

DARK ENERGY: EVIDENCE AND FUTURE

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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

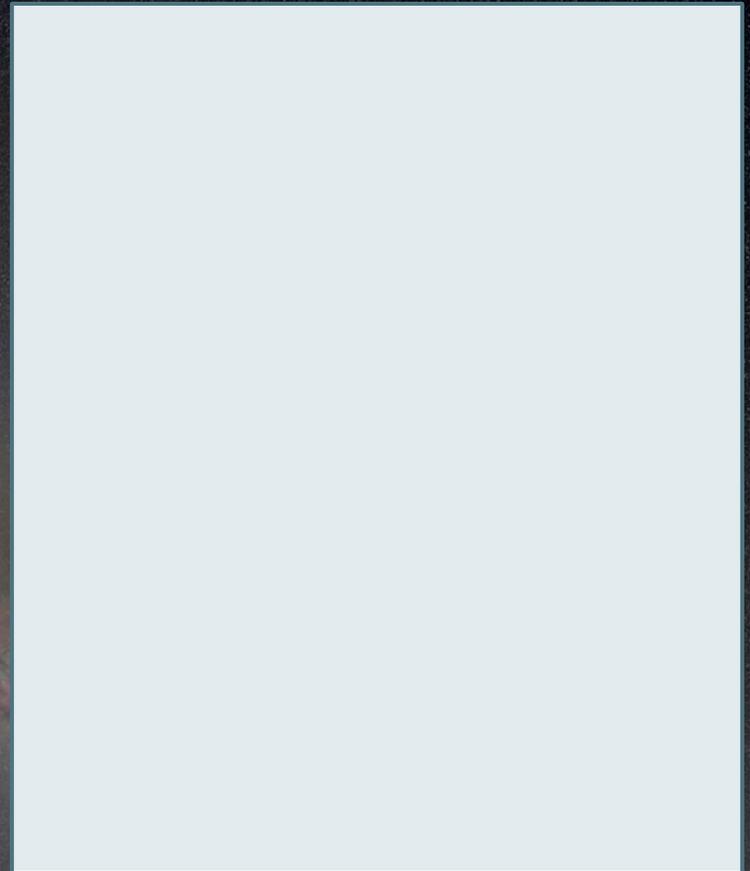
- ⊙ Geodesic motion for light

$$k^\alpha \nabla_\alpha k^\mu = 0 \quad \frac{u_{\text{em}}^\mu k_\mu}{u_{\text{obs}}^\mu k_\mu} = \frac{\omega_{\text{em}}}{\omega_{\text{obs}}} \equiv 1 + z$$

- ⊙ Distances: corrected by gravitational field

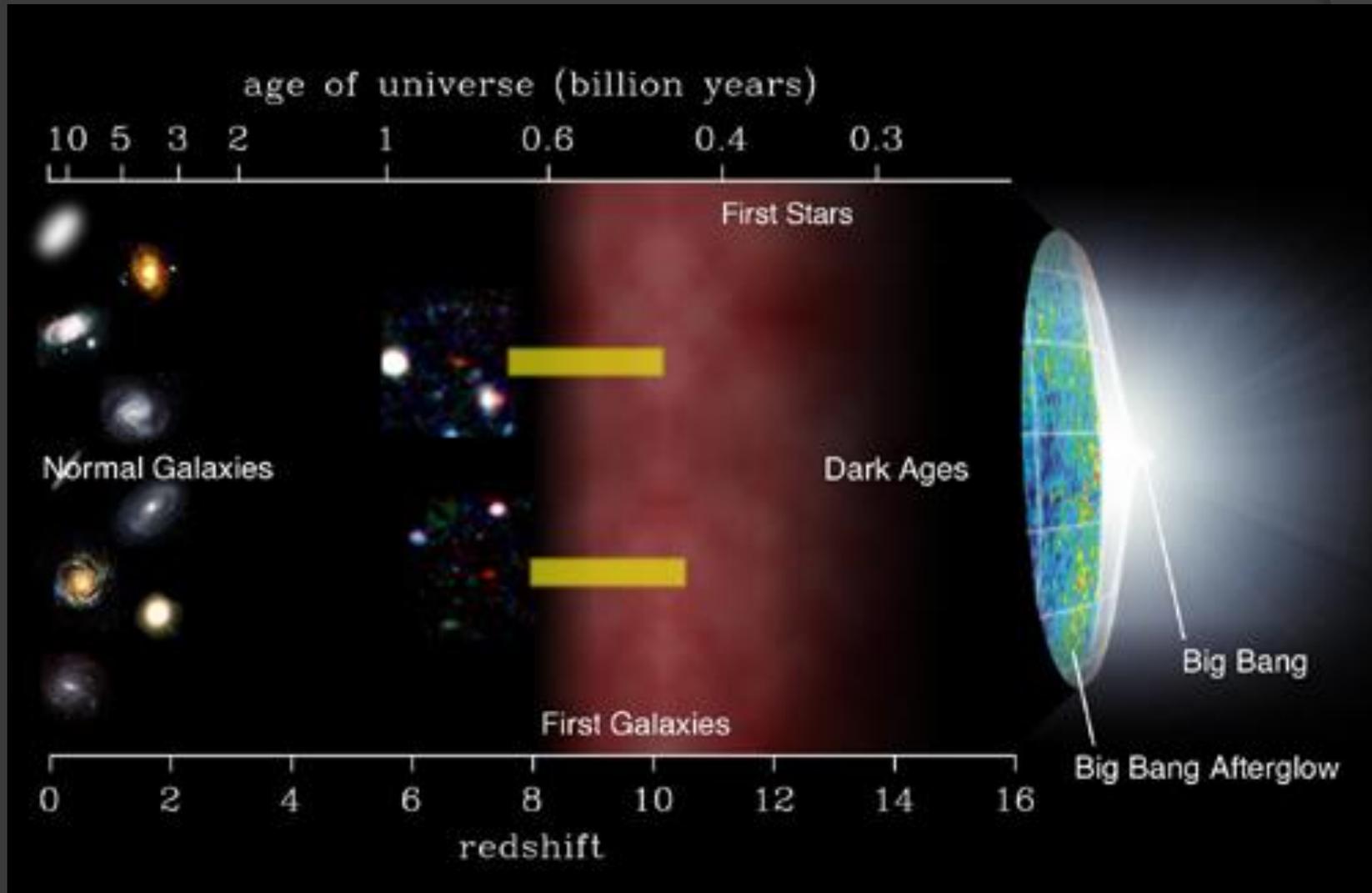
- Luminosity $F = L/4\pi d_L^2$
- Angular diameter $\theta = \ell/d_A$

$$d_L = (1 + z)^2 d_A$$



Ordering by redshift

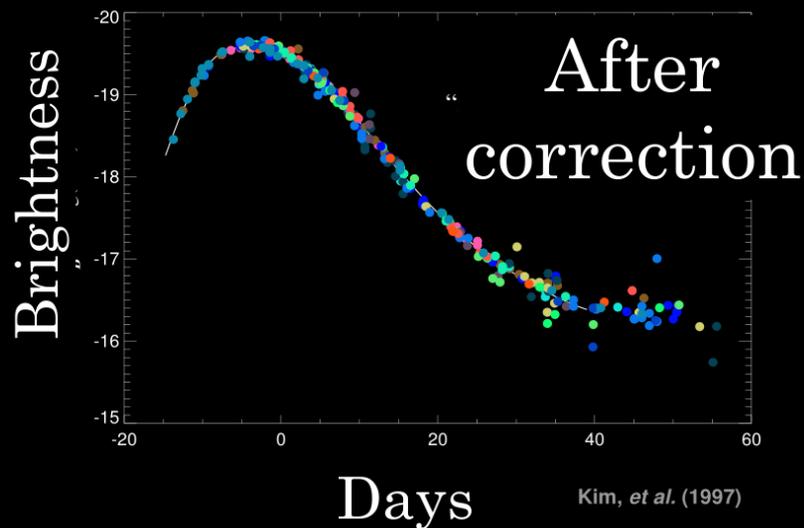
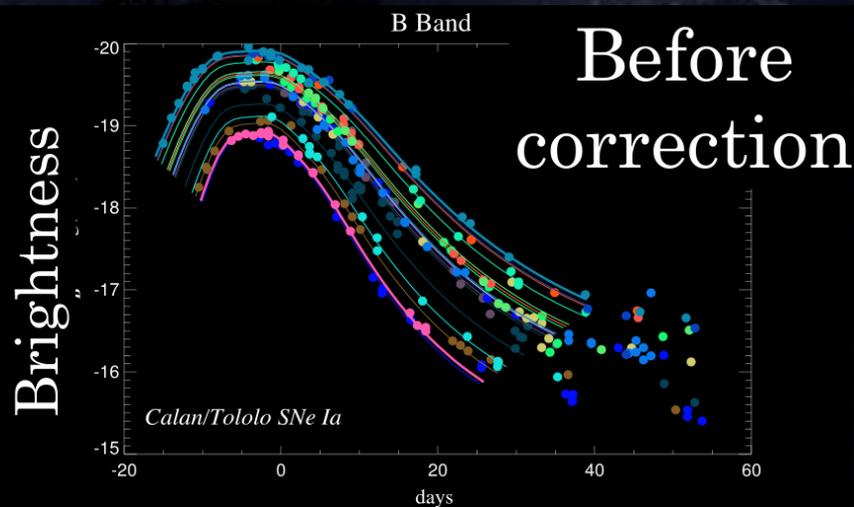
Image credit: Ivo Labbé



Use Standard Candles to Map



Use Standard Candles to Map



- Nearby: Broader is intrinsically brighter
- Standardise to some (unknown) intrinsic luminosity
- Obtain luminosity distance as function of redshift $d_L(z)$
- To interpret *need a model*
 - Gravity
 - Composition

