PARTICLE COSMOLOGY

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Outline

- Methods: Cosmic Microwave Background (CMB), Large scale Structure of the universe: Weak Lensing (WL), Galaxy clustering and Redshift space distortions (RSD), Lyman alpha forest (LYA), Supernovae (SN)
- Goals:
  - Initial seeds of structure: Inflation
  - Content of the universe: matter, neutrinos, dark matter, dark energy, baryons
  - Past and present of the universe: dark energy etc.
  - New physics, new interactions, new particles
- Current experiments
  - CMB: Planck, WMAP, ACT, SPT, BICEP etc.
  - LSS WL: KIDS, DES, HSC, Planck, SPT
  - LSS RSD: SDSS etc.
  - LSS WL+galaxy clustering: SDSS, DES etc.
  - LSS LYA: SDSS
- Future experiments
  - CMB: SO, SPT, BICEP, CMB S4 etc.
  - LSS: DESI, Euclid, Rubin, Roman etc.

Most plots and tables from PDG

Particle Data Group Machine Learning Review for HEP

New ML review
in PDG (60 pages)

41. Machine Learning

Written November 2021 by K. Cranmer (NYU), U. Seljak (UC Berkeley; LBNL) and K. Terao (SLAC; Stanford U.).

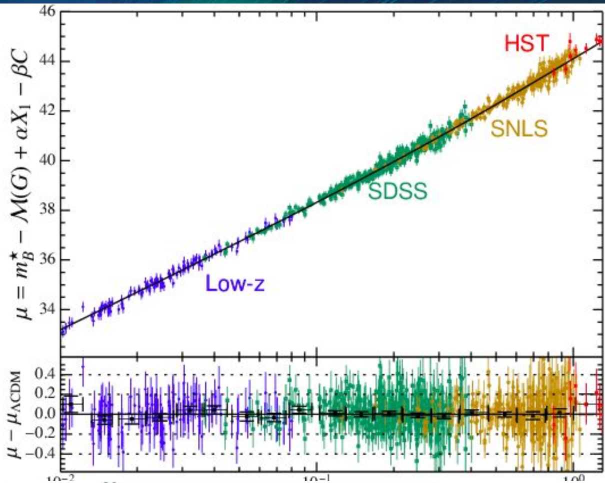
Redshift distance relation

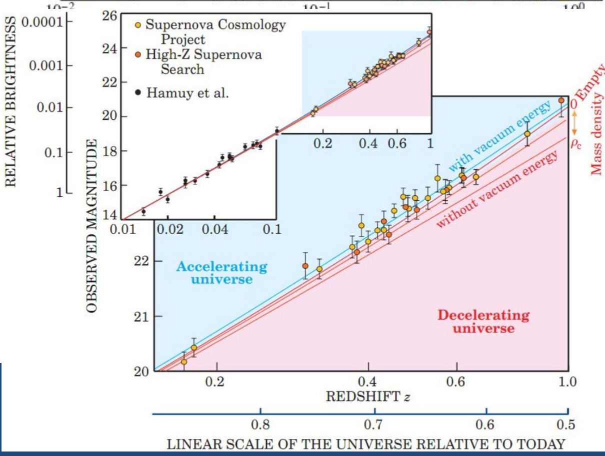
- We wish to test Friedmann equation: expansion a=1/(1+z)

$$\left(\frac{\dot{a}}{a}\right)^2 = H^2 = \frac{8}{3}\pi G\bar{\rho} - Ka^{-2} \qquad D_C(z) = \frac{c}{H_0}\int_0^z dz' \frac{H_0}{H(z')}$$

$$\bar{\rho} = \rho_m a^{-3} + \rho_{\rm de} a^{-3(1+w)} + \rho_\gamma a^{-4} + \rho_\nu F(a)$$

- Doing this as a function of redshift tells us about matter content in the universe: no need to know absolute scale of Hubble parameter. This led to discovery of **dark energy** in 1999
- Doing this in terms of physical units gives us **Hubble parameter** of expansion
- We can measure redshifts of distant objects such as supernovae SN1A
- We can measure their flux. If they are **standard candles** this gives us distance
- Latest analyses suggest SN1A have scatter of 0.1mag (Stein, Seljak…)



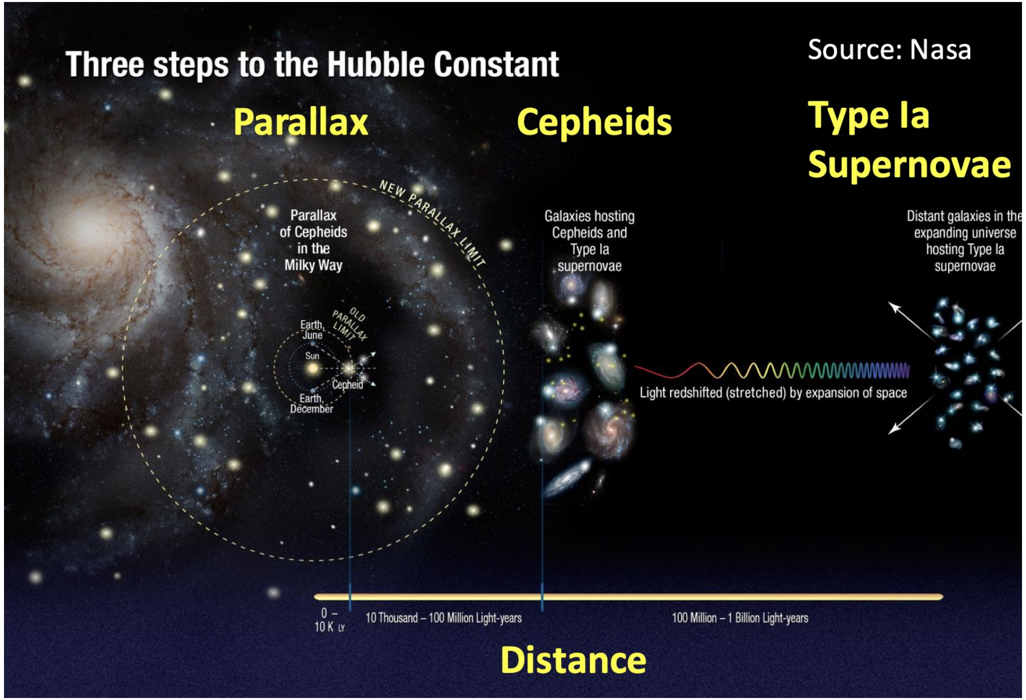


How to measure Hubble constant? Distance ladder

We start by obtaining local distance scale and then use several steps to take it to the Hubble flow

We use Earth-Sun distance, parallax to stars, identify standard candle stars (cepheids), identify these in nearby galaxies which also have SN1A etc.

