Cosmic Complementarity:
constraining neutrinos, inflation & dark energy

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Outline

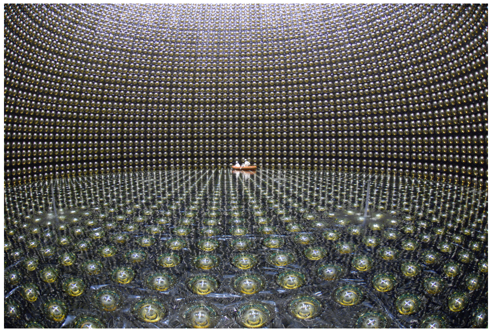
- Neutrino mass constraints and the primordial power spectrum

- Combining weak lensing and galaxy clustering to probe dark energy, gravity and neutrinos

- Primordial non-Gaussianity from LSS:
  what does an ideal experiment look like?

The absolute mass scale Σm_ν is a crucial property of neutrinos

- Neutrino Oscillations: $\Sigma m_\nu > 0.06\ eV$



- Tritium Beta Decay:

$m_\beta < 2.05\ eV\ (95\ \%\ CL) \Rightarrow \Sigma m_\nu < 6.2\ eV$

Troitsk Collaboration 2011

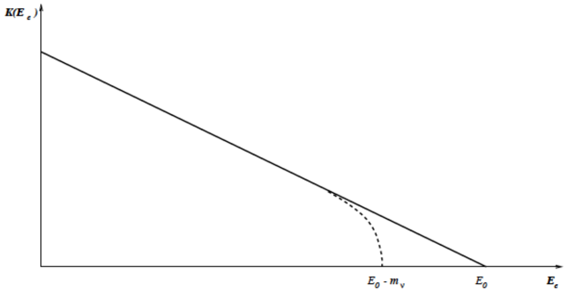
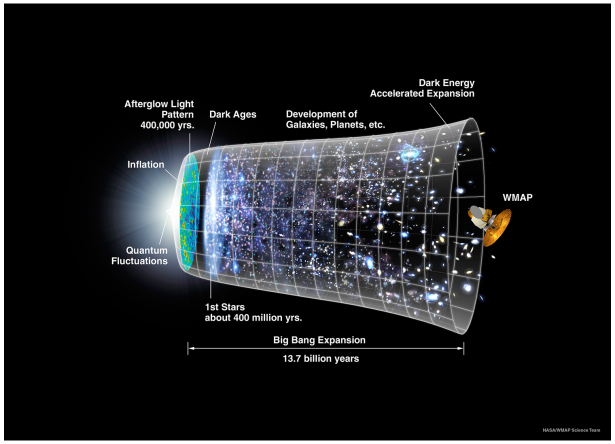


Figure 1: Kurie plots for $m_\nu = 0$ (solid line) and $m_\nu \neq 0$ (dashed line)

- *COSMOLOGY*



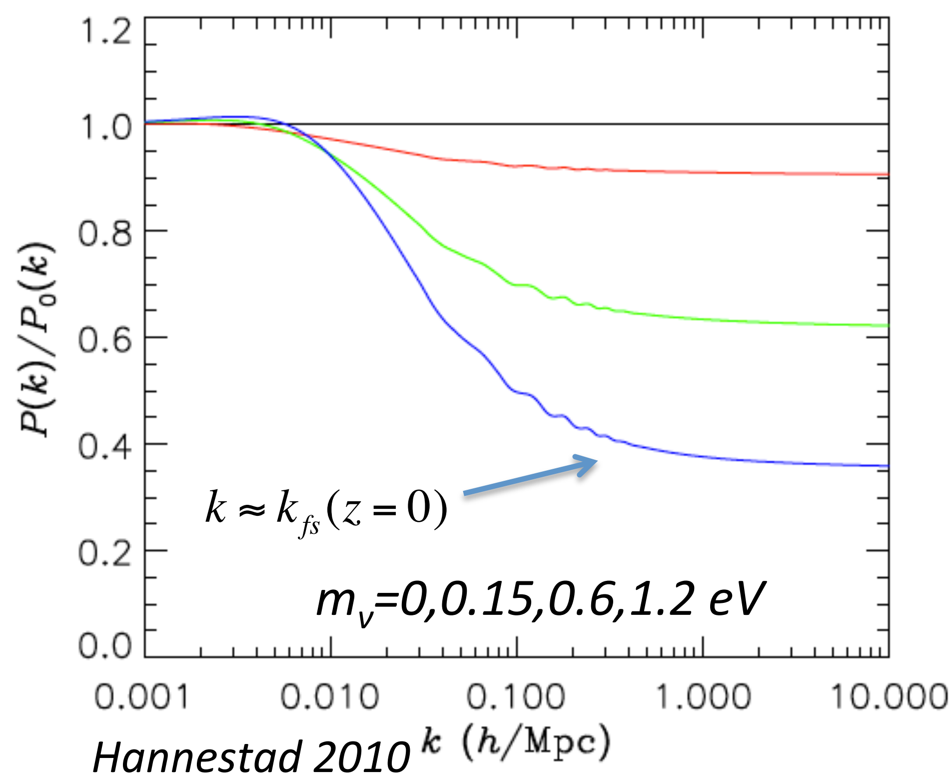
The Cosmic Neutrino Background affects cosmological observables in 2 ways:

1. Background Evolution:

- effect on cosmic distances, BAO, …

2. Growth of Structure:

- neutrinos do not cluster on scales below free-streaming length



Hannestad 2010

The strongest limits on Σm_ν come from cosmological data:

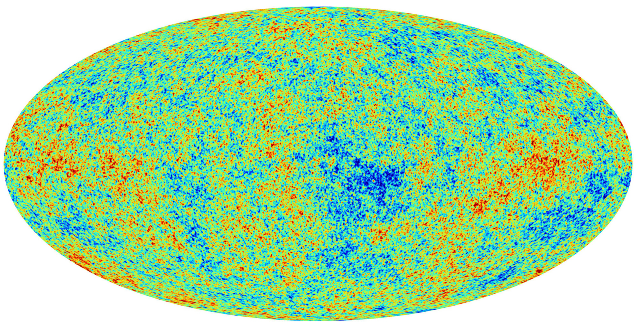
Σm_ν < 0.23 eV (95 % CL) from **Planck CMB + BAO**

Planck Collaboration XVI

These bounds assume a power law primordial power spectrum (PPS)!

$$\Delta^2_R(k) = \Delta^2_R(k_0)\left(\frac{k}{k_0}\right)^{n_s - 1}$$

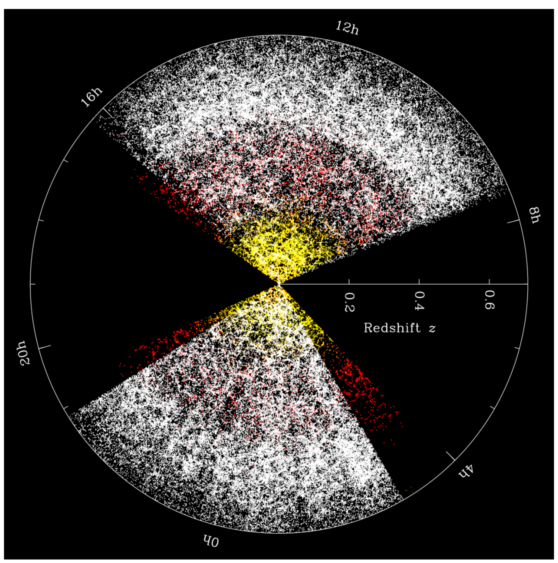
Power spectra of cosmic fluctuations are the “product” of PPS and transfer functions



CMB anisotropies

$$C_l = \int d\ln k \; W_l(k) \; \Delta_R^2(k)$$

transfer function PPS



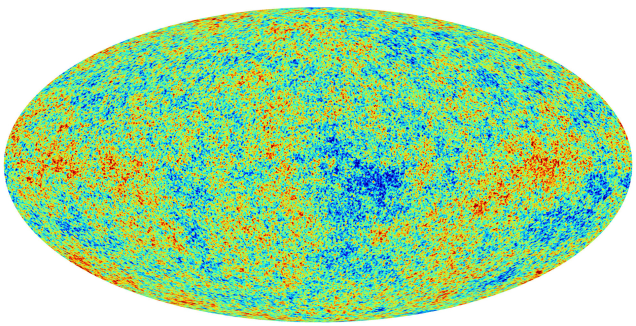
Galaxy Clustering

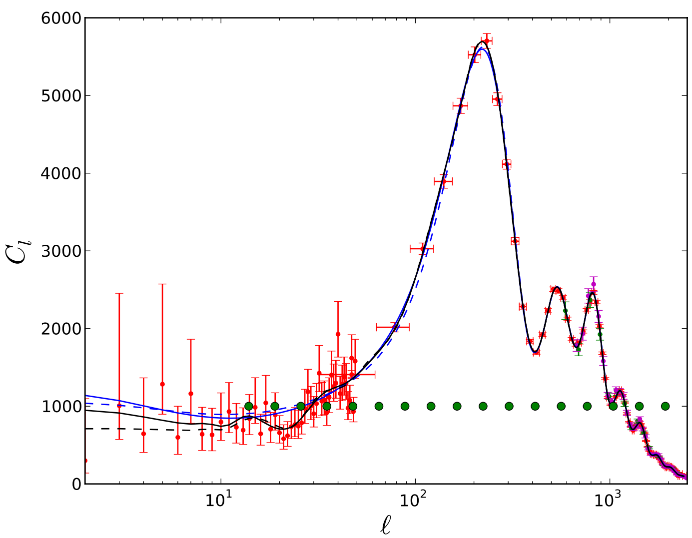
Agnostic approach: model the PPS by a 20-node spline at ***k = 0.001 – 0.35 Mpc^{-1}***

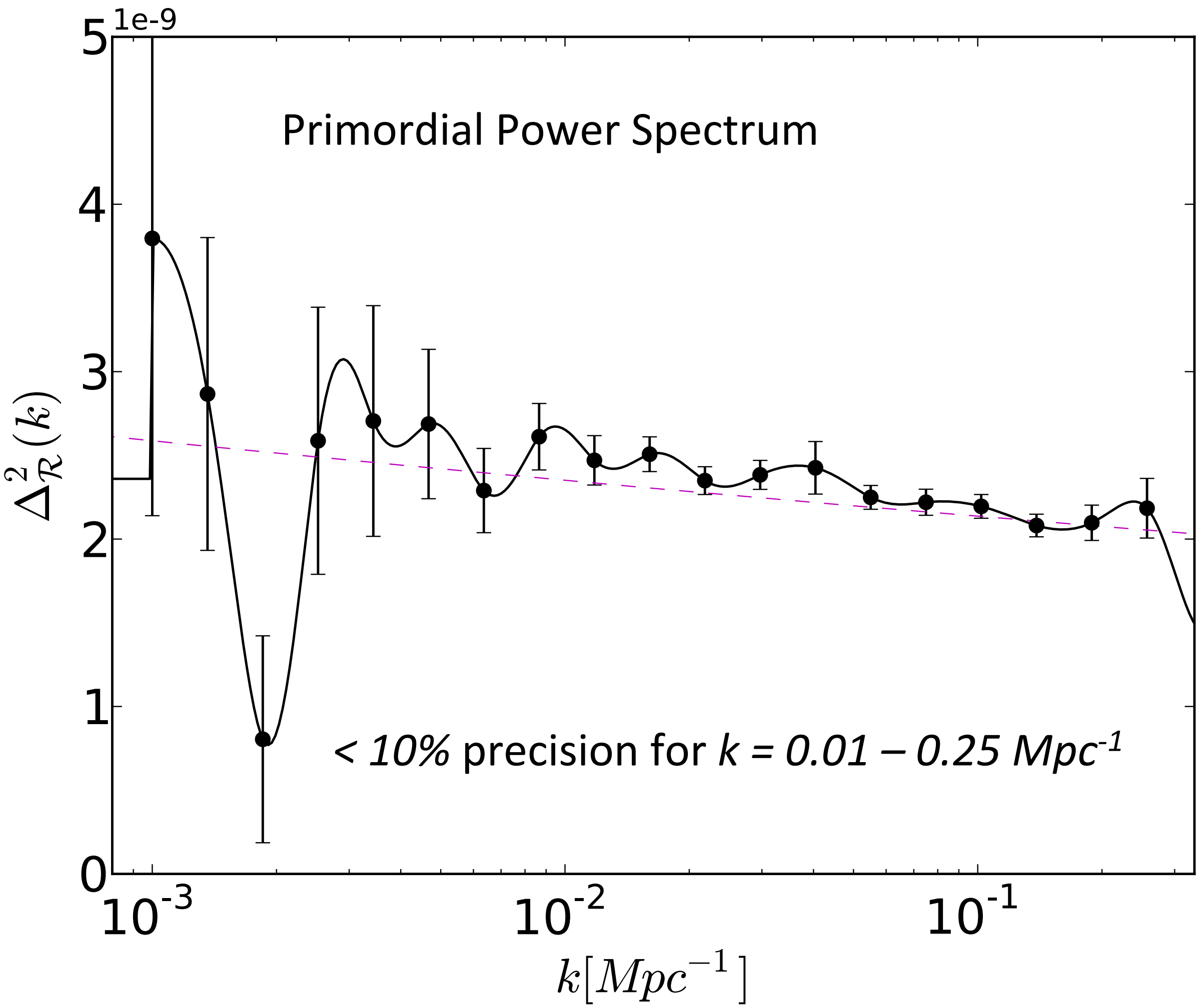
$$\Delta_R^2(k) = \Delta_{R,0}^2 \cdot \mathrm{spline}[p\{k_i\}]$$

