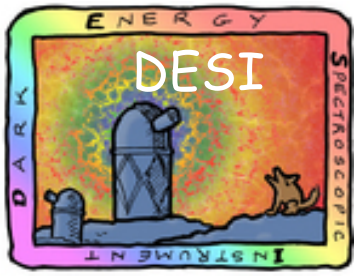
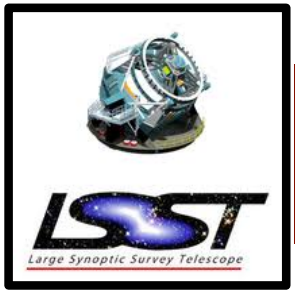
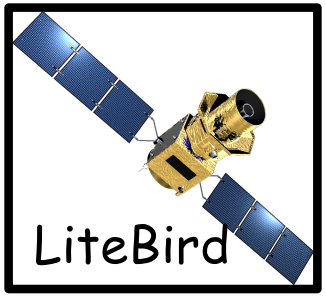
Neutrino masses with multi-probes







Christophe Yèche
CEA-Saclay

Dark Energy Workshop, Paris, June 12, 2019

Context

Cosmic neutrino background

At early times ($T_\nu \gg m_\nu$), neutrinos contribute as radiation $\rho_\nu \propto T_\nu^4$

At late times ($T_\nu \ll m_\nu$), neutrinos contribute as matter $\rho_\nu = m_\nu n_\nu$

$$\Omega_\nu = \frac{\Sigma m_\nu}{93.1 eV}$$

Non-relativistic transition

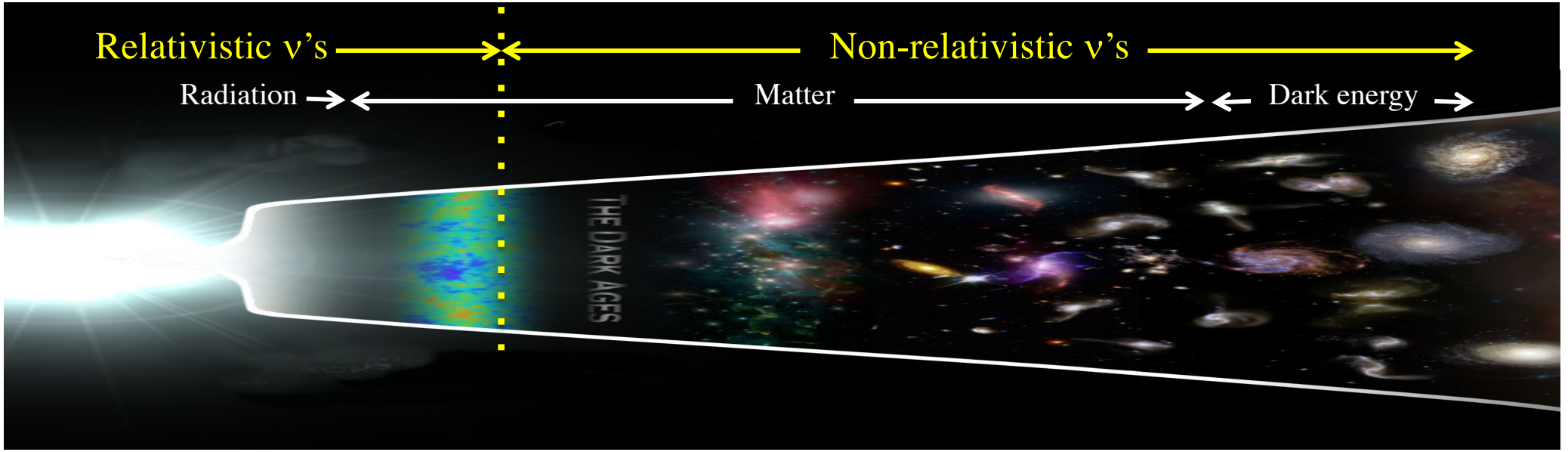
$$m_\nu \sim \langle p \rangle = \frac{\int p f(p) d^3p}{\int f(p) d^3p} = 3.15\, T_\nu \quad \text{with} \quad f(p) = \frac{1}{e^{p/T_\nu} + 1}$$