SN 2011fe

First Attempt at Model

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

$$ds^2 = dt^2 - a^2(t)\delta_{ij}dx^i dx^j$$

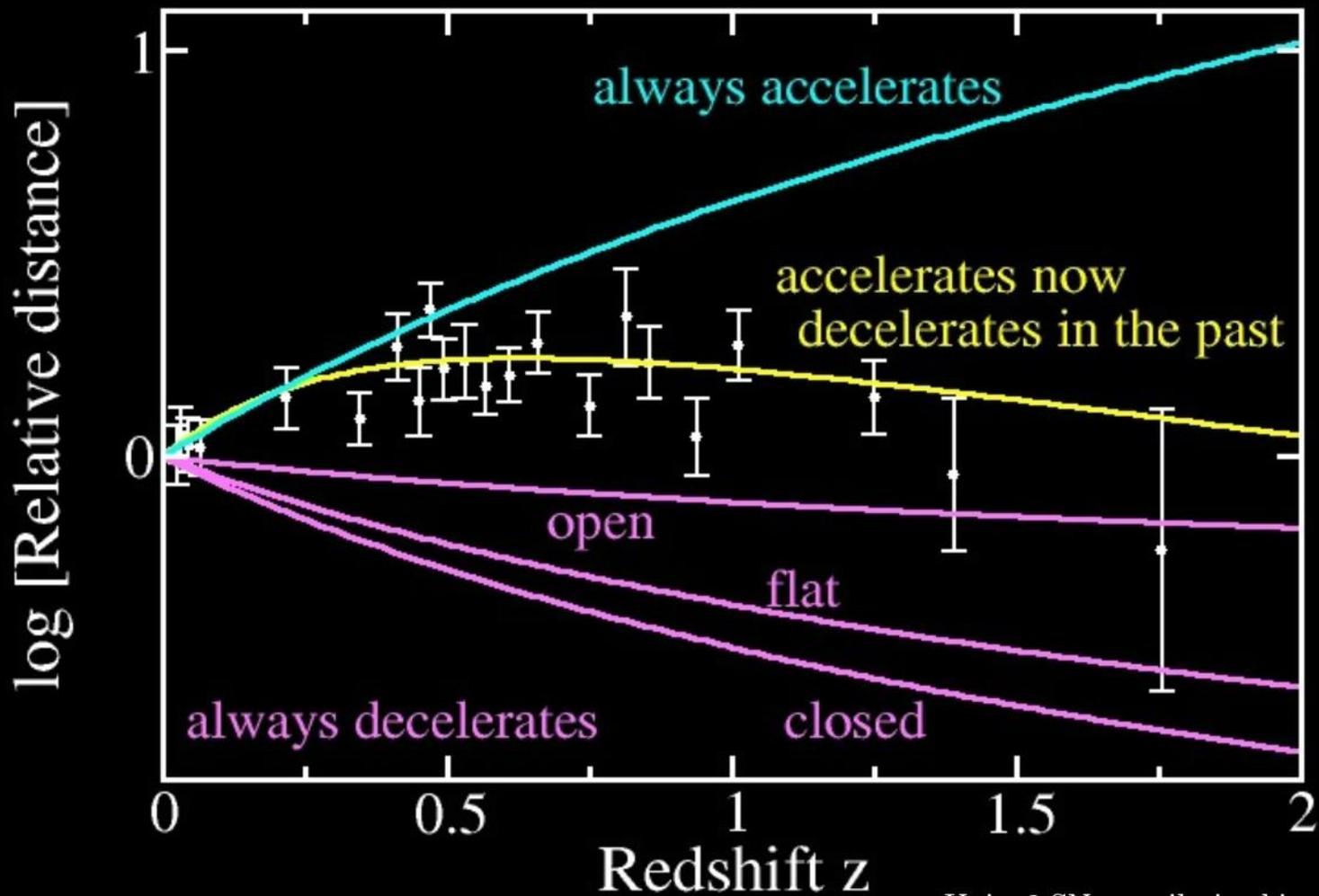
- ⊙ Gravity is *General Relativity*

$$H^2 \equiv \left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi G_{\text{N}}}{3} \rho \quad d_L = (1+z) \int \frac{dz}{H(z)}$$

- ⊙ Matter *non-relativistic*

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

First Attempt at Model: FAIL



Acceleration

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

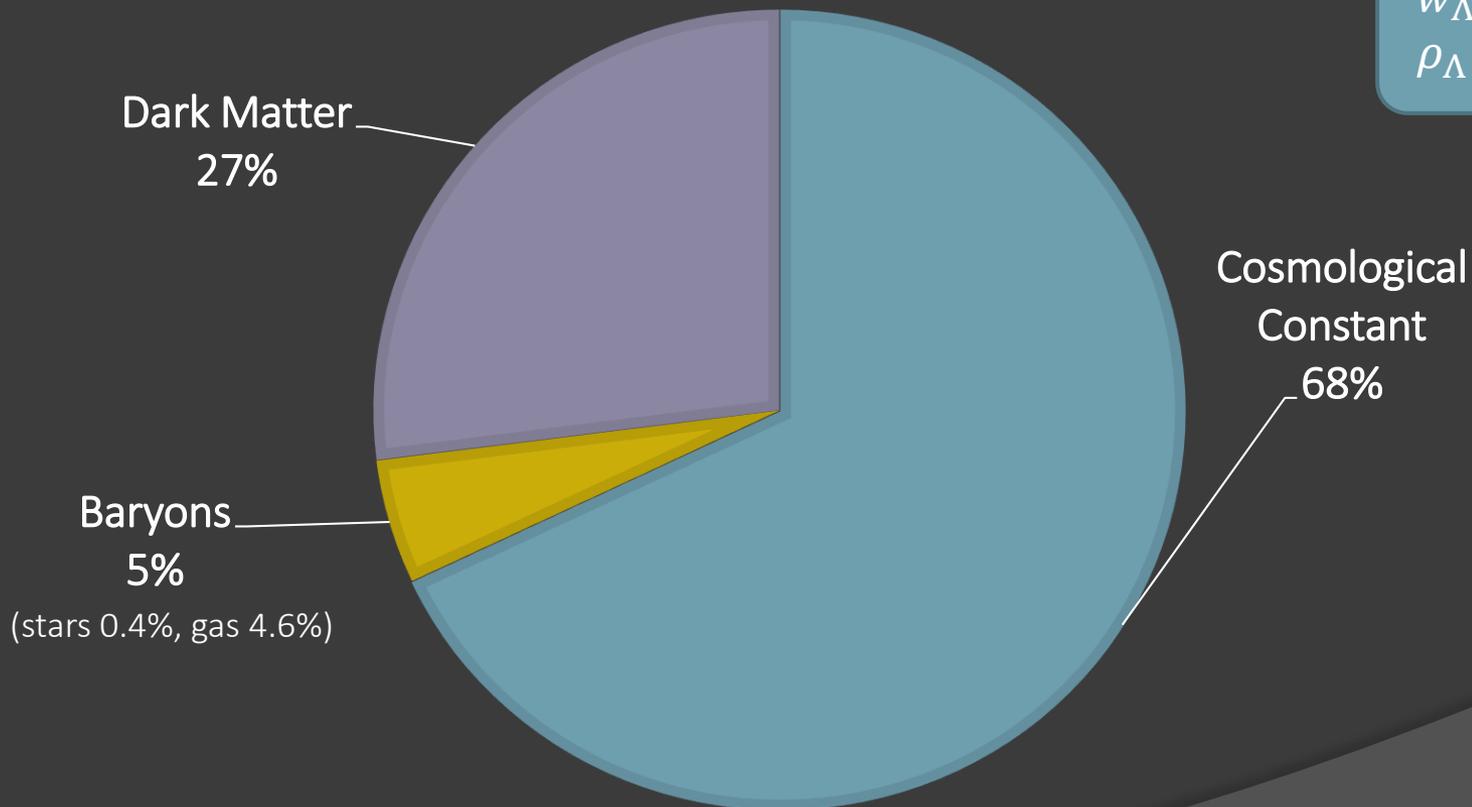
Dimmer

Union2 SN compilation binned in redshift

Second Attempt: Λ CDM \Rightarrow NOBEL

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COMPOSITION OF UNIVERSE IF Λ CDM



Is the Universe fooling us?

- ⊙ Light dims/SNe evolve (*“tired light”*)
 - d_A matches d_L : photons conserved (BAO)
- ⊙ Here is special (*“inhomogeneous 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?



But is it actually Λ ?

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

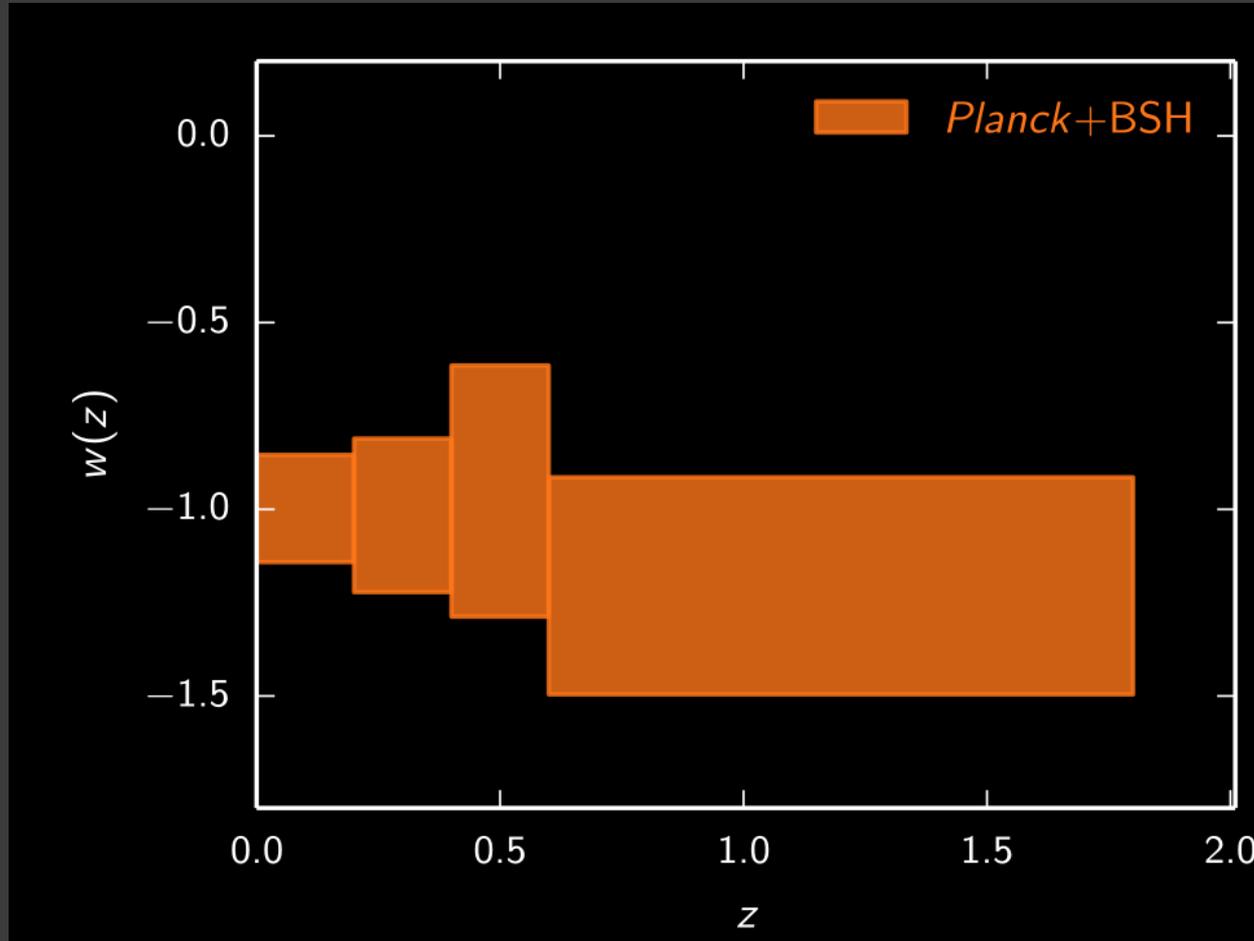
- ⊙ Old c.c. problem: *new* fine-tuning at every order
- ⊙ Coincidence problem: $\rho_{\Lambda} \sim 2\rho_m$
- ⊙ Wishful thinking

