THE FRONTIER OF GRAVITATIONAL LENSING OF THE COSMIC MICROWAVE BACKGROUND

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TEXAS TACOS @ UT AUSTIN; 28 OCTOBER 2024

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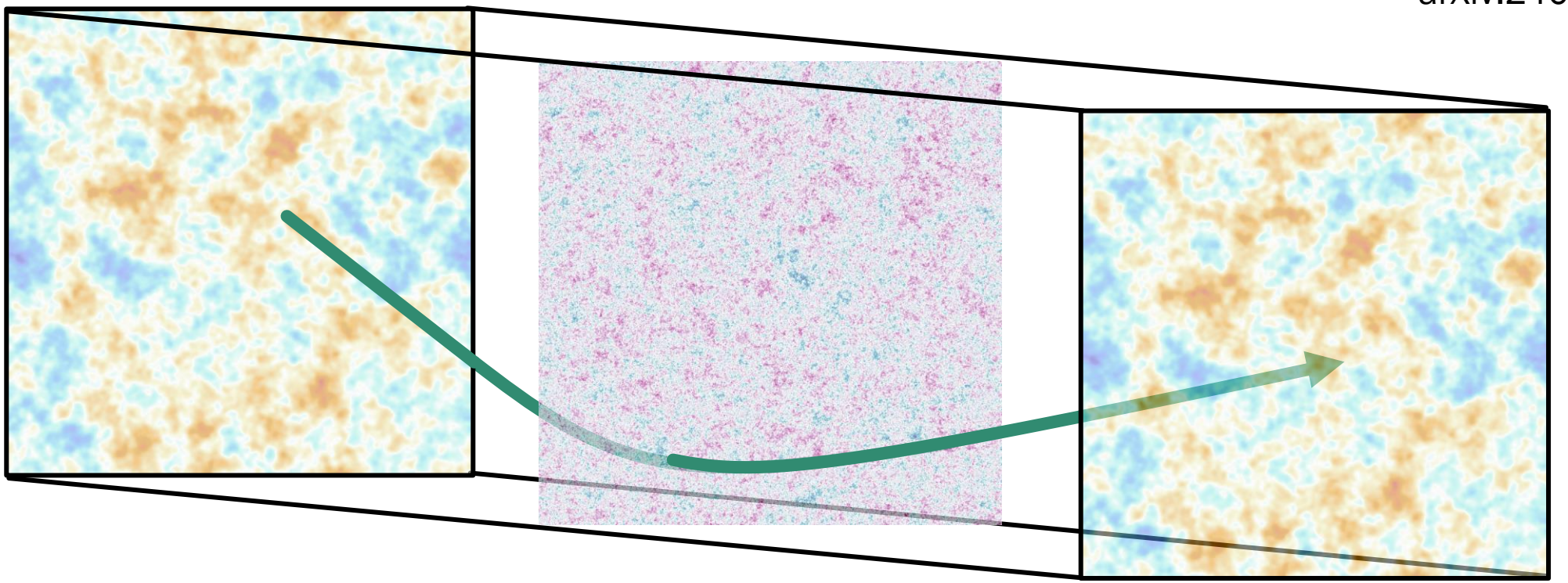
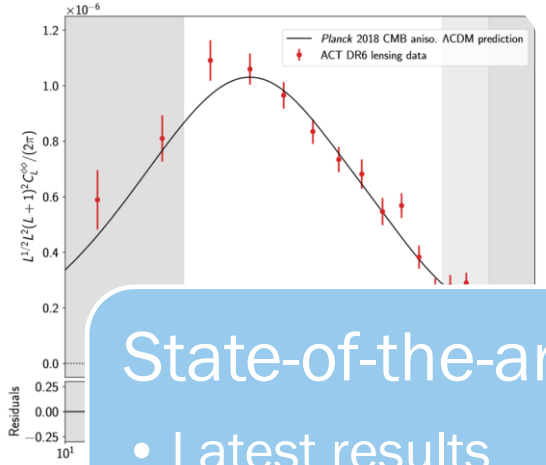


Basics

- A crash course on CMB lensing and clustering physics

Techniques

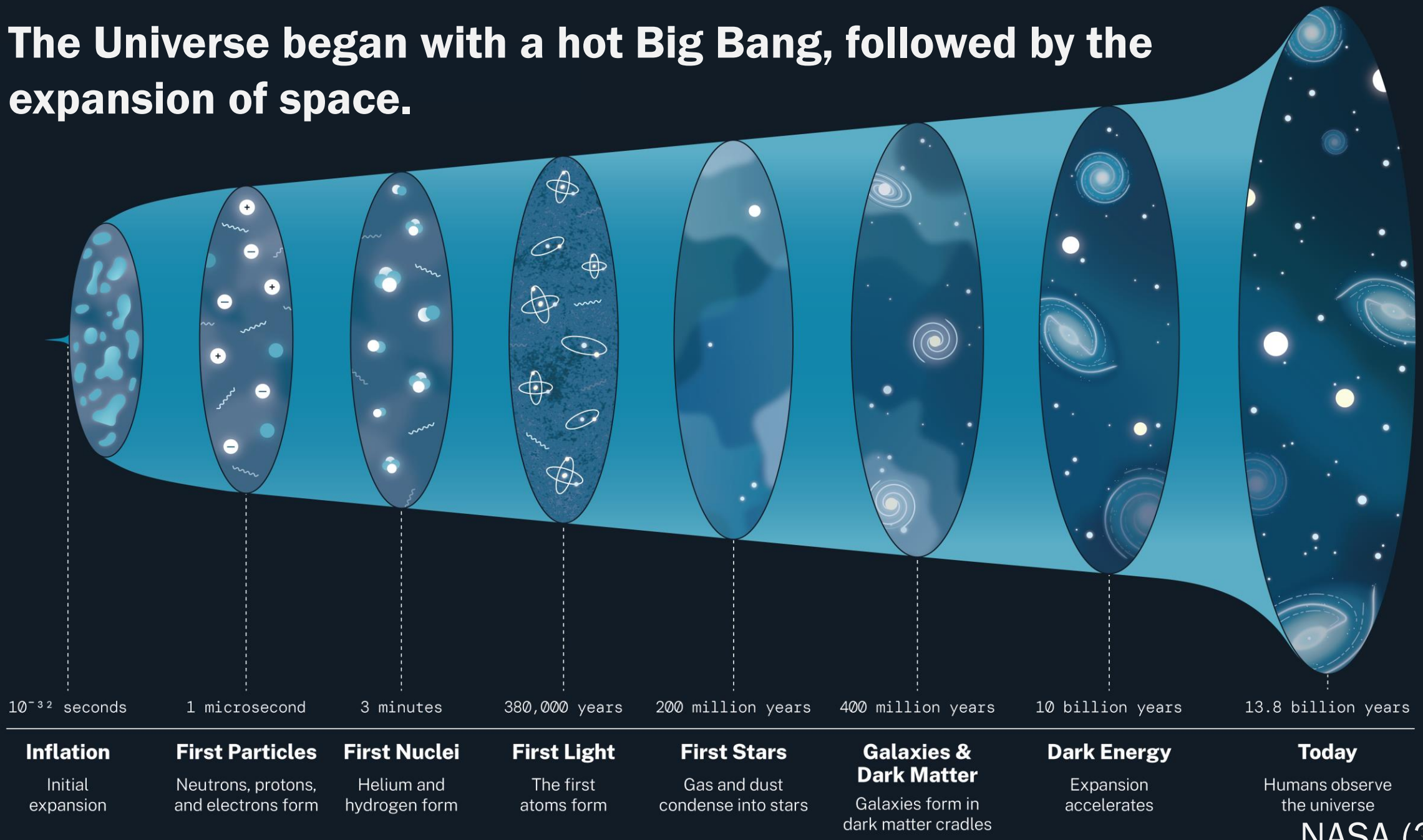
- Methods for observing and quantifying CMB lensing



State-of-the-art

- Latest results and prospects for future methods and data

The Universe began with a hot Big Bang, followed by the expansion of space.



NASA (2019)

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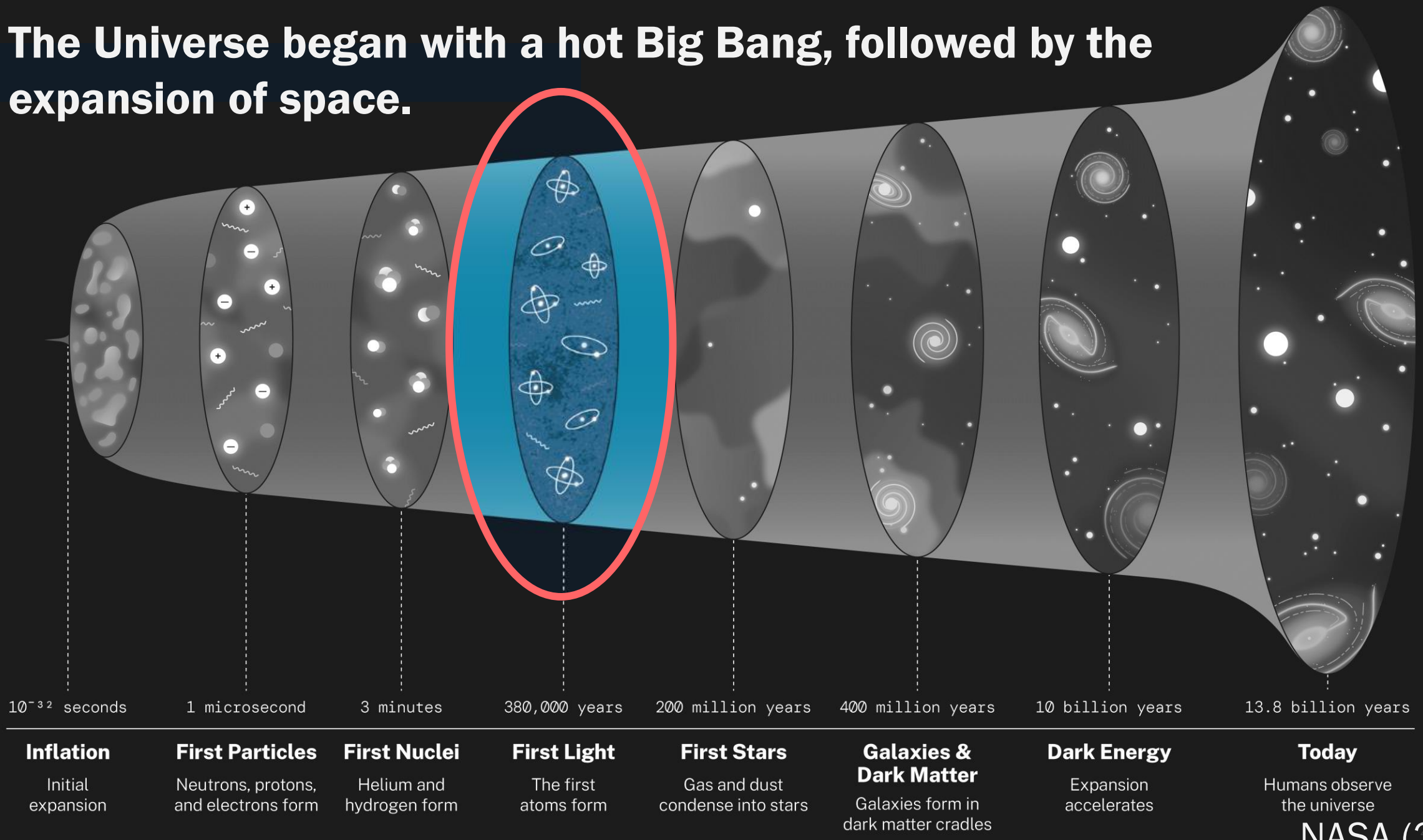
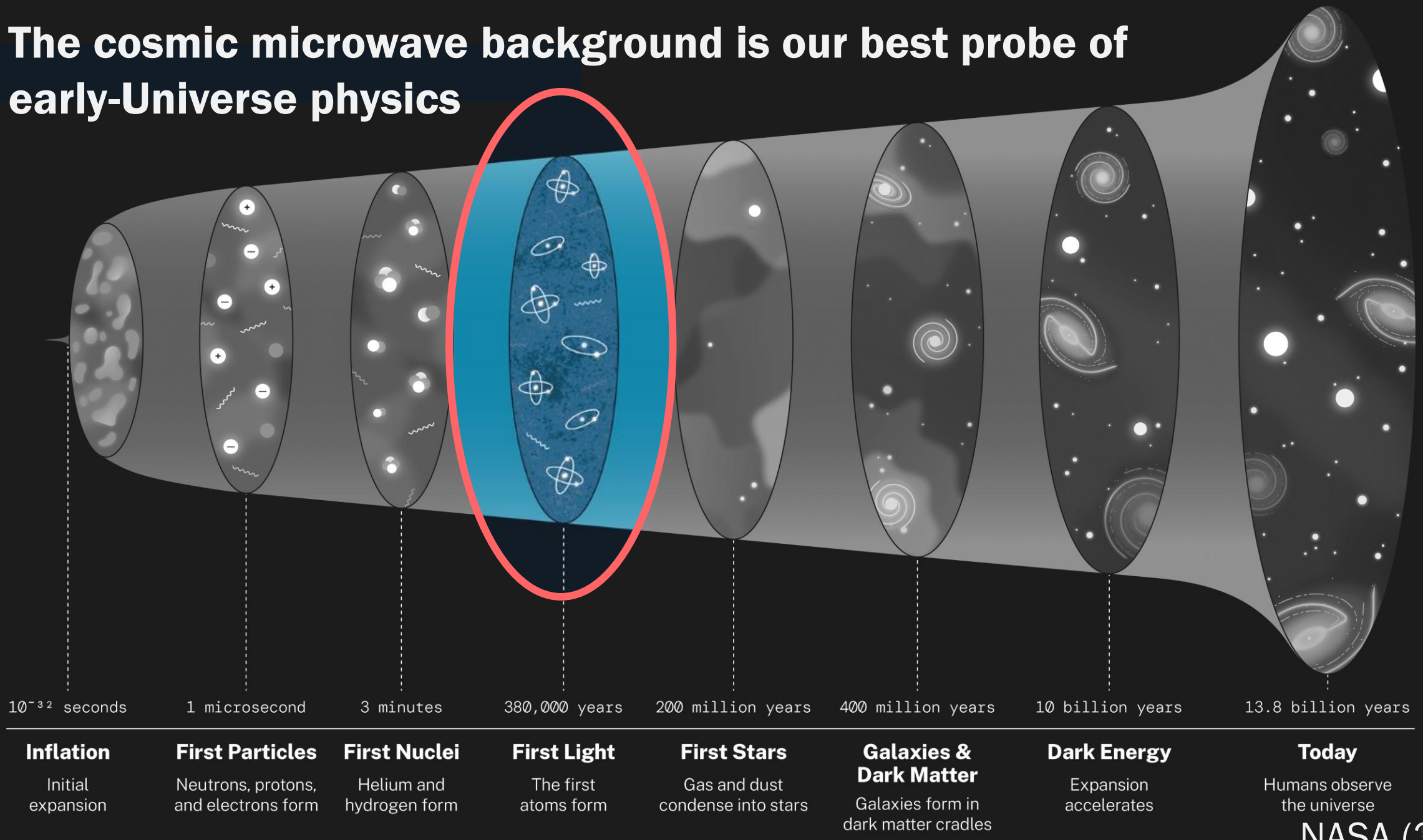


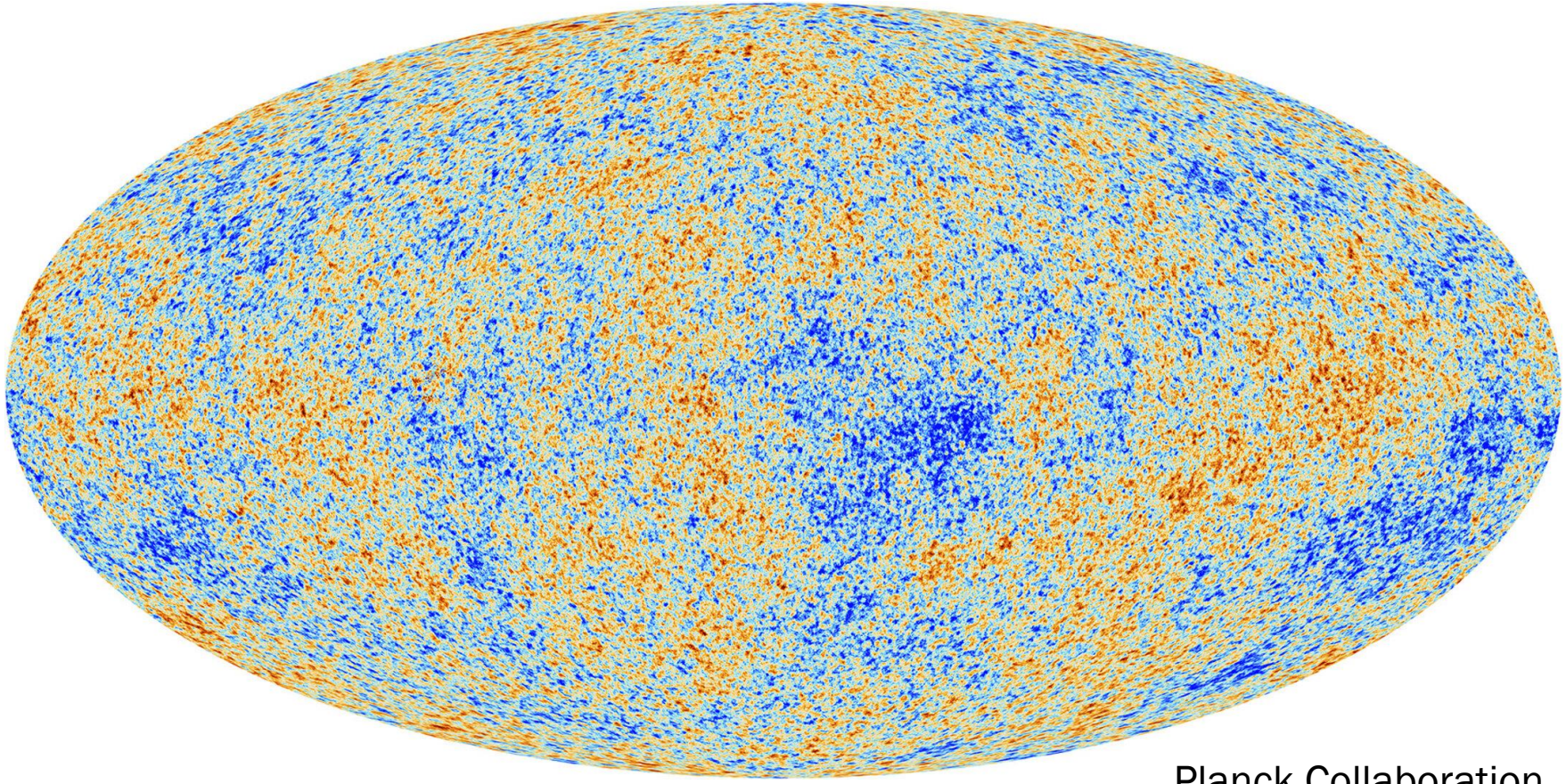
NASA (2019)

The cosmic microwave background is our best probe of early-Universe physics



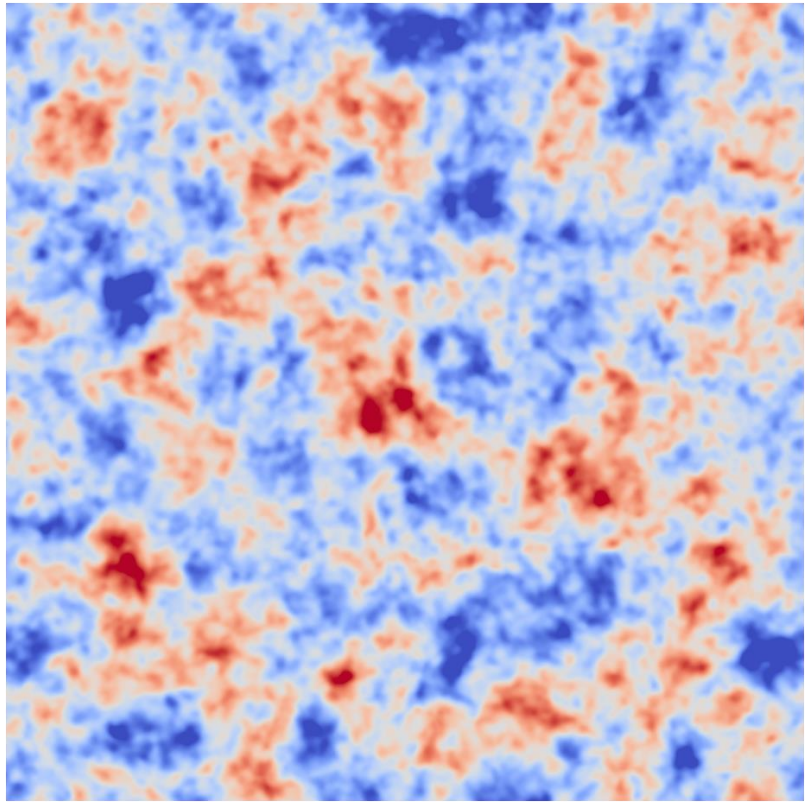
NASA (2019)

Temperature variations (1:100 000) are a main feature of the CMB



Planck Collaboration, ESA (2013)

Temperature fluctuations can be characterized by strength and size



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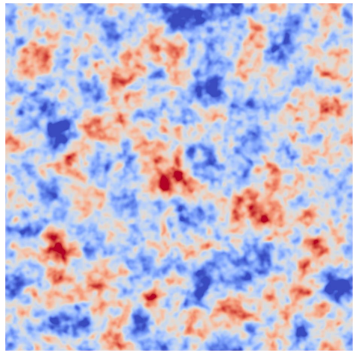

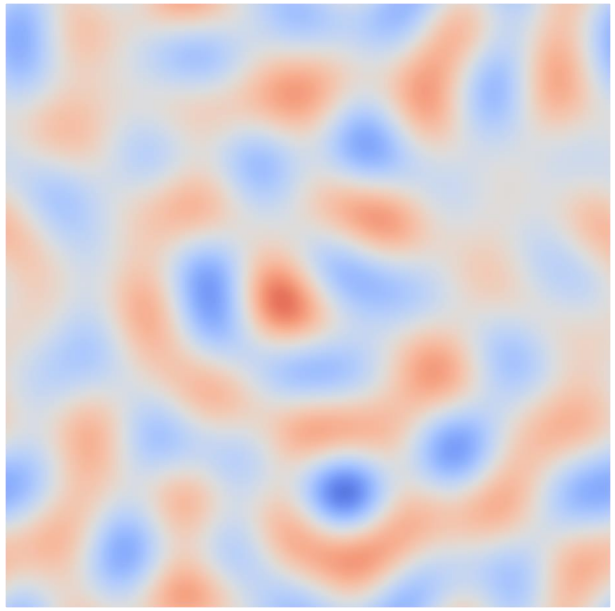

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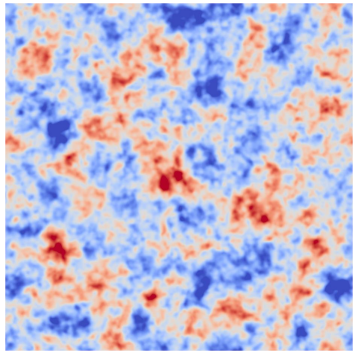

