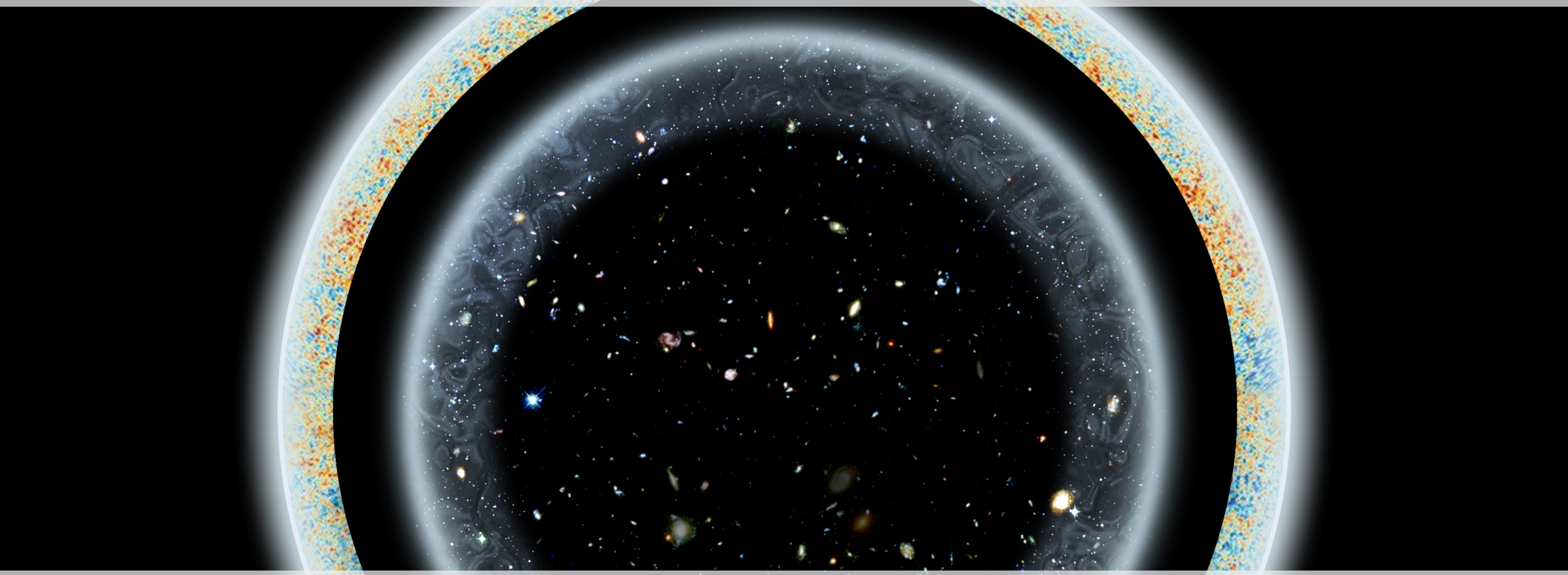
The CMB as a Backlight



Alexander van Engelen

Arizona State University

Beus Center for Cosmic Foundations
ASU School of Earth and Space Exploration

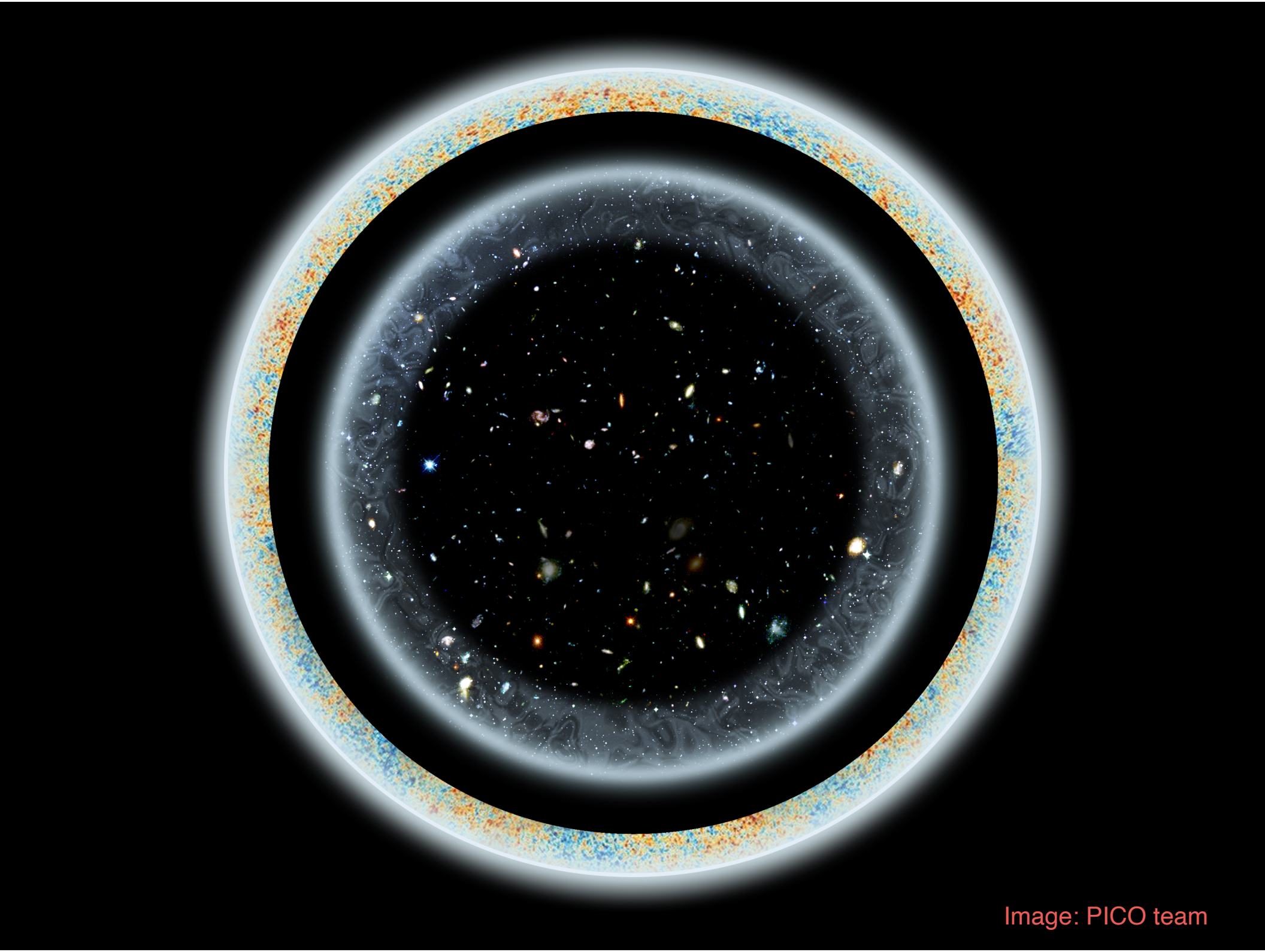
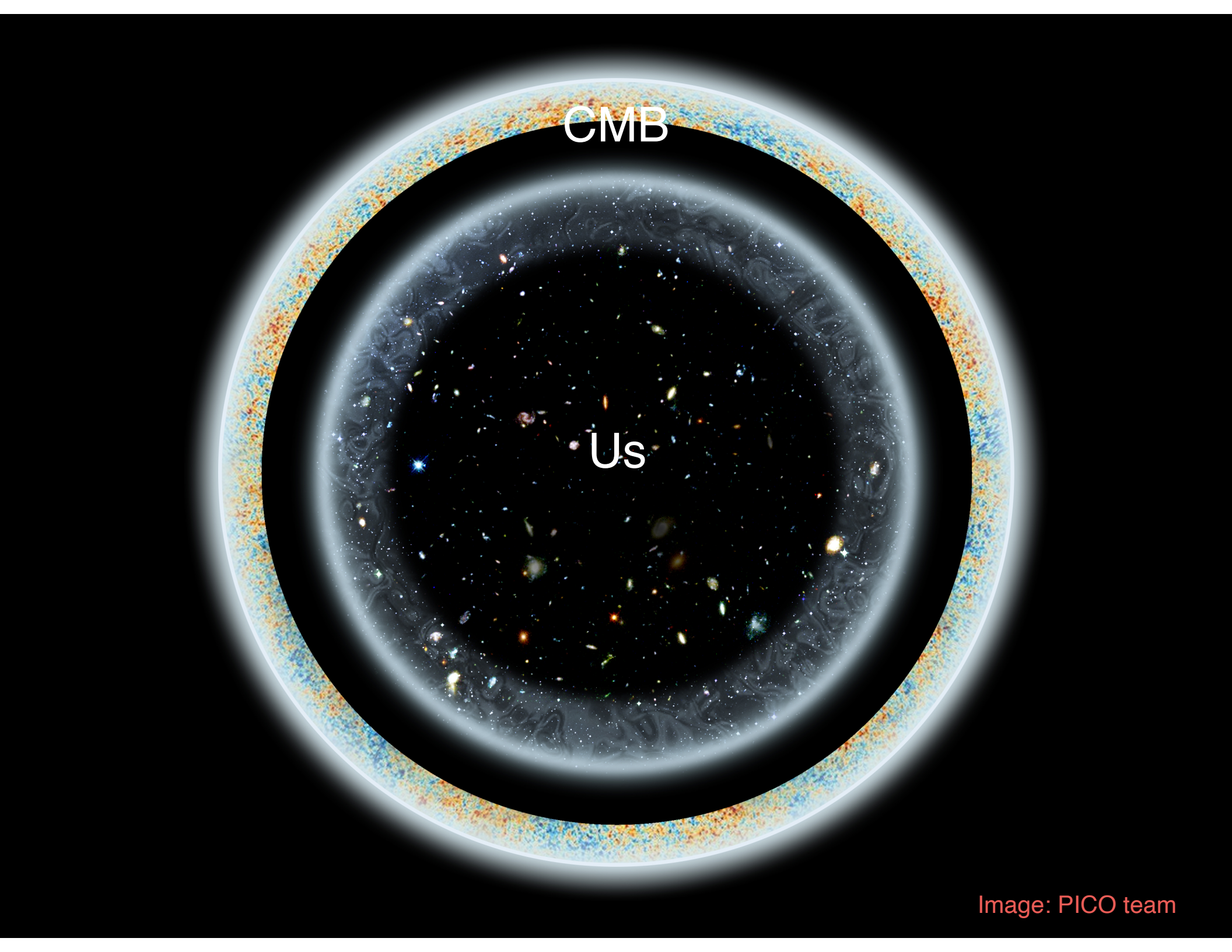


Image: PICO team



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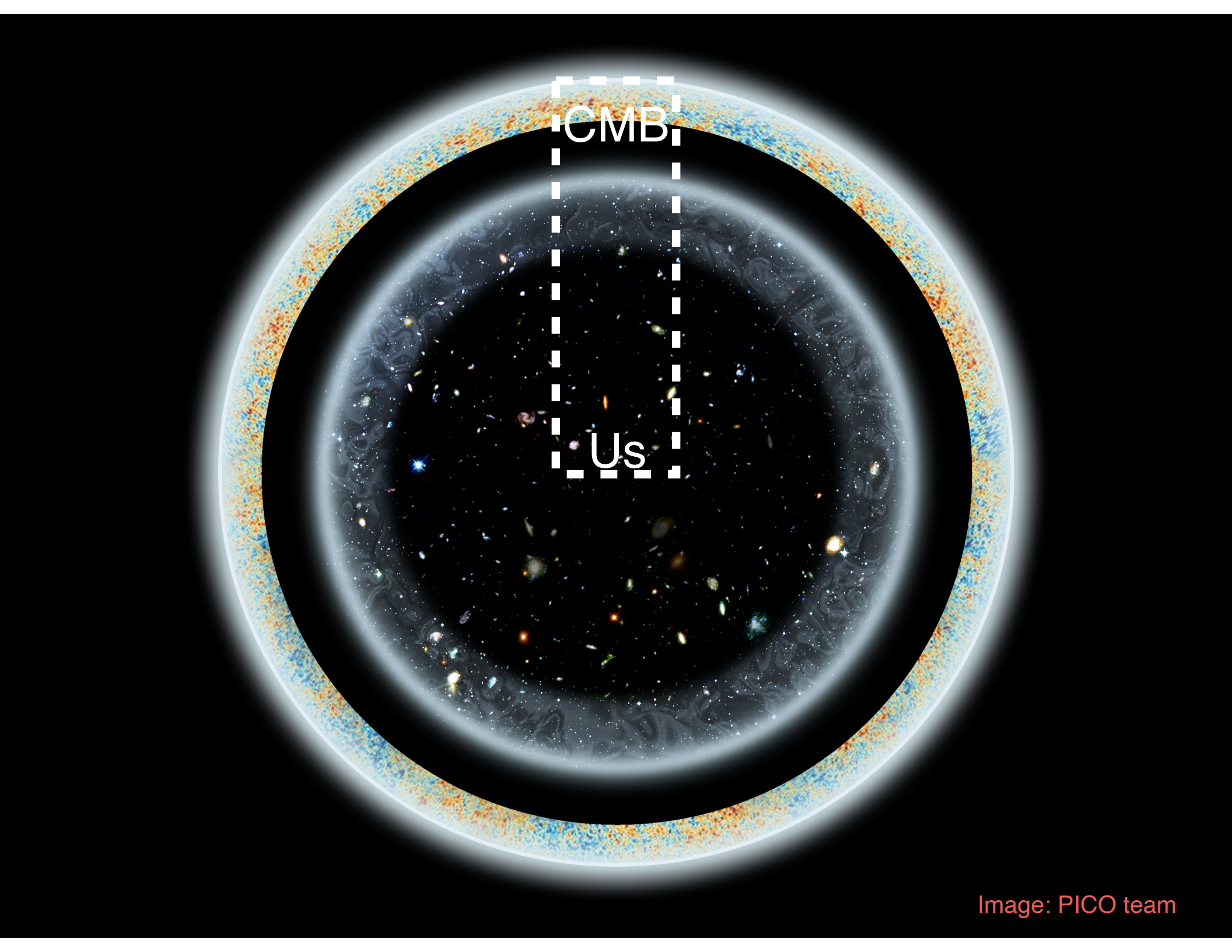
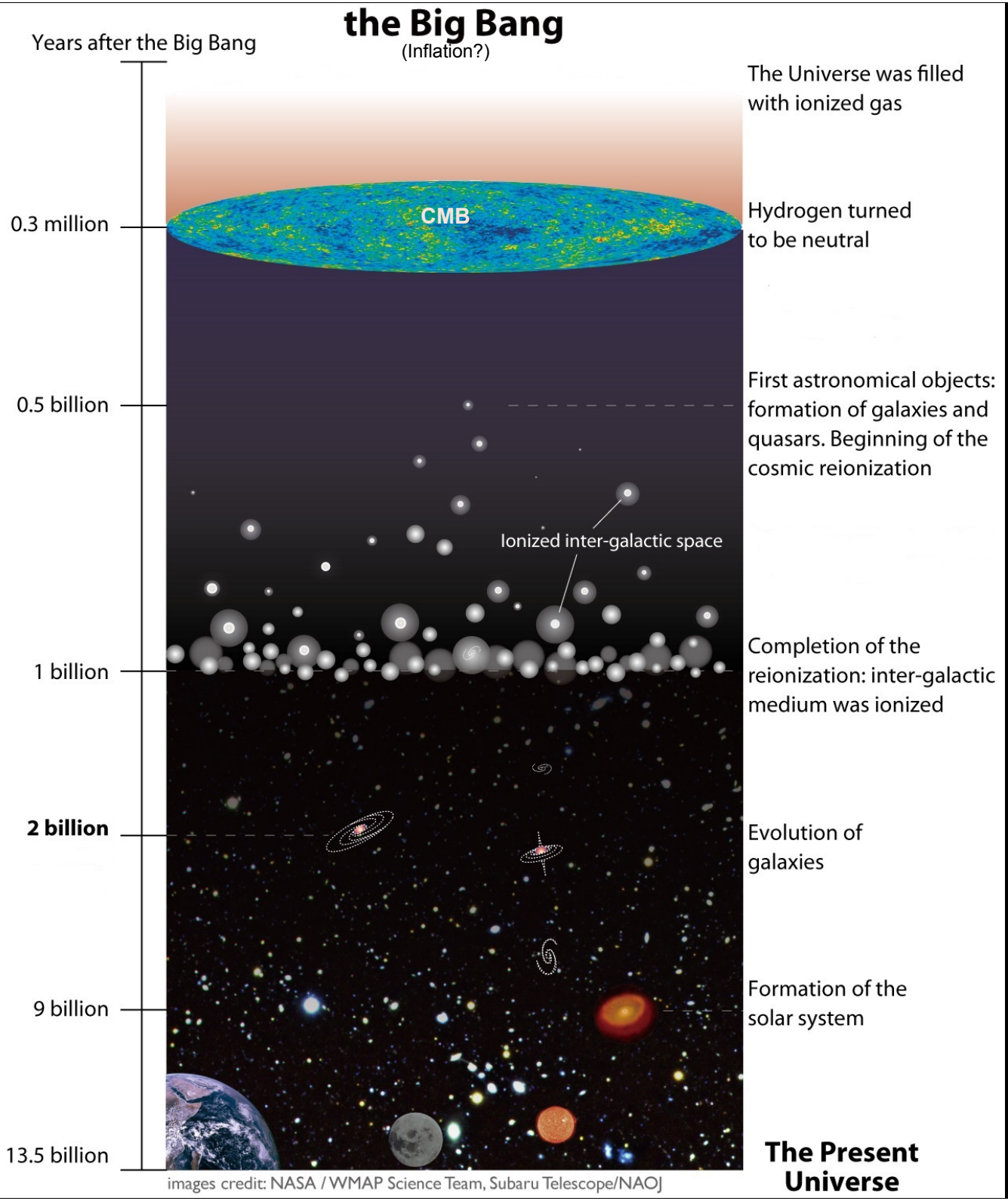


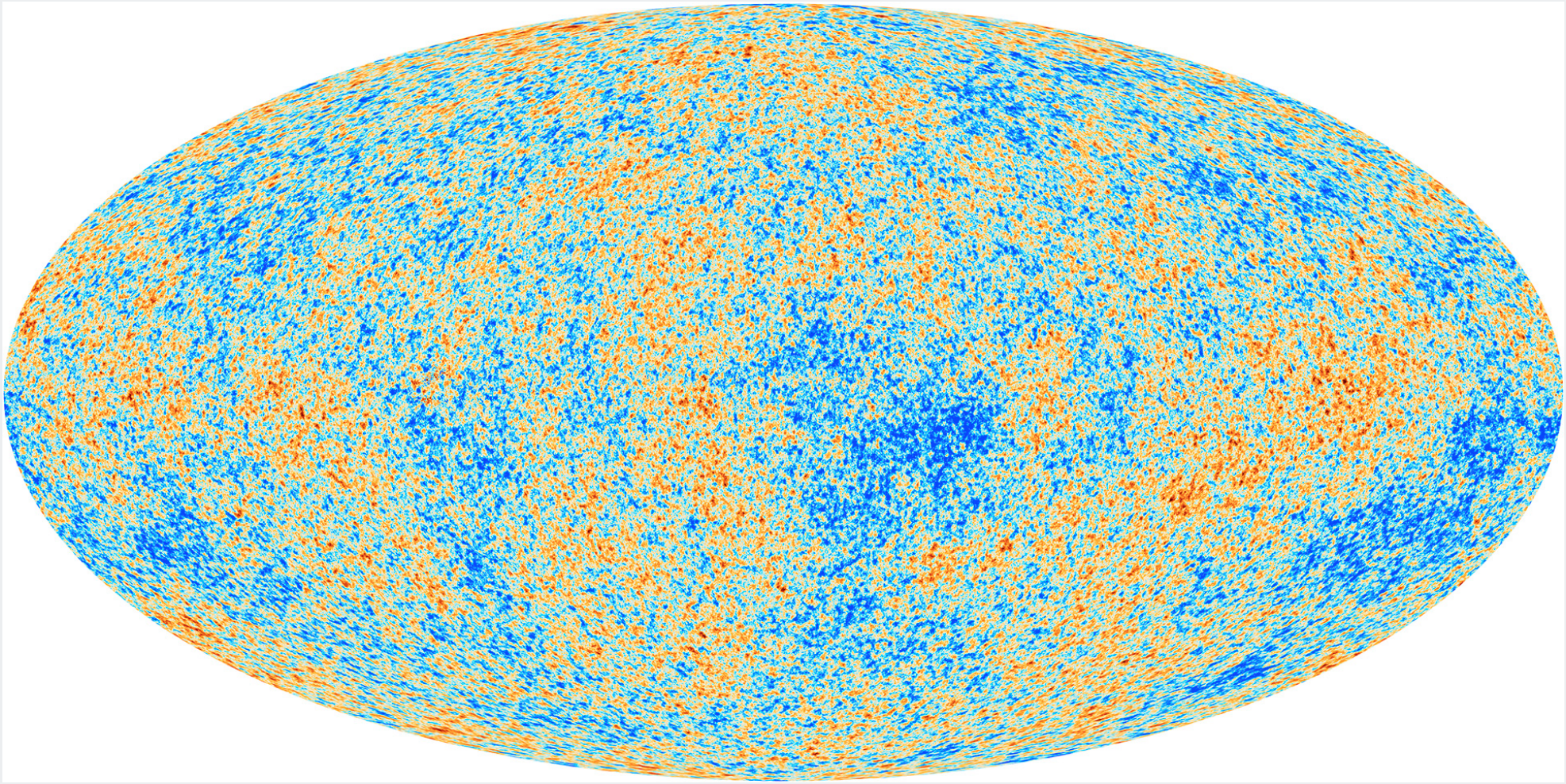
Image: PICO team

History of the Universe



The Primordial CMB

Planck 2013-18



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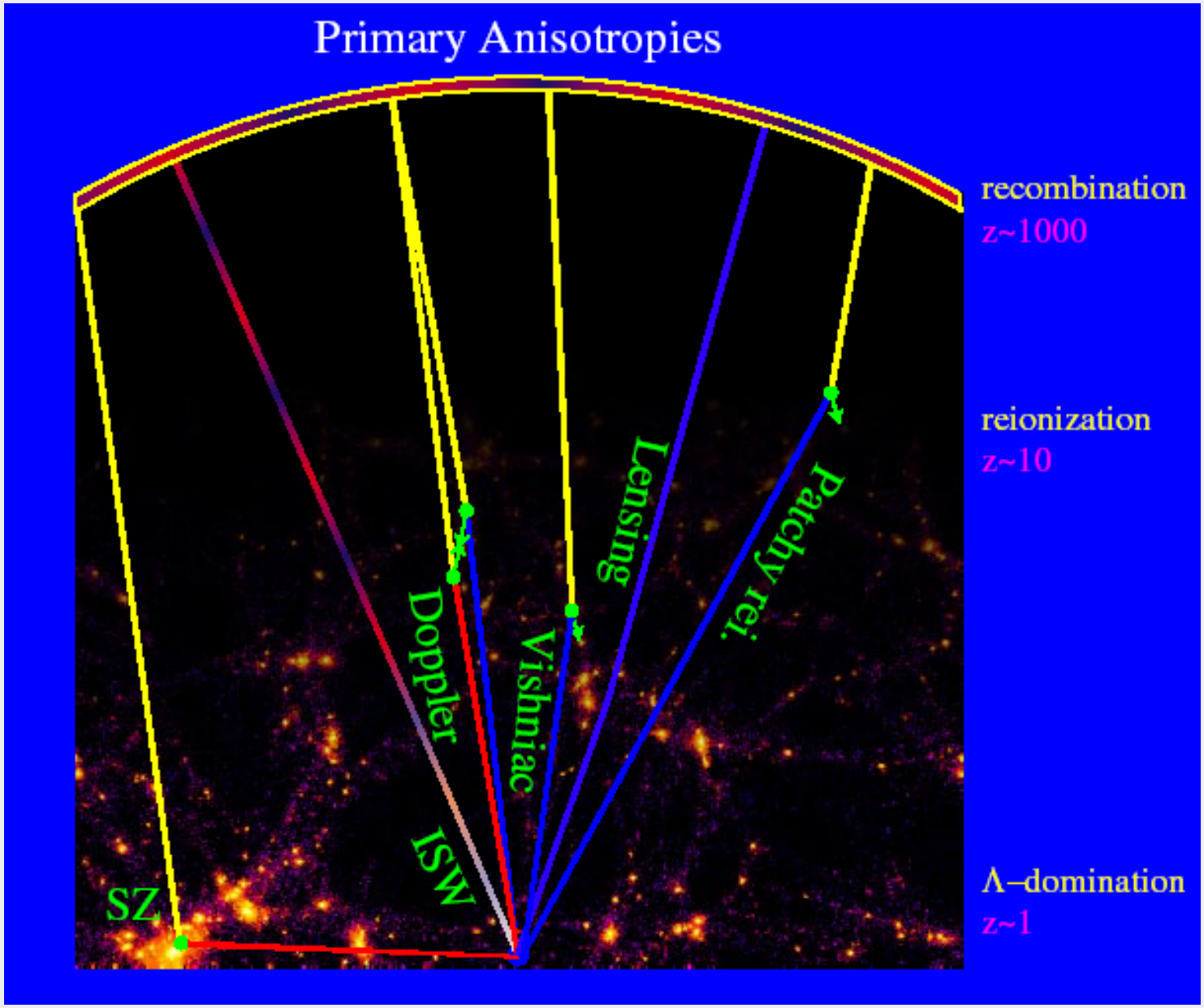

plus, emission in mm from dusty galaxies and AGN

Wayne Hu's website

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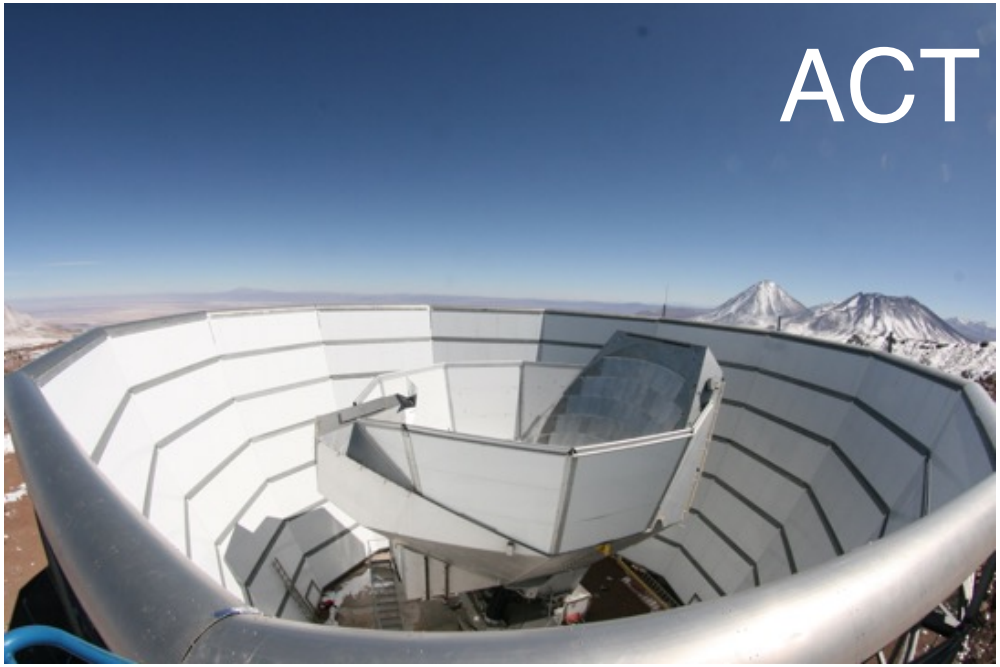
Surveys



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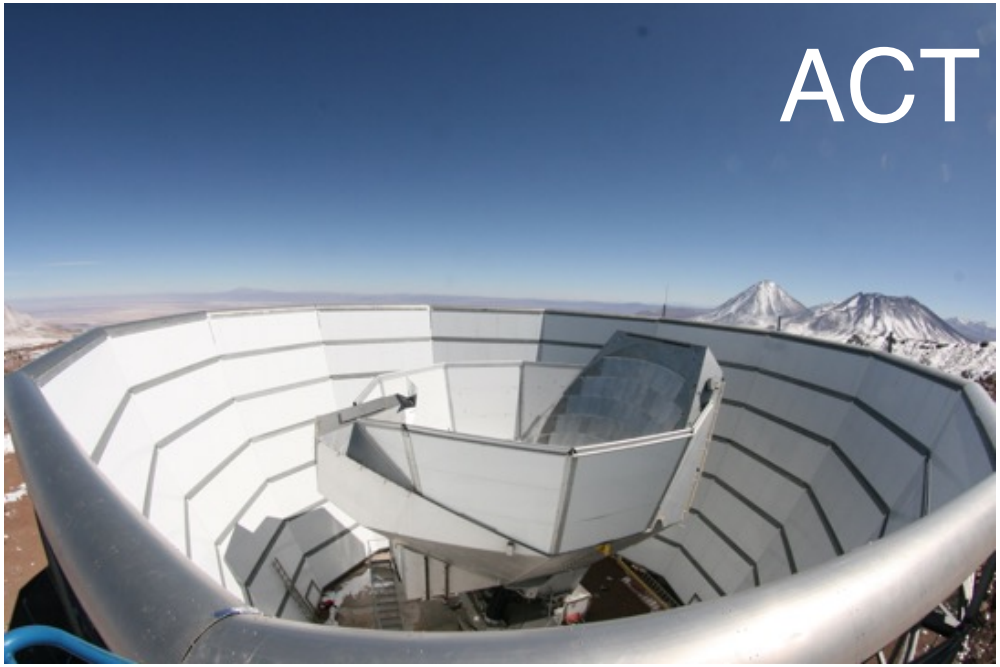
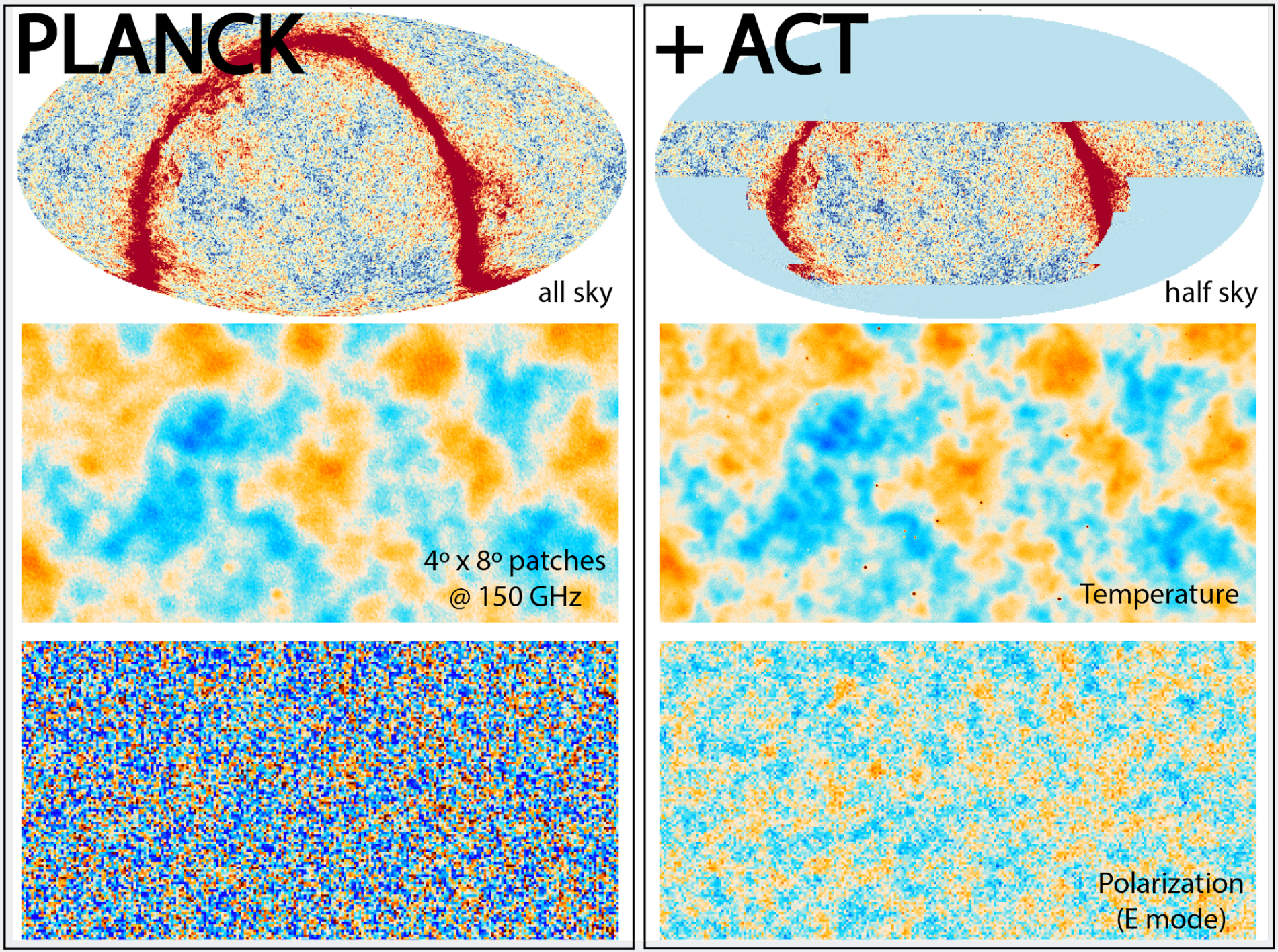


- Millimeter observations: 30, 40, 90, 150, 220 GHz
- Large telescope: 1-2 arcmin resolution, 5x higher than Planck
- Noise 3-6x lower than Planck
- Location in Chile: sees lots of sky (70%); but not as deep as SPT (worse atmosphere)

Atacama Cosmology Telescope

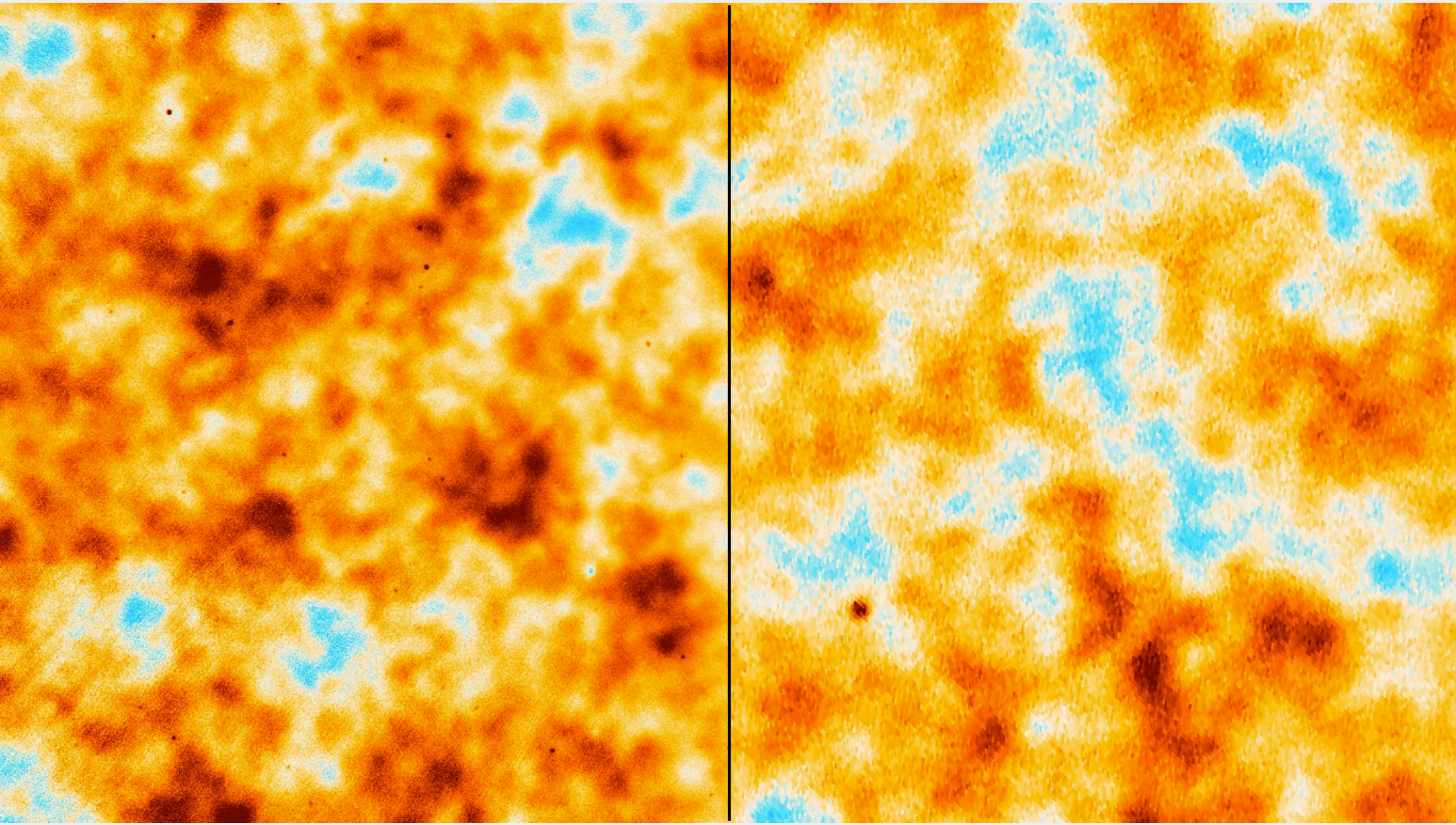
2019

2022


PLANCK
all sky
4º x 8º patches
@ 150 GHz
+ ACT
half sky
Temperature
Polarization
(E mode)

ACT

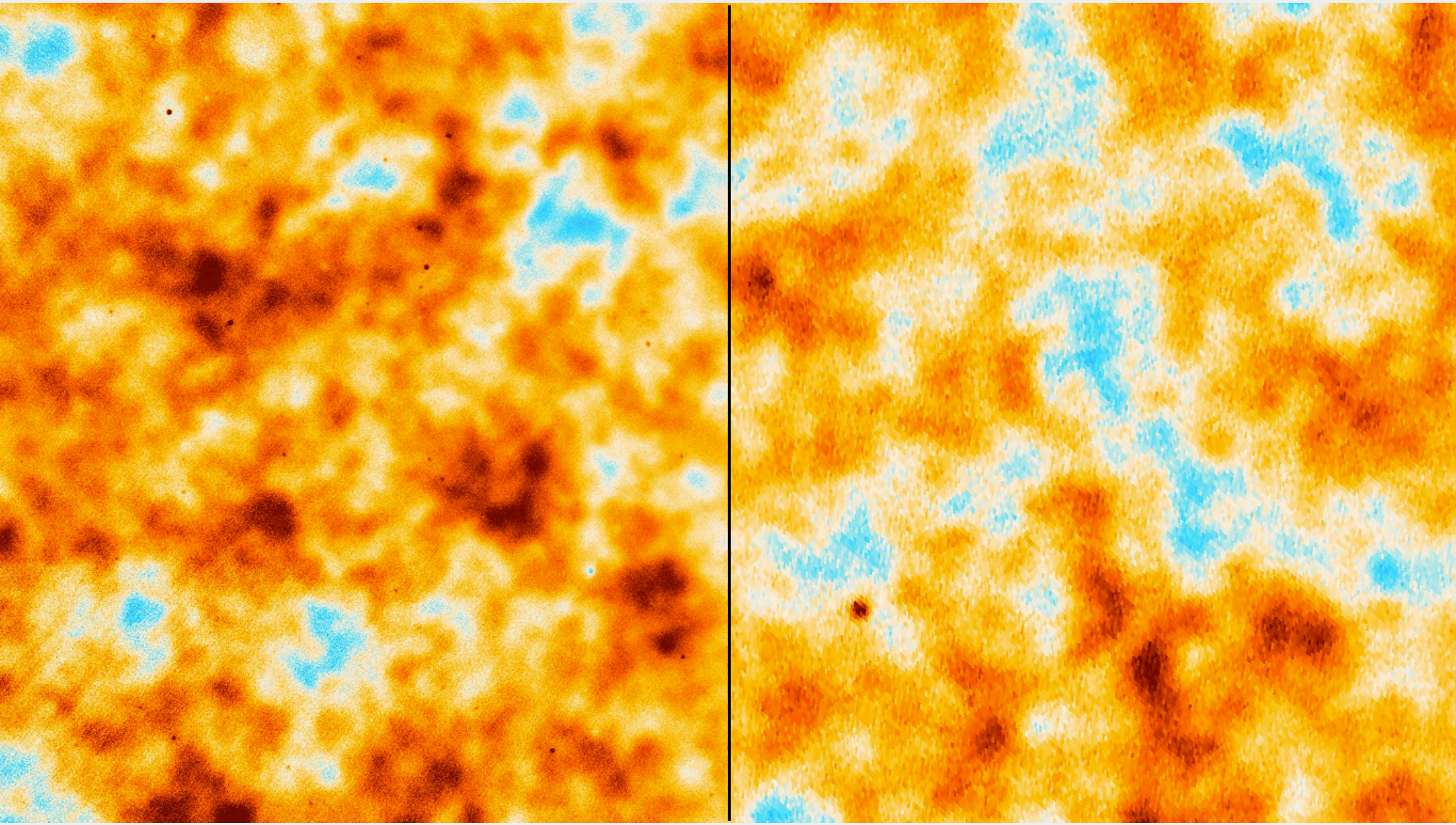
Planck



Credit Sigurd Naess, ACTPol team

ACT

Planck



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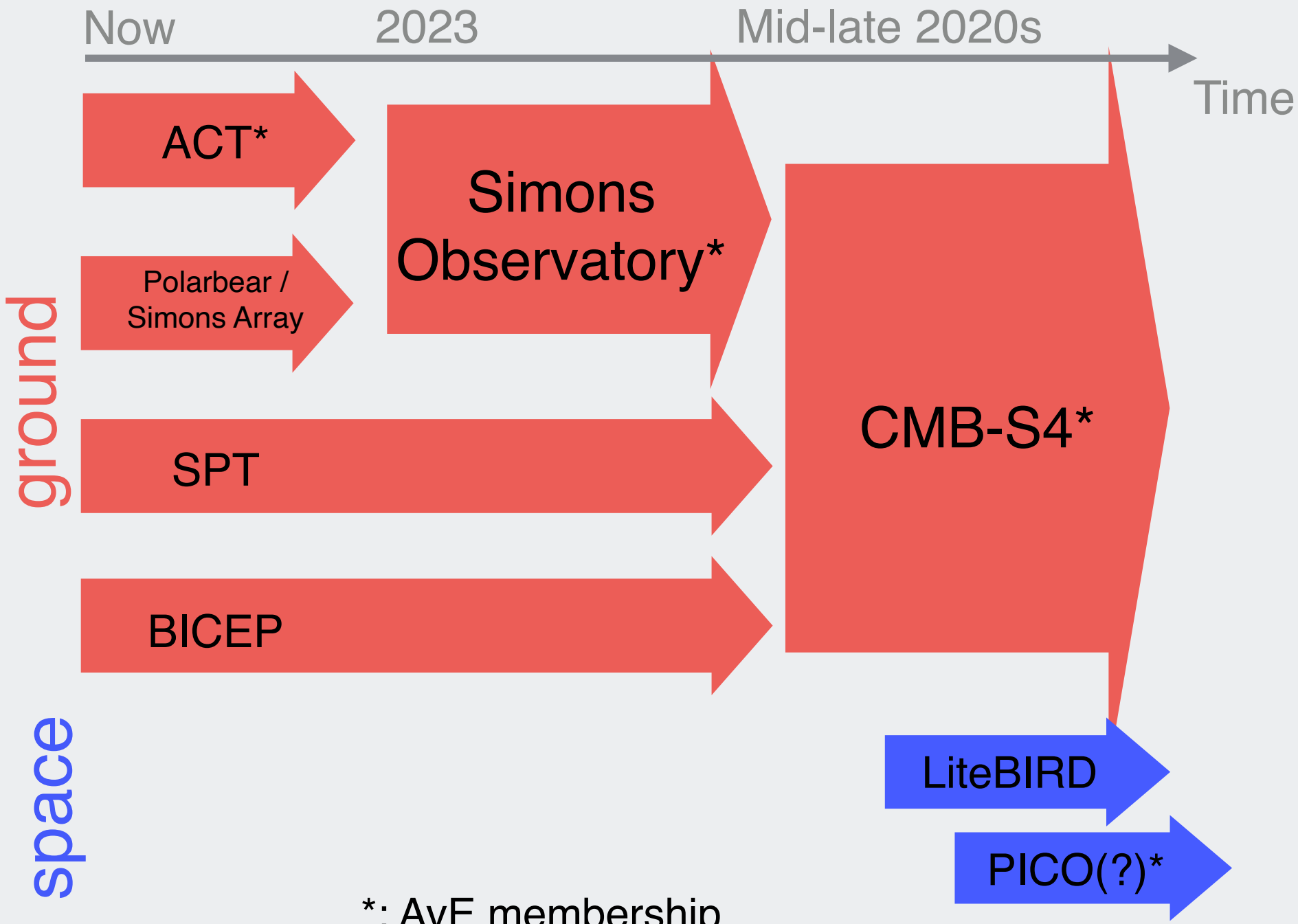
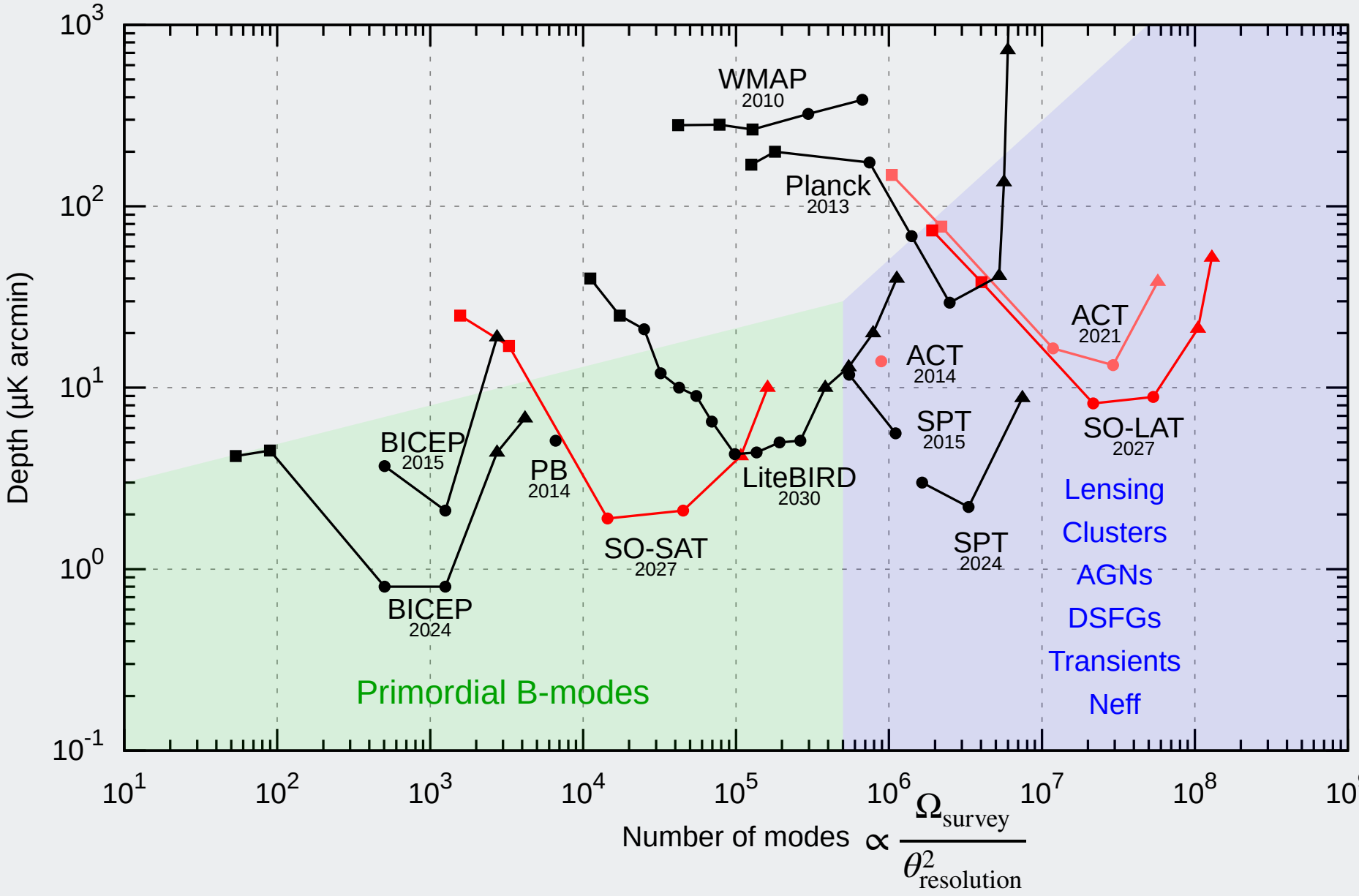
Rough experimental timeline



