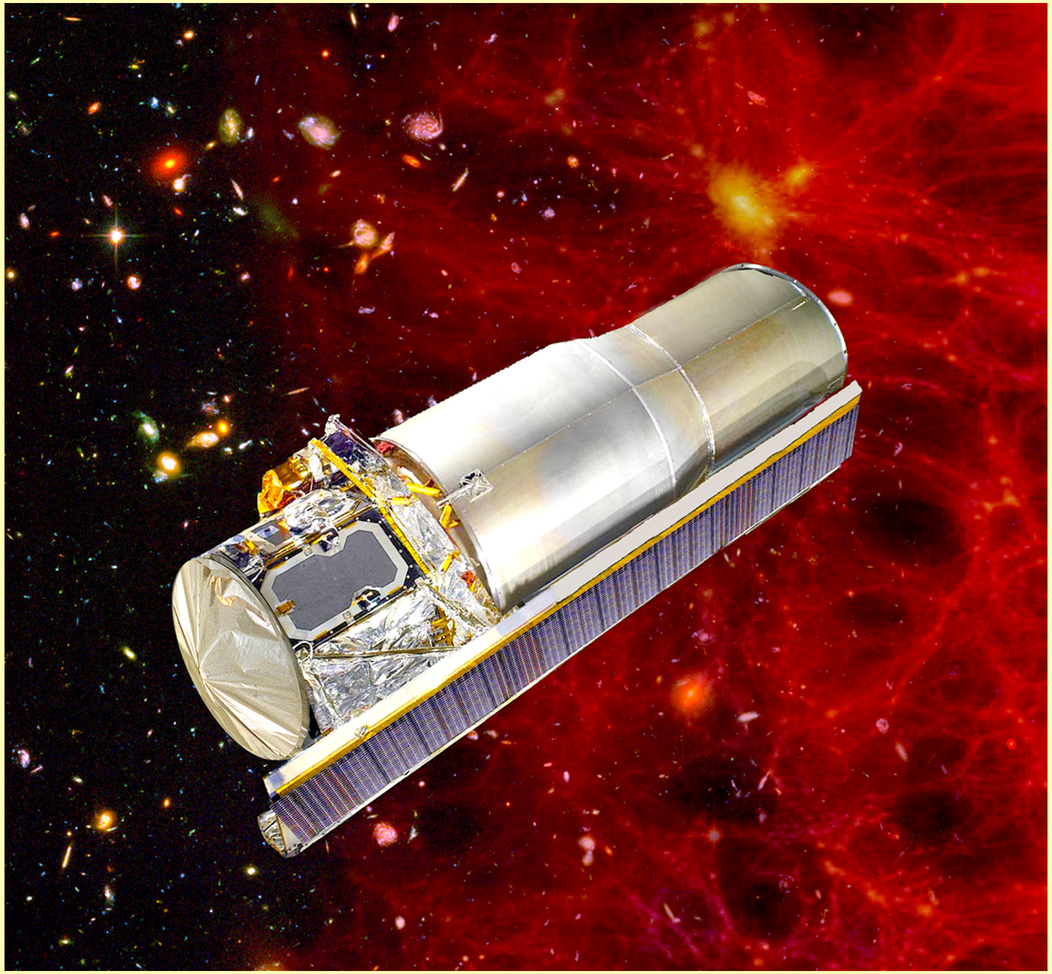
Cosmology in the ATLAS era

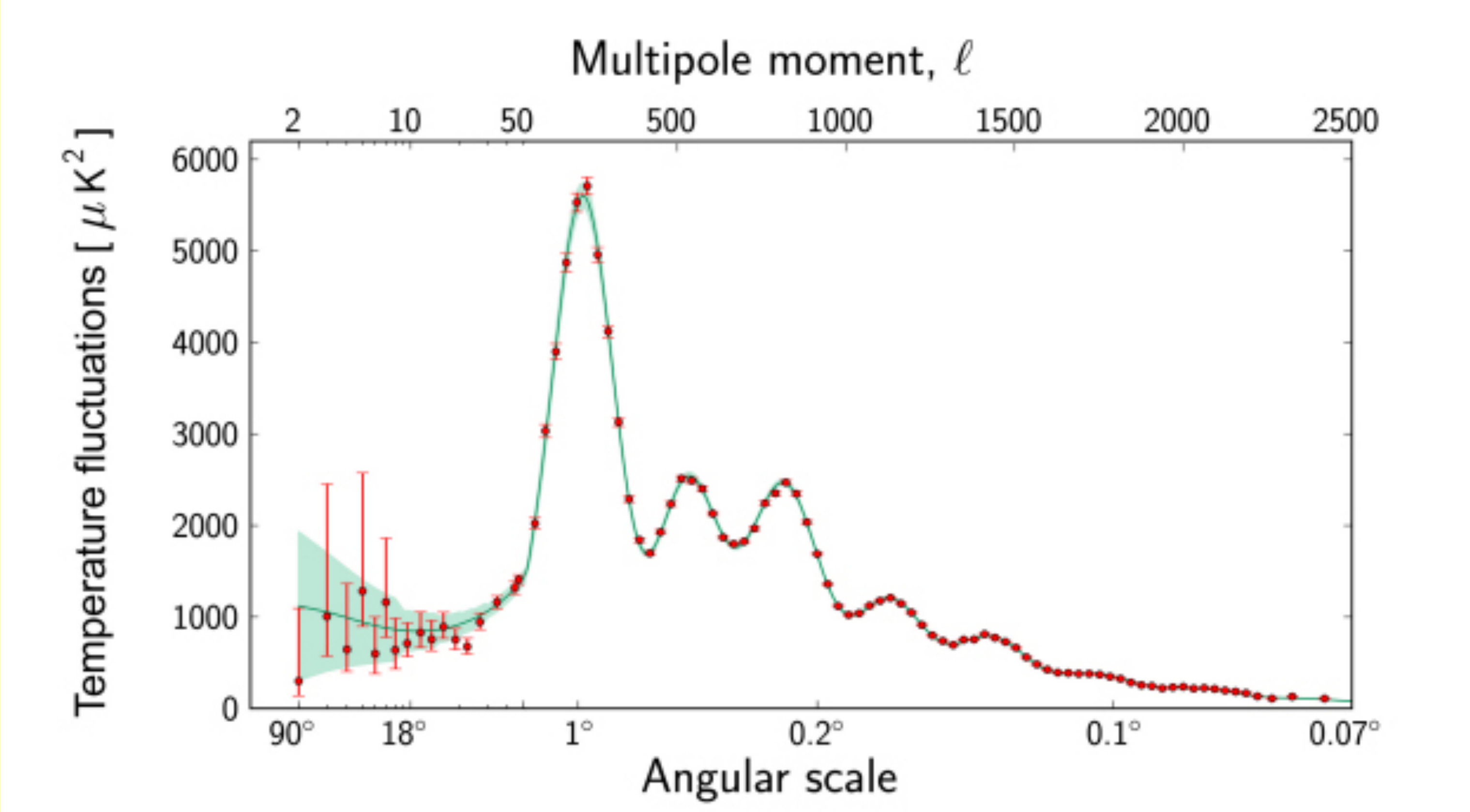


John Peacock

Spectroscopy from space

21 June 2021

The big cosmological questions



- Cosmology has had inflationary LCDM as a standard model for structure formation for ~ 25 years
  - Established during 1990s using galaxy clustering + CMB
  - Validated independently by SNe and BAO
  - Has survived huge improvements in data precision
- But we've never been happy

The big cosmological questions

✓ = via galaxy surveys

- Nature of dark energy
  - Does it evolve? ✓
  - Does it fluctuate?
  - Is it a field that couples to dark matter? ✓

- Nature of dark matter
  - Thermal relic WIMP or scalar field?
  - Mass(es) and cross-sections?
  - Neutrino hierarchy? ✓

- Nature of gravity?
  - Distinctive non-Friedmann expansion history? ✓
  - Non-standard fluctuation growth? ✓

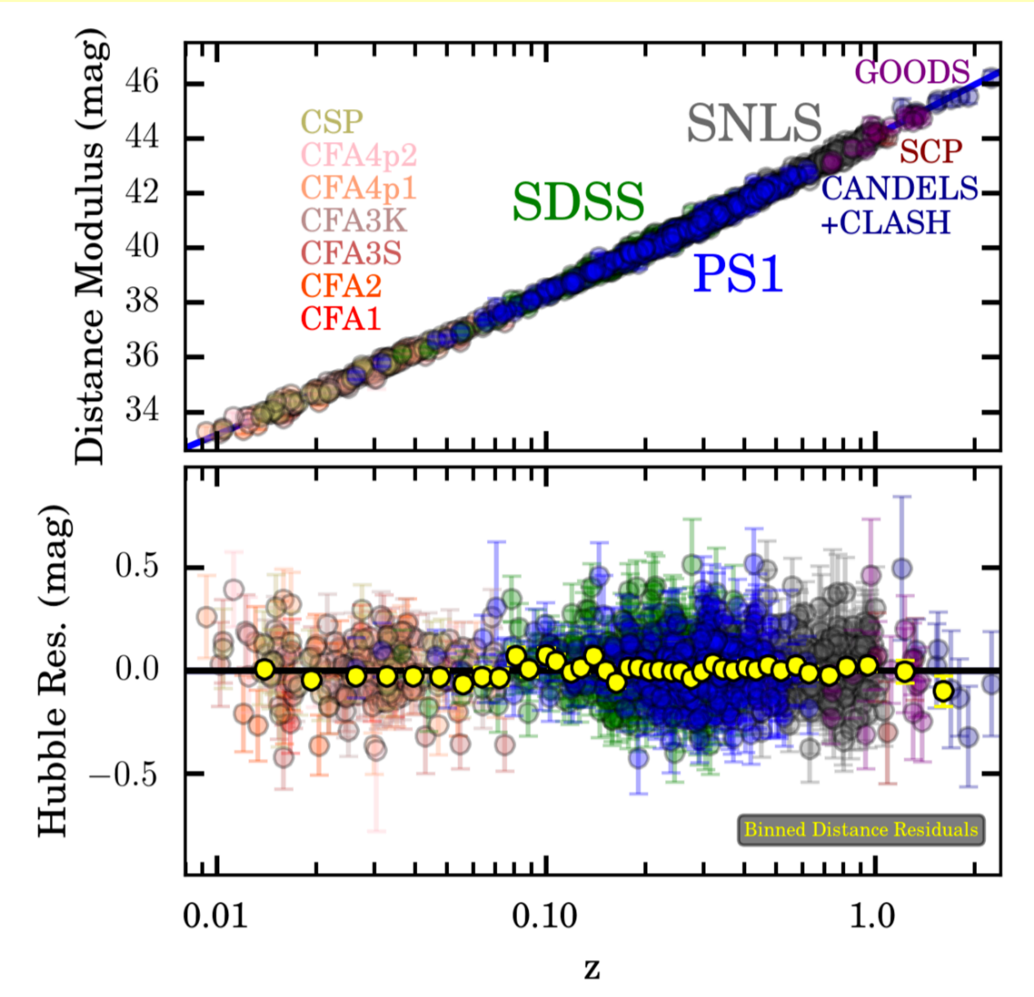
The big cosmological questions

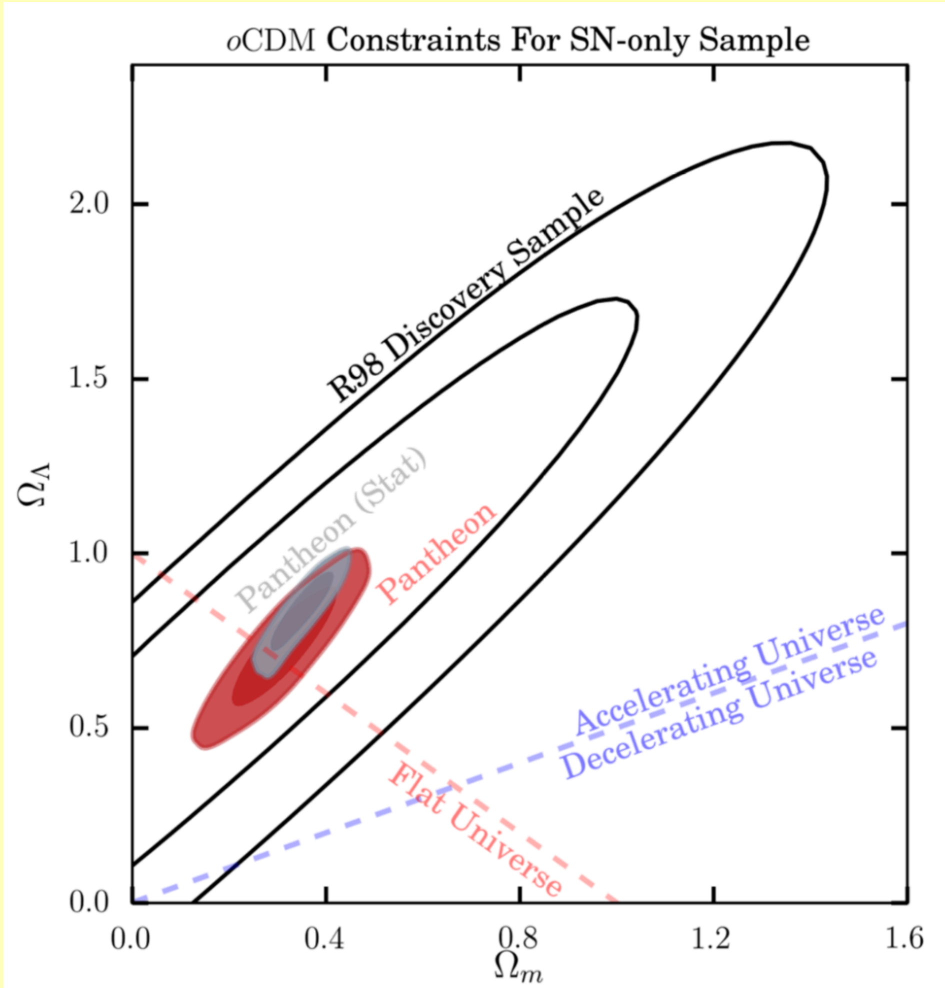
- Initial conditions
  - Did inflation happen?
  - Tensor modes?
  - Isocurvature modes?
  - Non-Gaussianity? ✓

