Neutrinos and Cosmological Perturbations

Napoli, 3rd December 2004

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+Laurence Perotto (PCC, CdF)

1) a powerful tool: cosmological perturbations

brief review of observations / theory

2) effect of neutrino masses

perturbations damped by neutrino free-streaming

3) current cosmological bounds on the masses

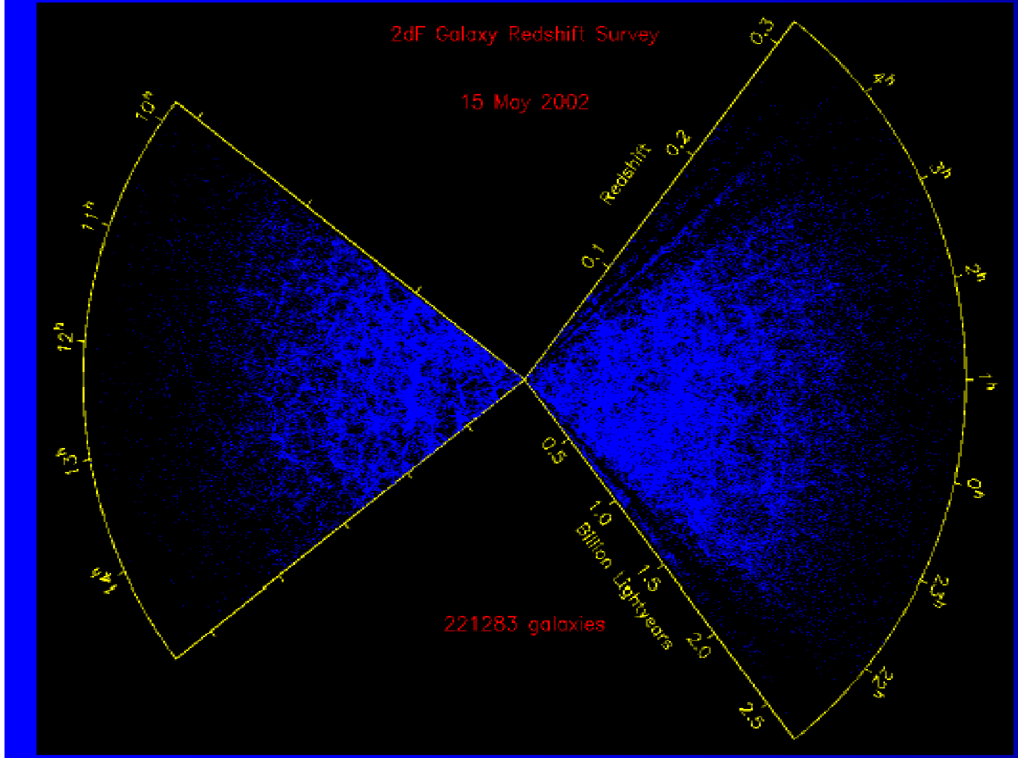
using CMB, redshift surveys, Lyman-α ...

4) future prospects

future CMB experiments, weak lensing ...

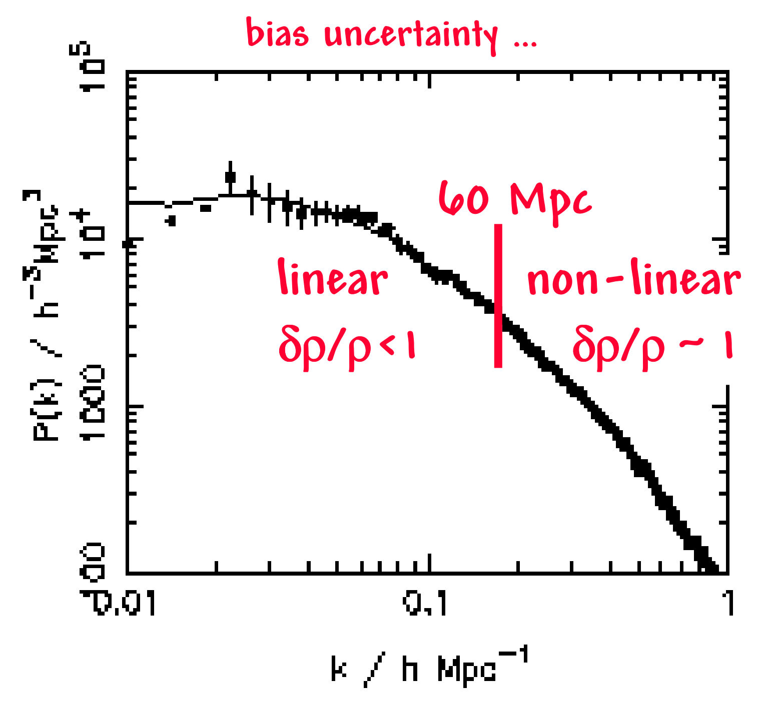
Observing cosmological perturbations

1) Large Scale Structure (LSS)


2dF Galaxy Redshift Survey

15 May 2002

221283 galaxies


bias uncertainty ...

