Lecture 2: ULDM searches

Cont. gravitational signatures

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Outlook

Lecture 1: Cosm. Signatures 1

Part I:

- Evidences
- ULDM models
- Observational signatures
- GravitationalBounds

Part II: *Practice!*

Notebook 1: linear

- Linear observational signature of ULDM: suppression of structures

Lecture 2: Cosm. Signatures 2

Part I:

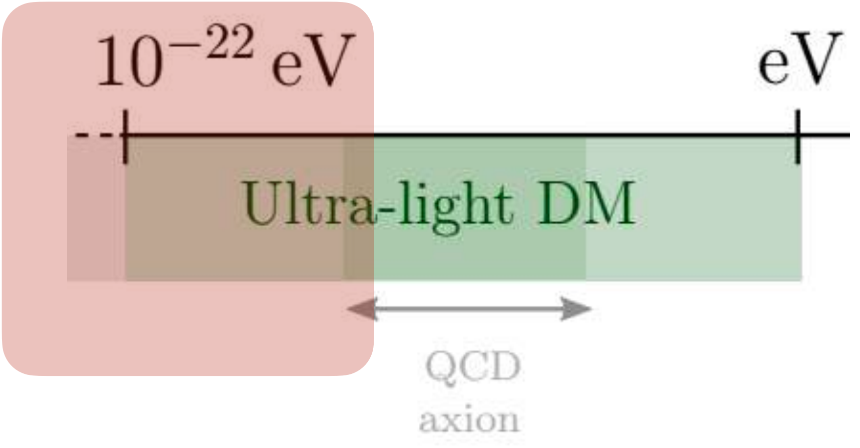
Notebook 2: linear

Part II:

- Cont. ULDM gravitational bounds
- Future of grav. observations

Lecture 3: interac. with SM

- Cont. ULDM gravitational bounds
- DM Superfluid
- Interaction of ULDM with SM
  - Axion/ALPs interaction in astrophysical systems
  - Direct detection



Ultra-light Dark Matter -classes

3 classes:

Fuzzy DM (FDM)

- Gravitationally bounded ultra-light scalar field model
- Condensation under gravity (BEC)

Self Interacting FDM (SIFDM)

- Presence of (weakly) self-interaction
- Condensation under gravity + SI (superfluid)

DM Superfluid

- Forms a superfluid in galaxies
- MOND behaviour interior of galaxies

DOFs: FDM: m — SIFDM: m, g

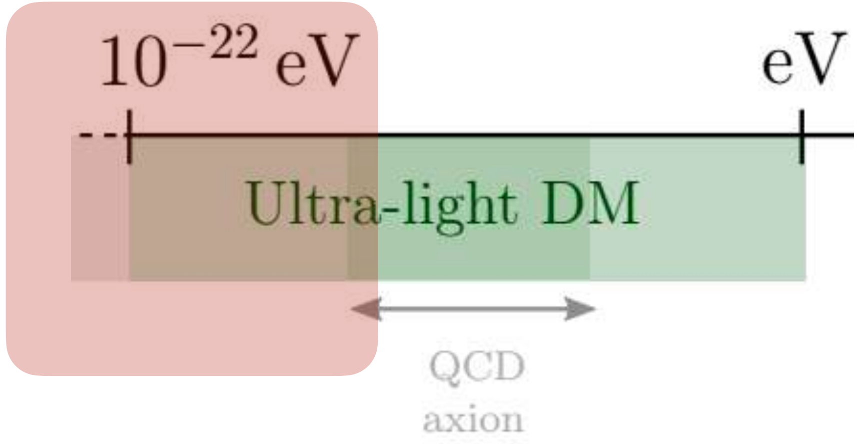
Axion and ALP (axion like particles)

$$i\dot{\psi} = \left(-\frac{1}{2m}\nabla^2 + \frac{g}{8m^2}|\psi|^2 - m\Phi\right)\psi$$

$$\mathcal{L} = P(X)$$

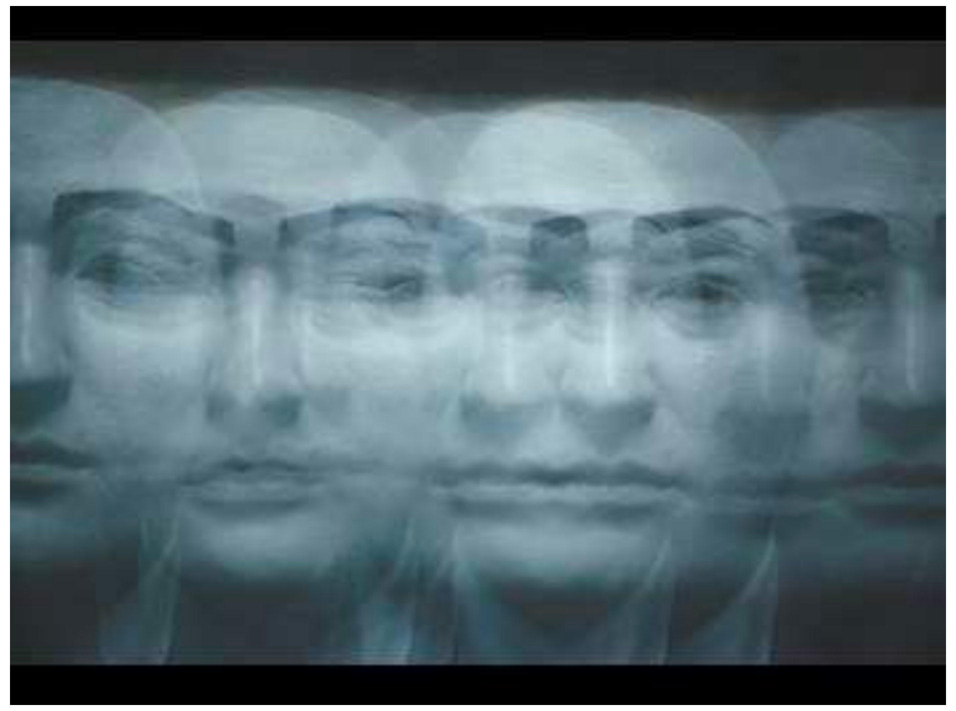
$\longrightarrow$ Connection with condensed matter and particle physics!

"Ultra-light dark matter", **E.Ferreira**, 2020. The Astronomy and Astrophysics Review.

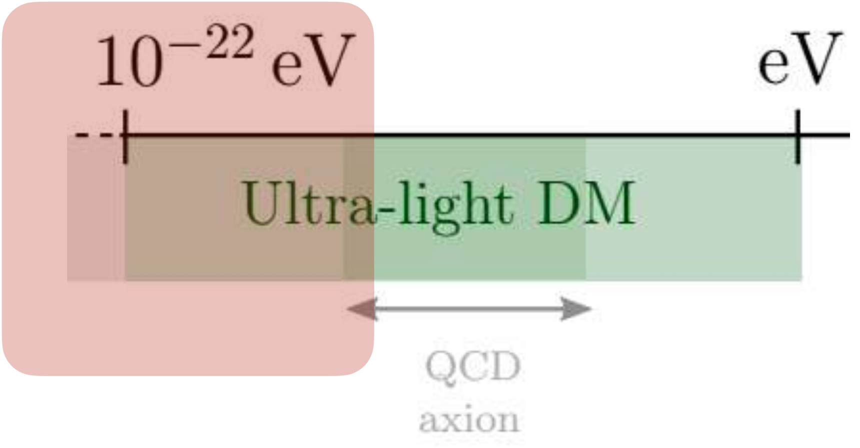


Fuzzy dark matter

Self interacting fuzzy dark matter



Structure formation - non-relativistic regime



Evolution on small scales: take non-relativistic regime of the theory, relevant for structure formation.

Schrödinger-Poisson system : describe the FDM and the SIFDM

$$\begin{cases} i\dot{\psi} = \left(-\dfrac{1}{2m}\nabla^2 + \dfrac{g}{8m^2}|\psi|^2 - m\Phi\right)\psi \\ \nabla^2\Phi = 4\pi G(m|\psi|^2 - \bar{\rho}) \end{cases}$$

Schrödinger equation (Gross-Pitaevskii)

Poisson equation

$g = 0 \longrightarrow$ FDM

$g \neq 0 \longrightarrow$ SIFDM

Fundamentally different than CDM/WDM/SIDM!

Madelung equations $\quad (\psi \equiv \sqrt{\rho/m}\, e^{i\theta}$ and $\mathbf{v} \equiv \nabla\theta/m)$

$$P_{int} = K\rho^{(j+1)/j} = \frac{g}{2m^2}\rho^2$$

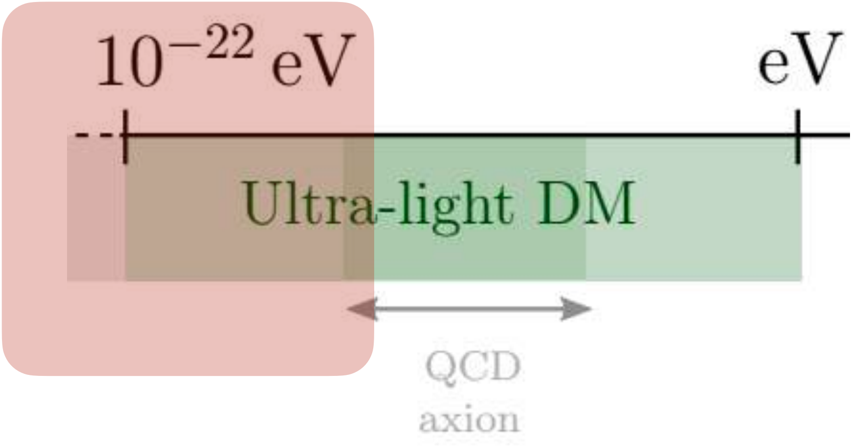
$$\dot{\rho} + \nabla\cdot(\rho\,\mathbf{v}) = 0$$

$$\dot{\mathbf{v}} + (\mathbf{v}\cdot\nabla)\mathbf{v} = -\frac{1}{m}\left(V_{grav} - P_{int} - \boxed{\frac{1}{2m}\frac{\nabla^2\sqrt{\rho}}{\sqrt{\rho}}}\right)$$

Quantum pressure

FLUID DESCRIPTION

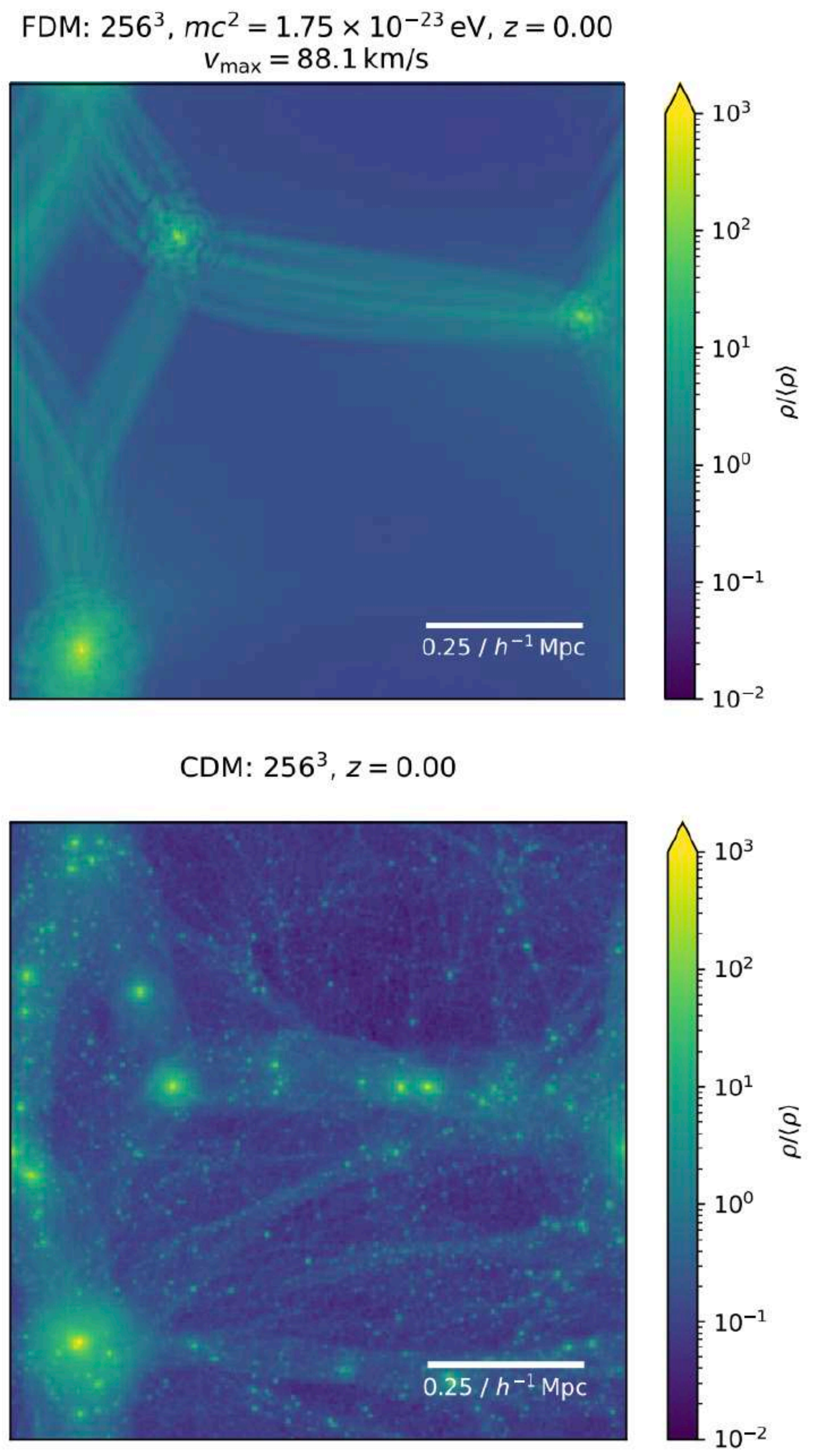
Phenomenology



RICH PHENOMENOLOGY ON SMALL SCALES

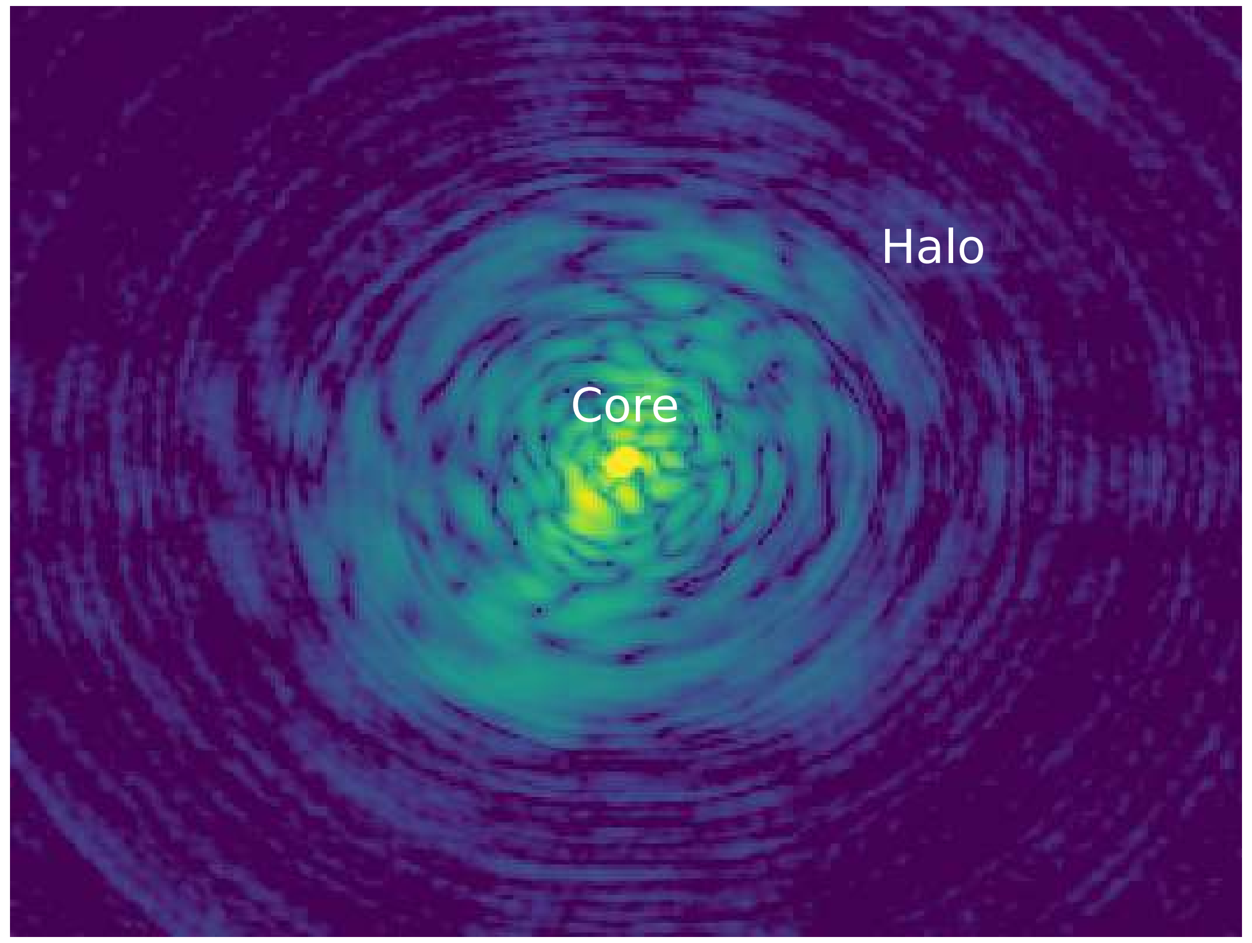
* Focus only in gravitational signatures

Suppression of small structures

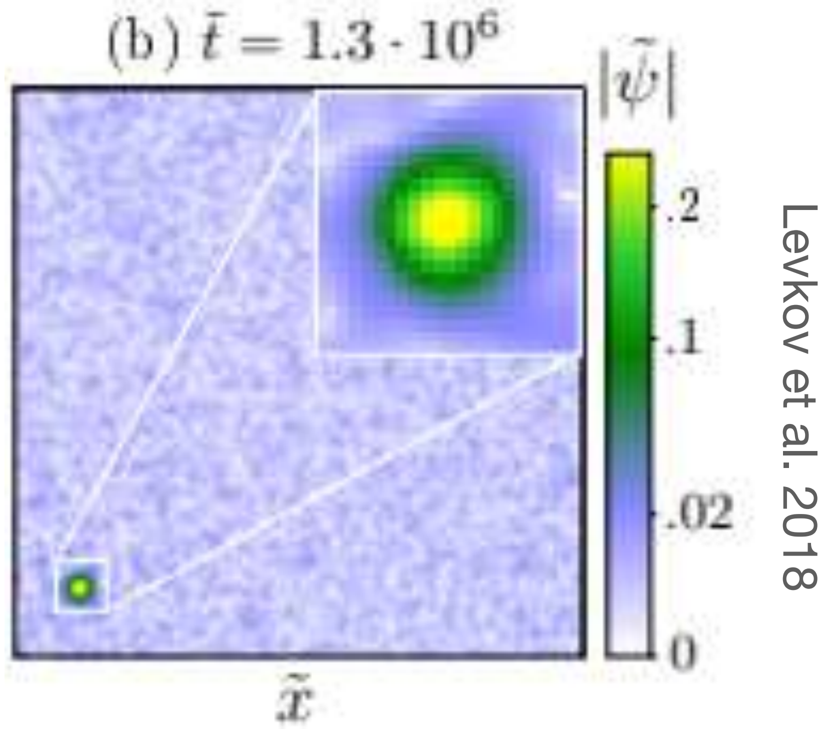


S. May et al. 2021

Formation of a solitonic core

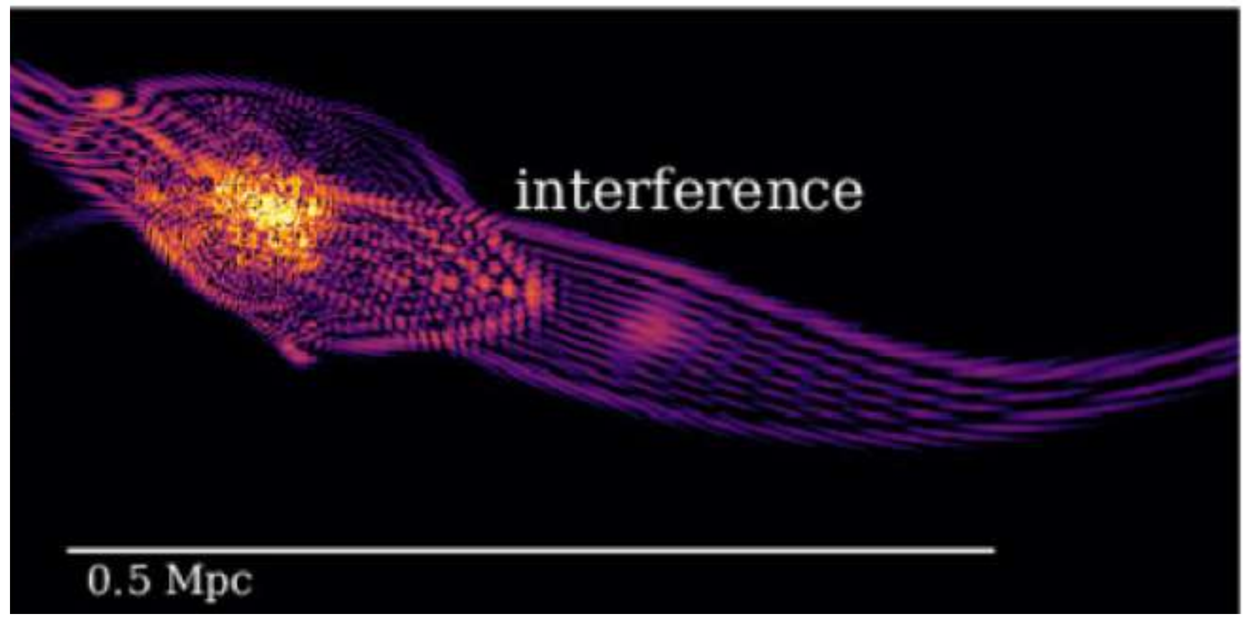


Dynamical effects



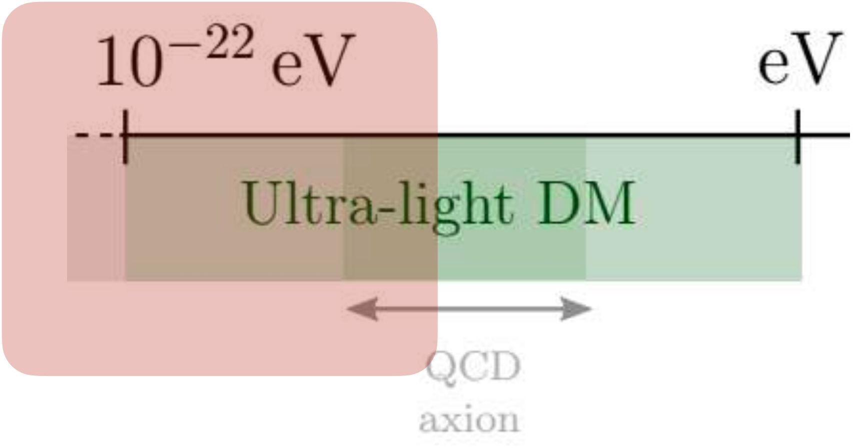
Levkov et al. 2018

Wave interference



Mocz et al. 2017

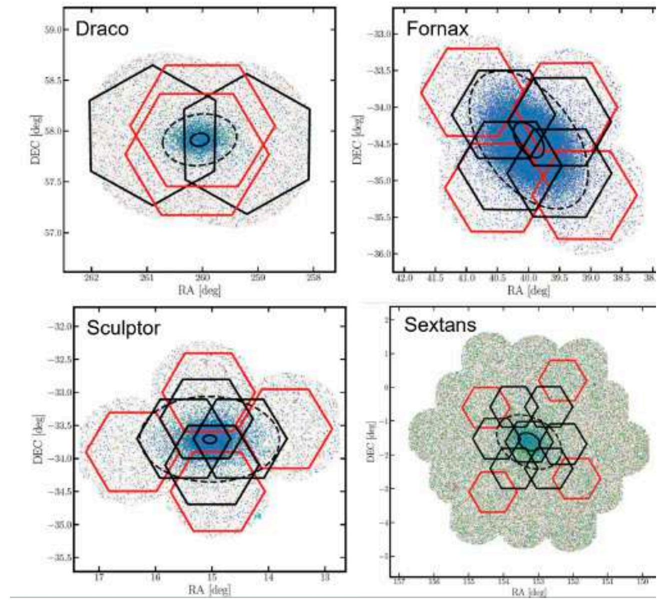
Observational implications and constraints



