Rencontre at the Colegio de España - 18 may 2007

Neutrino properties from Cosmology:

the usual and the less usual

Marco Cirelli

(SPhT-CEA/Saclay & INFN)

with:
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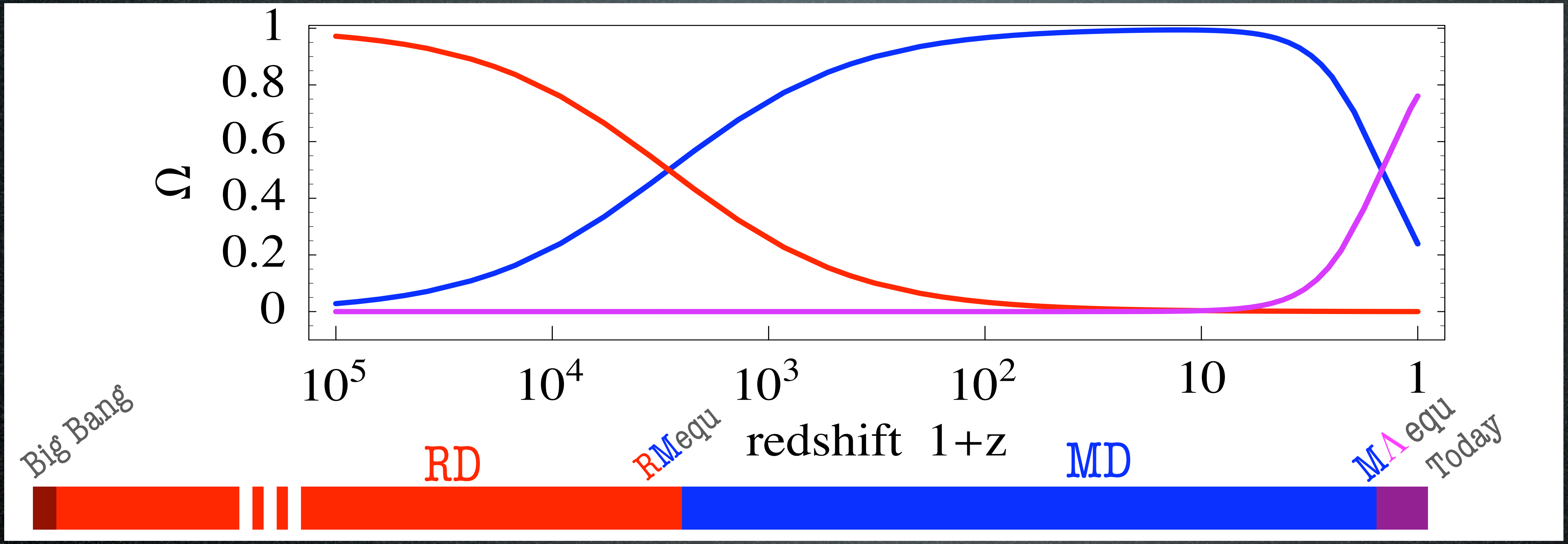
Y.-Z. Chu (Yale)
G.Marandella (UC Davis)
F.Vissani (Gran Sasso)

based on:
NPB 708 (2005) 215, hep-ph/0403158
JCAP 12 (2006) 013, hep-ph/0607086
PRD 74 (2006) 085015, astro-ph/0608206

Neutrinos in the Cosmo

The Universe is made of: radiation, matter (DM+b+e), dark energy



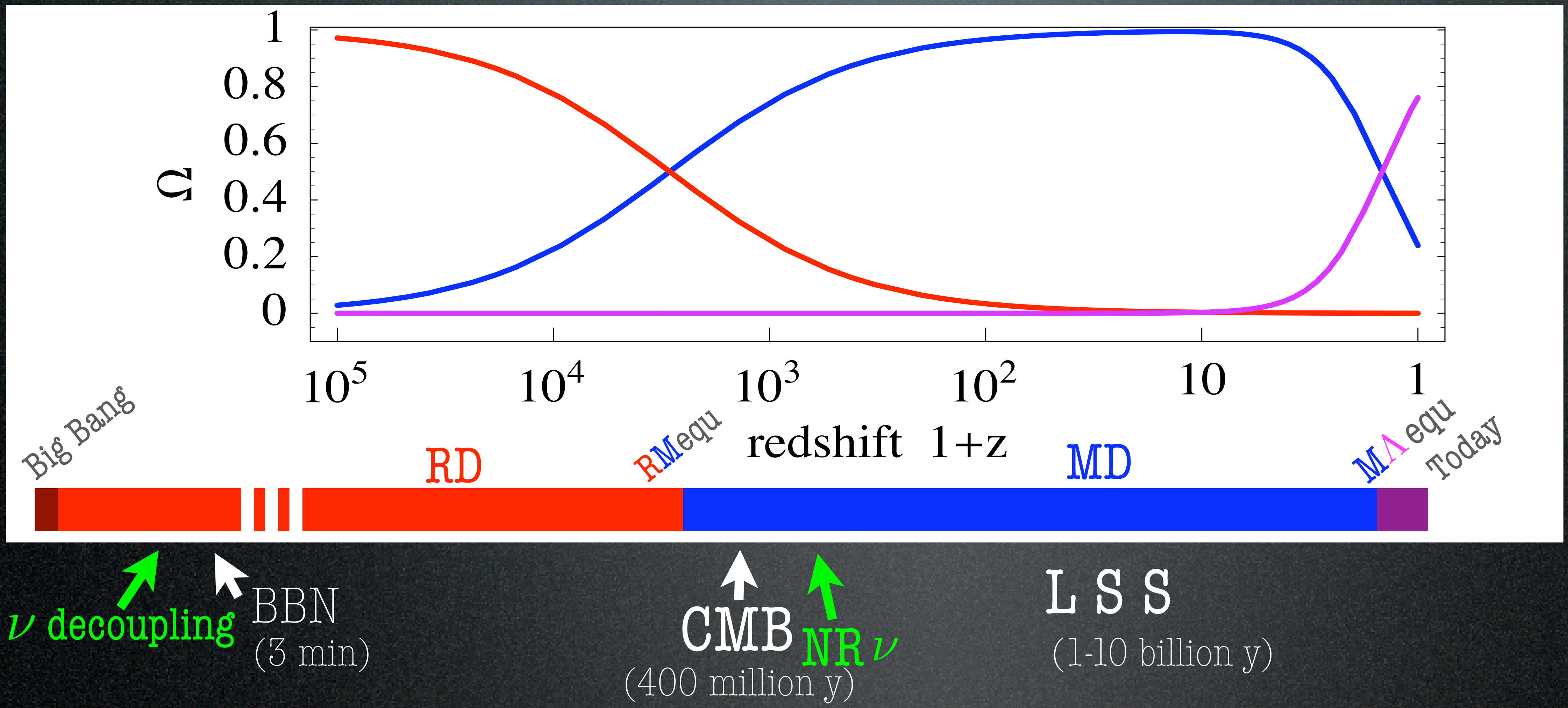
BBN
(3 min)

CMB
(400 million y)

L S S
(1-10 billion y)

Neutrinos in the Cosmo

The Universe is made of: radiation, matter (DM+b+e), dark energy and neutrinos

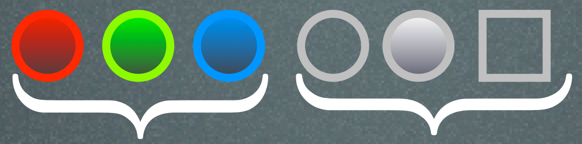


Neutrinos are significant because:

- main component of the rel energy density that sets expansion rate of the Universe
- (ordinary neutrinos have a mass, so) turn from Rel to NRel at a crucial time
- may free-stream or interact among themselves, or with new light particles

Neutrinos in the Cosmo

So what “neutrinos”?



3 ordinary,
SM neutrinos

extra light degrees of freedom,
very weakly coupled to SM forces

So what properties are probed by cosmology?

- neutrino number
- total neutrino mass
- non-conventional interactions

What are the relevant cosmological probes?

- BBN ($T \sim \mathrm{MeV}$, flavor is important, primordial plasma)

- later cosmology i.e. CMB+LSS ($T \lesssim \mathrm{eV}$, $\approx m_\nu$, gravity is the only force)

Cosmological data are (mostly) *not* sensitive to:

θ_{active} , $m_{1,2,3}$ (or $\Delta m^2_{\text{active}}$), $CP-$violation...

Neutrinos in the Cosmo

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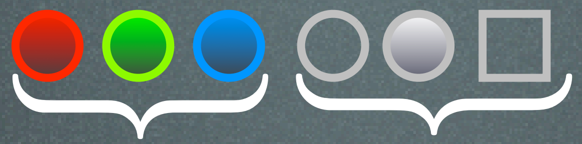

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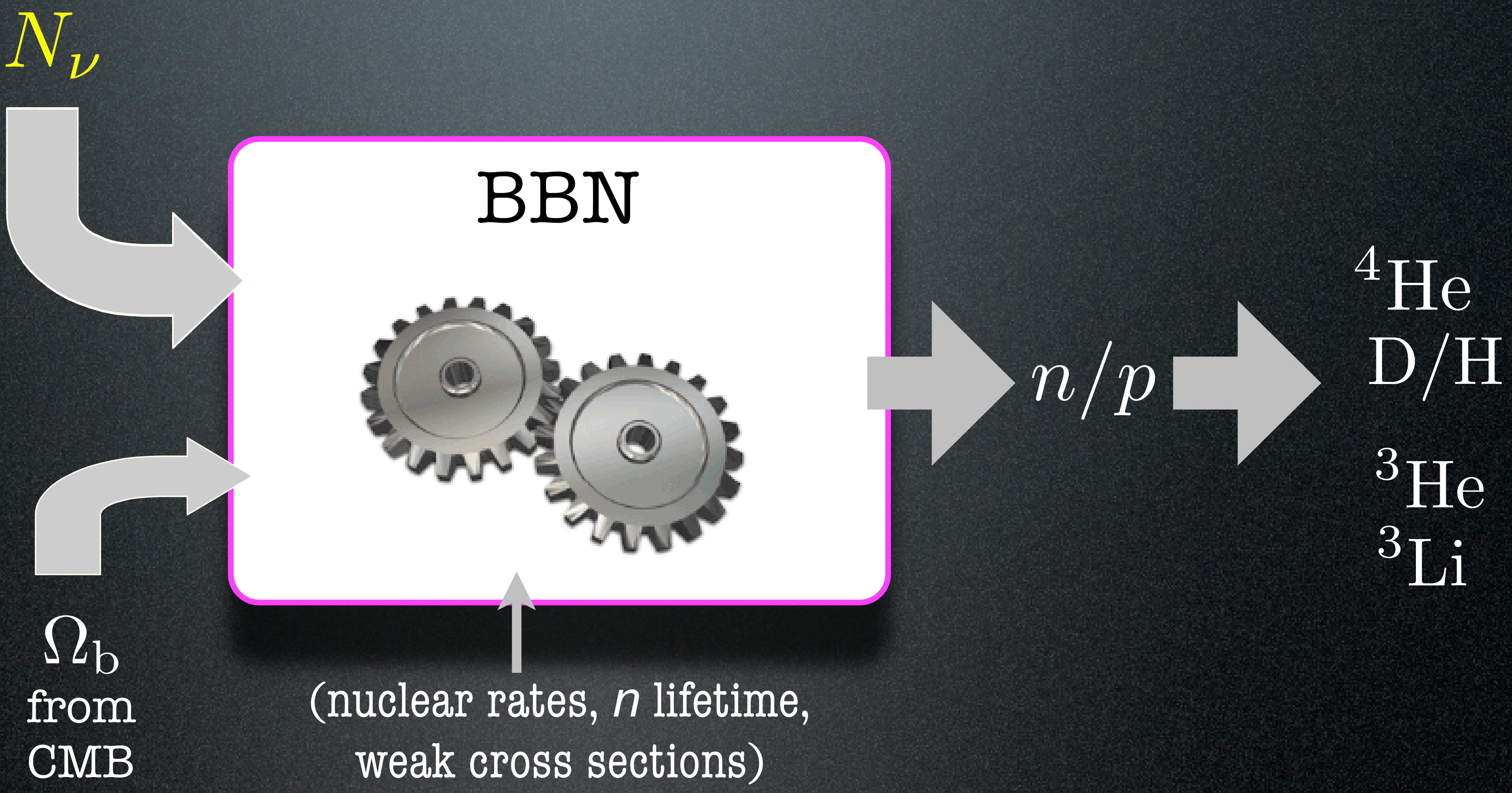
Neutrinos in BBN

Neutrinos affect the primordial production of light elements.



