THE SMALL-CORRELATED-AGAINST-LARGE-ESTIMATOR FOR COSMIC MICROWAVE BACKGROUND LENSING

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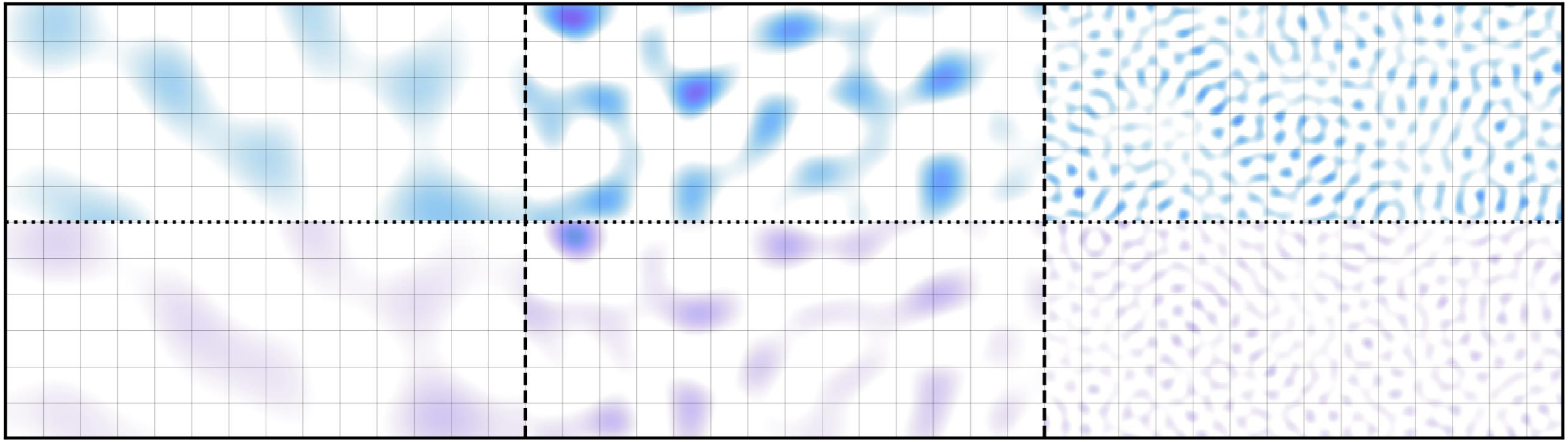
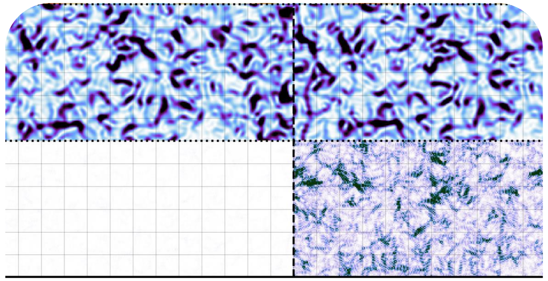
INTERNATIONAL WORKSHOP ON MULTI-PROBE APPROACH TO WAVY DARK MATTER - KOREA UNIVERSITY; 30 NOVEMBER 2023



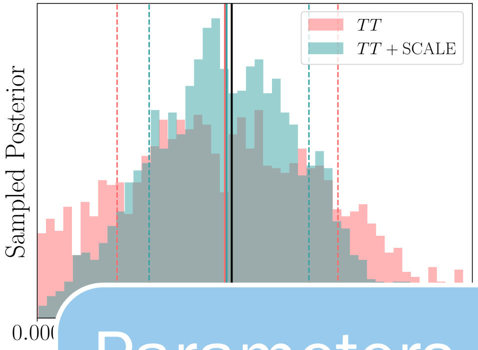
CMB Lensing

- Cosmic history
- Lensing and clustering physics



SCALE

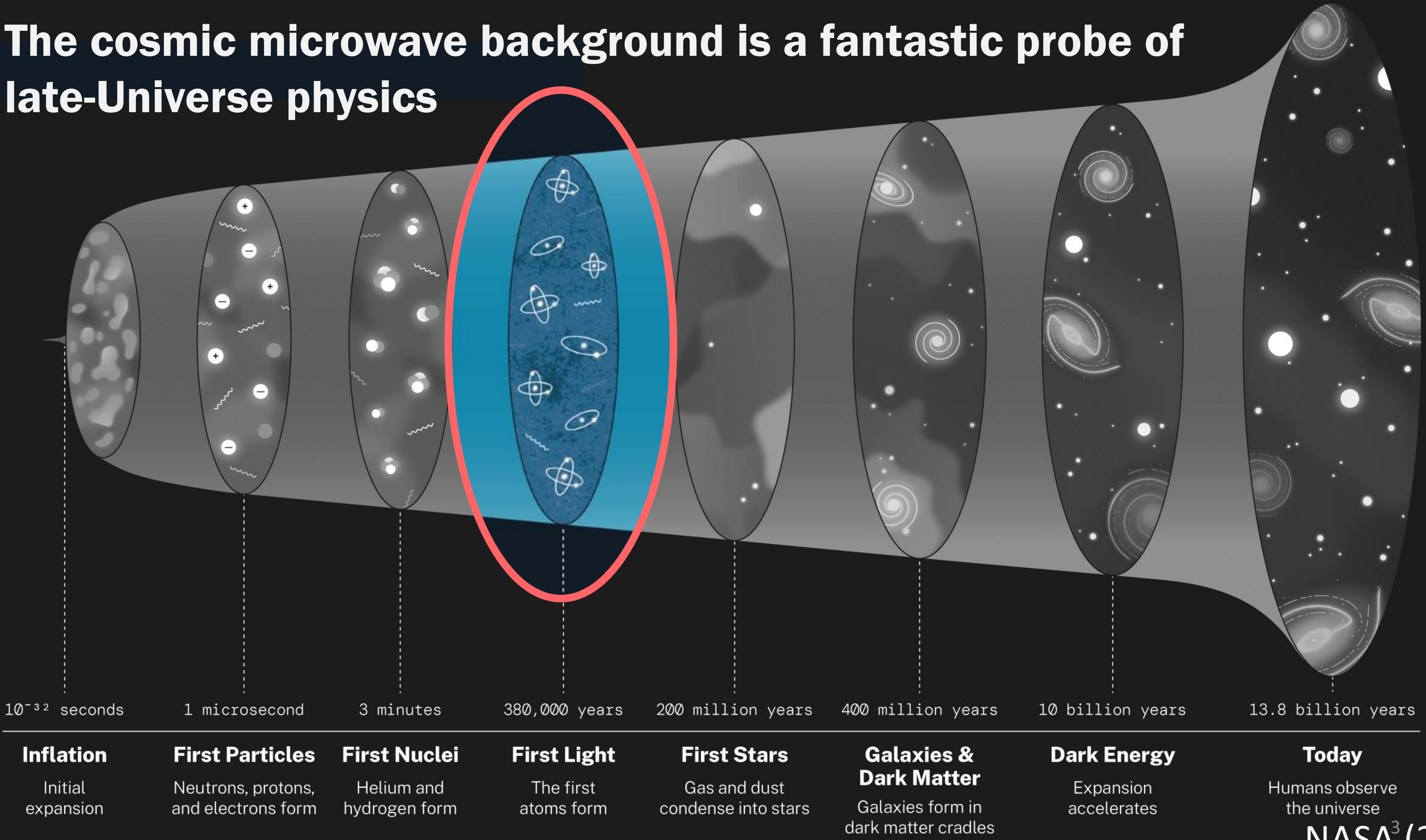
- A new method for quantifying CMB lensing at small scales



Parameters

- Impact of SCALE on cosmological parameter constraints

The cosmic microwave background is a fantastic probe of late-Universe physics



NASA (2019)

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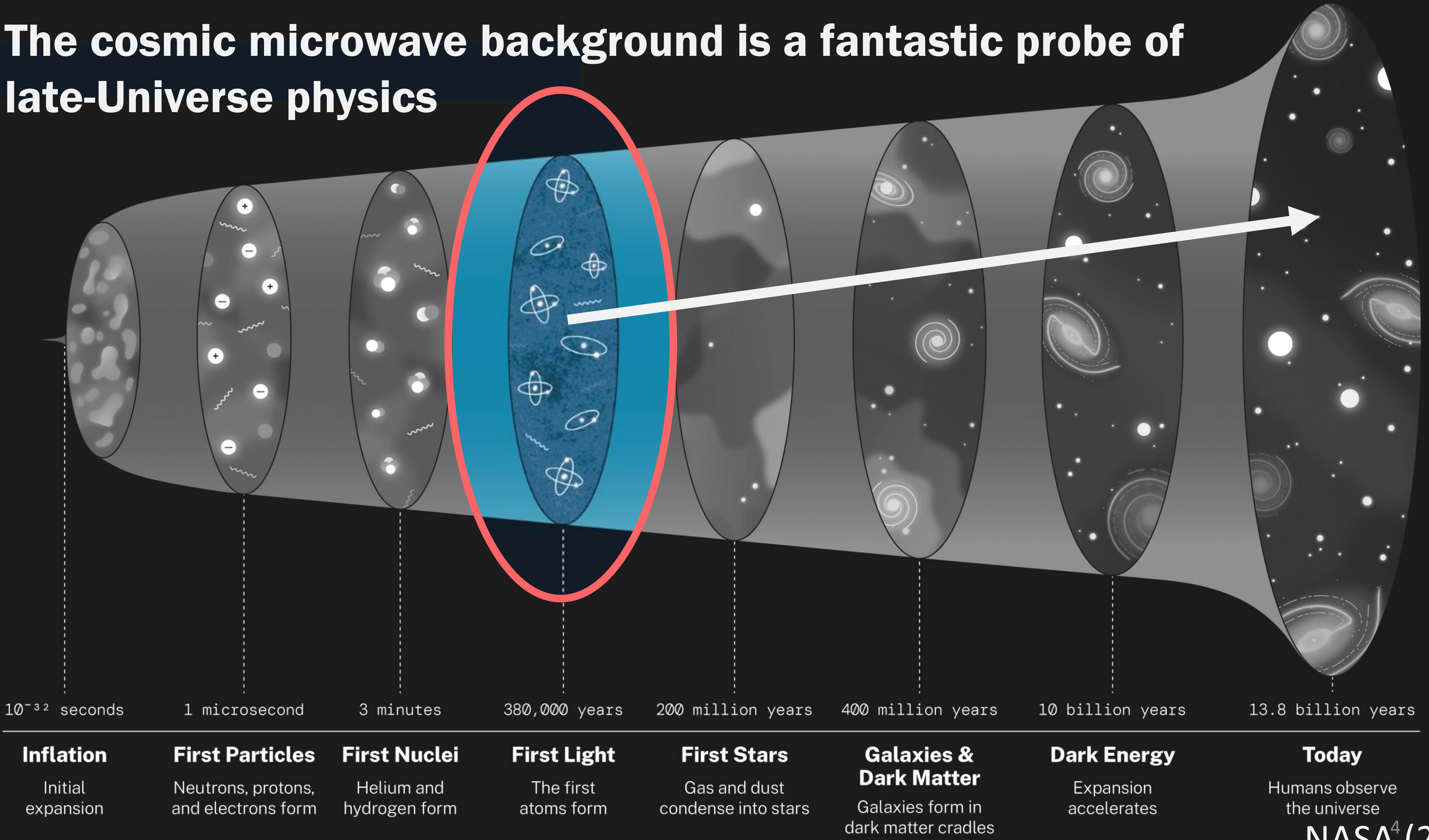

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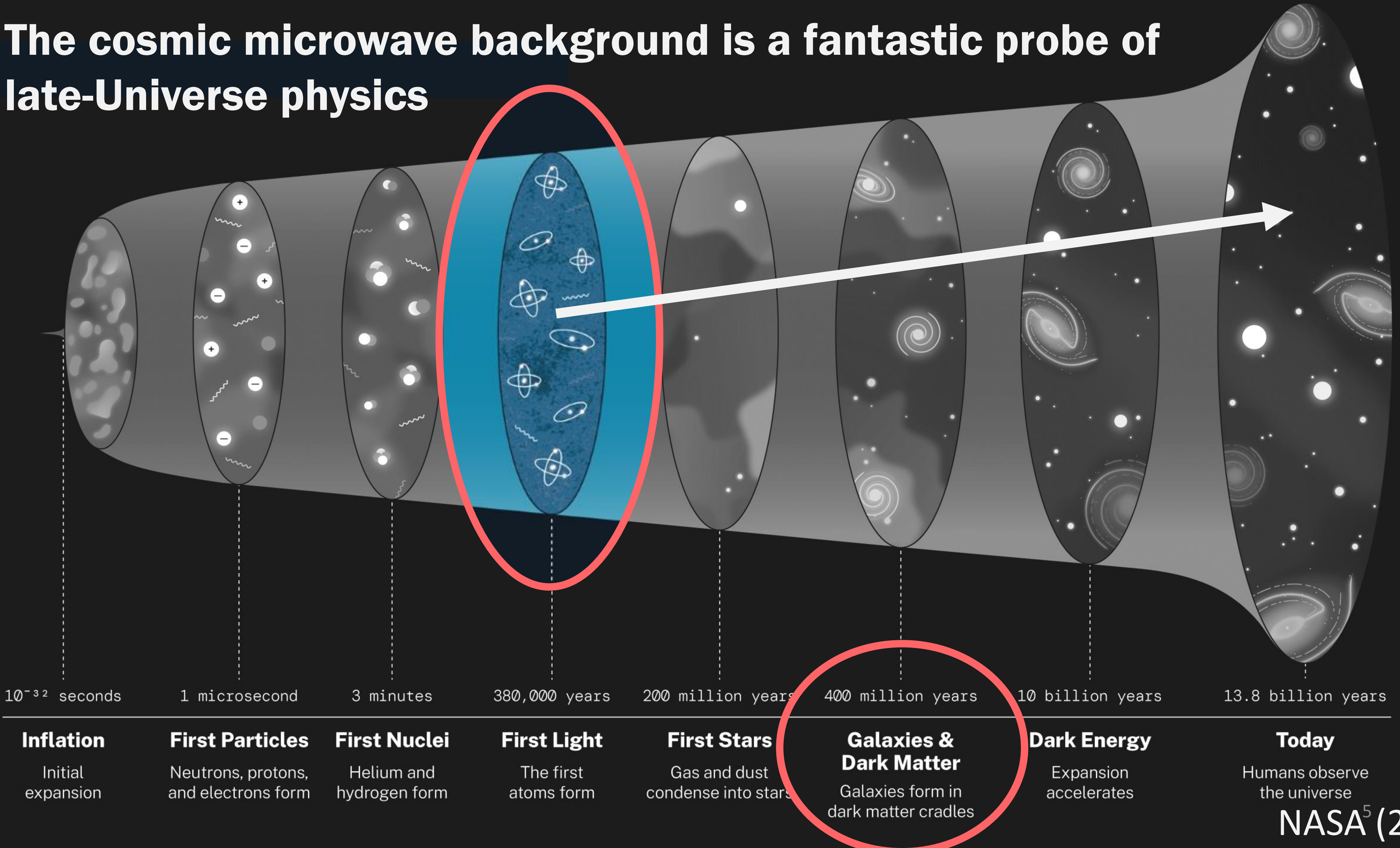
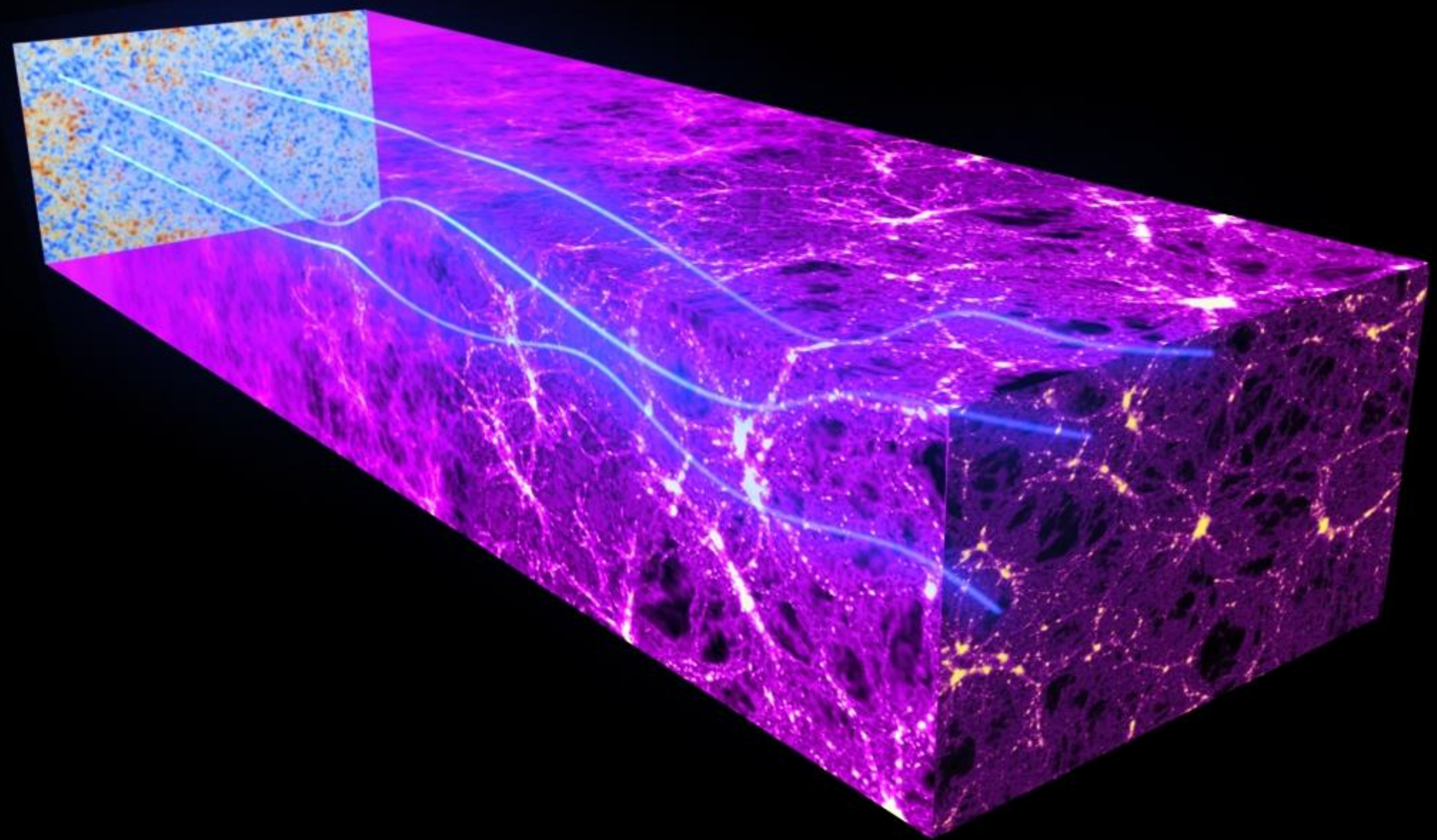


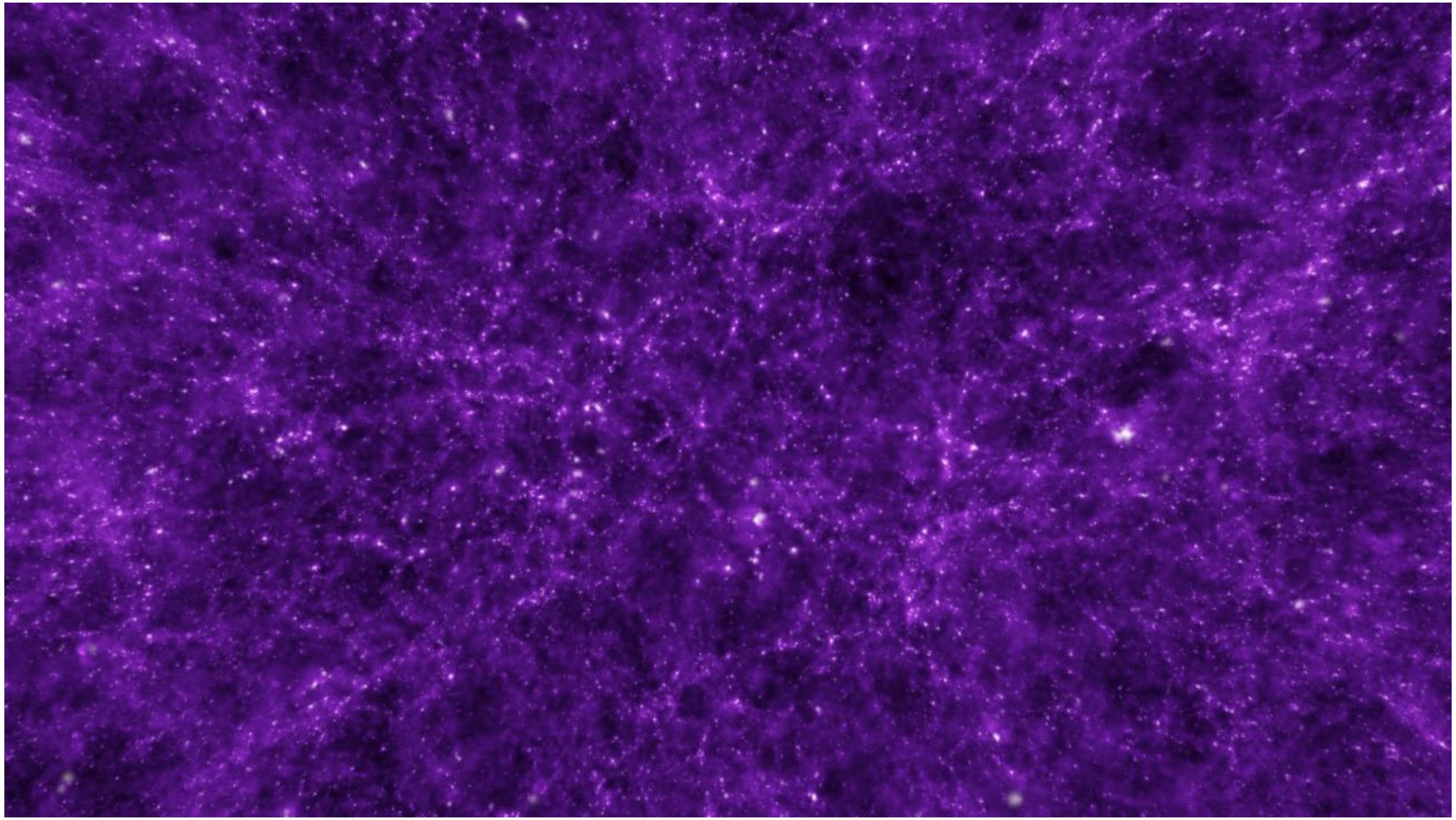
NASA (2019)

Cosmic microwave background photons get gravitationally lensed by massive structures along their trajectories



ESA (2013)

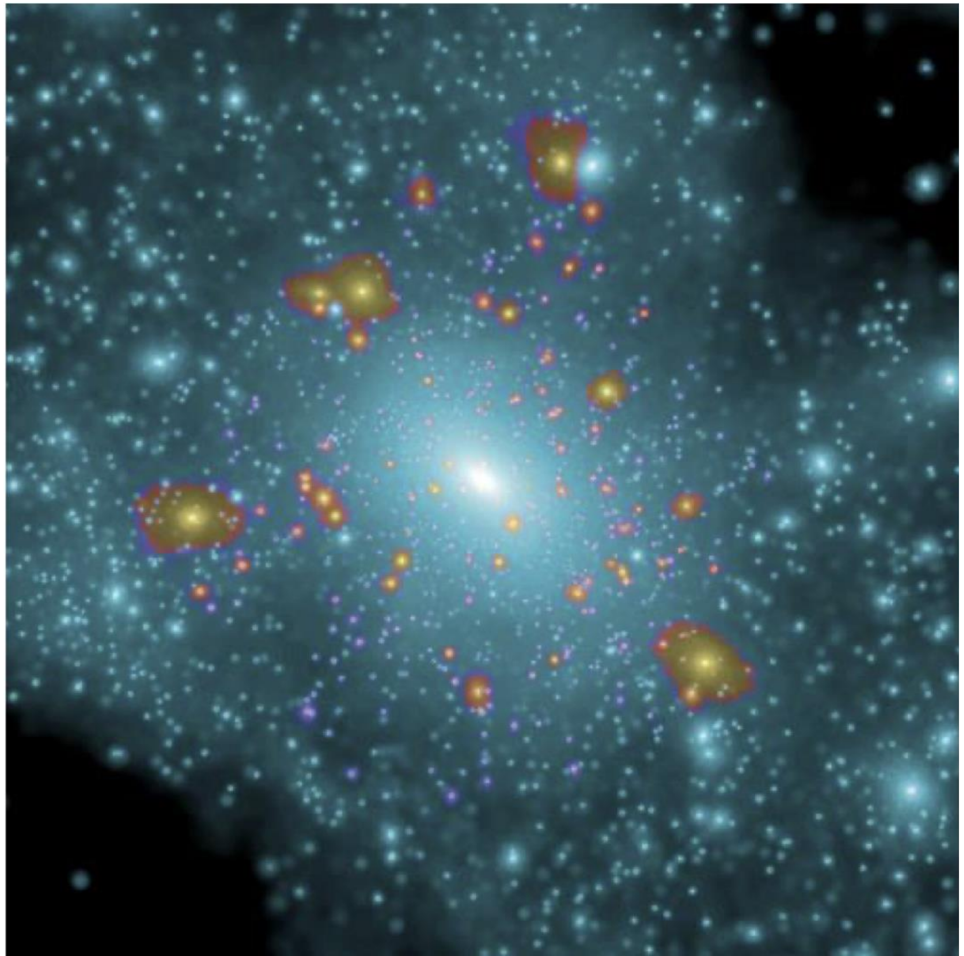
Clusters of galaxies are composed primarily of dark matter



NASA (2007)

Models of dark matter predict different levels of clustering depending on mass, interactions, etc.

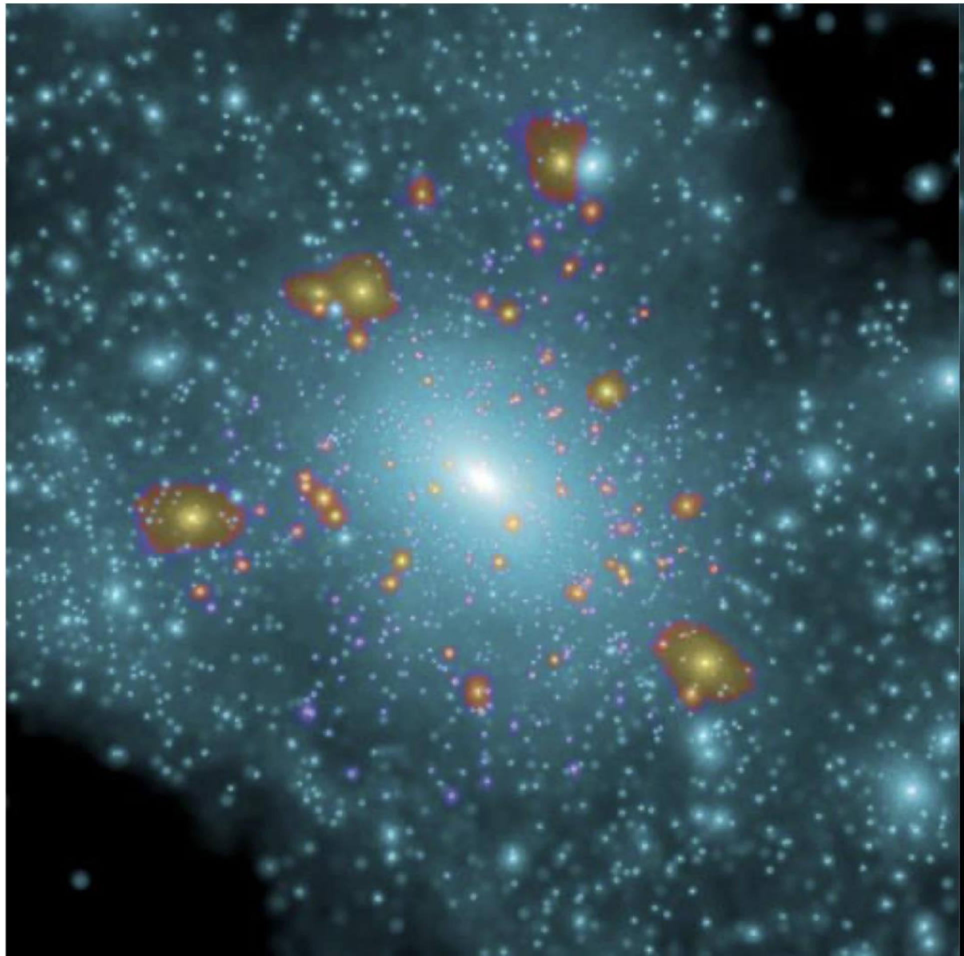
Cold Dark Matter



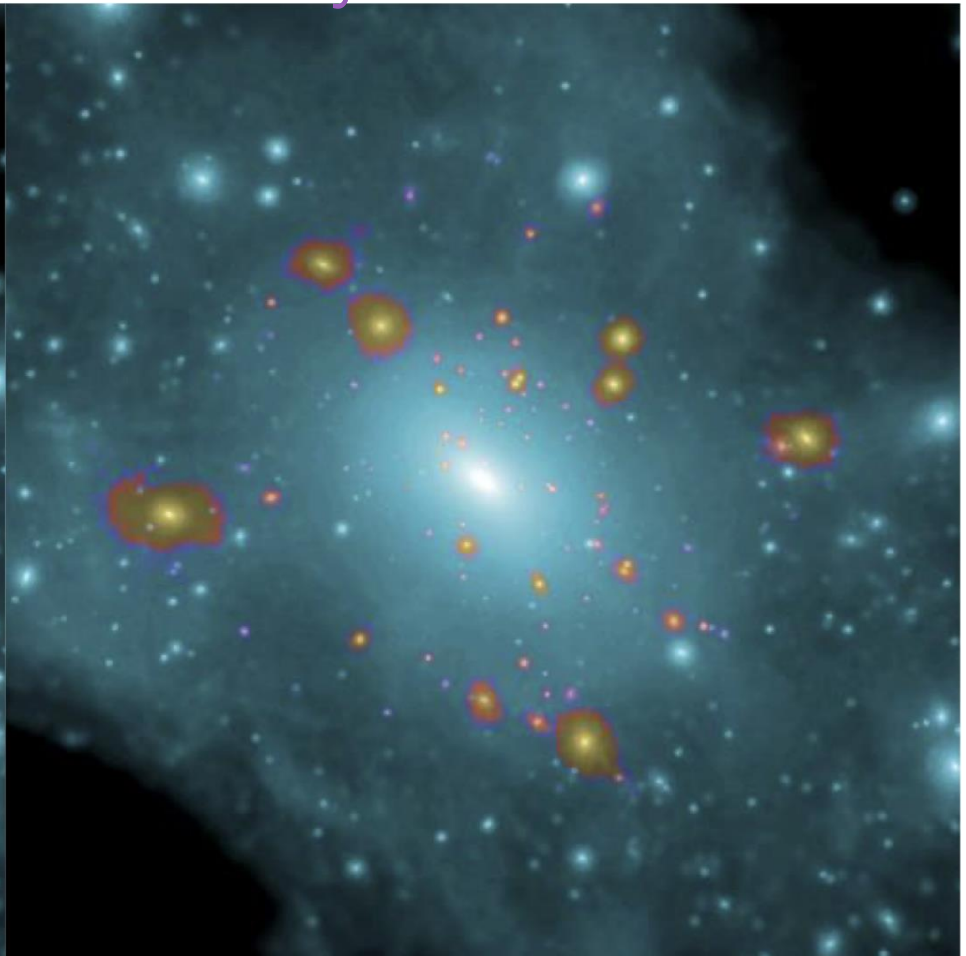
ESA (2023)

The abundance and distribution of massive clusters is dependent on the nature/composition of matter, as well as gravity

Cold Dark Matter



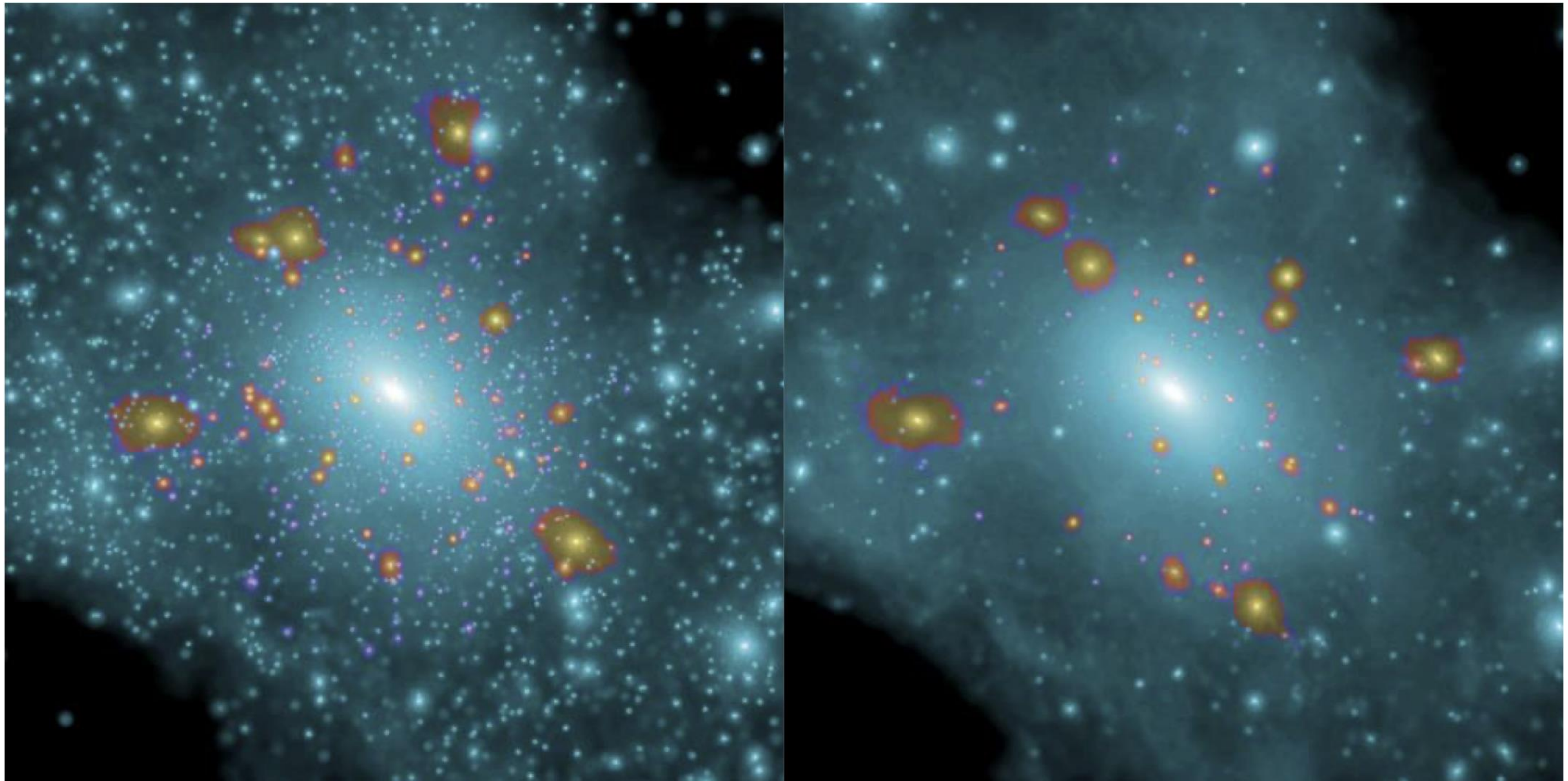
Wavy Dark Matter



ESA (2023)

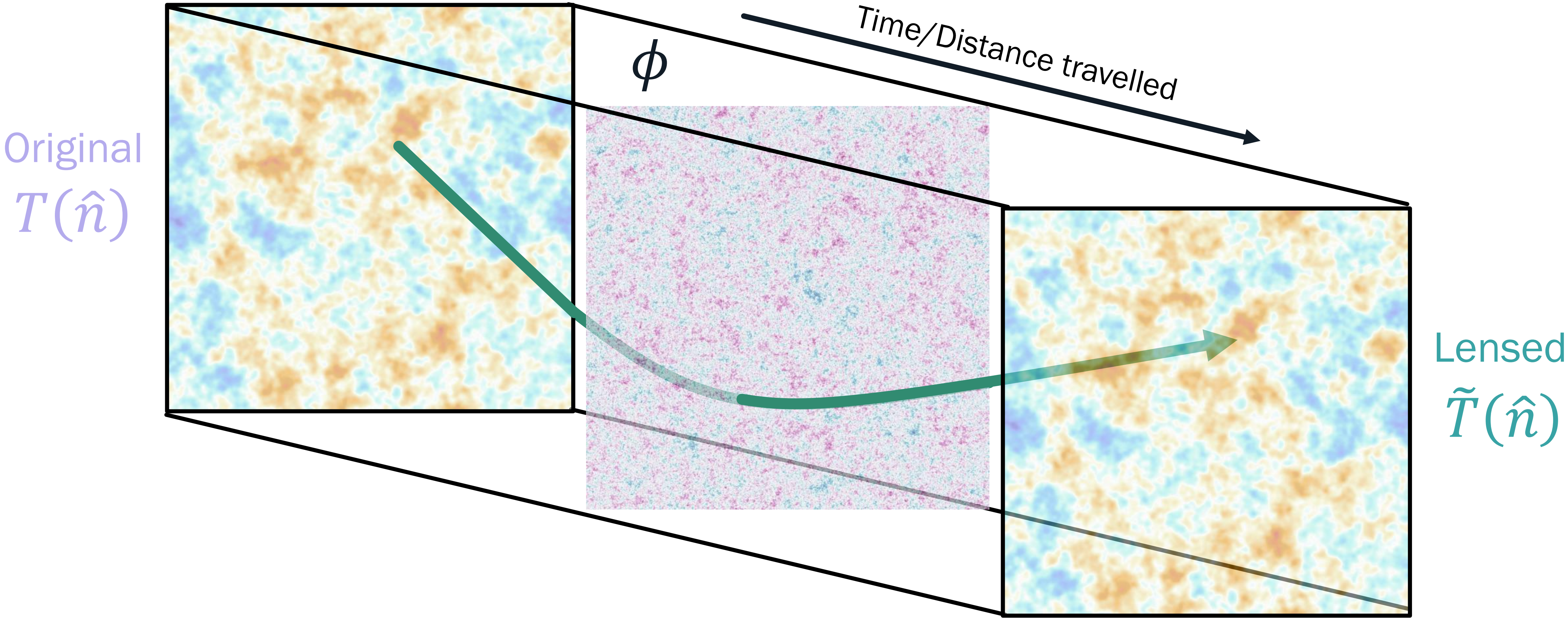
Massive neutrinos have high velocity dispersion, contributing to less concentrated structures