- Fine tunings
  - Why are DM and baryon densities similar?
  - Why is the vacuum density so low?
  - Is there a multiverse? ✓

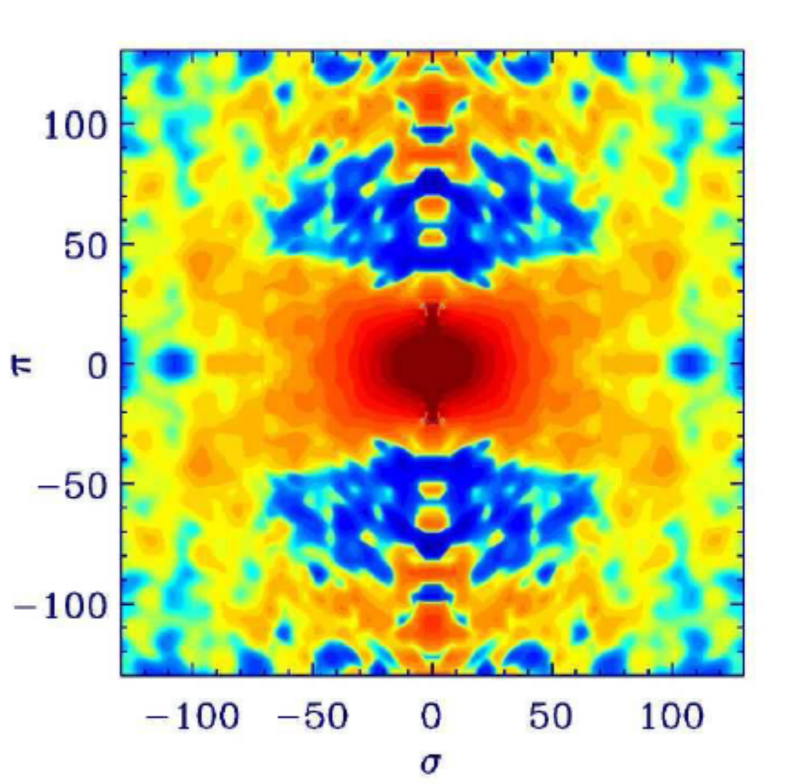
The expansion history from SNe Ia

Pantheon (1710.00845): 1048 SNe



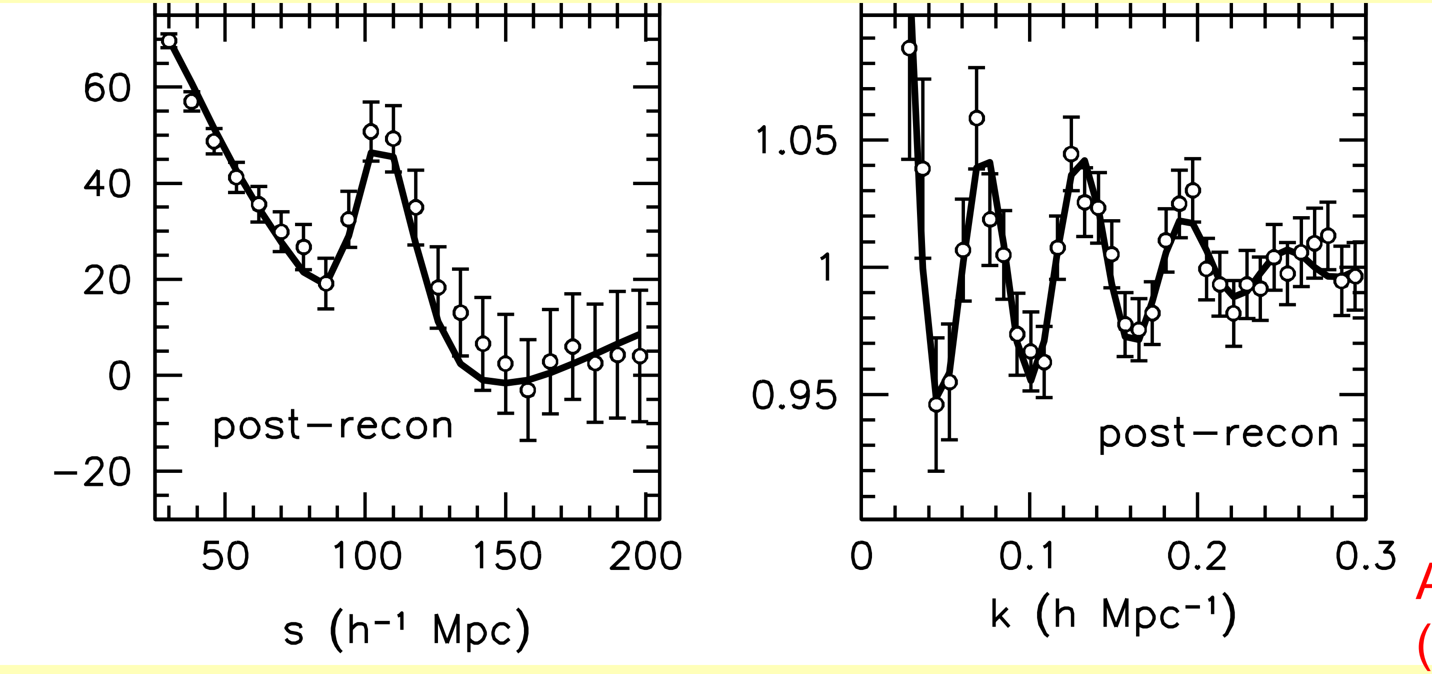


BAO: the acoustic horizon in SDSS



Acoustic horizon at drag era (z=1020):

$s = 147 \, (\Omega_m h^2 / 0.142)^{-0.26} \, (\Omega_b h^2 / 0.0225)^{-0.13}$ Mpc

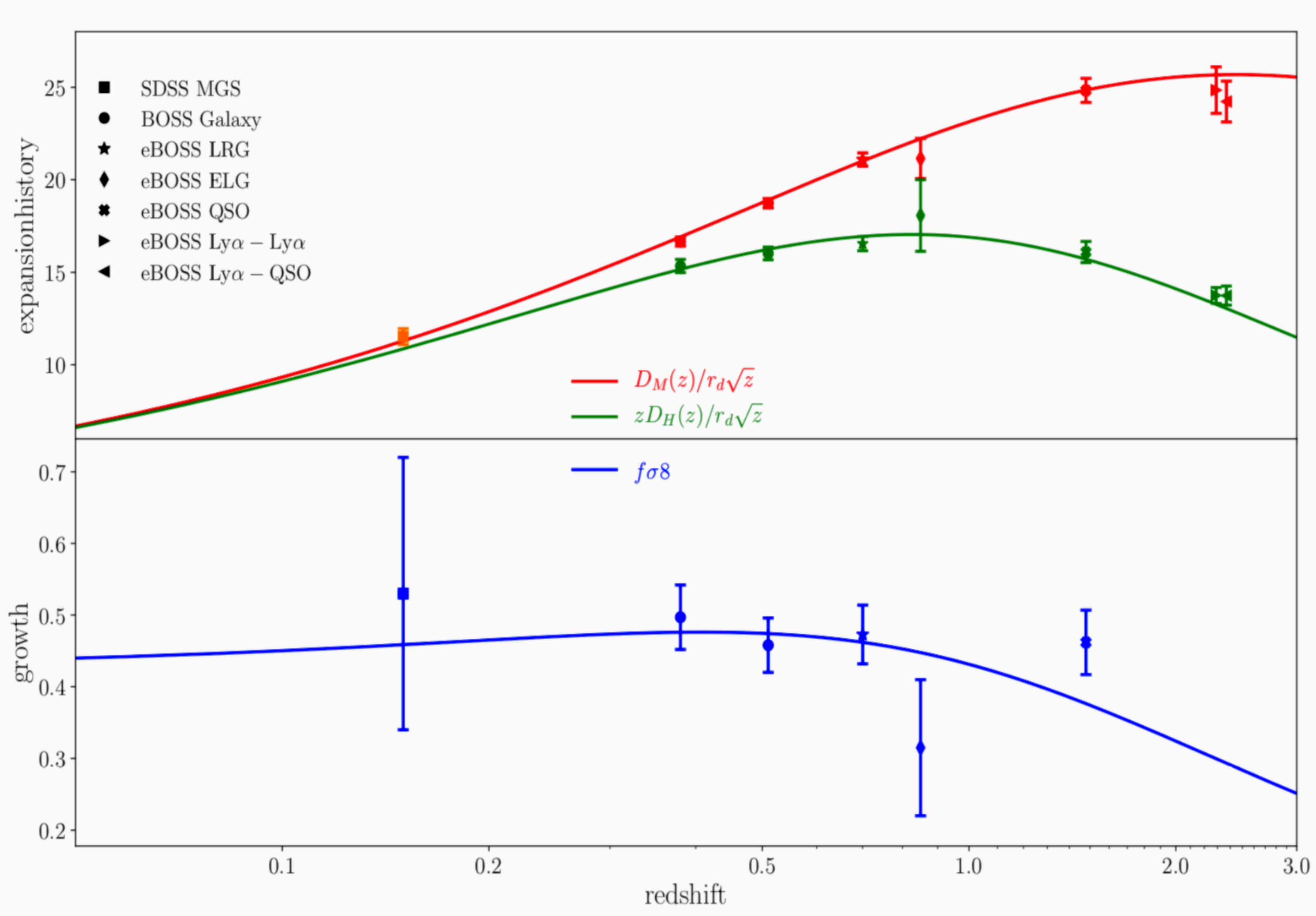


Measure transversely and radially:

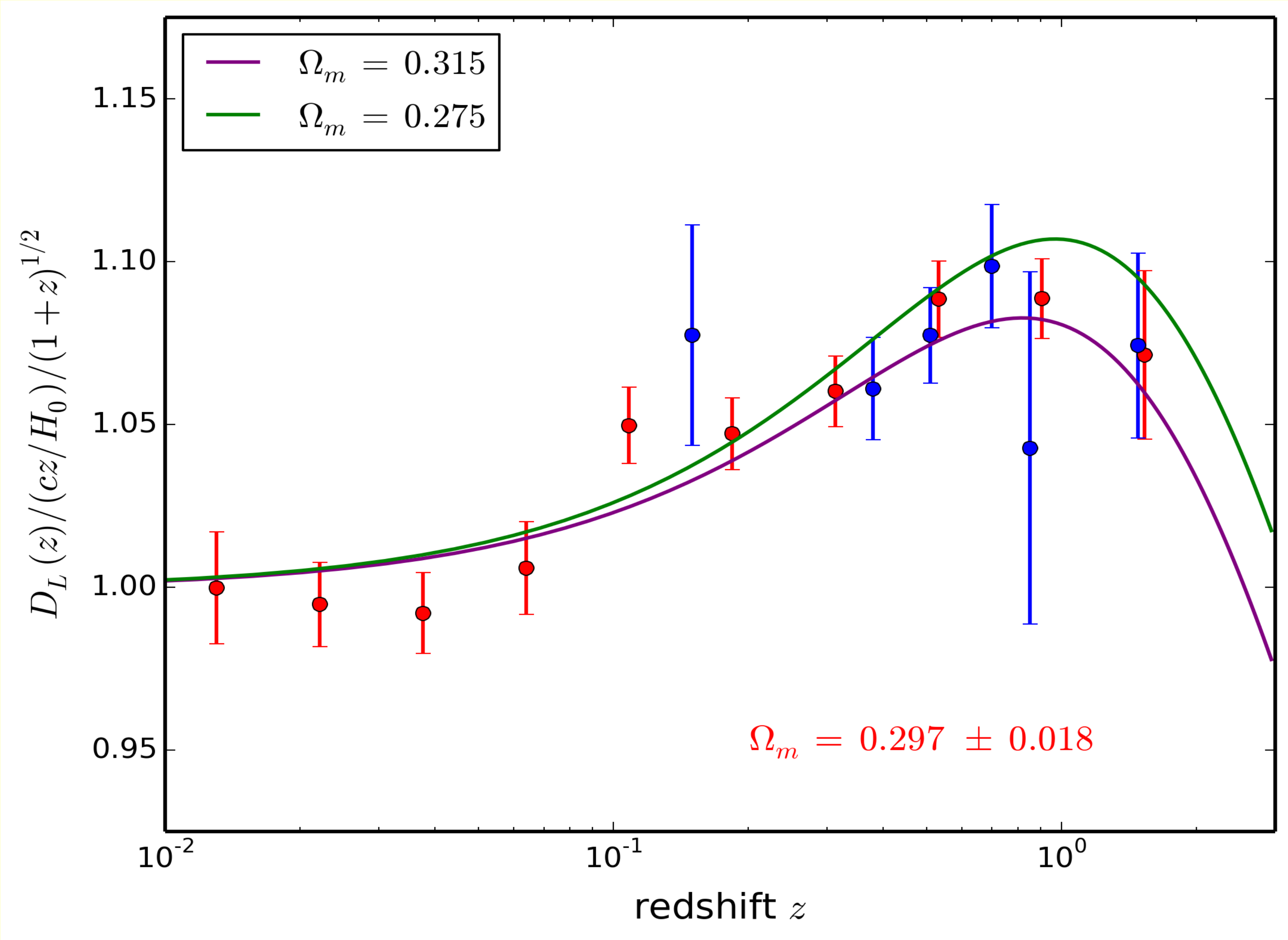
=> D(z) & H(z)

Anderson et al. (2014)

20 years of SDSS (2007.08991)

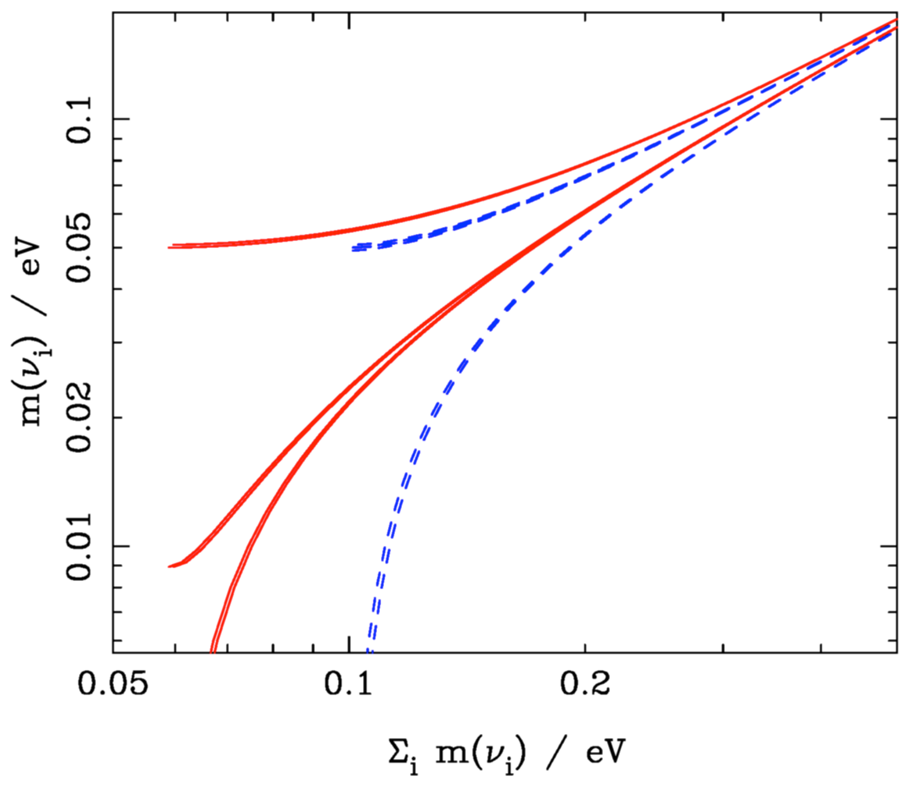


D(z) zoom in

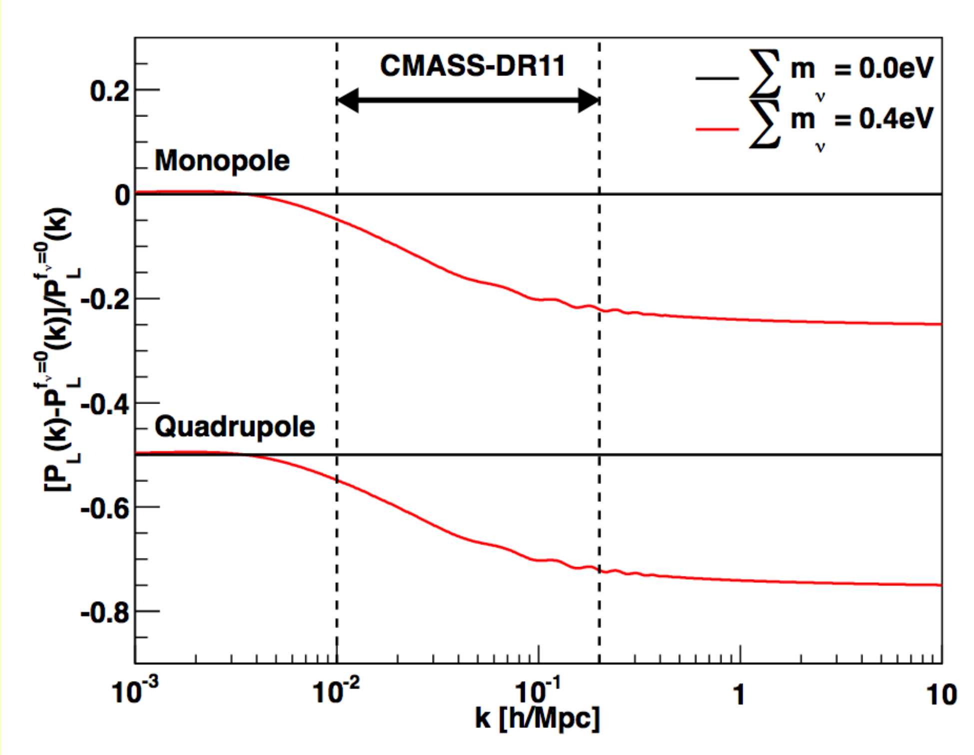


BAO less constraining treated as an empirical ruler

Neutrinos



Normal or inverted hierarchies fit oscillation data



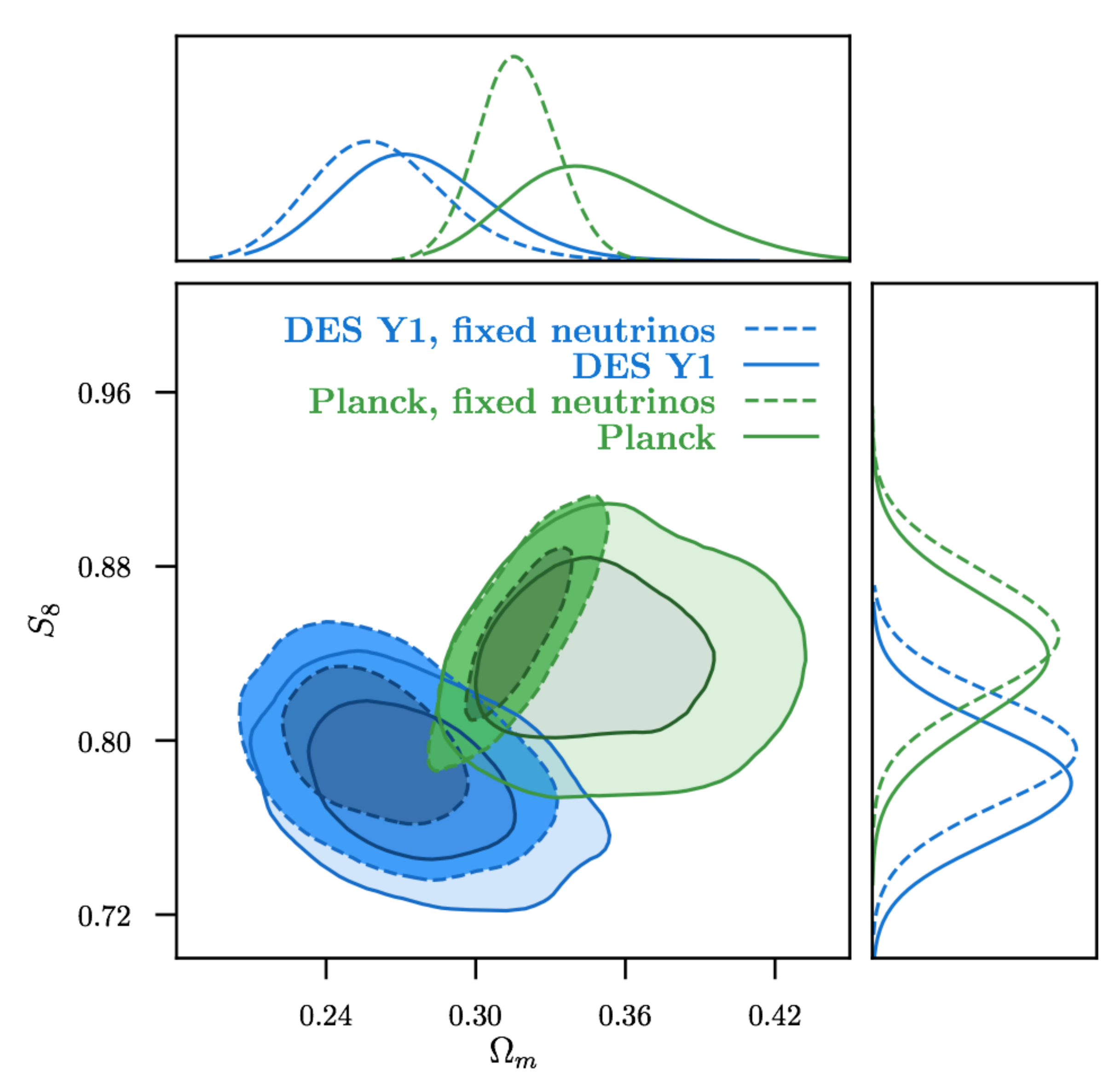
Free-streaming erases neutrino fluctuations

Reduced growth rate for k > ~ 0.01 − reduced σ_8

Claims of detection at m = 0.36 +/- 0.10 eV (1403.4599)

Planck++ 2018: m < 0.12 eV (0.06 eV smallest possible)

Signature on $S_8 - \Omega_m$ plane



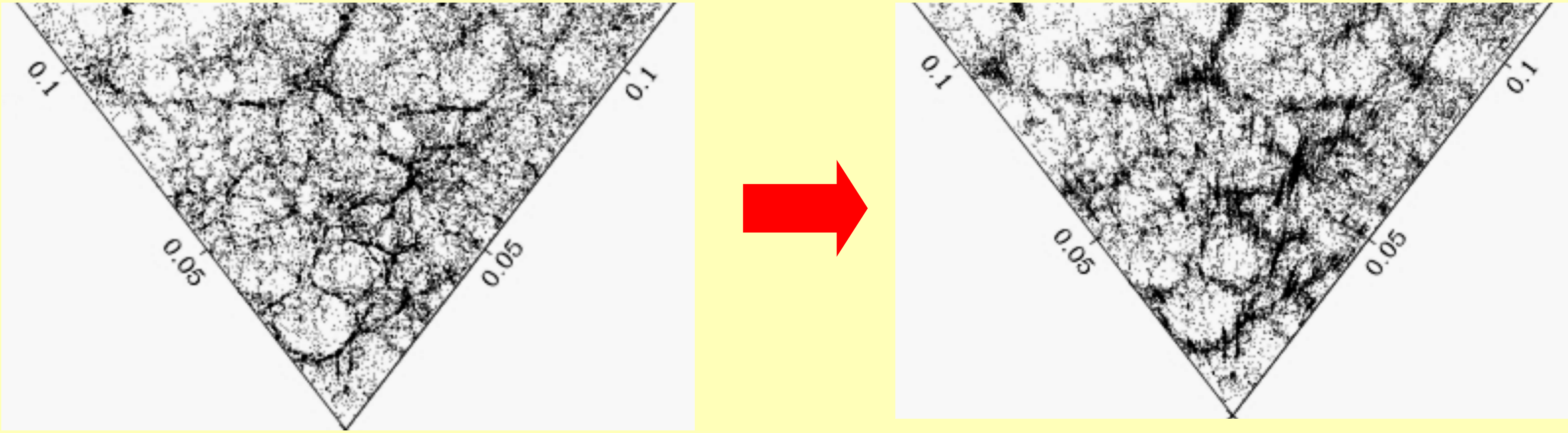
$S_8 = \sigma_8 (\Omega_m/0.3)^{0.5}$

Planck CMB inferences with assumed larger neutrino mass:
(1) lower normalization;
(2) higher density – reflecting altered D(z)

