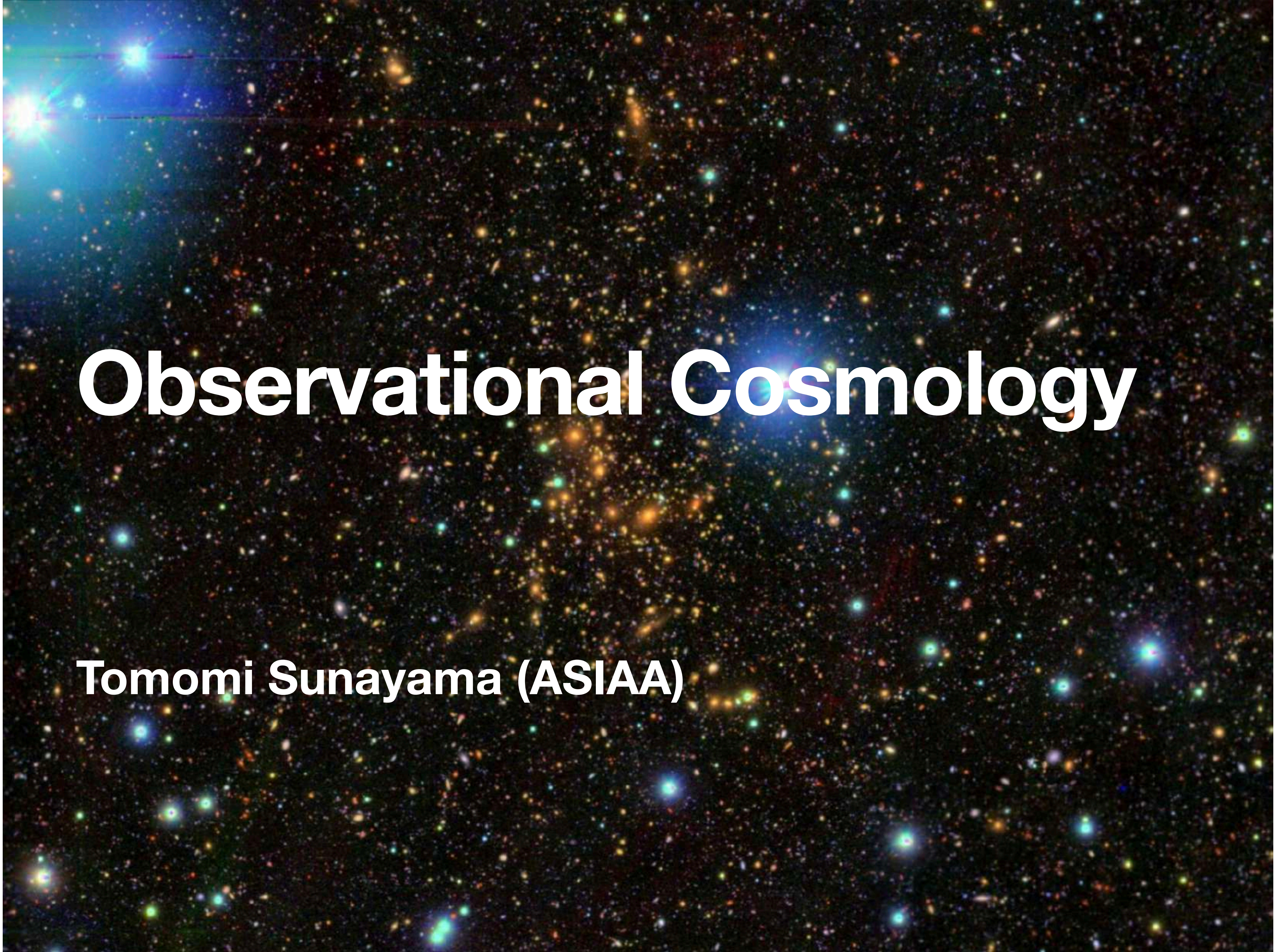
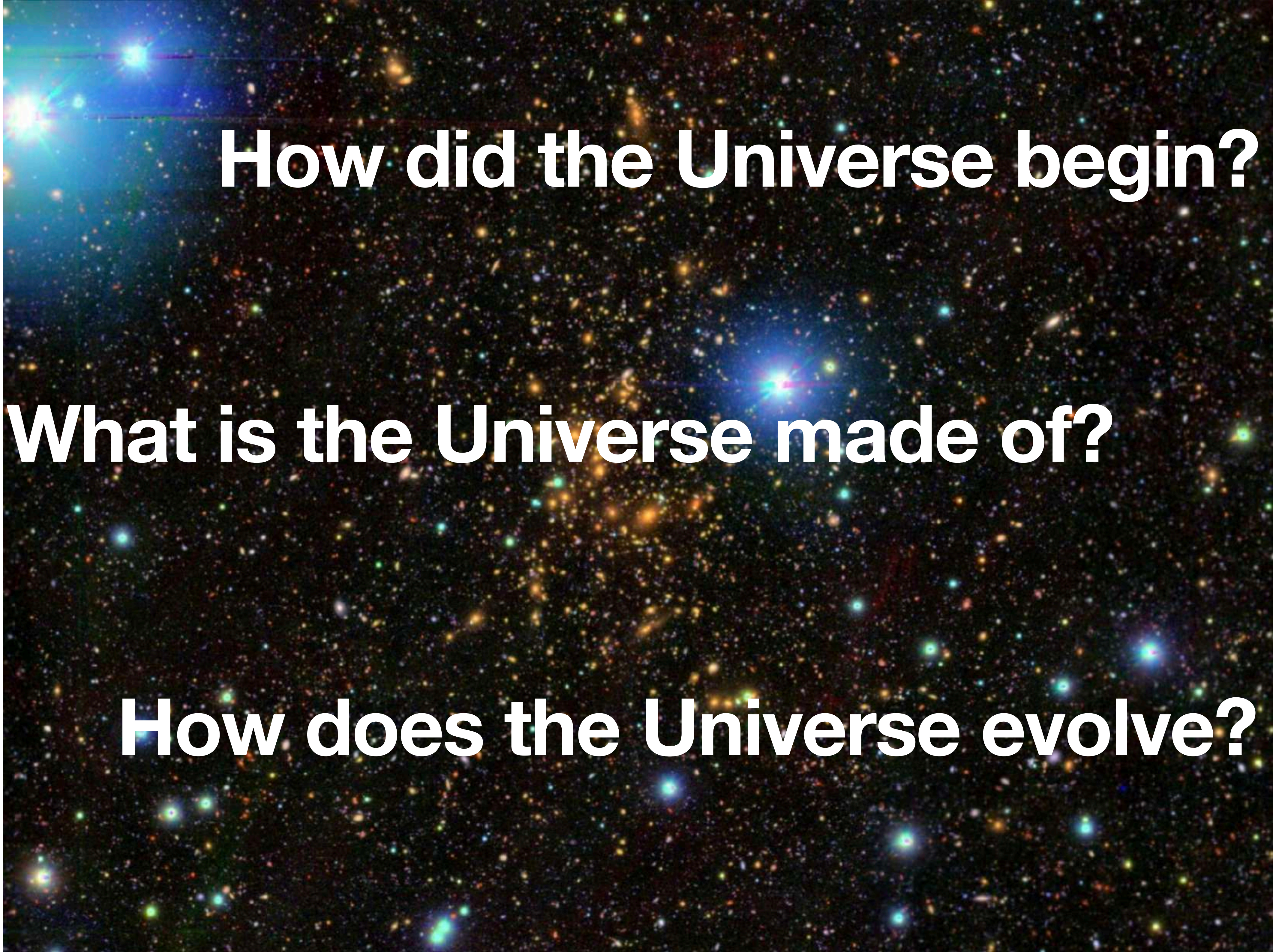
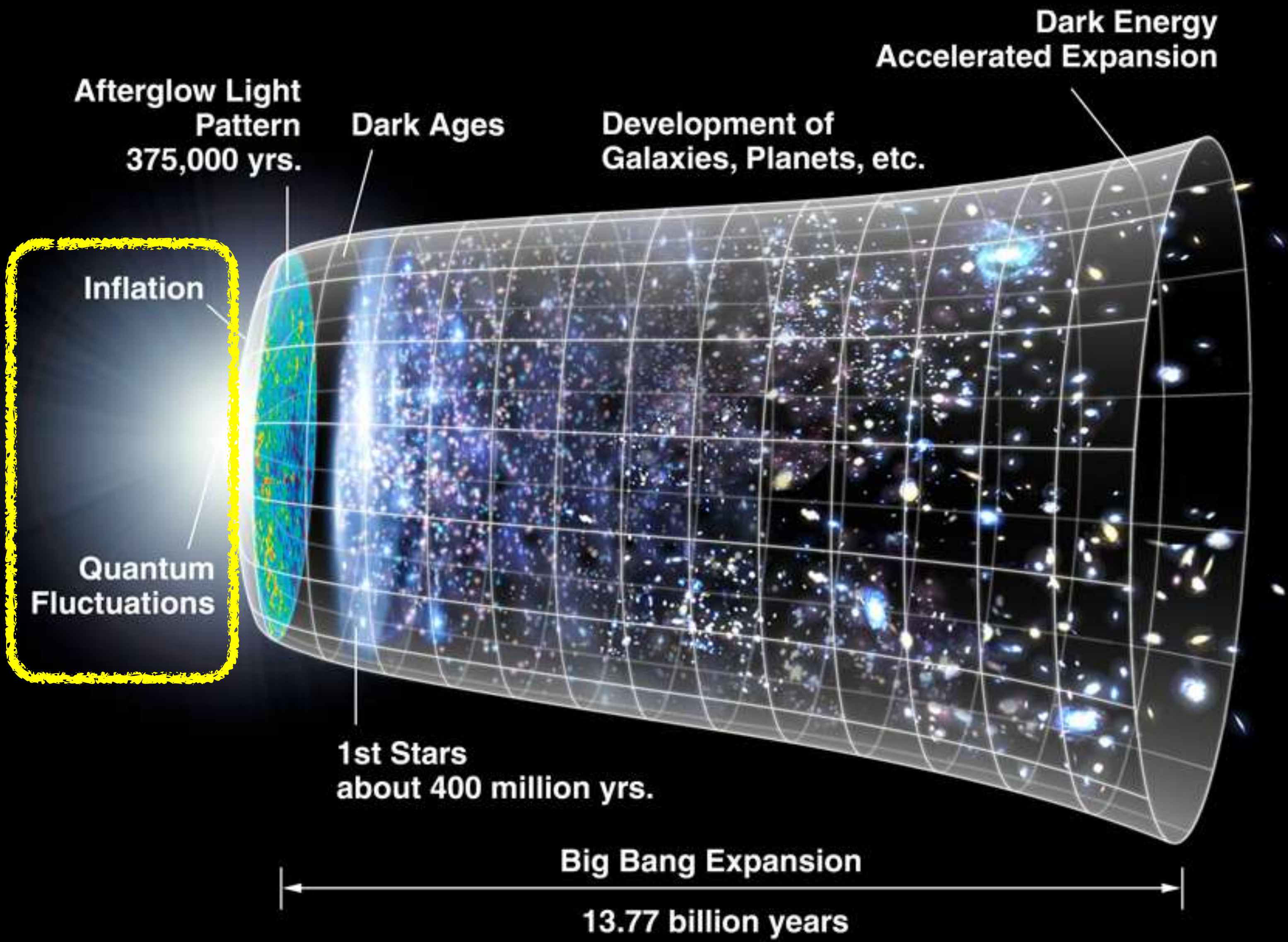


Observational Cosmology

Tomomi Sunayama (ASIAA)

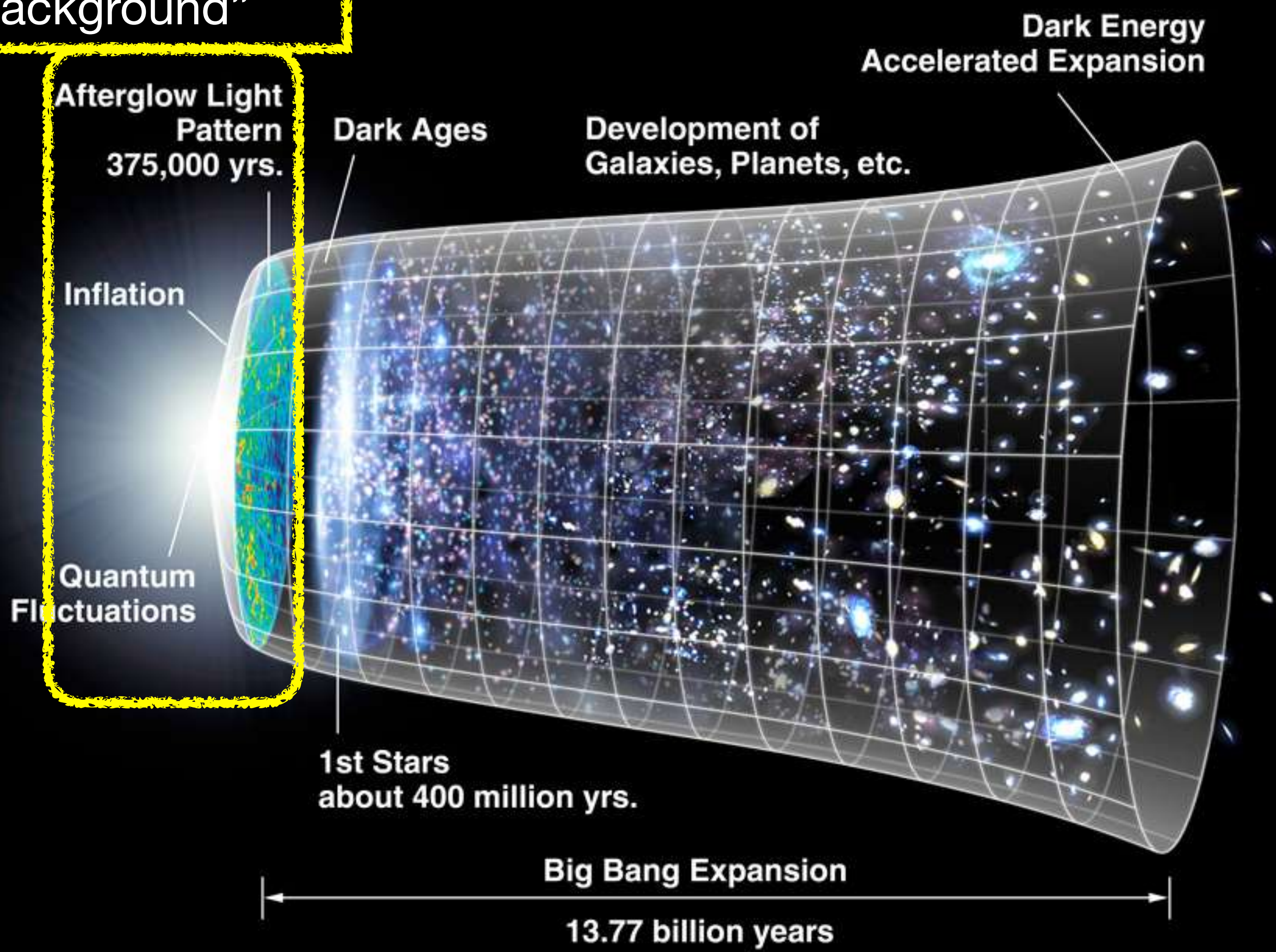

How did the Universe begin?
What is the Universe made of?
How does the Universe evolve?

How does our Universe evolve? - Brief history of the Universe



How does our Universe evolve? - Brief history of the Universe

“Cosmic Microwave Background”



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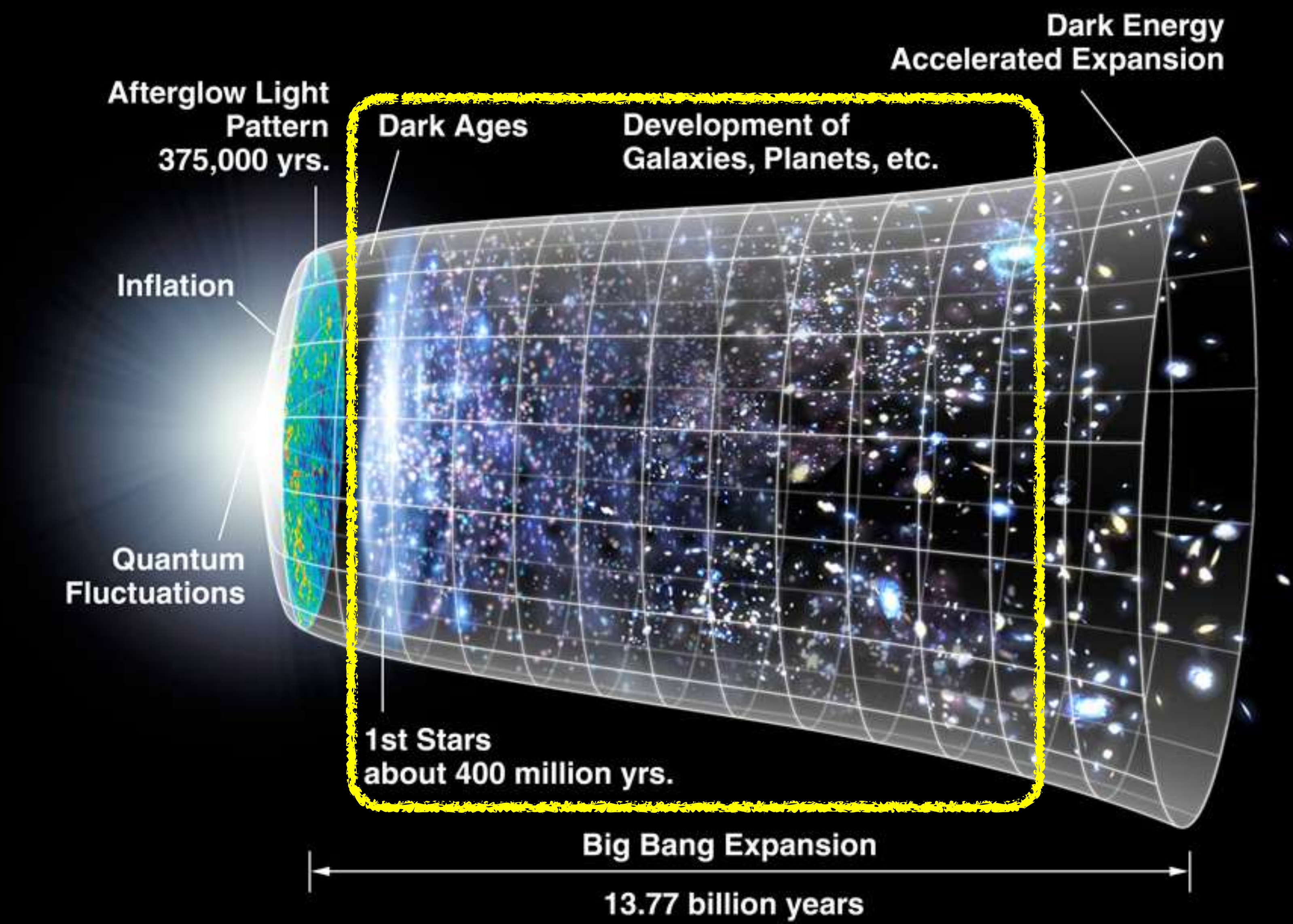

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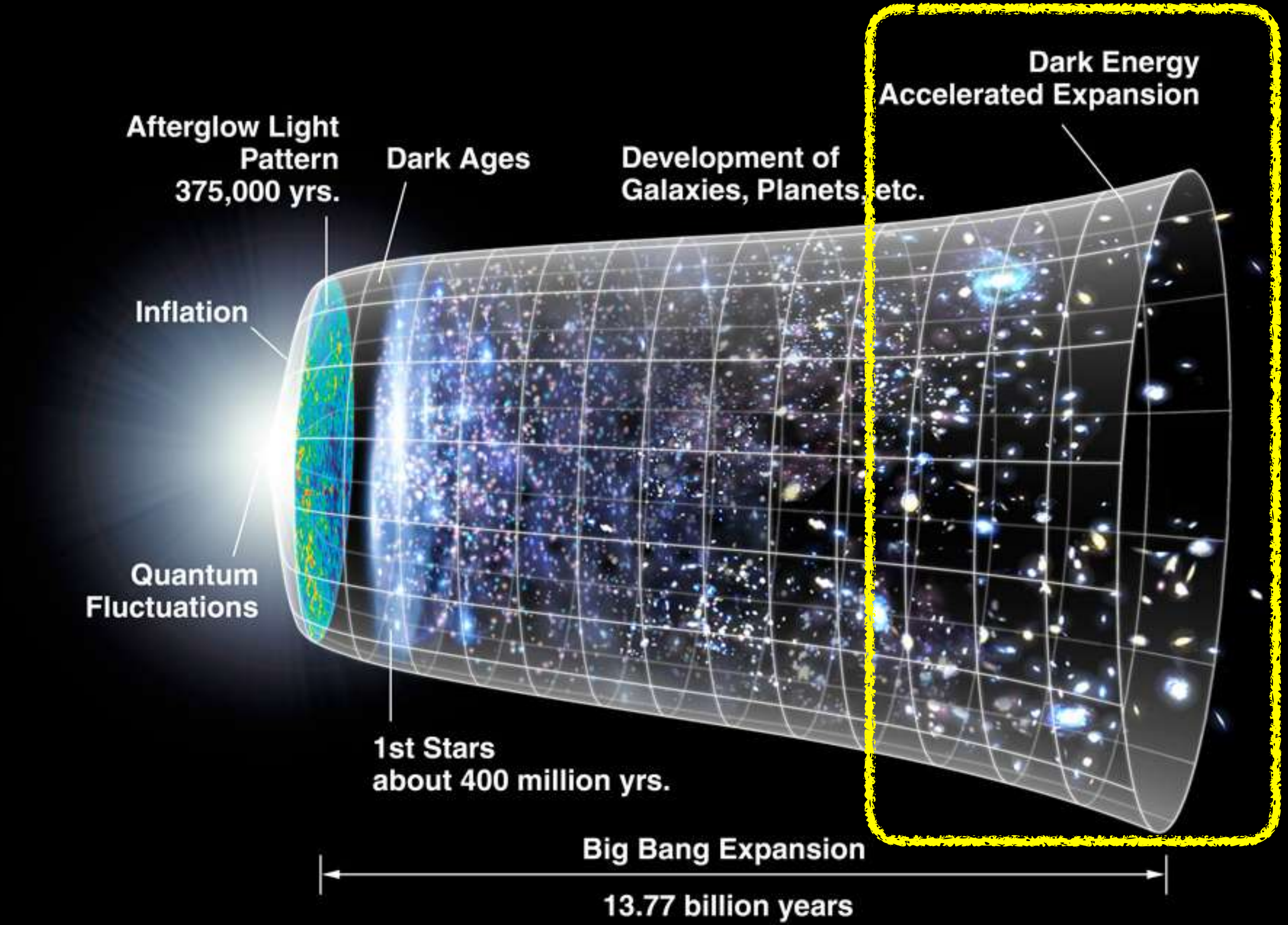

