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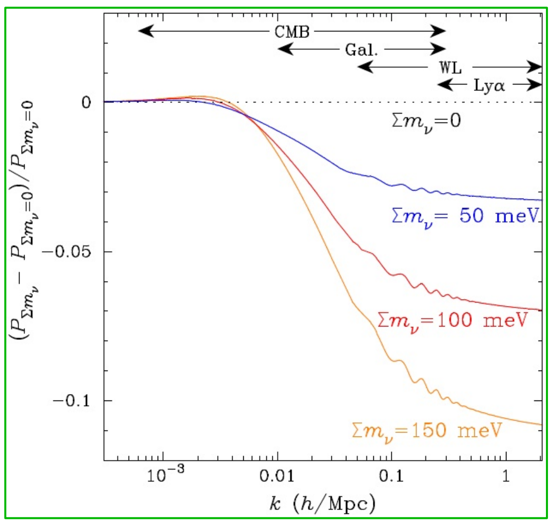
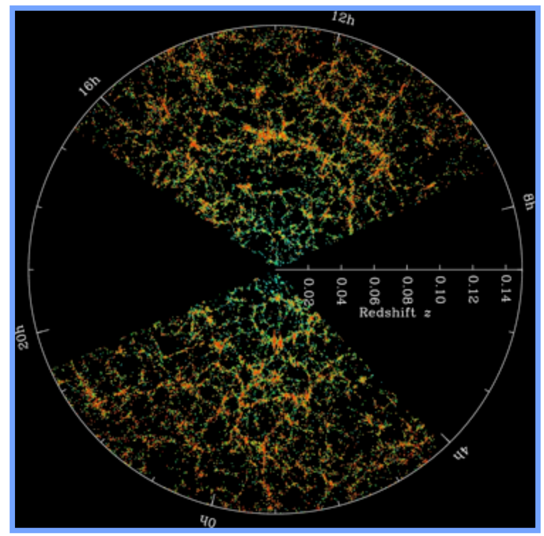
Dark Freedom,
Early Universe Bounds,
and Sky Surveys



Eric Linder

KASI

LBNL & UC Berkeley



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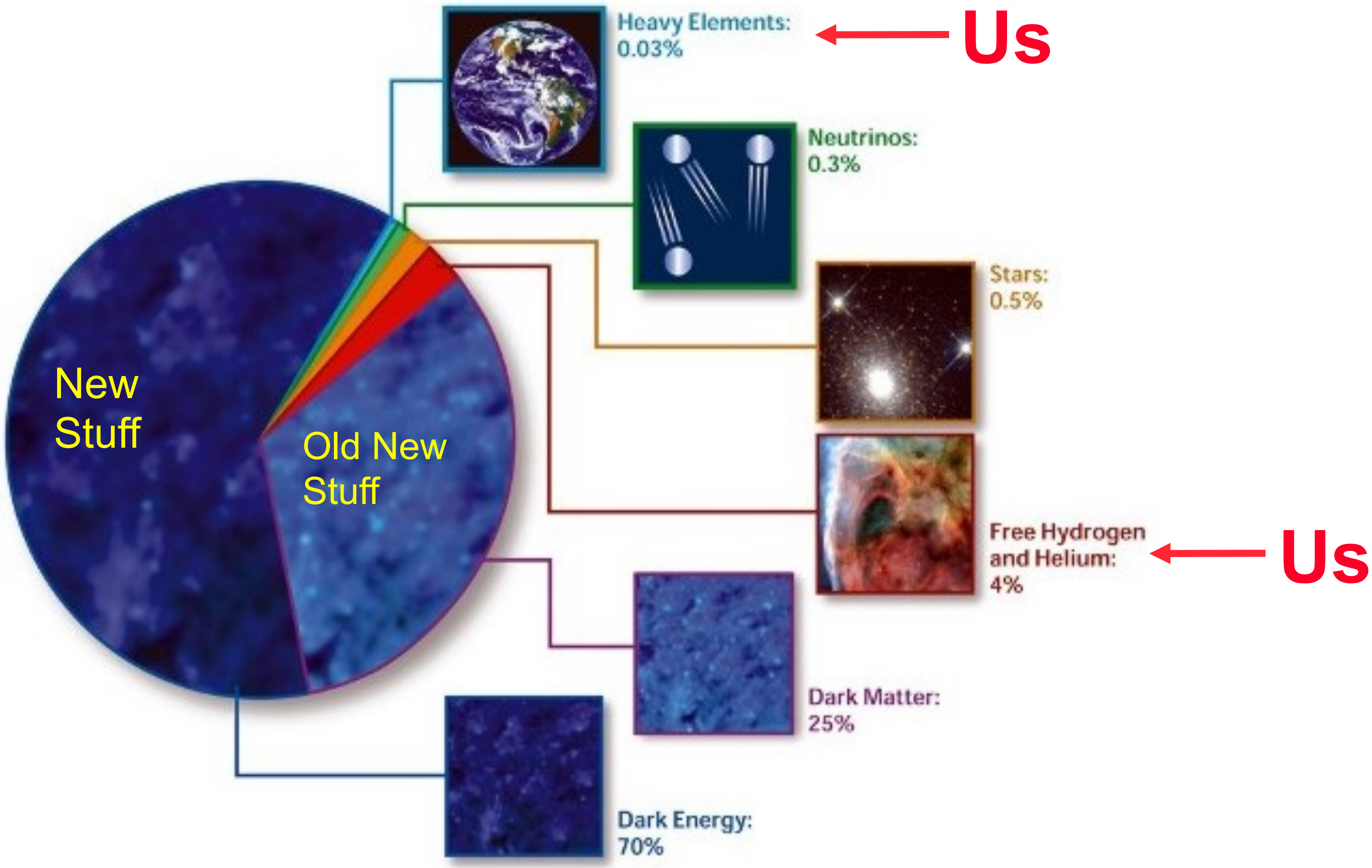
Describing Our Universe



STScI

95% of the universe is unknown!

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Role of Theory

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Cosmic acceleration – in the early universe and at present – are fundamental mysteries in understanding our universe.

Copernican Principle / Cosmic Modesty:

- **Our galaxy is not the center of the universe.**
- **Our particles are not the matter/energy of the universe.**
- **Is our vacuum the vacuum of the universe?**
- **Is our gravity the gravity of the universe?**

Role of Observations

But Λ, what big teeth you have!

Before we jump into bed with Λ, we should be sure it is not something more beastly.

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High Energy Physics

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Cosmic Microwave Background (CMB) radiation gives direct access to high energy physics.

Inflation may happen at the GUT scale $\sim 10^{15}$ GeV, leaving its signatures in Shape of the scalar (density) power spectrum, Amplitude of the tensor (primordial GW) power spectrum, Non-Gaussianity.

The CMB also sees the linear transfer function of density perturbations modes entering the horizon from $z \sim 10^{5}$ to $z=0$, probing Dark matter.

CMB tests the growth of cosmic structure, probing Dark energy and Neutrino free streaming, through e.g. CMB lensing.

Large Scale Structure

Large scale structure complements the CMB through late time measurements of the growth of clustering.

LSS also has access to smaller scales

- Long lever arm
- Nonlinear amplification of growth
- Within a neutrino free streaming length

CMB + LSS (and CMB x LSS) give strong constraints on inflation and neutrino mass.

Inflation and Neutrino Mass

We focus first on **inflationary** parameters in terms of

- Scalar tilt n_s
- Running α_s
- Shape of scalar primordial power spectrum
- Tensor/scalar power ratio r

$$\Delta^2_{\mathcal{R}}(k) = \Delta^2_{\mathcal{R}}(k_0)\left(\frac{k}{k_0}\right)^{n_s - 1 + (\alpha_s/2)\ln(k/k_0)}$$

And **neutrino** parameters

- sum of neutrino masses m_ν
- Number of effective relativistic species $N_{\nu,\mathrm{eff}}$

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Primordial Power Spectrum

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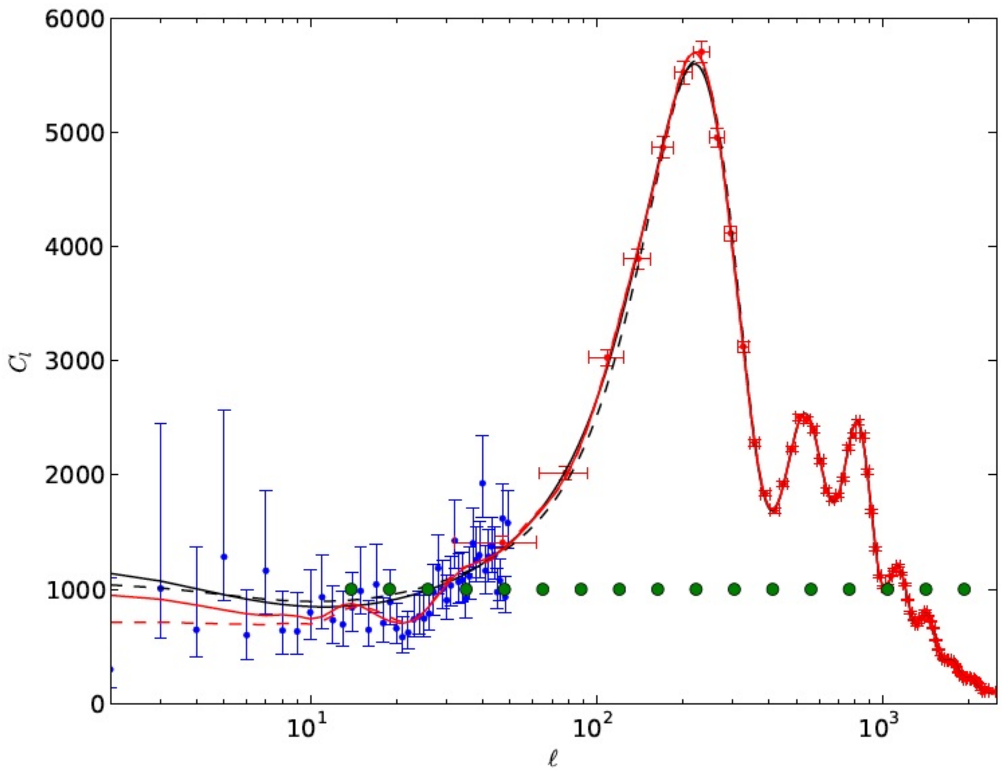
Is the primordial spectrum a power law, or does inflationary physics have a scale, teaching new high energy physics? e.g. axion monodromy **Silverstein & Westphal 2008**

BICEP2+Planck disfavor power law.

