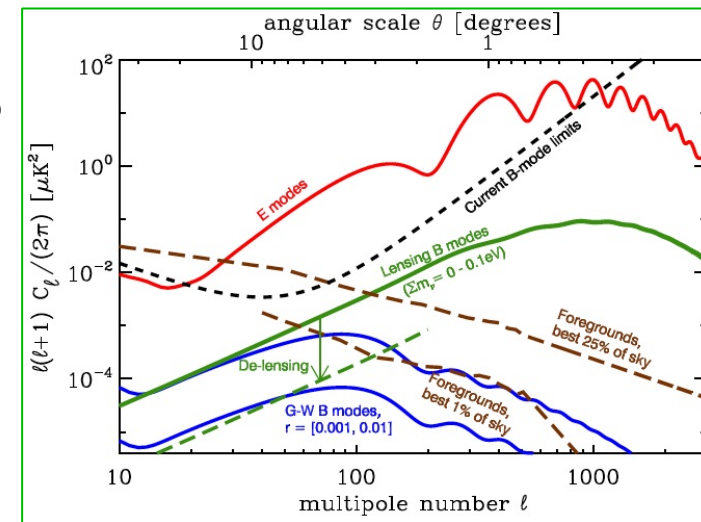
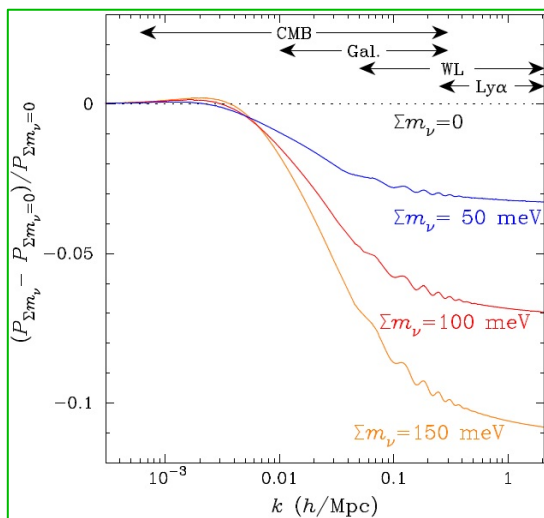


Future of Cosmology

TIARA winter school on cosmology
 Taipei, February 2014

Eric Linder

UC Berkeley & Berkeley Lab
 KASI Korea



The 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 gravitational wave) power spectrum**
- **Non-Gaussianity**

These can even constrain some Planck scale physics.

The CMB also sees the linear transfer function of density perturbations modes entering the horizon at various epochs, mapping physics from $z \sim 10^5$ ($T \sim 10$ eV) to $z \sim 0$ ($T \sim 10^{-4}$ eV).

CMB reveals the energy density of dark matter, constraining WIMP/SUSY models to complement direct detection cross-section limits.

CMB tests the growth of cosmic structure, and its suppression by dark energy and neutrino free streaming, through secondary anisotropies such as CMB lensing and Integrated Sachs-Wolfe (ISW).

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.

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

And neutrino parameters

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

Scalar inflationary perturbations appear in the temperature power spectrum, but also give rise to E- and B-mode **polarization** through scattering and **lensing**.

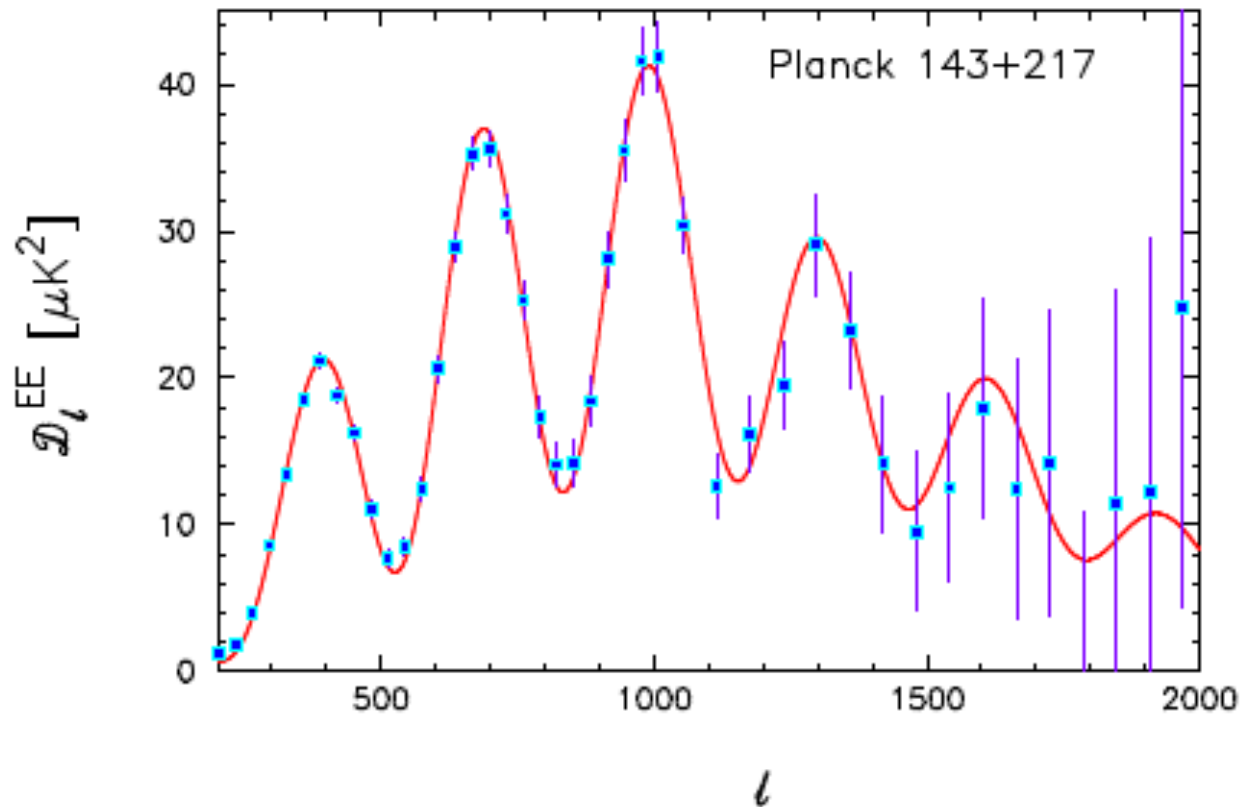
Tilt, running, and more generally the shape of the scalar primordial power spectrum show up most clearly in **temperature**, though E and B give some further constraints.

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

CMB Polarization

Planck from space, and Atacama Cosmology Telescope (ACT) and South Pole Telescope (SPT) from the ground, map TT thoroughly.

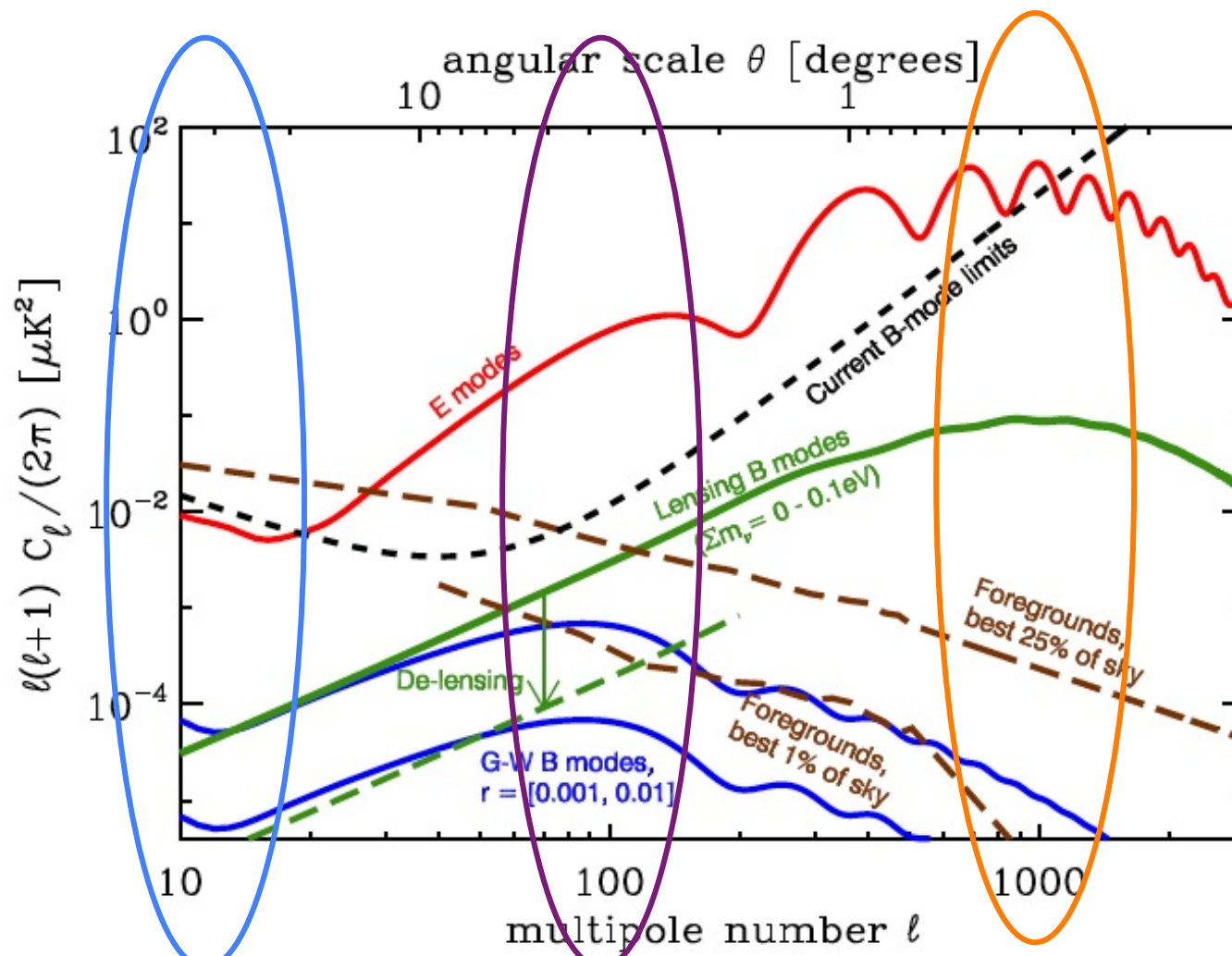
Planck (not fully released) and ground experiments will map TE, EE thoroughly.



Planck XVI 2013

Tensor Modes

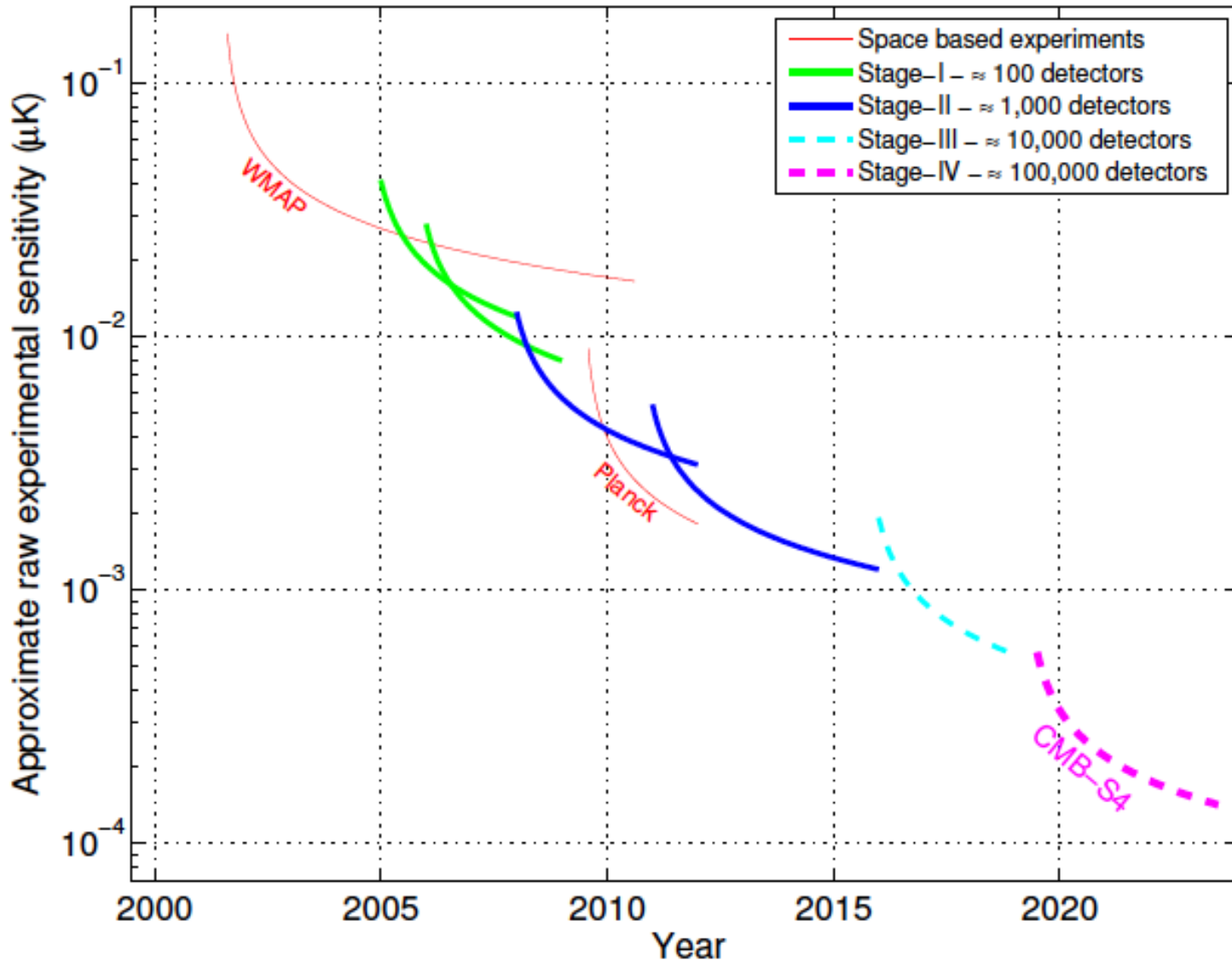
But B-mode polarization, and in particular inflationary gravitational waves, are not yet detected (directly and publicly).



1308.5381

CMB Sensitivity

Continued progress in experimental reach.
Recall $3 \times 10^{-3} \mu\text{K}$ is 10^{-9} in sensitivity.



1308.5383

Generations of CMB Experiments

Generation 2:

Large angle experiments –

BICEP/Keck Array – South Pole, has data

EBEX – balloon, Antarctica, has data

SPIDER – balloon, Antarctica, Dec ~~2013~~ 2014

PIPER, ABS, CLASS...