$$z_{nr} \sim 1900\, \frac{m_\nu}{1\,\mathrm{eV}} \longrightarrow$$

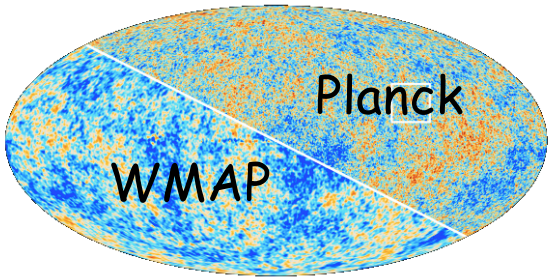
At recombination

$m_\nu < 0.6$ eV ($\Sigma m_\nu < 1.7$) : relativistic

$m_\nu > 0.6$ eV ($\Sigma m_\nu > 1.7$) : matter-like



Impact on CMB

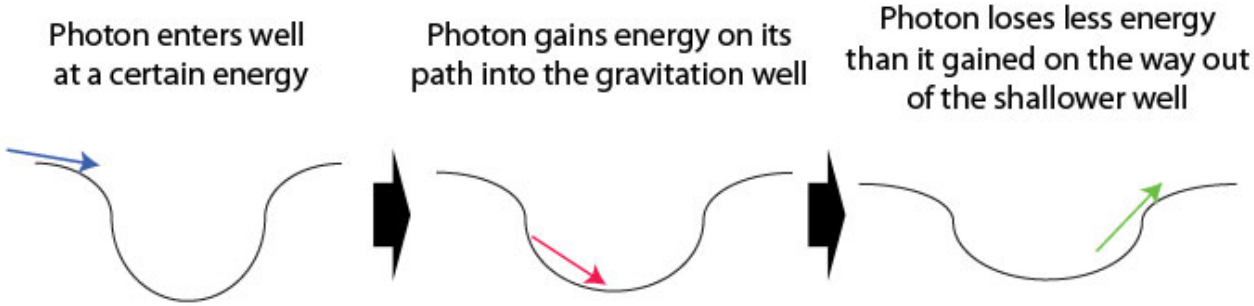


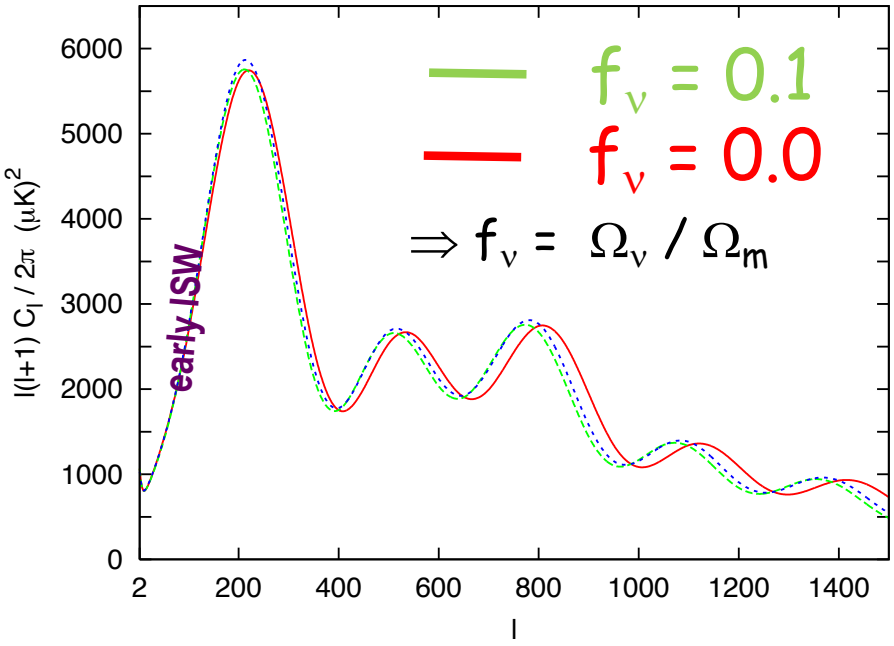
- m_ν < 0.6 eV (Σm_ν < 1.7 eV) - relativistic at CMB

  ⇒ "No" impact on baryon-photon plasma

  ⇒ Subtle changes in peak position & amplitude

  ⇒ Main effect is the early Integrated Sachs-Wolfe effect (ISW) after recombination (50<l<300) - position and amplitude of first peak.

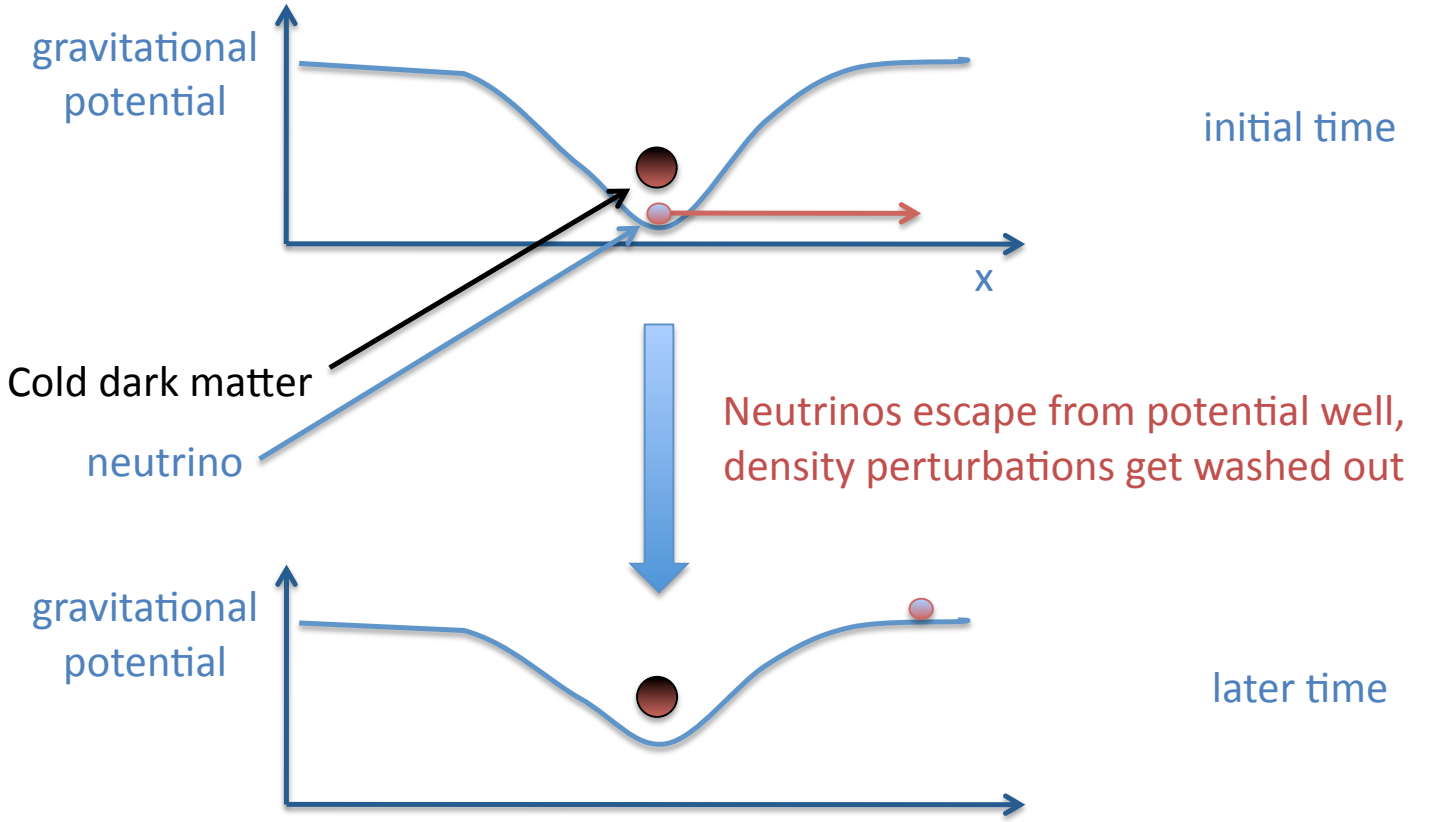


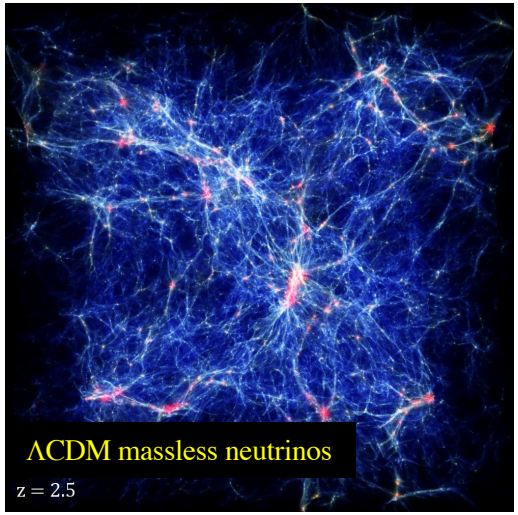


- CMB alone not sufficient for neutrinos masses sub-eV
- Add information directly from the matter distribution