N_ν

BBN

n/p

^{4}He

D/H

^{3}He

^{3}Li

Ω_b
from
CMB

(nuclear rates, *n* lifetime,
weak cross sections)

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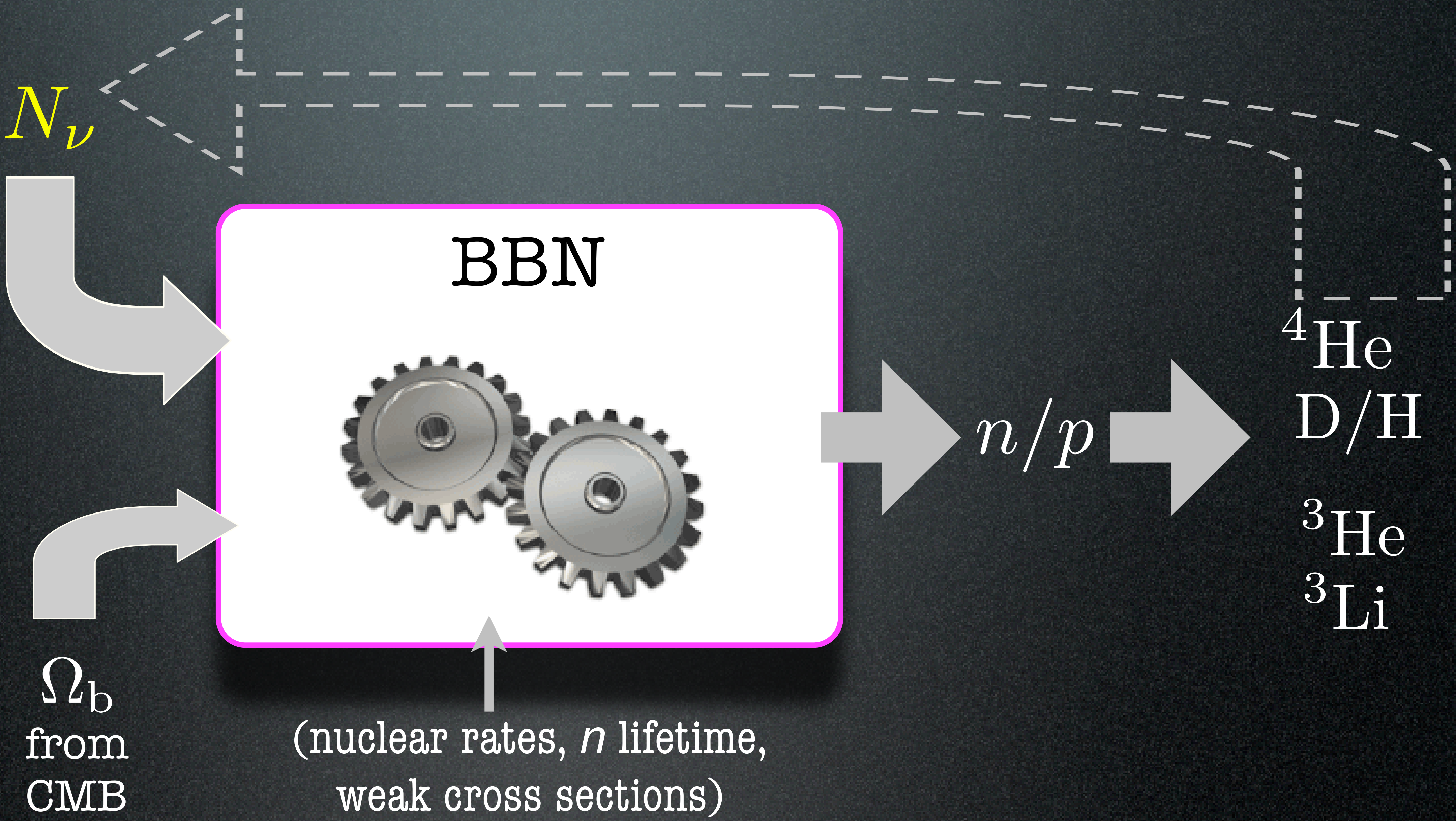

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Neutrinos in BBN

Equation for neutron/proton ratio:

$$\dot{r} \equiv \frac{dT}{dt}\frac{dr}{dT} = \Gamma_{p\to n}(1-r) - r\Gamma_{n\to p} \qquad r = \frac{n_n}{n_n+n_p}$$

weak interactions

$$\dot{T} \sim -H(T,\rho)T$$

Hubble parameter
depends on
total energy density
(A)

$$\begin{aligned} n &\longleftrightarrow p + e^- + \bar{\nu}_e \\ n + \nu_e &\longleftrightarrow p + e^- \\ n + e^+ &\longleftrightarrow p + \bar{\nu}_e . \end{aligned}$$

depend on ν_e and $\bar{\nu}_e$ densities
(B)

(A) more neutrinos ⇒ faster expansion

(B) depletion of ν_e density ⇒ modified weak rates

Neutrinos in BBN

Compare BBN output with observations:

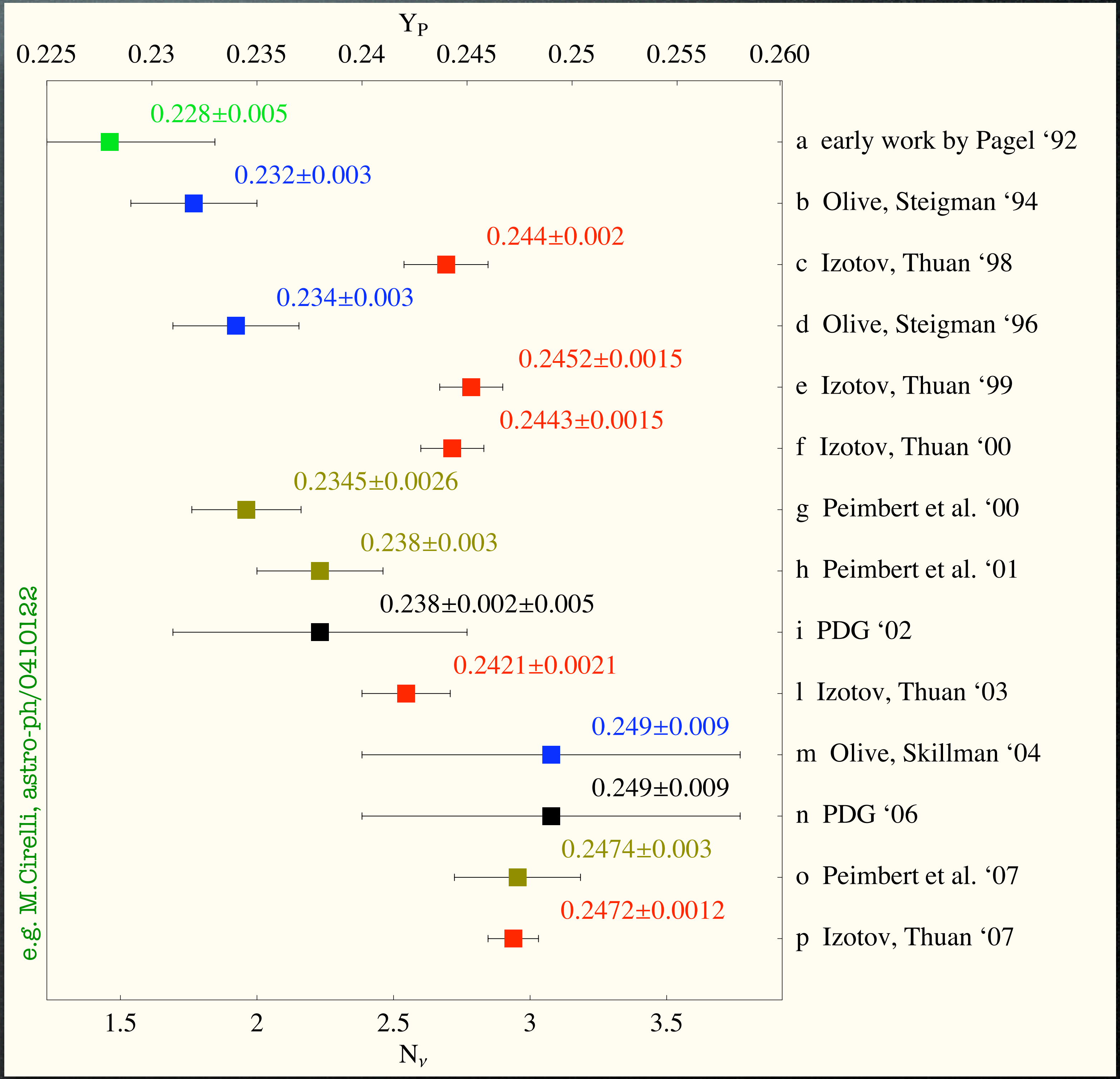
Determinations of primordial ^{4}He are somehow controversial.

Conservatively, take

$$Y_\text{p} = 0.249 \pm 0.009$$

(Determinations of D/H are currently less useful.)

$$\boxed{N_\nu \simeq 3.1 \pm 0.3}$$



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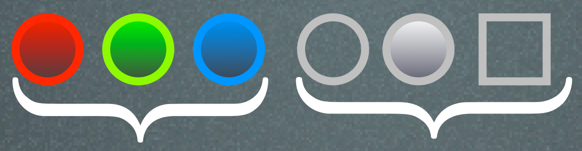

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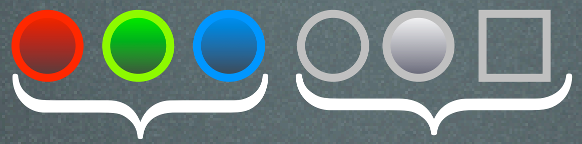

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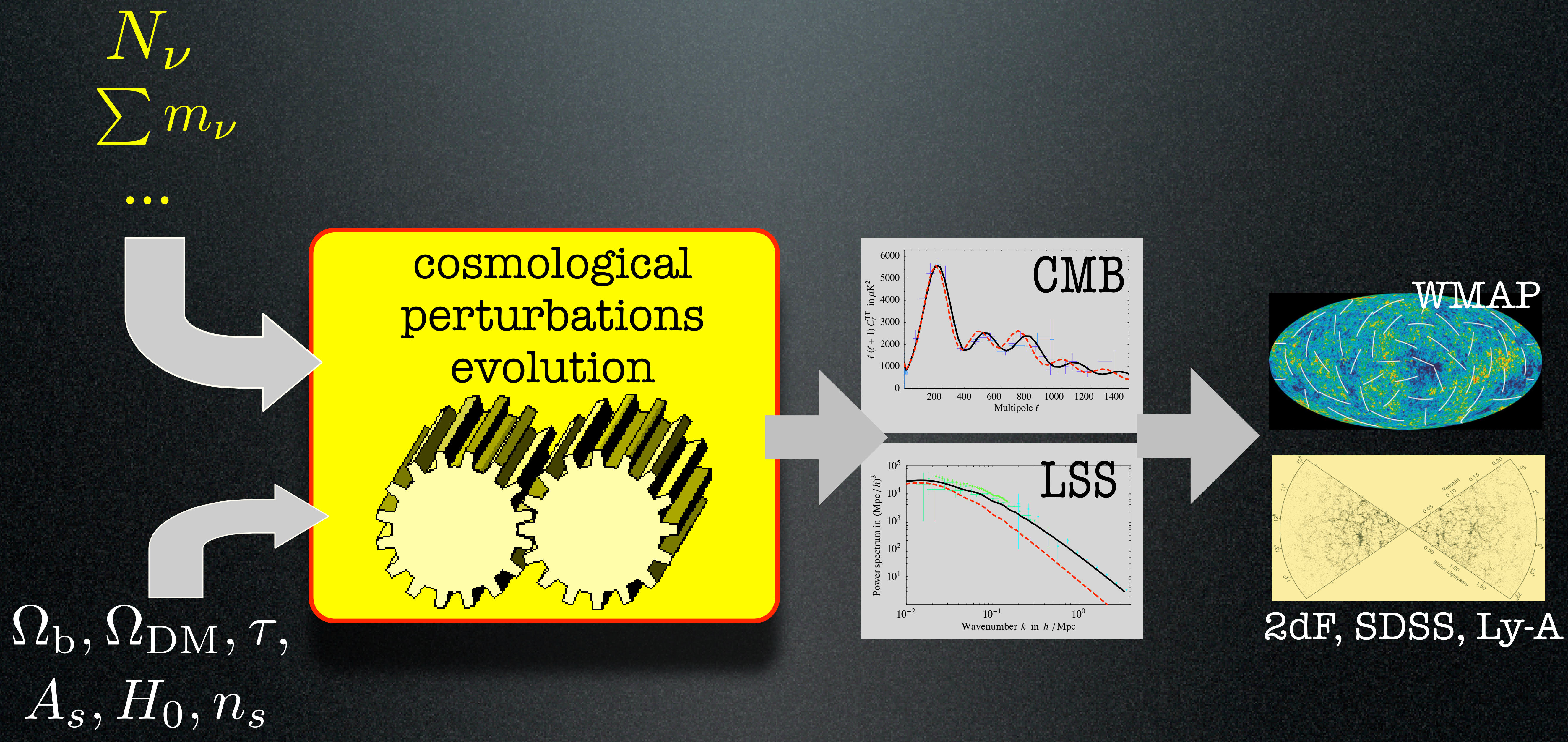
Neutrinos in CMB+LSS

Neutrinos affect (indirectly, i.e. gravitationally) the evolution of cosmological perturbations in radiation and matter.



