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ISAPP 2011 - Heidelberg

# **Neutrinos** as a **dark component** of the Universe


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Reviews on Neutrinos in cosmology:

Lesgourgues, Pastor, Phys.Rept. 429 (2006) 307-379, astro-ph/0603494

Strumia, Vissani,hep-ph/0606054

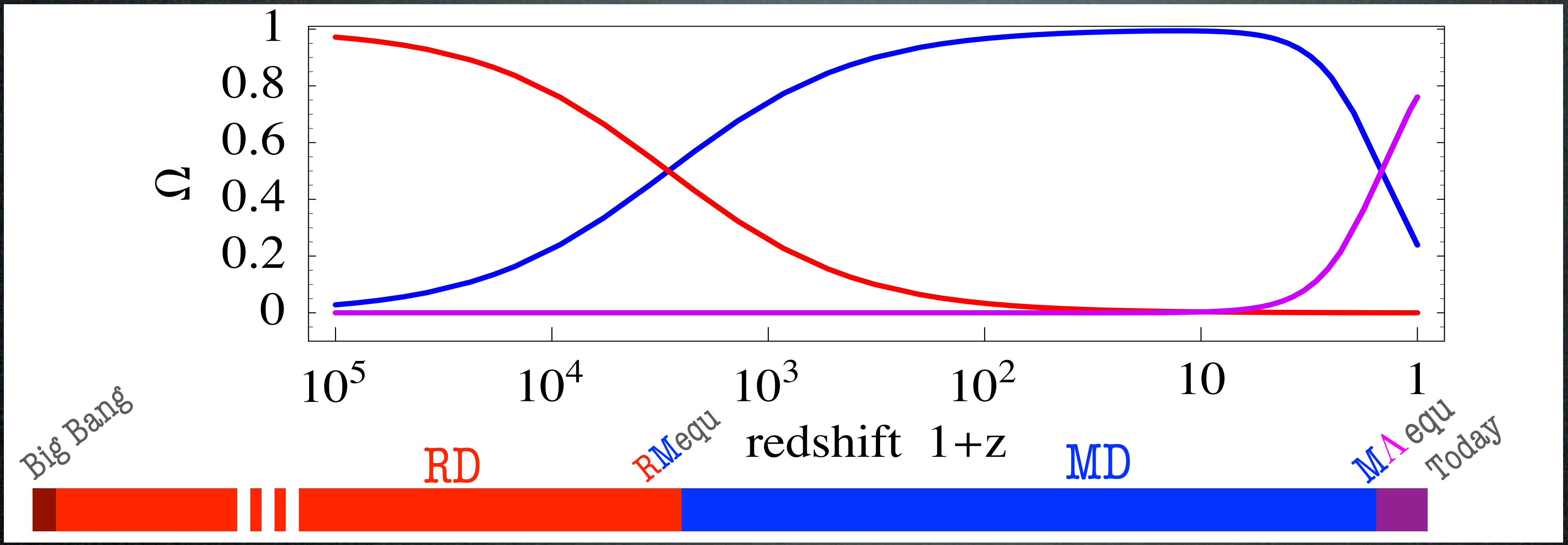

in collaboration with:

A.Strumia (Pisa)

Y.Z. Chu (Yale, CWRU)

# Neutrinos in the Cosmo

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



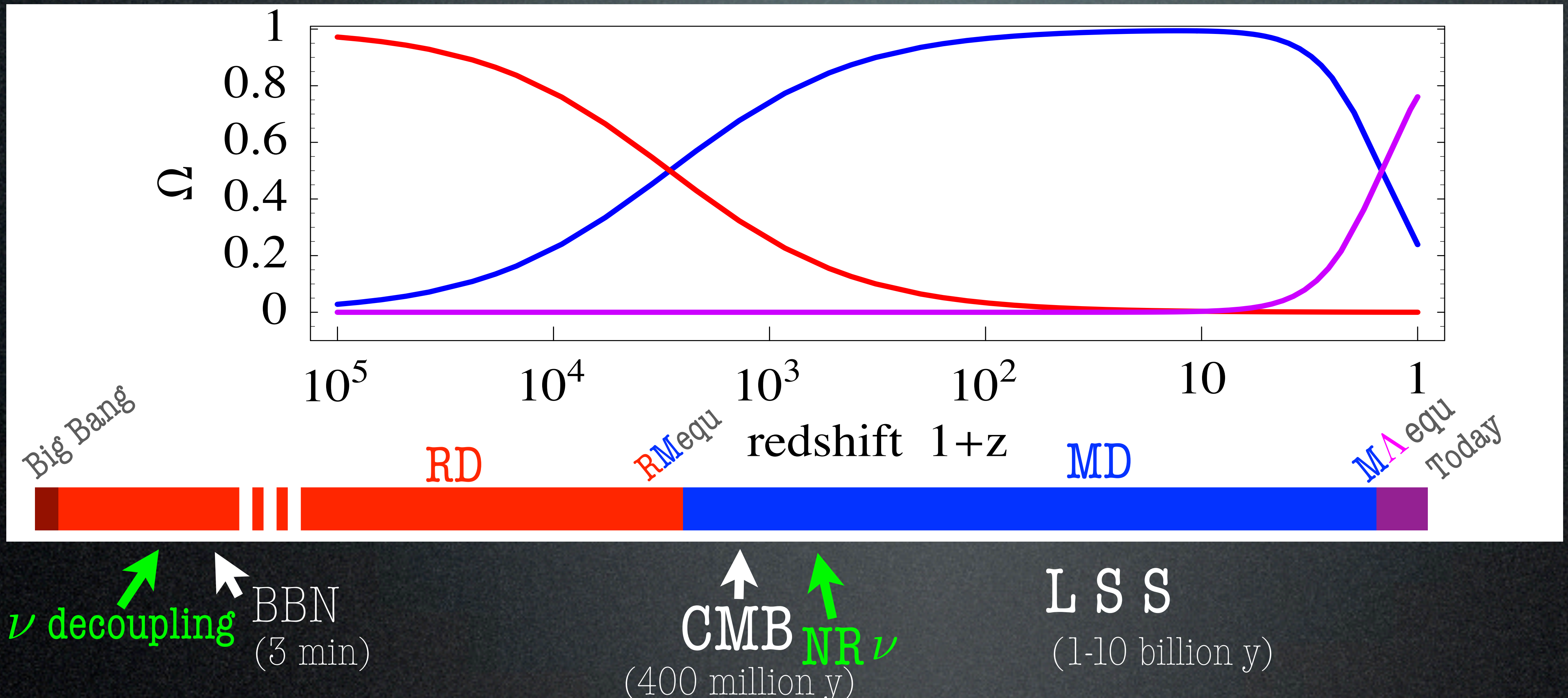

BBN
(3 min)

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

[thanks to M.Frigerio]

# 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:

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

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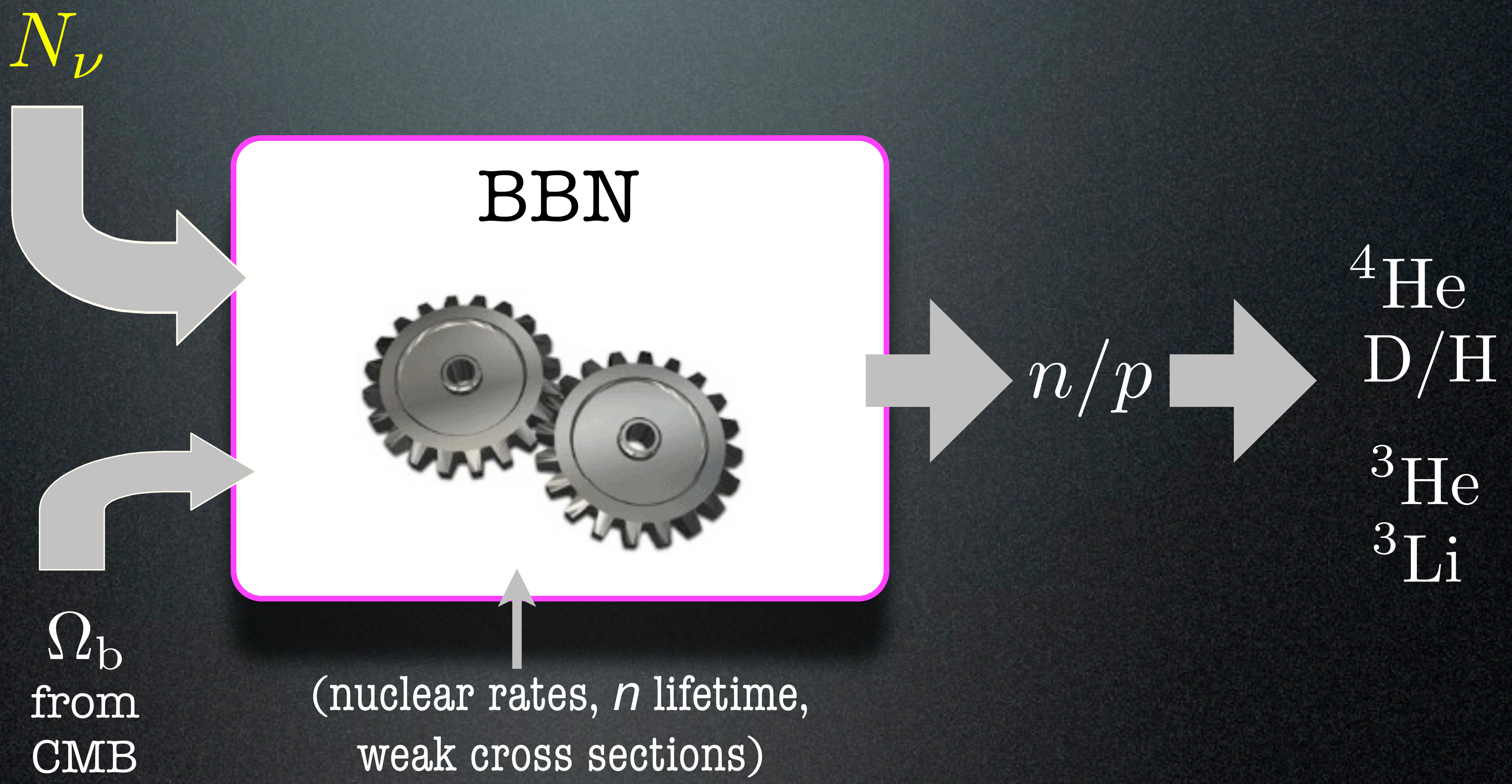
# Neutrinos in BBN

Neutrinos affect the primordial production of light elements.