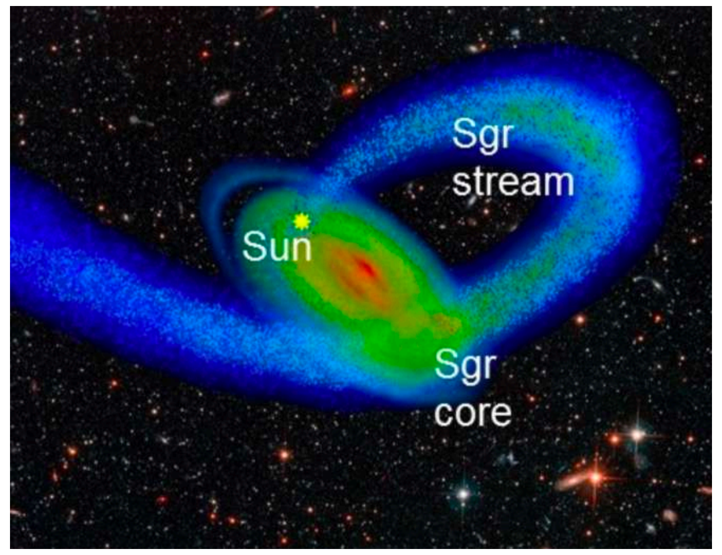
Galaxies

NASA and ESA

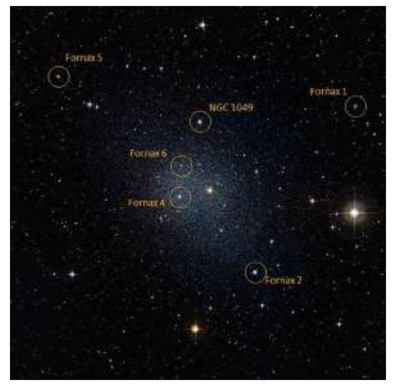
Dwarfs



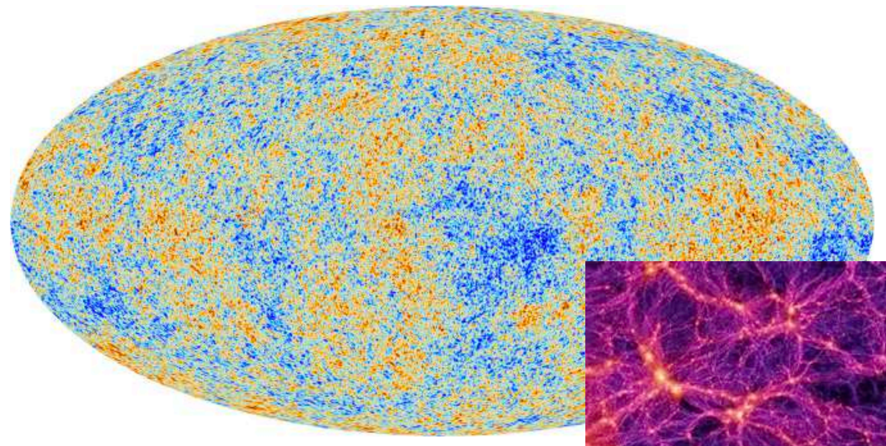
Stellar stream



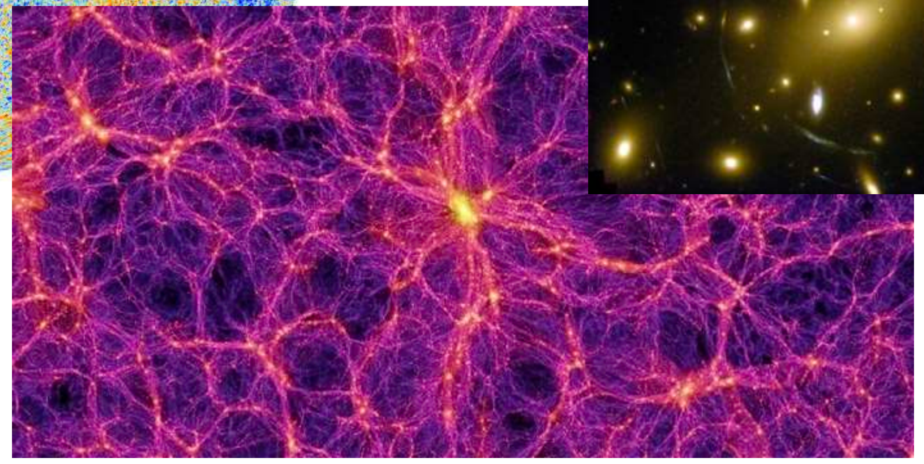
Globular clusters



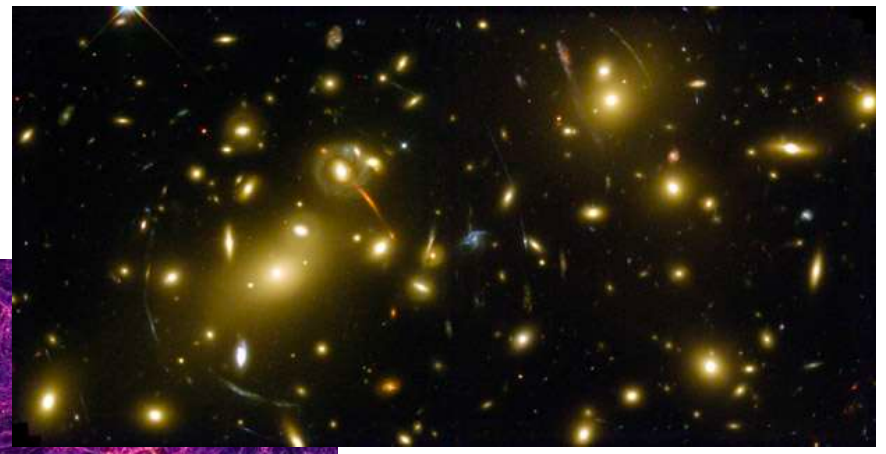
CMB+LSS



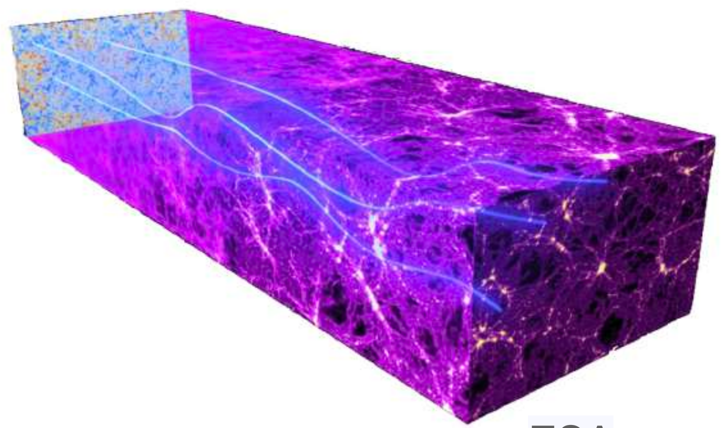
ESA and the Planck Collaboration



Springel & others / Virgo Consortium

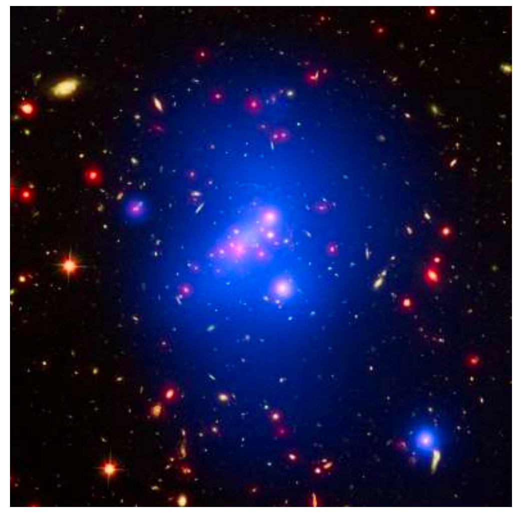


NASA and ESA



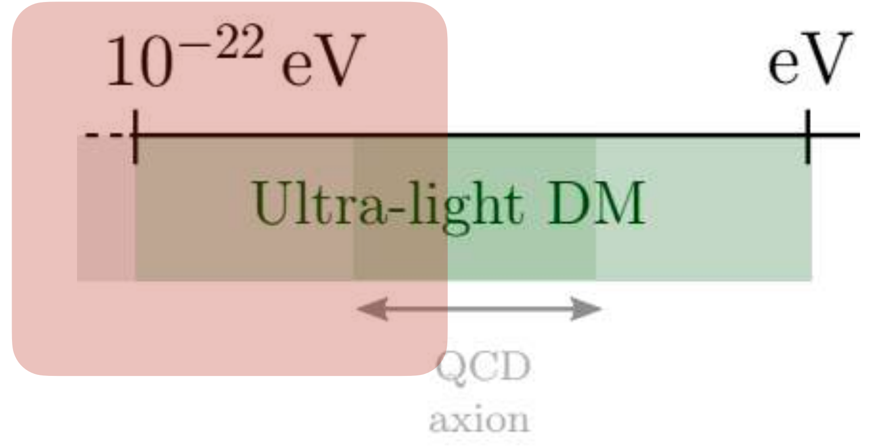
ESA

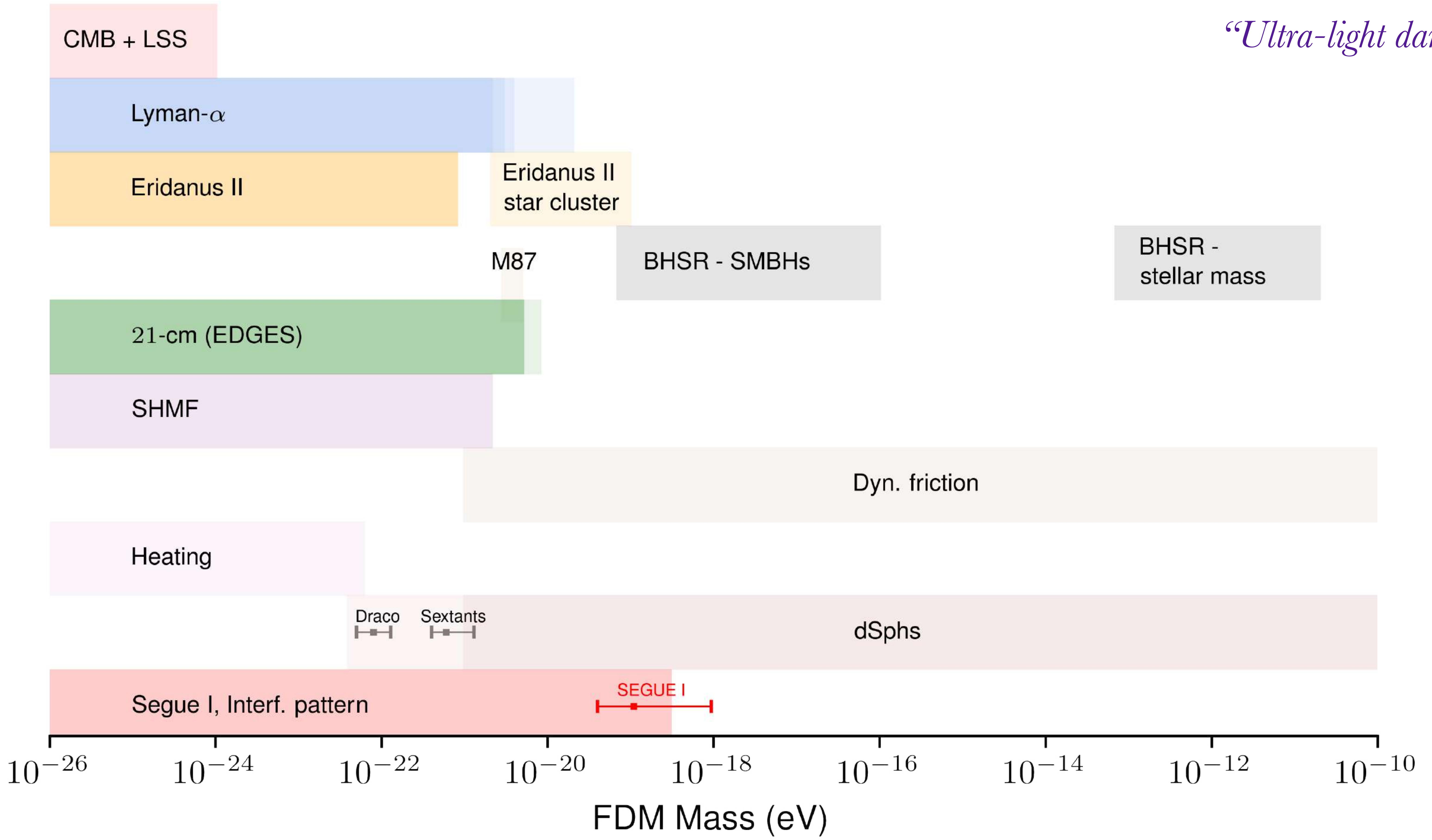
Clusters



Observational implications and constraints

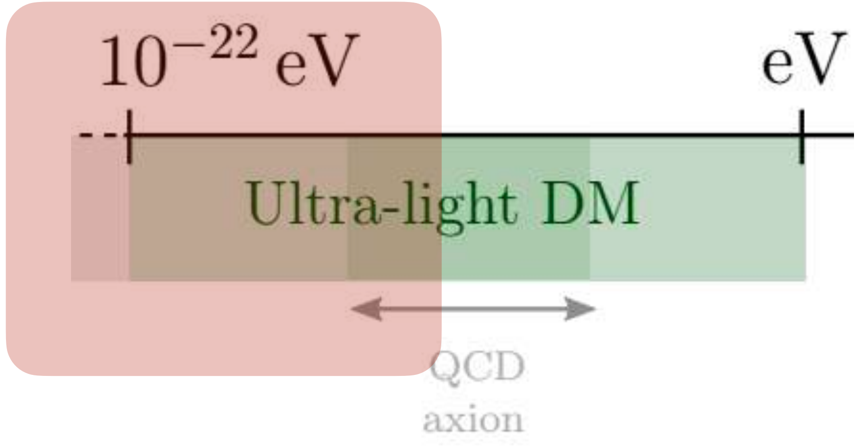
Fuzzy Dark Matter - bounds on the mass





"Ultra-light dark matter", **E.F.**, 2020. The Astronomy and Astrophysics Review.

Bounds consider FDM is *all* DM



Observational implications and constraints

Suppression of small scale structures

Observational implications and constraints

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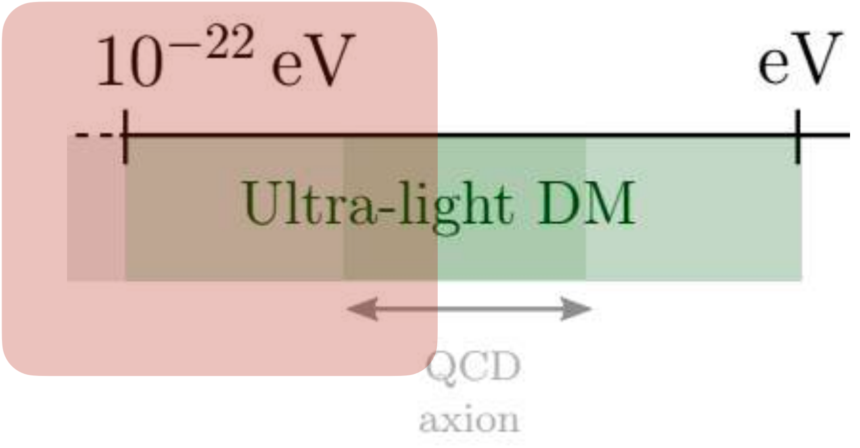

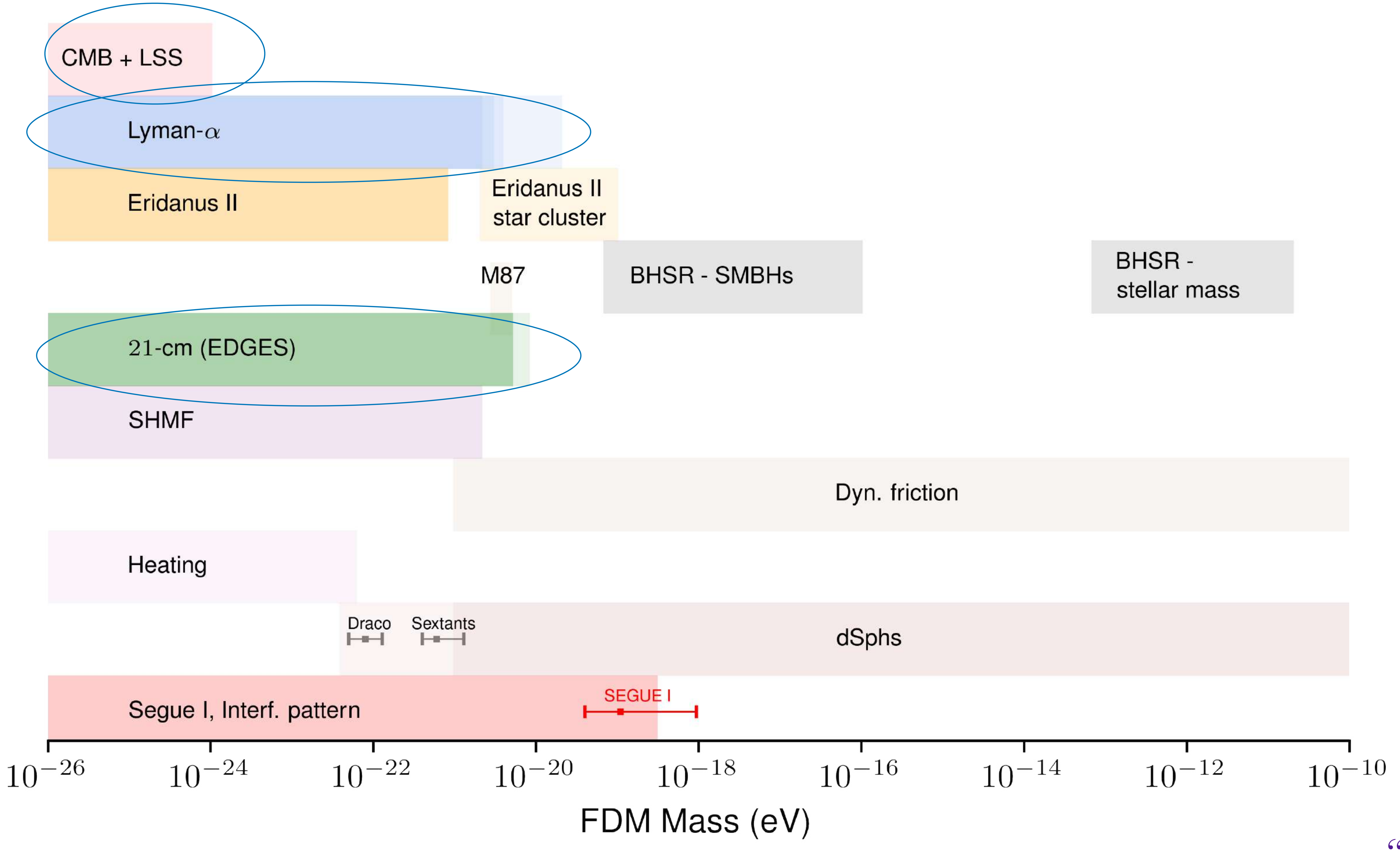

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Observational implications and constraints

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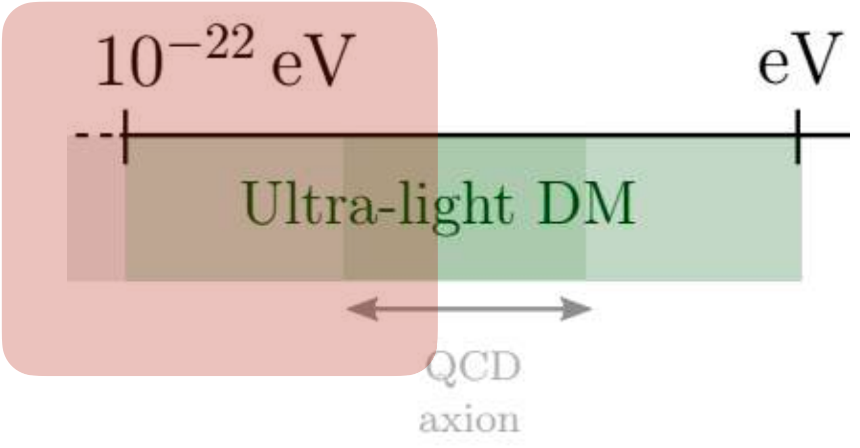
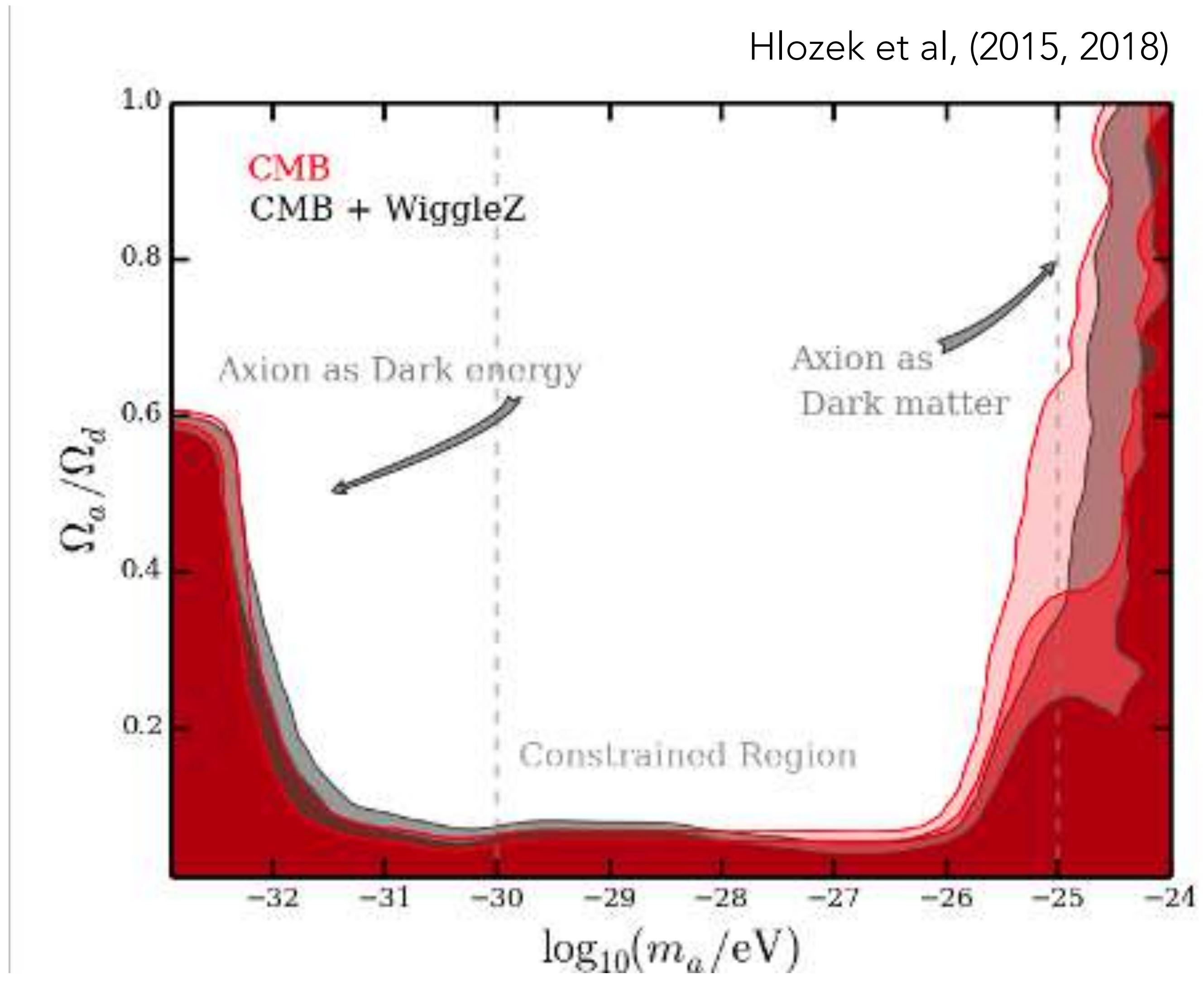


Suppression of small structures

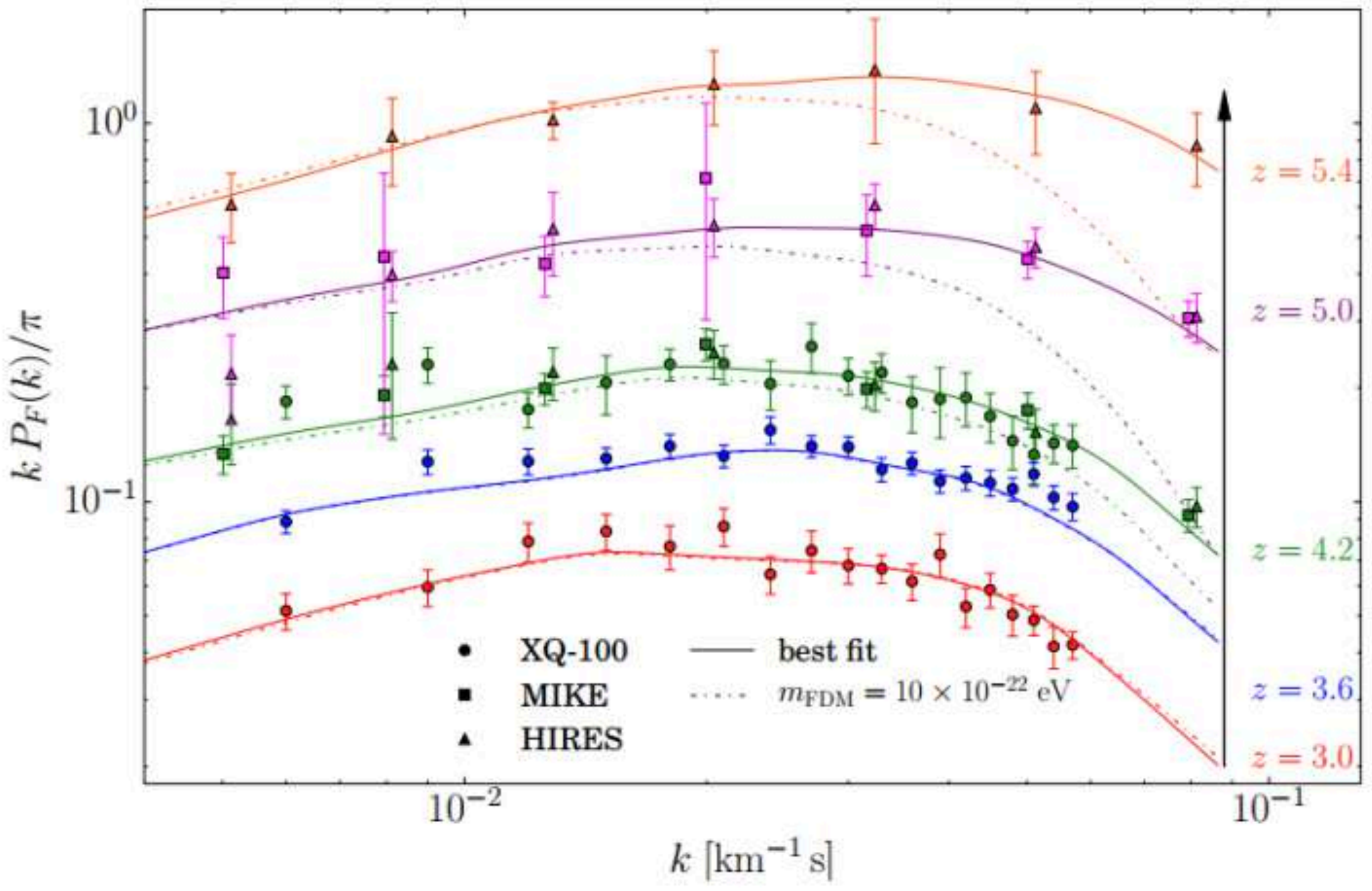
CMB/LSS



$$m \gtrsim 10^{-24}\,\mathrm{eV}$$

Lyman alpha

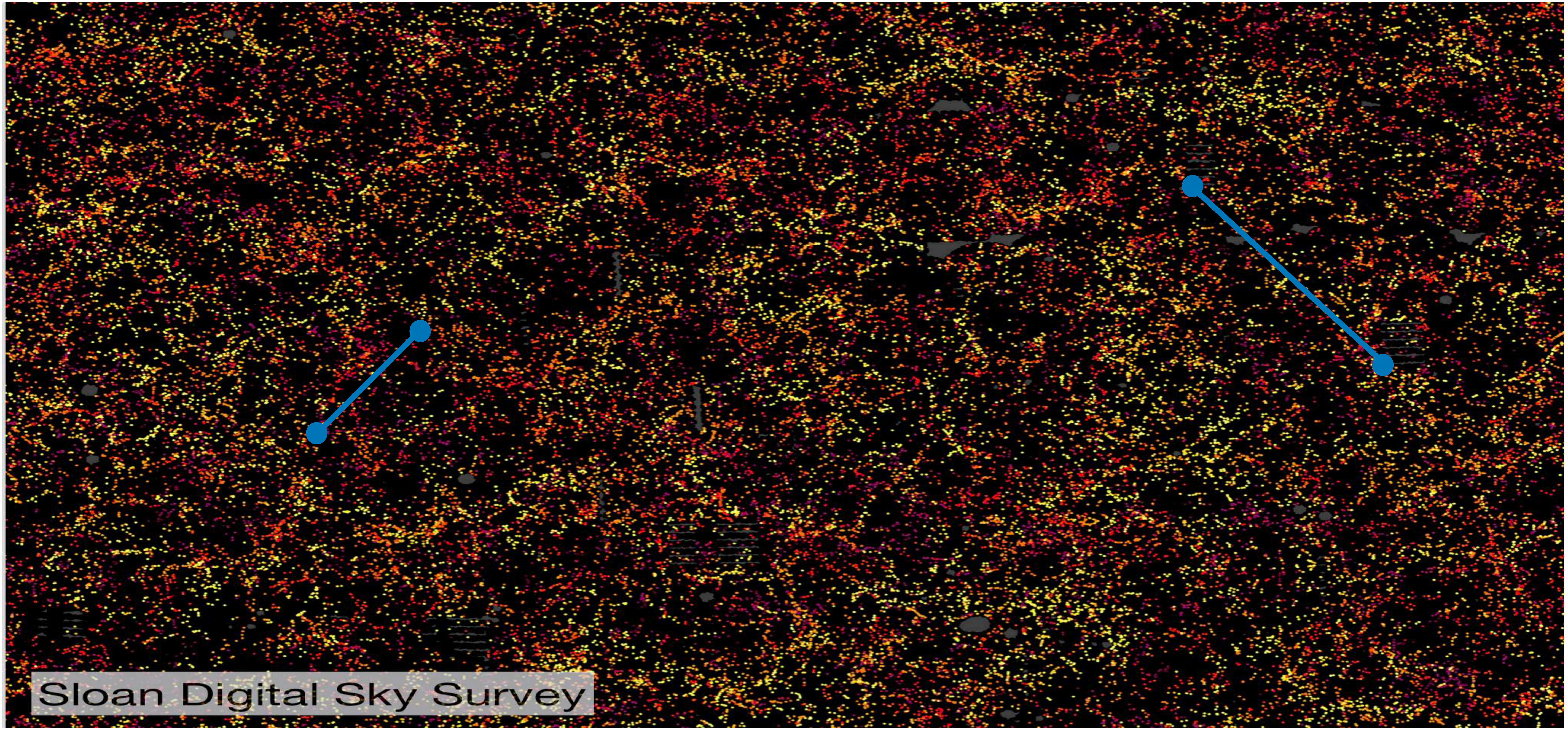
Armengaud et al. (2017); Iršič et al. (2017); Rogers et al. (2020)



