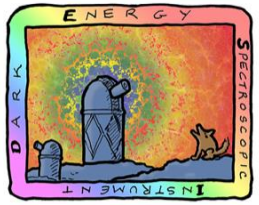

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Cross correlations between CMB lensing and Lyman-alpha forest

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Center for Cosmology and AstroParticle Physics (CCAPP)

THE OHIO STATE UNIVERSITY

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It is all about gravity

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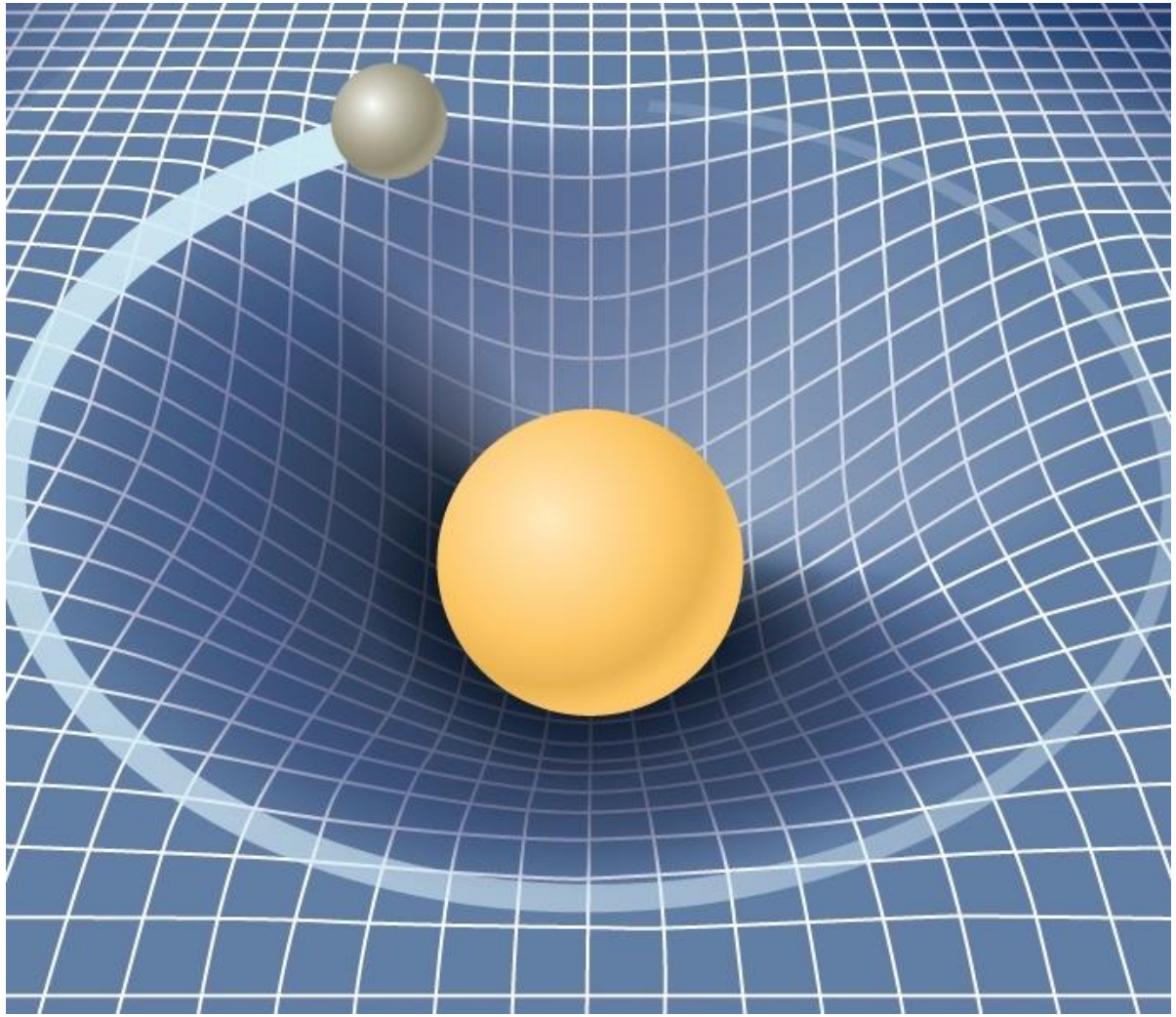
Einstein field equations:

Geometry ⇔ Energy-momentum

- Black holes
- Gravitational lensing
- Modern cosmology



Gravity bends the light's path

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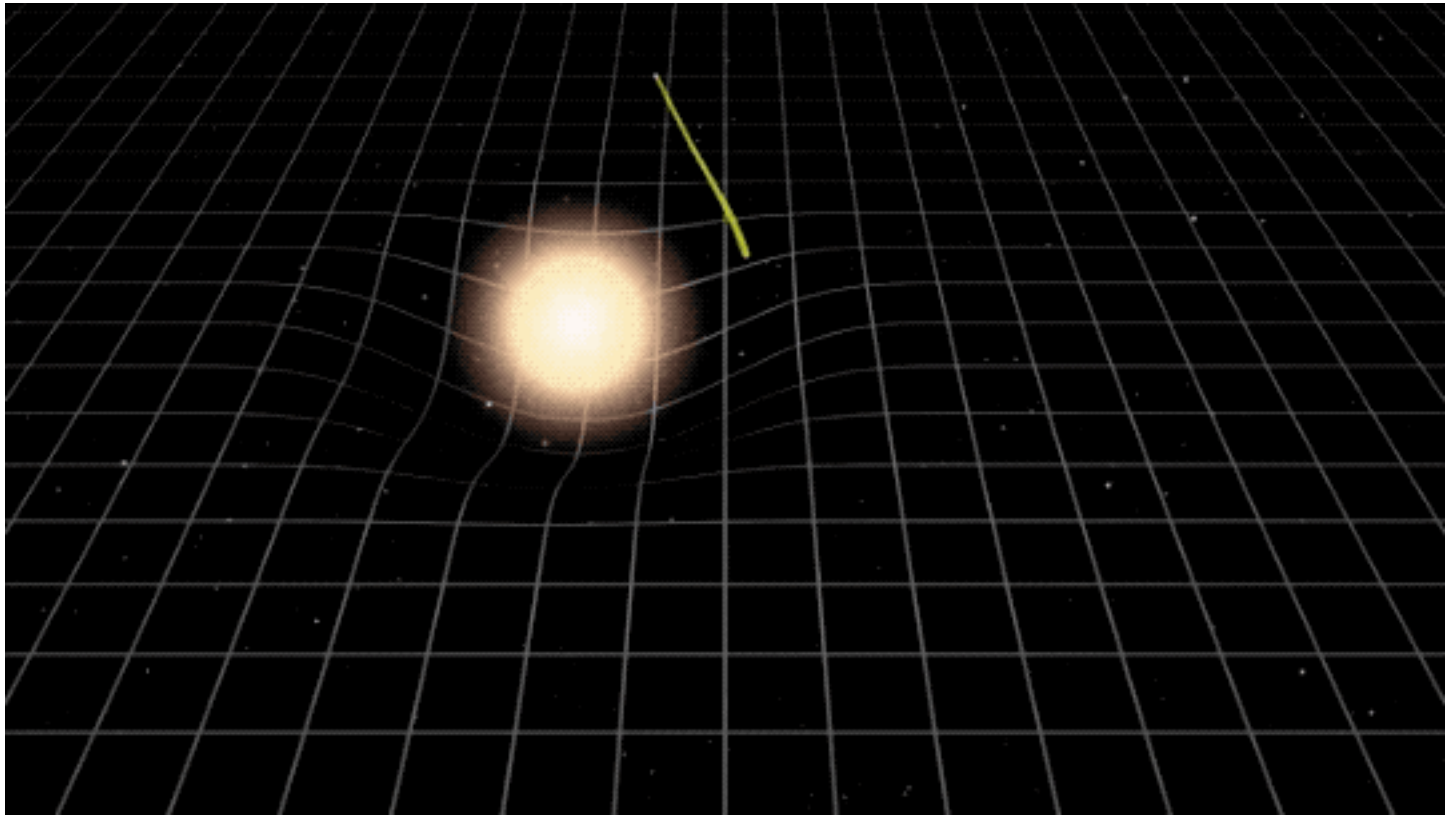
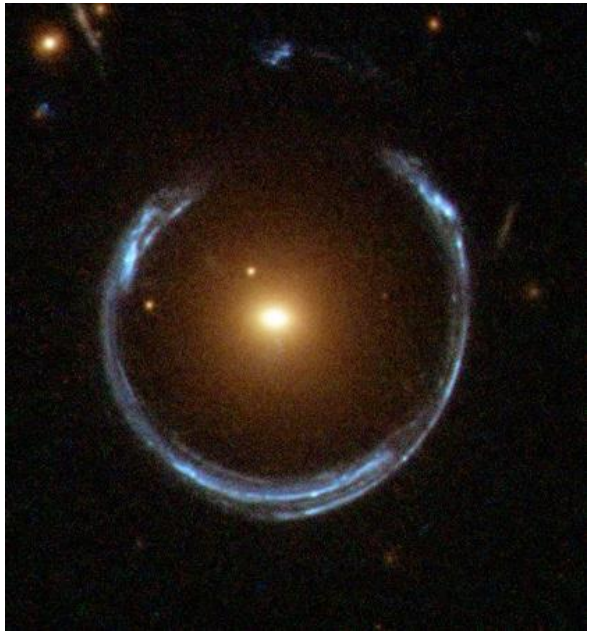
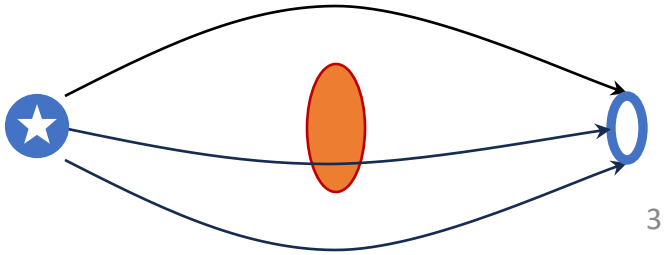