$$n_s - 1 = -\frac{1}{4}(1 + w) = -0.0333 \pm 0.0040$$

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

Λ CDM as Null Hypothesis

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Background has close to constant *pressure*

w is *not* an observable

- Distances only depend on

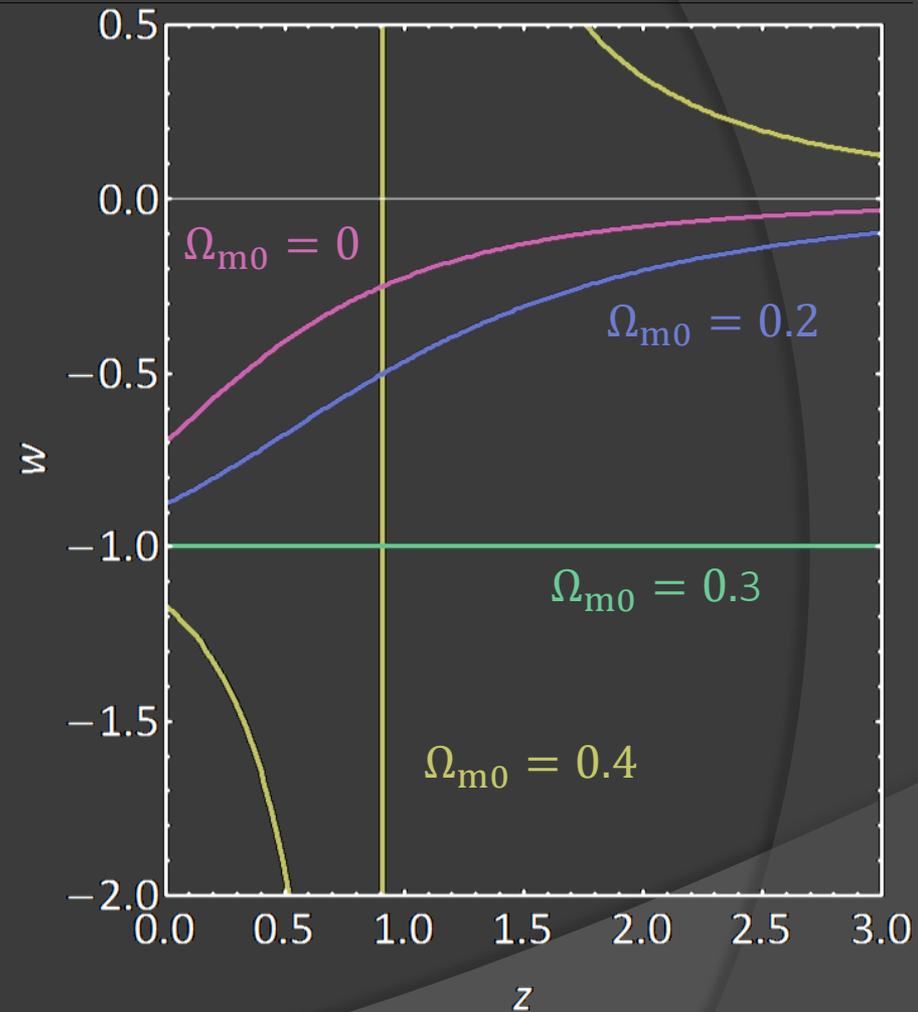
$$d = \int \frac{dz H_0}{H(z)}$$

- We measure *geometry* only

- DM/DE split is *ambiguous*

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

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



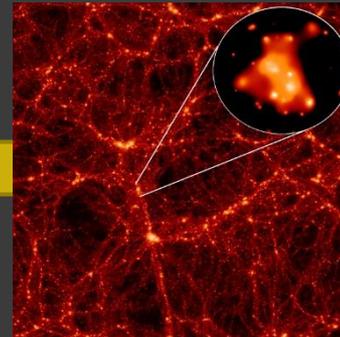
CMB is Gravitational Collapse



Initial conditions (inflation)

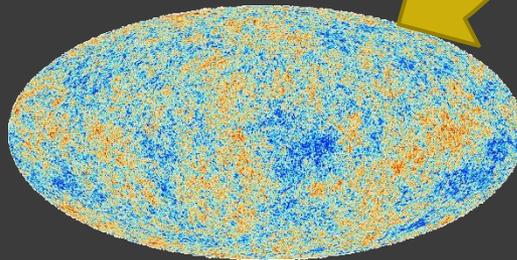


Photon decoupling, $T = T_{\text{dec}}$



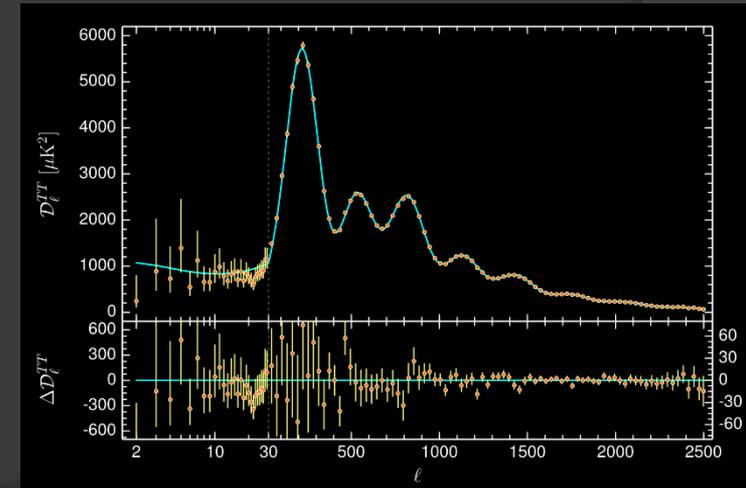
Galaxy formation

gravitational collapse



Vacuum in
quasi-de Sitter

(nearly) scale
invariant Gaussian
fluctuations



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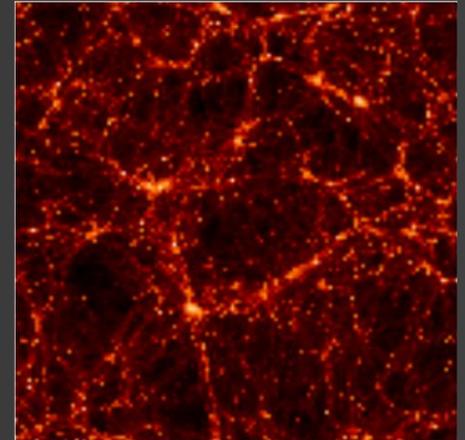
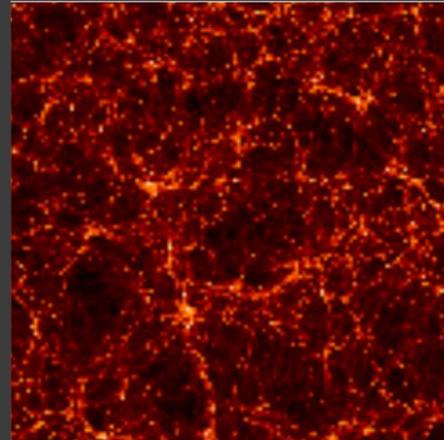
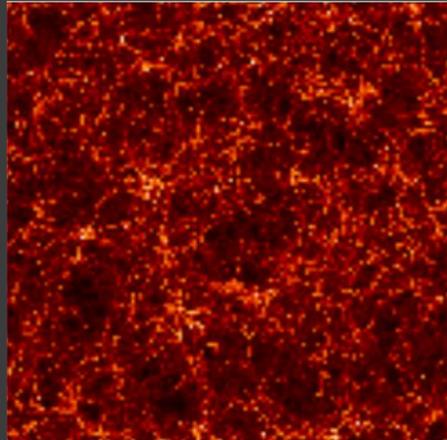
Dark Energy Changes Growth

$z = 3$

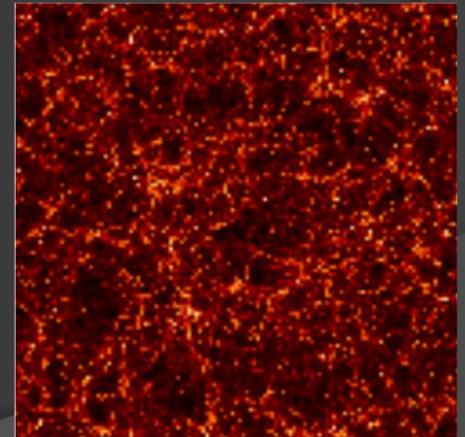
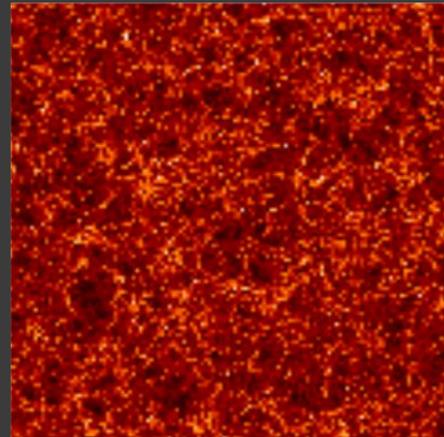
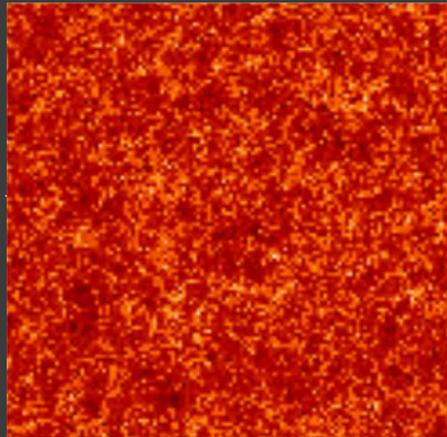
$z = 1$