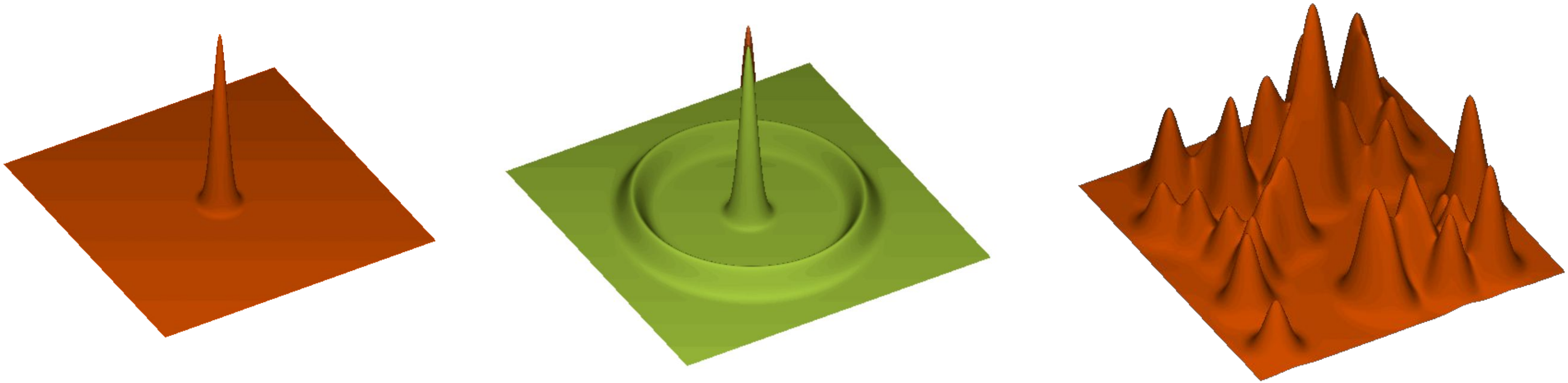
Other methods are also possible (TRGB)



This method gives H0=73km/s/Mpc (Riess etal)

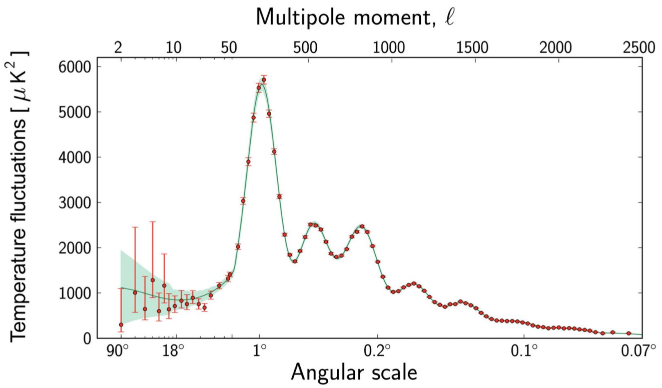
How to measure Hubble constant? Baryonic Acoustic Oscillations

- Here we first measure a physical scale in the early universe, and then transport this scale down today
- Baryonic acoustic oscillations (BAO) provide a physical scale, which is determined by early universe physics
- Each initial overdensity (in DM & gas) is an overpressure that launches a spherical sound wave. This wave travels outwards at 57% of the speed of light. Pressure-providing photons decouple at recombination. CMB travels to us from these spheres. Sound speed plummets. Wave stalls at a radius of 147 Mpc.