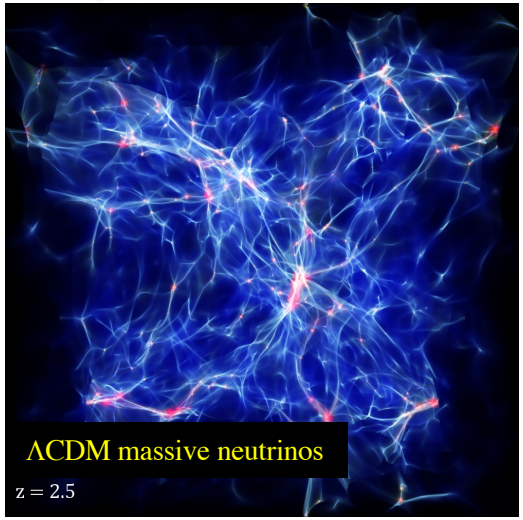
→ **Neutrino free-streaming**

Free-streaming



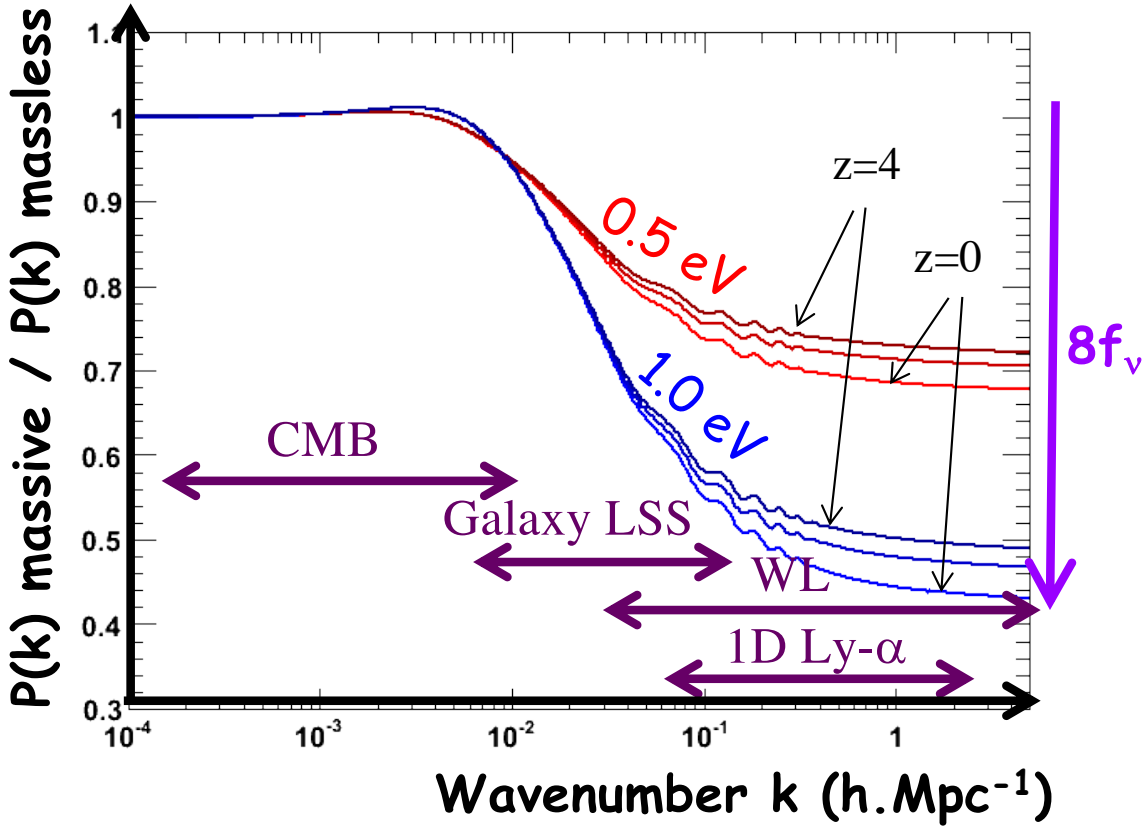


Suppression of the small scales



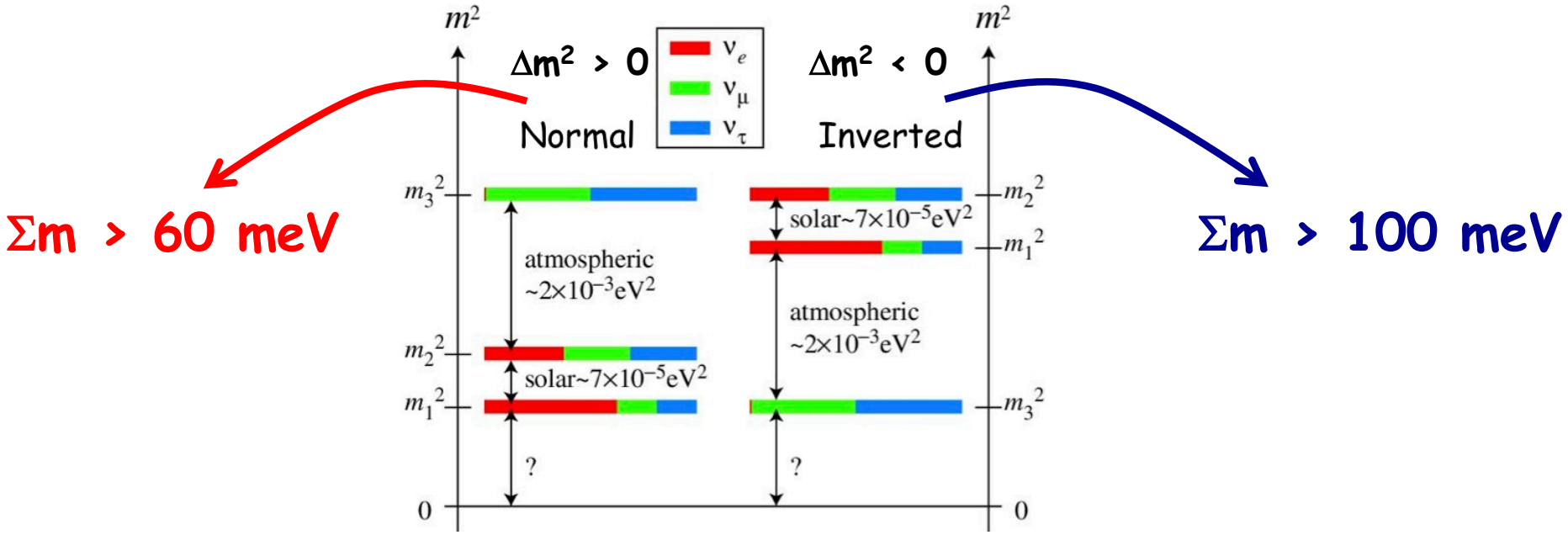
Impact on matter power spectrum

- Impact in CMB-alone only for non-relativist neutrinos ⇒ ~1-2 eV limit



- Free-streaming:
  - Wash out the fluctuations
  - Suppression of small scales in P(k)
- Suppression factor $\Leftrightarrow \Sigma m_\nu$ $\Leftrightarrow f_\nu = \Omega_\nu/\Omega_m$
- Three probes directly sensitive to free-steaming
  - Galaxy Power spectrum
  - Weak lensing
  - Ly-a absorption along the line of sight
- CMB- lensing is similarly affected by free-steaming

