Cosmic Complementarity:

constraining neutrinos, dark energy & gravity

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IPMU Seminar 5/1/2014

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Outline

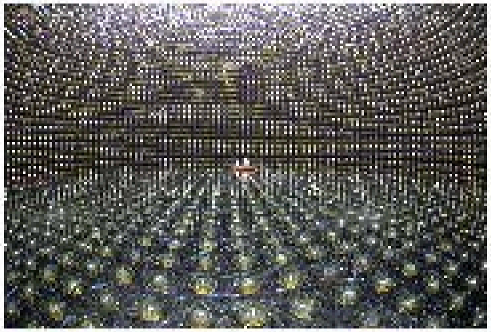
- Neutrino mass constraints and the primordial power spectrum

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

- Using cross-correlations to calibrate photometric redshifts in cosmic shear surveys

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) ➔ $\Sigma m_\nu < 6.2\ eV$

Troitsk Collaboration 2011

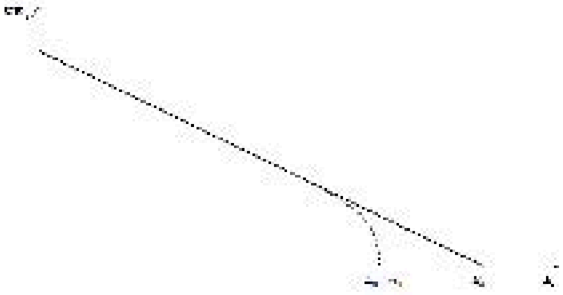
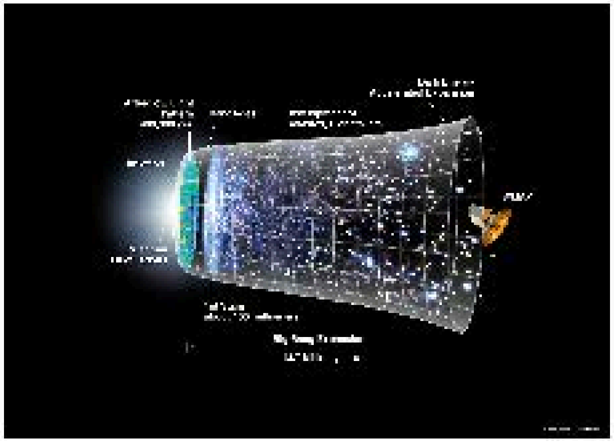


Figure 1: Kurie plots for $m_\nu = 0$ (solid line) and $m_\nu \neq 0$ (dashed line)

- ***COSMOLOGY***



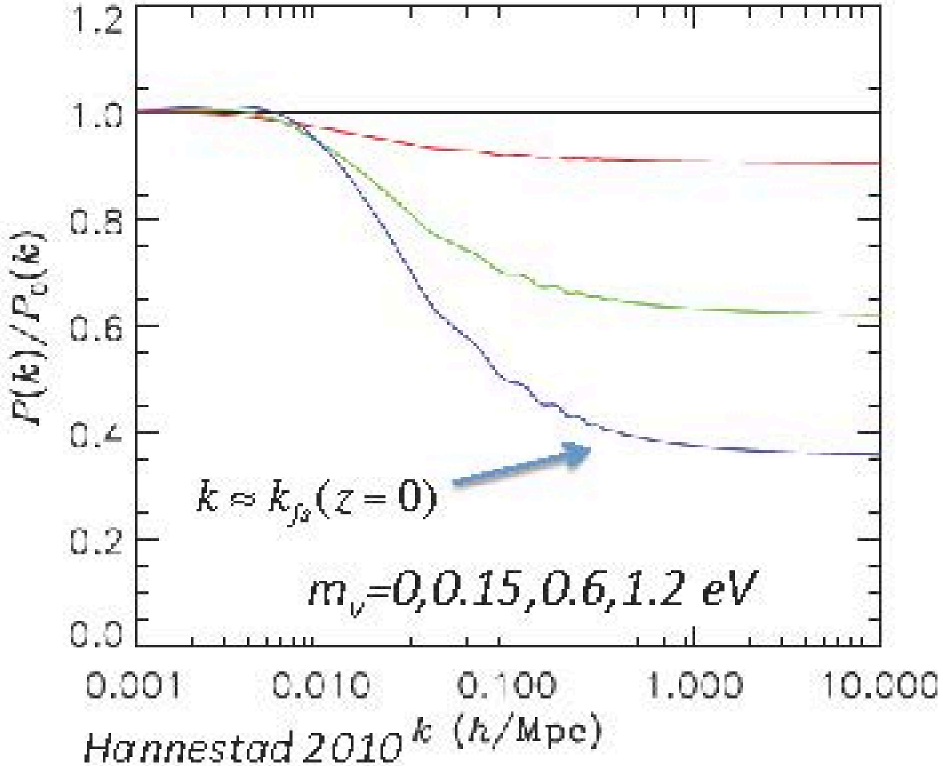
CNB affects cosmological observables through expansion history and growth of perturbations

1. Background Evolution:

- effect on cosmic distances, BAO, …

2. Growth of Structure:

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



$k \approx k_{fs}(z=0)$

m_ν=0,0.15,0.6,1.2 eV

Hannestad 2010

The strongest limits on Σm_ν come from cosmological data:

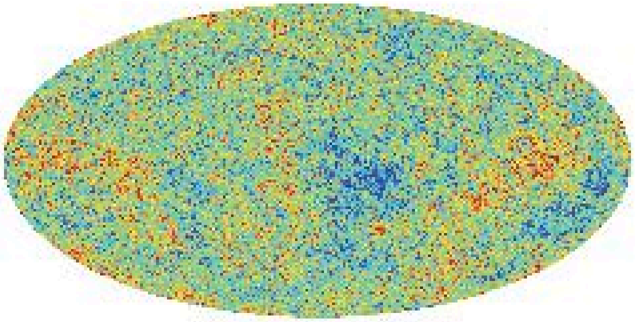
$\boldsymbol{\Sigma m_\nu}$ < 0.23 eV (95 % CL) from **Planck CMB + BAO**

Planck Collaboration XVI

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

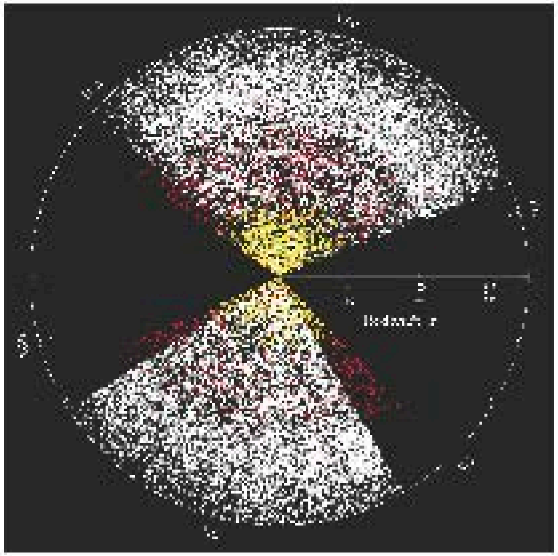
$$\Delta_R^2(k) = \Delta_R^2(k_0)\left(\frac{k}{k_0}\right)^{n_s - 1}$$

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



CMB anisotropies

$$C_\ell = \int d\ln k \; \underset{\substack{\uparrow \\ \text{transfer function}}}{W_\ell(k)} \; \underset{\substack{\nwarrow \\ \text{PPS}}}{\Delta^2_R(k)}$$



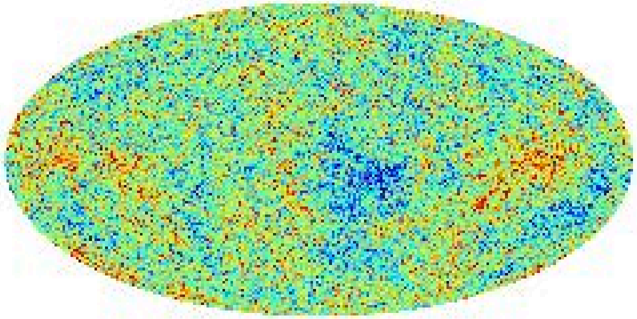
Galaxy Clustering

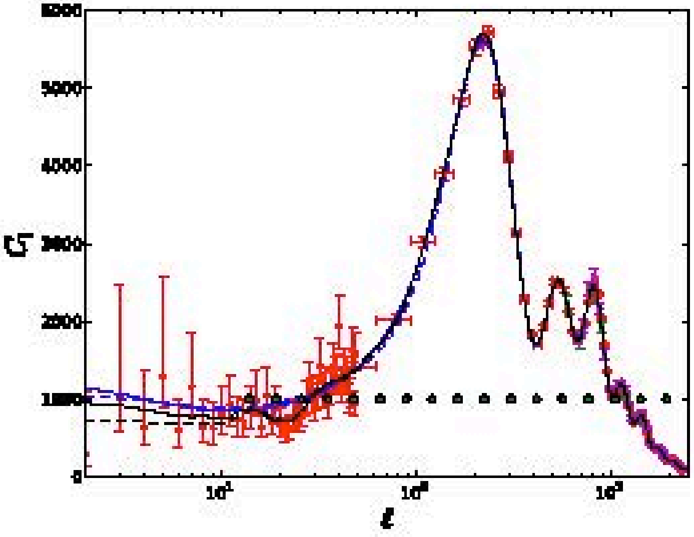
Agnostic approach: model the PPS by a 20-node spline at ***k = 0.001 – 0.35 Mpc^{-1}***

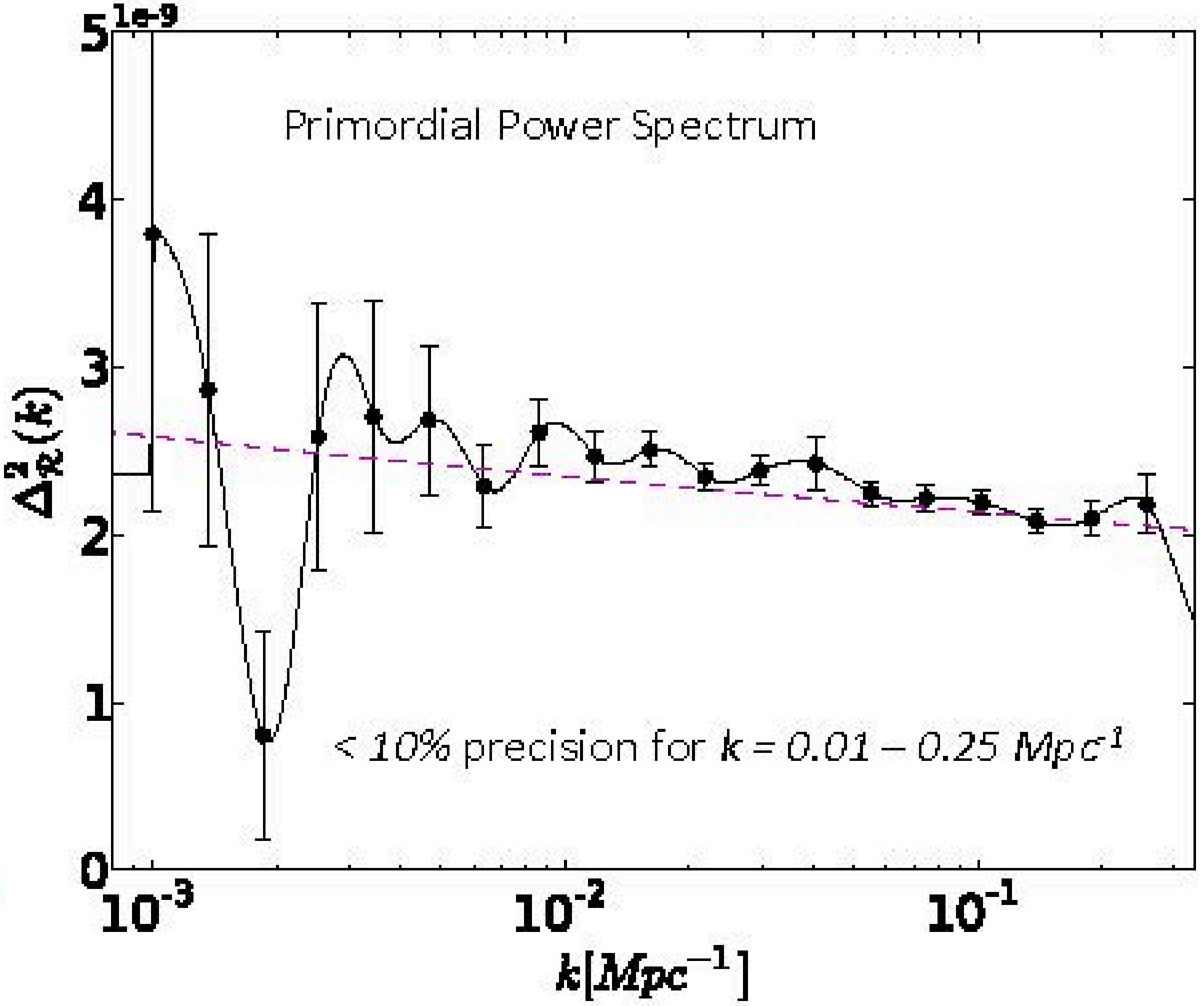
$$\Delta^2_R(k) = \Delta^2_{R,0} \cdot \mathrm{spline}[p\{k_i\}]$$