RdP, Linder & Mishra, Phys Rev D 2014 (arXiv:1401.7022)

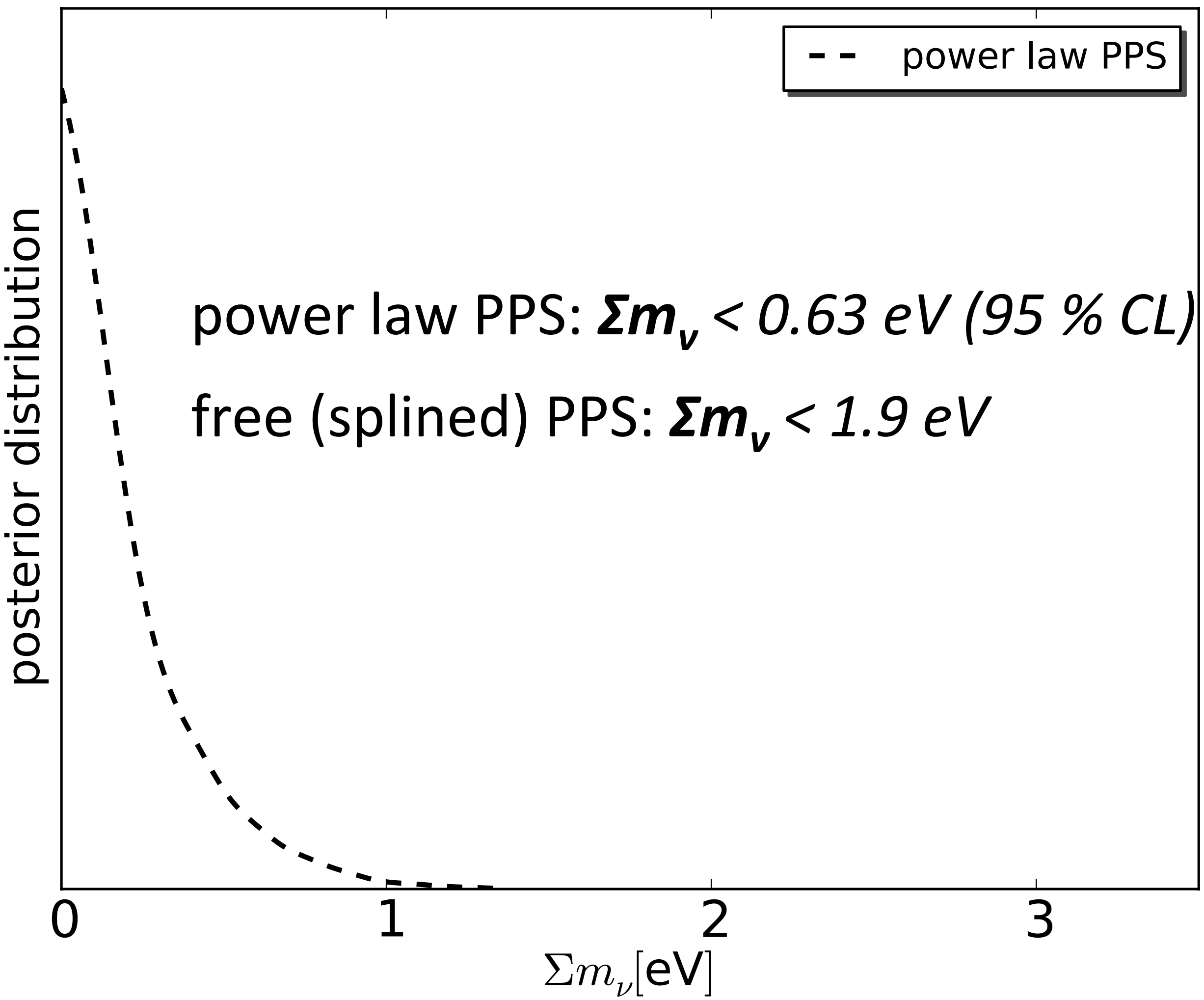
CMB data (Planck + SPT/ACT + WMAP Polarization) strongly constrain the primordial power spectrum





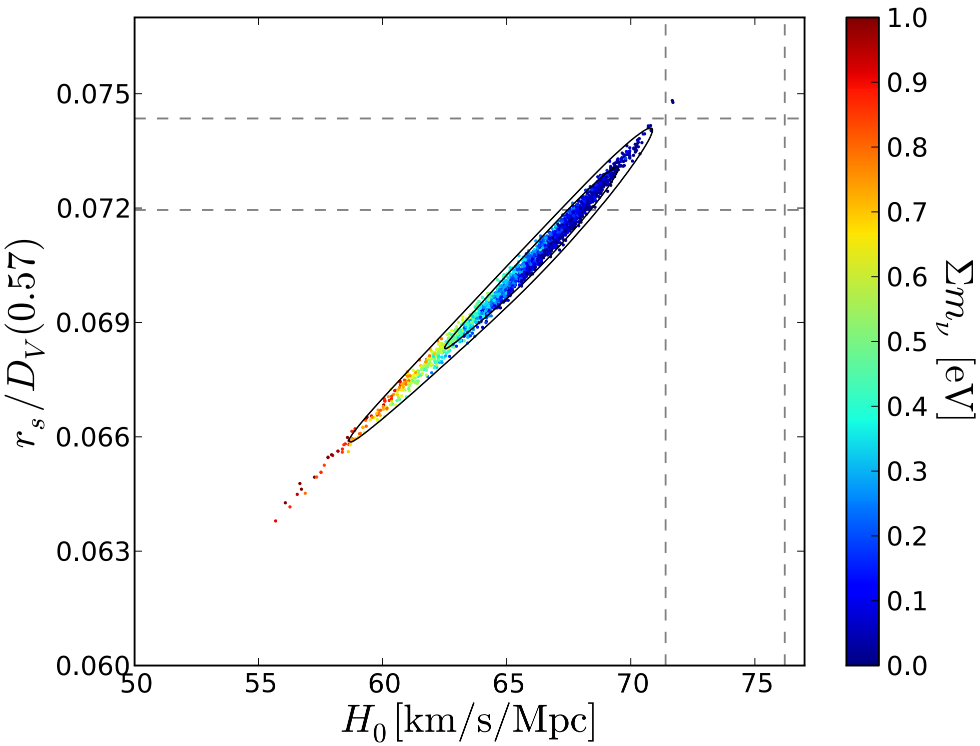


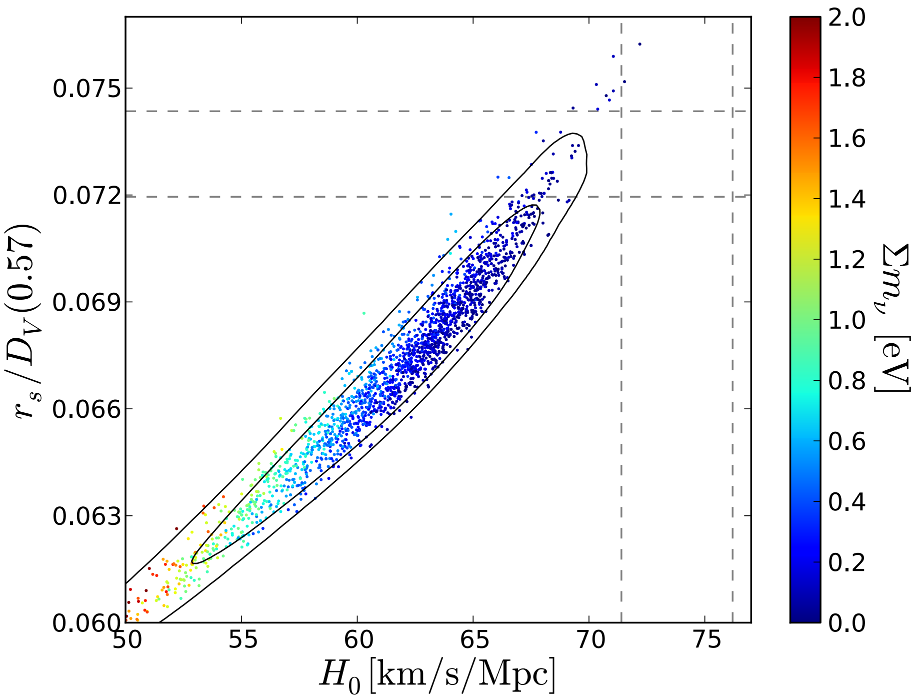
The CMB-only neutrino mass bound weakens by a factor 3 when the PPS is left free



Adding low-redshift data breaks the degeneracy between “late-universe parameters” ***Σm_ν*** and ***H_0***

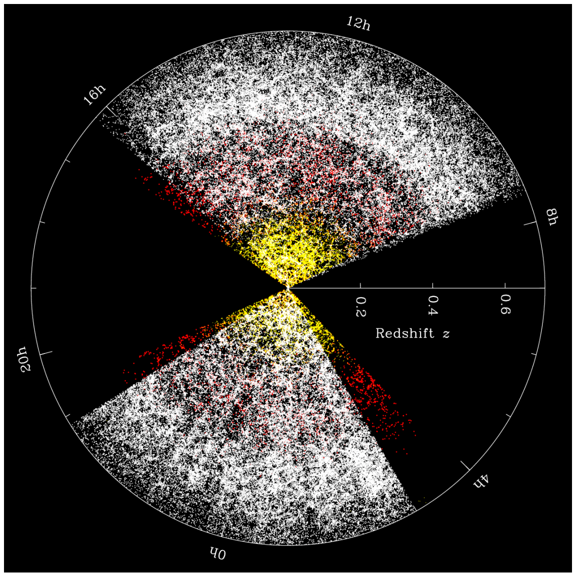
measured from BAO feature in galaxy clustering (in power law case)