Plus, late time parameter estimation is affected by assumptions for primordial power spectrum.



Black curves have power law PPS.

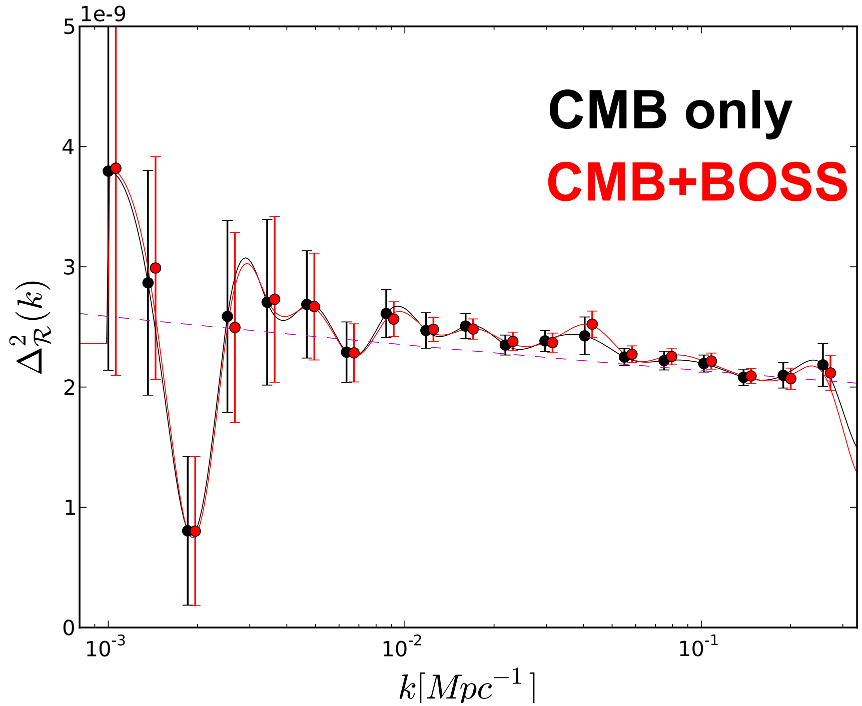
Red curves have free PPS.

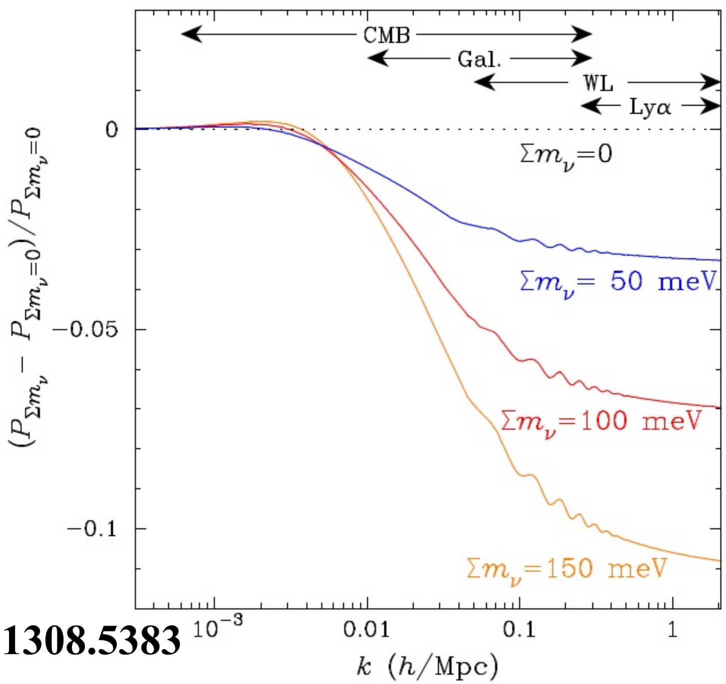
Dashed curves **have m_ν=2.5 eV.**

Easily seen if assume power law PPS.

Primordial + Late Time

Free spline fit to primordial power spectrum has improvement $\Delta\chi^2$=34, for 18 more parameters.





1308.5383

CMB plus Large Scale Structure work together well to constrain the **sum of neutrino masses**, probing above and below the neutrino free streaming scale.

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CMB + Sky Surveys

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Primordial power spectrum (inflation) is convolved with later time transfer function (m_ν). Can't separate with single measurement! (CMB has TT, EE, etc.)

Any quantity (dark energy, gravity, neutrino mass) affecting growth will be affected by PPS.

CMB+LSS has excellent complementarity.

Each redshift slice sees the same PPS, convolved with given transfer function scaled by the redshift z.

Tomographic survey (SuMIRE, DESI) will be powerful probe of inflation, as well as "late time" cosmology!

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CMB + Sky Surveys

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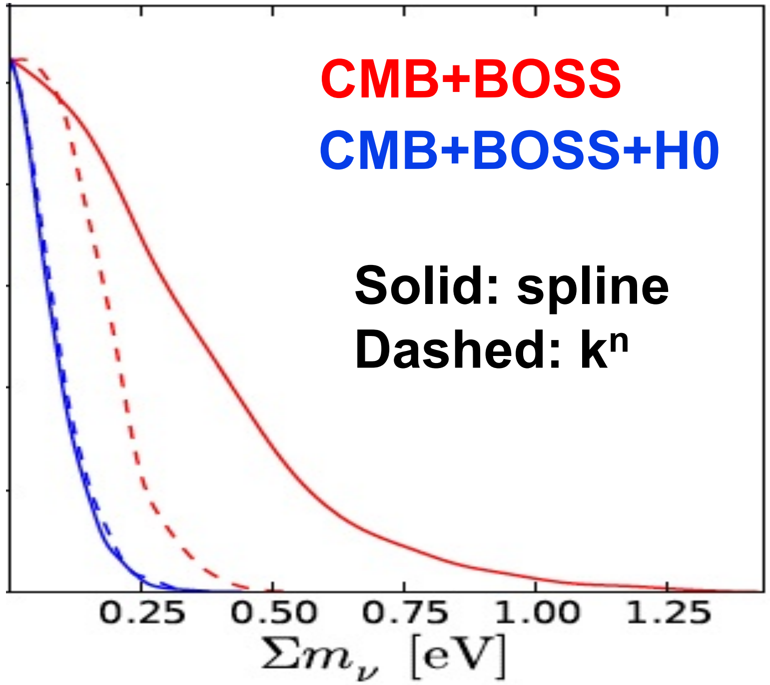


de Putter, Linder, Mishra 2014

CMB+galaxy measurement improves by ~2 over CMB.

Multiple z measurements (such as H_0) helps further, immunizing vs primordial variation.

PPS	CMB	CMB+BOSS	CMB+BOSS+H_0
Power law	$\Sigma m_\nu < 0.63$	$\Sigma m_\nu < 0.34$	$\Sigma m_\nu < 0.19$
Spline	$\Sigma m_\nu < 1.9$	$\Sigma m_\nu < 0.72$	$\Sigma m_\nu < 0.18$

Since direct H_0 in tension with CMB, get tight constraint, else 0.18→0.27 (still immunizes).

PPS	CMB+BOSS+H_0 for $N_{\rm eff}$ free
Power law	$\Sigma m_\nu < 0.26$, $N_{\rm eff} = 3.59 \pm 0.25$
Spline	$\Sigma m_\nu < 0.43$, $N_{\rm eff} = 3.92 \pm 0.42$

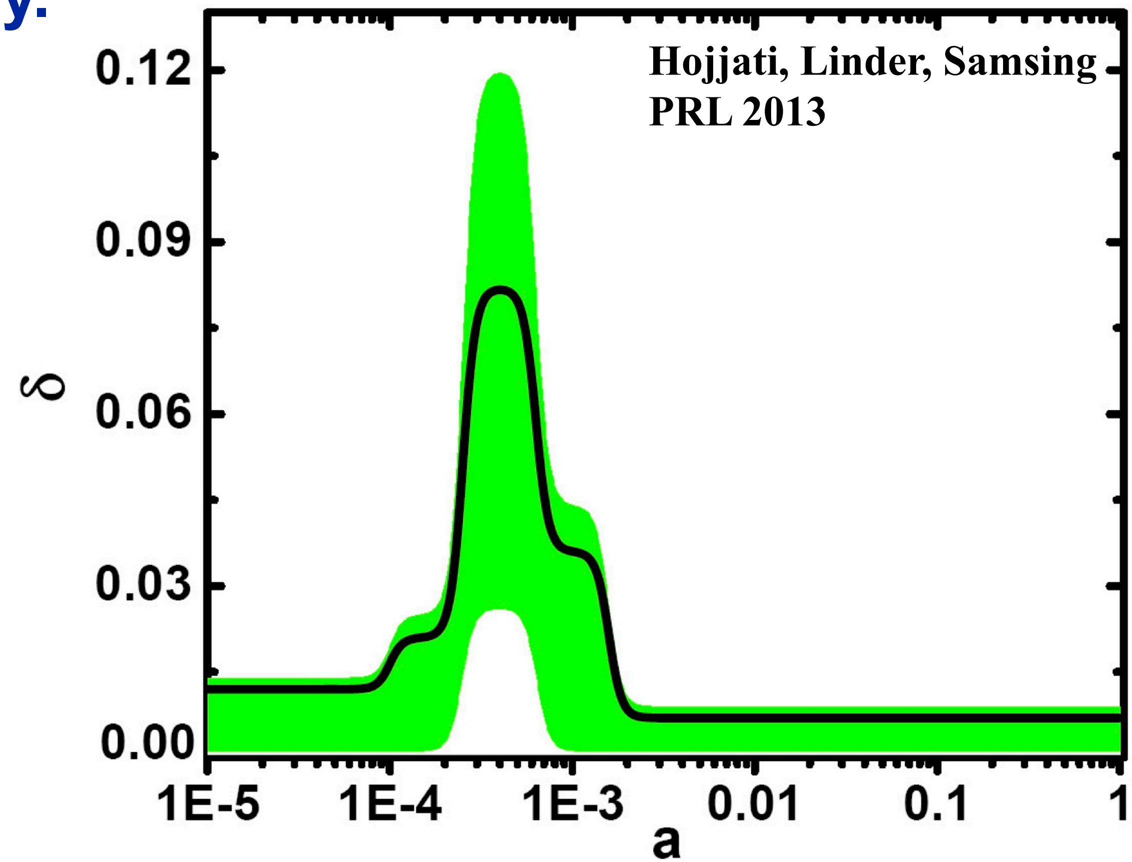
Further freedom requires further z measurements: Euclid tomography!