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

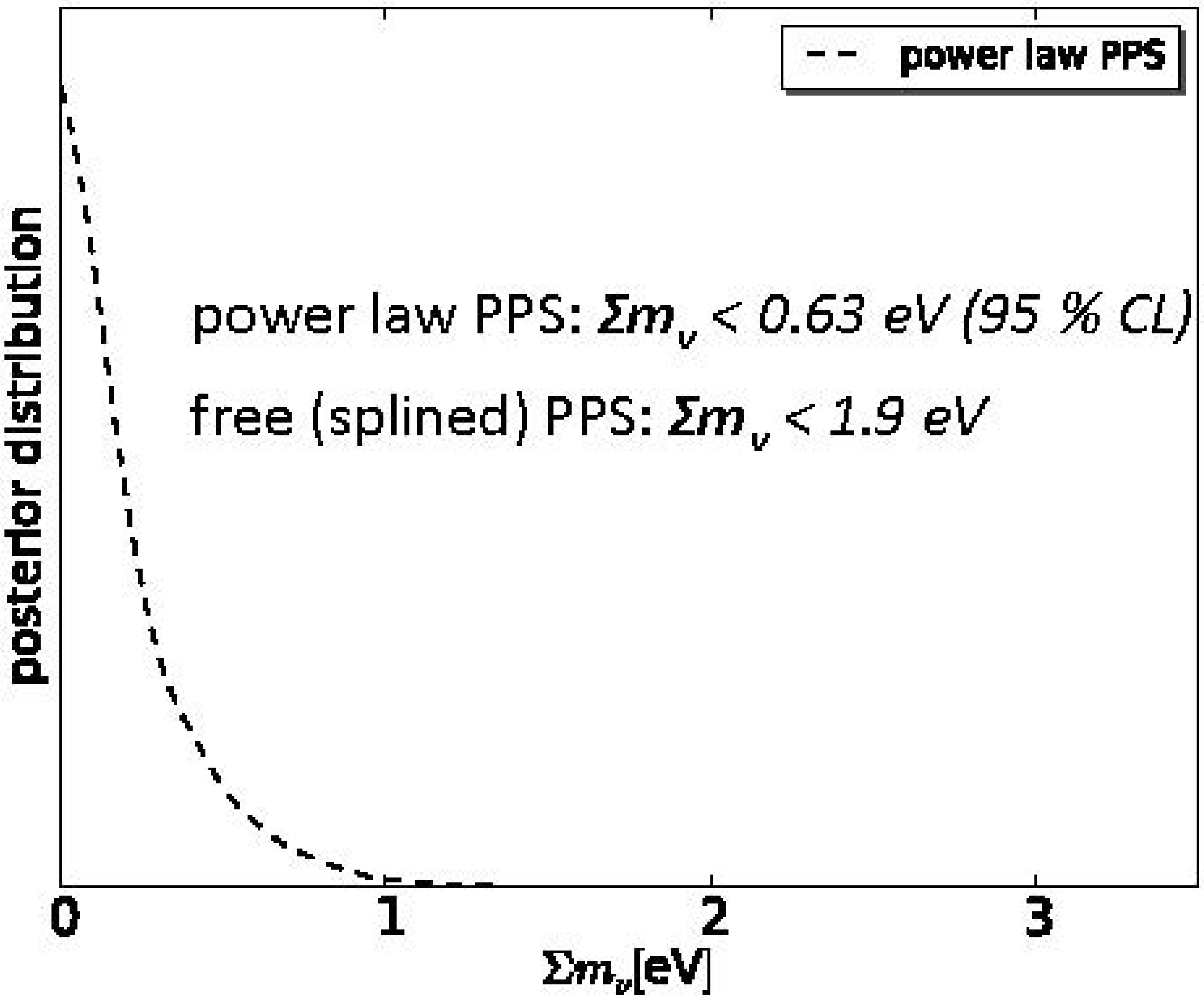
CMB data (Planck + SPT/ACT + WMAP Polarization) strongly constrain the primordial power spectrum







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

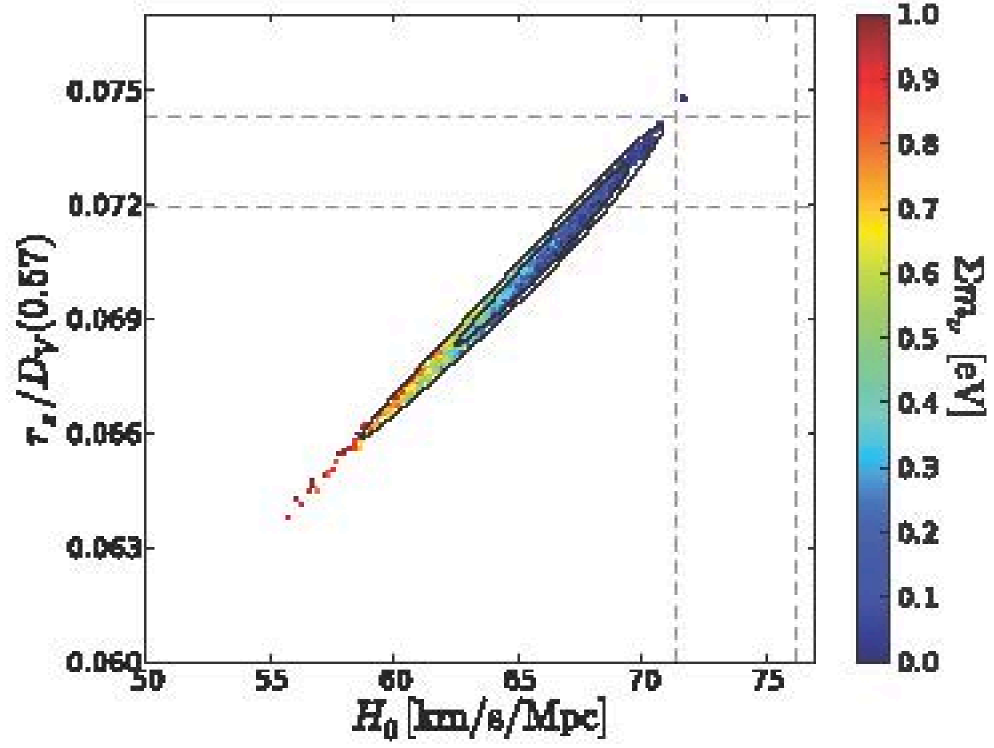


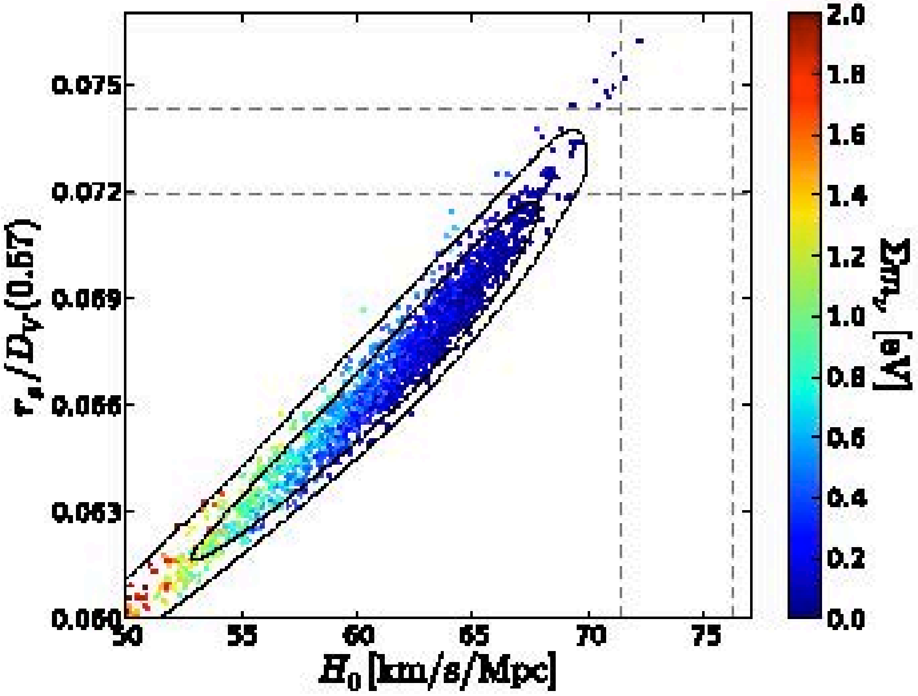
power law PPS: $\Sigma m_\nu < 0.63$ eV (95 % CL)

free (splined) PPS: $\Sigma m_\nu < 1.9$ eV

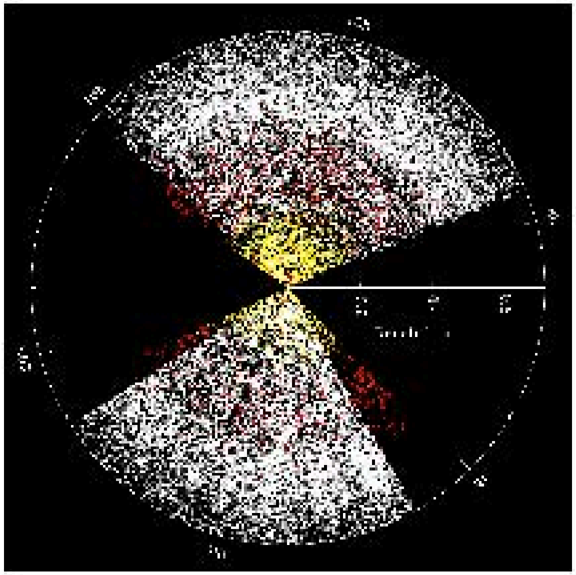
Adding low-redshift data breaks the degeneracy between "late-universe parameters" $\boldsymbol{\Sigma m_\nu}$ and $\boldsymbol{H_0}$

