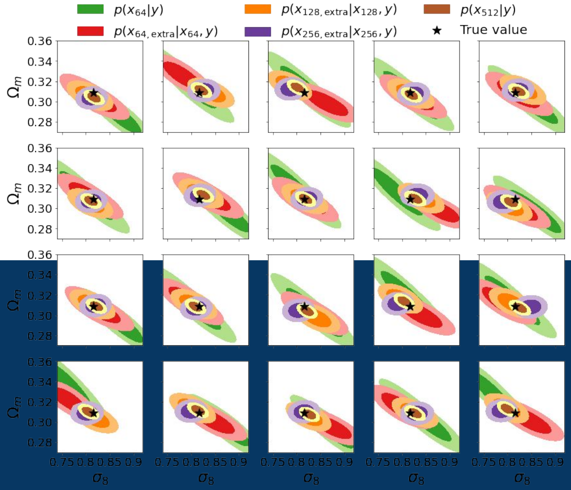
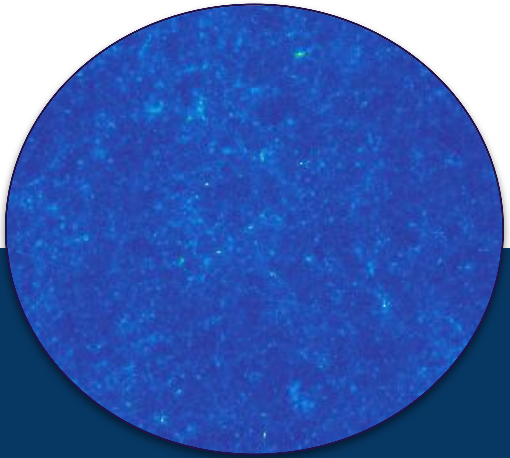
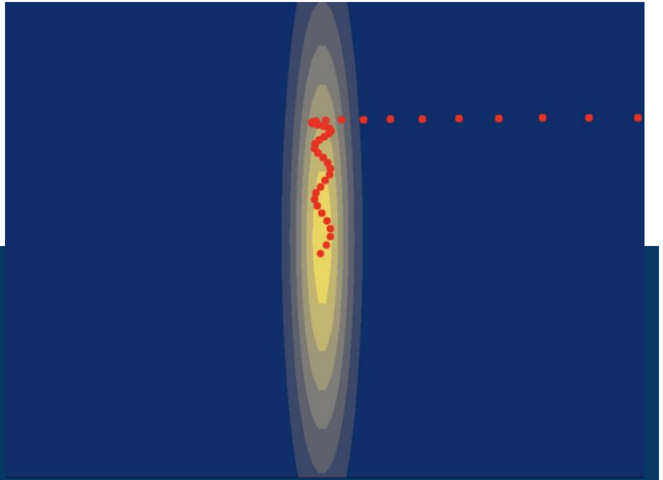
Lambda CDM cosmology model: current status, future prospects







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BERKELEY CENTER *for* COSMOLOGICAL PHYSICS

What is Lambda CDM model and how we test it?

- Lambda CDM model is being tested with a variety of observational probes, primarily Cosmic Microwave Background (CMB) and Large Scale Structure (LSS)
- Standard model: inflation sets the amplitude and slope of density fluctuation initial conditions (2 parameters), as well as gravity waves amplitude (tensor to scalar ratio r)
- Some other physics sets the expansion rate (Hubble parameter), matter density, cosmological constant density (dark energy) or equivalently curvature, and baryon density (set by BBN)
- In total we have about 5-7 parameters that define Lambda CDM in its simplest form
- Many extensions are possible, but so far no conclusive evidence has been found that they are needed. Examples are dark energy equation of state or other deviations of dark energy from cosmological constant, neutrino mass, non-standard inflation or alternative to it…

Neoclassical tests: use a standard ruler

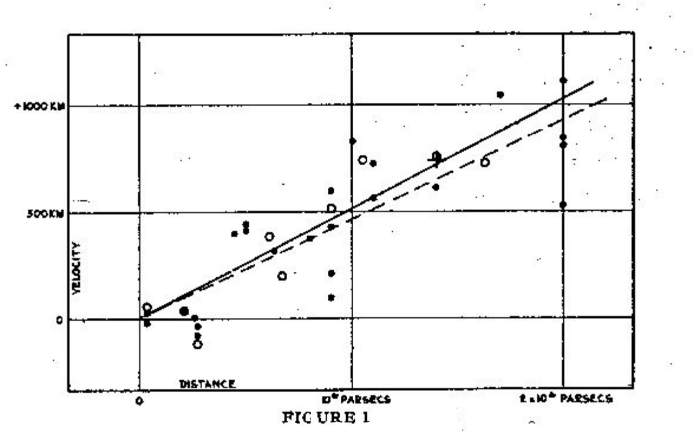
We wish to test Friedmann equation: redshift-distance relation

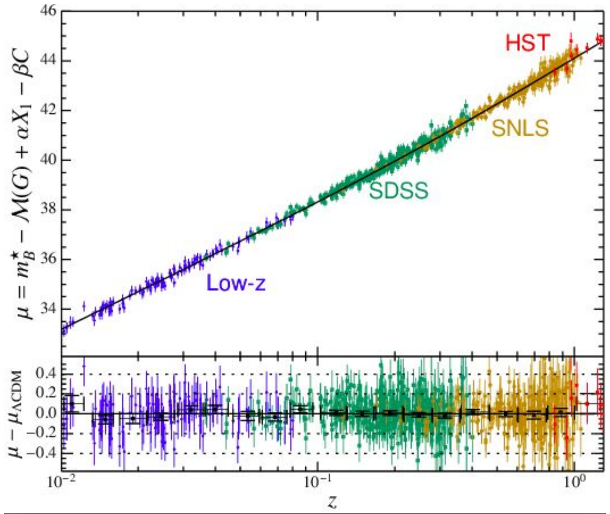
$$\left(\frac{\dot{a}}{a}\right)^2 = H^2 = \frac{8}{3}\pi G\bar{\rho} - Ka^{-2}$$

$$D_C(z) = \frac{c}{H_0}\int_0^z dz' \frac{H_0}{H(z')}$$

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

Redshift-distance relation has come a long way since the days of Hubble (and people before him): distance ladder





Baryonic Acoustic Oscillations: a standard ruler

Each initial overdensity (in DM & gas) is an overpressure that launches a spherical sound wave.

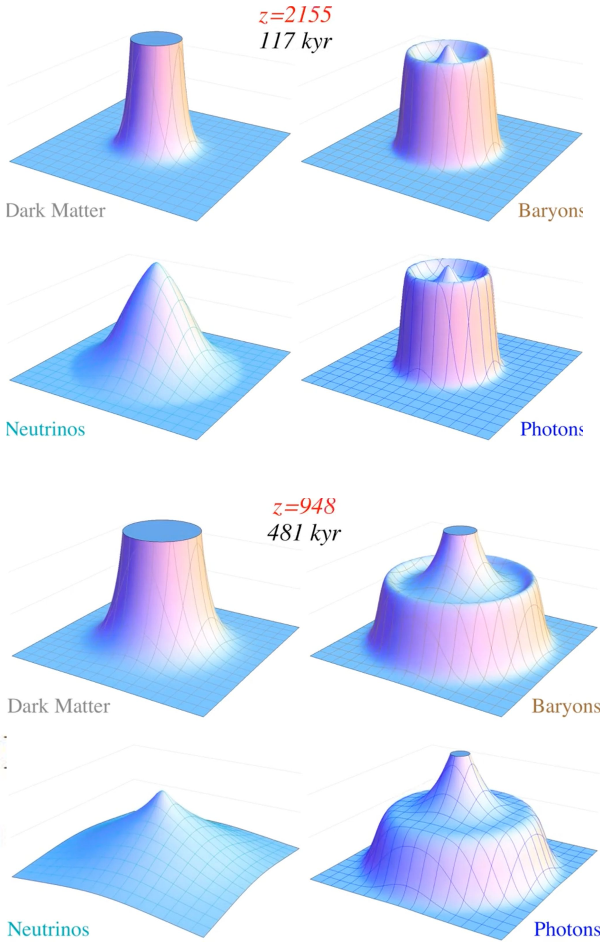
This wave travels outwards at 57% of the speed of light.

Pressure-providing photons decouple at recombination. CMB travels to us from these spheres.

Sound speed plummets. Wave stalls at a radius of 147 Mpc.

Seen in CMB as acoustic peaks

Overdensity in shell (gas) and in the original center (DM) both seed the formation of galaxies. Preferred separation of 147 Mpc.



Sound horizon at drag epoch (from Planck) : $r_d = 147.49 \pm 0.59$

$$r_d = \int_{z_d}^{\infty} \frac{c_s(z)}{H(z)} dz \qquad c_s(z) = 3^{-1/2} c \left[1 + \tfrac{3}{4}\rho_b(z)/\rho_\gamma(z)\right]^{-1/2}$$

BAO is a Standard Ruler

The acoustic oscillation scale depends on the matter-to-radiation ratio ($\Omega_m h^2$) and the baryon-to-photon ratio ($\Omega_b h^2$)

$$r_d \approx \frac{56.067 \exp\left[-49.7(\omega_\nu + 0.002)^2\right]}{\omega_{cb}^{0.2436}\, \omega_b^{0.128876}\left[1 + (N_{\rm eff} - 3.046)/30.60\right]}\ \mathrm{Mpc}$$

The CMB anisotropies measure these and fix the oscillation scale to <1%.