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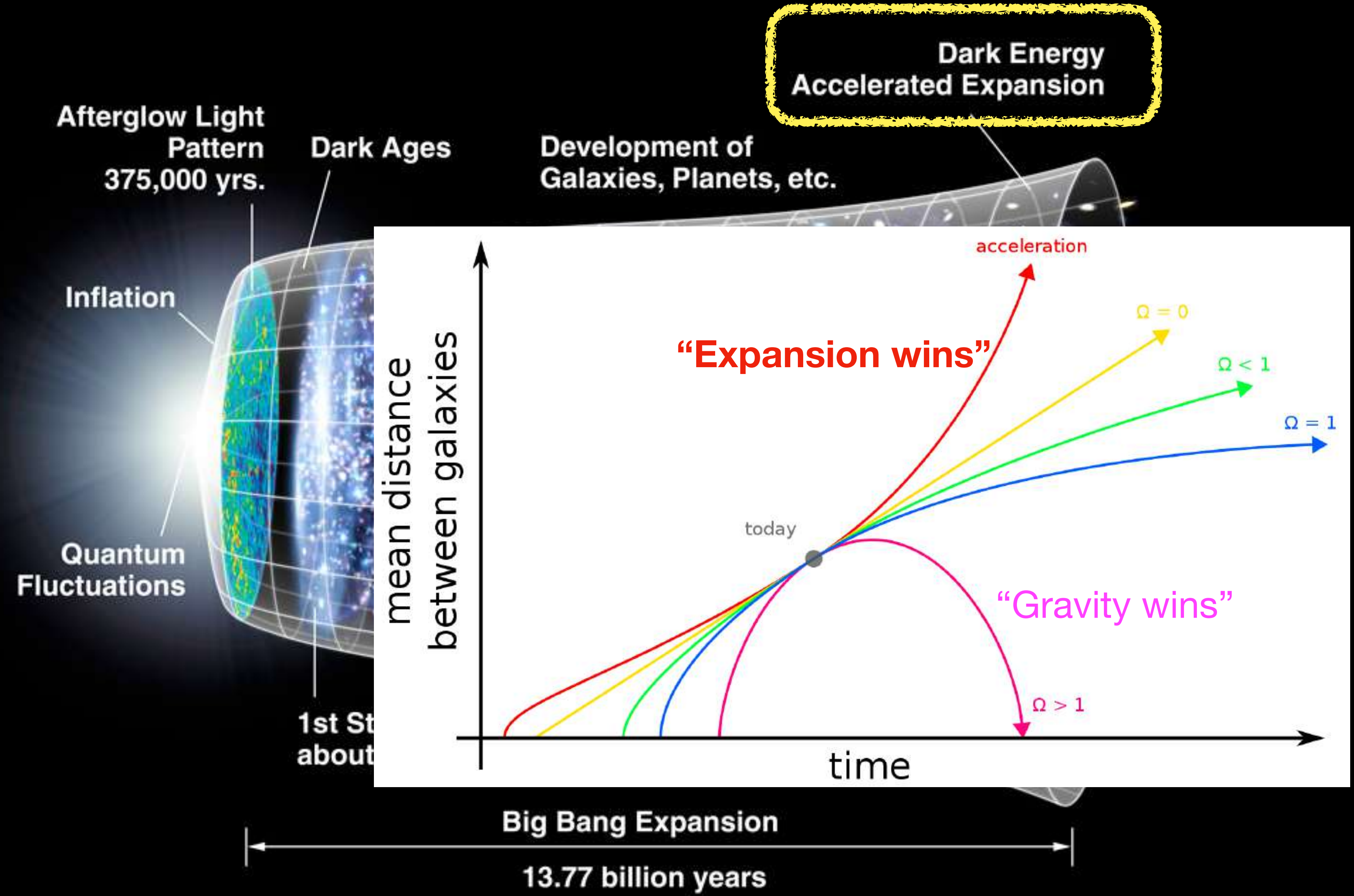
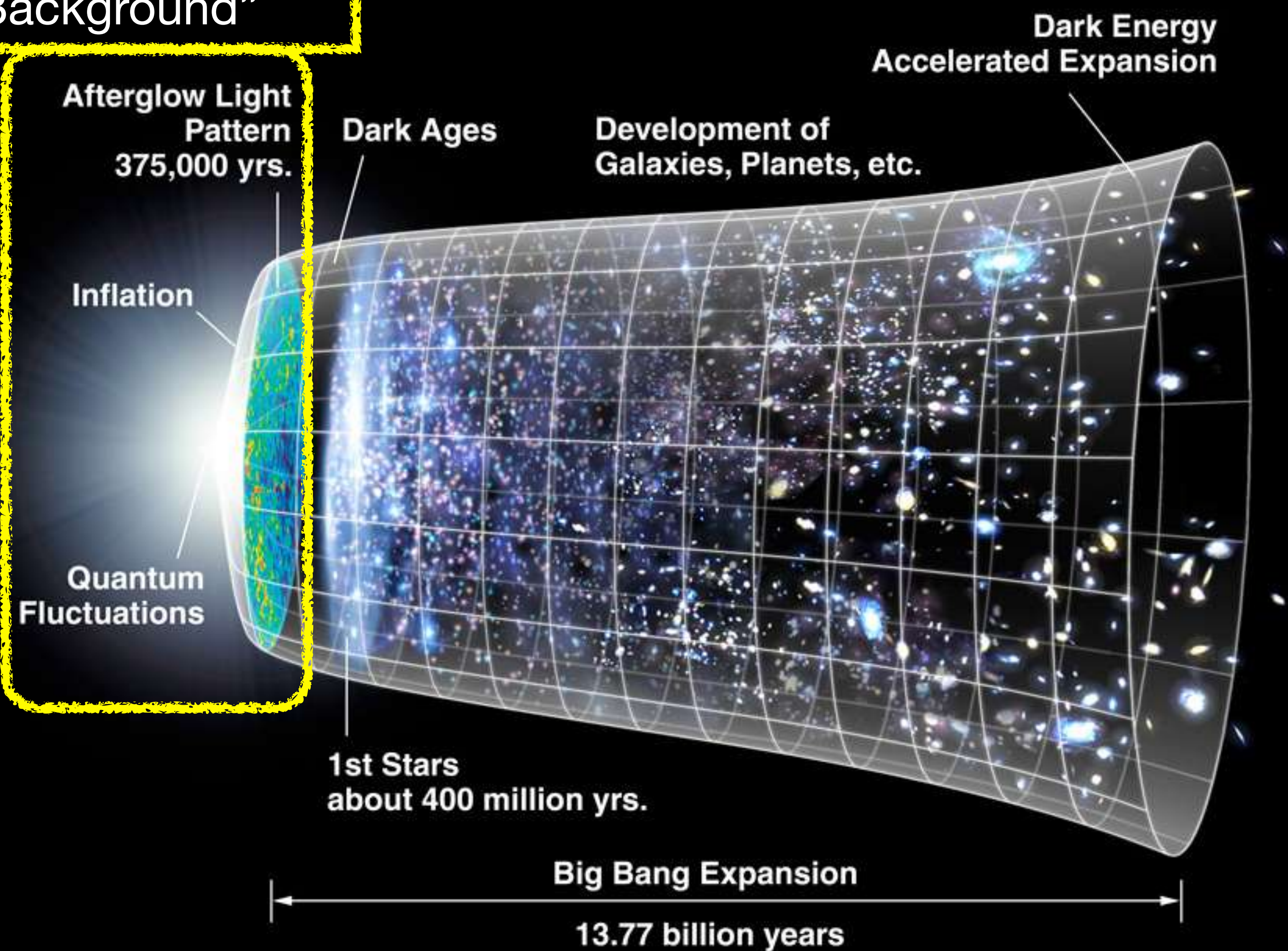


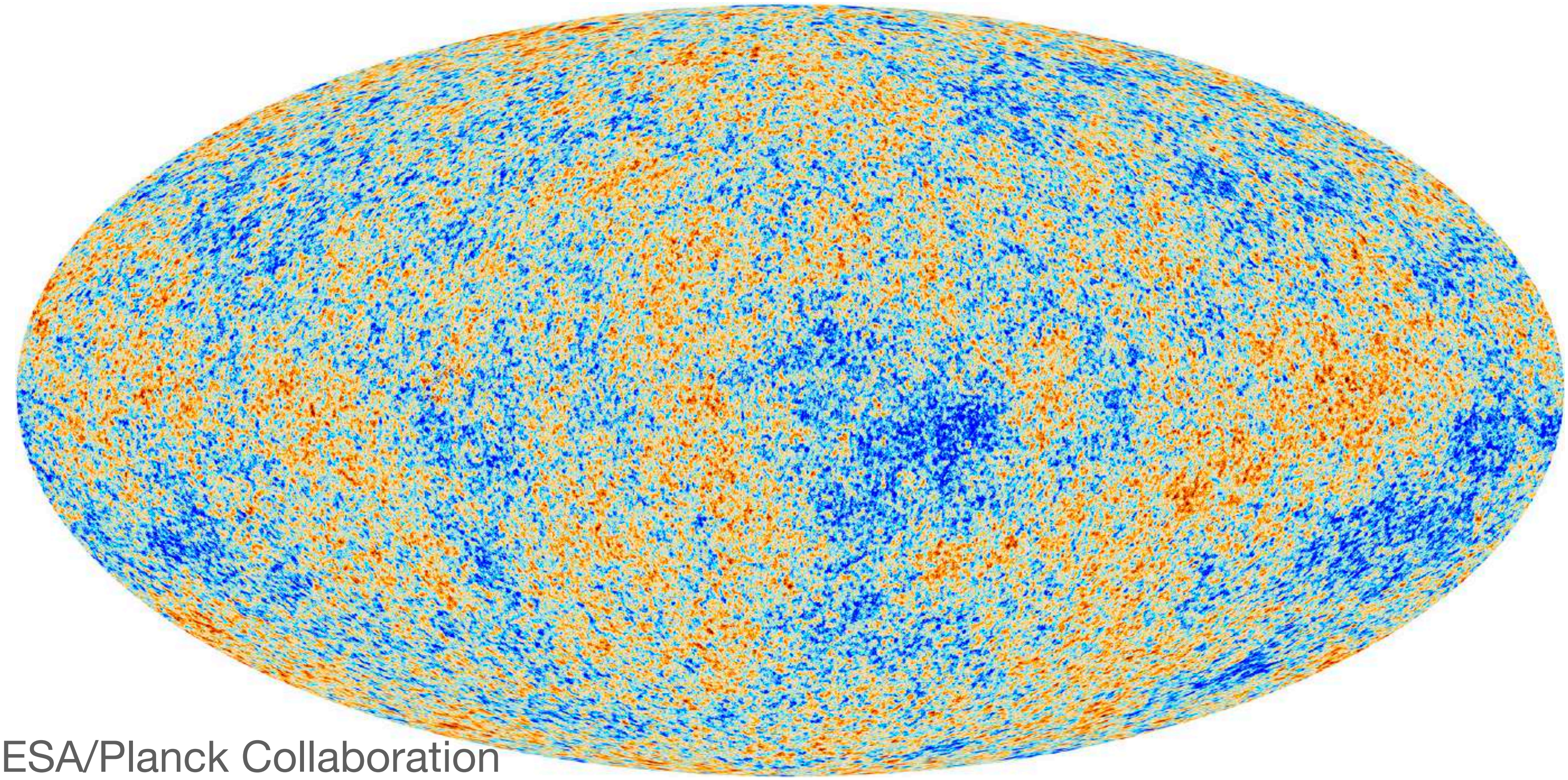
How does our Universe evolve? - Brief history of the Universe

“Cosmic Microwave Background”



Cosmic Microwave Background (CMB)

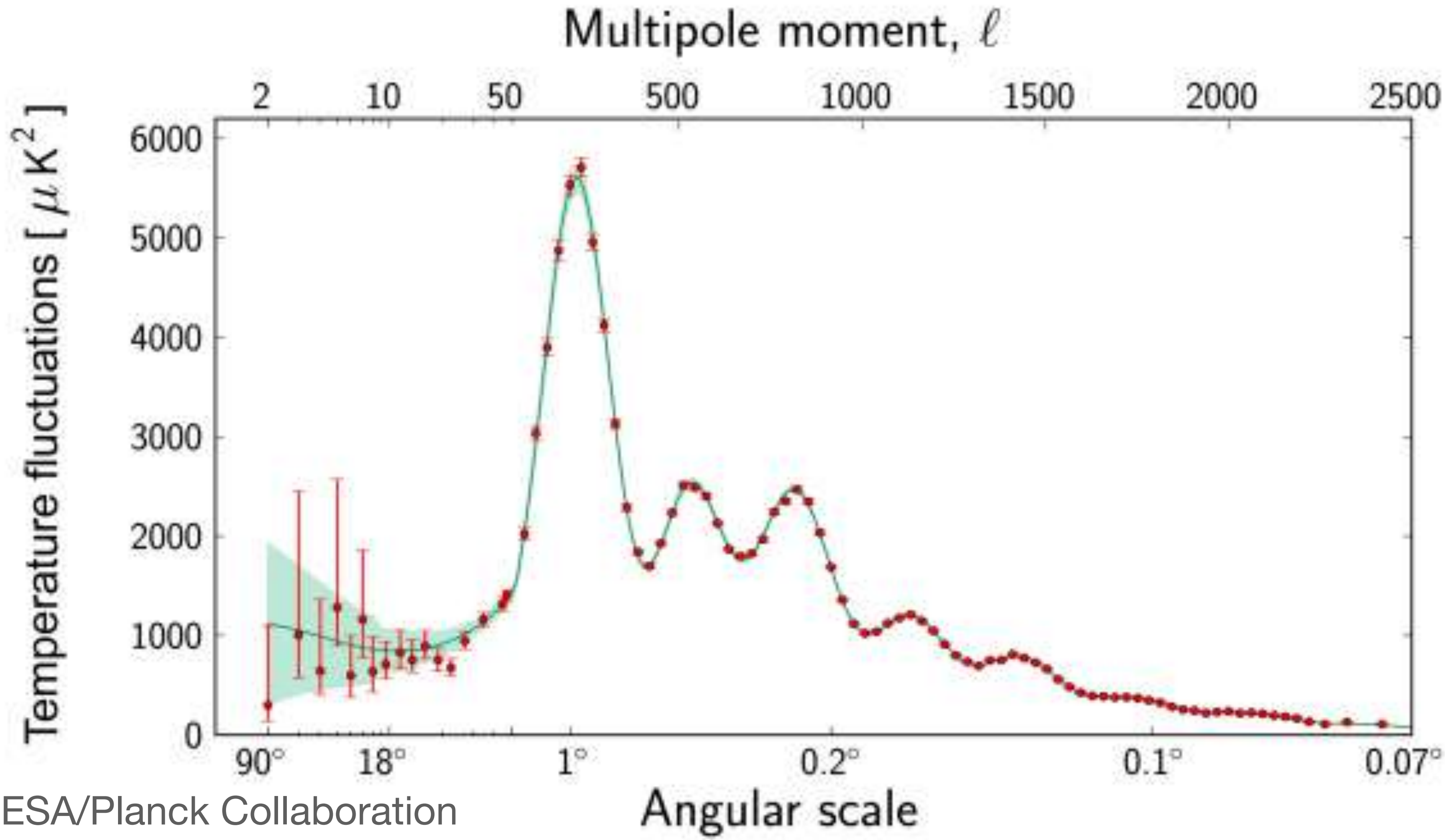
- The farthest and oldest light that we can observe directly
- The Universe is homogeneous and isotropic



Credit: ESA/Planck Collaboration

CMB can tell us energy budget of our Universe

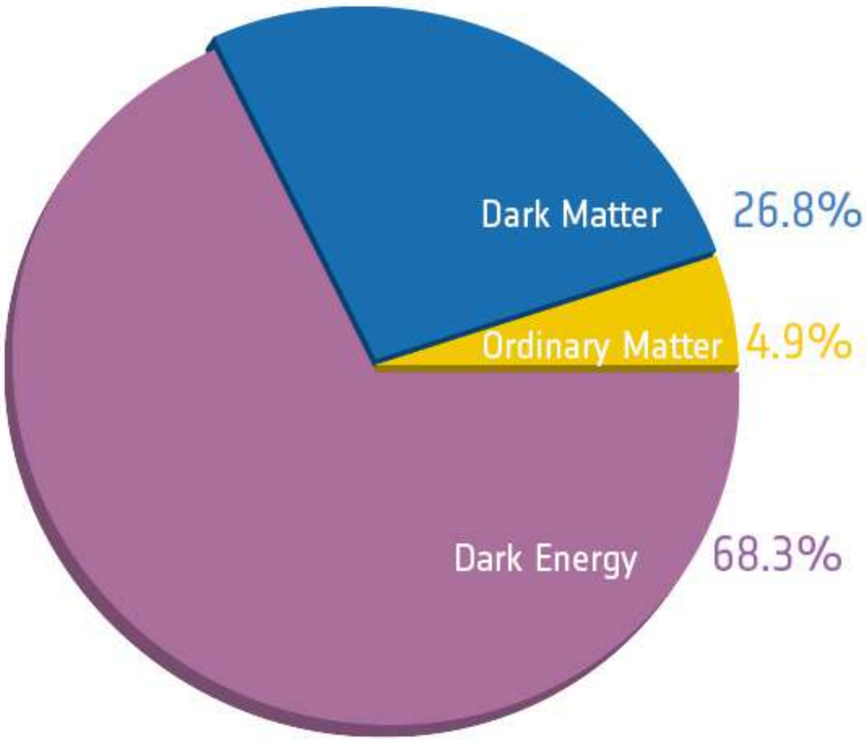
- The model fits the data remarkably well!



Credit: ESA/Planck Collaboration

Standard Cosmological Model

Our Universe can be explained by six parameters (ΛCDM model)

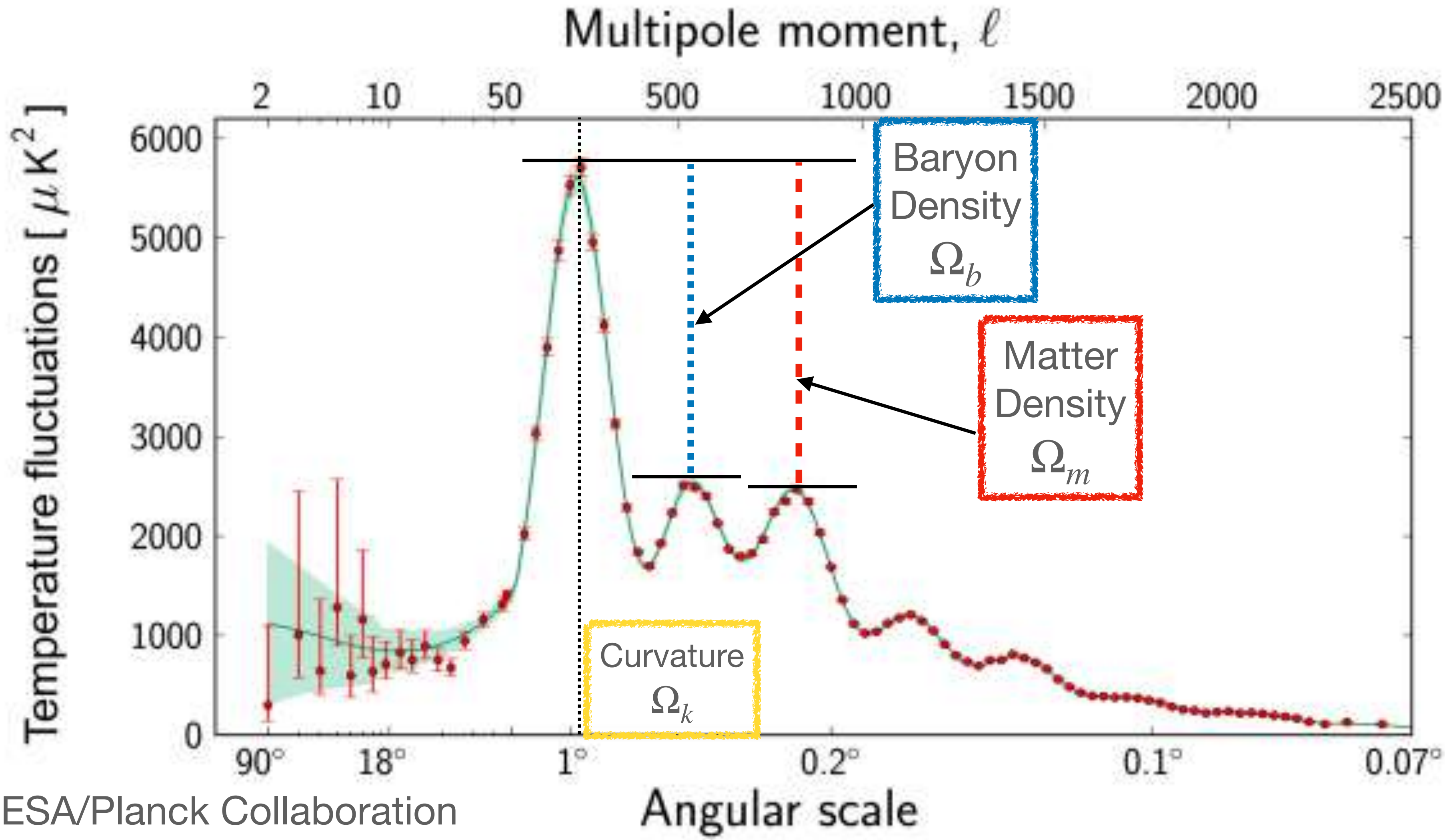


ESA / Planck

- Matter density Ω_m
- Baryon density Ω_b
- Hubble parameter h
- Cosmological constant Λ
- Initial amplitude σ_8 and slope n of power spectrum of fluctuations

CMB Power Spectrum can tell us energy budget of our Universe

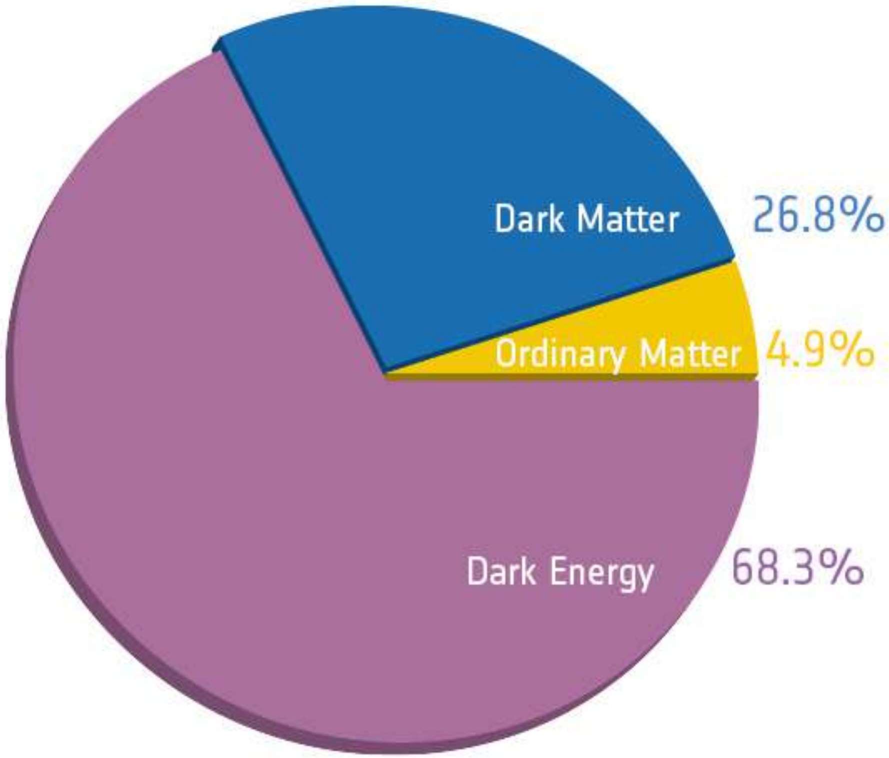
- The amplitude and the location of peaks can tell us about the energy content of the Universe.



Credit: ESA/Planck Collaboration

Standard model of the Universe: ΛCDM

Era of precision cosmology



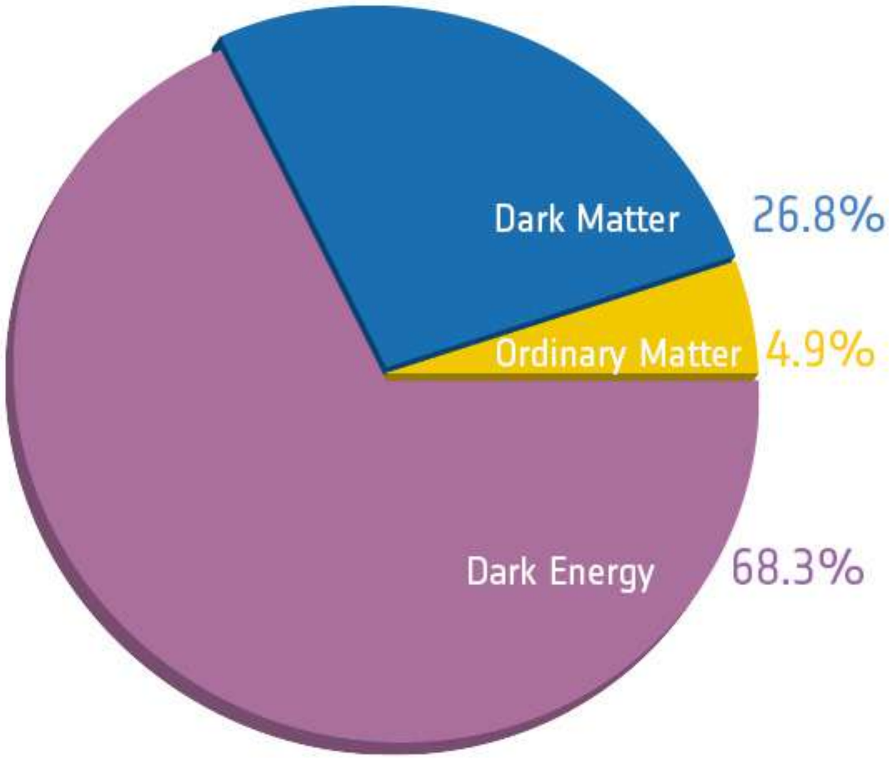
Credit: ESA/Planck Collaboration

- Dark Energy(DE)
  - accelerates the expansion
  - dominate the total energy density
  - first measured by SNeIa
- geometrically flat

We assume DE density doesn't change in time (cosmological constant: Λ) and GR works on all scale

Standard model of the Universe: ΛCDM

Things we don't know…



Credit: ESA/Planck Collaboration

DE **requires** new physics beyond the standard model of elementary particles and fields

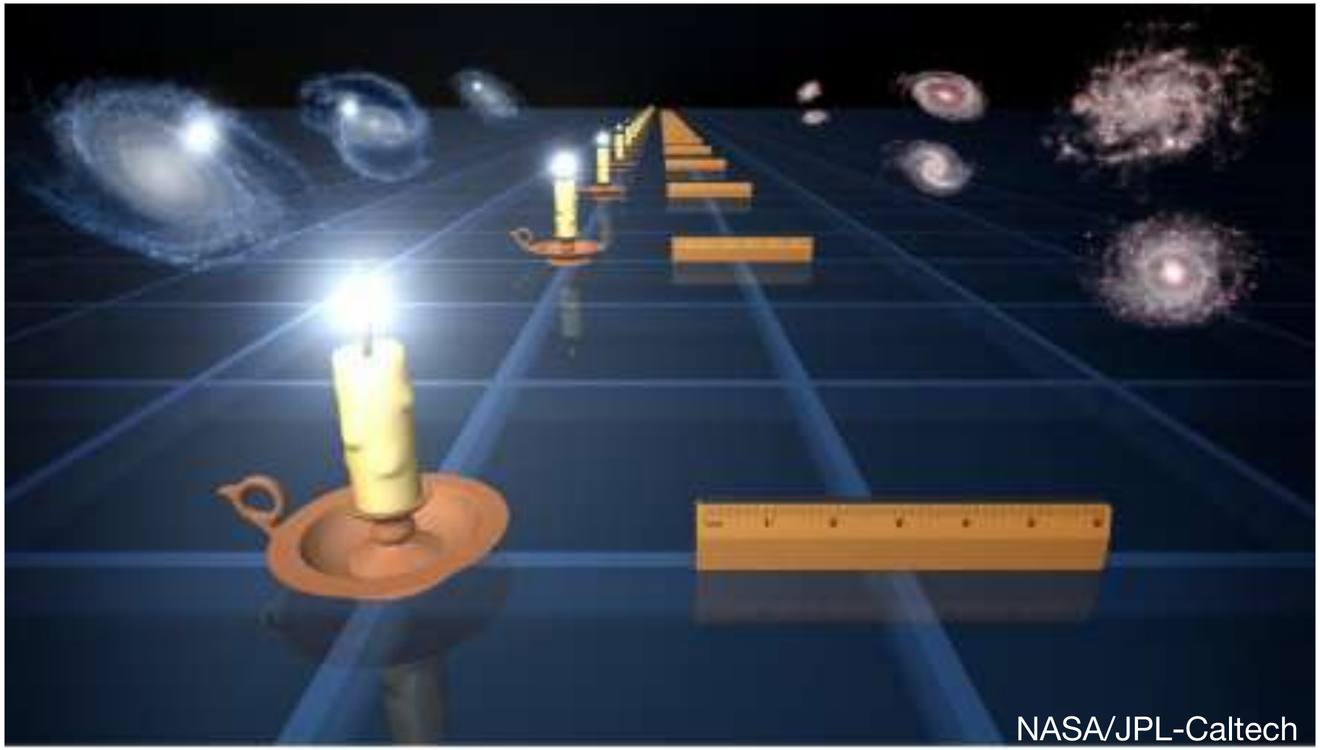
- Dark Energy
  - cosmological constant Λ
  - does the DE density change in time? (e.g., dynamic scalar field)
  - due to break down of General Relativity (GR)?