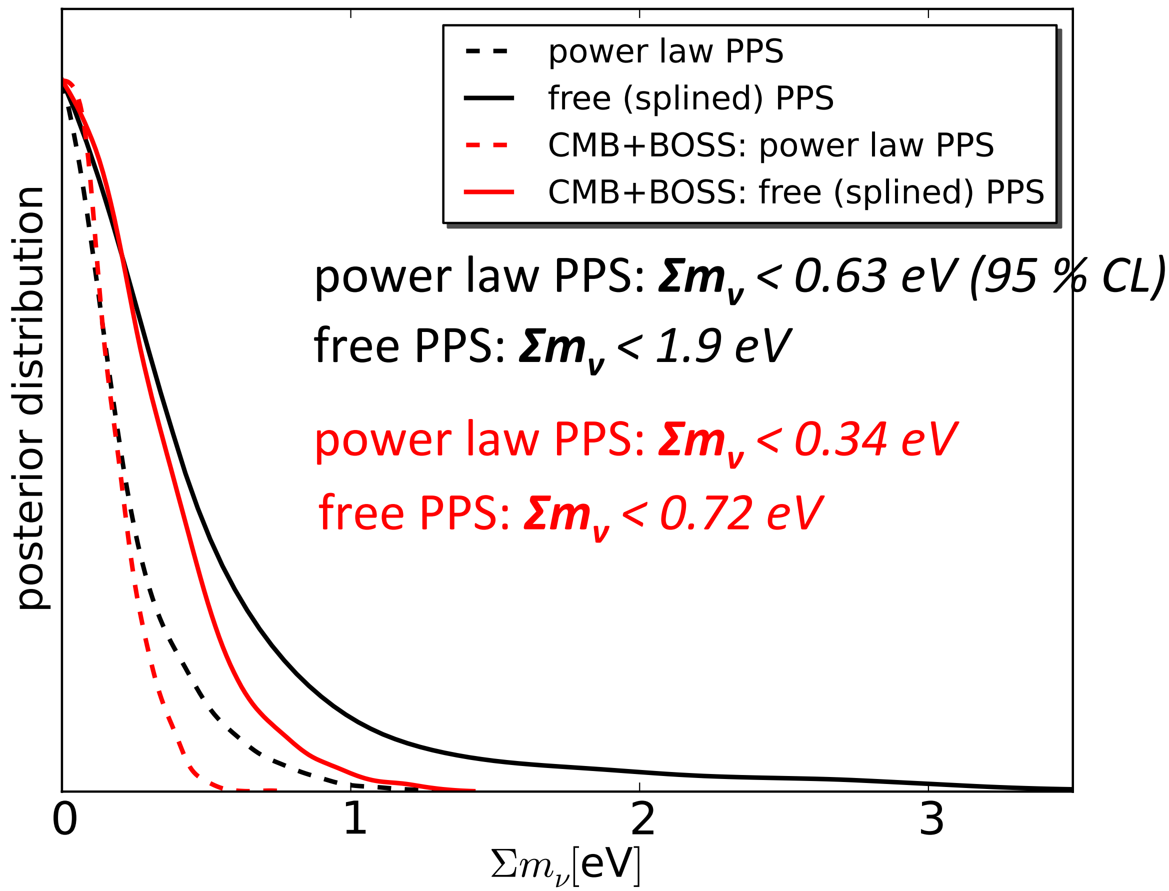
0.075
0.072
0.069
0.066
0.063
0.060
$r_s/D_V(0.57)$
50
55
60
65
70
75
H_0 [km/s/Mpc]
2.0
1.8
1.6
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
Σm_ν [eV]

CMB + BOSS Galaxy Power Spectrum tightens the constraint and makes it less dependent on the assumed PPS

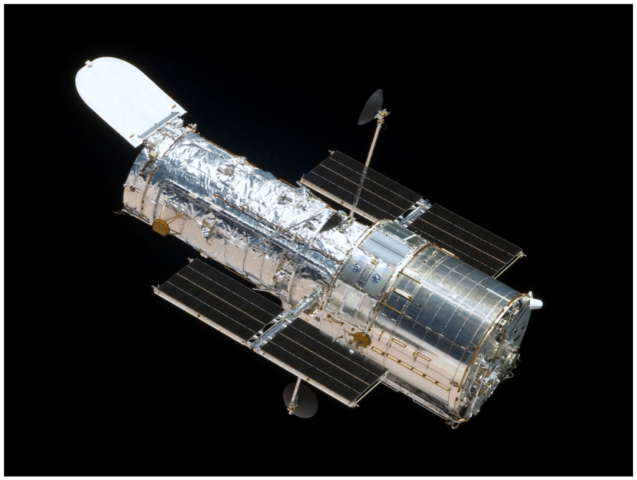


BOSS = Data Release 9 CMASS galaxy sample (z=0.57)

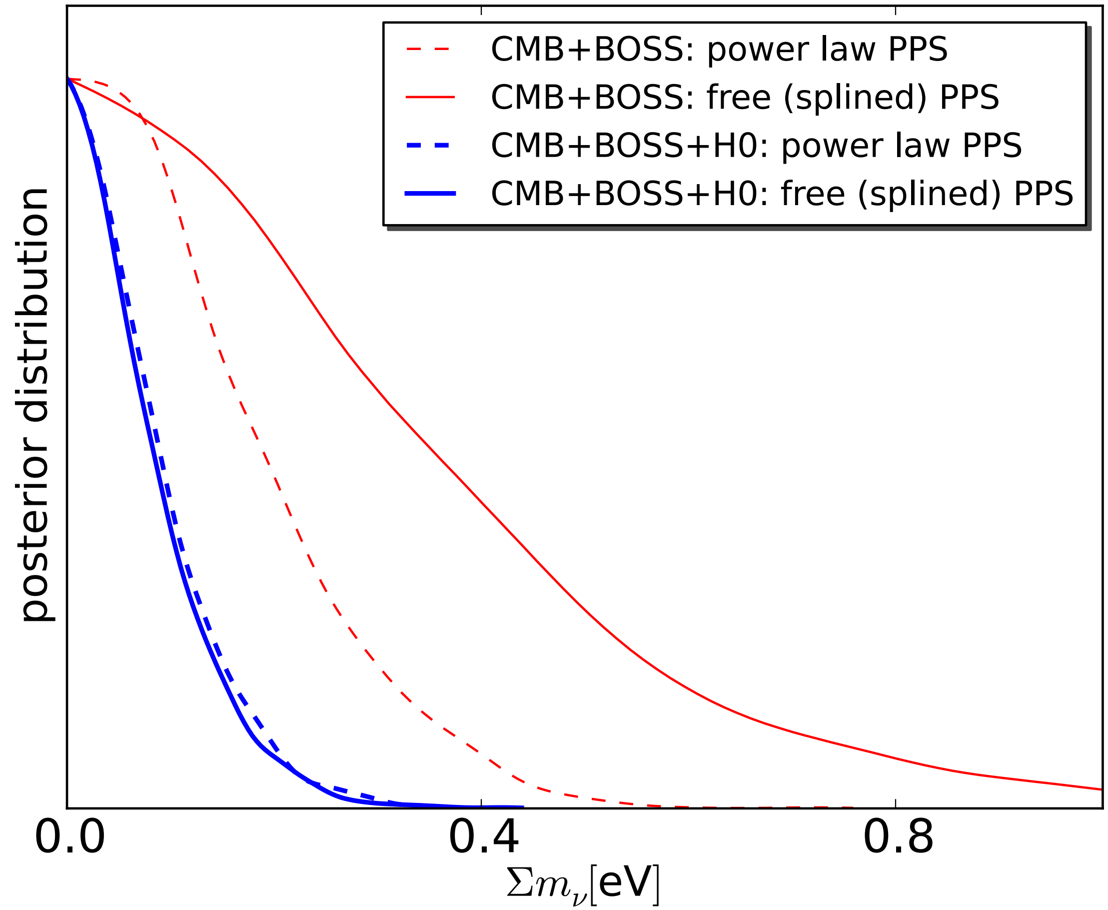
Anderson et al 2012



Adding a direct measurement H_0=73.8 +/- 2.4 km/s/Mpc yields a constraint Σm_ν< 0.19 eV, independent of PPS



Riess et al 2001 ***H_0*** measurement uses Hubble Cepheids to calibrate supernova distance ladder



- Tension ($\Delta\chi^2 \approx 10.5$) between CMB and H0 data
- Variations in H_0 analysis lead to upper limit ***0.18 eV – 0.28 eV***

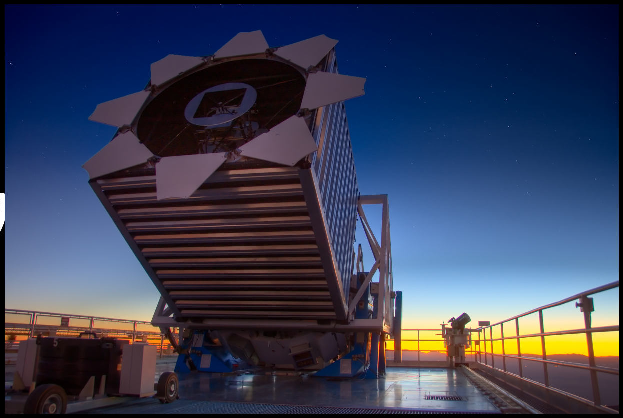
a robust, consensus H0 measurement will be incredibly useful

Part 2

- Neutrino mass constraints and the primordial power spectrum
- *Combining weak lensing and galaxy clustering to probe dark energy, gravity and neutrinos*
- Primordial non-Gaussianity from LSS:
  what does an ideal experiment look like?

Galaxy Clustering:

- 3D maps of galaxies -> 3D power spectrum ***P(k,mu)***
- BOSS: $V = 4.4\ (h^{-1}\ Gpc)^3$, $\Omega \approx 10{,}000\ deg^2$



The SDSS telescope at Apache Point, New Mexico

Weak Gravitational Lensing:

- ***Cosmic shear*** -> angular power spectra C_l of shear and source density
- CFHTLS: $\Omega \approx 150\ deg^2$
- soon: *DES, KIDS, HSC, LSST, EUCLID,…*

The Canada France Hawaii Telescope (Mauna Kea)

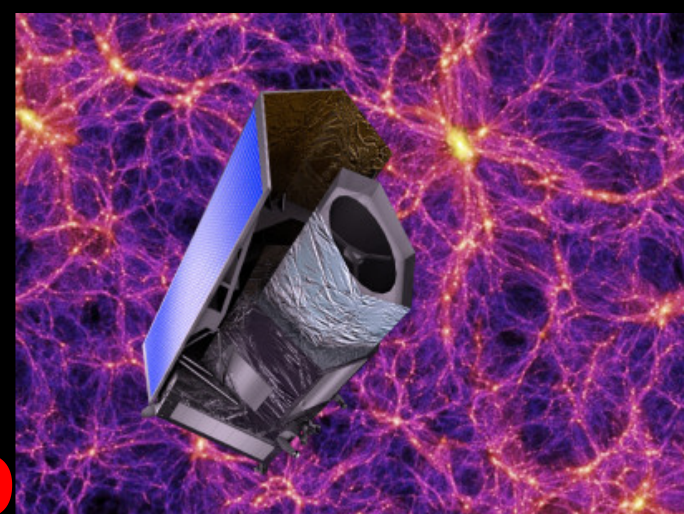
Major Development: Advent of Large, Overlapping Surveys