In a redshift survey, we can measure this along and across the line of sight:

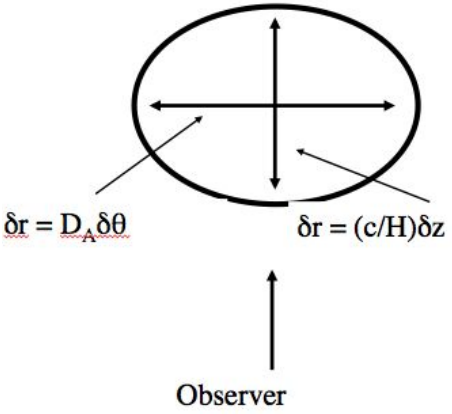
BAO along los $$\Delta v_{BAO} = \frac{r_d}{1+z}\boxed{H(z)}$$

BAO tranverse $$\Delta\theta_{BAO} = \frac{r_d}{1+z}\frac{1}{\boxed{D_A(z)}}$$

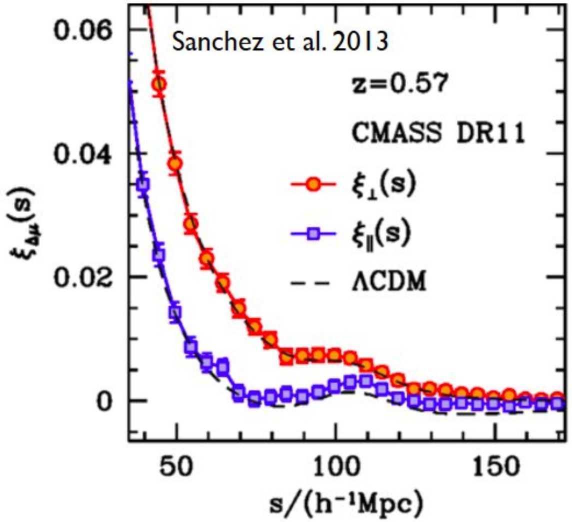
Yields H(z) and $D_M(z)$

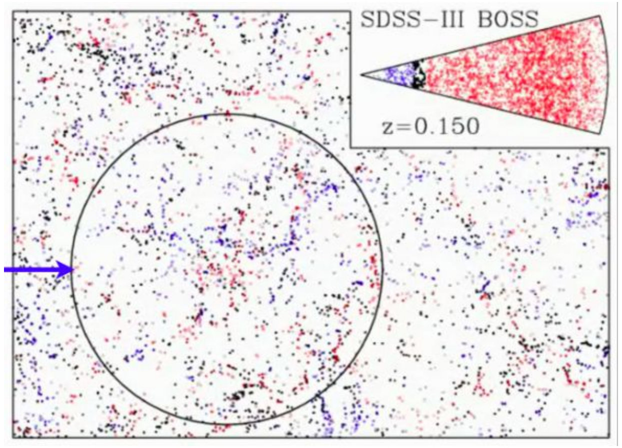
$$D_M(z) = \frac{c}{H_0} S_k\left(\frac{D_C(z)}{c/H_0}\right) \qquad D_H(z) = c/H(z)$$

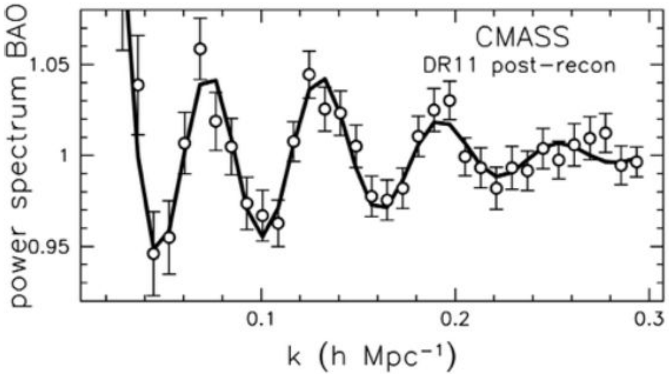
$$D_V(z) = \left[z D_H(z) D_M^2(z)\right]^{1/3}$$



Hunting for BAO: correlation function and power spectrum







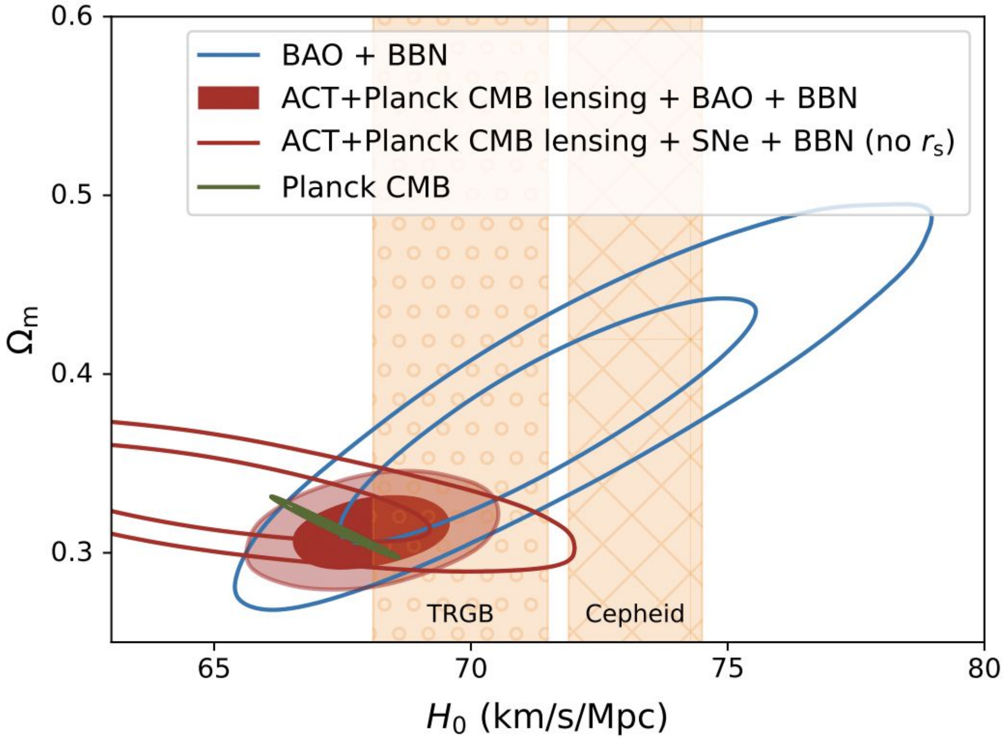
Another distance measure: use matter radiation equality rather than acoustic horizon

Recent CMB lensing

measurement

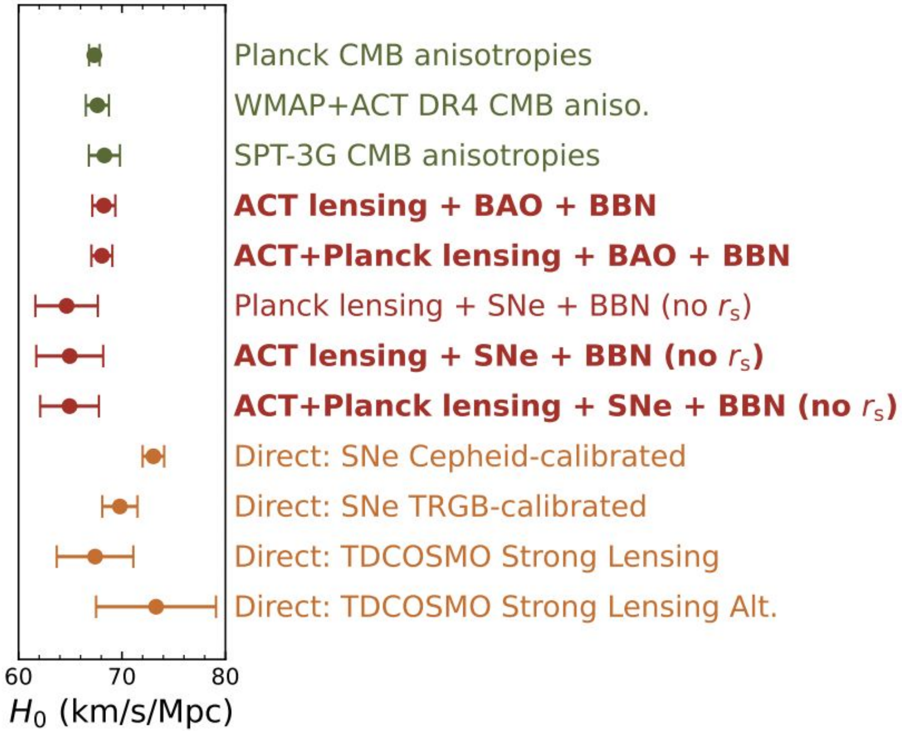
from ACT (Qu etal,

Madchaveracheril etal)



Current status of Hubble tension

Good consensus between independent probes, with the exception of SNe cepheid calibrated, which is out of line with the rest (also because of its small error



Initial conditions: inflation

If we have a nearly homogeneous scalar field (inflaton), whose potential is flat somewhere such that its potential energy dominates then we get nearly exponential expansion

The simplest models of inflation predict

- Nearly scale invariant power law power spectrum
- Density fluctuation domination with **subdominant gravity waves**
- Nearly Gaussian
- Adiabatic
- Spatially flat

Open questions:

- What is energy scale of inflation
- How far did the inflation field travel (in Planck units)
- How did inflation begin

Initial conditions: inflation

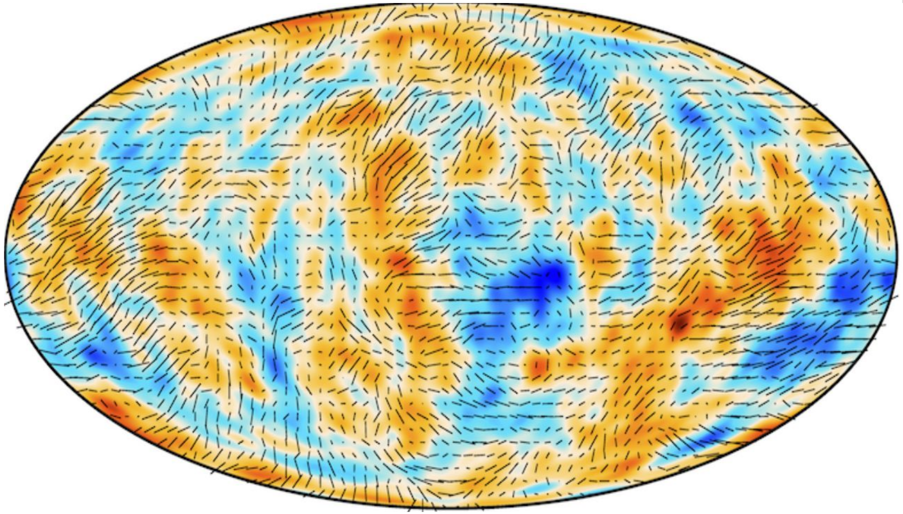
Inflation can be tested with slope of density fluctuations, with tensor to scalar ratio r, with primordial non-Gaussianity (PNG) etc.

