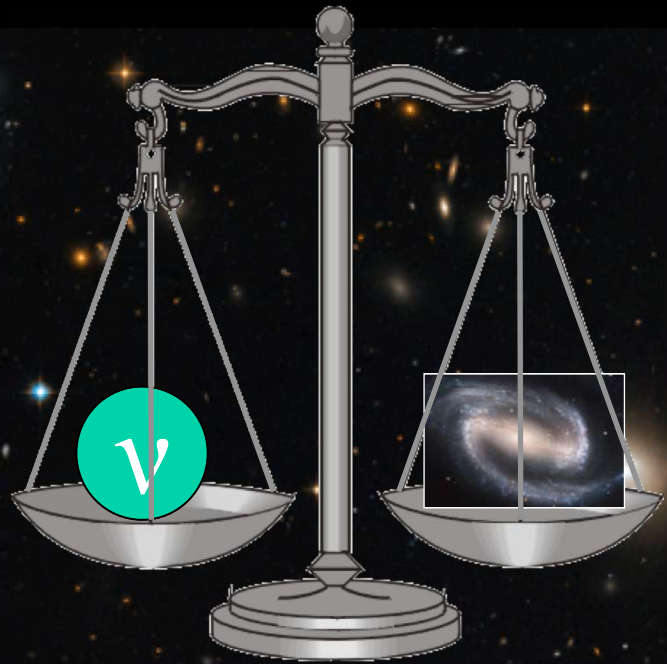
Neutrinos in the Early Universe



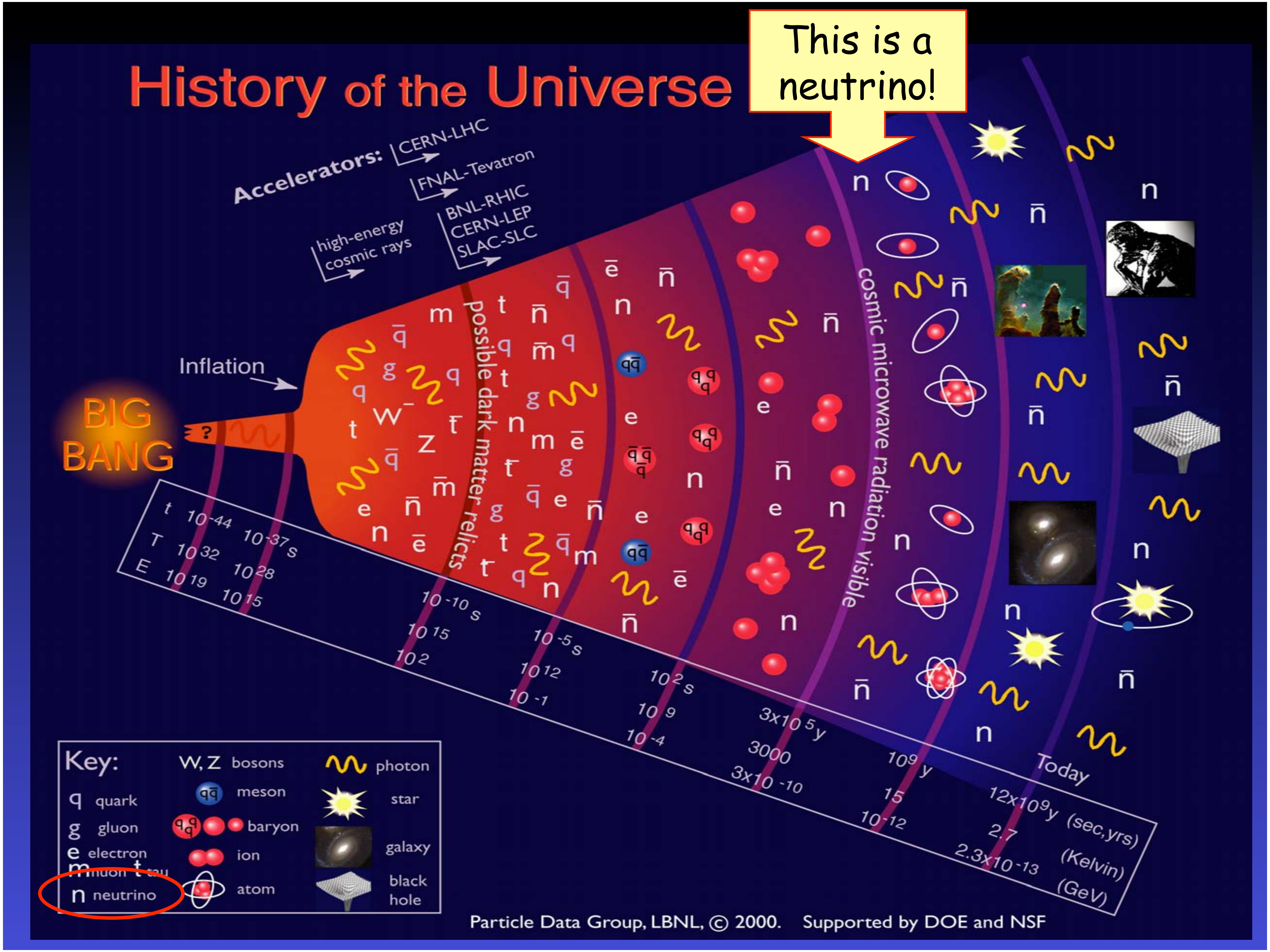
Sergio Pastor
(IFIC Valencia)

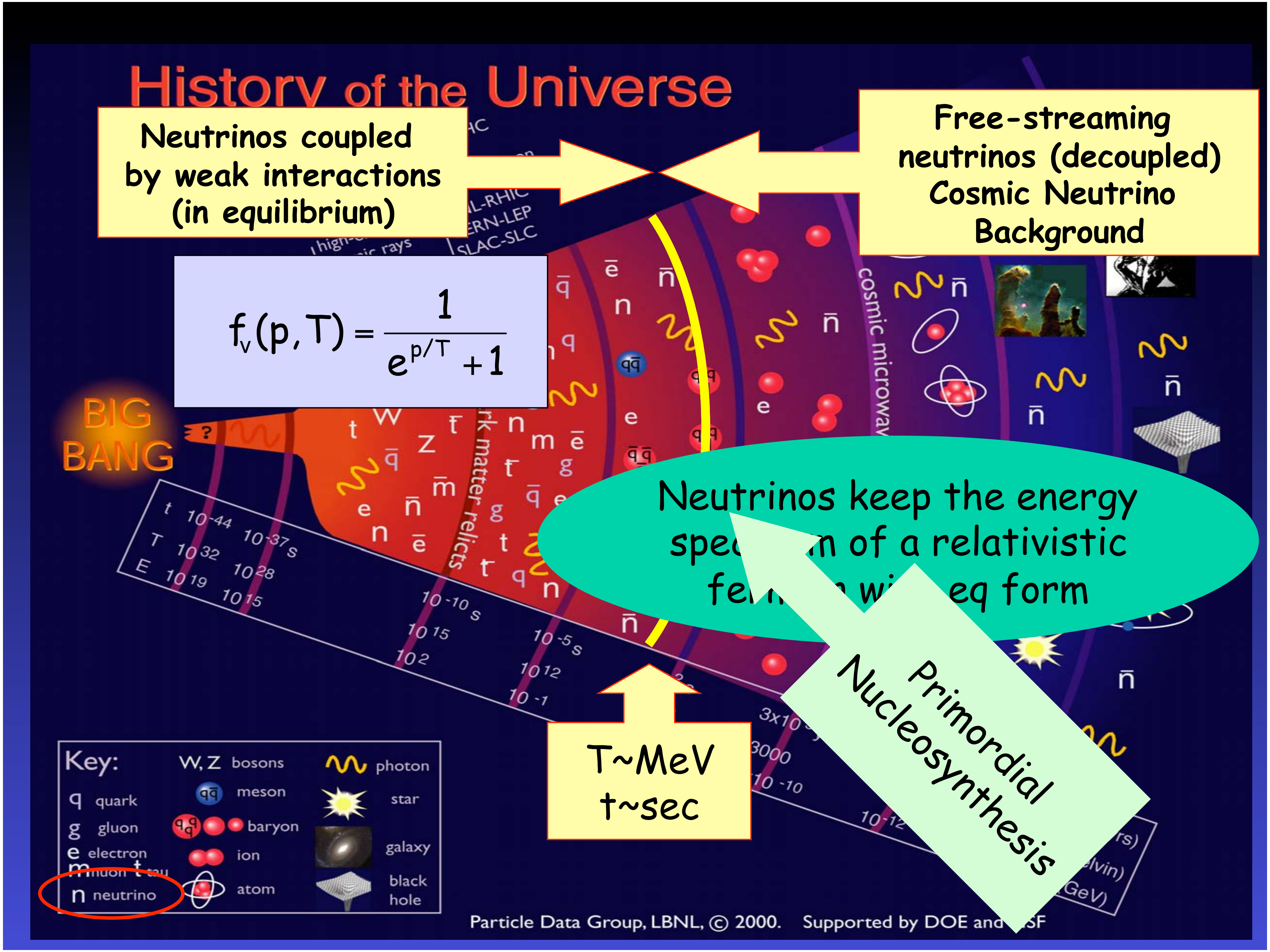
Colloquium Physics of the Standard Model of the Universe
Colegio de España, Paris
June 2009

Picture from Hubble ST

Outline

- Introduction: the Cosmic Neutrino Background
- Primordial Nucleosynthesis, neutrinos and radiation
- Effect of neutrino masses on cosmological observables
- Current cosmological bounds on neutrino masses
- Future sensitivities


History of the Universe
This is a neutrino!
Accelerators:
CERN-LHC
FNAL-Tevatron
BNL-RHIC
CERN-LEP
SLAC-SLC
high-energy cosmic rays
Inflation
BIG BANG
possible dark matter relicts
cosmic microwave radiation visible
t 10-44 10-37s
T 1032 1028
E 1019 1015
10-10 s
1015
102
10-5s
1012
10-1
102 s
109
10-4
3x105y
3000
3x10-10
109y
15
10-12
Today
12x109y (sec,yrs)
2.7 (Kelvin)
2.3x10-13 (GeV)
Key:
q quark
g gluon
e electron
m muon t tau
n neutrino
W, Z bosons
meson
baryon
ion
atom
photon
star
galaxy
black hole
Particle Data Group, LBNL, © 2000. Supported by DOE and NSF


History of the Universe
Neutrinos coupled by weak interactions (in equilibrium)
Free-streaming neutrinos (decoupled) Cosmic Neutrino Background
$$f_\nu(p,T) = \frac{1}{e^{p/T}+1}$$
BIG BANG
Neutrinos keep the energy
m of a relativistic
eq form
T~MeV
t~sec
Primordial Nucleosynthesis
cosmic microwave
dark matter relicts
L-RHIC
CERN-LEP
SLAC-SLC
t 10-44 10-37 s
T 10 32 10 28
E 10 19 10 15
10 -10 s
10 15
10 2
10 -5 s
10 12
10 -1
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Key:
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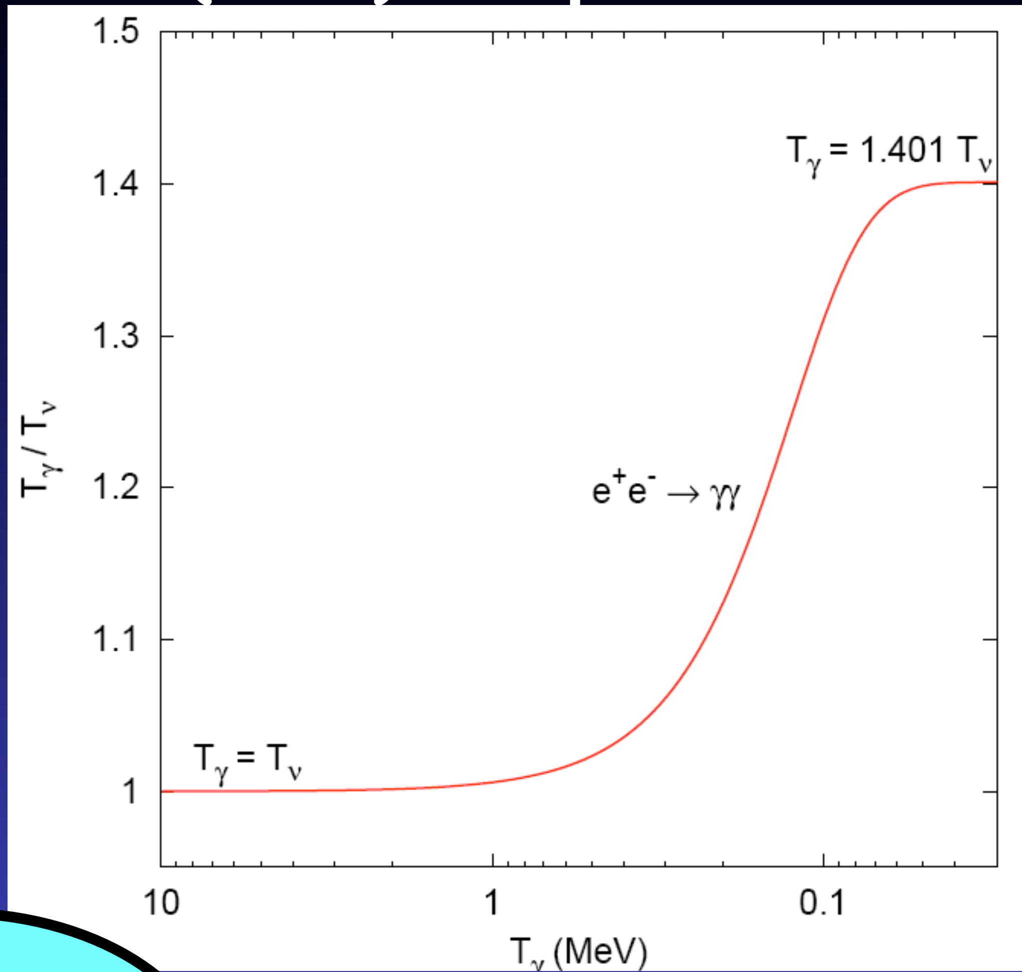
Particle Data Group, LBNL, © 2000. Supported by DOE and NSF