N_ν

$\sum m_\nu$

$\dots$

cosmological perturbations evolution

$\Omega_{\rm b}, \Omega_{\rm DM}, \tau,$

A_s, H_0, n_s

CMB

LSS

WMAP

2dF, SDSS, Ly-A

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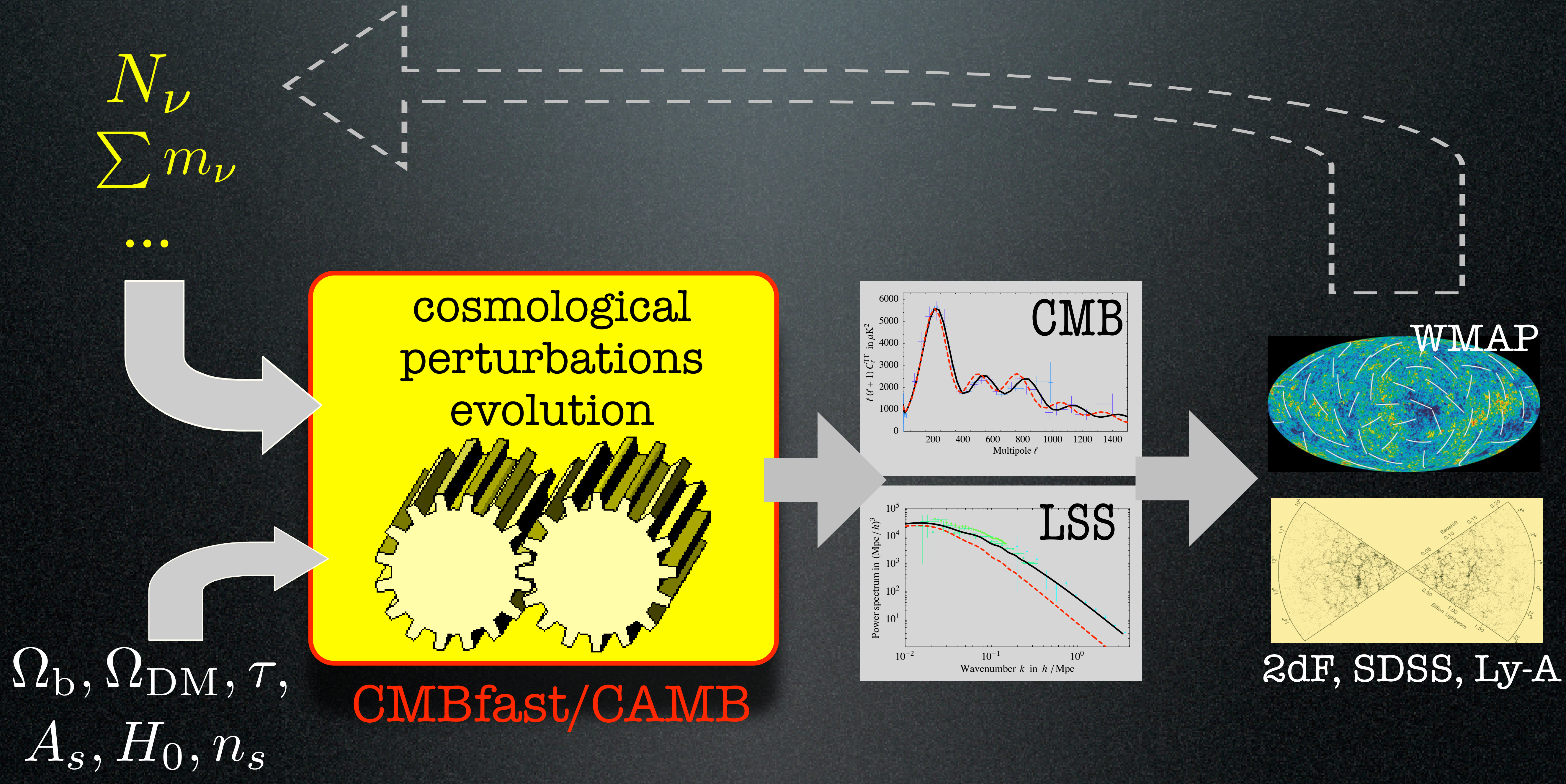

N_ν
$\sum m_\nu$
$\ldots$

cosmological perturbations evolution

CMBfast/CAMB

$\Omega_{\rm b}, \Omega_{\rm DM}, \tau,$
A_s, H_0, n_s

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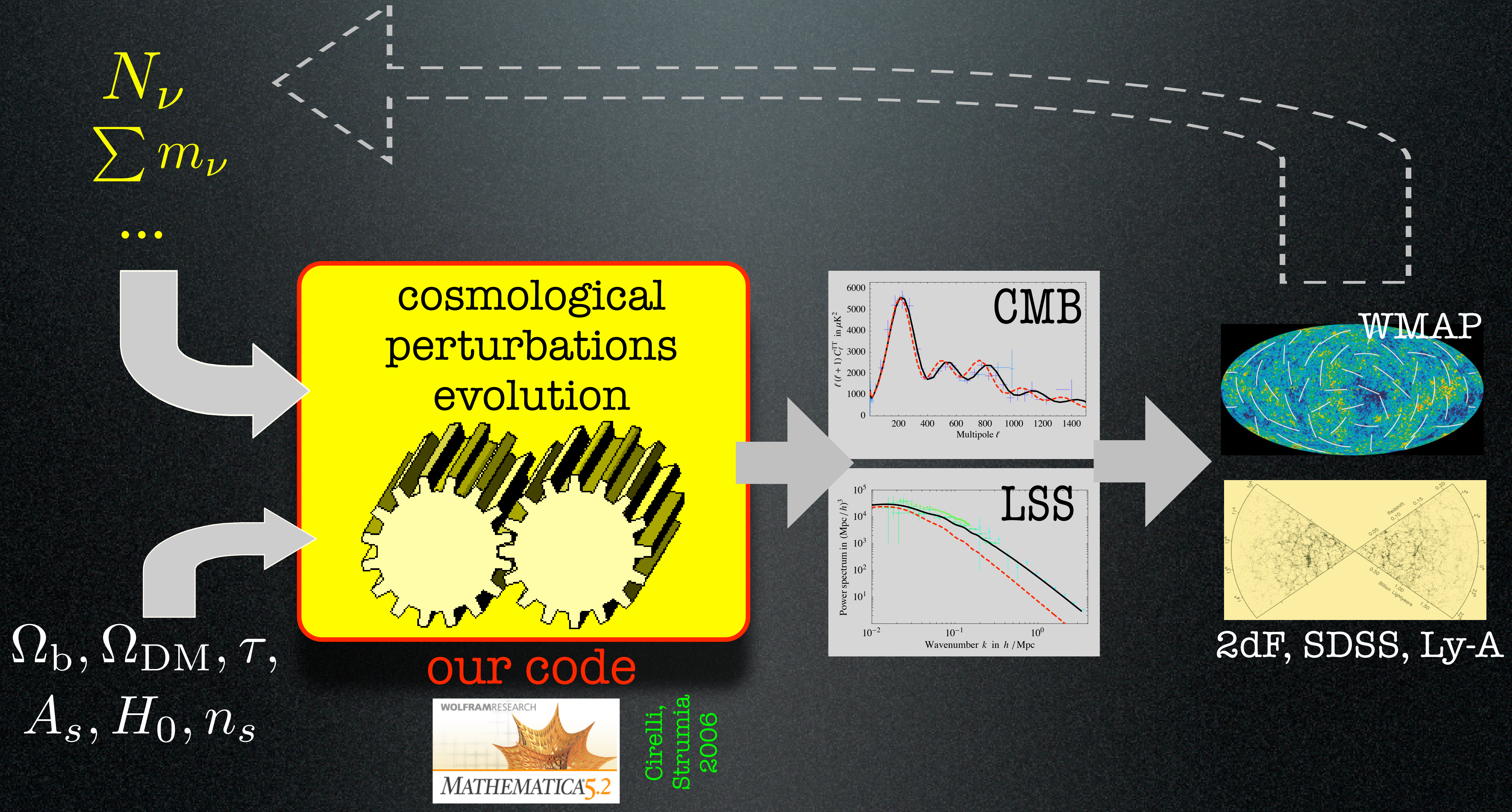


N_ν

$\sum m_\nu$

...

cosmological perturbations evolution

our code

$\Omega_{\rm b}, \Omega_{\rm DM}, \tau,$

A_s, H_0, n_s

Cirelli, Strumia, 2006

CMB

LSS

WMAP

2dF, SDSS, Ly-A

Neutrinos in CMB+LSS

Cosmological perturbation equations:

Dodelson's (Chicago, 2003) notations

$$\dot\Theta + ik\mu\Theta = -\dot\Phi - ik\mu\Psi - \dot\tau\left[\Theta_0 - \Theta + \mu v_\mathrm{b} - 1/2\,\mathcal{P}_2(\mu)\Pi\right]$$

$$\dot\tau = d\tau/d\eta = -n_e\sigma_T a \qquad \Pi = \Theta_2 + \Theta_{P2} + \Theta_{P0}$$

$$\dot\Theta_P + ik\mu\Theta_P = -\dot\tau\left[\Theta_P + 1/2\big(1 - \mathcal{P}_2(\mu)\big)\Pi\right]$$

photons

$$\dot\delta_\mathrm{dm} + ikv_\mathrm{dm} = -3\dot\Phi$$

$$\dot v_\mathrm{dm} + \frac{\dot a}{a}v_\mathrm{dm} = -ik\Psi$$

dark matter

$$\dot\delta_\mathrm{b} + ikv_\mathrm{b} = -3\dot\Phi \qquad R = 3\rho_\mathrm{b}^0/4\rho_\gamma^0$$

$$\dot v_\mathrm{b} + \frac{\dot a}{a}v_\mathrm{b} = -ik\Psi + \frac{\dot\tau}{R}\left[v_\mathrm{b} + 3i\Theta_1\right]$$

baryons

$$\dot{\mathcal{N}} + i\frac{q_\nu}{E_\nu}k\mu\mathcal{N} = -\dot\Phi - i\frac{E_\nu}{q_\nu}k\mu\Psi$$

neutrinos

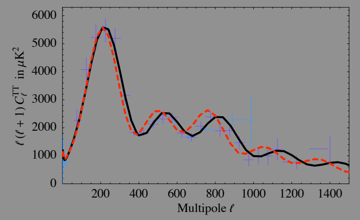
$$k^2\Phi + 3\frac{\dot a}{a}\left(\dot\Phi - \Psi\frac{\dot a}{a}\right) = 4\pi G_N a^2\left[\rho_\mathrm{m}\delta_\mathrm{m} + 4\rho_\mathrm{r}\delta_\mathrm{r}\right]$$

$$k^2\left(\Phi + \Psi\right) = -32\pi G_N a^2 \rho_\mathrm{r}\Theta_{\mathrm{r},2}$$

metric

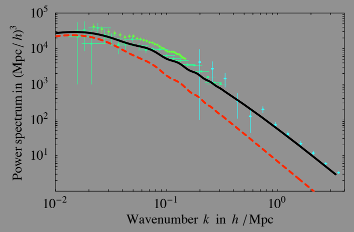
CMB Power spectrum

$$C_\ell \propto \int dk[\ldots]\,\Theta_\ell(k)$$



Matter Power spect.

$$P(k) \propto \langle\delta_\mathrm{m}(k)^2\rangle$$



Neutrinos in CMB+LSS

Massive neutrinos affect the growth of matter perturbations during MD:

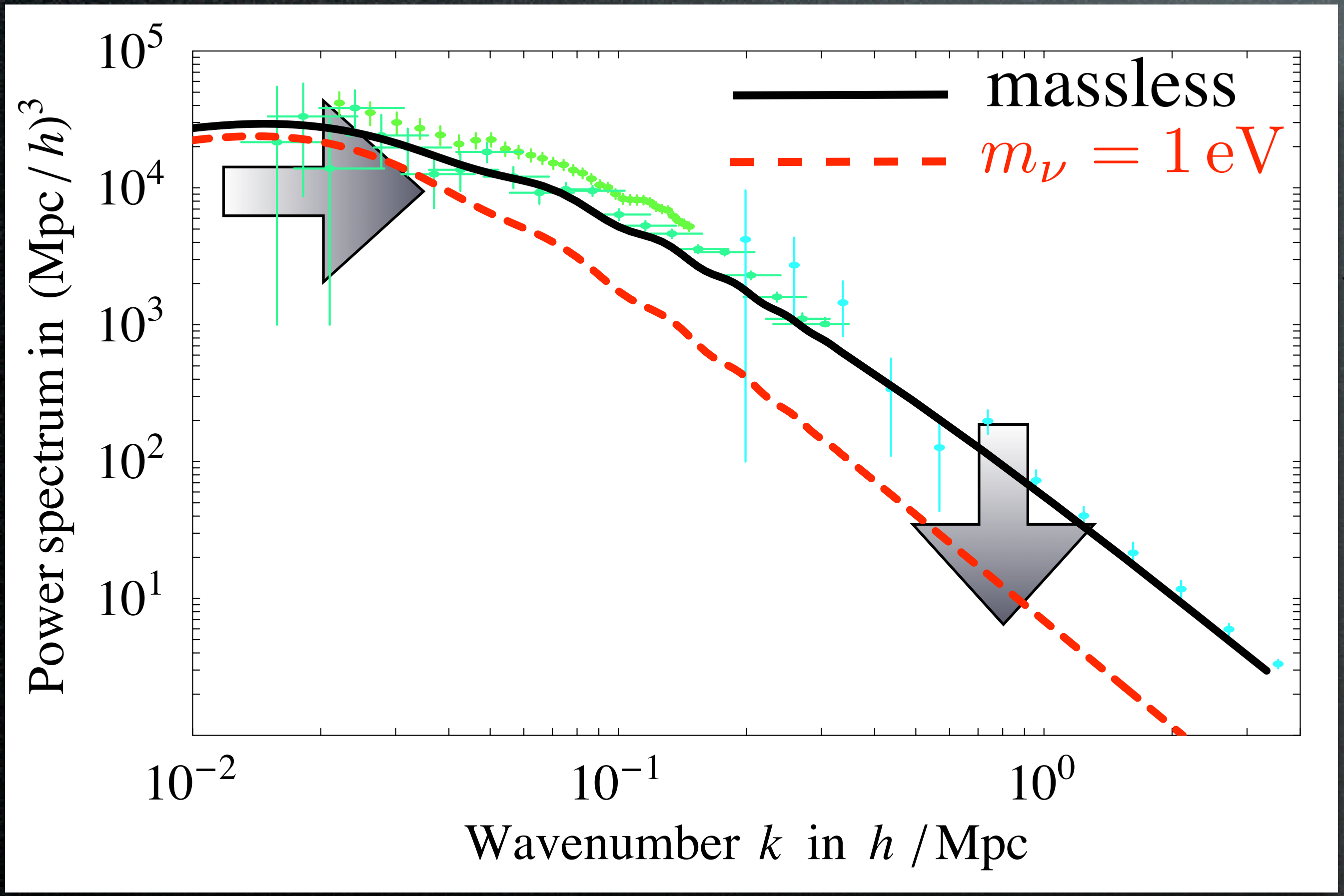
$$\ddot{\delta}_{\rm dm} + \frac{\dot{a}}{a}\dot{\delta}_{\rm dm} \simeq 4\pi G_N a^2 \rho_{\rm m} \delta_{\rm m}$$