Probing Early Expansion

Fit real Planck data (+WP) to *any* deviation from ΛCDM in bins of log a = [-5,-4], [-4,-3.6], [-3.6,-3.2], [-3.2,-2.8], [-2.8,0].

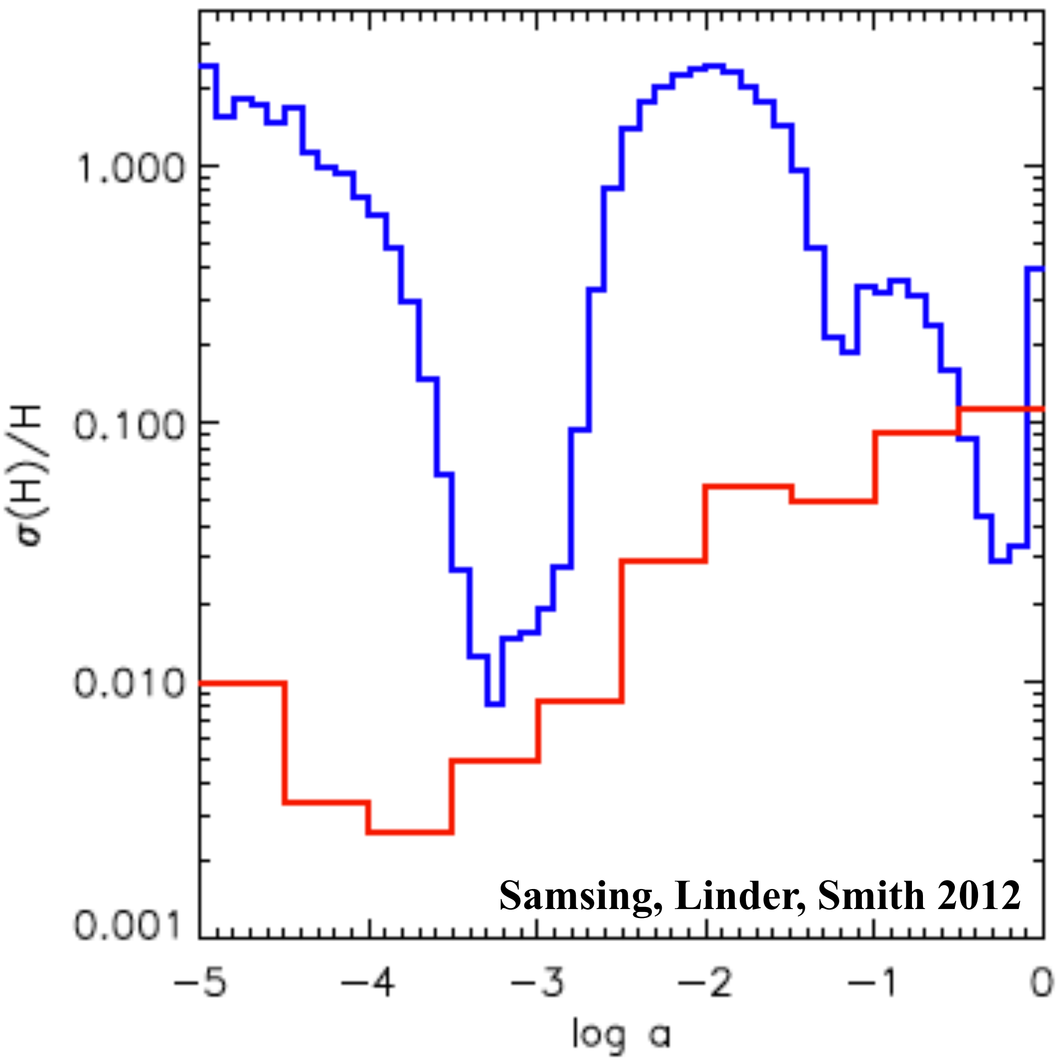
Basically testing standard radiation/matter domination in a model independent way.

Slight hint of extra radiation energy, i.e. N_{eff}=3.35.



Model Independent Constraints

Planck will have some sub-1%, model independent constraints on expansion.



10 bands/decade

2 bands/decade

Marginalized over vanilla cosmology parameters

Early Dark Energy

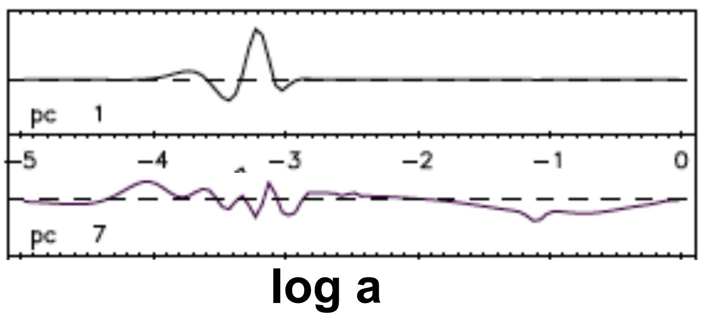
Planck+ bound of <0.9% (95% CL) early dark energy only applies to easiest case.

	Aether (rising)	Dark Radiation (falling)	Doran-Robbers (constant)
Ω_e	0.019	0.033	0.012

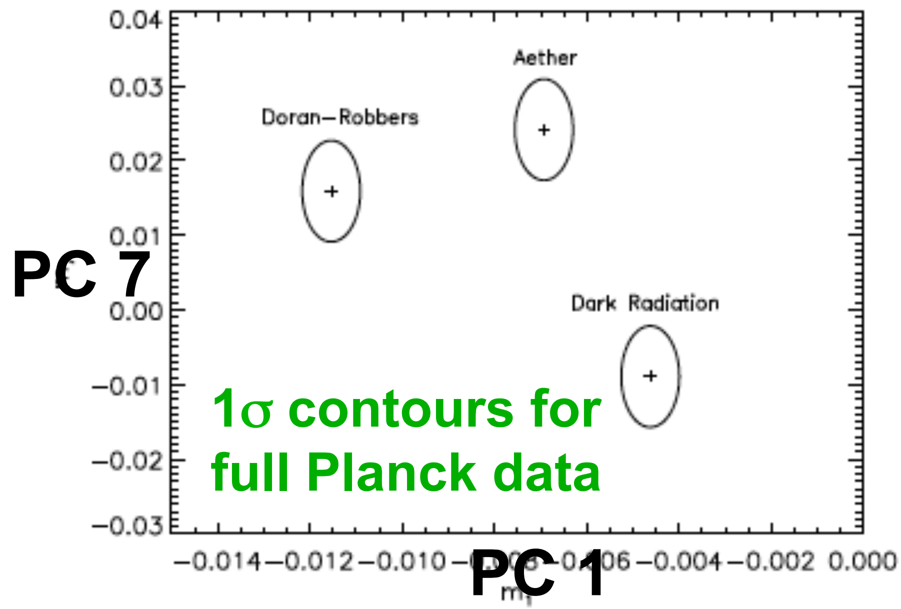
gives $N_{eff}>3$

Hojjati, Linder, Samsing 2013

PCA of Planck data will easily separate the 3 classes into distinct regions of eigenspace.



