Understanding Dark Energy

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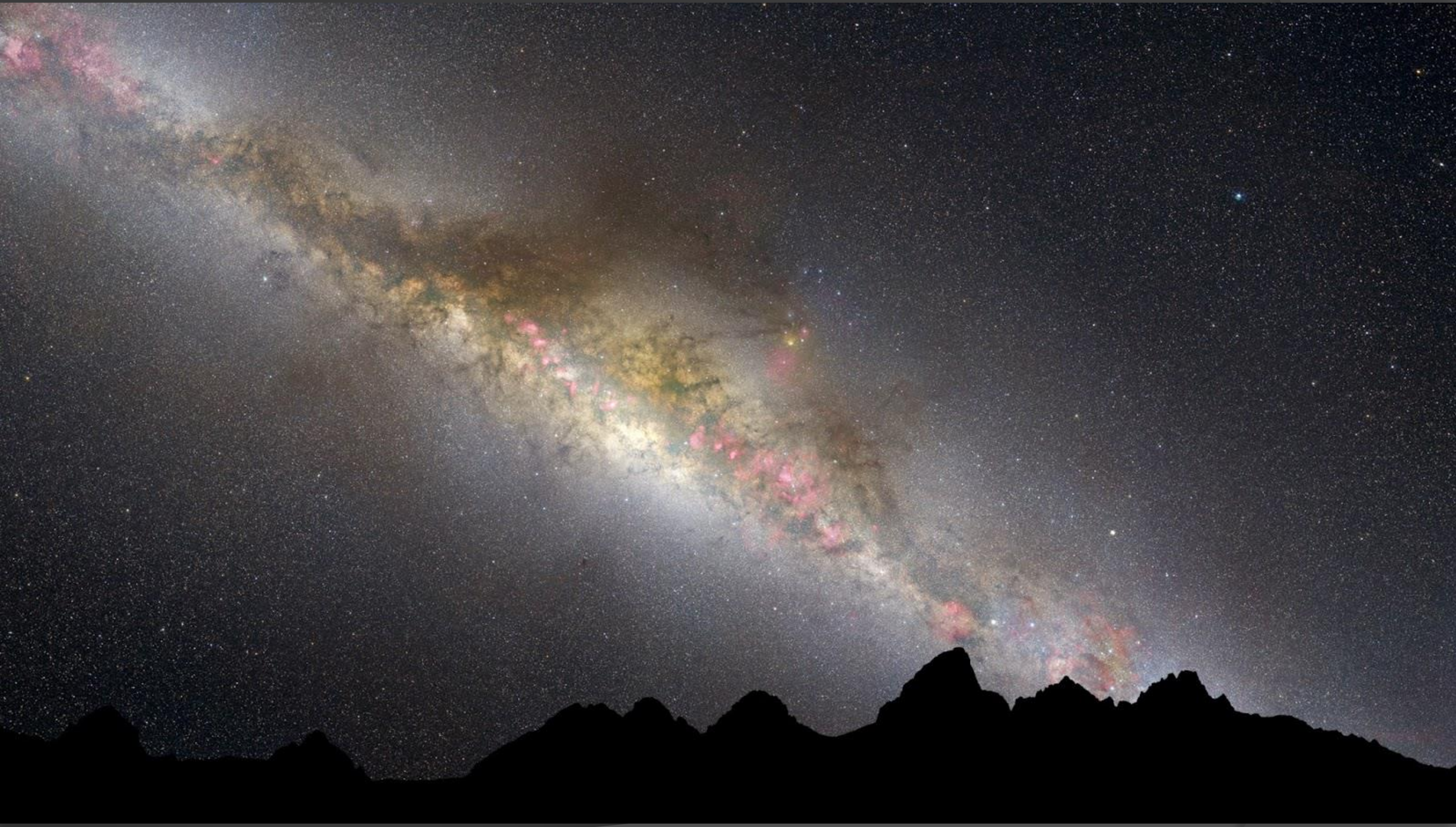
Making Sense of the Sky

Image credit: NASA and ESA



Making Sense of the Sky

- Metric $g_{\mu\nu}$ to define distances/causality

- Geodesic motion for light

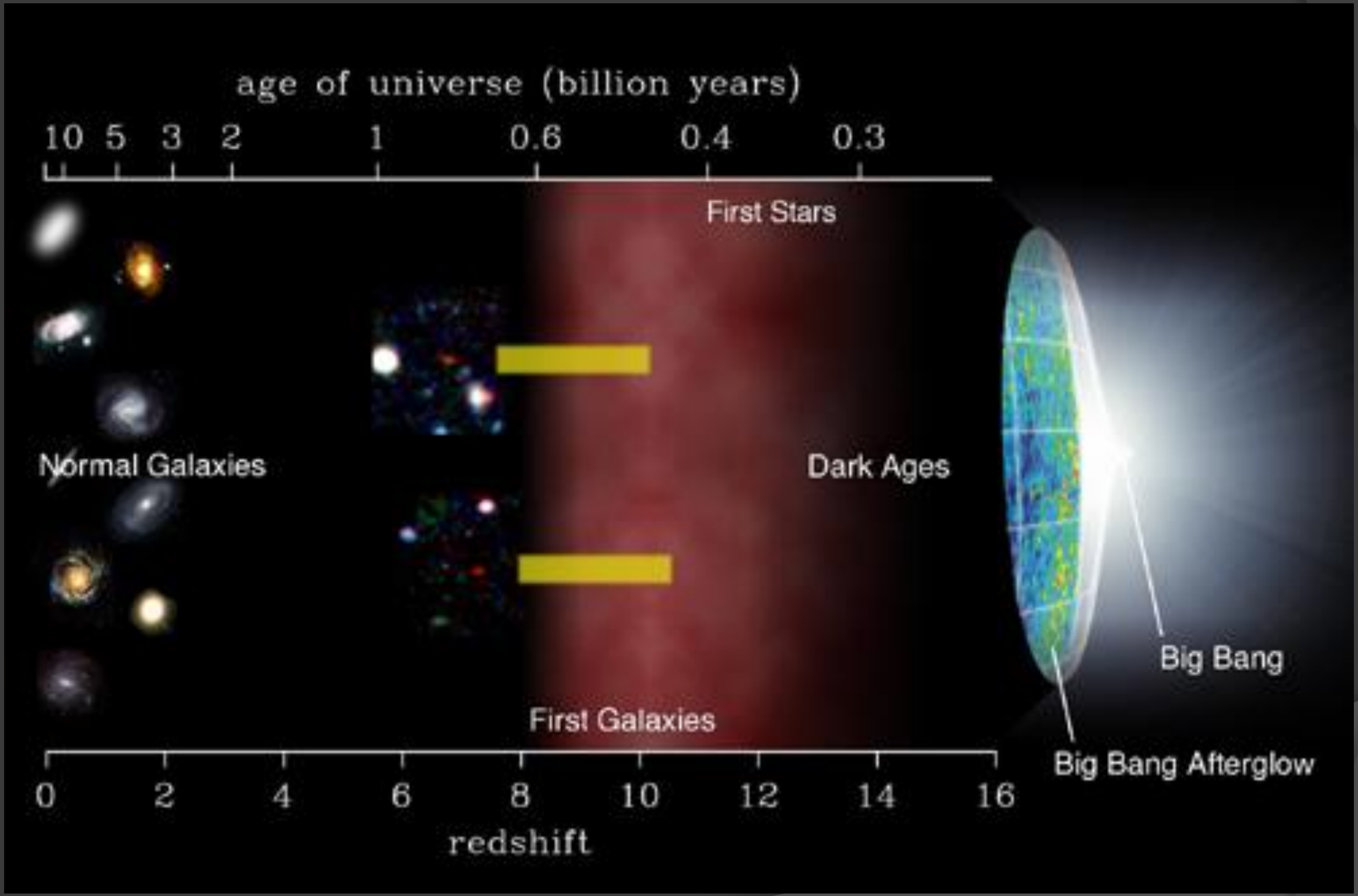
$$k^\alpha \nabla_\alpha k^\mu = 0 \qquad \frac{u^\mu_{\mathrm{em}} k_\mu}{u^\mu_{\mathrm{obs}} k_\mu} = \frac{\omega_{\mathrm{em}}}{\omega_{\mathrm{obs}}} \equiv 1 + z$$

