LPT Orsay - 21 February 2008

Neutrino properties from Cosmology:

the usual and the less usual

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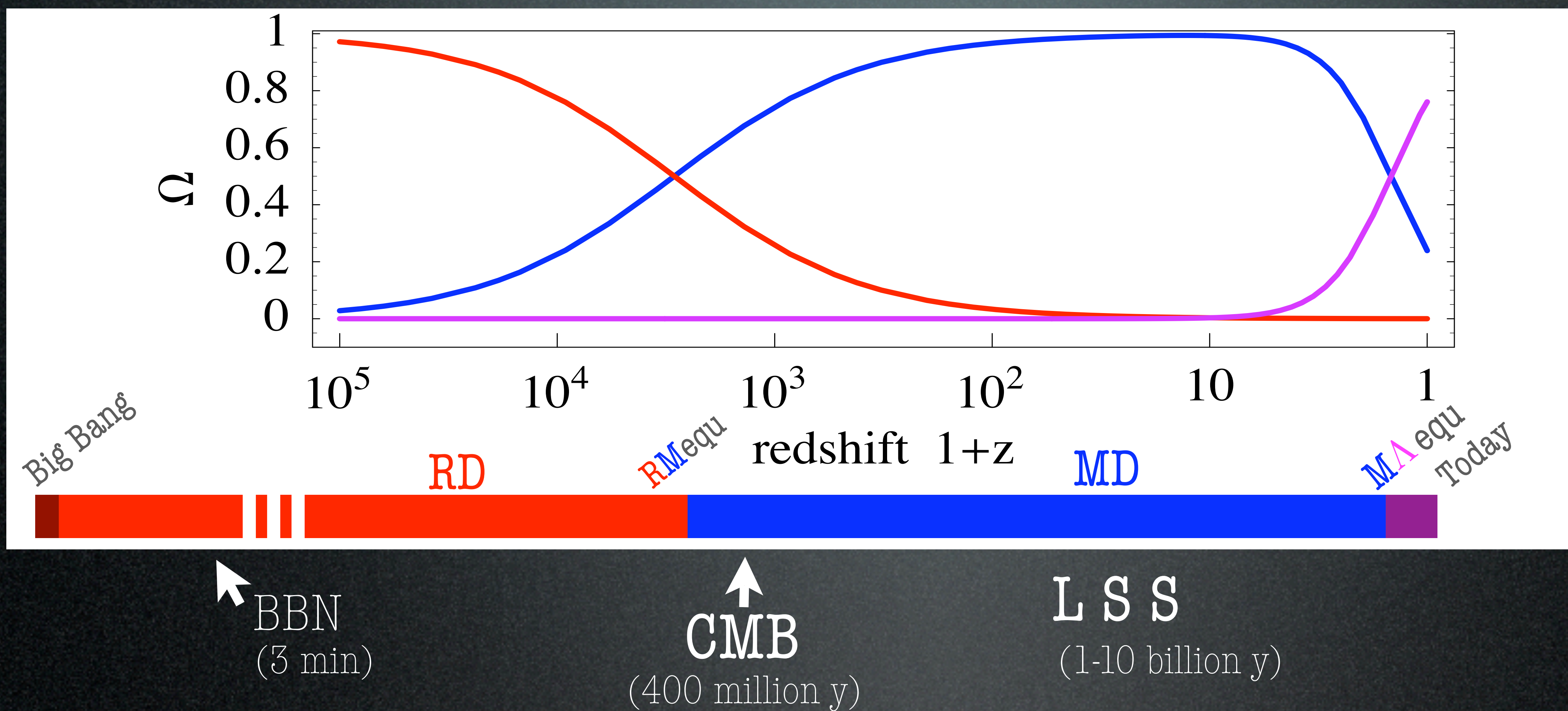
  - Formalism
  - Data set
  - Computational tool
- Results