$z = 0$

Λ CDM



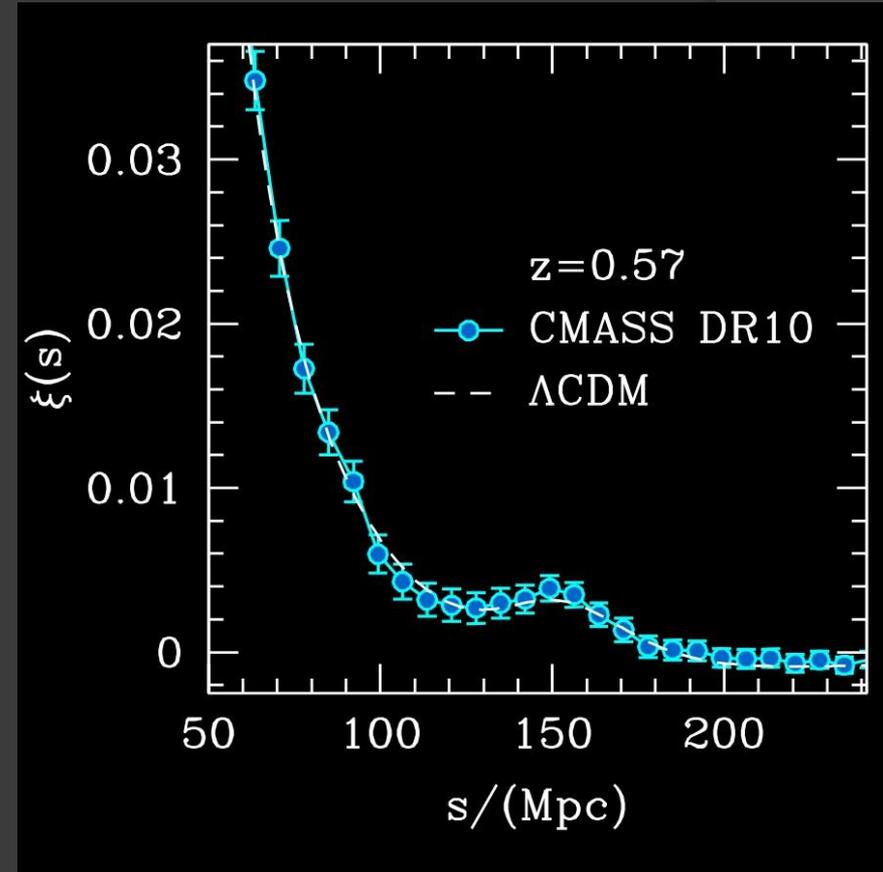
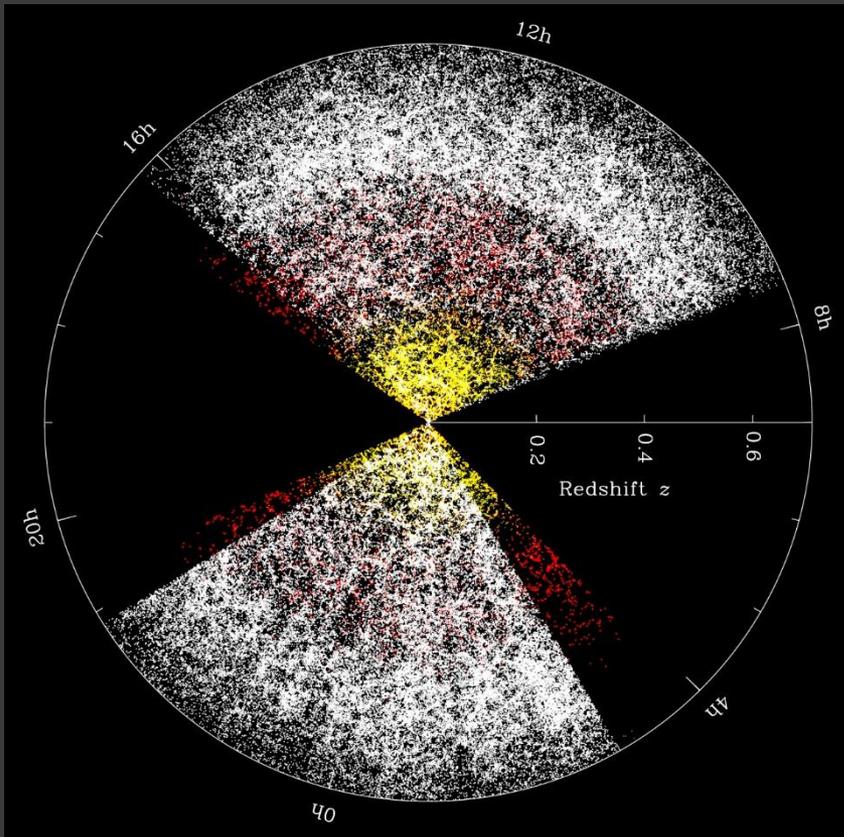
Dynamical
DE
($w > -1$)



Use Structure to Probe Gravity/DE

SDSS/BOSS

SDSS/BOSS DR10



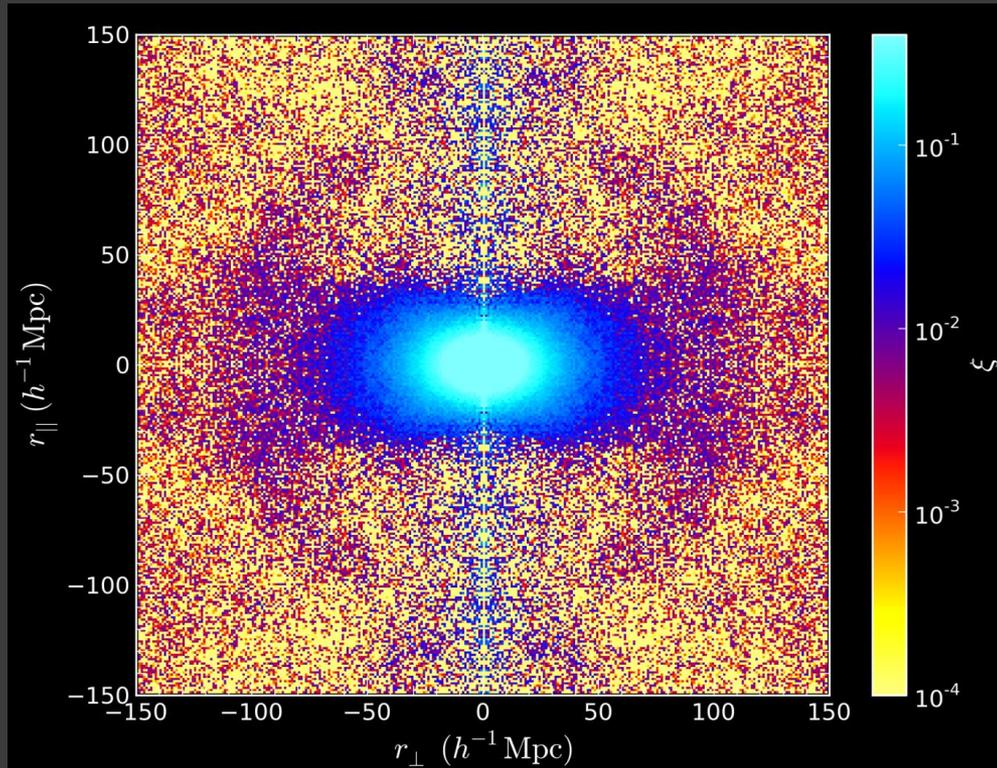
2500 deg² up to $z = 0.7$

Redshift-Space Distortions

Kaiser (1985)



Samushia et al. (2013)/BOSS



Monopole:

$$\langle \delta_g \delta_g \rangle = b^2 \langle \delta_m \delta_m \rangle$$

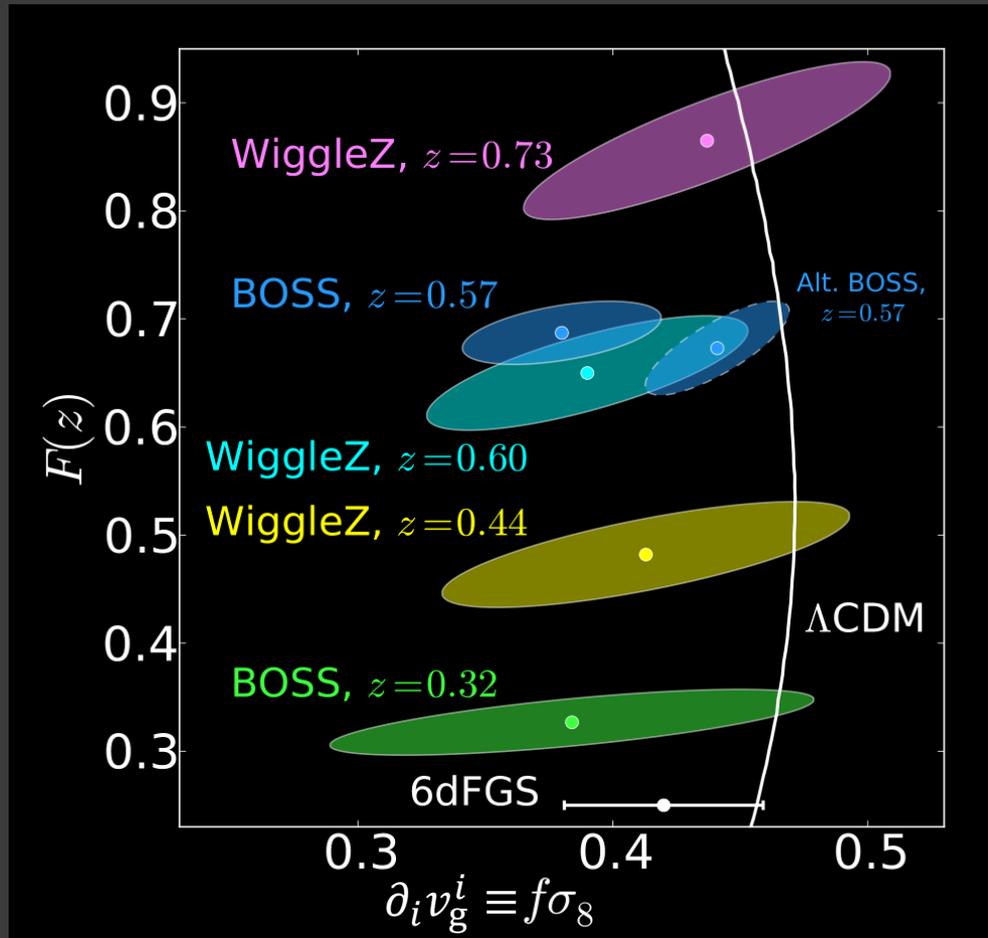
Quadrupole:

$$\langle \partial_i v_g^i \delta_g \rangle$$

$$\dot{v}_g^i = \dot{v}_m^i = \partial_i \Psi$$

Redshift-Space Distortions

Ruiz & Huterer (2014)