- Distances: corrected by gravitational field
  - *Luminosity* $F = L/4\pi d_{\mathrm{L}}^2$
  - *Angular diameter* $\theta = \ell/d_{\mathrm{A}}$

$$d_{\mathrm{L}} = (1+z)^2 d_{\mathrm{A}}$$

Ordering by redshift

Image credit: Ivo Labbé



Use Standard Candles to Map

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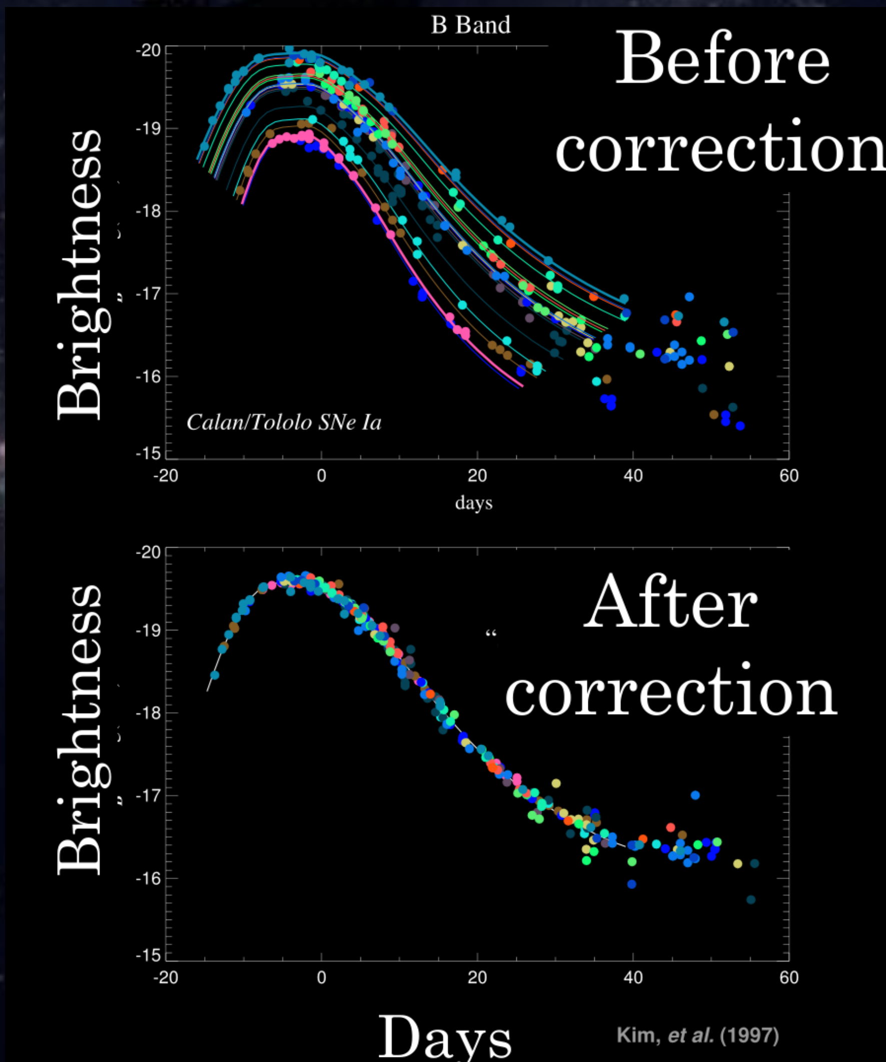


- Broader is intrinsically brighter
- Standardise to some (unknown) intrinsic luminosity
- Obtain luminosity distance as function of redshift $d_{\mathrm{L}}(z)$
- To interpret *need a model*
  - Gravity
  - Composition

SN 2011fe

First Attempt at Model

- Copernican Principle: *here* is *not* special
  - Universe grossly *homogeneous* and *isotropic*

$$\mathrm{d}s^2 = \mathrm{d}t^2 - a^2(t)\delta_{ij}\mathrm{d}x^i\mathrm{d}x^j$$

- Gravity is *General Relativity*

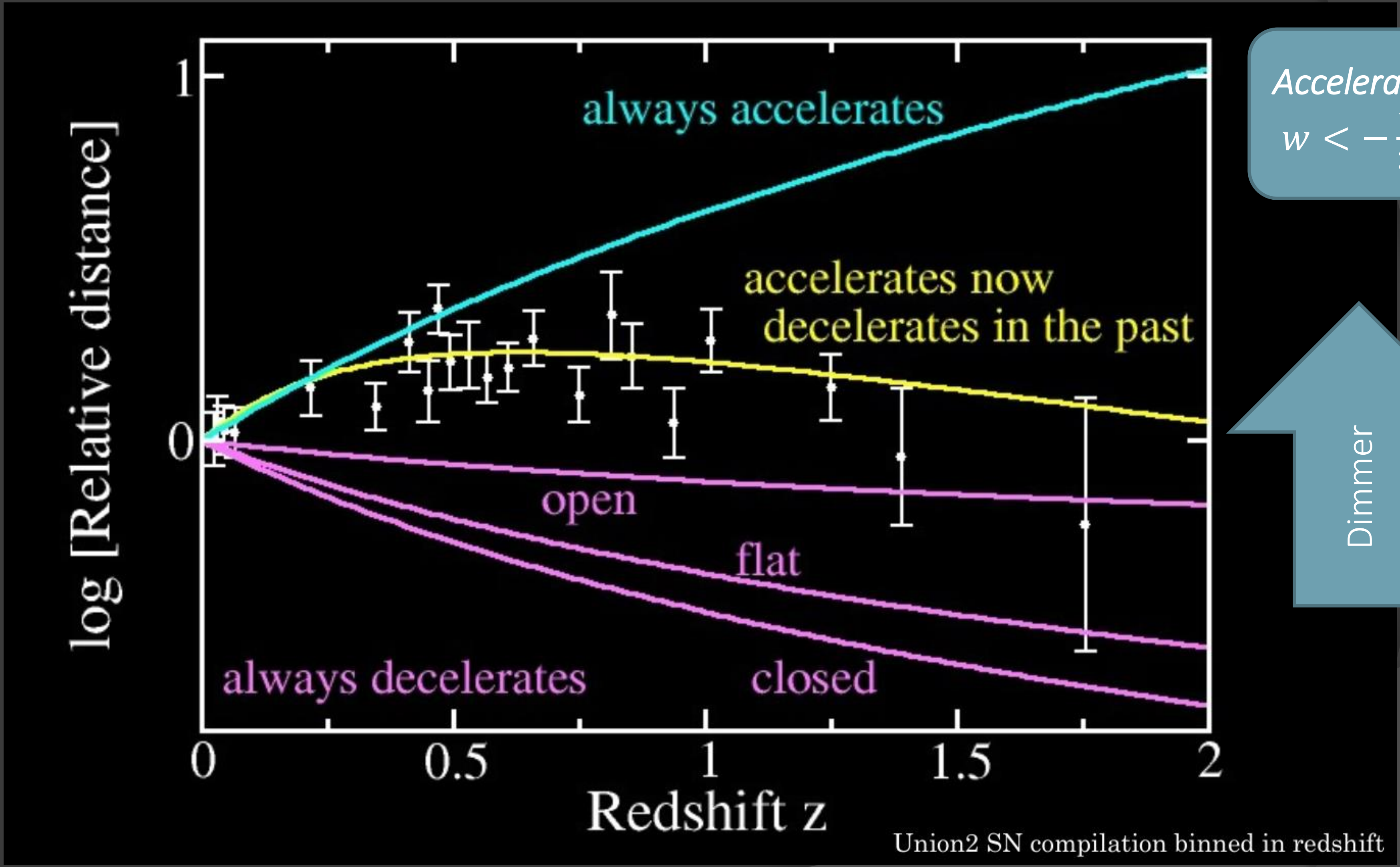
$$H^2 \equiv \frac{\dot{a}}{a} = \frac{8\pi G_\mathrm{N}}{3}\rho \qquad d_\mathrm{L} = (1+z)\int\frac{\mathrm{d}z}{H(z)}$$