Ideally need independent constraint on density, independent of S_8

Redshift-space distortions as a probe of gravity

$$D \simeq cz/H \rightarrow (cz_{\cos} + \delta v)/H$$



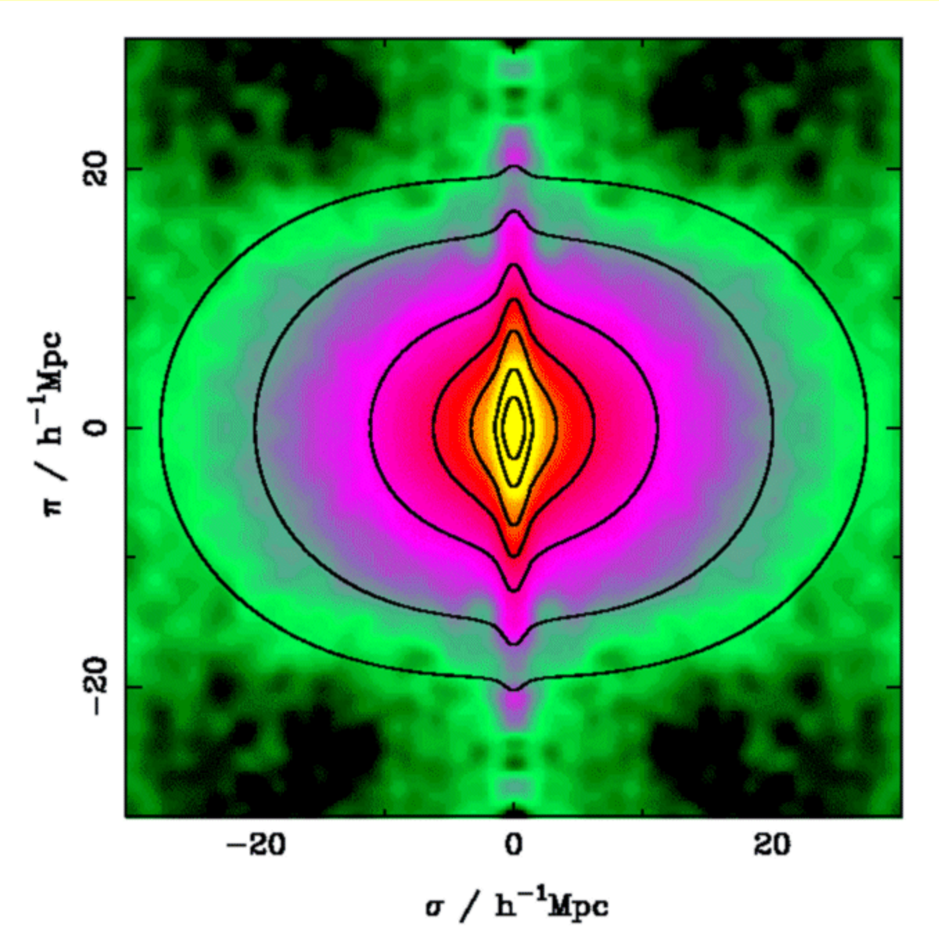
Mass: measure $f_g \equiv d\ln\delta/d\ln a$ $\quad$ ($\simeq \Omega_m^{0.55}$ for standard gravity)
Galaxies: measure $\beta \equiv f_g/b$; $\quad$ b unknown, but $f_g\sigma_8$ observable

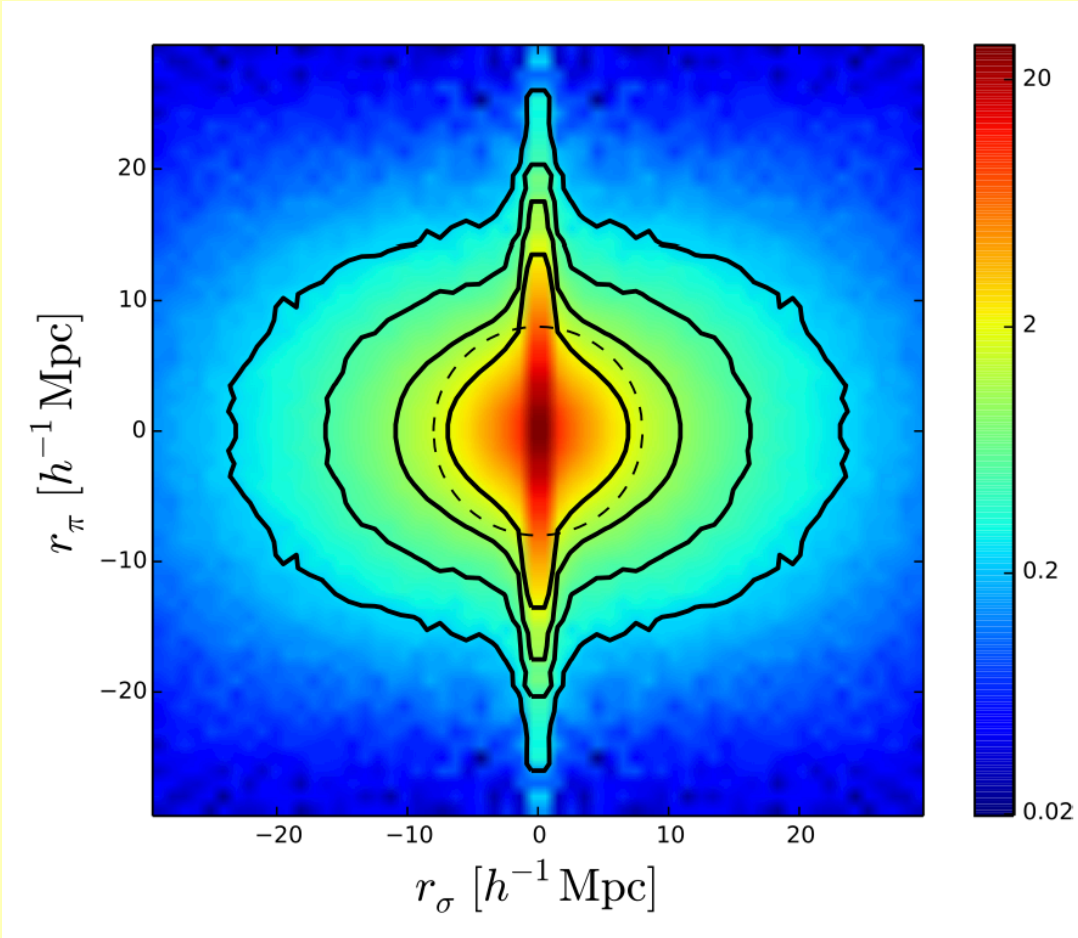
$P(k)$ approximately Kaiser-Lorentz: $P(k,\mu) = P_{\rm real}(1+\beta\mu^2)^2(1+k^2\sigma_p^2/2)^{-1}$

Infer β from quadrupole-to-monopole ratio in anisotropic power spectrum
Use simulations to assess deviations from simple distortion model (and to assign errors)

2 decades of RSD

Split 2-point correlations in transverse and radial directions

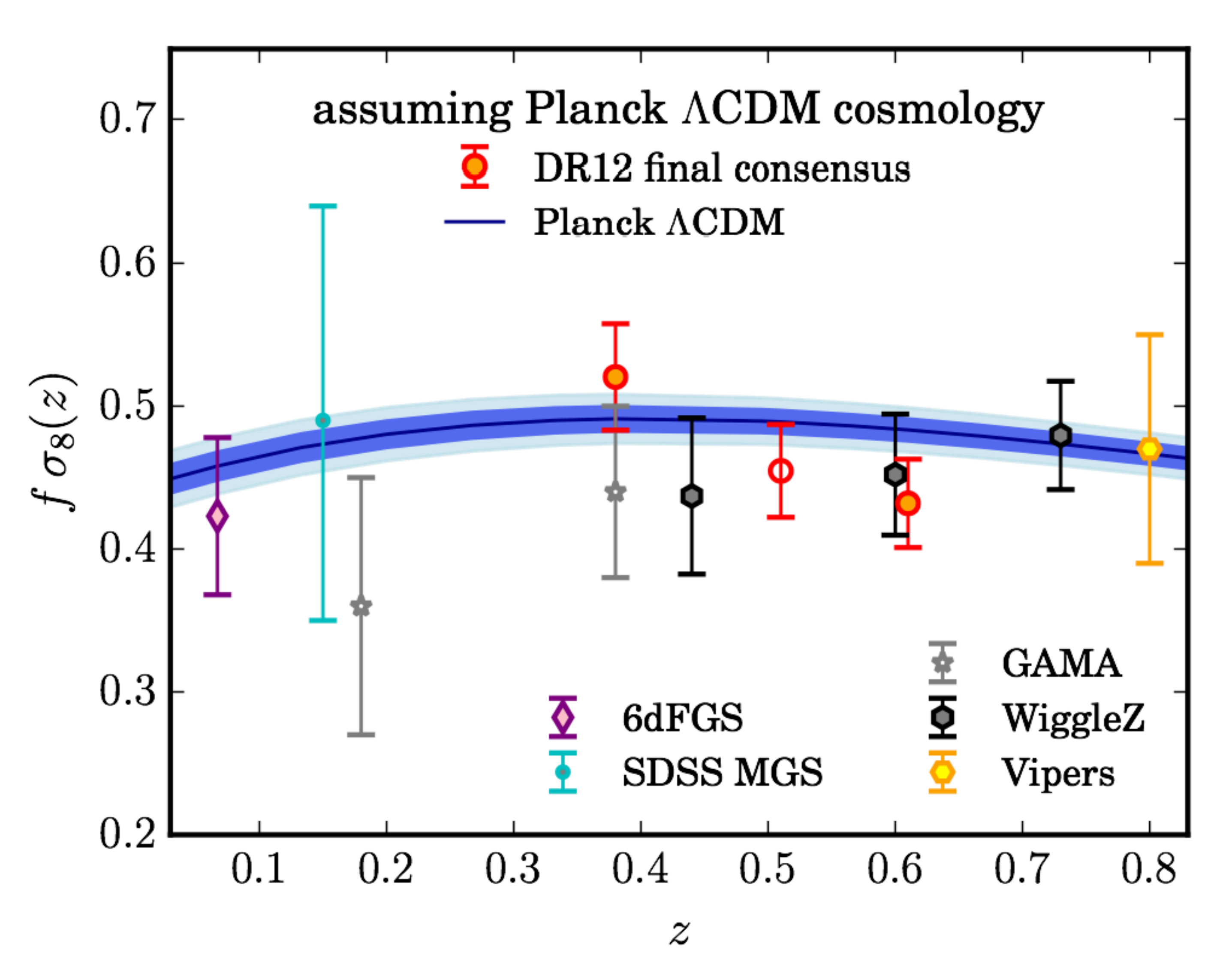




2001: 2dFGRS 8% on $f_g\sigma_8$

2014: SDSS LRG 2.5% on $f_g\sigma_8$

Growth rate: Einstein OK at 5-10%



1607.03155

DESI, Euclid will push towards <1% precision at higher z

The modified gravity programme

$$S[g_{\mu\nu},\phi] = \int \mathrm{d}^4x \sqrt{-g}\left[\sum_{i=2}^{5} \frac{1}{8\pi G_{\mathrm{N}}}\mathcal{L}_i[g_{\mu\nu},\phi] + \mathcal{L}_{\mathrm{m}}[g_{\mu\nu},\psi_M]\right]$$

$$\mathcal{L}_2 = G_2(\phi,\, X)$$

$$\mathcal{L}_3 = G_3(\phi,\, X)\Box\phi$$

$$\mathcal{L}_4 = G_4(\phi,\, X)R + G_{4,X}(\phi,\, X)\left[(\Box\phi)^2 - \phi_{;\mu\nu}\phi^{;\mu\nu}\right]$$

$$\mathcal{L}_5 = G_5(\phi,\, X)G_{\mu\nu}\phi^{;\mu\nu} - \frac{1}{6}G_{5,X}(\phi,\, X)\left[(\Box\phi)^3 + 2\phi_{;\mu}{}^{\nu}\phi_{;\nu}{}^{\alpha}\phi_{;\alpha}{}^{\mu} - 3\phi_{;\mu\nu}\phi^{;\mu\nu}\Box\phi\right]$$

$$\Box\phi \equiv g^{\mu\nu}\phi_{;\mu\nu}\ , X \equiv -1/2 g^{\mu\nu}\phi_{;\mu}\phi_{;\nu}$$

Horndeski Lagrangian:
general form of scalar-tensor theory for 2$^{\mathrm{nd}}$-order equations
– constrained by c(GW)=c(EM), but still much freedom
– strong activity in linear and nonlinear phenomenology
– why should it look so like LCDM?