Measurement of Expansion History

Geometrical probes

- "Standard Candle": Supernovae (SNe) Ia → measure relative distances assuming brightness of SNe Ia is understood for any SNe Ia

- "Standard Ruler": Baryon Acoustic Oscillation (BAO) → measure absolute distance since the peak location of BAO does not change as a function of time



Cosmology 101

FRW metric and Hubble Parameter

- Flat geometry under special relativity (no expansion of space)

$$ds^2 = c^2dt^2 - dx^2 - dy^2 - dz^2$$

- Flat geometry under general relativity (space can be expanded)

$$ds^2 = c^2dt^2 - a^2(t)(dx^2 + dy^2 + dz^2)$$

(Friedmann–Robertson–Walker (FRW) metric)

Hubble Parameter H(t) measures the expansion rate of the Universe:

$$H(t) = \dot{a}(t)/a(t)$$

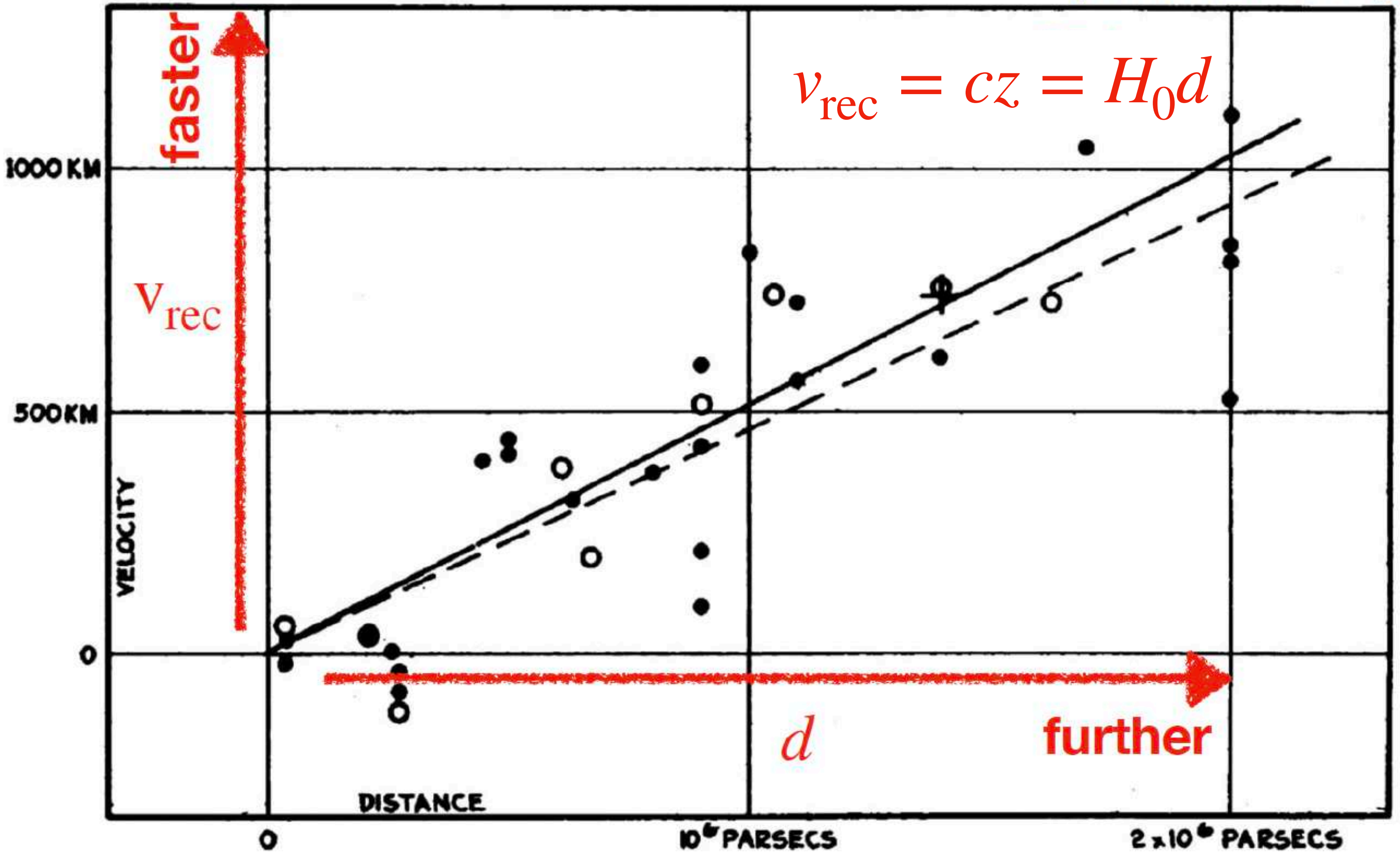
Hubble's Law

- Hubble discovered that galaxies are moving away from us, and distant galaxies recedes faster

"Redshift"

$$a(z) = \frac{1}{1+z}$$

(Edwin Hubble 1929)



Cosmology 102

Expansion rate of the Universe

$$H^2(a) = H_0^2 \left[\Omega_R a^{-4} + \Omega_M a^{-3} + \Omega_k a^{-2} + \Omega_{DE} \exp \left\{ 3 \int_a^1 \frac{da'}{a'} [1 + w(a')] \right\} \right].$$

$$w(a) = w_0 + w_a(1 - a),$$

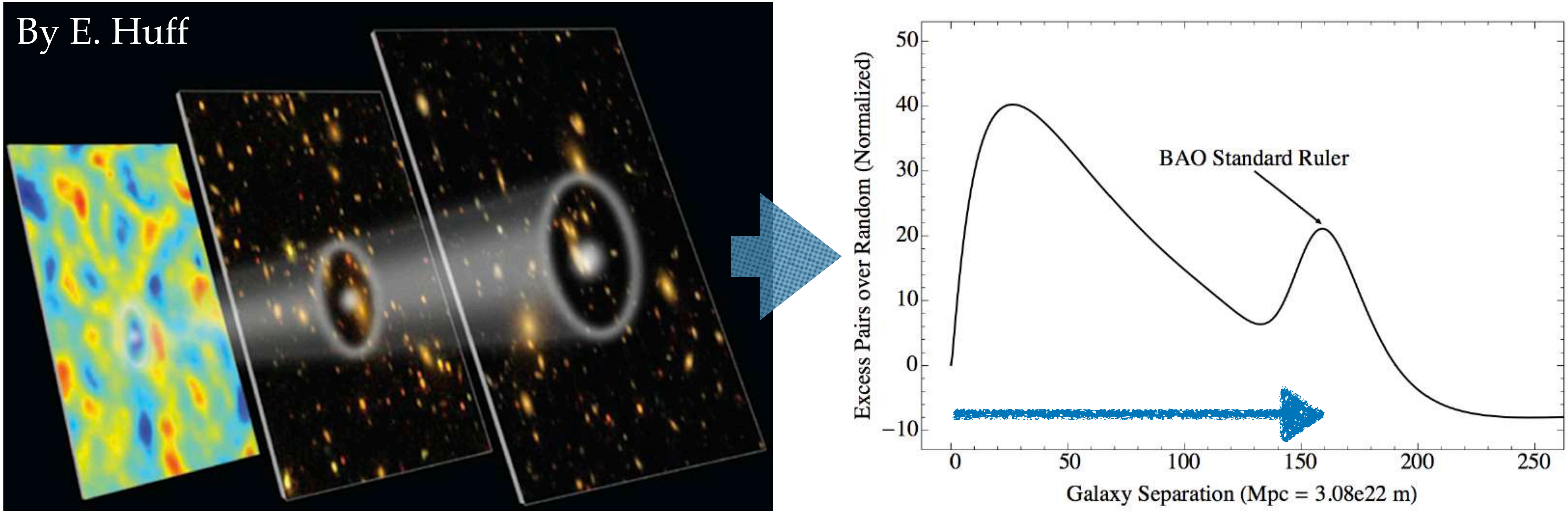
Distances (Comoving, and angular diameter)

$$D_C(z) = \frac{c}{H_0} \int_0^z dz' \frac{H_0}{H(z')} .$$

$$D_A(z) = K^{-1/2} \sin \left(K^{1/2} D_C \right)$$

Baryon Acoustic Oscillations (BAO)

Standard Ruler

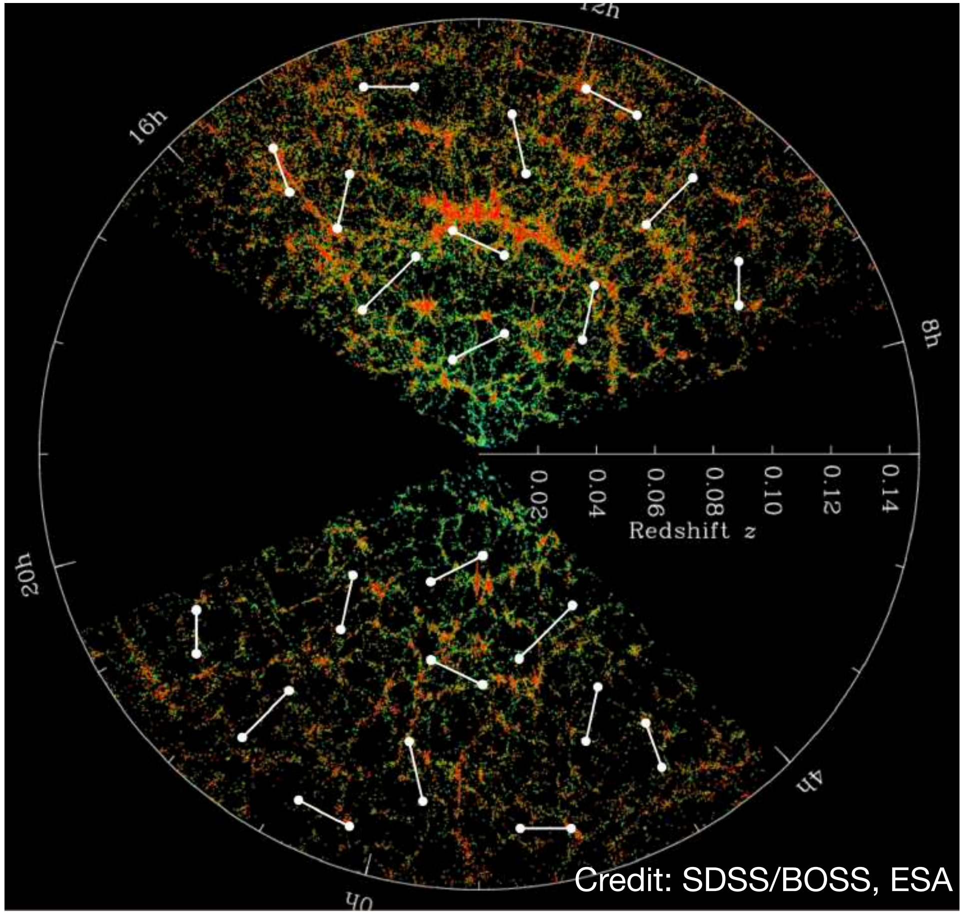


- Imprint of sound waves frozen in the early Universe
- Scale set by sound horizon and does not change in time, but depends on the amount of dark energy

Statistical tool to quantify galaxy distributions

2-point correlation functions/Power spectrum

- Galaxy correlation functions measure an excess probability (relative to Poisson) of galaxy pairs separated by distance r.



Matter Density Contrast

$$\delta(r) = \frac{n(r,t) - \bar{n}(t)}{\bar{n}(t)}$$

2 point correlation function

$$\xi(r) = \frac{DD(r)}{RR(r)} - 1$$

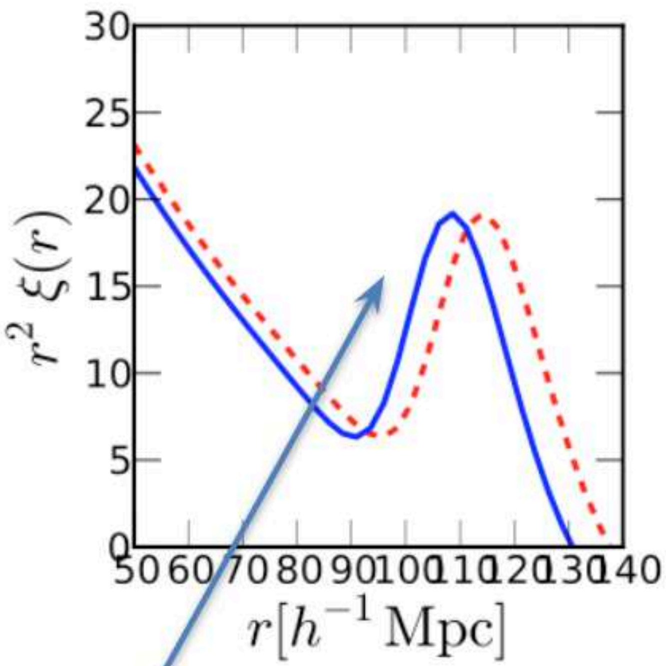
Fourier Transformation

Power spectrum

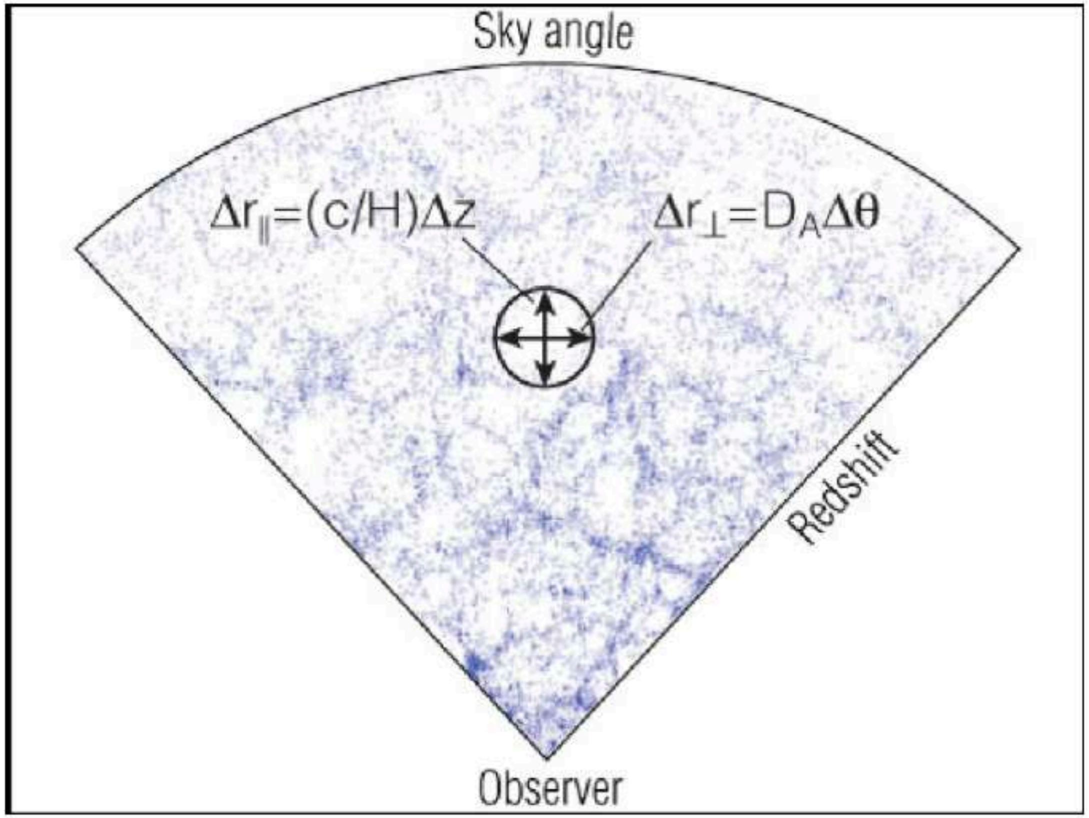
$$\left\langle \delta(\overrightarrow{k})\delta(\overrightarrow{k'}) \right\rangle = (2\pi)^3 \delta_D(\overrightarrow{k} - \overrightarrow{k'})P(k)$$

Position x Position: galaxy clustering
Position x Shape: galaxy lensing
Shape x Shape: cosmic shear

Measuring distance with standard ruler



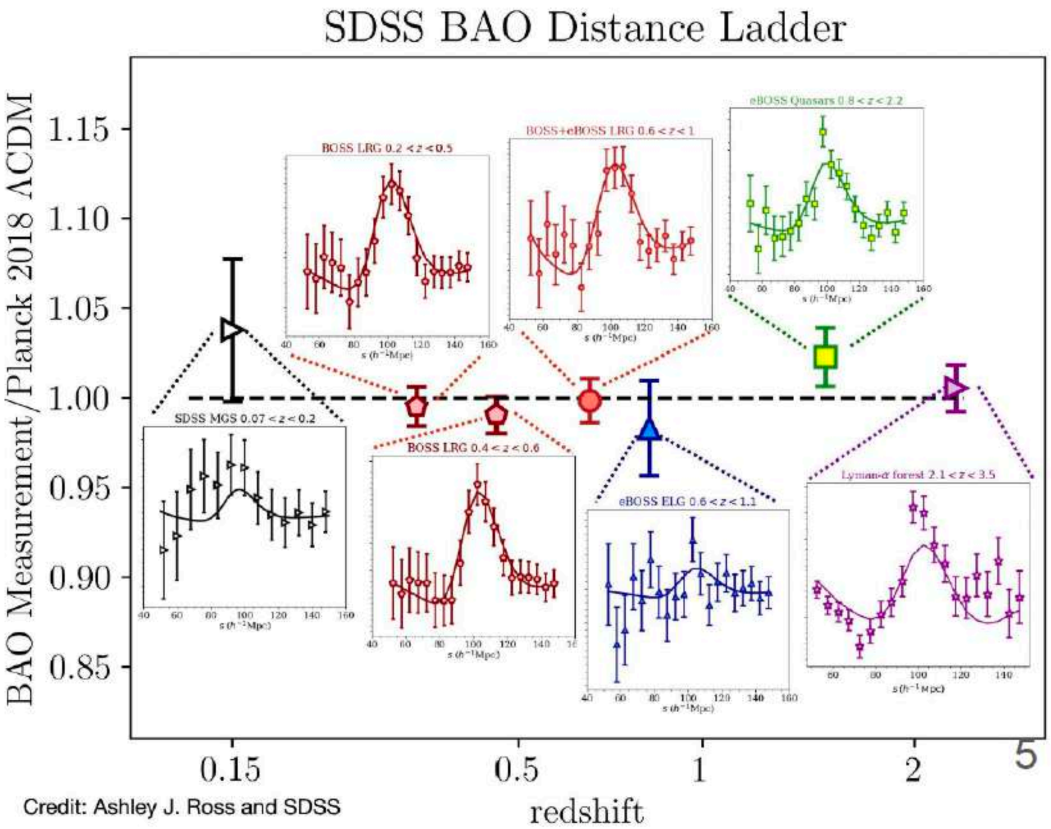
$$\alpha \equiv \left(\frac{D_{\mathrm{V}}(z)}{r_{\mathrm{d}}}\right)\left(\frac{r_{\mathrm{d,fid}}}{D_{\mathrm{V}}^{\mathrm{fid}}(z)}\right)$$



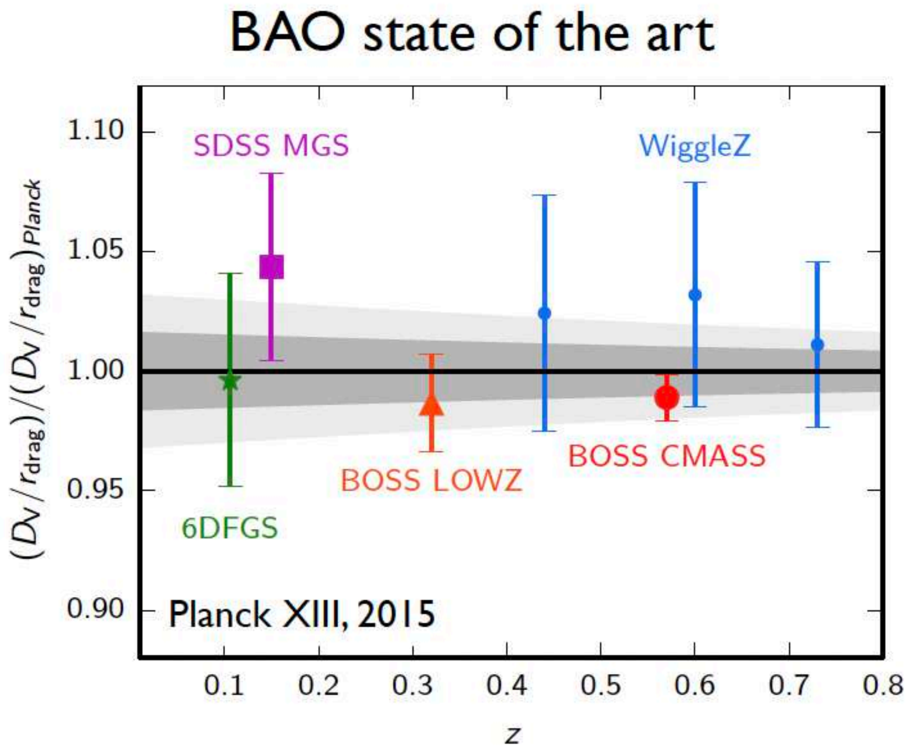
$$D_{\mathrm{V}} \equiv \left[cz(1+z)^2 D_{\mathrm{A}}(z)^2 H^{-1}(z)\right]^{1/3}$$

BAO distance measurement

- Planck CMB and BAO measurements are consistent under ΛCDM model
- Note that I am not including the recent result from Dark Energy Spectroscopic Instrument (DESI)