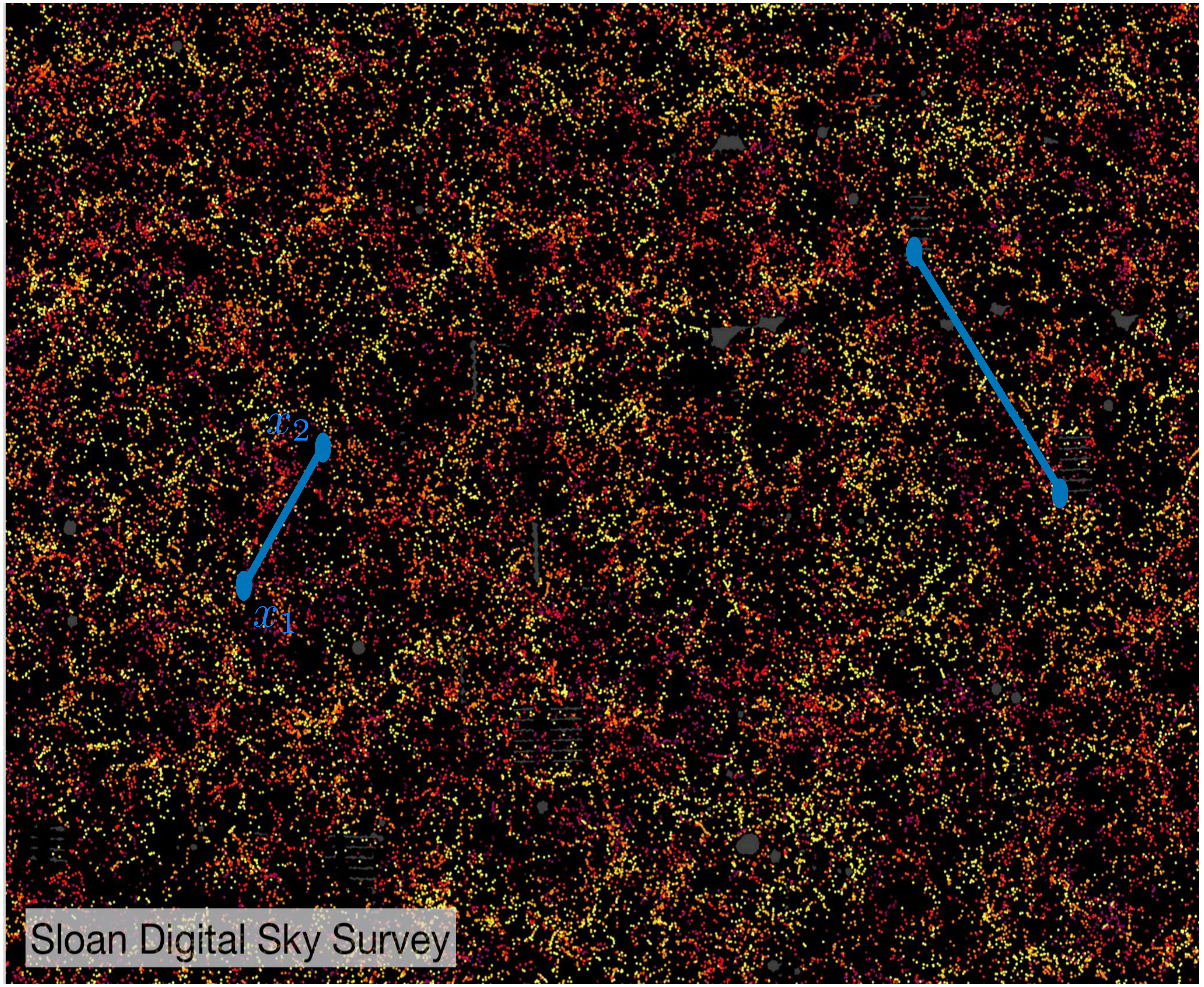
$$m \gtrsim 2 \times 10^{-20}\,\mathrm{eV}$$

so enough Mpc-scale power in Ly-α forest at z = 5.

How to measure structures



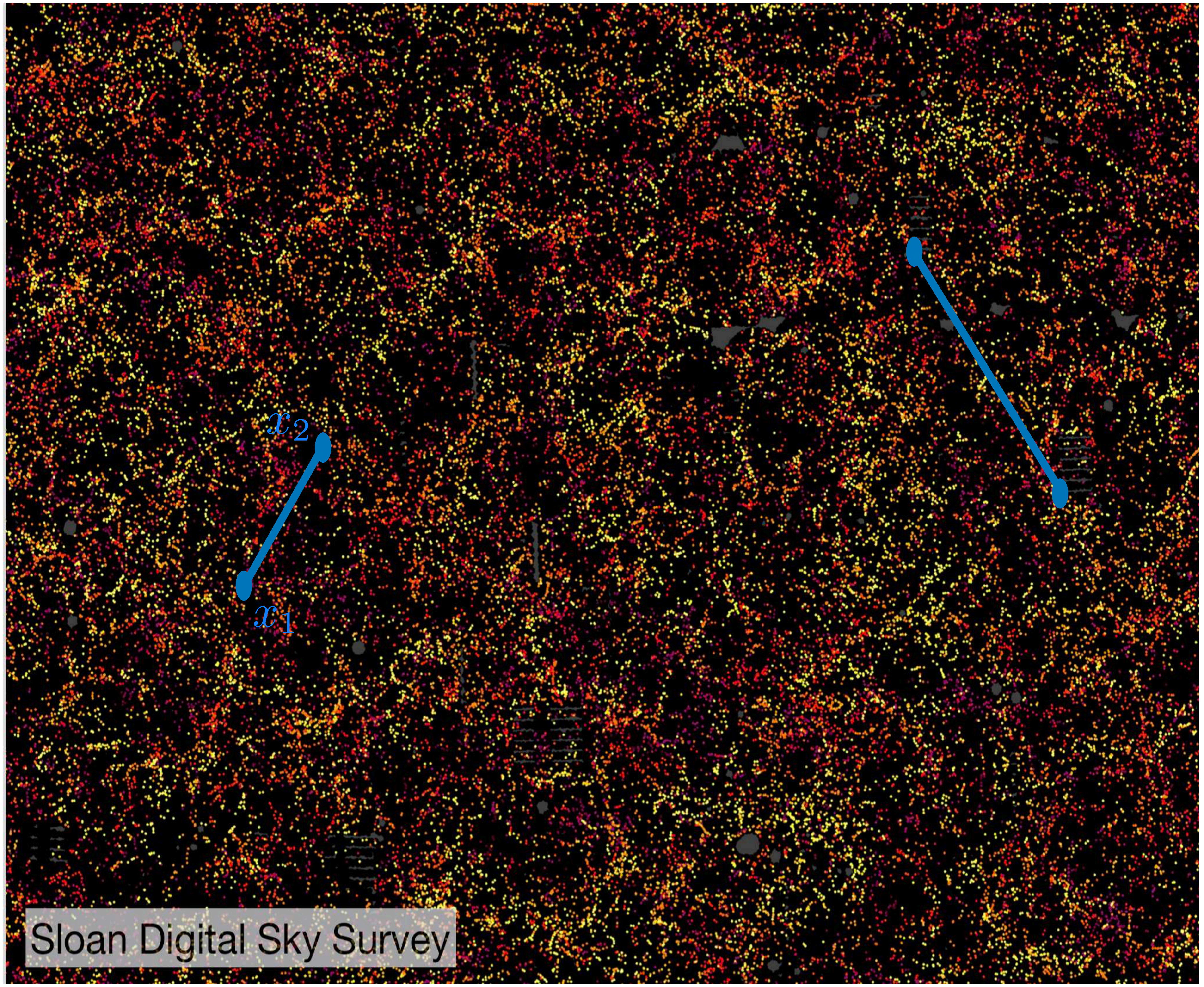
How to measure structures



2 point correlation function

$$\langle \delta(x_1)\delta(x_2) \rangle$$

How to measure structures



2 point correlation function

$$\langle \delta(x_1)\delta(x_2) \rangle$$

Decompose in Fourier modes:

$$\delta(x) = \sum_k \delta_k \, \sin(kx + \phi_k)$$

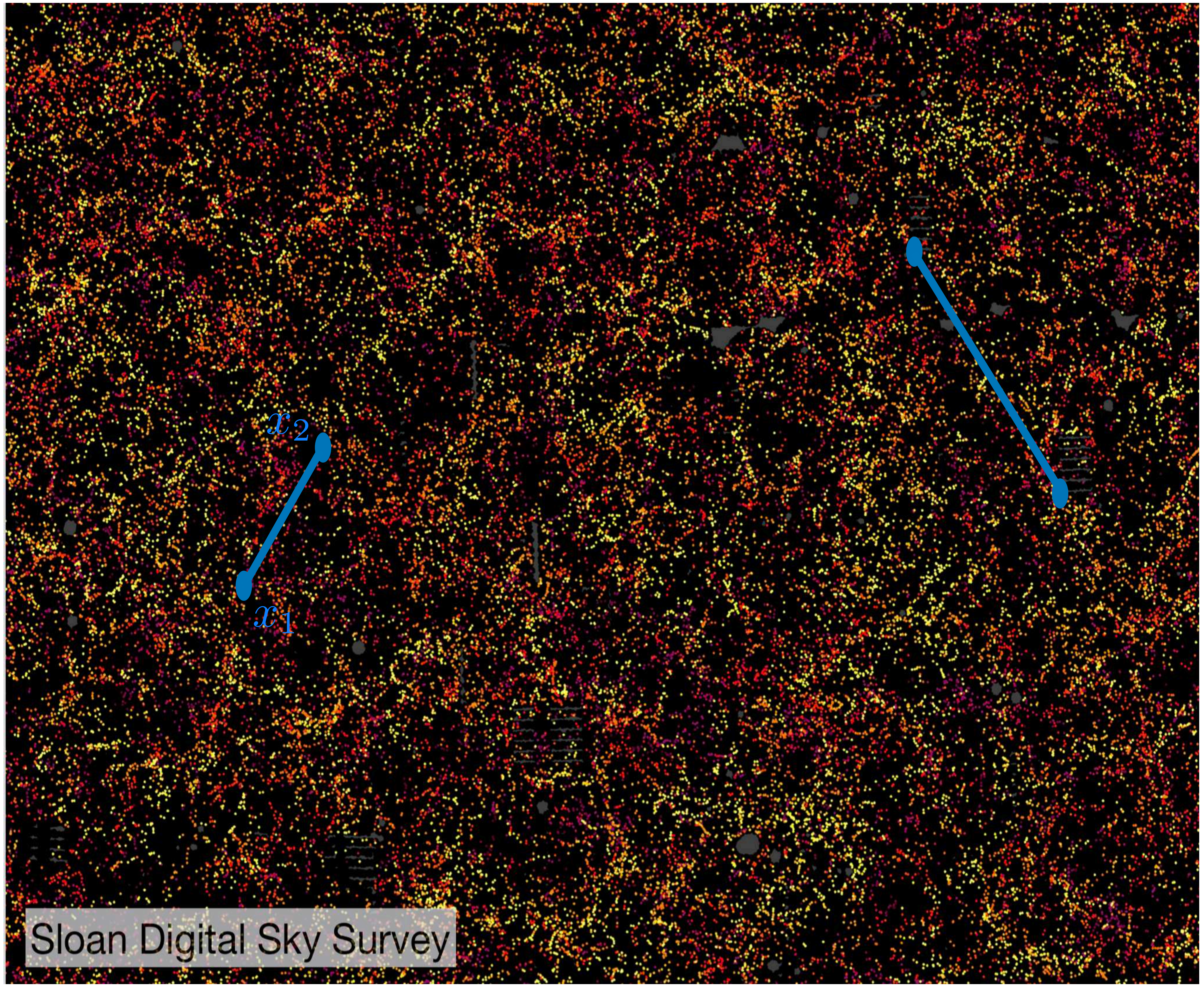
$$k = 2\pi/\lambda$$

$$\implies \boxed{P(k) = |\delta_k|^2}$$

Espectro de potências

Um dos principais objetos estatísticos da cosmologia!

How to measure structures



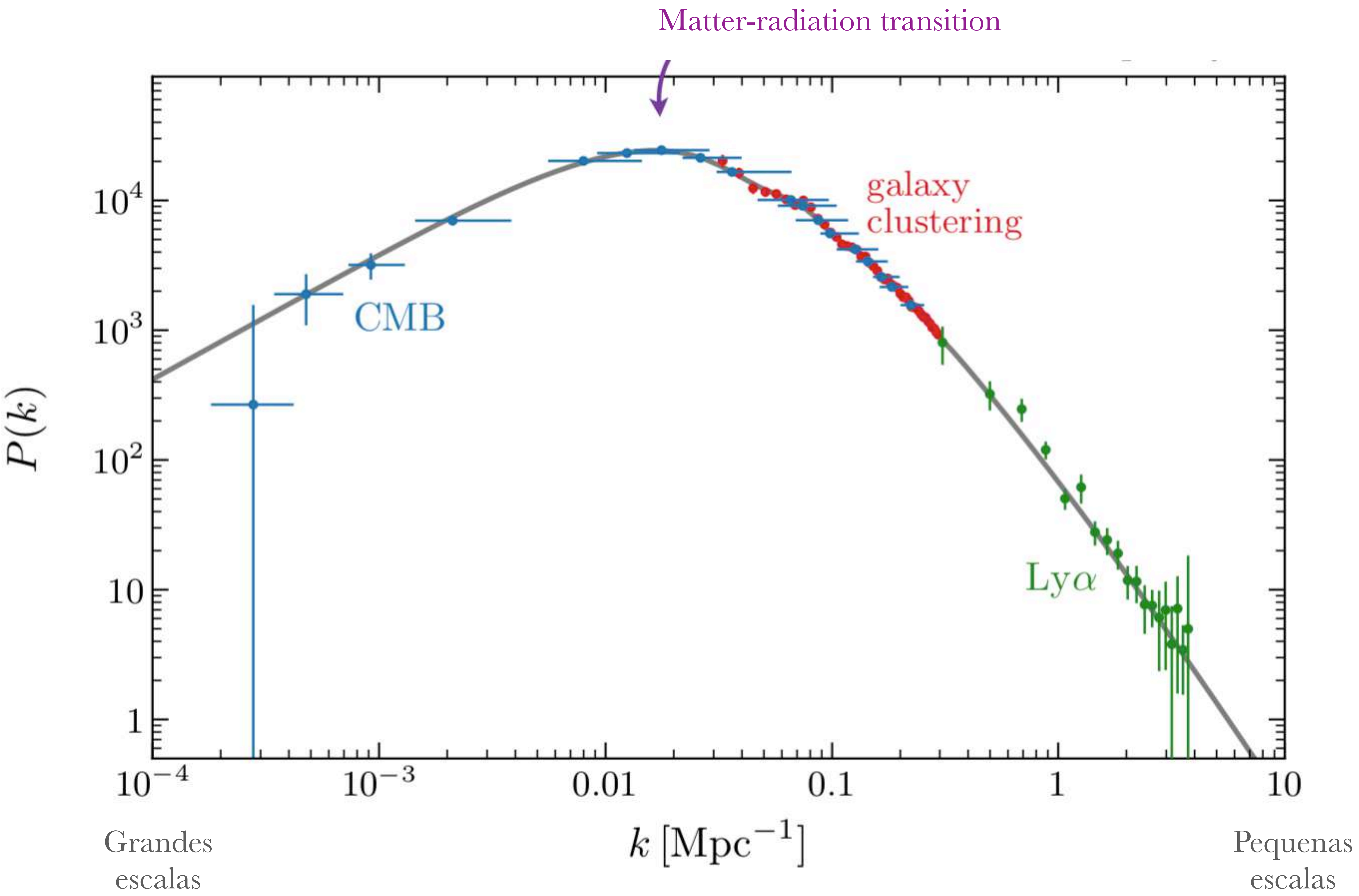
2 point correlation function

$$\langle \delta(x_1)\delta(x_2) \rangle$$

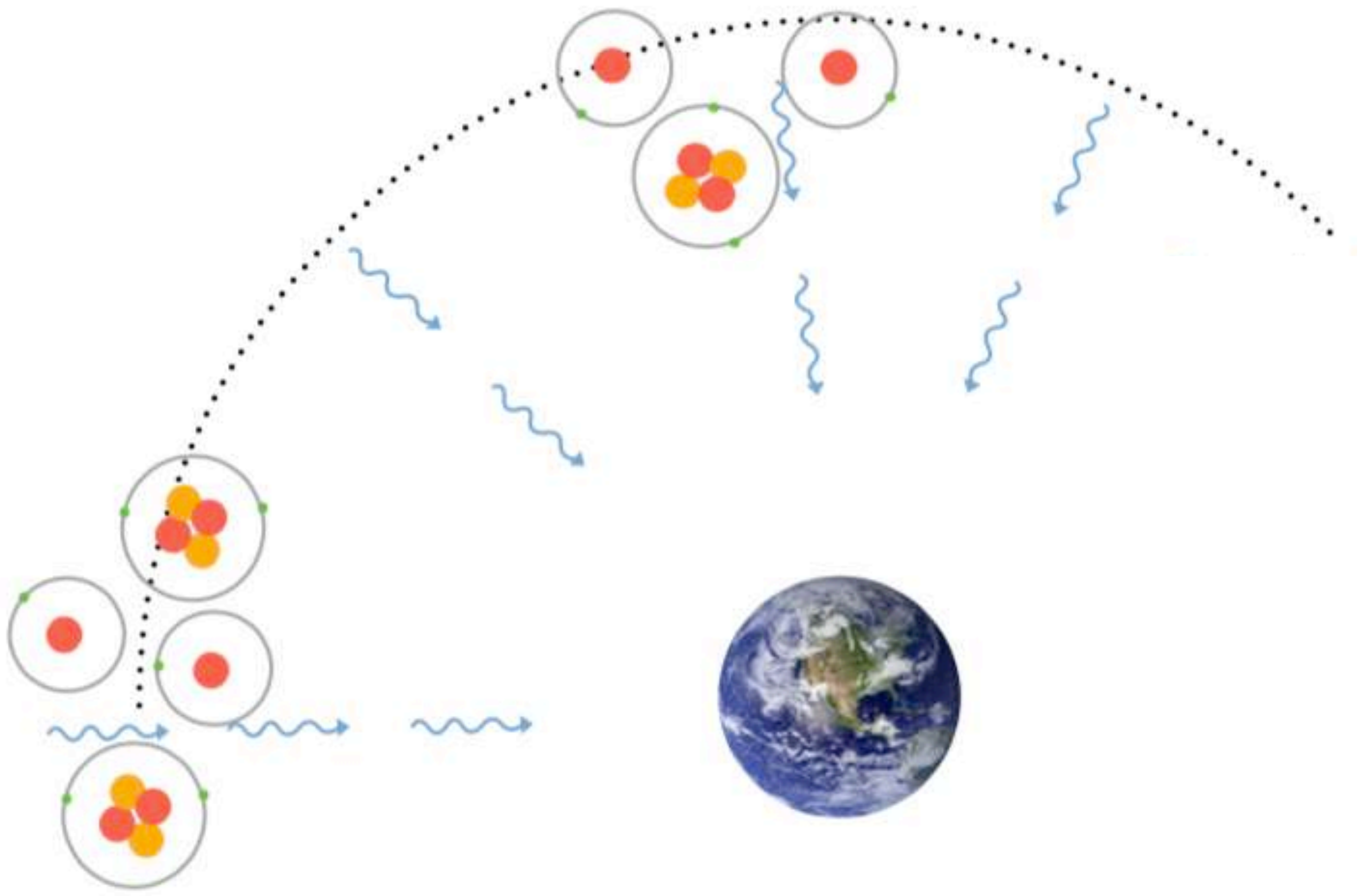
If Gaussian, all the information in the 2pt CF. If not, n-point correlation function:

$$\langle \delta\delta\delta \rangle \quad \langle \delta\delta\delta\delta \rangle \quad \langle \delta \dots \delta \rangle$$

Matter power spectrum



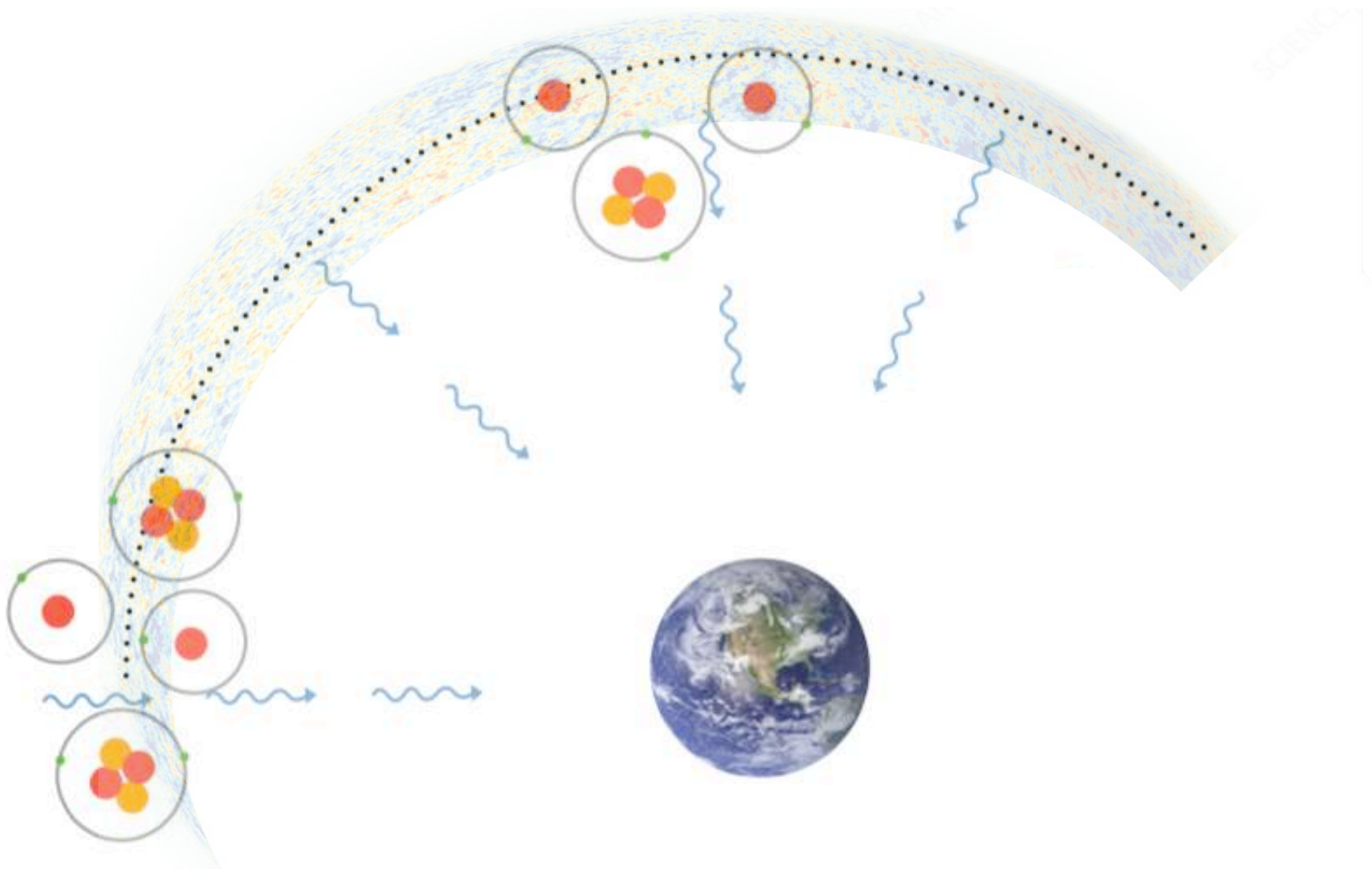
These photons are the first light of our universe…



Crédito: D. Baumann

… e tell us how the universe was at early times.