High resolution experiments –

ACTpol – Chile

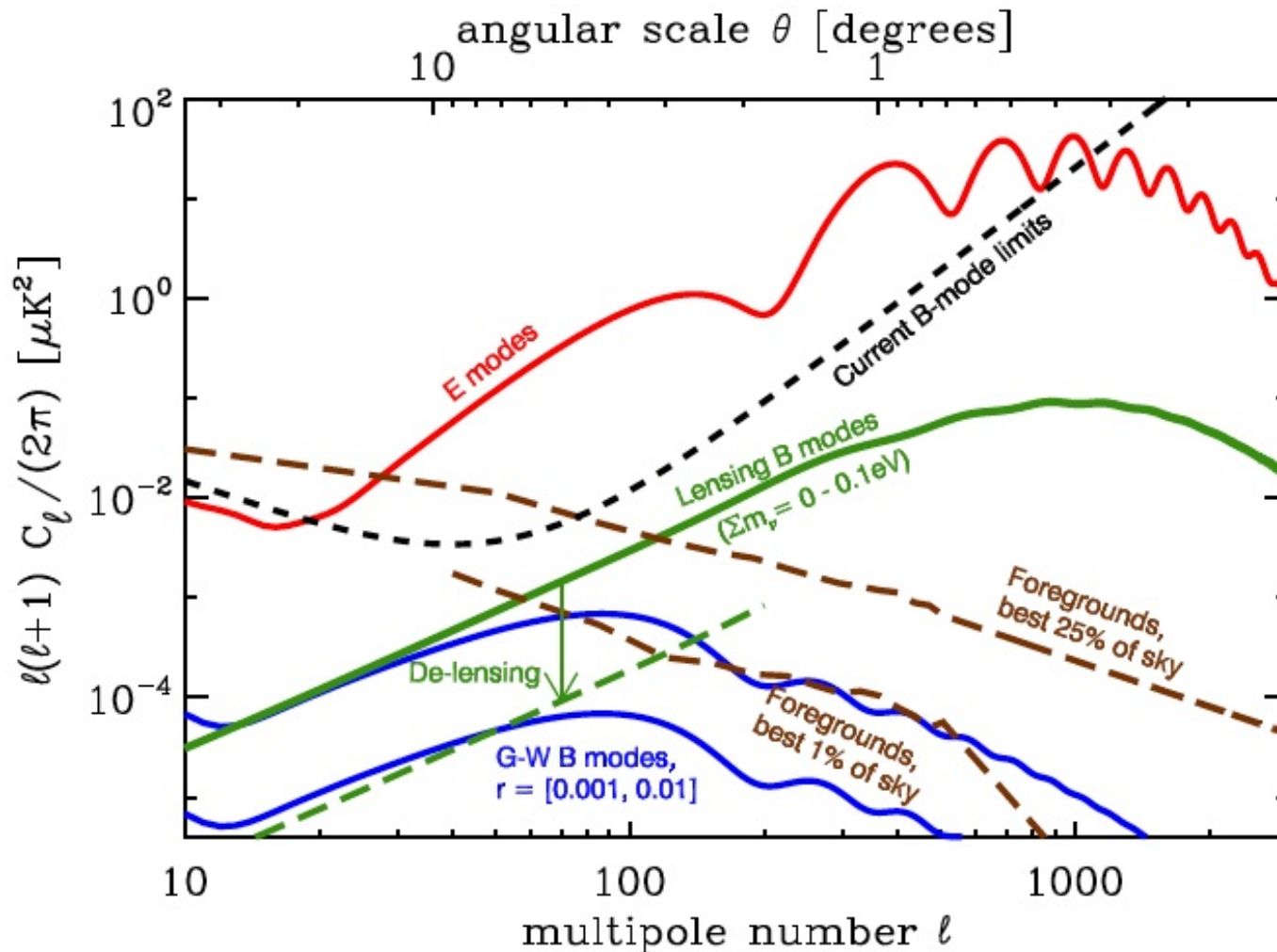
POLARBEAR – Chile, has data

SPTpol – South Pole, has data

Future Generations: POLARBEAR-2/Simons Array,
SPT-3G, GroundBIRD... ; **Satellites** – LiteBIRD, ~~PRISM~~

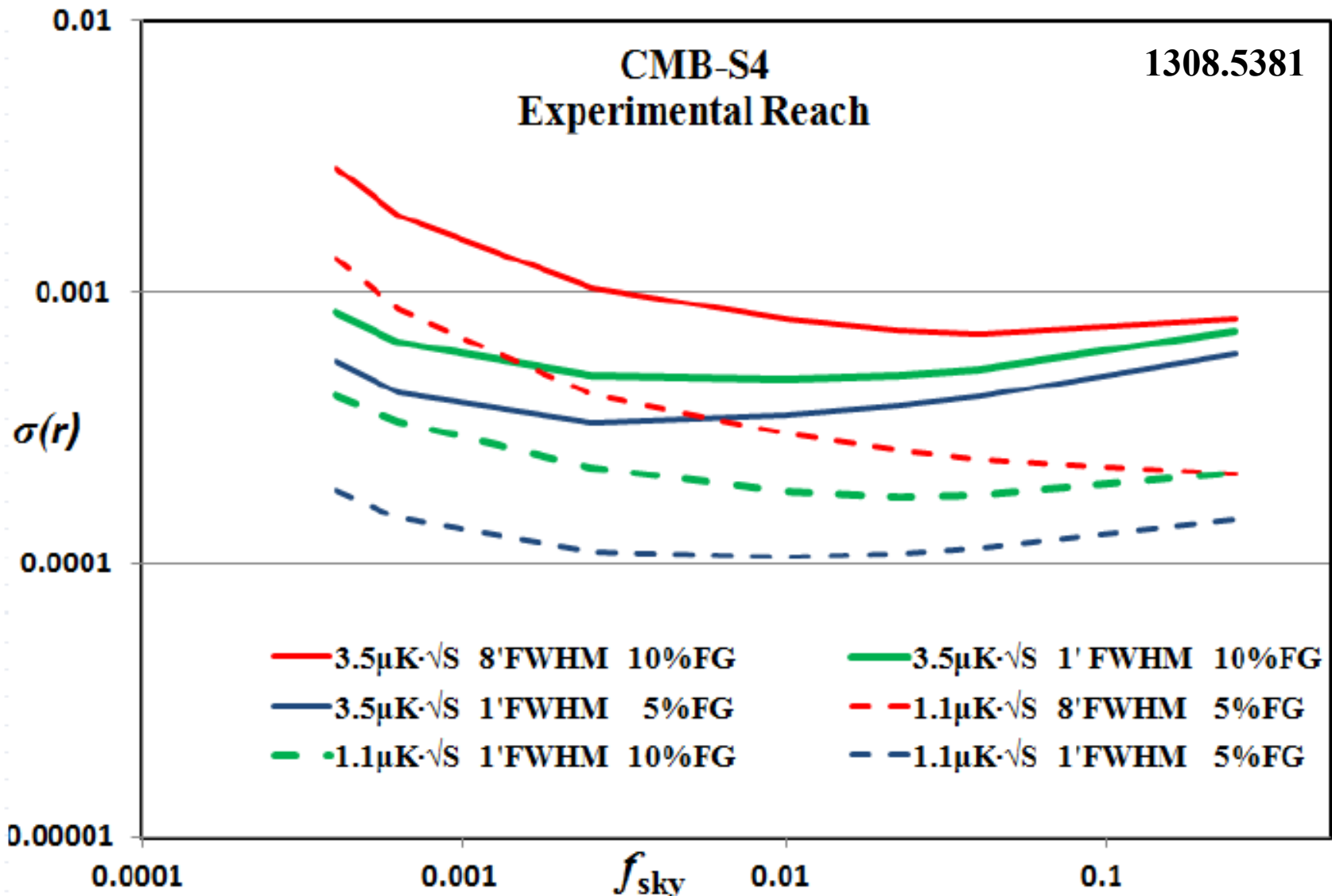
Energy Scale of Inflation

Tensor modes directly give the energy scale of inflation. This can be between 10^3 - 10^{16} GeV, though specific model classes have limits.

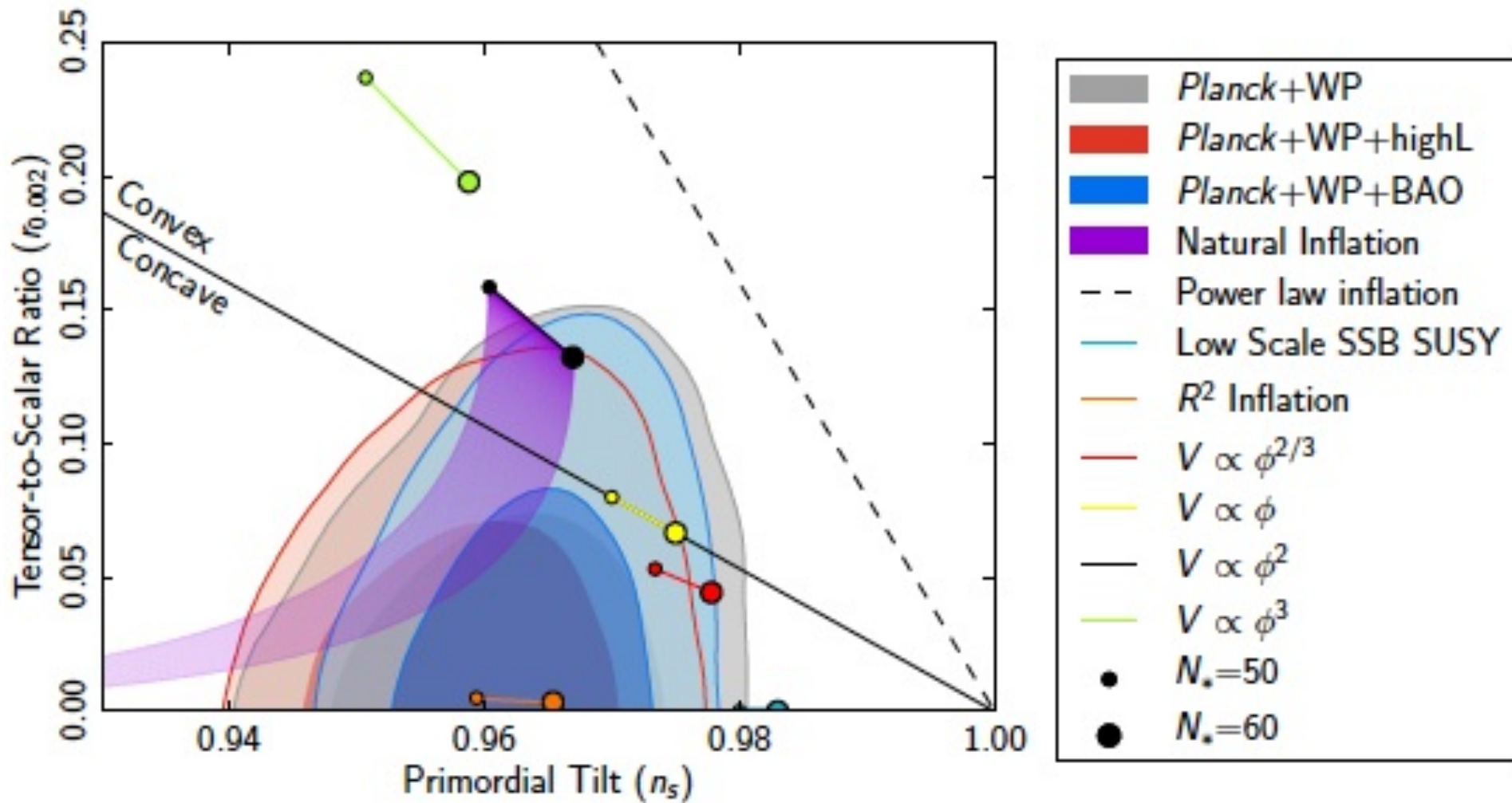


Inflationary Gravitational Waves

Generation 4 aims for 500,000 detectors (100x gain).

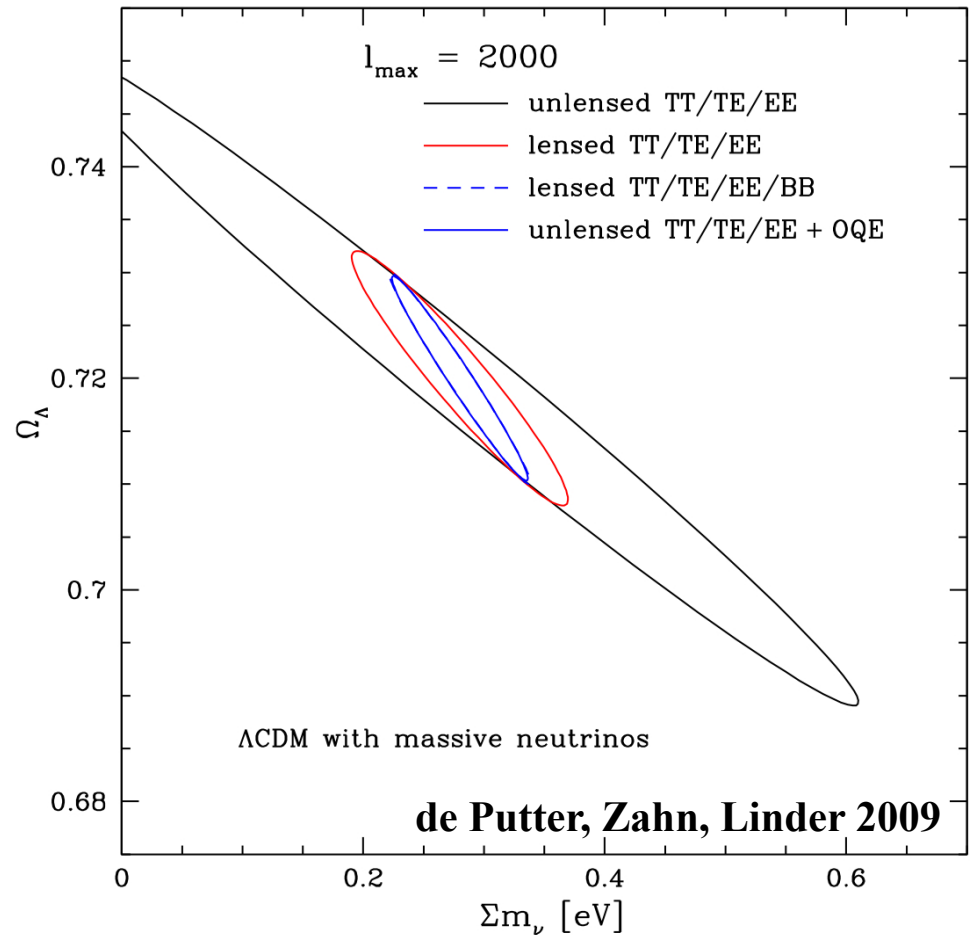


Inflation Phase Space



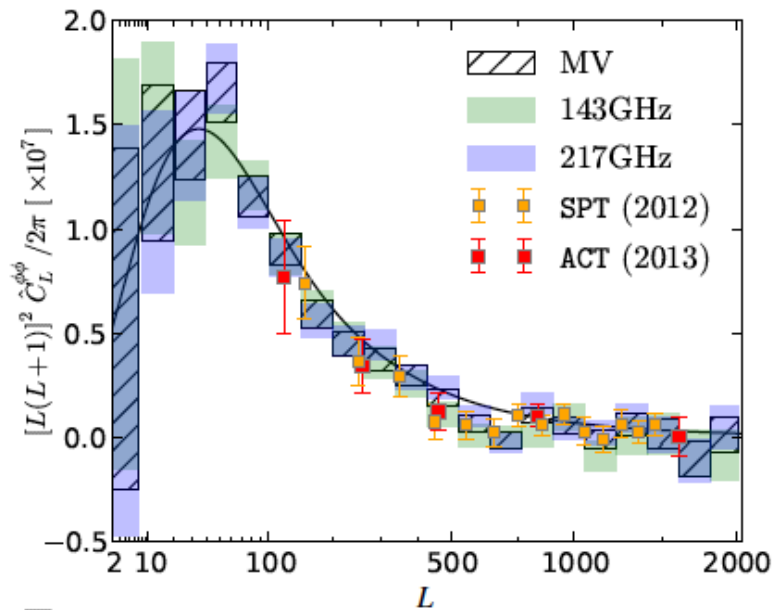
CMB Lensing

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



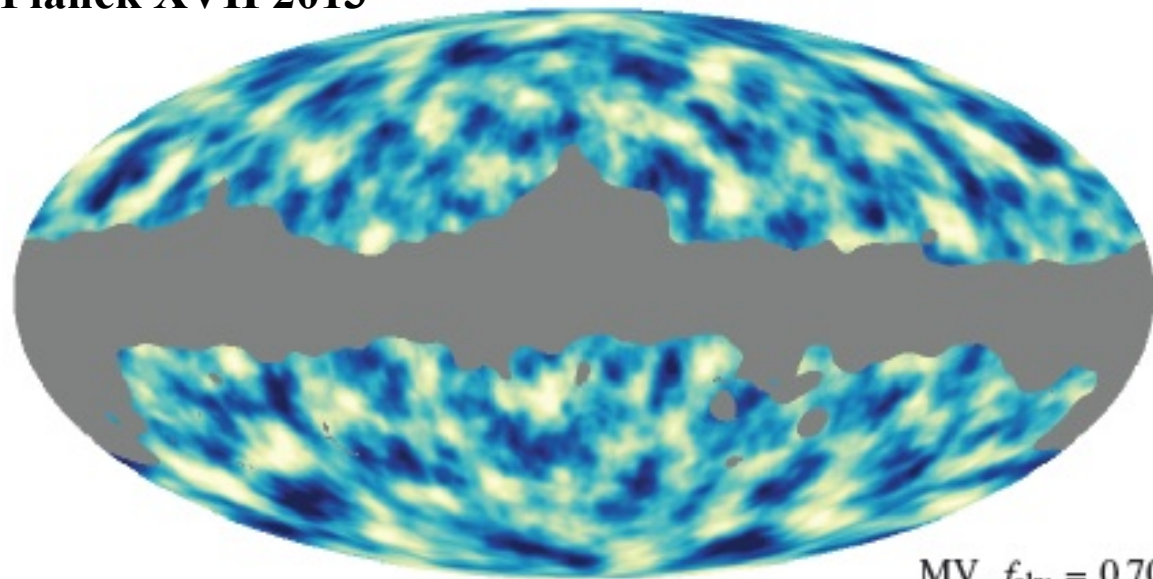
CMB Lensing

Detected in temperature, and in polarization by cross correlation. Direct polarization detection (B mode lensing) Dec 2013!