NASA, ESA, and Goddard Space Flight Center/K. Jackson



ESA/Hubble & NASA



Standard model of cosmology

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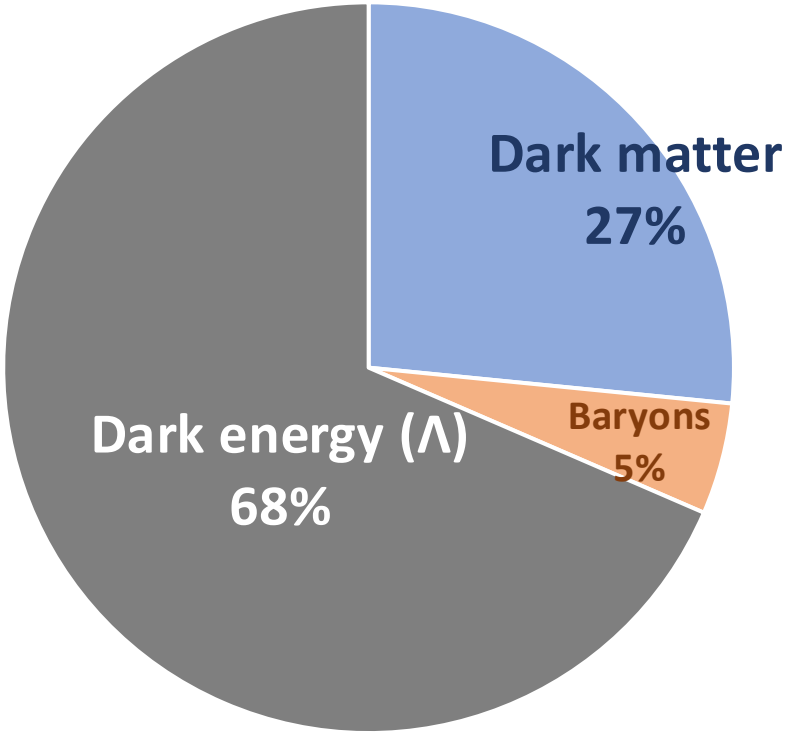
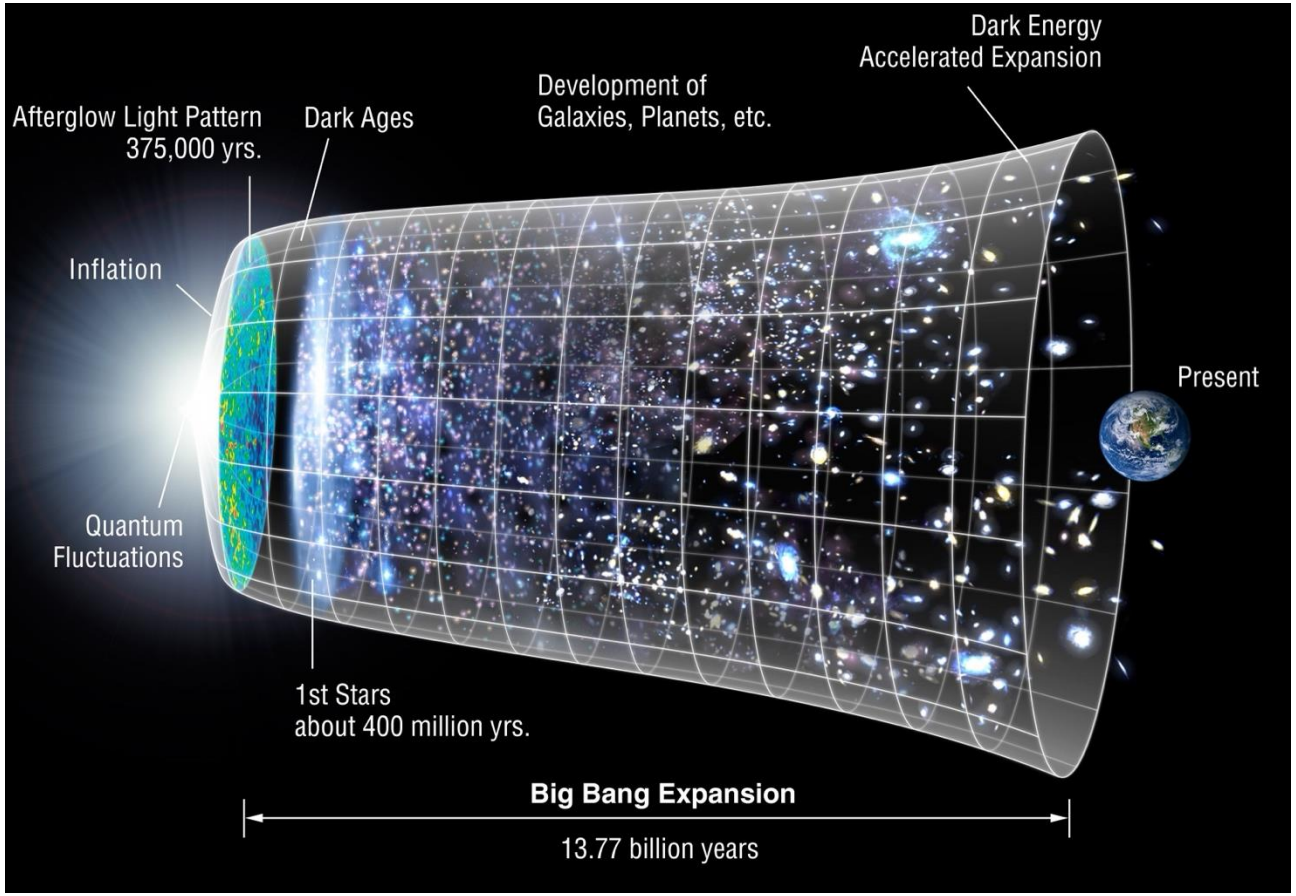
Homogeneous universe + density perturbations





