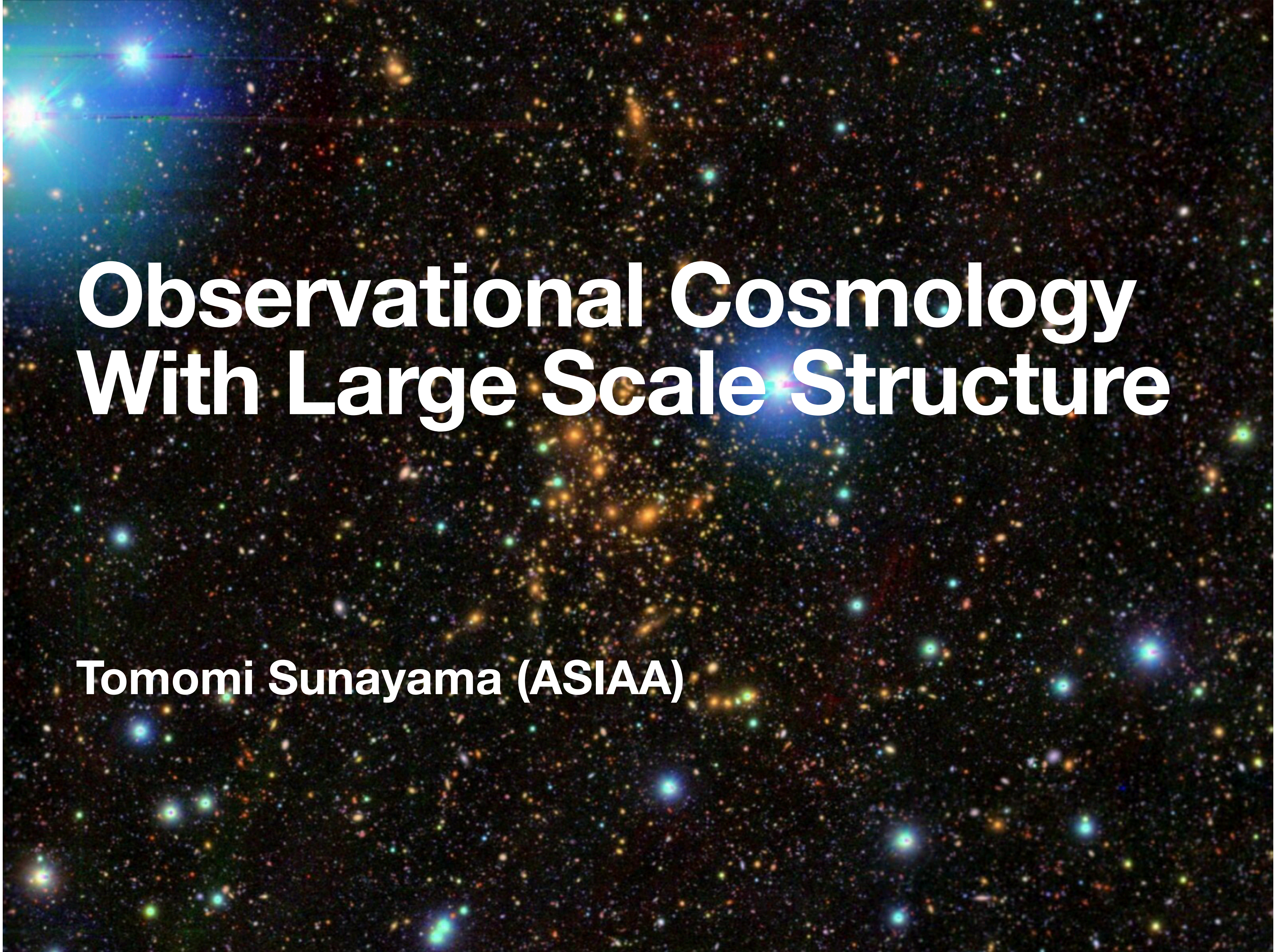


Observational Cosmology With Large Scale Structure

Tomomi Sunayama (ASIAA)

About me

Education and career path

Knox College
Major: Physics/ Mathematics
Grew Scholar

Yale University
Physics
Advisor: Nikhil Padmanabhan

Kavli IPMU
Advisor: Masahiro Takada
- Leader of Subaru PFS Cosmology WG since 2019

JSPS/ACL Fellow
(Nagoya U./U.Arizona)
2020-present
Collaborators:
Elisabeth Krause
Hironao Miyatake
Eduardo Rozo

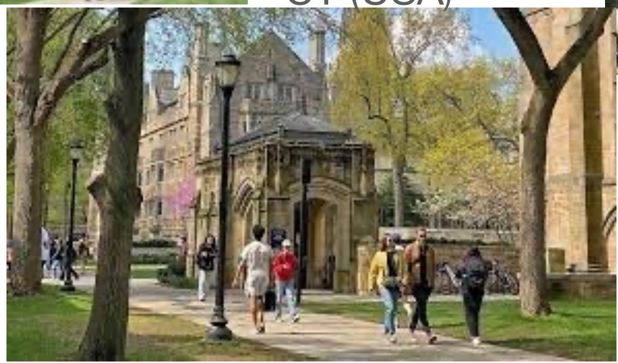
Spectroscopic Survey: BAO, RSD

Subaru PFS: clustering, forecast

Subaru HSC: Clusters/LSST, Roman

IL (USA)

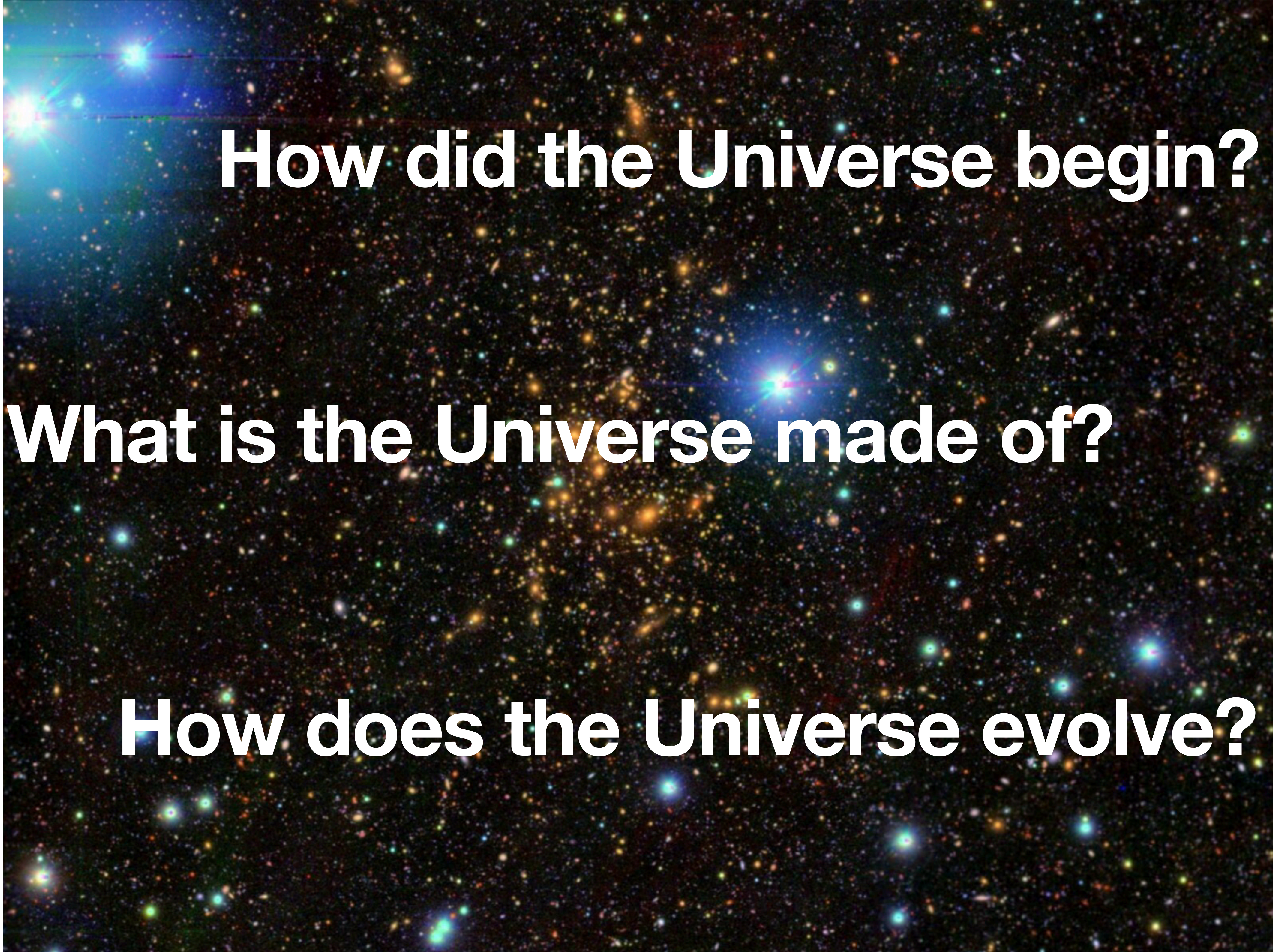
CT (USA)

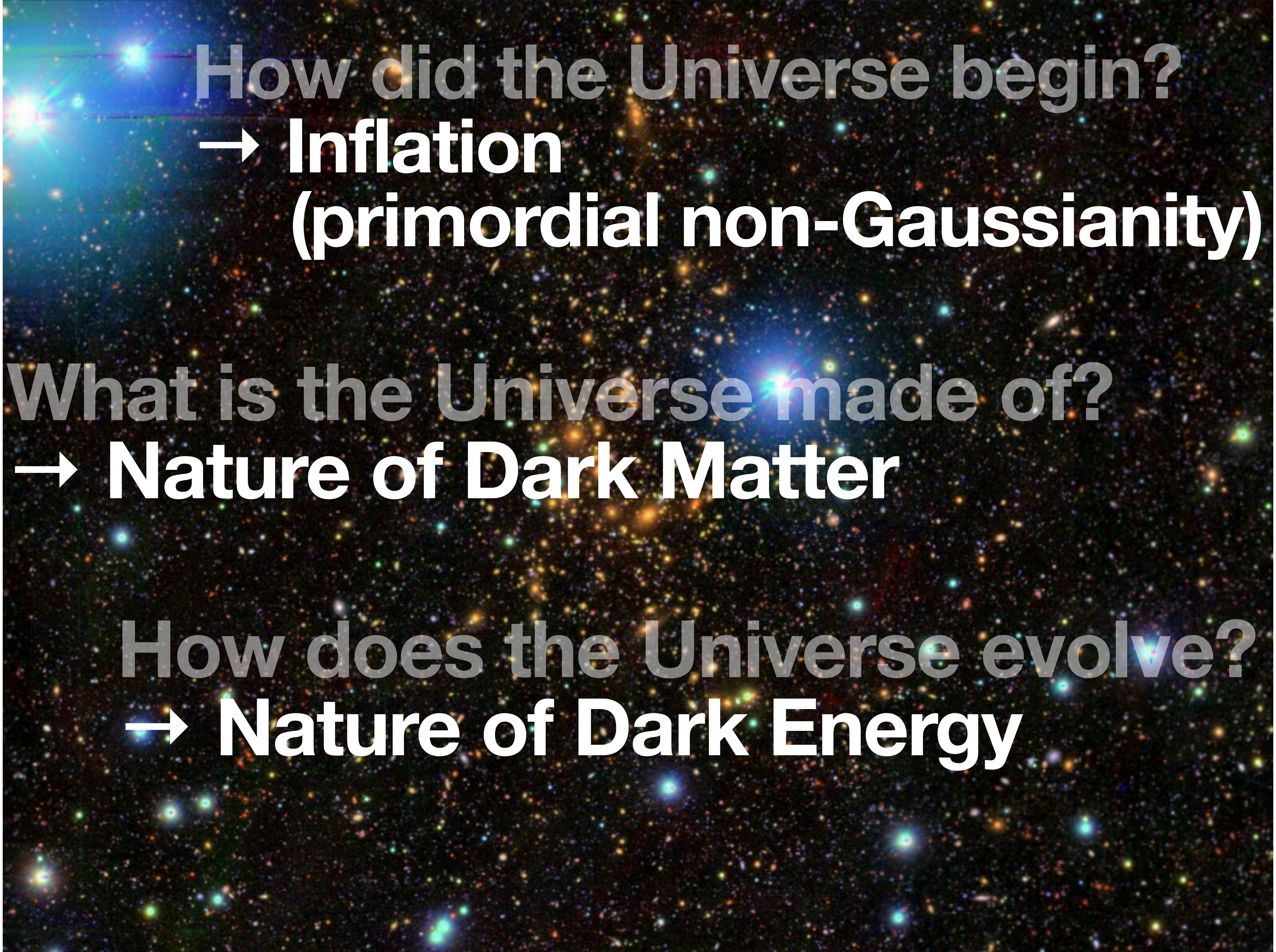


Chiba (Japan)

AZ (USA)

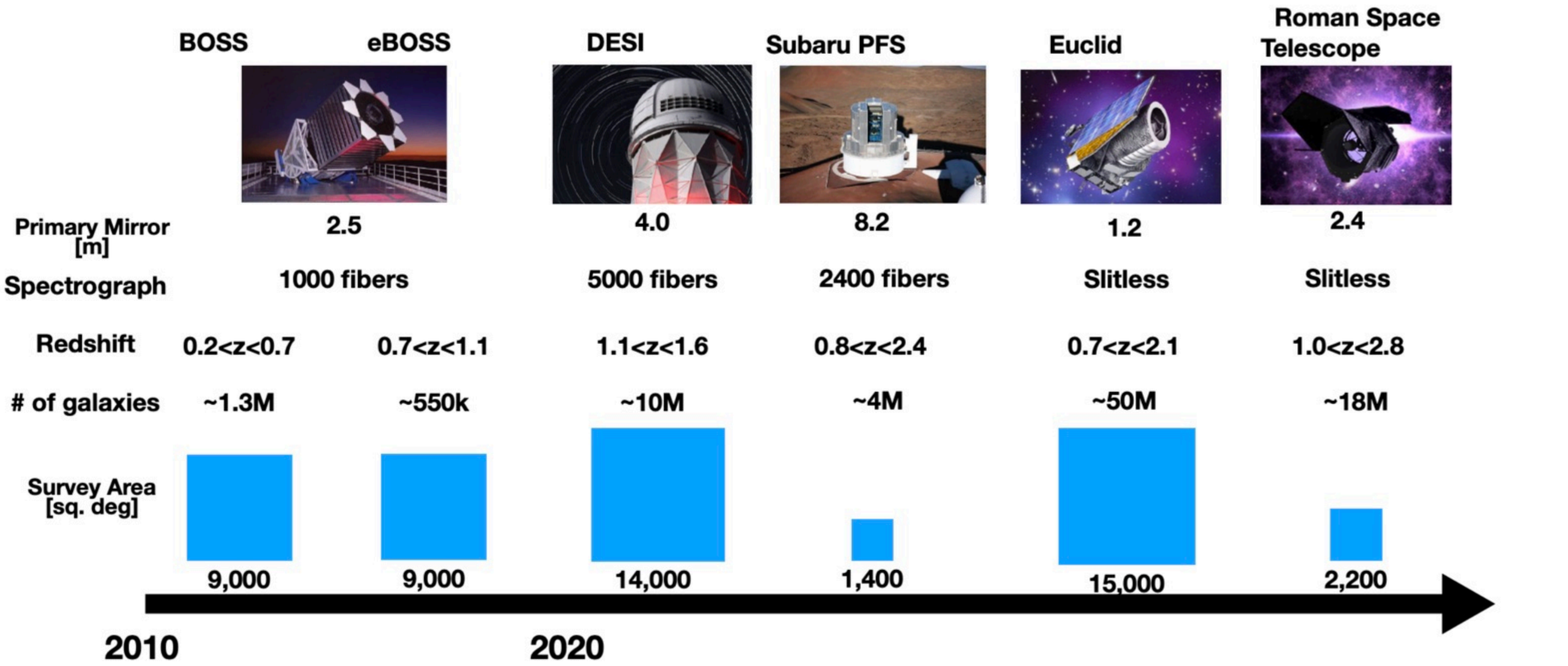
Nagoya (Japan)


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


How did the Universe begin?
→ Inflation
(primordial non-Gaussianity)
What is the Universe made of?
→ Nature of Dark Matter
How does the Universe evolve?
→ Nature of Dark Energy

Large Scale Structure as a Cosmic Census

“The large-scale structure of the Universe is like a cosmic census—it tells us how matter is distributed across space, much like a national census reveals how people are distributed across a country.”



Credit: SDSS, NOIRLab, NAOJ, ESA/C. Carreau, NASA

Large Scale Structure as a Cosmic Census

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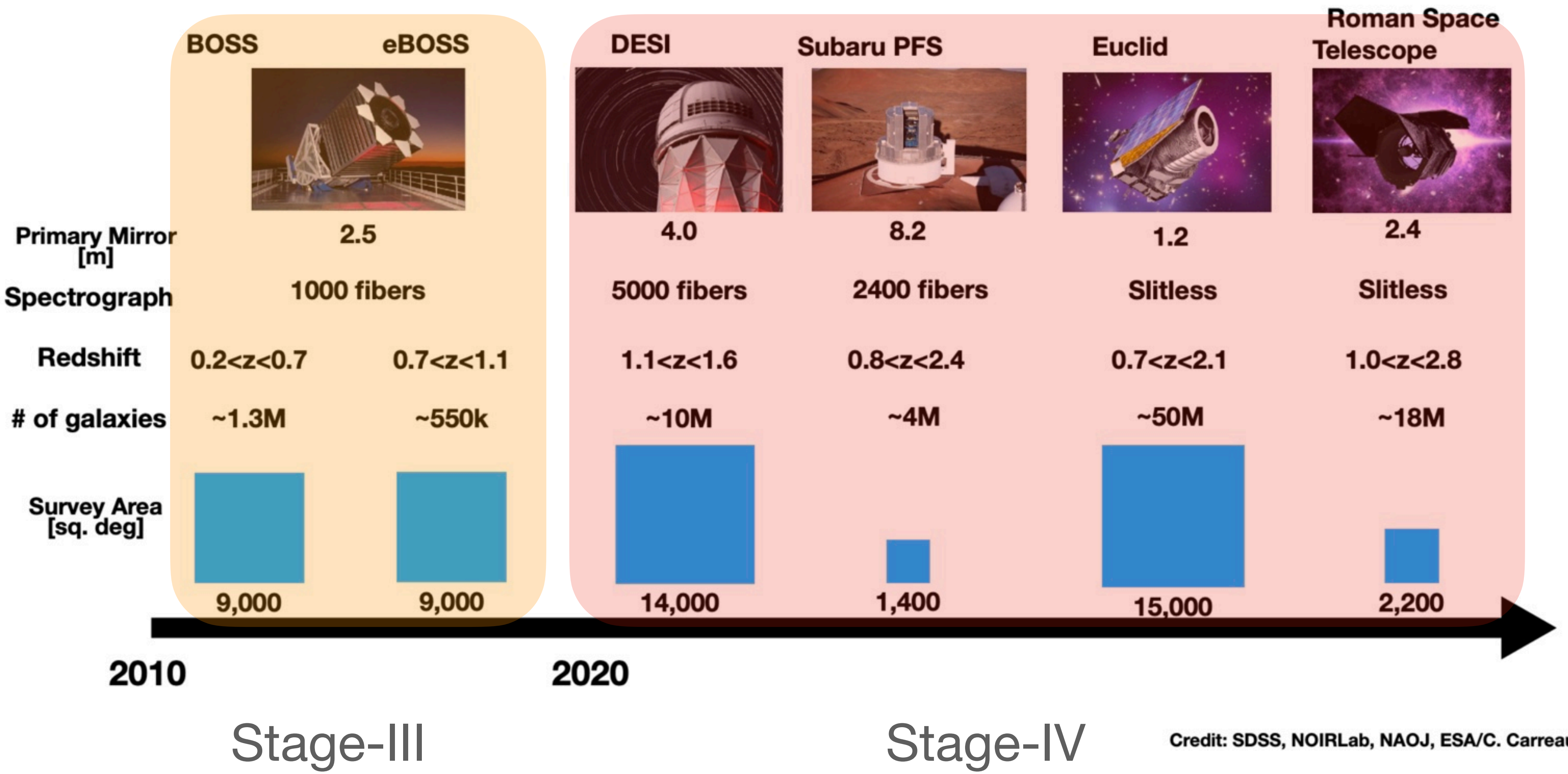


Credit: SDSS, NOIRLab, NAOJ, ESA/C. Carreau, NASA

Statistics is an essential part of Cosmology

Frequentist Way

- The likelihood function expresses how likely the observed data is for different parameter values
- The goal is to find the value of θ that maximizes the likelihood
- No probabilities are assigned to the parameters (since parameters are not considered random)

"Data"

$$L = p(d|\theta)$$

"Model Parameters"

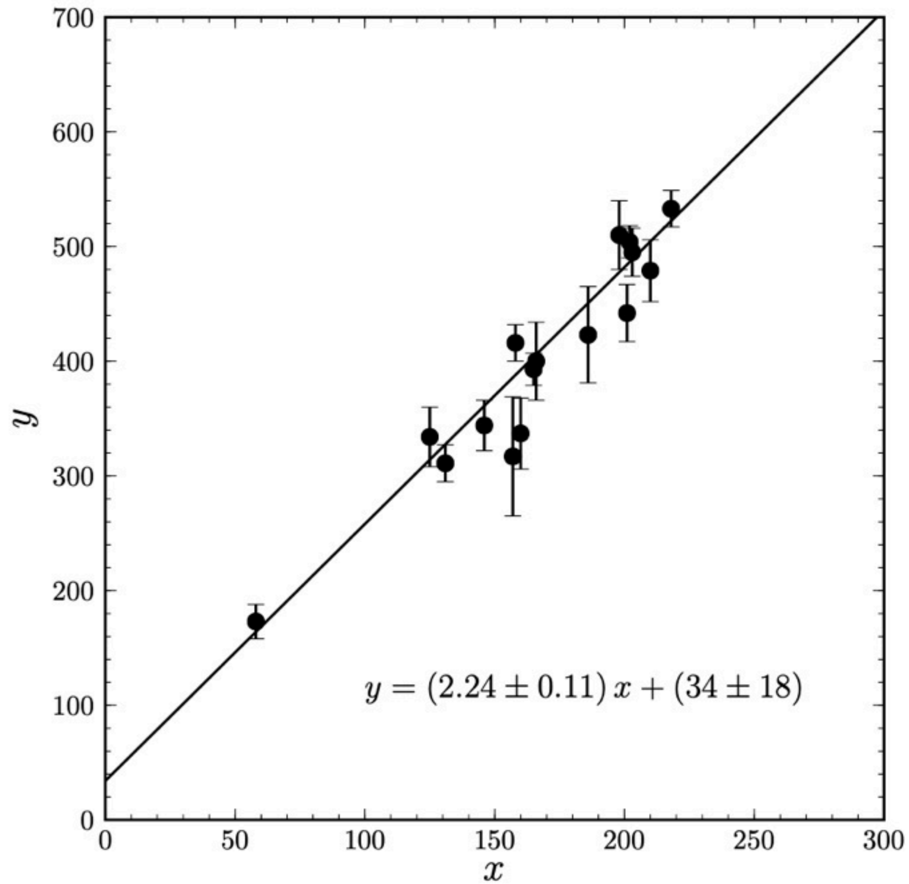
Example: Fitting to a model

$$p(y_i|x_i, \sigma_{yi}, m, b) = \frac{1}{\sqrt{2\,\pi\,\sigma_{yi}^2}} \exp\left(-\frac{[y_i - m\,x_i - b]^2}{2\,\sigma_{yi}^2}\right)$$

$=\chi^2$

- Maximizing the likelihood and minimizing χ^2 ("least-chisquare fitting") are the same thing

- By maximizing the likelihood, we find a model which generates the data most likely



Bayesian Statistics

- We only have one Universe: We want to find likelihood of the model for data
- The likelihood is **used to update** the prior belief $p(\theta)$
- Parameters θ are treated as random variables
- We measure probabilities of the parameters from posteriors $p(\theta \mid d)$

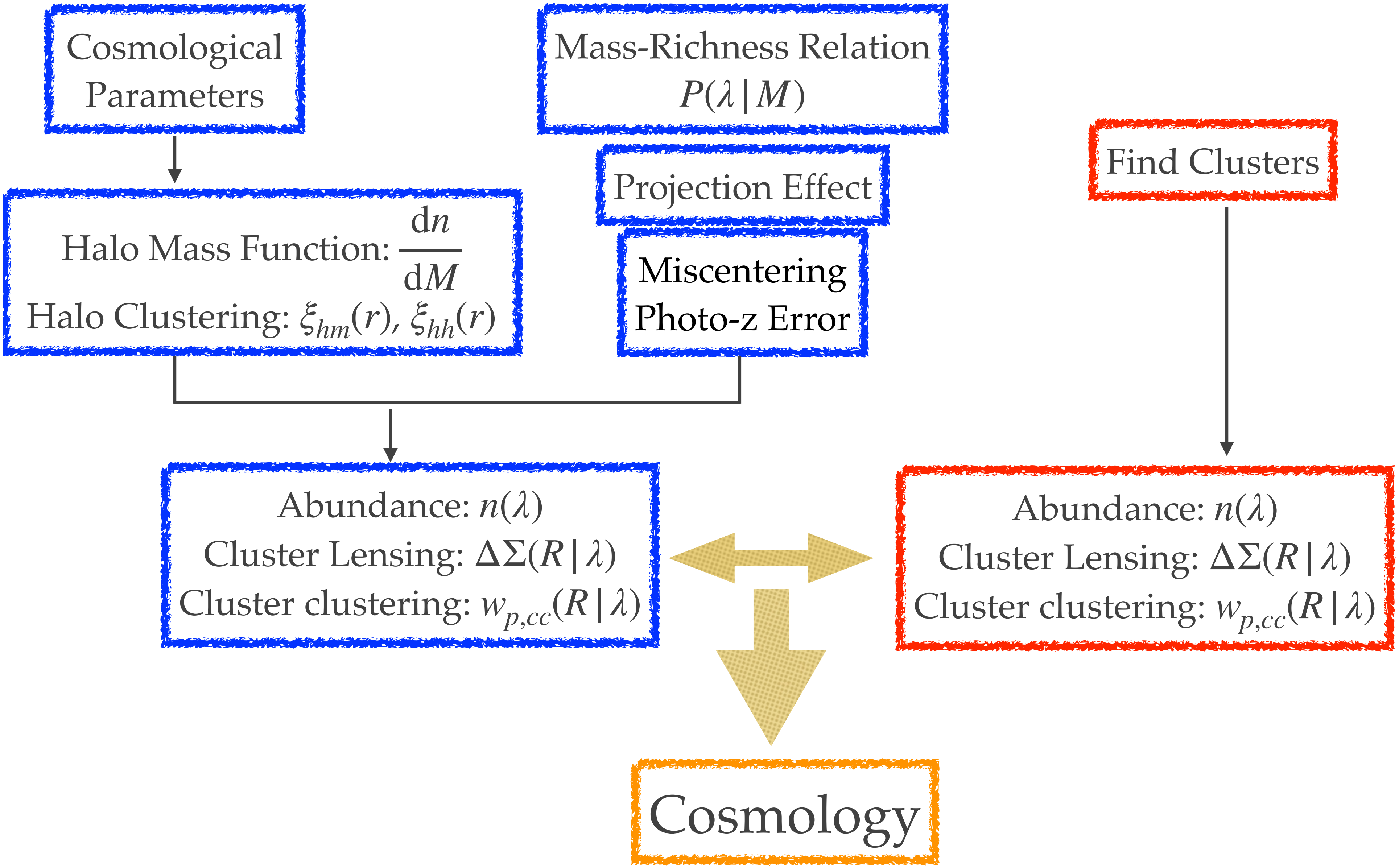
“Likelihood” “Prior”

$$p(\theta \mid d) = \frac{p(d \mid \theta)\, p(\theta)}{p(d)}$$

“Posterior”