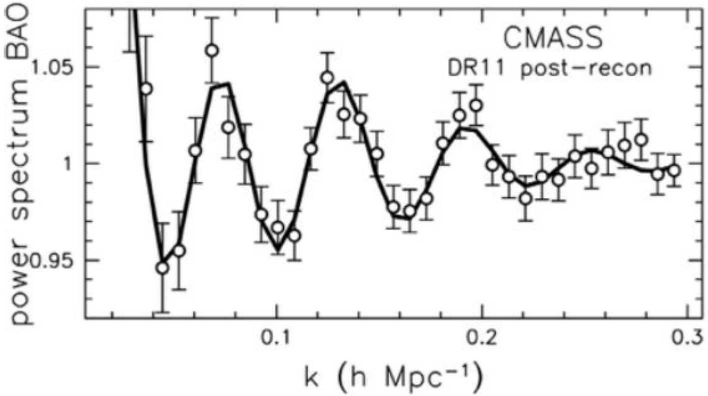


We can measure BAO in CMB and in LSS

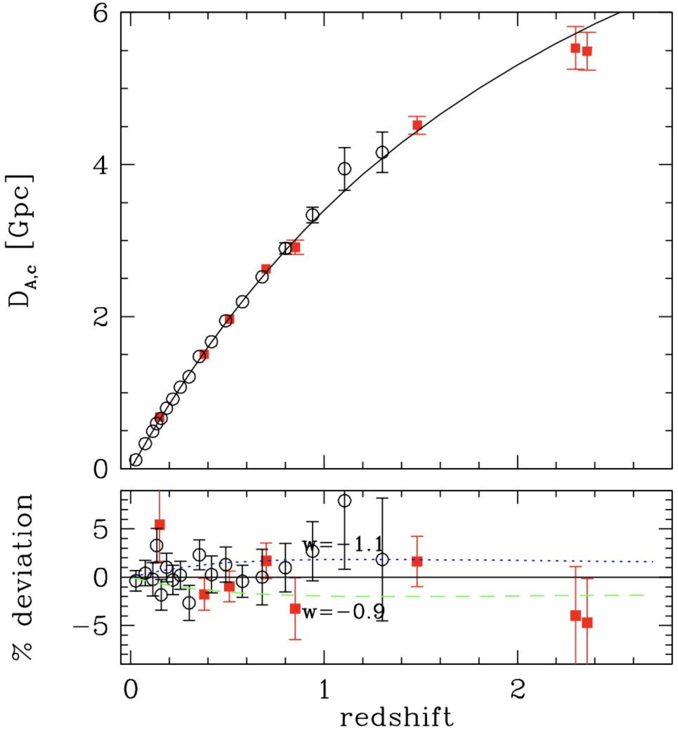
CMB
Planck



BAO
SDSS



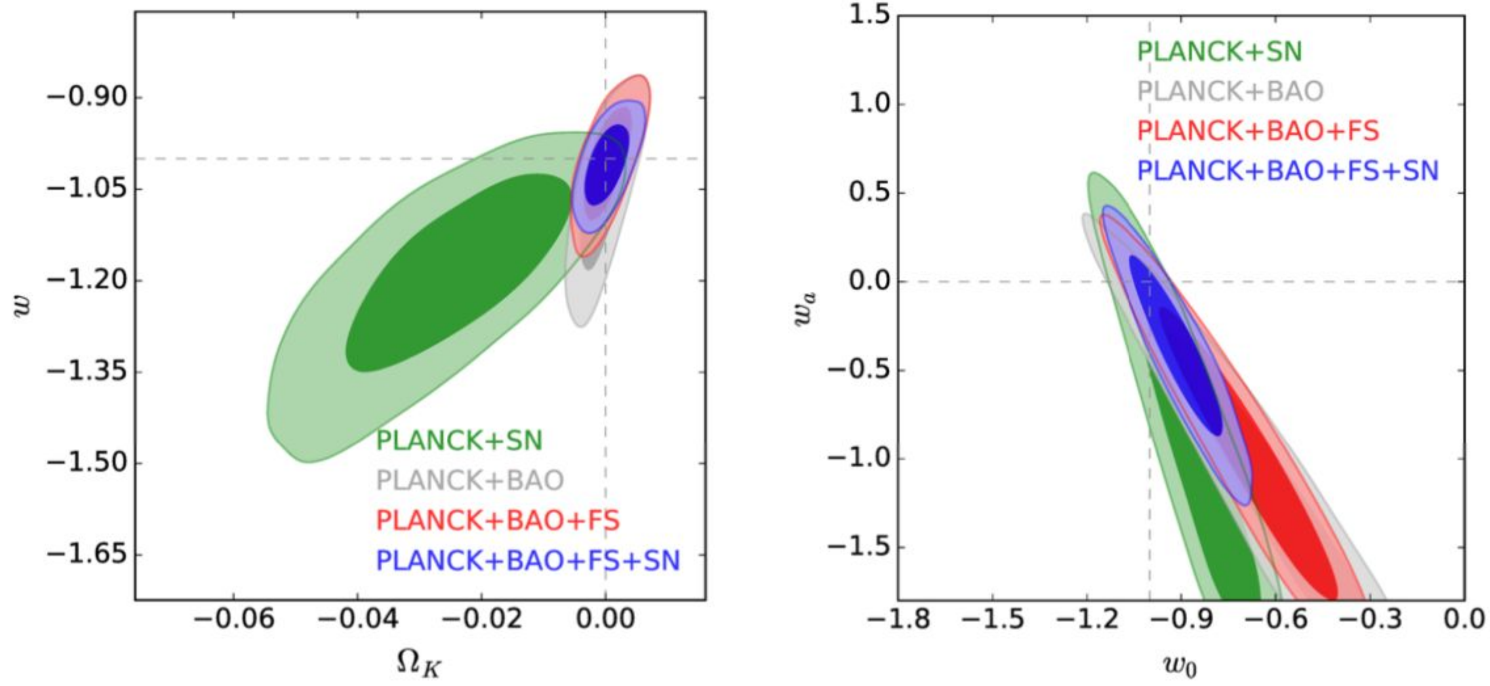
BAO+SN Hubble diagram



Dark energy constraints: CMB+LSS

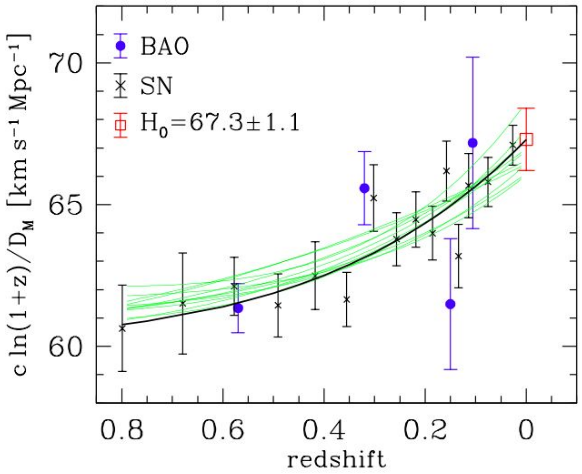
No evidence for deviations

$$w(a) = w_0 + w_{\mathrm{a}}(1 - a)$$

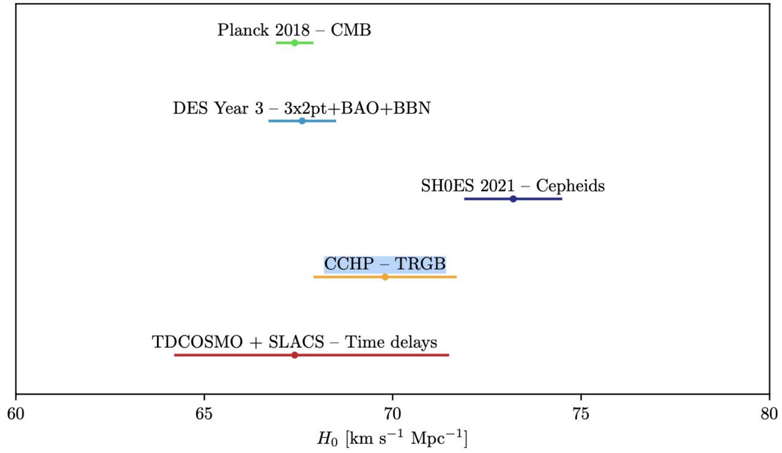


How to measure Hubble constant? Inverse distance ladder

- SN1A are standard candles, but to get H_0 need absolute calibration
- Inverse ladder: BAO is a standard ruler with a known absolute calibration, and at z=0.57 overlaps with SN1A, allowing absolute calibration of SN1A, bringing it down to z=0 gives H_0
- This method gives H_0 of 67, similar to Planck

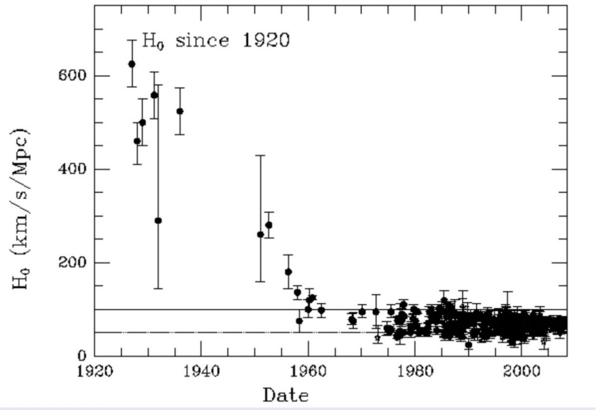


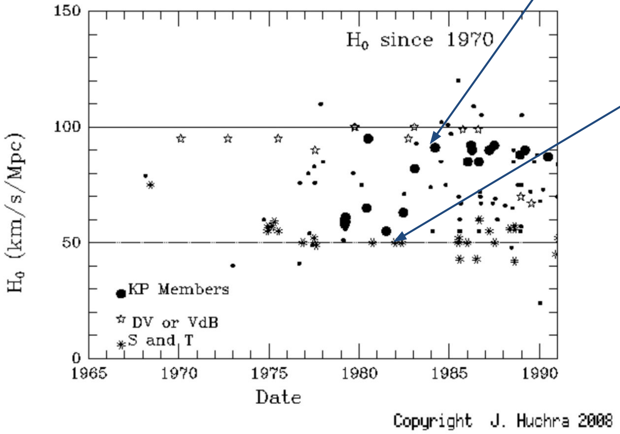
Summary of current constraints (PDG)

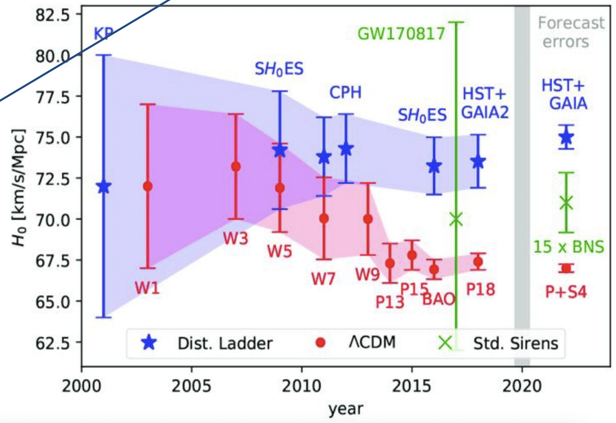


Hubble tension?

- Historically we always had Hubble tension. E.g. Sandage (100) vs Tammann (50)







- Cosmologists are often wrong, but never in doubt (Lev Landau)
- Today we are debating whether it is 67 or 73: progress!
- Maybe in 20 years we will have fierce debates whether it is 68.3 or 68.9?

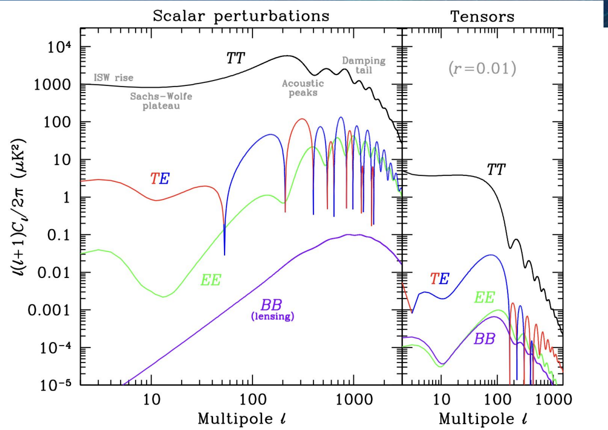
Is Hubble tension pointing to new physics?