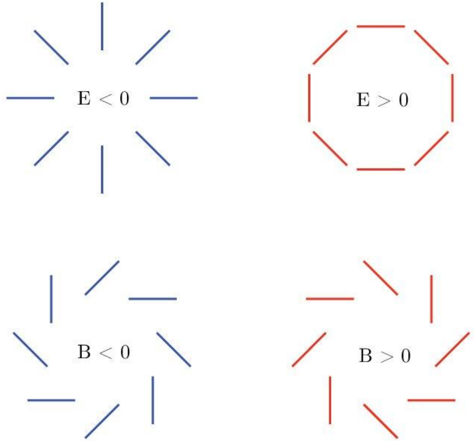
Best probe for ns is CMB+LSS

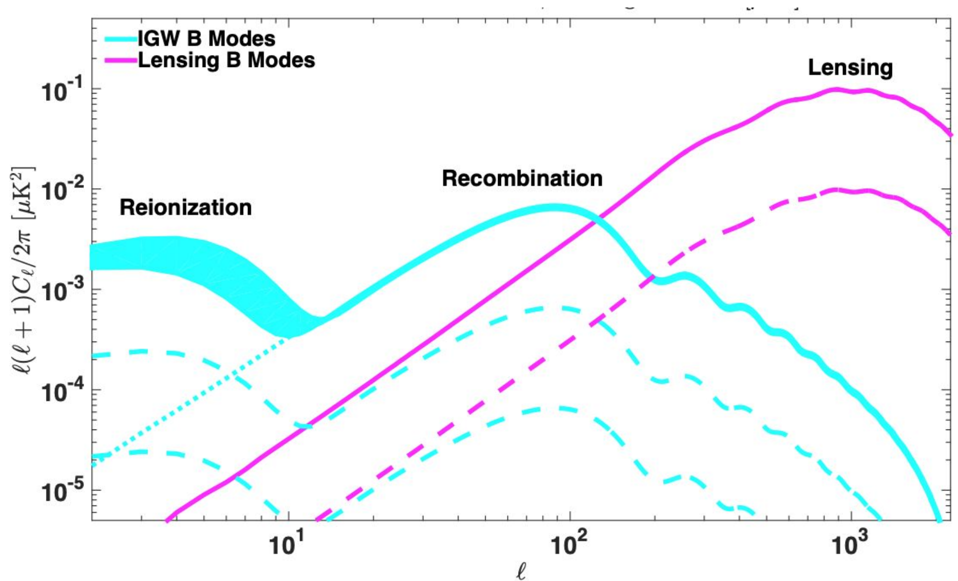
Best probe for r is B mode polarization

Best current probe for PNG is CMB, future will be LSS.

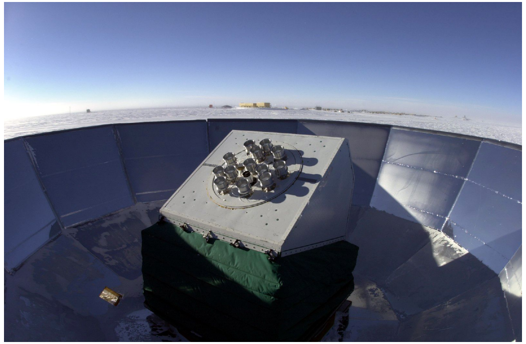
B modes of polarization

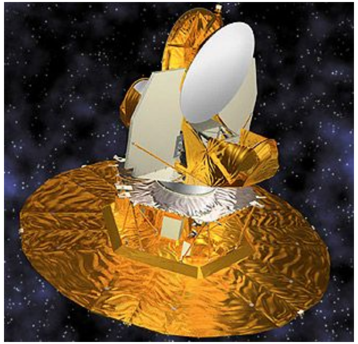


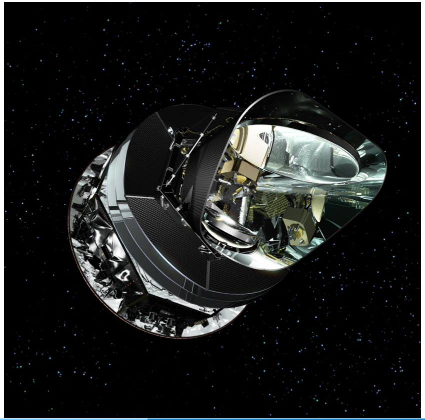


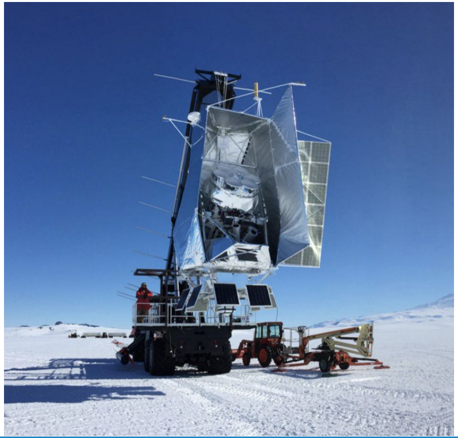


Experiments







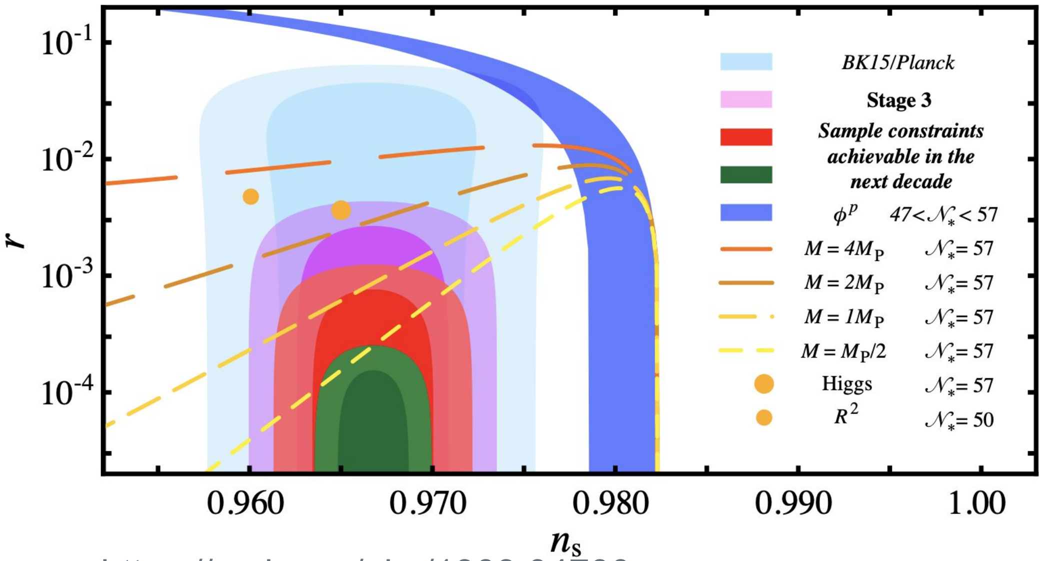


Current and future constraints on single field models

Current limit: r<0.06

Power law models: almost excluded

Plateau and hilltop models: characteristic scale



https://arxiv.org/abs/1903.04700

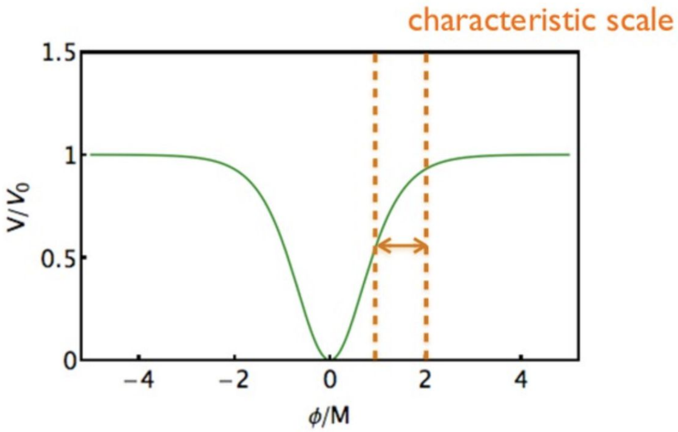


Figure 1: *Predictions for the tensor-to-scalar ratio r and spectral index n_s for some representative single-field inflationary models in which $n_s - 1 \propto -1/\mathcal{N}_*$. This class includes monomial models with $V(\phi) \propto \phi^p$ (dark blue), the Starobinsky (R^2) model, and Higgs inflation (orange filled circles). The dashed lines show the predictions of models in this class as function of the scale in the potential. All models with Planckian scale can be detected or excluded in the next decade.*

The other tension: amplitude of LSS vs CMB

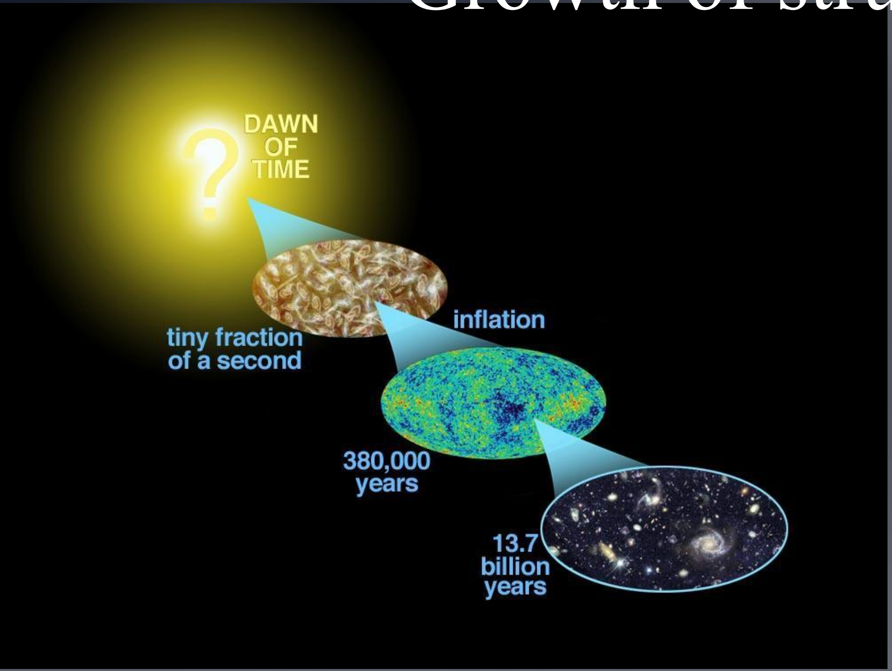
There have been many claims that LSS amplitude is lower than CMB (Planck etc.)