*: AvE membership

CMB experiments



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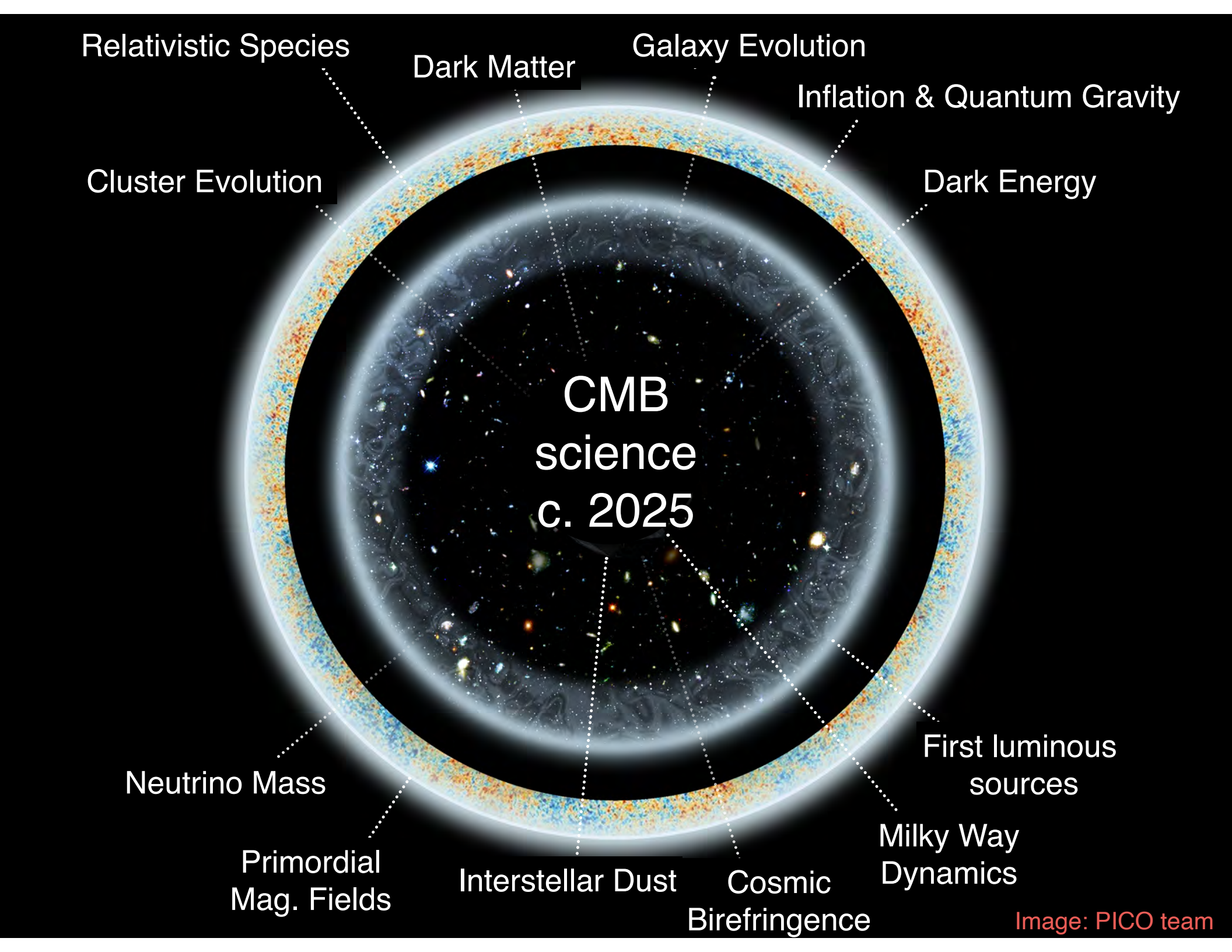
Relativistic Species
Dark Matter
Galaxy Evolution
Inflation & Quantum Gravity
Cluster Evolution
Dark Energy
CMB
science
c. 2025
First luminous
sources
Neutrino Mass
Milky Way
Dynamics
Primordial
Mag. Fields
Interstellar Dust
Cosmic
Birefringence
Image: PICO team

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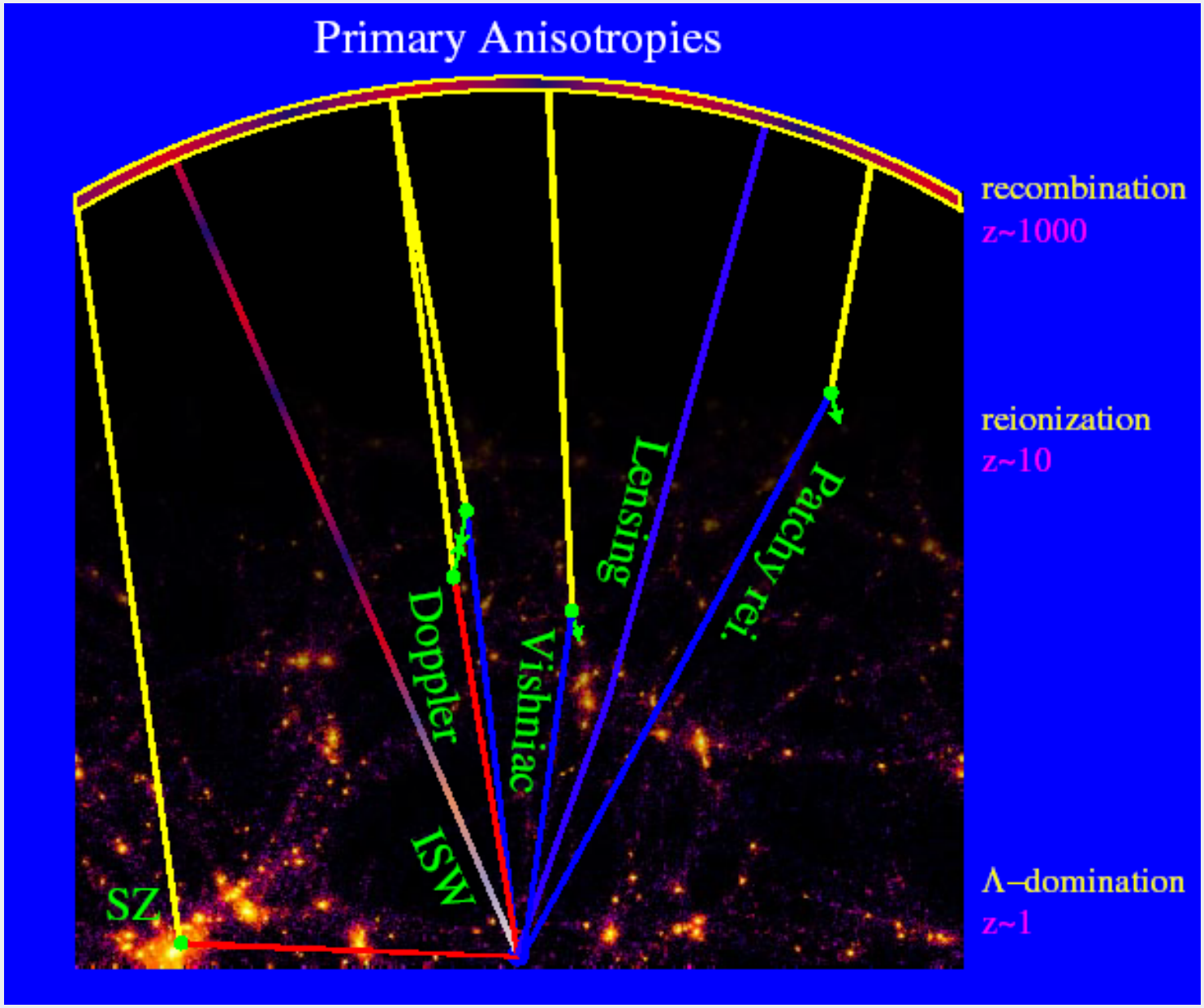

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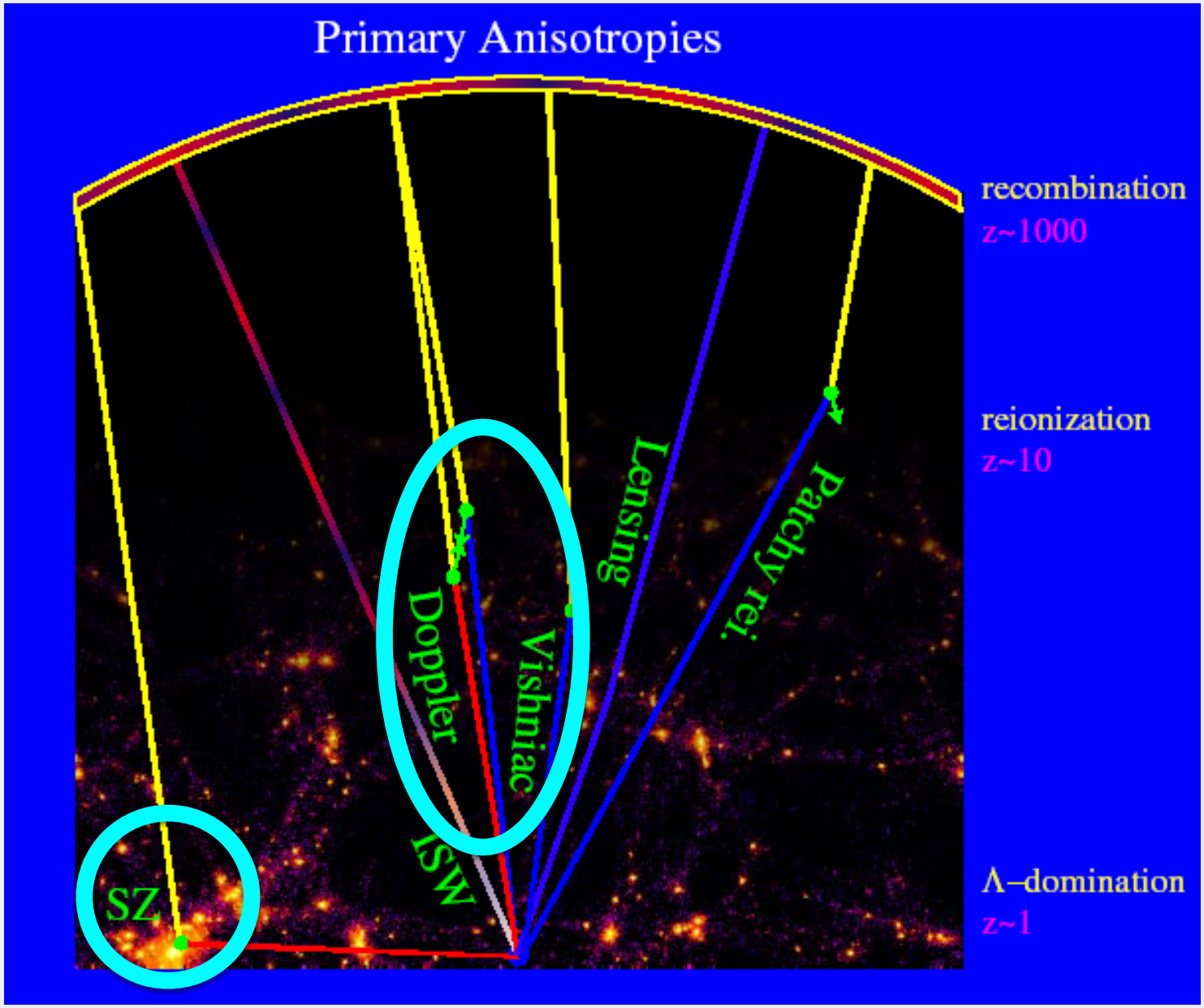

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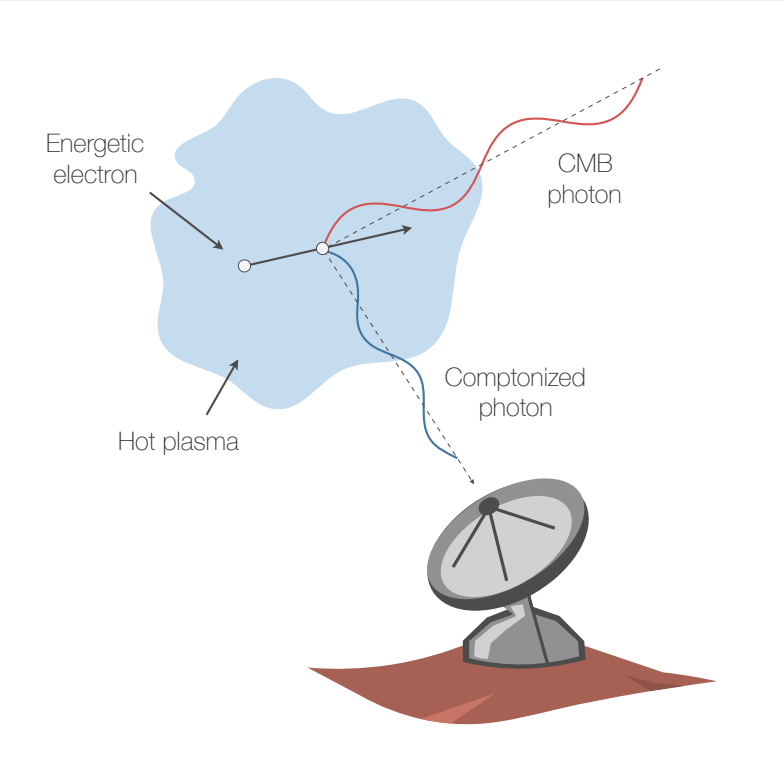
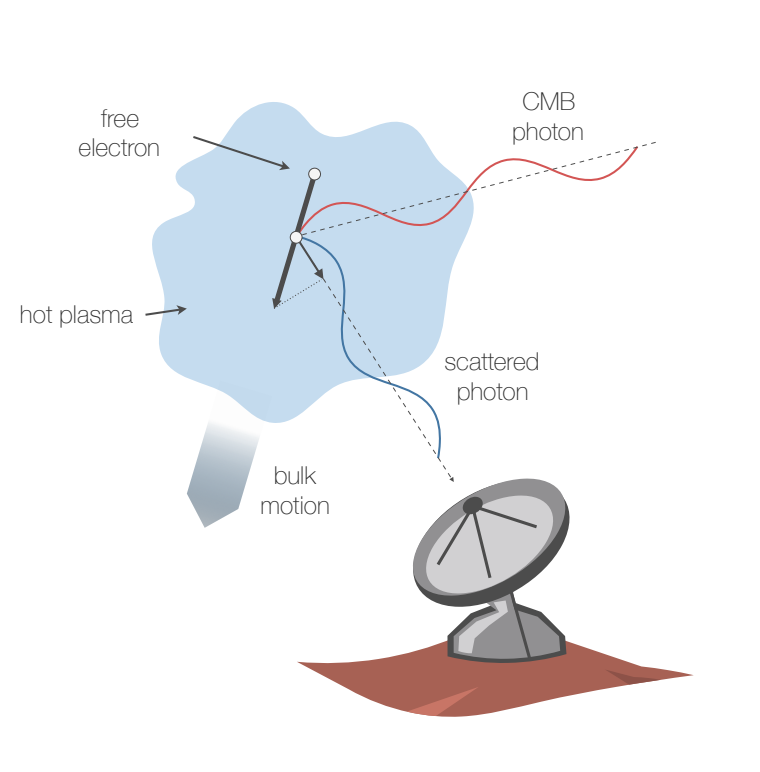
SZ effects





Figs: Mroczkowski++ review article 2019

$$\mathrm{tSZ} \propto \int dl\, n_e\, T_e$$

e⁻ density x e⁻ temperature

$$\mathrm{kSZ} \propto \int dl\, n_e\, \frac{v_{los}}{c}$$

e⁻ density x l.o.s. velocity

Thermal SZ

Kinetic SZ

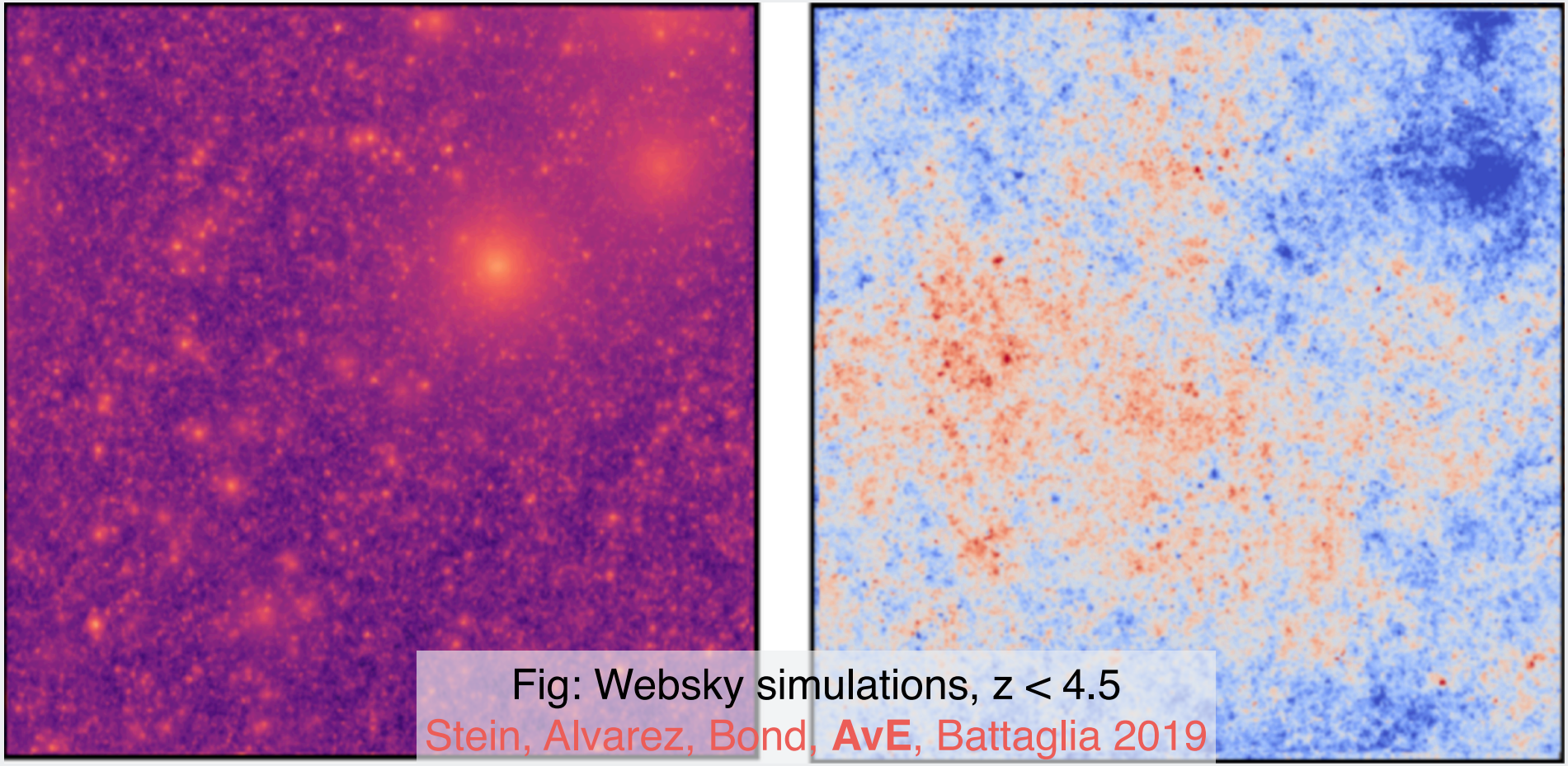


Fig: Websky simulations, z < 4.5
Stein, Alvarez, Bond, **AvE**, Battaglia 2019

$$\text{tSZ} \propto \int dl\, n_e\, T_e$$

electron density x temperature

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electron density x l.o.s. velocity

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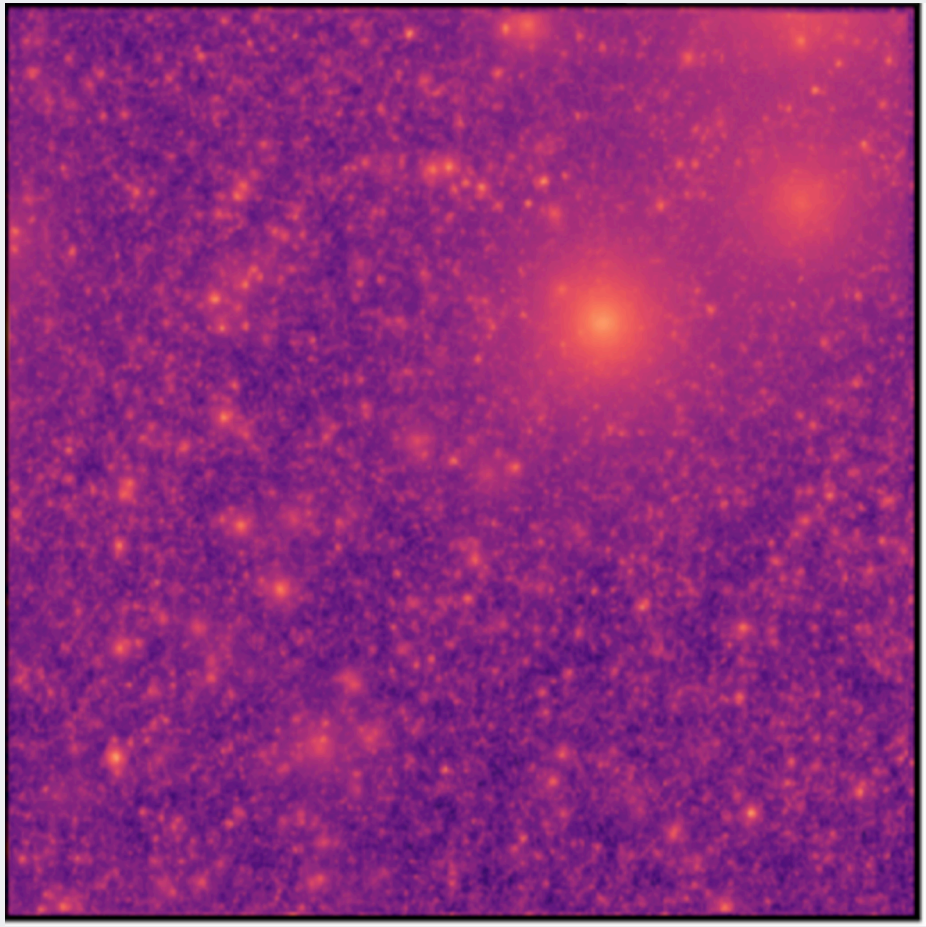
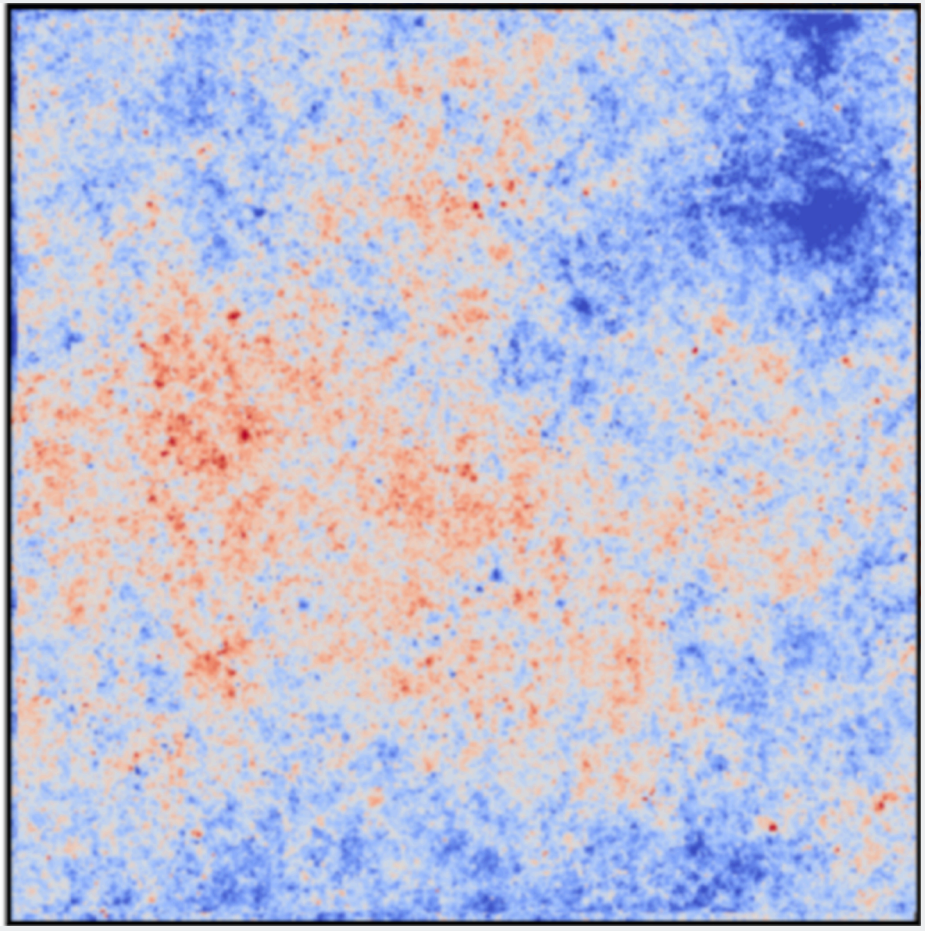
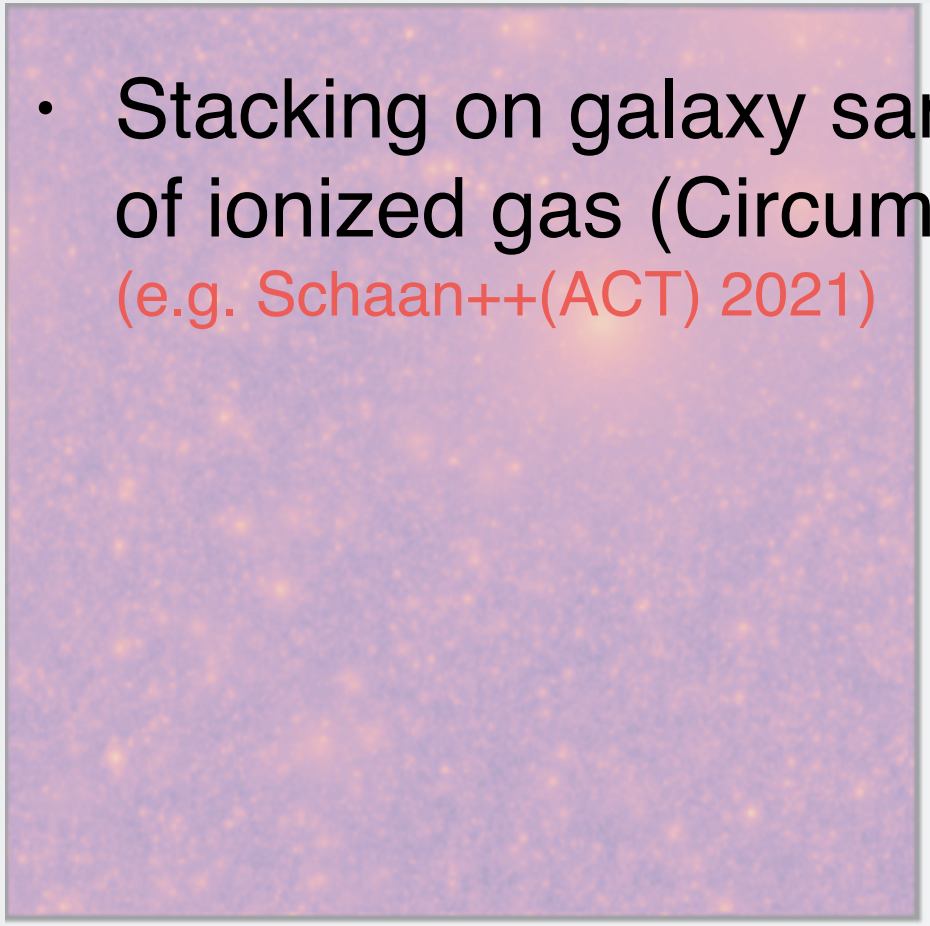


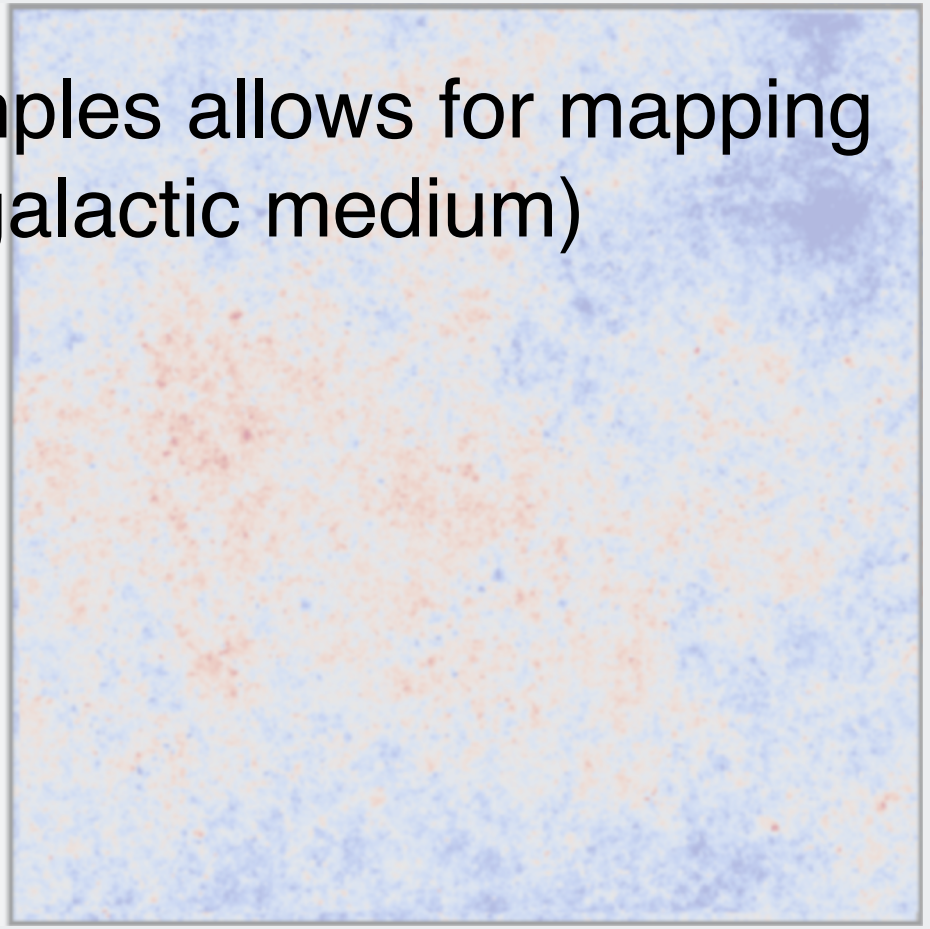
Kinetic SZ



Thermal SZ

Kinetic SZ





- Stacking on galaxy samples allows for mapping of ionized gas (Circumgalactic medium)
  (e.g. Schaan++(ACT) 2021)

Thermal SZ

Kinetic SZ

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  (e.g. Schaan++(ACT) 2021)
  - tSZ: gas pressure/energy

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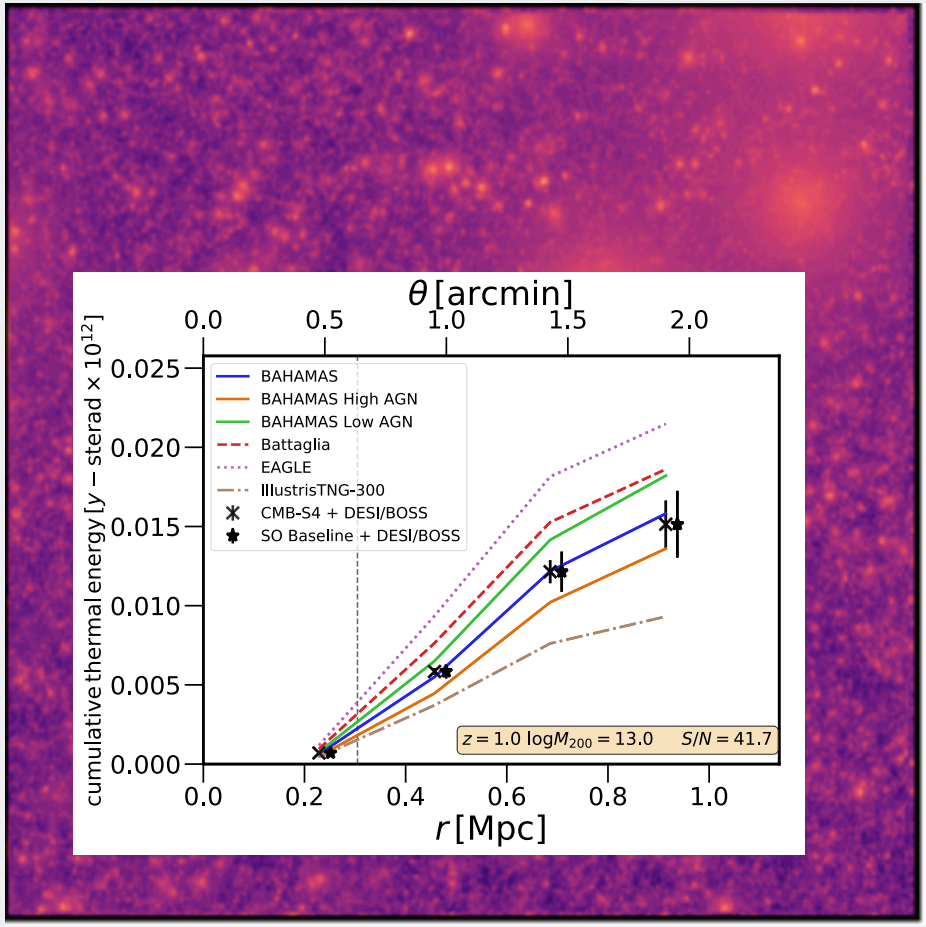
  - tSZ: gas pressure/energy
  - kSZ: gas density (but need to know velocities)

Thermal SZ

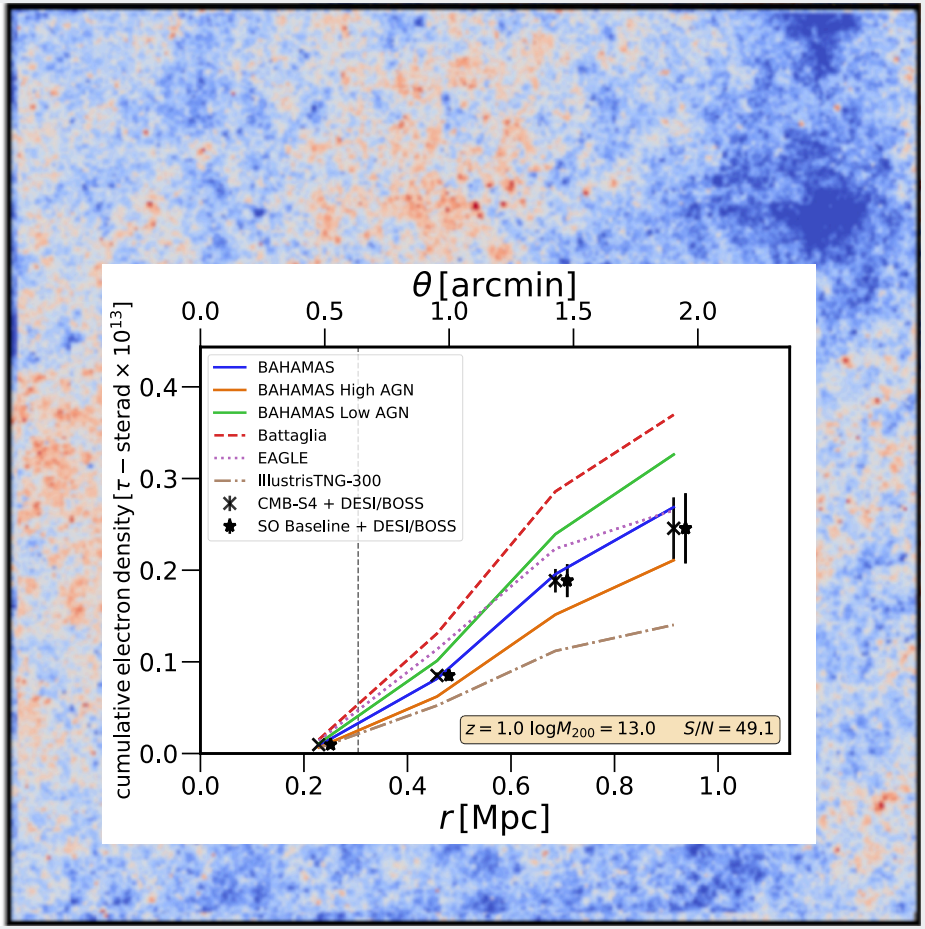
Kinetic SZ

- Stacking on galaxy samples allows for mapping of ionized gas (Circumgalactic medium) (e.g. Schaan++(ACT) 2021)
  - tSZ: gas pressure/energy
  - kSZ: gas density (but need to know velocities)
- Recent results show surprisingly strong feedback (e.g. Hadzhiyska++(ACT) 2024)

Thermal SZ



Kinetic SZ



Future possibilities: CMB-S4 stacked on DESI

CMB-S4 DSR Report

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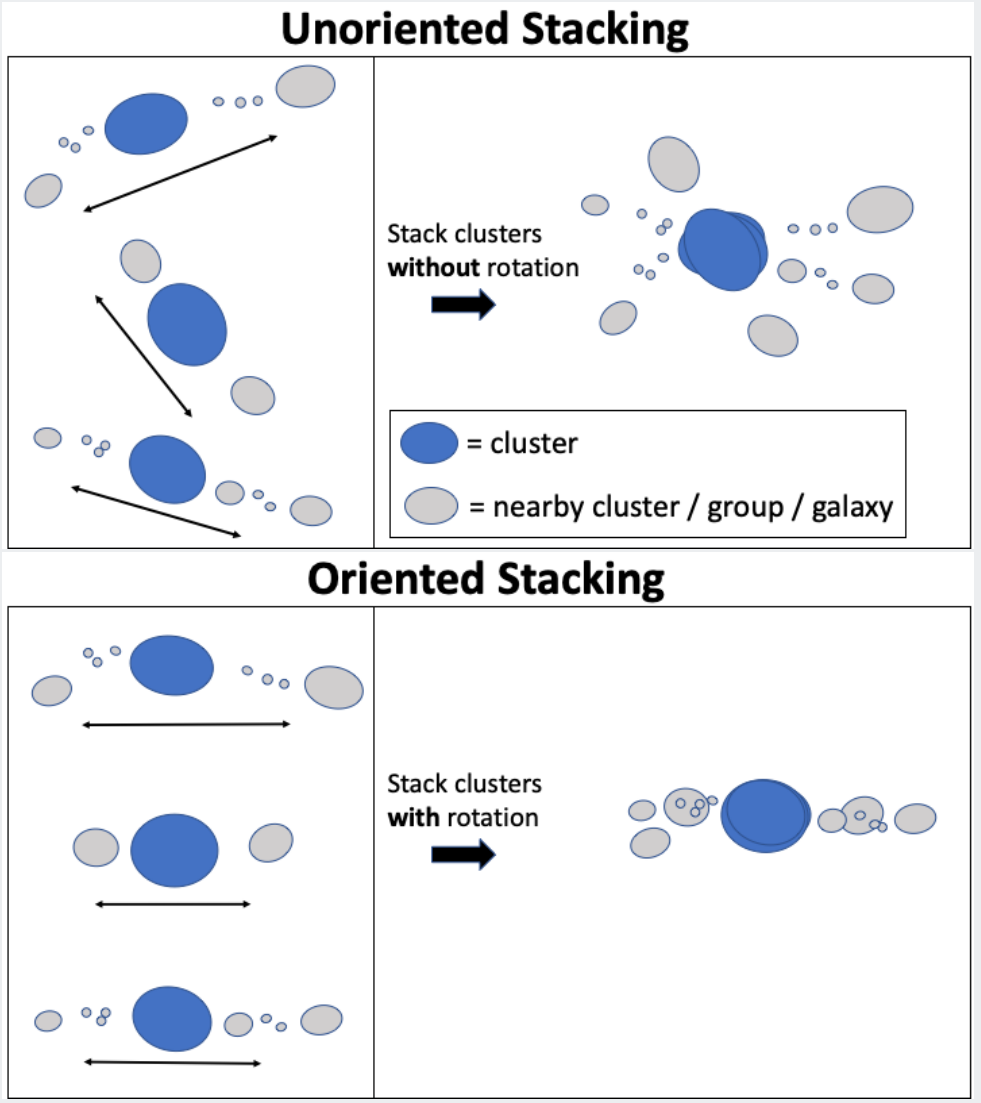
Oriented stacking