Neutrinos in the Cosmo

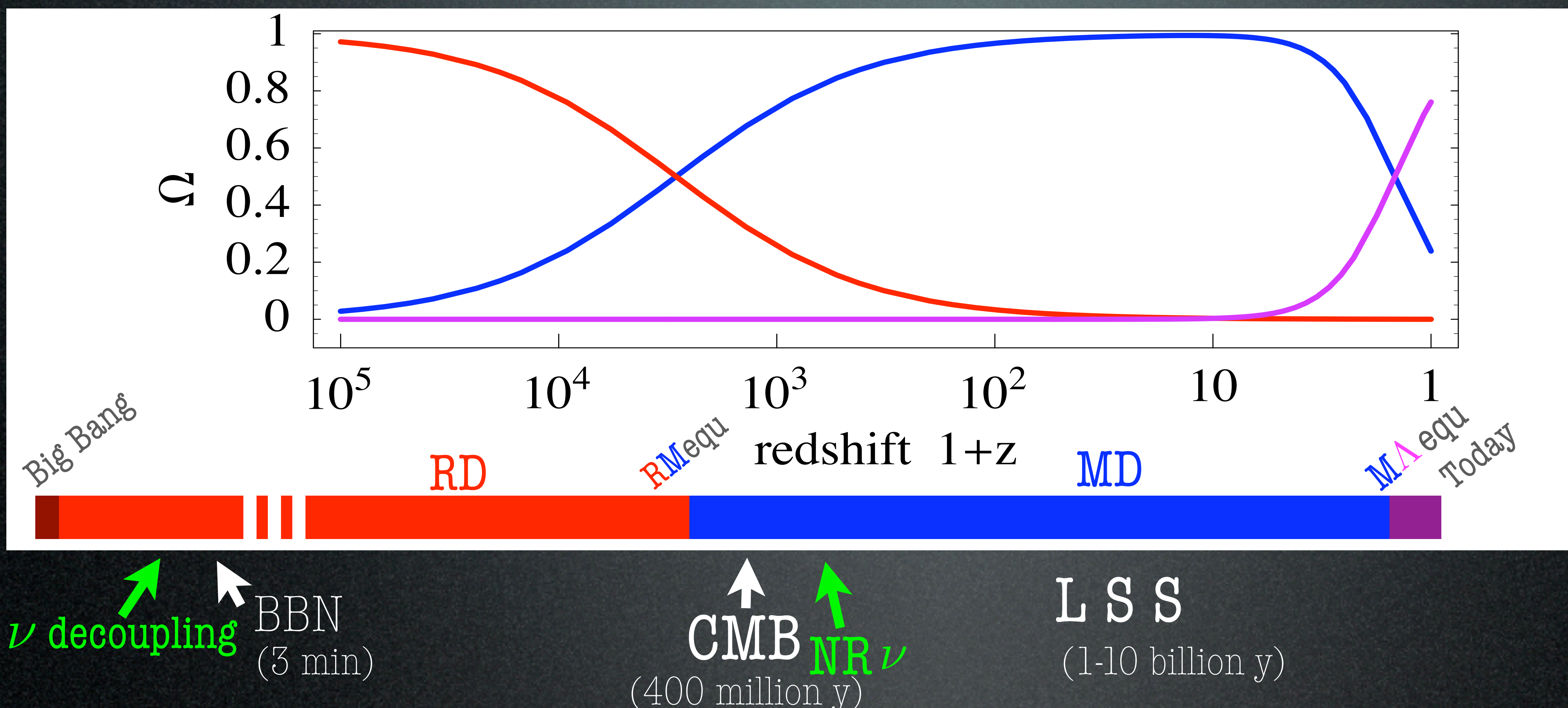
The Universe is made of: radiation, matter (DM+b+e), dark energy



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:

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

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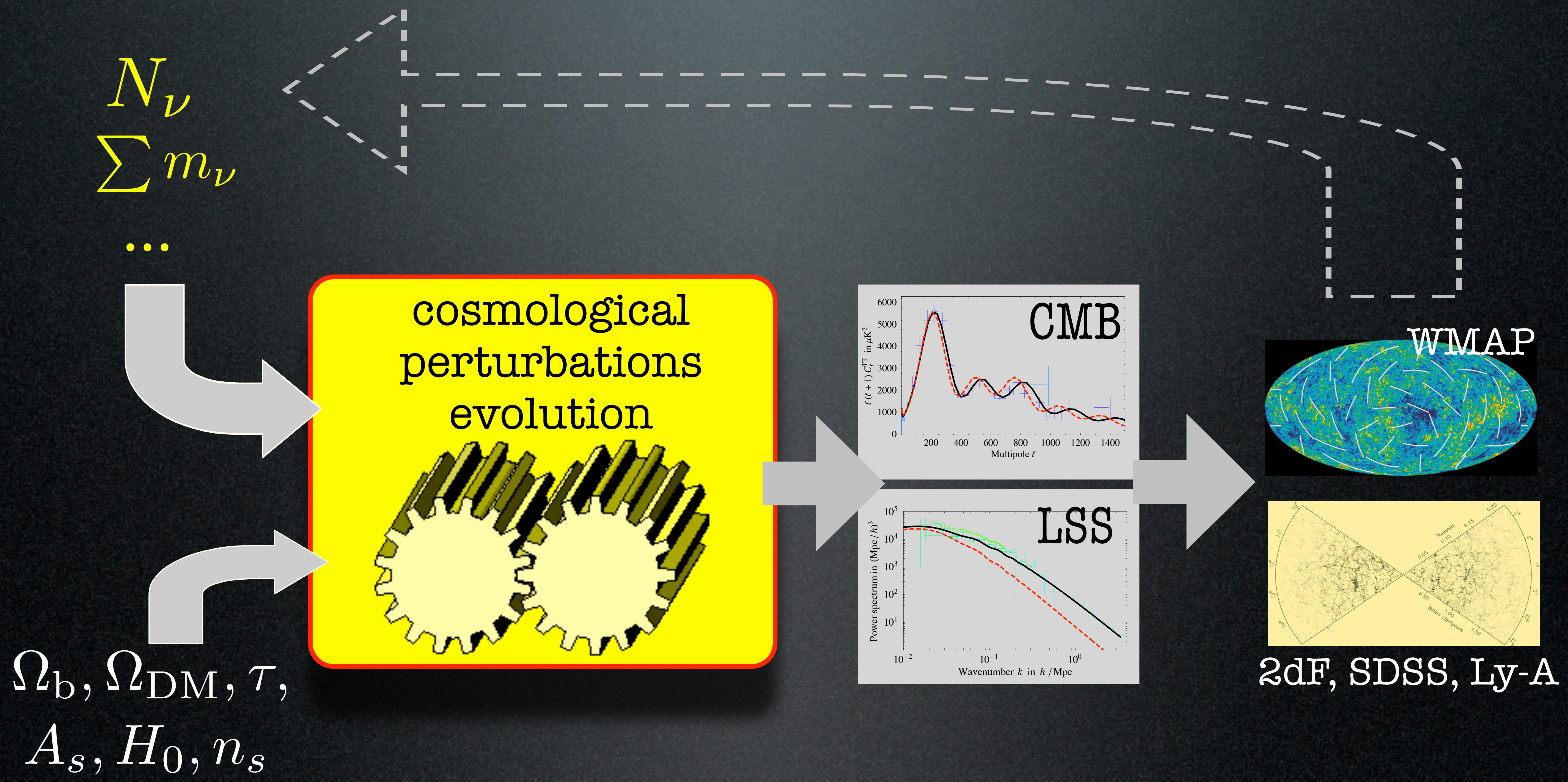
Neutrinos in CMB+LSS

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



Formalism

(=cosmological perturbation theory in one slide)

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

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

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

} 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

$$\dot{\delta}_\mathrm{b} + ikv_\mathrm{b} = -3\dot{\Phi}$$

$R = 3\rho_\mathrm{b}^0/4\rho_\gamma^0$

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

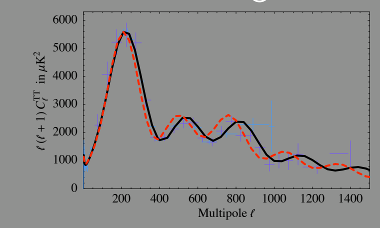
} baryons

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

} neutrinos

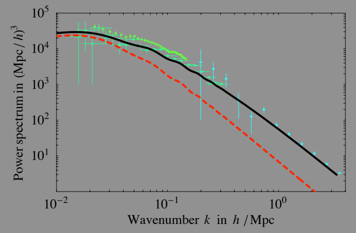
CMB Power spectrum

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



Matter Power spect.