Samsing, Linder, Smith 2012



CMB Lensing

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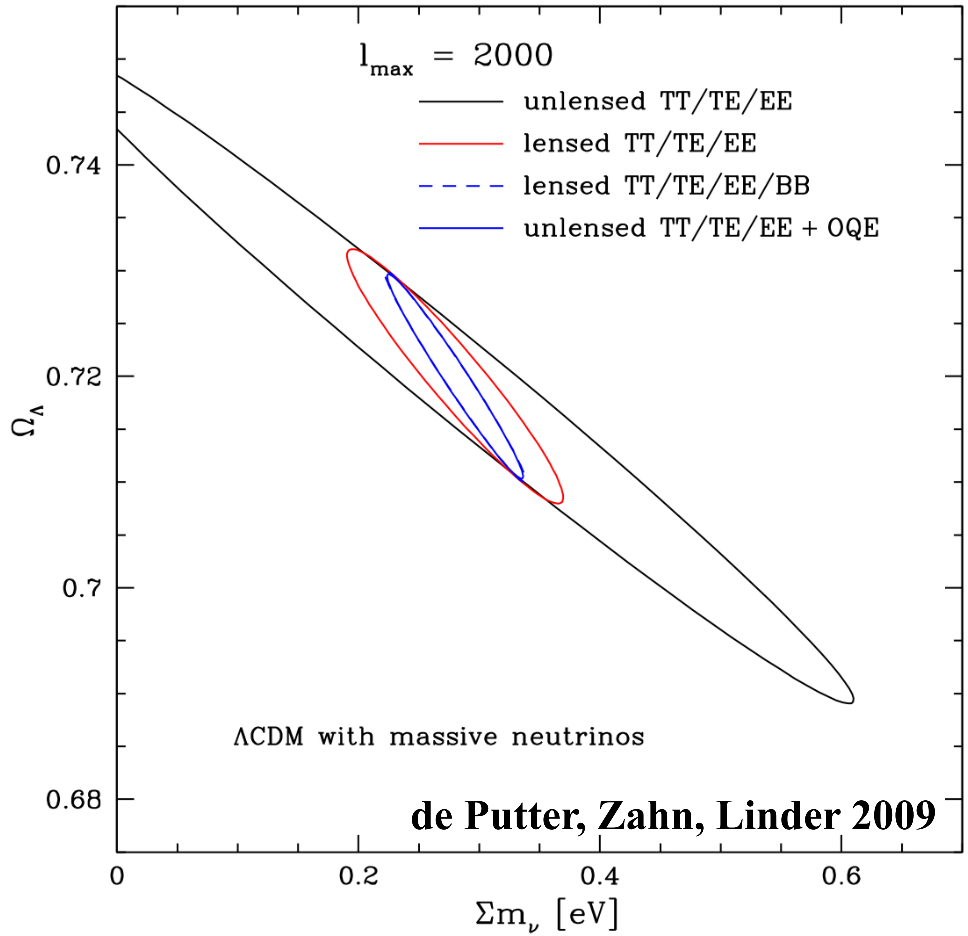
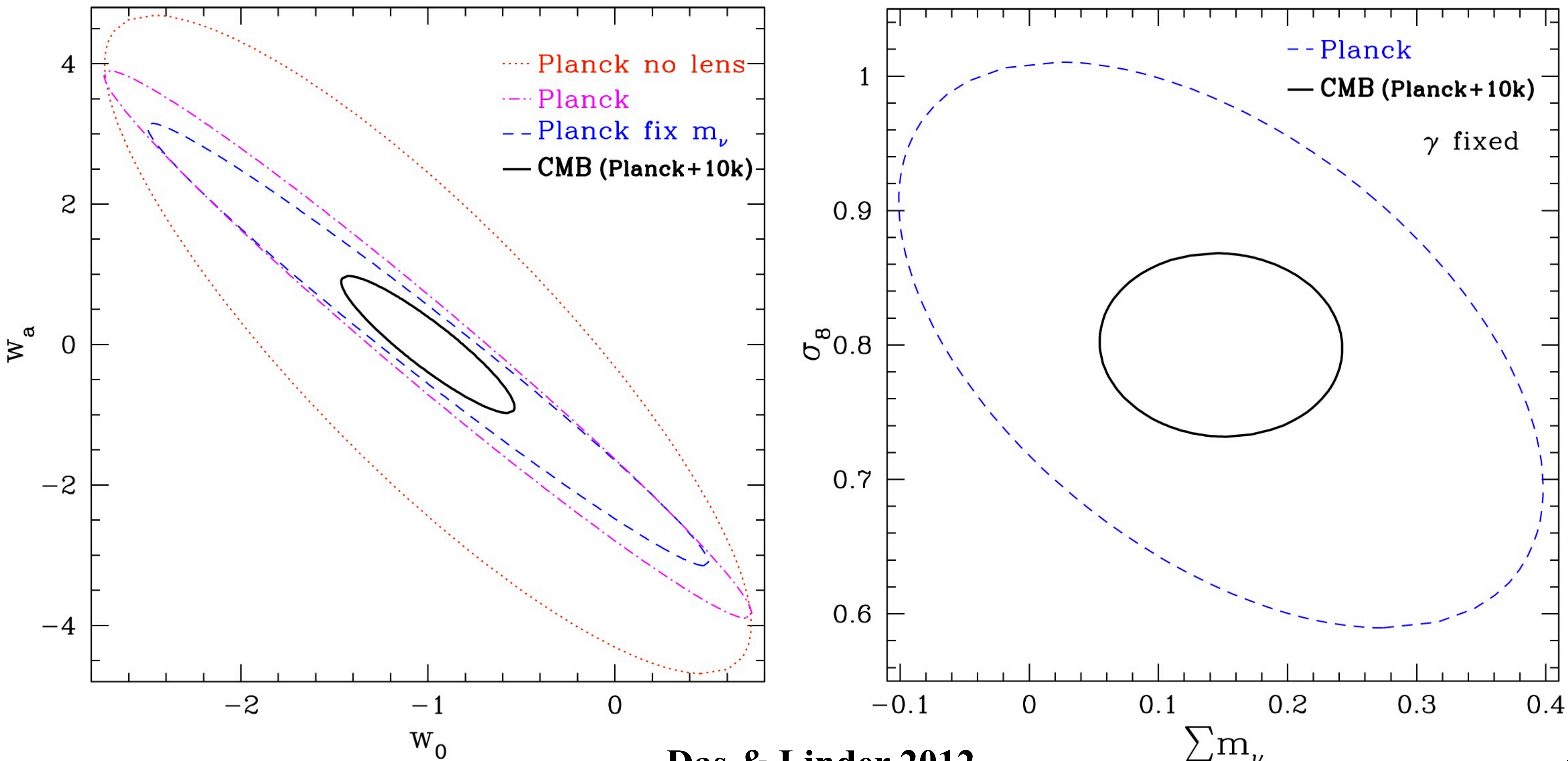
CMB lensing is a noise for primordial B-mode detections, but also a cosmological signal. CMB is a source pattern for weak lensing. Probes z~1-5 effects, e.g. neutrino masses.



de Putter, Zahn, Linder 2009

Neutrino Mass (and Dark Energy)

Ground based experiments (ACTpol, Polarbear, SPTpol) are doing CMB lensing *now*. They strongly improve Planck constraints: m_ν by 2.6, DE FOM by 6.6



Das & Linder 2012

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B-mode Lensing

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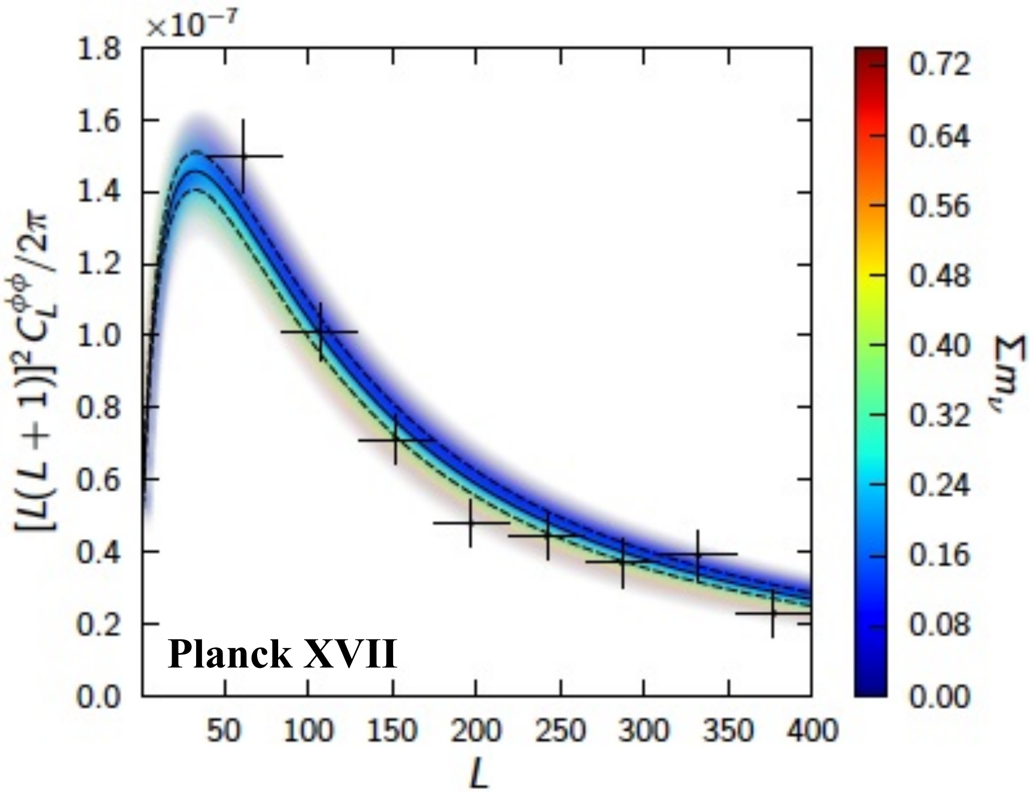
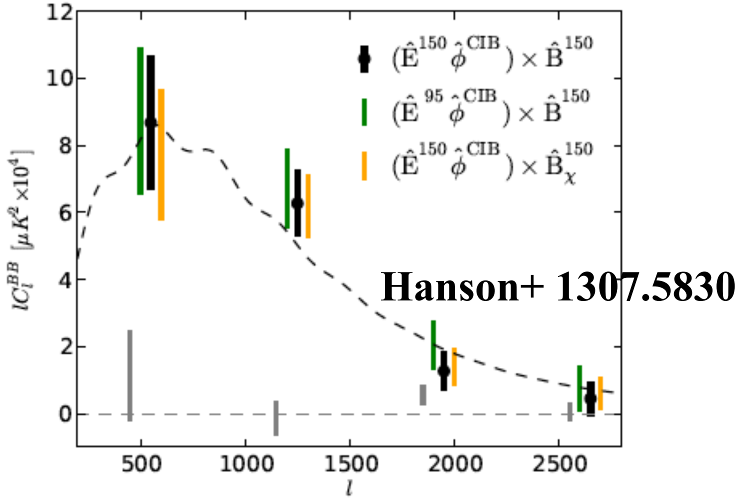
B-mode lensing carries more information than TT smearing.

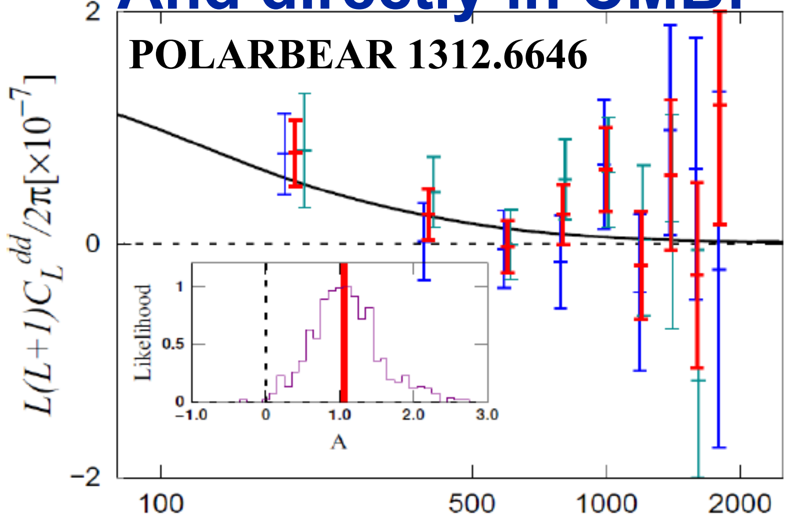


Neutrino mass effect on deflection field

B-mode lensing detected in cross-correlation.