Standard model of cosmology

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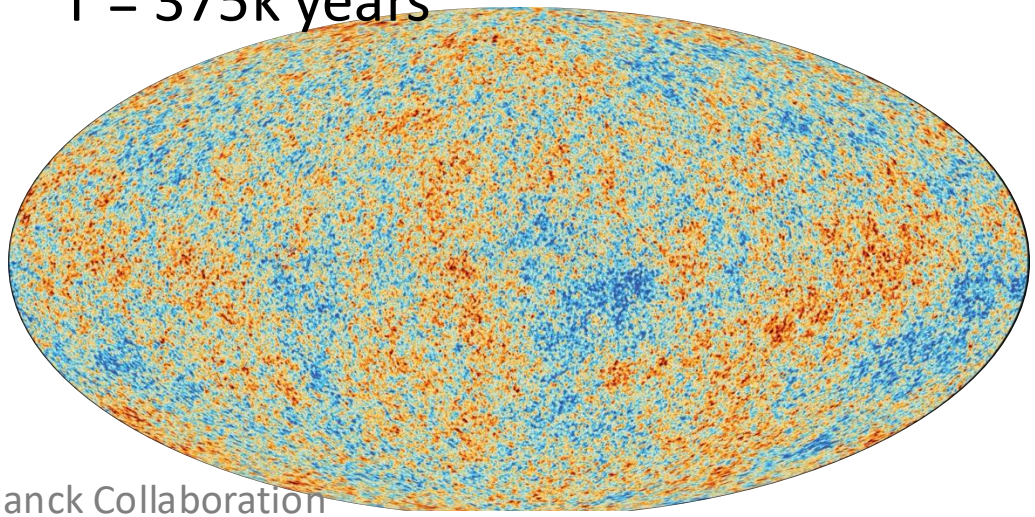
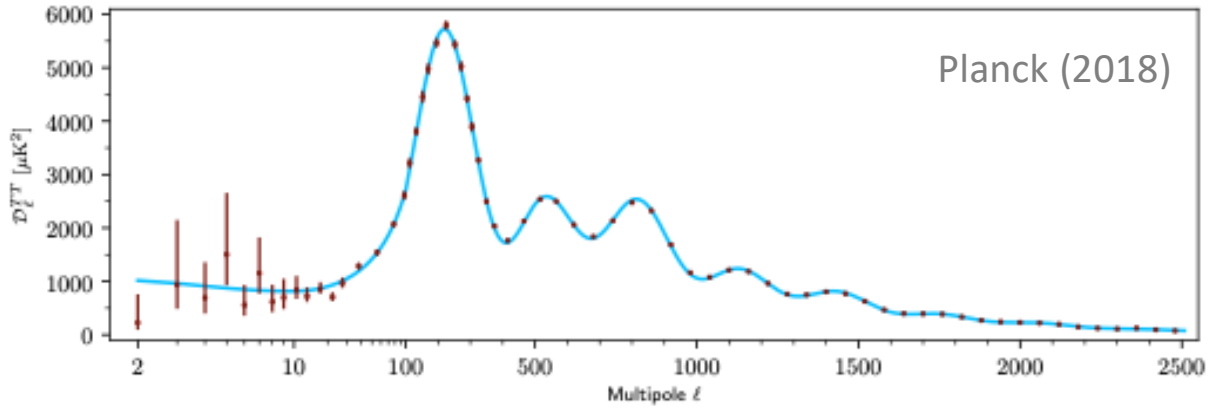
Cosmic microwave background (CMB)

T = 375k years

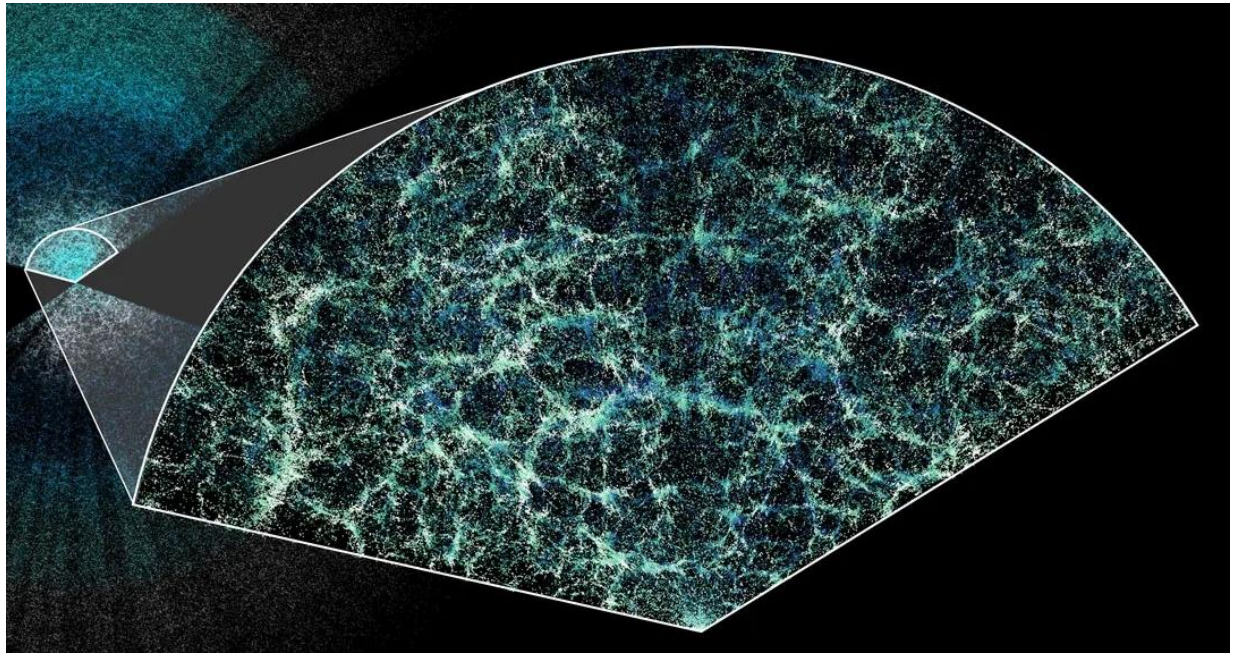


ESA/Planck Collaboration

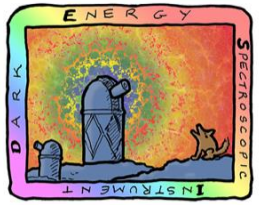


DESI Galaxy map

T > 10 Gyr



Claire Lamman/DESI Collaboration



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Let’s talk first about structure formation.

Late time large-scale structure

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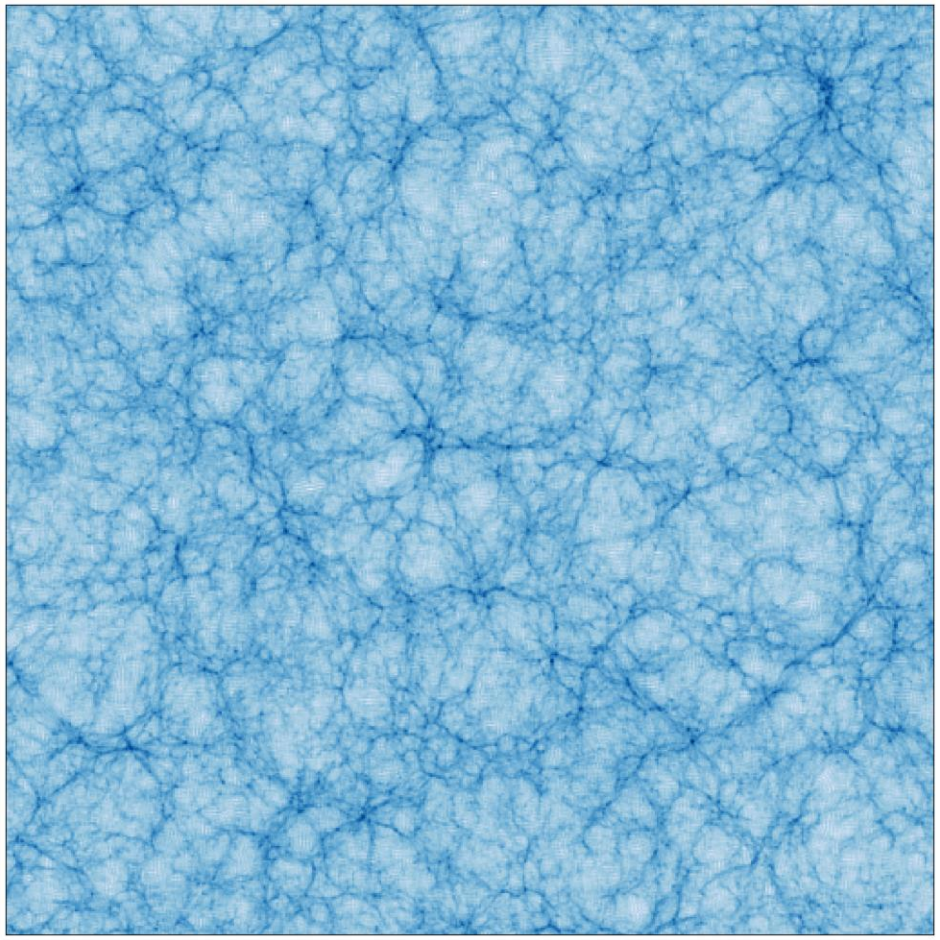
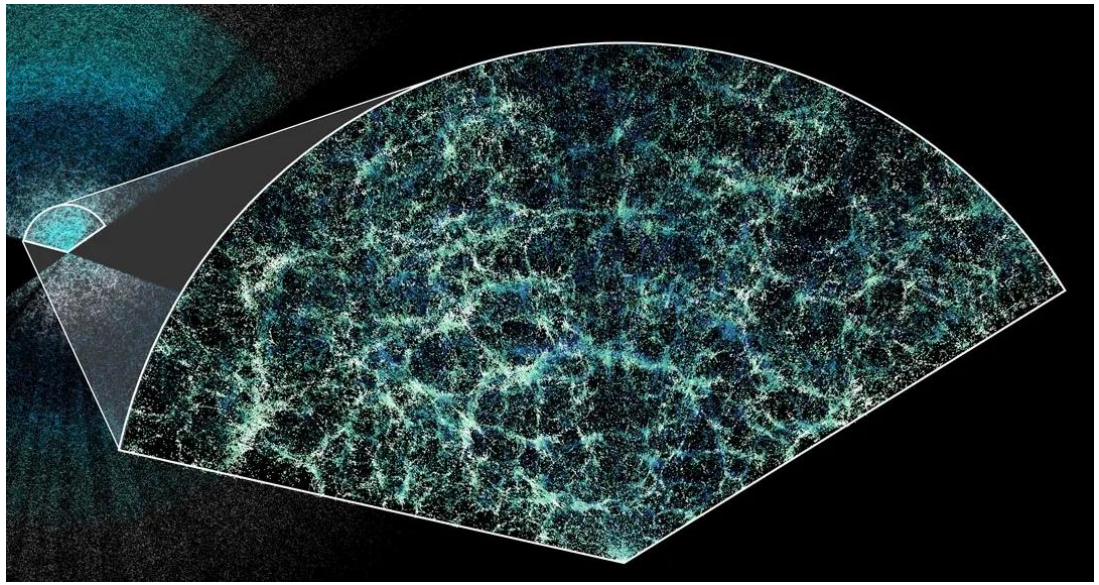


