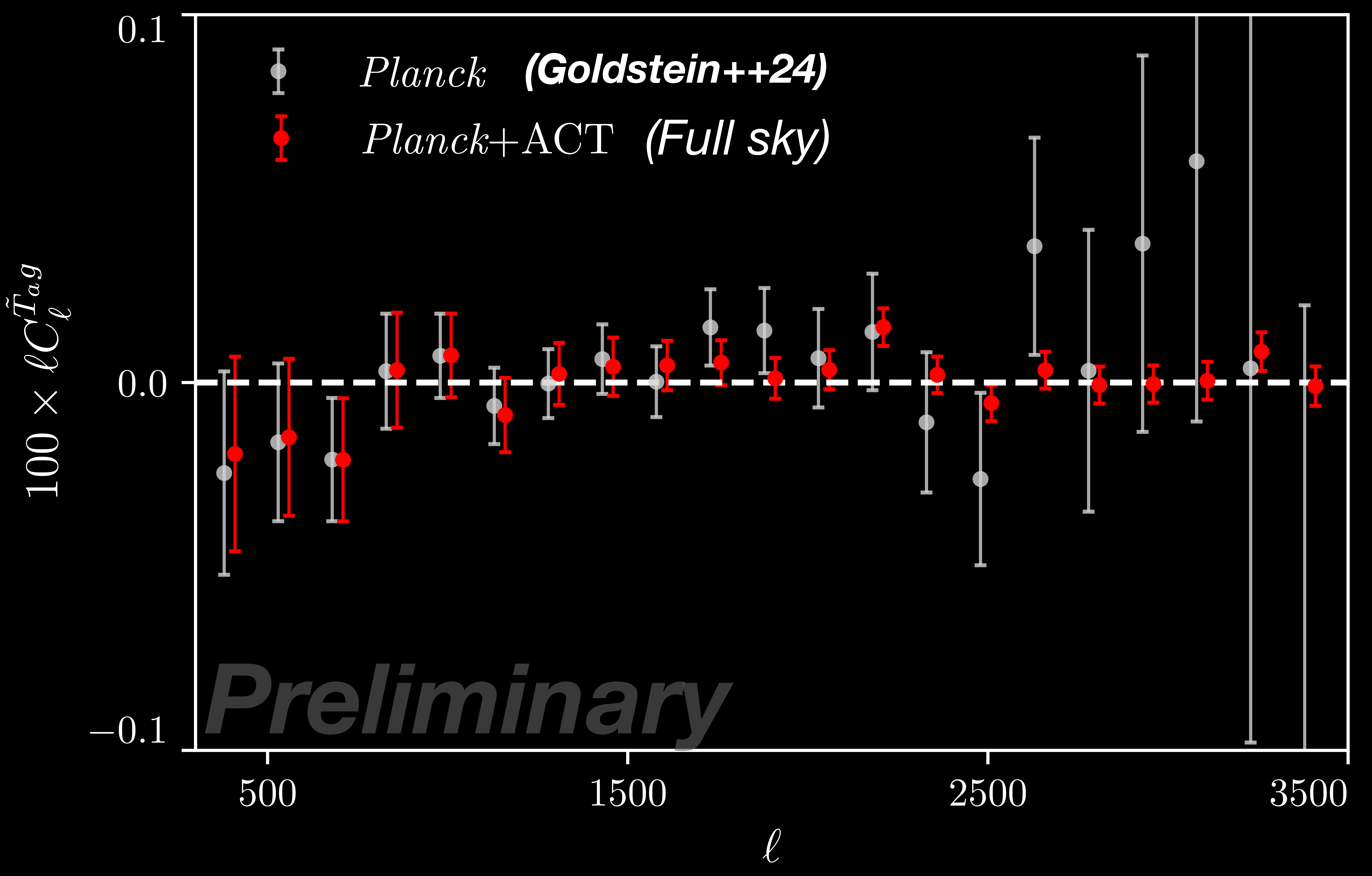
New axion-induced screening measurement



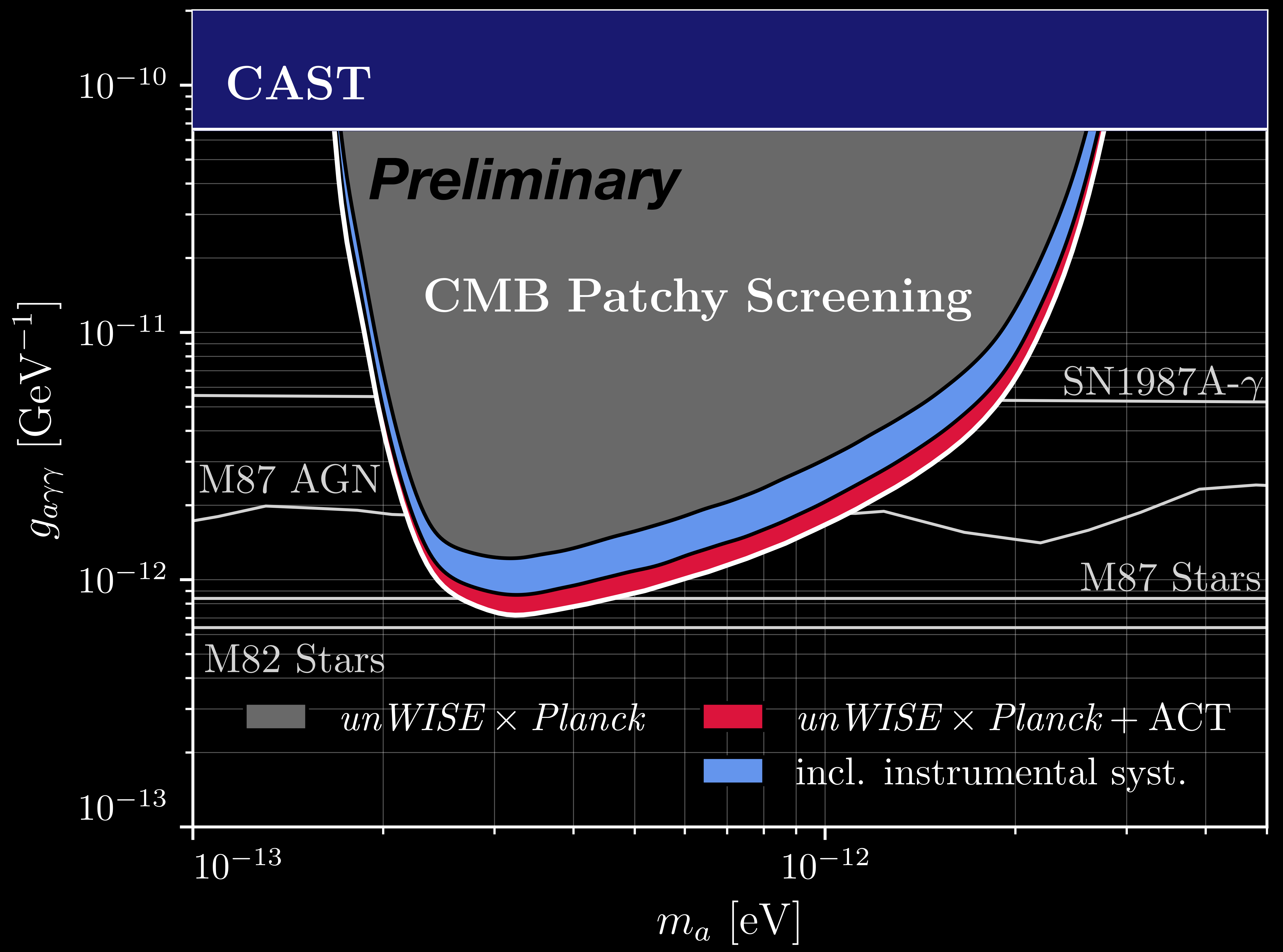
New axion-induced screening measurement



New axion-induced screening measurement

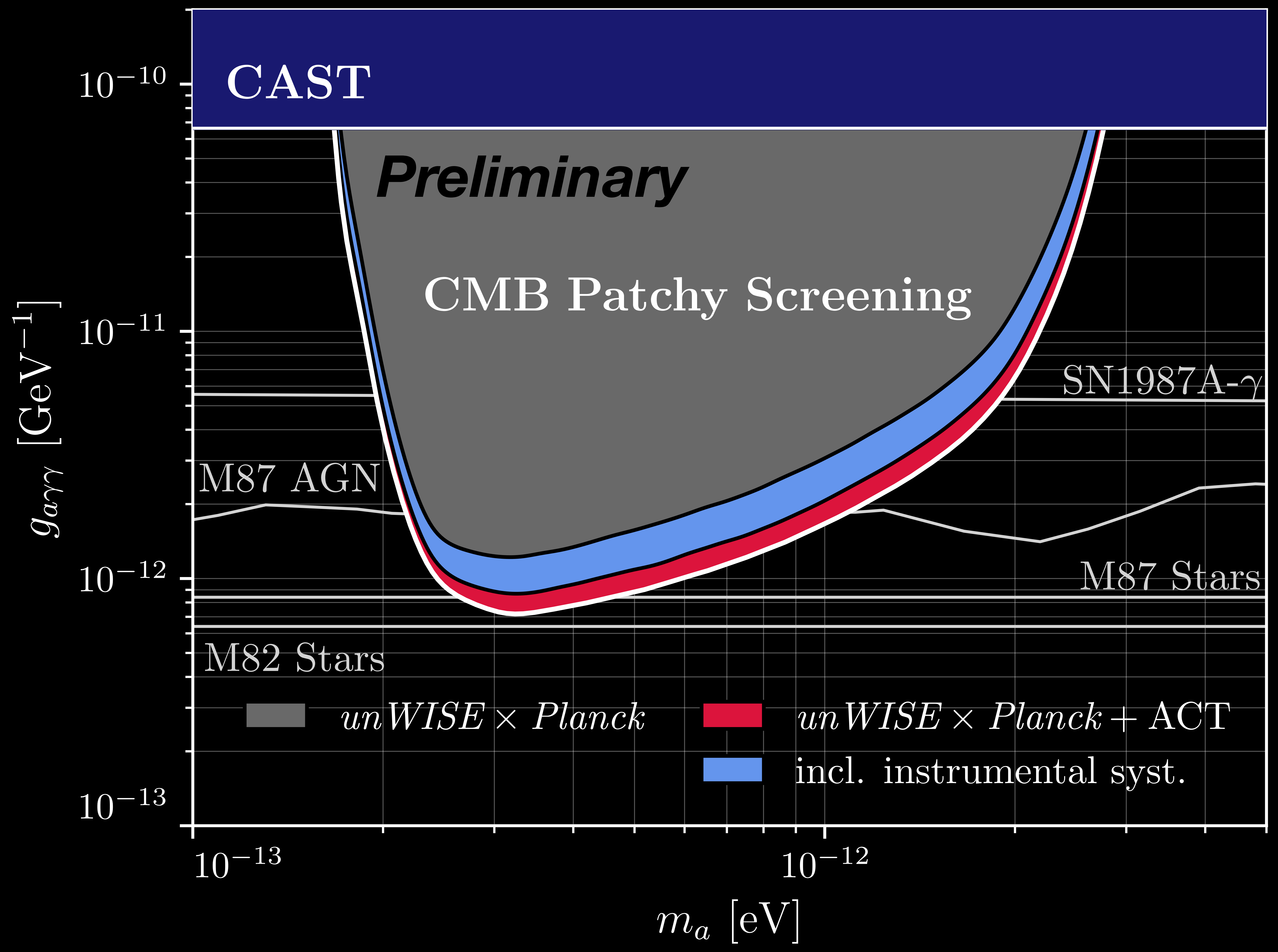


New axion-induced screening constraints



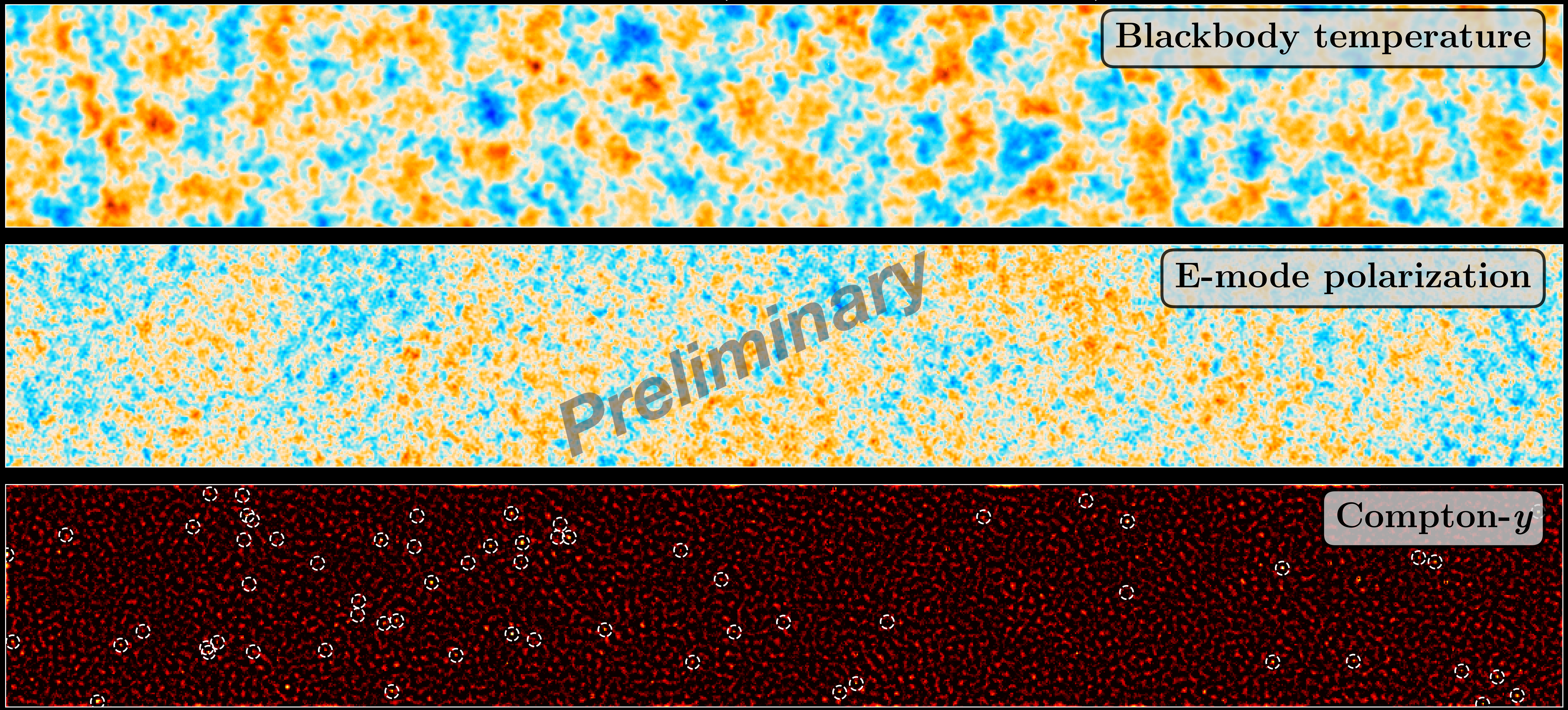
- New data+new techniques -> **nearly a factor of two reduction in stat. error**
- New pipeline enables estimate of **syst. error** from instrument (requires $\mathcal{O}(1000)$ NILC maps)

New axion-induced screening constraints



What's next for dark screening?

Future outlook: improvements from the CMB side



Have run NILC pipeline on early SO Large Aperture Telescope (LAT) data

Credit: Simons Observatory Collaboration

Goldstein++ (in prep.)

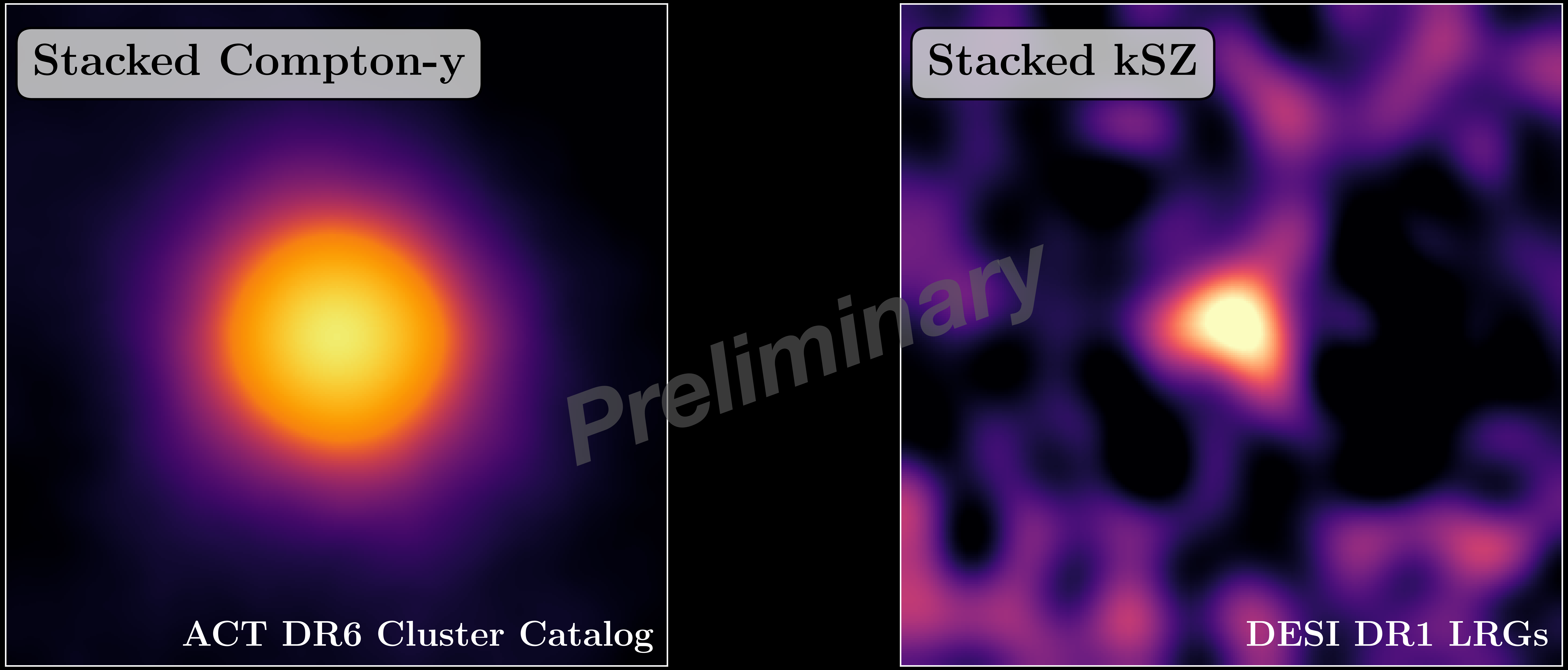
Future outlook: improvements from the CMB side

Signal-dominated T and E-mode maps from < 200 hours of data

Credit: Simons Observatory Collaboration

Goldstein++ (in prep.)

Future outlook: improvements from the CMB side



- Already have a significant detection of kSZ (***thanks also to DESI***)

Credit: Simons Observatory Collaboration

Goldstein++ (in prep.)

Future outlook: improvements from the LSS side

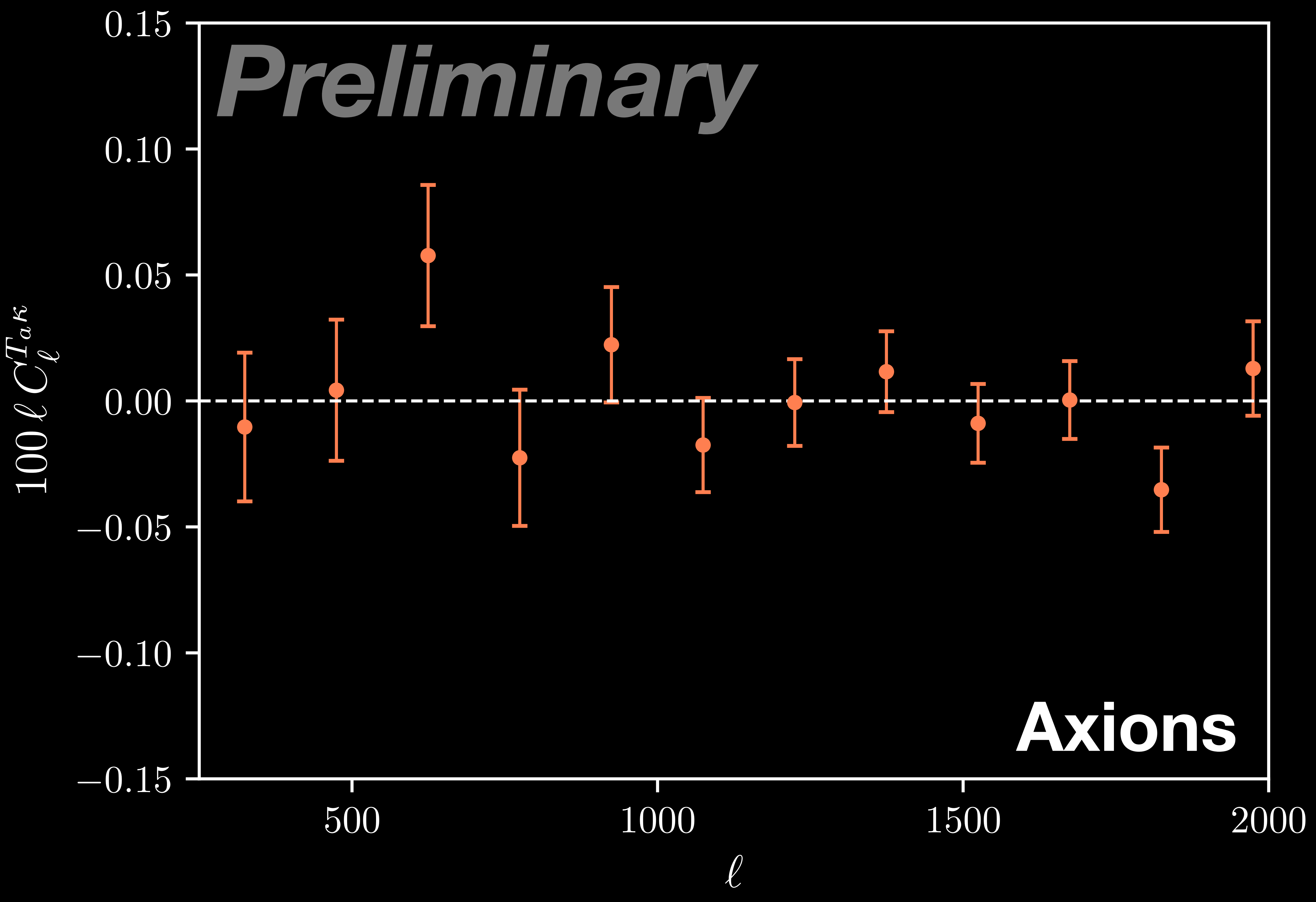
- *unWISE* is great for cross-correlations, but broad and photometric

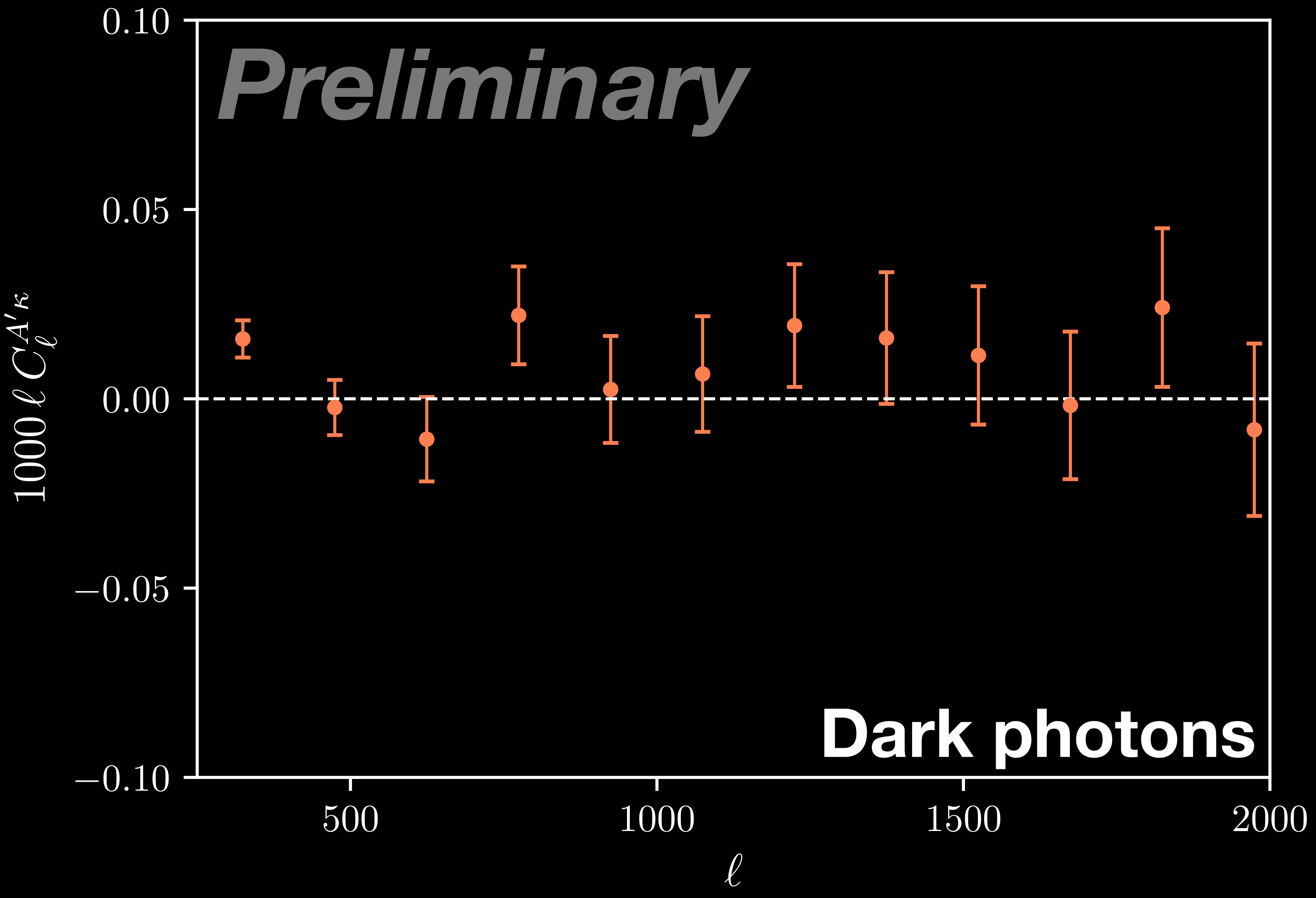
- Can do better with DESI
  - Spectroscopy -> tomography: wider range of m_a and better control of CIB and HOD
  - DESI Legacy Imaging Survey DR11: 4 billion sources of 75% of the sky

- Large overlap between DESI-II and SO

(Credit: Claire Lamman/DESI collaboration)