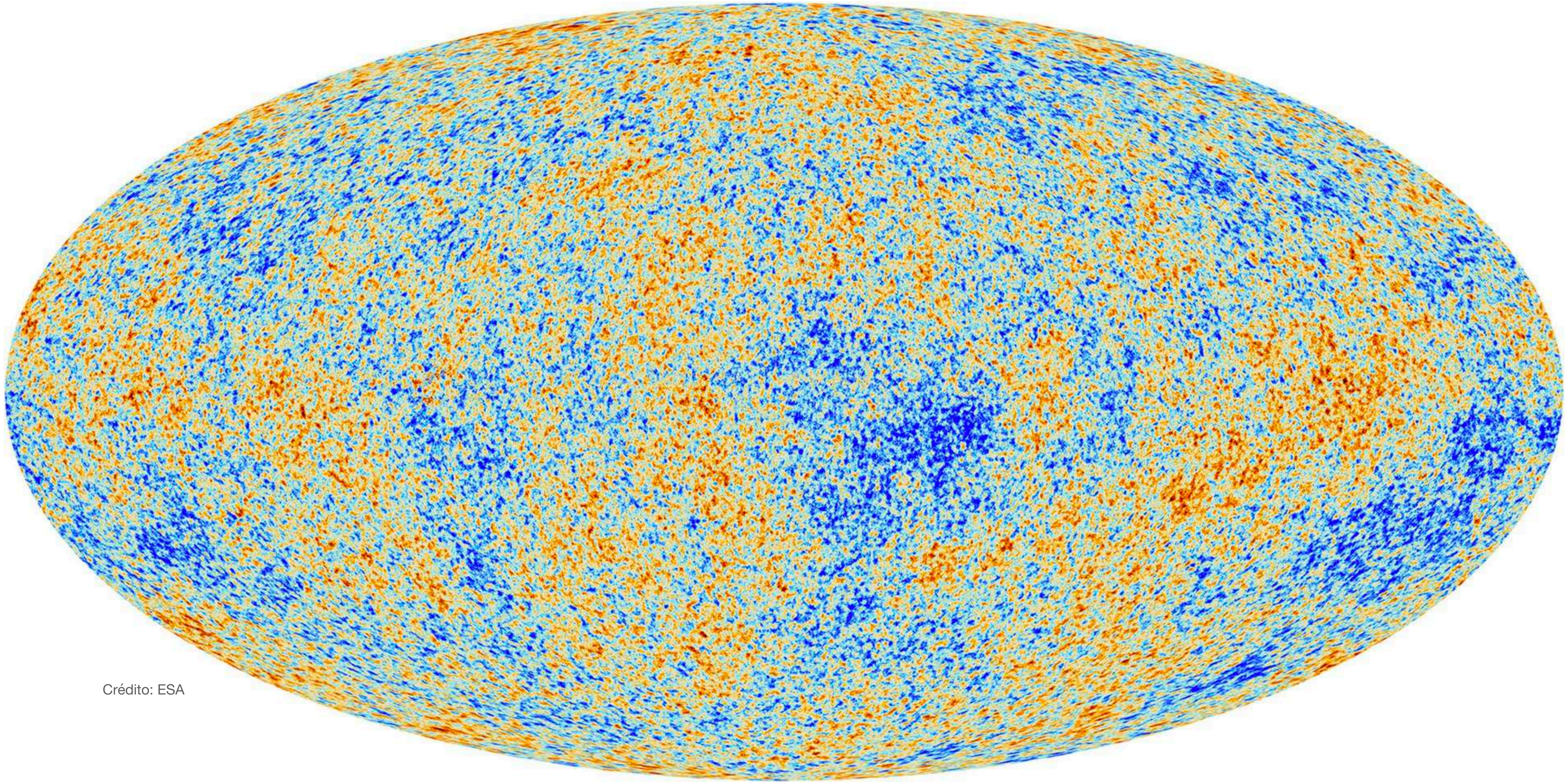
Cosmic **M**icrowave **B**ackground *(CMB)*



Crédito: D. Baumann

Given the expansion of the universe, we observe these photons in microwave.

Cosmic **M**icrowave **B**ackground *(CMB)*

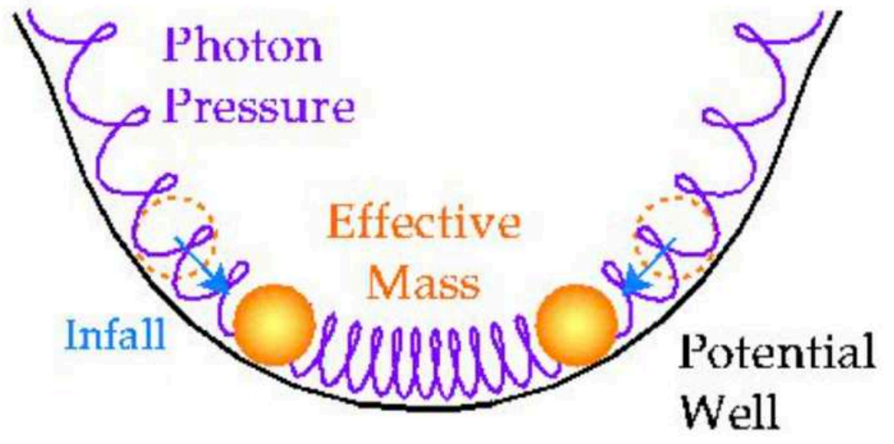


Crédito: ESA

Temperature 2.7 K. Small fluctuations - initial condition for the structures of our universe

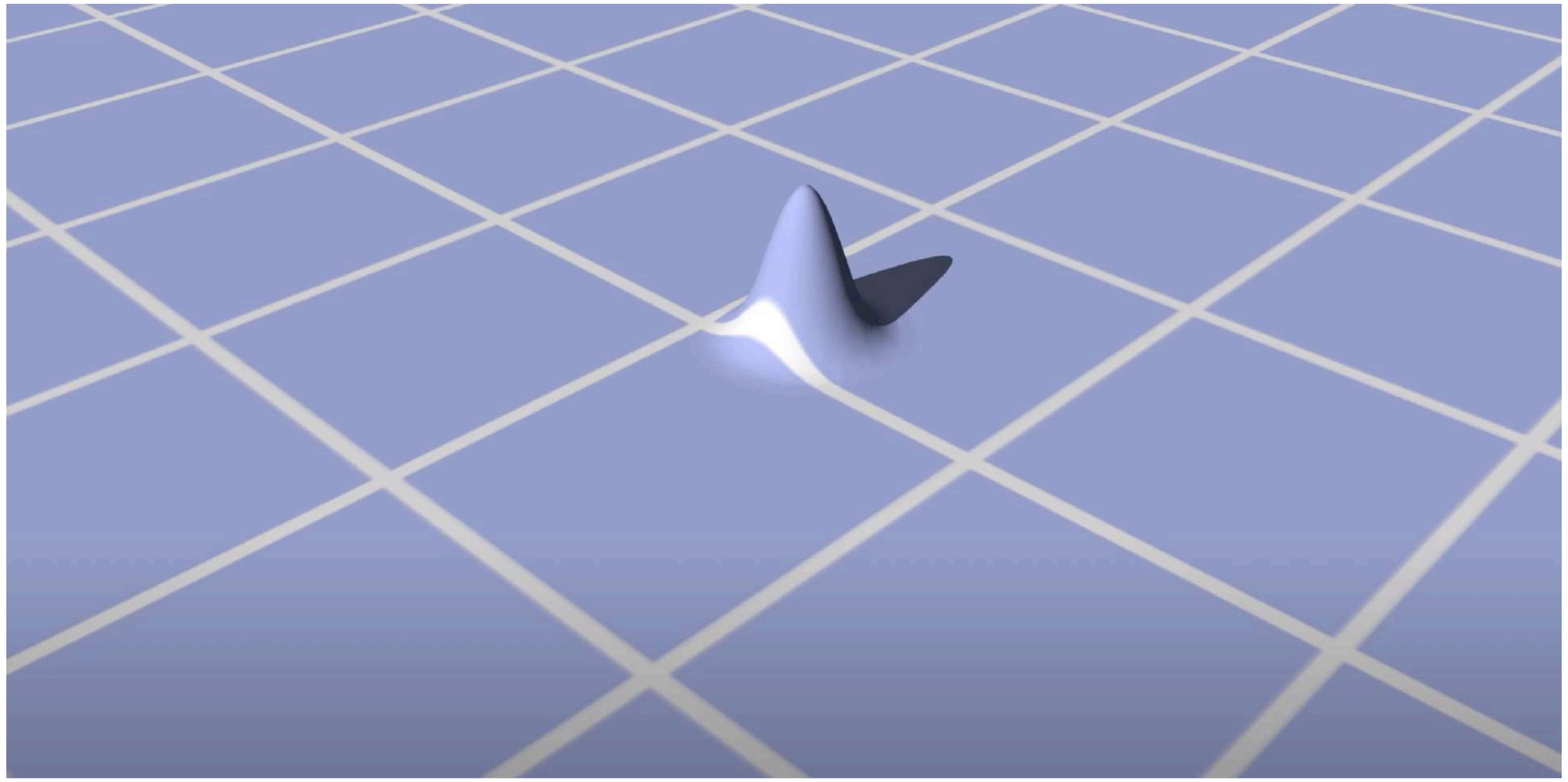
Baryon Acoustic Oscillation (BAO)

- Oscillation in the baryon-photon fluid: pressure vs gravity
- This wave propagates until matter/radiation decoupling
- Its signature is imprinted in the CMB and the distribution of galaxies



(Wayne Hu)

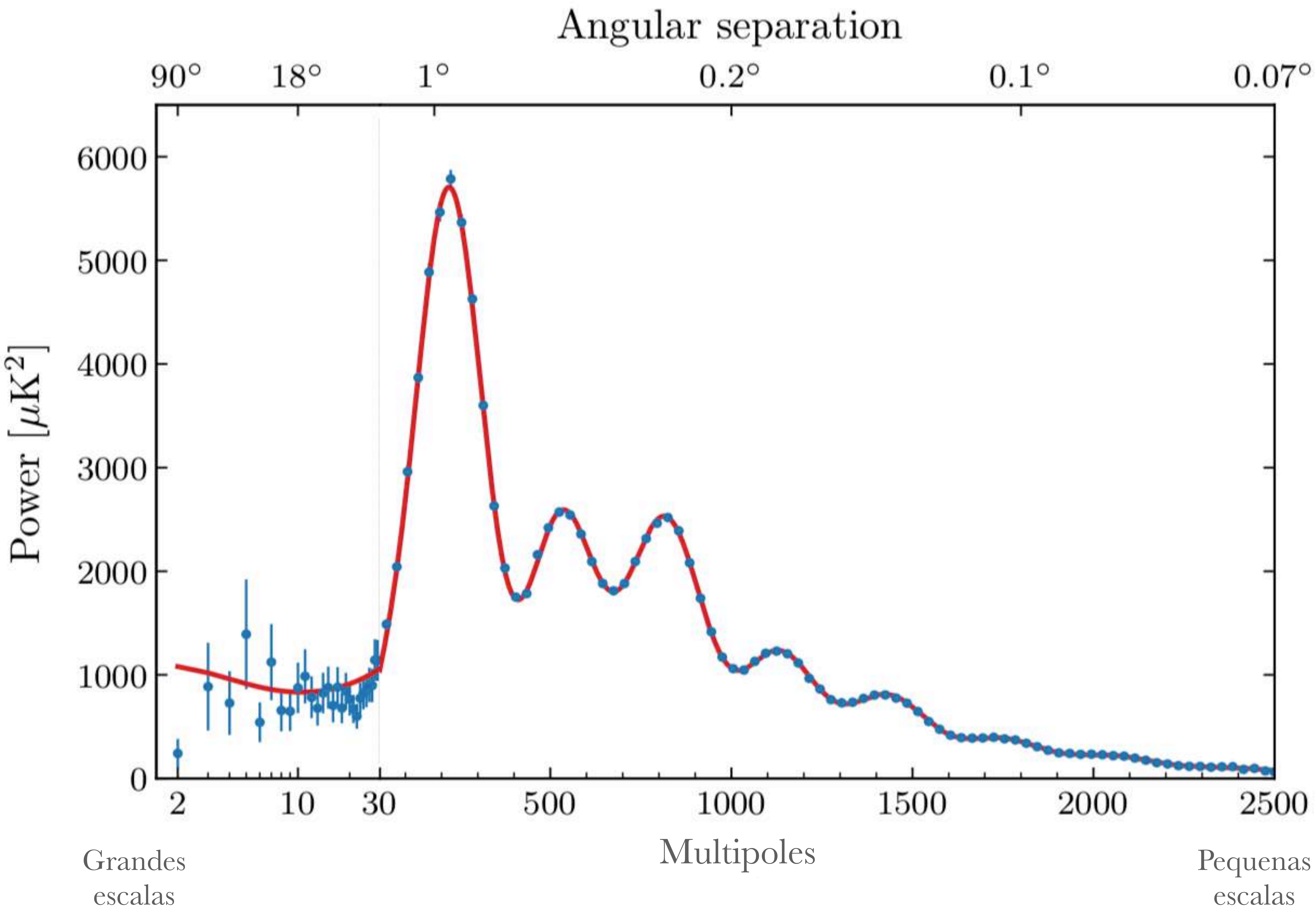
Scale known to 0.2% precision from CMB power spectrum (147.4±0.3 Mpc)



Crédito: CASTRO

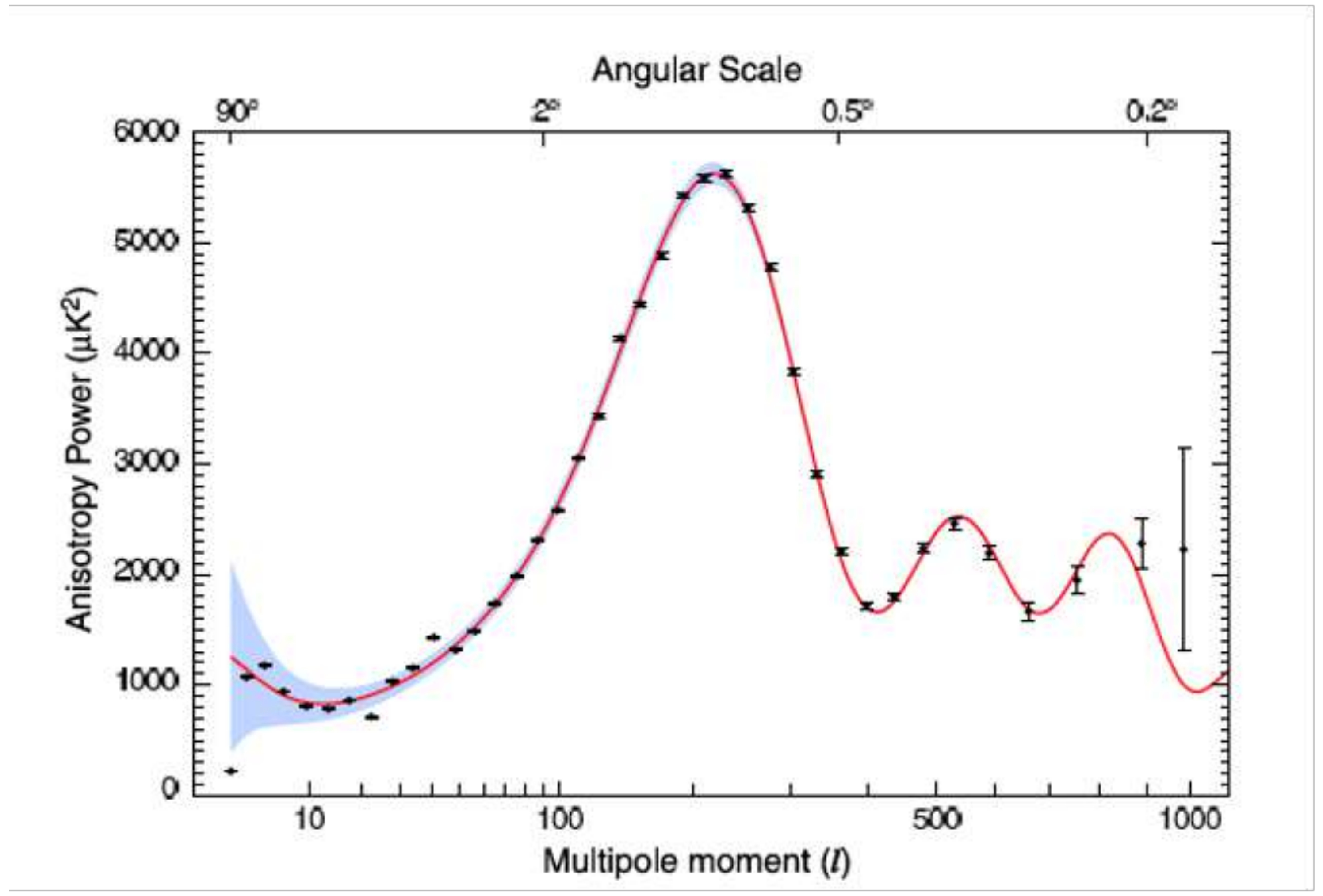
CMB

$$f(\theta,\varphi) = \sum_{\ell=0}^{\infty} \sum_{m=-\ell}^{\ell} C_\ell^m \, Y_\ell^m(\theta,\varphi)$$



Baryon Acoustic Oscillation (BAO)

Cosmic Microwave Background



Using CMB and other LSS probes, can constraint the parameters with incredible precision.

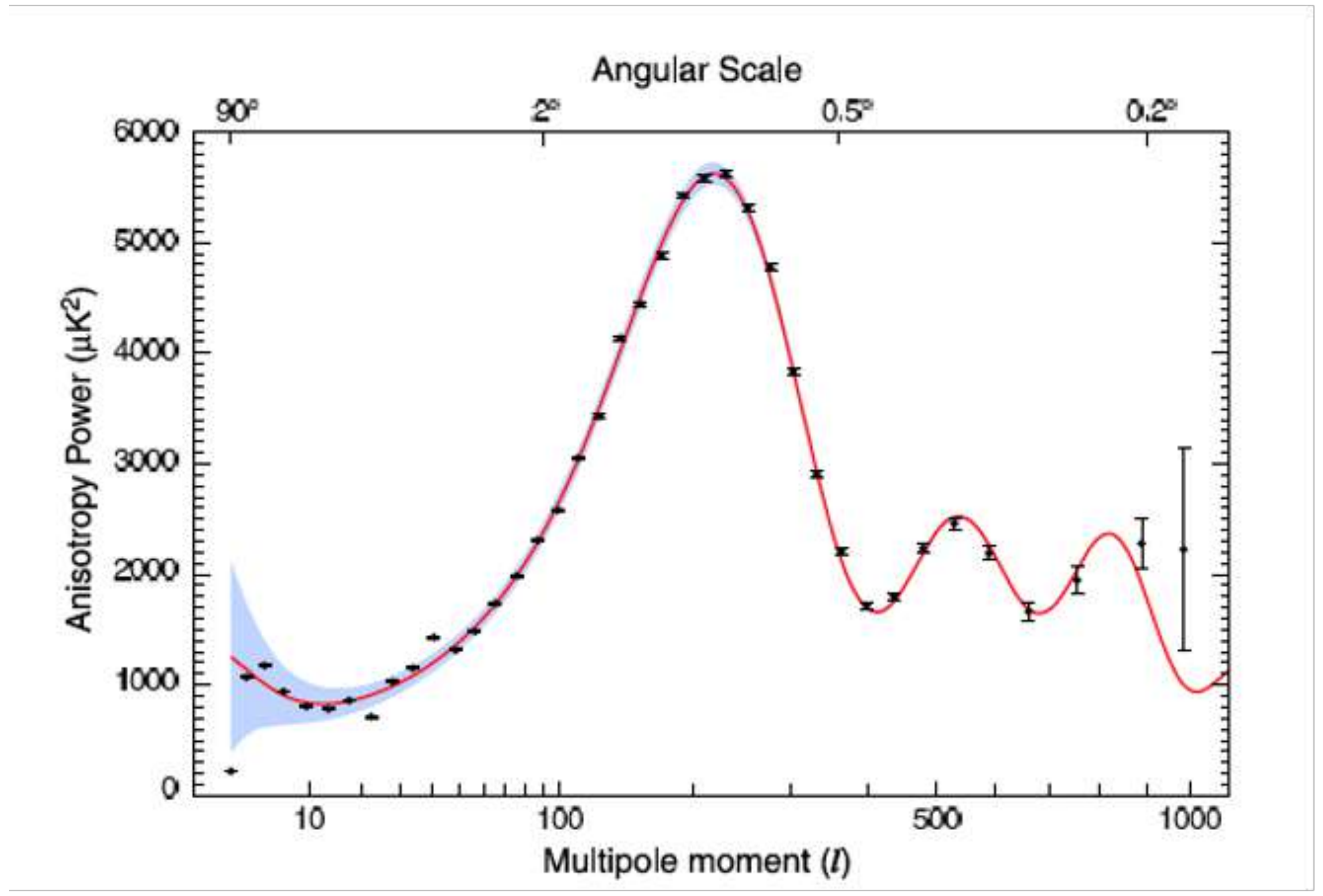
$$\Omega_b = 0.0484 \pm 0.0003$$
$$\Omega_m = 0.308 \pm 0.012$$
$$\Omega_\Lambda = 0.692 \pm 0.012$$
$$\mathrm{n}_s = 0.9626 \pm 0.0057$$
$$10^9\ A_s = 2.092 \pm 0.034$$
$$\tau = 0.0522 \pm 0.0080$$

Scale known to 0.2% precision from CMB power spectrum (147.4±0.3 Mpc)

Standard cosmological model - LCDM model

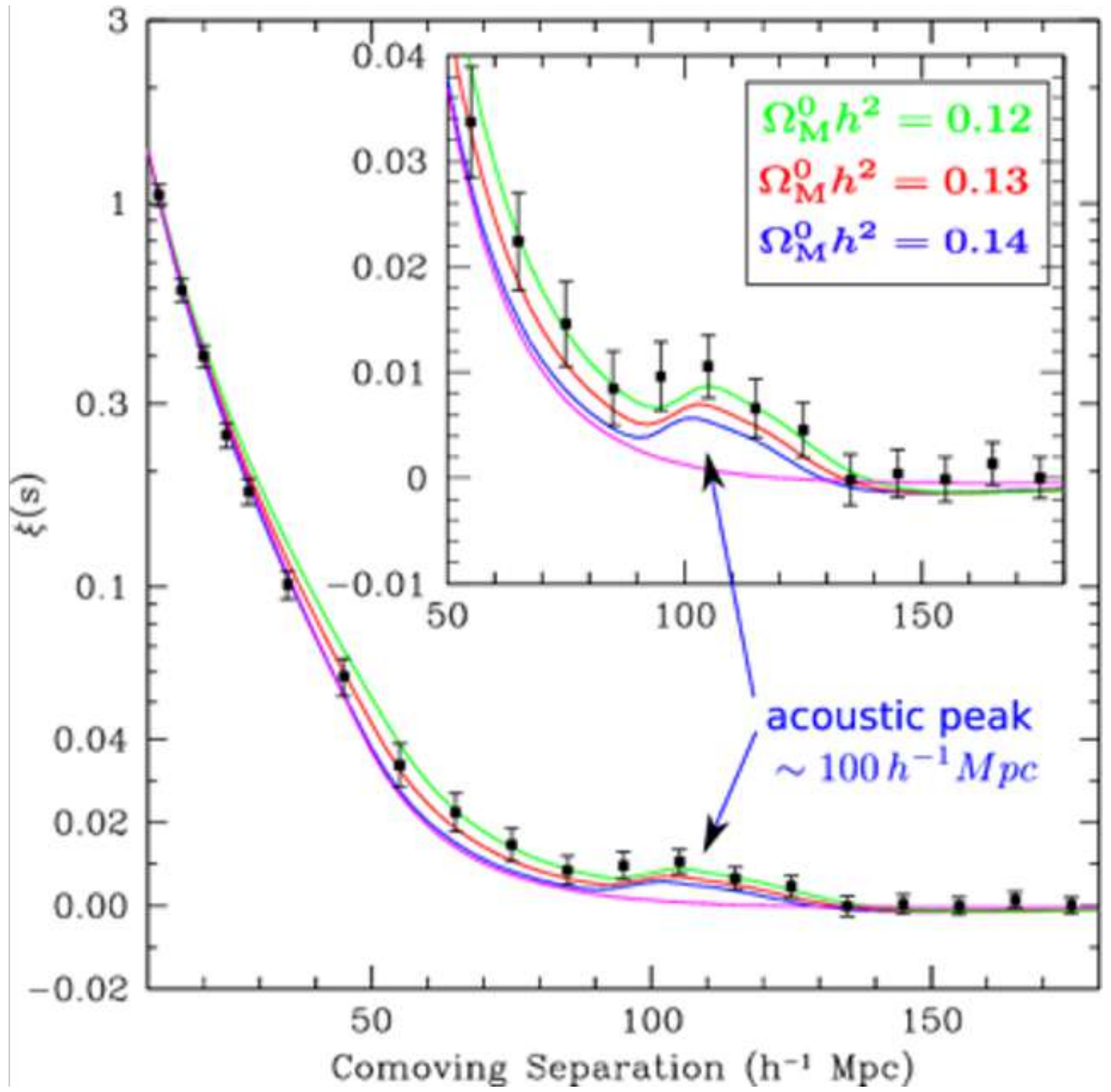
Baryon Acoustic Oscillation (BAO)

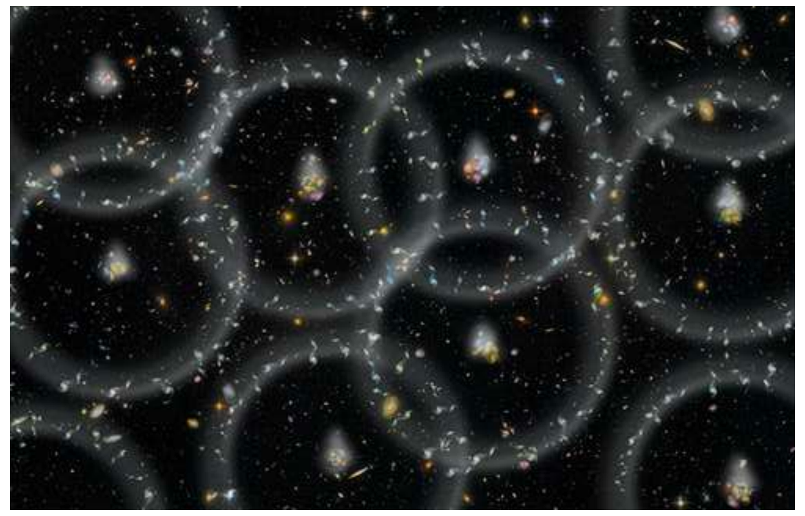
Cosmic Microwave Background



Scale known to 0.2% precision from
CMB power spectrum (147.4±0.3 Mpc)

