Physical effects involved in the measurements of neutrino masses with future cosmological data

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Abstract. Future Cosmic Microwave Background experiments together with upcoming galaxy and 21-cm surveys will provide extremely accurate measurements of different cosmological observables located at different epochs of the cosmic history. The new data will be able to constrain the neutrino mass sum with the best precision ever. In order to exploit the complementarity of the different redshift probes, a deep understanding of the physical effects driving the impact of massive neutrinos on CMB and large scale structures is required. The goal of this work is to describe these effects, assuming a summed neutrino mass close to its minimum allowed value. We find that parameter degeneracies can be removed by appropriate combinations, leading to robust and model independent constraints. A joint forecast of the sensitivity of Euclid and DESI surveys together with a CORE-like CMB experiment leads to a 1σ uncertainty of 14 meV on the summed neutrino mass. However this particular combination gives rise to a peculiar degeneracy between M_ν and the optical depth at reionization. Independent constraints from 21-cm surveys can break this degeneracy and decrease the 1σ uncertainty down to 12 meV.

Cosmo club, Saclay **December 19, 2017**

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

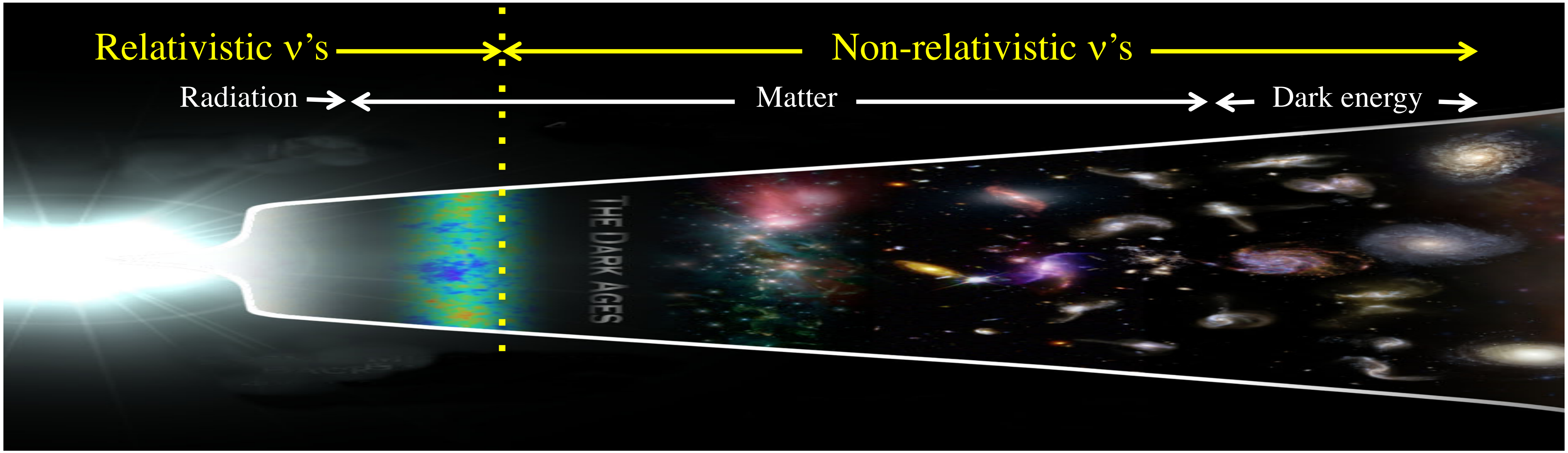
$$m_\nu \sim \langle p \rangle = \frac{\int p f(p) d^3p}{\int f(p) d^3p} = 3.15\, T_\nu \quad \text{with} \quad f(p) = \frac{1}{e^{p/T_\nu} + 1}$$