SuMIRe: *Subaru Measurement of Images and Redshifts (1500 deg^2)*

8.2 m Subaru telescope

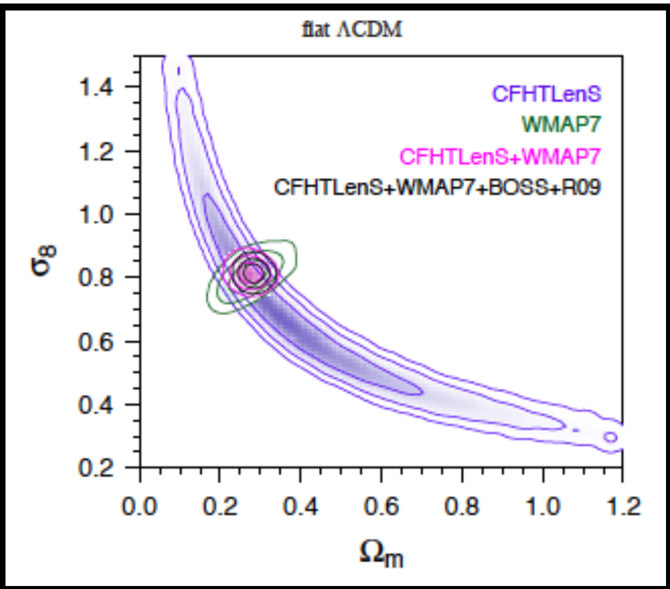
- Hyper Suprime Cam (HSC) lensing survey
- Prime Focus Spectrograph (PFS) redshift survey

WFIRST



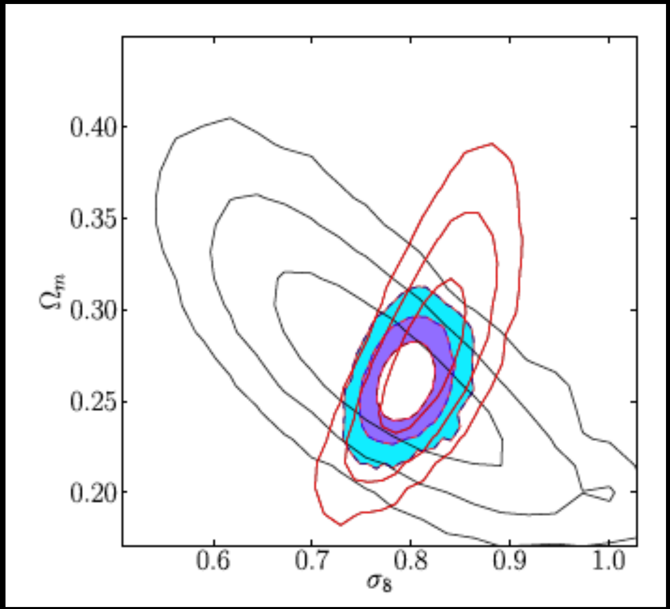
EUCLID

- How much improvement when Weak Lensing and Galaxy Clustering combined?



Kilbinger et al 2012 (***CFHTLS***)

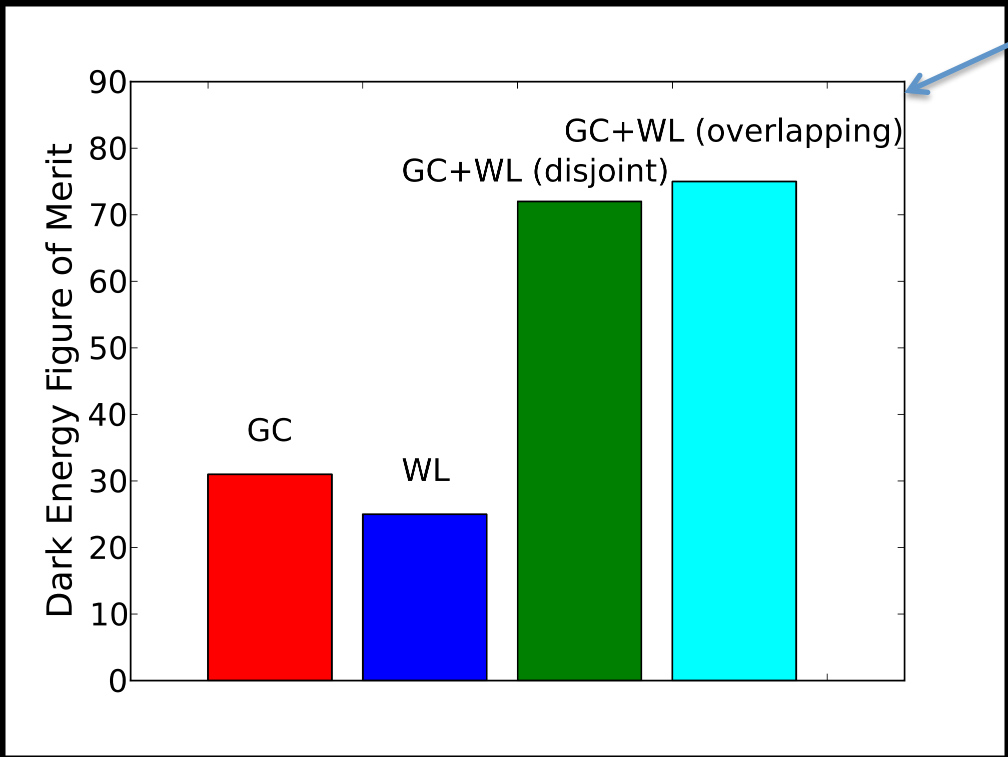
- How important is overlap between surveys?



Mandelbaum et al 2013 (***SDSS***)

SuMIRe ***Dark Energy:*** Strong WL + GC complementarity, but overlap not crucial

$$\mathrm{FOM} = (\mathrm{Det}(\mathrm{Cov}[w_0, w_a]))^{-\frac{1}{2}}$$



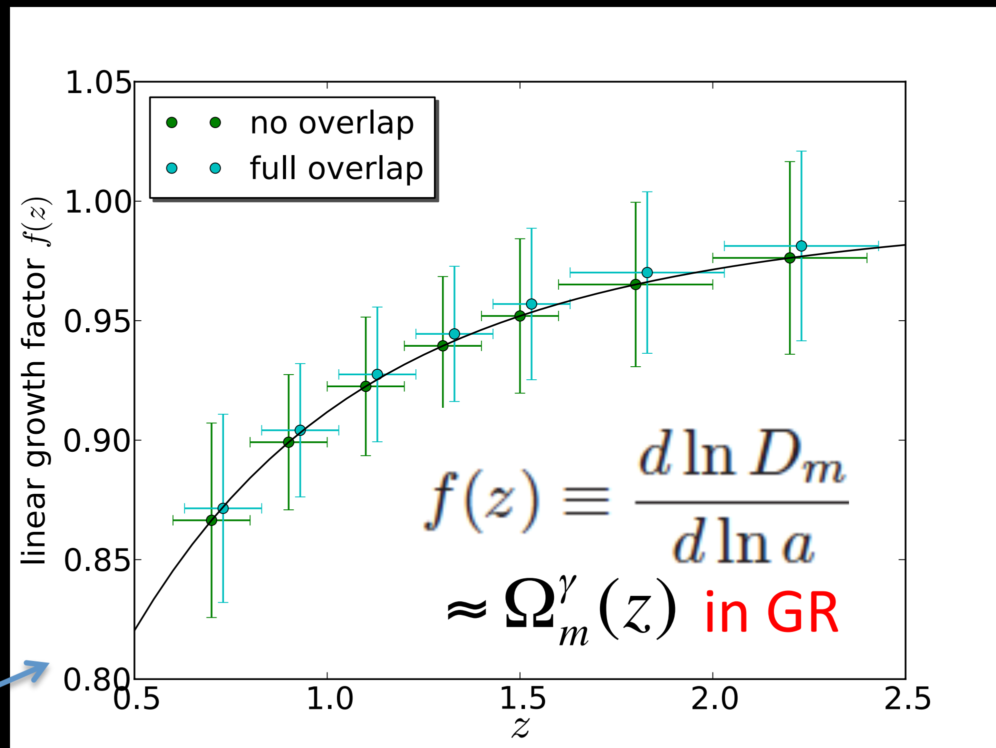
Tight bounds on time-varying DE equation of state

CMB prior (Planck) included

RdP, Dore & Takada 2013

SuMIRe growth rate: Strong WL + GC complementarity, but overlap not crucial

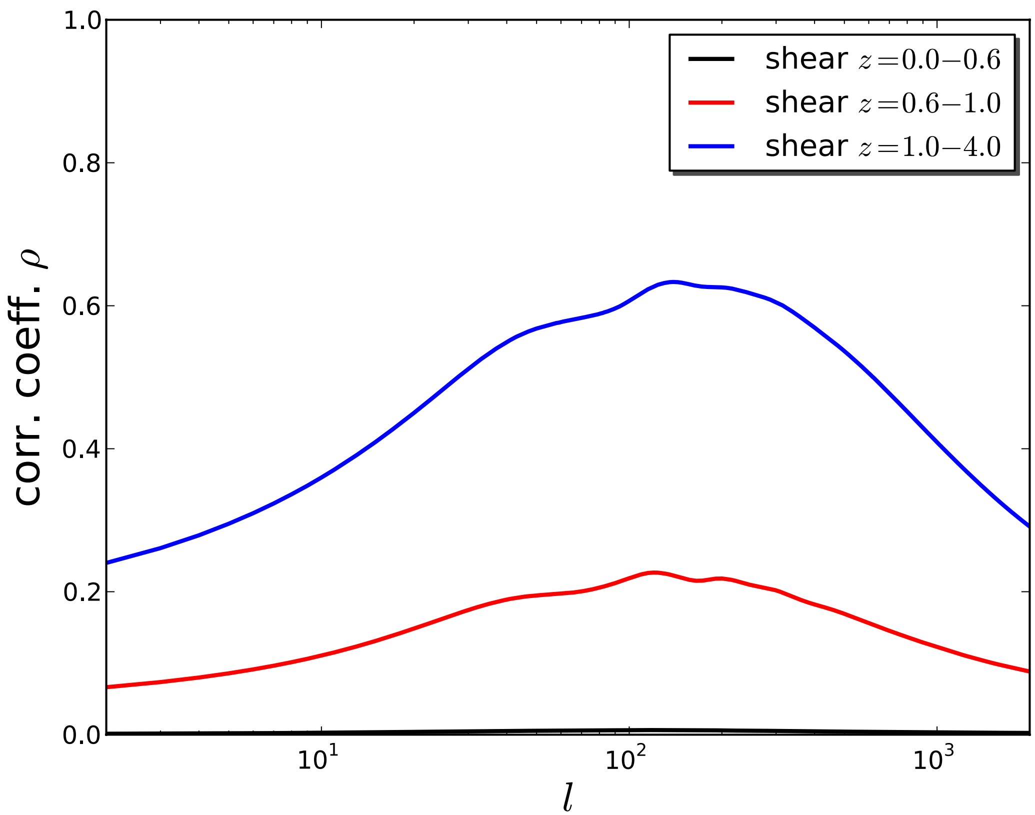
CMB prior (Planck) included



Bounds on growth rate of large scale structure
Combination of WL + GC crucial!