- Ambulance chasing is popular in cosmology too
- It is however remarkable that the tension is not easily explained by new physics: most modifications reduce the tension, but not remove it
- Di Valentino etal (2021): “While no specific proposal makes a strong case for being highly likely or far better than all others, solutions involving early or dynamical dark energy, neutrino interactions, interacting cosmologies, primordial magnetic fields, and modified gravity provide the best options until a better alternative comes along.”
- Some people are loosing sleep over the Hubble tension, others are not
- Perhaps new methods such as Gravitational Wave distance redshift relation (standard sirens) will resolve the tension (see talk by Palmese)

CMB+BAO measures standard model of cosmology

- CMB alone determines 6 parameters of the standard model
- CMB Planck is a lot of measurements: Temperature (TT), polarization (EE), cross-correlation (TE), lensing of CMB

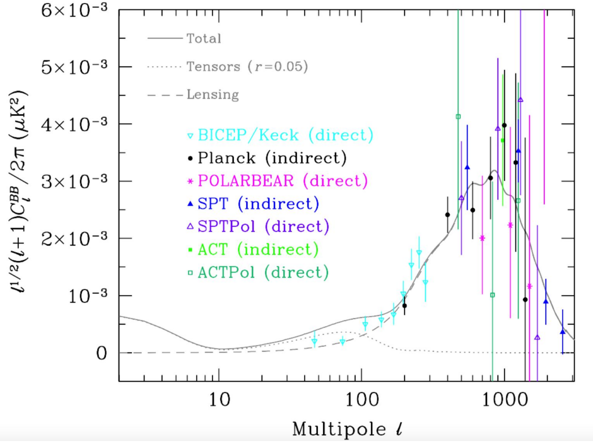
- Primordial non-Gaussianity consistent with 0: $f_{local} = -1 \pm 5$, $f_{equil} = -26 \pm 47$, and $f_{ortho} = -38 \pm 24$

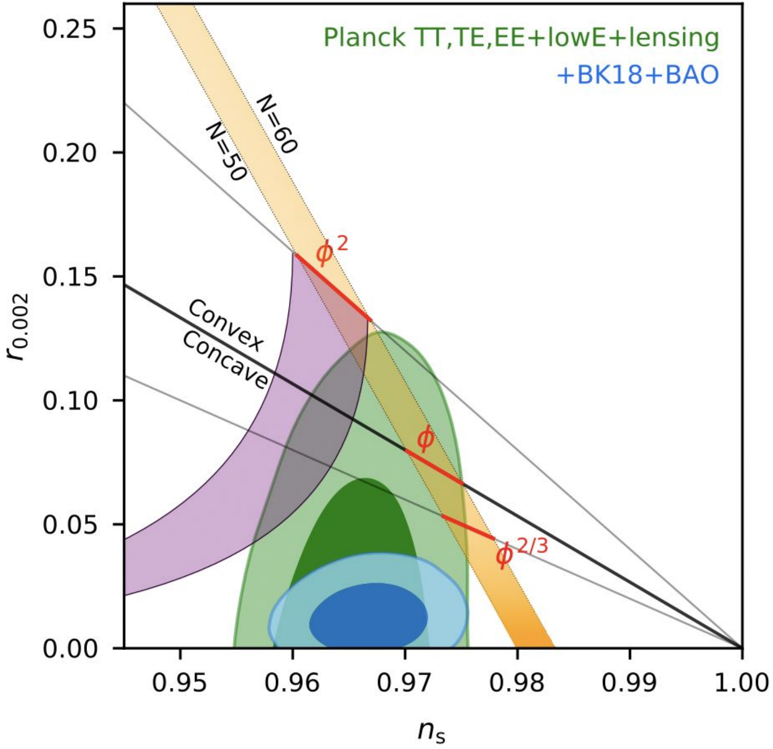


	Planck TT,TE,EE+lowE+lensing	+BAO
$\Omega_b h^2$	0.02237 ± 0.00015	0.02242 ± 0.00014
$\Omega_c h^2$	0.1200 ± 0.0012	0.1193 ± 0.0009
$100\,\theta_{MC}$	1.0409 ± 0.0003	1.0410 ± 0.0003
n_s	0.965 ± 0.004	0.966 ± 0.004
τ	0.054 ± 0.007	0.056 ± 0.007
$\ln(10^{10}\Delta^2_{\mathcal{R}})$	3.044 ± 0.014	3.047 ± 0.014
h	0.674 ± 0.005	0.677 ± 0.004
σ_8	0.811 ± 0.006	0.810 ± 0.006
Ω_m	0.315 ± 0.007	0.311 ± 0.006
Ω_Λ	0.685 ± 0.007	0.689 ± 0.006

No evidence of primordial B modes (yet)

- B modes of polarization would measure directly gravitational waves from early universe, as close to a proof of inflation as possible
- No evidence of signal, with r<0.036 (95%) with BICEP+Planck
- This is now placing tension on many popular inflationary models, such as power law models (and related string inflation monodromy models)





Constraints on inflation potential V

- Slow roll parameters

$$\epsilon \equiv \frac{M_P^2}{16\pi}\left(\frac{V'}{V}\right)^2, \quad \eta \equiv \frac{M_P^2}{8\pi}\left(\frac{V''}{V}\right) \qquad \xi^2 = \frac{M_P^4}{64\pi^2}\frac{V'V'''}{V^2}$$

- Somewhat un-natural

$$r \equiv \frac{\mathcal{P}_t}{\mathcal{P}_\zeta} \simeq 16\epsilon_*$$

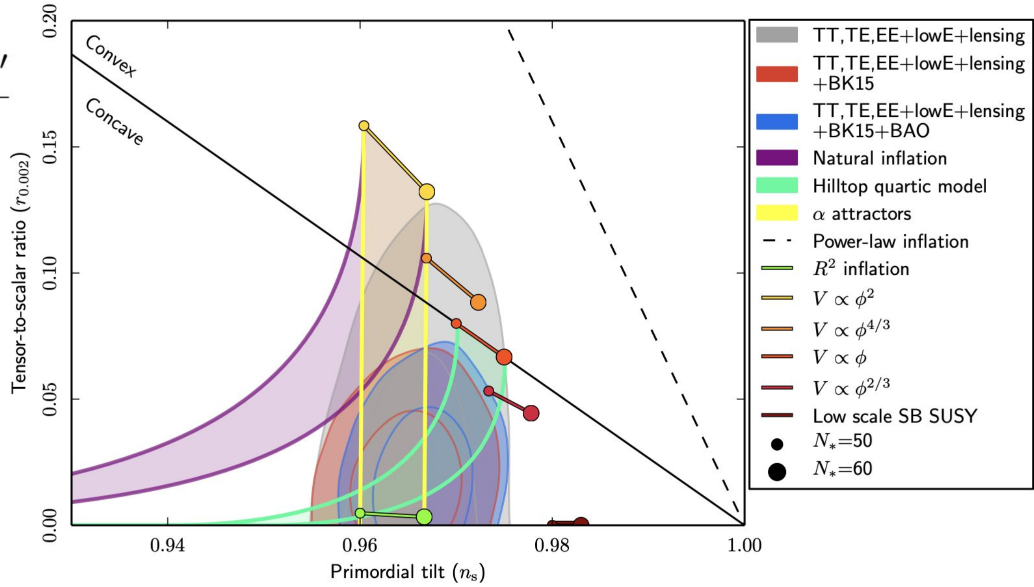
$$\epsilon < 0.0044\,, \quad \eta = -0.015 \pm 0.006\,, \quad \xi^2 = 0.0029^{+0.0073}_{-0.0069}\,,$$