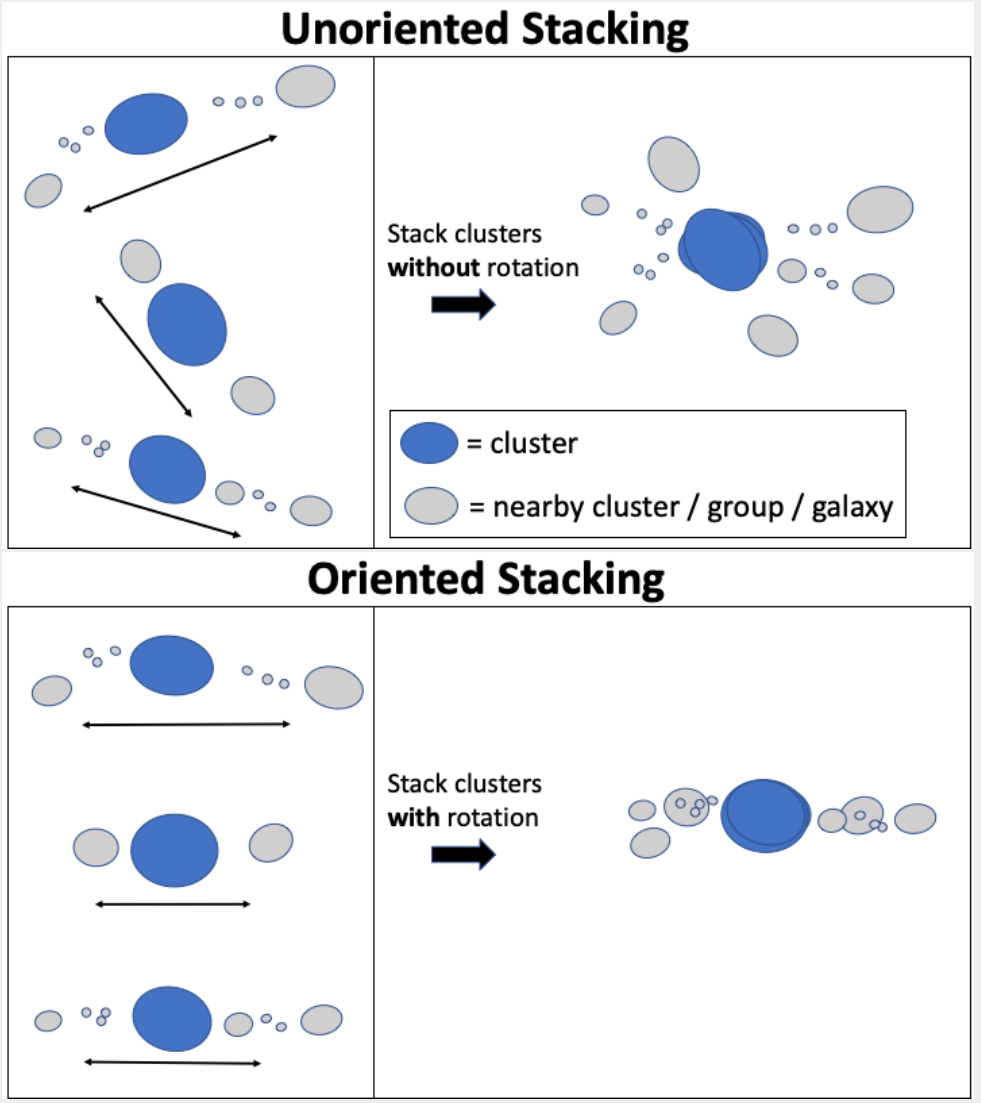


Martine Lokken, IFAE Barcelona

Lokken, Hlozek, **AvE**, Madhavacheril++ (ACT & DES teams) 2022
Lokken, **AvE**++ (ACT & DES teams) 2024

Oriented stacking

- A unique way to measure gas *outside* halos



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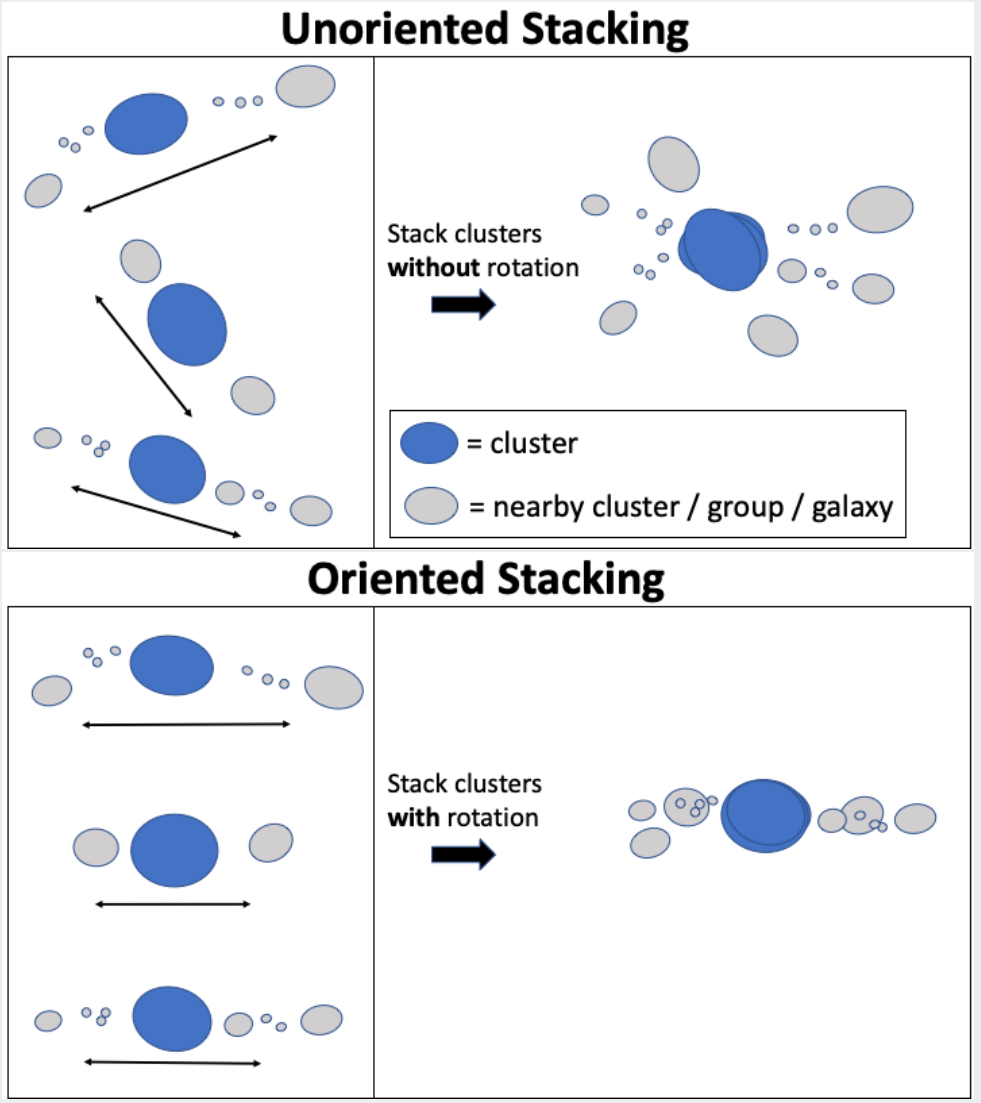

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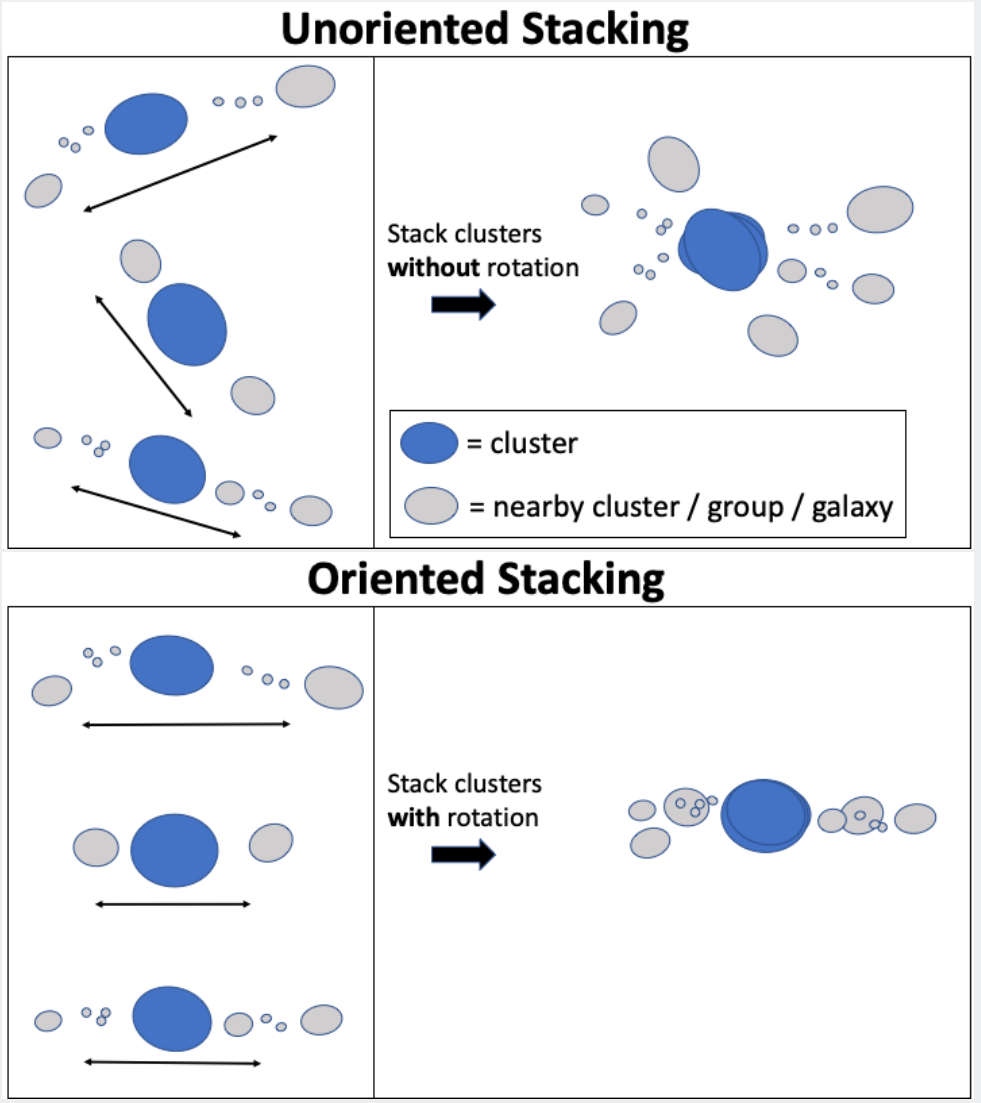
- Our approach:



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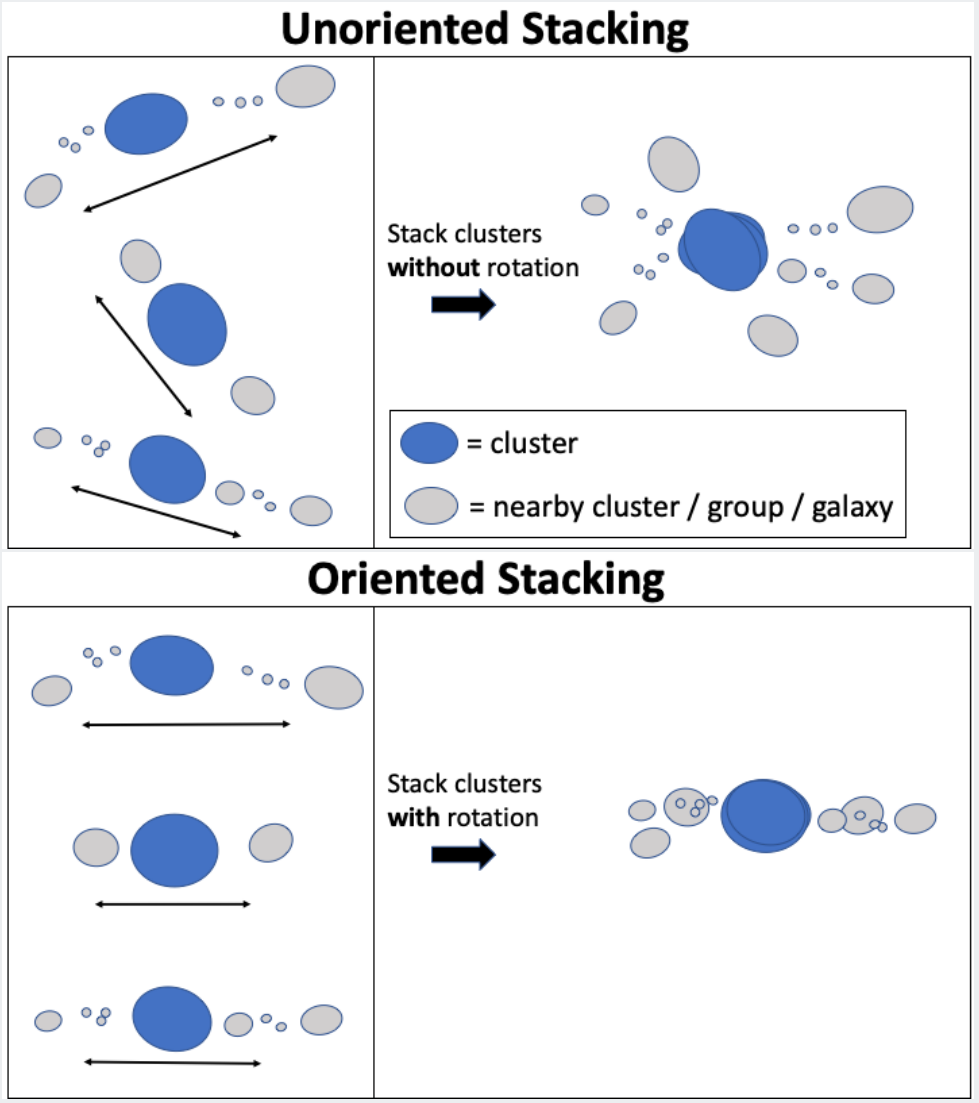
- Our approach:
  - ***Stack observed maps*** on the locations of clusters (DES-Y3 redMaPPer)



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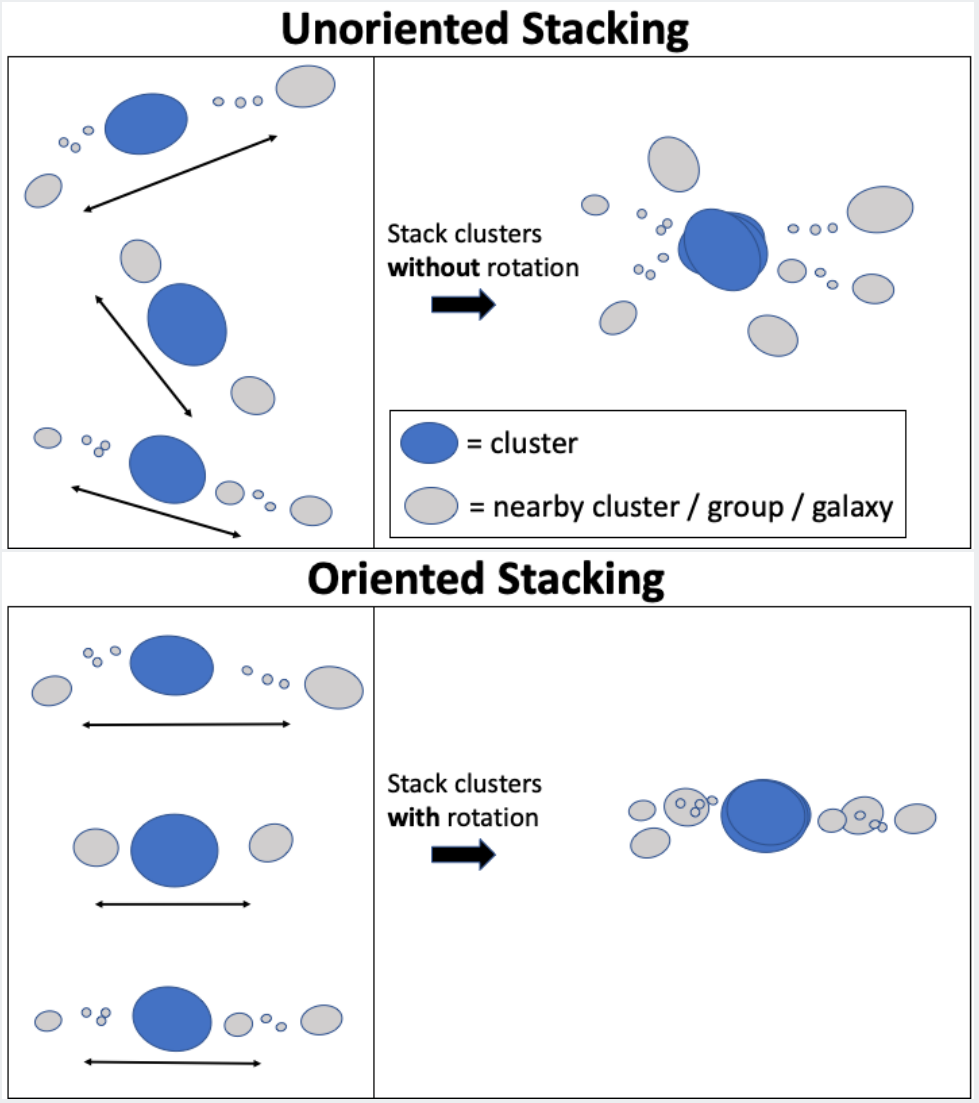
Oriented stacking

- A unique way to measure gas *outside* halos

- Our approach:
  - ***Stack observed maps*** on the locations of clusters (DES-Y3 redMaPPer)
  - … ***oriented*** **by large-scale structure** (DES-Y3 redMaGiC galaxies in thin slices)



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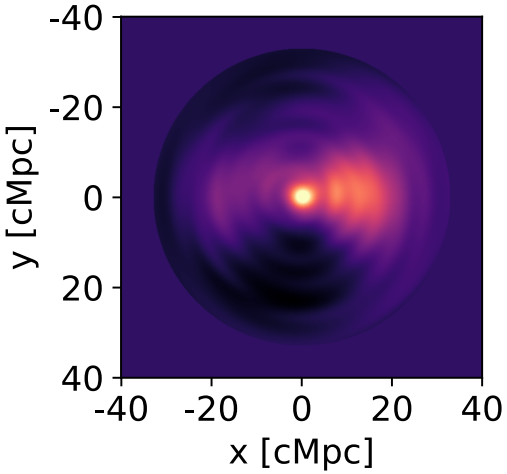
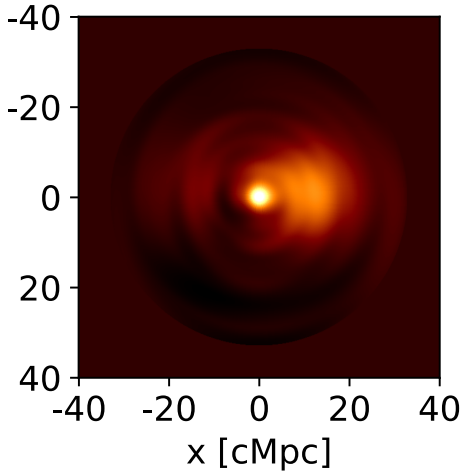
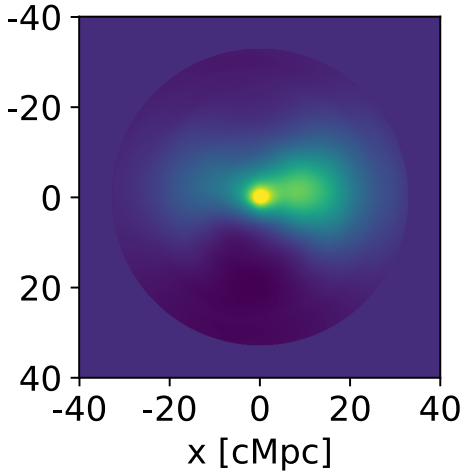
Oriented stacking Results



DES lensing



ACT tSZ (DR6)



DES galaxies

Lokken, Hlozek, **AvE**, Madhavacheril++ (ACT & DES teams) 2022
Lokken, **AvE**++ (ACT & DES teams) 2024

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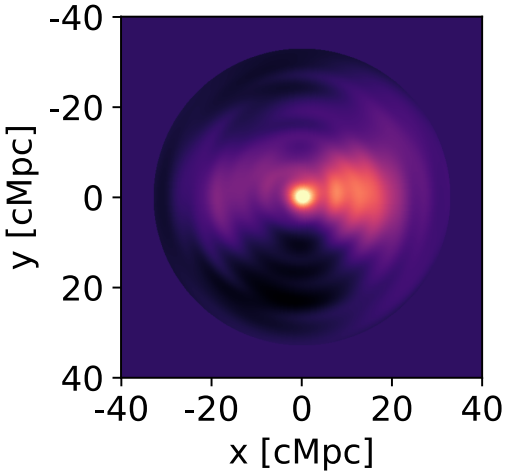

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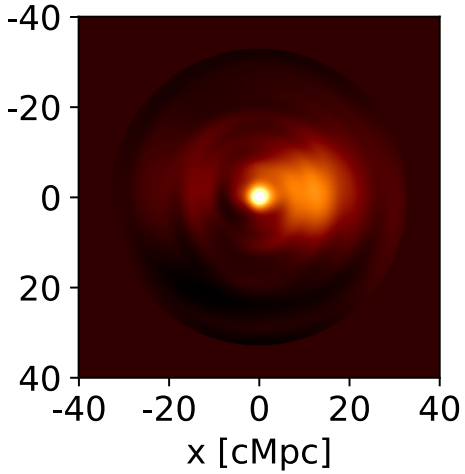

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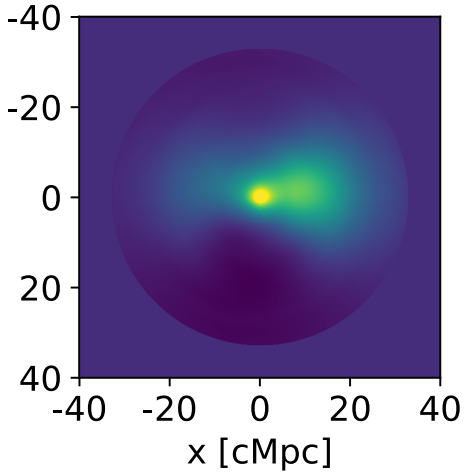

DES galaxies

- Shown: “bowtie” extending to large distances - cluster environment

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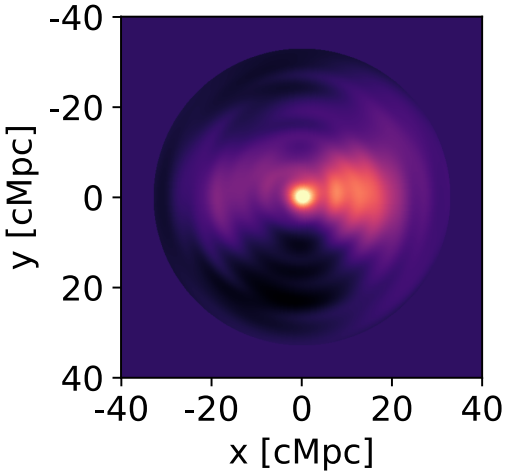

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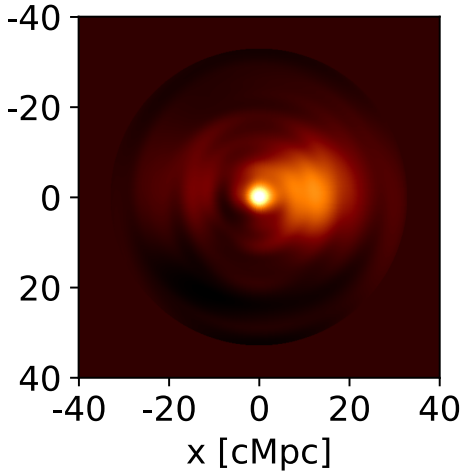

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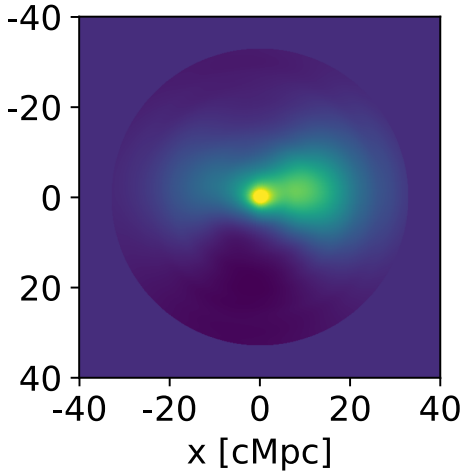

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- Shown: “bowtie” extending to large distances - cluster environment
- Decompose result into angular *multipoles &* compare with mocks

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Lokken, **AvE**++ (ACT & DES teams) 2024

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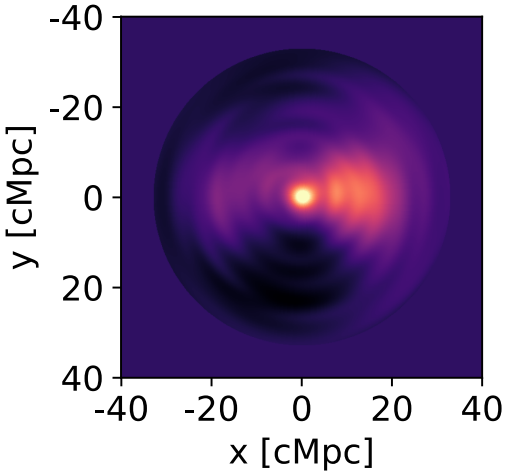

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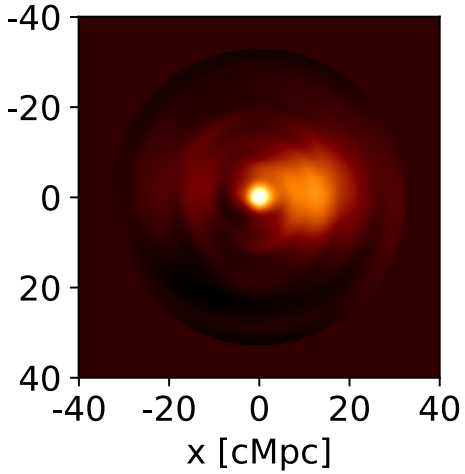

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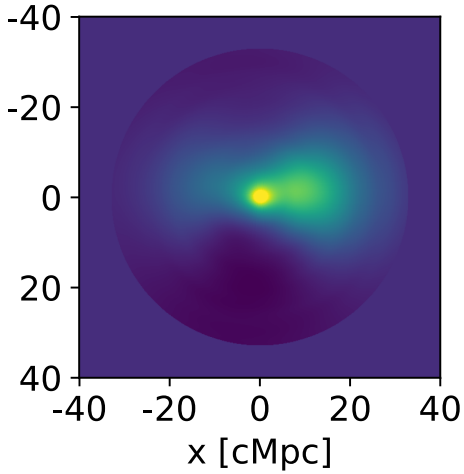

DES galaxies

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- Decompose result into angular *multipoles &* compare with mocks
  - 8-10σ significance for $m > 0$; signature of beyond-GRF by 6σ

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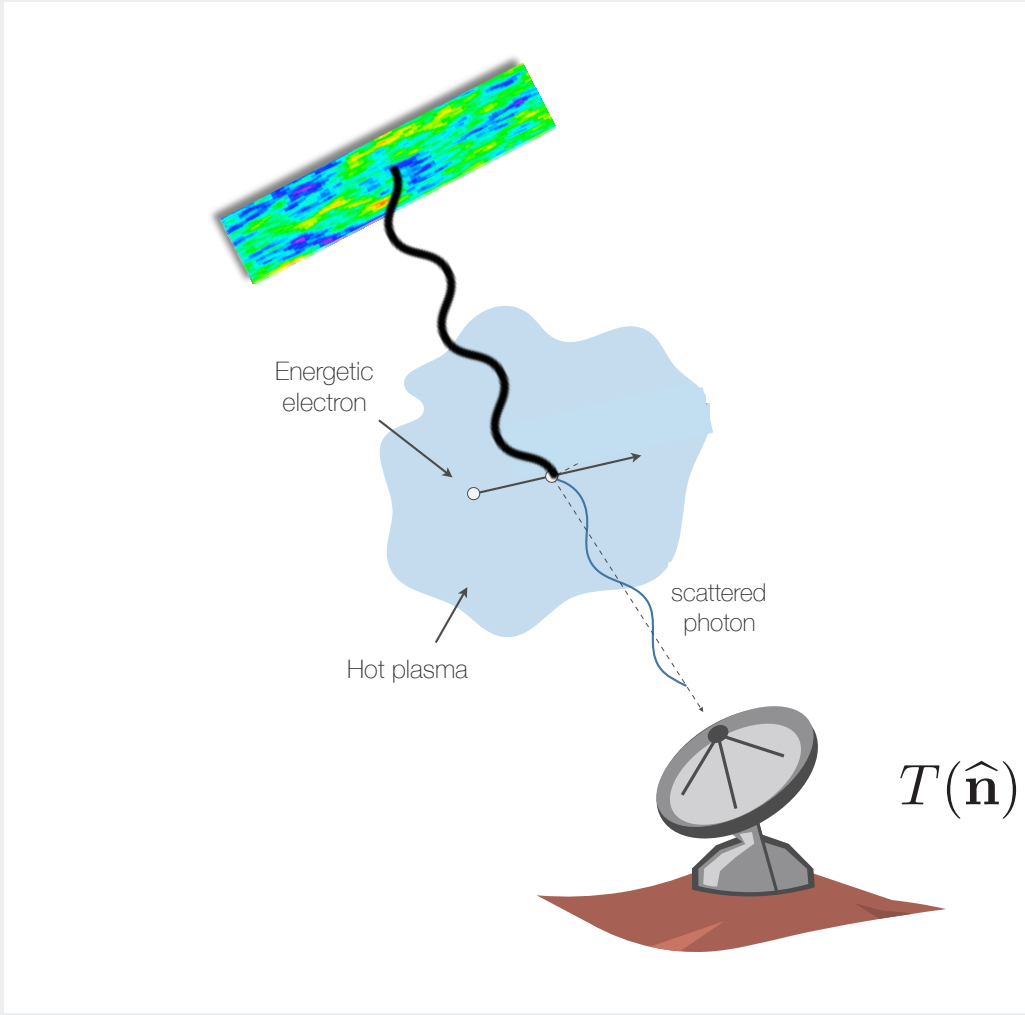
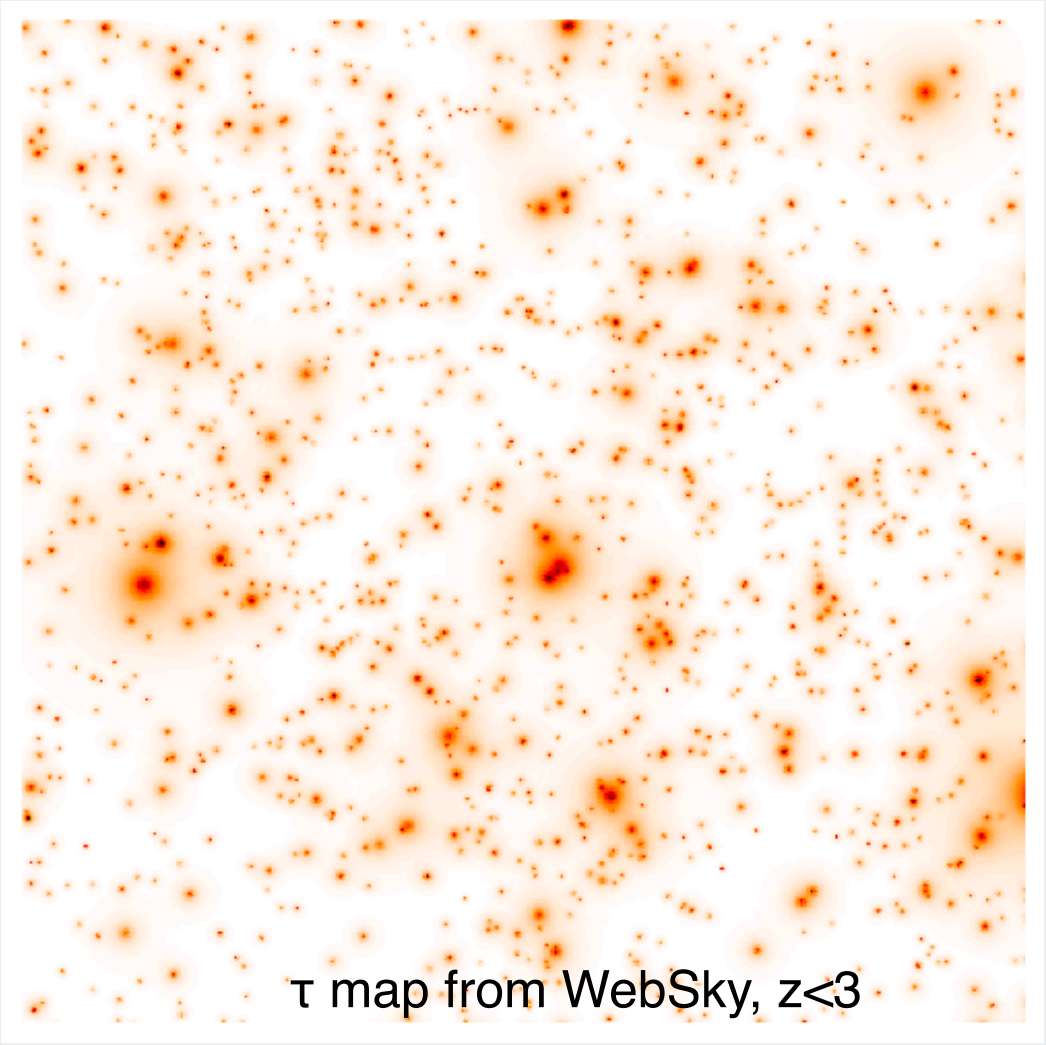
Patchy Screening



$$T(\hat{\mathbf{n}}) = e^{-\tau(\hat{\mathbf{n}})} T^{(\mathrm{rec})}(\hat{\mathbf{n}})$$

$$\tau \propto \int dl\, n_{\mathrm{e}}$$

Patchy Screening



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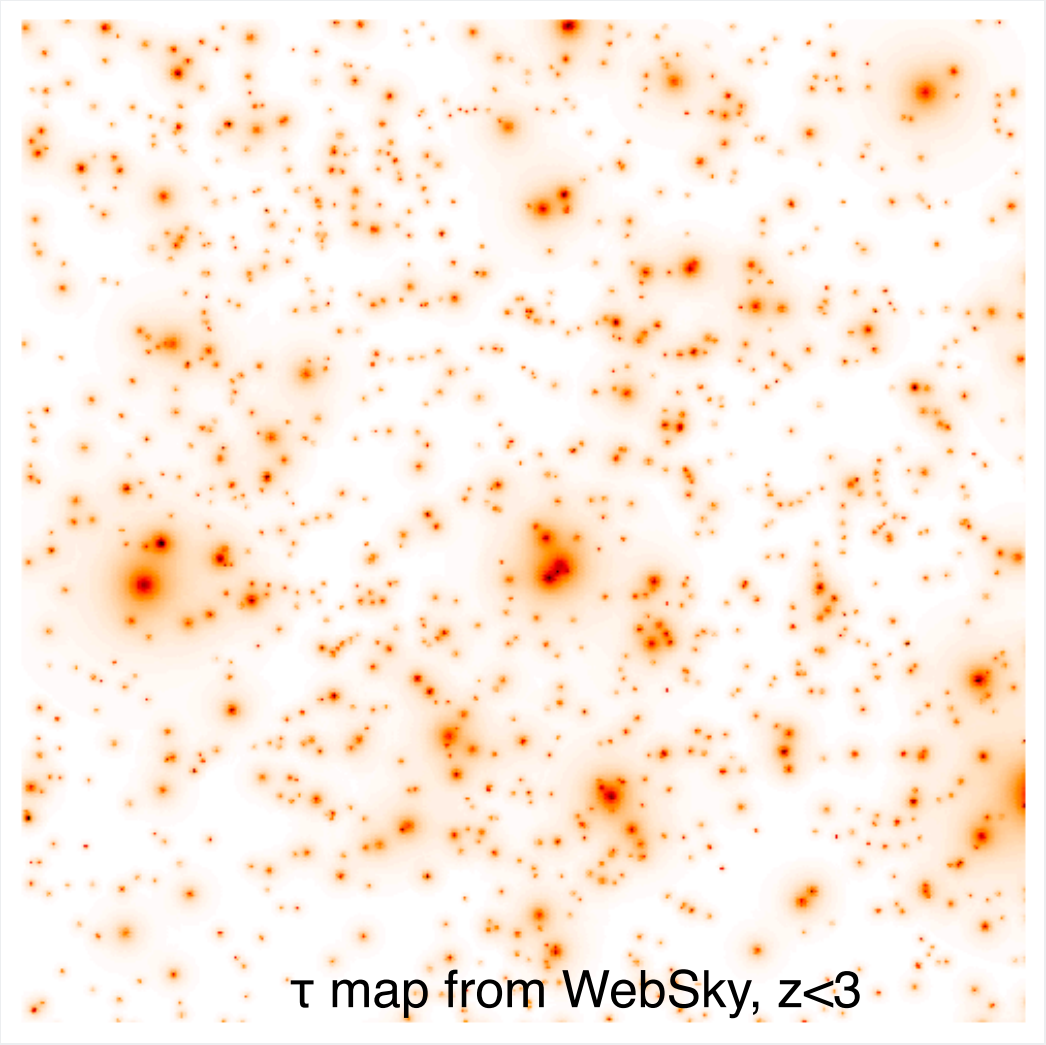
Yasini+
AstroPaint

Patchy Screening

- τ reconstruction idea:
  low var(T) $\Longrightarrow$ τ > 0



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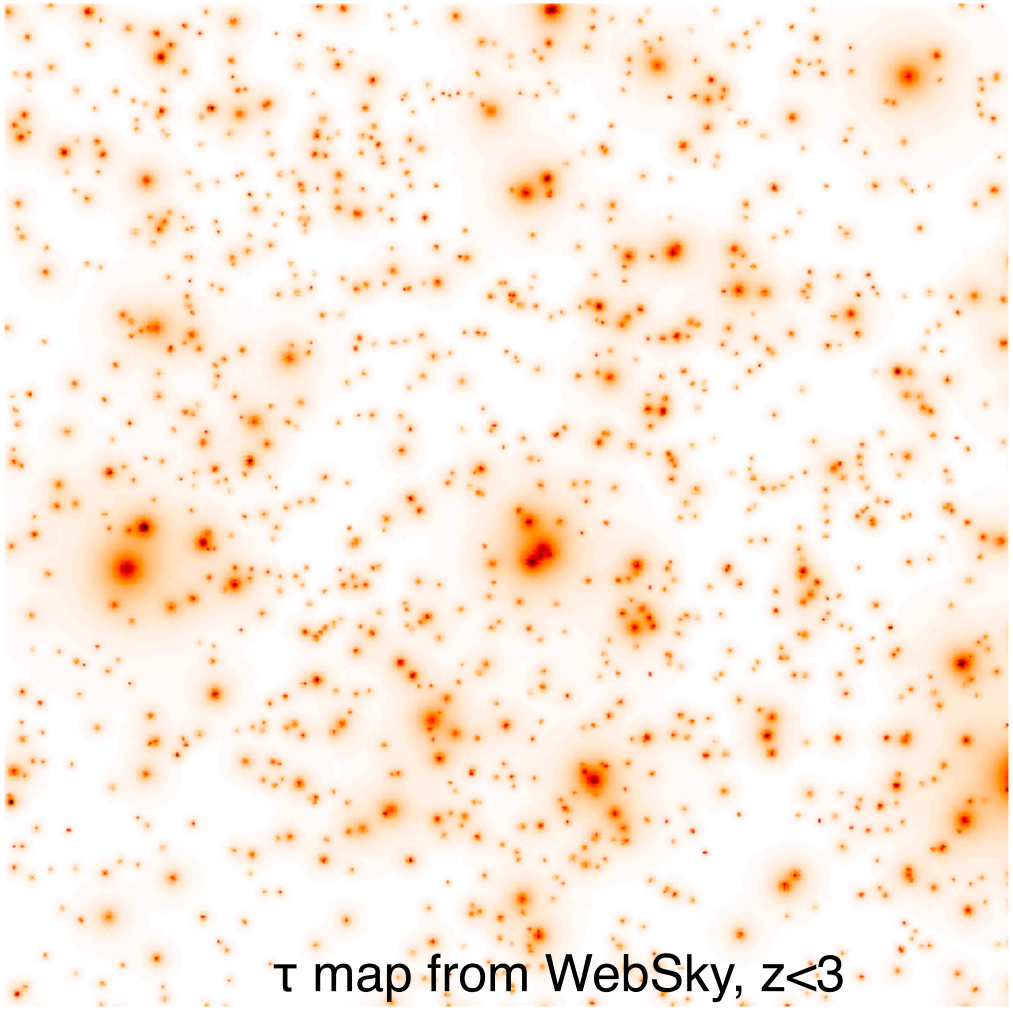