Large Scale Structure





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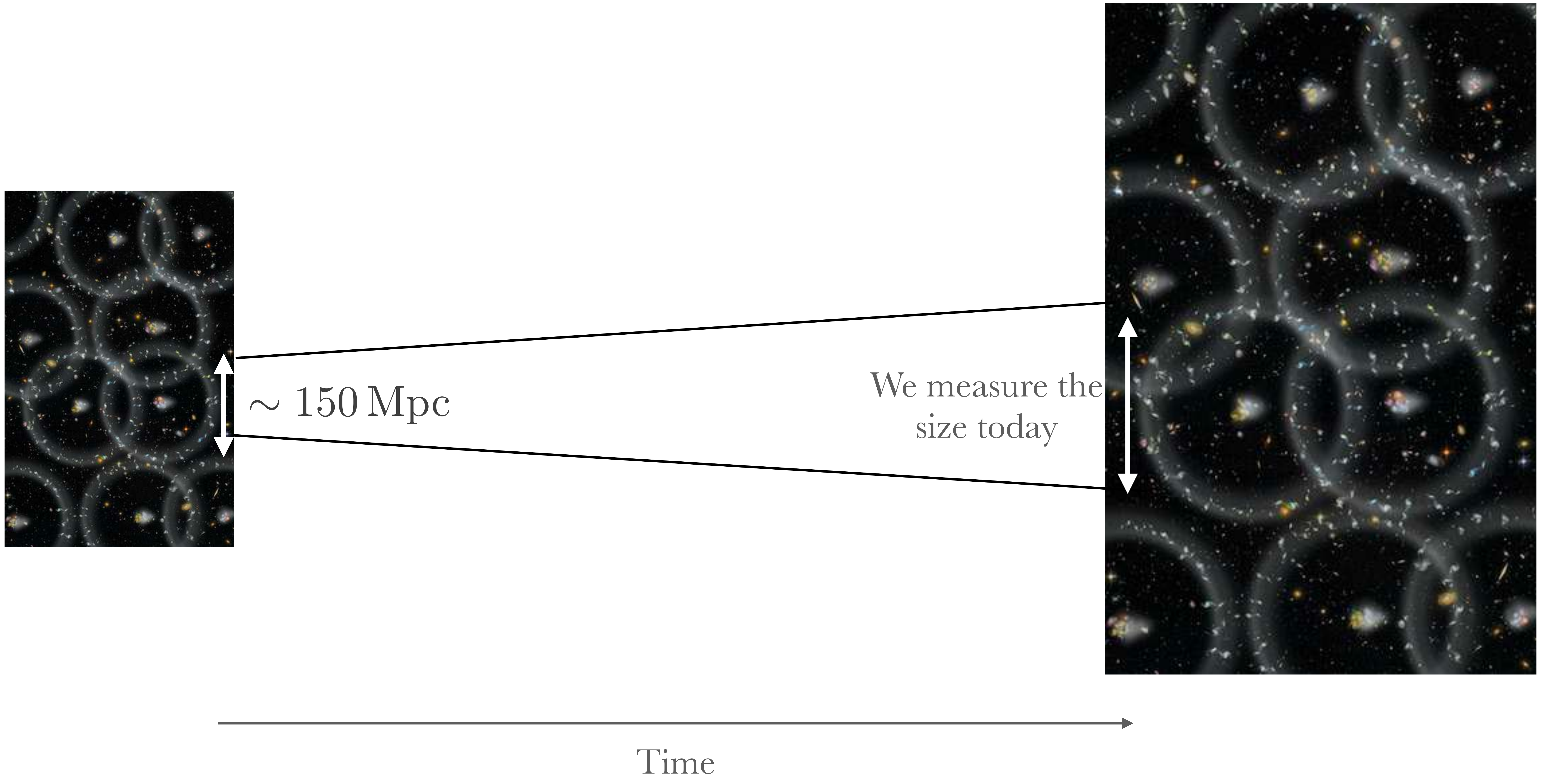
Baryon Acoustic Oscillation (BAO)

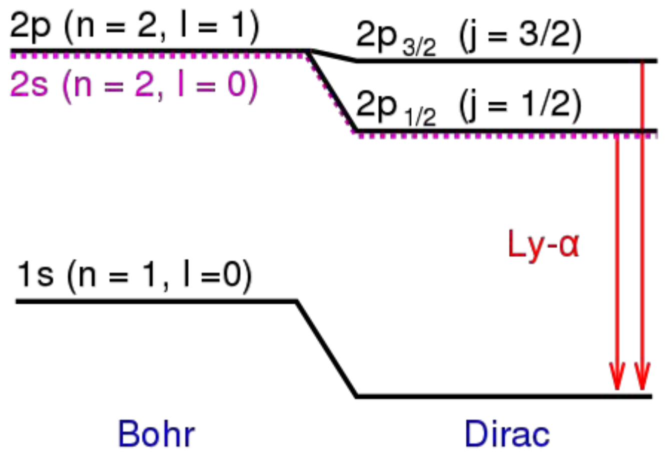


- BAOs are "standard rulers" to measure expansion

Cosmological and astrophysical ***probes*** *of dark matter*

Lyman α

Spectral line of hydrogen



Tobix10

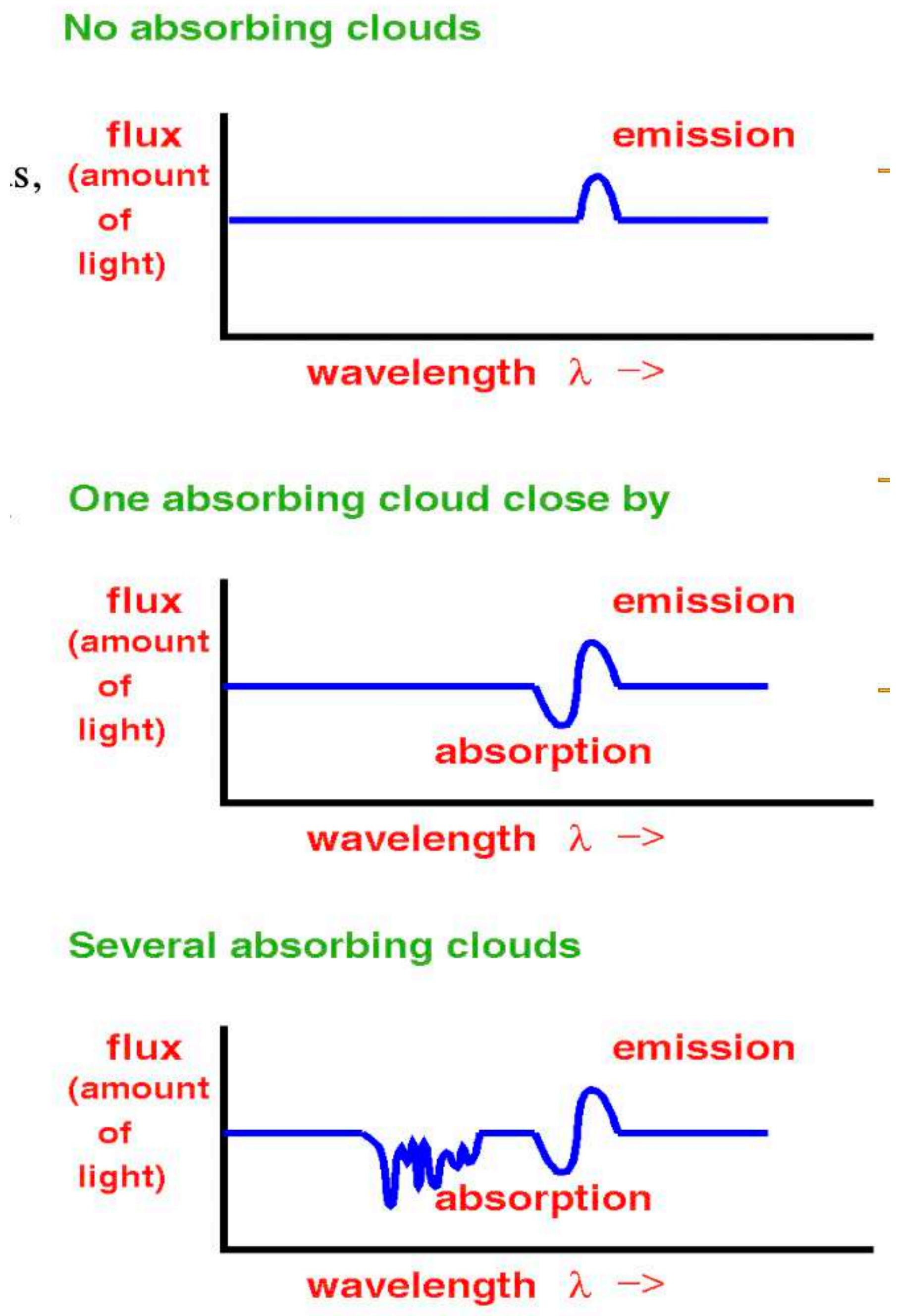
Lyman-alpha forest is a series of absorption lines in the spectra of distant galaxies and quasars arising from the Lyman-alpha electron transition of the neutral hydrogen atom

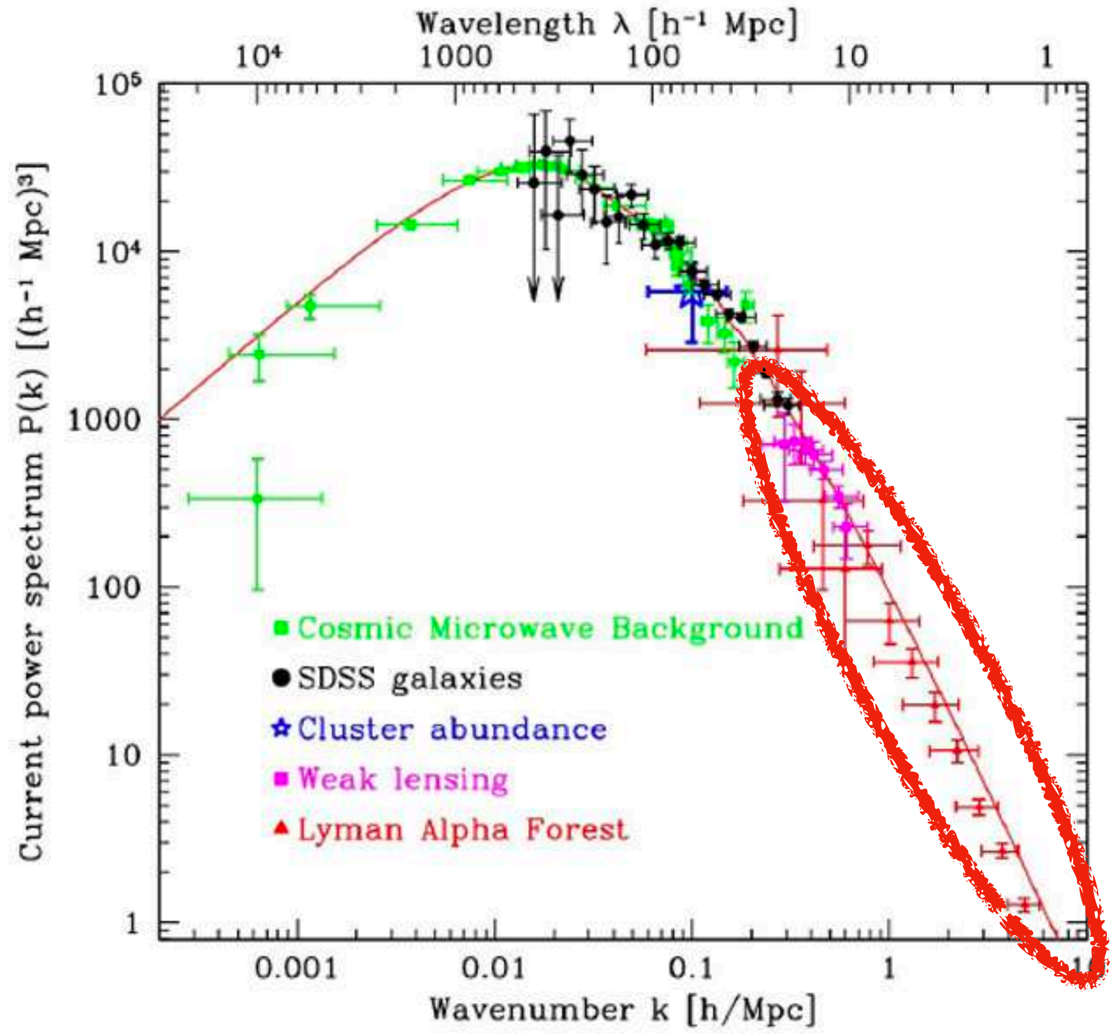
Armengaud

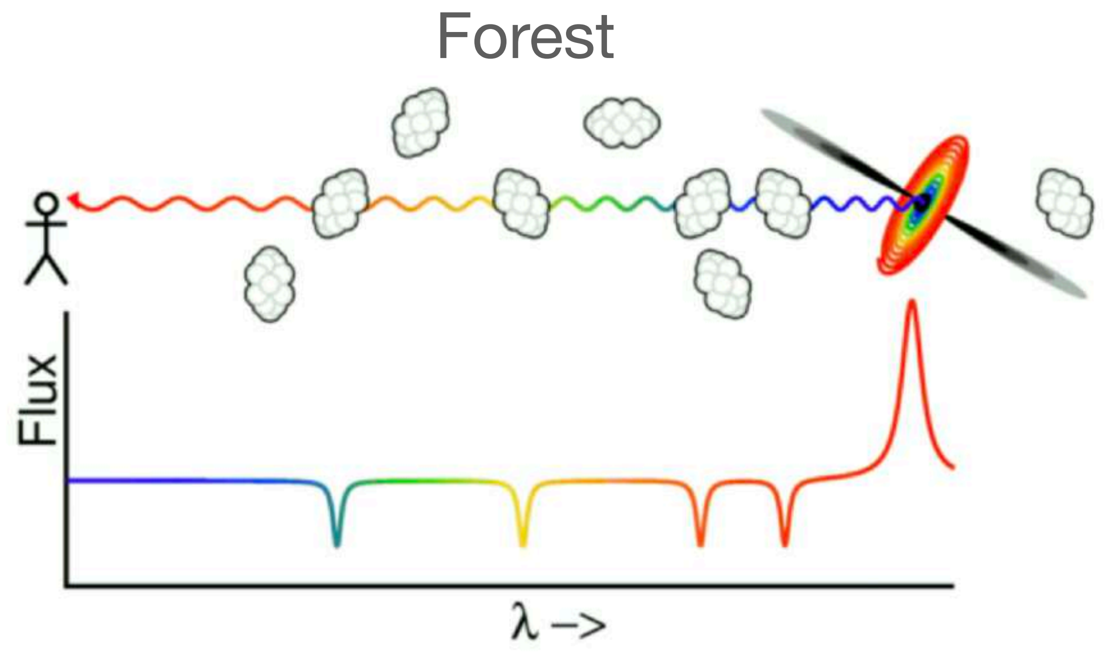
$$\delta(\lambda) = \frac{f(\lambda)}{C_q(\lambda)\bar{f}(z)} - 1$$

$P_{1D}(k) = < (FFT(\delta))^2 >$

related to 3D matter P(k)







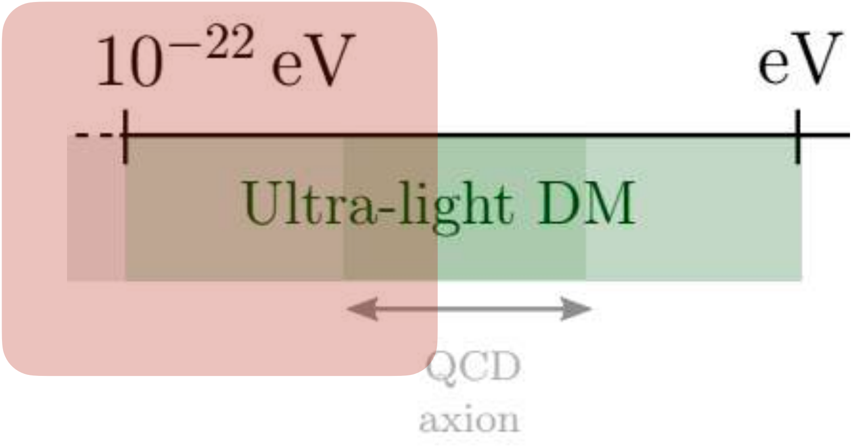
Lyα forest: series of absorption lines

<u>Advantage</u>: provide PS on intermediary scales

It probes the matter power spectrum in the mildly nonlinear regime over a large range of redshifts ($z = 2-6$) down to small scales ($1-80\ h^{-1}$ Mpc)

<u>Challenges</u>:

- Modelling/simulating of DM on NL scales
- Modelling/simulating Lyα
  - Reionization



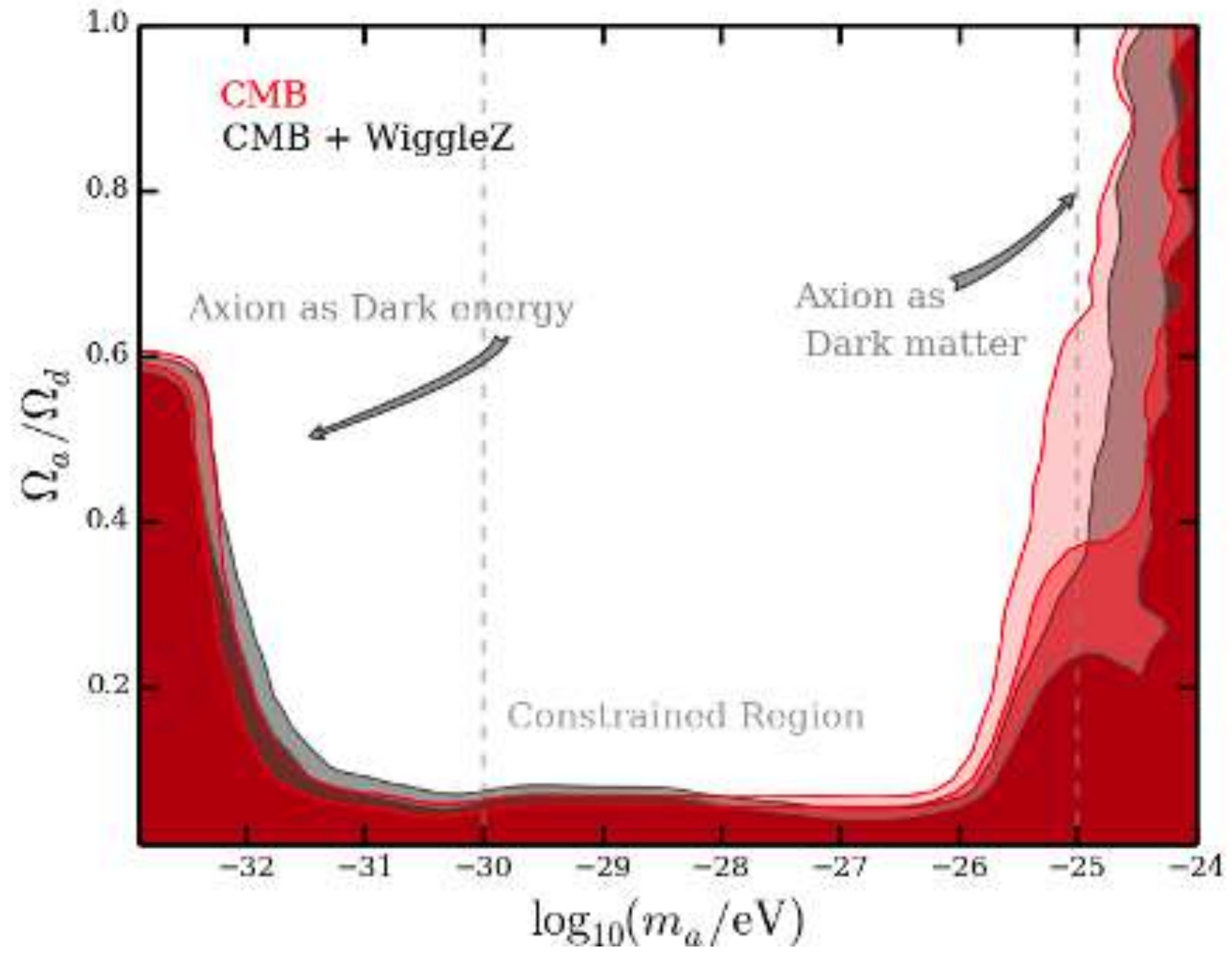
Observational implications and constraints

Fuzzy Dark Matter - bounds on the mass

Suppression of small structures

CMB/LSS

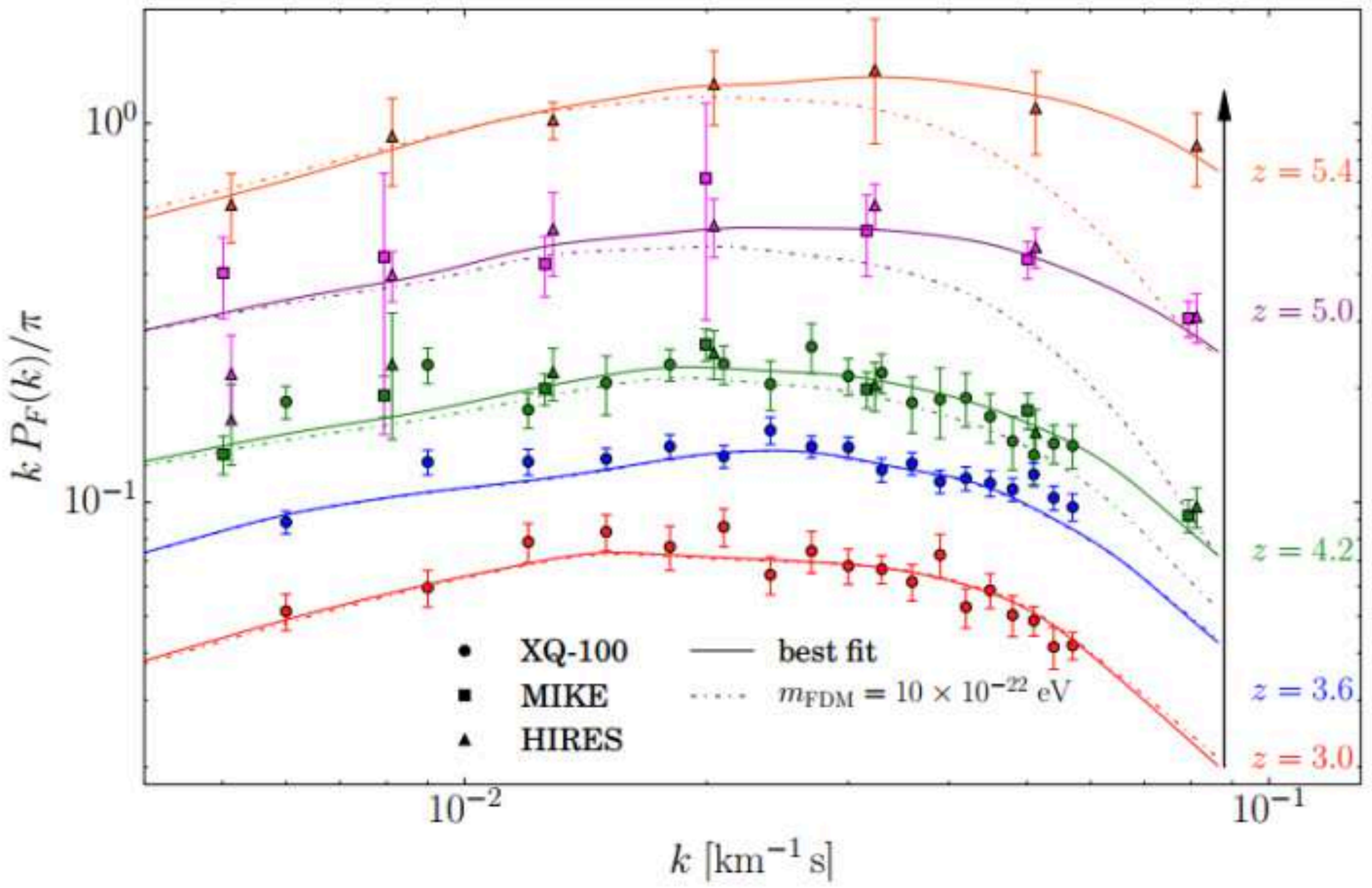
Hlozek et al, (2015, 2018)



$$m \gtrsim 10^{-24}\,\mathrm{eV}$$

Lyman alpha

Armengaud et al. (2017); Iršič et al. (2017); Rogers et al. (2020)

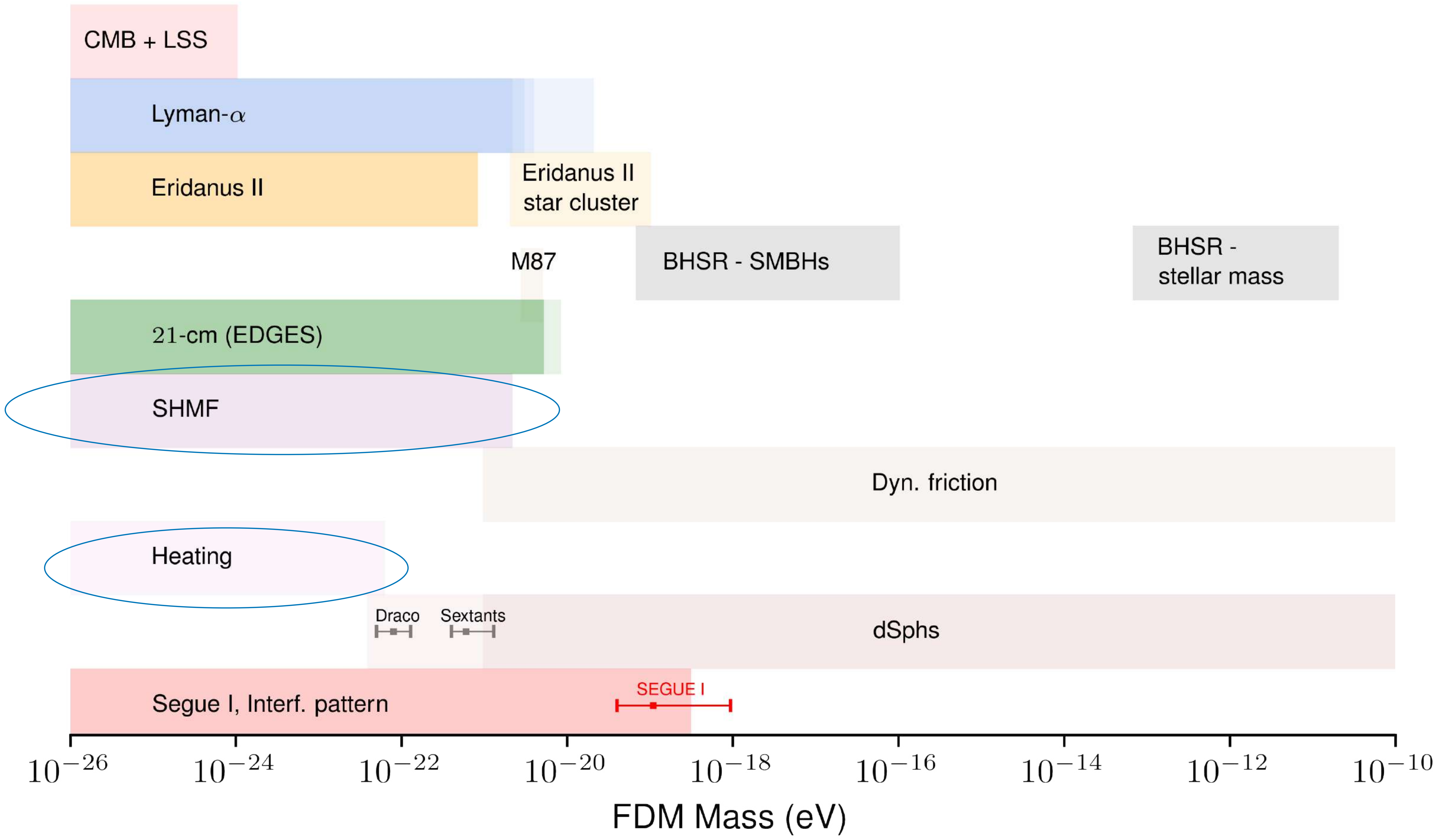


$$m \gtrsim 2 \times 10^{-20}\,\mathrm{eV}$$

so enough Mpc-scale power in Ly-α forest at z = 5.