And directly in CMB:



CMB + Late Time Probes

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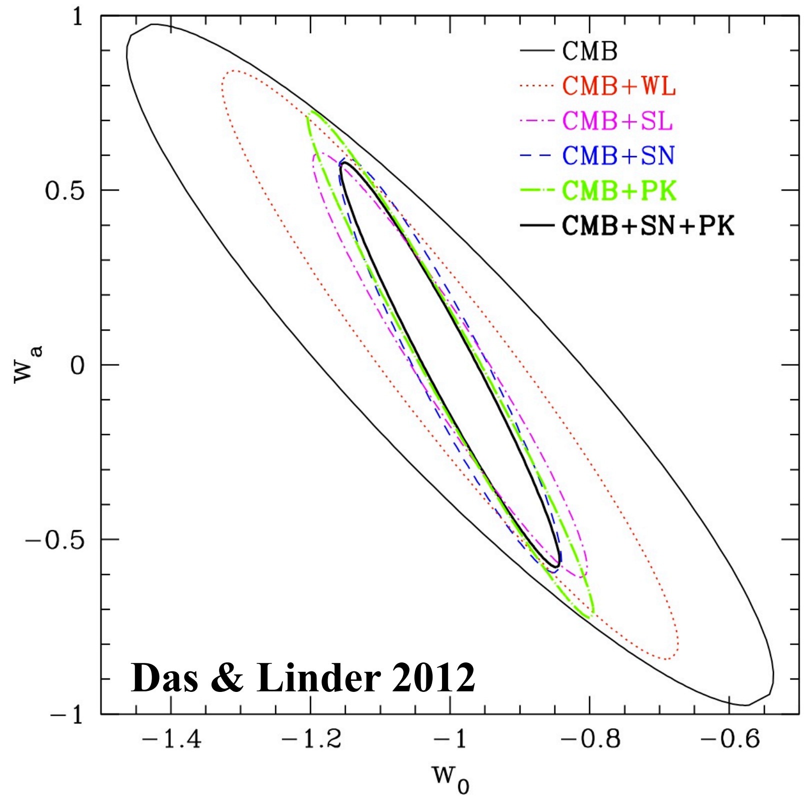
Strong constraints by combining CMB (early), CMB lensing (mid), and late time probes.

	ω_b	ω_c	ω_ν	Ω_{de}	n_s	τ	σ_8	w_0	w_a	γ
Fiducial	0.02258	0.1093	0.001596	0.734	0.963	0.086	0.8	-1	0	0.55
σ(Planck)	0.000137	0.00117	0.00175	0.124	0.00337	0.00426	d	1.10	2.48	d
σ(Planck+10k)	0.0000492	0.000682	0.000666	0.042	0.00207	0.00297	d	0.305	0.642	d
Gain	2.78	1.72	2.63	2.95	1.63	1.43	d	3.61	3.86	d

Improve m_ν constraint by 2.6, DE FOM by 6.6, m_ν-σ_8 FOM (fixing GR) by 5.2.



Large scale structure probes, and distance probes, each add to dark energy knowledge.

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Large Scale Structure

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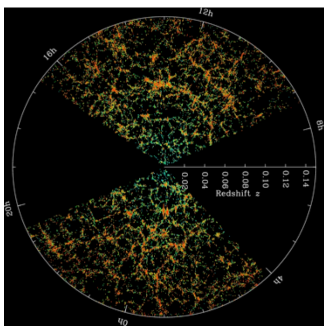
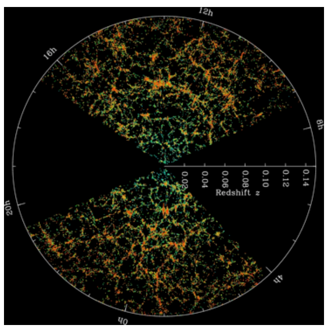
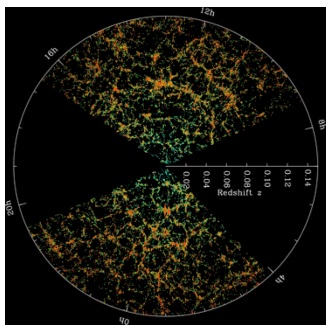
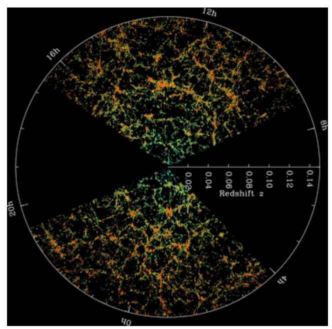
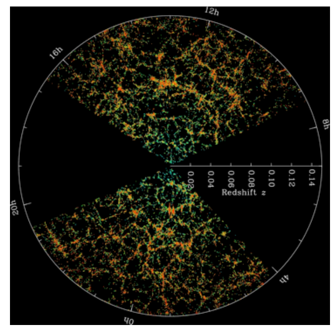
Galaxy clustering contains information on:

- **Growth** - evolving amplitude
- **Matter/radiation density, H** - peak turnover
- **Distances** - baryon acoustic oscillations
- **Growth rate** - redshift space distortions
- **Neutrino mass**, non-Gaussianity, **gravity**, etc.

(and not just CMB+LSS but CMB x LSS)

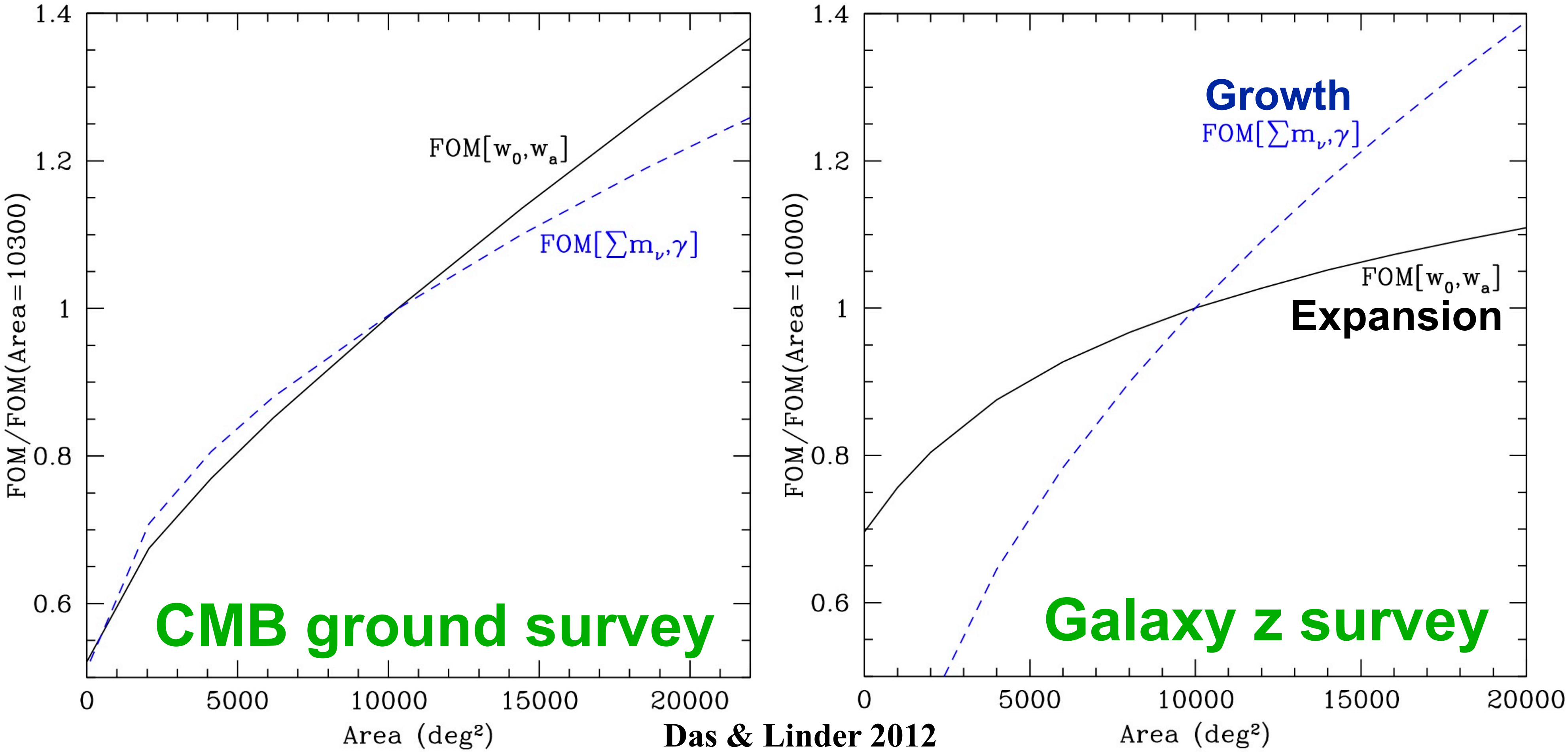





x25
(x7 LRG)
...