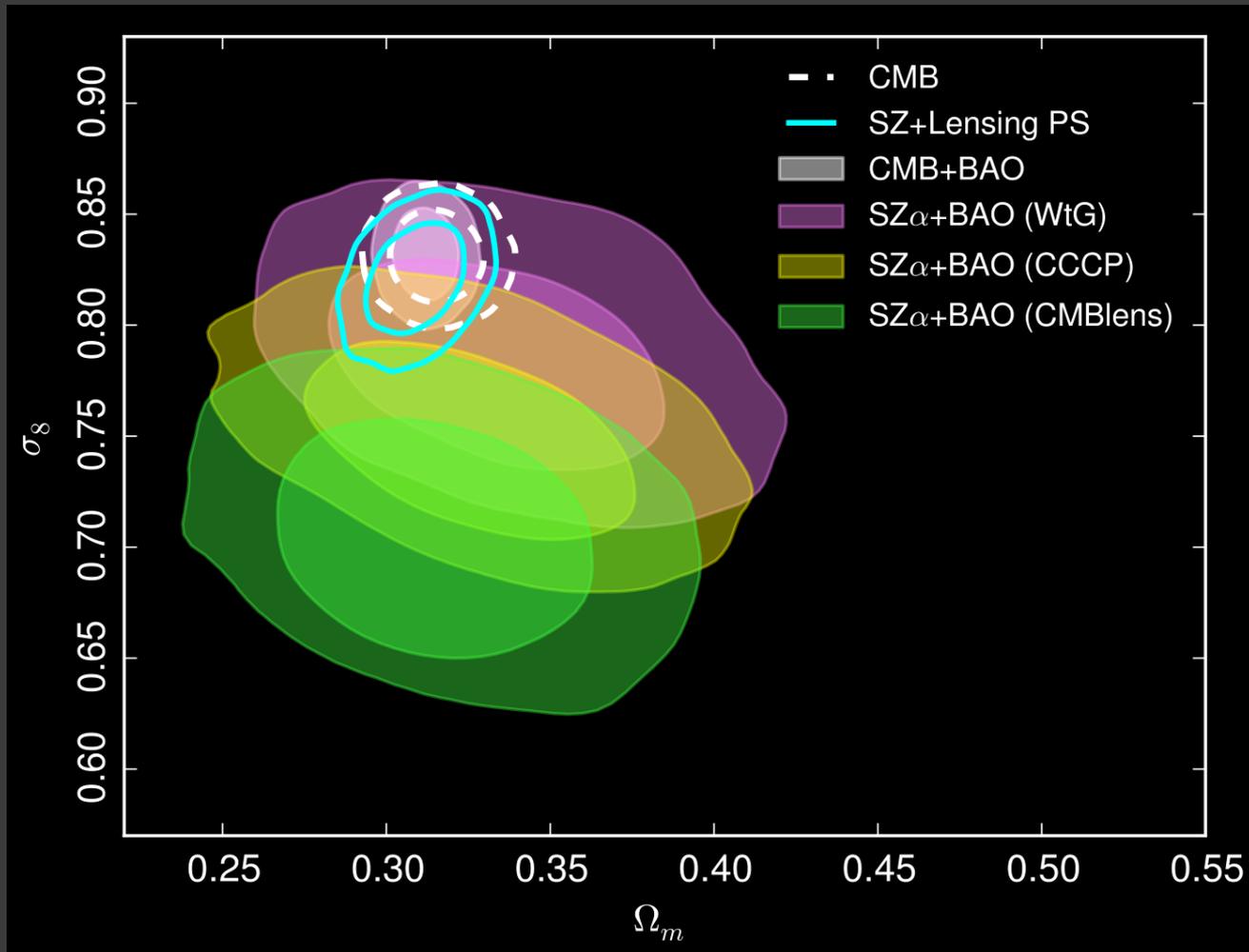


- Galaxy velocities tend to be lower than Λ CDM would imply

$$\dot{v}_g^i = \dot{v}_m^i = \partial_i \Psi$$

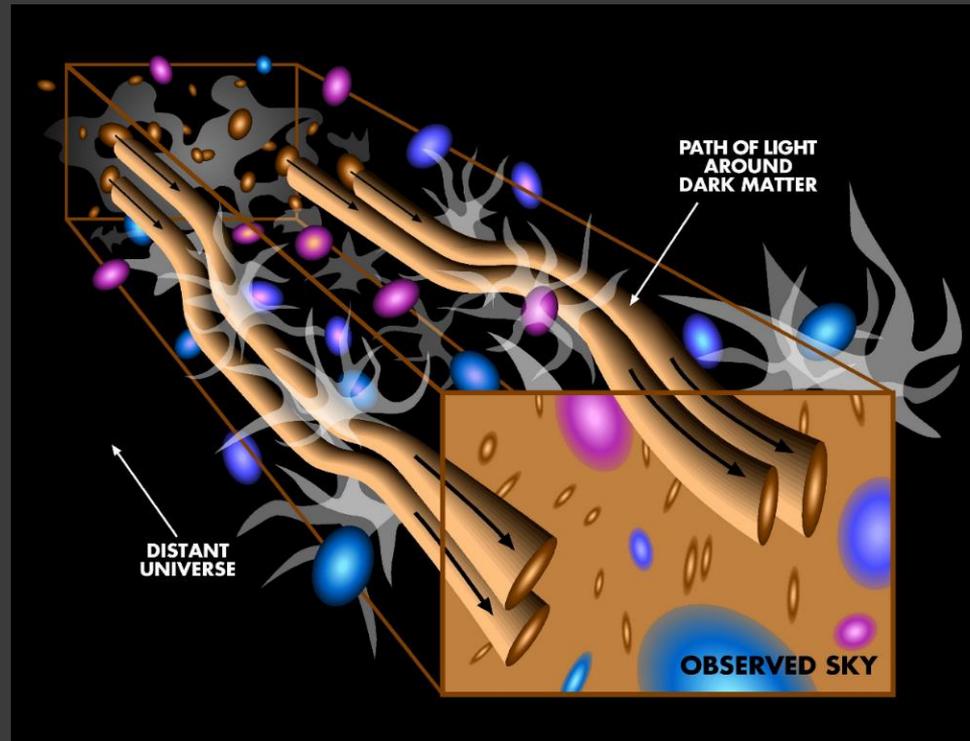
Cluster Number Counts

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Weak Lensing

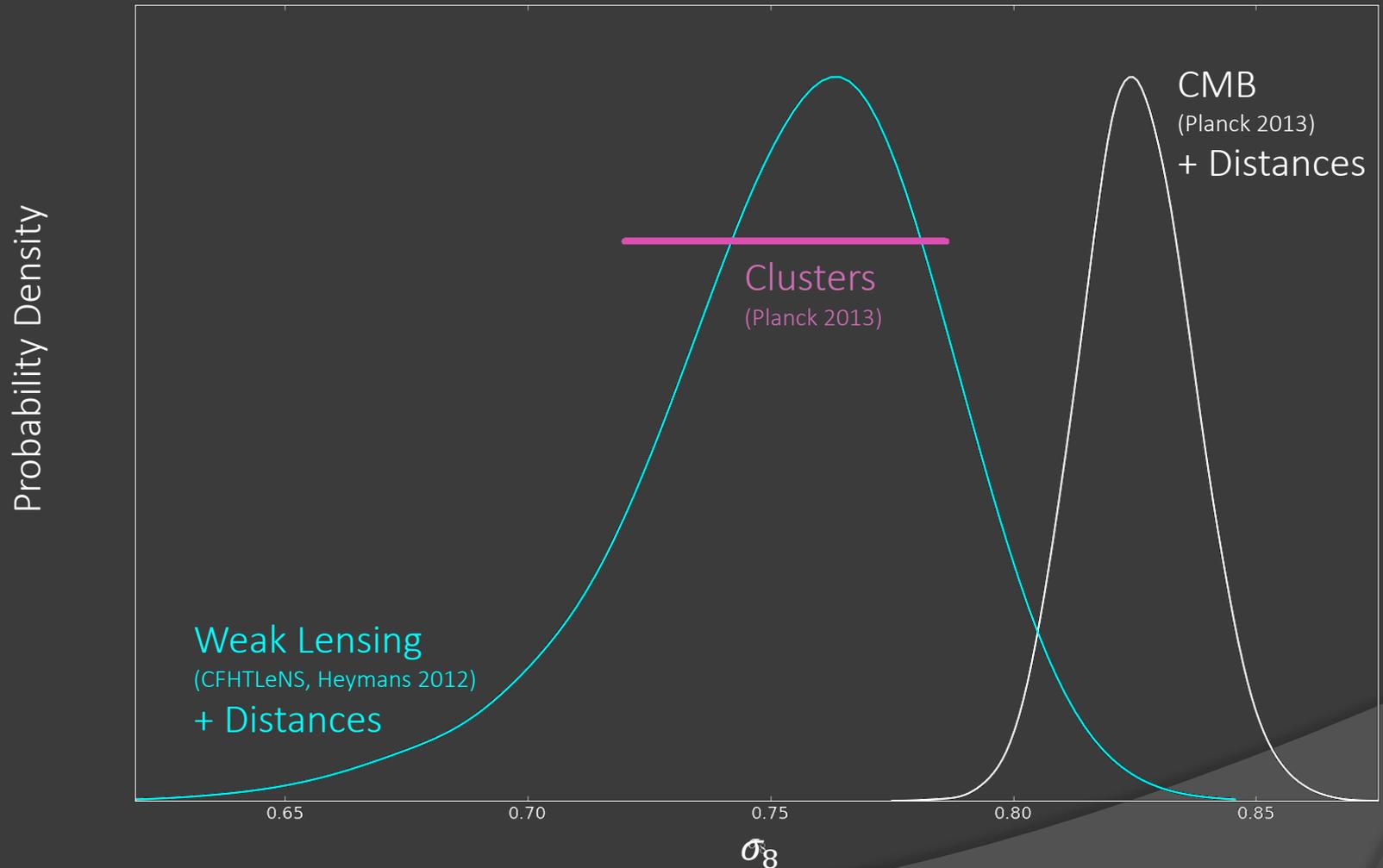
$$ds^2 = -(1 + 2\Psi)dt^2 + a^2(t)(1 - 2\Phi)d\mathbf{x}^2$$