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

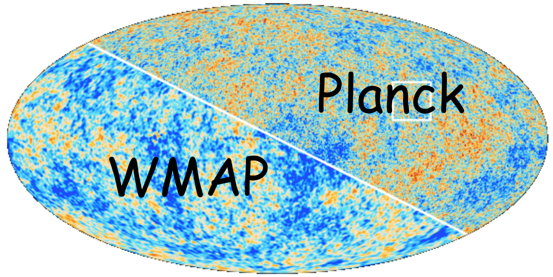
At recombination

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

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



Impact on CMB

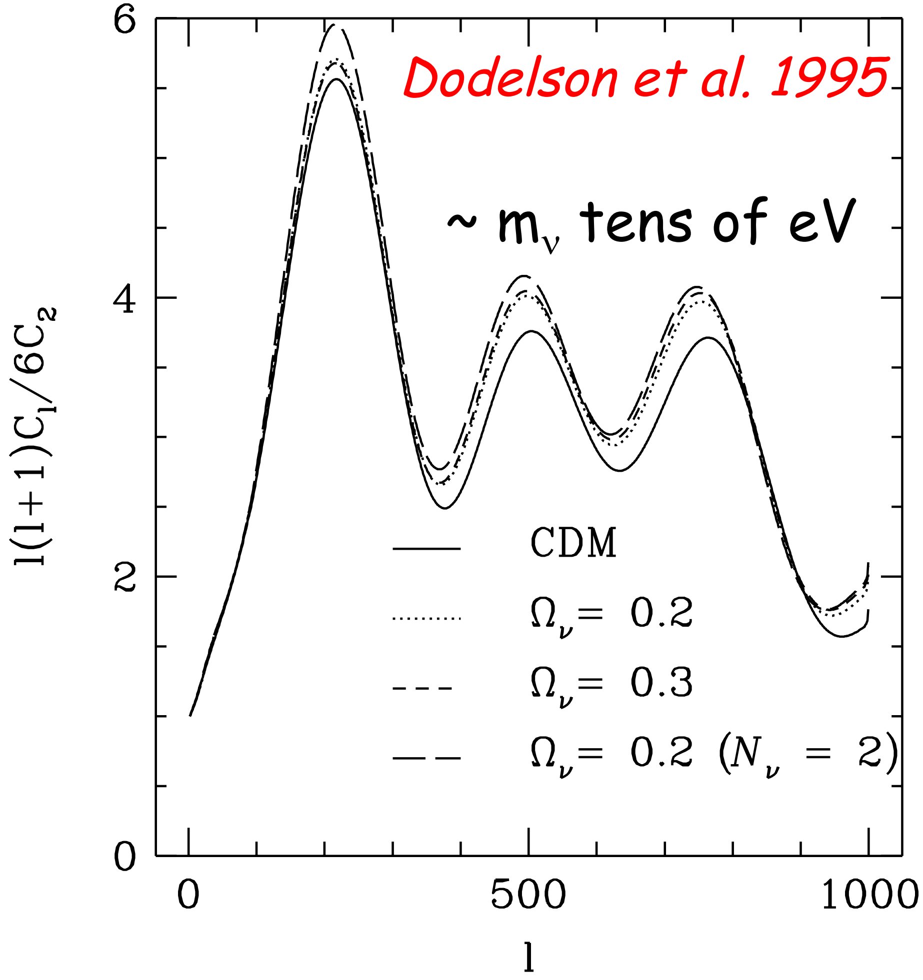


- m_ν > 0.6 eV (Σm_ν > 1.7 eV)
  - Non relativistic at CMB
  - Hot Dark Matter (HDM)

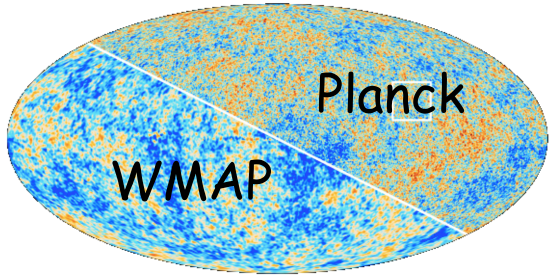
⇒ Direct impact on CMB power spectrum:

⇒ Even with pre-WMAP (COBE…), in late 90s, the damping of C_ℓ on intermediate scales (100<l<1000) cannot be explained without relativistic neutrinos

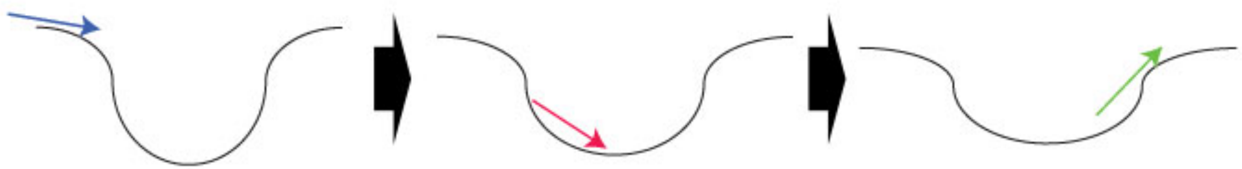
⇒ Fully excluded with WMAP including HCDM models (10% of HDM)