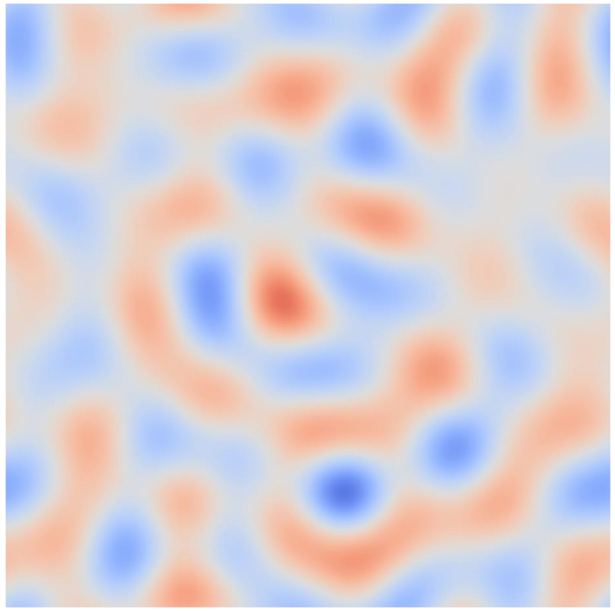

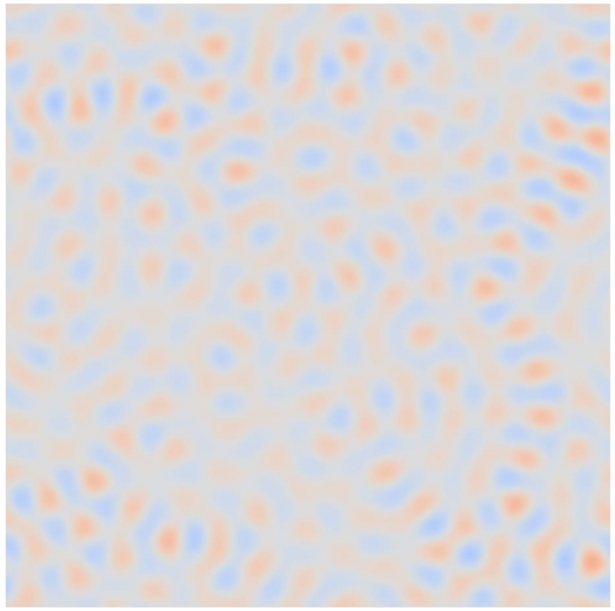

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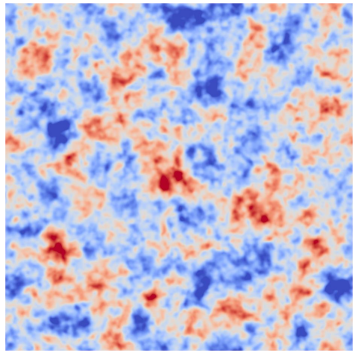

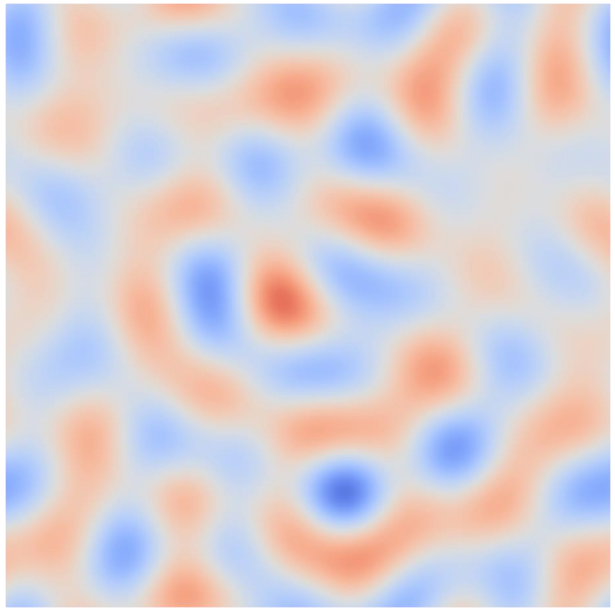

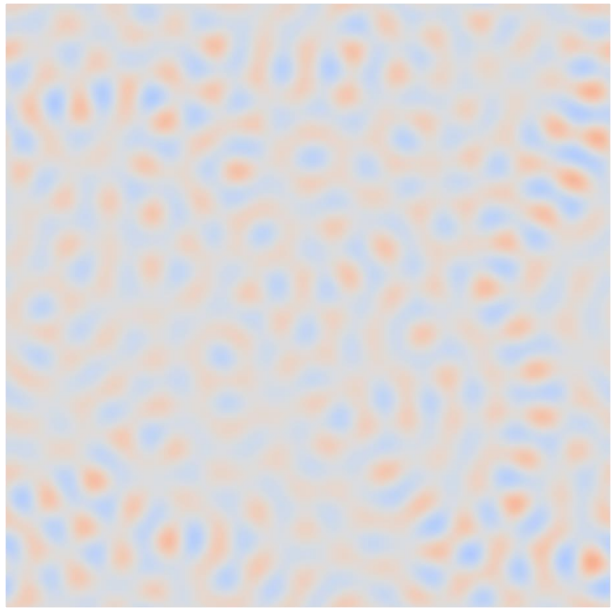

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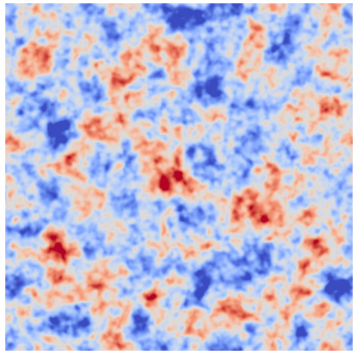
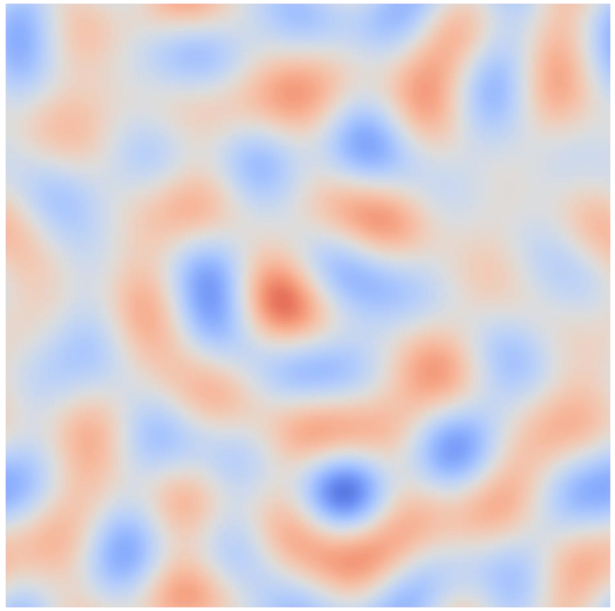
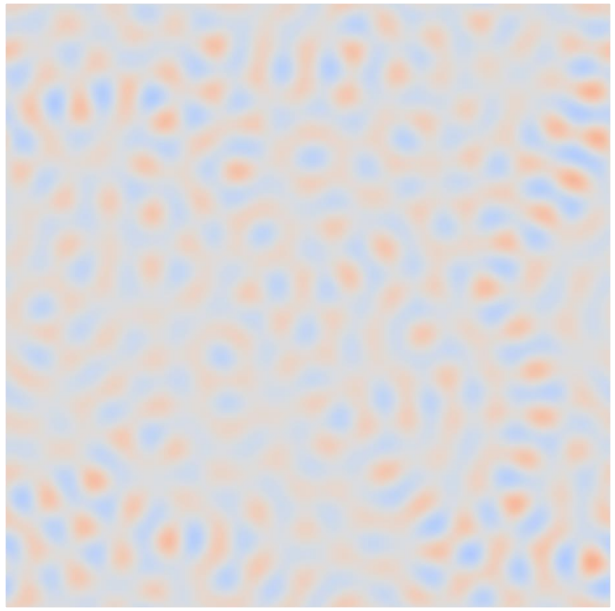
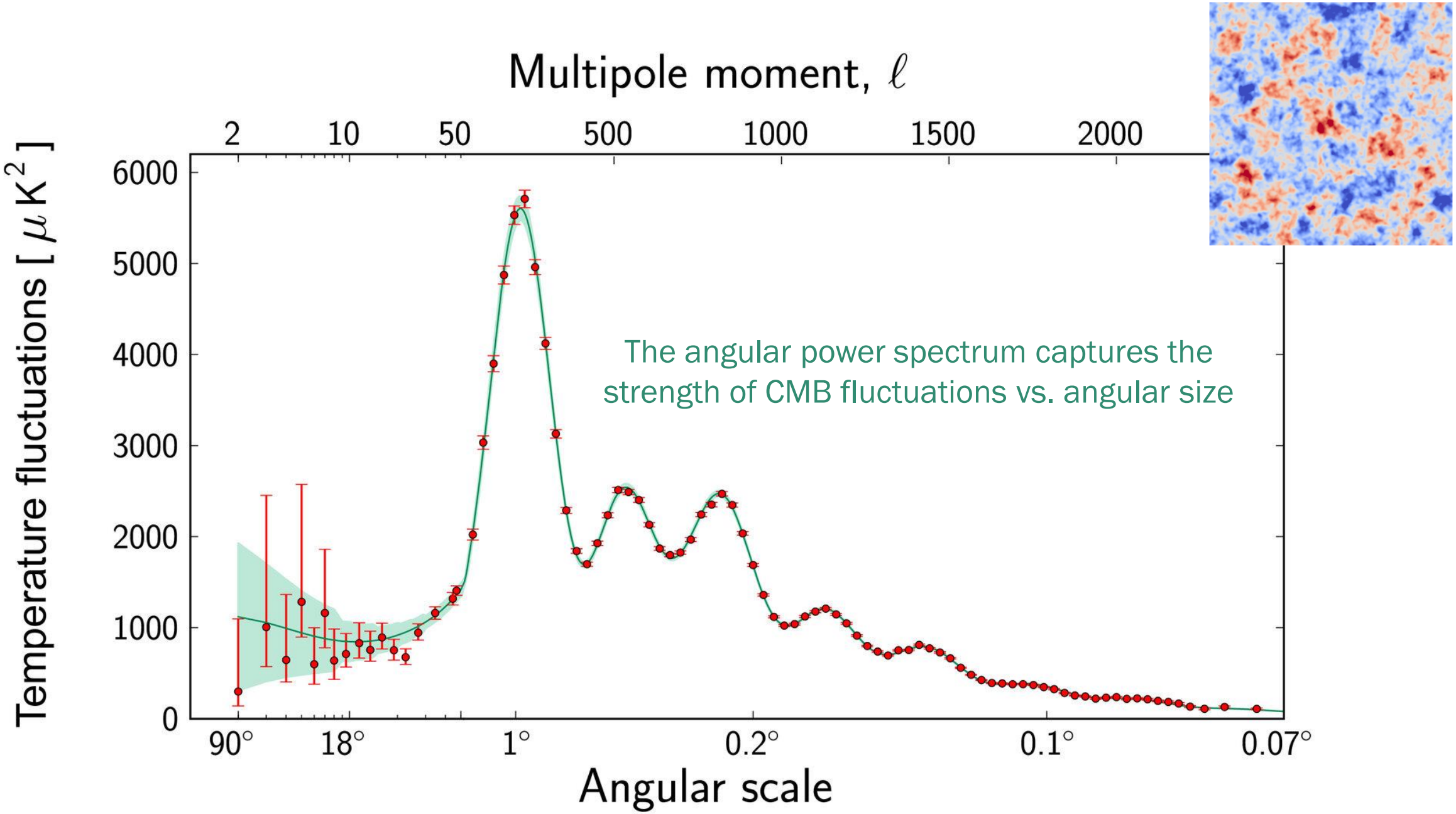


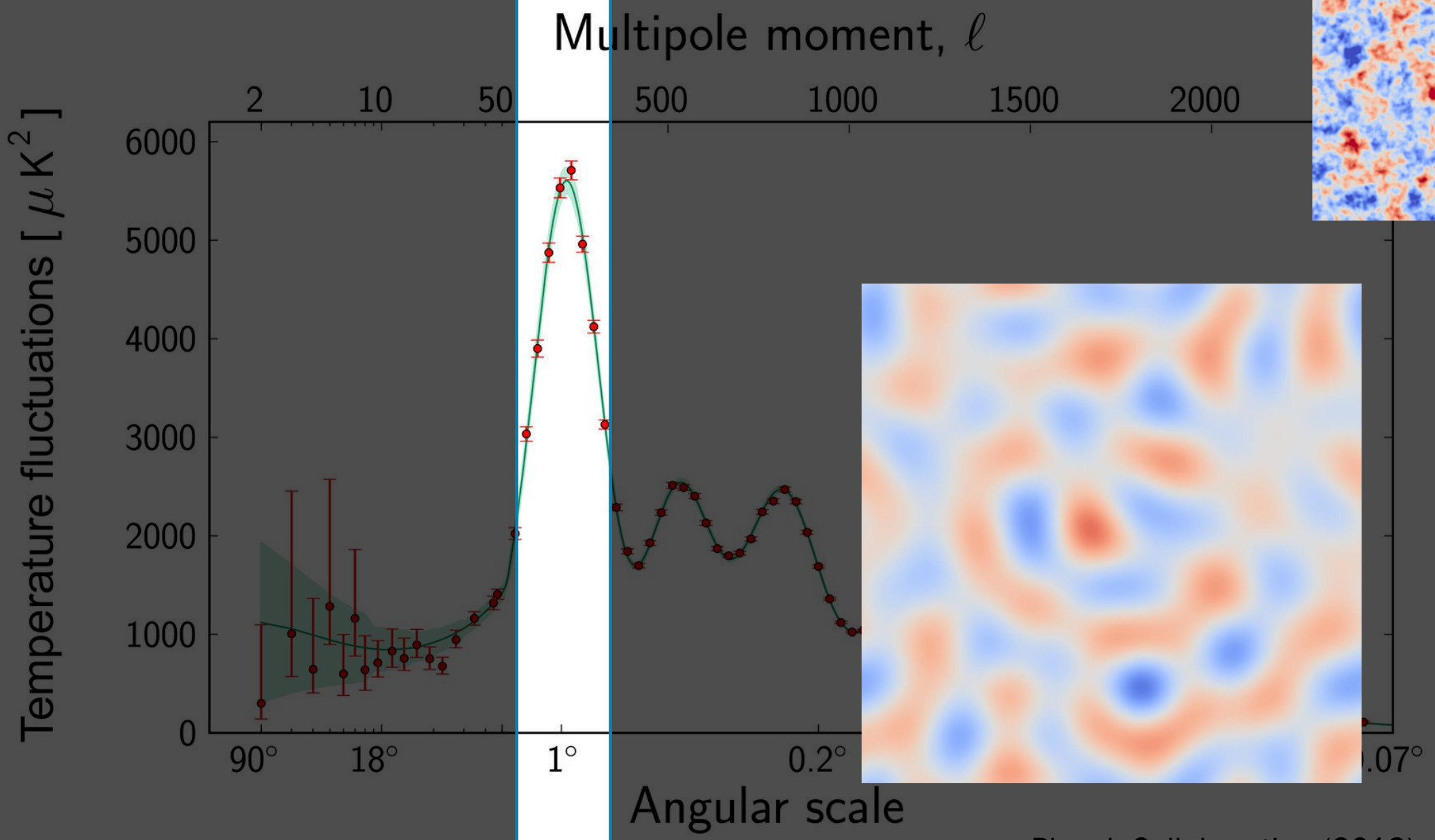
The angular power spectrum captures the strength of CMB fluctuations vs. angular size







Planck Collaboration (2013)



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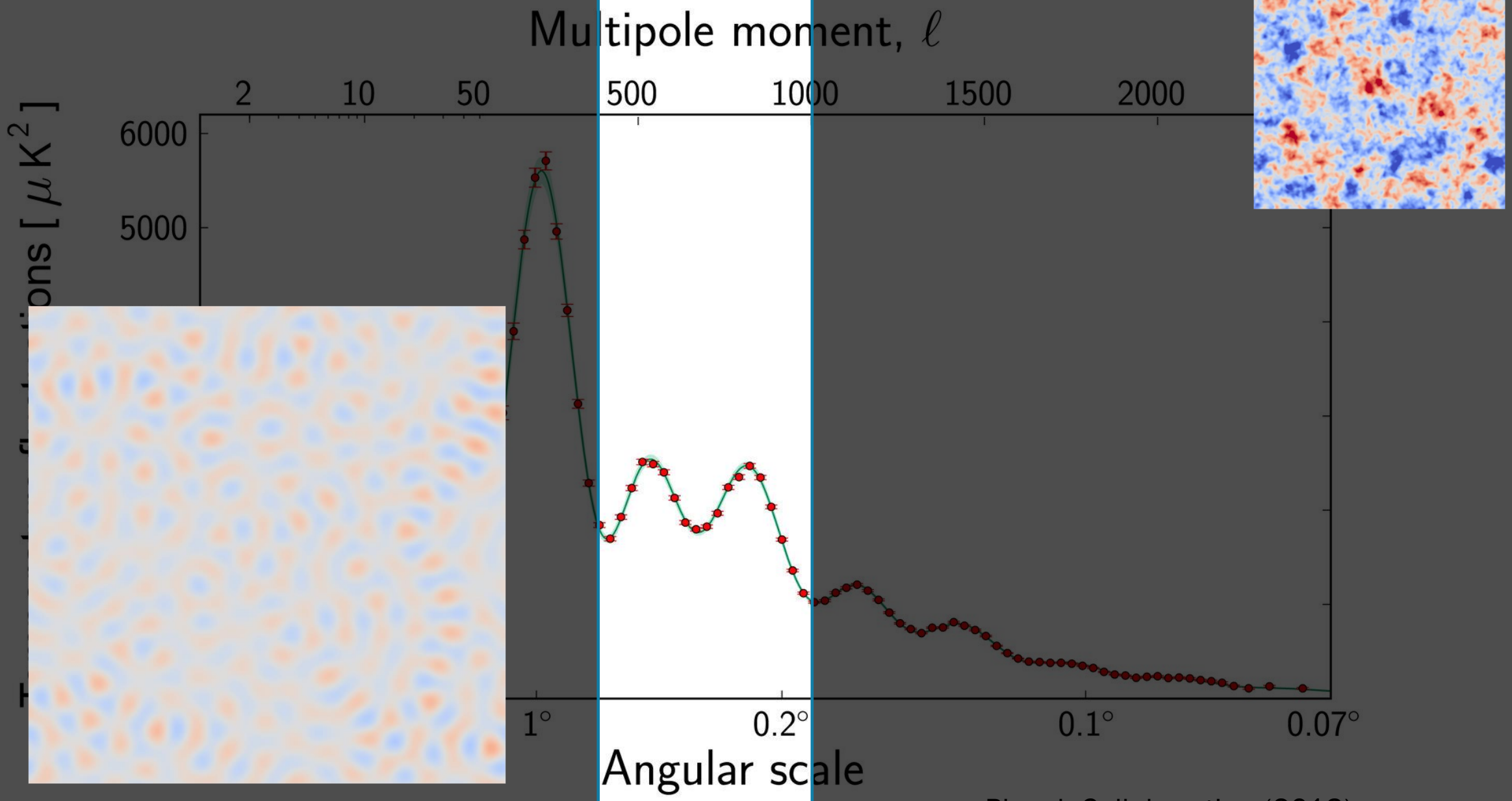

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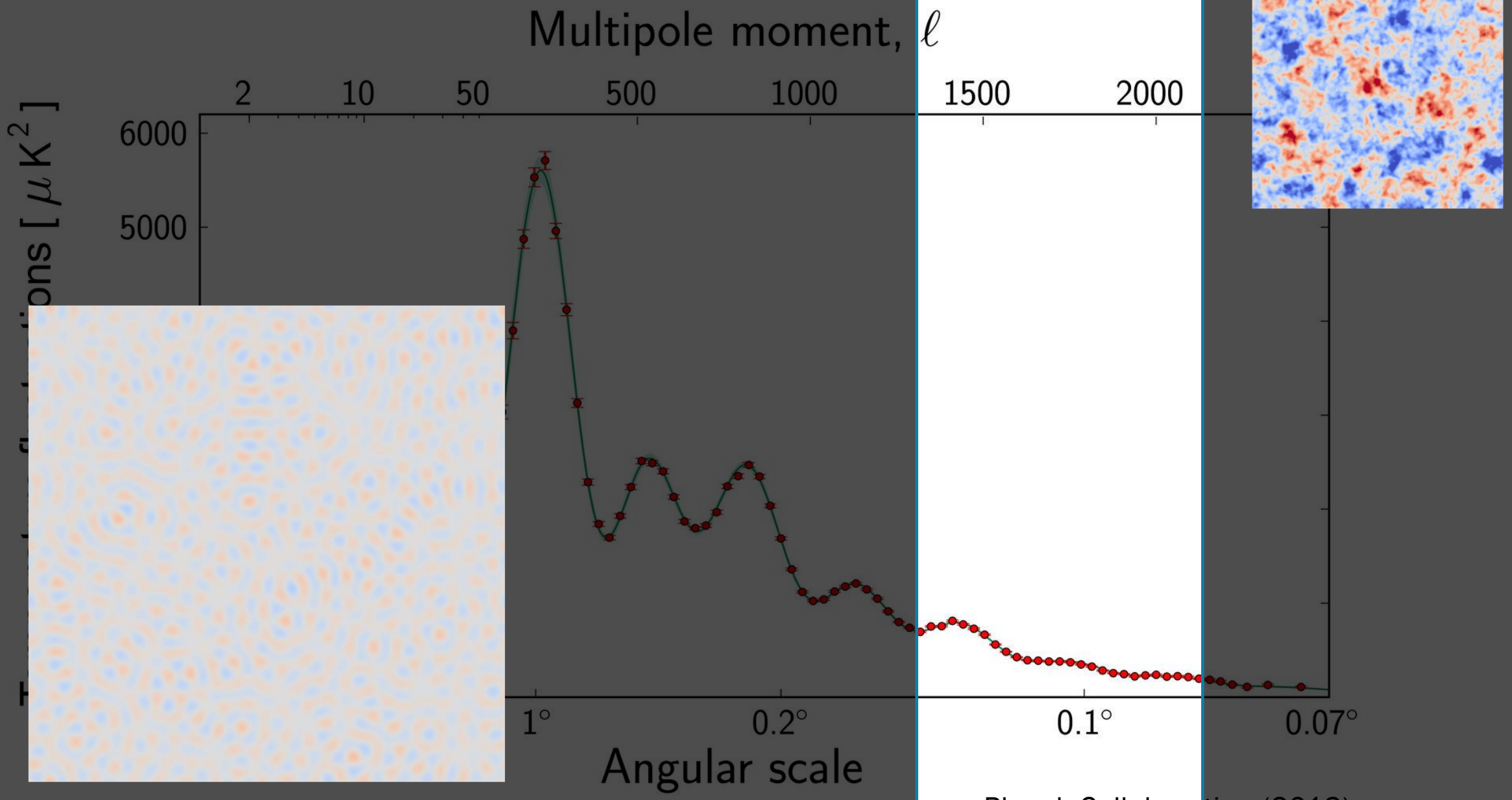