Surveys + Surveys

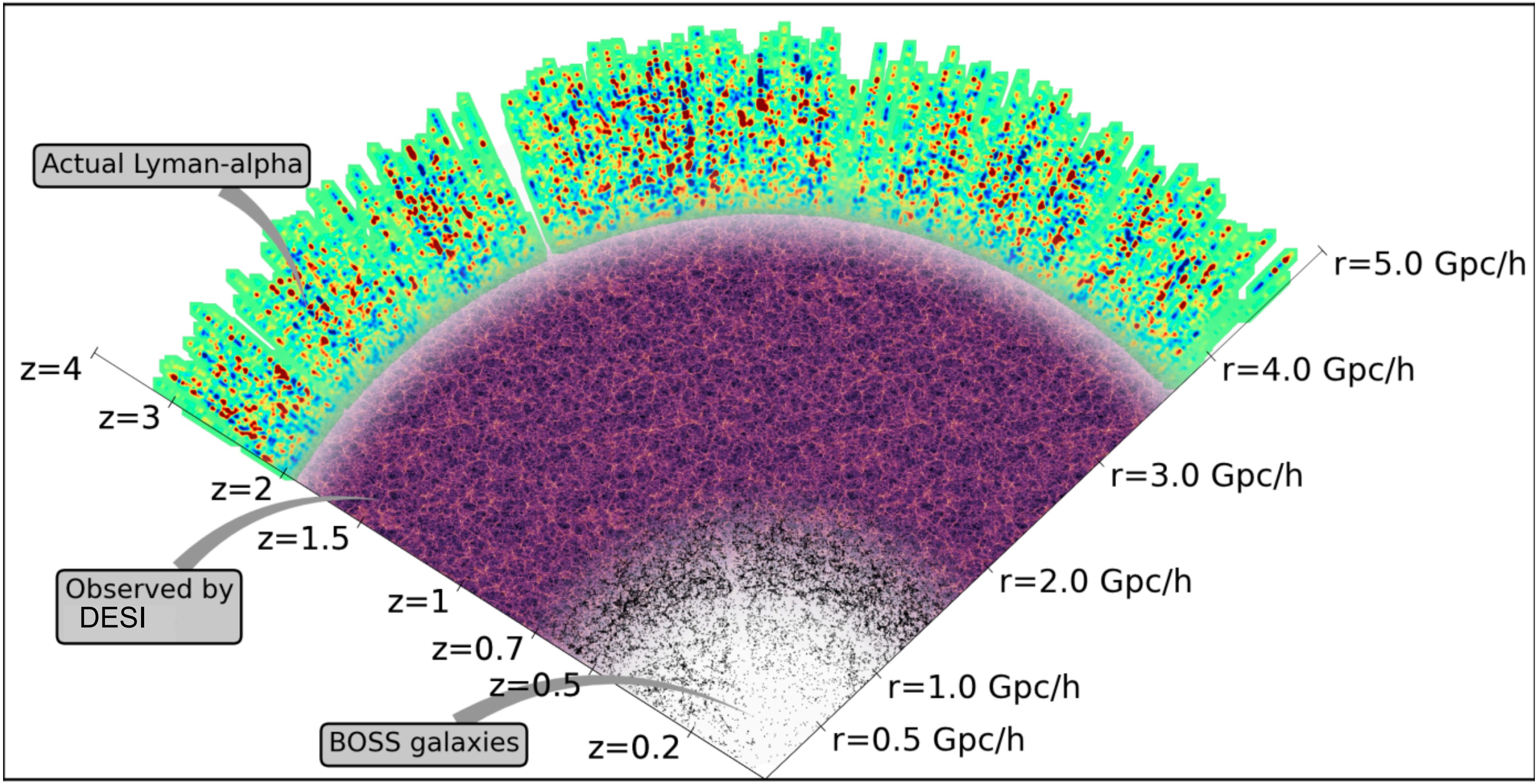
Near term: CMB+BOSS+DES/SN



Das & Linder 2012

Also see Wu+ 1402.4108 for CMB-S4.

DESI Survey



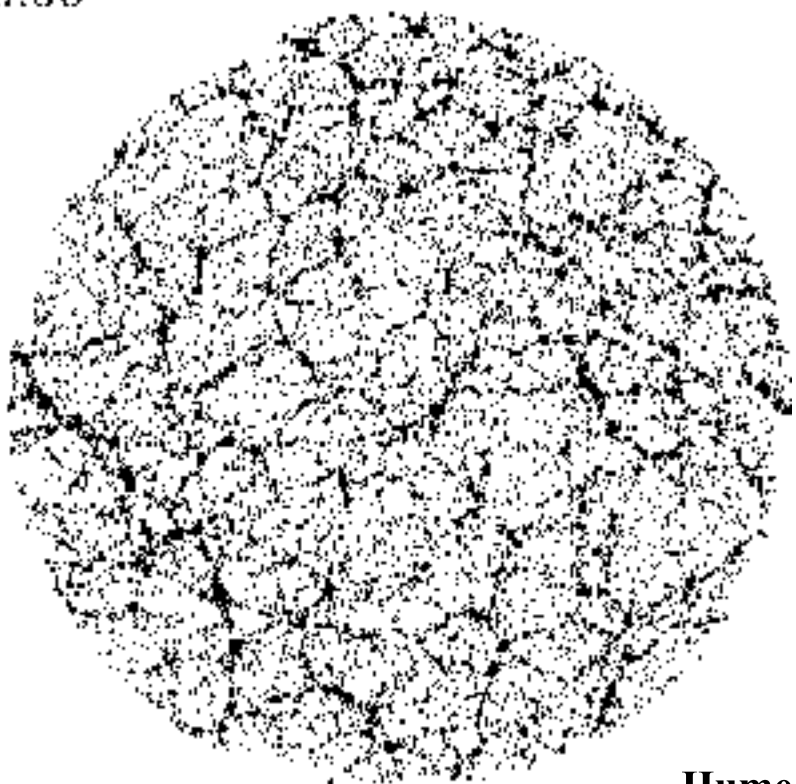
3D map of 50 (Gpc/h)^3 volume with 4M Luminous Red Galaxies, 14 M Emission Line Galaxies, 2M Quasars

Tomographic surveys of density/velocity field.

Redshift Space Distortions

Redshift space distortions (RSD) map velocity field along line of sight. Gets at growth rate f, one less integral than growth factor (like H vs d).

Ω_m = 0.00



Hume Feldman

$$f = \frac{d\ln D}{d\ln a} \sim \Omega_m(a)^\gamma$$

Linder 2005

gravitational growth index γ

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Latest LSS Data

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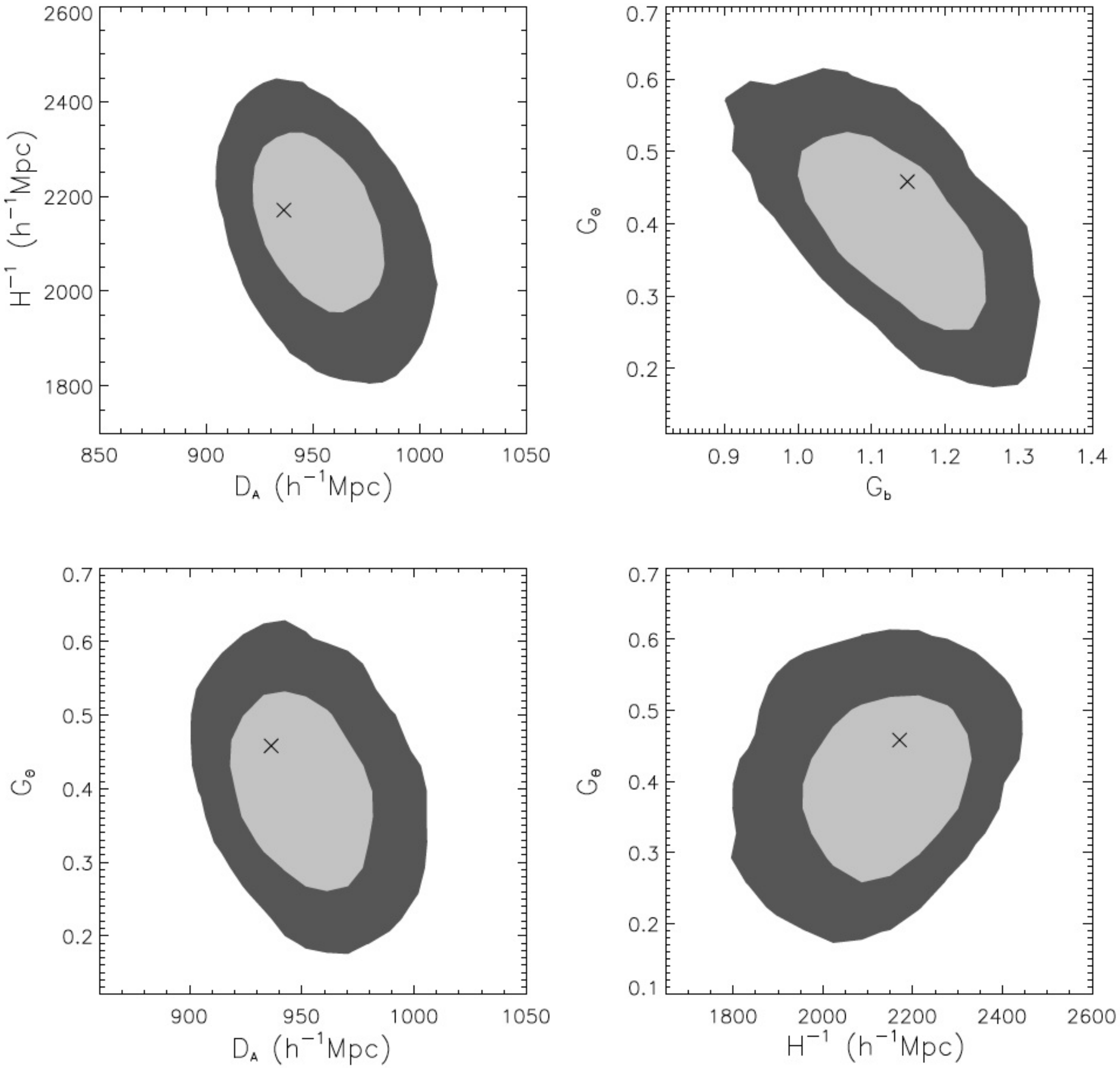
BOSS DR11 galaxy clustering along/transverse to line of sight measures D_A, 1/H, growth rate.



Not just parameters but tests of the framework.