(Newton equ.)

massive neutrinos contribute
to evolution of a w.r.t. time

$\delta_\nu = 0$ because neutrinos
free stream on small scales

Effect: suppression of matter power spectrum at small scales:



Caveat: plot for illustration only, all parameters fixed except neutrino mass.

$$k_{\rm NR} = 0.018\ \Omega_{\rm m}^{-1/2} \left(\frac{\sum m_\nu}{\rm eV}\right)^{1/2} h_0\ {\rm Mpc}^{-1}$$

$$\frac{\Delta P}{P} \simeq -8 f_\nu = -8\frac{\sum m_\nu}{(93\ {\rm eV}^2)h^2\Omega_{\rm m}}$$

a bound on $\sum m_\nu$:

$$\sum m_{\nu_i} < 0.40\ {\rm eV}$$

(@ 99.9% CL, global fit)
Cirelli, Strumia 2006
(others also)

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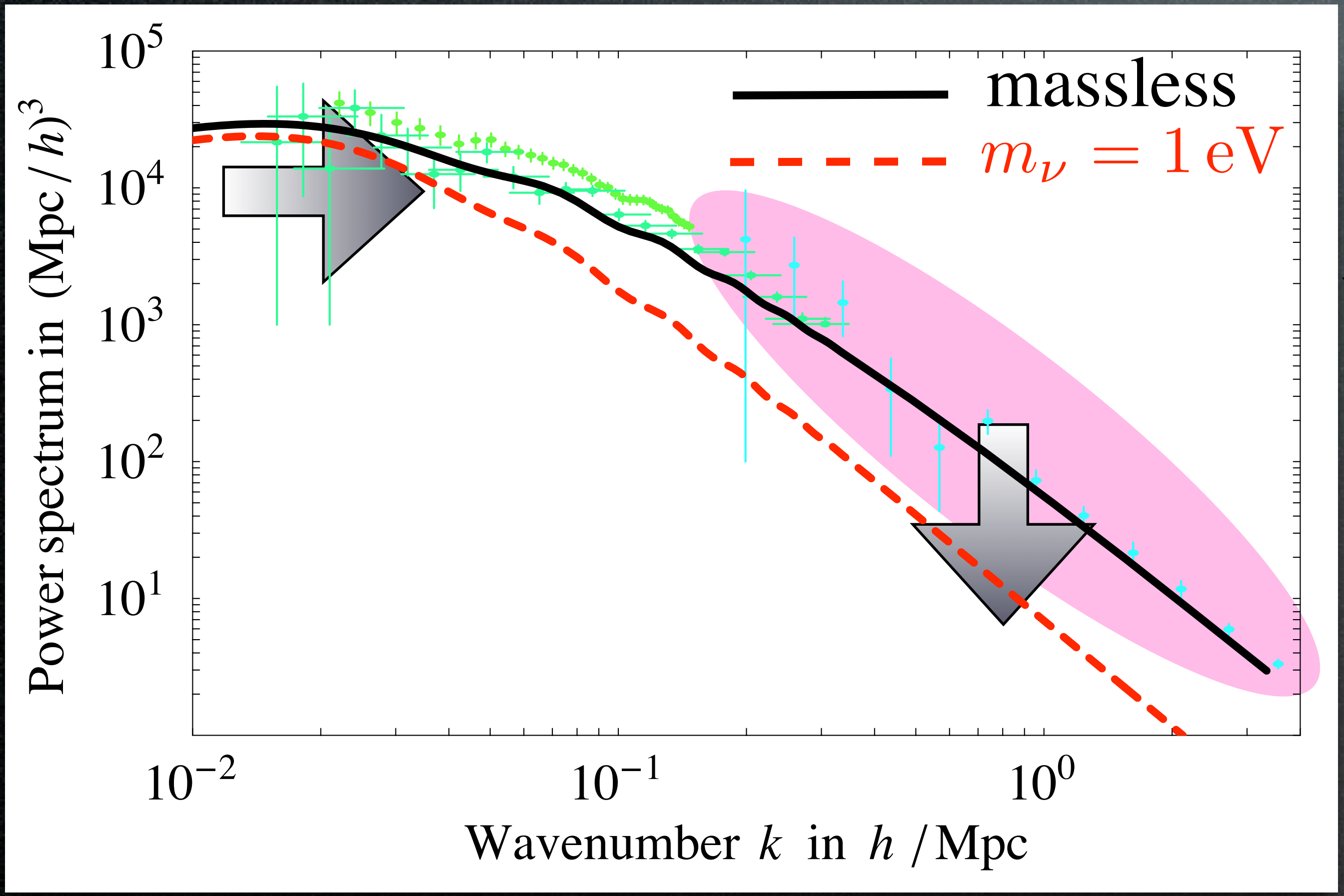

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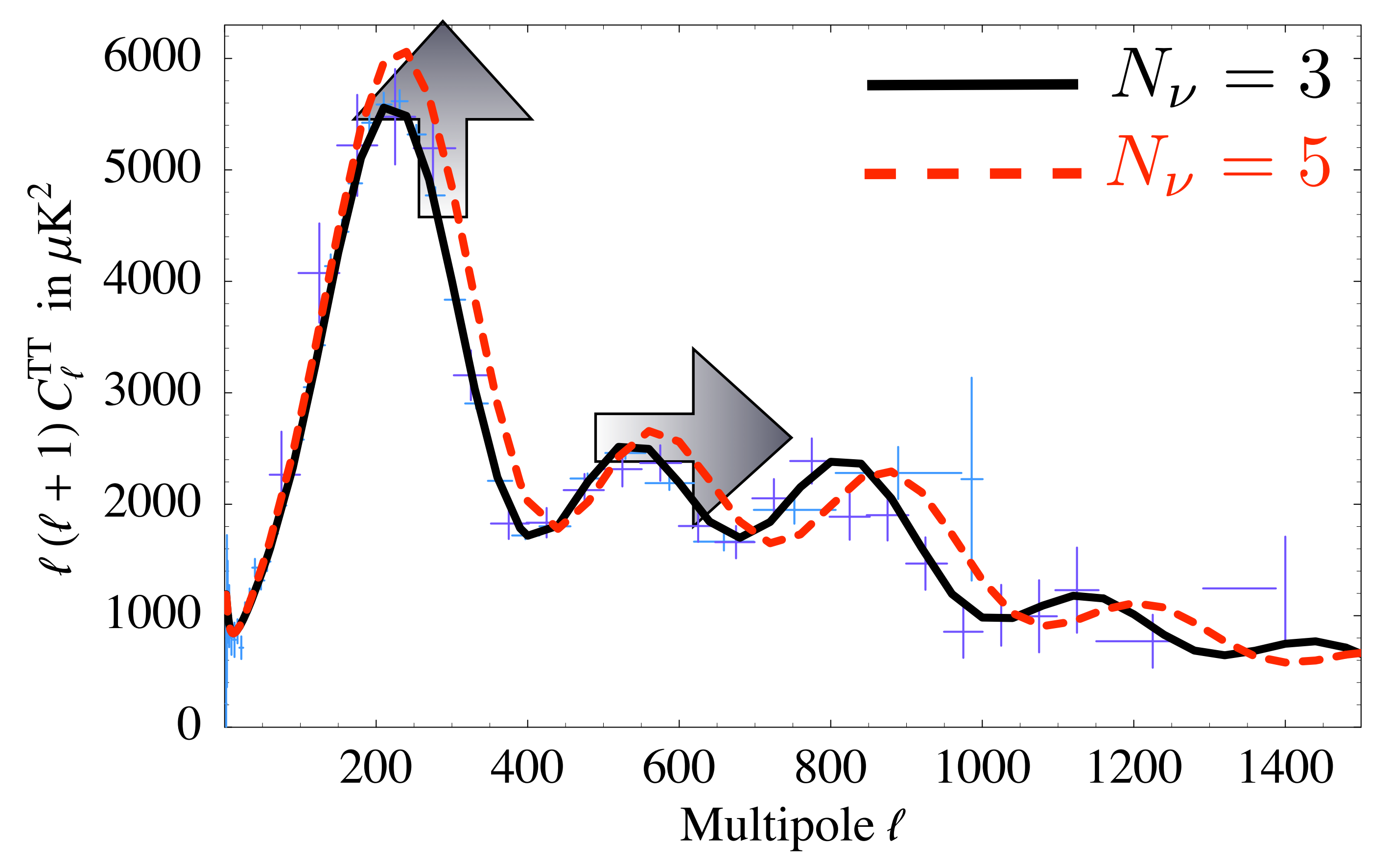
Cirelli, Strumia 2006
(others also)

without Lyman-α :

$$\boxed{\sum m_{\nu_i} < 0.73\ {\rm eV}}$$

Neutrinos in CMB+LSS

N_ν sets the total relativistic energy content and affects the peaks of CMB (and LSS) spectra:



Caveat: plot for illustration only, all parameters fixed except N_ν

a determination of N_ν :

$$N_\nu = 5 \pm 1$$

○ ○ ○ ○ ○

(global fit)
Cirelli, Strumia 2006
Seljak et al. 2006
Mangano et al. 2006
...

BUT dropping Ly-α gives back

$$N_\nu \simeq 3$$

Cirelli, Strumia 2006

○ ○ ○

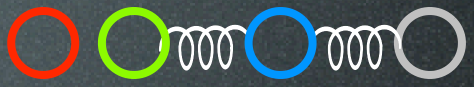
Tension with $N_\nu \simeq 3.1 \pm 0.3$ from BBN?

Ichikawa et al. (2007): production of degrees of freedom between BBN and CMB via decay of heavy particles.

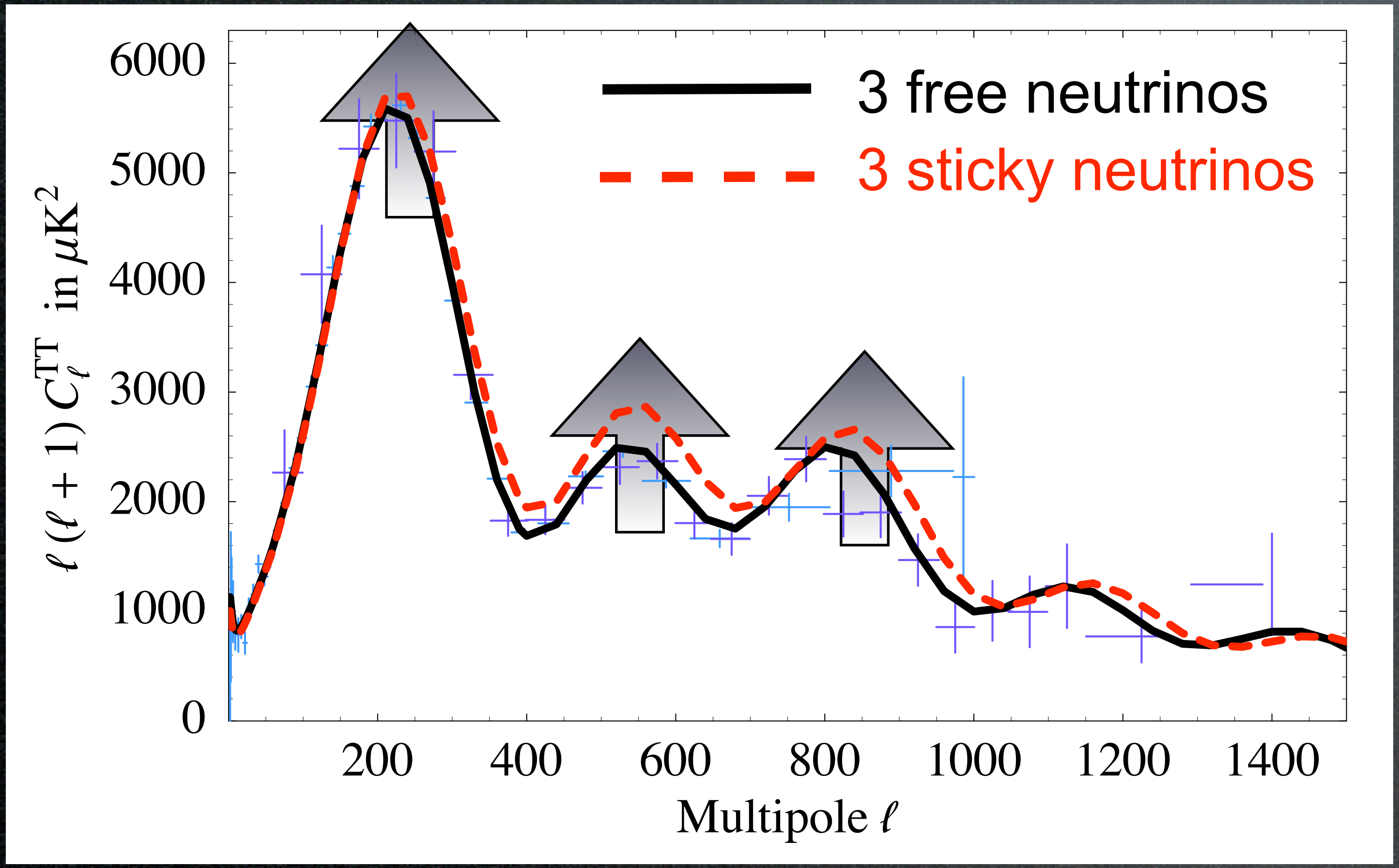
Neutrinos in CMB+LSS

Many models postulate non-conventional neutrino interactions:

Mass Varying Neutrinos (N.Weiner et al.),
Neutrinoless Universe (J.Beacom et al.),
Light Dark Matter (P.Fayet, C.Boehm)...