Deflection power spectrum gives information on early matter power spectrum.

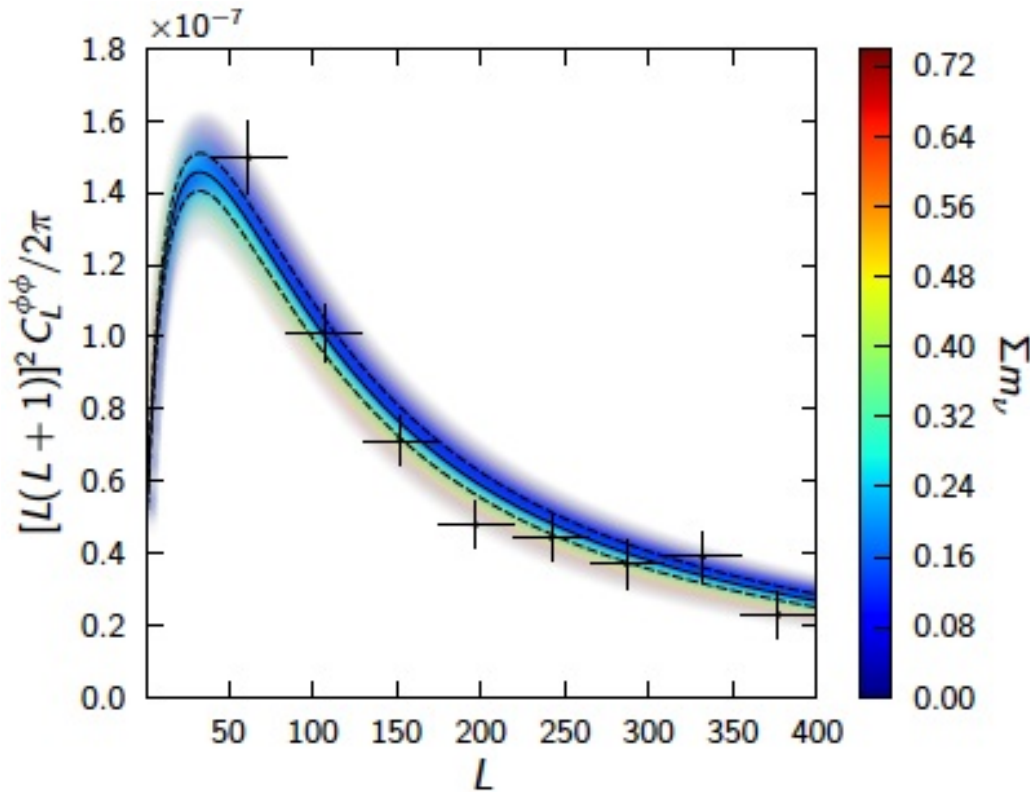
Planck XVII 2013



Planck recreation of cosmic matter distribution from CMB lensing of TT.

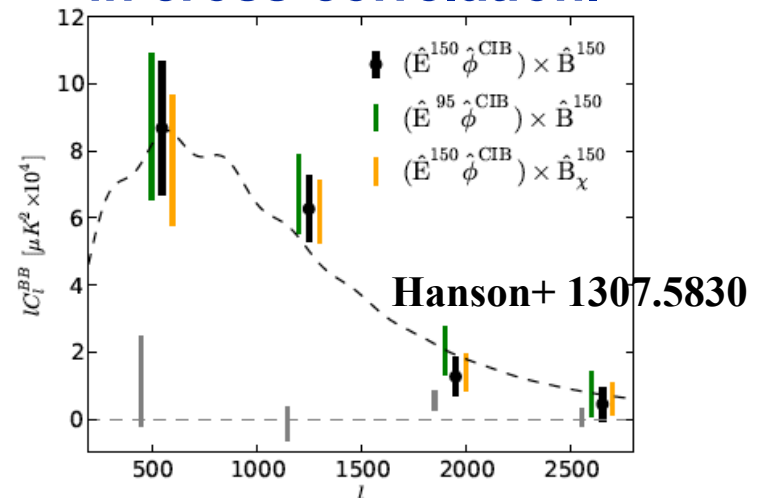
B-mode Lensing

B-mode lensing carries more information than TT smearing.

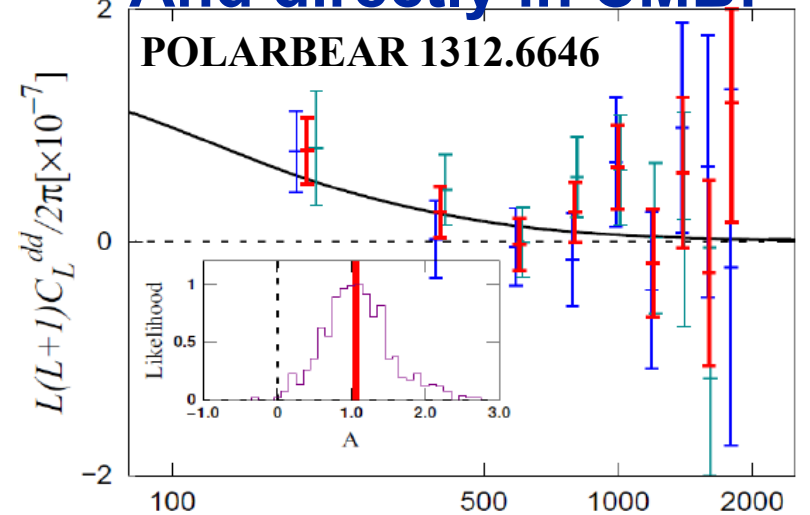


Neutrino mass effect on deflection field

B-mode lensing detected in cross-correlation.



And directly in CMB:



CMB Lensing

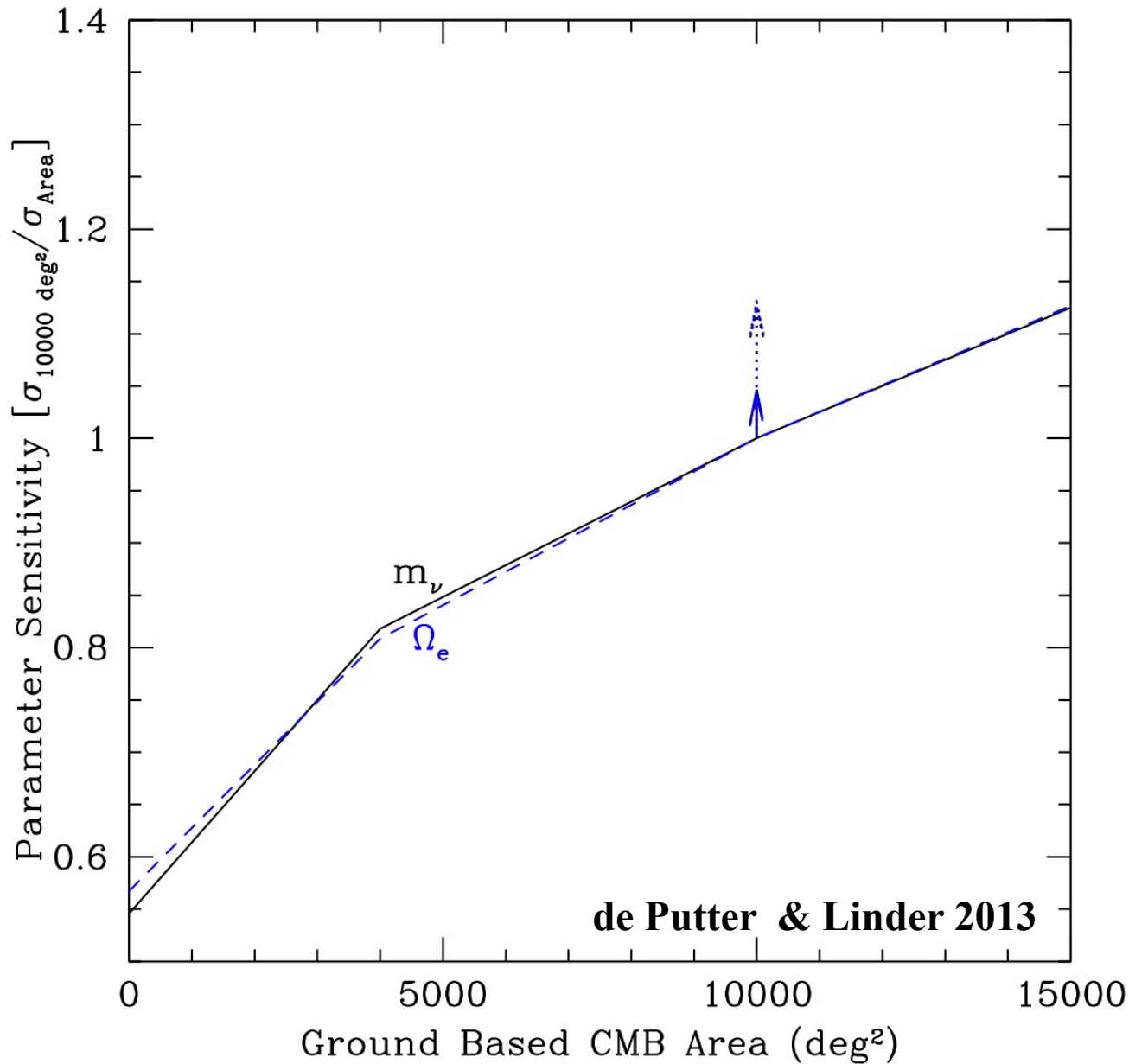
High resolution experiments important for CMB lensing, add strong constraints.

	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
$\sigma(\text{Planck})$	0.000137	0.00117	0.00175	0.124	0.00337	0.00426	d	1.10	2.48	d
$\sigma(\text{Planck}+10k)$	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.

Case	$10^5 \omega_b$	$10^4 \omega_c$	$m_\nu(\text{meV})$	Ω_m	$10^3 \tau$	$10^3 n_s$	σ_8	w_0	Ω_c
Planck	13.0	15.2	165	0.0534	4.32	3.36	0.0552	0.214	0.00455
Pl+4000	6.75	10.8	110	0.0445	3.75	2.56	0.0459	0.177	0.00319
Pl+10000	5.13	9.22	90	0.0378	3.24	2.26	0.0390	0.151	0.00258
Pl+15000	4.46	8.38	80	0.0341	2.94	2.09	0.0352	0.137	0.00229
Pl+10k@1 μ K-arcmin	3.77	8.58	80	0.0332	3.19	2.17	0.0348	0.133	0.00228
Pl+10k, $l_{\text{max}}^P = 5000$	4.46	8.73	86	0.0332	3.23	2.21	0.0347	0.133	0.00247
Gain	2.53	1.65	1.83	1.41	1.33	1.49	1.42	1.42	1.76

High Resolution Experiments



CMB + Late Time Probes

Stronger 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
$\sigma(\text{Planck})$	0.000137	0.00117	0.00175	0.124	0.00337	0.00426	d	1.10	2.48	d
$\sigma(\text{Planck}+10k)$	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

	$10^5 \omega_b$	$10^4 \omega_c$	$10^4 \omega_\nu$	Ω_{de}	n_s	σ_8	w_0	w_a	γ
$\sigma(\text{CMB}+\text{SN}+\text{PK})$	4.76	6.47	6.21	0.00507	0.00200	0.0110	0.103	0.382	0.0322
$\sigma(\text{CMB}+\text{SN}+\text{PK}+\text{WL})$	4.71	5.85	5.97	0.00470	0.00192	0.00934	0.0927	0.339	0.0256
$\sigma(\text{CMB}+\text{SN}+\text{PK}+\text{SL})$	4.74	6.03	6.12	0.00414	0.00195	0.0107	0.0801	0.292	0.0319
$\sigma(\text{CMB}+\text{SN}+\text{PK}+\text{WL}+\text{SL})$	4.70	5.63	5.89	0.00403	0.00189	0.00808	0.0774	0.280	0.0241

Inflation and neutrino parameters determined by CMB, unless fix other sources of variation.

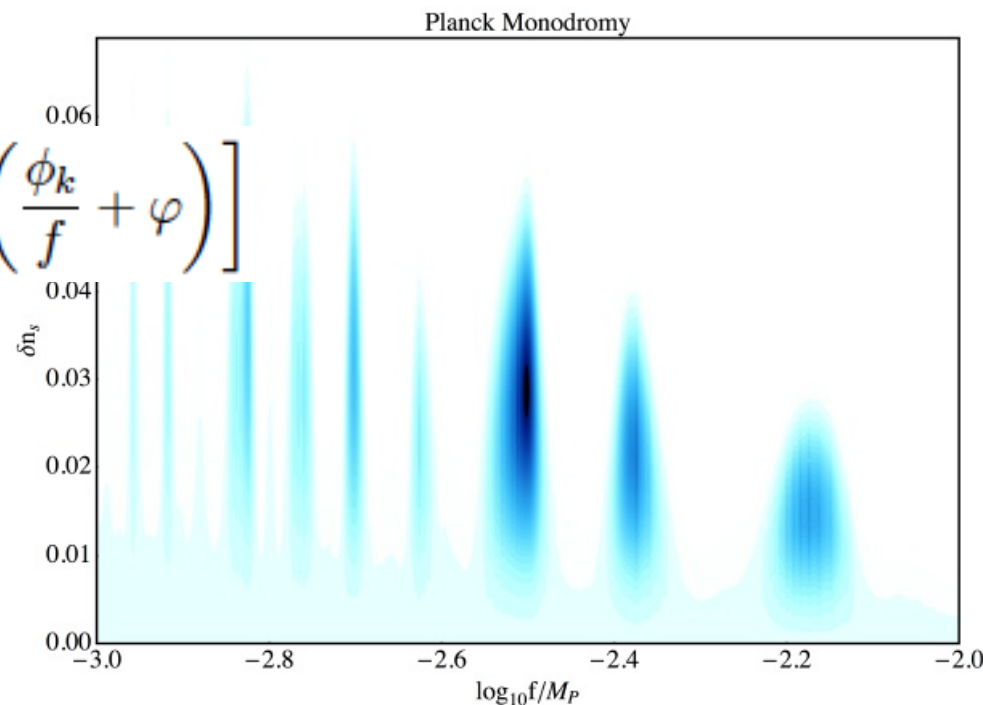
Primordial Power Spectrum

CMB can also test deviations from power law primordial spectrum. Recall $P_k \sim k^n$ is scale free. Does inflationary physics have a scale, teaching new high energy physics?

E.g. axion monodromy, bending curvaton.