Future outlook: new tracers



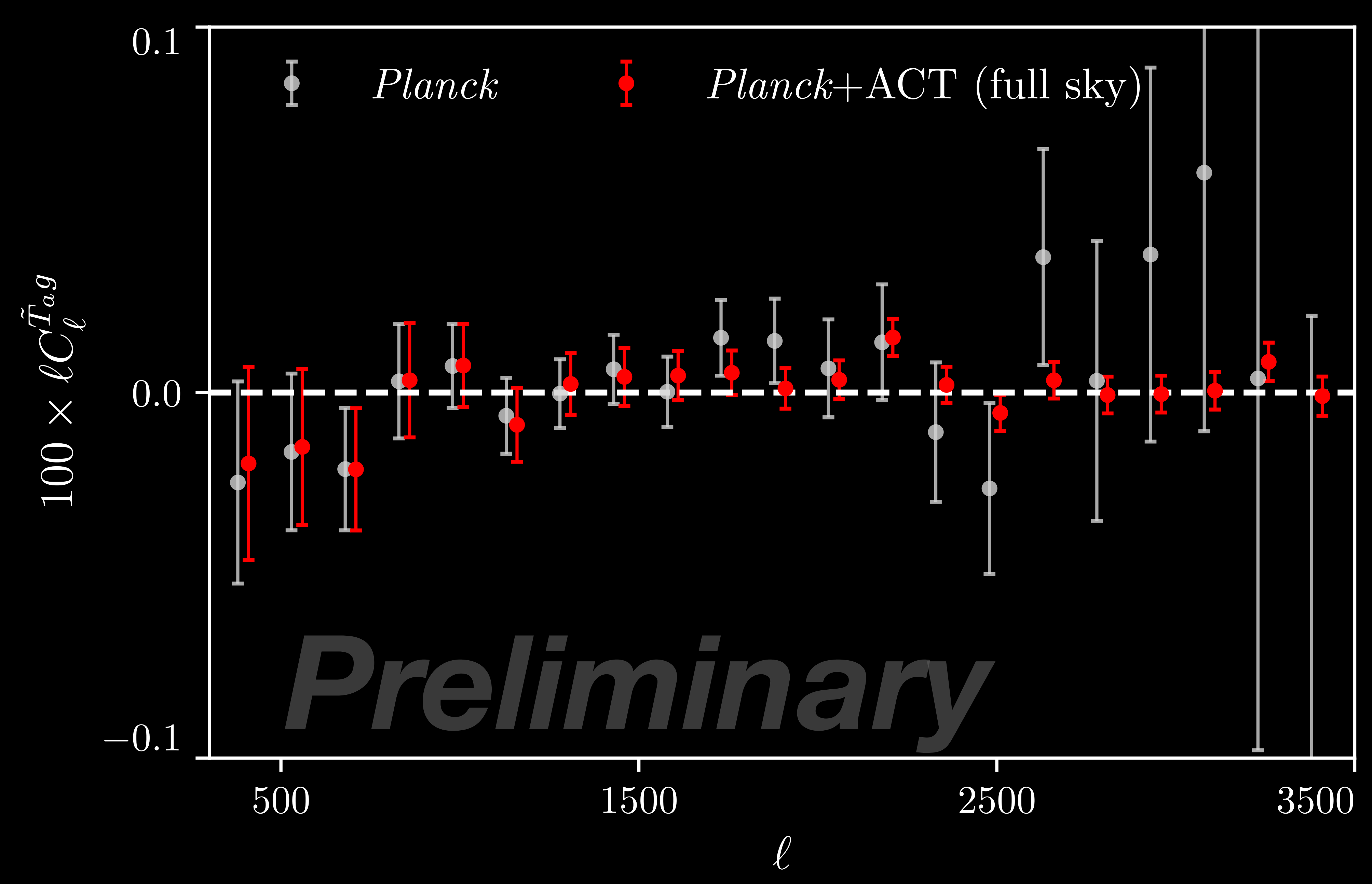


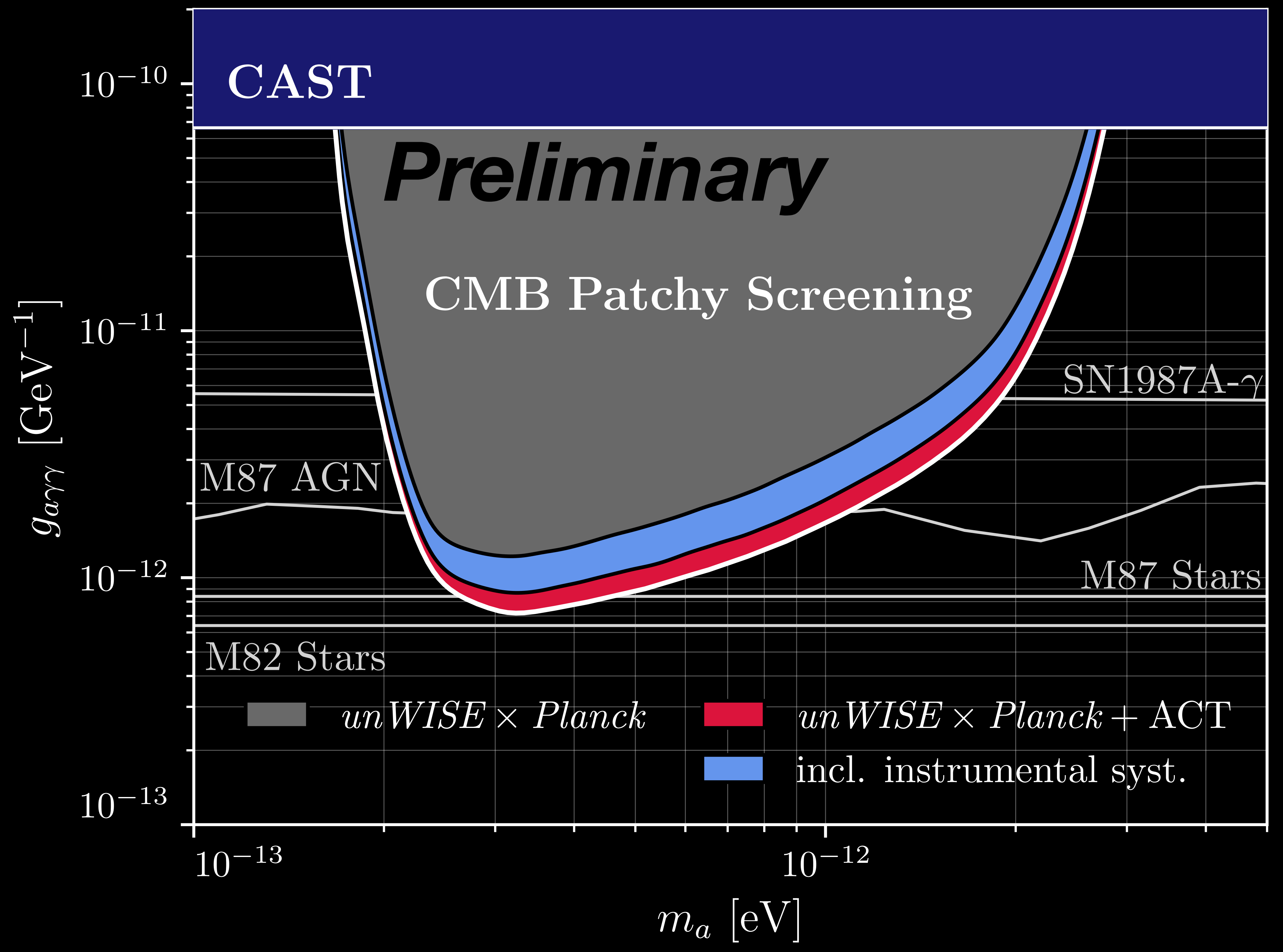
- Cross-correlate with ACT DR6 CMB lensing map (*Madhavacheril++23*)
    - Sensitive to lower mass axions and dark photons

Conclusion

- CMB secondaries are a powerful probe of the dark sector
  - No evidence for axion-induced screening in *unWISExPlanck*+ACT
  - Constrains $g_{a\gamma\gamma} \lesssim 8 \times 10^{-13}\ \mathrm{GeV}^{-1}$at $m_a \sim 3 \times 10^{-13}\ \mathrm{eV}$

- ***Along the way:*** public NILC pipeline for Simons Observatory, new foreground-mitigation techniques, and high-resolution *Planck*+ACT NILC maps





Part ii: uncovering the physics of inflation with galaxy surveys

Edmond Chaussidon

Simone Ferraro

Noah Sailer

U.S. DEPARTMENT OF ENERGY

Office of Science
SCGSR Program

BERKELEY LAB

Cosmic Inflation

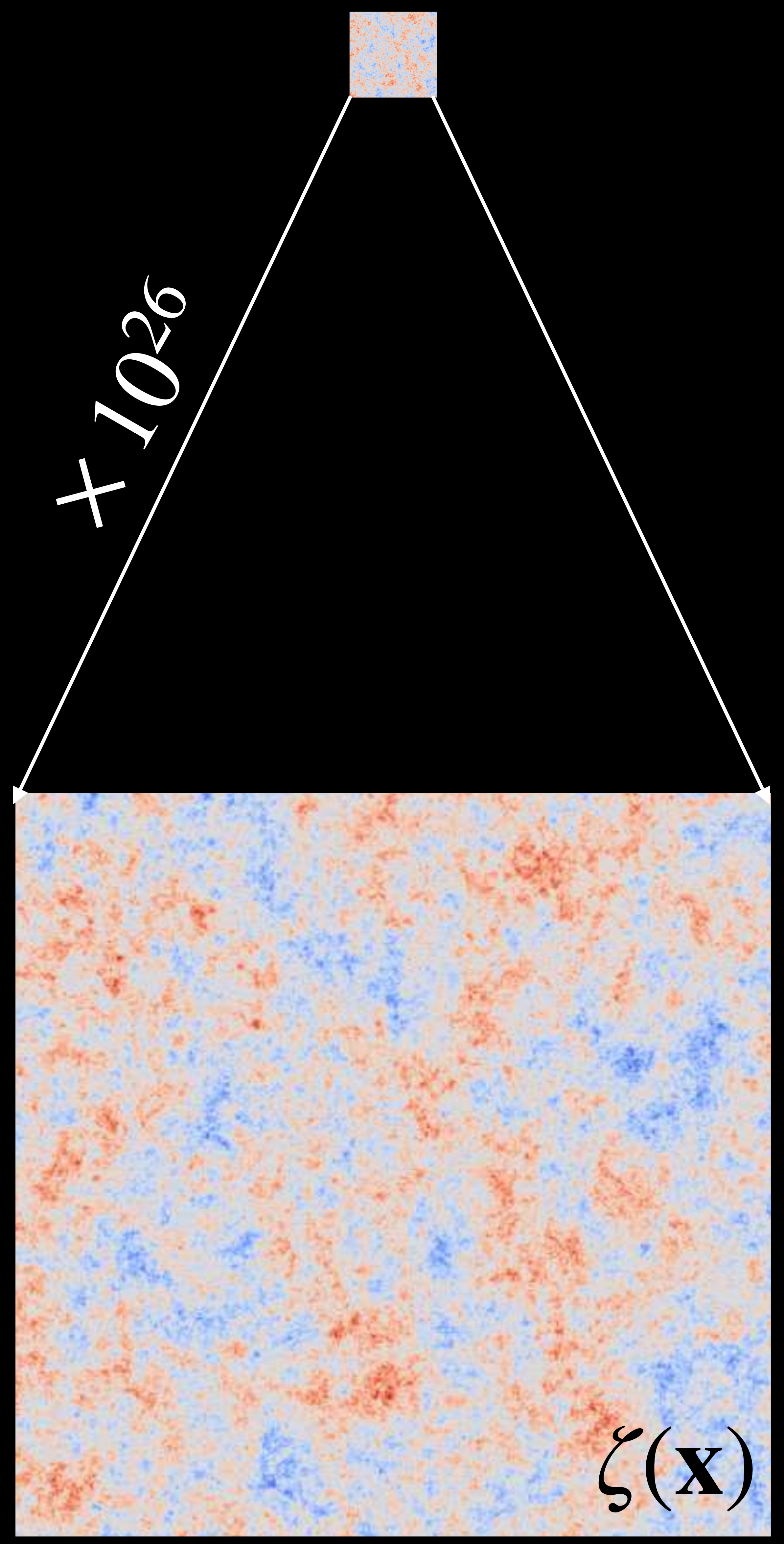
- Period of accelerated expansion in early Universe ($t \approx 10^{-34}$ seconds)
  - **Quantum fluctuations seed structure**

Stats. of fluctuations <-> inflationary physics

$\langle \zeta \ldots \zeta \rangle$ $\mathscr{L}_{\rm inf}(\phi, \chi, \psi_S)$

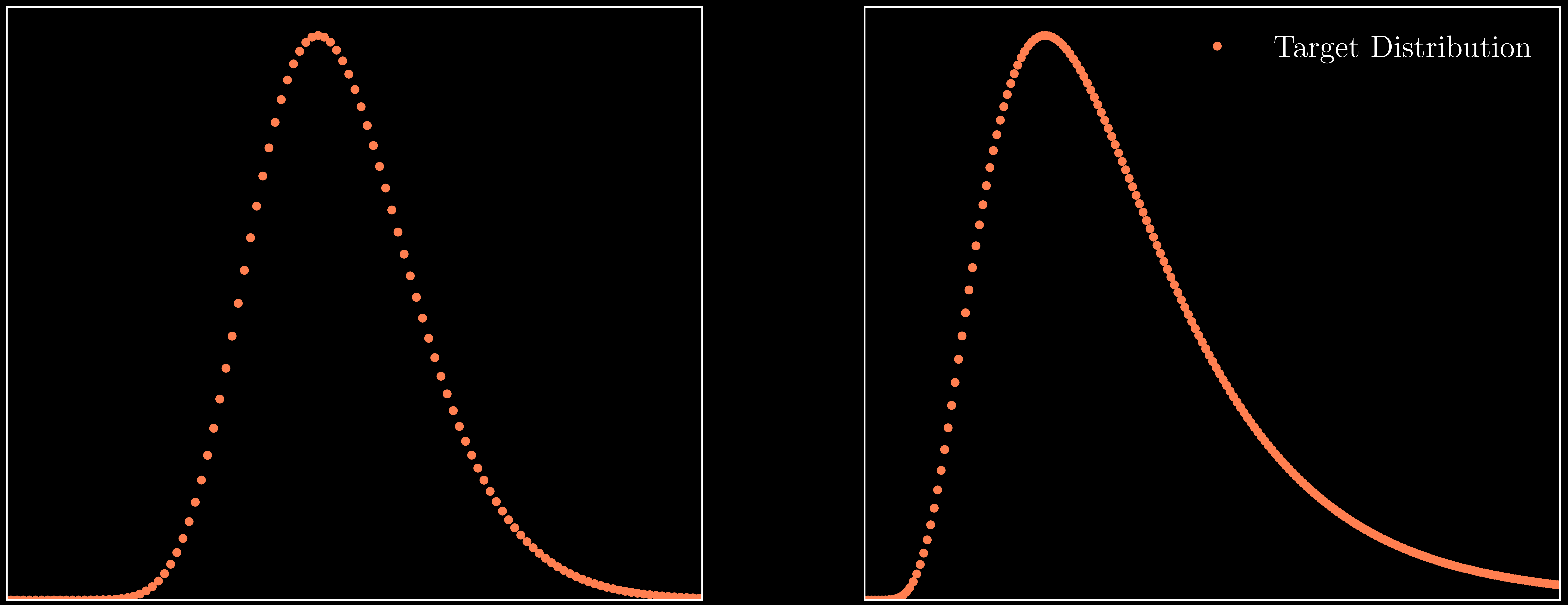
- Simplest models: **Gaussian** perturbations, $\zeta(\boldsymbol{x})$

What about primordial non-Gaussianity (PNG)?