N-body dark matter only simulation

DESI Galaxy map



Claire Lamman/DESI Collaboration

In some regions dark energy wins

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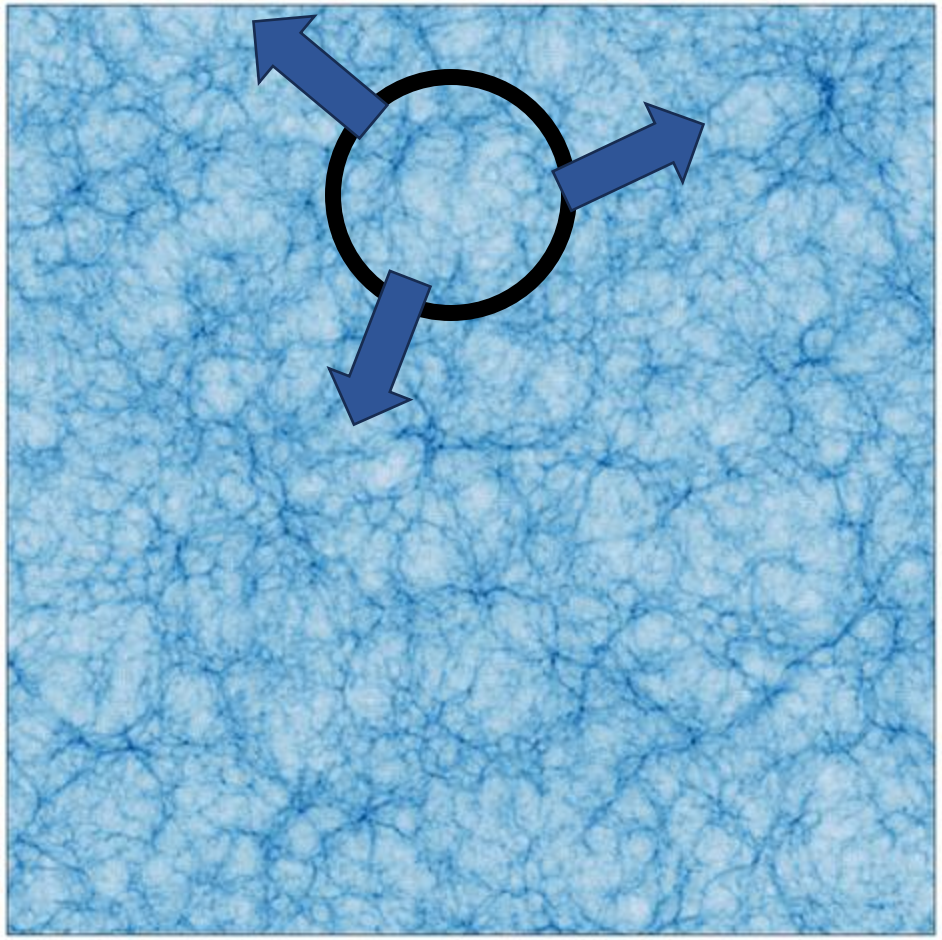
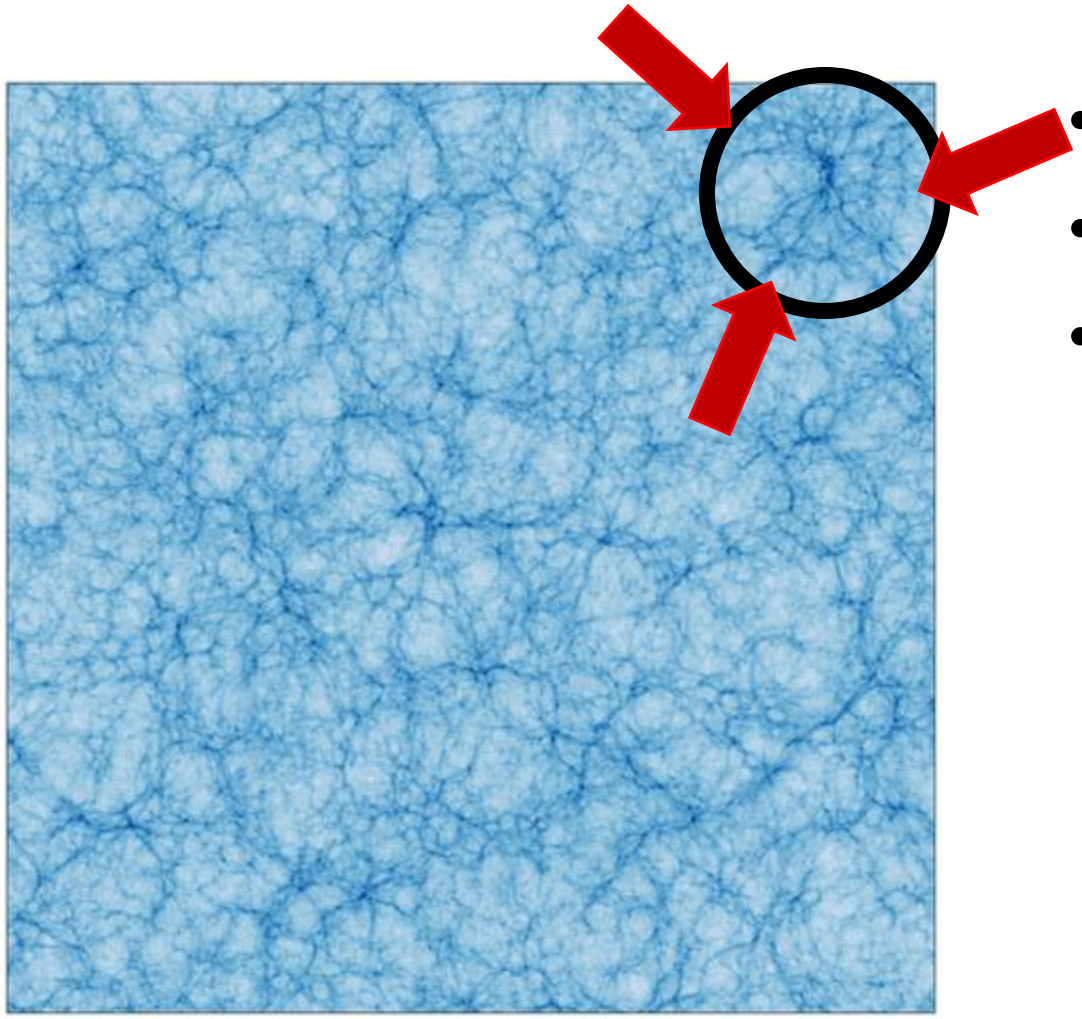


- Less matter, more dark energy.
- Push from dark energy is stronger.
- Less clumpy.