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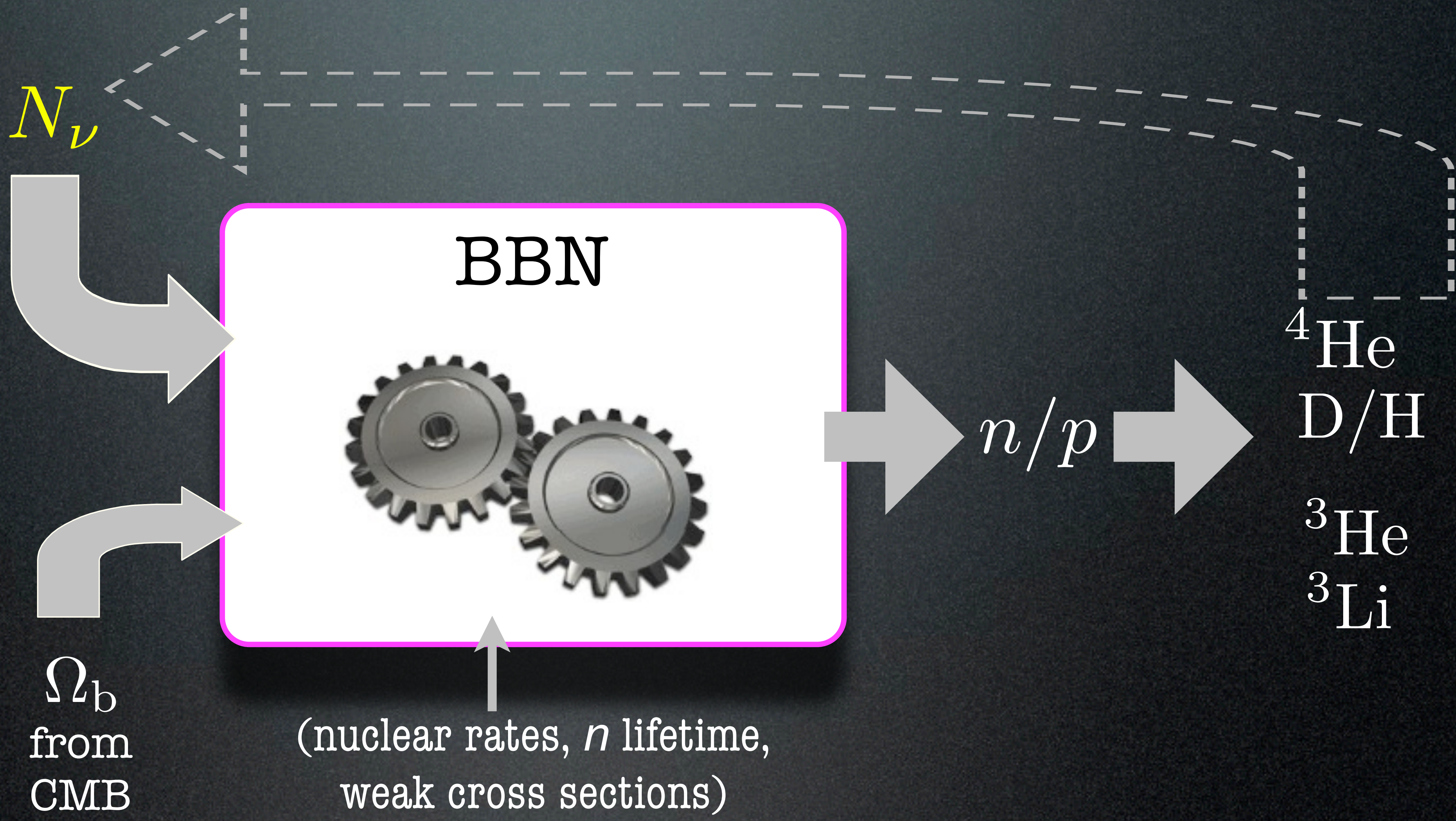


# Neutrinos in BBN

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)

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

$$n + \nu_e \longleftrightarrow p + e^-$$

$$n + e^+ \longleftrightarrow p + \bar{\nu}_e.$$

depend on $\nu_e$ and $\bar{\nu}_e$ densities

(B)

$$H = \sqrt{\frac{8\pi}{3} G_N \, \rho_{rel}}$$

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

(A) more neutrinos $\Rightarrow$ faster expansion

(B) depletion of $\nu_e$ density $\Rightarrow$ modified weak rates

# Neutrinos in BBN

## Compare BBN output with observations:

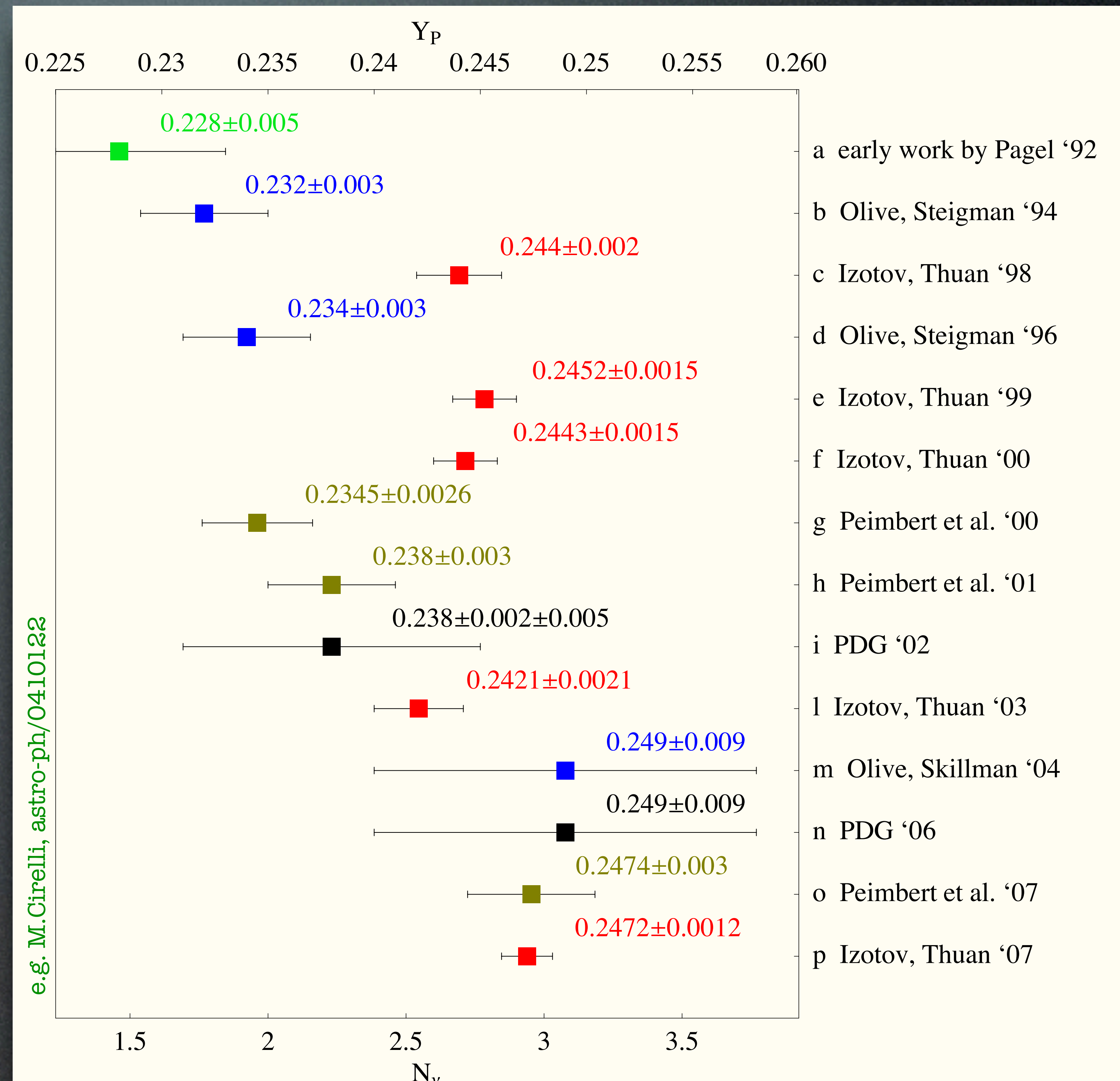
Determinations of primordial $^4\mathrm{He}$ are somehow controversial.