60 Mpc

linear

$\delta\rho/\rho < 1$

non-linear

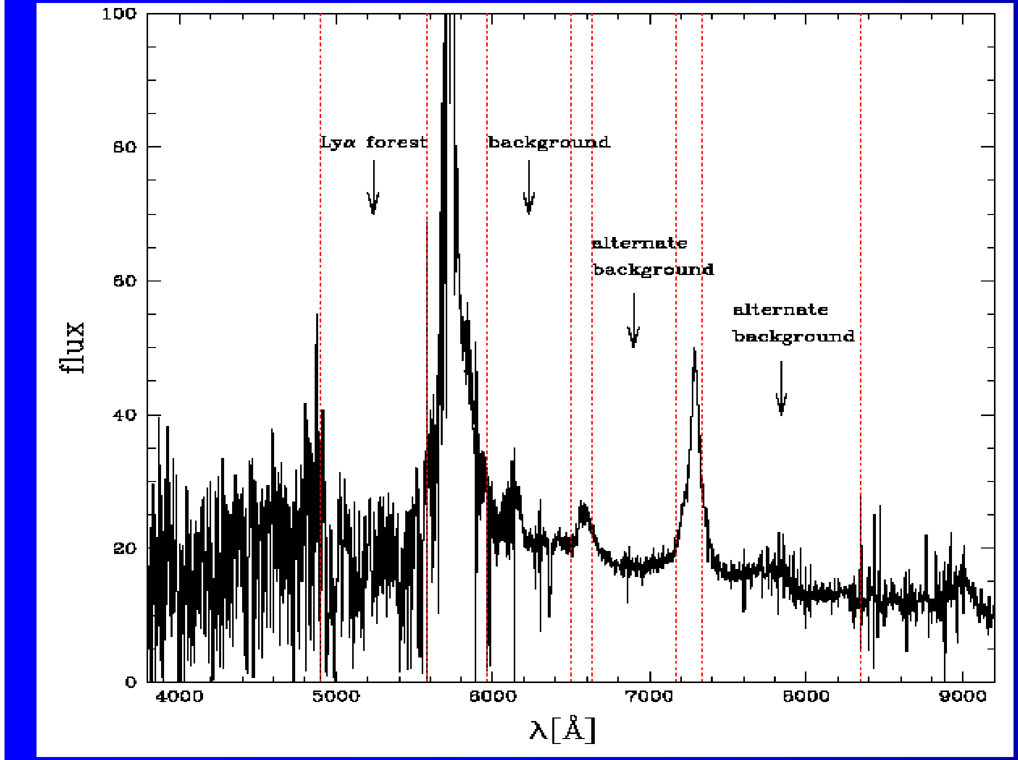
$\delta\rho/\rho \sim 1$

Percival et al. 02

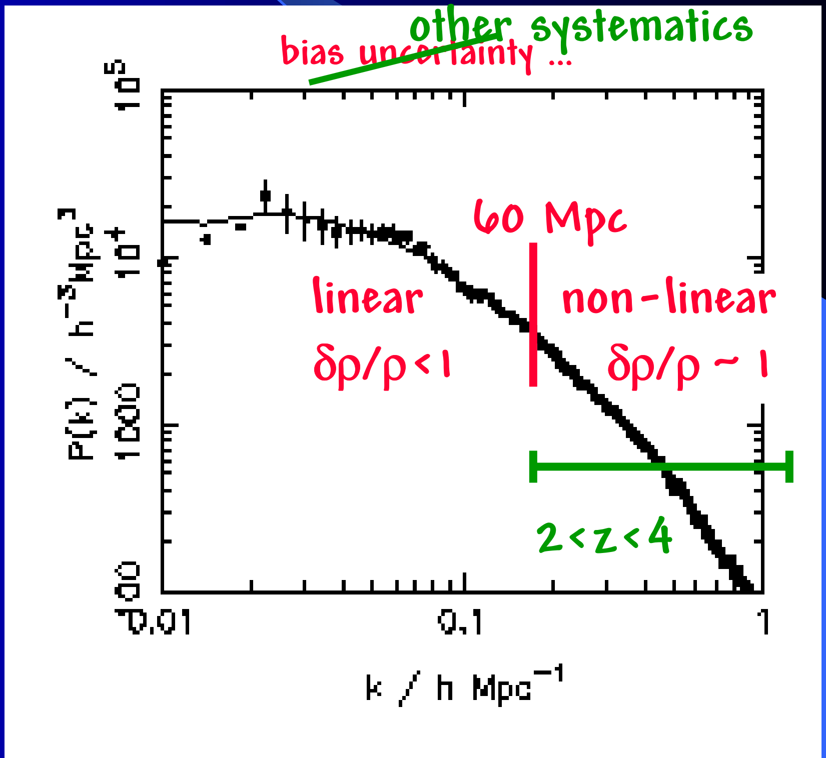
redshift surveys (here from 2dF) $\Rightarrow \delta\rho/\rho(x) \Rightarrow$ power spectrum $P(k)$

Observing cosmological perturbations

1) Large Scale Structure (LSS)



McDonald et al. 02

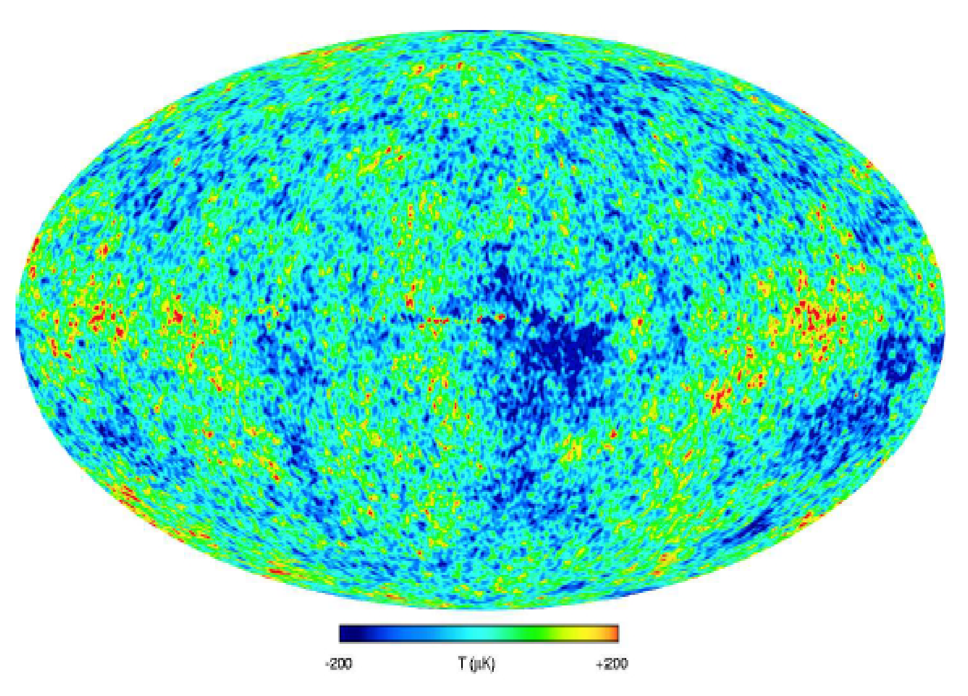


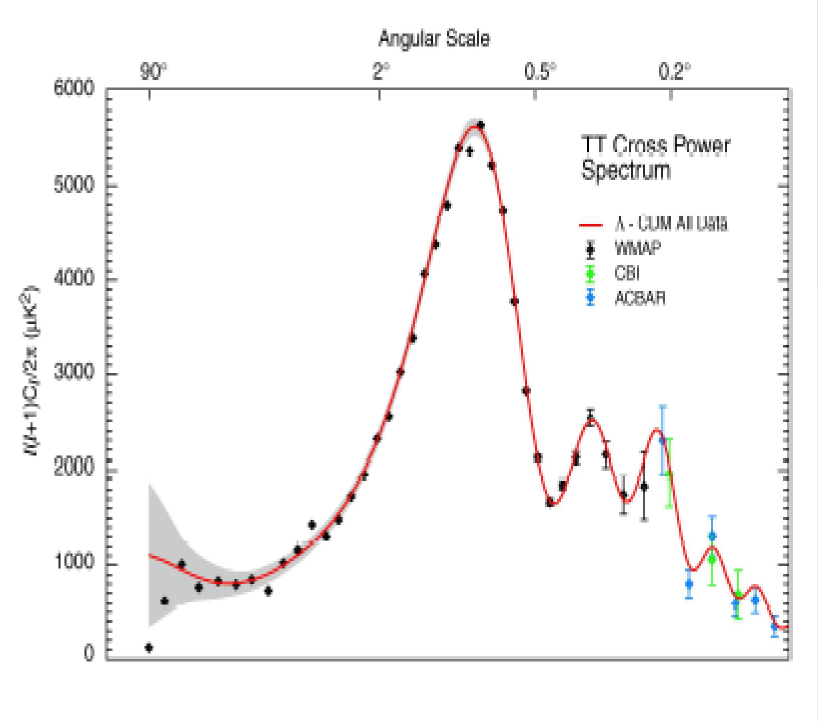
Percival et al. 02

Lyman-α (here from SDSS) $\Rightarrow \delta\rho/\rho(x) \Rightarrow$ power spectrum $P(k)$