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



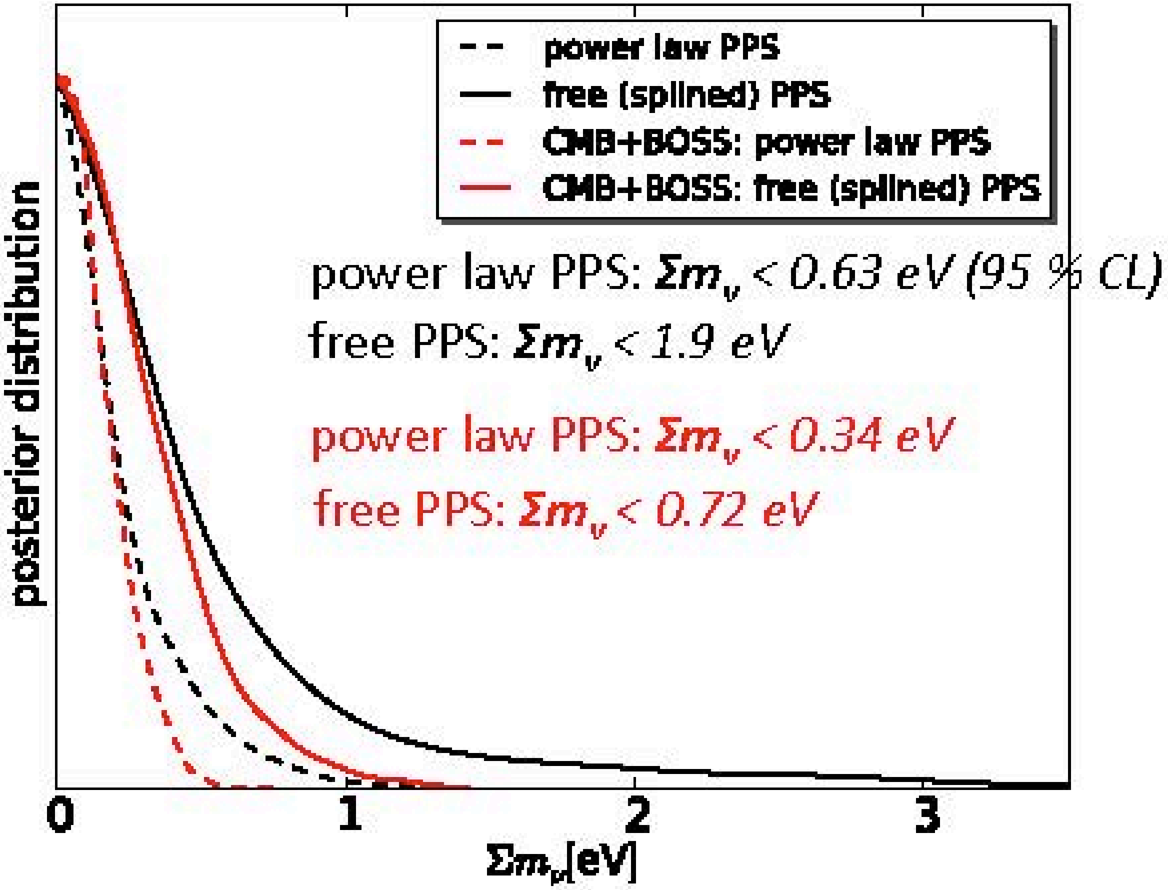

$r_s/D_V(0.57)$
0.075
0.072
0.069
0.066
0.063
0.060
50
55
60
65
70
75
H_0 [km/s/Mpc]
Σm_ν [eV]
2.0
1.8
1.6
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0

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



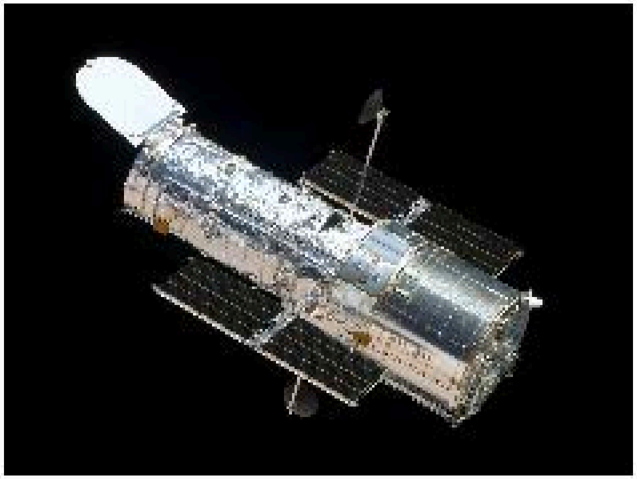
power law PPS: $\boldsymbol{\Sigma m_\nu} < 0.63$ *eV (95 % CL)*

free PPS: $\boldsymbol{\Sigma m_\nu} < 1.9$ *eV*

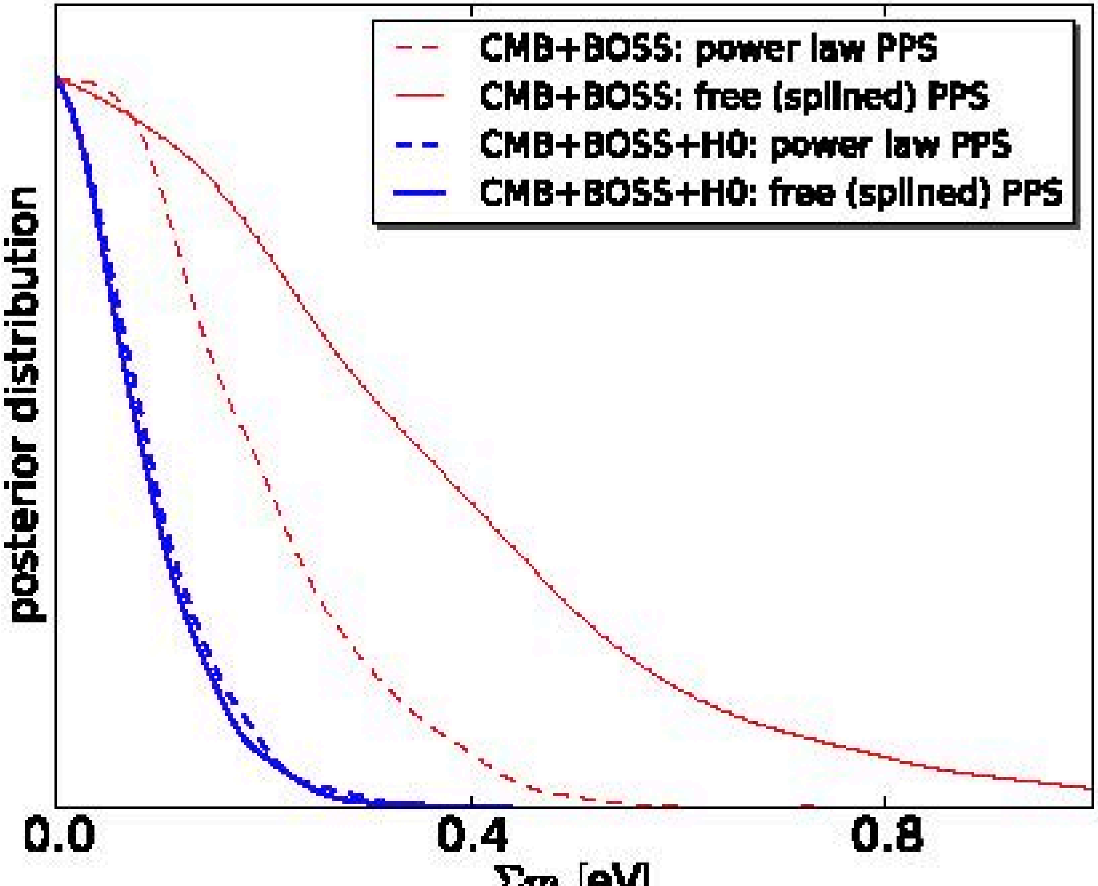
power law PPS: $\boldsymbol{\Sigma m_\nu} < 0.34$ *eV*

free PPS: $\boldsymbol{\Sigma m_\nu} < 0.72$ *eV*

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

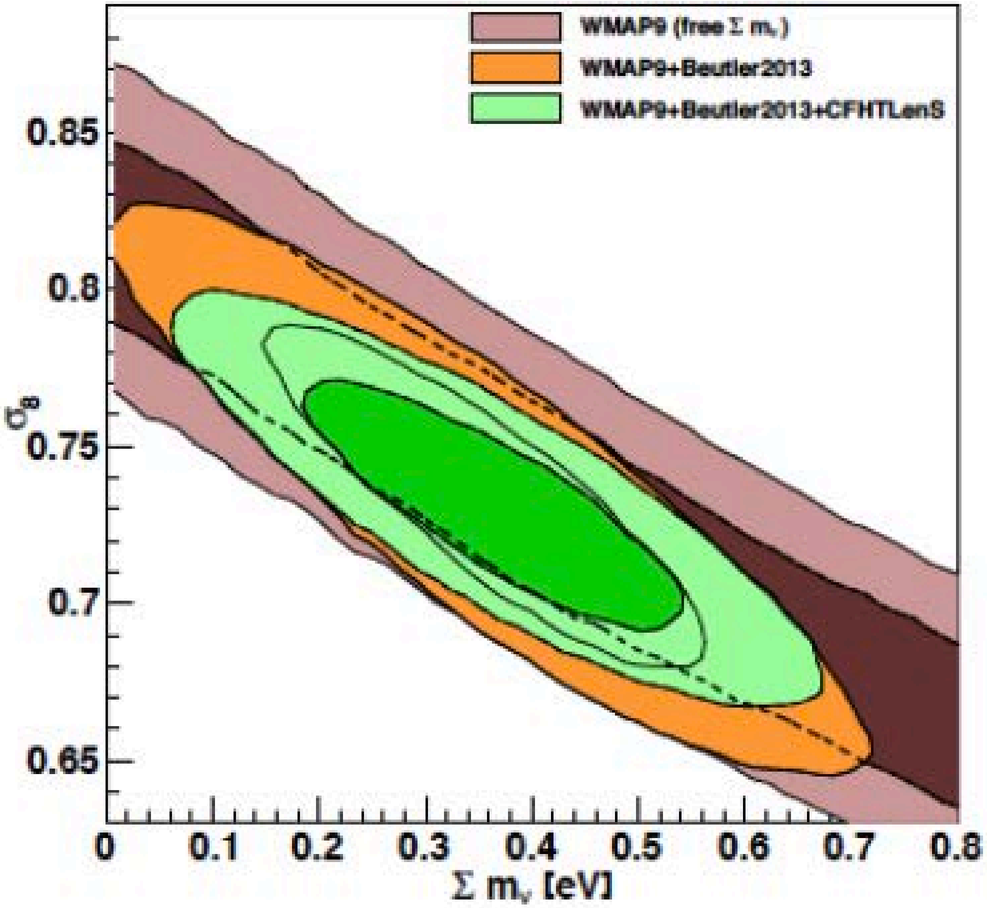


- Tension ($\Delta\chi^2 \approx 10.5$) between CMB and H0 data
- Variations in H_0 analysis lead to upper limit ***0.18 eV – 0.28 eV***

a robust, consensus H0 measurement will be incredibly useful

Conclusions so far

- The strongest bounds on absolute neutrino mass scale come from cosmological data
- However, published bounds assume a simple functional form for the primordial power spectrum
- With CMB data only, allowing a free PPS weakens the neutrino bound by factor 3
- Adding low redshift data (galaxy clustering, H0) creates PPS-independent, strong upper limits **$\Sigma m_\nu < 0.2$ eV**