In others dark matter wins



- More matter, less dark energy.
- Pull from dark matter is stronger.
- Clumpier.

Clumpiness (Power Spectrum)	$\propto$	Average density
Lyman-alpha forest		CMB lensing

$$P_S(k) \propto \bar{\delta}_L \qquad \delta = \frac{\rho}{\bar{\rho}} - 1$$

CMB photons are lensed!

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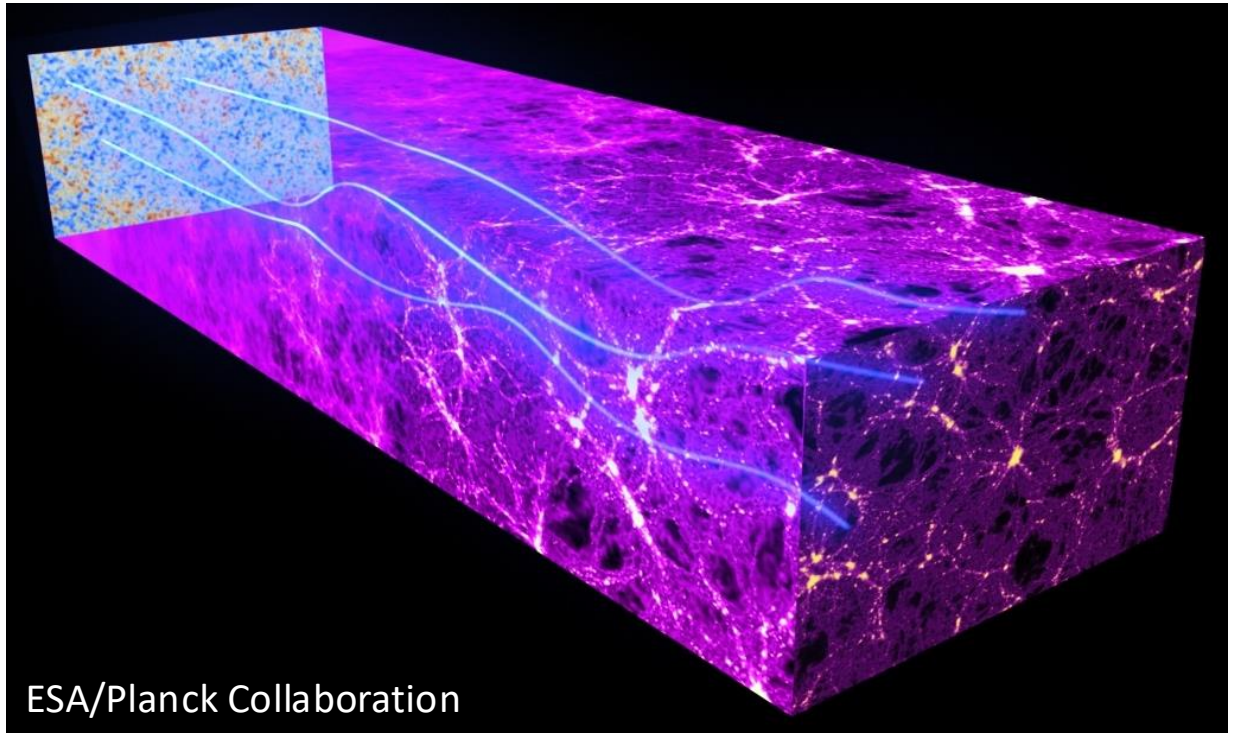
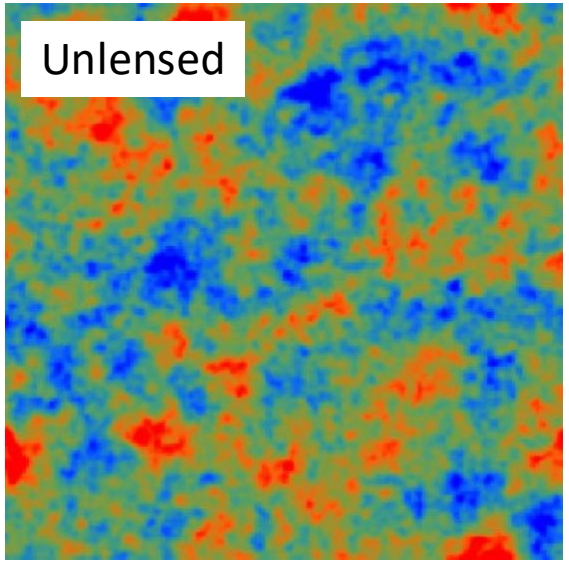
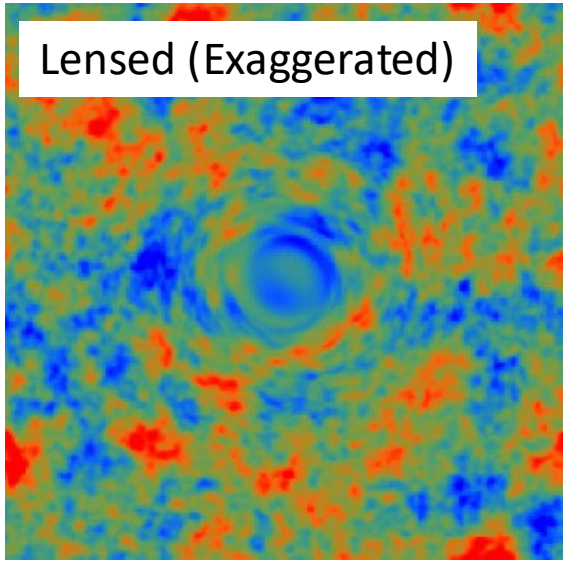


Hu & Okamoto (2002)

