Dark Matter in « Dark-Energy » Galaxy Surveys

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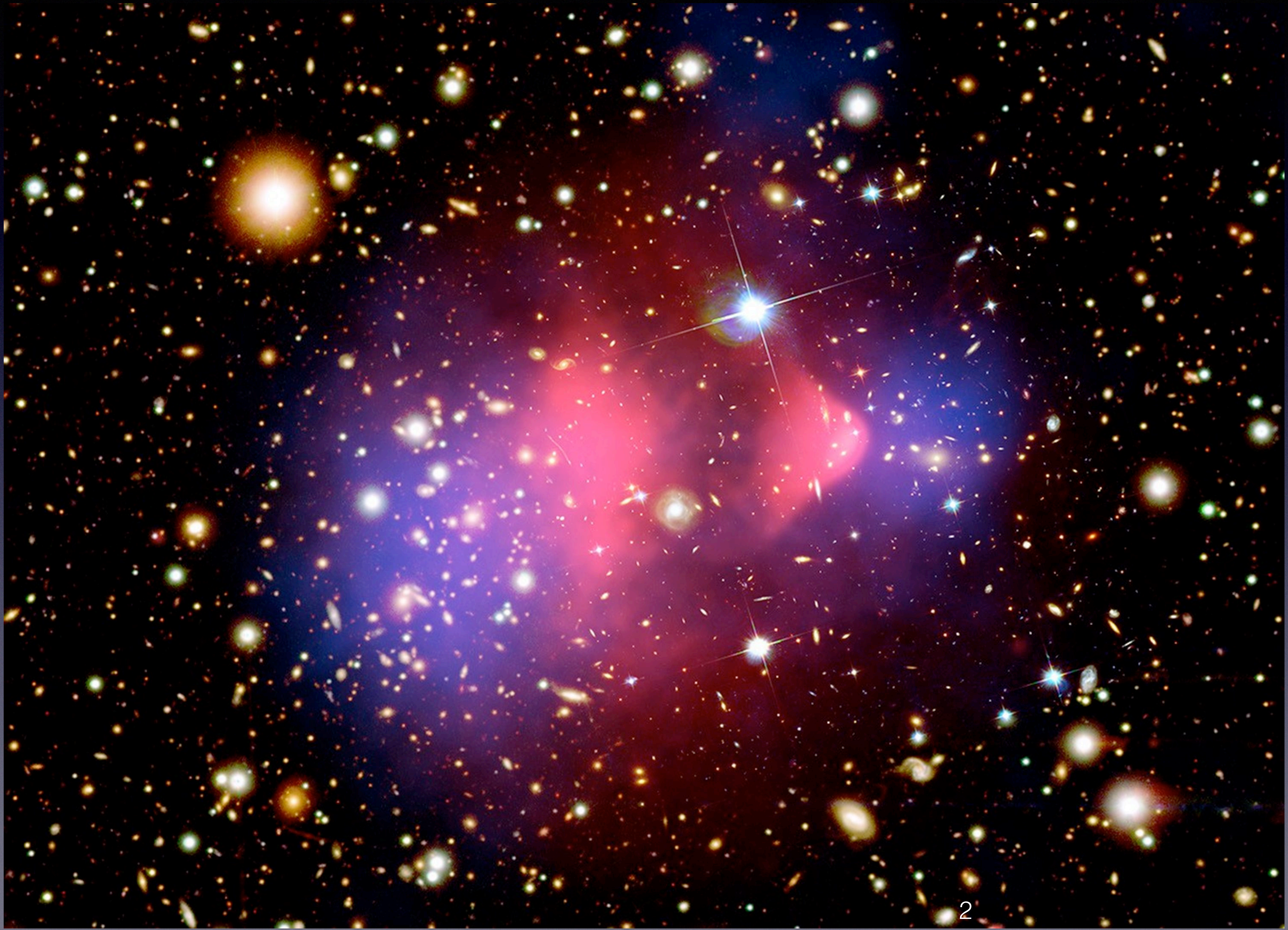
- **Theory**: Universe timeline, density perturbation theory, ΛCDM and parameters , DM-structures power spectrum P(k)
- **Galaxy surveys**: DES/DESI/LSST/Euclid, precision on $w(z)$
- **Probes**: Cluster counts (Ω_m, σ_8), BAO $(H(z), D_A(z))$, Weak lensing
- **Latest: DESI's redshift-dependent dark energy**,
  - —>New physics for Rubin-LSST/Euclid, dark matter implication
- Take Home message cosmology/dark matter search

Direct Evidence for Dark Matter



- Discovery: In 2006, observations of the Bullet Cluster provided some of the strongest direct evidence for dark matter.

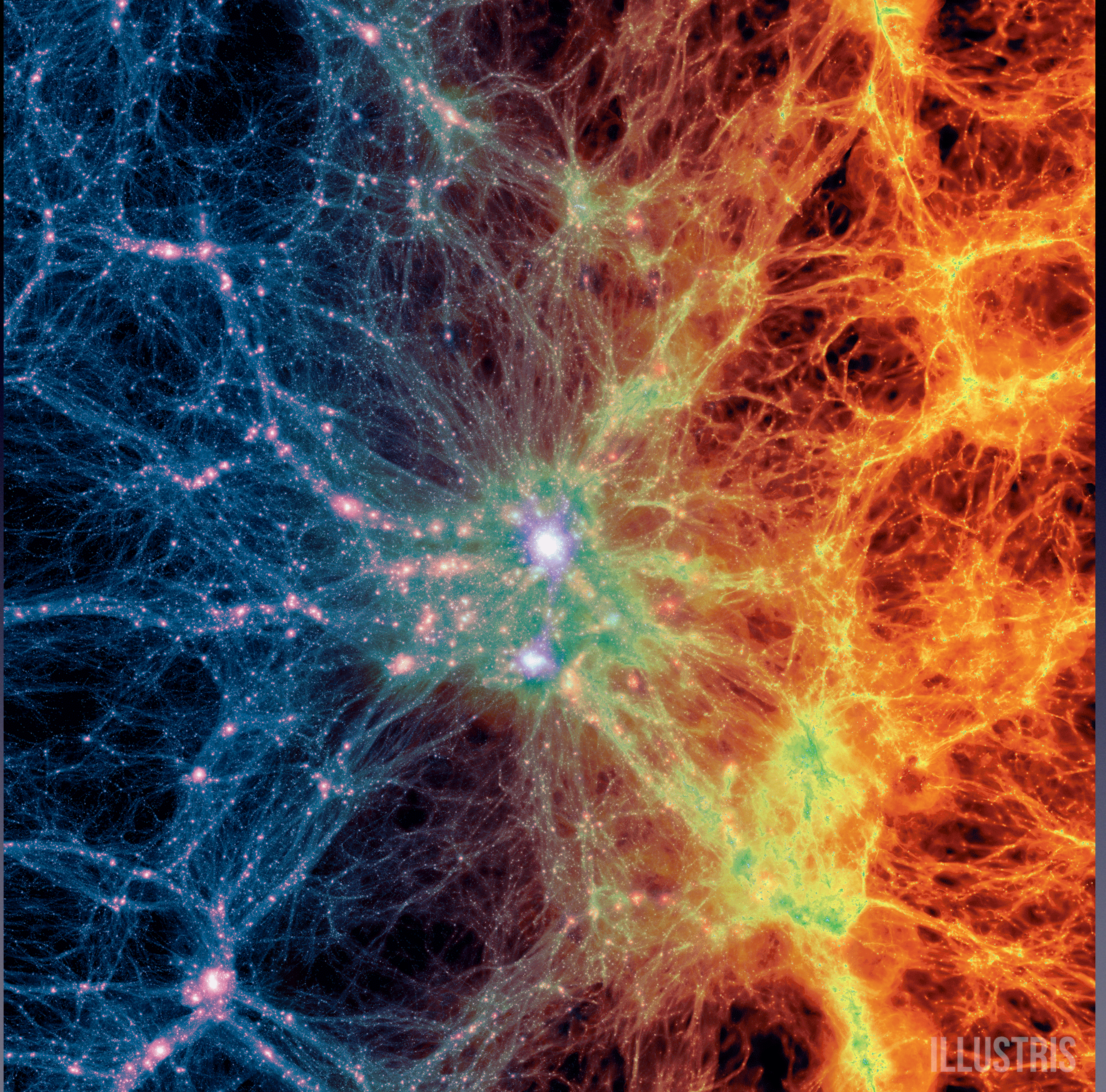
- collision of two large galaxy clusters, located ~3.8 billion light-years from Earth.

- Hot Gas in X-rays from ordinary matter(Pink)

- Dark Matter « gravitational lensing » (Blue)

Section 1 : Theory for density perturbations and cosmological simulations

- Universe history
- Structure growth
- (DM) - Matter power spectrum



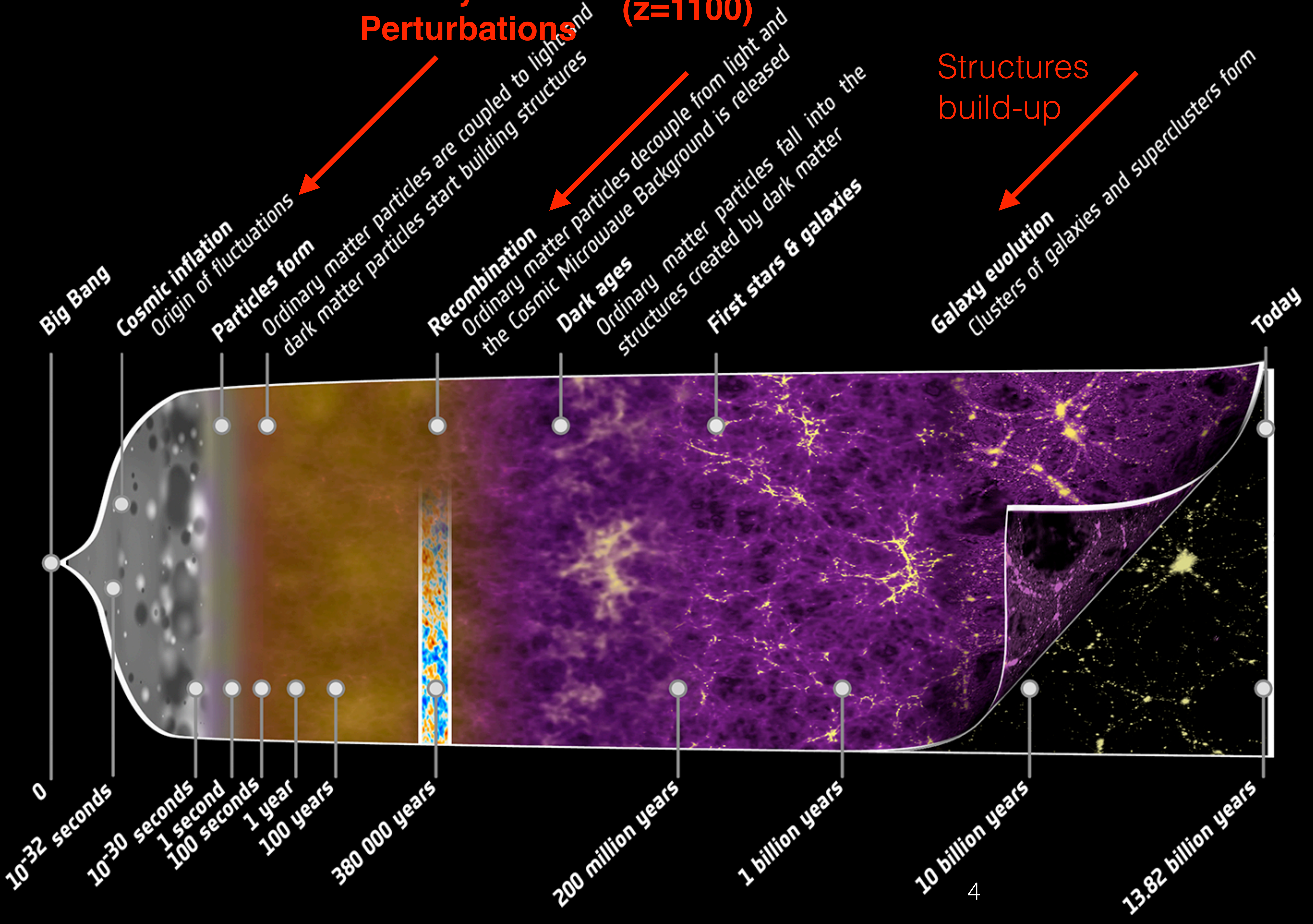
Universe Timeline

Injection of density Perturbations

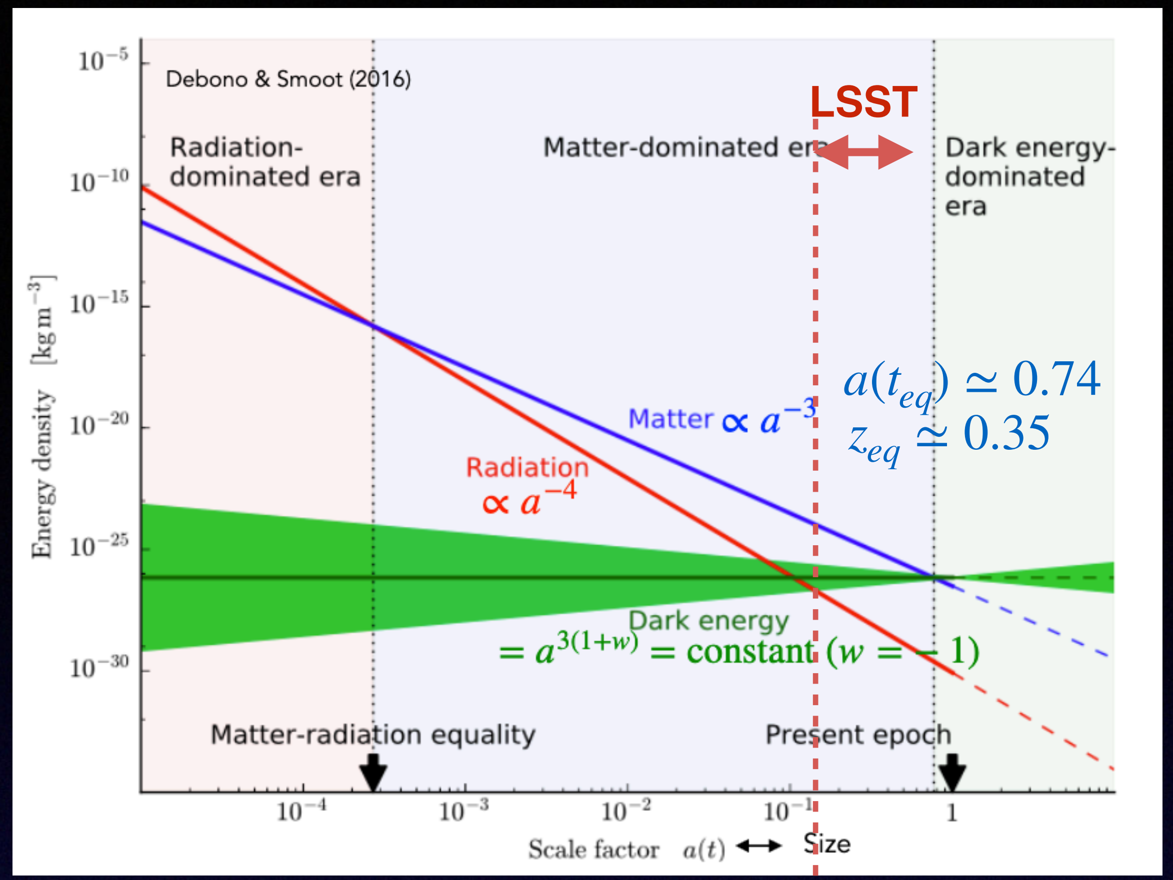
Recombination (z=1100)

LSST z < 3 (age > 2 By)

Structures build-up



Evolution of densities

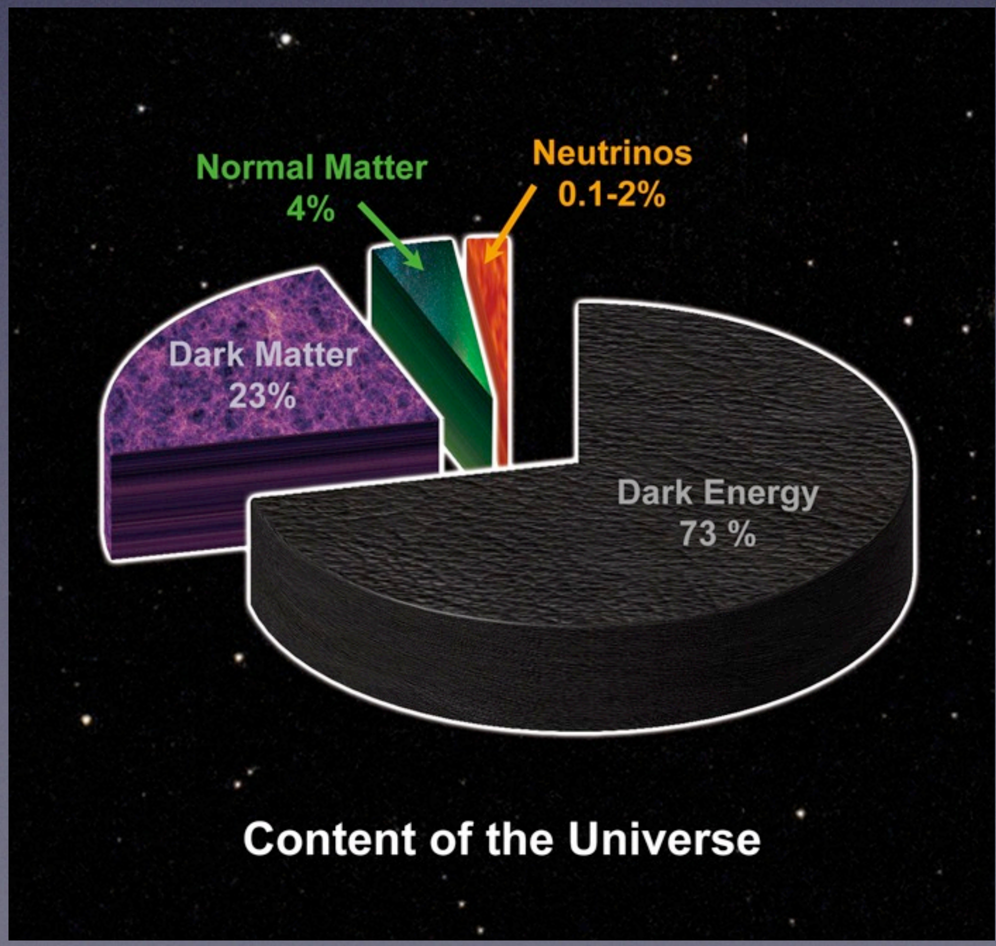


$$z \ll z_{rec} = 1100 \;\&\; \Omega_K = 0$$

$$\begin{cases} H(z) \simeq H_0\sqrt{\Omega_M(1+z)^3 + \Omega_{DE}(z)} \\ \Omega_{DE}(z) = \Omega_{DE,0} \cdot \exp\left(3\int_0^z \frac{1+w(z')}{1+z'}\,dz'\right) \\ w(z) = \frac{P_{DE}}{\rho_{DE}} \\ a(z) = \frac{1}{1+z} \end{cases}$$

ΛCDM model

$$\begin{cases} \rho_\Lambda = \frac{\Lambda c^2}{8\pi G} \\ \rho_c = \frac{3H_0^2}{8\pi G} \\ \Omega_\Lambda = \frac{\rho_\Lambda}{\rho_c} = \frac{\Lambda c^2}{3H_0^2} \\ \Omega_M = \Omega_{DM} + \Omega_b \end{cases}$$



Large scale structures growth

Equations and cosmological simulations

Primordial Density fluctuations arise from a perturbative solution of the perturbed metrics from the Friedman eq from GR

DM density fluctuations

$$\boxed{\delta(\mathbf{x}, t) = \frac{\rho(\mathbf{x}, t) - \bar{\rho}(t)}{\bar{\rho}(t)}}$$

3D Fourier Transform $P(k, z)$

Linear growth factor: D(z)

Power spectrum of DM

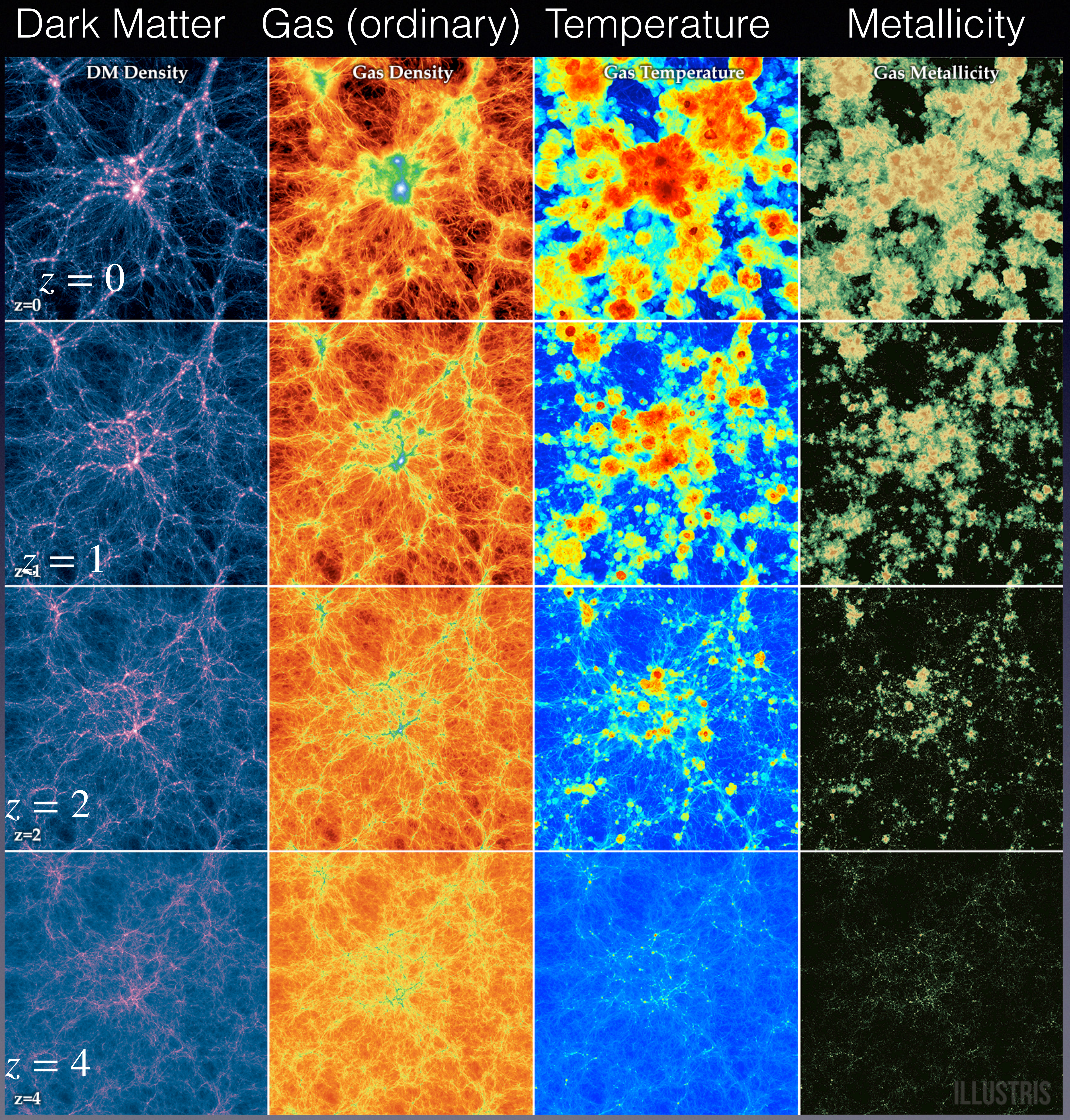
$$\boxed{P(\mathbf{k}, z) = P(\mathbf{k}, z_{init}) \cdot \left(\frac{D(z)}{D(z_{init})}\right)^2}$$

Boltzmann equation (linear effects only)

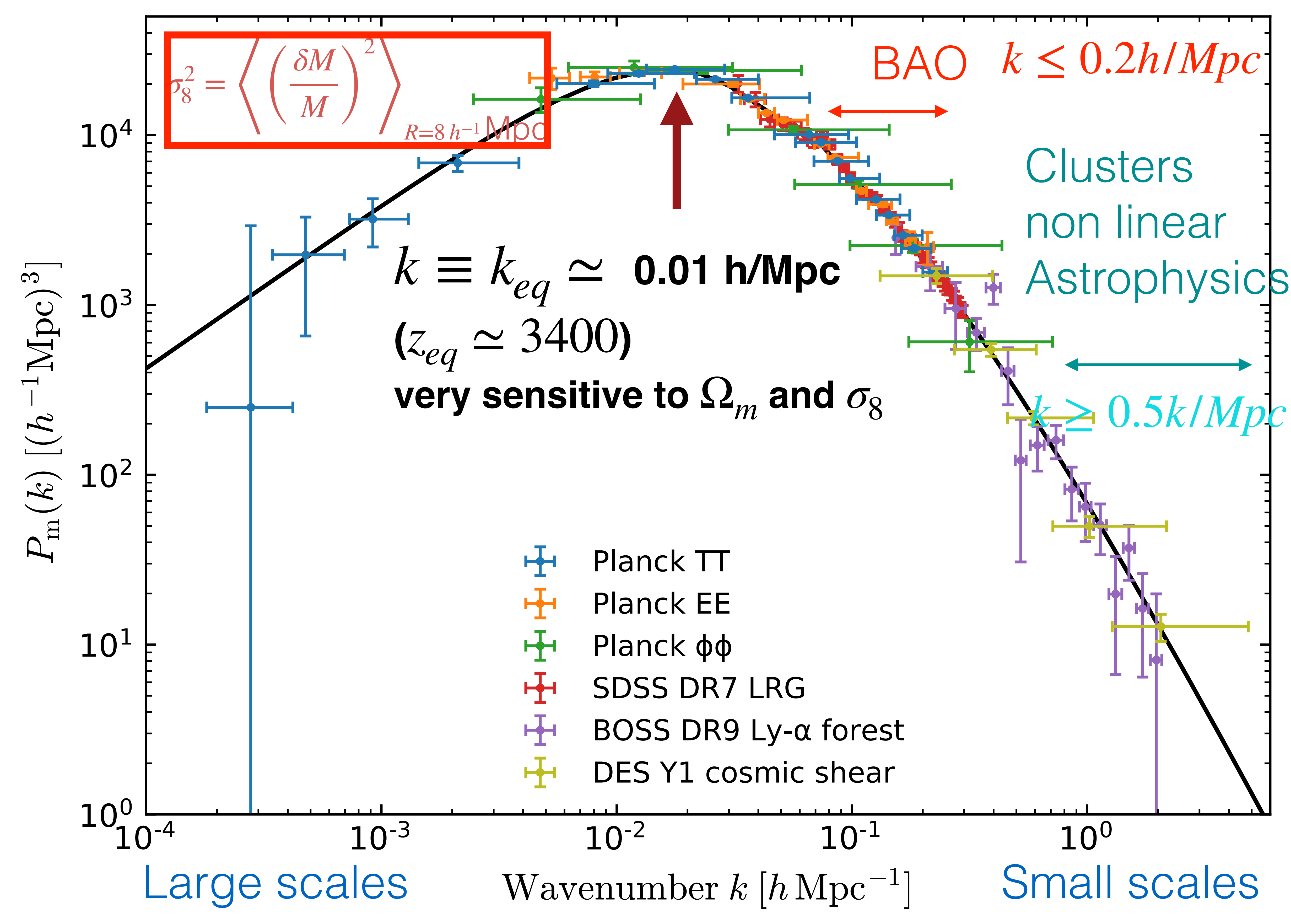
$$\frac{d^2D}{dz^2} + \left(\frac{1}{H(z)}\frac{dH}{dz} + \frac{2}{1+z}\right)\frac{dD}{dz} - \frac{3}{2}\frac{\Omega_m(1+z)^3}{E(z)^2}D = 0$$

Injection of $P(k, z_{init})$ in the cosmo. simul. at $z_{init} \simeq 127$.