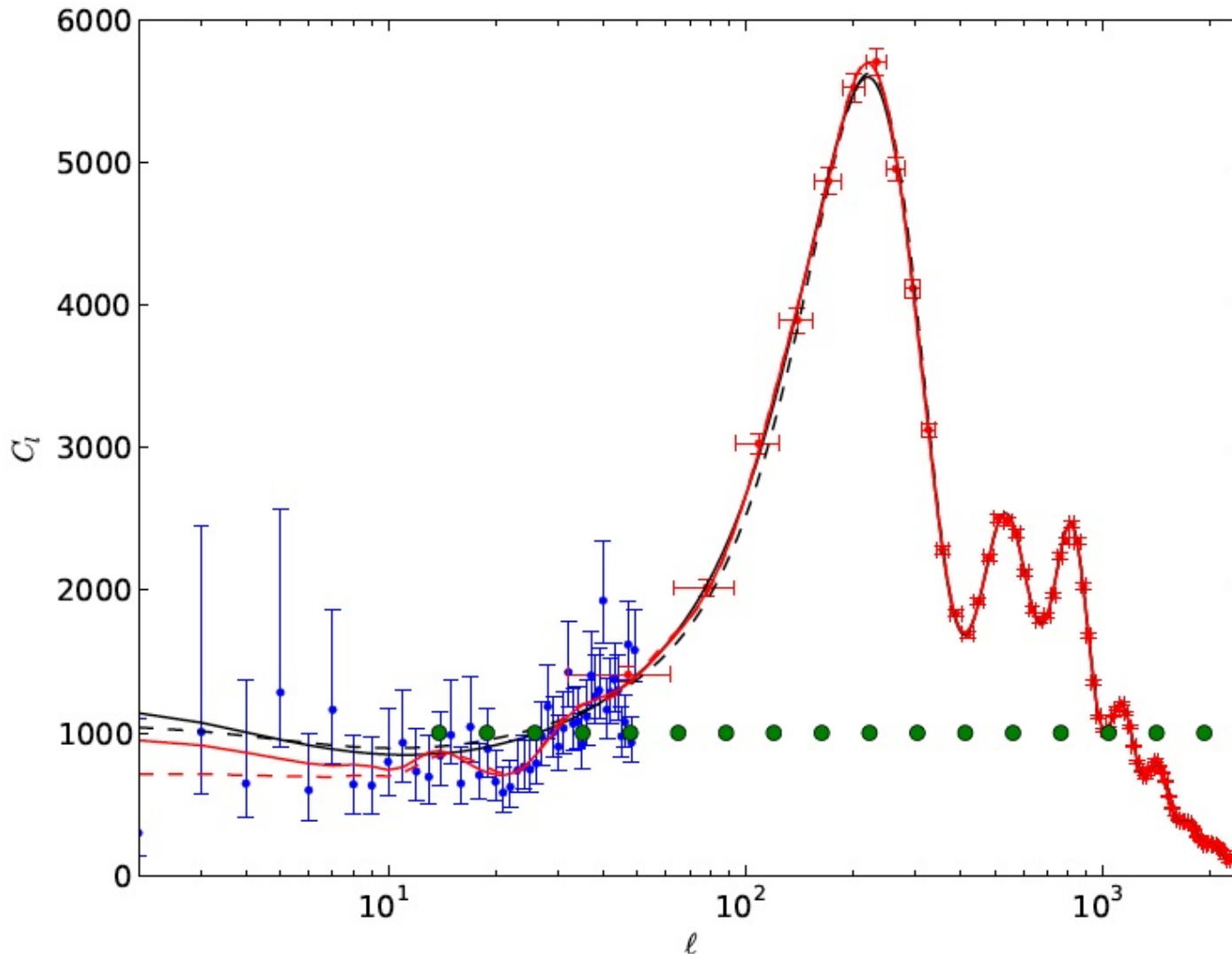
$$V(\phi) = \mu^3 \left[\phi + bf \cos \left(\frac{\phi}{f} + \psi \right) \right]$$

$$\Delta_{\mathcal{R}}^2(k) = \Delta_{\mathcal{R}}^2(k_*) \left(\frac{k}{k_*} \right)^{n_s-1} \left[1 + \delta n_s \cos \left(\frac{\phi_k}{f} + \varphi \right) \right]$$



Primordial + Late Time

Late time parameter estimation is affected by assumptions for primordial power spectrum.



Black curves
have power law
PPS.

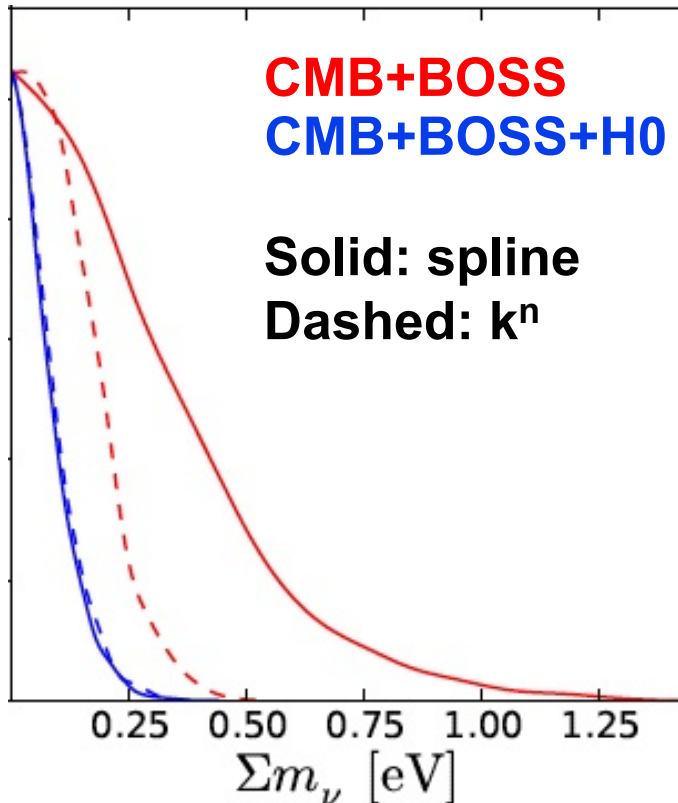
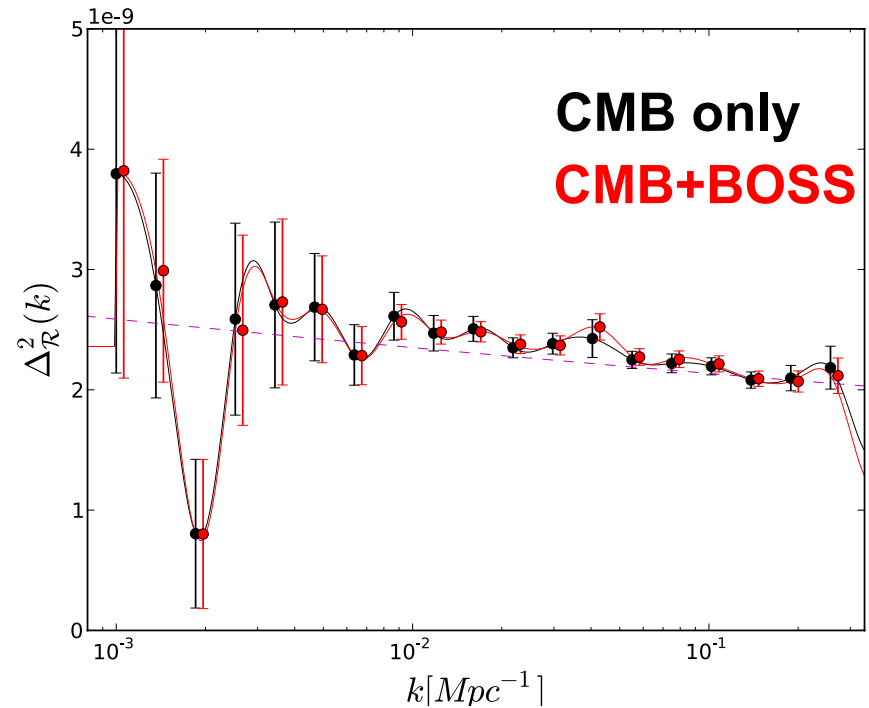
Red curves have
free PPS.

Dashed curves
have $m_\nu = 2.5$ 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.

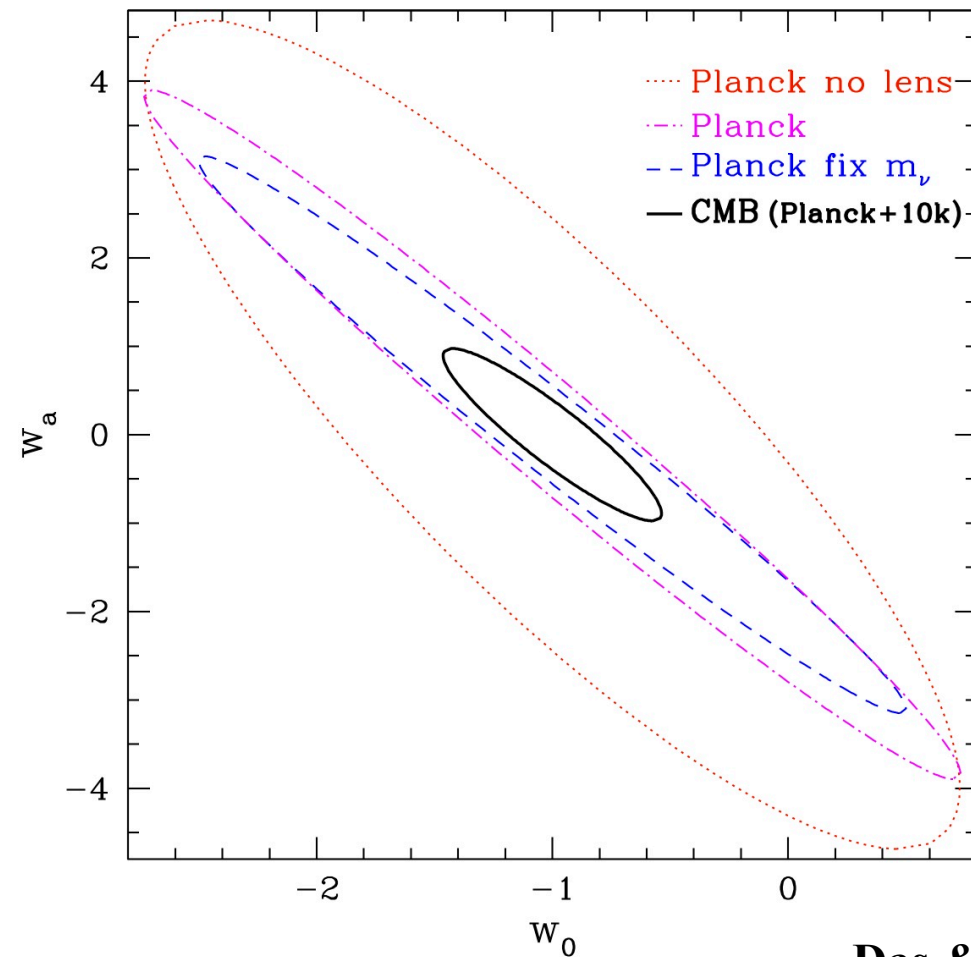


Cosmology parameters can get shifted and broadened ($\Omega_b h^2, \Omega_c h^2, H_0, m_\nu$).

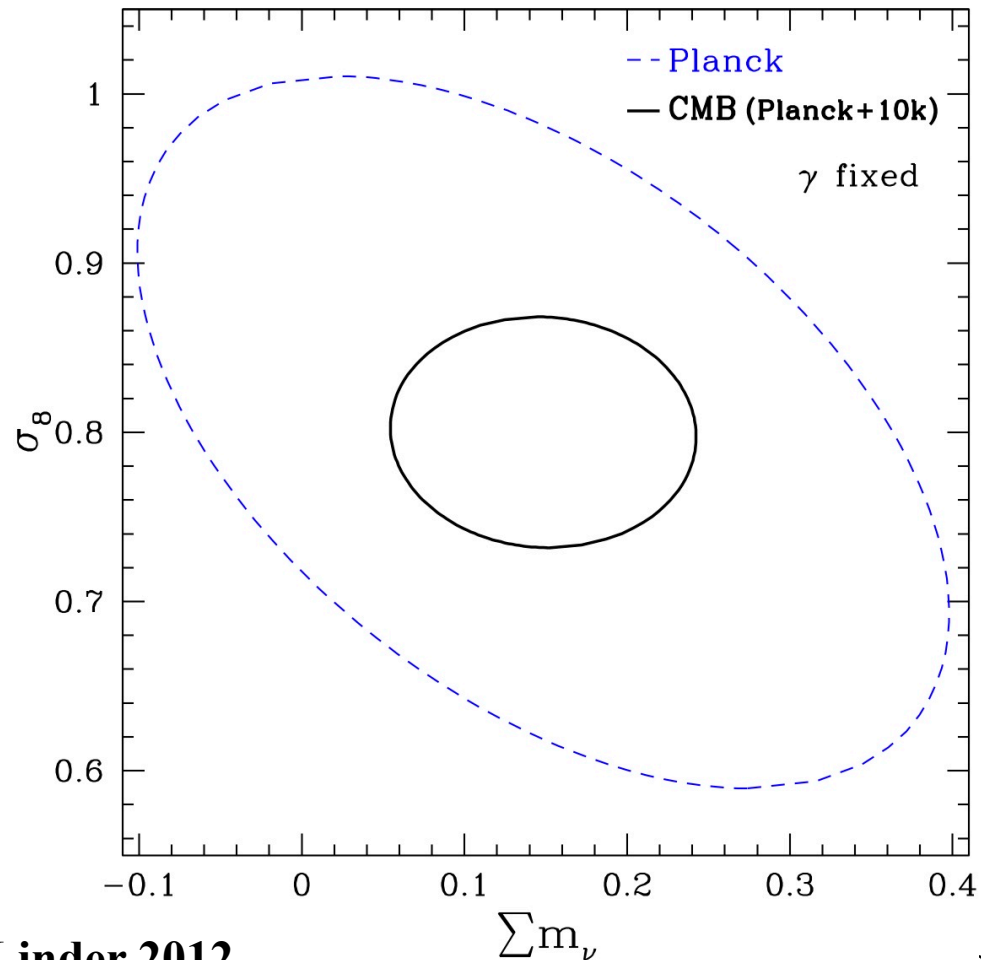
Prior on H_0 important.