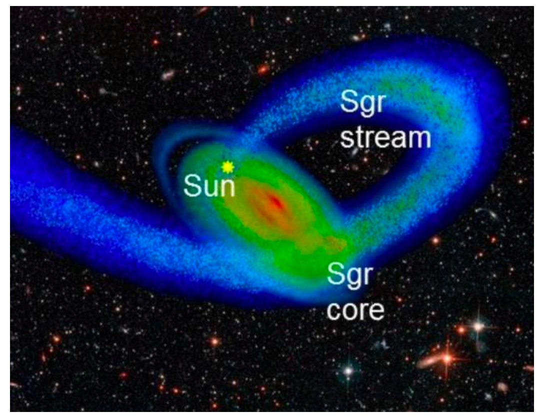
Observational implications and constraints

Fuzzy Dark Matter - bounds on the mass



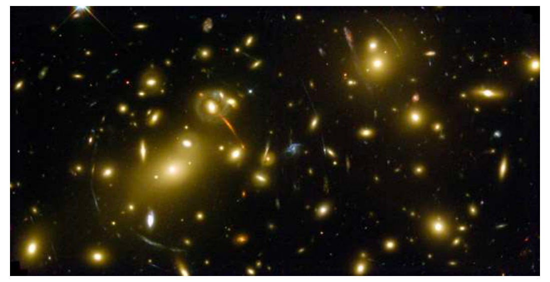
Suppression of small structures

Stellar streams



Schutz 2020: bound in the FDM SHMF using stellar streams and grav. lensing

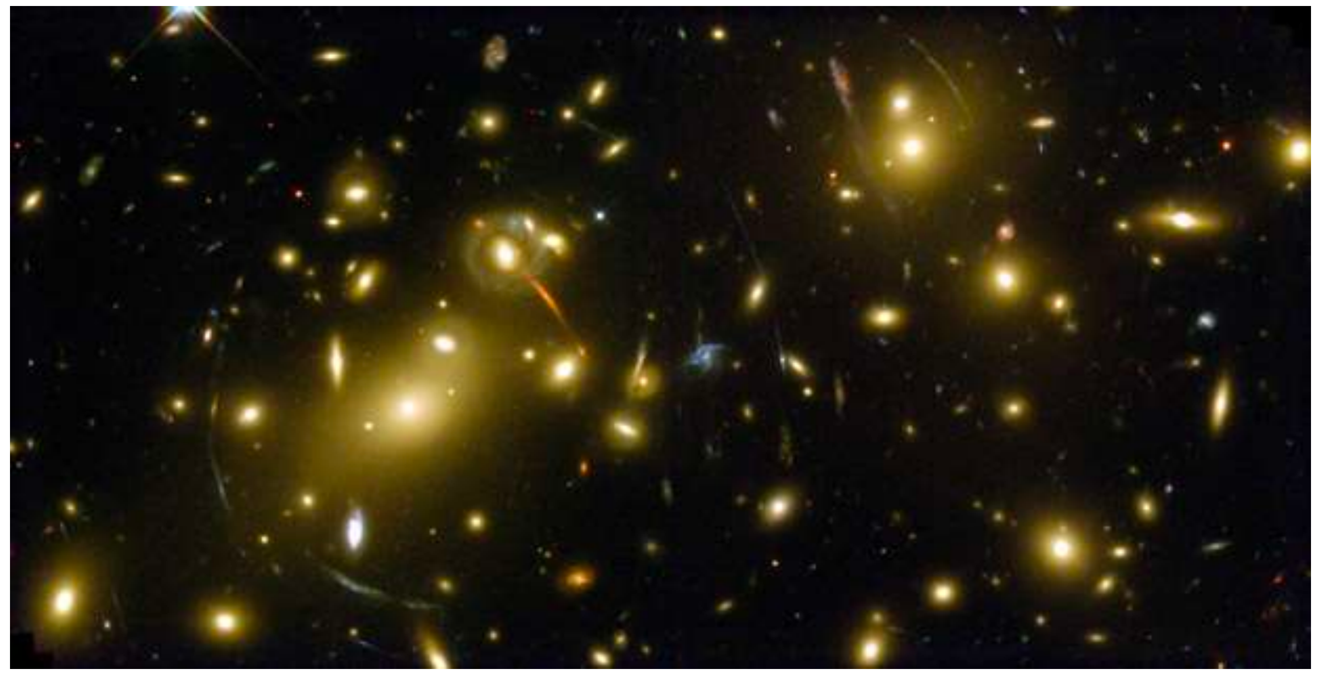
Grav. lensing



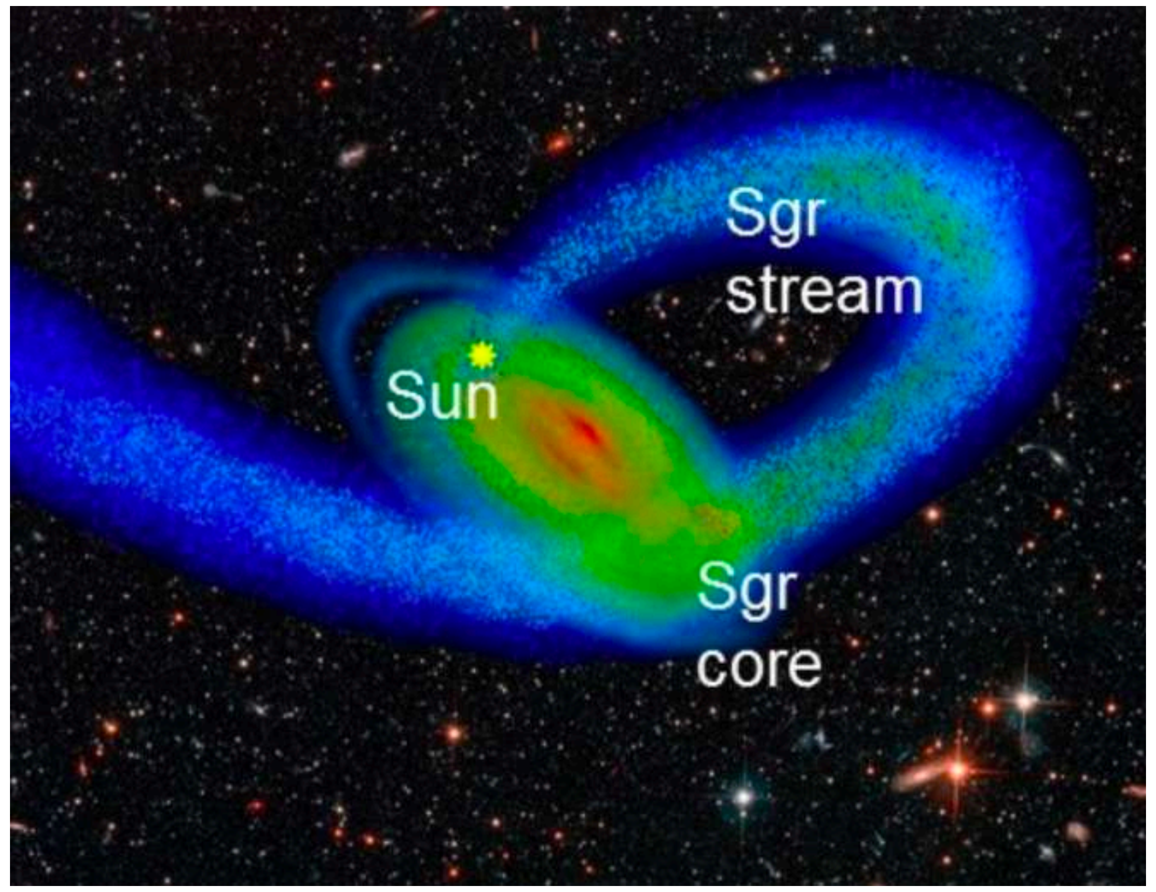
Gravitational probes

Probes that are sensitive to changes in the gravitational potential - total mass

Gravitational lensing

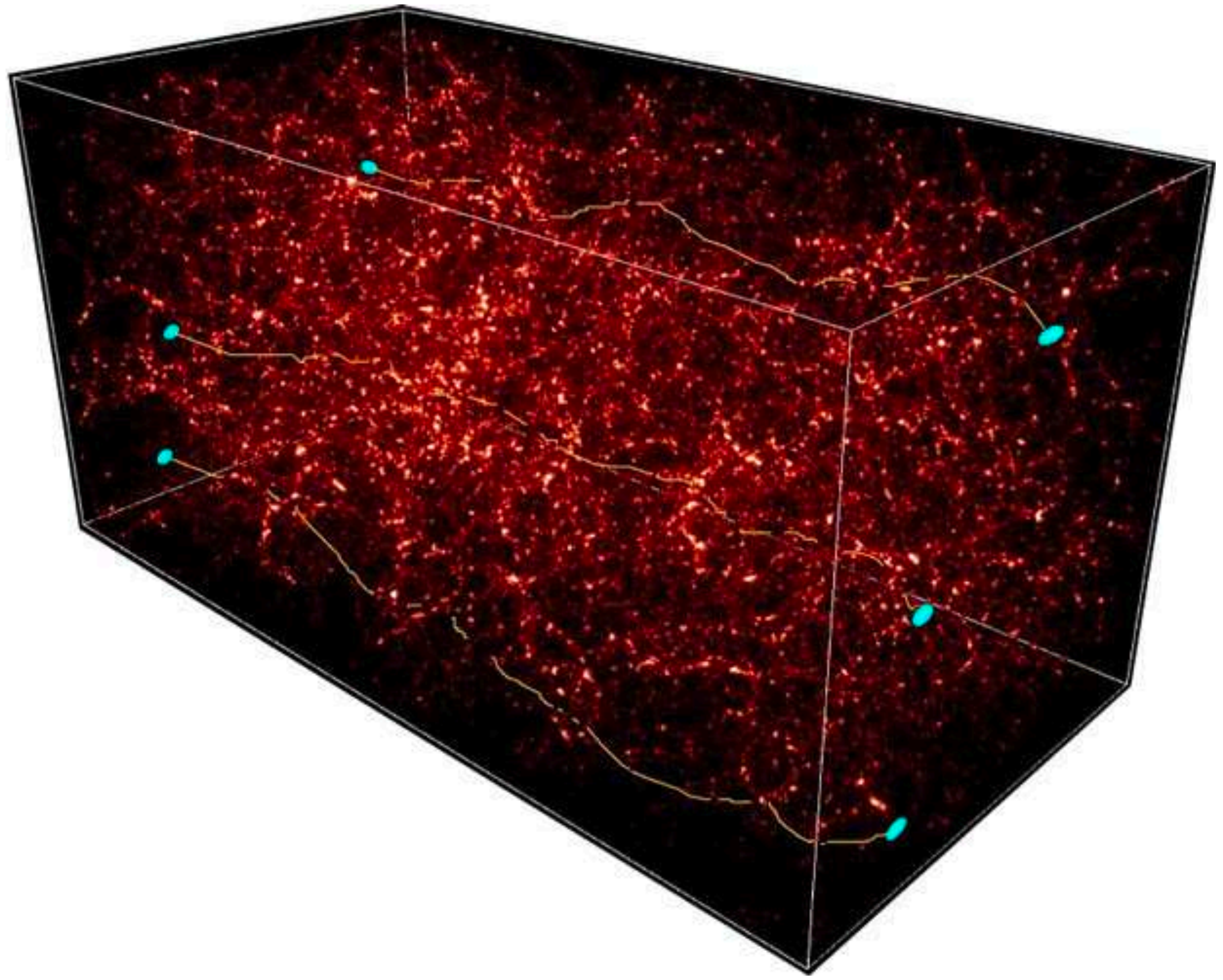


Stellar stream



Gravitational lensing

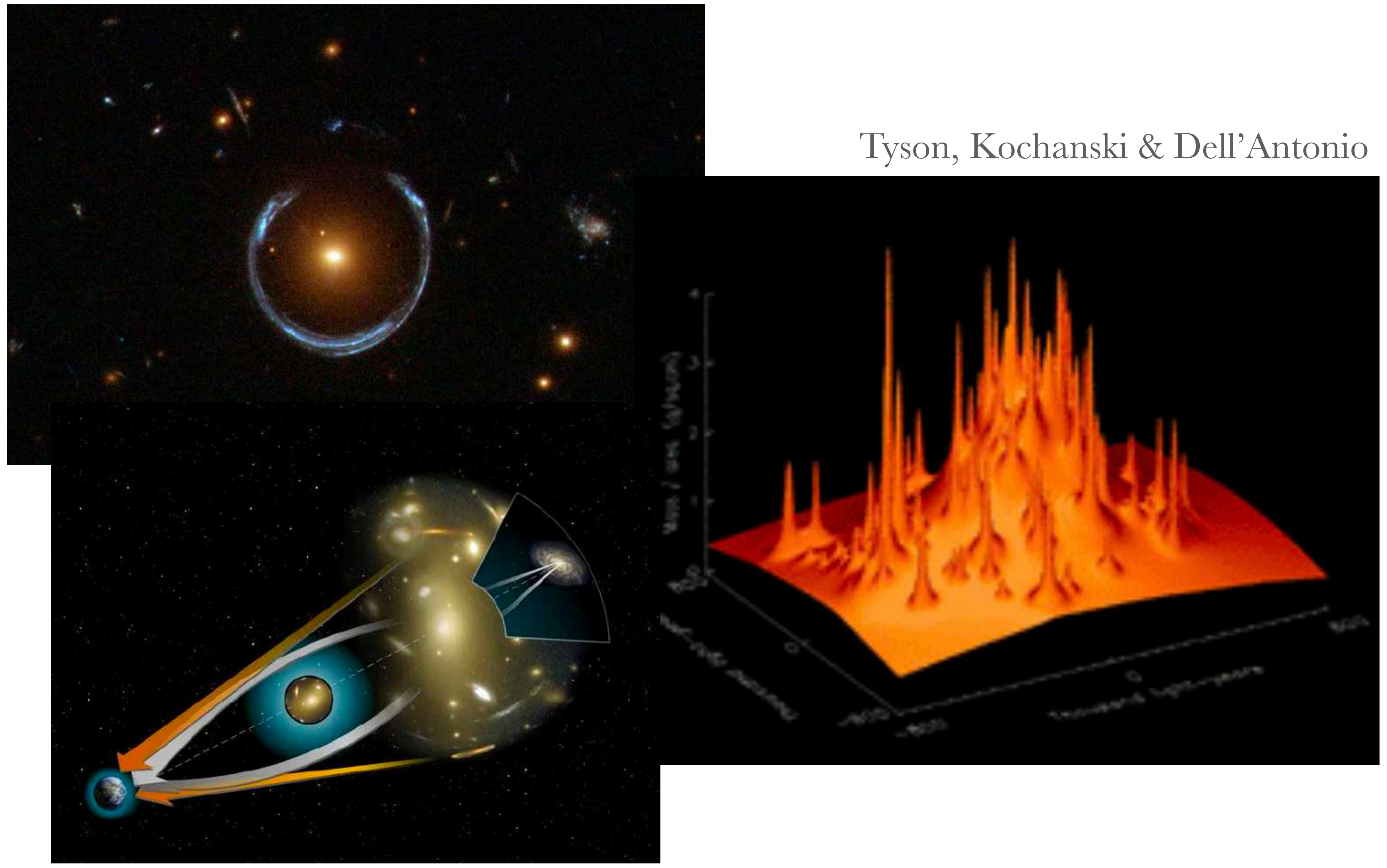
Weak lensing



- Background image is perturbed by matter in its path
- Statistical signal
- Total mass on large scales

Strong lensing

Image: © ESA/Hubble/NASA)



Tyson, Kochanski & Dell'Antonio

NASA / STSCI

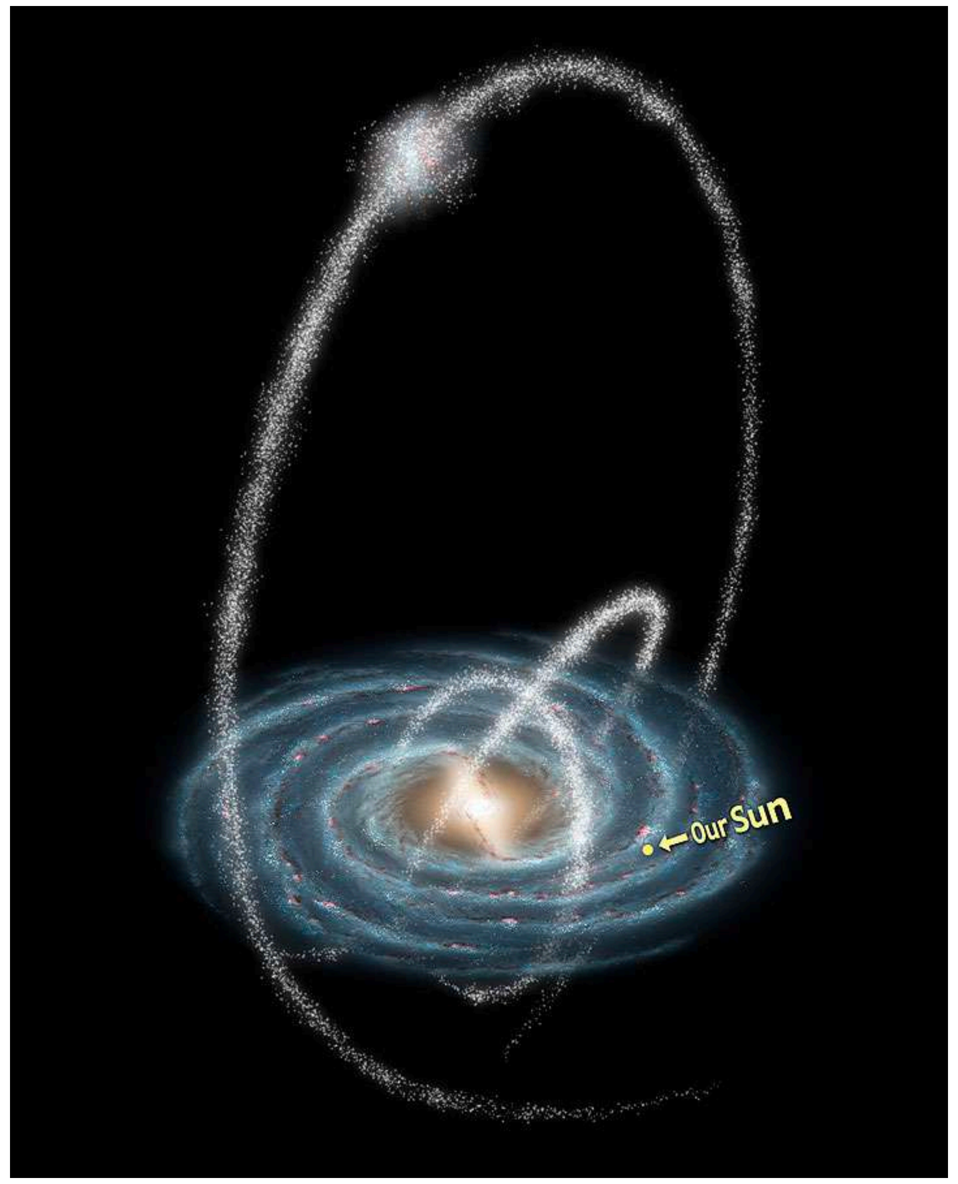
- Reconstruct the gravitational potential (total enclosed mass) of the lens
- Total mass on small scales

Stellar streams

Stellar streams are a stream of stars orbiting a galaxy which are remnants of a tidally disrupted globular clusters or dwarf galaxies, that was torn apart by a more massive system.

These streams are usually thin and very long, extending to dozens of kpc across the 3-dimensions of the halo, and wrap around the disrupting galaxy.

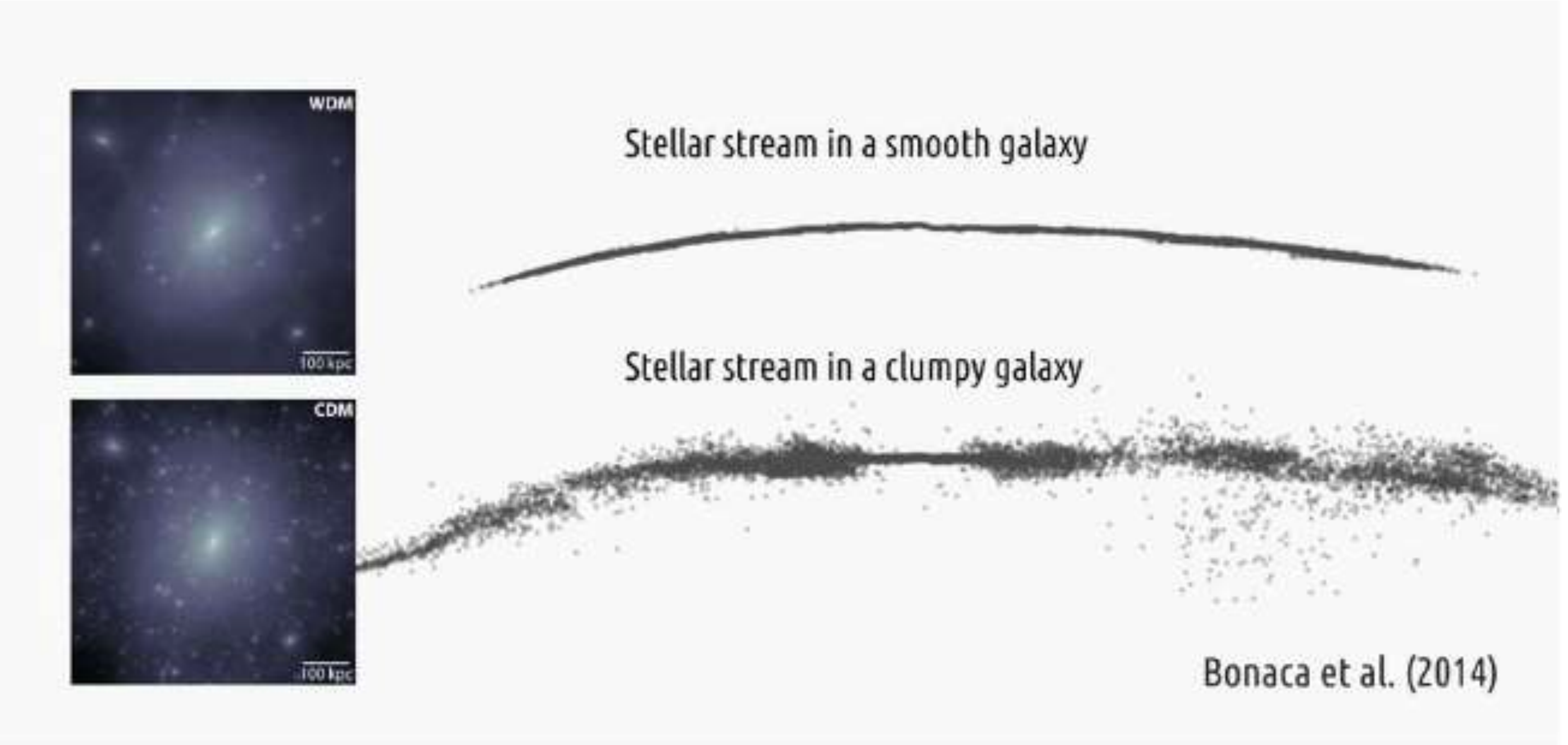
Streams are good dynamical probes since they are initially cold and very sensitive to the gravitational potential