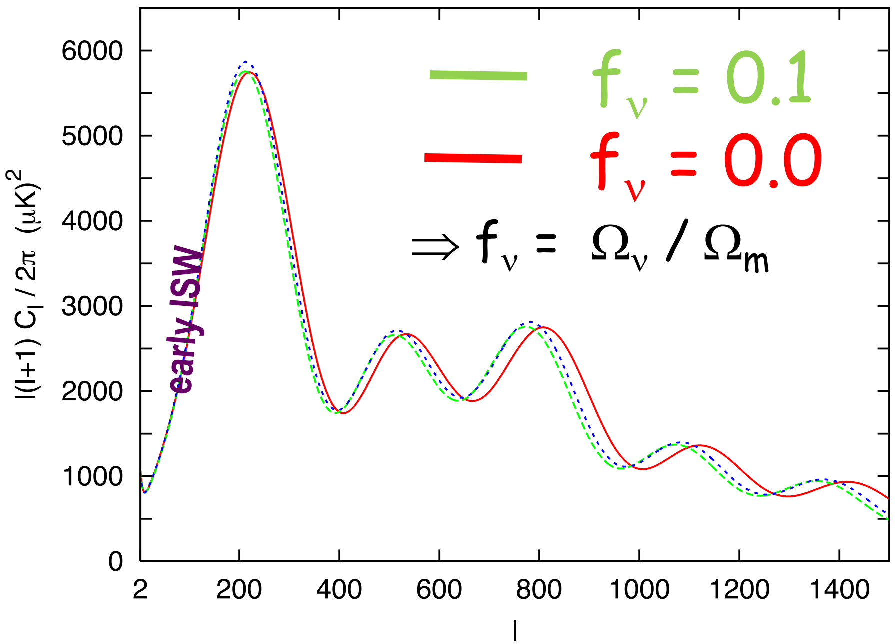


Impact on CMB



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

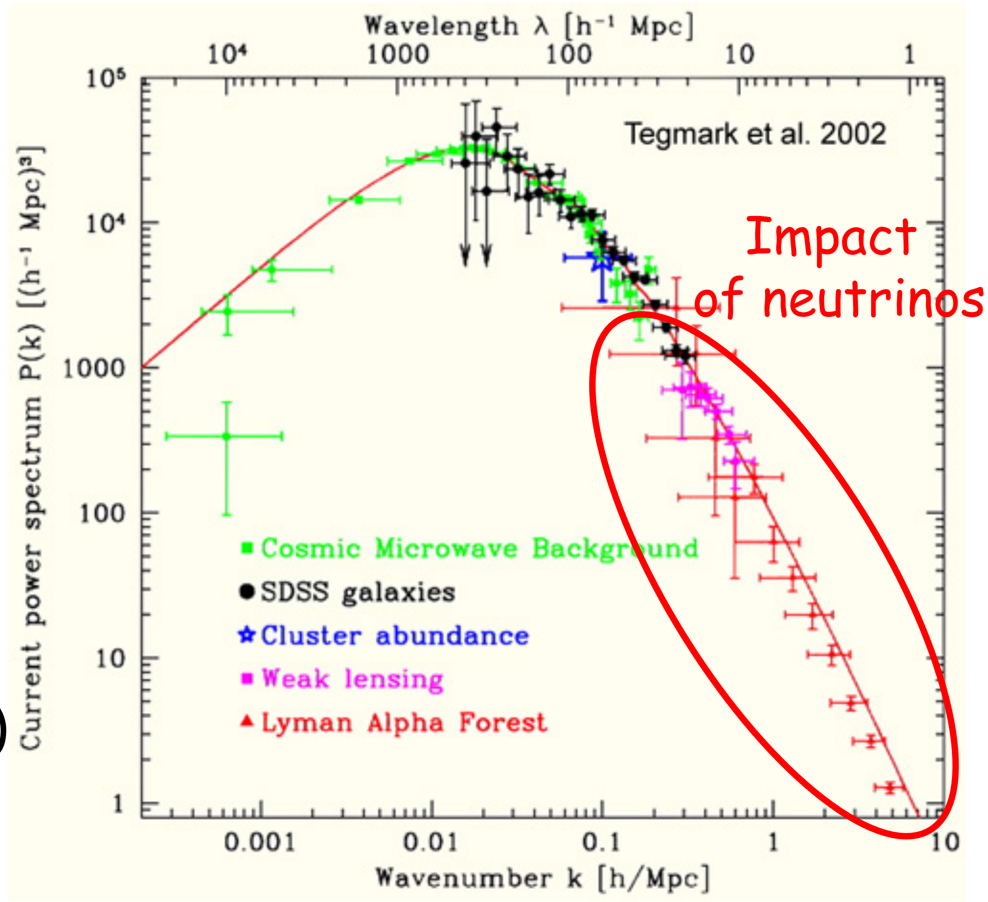




- ➢ CMB alone not sufficient for neutrinos masses sub-eV
- ➢ Add information directly from **the matter distribution**

Matter power spectrum

Matter era | Radiation era



Large scales | Small scales

$\mathbf{k_{eq}}$

Matter power spectrum

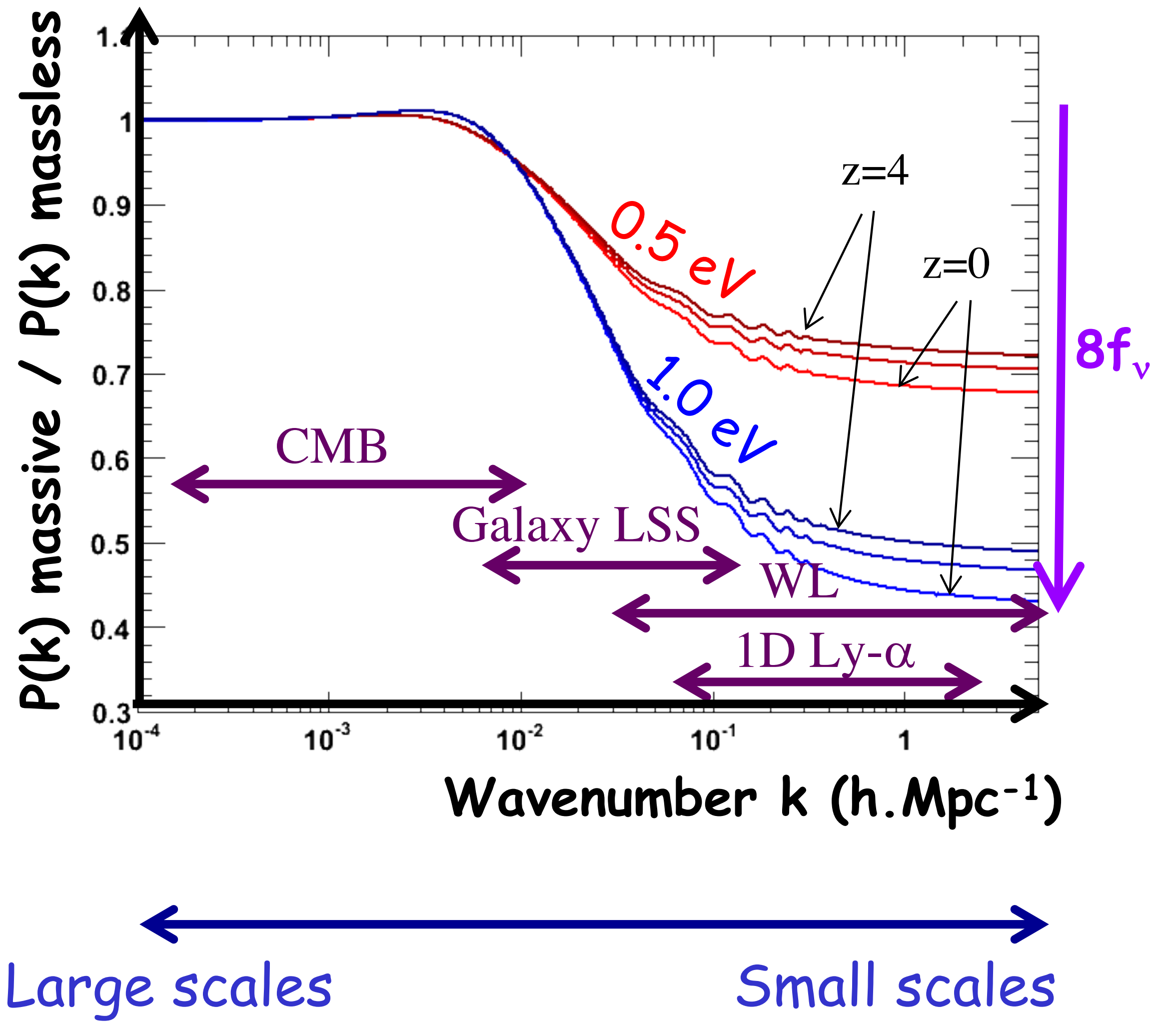
- Analogy with sound: higher at certain frequencies
- Real space ⟹ k-space (Mpc^{-1})
- First observation of "total" power spectrum with different tracers of the matter