Observing cosmological perturbations

2) Cosmic Microwave Background (CMB) anisotropies





Spergel et al. 03

WMAP $\Rightarrow$ $\delta T/T(\theta,\phi)$ $\Rightarrow$ power spectrum C_l

Theory of cosmological perturbations

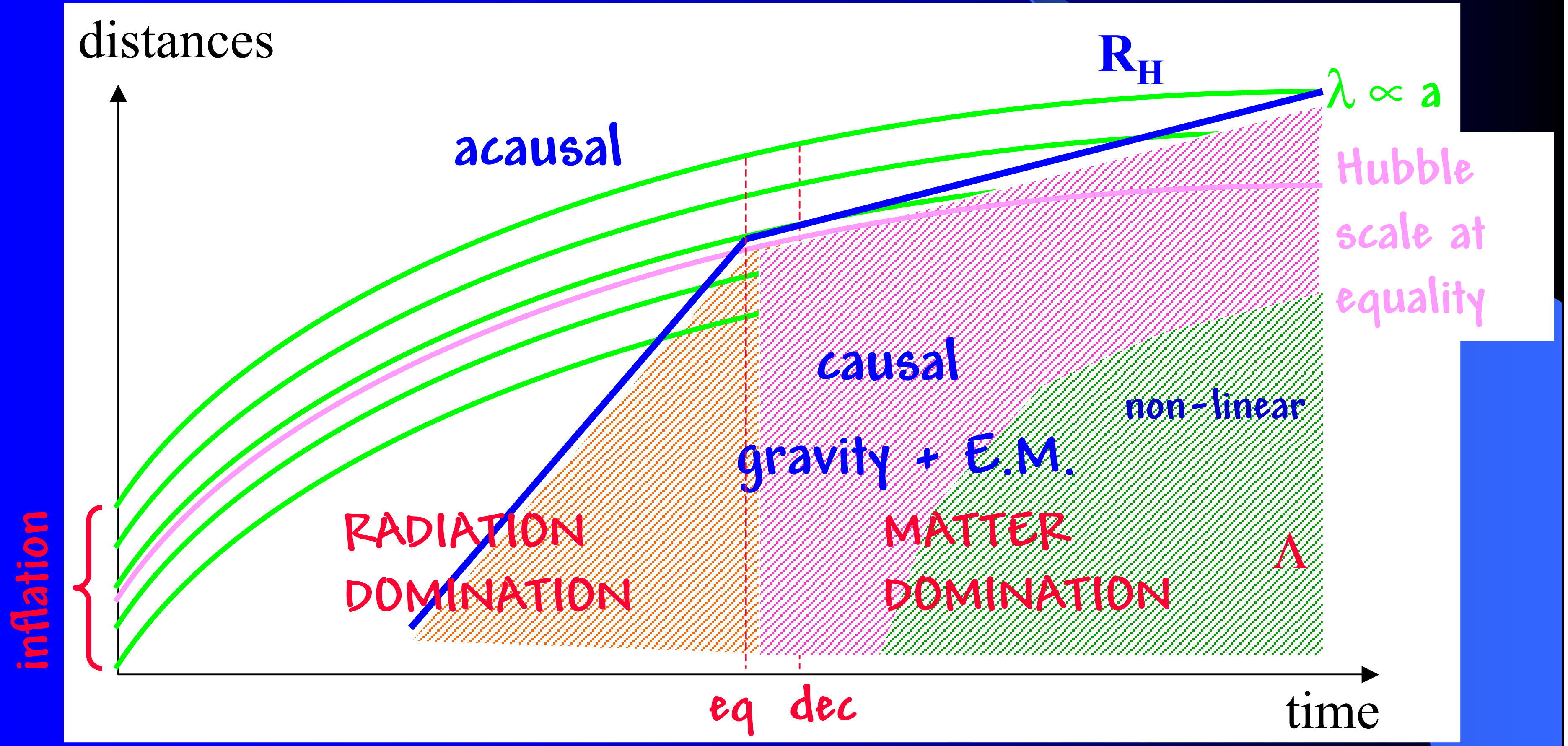
- ☐ inhomogeneities decomposed in Fourier space

- ☐ physical wavelengths grow with scale factor :

$$\lambda(t) = (2\pi/k)\, a(t)$$

Before decoupling:
gravity / photon pressure
acoustic oscillations of γ , b

After equality:
gravity only
structure formation for cdm, b



Cosmological neutrino background

- thermalization before decoupling, then collisionless :

$T_{dec}(\nu_e) \approx 2.3$ MeV

$T_{dec}(\nu_{\mu,\tau}) \approx 3.5$ MeV

$$f_\nu = [e^{p/T}+1]^{-1}$$

- relativistic regime : $\langle p \rangle = 3\, k_B T_\nu >> m_\nu$

$$\rho_\nu = N_\nu\, (7/8)\, (\pi^2/30)\, T_\nu^{\,4} \propto a^{-4} \quad \begin{cases} N_\nu = 3.04 \\ T_\nu = (4/11)^{1/3}\, T_\gamma \end{cases}$$

Mangano et al. 02

- non-relativistic regime :

$$\rho_\nu = m_\nu\, n_\nu \propto a^{-3}$$

Cosmological neutrino background

- thermalization before decoupling, then collisionless :

$= [e^{p/T}+1]^{-1}$

$T_{dec}(\nu_e) \approx 2.3$ MeV

$T_{dec}(\nu_{\mu,\tau}) \approx 3.5$ MeV

- relativ $= 3\, k_B\, T_\nu >> m_\nu$

ρ_ν $)\, T$ $\propto a^{-4}$

$$\begin{cases} N_\nu = 3.04 \\ T_\nu = (4/11)^{1/3}\, T_\gamma \end{cases}$$

Mangano et al. 02

- non-r :

$\rho_\nu = m_\nu\, n_\nu$ $\propto a^{-3}$

testable assumptions ▷ (BBN, CMB + LSS)

Effect of neutrino mass

- ☐ since collisionless after decoupling
  - ➢ couple only through Einstein equations
- ☐ Background :

$$a(t) \Leftrightarrow \Sigma_i \rho_i(t)$$ (Friedmann eq.)

  - ➢ can change characteristic times and scales
- ☐ Perturbations :

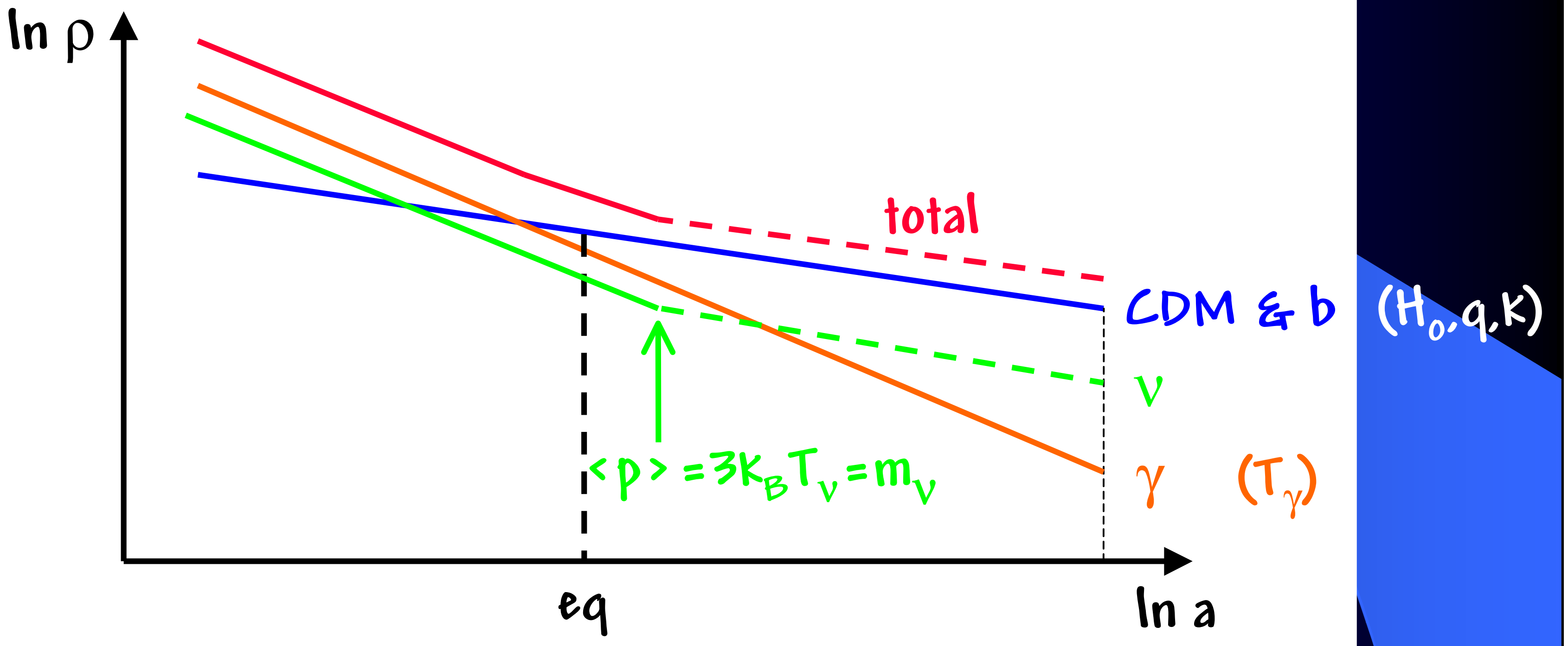
$$\delta g_{\mu\nu} \Leftrightarrow \delta T_{\mu\nu}$$

  - ➢ inside horizon :

$$\Delta\phi_{grav} = 4\pi G\, a^2\, (\Sigma_i\, \delta\rho_i)$$ (Poisson eq.)