Low m_ν High m_ν

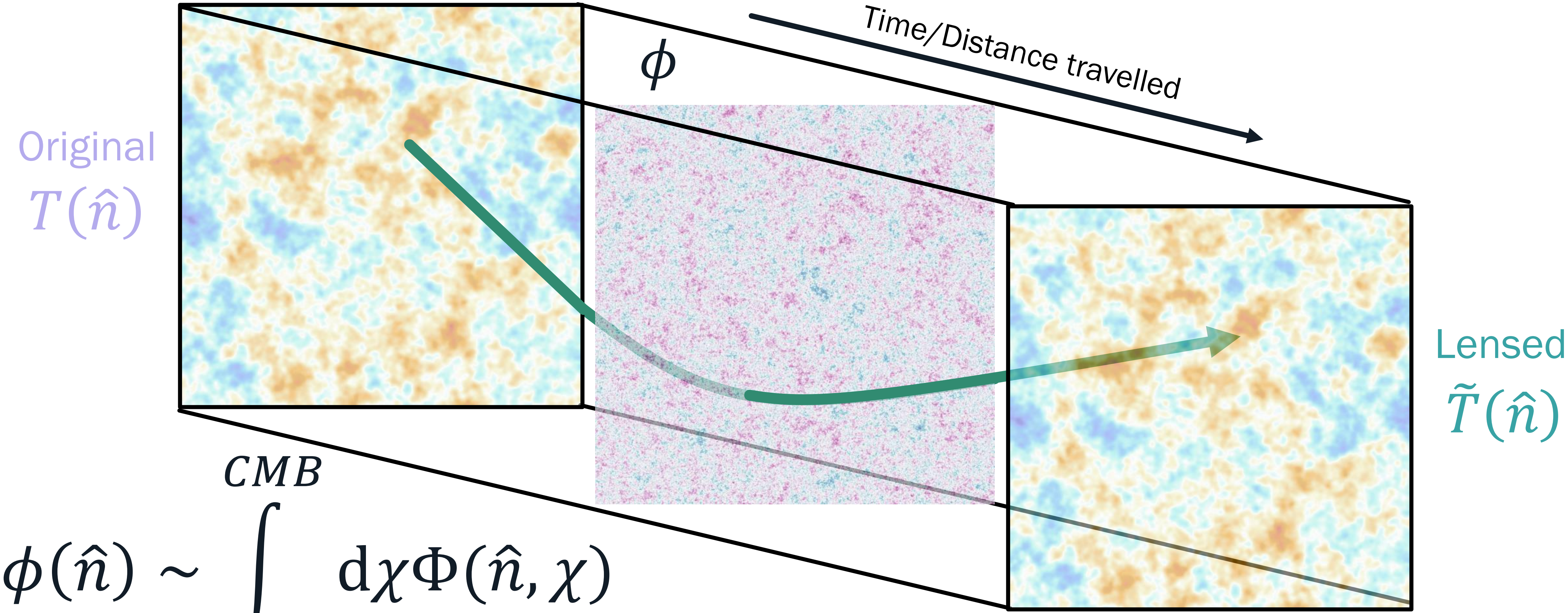


ESA (2023)

Gravitational lensing of cosmic background photons generally imparts small angle deflections



The gravity of massive clusters deflects photons from the original temperature field



$$\phi(\hat{n}) \sim \int_{Us}^{CMB} \mathrm{d}\chi \Phi(\hat{n}, \chi)$$

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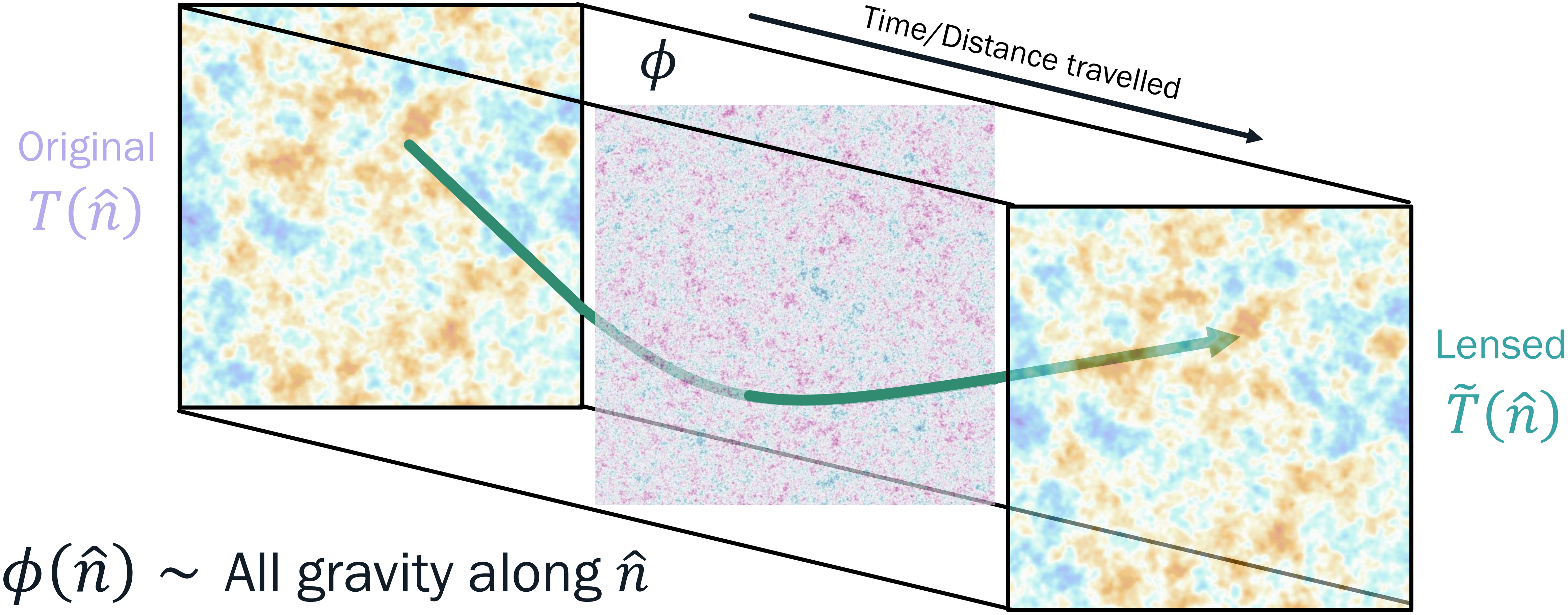

$\phi(\hat{n}) \sim$ All gravity along $\hat{n}$

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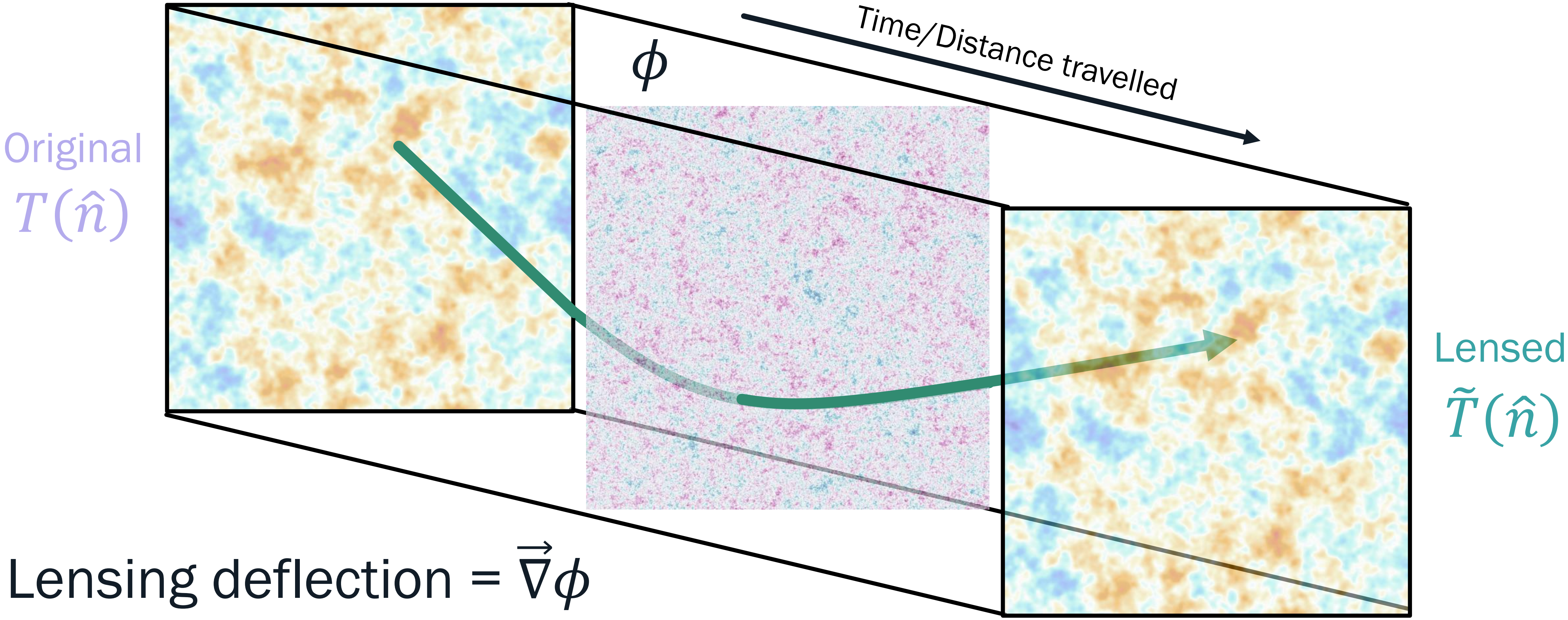
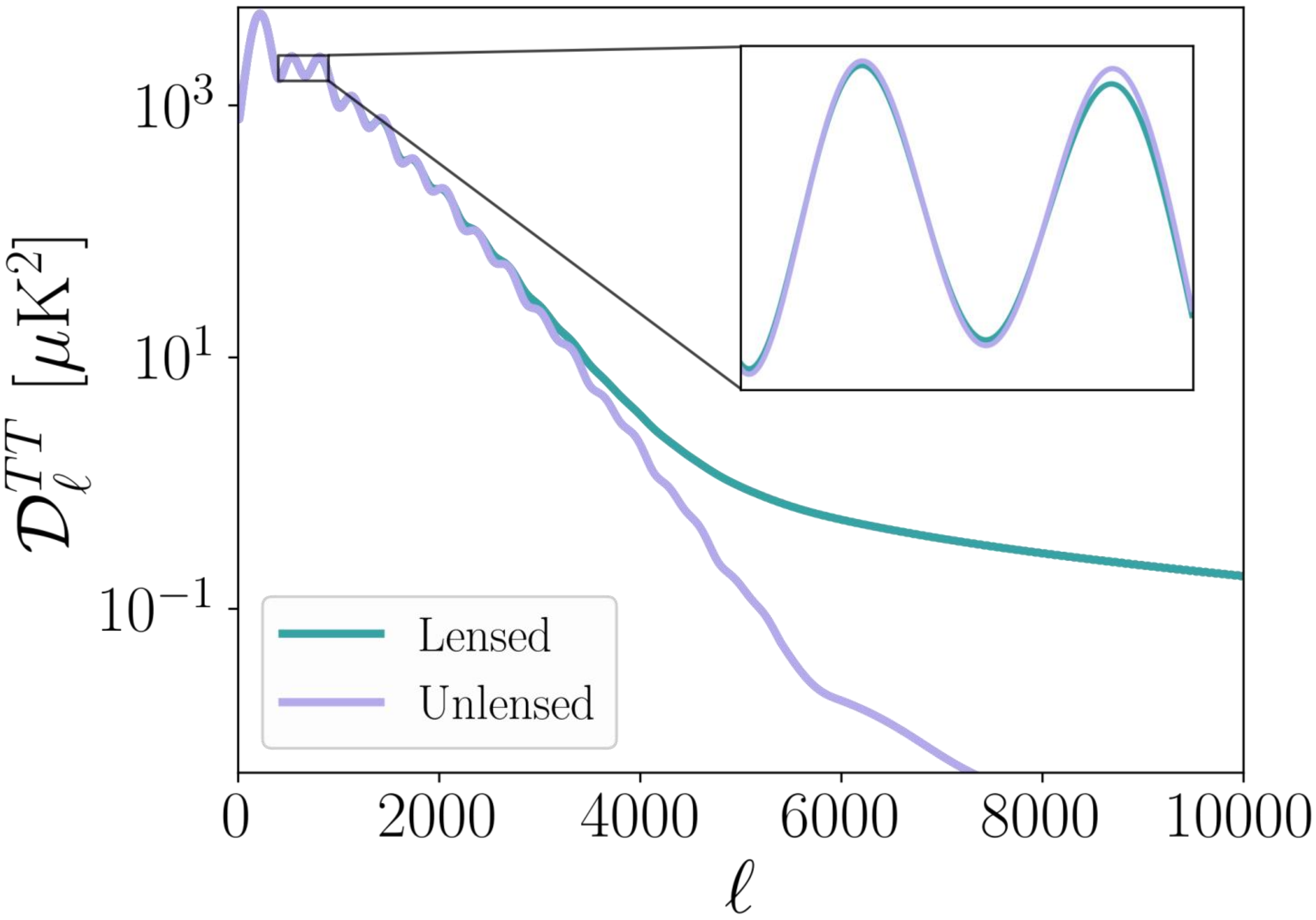


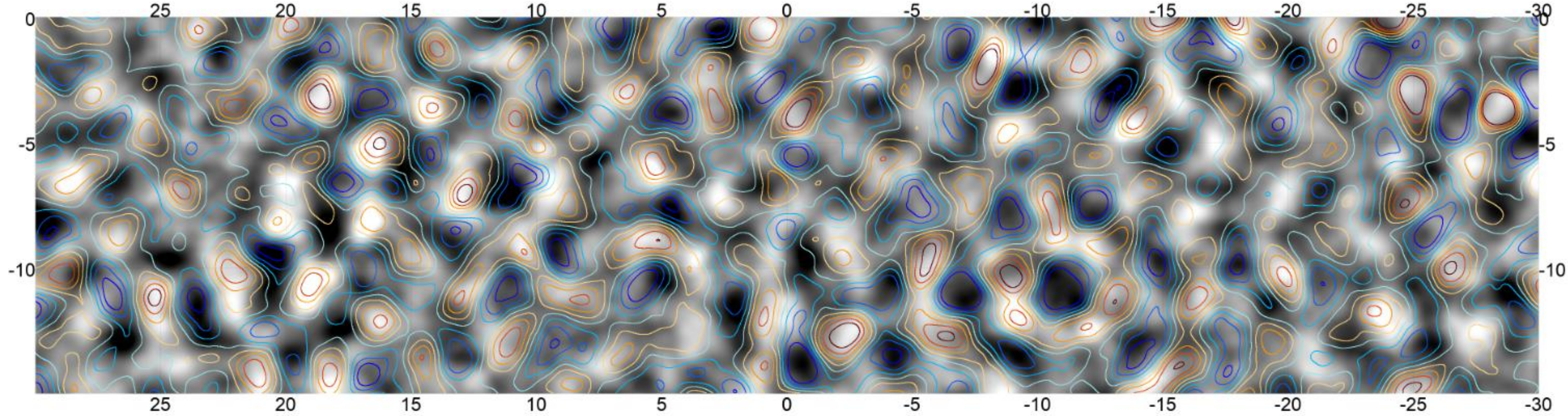
Lensing deflection = $\vec{\nabla}\phi$

Lensing re-distributes CMB power across angular scales (correlated!!!)



Existing "quadratic estimators" work to statistically "reconstruct" the lensing field

$\phi(\hat{n}) \sim$ All gravity along $\hat{n}$



Madhavacheril+ (ACT, 2023)

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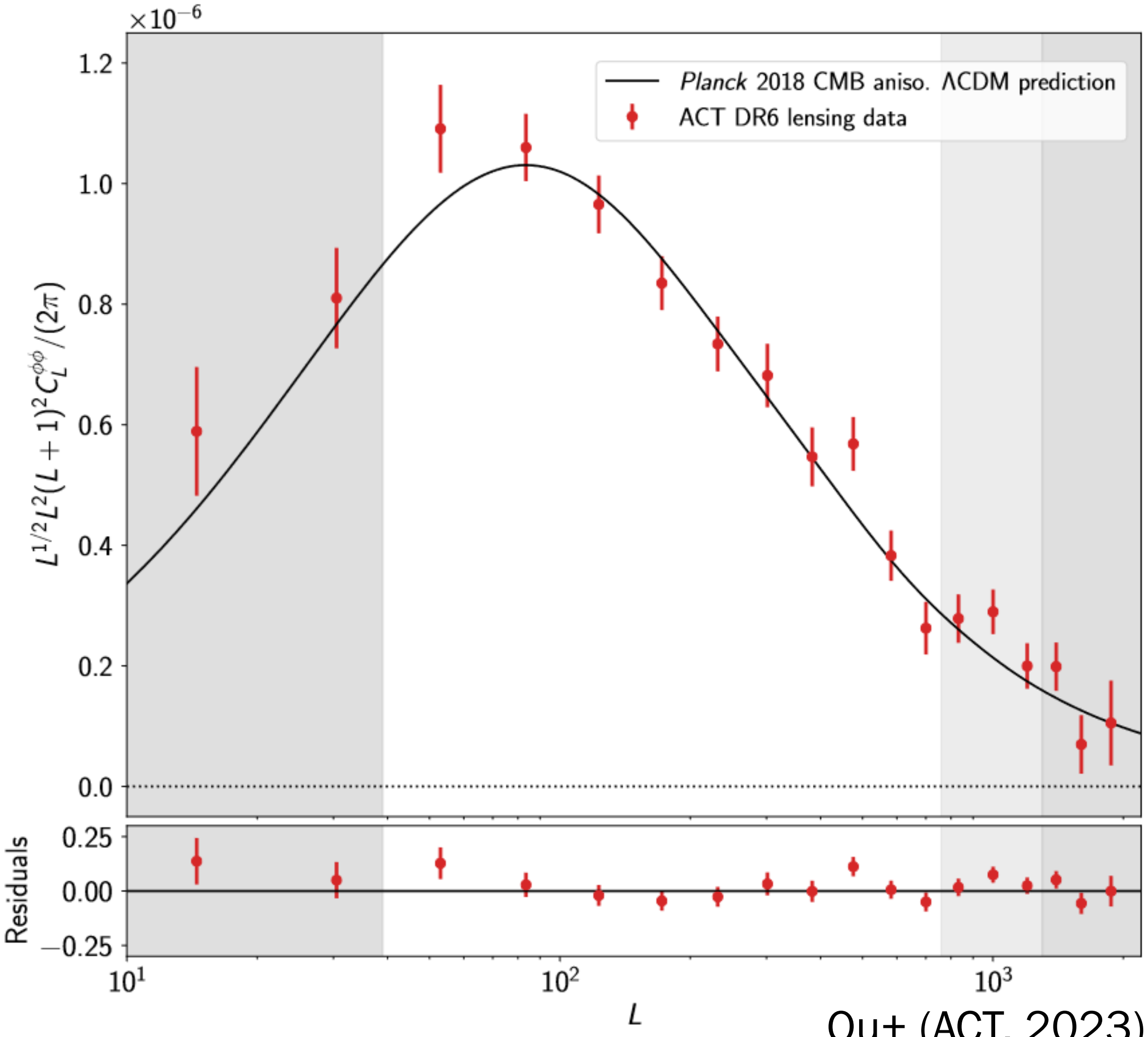
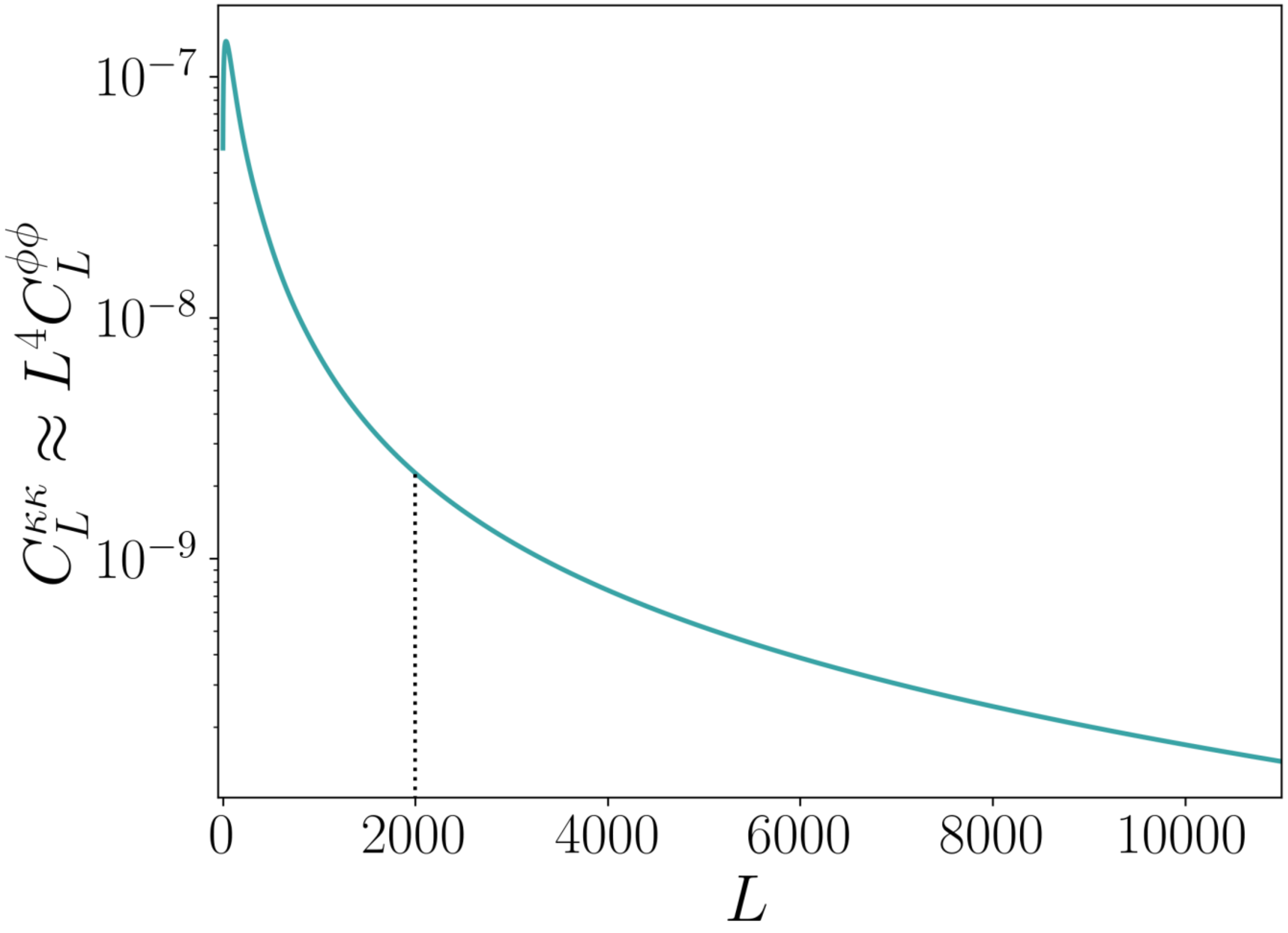


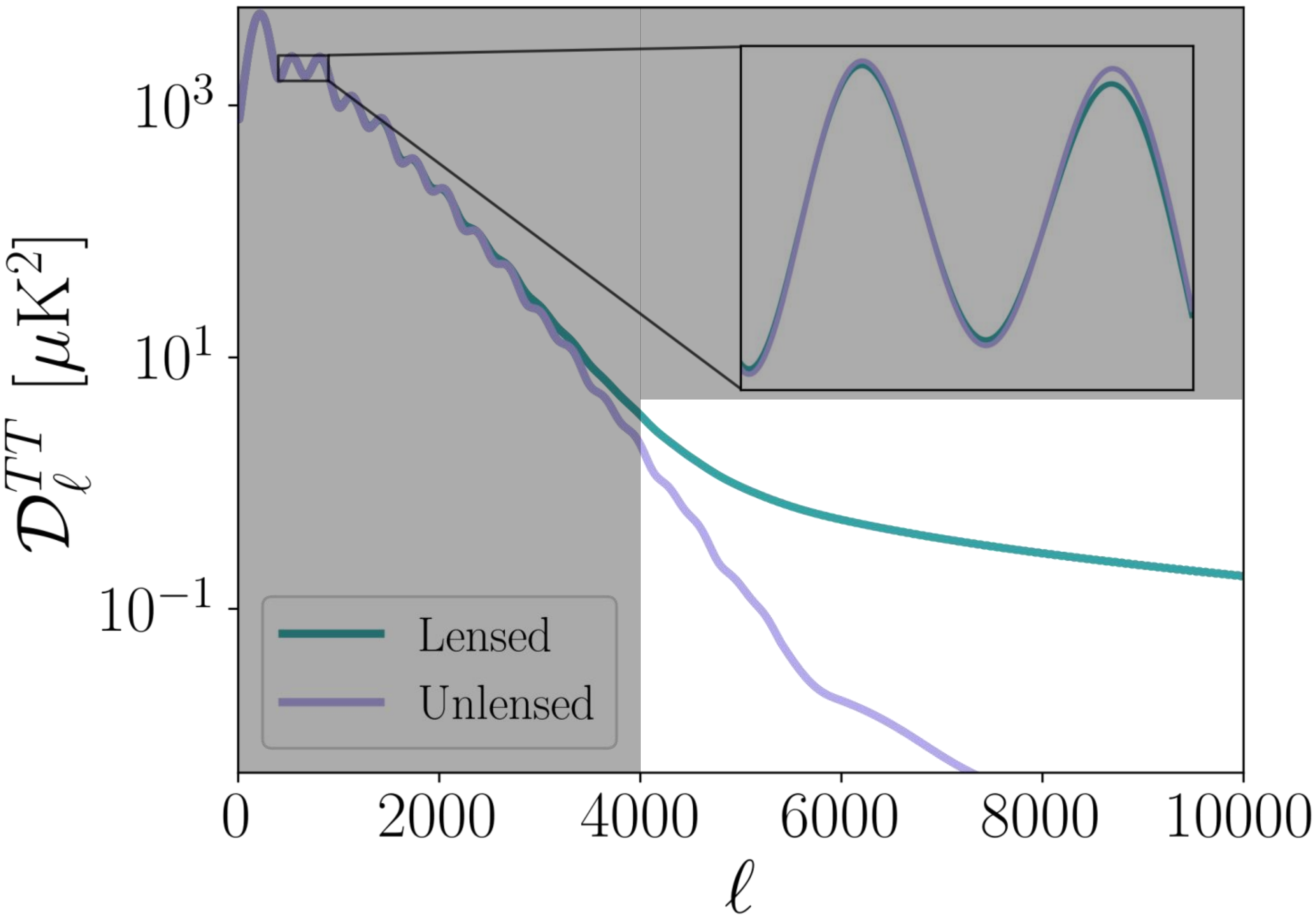
Qu+ (ACT, 2023)

$\phi(\hat{n})$ ~ All gravity along $\hat{n}$

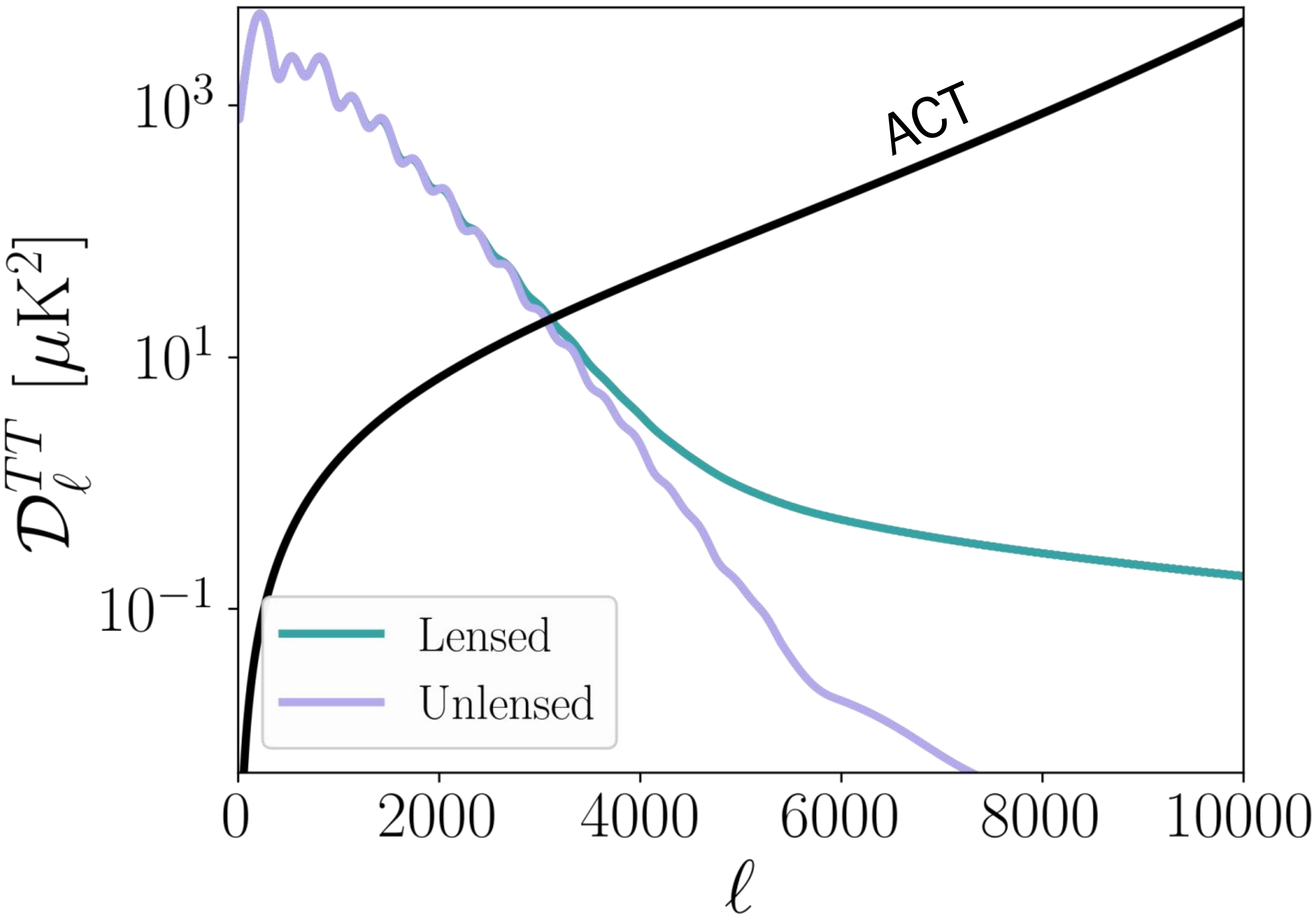
Current results measure the lensing power spectrum to L~2000



Lensing dominates the observed cosmic microwave background signal at small angular scales



Small-scale features in the cosmic microwave background are currently dominated by instrument noise and foregrounds

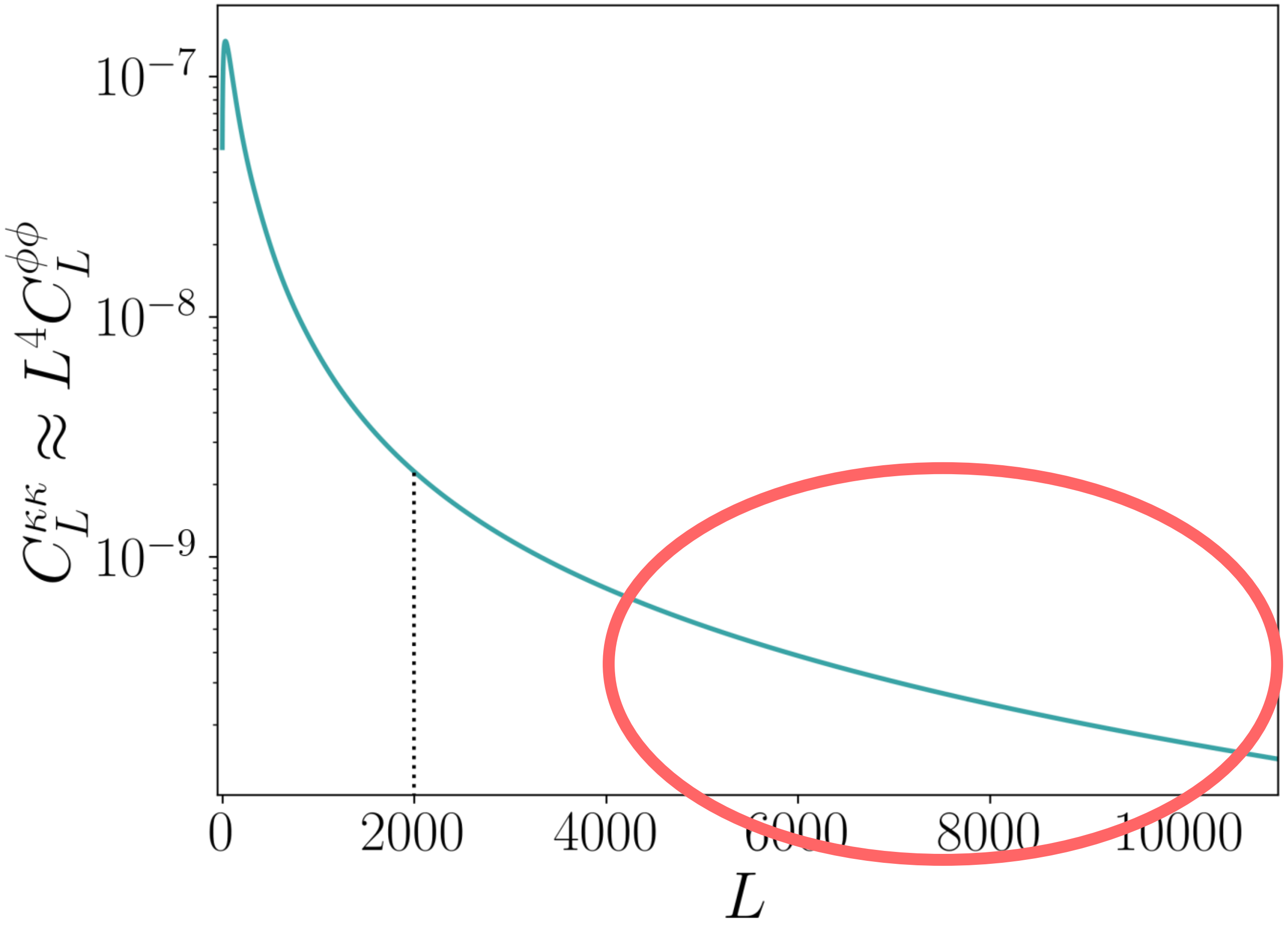


Upcoming and future experiments will allow us to access smaller scale features with lower noise levels

SIMONS OBSERVATORY

CMB-S4
Next Generation CMB Experiment

Galaxy clustering models can predict different lensing amplitudes at small scales



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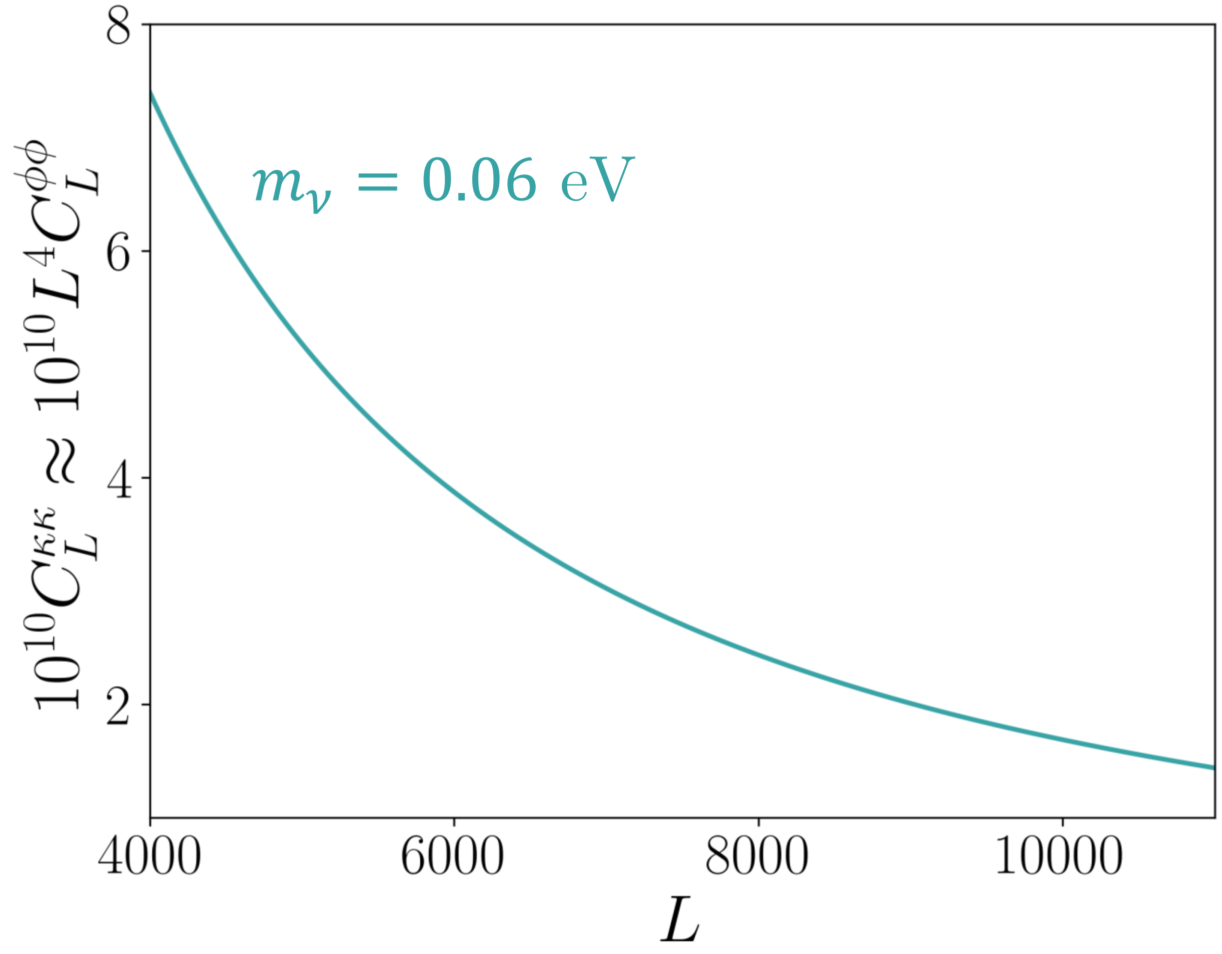
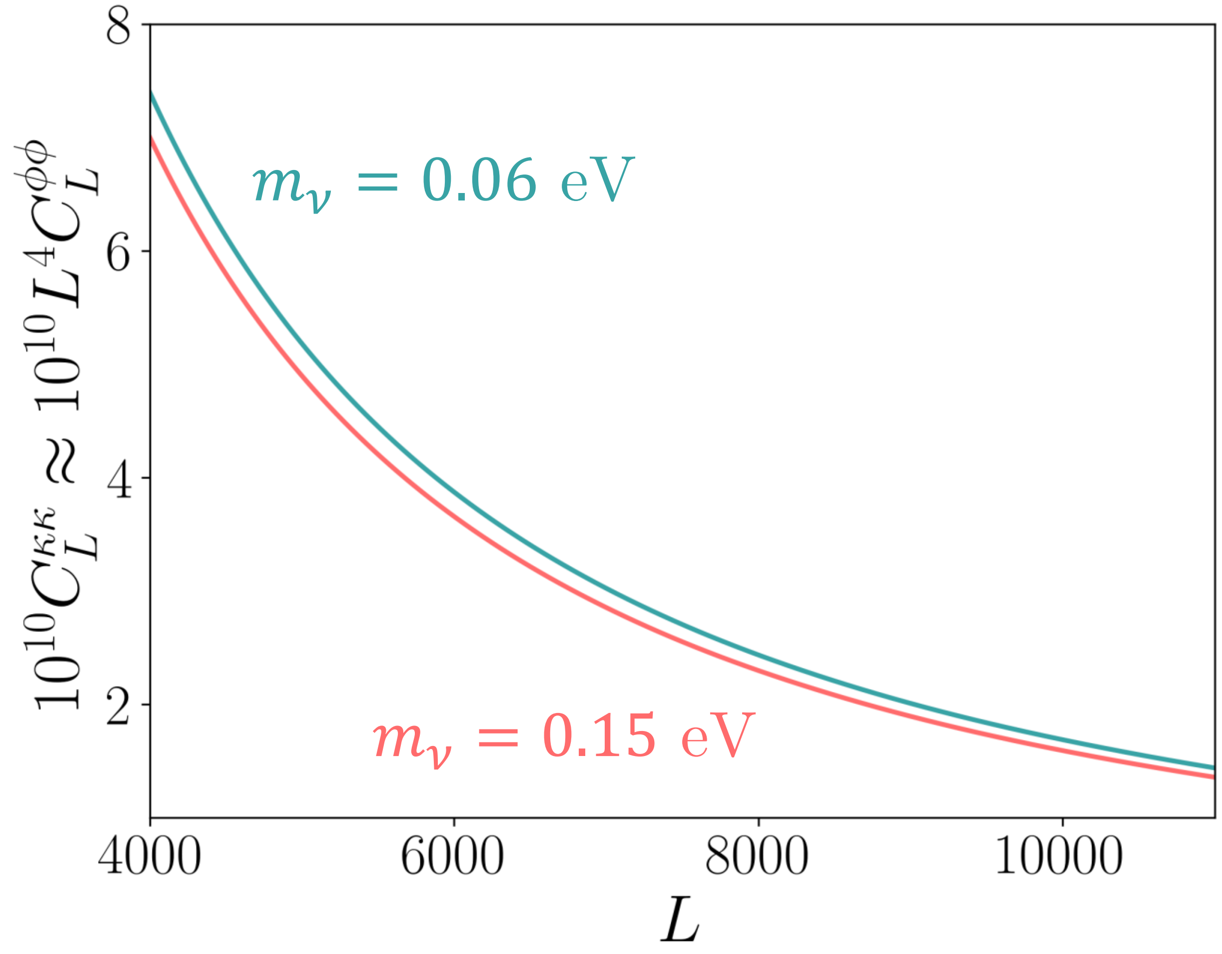
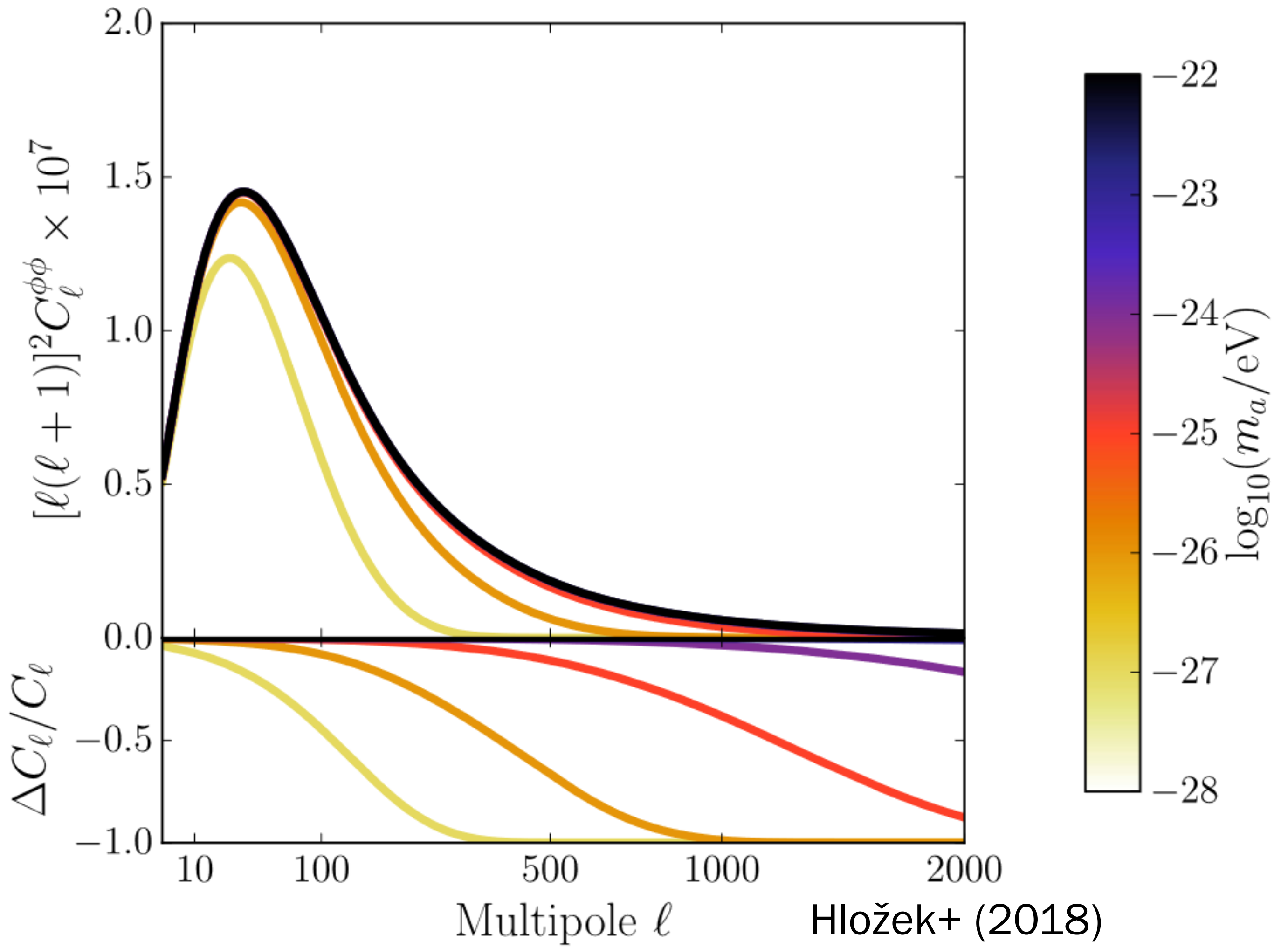