Finite velocity of light

- Causality "horizon" (↗ with time)
- Small scales enter horizon early
  Large scales enter horizon late
- Relativistic neutrinos will affect 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 ⇔ Σm_ν
- 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

Neutrino oscillations

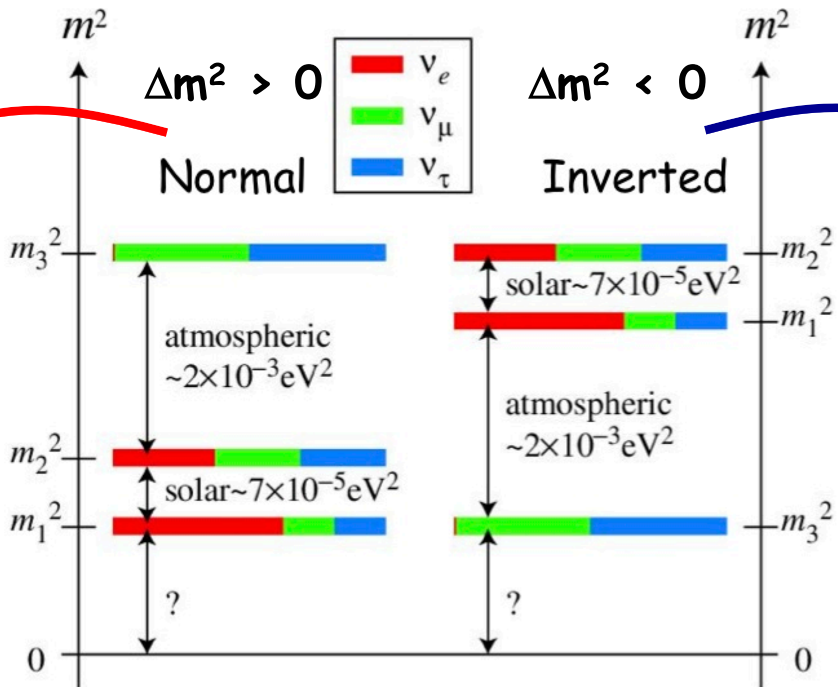
Mass eigenstates $m_{1,2,3}$ and flavor eigenstates $m_{e,\mu,\tau}$

Solar	$\delta m^2 = m_2^2 - m_1^2$	$\sim 7.5\ 10^{-5}\ eV^2$
Atmospheric	$\Delta m^2 = m_3^2 - (m_1^2 + m_2^2)/2$	$\sim 2.4\ 10^{-3}\ eV^2$

→ No constraint on absolute masses

→ 2 schemes (sign of Δm^2)

$\Sigma m > 0.06$ eV

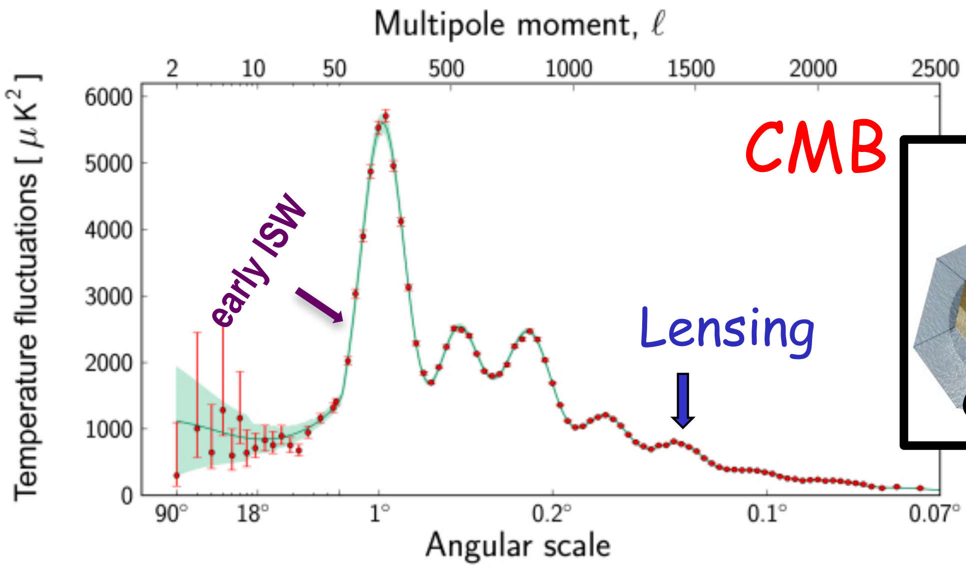


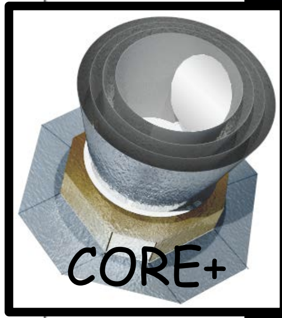
$\Sigma m > 0.10$ eV

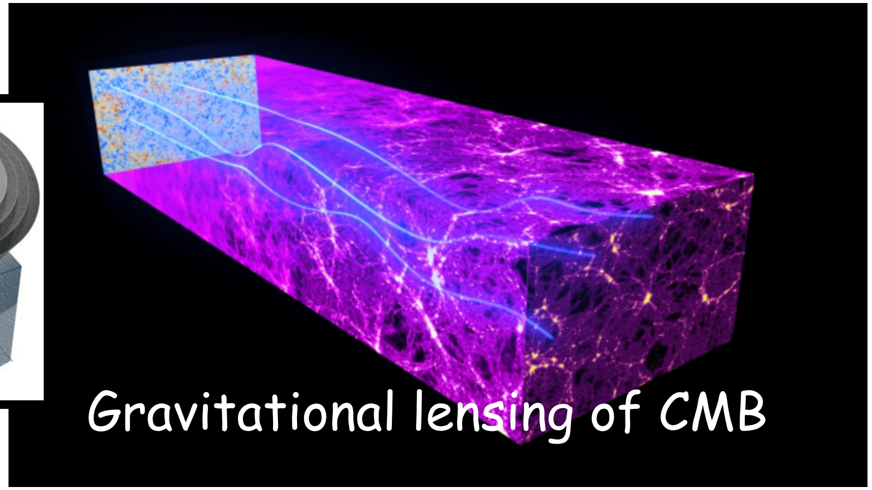
An answer with the cosmological neutrinos?