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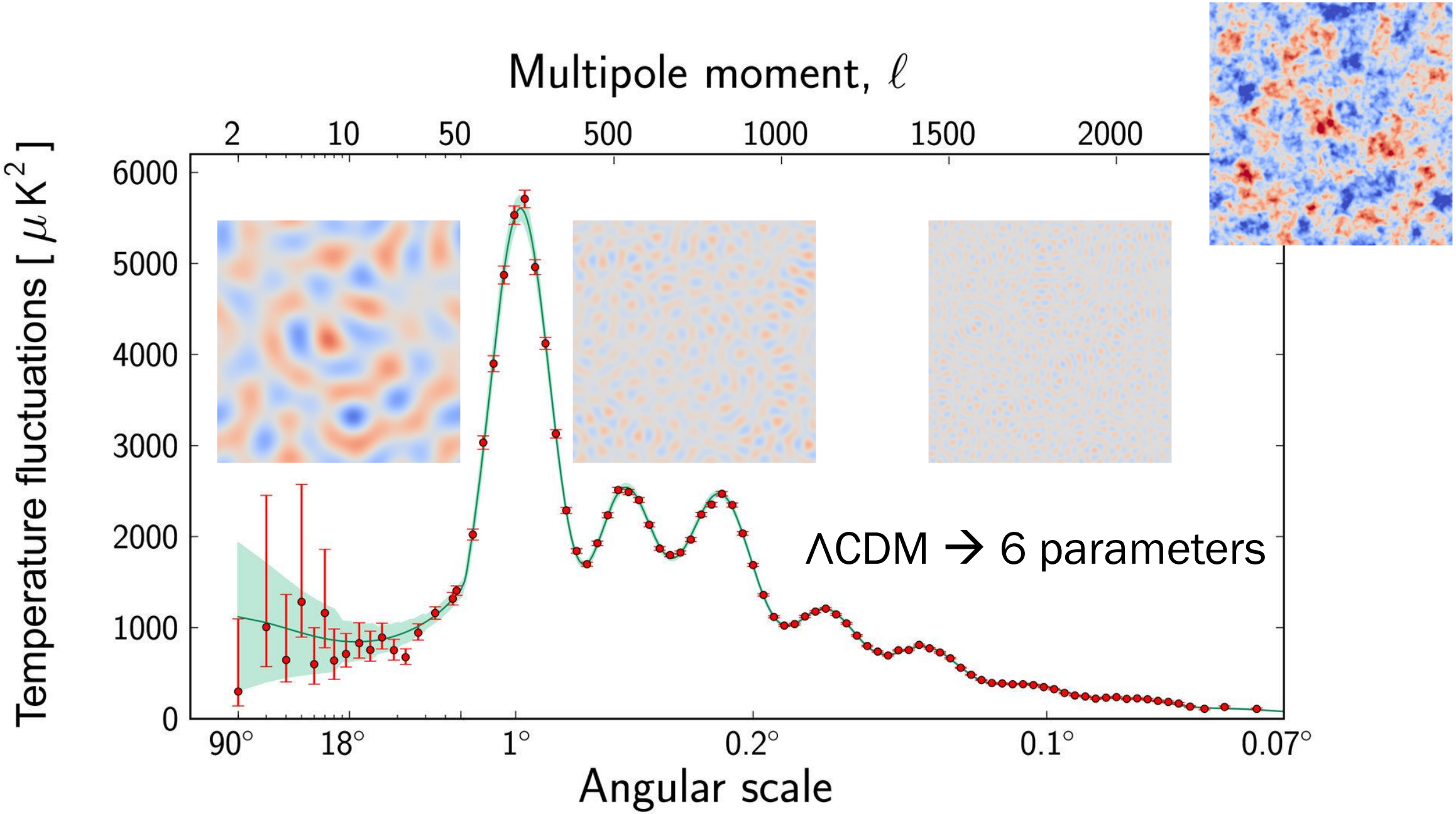
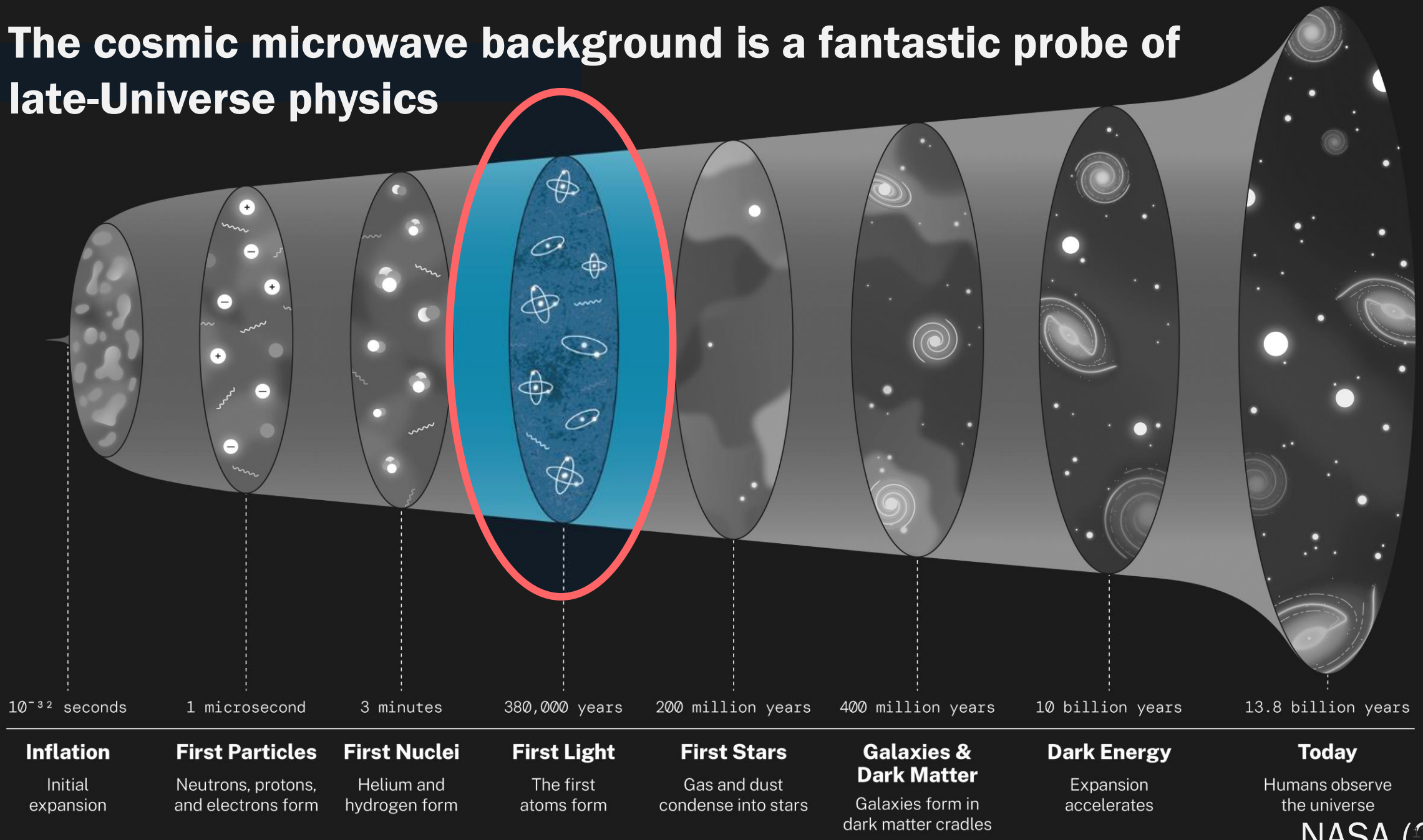


Planck Collaboration (2013)

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



NASA (2019)

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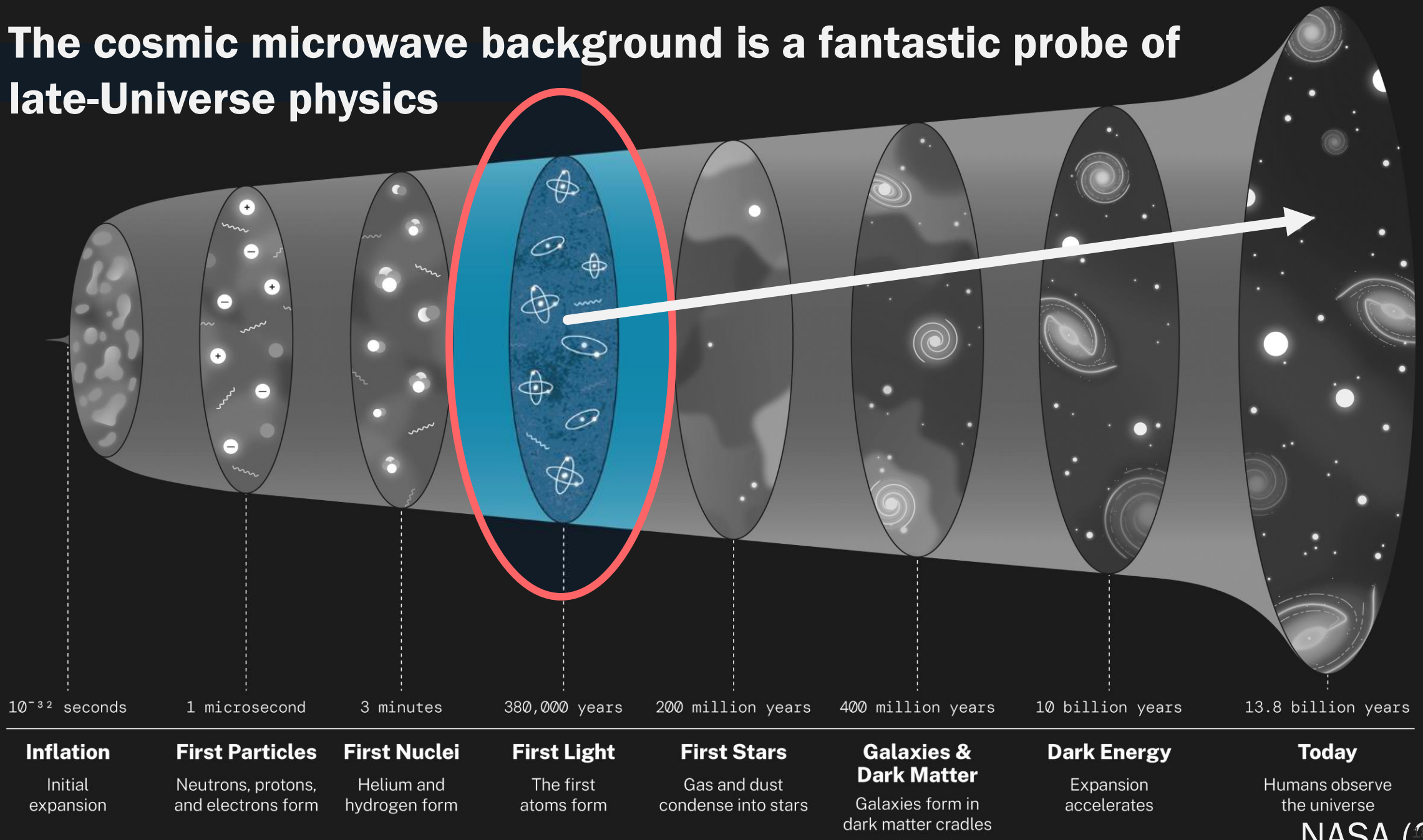

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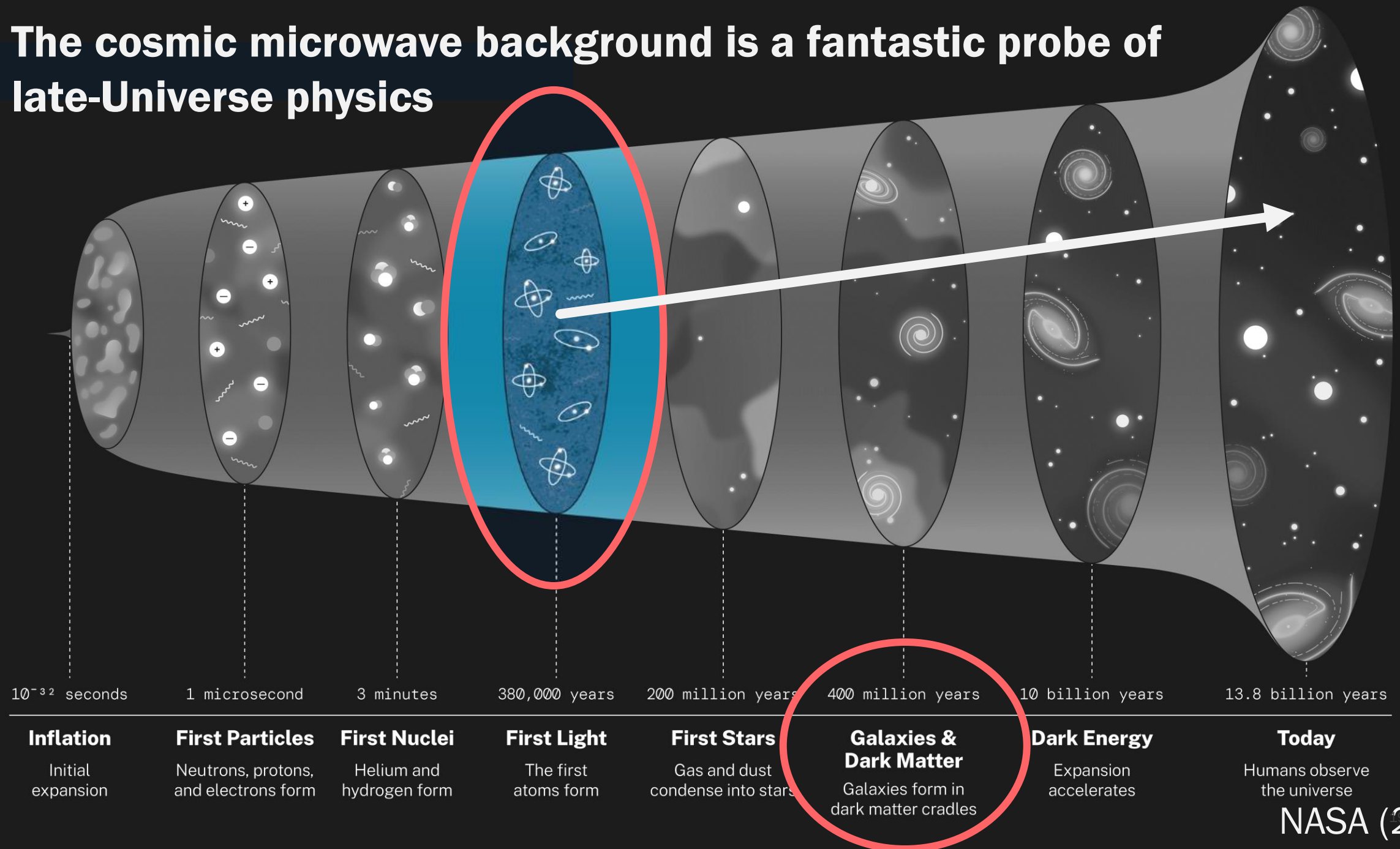
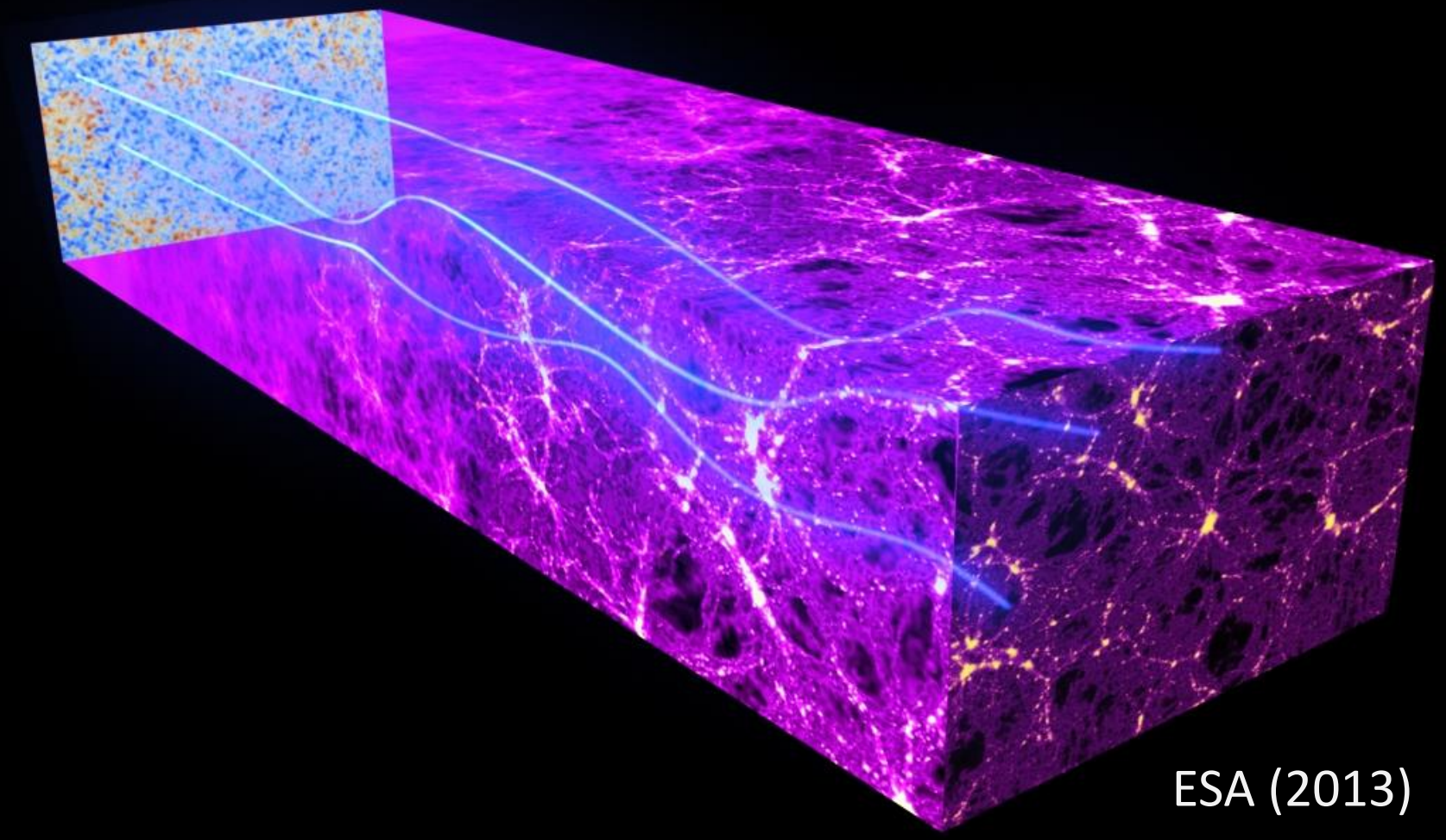


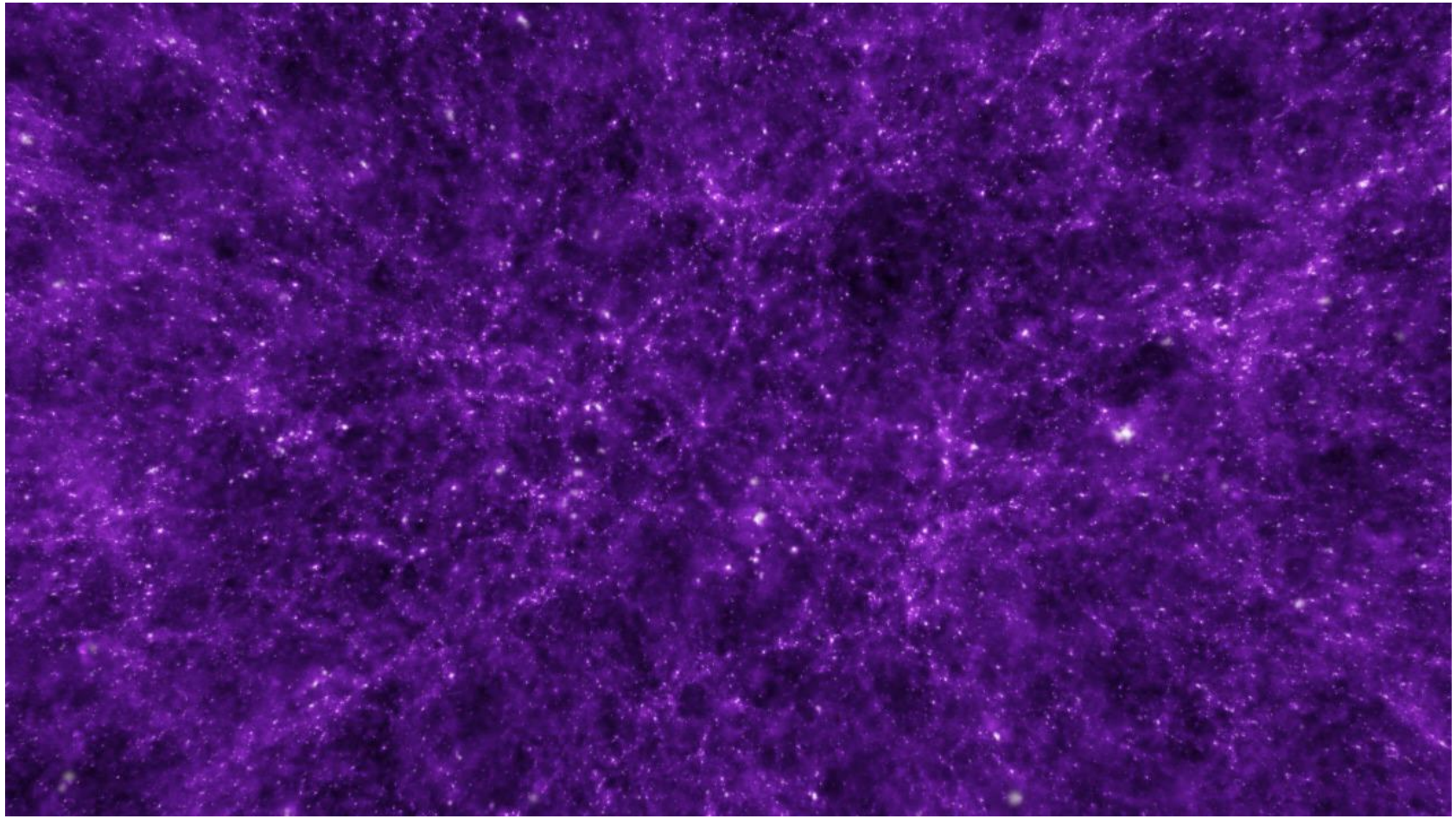
NASA (2019)

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



ESA (2013)

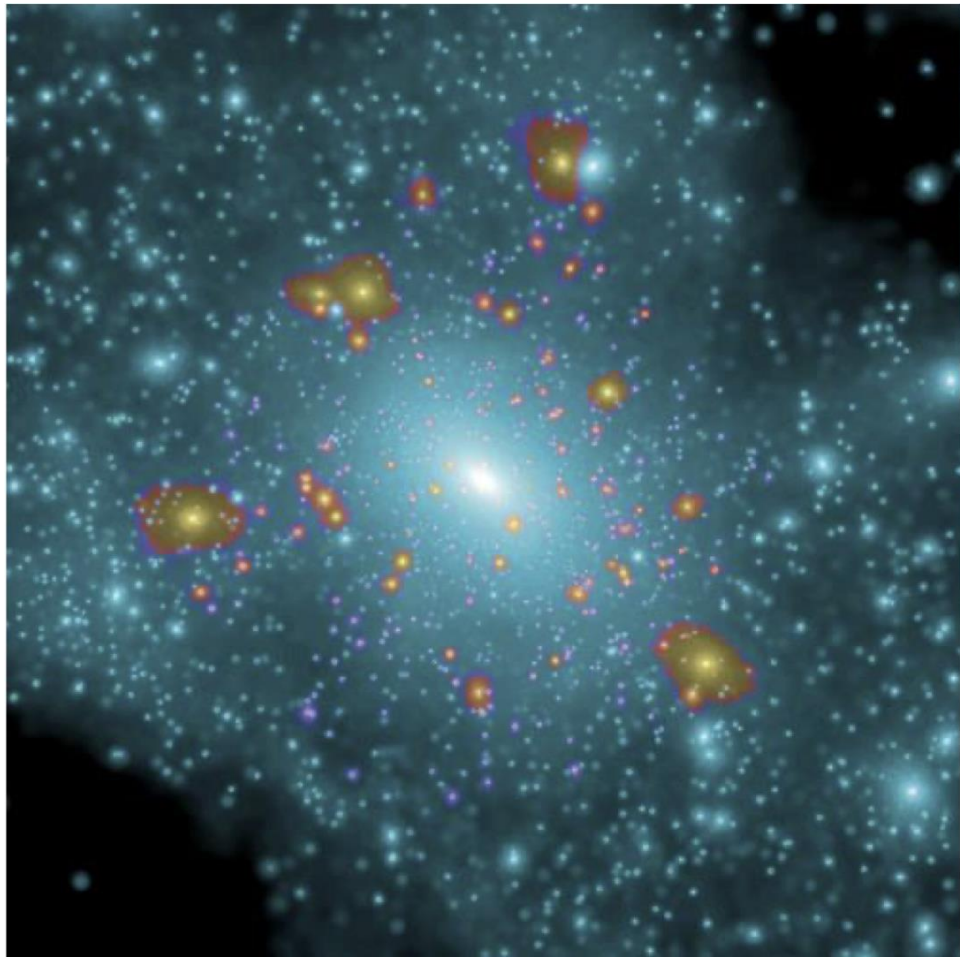
Clusters of galaxies are composed primarily of dark matter