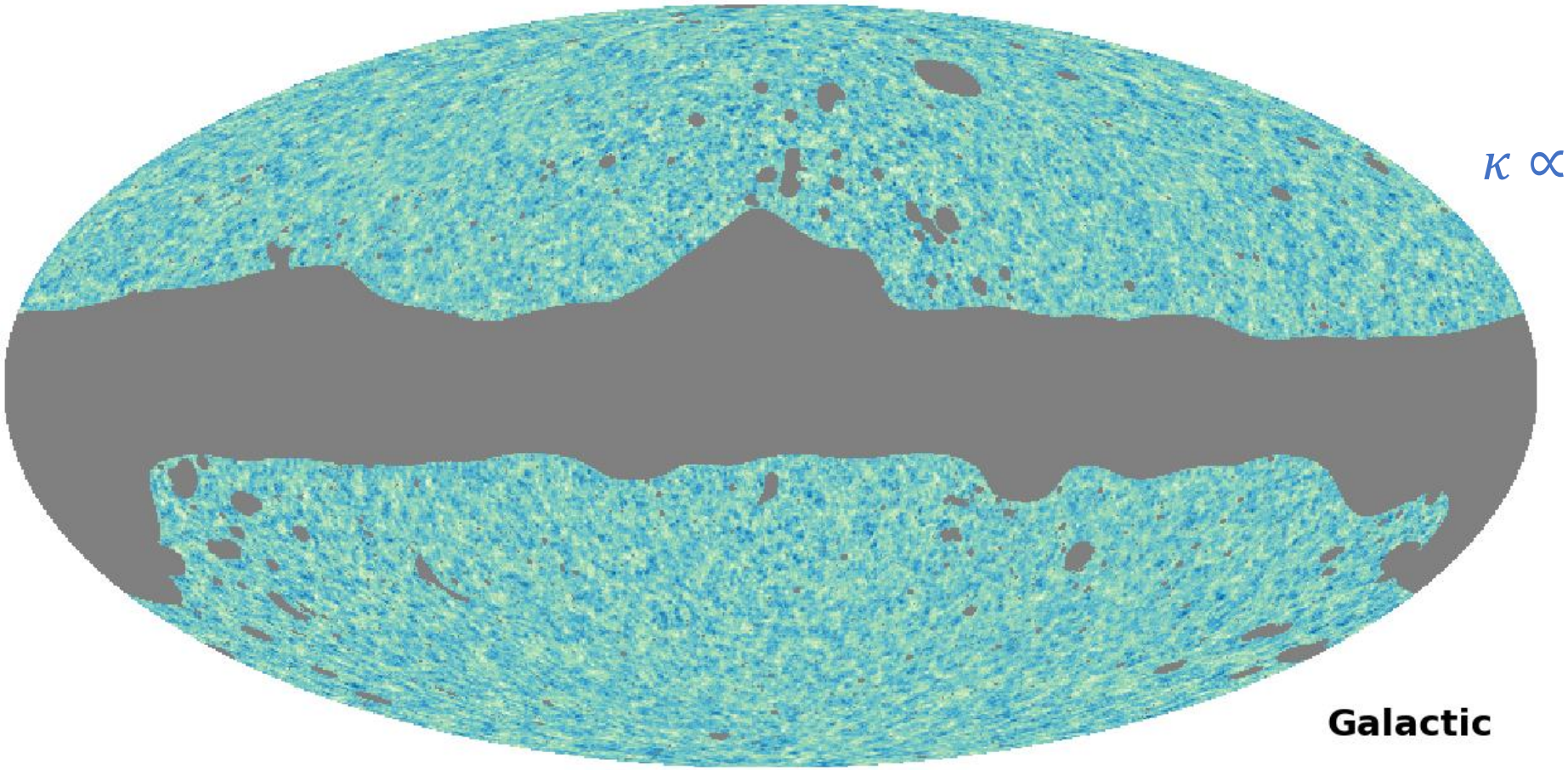




Integrated density field along the line of sight.

$$\kappa \propto \int_0^{\chi_{\rm CMB}} \mathrm{d}\chi\, W(\chi)\delta(\chi)$$

Planck lensing map



$$\kappa \propto \int_0^{\chi_{\rm CMB}} \mathrm{d}\chi\, W(\chi)\delta(\chi)$$

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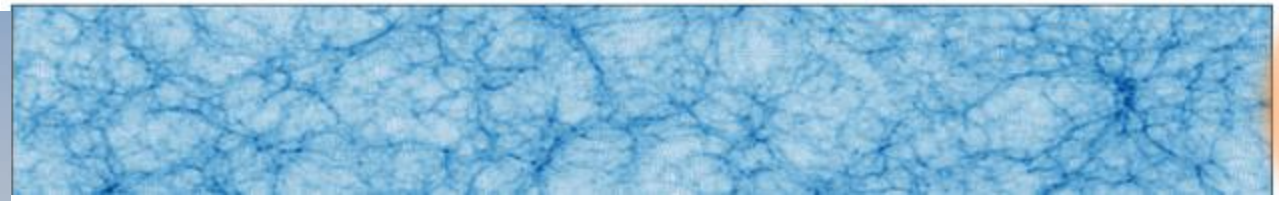
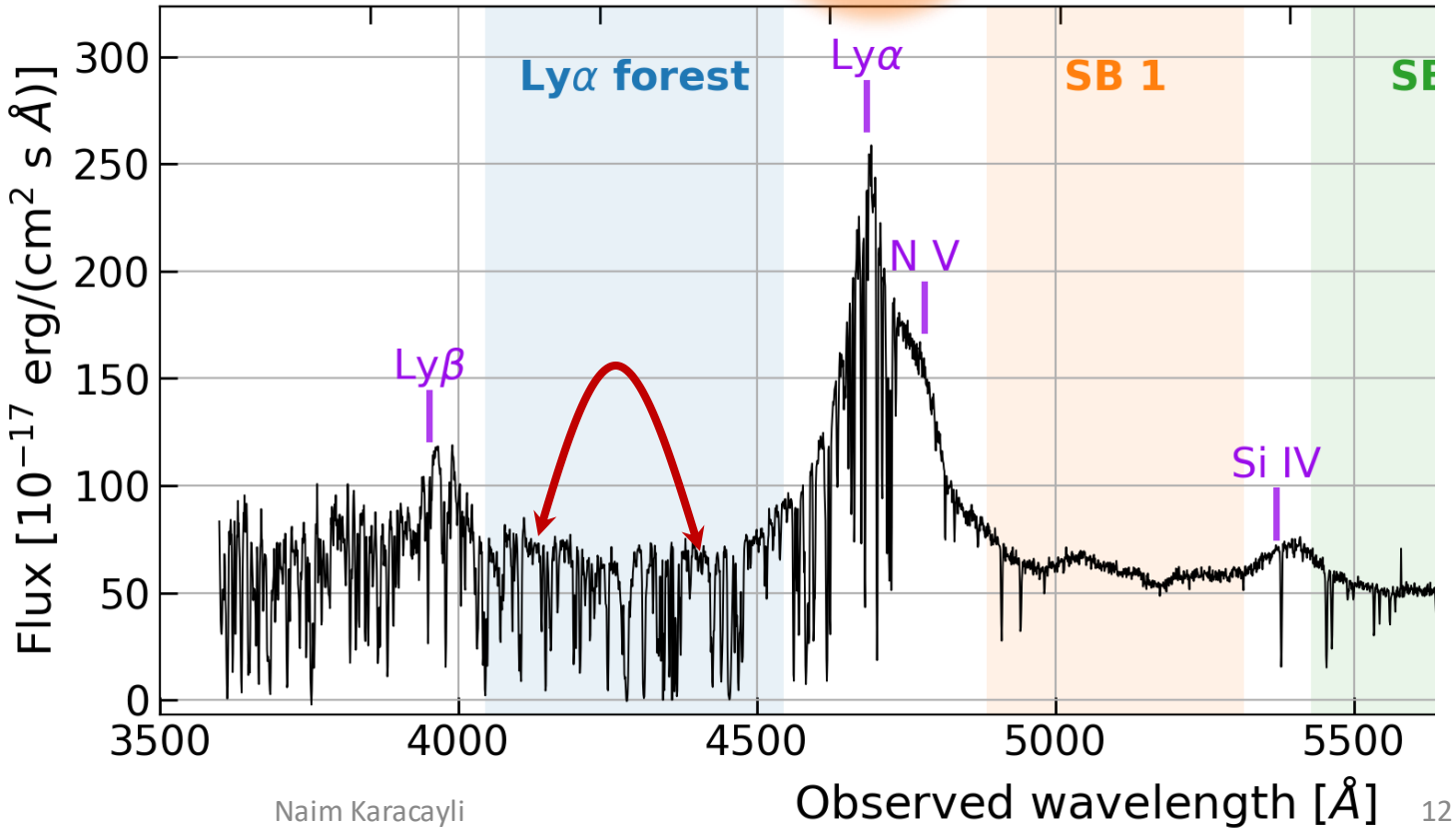
Lyman-alpha forest

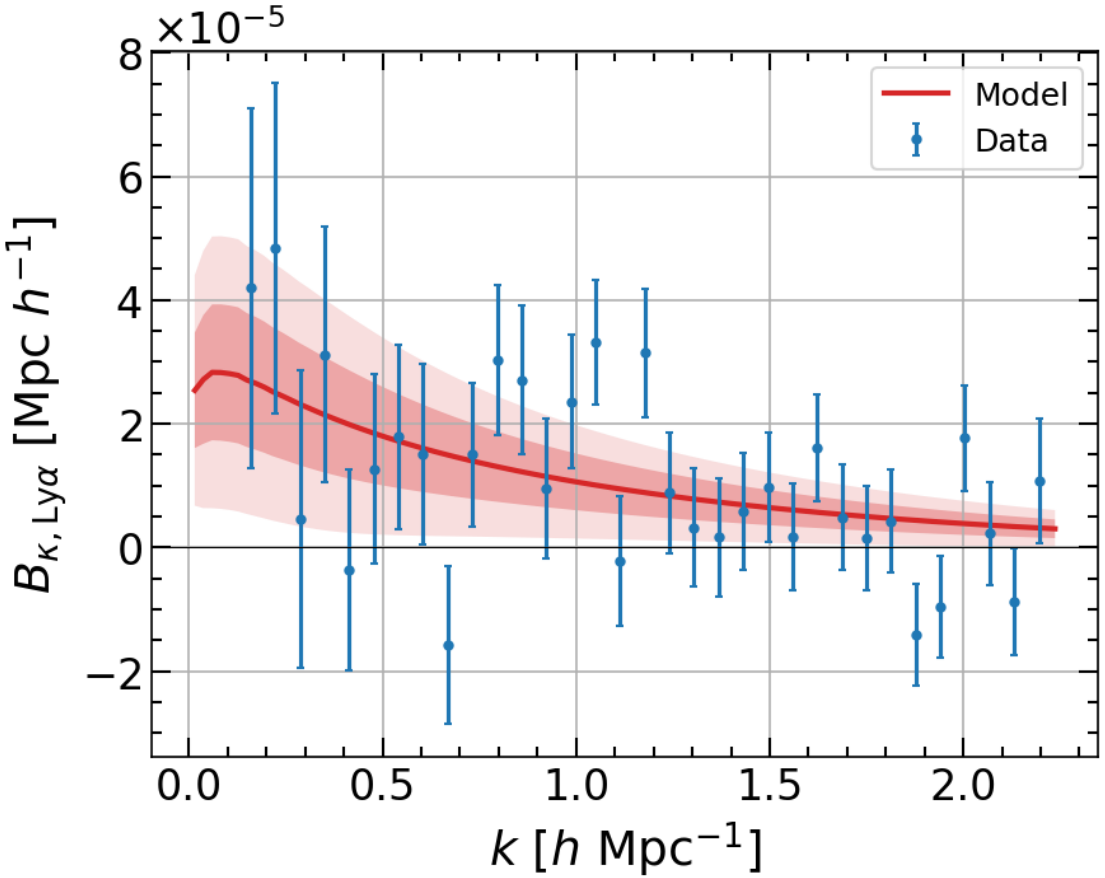


"1D" Power spectrum measured in each light of sight.