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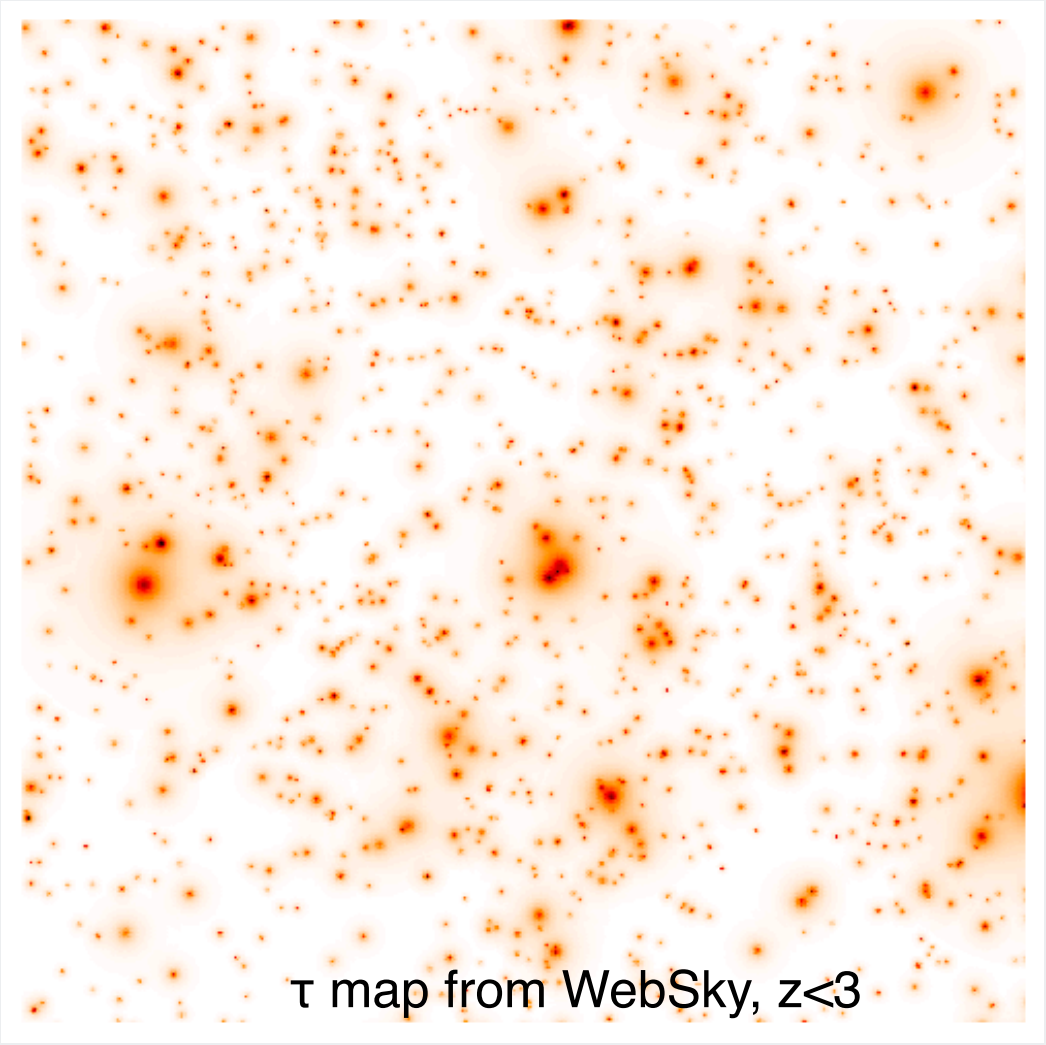

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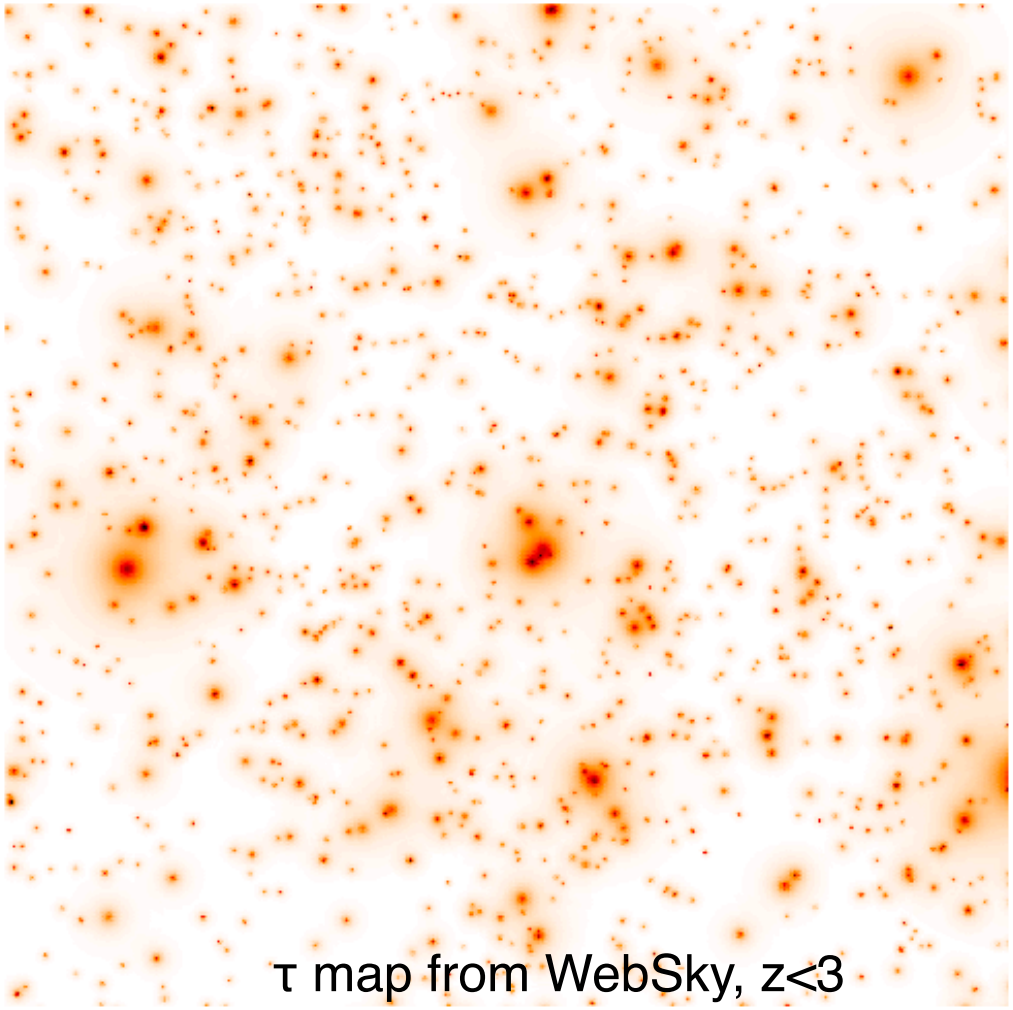
- First measurement reported by ACT team with unWISE at z < 1 (currently under review)
  Coulton, Schutt, Maniyar, Schaan++ (ACT) 2024, arXiv



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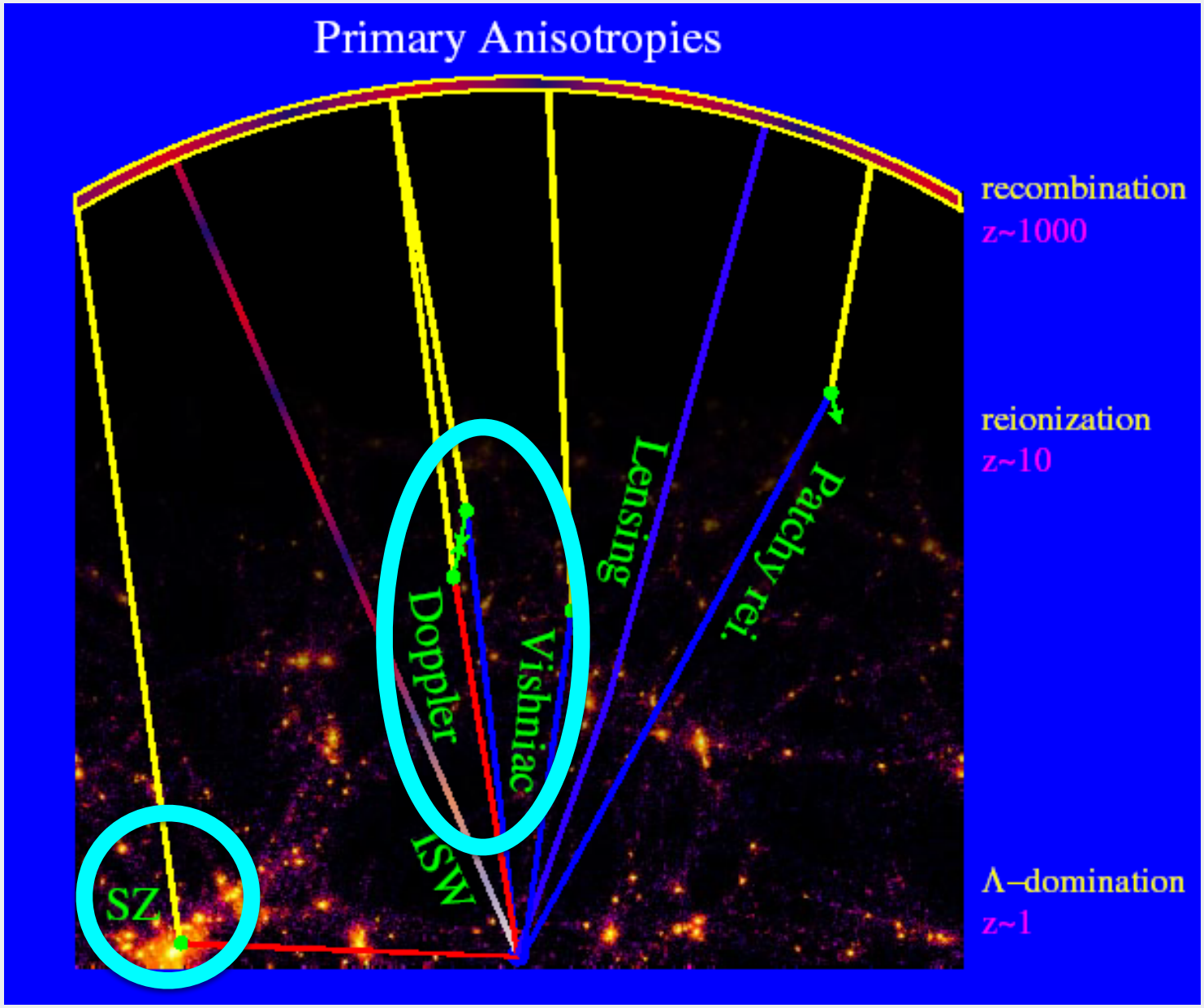
The CMB as a backlight



plus, emission in mm from dusty galaxies and AGN

Wayne Hu's website

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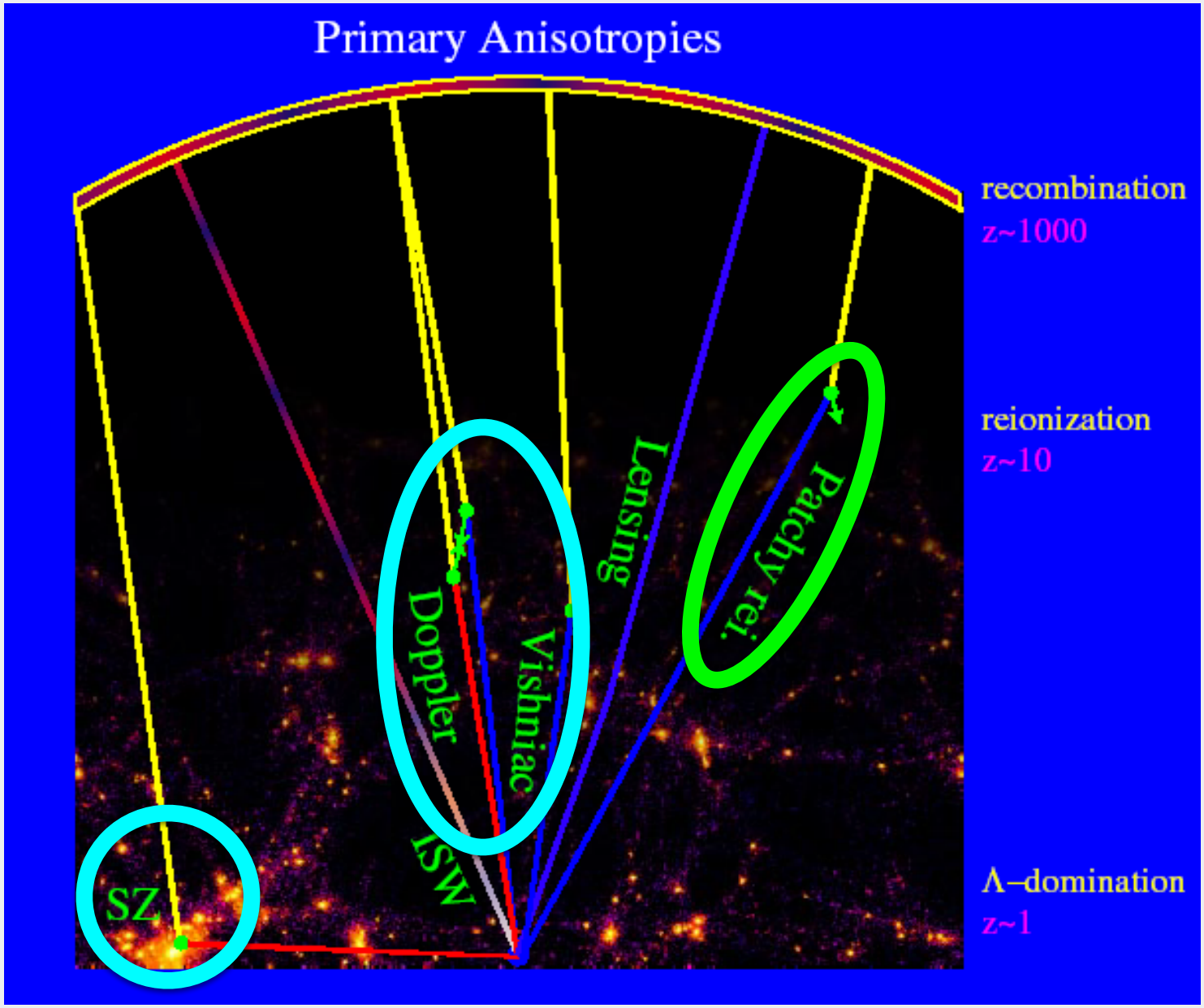

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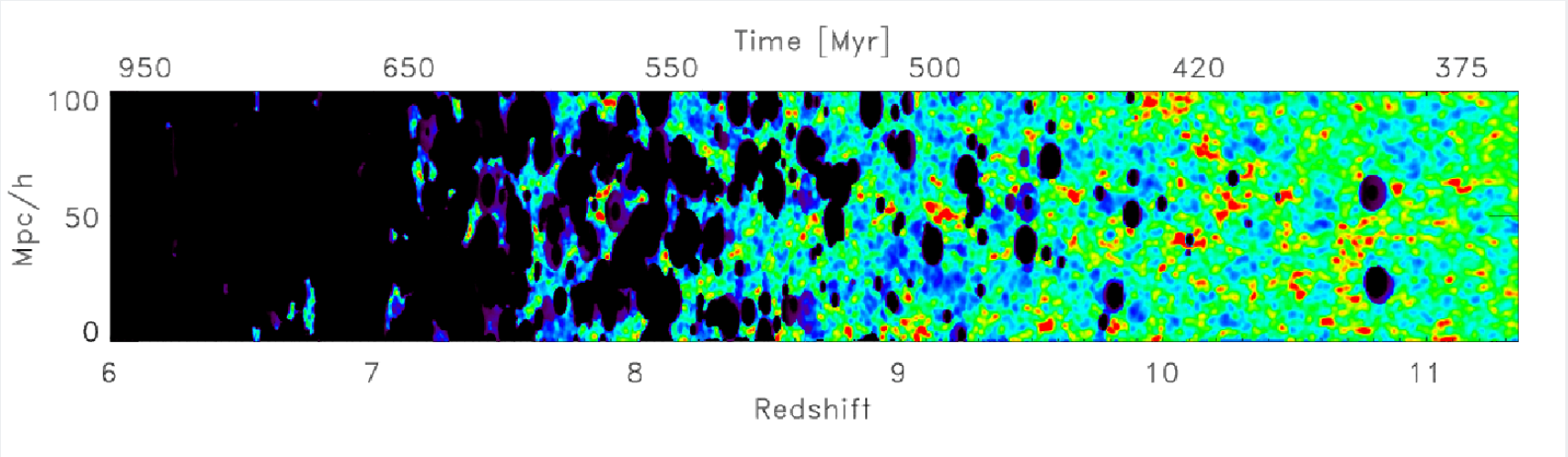
Reionization



- From CMB we know $\tau_{mean} = 0.06$
  $\Longrightarrow$ Midpoint $z_{mid} \sim 8$
- Duration? Morphology?

Reionization forecasts with the CMB

Spectrum Type	Reionization Probe	Example Reference(s)	Forecasted "S4" SNR Range
Auto-spectra	$\langle T_{\rm kSZ} \times T_{\rm kSZ} \rangle$	Raghunathan & Omori (2023)	$\sim 70 - 80\sigma$
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Kramer, **AvE**, Cain, MacCrann, ++ 2025

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	$\langle \delta_{\rm g} \times y \rangle$	Baxter et al. (2021)	$< 2\sigma$
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- τ: weaker, but can be reconstructed with polarization (cleaner)
  - What about *K* x τ?

Kramer, **AvE**, Cain, MacCrann, ++ 2025

Cross-correlating the patchy screening and kinetic Sunyaev-Zel'dovich effects as a new probe of reionization

Darby M. Kramer,[1] Alexander van Engelen,[1] Christopher Cain,[1] Niall MacCrann,[2] Hy Trac,[3,4] Skylar Grayson,[1] Evan Scannapieco,[1] and Blake Sherwin[2]

arXiv, submitted to ApJ

Darby Kramer (ASU)

Reionization τ and kSZ signals

Forming power spectra

Kramer, **AvE**, Cain, MacCrann, ++ 2025

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$$\tau \sim \delta_e$$

$$\frac{\Delta T_{\rm kSZ}}{T_0} \sim v * \delta_e$$

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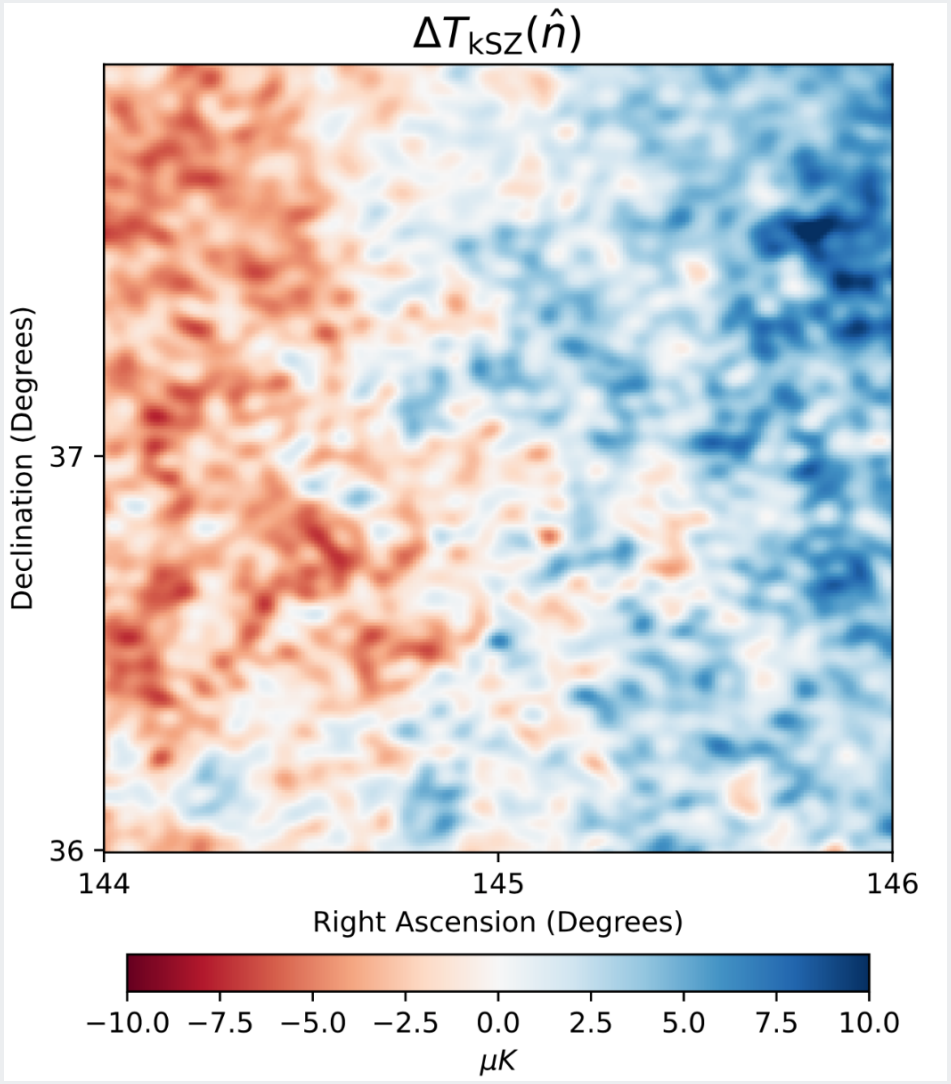
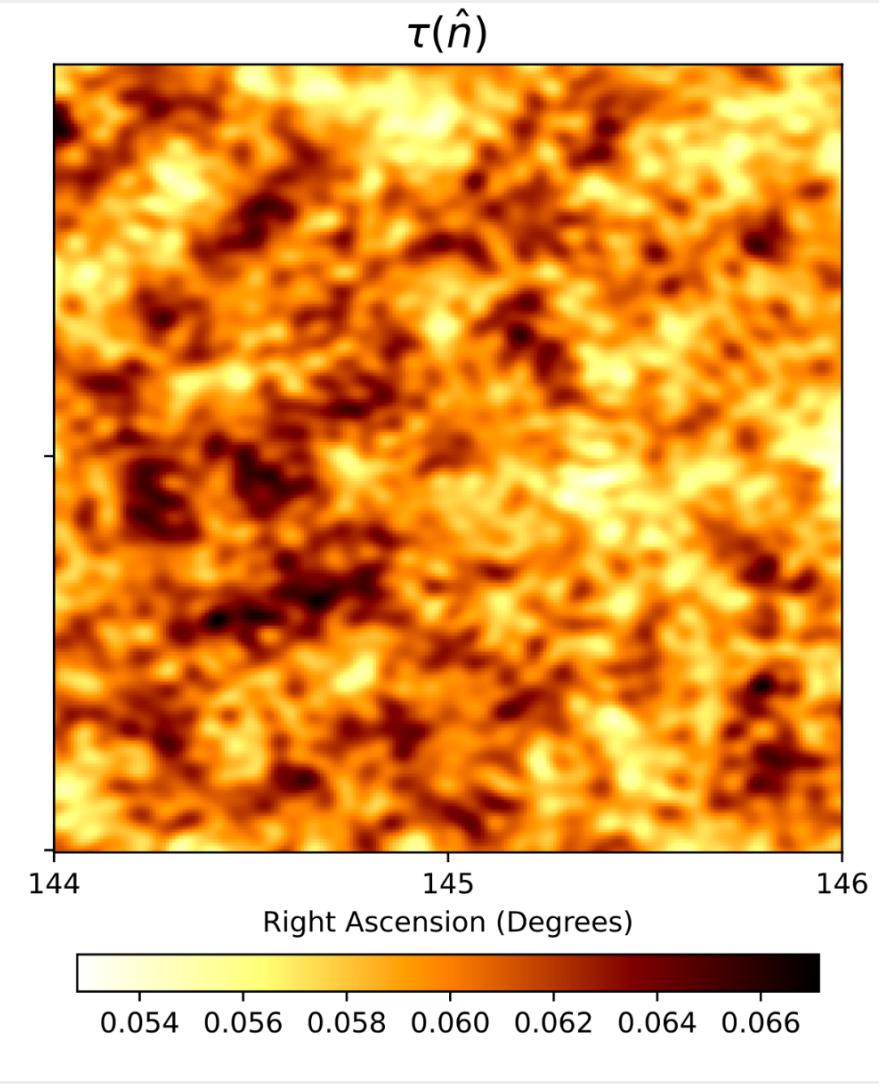
Kramer, **AvE**, Cain, MacCrann, ++ 2025

Reionization τ and kSZ signals

AMBER mocks Trac++ 2022, Chen++ 2023

https://github.com/hytrac/amber





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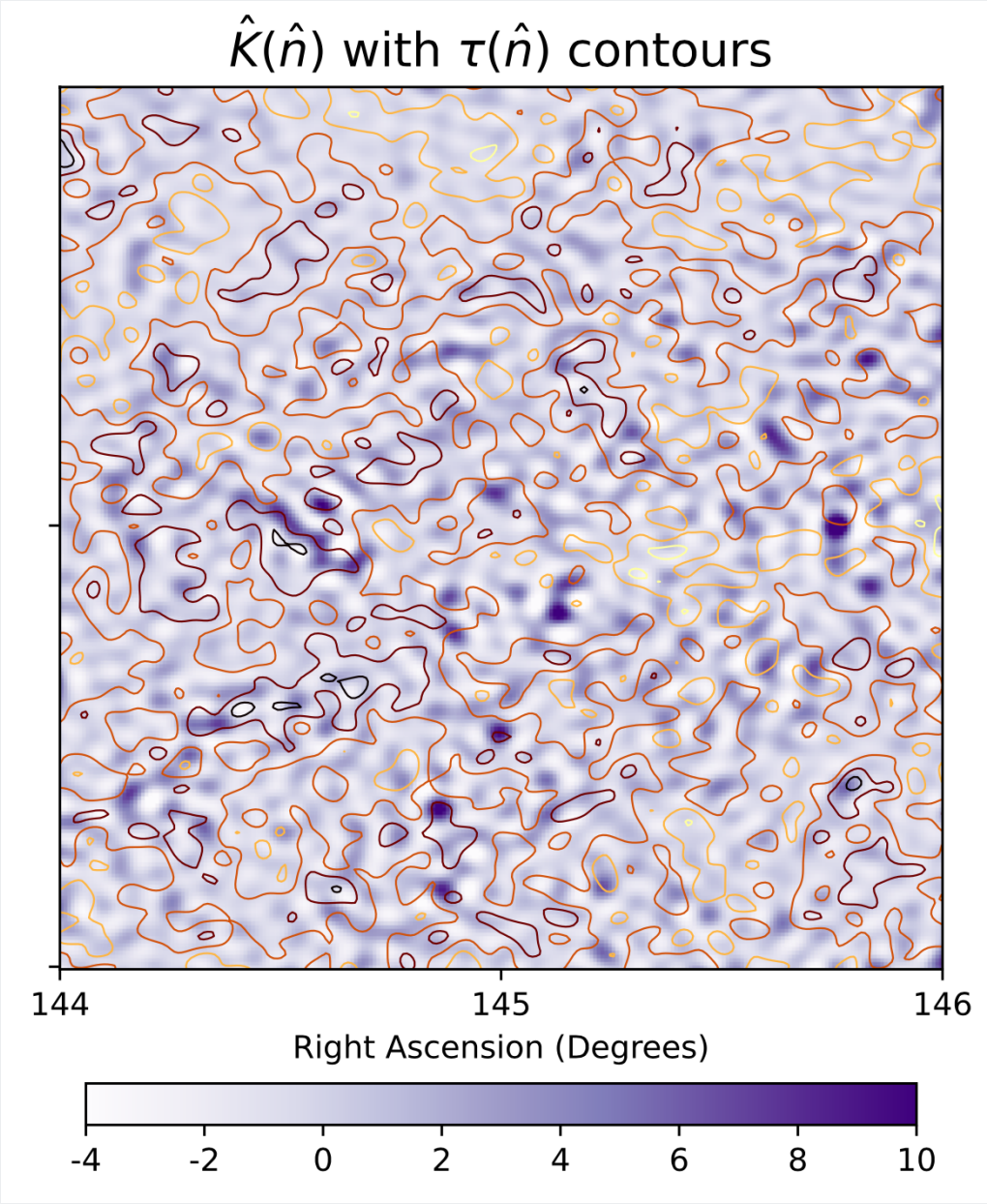

Kramer, **AvE**, Cain, MacCrann, ++ 2025

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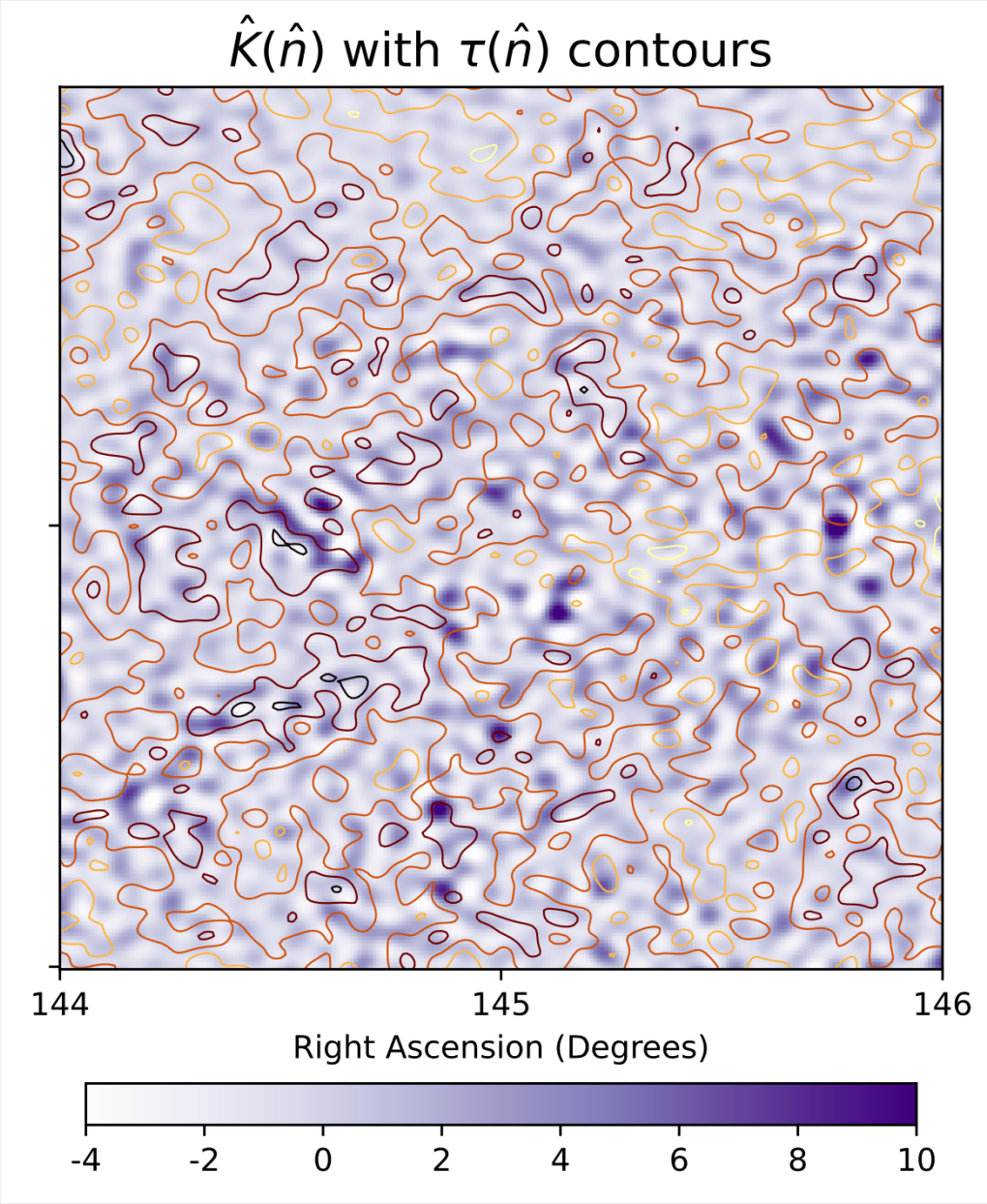
Reconstructed *K* using the AMBER patchy kSZ maps



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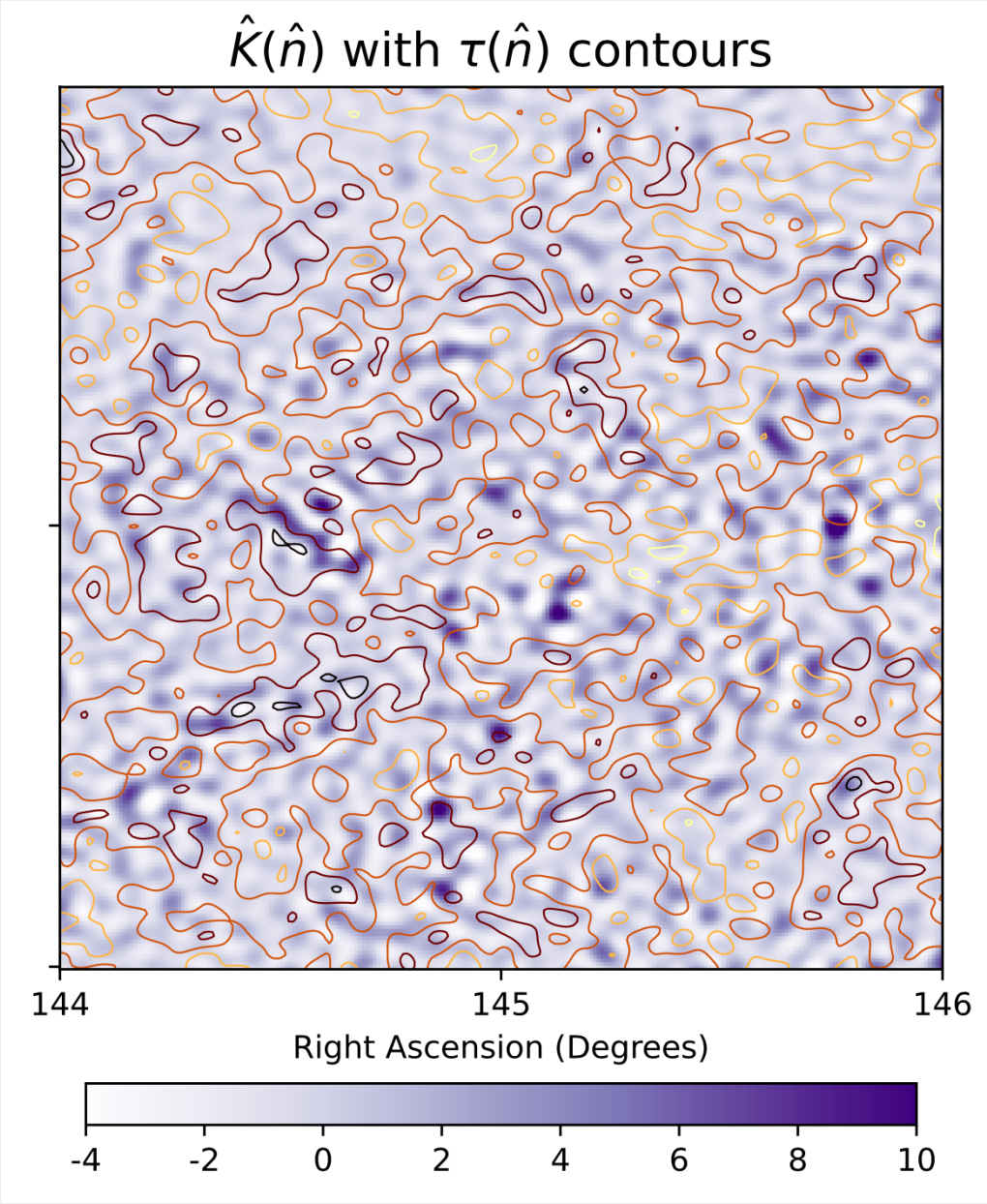

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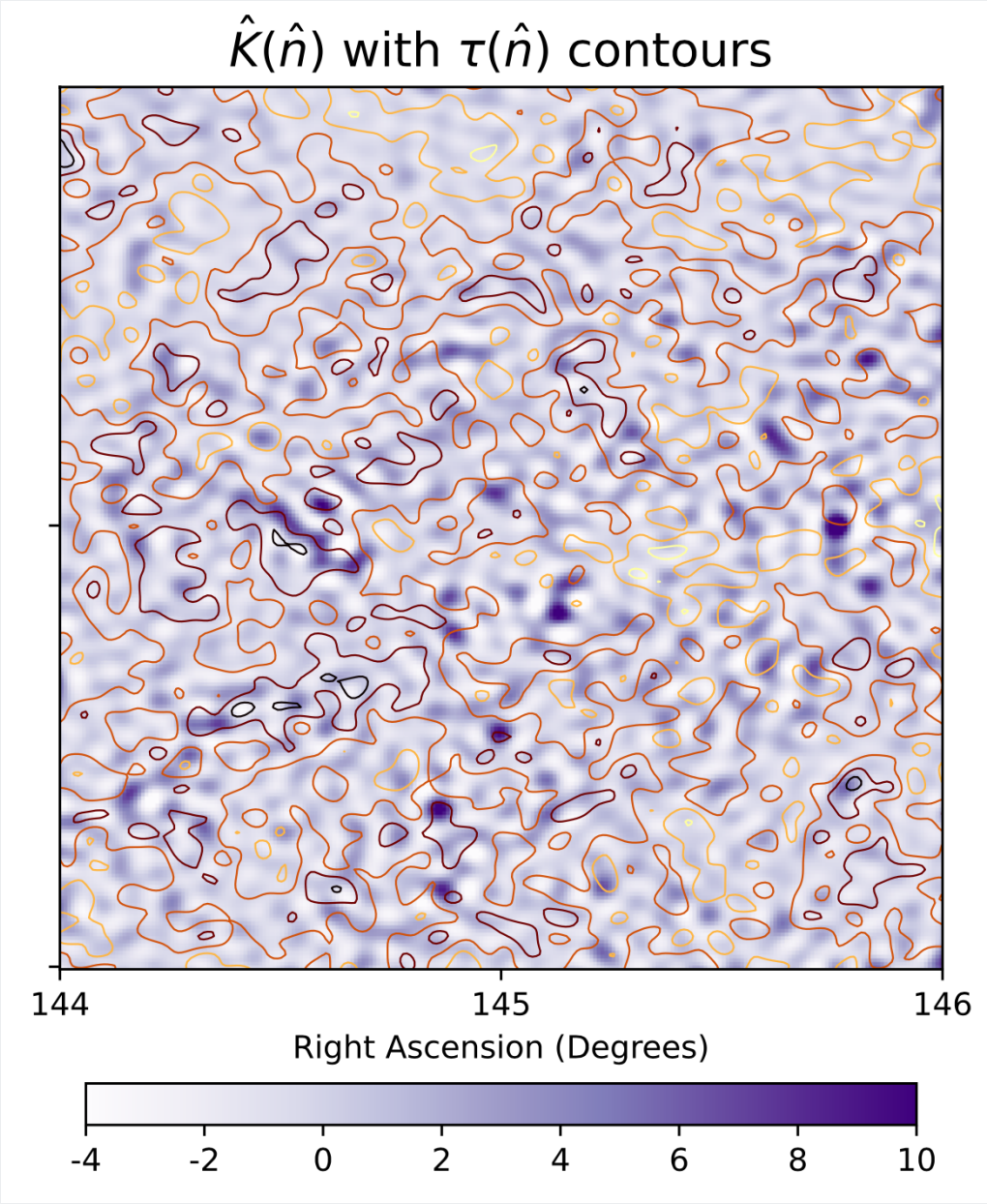

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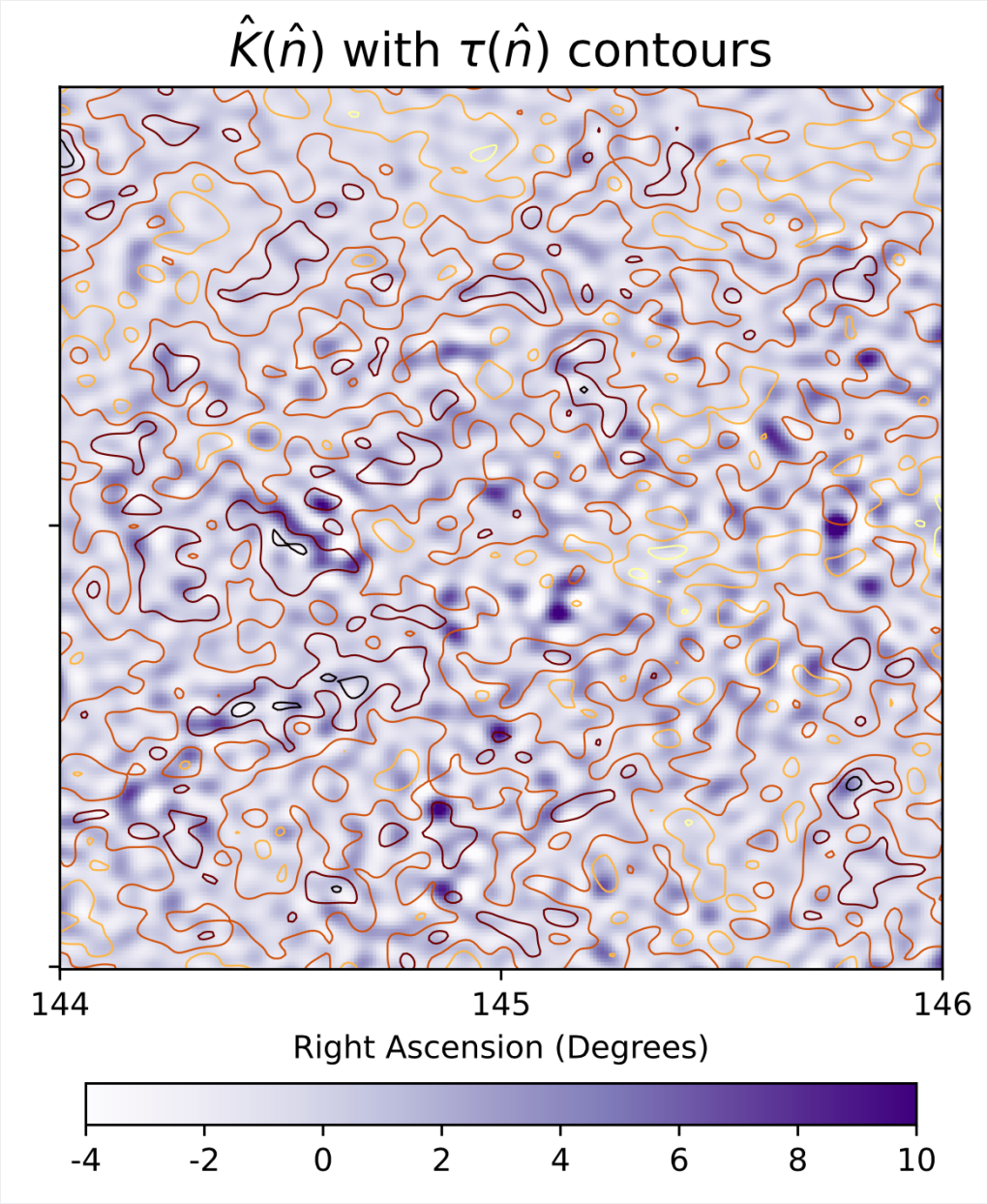
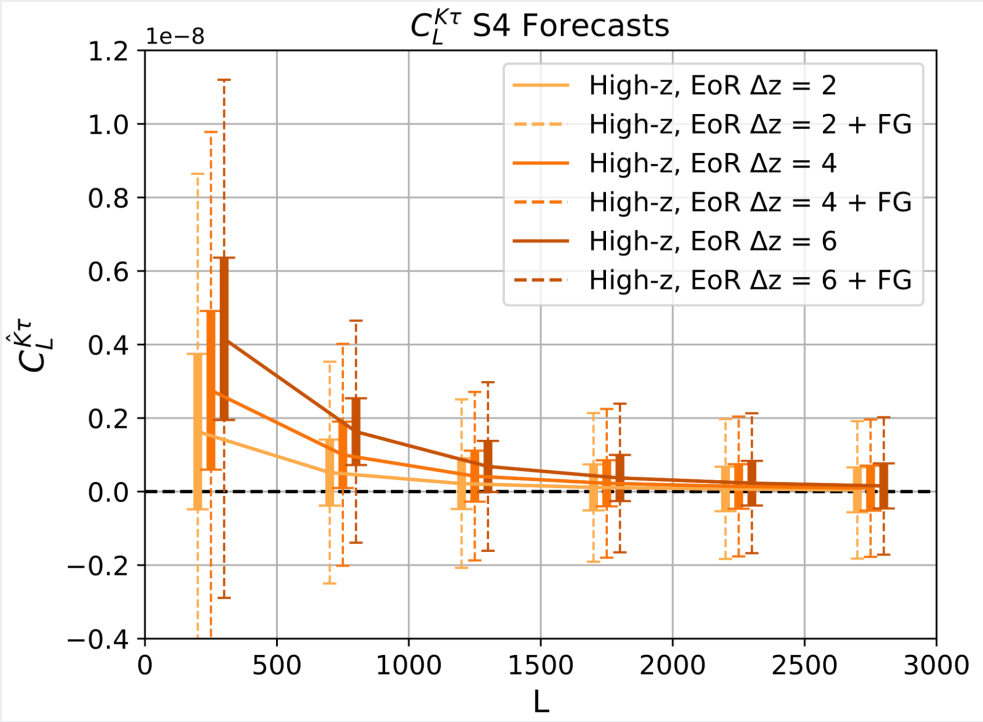
- K and τ are ~50% correlated