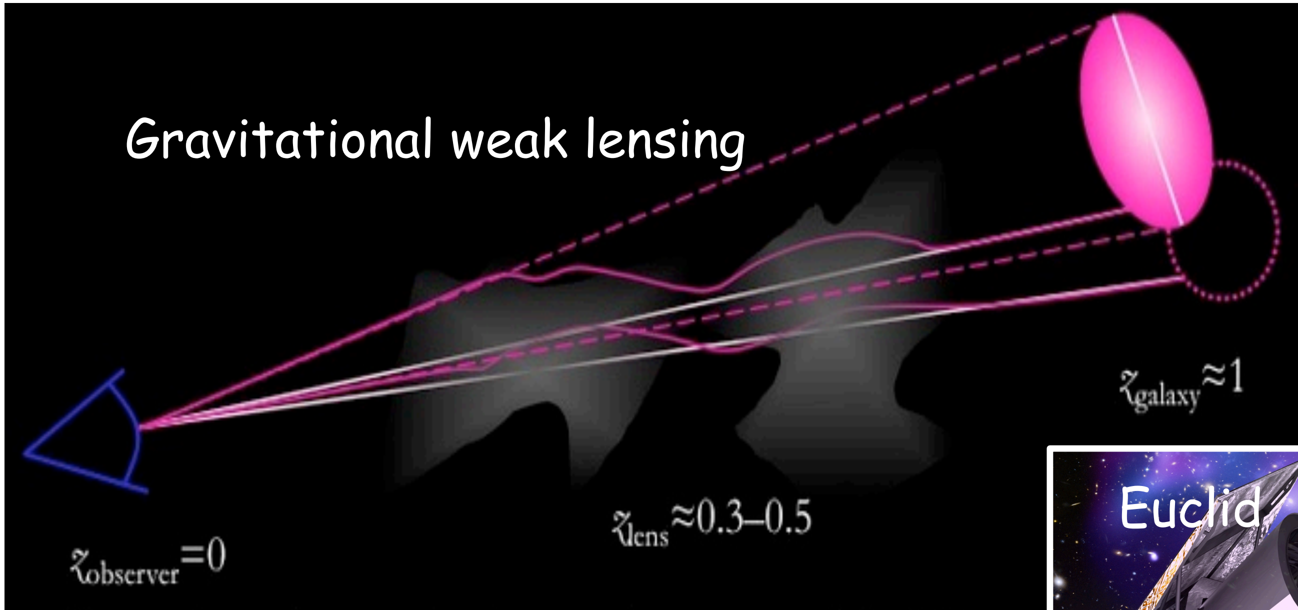
Forecast on neutrino masses with future cosmological projects