Galaxy clustering models can predict different lensing amplitudes at small scales



Dark matter models can predict both amplitude and shape changes to the lensing power spectrum → largest effect at smaller scales



Hložek+ (2018)

Takeaways:

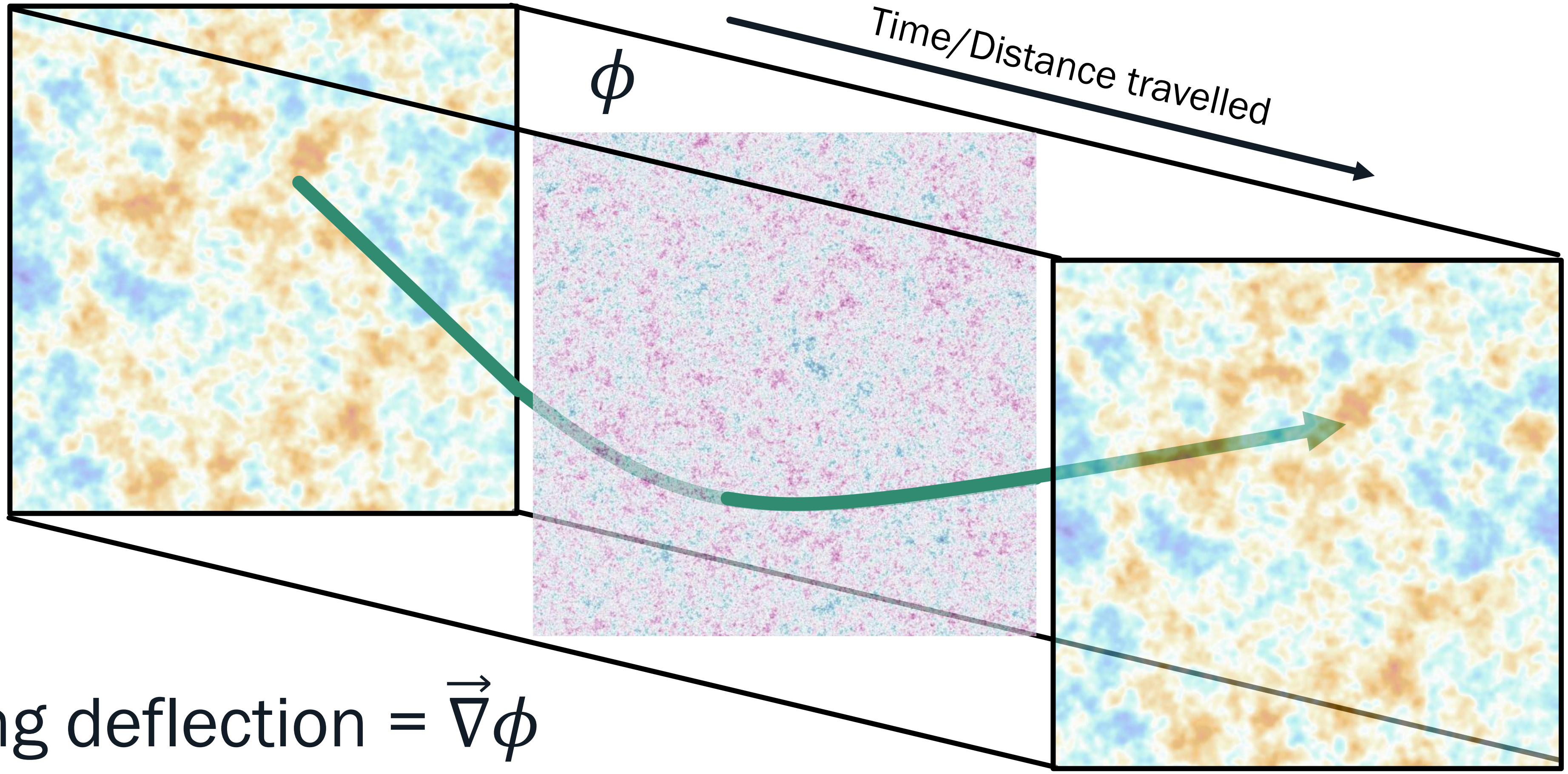
- Upcoming experiments will allow for lower noise observations of small-scale cosmic microwave background features
- Lensing features at small scales are sensitive to matter clustering: Dark matter, massive neutrinos, more!
- We need new techniques to take full advantage of future datasets

HOW DO WE MEASURE SMALL-SCALE LENSING?

The gravity of massive clusters deflects photons from the original temperature field

Original

$T(\hat{n})$



Lensed

$\tilde{T}(\hat{n})$

Lensing deflection = $\vec{\nabla}\phi$

The observed T field is a remapping of the original T field

$$\tilde{T}(\hat{n})$$

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$$\tilde{T}(\hat{n}) = T\left(\hat{n} + \vec{\nabla}\phi\right)$$

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The observed T field is a remapping of the original T field

$$\tilde{T}(\hat{n}) = T\left(\hat{n} + \vec{\nabla}\phi\right)$$

$\phi(\hat{n}) \sim$ All gravity along $\hat{n}$

The observed T field is a remapping of the original T field

$$\tilde{T}(\hat{n}) = T\left(\hat{n} + \vec{\nabla}\phi\right)$$

$$= T(\hat{n}) + \vec{\nabla}T(\hat{n}) \cdot \vec{\nabla}\phi(\hat{n}) + \cdots$$

$\phi(\hat{n}) \sim$ All gravity along $\hat{n}$

The observed T field is a remapping of the original T field

$$\tilde{T}(\hat{n}) = T\left(\hat{n} + \vec{\nabla}\phi\right)$$

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Original

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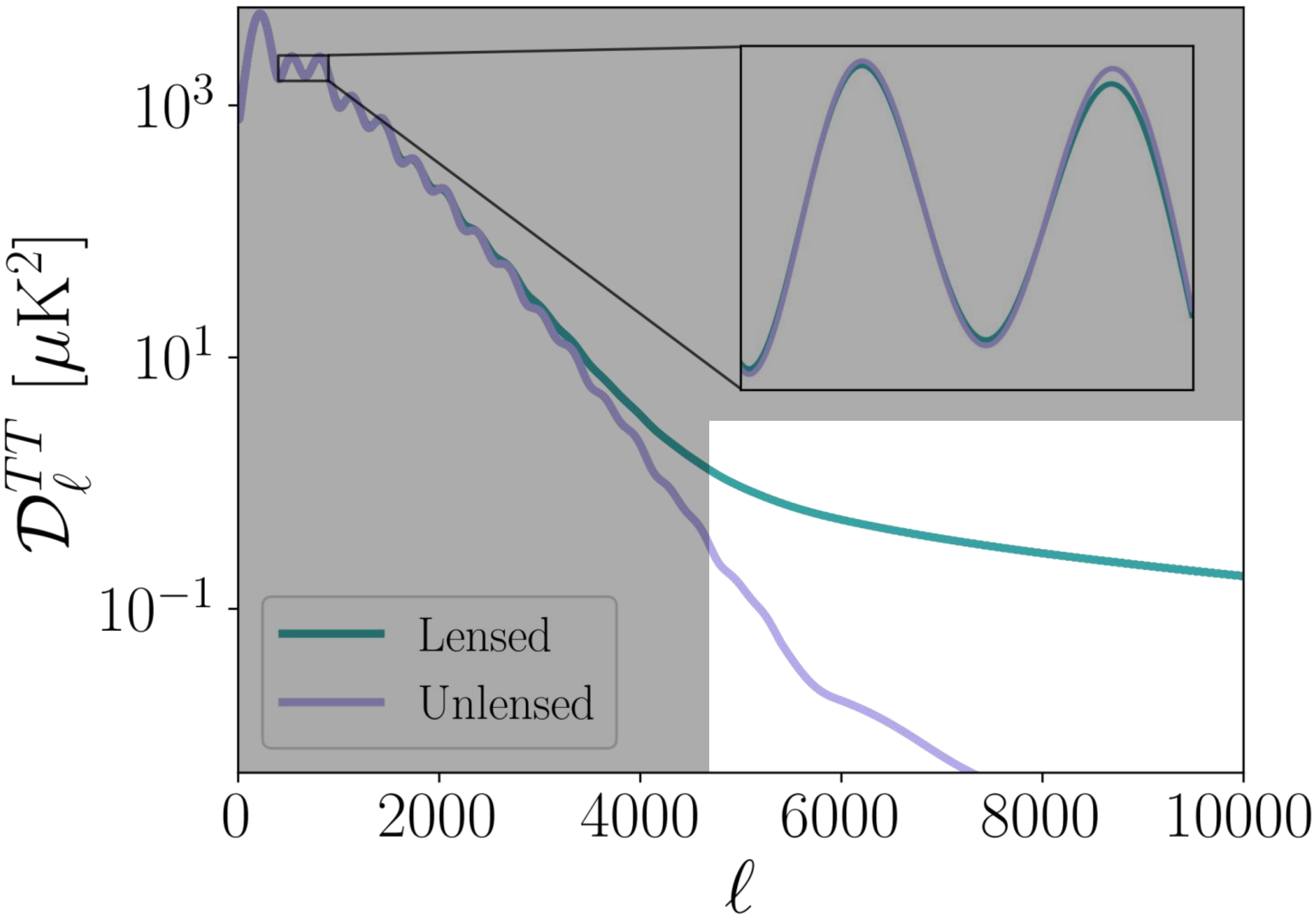
$$= T(\hat{n}) + \vec{\nabla}T(\hat{n}) \cdot \vec{\nabla}\phi(\hat{n}) + \cdots$$

Original   Lensing

$\phi(\hat{n}) \sim$ All gravity along $\hat{n}$

Small-scale T power is controlled by lensing & the T gradient itself

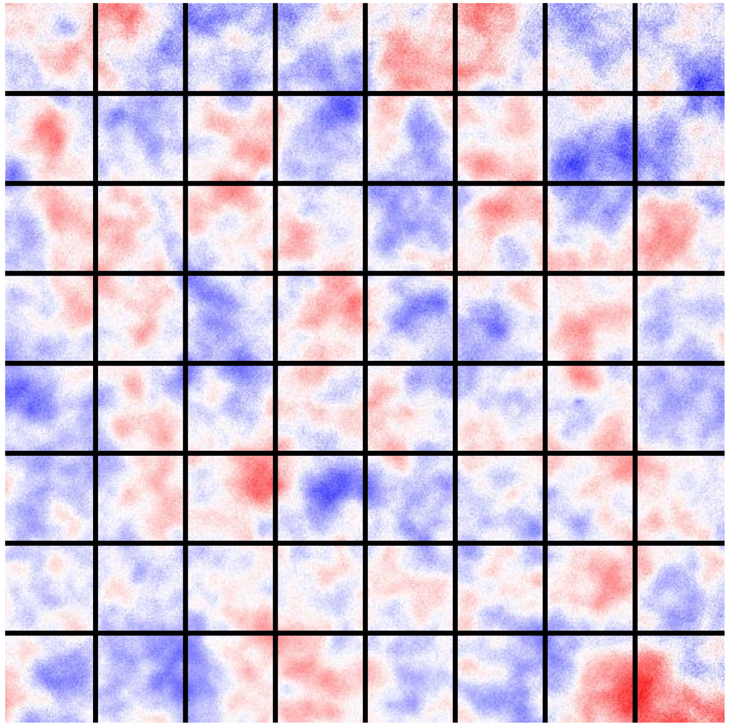


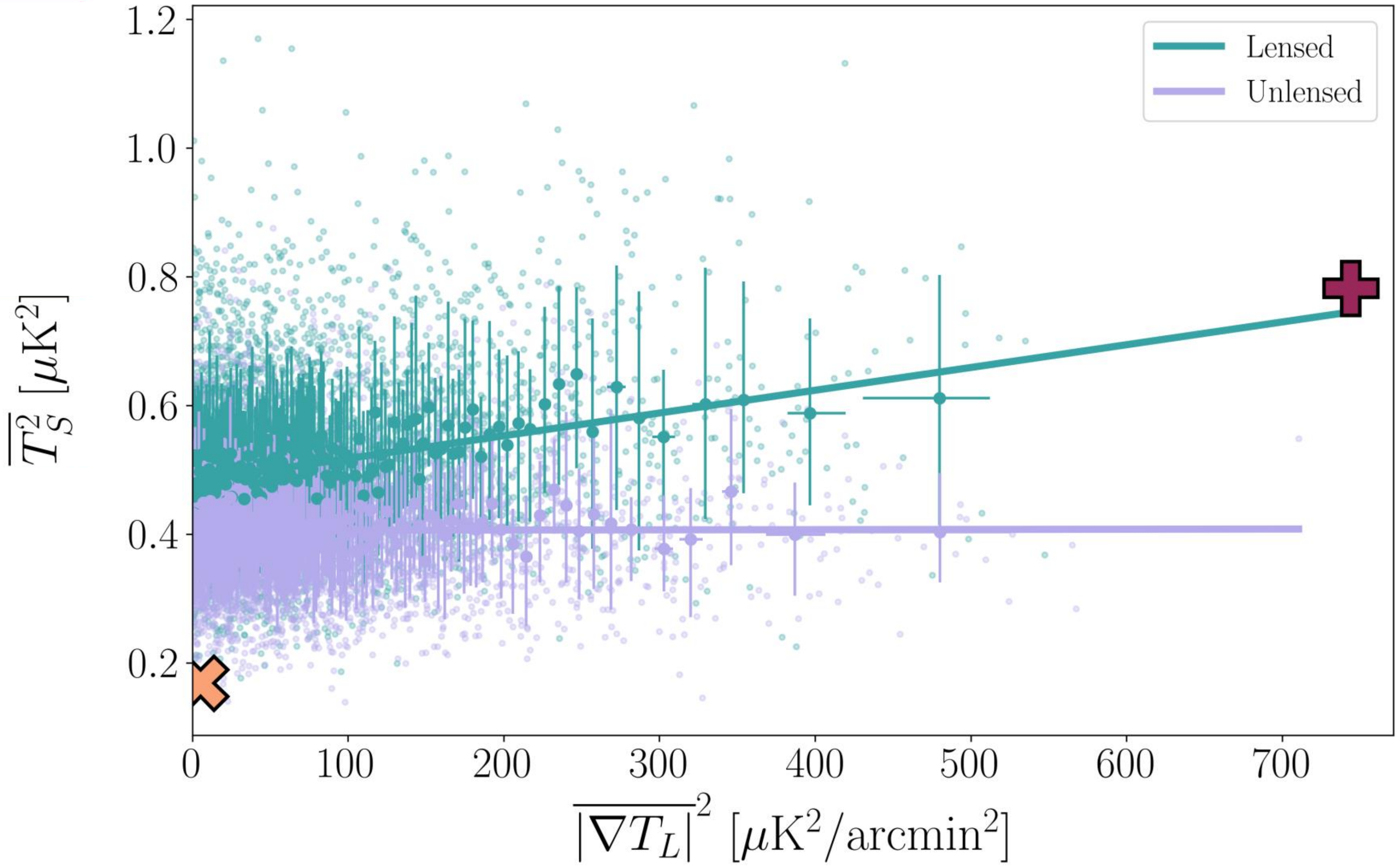
The T gradient varies across the sky; does the small-scale power induced by lensing change along with it?

$$\tilde{T}(\hat{n}) = T(\hat{n}) + \vec{\nabla} T(\hat{n}) \cdot \vec{\nabla} \phi(\hat{n}) + \cdots$$

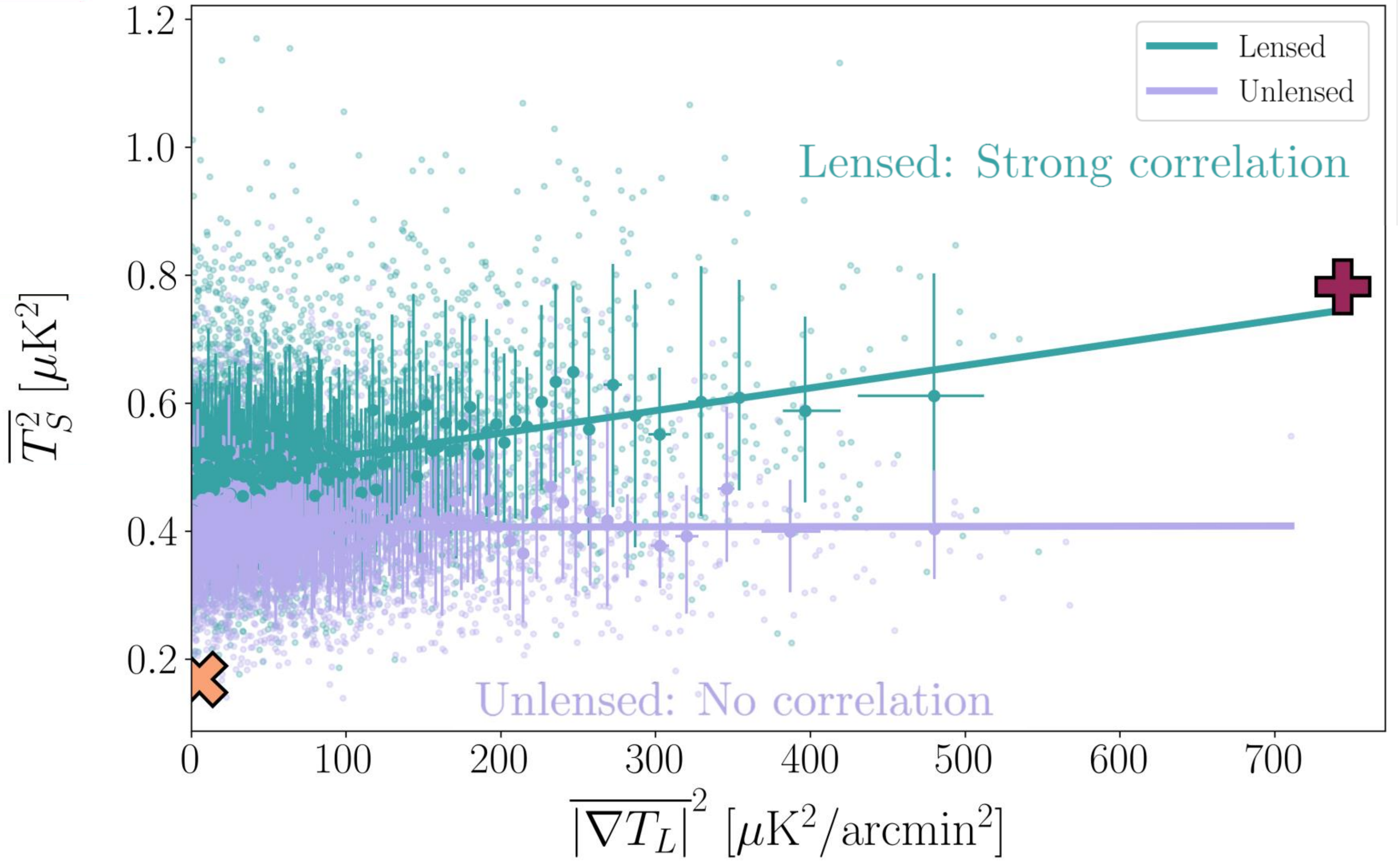
Original

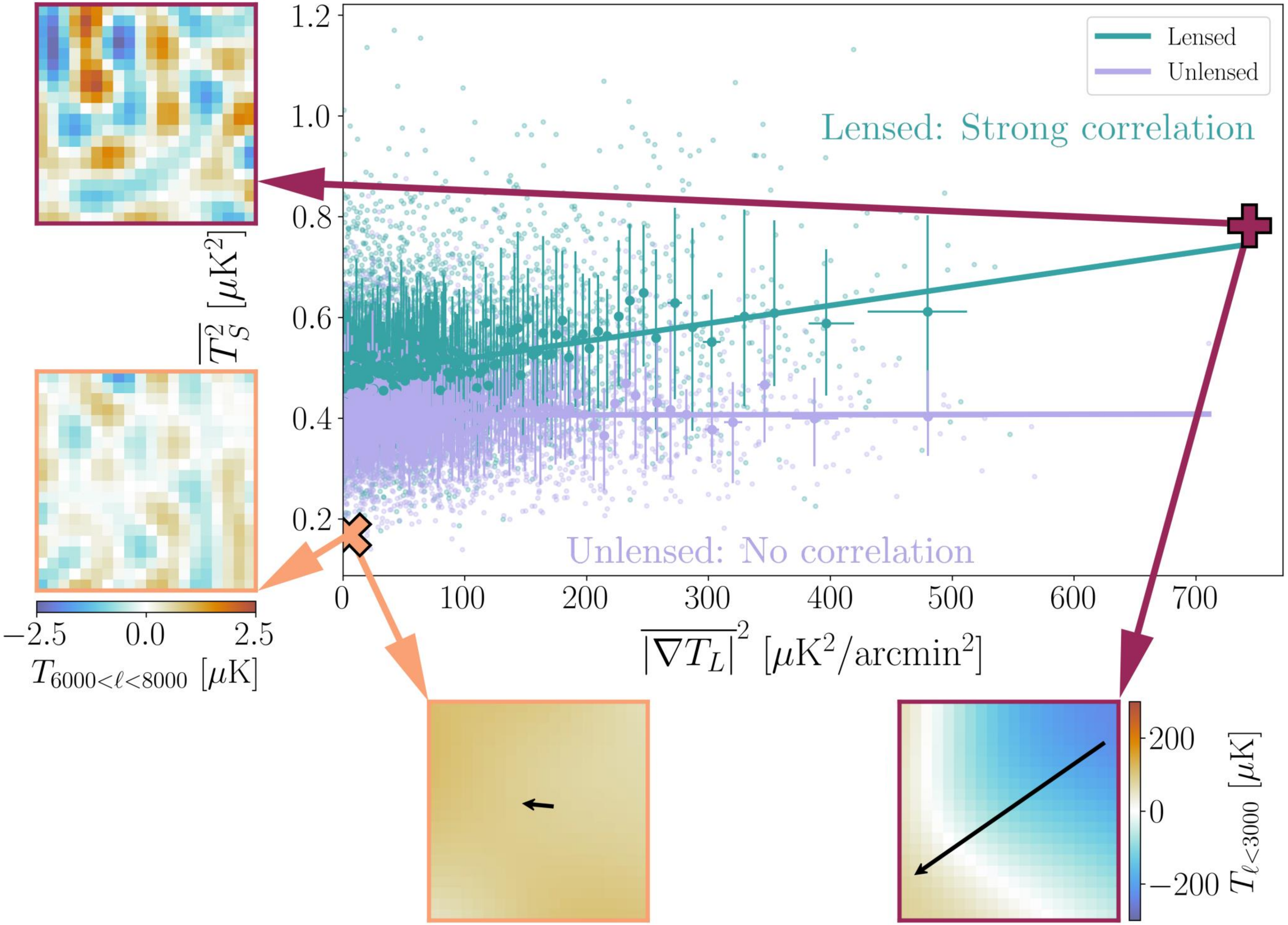
Lensing



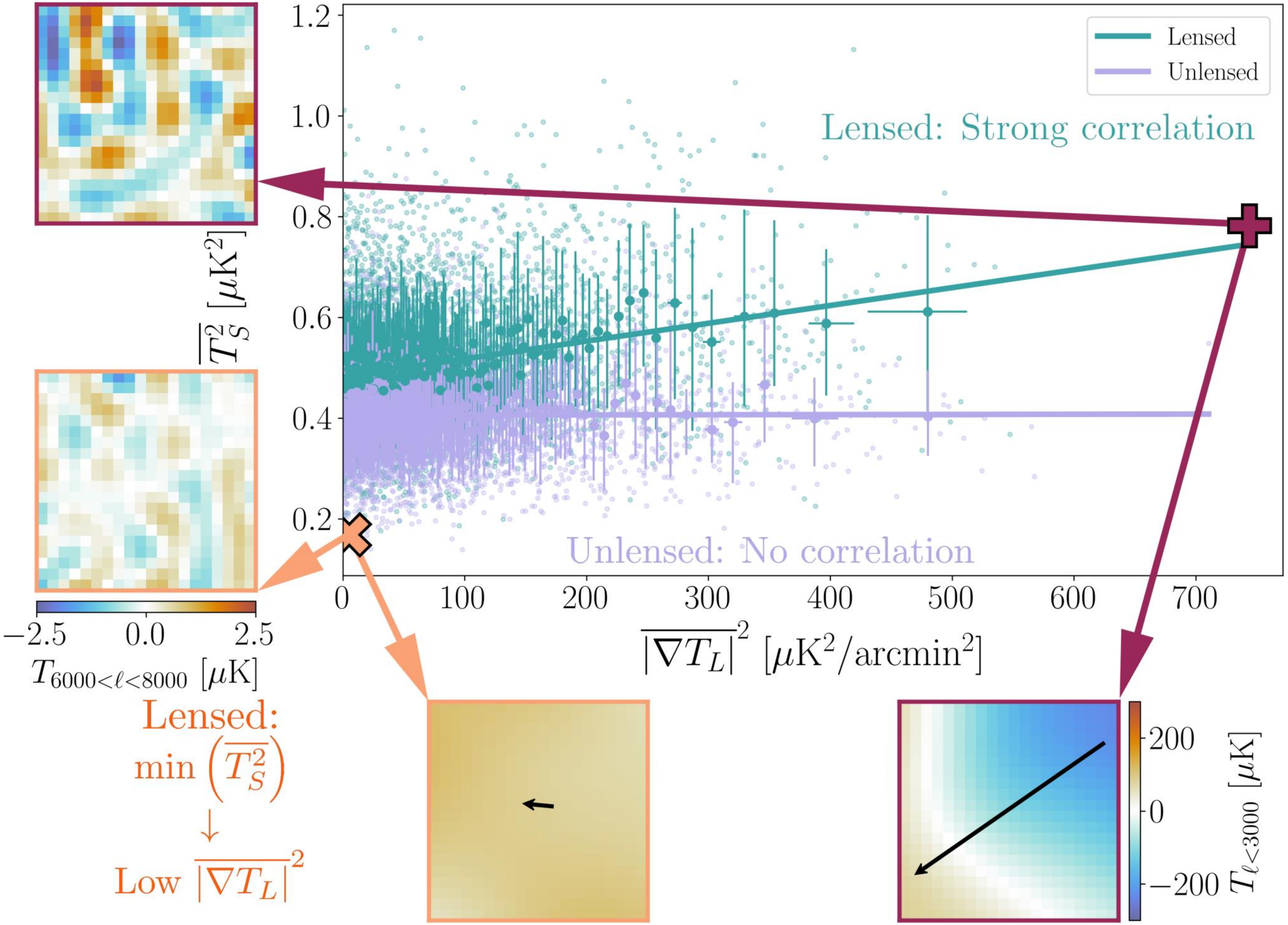


Lensed
Unlensed
$\overline{T_S^2}$ [μK^2]
$\overline{|\nabla T_L|}^2$ [μK^2/arcmin^2]

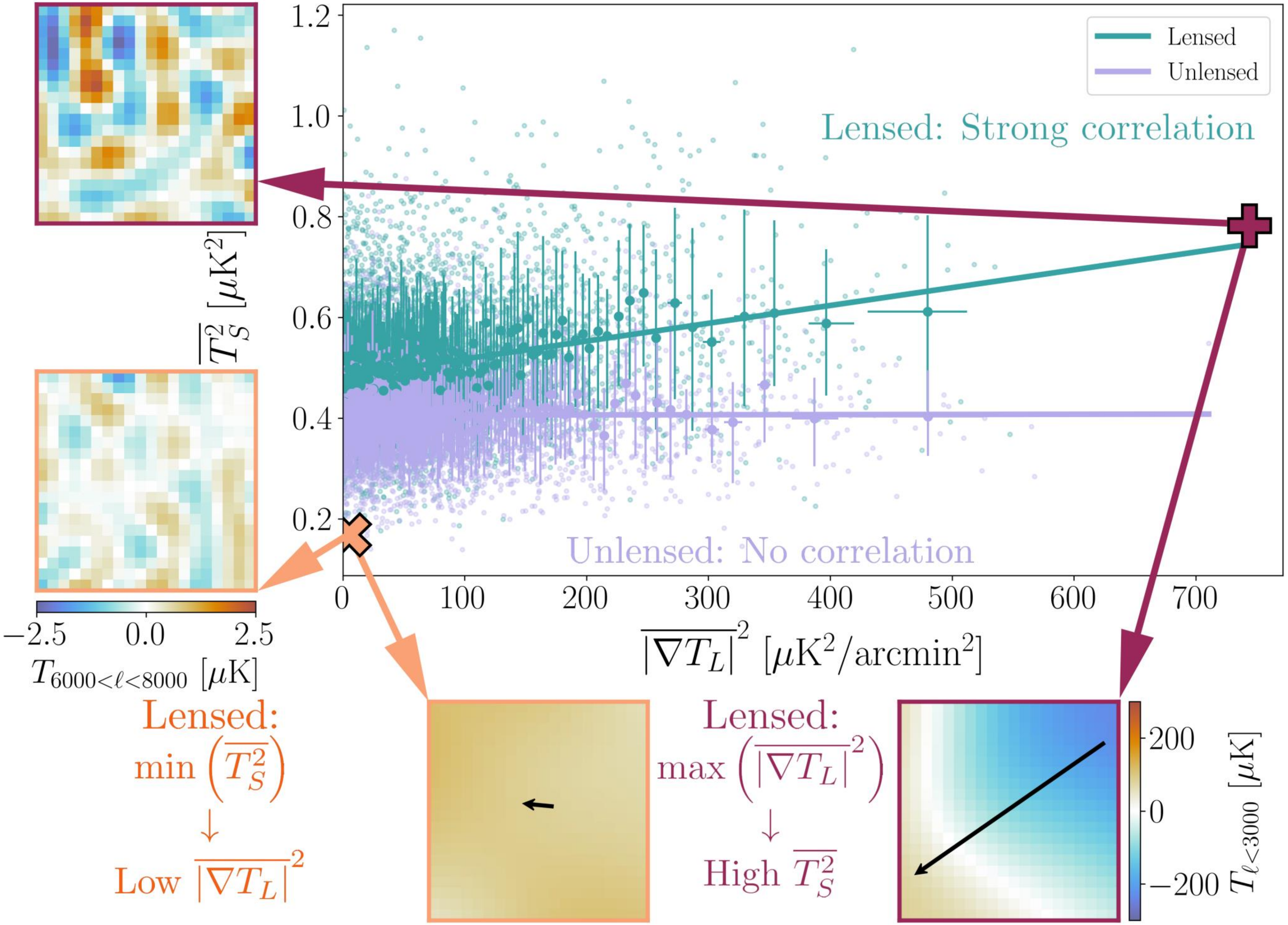

Lensed
Unlensed
Lensed: Strong correlation
Unlensed: No correlation
$\overline{T_S^2}$ [μK^2]
$\overline{|\nabla T_L|}^2$ [μK^2/arcmin^2]
1.2
1.0
0.8
0.6
0.4
0.2
0
100
200
300
400
500
600
700



Lensed
Unlensed
Lensed: Strong correlation
Unlensed: No correlation
$\overline{T_S^2}$ [μK^2]
$\overline{|\nabla T_L|}^2$ [μK^2/arcmin^2]
$T_{6000<\ell<8000}$ [μK]
$T_{\ell<3000}$ [μK]



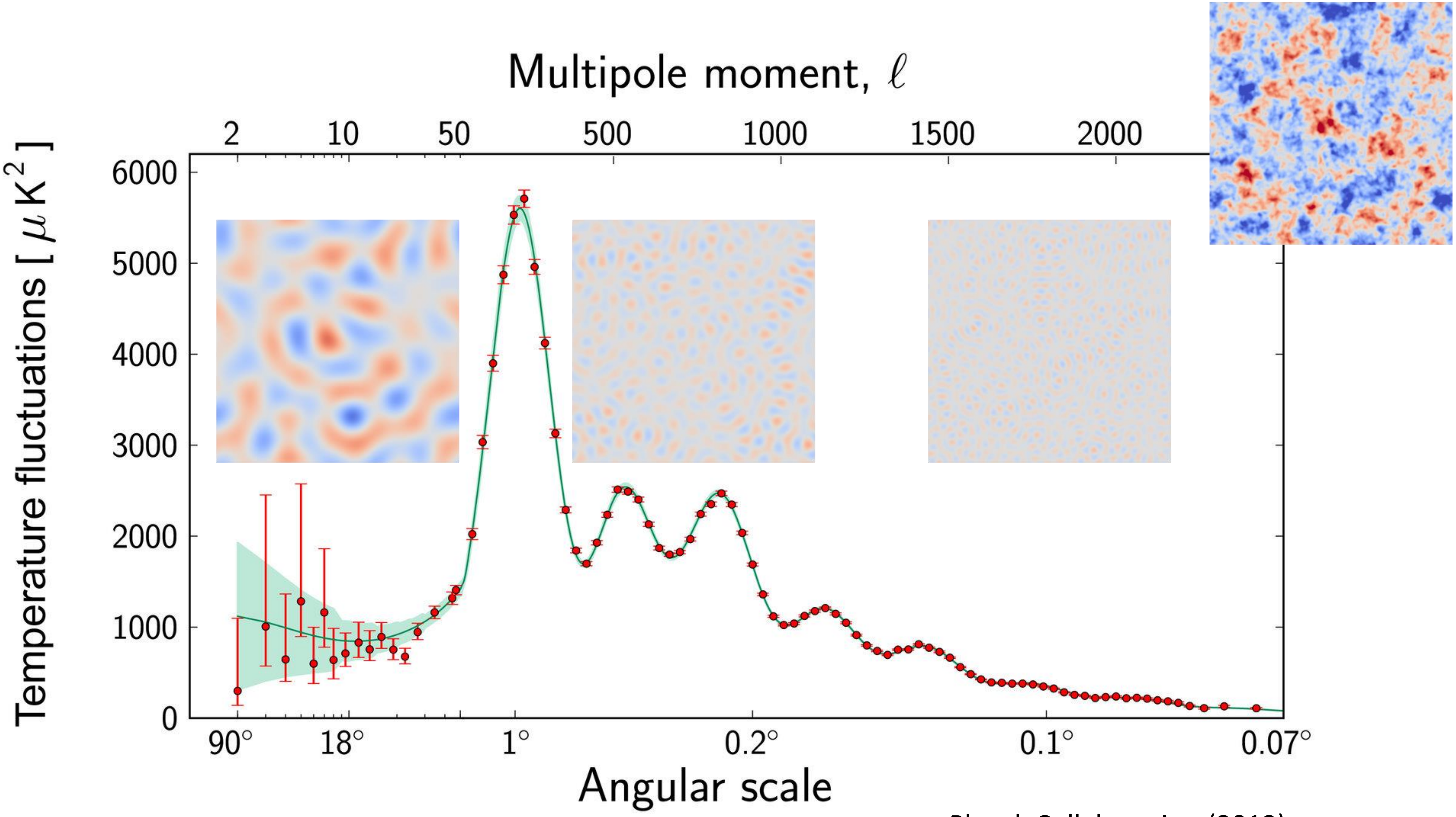
Lensed
Unlensed
Lensed: Strong correlation
Unlensed: No correlation
$\overline{T_S^2}$ [μK^2]
$\overline{|\nabla T_L|}^2$ [μK^2/arcmin^2]
$T_{6000<\ell<8000}$ [μK]
$T_{\ell<3000}$ [μK]
Lensed:
$\min\left(\overline{T_S^2}\right)$
↓
Low $\overline{|\nabla T_L|}^2$


Lensed
Unlensed
Lensed: Strong correlation
Unlensed: No correlation
$\overline{T_S^2}$ [μK^2]
$\overline{|\nabla T_L|}^2$ [μK^2/arcmin^2]
1.2
1.0
0.8
0.6
0.4
0.2
0
100
200
300
400
500
600
700
−2.5
0.0
2.5
$T_{6000<\ell<8000}$ [μK]
Lensed: min $\left(\overline{T_S^2}\right)$ ↓ Low $\overline{|\nabla T_L|}^2$
Lensed: max $\left(\overline{|\nabla T_L|}^2\right)$ ↓ High $\overline{T_S^2}$
200
0
−200
$T_{\ell<3000}$ [μK]

Takeaways:

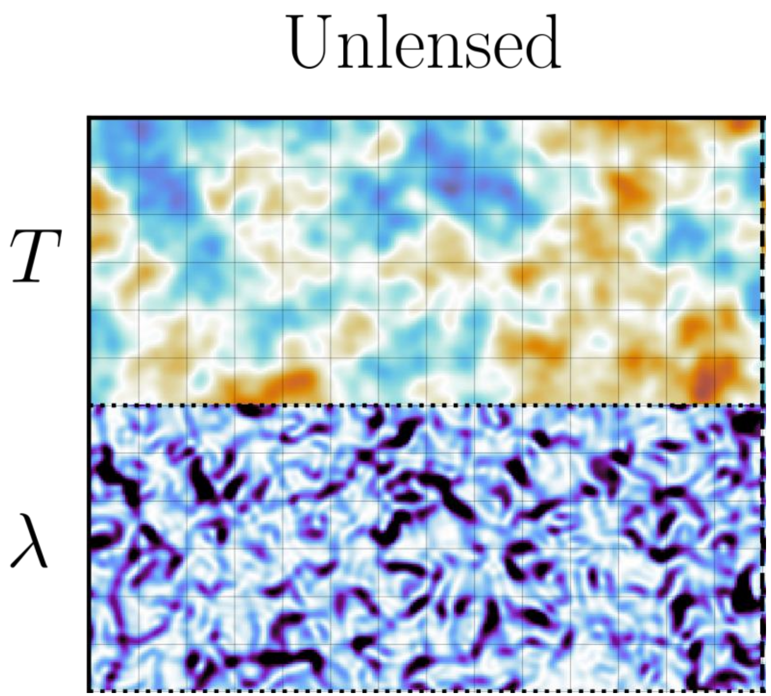
- Temperature power in the cosmic microwave background is dominated by lensing at small angular scales
- Small-scale power is highly correlated with the large-scale features of the cosmic microwave background
- Lensing features at small scales are sensitive to matter clustering: Dark matter, massive neutrinos, more!