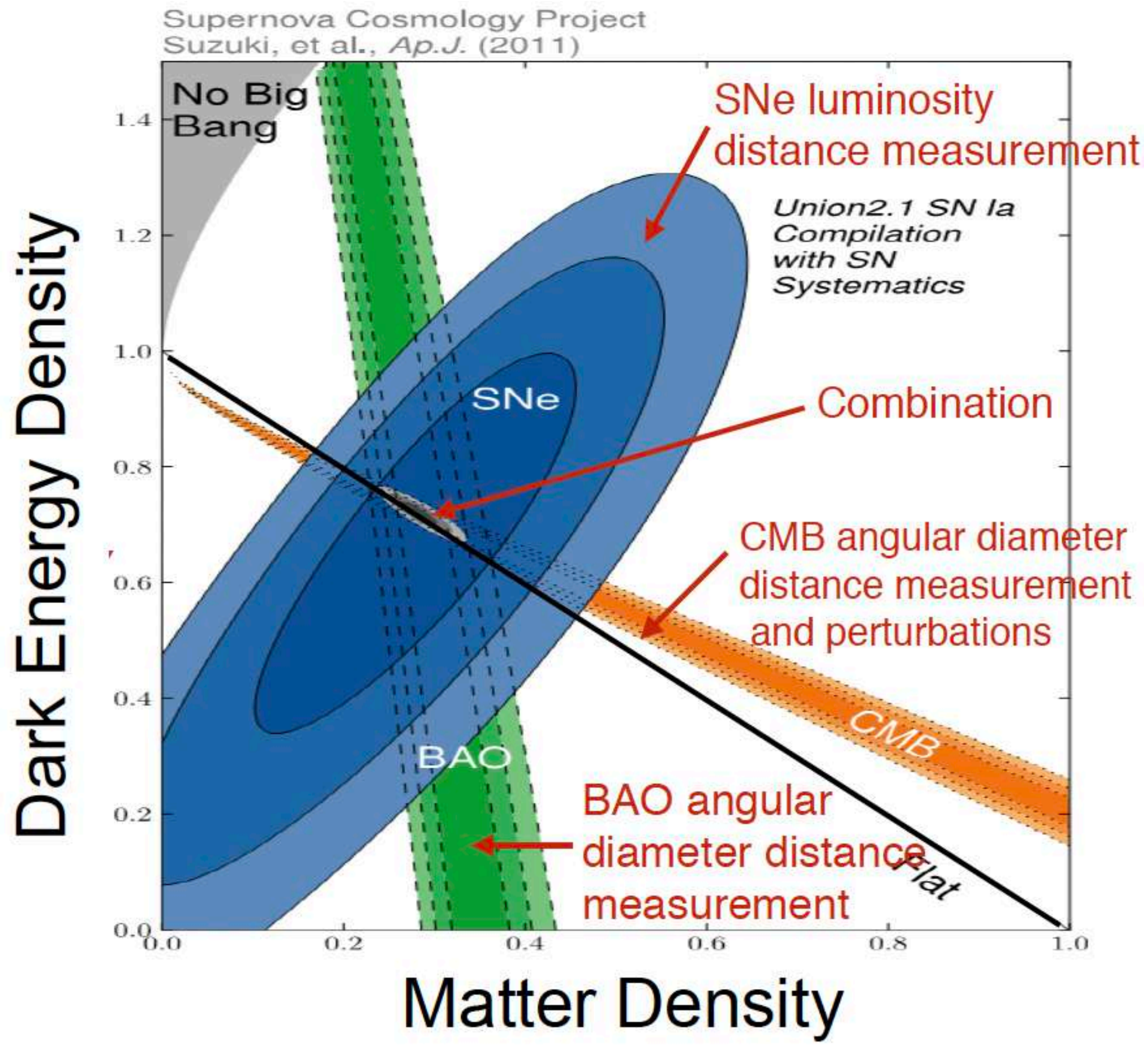


Credit: Ashley J. Ross and SDSS



Concordance Cosmology

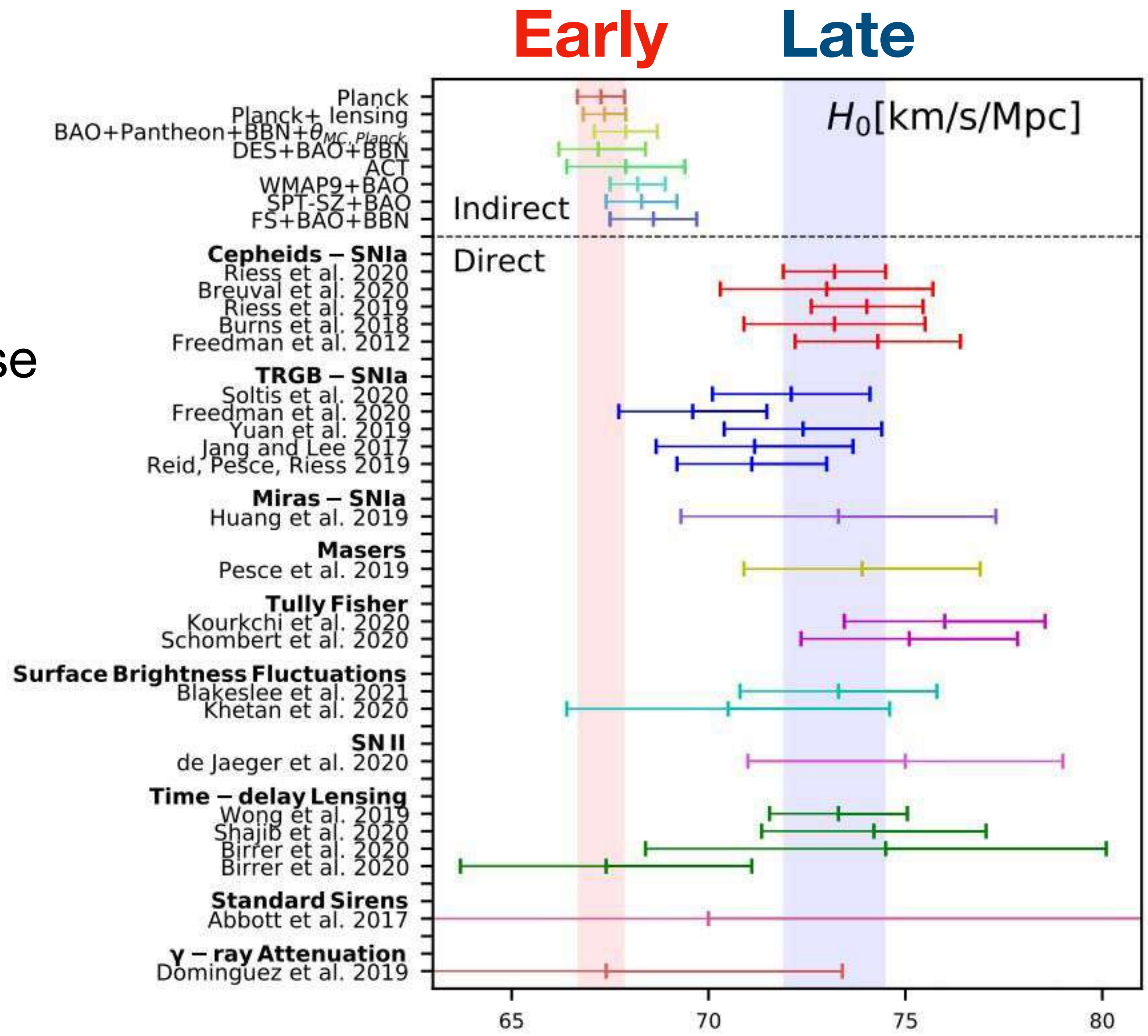
- CMB, SNe Ia, and BAO measurements seem to be consistent under Λ CDM model in early 2000s!



Credit: E. Krause

Concordance Cosmology…?

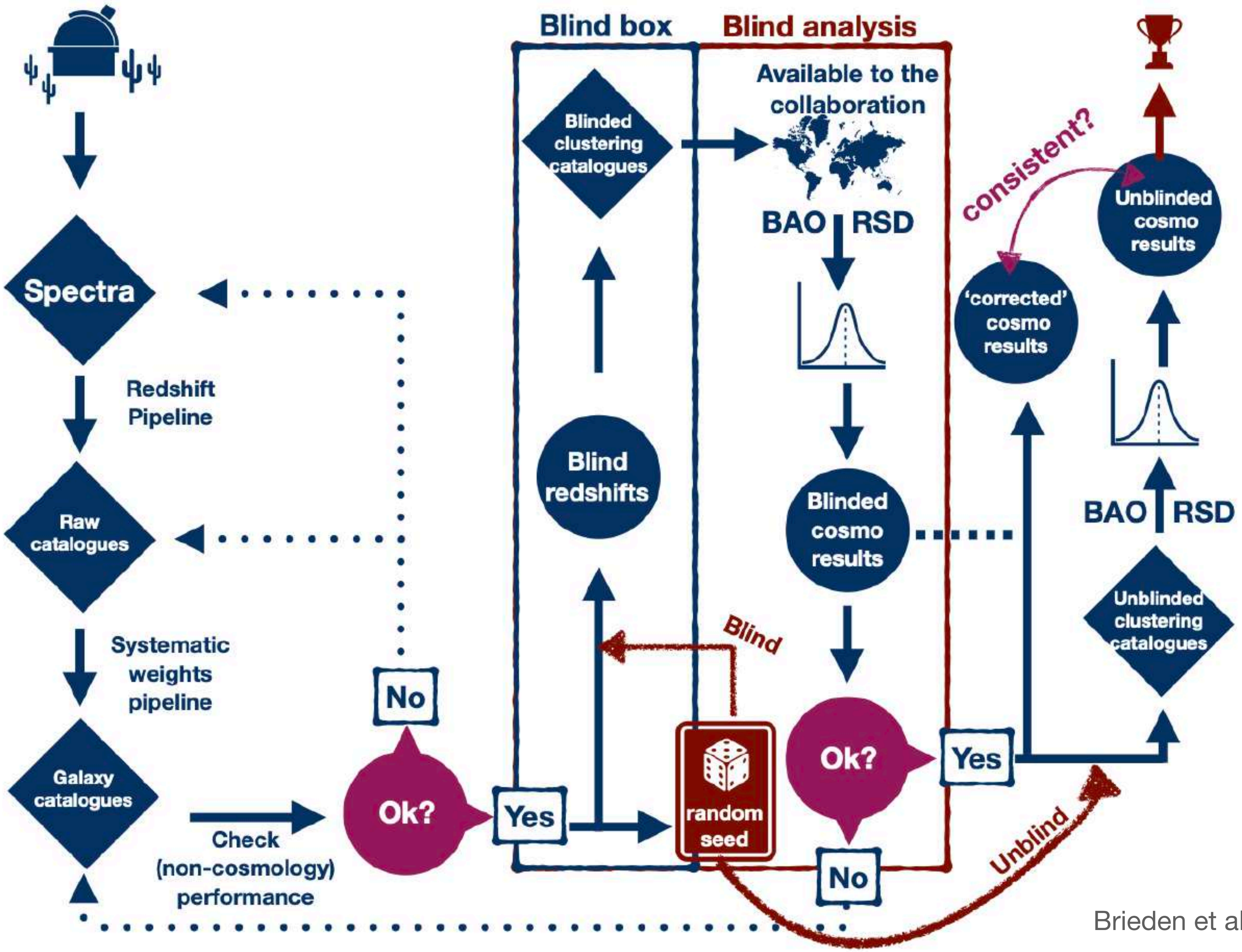
- Significant tension between early-Universe and late-Universe probes!
- “Hubble Tension”



DiValentino+2020

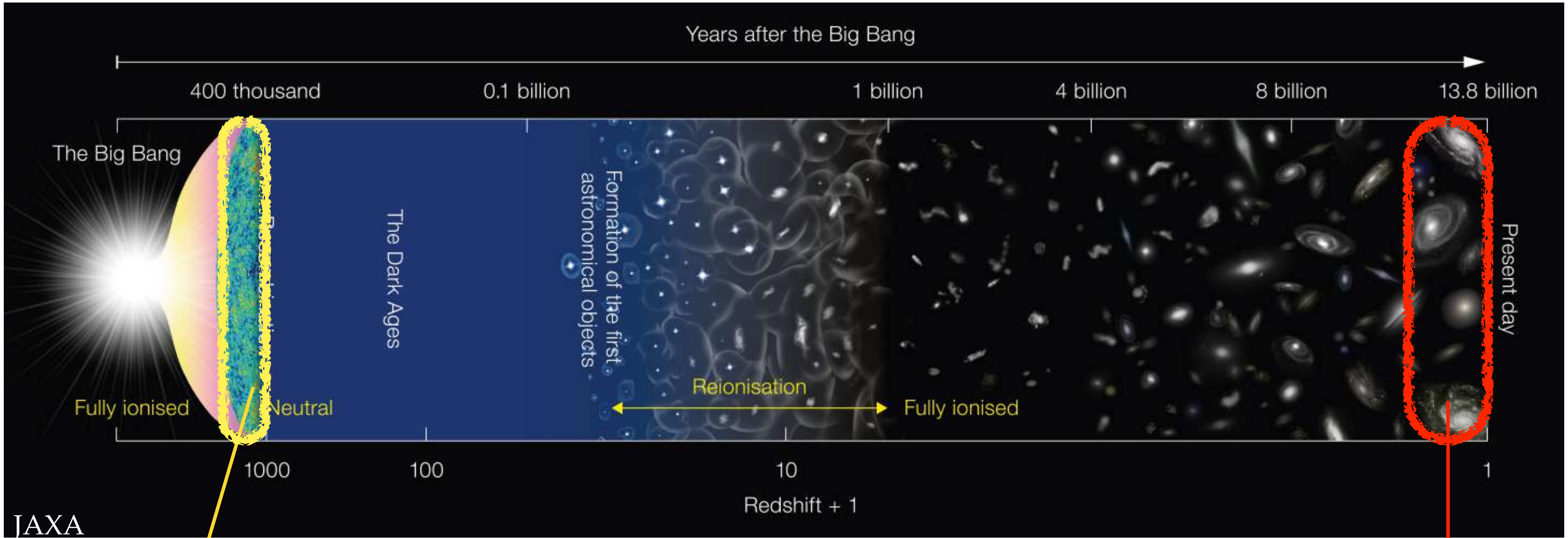
Blind Analysis

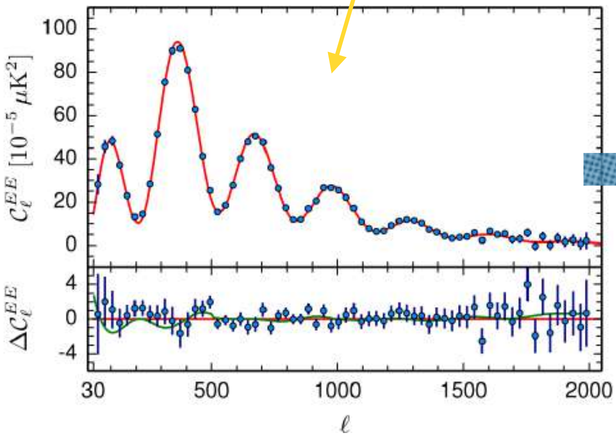
Avoid confirmation bias…



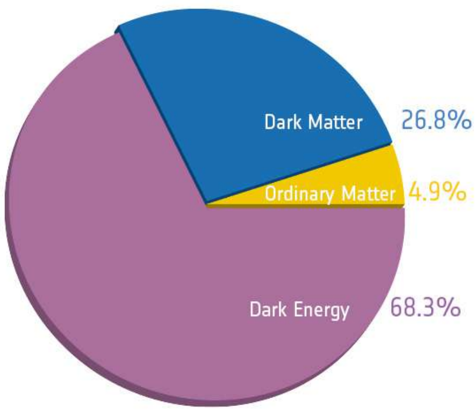
Brieden et al. 2020

Stress test ΛCDM using large-scale structure probes





ESA/Planck



?

Large scale structure probes

- Gravitational Lensing
- Galaxy clusters
- Galaxy clustering

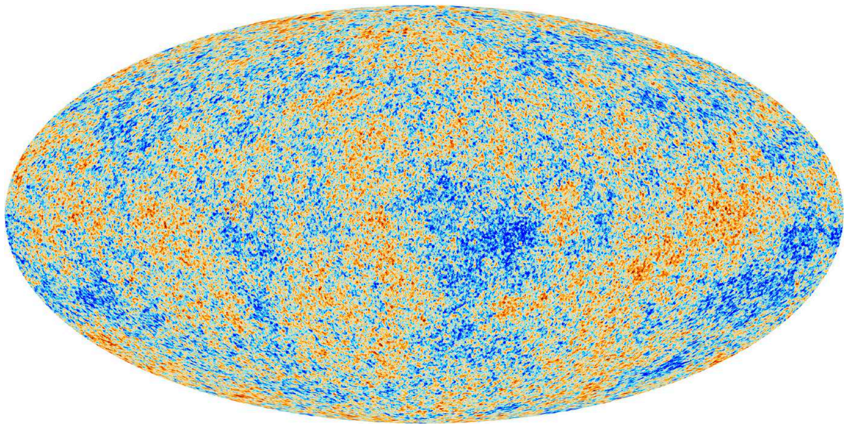
Test the evolution of the structure

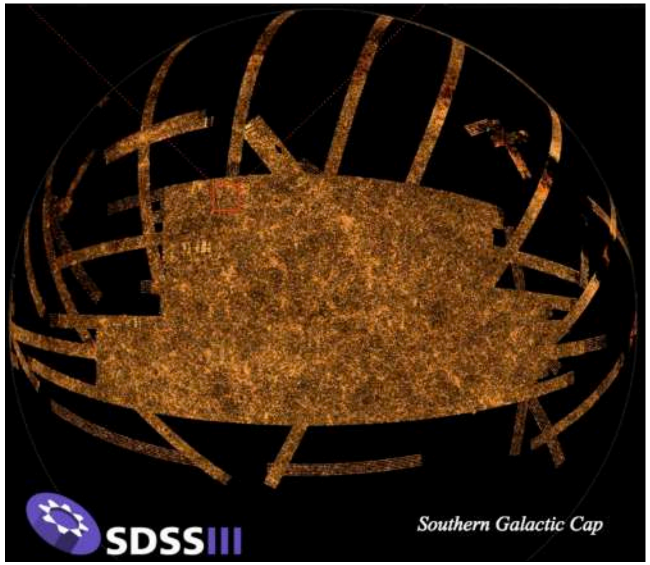
Amplitude of matter density fluctuations

A_s —— ΛCDM? ——→ σ_8

Primordial amplitude constrained by the CMB

Present-day amplitude constrained by late-time observations



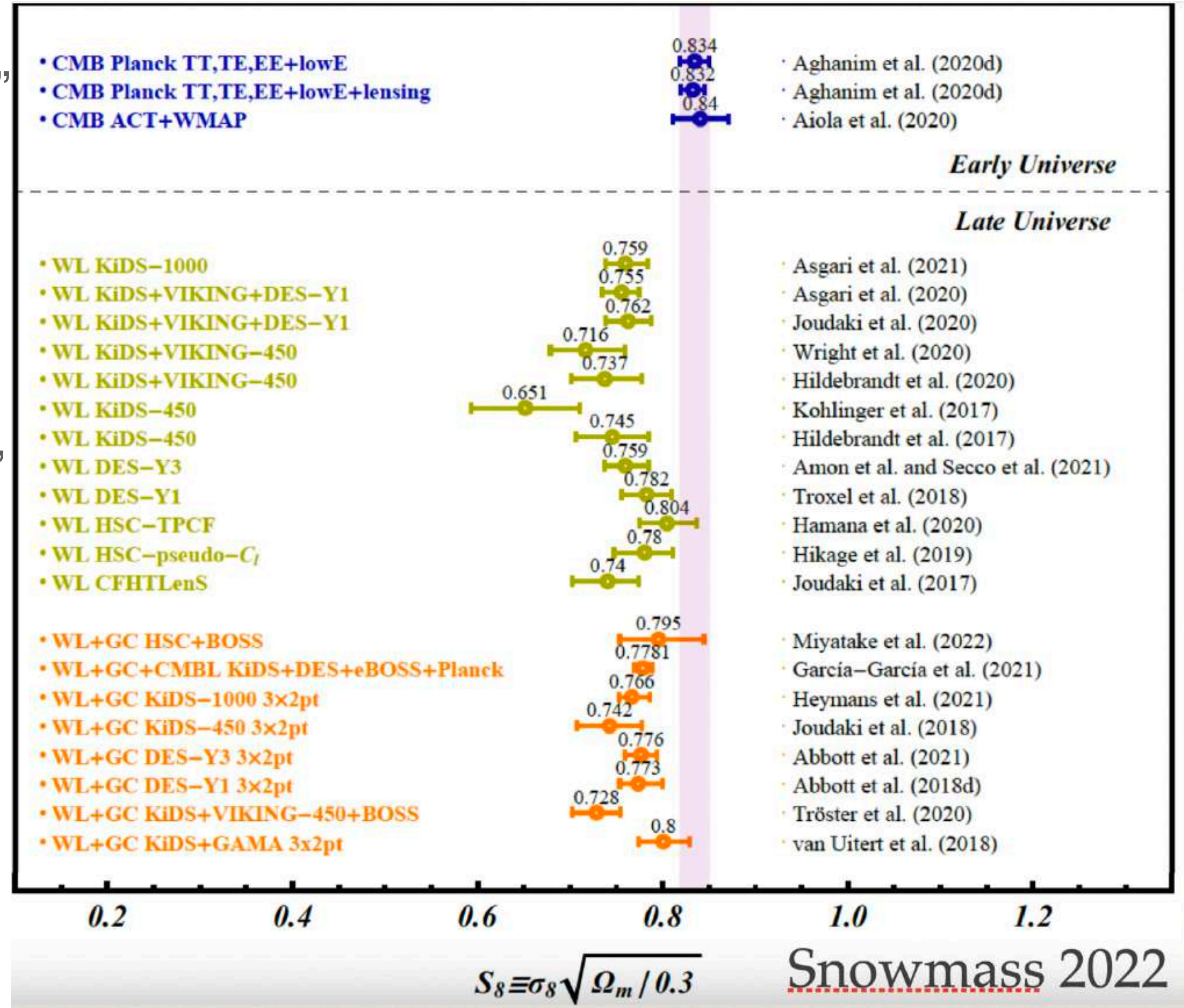


S8 Tension: accumulated evidence of disagreement

- σ_8 measures "clumpiness" of the Universe

"Early-Universe probe"

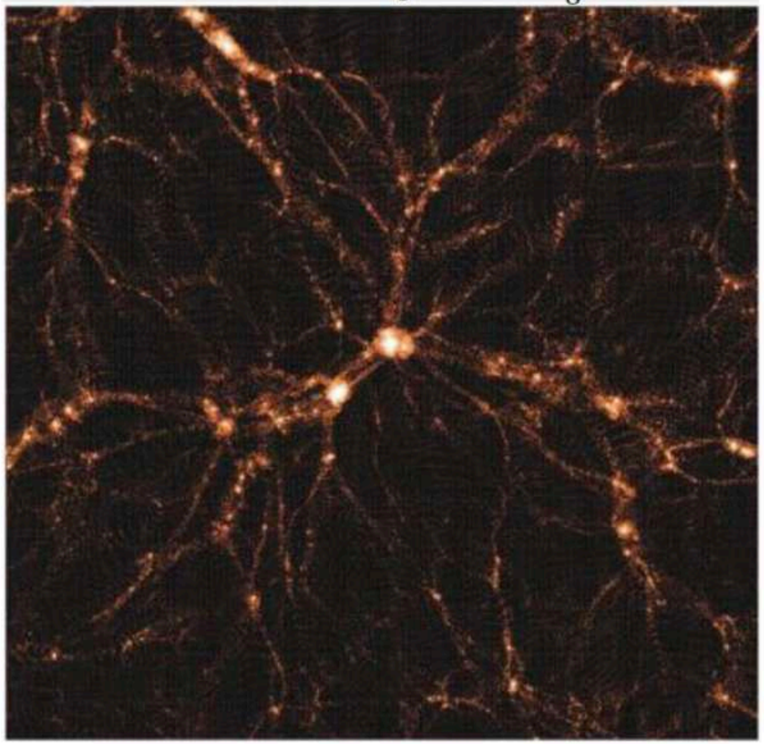
"Late-Universe probe"



How does S8 tension look like?

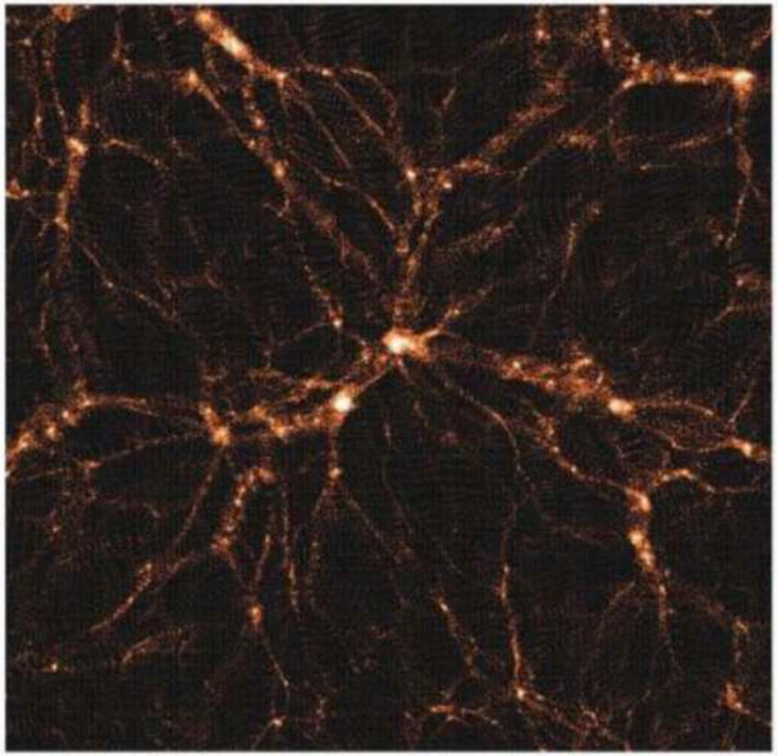
- Comparison between the Universe measured from HSC-Y1 lensing and predicted from Planck CMB

Planck 2020 Primary CMB: $S_8 = 0.83$



Planck Collaboration (2020)

HSC-Y1 cosmic shear: $S_8 = 0.78$



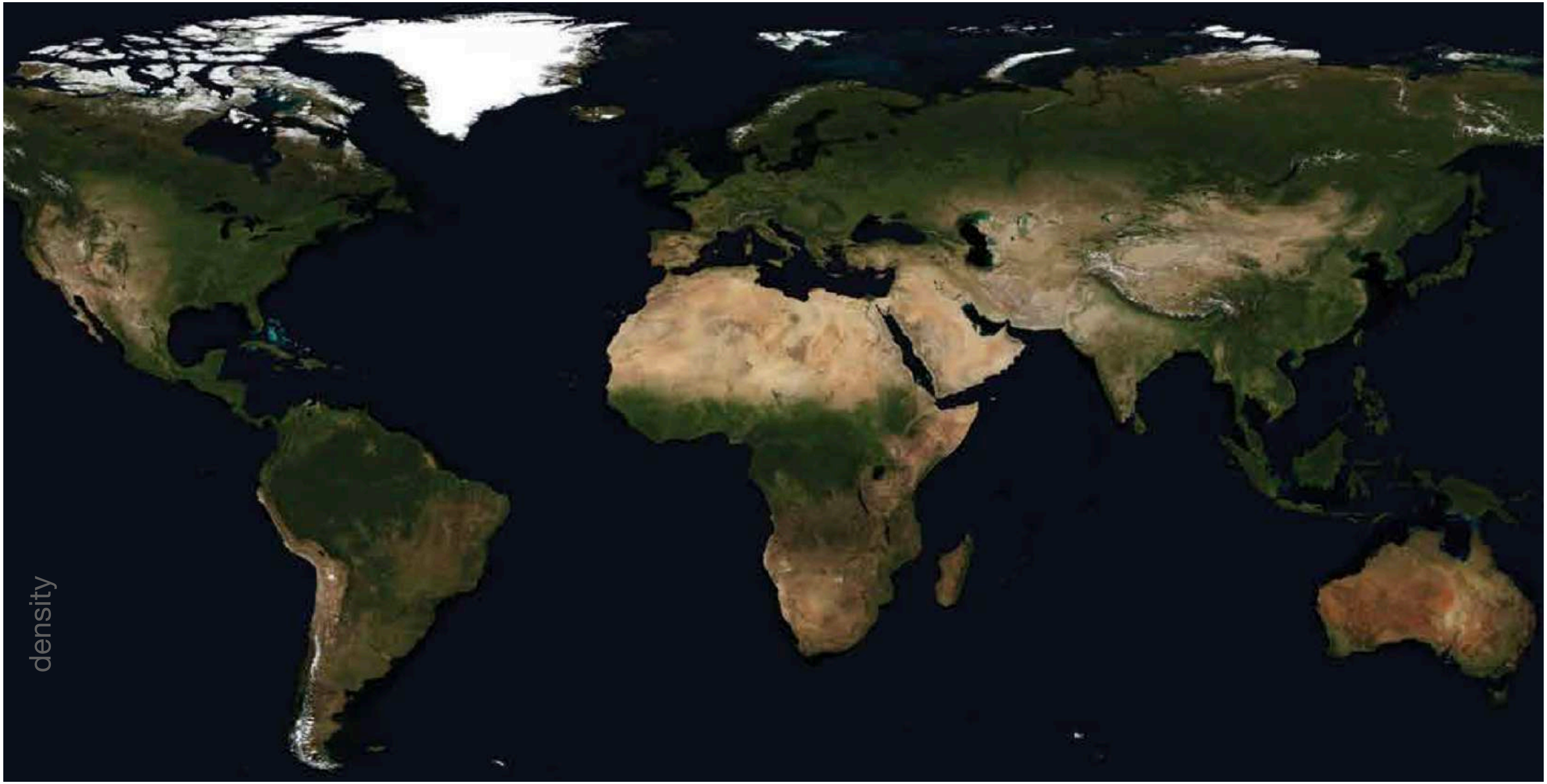
Hikage et al. (2019)

Credit: Takahiro Nishimichi

The difference by eye is really subtle! (i.e. era of precision cosmology)

Why measuring σ_8 is hard?