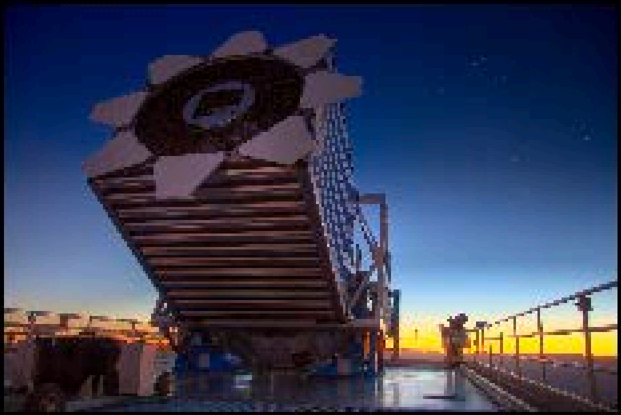


Beutler et al 1403.4599

- Neutrino mass constraints and the primordial power spectrum
- *Combining weak lensing and galaxy clustering to probe dark energy, gravity and neutrinos*
- Using cross-correlations to calibrate photometric redshifts in cosmic shear surveys

Galaxy Clustering:

- Large volume, 3D maps of galaxies allow measurement of clustering and growth of structure
- BOSS: ***$V = 4.4\ (h^{-1}\ \mathrm{Gpc})^3$, $\Omega \approx 10{,}000\ \mathrm{deg}^2$***



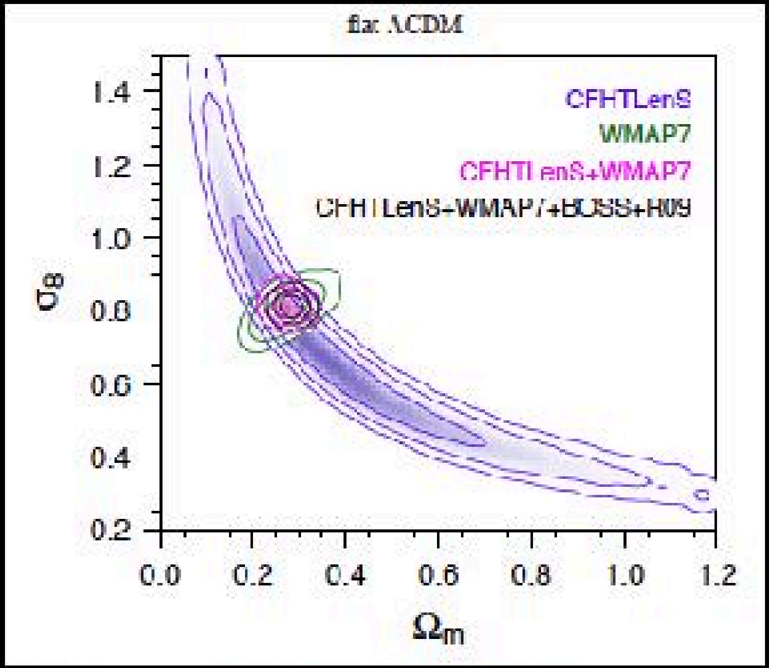
The SDSS telescope at Apache Point, New Mexico

Weak Gravitational Lensing:

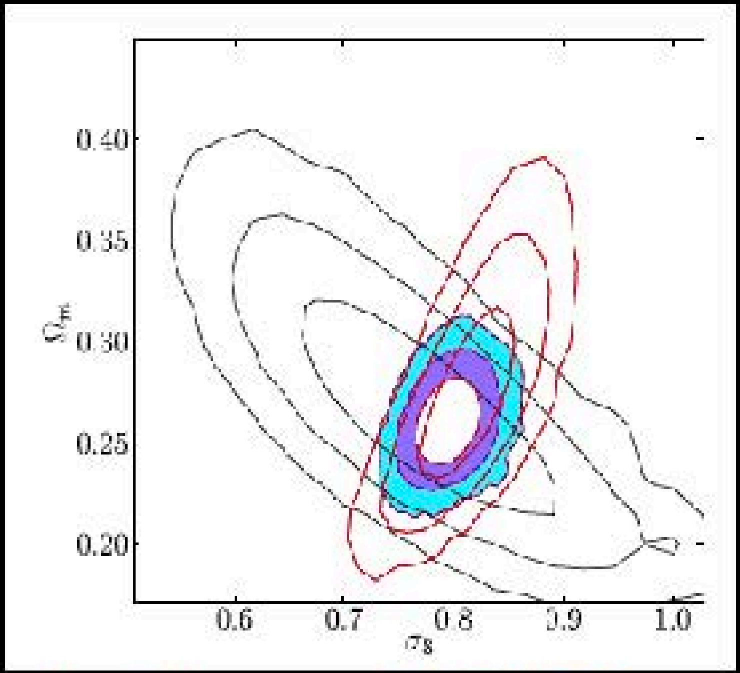
- ***Cosmic shear*** directly measures metric perturbations and also has strong dependence on expansion history
- CFHTLS: ***$\Omega \approx 150\ \mathrm{deg}^2$***

The Canada France Hawaii Telescope (Mauna Kea)

Weak lensing and galaxy clustering are complementary probes of cosmology



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



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

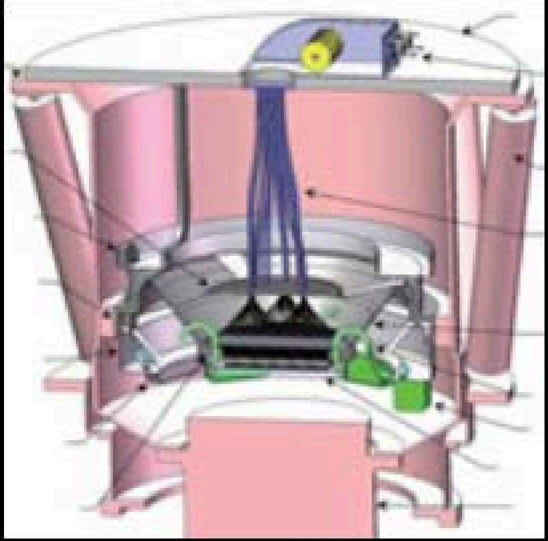
SuMIRe: *Subaru Measurement of Images and Redshifts*

8.2 m Subaru telescope

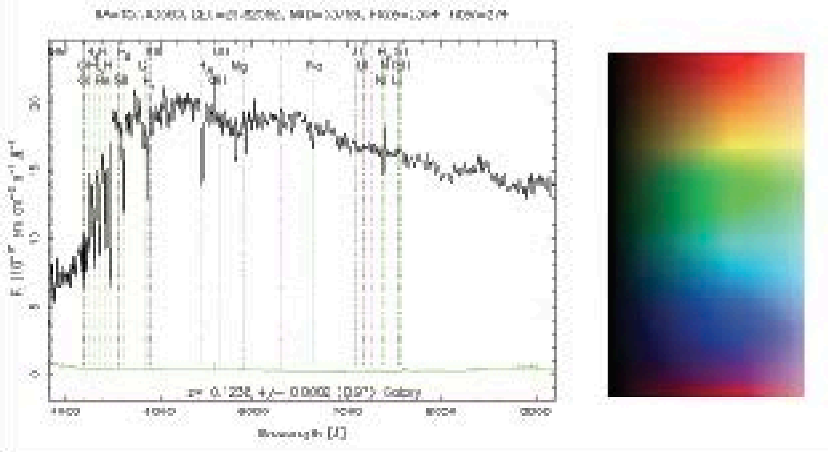
The Hyper Suprime Cam (**HSC**) wide field imaging survey will measure cosmic shear across *1500 deg*^{2}

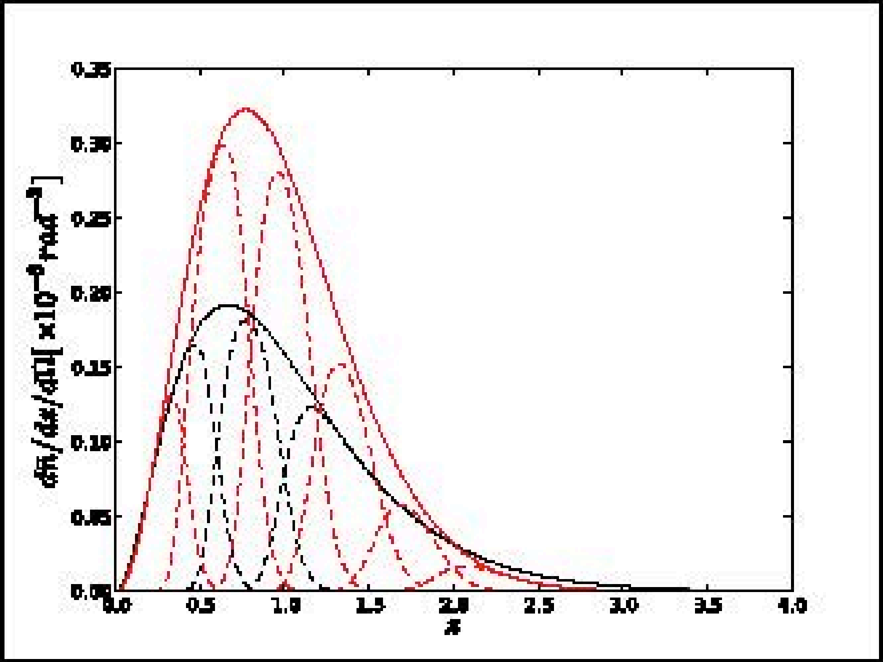
- 2014 – 2019
- Wide ***1.5 deg*** field of view
- Deep multi-band imaging (grizy; $i \approx 26$, $y \approx 24$)
- $n = 20$ *arcmin*$^{-2}$
- $\langle z \rangle = 1$

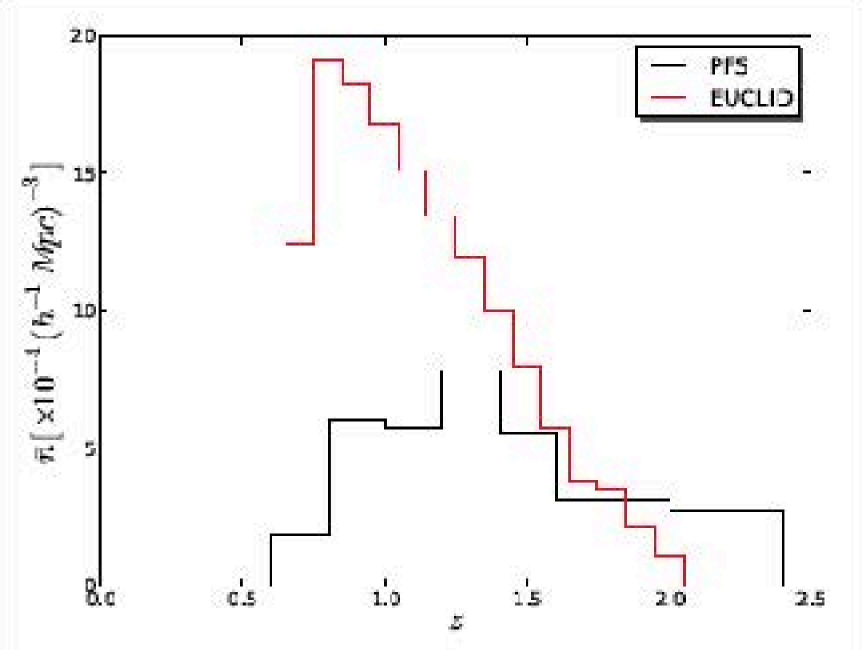
The Prime Focus Spectrograph (**PFS**) cosmology survey will measure 3D clustering at *z=0.6-2.4*