Kramer, **AvE**, Cain, MacCrann, ++ 2025

Detectability of reionization K x τ



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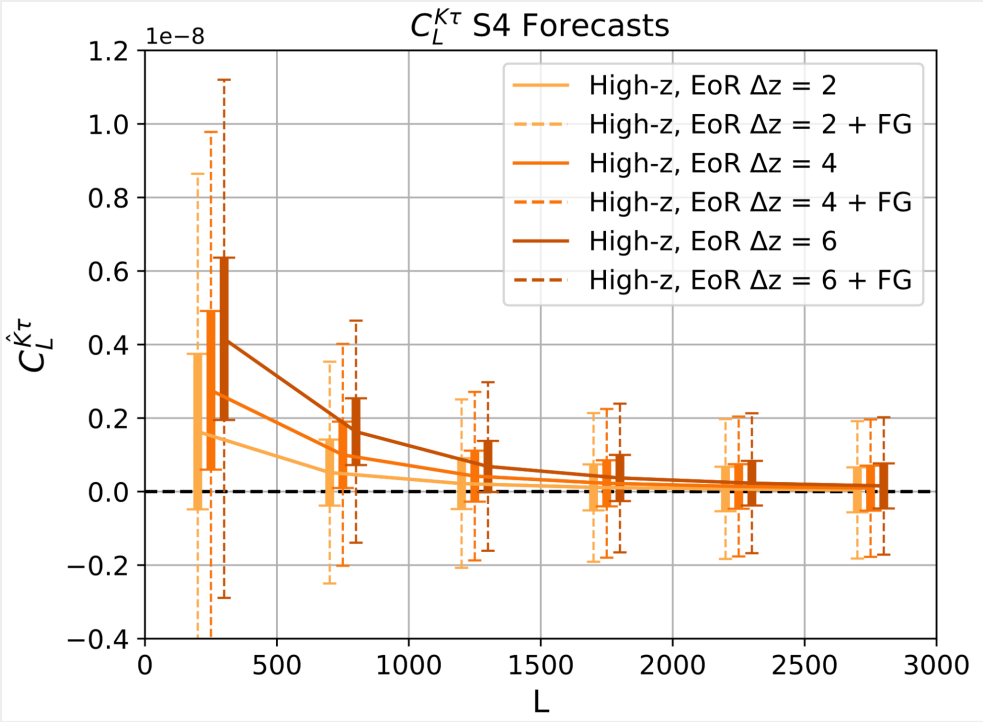

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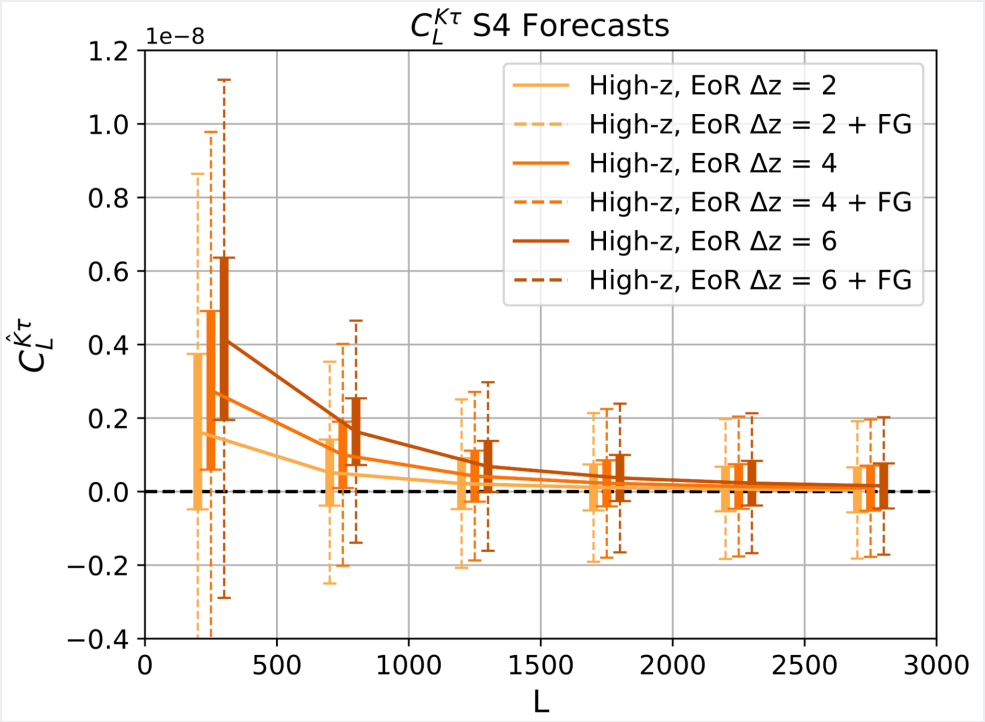

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Survey	**KK**	$\tau_{\mathbf{EB}}$ $\tau_{\mathbf{EB}}$	**K** $\times$ $\tau_{\mathbf{EB}}$
CMB-S4	140	0.49	1.8
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Kramer, **AvE**, Cain, MacCrann, ++ 2024

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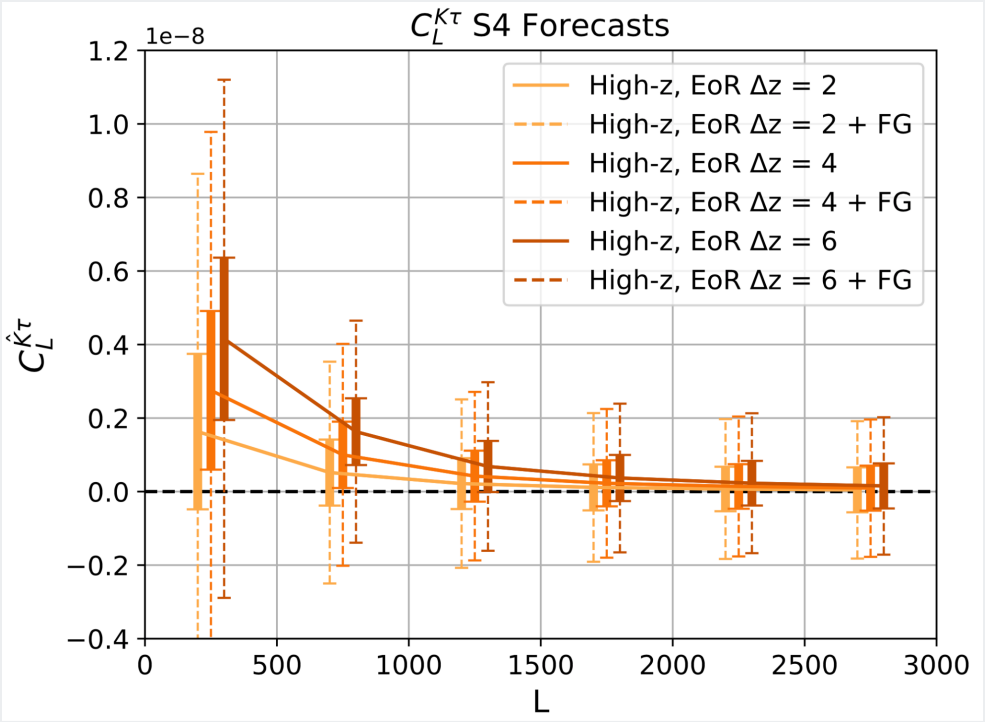

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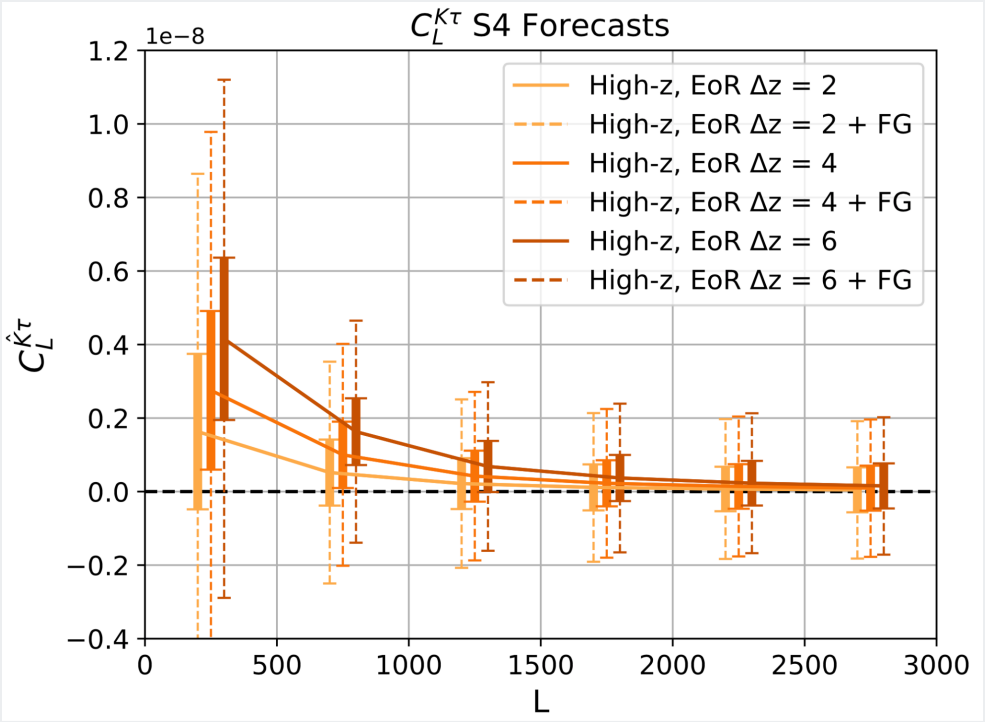

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K x τ Takeaway:

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K x τ is a *new* EoR statistic that may be within reach of planned CMB surveys.

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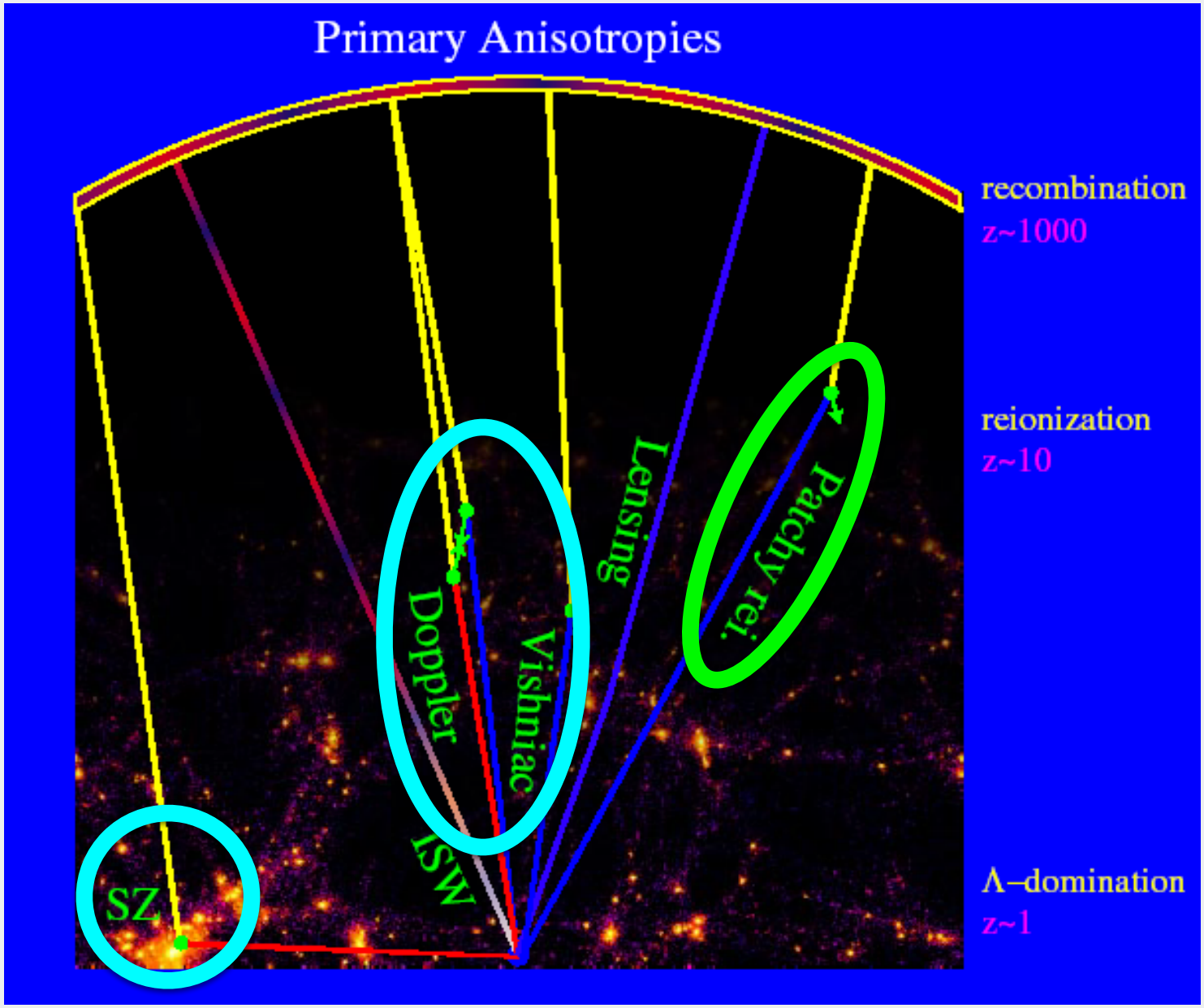
  - Sensitive to electron bispectrum during EoR
  - High-redshift analog of "projected-field kSZ²" studies, with τ as tracer

Kramer, **AvE**, Cain, MacCrann, ++ 2024

OUTLINE

1. The CMB as a backlight
2. Scattering effects: ionized gas
   - Oriented tSZ stacking: CGM and feedback
   - Patchy screening and kSZ: CGM, Reionization
3. CMB lensing: dark matter
   - State of the art: ACT & SPT, Simons Observatory, CMB-S4
   - New lensing estimators

The CMB as a backlight



plus, emission in mm from dusty galaxies and AGN

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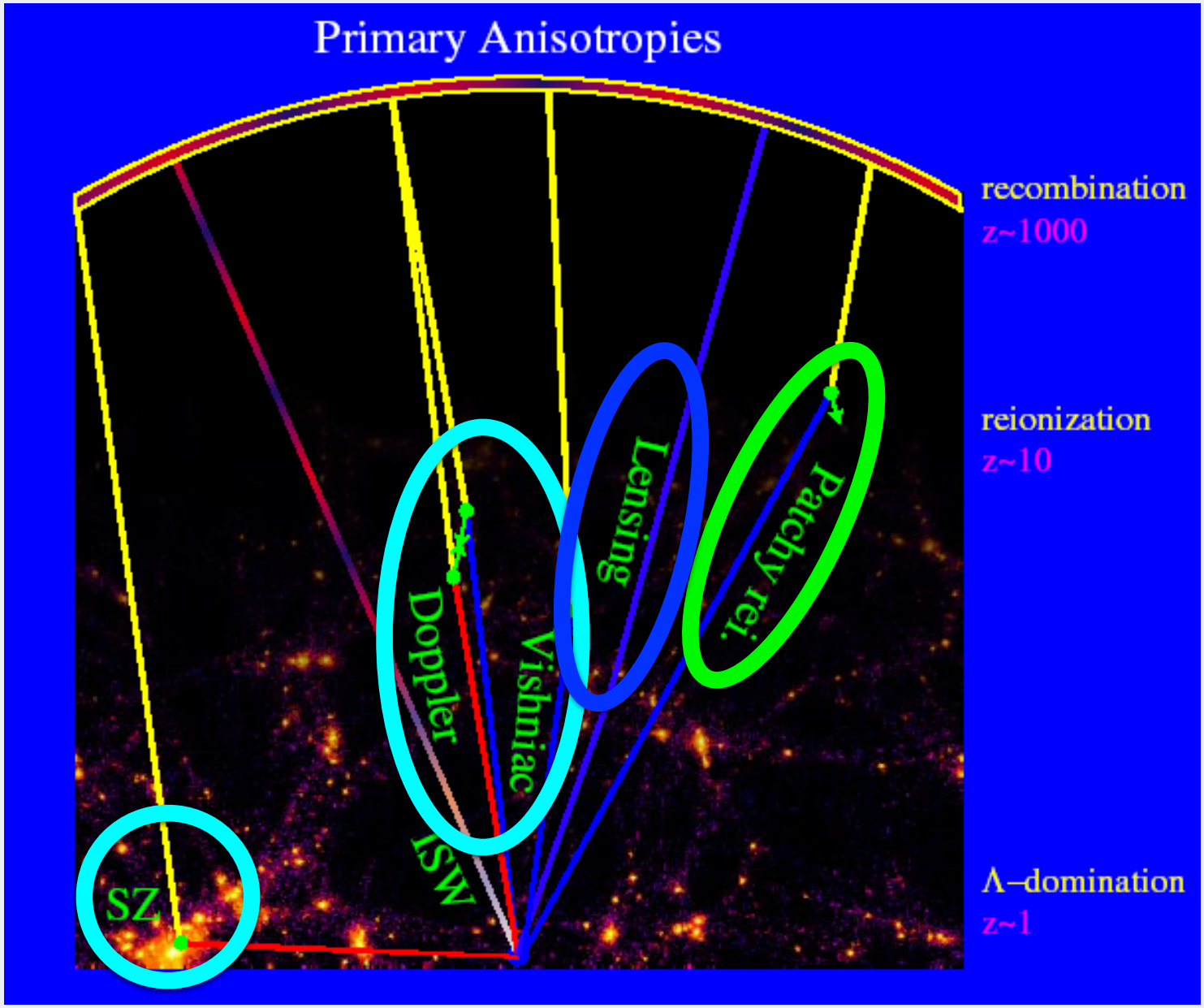

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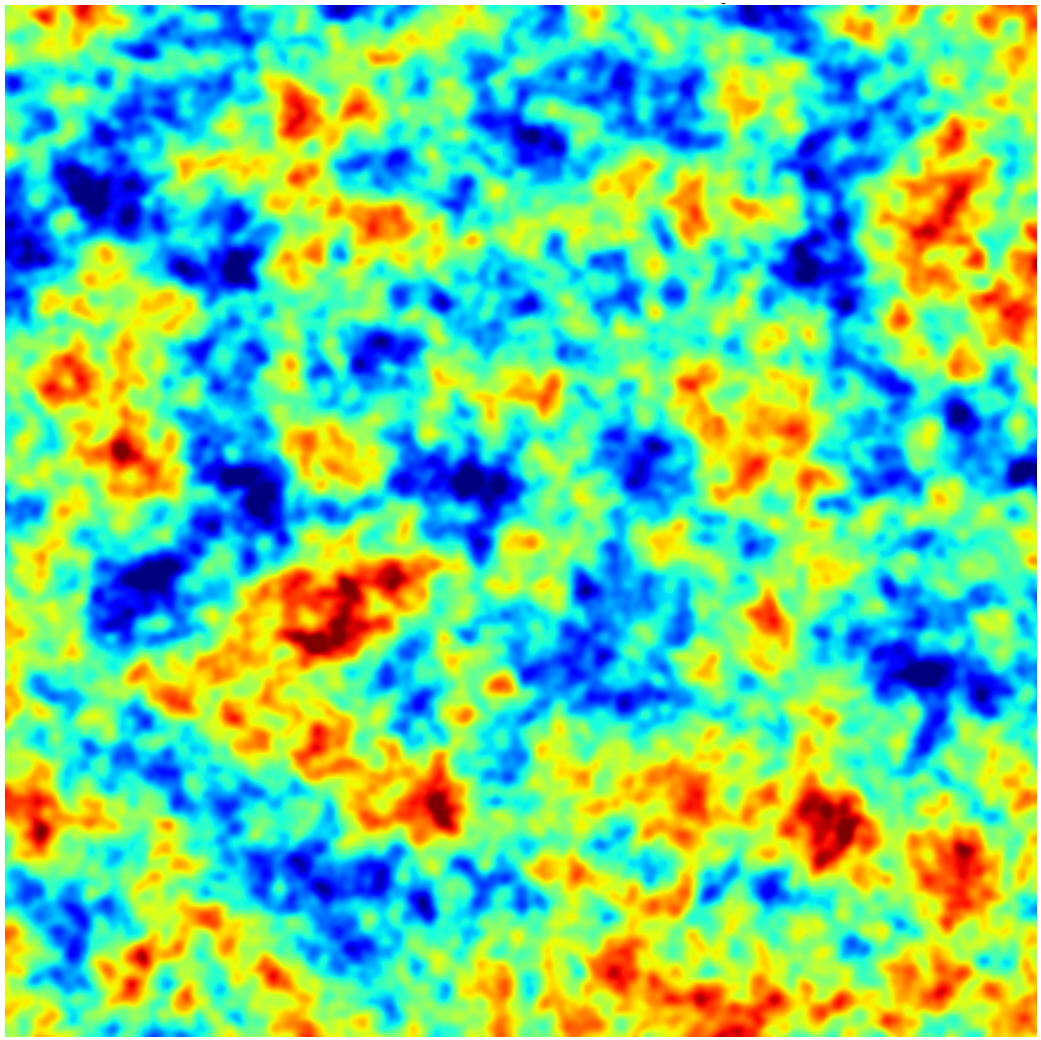
Wayne Hu's website

Unlensed CMB



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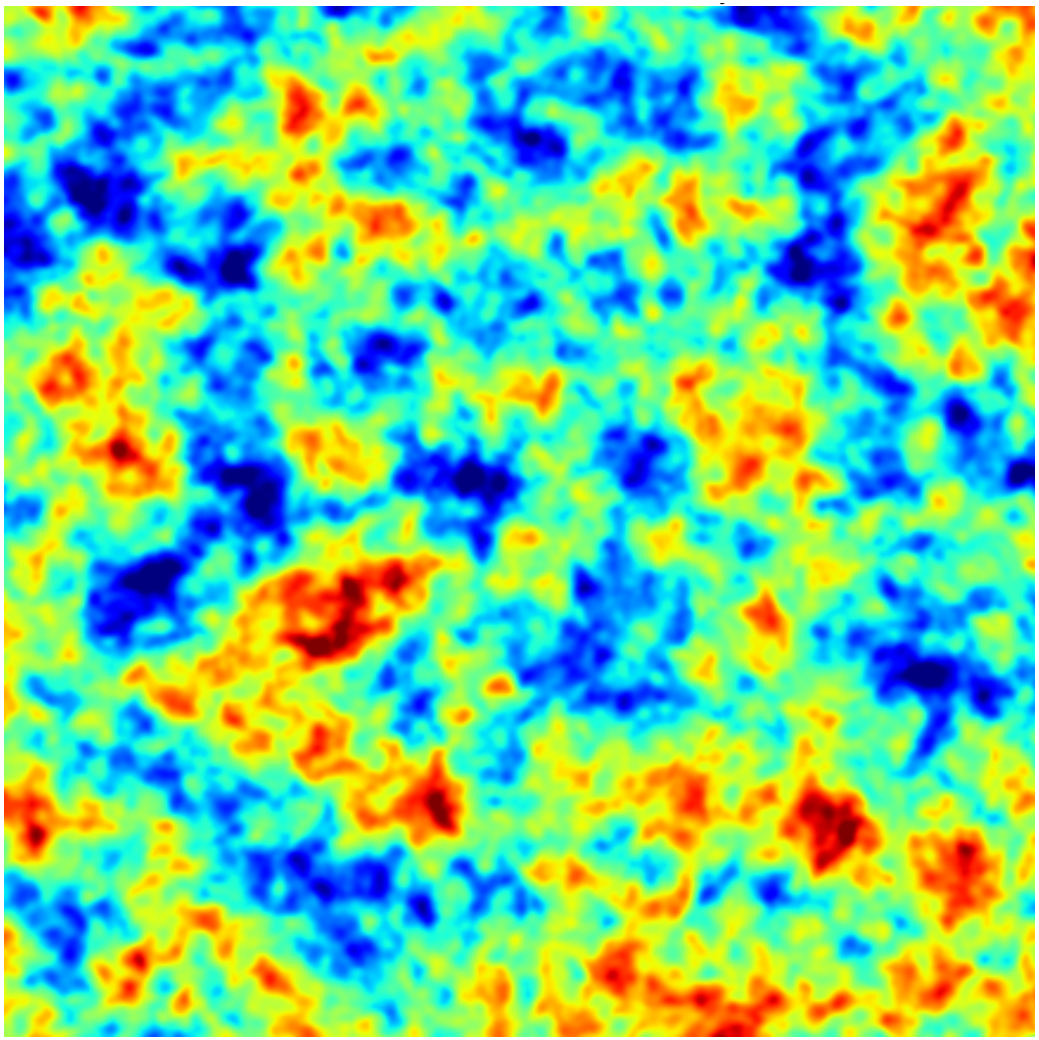

CMB lensing

- CMB is at a known, single z - behind everything
- Statistical properties completely understood

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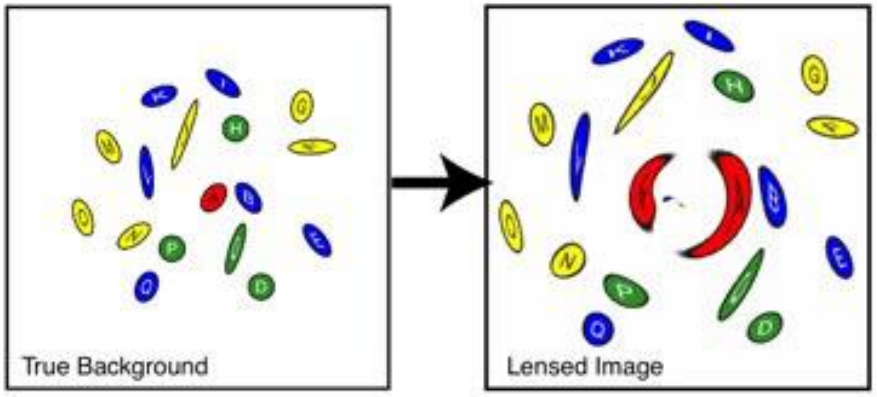
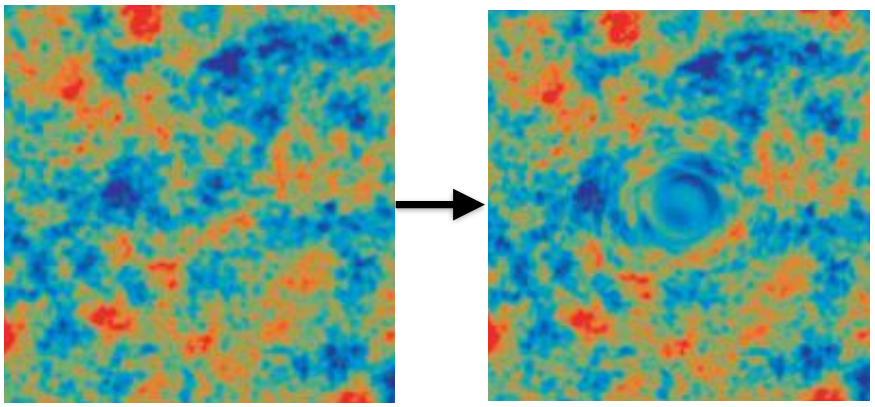
Optical galaxies



CMB

(highly exaggerated)



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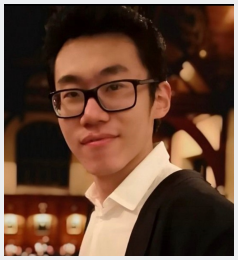
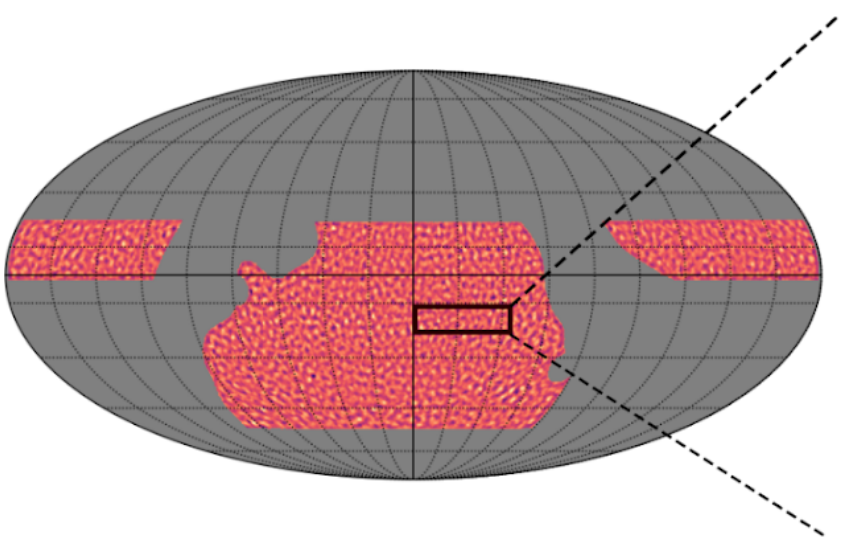
AdvACT DR6 lensing convergence maps

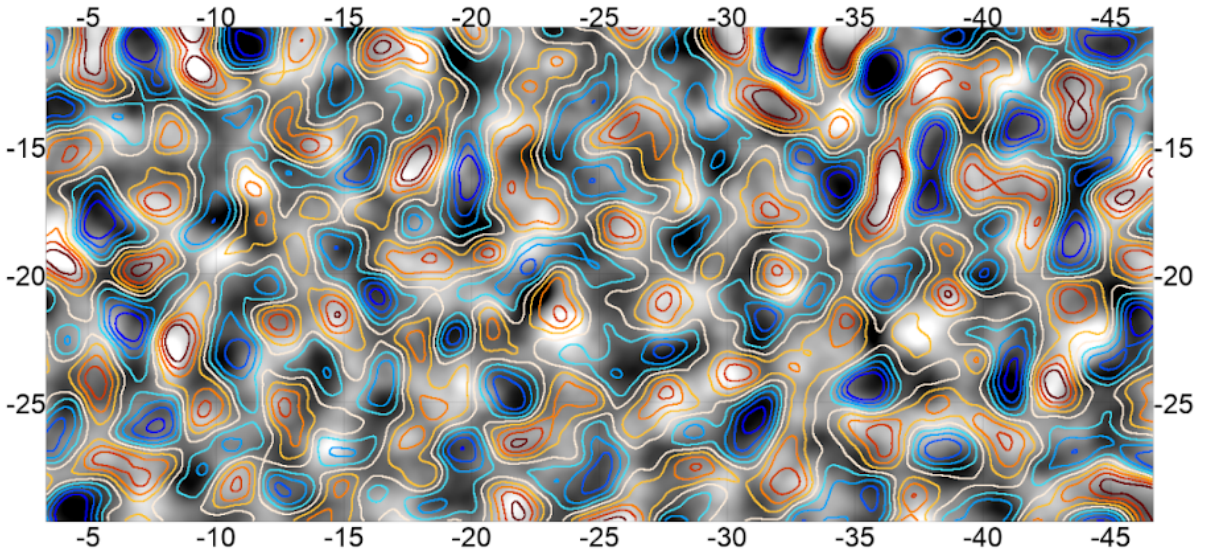
Qu++(ACT) 2023, Madhavacheril++(ACT) 2023, MacCrann++(ACT) 2023



Frank Qu (Stanford)

All matter in the Universe, including dark matter, in projection





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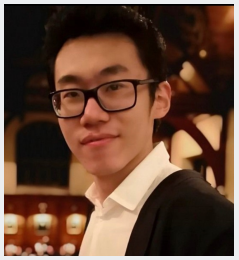

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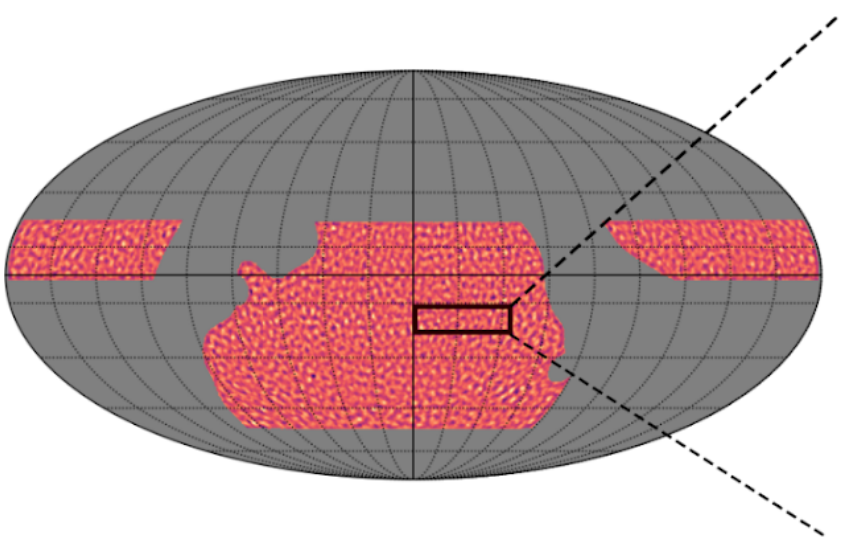
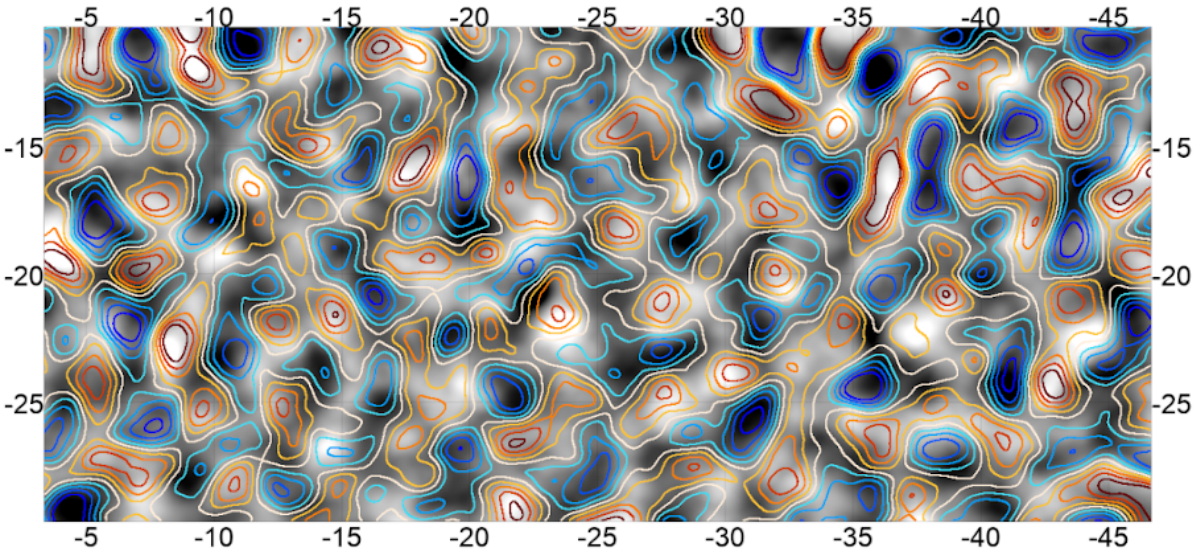
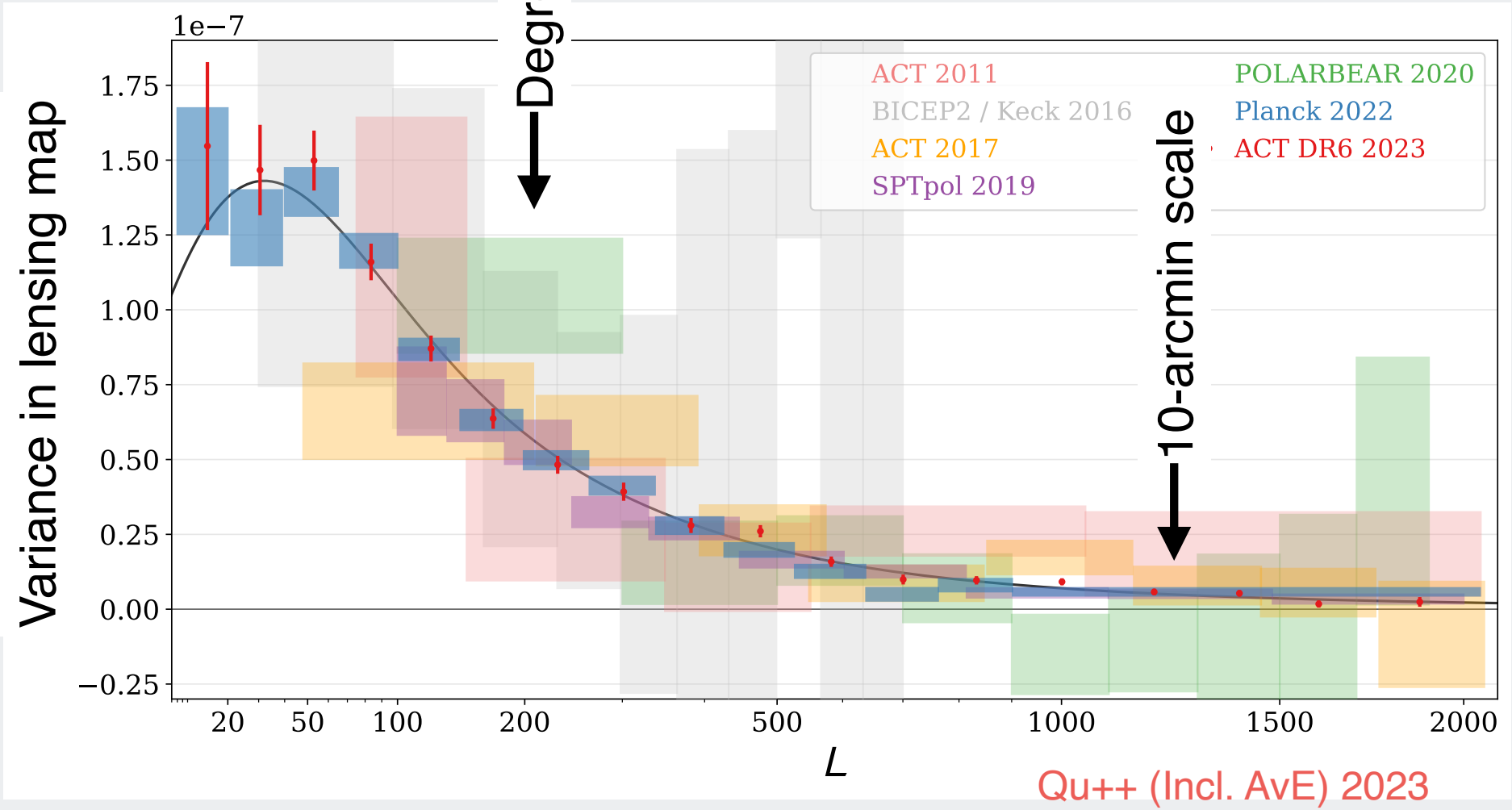




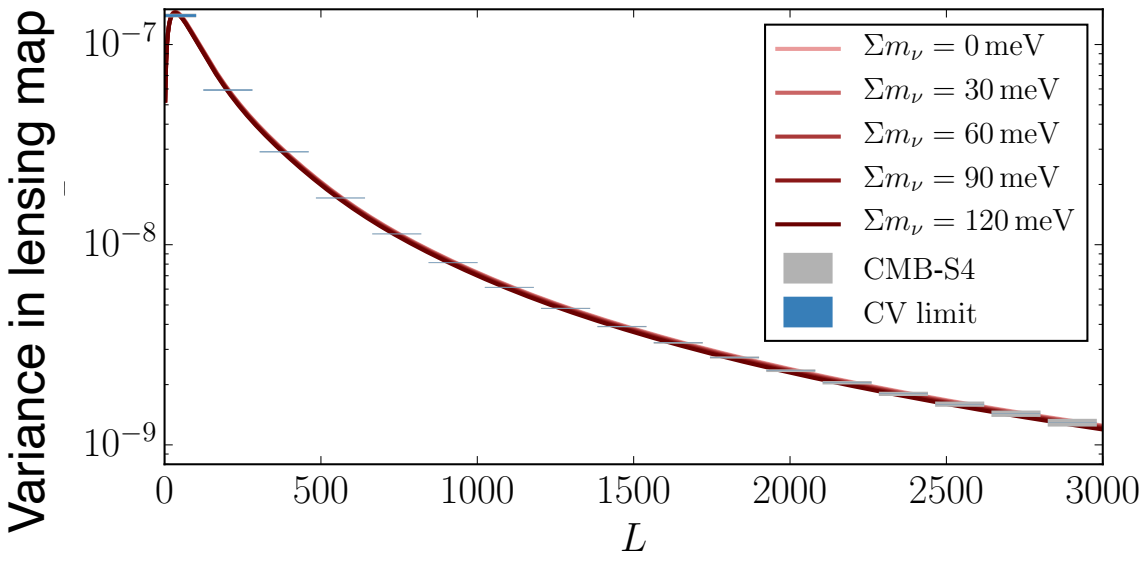
- Visible correlation with far-infrared galaxies (color contours)

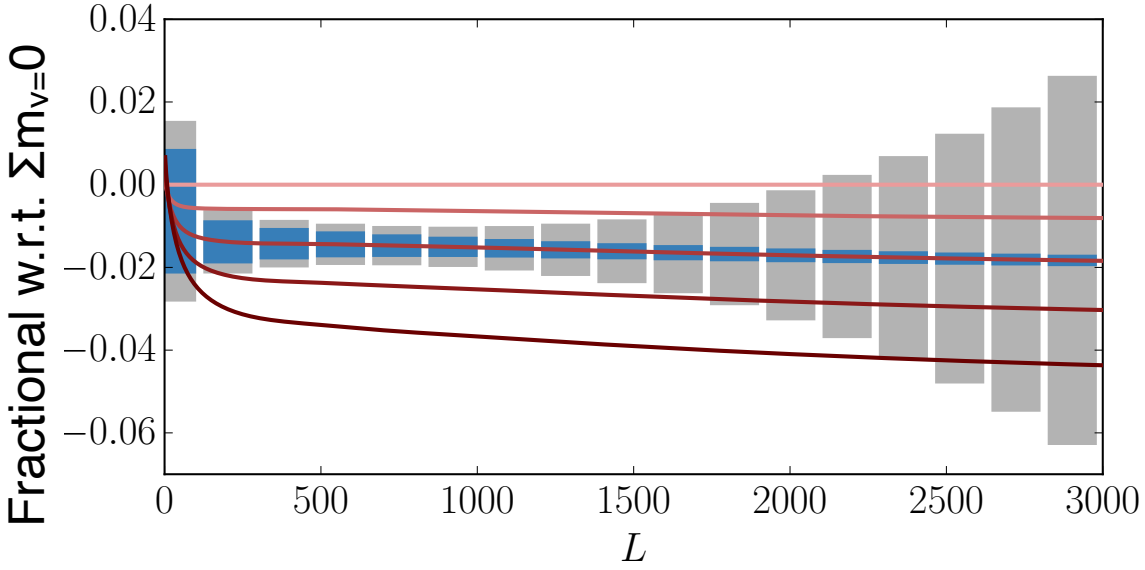
Yogesh Mehta (ASU)
ACT lensing x Planck CIB
in prep

Recent CMB lensing measures



CMB-S4 forecast (early 2030s)





500σ
~0.2% precision

σ(Σm$_\nu$) ~ 15-30 meV
(minimal is 60 meV)

CMB-S4
science book

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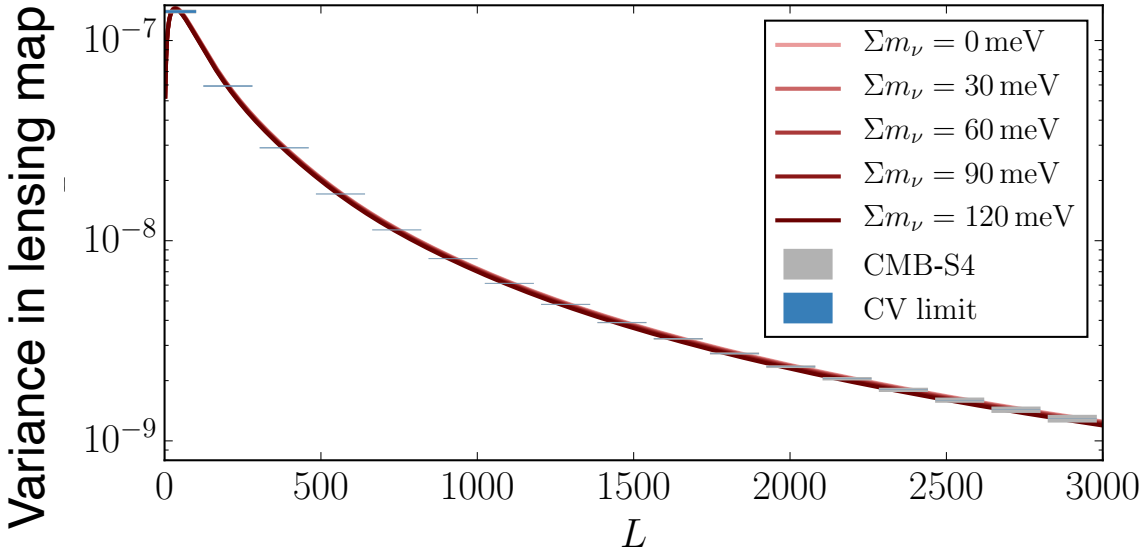

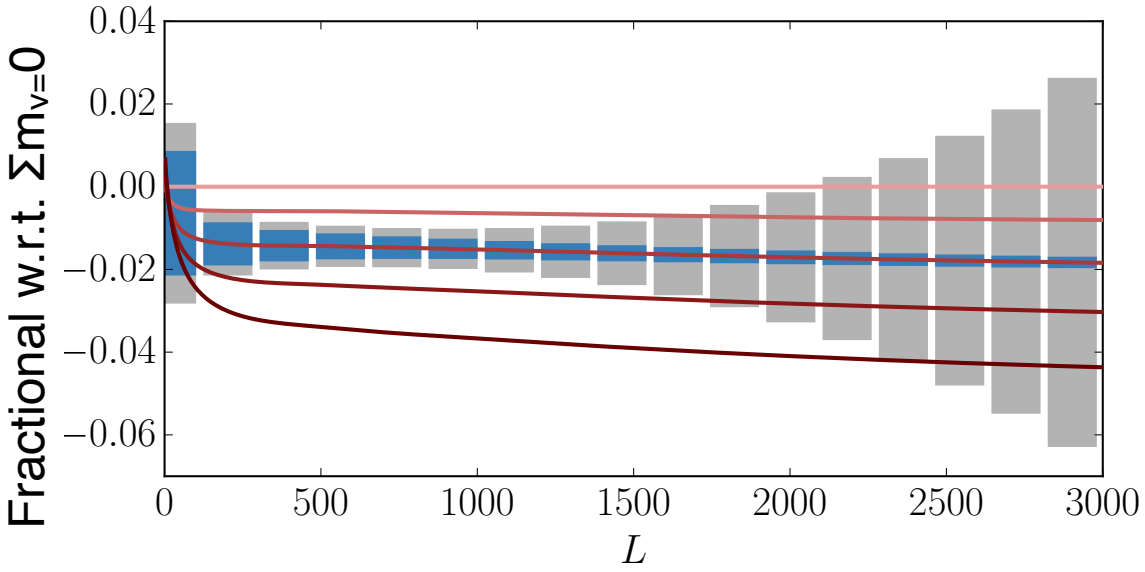

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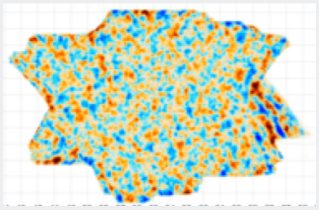
Task for next 5-10 years: do this measurement

CMB-S4 science book

The path to 0.2% precision



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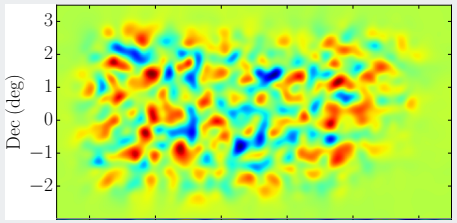

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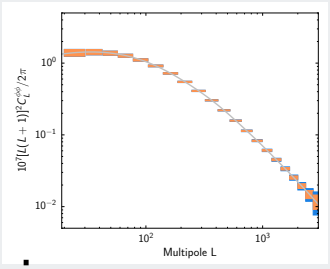

Lensing power spec.