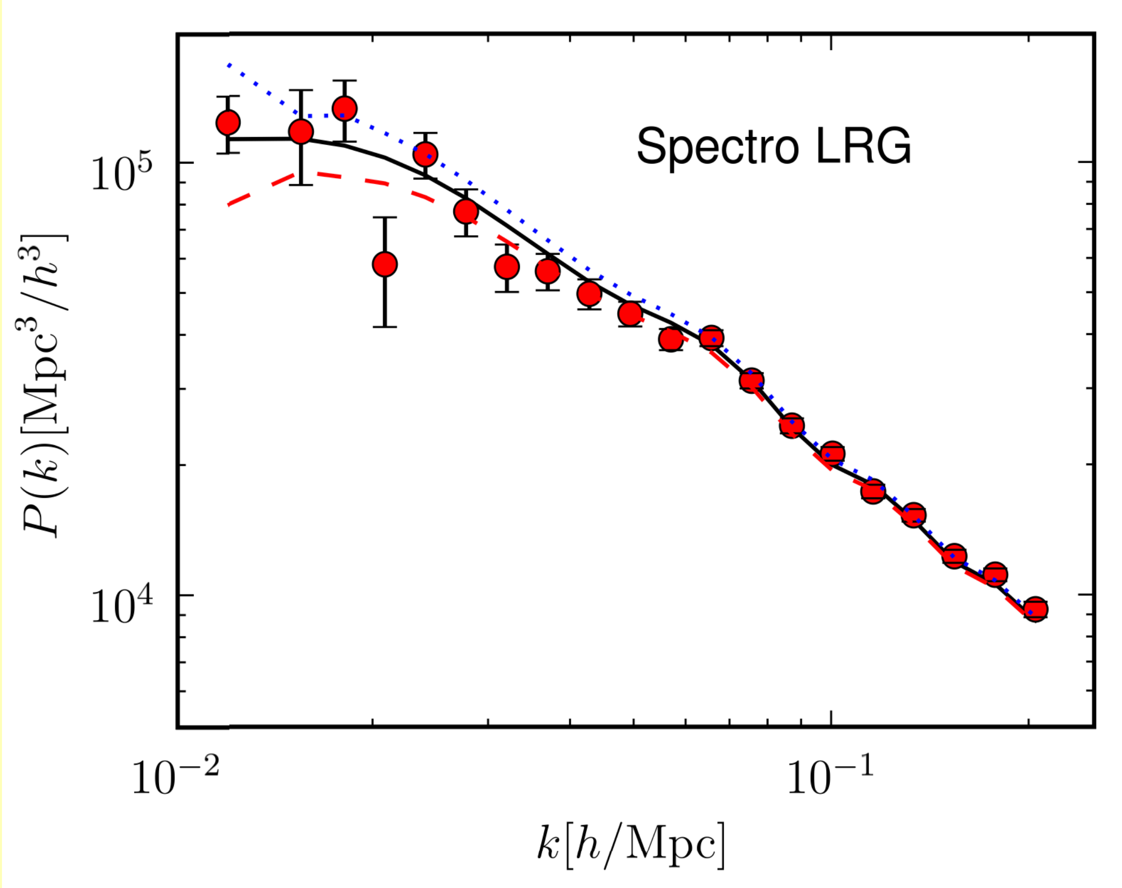
Non-Gaussianity

Potentially deepest impact of LSS on initial conditions

Dalal et al., Matarrese & Verde, Slozar et al., 2008

$$\Phi \to \Phi + f_{\rm NL}(\Phi^2 - \langle \Phi^2 \rangle)$$

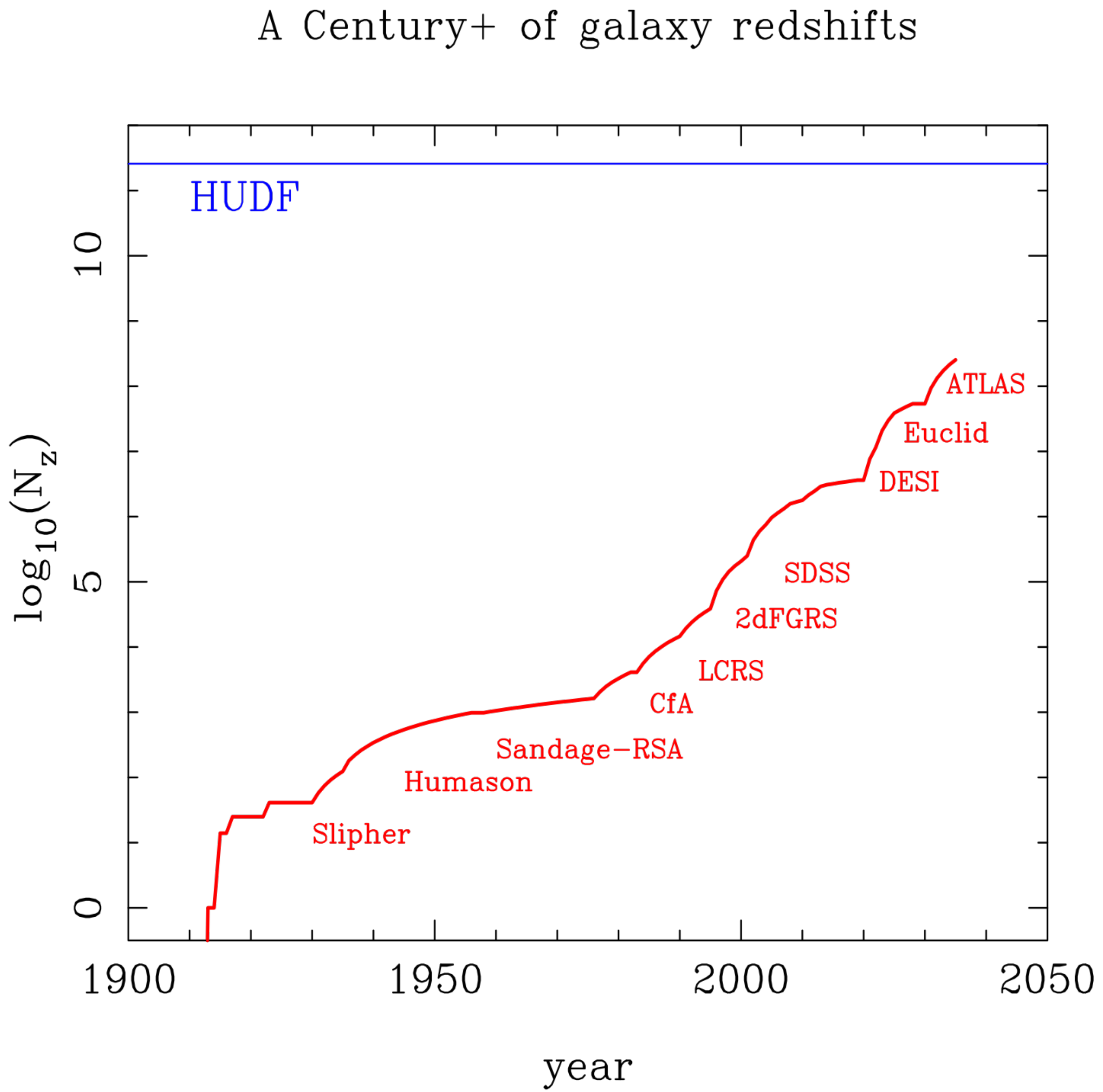
$$\Rightarrow b(k) \to b(k) + O\left[f_{\rm NL}\left(\frac{kc}{H_0}\right)^{-2}\right]$$



Scale-dependent bias limits f_{NL} with precision ~ 25

− less strong than Planck, but DESI/Euclid should reach f_{NL} ~ 1

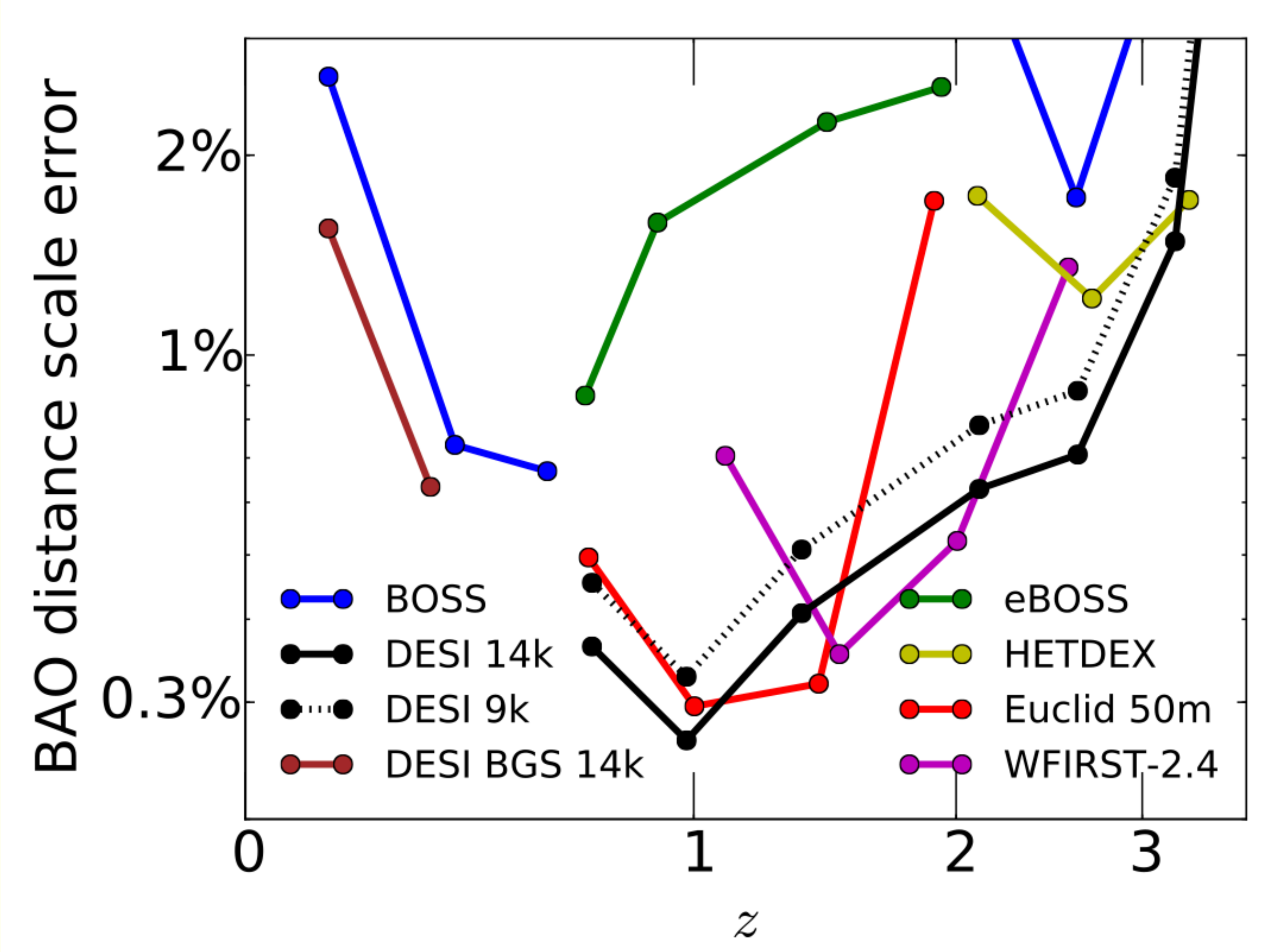
What can ATLAS contribute?