- 2018 – 2023
- 2400 fibers
- *λ = 380 – 1260 nm*
- ELG's ([OII])







SuMIRe: 3 tomographic bins

Takada et al 2012, Oguri & Takada 2011

EUCLID: 6 tomographic bins

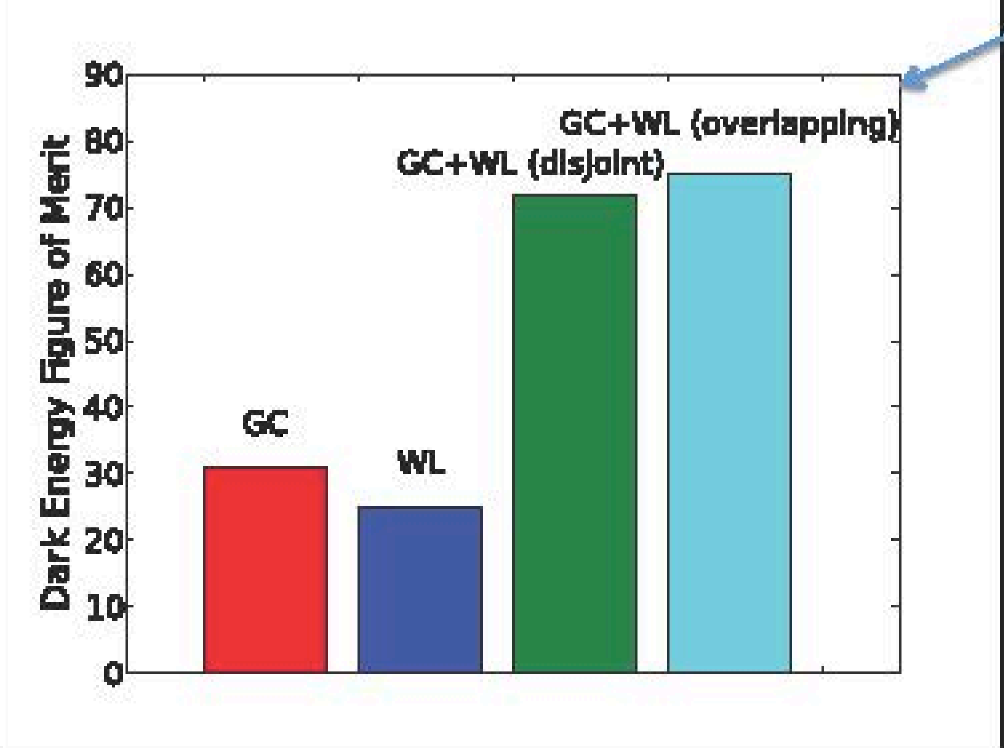
Amendola et al 2012

- How much improvement when Weak Lensing and Galaxy Clustering Combined?
- How important is overlap between surveys?

RdP, Dore & Takada arXiv:1308.6070

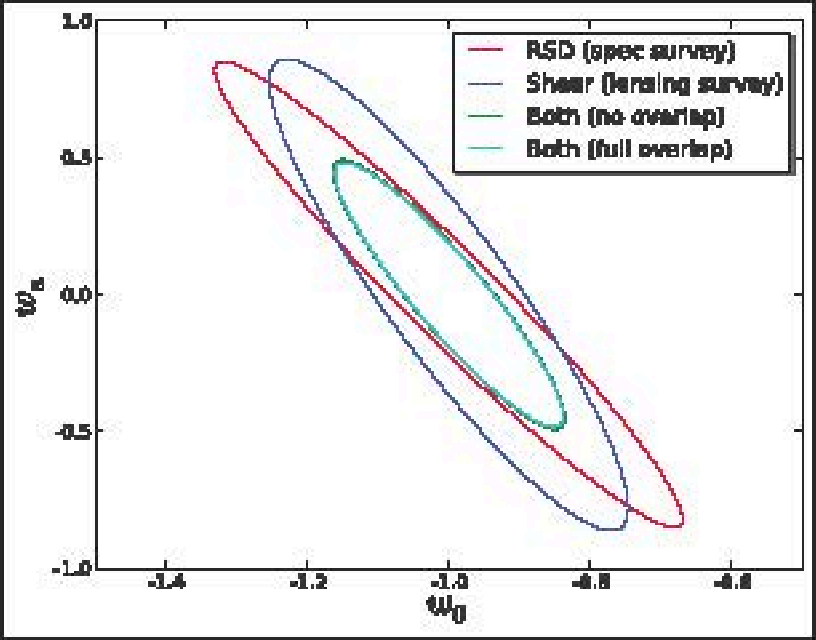
SuMIRe ***Dark Energy:*** Strong WL + GC complementarity, but overlap not crucial

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



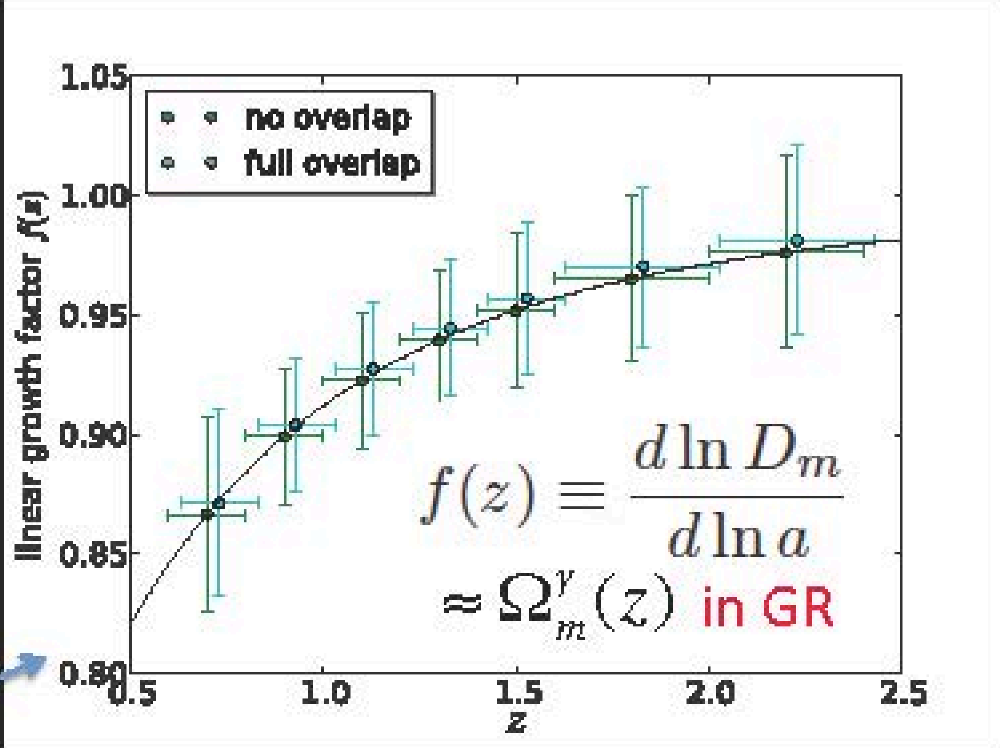
Tight bounds on time-varying DE equation of state

CMB prior (Planck) included



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

CMB prior (Planck) included



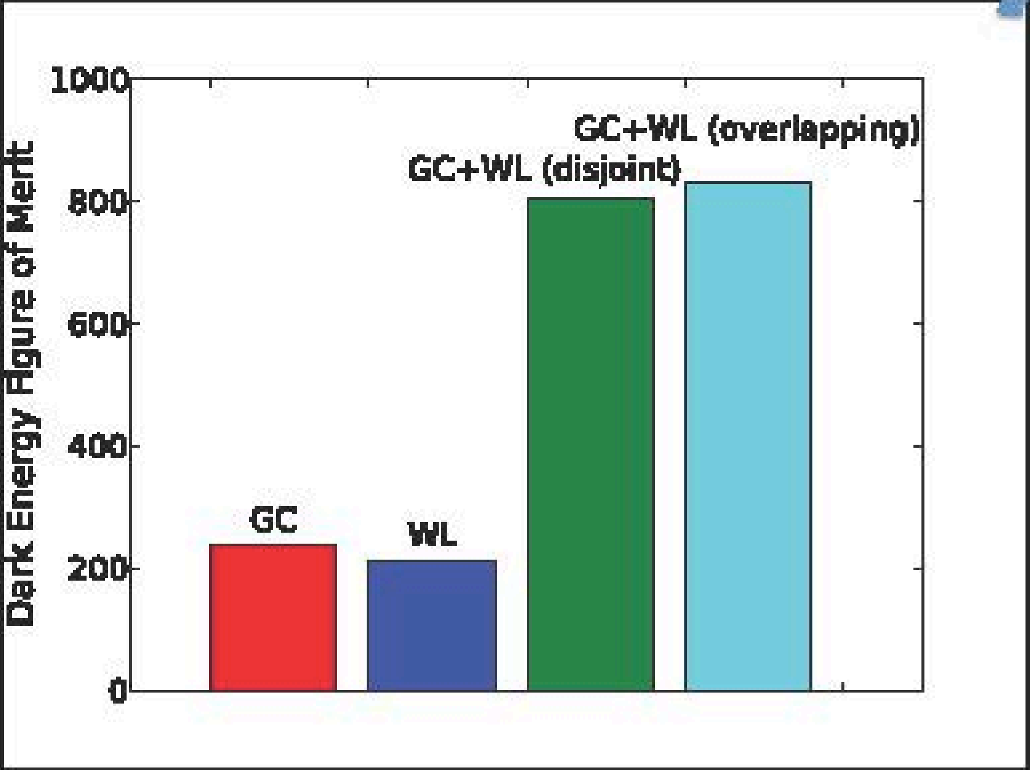
$$f(z) \equiv \frac{d\ln D_m}{d\ln a}$$

$$\approx \Omega_m^{\gamma}(z)$$ in GR

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

EUCLID ***dark energy:*** Strong WL + GC complementarity, but overlap not crucial