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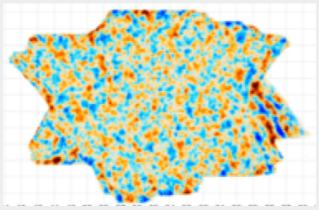

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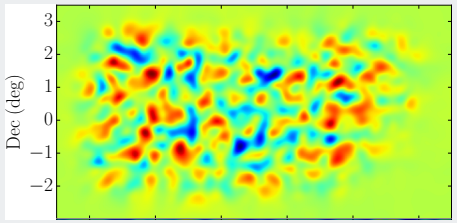

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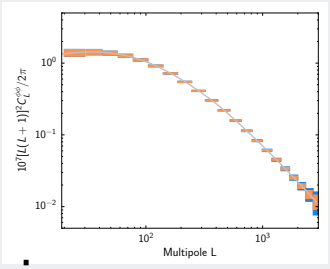

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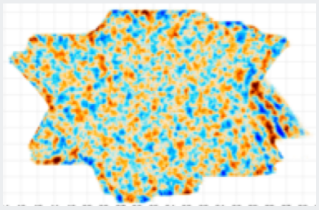

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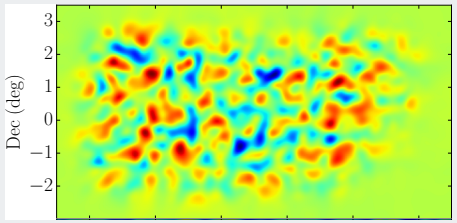

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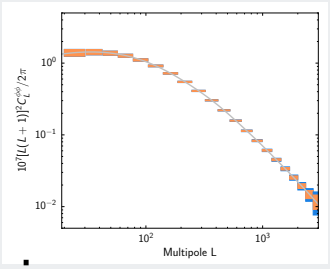

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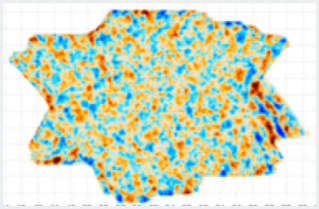

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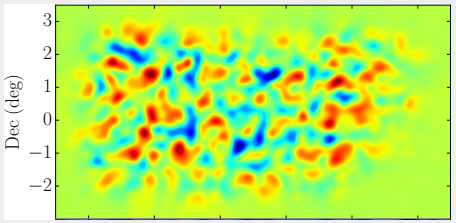

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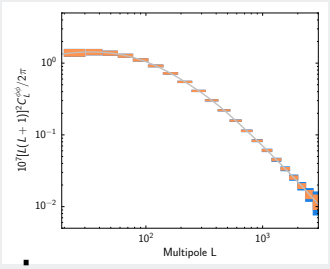

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  Chung, Foreman,**AvE** 2019; McCarthy, Foreman, **AvE** 2021
- Current lensing estimators will not be good enough for S4 precision - need new estimators
  E.g. Chan, Hlozek, Meyers, **AvE** 2023, Hotinli.. **AvE**++ 2021

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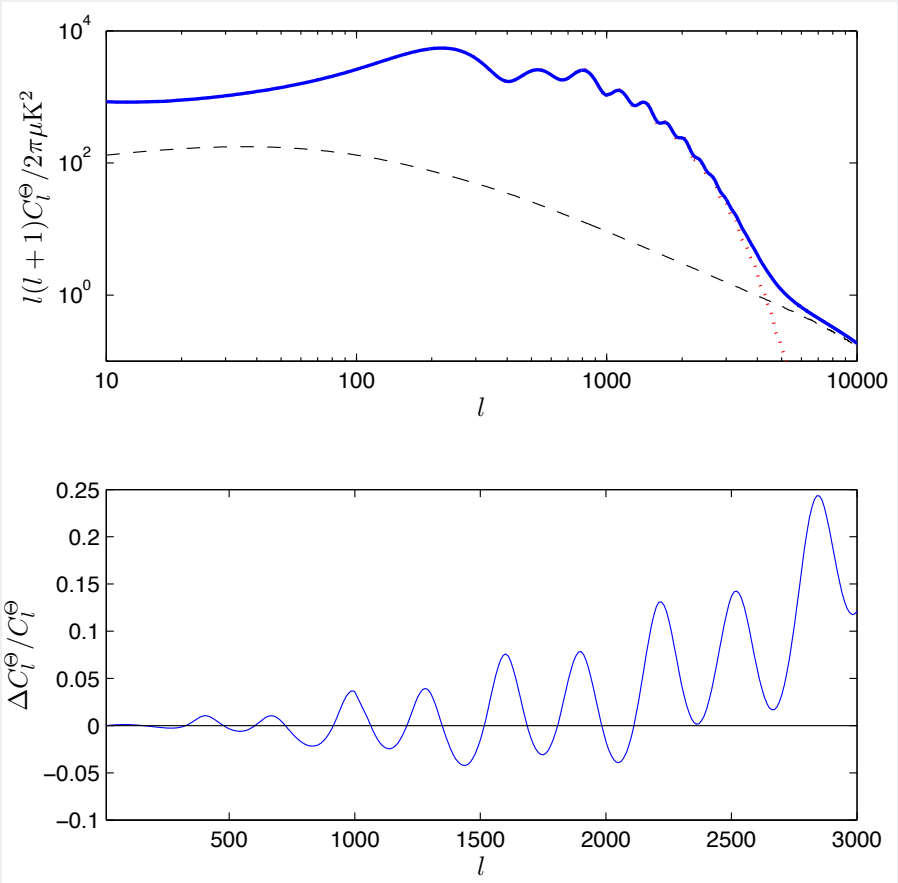
Lensed CMB power spectrum



Lewis & Challinor 2006

Lensed CMB power spectrum

- Mid-l: “peak smearing”
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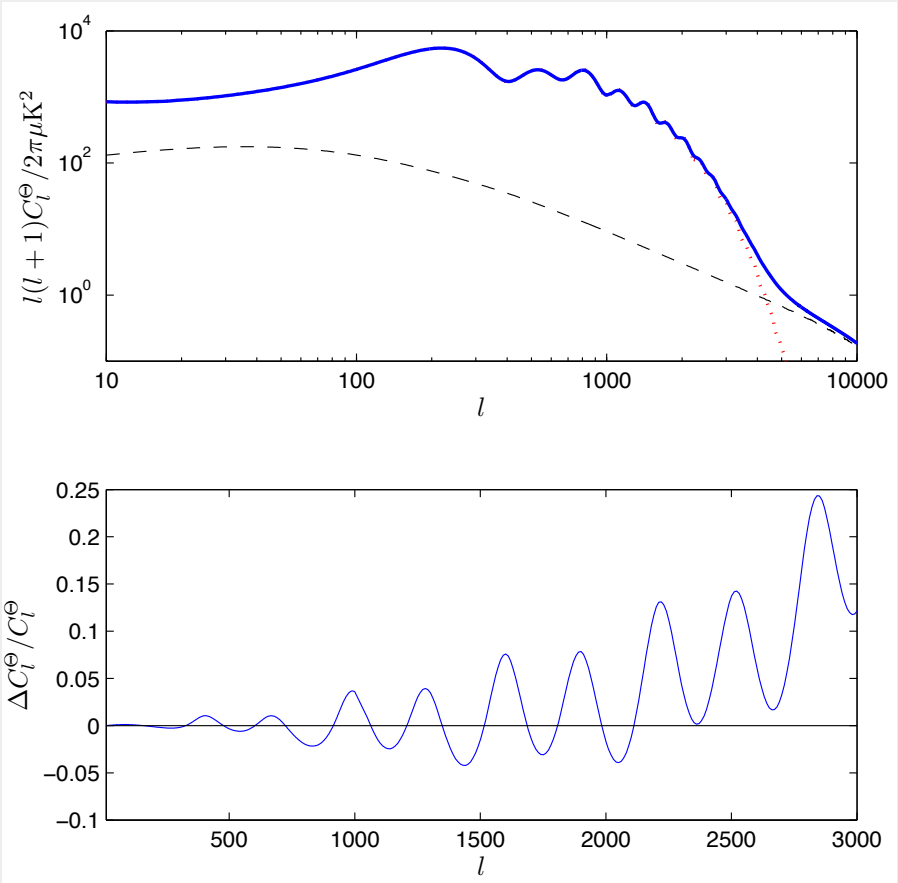

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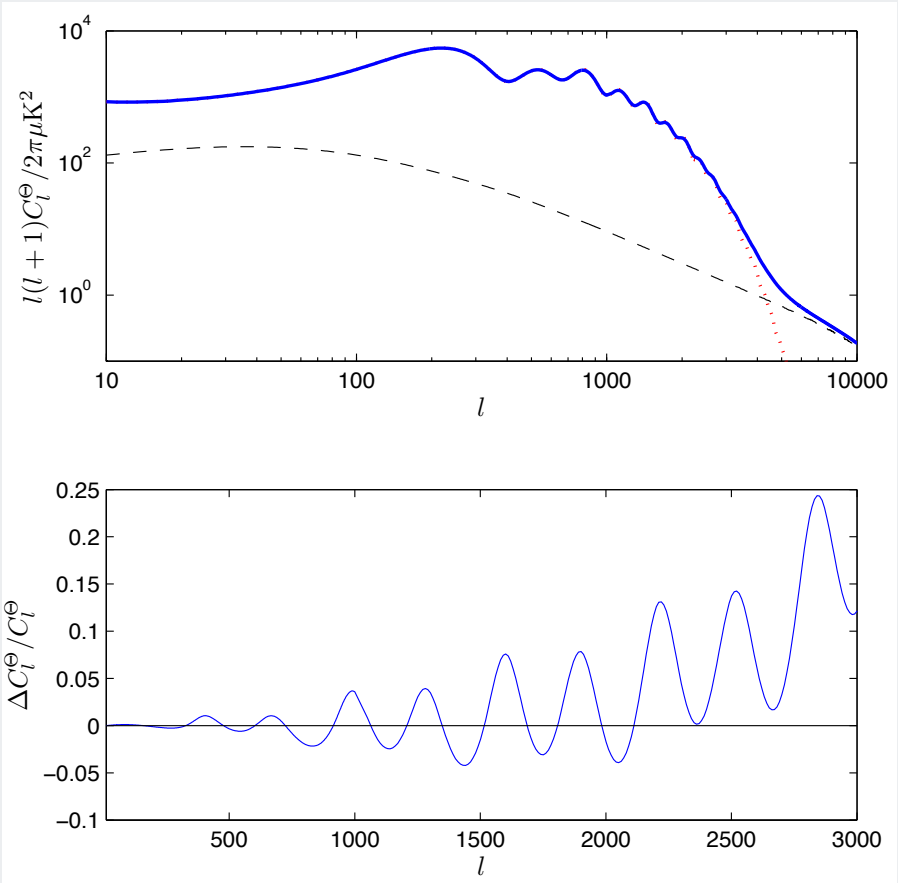

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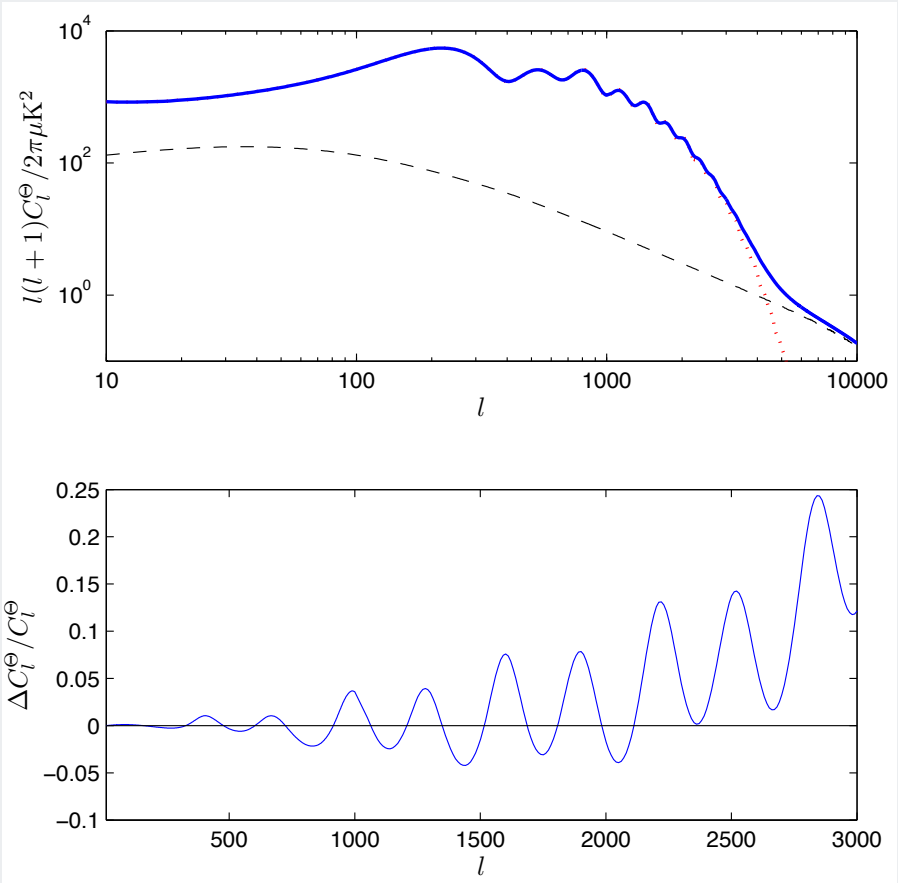

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The SCALE estimator

Small-correlated-against-large estimator for the lensing of the cosmic microwave background

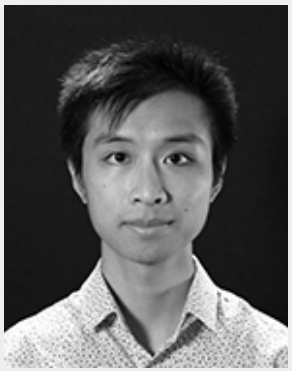
Victor C. Chan,[1] Renée Hložek,[2,1] Joel Meyers,[3] and Alexander van Engelen[4]

PRD 2024

SCALE at Scale: Cosmological applications of small-scale CMB lensing

Victor C. Chan,[1,2] Renée Hložek,[3,1] Joel Meyers,[2] and Alexander van Engelen[4]

ArXiv 2024, PRD submitted

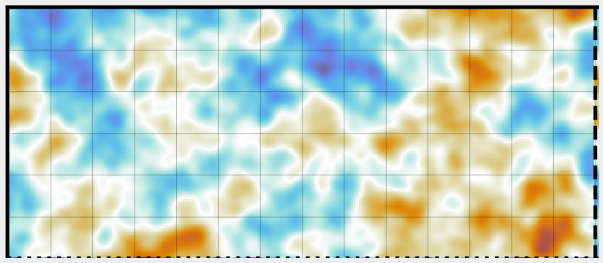


Victor Chan
U of Toronto ->
SMU

The SCALE estimator

Unlensed

T



Chan, Hlozek, Meyers, **AvE** (2023, 2024)

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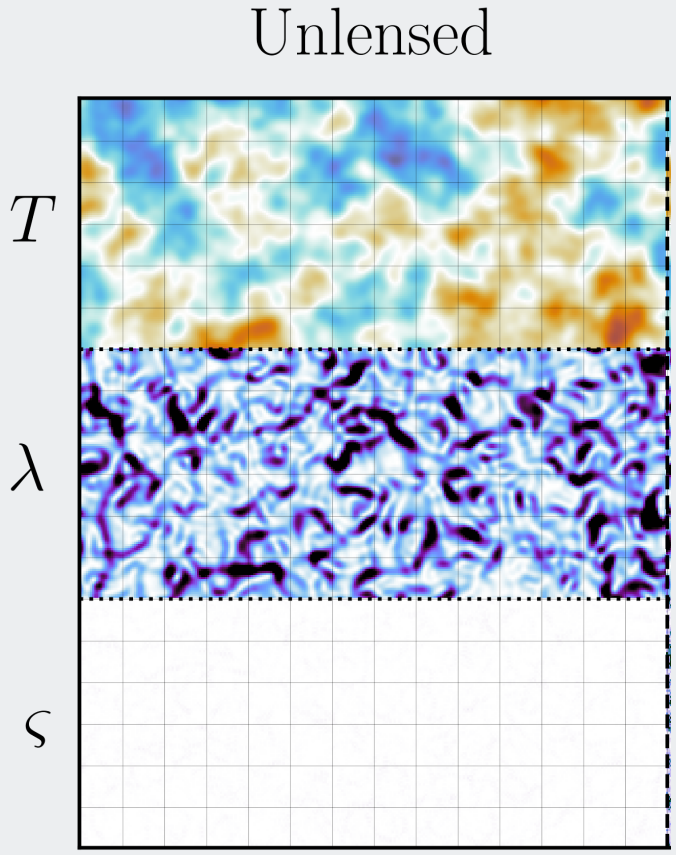

$\ell < 3000$
Large features

$6000 < \ell < 8000$
Small features

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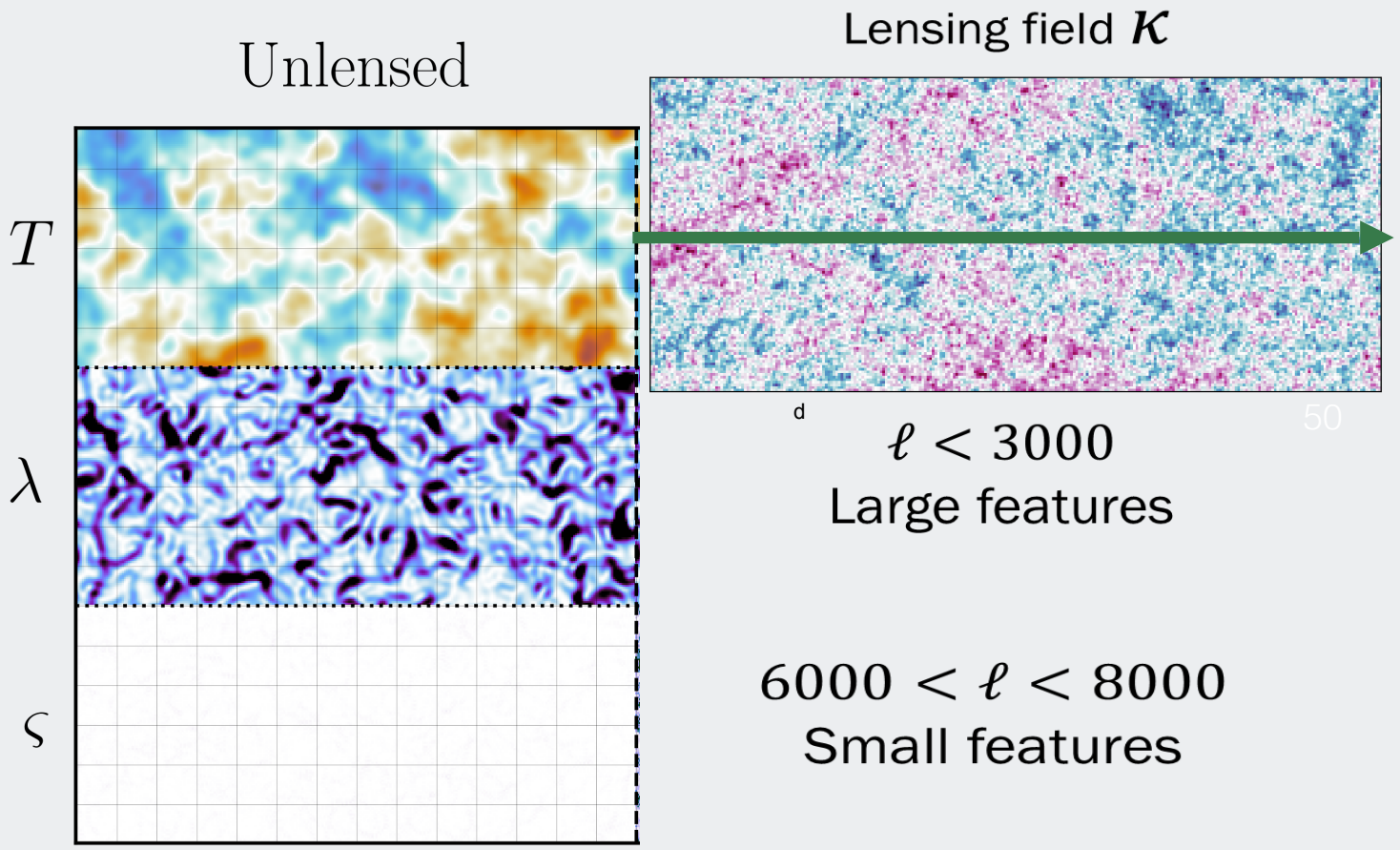

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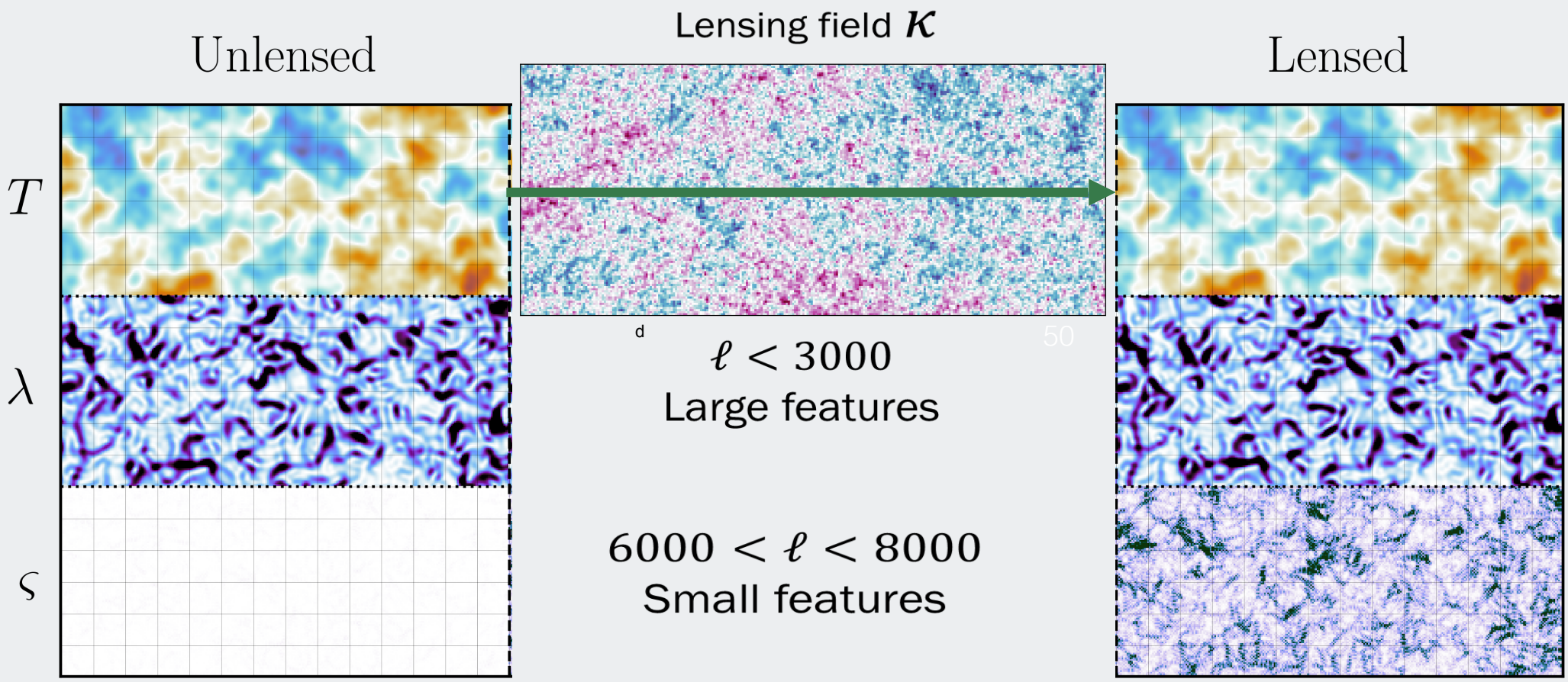

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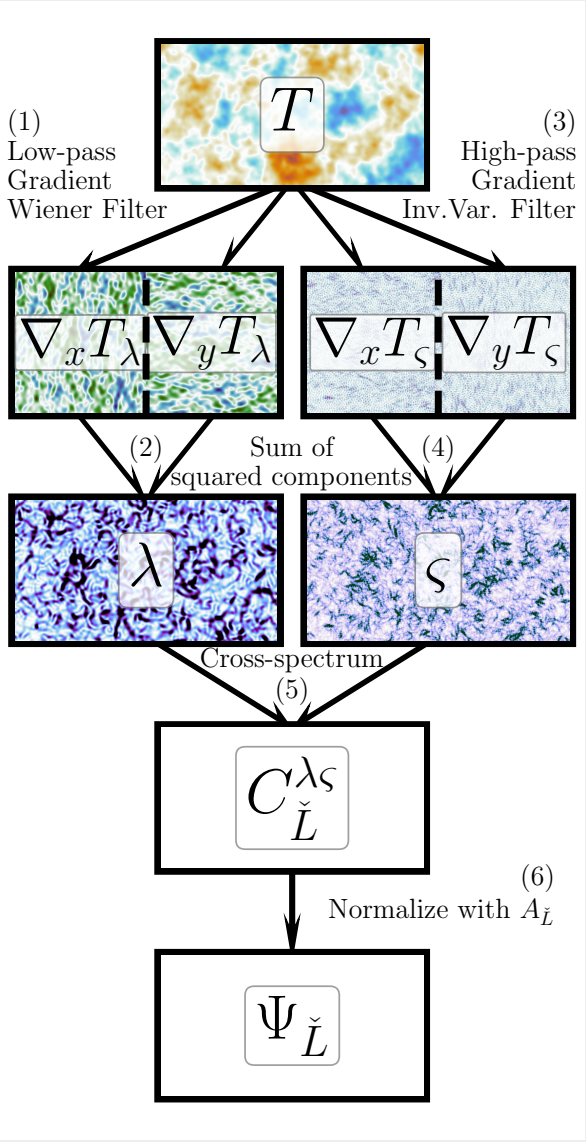
The SCALE estimator

- Look for correlation between CMB *gradient squared* and *small-scale pixel variance*

  c.f., Zaldarriaga 1997



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The SCALE estimator

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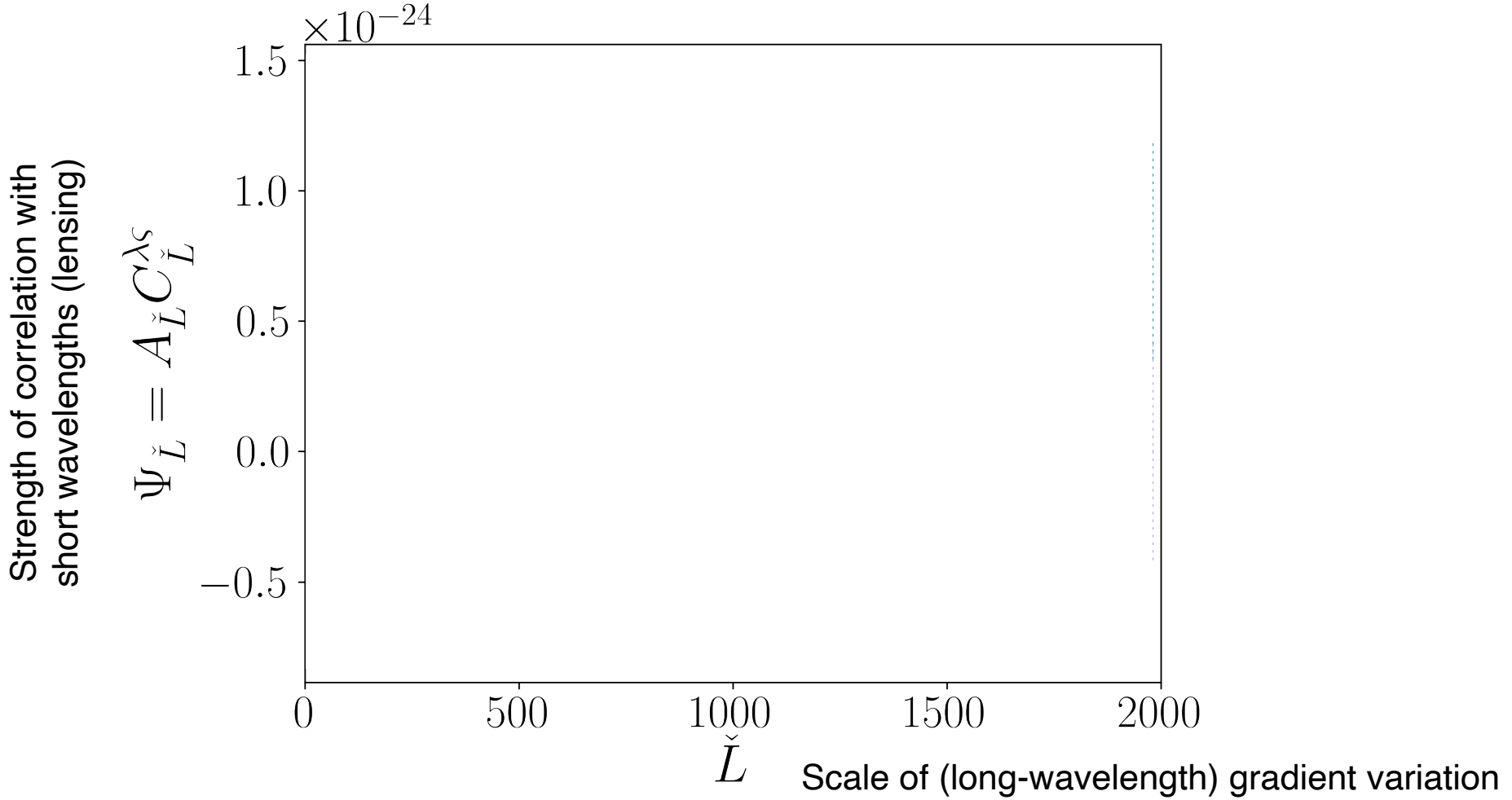
w/ S4-like Noise



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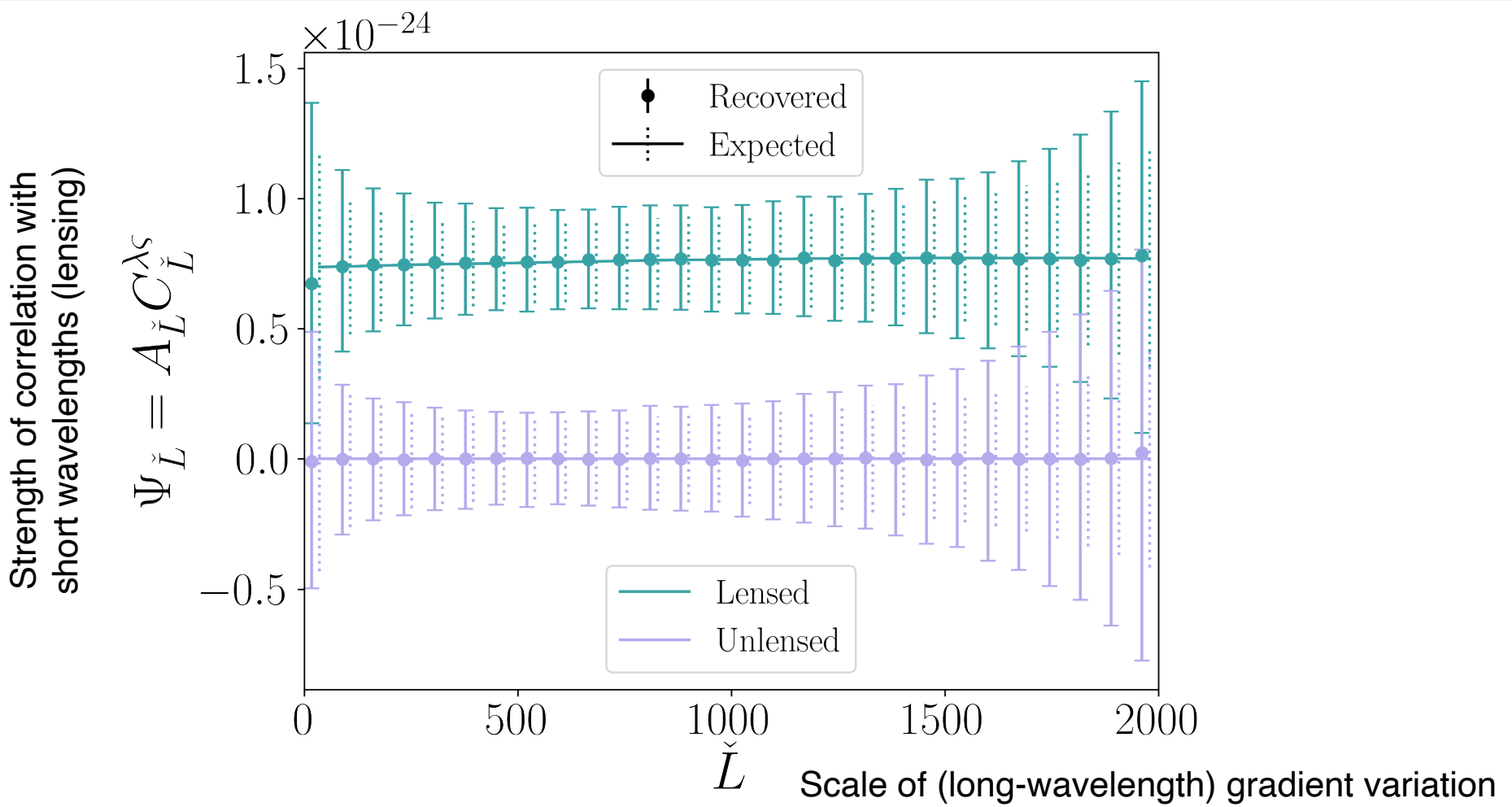

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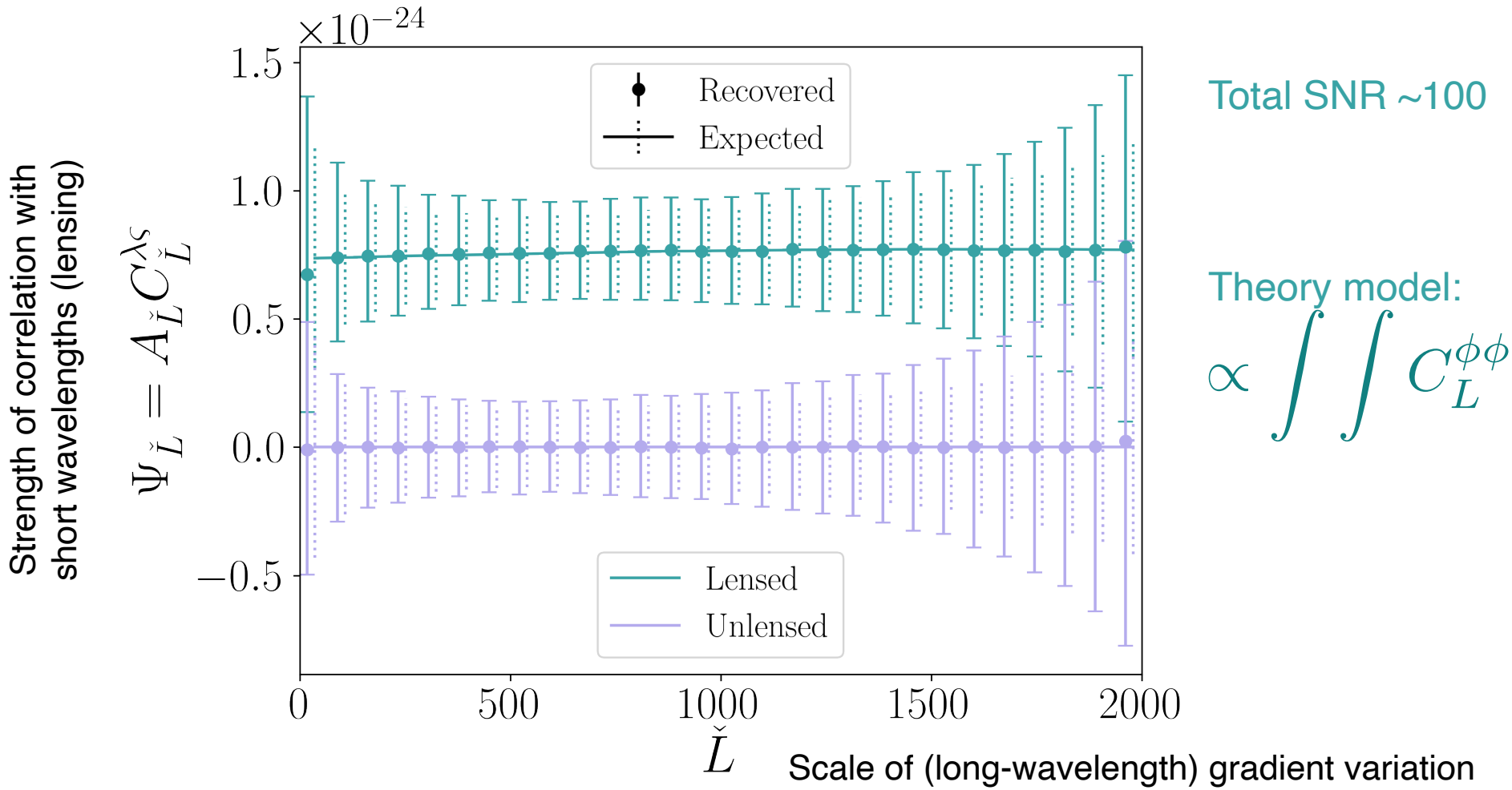

Total SNR ~100

Theory model:

$$\propto \int\int C_L^{\phi\phi}$$

Chan, Hlozek, Meyers, **AvE** (2023, 2024)

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Chan, Hlozek, Meyers, **AvE** (2023, 2024)

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- More sensitive than standard QE

Chan, Hlozek, Meyers, **AvE** (2023, 2024)

The SCALE estimator

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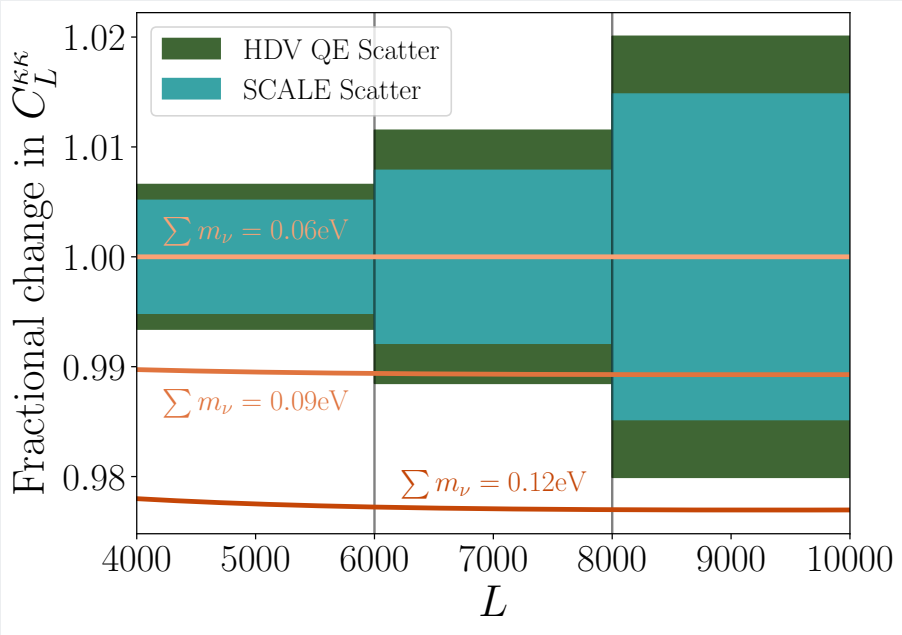