Conservatively, take

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

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

$$N_\nu \simeq 3.1 \pm 0.6 \quad (2\sigma)$$



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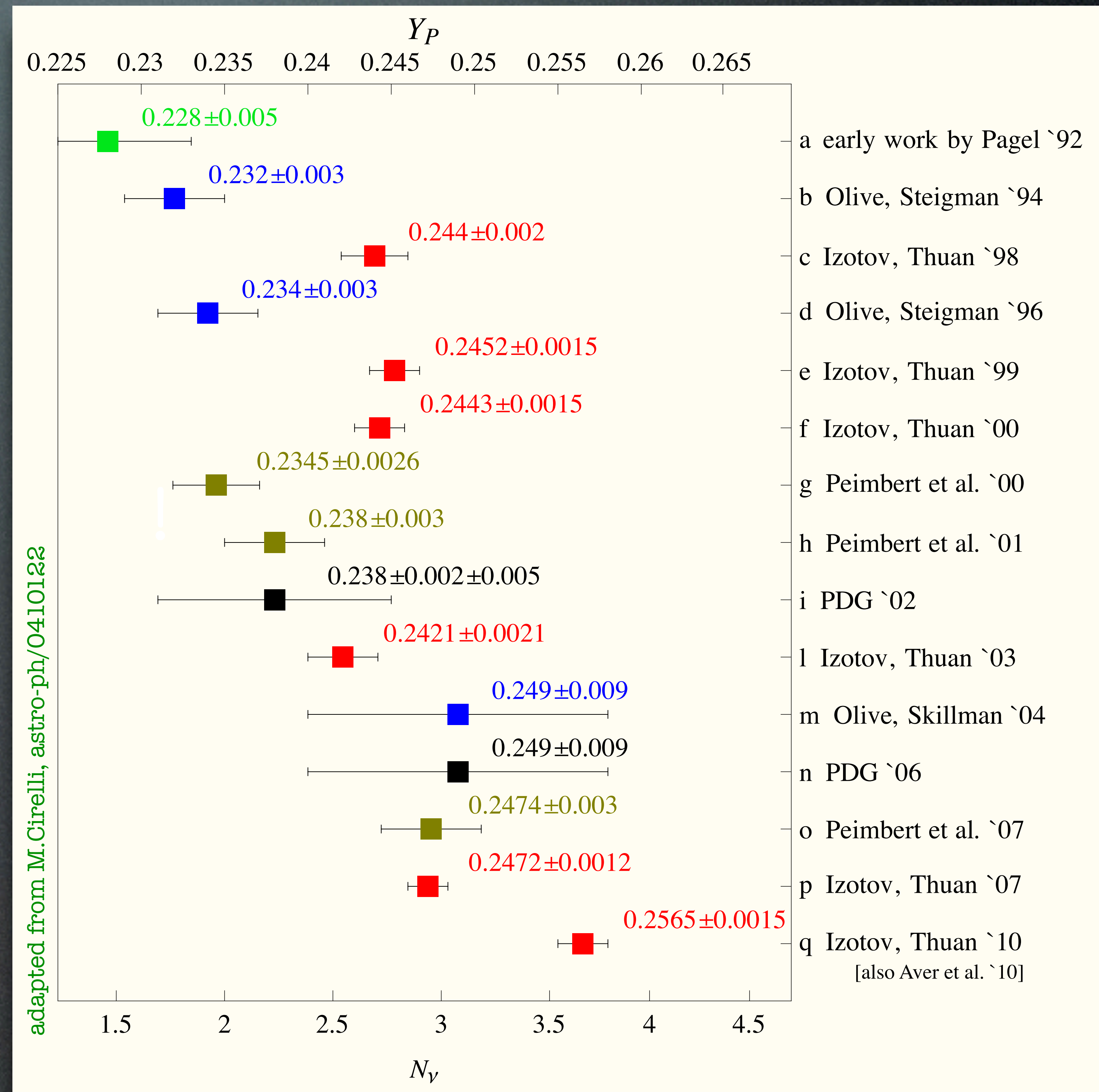


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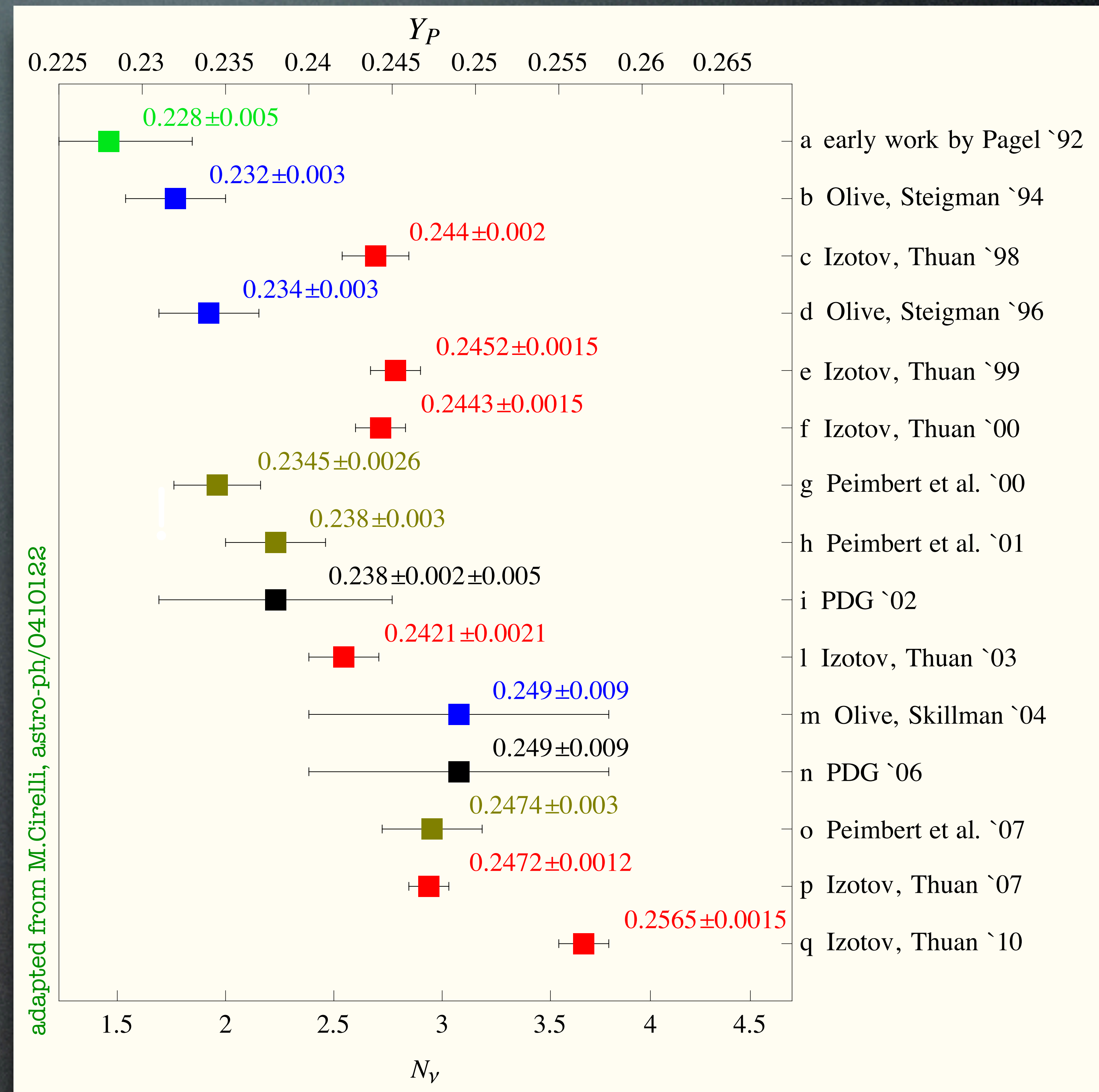


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*Determine $^4$He from CMB?* Yes, but not yet competitive.

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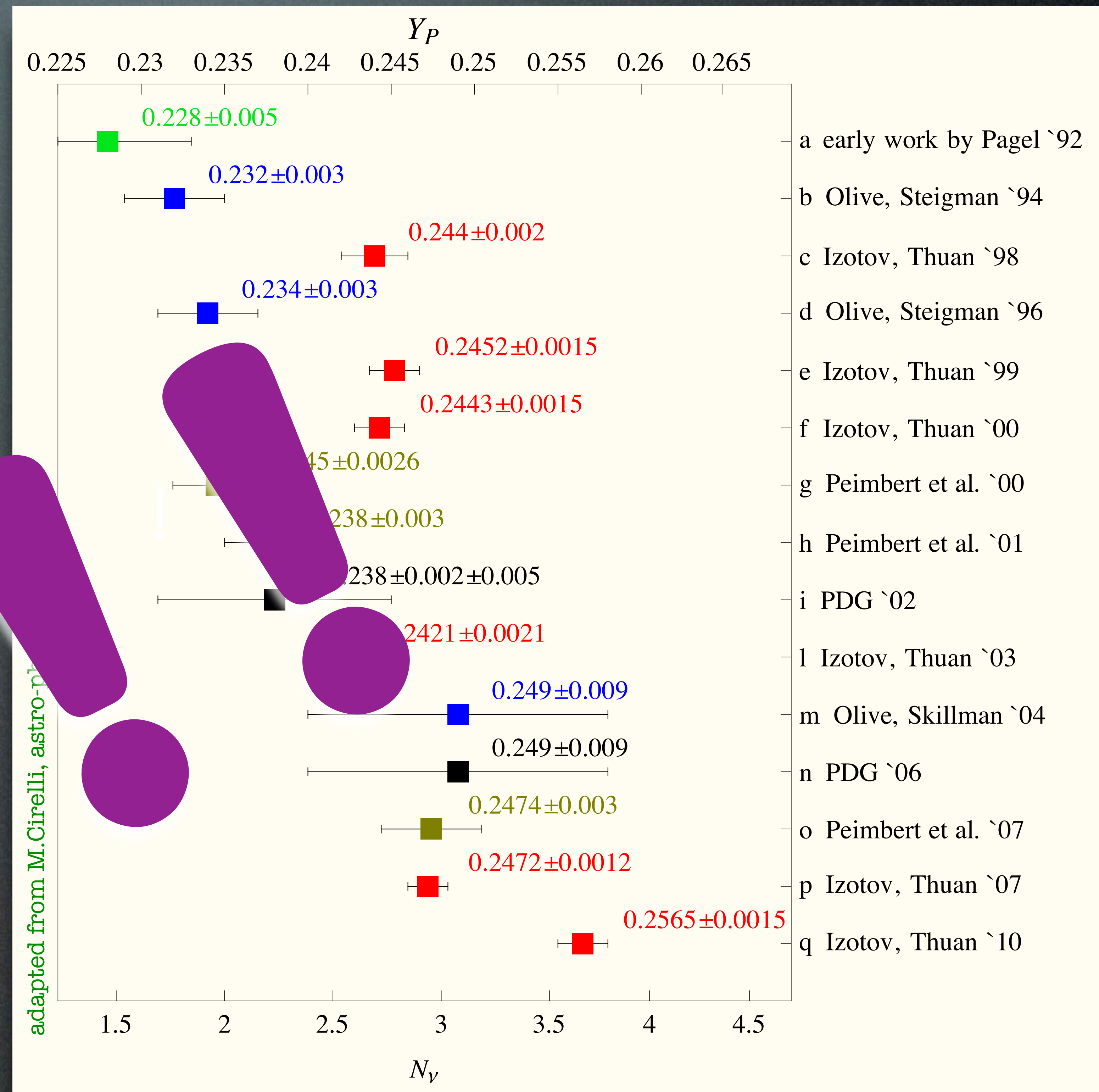