$$P_F(k) = \langle |\widetilde{\delta_F}(k)|^2 \rangle$$



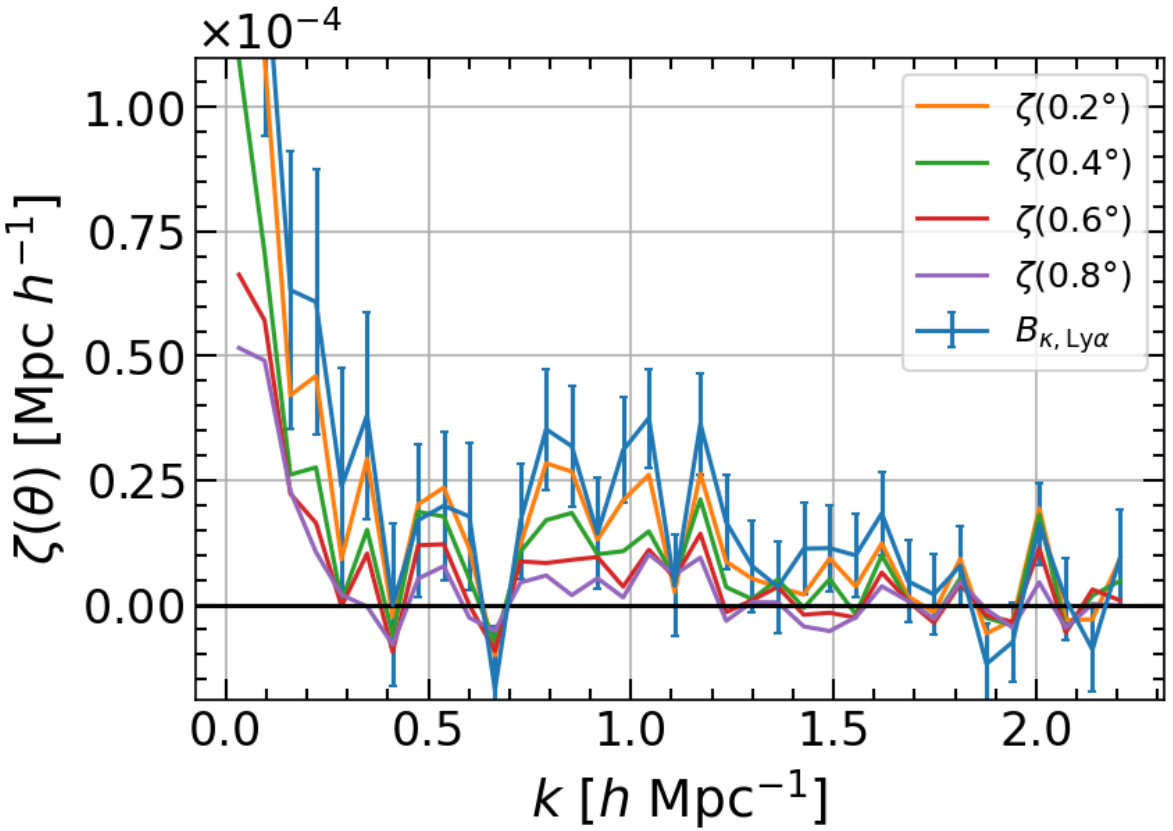
The cross-correlation signal

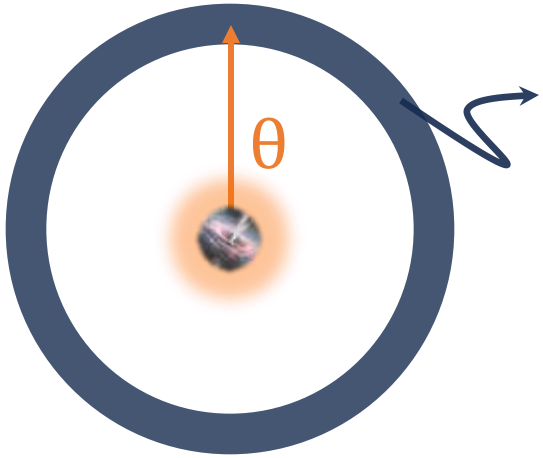


$$\left\langle \left(P_q(k) - \langle P \rangle\right)\left(\kappa_q - \langle \kappa \rangle\right)\right\rangle = B(k)$$

- Average over quasars (*q).*
- First detected in Doux et al. (2016) at 5 sigma.
- This is the second detection of 4.8 sigma.
- 2.7 after accounting for non-Lya sources (not in Doux+16).