Bayes’s theorem

Example: Cluster Cosmology Analysis



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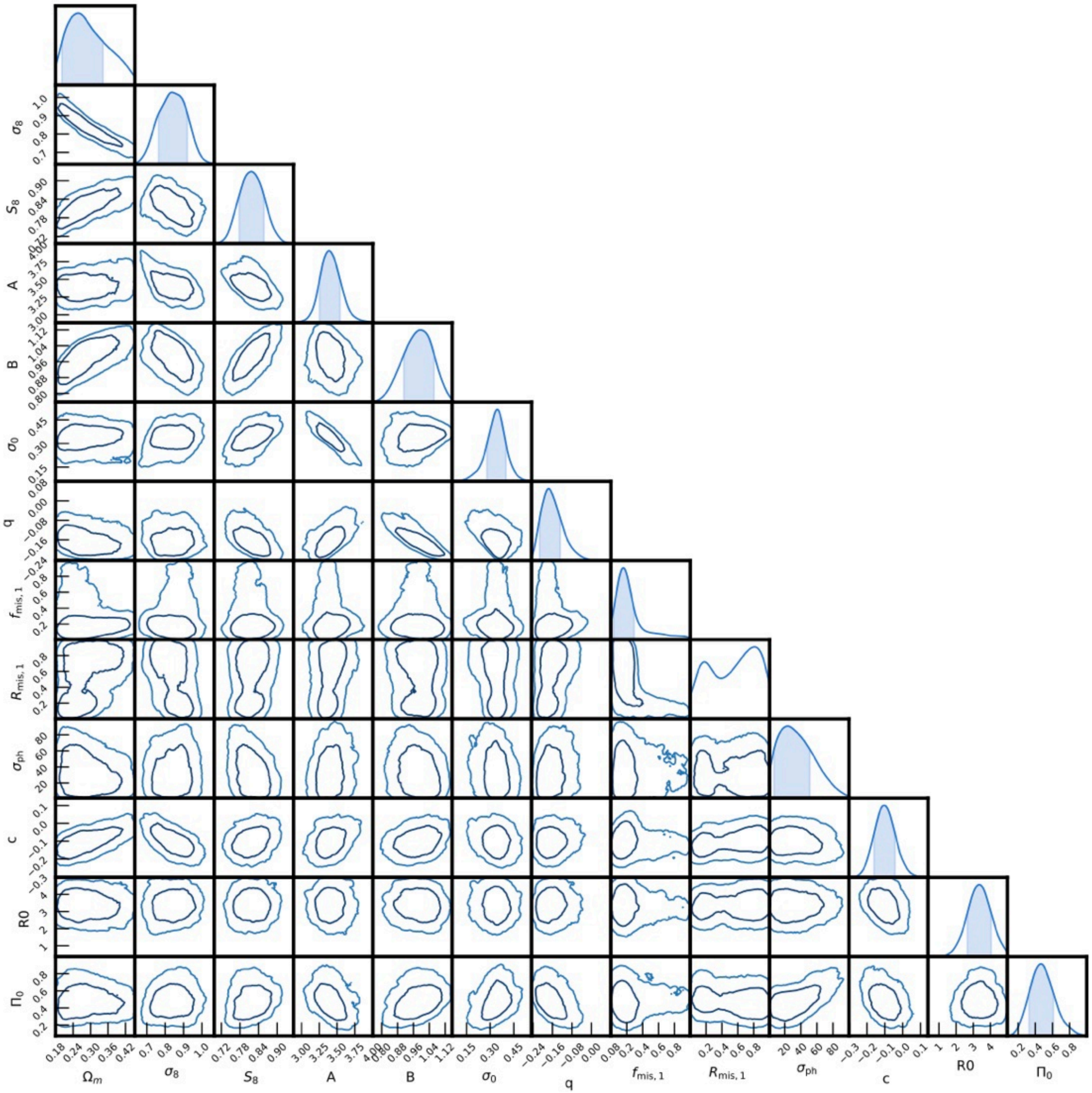
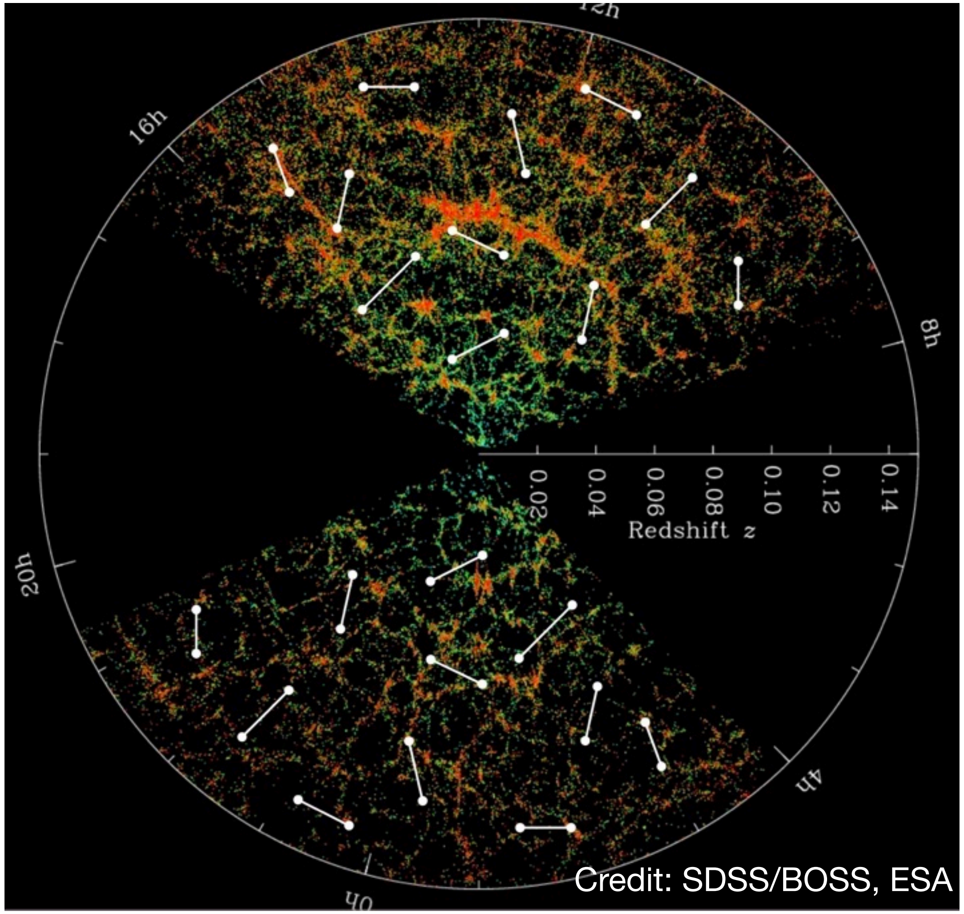


Statistical tool to quantify galaxy distributions

2-point correlation functions/Power spectrum

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



Credit: SDSS/BOSS, ESA

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

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

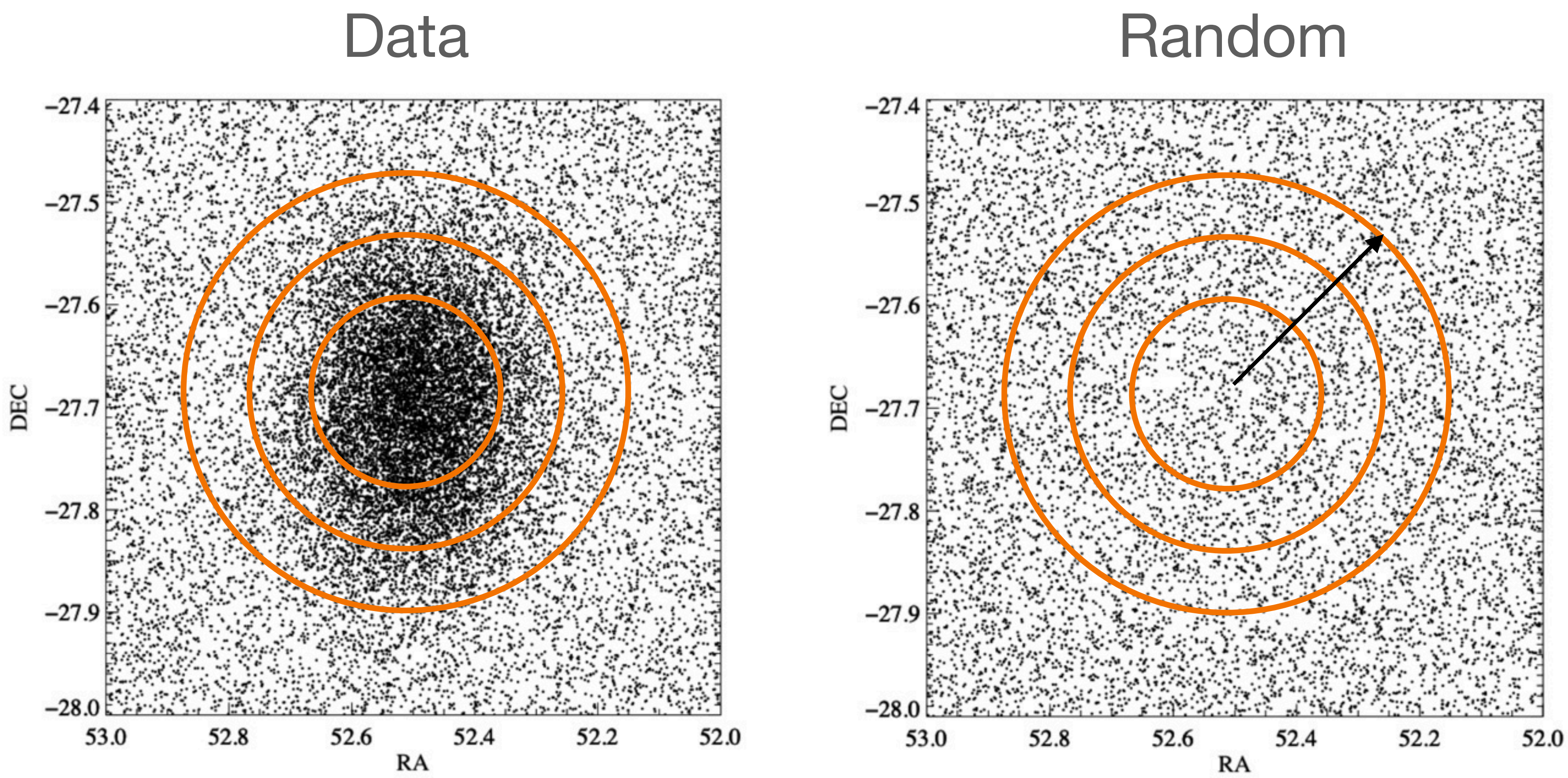
Position x Position: galaxy clustering
Position x Shape: galaxy lensing
Shape x Shape: cosmic shear

In practice…

- Then, count the number of pairs as a function of separation r

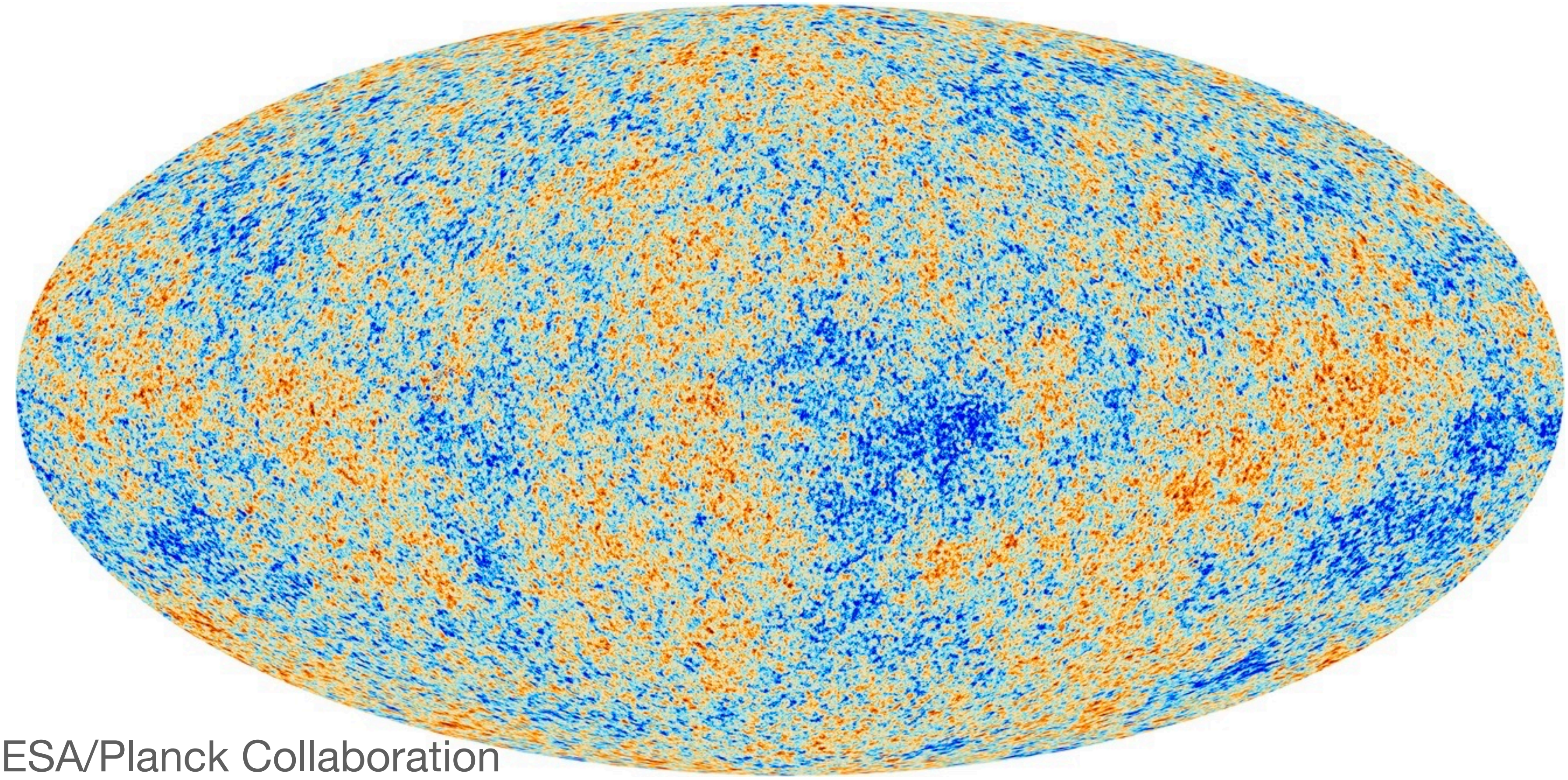
$$\xi(r) = \frac{DD(r)}{RR(r)} - 1$$

Natural Estimator



Cosmic Microwave Background (CMB)

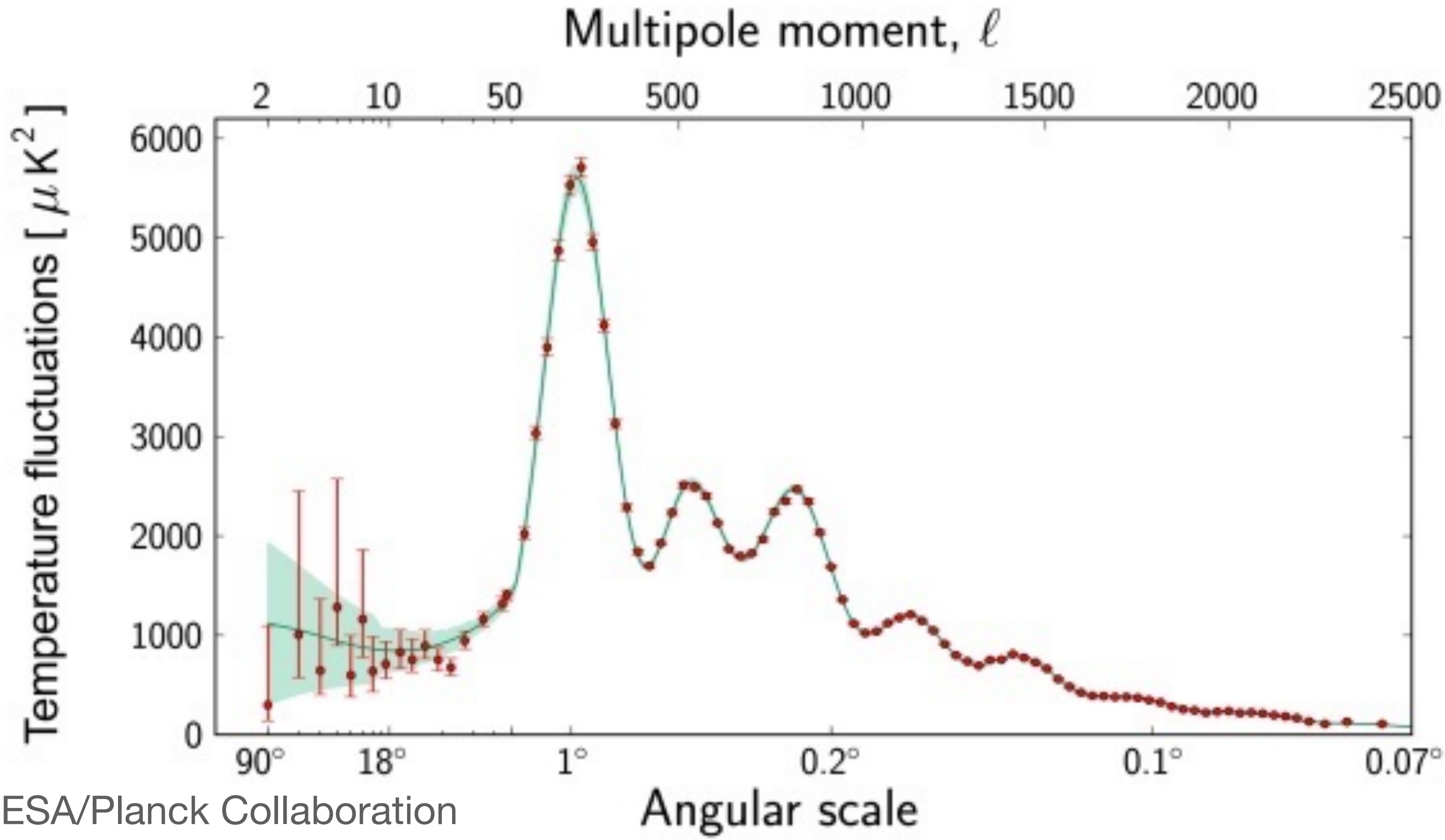
- The farthest and oldest light that we can observe directly
- The Universe is homogeneous and isotropic



Credit: ESA/Planck Collaboration

CMB can tell us energy budget of our Universe

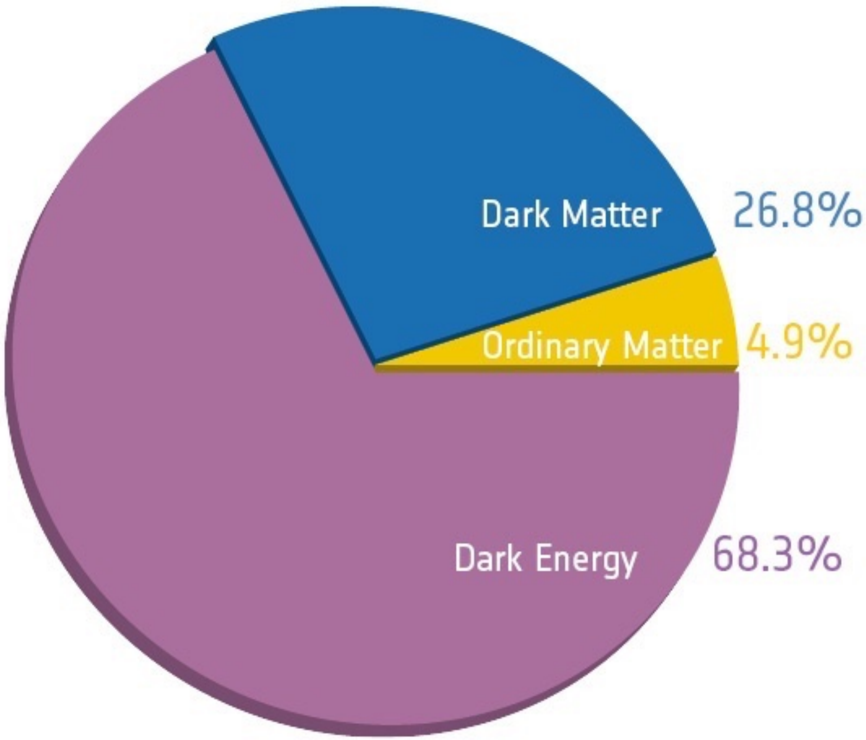
- The model fits the data remarkably well!



Credit: ESA/Planck Collaboration

Standard Cosmological Model

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

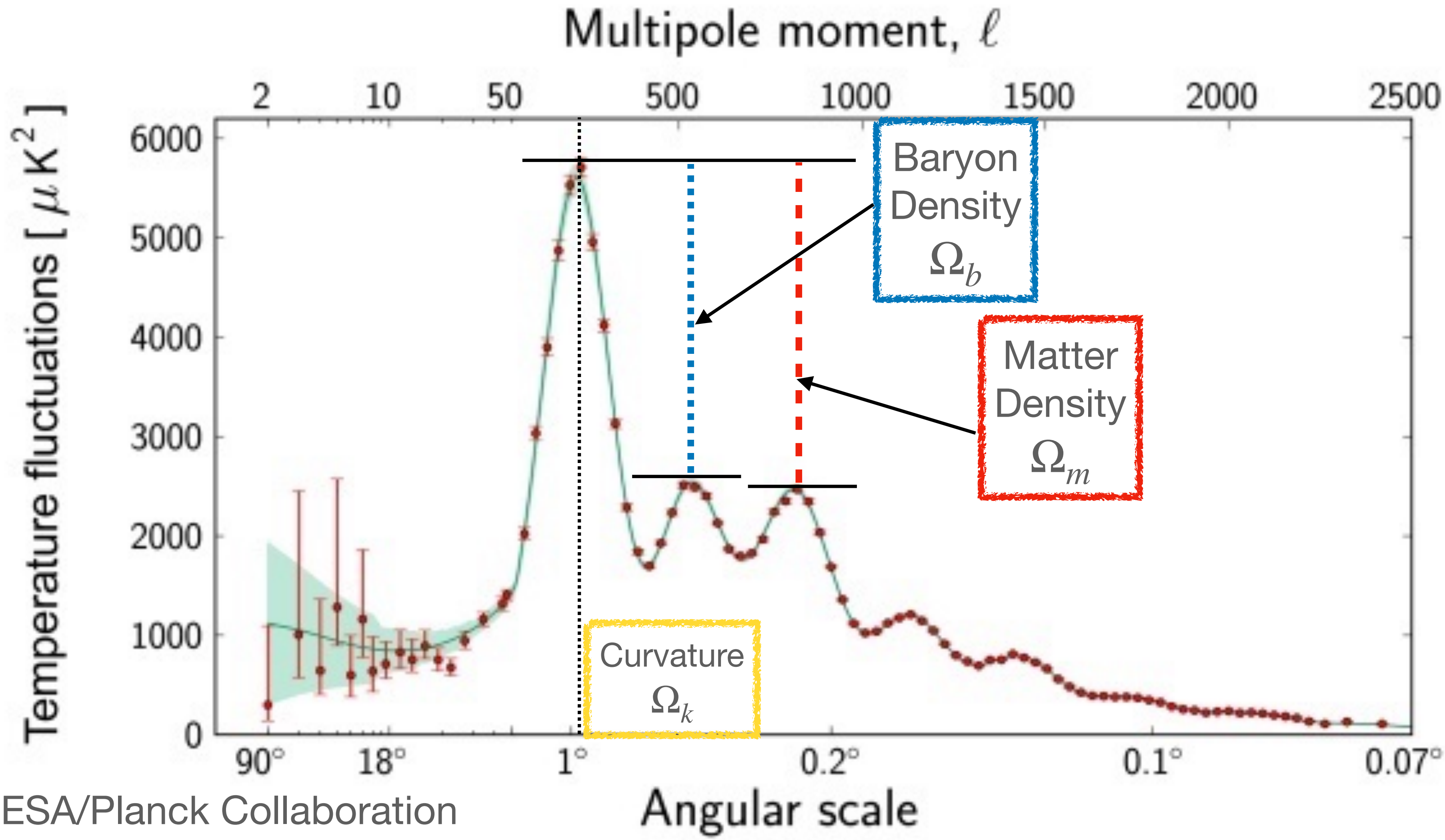


ESA / Planck

- 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

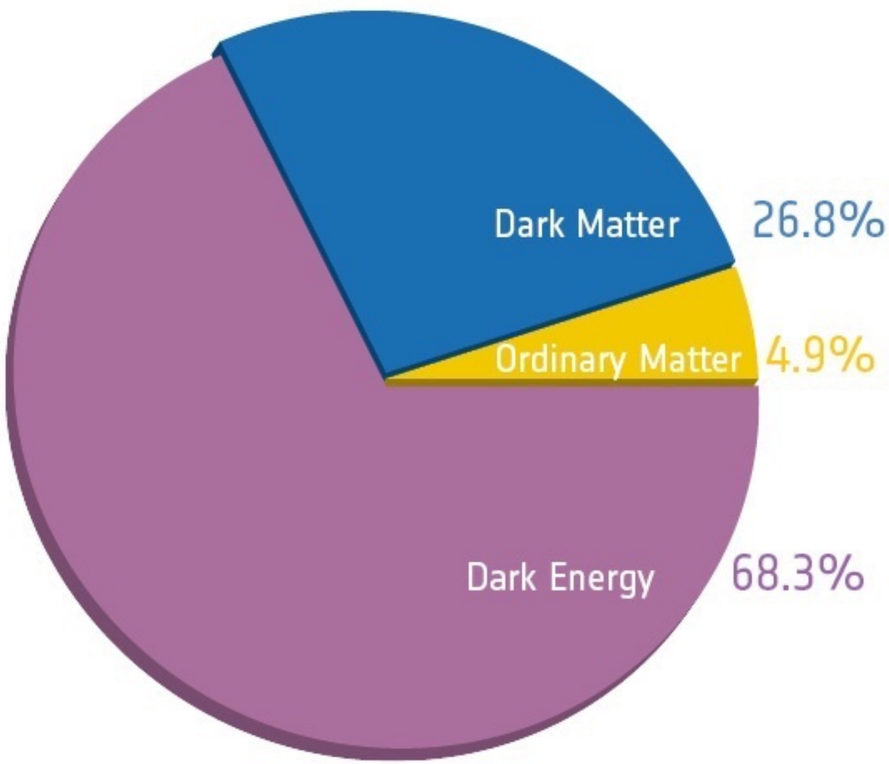
- The amplitude and the location of peaks can tell us about the energy content of the Universe.