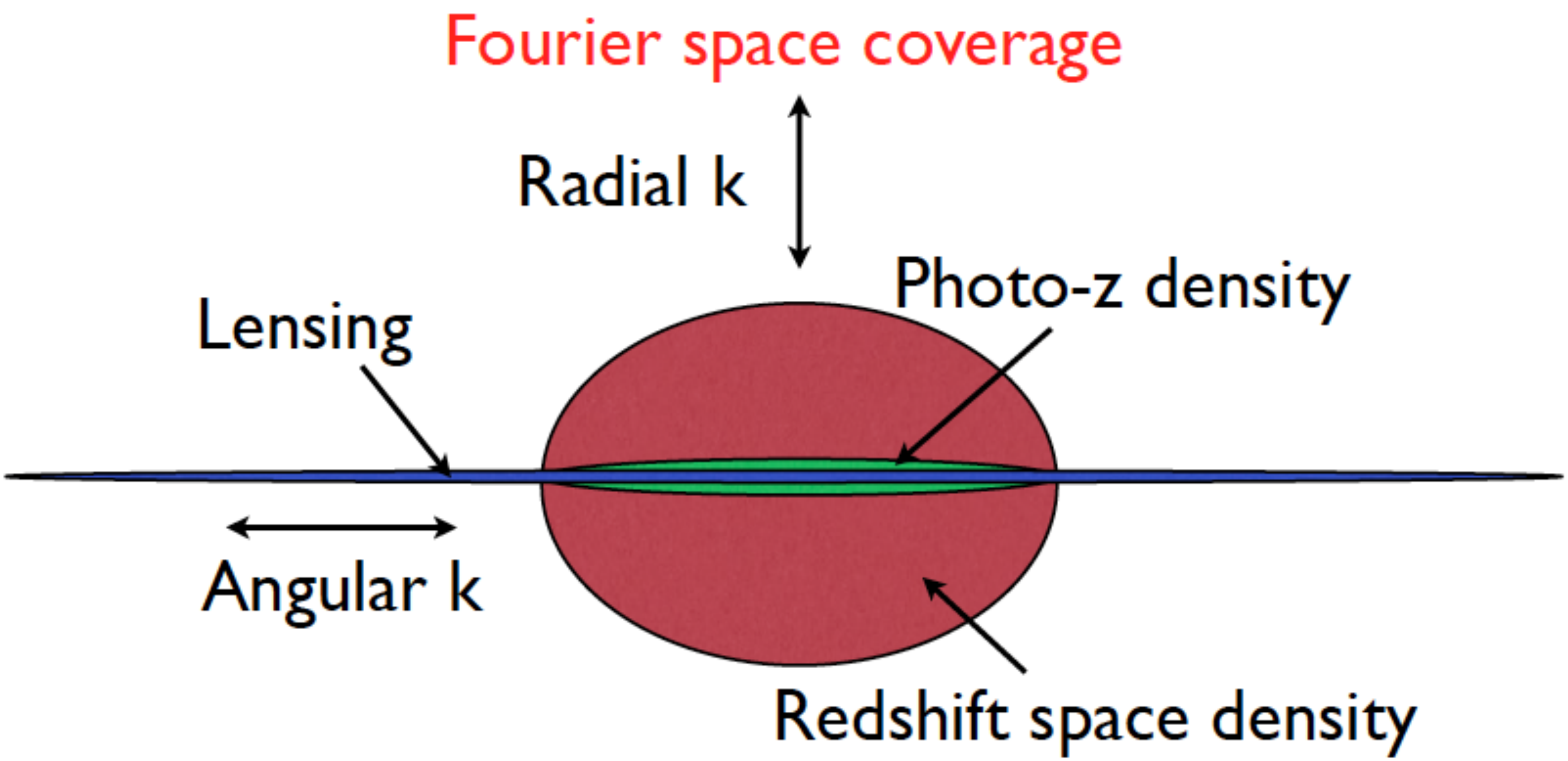
RdP, Dore & Takada 2013

Correlation between shear and galaxy density is modest because of limited redshift overlap



"global correlation coefficient" of shear with spectroscopic galaxy density

The number of modes probed by cross-correlations is small compared to that probed my RSD or WL alone



Font-Ribera et al, 2014

Cosmological information in shear-galaxy cross power spectra is limited, but other "same-sky" benefits do exist

See also: Cai & Bernstein 2012, Font-Ribera et al 2013
BUT: Gaztanaga 2012, Kirk et al 2013

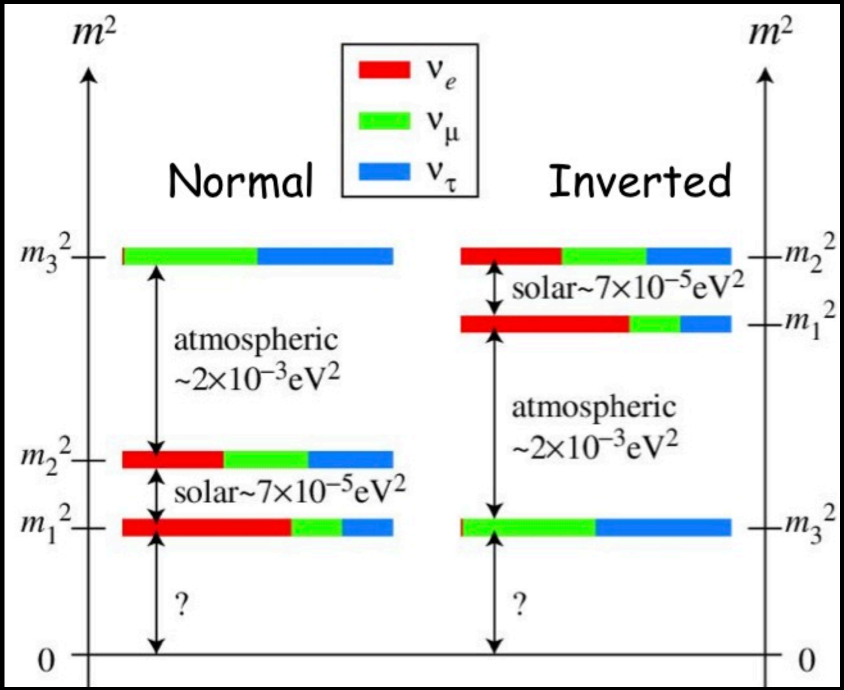
- *imaging survey provides target catalog*
- *information from non-linear regime*

Hikage, Takada & Spergel 2011
Yoo & Seljak 2012
Hikage et al 2013
Cacciato et al 2013

- *higher order statistics*
- *Identifying/constraining systematics*

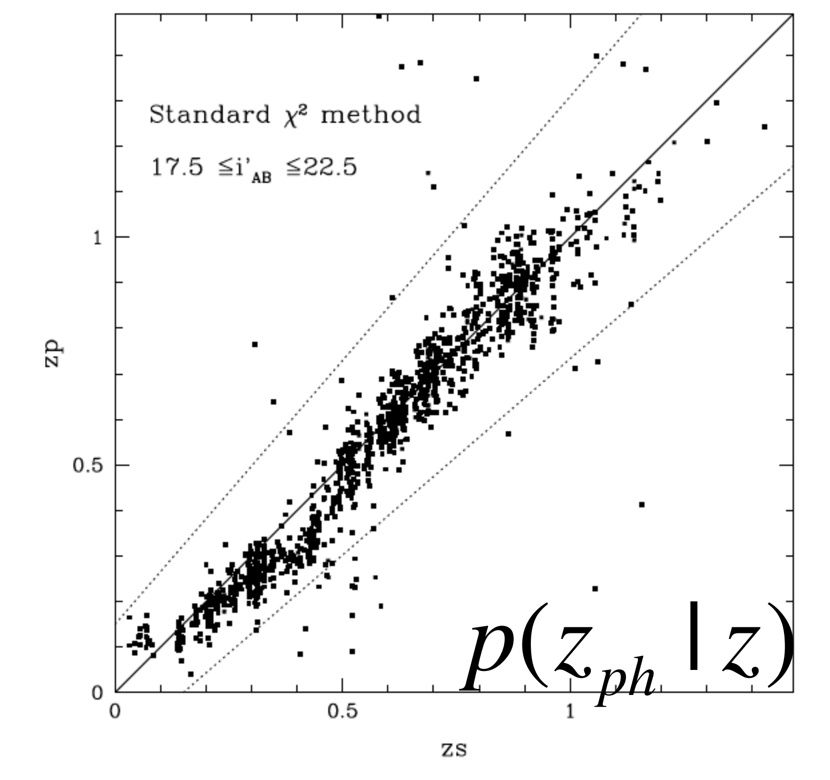
Neutrino mass detection should be possible with EUCLID (and DESI)

- *$\sigma(\Sigma m_\nu) = 0.03$ eV*



Upcoming cosmic shear surveys require < 1 % level calibration of photometric redshifts

Huterer et al 2005; Ma, Hu & Huterer 2005; etc



Ilbert et al 2006

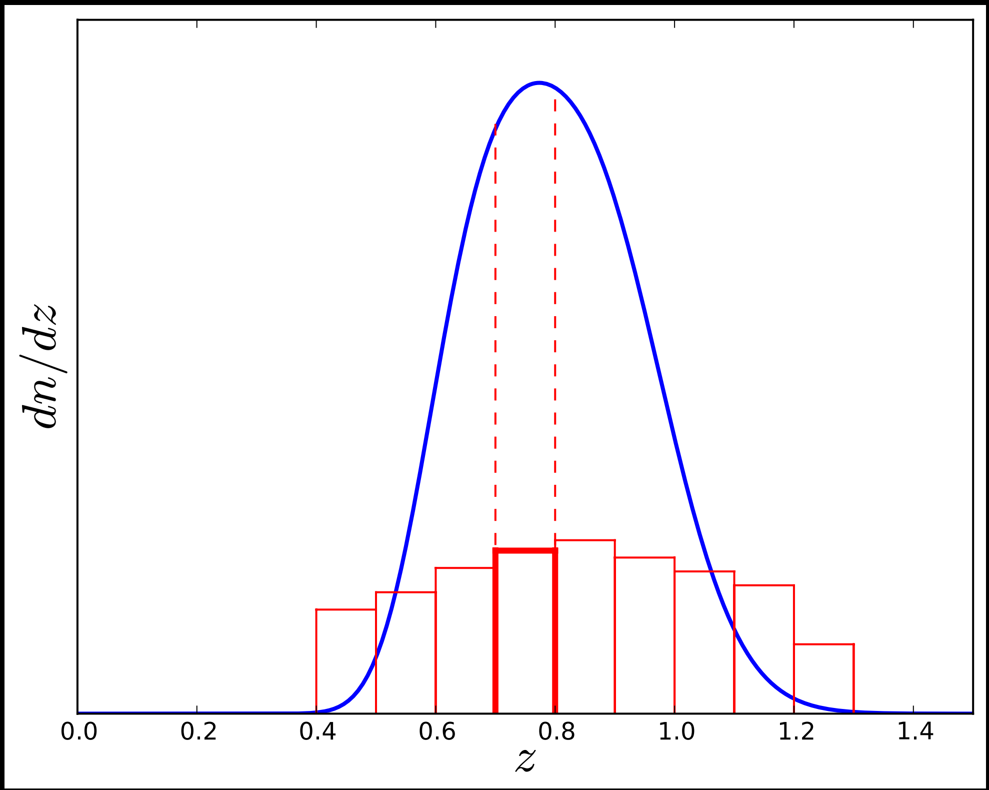
In forecasts, distribution defined by scatter $\sigma_z(z)$ and bias $b_z(z)$:

$$p(z_{\rm ph}|z) = \frac{1}{\sqrt{2\pi}\sigma_z(z)} e^{-\frac{1}{2}(z_{\rm ph}-z-b_z(z))/\sigma_z^2(z)}$$

See, e.g. *Ma, Hu & Huterer (2006), Huterer et al (2006), Ma & Bernstein (2008), Hearin et al (2010)*

(Source) redshift distributions can be estimated using cross-correlations with overlapping spectroscopic sample

Newman 2008, Schulz 2010, Matthews & Newman 2010, McQuinn & White 2013, Menard et al 2013, Rahman et al 2014