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



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

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

} metric

Formalism

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

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

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:

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

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

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

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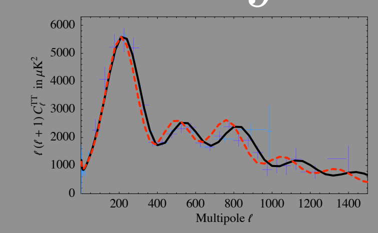

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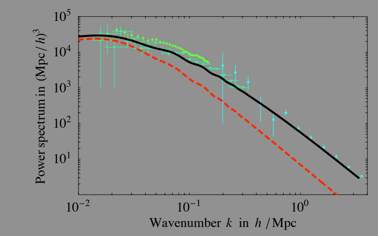

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metric

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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

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

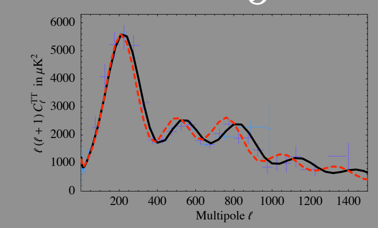
and velocity $v_{\rm dm}$

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

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

CMB Power spectrum

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



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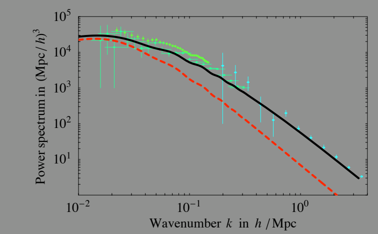

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baryons

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

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

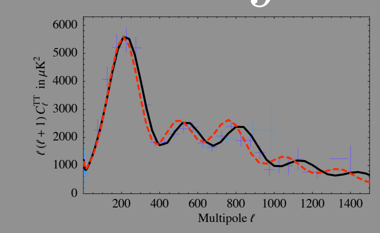
$v_{\rm b}(k,\eta)$

Thomson scattering

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

CMB Power spectrum

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



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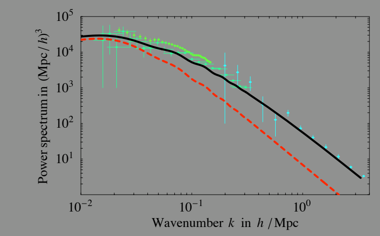

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dark matter

$\dot\delta_{\rm b}$

$\dot v_{\rm b}$

$\dot{\mathcal{N}}$

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

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

Fourier: $\Psi(\vec{x},t) \longrightarrow \Psi(k,\eta)$

$\Phi(\vec{x},t) \longrightarrow \Phi(k,\eta)$

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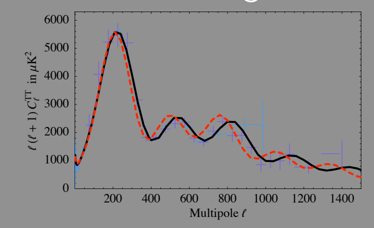

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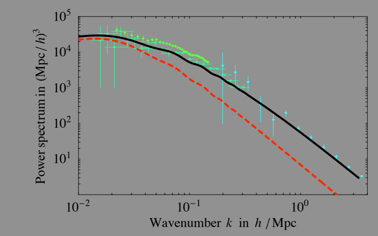

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$$\dot{\mathcal{N}} + i\frac{q_\nu}{E_\nu}k\mu\mathcal{N} = -\dot{\Phi} - i\frac{E_\nu}{q_\nu}k\mu\Psi$$