Credit: ESA/Planck Collaboration

Standard model of the Universe: ΛCDM

Era of precision cosmology



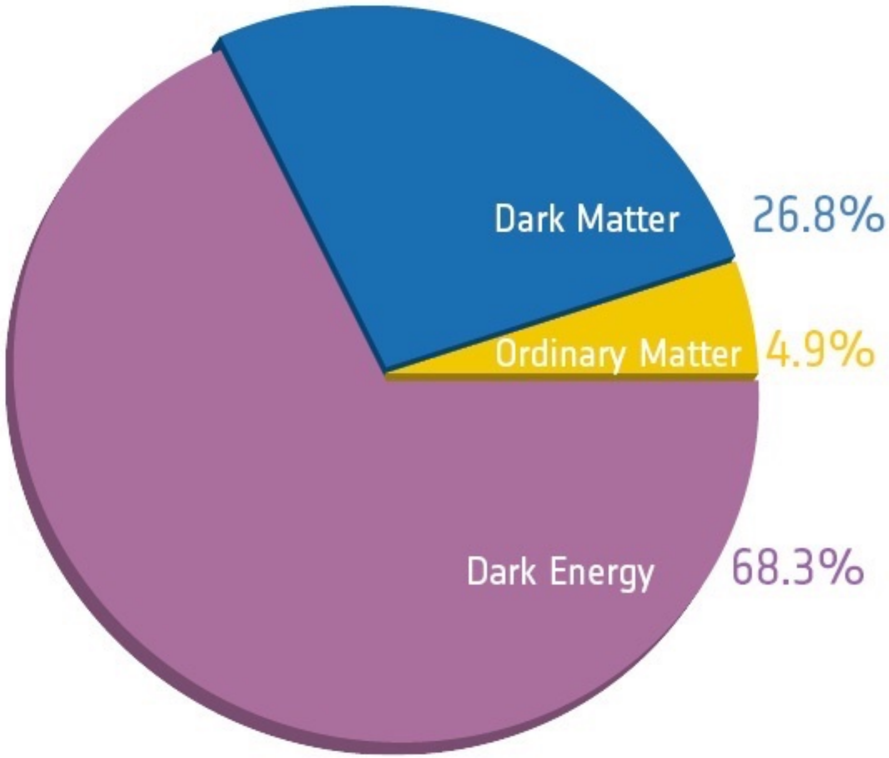
Credit: ESA/Planck Collaboration

- 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

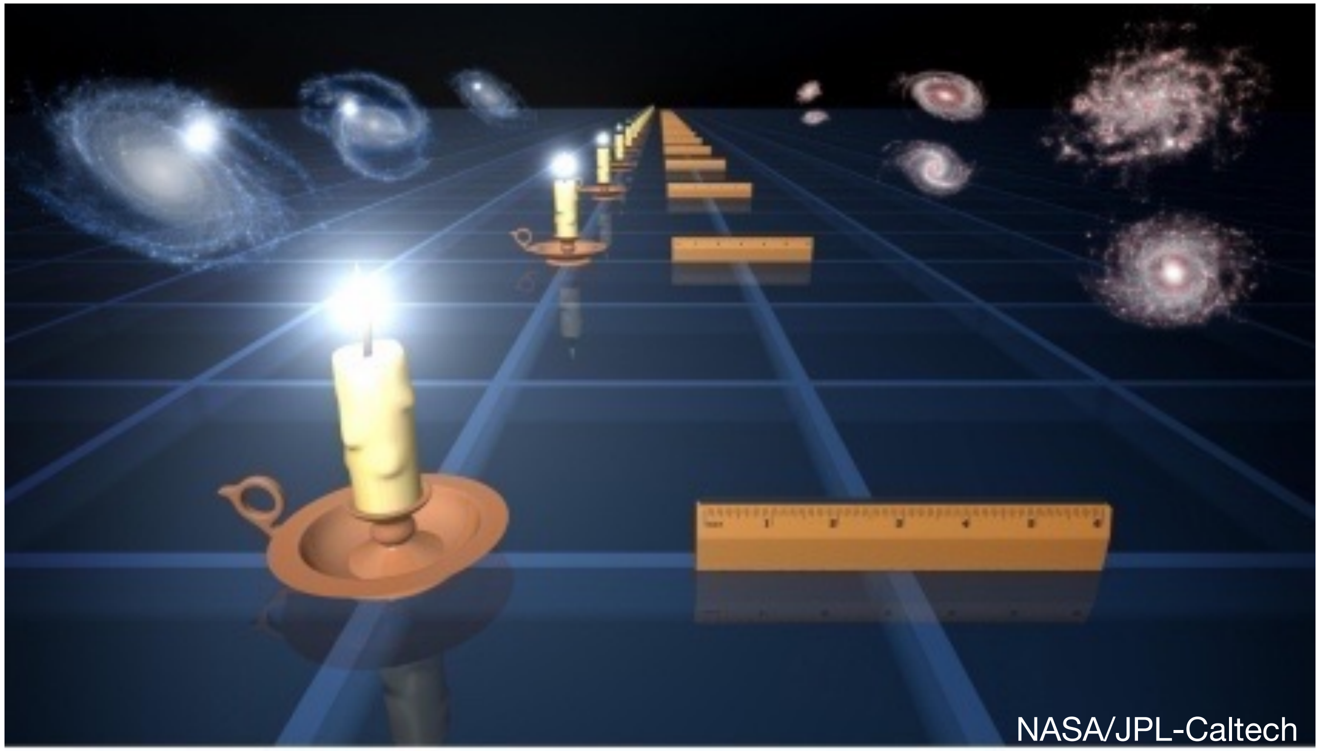
DE **requires** new physics beyond the standard model of elementary particles and fields

- 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:

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

Cosmology 101: Hubble Parameter

- In GR, the expansion of a homogeneous and isotropic universe is governed by the Friedman equation:

$$\frac{H^2(z)}{H_0^2} = \Omega_m(1+z)^3 + \Omega_r(1+z)^4 + \Omega_k(1+z)^2 + \Omega_\phi \frac{u_\phi(z)}{u_\phi(z=0)}$$

where $H(z) = \dot{a}/a$, $(1+z) = a^{-1}(z)$, and a(t) is the expansion factor relating physical separations to comoving separation.

$$\Omega_X = \frac{u_X}{\rho_{\rm crit} c^2} \qquad \rho_{\rm crit} = \frac{3H_0^2}{8\pi G}$$

- Redshift evolution of dark energy is described as

$$\frac{u_\phi(z)}{u_\phi(z=0)} = (1+z)^{3(1+w)} \text{ where } w(a) = w_0 + w_a(1-a)$$

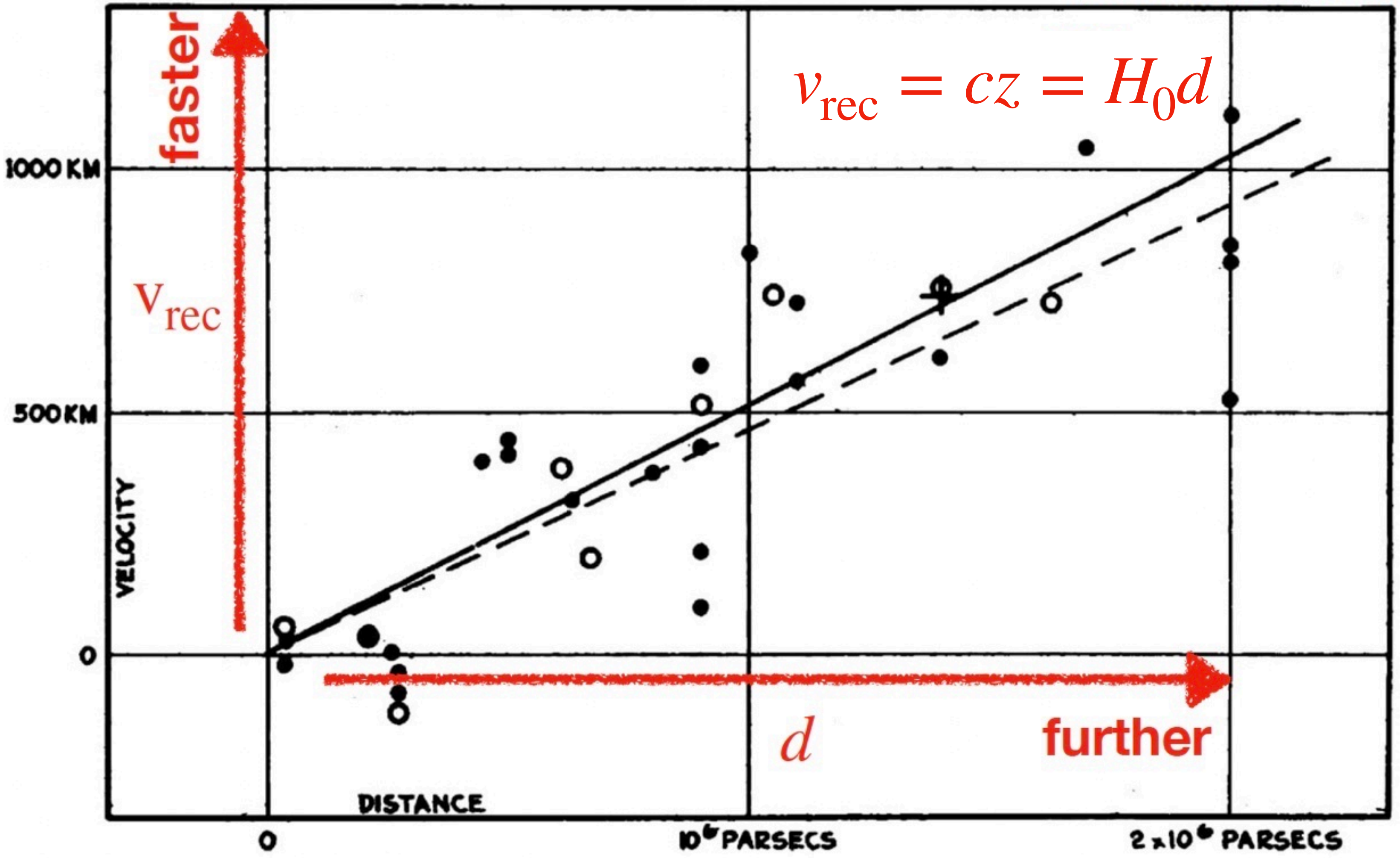
Hubble's Law

- 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: Distances

- The comoving line-of-sight (LOS) distance to an object at redshift z:

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

- The comoving angular diameter distance (relating an object's comoving size l to its angular size $\theta = l/D_A$):

$$D_A(z) = K^{-1/2}\sin(K^{1/2}D_C) \approx D_C[1 + \frac{1}{6}\Omega_k(\frac{D_C}{c/H_0})^2]$$

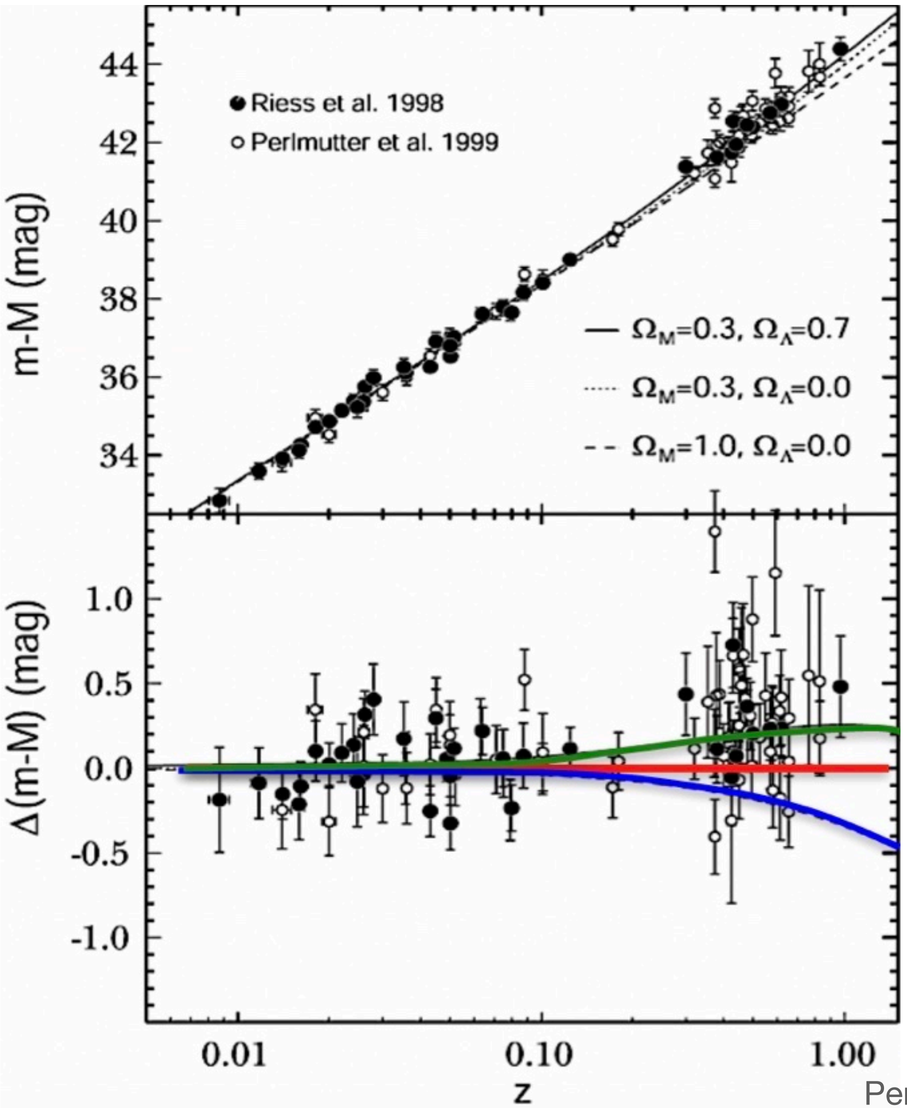
$$K = -\Omega_k(c/H_0)^{-2}$$

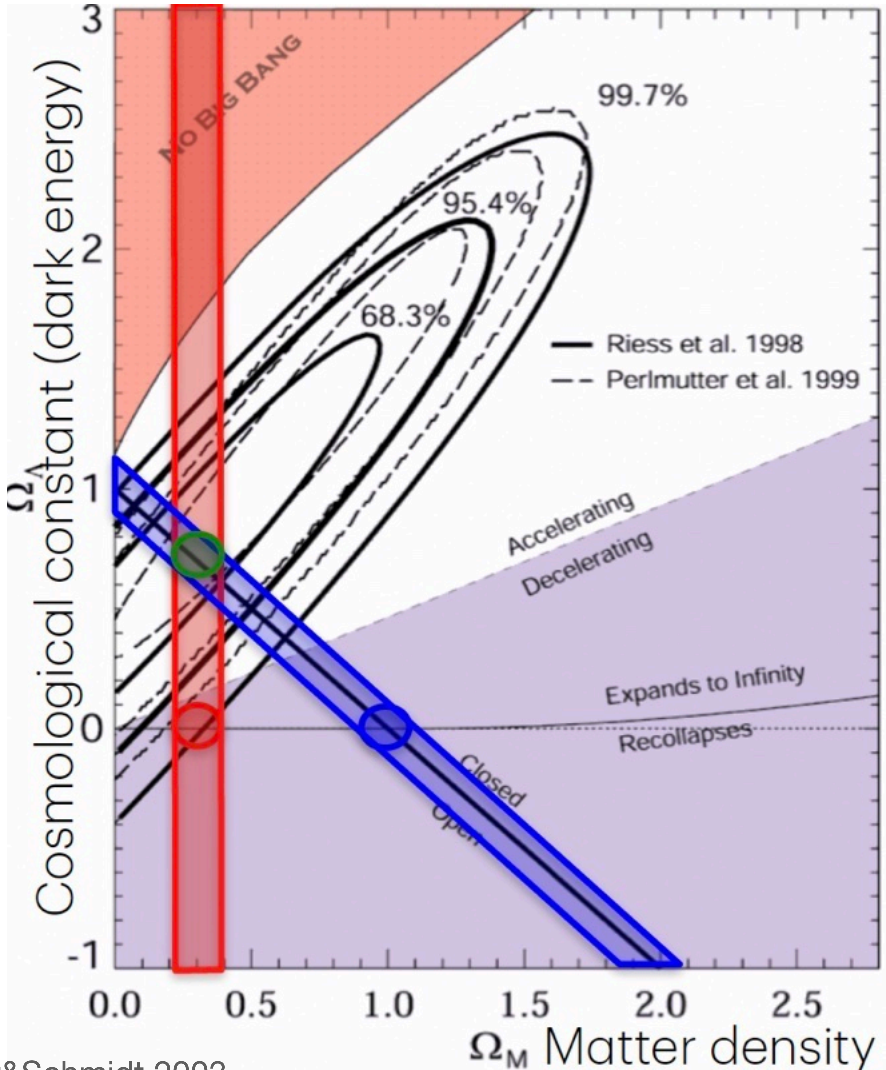
- The luminosity distance relating an object's flux f to its luminosity L:

$$D_L = \sqrt{L/4\pi f} = D_A(1+z)$$

First discovery of cosmic acceleration

Supernovae Type Ia (SNe Ia)

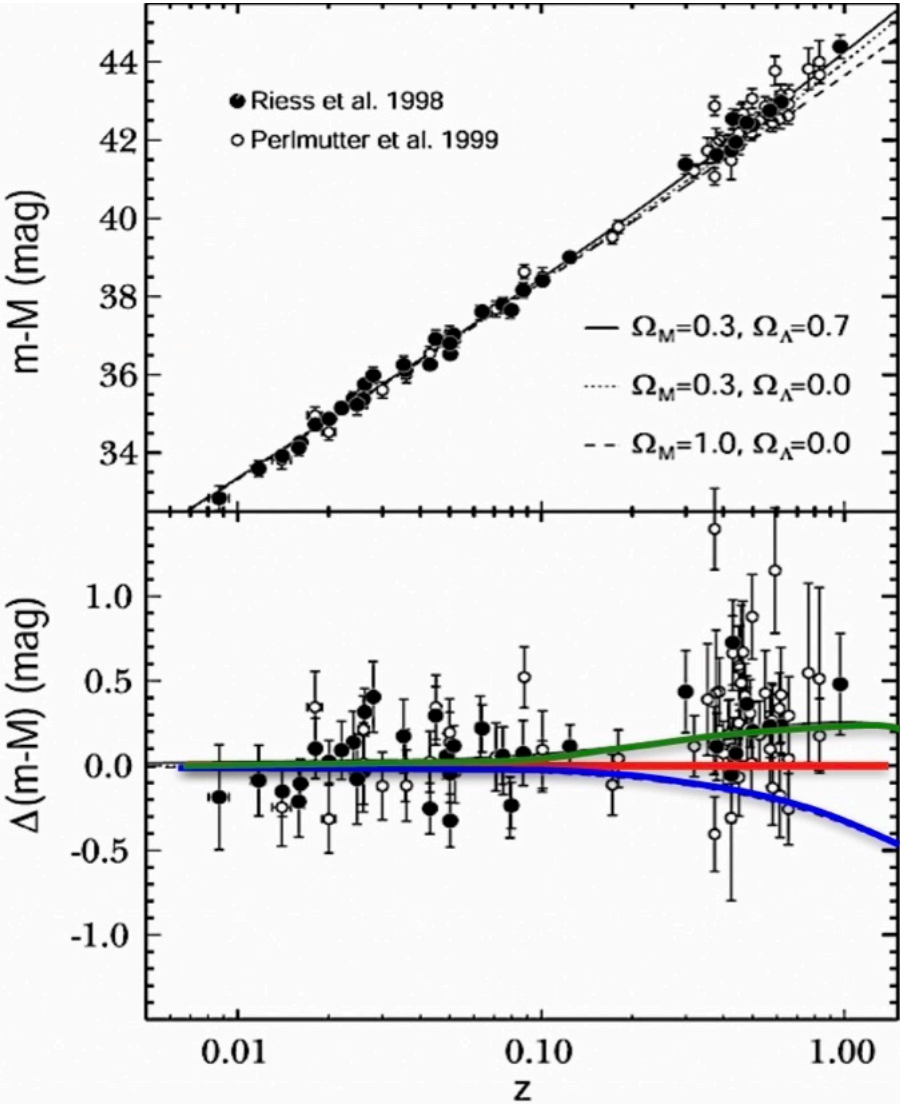


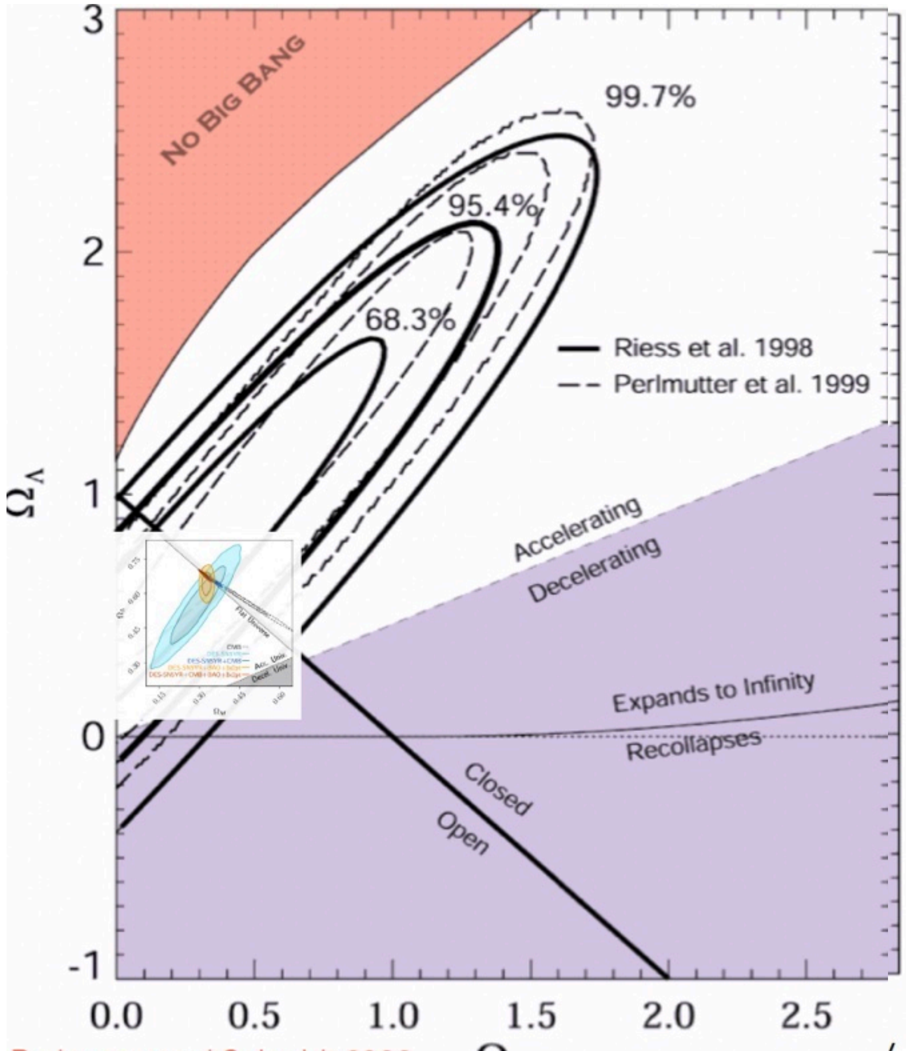


Perlmutter&Schmidt 2003

First discovery of cosmic acceleration

Supernovae Type Ia (SNe Ia)

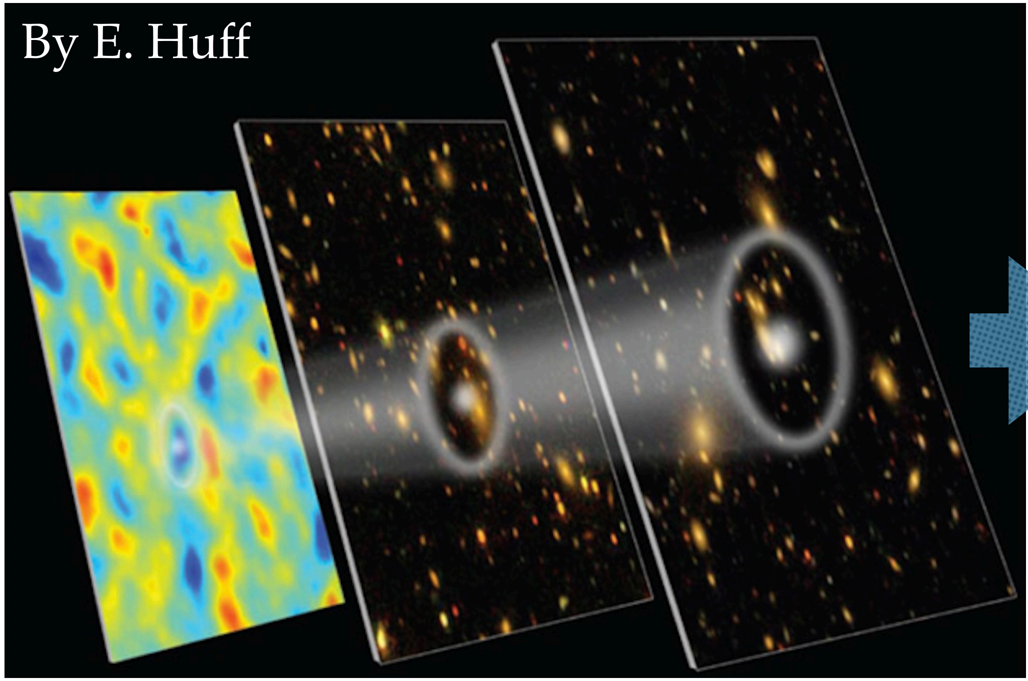


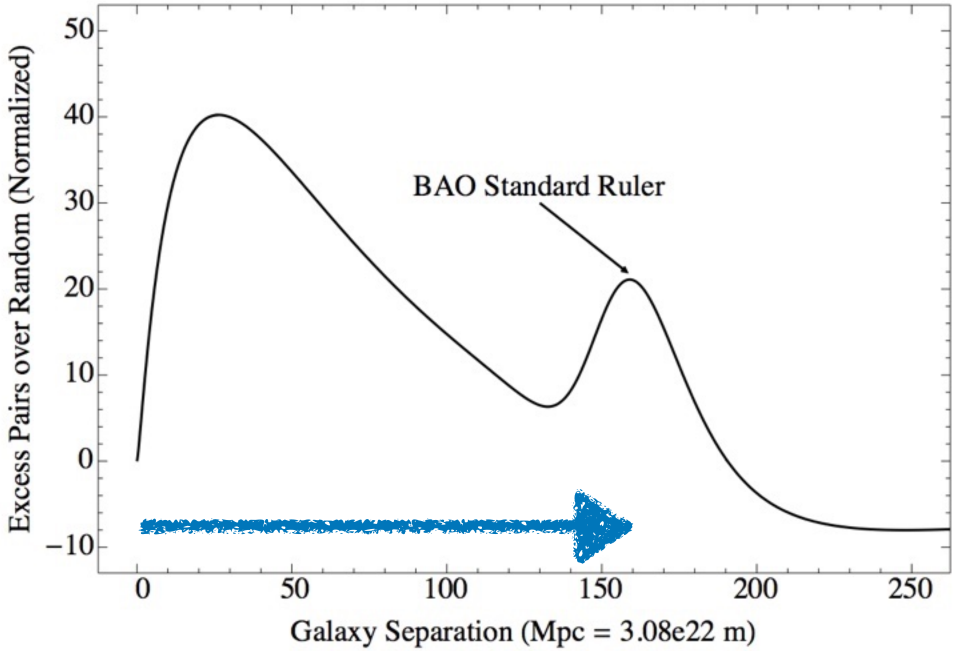


Perlmutter and Schmidt 2003

Baryon Acoustic Oscillations (BAO)

Standard Ruler

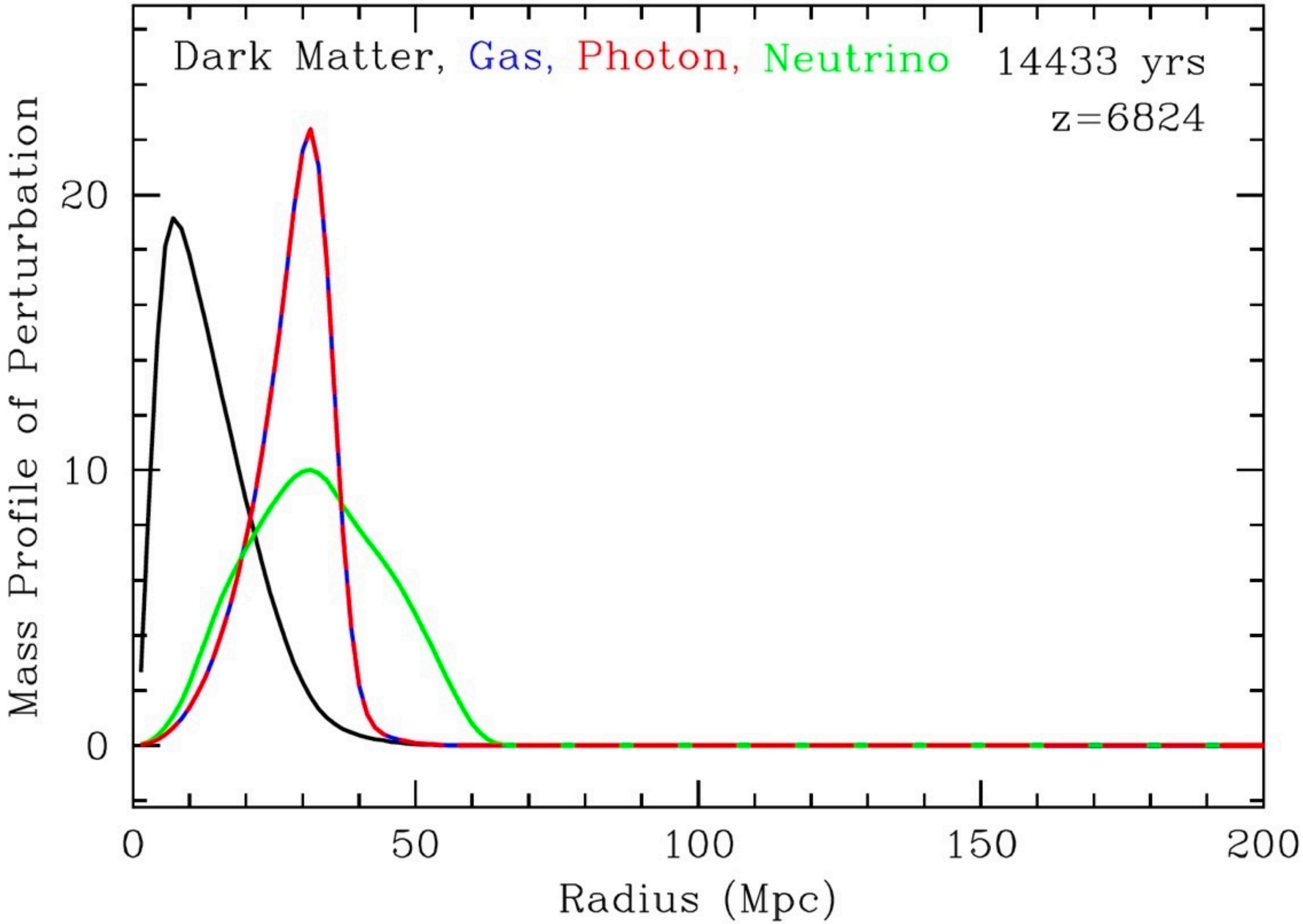




- Imprint of sound waves frozen in the early Universe
- Scale set by sound horizon and does not change in time, but depends on the amount of dark energy