- with $\Omega_m$and σ_8 already included in $P(k, z_{init})$



Matter Power Spectrum

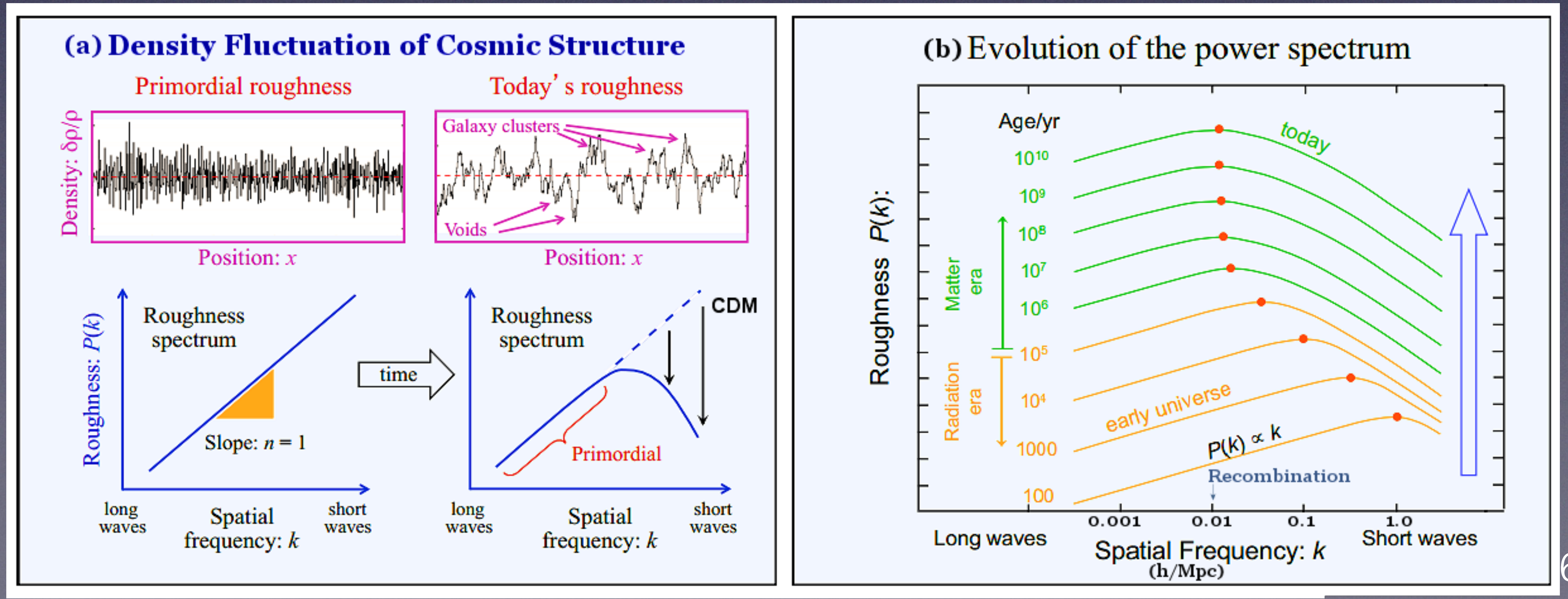


$k \equiv k_{eq} \simeq$ **0.01 h/Mpc**

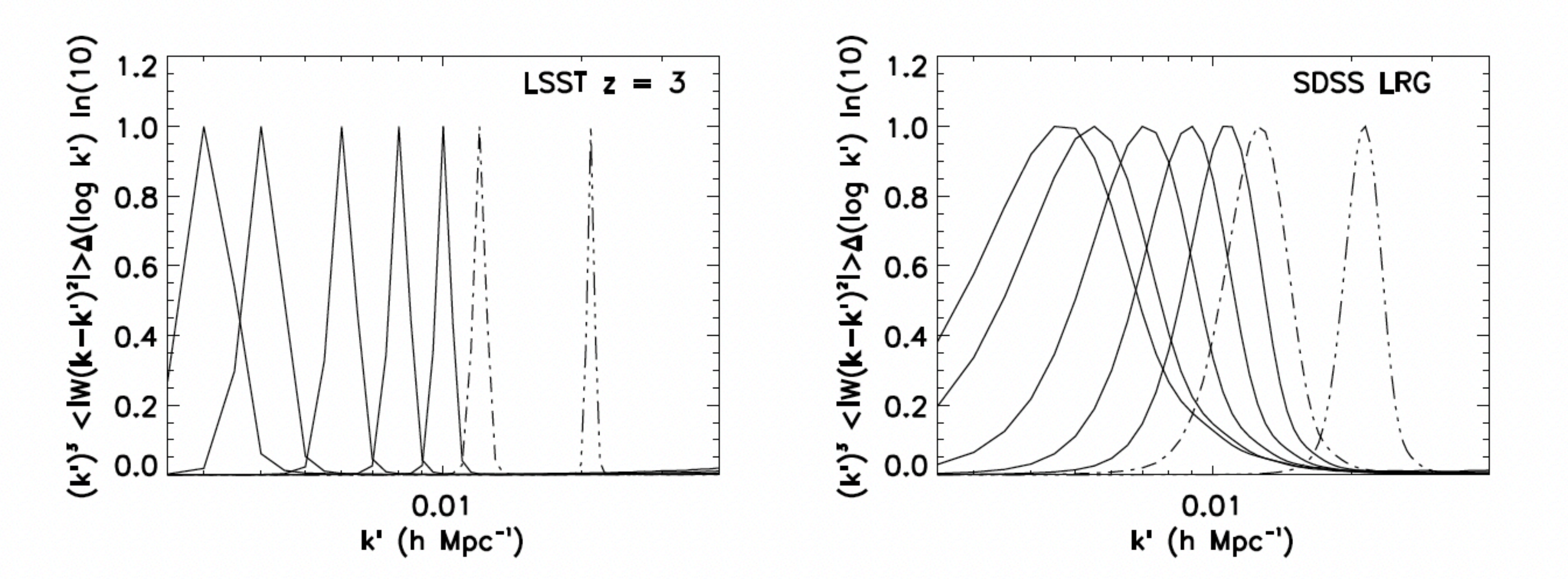
($z_{eq} \simeq 3400$)

very sensitive to Ω_m and σ_8

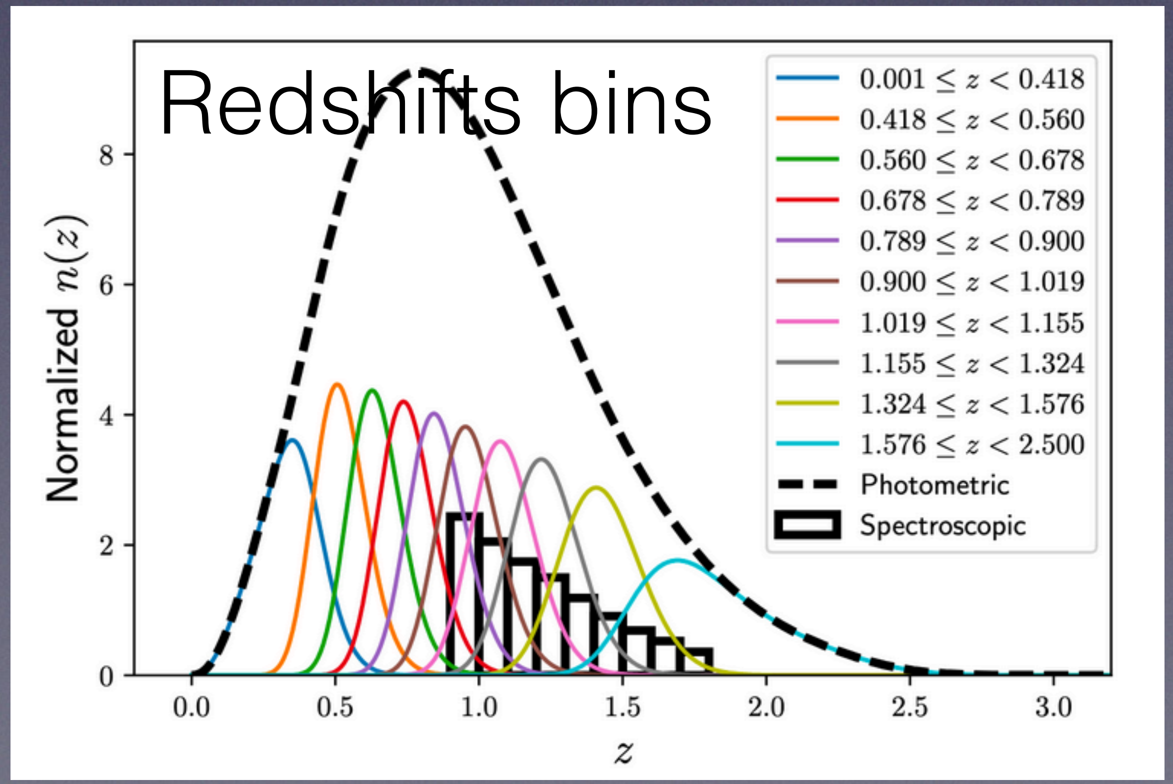
- The power spectrum $P(k)$ directly encodes the **statistical distribution of primordial energy density fluctuations**, which seed the formation of all cosmic structures—from galaxies to galaxy-clusters and filaments.
- Measuring $P(k)$ constrains $\Omega_m$and σ_8, and tests dark matter models.

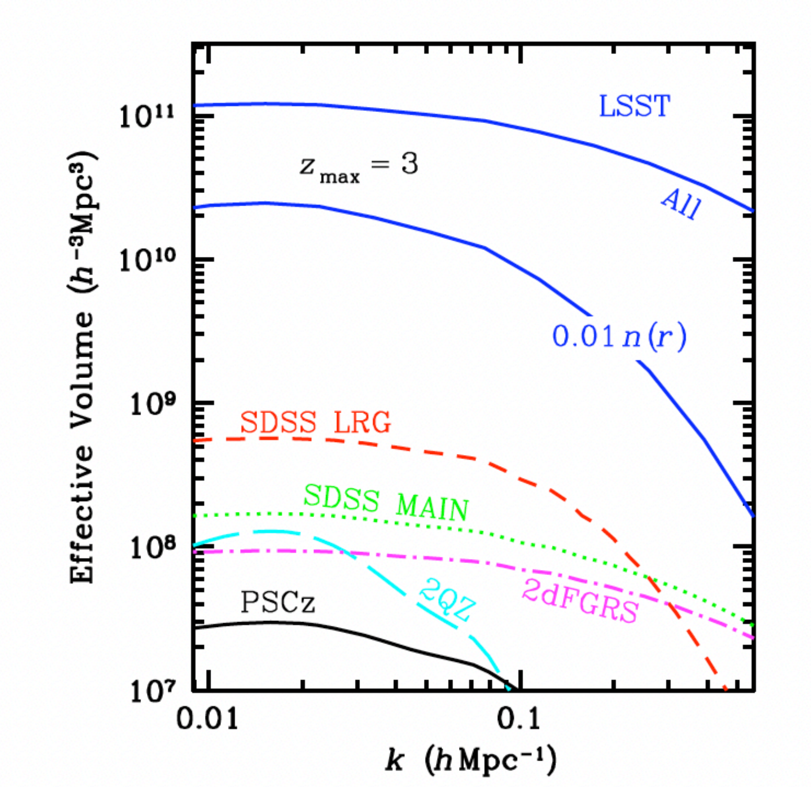


Resolution in k-space and in redshift bins



Space Volume


Redshifts bins



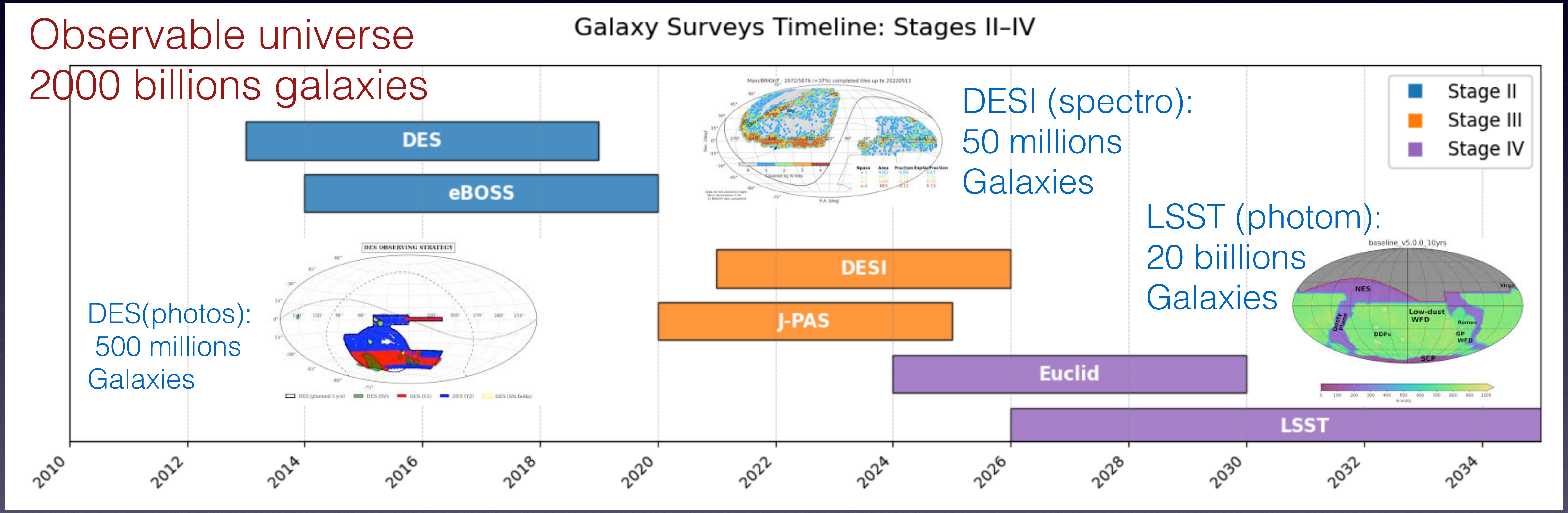
Section 2: Large Galaxy Surveys overview and their scientific goals

$$\rho_{\mathrm{DE}}(z) = \rho_{\mathrm{DE},0} \cdot \exp\left(3\int_0^z \frac{1+w(z')}{1+z'}\,dz'\right)$$

$$\boxed{w(a) = w_0 + (1-a)w_a \quad \text{where} \quad a = \frac{1}{1+z}}$$

The Dark Energy Task Force (2006) established the roadmap for galaxy surveys, defining precision and accuracy requirements on w_0 and w_a

$$z \leq 3$$



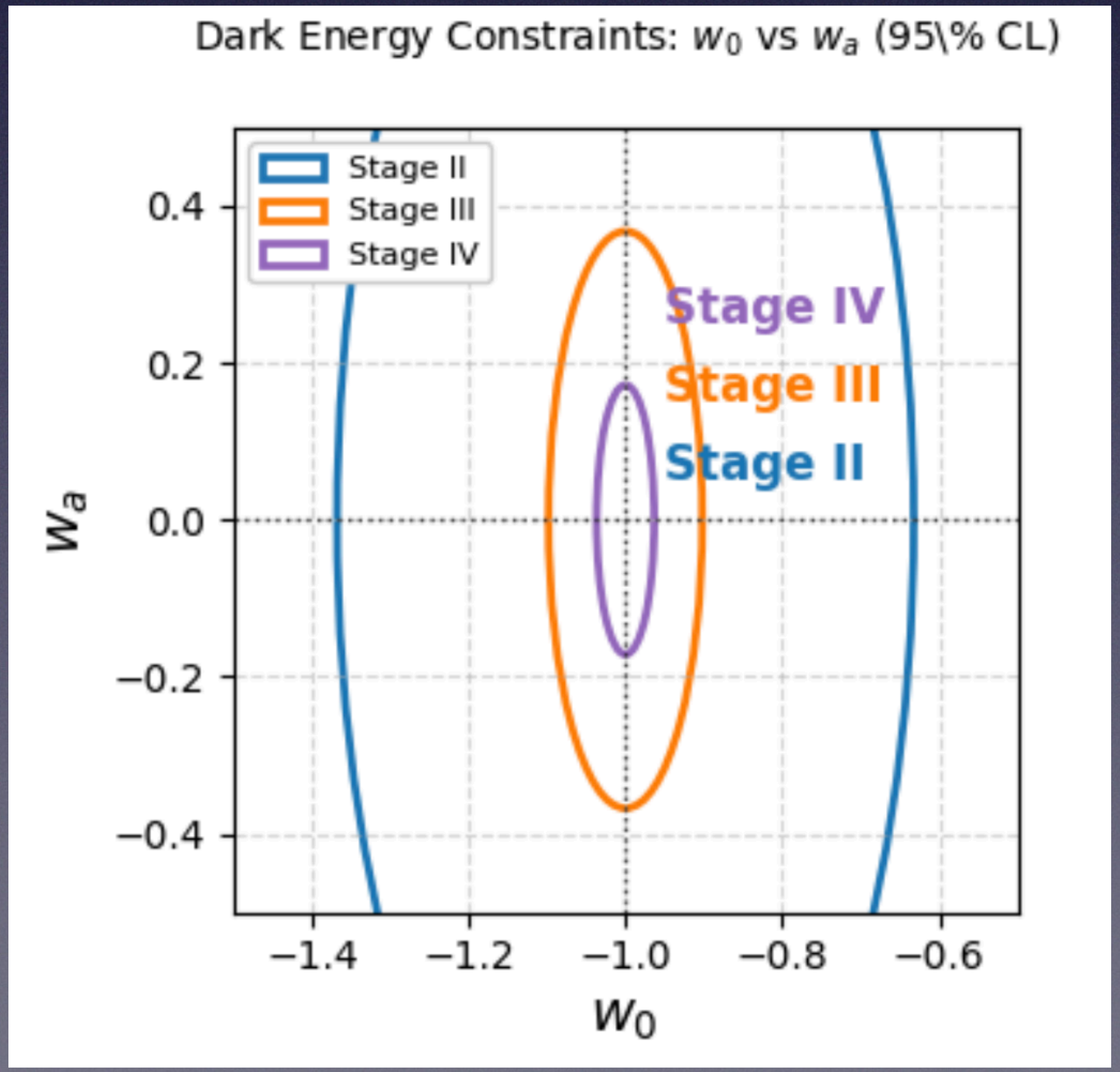
Observable universe
2000 billions galaxies

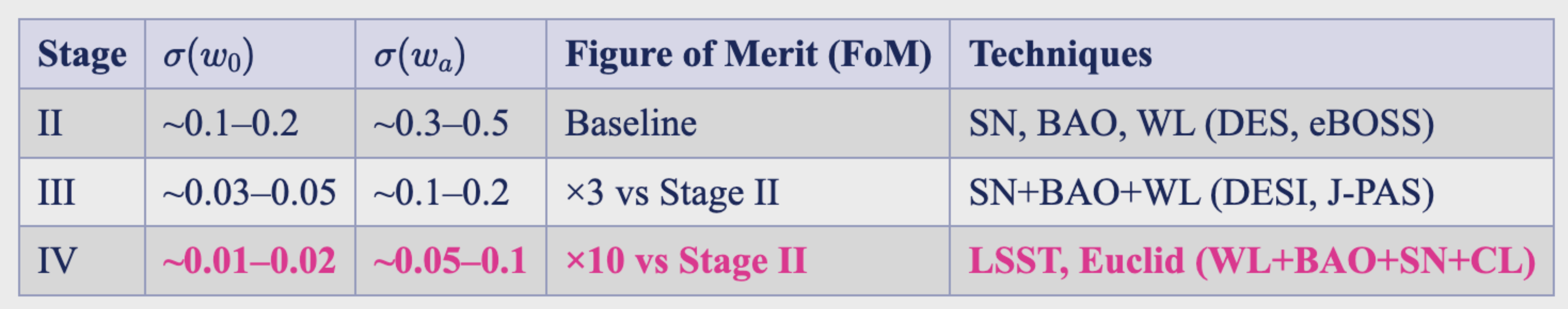
DESI (spectro):
50 millions
Galaxies

LSST (photom):
20 biillions
Galaxies

DES(photos):
500 millions
Galaxies

$$FoM = \frac{1}{\text{Area of } 95\,\% \text{ CL ellipse in } (w_0, w_a) \text{ plane}}$$