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



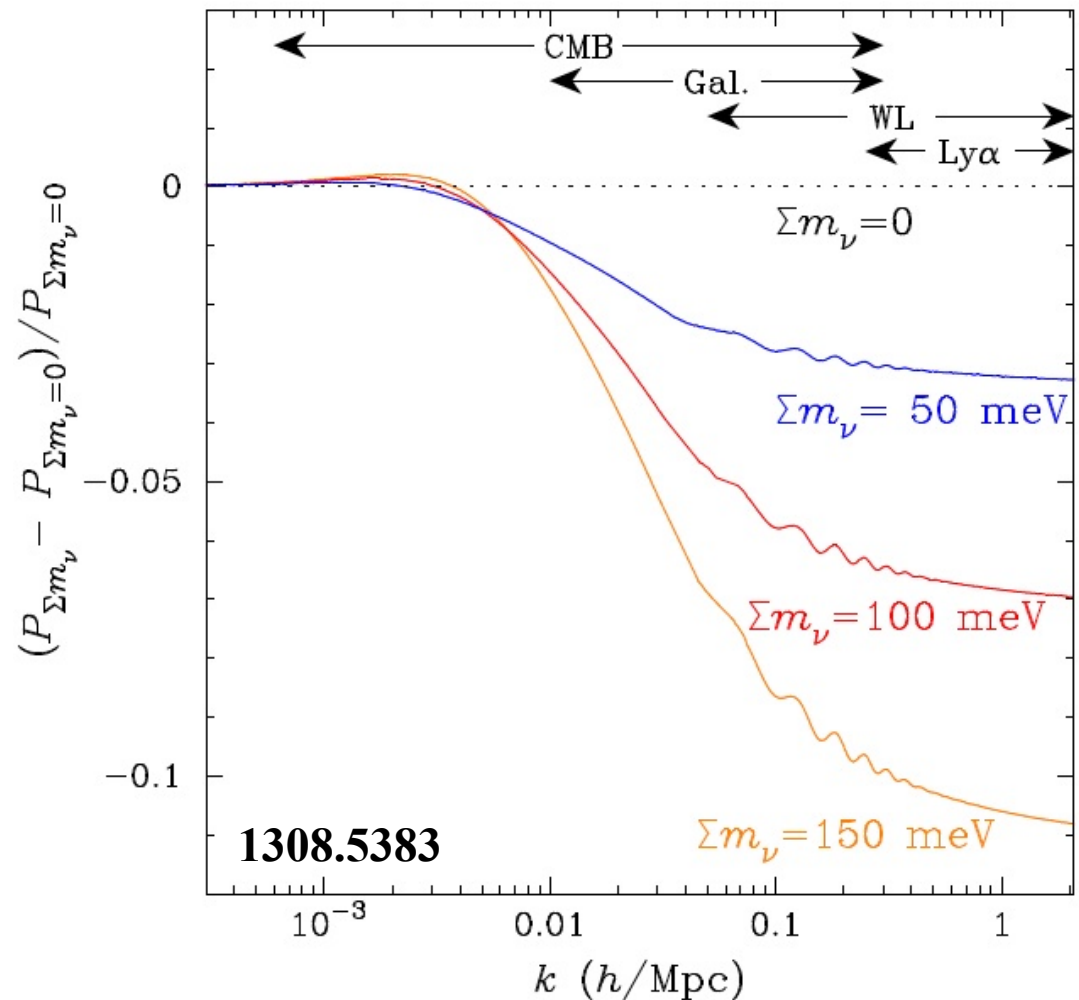
Das & Linder 2012



Neutrino Mass

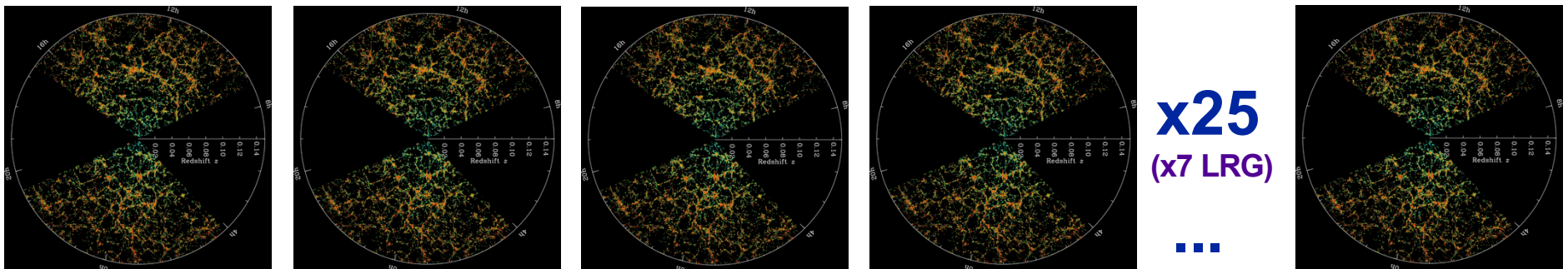
CMB plus Large Scale Structure work together well to constrain the sum of neutrino masses, since they probe above and below the neutrino free streaming scale.

The scale shifts slightly with m_ν but the stronger signal is the amount of suppression of growth.



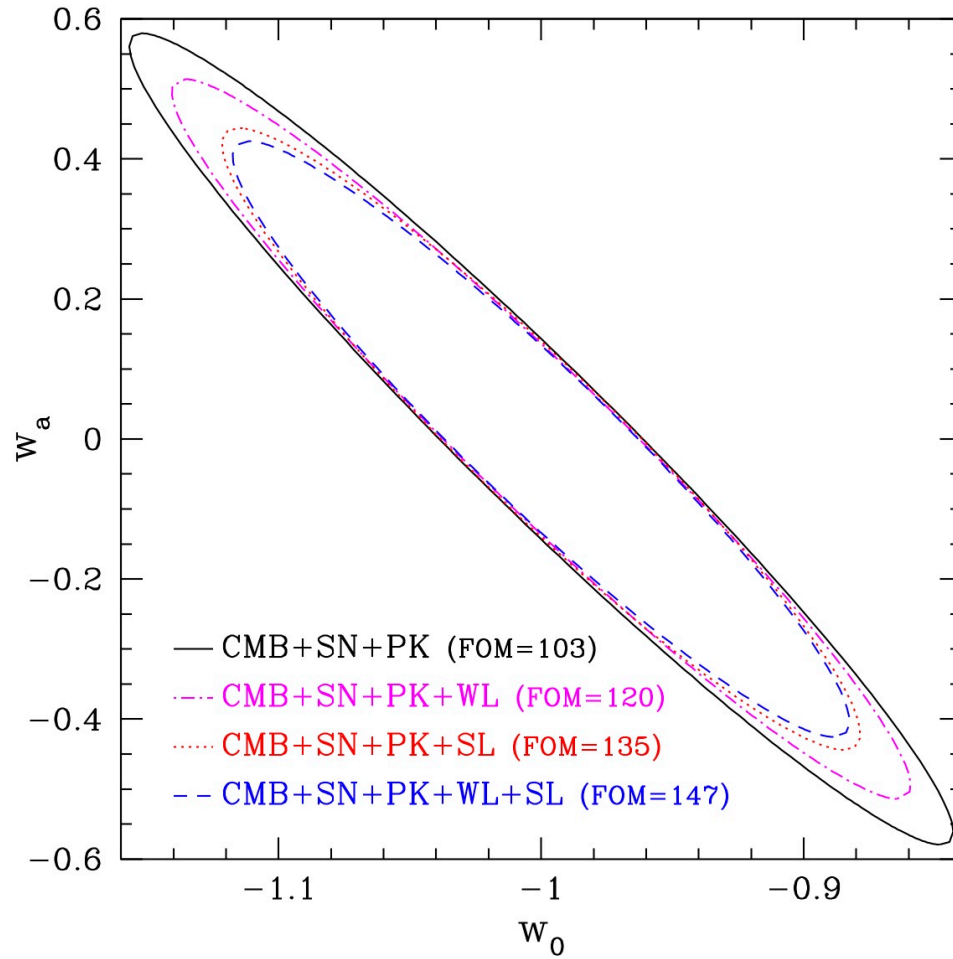
Galaxy 3D distribution or power spectrum contains information on:

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

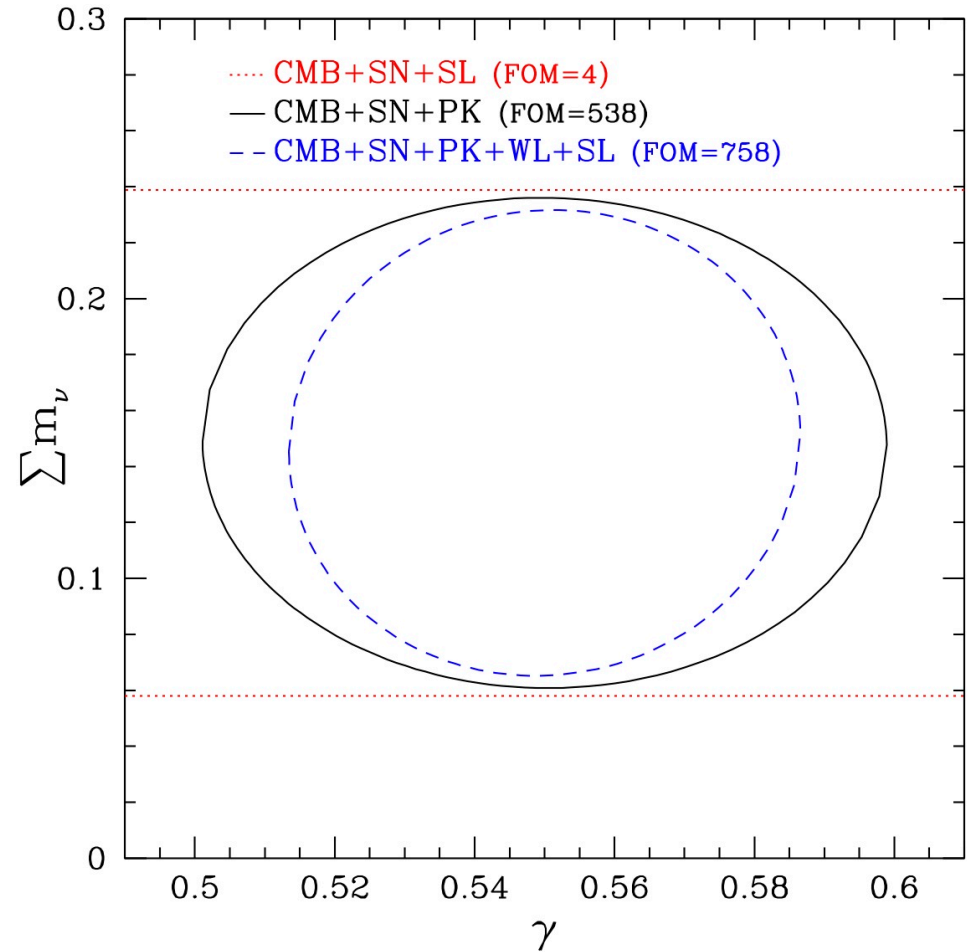


CMB + LSS – near term

Expansion

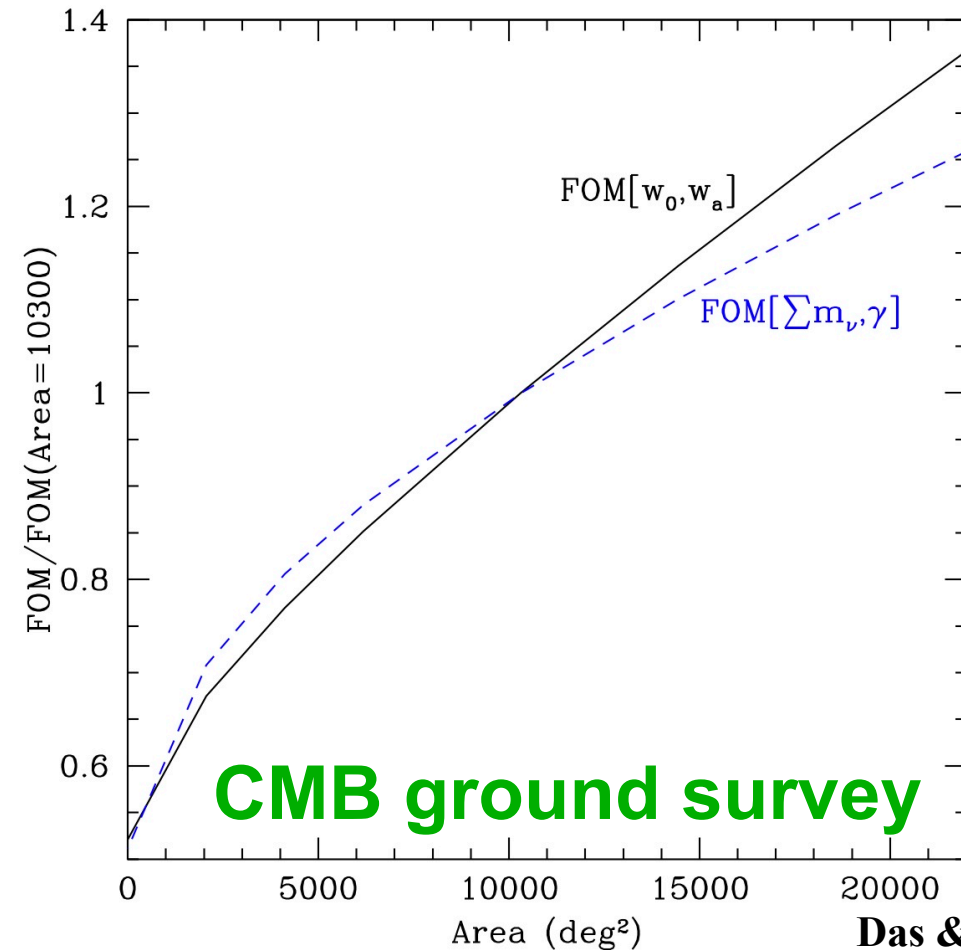


Growth

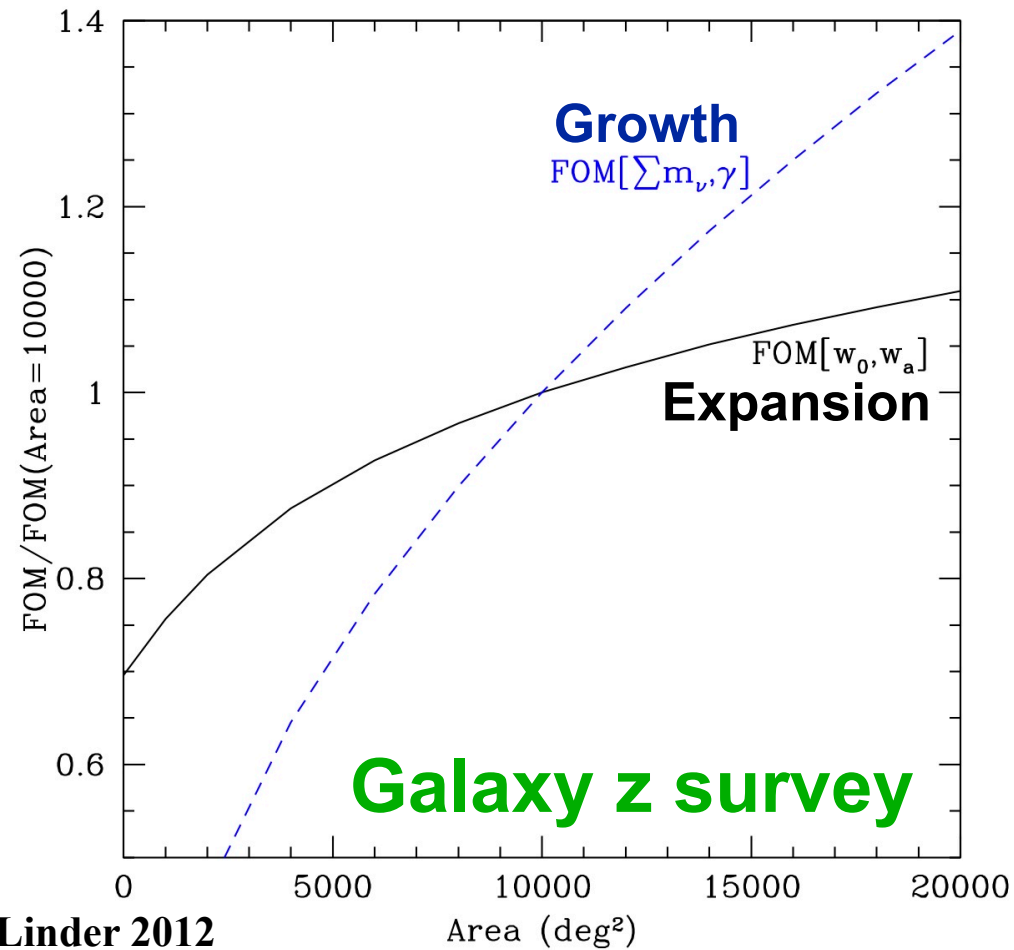


Surveys + Surveys

Near term: CMB+BOSS+DES/SN

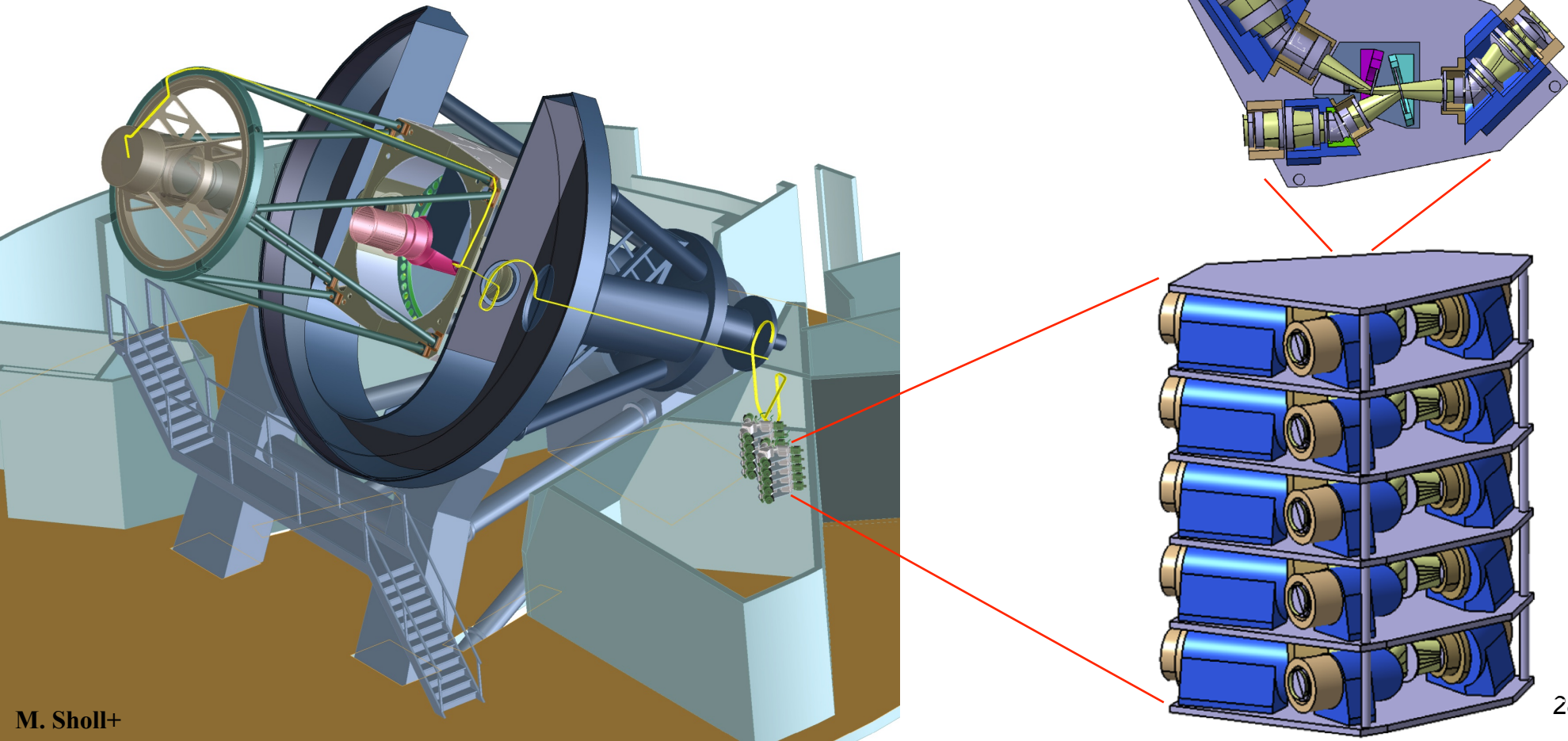


Das & Linder 2012

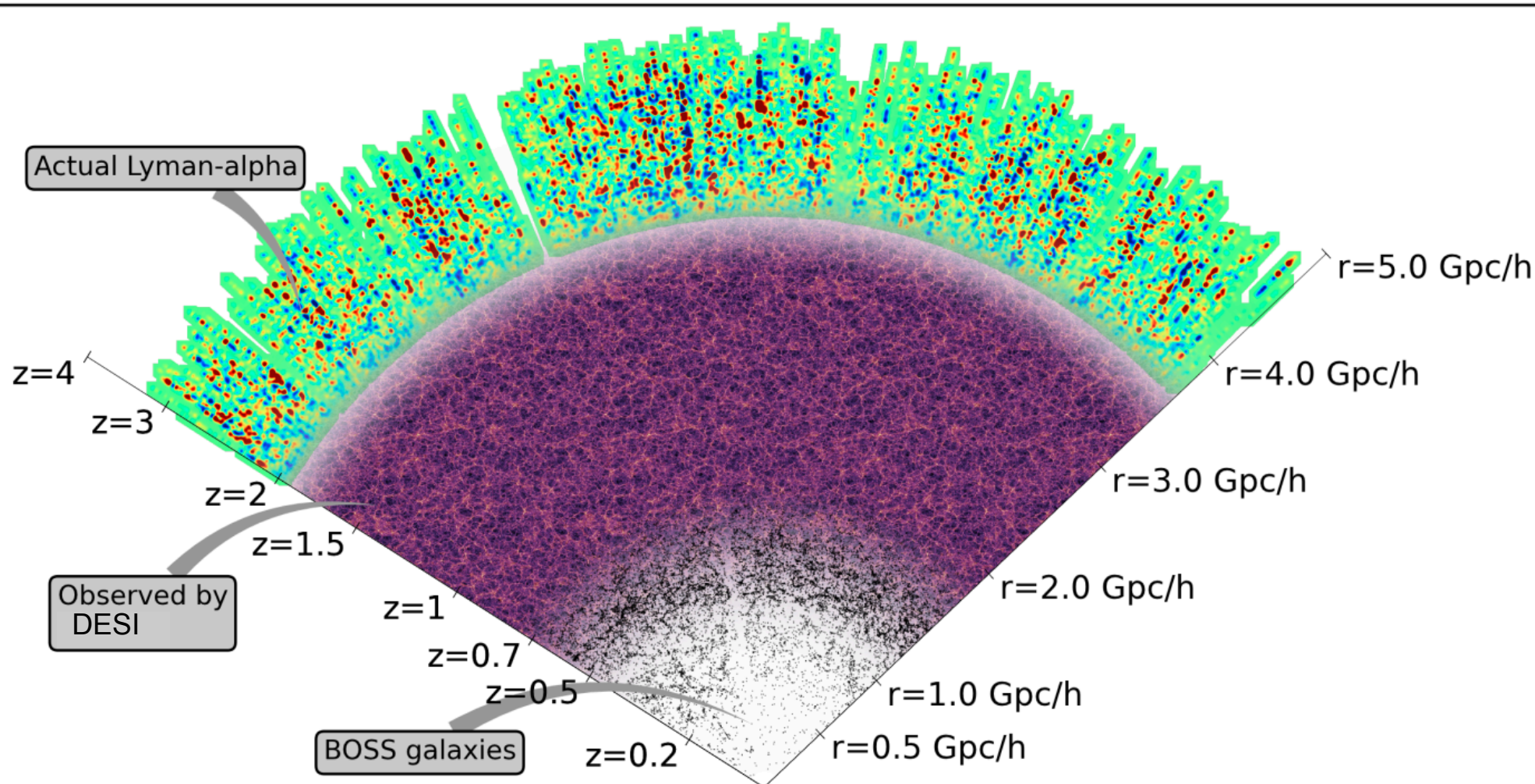


DESI (Dark Energy Spectroscopic Instrument)

- 50 (Gpc/h)^3 volume, $z=0.2-3$ (galaxy + Ly α)
- 20 million spectra, 5000 robotic fiber positioners
- 3 degree field



DESI Survey



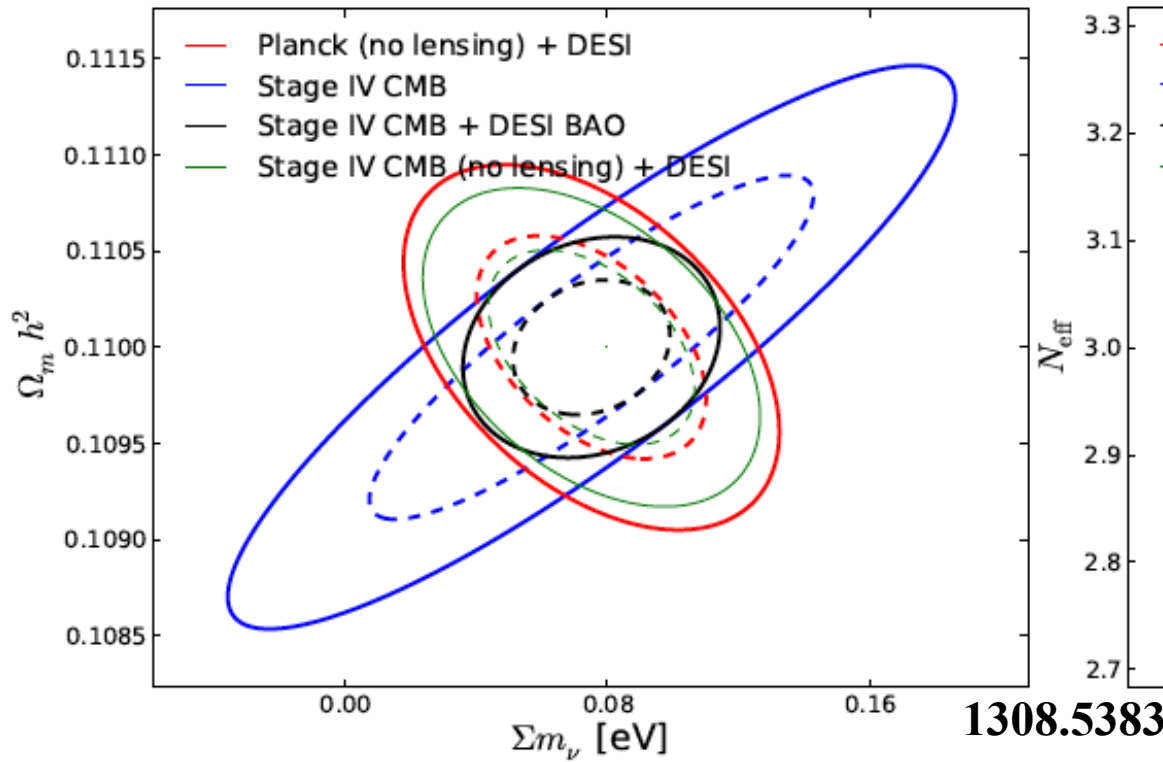
3D map of 50 (Gpc/h)^3 volume with 4M Luminous Red Galaxies, 14 M Emission Line Galaxies, 2M Quasars
Tomographic surveys of density/velocity field.

CMB + LSS – next generation

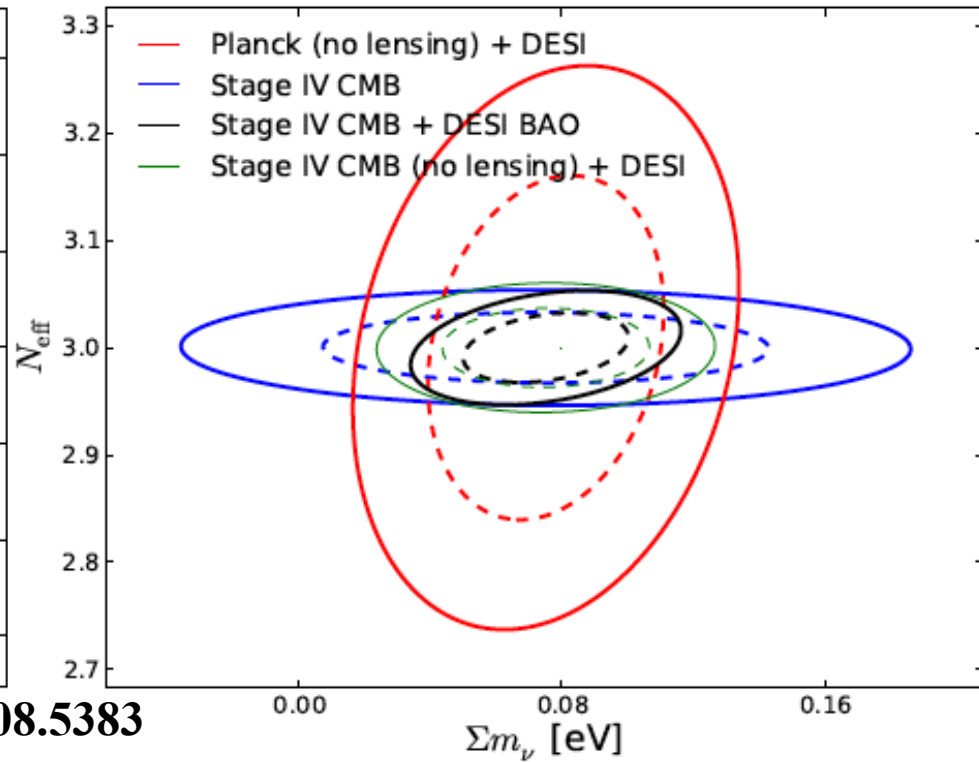
Potentially **20 meV** sensitivity (3σ even for minimal mass hierarchy) and **0.02** sensitivity on N_{eff} (2σ probe of e^+e^- annihilation).

Dataset	$\sigma(\sum m_\nu)$ [meV]	$\sigma(N_{\text{eff}})$
Galaxy Clustering (current CMB):		
Planck + BOSS BAO	100	0.18
Planck + BOSS galaxy clustering	46/68	0.14/0.17
Planck + eBOSS BAO	97	0.18
Planck + eBOSS galaxy clustering	36/52	0.13/0.16
Planck + DESI BAO	91	0.18
Planck + DESI galaxy clustering	17/24	0.08/0.12
CMB Lensing (current galaxy clustering):		
Stage-IV CMB	45	0.021
Stage-IV CMB + BOSS BAO	25	0.021
CMB Lensing + Galaxy clustering:		
Stage-IV CMB + eBOSS BAO	23	0.021
Stage-IV CMB + DESI BAO	16	0.020
Stage-IV CMB no lensing + DESI galaxy clustering	15/20	0.022/0.024
Galaxy Weak Lensing:		
Planck + LSST	23	0.07
Planck + Euclid	25	NA [†]

Particle physics constraints from cosmology



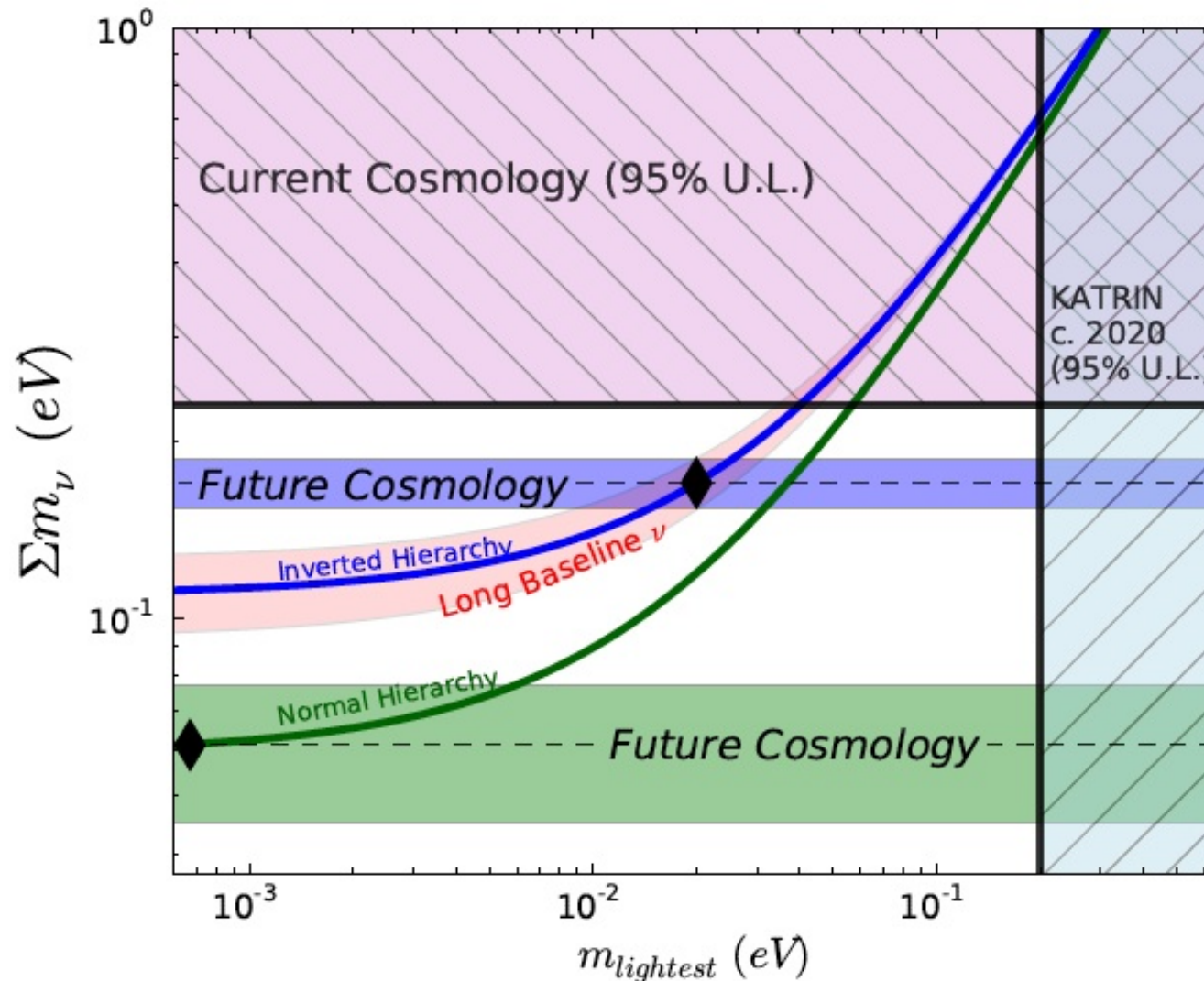
**Dark matter abundance
and neutrino mass**