  - ➢ can change growth of matter perturbations

Effect of neutrino mass



$\rho_\nu = m_\nu n_\nu$: current density given by $(\Sigma_i \, m_{\nu i})$

Effect of neutrino mass

1) background effect :

ν masses change total density for $t > t_{n.r.}$

$\Rightarrow$ change geometry

or for $\Omega_0 = 1$:

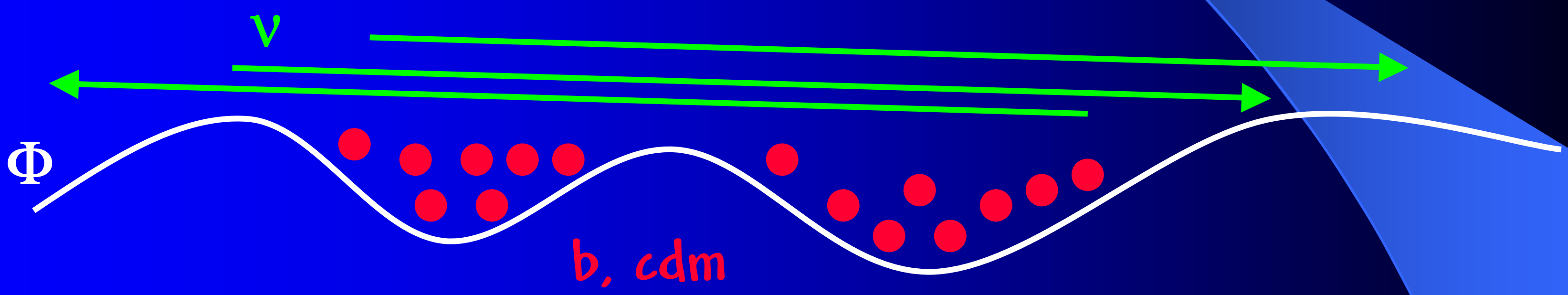
$\Rightarrow$ change Ω_m , Ω_Λ , matter/vacuum density and $t_{equality}$

$\Omega_\nu \sim (\Sigma m_\nu) / (50 \text{ eV}) \rightarrow$ SMALL for $\Sigma m_\nu < 1$ eV

Effect of neutrino mass

2) perturbation effect :

$$\Delta\phi_{grav} = 4\pi G\, a^2\, (\delta\rho_m + \boxed{\delta\rho_\nu} + \dots)$$

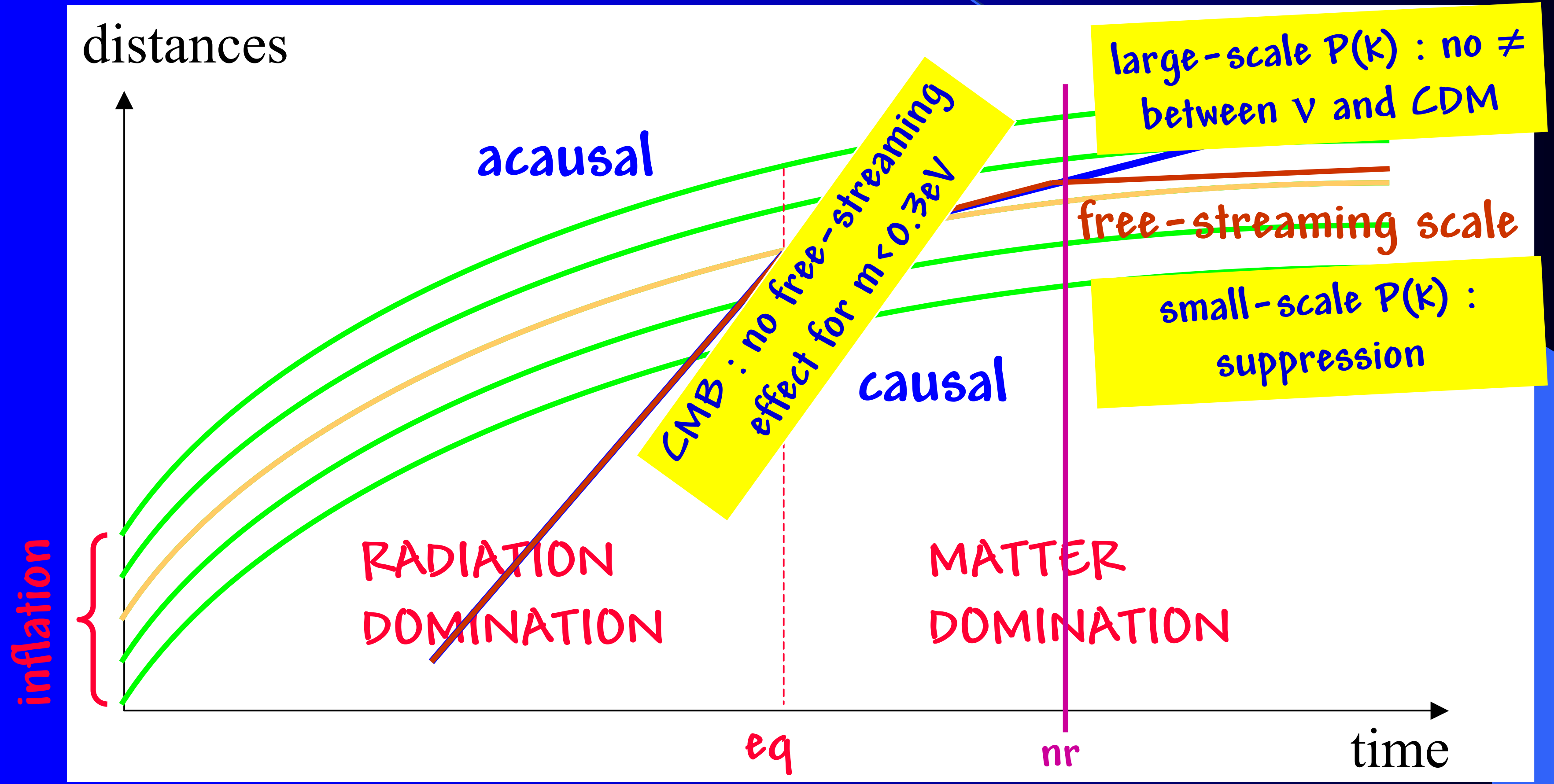


Free-streaming prevents growth of structure during MD

Efficient on wavelengths $\begin{cases} \text{rel.} & : \leq \; c/H = R_H \\ \text{non-rel.} & : \leq \; \langle v \rangle / H = (\langle p \rangle / m)\, R_H \end{cases}$

Effect of neutrino mass

2) perturbation effect :