Neutrino and Photon (CMB) temperatures

At $T \sim m_e$, electron-positron pairs annihilate

$$e^+e^- \rightarrow \gamma\gamma$$

heating photons but not the decoupled neutrinos



$$\frac{T_\gamma}{T_\nu} = \left(\frac{11}{4}\right)^{1/3}$$

$$f_\nu(p,T) = \frac{1}{e^{p/T_\nu}+1}$$

Neutrino and Photon (CMB) temperatures

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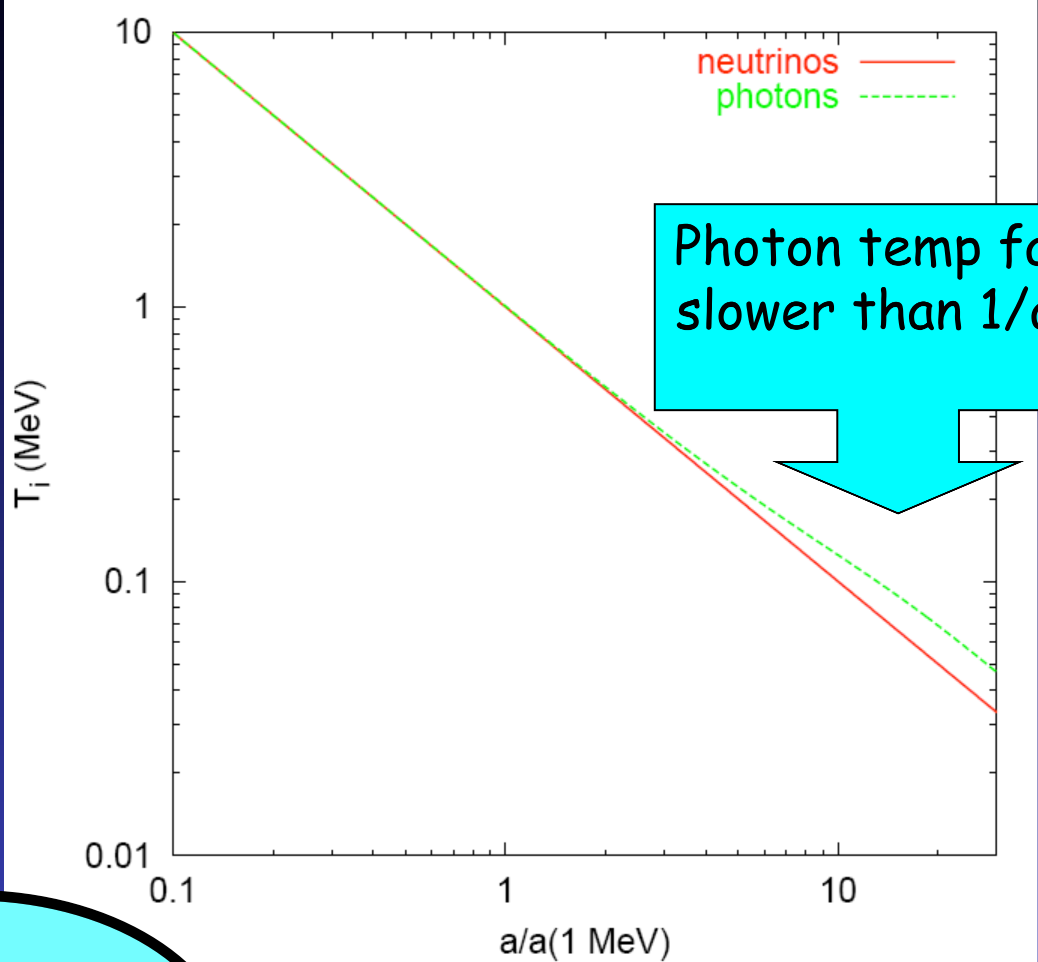
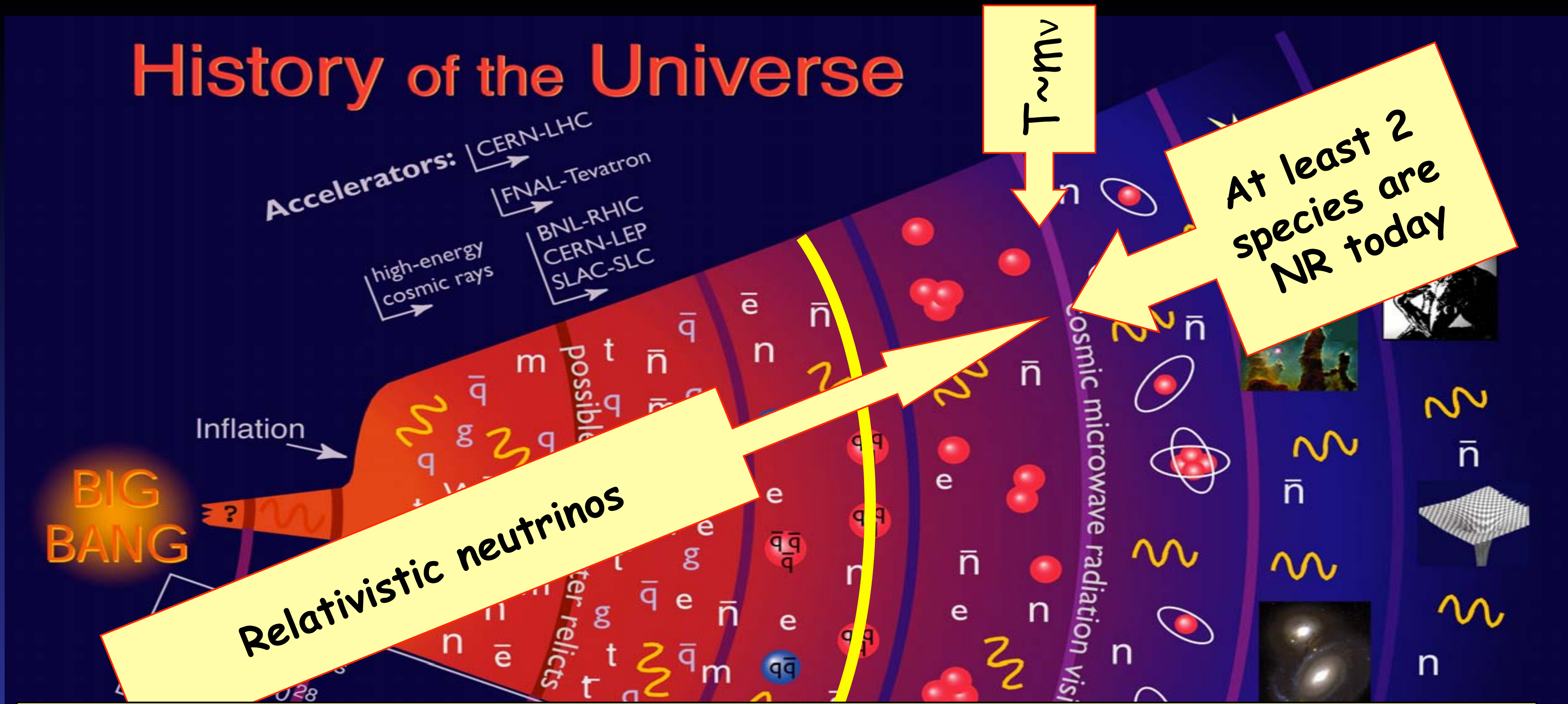


Photon temp falls slower than 1/a(t)

$$\frac{T_\gamma}{T_\nu} = \left(\frac{11}{4}\right)^{1/3}$$

$$f_\nu(p, T) = \frac{1}{e^{p/T_\nu} + 1}$$



Neutrino cosmology is interesting because Relic neutrinos are very abundant:

- The CNB contributes to radiation at early times and to matter at late times (info on the number of neutrinos and their masses)
- Cosmological observables can be used to test non-standard neutrino properties

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The Cosmic Neutrino Background

Neutrinos decoupled at T~MeV, keeping a spectrum as that of a relativistic species $f_\nu(p,T) = \frac{1}{e^{p/T_\nu}+1}$

- Number density

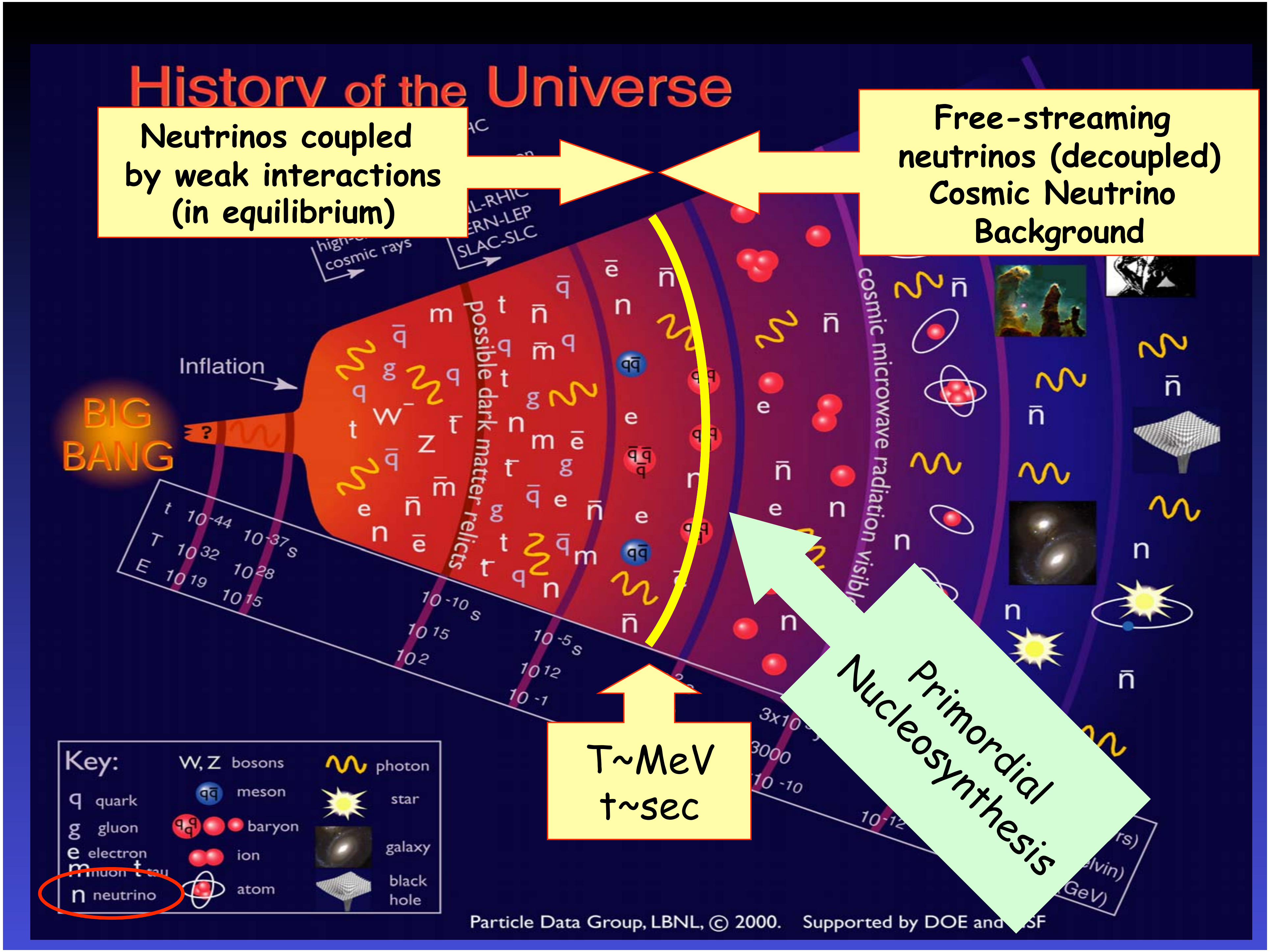
At present $112\,(\nu+\bar{\nu})\,\mathrm{cm}^{-3}$ per flavour

- Energy density

Contribution to the energy density of the Universe

$$\Omega_\nu h^2 = 1.7\times10^{-5}$$ Massless

$$\Omega_\nu h^2 = \frac{\sum_i m_i}{93.2\ \mathrm{eV}}$$ Massive $m_\nu \gg T$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T~MeV t~sec
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meson
baryon
ion
atom
photon
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galaxy
black hole
Particle Data Group, LBNL, © 2000. Supported by DOE and NSF

Relativistic particles in the Universe

At $T<m_e$, the radiation content of the Universe is

$$\rho_r = \rho_\gamma + \rho_\nu = \frac{\pi^2}{15}T_\gamma^4 + 3\times\frac{7}{8}\times\frac{\pi^2}{15}T_\nu^4 = \left[1+\frac{7}{8}\left(\frac{4}{11}\right)^{4/3} 3\right]\rho_\gamma$$

$$\rho_r = \rho_\gamma + \rho_\nu = \left[1+\frac{7}{8}\left(\frac{4}{11}\right)^{4/3} N_{\rm eff}\right]\rho_\gamma$$

Relativistic particles in the Universe

At $T<m_e$, the radiation content of the Universe is

$$\rho_r = \rho_\gamma + \rho_\nu + \rho_x = \left[1 + \frac{7}{8}\left(\frac{4}{11}\right)^{4/3} N_{\rm eff}\right] \rho_\gamma$$

Effective number of relativistic neutrino species

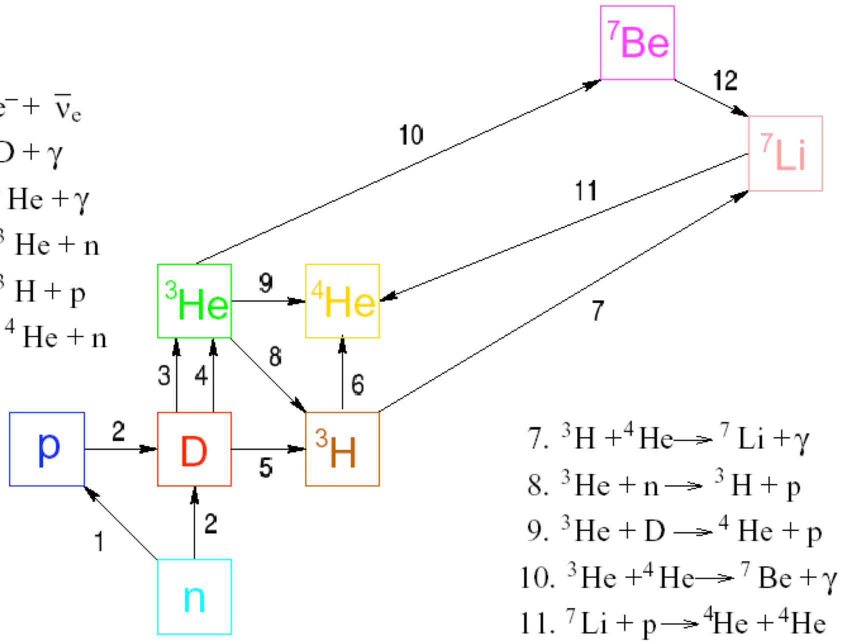
Traditional parametrization of the energy density stored in relativistic particles

# of flavour neutrinos: $N_\nu = 2.984 \pm 0.008$ (LEP data)

Constraints on $N_{\rm eff}$ from BBN and from CMB+LSS

BBN: Creation of light elements

1. $n \rightarrow p + e^- + \bar{\nu}_e$
2. $p + n \rightarrow D + \gamma$
3. $D + p \rightarrow {}^3He + \gamma$
4. $D + D \rightarrow {}^3He + n$
5. $D + D \rightarrow {}^3H + p$
6. ${}^3H + D \rightarrow {}^4He + n$



7. ${}^3H + {}^4He \rightarrow {}^7Li + \gamma$
8. ${}^3He + n \rightarrow {}^3H + p$
9. ${}^3He + D \rightarrow {}^4He + p$
10. ${}^3He + {}^4He \rightarrow {}^7Be + \gamma$
11. ${}^7Li + p \rightarrow {}^4He + {}^4He$
12. ${}^7Be + n \rightarrow {}^7Li + p$

Produced elements: D, ${}^3He$, ${}^4He$, ${}^7Li$ and small abundances of others

Theoretical inputs:

- τ_n, the neutron lifetime;
- G_N, the Newton gravitational constant;
- η, the baryon to photon number density ratio;
- the nuclear rates.

The first two parameters are now known with a satisfactory accuracy

$$\tau_n = 885.7 \pm 0.8\, s \quad ,$$
$$G_N = 6.7087 \pm 0.0010 \cdot 10^{-39}\, GeV^{-2} \quad .$$