Neutrinos become “Sticky”: free-streaming is prevented,
form a tightly coupled fluid at CMB.



Additional Boltzmann equations for the sticky fluid component:

$$\begin{cases} \dot{\delta}_{\mathrm{x}} + i\frac{4}{3}kv_{\mathrm{x}} = -4\dot{\Phi} \\ \dot{v}_{\mathrm{x}} + \frac{i}{4}k\delta_{\mathrm{x}} = -ik\Psi \end{cases}$$

CMB and LSS peaks are modified.

Caveat: plot for illustration only, all parameters fixed except the fraction of sticky neutrinos.

Quantitatively: (Friedland et al. 2007)

$$\left\{\frac{\Delta C_\ell}{C_\ell}, \Delta\ell\right\} \approx -\{0.53, 57\}\,\frac{\rho_{\mathrm{free}}}{\rho_{\mathrm{free}} + \rho_{\mathrm{sticky}} + \rho_\gamma}$$

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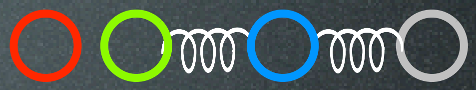

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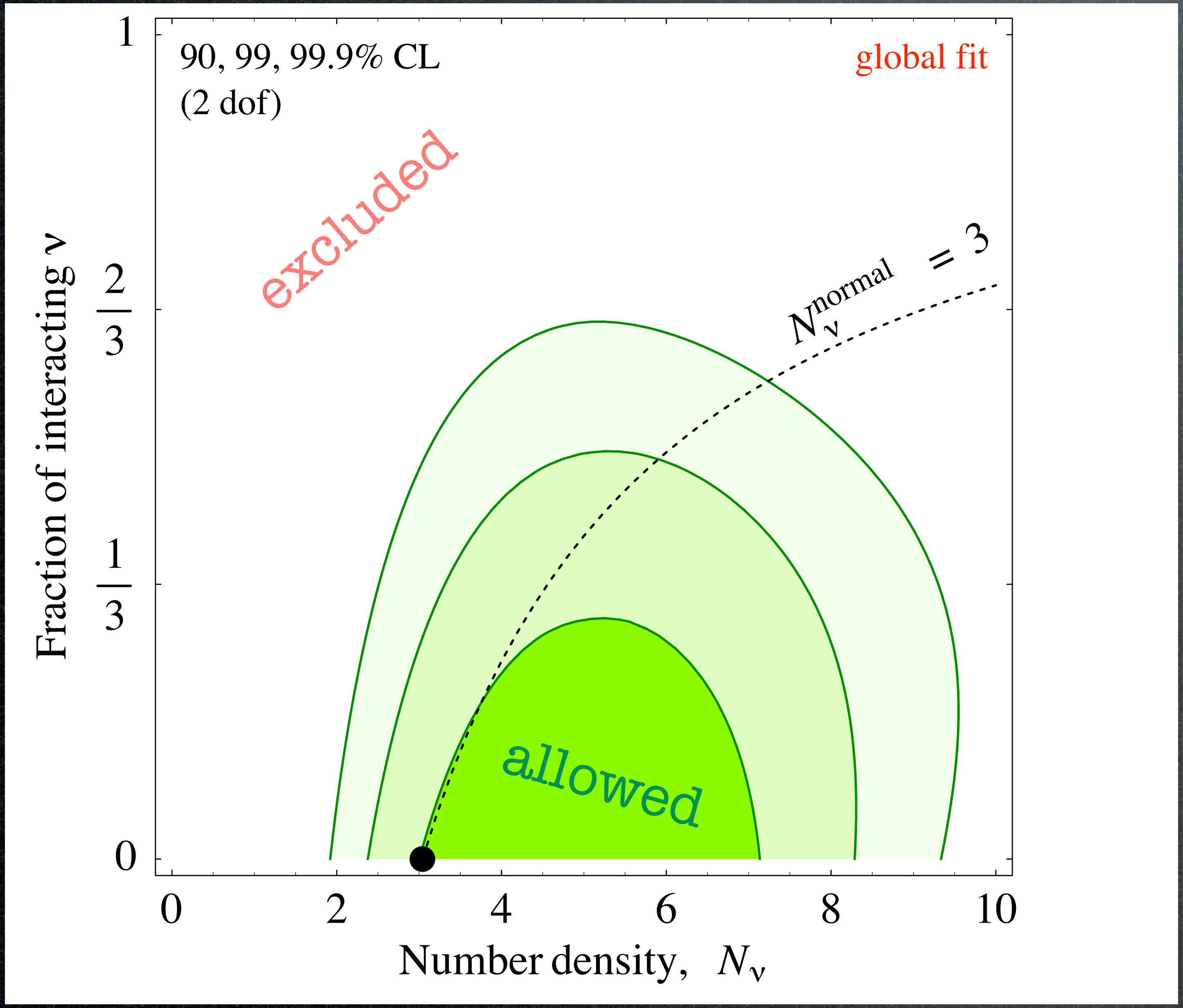

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Cirelli, Strumia 2006

~ 1 sticky ν allowed (@ 99% CL, global fit)

3 sticky ν excluded (at 5σ)

also: Friedland et al. 2007
Bell et al. 2005

Summary

- Cosmology is a (the most) sensitive probe of many neutrino properties (use BBN, CMB, LSS etc...).

  Results are becoming solid but there are puzzling tensions.

- Current status:

$N_\nu \simeq 3.1 \pm 0.3$ (BBN)

$N_\nu = 5 \pm 1$ (CMB+LSS)

$N_\nu \simeq 3$ (without Ly-α)

$\sum m_{\nu_i} < 0.40 \text{ eV}$ (CMB+LSS incl Ly-α, at 99.9% CL)

~ 1 sticky ν allowed (@ 99% CL, global fit)

3 sticky ν excluded (at 5σ)

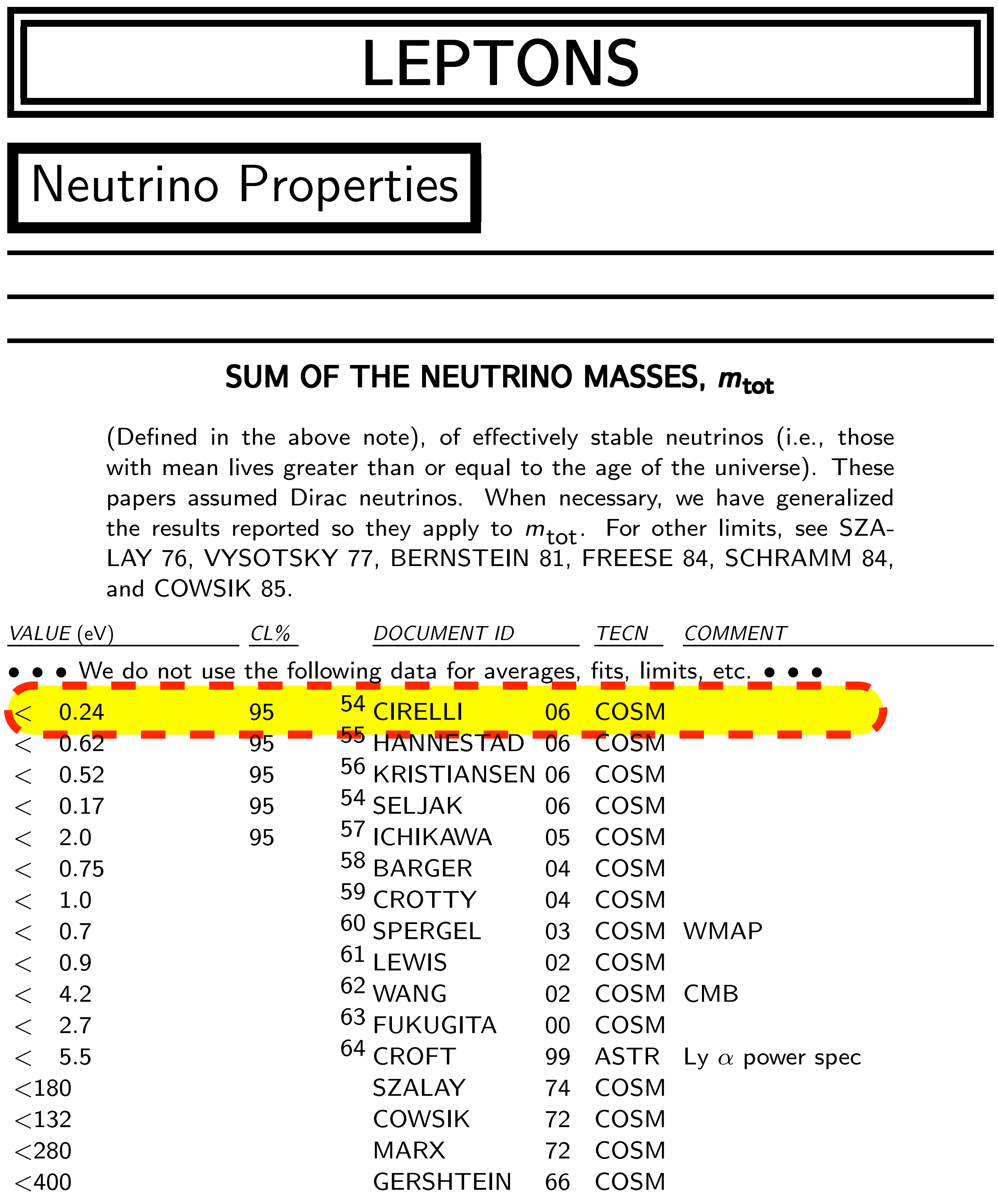
- Outlook:
  - better ^{4}He for N_ν , PLANCK will determine N_ν within 0.26
  - sensitivity $\sum m_{\nu_i} \approx 0.03$ eV (weak lensing): sure detection!

    Hannestad 2005
  - PLANCK will test 1 sticky ν at 4 σ

    Friedland et al. 2007
  - ...

Extra slides

Neutrinos in the Cosmo



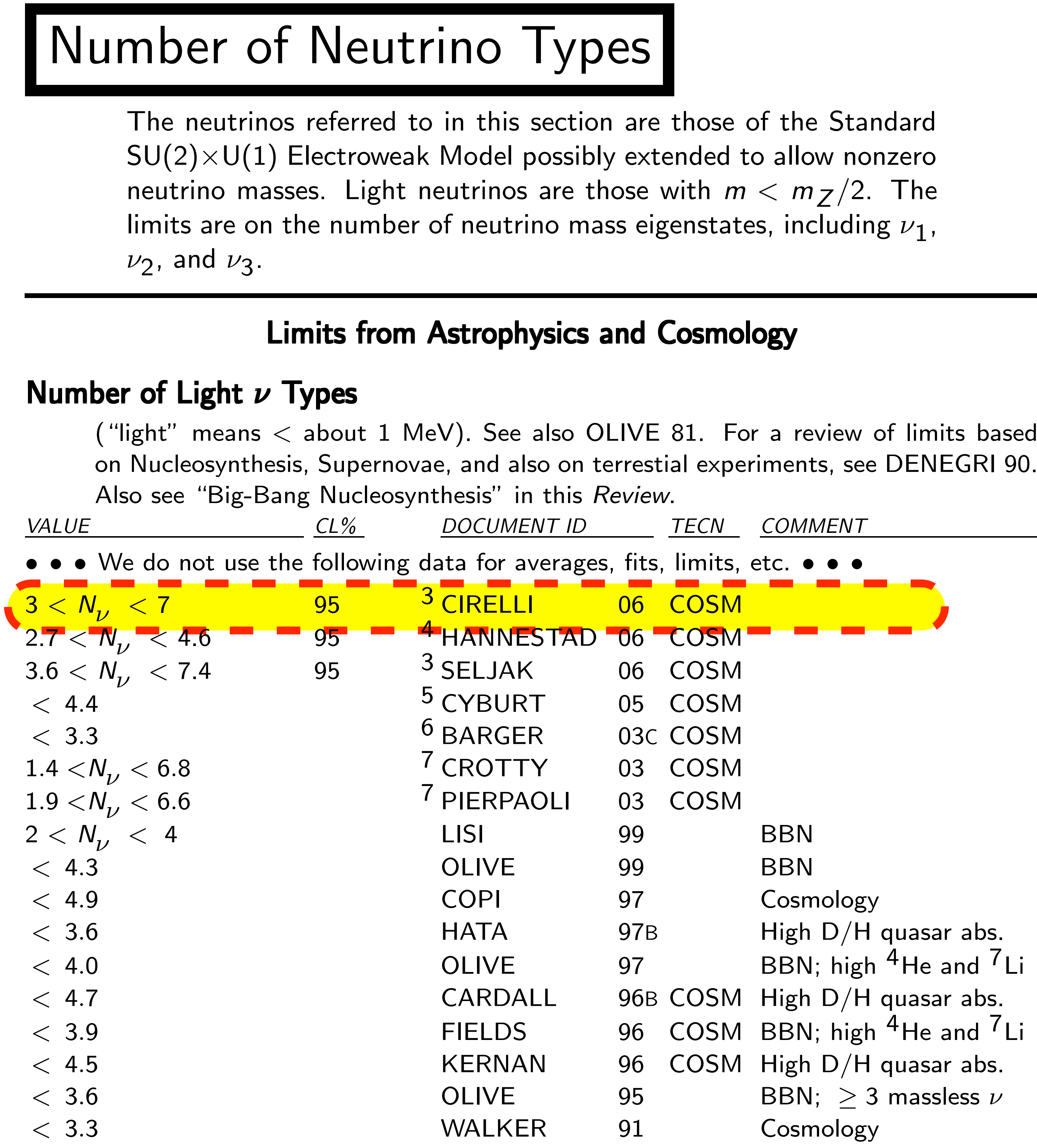
LEPTONS

Neutrino Properties

SUM OF THE NEUTRINO MASSES, m_{tot}

(Defined in the above note), of effectively stable neutrinos (i.e., those with mean lives greater than or equal to the age of the universe). These papers assumed Dirac neutrinos. When necessary, we have generalized the results reported so they apply to m_{tot}. For other limits, see SZALAY 76, VYSOTSKY 77, BERNSTEIN 81, FREESE 84, SCHRAMM 84, and COWSIK 85.