CMB : no free-streaming effect for $m<0.3$eV

large-scale P(k) : no ≠ between ν and CDM

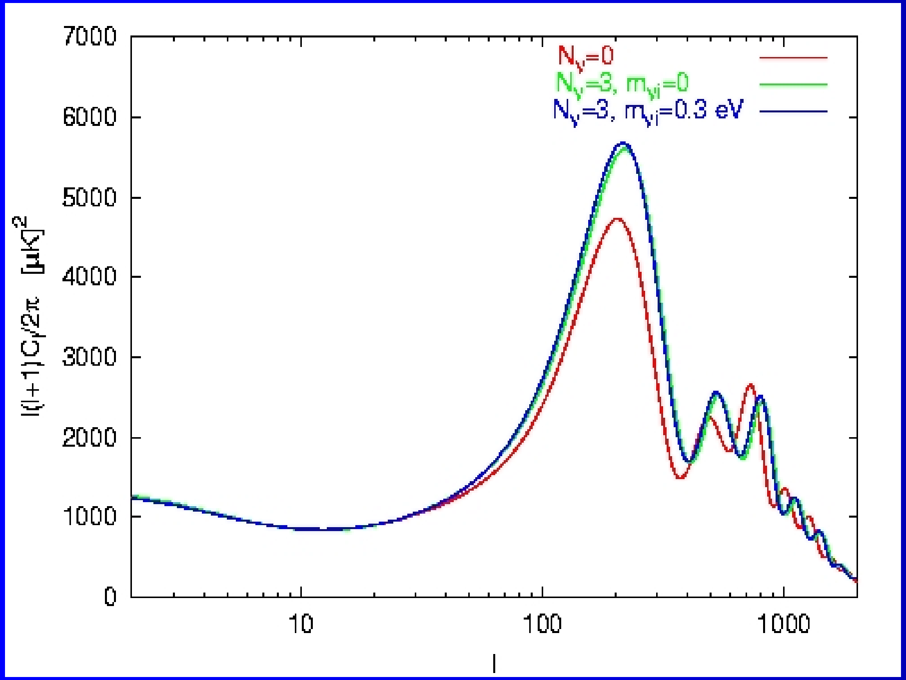
small-scale P(k) : suppression

▷ numerical simulations

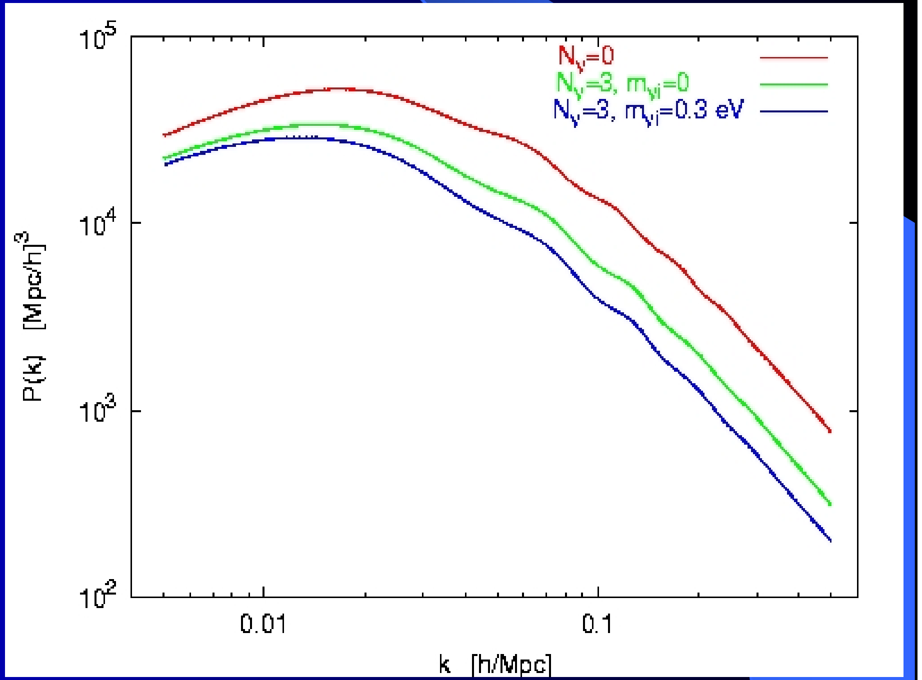
Effect of neutrino mass

change in Ω_ν + free-streaming

Consequence on CMB



Consequence on LSS



(fixed $\Omega_\nu + \Omega_\Lambda$, $\Omega_\nu \sim 0.02$, $\Sigma\, m_\nu \sim 0.9$ eV)

Effect of neutrino mass

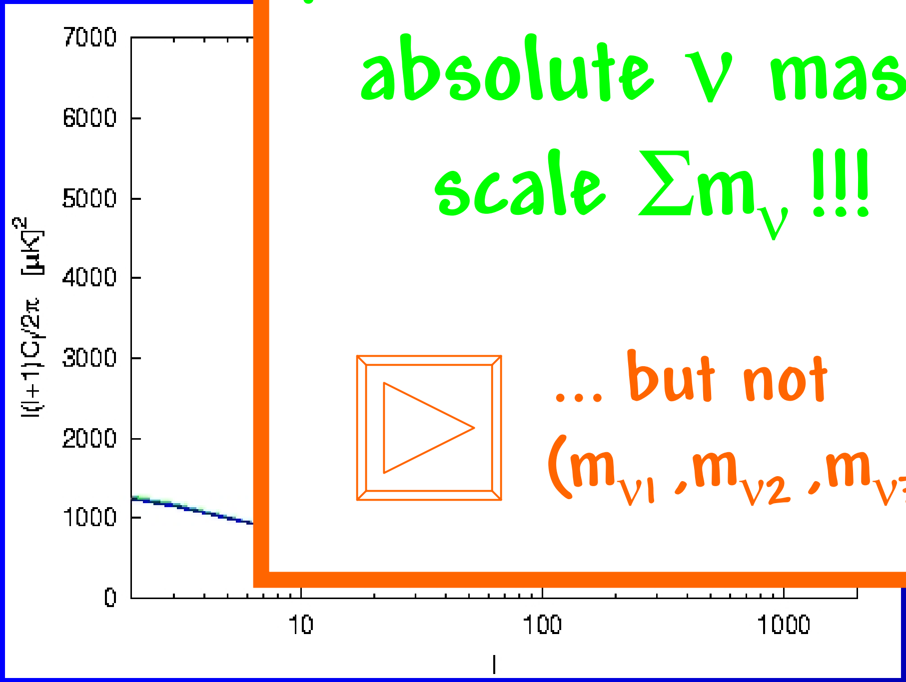
change in Ω_ν + free-streaming

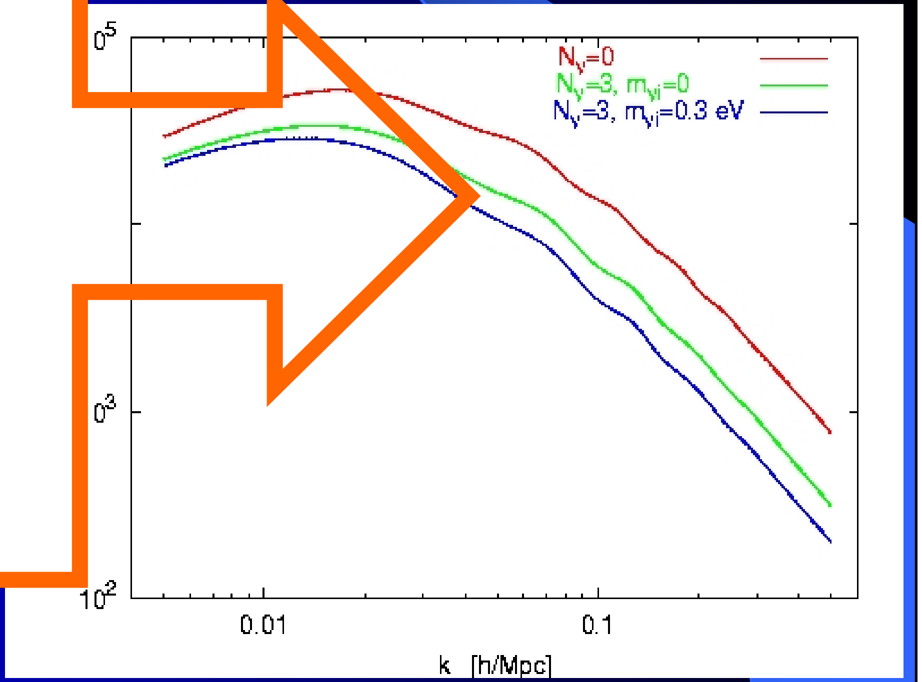
Co

possible to measure absolute ν mass scale Σm_ν !!!