NASA

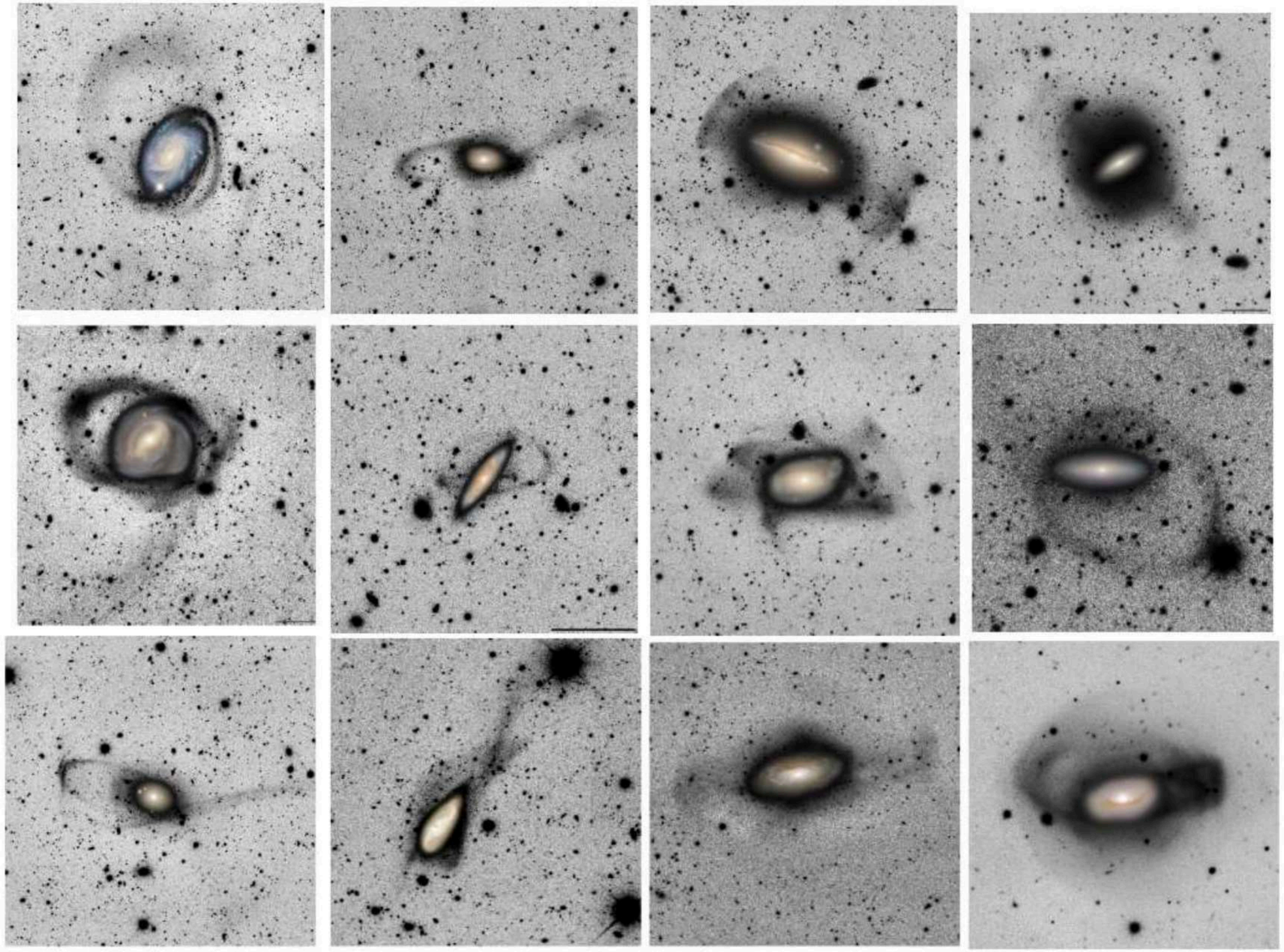
⟶ Substructures present in the halo when encounter the streams disturb it causing:

- Dynamical heating: which are changes in the velocities in the stream,
- Disturbances in the morphology of the stream: formation of gaps which are underdensities caused by the sub-halos encountered



It is estimated that we can observe gaps in streams cause by substructures with mas as low as $M \sim 10^5 - 10^6\, M_\odot$ (Erkal and Belokurov 2015; Erkal et al. 2016; Bovy et al. 2017)

Stellar streams



Martinez-Delgado et al. 2021;arXiv:2104.06071

Practice session:

Suppression of small scale structures

S8 tension

Ref.: K. Rogers et al 2023

Changes in the small scale paradigm can change the behaviour of DM in many scales, including cosmology

Ex.: Fuzzy DM

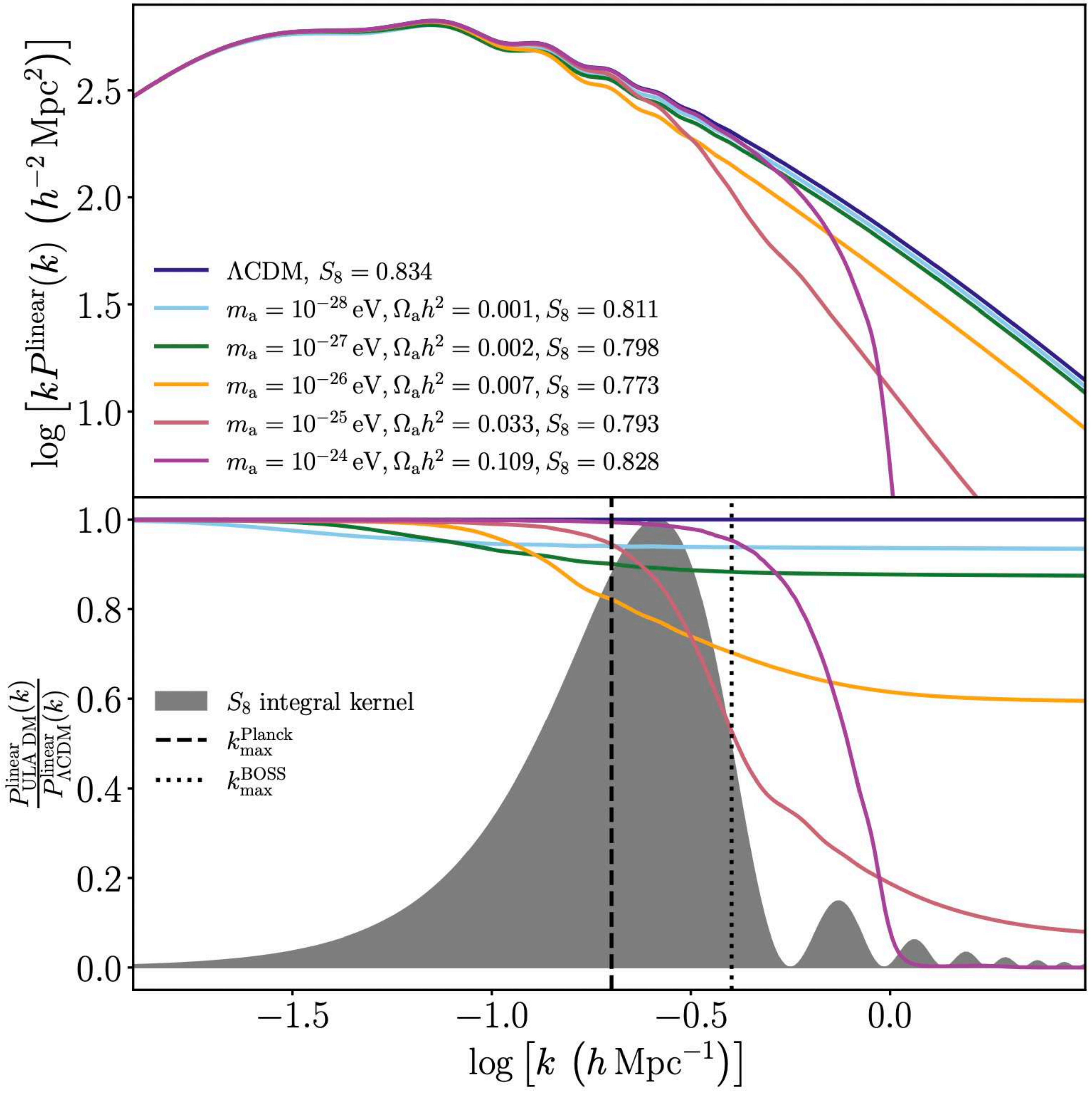
$$\sigma_8 = \int \mathrm{dln}k \, \frac{k^3}{2\pi} W^2(k) P^{\mathrm{linear}}(k)$$

$$S_8 = \sqrt{\frac{\Omega_\mathrm{m}}{0.3}} \sigma_8$$

The presence of ULAs can significantly lowers S8 for:

$$m_\mathrm{a} \in [10^{-27}, 10^{-25}]\,\mathrm{eV}$$

S8 is lowered because the Jeans scale today for $m_a = 10^{-25} - 10^{-26}\,\mathrm{eV}$ is about $\lambda_J = 4 - 12\,h^{-1}\,\mathrm{Mpc}$



S8 tension

Ref.: K. Rogers et al 2023

Ex.: Fuzzy DM

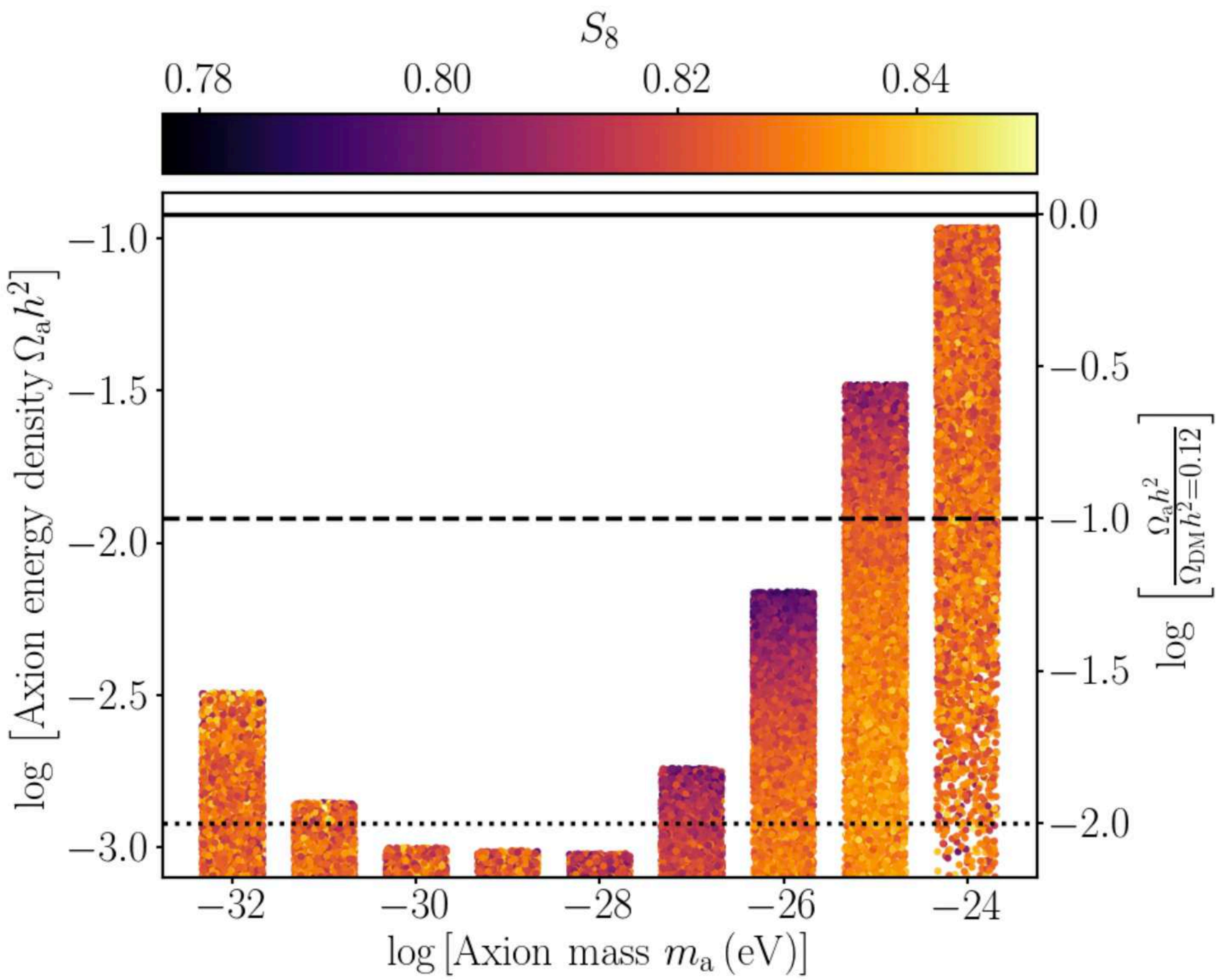
Planck + BOSS

The presence of ULAs with mass

$$10^{-28}\,\text{eV} \leq m_a \leq 10^{-25}\,\text{eV}$$

can improve consistency between CMB and galaxy clustering
(reduce the S8 discrepancy)

from 2.6σ to 1.7σ

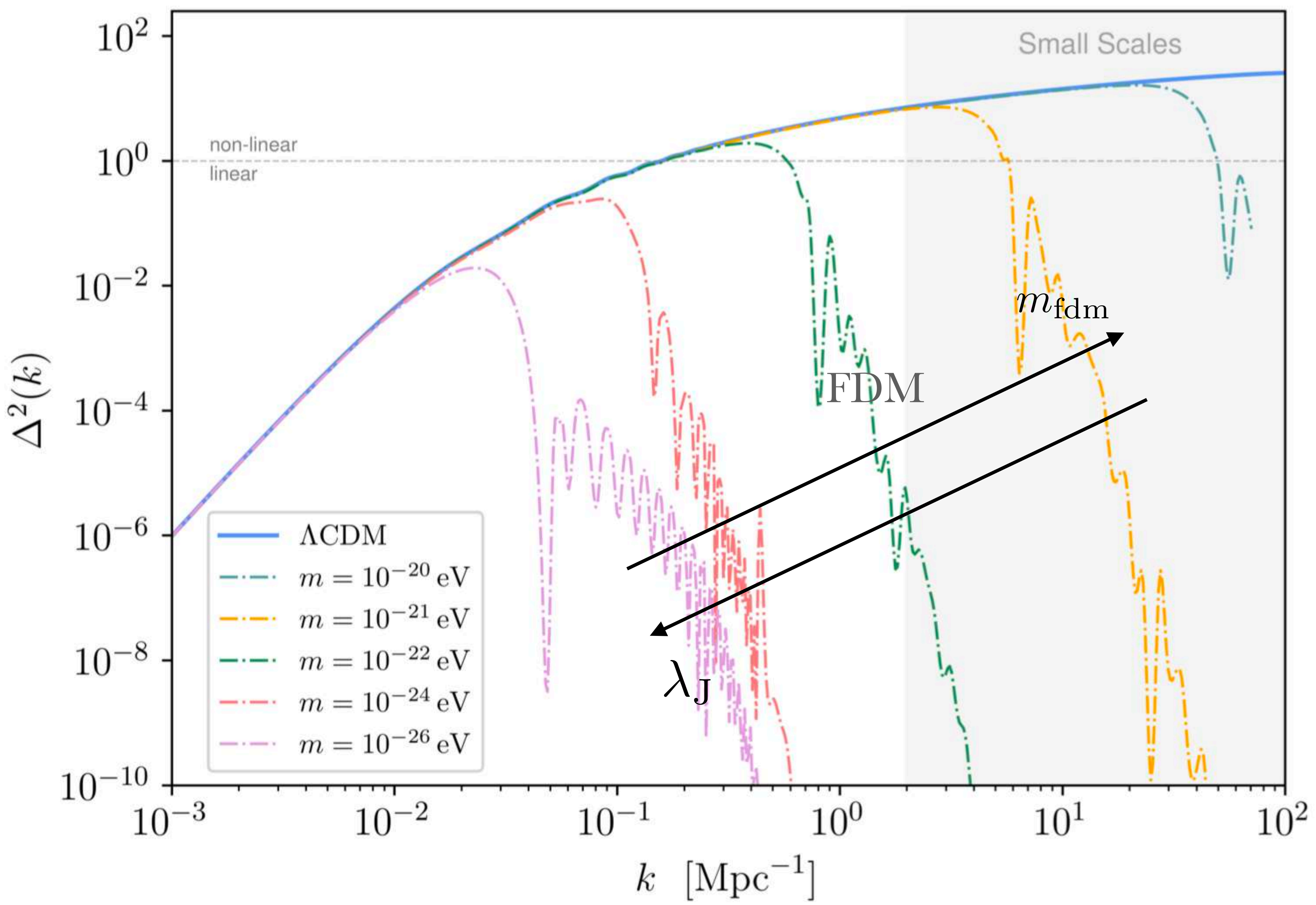


Ex.:
- H0 tension: Early dark energy - axion-like particle
- Model address H0 and S8 tensions: *"Chameleon EDE"*, Karwal et al 2021

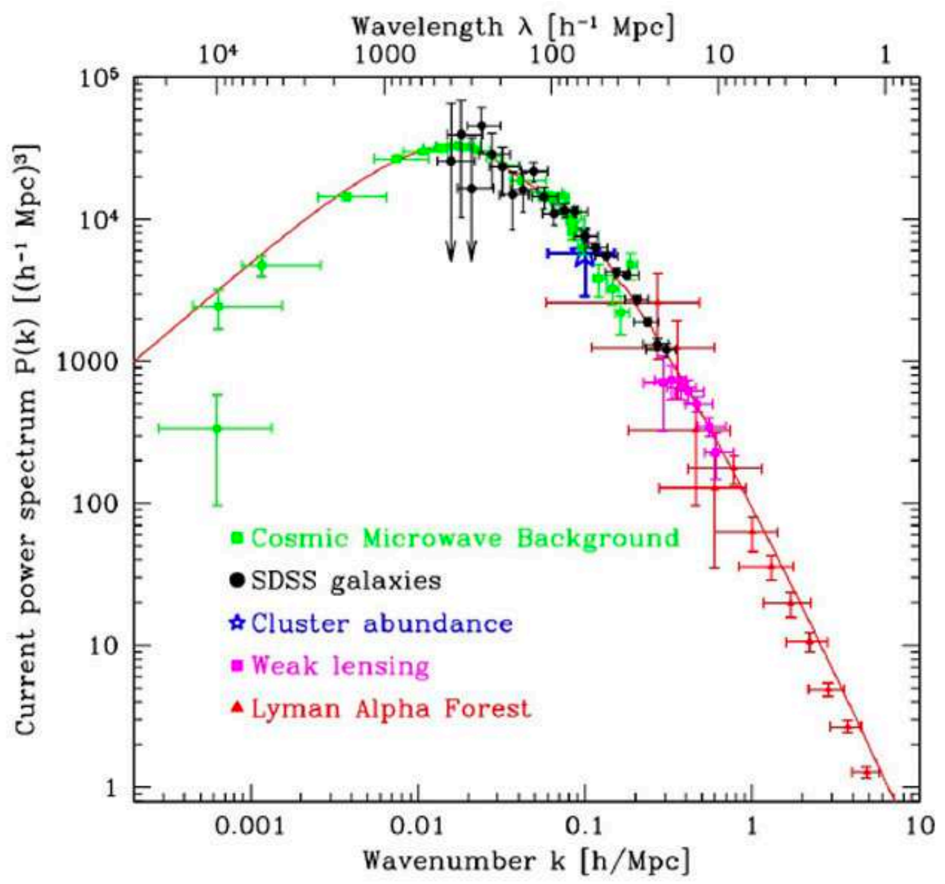
Suppression of small scale structure

Can we probe the small scales?

POWER SPECTRUM



CDM

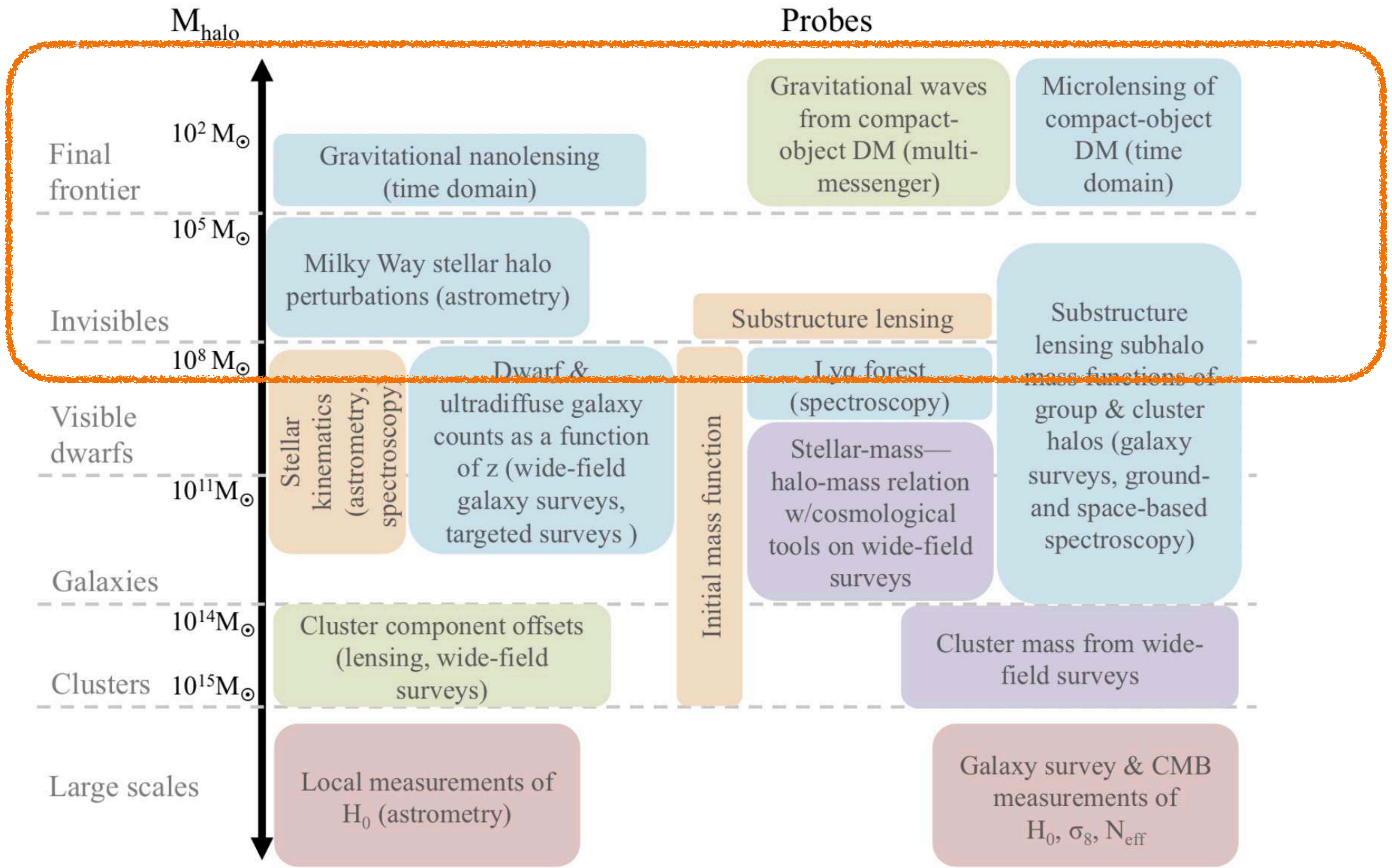


Measure PS well until scales
$k \sim 10 - 20\,\mathrm{Mpc}^{-1}$

Can we measure the power spectrum on scales
$k < 10\,\mathrm{Mpc}^{-1}$?

Power spectrum: highly constrained for $k > 10\,\mathrm{Mpc}^{-1}$
highly unconstrained for $k < 10\,\mathrm{Mpc}^{-1}$

Cosmological and astrophysical ***probes*** *of dark matter*



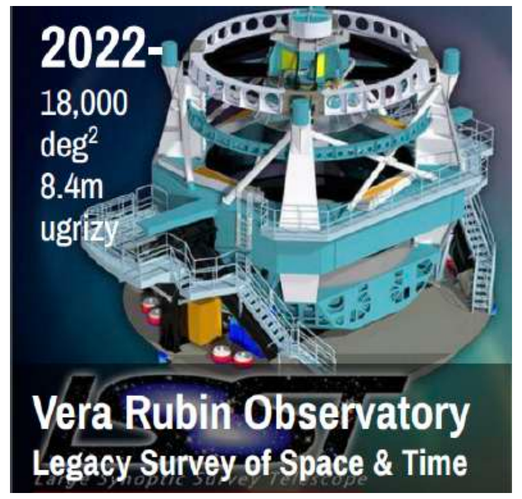
Future

Bucklea et al 2017

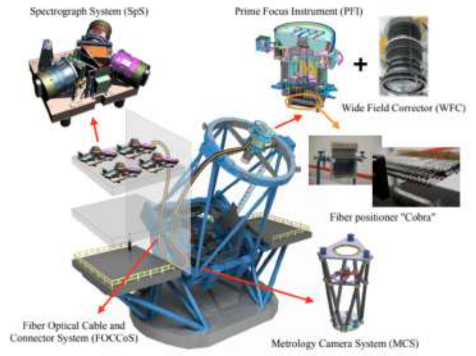
Future - signals in cosmology

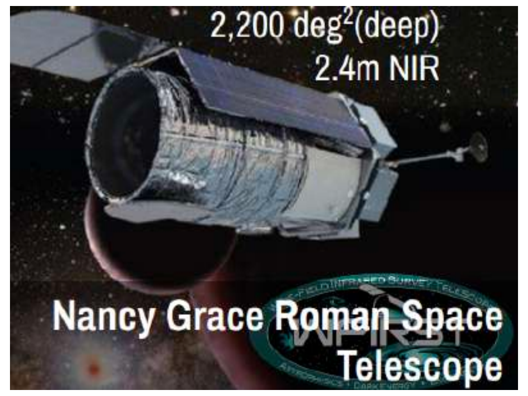
Observations

Photometric and spectroscopic surveys



Prime Focus Spectrograph (PFS)