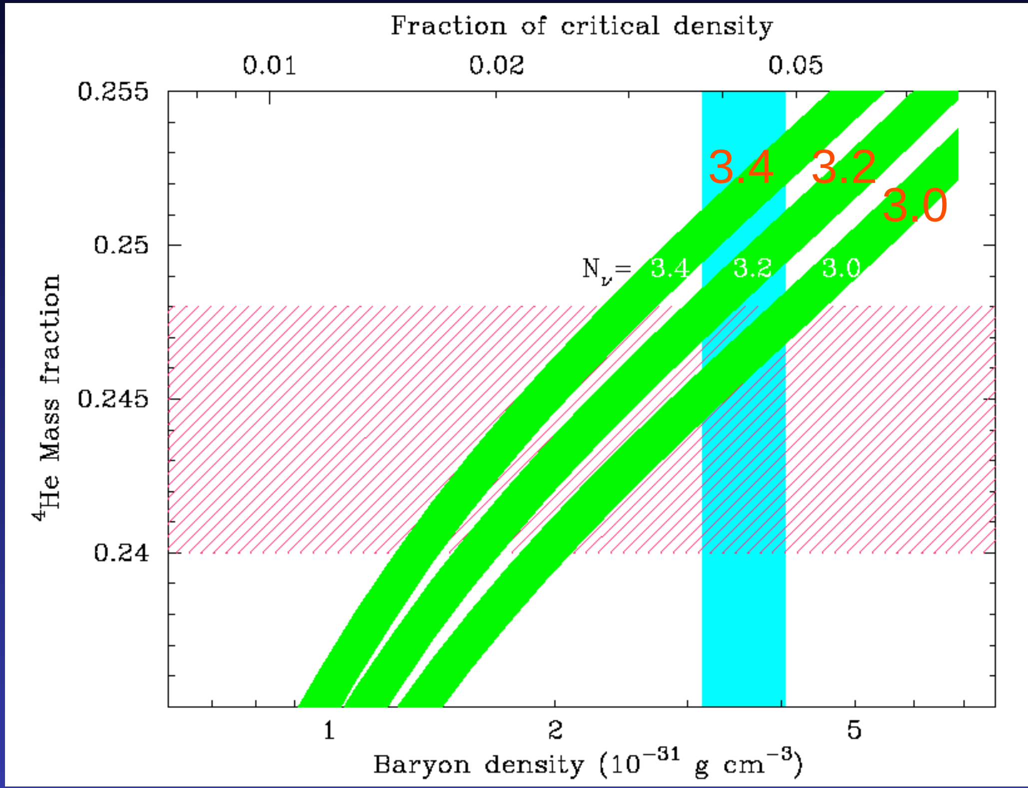
Effect of neutrinos on BBN

1. N_{eff} fixes the expansion rate during BBN

$$H = \sqrt{\frac{8\pi\rho}{3M_p^2}}$$

$\rho(N_{eff}) > \rho_0 \quad \rightarrow \quad \uparrow {}^4He$

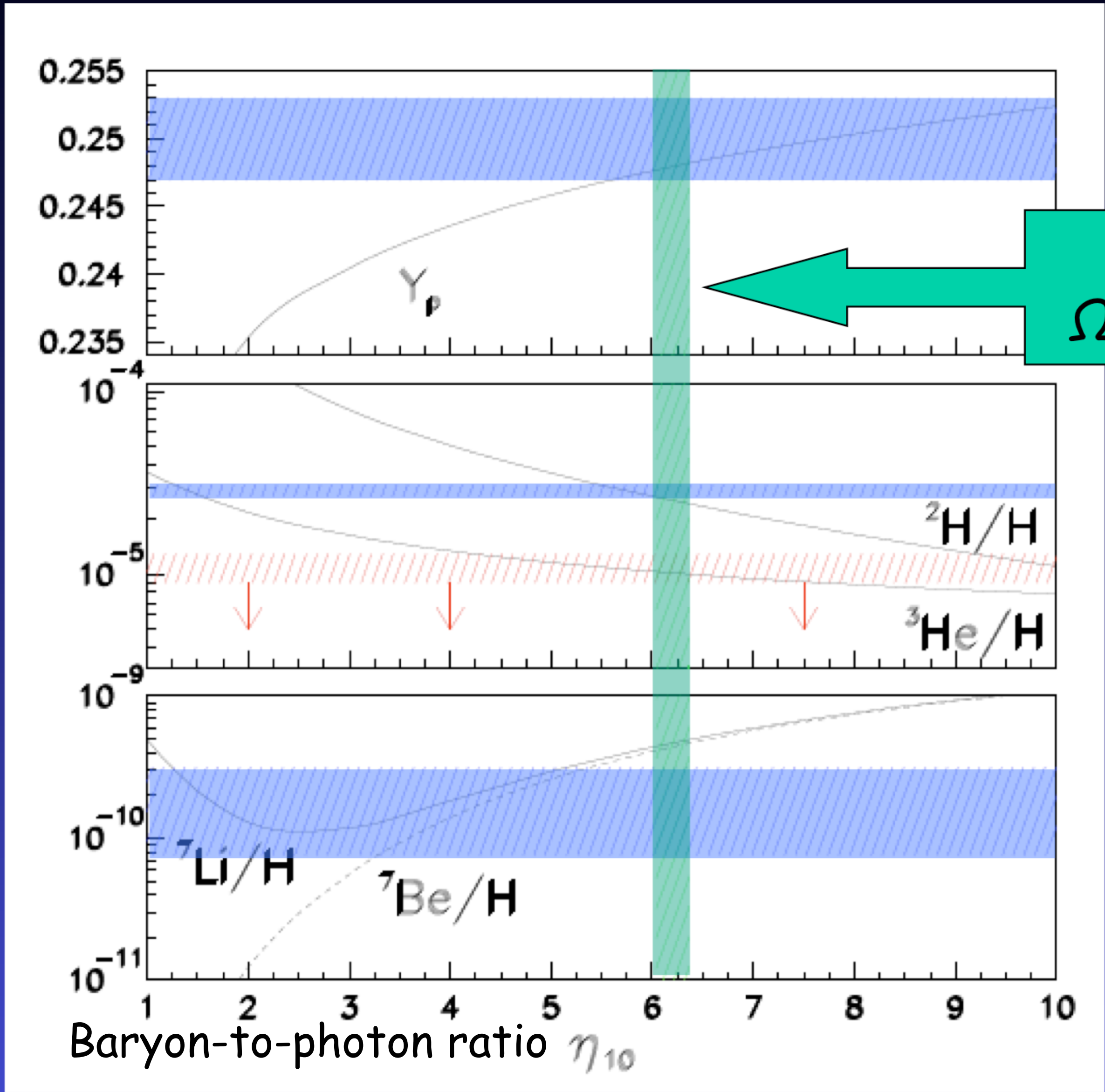
Burles, Nollett & Turner 1999



2. Direct effect of electron neutrinos and antineutrinos on the n-p reactions

$$\nu_e + n \longleftrightarrow p + e^- \qquad e^+ + n \longleftrightarrow p + \bar{\nu}_e$$

BBN: Predictions vs Observations

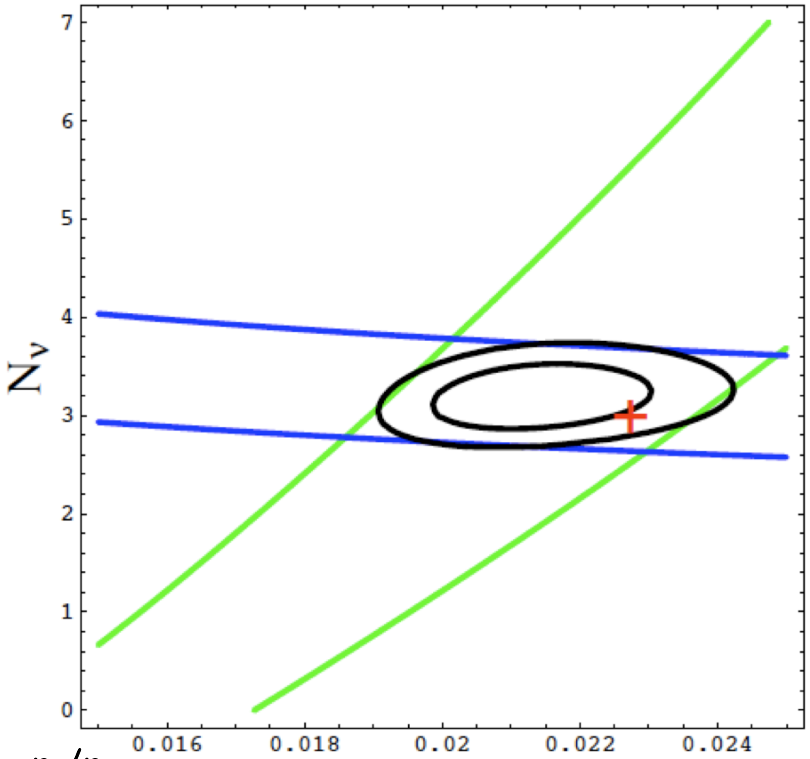


$$\eta_{10} = \frac{n_B/n_\gamma}{10^{-10}} \cong 274\Omega_B h^2$$

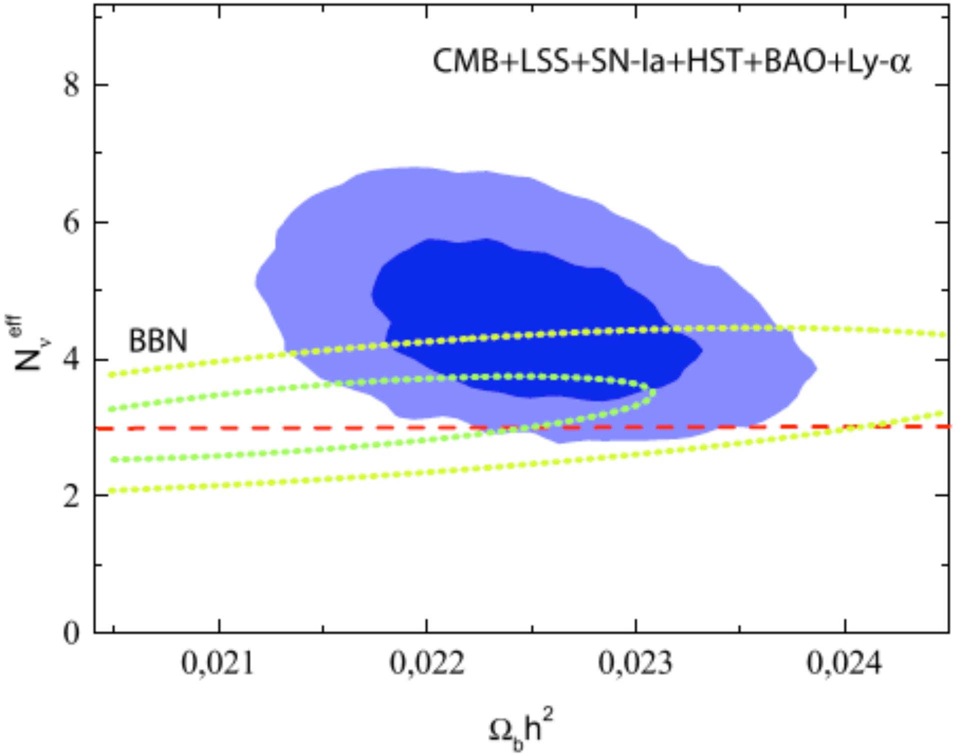
after WMAP5
$\Omega_B h^2 = 0.02273 \pm 0.00062$

F. Iocco et al,
Phys. Rep. 472 (2009) 1

BBN: allowed ranges for N_{eff}



$\eta_{10} = \frac{n_B/n_\gamma}{10^{-10}} \cong 274\Omega_B h^2$



F. Iocco et al, Phys. Rep. 472 (2009) 1

$$N_{eff} = 3.18^{+0.44}_{-0.41}$$

(95% CL)

Bounds from non-BBN data

Mangano et al, JCAP 0703 (2007) 006

$$3.0 < N_{eff} < 7.9 \quad \text{(CMB + LSS data)}$$

$$3.1 < N_{eff} < 6.2 \quad (+\text{BAO and Ly}-\alpha)$$

Future bounds on N_{eff}

Forecast analysis:
Bowen et al,
MNRAS 334 (2002) 760

ΔN_{eff} ~ 3 (WMAP)

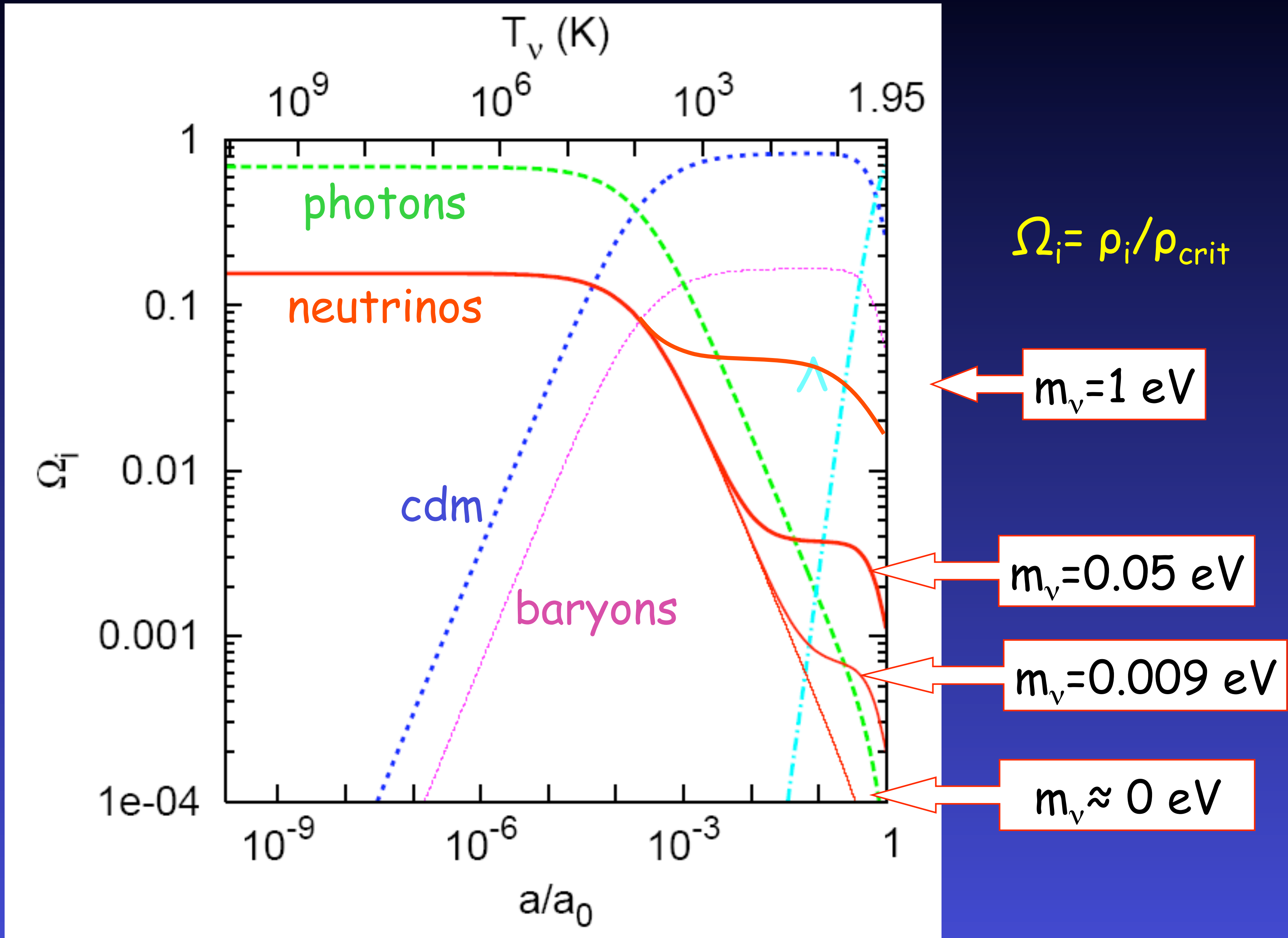
ΔN_{eff} ~ 0.2 (Planck)

ERROR FORECASTS

Experiment	f_{sky}	θ_b	$w_T^{-1/2}$ [μ K']	$w_P^{-1/2}$ [μ K']	ΔN_ν TT	ΔN_ν TT+TE+EE	ΔN_ν (free Y) TT+TE+EE
Planck	0.8	7'	40	56	0.6	0.20	0.24
ACT	0.01	1.7'	3	4	1	0.47	0.9
ACT + Planck					0.4	0.18	0.24
CMBPOL	0.8	4'	1	1.4	0.12	0.05	0.09

Bashinsky & Seljak, PRD 69 (2004) 083002

Evolution of the background densities: 1 MeV → now



Neutrinos as Dark Matter

- Neutrinos are natural DM candidates

$$\Omega_\nu h^2 = \frac{\sum_i m_i}{93.2\ \mathrm{eV}} \qquad \Omega_\nu < 1 \rightarrow \sum_i m_i < 46\ \mathrm{eV}$$

$$\Omega_\nu < \Omega_m \approx 0.3 \rightarrow \sum_i m_i < 15\ \mathrm{eV}$$

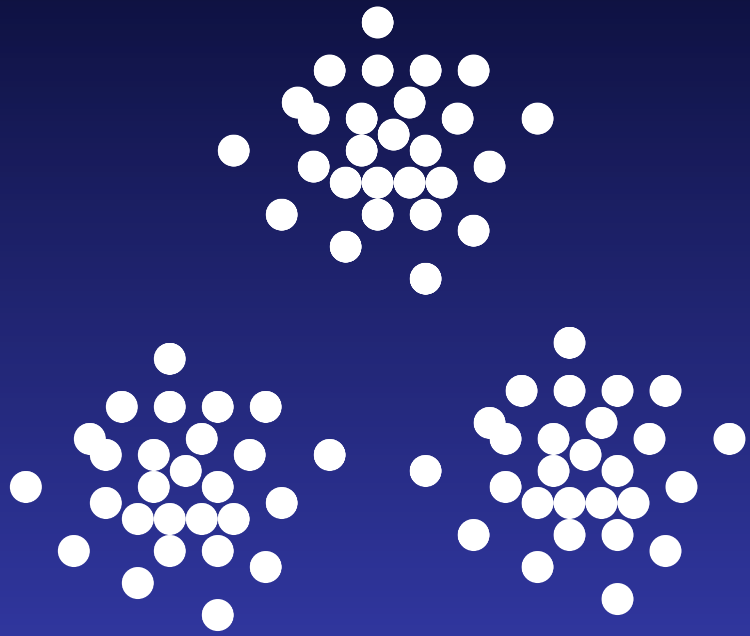
- They stream freely until non-relativistic (collisionless phase mixing) → Neutrinos are HOT Dark Matter
- First structures to be formed when Universe became matter -dominated are very large
- Ruled out by structure formation → CDM

Neutrinos as Hot Dark Matter

Massive Neutrinos can still be subdominant DM: limits on m_ν from Structure Formation (combined with other cosmological data)

Structure formation after equality

baryons and CDM (matter) experience gravitational clustering



Structure formation after equality

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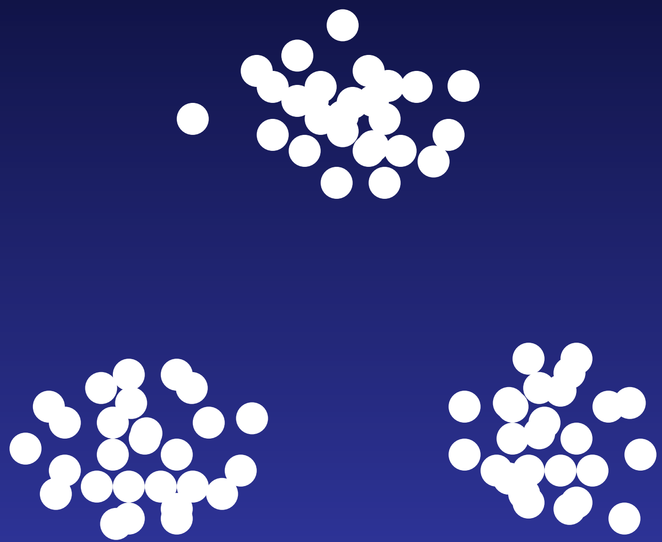

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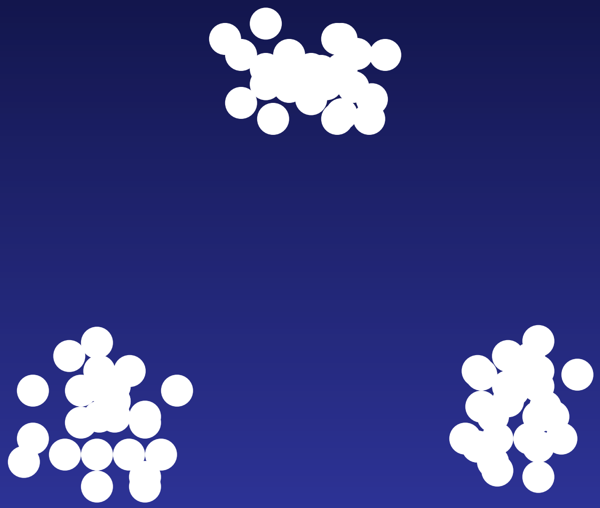