- Surviving models: R^2,

$$S = \frac{1}{2}\int d^4x\sqrt{-g}\left(R + \frac{R^2}{6M^2}\right)$$

- Hilltop models

$$V(\phi) = \Lambda^4\left[1 - \left(\frac{\phi}{\mu}\right)^p + \ldots\right]$$



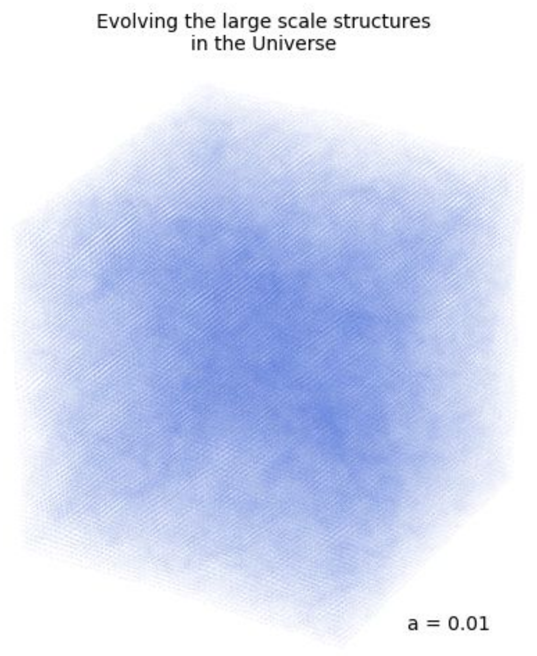
Alpha attractors

E-model ($n = 1$)	$\Lambda^4\left\{1 - \exp\left[-\sqrt{2}\phi\left(\sqrt{3\alpha_1^{\mathrm{E}}}M_{\mathrm{Pl}}\right)^{-1}\right]\right\}^{2n}$
E-model ($n = 2$)	$\Lambda^4\left\{1 - \exp\left[-\sqrt{2}\phi\left(\sqrt{3\alpha_2^{\mathrm{E}}}M_{\mathrm{Pl}}\right)^{-1}\right]\right\}^{2n}$
T-model ($m = 1$)	$\Lambda^4\tanh^{2m}\left[\phi\left(\sqrt{6\alpha_1^{\mathrm{T}}}M_{\mathrm{Pl}}\right)^{-1}\right]$
T-model ($m = 2$)	$\Lambda^4\tanh^{2m}\left[\phi\left(\sqrt{6\alpha_2^{\mathrm{T}}}M_{\mathrm{Pl}}\right)^{-1}\right]$

•

Large Scale Structure: dark matter, galaxies, gas

- We can measure LSS via weak lensing (WL) and galaxy clustering, which gives us dark matter clustering amplitude
- **Advantages of LSS**: we can measure in 3d (galaxy clustering, redshift space distortions, RSD). More modes to measure
- We can measure it as a function of redshift: growth of structure
- **Disadvantages**: galaxies are indirect tracers (biasing)
- Dark matter can only be observed in 2d (WL)
- Clustering is non-linear, and extracting optimal information becomes difficult
- Baryonic effects are difficult to model (astrophysics)

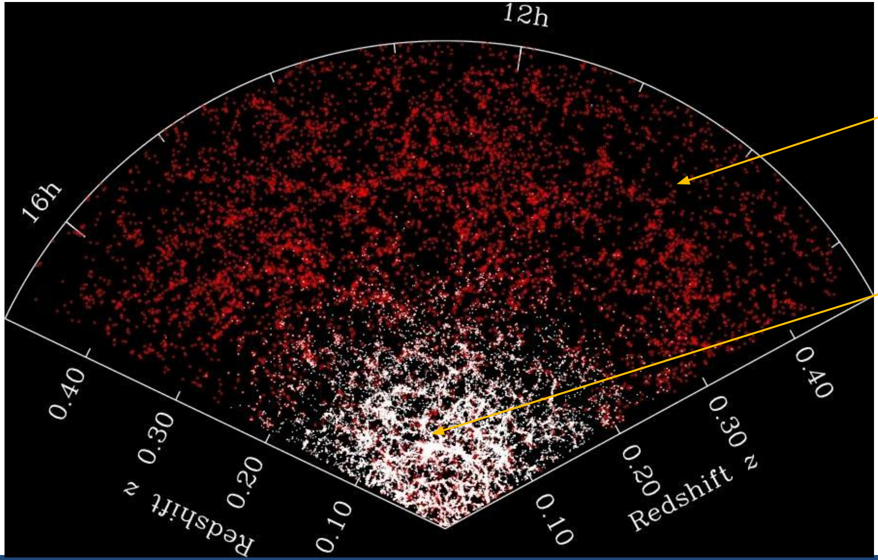


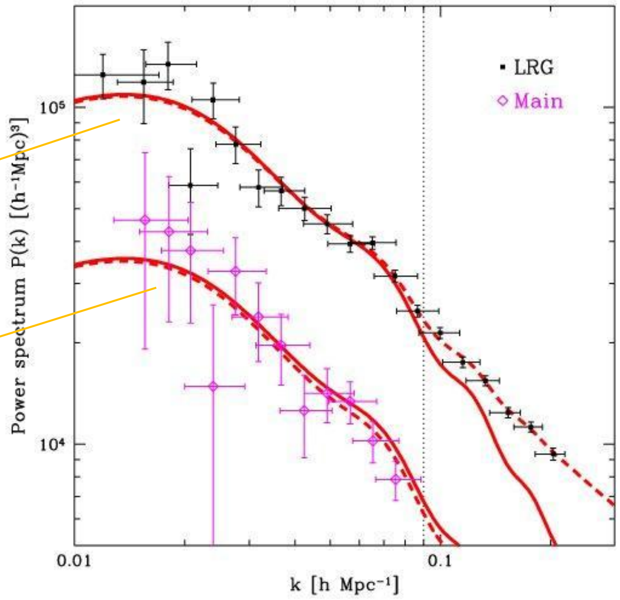
Modi, Lanusse, Seljak 2021

Galaxy clustering

+ Measures 3-d distribution, has many more modes than projected quantities like shear from weak lensing, easy to measure: effects of order unity, not 1%