LSS amplitude can be measured primarily in 2 ways:

1) weak lensing (including WL cross-correlation with LSS, and CMB lensing)

2) Galaxy clustering via redshift space distortions

Growth of structure by gravity



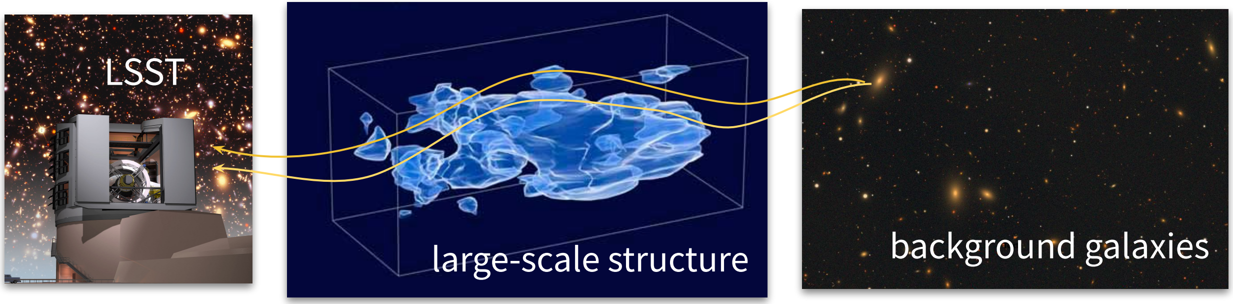
- Perturbations can be measured at different epochs:

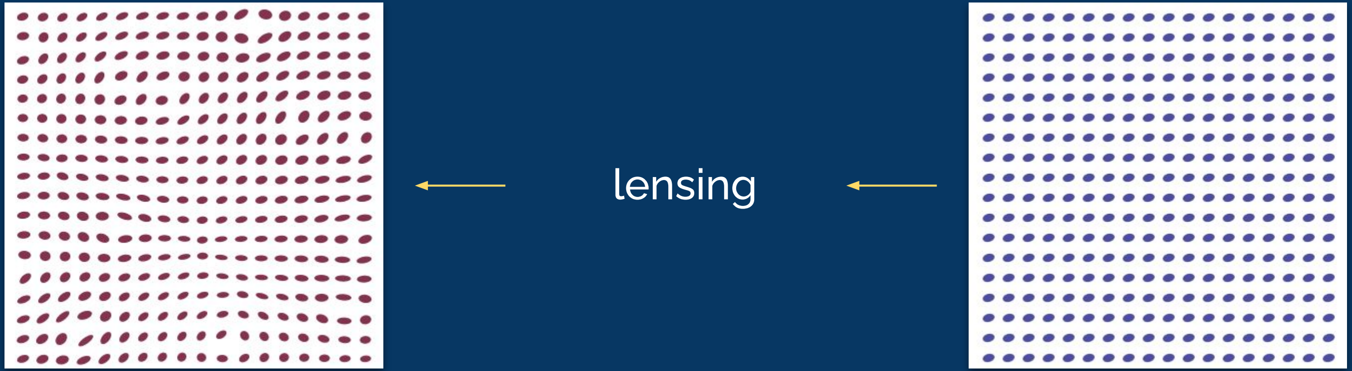
1. CMB z=1000
2. Ly-alpha forest z=2-4
3. Weak lensing z=0.3-2
4. Galaxy clustering, clusters z=0-2

Sensitive to matter components, initial conditions…

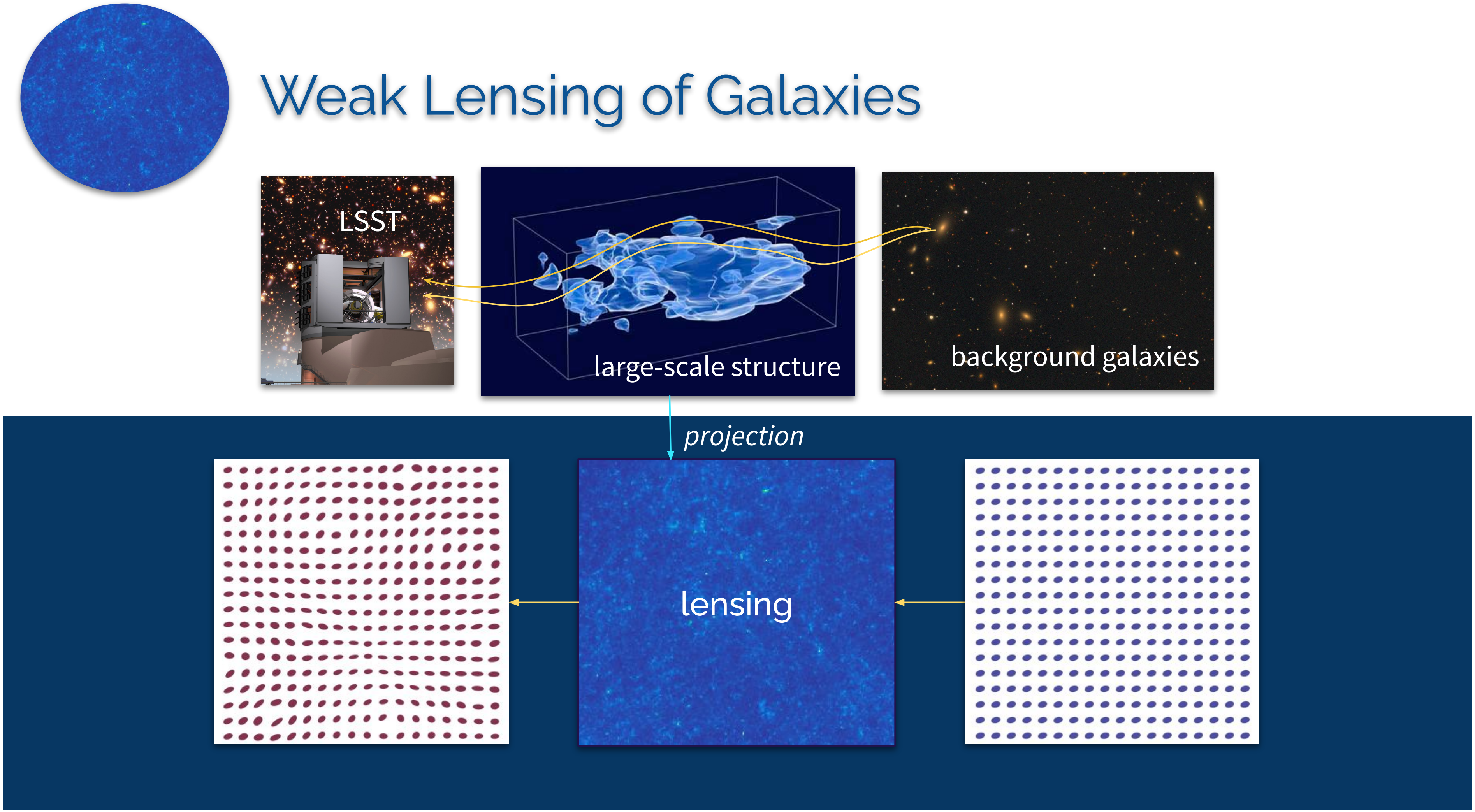
$$\ddot{\delta} + 2H\dot{\delta} = 4\pi G\bar{\rho}\delta \rightarrow \delta(t)$$

Weak Lensing of Galaxies

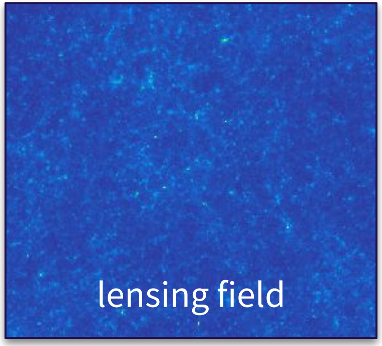




Weak Lensing of Galaxies



Weak Cosmic Shear



Lensing is sensitive to

- the total matter parameter ($\mathbf{\Omega}_m$)
- the amplitude of matter fluctuations ($\boldsymbol{\sigma}_8$)
- sum of neutrino masses ($\mathbf{M}_\nu$)
- time-varying dark energy (**w**)

What are advantages and disadvantages of WL?

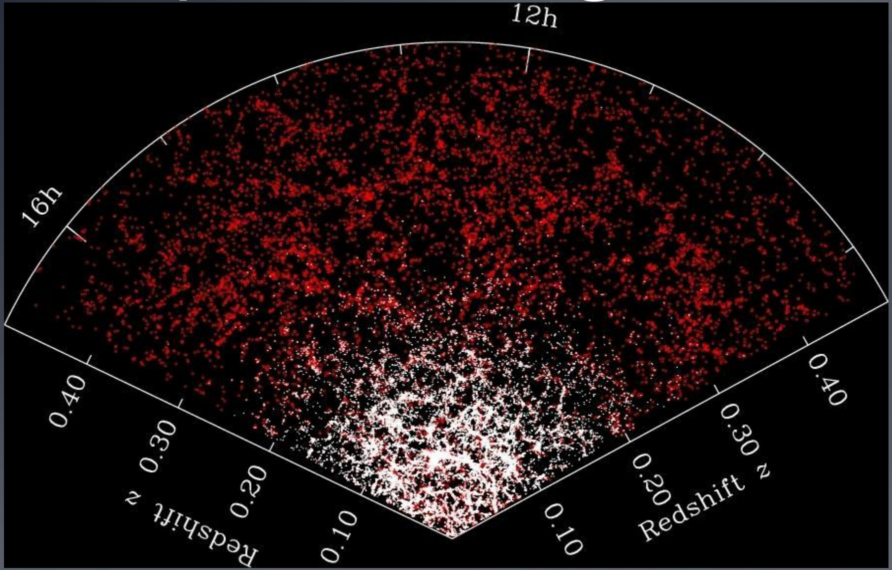
+ Sensitive to total matter distribution, relatively easy to relate to models

- Measures it in projection (d=2 for a single plane, some tomography possible with multiple source redshifts)

- Systematics: Intrinsic alignments (of GI type), baryonic effects, photometric redshift distribution, shear calibration etc

+ WL of CMB does not suffer from most of these systematics!

Galaxy clustering in redshift space



SDSS

Measures 3-d distribution, has many more modes than projected quantities like shear from weak lensing

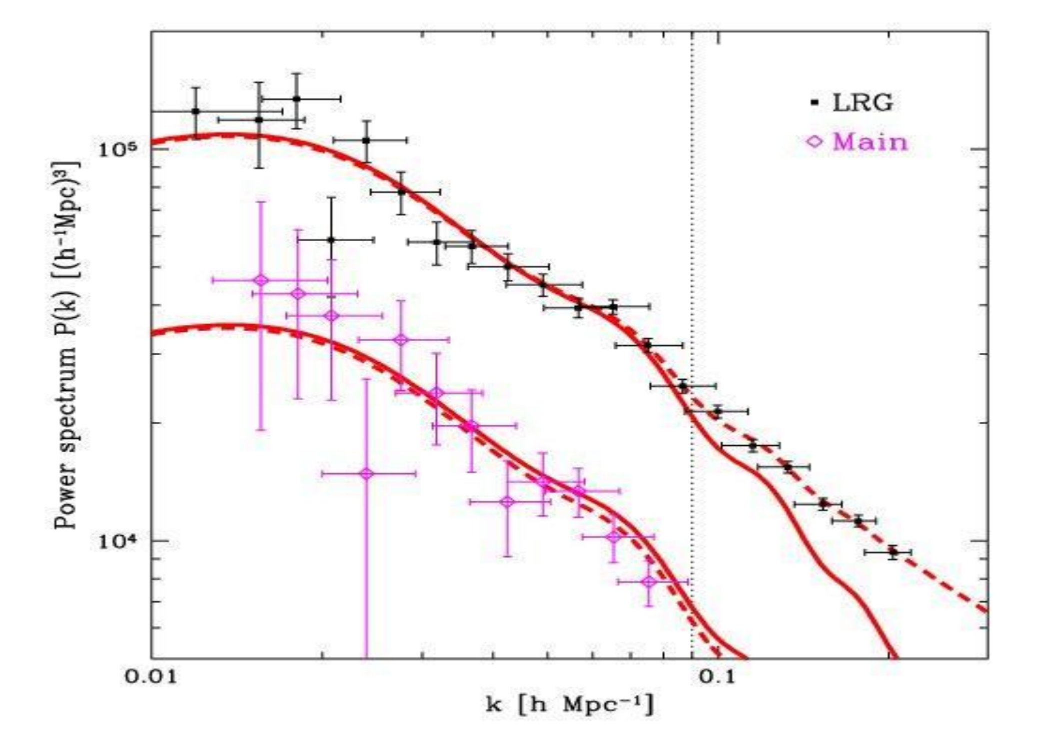
Easy to measure: effects of order unity, not 1%