Continuing 'MooreZ law' to boost sample size by 10

– so perhaps a factor 3 improvement in precision

Mid-2020s: 0.1% cosmology



Sensitivity to Dark Energy

$$D(z) = \frac{c}{H_0}\int_0^z \frac{dz}{[\Omega_v(1+z)^{3+3w}+\Omega_m(1+z)^3+\Omega_k(1+z)^2]^{1/2}}$$

Dark Energy affects H(z), D(z) and perturbation growth g(z)

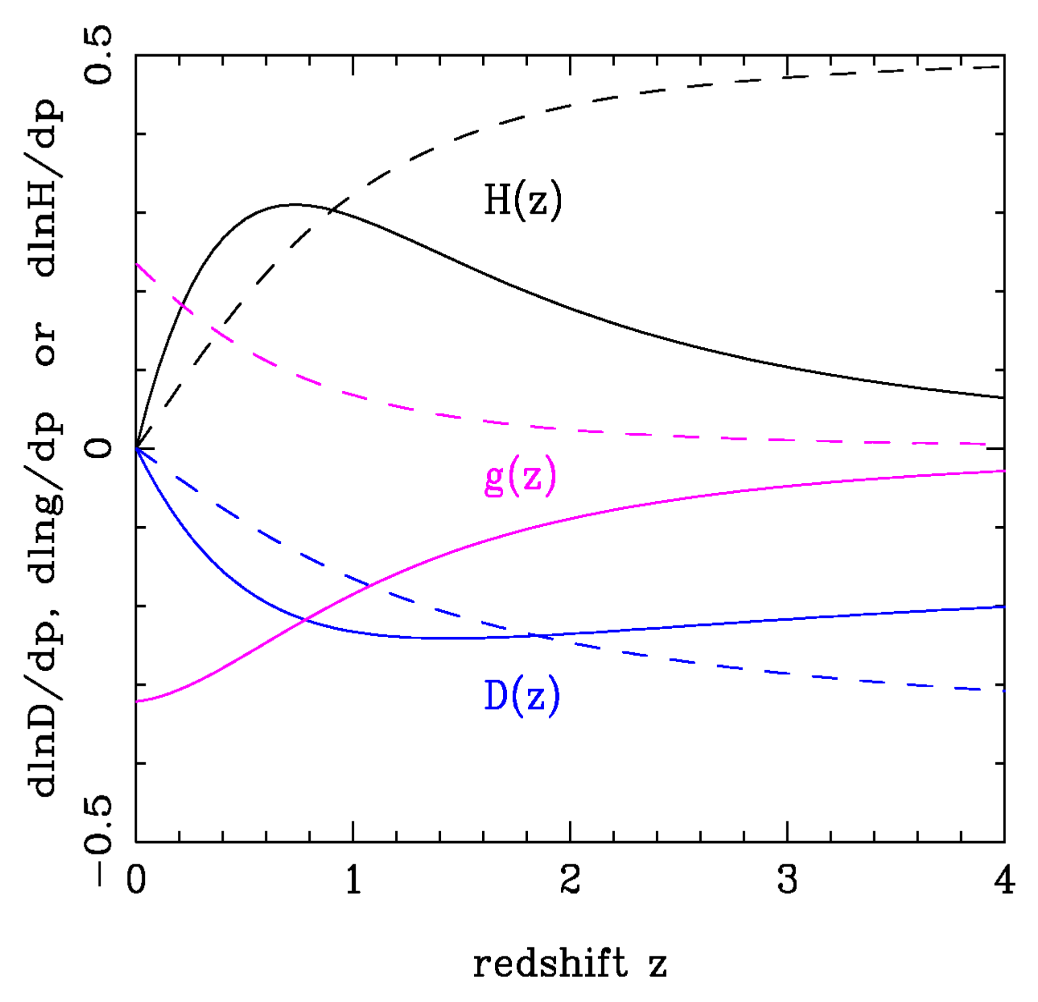
Effects of w are:

(1) Small (need D to 1% for w to 5%)