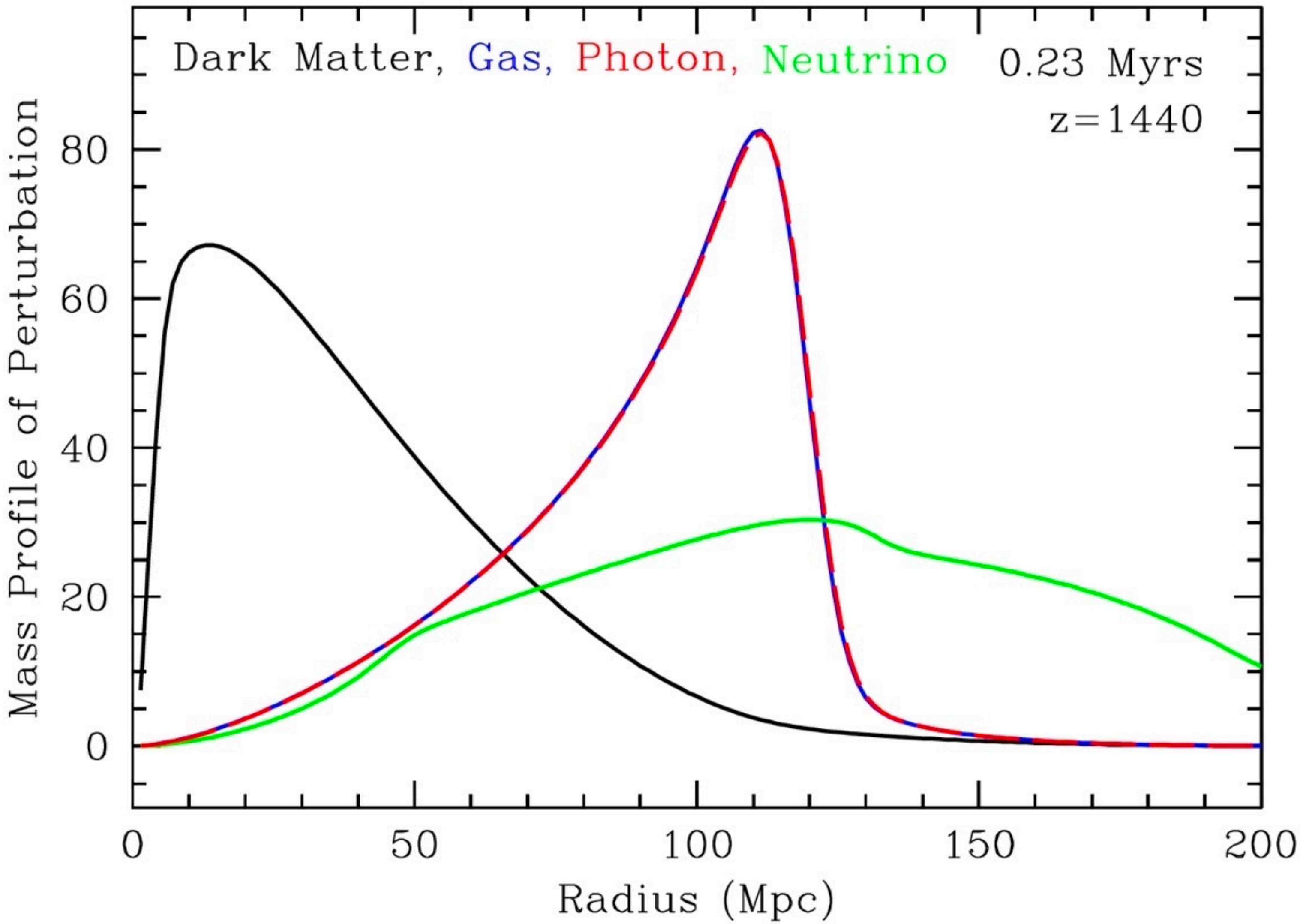
Sound Wave Imprint as a Standard Ruler

- Start from the initial density field (e.g., initially point-like overdensity at the origin)



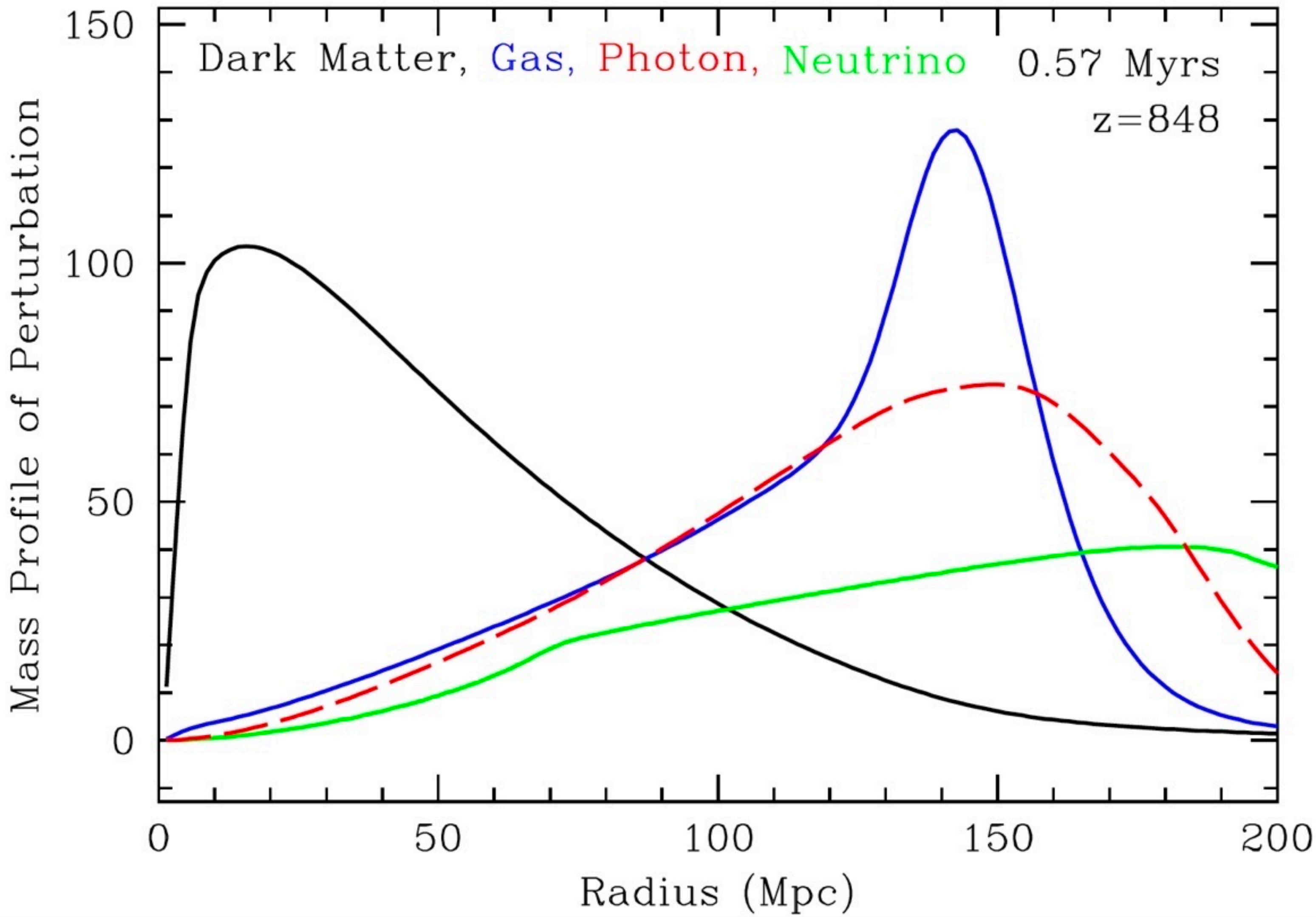
Sound Wave Imprint as a Standard Ruler

- Photon and baryons are couples and behave as a sound wave



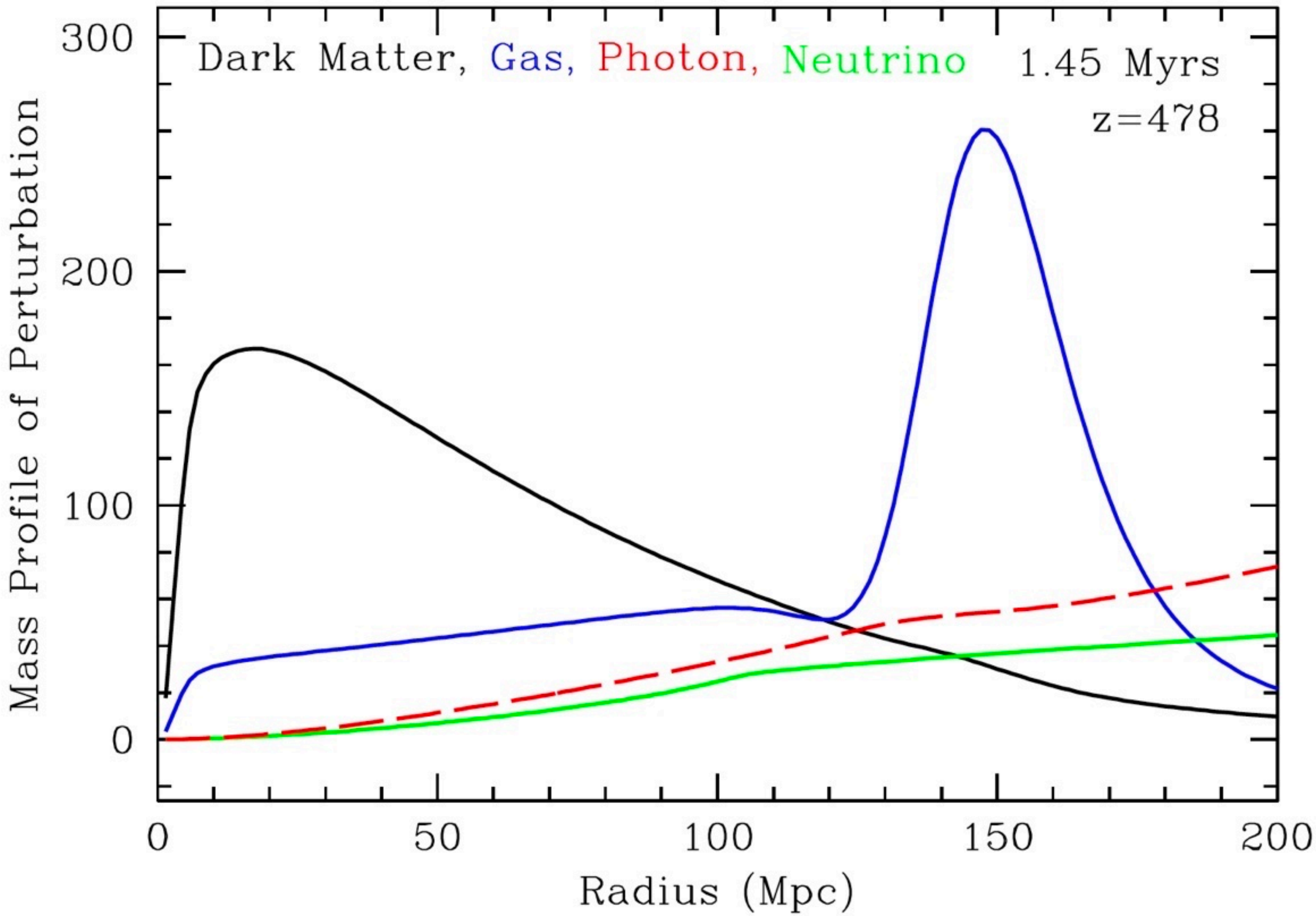
Sound Wave Imprint as a Standard Ruler

- When the temperature of the Universe becomes cold enough, photons and baryons are decoupled



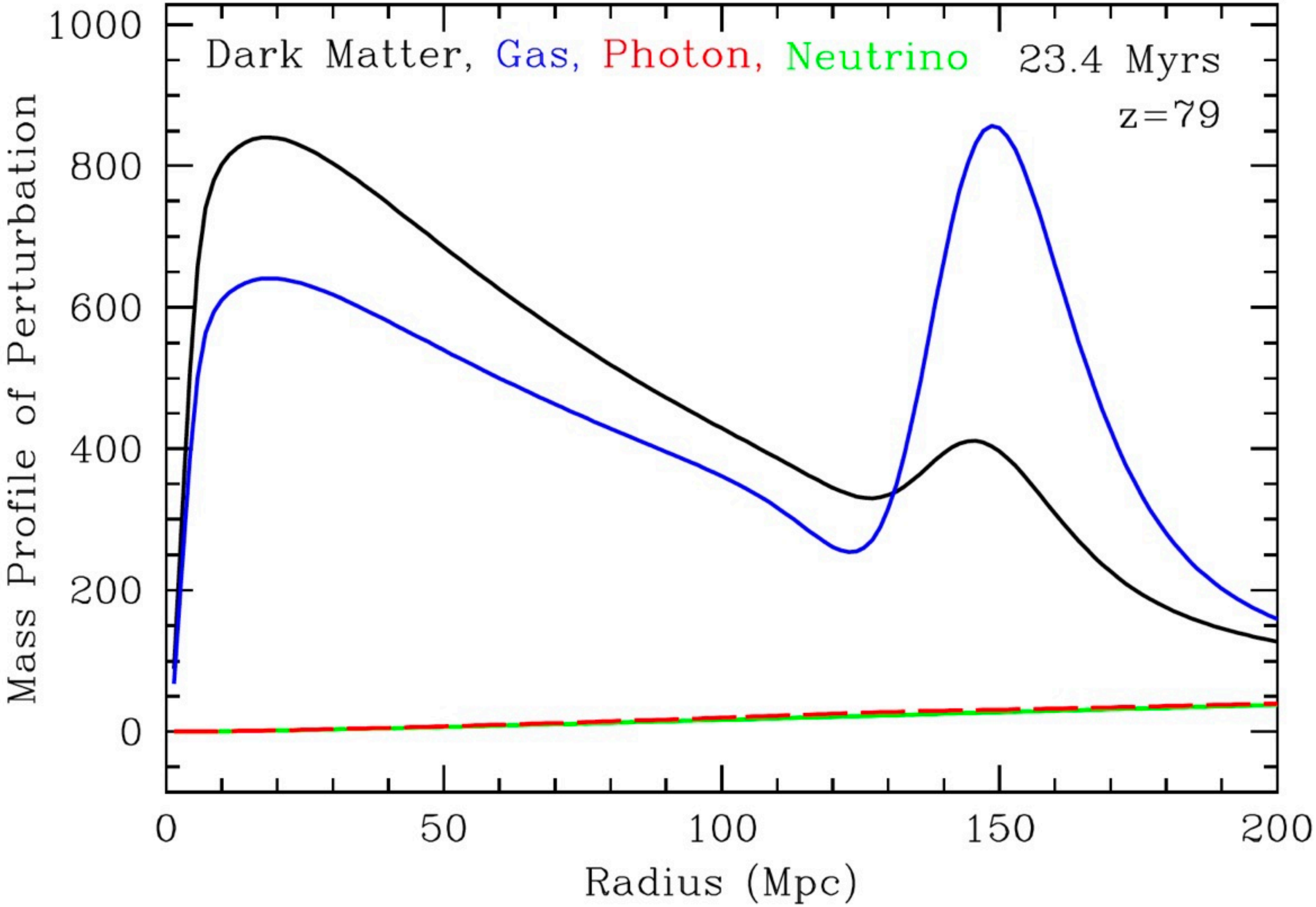
Sound Wave Imprint as a Standard Ruler

- Photons are free-streaming; baryons starts attracted to the gravitational potential created by dark matter



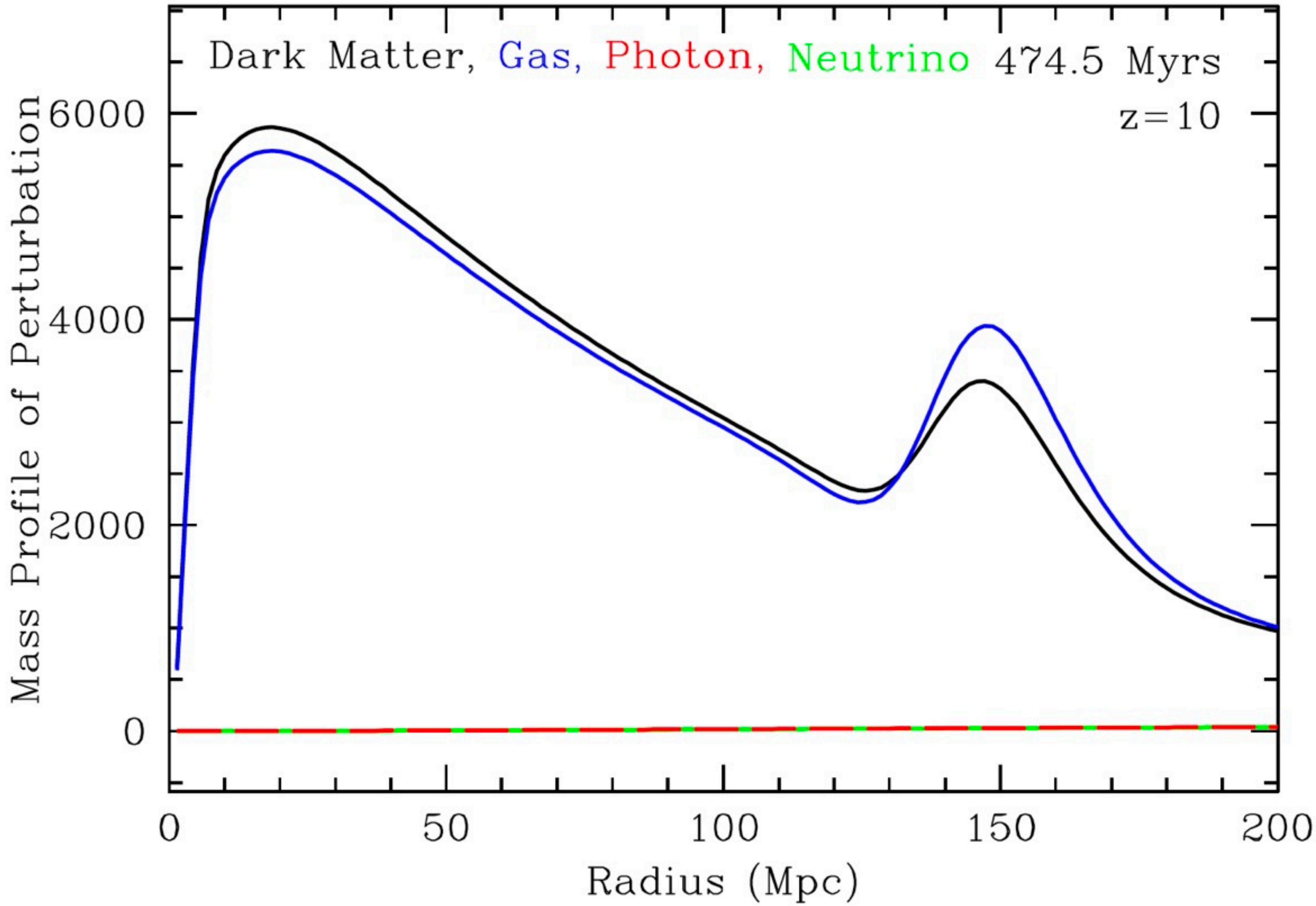
Sound Wave Imprint as a Standard Ruler

- With pressure forces now small, baryons and dark matter are attracted to these overdensities by gravitational instability

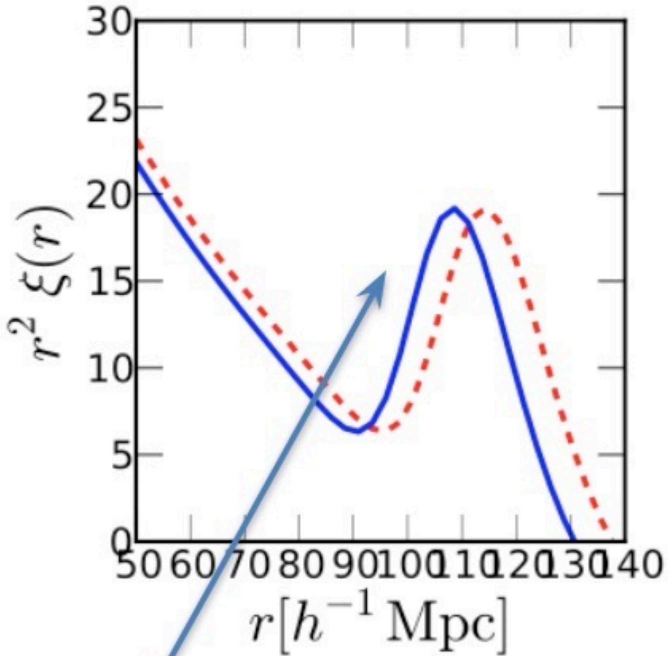


Sound Wave Imprint as a Standard Ruler

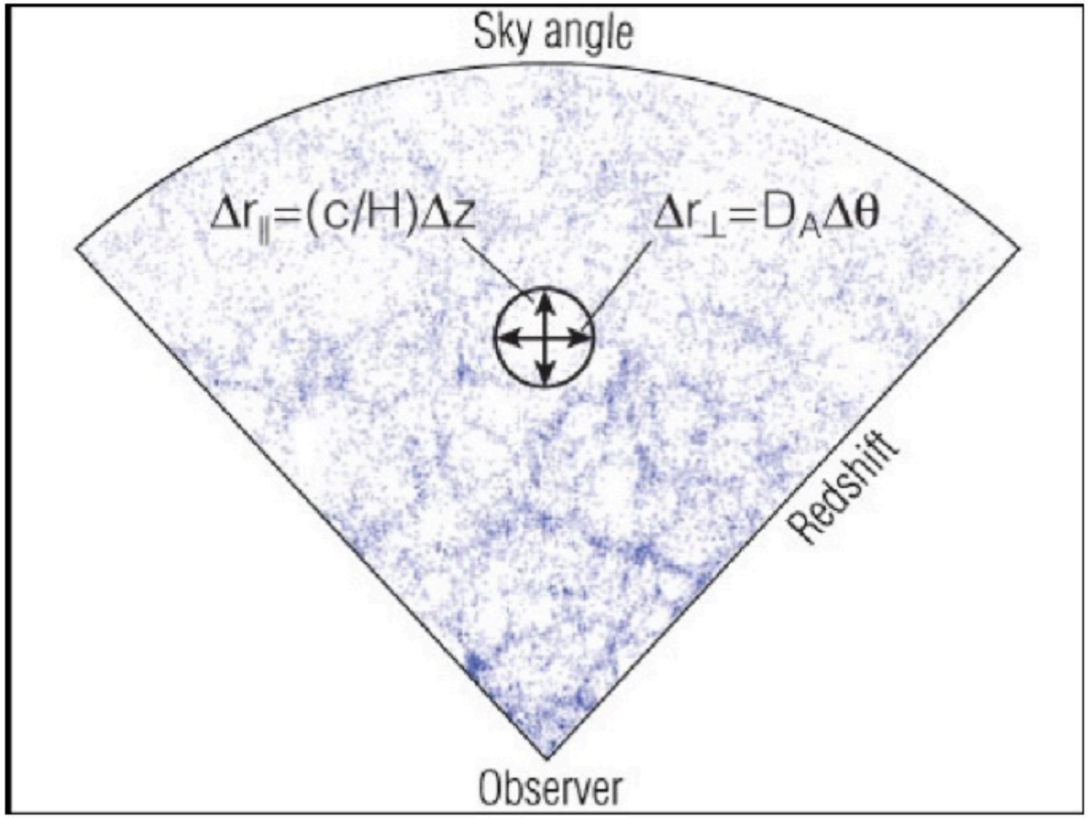
- Because most of the growth is drawn from the homogeneous bulk, the baryon fraction converges toward the cosmic mean at late times. Galaxy formation is favored near the origin and at a radius of 150 Mpc.



Measuring distance with standard ruler



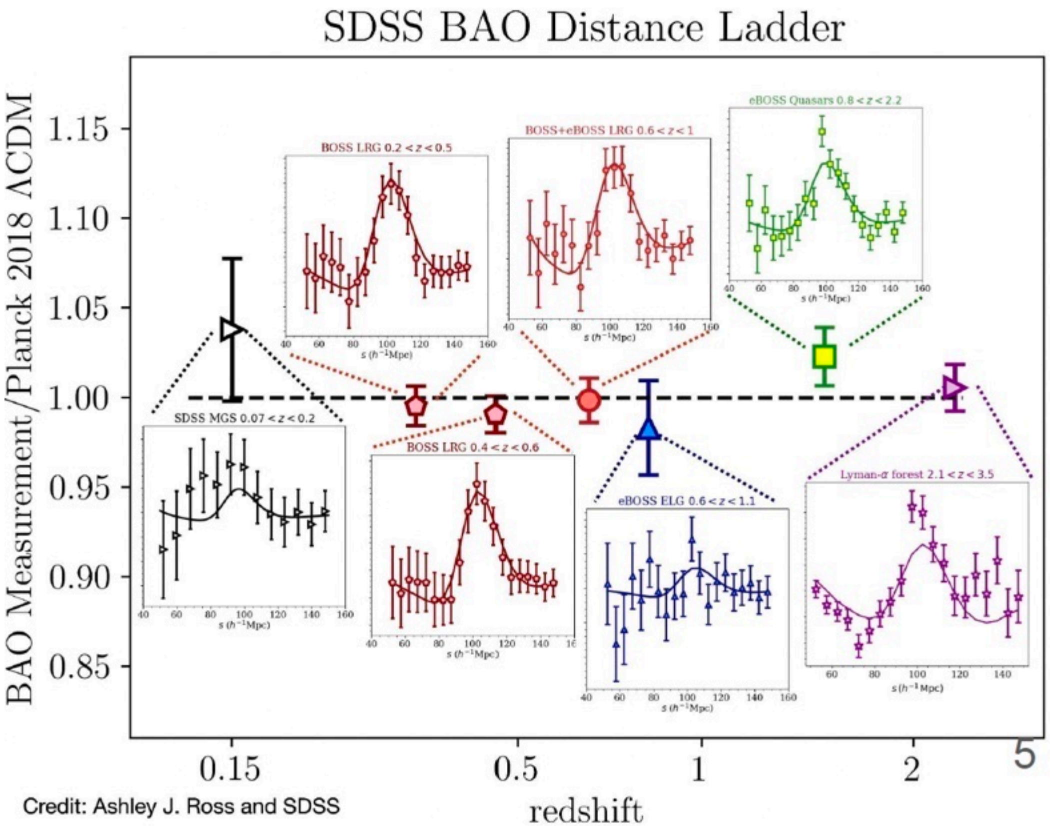
$$\alpha \equiv \left(\frac{D_{\mathrm{V}}(z)}{r_{\mathrm{d}}}\right)\left(\frac{r_{\mathrm{d,fid}}}{D_{\mathrm{V}}^{\mathrm{fid}}(z)}\right)$$



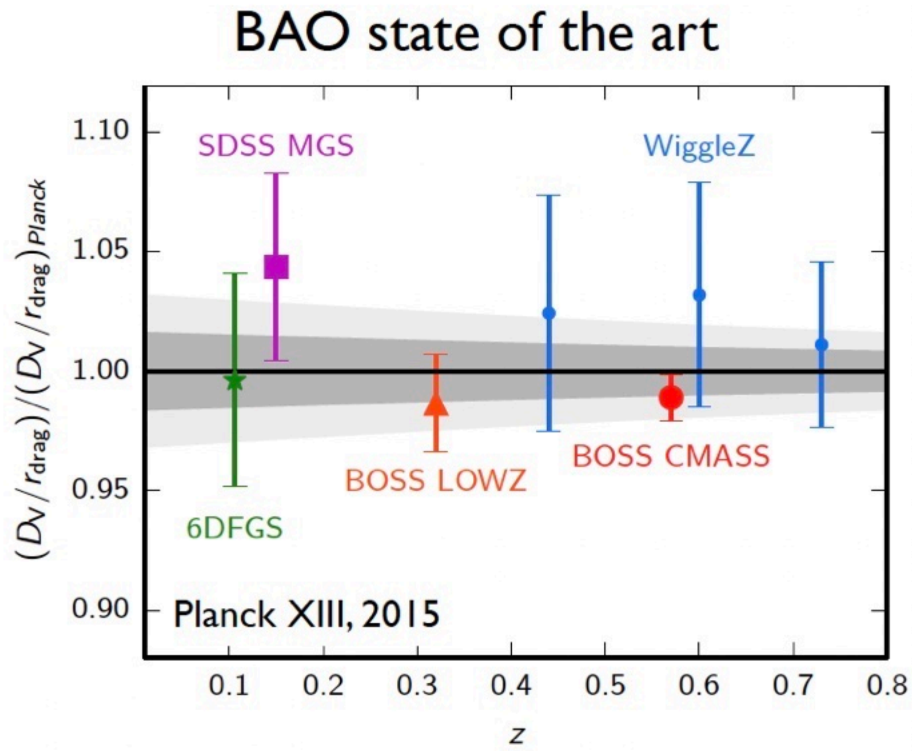
$$D_{\mathrm{V}} \equiv \left[cz(1+z)^2 D_{\mathrm{A}}(z)^2 H^{-1}(z)\right]^{1/3}$$