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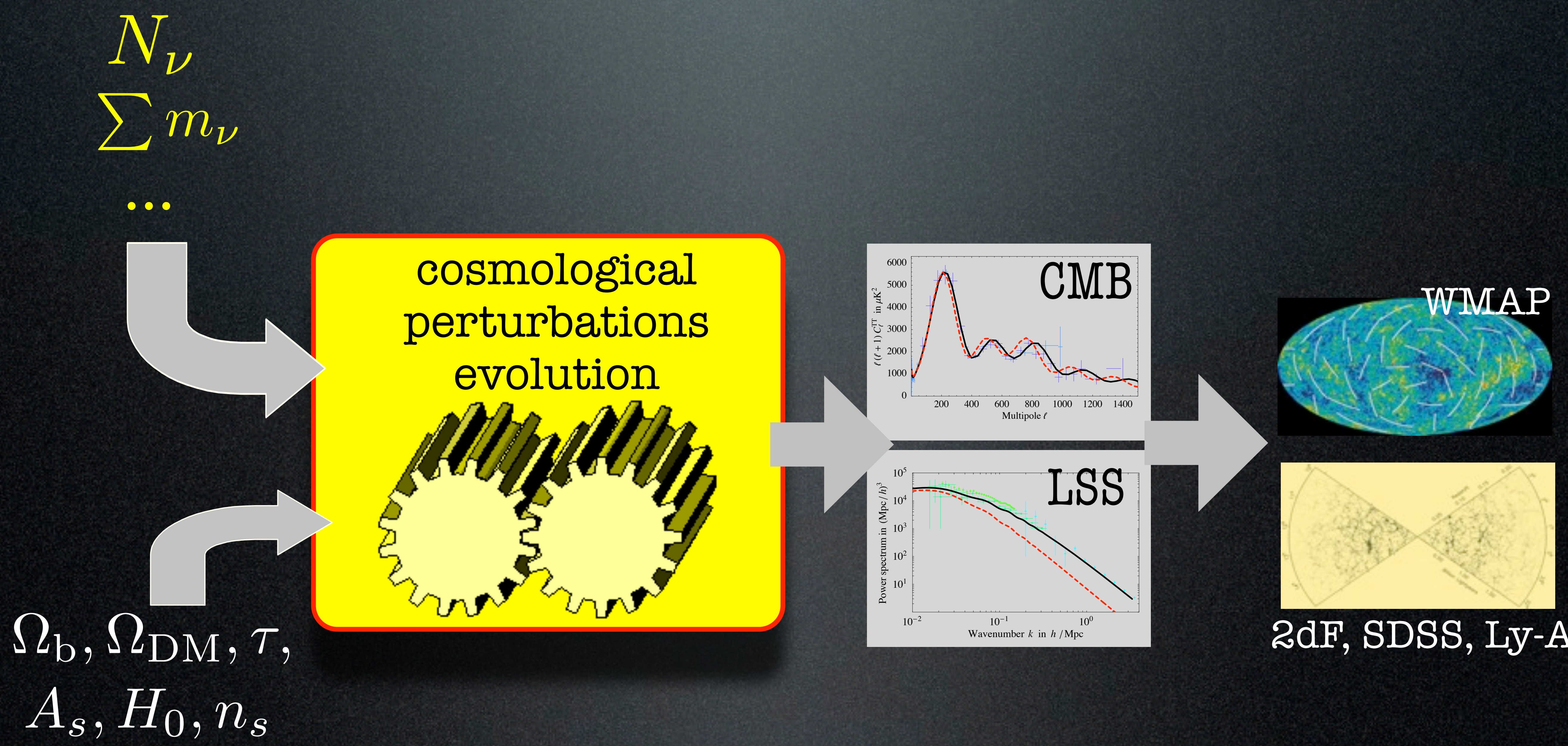

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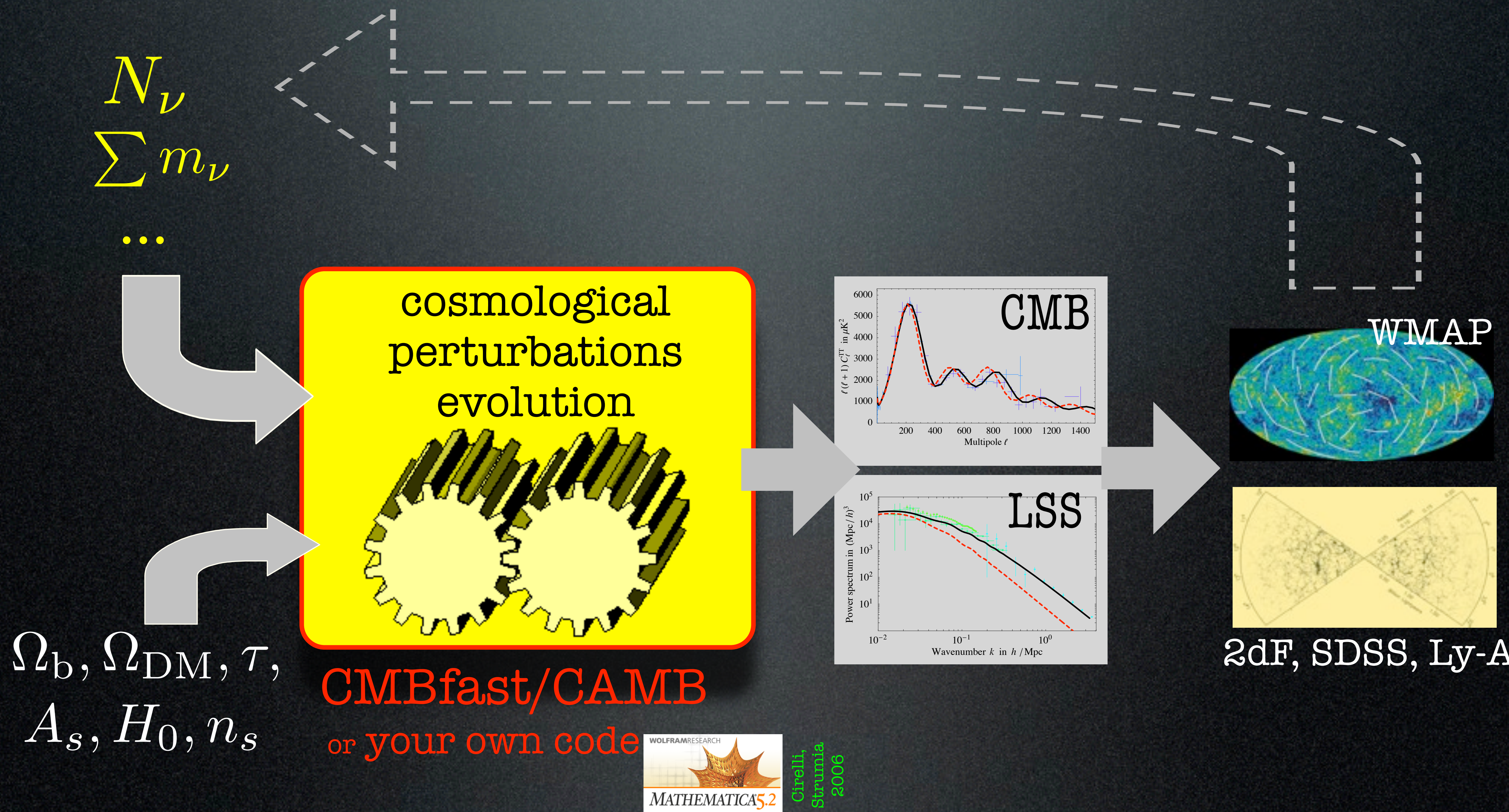


Dodelson's (Chicago, 2003) notations

# Formalism

## (=cosmological perturbation theory in one slide)

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

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

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

photons

$$\dot{\delta}_{\rm dm} + ikv_{\rm dm} = -3\dot{\Phi}$$

$$\dot{v}_{\rm dm} + \frac{\dot{a}}{a}v_{\rm dm} = -ik\Psi$$

dark matter

$$\dot{\delta}_{\rm b} + ikv_{\rm b} = -3\dot{\Phi} \qquad R = 3\rho^0_{\rm b}/4\rho^0_\gamma$$

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

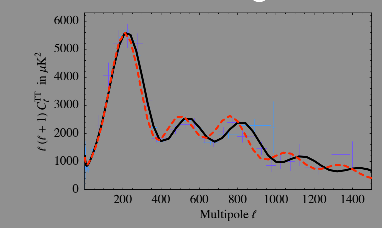
baryons

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

neutrinos

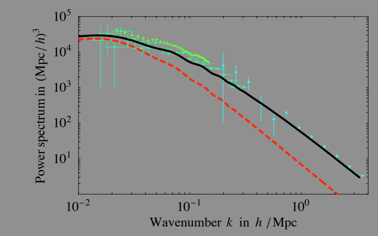
**CMB Power spectrum**

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




**Matter Power spect.**

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




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

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

metric

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photons

$$\Theta = \frac{\delta T}{T} \qquad f(\vec{x},\vec{p}) = \frac{1}{e^{\frac{p}{T+\delta T}} - 1}$$

Fourier: $\Theta(\vec{x},\vec{p},t) \longrightarrow \Theta(k,\mu,\eta) \qquad \mu = \hat{k}\cdot\hat{p}$

Expand in multipoles:

$$\Theta_\ell(k,\eta) = \frac{1}{(-1)^\ell}\int_{-1}^{1} d\mu \frac{1}{2}\mathcal{P}(\mu)\Theta(k,\mu,\eta)$$

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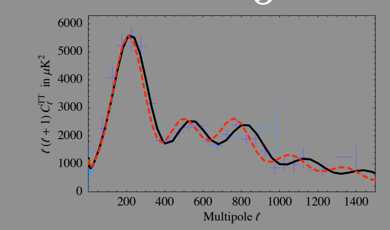


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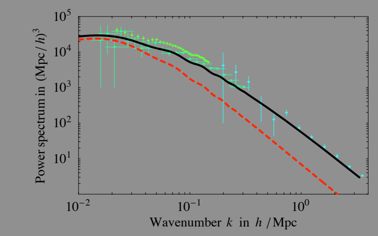