**Neutrino mass and
number of species**

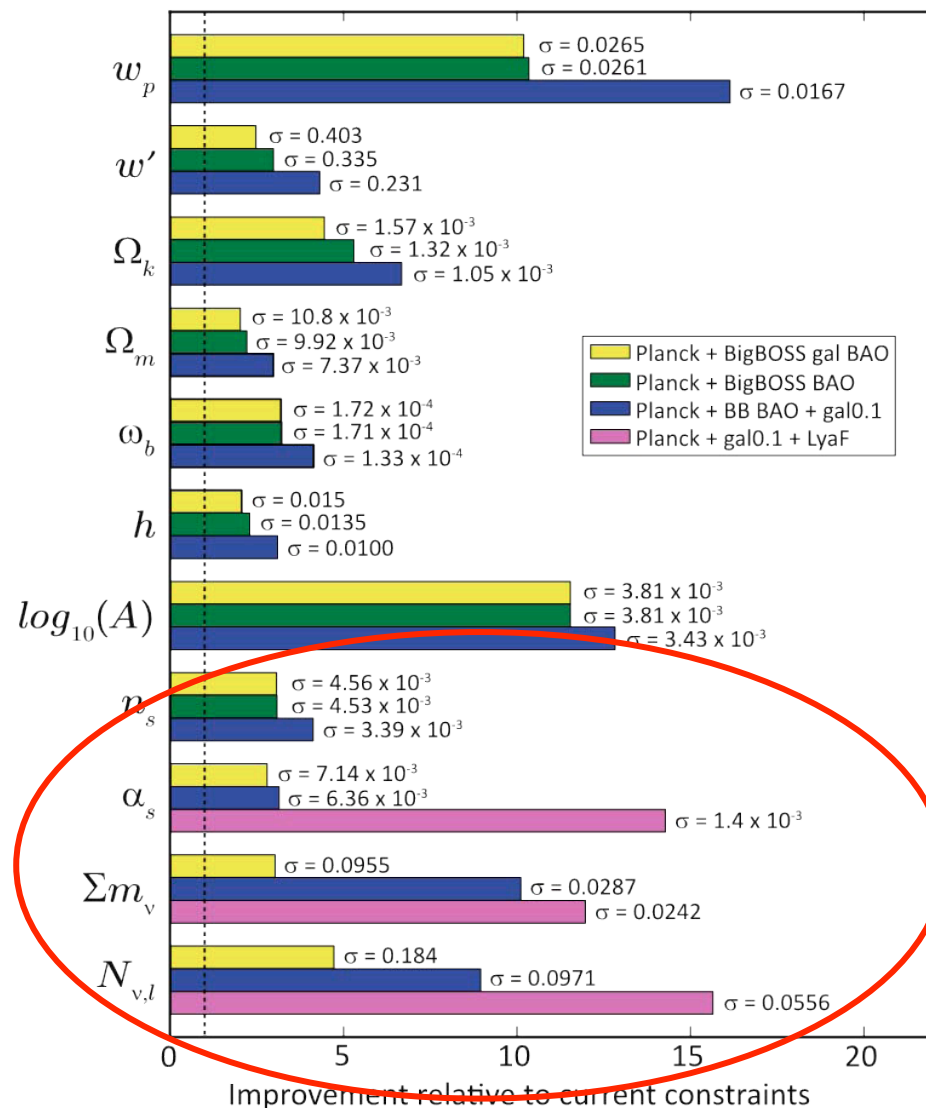
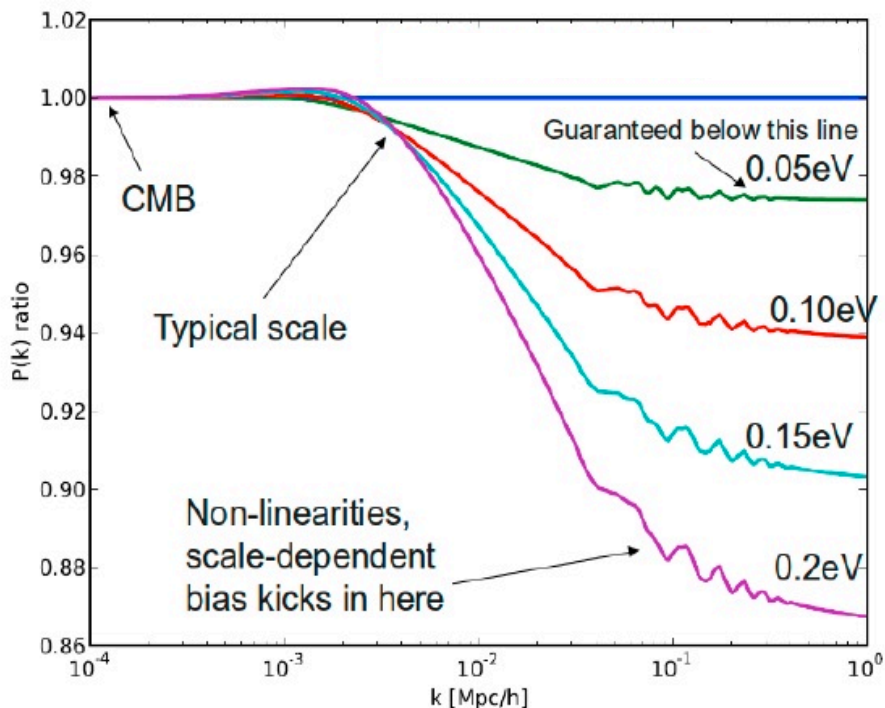
Neutrino Hierarchy

Complementarity between cosmic and lab experiments. Can distinguish mass hierarchy.



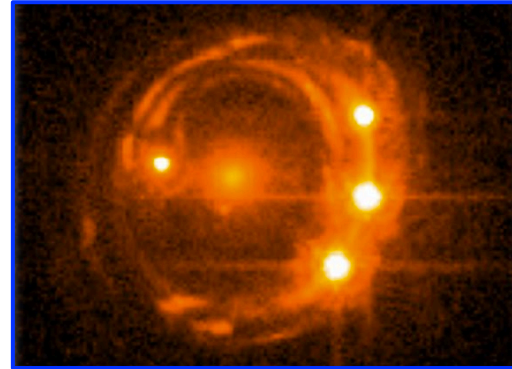
1308.5383

Long lever arm in k determines Σm_ν , tests running of primordial spectrum. Large scales test non-Gaussianity.



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.

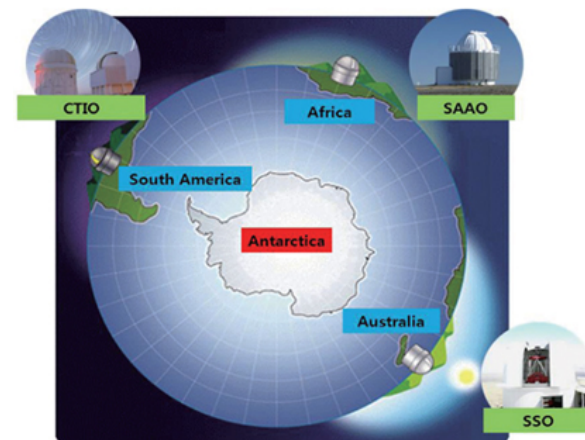
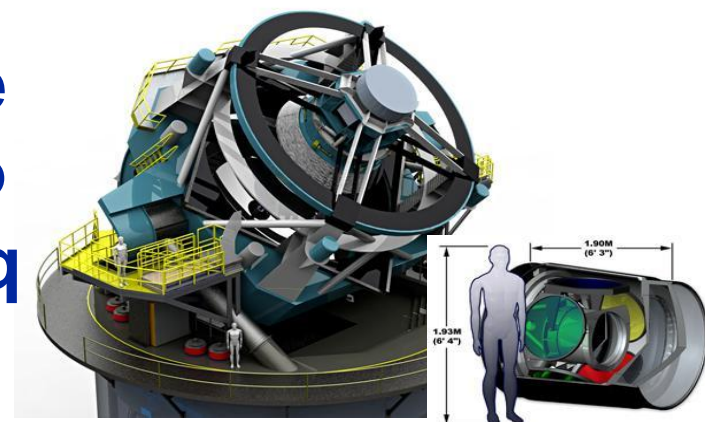
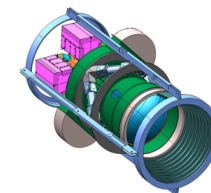
Large Synoptic Survey Telescope (LSST) will start in ~2020 at Cerro Pachon, Chile, covering 20,000 sq deg repeatedly in 10 years.

Output: ~8000 lensed AGN.

Monitoring: KMTNet (Korea Microlensing Telescope Network)

Three 1.6m telescopes

Three 340 Mpixel cameras with 4 deg² fields



Strong Lensing Cosmology

The Challenges:

Time delay estimation –

LSST Data Challenge: arXiv:1310.4830

Blind analysis has achieved 1% accuracy

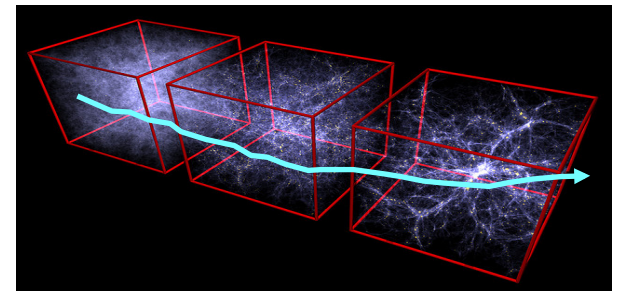
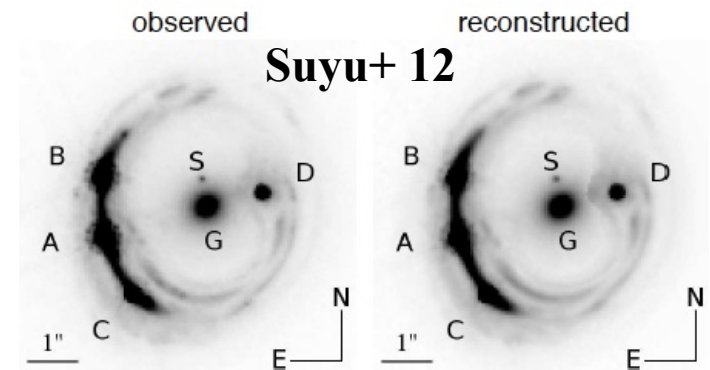
Lens modeling –

HST, Adaptive Optics

ASIAA world leading!