Probes –Projects

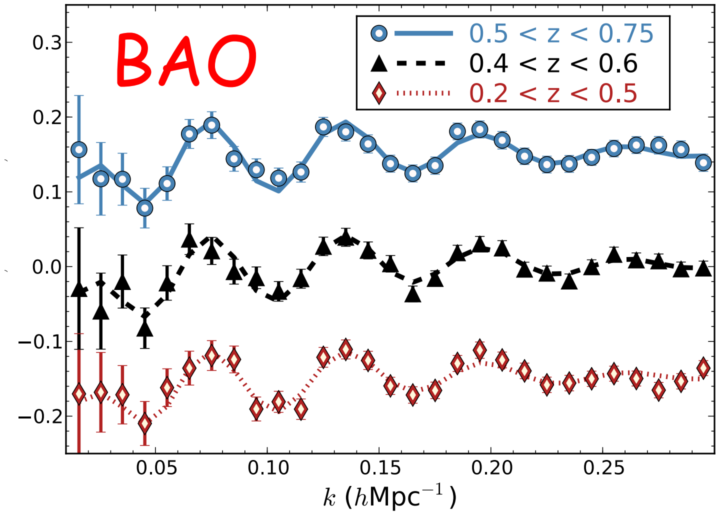




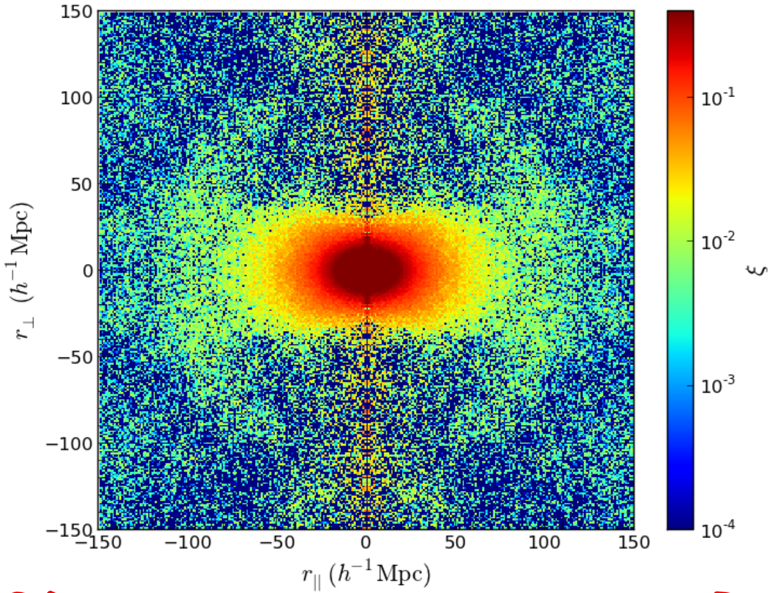




Probes - Projects

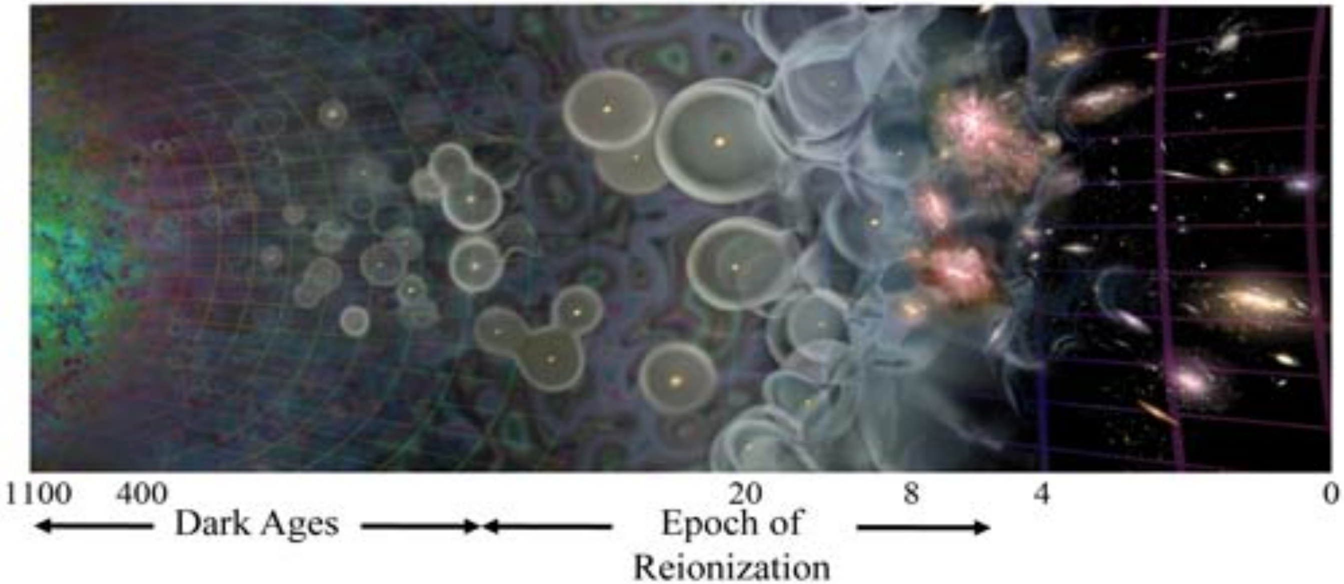


DESI



3D power spectrum - RSD

Epoch of Reionization - EoR



21cm projects
SKA -HERA

Strategy and goals of the papers

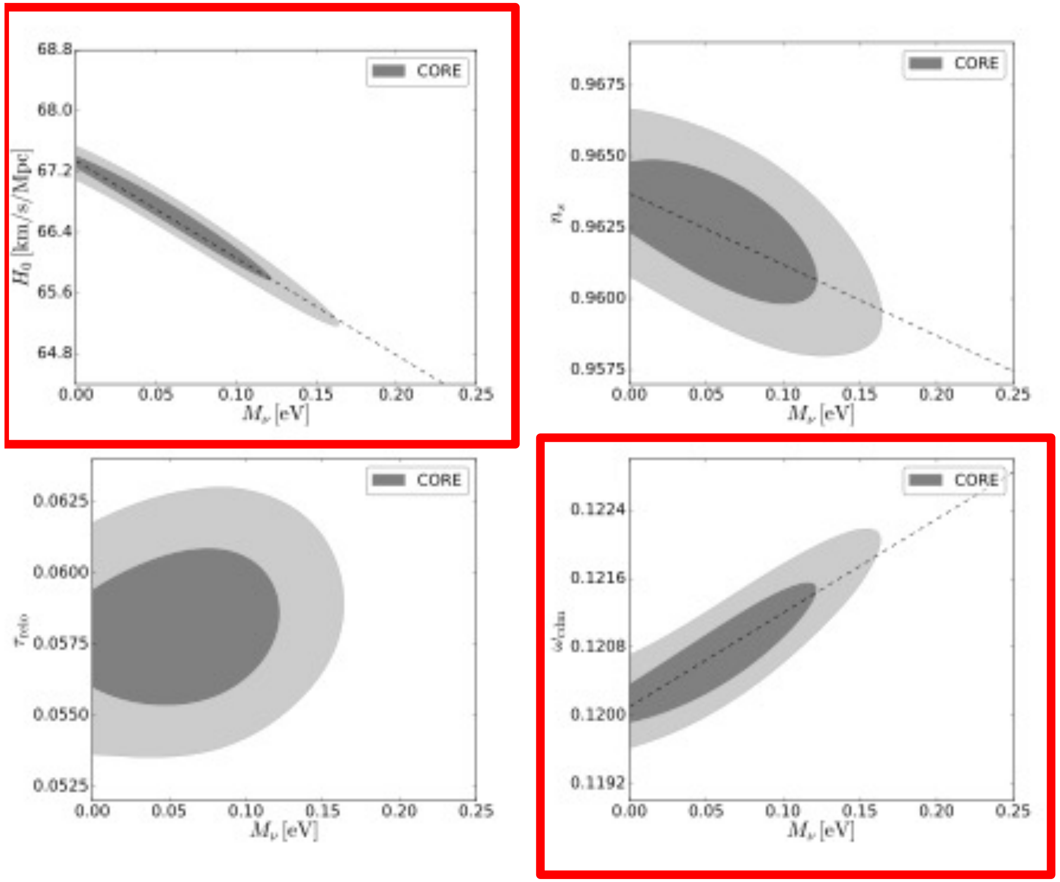
Range for the neutrino masses

- Many analyses in cosmology indicate that $\Sigma m_\nu < 0.15$ eV (even 0.12 eV)
- Lower limit 60meV (normal hierarchy)
- Range used for the study $60 < \Sigma m_\nu < 150$ meV