We want to measure mass distribution like this...



Credit: NASA

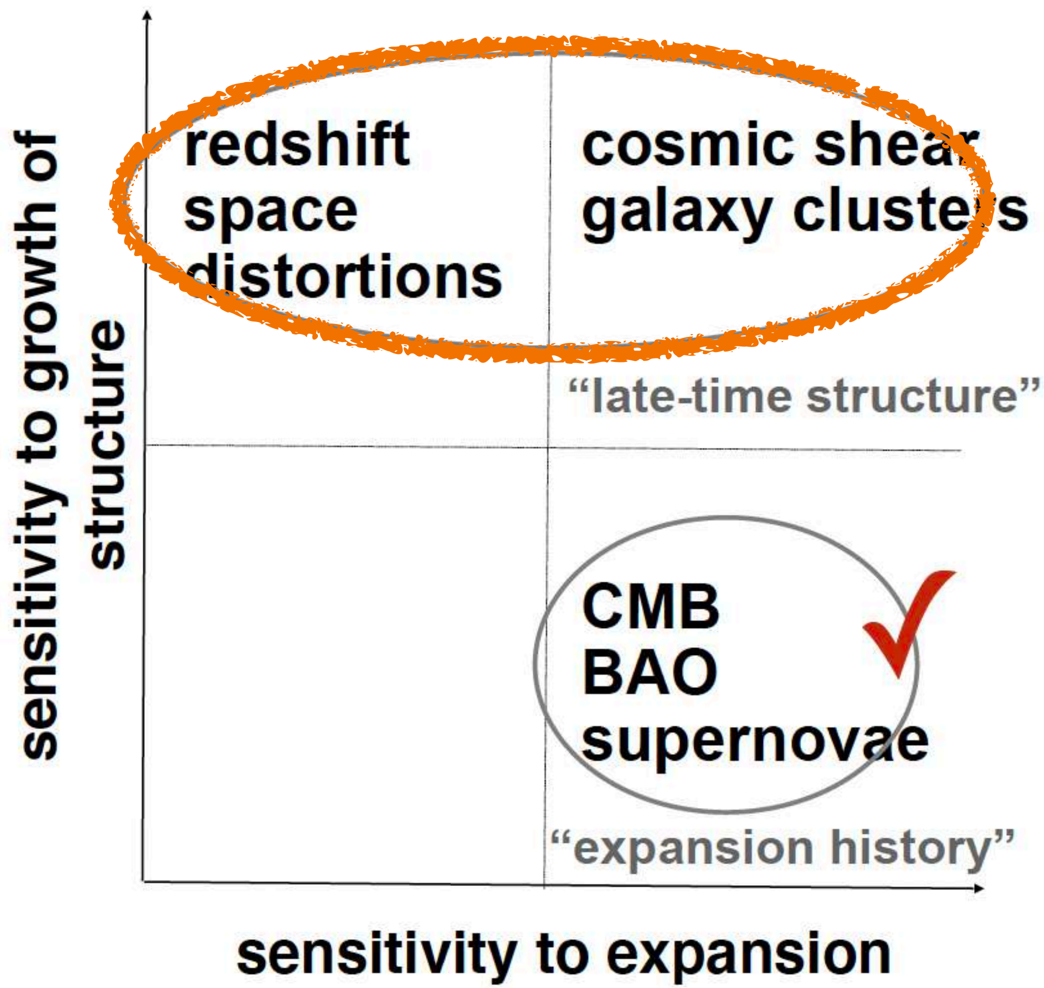
This is all we can see…

Light from galaxies: galaxies are a biased tracer of DM

Credit: NASA

Cosmological probes for growth of structure

- Redshift-space distortion through galaxy clustering
- Cosmic shear through weak gravitational lensing
- Galaxy clusters



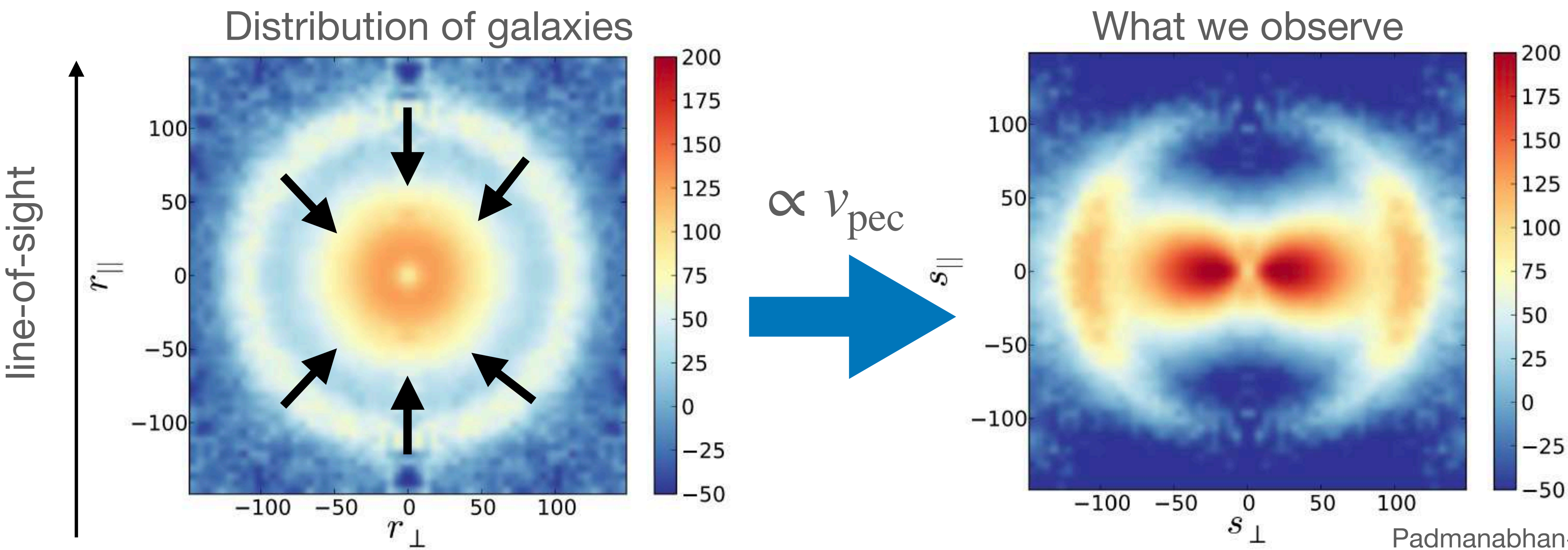
Credit: E. Krause

Redshift-Space Distortion (RSD)

- Redshift is a combination of Hubble expansion and peculiar motion of galaxies → isotropic galaxy distribution becomes anisotropic in redshift-space

$$cz = H_0 r + v_{\rm pec}$$

Redshift "What we measure" | Expansion of the Universe | Motion of Galaxies



Padmanabhan+2012

Redshift-Space Distortion (RSD)

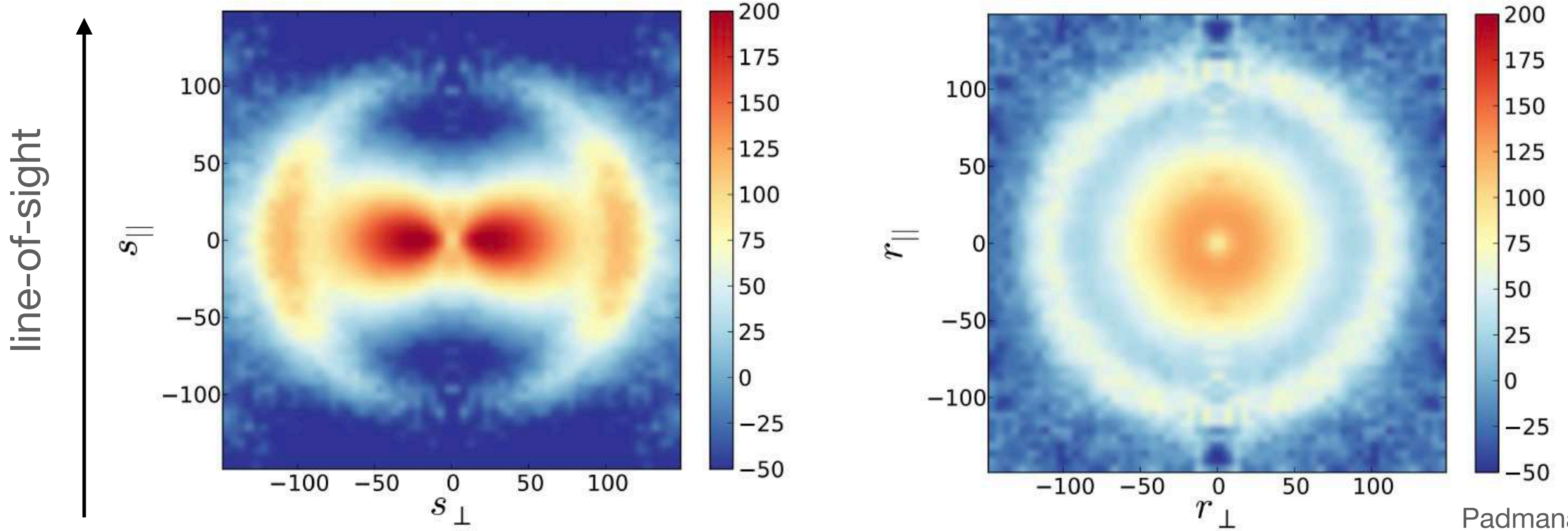
- On large scales, peculiar velocity can be computed as a function of growth rate

$$|v_{\rm pec}| \sim \frac{d\sigma_8}{d\ln a} = f\sigma_8 \quad \text{where} \quad f = \frac{d\ln\sigma_8}{d\ln a} \approx \Omega_m^{\gamma}$$

$$\delta_g^{(s)}(k,\mu) = (b + f\mu^2)\,\delta_m^{(r)}(k)$$

"redshift-space"(s) "real-space"(r)

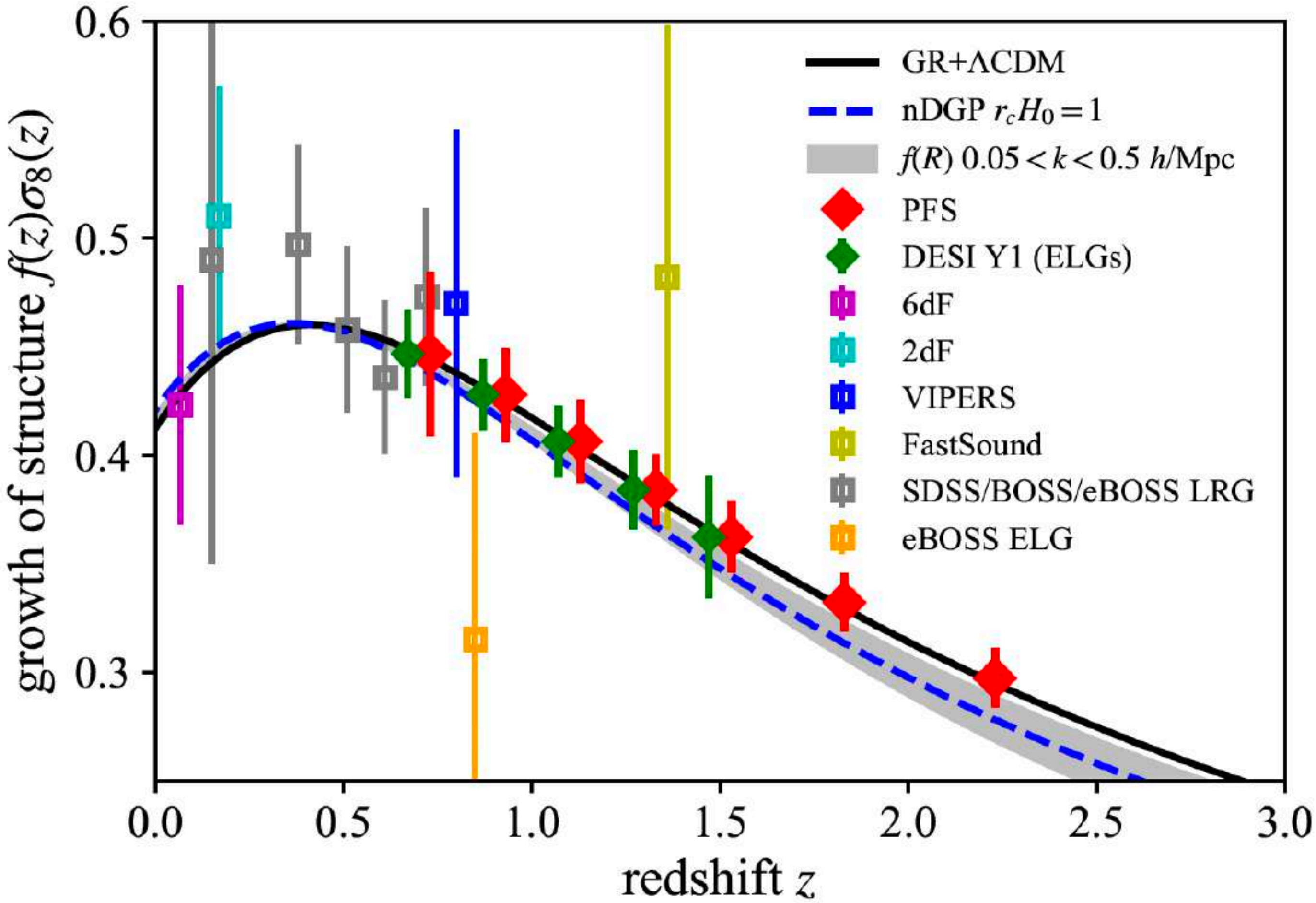
μ is angle between r and LOS



Padmanabhan+2012

Forecast for DESI Y1 and PFS in a few years

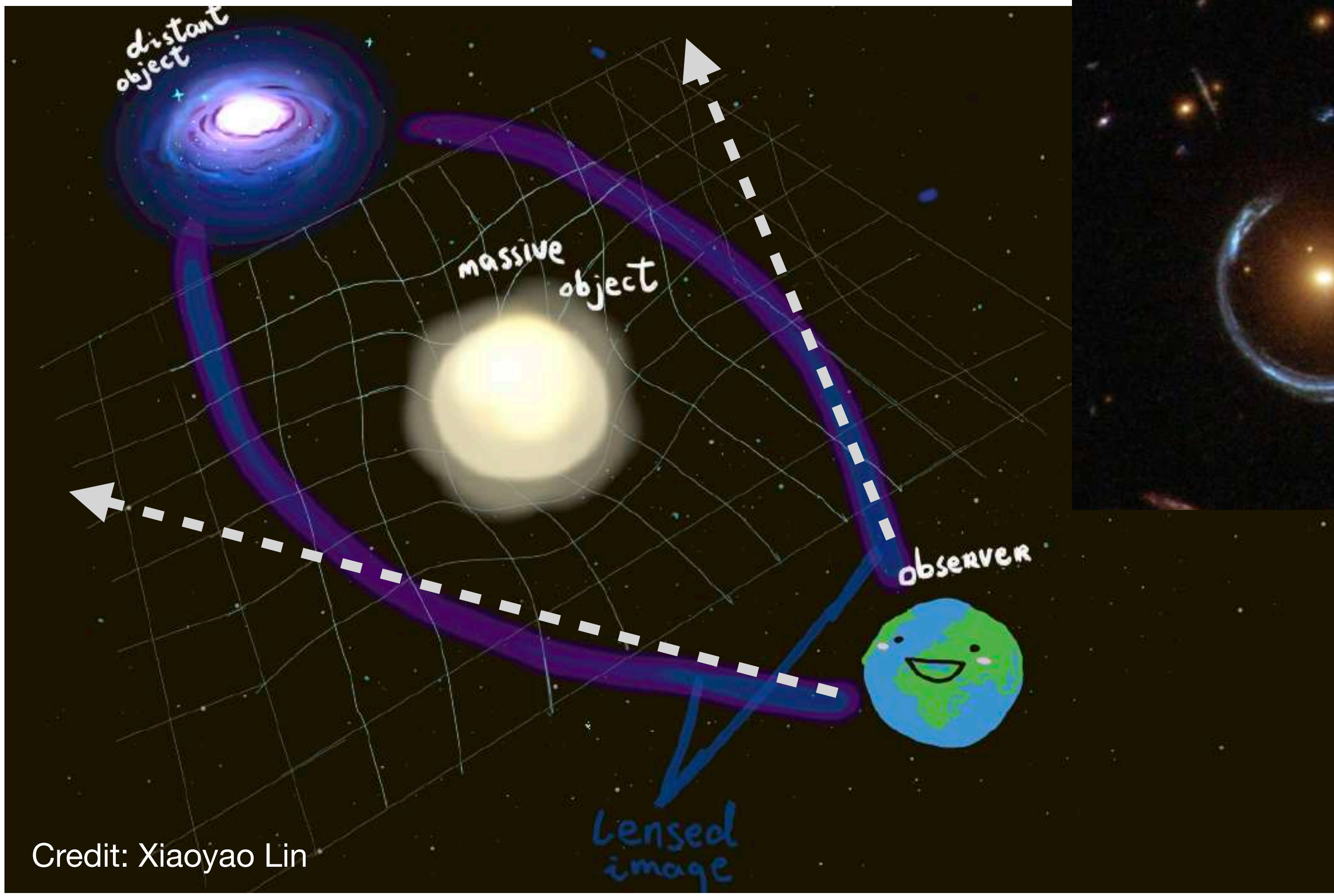
- Can constrain the growth of structure with 6% up to z~2.4

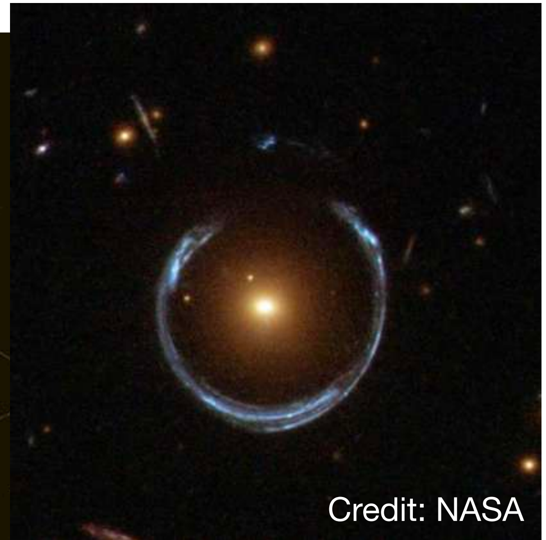


PFS forecast: TS+,in prep.

Gravitational Lensing

- When massive objects in the Universe distort spacetime, the path of light around it is bent, as if by a lens.
- Create multiple images of the same objects or distort the image of galaxies (strong lensing)

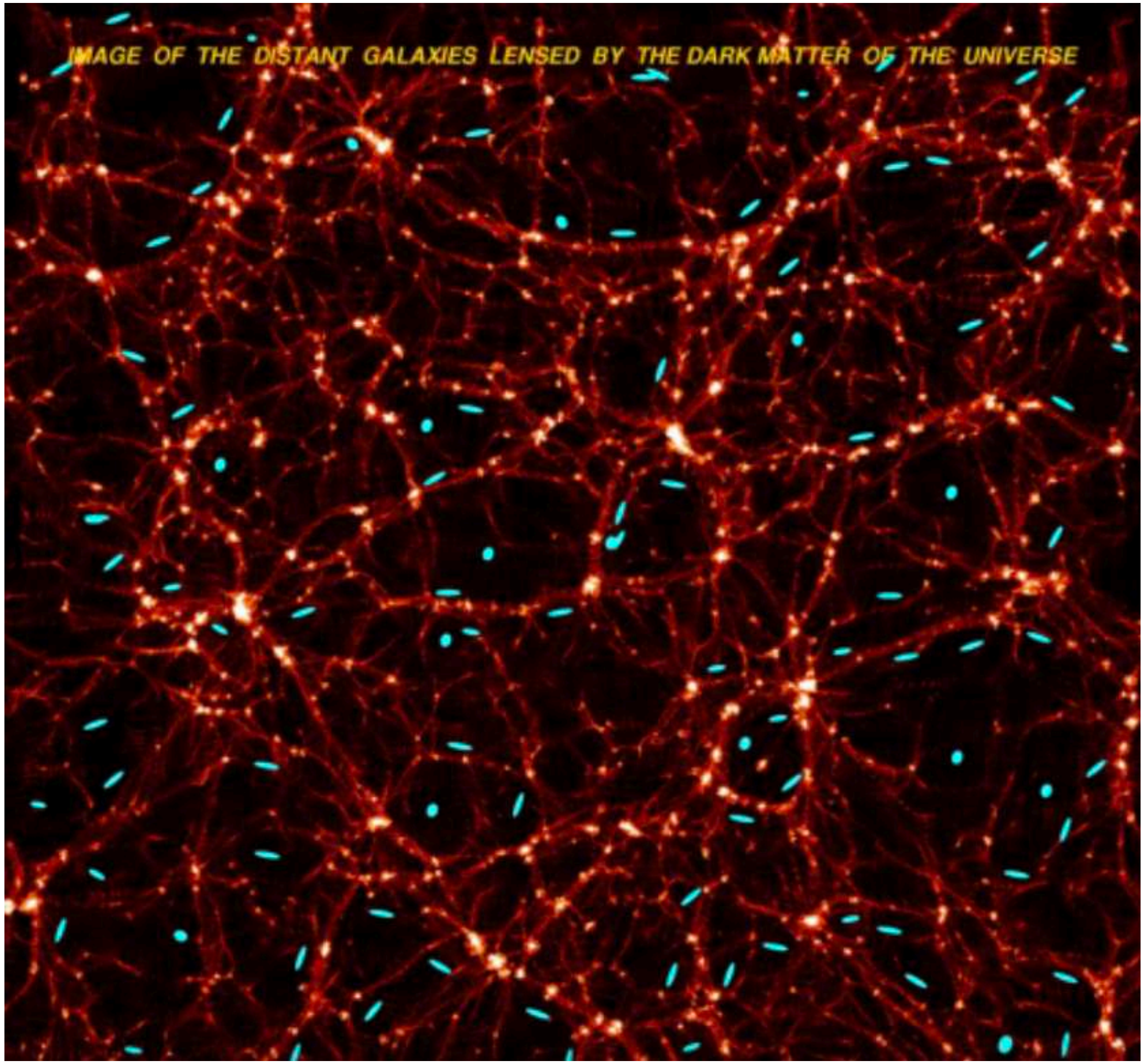




Weak Gravitational Lensing

Can measure halo mass of clusters

- Coherent distortion of galaxy shapes (“shear”)



Credit:CFHT

Weak Gravitational Lensing

Can measure halo mass of clusters

- Coherent distortion of galaxy shapes ("shear") is ~1% effect
- Required many galaxy images!

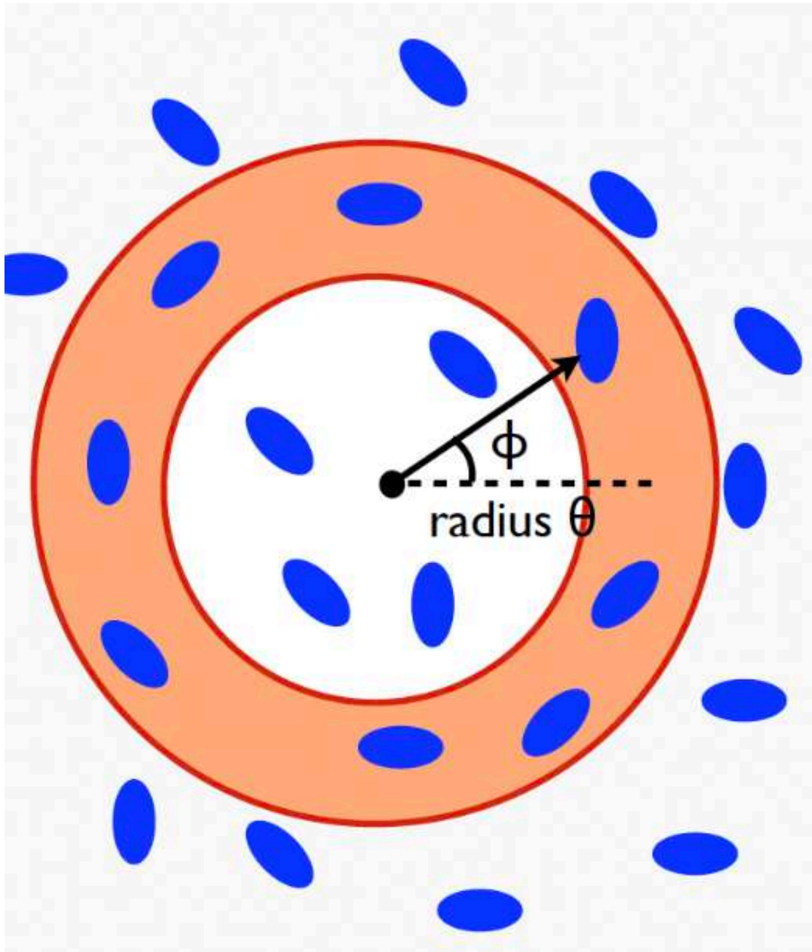
Credit: S. Bridle

$$\gamma \propto \frac{D_A(z_l, z_s) D_A(z_l)}{D_A(z_s)} \delta(z_l)$$

Weak lensing shear

Geometry of the Universe

Matter density fluctuation



Credit: M. Oguri

Weak Gravitational Lensing

Can measure halo mass of clusters

- Coherent distortion of galaxy shapes ("shear") is ~1% effect
- Required many galaxy images!