Rule of 5

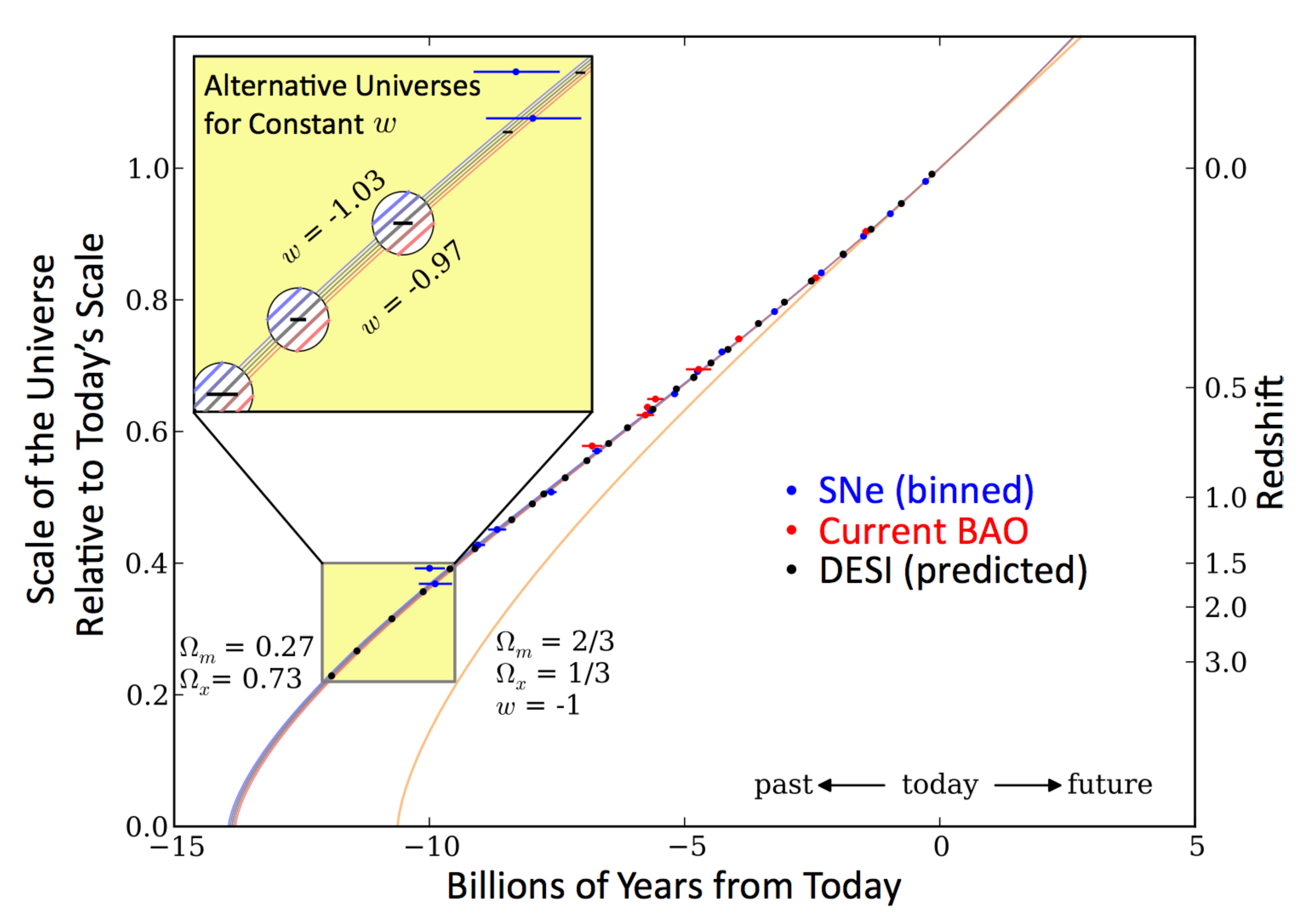
(2) Degenerate with changes in Ω_m

< 0.1% on BAO scale feasible with DESI/Euclid – but not in growth rate

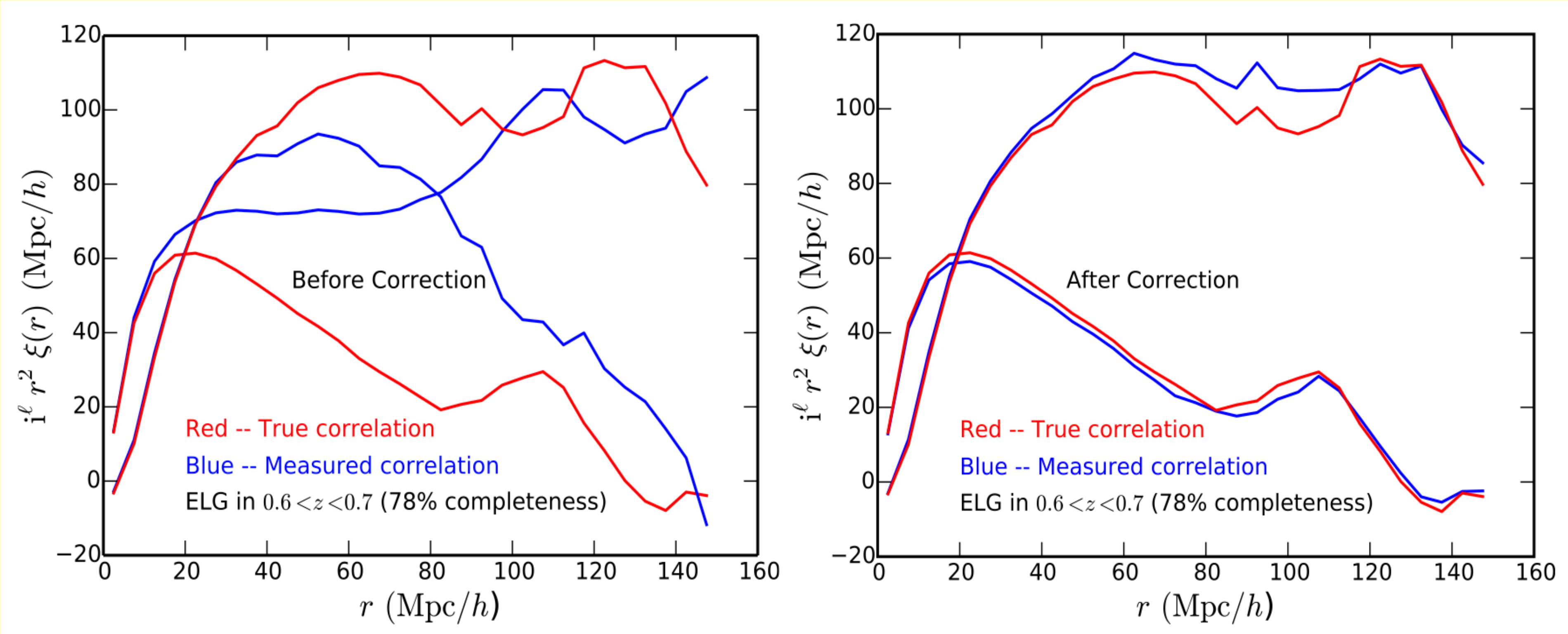


Solid: vary w Dashed: vary Ω_m

but precision is challenging

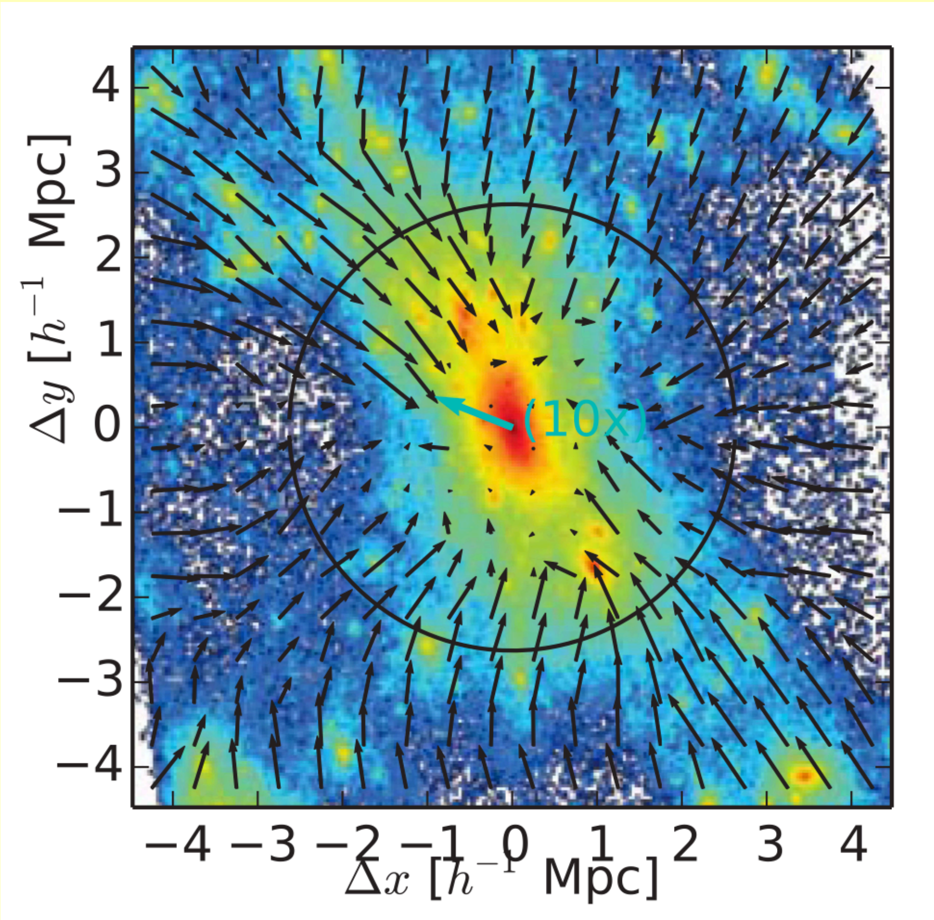


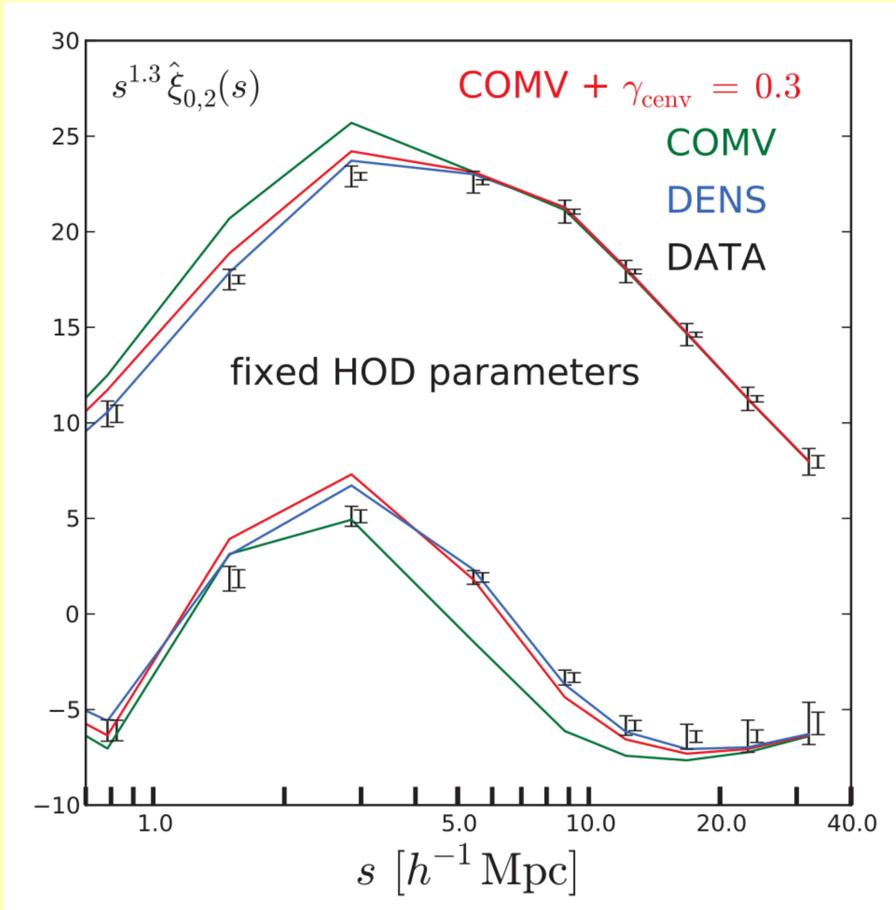
Vulnerability to data imperfections



Spectroscopic target selection causes O(1) raw systematics from missing close pairs, which must be corrected to 0.1% precision

Vulnerability to nonlinear modelling





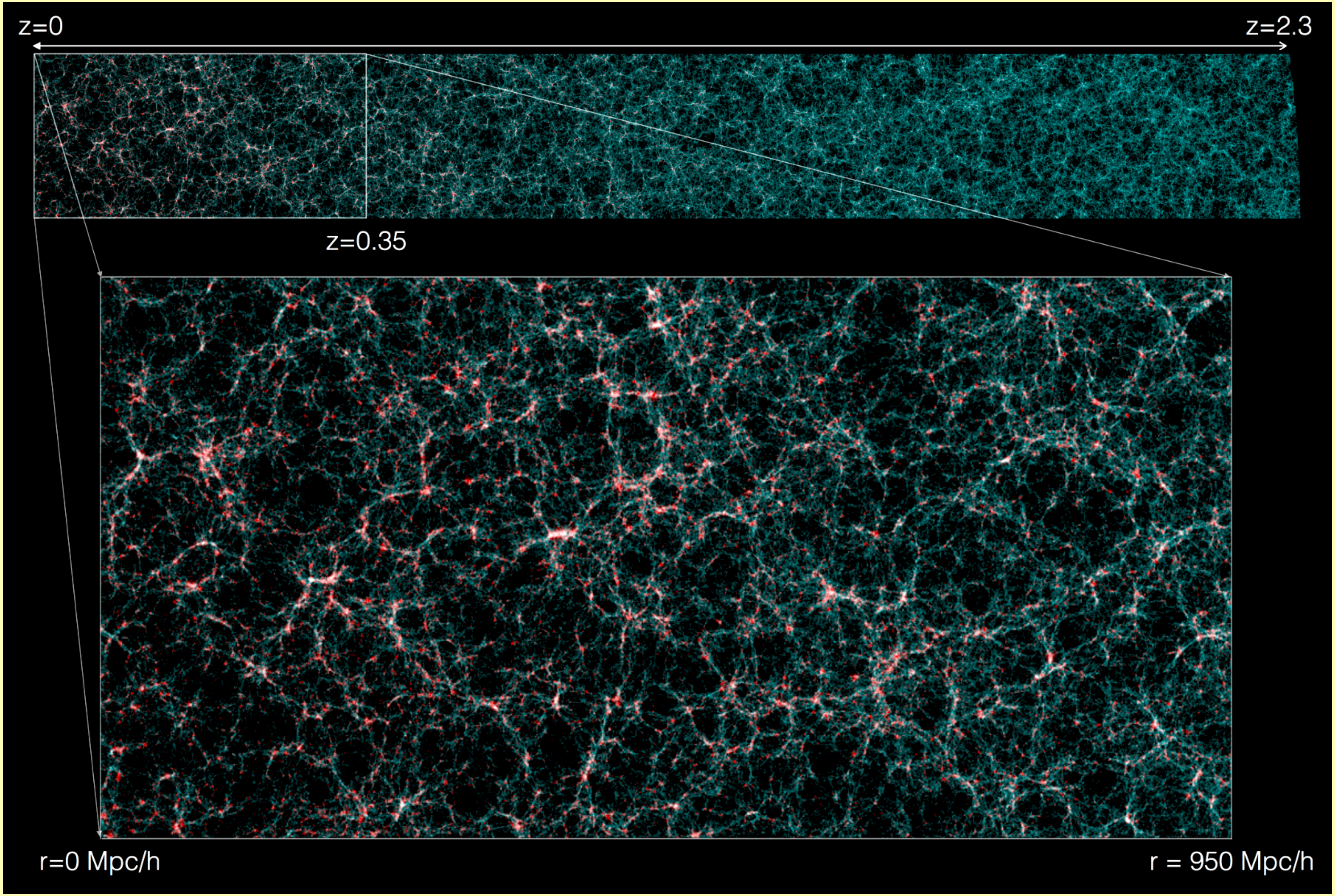
e.g. Reid et al. (2014): central galaxy velocity offset matters in RSD modelling at % level

Necessary astrophysical issues

- Galaxy-halo connection
  - bias and nonlinear clustering
  - need mock data even with analytic theory

- Environmental effects
  - ‘assembly bias’: halo galaxy contents not just N(M)
  - gravitational lensing
    - shear from tidal forces
    - baryonic modification of mass distribution from feedback

Euclid Flagship Mock



2 trillion particles; 2 billion ‘galaxies’ from halo model $N_g(M_{halo})$

N(M+++)? Assembly bias

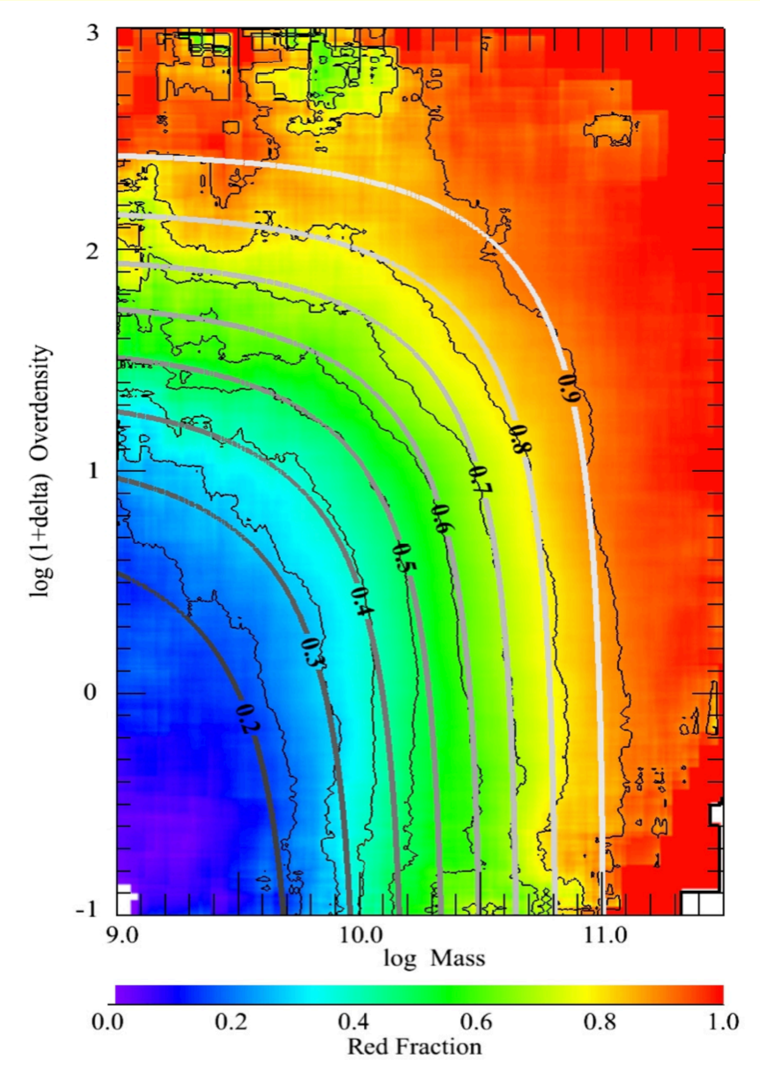
- Not just that haloes collapsing early are more clustered
  - Always present in Kaiser (1984)
  - Halo model averages over such effects:

$b(M,z_f) + N(M)$: $< b\,N > \;=\; < b > \; < N >$

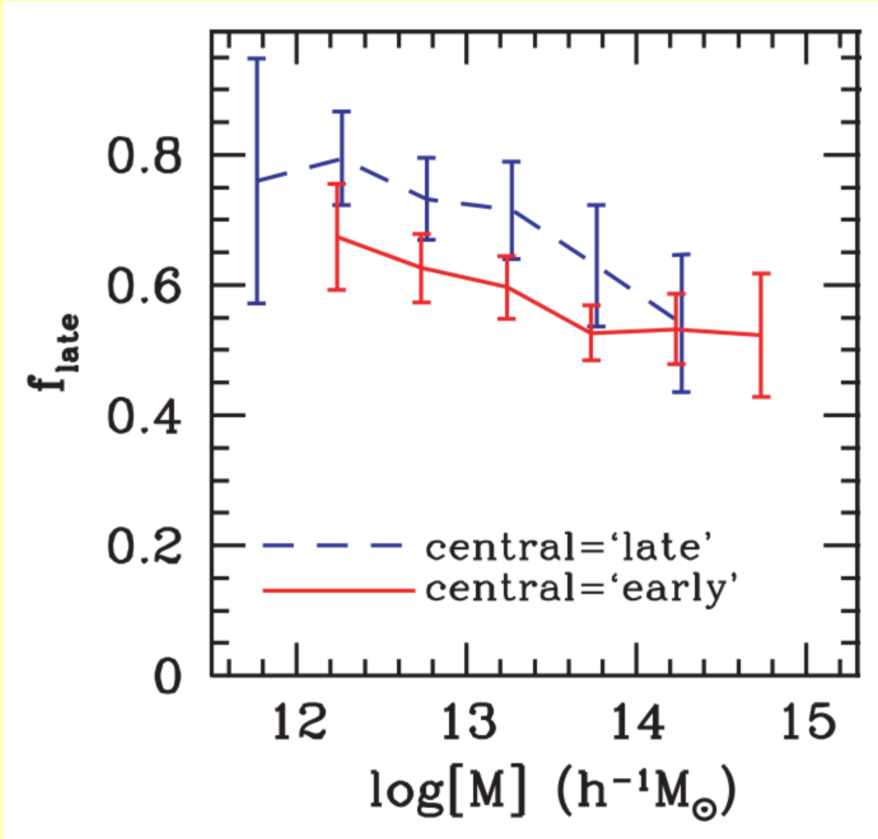
- But galaxy contents(M) can couple to formation z:
  - Early formation yields older stars
  - But deeper potential: harder to quench?
  - Early formation gives fewer subhaloes (= satellites)