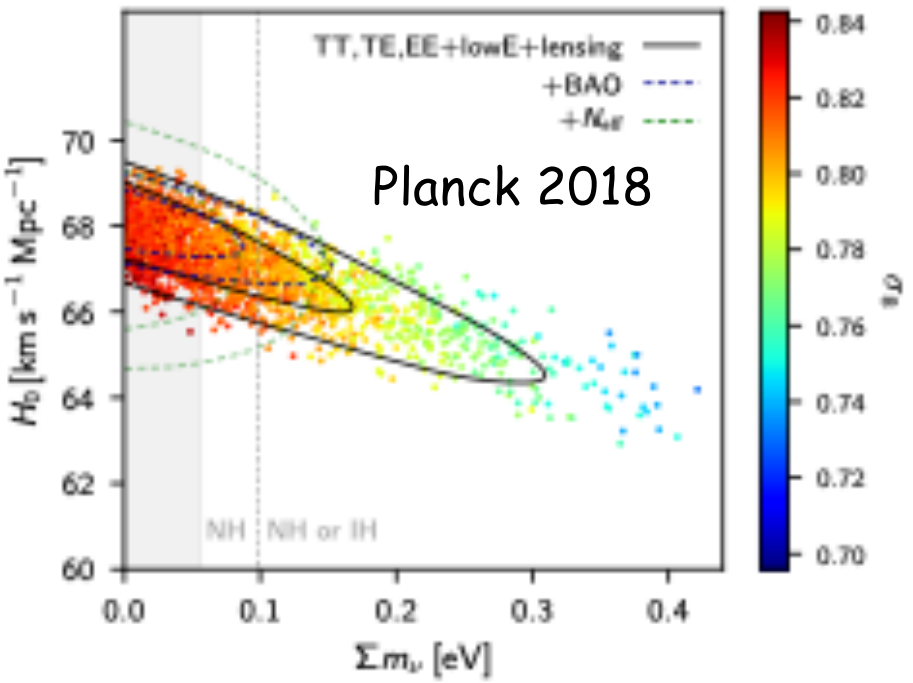
Neutrino Masses and Hierarchy

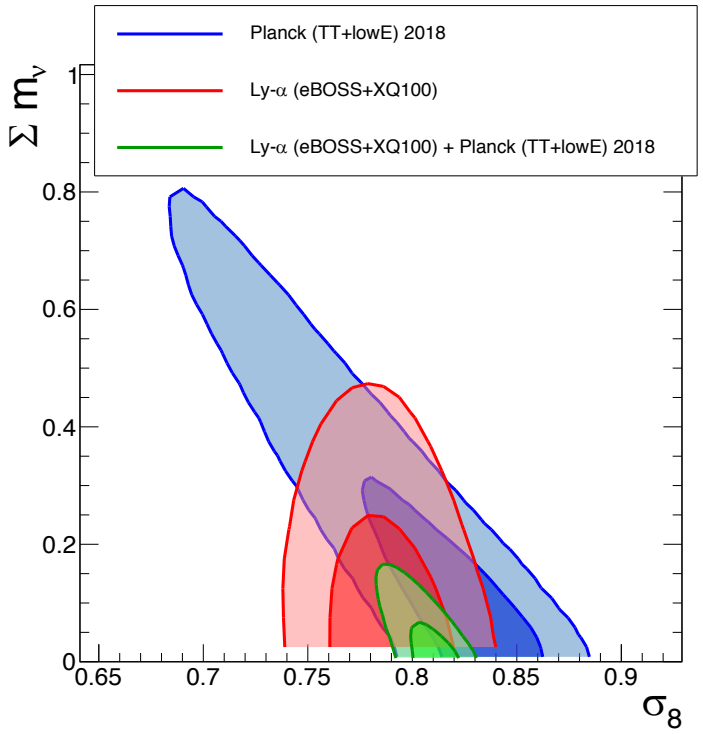


An answer to mass hierarchy with cosmological neutrinos

- Particles Physics: atmospheric and solar oscillations
- No constraint on absolute masses
- 2 possible schemes: normal vs inverted hierarchy
- With $\sigma(\Sigma m_\nu)$~20/12 meV, we measure the mass of the neutrinos with a precision better than $3\sigma/5\sigma$
- With $\sigma(\Sigma m_\nu)$~8 meV, we may have a decision at 5σ on mass hierarchy