NASA (2007)

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

Cold Dark Matter



ESA (2023)

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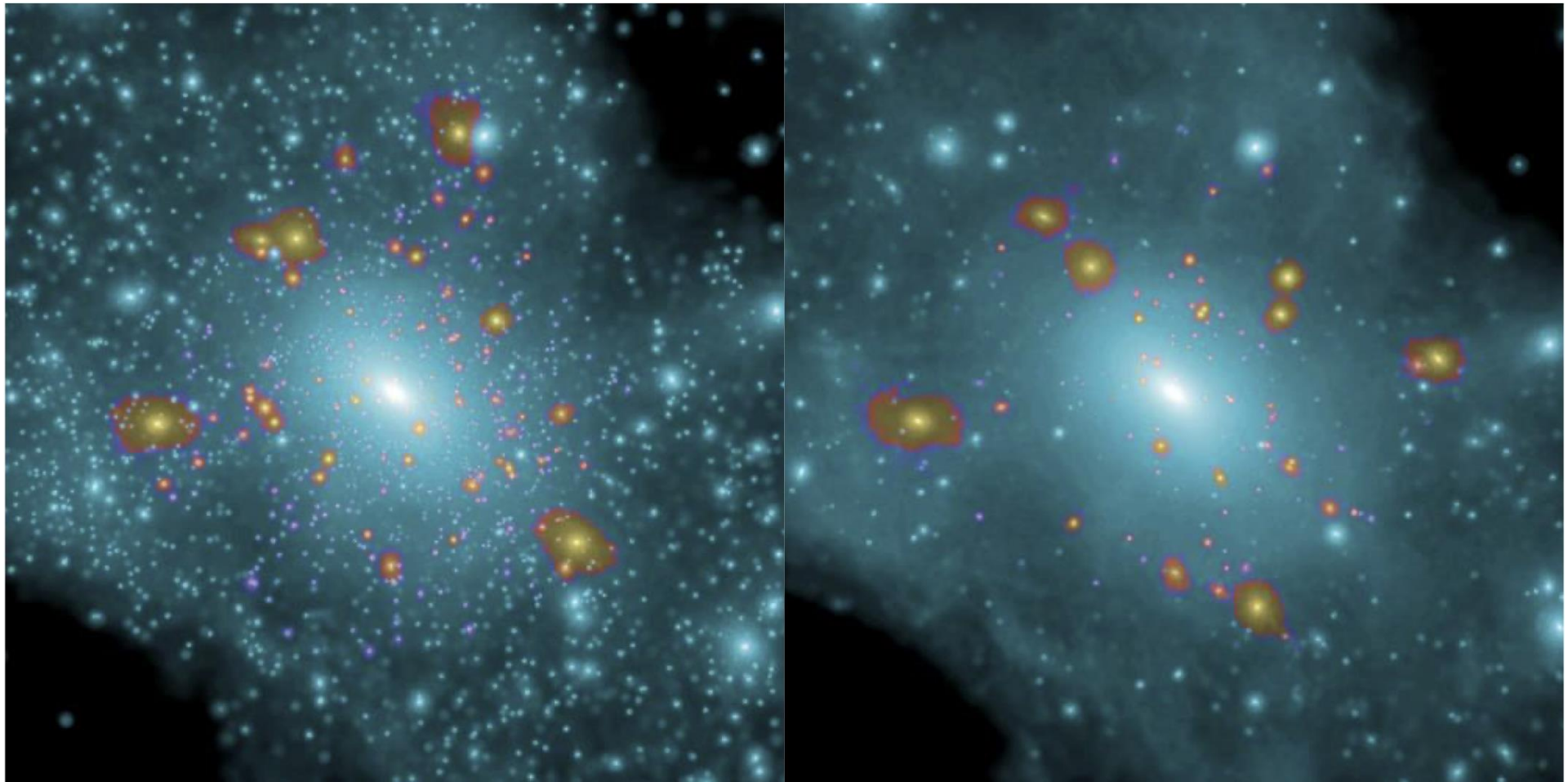
Cold Dark Matter

Warm Dark Matter

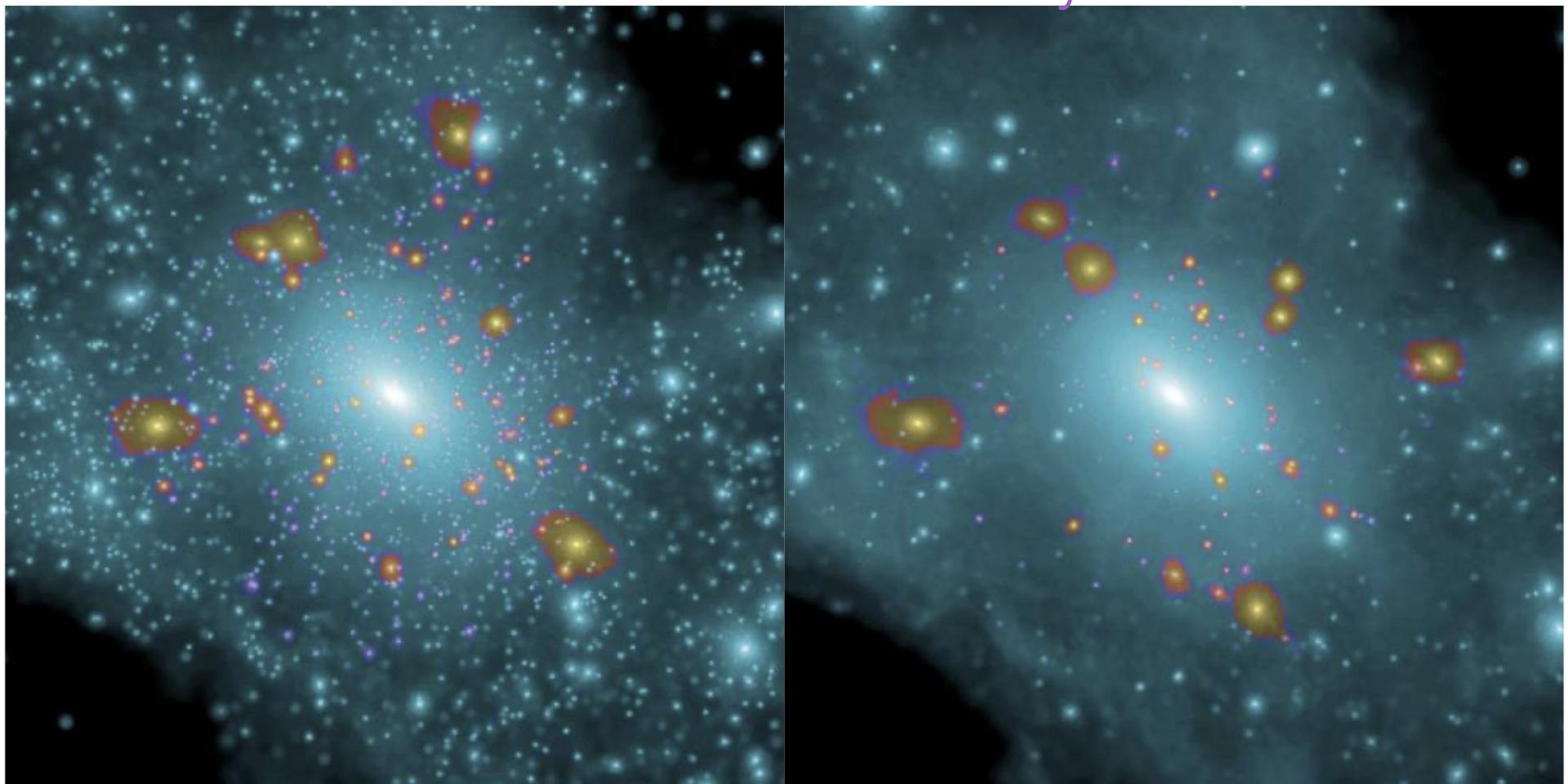


ESA (2023)

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

Cold Dark Matter

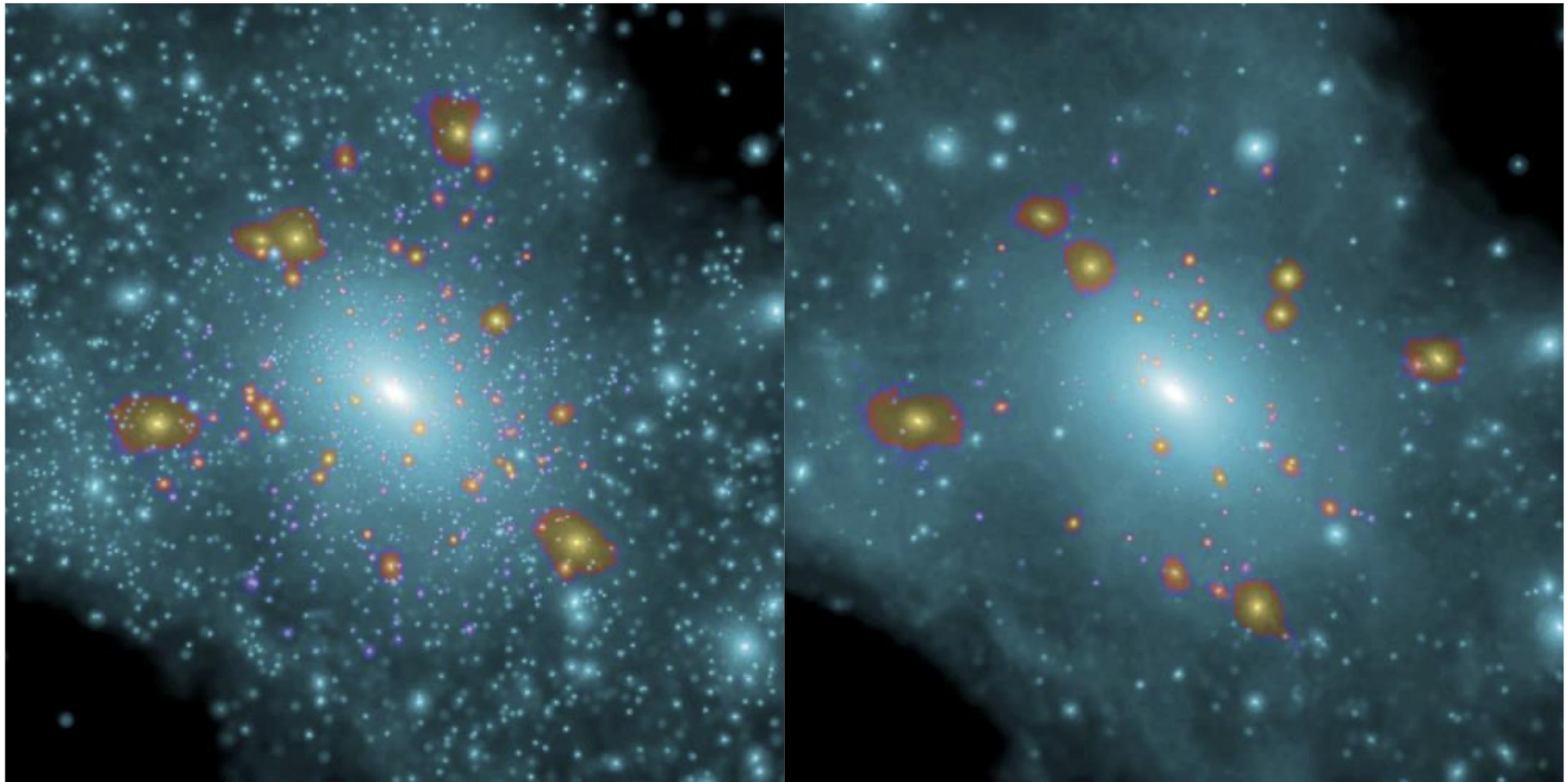
Fuzzy Dark Matter



ESA (2023)

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

Low m_ν High m_ν



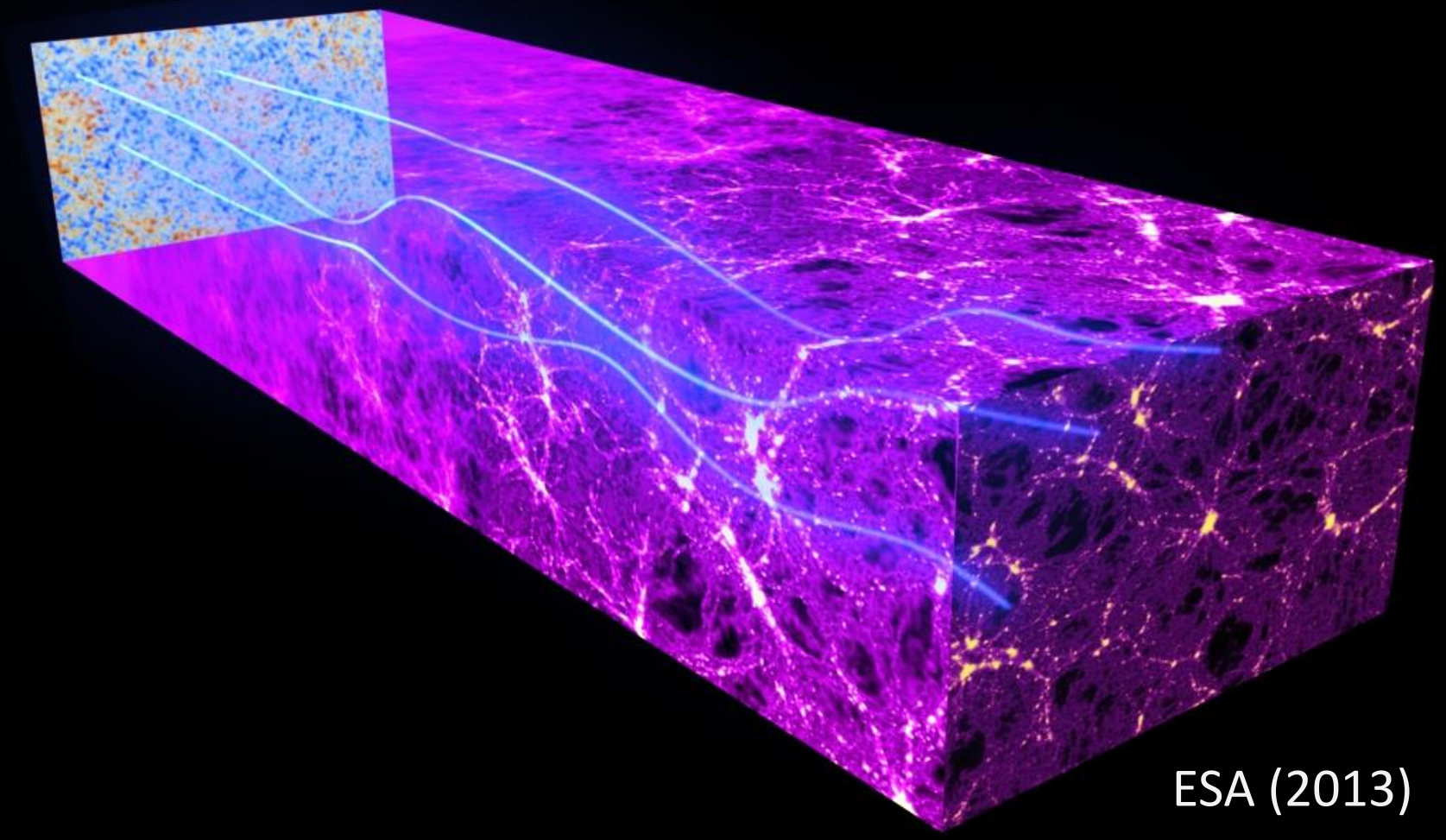
ESA (2023)

Takeaways:

- Cosmic microwave background experiments have been extremely successful at measuring ΛCDM parameters
- Lensed features in the cosmic microwave background can teach us about massive structures
- The abundance and distribution of massive structures is dictated by matter clustering
  - Dark matter models, gravity, massive neutrinos, …

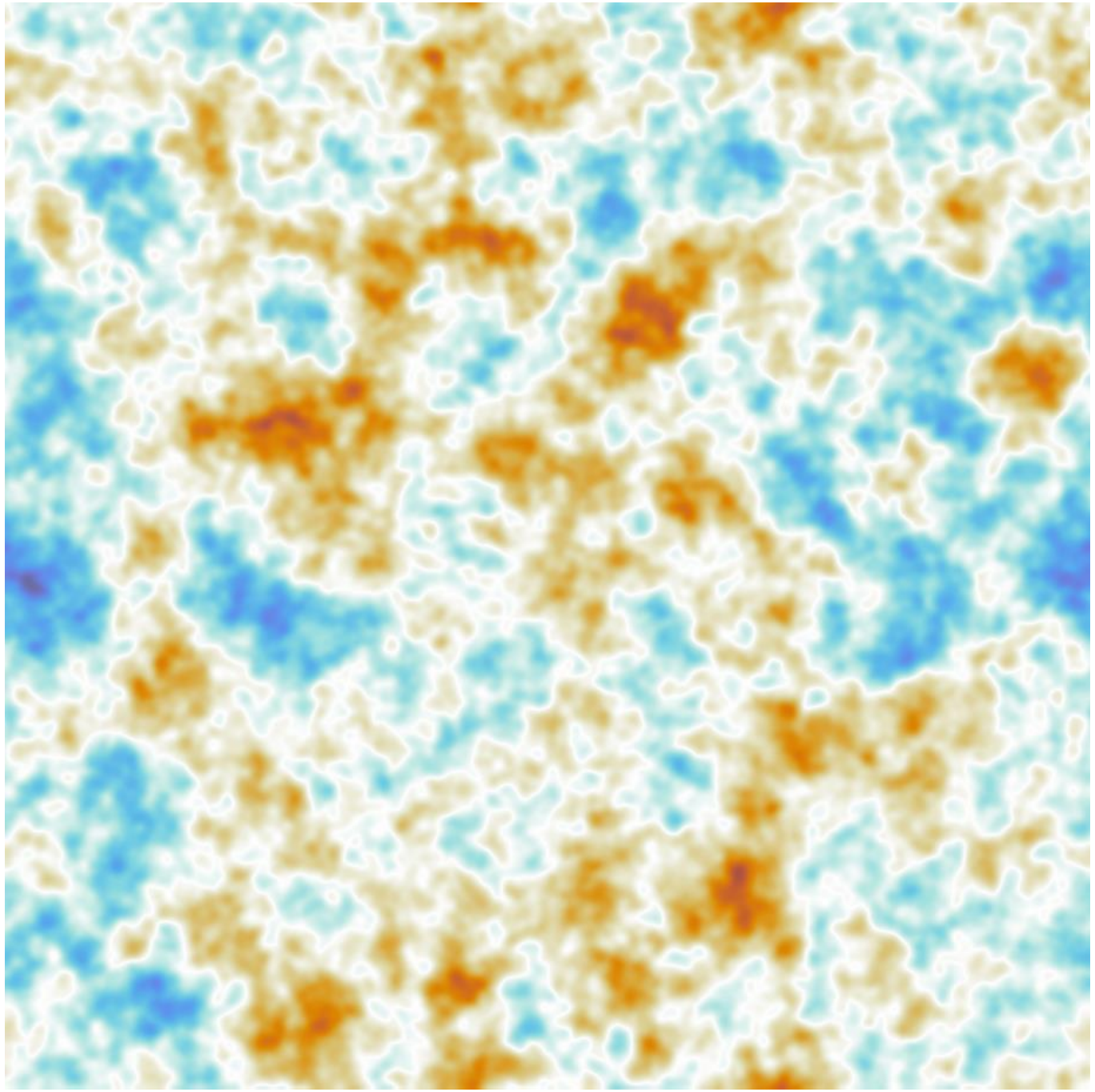
HOW DOES LENSING AFFECT THE COSMIC MICROWAVE BACKGROUND?