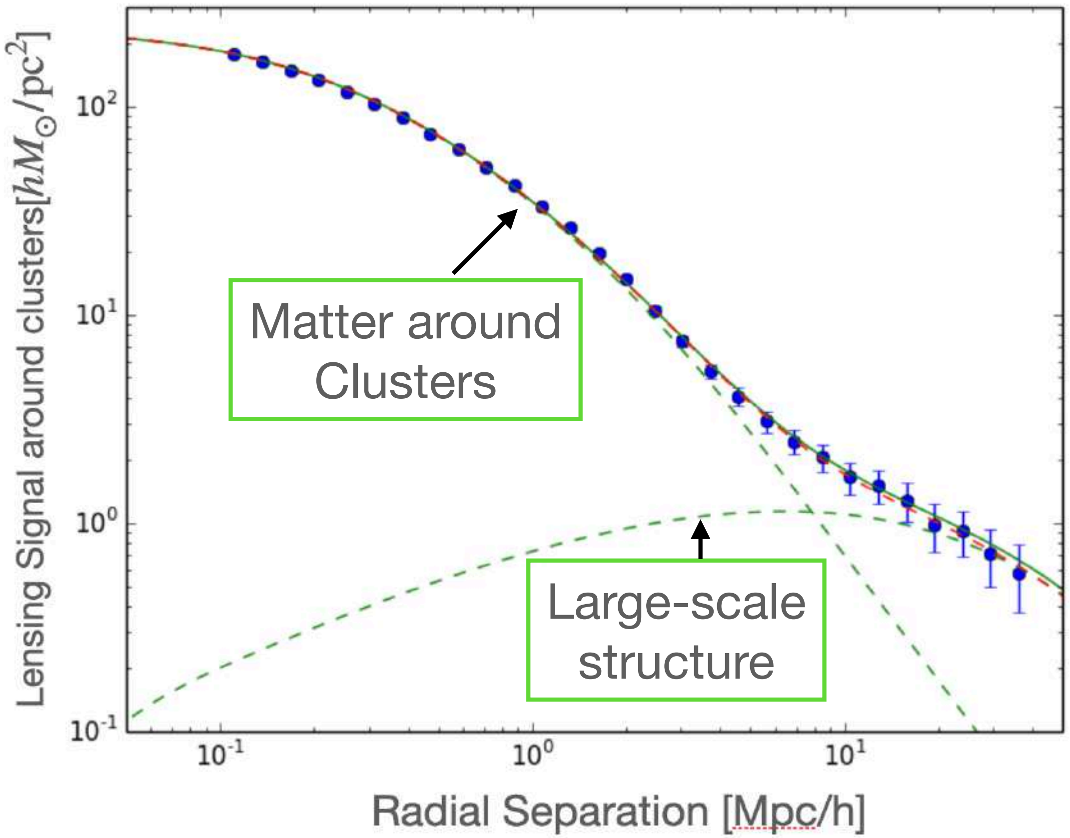
Credit: S. Bridle

$$\gamma \propto \frac{D_A(z_l, z_s) D_A(z_l)}{D_A(z_s)} \delta(z_l)$$

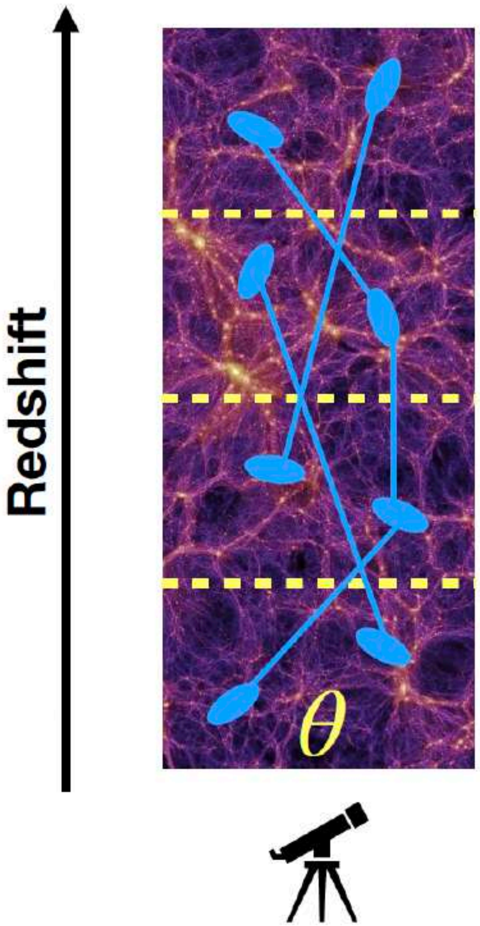
Weak lensing shear

Geometry of the Universe

Matter density fluctuation



Cosmic Shear



$$\xi_{\pm}(\theta) = \langle \gamma_+(\theta')\gamma_+(\theta'+\theta)\rangle_{\theta'} \pm \langle \gamma_\times(\theta')\gamma_\times(\theta'+\theta)\rangle_{\theta'}$$
$$\sim \xi_{\rm mm}(\theta; \sigma_8, \Omega_{\rm m})$$

Note: θ is angular scales (not separation between galaxies)

Correlation can be computed within a redshirt bin or across redshift bins

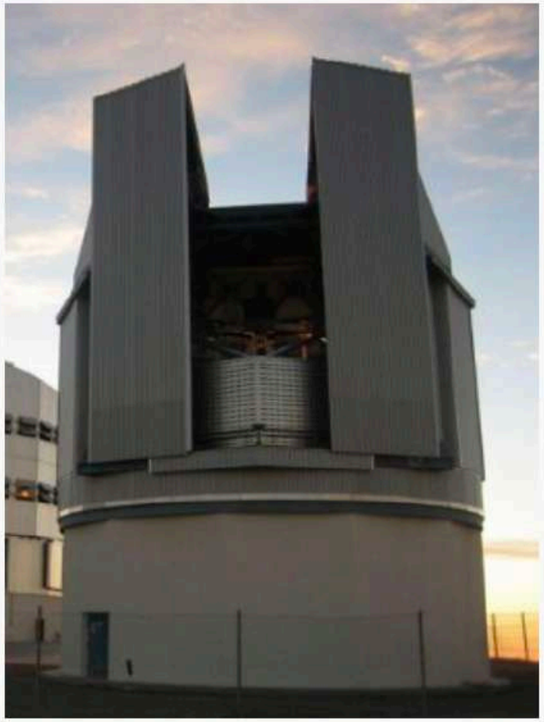
Fourier space measurements $C_{\rm EE}(l)$, $C_{\rm BB}(l)$ are also common now.

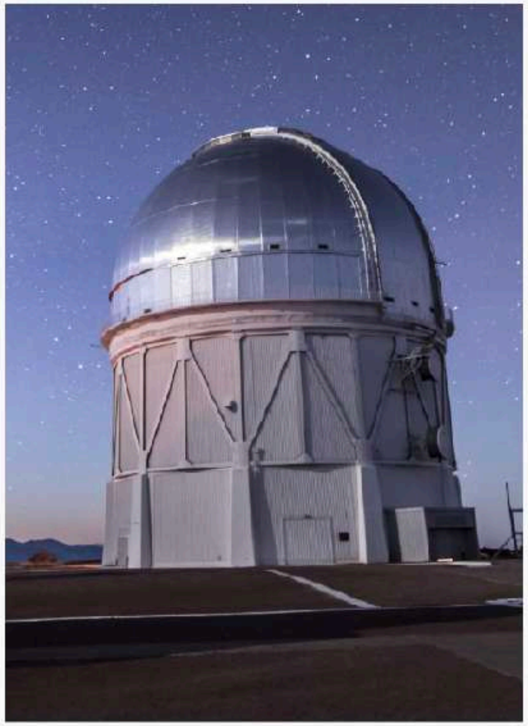
Credit: Millennium Simlations

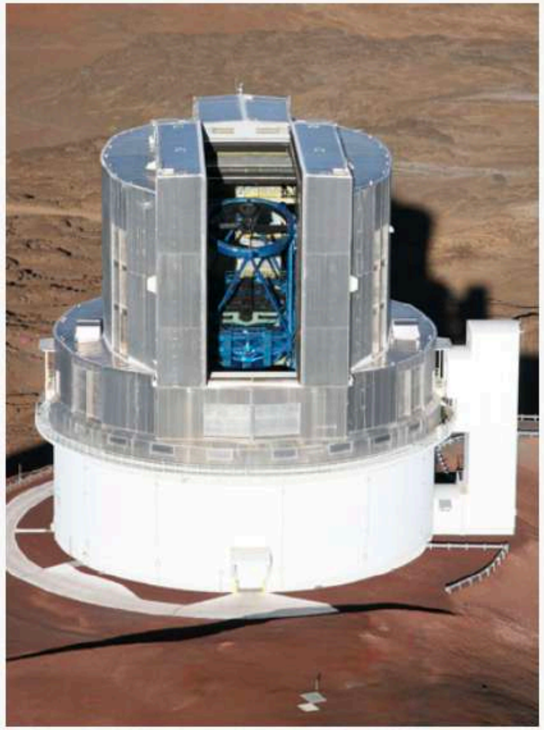
Cosmic Shear Surveys

Imaging/Photometric Galaxy Surveys

- 'stage-III' dark energy surveys





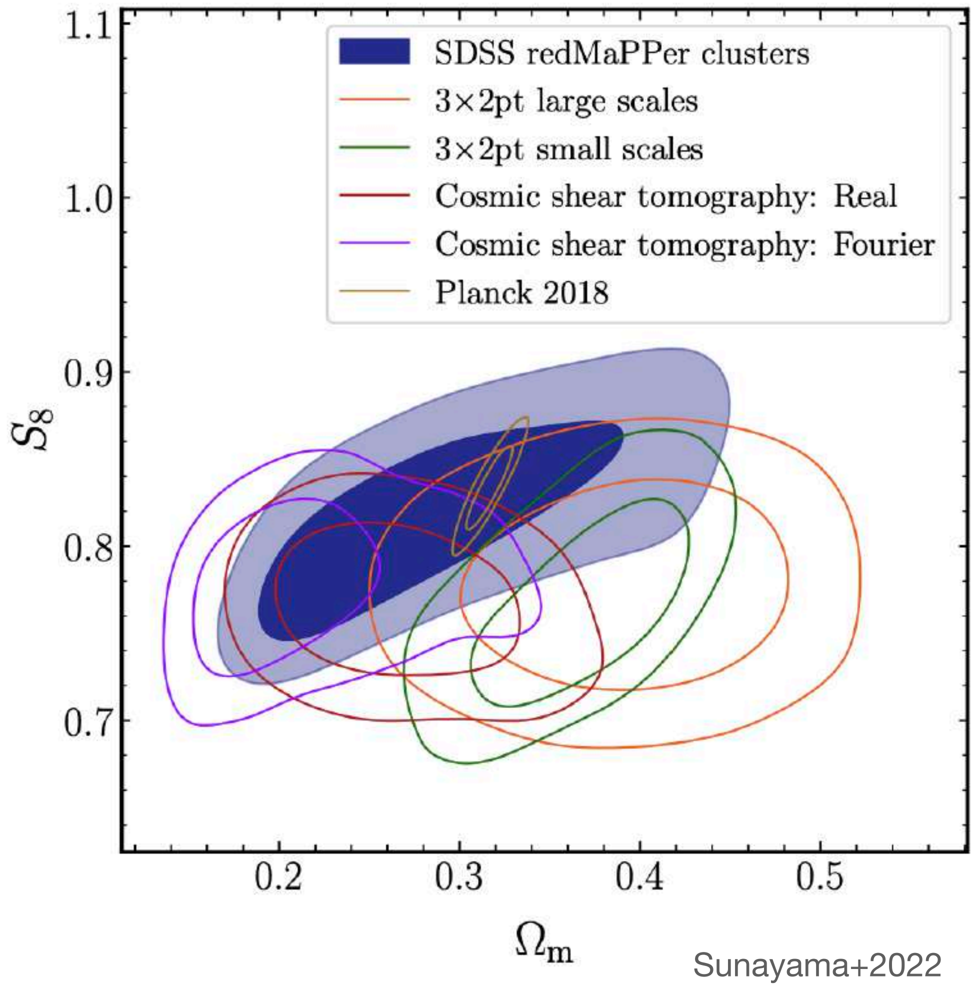


KiDS (2012-2019) **DES** (2013-2019) **HSC** (2014-2020)

1500 deg^2, r_{lim}~25 5000 deg^2, r_{lim}~25 1400 deg^2, r_{lim}~26

Result from HSC Y3

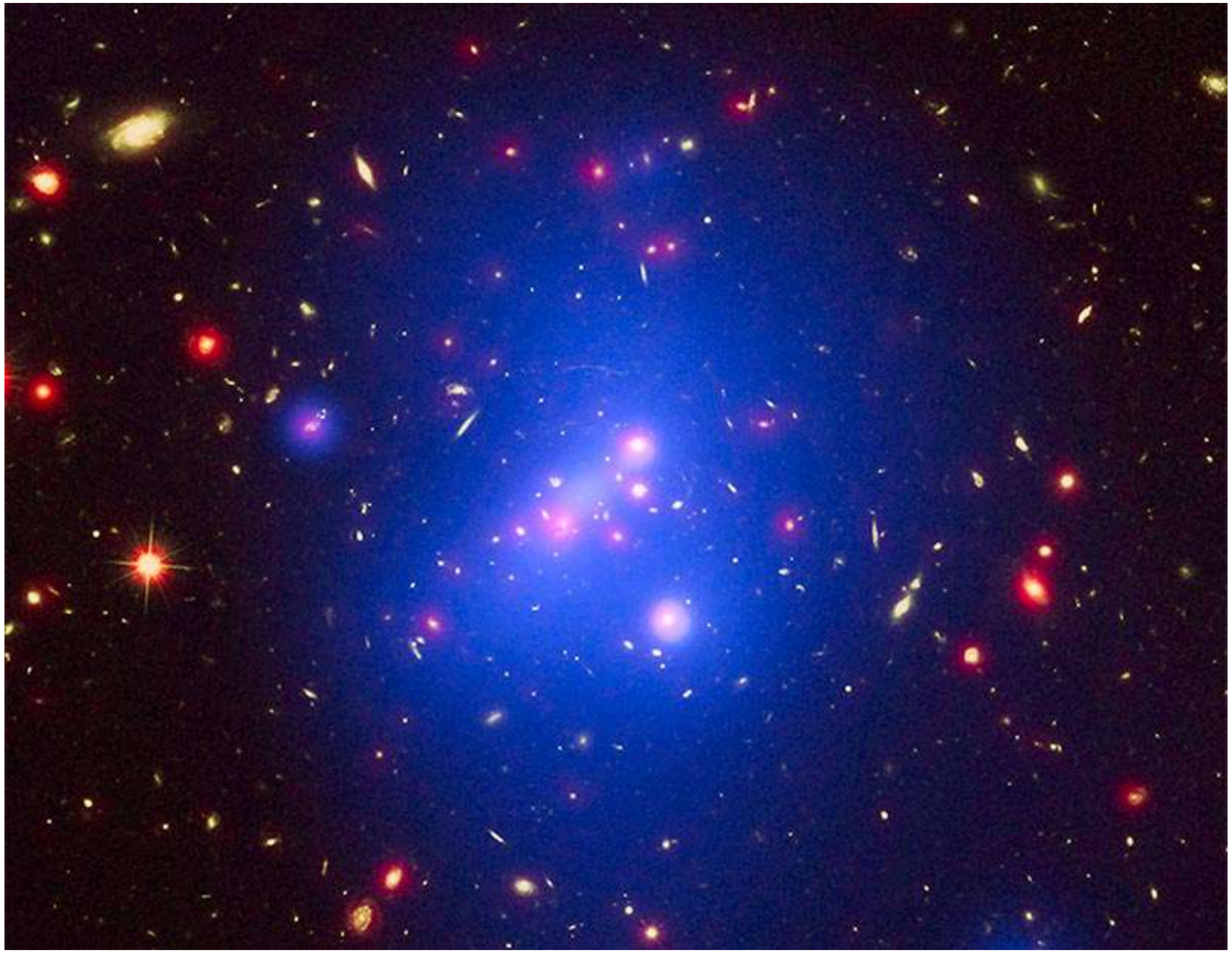
- Mild tensions (~2σ) between cosmic shear and Planck CMB measurements



Sunayama+2022

Galaxy Clusters

The most massive self-gravitationally bound object



Credit: NASA/CXC/U. Missouri/STScI/JPL/CalTech

- Mass~$10^{14} - 10^{15}\mathrm{M}_{\odot}/h$
- Size~a few Mpc/h

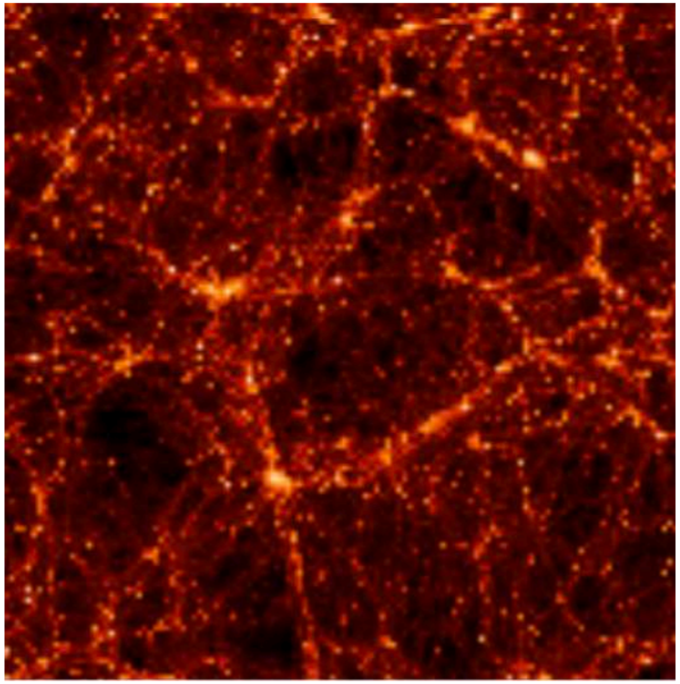
(Mpc=3×10^{19}km)

- “Optical”: identified from imaging (photometric) data by finding over-dense regions of galaxies

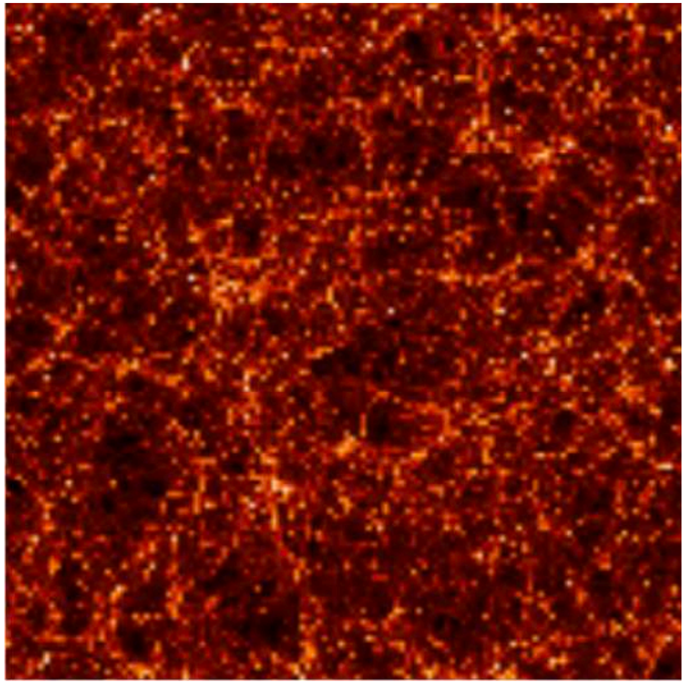
Clusters as a cosmological probe

- Count the number of clusters (as a function of cluster mass)

With Dark Energy



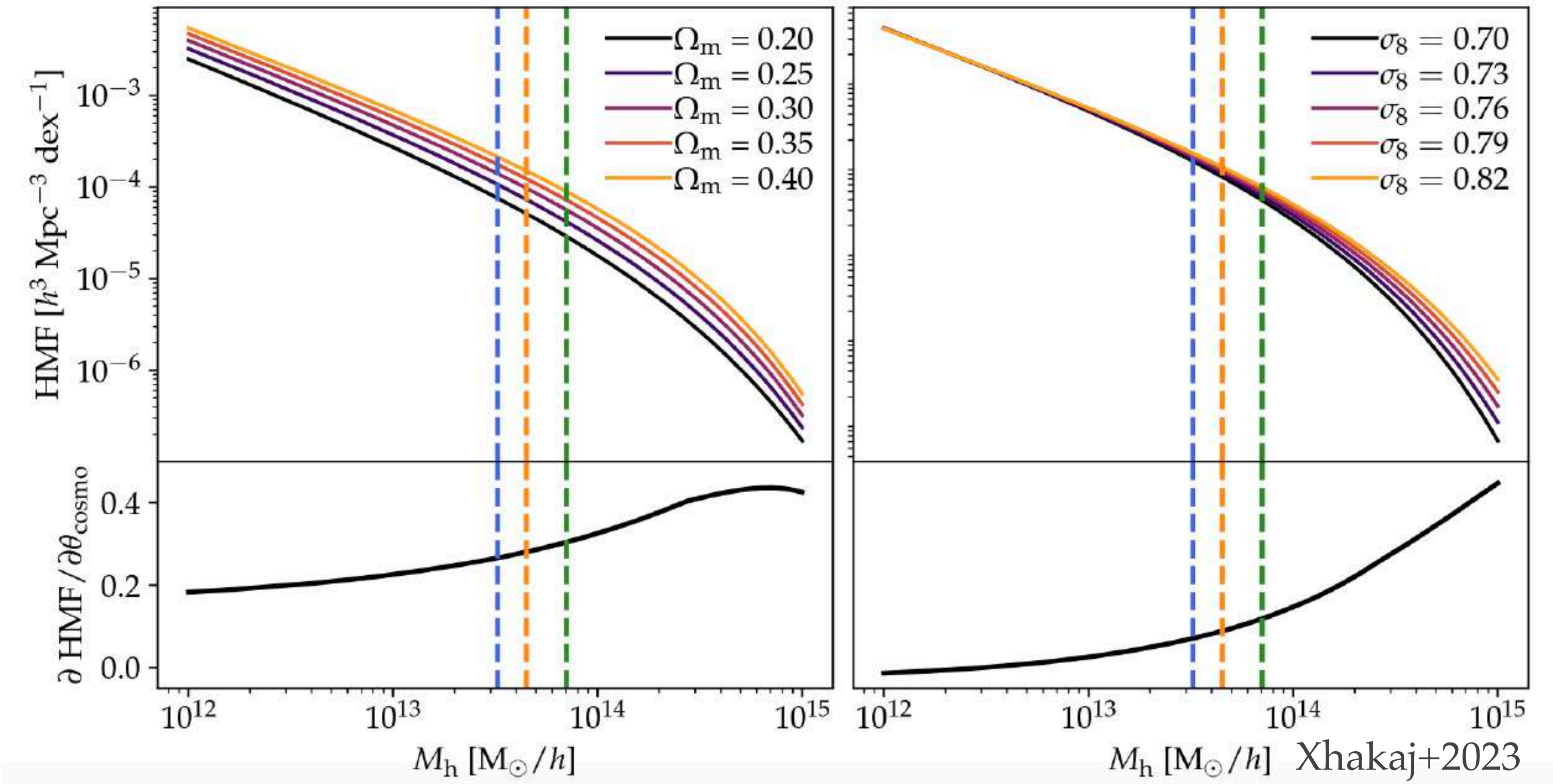
Without Dark Energy



Virgo consortium

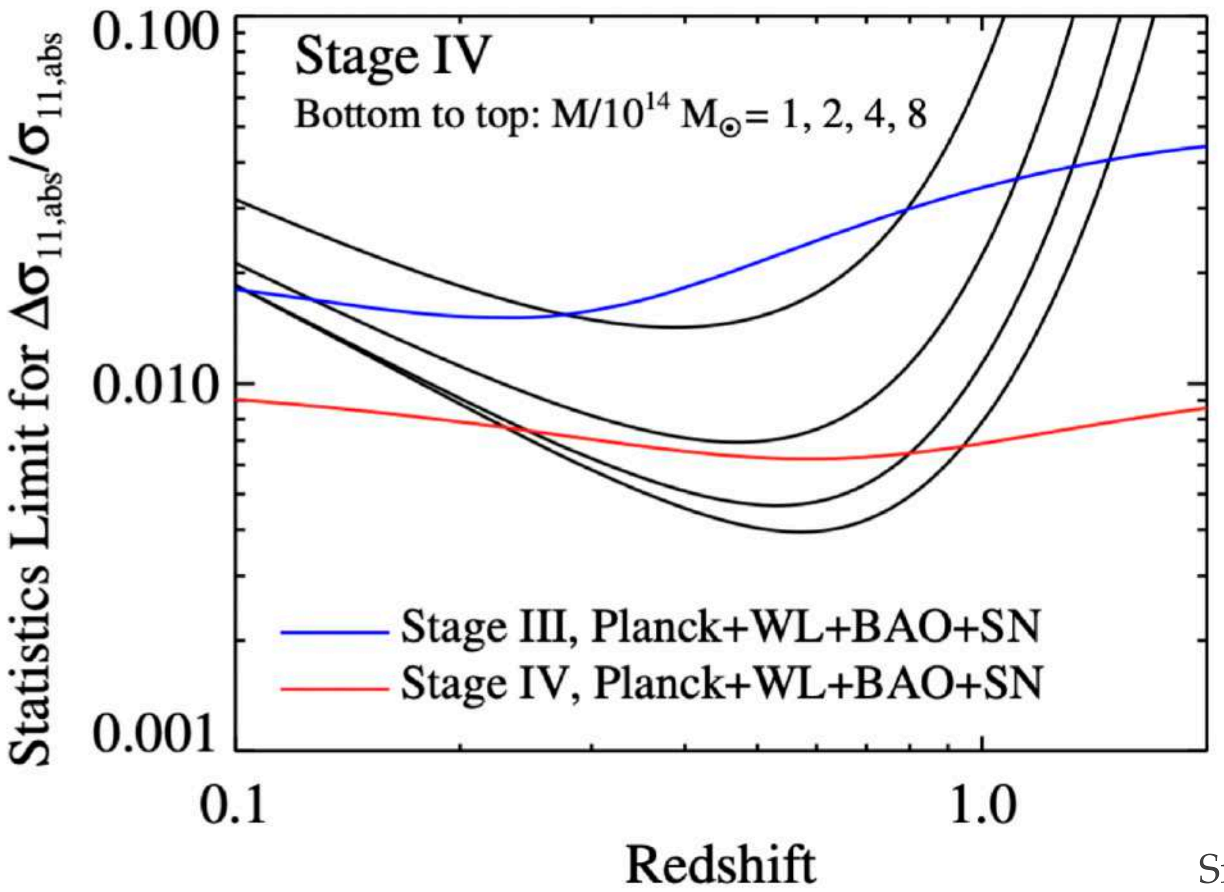
Clusters as a cosmological probe

- Background cosmology (i.e., Ω_m) impacts the number density
- Clusters form from the highest density peaks in the initial density field
- σ_8 (="clumpiness"): higher σ_8 → more high-density peaks → more massive clusters