VALUE (eV)	*CL%*	*DOCUMENT ID*	*TECN*	*COMMENT*
• • • We do not use the following data for averages, fits, limits, etc. • • •				
$<$ 0.24	95	[54] CIRELLI 06	COSM	
$<$ 0.62	95	[55] HANNESTAD 06	COSM	
$<$ 0.52	95	[56] KRISTIANSEN 06	COSM	
$<$ 0.17	95	[54] SELJAK 06	COSM	
$<$ 2.0	95	[57] ICHIKAWA 05	COSM	
$<$ 0.75		[58] BARGER 04	COSM	
$<$ 1.0		[59] CROTTY 04	COSM	
$<$ 0.7		[60] SPERGEL 03	COSM	WMAP
$<$ 0.9		[61] LEWIS 02	COSM	
$<$ 4.2		[62] WANG 02	COSM	CMB
$<$ 2.7		[63] FUKUGITA 00	COSM	
$<$ 5.5		[64] CROFT 99	ASTR	Ly α power spec
$<$180		SZALAY 74	COSM	
$<$132		COWSIK 72	COSM	
$<$280		MARX 72	COSM	
$<$400		GERSHTEIN 66	COSM	



Number of Neutrino Types

The neutrinos referred to in this section are those of the Standard SU(2)×U(1) Electroweak Model possibly extended to allow nonzero neutrino masses. Light neutrinos are those with $m < m_Z/2$. The limits are on the number of neutrino mass eigenstates, including ν_1, ν_2, and ν_3.

Limits from Astrophysics and Cosmology

Number of Light ν Types

("light" means $<$ about 1 MeV). See also OLIVE 81. For a review of limits based on Nucleosynthesis, Supernovae, and also on terrestial experiments, see DENEGRI 90. Also see "Big-Bang Nucleosynthesis" in this *Review*.

VALUE	*CL%*	*DOCUMENT ID*	*TECN*	*COMMENT*
• • • We do not use the following data for averages, fits, limits, etc. • • •				
$3 < N_\nu < 7$	95	[3] CIRELLI 06	COSM	
$2.7 < N_\nu < 4.6$	95	[4] HANNESTAD 06	COSM	
$3.6 < N_\nu < 7.4$	95	[3] SELJAK 06	COSM	
< 4.4		[5] CYBURT 05	COSM	
< 3.3		[6] BARGER 03C	COSM	
$1.4 < N_\nu < 6.8$		[7] CROTTY 03	COSM	
$1.9 < N_\nu < 6.6$		[7] PIERPAOLI 03	COSM	
$2 < N_\nu < 4$		LISI 99		BBN
< 4.3		OLIVE 99		BBN
< 4.9		COPI 97		Cosmology
< 3.6		HATA 97B		High D/H quasar abs.
< 4.0		OLIVE 97		BBN; high ^{4}He and ^{7}Li
< 4.7		CARDALL 96B	COSM	High D/H quasar abs.
< 3.9		FIELDS 96	COSM	BBN; high ^{4}He and ^{7}Li
< 4.5		KERNAN 96	COSM	High D/H quasar abs.
< 3.6		OLIVE 95		BBN; $\geq$ 3 massless ν
< 3.3		WALKER 91		Cosmology

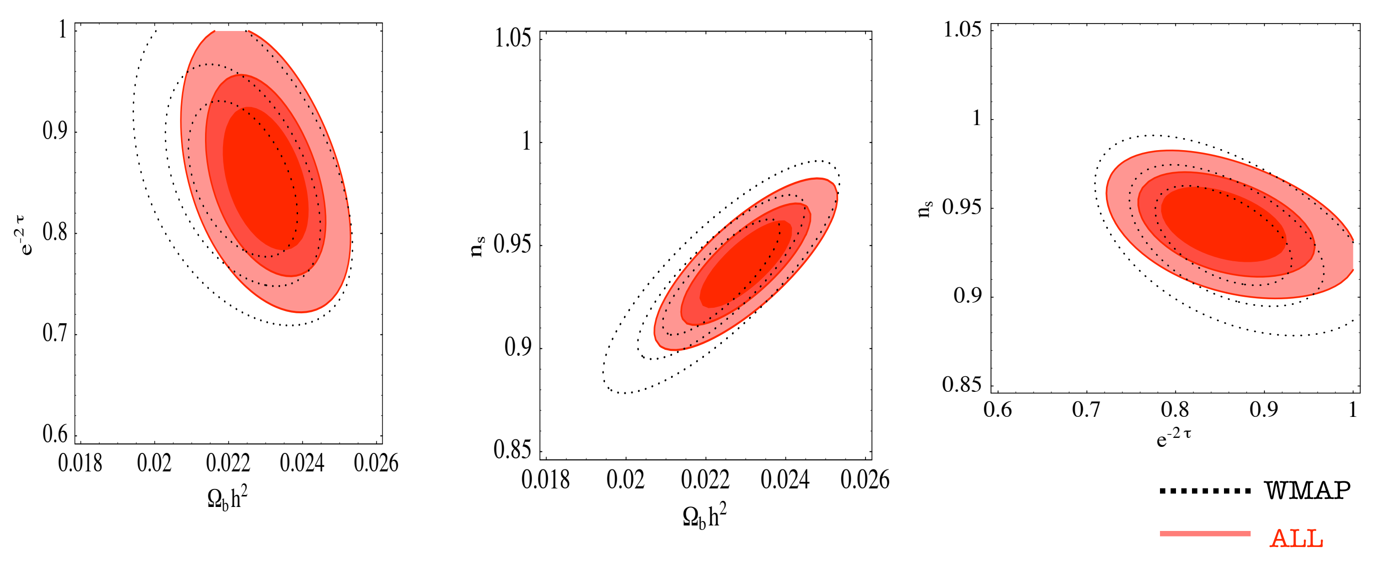
(from Particle Data Book 2008)

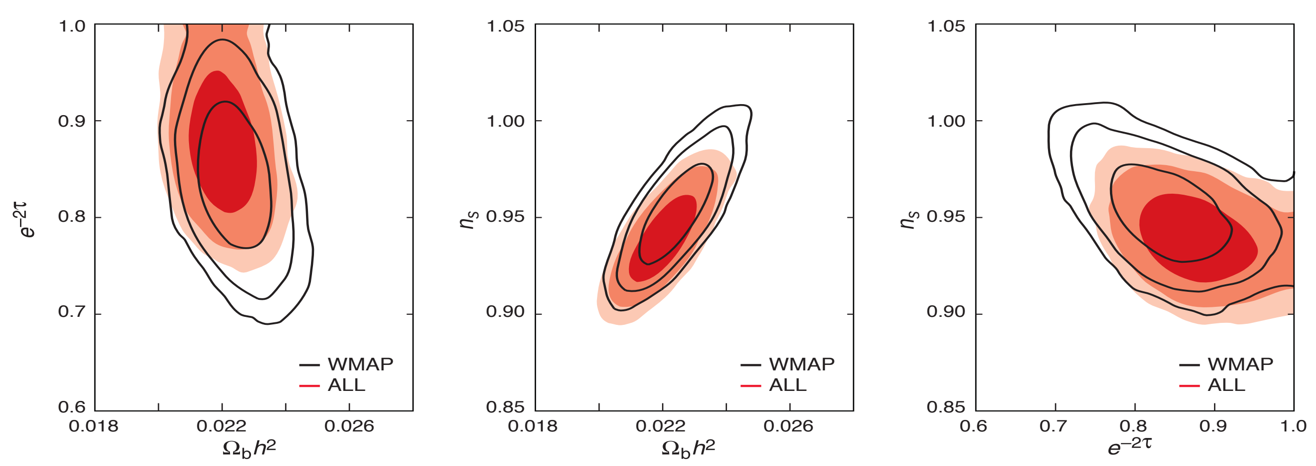
Comparing our code

[back]

Our analysis:

WMAP Science Team analysis:

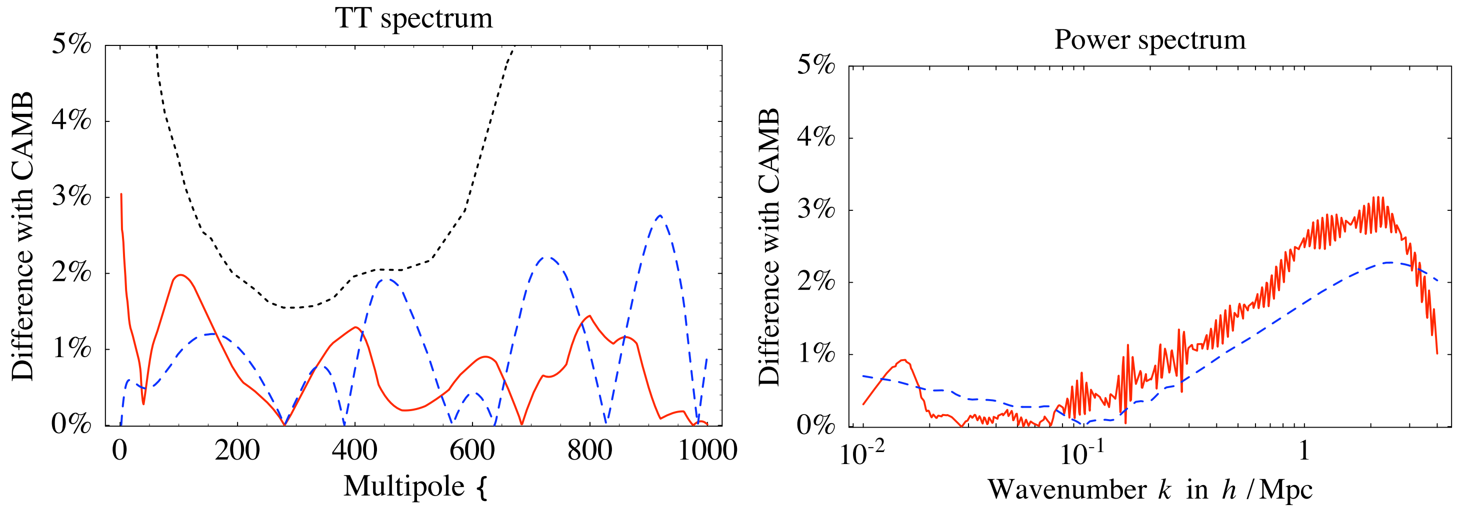




[Spergel et al. WMAP 3yr results '05]

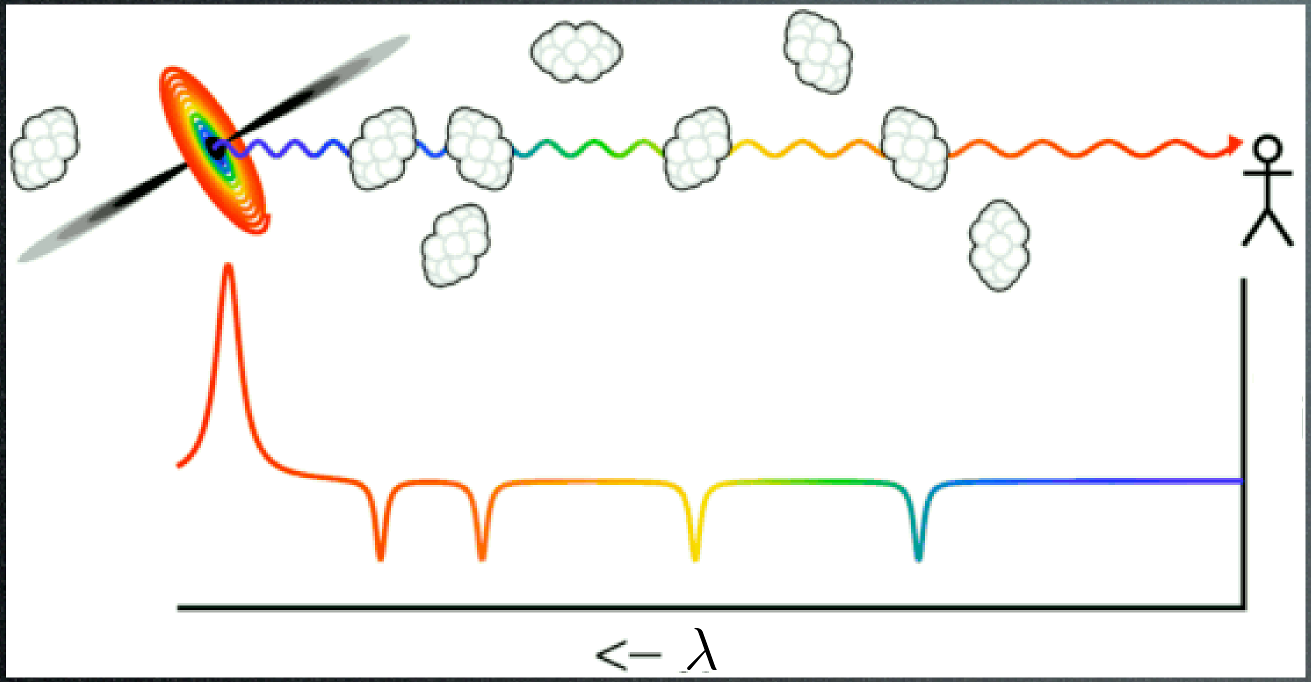
fit	A_s	h	n_s	τ	$100\Omega_b h^2$	$\Omega_{\rm DM} h^2$
WMAP3	0.80 ± 0.05	0.704 ± 0.033	0.935 ± 0.019	0.081 ± 0.030	2.24 ± 0.10	0.113 ± 0.010
Global	0.84 ± 0.04	0.729 ± 0.013	0.951 ± 0.012	0.121 ± 0.025	2.36 ± 0.07	0.117 ± 0.003