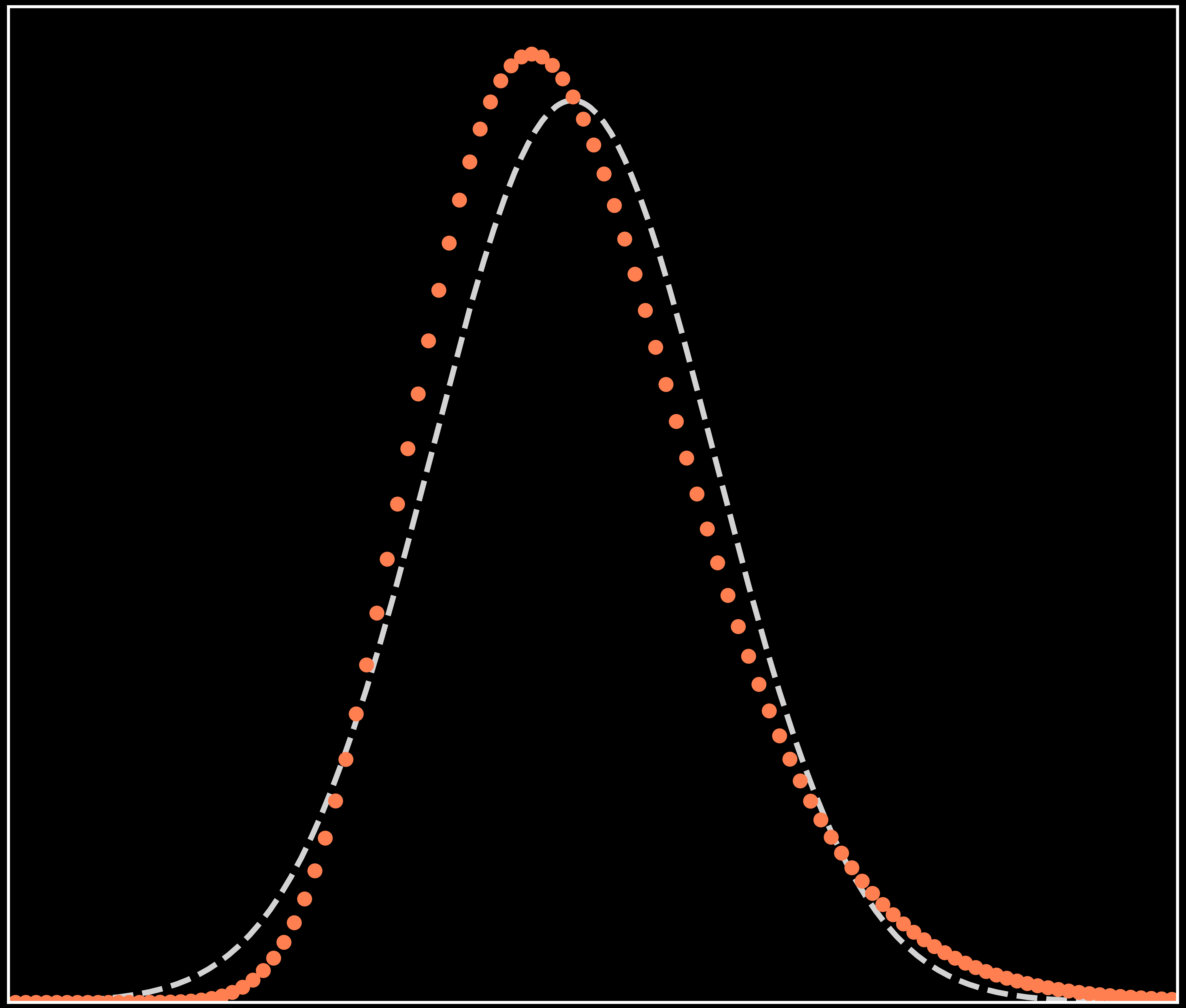
1). Weak non-Gaussianity

2). Strong non-Gaussianity

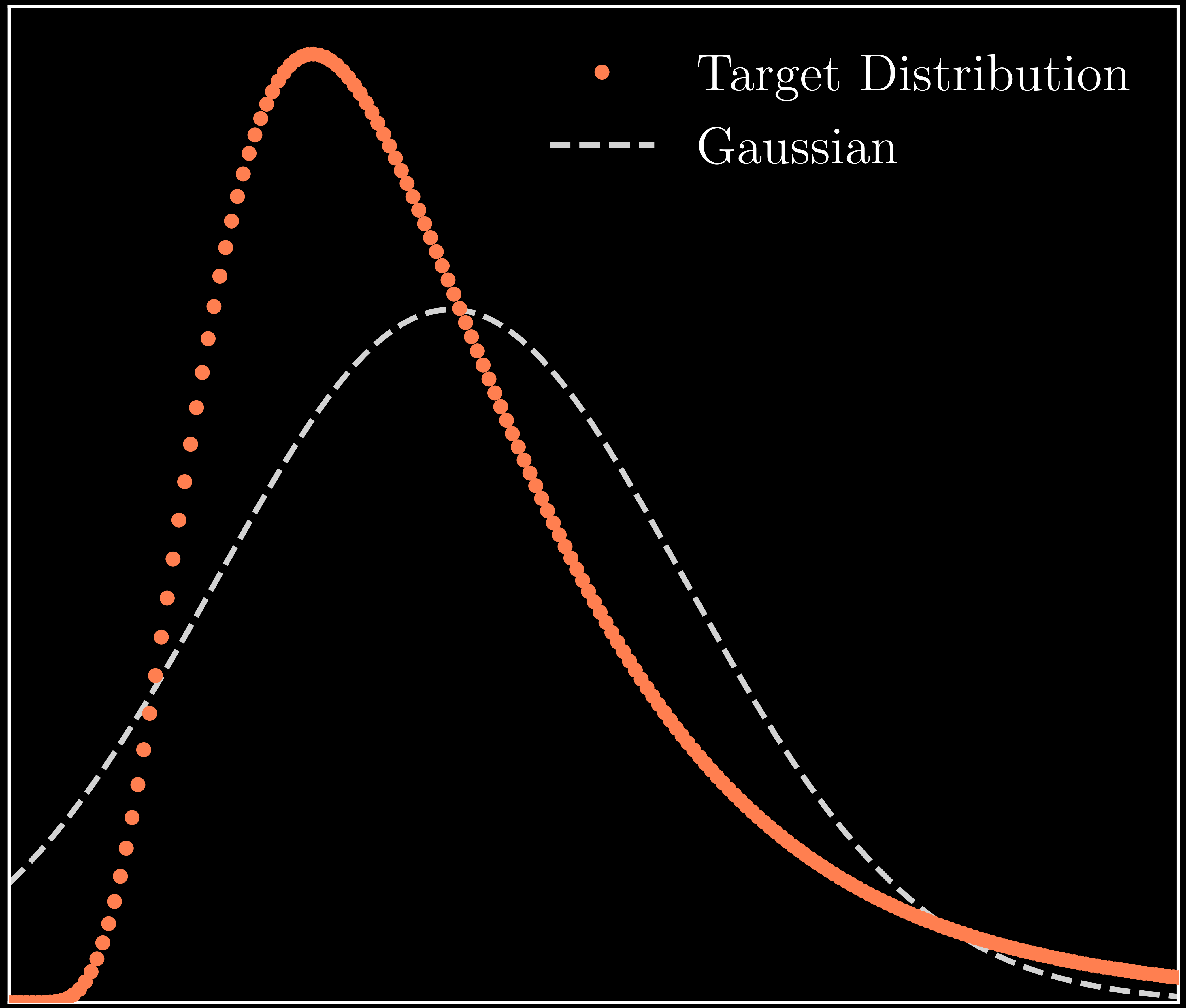


The two regimes of non-Gaussianity

1). Weak non-Gaussianity



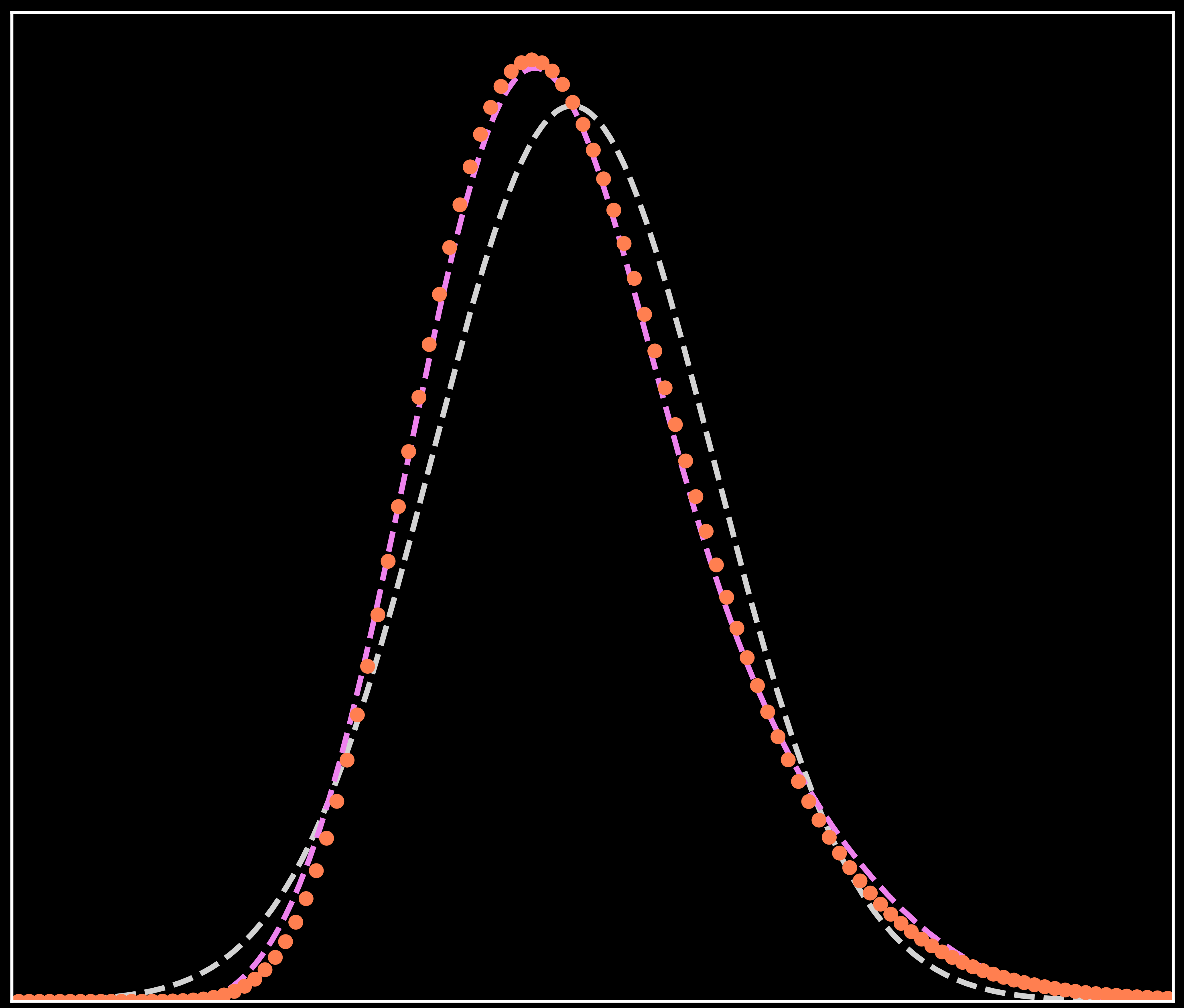
2). Strong non-Gaussianity



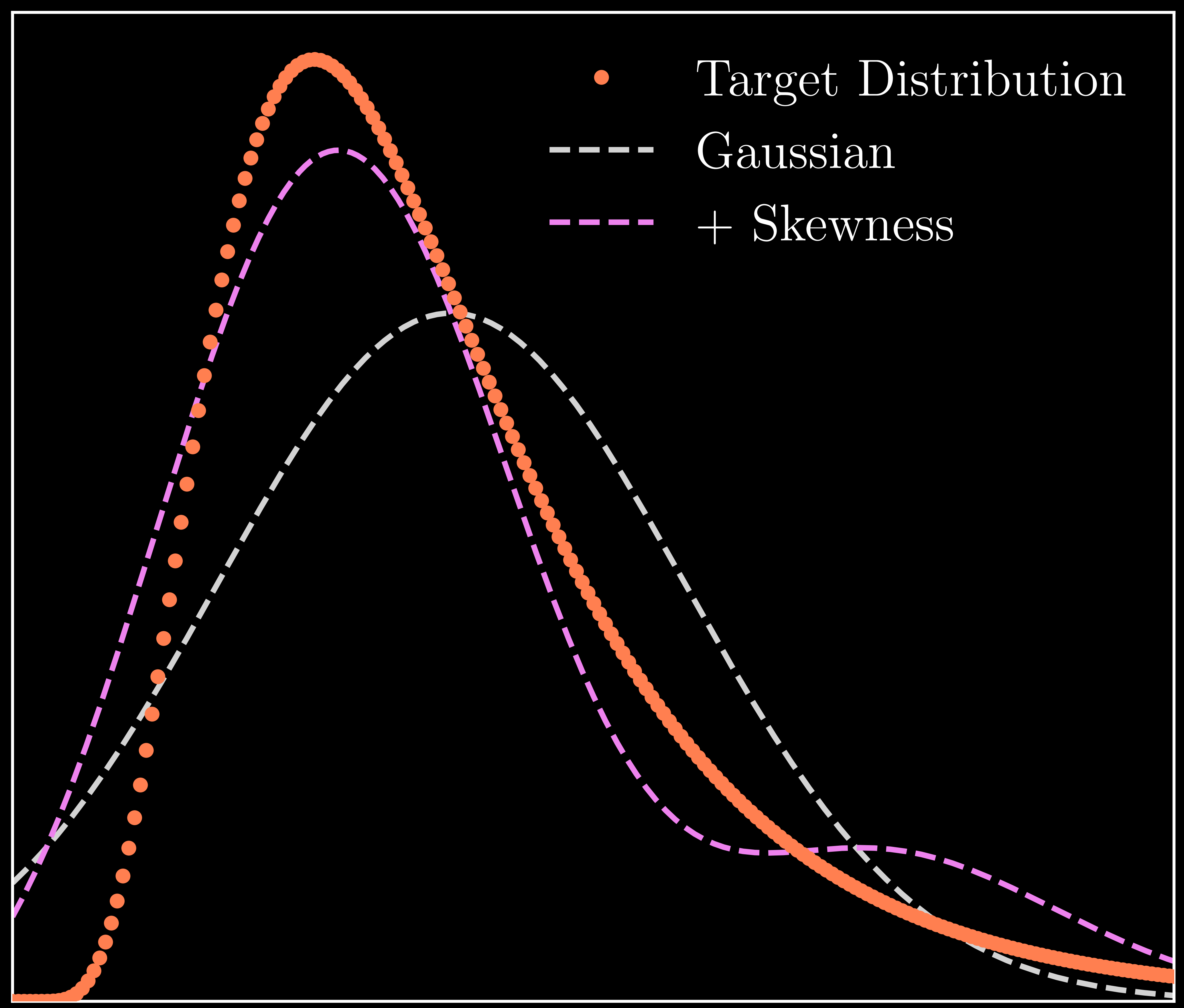
Start with a Gaussian

$$P(x) \approx \phi\left(\tilde{x} \equiv \frac{x-\mu}{\sigma}\right)$$

1). Weak non-Gaussianity



2). Strong non-Gaussianity

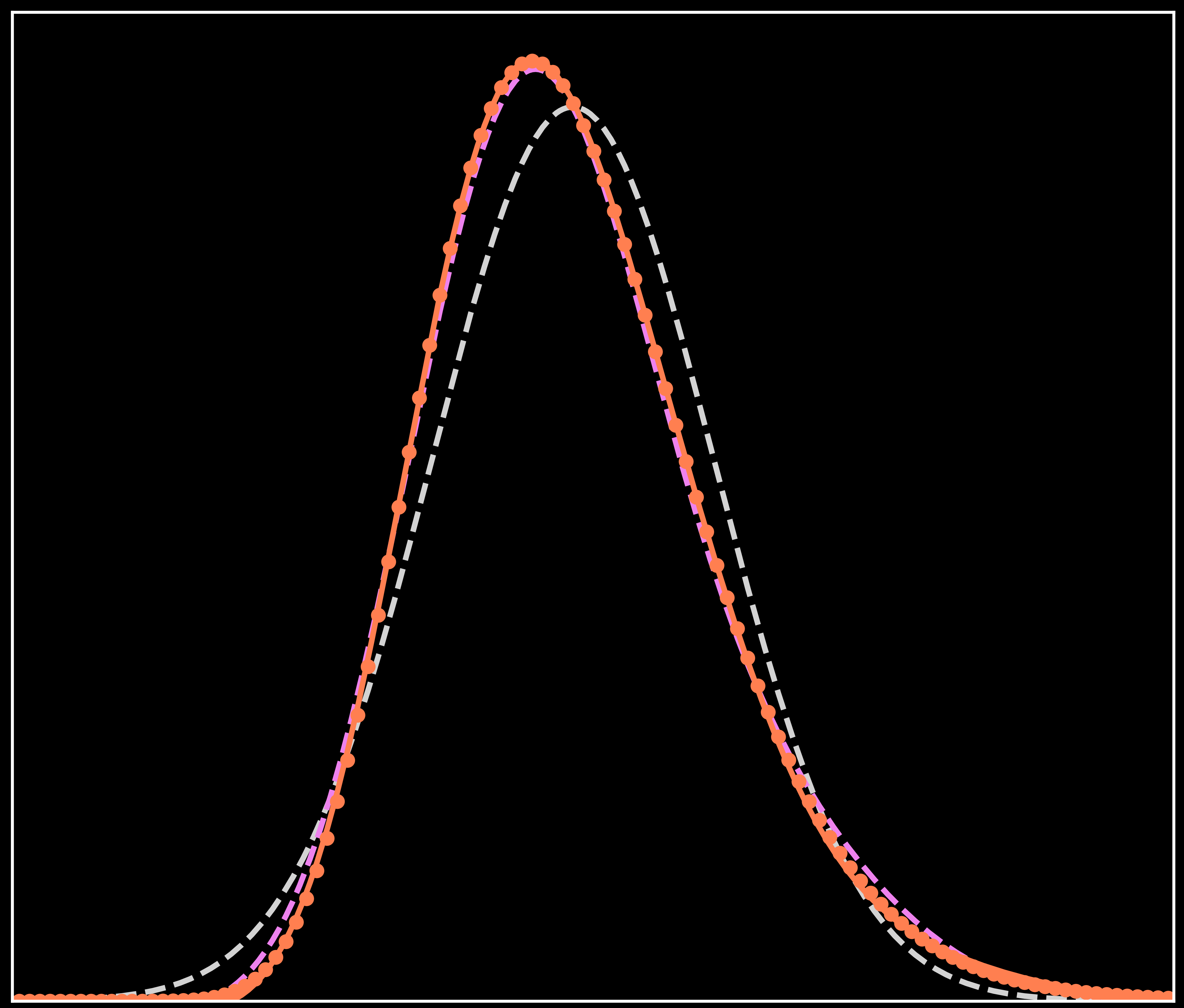


Add in skewness

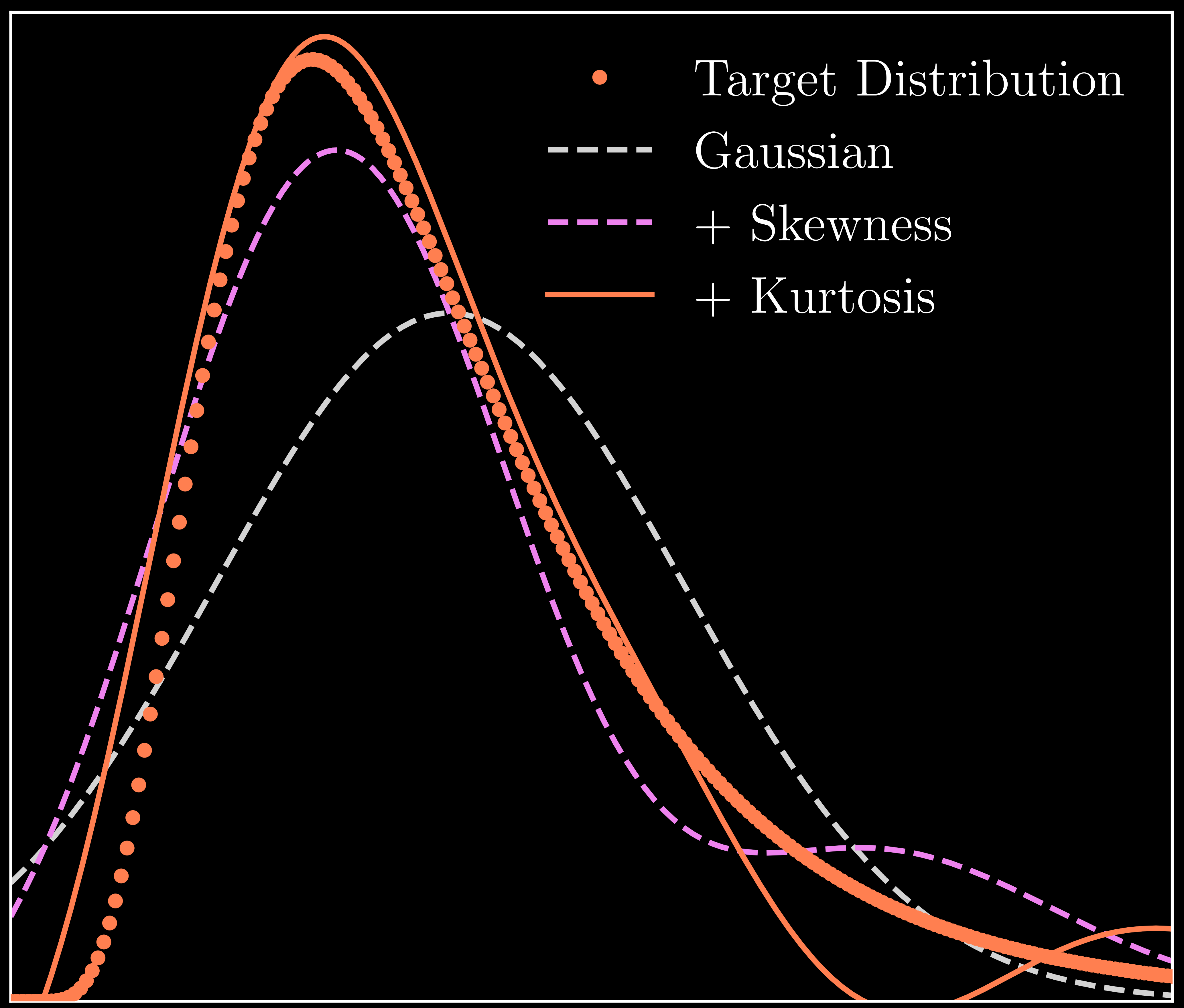
$$P(x) \approx \phi(\tilde{x})\left[1+\frac{\gamma_1}{6}\mathrm{He}_3(\tilde{x})\right]$$

"Edgeworth expansion"

1). Weak non-Gaussianity



2). Strong non-Gaussianity

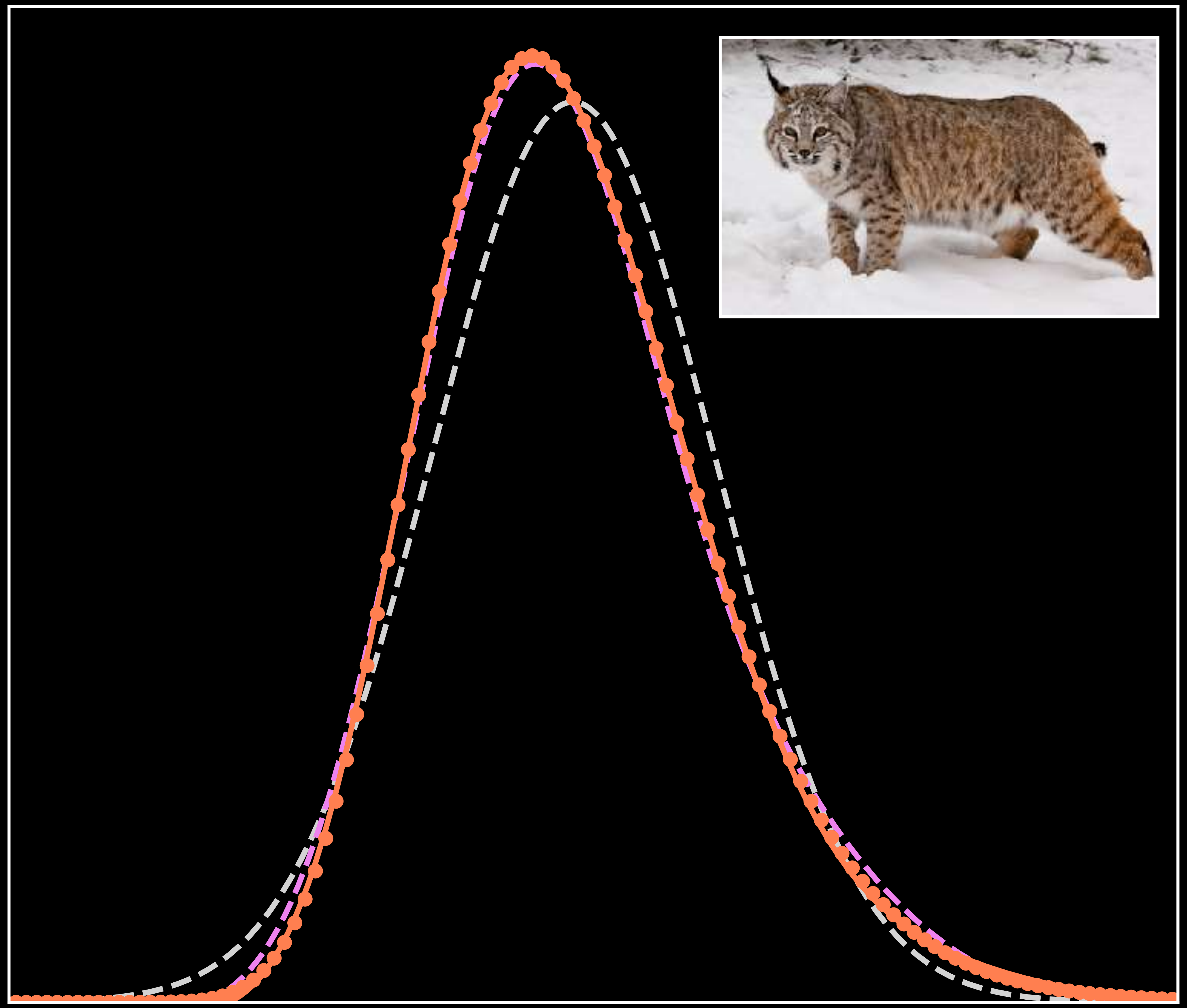


Add in kurtosis

$$P(x) \approx \phi(\tilde{x})\left[1+\frac{\gamma_1}{6}\mathrm{He}_3(\tilde{x}) + \frac{\gamma_2}{24}\mathrm{He}_4(\tilde{x}) + \frac{\gamma_1^2}{72}\mathrm{He}_6(\tilde{x})\right]$$

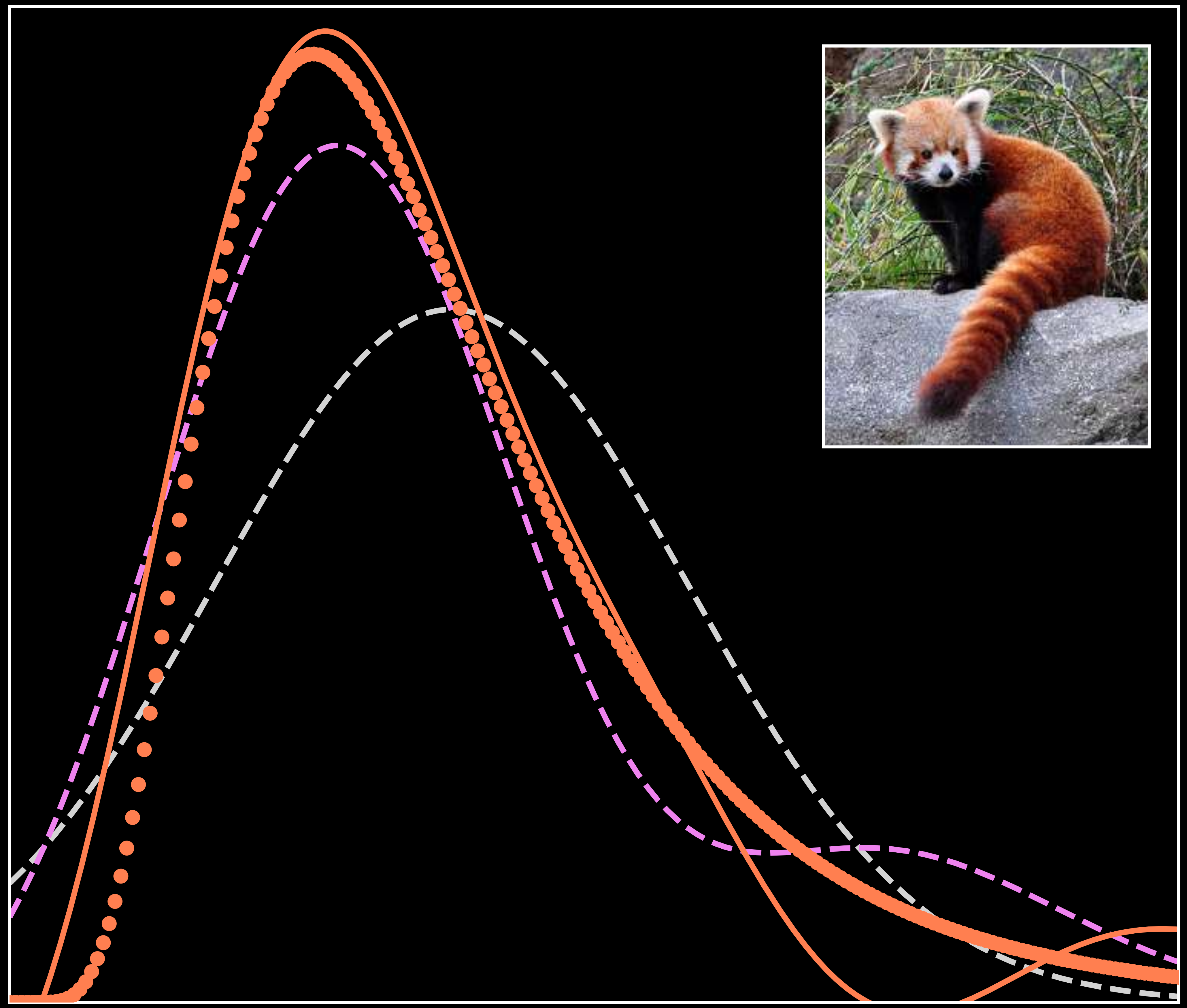
"Edgeworth expansion"

1). Weak non-Gaussianity



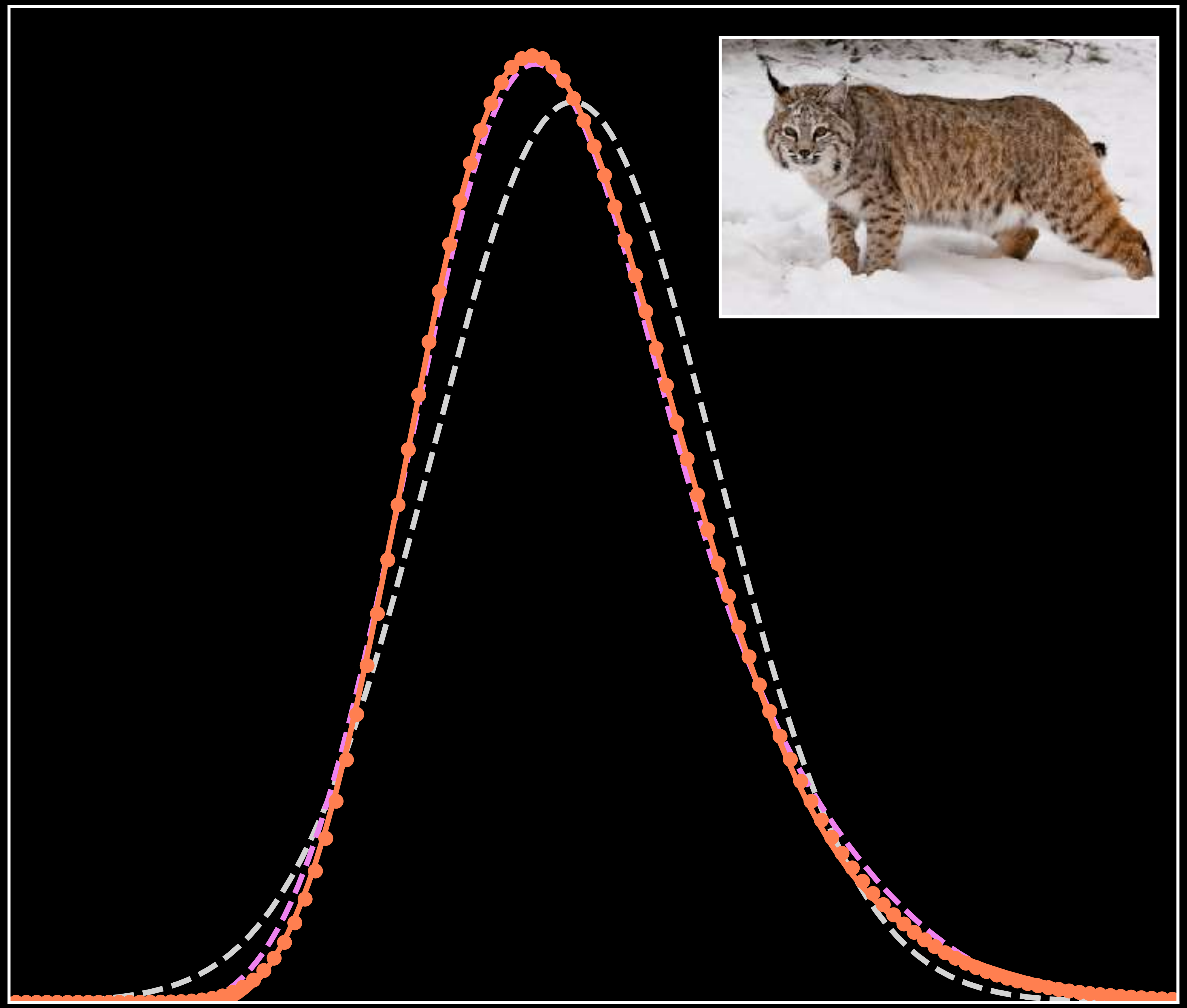
- **Optimal summary statistic:** N-point correlation functions with N~3, 4,…

2). Strong non-Gaussianity

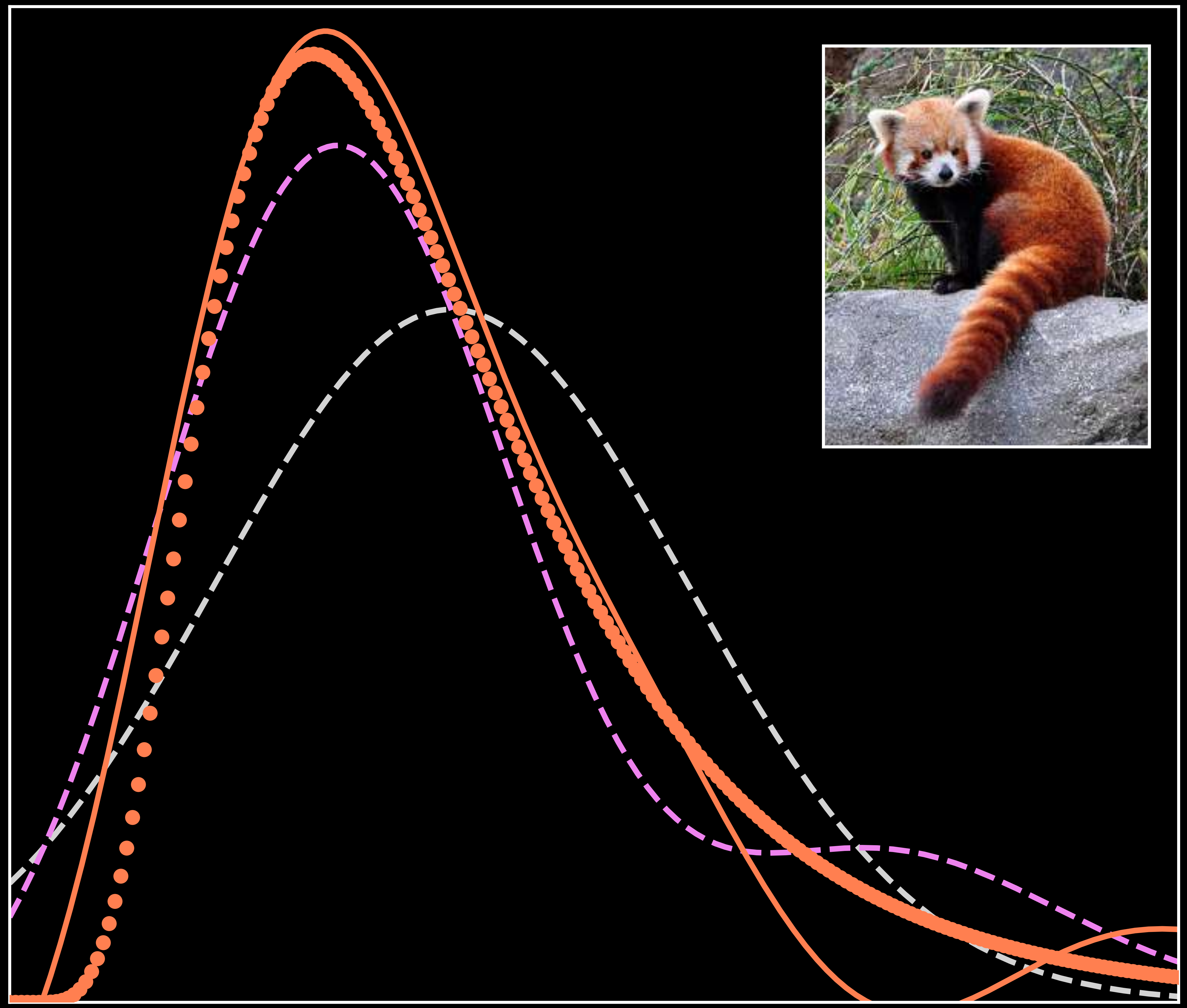


- **Optimal summary statistic:** matched filter, ask a neural network

1). Weak non-Gaussianity



2). Strong non-Gaussianity



This talk

- **Optimal summary statistic:** N-point correlation functions with N~3, 4,…

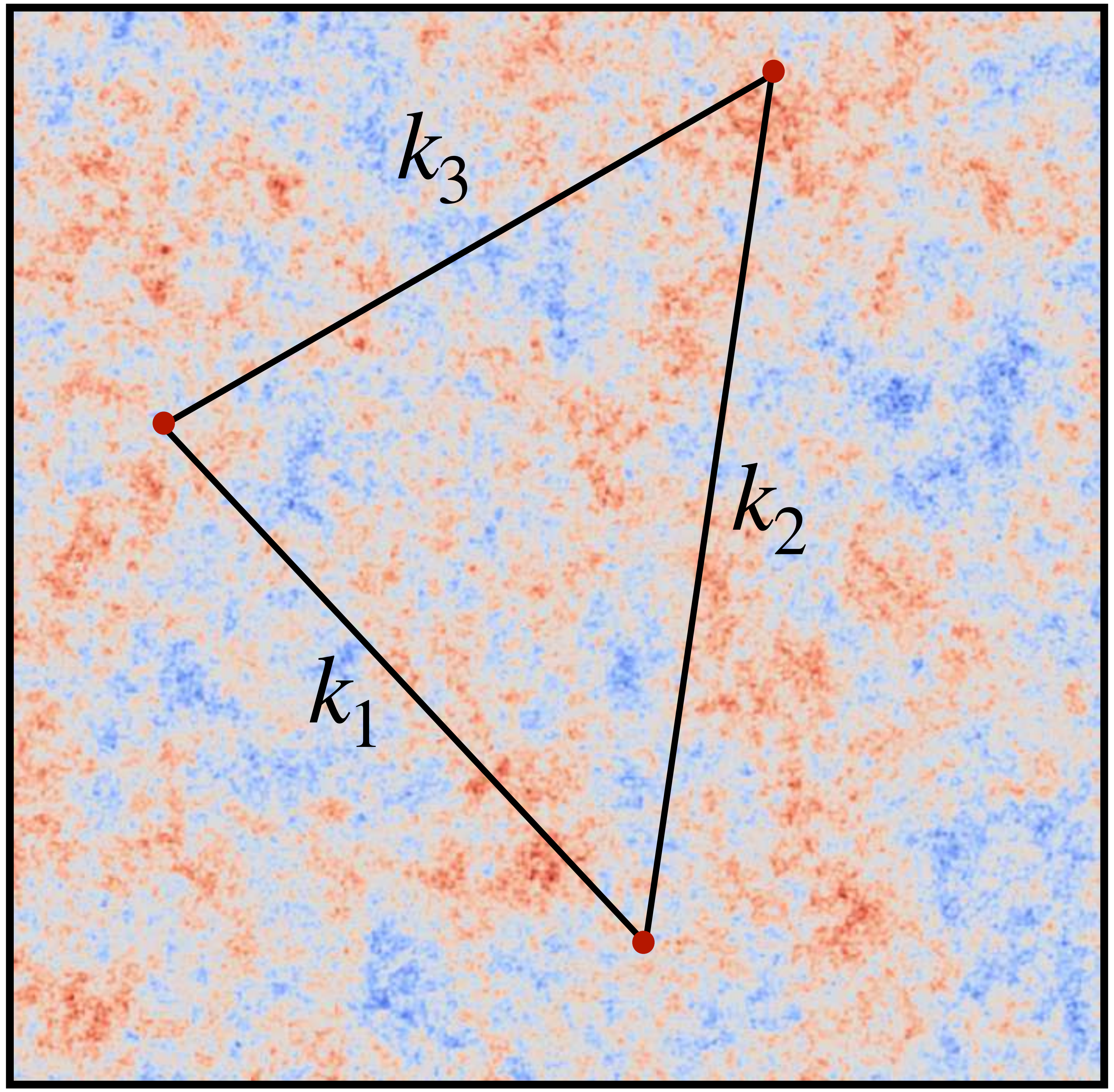
- **Optimal summary statistic:** matched filter, ask a neural network

The 3-point function (bispectrum)

- Natural higher-order statistic to consider

$$\langle \zeta(\boldsymbol{k}_1)\zeta(\boldsymbol{k}_2\zeta(\boldsymbol{k}_3)) \rangle \equiv (2\pi)^3 \delta_D(\boldsymbol{k}_1 + \boldsymbol{k}_2 + \boldsymbol{k}_3)\, B_\zeta(k_1, k_2, k_3)$$

- Fully described by three side lengths of the triangle
- Is this an *interesting/useful* statistic…



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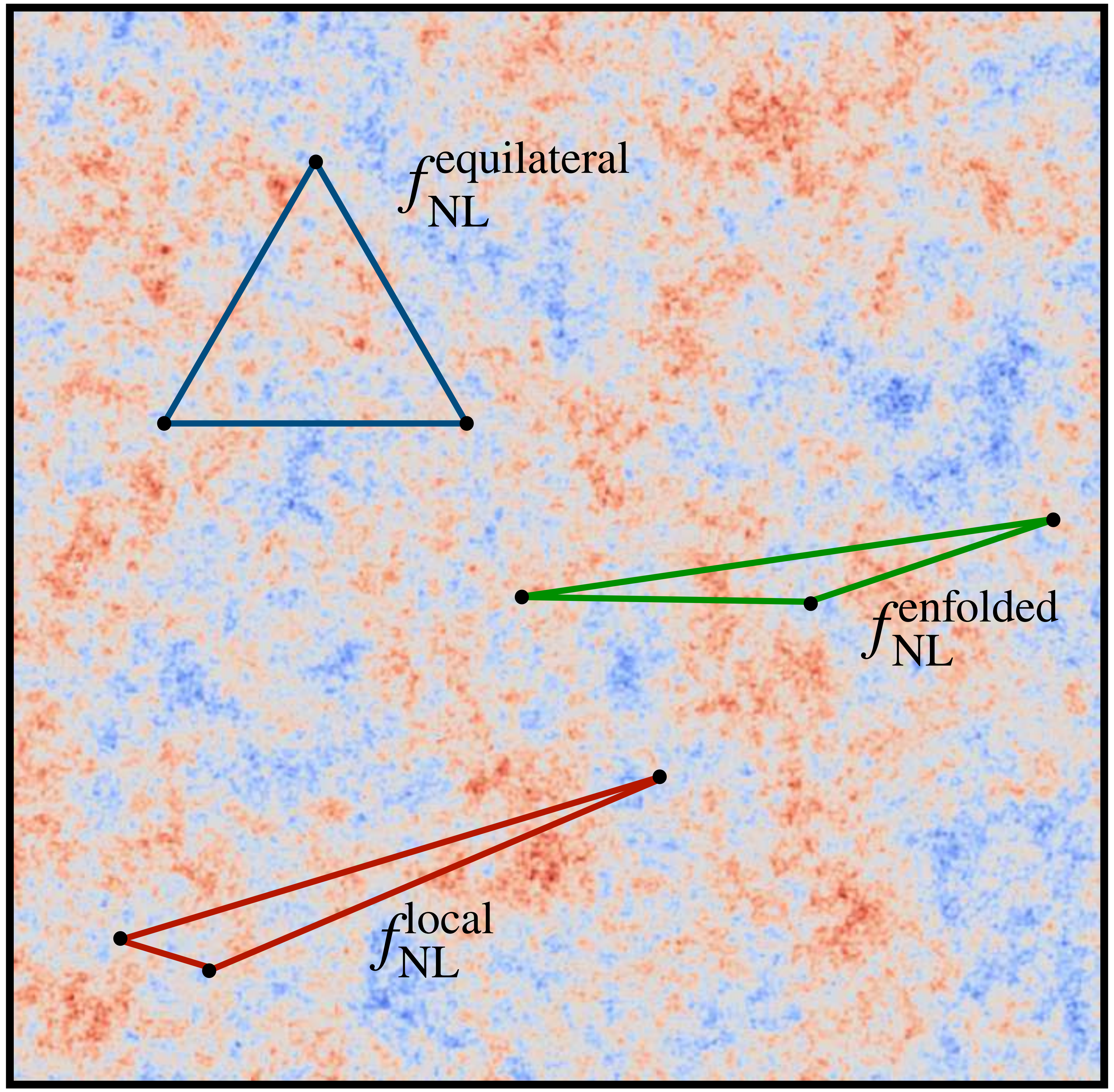
- Fully described by three side lengths of the triangle
- Is this an *interesting/useful* statistic… **YES**
  - Triangle shapes probe various early universe models!