Current limits on Σm_ν

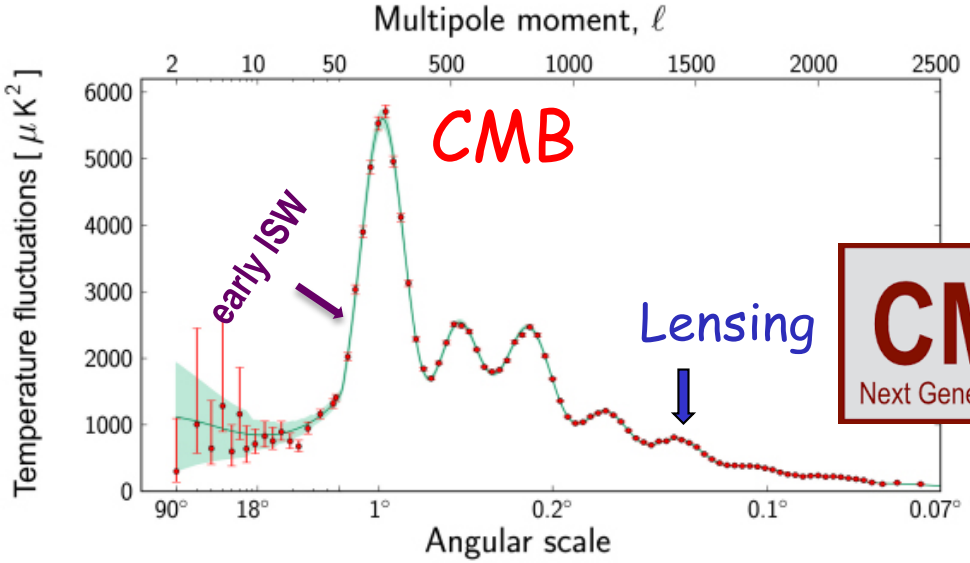




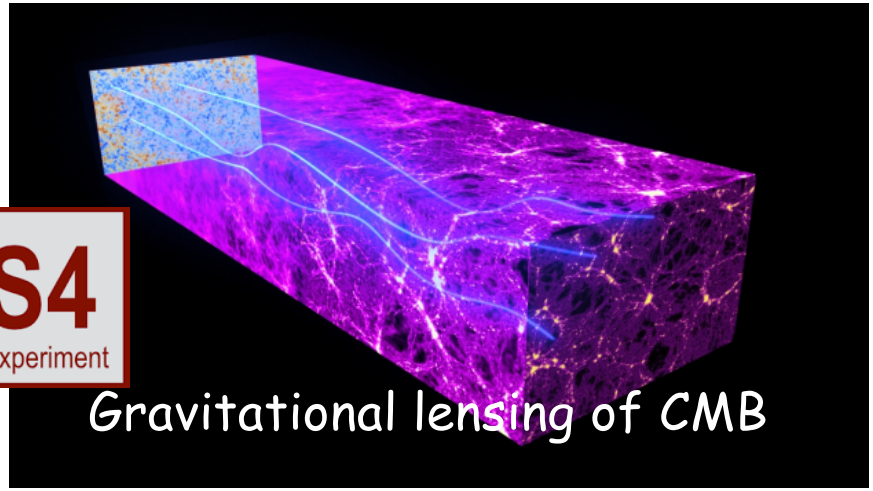
- With Ly-α alone (SDSS/eBOSS+VLT/XQ100):
  Σm_ν < 0.35 eV @95%CL
- With Planck 2018 alone:
  Σm_ν < 0.54 eV @95%CL
- Ly-α combined with CMB (Planck 2018) (just TT)
  Σm_ν <0.12 eV @95%CL
- BAO combined with CMB (Planck 2018) (TT,TE,EE and lensing)
  Σm_ν <0.12 eV @95%CL

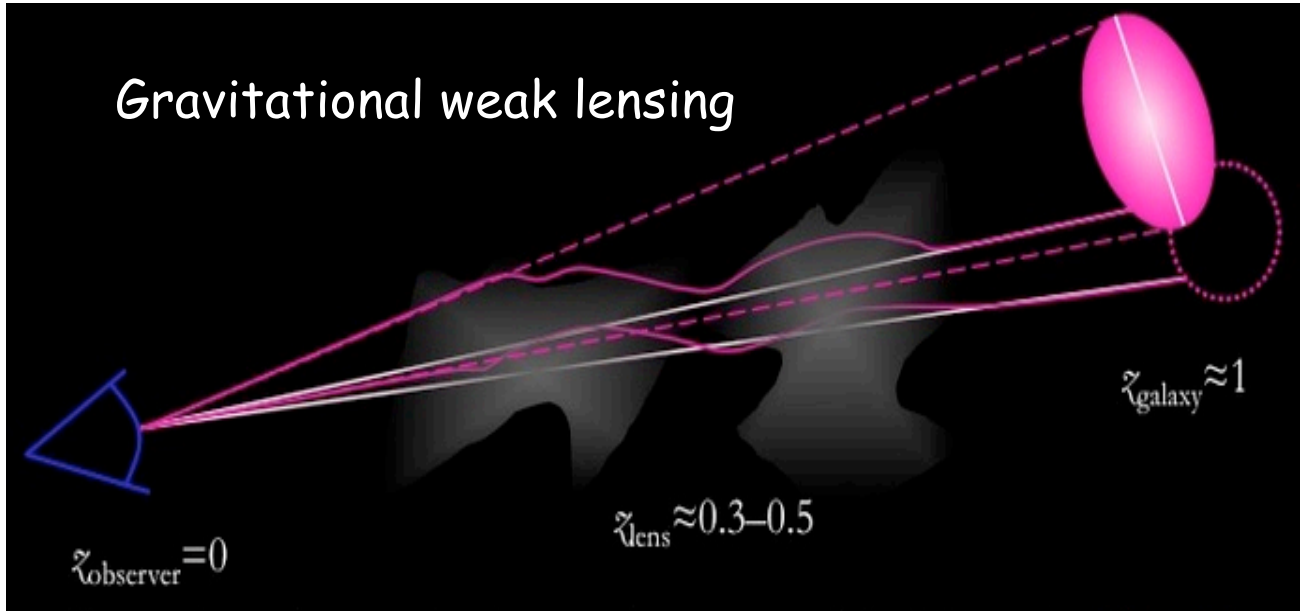
Forecast on neutrino masses with future cosmological projects