Galaxy power spectrum: biasing

- Galaxy clustering traces dark matter clustering
- Amplitude depends on galaxy type: galaxy bias b

$$P_{gg}(k)=b^2(k)P_{mm}(k)$$

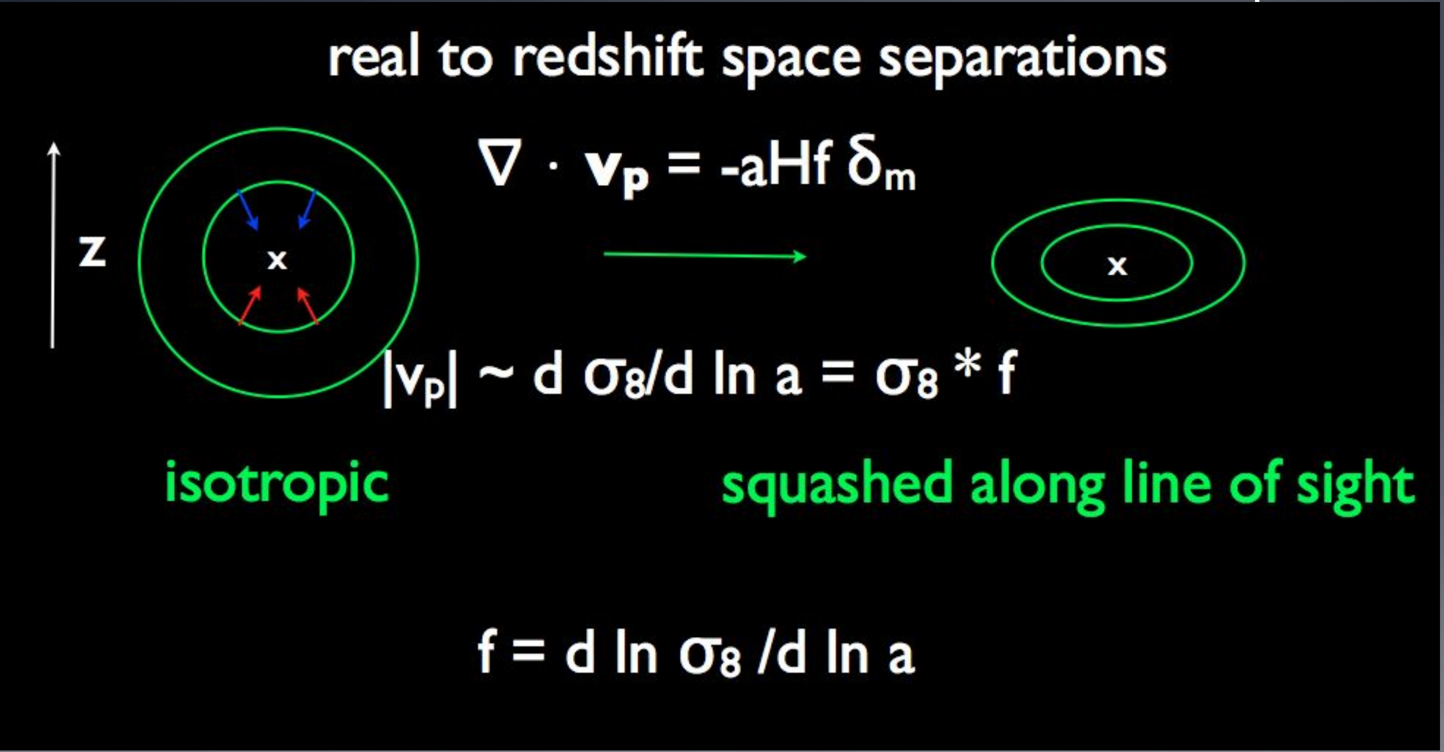
- To determine bias we need additional information
- Galaxy bias can be scale dependent: b(k)
- Once we know bias we know how dark matter clustering grows in time



Tegmark et al. (2006)

Redshift space distortions

redshift cz=aHr+v_p



Linear and nonlinear effects

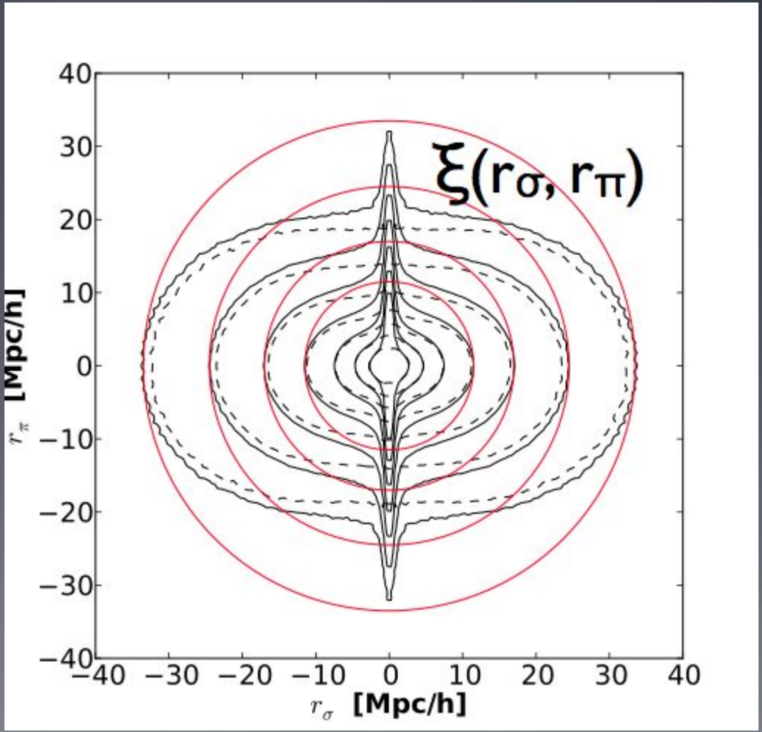
On very large scales linear RSD distortions: Kaiser formula

$$\delta_g = (b + f\mu^2)\delta = b(1+\beta\mu^2)\delta$$

$$\mu = \vec{k}\cdot\vec{n}/k \qquad \beta = f/b$$

From angular dependence we can determine velocity power proportional to $f\sigma_8$

On small scales: virialized velocities within halos lead to FoG, extending radially 10 times farther than transverse



White etal 2011

What are advantages and disadvantages of RSD?

+ Sensitive to velocities, which trace total matter

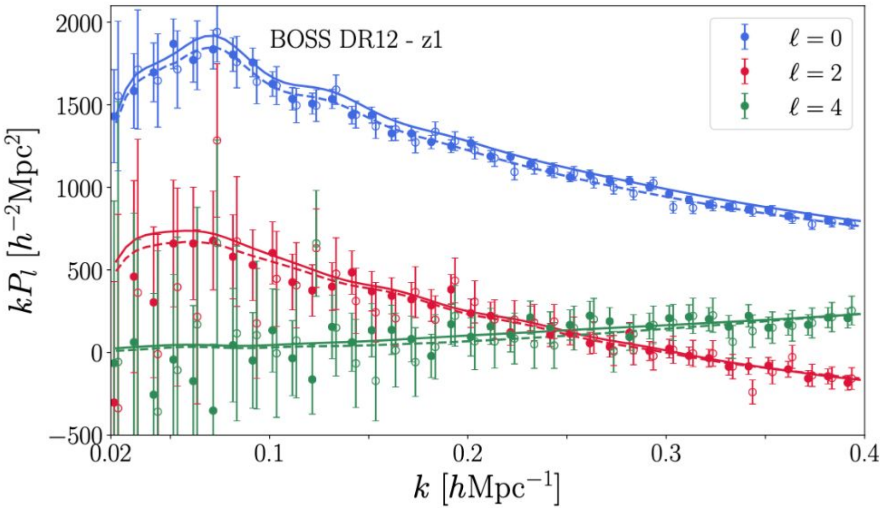
+ 3d data and high signal means a lot of information

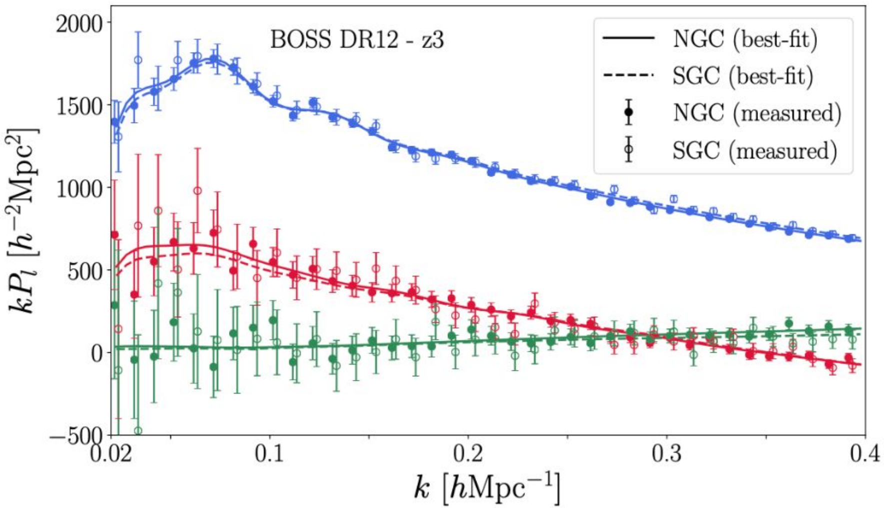
- Systematics: modeling of nonlinearity in bias and in velocities requires a lot of free parameters, and their priors

- Significant disagreement between different analyses on the same data, and same analyses truncated at a different minimal scale. Unclear how to choose this scale cut.