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dark matter

$$\delta_{\mathrm{dm}} = \frac{\delta\rho_{\mathrm{dm}}}{\rho_{\mathrm{dm}}} \qquad \rho_{\mathrm{dm}}(\vec{x},t) = \rho^0_{\mathrm{dm}}\Big(1 + \delta_{\mathrm{dm}}(\vec{x},t)\Big)$$

and velocity $v_{\mathrm{dm}}$

Fourier: $\delta_{\mathrm{dm}}(\vec{x},t) \longrightarrow \delta_{\mathrm{dm}}(k,\eta)$

$v_{\mathrm{dm}}(\vec{x},t) \longrightarrow v_{\mathrm{dm}}(k,\eta)$

CMB Power spectrum

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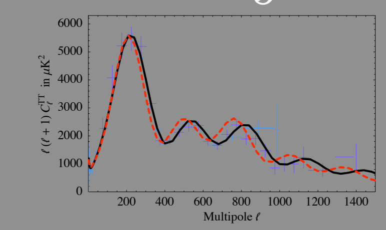

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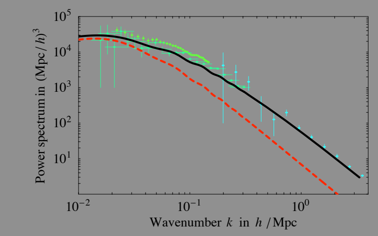

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baryons

$\delta_{\rm b}(k,\eta)$

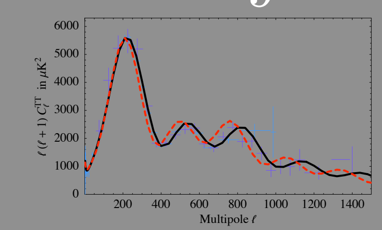
$v_{\rm b}(k,\eta)$

Thomson scattering

$e^-\gamma \longleftrightarrow e^-\gamma$

## CMB Power spectrum

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



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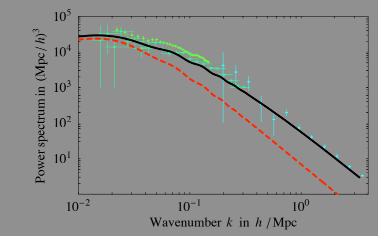

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$\dot\delta_{\rm b}$

$\dot v_{\rm b}$

$\dot{\mathcal{N}}$

scalar metric perturbations: $g_{\mu\nu} = \eta_{\mu\nu} + \delta\eta_{\mu\nu}(\Psi,\Phi)$

$$g_{\mu\nu} = \begin{pmatrix} -1-2\Psi & 0 & 0 & 0 \\ 0 & a^2(1+2\Phi) & 0 & 0 \\ 0 & 0 & a^2(1+2\Phi) & 0 \\ 0 & 0 & 0 & a^2(1+2\Phi) \end{pmatrix}$$

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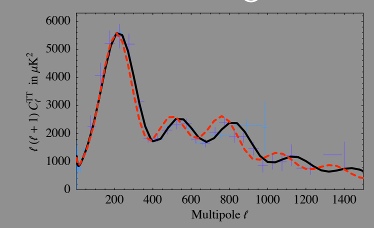


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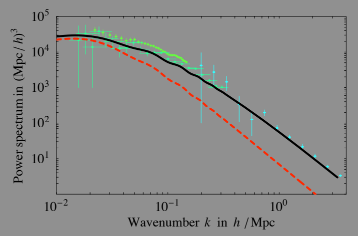

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neutrinos

massless or massive neutrinos $\quad E_\nu = \sqrt{p_\nu^2 + m_\nu^2}$

Fourier: $\mathcal{N}(\vec x, \vec p, t) \longrightarrow \mathcal{N}(k, \mu, \eta)$

Expand in multipoles: $\mathcal{N}_\ell(k, \mu, \eta)$

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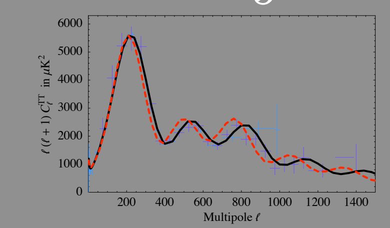


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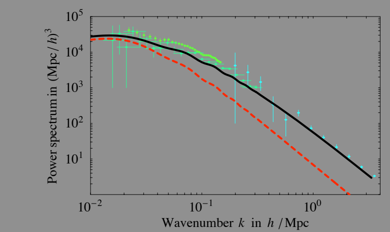

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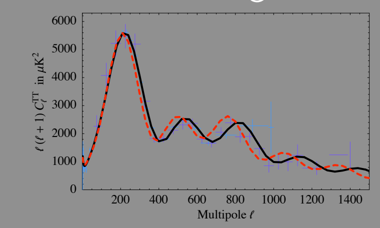
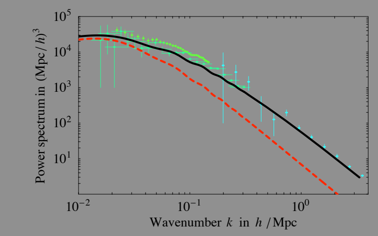
**CMB Power spectrum**

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




**Matter Power spect.**

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

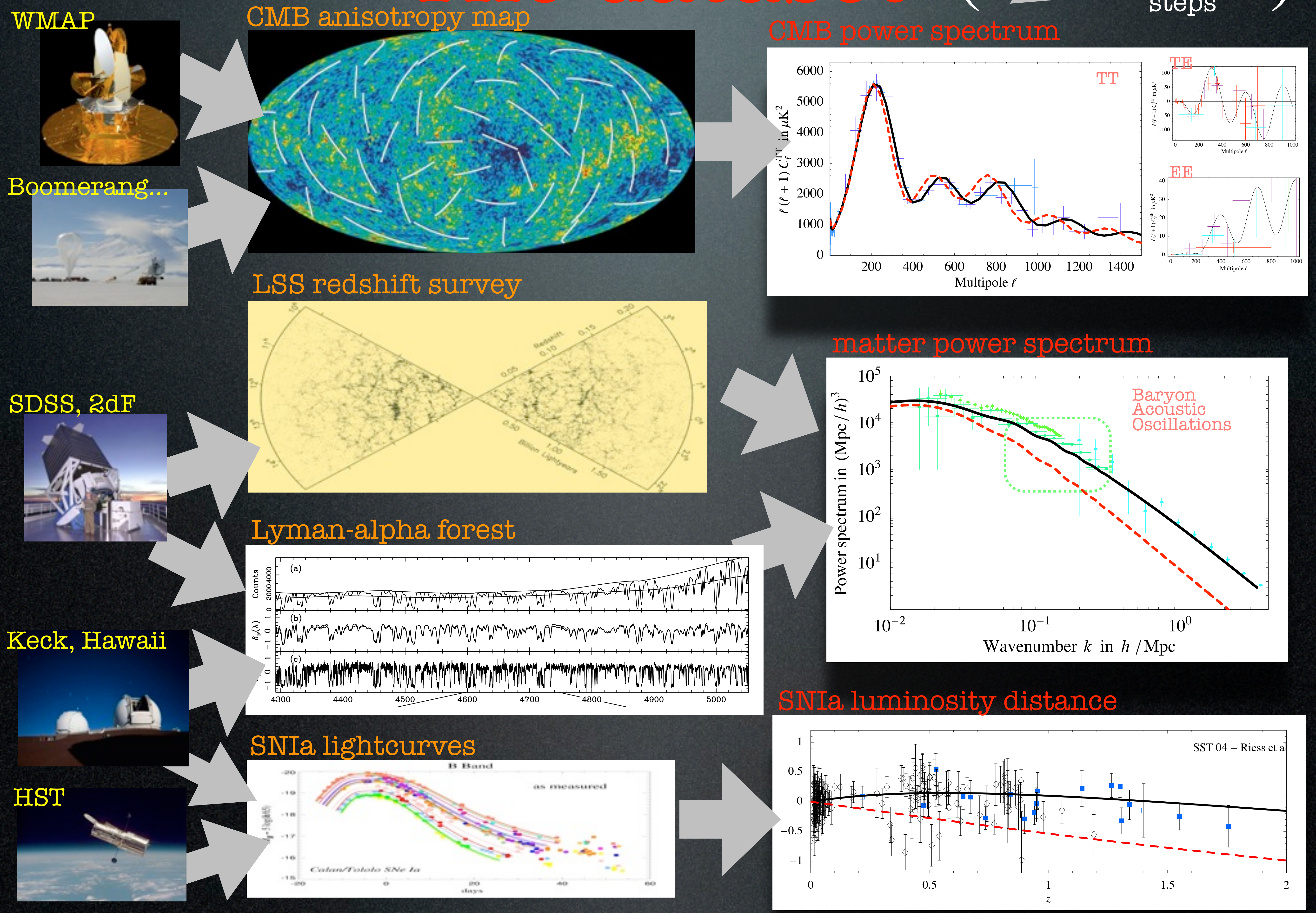



$$k^2\Phi + 3\frac{\dot{a}}{a}\left(\dot{\Phi} - \Psi\frac{\dot{a}}{a}\right) = 4\pi G_N a^2\left[\rho_{\rm m}\delta_{\rm m} + 4\rho_{\rm r}\delta_{\rm r}\right]$$

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

metric

# The dataset


( = some highly non trivial steps )
WMAP
Boomerang...
SDSS, 2dF
Keck, Hawaii
HST
CMB anisotropy map
LSS redshift survey
Lyman-alpha forest
SNIa lightcurves
CMB power spectrum
TT
TE
EE
Multipole ℓ
matter power spectrum
Baryon Acoustic Oscillations
Power spectrum in (Mpc / h)^3
Wavenumber k in h / Mpc
SNIa luminosity distance
SST 04 – Riess et al