$$B_\zeta(k_1, k_2, k_3) \sim f_{\mathrm{NL}} \times S(k_1, k_2, k_3)$$

Amplitude (zero for GRF)

Shape



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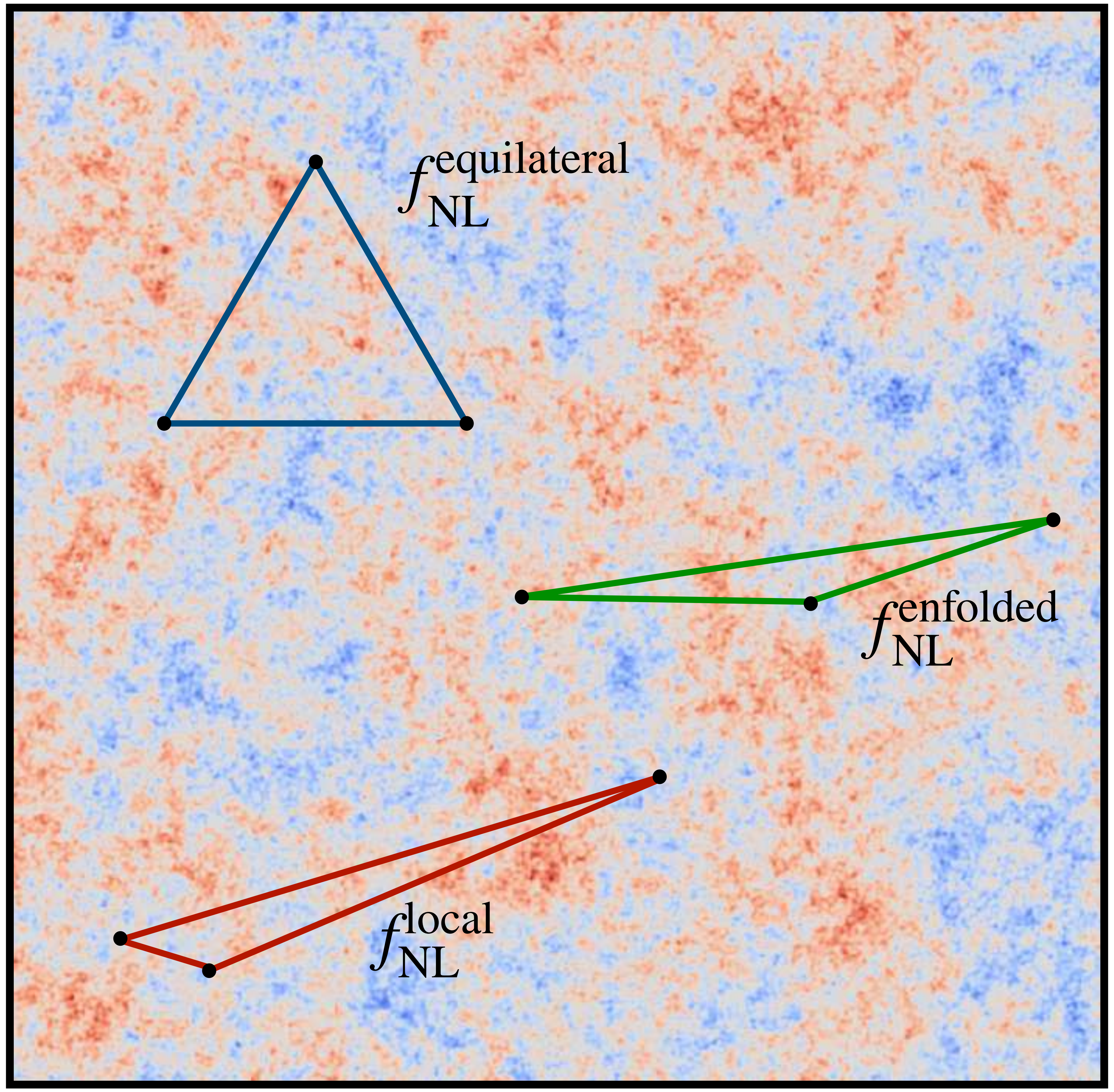
- Fully described by three side lengths of the triangle
- Is this an *interesting/useful* statistic… **YES**
  - $f_{\rm NL}^{\rm eq.}$: *Details of particle sourcing inflation*
  - $f_{\rm NL}^{\rm enf.}$: *Initial quantum state of inflation*
  - $f_{\rm NL}^{\rm loc.}$: ***Multiple fields***

$$\Phi(\boldsymbol{x}) = \phi_G(\boldsymbol{x}) + f_{\rm NL}^{\rm loc}\left(\phi_G^2(\boldsymbol{x}) - \langle\phi^2\rangle\right)$$



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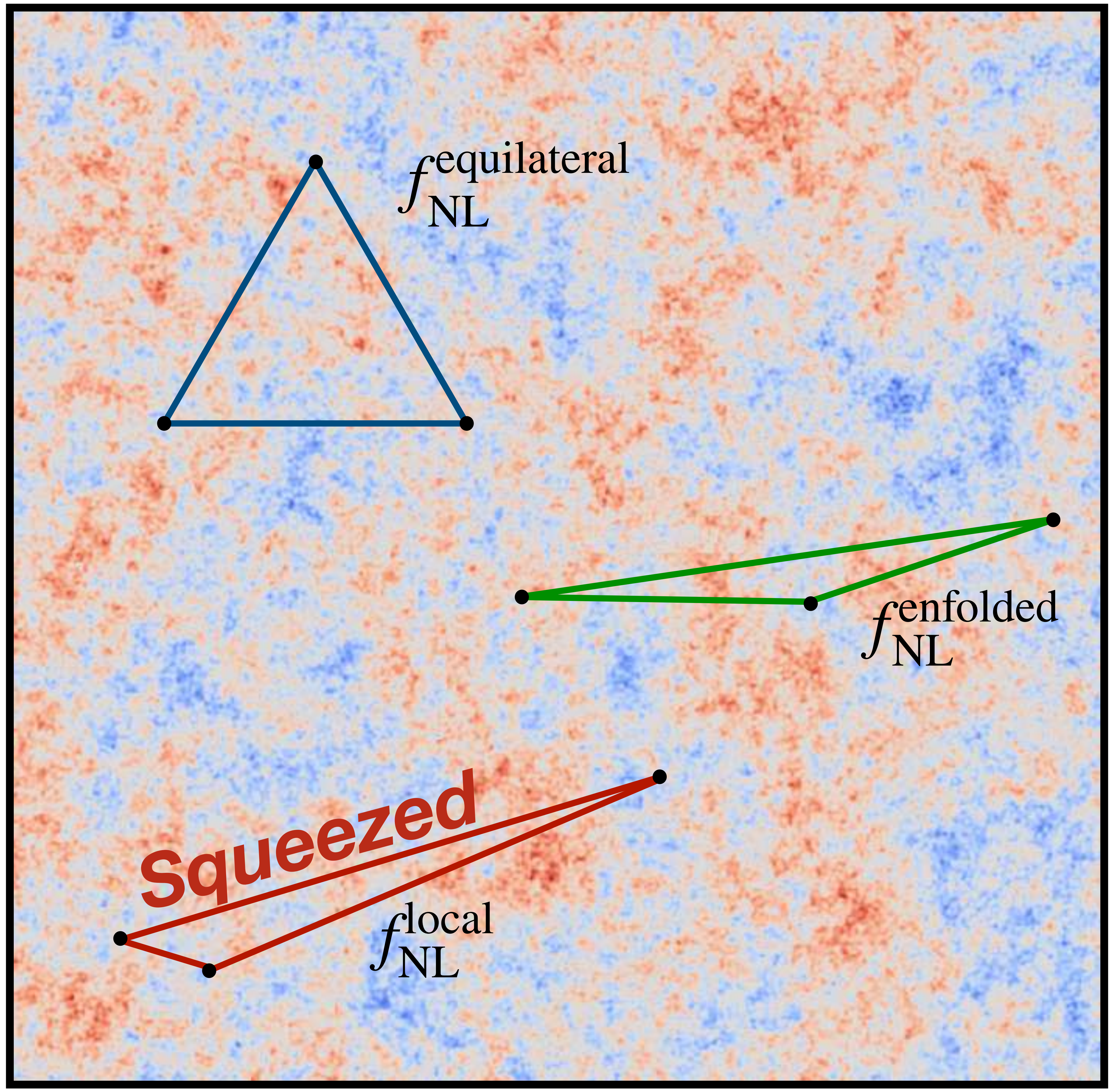
  - $f_{\rm NL}^{\rm eq.}$: *Details of particle sourcing inflation*
  - $f_{\rm NL}^{\rm enf.}$: *Initial quantum state of inflation*
  - $f_{\rm NL}^{\rm loc.}$: ***Multiple fields***

$f_{\rm NL}^{\rm loc.} \neq 0$ would rule out single-field inflation

Maldacena, 2002; Creminelli & Zaldarriaga, 2004



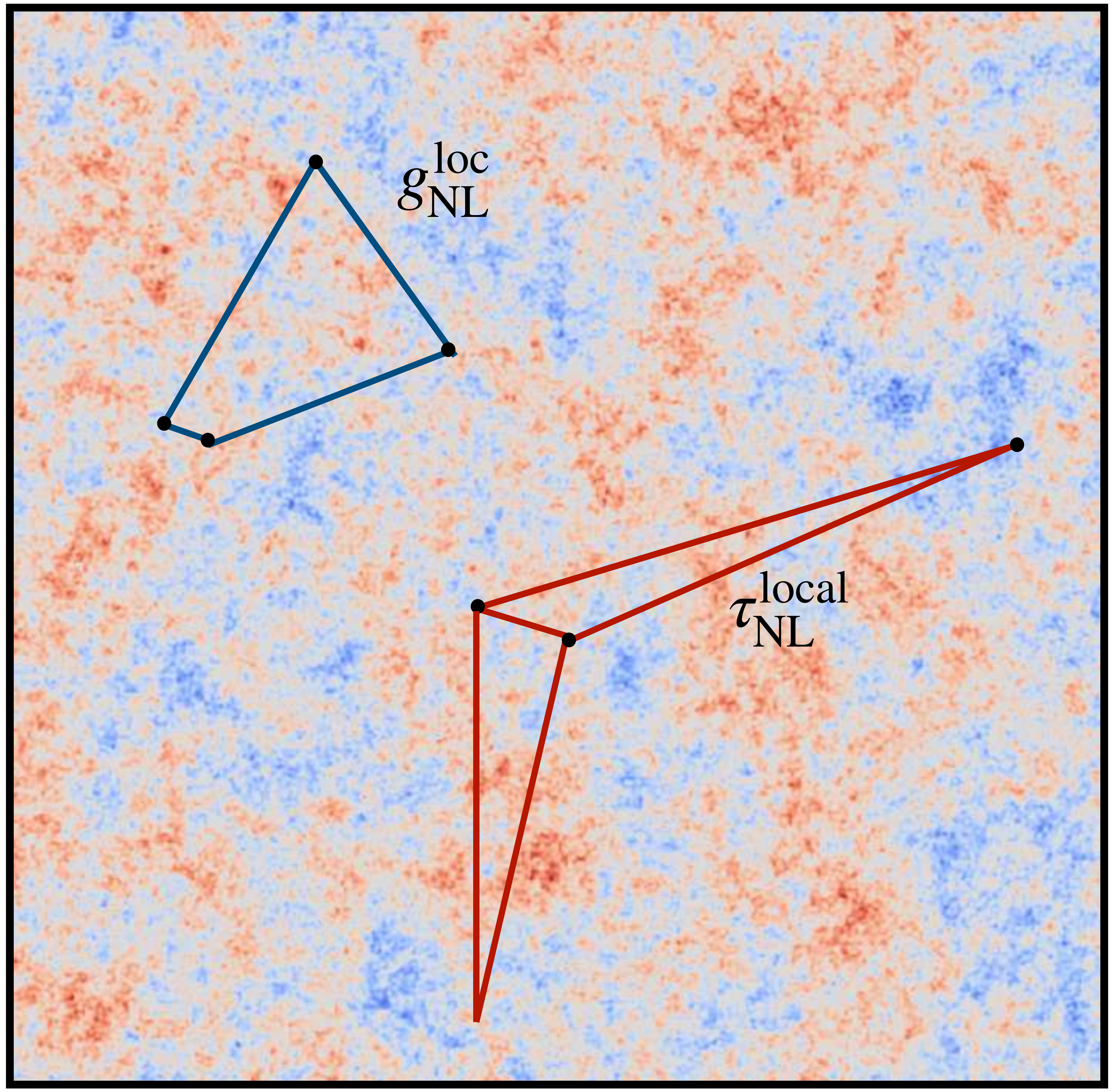
The 4-point function (trispectrum)

- Natural higher-order statistic to consider

$$\langle\zeta(\boldsymbol{k}_1)\zeta(\boldsymbol{k}_2)\zeta(\boldsymbol{k}_3)\zeta(\boldsymbol{k}_4)\rangle \equiv (2\pi)^3\delta_D(\boldsymbol{k}_1+\boldsymbol{k}_2+\boldsymbol{k}_3+\boldsymbol{k}_4)\, T_\zeta(k_1,k_2,k_3,k_4,k_{12},k_{14})$$

- Fully described by four side lengths and two diagonals

- Is this an *interesting/useful* statistic… **YES**
    - Parity violation
    - $g_{\rm NL}^{\rm loc}$: cubic non-Gaussianity
    - $\tau_{\rm NL}^{\rm loc}$: direct probe of # of fields responsible for ζ



The 4-point function (trispectrum)

- Natural higher-order statistic to consider

$$\langle \zeta(\boldsymbol{k}_1)\zeta(\boldsymbol{k}_2)\zeta(\boldsymbol{k}_3)\zeta(\boldsymbol{k}_4)\rangle \equiv (2\pi)^3\delta_D(\boldsymbol{k}_1+\boldsymbol{k}_2+\boldsymbol{k}_3+\boldsymbol{k}_4)\, T_\zeta(k_1,k_2,k_3,k_4,k_{12},k_{14})$$

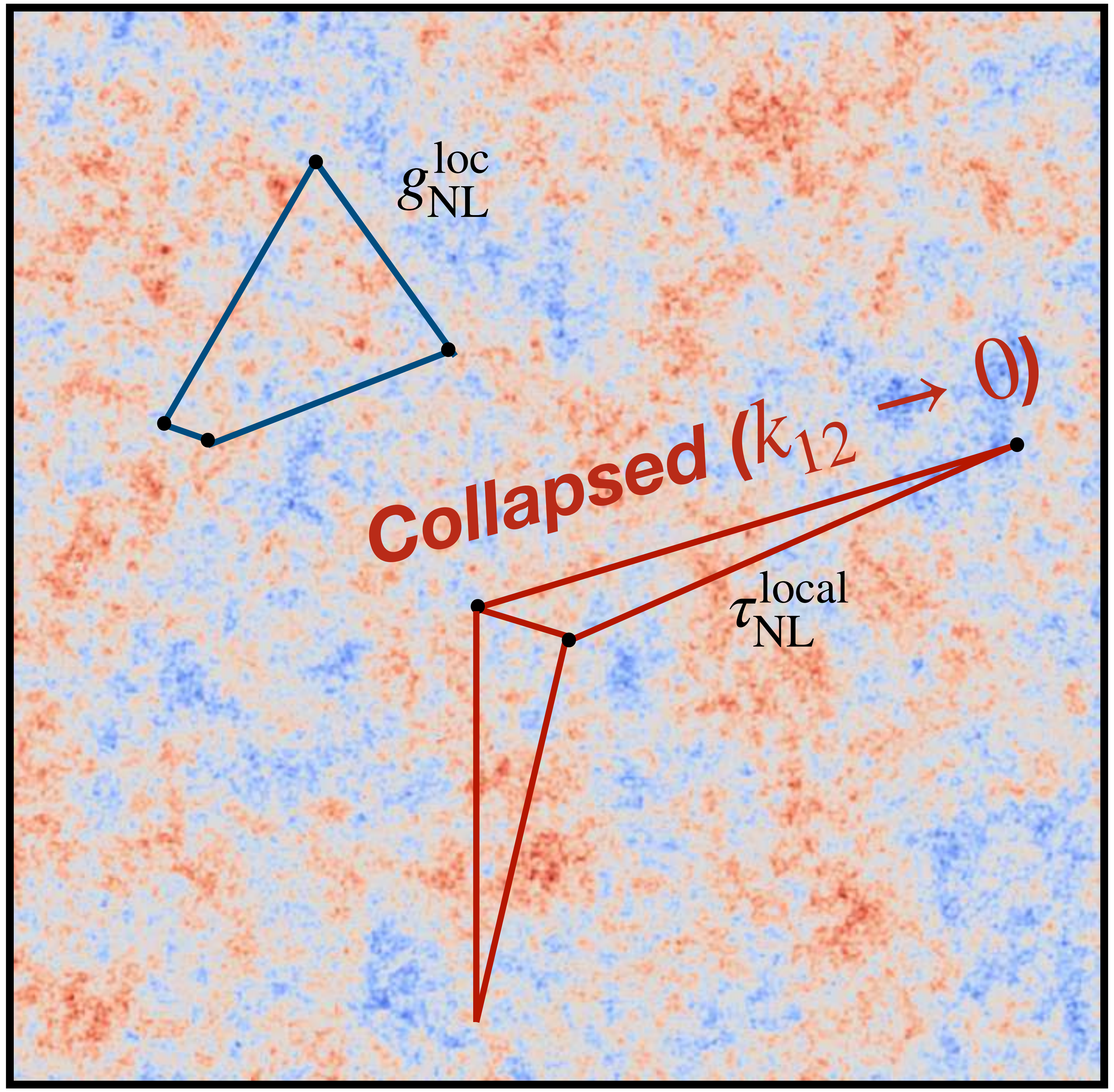
- Fully described by four side lengths and two diagonals

- Is this an *interesting/useful* statistic… **YES**
  - Parity violation (*e.g.*, ***Cahn++21***)
  - $g_{\rm NL}^{\rm loc}$: cubic non-Gaussianity
  - $\tau_{\rm NL}^{\rm loc}$: direct probe of # of fields responsible for ζ

Suyama-Yamaguchi (SY) inequality

$\tau_{\rm NL}^{\rm loc} > \left(\frac{6}{5}f_{\rm NL}^{\rm loc}\right)^2$ would rule out single-source inflation

Byrnes++2006, Suyama & Yamaguchi, 2008, Smith++ 2010



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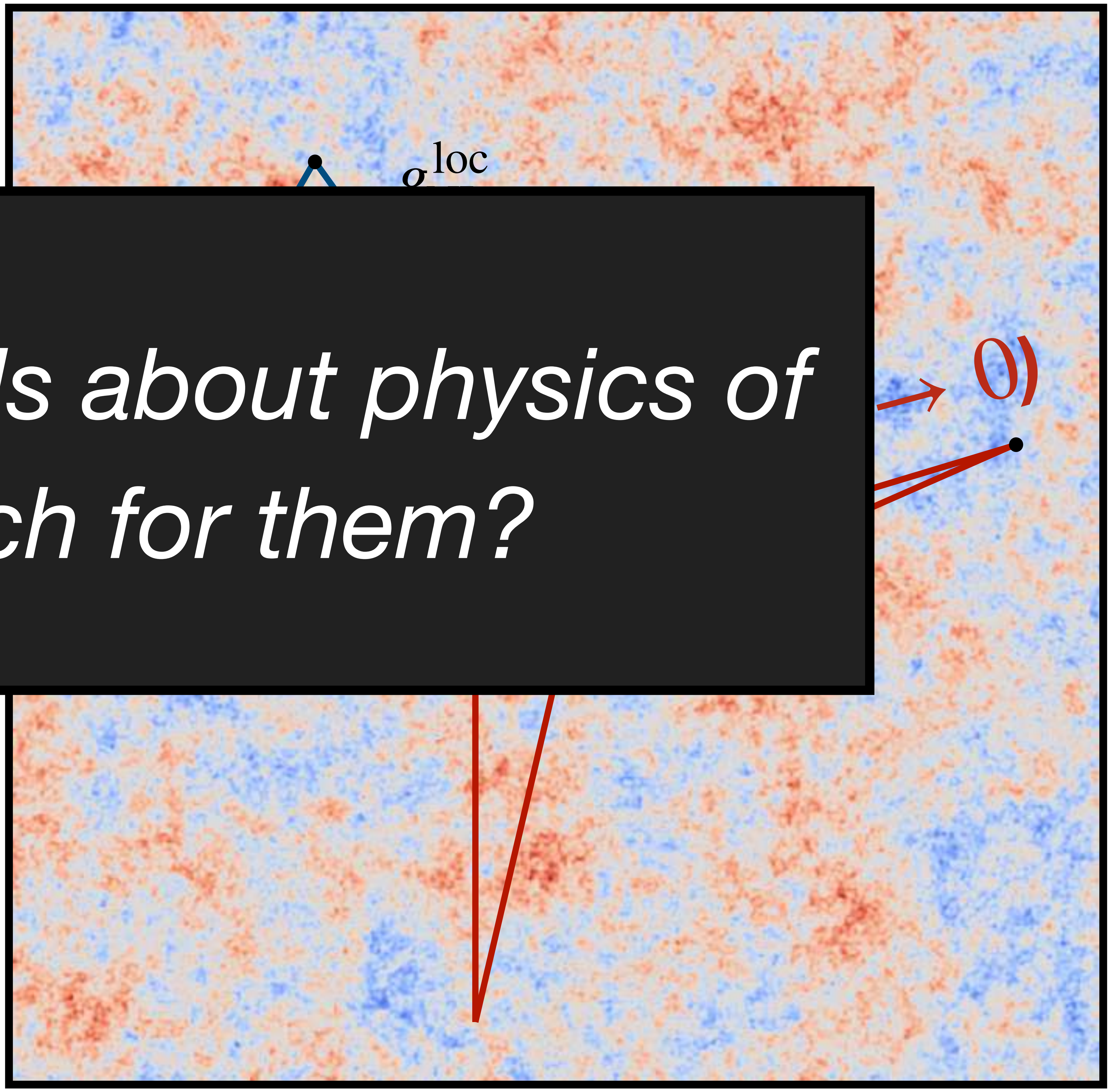
- Fully d
- Is this
  - Parit
  - $g_{\rm NL}^{\rm loc}$: cubic non-Gaussianity
  - $\tau_{\rm NL}^{\rm loc}$: direct probe of # of fields responsible for ζ

$f_{\rm NL}^{\rm loc}$ and $\tau_{\rm NL}^{\rm loc}$ encode crucial details about physics of inflation. How can we search for them?

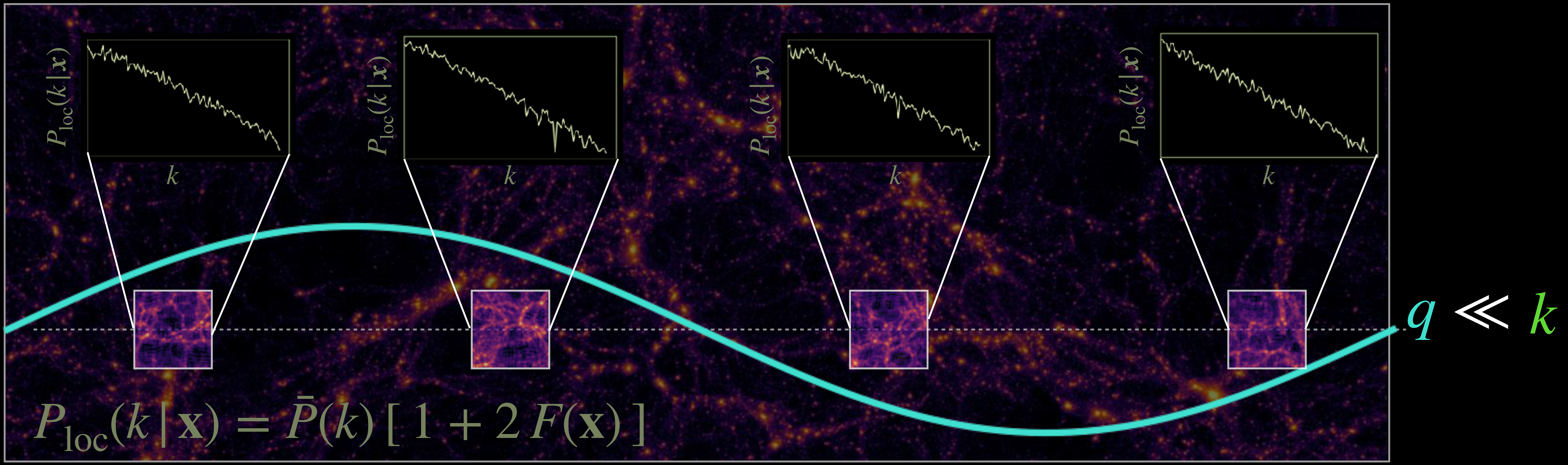


Suyama-Yamaguchi (SY) inequality

$\tau_{\rm NL}^{\rm loc} > \left(\frac{6}{5}f_{\rm NL}^{\rm loc}\right)^2$ **would rule out single-source inflation**

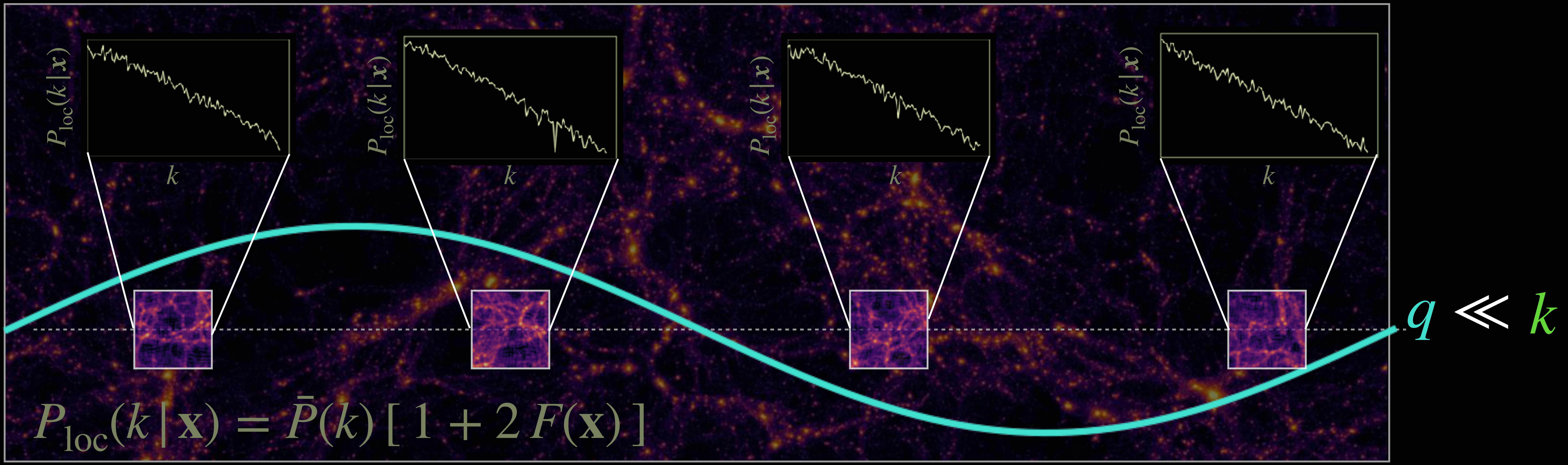
Byrnes++2006, Suyama & Yamaguchi, 2008, Smith++ 2010

What are $f_{\rm NL}^{\rm loc}$ and $\tau_{\rm NL}^{\rm loc}$ REALly?