HaloPT SDSS analysis: SGC, NGC: CMASS, LOWZ

Yu, Seljak, Li, Singh 2022





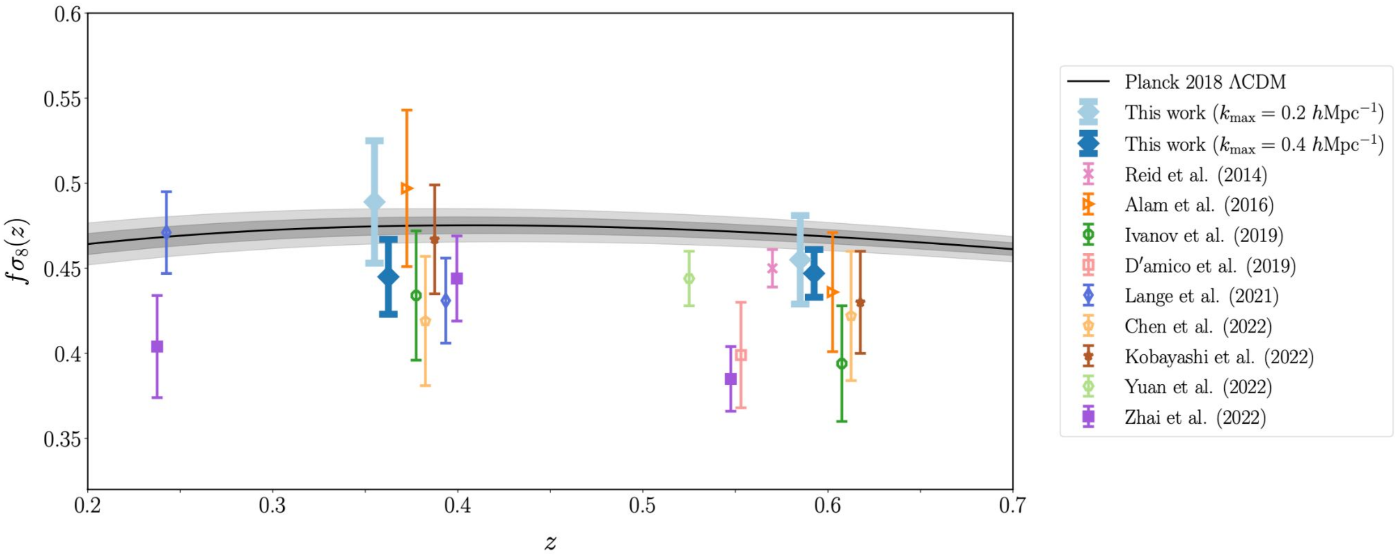
10 or 11 parameter fit (3 halo mass components)

$$[f(z_{\mathrm{eff}}), \sigma_8(z_{\mathrm{eff}}), b_{1,c_A}, b_{1,s_A}, b_{1,s_B}, f_s, f_{s_B}, \langle N_{>1,s}\rangle, \sigma_c, \sigma_{s_A}, f^{1h}_{s_B s_B}]$$

RSD constraints compilation

Yu, Seljak, Li, Singh 2022

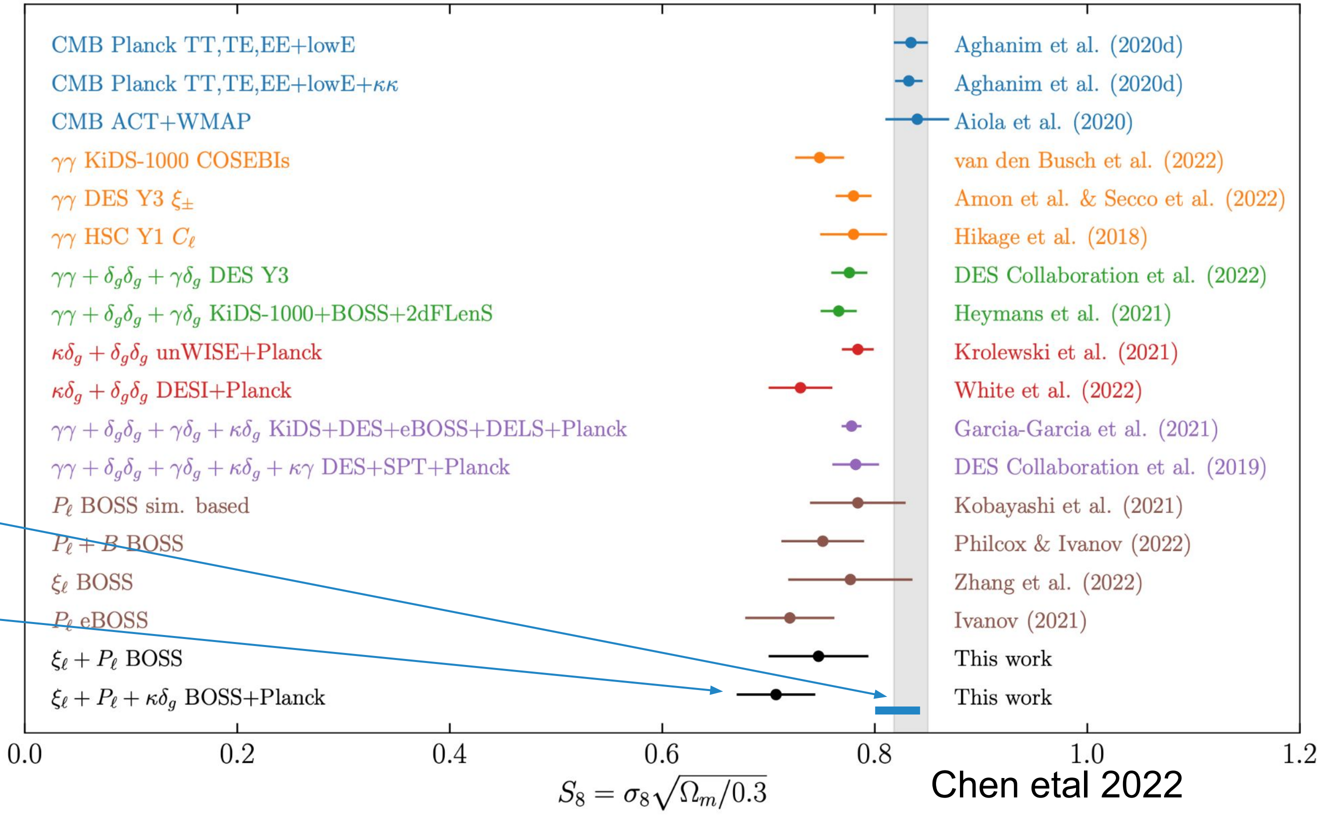
- There is evidence that **different RSD analyses of the same data reach very different results, as do different scale cuts**



Halo PT k=0.2 is consistent with Planck at 1 sigma!

Sigma8 tension?

- WL discrepancy between Chen etal and Singh etal almost certainly due to the modeling
- Chen combined RSD + WL is strongly below Planck
- Corresponding analysis of Halo PT (Yu etal) is consistent with Planck: same data as Chen etal
- **Modeling crisis?**
- **Too early to claim LSS is low compared to Planck?**



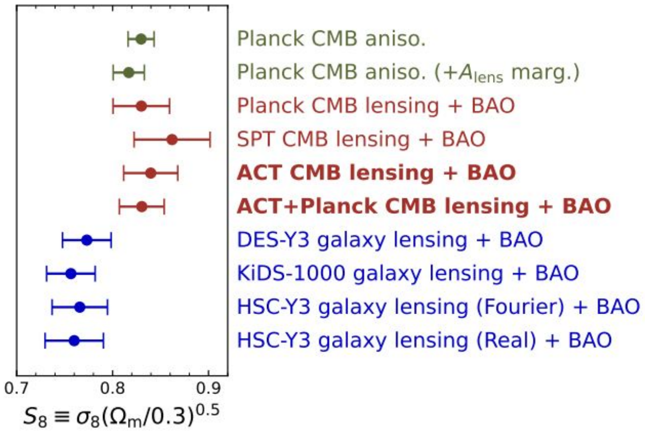
Chen etal 2022

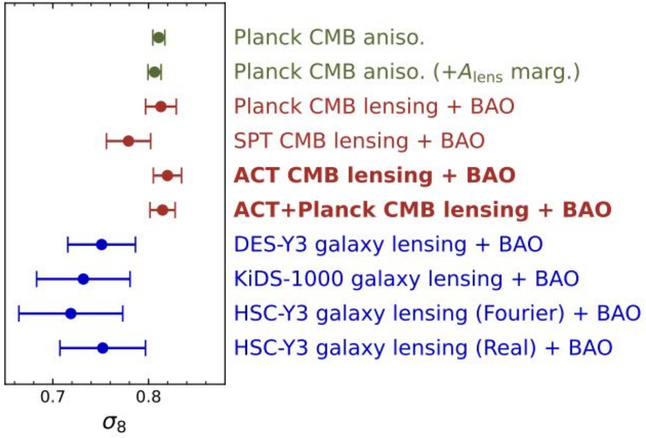
Lensing of CMB to the rescue

Lensing of CMB has very few systematics, and Planck lensing is consistent with Planck CMB

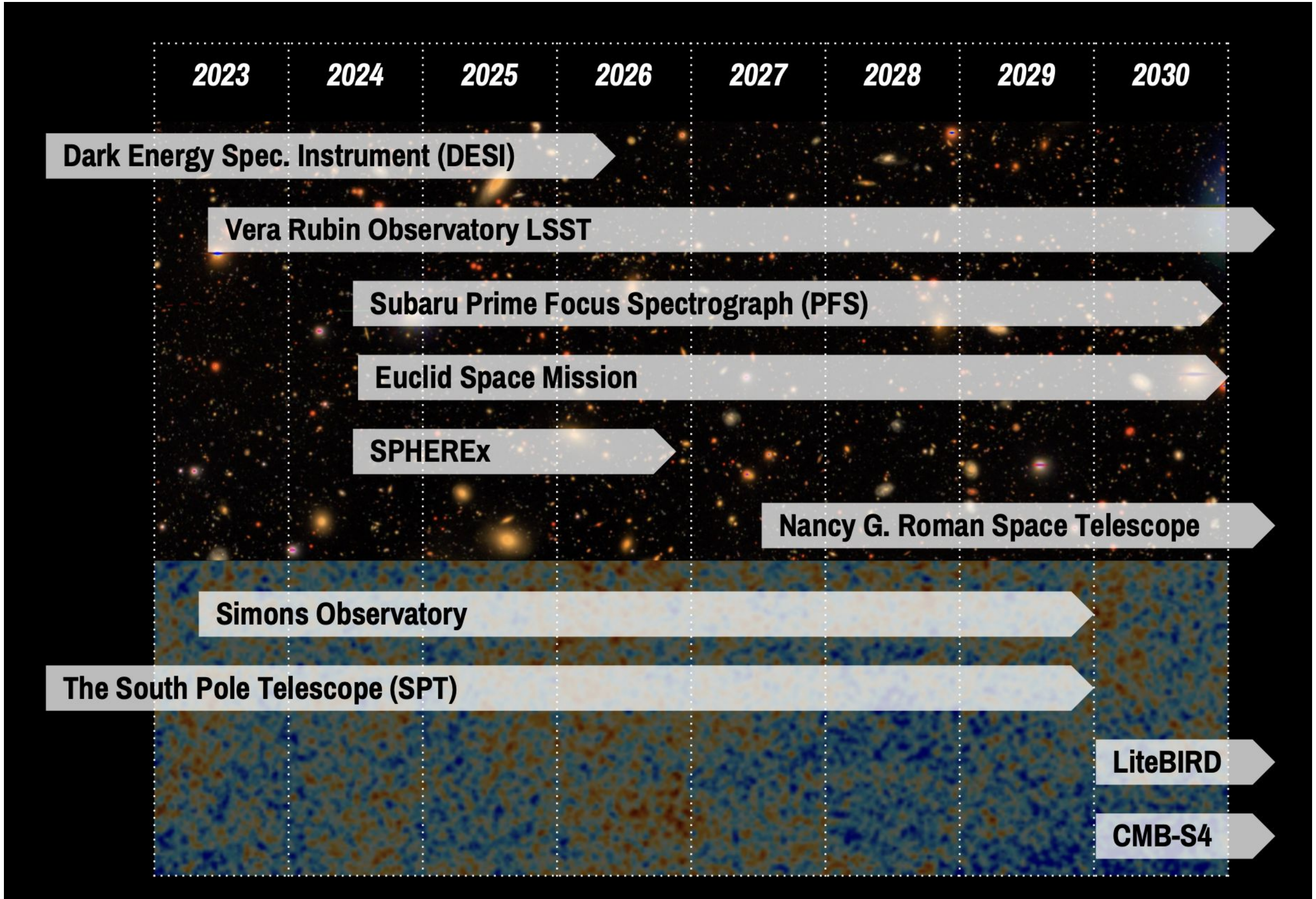
Recent ACT results are striking in their quality and show no tension with Planck

Similar results with CMB+Wise reanalysis (Krolewski etal)





The future is bright!