- Matter *non-relativistic*

$$w \equiv \frac{p}{\rho} \approx 0 \qquad \rho \propto a^{-3}$$

First Attempt at Model: FAIL

From D. Huterer



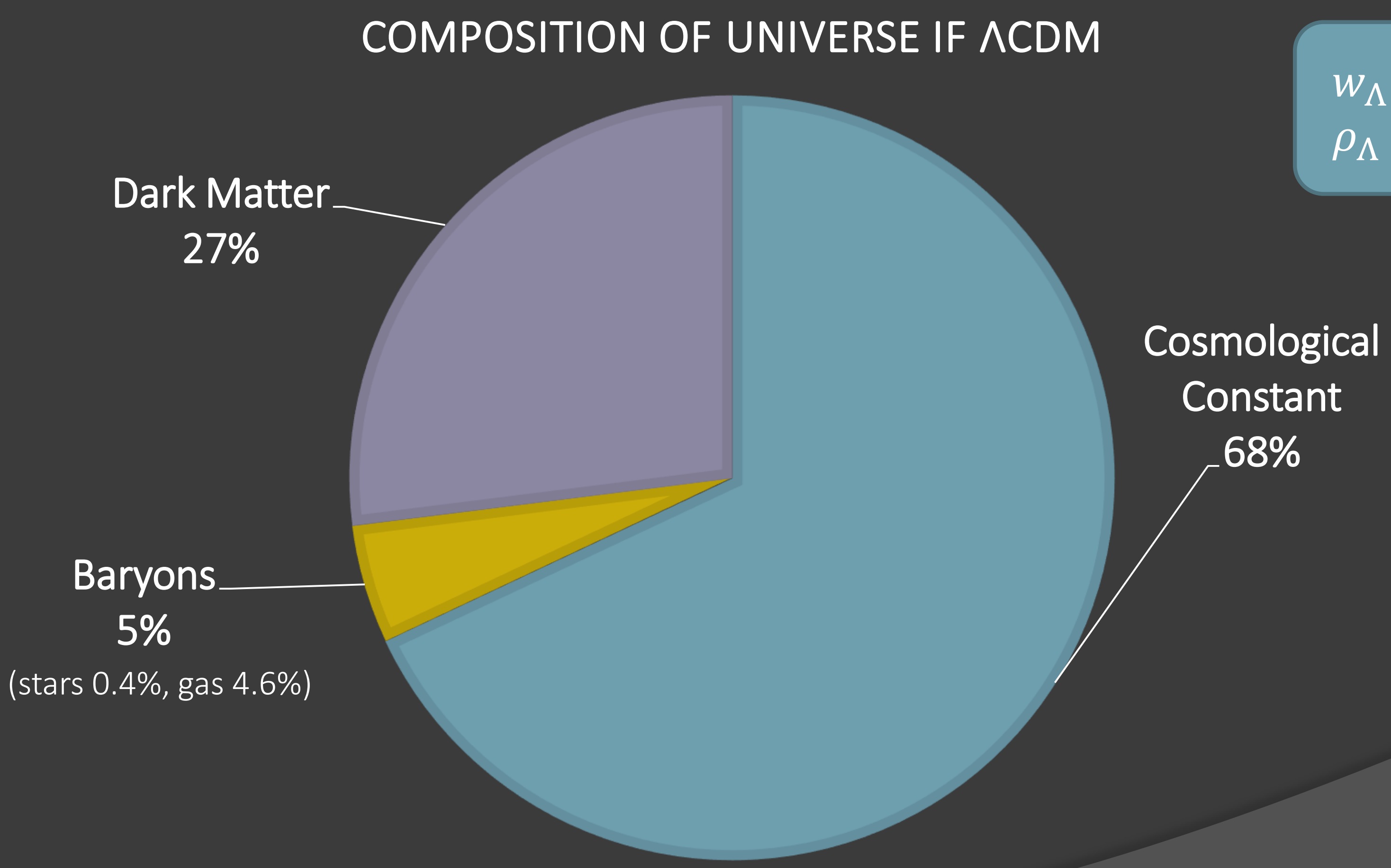
Acceleration
$w < -\frac{1}{3}$

Dimmer

Second Attempt: ΛCDM ⇒ NOBEL

Planck 2015

$w_\Lambda = -1$
$\rho_\Lambda = \text{const}$



Is the Universe fooling us?

- Light dims/SNe evolve (*"tired light"*)
  - ***d_A matches d_L***: photons conserved (BAO)
- Here is special (*"inhomogenous universe"*)
  - Distant clusters do not see anisotropic sky (kSZ)
- Non-linear fluctuations (*"averaging problem"*)
  - True, but no prescription gets more than 0.1% effect

Is the Universe fooling us?

Acceleration
detected at 64σ

But is it actually Λ?

$$\frac{M_\Lambda}{M_{\mathrm{weak}}} \sim 10^{-16}$$

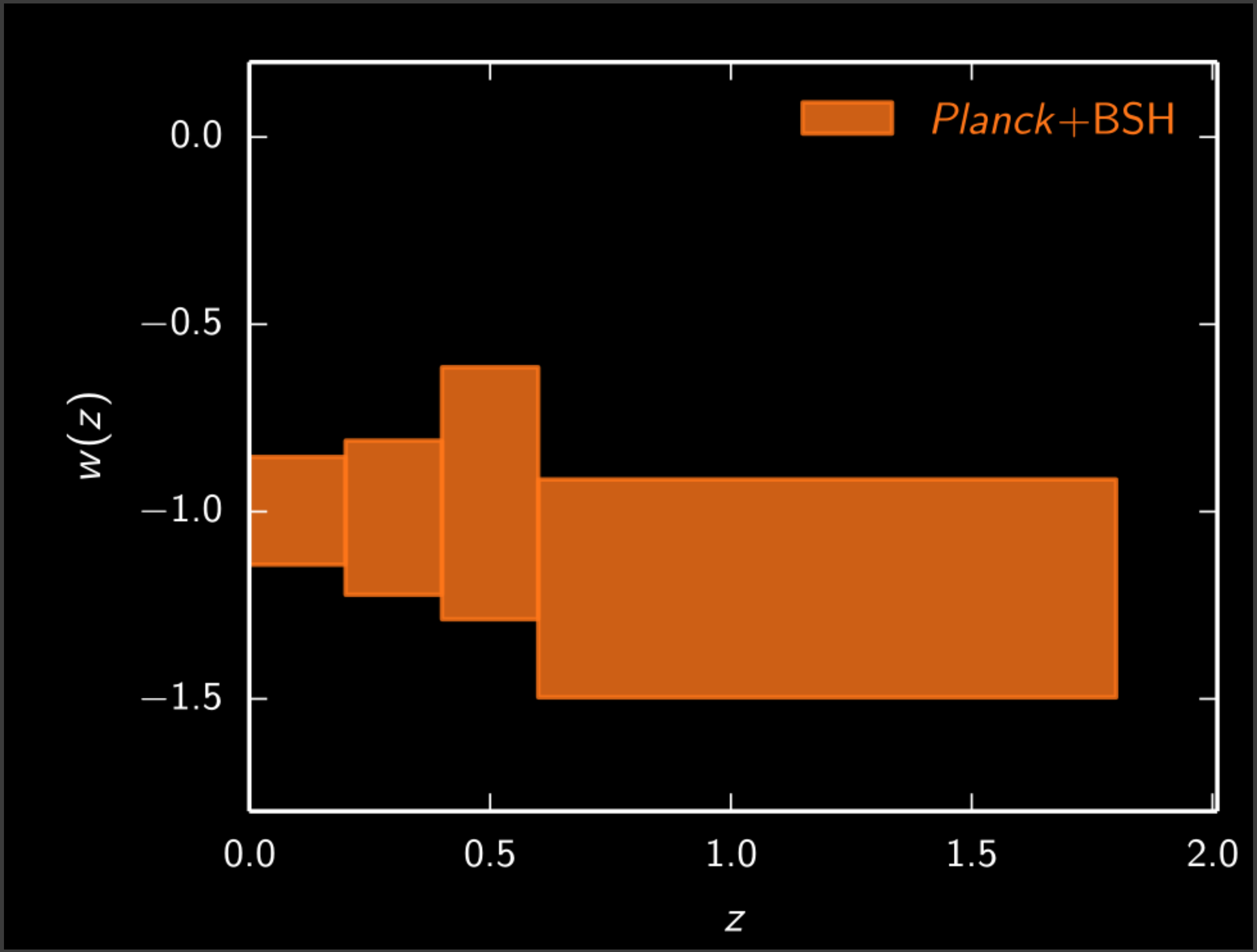
- Old c.c. problem: *new* fine-tuning at every order
- Coincidence problem: $\rho_\Lambda \sim 2\rho_{\mathrm{m}}$
- Wishful thinking

$$n_{\mathrm{s}} - 1 = -{}^{1}/_{4}\,(1 + w) = -0.0333 \pm 0.0040$$

Alternatives to Λ must be *dynamical*:
search for time- and scale-dependence

ΛCDM as Null Hypothesis

Planck 2015

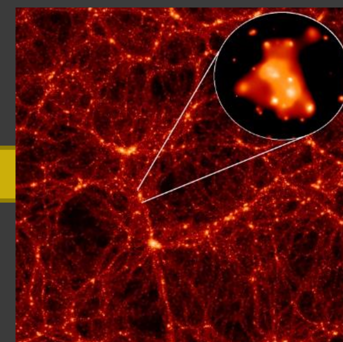


Background close to ΛCDM

CMB is Gravitational Collapse

Initial conditions (inflation)