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)

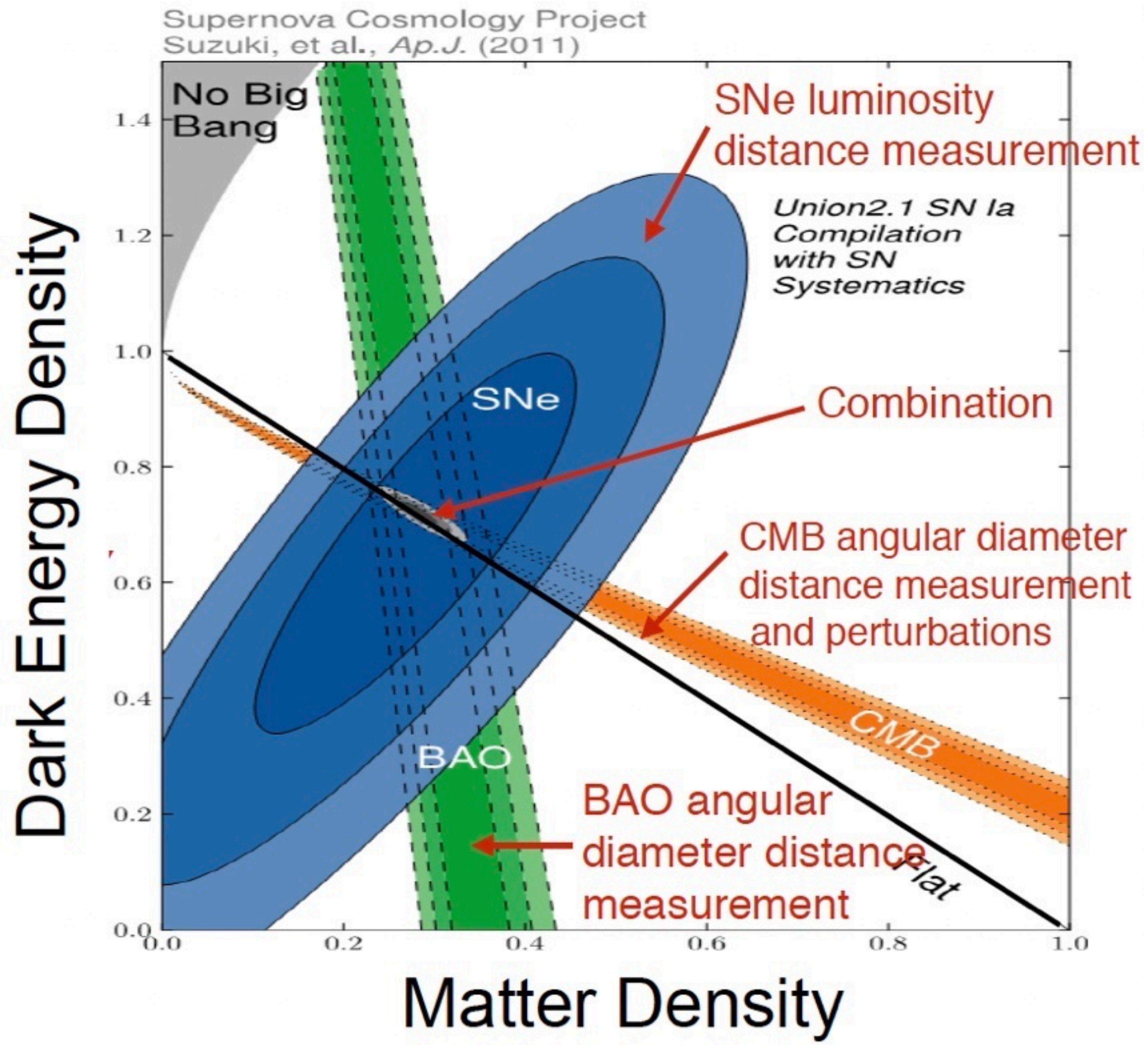


Credit: Ashley J. Ross and SDSS



Concordance Cosmology in early 2000s

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

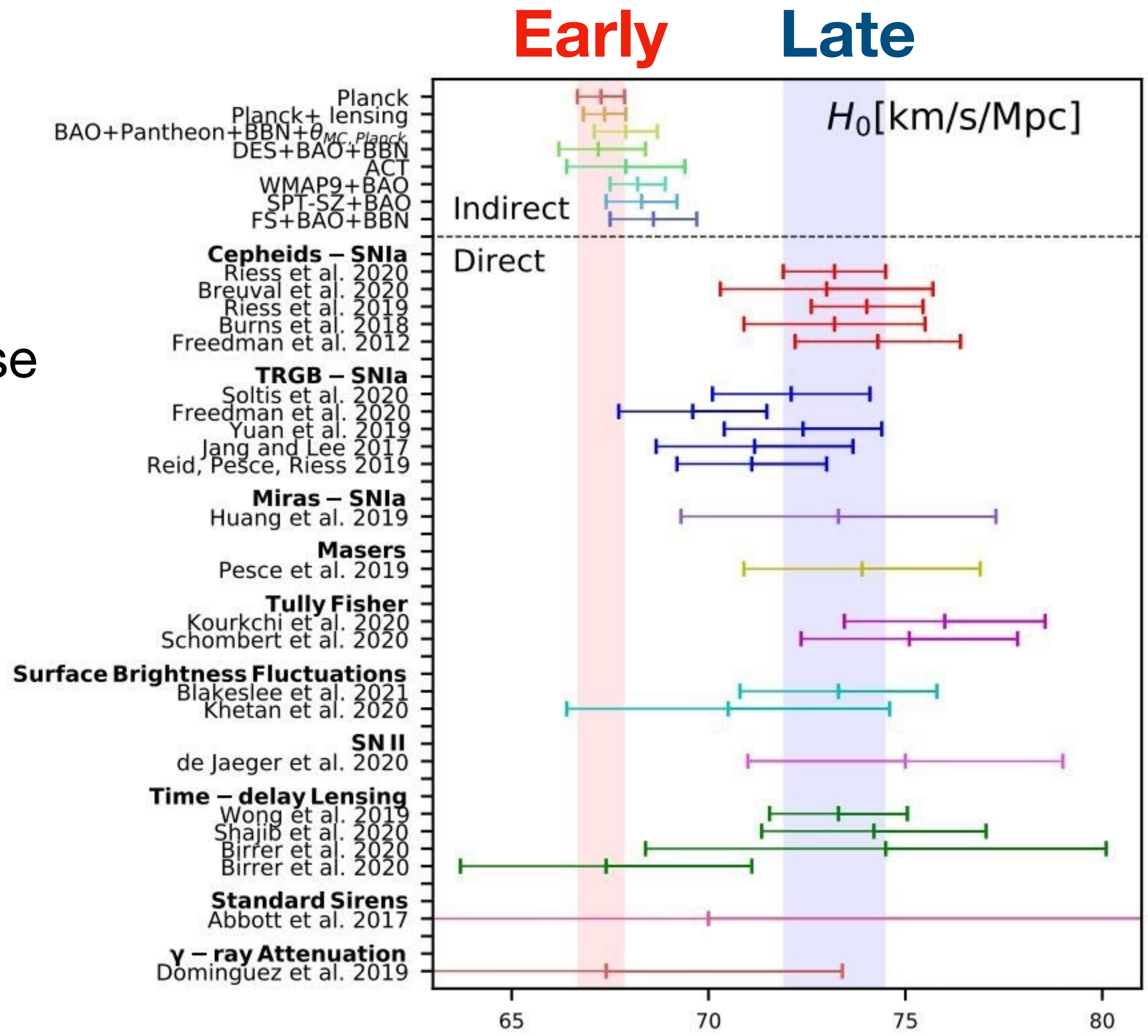


Credit: E. Krause

Concordance Cosmology…?

- Significant tension between early-Universe and late-Universe probes!

- “Hubble Tension”

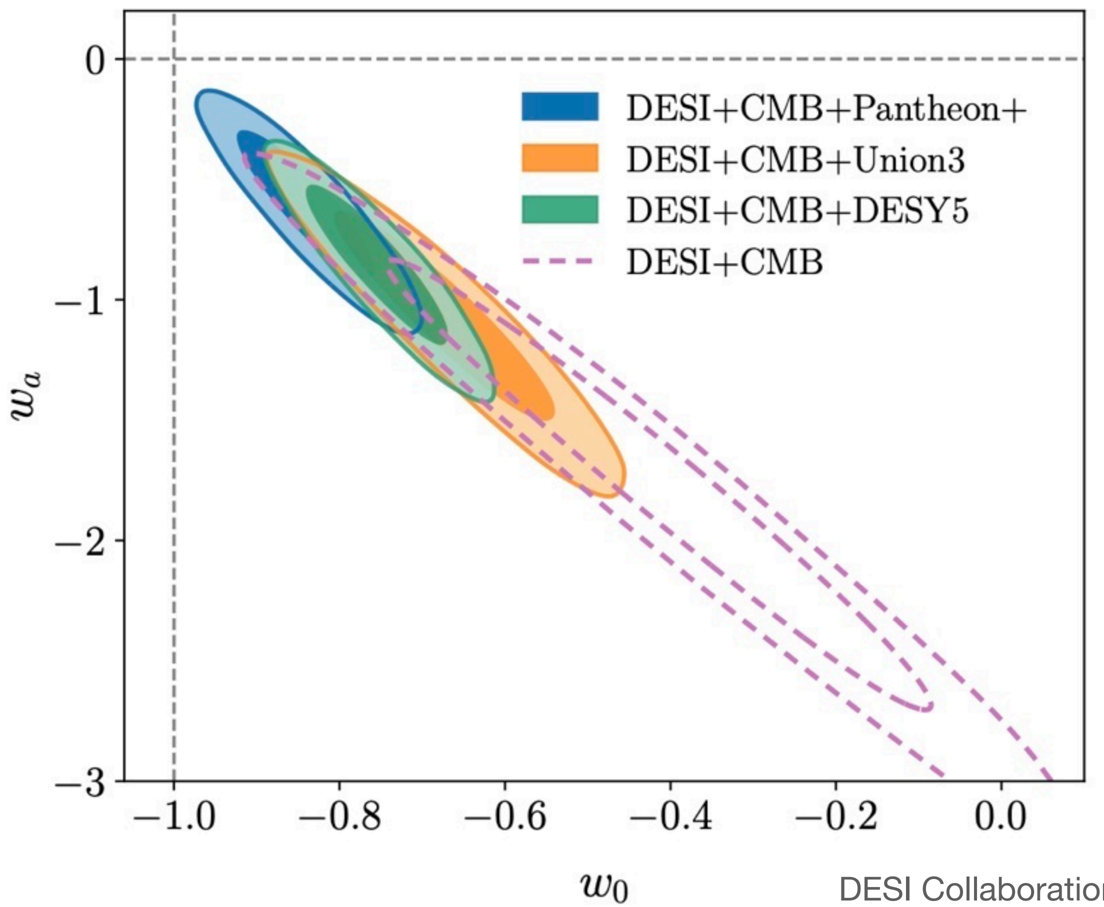


DiValentino+2020

Coming back to BAO

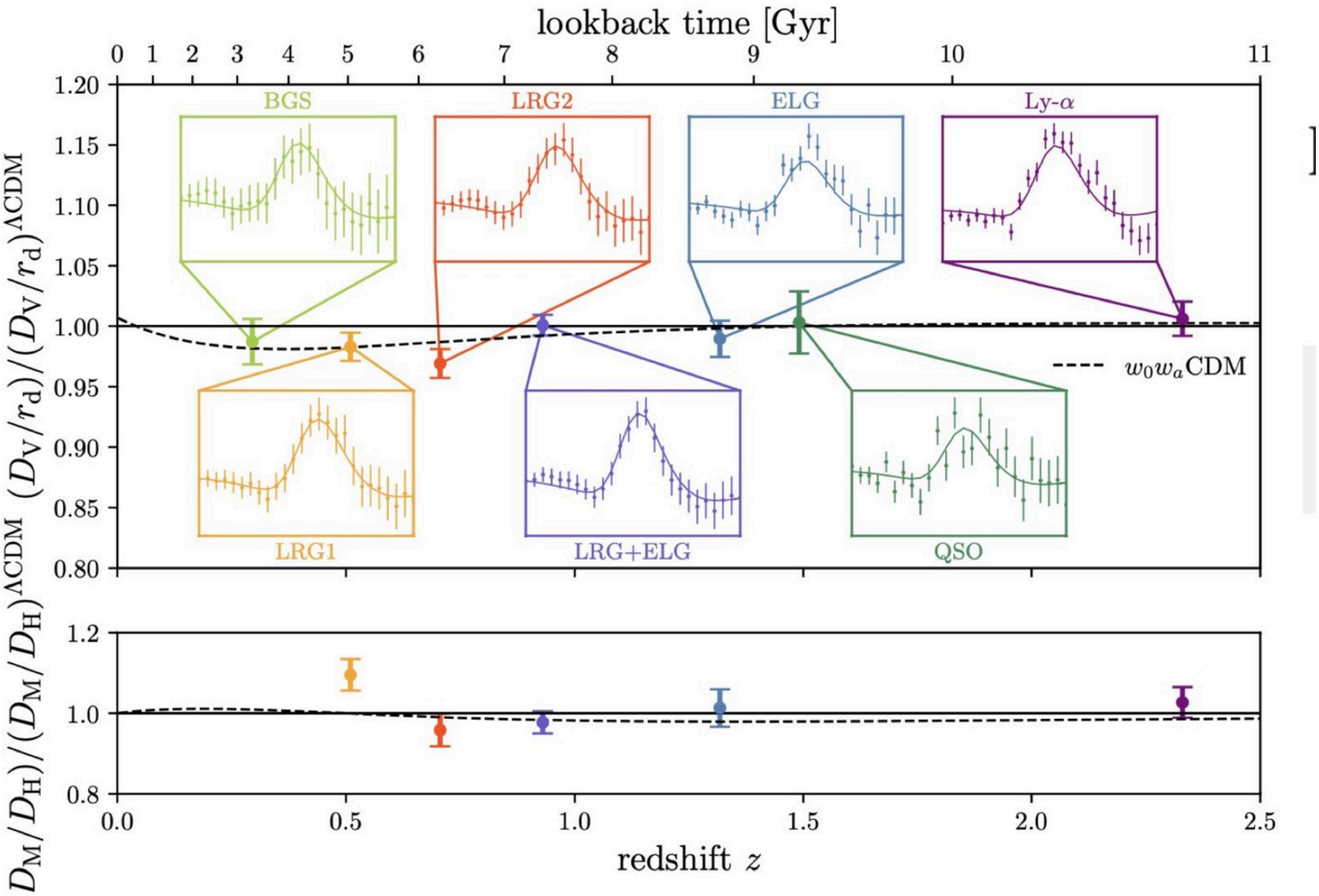
Recent results from DESI

Evidence of time-evolving dark energy?

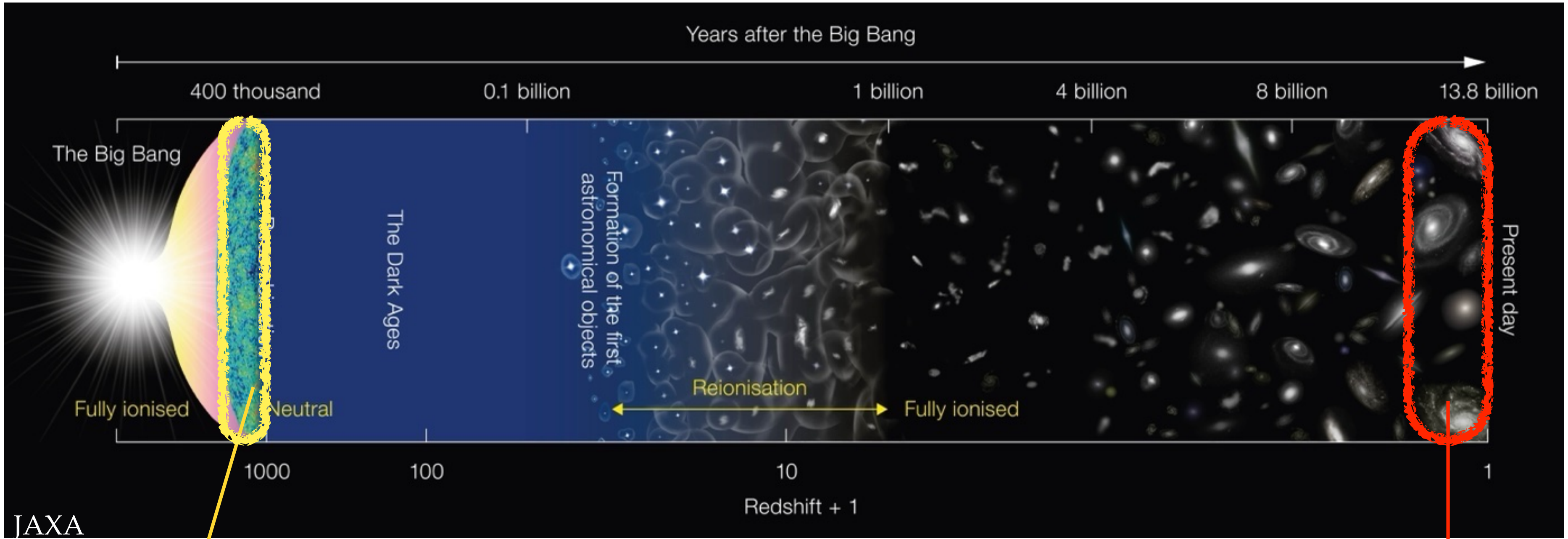


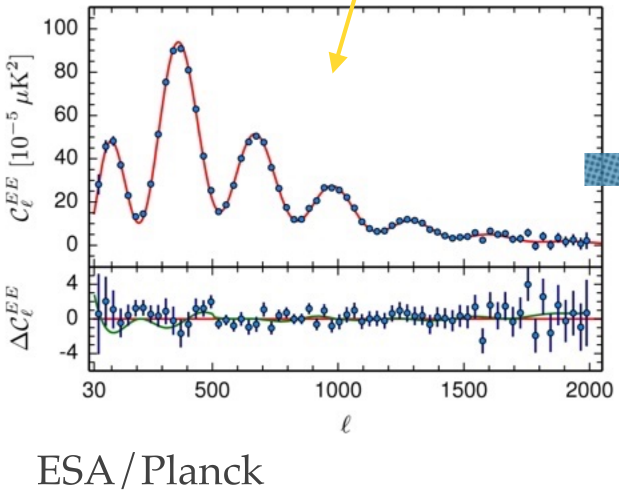
DESI Collaboration 2025

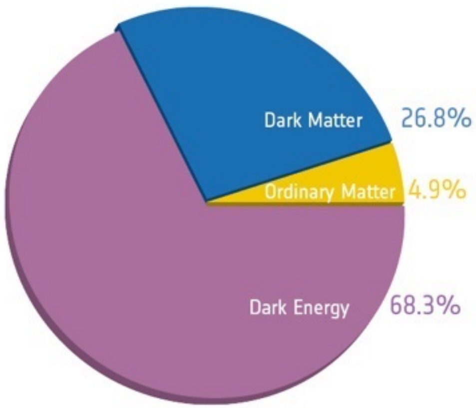
Tantalizing hint of dynamical DE?



Stress test ΛCDM using large-scale structure probes







?

Large scale structure probes

- Gravitational Lensing
- Galaxy clusters
- Galaxy clustering

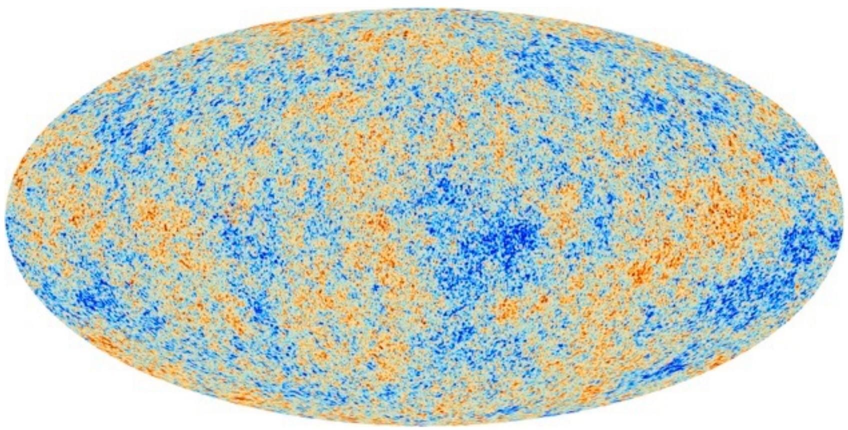
Test the evolution of the structure

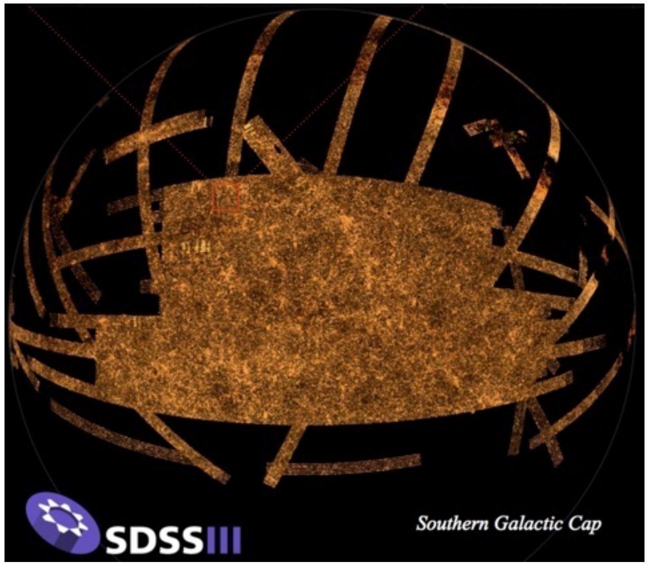
Amplitude of matter density fluctuations

$$A_s \xrightarrow{\Lambda\text{CDM?}} \sigma_8$$

Primordial amplitude constrained by the CMB

Present-day amplitude constrained by late-time observations



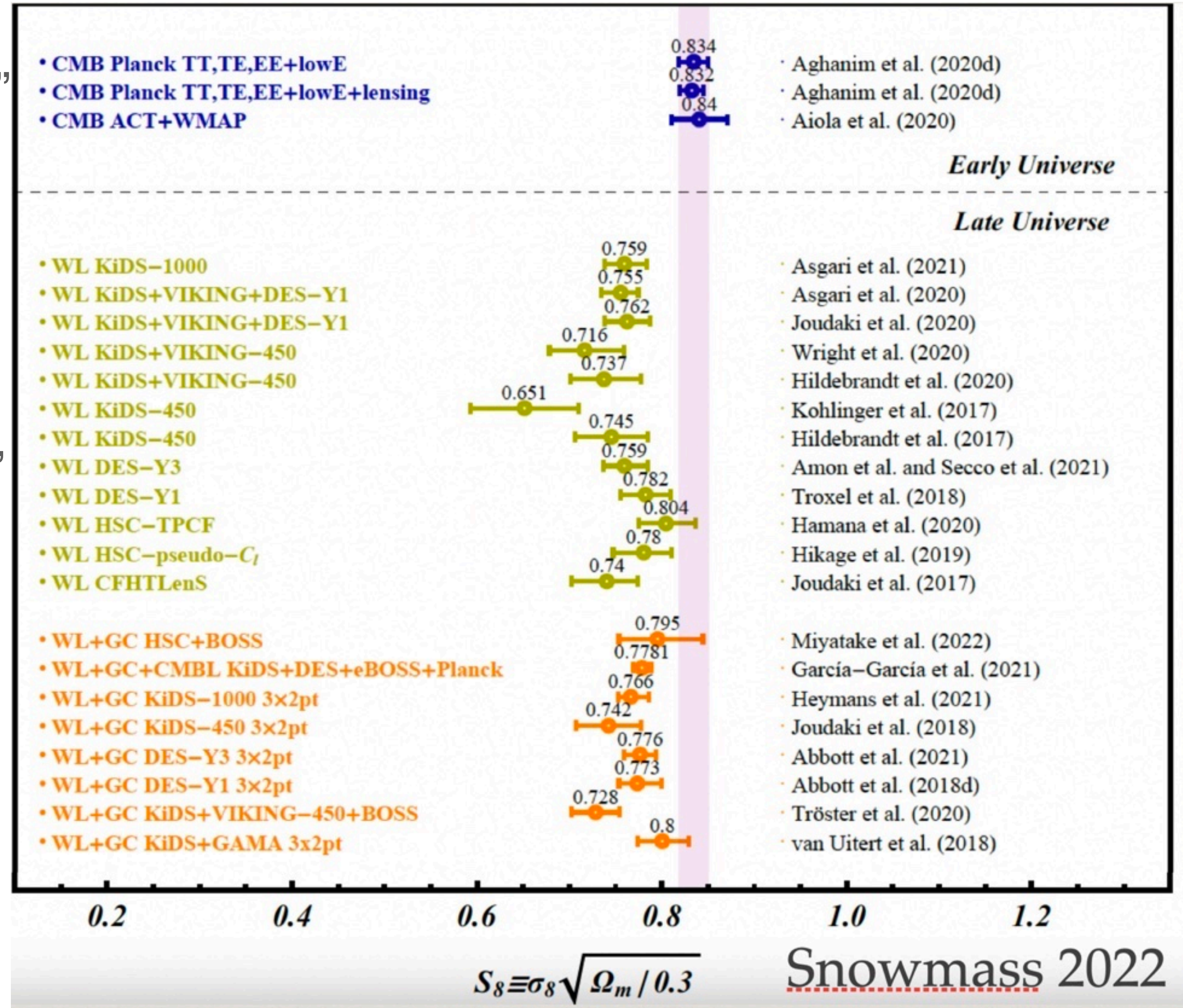


S8 Tension: accumulated evidence of disagreement

- σ_8 measures "clumpiness" of the Universe

"Early-Universe probe"

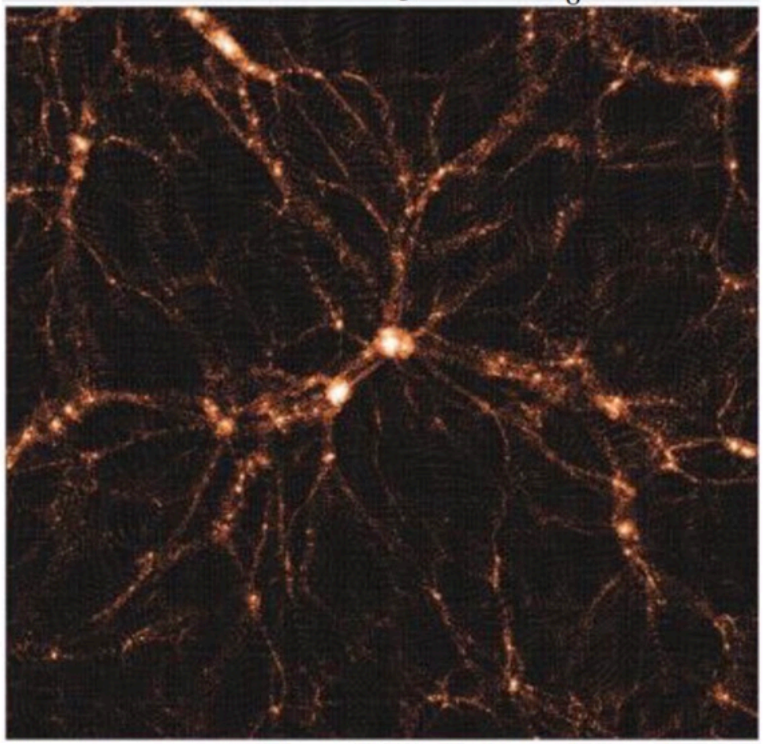
"Late-Universe probe"



How does S8 tension look like?