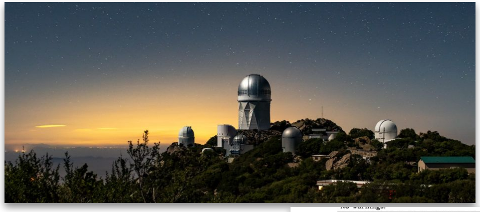


New surveys

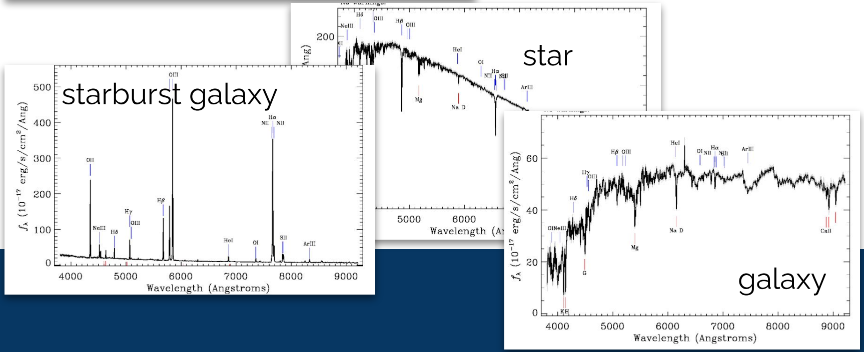
Vera Rubin Observatory (LSST)

20 *billion* galaxies
17 *billion* stars
20 *terabyte* data/day

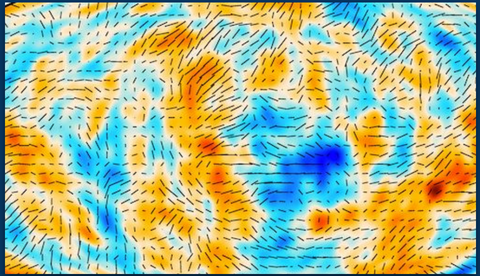
Dark Energy Spectroscopic Instrument (DESI)



35 million galaxies
10 million stars



CMB-S4



Cosmic Microwave Background

50 PB total database

New Methods: Machine Learning and more

LSS is very nonlinear, and power spectrum analyses miss a lot of information

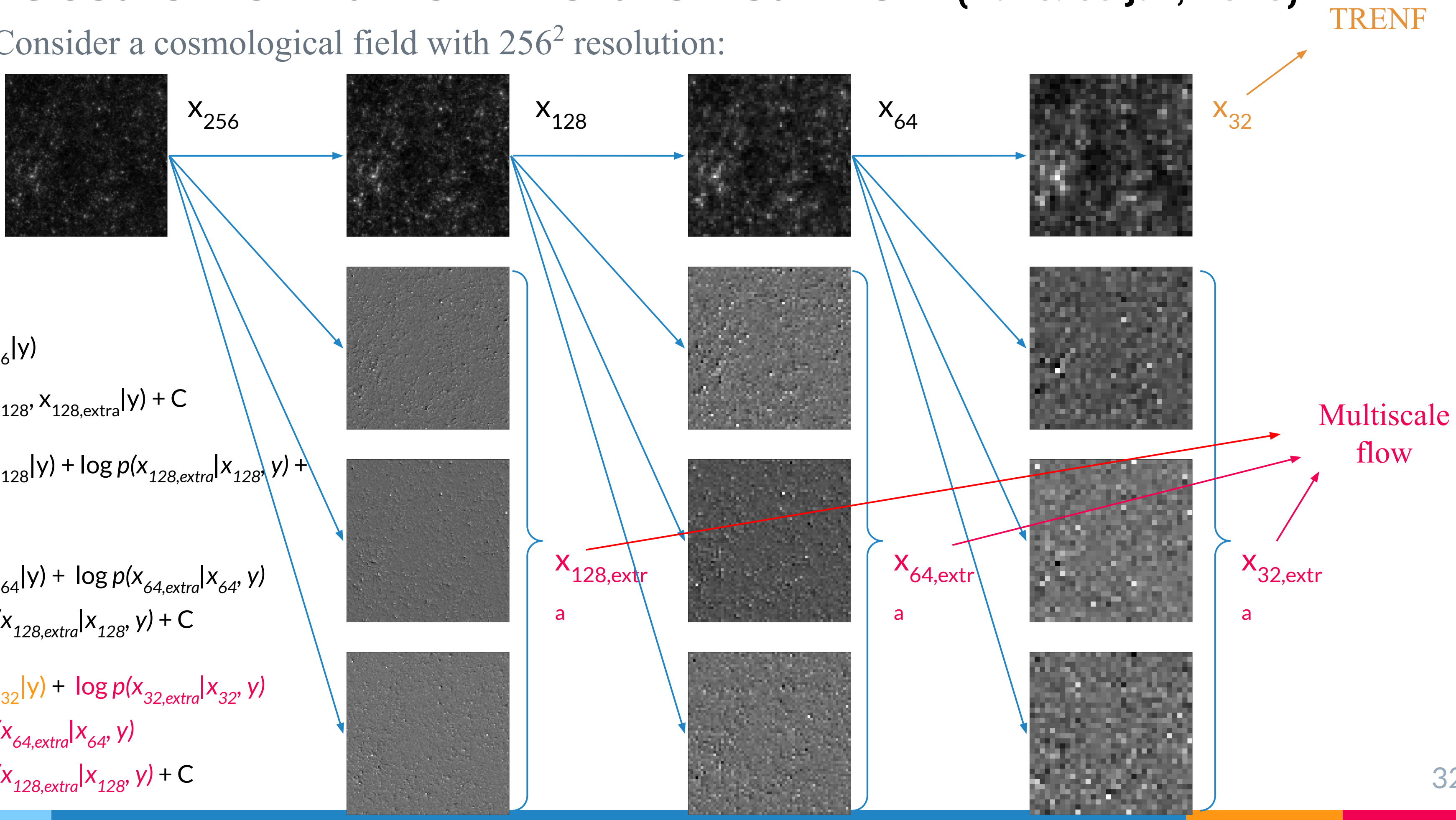
Sometimes we can do a full explicit likelihood analysis, e.g. CMB lensing and RSD (expensive to sample)

Otherwise we can use implicit likelihood analysis using ML, eg WL

These methods show promise of a large information gain relative to power spectrum

Multiscale flow: a new hierarchical flow (Dai & Seljak, 2023)

- Consider a cosmological field with 256^2 resolution:



$\log p(x_{256}|y)$

$= \log p(x_{128}, x_{128,extra}|y) + C$

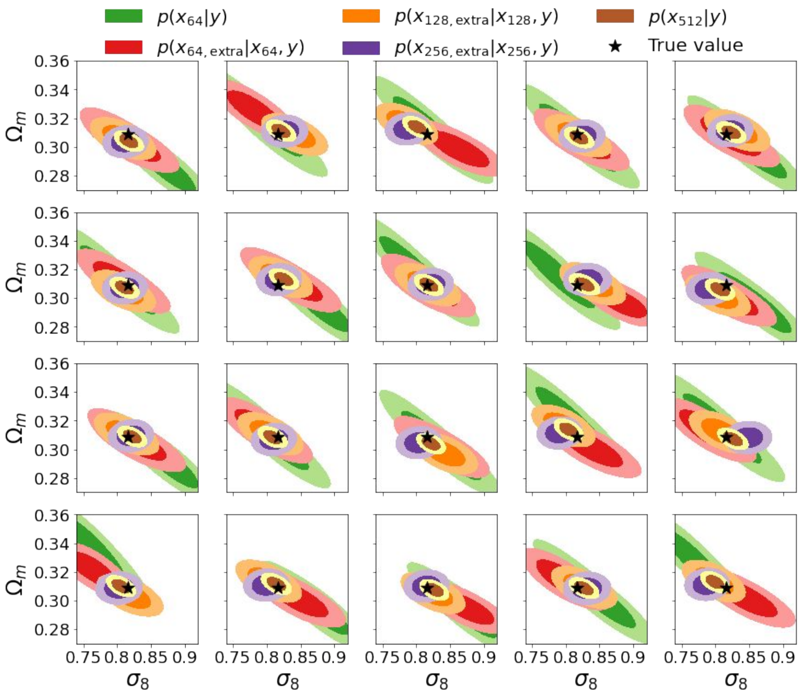
$= \log p(x_{128}|y) + \log p(x_{128,extra}|x_{128}, y) + C$

$= \log p(x_{64}|y) + \log p(x_{64,extra}|x_{64}, y)$
$\quad + \log p(x_{128,extra}|x_{128}, y) + C$

$= \log p(x_{32}|y) + \log p(x_{32,extra}|x_{32}, y)$
$\quad + \log p(x_{64,extra}|x_{64}, y)$
$\quad + \log p(x_{128,extra}|x_{128}, y) + C$

Reliable Uncertainty Quantification with NF posteriors

- Consistent posteriors from different scales



Posterior is proportional to likelihood p(x|y) times prior p(y) (which is assumed to be flat here)

We worked hard to train NF to give reliable uncertainty quantification in terms of 68% and 95% c.l. coverage probability

Method	$n_g = 10\mathrm{arcmin}^{-2}$	$n_g = 20\mathrm{arcmin}^{-2}$	$n_g = 50\mathrm{arcmin}^{-2}$	$n_g = 100\mathrm{arcmin}^{-2}$
Multiscale Flow $p(x_{512}|y)$	72.8%, 96.8%	74.4%, 95.2%	73.6%, 97.6%	66.4%, 97.6%
Multiscale Flow $p(x_{256}|y)$	70.4%, 96.0%	76.8%, 95.2%	74.4%, 97.6%	68.8%, 96.8%
Multiscale Flow $p(x_{128}|y)$	76.0%, 96.0%	74.4%, 97.6%	76.0%, 97.6%	73.6%, 96.8%
Multiscale Flow $p(x_{64}|y)$	80.8%, 95.2%	70.4%, 94.4%	72.0%, 95.2%	74.4%, 95.2%

Robustness — unknown systematic effects on WL maps: baryonic effects

Likelihood, ie density estimation, can be used for anomaly detection (generalization of reduced chi^2 test, ie PPD): if the data are from Out of Distribution then the density will be low

This can be done as a function of scale

Scale dependence of posteriors is an independent test

Both are comparable in ROC and powerful!