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

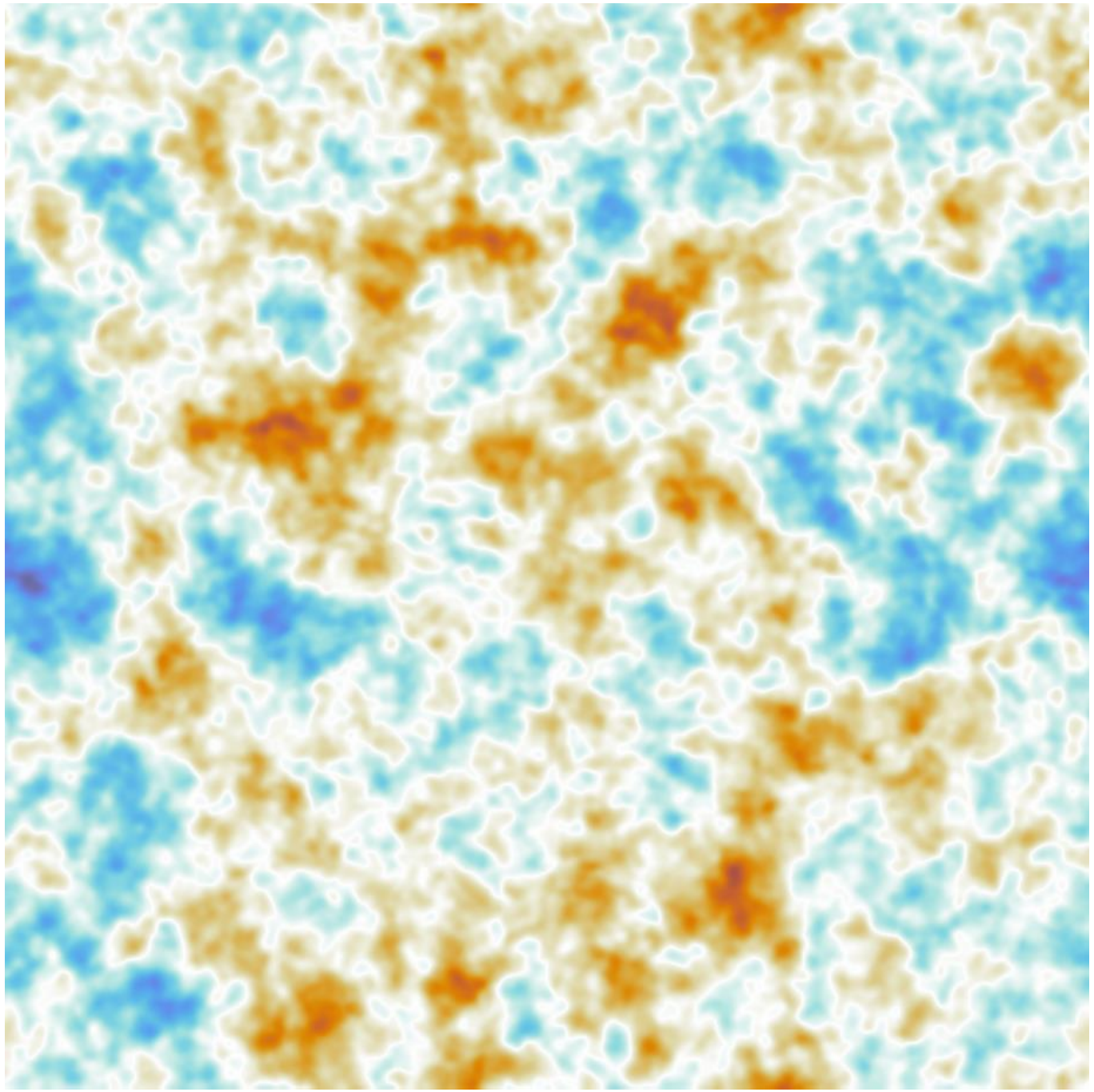


ESA (2013)

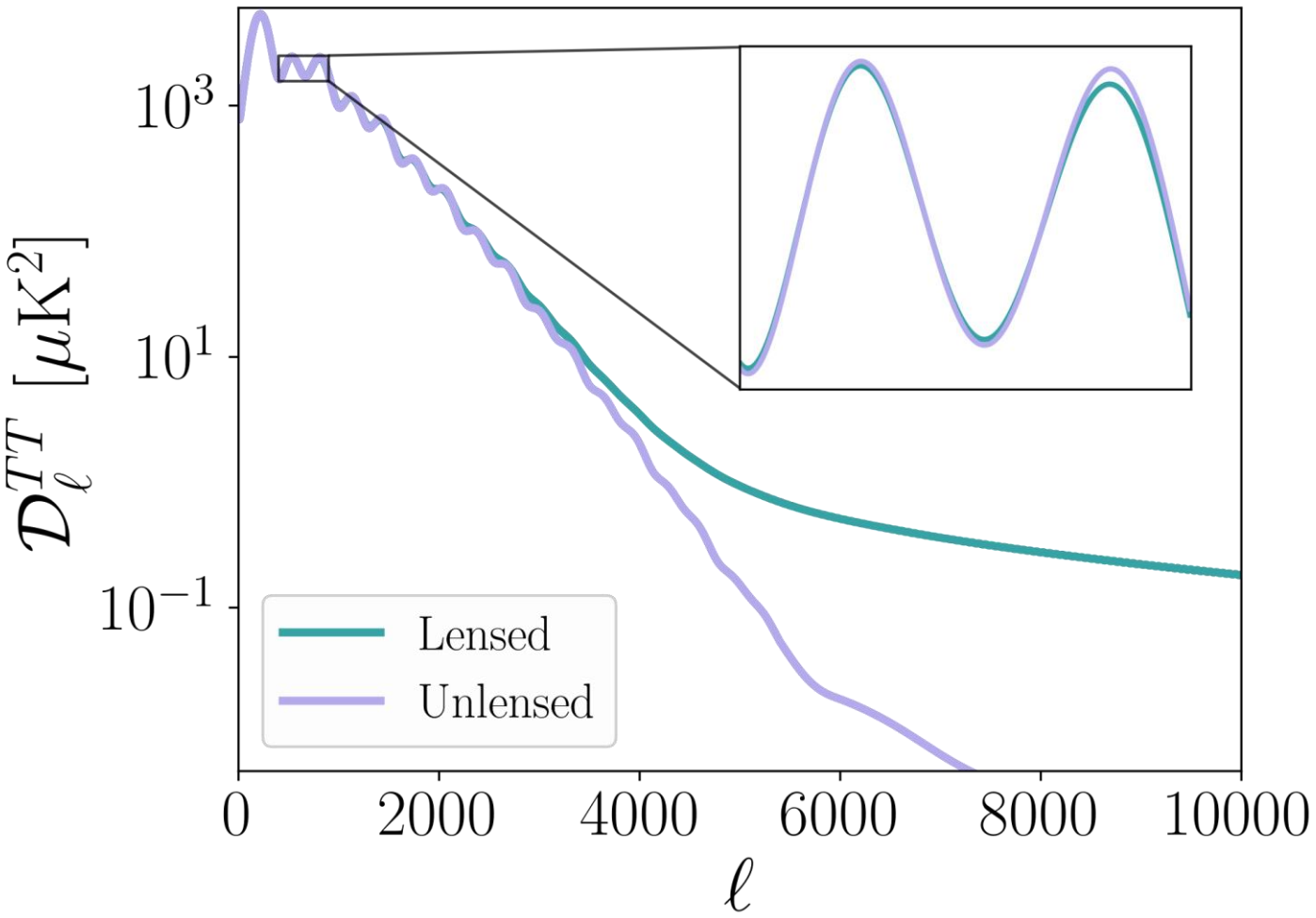
Original



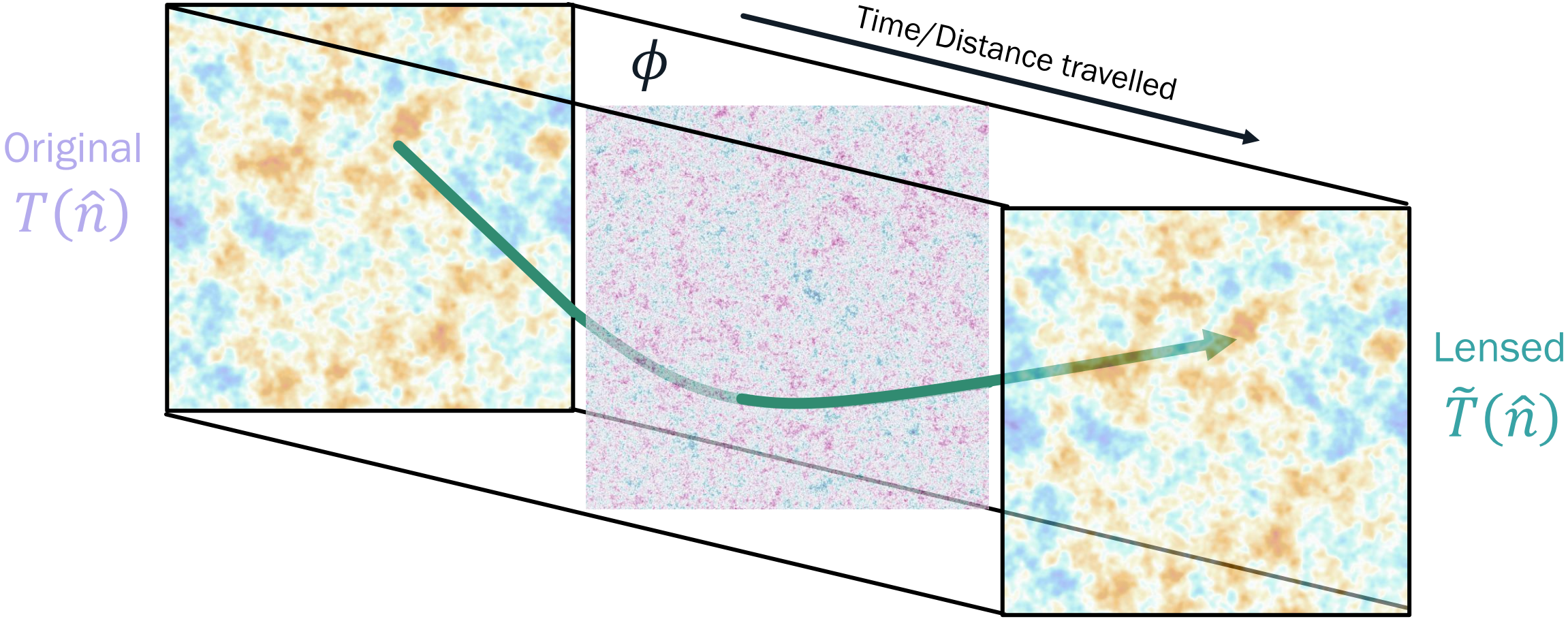
Lensed



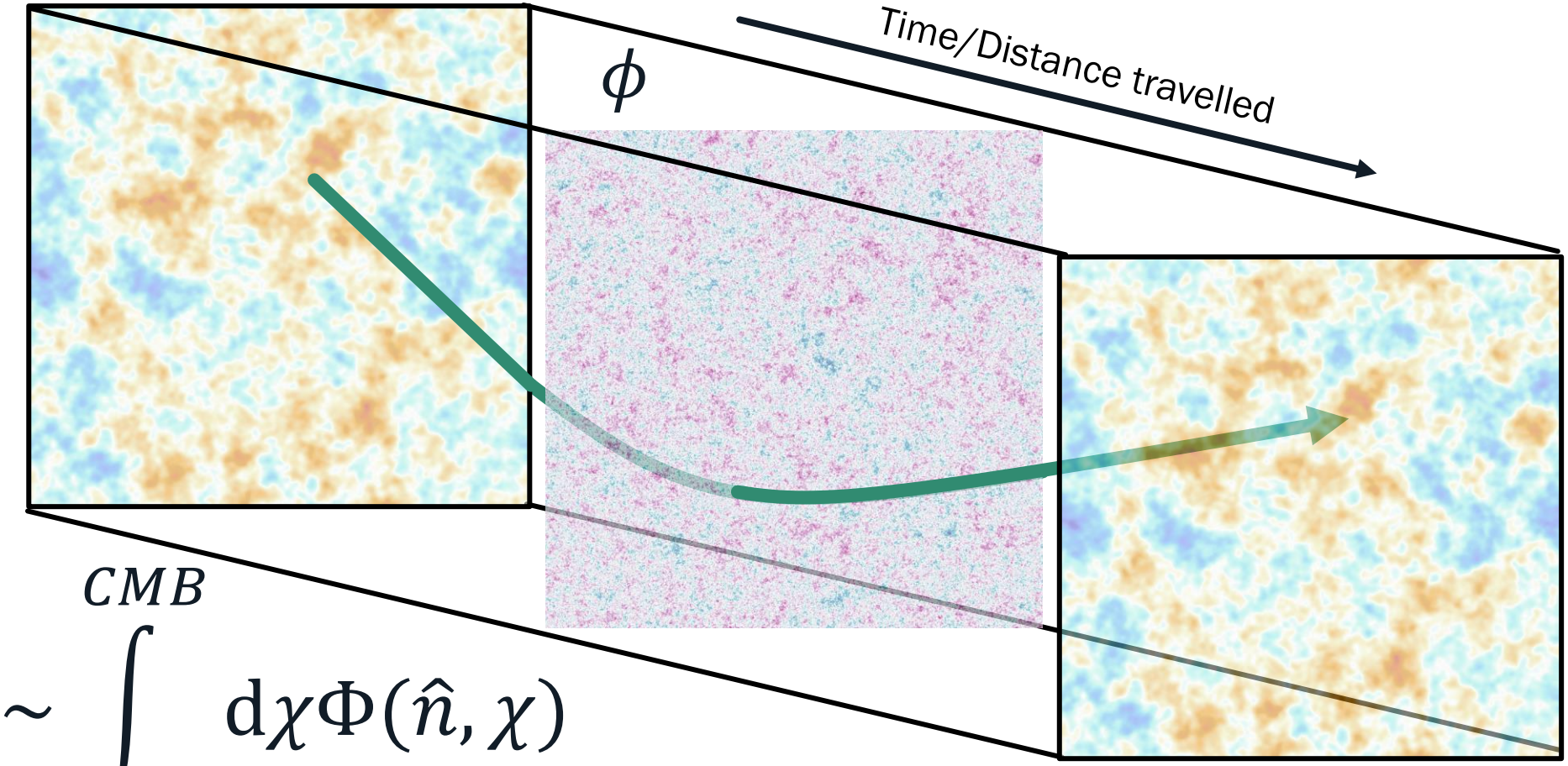
Features are magnified and de-magnified: Lensing re-distributes CMB power across angular scales



Gravitational lensing of cosmic background photons is well described with the Born approximation



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



Original
$T(\hat{n})$

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

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

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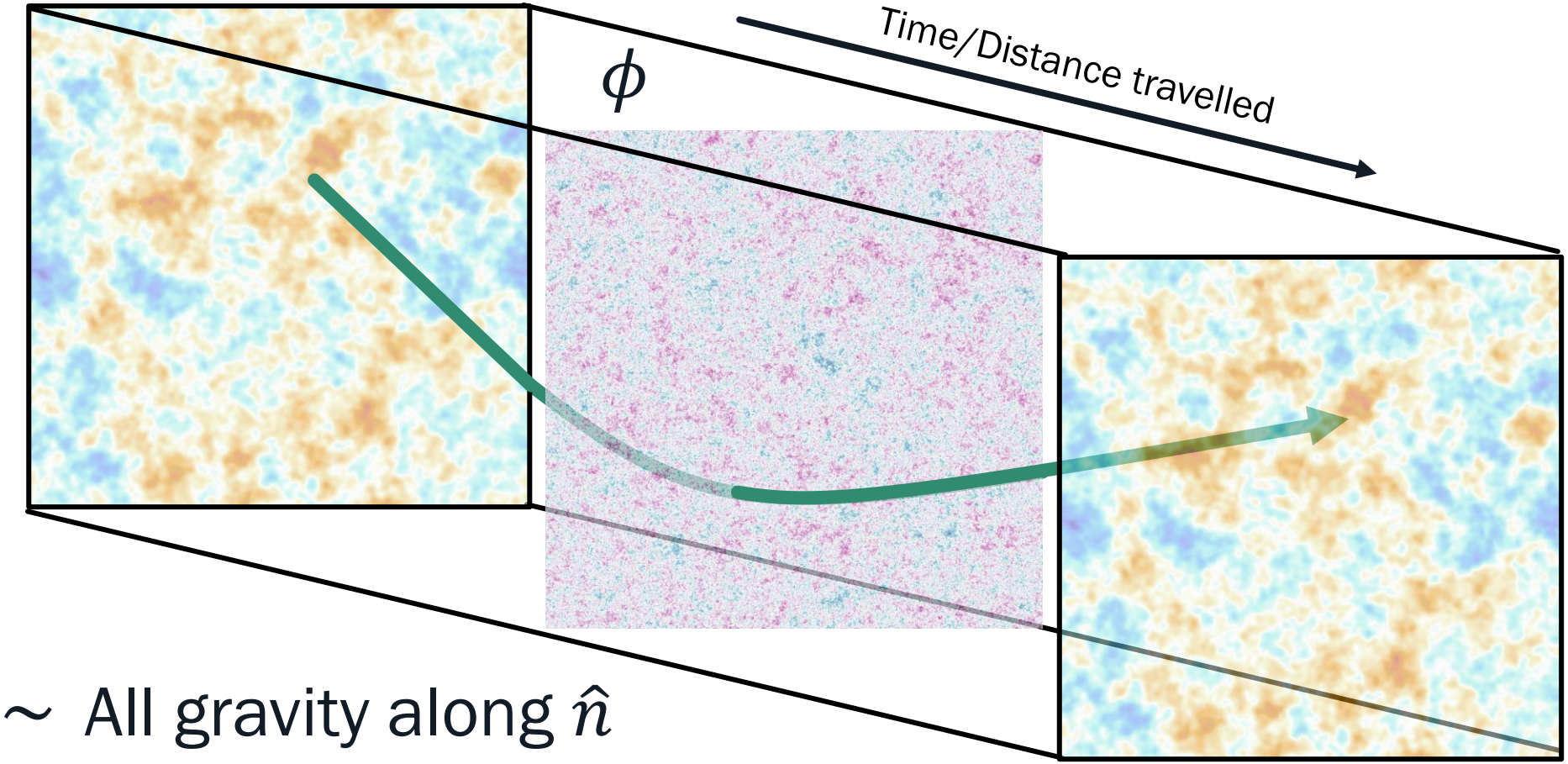

Original
$T(\hat{n})$

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

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

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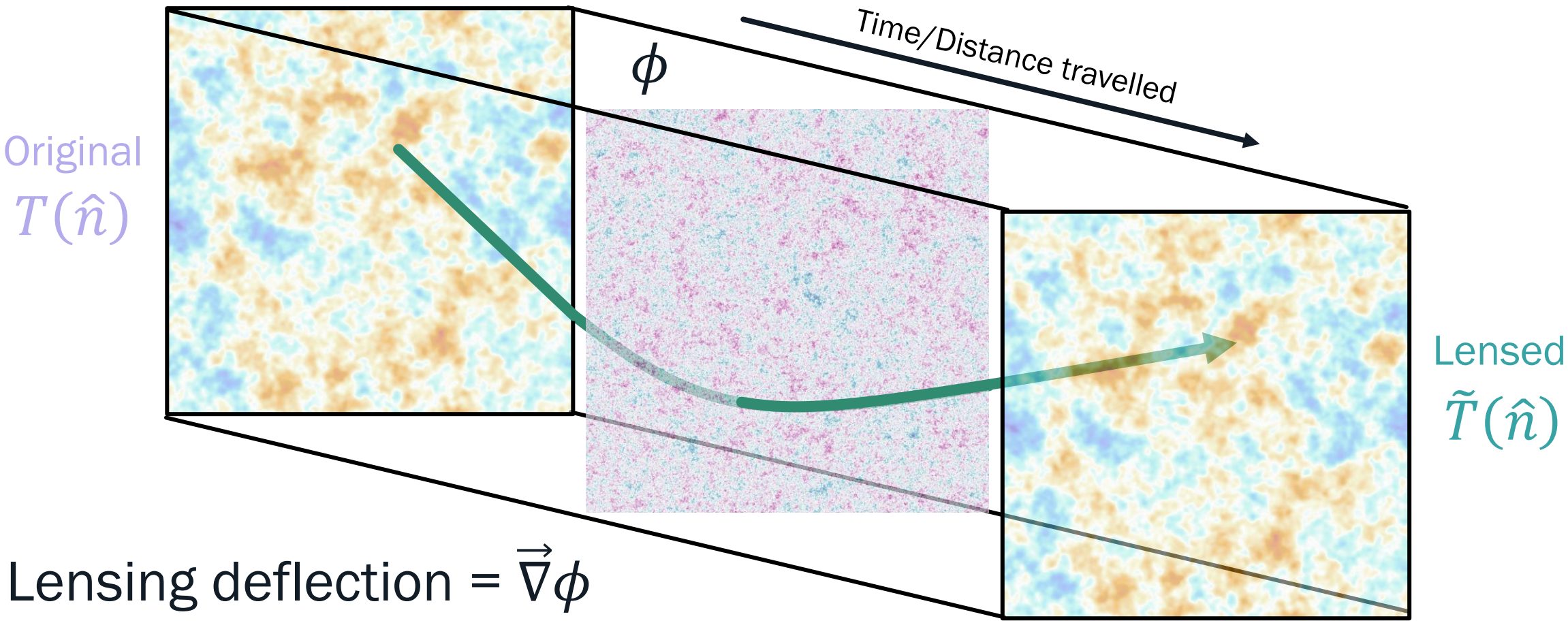
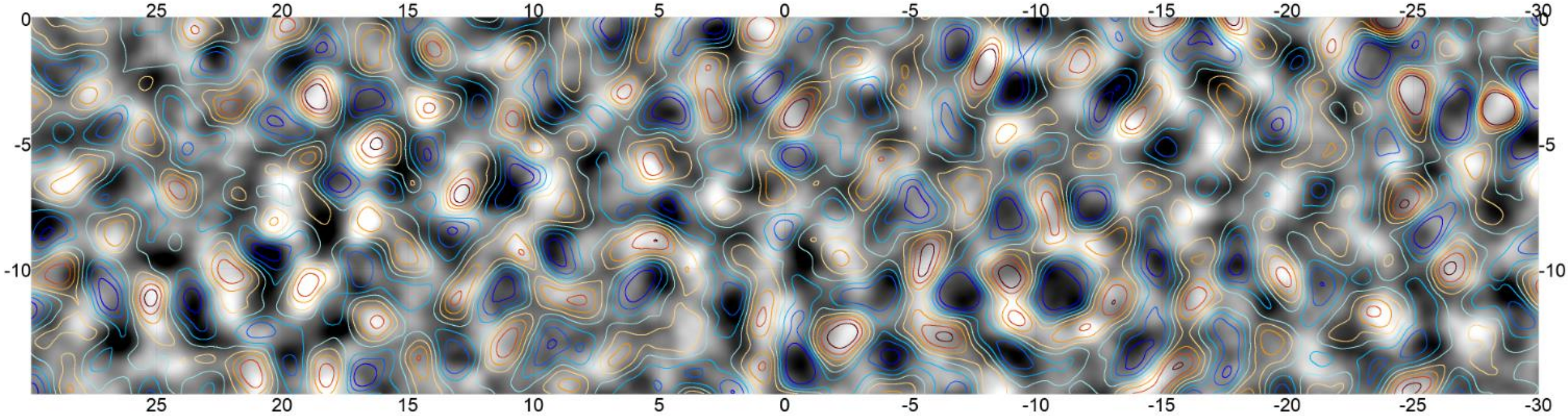


Lensing deflection = $\vec{\nabla}\phi$

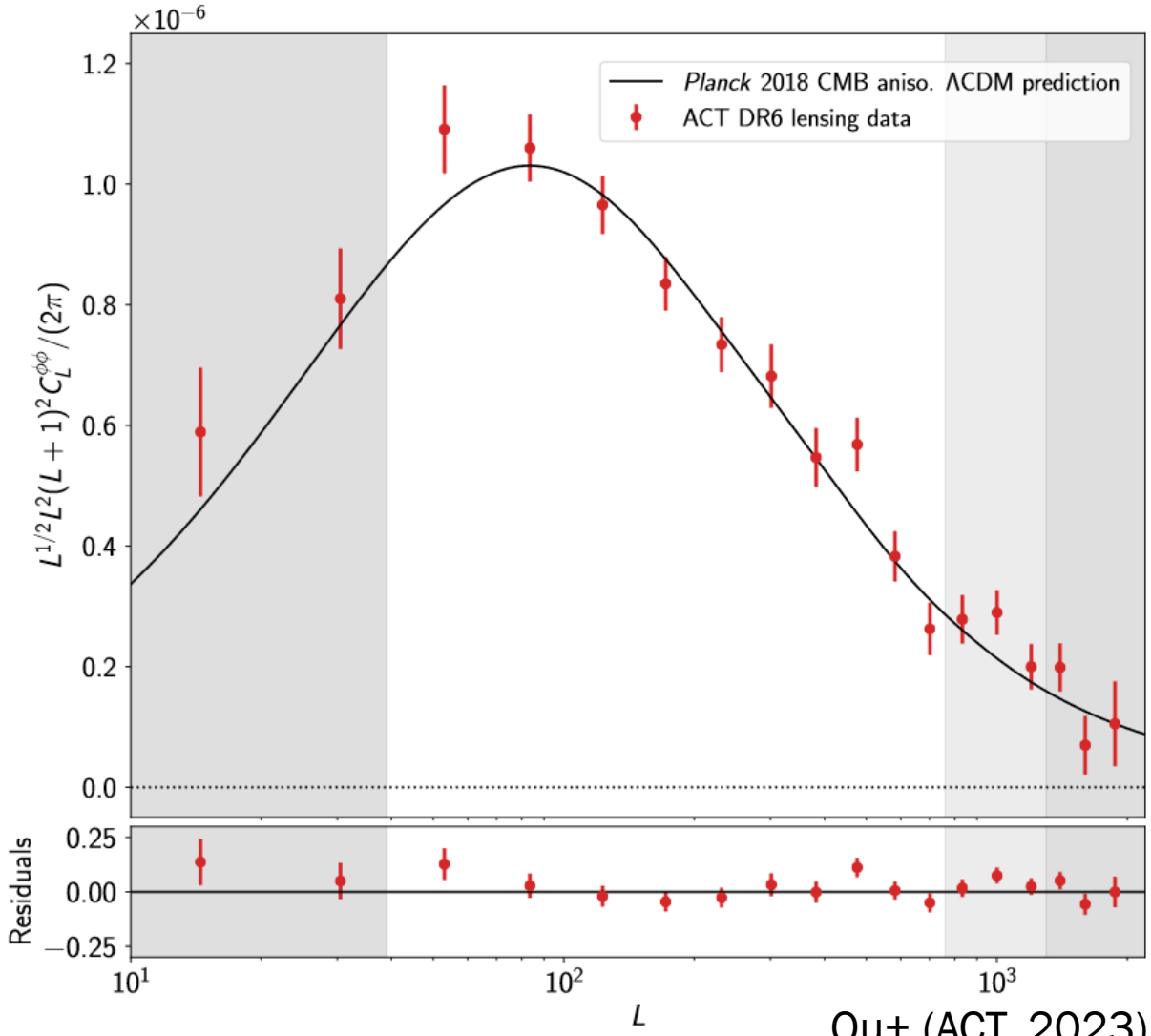
Existing "quadratic estimators" work to statistically "reconstruct" the lensing field