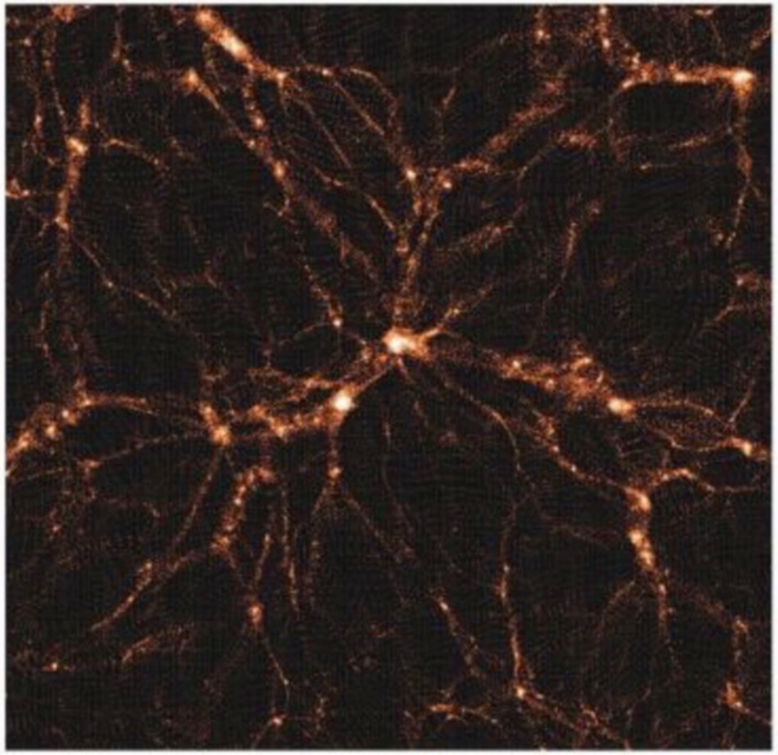
- Comparison between the Universe measured from HSC-Y1 lensing and predicted from Planck CMB

Planck 2020 Primary CMB: $S_8 = 0.83$



Planck Collaboration (2020)

HSC-Y1 cosmic shear: $S_8 = 0.78$



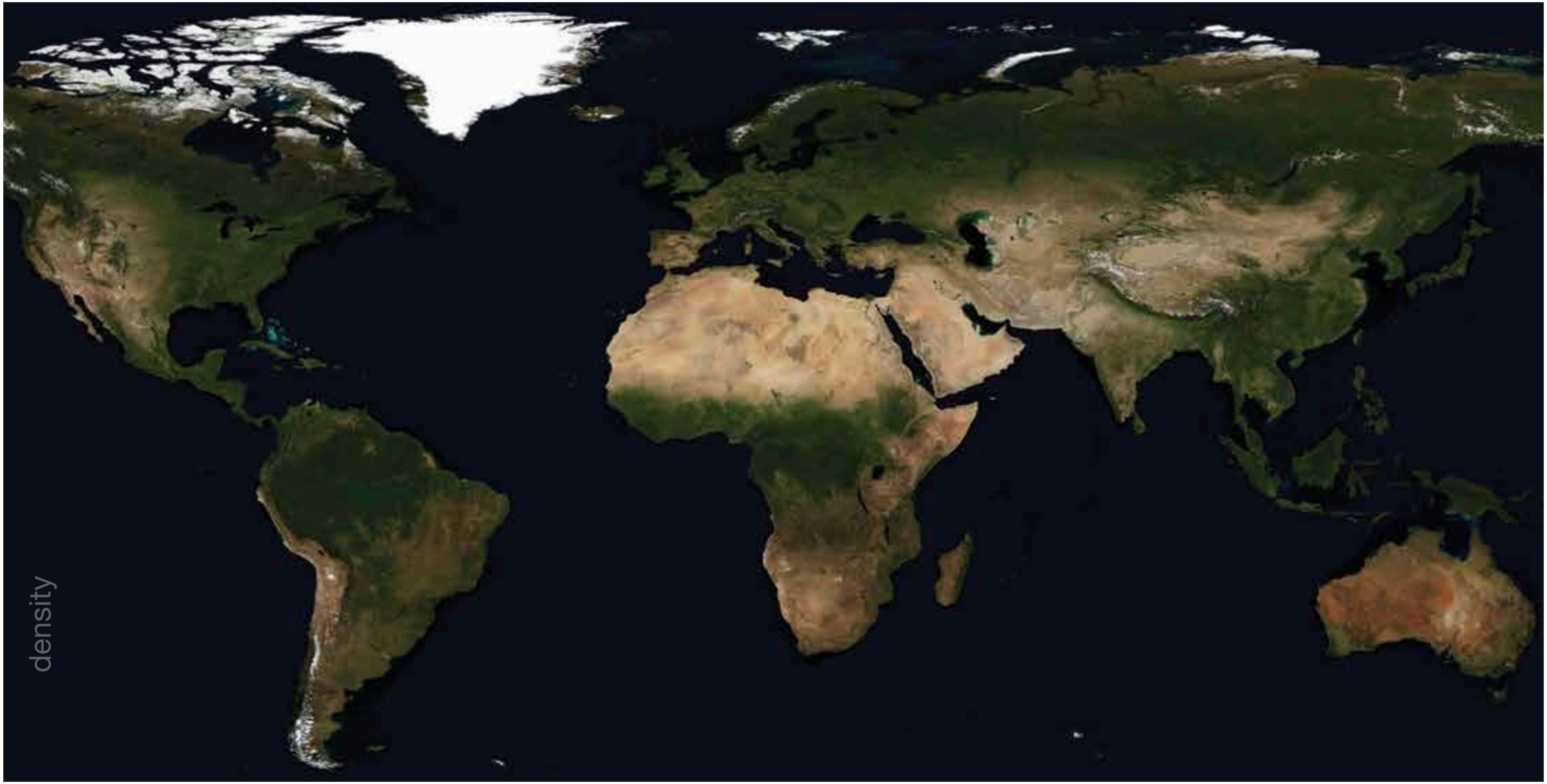
Hikage et al. (2019)

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

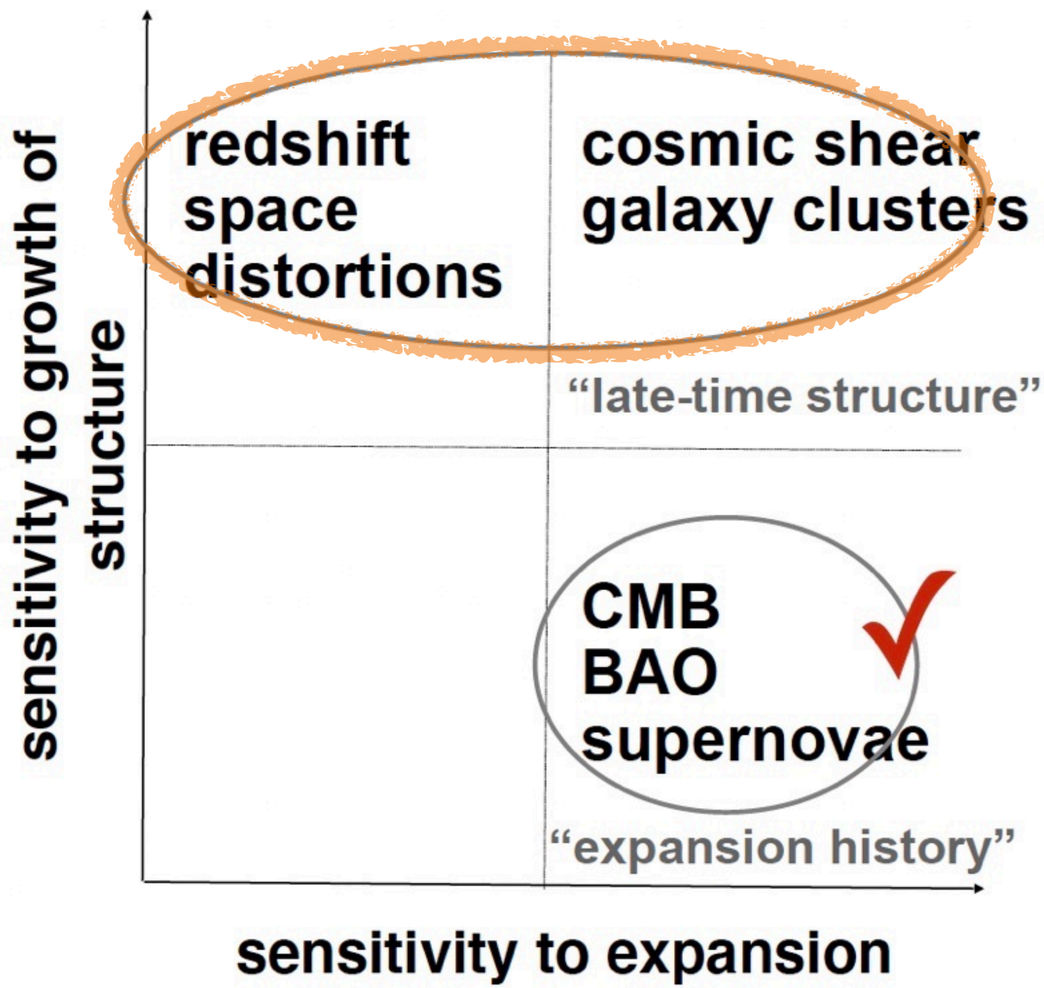
This is all we can see…

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)

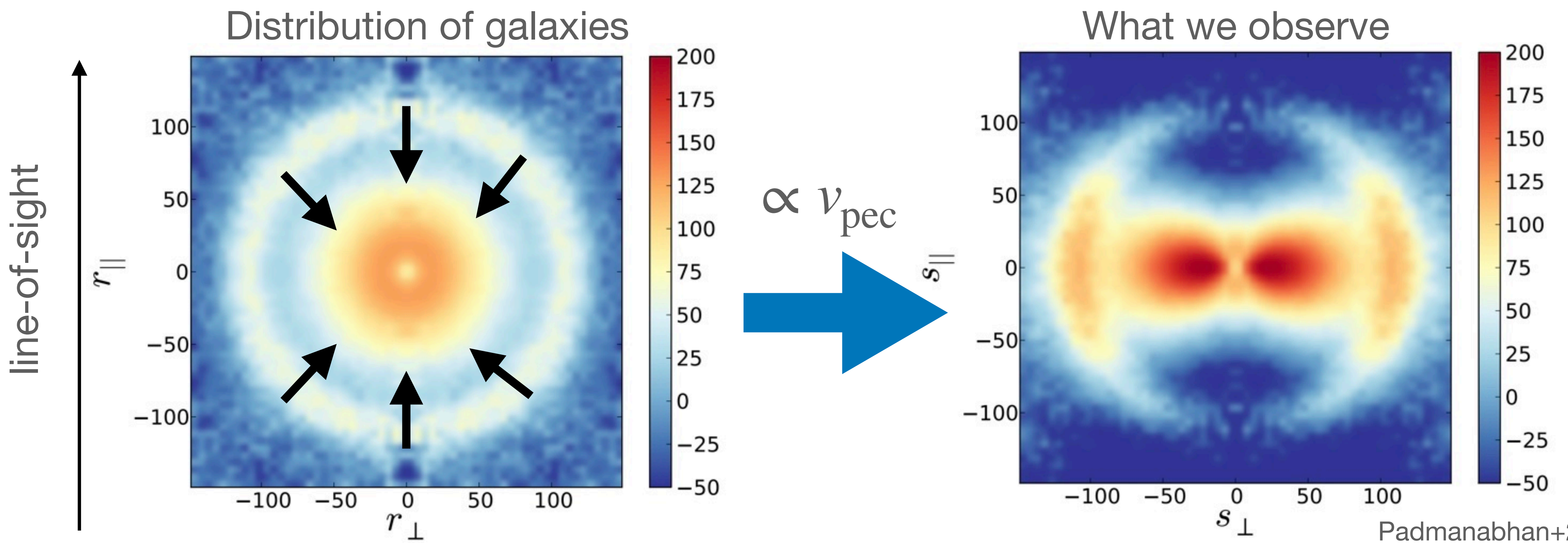
- Redshift is a combination of Hubble expansion and peculiar motion of galaxies → isotropic galaxy distribution becomes anisotropic in redshift-space

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

Redshift "What we measure"

Expansion of the Universe

Motion of Galaxies



Padmanabhan+2012

Redshift-Space Distortion (RSD)

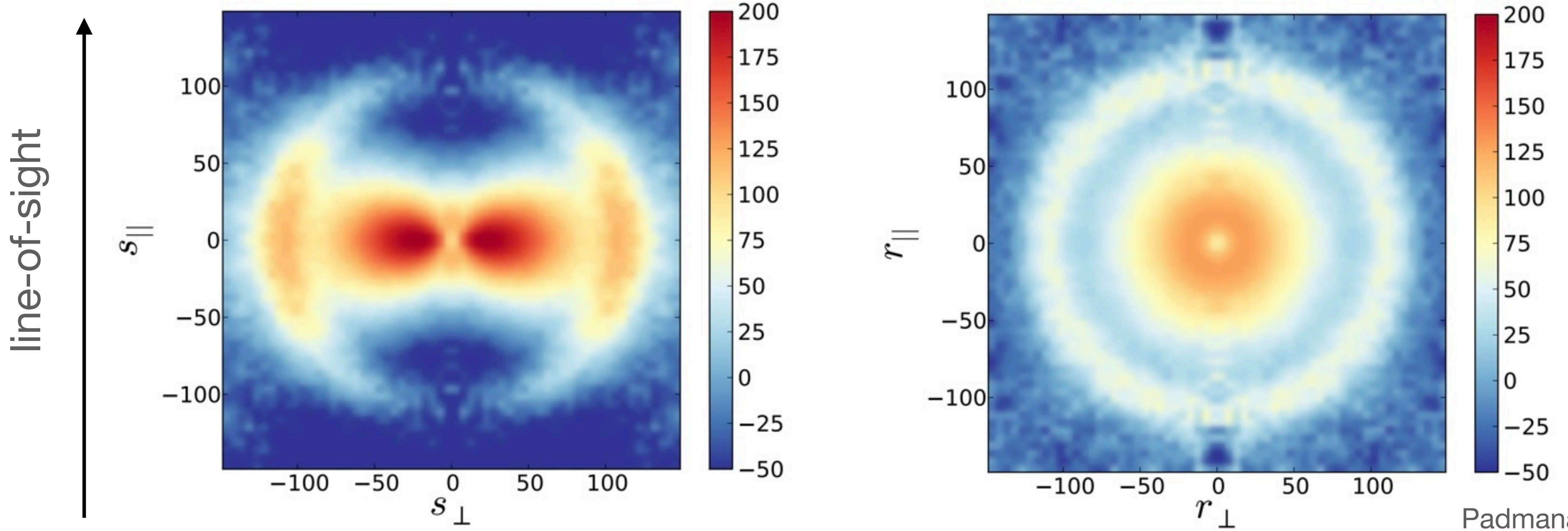
- On large scales, peculiar velocity can be computed as a function of growth rate

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

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

μ is angle between r and LOS

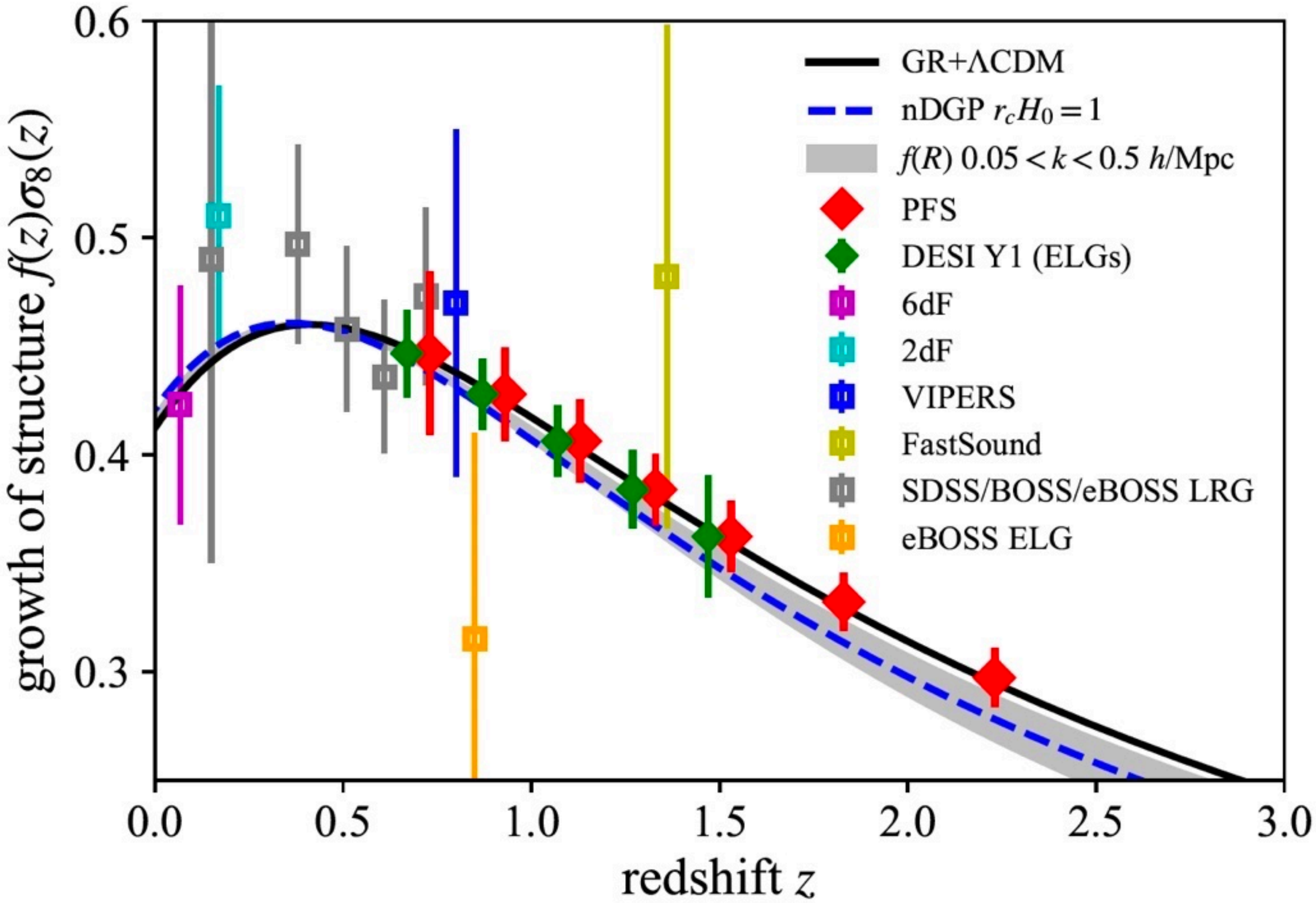
"redshift-space"(s) "real-space"(r)



Padmanabhan+2012

Forecast for DESI Y1 and PFS in a few years

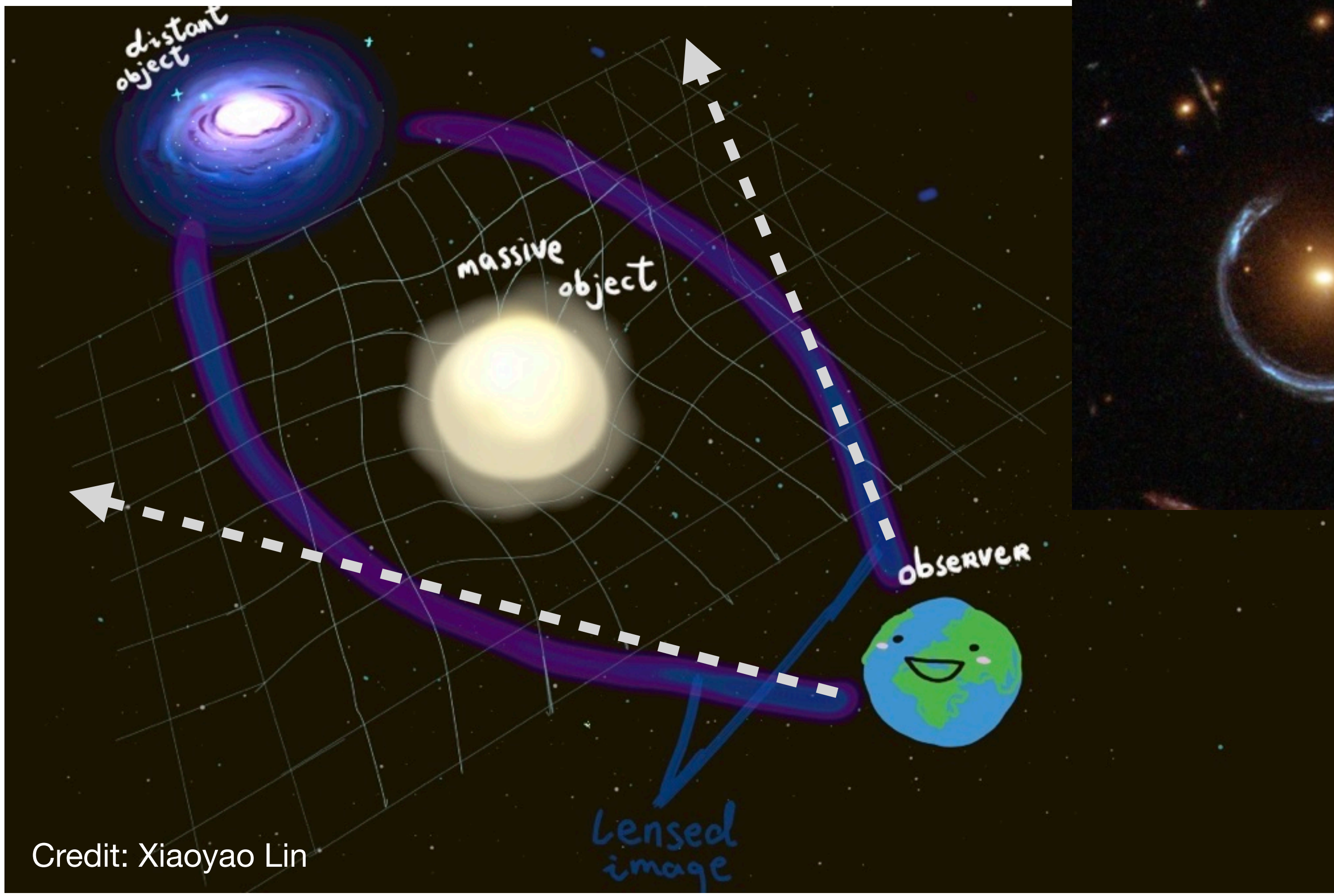
- Can constrain the growth of structure with 6% up to z~2.4



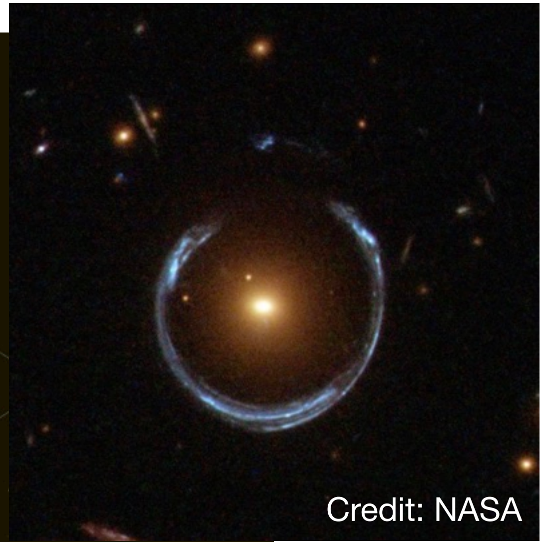
PFS forecast: TS+,in prep.

Gravitational Lensing

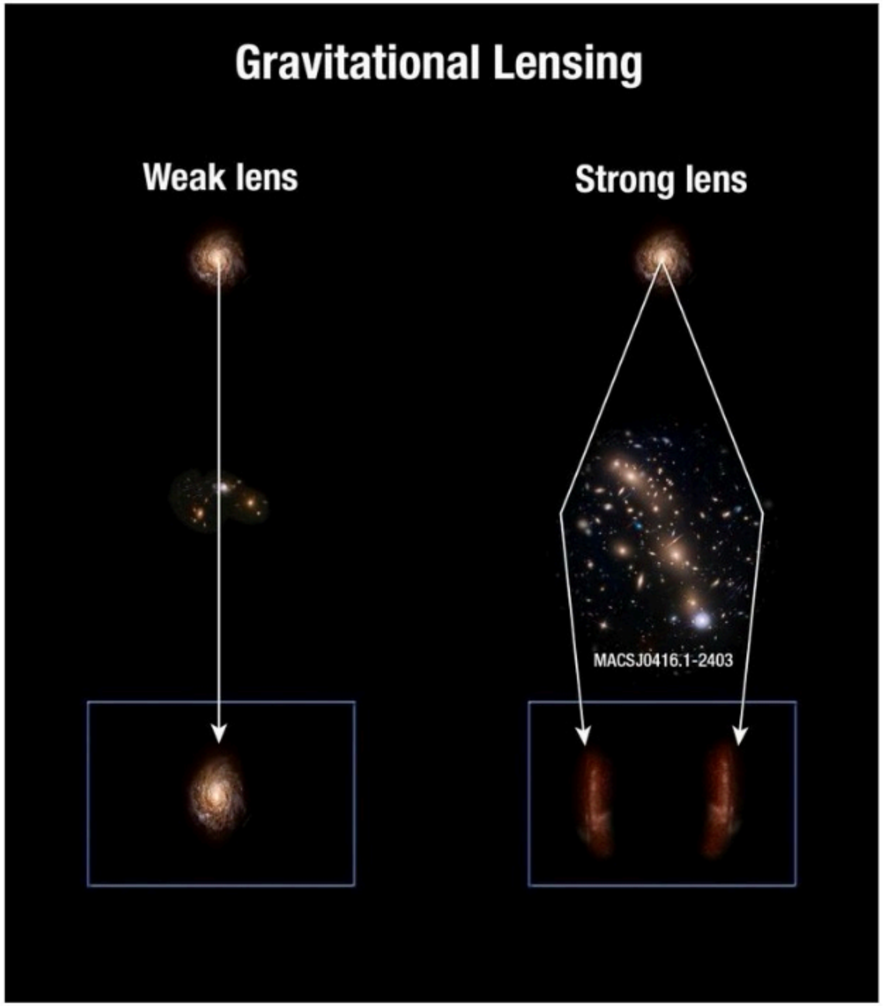
- When massive objects in the Universe distort spacetime, the path of light around it is bent, as if by a lens.
- Create multiple images of the same objects or distort the image of galaxies (strong lensing)



Credit: Xiaoyao Lin


Credit: NASA

Strong and Weak Gravitational Lensing

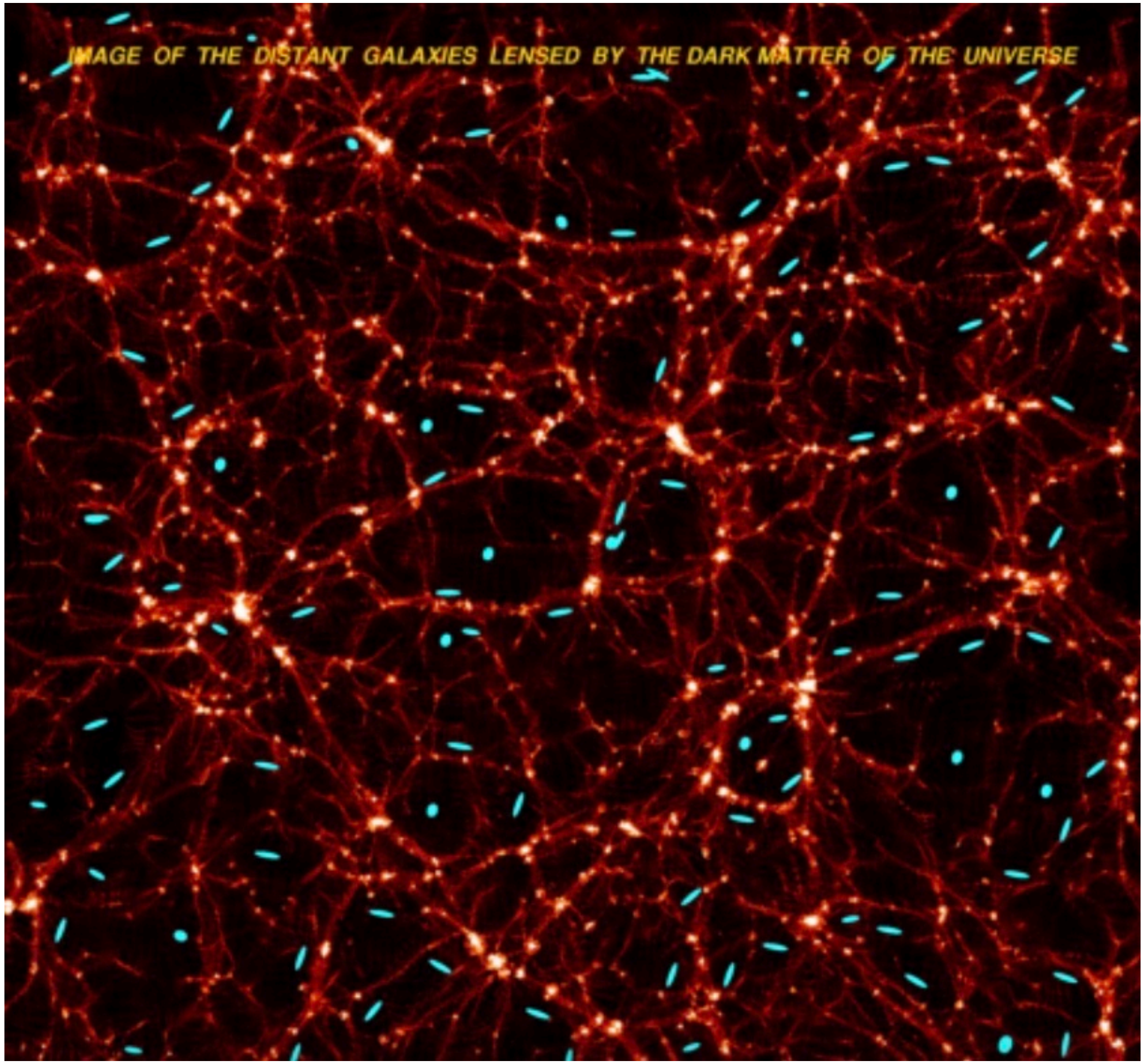


- Strong gravitational lensing
  - Multiple images of the same object
  - Shapes are distorted in a noticeable way
- Weak gravitational lensing
  - Distortion of the shape is subtle
  - Only detectable via statistical analysis

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!