Photon decoupling, $T = T_{\mathrm{dec}}$

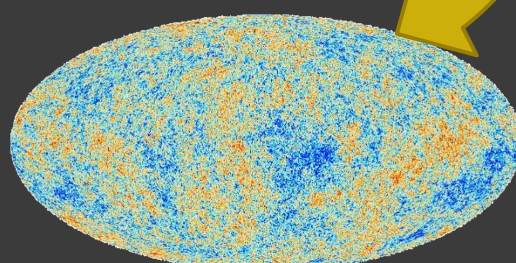


Galaxy formation

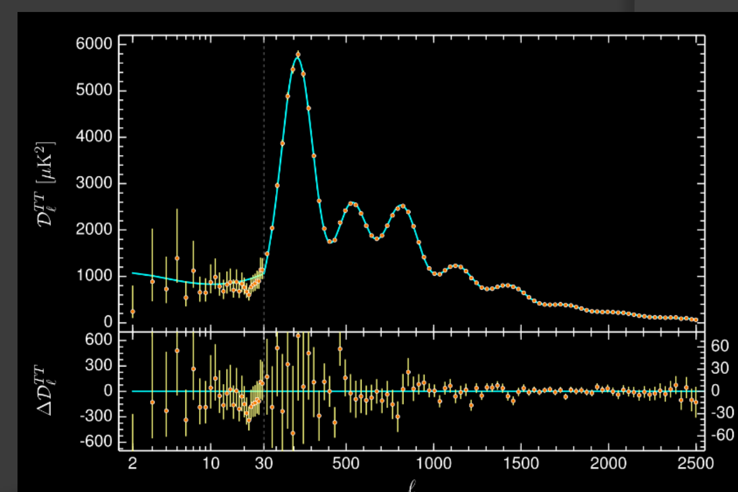
gravitational collapse

Vacuum in
quasi-de Sitter

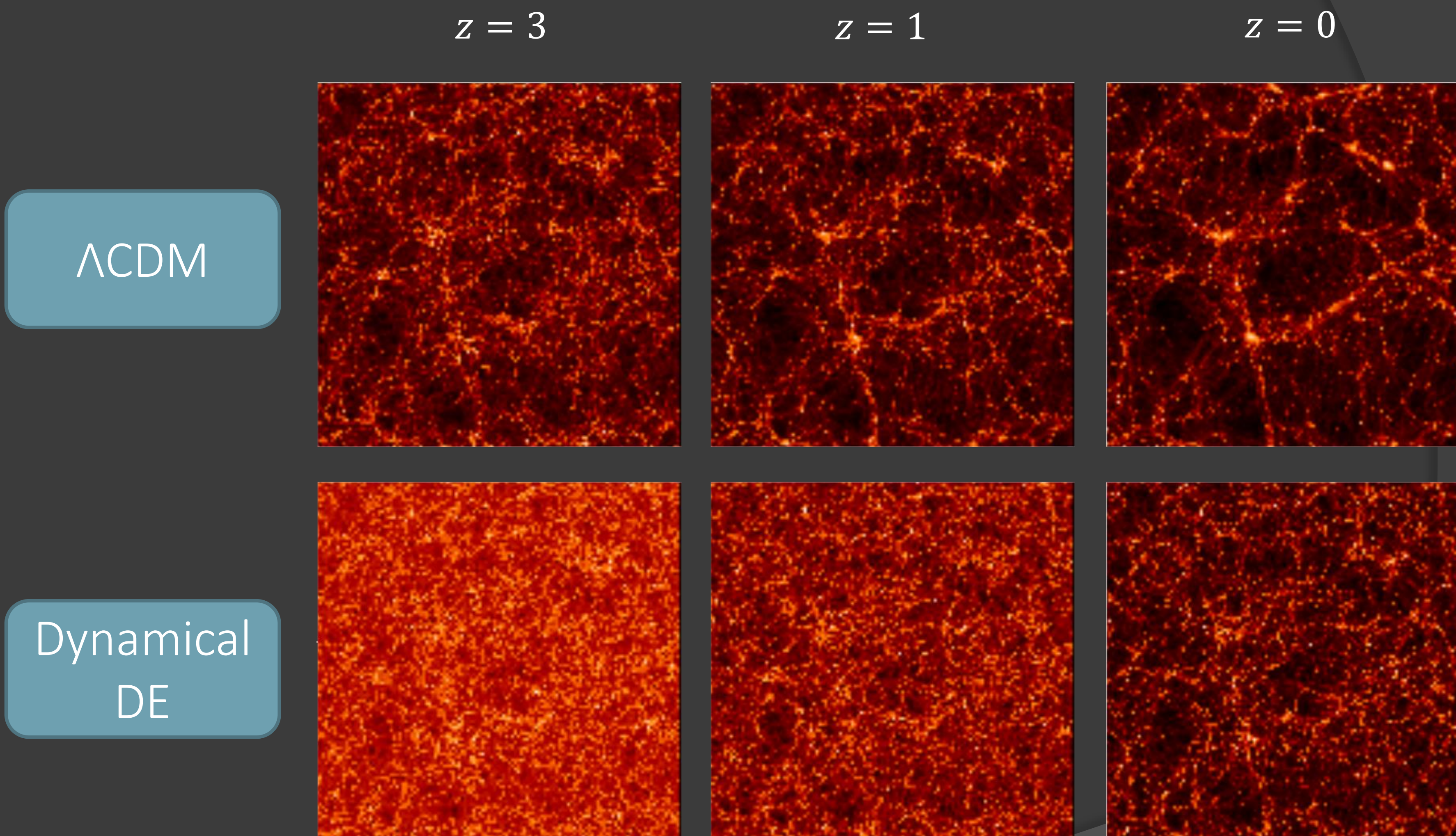
(nearly) scale
invariant Gaussian
fluctuations