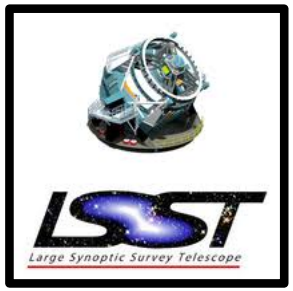
Probes –Projects



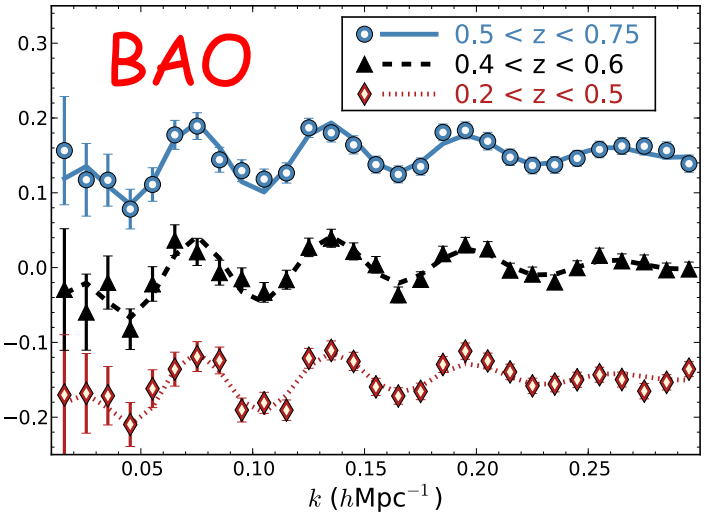
CMB-S4
Next Generation CMB Experiment

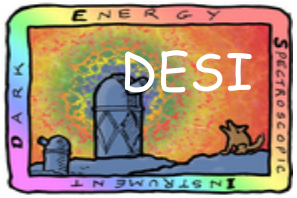


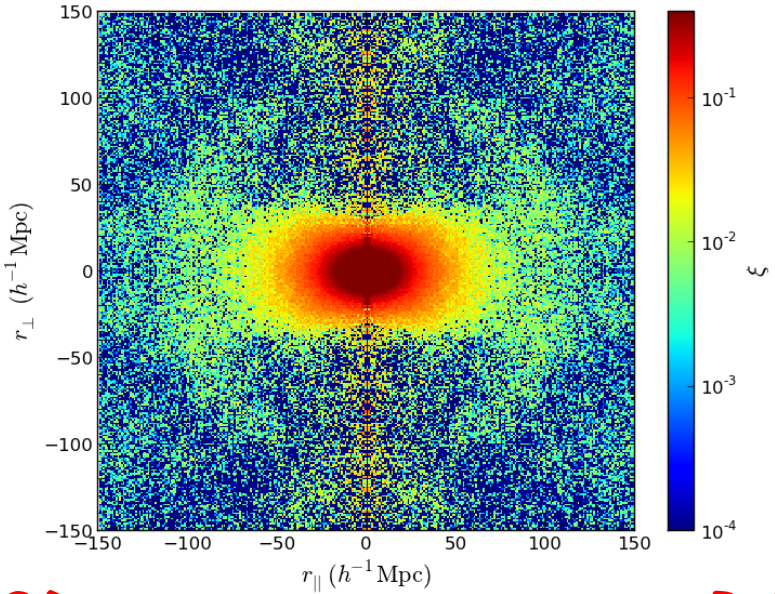




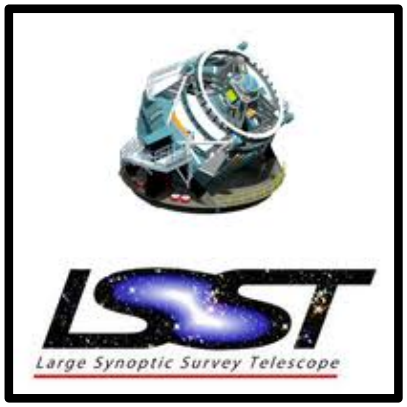
Probes - Projects

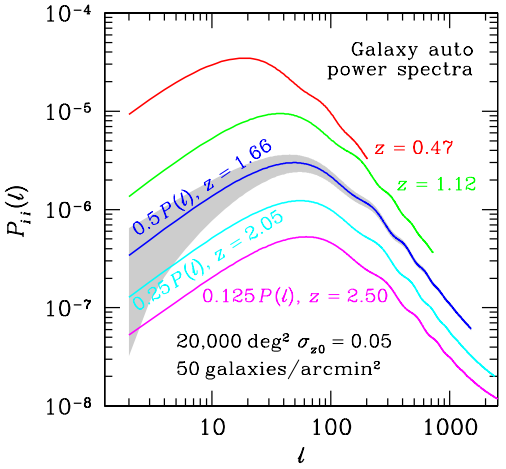


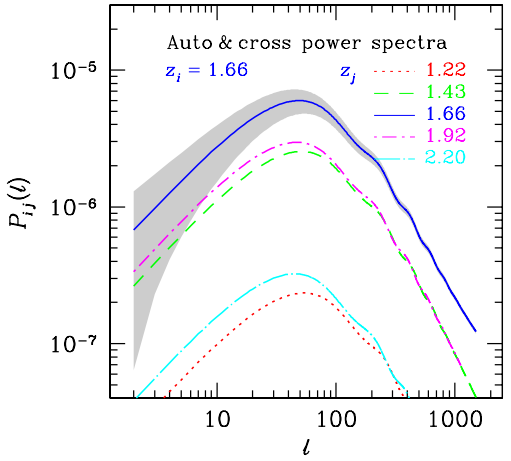




3D power spectrum - RSD







Angular power spectrum

DESI : 3D mapping of Universe

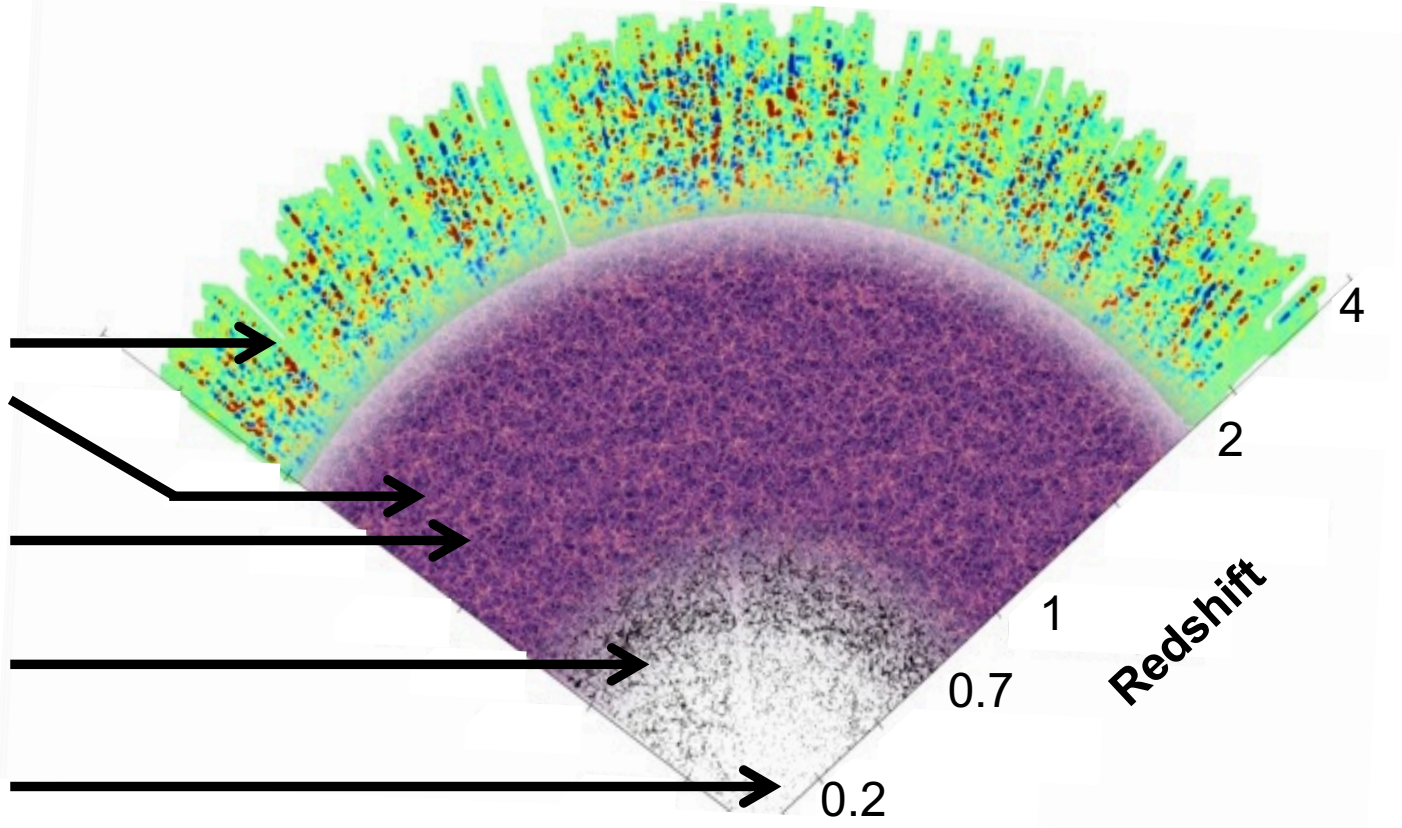
Five target classes spanning redshifts z=0.05 ➔ 3.7 for clustering
~35 million redshifts over 14,000 sq. degrees in five years