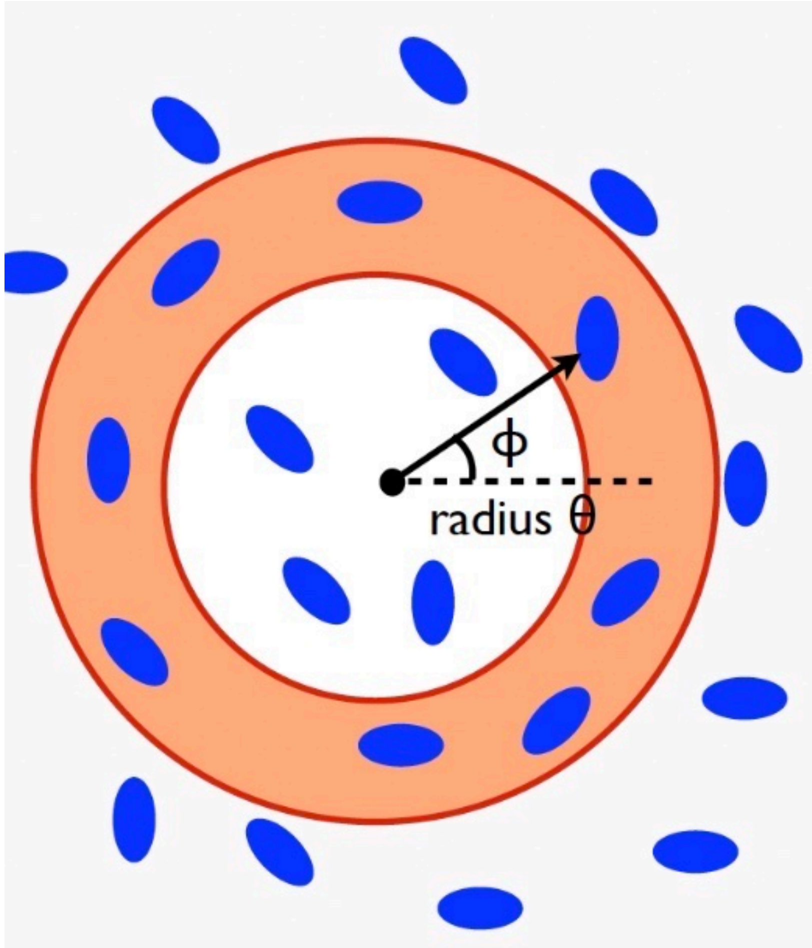
Credit: S. Bridle

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

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

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Weak lensing shear

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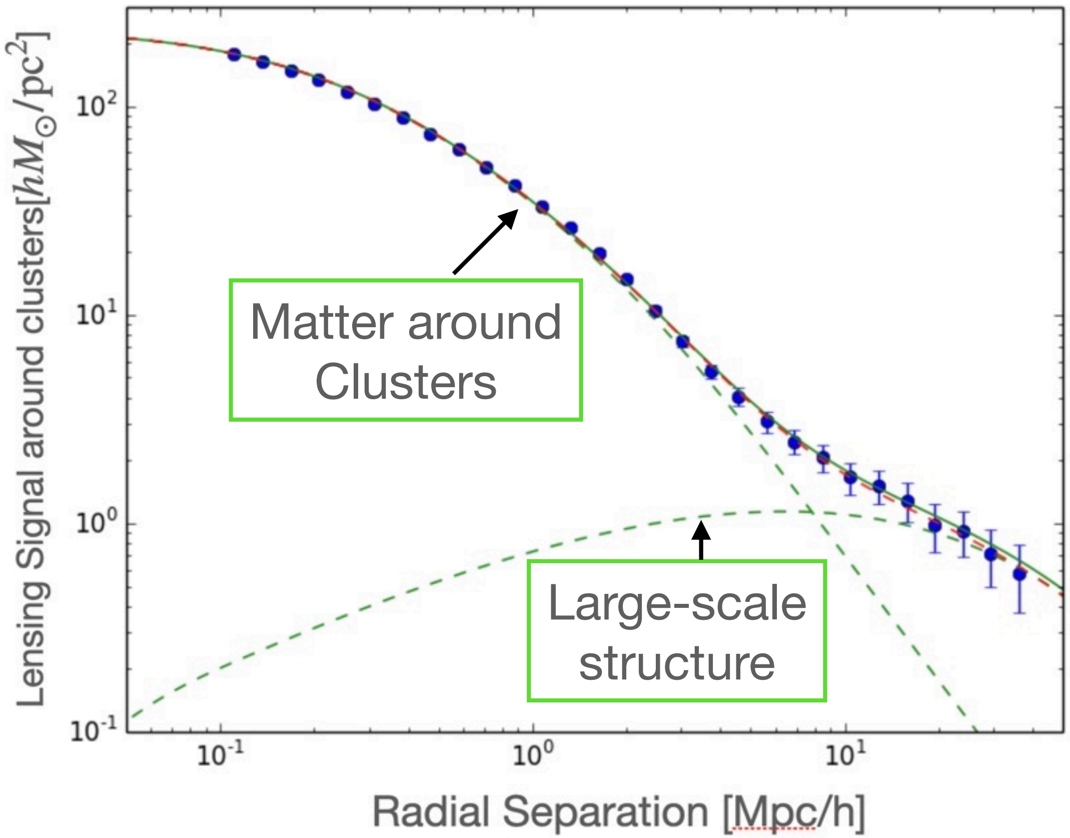
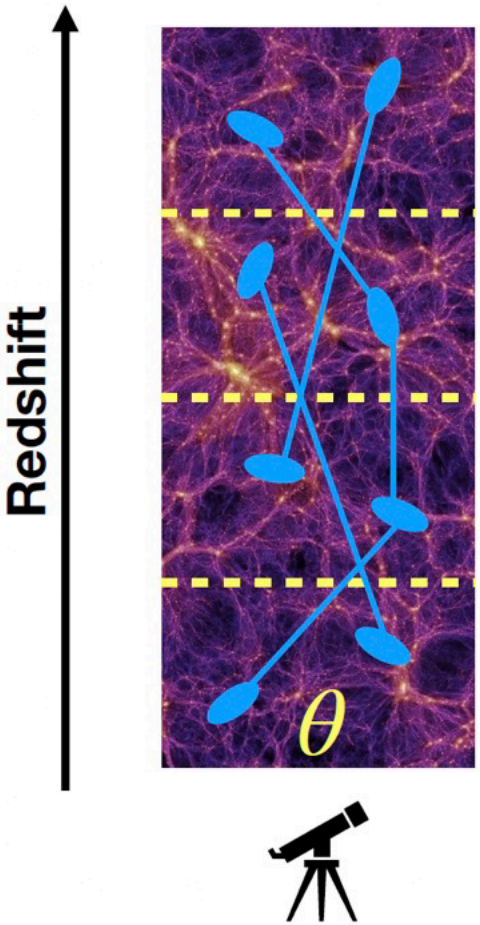


Cosmic Shear



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

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

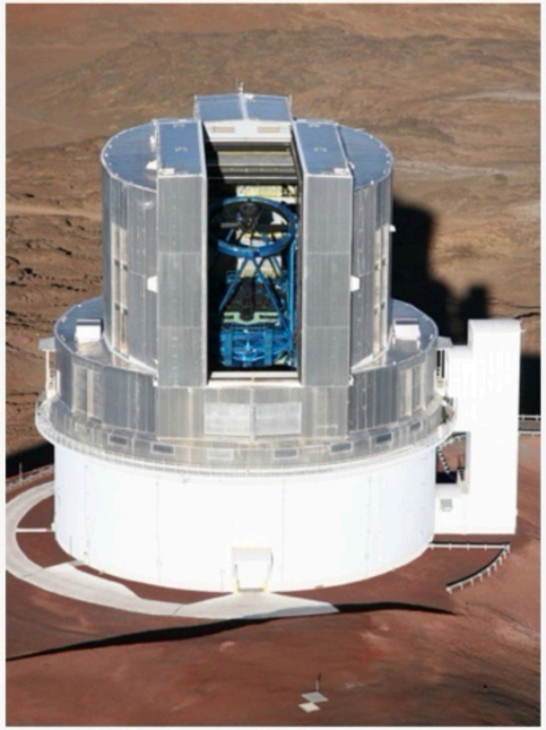
Cosmic Shear Surveys

Imaging/Photometric Galaxy Surveys

- ‘stage-III’ dark energy surveys

KiDS (2012-2019)
1500 deg², r_{lim}~25

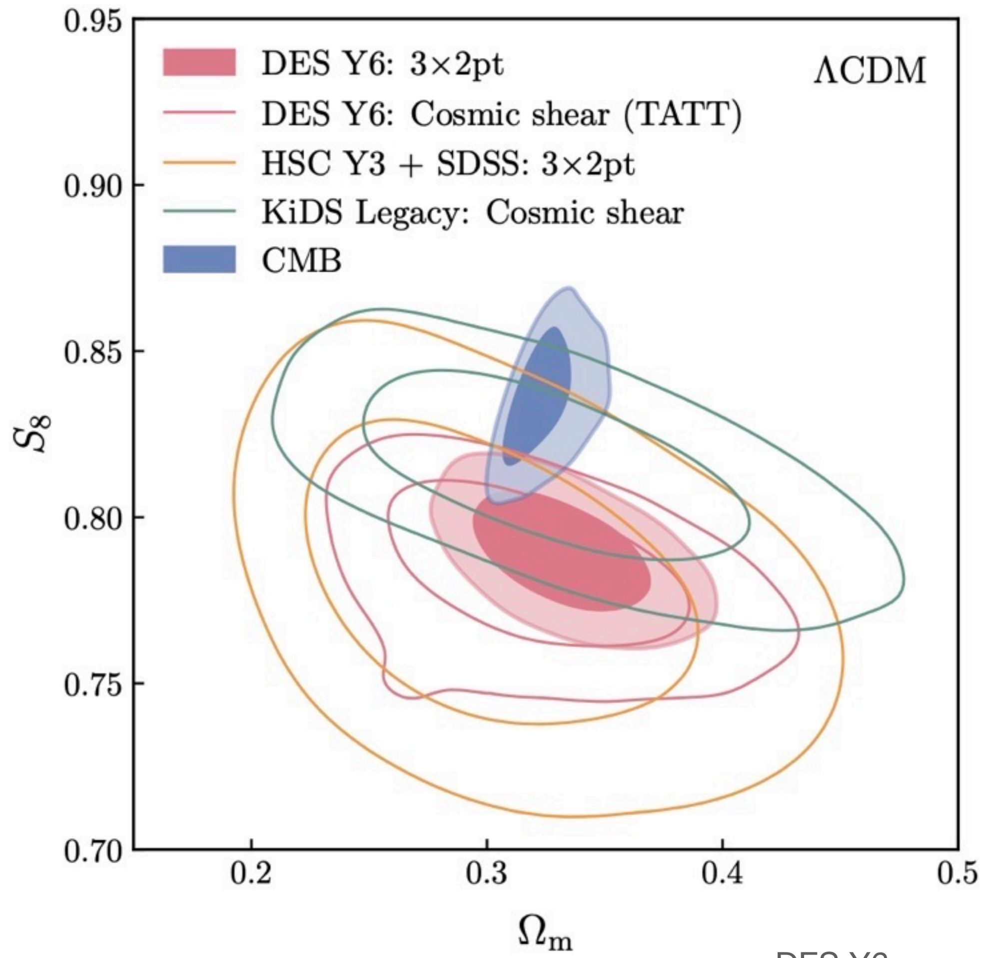
DES (2013-2019)
5000 deg², r_{lim}~25



HSC (2014-2020)
1400 deg², r_{lim}~26

Result from Imaging Surveys

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



DES Y6

Testing theory of gravity on cosmological scales

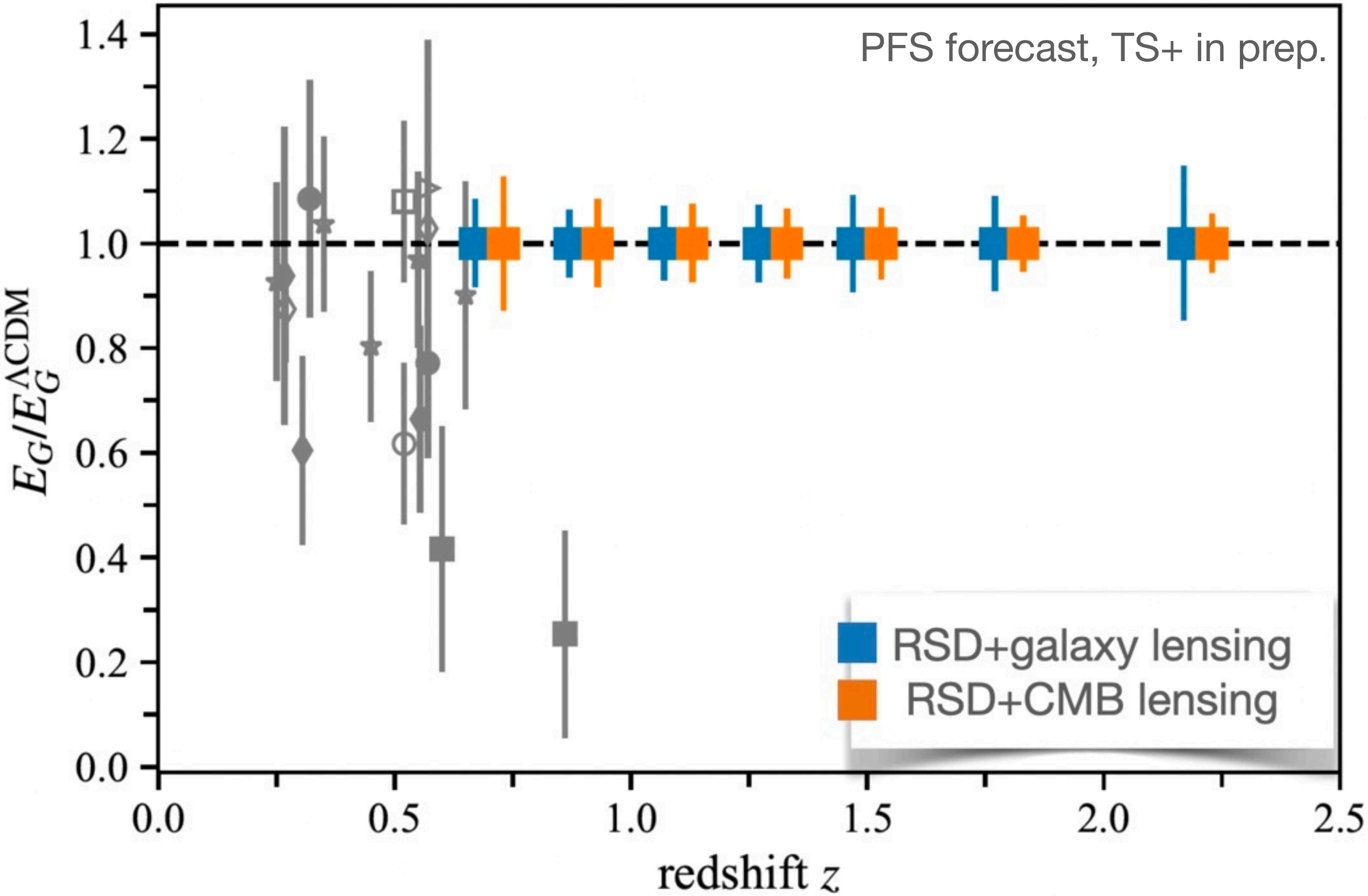
Combining galaxy velocities and lensing

- Photons (light rays for lensing) are sensitive to $\Phi + \Psi$, and galaxies experience the Newtonian potential Ψ
- GR predicts $\Phi = \Psi$

Testing theory of General Relativity

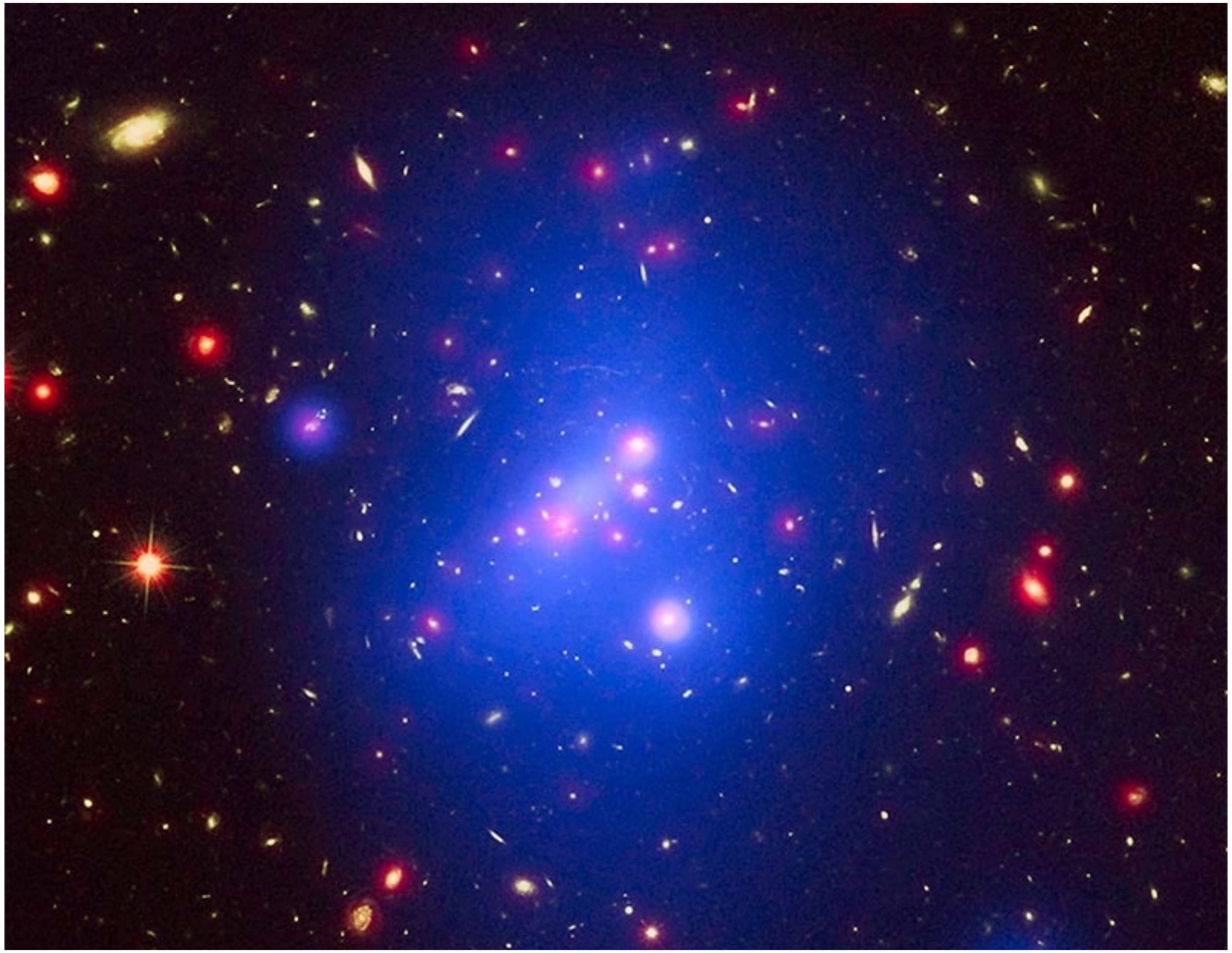
- E_G statistics combines galaxy velocity and lensing
- Spectroscopic data provides galaxy velocity information, and photometric data provides galaxy lensing measurements
- GR predicts $\Phi = \Psi$

Gray points are existed constraints:
Blake+2016: WiggleZ/BOSS+CFHTLenS
Pullen+2016: BOSS+Planck
delaTorre+2016: VIPERS+CFHTLenS
Alam+2016: BOSS+CFHTLenS
Amon+2018: GAMA+KiDS/2dFLens
Singh+2019: BOSS+SDSS/Planck
Jullo+2019: BOSS+CFHTLenS
Blake+2020: BOSS+KiDS-1000/2dFLen



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

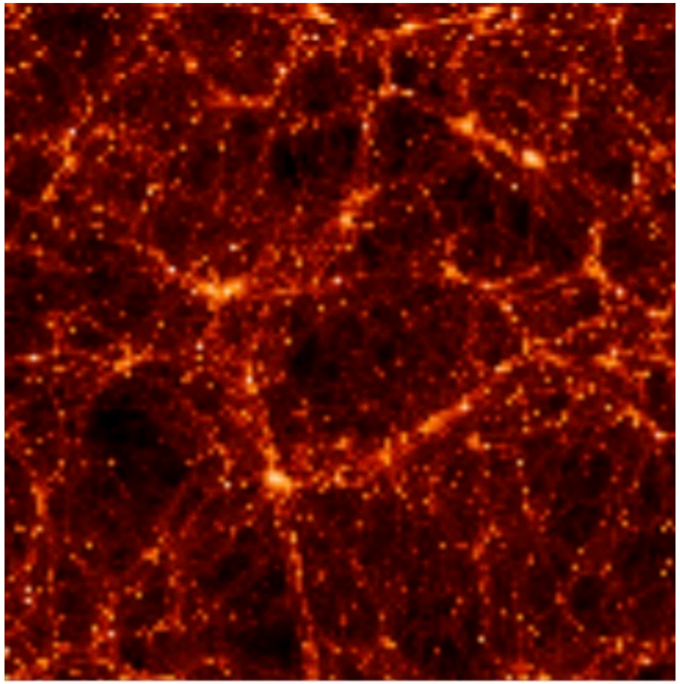
(Mpc=3×10^{19}km)

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

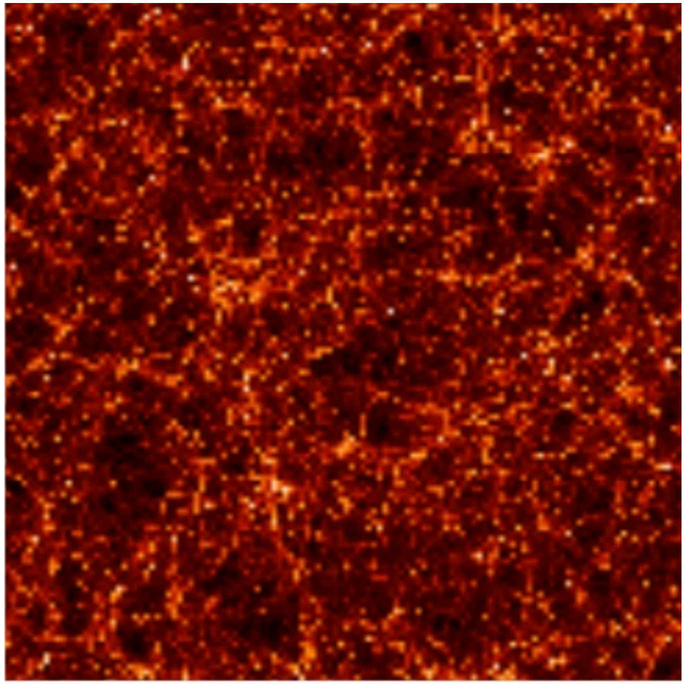
Clusters as a cosmological probe

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

With Dark Energy



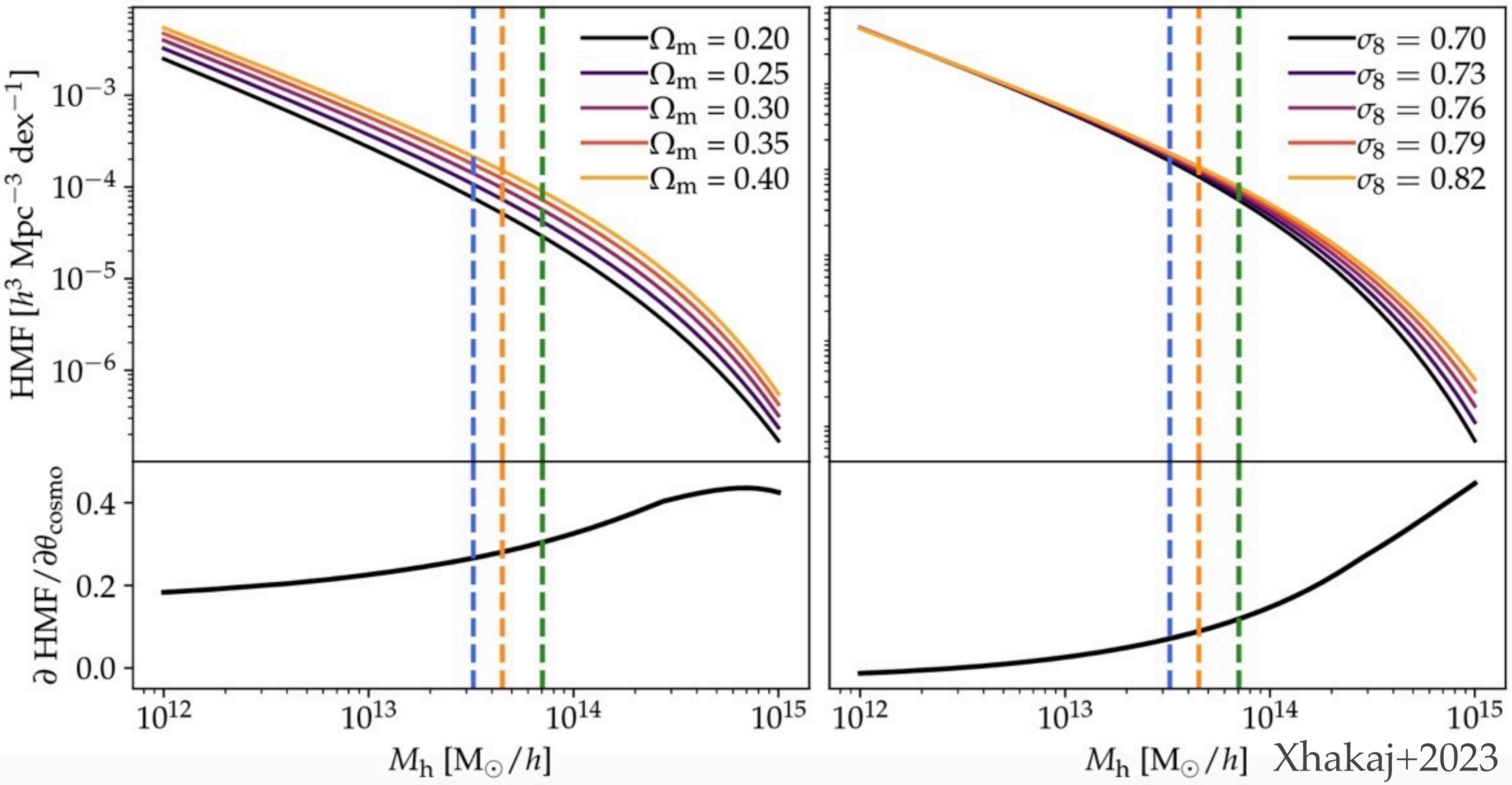
Without Dark Energy



Virgo consortium

Clusters as a cosmological probe

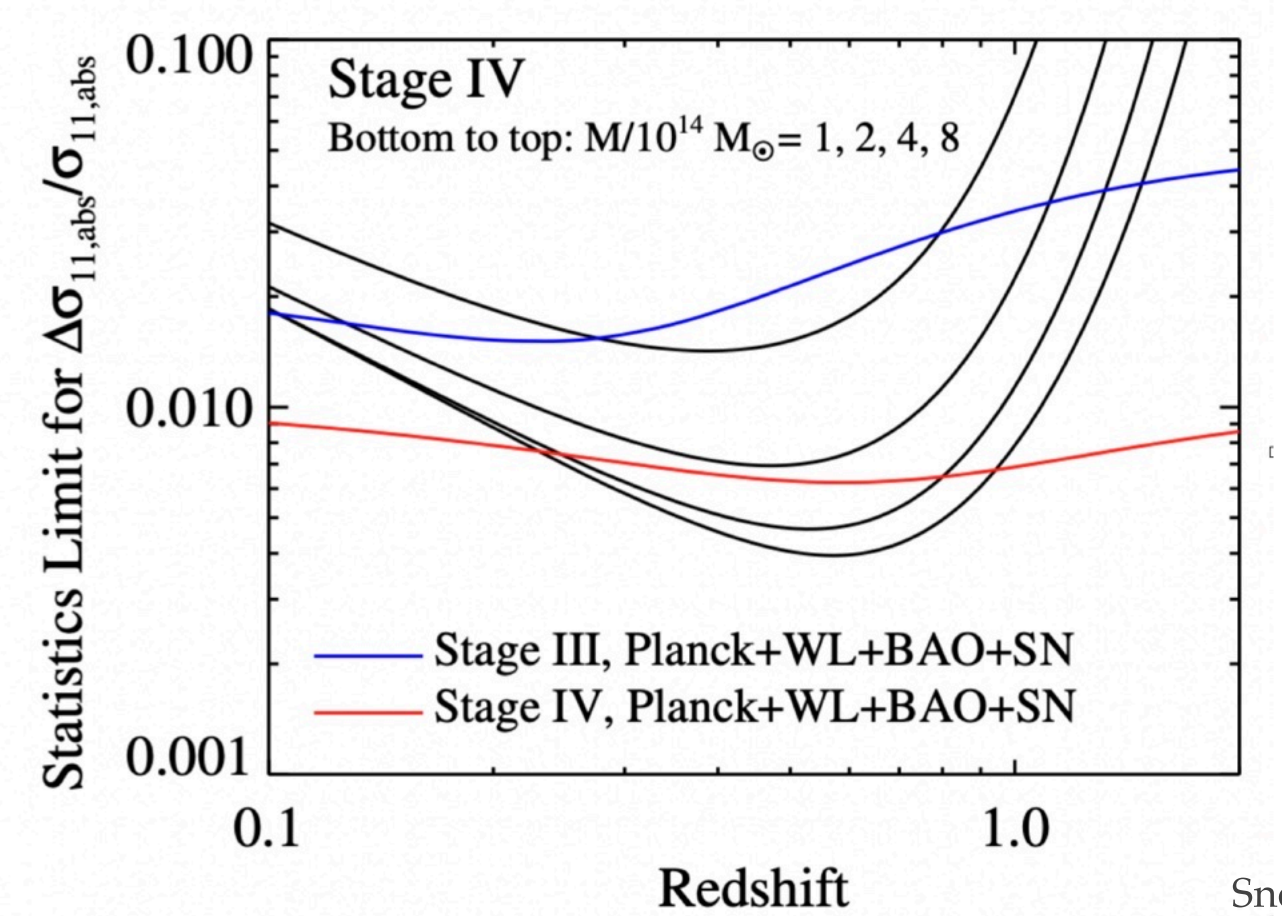
- Background cosmology (i.e., Ω_m) impacts the number density
- Clusters form from the highest density peaks in the initial density field
- σ_8 (="clumpiness"): higher σ_8 → more high-density peaks → more massive clusters