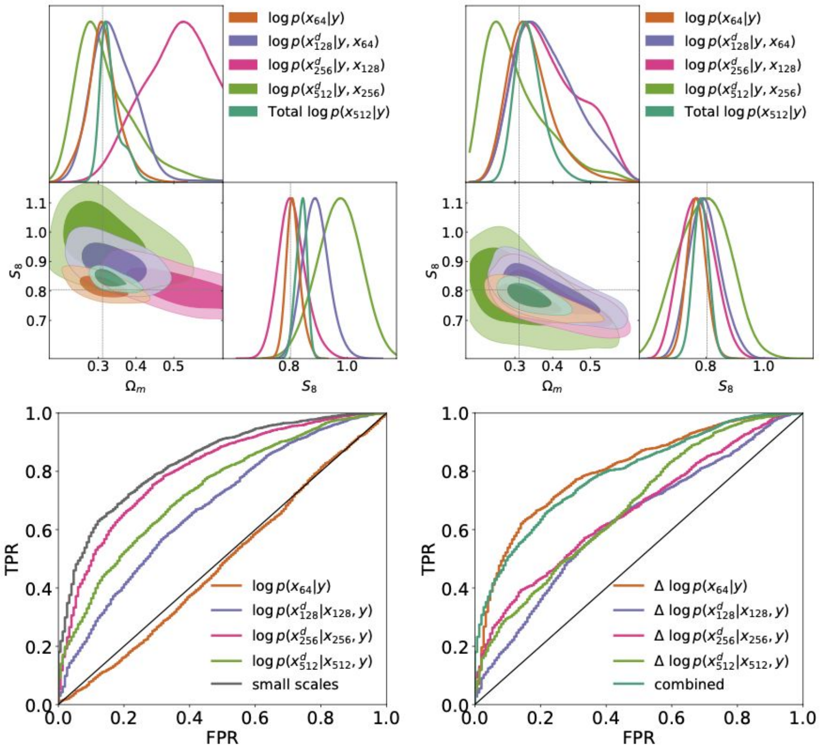


Fig. 5. Top panel: scale-dependent posterior analysis of a baryon-corrected convergence map using Multiscale Flow trained on dark-matter-only maps (left), and Multiscale Flow trained on BCM maps (right). Bottom panel: ROC curve of identifying distribution shift with $\log p$ (left) and $\Delta \log p$ (right). The "small scales" in the lower left panel represent combining the three small scale terms. In these experiments, we consider $30\mathrm{arcmin}^{-2}$ galaxy shape noise.

Two independent ways to identify unknown unknowns!

Figure of Merit: inverse error area on matter density and amplitude

Method	$n_g = 10\text{arcmin}^{-2}$	$n_g = 30\text{arcmin}^{-2}$	$n_g = 100\text{arcmin}^{-2}$
Multiscale Flow $p(x_{512}\|y)$	**95**	**246**	**733**
Multiscale Flow $p(x_{256}\|y)$	91	229	644
Multiscale Flow $p(x_{128}\|y)$	74	180	435
Multiscale Flow $p(x_{64}\|y)$	52	123	272
power spectrum	30 (30)	52 (51)	81 (79)
peak count	(30)	(89)	(162)
CNN	(44)	(121)	(292)
scattering transform $s_0 + s_1 + s_2$	($\lesssim 50$)	($\lesssim 140$)	($\lesssim 329$)

Table 2. Similar to Table 1, with baryonic effects.

	Method	$n_g = 10\text{arcmin}^{-2}$	$n_g = 20\text{arcmin}^{-2}$	$n_g = 50\text{arcmin}^{-2}$	$n_g = 100\text{arcmin}^{-2}$
Fix baryon parameters at fiducial values	Multiscale Flow $p(x_{512}\|y)$	**166**	**310**	**617**	**1072**
	Multiscale Flow $p(x_{256}\|y)$	164	297	558	947
	Multiscale Flow $p(x_{128}\|y)$	124	214	415	704
	Multiscale Flow $p(x_{64}\|y)$	81	136	247	387
	power spectrum	41(41)	61 (58)	95(87)	127(111)
	CNN	-	(~ 93)	(~ 146)	(~ 194)
Marginalize over baryon parameters	Multiscale Flow $p(x_{512}\|y)$	**149**	**220**	**362**	**521**
	Multiscale Flow $p(x_{256}\|y)$	147	213	341	494
	Multiscale Flow $p(x_{128}\|y)$	112	166	269	398
	Multiscale Flow $p(x_{64}\|y)$	75	113	183	259
	power spectrum	34(33)	48(48)	68(65)	84 (78)
	CNN	-	(~ 77)	(~ 109)	(~ 136)

1. When fixing the baryon parameters at fiducial values, the FoM of CNN are estimated from Lu et al. (51). Lu et al. (51) estimated the 1σ area of a 1500deg^2 survey, and we scale their results by the area ratio for a direct comparison with our experiments.

Factor of 5 better than power spectrum

Factor of 3 better than other recent methods (CNN, scattering transform)

Equivalent to 3-5 larger survey area of the sky!

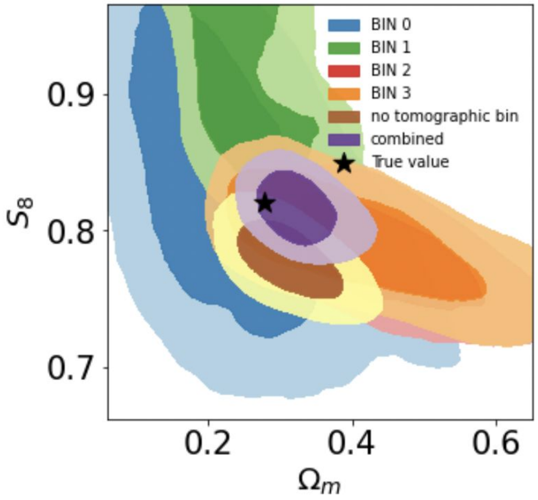
Next Step: include systematics (photoz calibration, shear calibration, intrinsic alignments…)

Next step: **apply to the real data.**
First HSC on Subaru
Later Rubin etc.

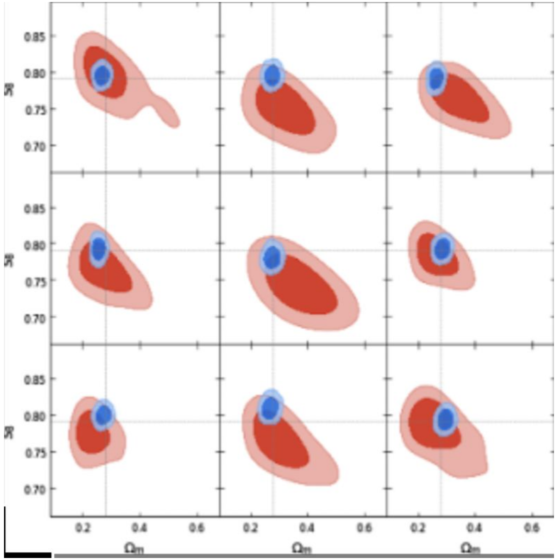
Tomographic bins: conditional likelihoods

- $\log p(x_{512}) = \log p(x_{32}) + \log p(x^{d}{}_{32}|x_{32}) + \log p(x^{d}{}_{64}|x_{64}) + \log p(x^{d}{}_{128}|x_{128}) + \log p(x^{d}{}_{256}|x_{256})$
- $\log p(x) = \log p(x_{BIN1}) + \log p(x_{BIN2}|x_{BIN1}) + \log p(x_{BIN3}|x_{BIN2}) + \log p(x_{BIN4}|x_{BIN3})$

p(x_128 | x_64, y) scale ~ 7.5 - 15 arcmin



Up to 10x higher Figure of Merit for realistic HSC data!



p(bin1,bin2,bin3,bin4) = p(bin1) * p(bin2|bin1) * p(bin3|bin1,bin2) * p(bin4|bin1,bin2,bin3)

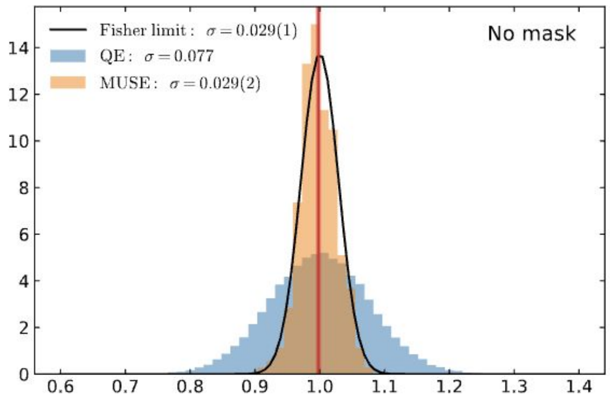
Explicit Likelihood Lensing of CMB: the ultimate LSS probe?

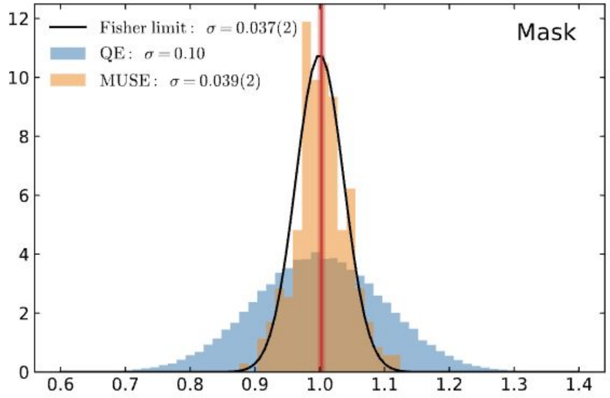
CMB lensing is almost systematics free

Current state of the art (e.g. ACT analysis): Quadratic Estimators (QE)

With low noise (eg SPT, CMB S4) explicit likelihood analysis (Hirata & Seljak 2003, Millea & Seljak 2022) gets much better results

High dimensional sampling at field level is slow, but new methods of sampling such as MicroCanonical Langevin Monte Carlo make it feasible





Summary

- Lambda CDM is the current standard model of our universe and currently explains all the data
- Recent analyses do not support claims of tensions in the data (e.g. Hubble and amplitude tensions)
- Next generation surveys are coming online soon (DESI, Euclid, Rubin, SO etc.)
- Next generation analyses are being developed and in some cases will be equivalent to an order of magnitude increase in data volume