Planck 2015



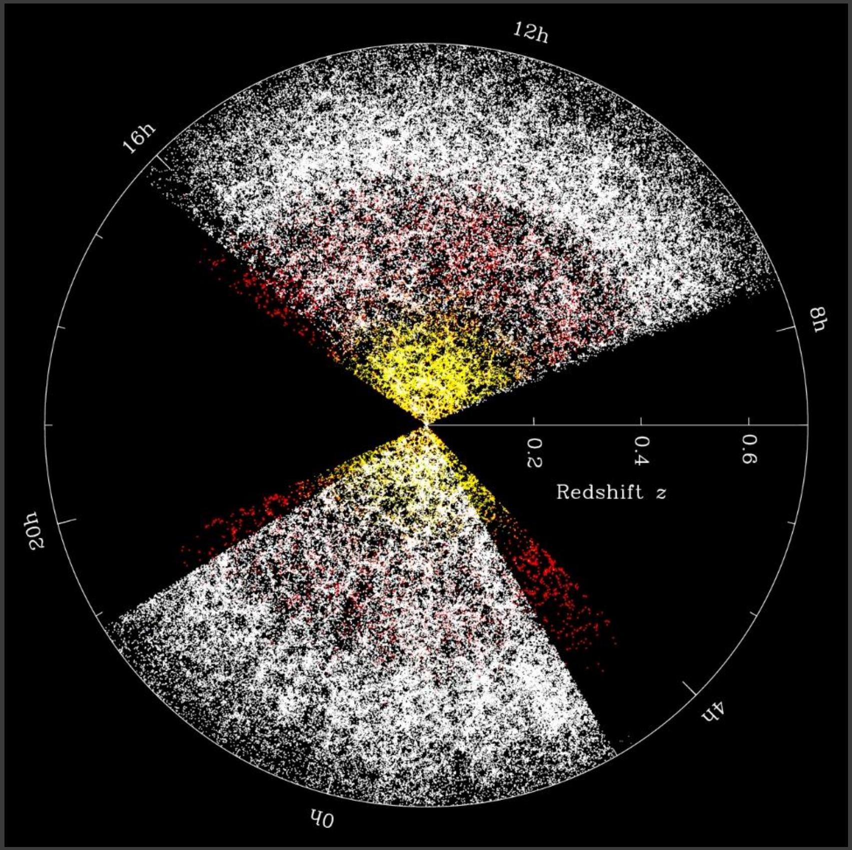
Dark Energy Changes Growth



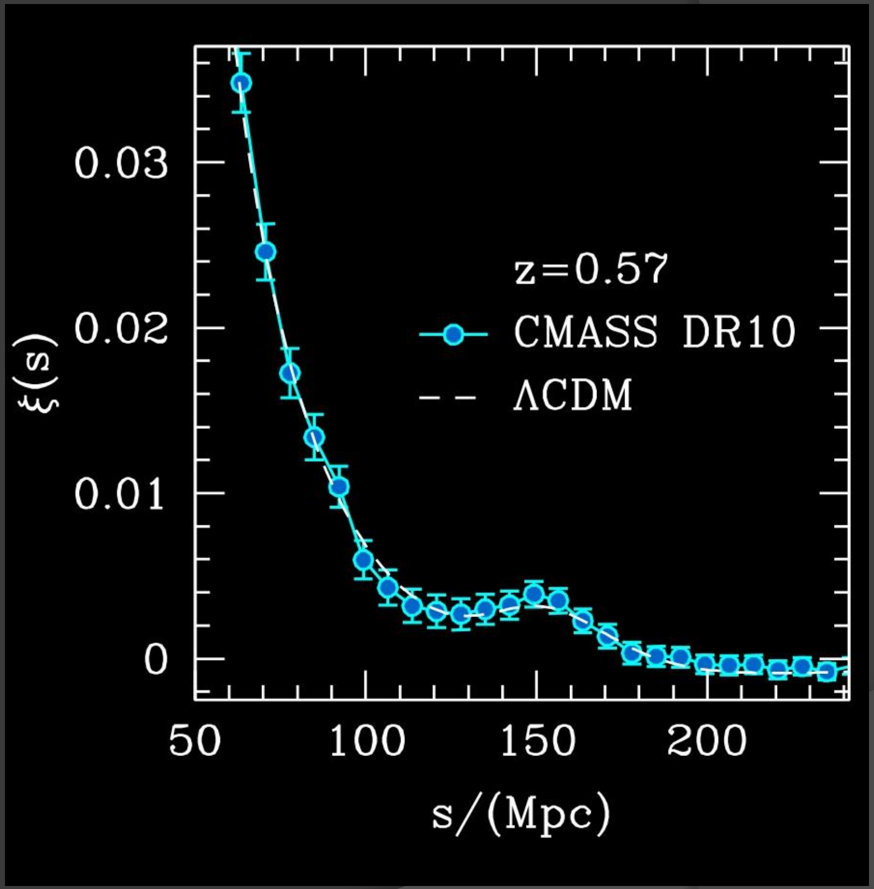
Snowmass Report
1309:5385

Use Structure to Probe Gravity/DE

SDSS/BOSS



SDSS/BOSS DR10



2500 deg^2 up to $z = 0.7$

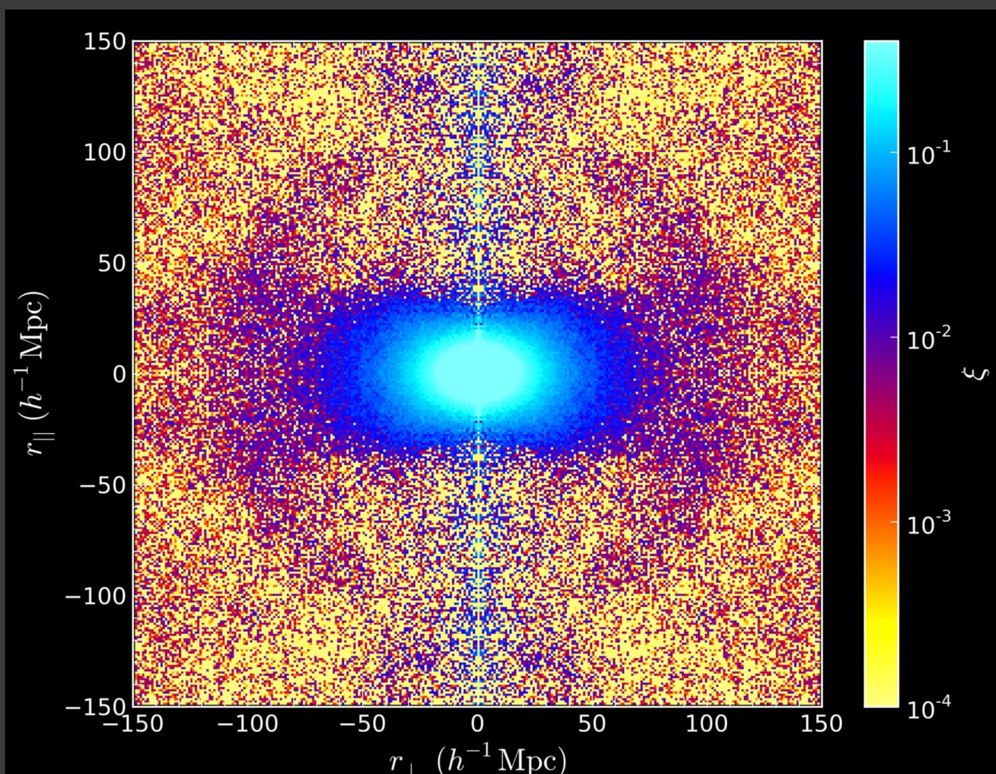
Redshift-Space Distortions

Kaiser (1985)

Real space

Redshift space

Samushia et al. (2013)/BOSS



Monopole:

$$\langle \delta_{\mathrm{g}} \delta_{\mathrm{g}} \rangle = b^2 \langle \delta_{\mathrm{m}} \delta_{\mathrm{m}} \rangle$$

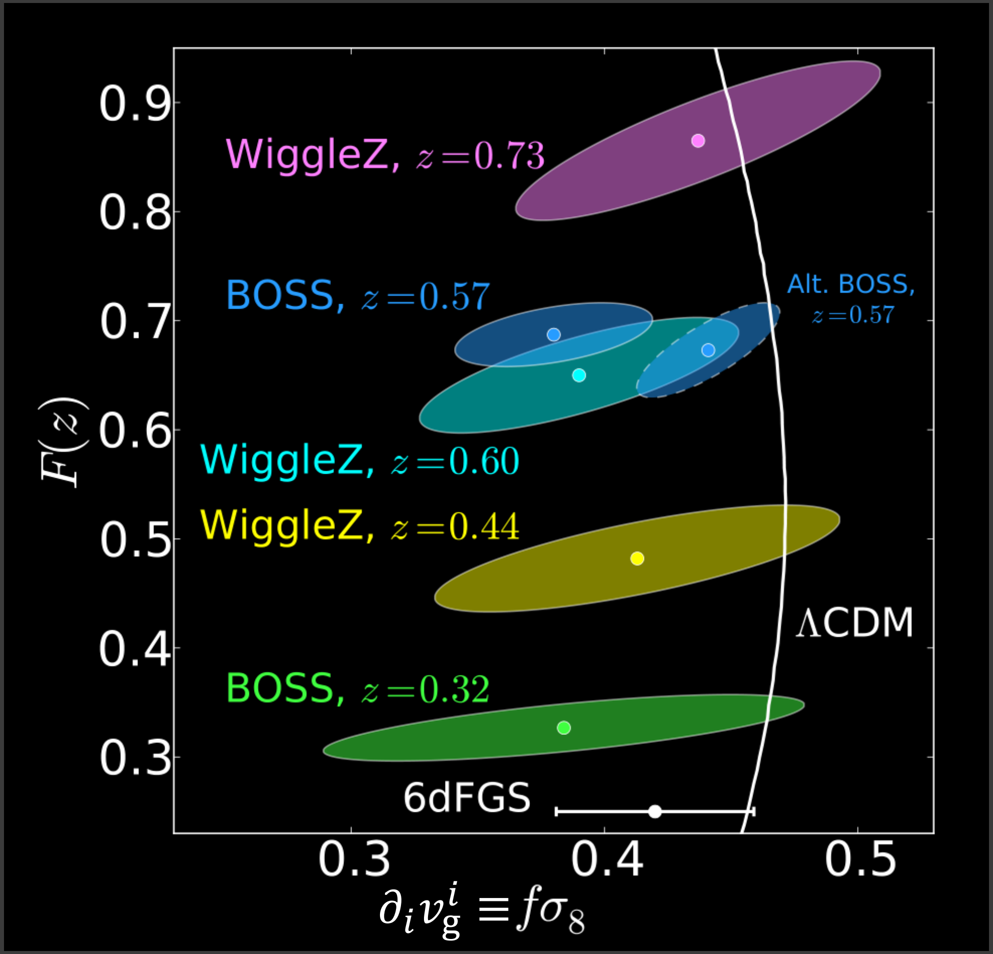
Quadrupole:

$$\langle \partial_i v_{\mathrm{g}}^i\, \delta_{\mathrm{g}} \rangle$$

$$\dot{v}_{\mathrm{g}}^i = \dot{v}_{\mathrm{m}}^i = \partial_i \Psi$$

Redshift-Space Distortions

Ruiz & Huterer (2014)