Xhakaj+2023

Clusters can be powerful…

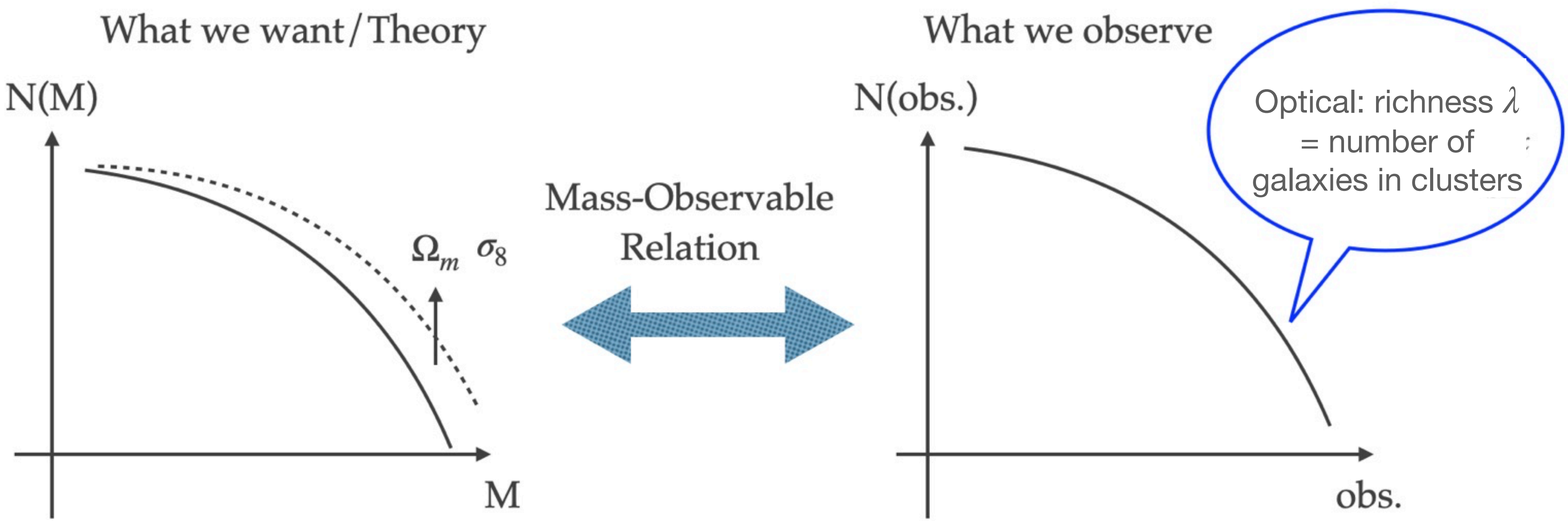
- Cosmic Visions Report (2016): “ The number of massive galaxy clusters could emerge as the most powerful cosmological probe…”



Snowmass2013; Huterer et al.

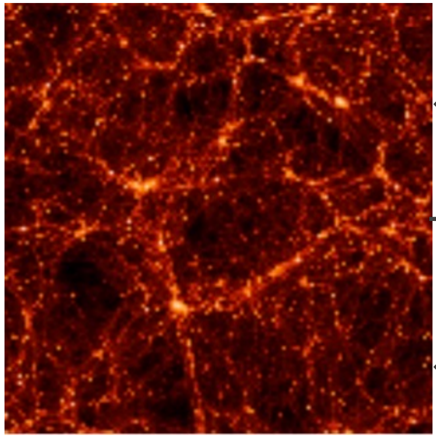
Challenge in Cluster Cosmology

- 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



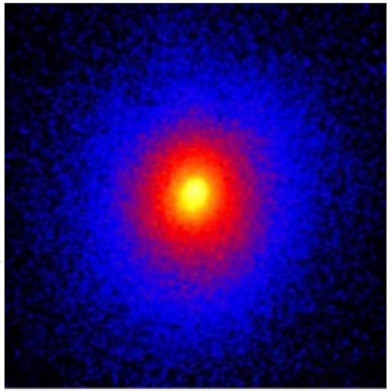
Challenge in Cluster Cosmology

Theory: N-body

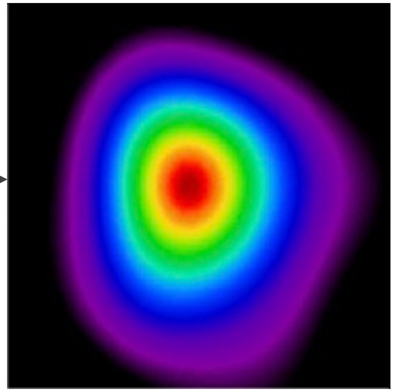


Millennium-II

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



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 need of follow-up survey for gravitational lensing !

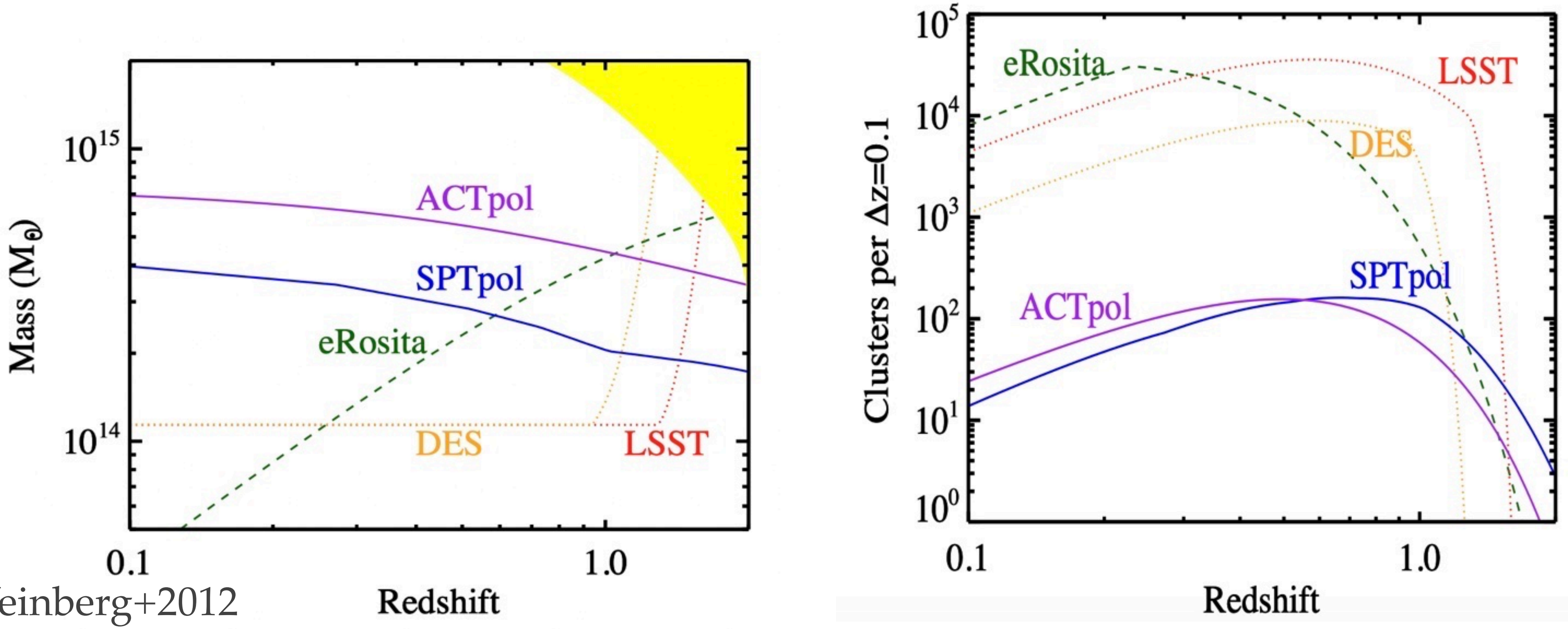
Small

Systematics

Large

Why optical?

- Optical allows to detect lower mass clusters
- More number of clusters = better weak lensing mass measurement
- Better constraining power on cosmological parameters

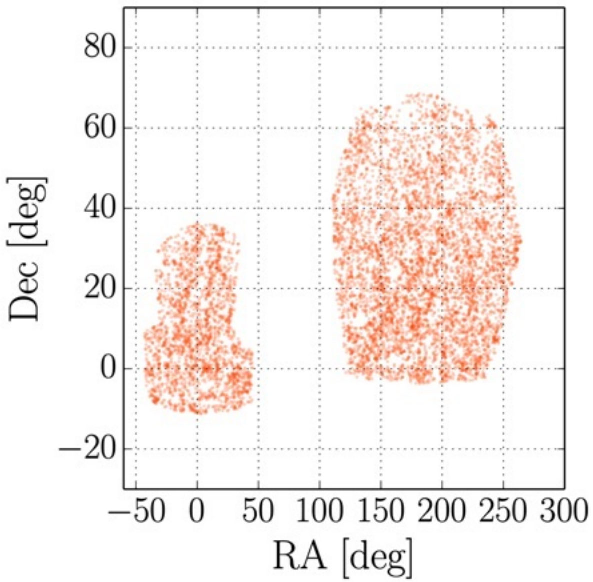


Weinberg+2012

SDSS redMaPPer clusters x HSC WL Measurement

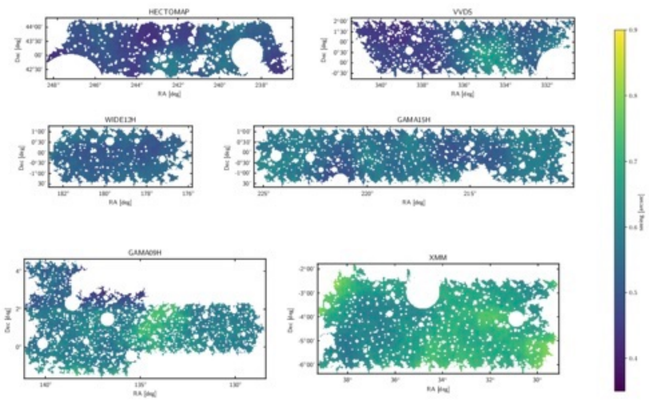
SDSS redMaPPer cluster sample

- Area ~ 8300 deg²
- 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 deg² in total
- <z>~1.2.
- $n_s \sim 16 \mathrm{arcmin}^{-2}$

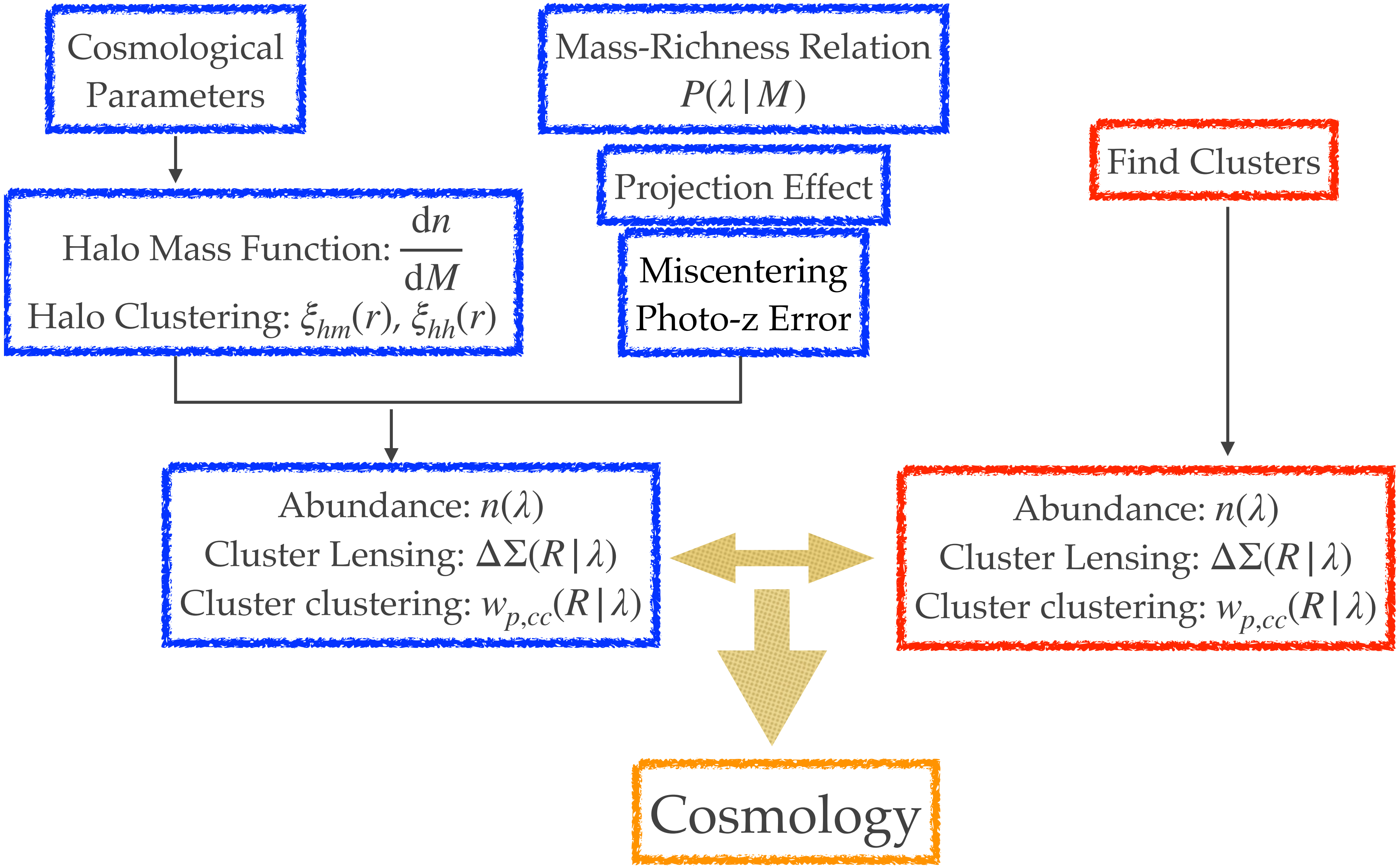


Cluster lensing signal

Cluster abundance

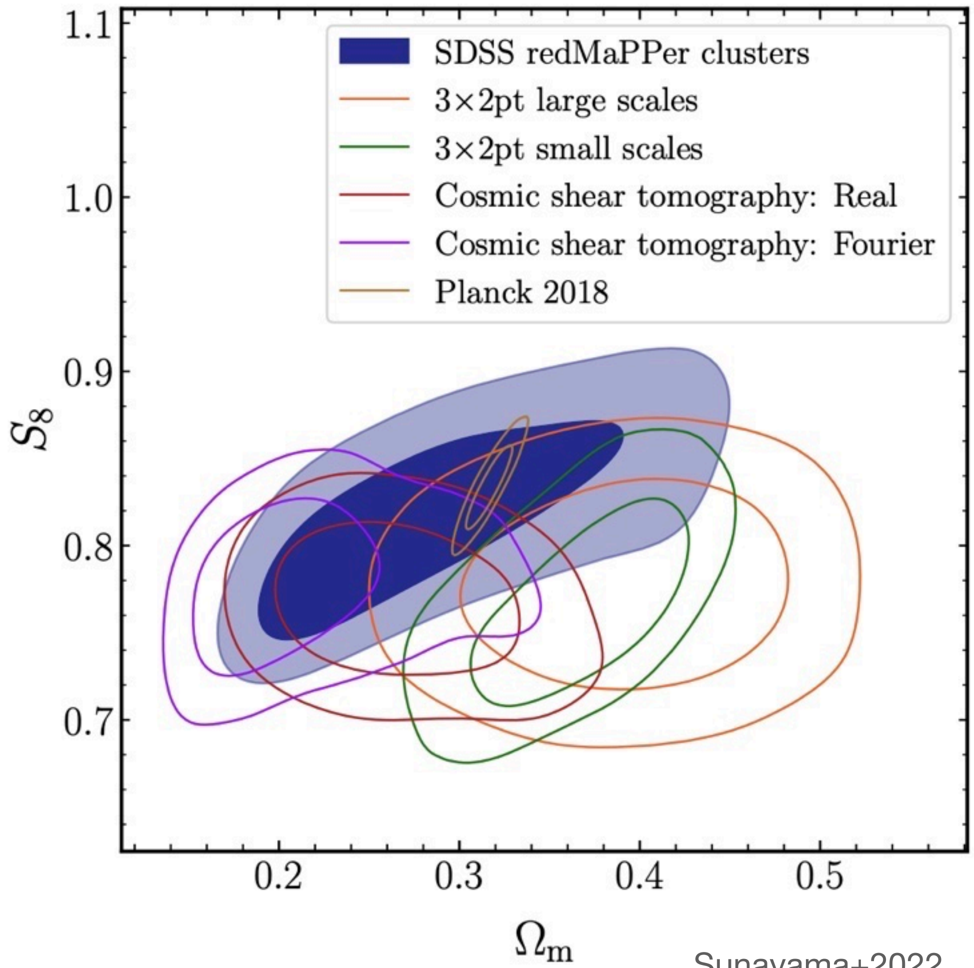
Cluster clustering signal

Example: Cluster Cosmology Analysis



Result from SDSSxHSC Y3

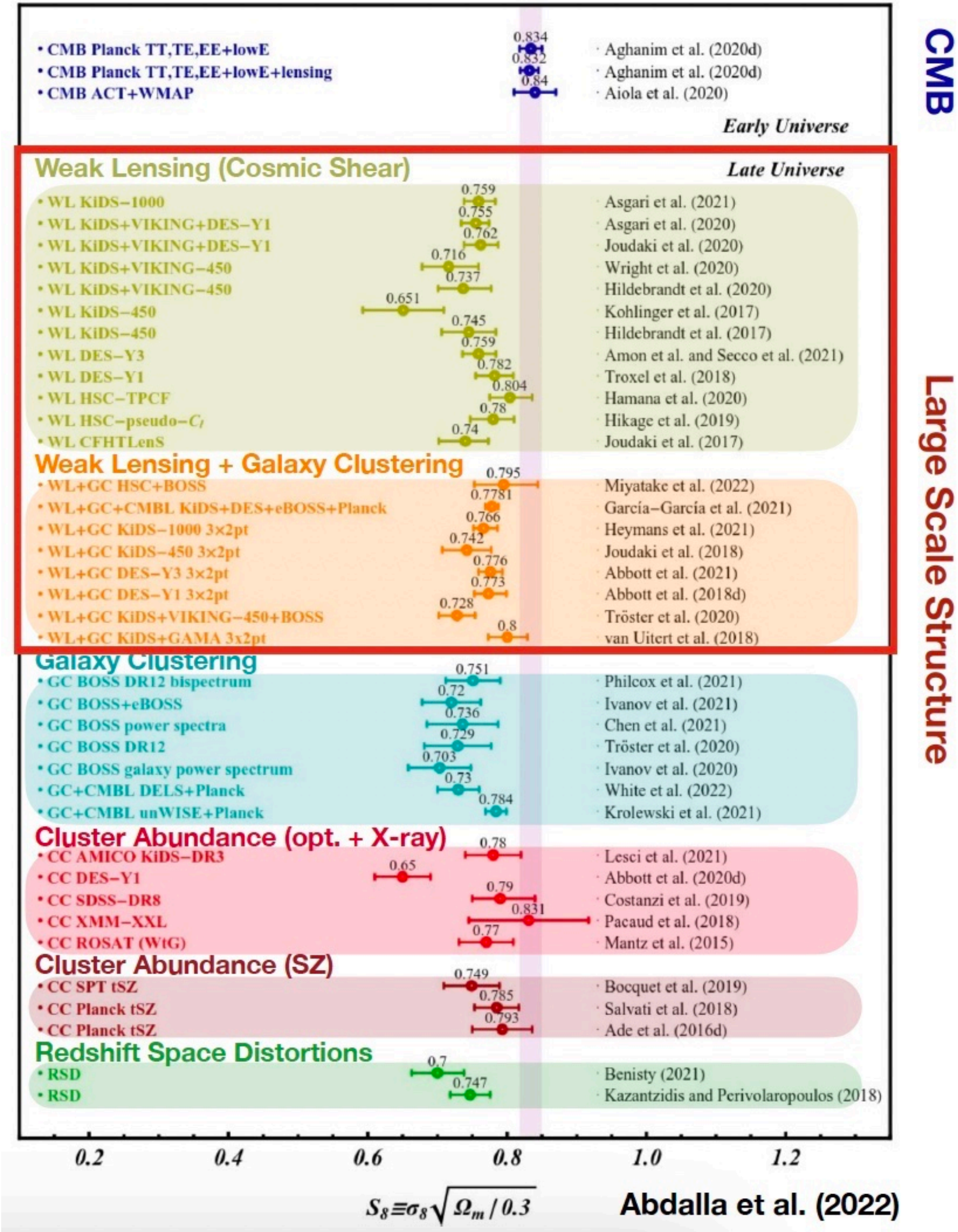
- Cosmological constraints from optical clusters and Planck CMB are constant



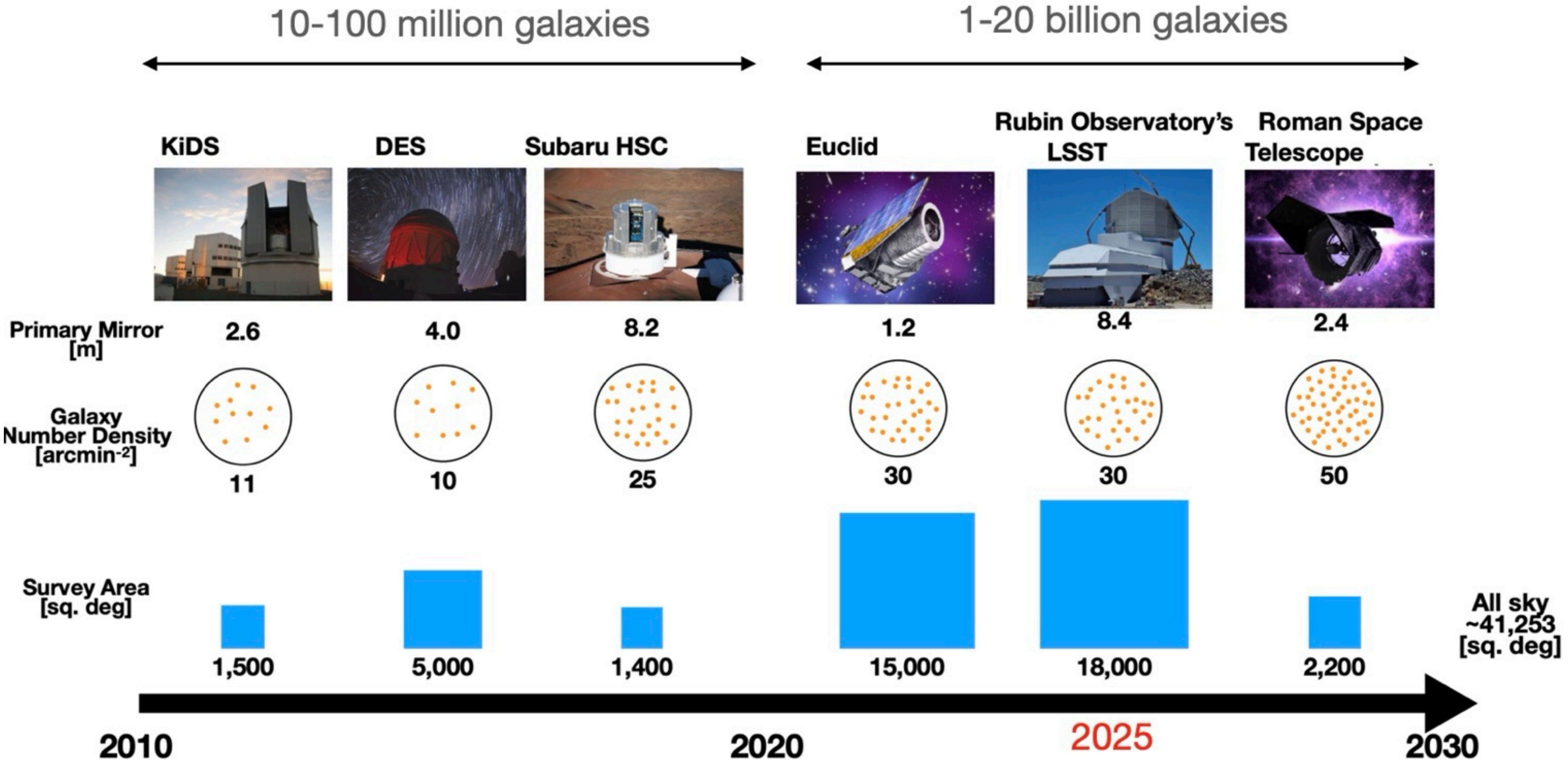
Sunayama+2022

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

Thank you!