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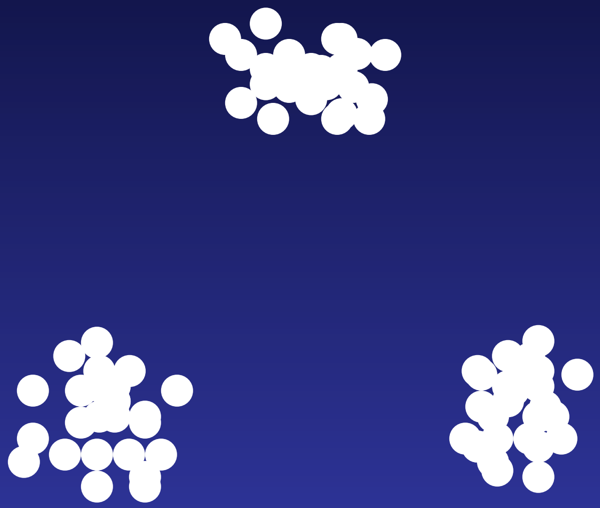


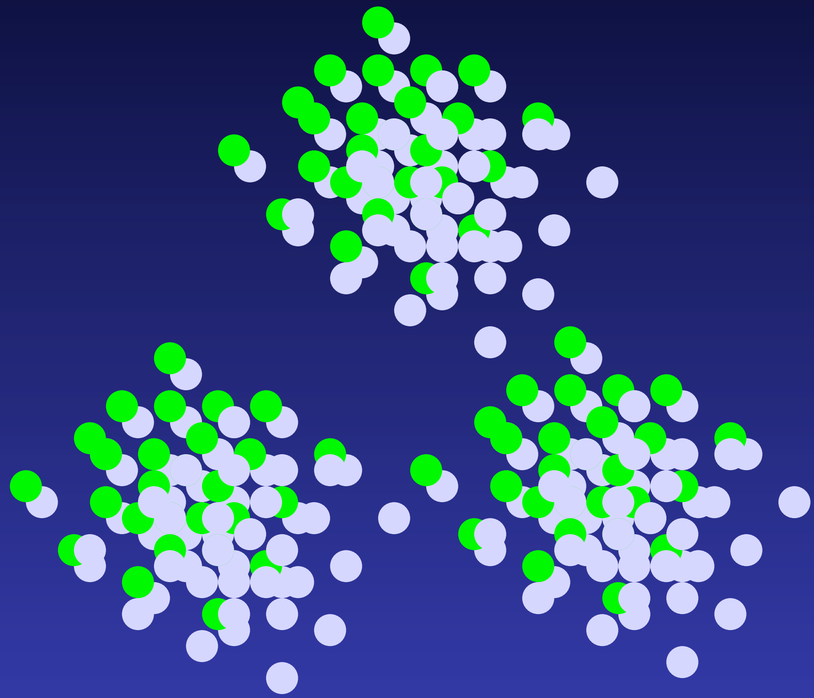
growth of $\delta\rho/\rho$ (k,t) fixed by

gravity vs expansion balance

$\Rightarrow \delta\rho/\rho \; \alpha \; a$

Structure formation after equality

baryons and
CDM (matter)
experience
gravitational
clustering



neutrinos
experience
free-streaming
with
v = c or <p>/m

Structure formation after equality

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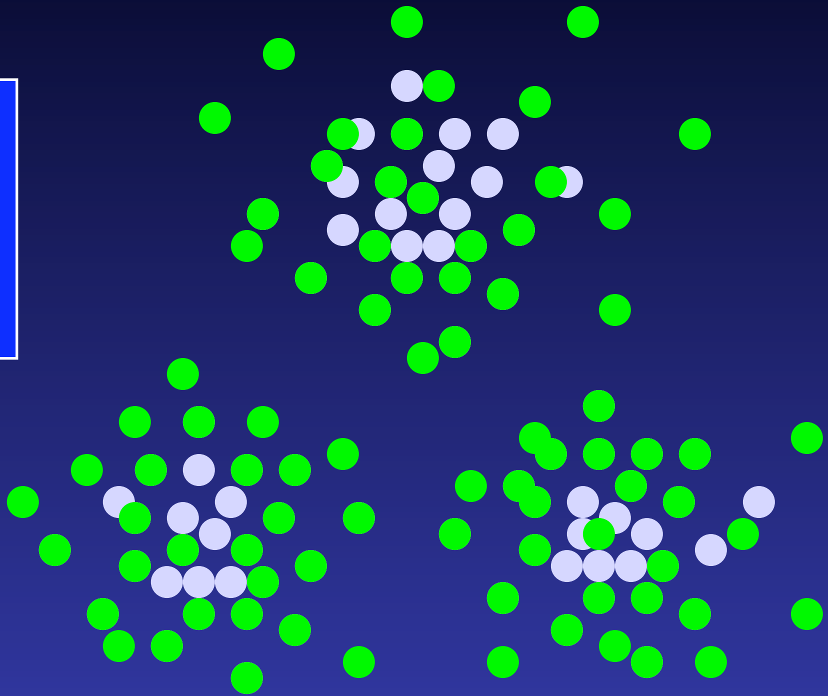

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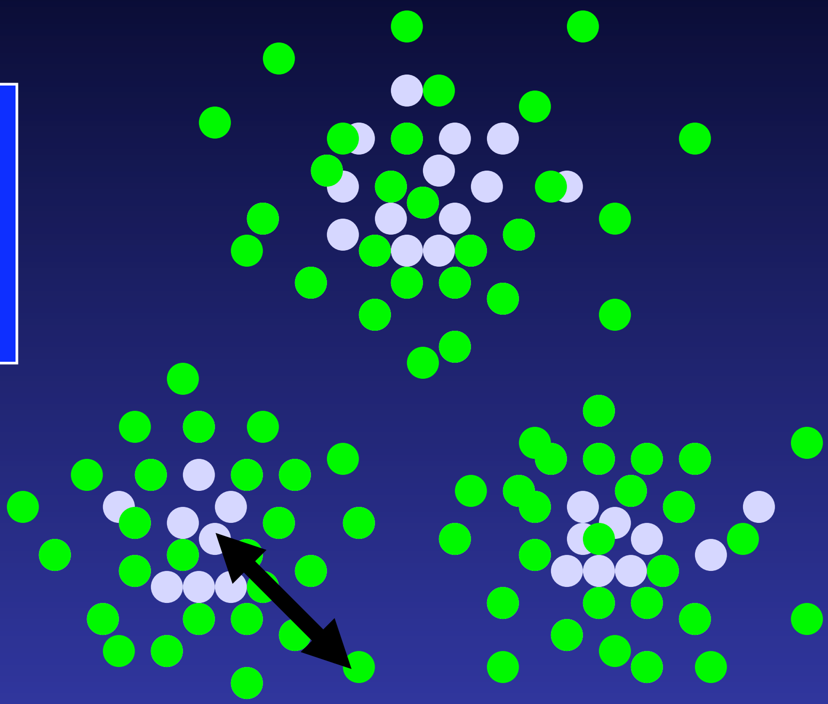


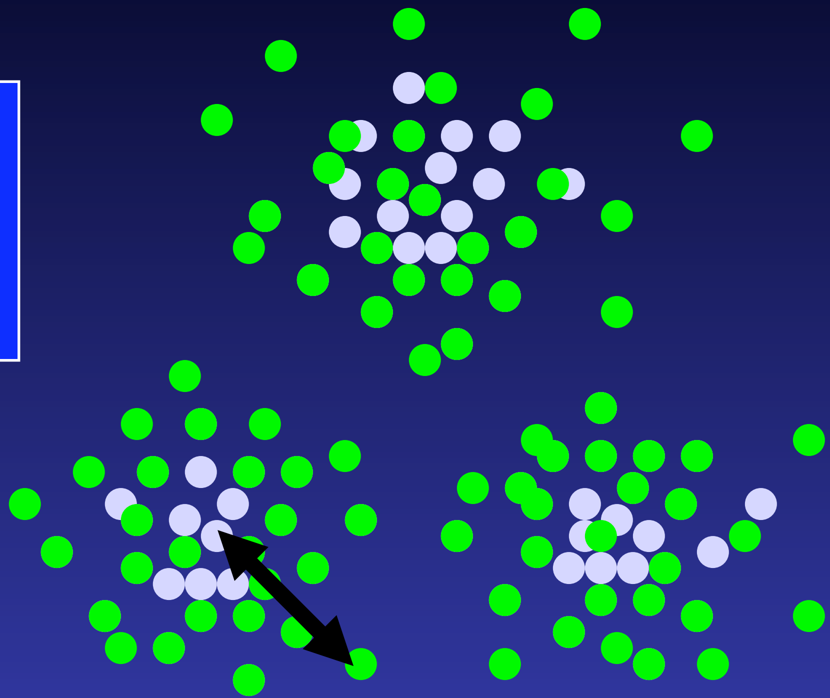
neutrinos experience free-streaming with $v = c$ or $\langle p \rangle / m$

neutrinos cannot cluster below a diffusion length

$$\lambda = \int v \, dt \; < \int c \, dt$$

Structure formation after equality

baryons and CDM (matter) experience gravitational clustering



neutrinos experience free-streaming with
$v = c$ or $\langle p \rangle / m$

for $(2\pi/k) < \lambda$,

free-streaming supresses growth of structures during MD

$\Rightarrow \quad \delta\rho/\rho \propto a^{1-3/5\, f\nu}$ with $f_\nu = \rho_\nu/\rho_m \approx (\Sigma m_\nu)/(15\ \mathrm{eV})$

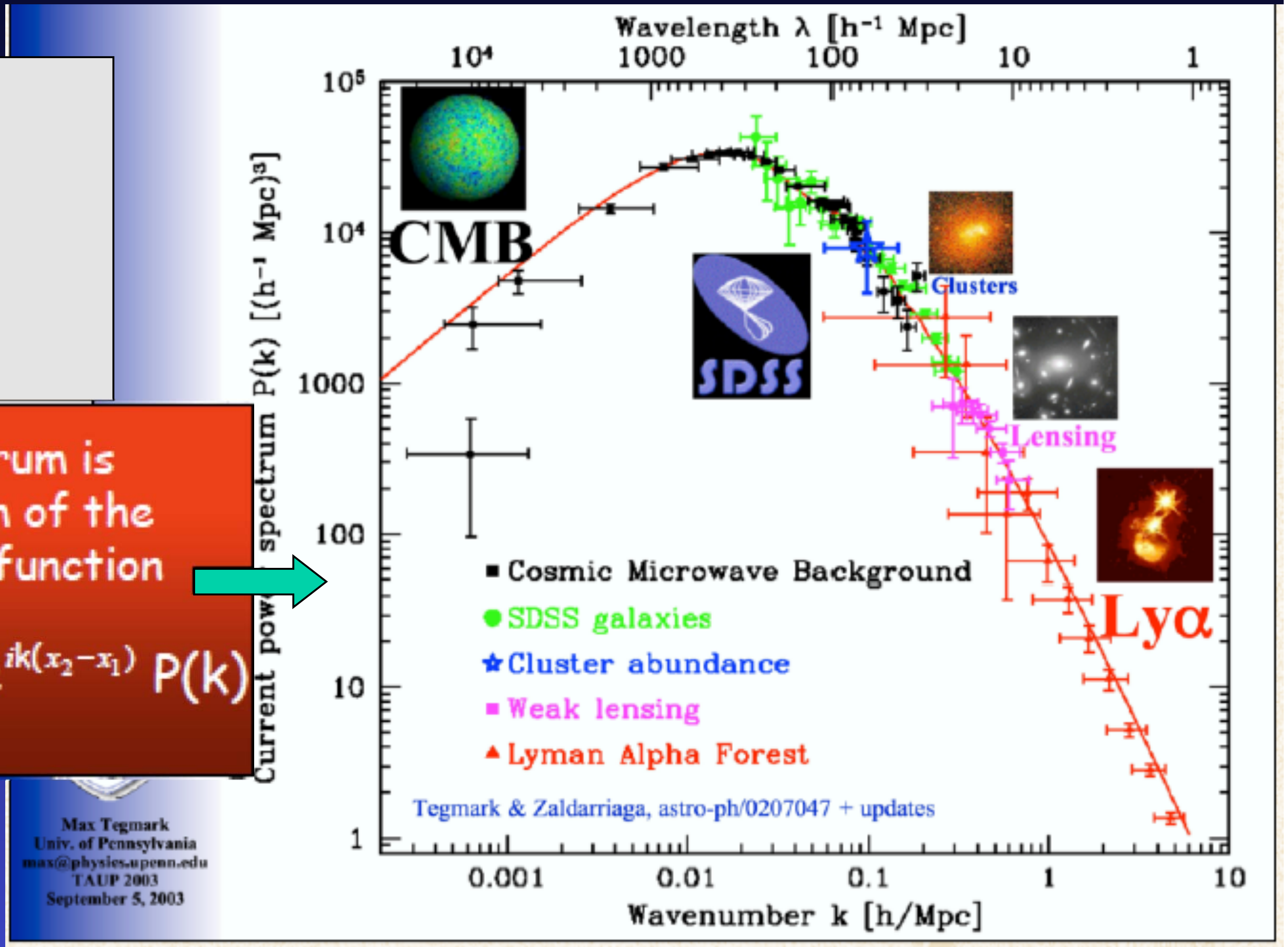
Power Spectrum of density fluctuations

Field of density Fluctuations

$$\delta(x) = \frac{\delta\rho(x)}{\bar{\rho}}$$

Matter power spectrum is the Fourier transform of the two-point correlation function

$$\langle \delta(x_1)\delta(x_2) \rangle = \int \frac{d^3k}{(2\pi)^3} e^{ik(x_2 - x_1)} P(k)$$



Neutrinos as Hot Dark Matter: effect on P(k)

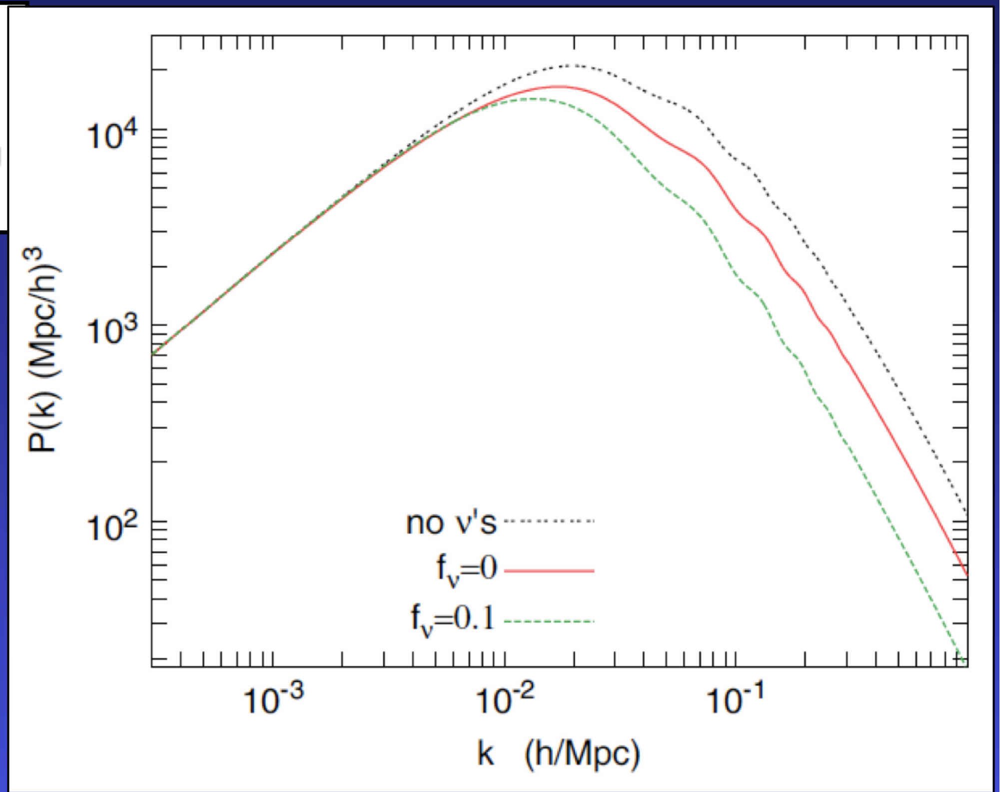
Massive Neutrinos can still be subdominant DM: limits on m_ν from Structure Formation (combined with other cosmological data)

- Effect of Massive Neutrinos: suppression of Power at small scales

The small-scale suppression is given by

$$\left(\frac{\Delta P}{P}\right) \approx -8\frac{\Omega_\nu}{\Omega_m} \approx -0.8\left(\frac{m_\nu}{1\,\mathrm{eV}}\right)\left(\frac{0.1N}{\Omega_m h^2}\right)$$