FRW: D_A vs 1/H

General relativity: D_A vs growth

Neutrino mass: suppression of growth

Song et al 2014

Latest LSS Data

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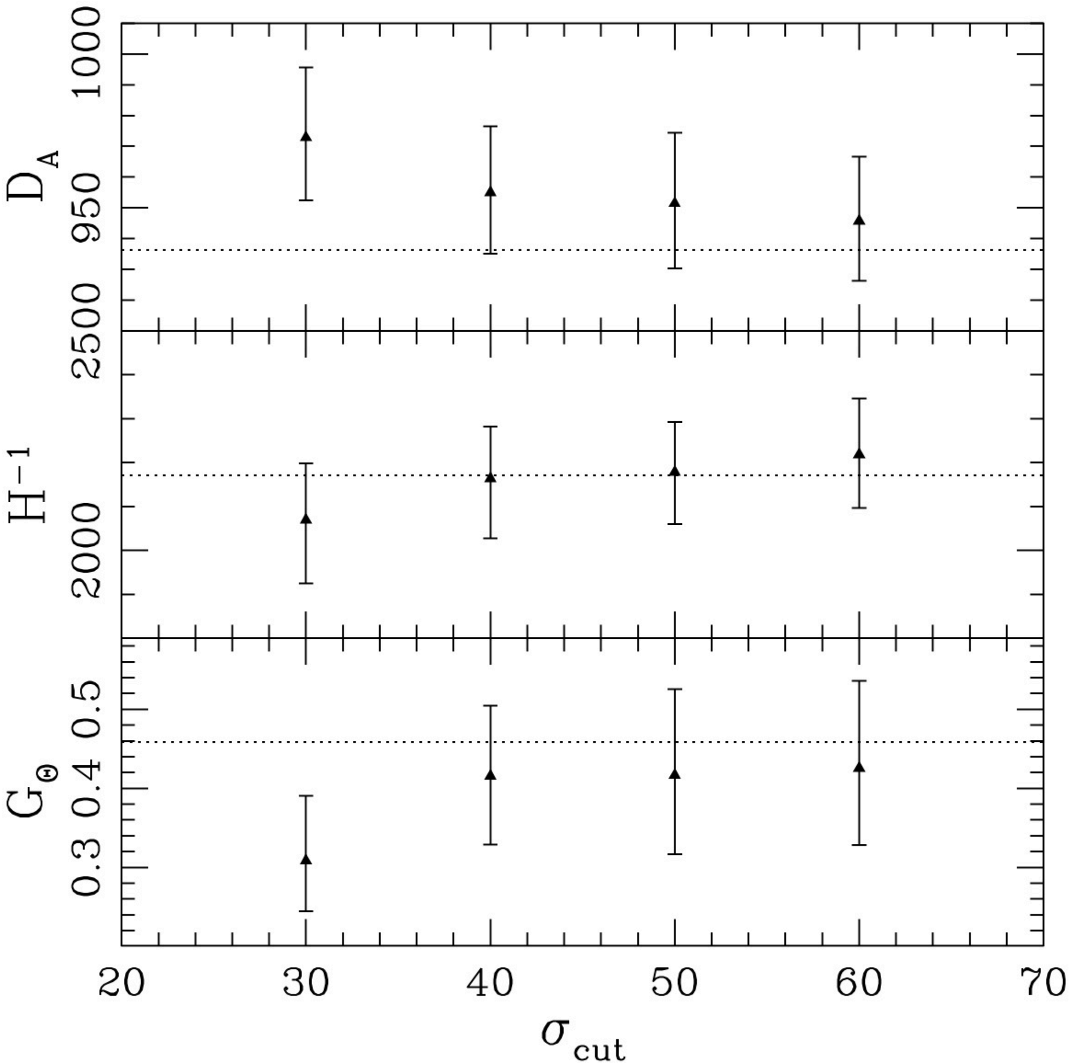
Small scale structure (e.g. FOG) is beyond PT form and biases results if uncut.



Results converge for line of sight separations σ_{cut}>40 Mpc/h.

Bias enters if keep smaller scales.

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Simulations + Analytics

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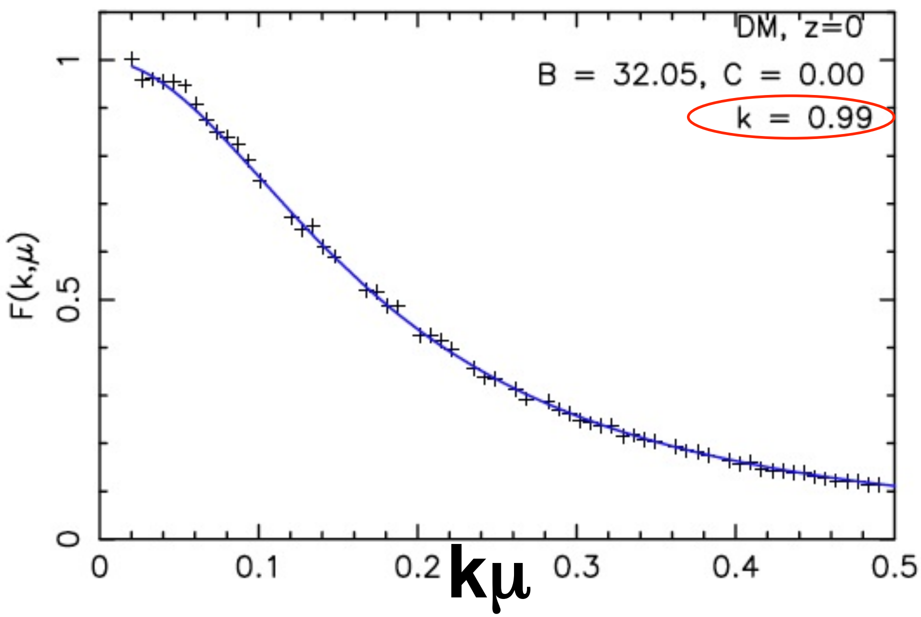
Linear theory (Kaiser form) is inaccurate. Simulations allow calibration of RSD into nonlinear regime, where most of the information is.

Analytic form for mapping $P^{true}(k,\mu)=F(k\mu)\ P^{lin}(k,\mu)$

$$F(k\mu) = \frac{A}{1+Bk^2\mu^2} + Ck^2\mu^2$$

Kwan, Lewis, Linder 2012

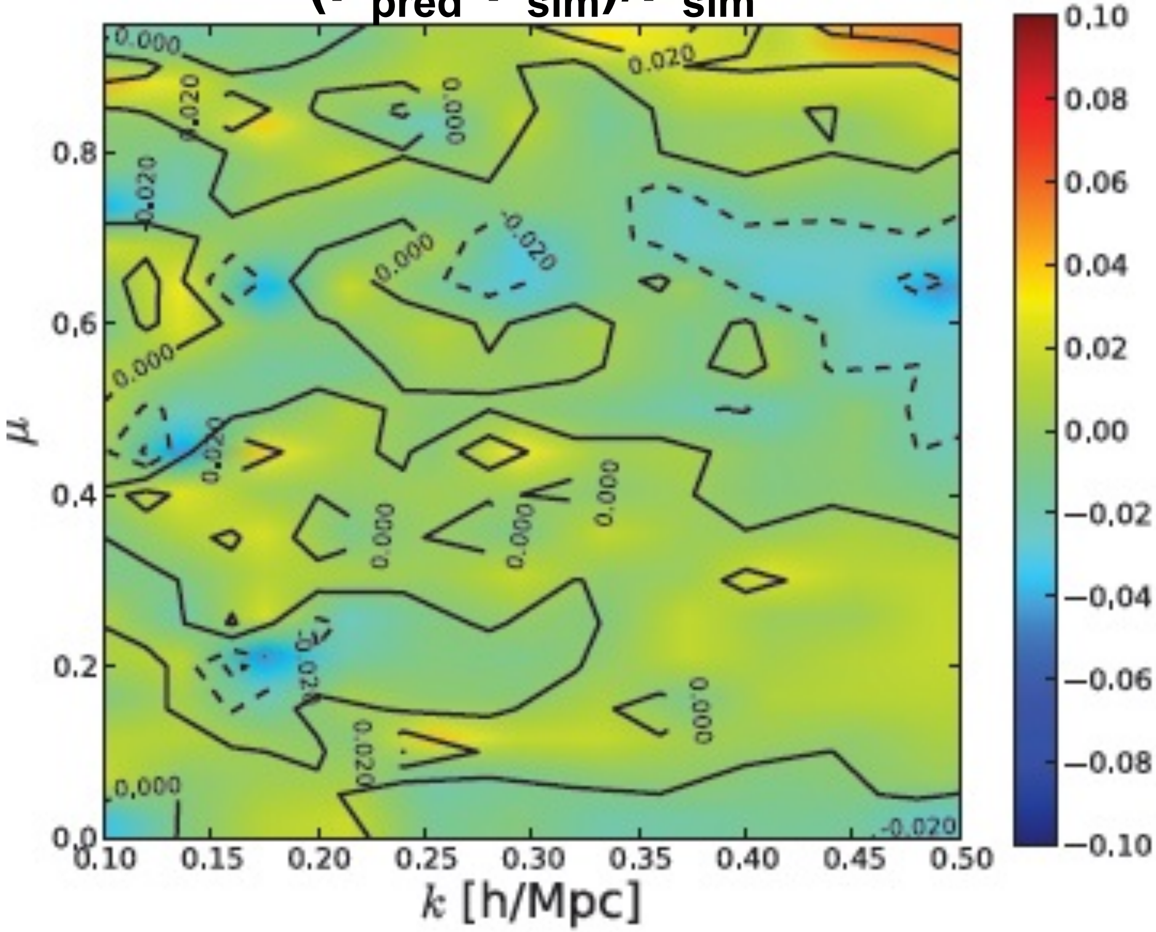


Use simulations to calibrate A, B, C(k,z).

Simulations to Fit RSD

KLL analytic reconstruction form is accurate to ~2% out to k=0.5 h/Mpc for z=0-2.

$(P_{pred}-P_{sim})/P_{sim}$



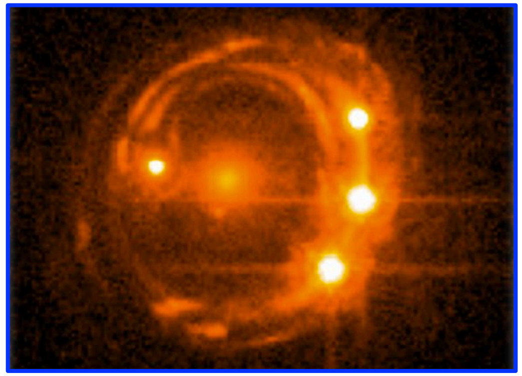
Kwan, Linder, Lukic 2014

extending to higher precision with suite of 2 Gpc/h, 4096^3 simulations.

Vallinotto, Linder, Lukic 2013

Strong Lensing Time Delays

Strong gravitational lensing creates multiple images (light paths) of a source.