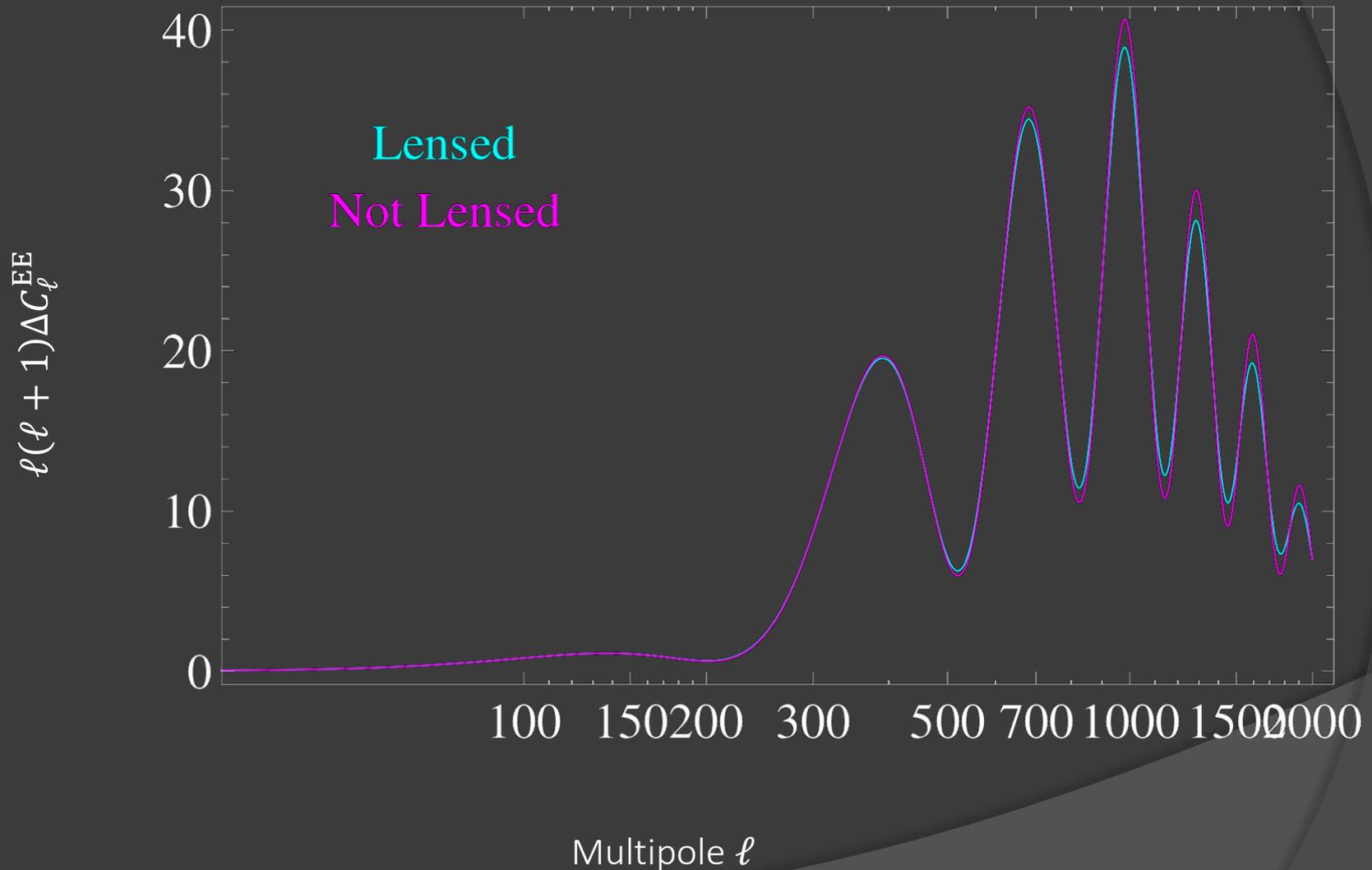
$$\sigma_{ij} = \int_{z_s}^{z_0} dz \partial_i \partial_j (\Psi + \Phi) K(z, z_s)$$

Is everything OK with Λ CDM?

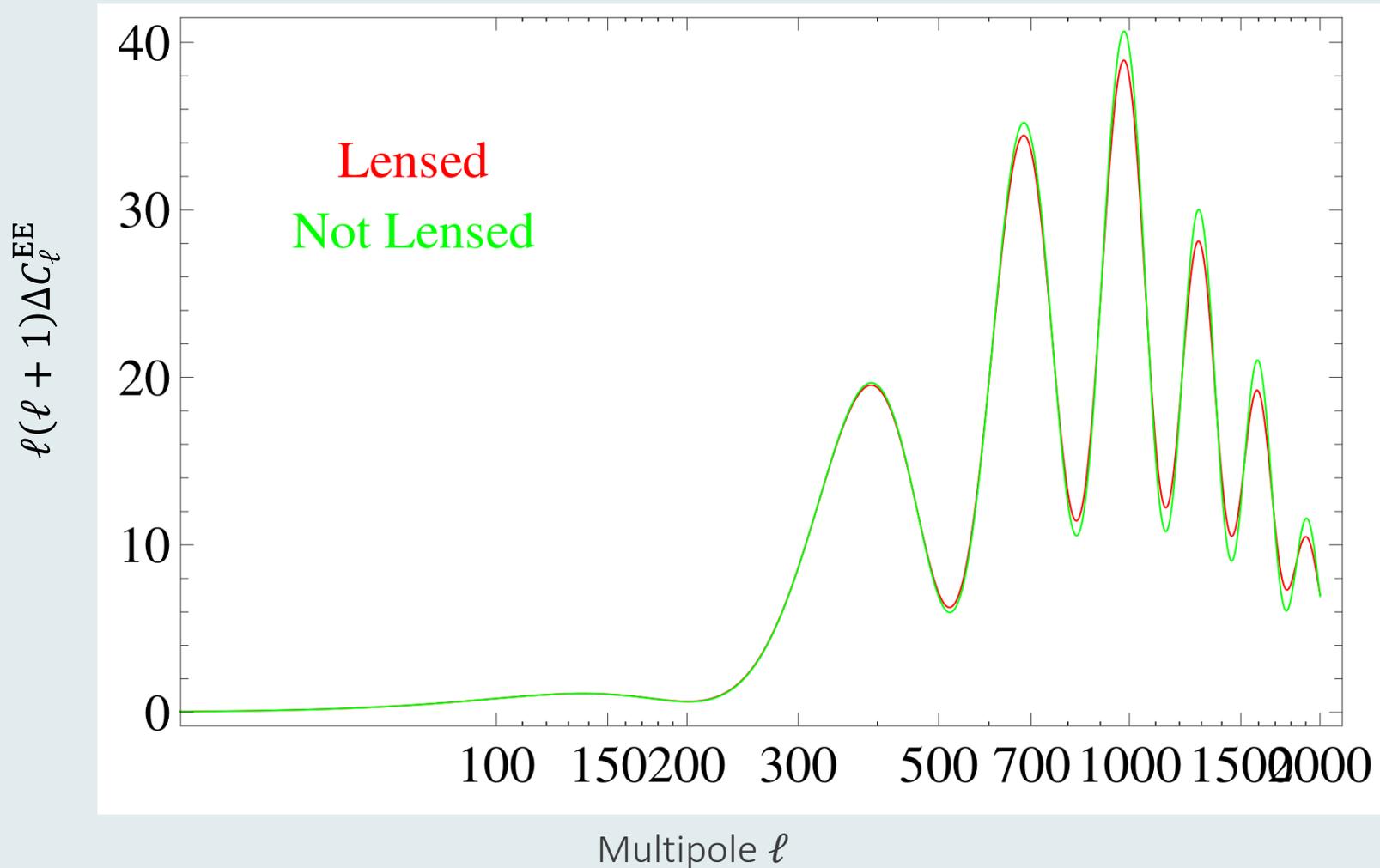
Kunz, Nesseris, Sawicki (2015)