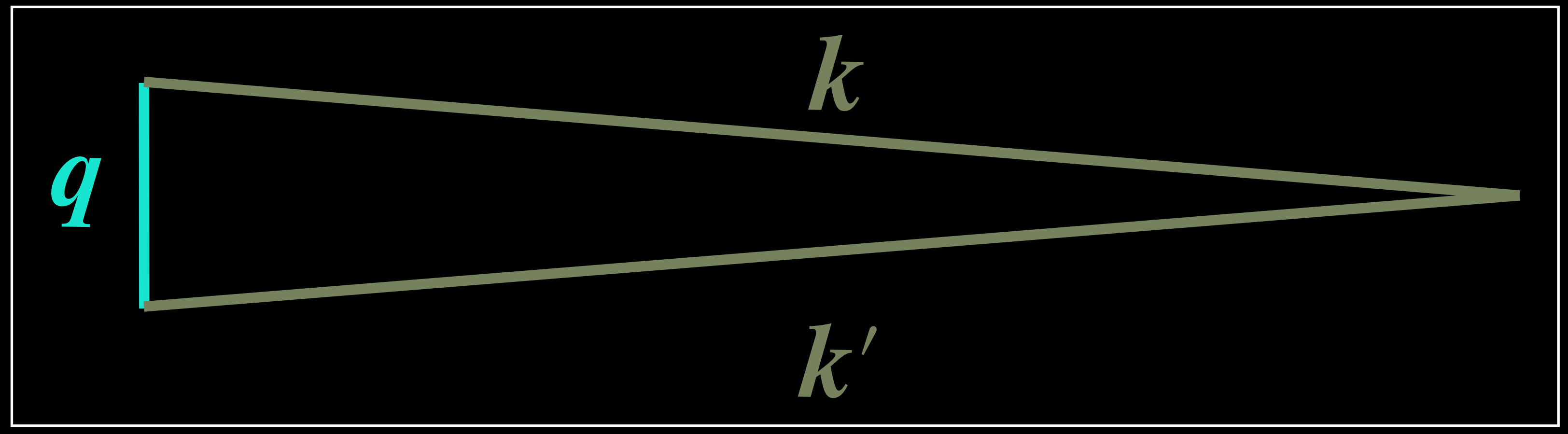
"Squeezed/soft limits -> long-wavelength modulations of small-scale (local) power spectra" — Dr. Soft Limit

What are f_{NL}^{loc} and τ_{NL}^{loc} REALly?



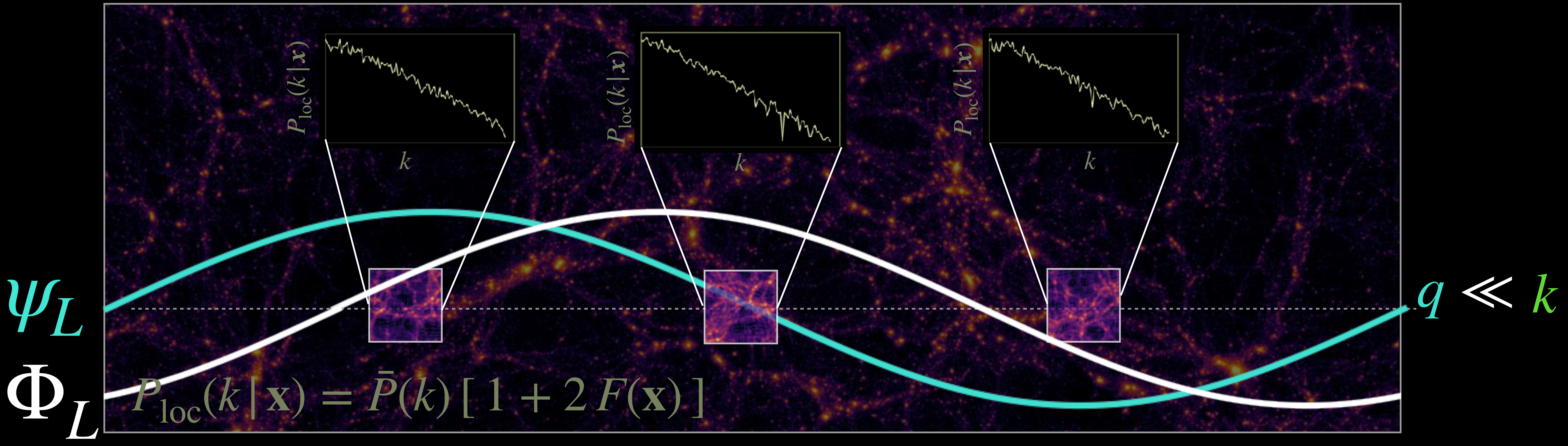
$$f_{NL}^{loc}\text{: } \Phi \equiv \Phi + f_{NL}^{loc}\Phi^2 \implies \Phi_S = \phi_S\,(1 + 2 f_{NL}^{loc}\Phi_L)$$

$$F(x) \propto f_{NL}^{loc}\Phi_L(x)$$



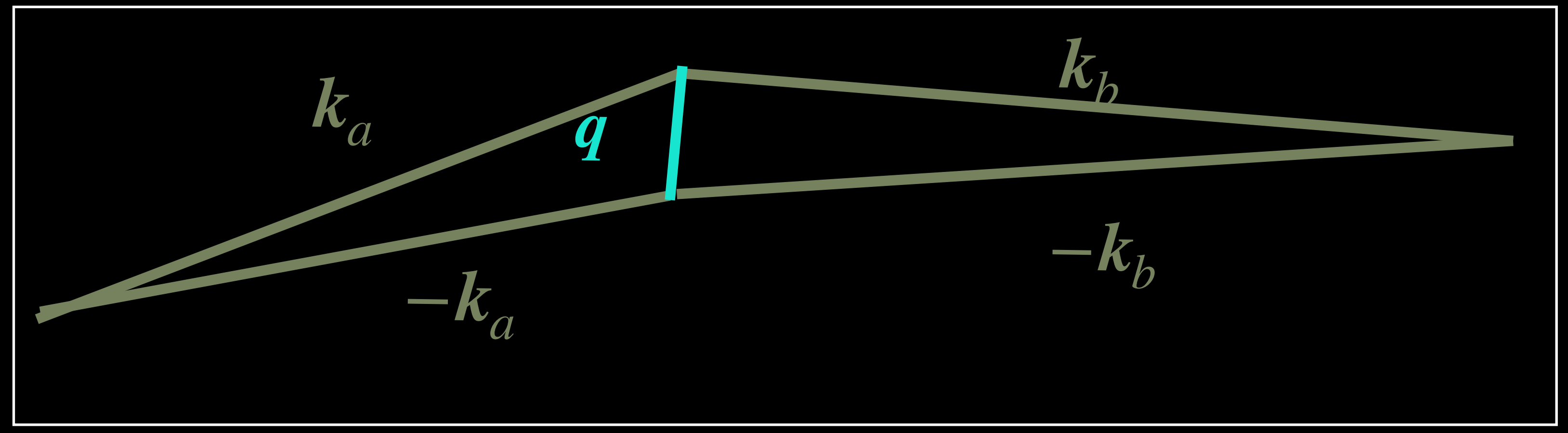
Squeezed bispectrum $\sim \langle \Phi_L F \rangle$

What are $f_{\rm NL}^{\rm loc}$ and $\tau_{\rm NL}^{\rm loc}$ **REALly**?



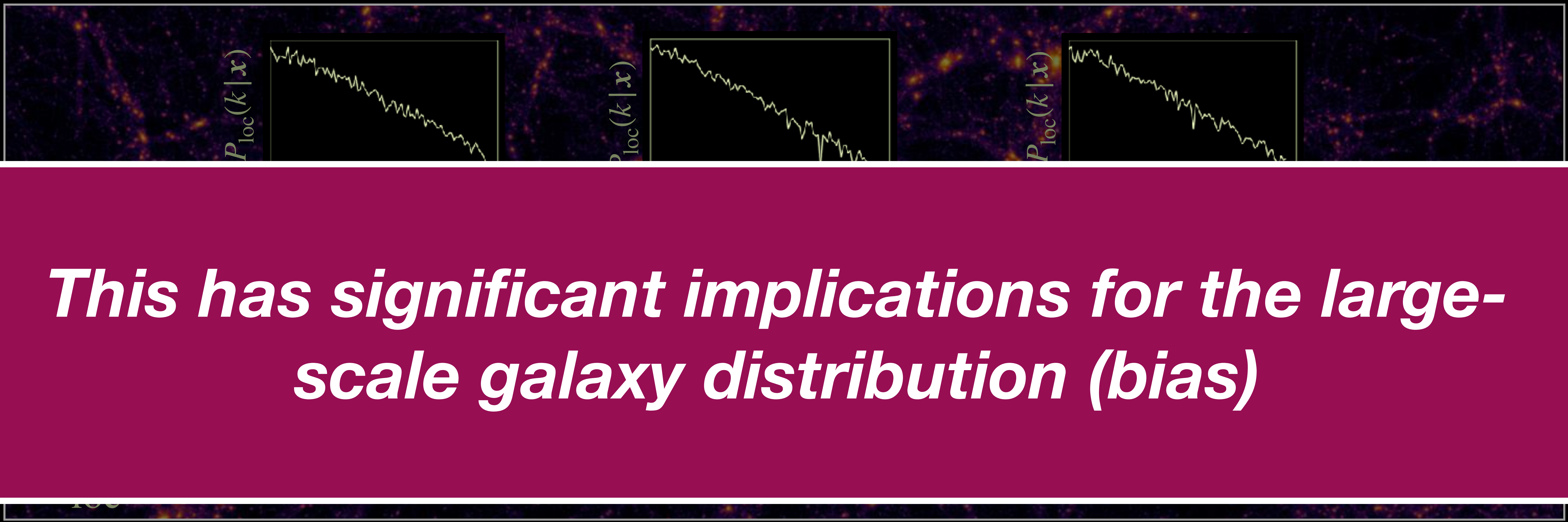
$\tau_{\rm NL}^{\rm loc}$*: power spectrum of the modulating field*

$$F(\mathbf{x}) \;=\; f_{\rm NL}^{\rm loc}\,\Phi_L(\mathbf{x}) \;+\; \sqrt{\tau_{\rm NL}^{\rm loc} - (\tfrac{6}{5}\,f_{\rm NL}^{\rm loc})^2}\;\;\psi_L(\mathbf{x}),$$



Collapsed trispectrum $\sim \langle F\,F \rangle$

What are $f_{\rm NL}^{\rm loc}$ and $\tau_{\rm NL}^{\rm loc}$ REALly?

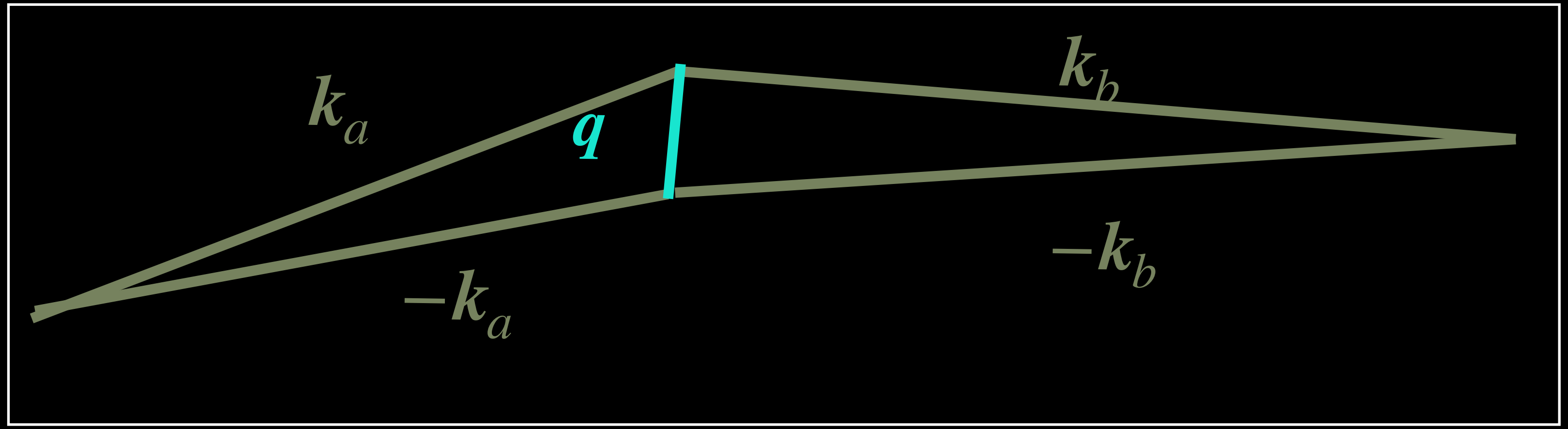


This has significant implications for the large-scale galaxy distribution (bias)

$q \ll k$

$\tau_{\rm NL}^{\rm loc}$: *power spectrum of the modulating field*

$$F(\mathbf{x}) \;=\; f_{\rm NL}^{\rm loc}\,\Phi_L(\mathbf{x}) \;+\; \sqrt{\tau_{\rm NL}^{\rm loc} - (\tfrac{6}{5} f_{\rm NL}^{\rm loc})^2}\;\; \psi_L(\mathbf{x}),$$



Collapsed trispectrum $\sim \langle F\,F \rangle$

Scale-dependent galaxy bias

- **Gaussian initial conditions**

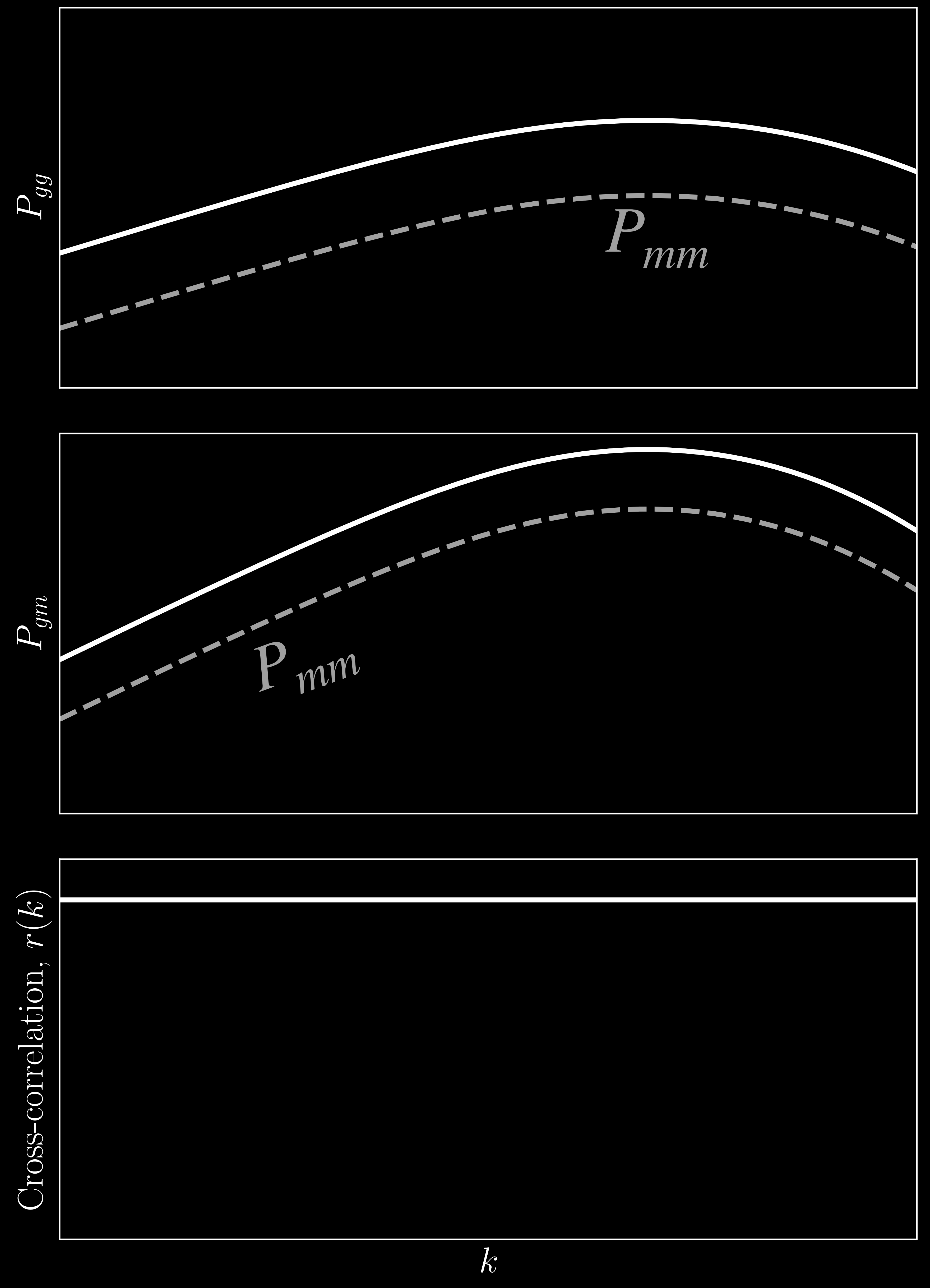
$$\delta_g(\boldsymbol{x}) = b\delta_m(\boldsymbol{x}) \sim b\,\nabla^2\Phi(\boldsymbol{x})$$

$$\implies P_{gg} = b^2 P_{mm}, \quad P_{gm} = b\,P_{mm}$$

- **Galaxies trace matter:** deterministic*

$$r \equiv P_{gm}/\sqrt{P_{gg}P_{mm}} = 1$$

Ignoring shotnoise for convenience here



Scale-dependent galaxy bias

- $f_{\rm NL}^{\rm loc}$: galaxies respond to modulating field Φ

$$\delta_g(\boldsymbol{x}) = b\delta_m(\boldsymbol{x}) + b_\phi^{*} f_{\rm NL} \Phi(\boldsymbol{x})$$

Poisson Eq. $\Phi(\boldsymbol{k}) = \delta_m(\boldsymbol{k})/\alpha(k)$

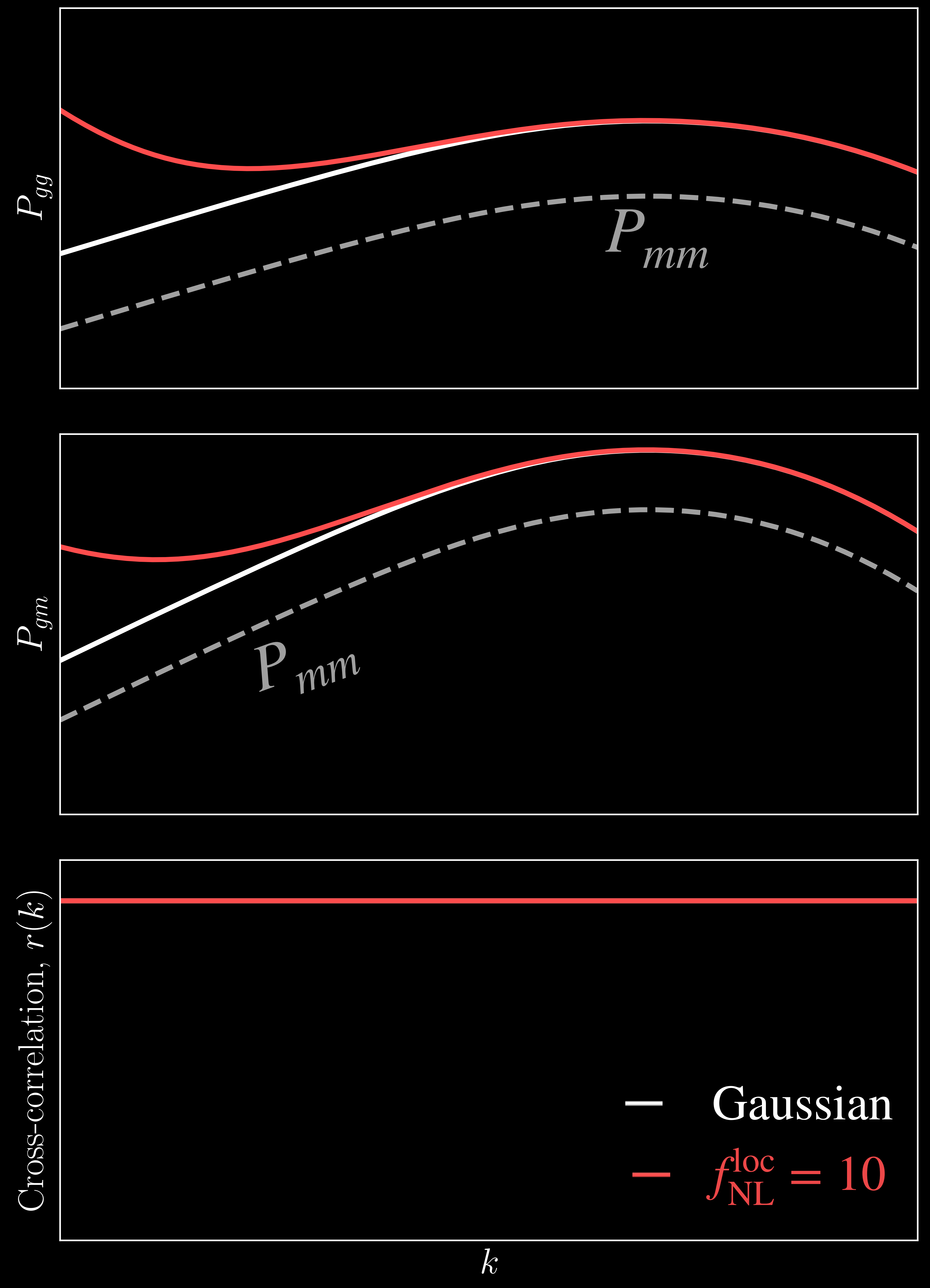
$$\alpha(k) = \frac{2k^2T(k)D(z)}{3\Omega_m H_0^2} \propto k^2$$

$$P_{gg} = \left[b + \frac{b_\phi f_{\rm NL}}{\alpha(k)}\right]^2 P_{mm}$$

$$P_{gm} = \left[b + \frac{b_\phi f_{\rm NL}}{\alpha(k)}\right] P_{mm}$$

- **Galaxies still trace matter:** deterministic

$$r \equiv P_{gm}/\sqrt{P_{gg}P_{mm}} = 1$$



*Here, we assume $b_\phi = 2\delta_c(b_1 - p)$ with $p = 1.4$ for QSO

Scale-dp bias: Dalal++07, Slosar++08, Desjacques++08

Scale-dependent galaxy bias

- $\tau_{\rm NL}^{\rm loc}$**:** a 2nd field $\psi \perp \Phi$ also modulates power

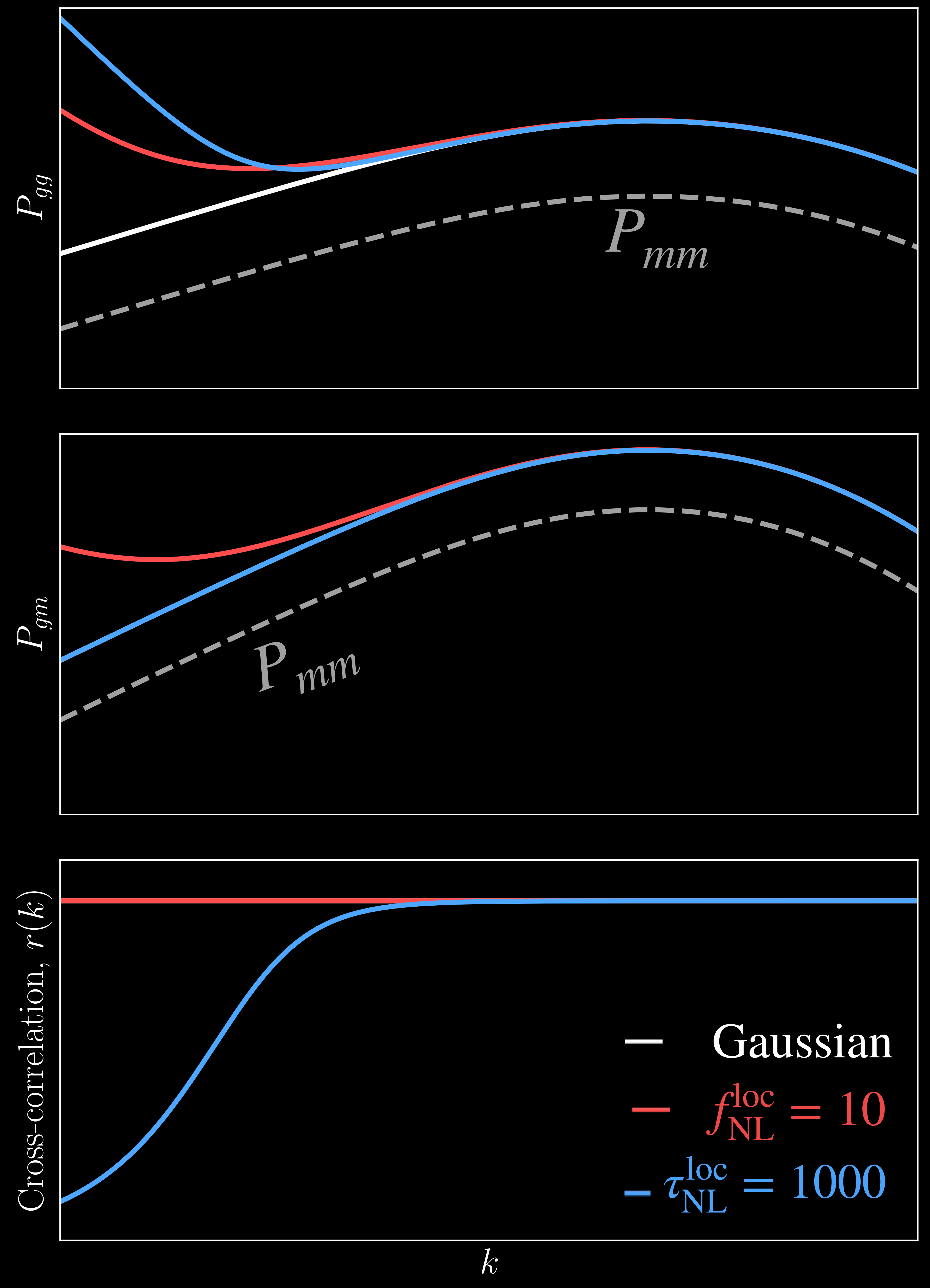
$$\delta_g(\mathbf{x}) = b\,\delta_m(\mathbf{x}) + b_\phi\left[f_{\rm NL}\,\Phi(\mathbf{x}) + \sqrt{\tau_{\rm NL} - (\tfrac{6}{5}f_{\rm NL})^2}\;\psi(\mathbf{x})\right]$$

$$P_{gg} = \left[b + \frac{b_\phi f_{\rm NL}}{\alpha(k)}\right]^2 P_{mm} + b_\phi^2\,\frac{\tau_{\rm NL} - (\frac{6}{5}f_{\rm NL})^2}{\alpha^2(k)}\,P_{mm}$$

$$P_{gm} = \left[b + \frac{b_\phi f_{\rm NL}}{\alpha(k)}\right] P_{mm}$$

- **Galaxies no longer fully trace matter:** stochastic

$$r \equiv P_{gm}/\sqrt{P_{gg}P_{mm}} < 1$$



Stochastic bias: Baumann++12, Ferraro & Smith14

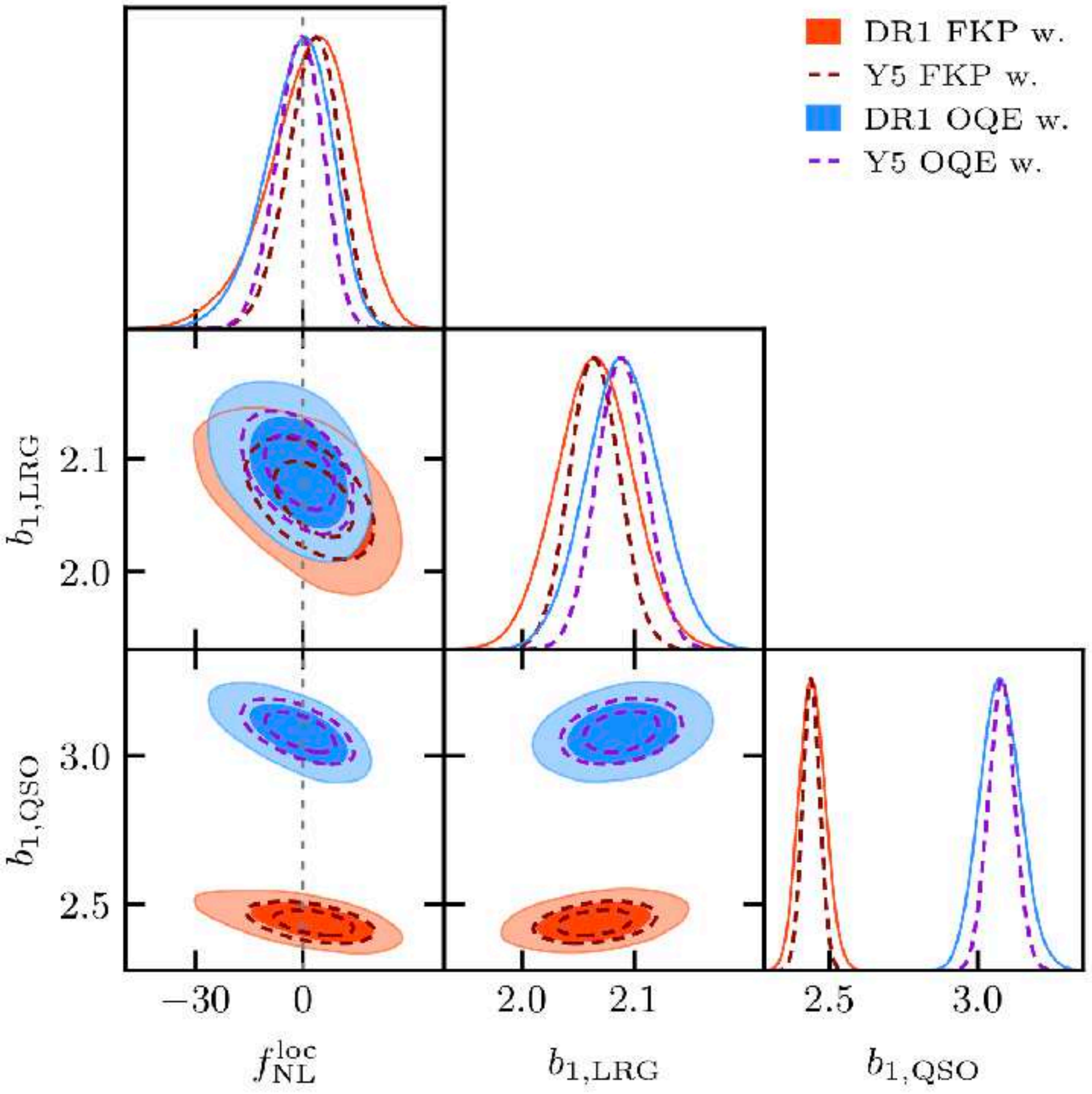
Observational status of PNG: LSS is the future