CAN WE QUANTIFY SMALL-SCALE LENSING CORRELATIONS?



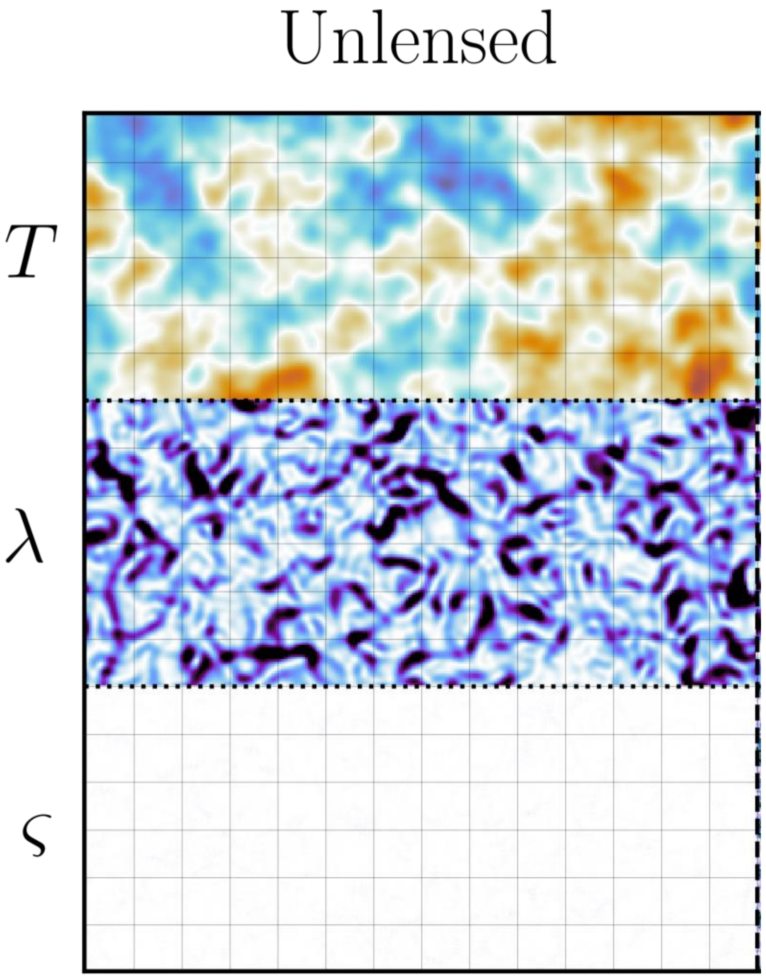
Planck Collaboration (2013)

Large-scale features originate from the primary temperature field



$\ell < 3000$

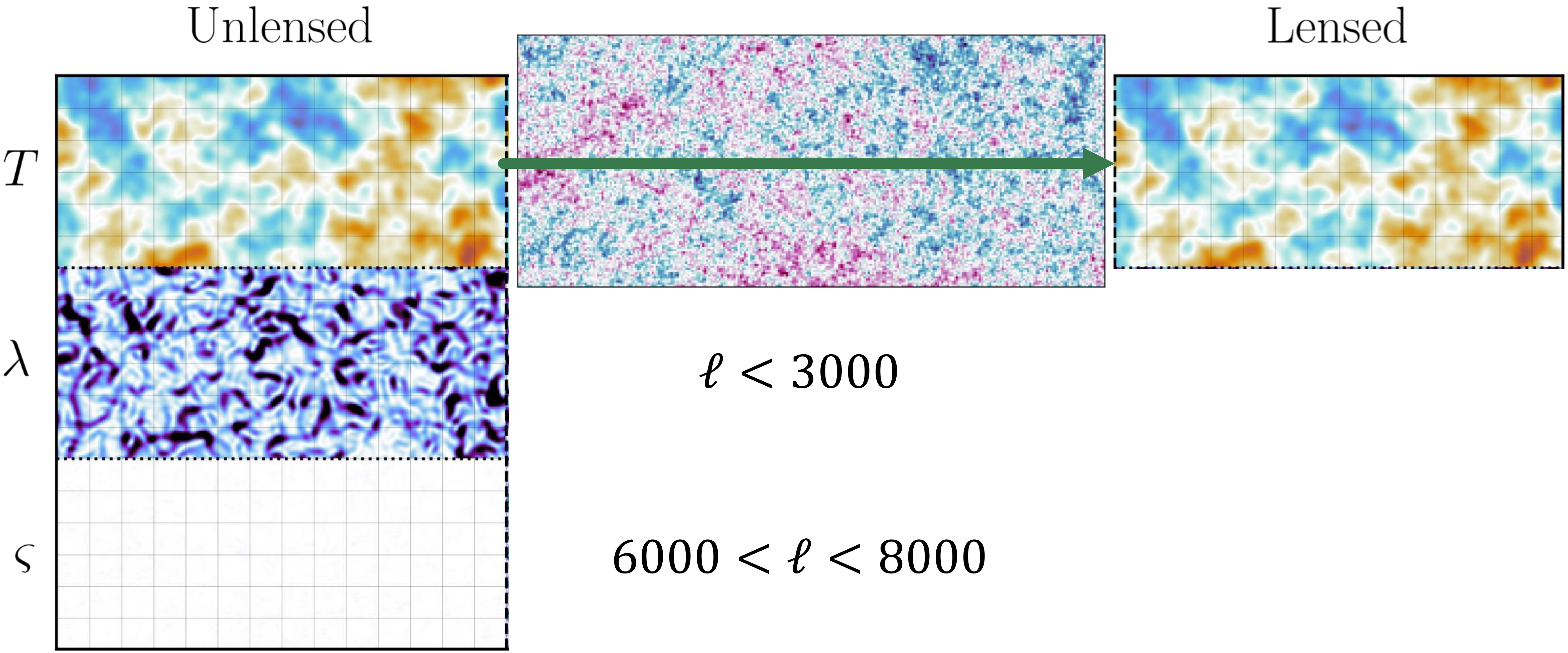
Large-scale features originate from the primary temperature field
Small-scale features are very weak in the primary temperature field



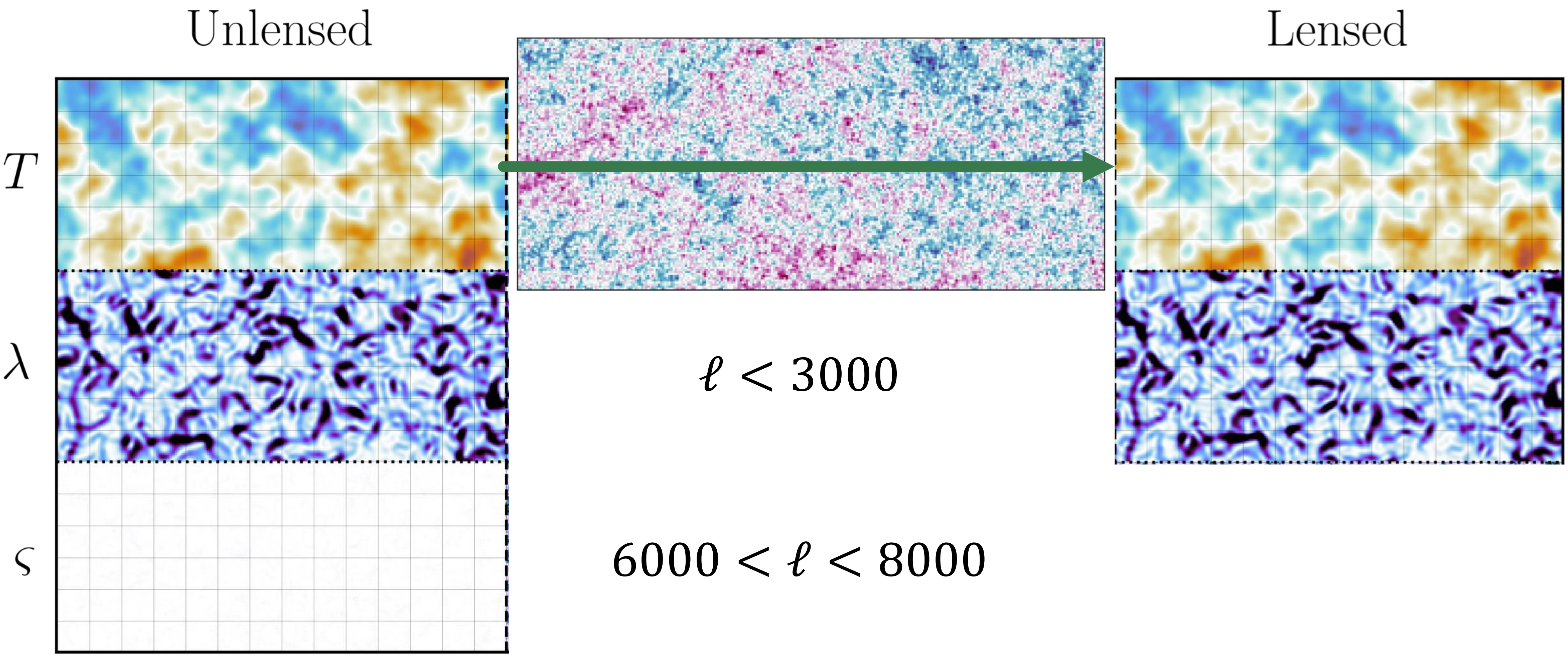
$\ell < 3000$

$6000 < \ell < 8000$

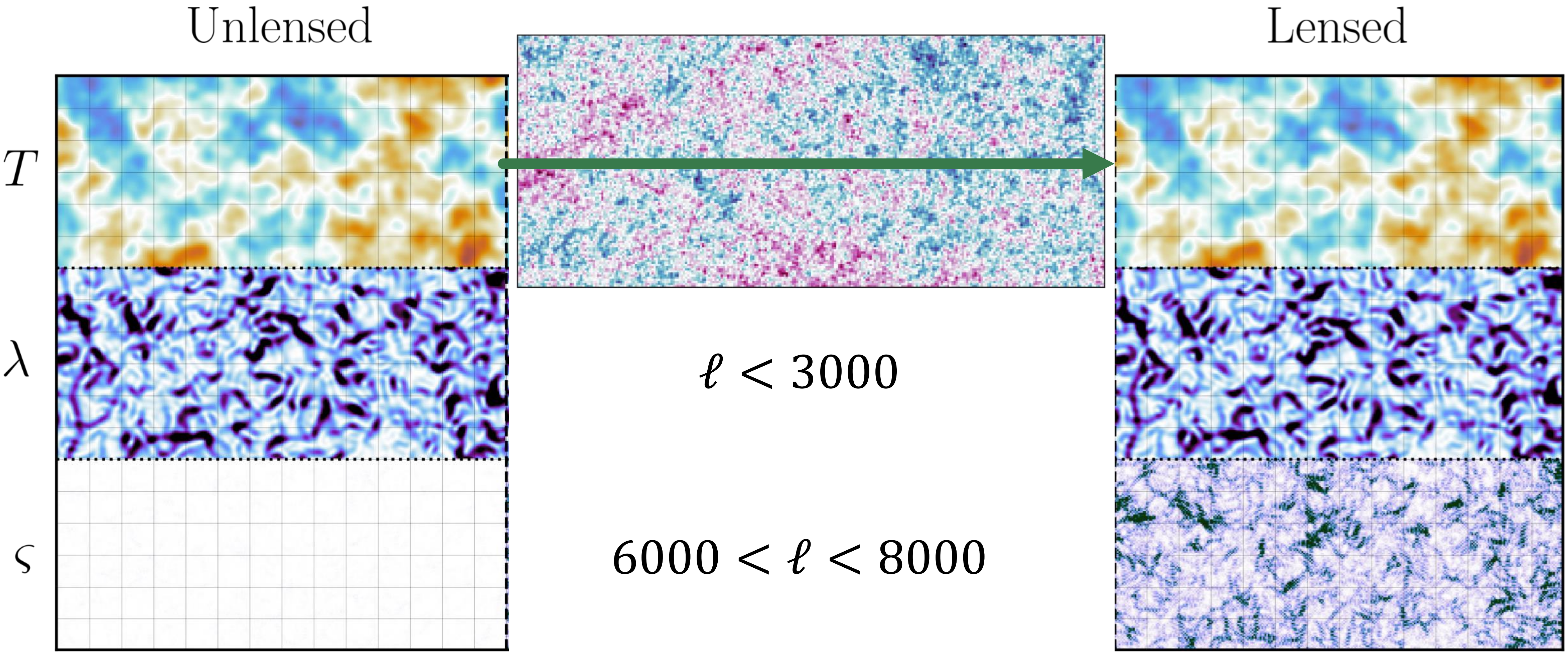
Gravitational lensing alters the observed temperature field



Large-scale features are mostly untouched by lensing



Large-scale features are mostly untouched by lensing
Small-scale features are generated by lensing (correlated with λ)



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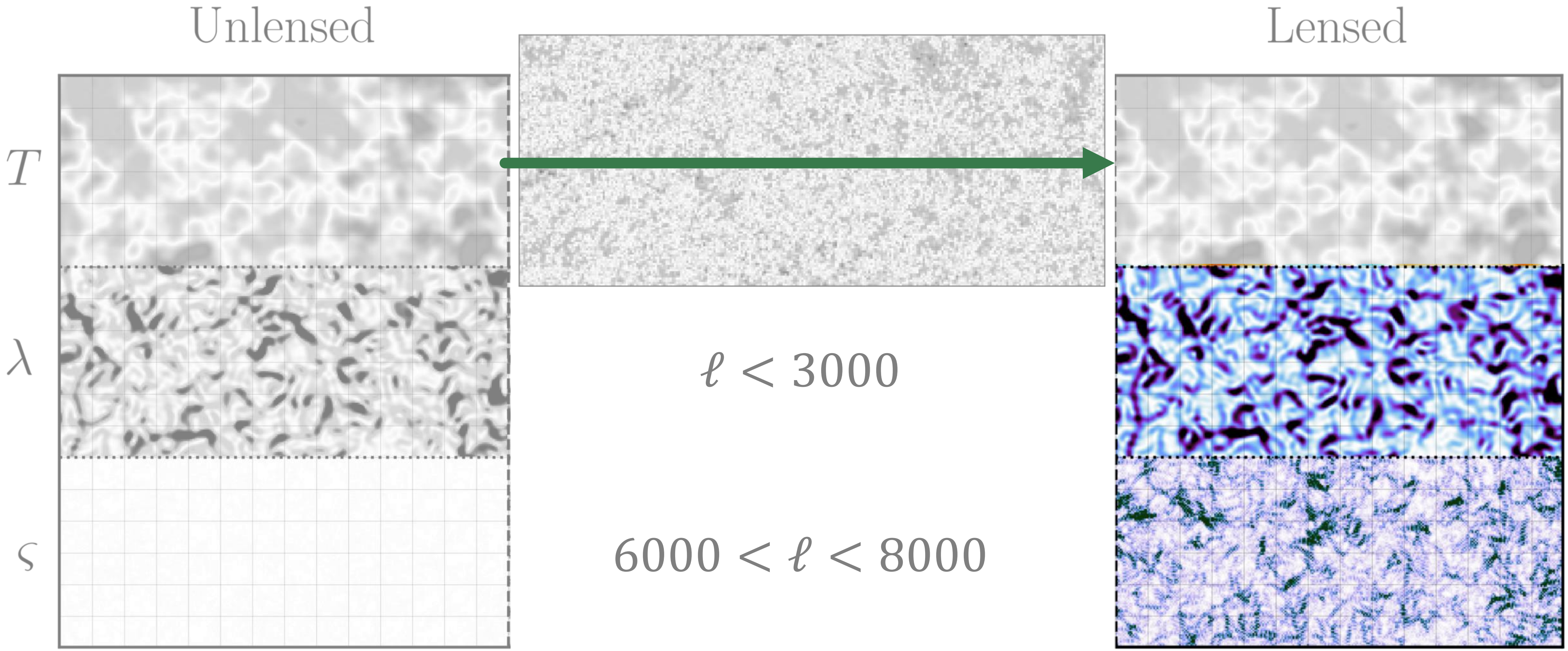
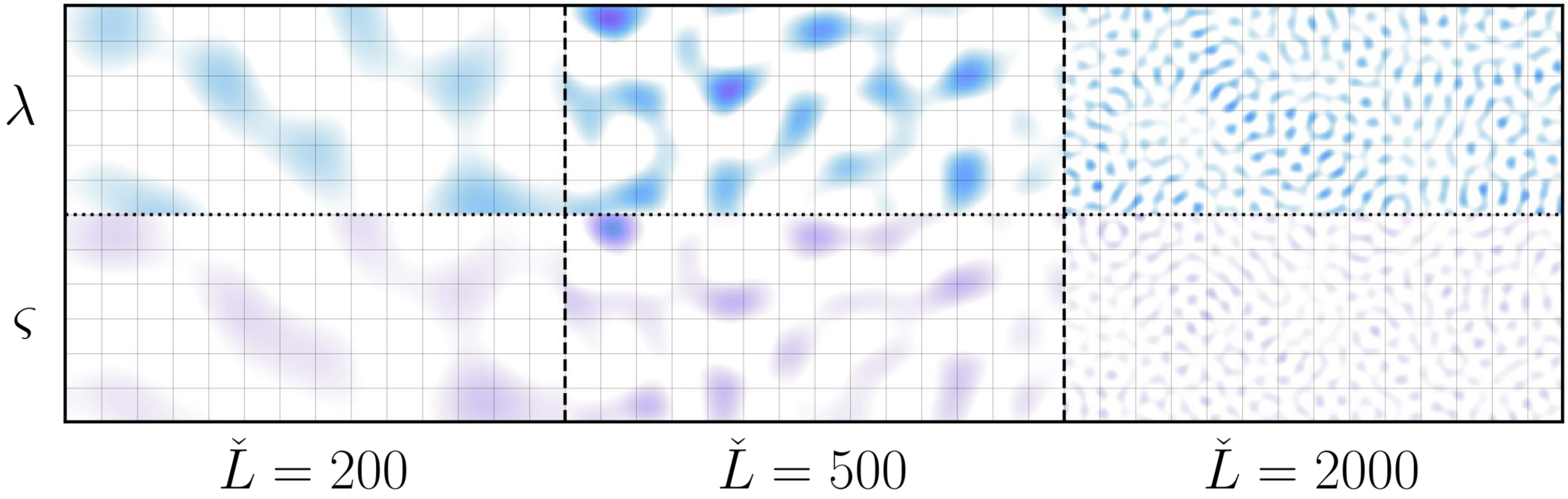
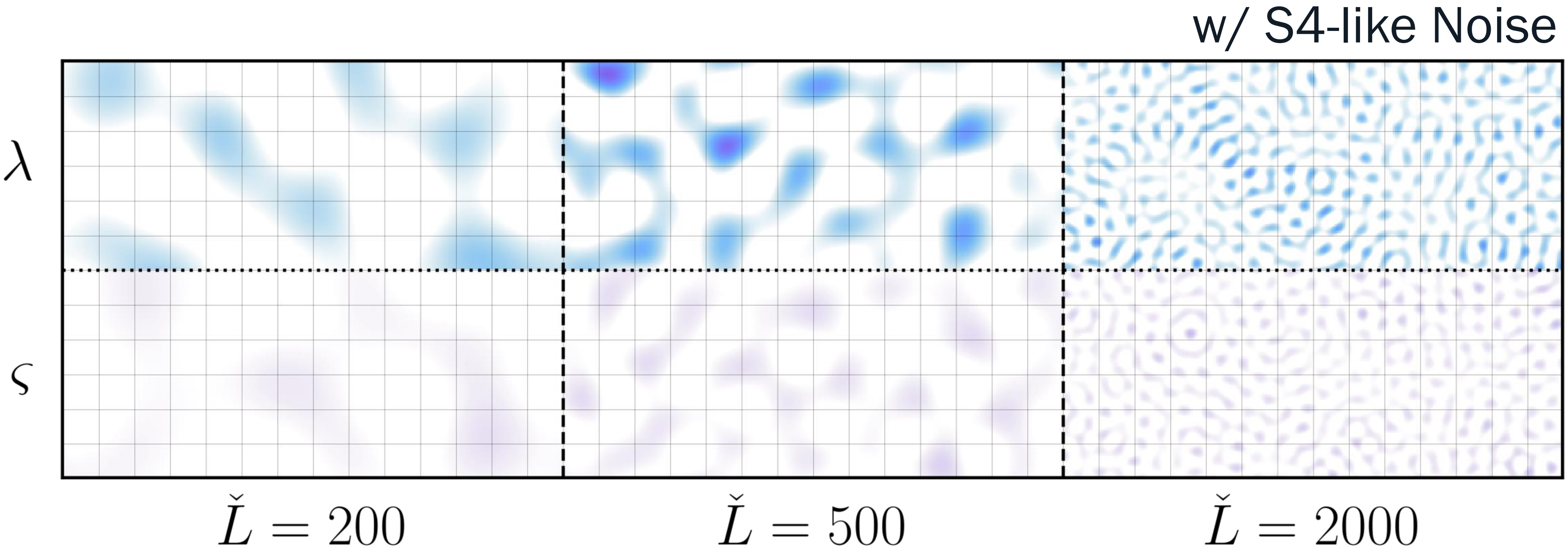


SCALE intermediate products are HIGHLY correlated!!!



Small-scale features from noise can be stronger than lensing signal, but NOT correlated with λ



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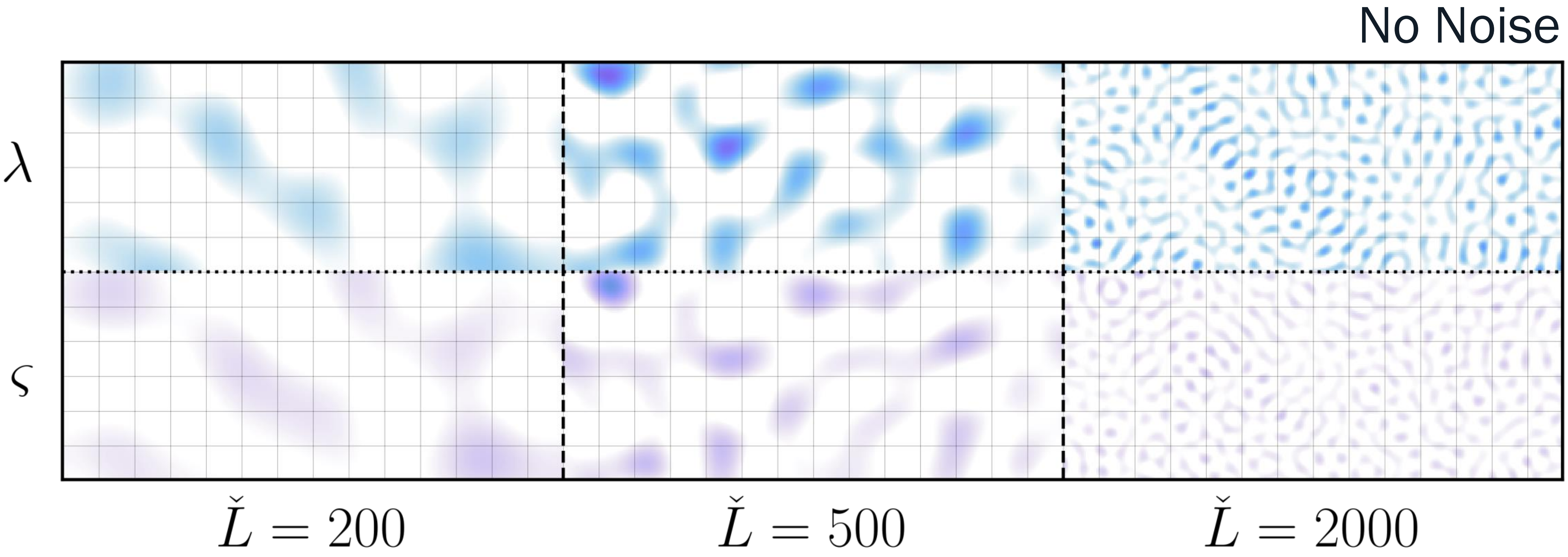
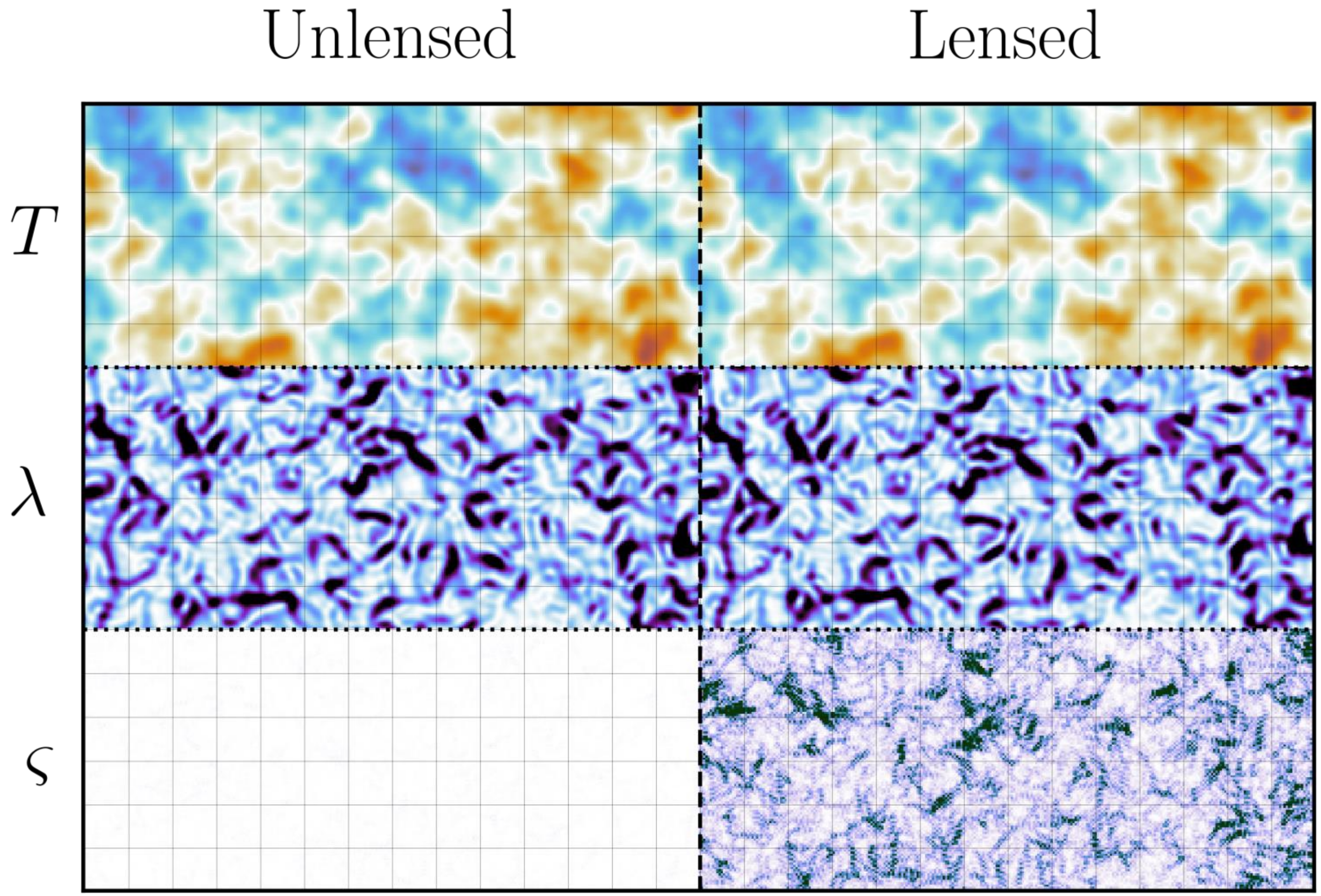
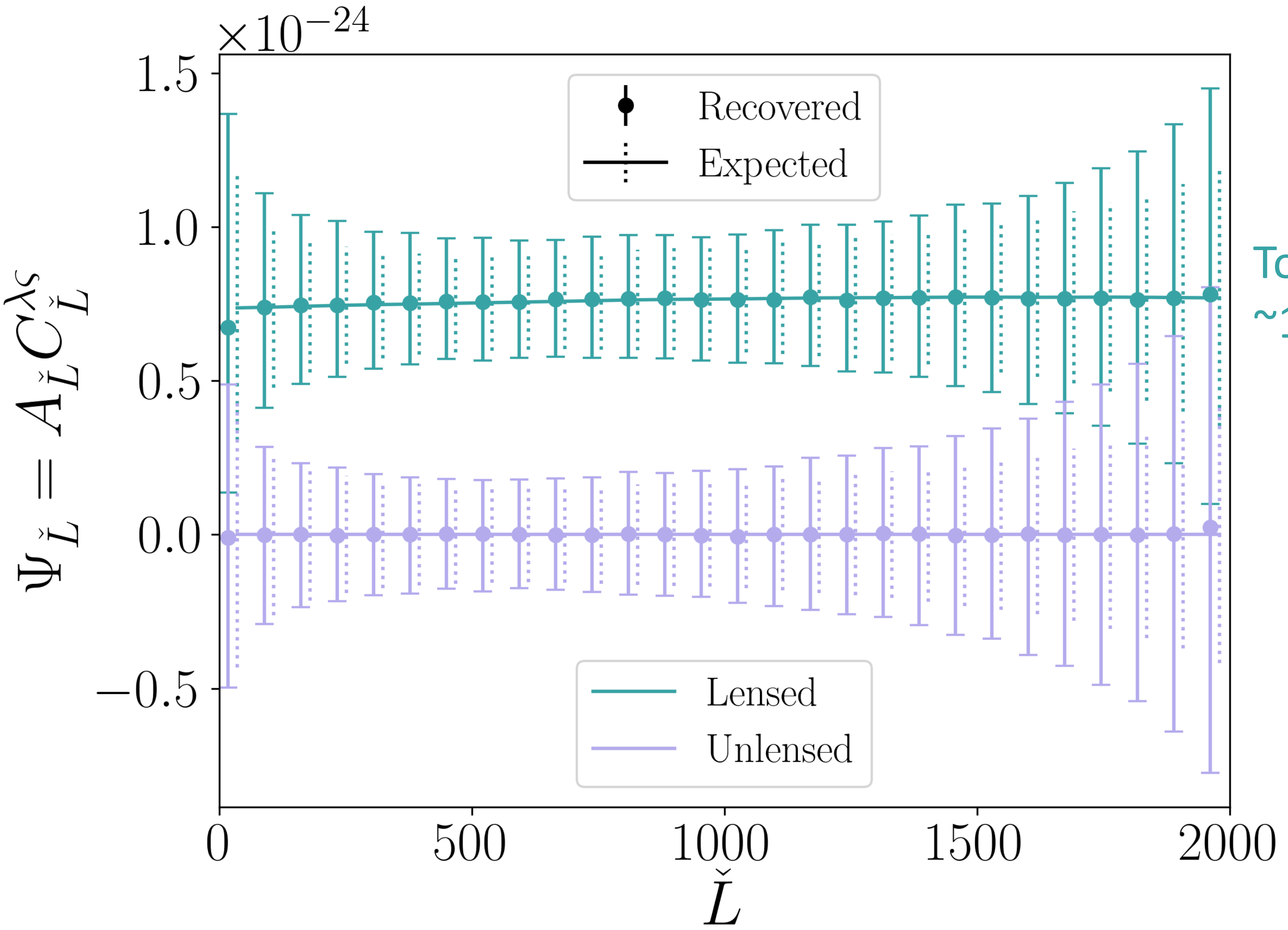


Small-Correlated-Against-Large-Estimator: Process T map into relevant SS/LS lensing info, and cross-correlate

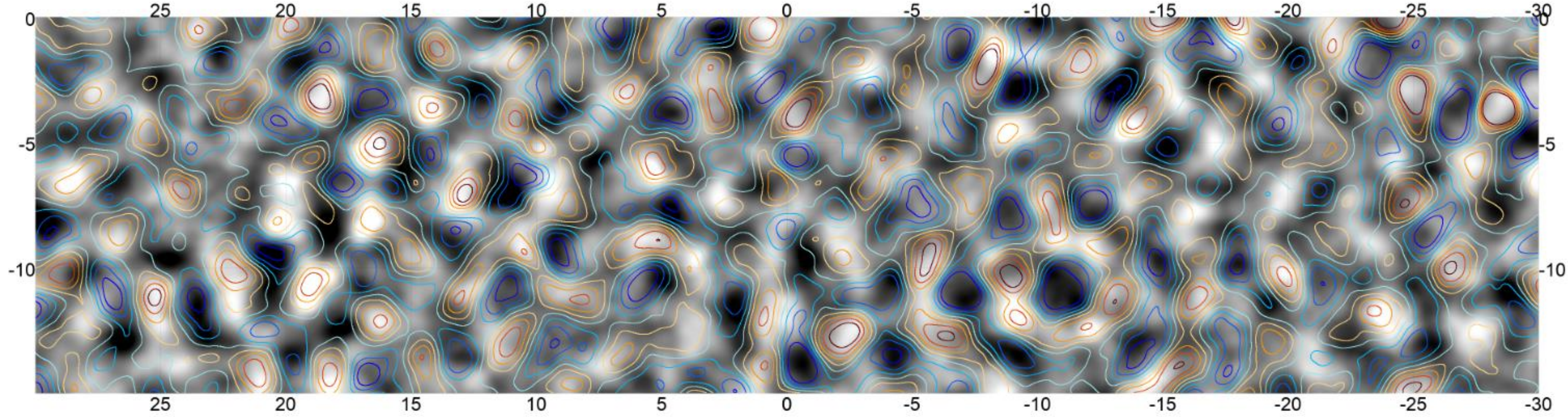




Total SNR ~100

Existing “quadratic estimators” work to statistically “reconstruct” the lensing field

$\phi(\hat{n}) \sim$ All gravity along $\hat{n}$



Madhavacheril+ (ACT, 2023)