Several scenarios

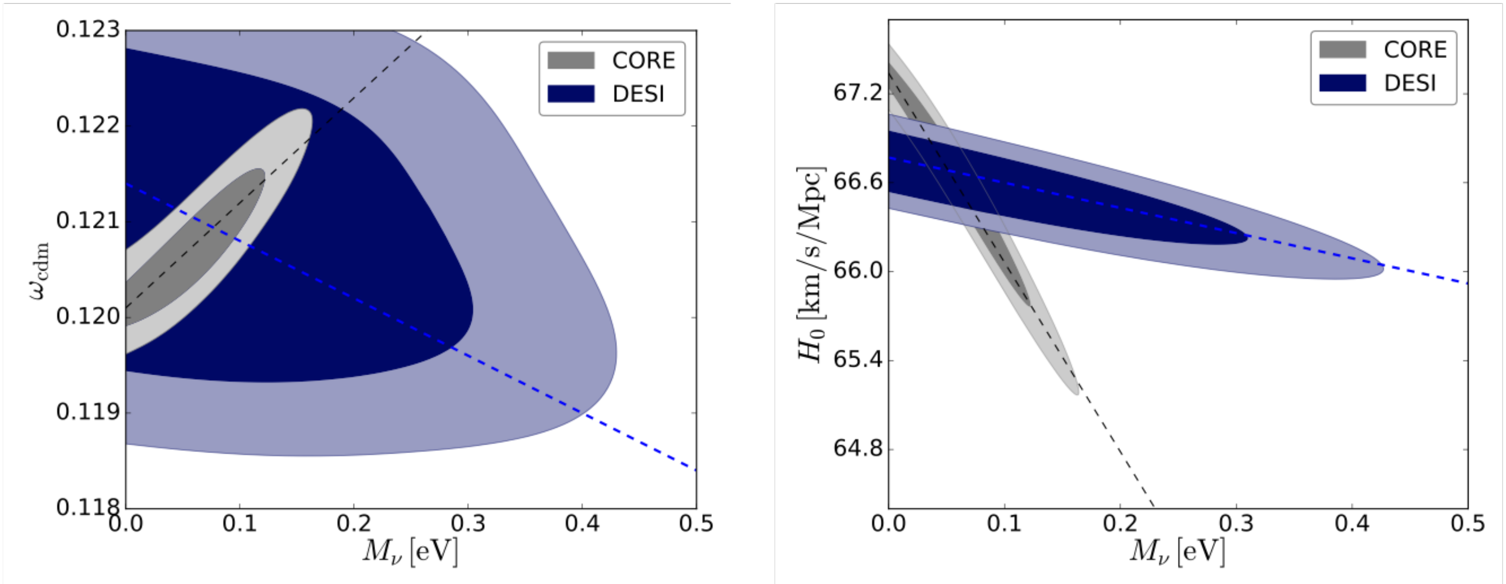
- CMB-alone (but with lensing!) **CORE-like**
- CMB+BAO **CORE+DESI**
- CMB+BAO+WL+P(k) **CORE+Euclid**
- CMB+BAO+WL+P(k)+EoR **CORE+Euclid+21cm**

CMB-alone - CORE



- In CMB strong correlation between H_0 and Σm_ν
- Origin: ***early ISW***
- Impact on first CMB peak therefore acoustic scale and H_0
- Correlation between ω_{CDM} and Σm_ν due to **lensing** of CMB

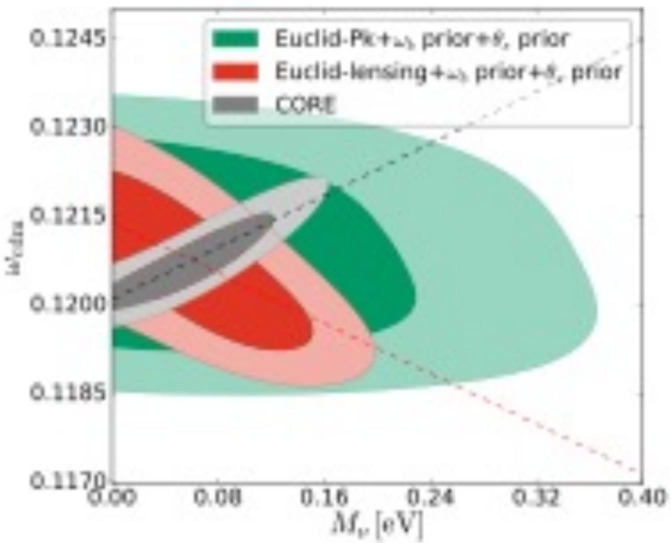
CMB+BAO - CORE+DESI

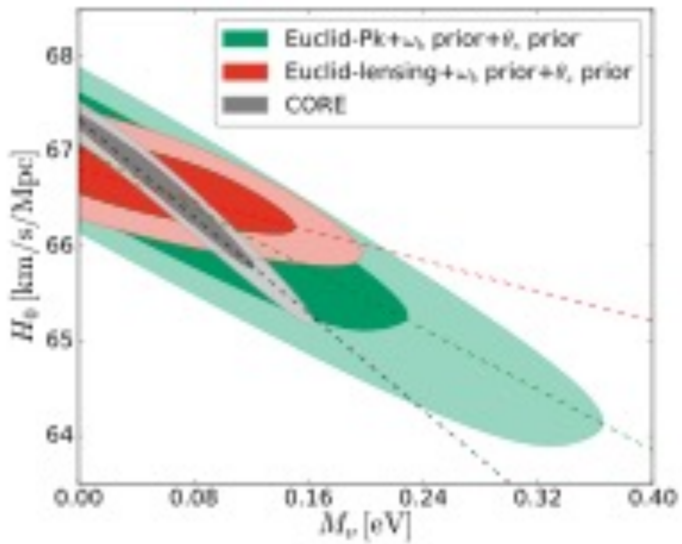


- BAO data alone can constrain Σm_ν but not with great accuracy
- See for instance in (ω_{CDM},Σm_ν) plane