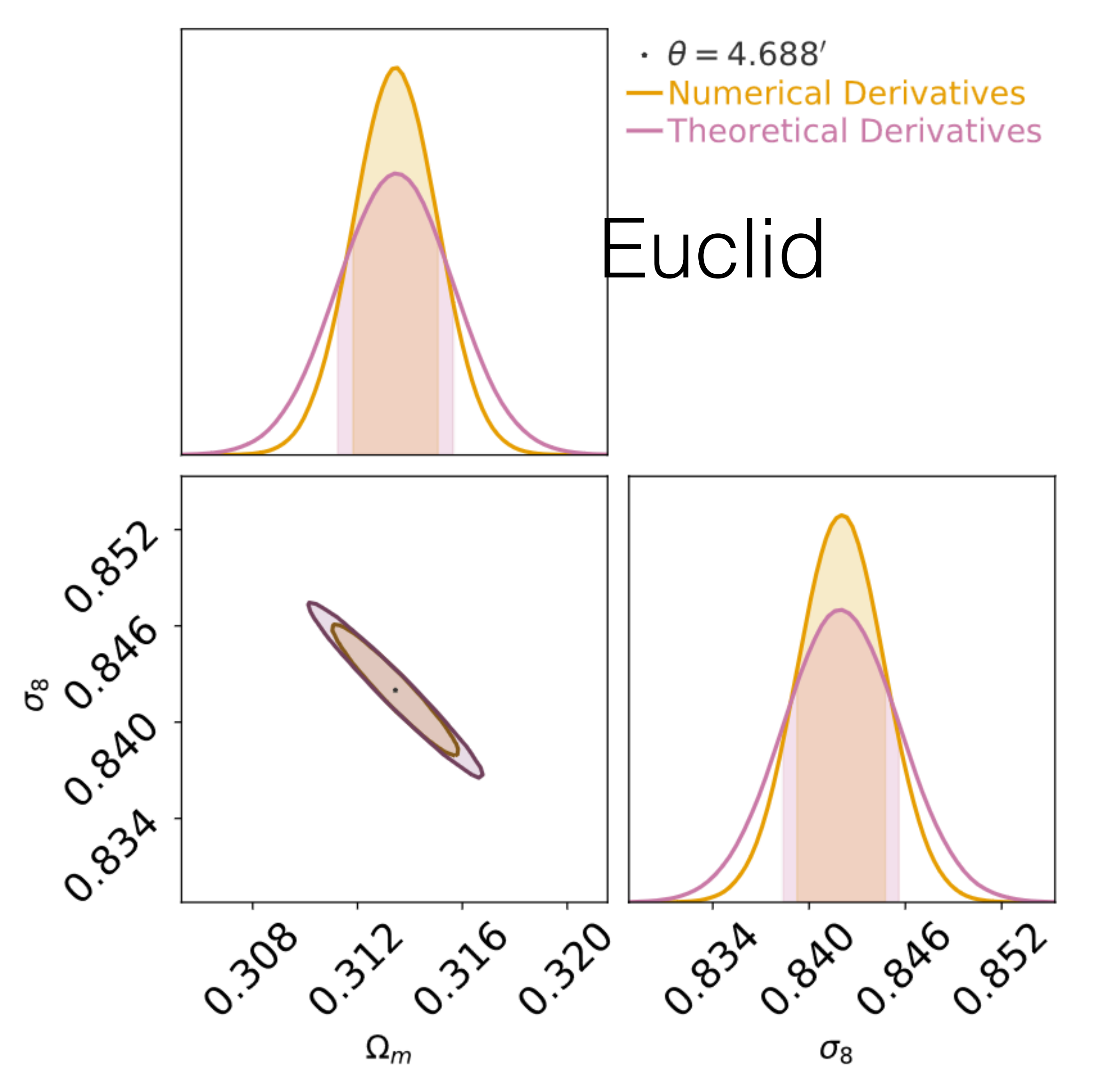


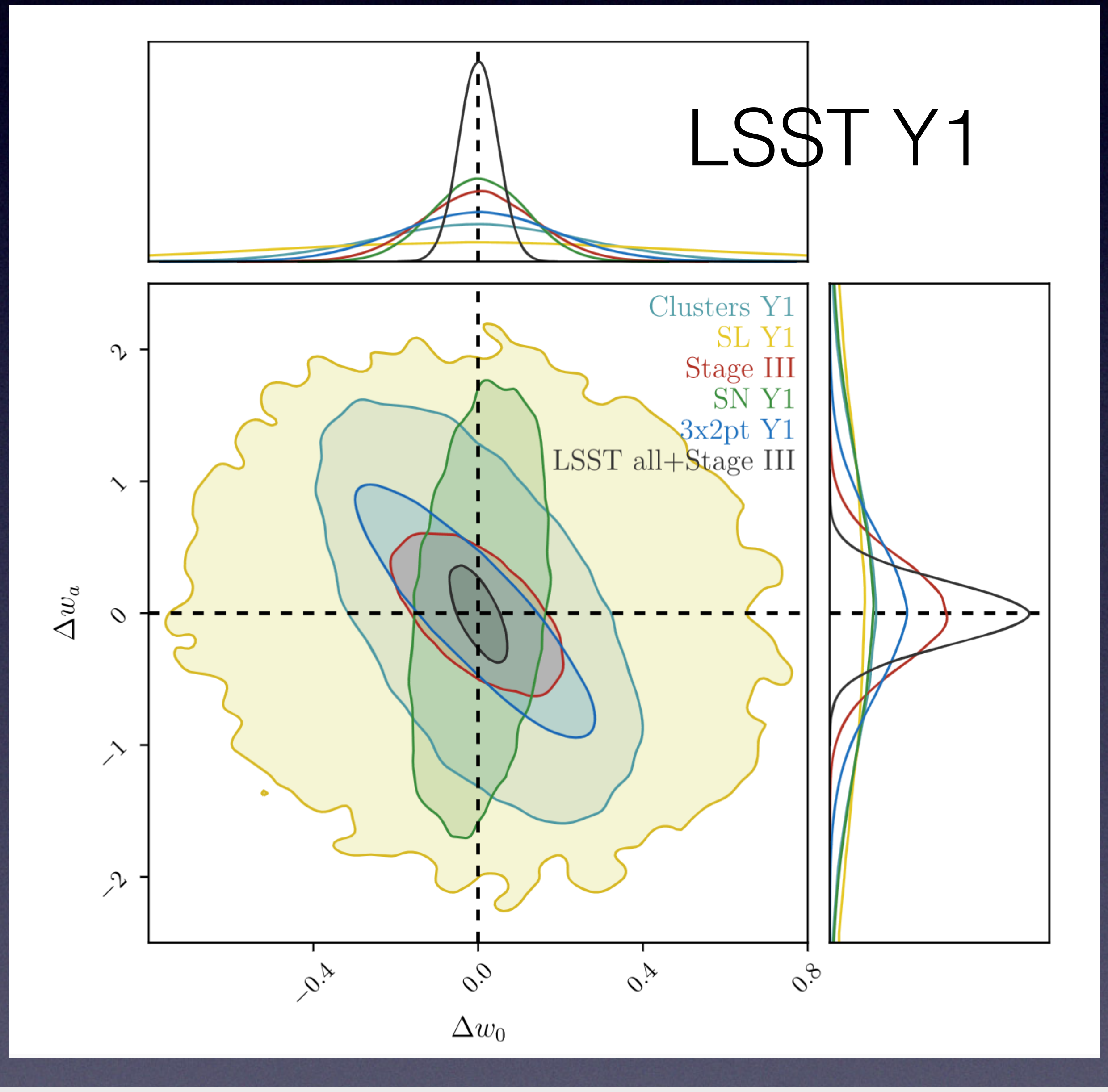
Stage	$\sigma(w_0)$	$\sigma(w_a)$	**Figure of Merit (FoM)**	**Techniques**
II	~0.1–0.2	~0.3–0.5	Baseline	SN, BAO, WL (DES, eBOSS)
III	~0.03–0.05	~0.1–0.2	×3 vs Stage II	SN+BAO+WL (DESI, J-PAS)
IV	**~0.01–0.02**	**~0.05–0.1**	**×10 vs Stage II**	**LSST, Euclid (WL+BAO+SN+CL)**

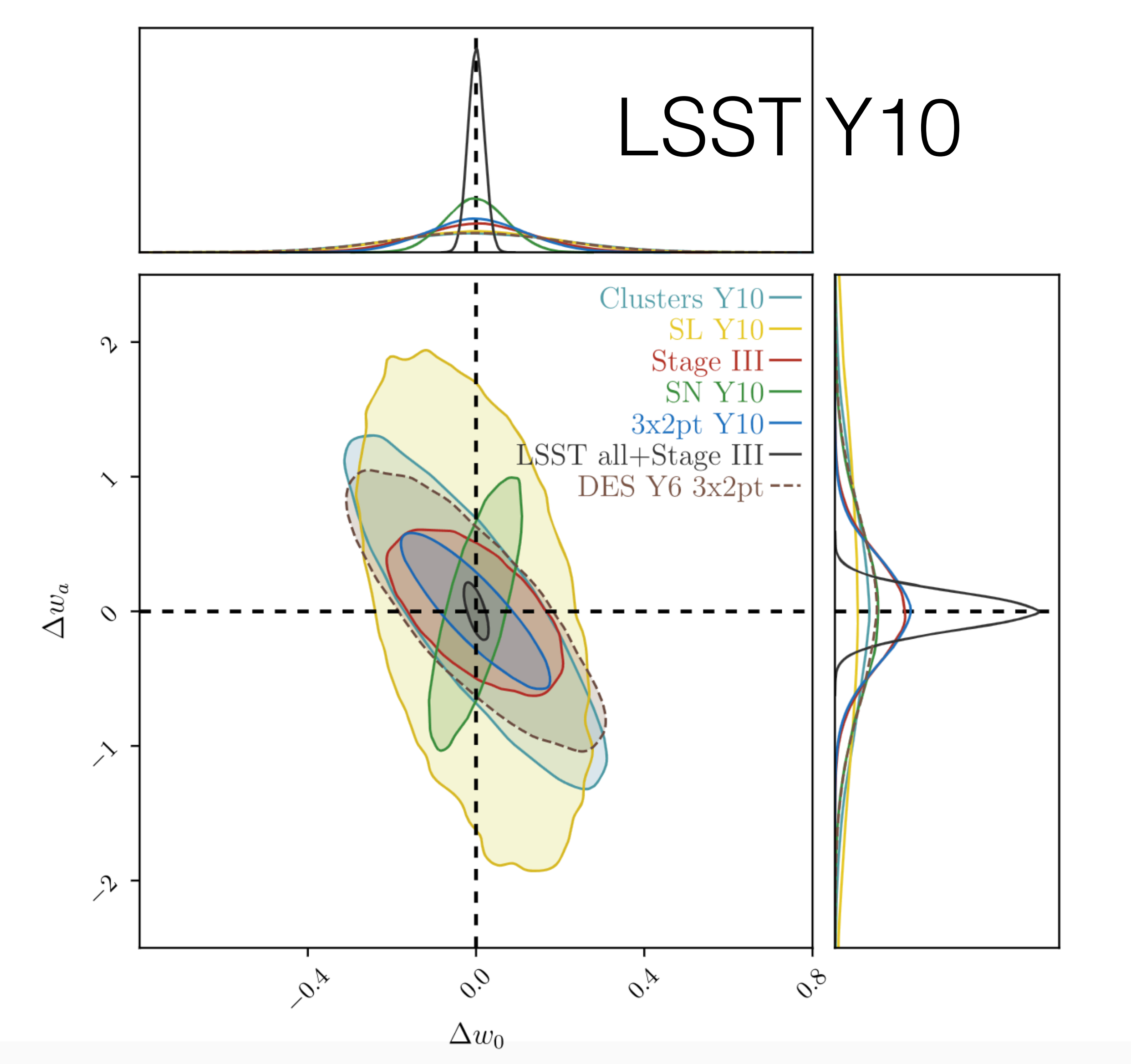
LSST and Euclid parameters Forecast

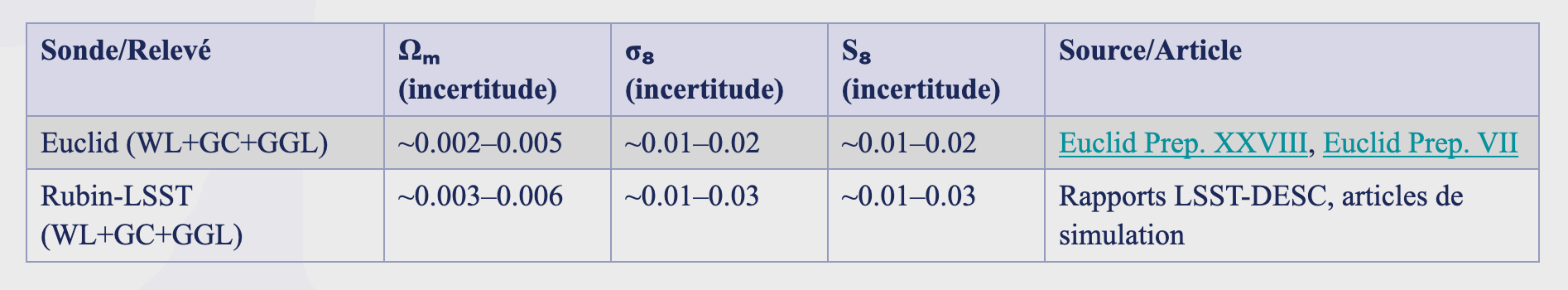
Need multi-cosmological probe combinations to achieve so called stage IV parameter resolution on $\Omega - m, \sigma_8, w_0, w_a$

LSST Y10









Sonde/Relevé	**Ω_m (incertitude)**	**σ_8 (incertitude)**	**S_8 (incertitude)**	**Source/Article**
Euclid (WL+GC+GGL)	~0.002–0.005	~0.01–0.02	~0.01–0.02	Euclid Prep. XXVIII, Euclid Prep. VII
Rubin-LSST (WL+GC+GGL)	~0.003–0.006	~0.01–0.03	~0.01–0.03	Rapports LSST-DESC, articles de simulation

Section 3 : Examples of Cosmological probes in galaxy surveys

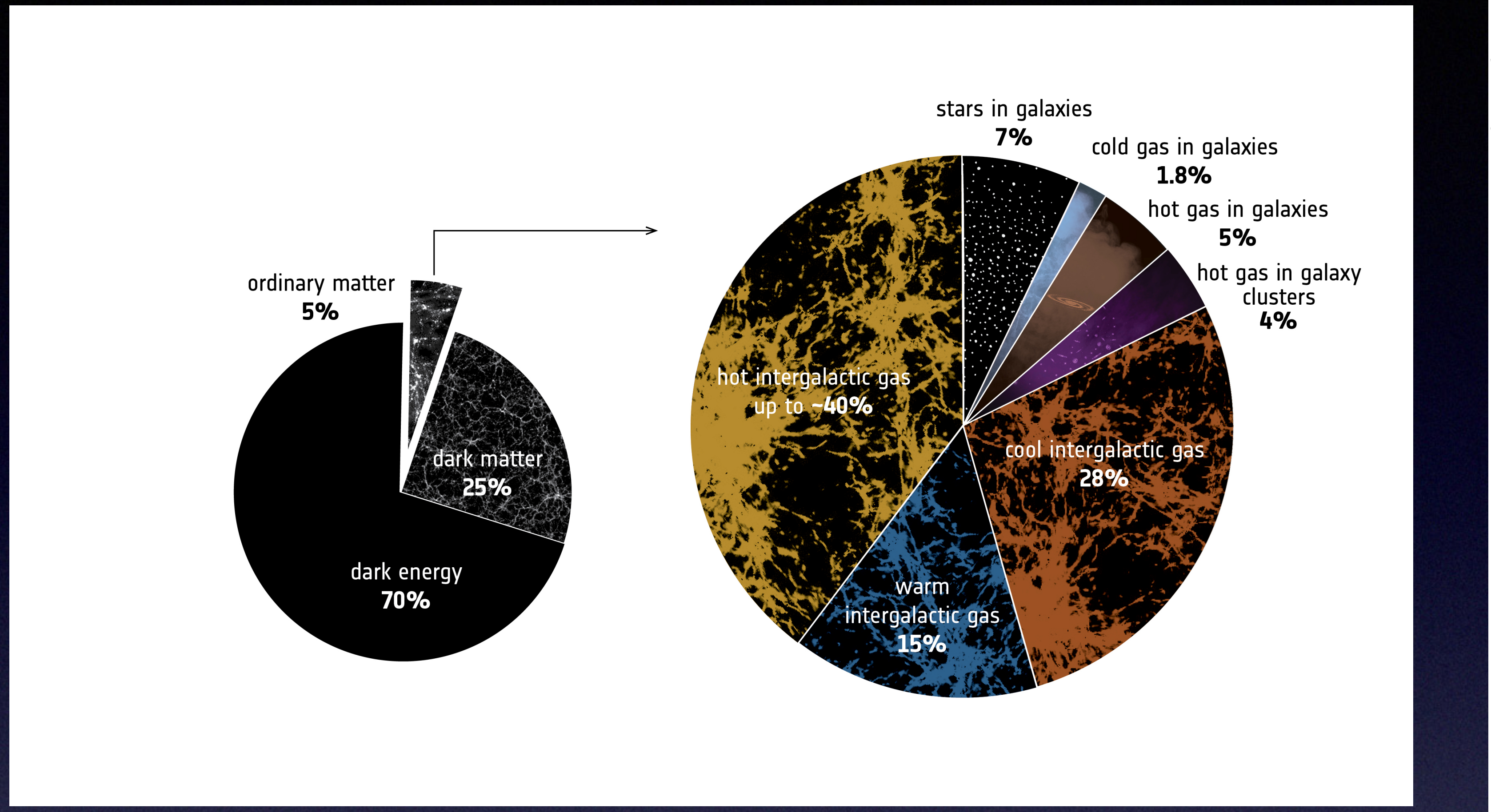
Two kind of probes:

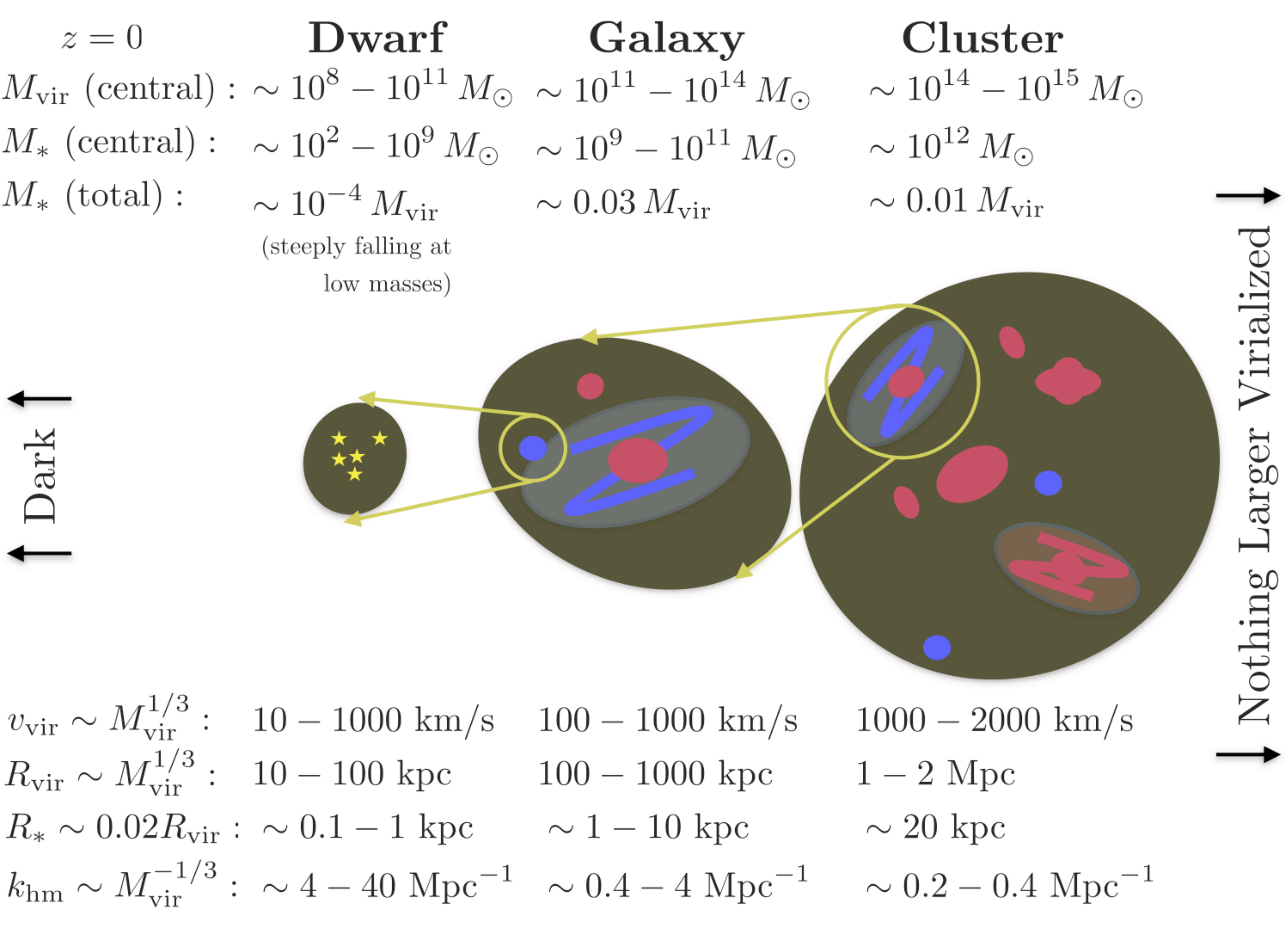
- **Geometrical probes (radial and transverse distances)**
  $H(z) \rightarrow \Omega_M, w(z)$ and $D_A(z)$
  - Baryon acoustic oscillations (BAO)
  - SN (not discussed)

- **Matter Structure-Growth probes**
  $P(k)$ (σ_8) and distances $H(z)$ $(\Omega_M, w(z))$
  - Clusters of galaxies
  - Gravitational lensing and mostly weak-lensing