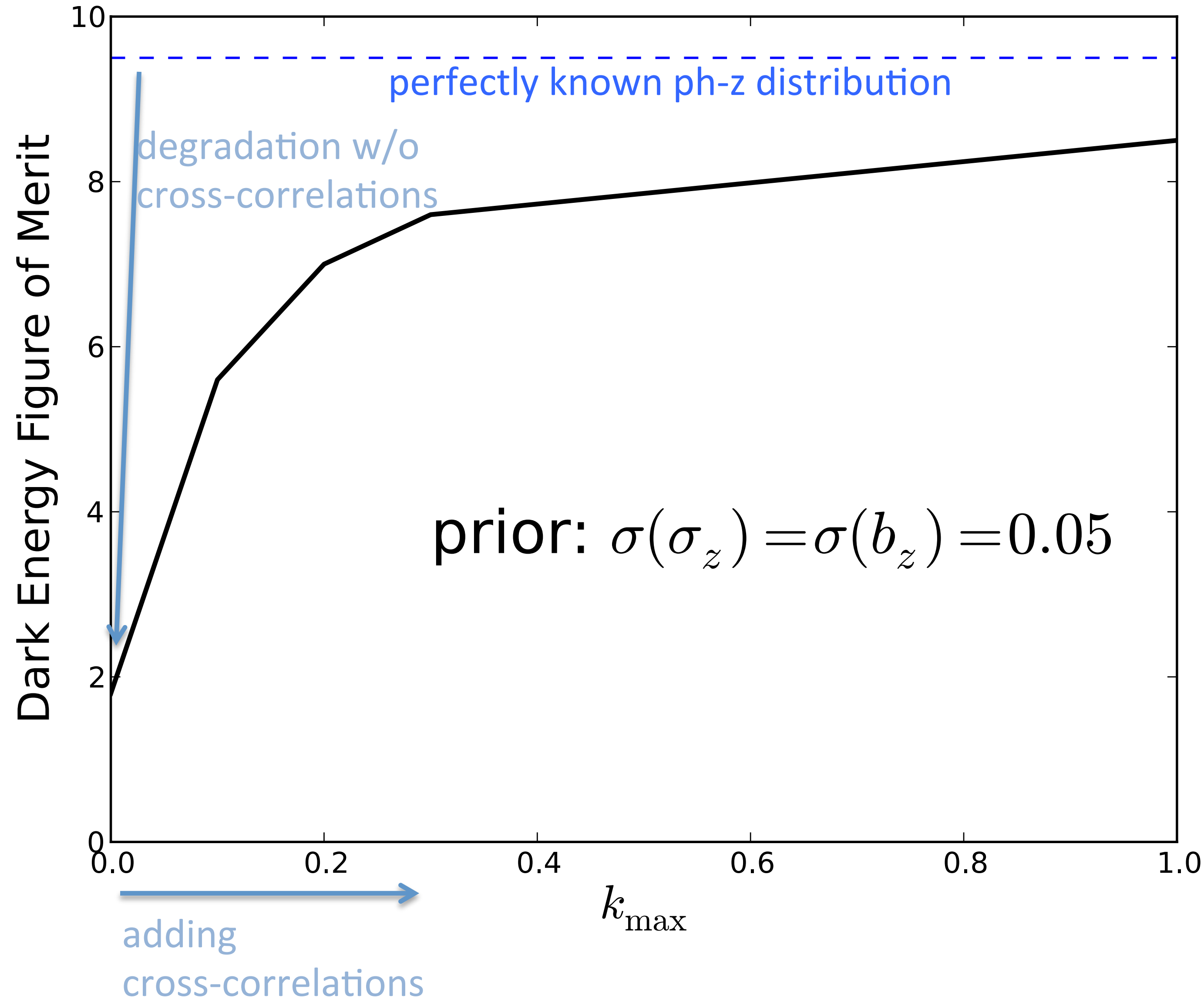
BUT: *Redshift distribution reconstruction crucially relies on knowledge of galaxy bias evolution* (***< 10 % needed***)

$$C_\ell^{ps_i} \propto b^{(s)}(z_i)\, b^{(p)}(z_i)\, \overline{n}^p(z_i)\, P(\ell / D_i)$$

Can cross-correlations technique improve cosmic shear constraints by calibrating photo-z distribution?

de Putter, Dore & Das 2013

Cross-correlations can partially restore *HSC* cosmic shear information lost due to poorly calibrated photo-z's



Cross-correlation technique looks promising, but major challenges remain

- *Breaking the n(z) – galaxy bias degeneracy*
- *Dealing with outliers/distributions beyond Gaussian*
- *Non-linear bias*
- *Confusion with magnification bias*
- *etc*

Part 3

- Neutrino mass constraints and the primordial power spectrum

- Combining weak lensing and galaxy clustering to probe dark energy, gravity and neutrinos

- *Primordial non-Gaussianity from LSS: what does an ideal experiment look like?*

Primordial (non-)Gaussianity provides crucial information on physics of inflation

$$P(k) \to P(k), \quad B(k_1,k_2,k_3) = \left\langle \Phi(\vec{k}_1)\Phi(\vec{k}_2)\Phi(\vec{k}_3) \right\rangle, \ \ldots$$

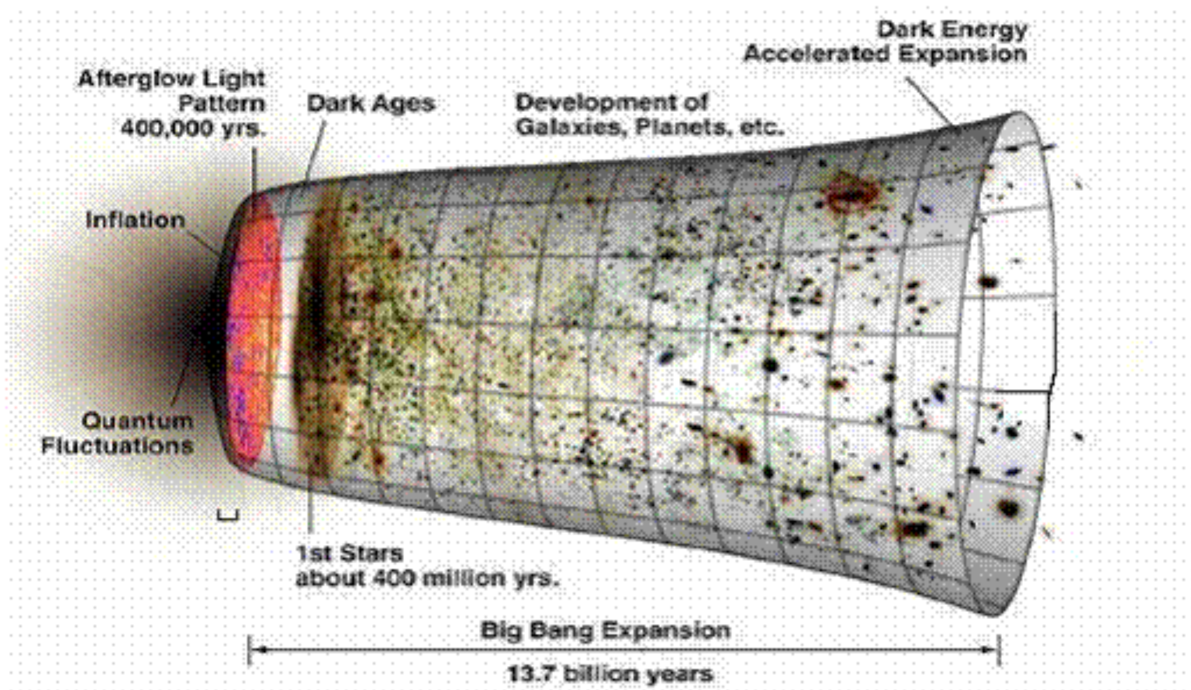
bispectrum

Local non-Gaussianity:

$$\Phi(\vec{x}) = \Phi_G(\vec{x}) + f_{NL}^{loc}\left(\Phi_G^2(\vec{x}) - \left\langle \Phi_G^2(\vec{x}) \right\rangle\right)$$

<u>*Planck bispectrum:*</u>

f_{NL} = 2.7 +/- 5.8 (1sigma)



Constraining primordial non-Gaussianity to $\sigma(f_{NL}) \sim 1$

Why constrain PNG further?

- Single-field inflation consistency relation:

"squeezed limit" $f_{NL} \sim (1 - n_s) \sim$ few %

- Lots of model space to be explored:

multi-field, non-standard vacuum, non-canonical kinetic terms, etc

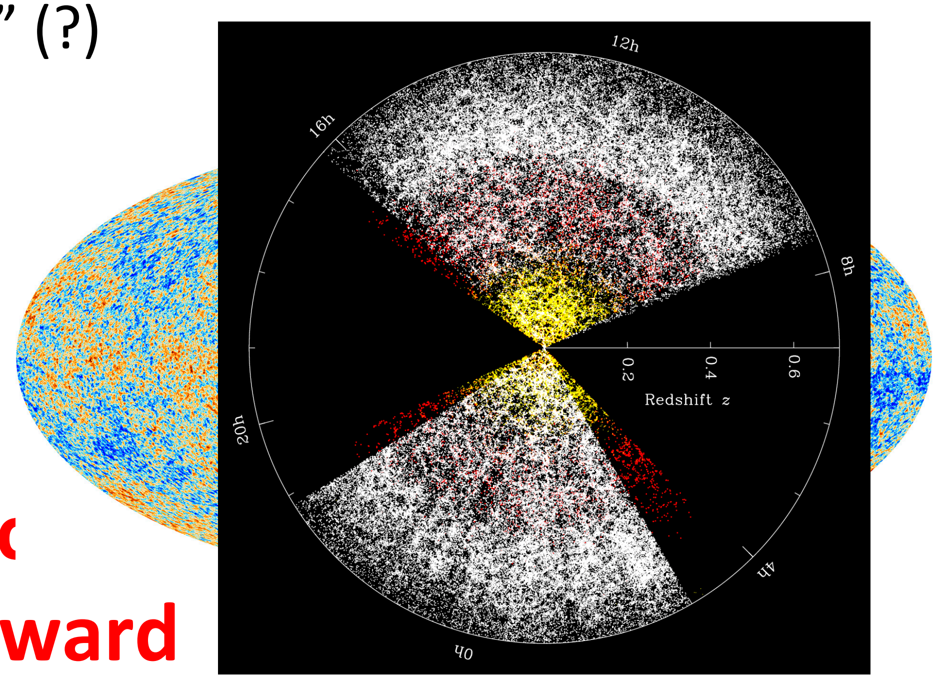
- Order unity f_{NL} from "GR effects" (?)

Cosmic Microwave Background

Planck temperature: $\sigma(f_{NL}) = 5.8$
→ $\sigma(f_{NL}) \sim 3$
(CV limited temperature and polarization)