- BAO breaks the (H_0,Σm_ν) degeneracy by adding another measurement of the acoustic scale at a different redshift

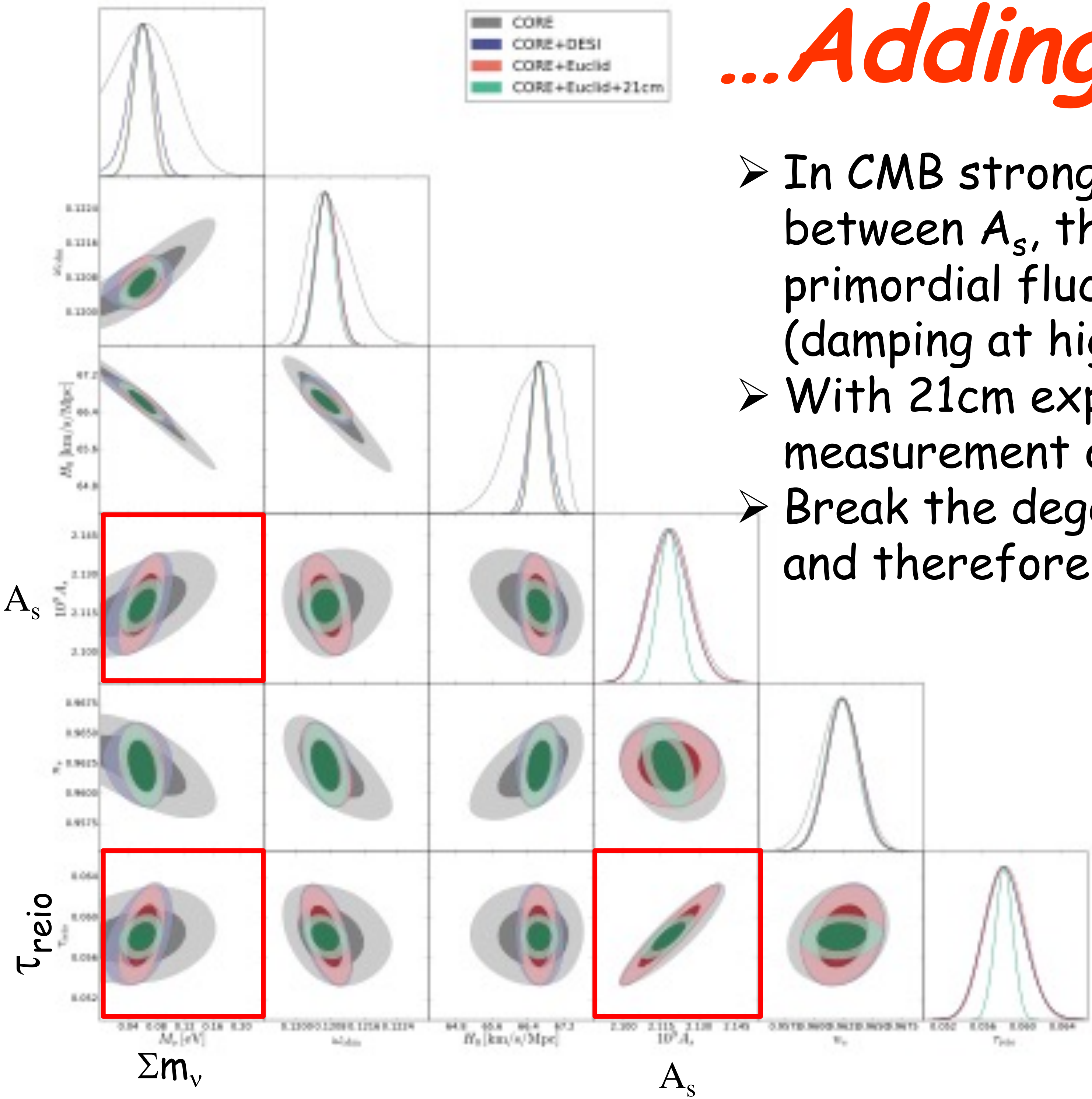
CMB+BAO+WL+P(k) CORE+Euclid





- WL and CMB have different direction of degeneracy in $(\omega_{CDM},\Sigma m_\nu)$ plane.

- As BAO, P(k) and WL prefers different directions of degeneracy in $(H_0,\Sigma m_\nu)$ plane.
- Reduce uncertainty on both H_0 and Σm_ν.



…Adding 21 cm

- In CMB strong correlation between A_s, the amplitude of primordial fluctuations and τ_{reio} (damping at high l) and (A_s, Σm_ν)
- With 21cm experiment measurement of z_{reio}
- Break the degeneracy (A_s, τ_{reio}) and therefore (A_s, Σm_ν)

Summary

	$\sigma(M_\nu)/[\mathrm{meV}]$	$\sigma(\tau_{\mathrm{reio}})$	$\sigma(10^9 A_s)$	$\sigma(n_s)$	$\sigma(\omega_{\mathrm{cdm}})$	$\sigma(h)$
CORE	42	0.0020	0.0084	0.0018	0.00052	0.0052
CORE+DESI	19	0.0020	0.0080	0.0014	0.00026	0.0022
CORE+DESI+Euclid-lensing	16	0.0020	0.0078	0.0014	0.00023	0.0019
CORE+Euclid (lensing+pk)	14	0.0020	0.0079	0.0015	0.00025	0.0017
CORE+Euclid (lensing+pk)+21cm	12	$--$	0.0042	0.0014	0.00021	0.0017

to compare with DESI forecast

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

Reasonable to think that we will measure neutrino masses at σ~20-25 meV in 2025 just with Planck+DESI

Additional Slides

Free-Streaming

Velocity dispersion large wrt size of potential well