Angular dependence

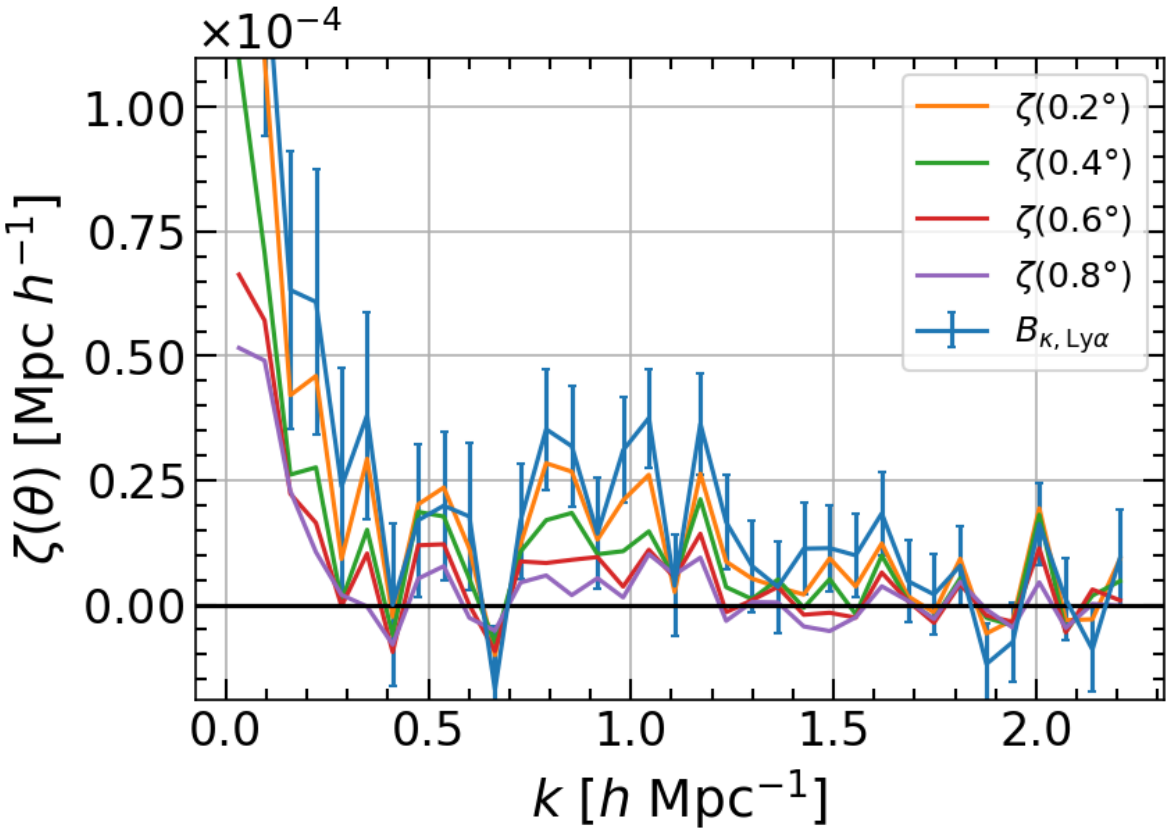


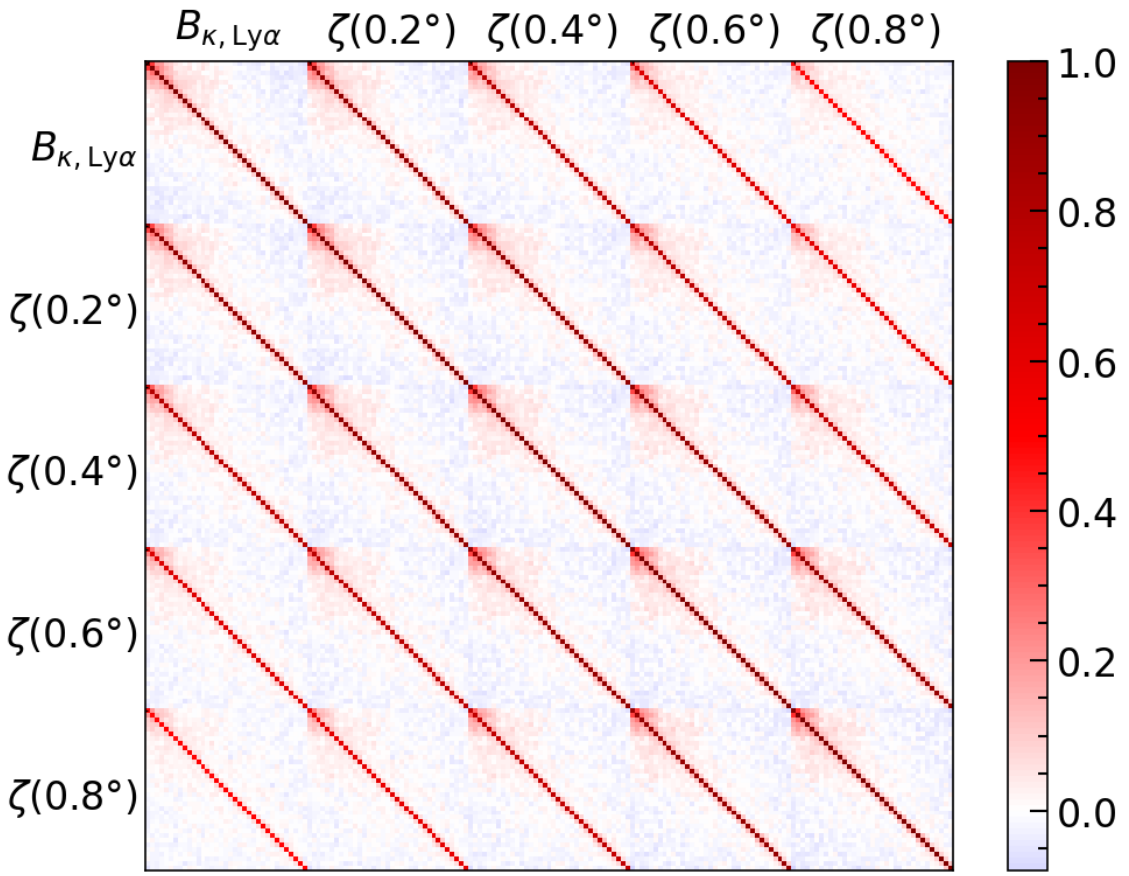


$\kappa(\theta)$: Average kappa inside the ring

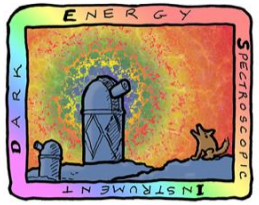
- The correlation naturally goes to zero at large angular separations.

Angular bins are highly correlated





Is it all about gravity?



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- Temperature-density relations of the intergalactic medium.

$$T = T_0(1+\delta)^{\gamma-1}$$

- Line broadening due thermal motion suppresses the power at high k.

$$P \propto e^{-k^2\sigma_{th}^2} \quad \text{and} \quad \sigma_{th} = \sqrt{\frac{k_B T}{m_p}} \sim 10 \text{ km/s}$$

- Maybe temperature density relation can also be studied with this cross-correlation measurement.

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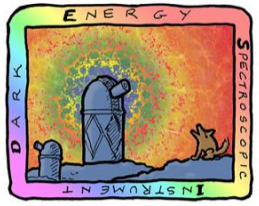
We are honored to be permitted to conduct scientific research on Iolkam Du'ag (Kitt Peak) in Arizona, a mountain with particular significance to the Tohono O'odham Nation.

Thanks to our sponsors and 69 Participating Institutions!



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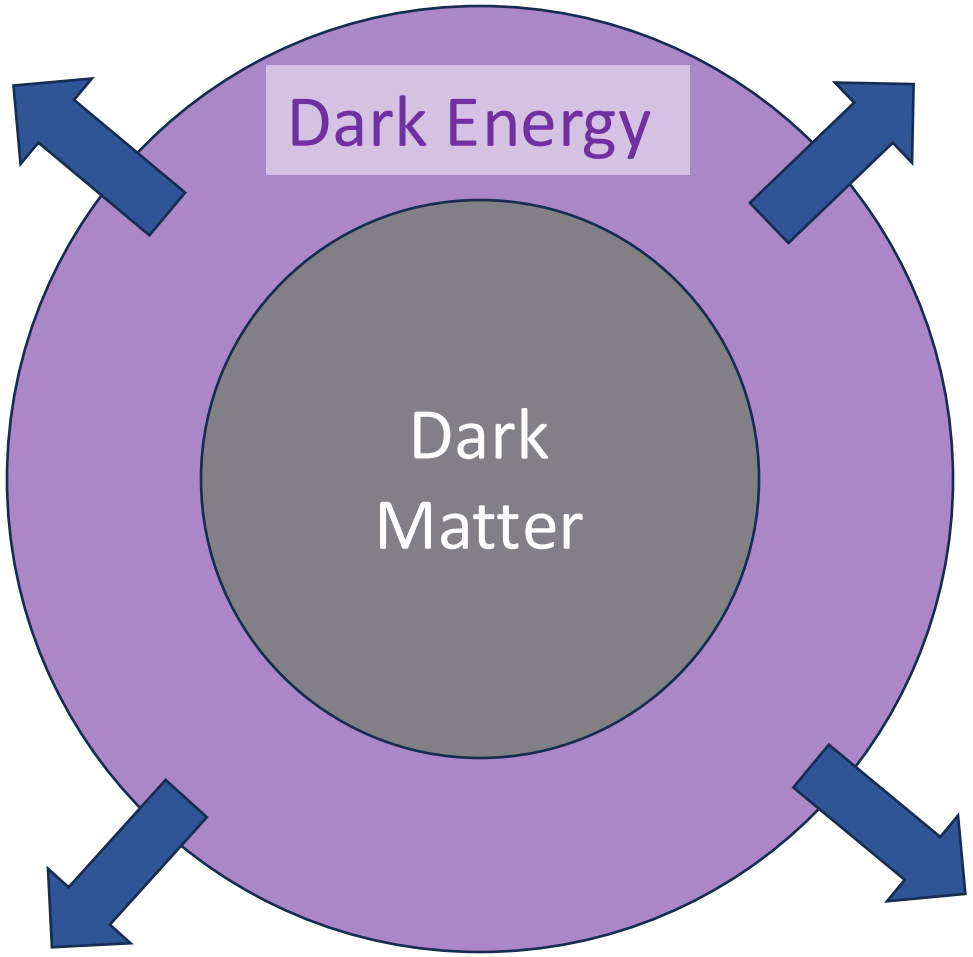
$$\langle \delta_F(k,\boldsymbol{x})\delta_F(k',\boldsymbol{x})\kappa(\boldsymbol{x})\rangle \equiv 2\pi\delta_D(k+k')B^{\rm 1D}_{FF\kappa}(k)$$

$$\propto \quad \langle \tilde{\delta}_F(\boldsymbol{q})\tilde{\delta}_F(\boldsymbol{q'})\tilde{\delta}_m(\boldsymbol{p})\rangle$$

In some regions dark energy wins



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In others dark matter wins