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



Madhavacheril+ (ACT, 2023)

Latest CMB lensing estimates agree well with ΛCDM predictions



Qu+ (ACT, 2023)

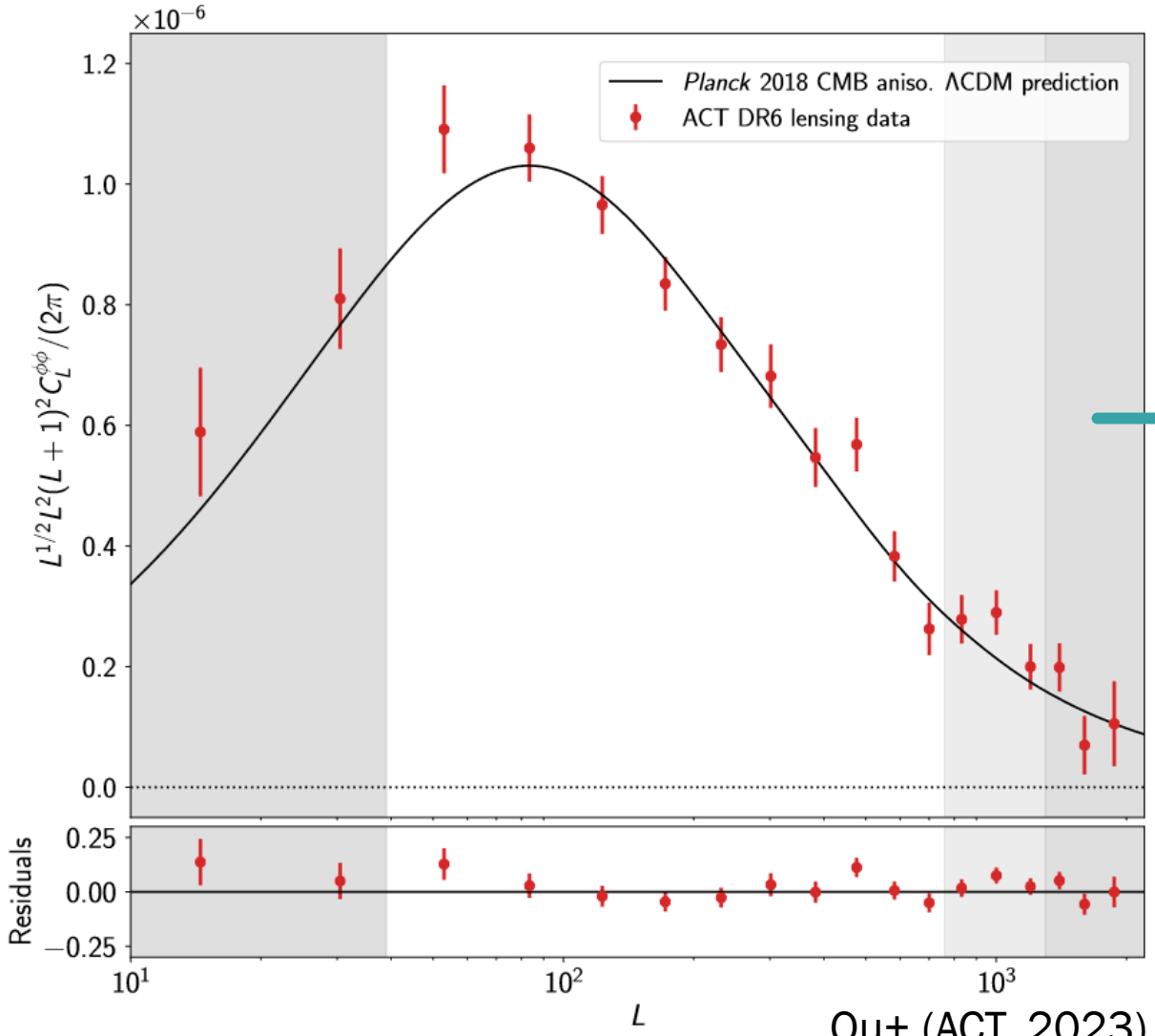
$\phi(\hat{n}) \sim$ All gravity along $\hat{n}$

Takeaways:

- The cosmic microwave background lensing field contains information about massive structures in our Universe
  - Dark matter, gravity, …
- Cosmic microwave background lensing techniques statistically ‘reconstruct’ the lensing field
- Current results agree well with those predicted by ΛCDM

HOW MUCH FURTHER WILL WE BE ABLE TO GO?

Current results measure the lensing auto-spectrum to L~1000
Limitations include foregrounds, noise, statistical optimality, …

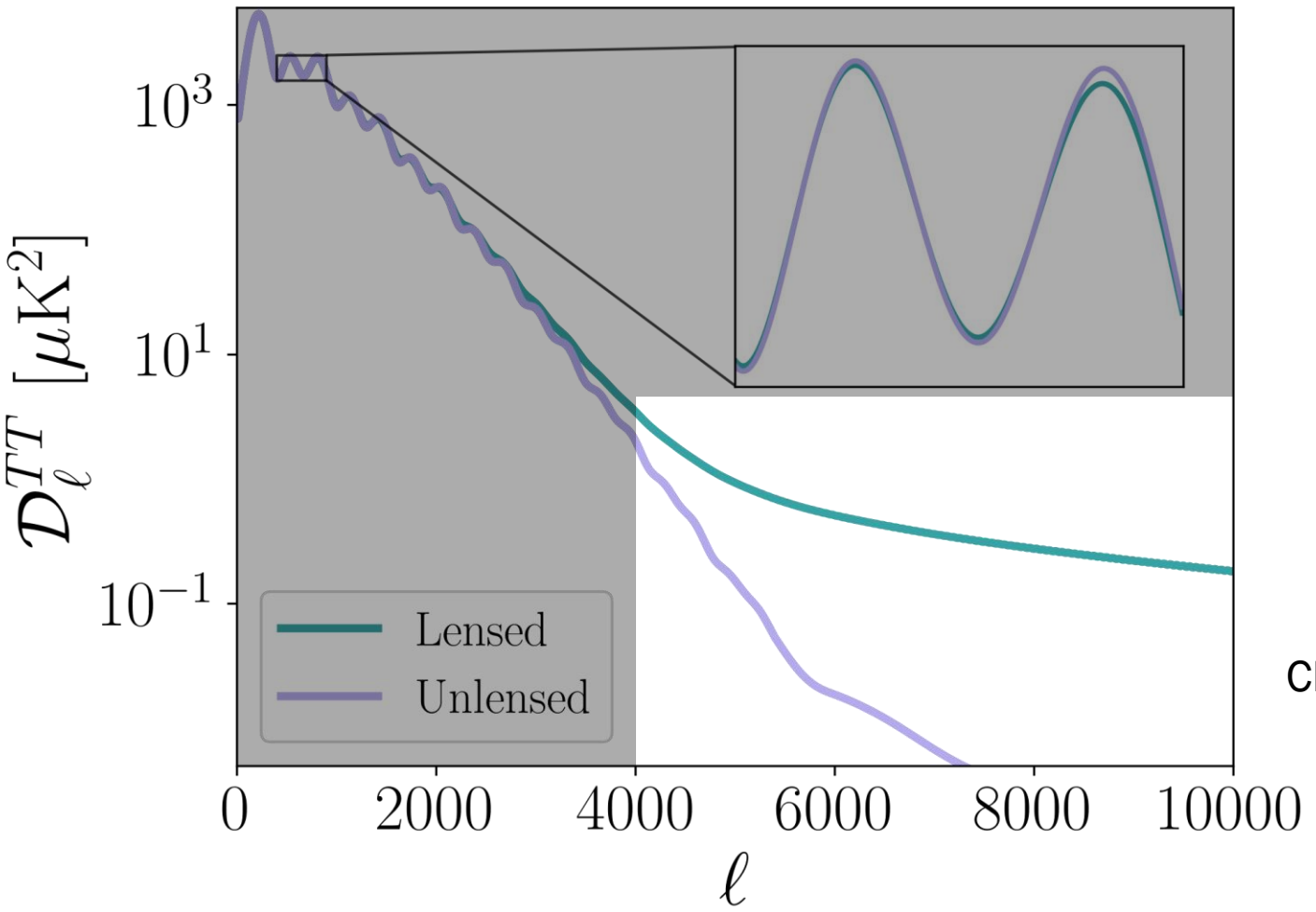


Qu+ (ACT, 2023)

Interesting clustering signals at smaller-scales

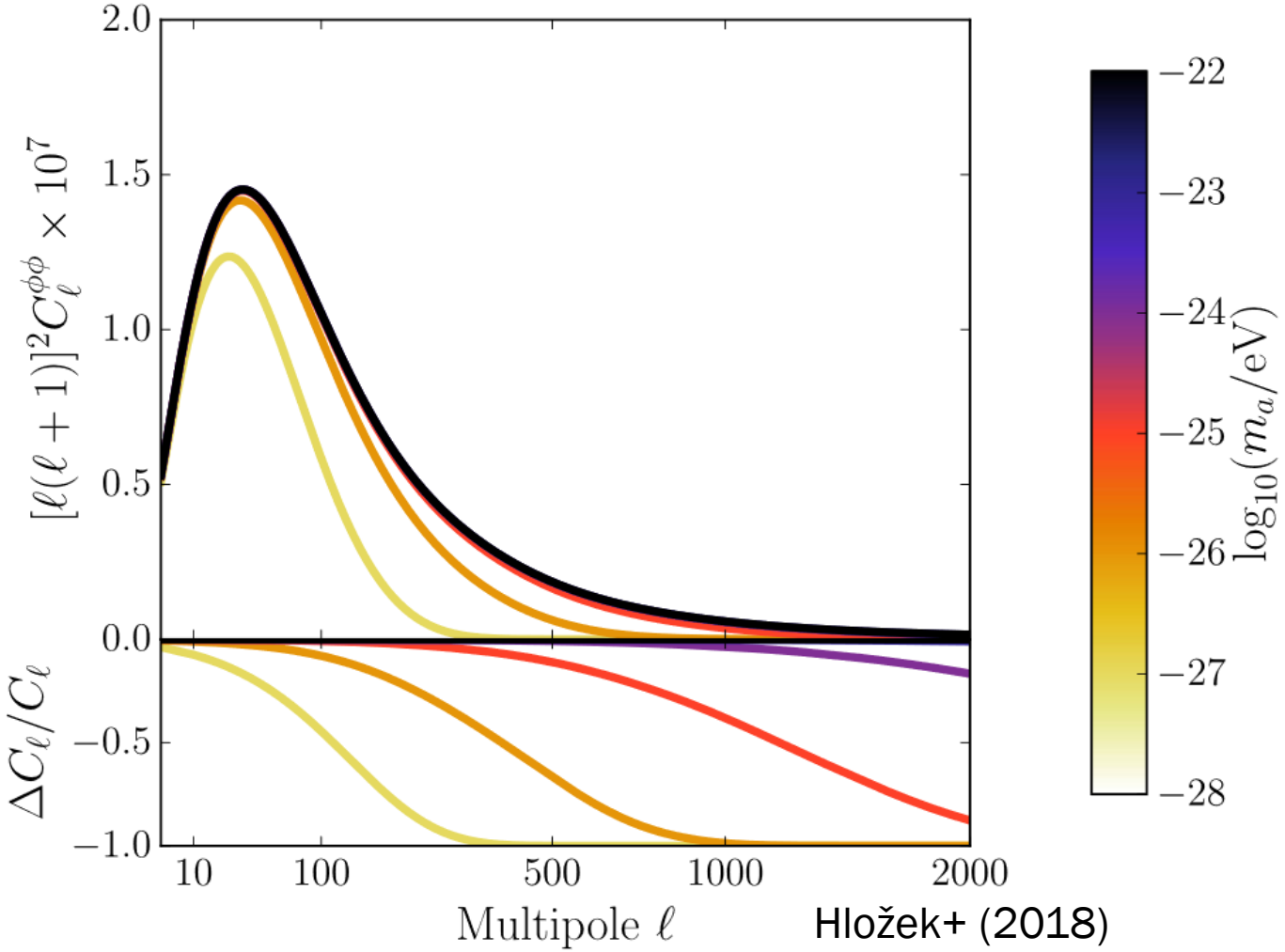
$\phi(\hat{n}) \sim$ All gravity along $\hat{n}$

Lensing dominates the observed cosmic microwave background signal at small angular scales; Future data with lower noise here



Untouched by
CMB lensing alone!

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

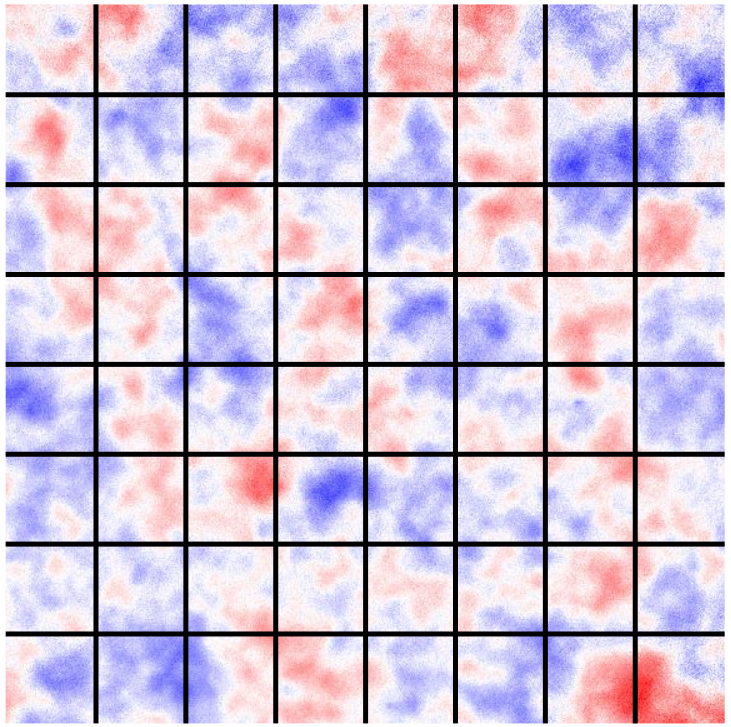


Hložek+ (2018)

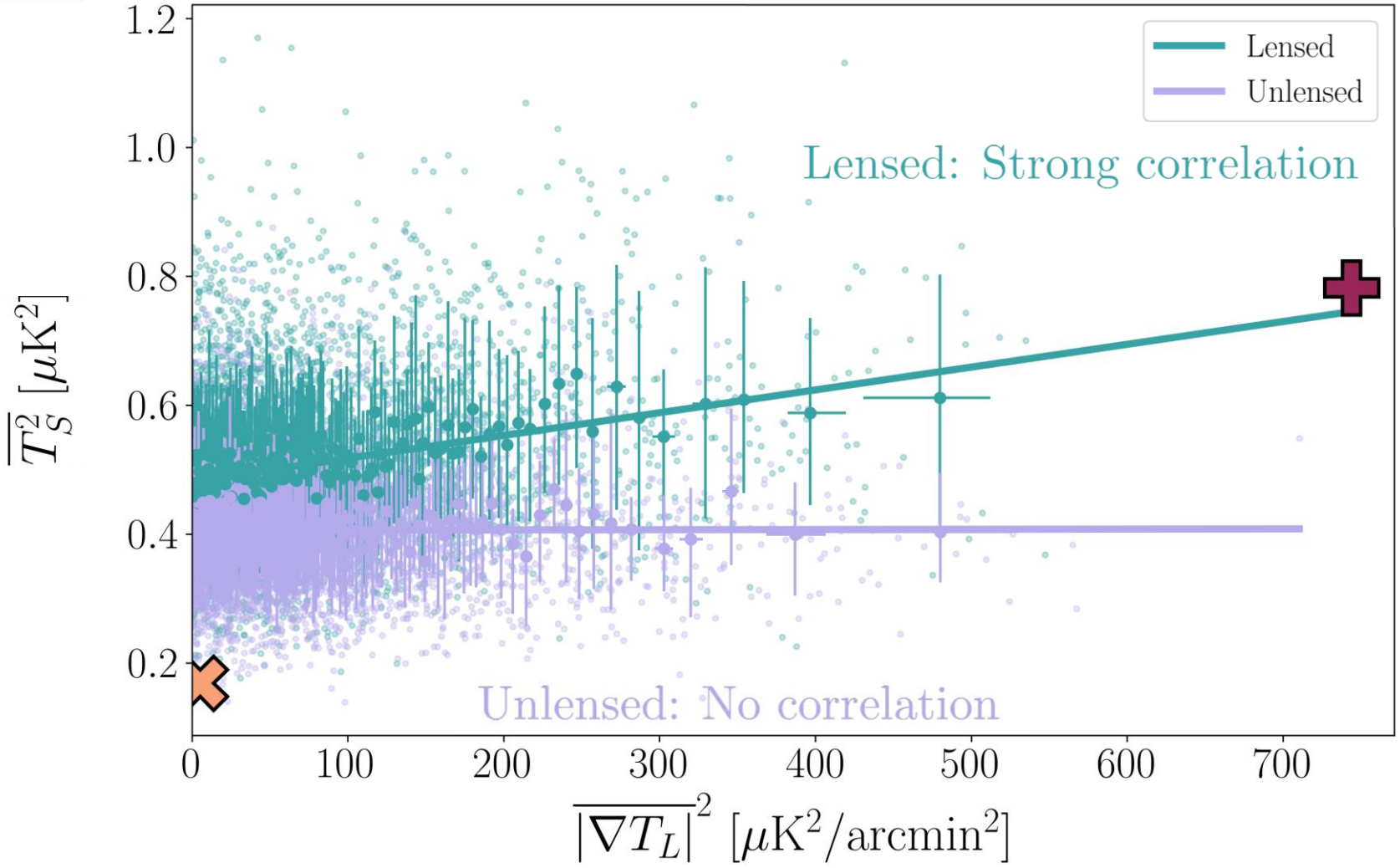
The T gradient varies across the sky

The small-scale power induced by lensing changes along with it

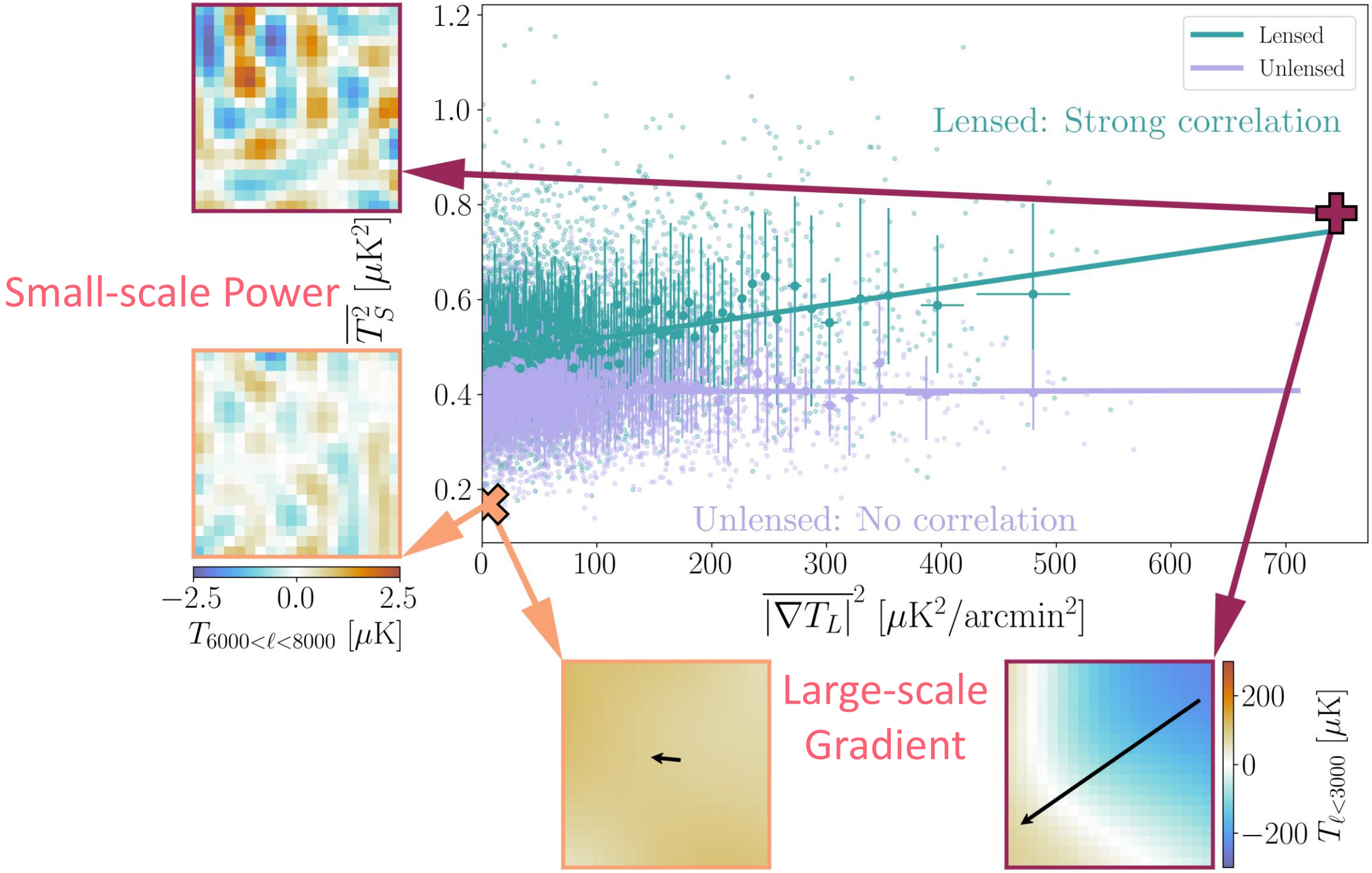
$$\tilde{T}(\hat{n}) = T\left(\hat{n} + \vec{\nabla}\phi\right) = \underbrace{T(\hat{n})}_{\text{Original}} + \underbrace{\vec{\nabla}T(\hat{n}) \cdot \vec{\nabla}\phi(\hat{n})}_{\text{Lensing}} + \cdots$$