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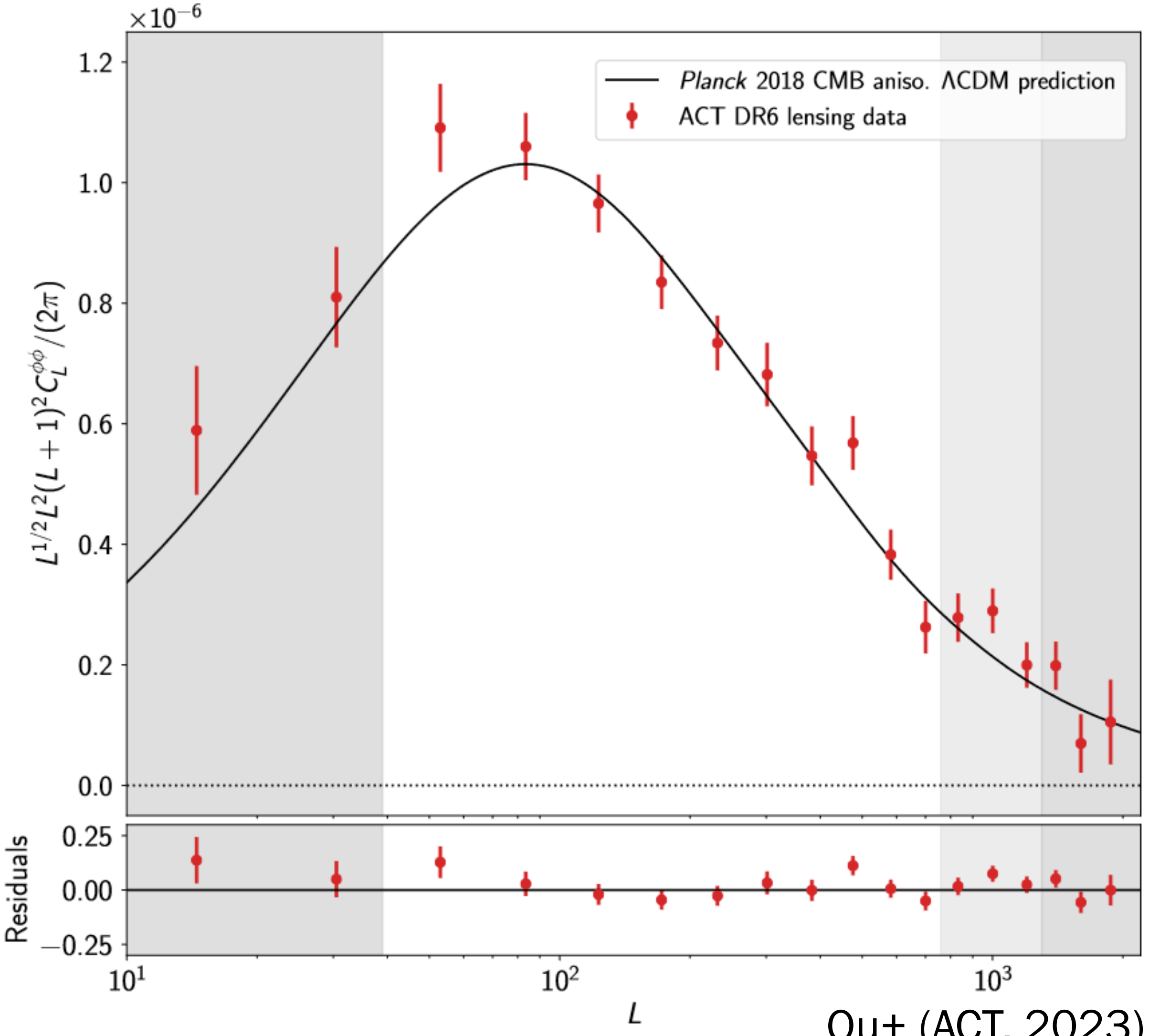
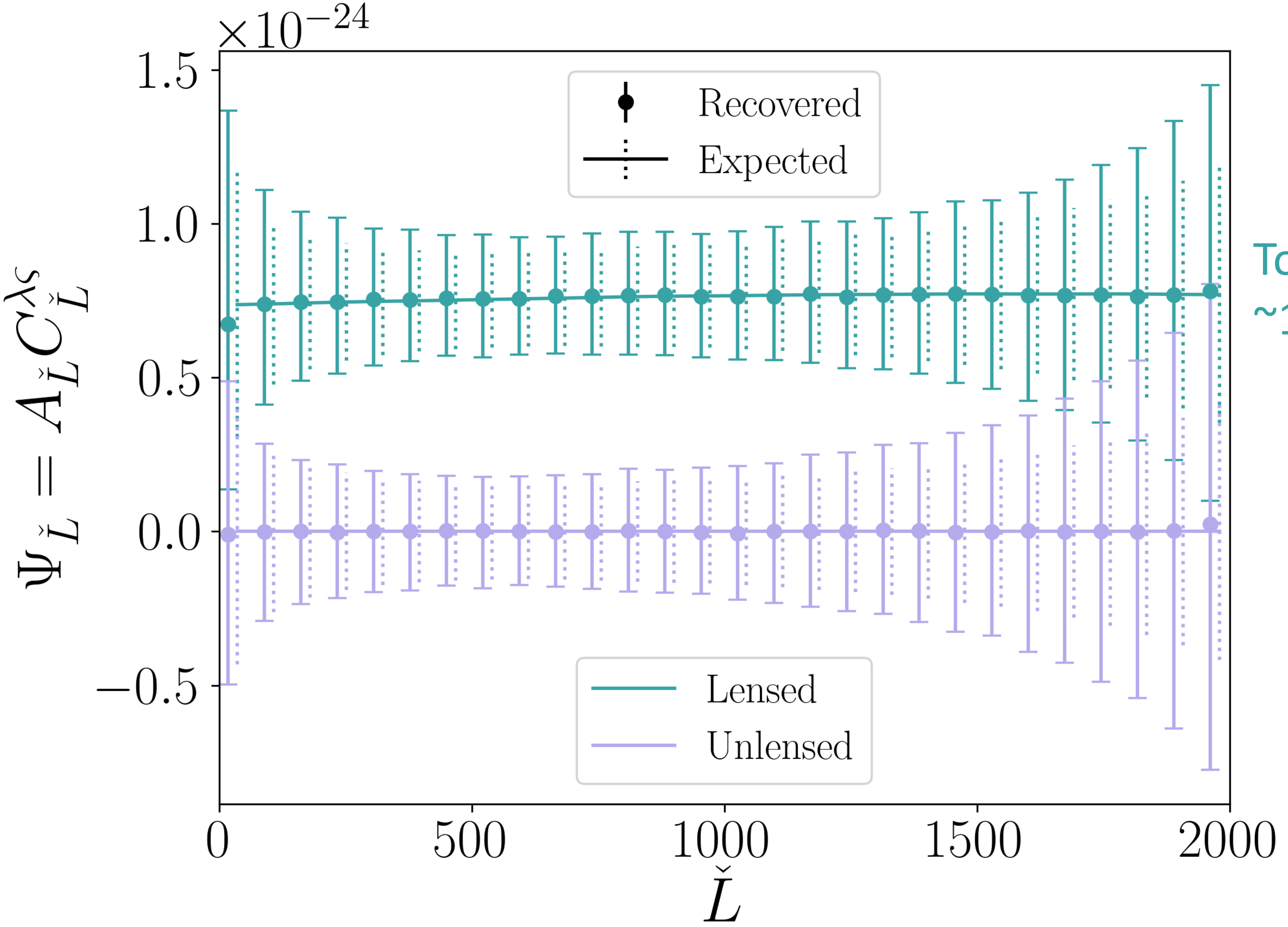


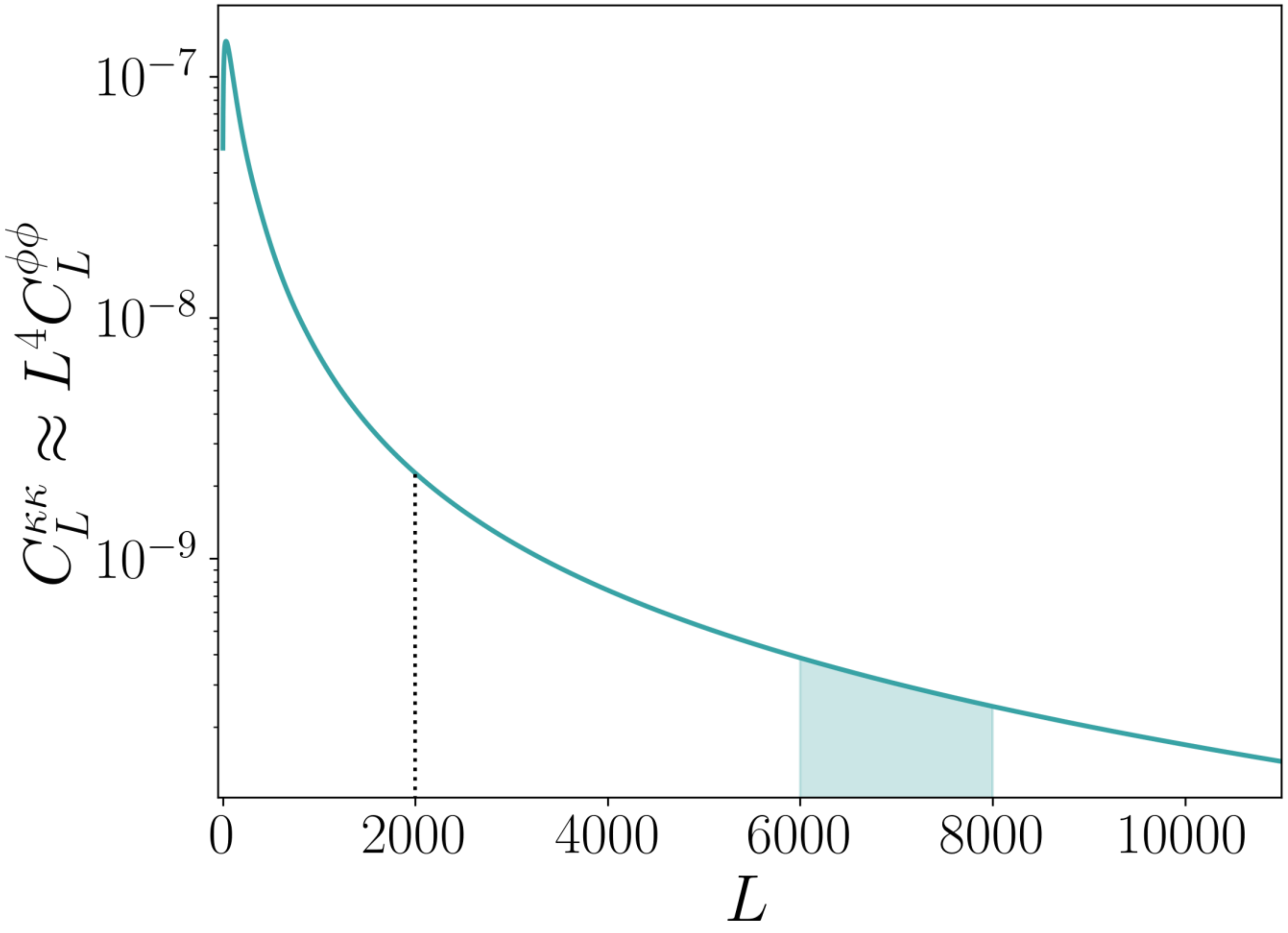
$\phi(\hat{n}) \sim$ All gravity along $\hat{n}$

Qu+ (ACT, 2023)

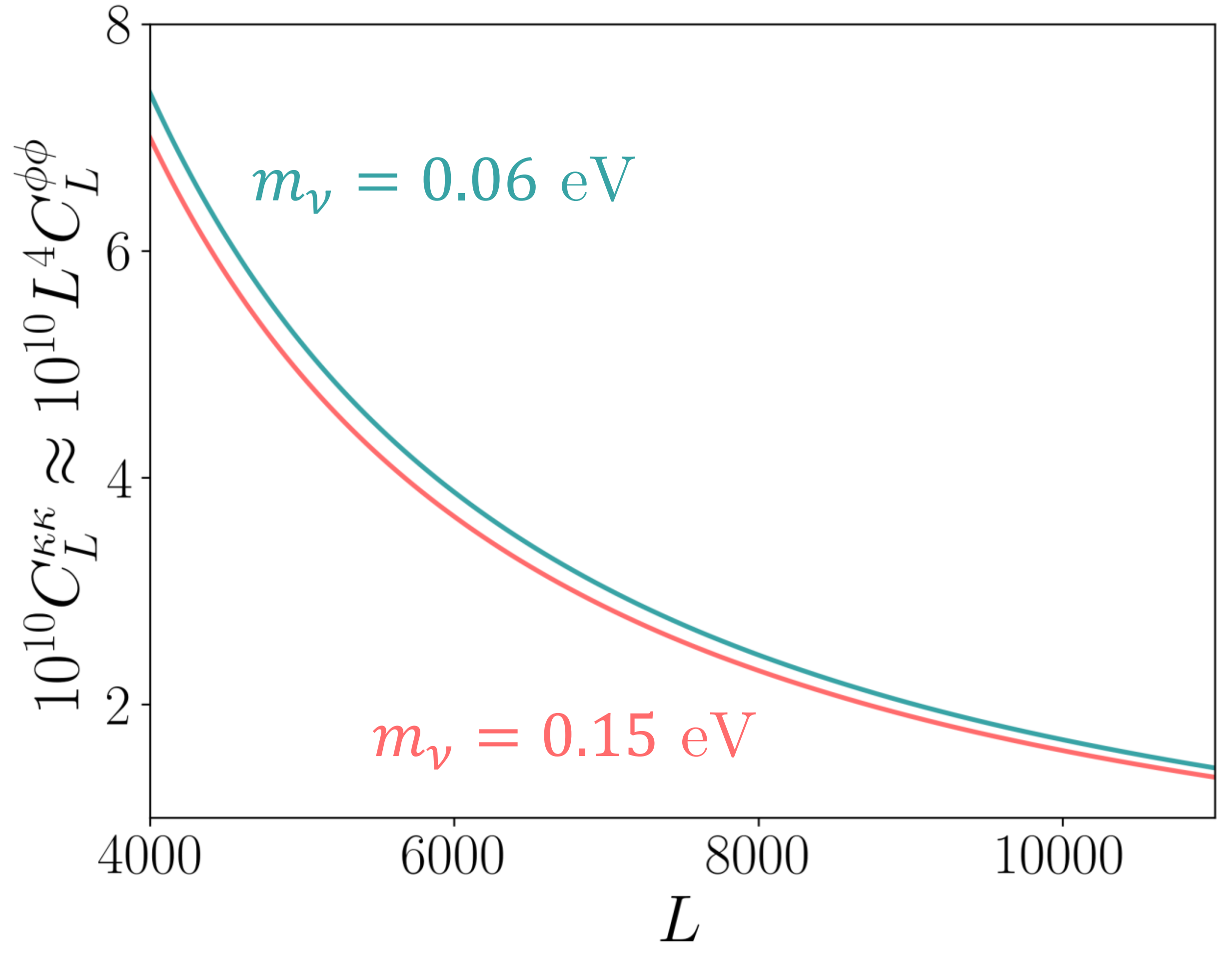


Total SNR
~100

SCALE observables are weighted integrals of the lensing power spectrum over a range of small-scale multipoles



Galaxy clustering models can predict different lensing amplitudes at small scales



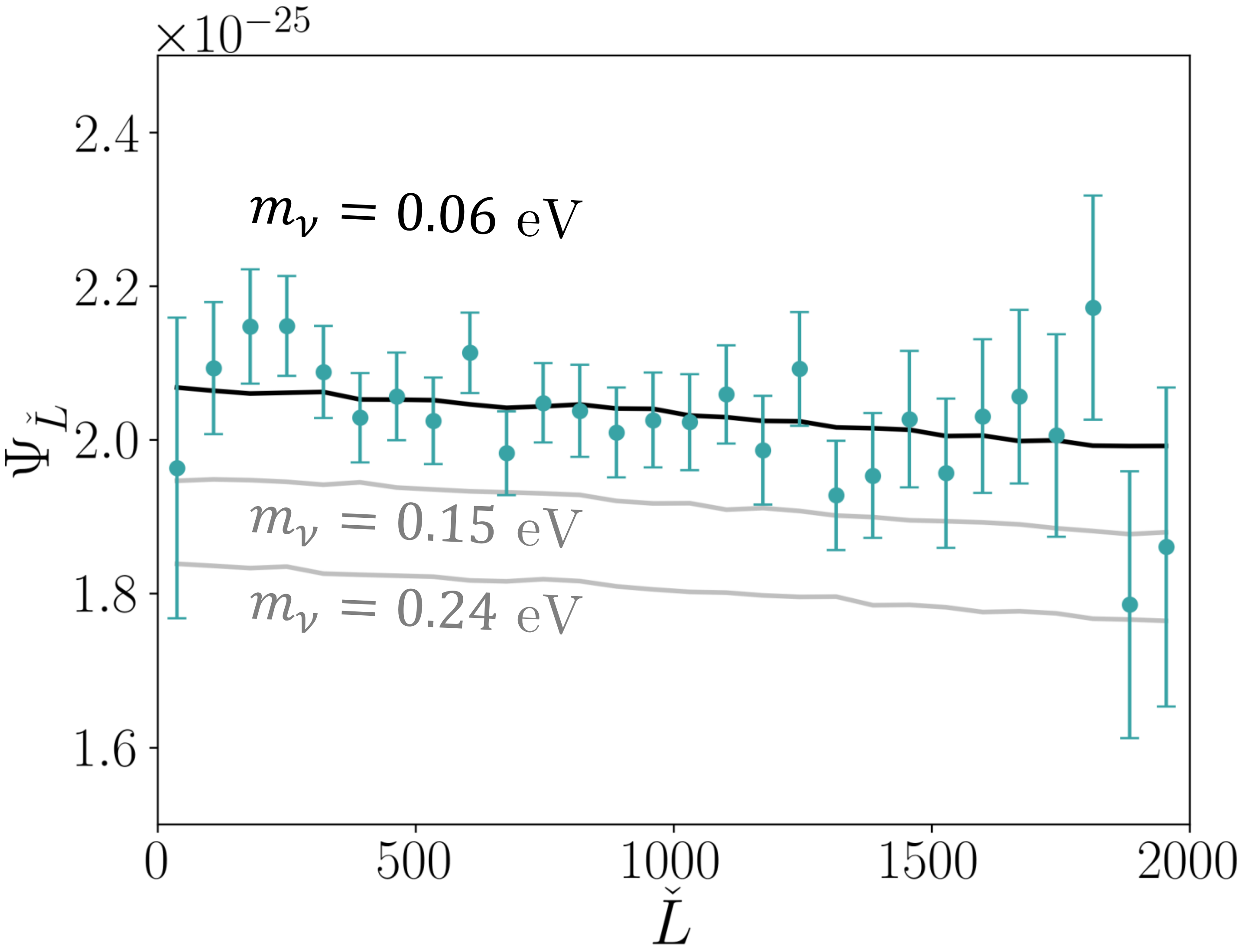
Takeaways:

- Cross-correlations between large- and small-scale cosmic microwave background features accurately recover the underlying lensing amplitude at specific small-scale regimes
- Lensing features at small scales are sensitive to matter clustering: Dark matter, massive neutrinos, more!

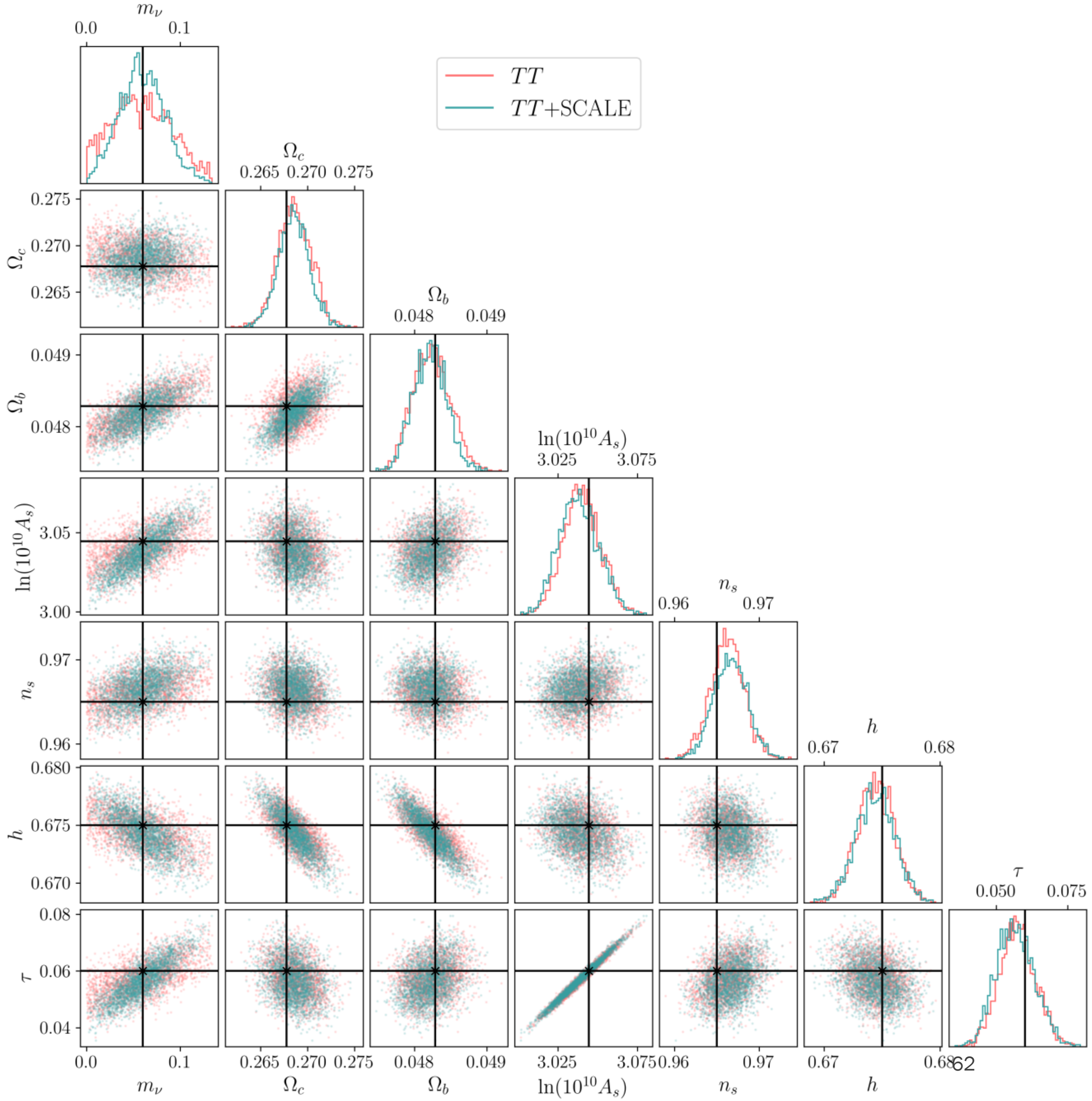
HOW DO WE APPLY SCALE TO GET PHYSICAL PARAMETERS?

SCALE observables depend on matter clustering parameters

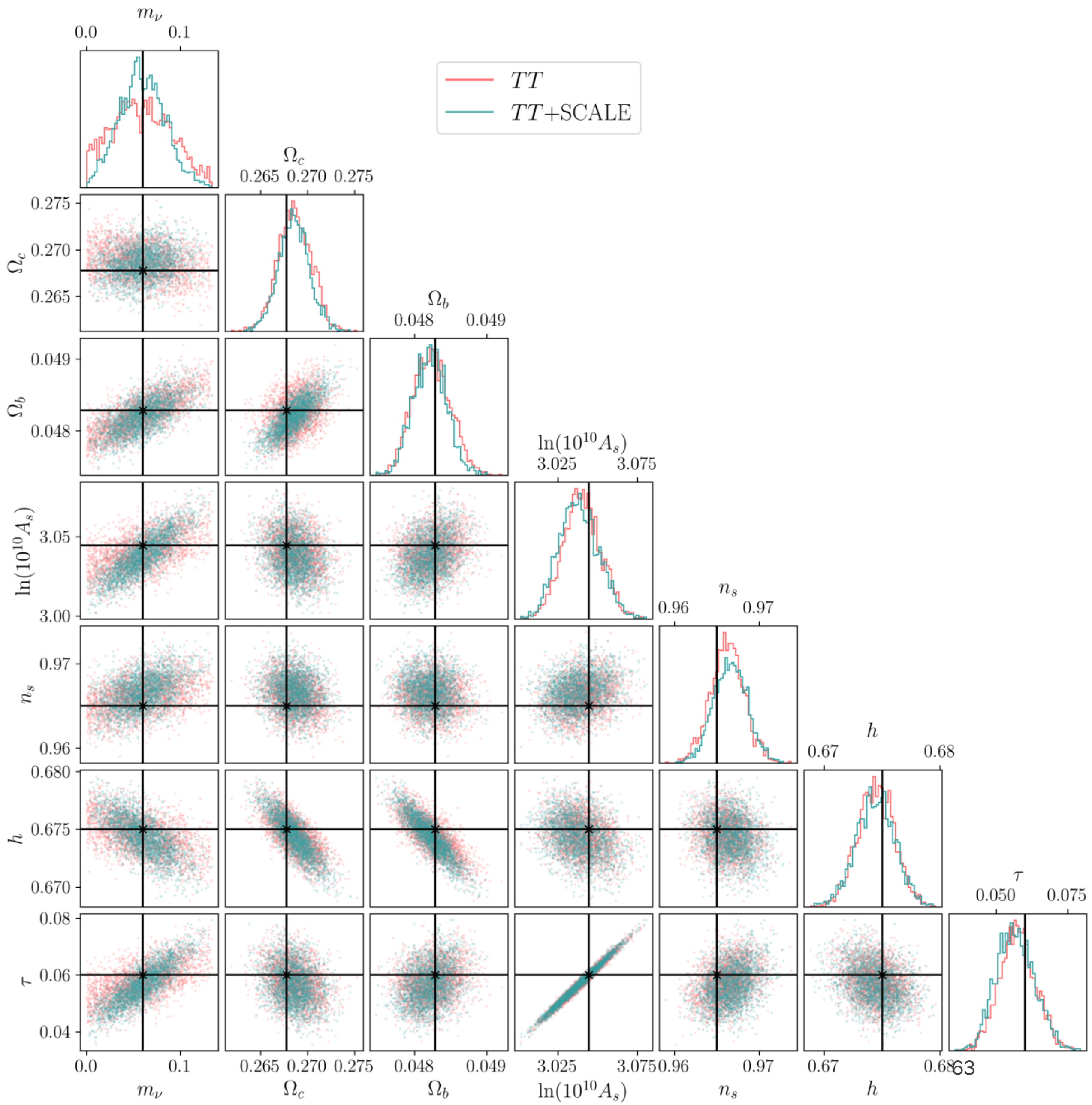
Recall more mass in neutrinos means less concentrated clusters, or weaker lensing



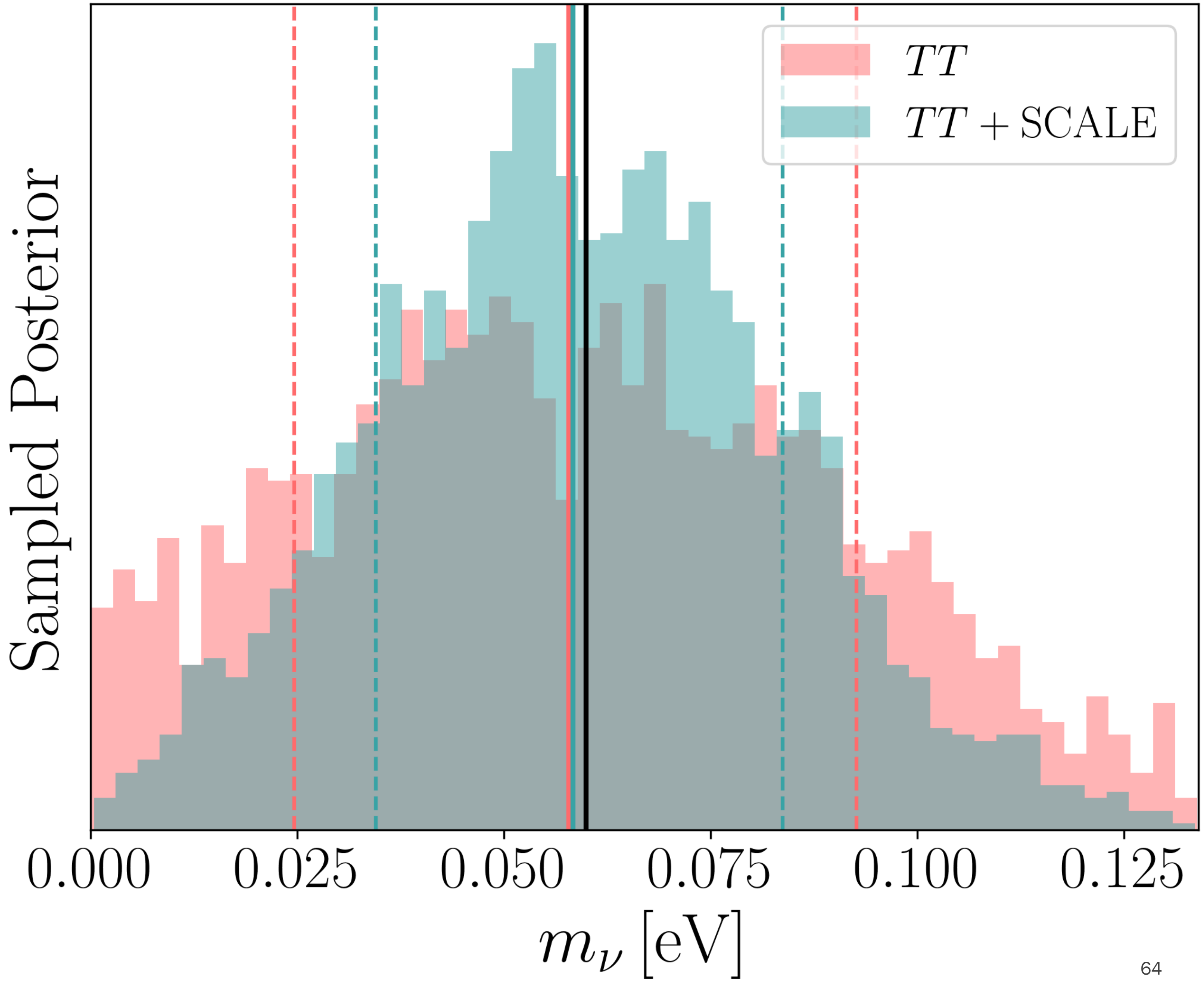
Cosmic microwave background observables can measure standard cosmological model parameters to high precision



Small-scale clustering parameters are sensitive to SCALE observables



SCALE enables a detection of the minimum neutrino mass!

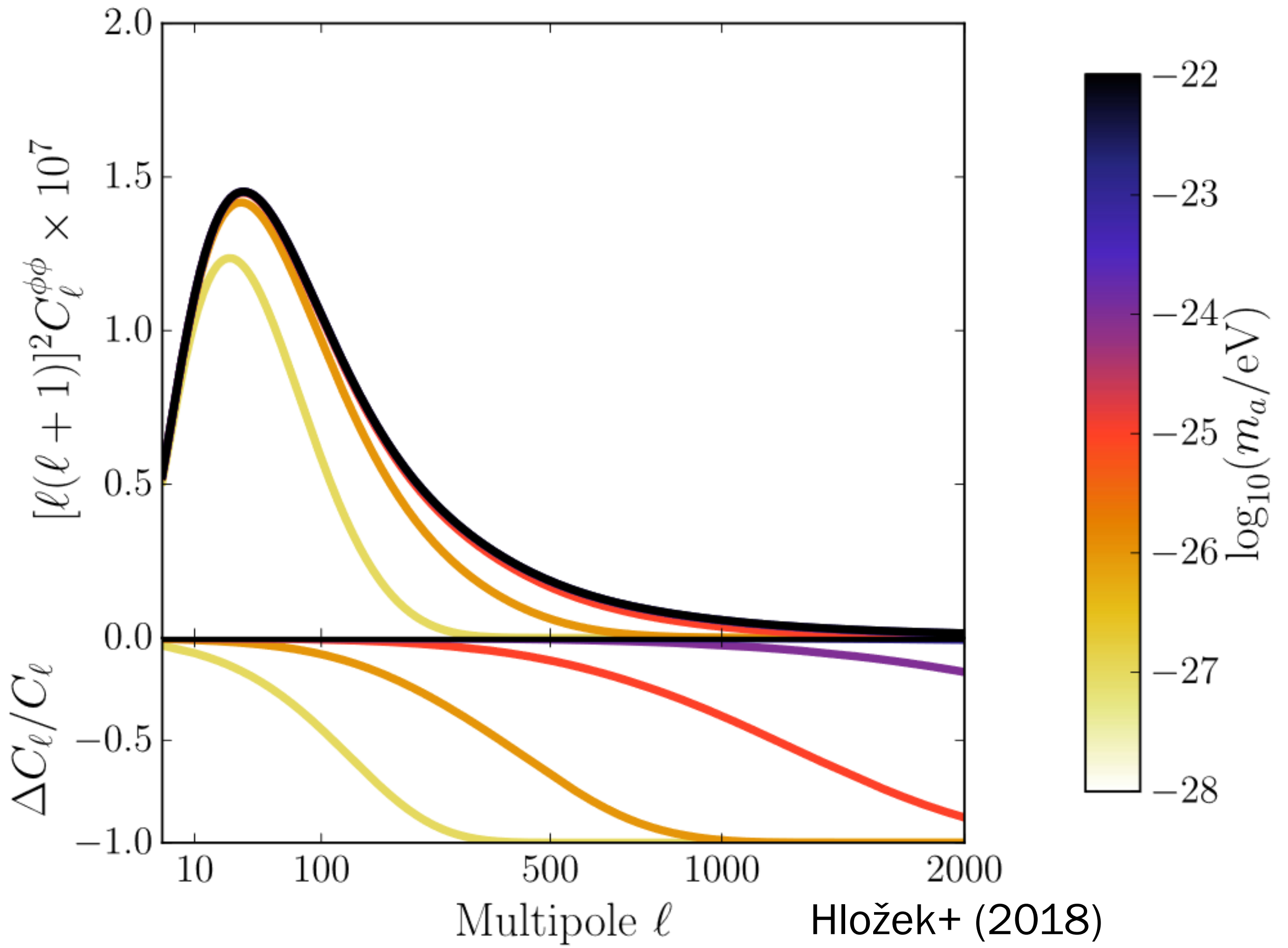


Takeaways:

- Neural network emulators can predict SCALE expected values given cosmological parameters
  - ~10^4 improvement in speed with <1% scatter
- Lensing information provided by SCALE enables a detection of the minimum neutrino mass!

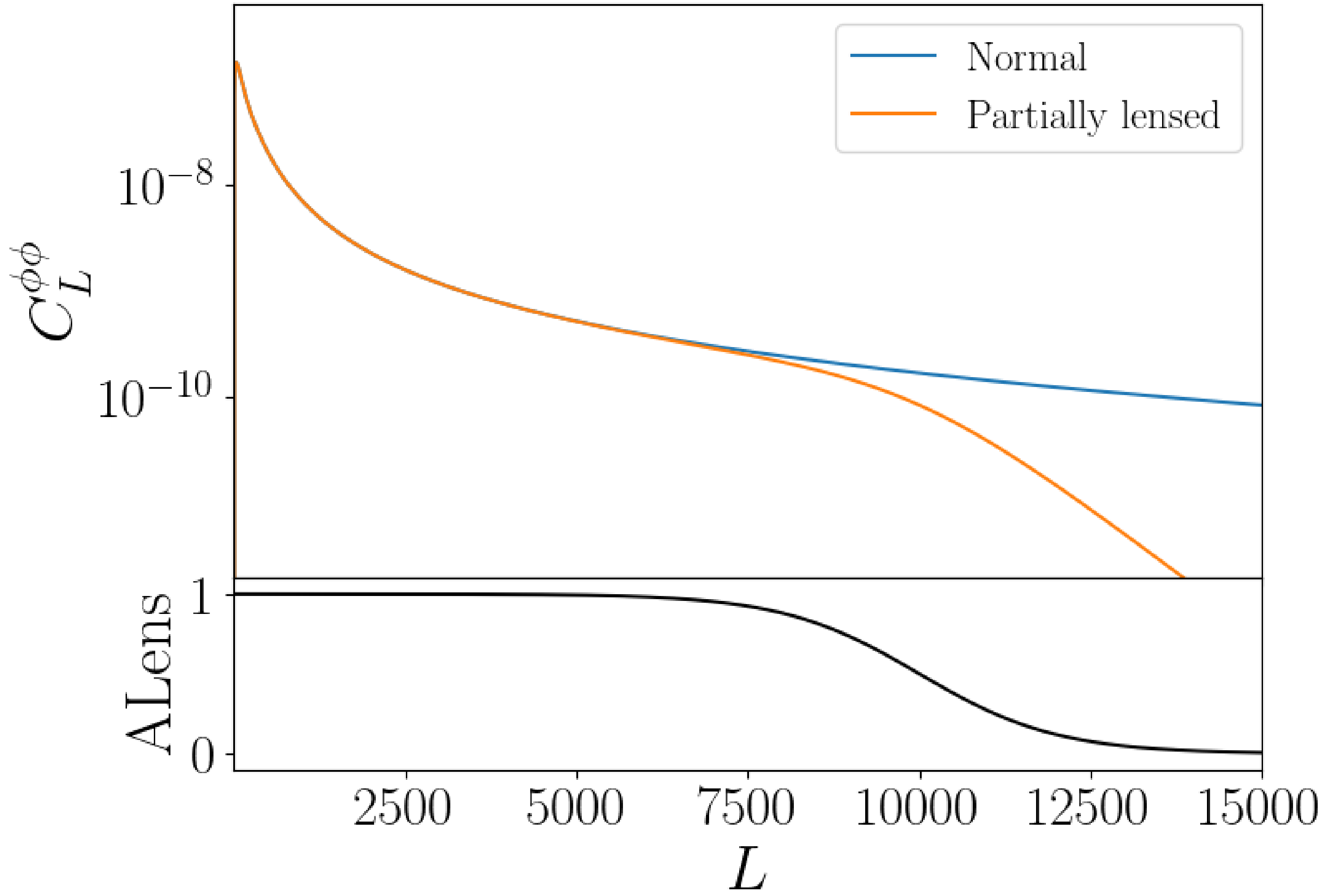
CAN WE LEARN ABOUT WAVY DARK MATTER?