... but not $(m_{\nu 1}, m_{\nu 2}, m_{\nu 3})$

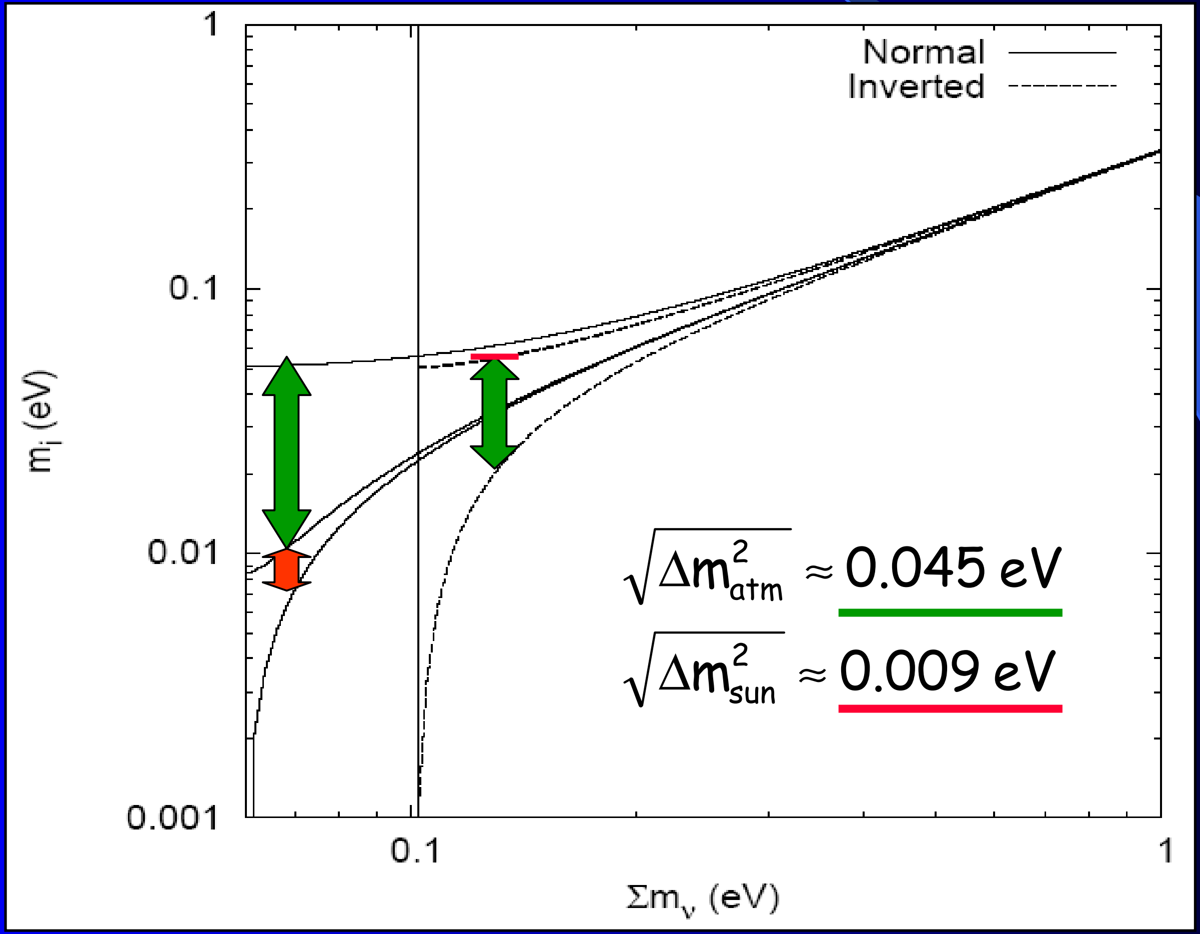
Consequence on LSS





Bounds on neutrino mass

- situation taking neutrino oscillation data into account:



Bounds on neutrino mass

- experiments sensitive to absolute neutrino mass scale :

Cosmology	$\sim \sum_i m_i$	next slides...
Tritium beta decay	$\left(\sum_i \lvert U_{ei}\rvert^2 m_i^2\right)^{1/2}$	< 2.3 eV
Neutrinoless double beta decay	$\left\lvert \sum_i U_{ei}^2 m_i \right\rvert$	< 0.3-1.2 eV

KATRIN:
0.2 eV ??
(2σ)

dep. on CP phases, Dirac/Majorana

Bounds on neutrino mass

- ☐ mass bounds for 3-ν scenarios :

THERE IS NOT A UNIQUE
« COSMOLOGICAL BOUND » !!!

- ➢depends on the exact data set and priors
- ➢depends on the underlying cosmological model

Bounds on neutrino mass

❑ mass bounds for 3-ν scenarios :

➢ method for given data:

1) compute $\mathcal{L}(\theta_1, \theta_2, \ldots, m_\nu)$ around its maximum
2) marginalize over the other parameters
3) bounds on m_ν

➢ final uncertainty depends on :

1) experimental errors
2) cosmic variance
3) parameter degeneracies (external priors: HST, SN,...)
4) underlying model (criterium of simplicity)

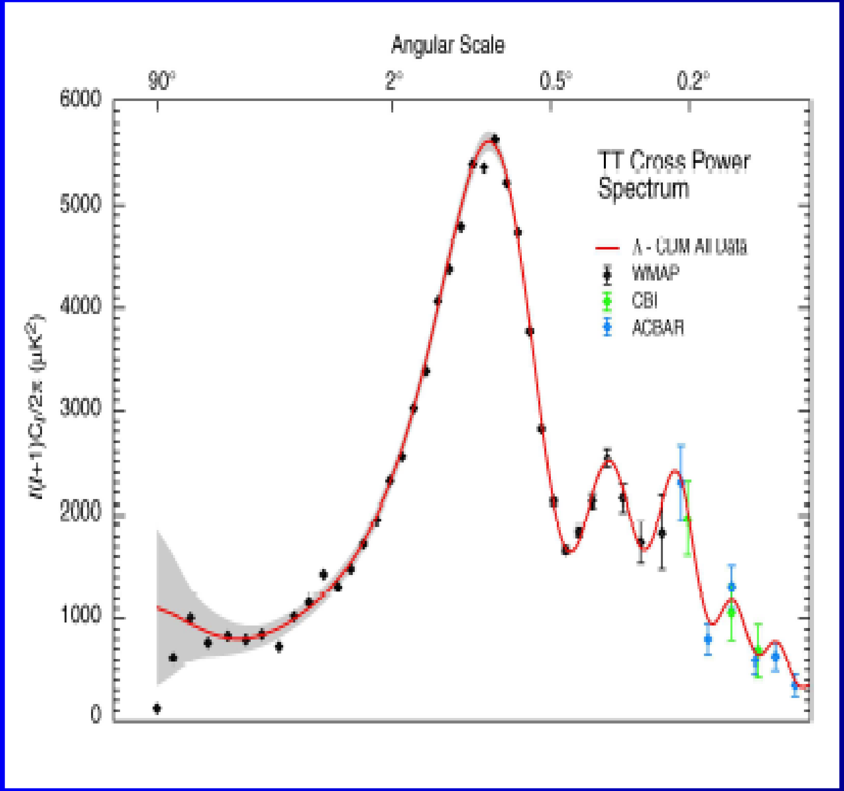
Bounds on neutrino mass

- ☐ mass bounds for 3-ν scenarios :

minimal model fitting most CMB+LSS data: **flat ΛCDM**

6 cosmological parameters $\{ H, \Omega_B, \Omega_{CDM}, A_S, \tau, n \}$ + bias

(even 5: $n=1$)



$\Omega_\Lambda + \Omega_B + \Omega_{CDM} = 1$

$m_\nu = 0$

WMAP only :

χ^2 = 1430 for 1347 points

(χ^2 / #dof = 1.07)

Bounds on neutrino mass

- ☐ mass bounds for 3-ν scenarios : 7-parameter fits

	Σm_ν (eV) at 95%CL	Data used
SDSS Coll. PRD 69 (2004) 103501	< 1.8	WMAP, SDSS
Hannestad JCAP 0305 (2003) 004	< 1.01	WMAP, other CMB, 2dF, HST
Crotty, JL & Pastor PRD 69 (2004) 123007	< 0.6	WMAP, other CMB, 2dF, SDSS, HST
WMAP Coll. ApJ Suppl 148 (2003) 17	< 0.7	WMAP, other CMB, 2dF, HST + bias
Seljak et al. astro-ph/0407372	< 0.42	WMAP, SDSS + bias , Ly-α from SDSS