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

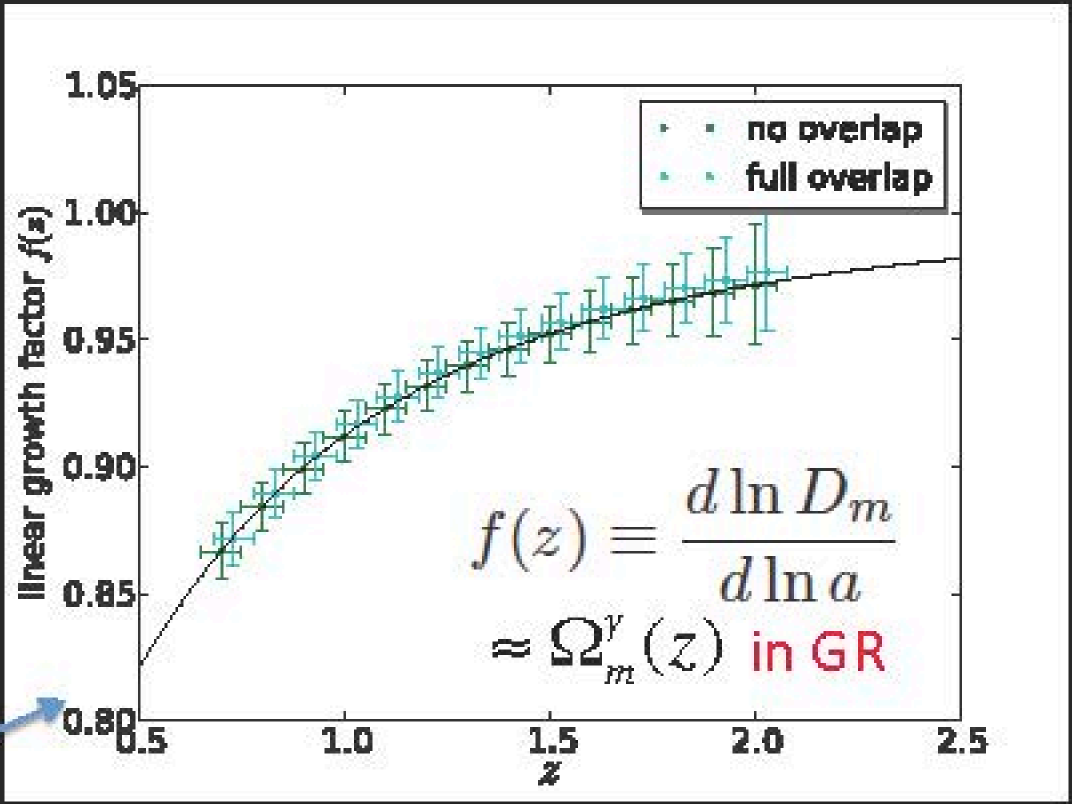


Tight bounds on time-varying DE equation of state

CMB prior (Planck) included

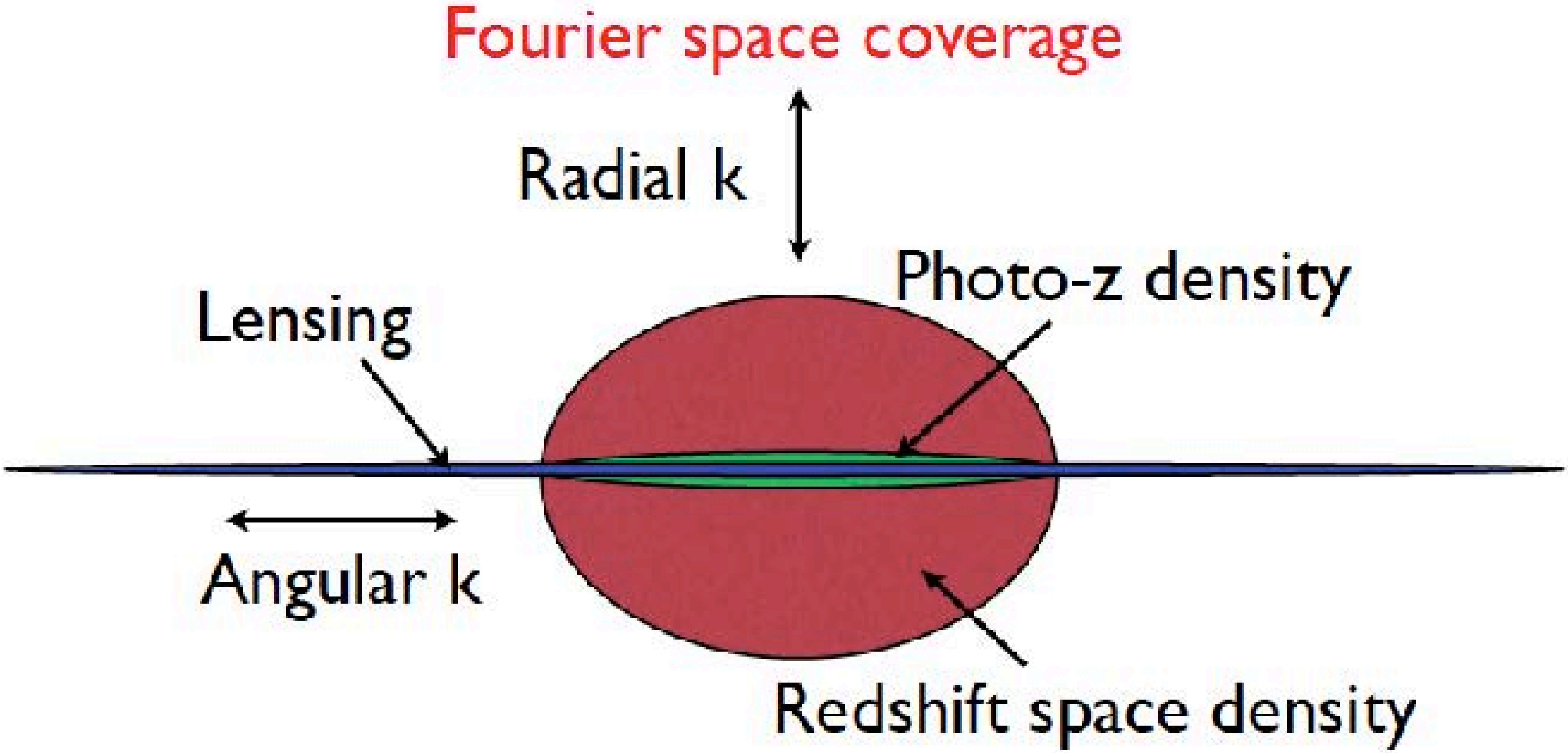
***EUCLID* growth rate:** Strong WL + GC complementarity, but overlap not crucial

CMB prior (Planck) included



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

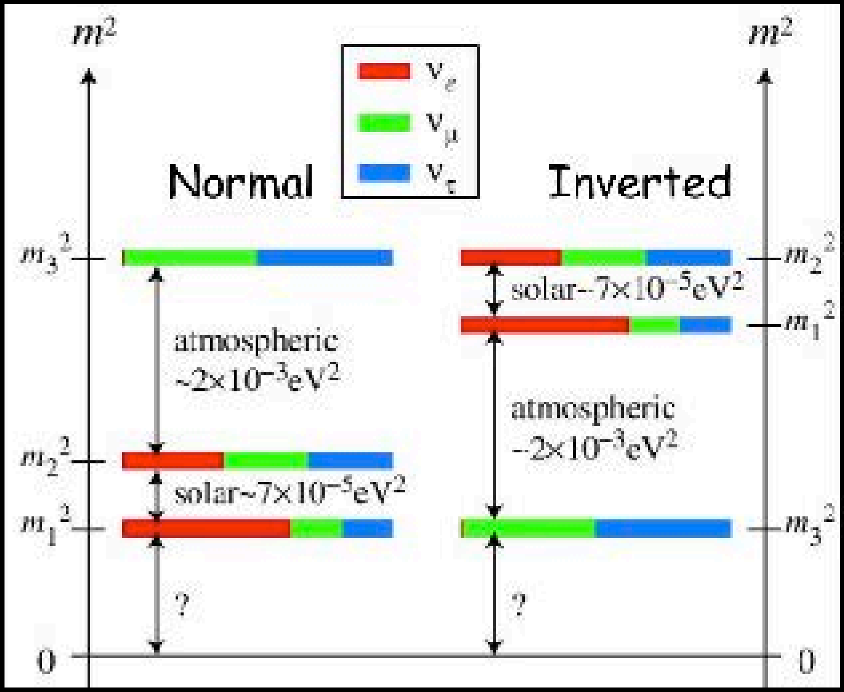
The number of modes probed by cross-correlations is small compared to that probed my RSD or WL alone



Font-Ribera et al, 2013

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

- $\sigma(\Sigma m_\nu) = 0.03$ eV
- Dominated by Galaxy Clustering (amplitude information)



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

- imaging survey provides target catalog
- *Identifying/constraining systematics*
- information from non-linear regime

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

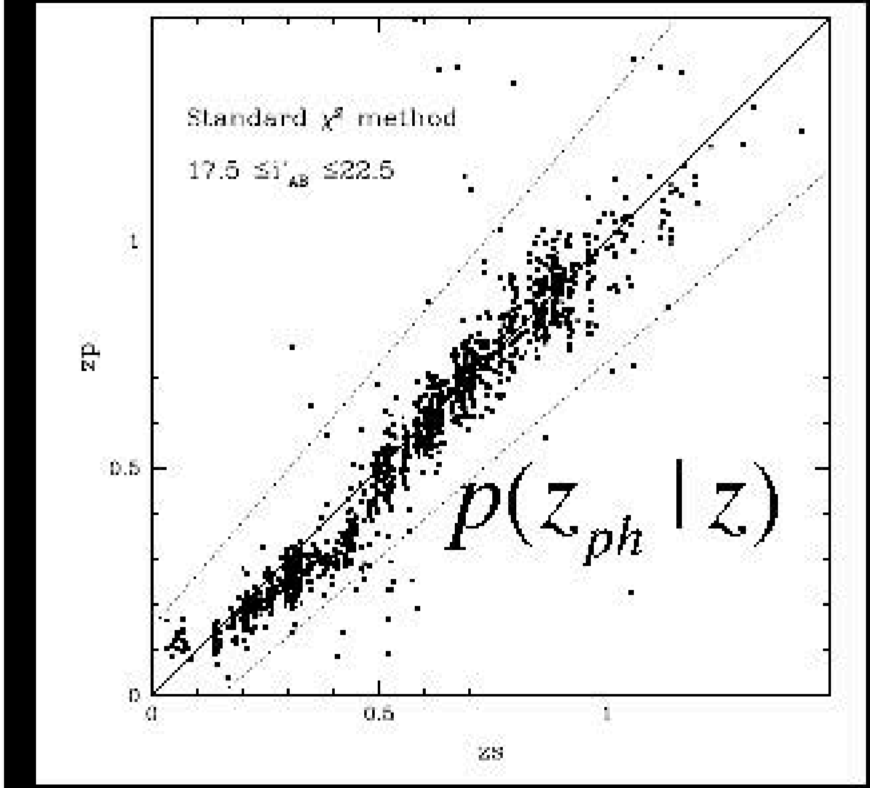
- higher order statistics

- Neutrino mass constraints and the primordial power spectrum

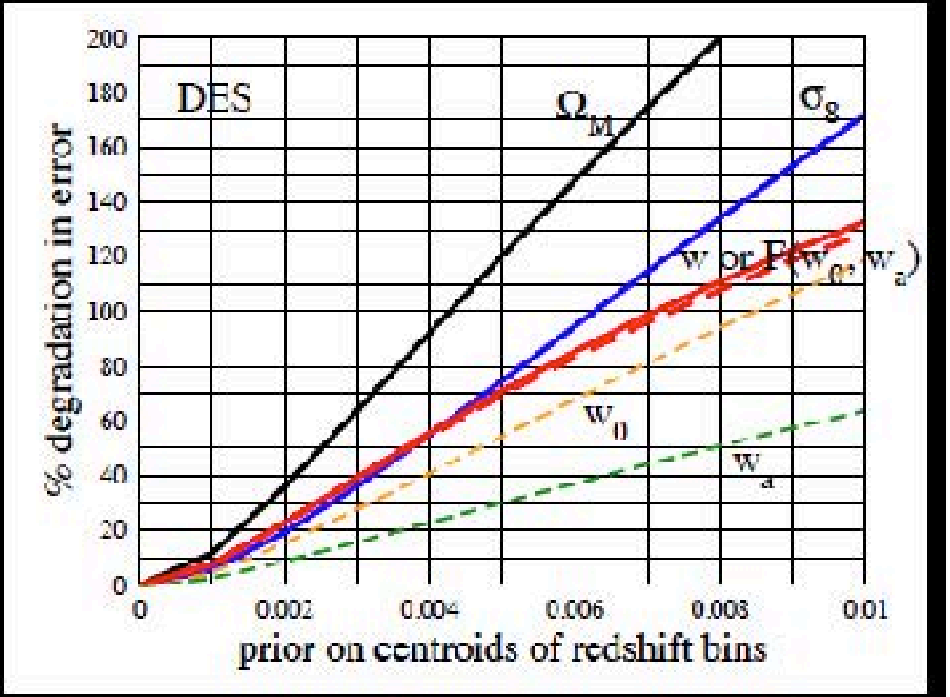
- Combining weak lensing and galaxy clustering to probe dark energy, gravity and neutrinos