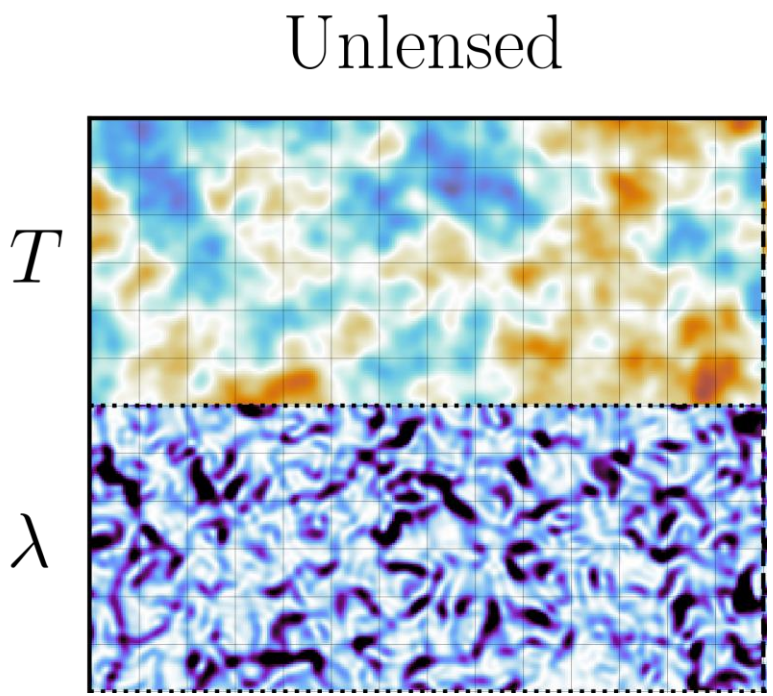
Small-scale Power



Large-scale Gradient


Lensed
Unlensed
Lensed: Strong correlation
Unlensed: No correlation
Small-scale Power
Large-scale Gradient
$\overline{T_S^2}$ [μK^2]
$\overline{|\nabla T_L|}^2$ [μK^2/arcmin^2]
$T_{6000<\ell<8000}$ [μK]
$T_{\ell<3000}$ [μK]
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
200
0
−200

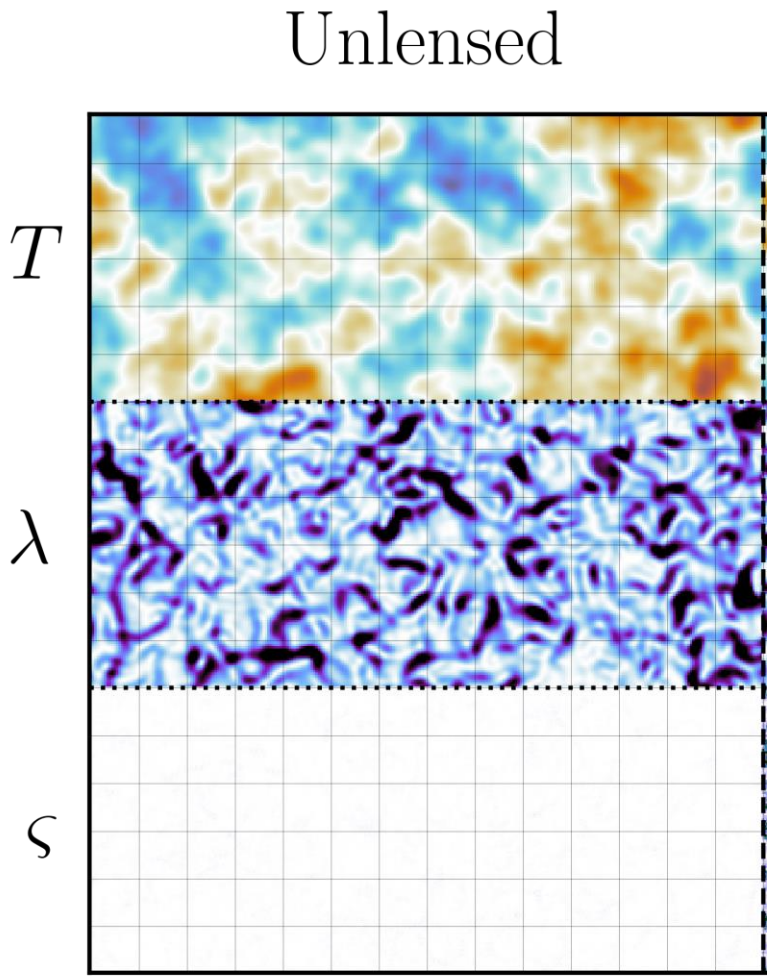
Large-scale features originate from the primary temperature field



$\ell < 3000$

Large features

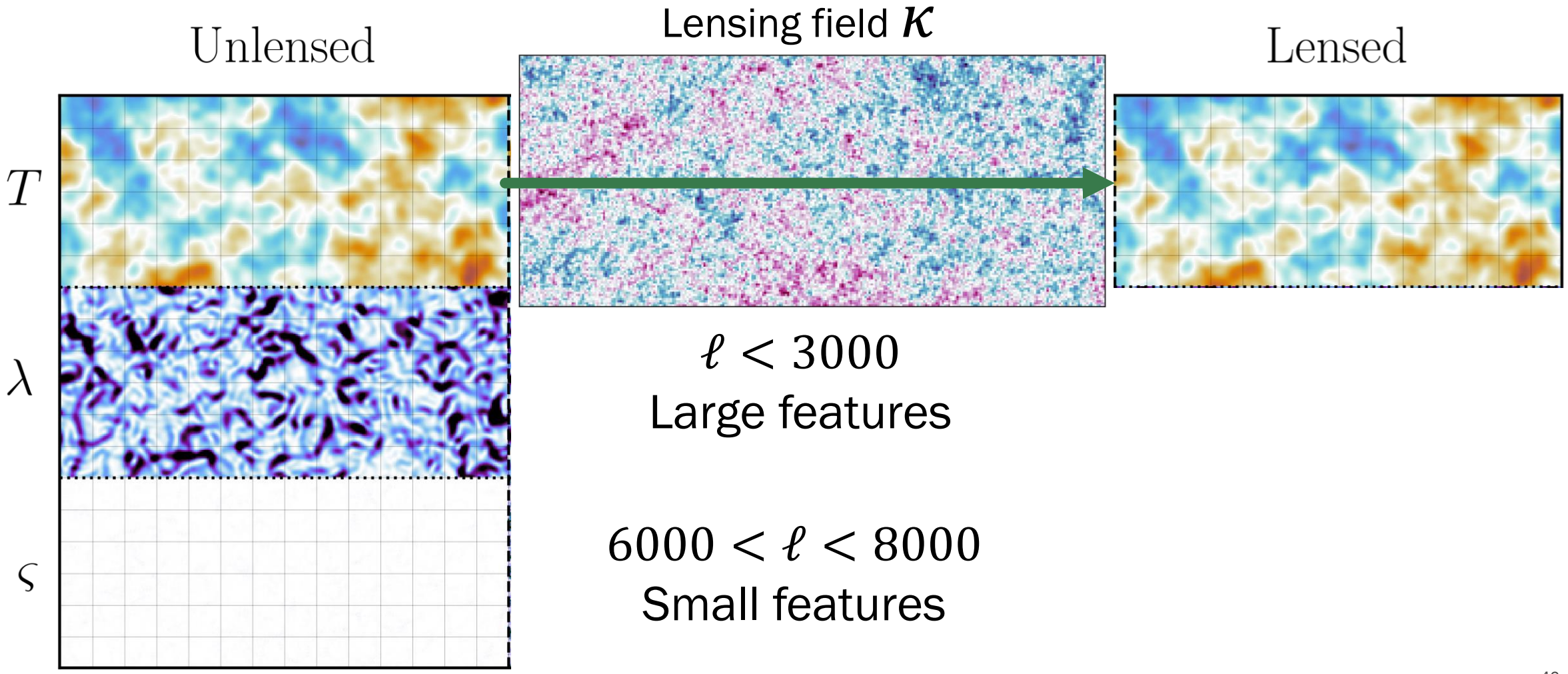
Large-scale features originate from the primary temperature field
Small-scale features are very weak in the primary temperature field



$\ell < 3000$
Large features

$6000 < \ell < 8000$
Small features

Gravitational lensing alters the observed temperature field



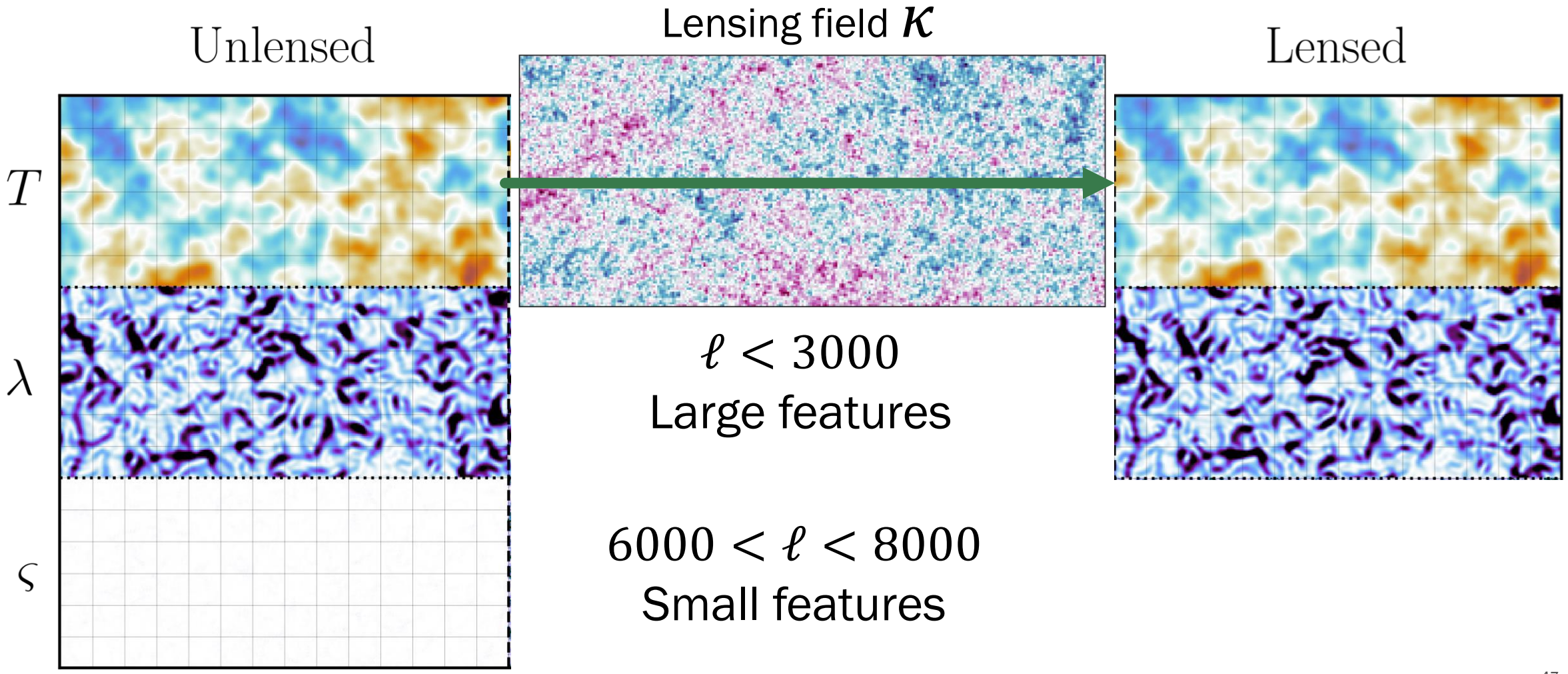
$\ell < 3000$

Large features

$6000 < \ell < 8000$

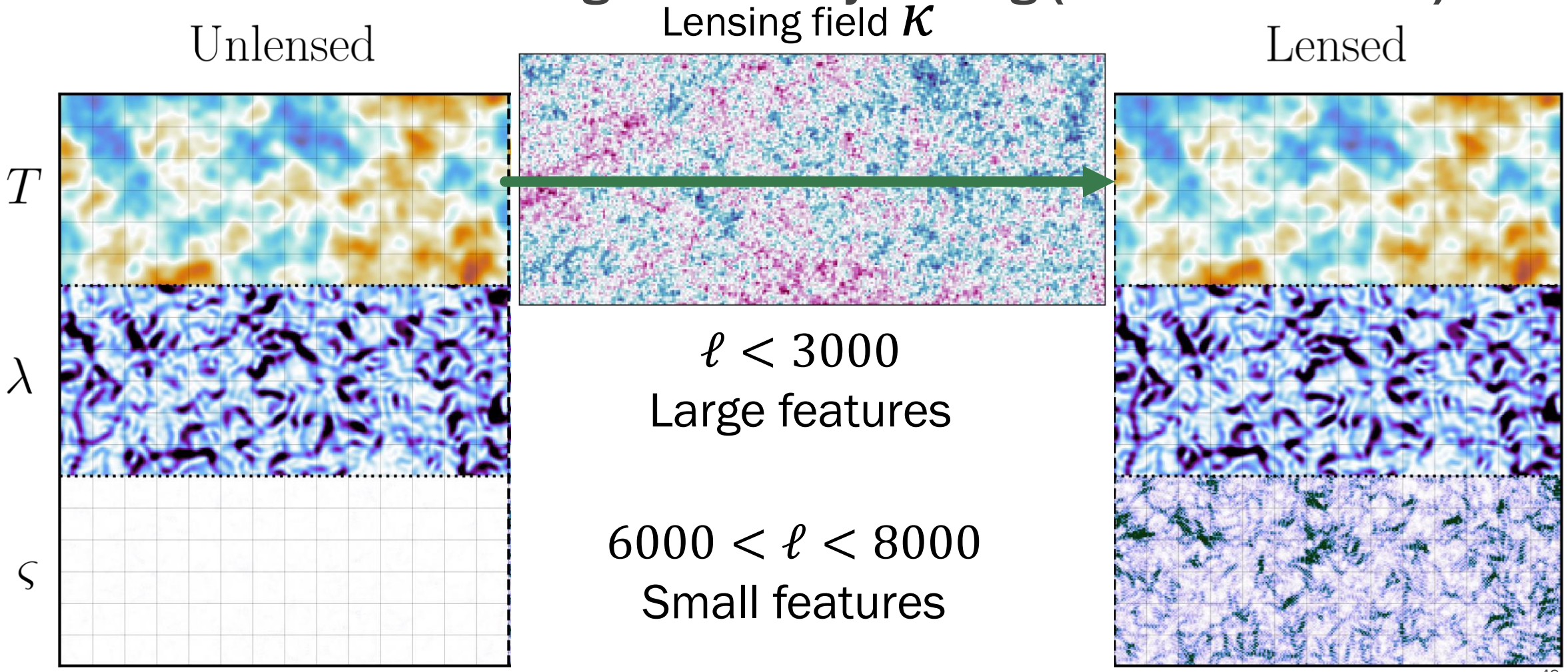
Small features

Large-scale features are mostly untouched by lensing

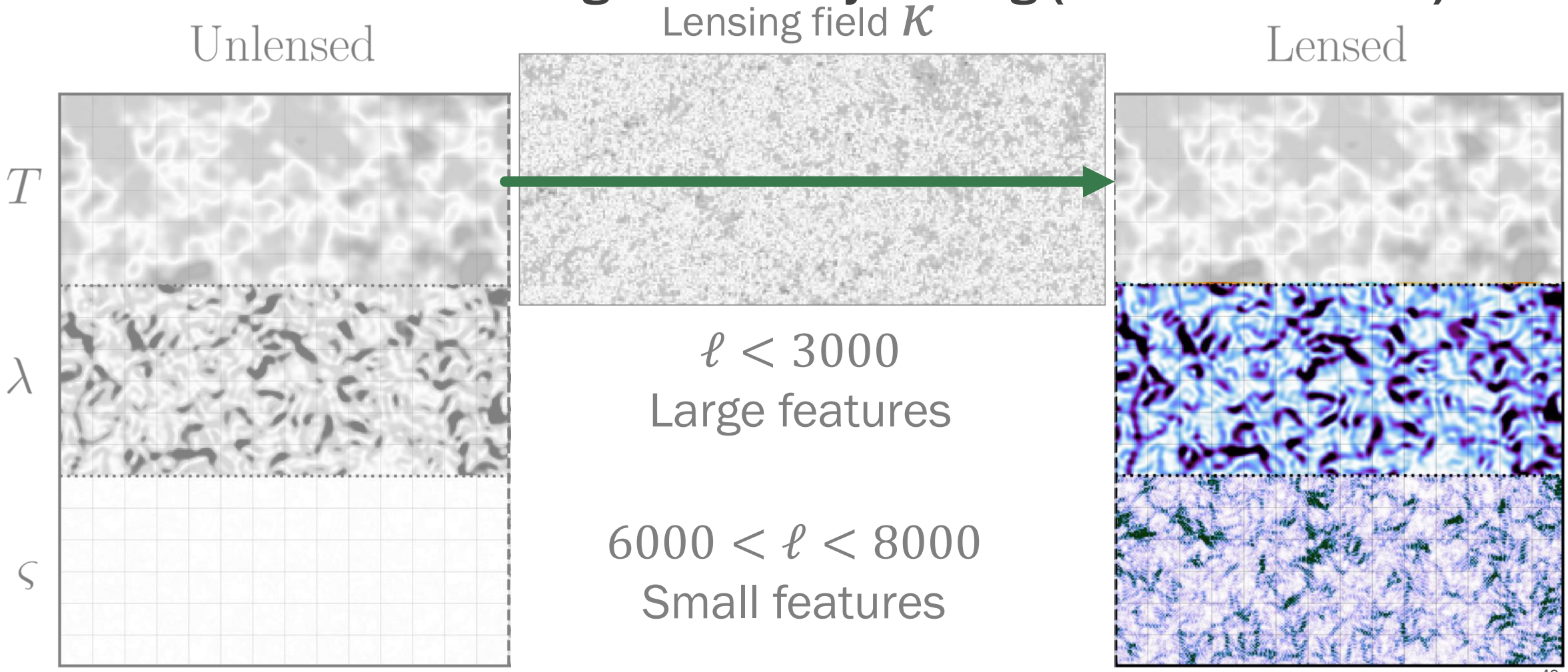


Large-scale features are mostly untouched by lensing

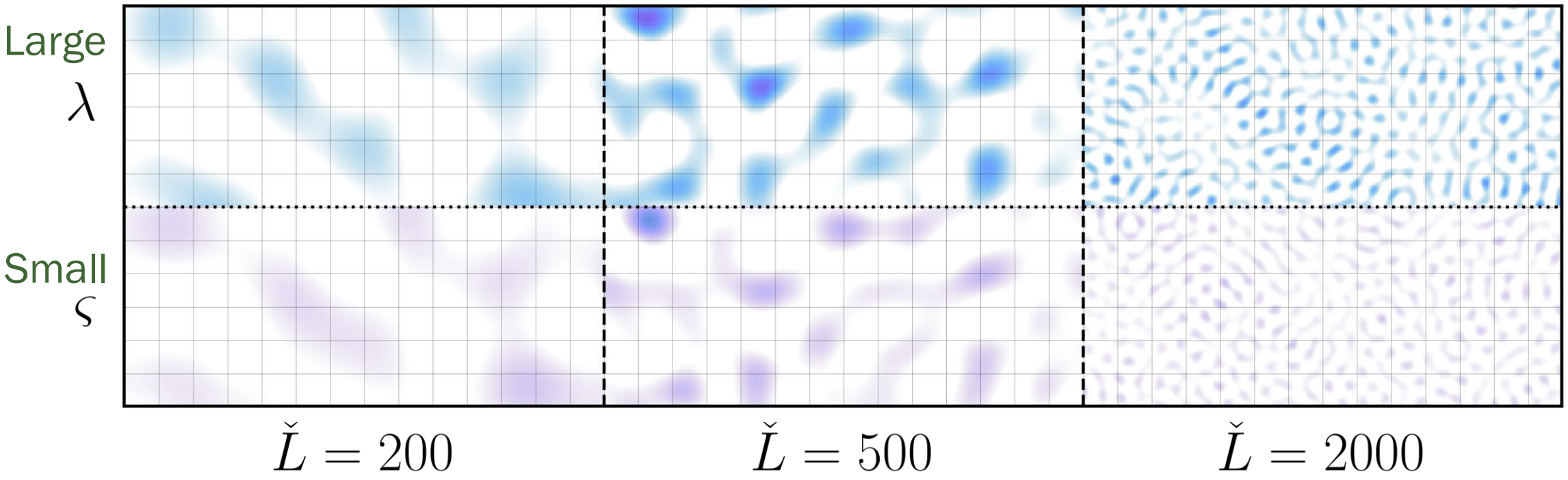
Small-scale features are generated by lensing (correlated with λ)



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



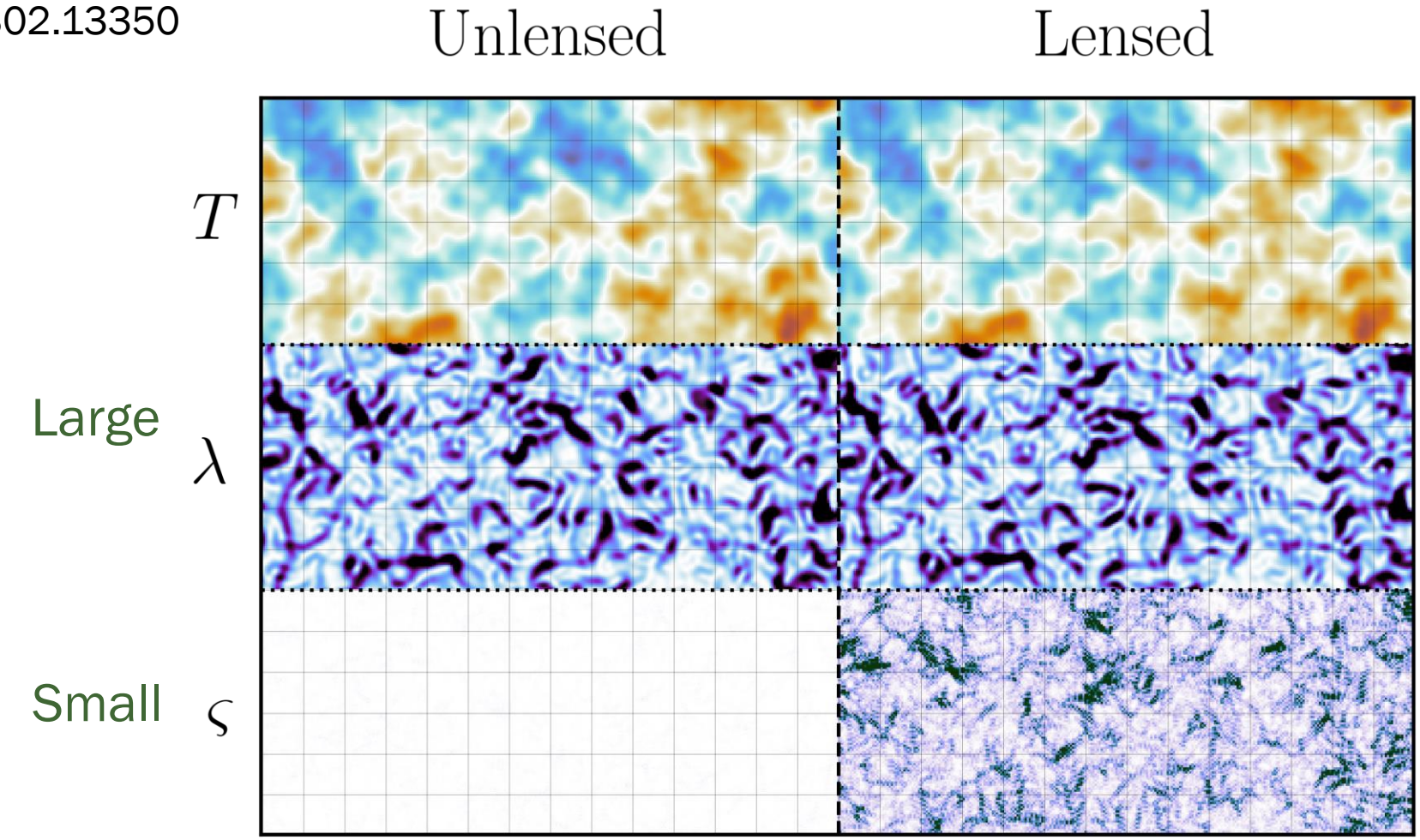
SCALE intermediate products are HIGHLY correlated!!!