- Tightest bounds on PNG are currently from **CMB**

$$f_{\rm NL}^{\rm loc} = -0.9 \pm 5.1 \quad \tau_{\rm NL}^{\rm loc} < 1700 \quad (95\%)$$

Planck 2018 Marzouk++22, Philcox++25

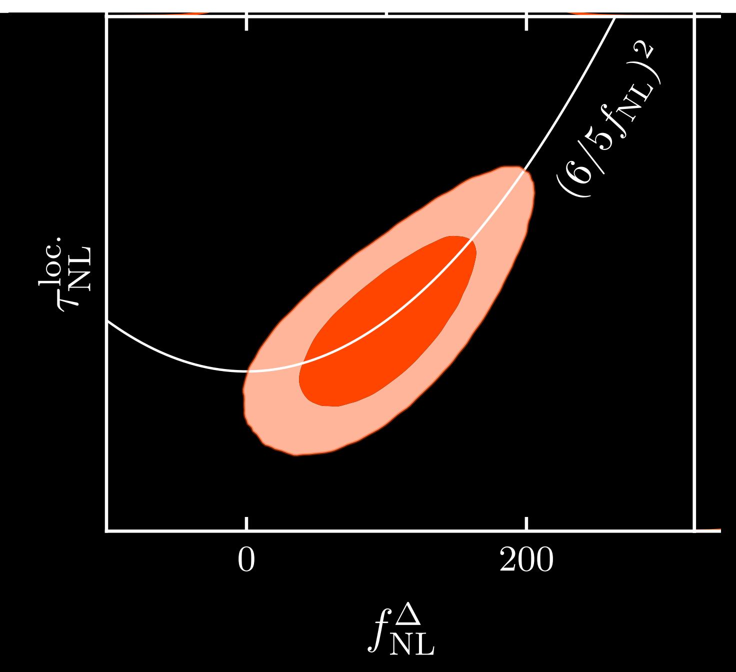
  - Limits are close to cosmic variance limit
  - CMB is 2D field: running out of modes
- **Galaxy surveys** can do much better
  - 3D volume, more modes, scale-dep bias
  - DESI already DR1 reached $\sigma(f_{\rm NL}^{\rm loc}) \sim 9$; DR2 will improve; SPHERE-X $\sigma(f_{\rm NL}^{\rm loc}) < 1$
  - ***Have never been used for*** $\tau_{\rm NL}$



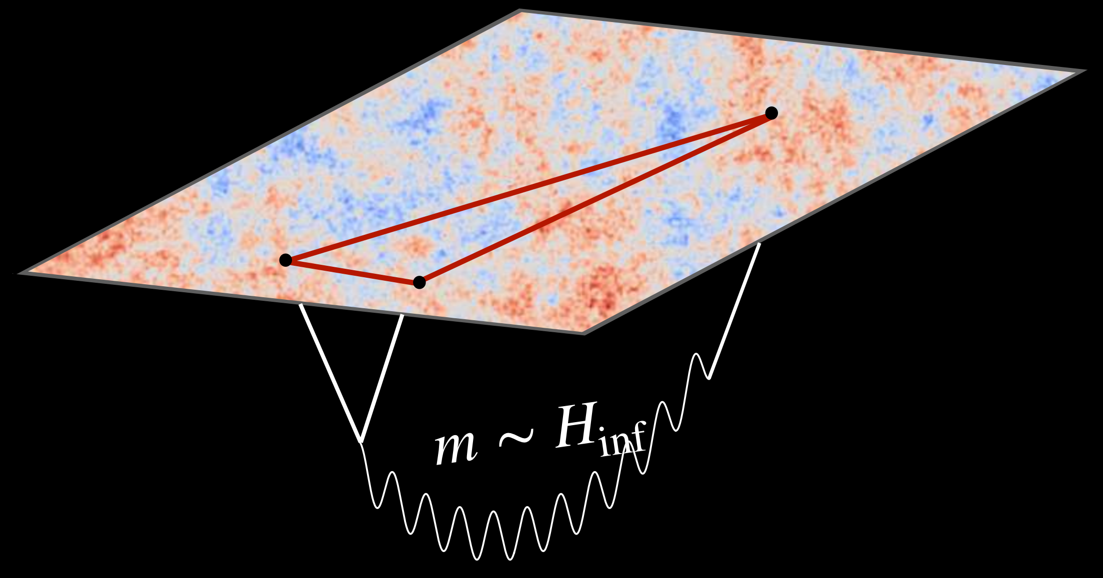
DESI DR1 constraints on $f_{\rm NL}^{\rm loc}$

Chaussidon++24

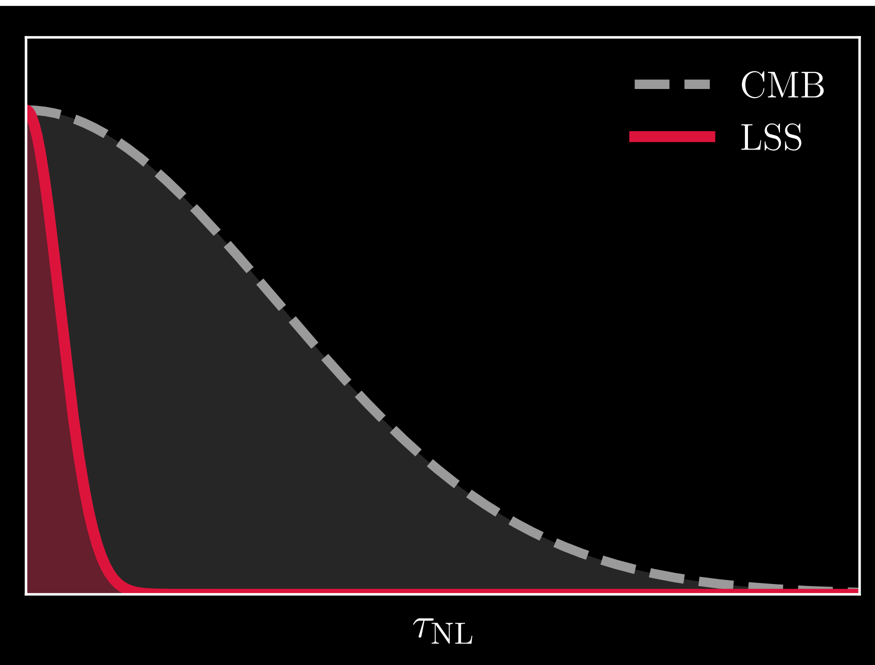
We should search for τ_{NL} with LSS



Theoretical motivation:
Multi-field inflation



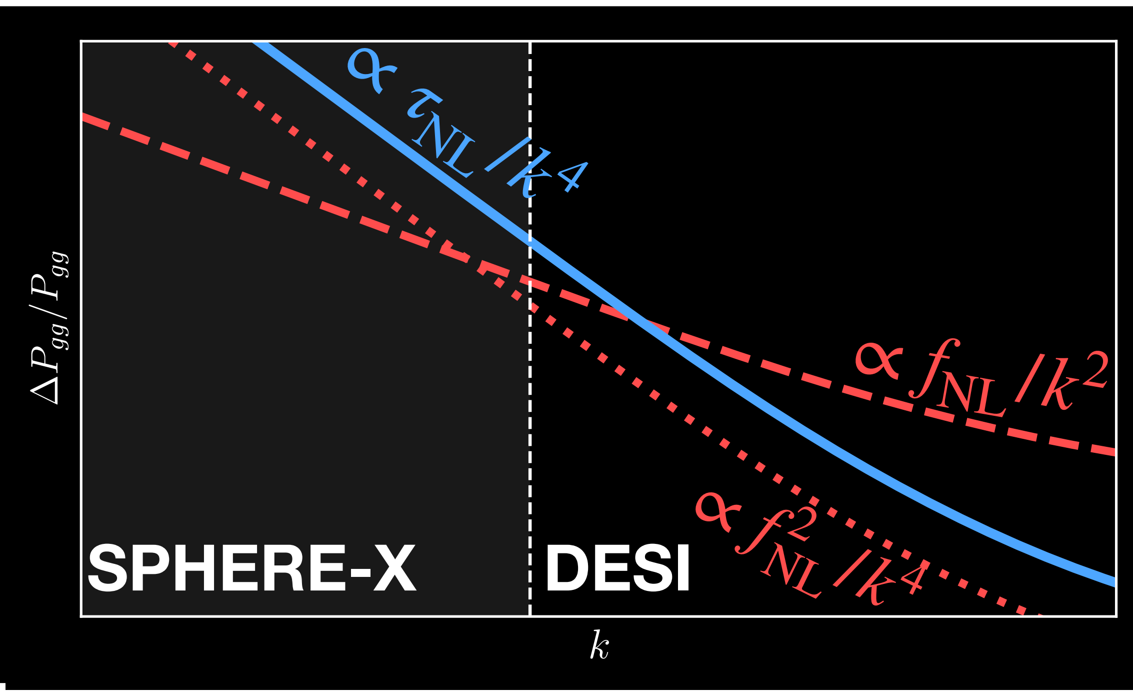
Theoretical motivation:
Cosmological collider



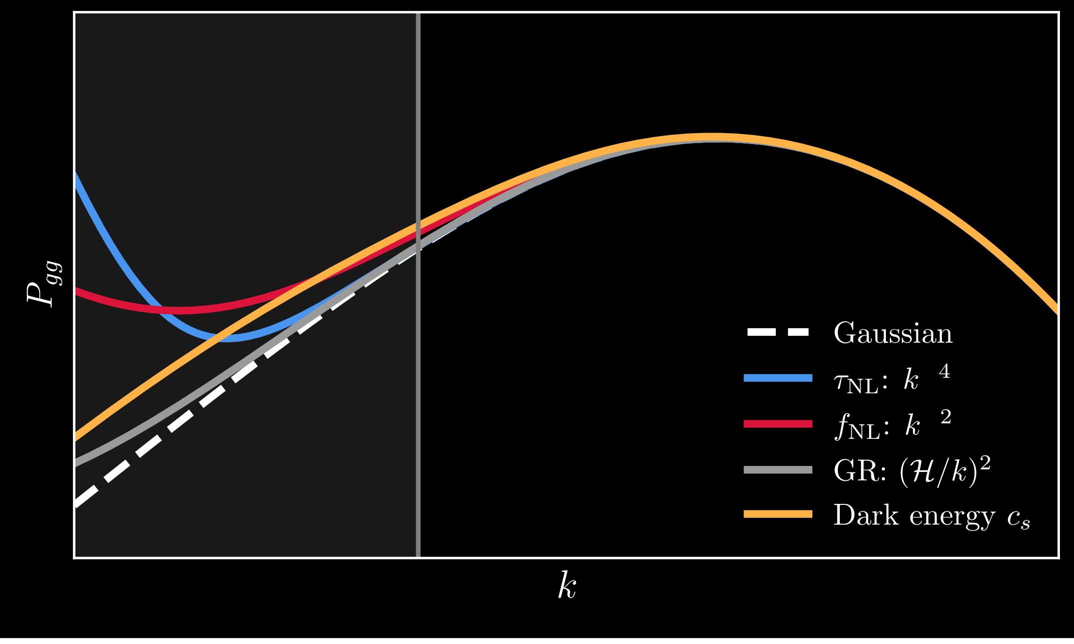
Near-term LSS surveys ***10-100*x**
more sensitive than CMB

?

Never before constrained with
LSS



τ_{NL} analysis of today is the f_{NL}
analysis of tomorrow



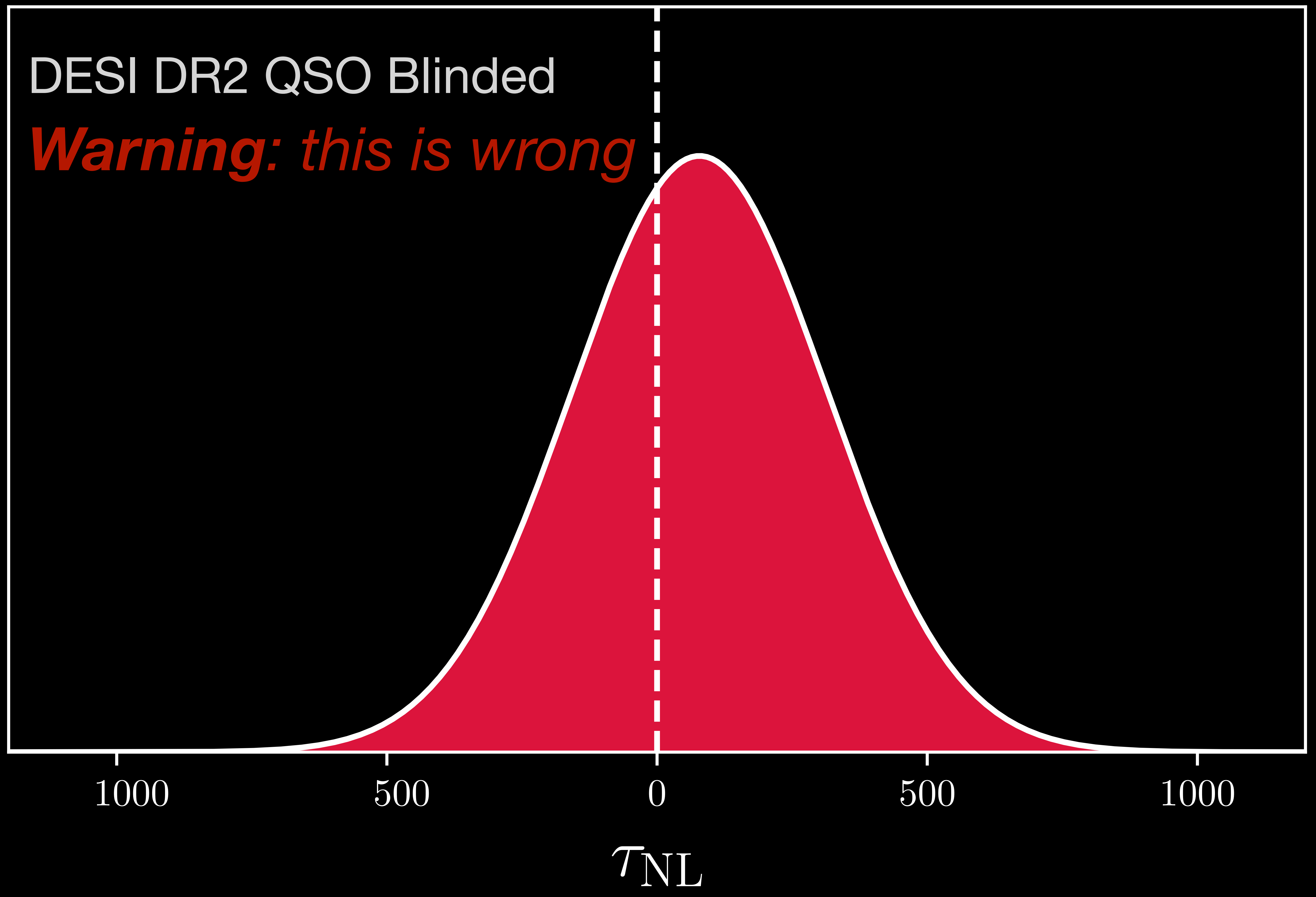
τ_{NL} pipeline can be used for
ultra-large scale P(k)

3-step plan to constraining τ_{NL} with DESI

```
tnl_exc_loc = params['tnl_exc_loc']
if bphiX is not None:
    pkmu = pkmu + jac * fog * (25. / 36.) * tnl_exc_loc * bphiX * bphiY * alpha**2 * pk_obs
self.power = self.to_poles(pkmu)
```

***Step 1**: Add τ_{NL} to DESI PNG pipeline (5 lines)*

3-step plan to constraining $\tau_{\rm NL}$ with DESI



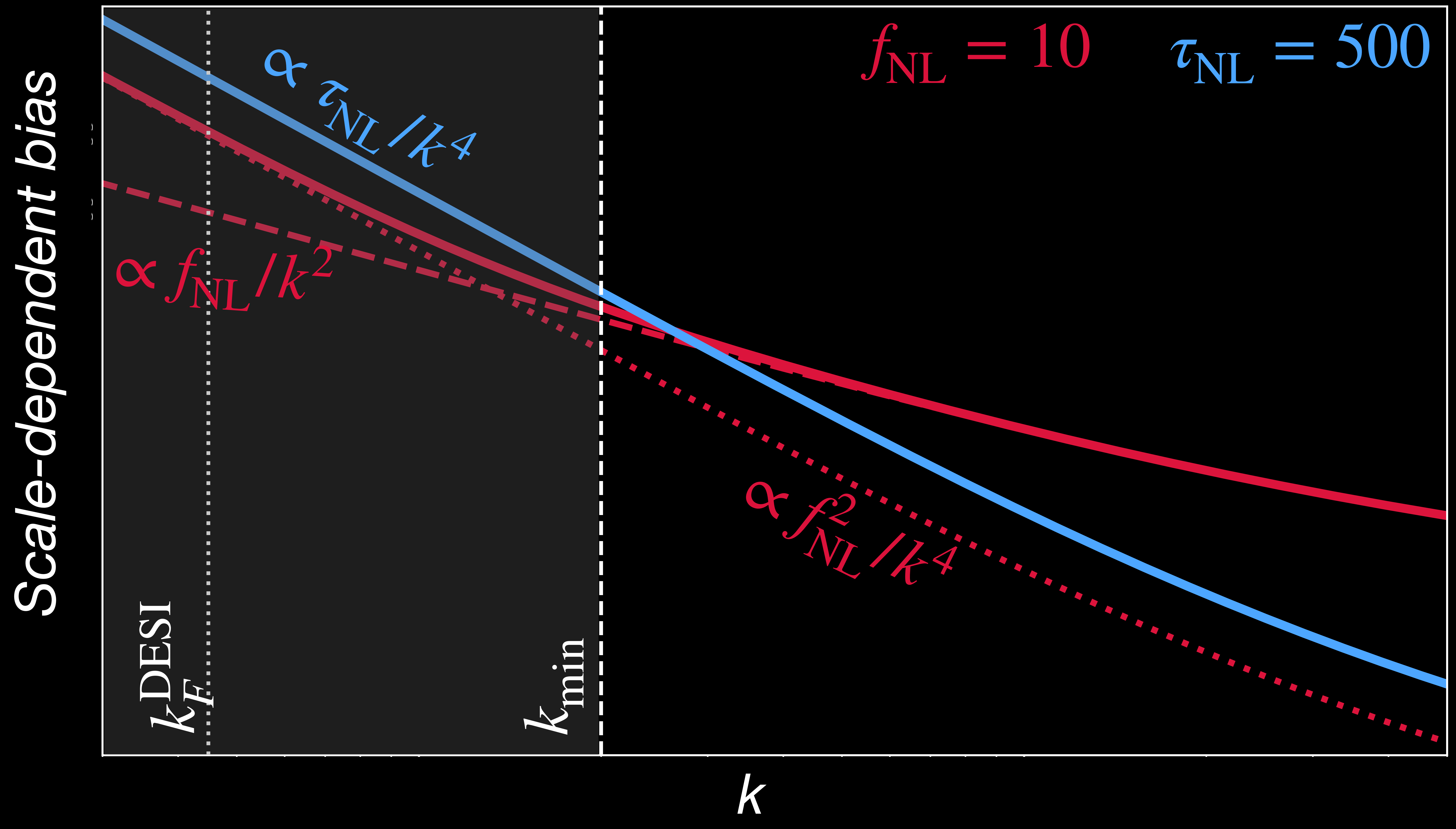
Step 2: *Run analysis on DESI DR2 blinded quasars* $\tau_{\rm NL} = 80 \pm 240$

3-step plan to constraining τ_{NL} with DESI

$$\sigma < \sigma_{\text{Cramér-Rao}}$$

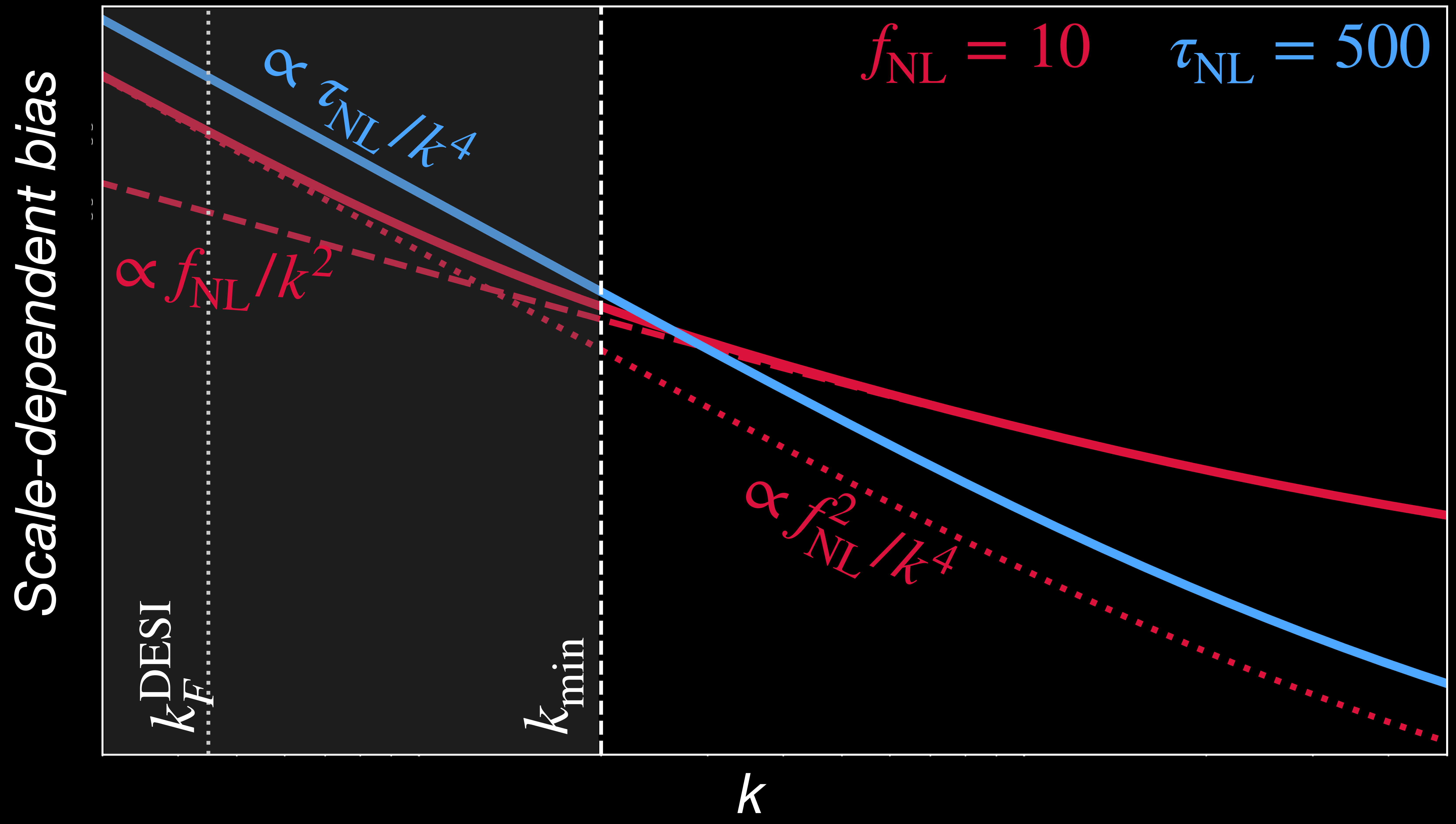
***Step 3:** find constraints that are tighter than a Fisher forecast with similar settings*

Why is it difficult to constrain $\tau_{\rm NL}$ with DESI?



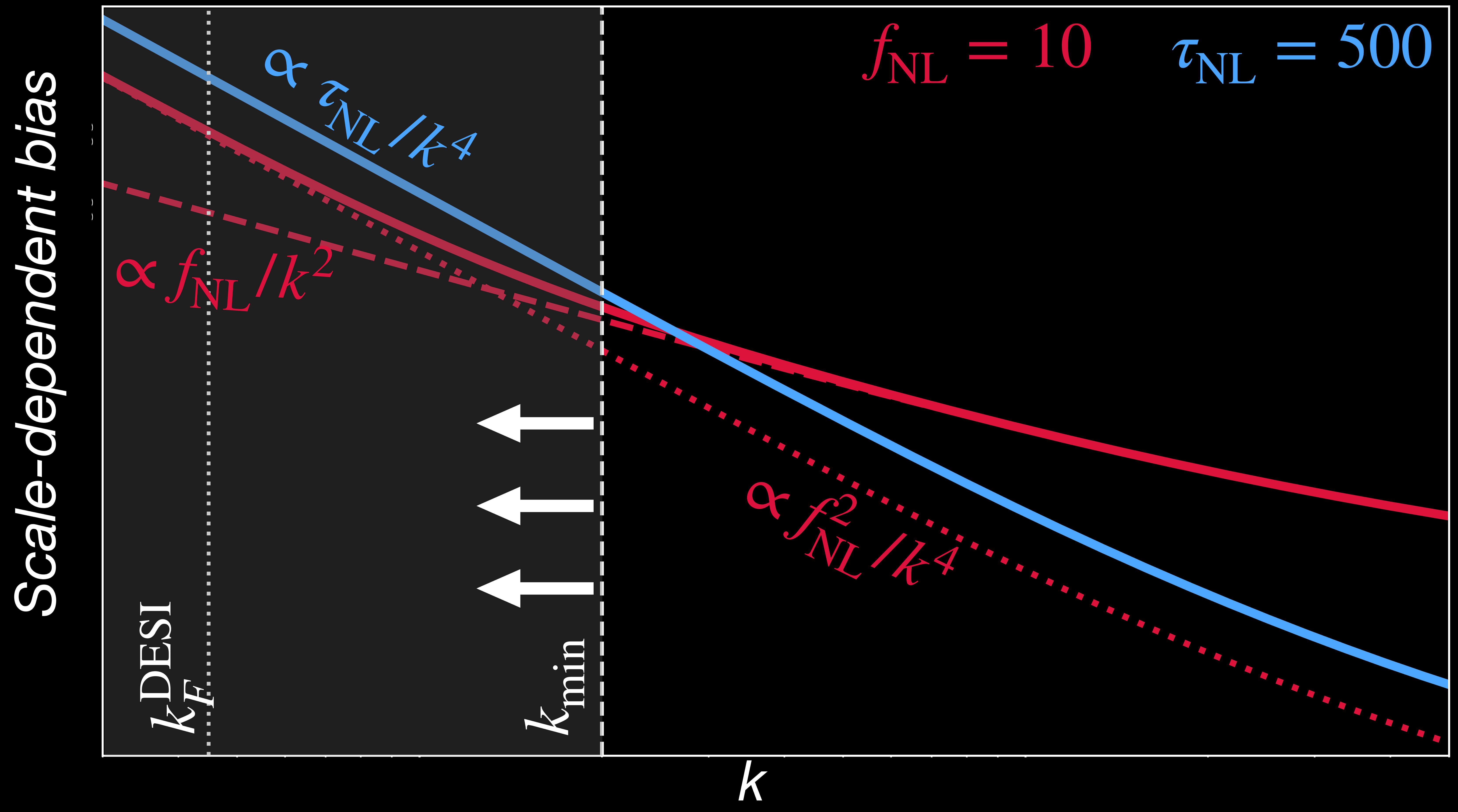
$\tau_{\rm NL}$: ***all*** *information is in the largest-scale modes*

Why is it difficult to constrain $\tau_{\rm NL}$ with DESI?