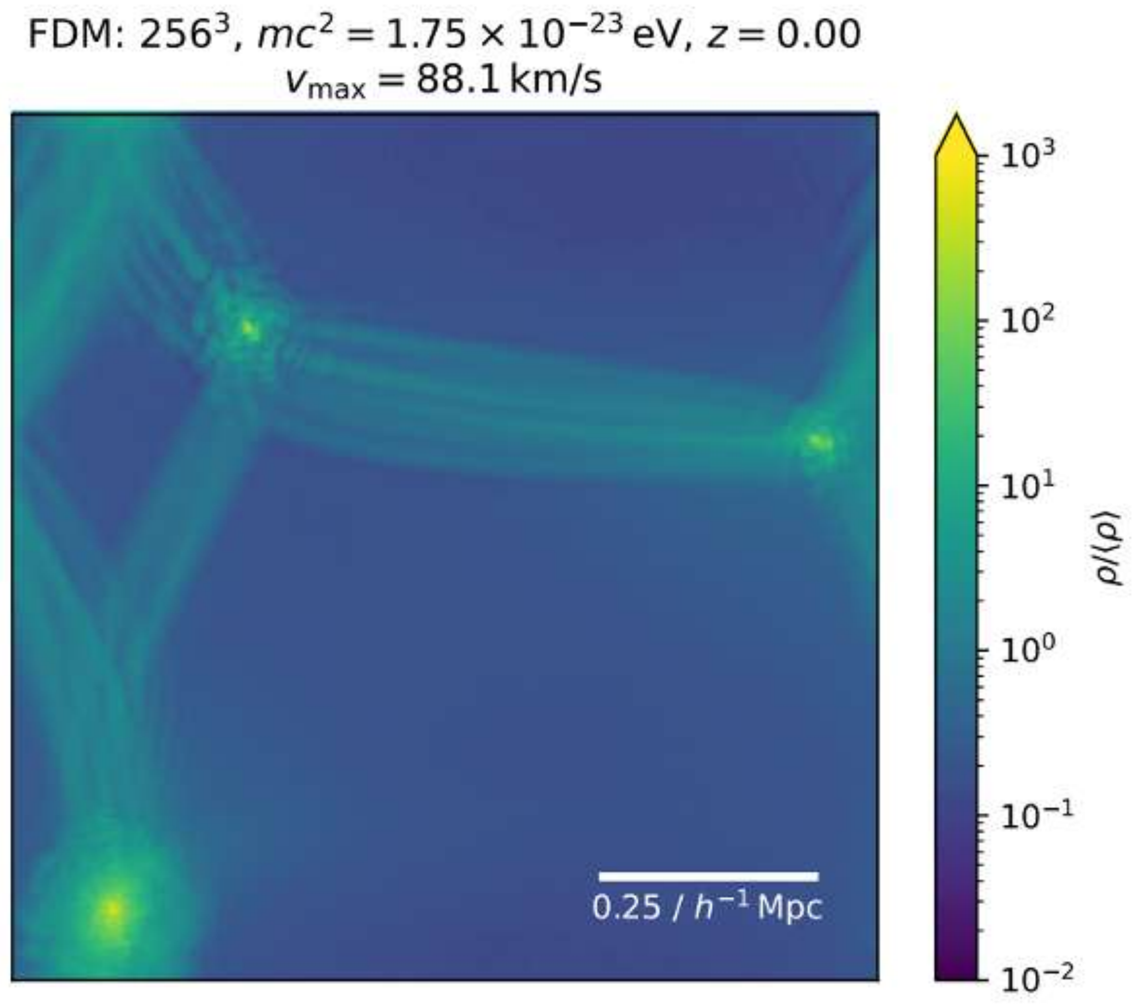
CMB

CMB-S4
Next Generation CMB Experiment

21cm

SKA
SQUARE KILOMETRE ARRAY

Simulations



New probes

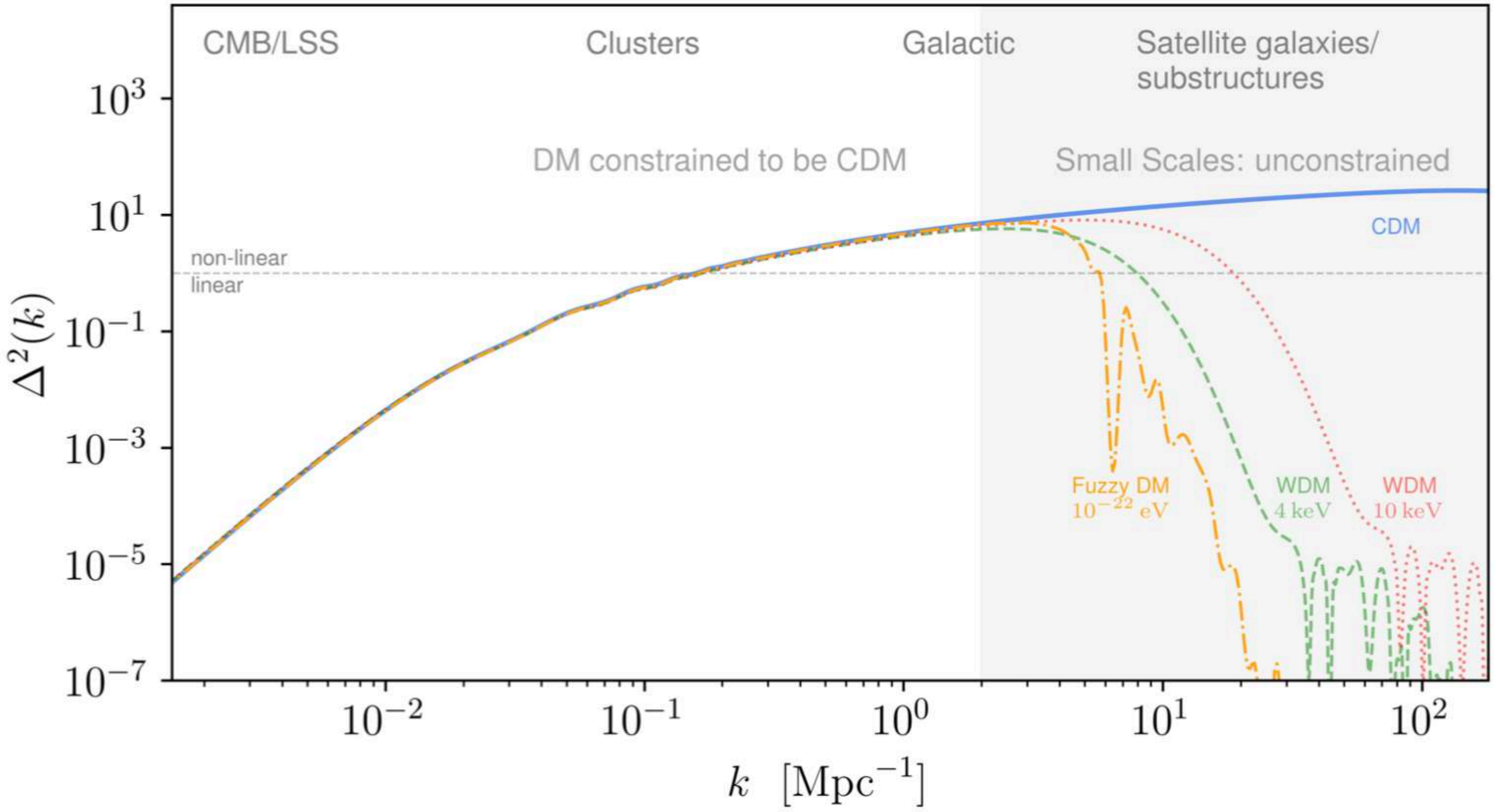
Substructures
- strong lensing
- stellar streams

Small scale information from PS
- substructure convergence PS

Modified from Jia Liu

Sub-galactic power spectrum

Using gravitational probes, strong lensing and stellar streams, to describe substructures



Sub-galactic power spectrum

Using gravitational probes, strong lensing and stellar streams, to describe substructures

Substructure convergence power spectrum

Develop a formalism to compute the substructure convergence power spectrum for different populations of dark matter subhalos.

A. Diaz Rivero, et al. (2017); Diaz Rivero, et al. , (2018)

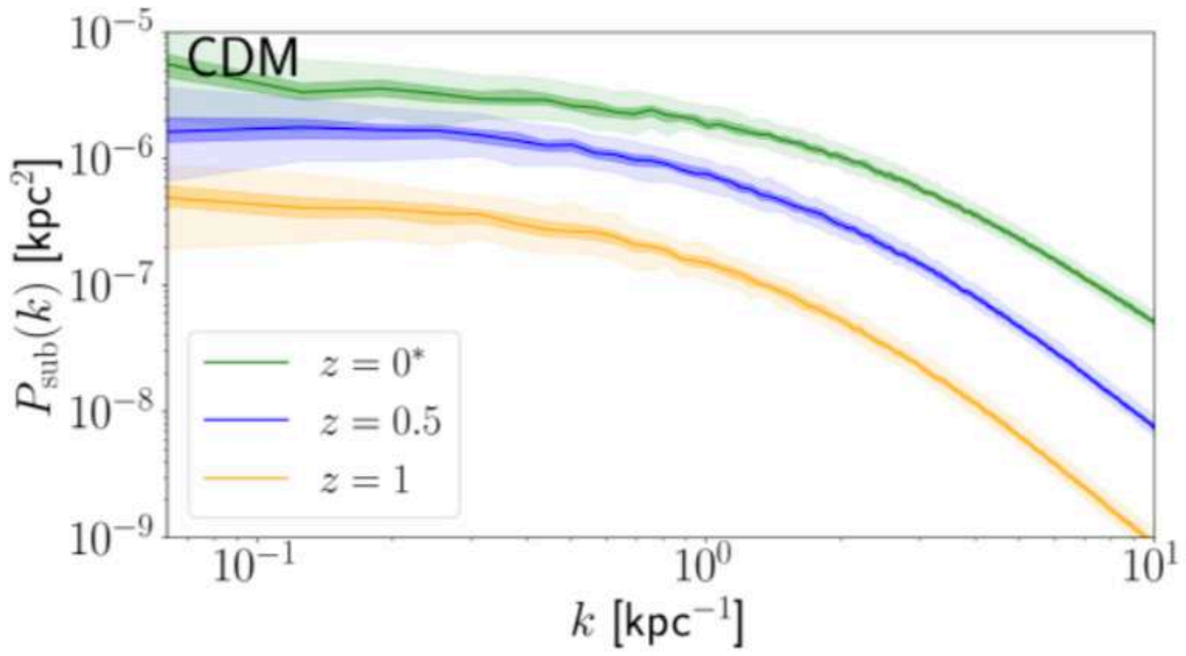
Bayer et al. (2018) ; Auger et al. 2009
FDM: *Kawai et al. (2021)*

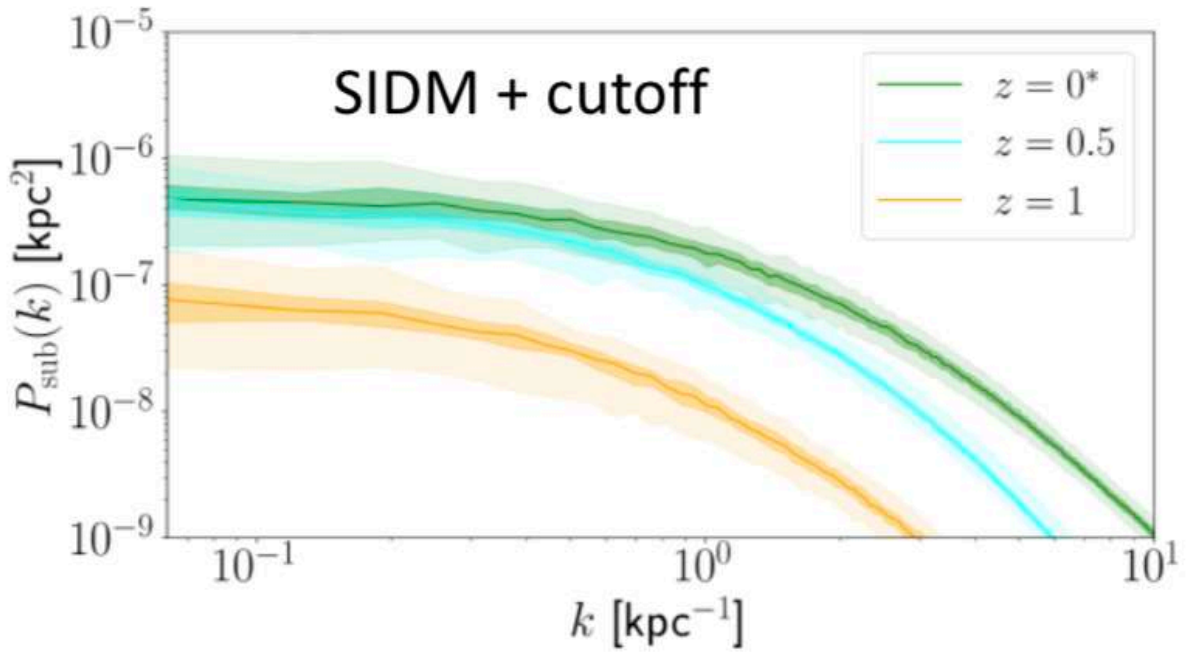
Hezaveh et al. (2016) (projected mPS by using strong lensing)

Change of language: instead of talking about lensing perturbations in terms of individual subhalos, look at the correlation function of the projected density field.

(based on Dvorkin's slide)

$$P_{\text{sub}}(k) = P_{1\text{sh}}(k) + P_{2\text{sh}}(k)$$





Sub-galactic power spectrum

Using gravitational probes, strong lensing and stellar streams, to describe substructures

Substructure convergence power spectrum

Sten Delos and Fabian Schmidt (2021)

Stellar streams: perturbed by passing substructure. Good gravitational probe, since given their low dynamical temperature and negligible self-interaction, it retains the memory of those encounters.

THIS WORK: Fully analytical understanding of the stream perturbations!

Power spectrum of a stream's stellar density is analytically related to that of the substructure background:

$$\underbrace{\boxed{P_*(k,t)}}_{\text{Stream power}} = \chi_*\left(k\sigma_0 t, \frac{D}{k\sigma_0^3}\right)\frac{k^2t^2}{3}P_{\Delta v}(k,t)$$

$$P_{\Delta v}(k,t) = 16\pi^4 G^2 \bar{\rho}^2 k^2 t \int_k^\infty \frac{\mathrm{d}q}{q}\overbrace{\boxed{\frac{\mathcal{P}(q)}{q^6}}}^{\text{Substructure power}} \int \mathrm{d}^3\boldsymbol{u}\,\frac{f(\boldsymbol{u})}{u}\theta_H(qu - kv)$$

Previous:

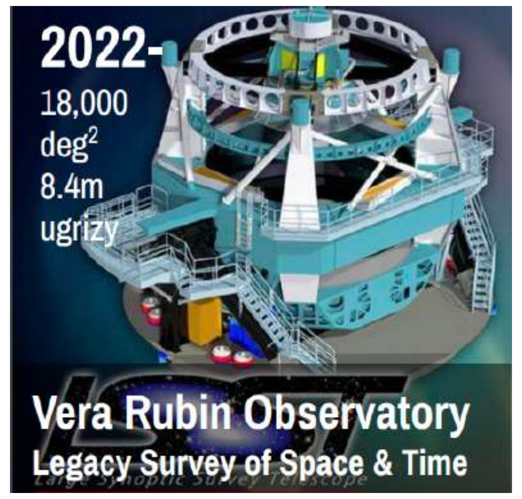
- Mostly numerical
- Perturbations $\longrightarrow$ sub-halo mass function

Relates the stellar stream perturbation to the surrounding matter distribution, from dark and luminous substructure

Future - signals in cosmology

Observations

Photometric and spectroscopic surveys



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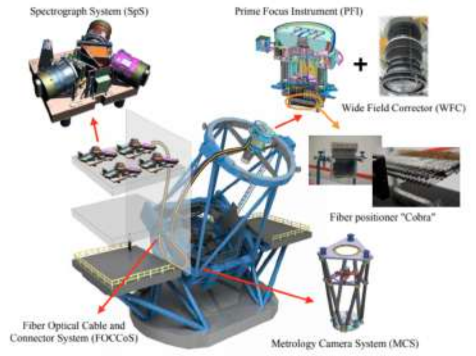
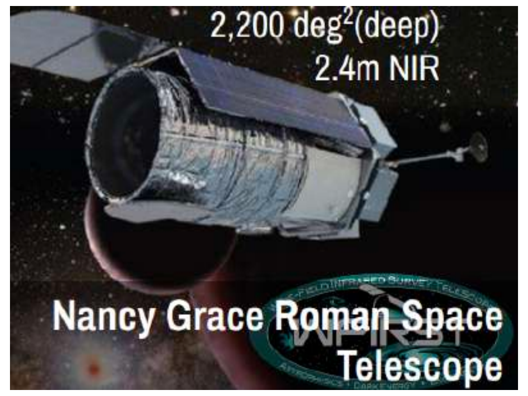




CMB

CMB-S4
Next Generation CMB Experiment

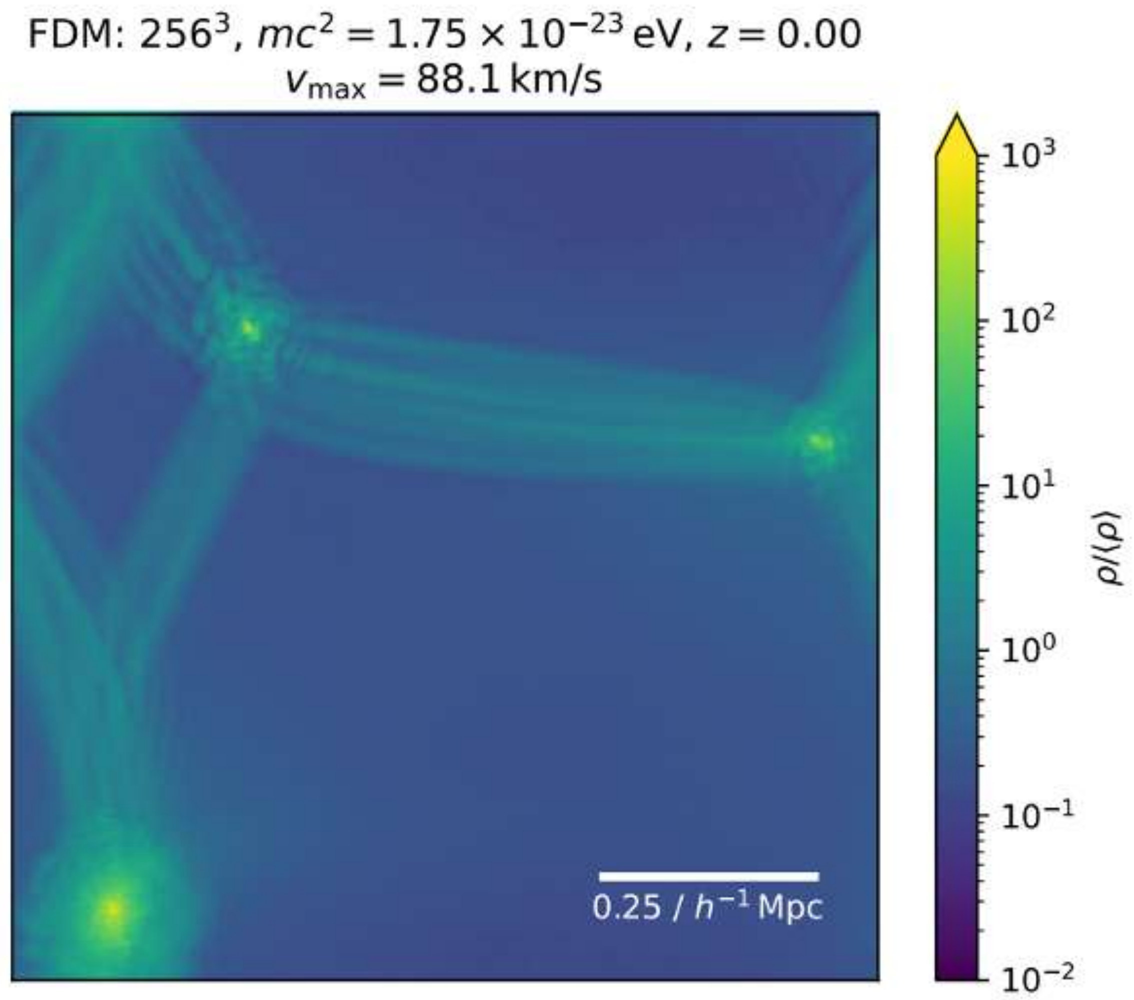
21cm

SKA
SQUARE KILOMETRE ARRAY

How to model the PS on these small scales?
Highly non-liner scales!
Challenge!

Simulations

(more later)



New probes

Substructures
- strong lensing
- stellar streams

Small scale information from PS
- substructure convergence PS

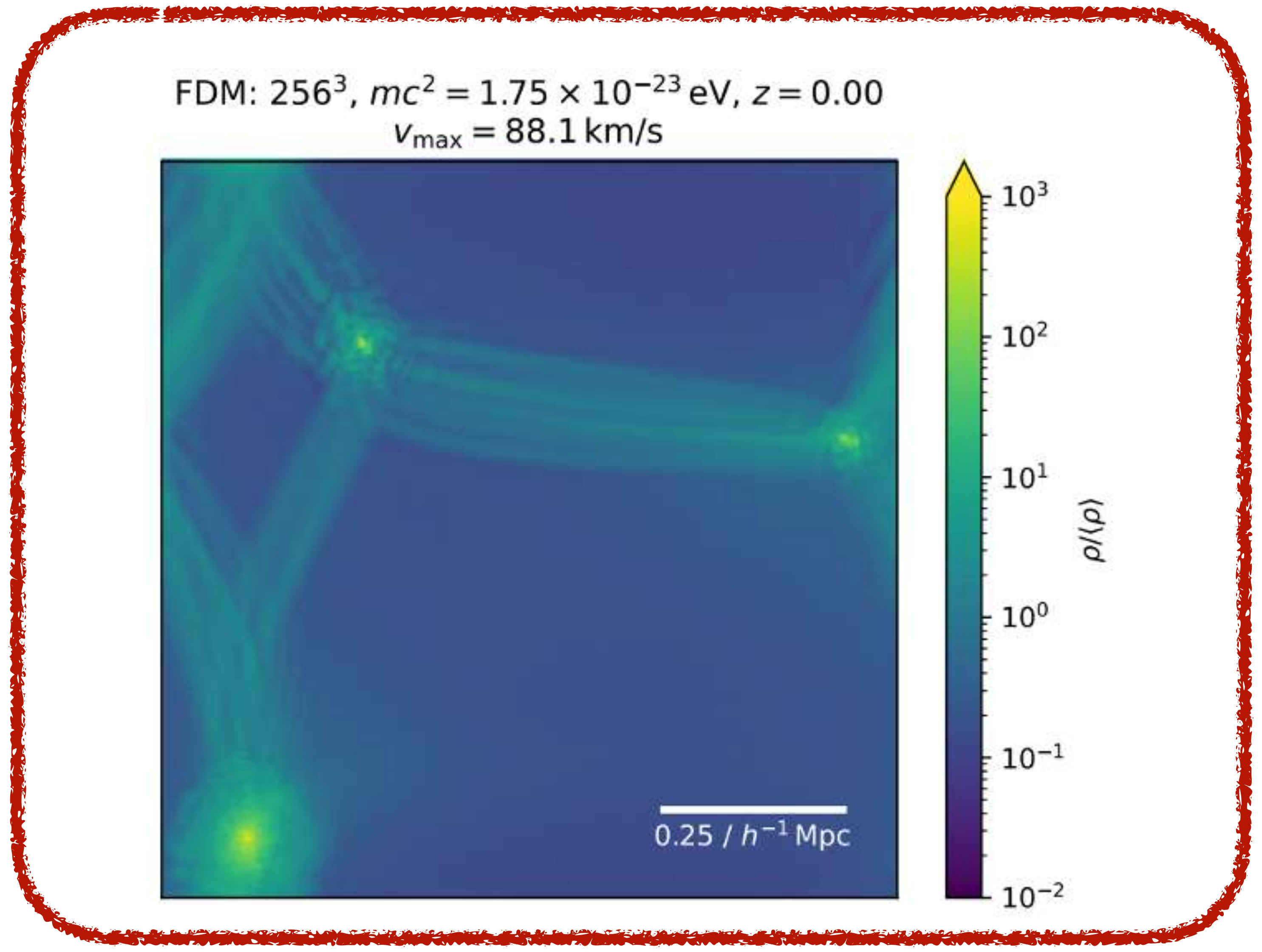
Modified from Jia Liu

Future - *signals in cosmology*

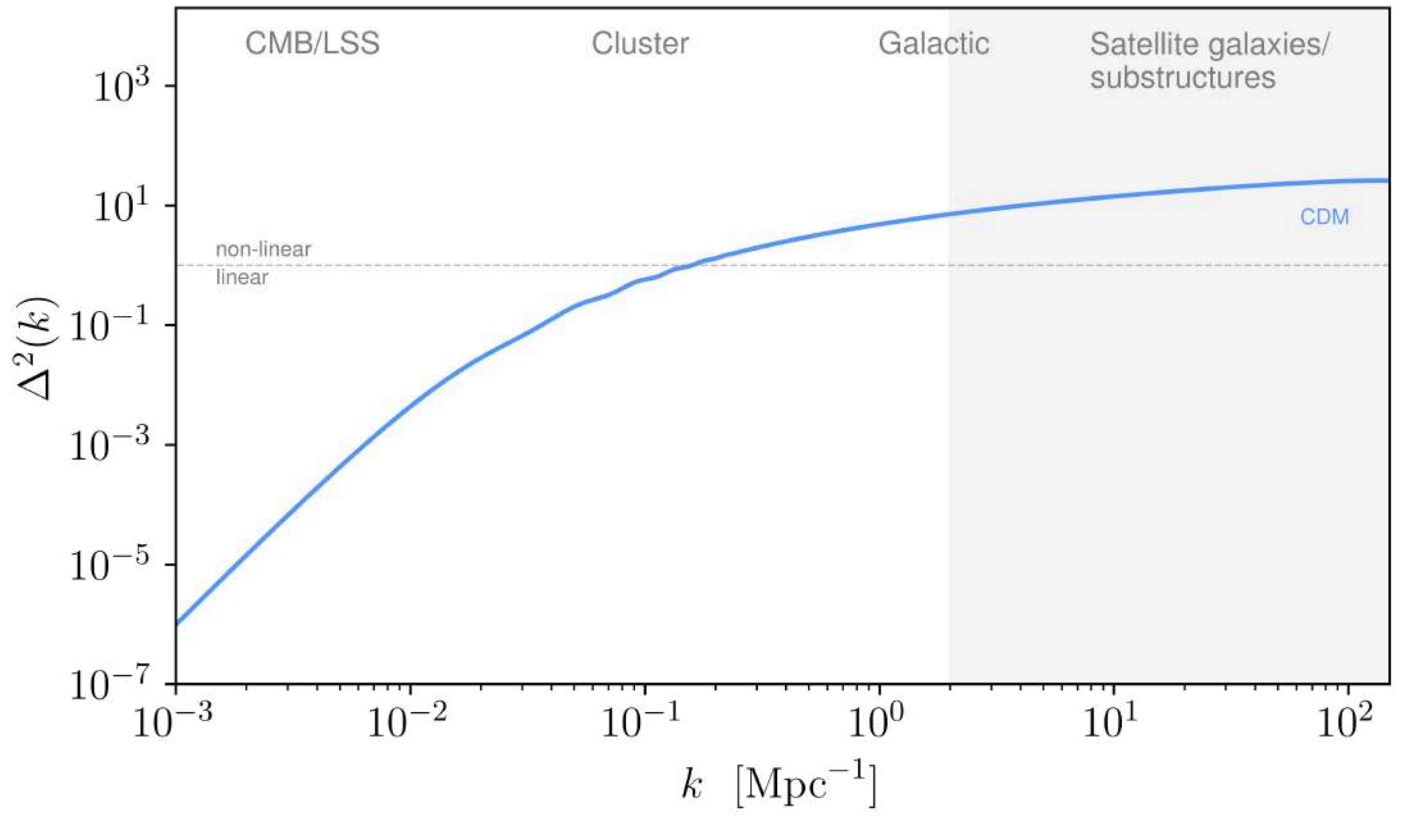
Simulations

All we computed in lecture 1 was the LINEAR power spectrum

How to model the PS on these small scales?
Highly non-liner scales!
Hard!



We can use EFT of LSS to compute mildly non-linear scales, but smaller scales are non-linear - Need simulations!



Need to improve simulations!
Challenge!

(more later)