Parameter	WMAP Only	WMAP+ SDSS	WMAP+ LRG	WMAP + SN Gold
$100\Omega_b h^2$	$2.233^{+0.072}_{-0.091}$	$2.233^{+0.062}_{-0.086}$	$2.242^{+0.062}_{-0.084}$	$2.227^{+0.065}_{-0.082}$
$\Omega_m h^2$	$0.1268^{+0.0073}_{-0.0128}$	$0.1329^{+0.0057}_{-0.0109}$	$0.1337^{+0.0047}_{-0.0098}$	$0.1349^{+0.0054}_{-0.0106}$
h	$0.734^{+0.028}_{-0.038}$	$0.709^{+0.024}_{-0.032}$	$0.709^{+0.016}_{-0.023}$	$0.701^{+0.020}_{-0.026}$
A	$0.801^{+0.043}_{-0.054}$	$0.813^{+0.042}_{-0.052}$	$0.816^{+0.042}_{-0.049}$	$0.827^{+0.045}_{-0.053}$
τ	$0.088^{+0.028}_{-0.034}$	$0.079^{+0.029}_{-0.032}$	$0.082^{+0.028}_{-0.033}$	$0.079^{+0.028}_{-0.034}$
n_s	$0.951^{+0.015}_{-0.019}$	$0.948^{+0.015}_{-0.018}$	$0.951^{+0.014}_{-0.018}$	$0.946^{+0.015}_{-0.019}$
σ_8	$0.744^{+0.050}_{-0.060}$	$0.772^{+0.036}_{-0.048}$	$0.781^{+0.032}_{-0.045}$	$0.784^{+0.035}_{-0.049}$
Ω_m	$0.238^{+0.027}_{-0.045}$	$0.266^{+0.025}_{-0.040}$	$0.267^{+0.017}_{-0.029}$	$0.276^{+0.022}_{-0.036}$



agreement is at **few %** level and within current precision of data

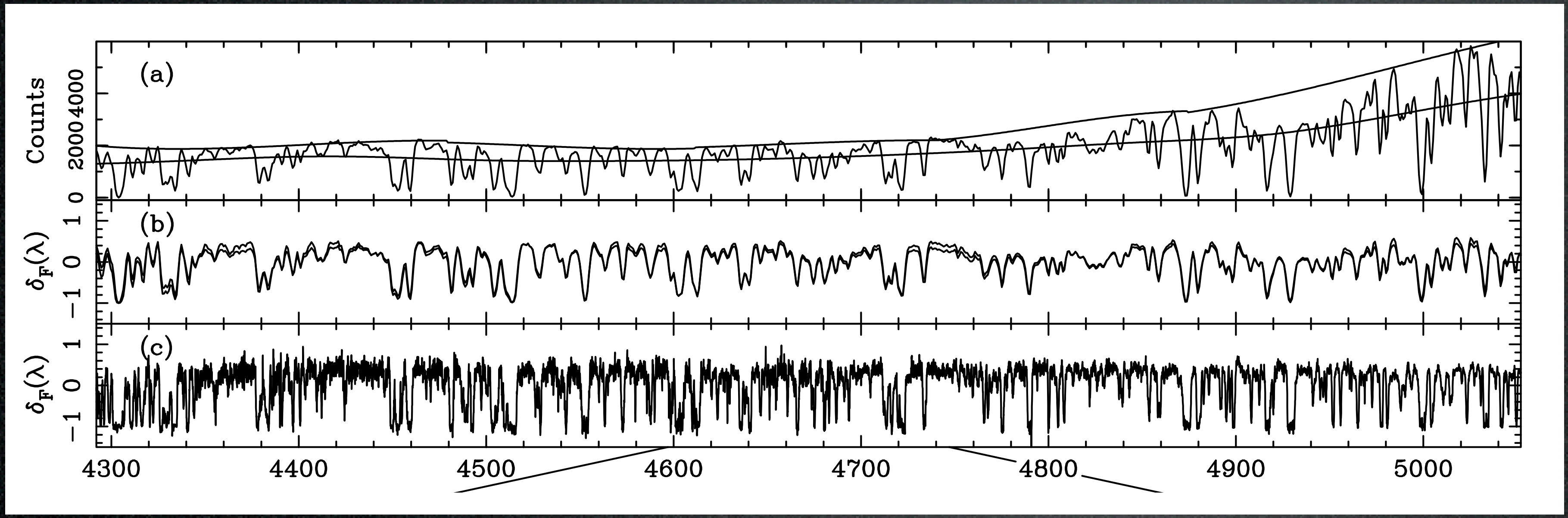
Lyman-alpha forest



E.Wright, UCLA

Distant quasar light, redshifted and absorbed at Ly-   frequency by intervening matter, allows to reconstruct matter distribution along the line of sight.

But: systematics and uncertainties

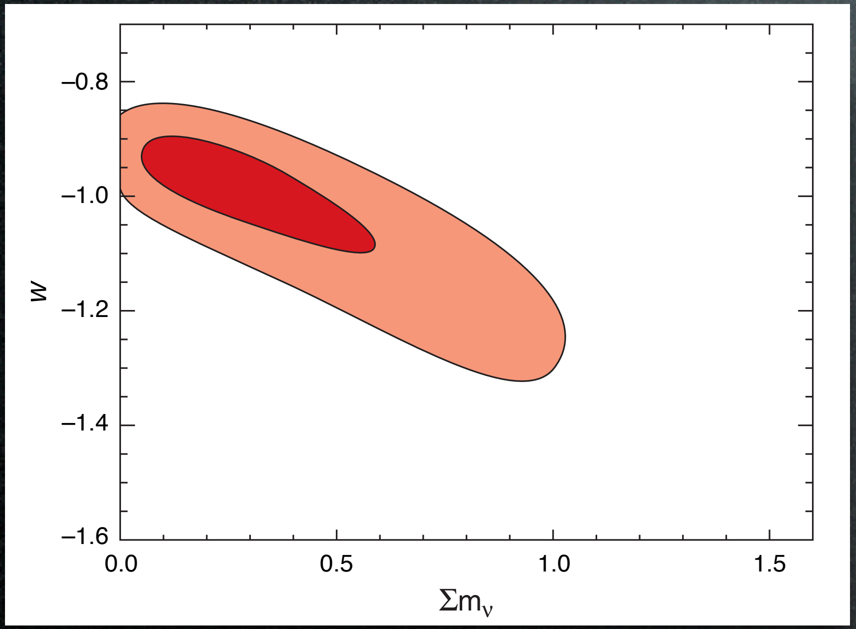


Degeneracies

m_ν effect can be cancelled by $w < -1.$

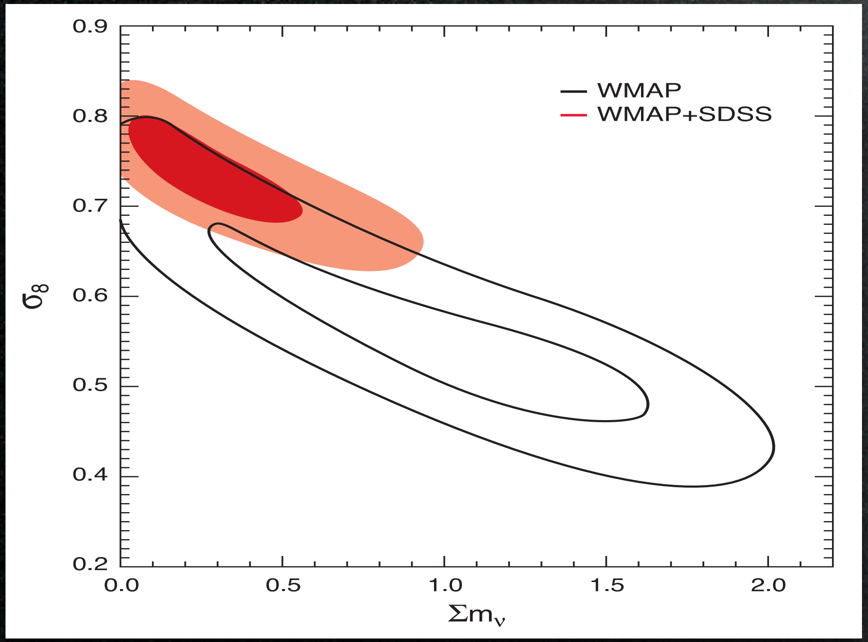
Hannestad, astro-ph/0505551

(SNIa data allow less Ω_Λ, hence more Ω_m, if $w < -1$; more Ω_m brings back up P(k))

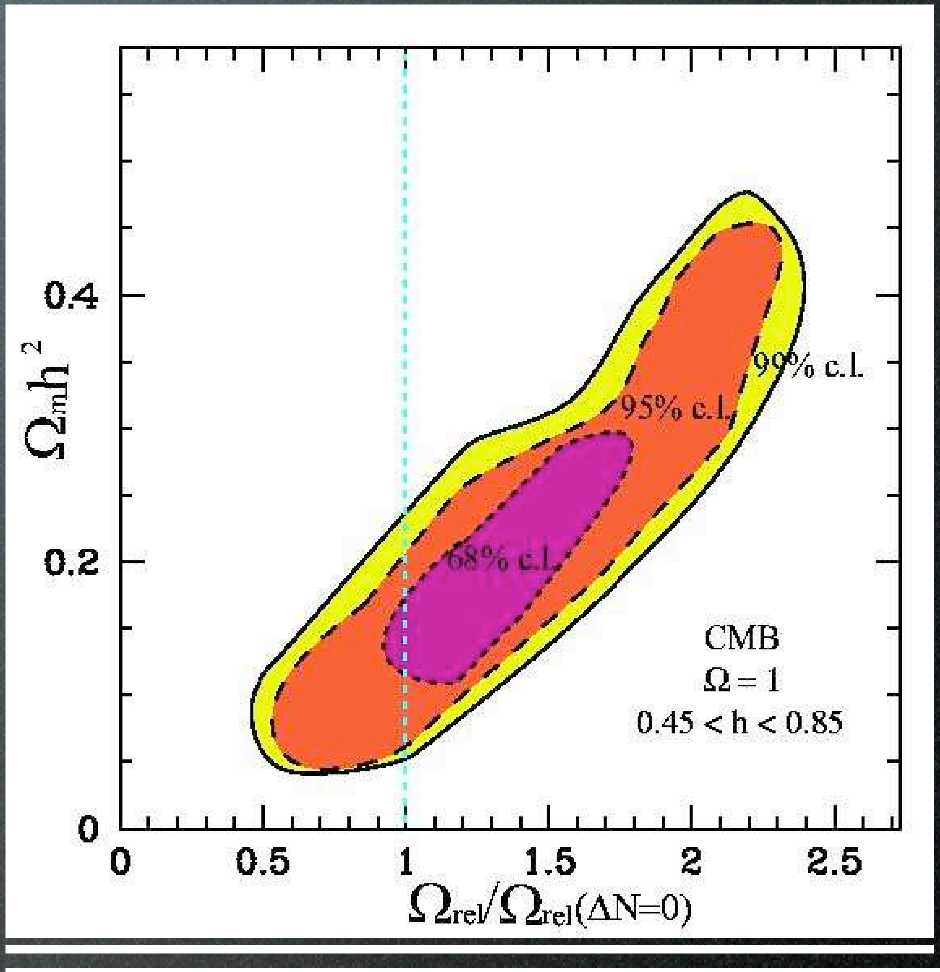


WMAP 3yr, Spergel et al.