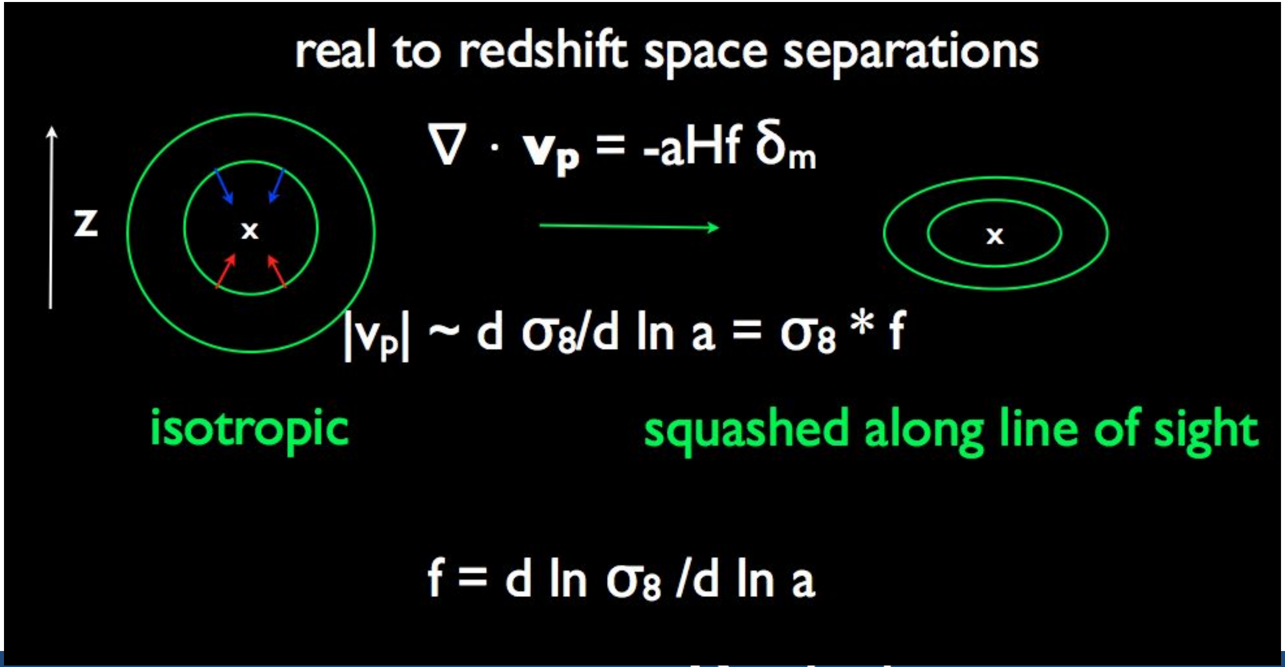
- clustering amplitude depends on galaxy type: galaxy bias





Solution: redshift space distortions

We measure redshift $cz=aHr+v_p$, velocity traces matter density, not bias

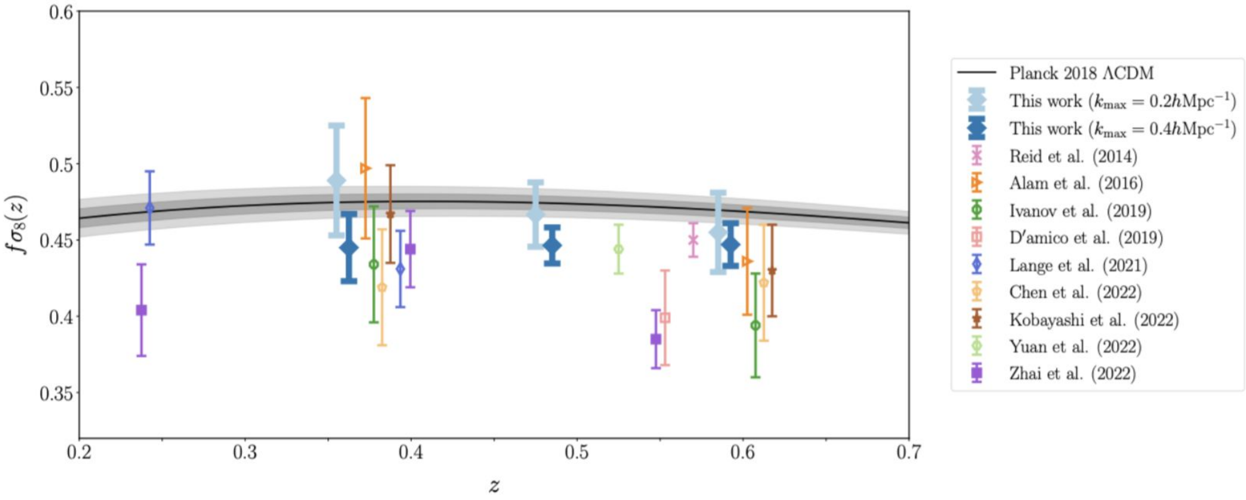


RSD from SDSS (BOSS)

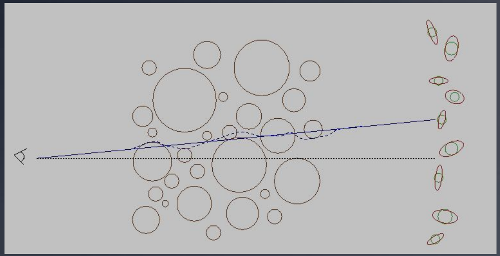
- There is evidence that different RSD analyses of the same data reach very different results: modeling uncertainty

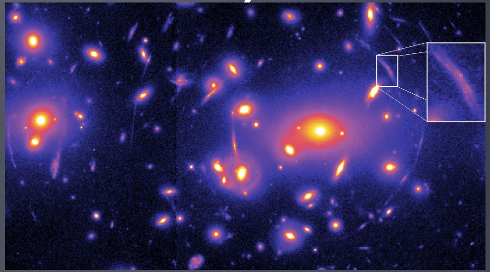
- Solution for cosmology: test the methods on several blind mock data challenges before applying to the data

Yu, Seljak, Singh 2022

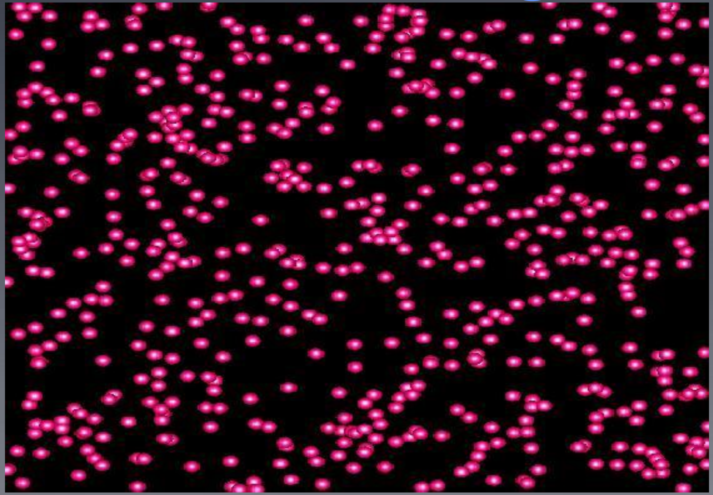


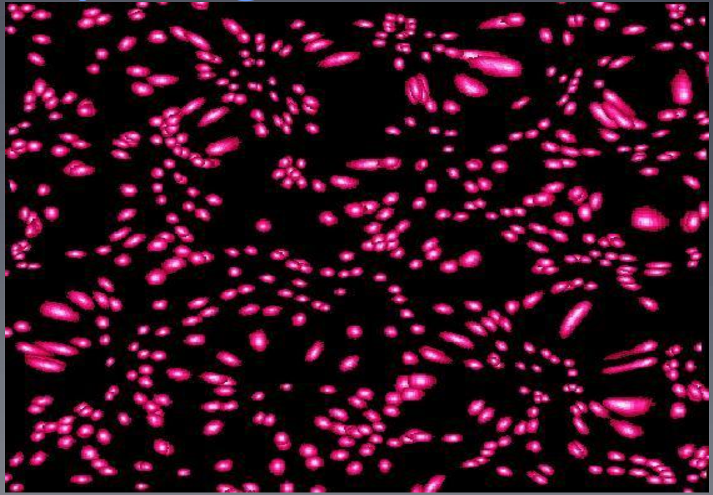
Weak Gravitational Lensing: sensitive to total mass distribution (DM dominated)