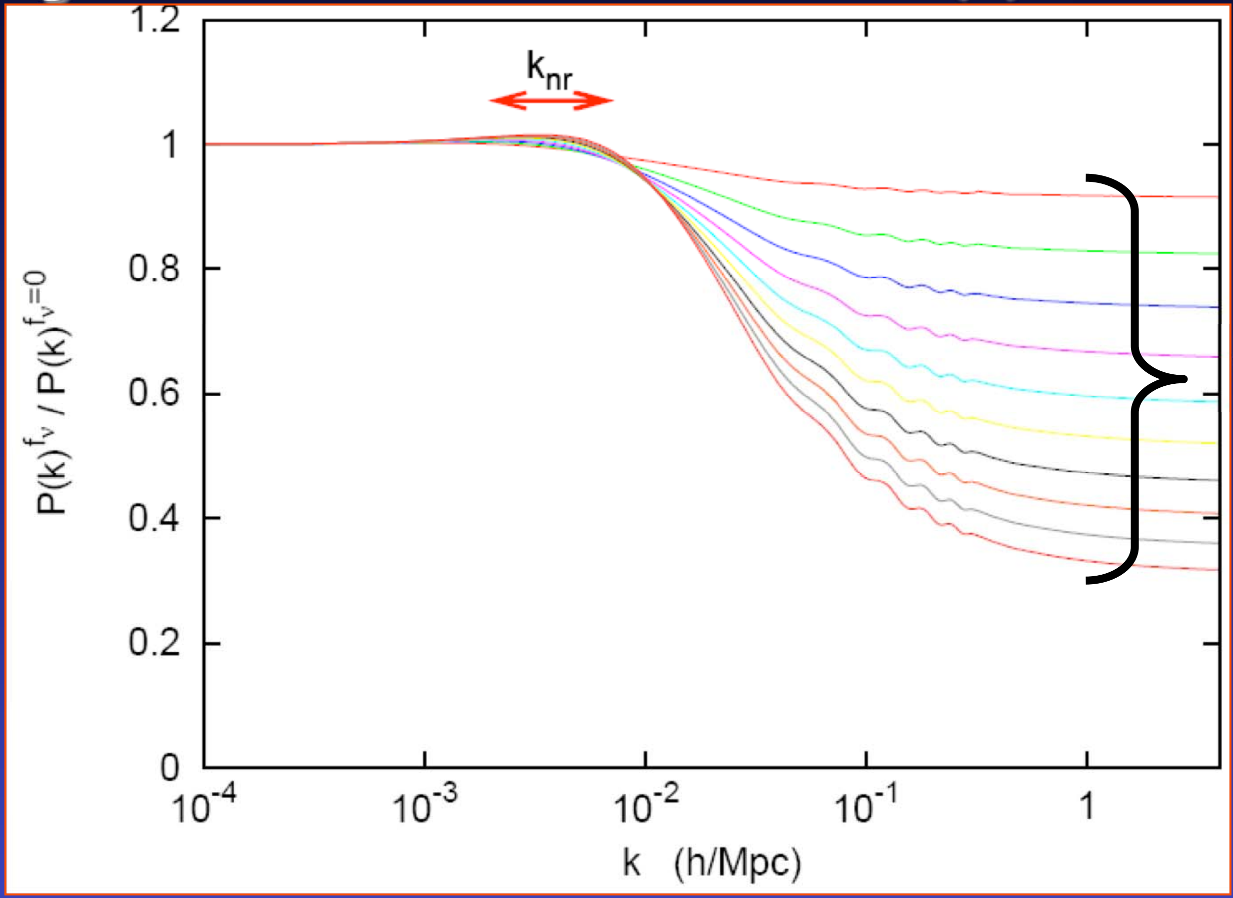
f_ν



Effect of massive neutrinos on P(k)

Observable signature of the total mass on P(k) :

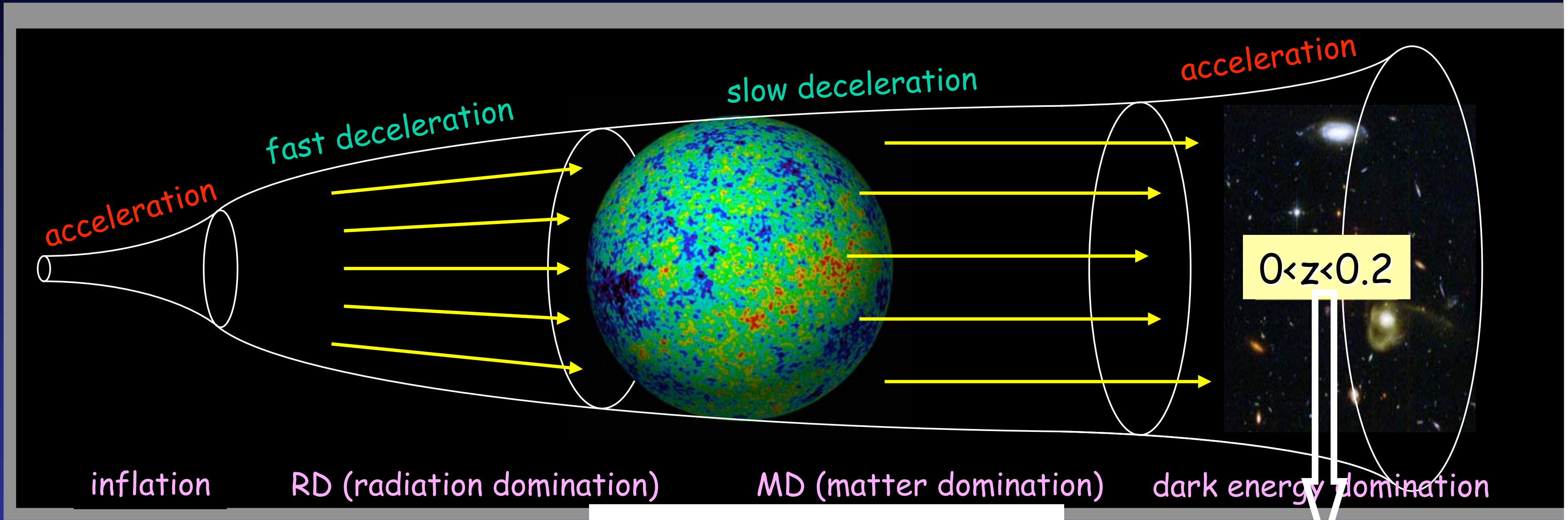
$$\frac{P(k)\ \text{massive}}{P(k)\ \text{massless}}$$



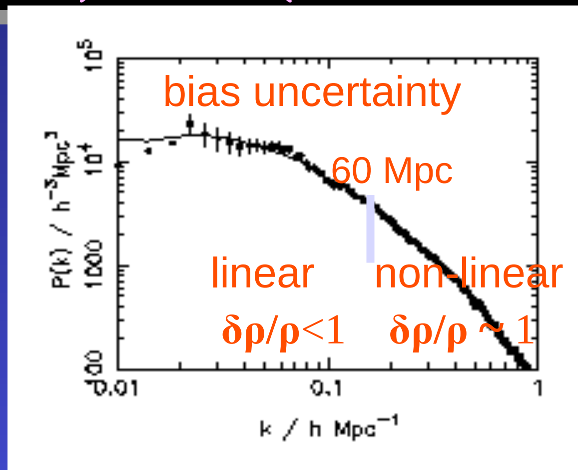
various f_ν

Lesgourgues & SP, Phys. Rep. 429 (2006) 307

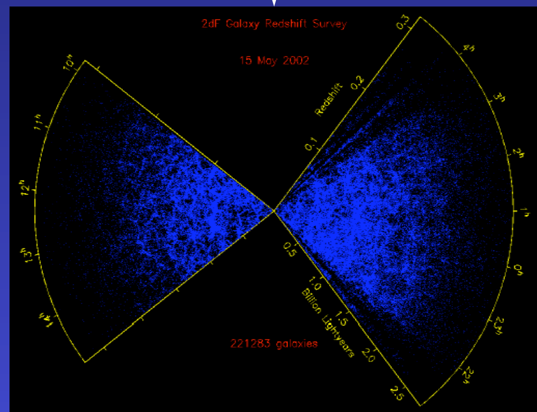
Cosmological observables: LSS



Distribution
of large-scale
structures at low z

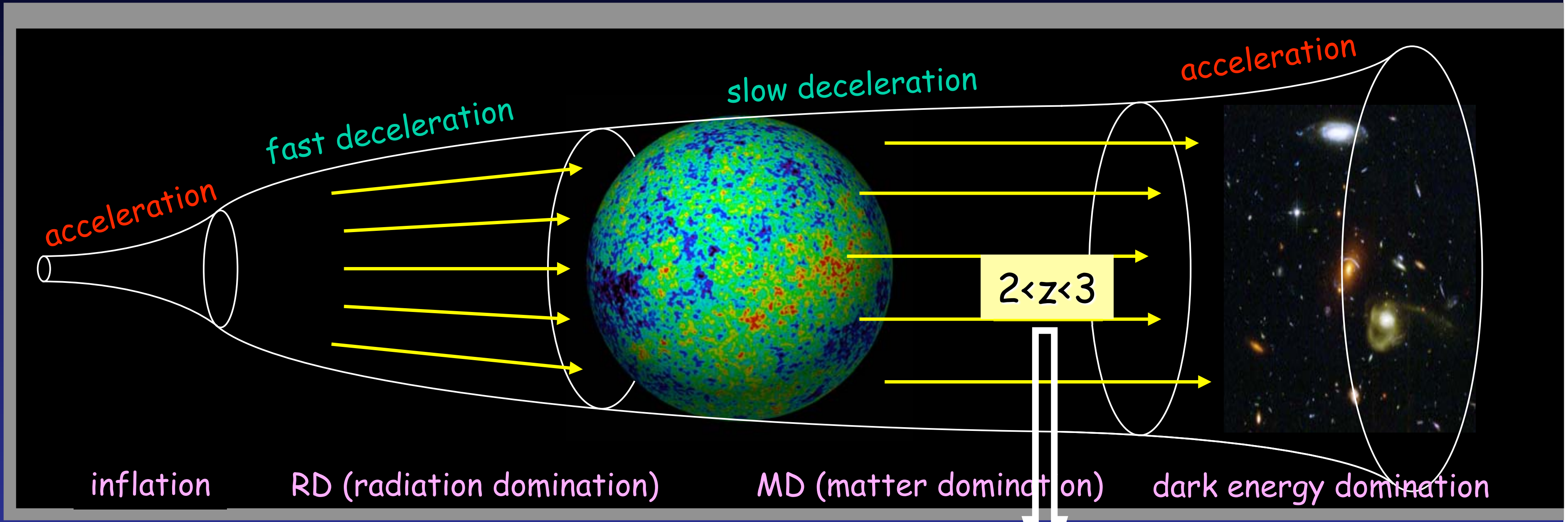


matter power spectrum P(k)

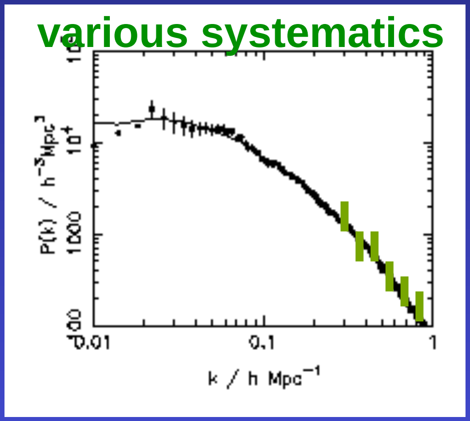


galaxy redshift surveys

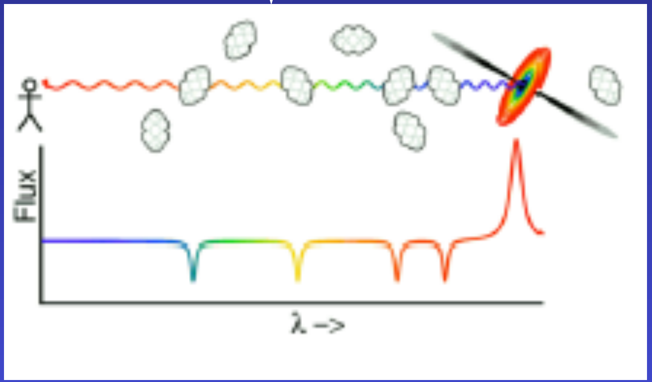
Cosmological observables : LSS



Distribution of large-scale structures at medium z

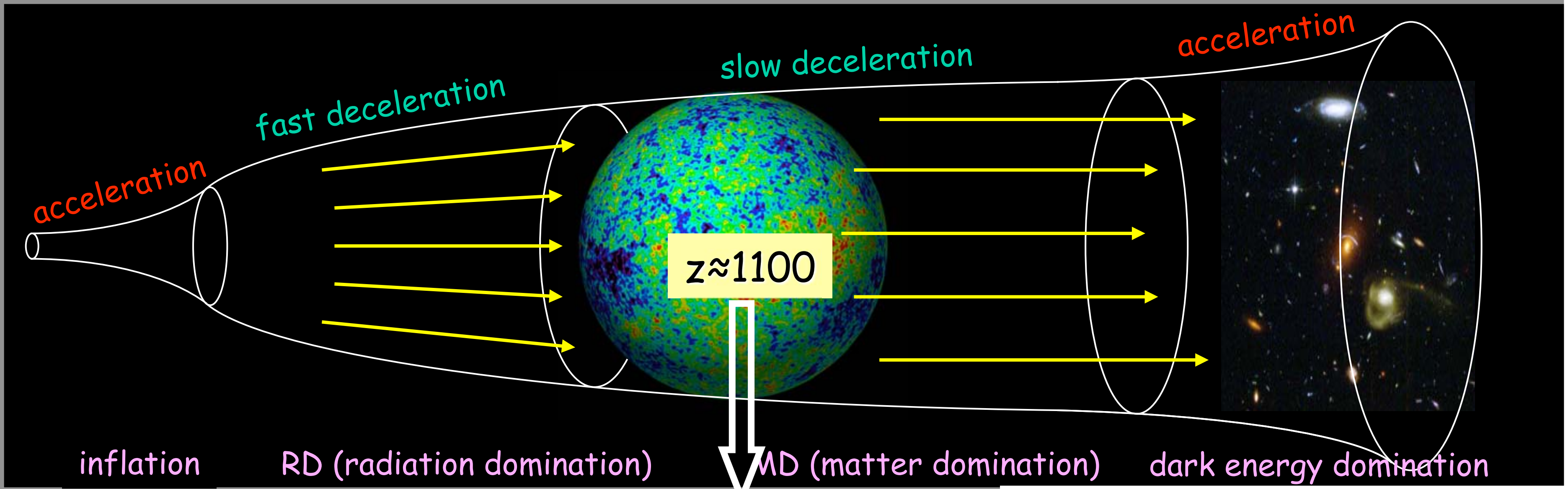


matter power spectrum P(k)

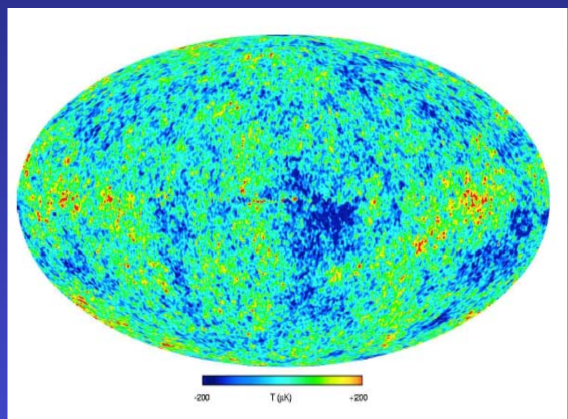


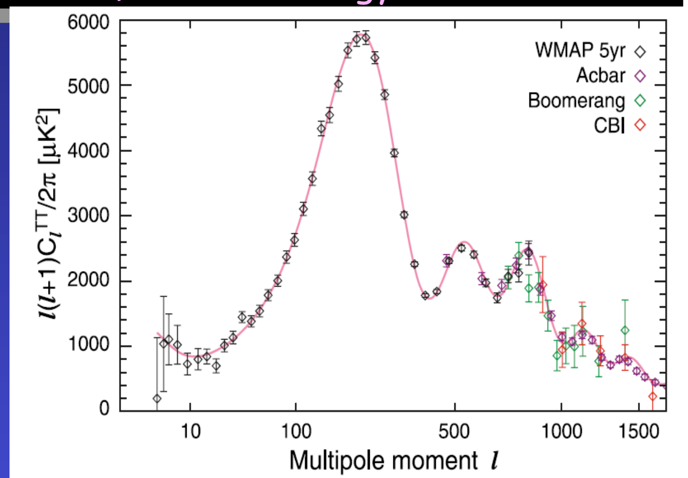
Lyman-α forests in quasar spectra

Cosmological observables: CMB



Anisotropies of the Cosmic Microwave Background





CMB temperature/polarization anisotropies ⇒ photon power spectra

Effect of massive neutrinos on the CMB spectra

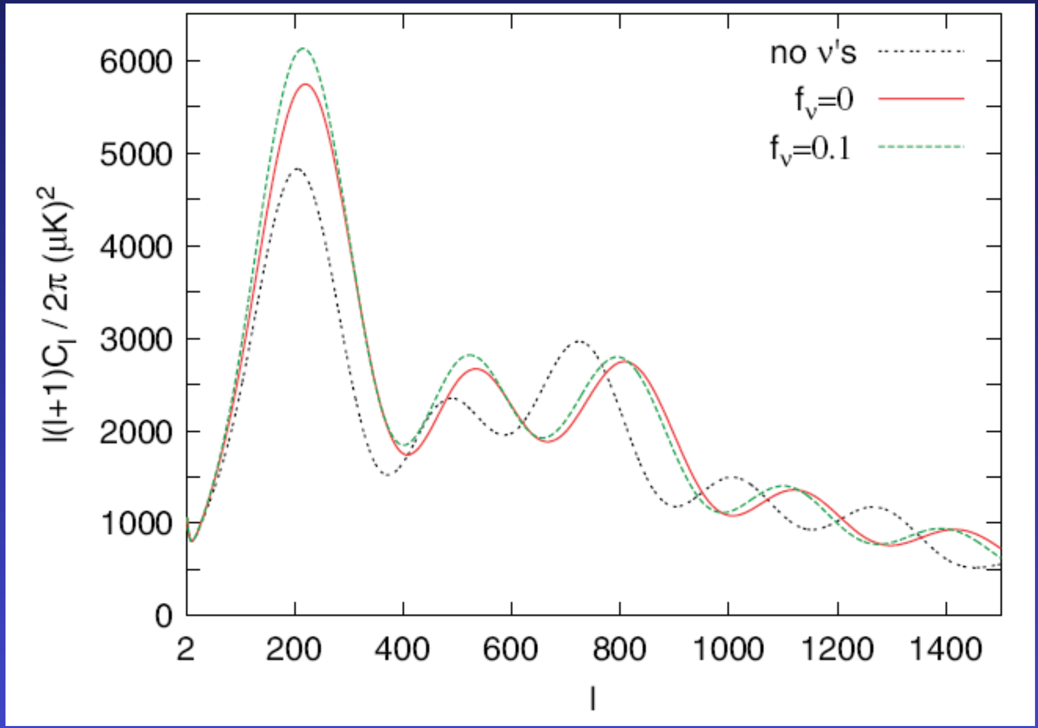
1) Direct effect of sub-eV massive neutrinos on the evolution of the baryon-photon coupling is very small