Clusters can be powerful…

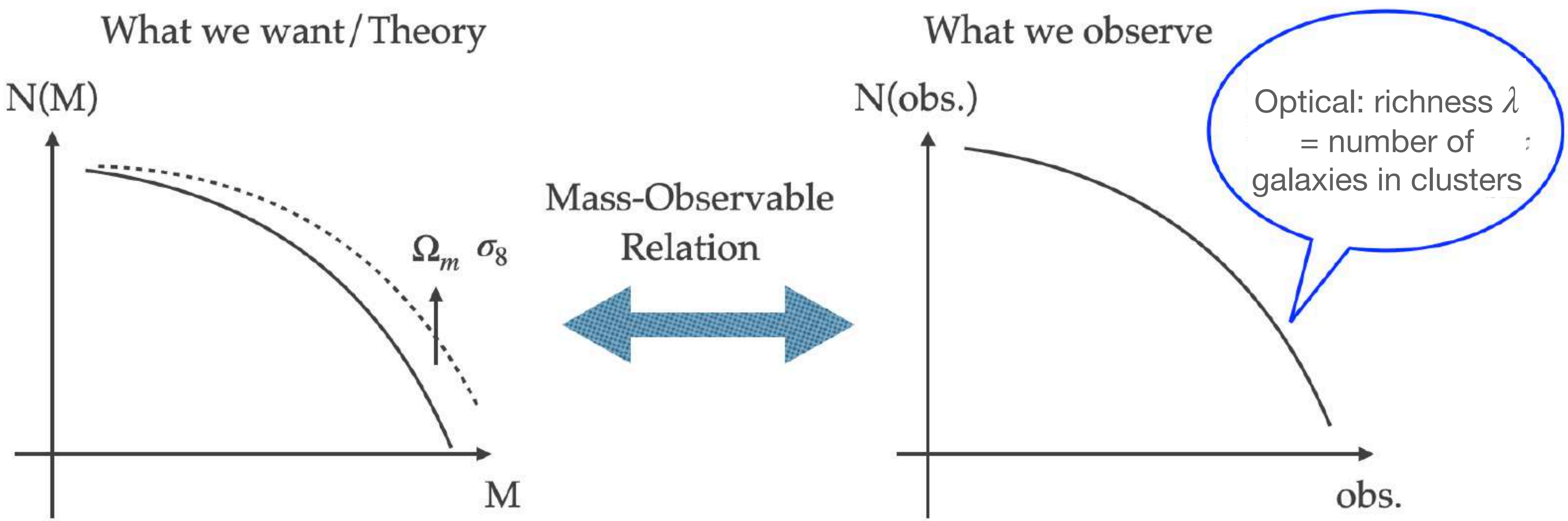
- Cosmic Visions Report (2016): " The number of massive galaxy clusters could emerge as the most powerful cosmological probe…"



Snowmass2013; Huterer et al.

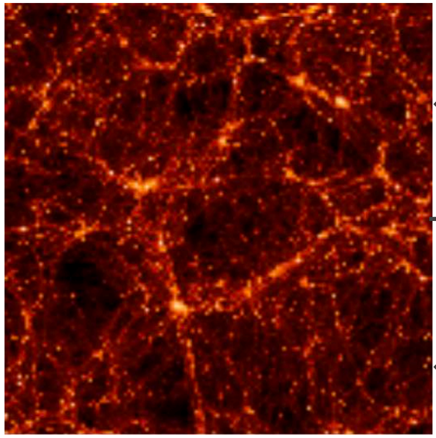
Challenge in Cluster Cosmology

- Cosmic Visions Report (2016): “ The number of massive galaxy clusters could emerge as the most powerful cosmological probe if the masses of the clusters can be accurately measured.”
- Cluster mass is not a direct observable

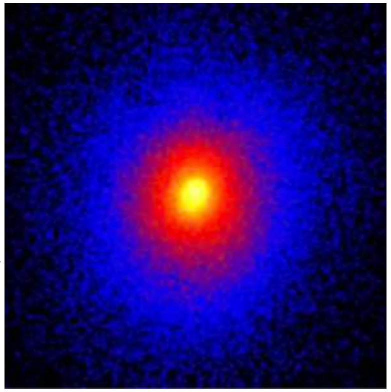


Challenge in Cluster Cosmology

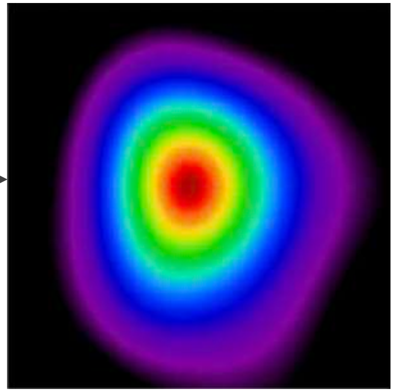
Theory: N-body



Millennium-II



X-ray
- X-ray brightness (L_x)
- High purity and completeness
- Scatter in mass-L_x
- Mass limit increases with redshift



CMB: Sunyaev-Zel'dovich (SZ) Effect
- Inverse Compton scattering of CMB photons in hot cluster gas
- SZ decrement (Y_{SZ})
- Redshift independent mass selection threshold
- Limited to massive clusters

Optical
- Number of galaxies (=richness λ)
- High completeness
- Susceptible to correlated structure
- No follow-up survey for gravitational lensing !

Small

Systematics

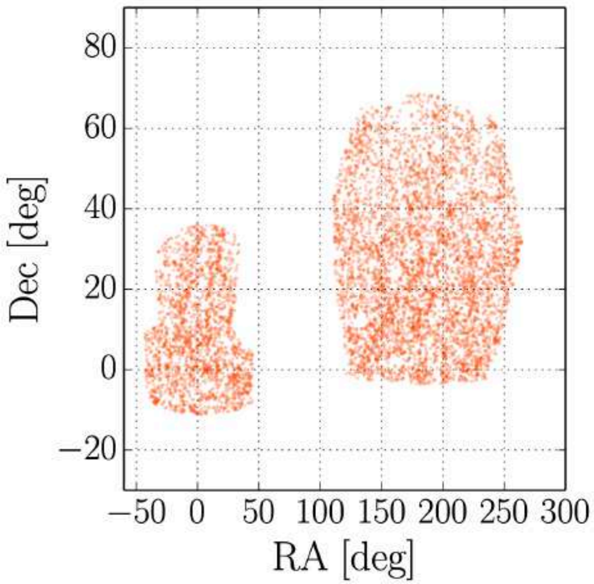
Large

Allen et al., 2011
Mantz et al., 2010

SDSS redMaPPer clusters x HSC WL Measurement

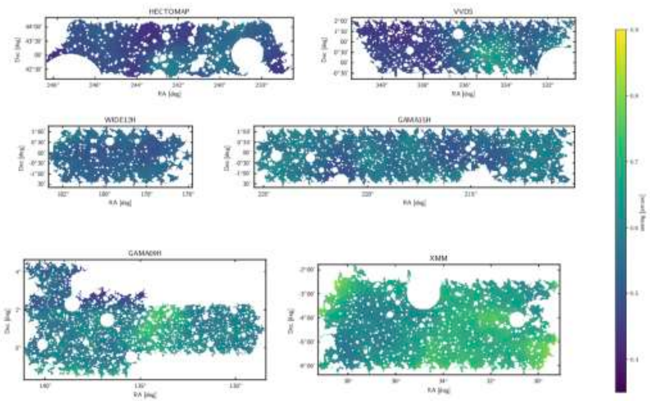
SDSS redMaPPer cluster sample

- Area ~ 8300 deg^2
- z = [0.1, 0.33]
- $\lambda =$ [20,30],[30,40],[40,55],[55,200]
- In total, ~8000 clusters
- Based on SDSS DR8 photometry



HSC-Y3 shape catalog

- Area ~ 433 deg^2 in total
- <z>~1.2.
- $n_s \sim 16\mathrm{arcmin}^{-2}$



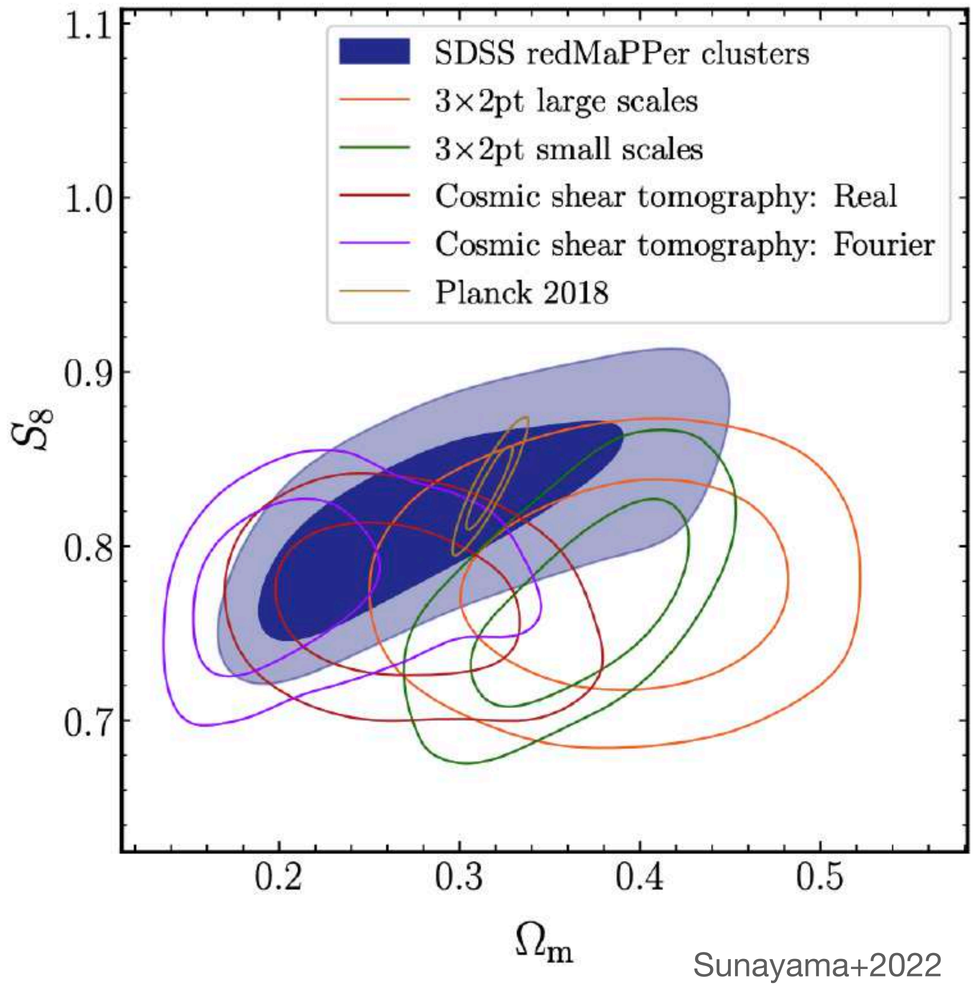
Cluster lensing signal

Cluster abundance

Cluster clustering signal

Result from SDSSxHSC Y3

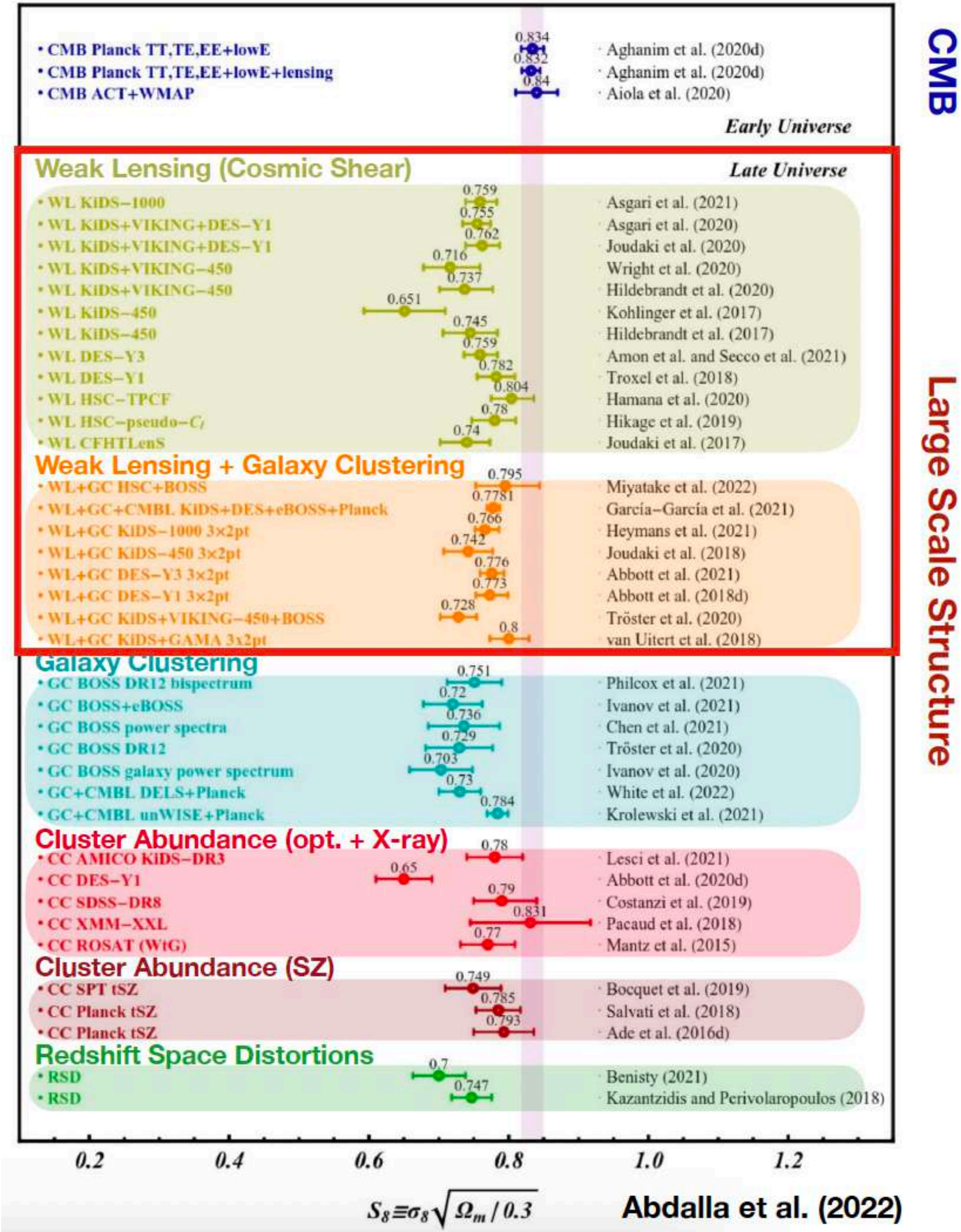
- Cosmological constraints from optical clusters and Planck CMB are constant



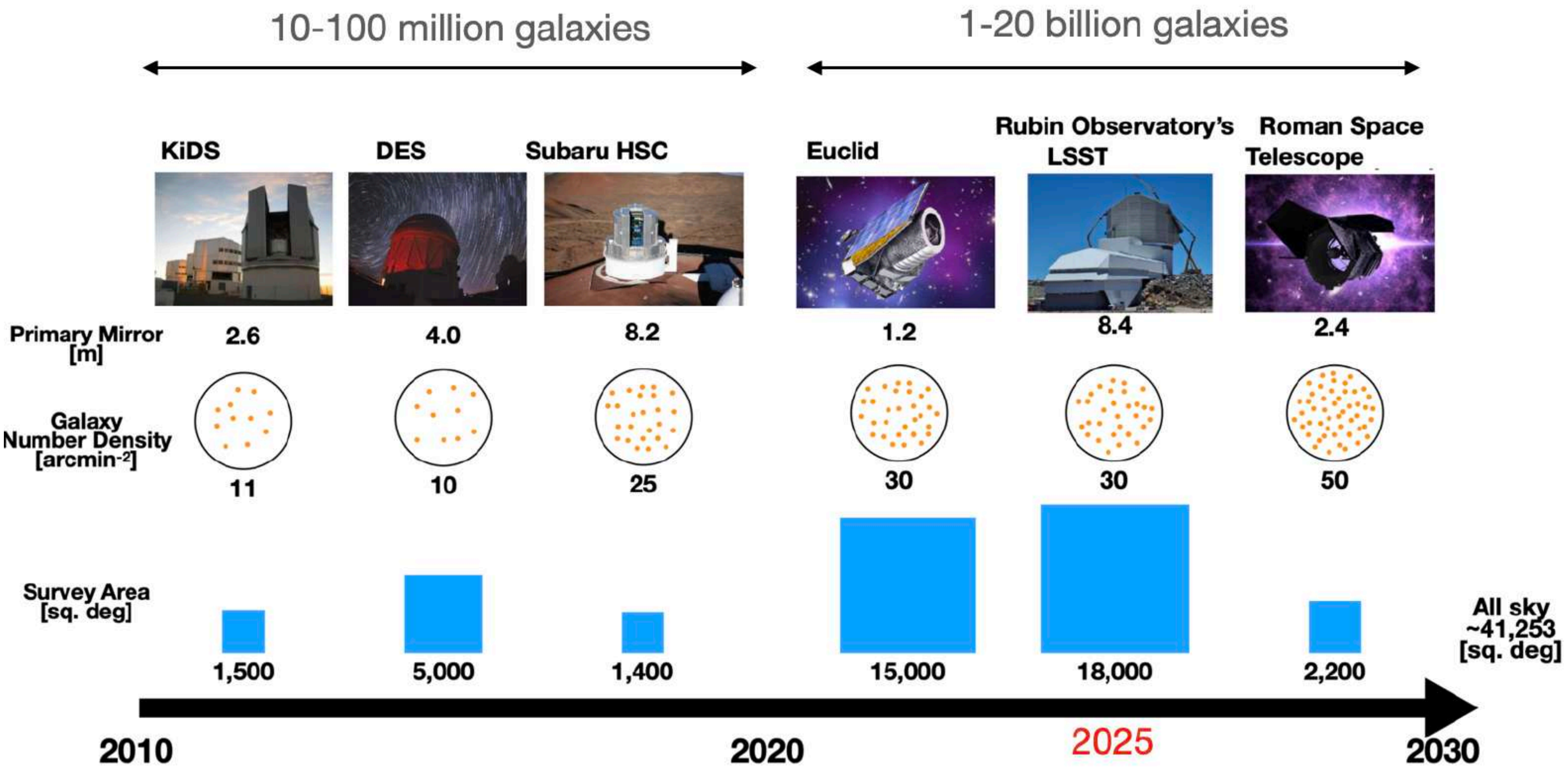
Sunayama+2022

S8 tension

- Different probes suffer from different systematics
- Need to wait for ongoing/future photometric surveys to improve statistical precisions!



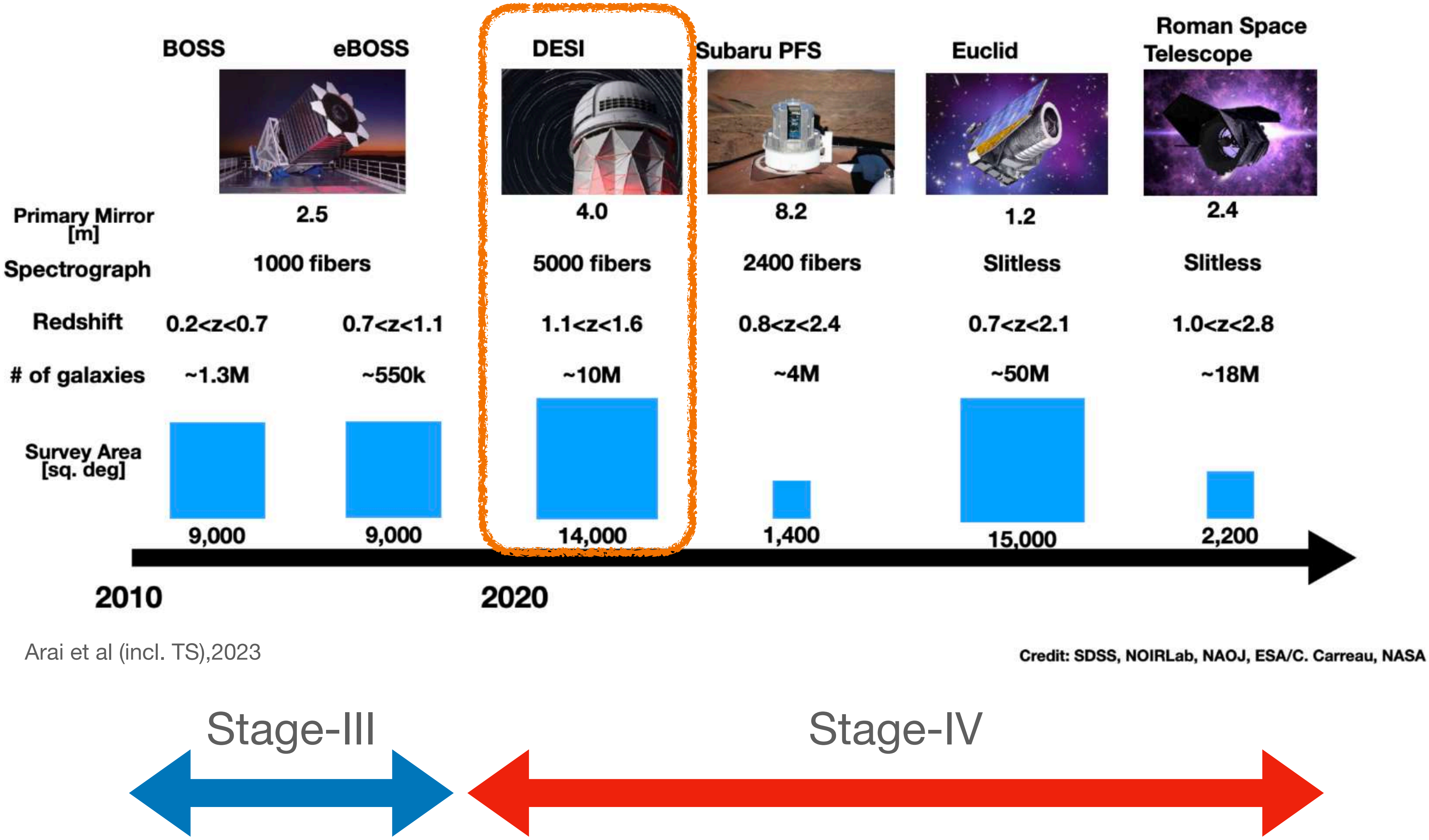
Photometric Surveys: Now and Future



Inspired by E. Krause   Credit: ESO, Fermilab/Reidar Hahn, NAOJ, ESA/C. Carreau, Rubin Obs/NSF/AURA, NASA

Arai et al (incl. TS),2023

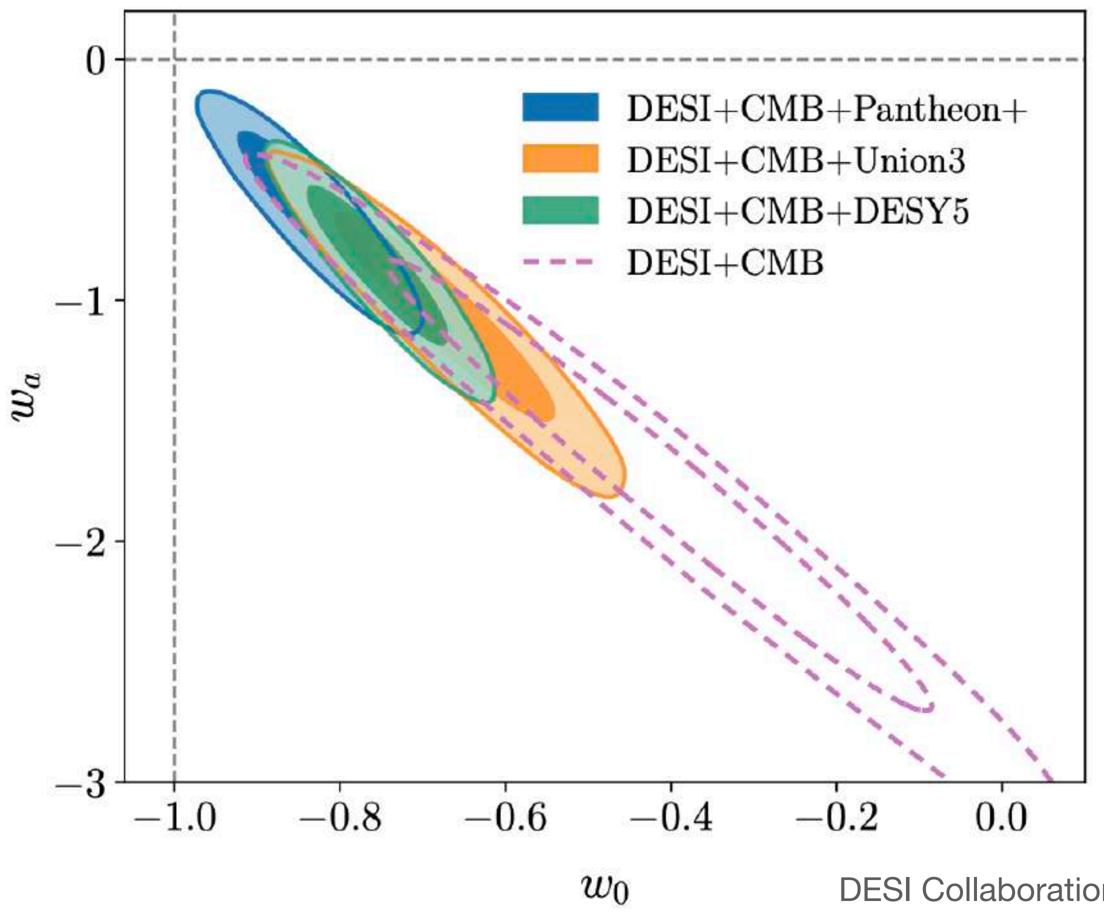
Roadmap of Spectroscopic Galaxy Surveys



Coming back to BAO

Recent results from DESI

Evidence of time-evolving dark energy?