Distortion of background images by foreground matter

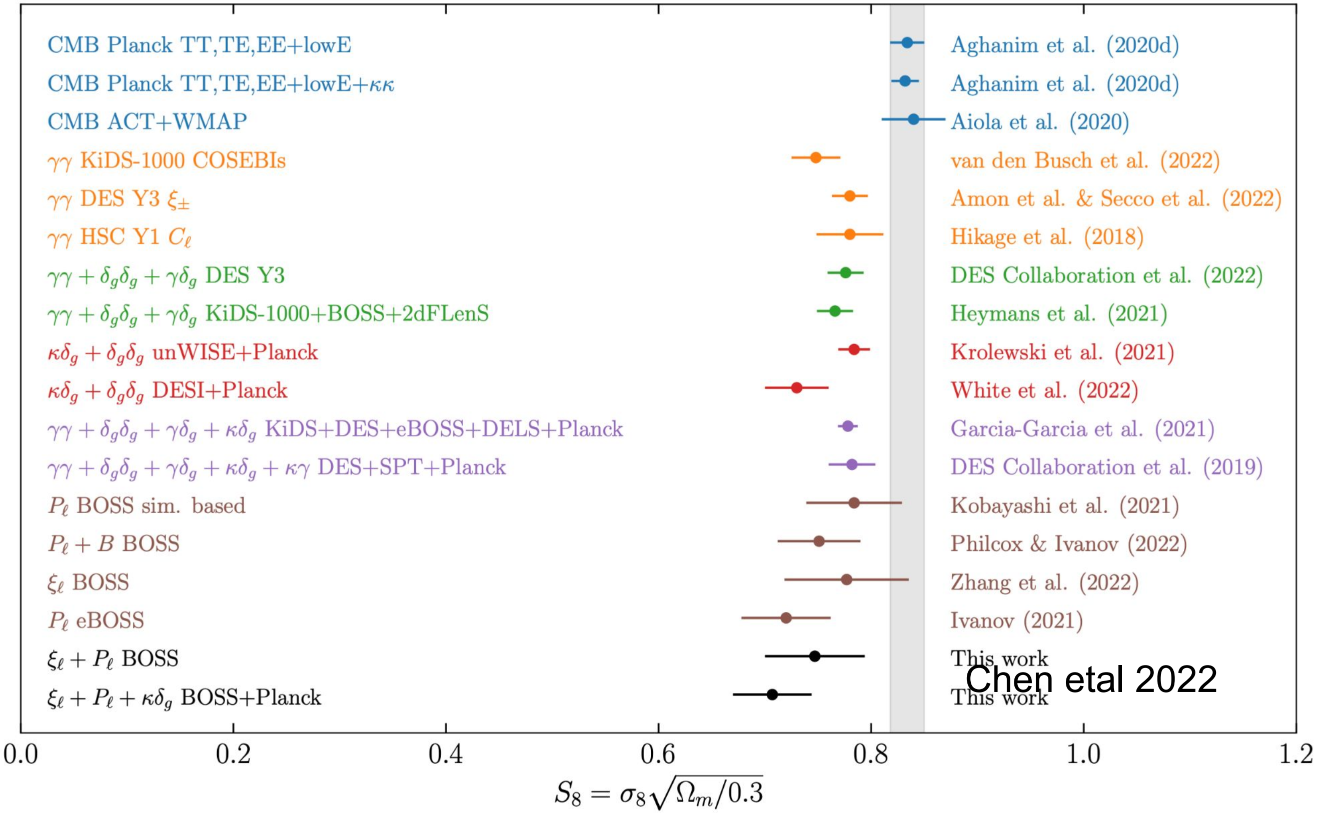




Unlensed **Lensed**

Sigma8 tension?

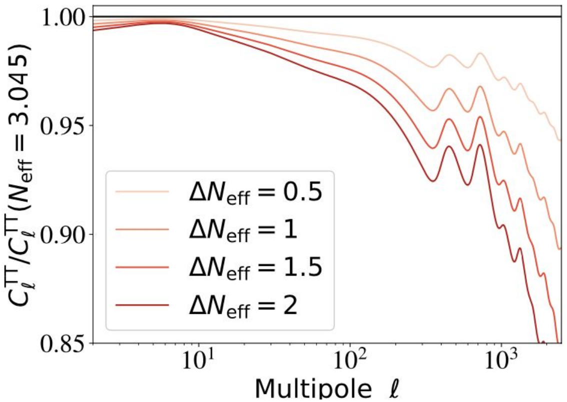
- There is evidence from WL that low redshift amplitude measurements are lower than Planck
- This is not universal: WL is low, but Planck lensing is not
- RSD some is low some is not
- Lyman alpha forest amplitude is high
- Thermal Sunyaev-Zeldovich is high

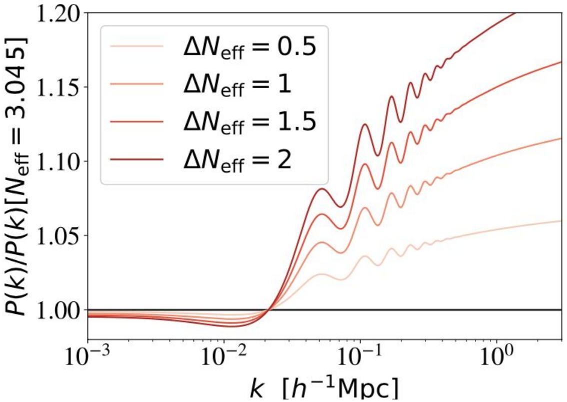


Neutrino physics: number of neutrino families

- We can learn about neutrinos from CMB/LSS
- Number of neutrino families changes matter radiation equality
- It is also a parameter that can describe other sources of dark energy
- Expectation N=3.04

(see talk by Pastor)

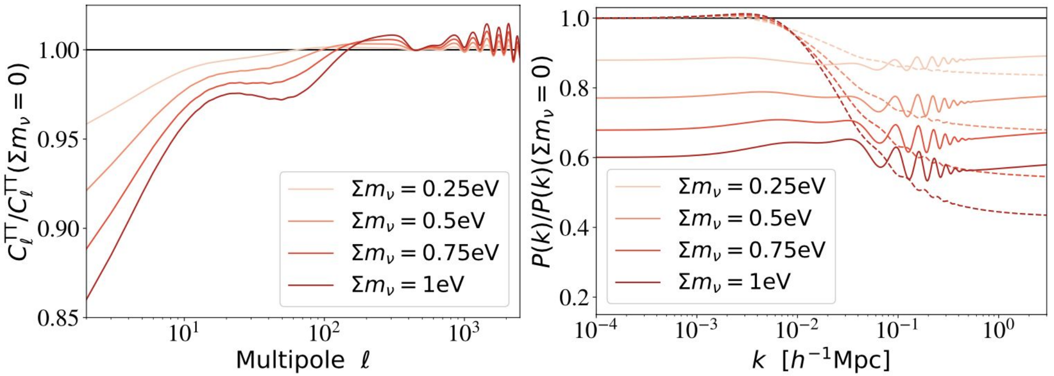




	Model	95%CL	Ref.
CMB alone			
Pl18[TT,TE,EE+lowE]	ΛCDM+$N_{\rm eff}$	$2.92^{+0.36}_{-0.37}$	[22]
CMB + background evolution + LSS			
Pl18[TT,TE,EE+lowE+lensing] + BAO	ΛCDM+$N_{\rm eff}$	$2.99^{+0.34}_{-0.33}$	[22]
" + BAO + R21	ΛCDM+$N_{\rm eff}$	3.34 ± 0.14 (68%CL)	[11]
"	" +5-params.	2.85 ± 0.23 (68%CL)	[23]