2) Impact on CMB spectra is indirect: non-zero Ω_ν today implies a change in the spatial curvature or other Ω_i . The background evolution is modified

Ex: in a flat universe,

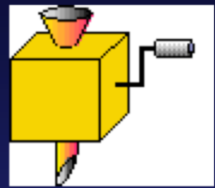
keep $\Omega_\Lambda+\Omega_{cdm}+\Omega_b+\Omega_\nu=1$

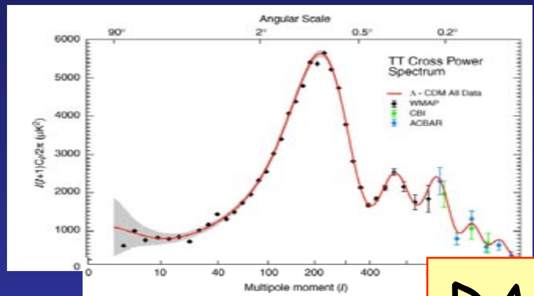
constant

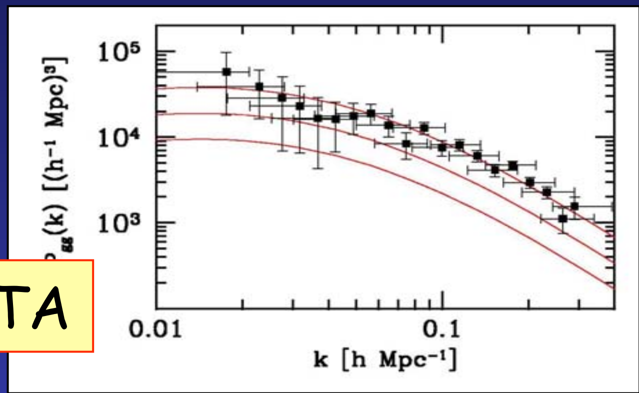


How to get a bound (measurement) of neutrino masses from Cosmology

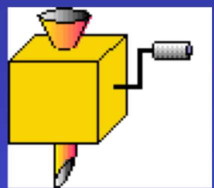
Fiducial cosmological model:
$(\Omega_b h^2 , \Omega_m h^2 , h , n_s , \tau, \Sigma m_\nu)$







DATA



PARAMETER ESTIMATES

Cosmological Data

- CMB Temperature: WMAP plus data from other experiments at large multipoles (CBI, ACBAR, VSA…)
- CMB Polarization: WMAP,…
- Large Scale Structure:
  - * Galaxy Clustering (2dF,SDSS)
  - * Bias (Galaxy, …): Amplitude of the Matter P(k) (SDSS,σ_8)
  - * Lyman-a forest: independent measurement of power on small scales
  - * Baryon acoustic oscillations (SDSS)

Bounds on parameters from other data: SNIa (Ω_m), HST (h), …

Cosmological Parameters: example

Parameter	Meaning	Status
τ	Reionization optical depth	Not optional
ω_b	Baryon density	Not optional
ω_d	Dark matter density	Not optional
f_ν	Dark matter neutrino fraction	Well motivated
Ω_Λ	Dark energy density	Not optional
w	Dark energy equation of state	Worth testing
Ω_k	Spatial curvature	Worth testing
A_s	Scalar fluctuation amplitude	Not optional
n_s	Scalar spectral index	Well motivated
α	Running of spectral index	Worth testing
r	Tensor-to-scalar ratio	Well motivated
n_t	Tensor spectral index	Well motivated
b	Galaxy bias factor	Not optional

SDSS Coll, PRD 69 (2004) 103501

Cosmological bounds on neutrino mass(es)

A unique cosmological bound on m_ν DOES NOT exist !

Different analyses have found upper bounds on neutrino masses, since they depend on

- The combination of cosmological data used
- The assumed cosmological model: number of parameters (problem of parameter degeneracies)
- The properties of relic neutrinos

Cosmological bounds on neutrino masses using WMAP

Dependence on the data set used:

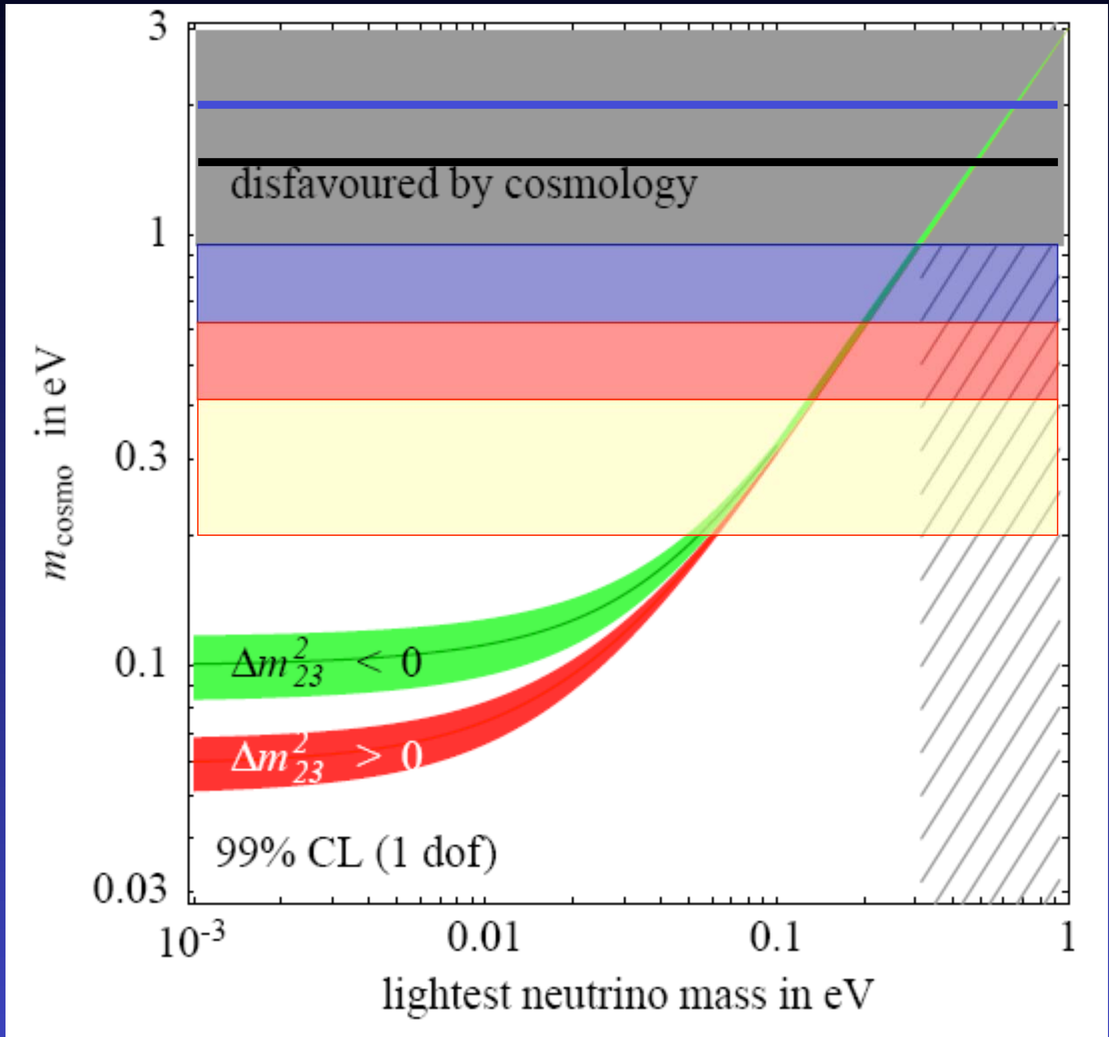
Cosmological data set	With WMAP3	Σ bound (2σ)
WMAP		< 2.3 eV
WMAP + SDSS		< 1.2 eV
WMAP + SDSS + SN_{Riess} + HST + BBN		< 0.78 eV
CMB + LSS + SN_{Astier}		< 0.75 eV
CMB + LSS + SN_{Astier} + BAO		< 0.58 eV
CMB + LSS + SN_{Astier} + Ly-α		< 0.21 eV
CMB + LSS + SN_{Astier} + BAO + Ly-α		< 0.17 eV

Fogli et al., PRD 75 (2007) 053001

Cosmological data set	With WMAP5	Σ (at 2σ)
CMB		< 1.19 eV
CMB + HST + SN-Ia		< 0.75 eV
CMB + HST + SN-Ia + BAO		< 0.60 eV
CMB + HST + SN-Ia + BAO + Lyα		< 0.19 eV

Fogli et al., PRD 78 (2008) 033010

Neutrino masses in 3-neutrino schemes



CMB (+cluster mass function)

CMB + galaxy clustering

+ HST, SNI-a…

+ **BAO** and/or bias

+ including Ly-α

Strumia & Vissani, hep-ph/0606054

Current cosmological bounds on neutrino masses

Dependence on the data set AND the cosmological model used.

Goobar et al, JCAP 06 (2006) 019

Data	m_ν (95% C.L.)
1: CMB, LSS, SNIa	0.70 eV
2: CMB, LSS, SNIa, BAO	0.48 eV
3: CMB, LSS, SNIa, Ly-α	0.35 eV
4: CMB, LSS, SNIa, BAO, Ly-α	0.27 eV

Standard cosmological model+neutrino masses (8 par)

Data	m_ν (95% C.L.)
1: CMB, LSS, SNIa	1.72 eV
2: CMB, LSS, SNIa, BAO	0.62 eV
3: CMB, LSS, SNIa, Ly-α	0.83 eV
4: CMB, LSS, SNIa, BAO, Ly-α	0.49 eV

SCM+neutrino masses+N_{eff}+n_s+w_{DE} (11 par)

Absolute mass scale searches

Tritium β decay	$m_{\nu_e} = \left(\sum_i \lvert U_{ei} \rvert^2 m_i^2 \right)^{1/2}$

$$[c_{13}^2 c_{12}^2 m_1^2 + c_{13}^2 s_{12}^2 m_2^2 + s_{13}^2 m_3^2]^{1/2}$$

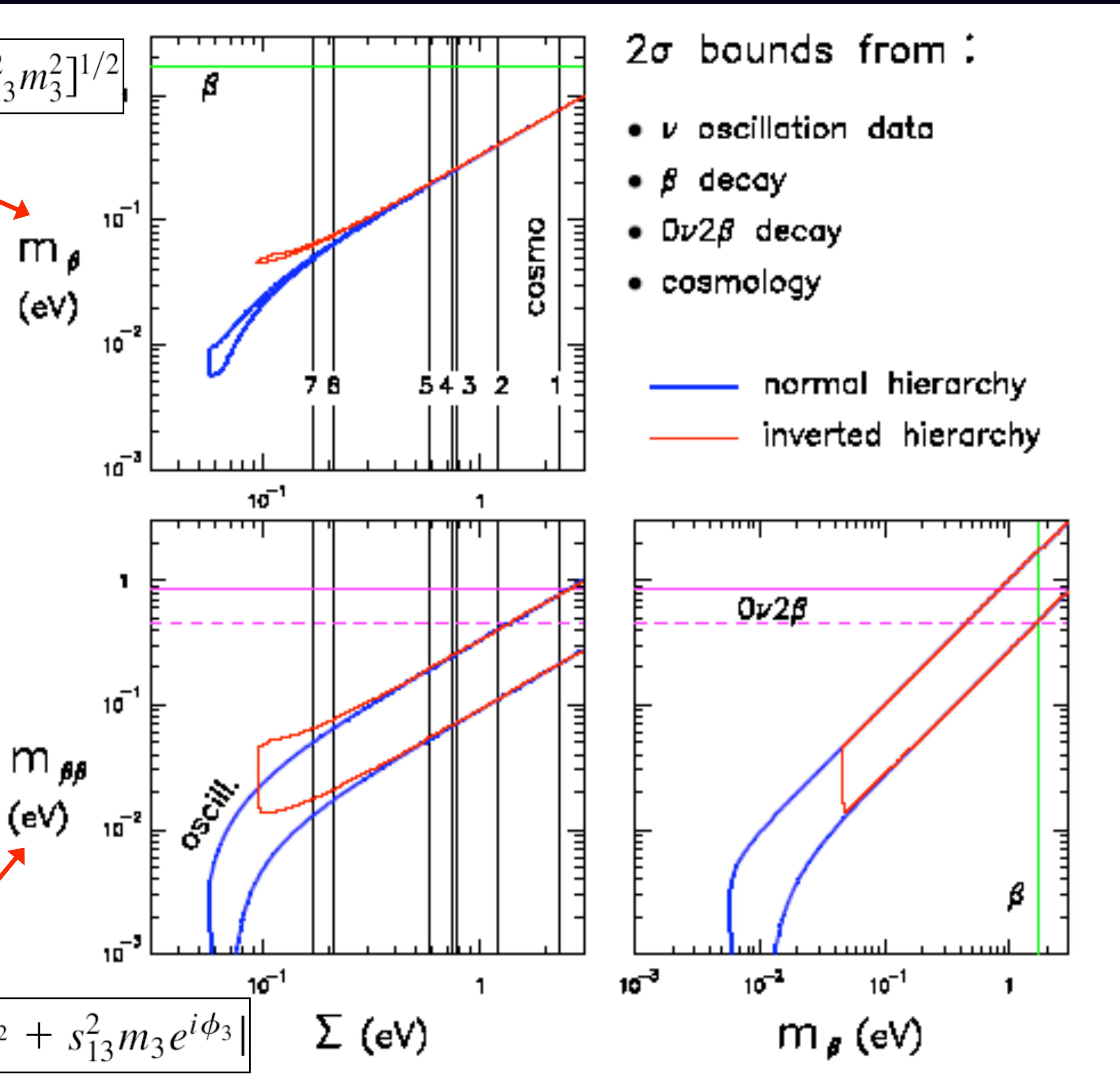
Neutrinoless double beta decay	$m_{ee} = \left\lvert \sum_i U_{ei}^2 m_i \right\rvert$

$$|c_{13}^2 c_{12}^2 m_1 + c_{13}^2 s_{12}^2 m_2 e^{i\phi_2} + s_{13}^2 m_3 e^{i\phi_3}|$$