Need Large Scale Struc

to move forward



Primordial non-Gaussianity leads to scale-dependent halo bias

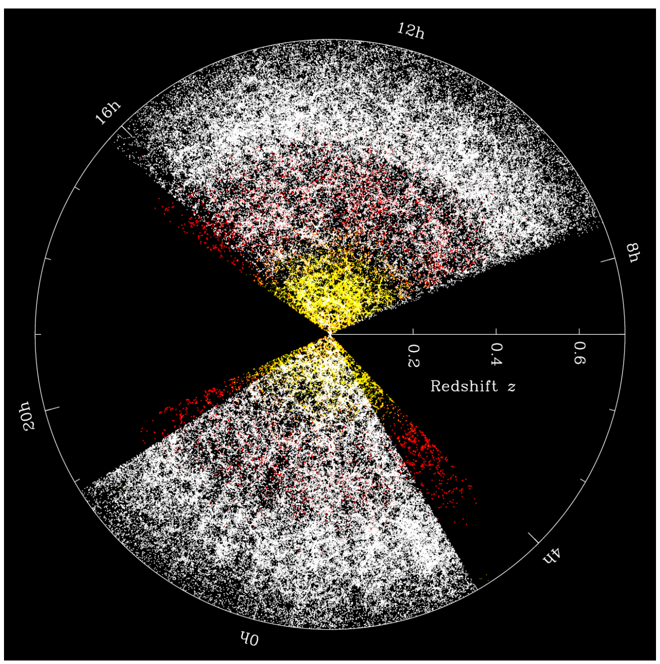
Dalal, Doré, Huterer & Shirokov 2008

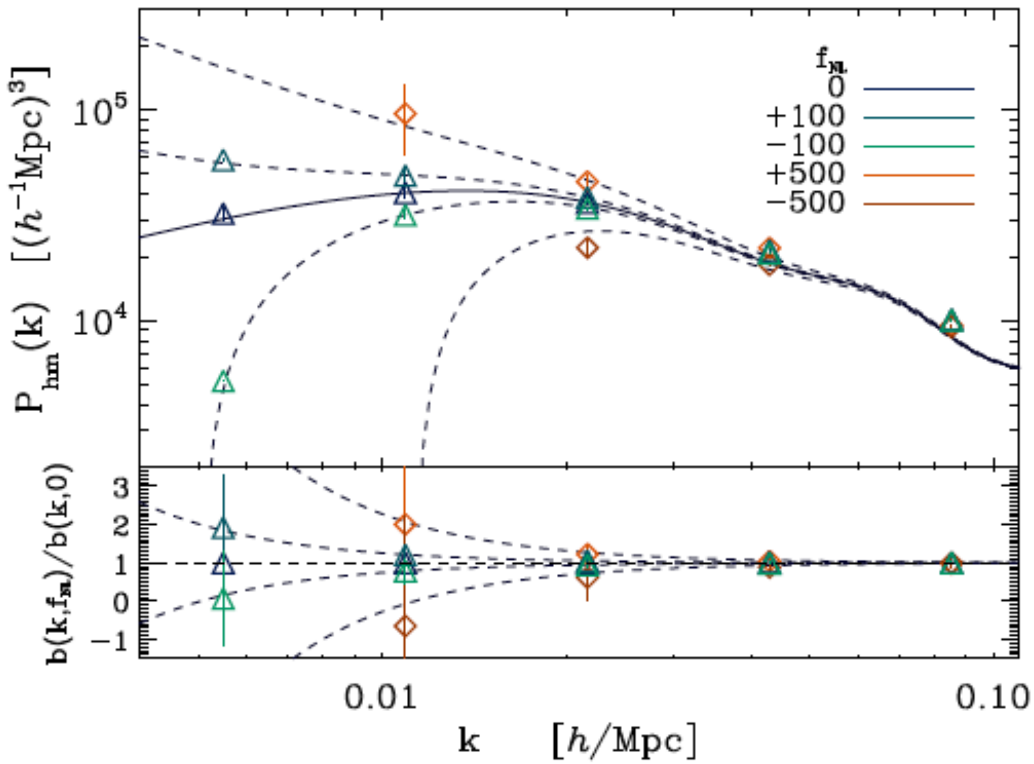
$$\Delta b = 2 f_{NL}(b-1)\delta_c \frac{3\Omega_m H_0^2}{k^2 T(k) D(z)}$$

Current bounds:

e.g. $f_{NL} = 5 \pm 21$

Giannantonio et al 2014





Can evade cosmic variance with multitracer technique

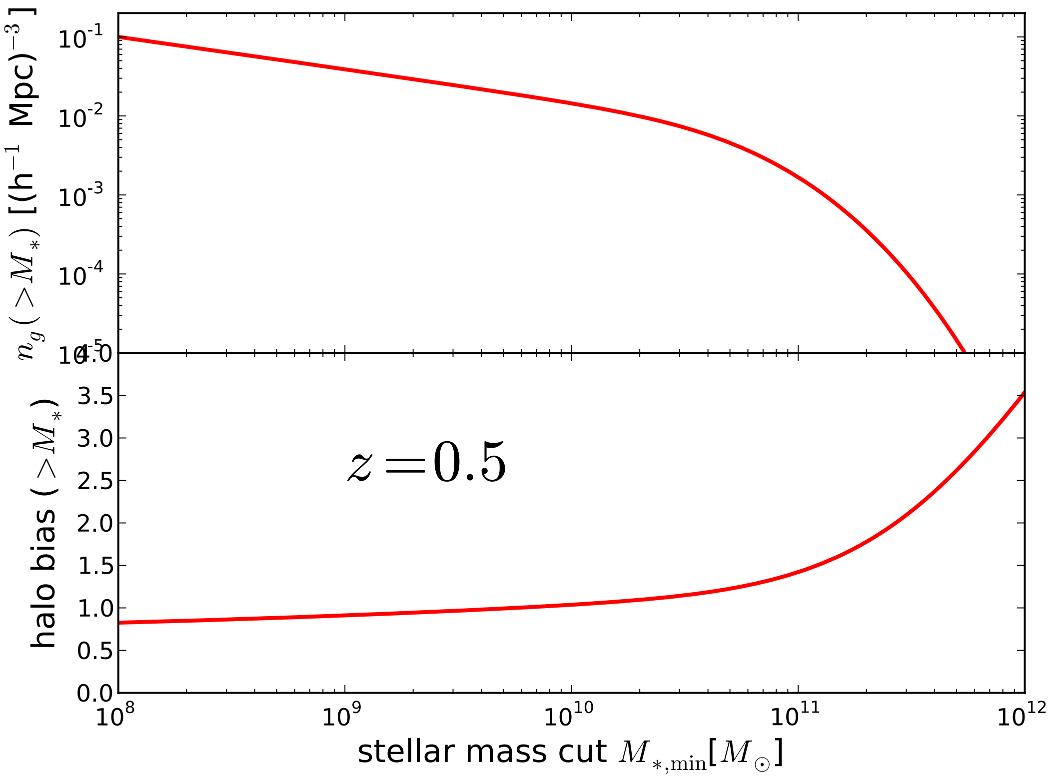
e.g. Seljak 2009

Optimizing a galaxy survey for f_{NL}

See also very recent studies: Ferraro & Smith, Raccanelli et al, Yamauchi et al, Camera et al

<u>What is dependence on:</u>

1. *Number density?*
2. *Survey volume?*
3. *Redshift accuracy?*

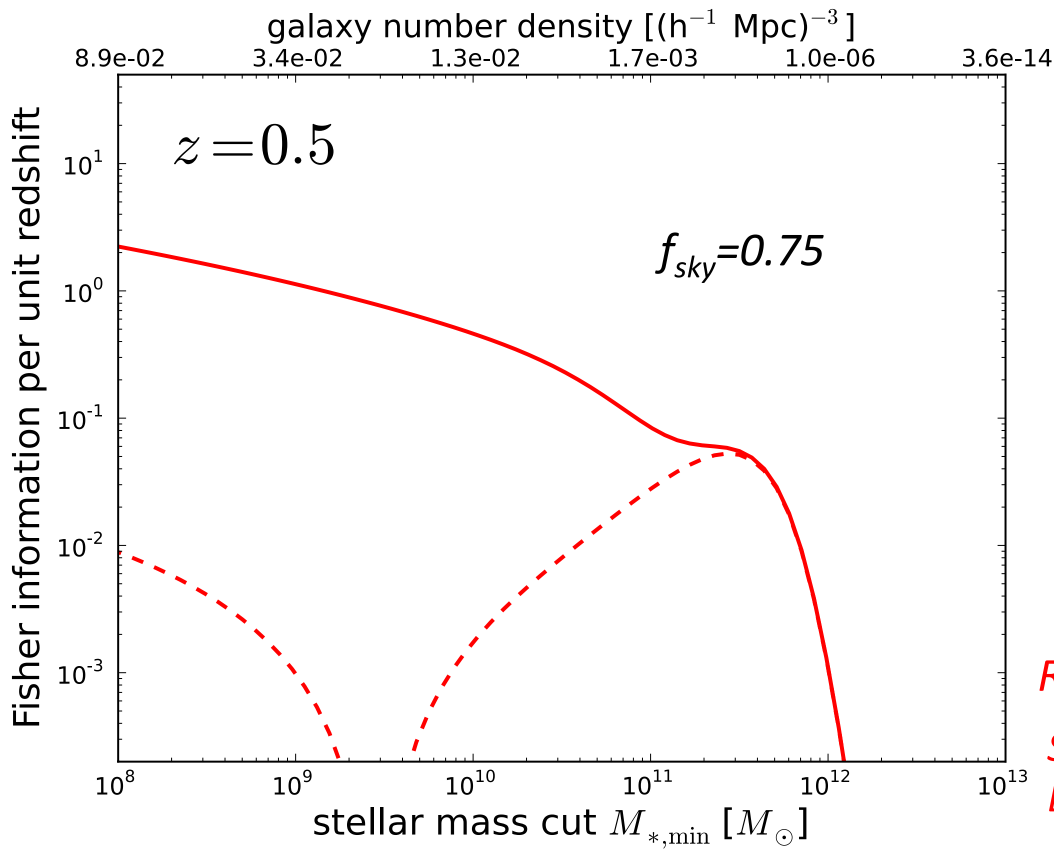


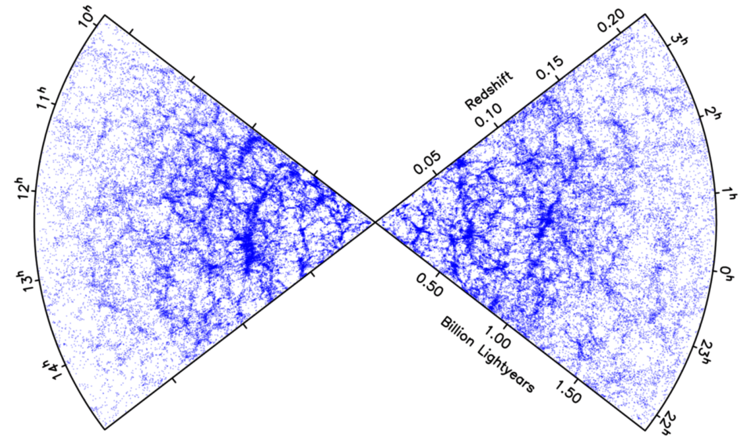
Galaxy sample defined in terms of stellar mass cuts

RdP & Doré in prep

Optimizing a galaxy survey for f_{NL}

1. Number density





RdP & Doré in prep

See also Hamaus, Seljak & Desjacques 2011

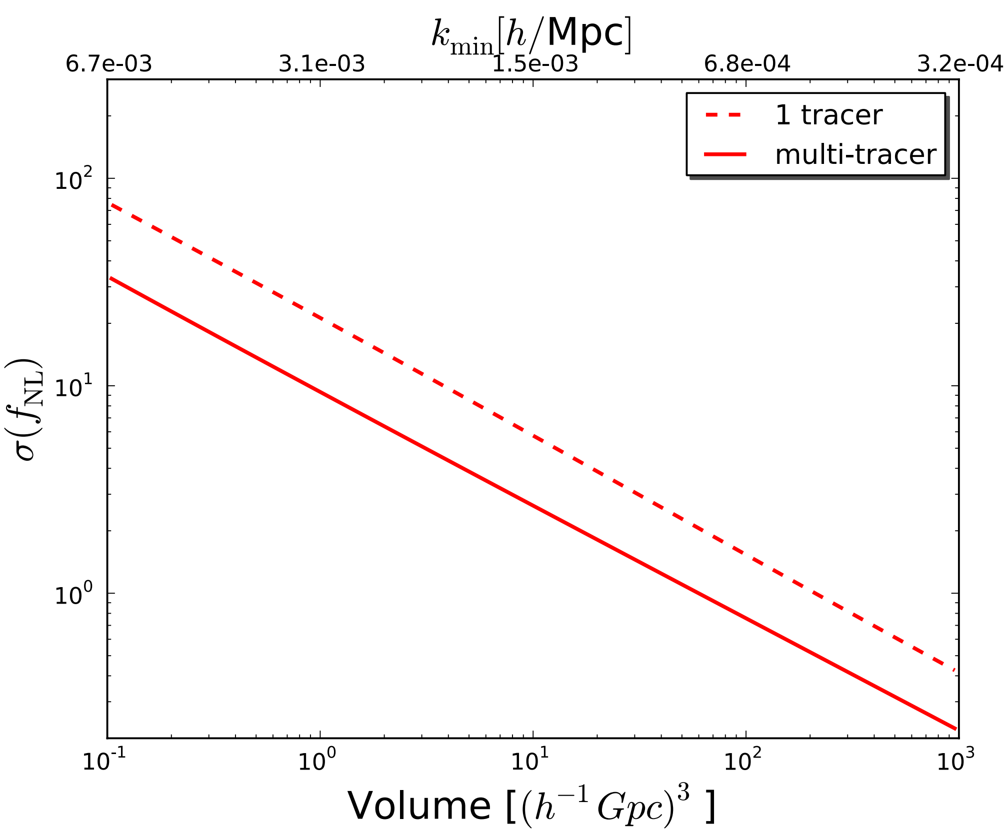
- *Single tracer:* need moderate number density