Galaxies (and gas) are optical tracers of Dark Matter

Only 5% of energy is « visible » through electromagnetic wave

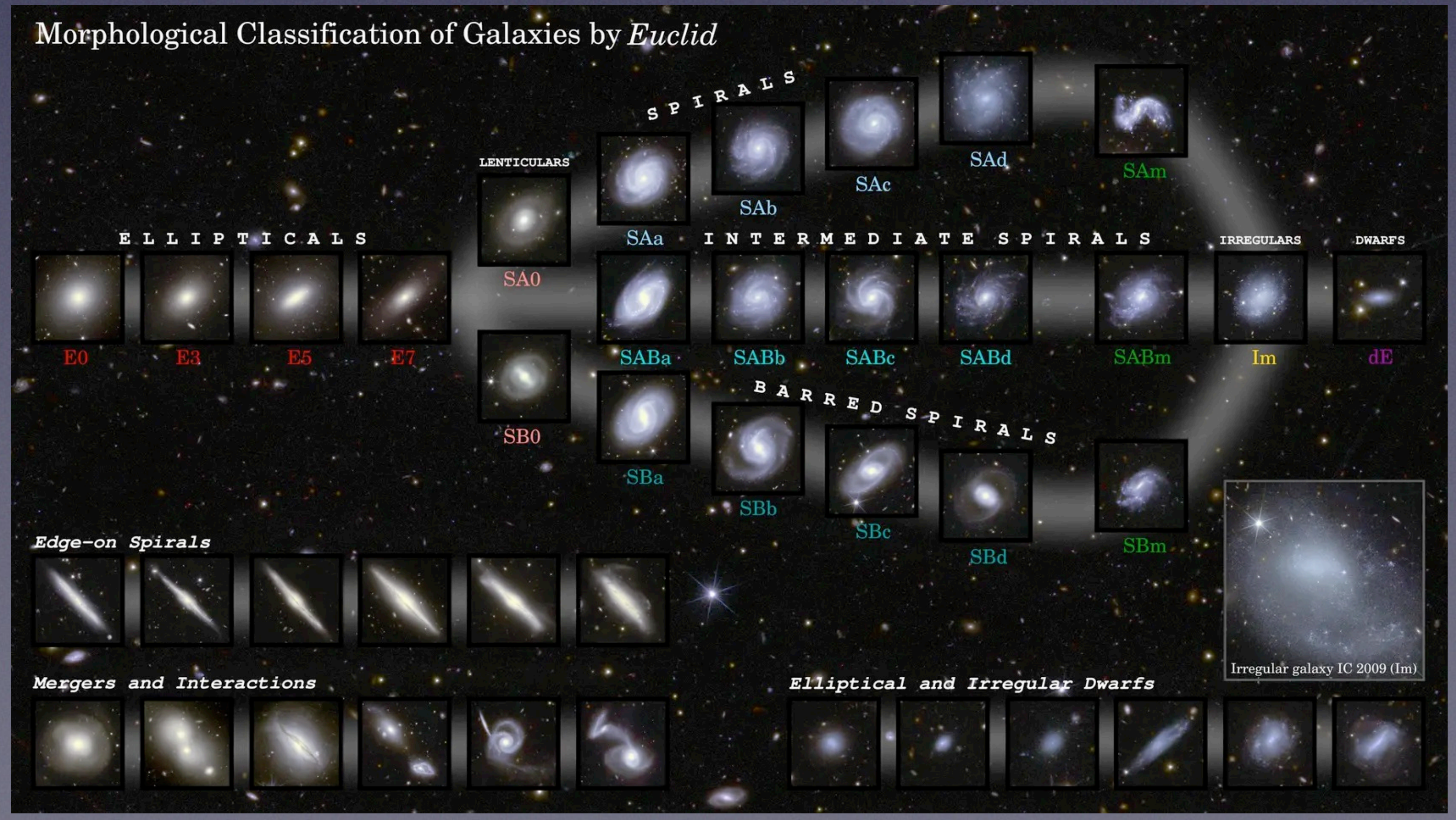




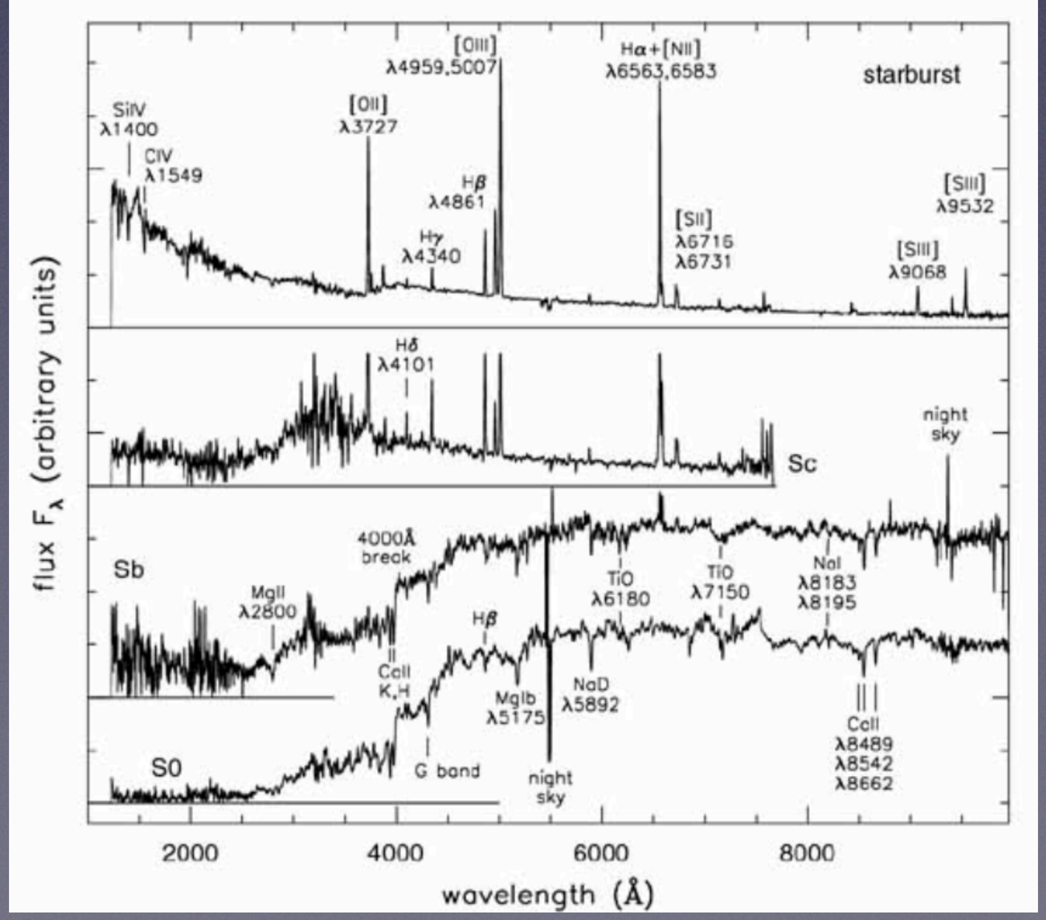
$z = 0$	**Dwarf**	**Galaxy**	**Cluster**
$M_{\rm vir}$ (central) :	$\sim 10^8 - 10^{11}\, M_\odot$	$\sim 10^{11} - 10^{14}\, M_\odot$	$\sim 10^{14} - 10^{15}\, M_\odot$
M_* (central) :	$\sim 10^2 - 10^9\, M_\odot$	$\sim 10^9 - 10^{11}\, M_\odot$	$\sim 10^{12}\, M_\odot$
M_* (total) :	$\sim 10^{-4}\, M_{\rm vir}$ (steeply falling at low masses)	$\sim 0.03\, M_{\rm vir}$	$\sim 0.01\, M_{\rm vir}$
$v_{\rm vir} \sim M_{\rm vir}^{1/3}$:	$10 - 1000$ km/s	$100 - 1000$ km/s	$1000 - 2000$ km/s
$R_{\rm vir} \sim M_{\rm vir}^{1/3}$:	$10 - 100$ kpc	$100 - 1000$ kpc	$1 - 2$ Mpc
$R_* \sim 0.02 R_{\rm vir}$:	$\sim 0.1 - 1$ kpc	$\sim 1 - 10$ kpc	~ 20 kpc
$k_{\rm hm} \sim M_{\rm vir}^{-1/3}$:	$\sim 4 - 40\ {\rm Mpc}^{-1}$	$\sim 0.4 - 4\ {\rm Mpc}^{-1}$	$\sim 0.2 - 0.4\ {\rm Mpc}^{-1}$

- Hierarchical structures forms from galaxies to Halo
- DM Halo decouple from Hubble expansion, and undergo a gravitational collapse and virialize
- No visible baryonic systems have been detected in halos below the dwarf galaxy scale $10^8 M_\odot$
- Dark matter halo structure and its baryonic population remain uncertain, impacting cosmological inferences

Many different galaxy type (age, morphology)



Many different Spectra (redshift estimation bias)

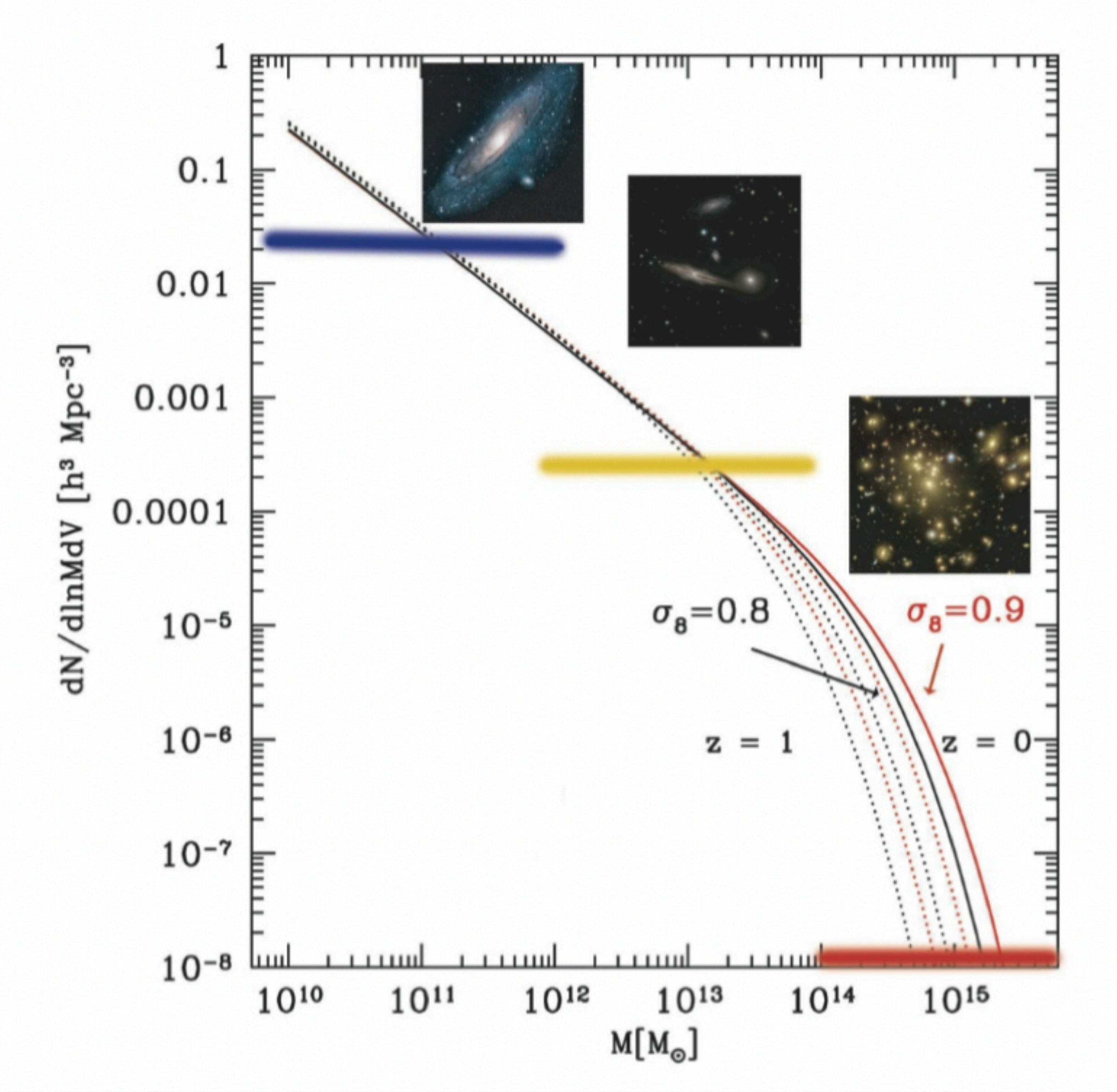


Probe 1 :Galaxy clusters abundance counting (mostly photometric surveys)

Structure growth-type probe

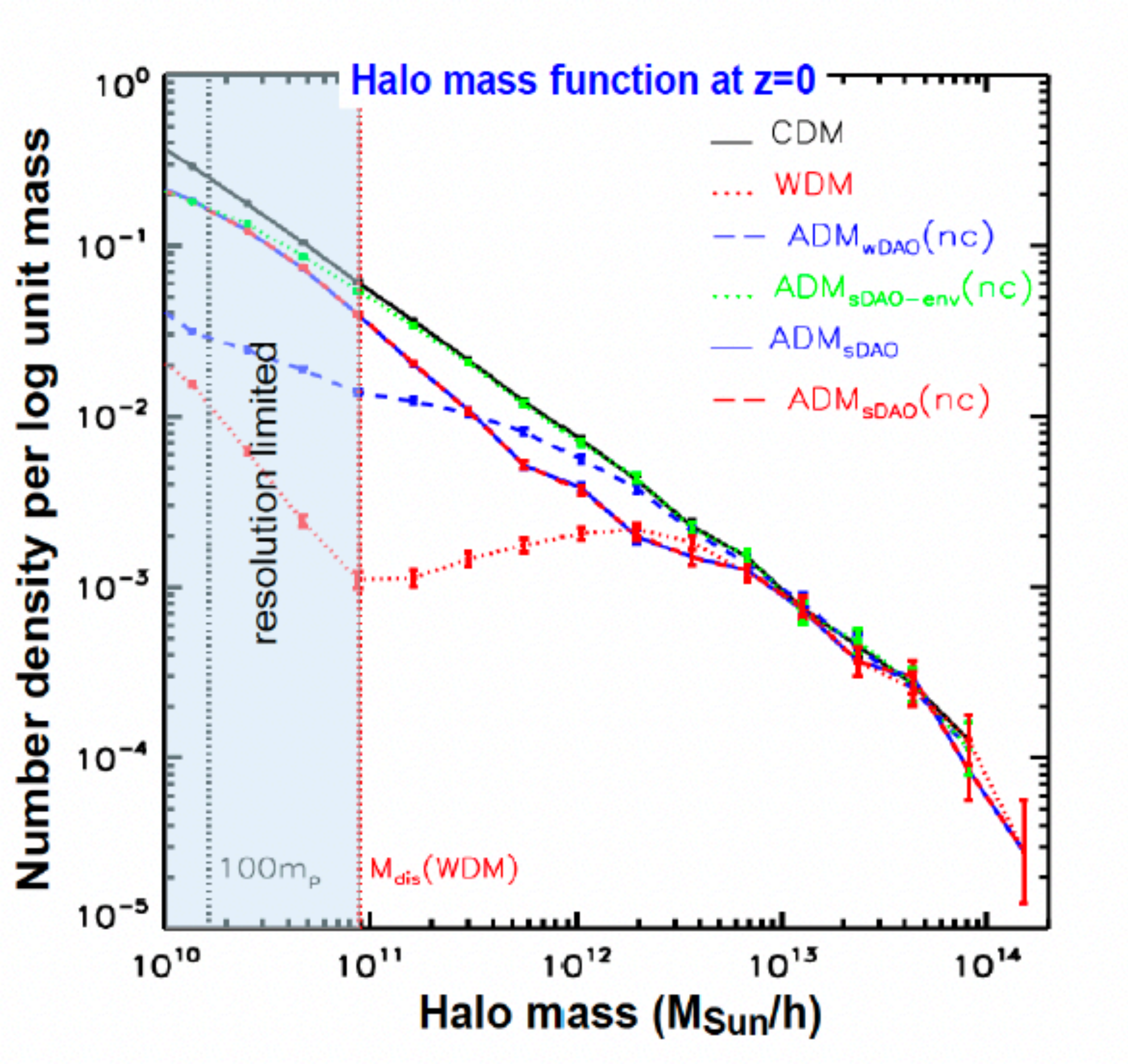
Predictions from theory:

High mass halo:



Halo mass function sensitivity to redshift and σ_8

Low mass halo:



The halo mass function at z = 0 for different models
(from cosmological simulations)

The observable: Halo mass count evolution

$$\boxed{\frac{dN}{dz\,dM_O} = \frac{dV}{dz}(z,\Theta_C)\int d\ln M\, P(M_O\,|\,M,z,\Theta_N)\,\lambda(M,z,\Theta_N)\,\frac{dn}{d\ln M}(M,z,\Theta_C)}$$

- Mass Proxy M_O of the true cluster mass M
    - Example : the cluster richness (nb of galaxies)

Theory : Known formula based on cosmological Parameters θ_C

$$\boxed{\frac{dn}{d\ln M}(M,z,\Theta_C)}$$

Experimental analysis:

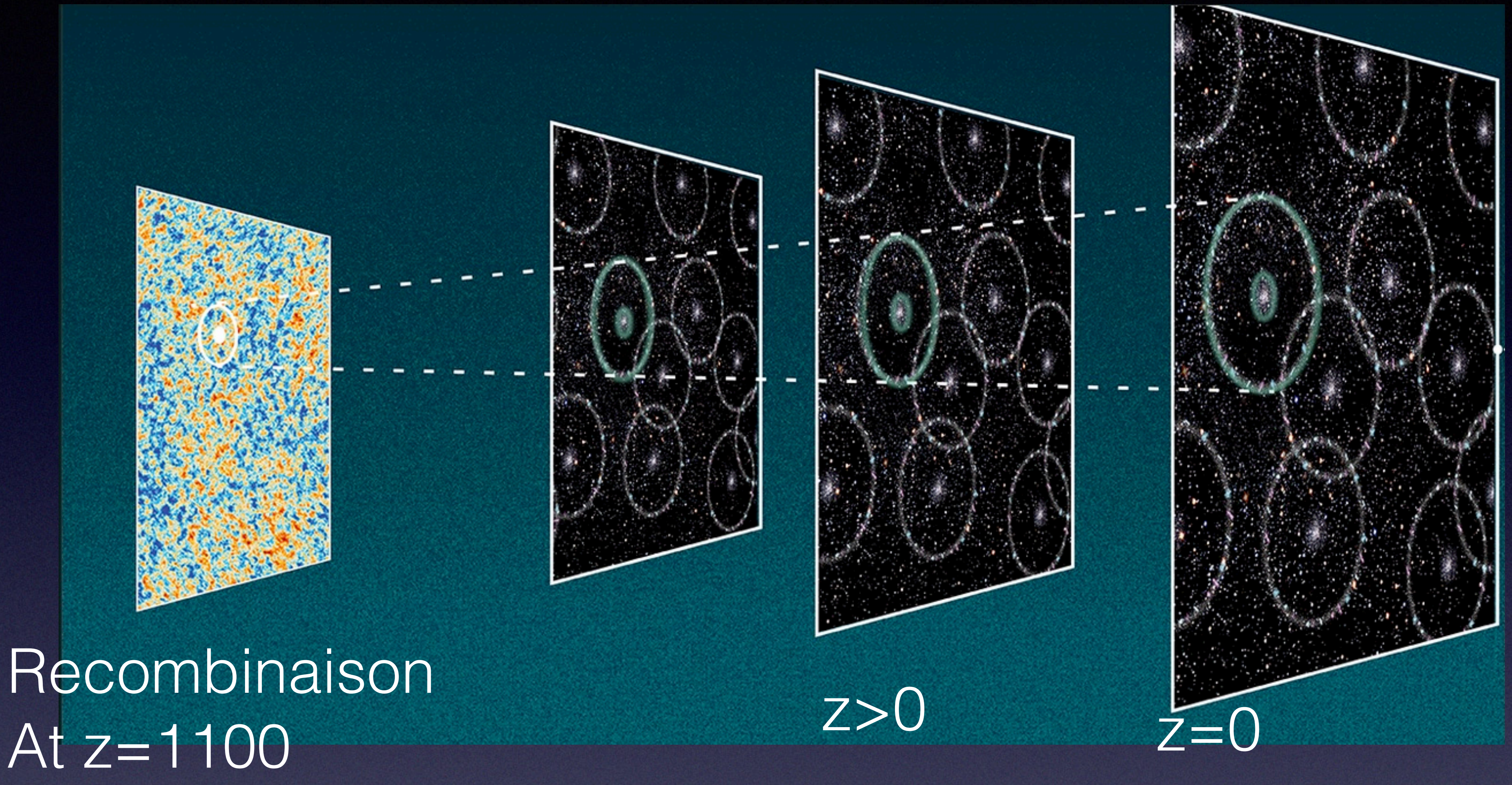
- Completeness or selection function $\lambda(M,z,\Theta_N)$

- Probability to observe M_0 for a given (M,z)

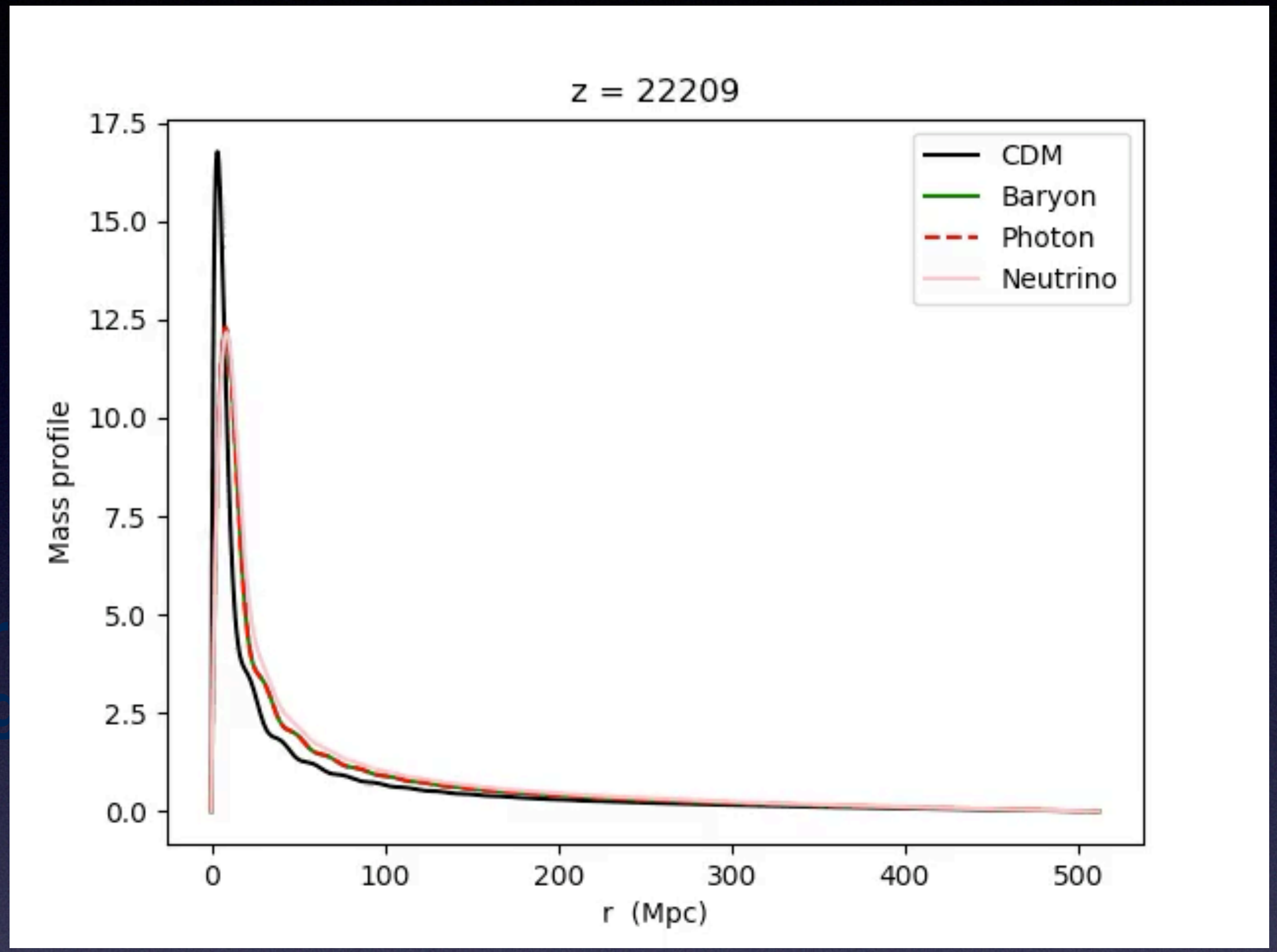
$P(M_O\,|\,M,z,\Theta_N)$

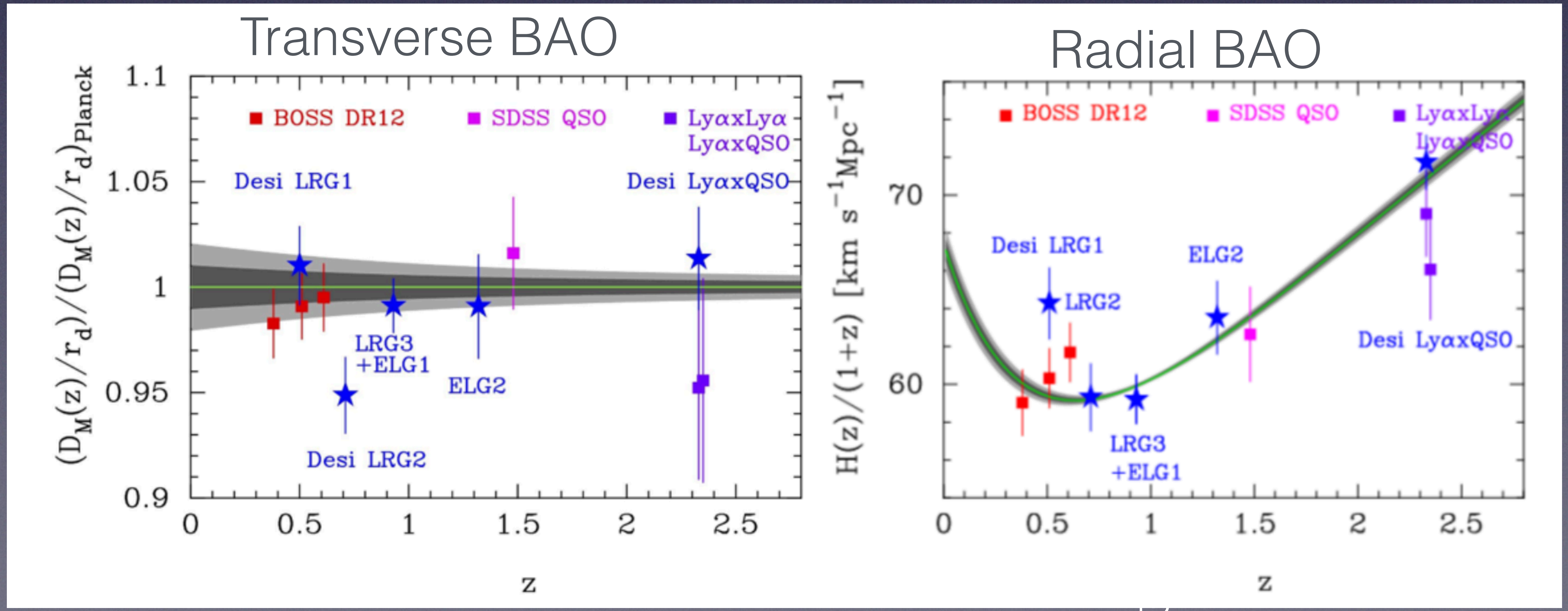
Probe 2 : Baryon Acoustic Oscillations

Measures $H(z)$ and $D_A(z)$ to constrain dark energy and cosmological models.