Cosmology	$\sim \sum_i m_i$

Tritium β decay, 0ν2β and Cosmology

$$[c_{13}^2 c_{12}^2 m_1^2 + c_{13}^2 s_{12}^2 m_2^2 + s_{13}^2 m_3^2]^{1/2}$$

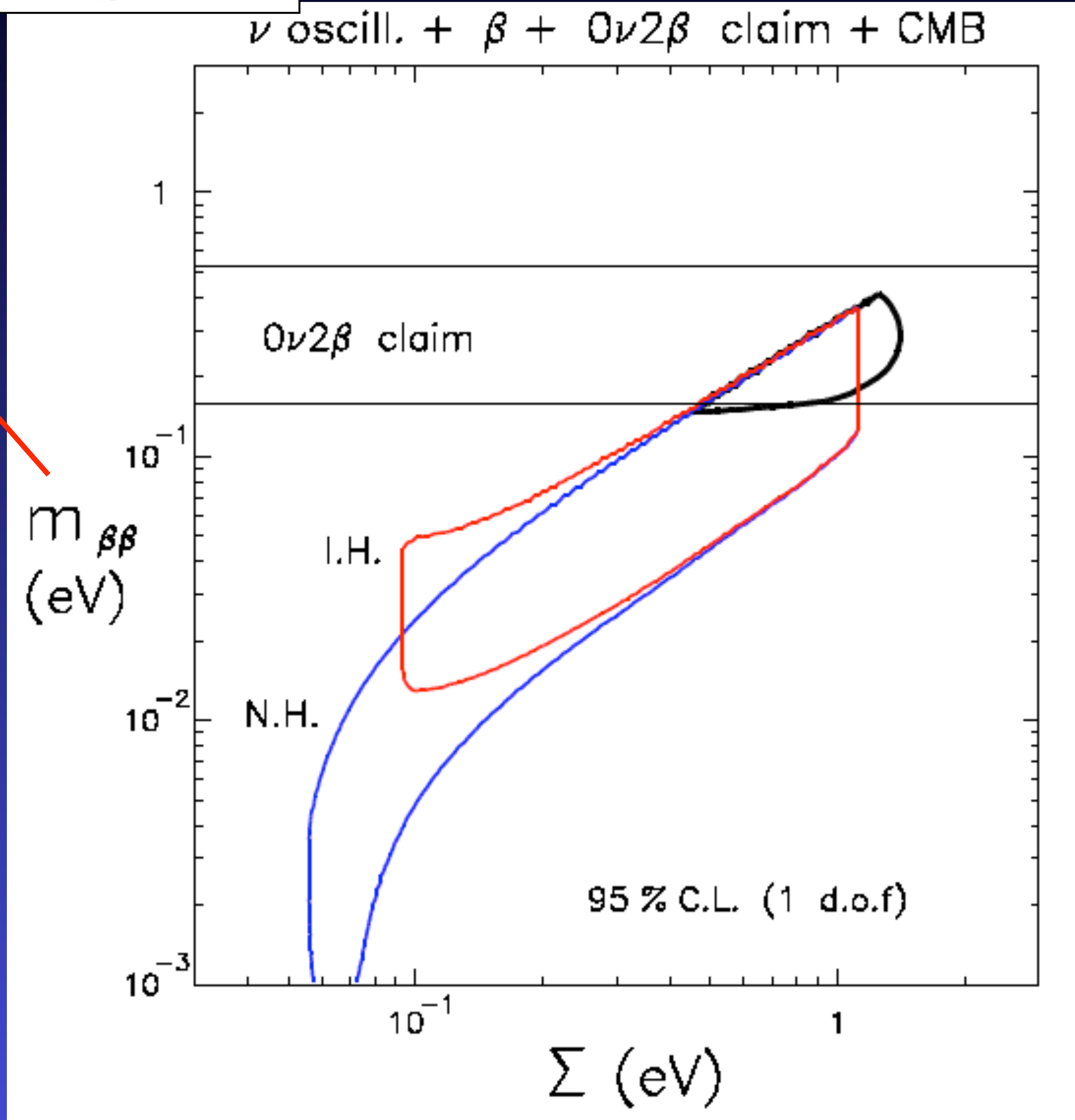


Fogli et al., PRD 75 (2007) 053001

$$|c_{13}^2 c_{12}^2 m_1 + c_{13}^2 s_{12}^2 m_2 e^{i\phi_2} + s_{13}^2 m_3 e^{i\phi_3}|$$

0ν2β and Cosmology

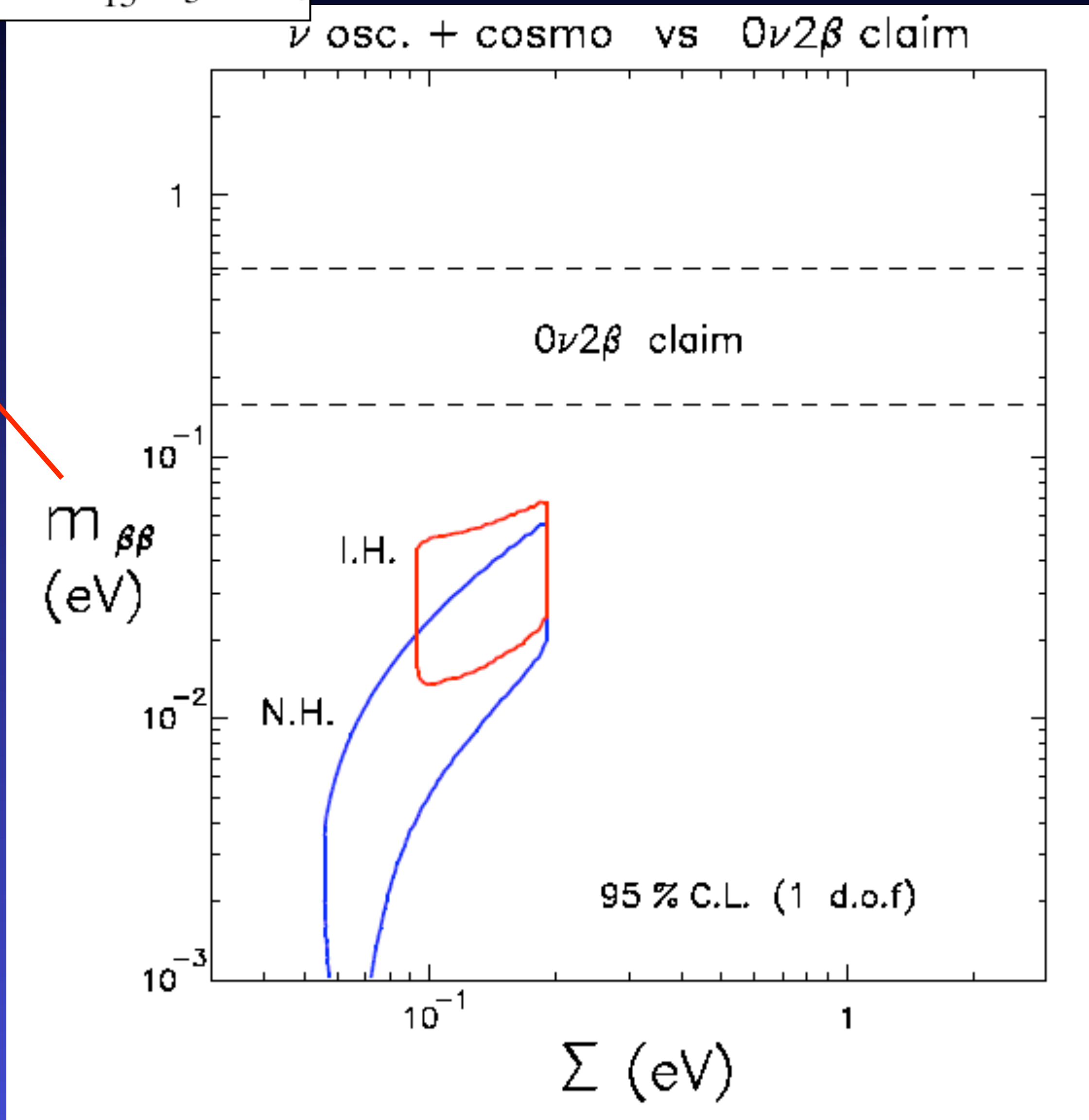
$$|c_{13}^2 c_{12}^2 m_1 + c_{13}^2 s_{12}^2 m_2 e^{i\phi_2} + s_{13}^2 m_3 e^{i\phi_3}|$$



Fogli et al., PRD 78 (2008) 033010

0ν2β and Cosmology

$$|c_{13}^2 c_{12}^2 m_1 + c_{13}^2 s_{12}^2 m_2 e^{i\phi_2} + s_{13}^2 m_3 e^{i\phi_3}|$$



Fogli et al., PRD 78 (2008) 033010

Future sensitivities to Σm_ν

Future cosmological data will be available from

- CMB (Temperature & Polarization anis.)
- High-z Galaxy redshift surveys

  Hannestad & Wong, JCAP 07 (2007) 004

  Takada et al, PRD 73 (2006) 083520
- Galaxy cluster surveys

  Wang et al, PRL 95 (2005) 011302
- Weak lensing surveys (tomography)

  Hannestad et al, JCAP 06 (2006) 025

  Song & Knox, PRD 70 (2004) 063510
- CMB lensing

  Perotto et al, JCAP 10 (2006) 013

  Lesgourgues et al, PRD 73 (2006) 045021
- Fluctuations in the 21 cm H line

  Loeb & Wyithe, PRL 100 (2008) 161301

  Pritchard & Pierpaoli, arXiv:0805.1920

Forecasts indicate 0.01-0.15 eV sensitivities to Σm_ν are possible

PLANCK+SDSS

- Fisher matrix analysis: expected sensitivities assuming a fiducial cosmological model, for future experiments with known specifications

Fiducial cosmological model:
$(\Omega_b h^2 , \Omega_m h^2 , h , n_s , \tau, \Sigma m_\nu) =$
$(0.0245 , 0.148 , 0.70 , 0.98 , 0.12, \Sigma m_\nu)$

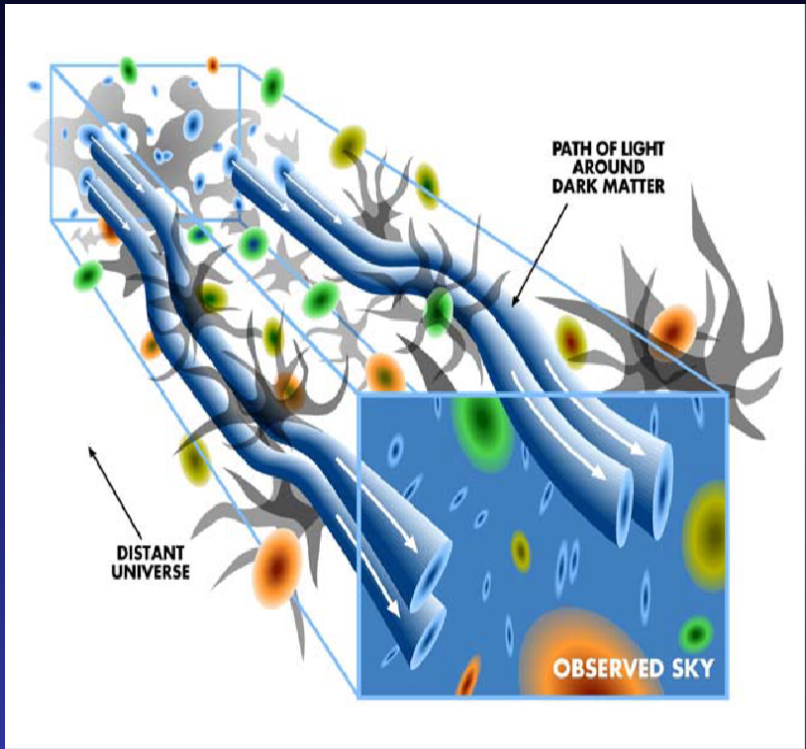
Σm detectable at 2σ if larger than

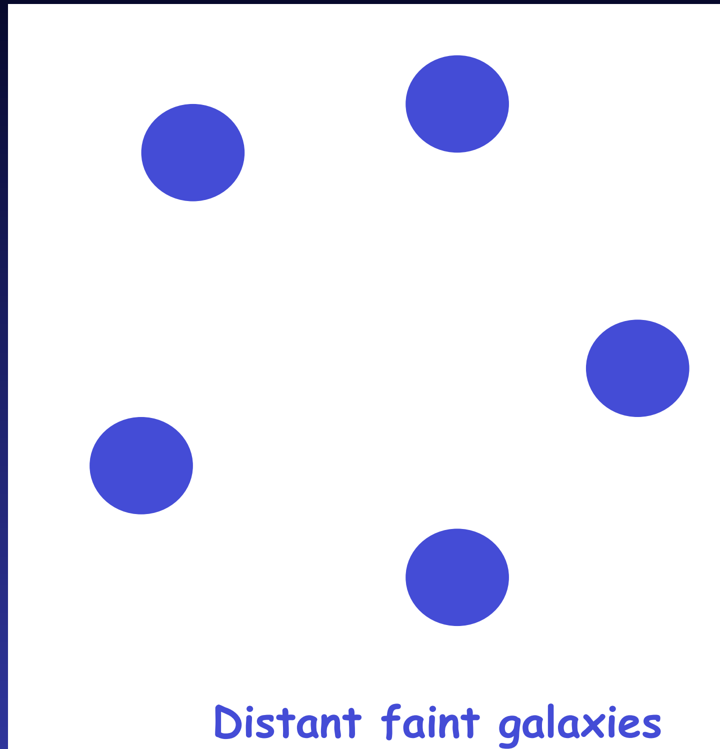
0.21 eV (PLANCK+SDSS)

0.13 eV (CMBpol+SDSS)

Lesgourgues, SP & Perotto, PRD 70 (2004) 045016

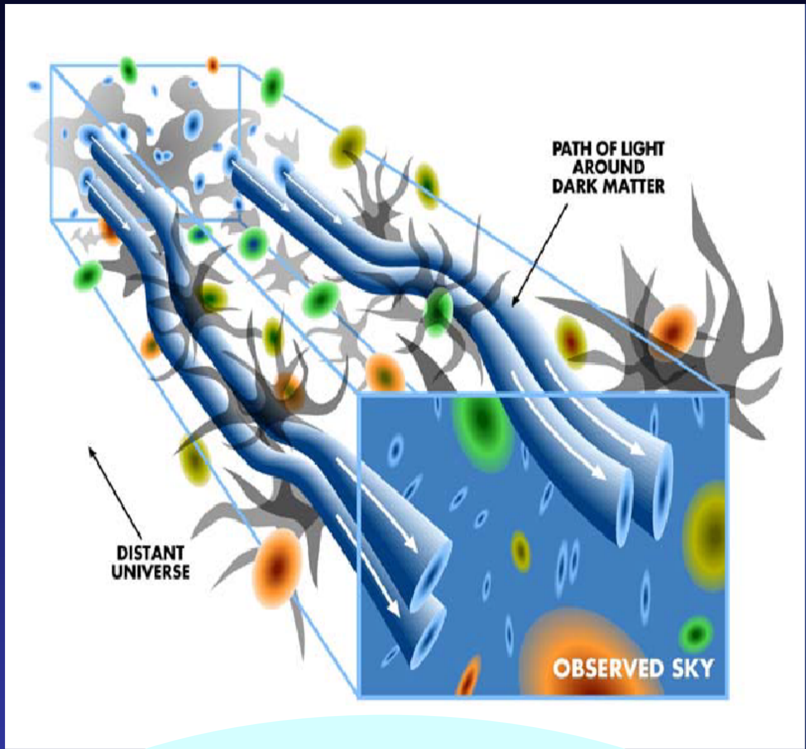
Future sensitivities to Σm_ν: weak gravitational lensing

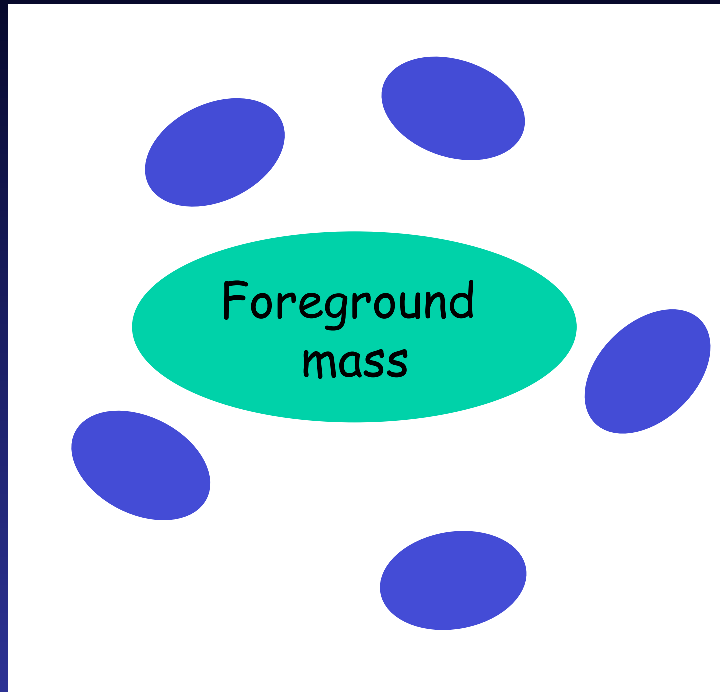




Frieman, Dodelson

Future sensitivities to Σm_ν: weak gravitational lensing





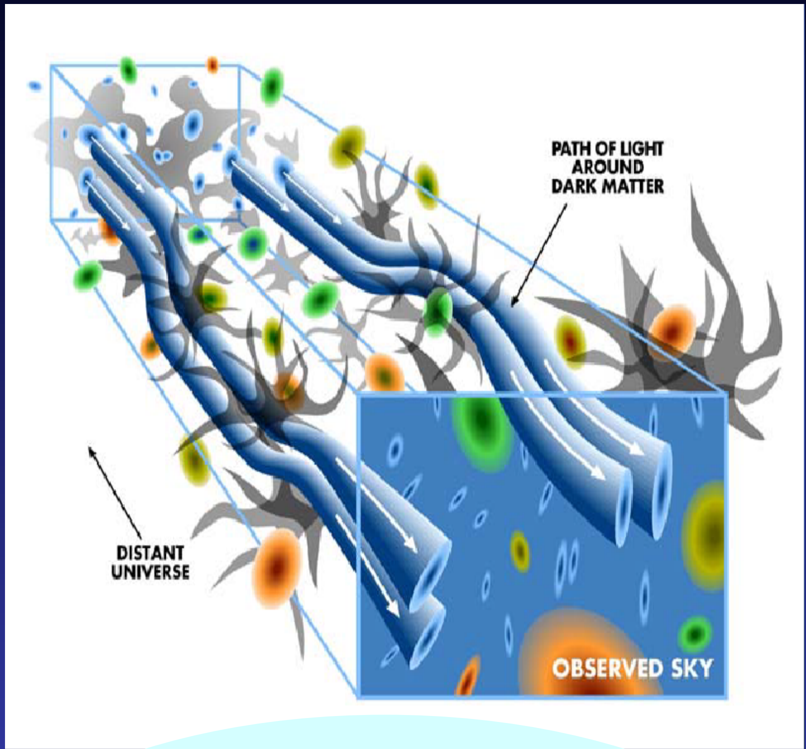
Weak lensing of faint galaxies

Frieman, Dodelson

No bias uncertainty
Small scales much closer to linear regime
Tomography:
3D reconstruction