Bounds on neutrino mass

- ☐ mass bounds for 3-ν scenarios 7-parameter fits

	Σm_ν (eV) at 95%CL	D a used
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extra parameters

⇩

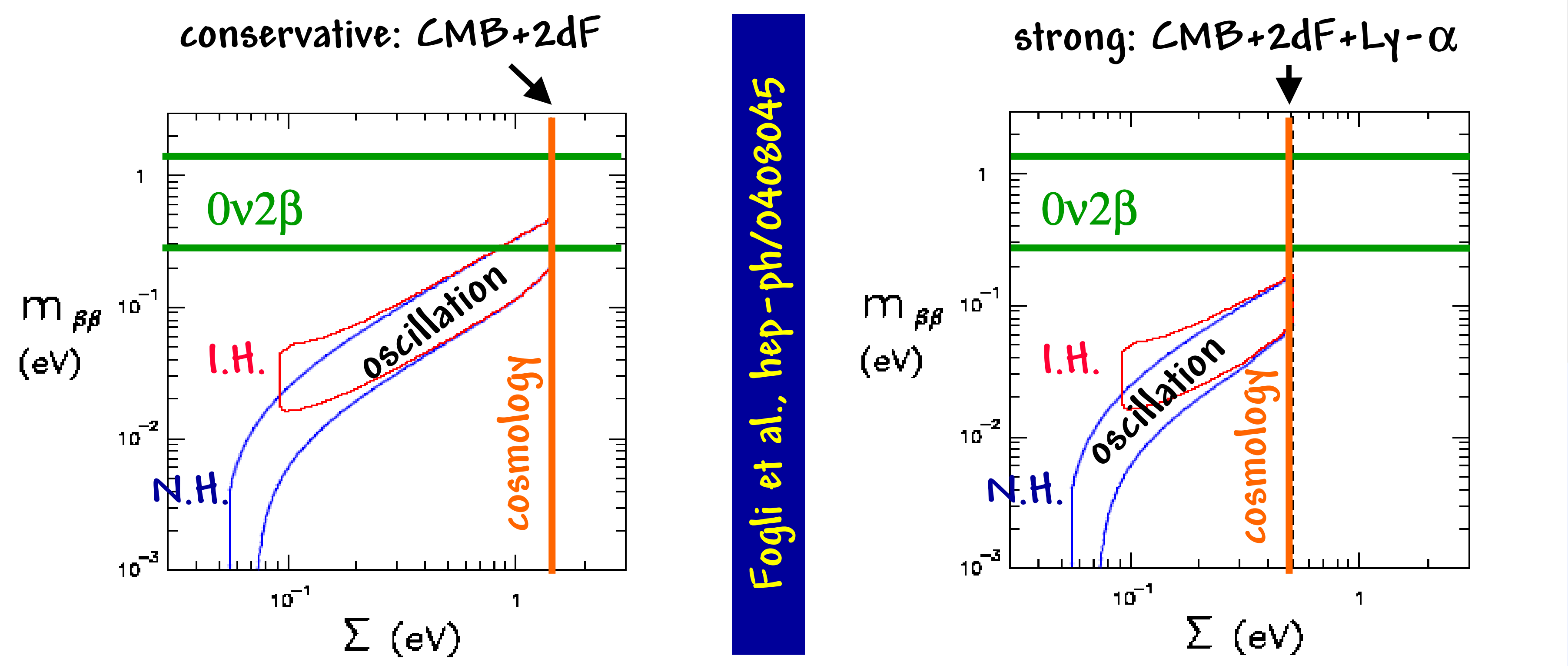
degeneracies

bounds grow by factor < 2

(e.g. ▷ extra rel. d.o.f., tilt running,...)

Bounds on neutrino mass

- ❑ lower bound from Heidelberg-Moscow experiment :


conservative: CMB+2dF

strong: CMB+2dF+Ly-α

Fogli et al., hep-ph/0408045

- ❑ lower bound from LSND : ▷ cosmological bound depends on assumptions on extra (sterile) ν's

3+1 scenario: M<0.8-1.2 eV

Hannestad & Raffaelt 04; Crotty, JL & Pastor 04

Prospects

Prospects on neutrino mass bounds

1) using current techniques:

CMB primary anisotropies+galaxy survey

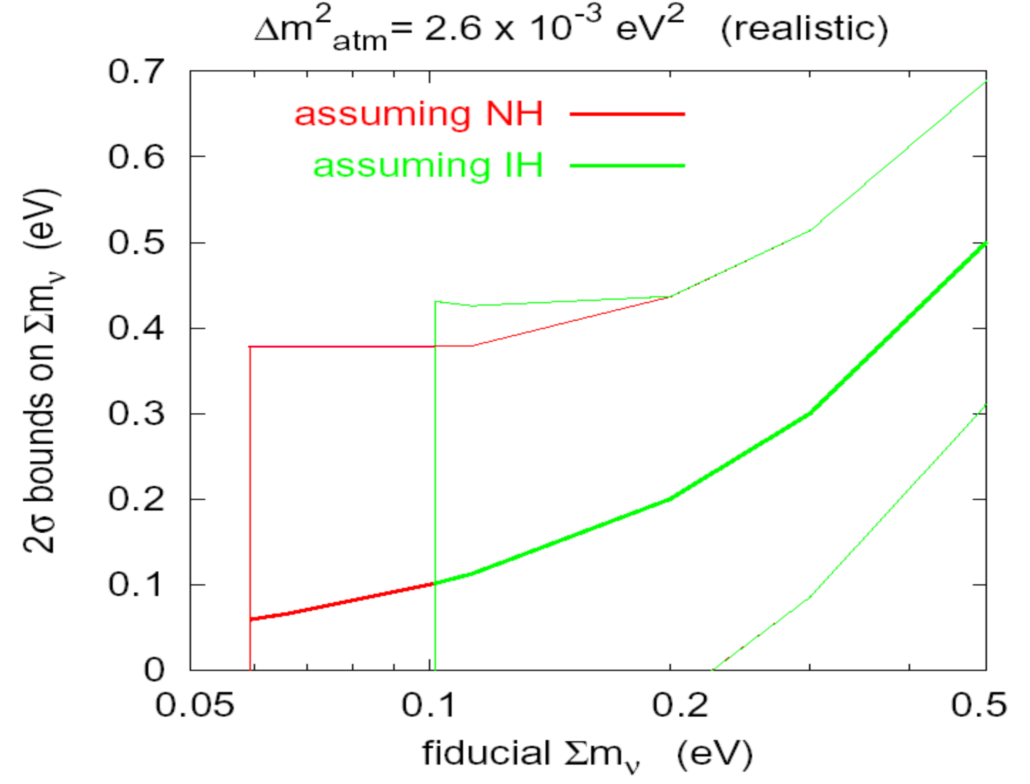
Fisher matrix analysis:

a) assume various « fiducial models » (NH or IH with given M)