2.4 million QSOs
Lya z > 2.1
Tracers 1.0 < z < 2.1

17 million ELGs
0.6 < z < 1.6

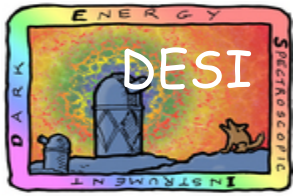
6 million LRGs
0.4 < z < 1.0

10 million brightest galaxies
0.05 < z < 0.4



DESI and Euclid forecast for Σm_ν

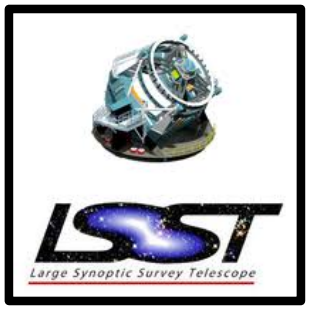
Data	$\sigma_{\Sigma m_\nu}$ [eV]	$\sigma_{N_{\nu,\mathrm{eff}}}$
Planck	0.56	0.19
Planck + BAO	0.087	0.18
Gal ($k_{\max} = 0.1h\,\mathrm{Mpc}^{-1}$)	0.030	0.13
Gal ($k_{\max} = 0.2h\,\mathrm{Mpc}^{-1}$)	0.021	0.083
Ly-α forest	0.041	0.11
Ly-α forest + Gal ($k_{\max} = 0.2$)	0.020	0.062



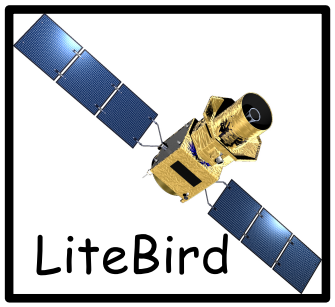
	Modified Gravity	Dark Matter	Initial Conditions	Dark Energy		
Parameter	γ	m_ν/eV	f_{NL}	w_p	w_a	*FoM*
Euclid Primary	0.010	0.027	5.5	0.015	0.150	430
Euclid All	0.009	0.020	2.0	0.013	0.048	1540
Euclid+Planck	0.007	0.019	2.0	0.007	0.035	4020
Current	0.200	0.580	100	0.100	1.500	~10
Improvement Factor	**30**	**30**	**50**	**>10**	**>50**	**>300**

- DESI and Euclid combined with Planck give $\sigma(m_\nu)$~20 meV

CMB-S4 and LSST forecast for Σm_ν



CMB-S4
Next Generation CMB Experiment



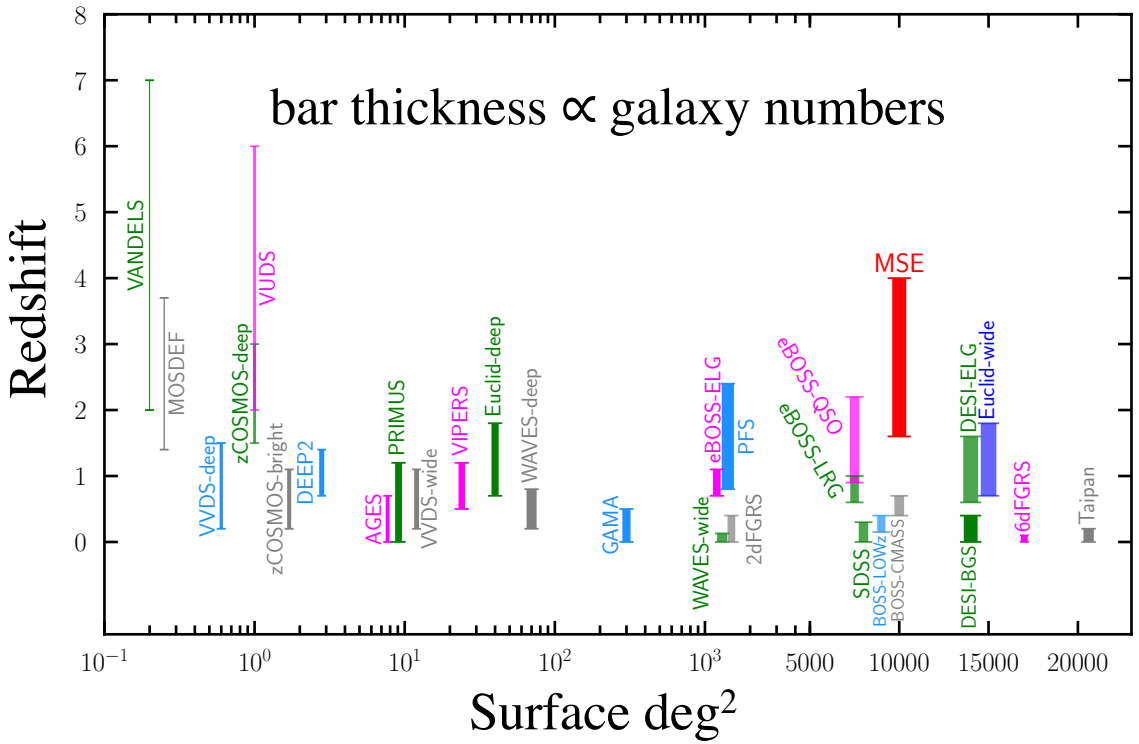
Setup	$\sigma(\Sigma m_\nu)$ [meV]	$\sigma(\Sigma m_\nu)$ [meV]	$\sigma(\Omega_k)$ [$\times 10^{-3}$]	$\sigma(w_0)$	$\sigma(w_a)$
S4	73	111	0.79	1.14	2.46
(+ DESI BAO)	29	76	0.48	0.13	0.41
LSST-clustering	69	91	3.33	0.42	1.22
LSST-shear	41	120	2.99	0.19	0.57
LSST-shear+clust	32	72	2.06	0.11	0.33
S4+LSST	23	28	0.49	0.10	0.26
	-	24	0.49	-	-