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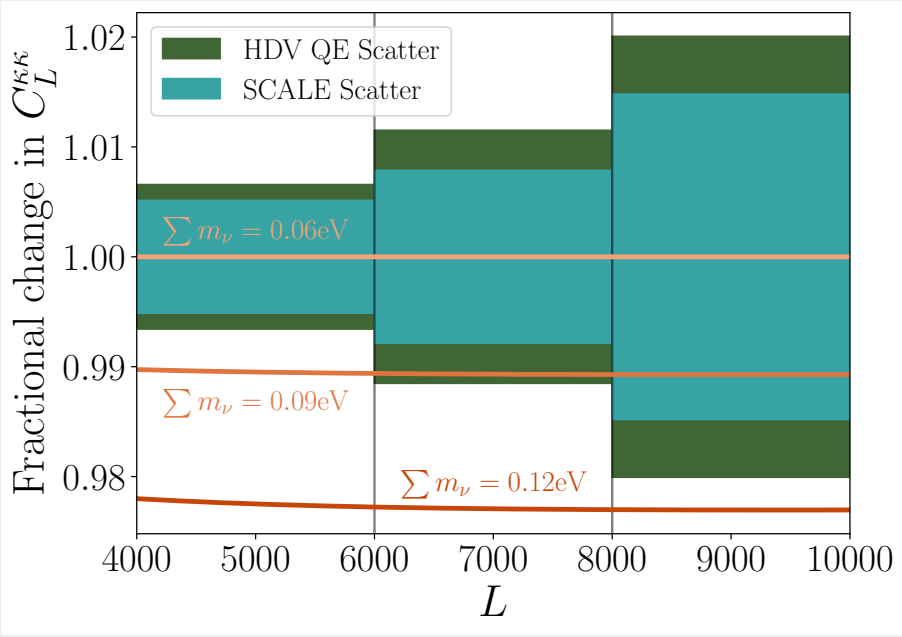

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The SCALE estimator

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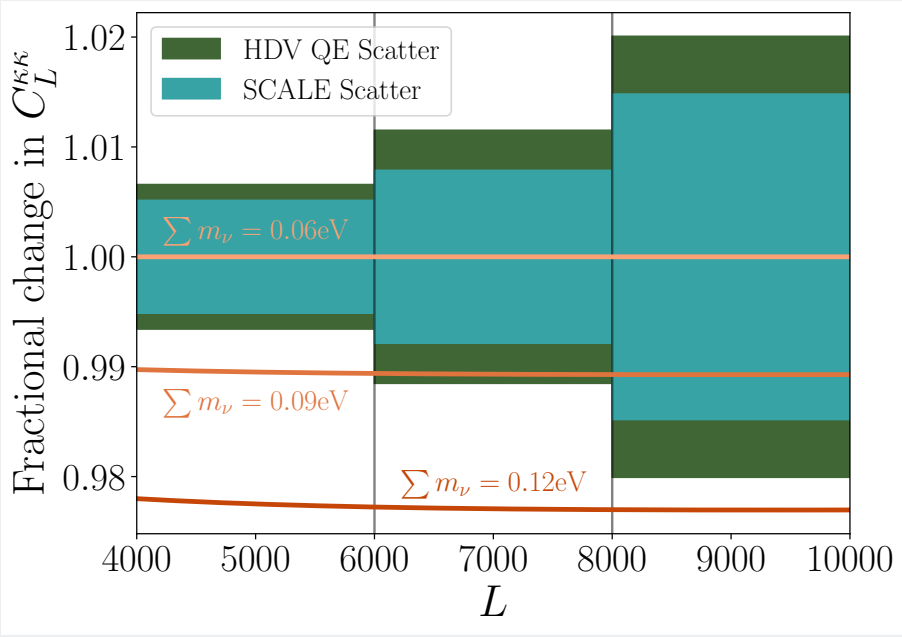
- More sensitive than standard QE
- Difference: with SCALE we never make a lensing map(!)
  - Directly probing the lensed CMB trispectrum



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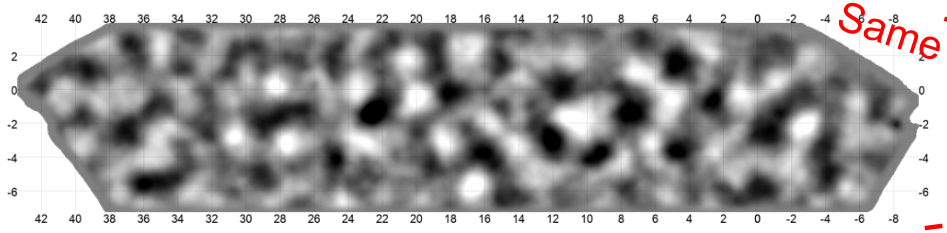
Lensing cross-correlations

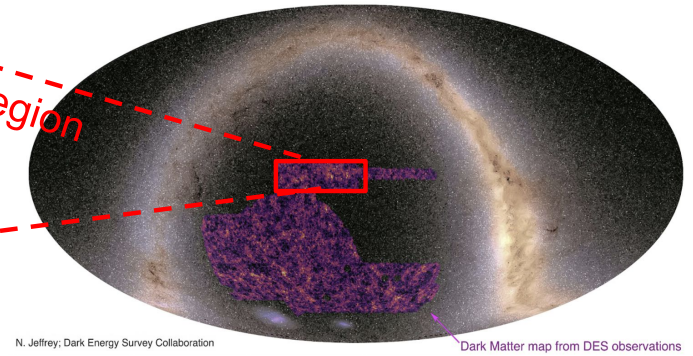
Mass (κ) map from CMB observations



ACT collaboration, Darwish et al. 2020

Same sky region

Mass map (κ) from galaxy observations



DES collaboration Jeffrey et al. 2021

Shaikh, Harrison, **AvE**, Marques++ (ACT & DES) 2024

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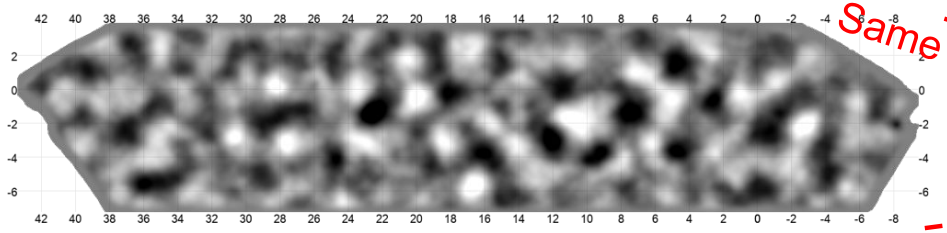

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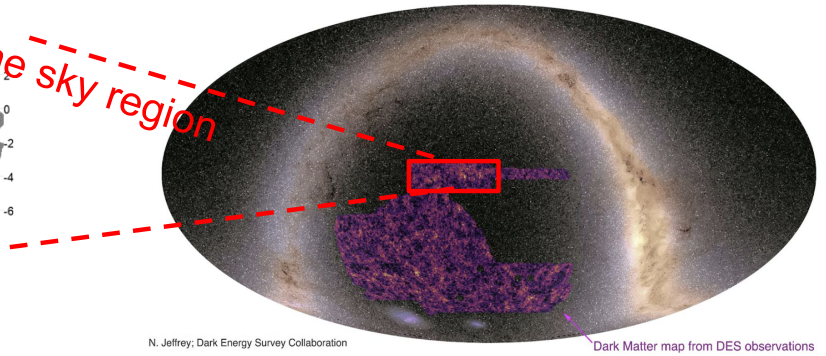

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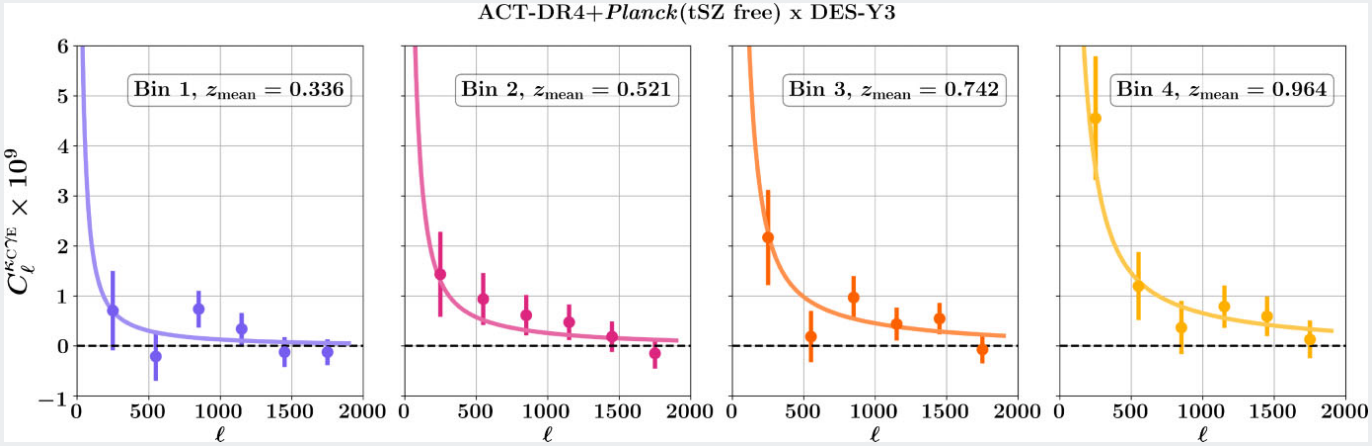

- Idea: use CMB as highest redshift source plane for lensing
- DES-Y3 shear x ACT DR4 κ: matter fluctuation amplitude to 6%
  - Looking forward to 2% with ACT DR6

Shaikh, Harrison, **AvE**, Marques++ (ACT & DES) 2024

Shabbir Shaikh (ASU)

Ian Harrison (Cardiff)

Gabriela Marques (Fermilab)

In memoriam

Eric Baxter

Summary

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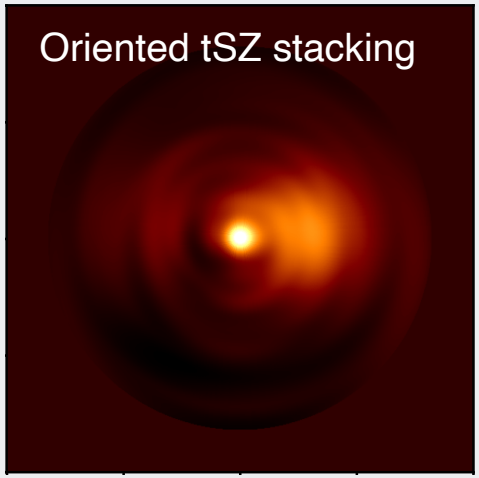

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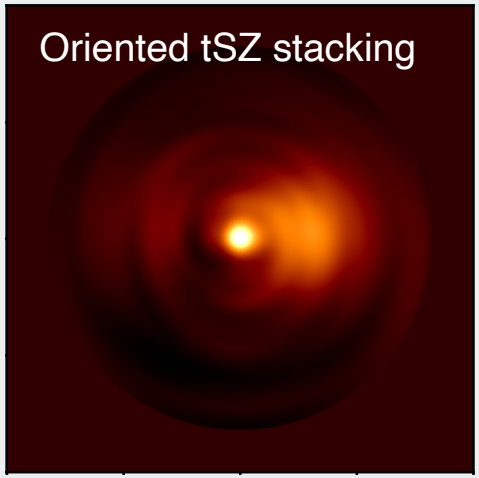

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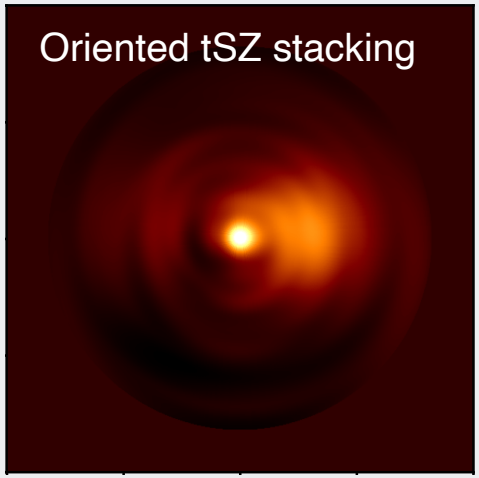

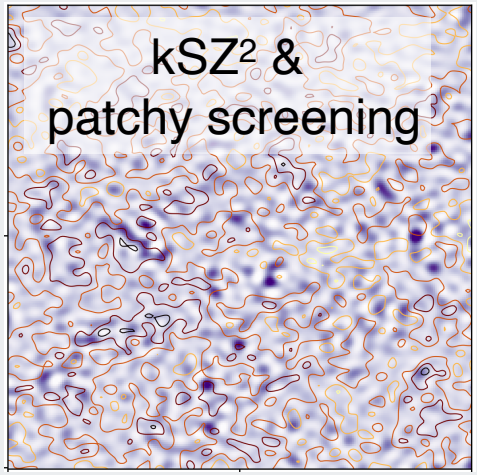

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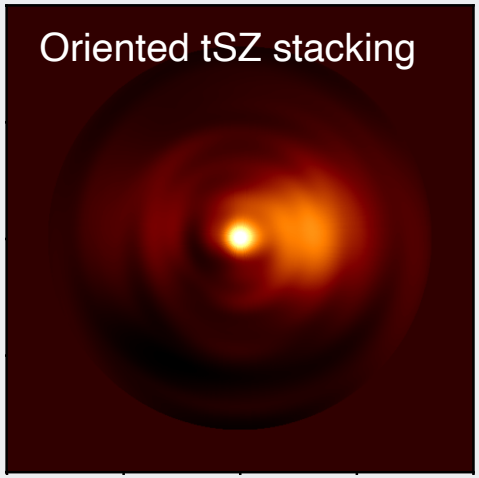

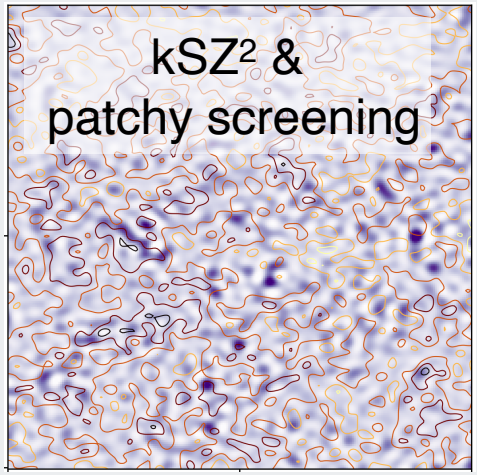

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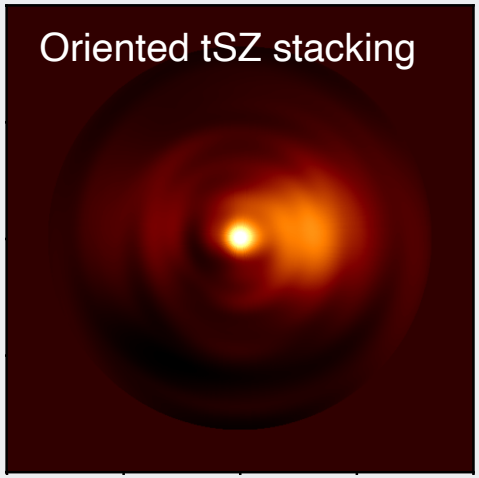

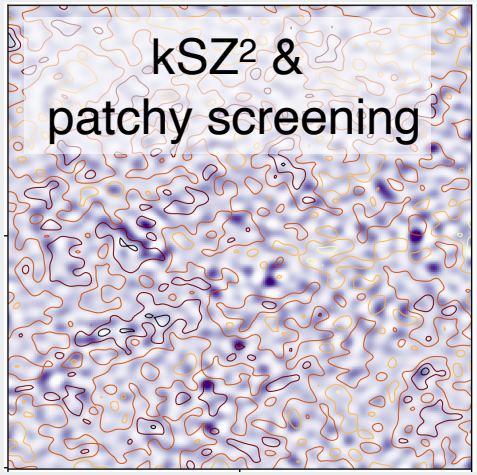

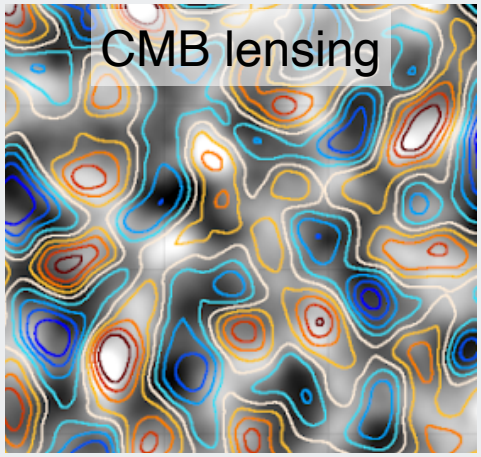

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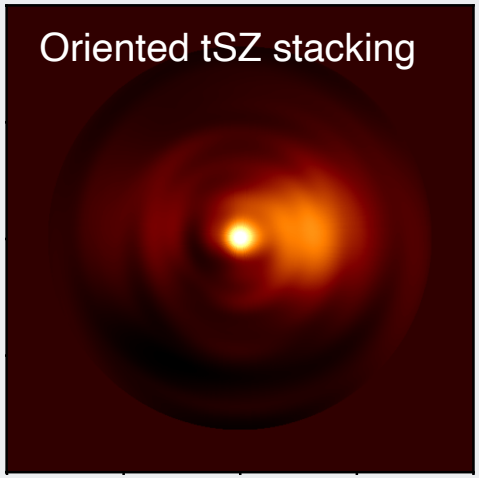

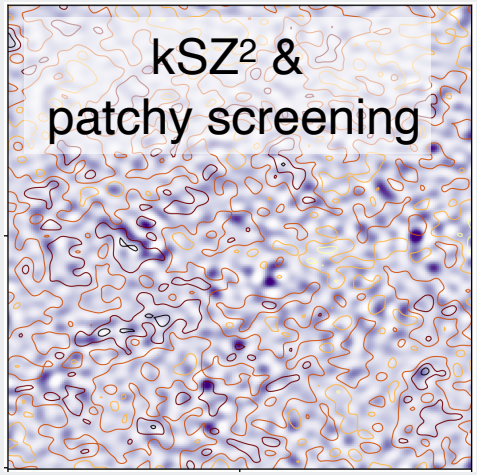

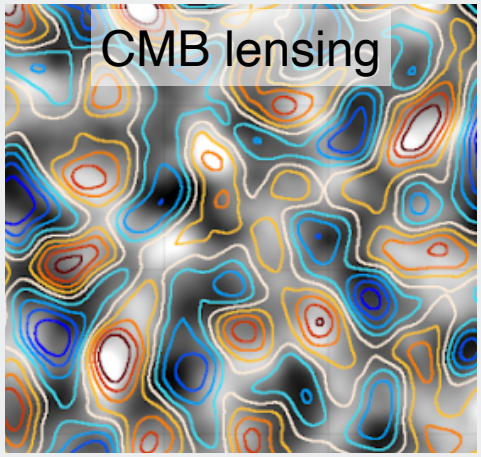

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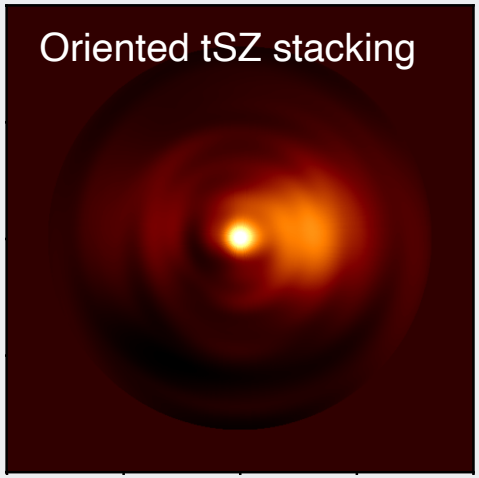

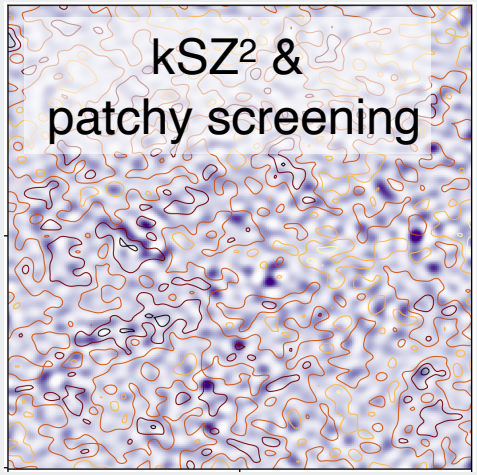

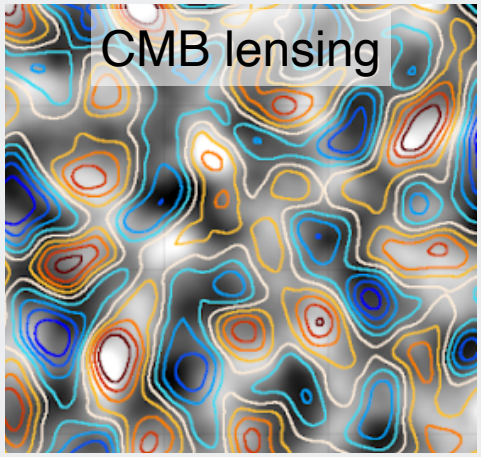

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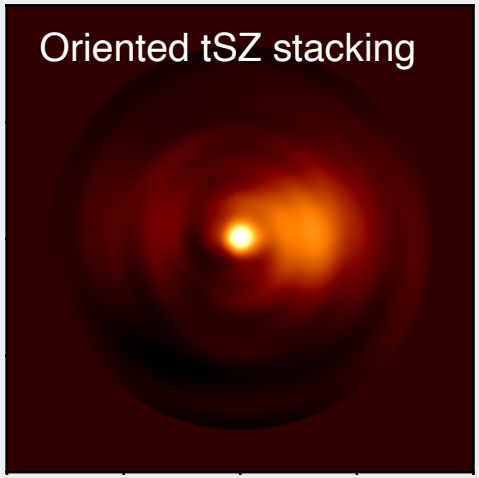
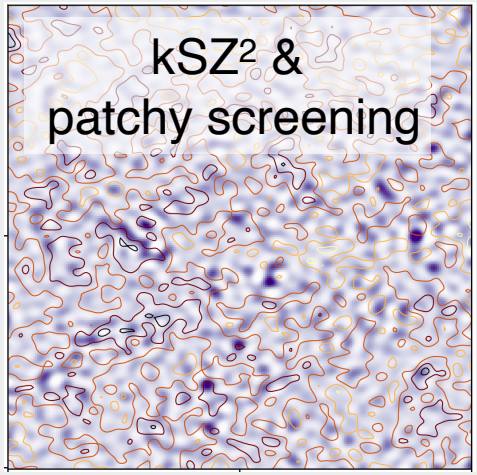
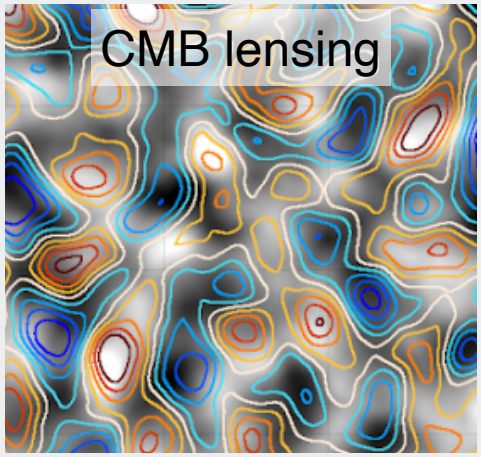
   - Cross correlations between optical and CMB lensing (Shaikh, Harrison++)





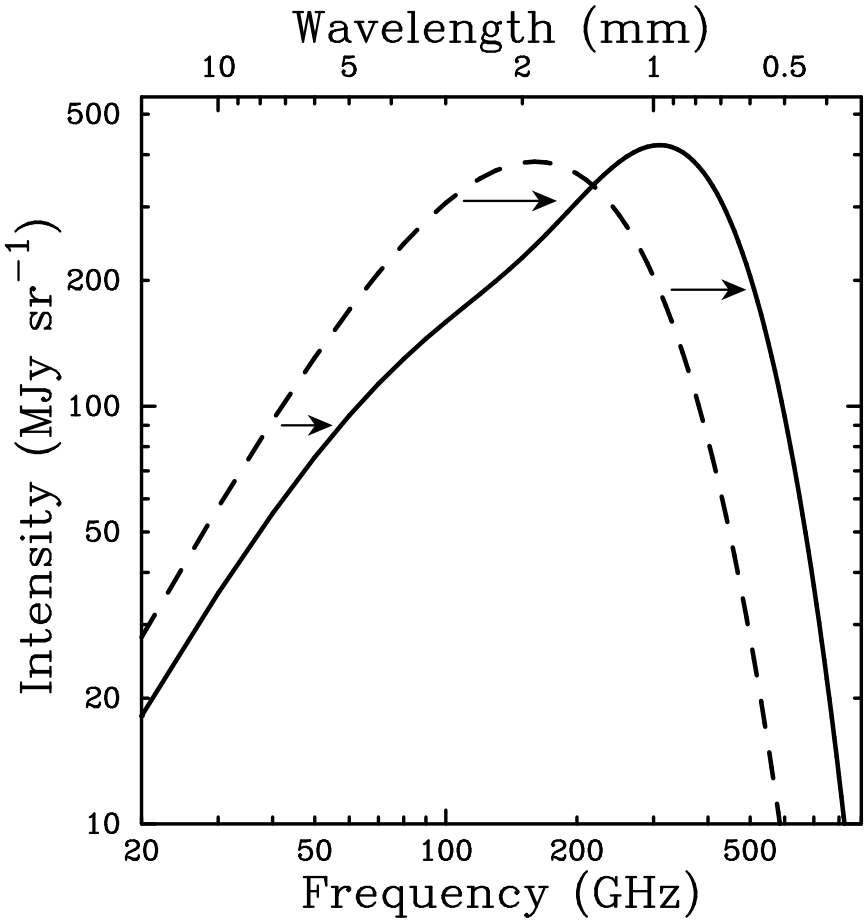


Summary

Secondary CMB anisotropies

Extra slides

SZ effects



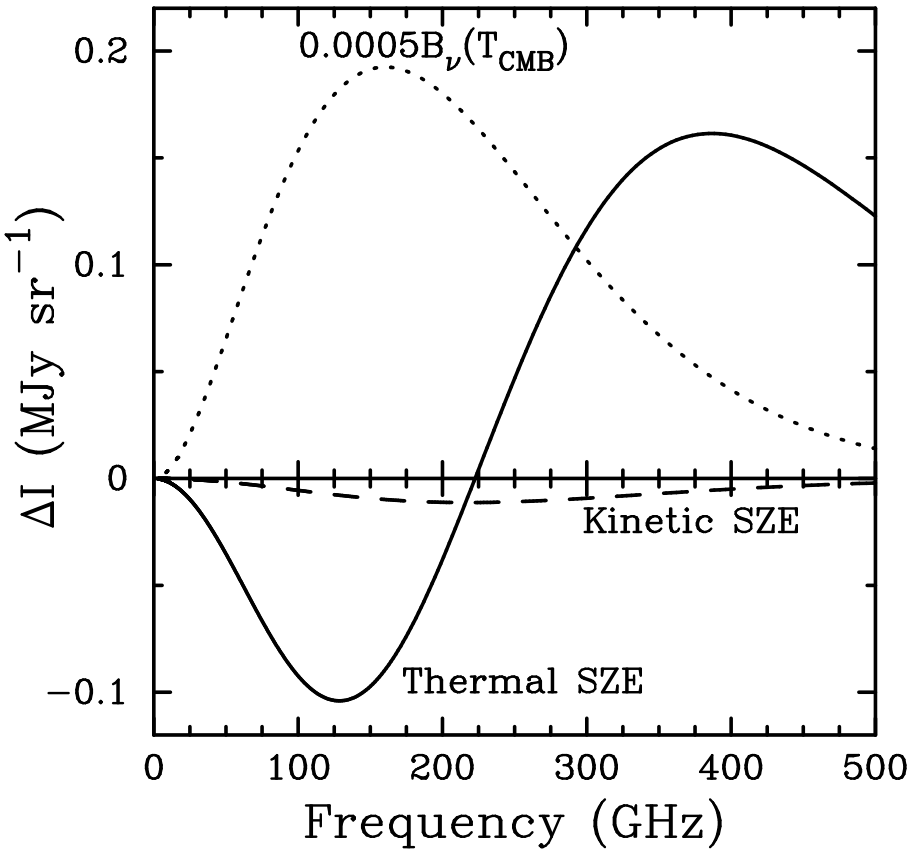
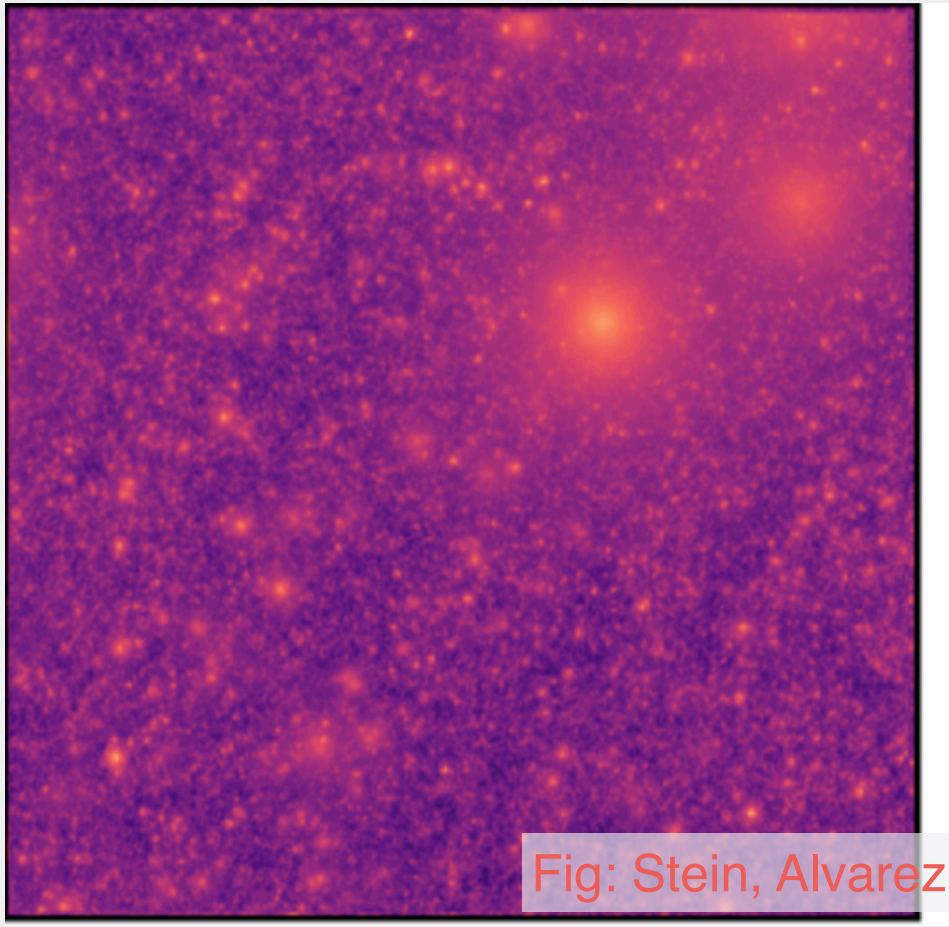


Fig: Carlstrom++ review article 2002

Thermal SZ

Kinetic SZ



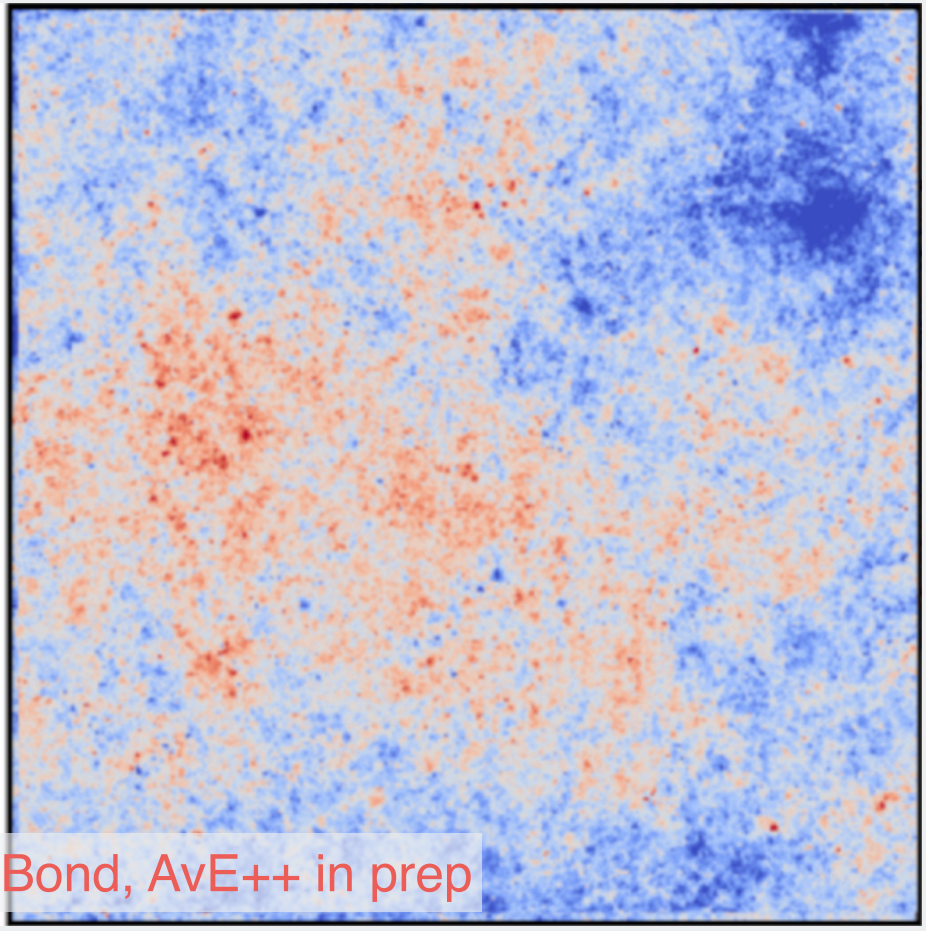


Fig: Stein, Alvarez, Bond, AvE++ in prep

$$y = \int \mathrm{d}\chi a \sigma_T \left(n_e \frac{k_B T_e}{m_e c^2} \right)$$

electron pressure
(= density x temperature)

$$\Theta_{\mathrm{kSZ}} = \int \mathrm{d}\chi a \sigma_T \left(n_e \right) \left(\frac{\mathbf{v}}{c} \cdot \mathbf{n} \right)$$

electron density x l.o.s. velocity

Kinetic SZ

$$\frac{\Delta T}{T} = \frac{v_{\rm los}}{c}\tau_{\rm e} \quad \text{where} \quad \tau_{\rm e} \equiv \int d\chi a \sigma_T n_e$$

Cosmology from velocities - large scales

- Growth rate, neutrino mass
- Remote dipoles
- Modified gravity
- Primordial non-Gaussianity from scale-dependent halo bias

Astrophysics from electron gas distributions - small scales

- AGN feedback/energetics
- Baryon cycle

But we always measure the *product*
Must assume one to get the other

Kinetic SZ

- 100-1000σ measurements coming!
- Most detection methods are from $\langle v_{long} g_{short} T_{short} \rangle$ bispectrum Smith+2019

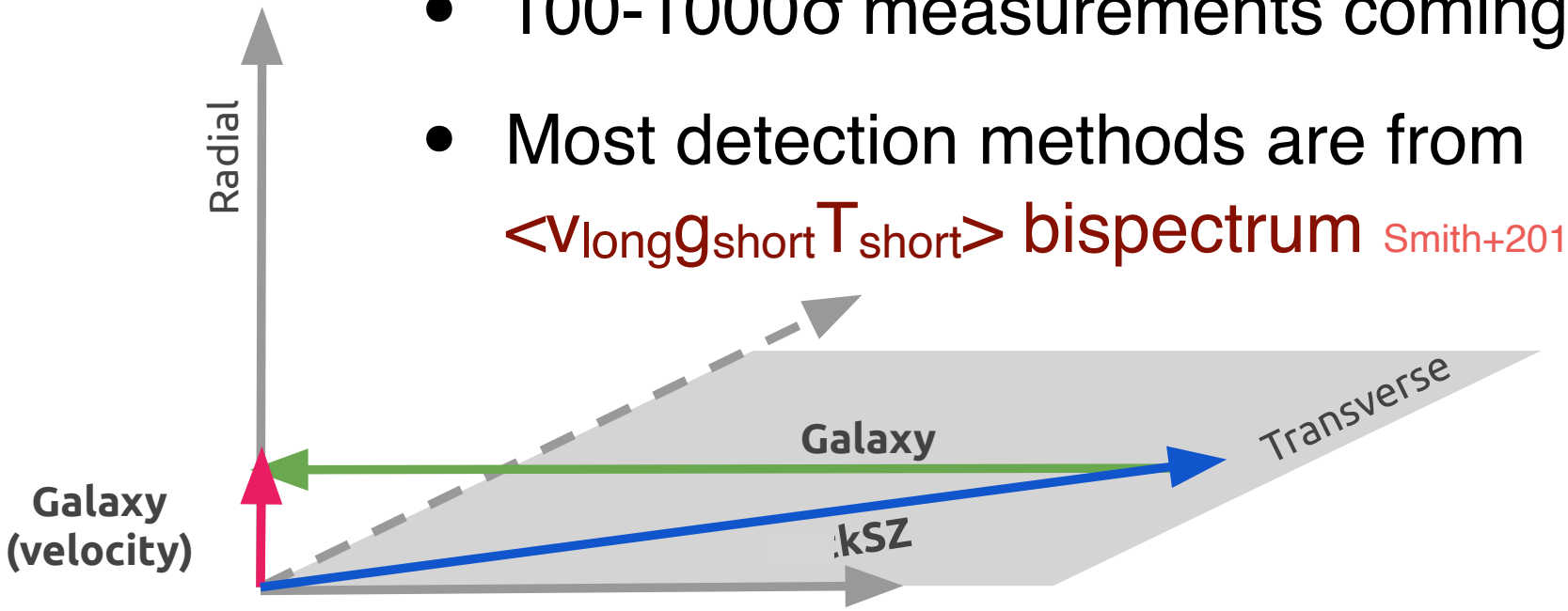


Fig: Mat Madhavacheril

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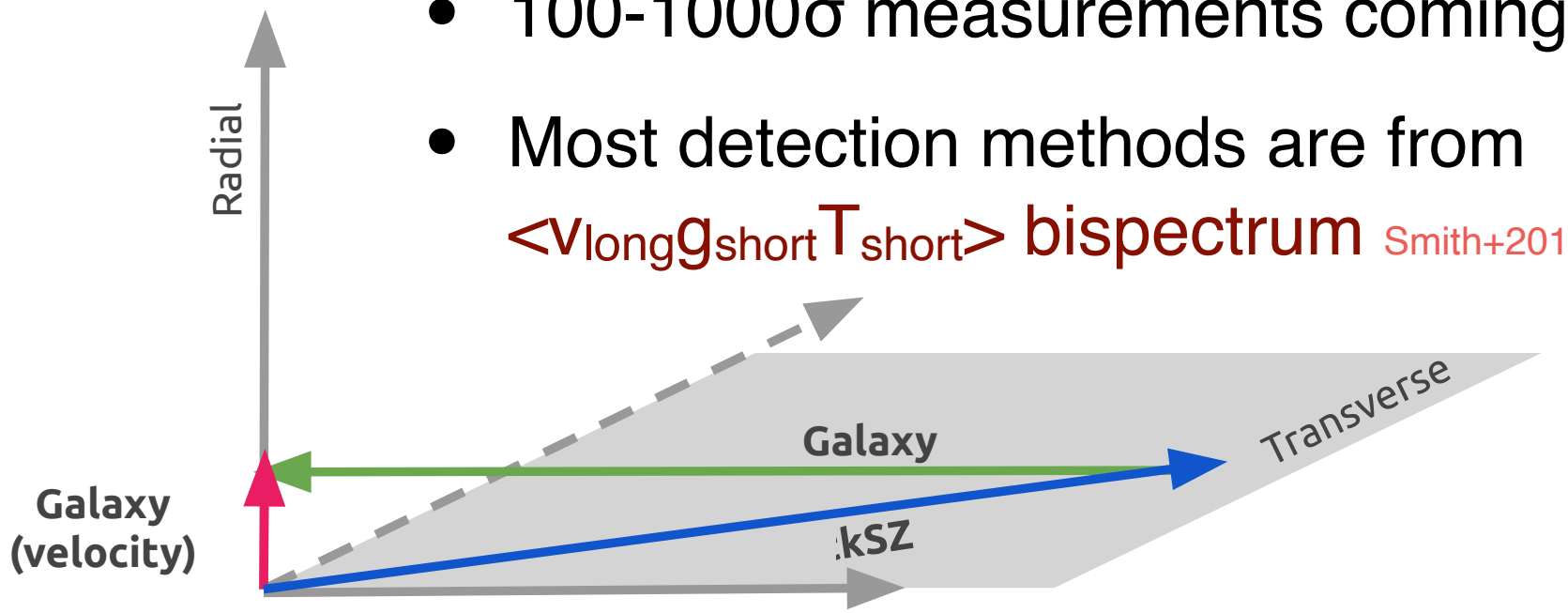


Fig: Mat Madhavacheril

E.g. velocity-weighted stack of T_{CMB} on galaxies:

$$\langle v_{long}\, g_{short}\, T_{short} \rangle$$

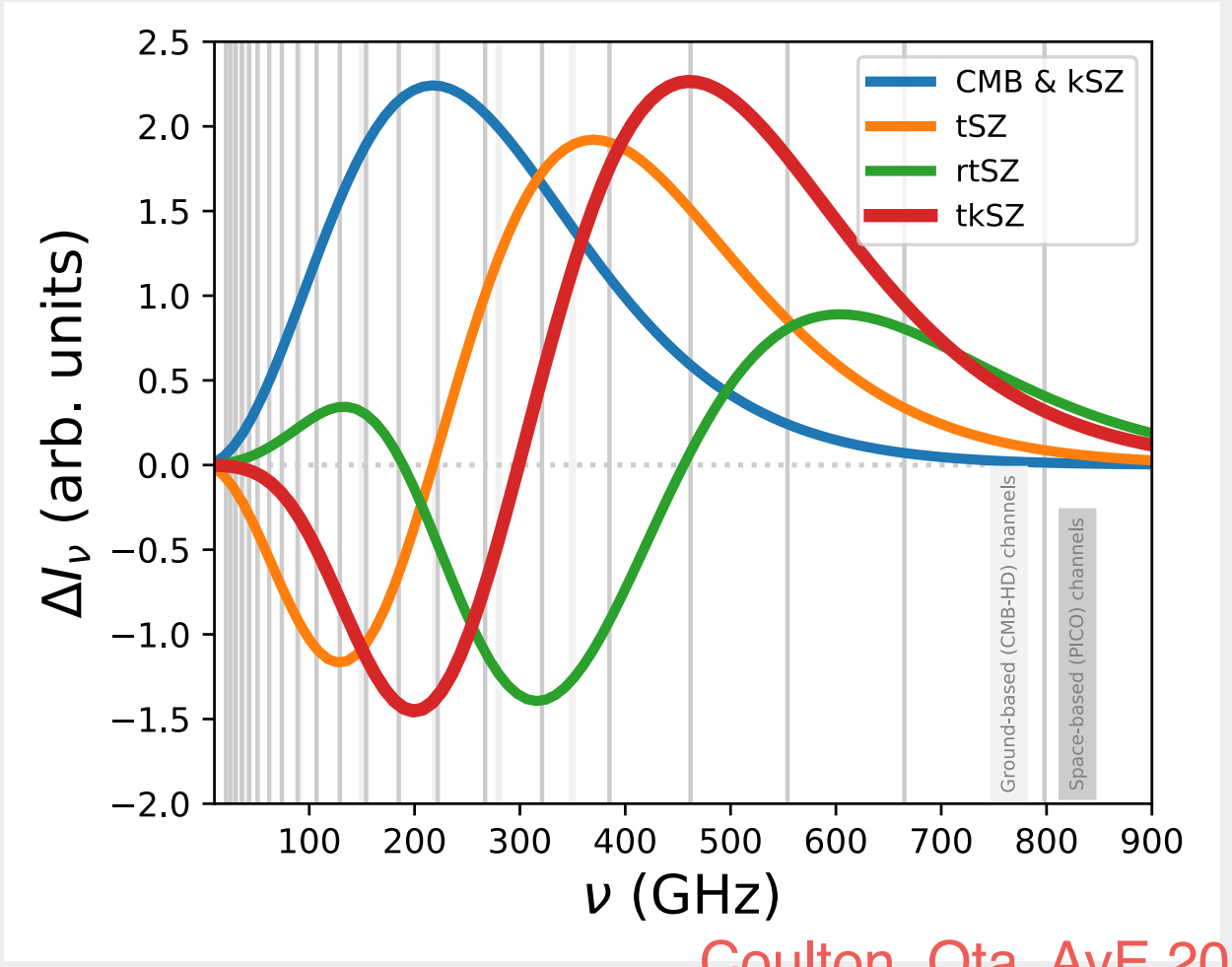
And since $T_{kSZ} = v_{long}/c * \tau_{short}$:

$$\langle v_{long}\, g_{short}\, T_{short} \rangle \sim \underbrace{\langle v_{long} g_{long} \rangle}_{\text{Astrophysics}} \underbrace{\langle g_{short} \tau_{short} \rangle}_{\text{Cosmology}}$$