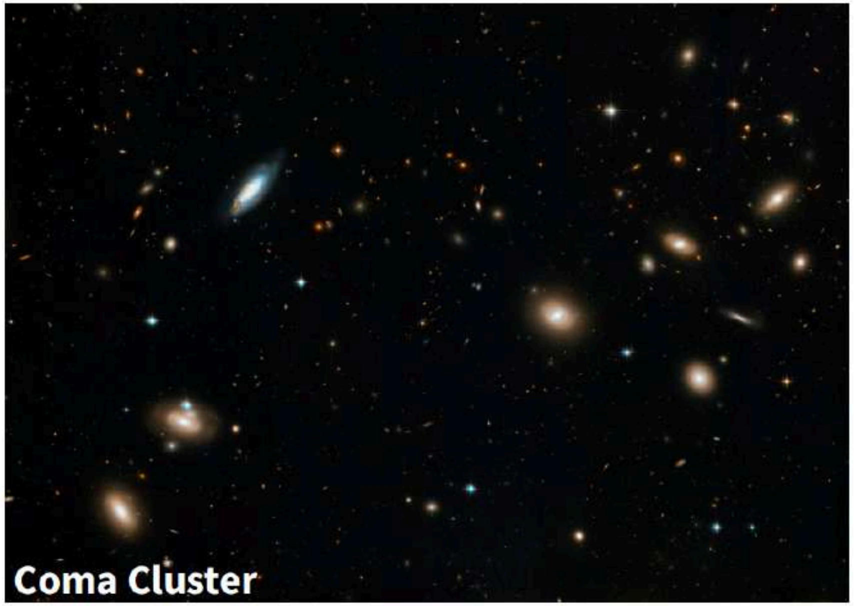
DESI Collaboration 2025

Some stories about Dark Matter

1933: "Dunkle Materie" in the Coma Cluster

$$M = RV^2/G$$

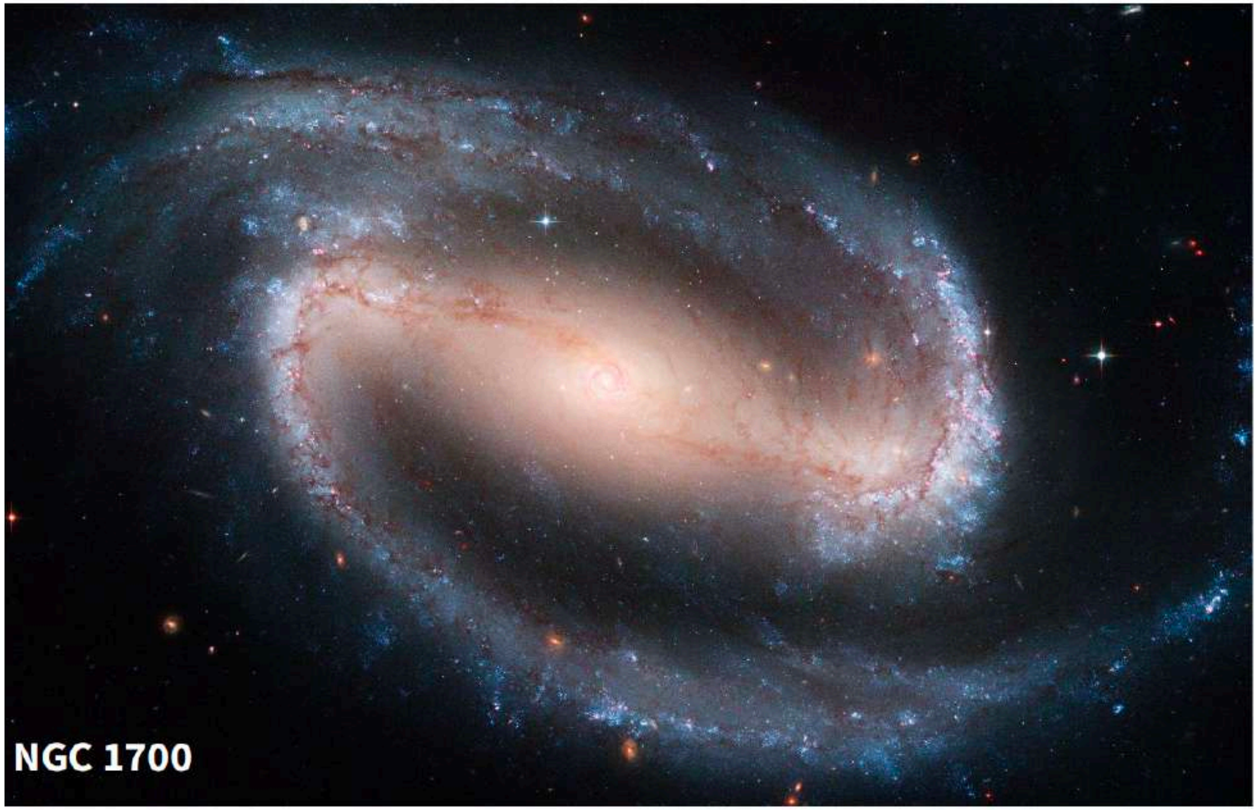
Cluster mass — Galaxy velocities



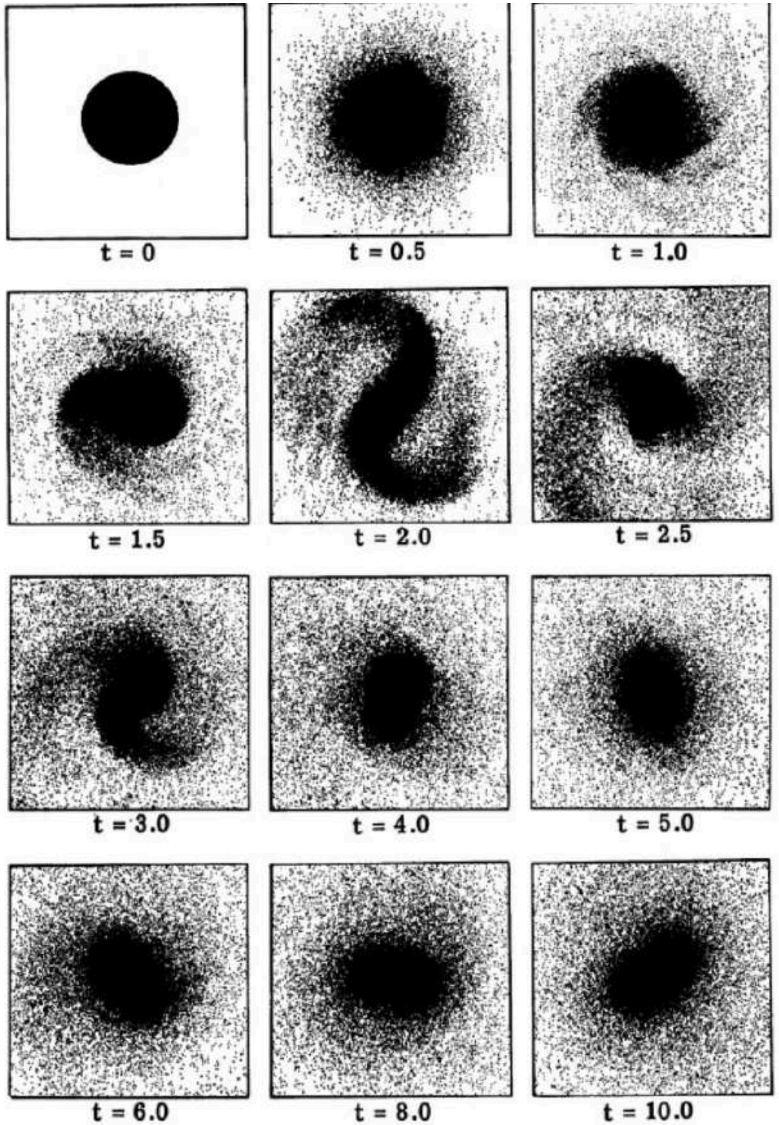
Credit: A. Salcedo

Some stories about Dark Matter

1971: Simulated bars and arms appear to be unstable



;A, ESA and the Hubble Heritage Team (STScI/AURA)

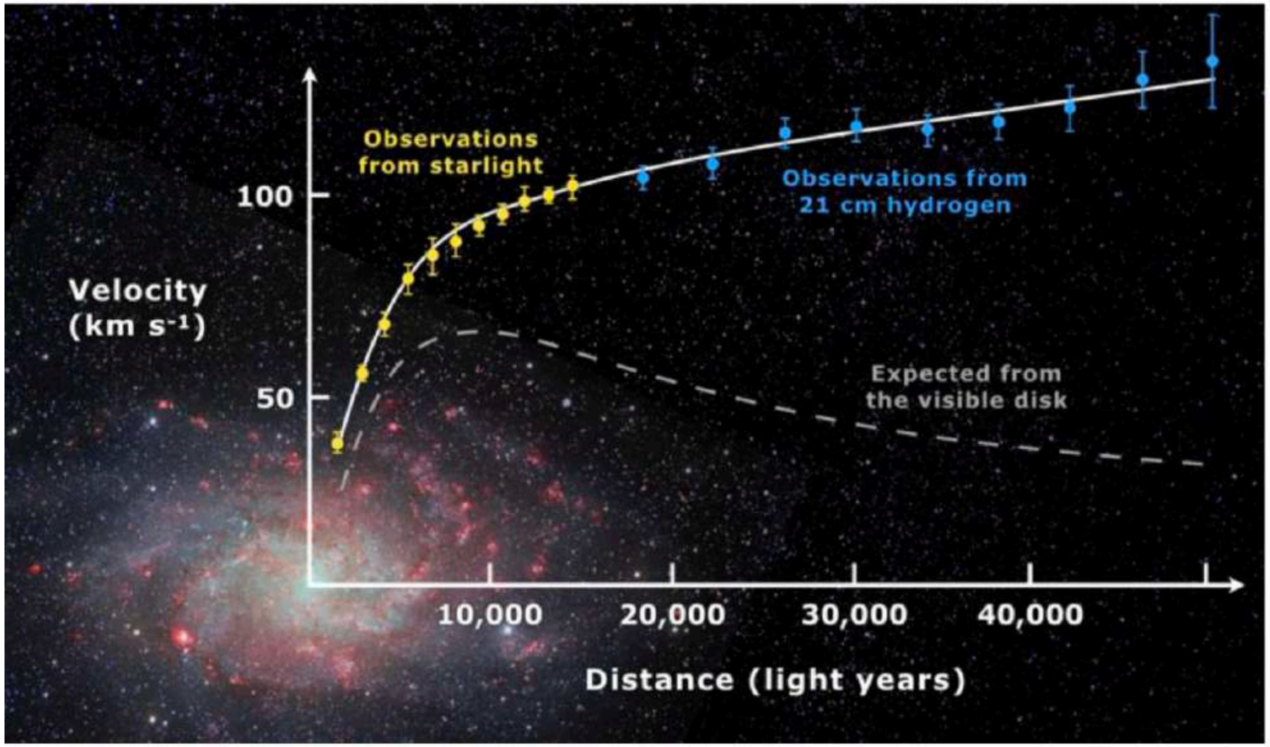


Hohl 1971

Credit: A. Salcedo

Some stories about Dark Matter

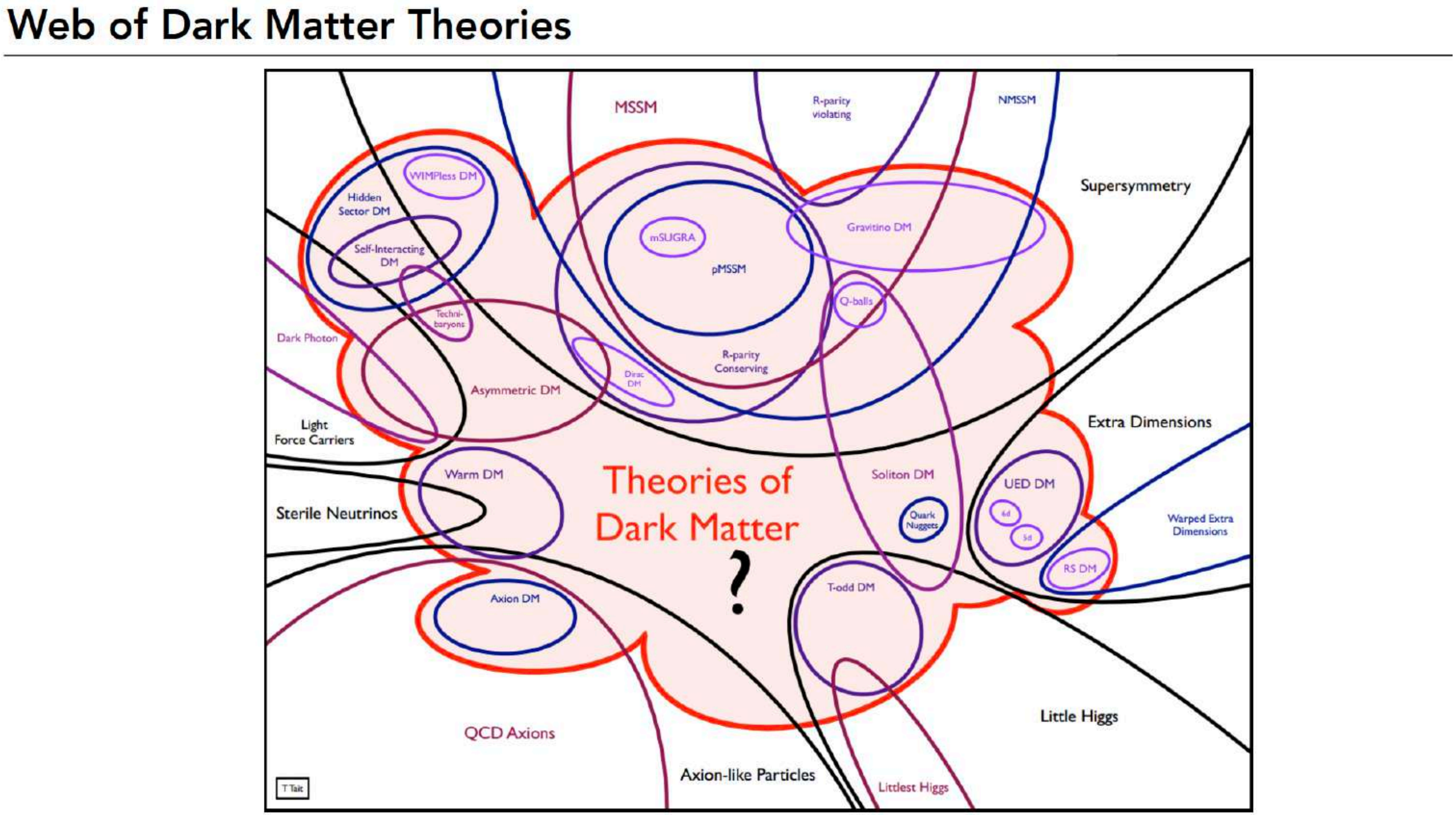
1970s: Rotation curves confirm dark matter in galaxies



Archives & Special Collections, Vassar College Library

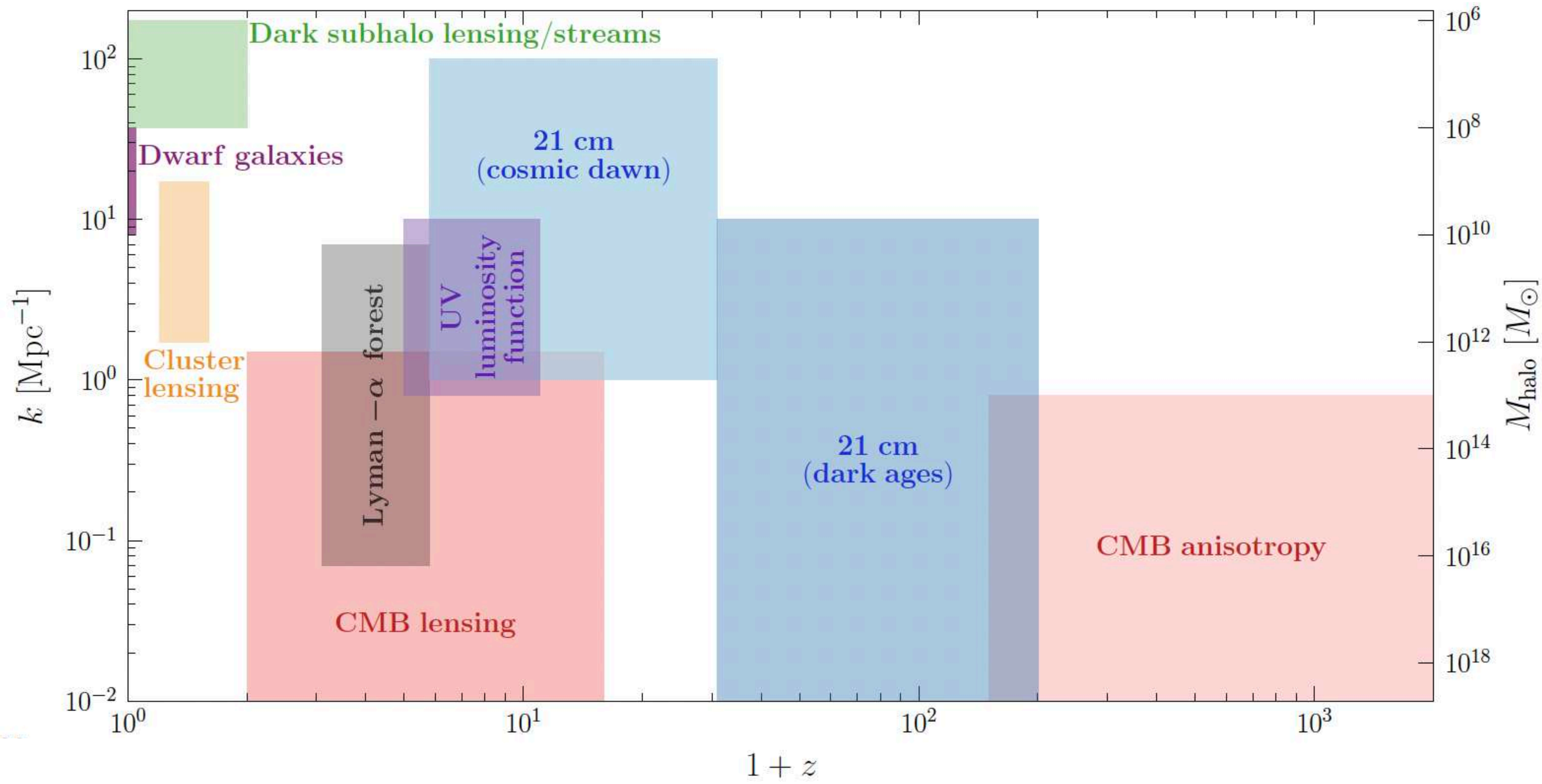
Credit: A. Salcedo

We still don't know what DM is…



Credit: K. Boddy

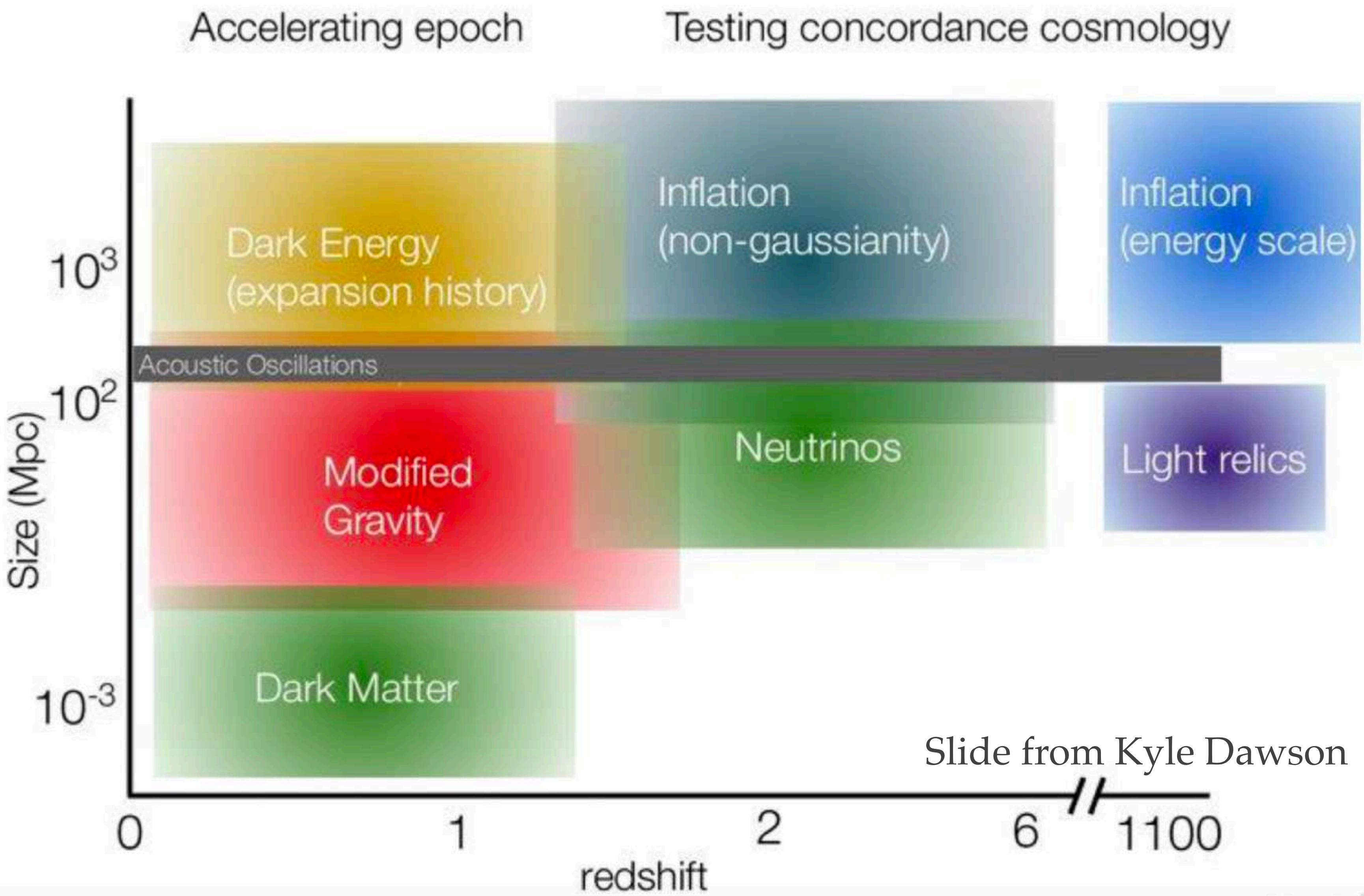
DM search is another topic…



Snowmass 2021 Theory Frontier: Astrophysical and Cosmological Probes of Dark Matter
KB, Lisanti, McDermott, Rodd, Weniger+ (2203.06380)

Credit: K. Boddy

Discovery Space: galaxy surveys are trying to explore…



Slide from Kyle Dawson

Thank you!