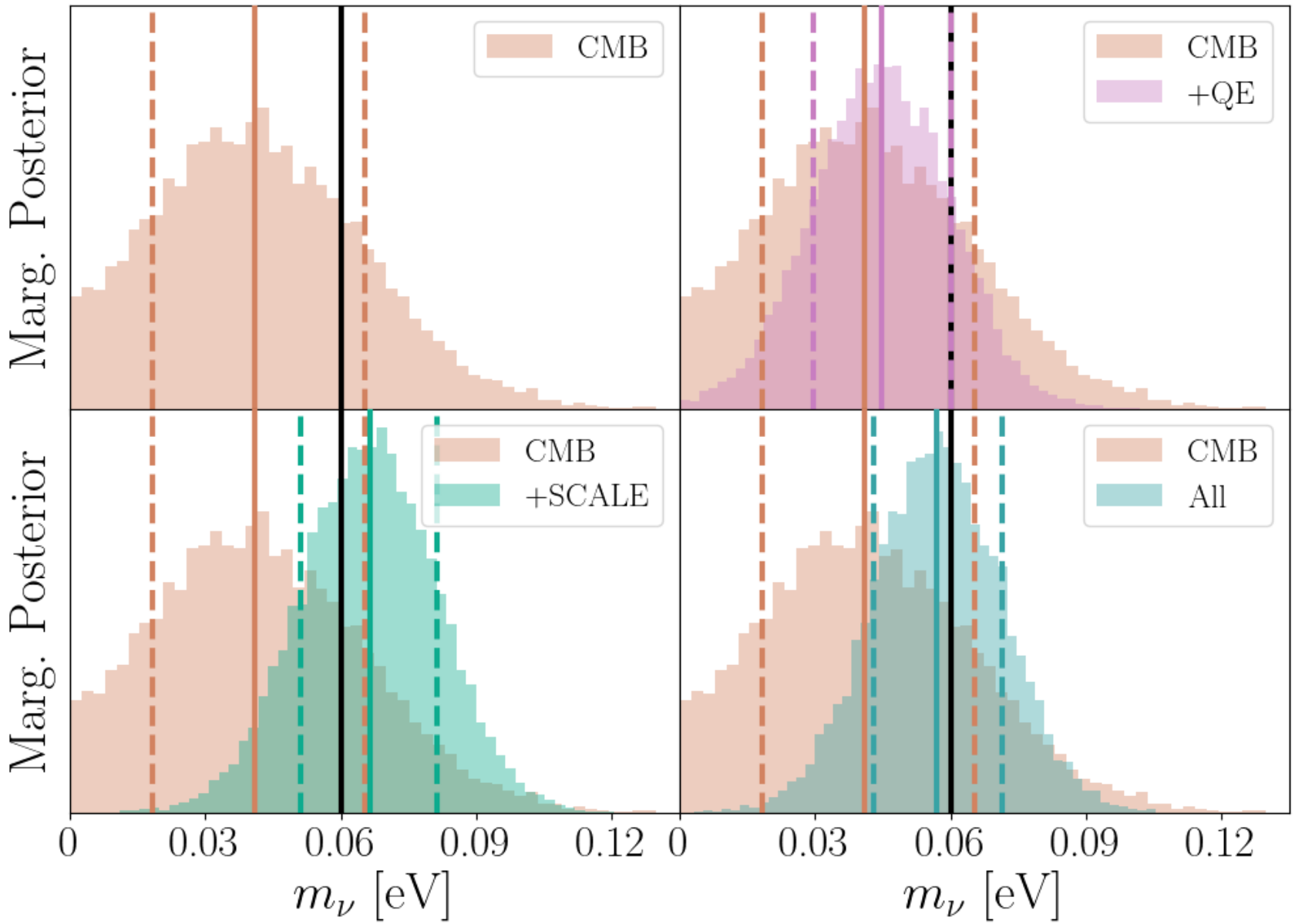
Small-Correlated-Against-Large-Estimator: Chan+ (2024)

Process T map into relevant SS/LS lensing info, and cross-correlate

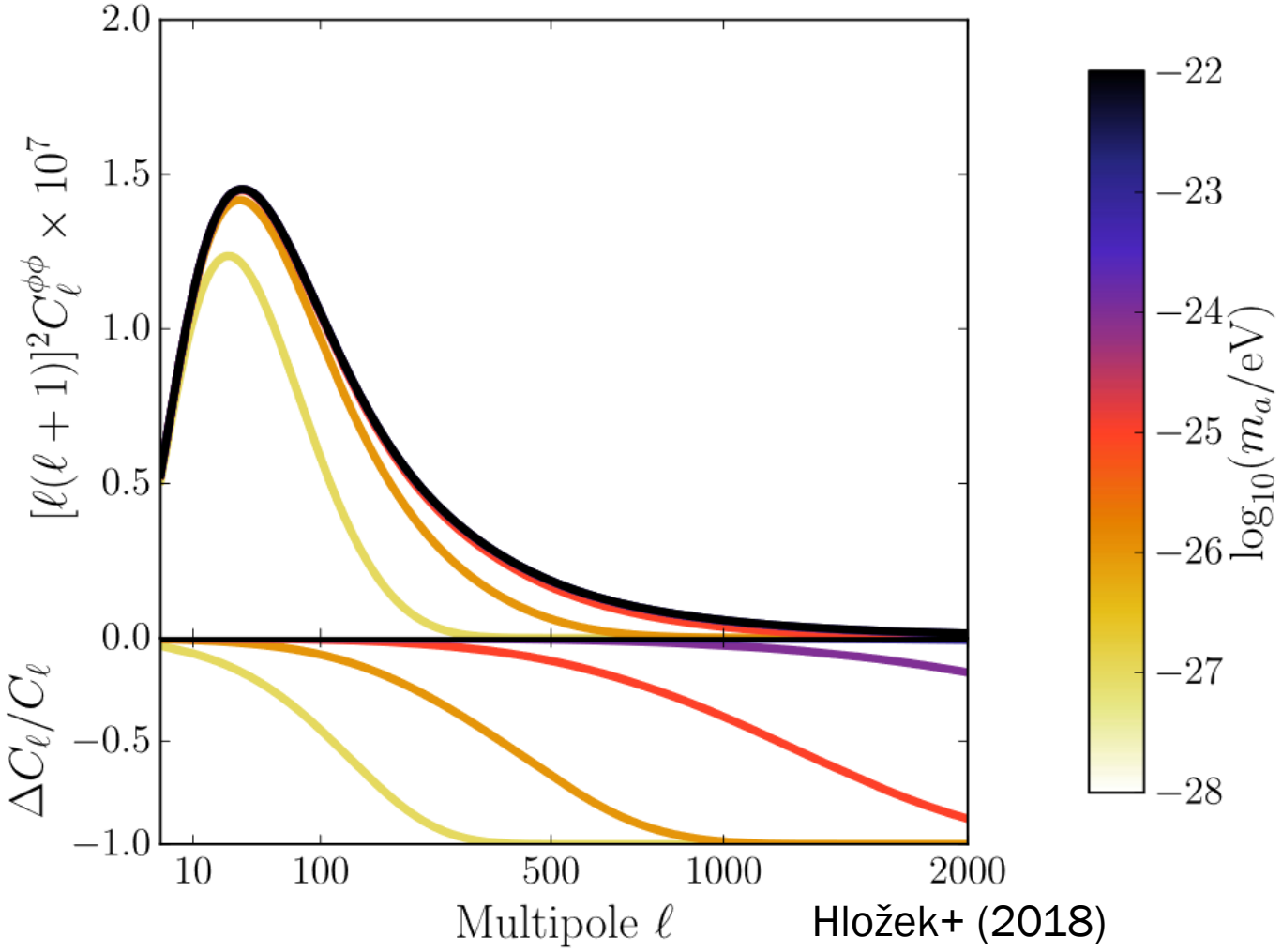
10.1103/PhysRevD.109.043527
arXiv:2302.13350



Lensing information enables a detection of minimal neutrino mass!

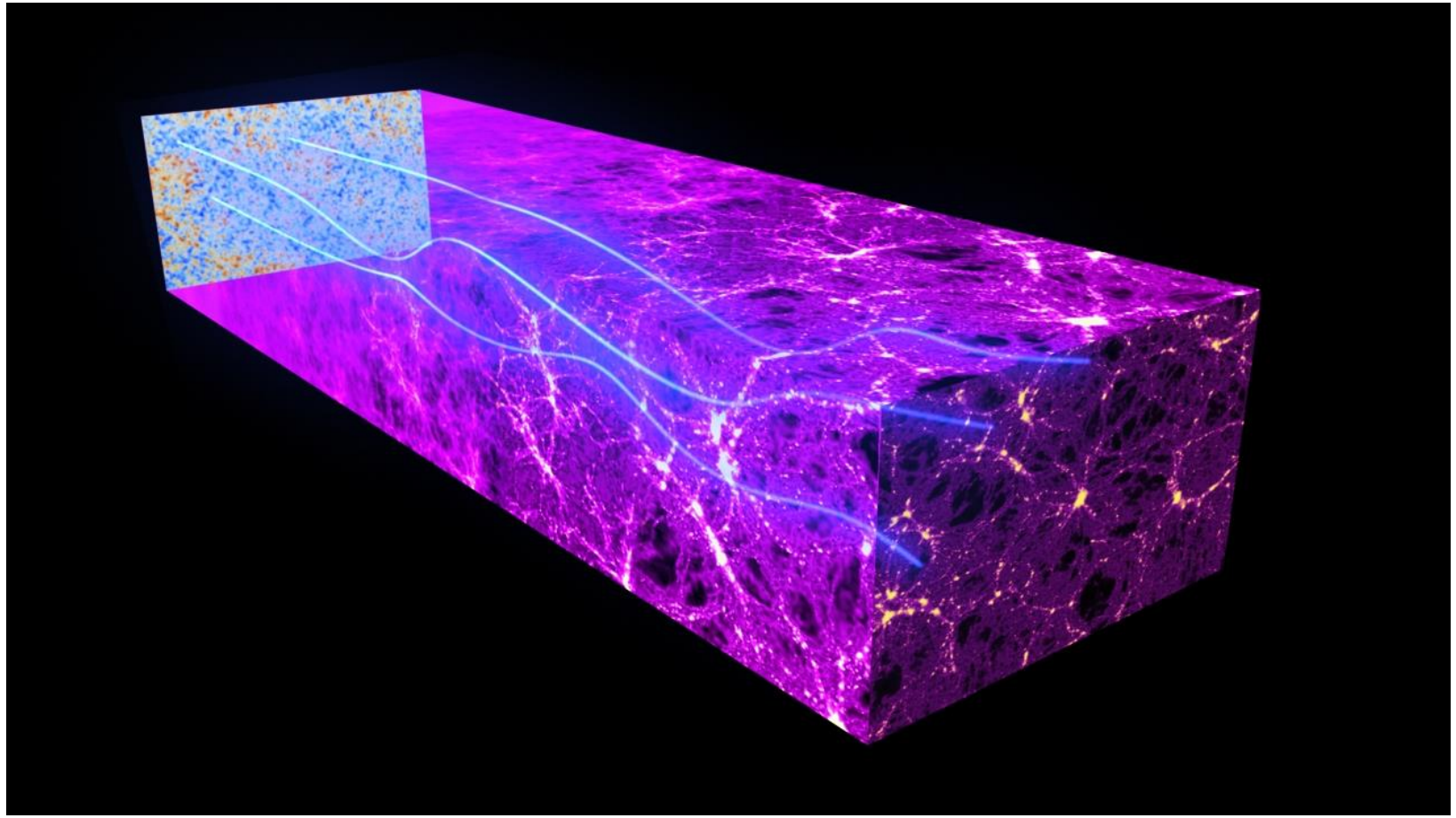


SCALE can be combined with conventional CMB observables to constrain more exotic dark matter models → arXiv:2409.05326



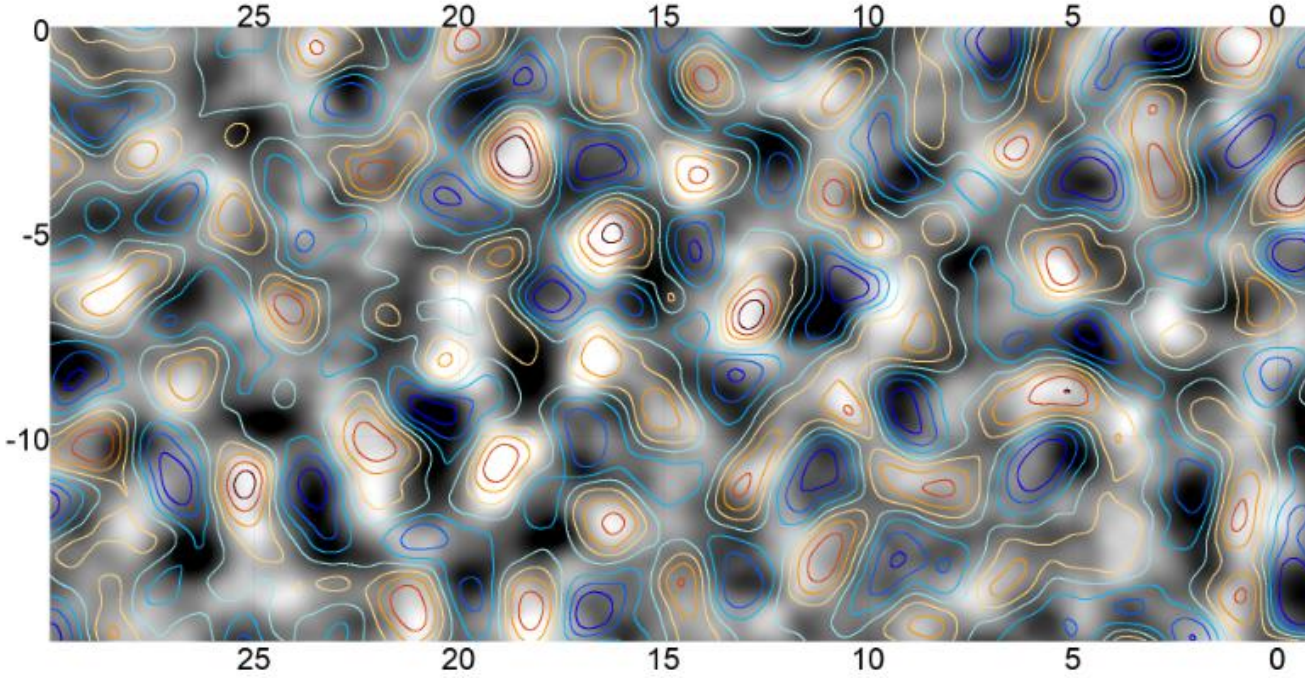
Hložek+ (2018)

- The nature of CMB lensing is intricately tied to the physics of galaxy clusters

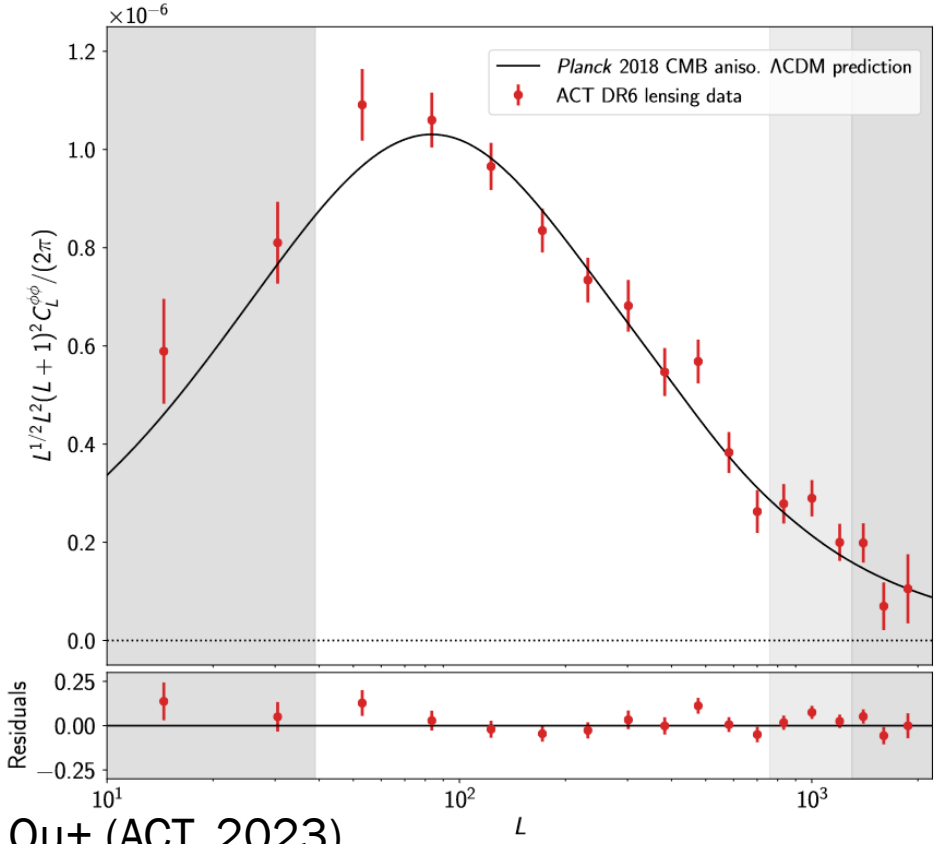


ESA (2013)

- The nature of CMB lensing is intricately tied to the physics of galaxy clusters
- Current results take advantage of lensing-induced correlations in observed CMB
  - Good agreement with standard cosmological model

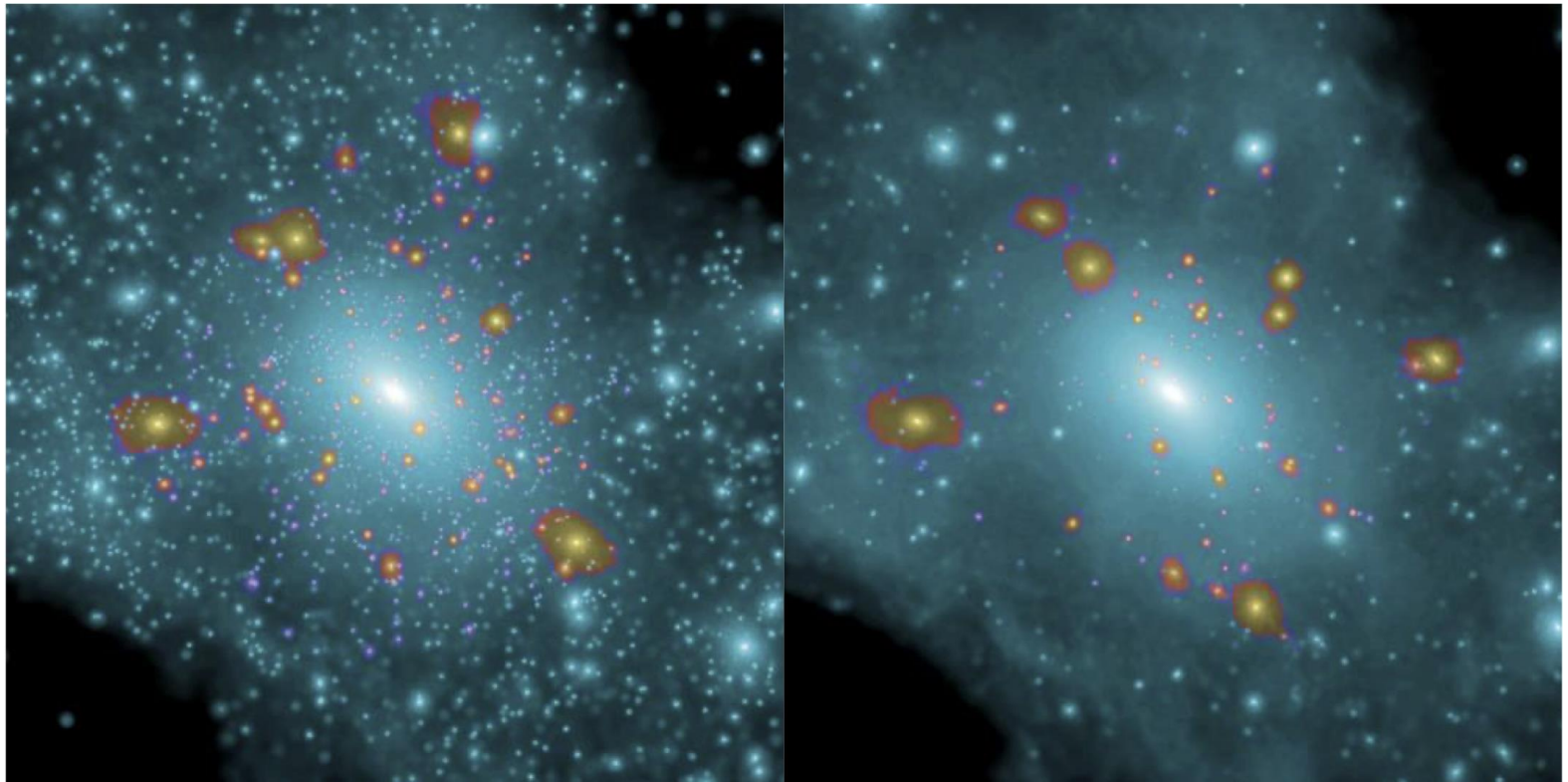


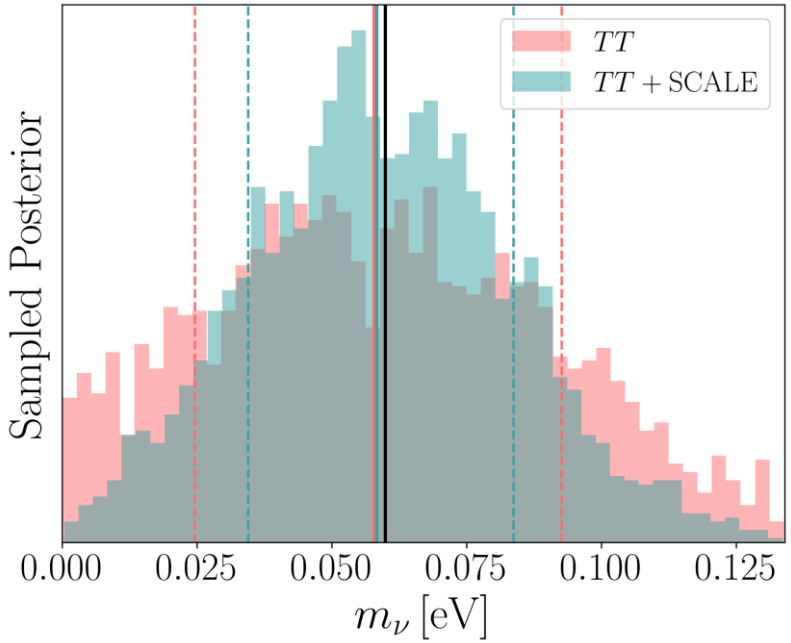
Madhavacheril+ (ACT, 2023)



Qu+ (ACT, 2023)

- The nature of CMB lensing is intricately tied to the physics of galaxy clusters
- Current results take advantage of lensing-induced correlations in observed CMB
  - Good agreement with standard cosmological model
- Future data will constrain dark matter models, gravity, massive neutrinos, etc.



ESA (2023)

- The nature of CMB lensing is intricately tied to the physics of galaxy clusters
- Current results take advantage of lensing-induced correlations in observed CMB
  - Good agreement with standard cosmological model
- Future data will constrain dark matter models, gravity, massive neutrinos, etc.
- I have developed a method to take good advantage of future data in the context of small-scale CMB lensing