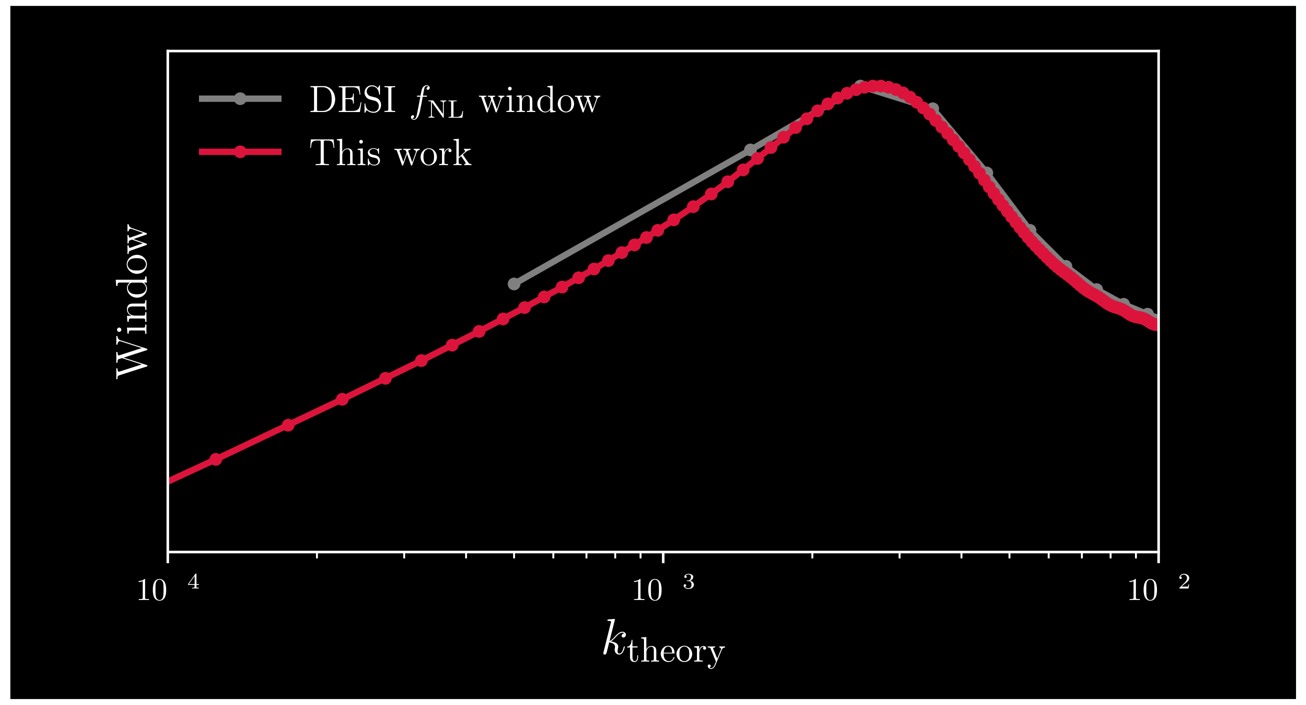
A robust $f_{\rm NL}$ pipeline is not necessarily a robust $\tau_{\rm NL}$ pipeline

Why is it difficult to constrain $\tau_{\rm NL}$ with DESI?

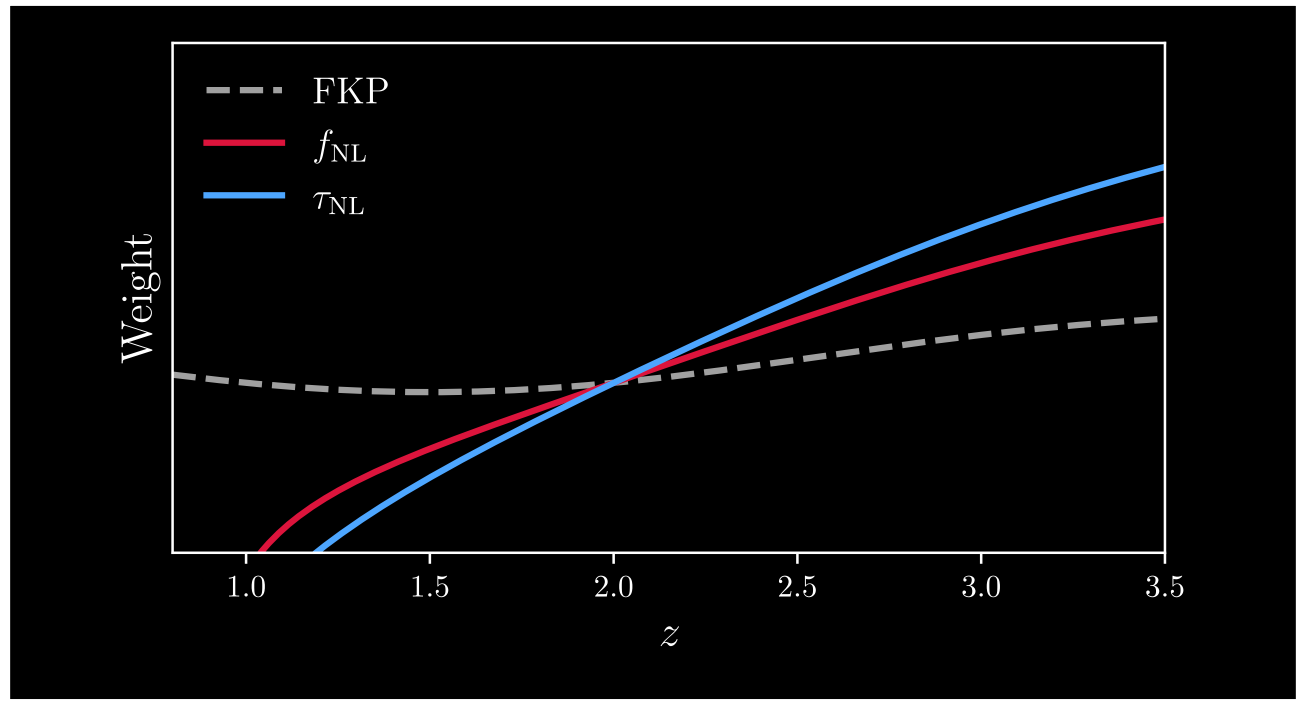


At low k, local fNL $\Delta b \propto f_{\rm NL}^2/k^4$. $\tau_{\rm NL}$ with DESI is a precursor for all future searches for $f_{\rm NL}$ using the scale-dependent bias

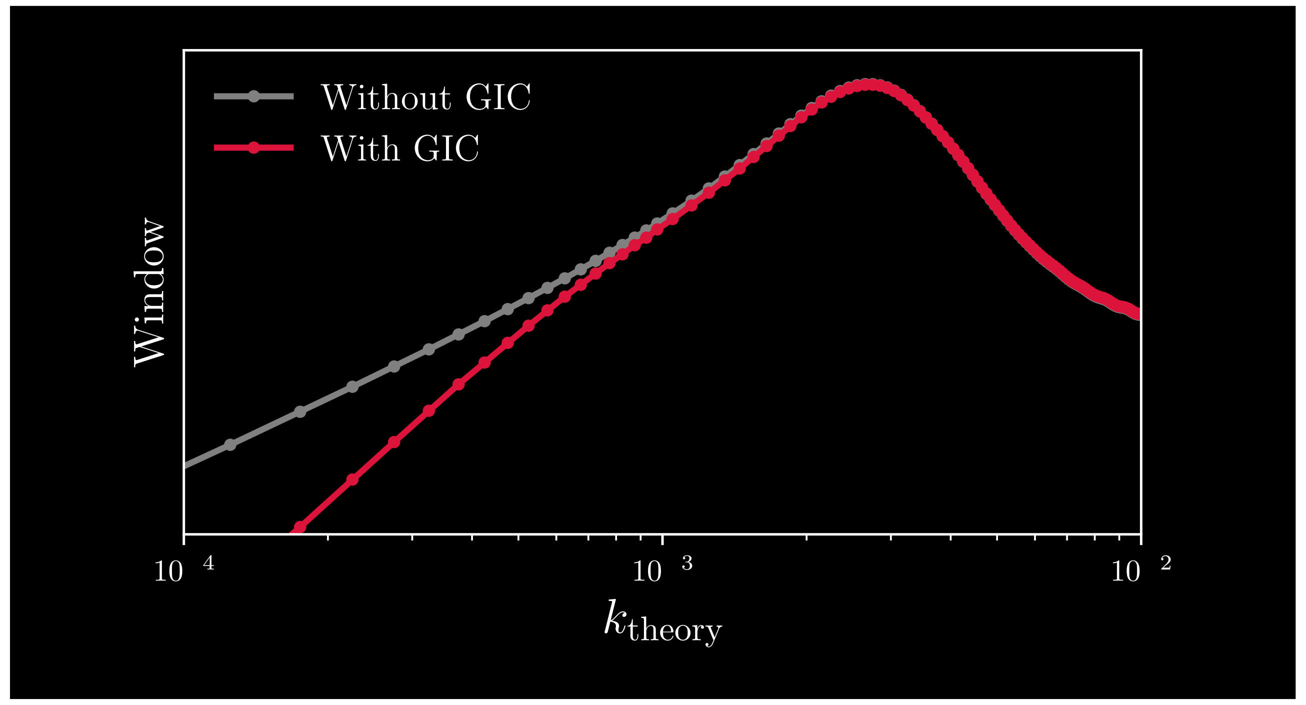
Creating a robust τ_{NL} pipeline for DESI quasars



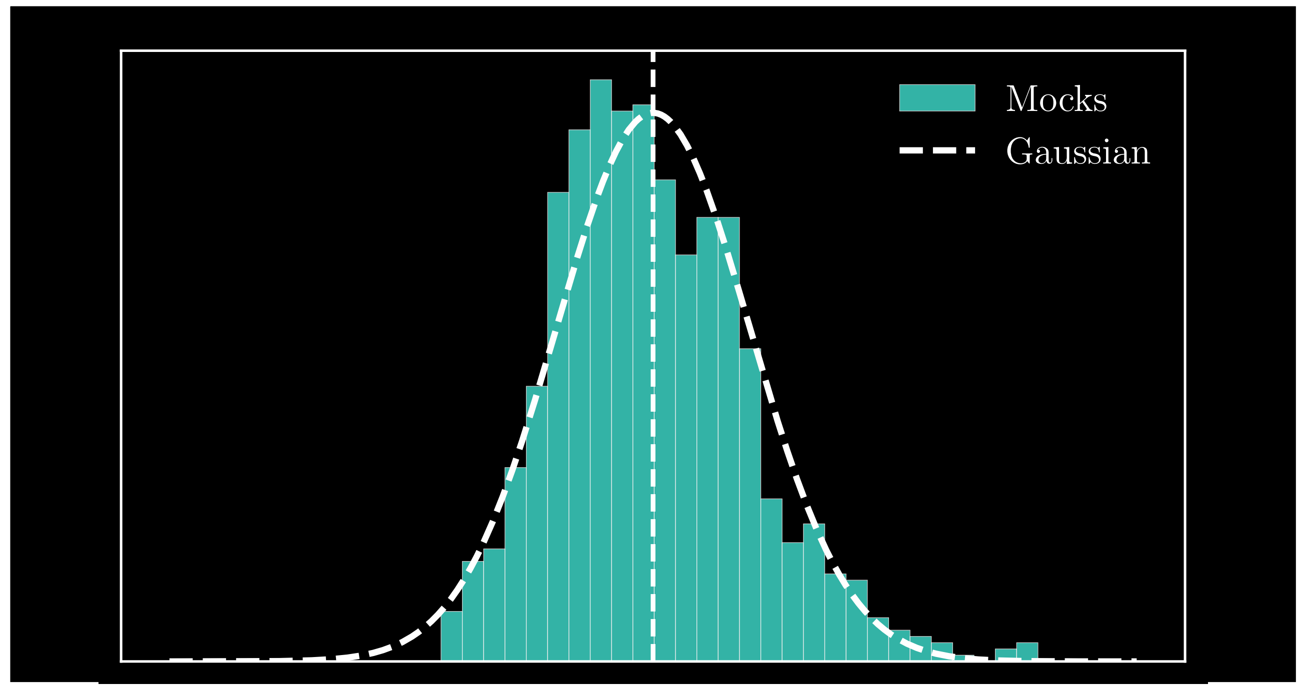
New window functions



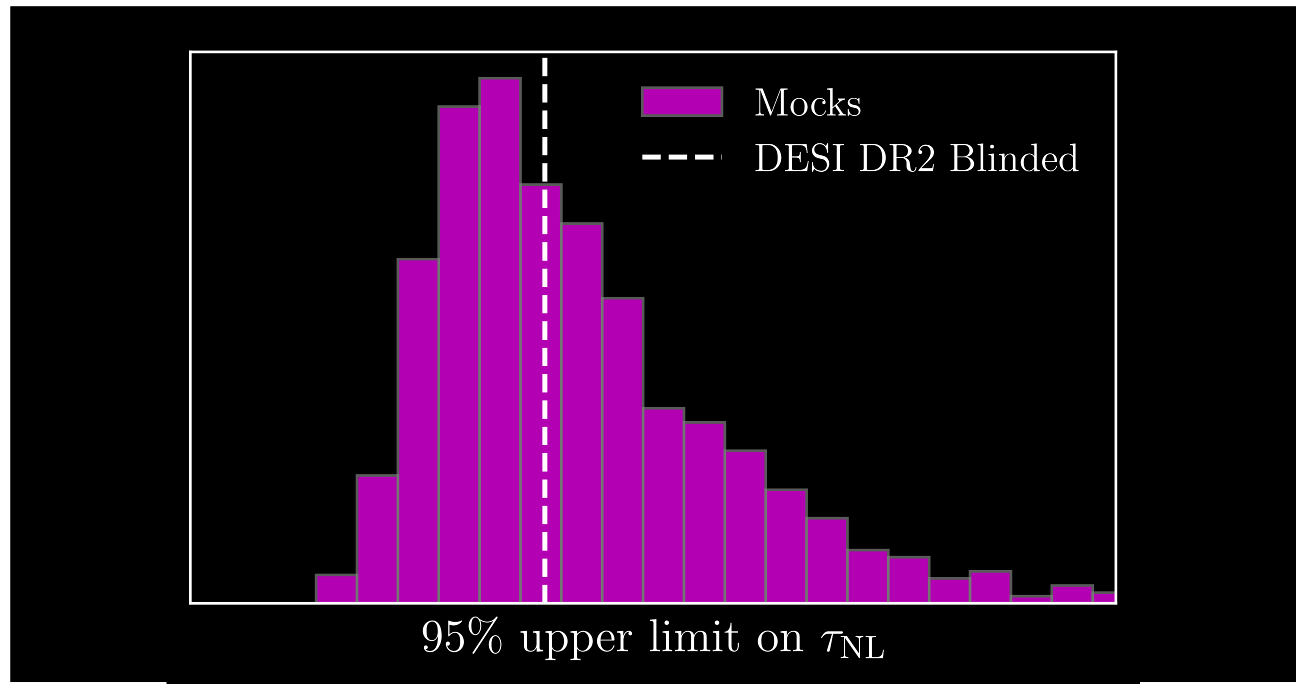
τ_{NL} optimal weights



Improved integral constraints

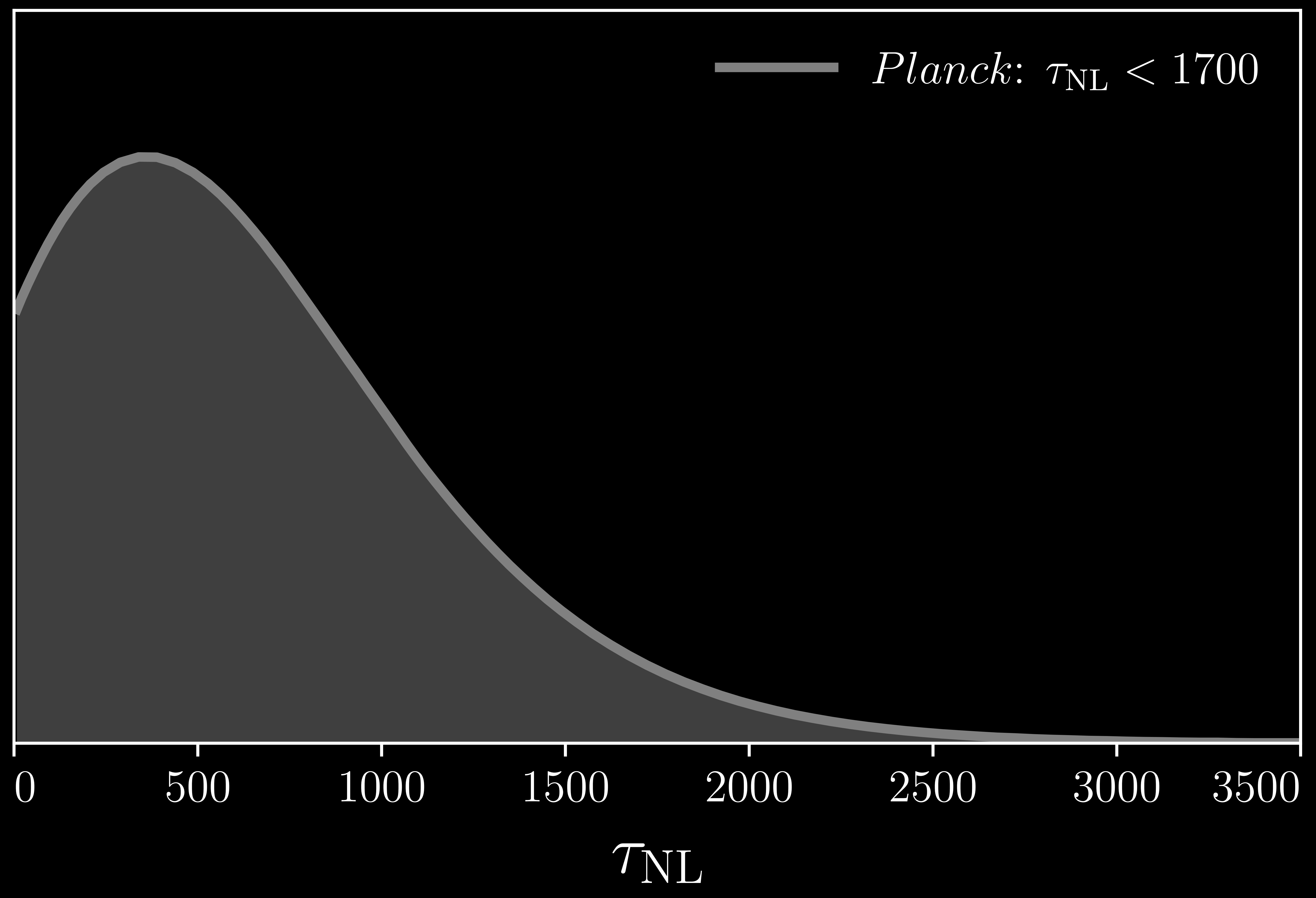


Non-Gaussian likelihood



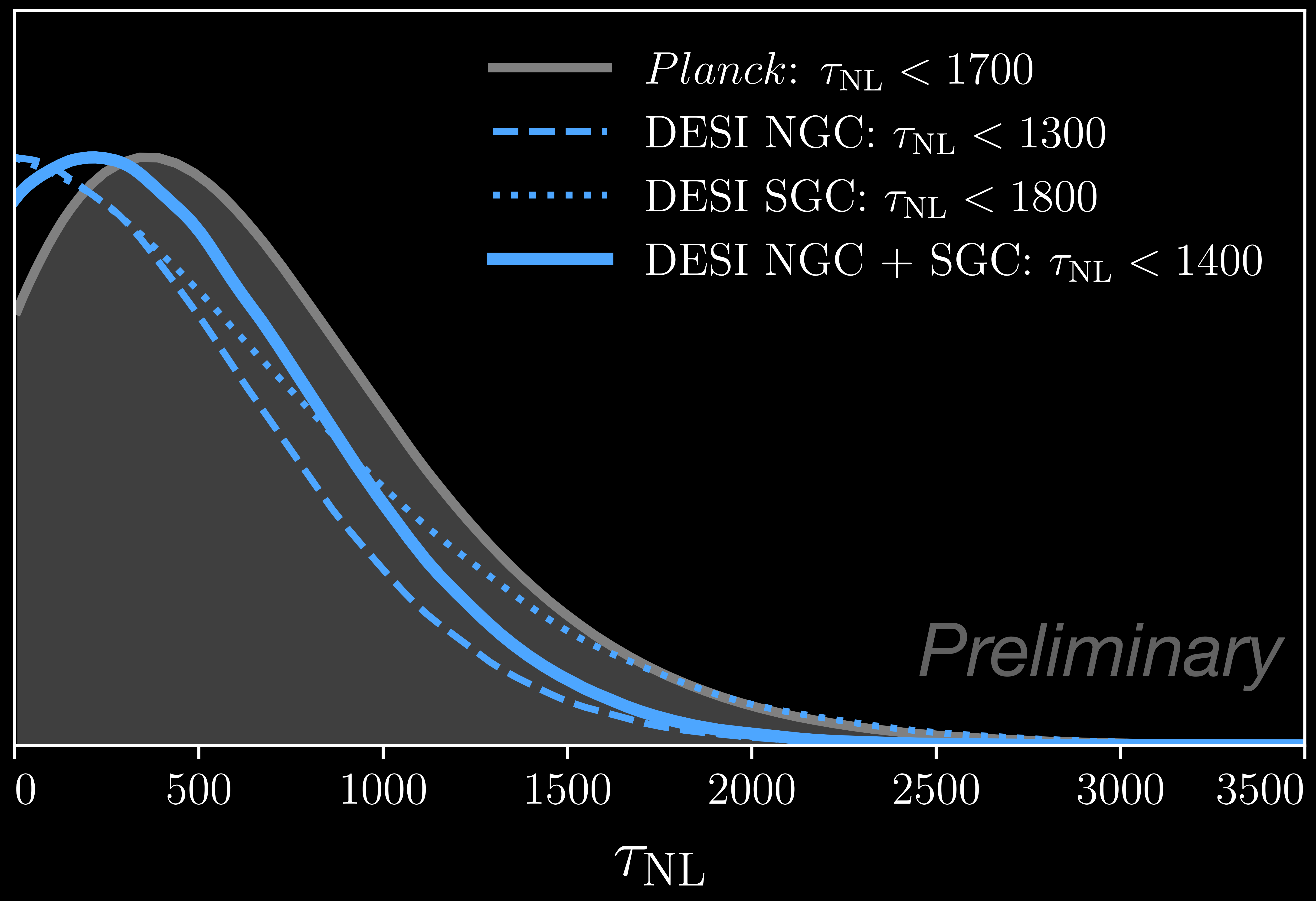
Systematics tests

Main result: first LSS constraints on $\tau_{\rm NL}$



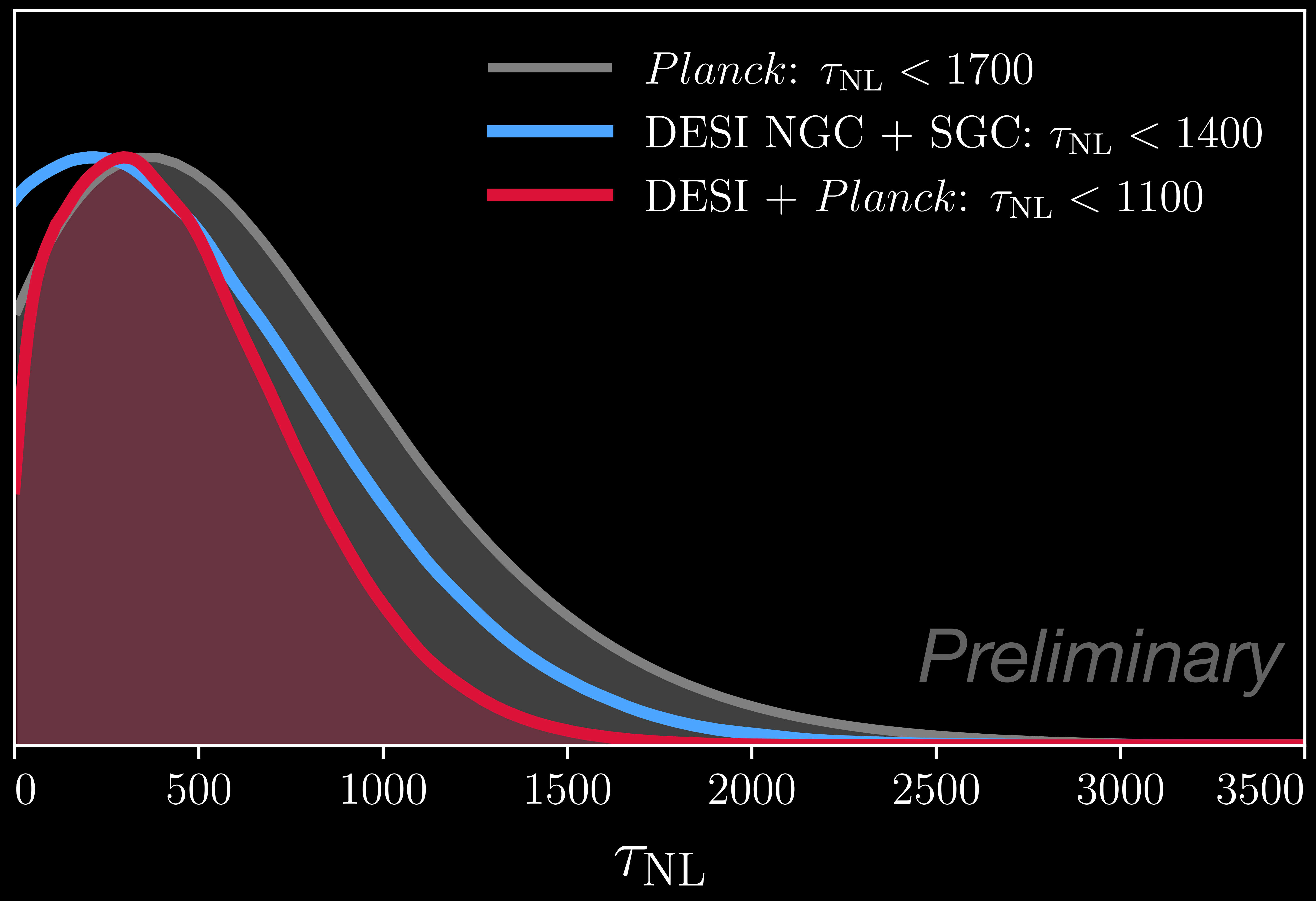
Constraints from DESI DR2 ***blinded*** *QSO: DESI DR2 data are already significantly more sensitive to* $\tau_{\rm NL}$ *than the primary CMB trispectrum*

Main result: first LSS constraints on $\tau_{\rm NL}$



Constraints from DESI DR2 ***blinded*** *QSO: DESI DR2 data are already significantly more sensitive to* $\tau_{\rm NL}$ *than the primary CMB trispectrum*

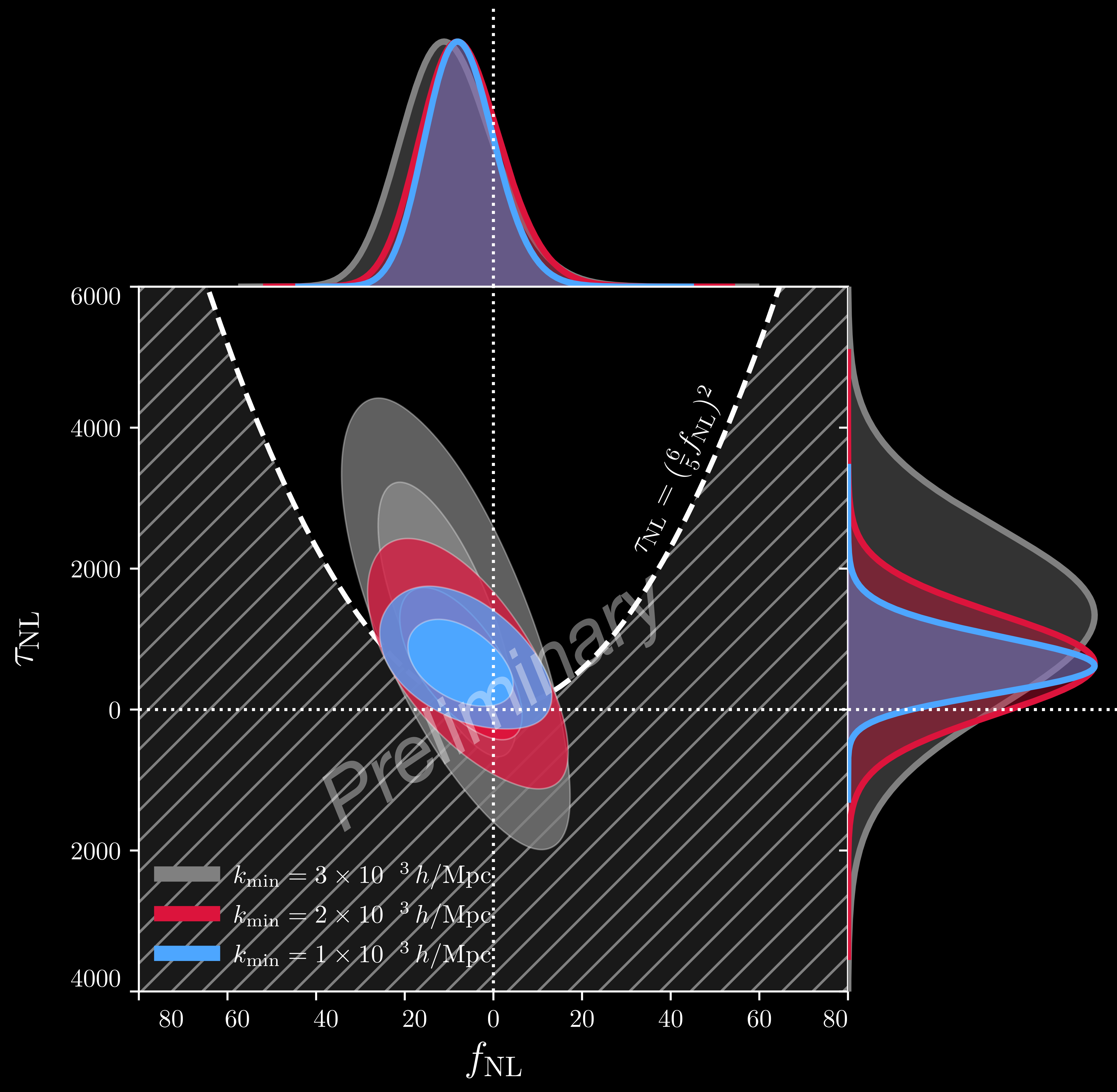
Main result: first LSS constraints on $\tau_{\rm NL}$