2-points corr
Function of g

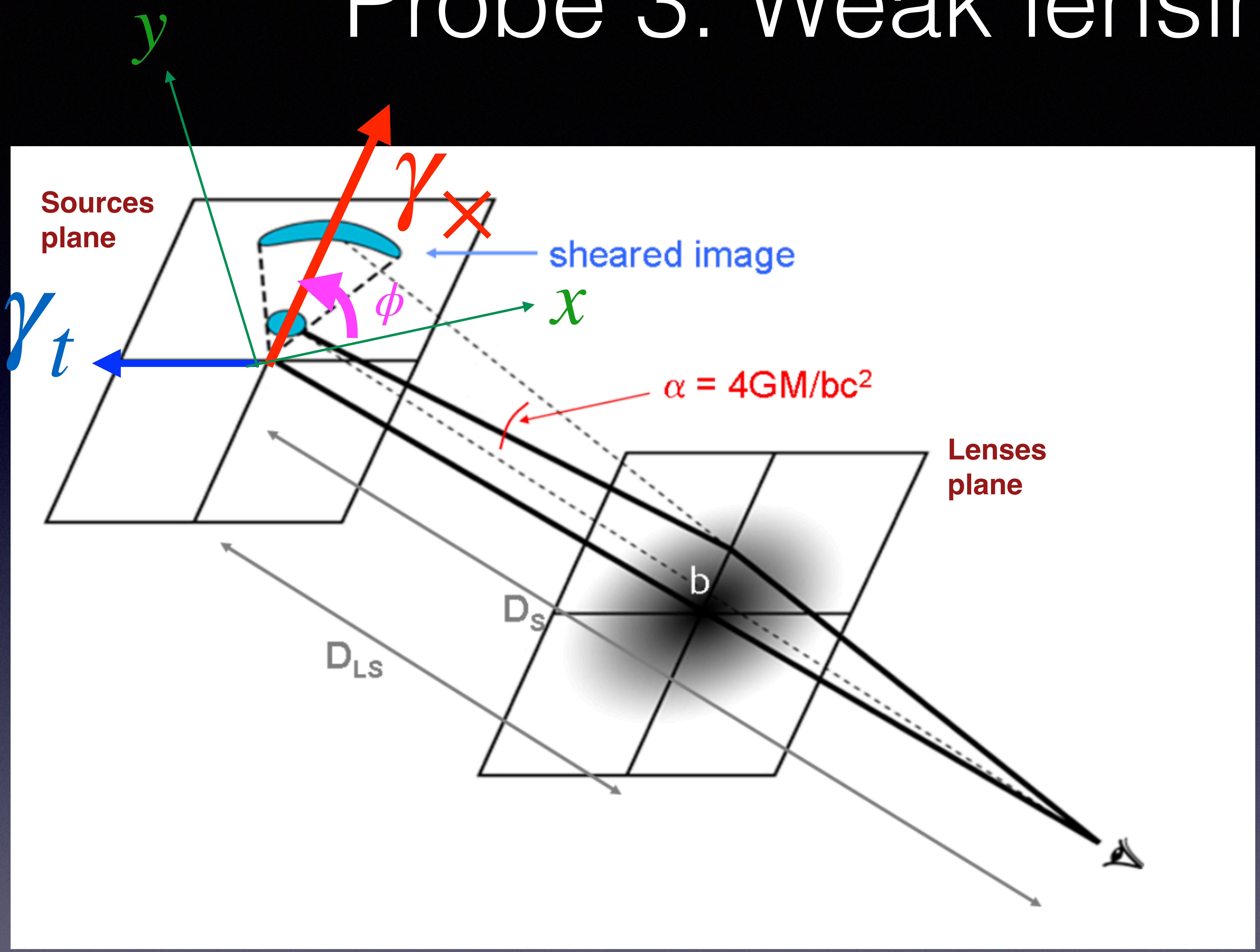


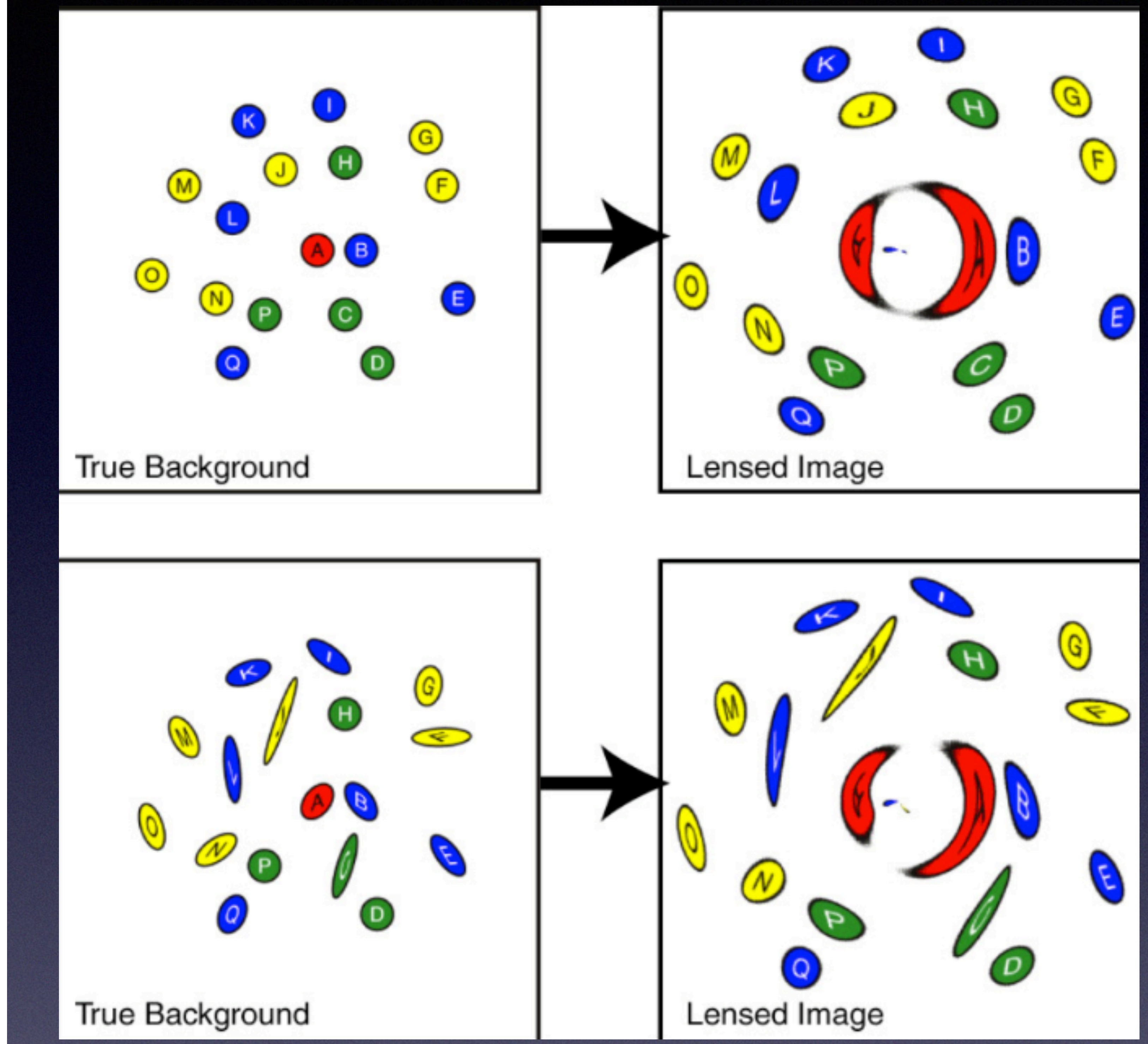


Spectroscopic surveys like DESI
(Good redshifts)
- radial and transverse BAO

$r_d \simeq 150Mpc(z=0)$

Probe 3: Weak lensing probe





$$\langle e_{intr} \rangle = 0$$

$$e = e_{intr} + \gamma$$

Einstein radius

$$\theta_E = \sqrt{\frac{M}{\pi \Sigma_{\rm crit} D_L^2}}$$

Galaxy : $\theta_E \simeq 1''$

Cluster : $\theta_E \simeq 10''$

Measurement of galaxy ellipticity (in the object catalog)

$$e = \frac{I_{xx} - I_{yy} + 2iI_{xy}}{I_{xx} + I_{yy} + 2\sqrt{I_{xx}I_{yy} - I_{xy}^2}}$$

Measurement of the shear

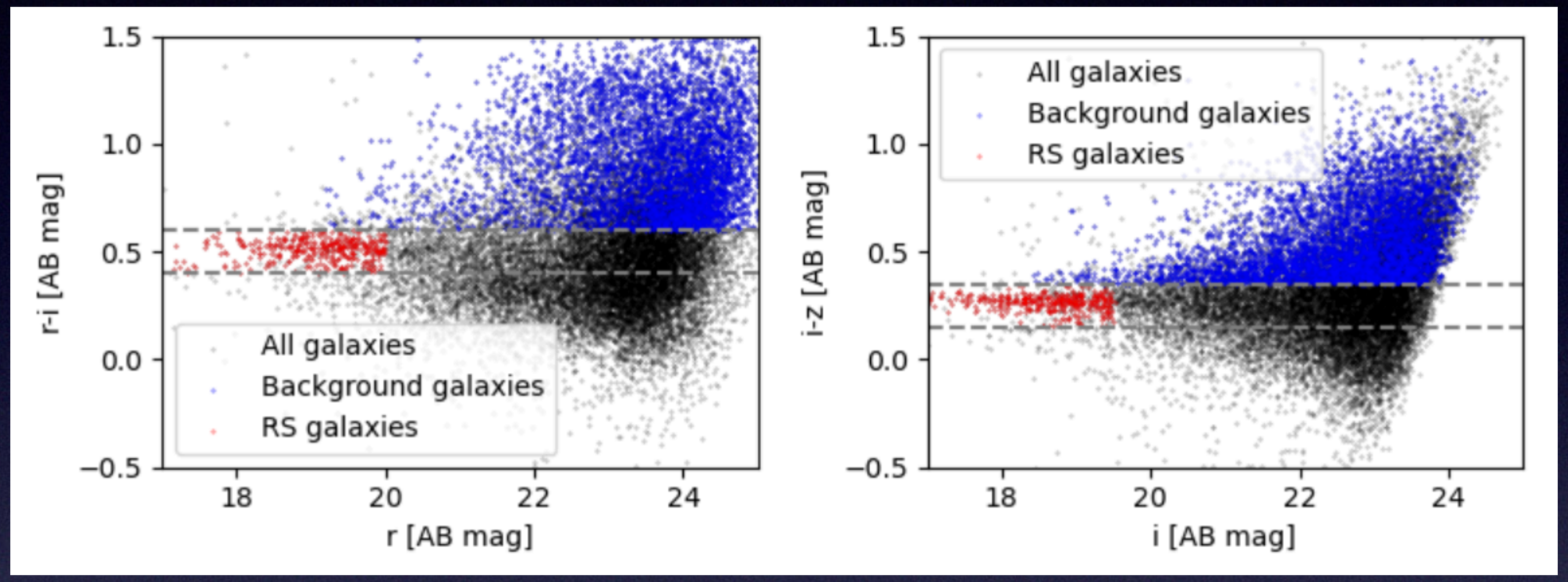
$$\gamma_1 = {\rm Re}(e) \qquad \gamma_2 = {\rm Im}(e)$$

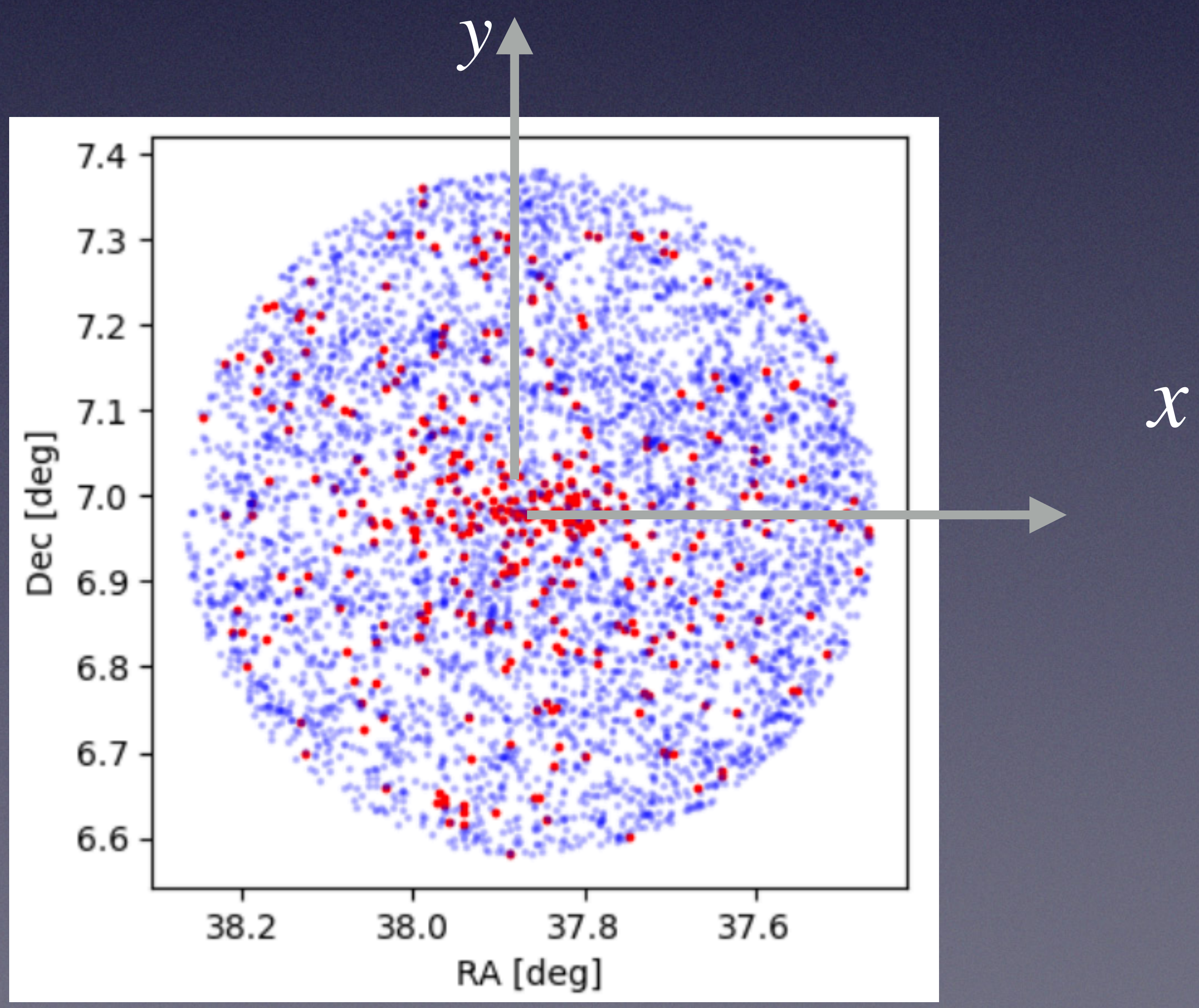
$$\gamma_t = -\gamma_1 \cos(2\phi) - \gamma_2 \sin(2\phi)$$

$$\gamma_\times = +\gamma_1 \sin(2\phi) - \gamma_2 \cos(2\phi)$$

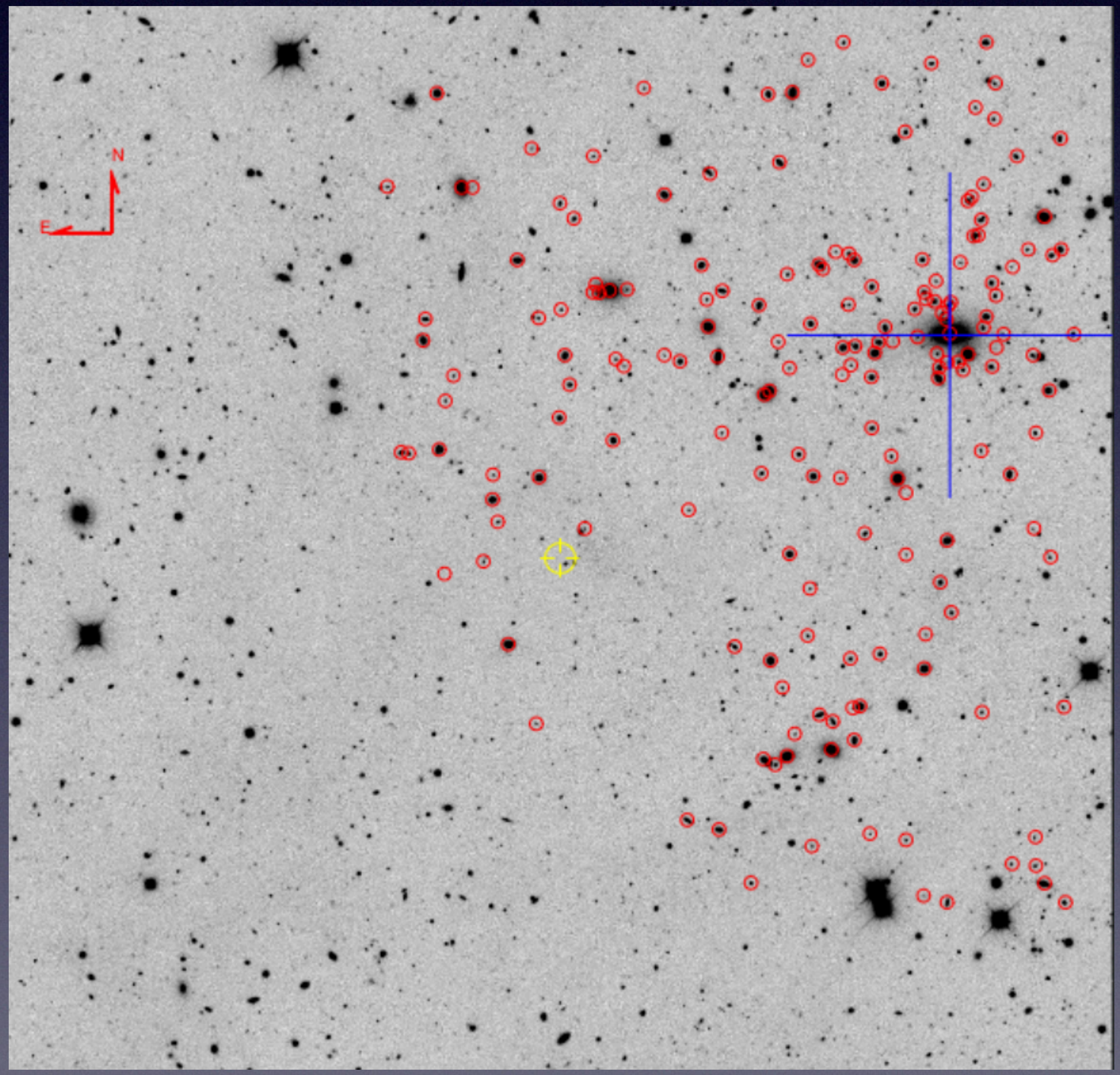
Example of WL shear signal in the Abell 360 red sequence galaxy selection (LSST-Data Preview 1, 2025)

Selection of distant sources galaxies by their red-colour selection (behind the cluster)



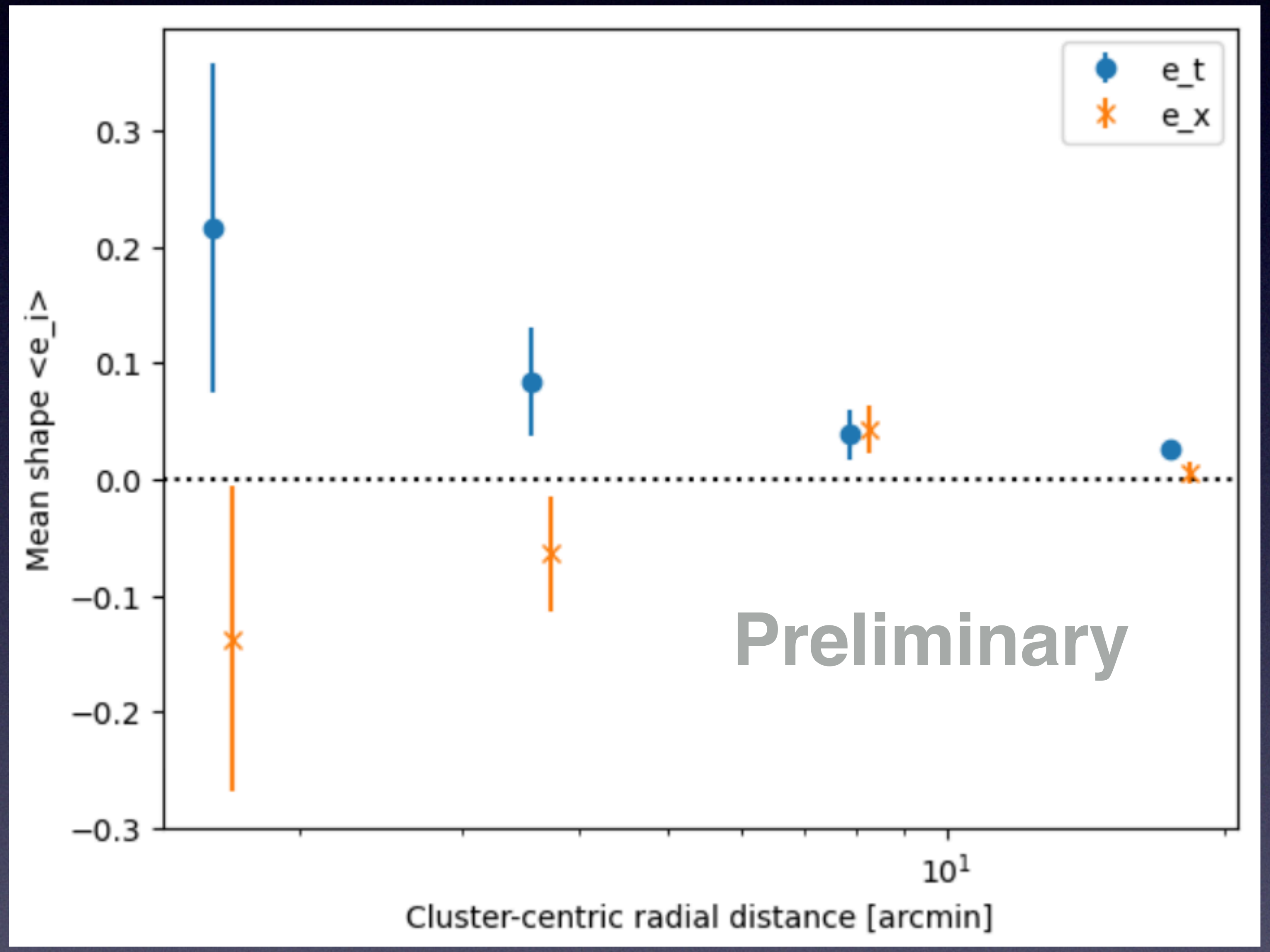


Coadded image in band r
FOV : 26 arcmin



$$e_t = -e_1\cos(2\varphi) - e_2\sin(2\varphi)$$

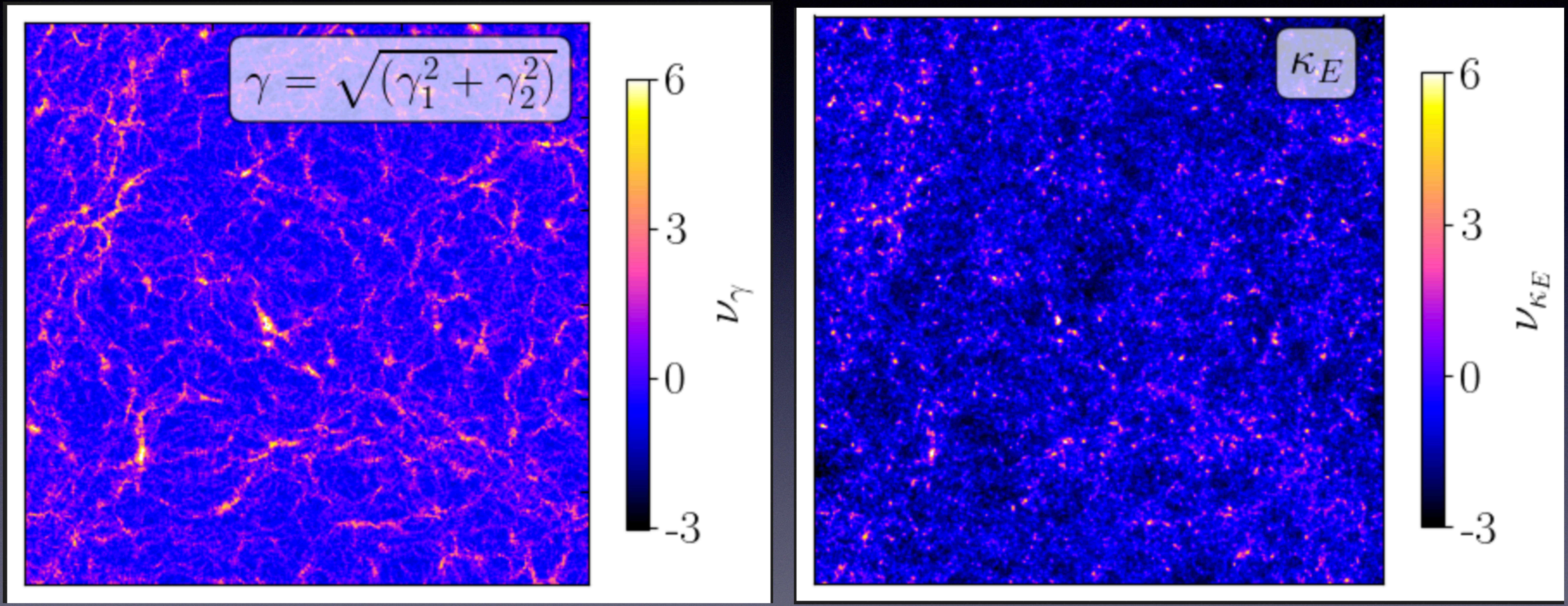
$$e_\times = e_1\sin(2\varphi) - e_2\cos(2\varphi)$$



This cluster shows a lensing signal, with higher mean tangential ellipticity near its center. The mean cross ellipticity fluctuates around zero, confirming the absence of significant systematics.