# Neutrinos in CMB+LSS

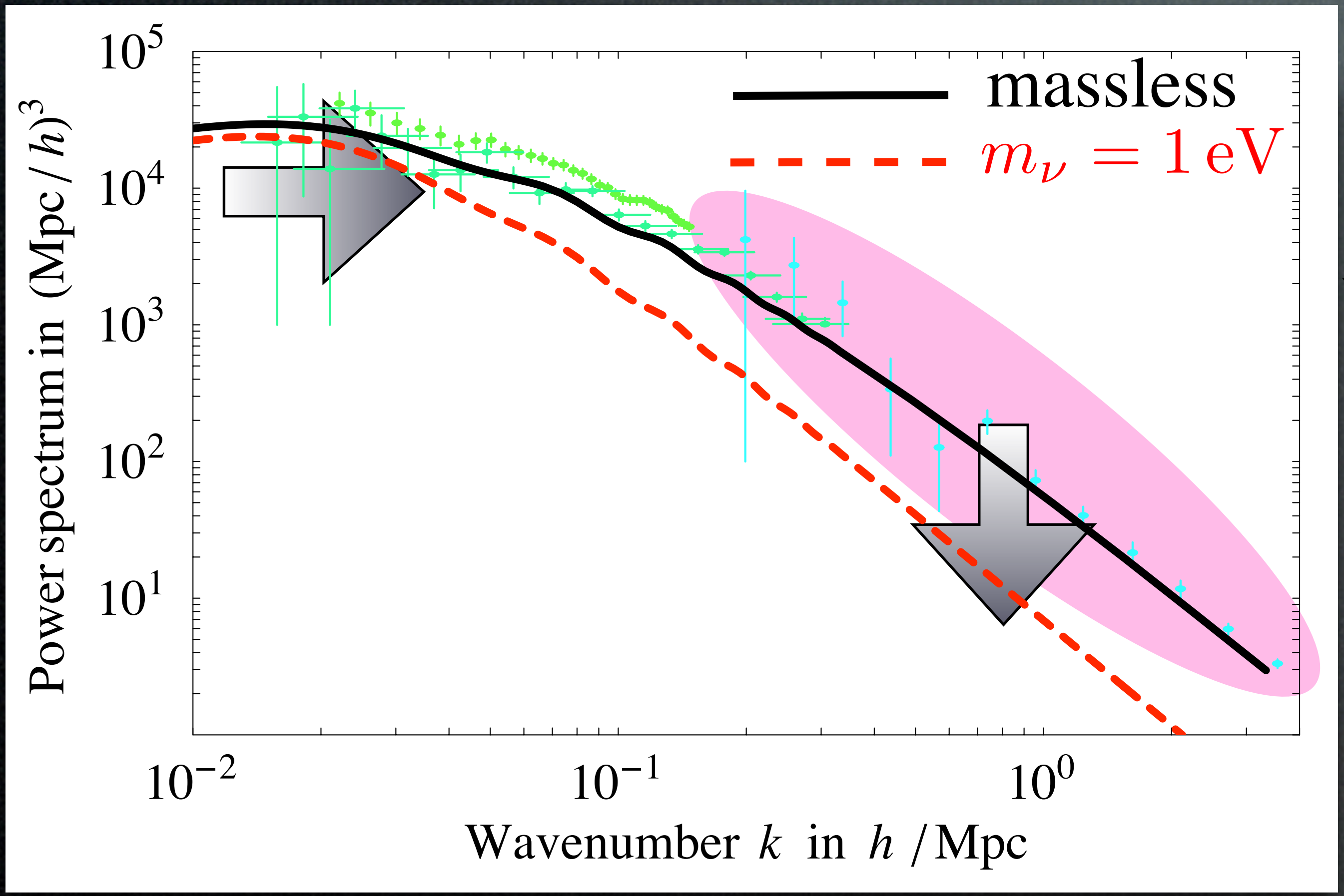
Massive neutrinos affect the growth of matter perturbations during MD:

$$\ddot{\delta}_{\rm dm} + \frac{\dot{a}}{a}\dot{\delta}_{\rm dm} \simeq 4\pi G_N a^2 \rho_{\rm m} \delta_{\rm m} \qquad \text{(Newton equ.)}$$

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.

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

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

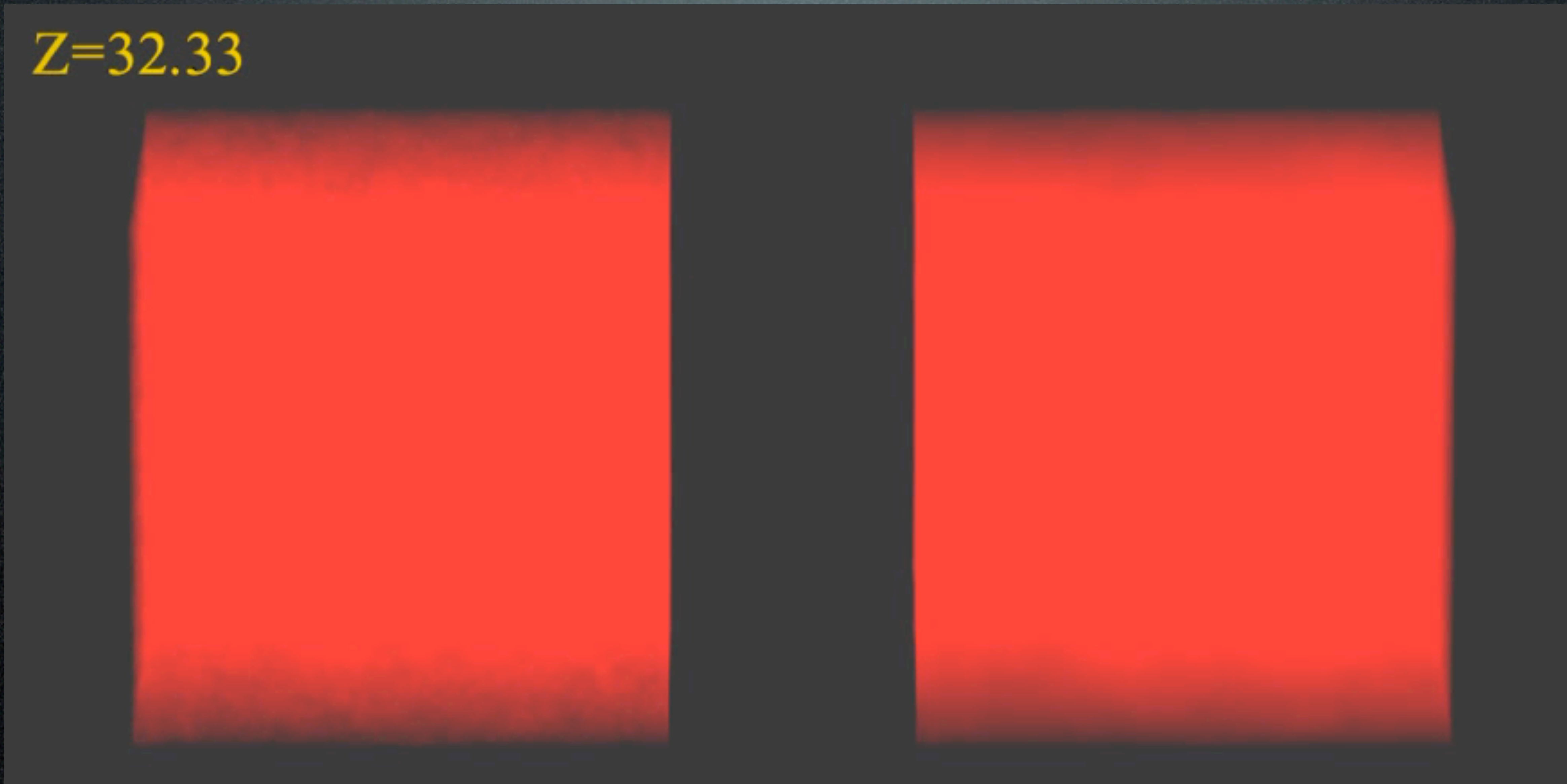
# Neutrino HDM in LSS

$\sum m_\nu = 0$ $\sum m_\nu = 6.9$ eV

$\Lambda$CDM - Gadget2 - 768 Mpc$^3$

T.Haugboelle, S.Hannestad, Aarhus University

# Neutrino HDM in LSS

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$\Lambda$CDM - Gadget2 - 768 $\text{Mpc}^3$

T.Haugboelle, S.Hannestad, Aarhus University

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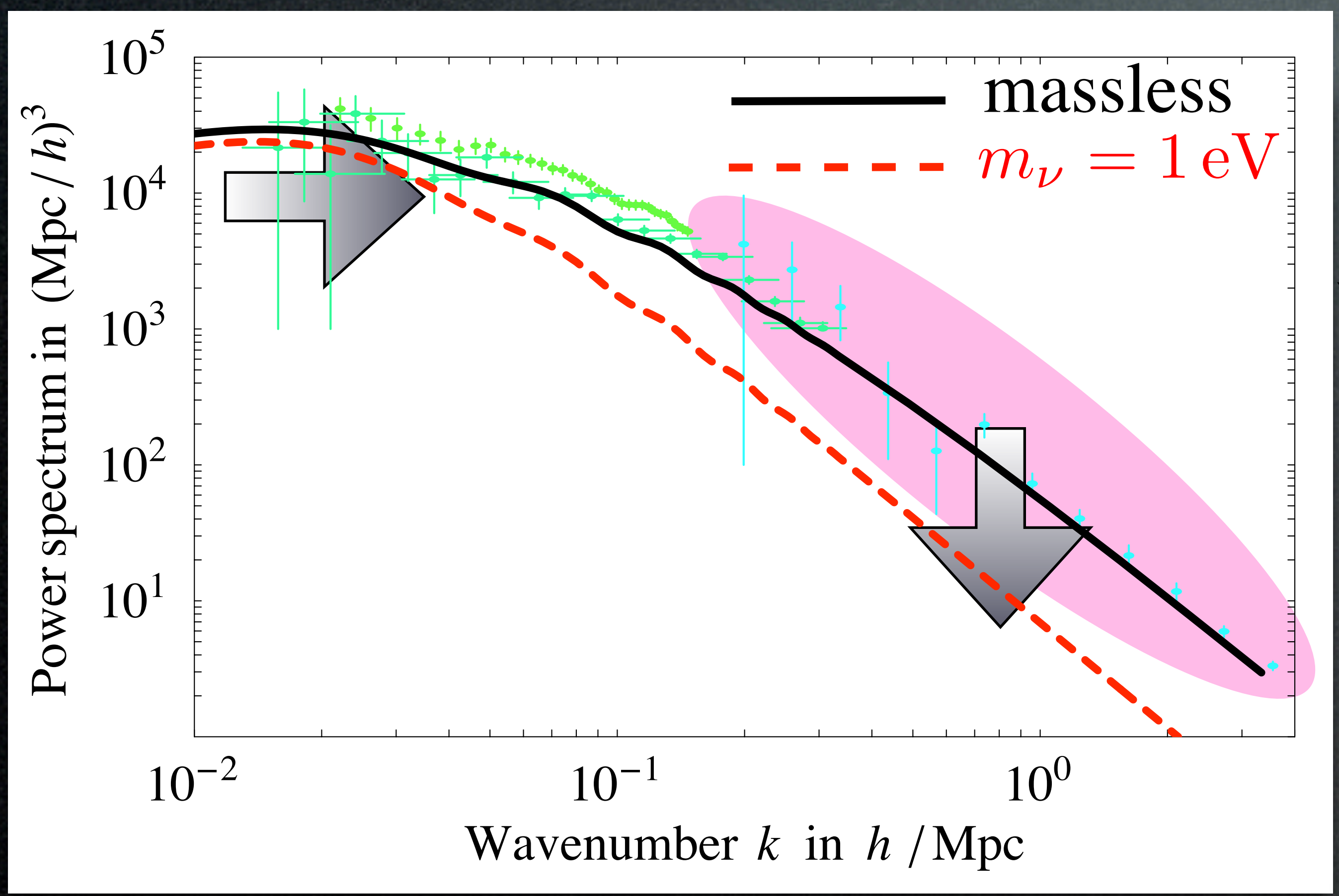