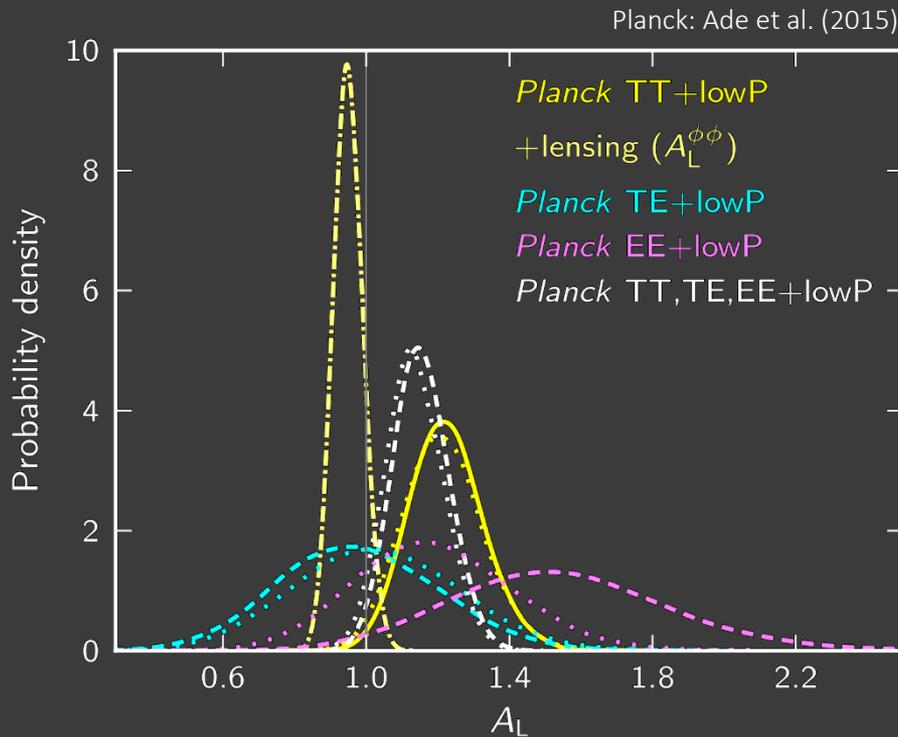
CMB Lensing: Smooths Peaks



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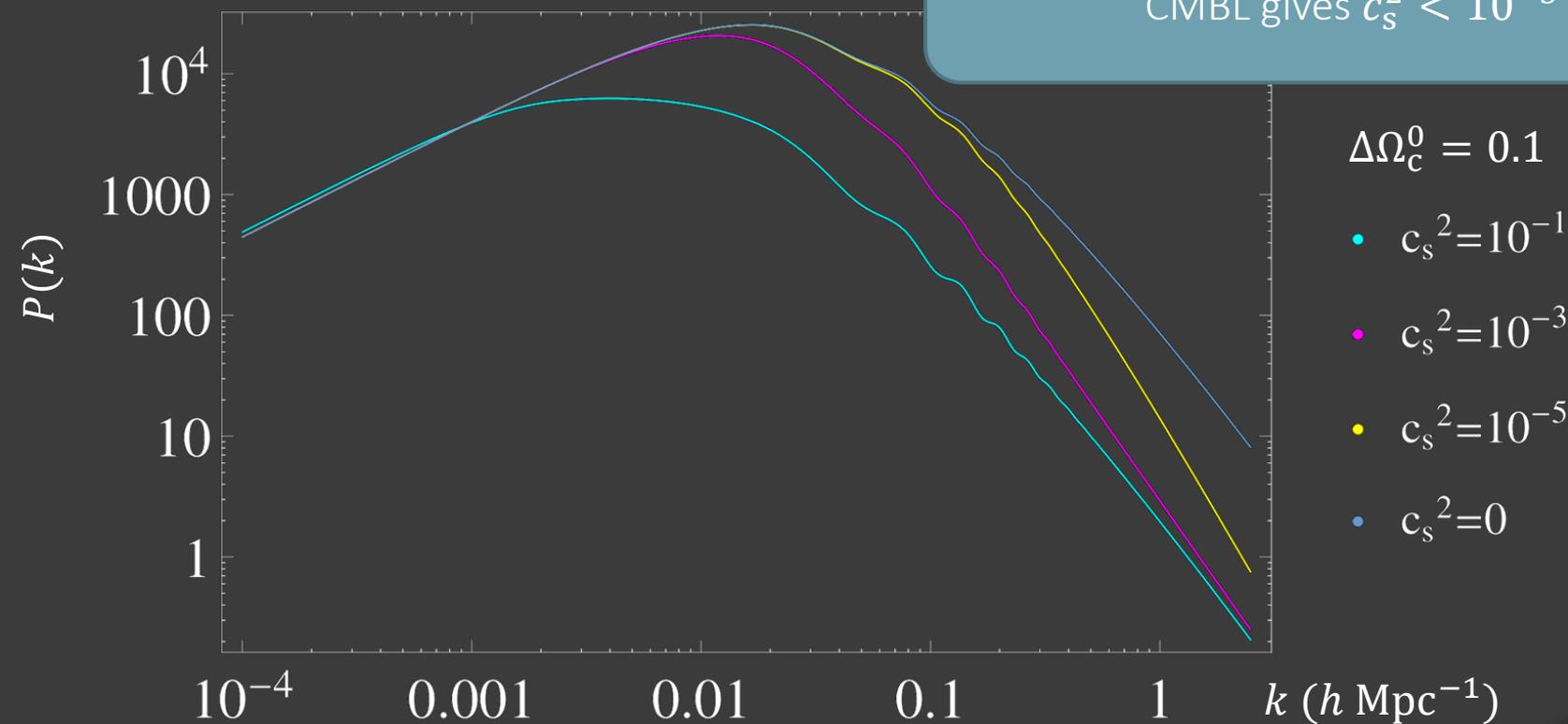


$$\varphi_{\text{lens}} \equiv A_L(\Phi + \Psi)$$

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

Scale-Dependent Growth Rate

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



$$\Phi = \Phi_{\Lambda\text{CDM}}$$

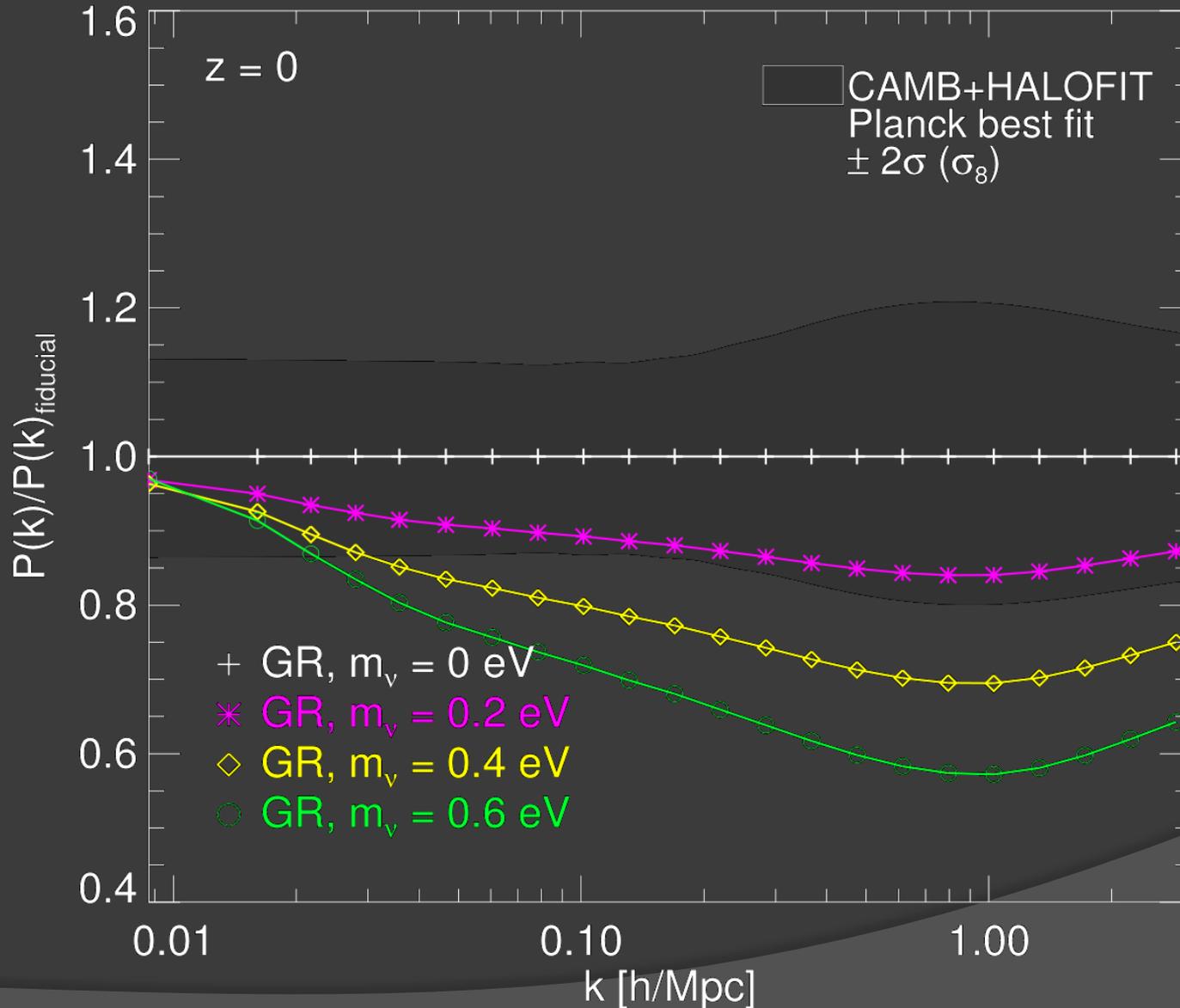
$$\delta = \delta_{\Lambda\text{CDM}}$$

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

$$\Phi = (1 - \Omega_{\text{DE}})\Phi_{\Lambda\text{CDM}}$$

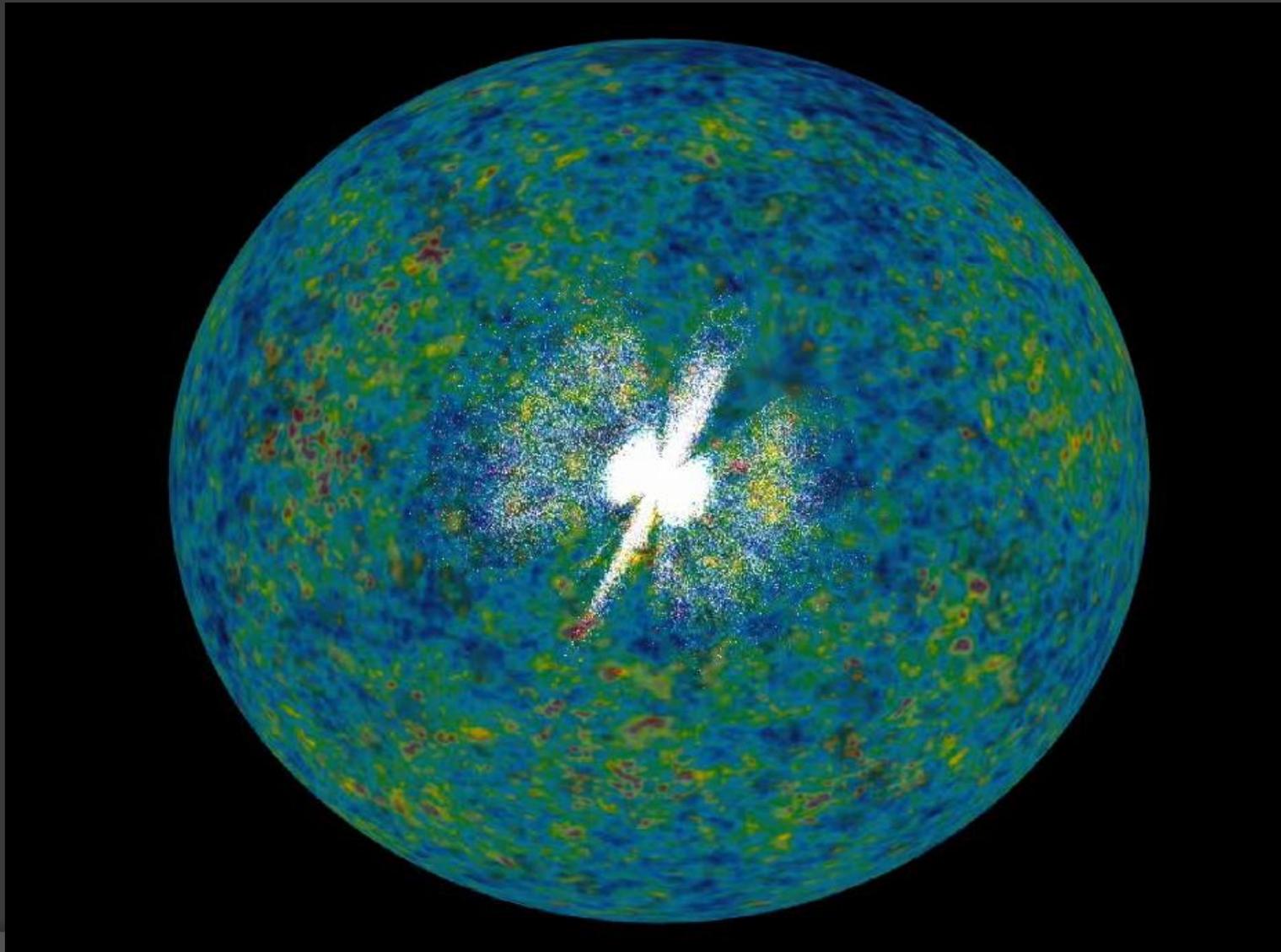
$$\delta = \left(\frac{k_J}{k}\right)^{6\Omega_{\text{DE}}/5} \delta_{\Lambda\text{CDM}}$$