$b(M,z_f) + N(M,z_f)$: $< b\,N > \;\neq\; < b > \; < N >$

Environment and galaxy formation



Quenching empirically relates to environment (Peng et al. 2010)



'galactic conformity' within haloes as sign of assembly bias (Weinmann et al. 2006). Also more controversial suggestions of conformity with neighbouring haloes (Kauffmann 2012, 2015)

A challenge for theory

$$
\begin{aligned}
P^{hh}(k) = \int d^3q\; e^{i\mathbf{k}\cdot\mathbf{q}} \exp\left[-\frac{1}{2}k_i k_j A_{ij}^{\rm lin}\right] \Bigg\{ & 1 - \frac{1}{2}k_i k_j A_{ij}^{\rm 1-loop} - \frac{i}{6}k_i k_j k_l W_{ijk}^{\rm 1-loop} \\
& - b_1\left(k_i k_j A_{ij}^{10} - 2ik_i U_i^{(1)}\right) + b_1^2\left(\xi_L + ik_i U_i^{11} - k_i k_j U_i^{(1)} U_j^{(1)}\right) \\
& + b_2\left(ik_i U_i^{20} - k_i k_j U_i^{(1)} U_j^{(1)}\right) + b_1 b_2\left(2ik_i U_i^{(1)}\xi_L\right) + b_2^2\left(\frac{1}{2}\xi_L^2\right) \\
& - b_{s^2}\left(k_i k_j A_{ij}^{20} - 2ik_i V_i^{10}\right) + b_1 b_{s^2}\left(2ik_i V_i^{12}\right) + b_2 b_{s^2}\chi^{12} + b_{s^2}^2\zeta_L \\
& - \frac{1}{2}\alpha_\xi k^2 + i2b_{\nabla^2}\left(k_i\frac{\nabla^2}{\Lambda_L^2}U_i^{(1)}\right) + 2b_1 b_{\nabla^2}\left(\frac{\nabla^2}{\Lambda_L^2}\xi_L\right) + \ldots \Bigg\} + \text{“stochastic”},
\end{aligned}
$$

EFT programme: supplement perturbation expansion with general terms of correct symmetry. Even for matter, hard to get beyond k = 0.2h Mpc^{-1}.

Vulnerability to Priors

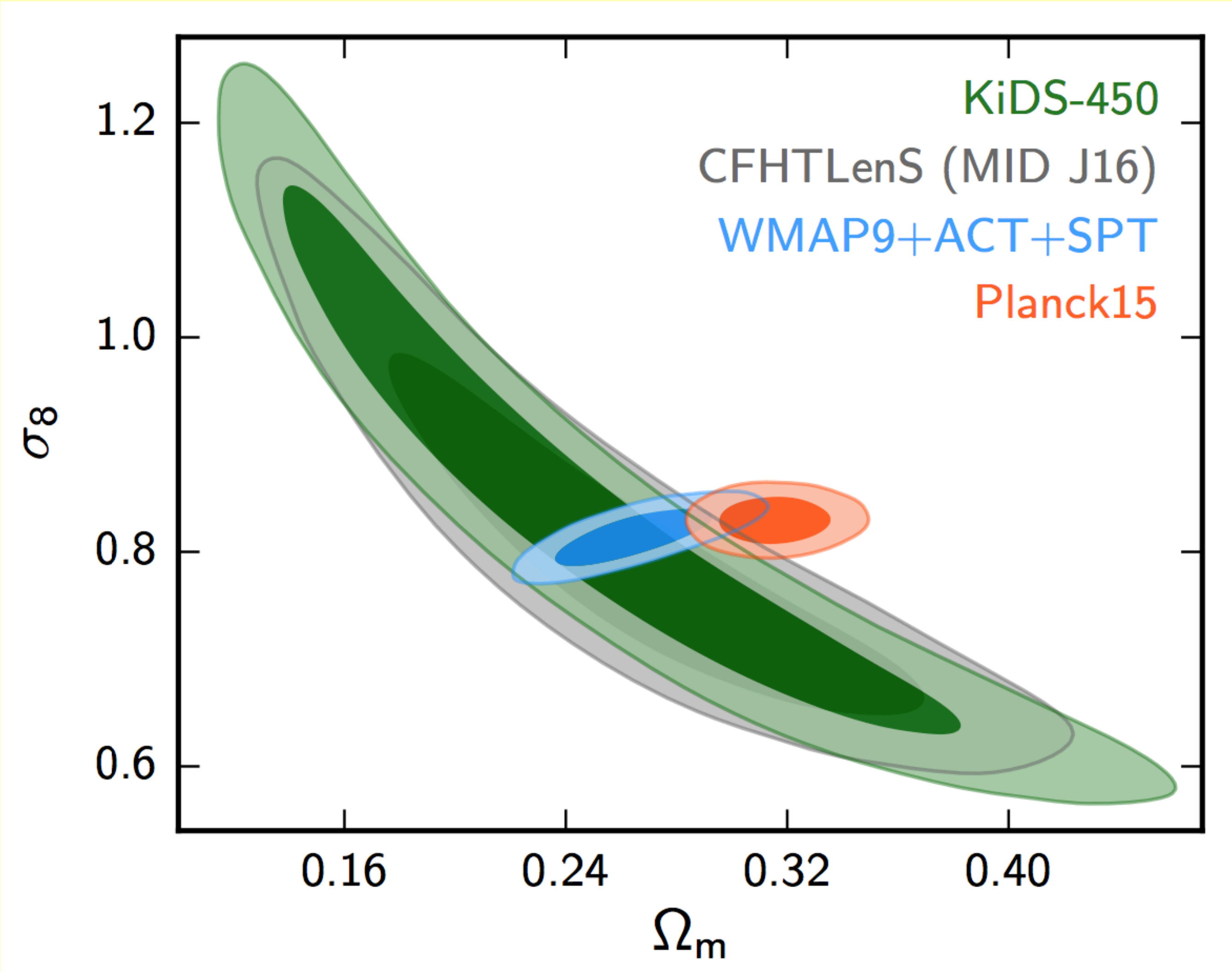
Will we believe any ‘detections’ of new physics?

P(model | data) ~ L(data | model) P(model)

- Moderate prior belief in simplest neutrino hierarchy
- Strong prior belief in unevolving Λ
- Even stronger prior belief in Einstein gravity

Already plenty of ‘detections’ that get ignored: e.g. Λ in 1990s; Bean 2009 GR disproof; 2014 Beutler et al. massive neutrino detection.

e.g. the lensing-CMB σ_8 tension



Evidence for Modified Gravity?
– or just systematics?

1606.05338

+ DES:

1708.01530
2105.13509

A conservative solution (2010.00466)

Total CMB lensing fits Planck:

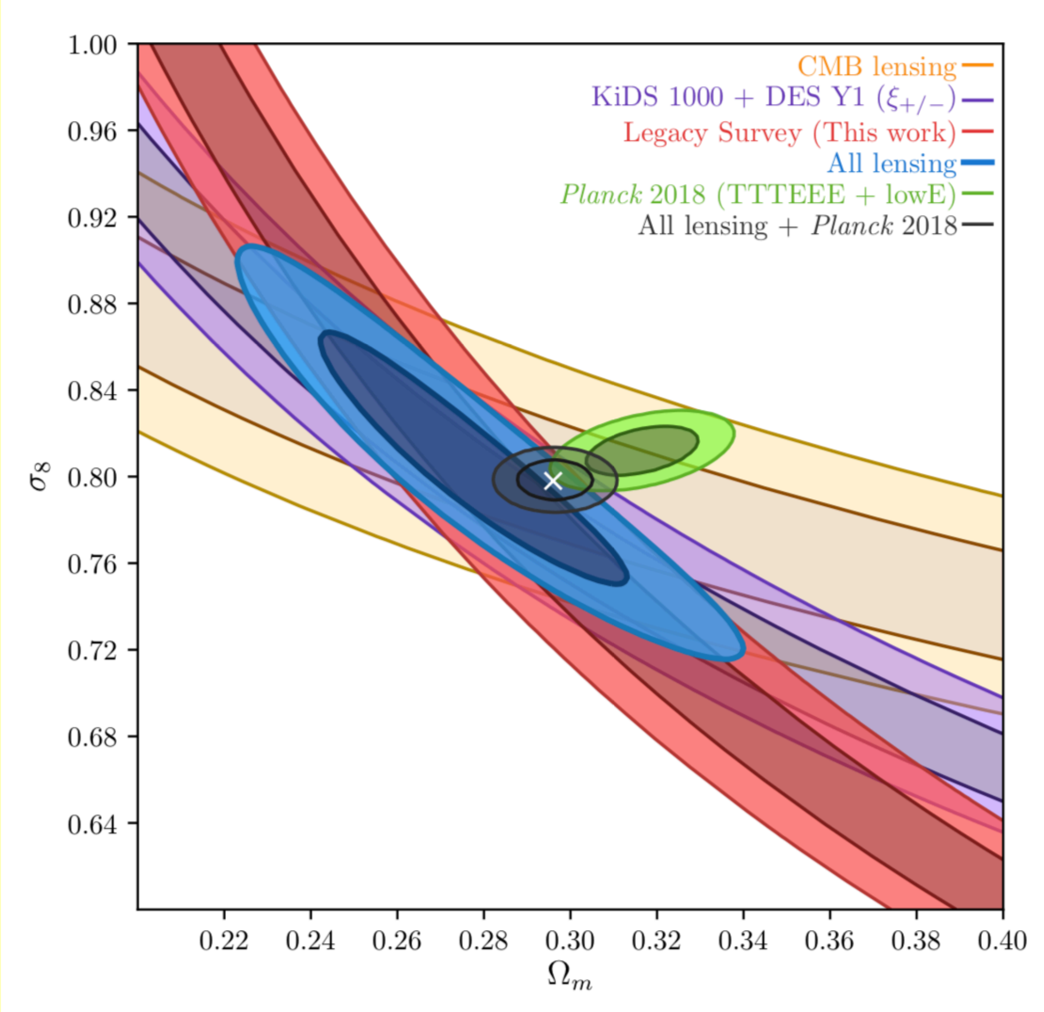
$\Omega_m^{0.25}\,\sigma_8 = 0.589 \pm 0.020$

Local CMB lensing is also low:

$\Omega_m^{0.78}\,\sigma_8 = 0.297 \pm 0.009$

Lensing is consistent, and needs lower density than Planck:

$\boxed{\Omega_m = 0.274 \pm 0.024}$



Formal combination with Planck just consistent with both constraints at 95%

$\boxed{\begin{array}{l}\Omega_m = 0.296 \\ \sigma_8 = 0.798\end{array}}$

Implications for the H_0 tension

CMB most robustly measures $\Omega_m h^3$ – from acoustic scale

– so lower density inevitably means higher h:

$$\Omega_m = 0.296: \quad h = 0.69$$

$$\Omega_m = 0.274: \quad h = 0.71$$

– lower density from lensing removes H_0 tension (although 73 is still too high)

Issues with systematics

- Internal consistency
  - Essential to pass null tests between data subsets
  - If cosmic variance dominates, can rule out many data systematics
  - But if noise dominates, systematics at 1σ level are undetectable
  - cf. Planck results at $\ell < 1000$ vs $\ell > 1000$

- External consistency
  - Some consistency tests are weak (Bayesian Evidence Ratio)
  - But consistency doesn't prove no systematics (1803.04470):
    - True posterior has non-Gaussian wings for 'unknown unknowns'
    - Naïve standard errors only work with many consistent experiments
    - Important role for independent techniques of moderate precision

Conclusions & outlook

- Cosmology has had LCDM as a standard model for structure formation for ~ 25 years
  - Has survived huge improvements in data precision
  - It may be the truth at the precision of even next-generation experiments (only guaranteed signal is neutrino mass)

- Searches for small deviations will remain important
  - But improvements in astrophysical modelling are needed

- Will we understand systematics well enough to believe detections of deviations from LCDM?