When the source is variable (quasar / AGN), we can measure the time delays between the images. This probes the geometric path difference (cosmology) and the lensing potential (dark matter).

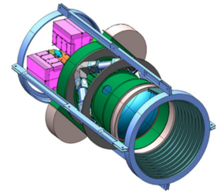
Key parameter is a distance ratio, the time delay distance

$$D_{\Delta t} \equiv \frac{d_l d_s}{d_{ls}} (1 + z_l)$$

Strong Lens Factories

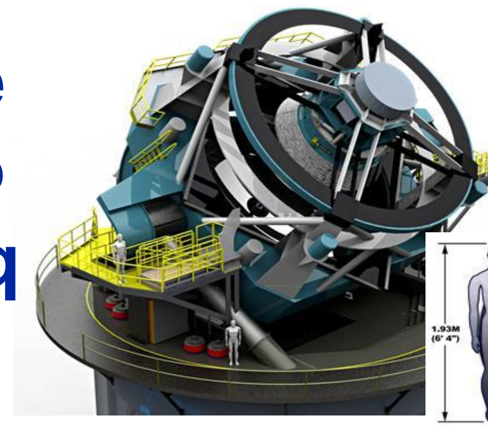
The Dark Energy Survey (DES) is underway at CTIO. It covers 5000 sq deg in 5 years.

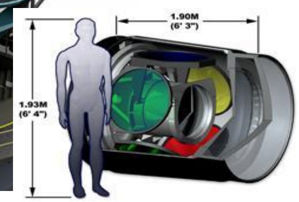
Output: ~800 lensed AGN.



Large Synoptic Survey Telescope (LSST) will start in ~2020 at Cerro Pachon, Chile, covering 20,000 sq deg repeatedly in 10 years.

Output: ~8000 lensed AGN.

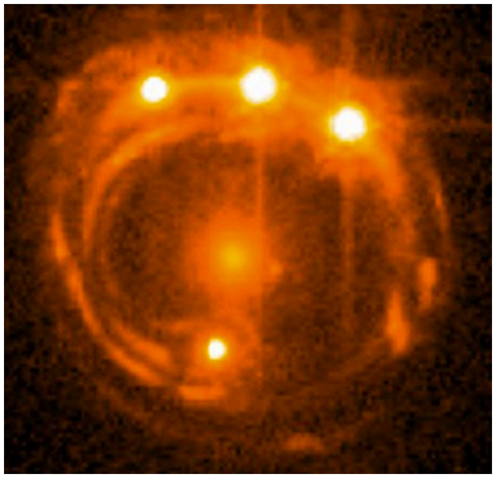


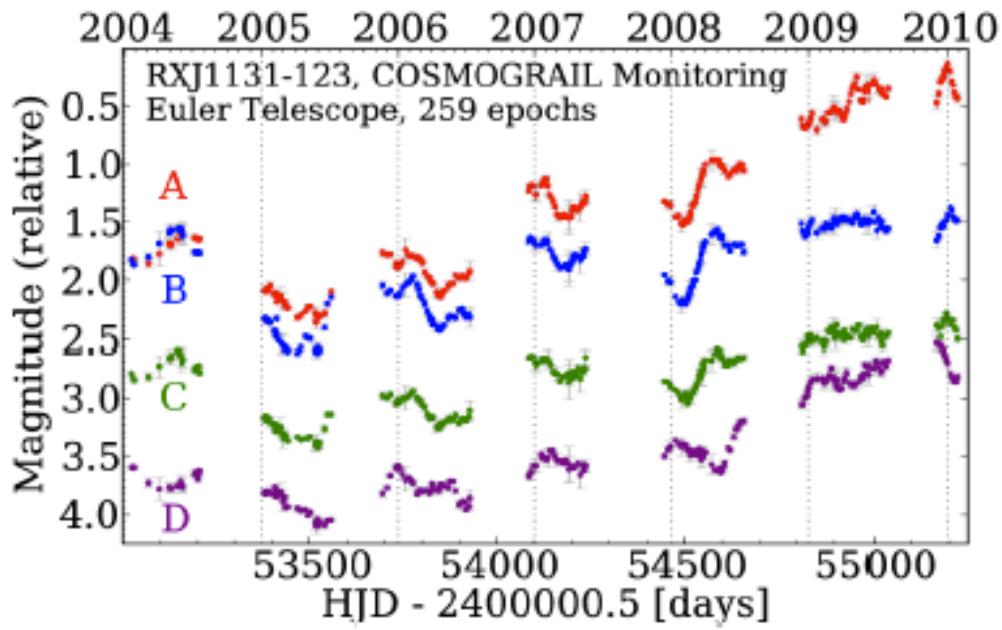


HSC?

Measuring Time Delays

One of the challenges is measuring time delays between images in the presence of 1) noise, 2) gaps, 3) variability, 4) microlensing.





Microlensing is fit simultaneously with the time delay and teaches us about dark matter substructure in the lens galaxy. Strong lensing probes DE and DM.

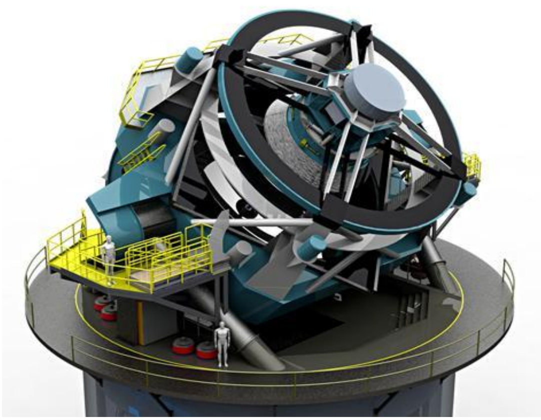
Time Delay Data Challenge

We use **Gaussian Process statistics** to find a family of light curves fitting the data, with correlations.
Factor of 2 improvement over previous literature.

Real data: accurate and more precise than literature.

Kernel	Δt_{AB}	Δt_{AC}	Δt_{AD}	Δt_{BC}	Δt_{BD}	Δt_{CD}
HE 0435-1223 GP-DRW	-9.5 ± 0.3	-1.9 ± 0.4	-15.6 ± 0.3	8.1 ± 0.3	-6.0 ± 0.3	-13.6 ± 0.4
HE 0435-1223 Lit(1) [3]	-8.4 ± 2.1	-0.6 ± 2.3	-14.9 ± 2.1	7.8 ± 0.8	-6.5 ± 0.7	-14.3 ± 0.8
HE 0435-1223 Lit(2) [27]	-8.8 ± 2.4	-2.0 ± 2.7	-14.7 ± 2.0	6.8 ± 2.7	-5.9 ± 1.7	-12.7 ± 2.5

Hojjati, Kim, Linder 2013



Currently participating in blinded **LSST Data Challenge** to reach next generation accuracy.
Achieved 1% accuracy on first step!

Bonus: Redshift Drift

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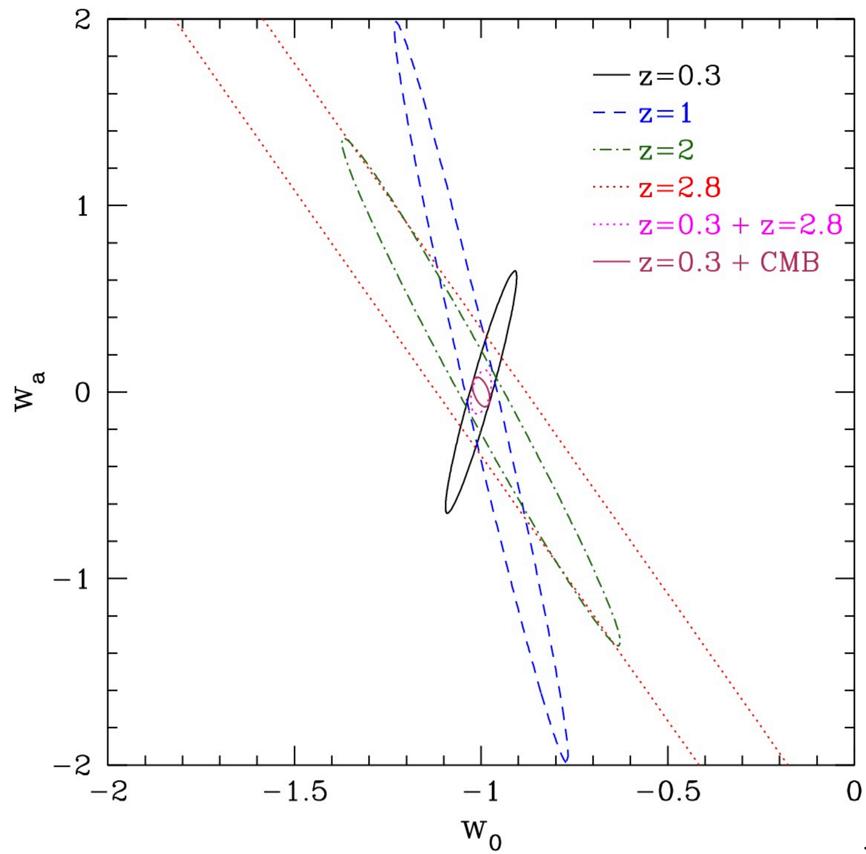
Redshift Drift (seeing the universe expand in our lives: dz/dt_0) known 50 years ago, but is very very challenging. Direct, kinematic probe of acceleration.

New theory + hardware developments.

Use ELGs at low z. Very sensitive in combo with CMB (DE FOM > 1000 for 1%).

Externally Dispersed Interferometers (EDI = FTS +dispersion) can reach $dz=10^{-9}$ in 8 hours on Keck.



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Summary

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The CMB is a high energy physics experiment in the sky, capable of reaching GUT or even Planck scale.

We can test for physics scales within inflation PPS by CMB+LSS. Assuming power law PPS has strong influence/bias on late time cosmology.

CMB+LSS has excellent complementarity for robust late time cosmology estimation.

CMB lensing is a maturing probe of Σm_ν, N_{eff}, DE.

Redshift space distortions, calibrated by simulations, probe growth into nonlinear regime.

Exciting new probes: strong lensing and redshift drift direct acceleration.