Setup (+CV-τ)	$\sigma(\Sigma m_\nu)$ [meV]	$\sigma(\Sigma m_\nu)$ [meV]	$\sigma(\Omega_k)$ [$\times 10^{-3}$]	$\sigma(w_0)$	$\sigma(w_a)$
LSST-clustering	69	91	3.3	0.42	1.20
LSST-shear	31	117	2.82	0.18	0.55
LSST-shear+clust	24	72	1.99	0.11	0.31
S4+LSST	14	21	0.49	0.10	0.26
	-	15	0.49	-	-

arXiv:2803.07561, S. Mishra-Sharma et al.

- Degeneracy with other cosmological parameters (Ω_k,w_0,w_a,...)
- Strong degeneracy between τ and m_ν for CMB lensing
- Need a measurement of τ with CMB polarization (LiteBird)
- LSST+S4+LiteBird gives **$\sigma(m_\nu)$~14 meV**

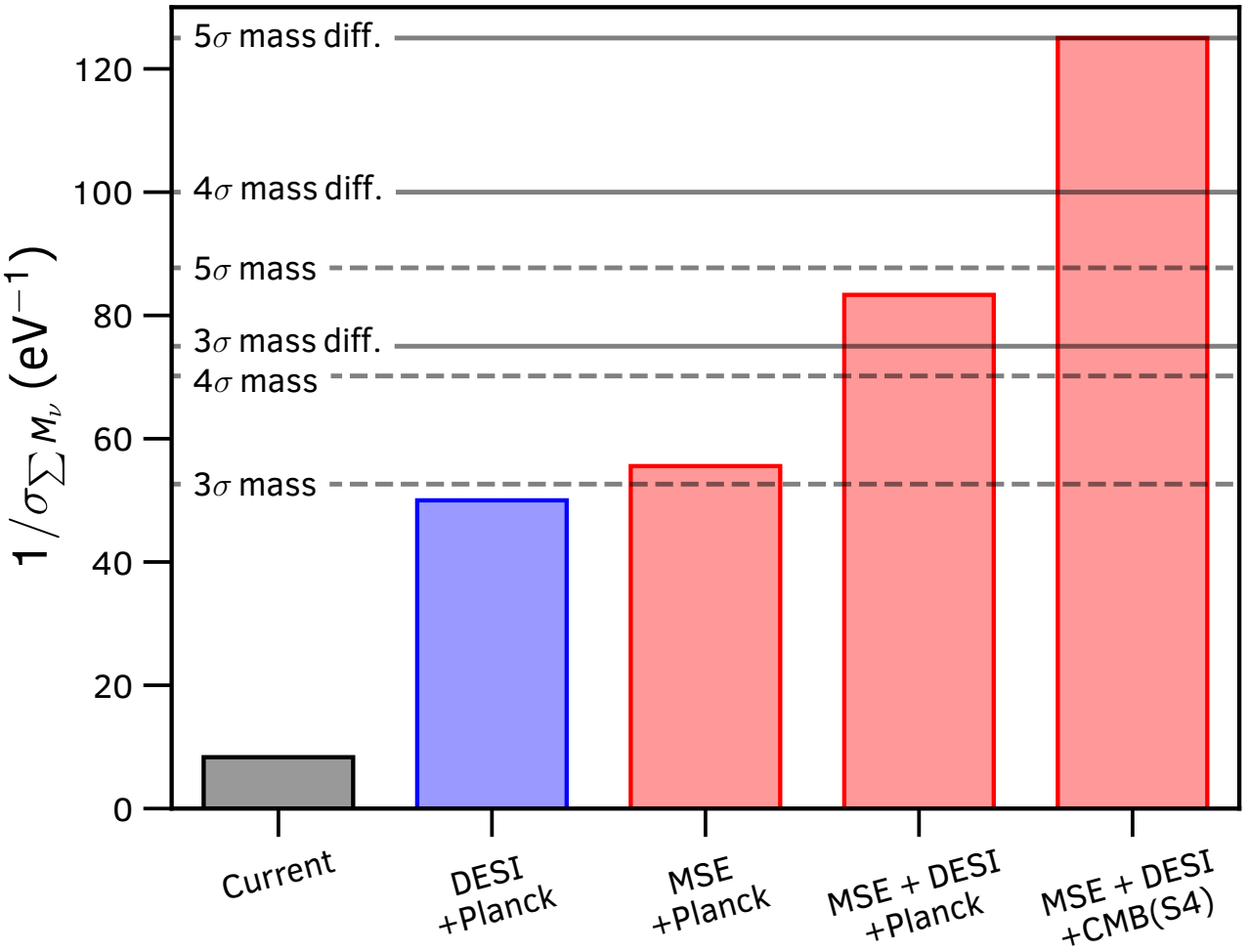
A wide and distant cosmological survey



Probing primordial Universe with SF galaxies and quasars

- Wide survey: 10,000 deg²
- Three tracers covering 1.6<z<4.0
  ELGs, Lyman Break Galaxy (LBG) and QSOs
- 100 nights per year for a 5-year MSE program
- In addition to BAO and RSD, test of Primordial Universe

MSE :Forecast for Σm_ν



A most precise measurement of neutrino mass

- With CMB(S4), accuracy on neutrino masses $\sigma(\Sigma m_\nu)$~8 meV
- Measure the neutrino masses and test the mass hierarchy
- Neutrino mass hierarchy at 5σ as precise as DUNE (ν beams)

Summary

- Short-term: ~2025, DESI+Euclid+Planck $\sigma(\Sigma m_\nu)$~20 meV
  - **3σ on neutrino masses**
- Mid-term: ~2030, LSST+CMB-S4+LiteBird $\sigma(\Sigma m_\nu)$~14 meV
  - **$4\text{-}5\sigma$ on neutrino masses**
- Long-term: ~2035, MSE+CMB-S4 $\sigma(\Sigma m_\nu)$~8 meV
  - **Mass hierarchy at ~5σ**