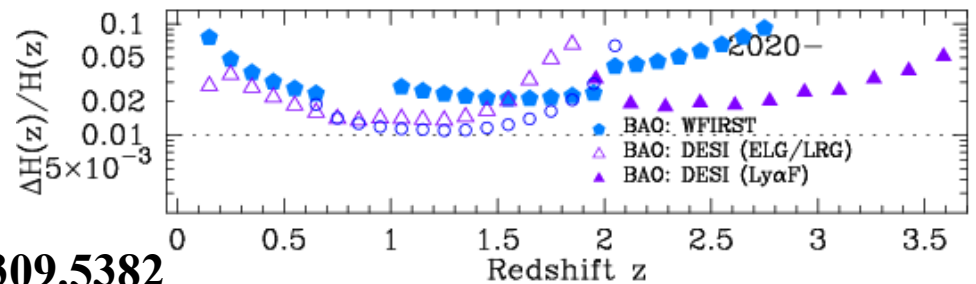
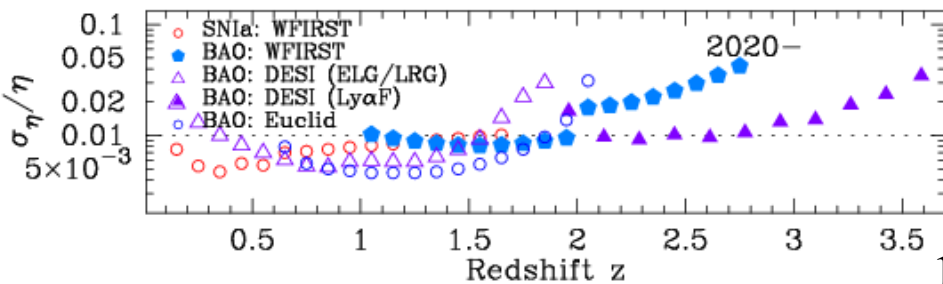
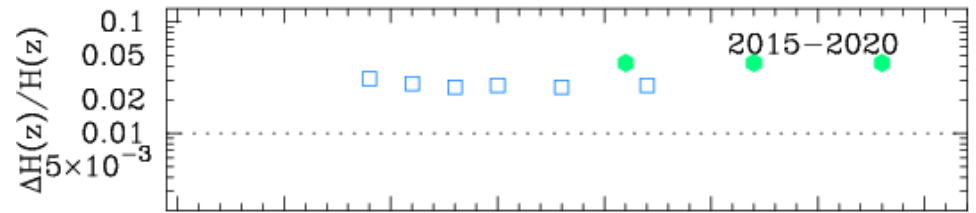
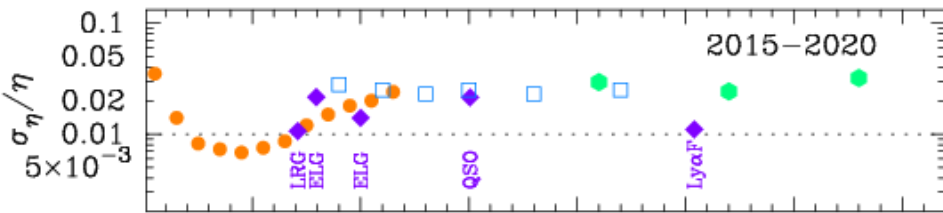
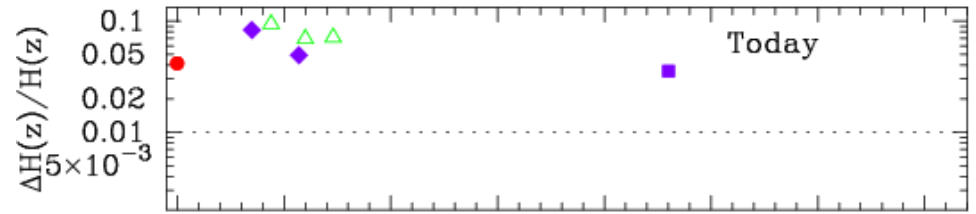
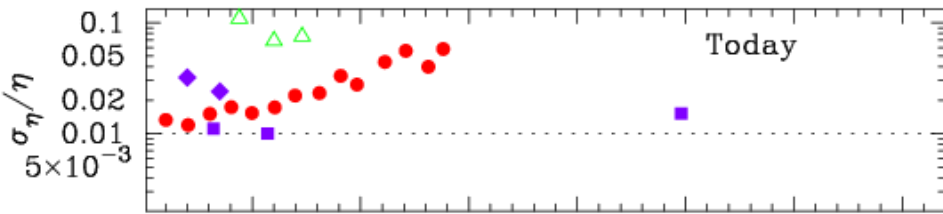
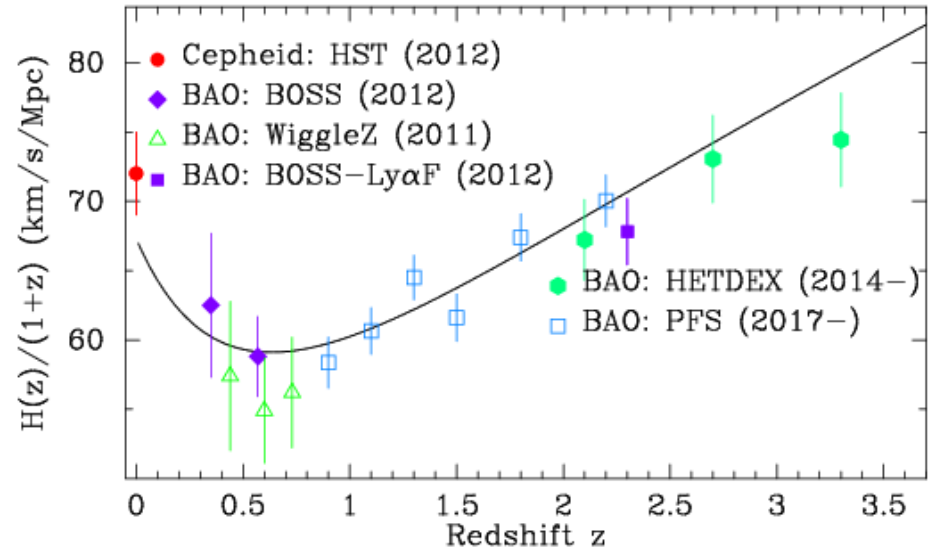
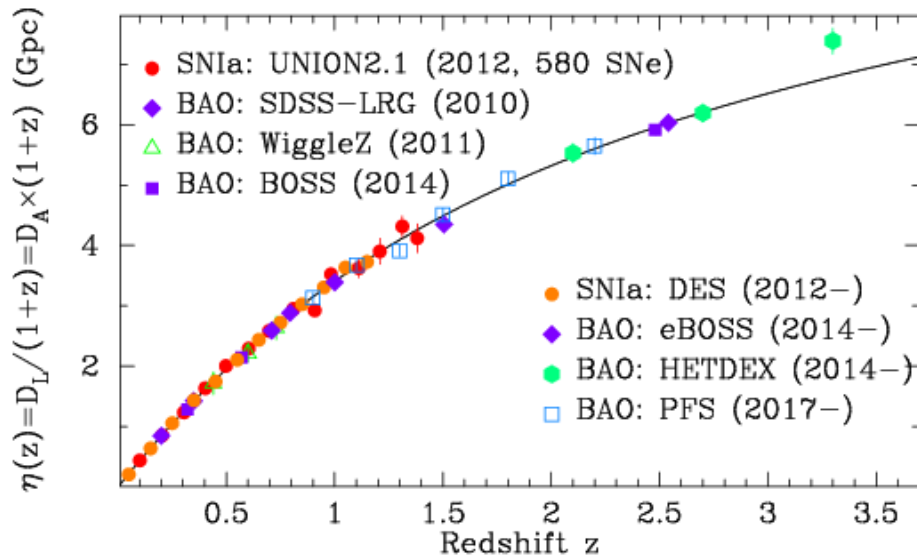
Line of sight mass –

**Important role for
simulations and xcorrs.**



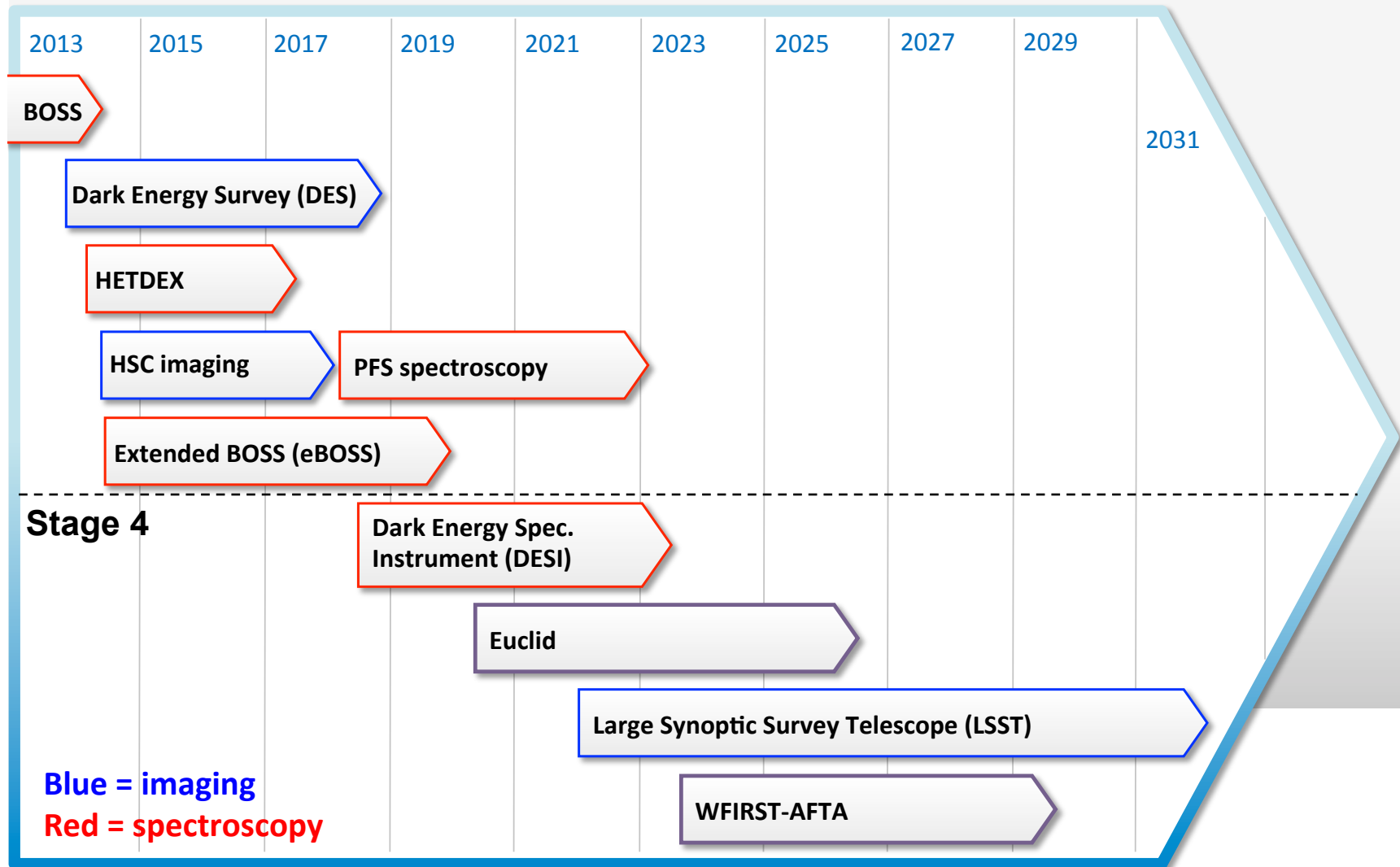
κ_{ext} from lens-weighted galaxy counts Greene+ 13 , full 3D
halo model mass recon using all photometric info Collett+ 13

Progress in Distances



An Active Future

Dark Energy Experiments: 2013 - 2031

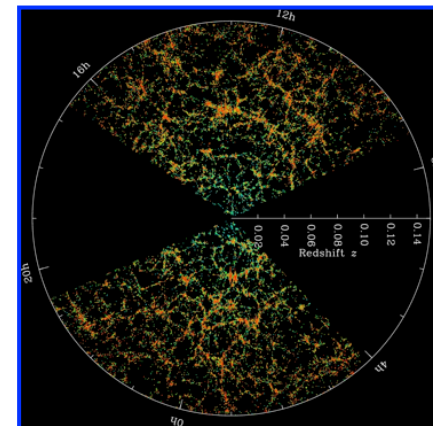
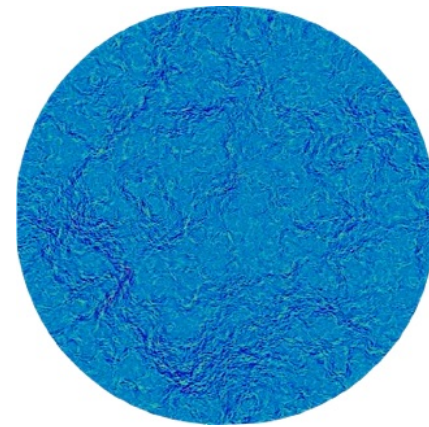


see 1309.5380 for details

How can we measure dark energy in detail?

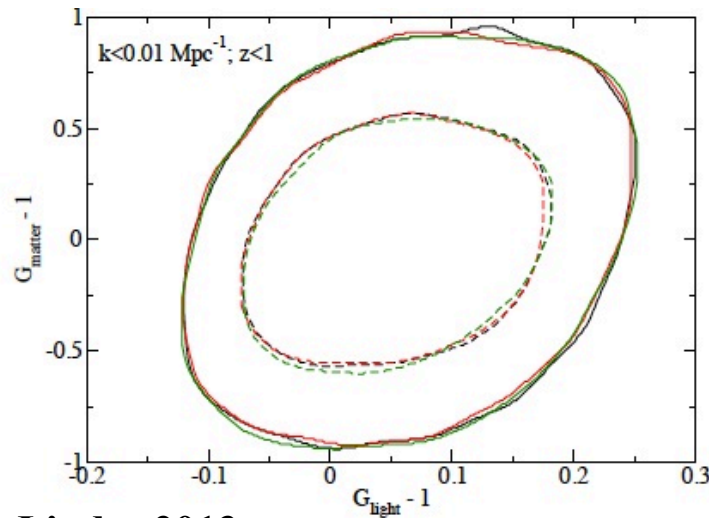
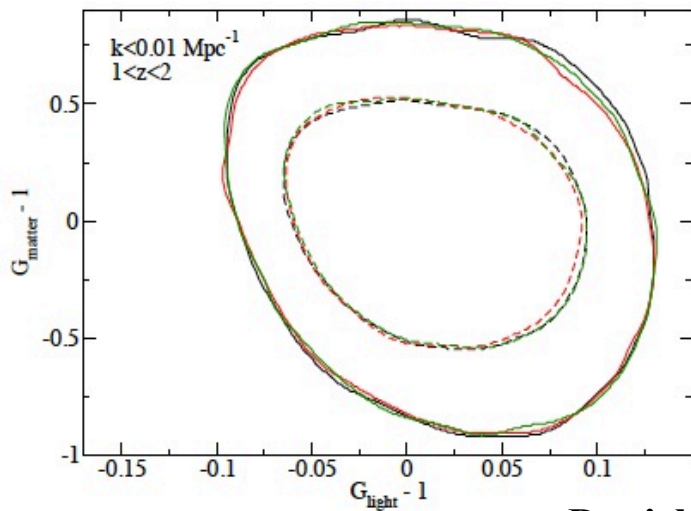
A strong program of techniques is in place, but **new**, complementary probes offer exciting prospects.

- Measuring **growth** and **neutrino mass** to **0.02 eV** with **CMB lensing**
- Measuring **growth** and **gravity** to **%-level** with **galaxy clustering**

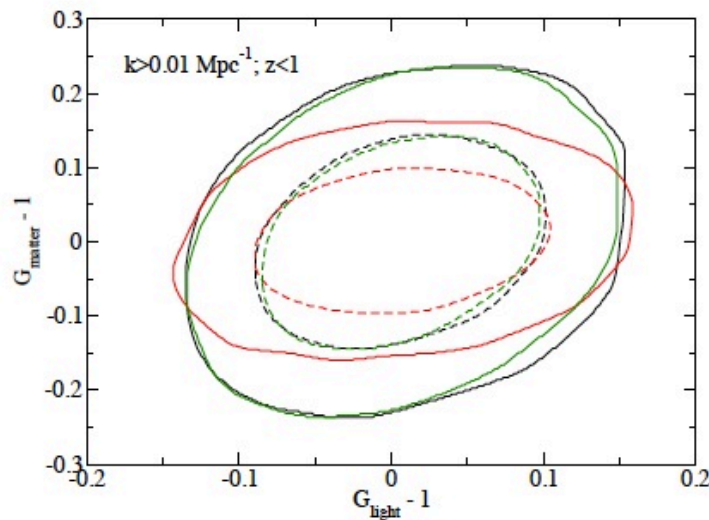
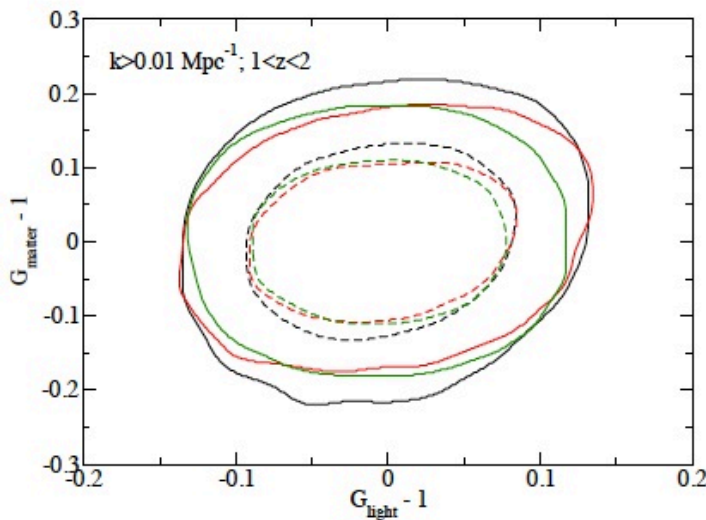


Testing Gravity

Model independent tests of gravity: two functions, at high/low z , high/low k (8 tests). Simultaneous fit for gravity, expansion (w_0, w_a), galaxy bias (27 bins).



Daniel & Linder 2013



**DESI/Euclid
+Planck**

**Fit all
Fix to Λ
Fix to $b \sim 1/D$**

Summary

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

Probes **inflation** through scalar perturbations, and B-mode polarization (tensor/GW) modes.

CMB lensing breaks degeneracies and measures the matter power spectrum, including effects of dark energy and neutrinos.

CMB+LSS can improve over current constraints by factor 15, and measure Σm_ν to **0.02 eV** and effective number of species N_{eff} to **0.02**.

1% measures of distance over $z \sim 0-2$.

5-10% general tests of gravity.

Further Reading

For more resources on dark cosmology and its future, see

Euclid Theory Group 2012, *Cosmology and Fundamental Physics with the Euclid Satellite* <http://arxiv.org/abs/1206.1225>

Snowmass CF5, *Distance Probes of Dark Energy*
<http://arxiv.org/abs/1309.5382>

Snowmass CF5, *Growth of Cosmic Structure: Probing Dark Energy beyond Expansion* <http://arxiv.org/abs/1309.5385>

Snowmass CF5, *Neutrino Physics from the Cosmic Microwave Background and Large Scale Structure* <http://arxiv.org/abs/1309.5383>

Snowmass CF5, *Inflation Physics from the Cosmic Microwave Background and Large Scale Structure* <http://arxiv.org/abs/1309.5381>

Snowmass CF5, *Facilities for Dark Energy Investigations*
<http://arxiv.org/abs/1309.5380>