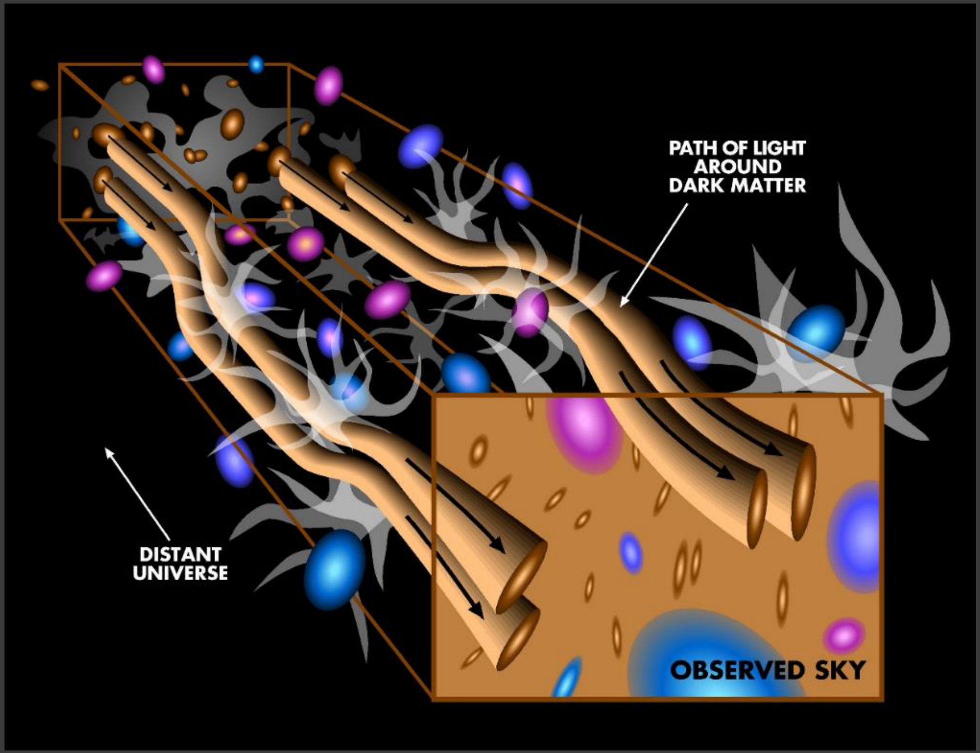


- Galaxy velocities tend to be lower than ΛCDM would imply

$$\dot{v}_{\rm g}^i = \dot{v}_{\rm m}^i = \partial_i \Psi$$

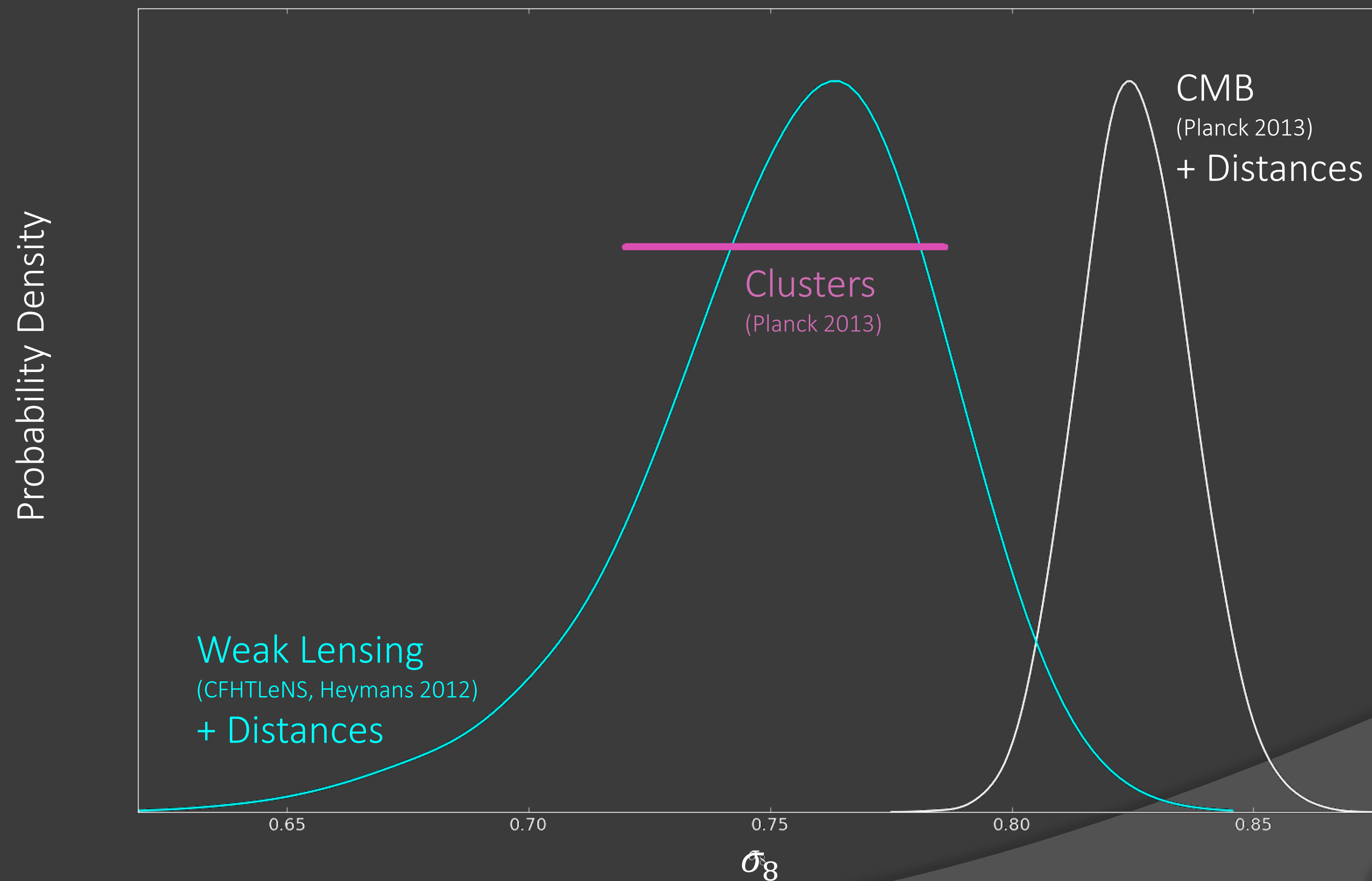
Weak Lensing

$$ds^2 = -(1 + 2\Psi)dt^2 + a^2(t)(1 - 2\Phi)d\boldsymbol{x}^2$$



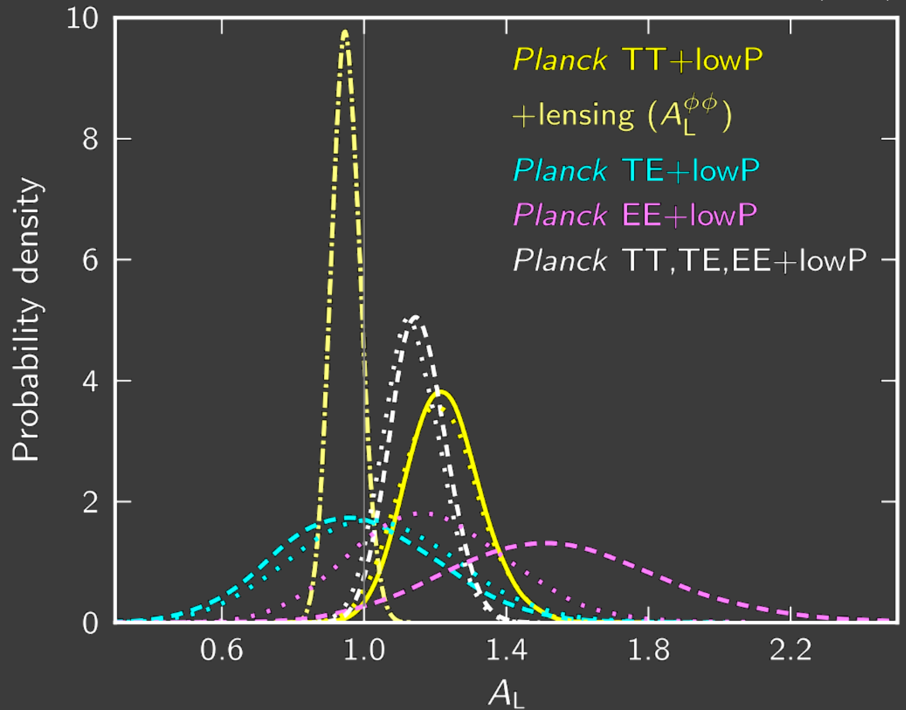
$$\sigma_{ij} = \int_{z_s}^{z_o} dz\, \partial_i \partial_j (\Psi + \Phi) K(z, z_s)$$

Is everything OK with ΛCDM?