Dark matter models can predict both amplitude and shape changes to the lensing power spectrum → largest effect at smaller scales



Hložek+ (2018)

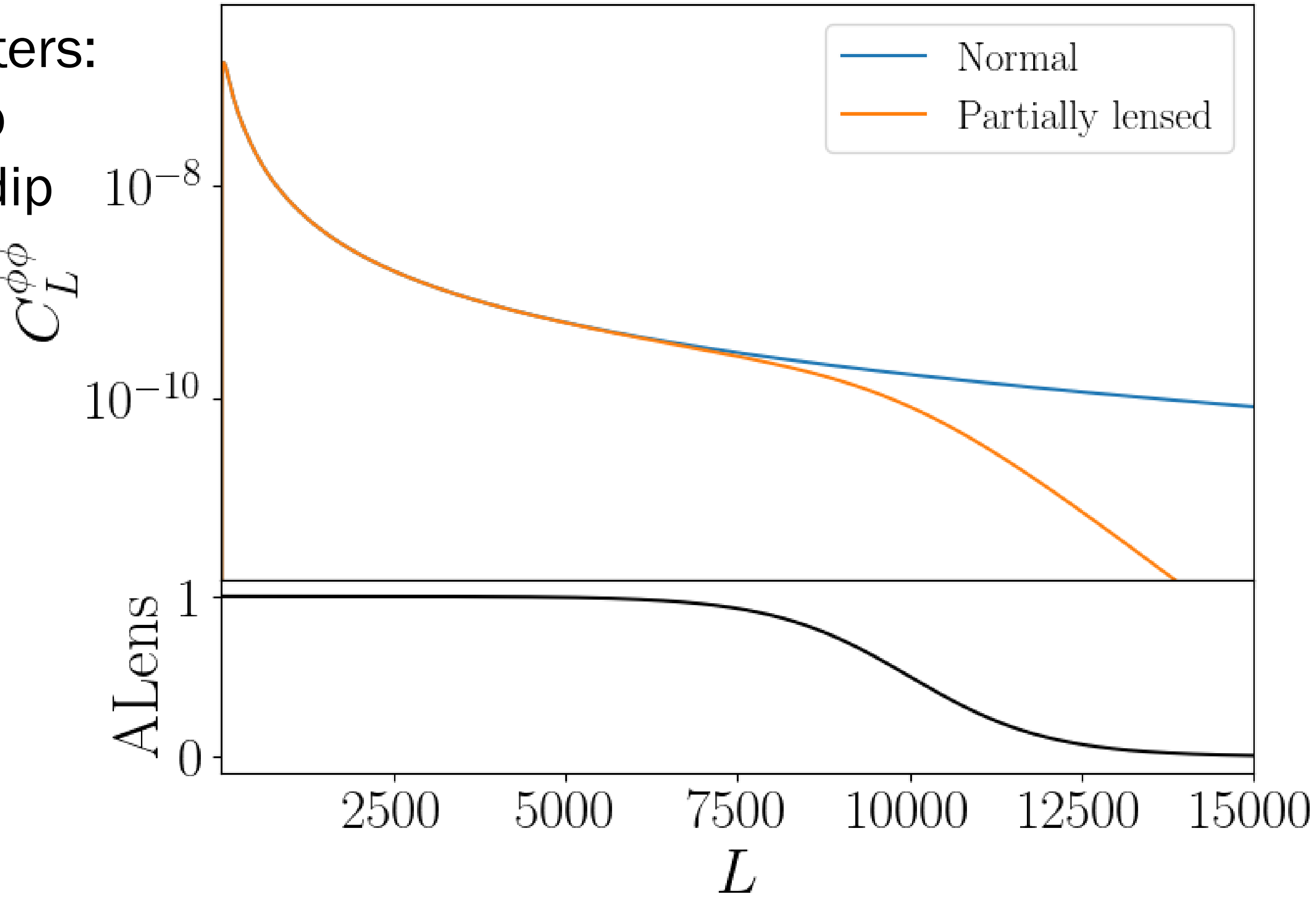
We can simulate CMB lensing with a suppressed lensing power spectrum → SCALE works the same



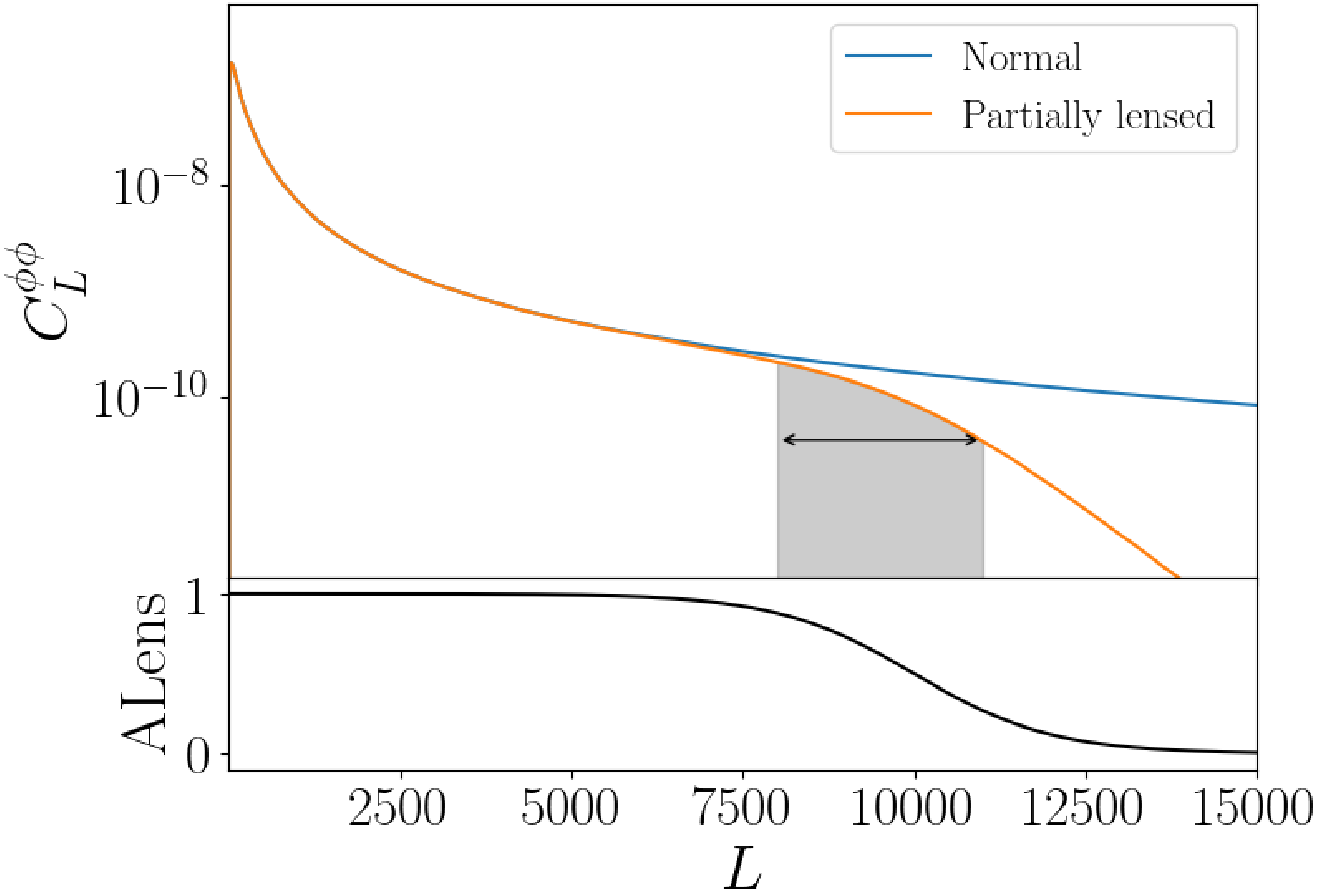
We can simulate CMB lensing with a suppressed lensing power spectrum → SCALE works the same

Add new parameters:

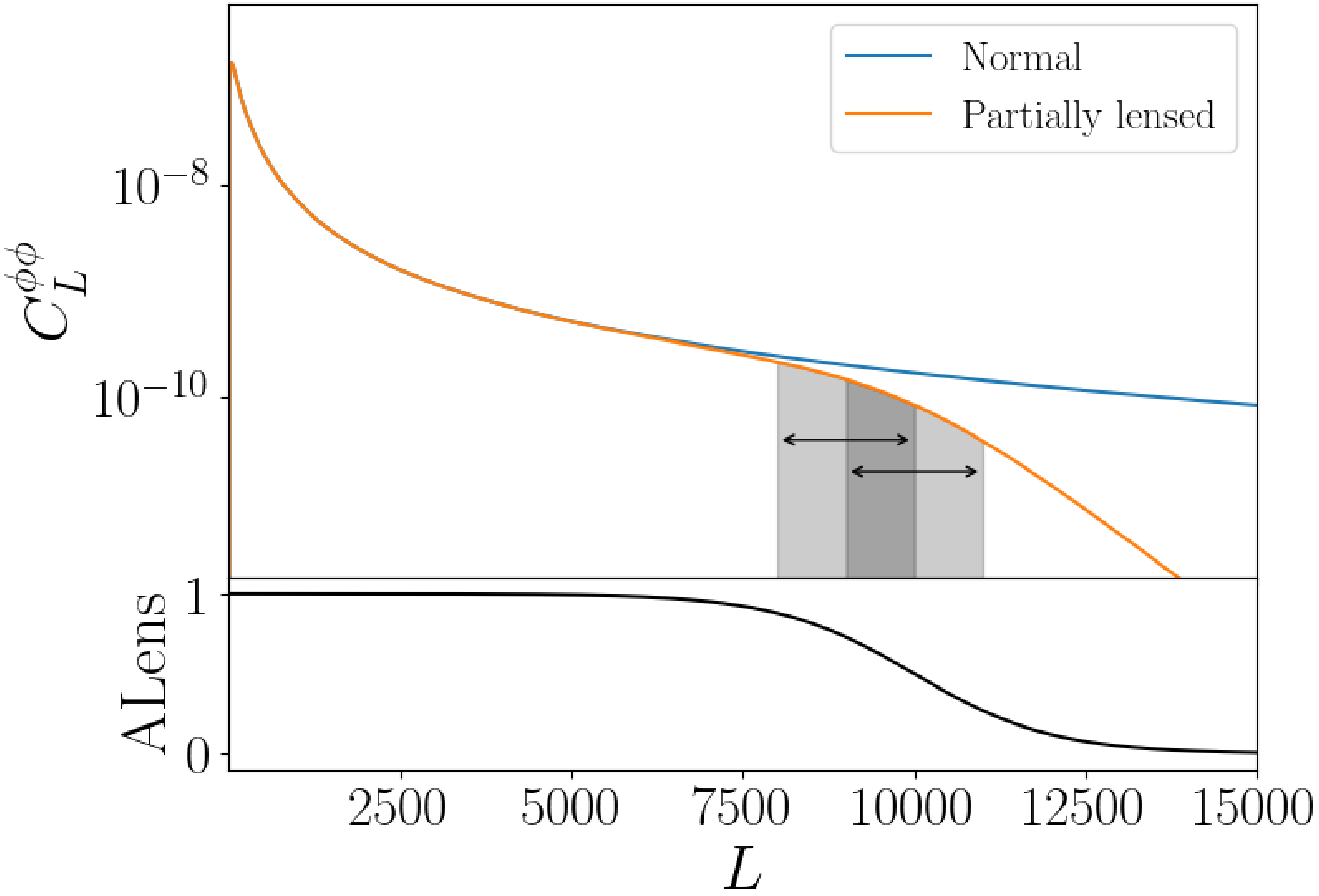
1. Location of dip
2. Steepness of dip



We may choose one version of SCALE → One lensing amplitude

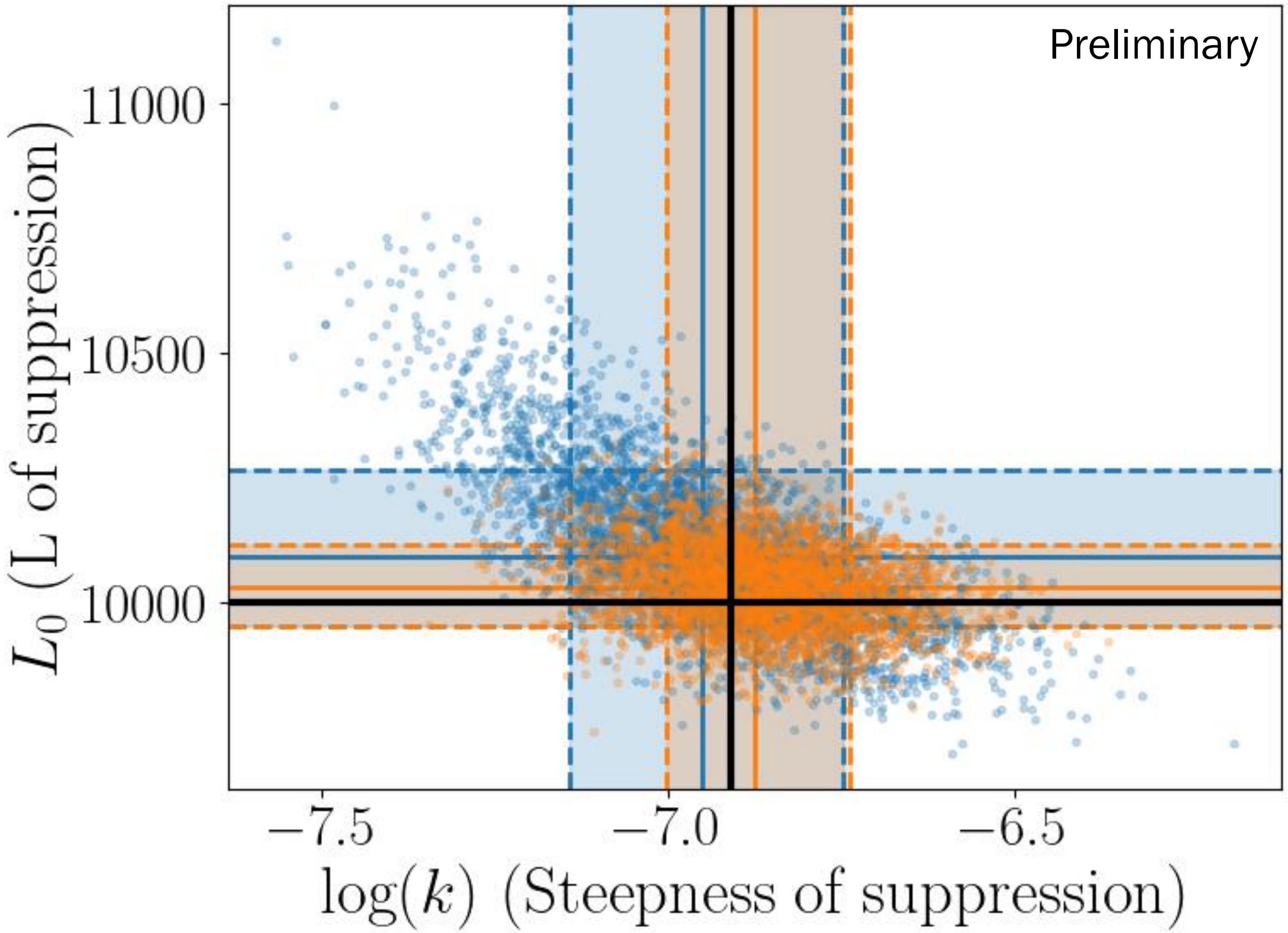


Two 'versions' of SCALE → Two lensing amplitudes → Shape change



$8000 < \ell_1 < 11000$: **Banana-shaped degeneracy**

$8000 < \ell_1 < 10000$ **&** $9000 < \ell_1 < 11000$: **Less degen. Tighter dist.**



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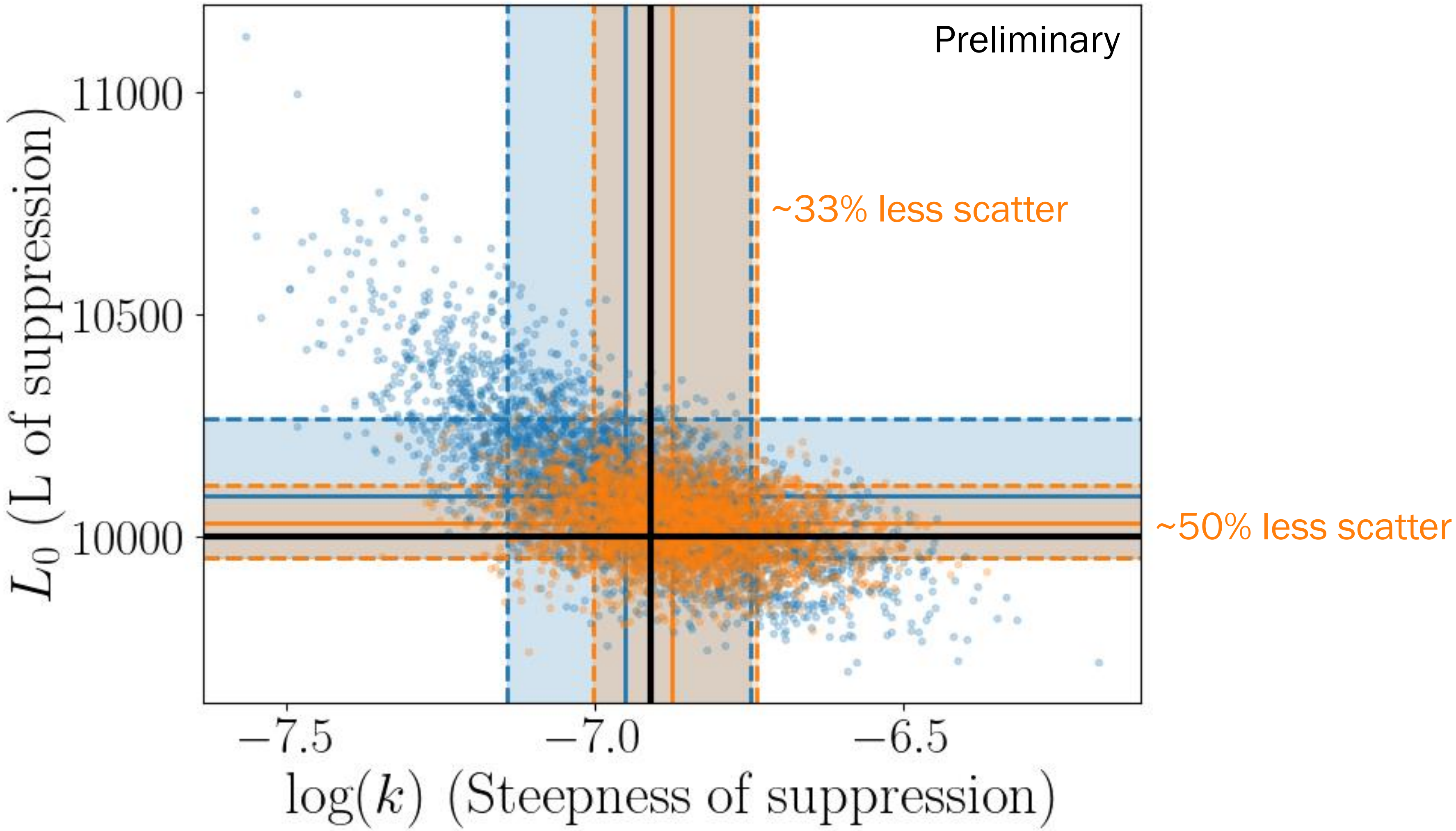
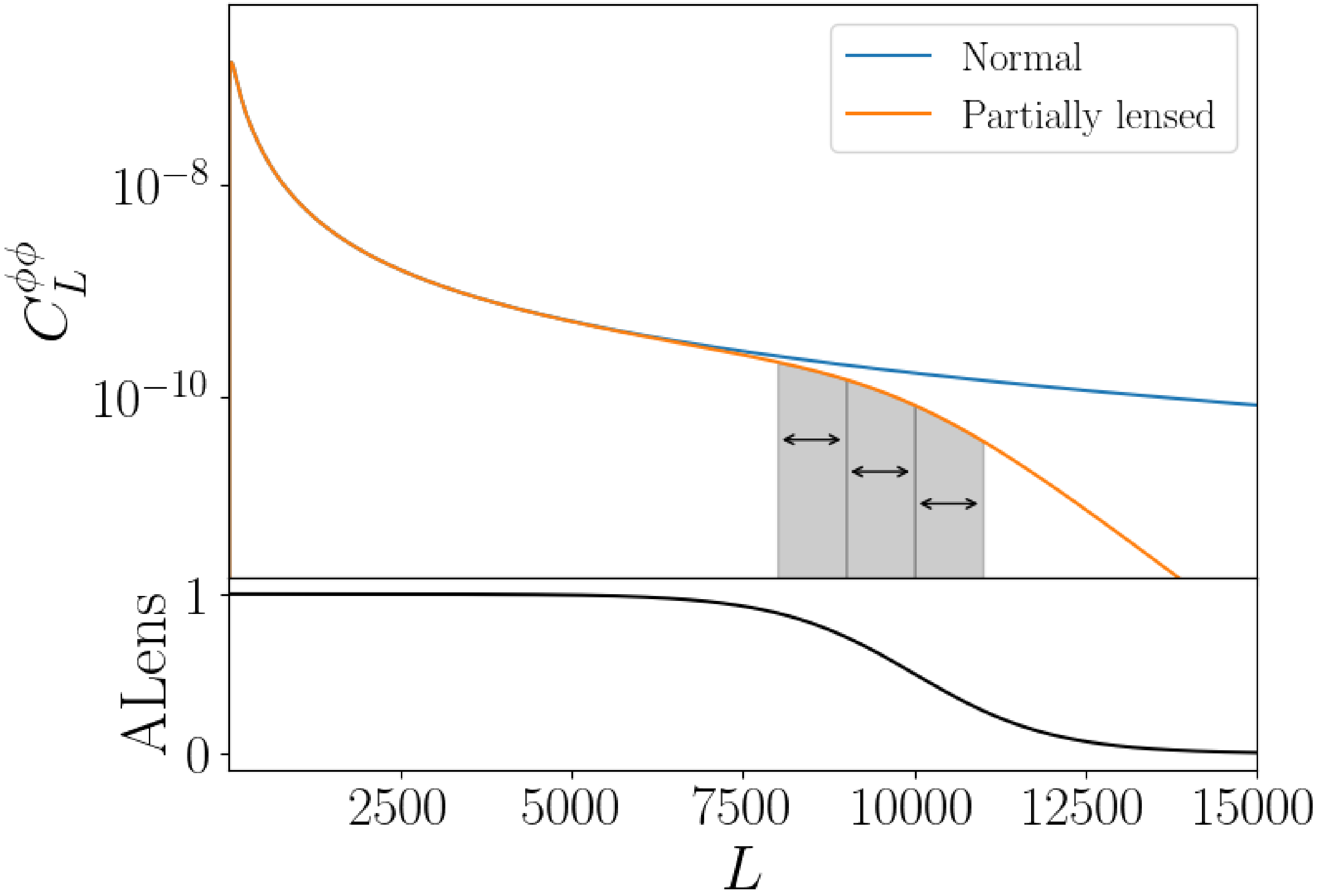
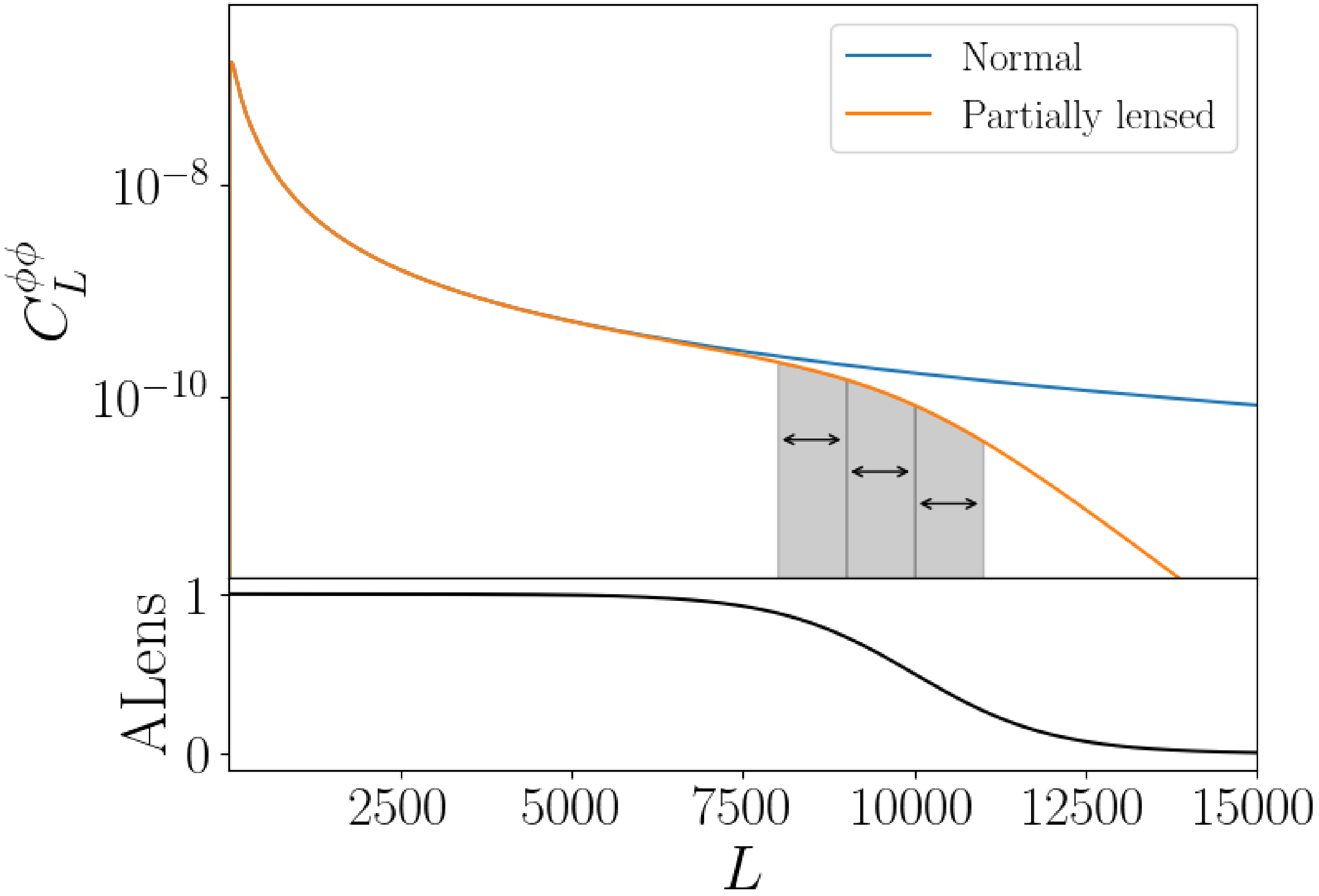


Do more applications of SCALE constrain more shape information?



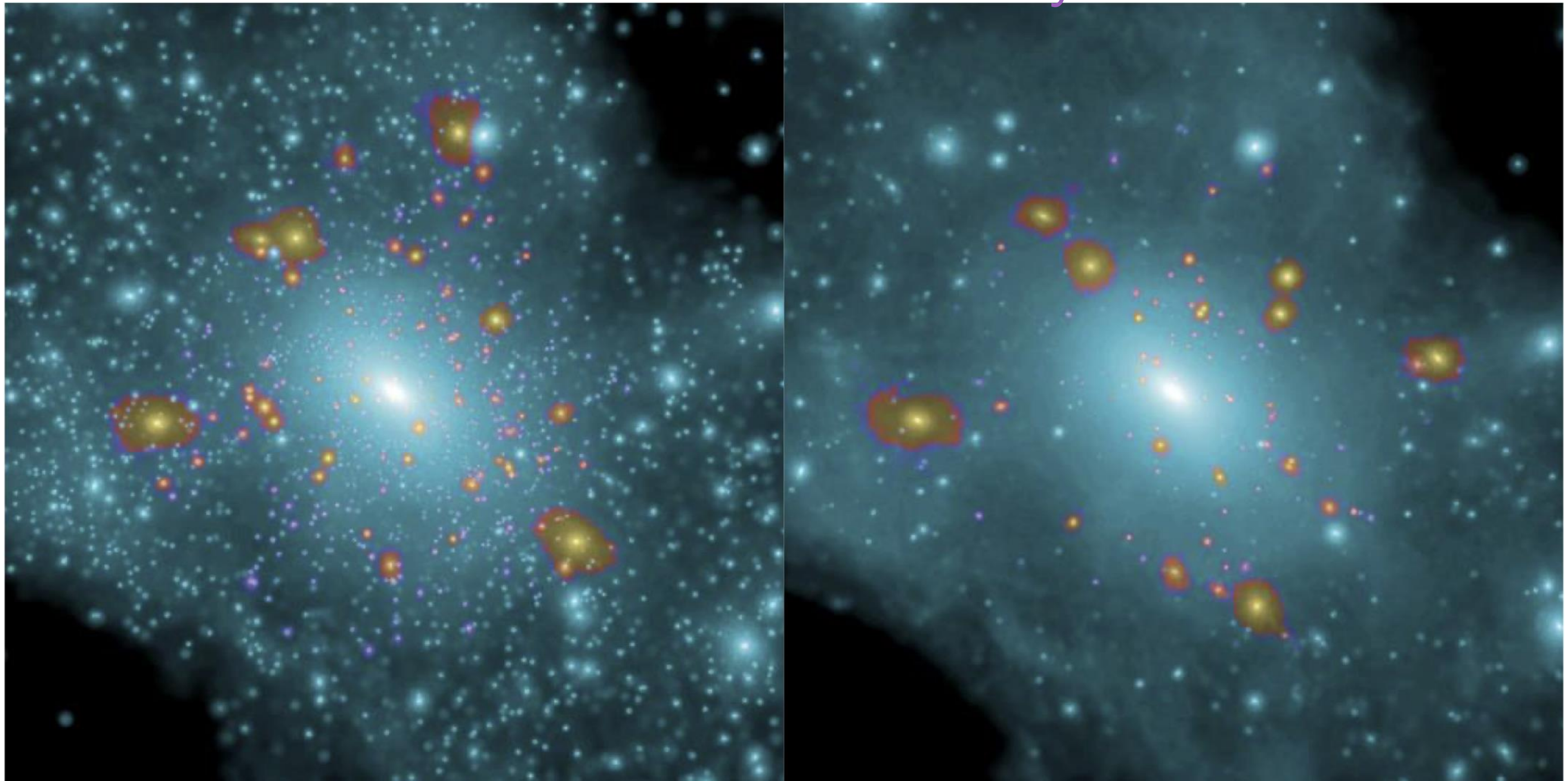
Do more applications of SCALE constrain more shape information?

Doesn't seem like it, but what's the optimal choice?



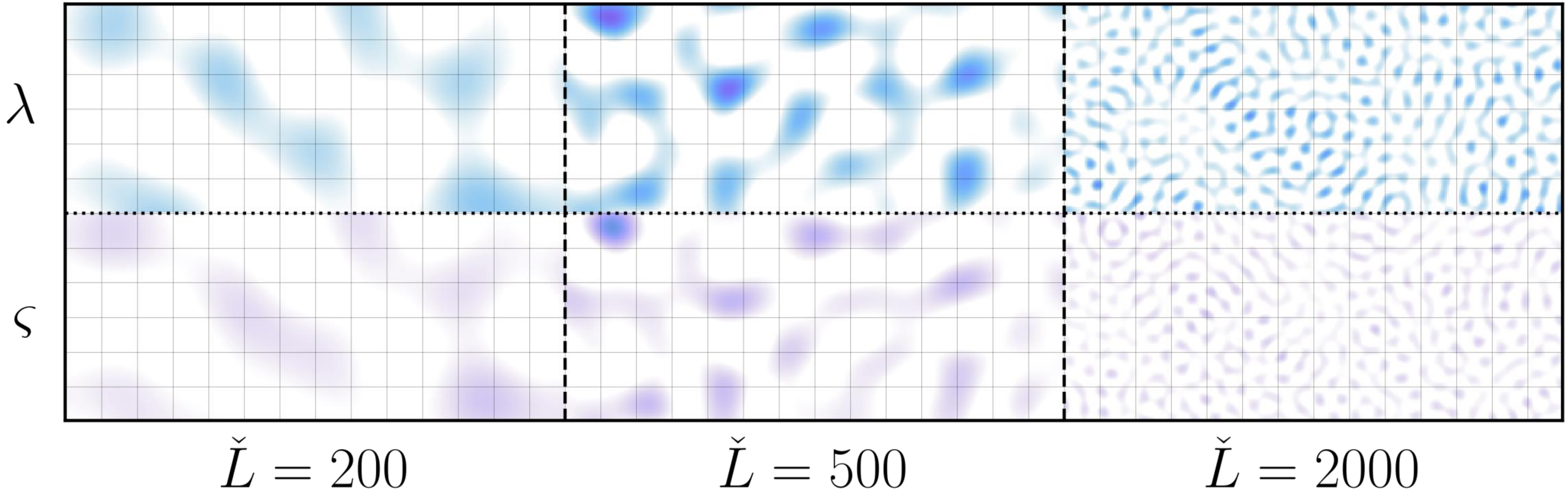
- Galaxy clusters at small-scales are sensitive to clustering physics such as dark matter models, massive neutrinos, and gravity

Cold Dark Matter | Wavy Dark Matter



ESA (2023)

- Galaxy clusters at small-scales are sensitive to clustering physics such as dark matter models, massive neutrinos, and gravity
- We have developed a novel estimator for the lensing amplitude by correlating cosmic microwave background features at large/small scales



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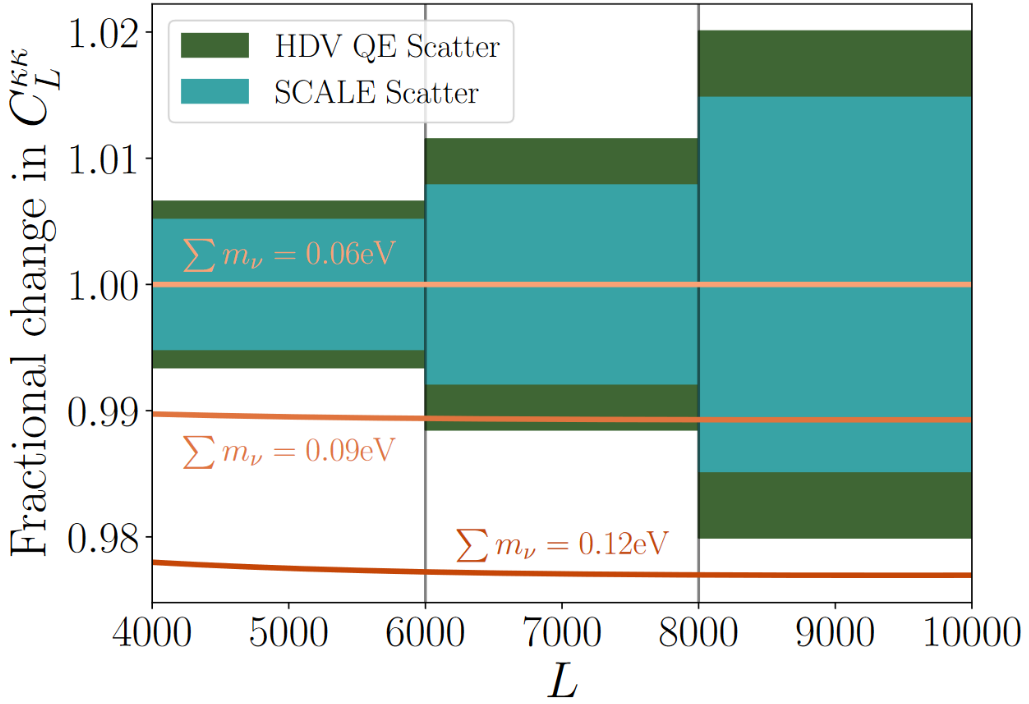

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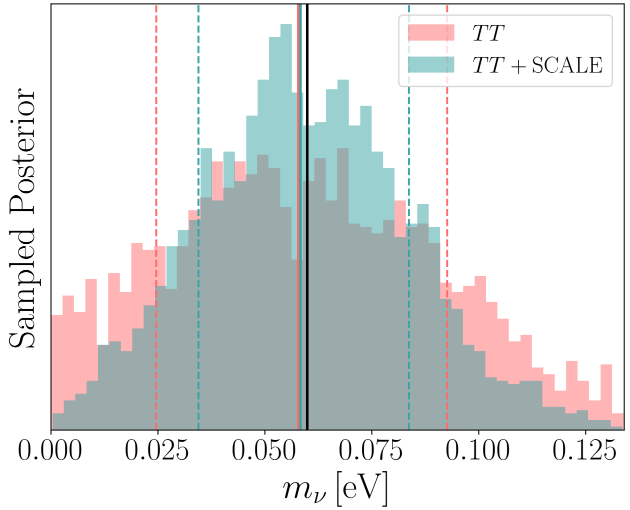

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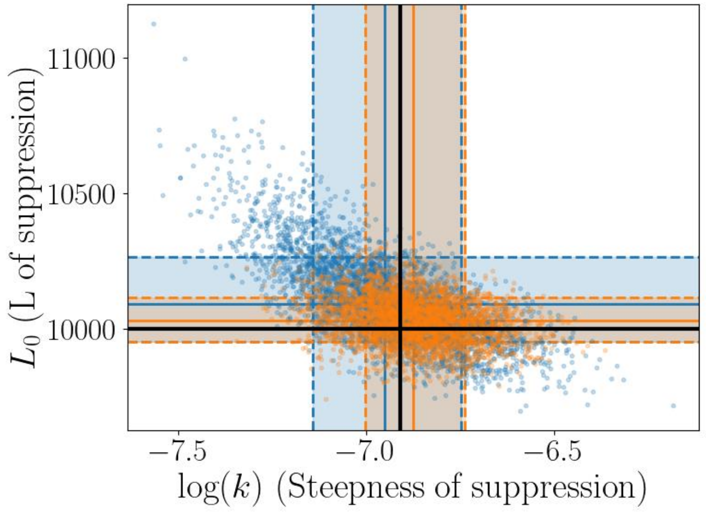
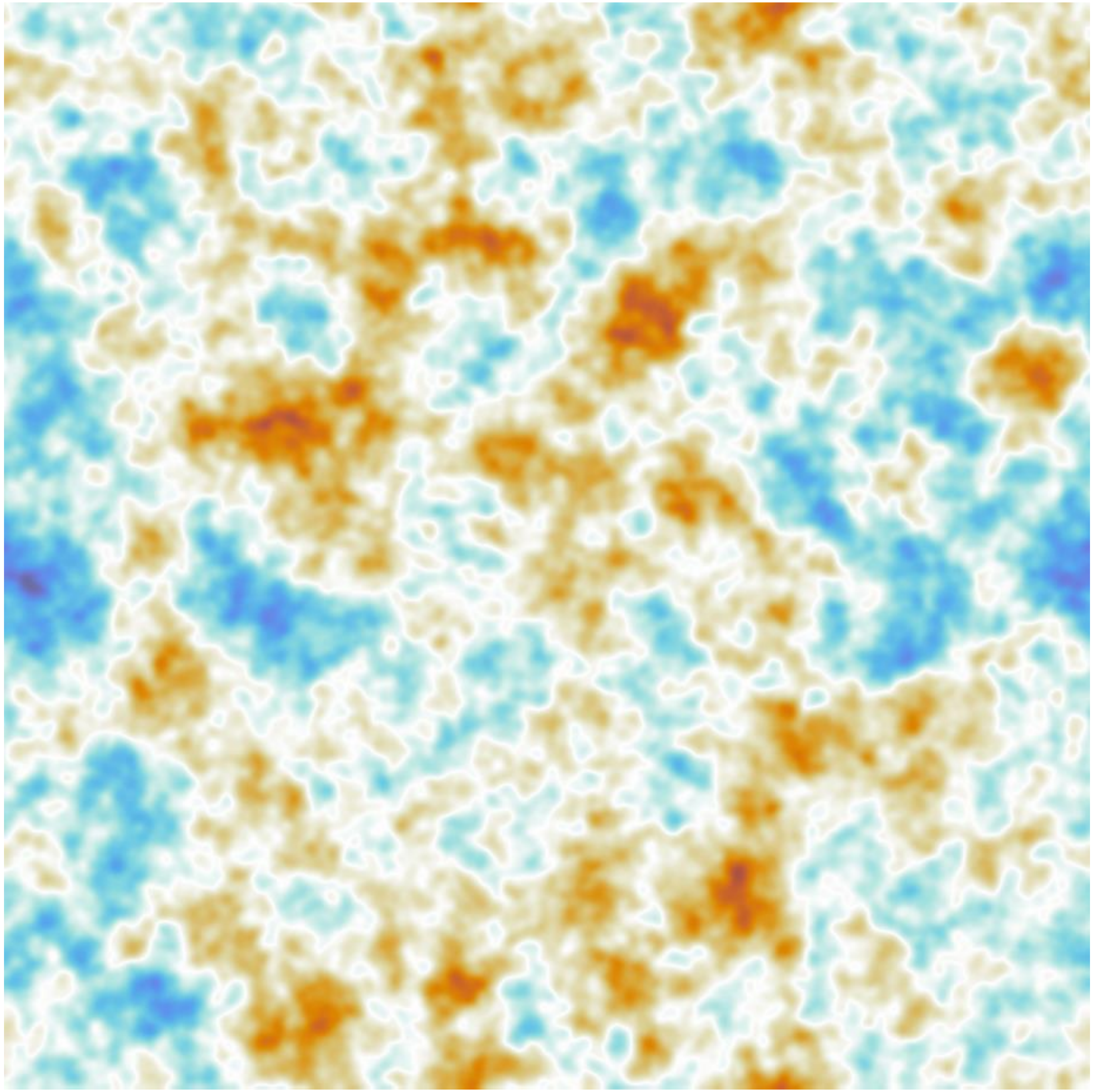
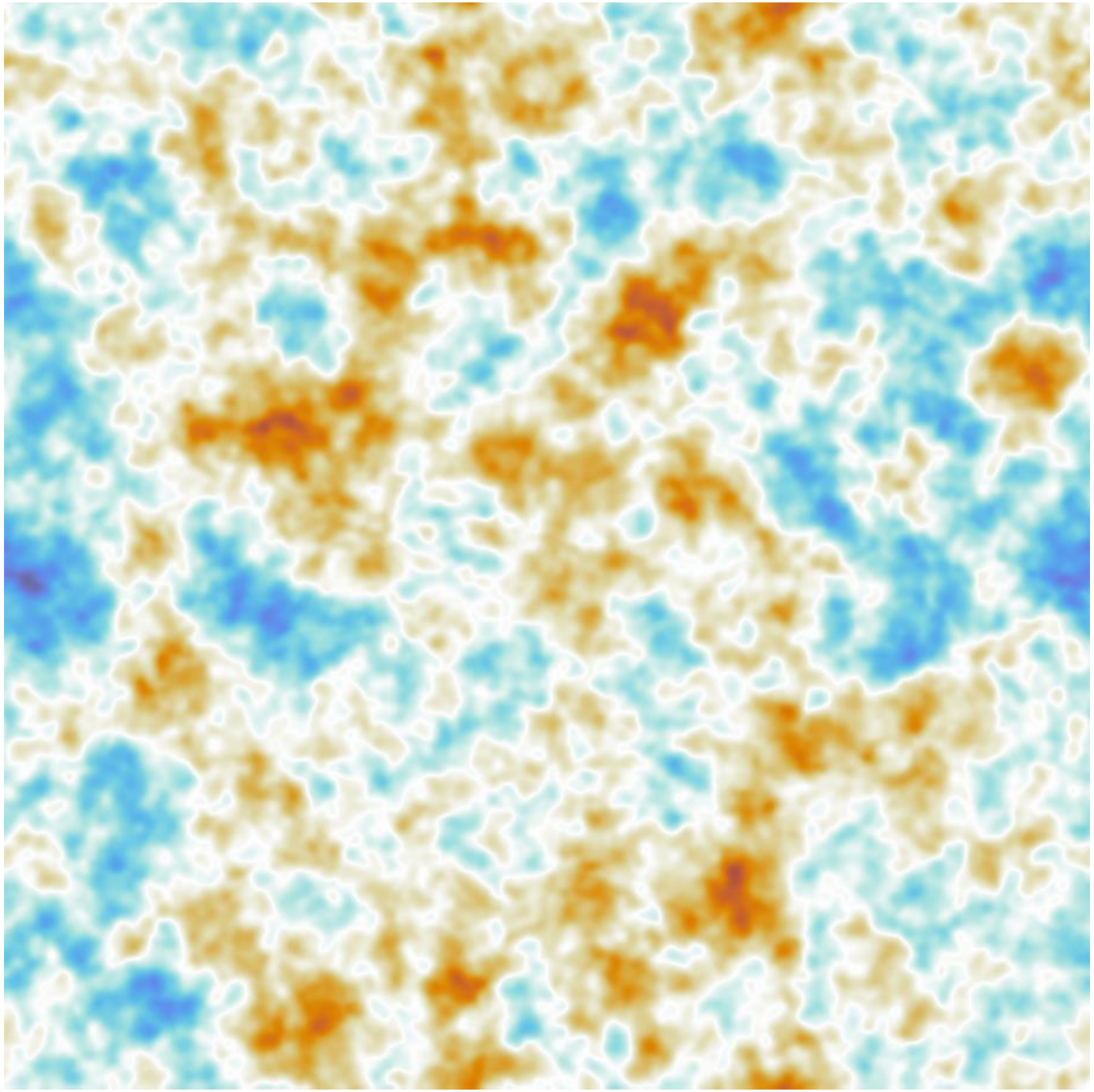
- Small-scale lensing information combined with conventional cosmic microwave background observables will provide a detection of the minimum neutrino mass
- Multiple versions of SCALE can constrain wavy dark matter models that predict non-trivial lensing suppression structure