Compton scattering - higher order

$$\delta f = \int \mathrm{d}\chi n_\mathrm{e} \sigma_\mathrm{T} a e^{-\tau} S,$$

$$S = \theta_\mathrm{e}\mathcal{Y}^{(2)} + \theta_\mathrm{e}^2\left(-\frac{3}{10}\mathcal{Y}^{(2)} - \frac{21}{10}\mathcal{Y}^{(3)} + \frac{7}{10}\mathcal{Y}^{(4)}\right) + \boldsymbol{v}\cdot\mathbf{n}\mathcal{G} + \theta_\mathrm{e}\boldsymbol{v}\cdot\mathbf{n}\left(\frac{2}{5}\mathcal{G} - \mathcal{Y}^{(2)} + \frac{7}{5}\mathcal{Y}^{(3)}\right)$$



Coulton, Ota, AvE 2019

SZ effects

tSZ

$$y = \int \mathrm{d}\chi a \sigma_T \left(n_e \frac{k_B T_e}{m_e c^2} \right)$$

pressure (= density * temperature)

kSZ

$$\Theta_{\mathrm{kSZ}} = \int \mathrm{d}\chi a \sigma_T \left(n_e \right) \left(\frac{\mathbf{v}}{c} \cdot \mathbf{n} \right)$$

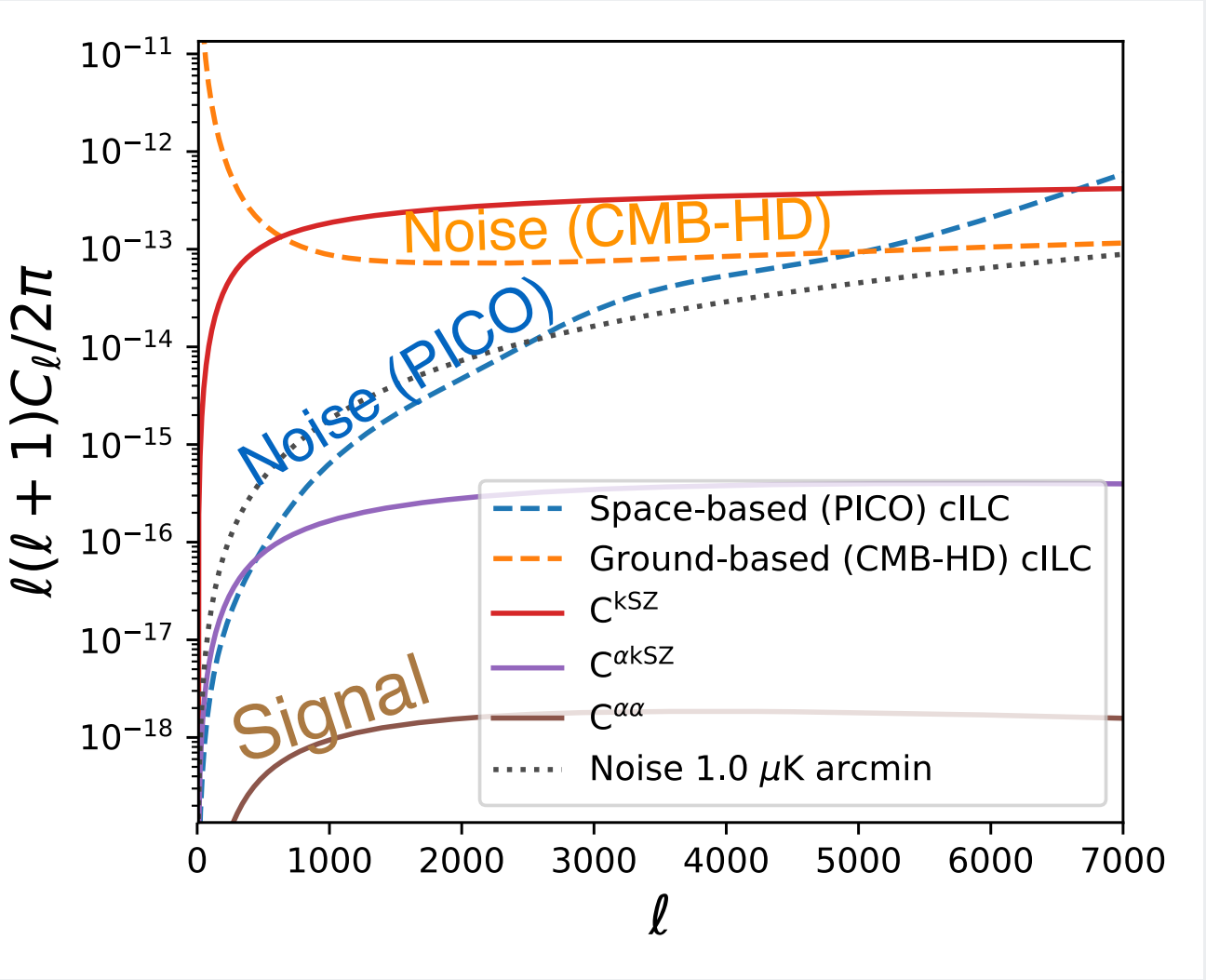
density * l.o.s. velocity

tkSZ

$$\alpha = \int \mathrm{d}\chi a \sigma_T \left(n_e \frac{k_B T_e}{m_e c^2} \right) \left(\frac{\mathbf{v}}{c} \cdot \mathbf{n} \right)$$

pressure * l.o.s. velocity

tkSZ power spectrum and noise

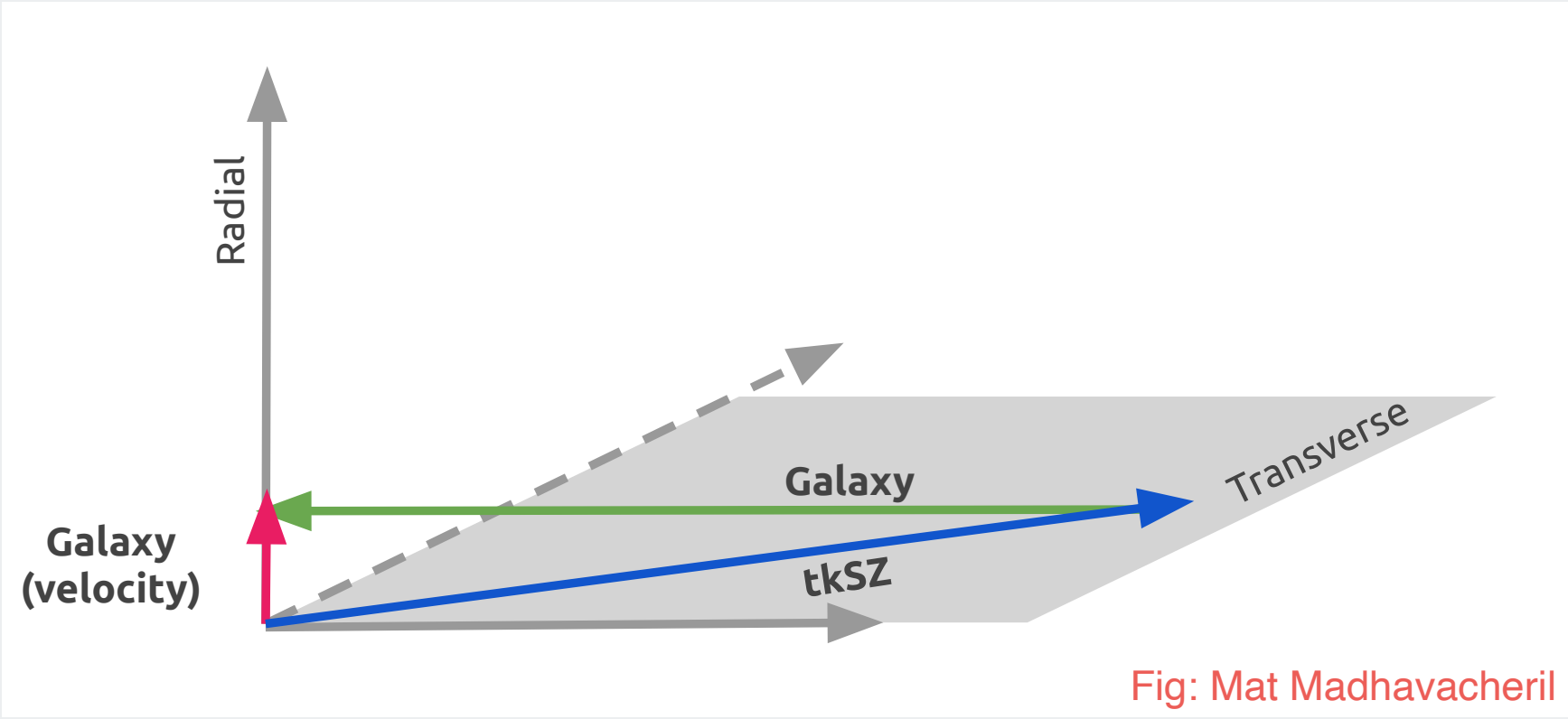


- tkSZ has a unique spectral signature - can be isolated

Component	Spectral dependence	Spatial dependence
CMB +kSZ	$\propto \nu^3 \mathcal{G}$	$C_\ell^{\Theta\Theta}$
tSZ	$\propto \nu^3 \mathcal{Y}$	C_ℓ^{yy}
CIB	$\propto \nu^{\beta_{\rm CIB}} B_\nu(T_{\rm CIB})$	$A_p^{\rm CIB} + A_c(\ell/\ell_c)^{\alpha_{\rm CIB}}$
Radio	$\propto \nu^{\beta_{\rm Radio}}$	$A_{\rm Radio}(\ell/\ell_c)^{\alpha_{\rm Radio}}$
Galactic Dust	$\propto \nu^{\beta_{\rm Dust}} B_\nu(T_{\rm Dust})$	$A_{\rm Dust}(\ell/\ell_c)^{\alpha_{\rm Dust}}$

Coulton, Ota, AvE 2019

tkSZ-galaxy-galaxy bispectrum



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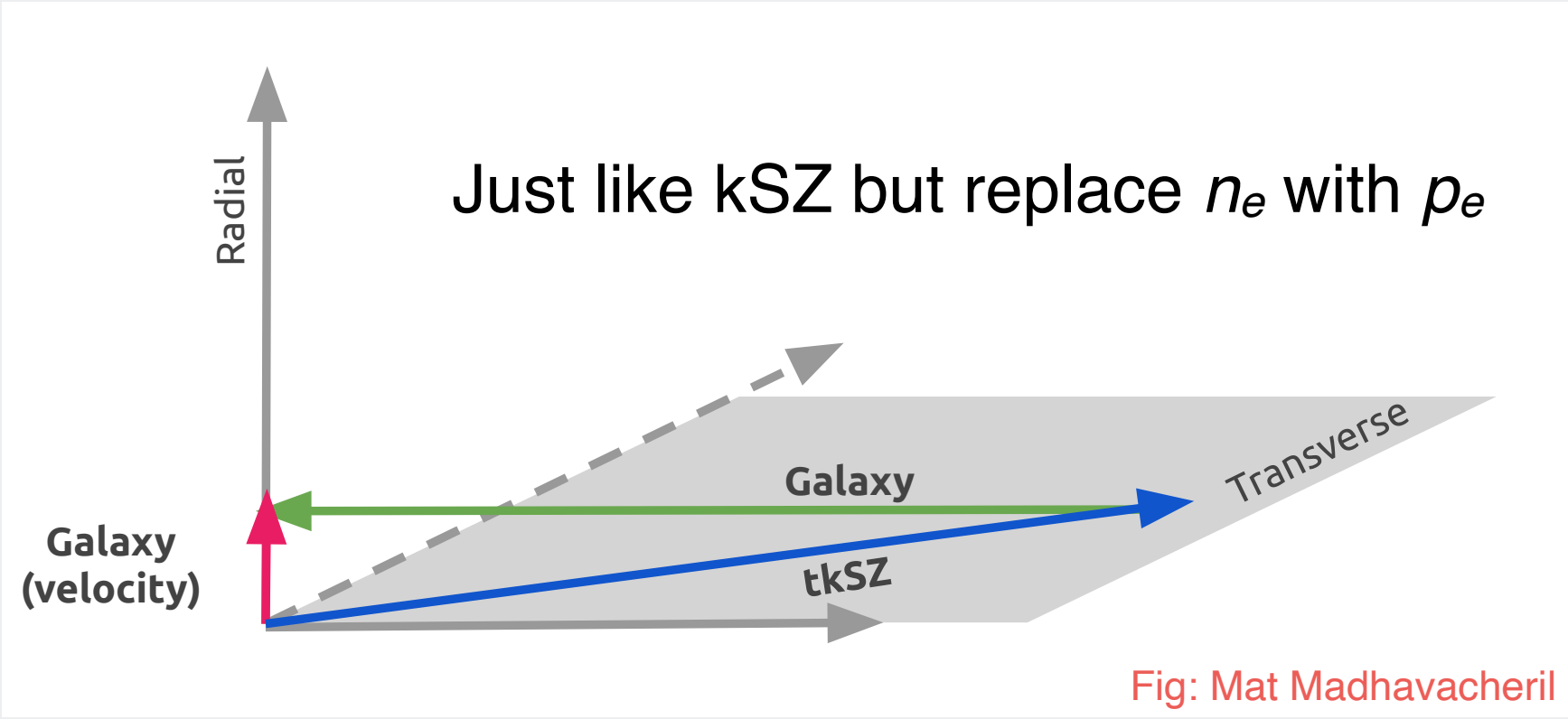

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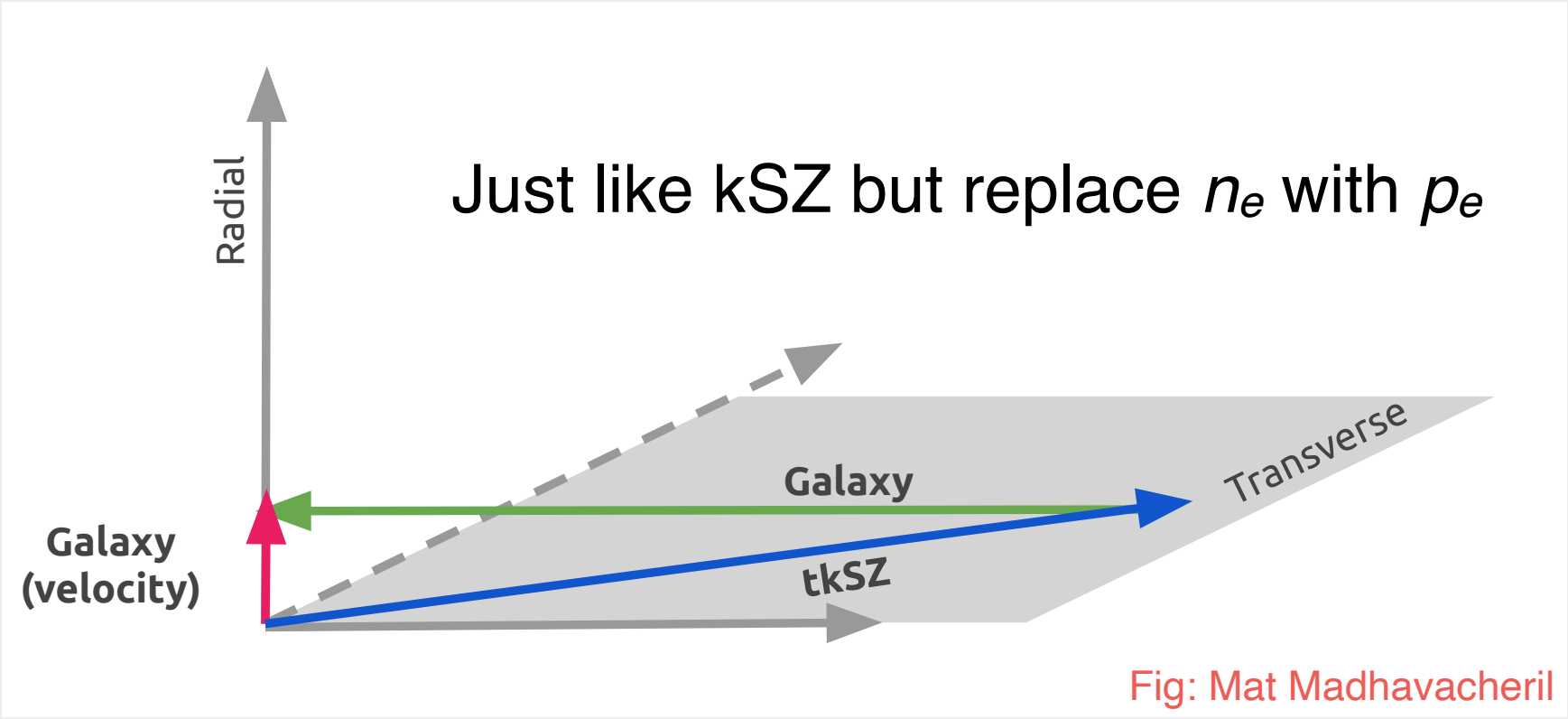

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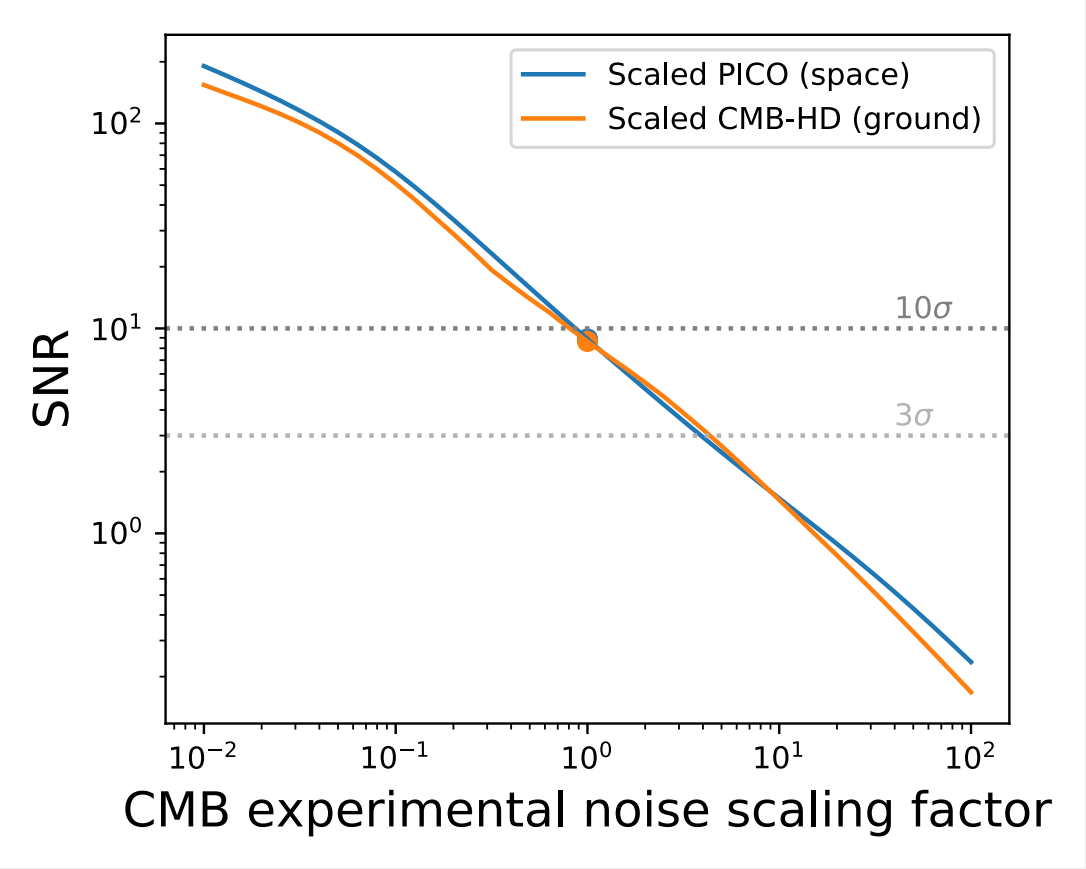

Coulton, Ota, AvE 2019

Together with DESI:

- 2σ with CMB-S4 + CCAT-p
- 8σ with PICO
- 8σ with CMB-HD

No bias from tSZ/CIB

tkSZ-galaxy-galaxy bispectrum

- Fundamental cosmology with tkSZ?
  Signal is weaker than kSZ, but:

tkSZ-galaxy-galaxy bispectrum

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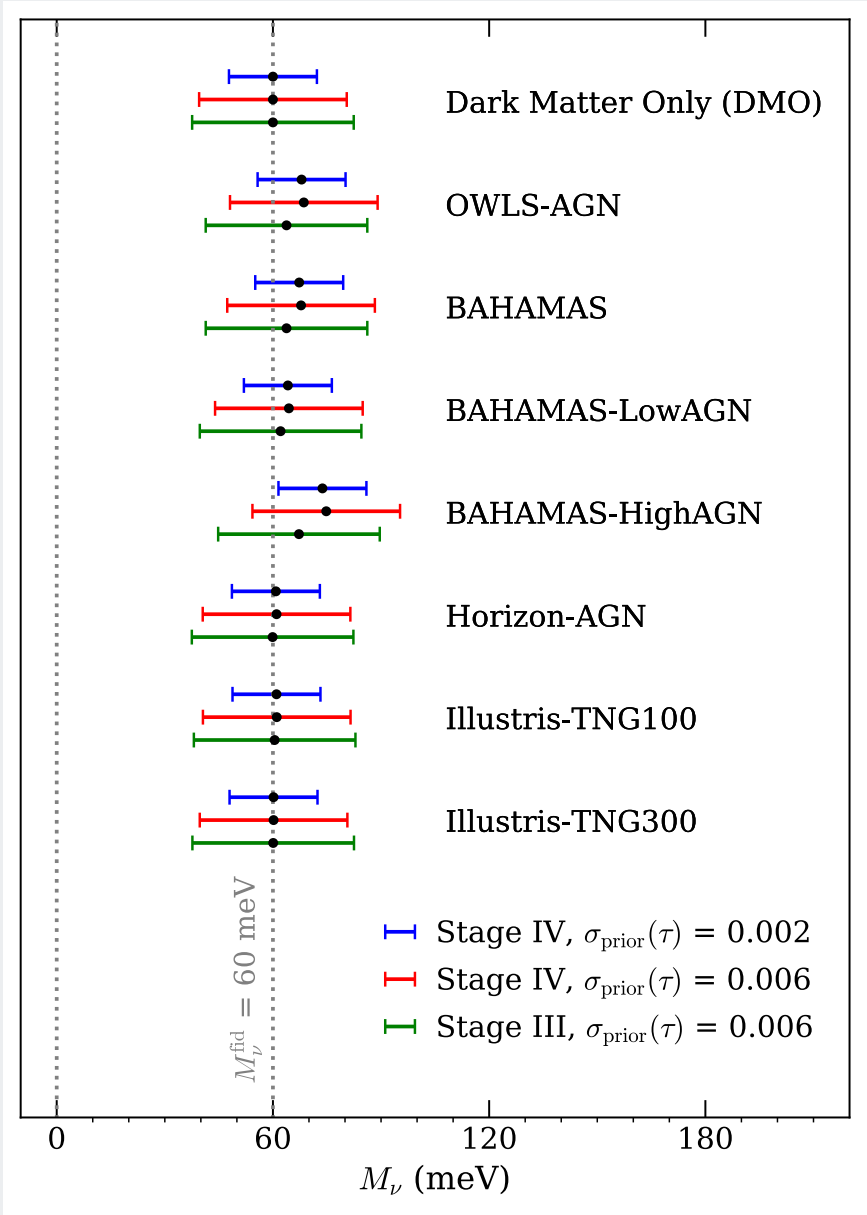
tkSZ-galaxy-galaxy bispectrum

- Fundamental cosmology with tkSZ?
  Signal is weaker than kSZ, but:

  - No degeneracy with (g)astrophysics —p_e profiles much better known than n_e profiles
  - Can be isolated - no noise floor e.g. from recombination or reionization
    —Ultimately higher S/N than kSZ in CV limit

Results: Biases on M_ν

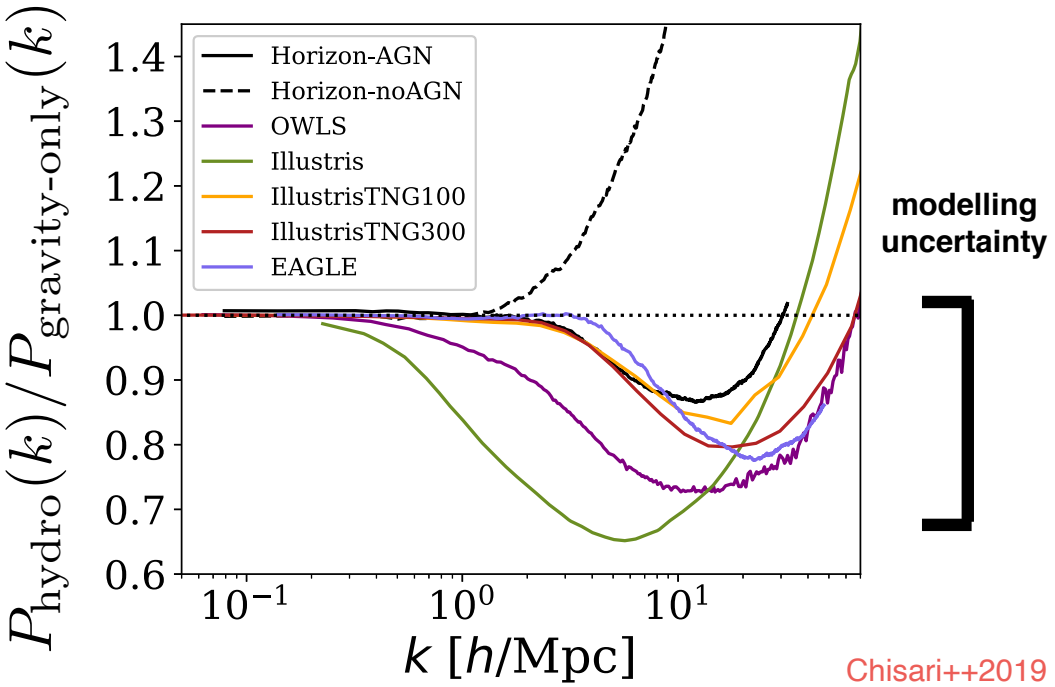
- We find significant dispersion for Stage IV, esp. with CVL tau



Chung, Foreman, AvE 2019

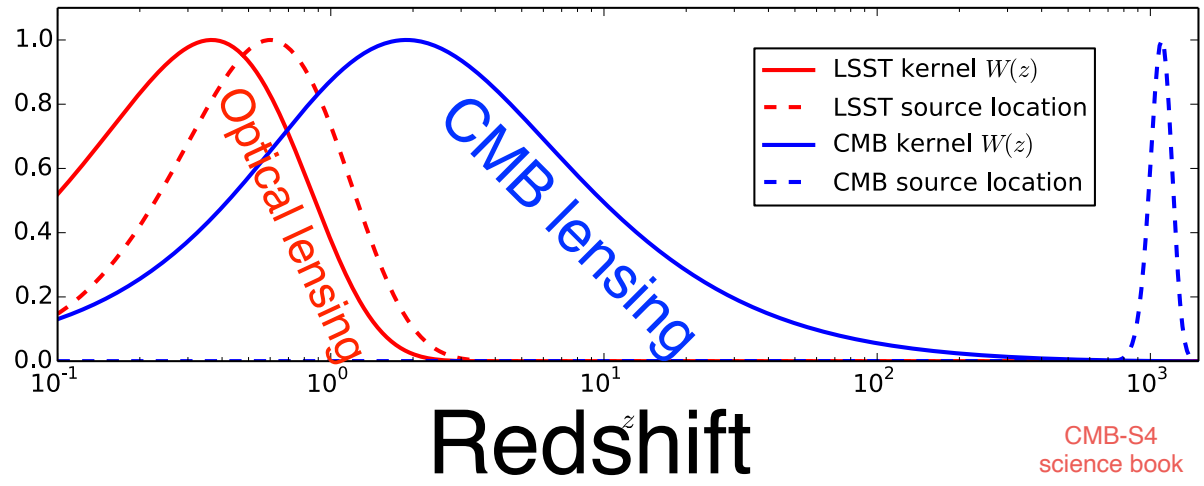
Baryons & CMB lensing

- Baryons (AGN/SN feedback; cooling/star formation) will impact matter power spectrum.
- Different simulations give different results.



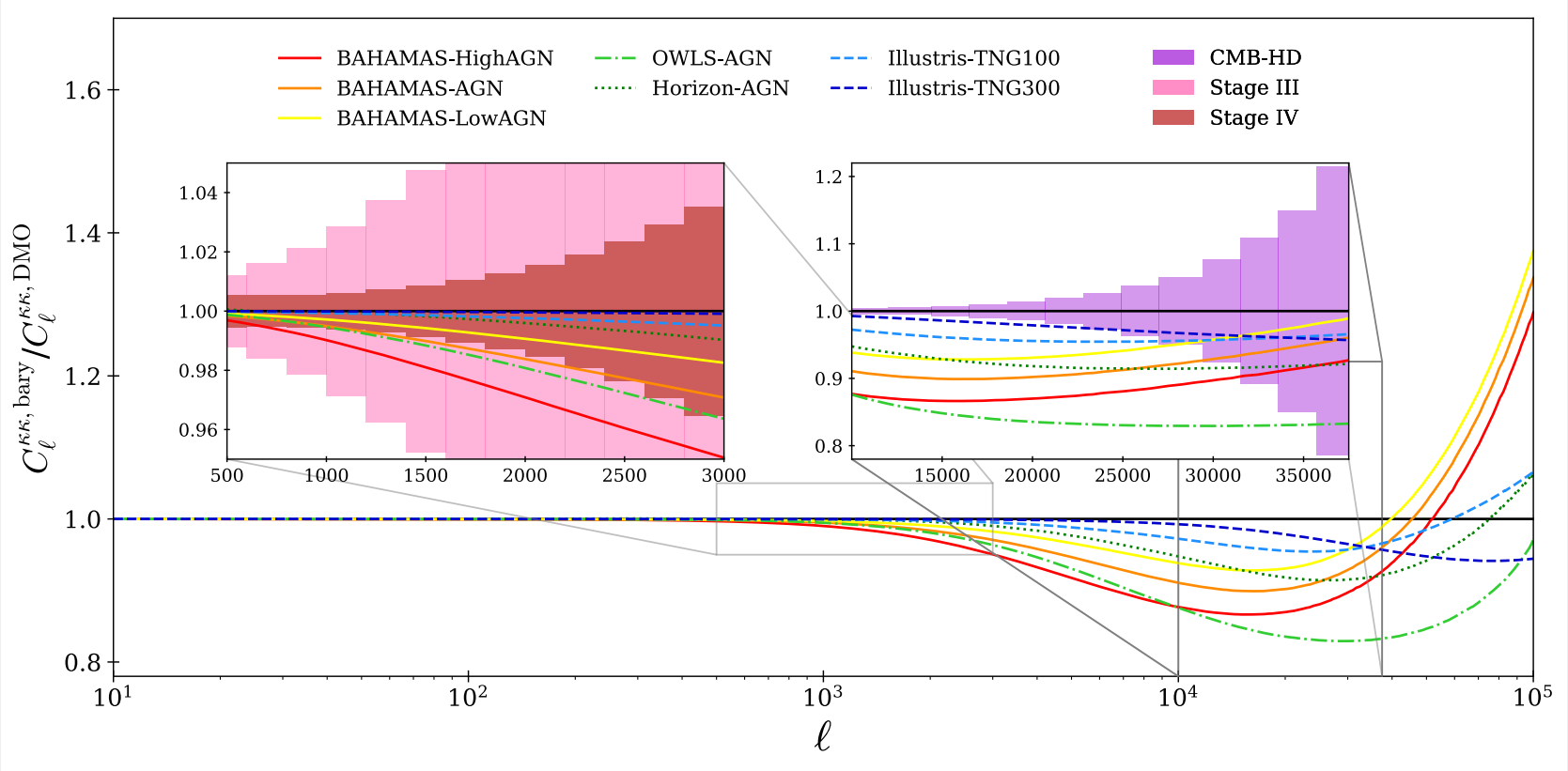
Chisari++2019

- A big issue for cosmic shear at $z < 1$. Impact on CMB lensing at higher z?



CMB-S4 science book

Baryons & CMB lensing



Clara Chung, U Toronto Ugrad

Simon Foreman, Perimeter

Chung, Foreman, AvE 2020

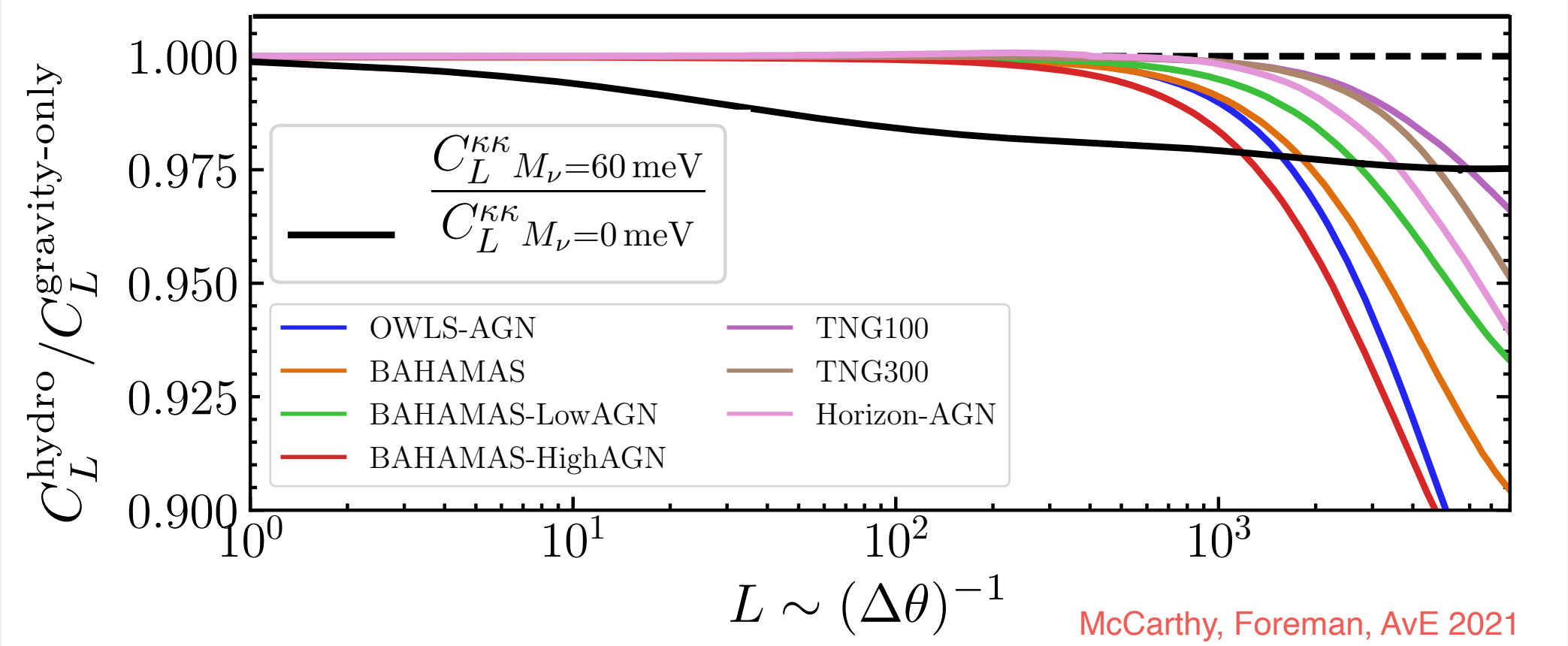
github.com/sjforeman/cmblensing_baryons

Baryons and Neutrino Mass

Higher M_ν → Slower growth of grav. potentials
(due to long neutrino free-streaming length)

↓

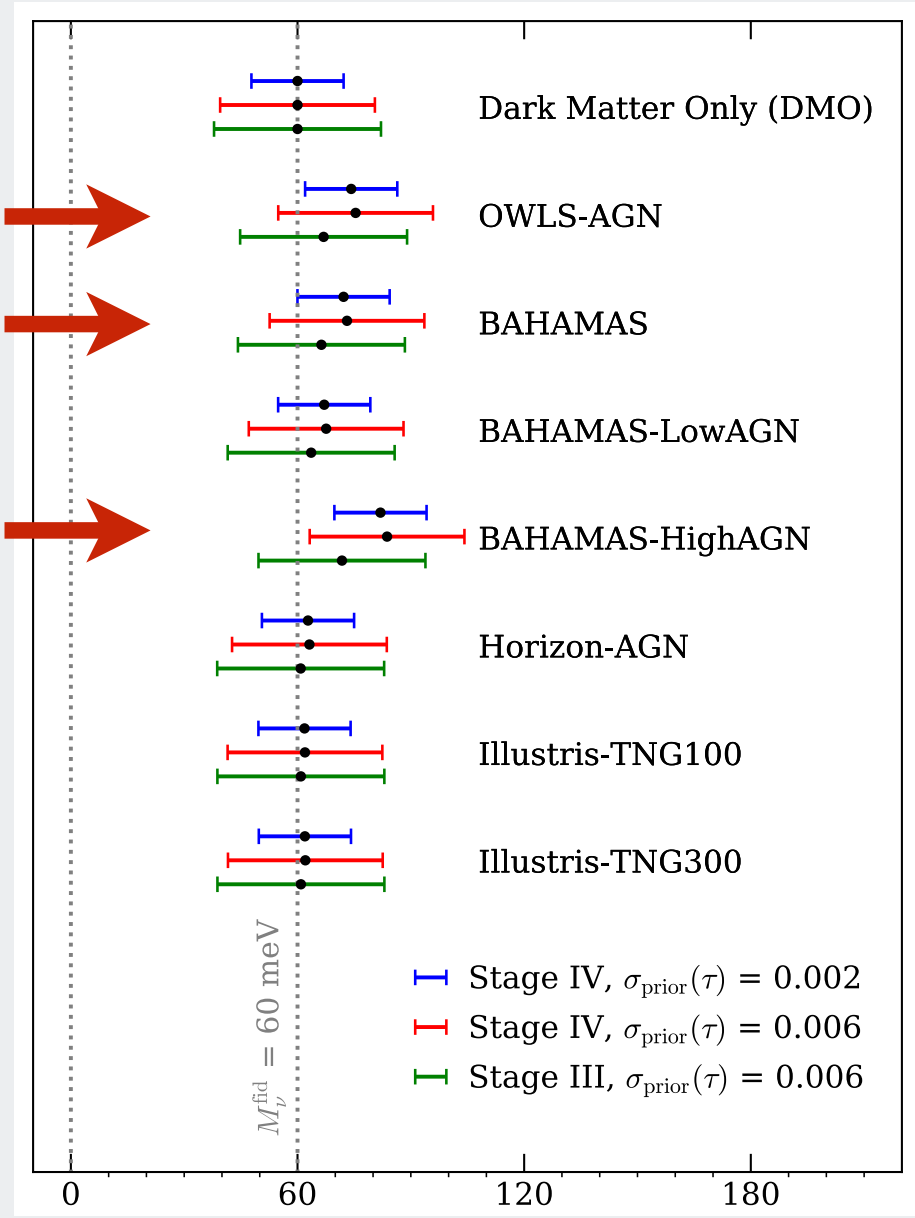
Suppressed lensing signal



McCarthy, Foreman, AvE 2021

Baryons and Neutrino Mass

- Forecasts*
  - Model ignores baryonic effects
  - True baryonic effects given by simulation



- Neutrino mass sum can be biased high by 1-2 σ!

Chung, Foreman, AvE 2020

Baryons and Neutrino Mass: Mitigation

Fiona McCarthy, Perimeter PhD

Simon Foreman, Perimeter

McCarthy, Foreman, AvE 2021

Baryons and Neutrino Mass: Mitigation

- We put forward three mitigation methods:

Fiona McCarthy, Perimeter PhD

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Baryons and Neutrino Mass: Mitigation

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  - 1. Reduce L_{max}

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  - 2. Subtract a low-z lensing survey (LSST) as a 'baryon proxy'

Fiona McCarthy, Perimeter PhD

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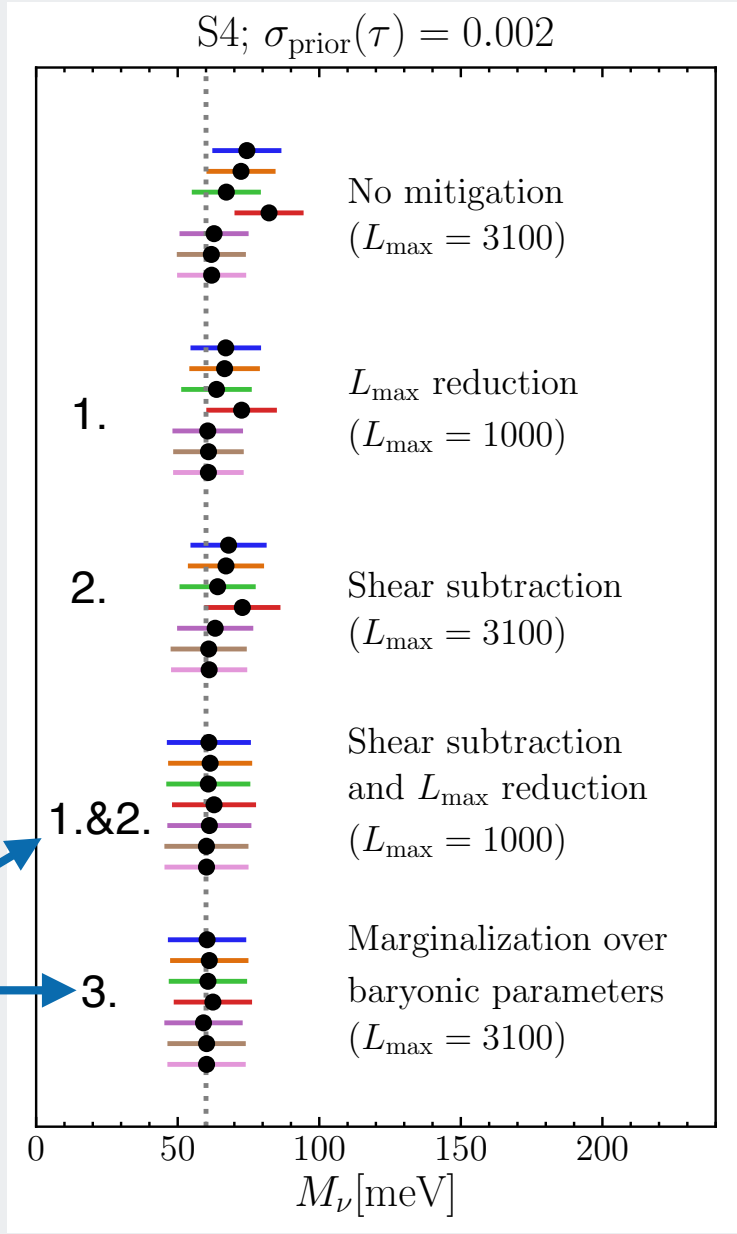
Results: 1.&2. or 3. render biases negligible.



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