- *Using cross-correlations to calibrate photometric redshifts in cosmic shear surveys*

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



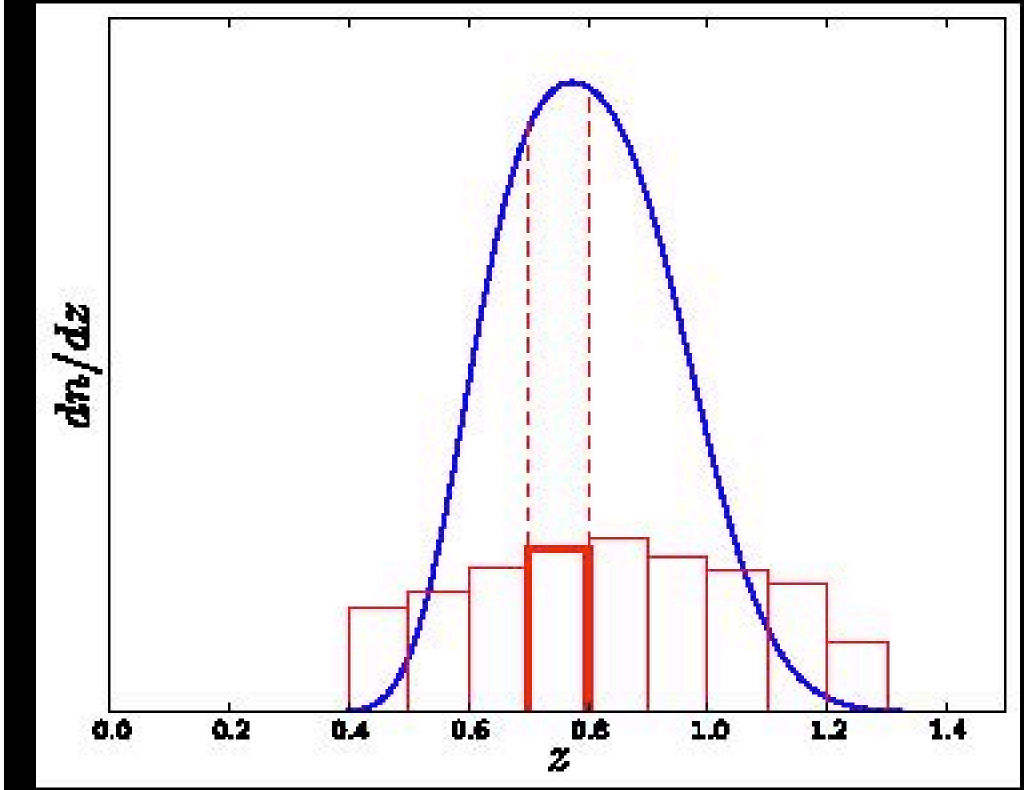
Ilbert et al 2006



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

(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



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

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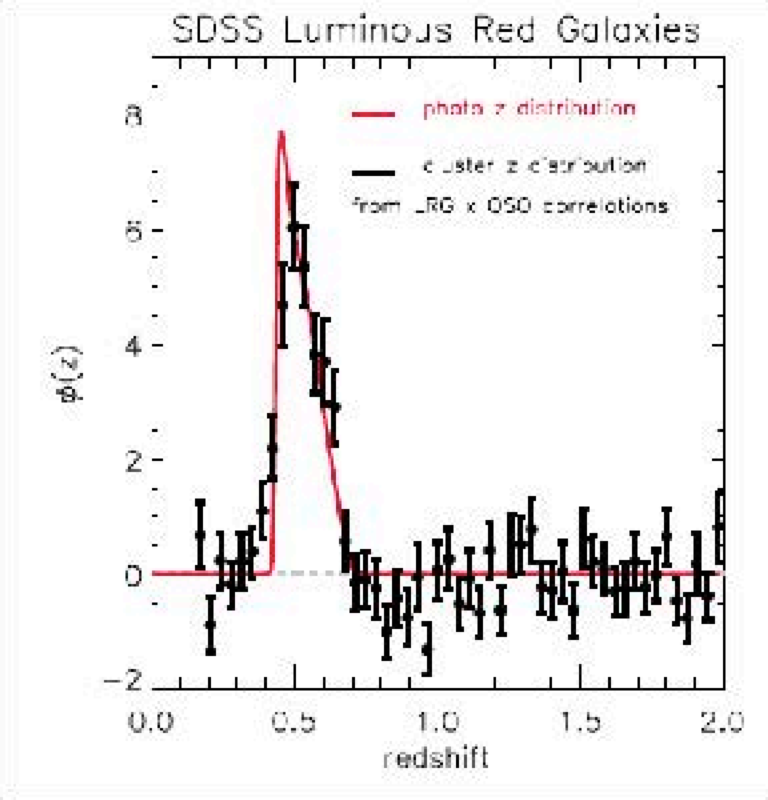
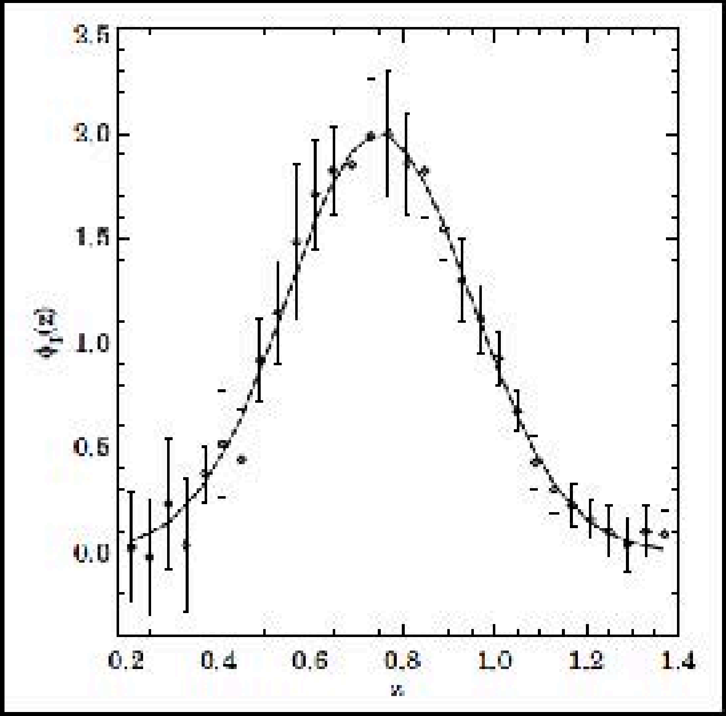
Newman 2008, Schulz 2010, Matthews & Newman 2010, McQuinn & White 2013, Menard et al 2013

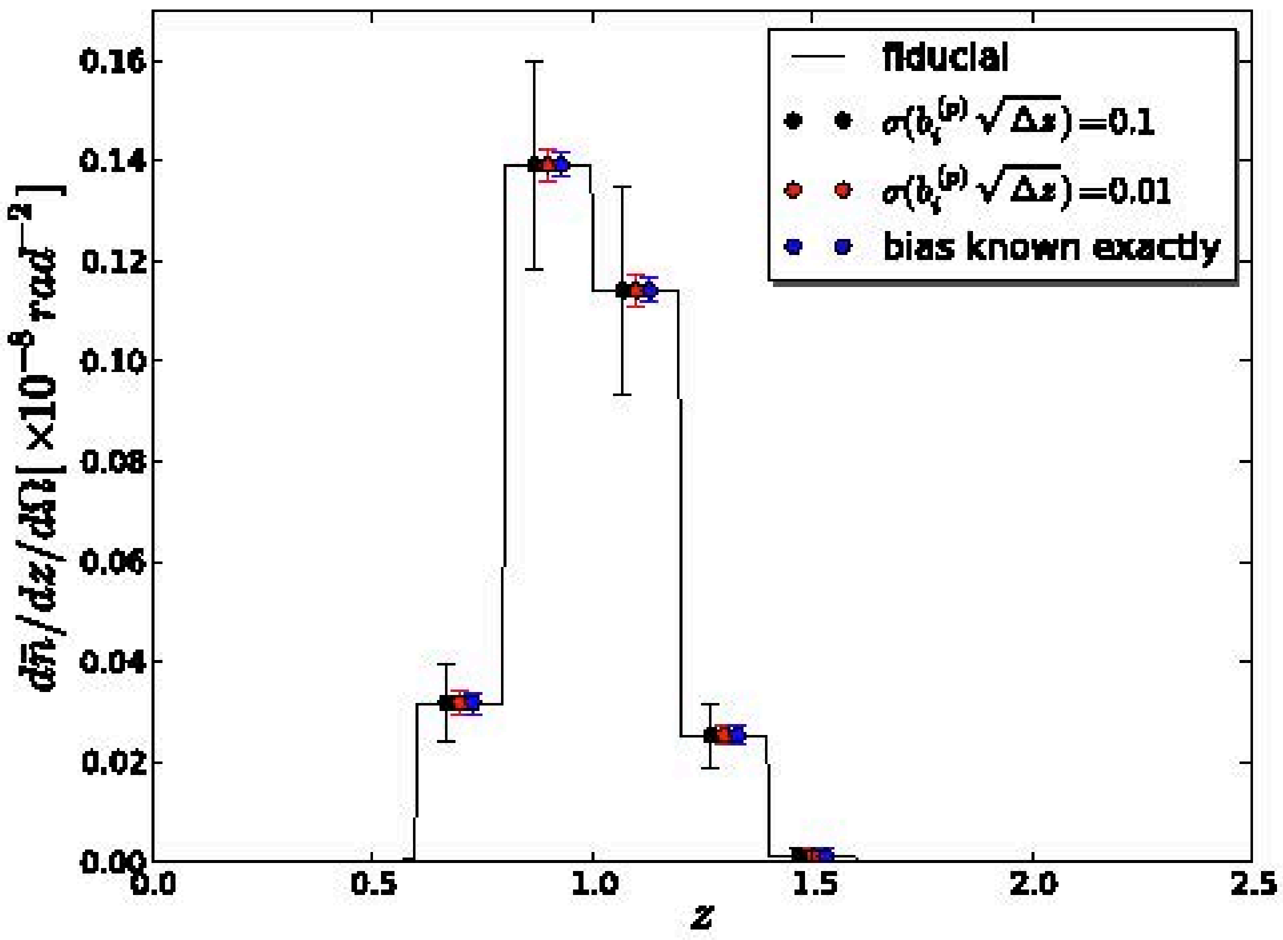


Menard et al 2013



Matthews & Newman 2010

Redshift distribution reconstruction crucially relies on knowledge of galaxy bias



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

de Putter, Dore & Das - ApJ 2013

We assume a Gaussian photo-z model

- Simple Gaussian model for photo-z distributions:

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

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

$$\frac{dn_i}{dz}(z) = \frac{dn}{dz}(z)\int_{z_i^{\rm low}}^{z_i^{\rm high}} dz_{\rm ph}\, p(z_{\rm ph}|z)$$