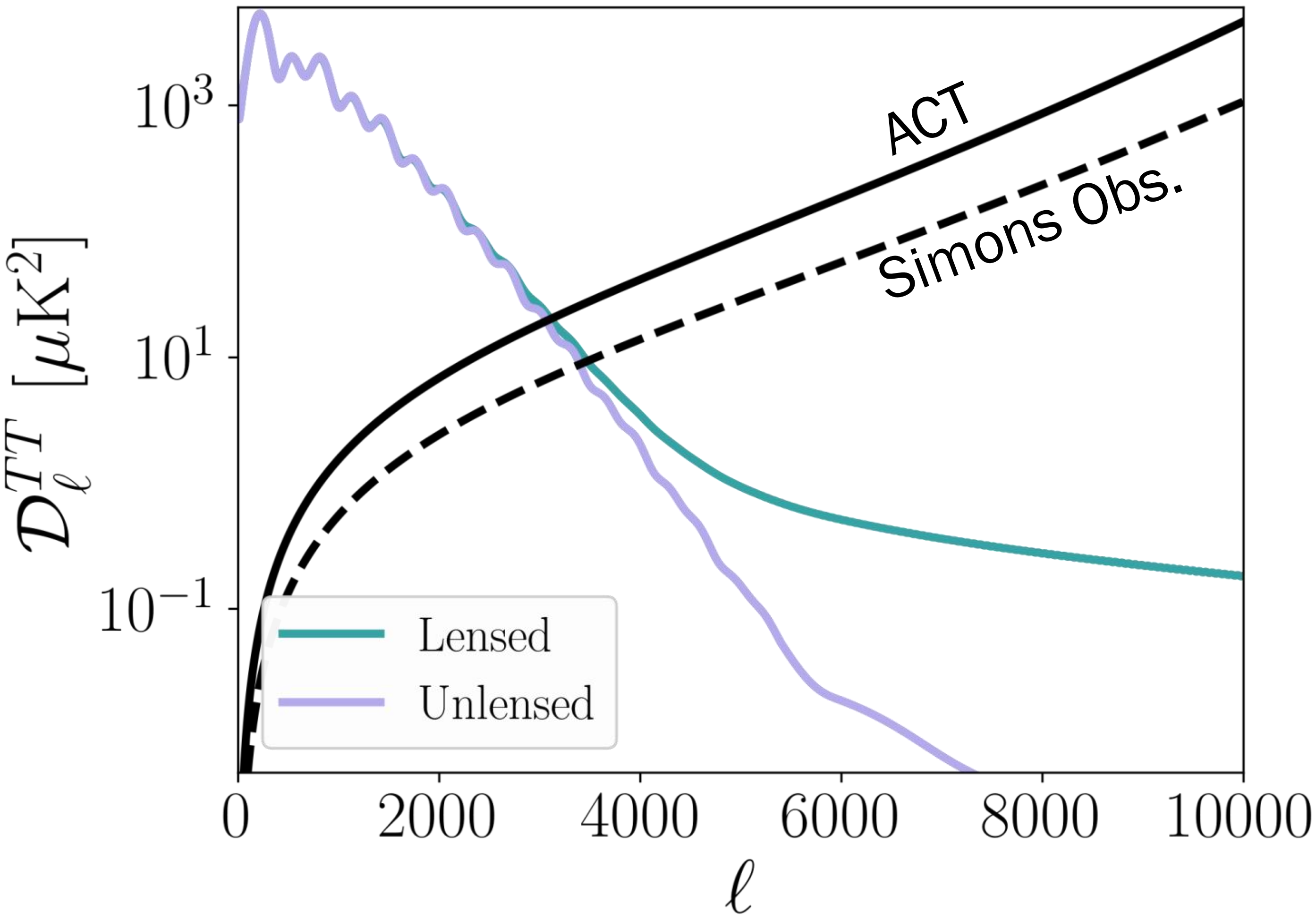
Original



Lensed



Upcoming and future experiments will allow us to access smaller scale features with lower noise levels



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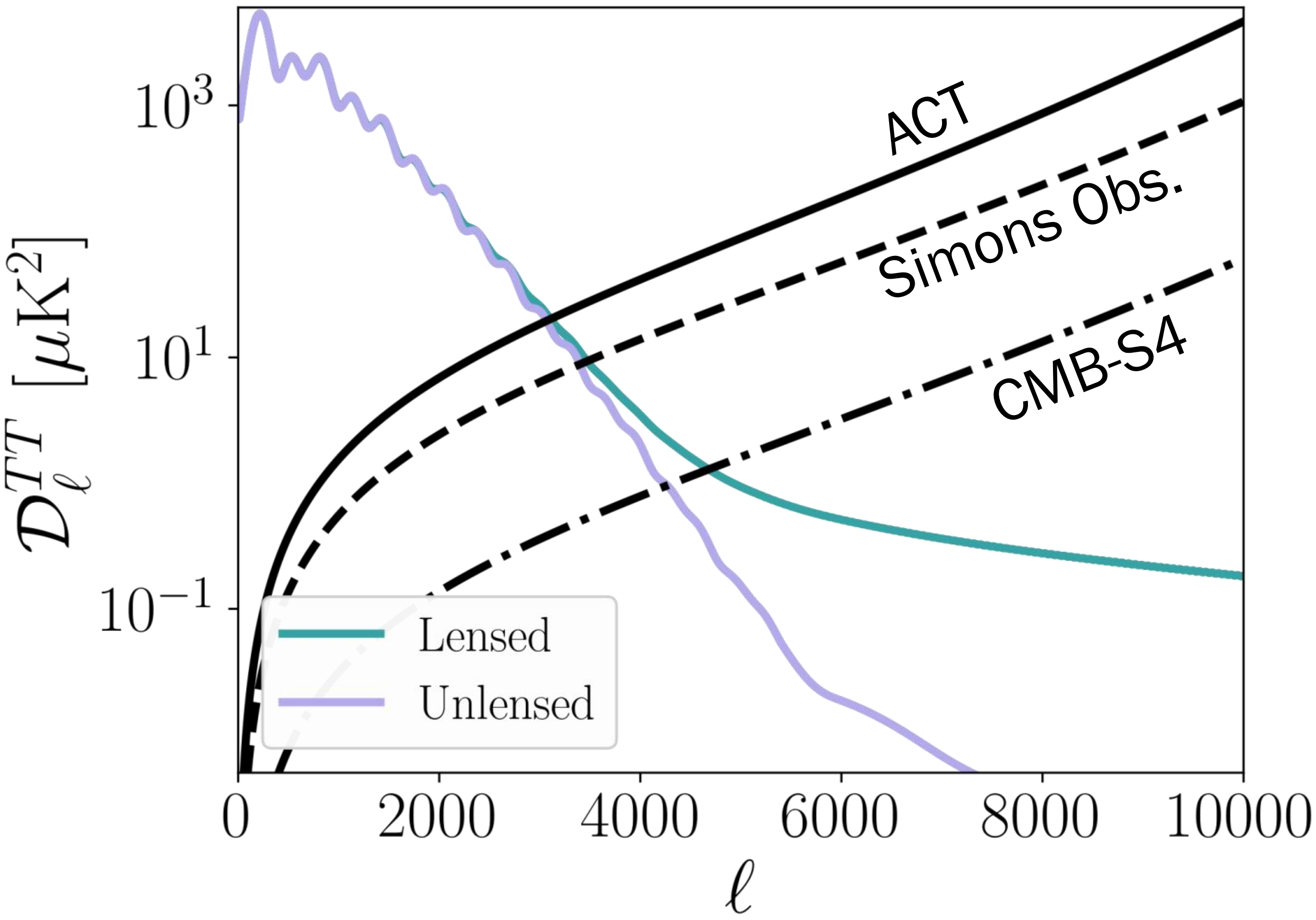
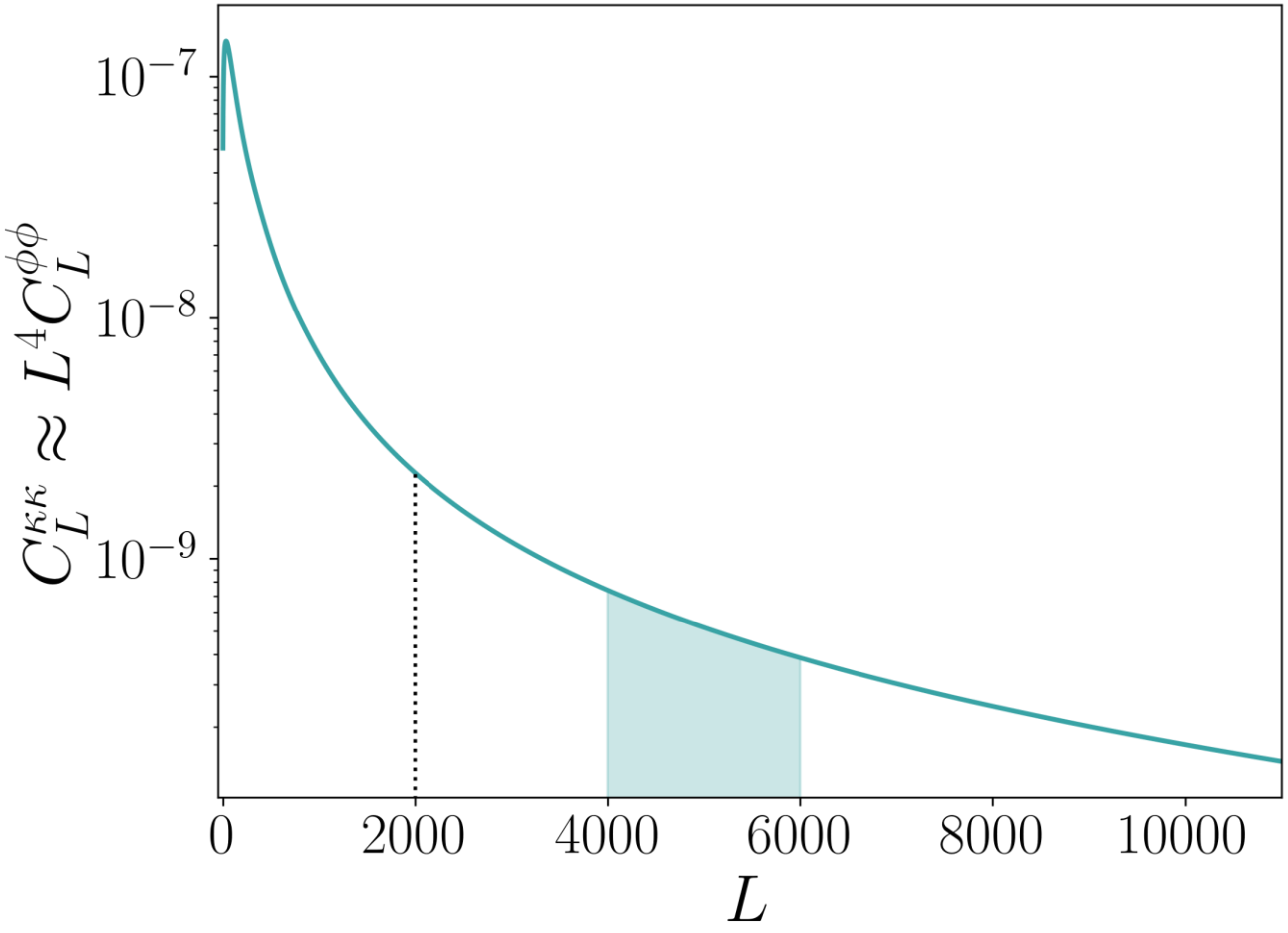


SCALE observables are weighted integrals of the lensing power spectrum over a range of small-scale multipoles



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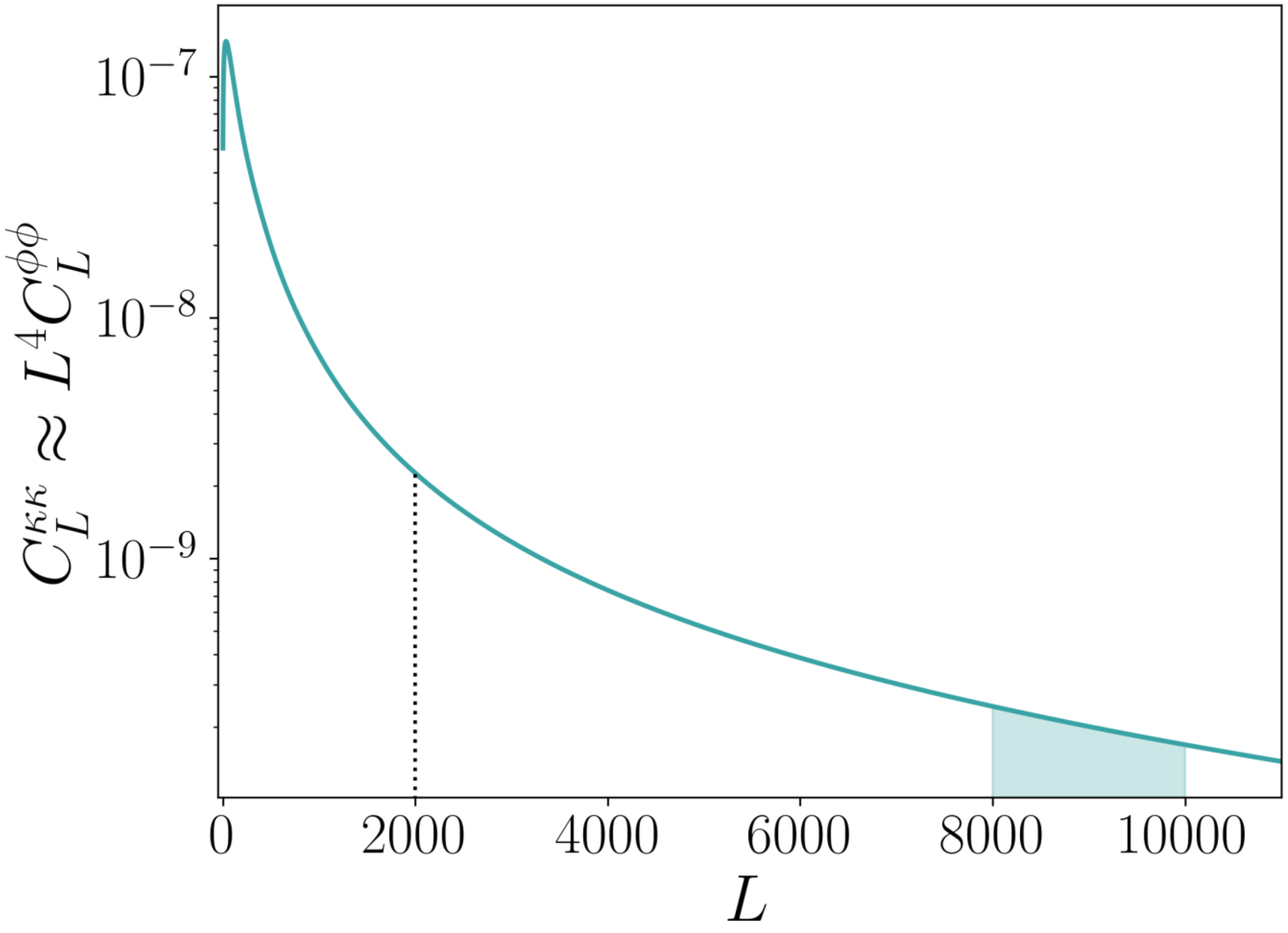
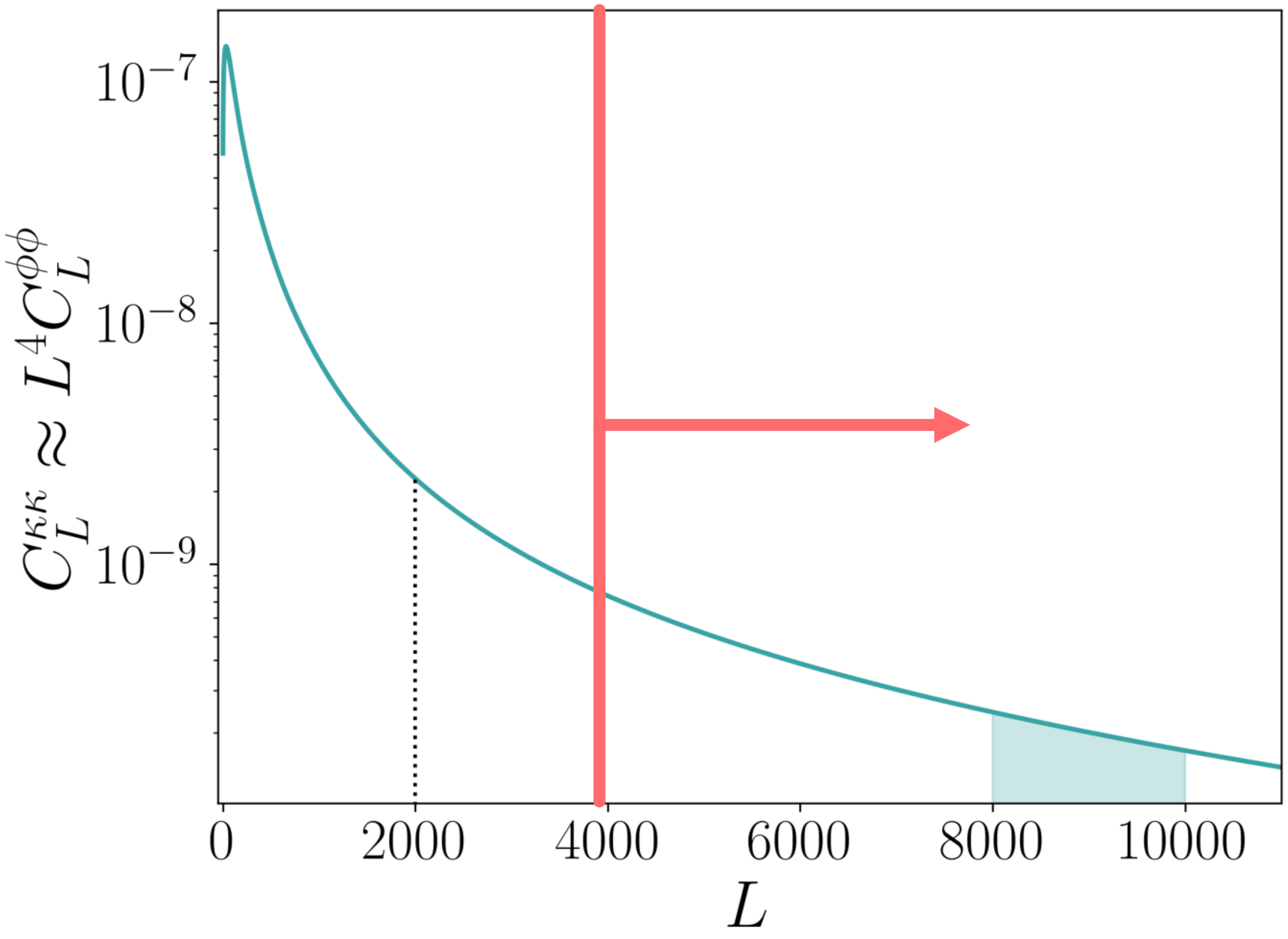


Galaxy clustering models can predict different lensing amplitudes at small scales



$$
\begin{aligned}
\langle \Psi_{\check{L}} \rangle = 2A_{\check{L}} \int \frac{\mathrm{d}^2\boldsymbol{\ell}_1}{(2\pi)^2} W_\varsigma(\boldsymbol{\ell}_1) W_\varsigma(\check{\boldsymbol{L}} - \boldsymbol{\ell}_1) \\
\times \left(\boldsymbol{\ell}_1 \cdot (\boldsymbol{\ell}_1 - \check{\boldsymbol{L}})\right) \frac{1}{C^{TT,\mathrm{obs}}_{\ell_1}} \frac{1}{C^{TT,\mathrm{obs}}_{|\check{\boldsymbol{L}}-\boldsymbol{\ell}_1|}} \\
\times \int \frac{\mathrm{d}^2\boldsymbol{\ell}_2}{(2\pi)^2} W_\lambda(\boldsymbol{\ell}_2) W_\lambda(\check{\boldsymbol{L}} - \boldsymbol{\ell}_2) \left(\boldsymbol{\ell}_2 \cdot (\boldsymbol{\ell}_2 - \boldsymbol{\ell}_1)\right) \\
\times \left((\check{\boldsymbol{L}} - \boldsymbol{\ell}_2) \cdot (\boldsymbol{\ell}_1 - \boldsymbol{\ell}_2)\right) \left(\boldsymbol{\ell}_2 \cdot (\boldsymbol{\ell}_2 - \check{\boldsymbol{L}})\right) \\
\times \frac{\left(C^{TT}_{\ell_2}\right)^2}{C^{TT,\mathrm{obs}}_{\ell_2}} \frac{\left(C^{TT}_{|\check{\boldsymbol{L}}-\boldsymbol{\ell}_2|}\right)^2}{C^{TT,\mathrm{obs}}_{|\check{\boldsymbol{L}}-\boldsymbol{\ell}_2|}} C^{\phi\phi}_{|\boldsymbol{\ell}_1-\boldsymbol{\ell}_2|} \, .
\end{aligned}
\tag{18}
$$

$$
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\langle \Psi_{\check{L}} \rangle = & \, 2A_{\check{L}} \int \frac{\mathrm{d}^2 \boldsymbol{\ell}_1}{(2\pi)^2} W_{\varsigma}(\boldsymbol{\ell}_1) W_{\varsigma}(\check{\boldsymbol{L}} - \boldsymbol{\ell}_1) \\
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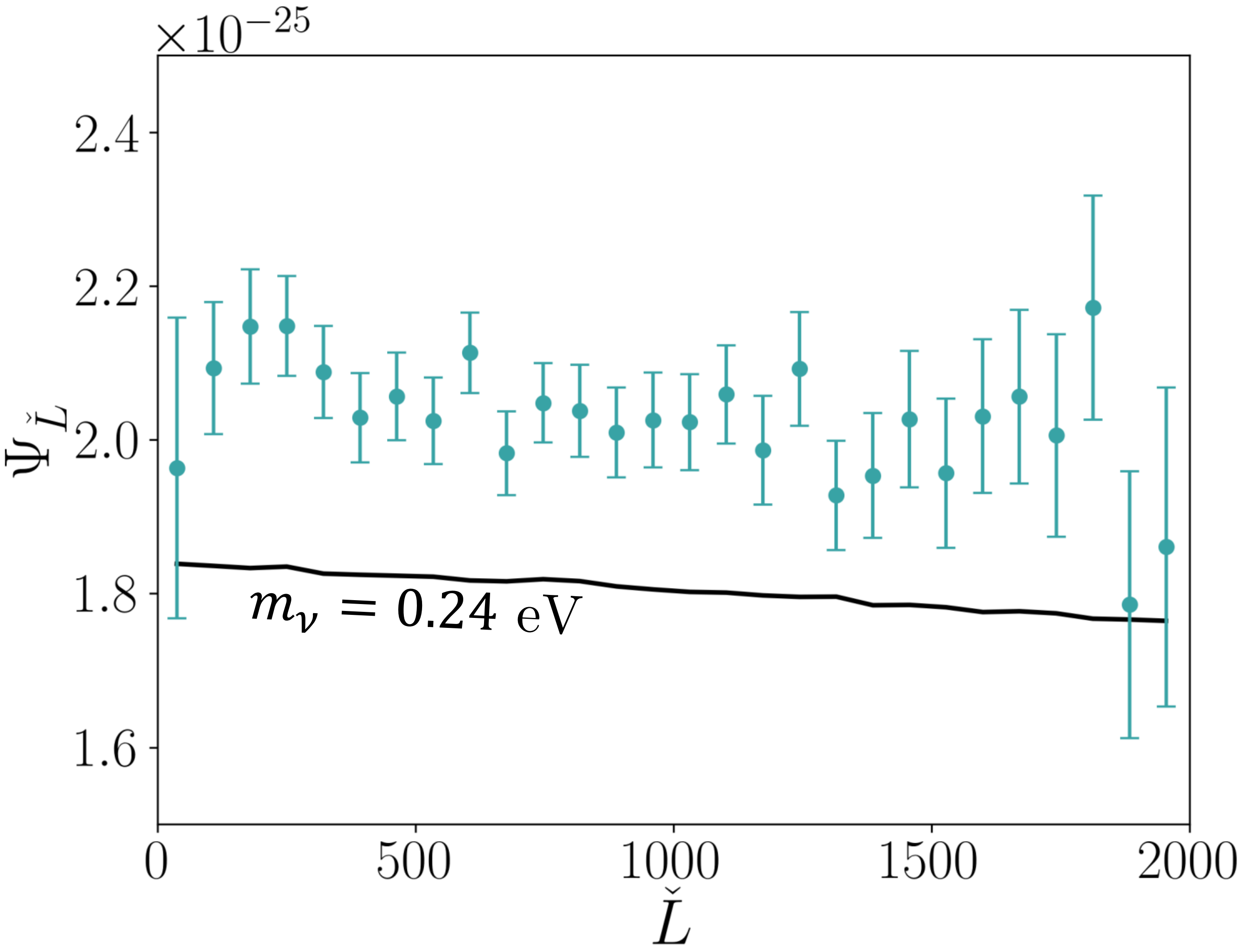
& \times \int \frac{\mathrm{d}^2 \boldsymbol{\ell}_2}{(2\pi)^2} W_{\lambda}(\boldsymbol{\ell}_2) W_{\lambda}(\check{\boldsymbol{L}} - \boldsymbol{\ell}_2) \left(\boldsymbol{\ell}_2 \cdot (\boldsymbol{\ell}_2 - \boldsymbol{\ell}_1)\right) \\
& \times \left((\check{\boldsymbol{L}} - \boldsymbol{\ell}_2) \cdot (\boldsymbol{\ell}_1 - \boldsymbol{\ell}_2)\right) \left(\boldsymbol{\ell}_2 \cdot (\boldsymbol{\ell}_2 - \check{\boldsymbol{L}})\right) \\
& \times \frac{\left(C_{\ell_2}^{TT}\right)^2}{C_{\ell_2}^{TT,\mathrm{obs}}} \frac{\left(C_{|\check{\boldsymbol{L}} - \boldsymbol{\ell}_2|}^{TT}\right)^2}{C_{|\check{\boldsymbol{L}} - \boldsymbol{\ell}_2|}^{TT,\mathrm{obs}}} C_{|\boldsymbol{\ell}_1 - \boldsymbol{\ell}_2|}^{\phi\phi} \, . \qquad (18)
\end{aligned}
$$

SCALE observables depend on matter clustering parameters

Recall more mass in neutrinos means less concentrated clusters, or weaker lensing



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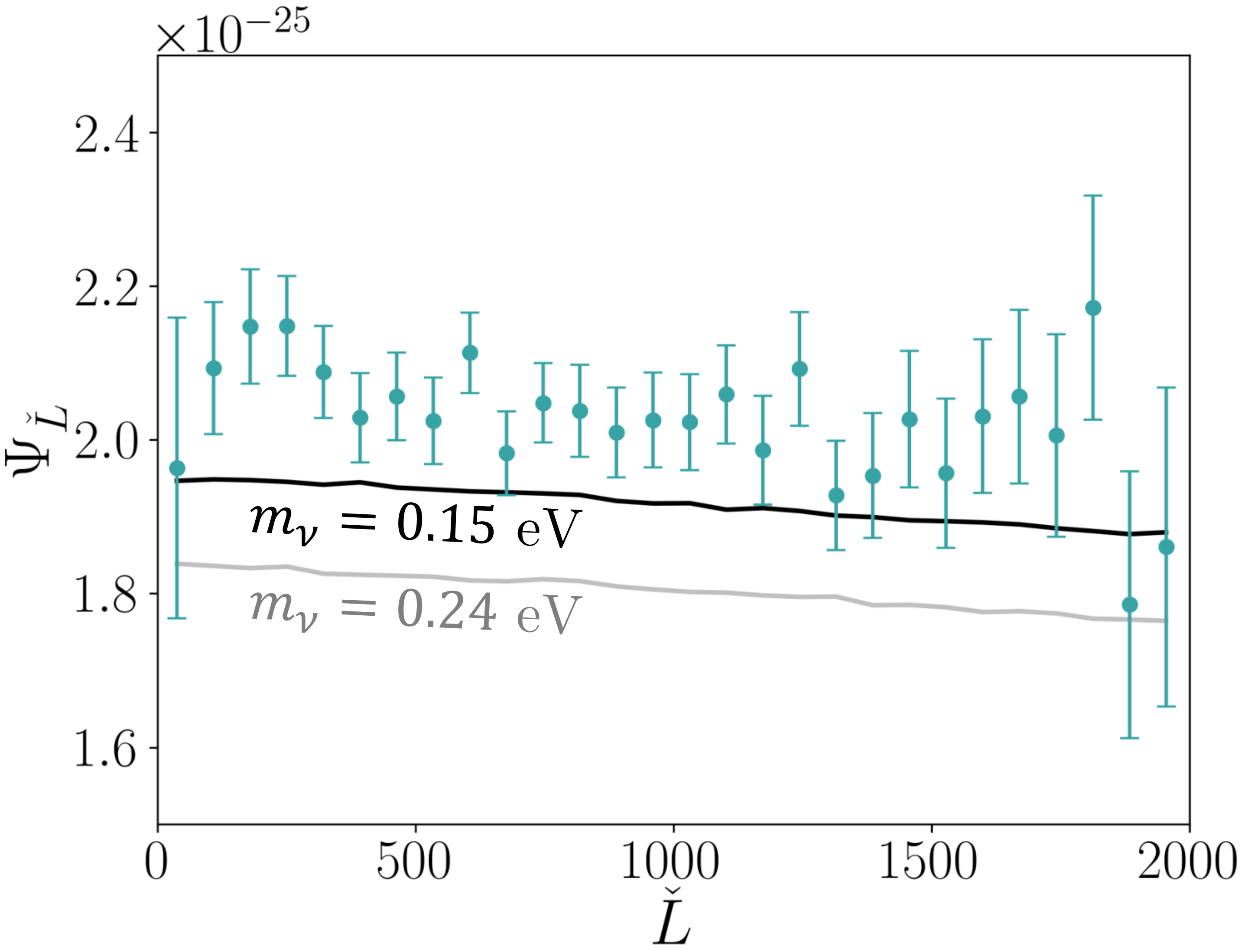

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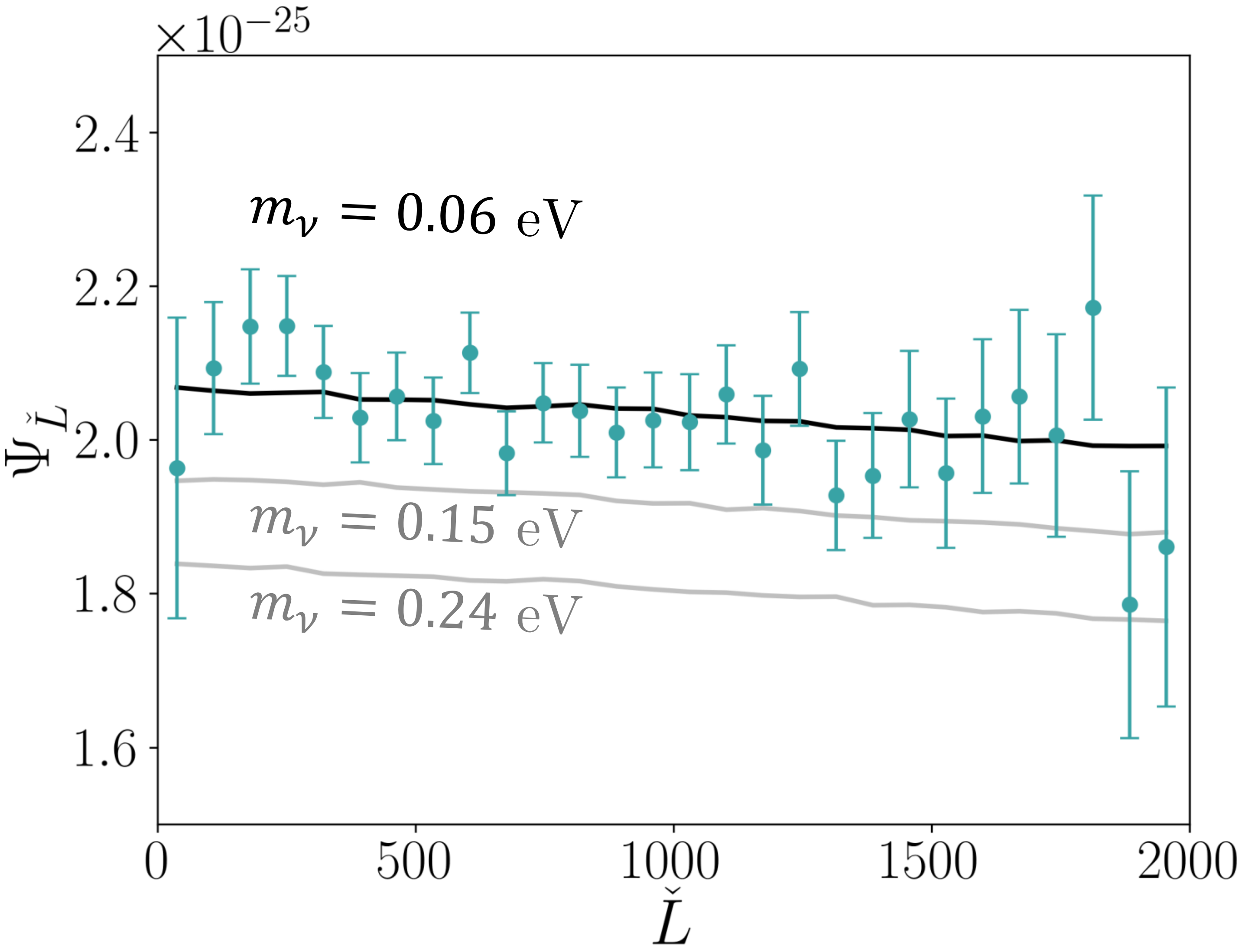

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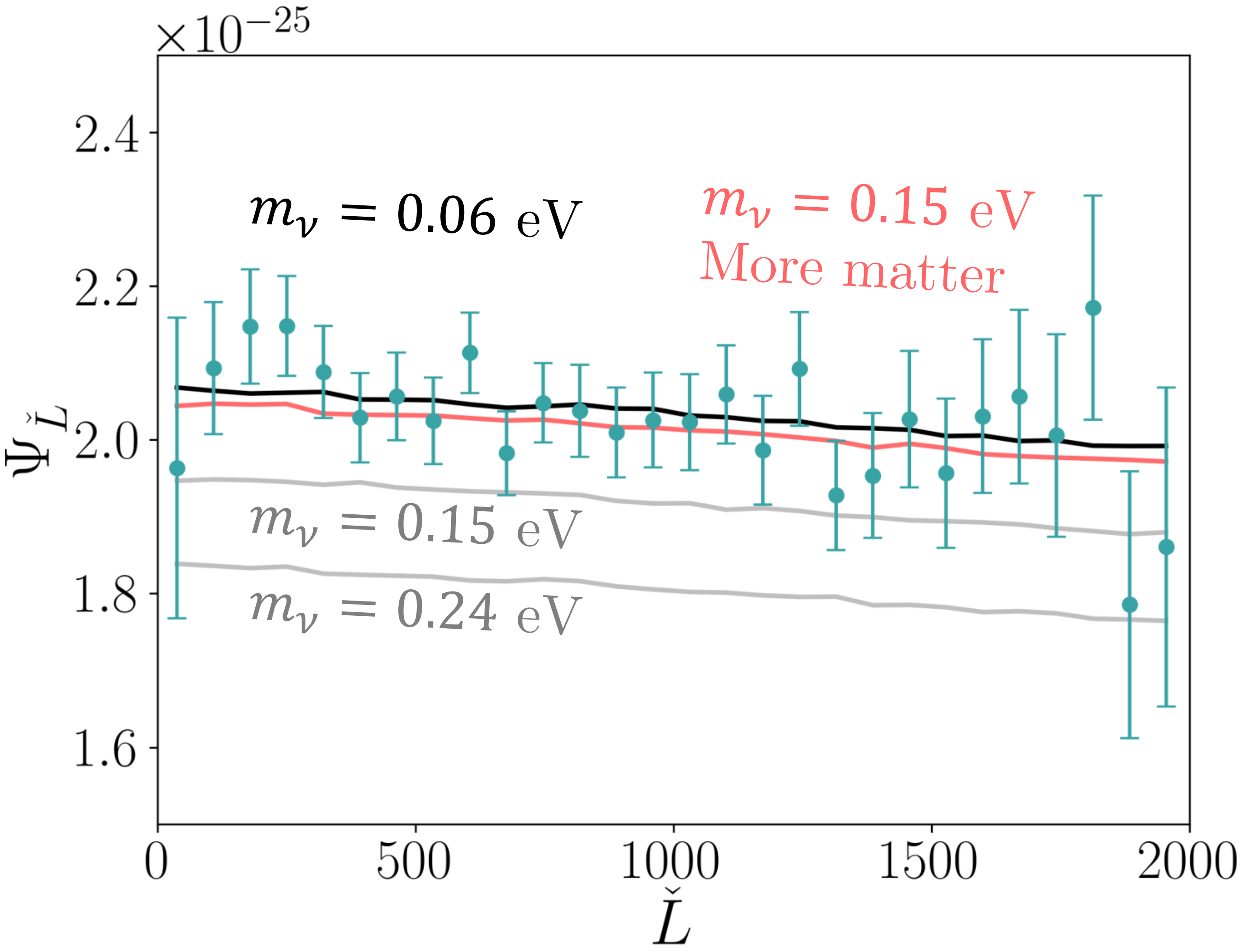
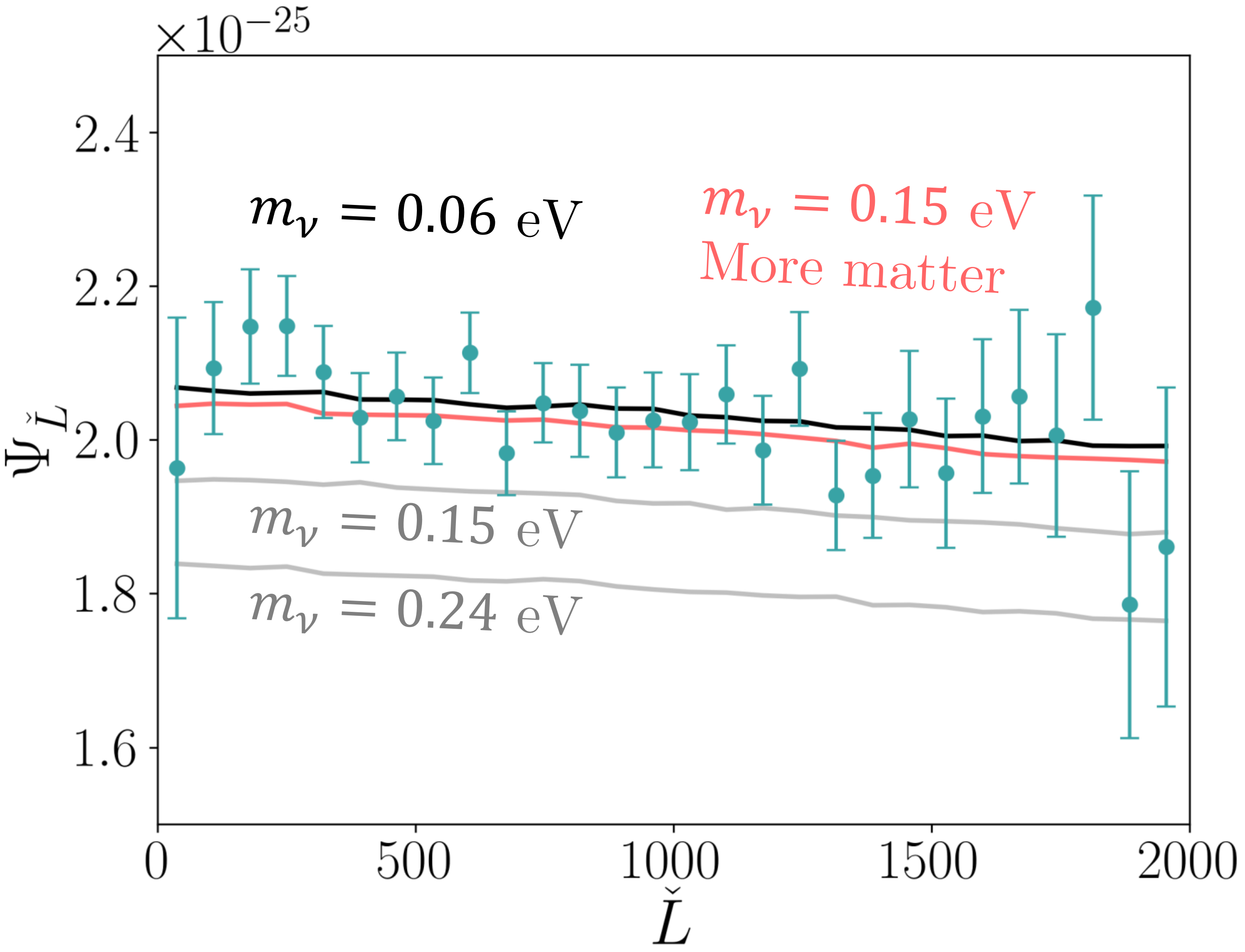


SCALE analytical form is non-trivial to compute



SCALE analytical form depends on the angular power spectra of the cosmic microwave background and the lensing field

$$\{\Omega_m, m_\nu, \ldots\} \Rightarrow \left\{C_\ell^{TT}, C_L^{\phi\phi}\right\} \Rightarrow \langle \Psi_{\check{L}} \rangle$$

The angular power spectra of the cosmic microwave background and the lensing field depend on a set of cosmological parameters

$$\{\Omega_m, m_\nu, \ldots\} \Rightarrow \left\{C_\ell^{TT}, C_L^{\phi\phi}\right\} \Rightarrow \langle \Psi_{\check{L}} \rangle$$

Is there a way to quickly map cosmological parameters to the theory prediction of SCALE observables?