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$$\frac{\Delta P}{P} \simeq -8 f_\nu = -8\frac{\sum m_\nu}{(93\ {\rm eV}^2)h^2\Omega_{\rm m}}$$

a bound on $\sum m_\nu$ :

$$\sum m_{\nu_i} < 0.58\ \text{eV}$$

(@ 95% CL, global fit)
Seljak 2006, Mangano 2007, Hannestad 2005, Cirelli, Strumia 2006, WMAP7 Komatsu et al. 2010, Abazajian et al. 1103.5083...

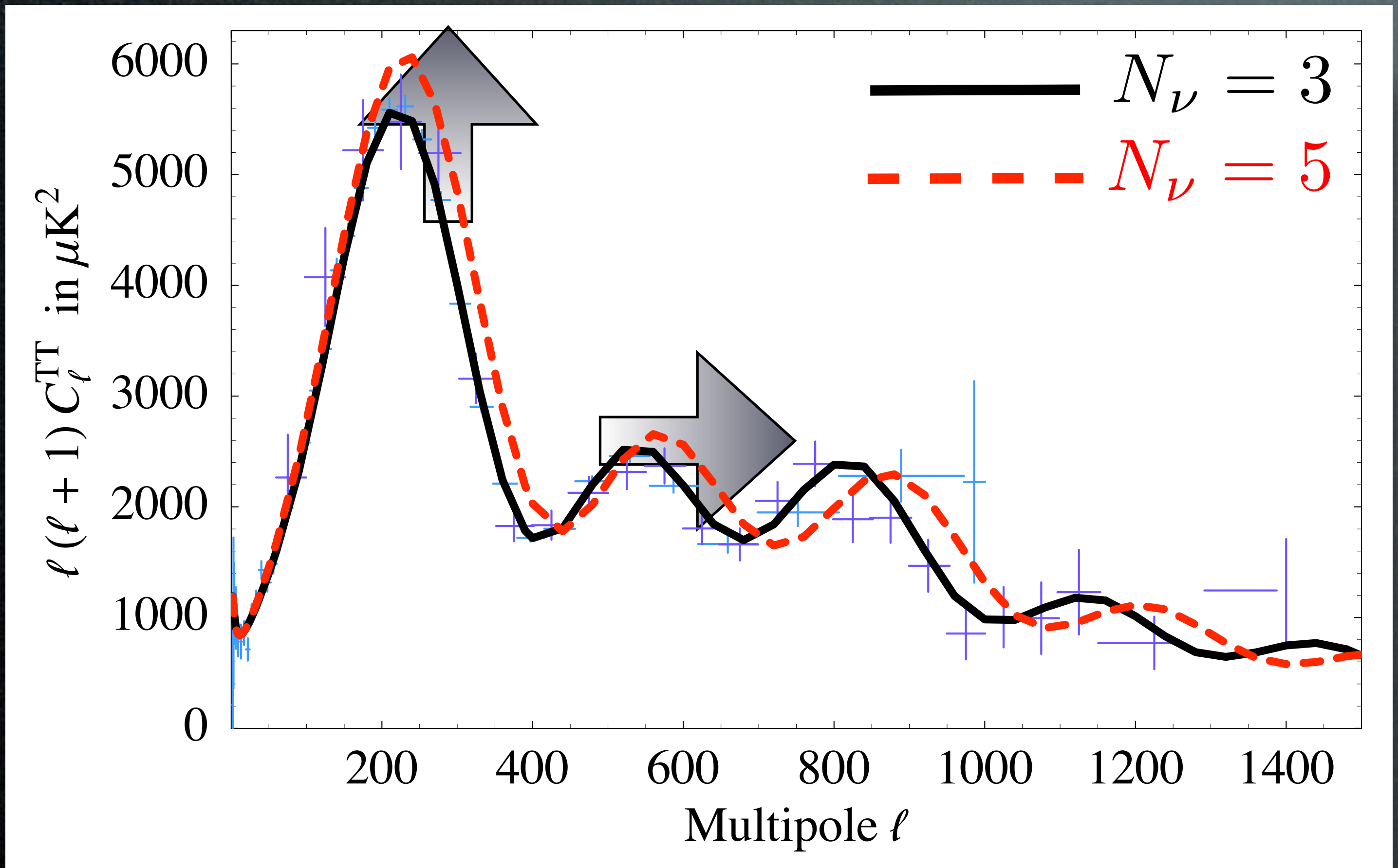
without Lyman-$\alpha$ :

$$\sum m_{\nu_i} < 0.73\ \text{eV}$$

Cirelli, Strumia 2006

# Neutrinos in CMB+LSS

$N_\nu$ sets the total **relativistic energy** content and affects the peaks of CMB (and LSS) spectra:




Caveat: plot for illustration only, all parameters fixed except $N_\nu$

# Results

## New neutrinos?

$3_{.04}$ $\Delta N_\nu$

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

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

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

photons

$$\dot\delta_{dm} + ikv_{dm} = -3\dot\Phi$$
$$\dot v_{dm} + \frac{\dot a}{a}v_{dm} = -ik\Psi$$

dark matter

$$\dot\delta_b + ikv_b = -3\dot\Phi \qquad R = 3\rho_b^0/4\rho_\gamma^0$$
$$\dot v_b + \frac{\dot a}{a}v_b = -ik\Psi + \frac{\dot\tau}{R}\left[v_b + 3i\Theta_1\right]$$

baryons

CMB Power spectrum

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

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

neutrinos

all $N_\nu$ rel degrees of freedom contribute to the energy density

$$\rho_r = \rho_\gamma\left[1 + \frac{7}{8}N_\nu\left(\frac{T_\nu}{T}\right)^4\right]$$

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

$$k^2\Phi + 3\frac{\dot a}{a}\left(\dot\Phi - \Psi\frac{\dot a}{a}\right) = 4\pi G_N a^2\left[\rho_m\delta_m + 4\rho_r\delta_r\right]$$
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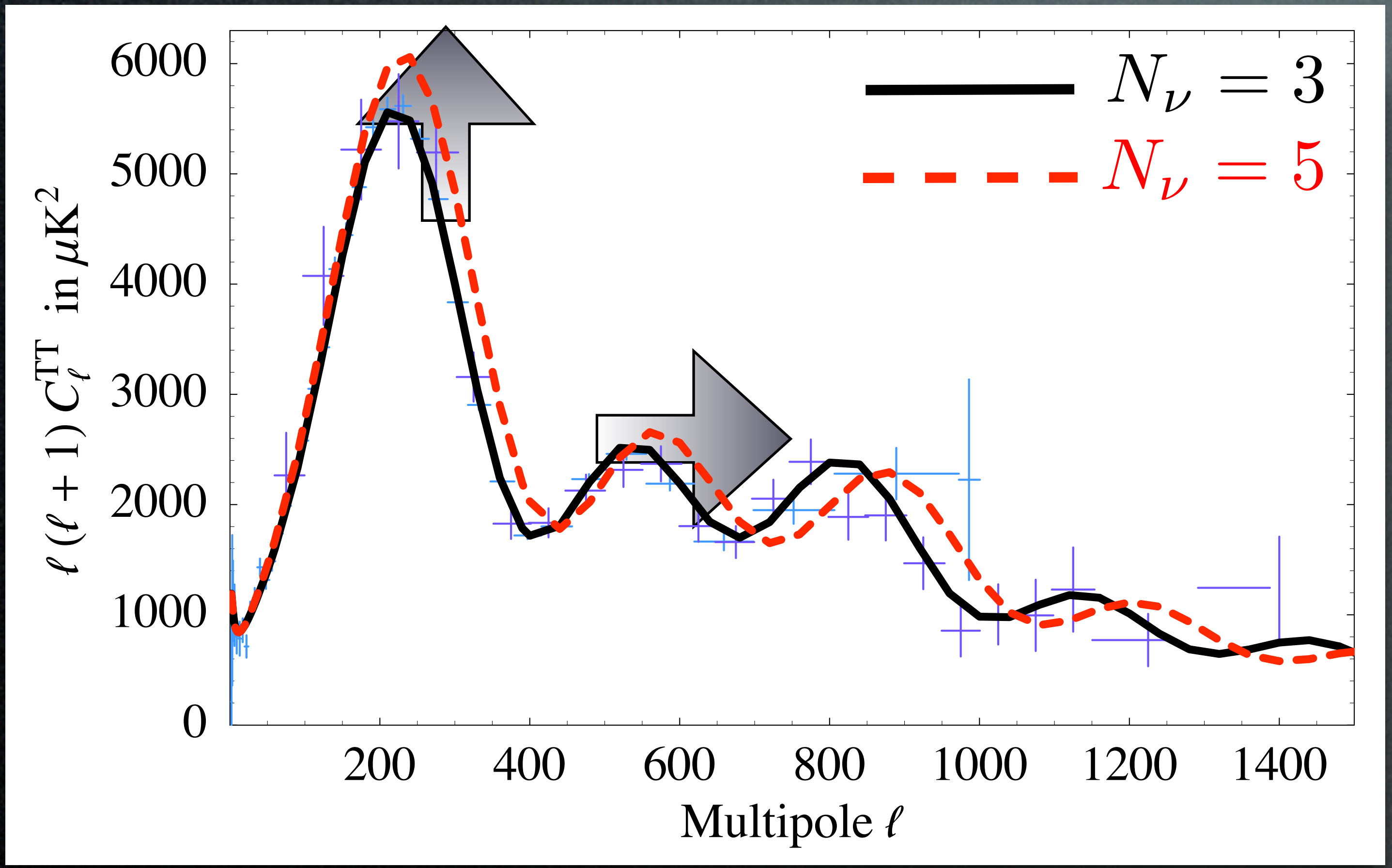