Constraints from DESI DR2 ***blinded*** *QSO: DESI DR2 data are already significantly more sensitive to $\tau_{\rm NL}$ than the primary CMB trispectrum*

Varying $f_{\rm NL}$ and $\tau_{\rm NL}$ jointly

- Best test of multi-field inflation to date
  - ζ generated by one source: $\tau_{\rm NL} = \left(\frac{6}{5} f_{\rm NL}\right)^2$
- Powerful test of DESI QSO data
  - Imaging systematics/target selection (Chaussidon++22)



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- Powerful test of DESI QSO data
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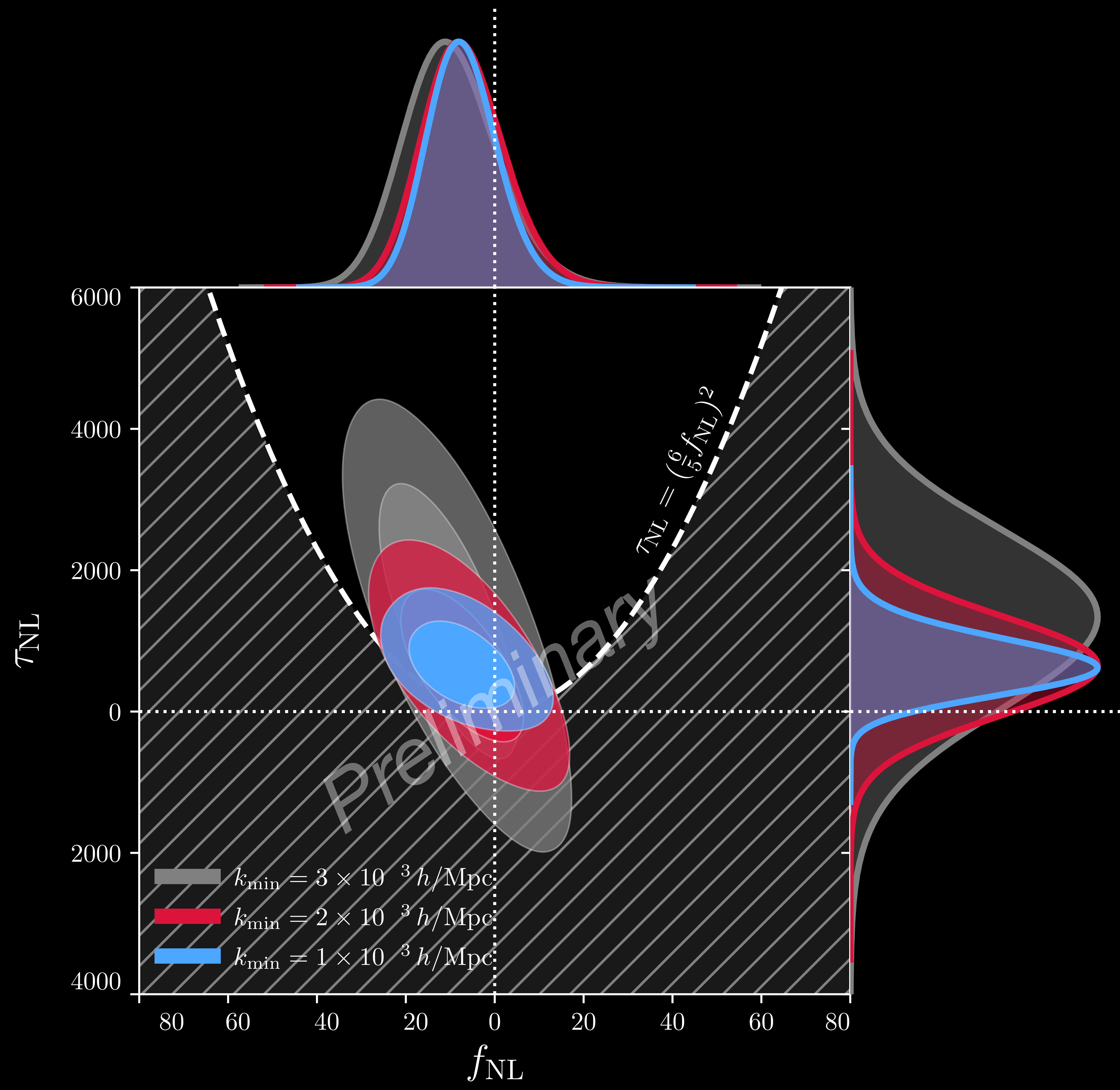
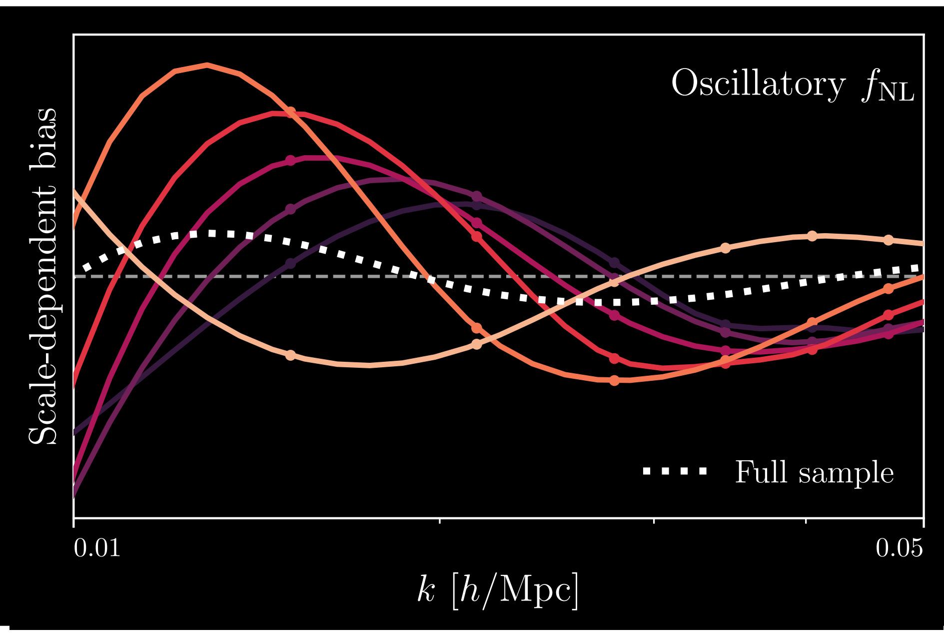
What's next?

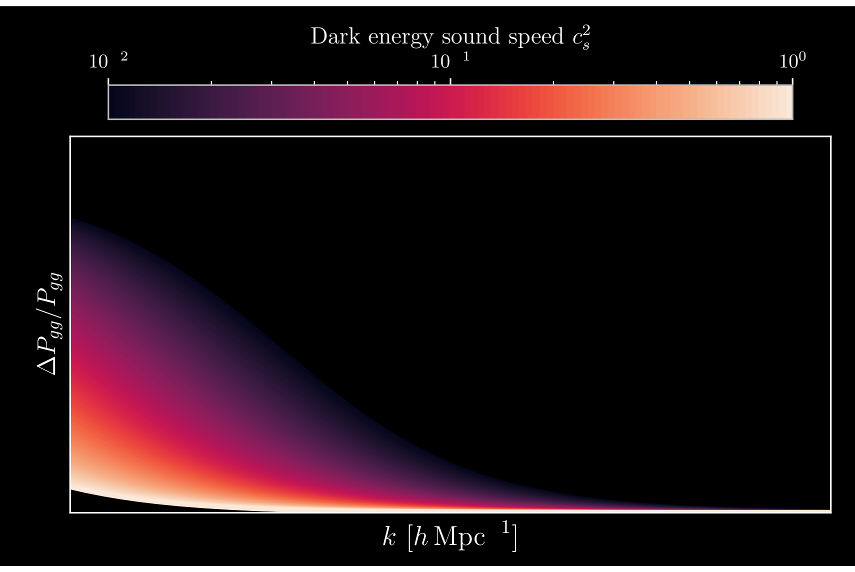


Near term: new physics with $\tau_{\rm NL}$ pipeline



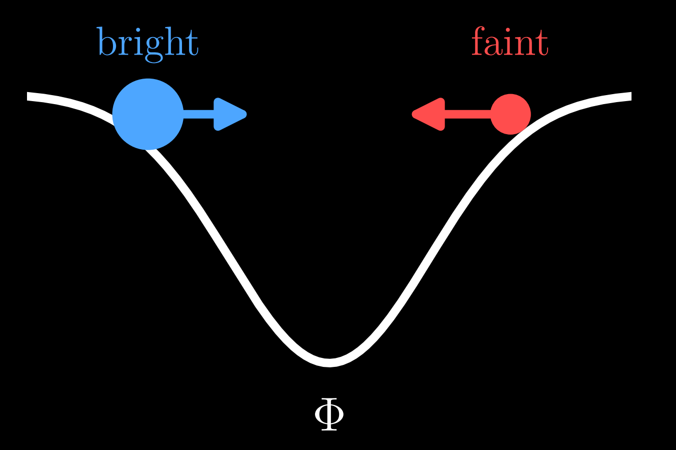
SG++2407.08731
SG++2505.13443
Green++26
Anbajagane & Dalal, 26

Cosmological collider/oscillatory bias



de Putter++10
SG++2507.16970

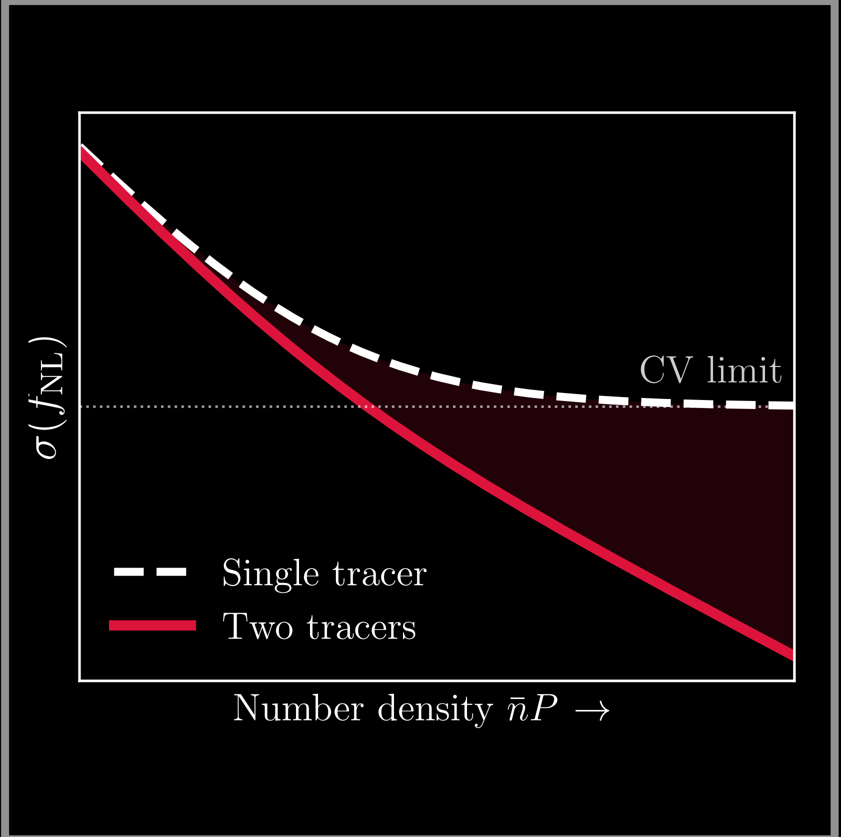
Dark energy perturbations



McDonald 2009
Creminelli++13

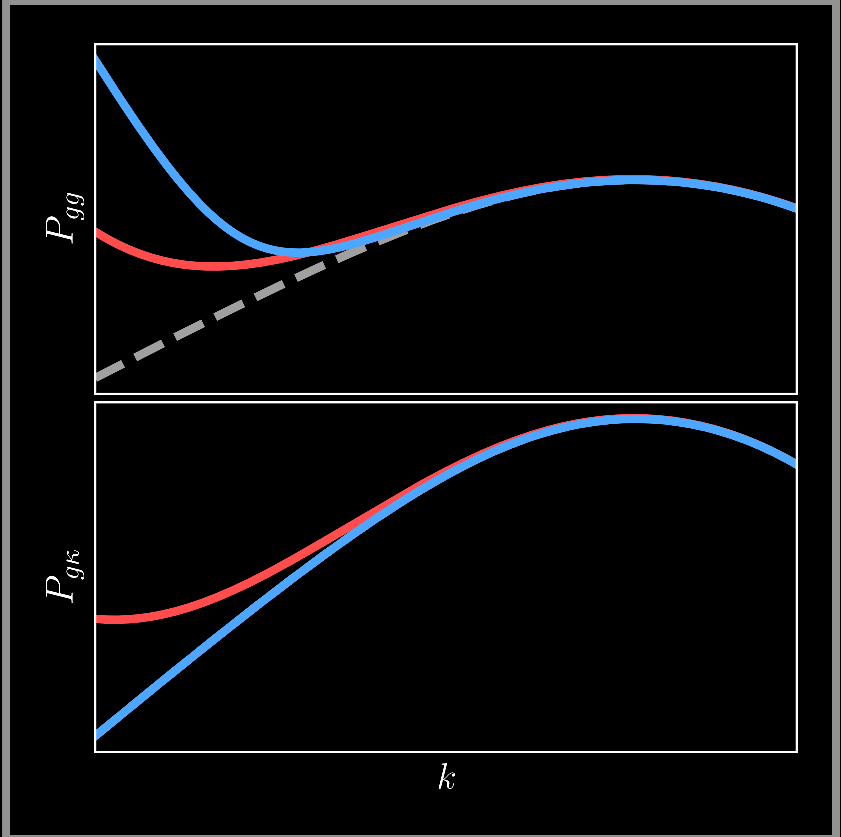
Gravity/equivalence principle

Medium term: multi-tracer and cross-correlations



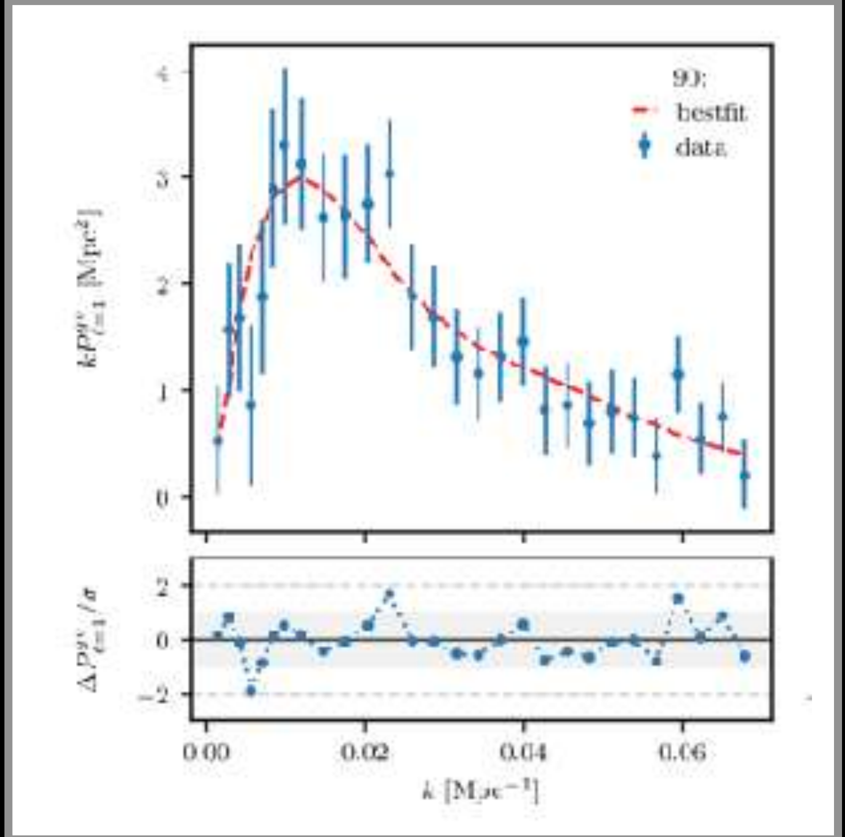
Multi-tracer

See *Seljak 08, McDonald & Seljak 08, Ferraro & Smith 14*



CMB lensing

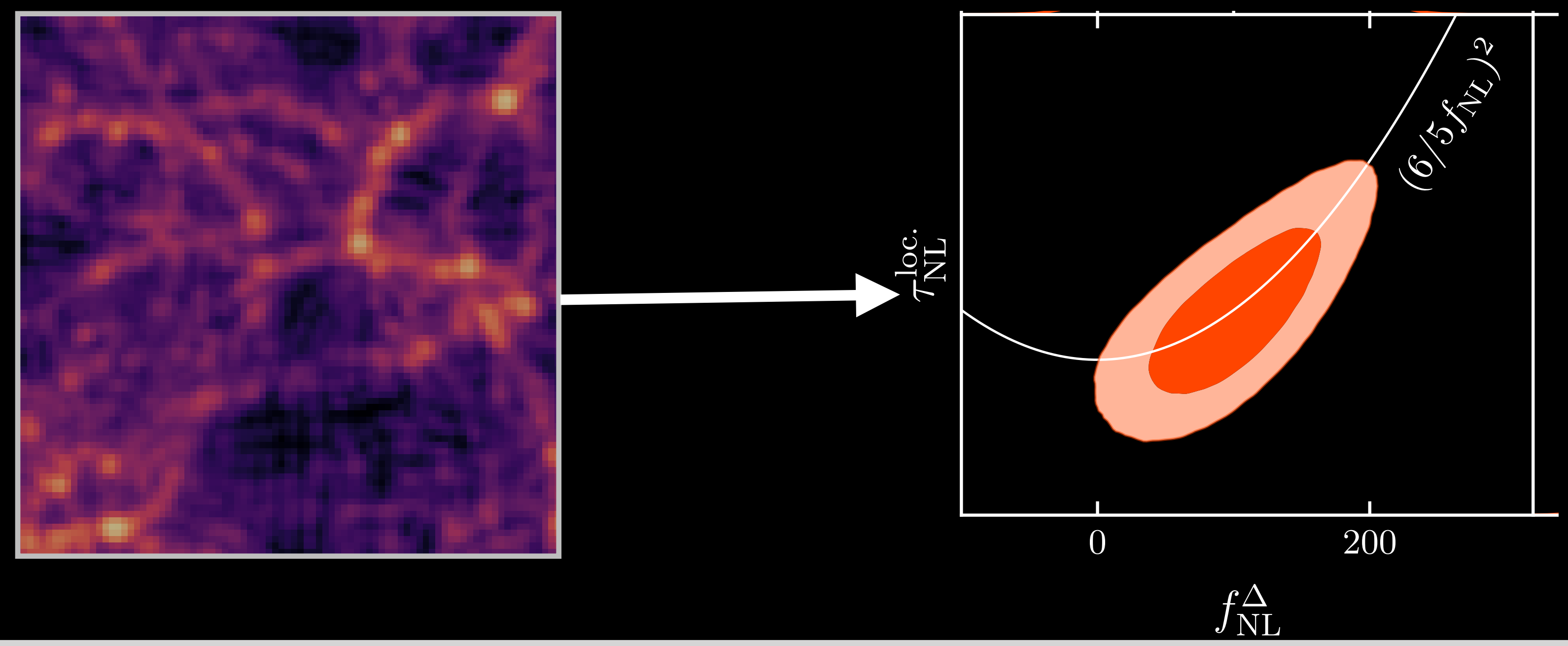
See *Schmittfull+Seljak, 17*



kSZ tomography

See *Anil Kumar++22, Chaussidon++26*

Long term: field-level inference/SBI



Seljak++17
Schmidt++18
Parker++25
Bayer++26

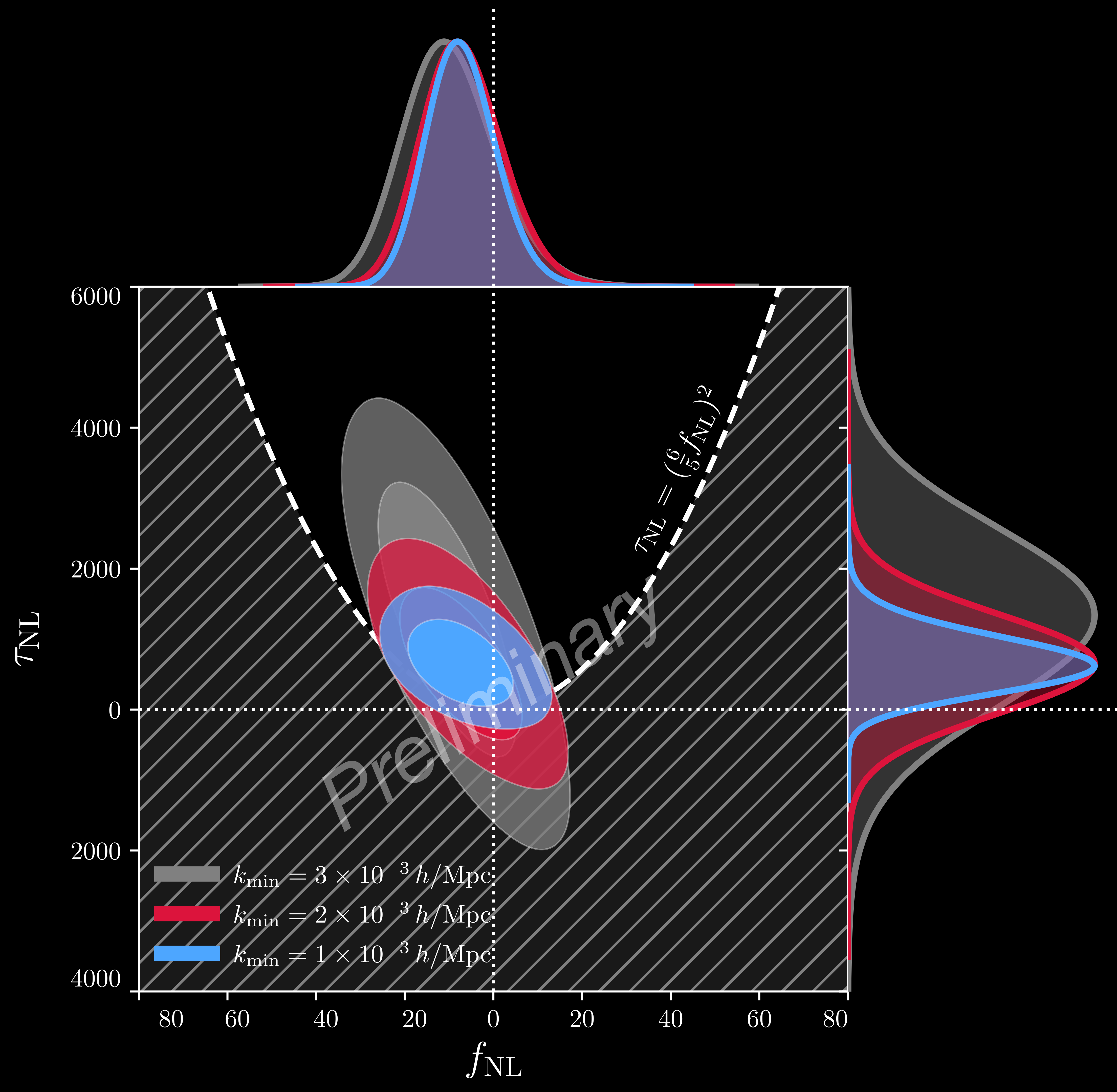
- Non-Gaussian likelihood
- Low dimensional dataset
- Optimal estimator -> complex weighting
- Real-space systematics (windows, integral constraints, etc.)

Conclusion

- Scale-dependent bias is more than f_{NL}^{loc}
  - First LSS search for τ_{NL}
    - DESI DR2 QSO analysis: still blinded, but expecting most sensitive search to date

- τ_{NL} pipeline is useful for range of BSM scenarios
  - Multifield inflation, dark energy perturbations, large-scale behavior of gravity

- **DESI:** first time LSS is more constraining than CMB for inflation



Wavenumber, k

Overall conclusion

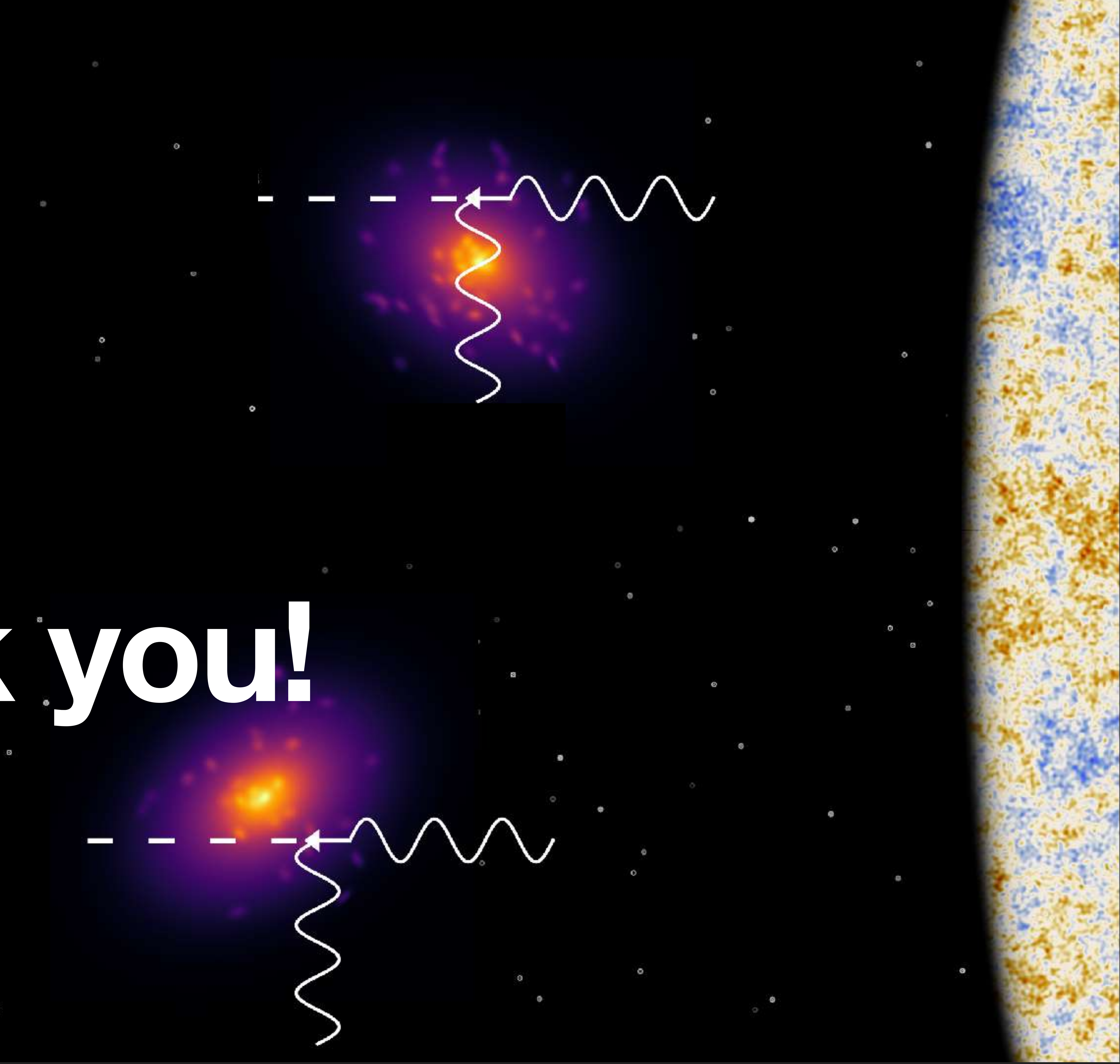
- Cosmology is invaluable probe of BSM physics

- Searching for BSM signals requires developing new pipelines that have applications even if no new physics is detected

  - **Example 1:** searching for axions led to stringent constraints on axions as well as component-separation pipeline with new methods for foreground cleaning that is now being used to produce component-separated maps for SO

  - **Example 2:** constraining $\tau_{\rm NL}$ with DESI has led to the most sensitive search for multifield inflation to date. Analysis is still blinded, but in absence of detection our new pipeline is starting point for range of BSM searches

Thank you!



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