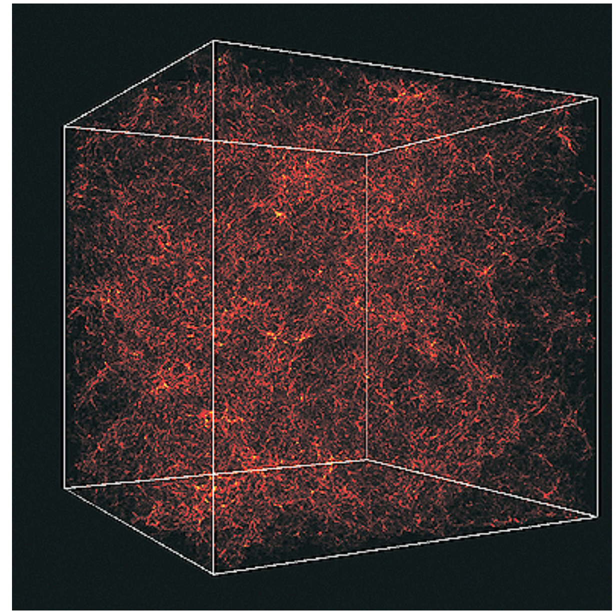
n = few 10^{-4} (h^{-1} Mpc)$^{-3}$ (n P ~ 1)

- *Multitracer:* need large number density, ***n = few 10^{-3} (h^{-1} Mpc)$^{-3}$***

Optimizing a galaxy survey for f_{NL}

2. Survey volume



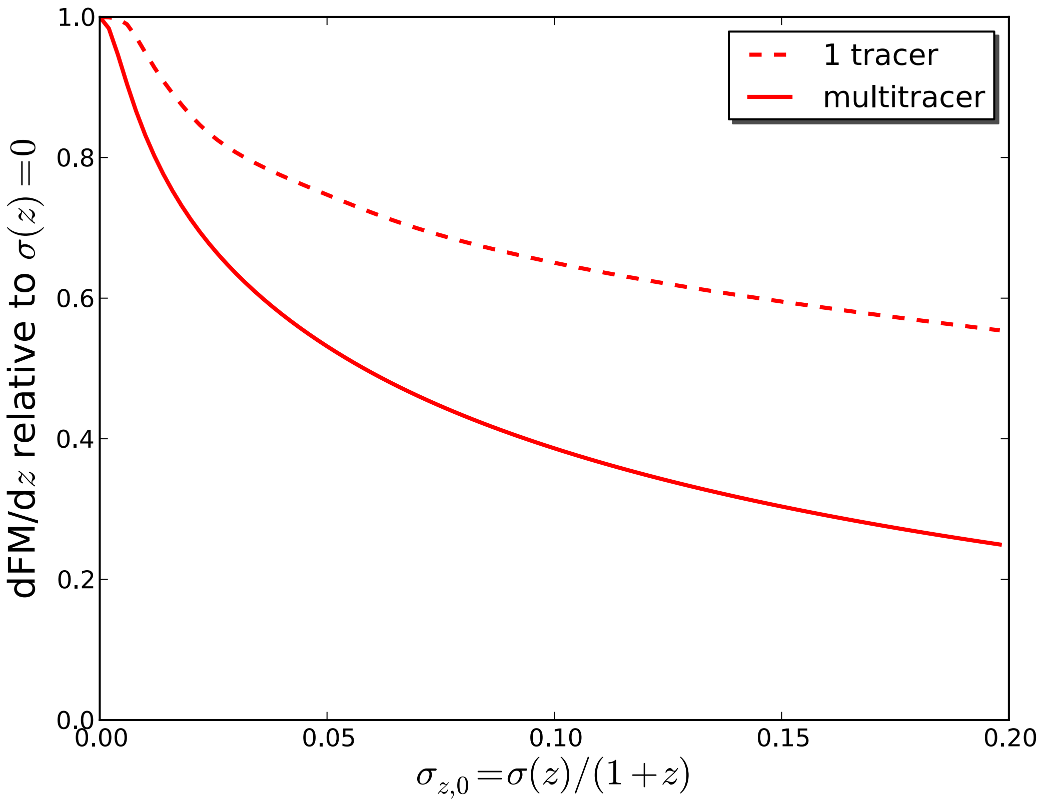


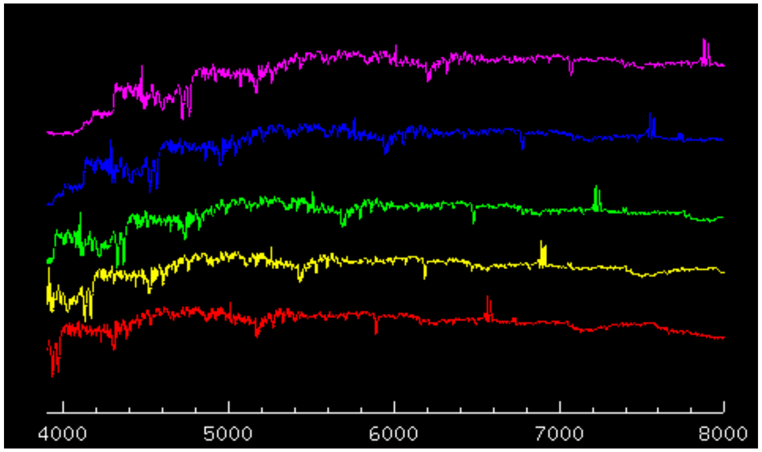
RdP & Doré in prep

- *Single tracer:* need ***V = many 100's $(h^{-1}$ Gpc$)^{-3}$*** for ***$\sigma(f_{NL})$~1***
- *Multitracer:* need ***V ~ 100 $(h^{-1}$ Gpc$)^{-3}$*** for ***$\sigma(f_{NL})$~1***

Optimizing a galaxy survey for f_{NL}

3. Redshift accuracy

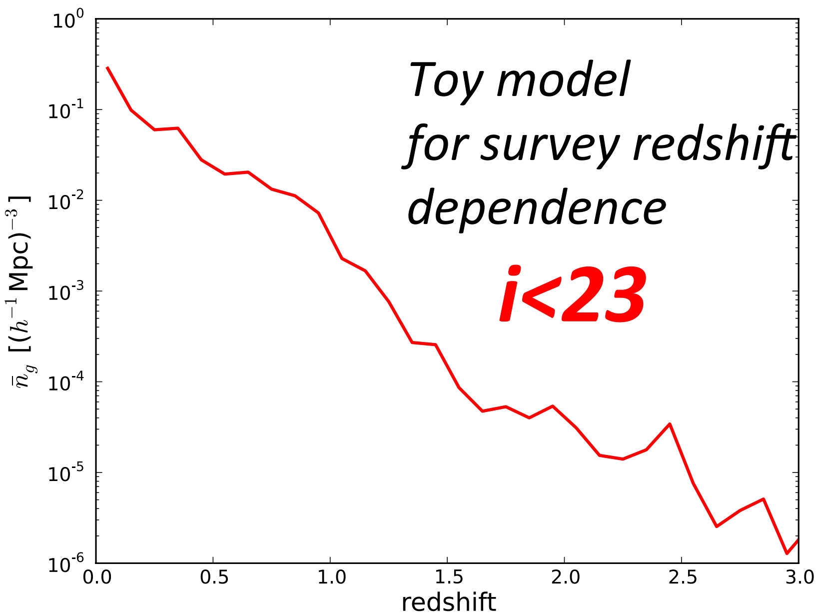


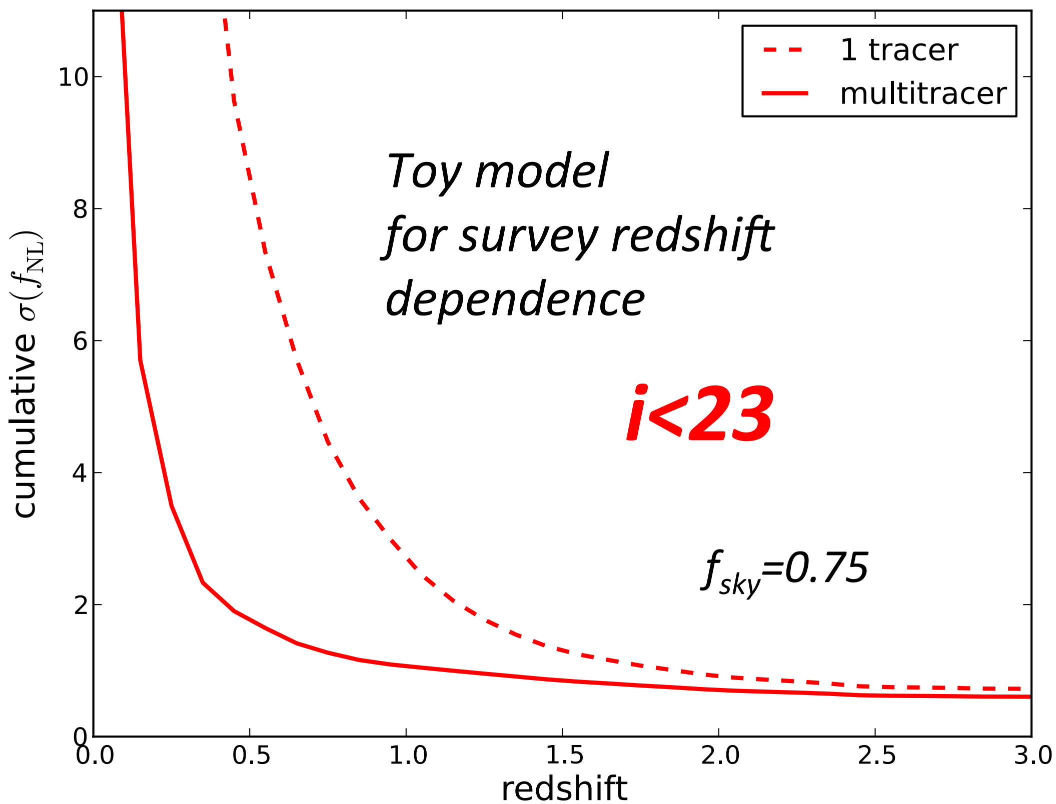


RdP & Doré in prep

- *High redshift accuracy NOT needed*
- *Even σ(z)=0.10 * (1+z) tolerable*

A large-area, multi-band imaging survey would be an ideal f_{NL} experiment





<u>2 regimes:</u>

- Low redshift (*z* ~< *1*), **multi-tracer**
- High redshift (*z* ~> *1*), **single tracer**

Summary/Conclusions

- *Robust joint constraints on neutrino mass and inflation can be obtained using complementary current data sets*

- *Combining Weak Lensing and Galaxy Clustering will improve DE FOM by factor 2-3 compared to either probe alone and will lead to strong cosmic growth constraints*

- *Cross-correlations between WL and GC surveys add limited direct cosmological information, but are crucial for constraining systematics such as photo-z calibration*

- ***SPHEREx: measuring the near-IR spectrum of the full sky. A space-based galaxy survey to constrain primordial non-Gaussianity to $\sigma(f_{NL})$~1***