CMB Lensing: Smooths Peaks

Planck: Ade et al. (2015)



$$\varphi_{\text{lens}} \equiv A_L(\Phi + \Psi)$$

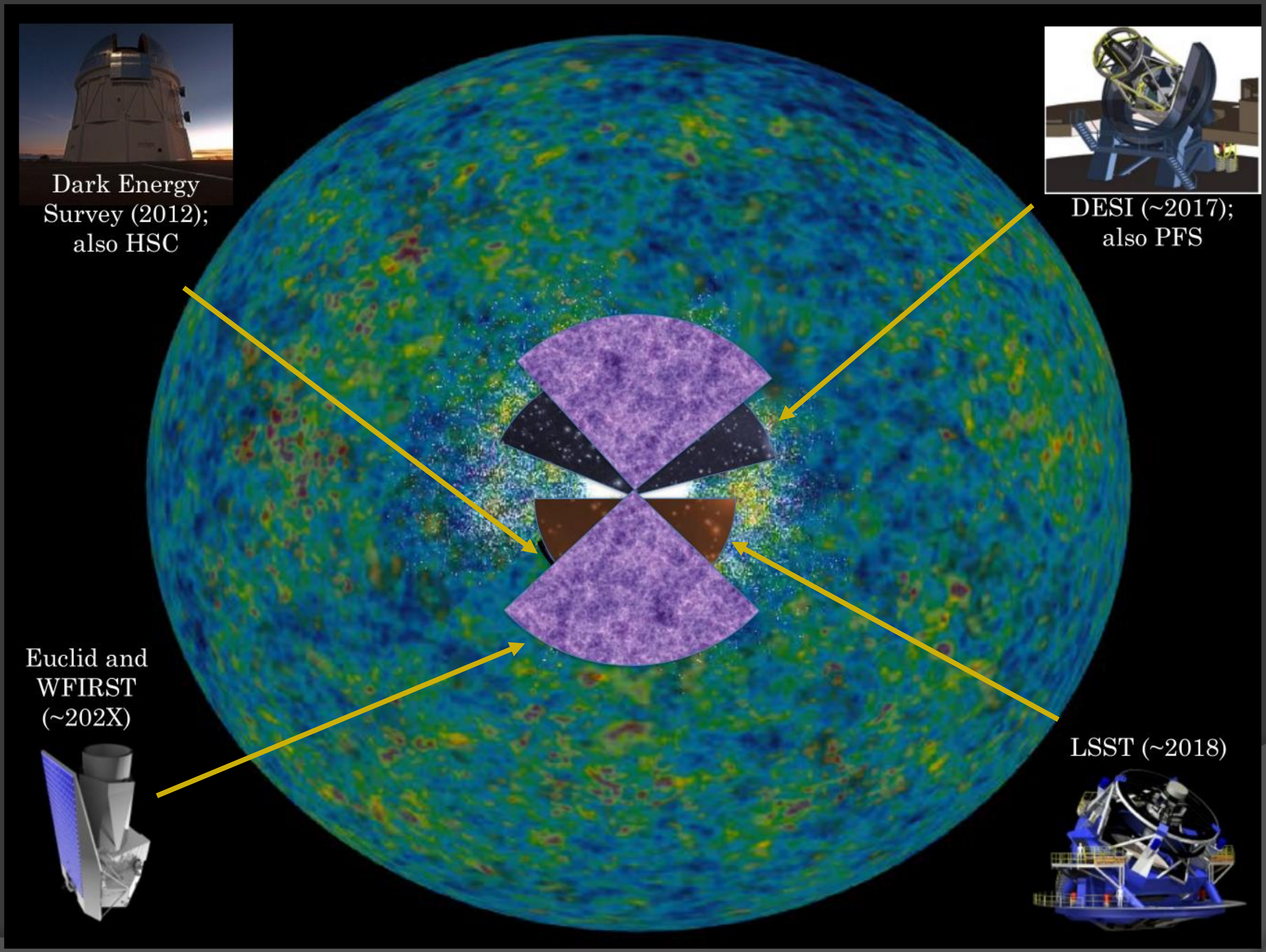
- Effect on CMB consistent with ΛCDM
- Galaxy shear:
  - *same physics*
  - Kernel includes approx. *same redshifts*
- Must it be systematics?
  - CMBL: $\ell \sim 40 - 400$
  - WL: $\ell \sim 300 - 10000$

The Takeaway

- Dark energy is not going away
- ΛCDM fits, but maybe first tensions are beginning to appear
  - Power seems to be lacking in many probes of growth
- It could well end up being other physics
  - Massive neutrinos can have similar physics
- *Caveat emptor*: All cosmological probes sensitive only to gravity; cannot say anything direct about composition

Watch this Space!

Credit: D. Huterer



THANK YOU!

w is ***not*** an observable

- Distances only depend on

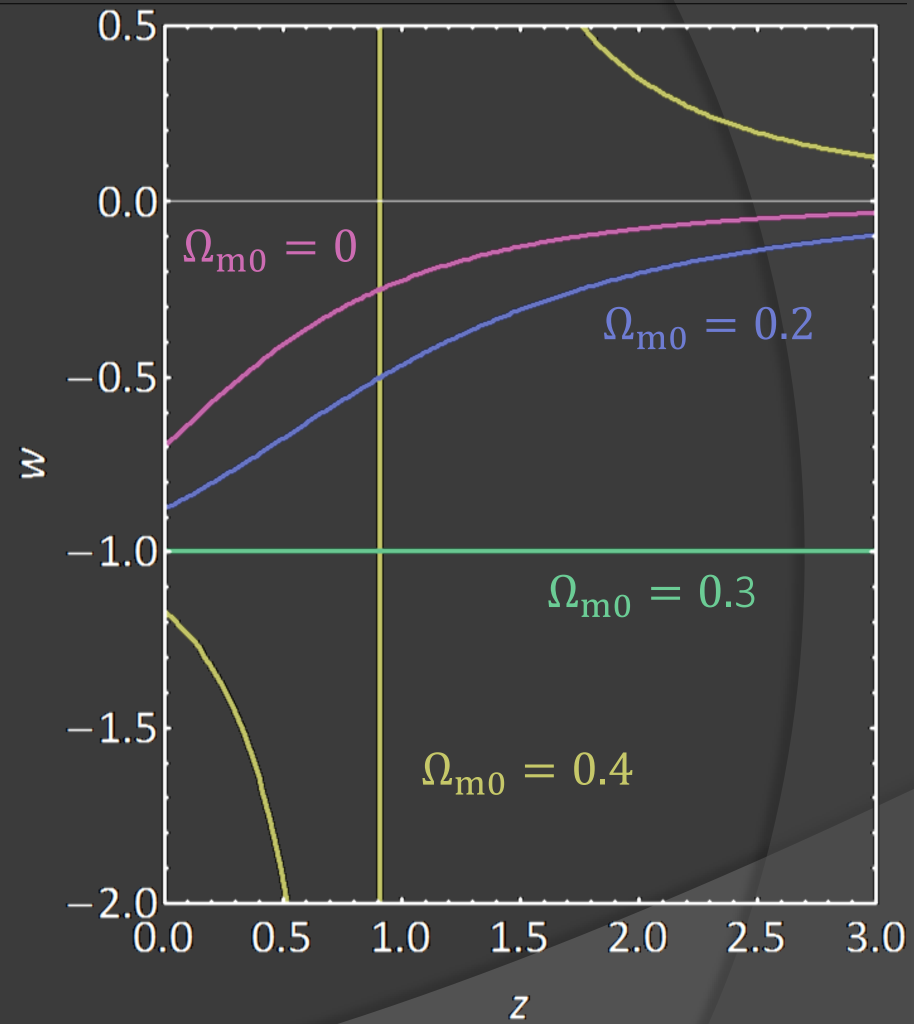
$$d = \int \frac{\mathrm{d}z\, H_0}{H(z)}$$