Measure a large number of elliptically shaped galaxies

Future sensitivities to Σm_ν: weak gravitational lensing



No bias uncertainty
Small scales much closer to linear regime
Tomography:
3D reconstruction

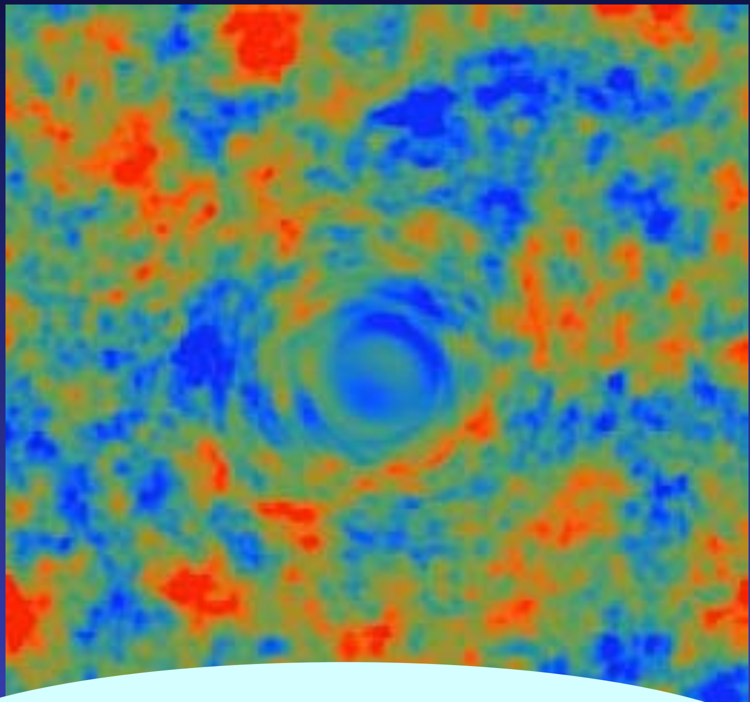
sensitivity of future weak lensing survey $(4000°)^2$ to m_ν

$\sigma(m_\nu) \sim 0.1$ eV

Abazajian & Dodelson
PRL 91 (2003) 041301

Future sensitivities to Σm_ν: weak gravitational lensing

lensing of the CMB signal



Makes CMB sensitive to smaller neutrino masses

sensitivity of CMB (primary + lensing) to m_ν

$\sigma(m_\nu)$ = 0.15 eV (Planck)

$\sigma(m_\nu)$ = 0.044 eV (CMBpol)

Kaplinghat, Knox & Song
PRL 91 (2003) 241301

CMB lensing: recent forecast analysis

σ(M_ν) in eV for future CMB experiments alone :

Lesgourgues et al,
PRD 73 (2006) 045021

Free parameters:	8 parameters of minimal ΛMDM			
Lensing extraction:	no	no	yes	yes
Foreground cleaning:	perfect	none	perfect	none
QUaD+BICEP	1.3	1.6	0.31	0.36
BRAIN+ClOVER	1.5	1.8	0.34	0.43
PLANCK	0.45	0.49	0.13	0.14
SAMPAN	0.34	0.40	0.10	0.17
PLANCK+SAMPAN	0.32	0.36	0.08	0.10
Inflation Probe	0.14	0.16	0.032	0.036

Free parameters:	same + $\{\alpha, w, N_{\rm eff}\}$			
Lensing extraction:	no	no	yes	yes
Foreground cleaning:	perfect	none	perfect	none
QUaD+BICEP	1.5	1.9	0.36	0.40
BRAIN+ClOVER	1.7	2.0	0.42	0.51
PLANCK	0.51	0.56	0.15	0.15
SAMPAN	0.37	0.44	0.12	0.18
PLANCK+SAMPAN	0.34	0.40	0.10	0.12
Inflation Probe	0.25	0.26	0.035	0.039

"Measuring" even m_ν=0.05 eV ?

New cosmological observable as a potential probe of fluctuations at intermediate redshifts (6<z<20) ⇒ study of fluctuations in the 21cm line emitted by neutral H

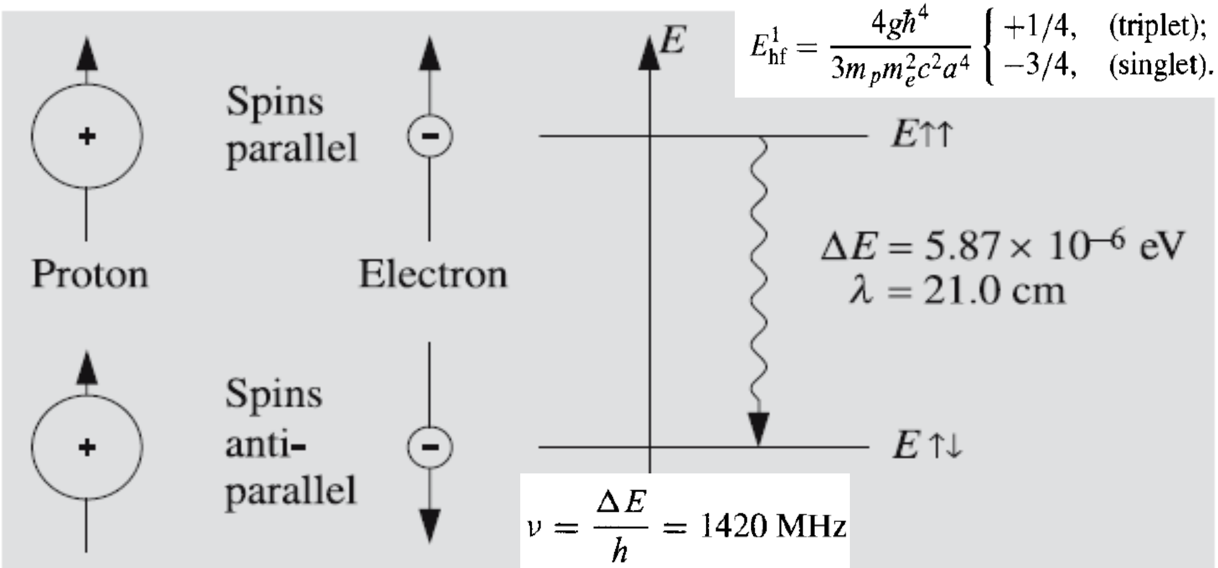
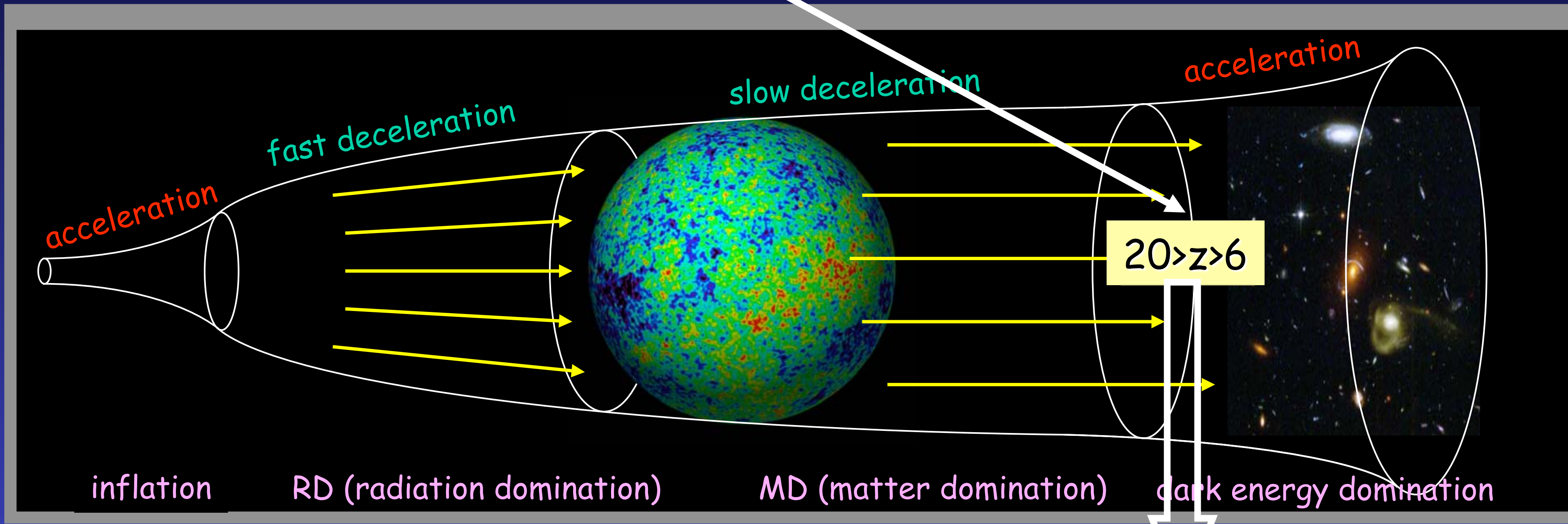


Fig. 5.8. The origin of the hydrogen 21 cm line. The spins of the electron and the proton may be either parallel or opposite. The energy of the former state is slightly larger. The wavelength of a photon corresponding to a transition between these states is 21 cm

Karttunen *et al. 2007*

"Measuring" even m_ν=0.05 eV ?

New cosmological observable as a potential probe of fluctuations at intermediate redshifts (6<z<20) ⇒ study of fluctuations in the 21cm line emitted by neutral H



Redshifted line:
2.1 m at
redshift 10

$$\left\langle \tilde{\delta}_{21}(\mathbf{k}_1)\,\tilde{\delta}_{21}(\mathbf{k}_2)\right\rangle \equiv (2\pi)^3\delta_D(\mathbf{k}_1+\mathbf{k}_2)P_{21}(\mathbf{k}_1)$$

power spectrum of 21 cm brightness fluctuations $P_{21}(k)$

Future sensitivities on Σm_ν from 21cm observ.

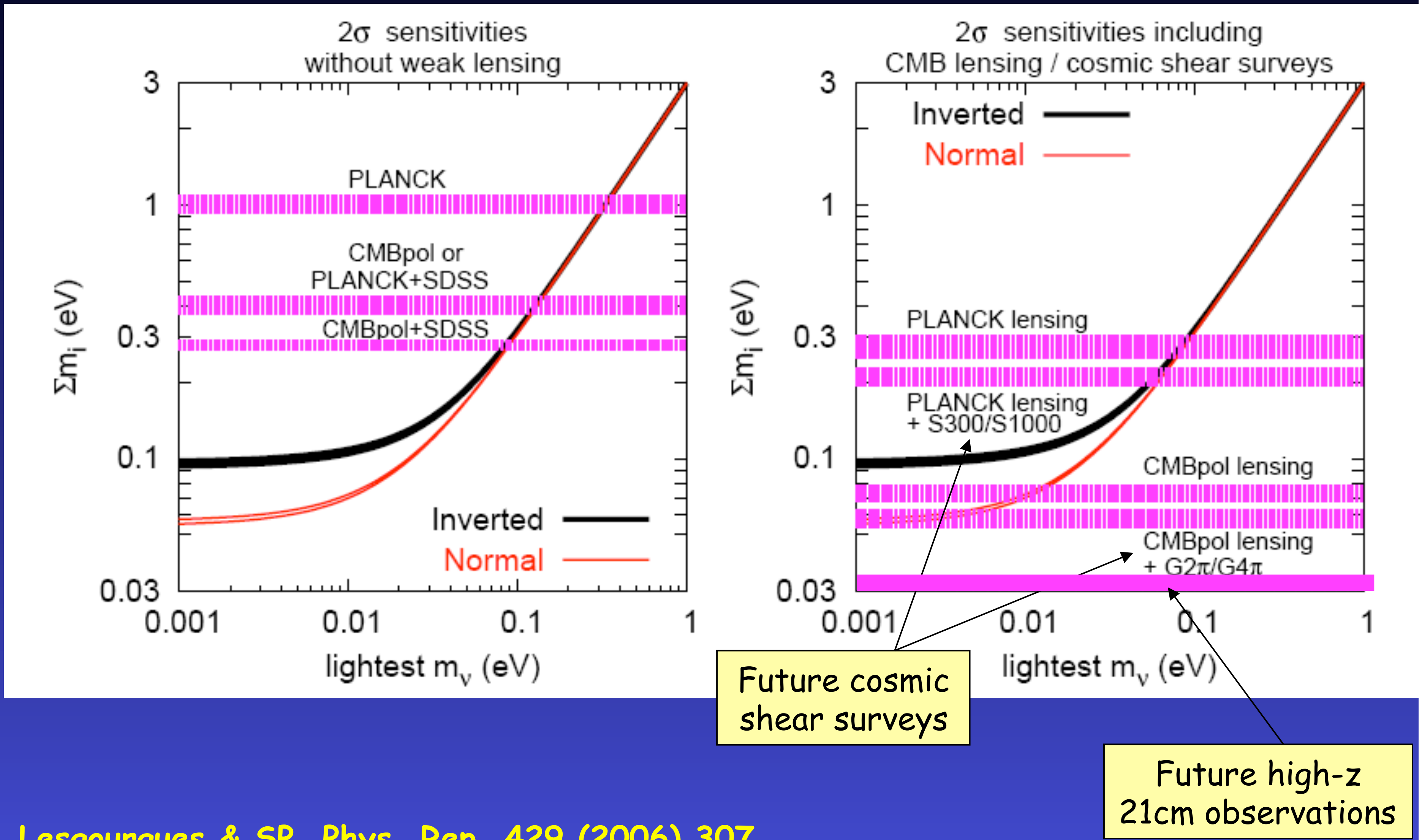
	$\Omega_m h^2$	$\Omega_b h^2$	Ω_Λ	w	n_s	A_s^2	τ	Y_{He}	M_ν
Fiducial	0.147	0.023	0.7	-1	0.95	26.6	0.1	0.24	0.3
SDSS	0.456	0.083	0.117	1.21	0.503	∞	-	-	6.16
G1	0.119	0.0207	0.0358	0.574	0.174	∞	-	-	1.28
G2	0.0354	0.00593	0.295	1.22	0.0482	∞	-	-	1.01
G3	0.0252	0.00438	0.0076	0.122	0.037	∞	-	-	0.272
MWA	0.0317	0.00761	0.972	3.13	0.0487	∞	-	-	0.749
SKA	0.00191	0.00056	0.234	0.747	0.0054	∞	-	-	0.175
FFTT	4.94e-05	4.77e-05	0.0045	0.014	0.0002	∞	-	-	0.009
Planck	0.0045	0.00024	0.068	0.18	0.0074	0.26	0.0048	0.011	0.38
+SDSS	0.0033	0.00024	0.023	0.11	0.0074	0.254	0.0046	0.0103	0.272
+G1	0.0016	0.00021	0.013	0.081	0.0068	0.245	0.0044	0.01	0.136
+G2	0.00089	0.00022	0.037	0.149	0.0067	0.243	0.0044	0.0099	0.104
+G3	0.00051	0.00016	0.003	0.021	0.0051	0.24	0.0043	0.0081	0.052
+MWA	0.00146	0.00021	0.053	0.17	0.0066	0.242	0.0044	0.0101	0.144
+SKA	0.00029	0.00014	0.020	0.065	0.003	0.236	0.0043	0.0044	0.080
+FFTT	4.23e-05	3.97e-05	0.004	0.011	0.0002	0.23	0.0043	0.0030	0.0075
CosmicVar	0.00244	4.16e-05	0.030	0.033	0.0024	0.124	0.0023	0.0028	0.222
+FFTT	3.3e-05	2.58e-05	0.0024	0.0076	0.0002	0.111	0.0021	0.0011	0.0068

Future Low-ν radio telescopes

Pritchard & Pierpaoli, PRD 78 (2008) 065009

(also Loeb & Wyithe, PRL 100 (2008) 161301; Mao et al, PRD 78 (2008) 023529)

Summary of future sensitivities

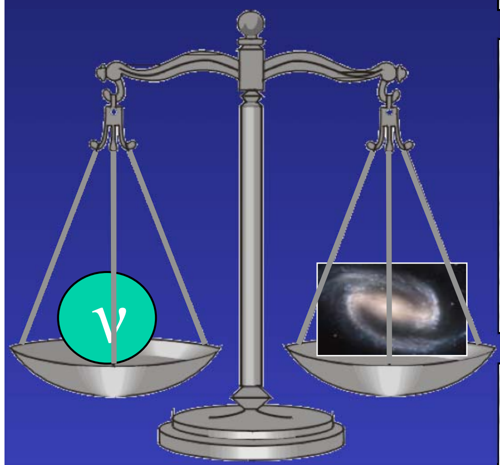


Lesgourgues & SP, Phys. Rep. 429 (2006) 307

Conclusions

Cosmological observables can be used to bound (or measure) neutrino properties, in particular the sum of neutrino masses (info complementary to laboratory results)

The radiation content of the Universe (N_{eff}) will be very constrained in the near future



Current bounds on the sum of neutrino masses from cosmological data (best Σm_ν<0.2-0.4 eV, conservative Σm_ν<1 eV)

Different cosmological observations in the next future → Sub-eV sensitivity (0.1-0.2 eV and better) → Test degenerate mass region and eventually the mimimum total mass for IH case