Lina Castiblanco et al.(2024) arXiv:2405.09651v

Weak lensing DM- mapping (simulations)



Shear maps

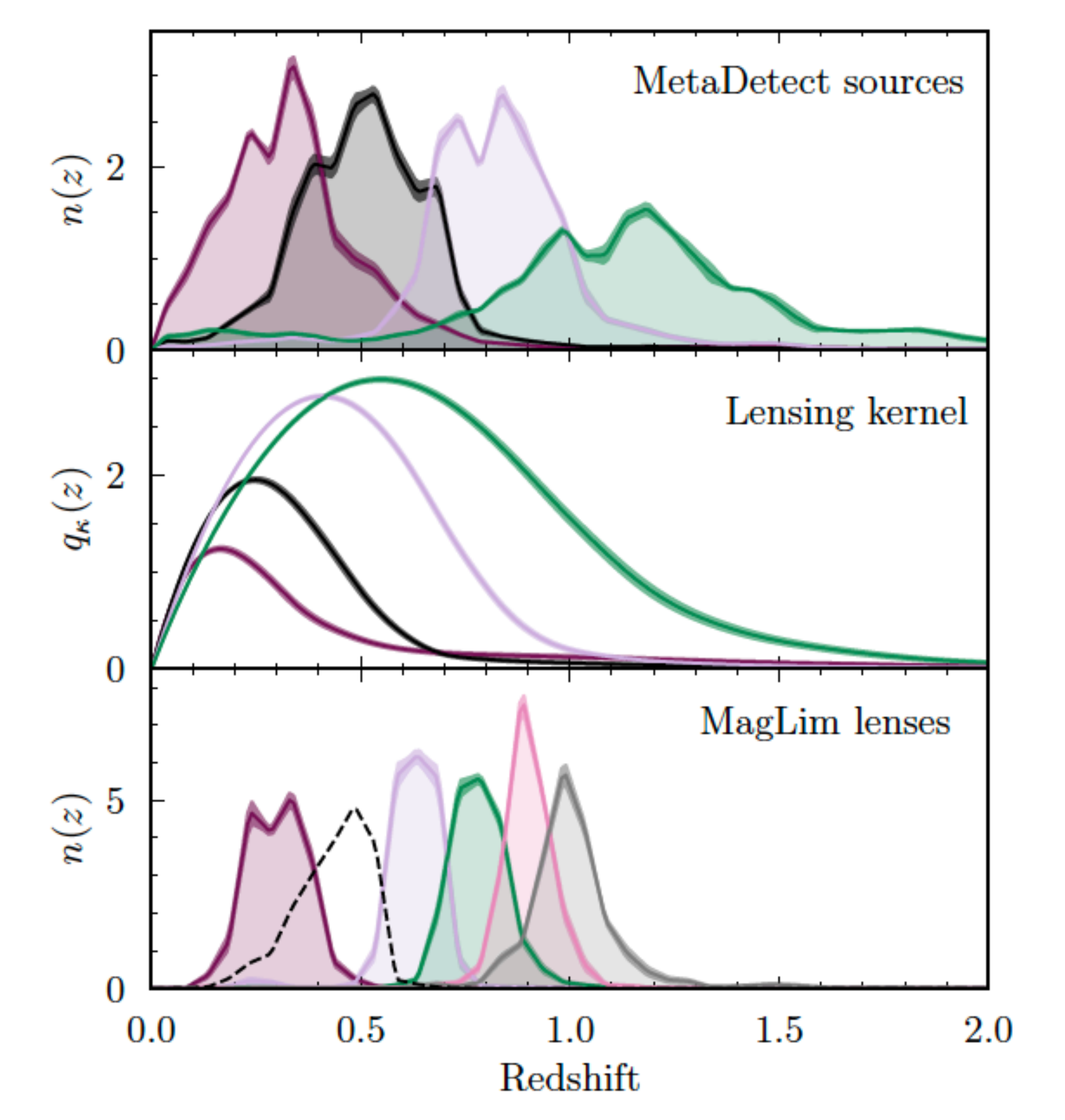
Convergence map

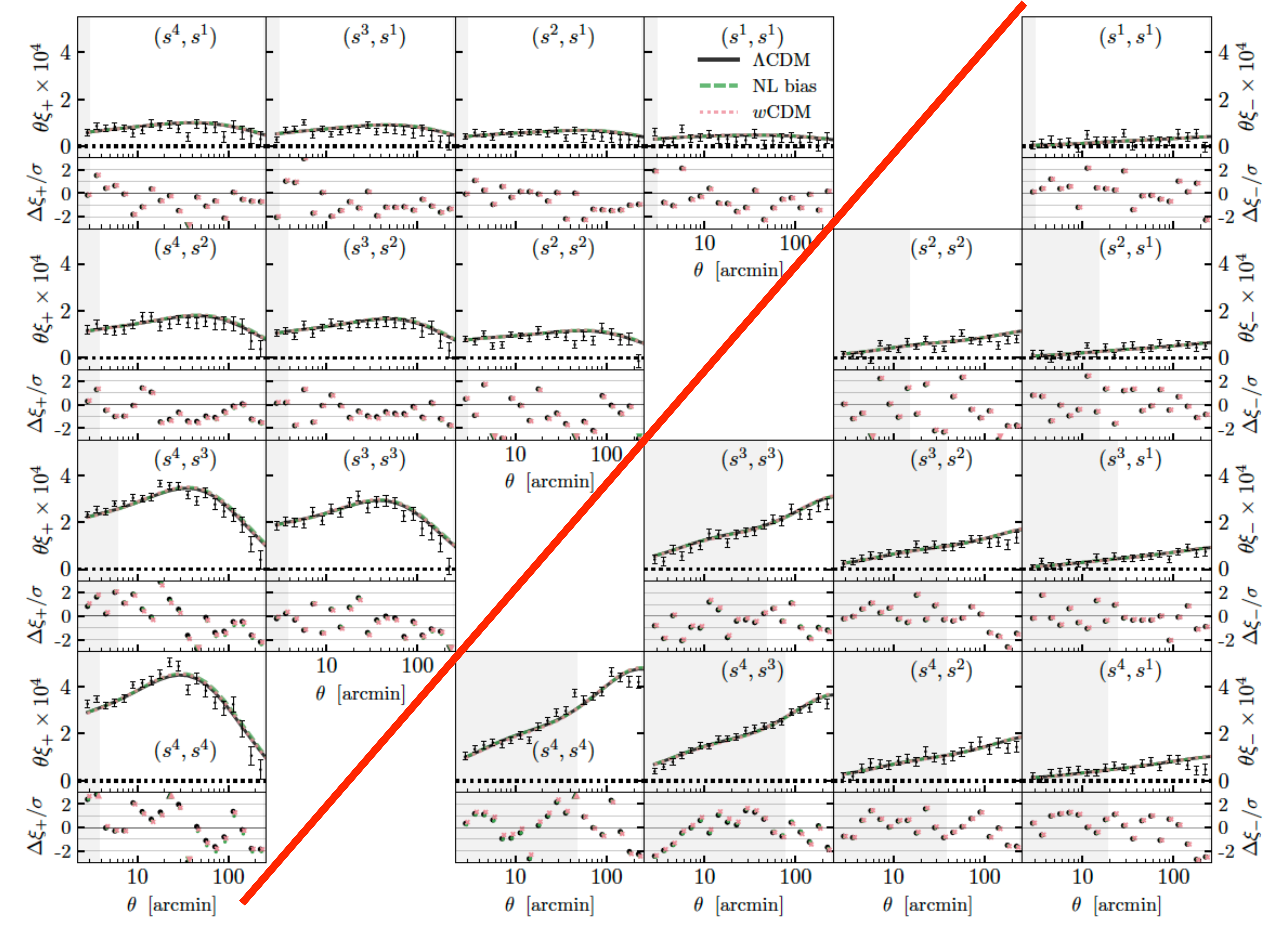
Weak lensing maps. Left: Absolute value of the shear field. Right: KS-reconstructed convergence map. The background colour represents the fluctuation field in units of the field standard deviation.

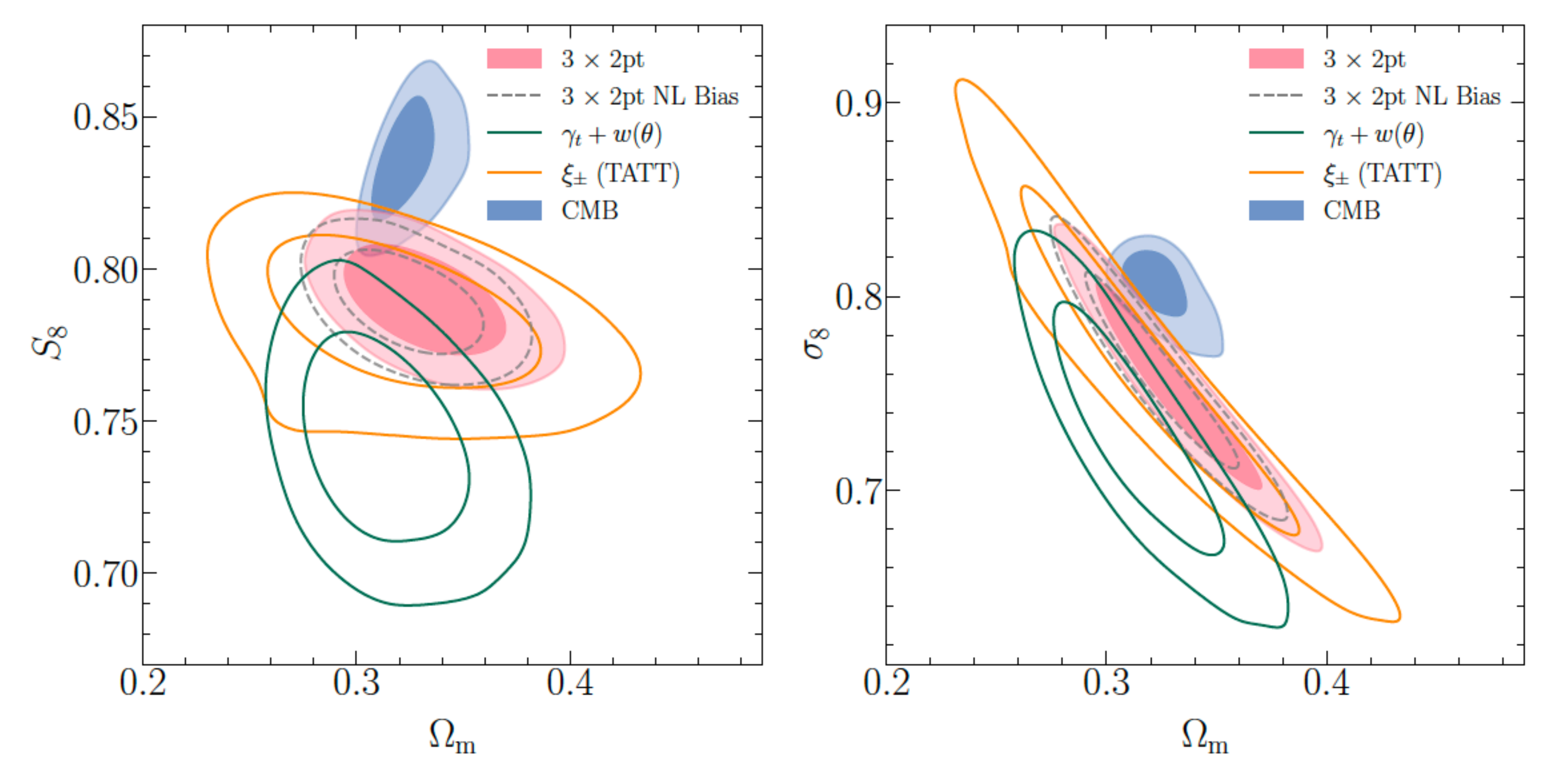
Weak lensing shear cross correlation in DES Y6 (2026)

$$\xi_+(\theta) = \langle \gamma_t(\vec{\theta}_1)\gamma_t(\vec{\theta}_2)\rangle + \langle \gamma_\times(\vec{\theta}_1)\gamma_\times(\vec{\theta}_2)\rangle$$

$$\xi_-(\theta) = \langle \gamma_t(\vec{\theta}_1)\gamma_t(\vec{\theta}_2)\rangle - \langle \gamma_\times(\vec{\theta}_1)\gamma_\times(\vec{\theta}_2)\rangle$$





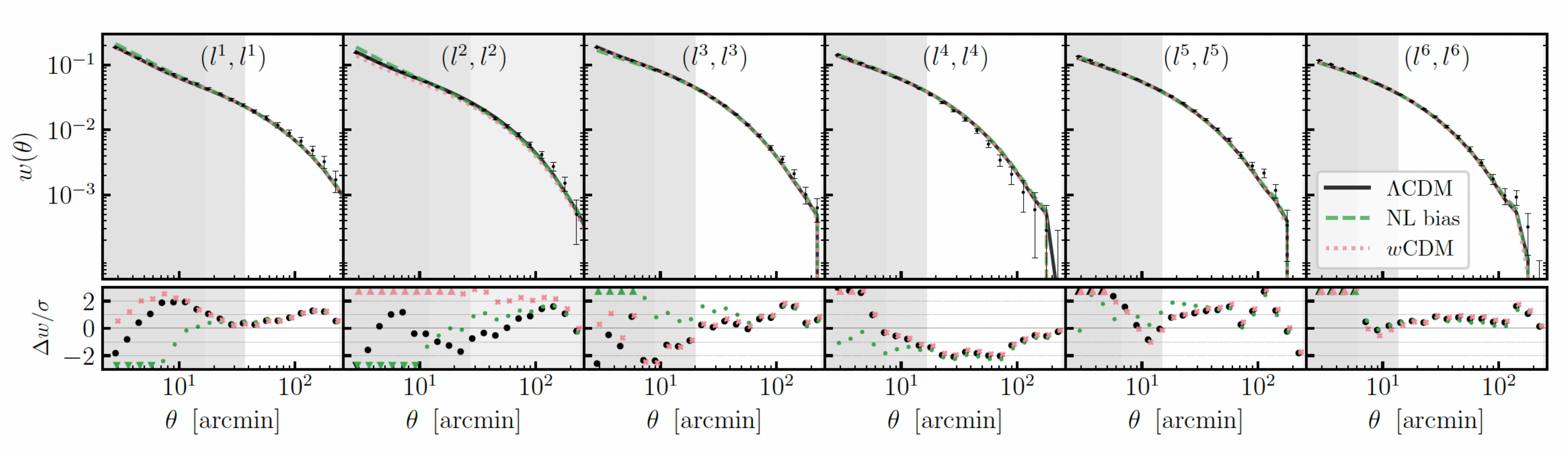


2026 : Dark Energy Survey Year 6 Results:
Cosmological Constraints from Galaxy Clustering and Weak Lensing

Other correlation functions DES Y6 (2026)

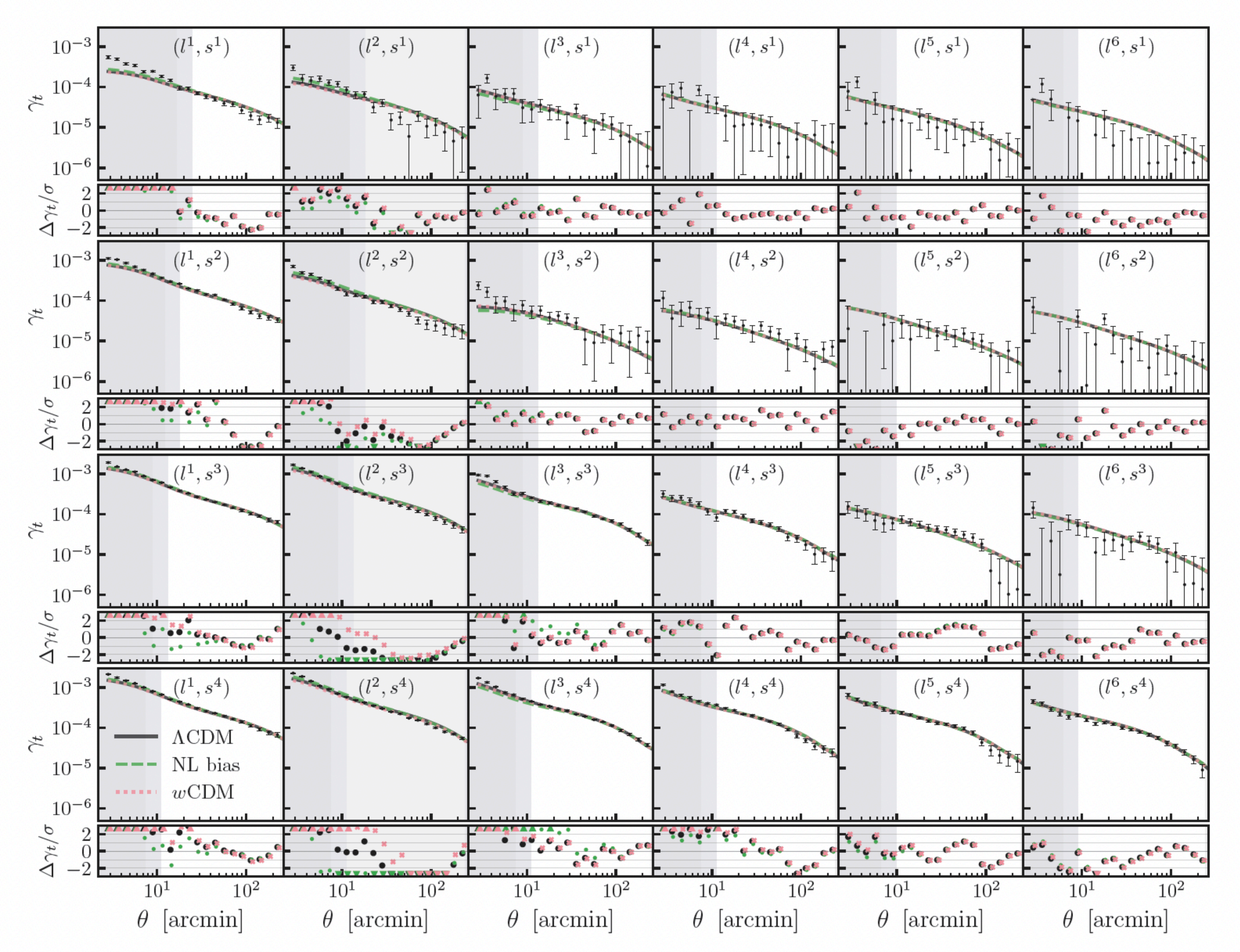
Galaxy-galaxy clustering

$$w(\theta) = \langle \delta_g(\vec{\theta}_1)\delta_g(\vec{\theta}_2) \rangle$$

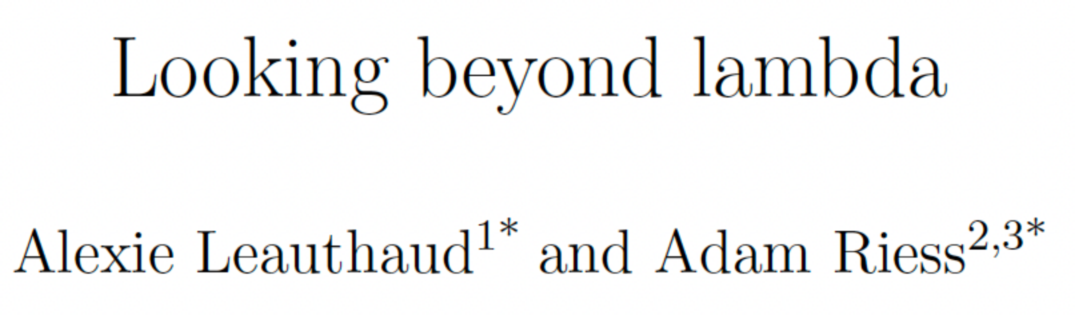


Galaxy-galaxy lensing

$$\gamma_t(\theta) = \left\langle \delta_g(\vec{\theta}_1)\, \gamma_t(\vec{\theta}_2; \vec{\theta}_1) \right\rangle$$



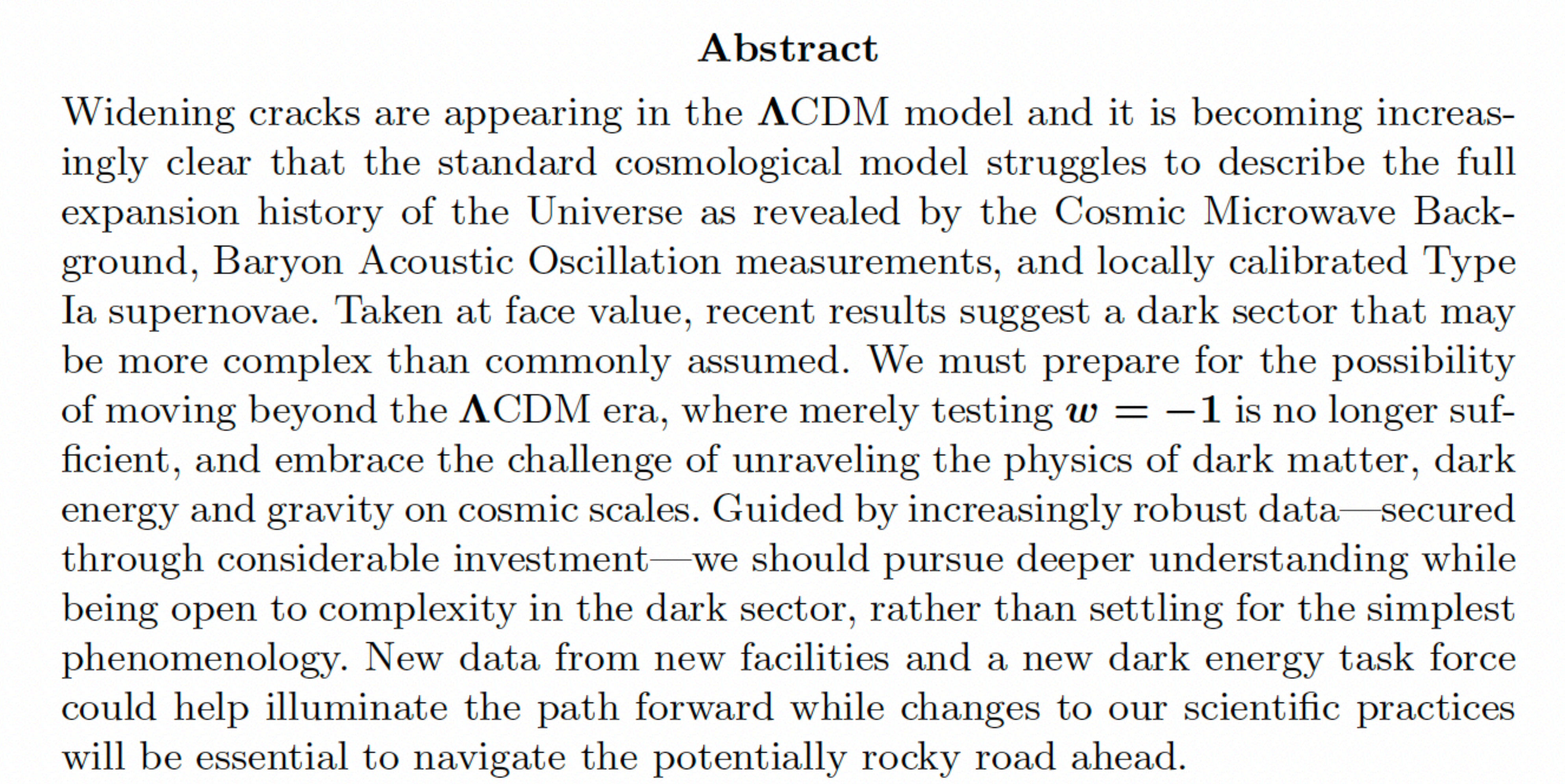
Section 4 : last results before LSST/Euclid