Careful: Massive ν



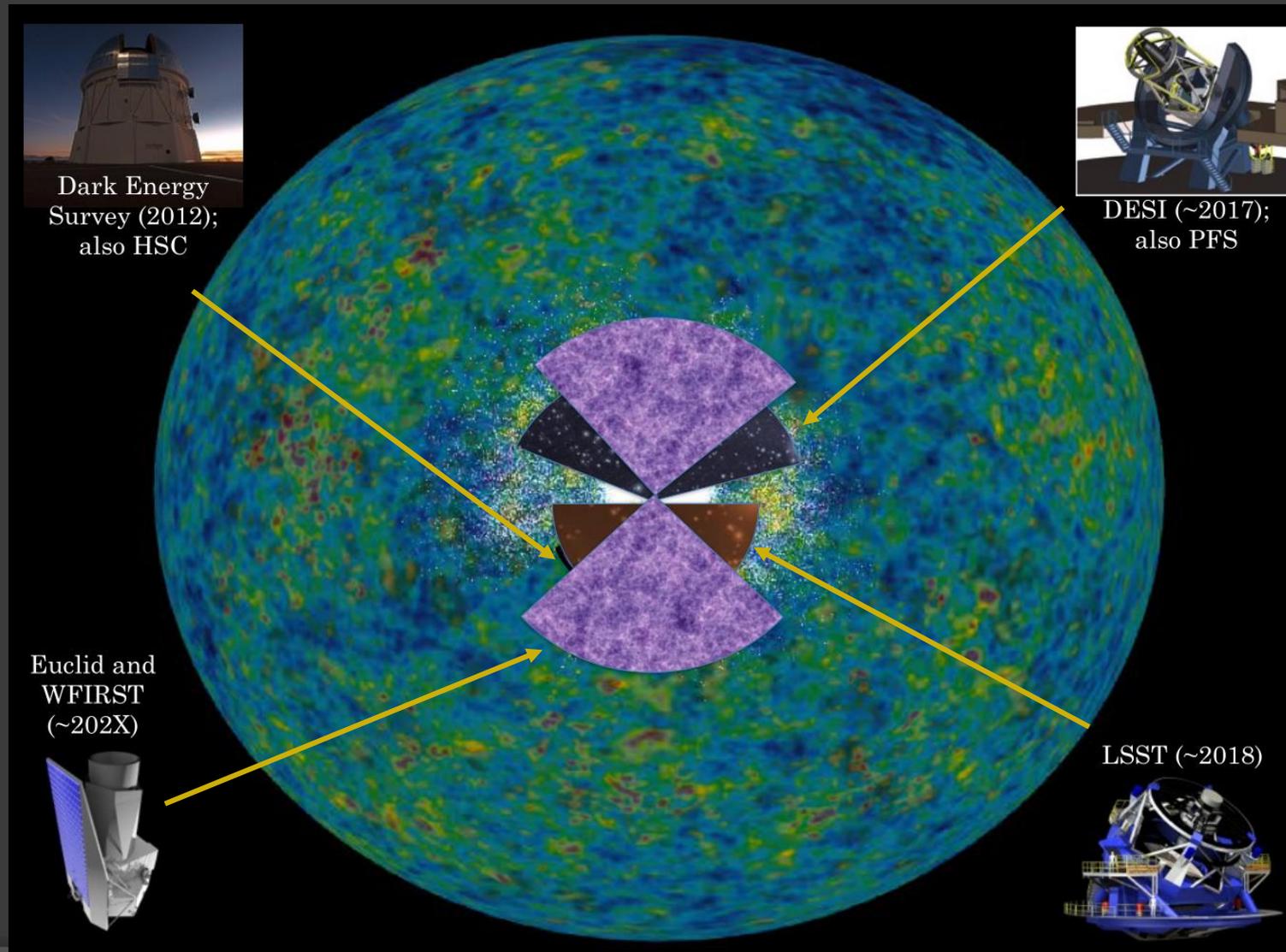
Watch this Space!

Credit: D. Huterer

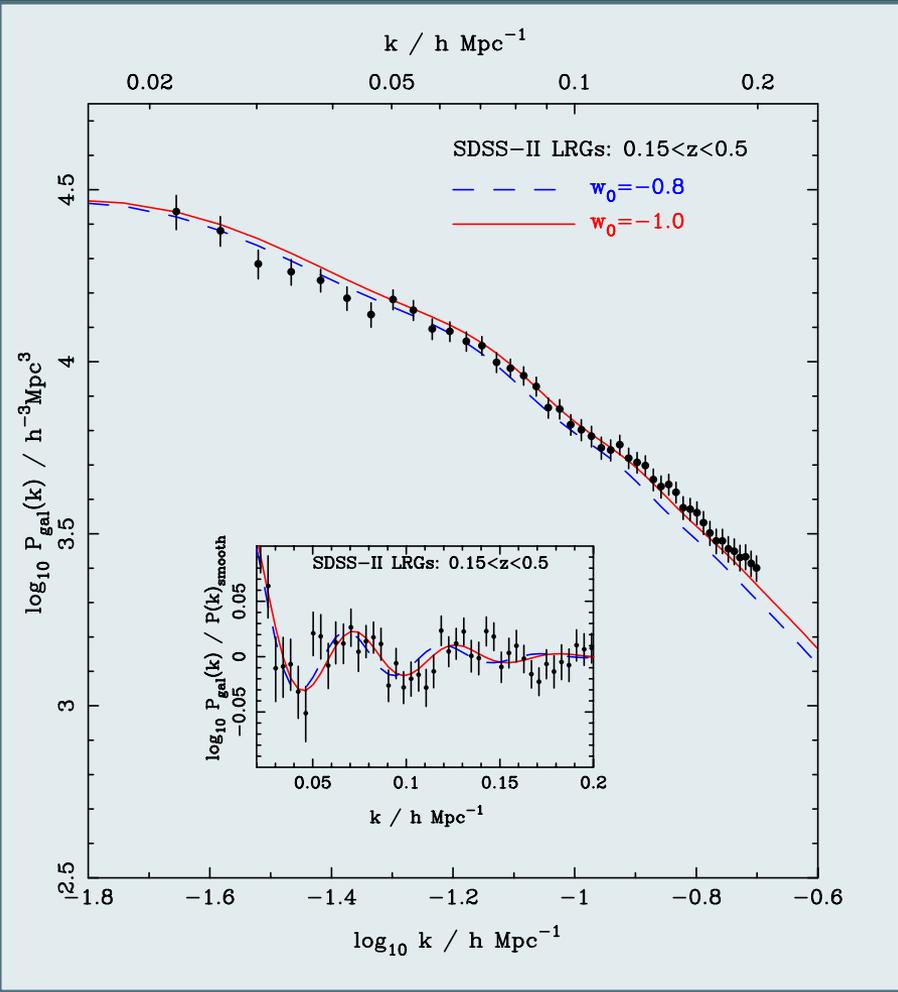


Watch this Space!

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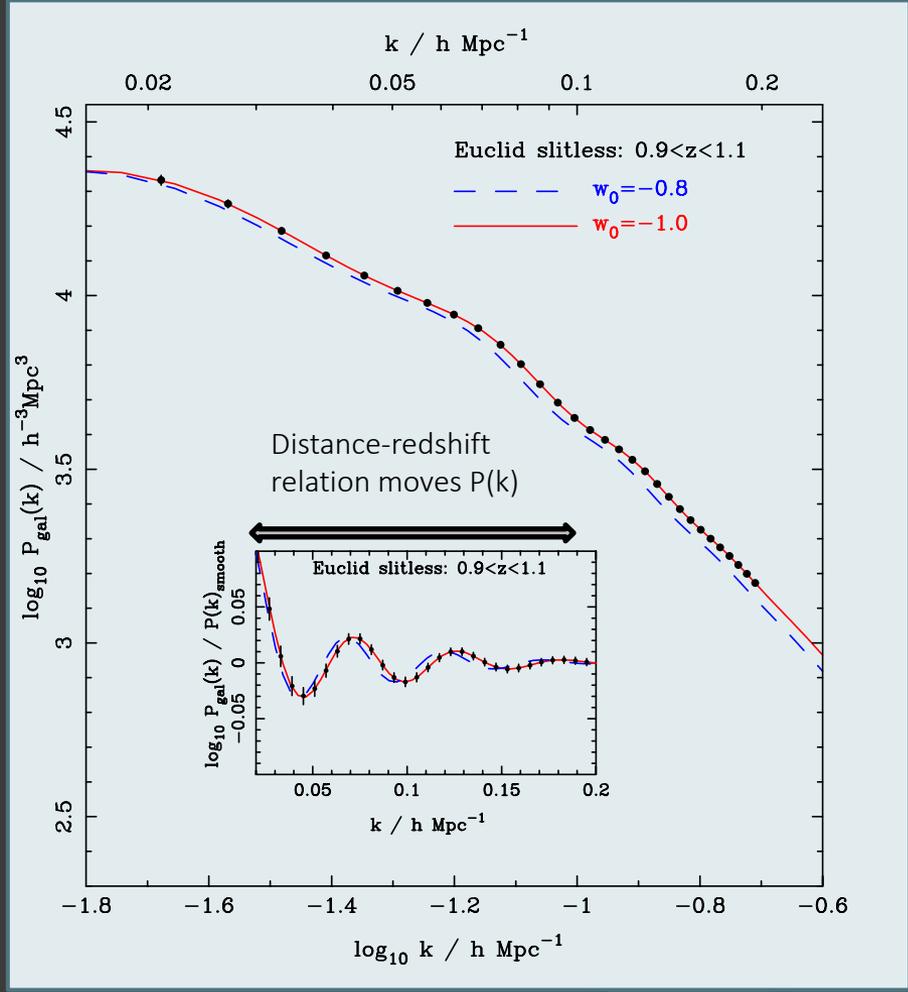


BAO : SDSS vs Euclid



SDSS today

$0.15 < z < 0.5$



EUCLID expected

$0.7 < z < 2.0$



The Takeaway

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

THANK YOU!