(distribution in tomographic bin)

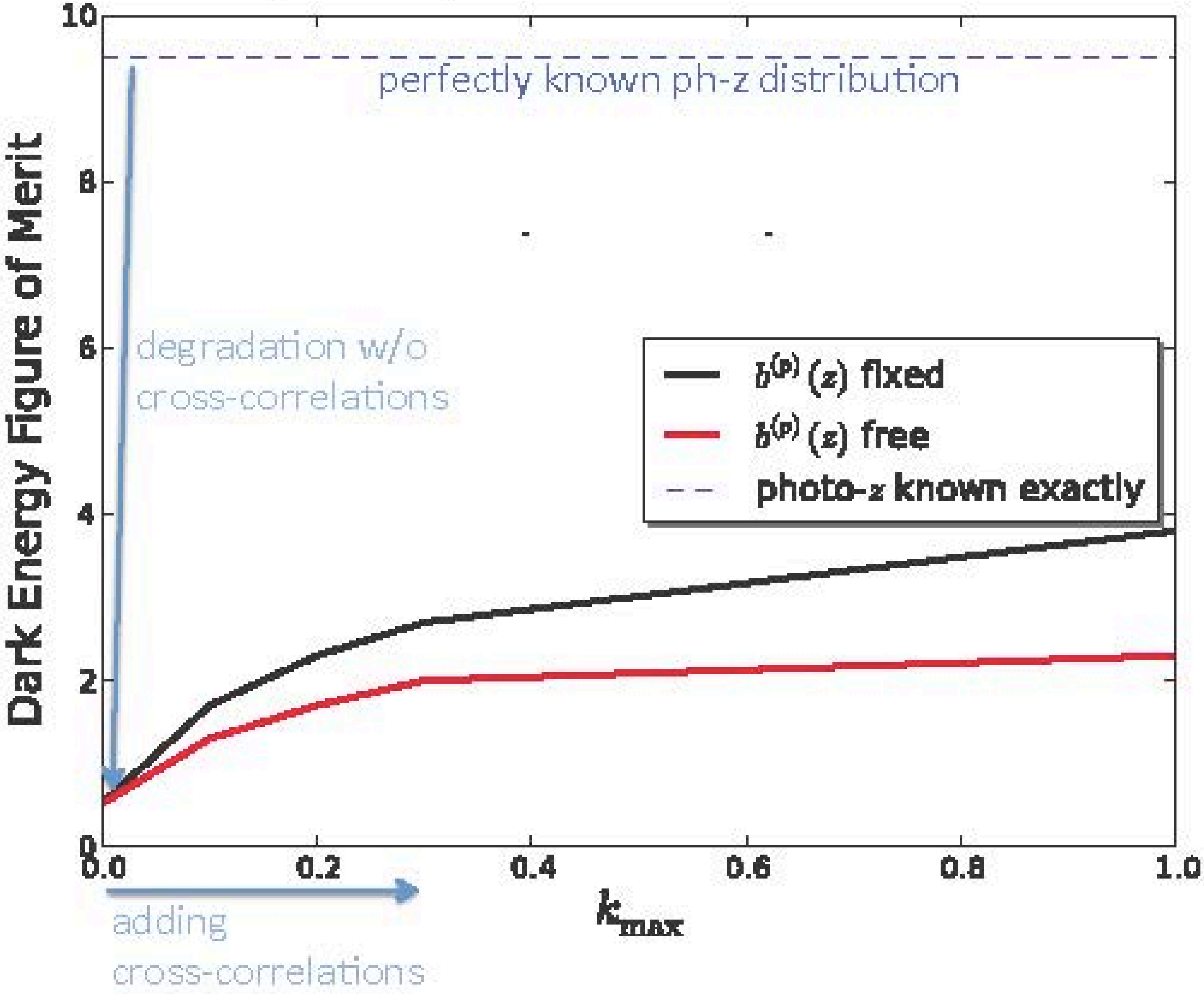
- Distribution defined by scatter $\sigma_z(z)$ and bias $b_z(z)$

- Parametrized by spline with 11 nodes in *z=0-3* : allows for very general redshift evolution

Fiducial:

$\sigma_z(z) = 0.05\,(1+z)$, $b_z(z) = 0$

SuMIRe Dark Energy Figure of Merit (no photo-z prior)

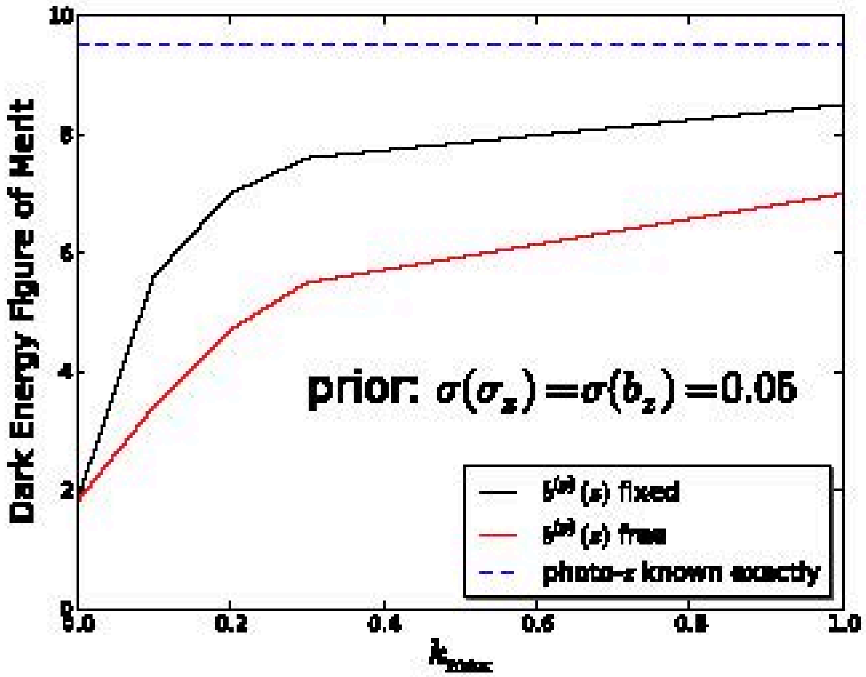


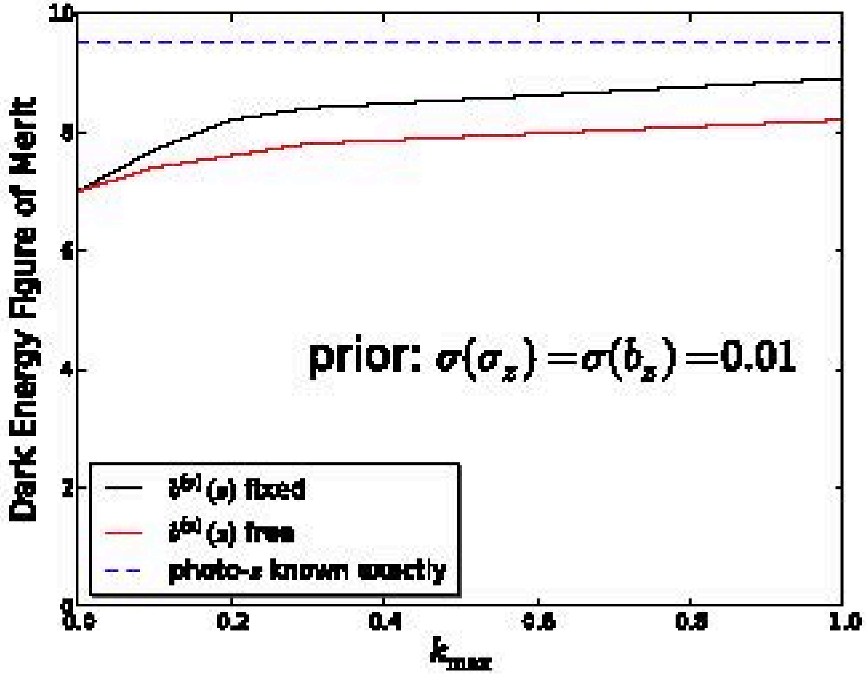
perfectly known ph-z distribution

degradation w/o cross-correlations

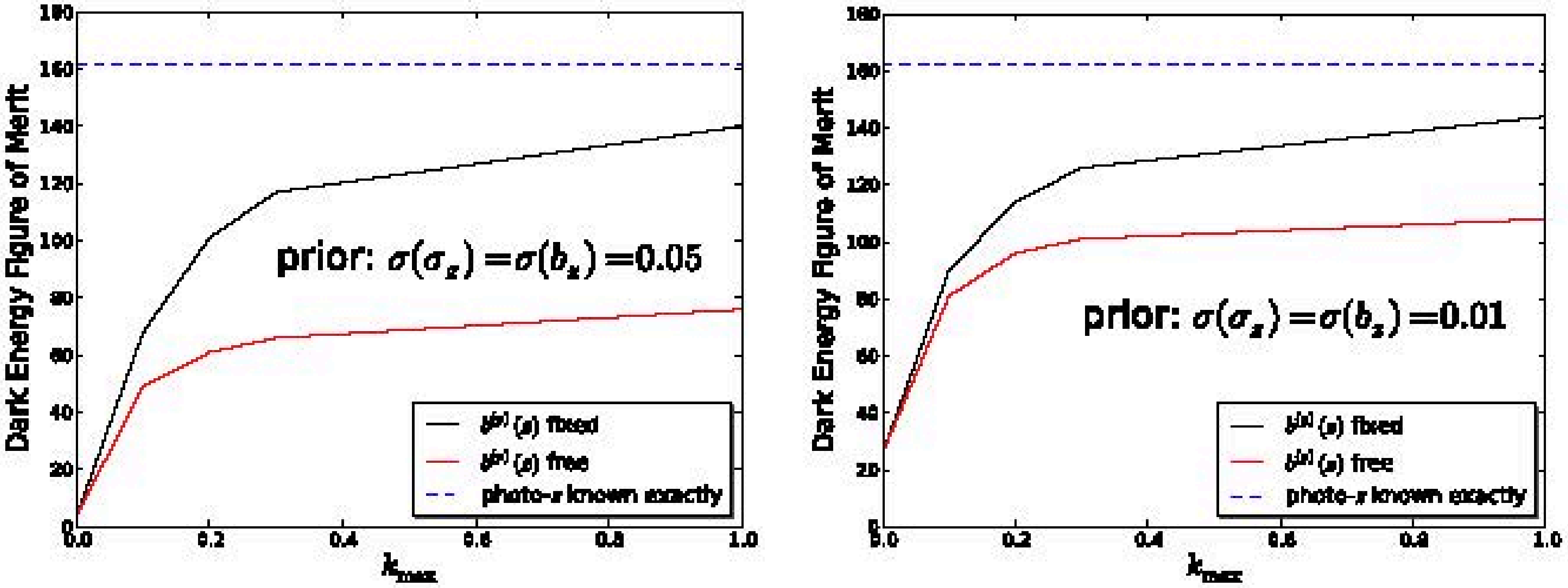
adding cross-correlations

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





Cross-correlations can partially restore EUCLID 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*

Summary/Conclusions

- Cosmological data are closing in on neutrino mass (*$\Sigma m_\nu < 0.2$ eV*); combining probes is crucial for robustness
- Combining future Weak Lensing and Galaxy Clustering data will improve DE FOM by factor 2-3 compared to either probe alone and leads to strong cosmic growth constraints
- Cross-correlations with overlapping spectroscopic survey ameliorate photo-z systematics in cosmic shear surveys

ありがとう

Thank You