  - We measure ***geometry*** only

- DM/DE split is ***ambiguous***

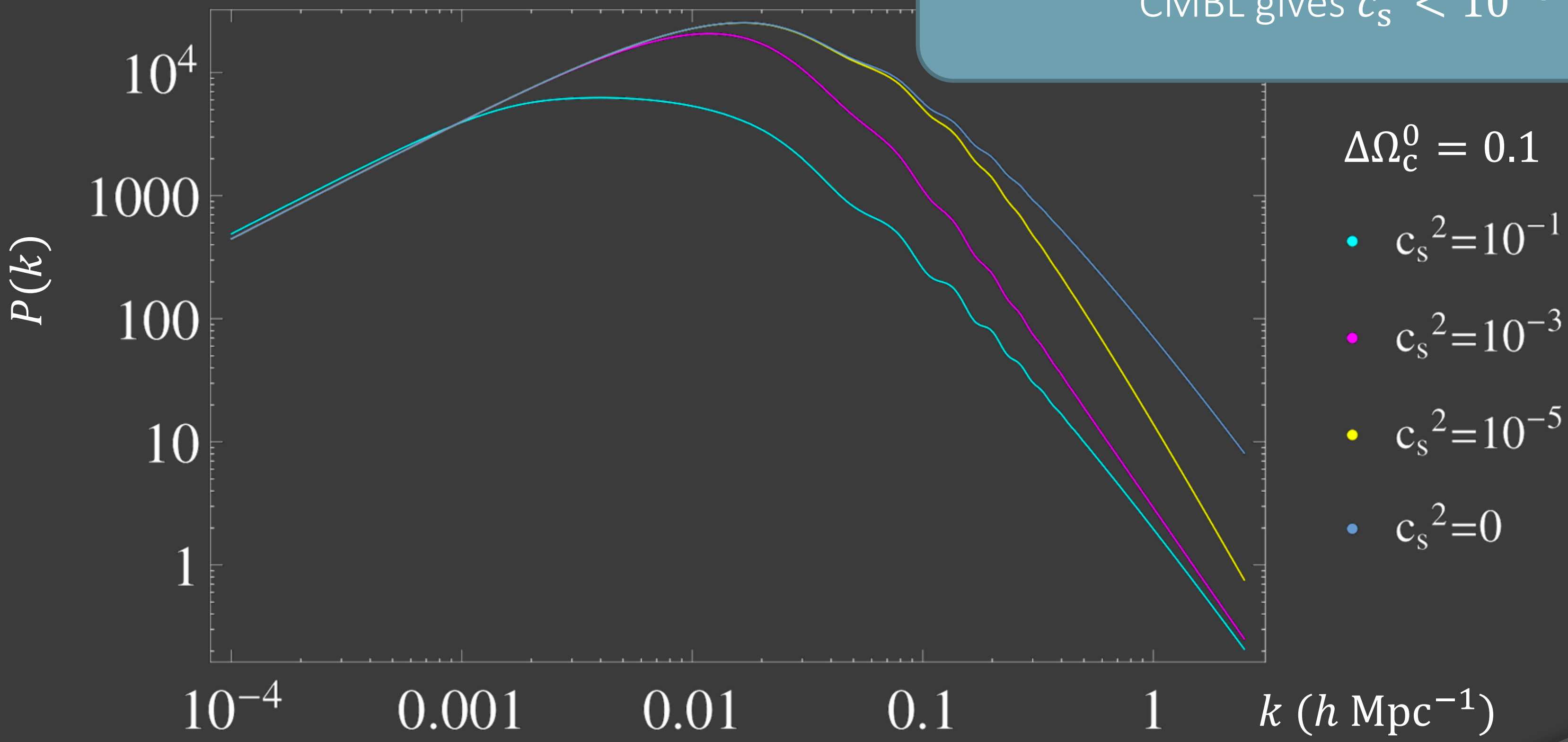
$$H^2 = H_0^2(\Omega_{m0} a^{-3} + \Omega_\Lambda)$$

$$H^2 = H_0^2\left(\widetilde{\Omega}_{m0} a^{-3} + \widetilde{\Omega}_{DE}(a)\right)$$



Scale-Dependent Growth Rate

Exploit DE *scale dependence*:
CMBL gives $c_s^2 < 10^{-5}$

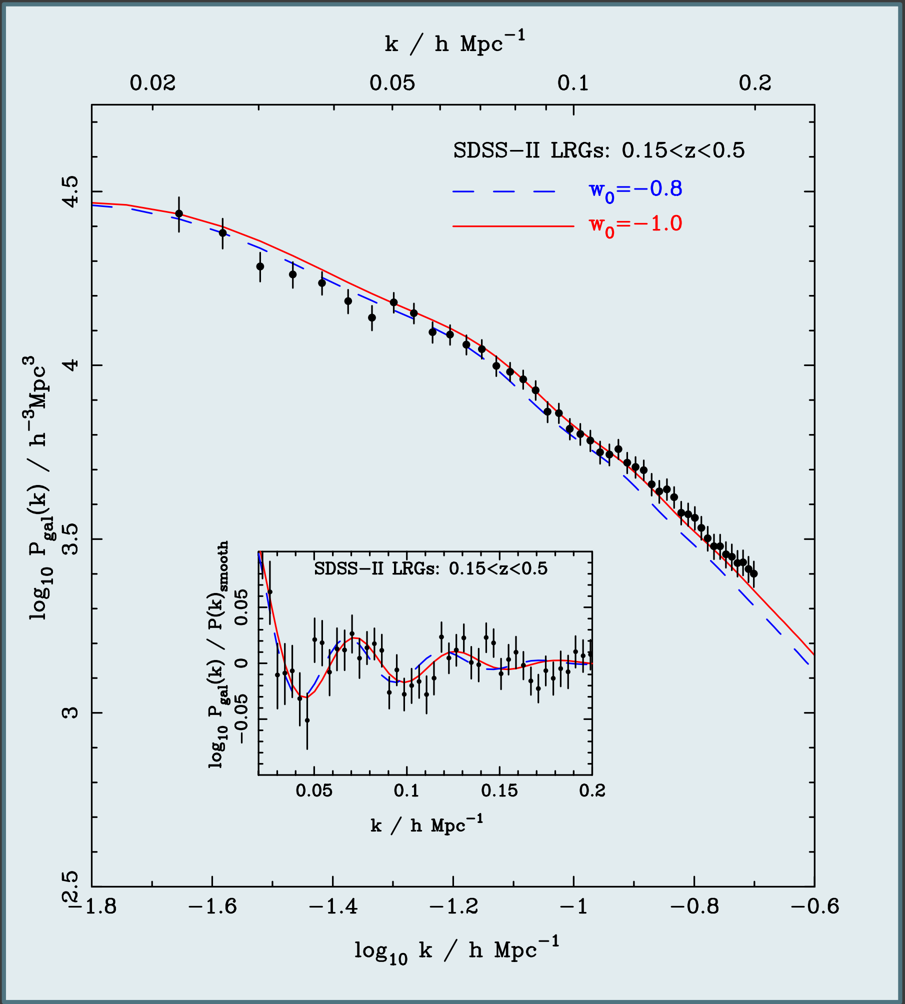


$$\Phi = \Phi_{\Lambda\mathrm{CDM}}$$
$$\delta = \delta_{\Lambda\mathrm{CDM}}$$

$$k_J = \frac{aH}{c_s}$$

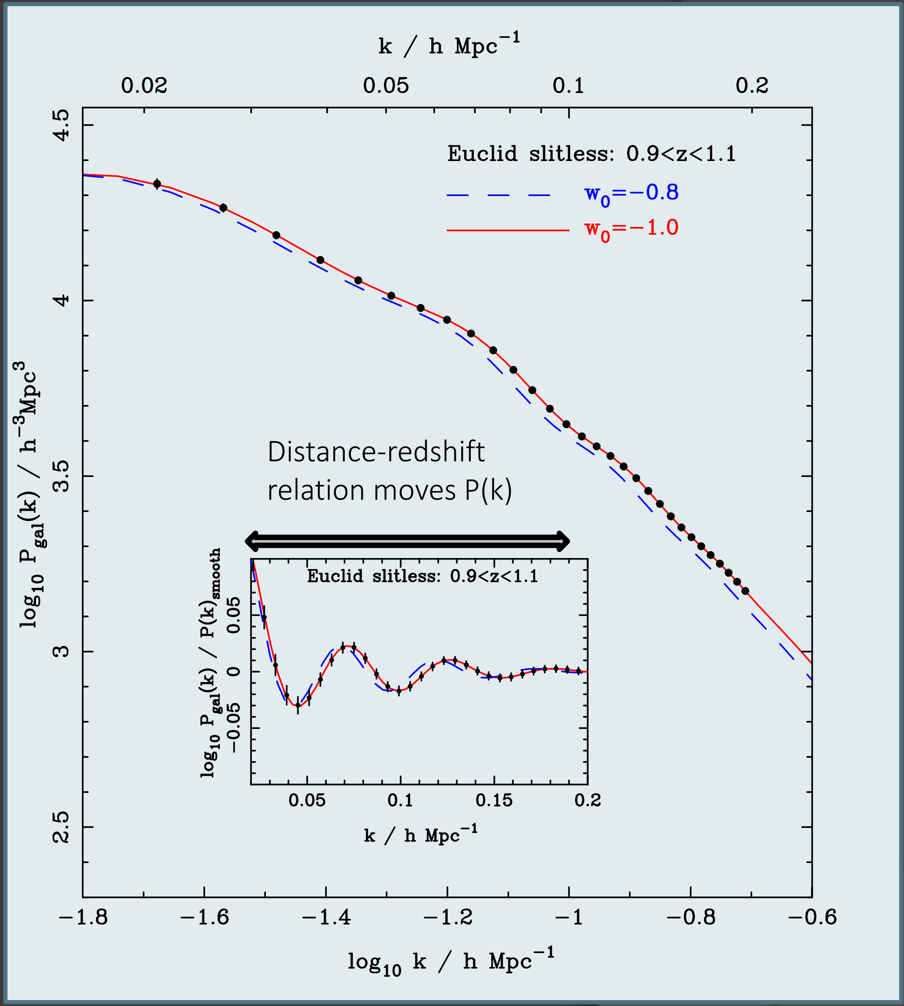
$$\Phi = (1 - \Omega_{\mathrm{DE}})\Phi_{\Lambda\mathrm{CDM}}$$
$$\delta = \left(k_J/k\right)^{6\Omega_{\mathrm{DE}}/5}\delta_{\Lambda\mathrm{CDM}}$$

BAO : SDSS vs Euclid



SDSS today

0.15<z<0.5



EUCLID expected

0.7<z<2.0

Measuring shear in next generation wide field cosmic shear surveys