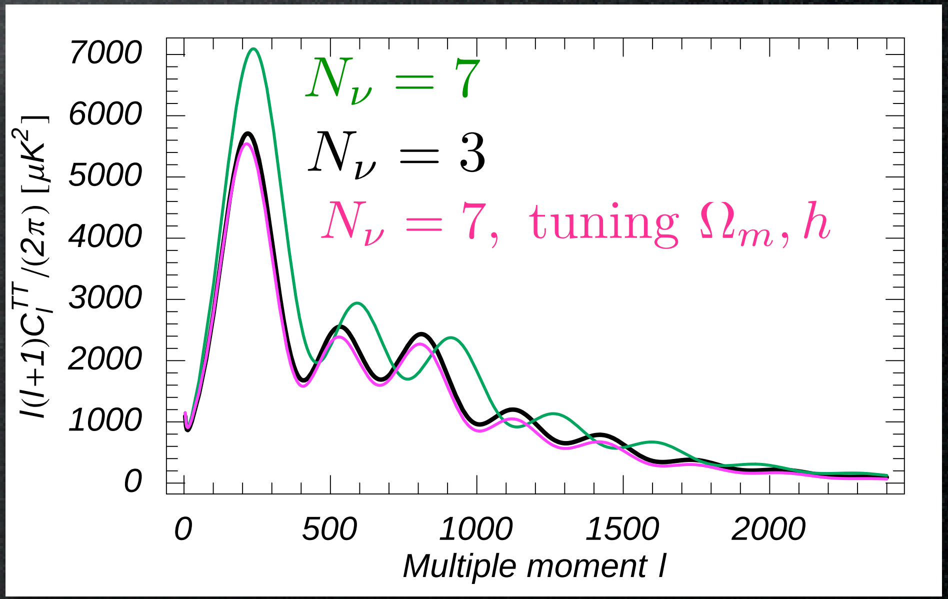
or by low σ_8



Large N_ν can be cancelled by large Ω_m or h



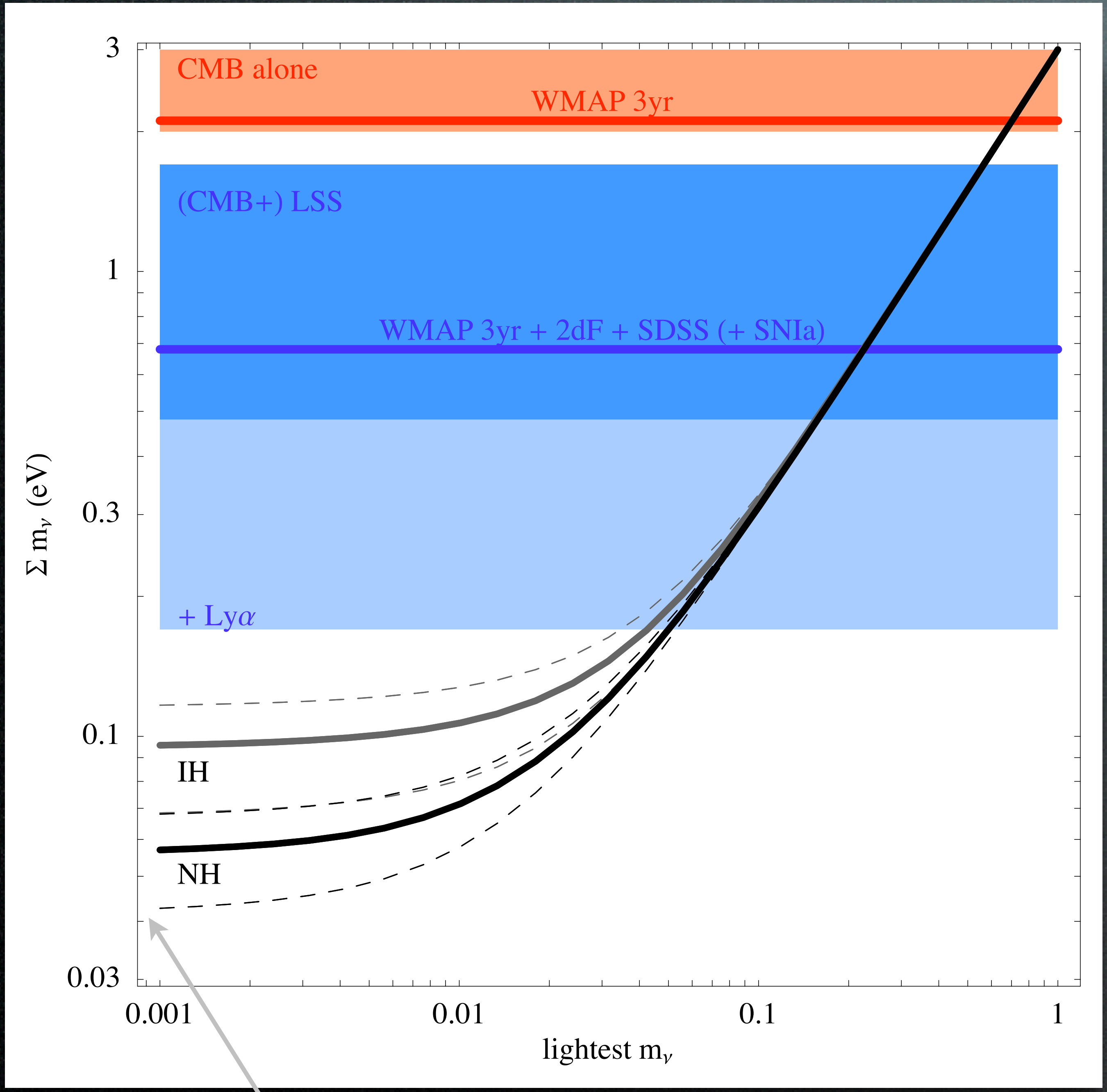
Bowen, Hansen, Melchiorri, Silk, Trotta, MNRAS 334 (2002)



Friedland et al. 2007

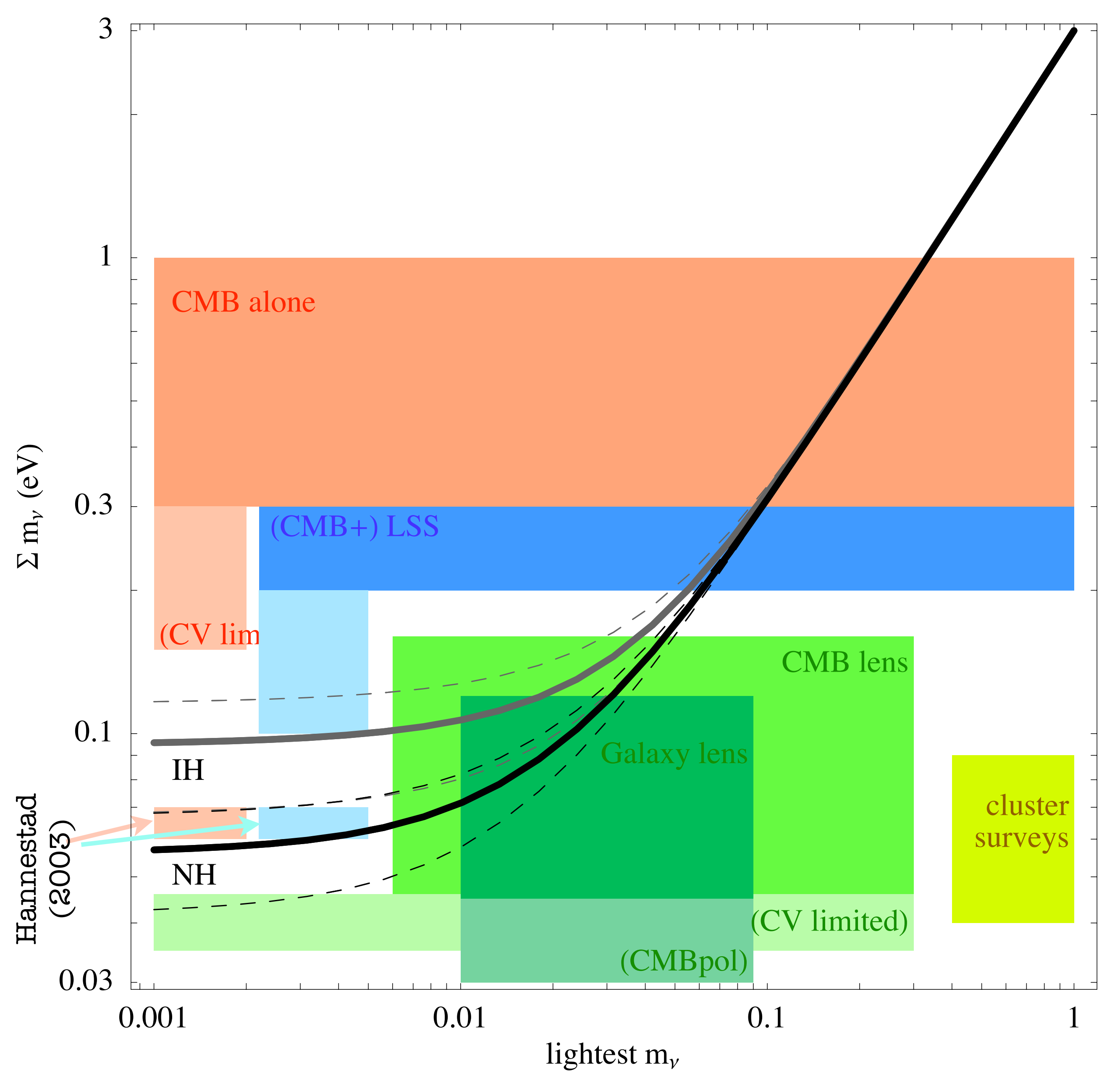
On neutrino masses

present bounds



$$\approx \sqrt{\Delta m^2_{\text{atm}}}$$

future sensitivities



Legenda: the bound or measurement will fall somewhere in the colored box; “where it’ll fall exactly” depends on the author, the experiment considered, priors, the weather...

best summary reference: Lesgourgues, Pastor review

On neutrino masses

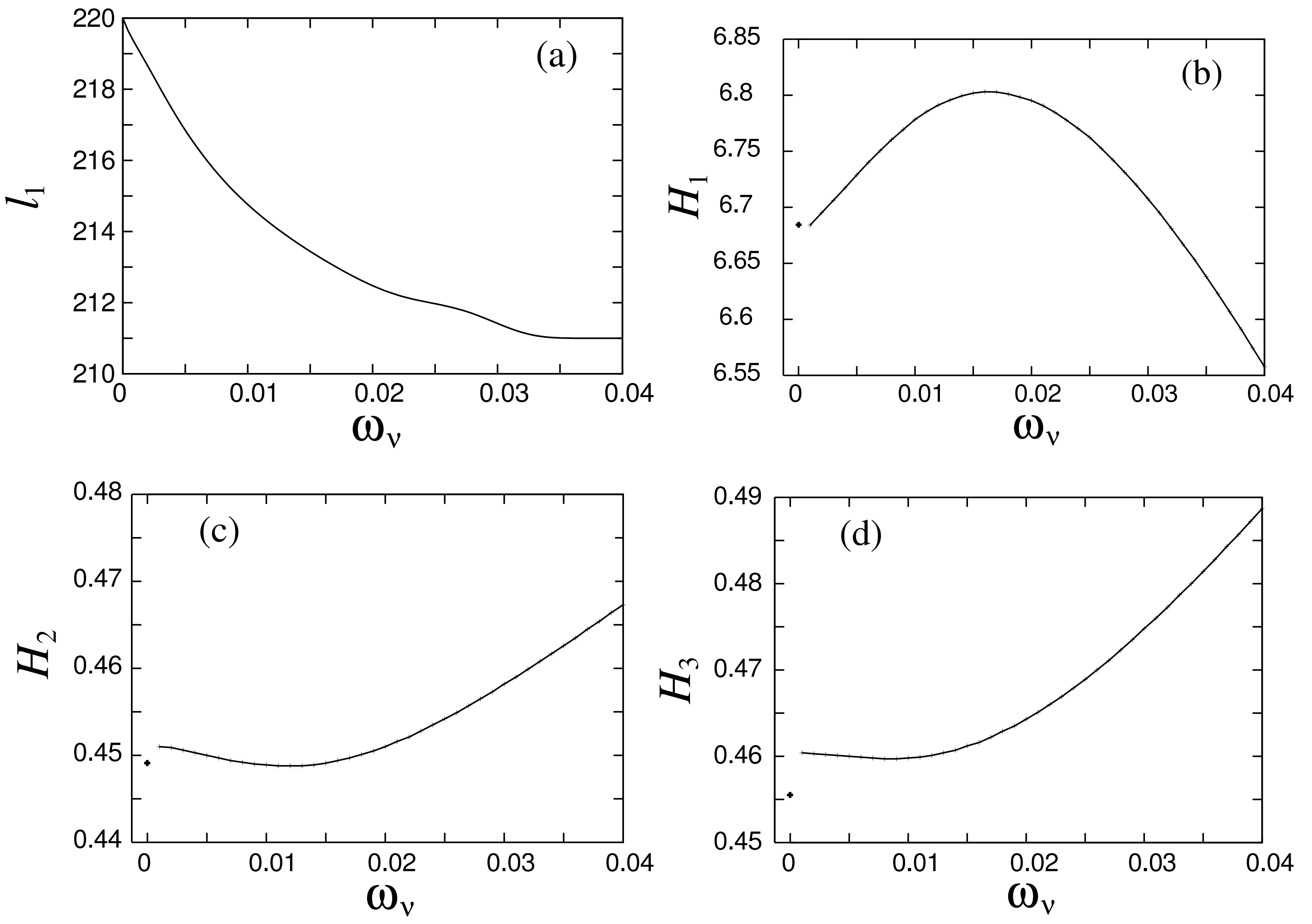


FIG. 5: Response of the four reduced CMB observables to the variation of ω_ν. The isolated points show the values at $\omega_\nu = 0$, which do not connect to the $\omega_\nu \neq 0$ values smoothly.

Ichikawa et al, 2004