Looking beyond lambda

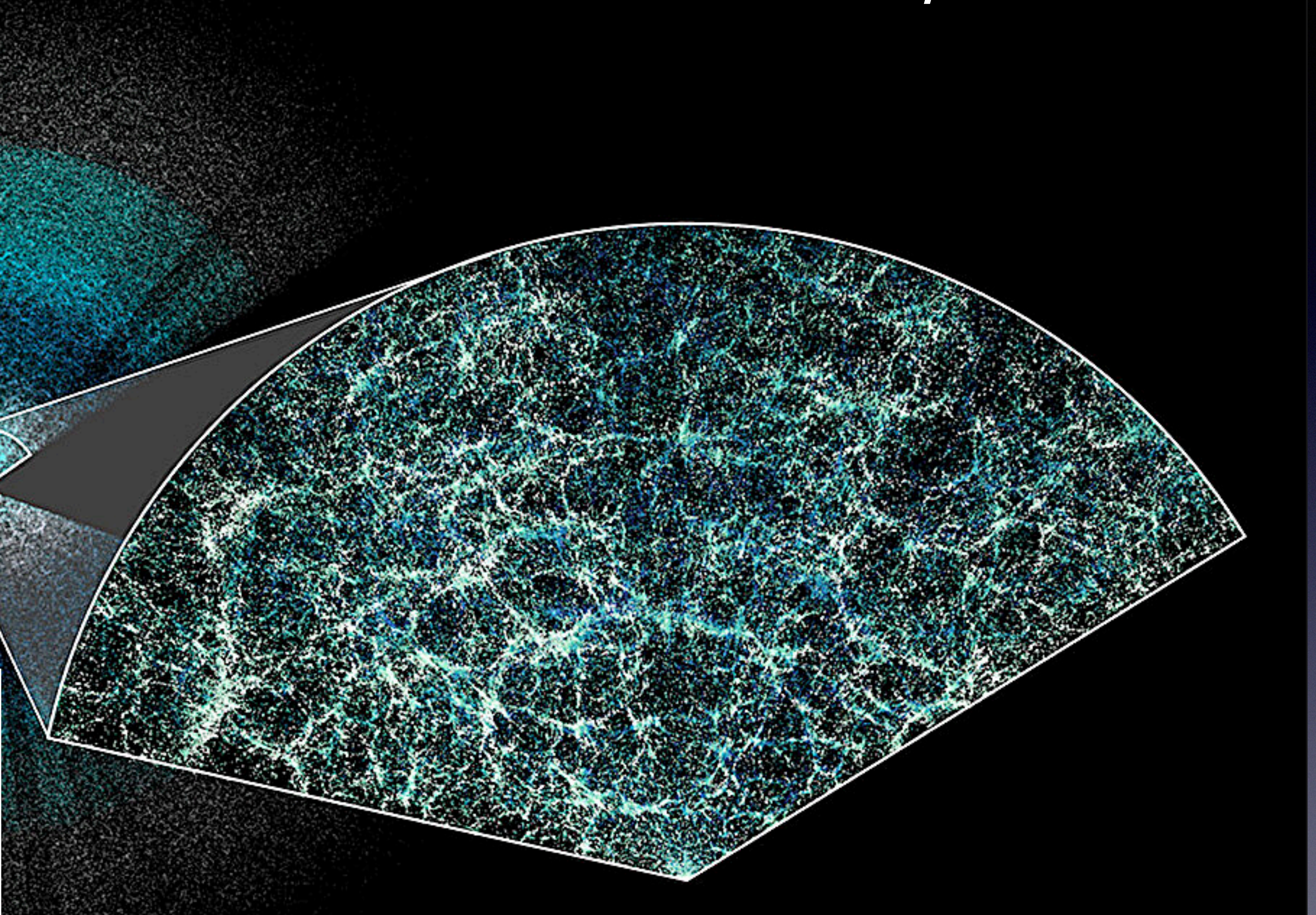
Alexie Leauthaud[1*] and Adam Riess[2,3*]

https://arxiv.org/pdf/2509.00359



Abstract

Widening cracks are appearing in the **Λ**CDM model and it is becoming increasingly clear that the standard cosmological model struggles to describe the full expansion history of the Universe as revealed by the Cosmic Microwave Background, Baryon Acoustic Oscillation measurements, and locally calibrated Type Ia supernovae. Taken at face value, recent results suggest a dark sector that may be more complex than commonly assumed. We must prepare for the possibility of moving beyond the **Λ**CDM era, where merely testing $\boldsymbol{w = -1}$ is no longer sufficient, and embrace the challenge of unraveling the physics of dark matter, dark energy and gravity on cosmic scales. Guided by increasingly robust data—secured through considerable investment—we should pursue deeper understanding while being open to complexity in the dark sector, rather than settling for the simplest phenomenology. New data from new facilities and a new dark energy task force could help illuminate the path forward while changes to our scientific practices will be essential to navigate the potentially rocky road ahead.

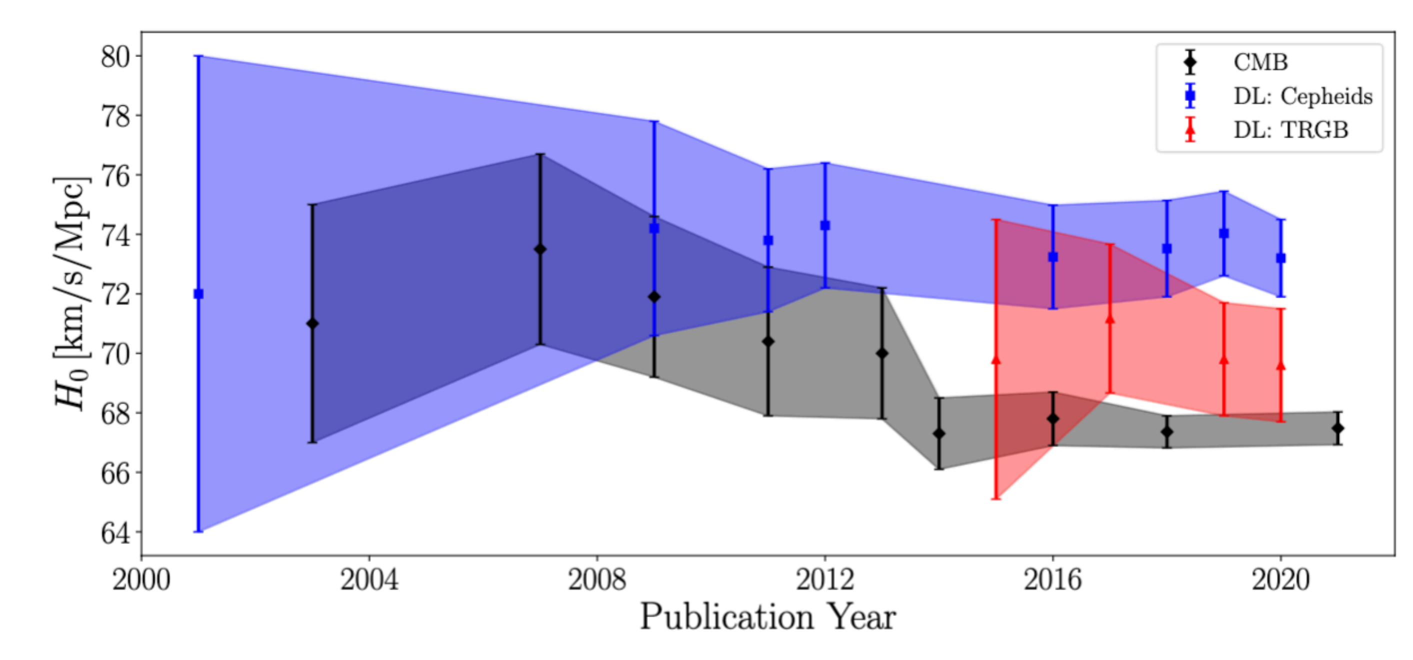


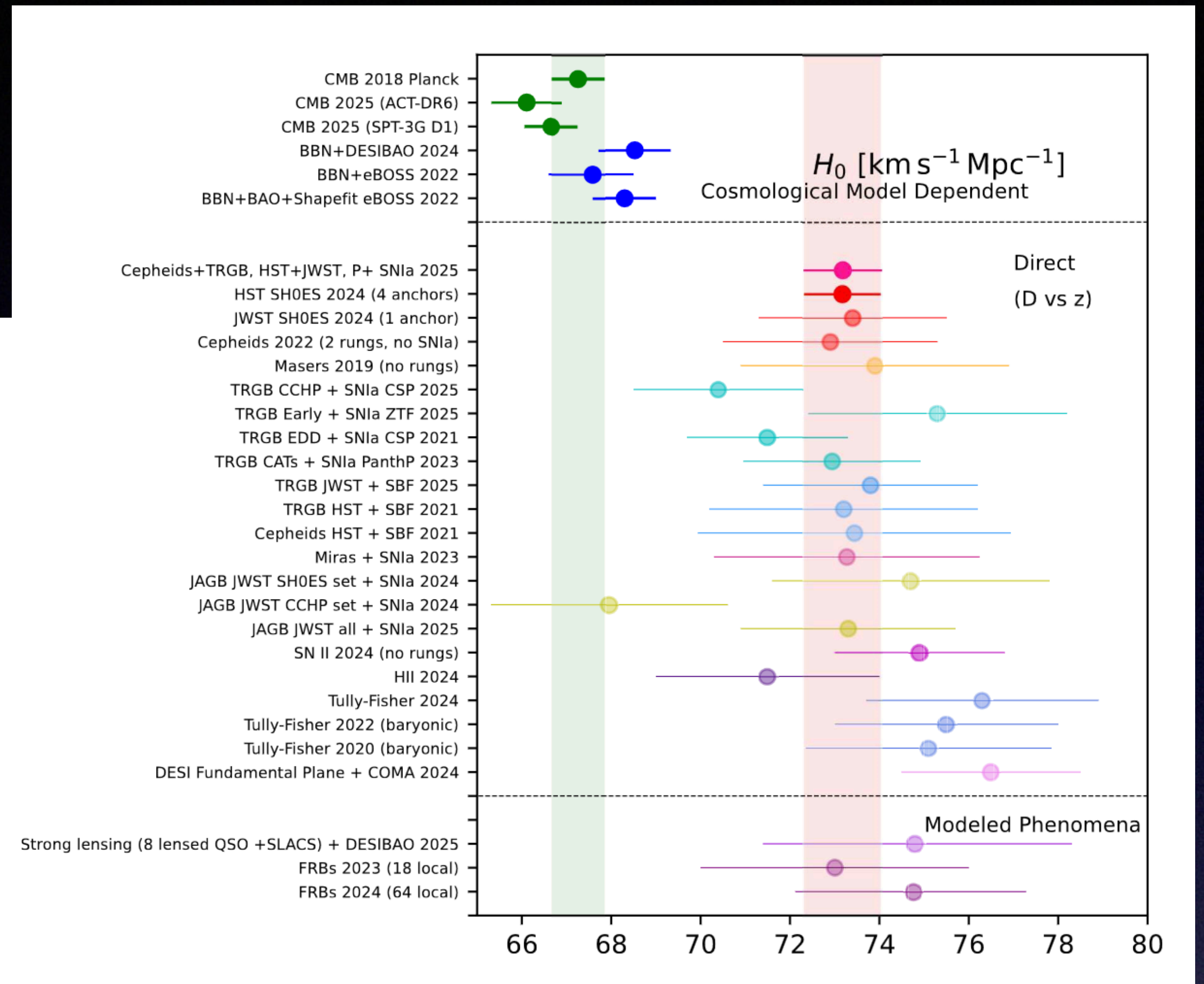
DESI's huge 3D map to study dark energy.
Earth is at the center of this map, and every point is one galaxy among 47 millions of galaxies and quasars.

ΛCDM tensions and new physics at the corner ?

Severe tensions in

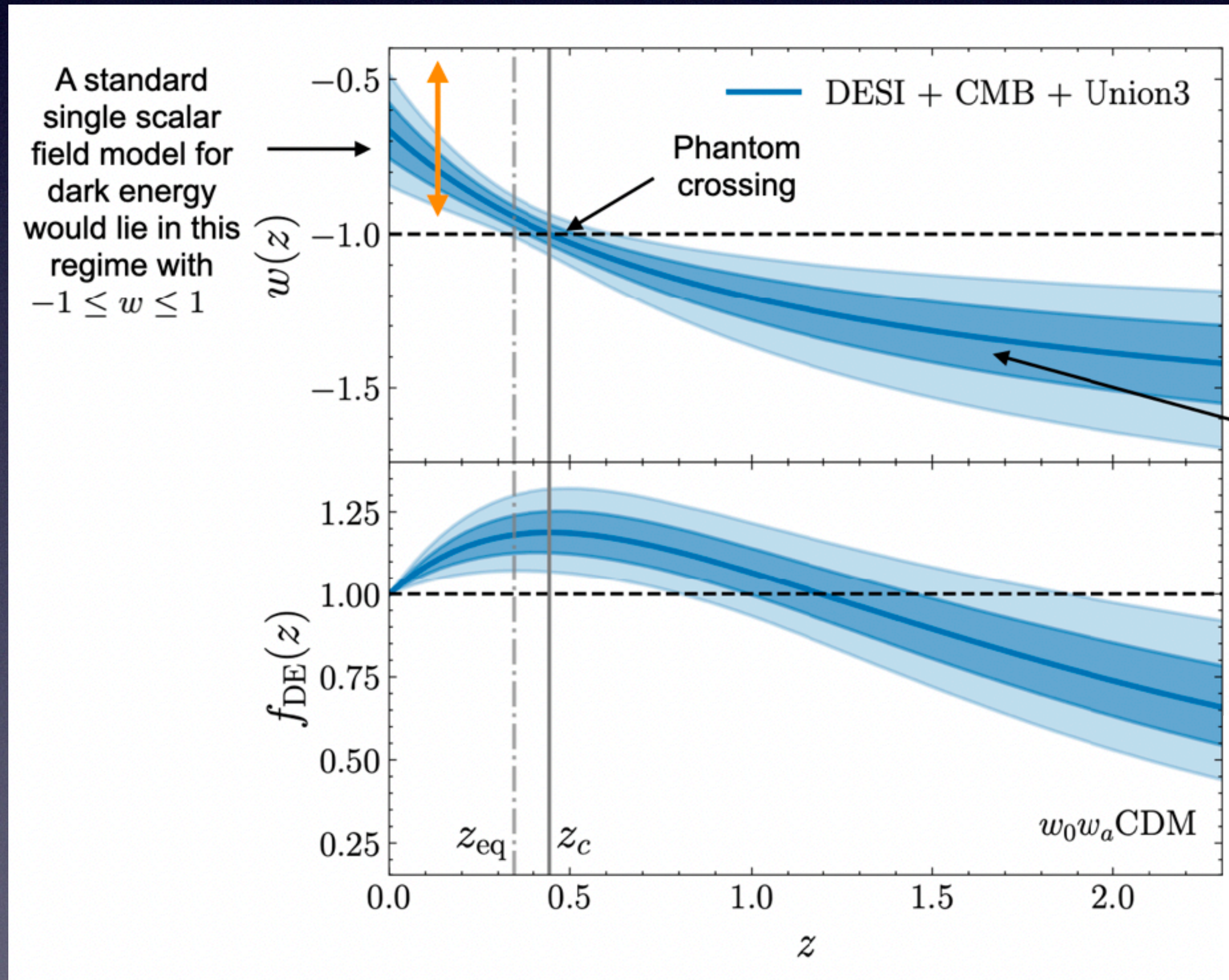
H_0





DESI (2025) :
dark energy vary with time

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



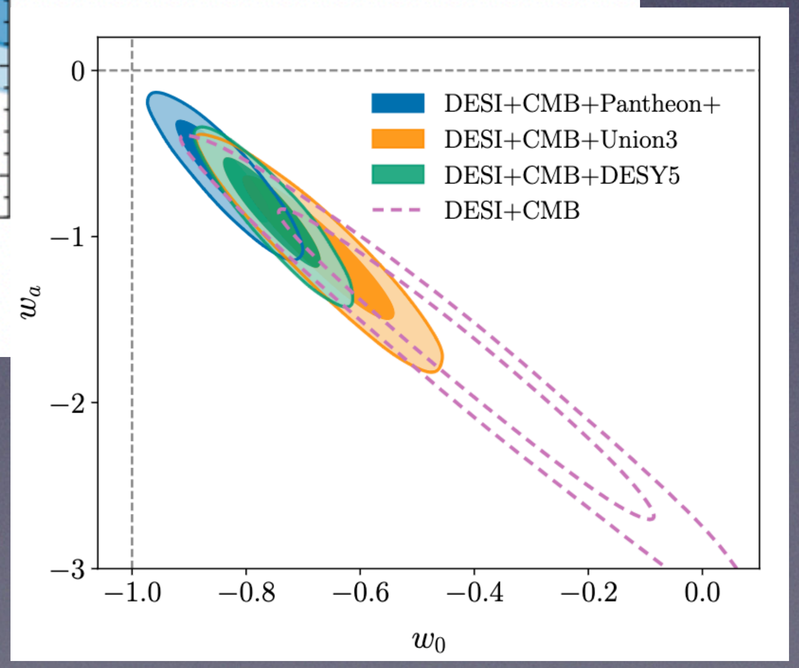
A standard single scalar field model for dark energy would lie in this regime with $-1 \le w \le 1$

Phantom crossing

ΛCDM assumes $w = -1$

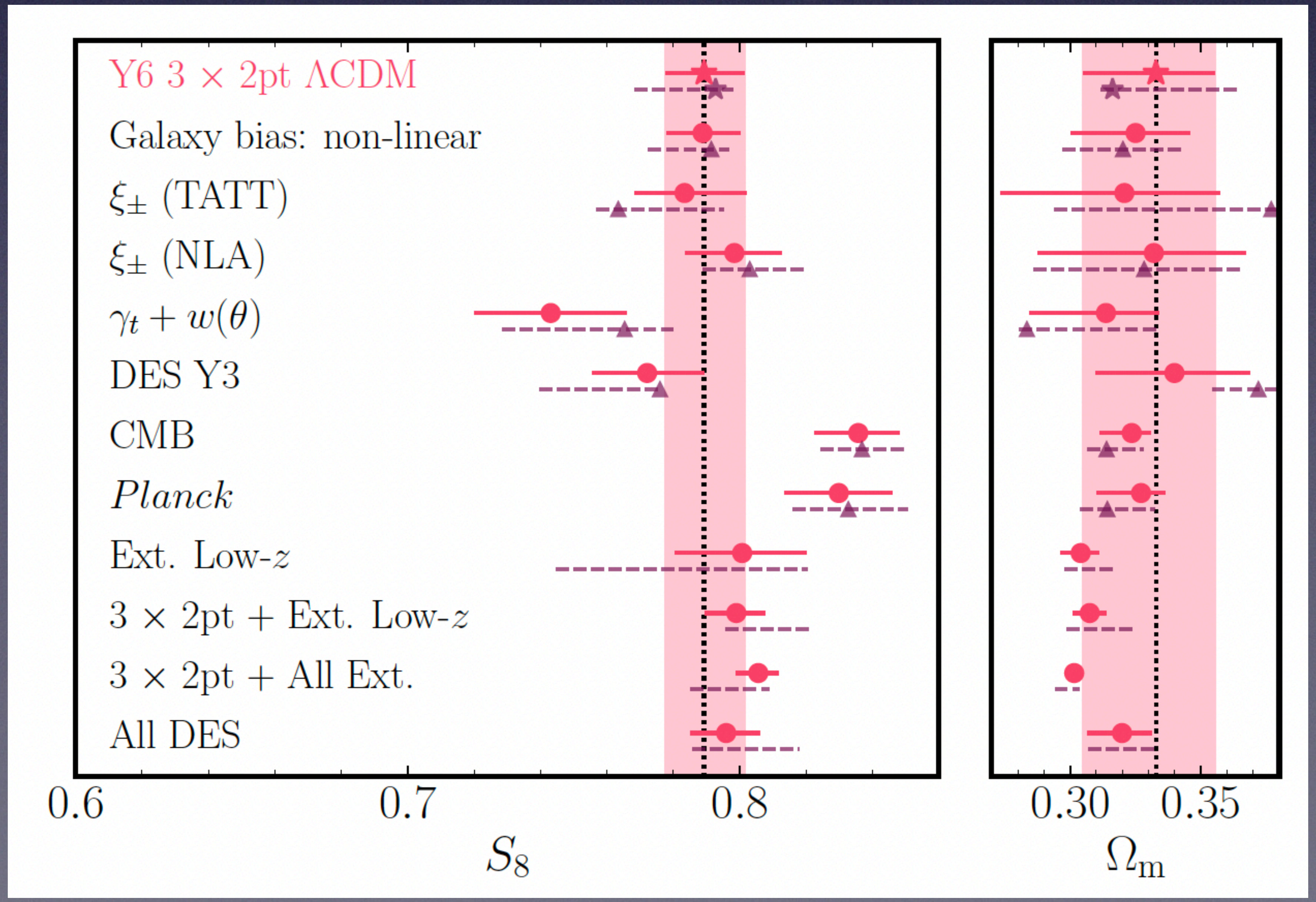
This phantom phase suggests a more complex type of dark energy

$$f_{\rm DE}(z) \equiv \frac{\rho_{\rm DE}(z)}{\rho_{\rm DE,0}} = \exp\left[3\int_0^z [1 + w(z')]\frac{dz'}{1+z'}\right].$$



Mild tensions in DM clustering

S_8, Ω_m



DESI DR2 Key Findings with BAO

✅ **ΛCDM is under pressure:** Dark energy appears dynamic and may have crossed a "phantom" phase ($w(z) < -1$).

✅ **Dark matter may not be so simple:** Interactions with dark energy or a multi-component composition (CDM + WDM) are possible.

✅ **No single model resolves all tensions:** We will likely need to combine multiple extensions (dynamic dark energy + curvature + interactions).

✅ **The coming years will be crucial:** DESI DR3, Euclid, Rubin, should confirm or refute these results by 2028.

→ We may be on the verge of a post-ΛCDM era, where the complexity of the dark sector becomes the norm.