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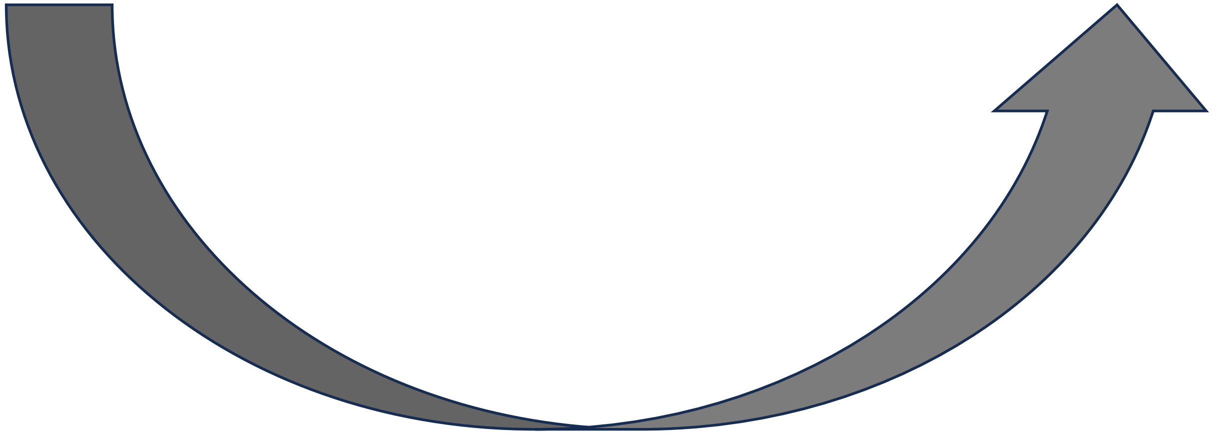
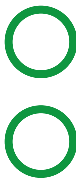


Is there a way to quickly map cosmological parameters to the theory prediction of SCALE observables?

Input

$x_{0,i}$



$\{\Omega_m, m_\nu, \ldots\}$

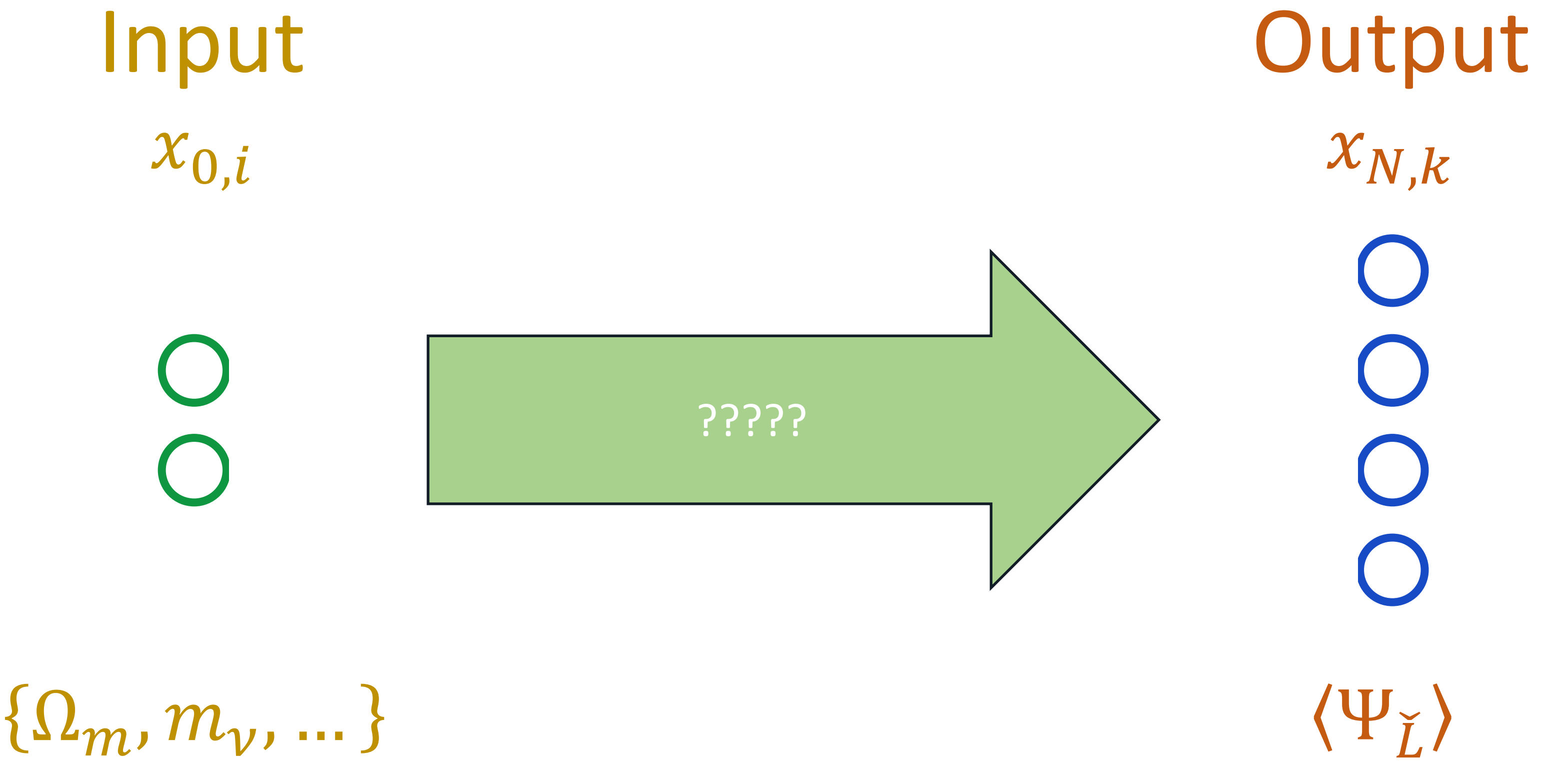
Is there a way to quickly map cosmological parameters to the theory prediction of SCALE observables?

Input | Output

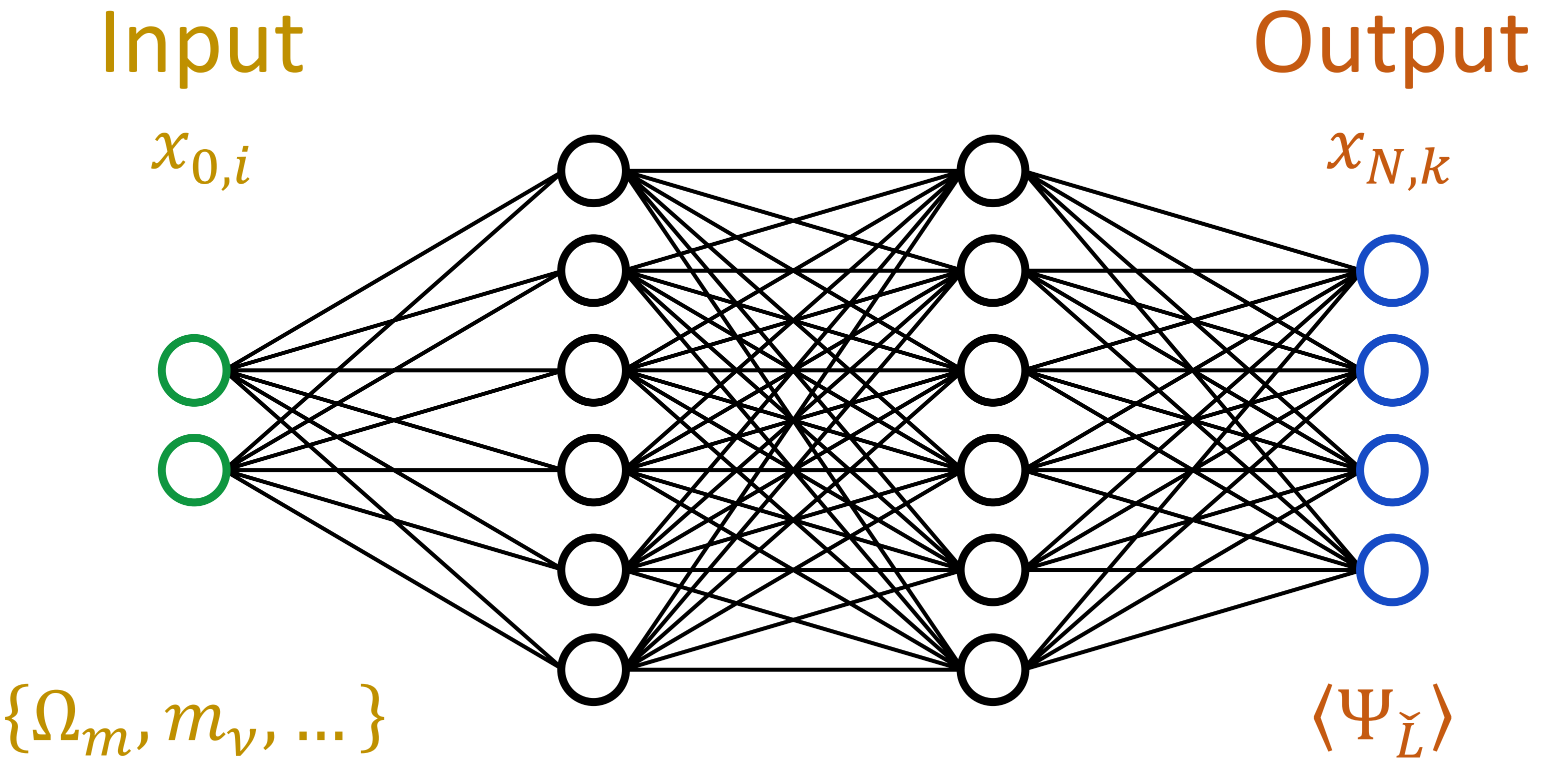
$x_{0,i}$ | $x_{N,k}$

$\{\Omega_m, m_\nu, \dots\}$ | $\langle \Psi_{\check{L}} \rangle$

Is there a way to quickly map cosmological parameters to the theory prediction of SCALE observables?



Neural networks can learn how to map a set of input labels to a set of predicted output labels (fancy interpolation)



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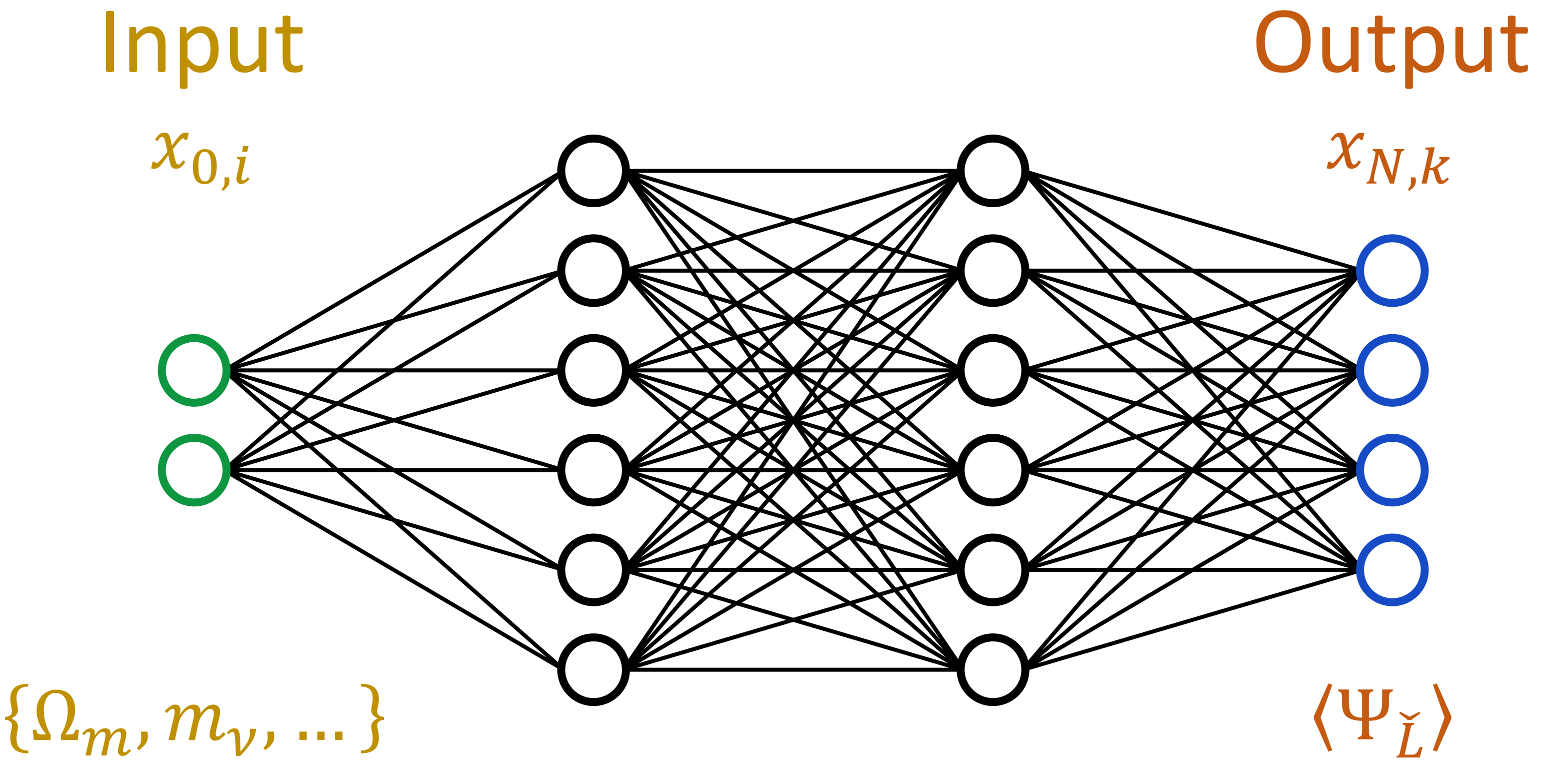
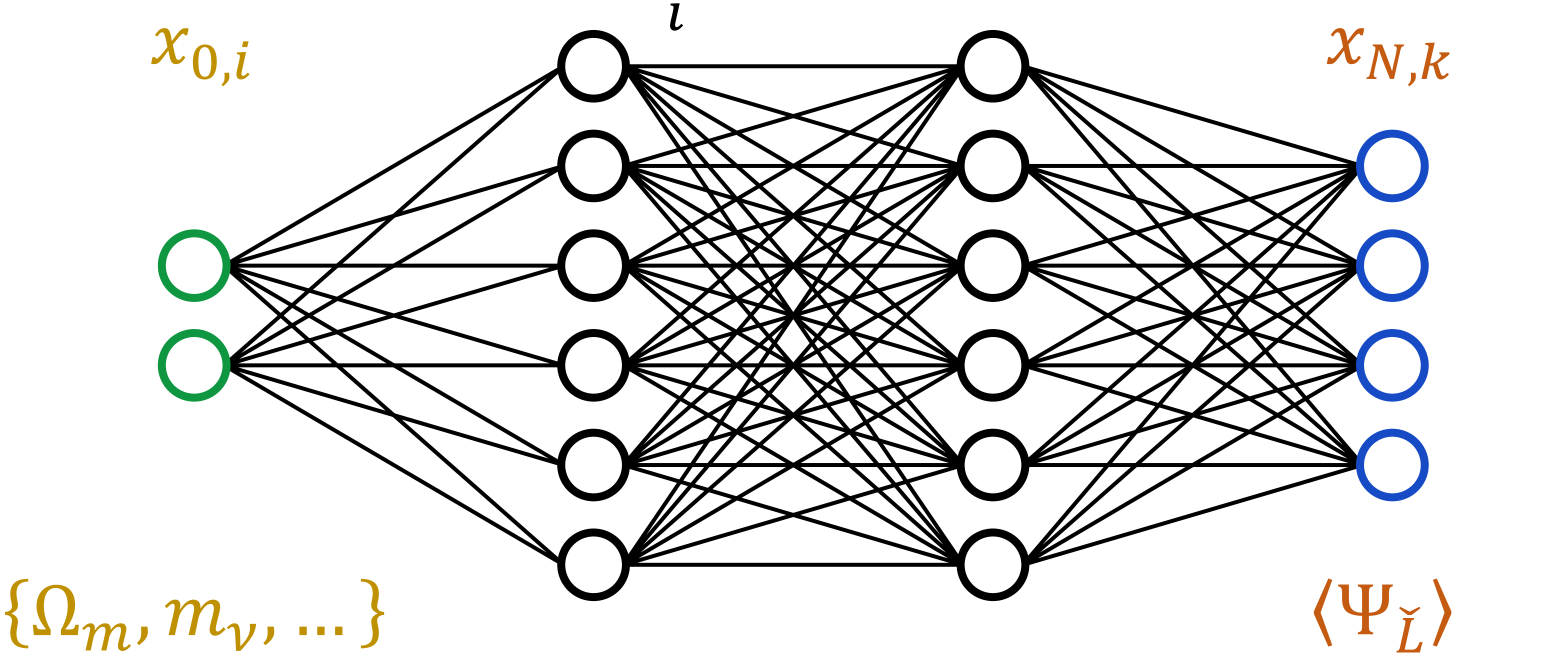


Neural networks can learn how to map a set of input labels to a set of predicted output labels

Input

$$x_{n,j} = \sum_i f(w_{n,ij} x_{n-1,i})$$

Output



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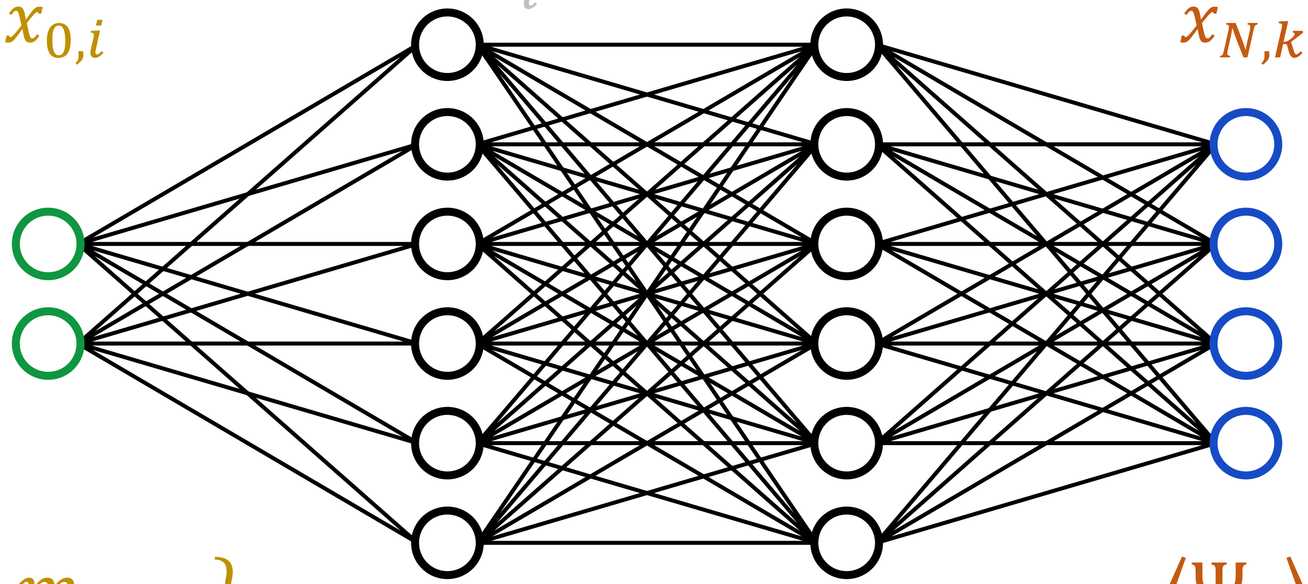
$x_{0,i}$

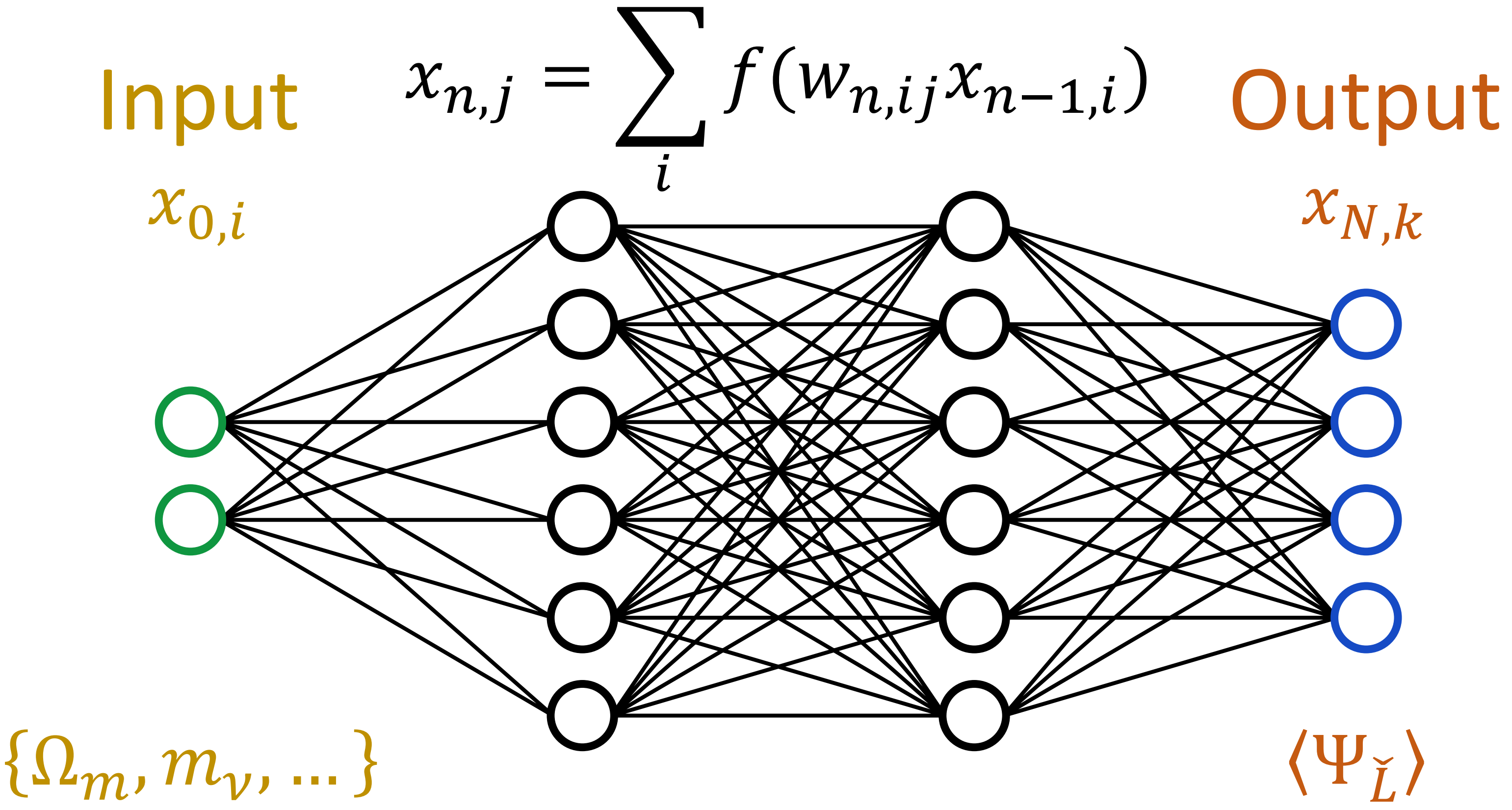
$x_{N,k}$



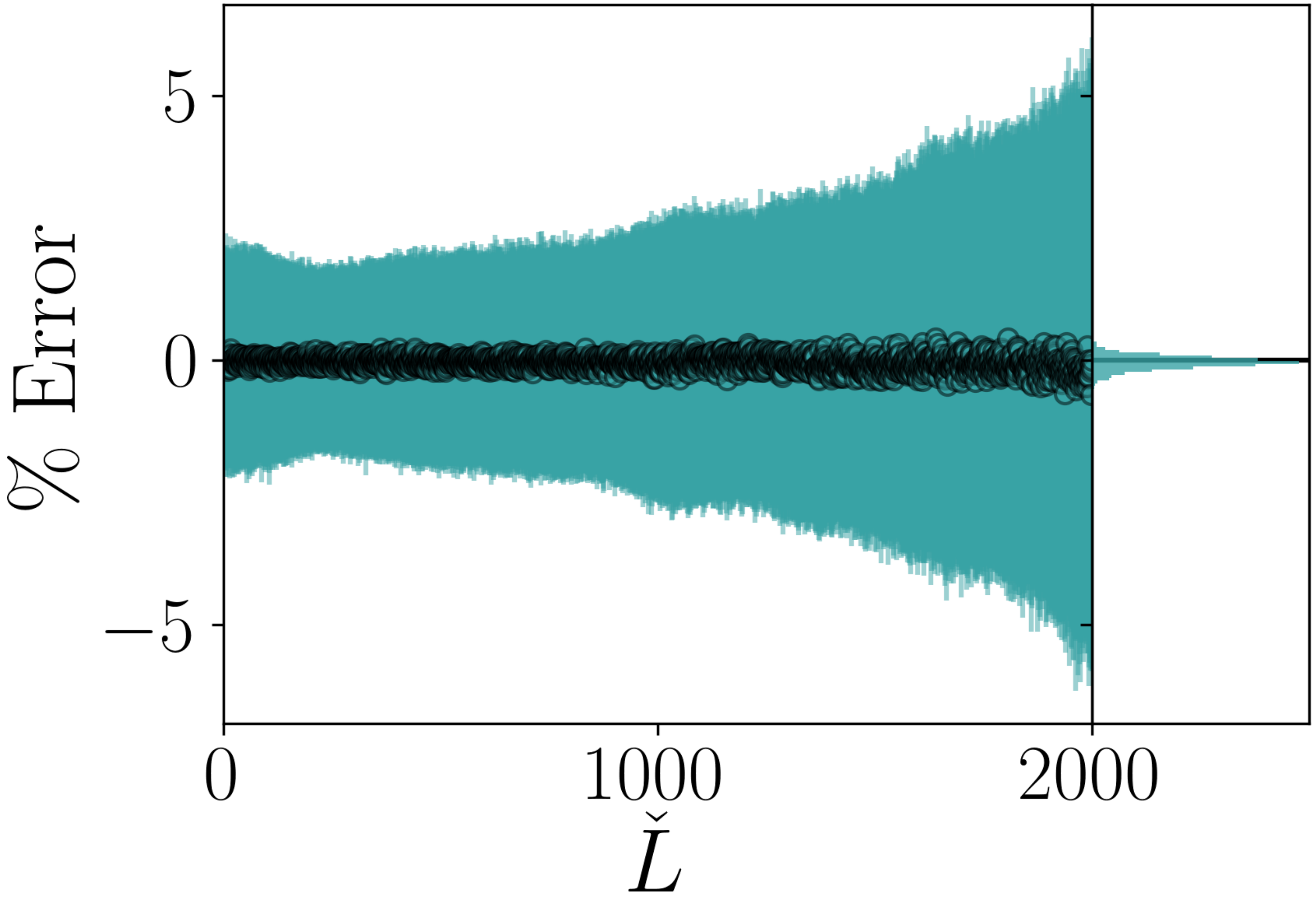
$\{\Omega_m, m_\nu, \ldots\}$

$\langle \Psi_{\check{L}} \rangle$

Neural networks in essence provide an interpolation between the trained input/output labels

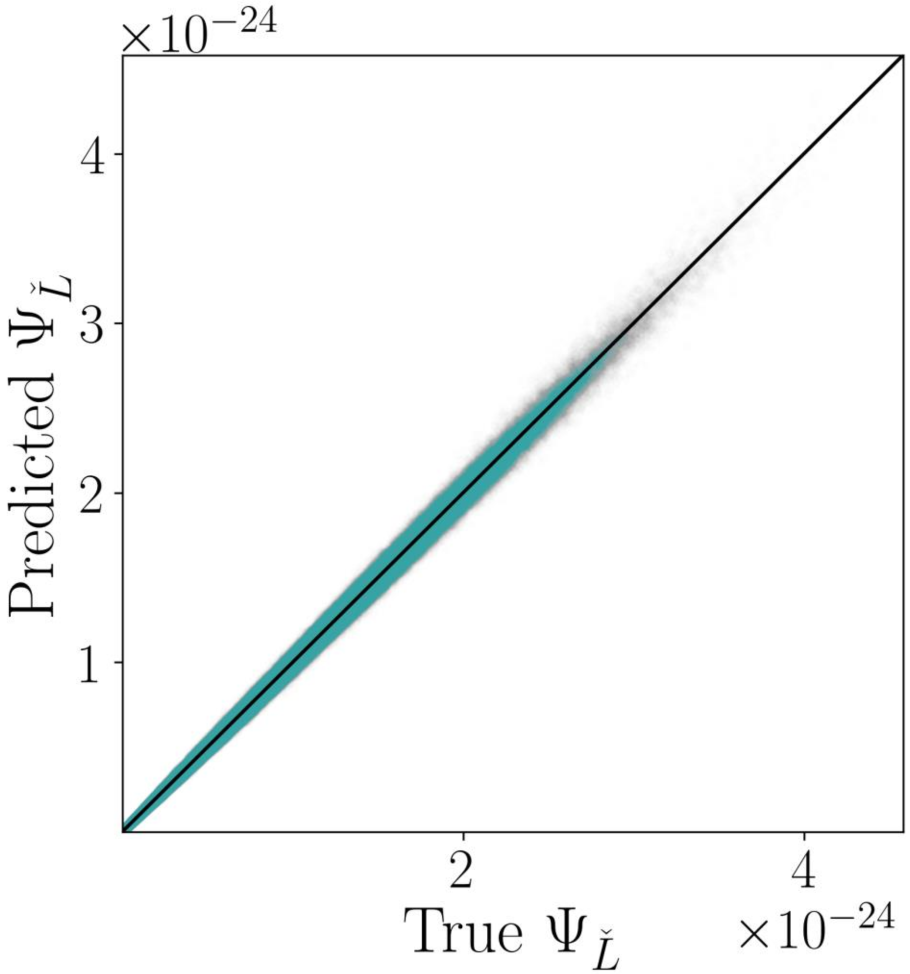


Neural network emulators predict SCALE spectra to <5% accuracy with drastic improvements in speed



Before: 10 s
After: 10^{-3} s

Precision of predicted SCALE spectra can be improved through simple binning (<5% scatter to <1% scatter)



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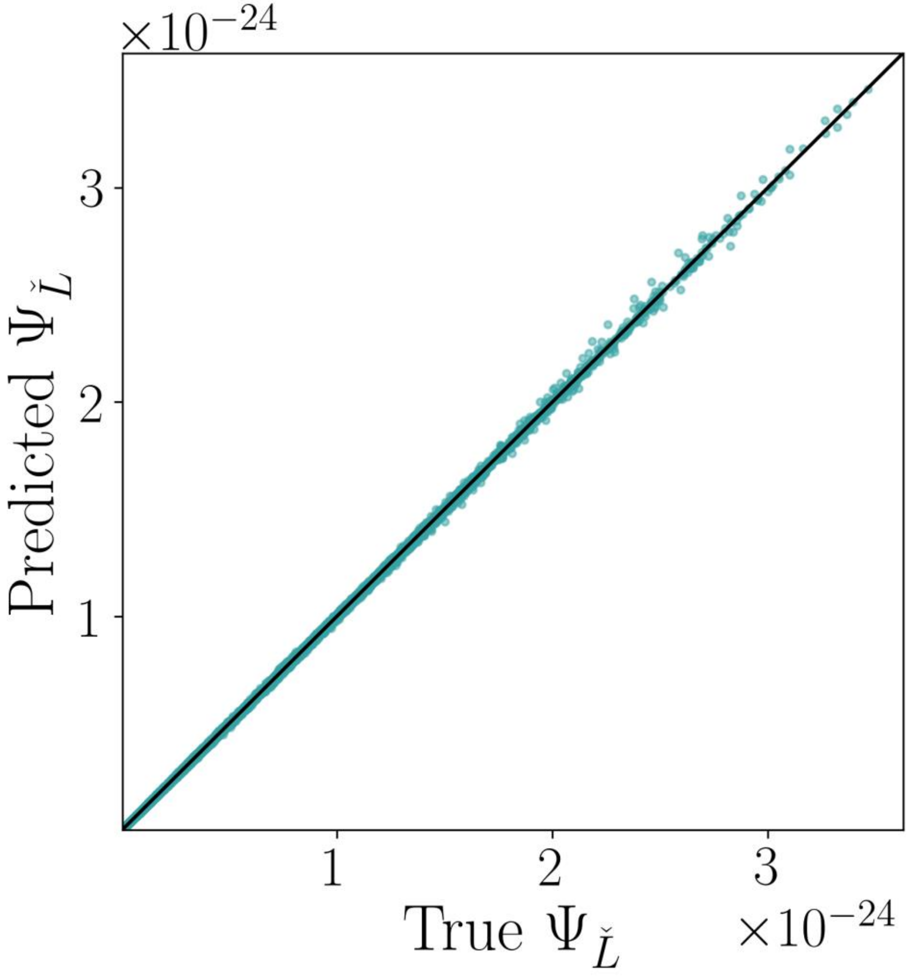
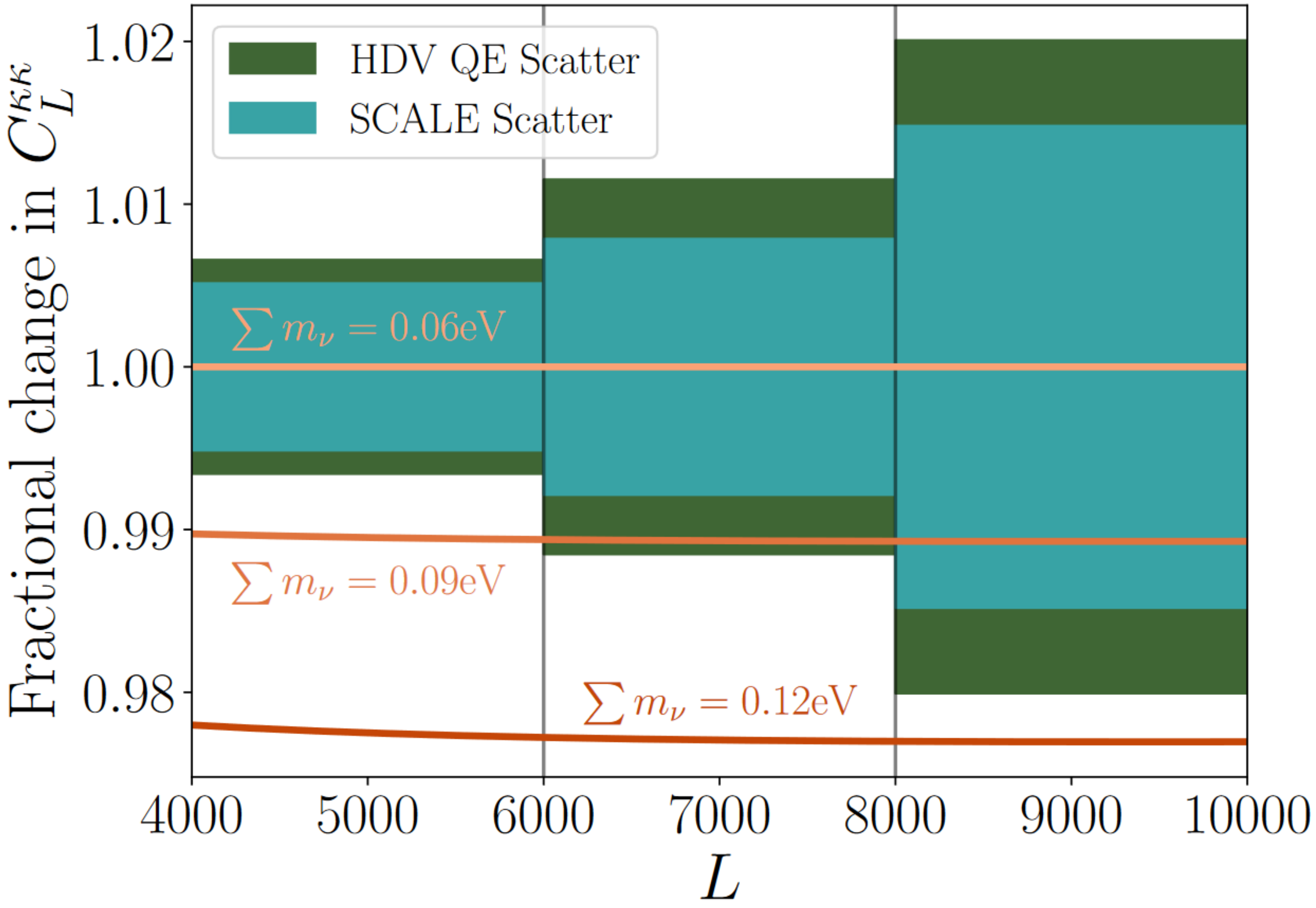


SCALE emulator combined with cosmic microwave background lensing simulations allow us to construct a mock likelihood

$$\log(P) \sim \frac{(Data - Theory)^2}{Covariance}$$

SCALE can have higher distinguishing power for clustering models



Investigate corrections to empirical covariance with simulated data observables from the “wrong” answer

$$\log(P) \sim \frac{(Data\ - Theory)^2}{Covariance}$$

Supplement data vector with standard quadratic estimator observables to quantify SCALE contributions/improvements

$$\log(P) \sim \frac{(Data - Theory)^2}{Covariance}$$

Foreground contamination should be uncorrelated with λ just like instrument noise, but does it bias SCALE observables?