b) given experimental specifications, compute $\sigma(M)$

Prospects on neutrino mass bounds

Planck + SDSS

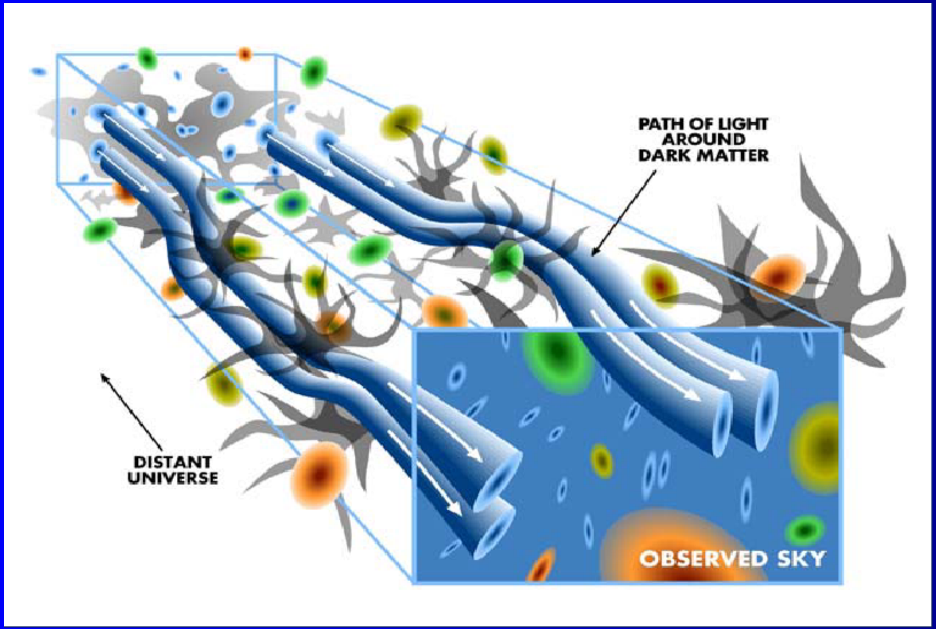


JL, Pastor & Perotto, PRD 2004

2σ detection threshold around M ~ 0.2 - 0.3 eV

Prospects on neutrino mass bounds

2) **using galaxy weak lensing**



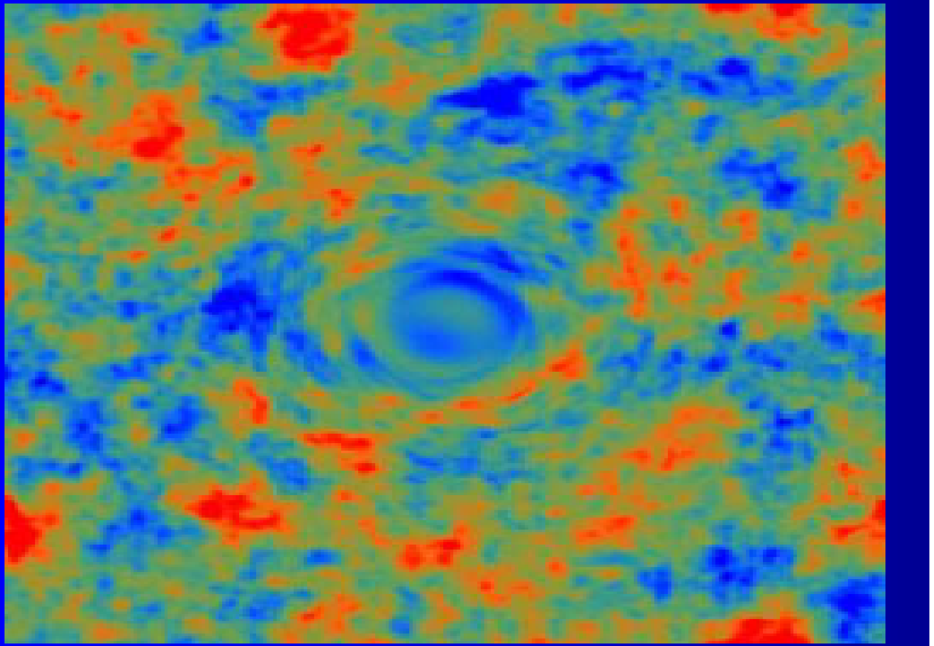
deflection sensitive to gravitational potential integrated along line-of-sight with window function centered on

$d \sim d_S/2$

- deflection field measurable statistically !!
  - no bias uncertainty
  - small scales close to linear regime
  - tomography: 3D reconstruction

Prospects on neutrino mass bounds

3) **using CMB weak lensing**



$dT/T_{obs}(n) = dT/T(n+\nabla\phi)$

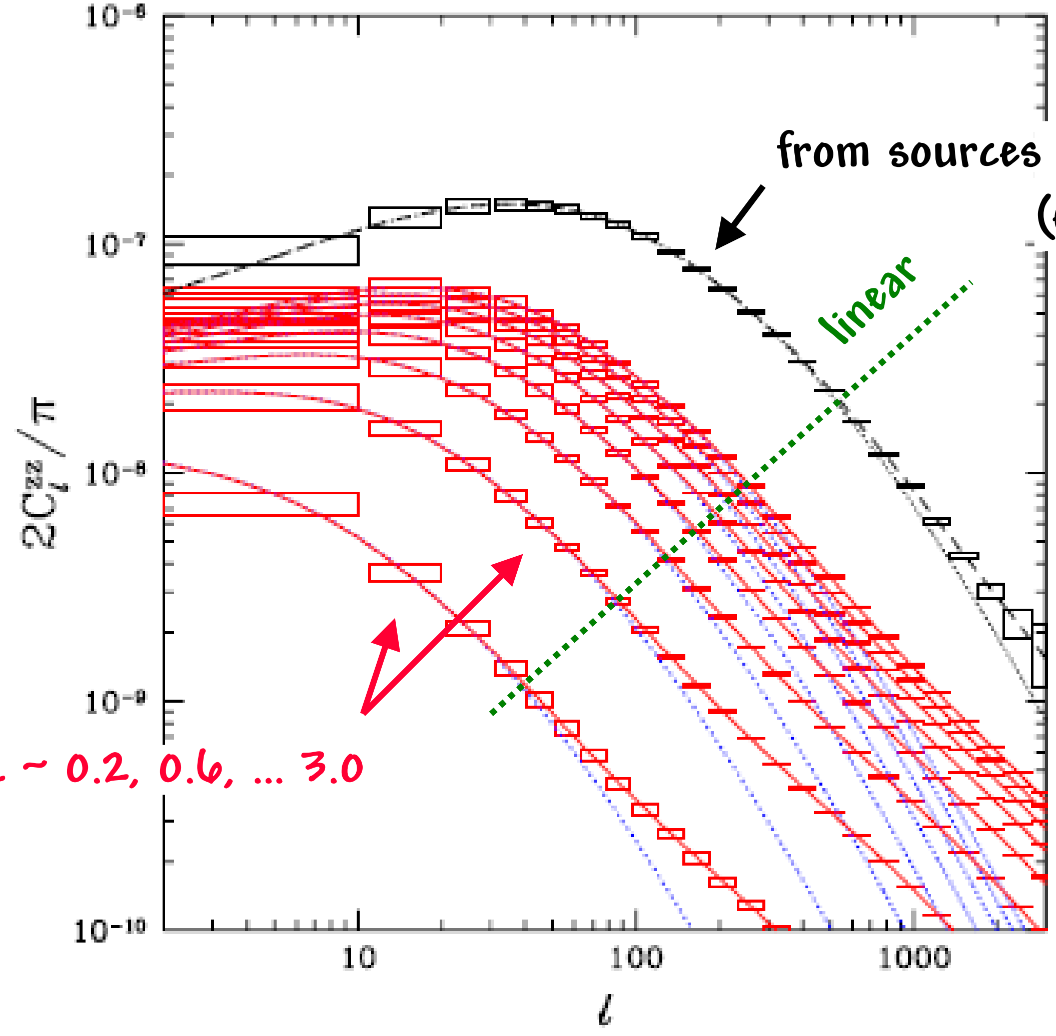
gravitational potential ⮥
integrated along
line-of-sight
with window function
centered on

z~3

- deflection field measurable statistically !!
  - no bias uncertainty
  - small scales much closer to linear regime
  - makes CMB alone sensitive to masses < 0.3eV

Prospects on neutrino mass bounds

expected power spectrum of deflection field



from sources at z ~ 1100 (CMB)
(error for CMBpol)

from sources at z ~ 0.2, 0.6, … 3.0
(error for LSST)

Prospects on neutrino mass bounds

- ☐ summary of 1σ expected errors on $M=\Sigma m_\nu$ (eV)

	none	SDSS	shear survey
none	-	1.3	0.21
Planck	0.31	0.13	0.05
Planck (lens. extr.)	0.15	0.10	0.05
CMBpol	0.07	0.07	0.03
CMBpol (lens. extr.)	0.04	0.03	0.02
Cos. var.	0.05	0.05	0.03
Cos. var. (lens. extr.)	0.02	0.02	0.01

Abazajian & Dodelson 03, Song & Knox 03, Kaplinghat et al. 03, JL et al. 2004 ...