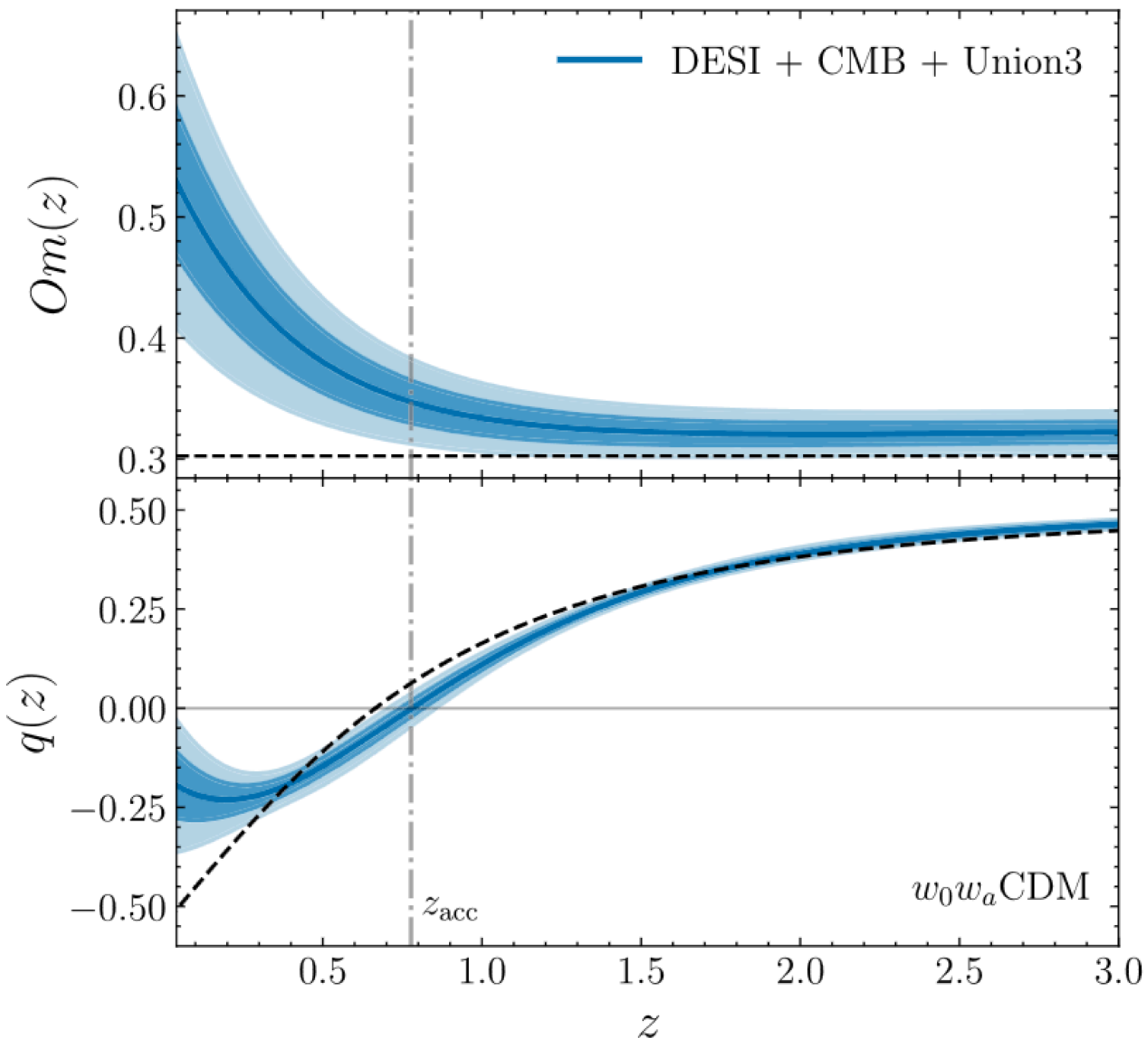
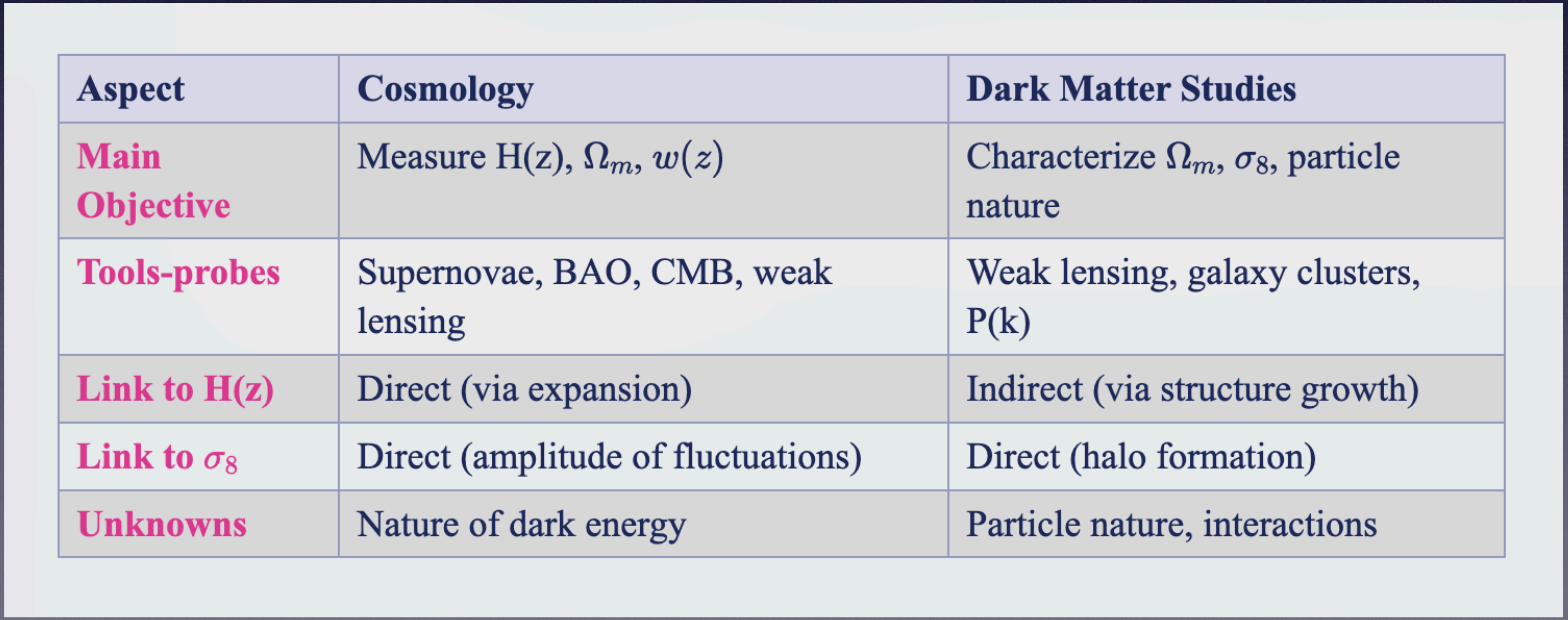


FIG. 3. Evolution of the $Om(z)$ diagnostic and deceleration parameter, $q(z)$, as a function of redshift in the w_0w_aCDM model. The solid blue lines correspond to the median, 68%, and 95% confidence levels obtained from the DESI + CMB + Union3 combination. The black dashed line depicts the best-fit ΛCDM for the same data combination. The gray vertical line shows the redshift ($z_{\rm acc}$) corresponding to the onset of cosmic acceleration ($\ddot{a} > 0$).

Respective Goal of cosmology/Dark Matter

- Cosmology and dark matter studies are **two sides of the same coin**:
  - Cosmology **measures** the expansion and structure growth of the Universe.
  - Dark matter studies **explore** the invisible building blocks shaping cosmic structures.
- Tensions between observations (e.g., galaxy surveys vs. CMB H_0, σ_8 measurements) $\longrightarrow$ **beyond the ΛCDM model**.

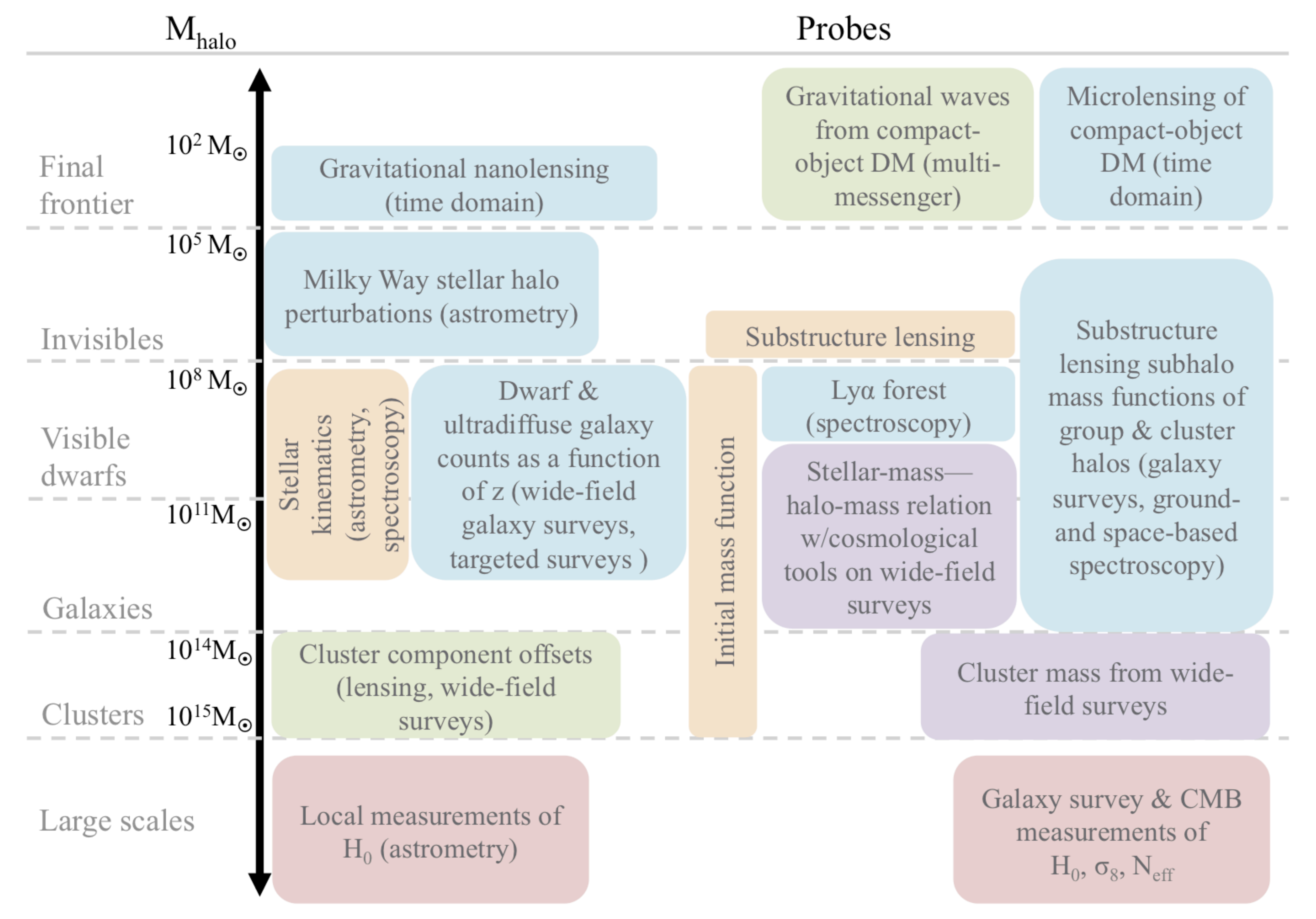


Aspect	**Cosmology**	**Dark Matter Studies**
Main Objective	Measure H(z), Ω_m, $w(z)$	Characterize Ω_m, σ_8, particle nature
Tools-probes	Supernovae, BAO, CMB, weak lensing	Weak lensing, galaxy clusters, P(k)
Link to H(z)	Direct (via expansion)	Indirect (via structure growth)
Link to σ_8	Direct (amplitude of fluctuations)	Direct (halo formation)
Unknowns	Nature of dark energy	Particle nature, interactions

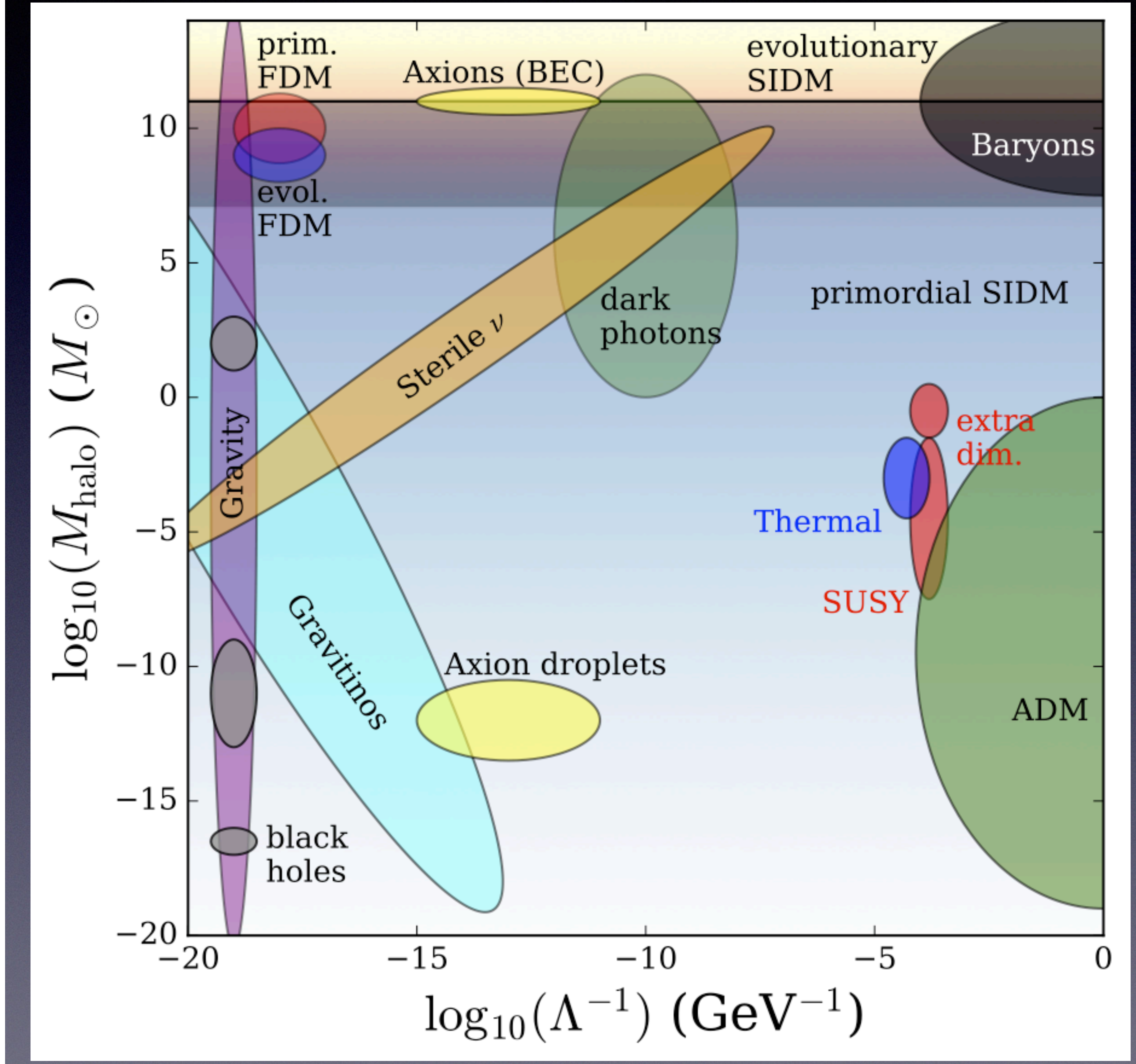
For discussion Only

Note : Sensitivity to DM models wrt Halo mass

Differents cosmological probes vs halo mass



Halo mass vs DM particle-particle coupling parameter Λ^{-1}



https://www.physicsmatt.com/blog/2017/12/18/paper-explainer-gravitational-probes-of-dark-matter-physics

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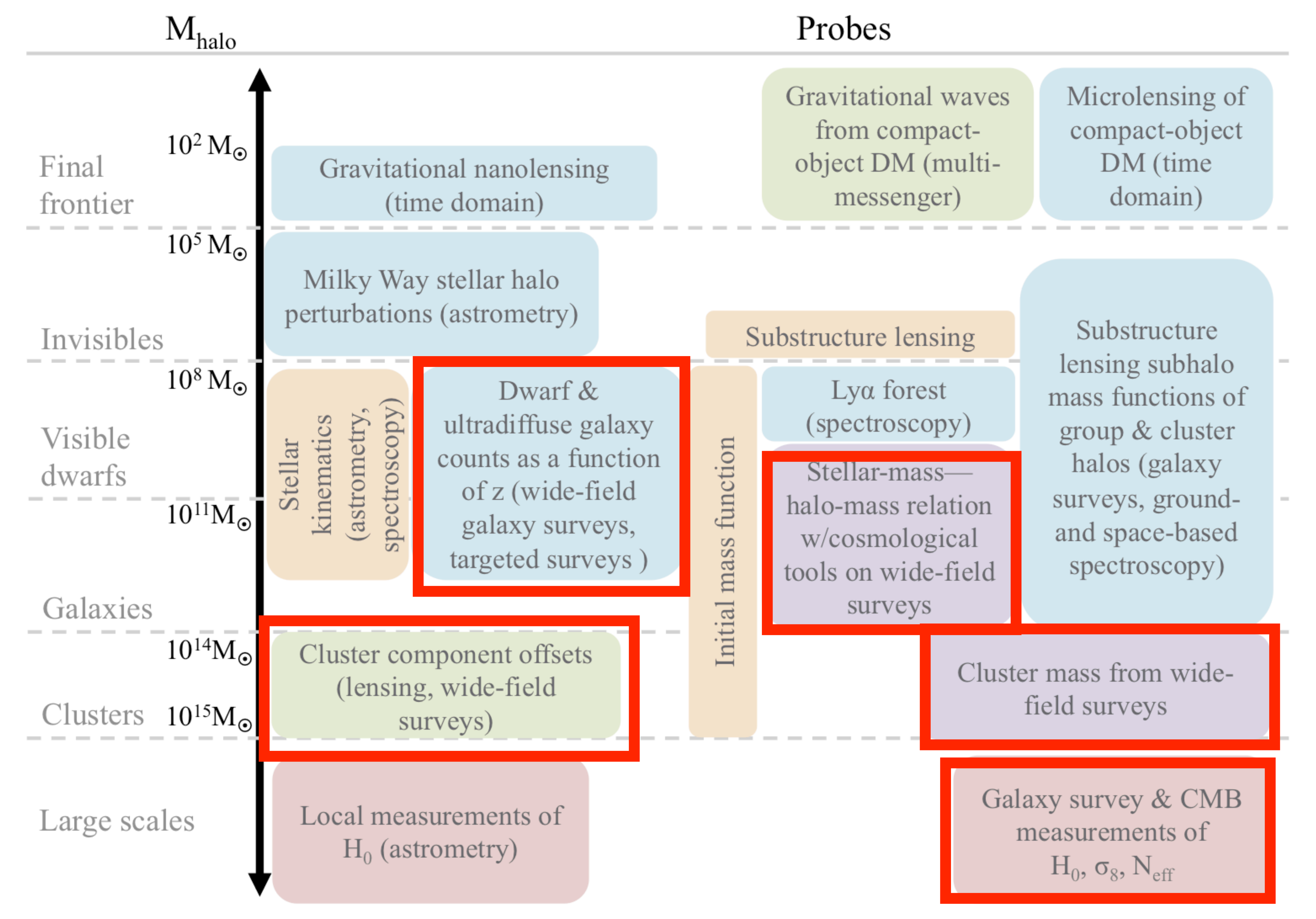

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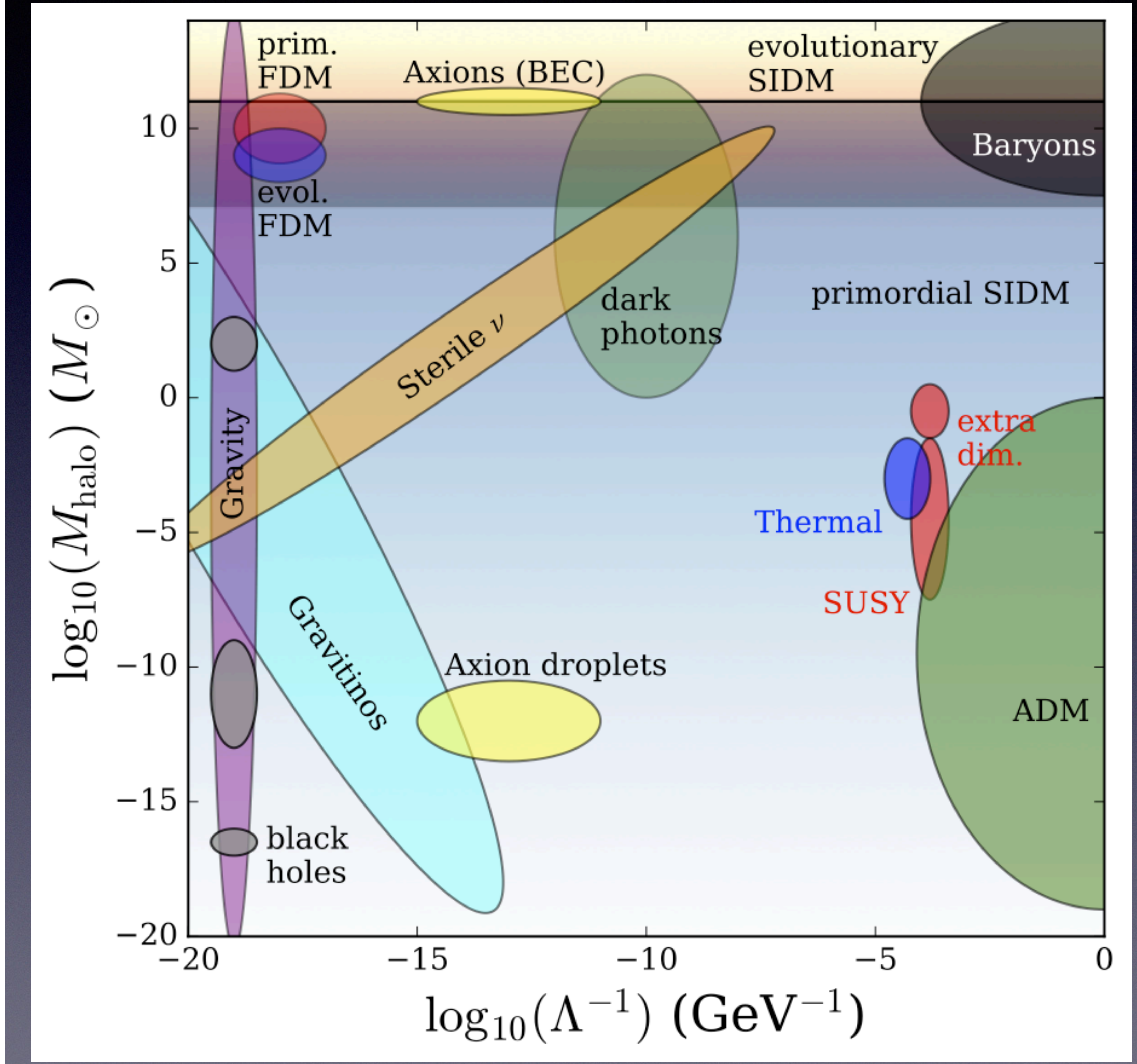

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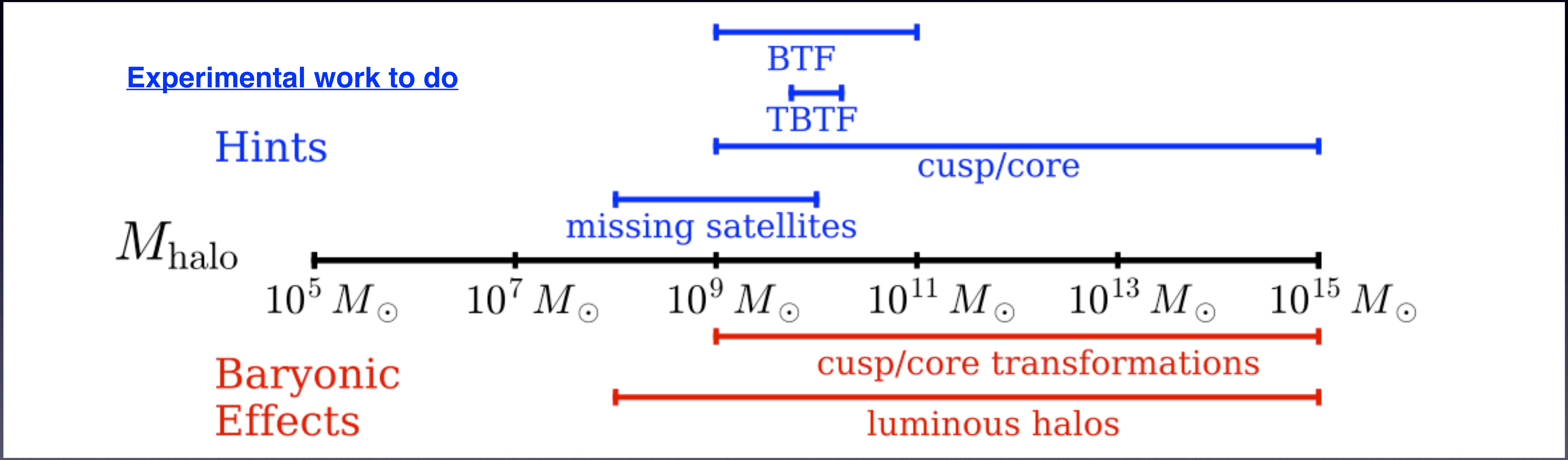
What kind of galaxies & clusters to search for DM



A summary of the hints for deviations from predictions of cold dark matter at particular halo mass scales (BTF is "baryonic Tully-Fisher relation" and "TBTF" is "too Big to Fail. »), compared to the halo masses where baryonic effects are expected to exist and must be correctly accounted for.

https://www.physicsmatt.com/blog/2017/12/18/paper-explainer-gravitational-probes-of-dark-matter-physics