Neutrino physics: sum of neutrino masses

- Neutrino mass reduces clustering of dark matter on small scales
- Most of current constrains are upper limits, some very tight. Most of these LSS do not show sigma8 tension (e.g. Lya forest, Planck lensing)
- If sigma8 tension is real it could point to nonzero neutrino mass, possibly consistent with inverted hierarchy of 0.1eV



CMB alone			
Pl18[TT+lowE]	ΛCDM+$\sum m_\nu$	< 0.54	[22]
Pl18[TT,TE,EE+lowE]	ΛCDM+$\sum m_\nu$	< 0.26	[22]
CMB + probes of background evolution			
Pl18[TT+lowE] + BAO	ΛCDM+$\sum m_\nu$	< 0.13	[43]
Pl18[TT,TE,EE+lowE]+BAO	ΛCDM+$\sum m_\nu$+5 params.	< 0.515	[23]
CMB + LSS			
Pl18[TT+lowE+lensing]	ΛCDM+$\sum m_\nu$	< 0.44	[22]
Pl18[TT,TE,EE+lowE+lensing]	ΛCDM+$\sum m_\nu$	< 0.24	[22]
CMB + probes of background evolution + LSS			
Pl18[TT,TE,EE+lowE] + BAO + RSD	ΛCDM+$\sum m_\nu$	< 0.10	[43]
Pl18[TT+lowE+lensing] + BAO + Lyman-α	ΛCDM+$\sum m_\nu$	< 0.087	[44]
Pl18[TT,TE,EE+lowE] + BAO + RSD + Pantheon + DES	ΛCDM+$\sum m_\nu$	< 0.13	[45]

Future (and current) surveys

Future is bright both in LSS with DESI **Euclid** (see contributed talks by Troja, Tutusaus, Sorce), Roman, Rubin/LSST and in

CMB with Simons Observatory, South Pole Telescope, BICEP, Litebird (see talk by Paoletti), CMB S4

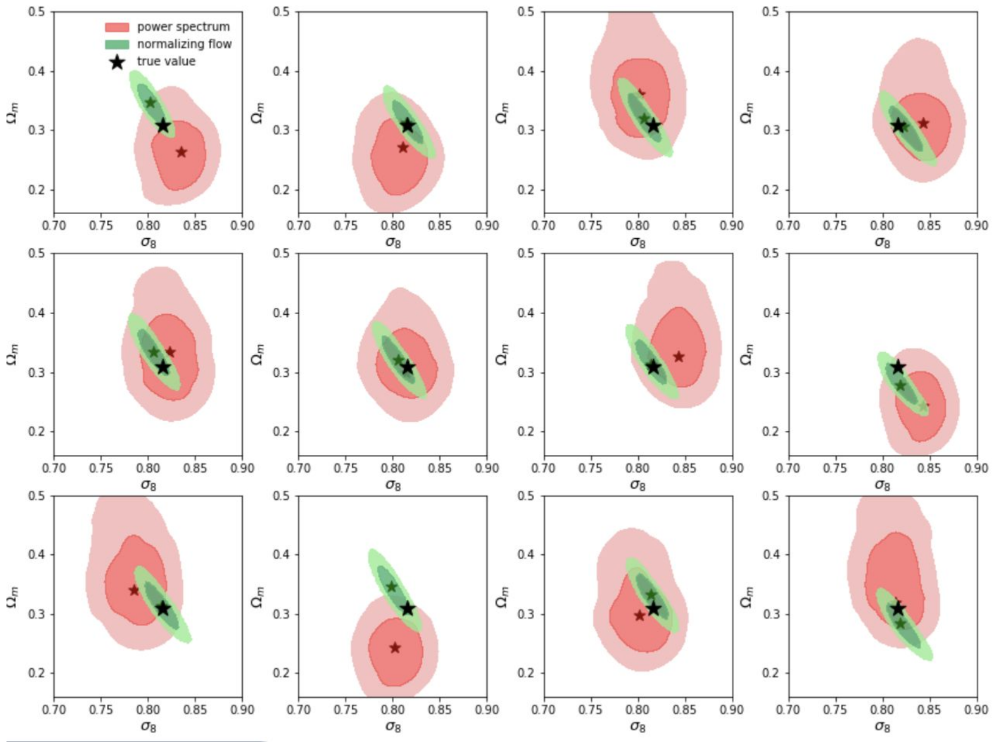
For HEP some of the most interesting future predictions are neutrino mass (0.02eV precision), primordial non-Gaussianity (fnl of order 1), B modes (r<0.001)

Large potential for unexpected discoveries and auxiliary science

Project	Dates	Area/deg^2	Data	Spec-z Range	Methods
BOSS	2008–2014	10,000	Opt-S	0.3–0.7 (gals) 2–3.5 (LyαF)	BAO/RSD
KiDS	2011–2019	1350	Opt-I	——	WL/CL
DES	2013–2019	5000	Opt-I	——	WL/CL SN/BAO
eBOSS	2014–2018	7500	Opt-S	0.6–2.0 (gal/QSO) 2–3.5 (LyαF)	BAO/RSD
SuMIRE	2014–2024	1500	Opt-I Opt/NIR-S	 0.8–2.4 (gals)	WL/CL BAO/RSD
HETDEX	2017–2023	450	Opt-S	$1.9 < z < 3.5$ (gals)	BAO/RSD
DESI	2021–2026	14,000	Opt-S	0–1.7 (gals) 2–3.5 (LyαF)	BAO/RSD
VRO/LSST	2022–2032	20,000	Opt-I	——	WL/CL SN/BAO
Euclid	2022–2028	15,000	Opt-I NIR-S	 0.7–2.2 (gals)	WL/CL BAO/RSD
Roman	2026–2031	2200	NIR-I NIR-S	 1.0–3.0 (gals)	WL/CL/SN BAO/RSD

Future: better analysis techniques in nonlinear regime

- Nonlinear evolution moves information from 2 point function to higher orders
- Traditional methods use higher order clustering statistics, but these are expensive and non optimal
- New methods use **Machine Learning**
- Example: Translation and Rotation Equivariant Normalizing Flow (TRENF, Dai & Seljak 2022) learns likelihood of the data as a function of cosmological parameters
- It extracts much more information than power spectrum, approaches optimality



Summary

- Cosmological observations are largely complementary to HEP: there are many theoretical ideas that can be probed with and only with cosmological datasets
- Cosmology has informed us about the standard model of the universe with 5 parameters
- It has determined the universe content, the origins of structure, and its evolution
- New data have significant potential to inform us about deviations from the standard model
- Two currently intriguing anomalies are Hubble tension and sigma8 amplitude tension
- These may amount to nothing, or they may revolutionize our understanding of the universe, or they may be explained by the expected unexpected (e.g. neutrino mass)
- Future datasets will be able to improve the precision several times and settle these controversies
- Better analysis techniques, such as Machine Learning methods for LSS, may also be able to improve the precision several fold