Caveat: plot for illustration only, all parameters fixed except $N_\nu$

a determination of $N_\nu$ :

$$N_\nu = 4.34 \pm 0.80$$

(global fit)

(Seljak 2006, Mangano 2007, Cirelli, Strumia 2006, Hamann et al. 2010

but dropping Ly-$\alpha$ gives back

$$N_\nu \simeq 3$$

Cirelli, Strumia 2006

*Just systematics?*

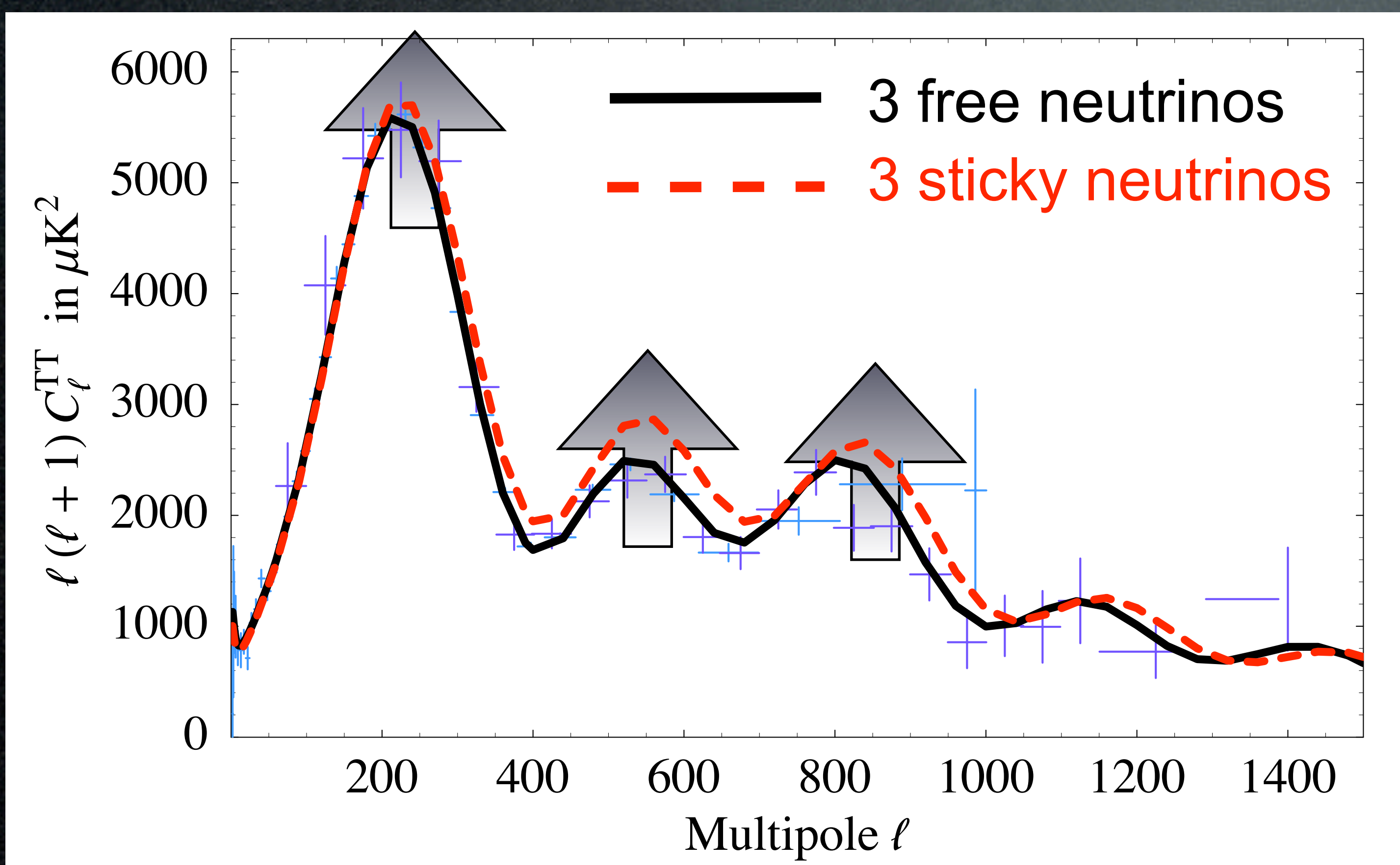
*Hamann et al 2007, Verde et al. 2011*

# 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:

$$\begin{cases} \dot{\delta}_x + i\frac{4}{3}kv_x = -4\dot{\Phi} \\ \dot{v}_x + \frac{i}{4}k\delta_x = -ik\Psi \end{cases}$$

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)

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

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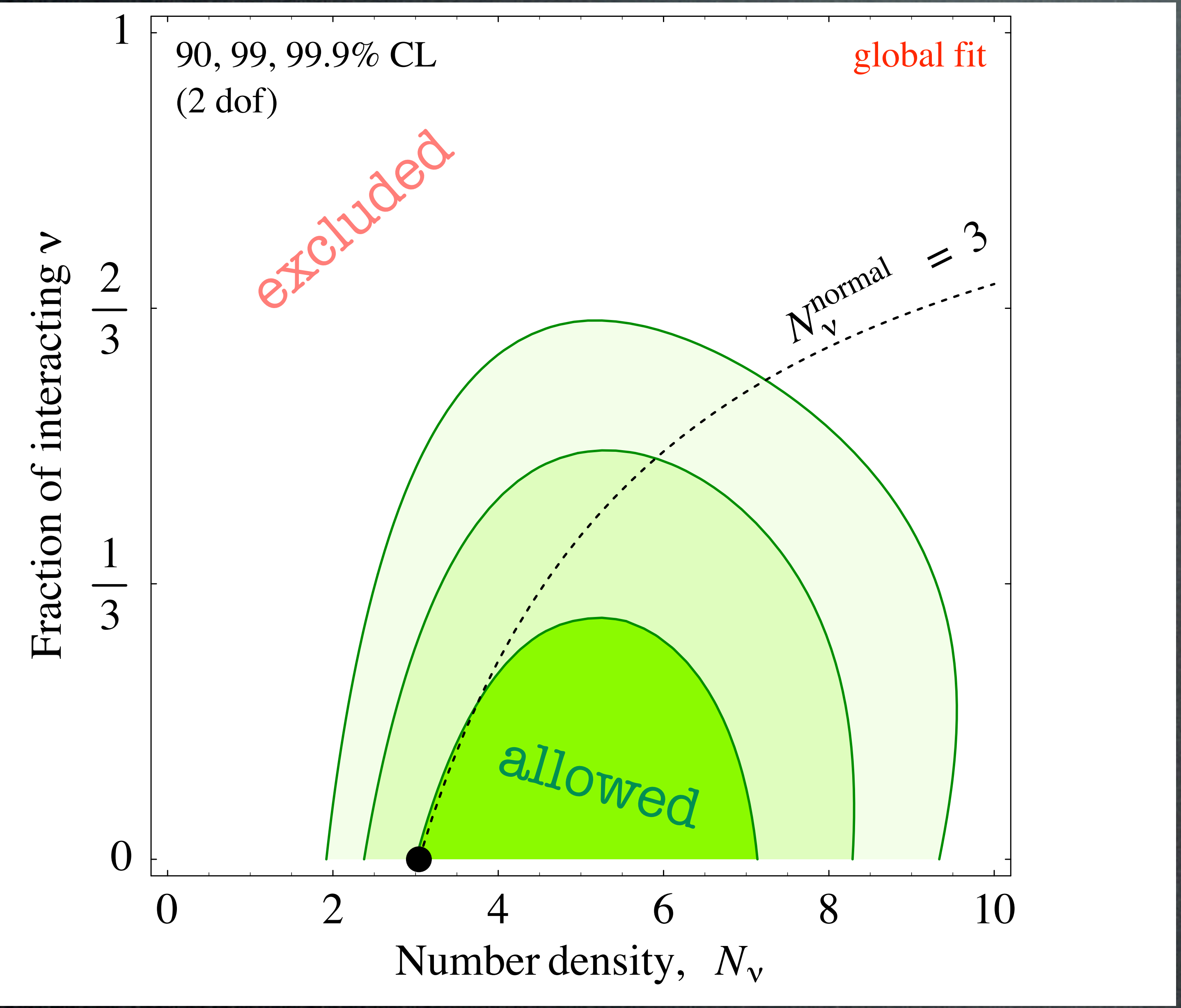


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$$\begin{cases} \dot\delta_{\rm x} + i\frac{4}{3}kv_{\rm x} = -4\dot\Phi \\ \dot v_{\rm x} + \frac{i}{4}k\delta_{\rm x} = -ik\Psi \end{cases}$$

CMB and LSS peaks are modified.

$\sim 1$ sticky $\nu$ allowed (@ 99% CL, global fit)

3 sticky $\nu$ excluded (at $5\sigma$)

Friedland et al. 2007
Bell et al. 2005
Cirelli, Strumia 2006

# Conclusions (of this other talk)

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

  Results are becoming solid but there are puzzling surprises.

- Current status:

$N_\nu \simeq 3.1 \pm 0.6$ (BBN)

$N_\nu = 4.34 \pm 0.80$ (CMB+LSS)

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

$\sim 1$ sticky $\nu$ allowed (@ 99% CL, global fit)

3 sticky $\nu$ excluded (at 5$\sigma$)

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

    Hannestad 2005
  - Planck will test 1 sticky $\nu$ at 4 $\sigma$

    Friedland et al. 2007
  - ...

# Back up slides