} neutrinos

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

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

} metric

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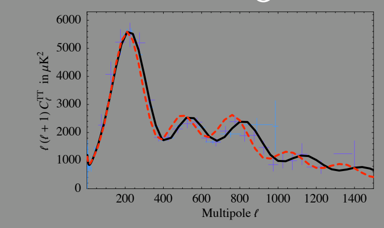

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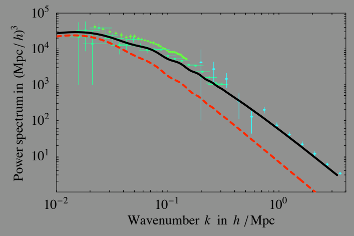

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neutrinos

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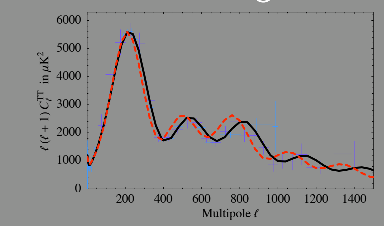

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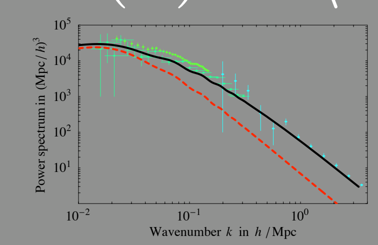

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$$k^2\left(\Phi + \Psi\right) = -32\pi G_N a^2\rho_{\rm r}\Theta_{\rm r,2}$$

metric

An application:

the effect of neutrino mass on the Matter Power Spectrum

e.g. Lesgourgues, Pastor review;
Bond, Efstathiou, Silk, 1980

- let's follow $\delta_{\rm dm}$ during MD (matter perturbations don't grow during RD)

$$\left.\begin{aligned} \dot{\delta}_{\rm dm} + ikv_{\rm dm} &= -3\dot{\Phi} \\ \dot{v}_{\rm dm} + \frac{\dot{a}}{a}v_{\rm dm} &= -ik\Psi \end{aligned}\right\} \text{dark matter}$$

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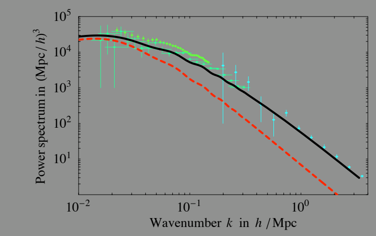

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dark matter

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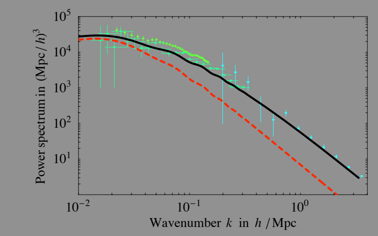

$$k^2\Phi = 4\pi G_N a^2[\rho_{\rm m}\delta_{\rm m} + 4\rho_{\rm r}\Theta_{\rm r,0} + \frac{3Ha}{K}(i\rho_{\rm m}v_{\rm m} + 4\rho_{\rm r}\Theta_{\rm r,1})]$$

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

An application:

the effect of neutrino mass on the Matter Power Spectrum

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

(Newton eq. for $\delta_{\rm dm}$) $\left(\dot{} = \frac{d}{d\eta} \right)$

An application:
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- with massless neutrinos:

FRW eq. $H^2 = \frac{8}{3}\pi G_N \rho_{\rm m}$ with $\rho_{\rm m} = (\rho_{\rm dm} + \rho_{\rm b}) \propto a^{-3}$ $\Rightarrow$ $a \propto t^{2/3}$

so $\delta''_{\rm dm} + \frac{4}{3}\frac{1}{t}\delta'_{\rm dm} - \frac{2}{3}\frac{1}{t^2}\delta_{\rm dm} = 0$ $\Rightarrow$ growing solution $\delta_{\rm dm} \propto t^{\frac{2}{3}} \propto a$

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- with massive neutrinos:

FRW eq. with $\rho_{\rm m} = (\rho_{\rm dm}+\rho_{\rm b}+\rho_\nu) = \rho_{\rm m}(1+f_\nu)$, $f_\nu = \dfrac{\Omega_\nu}{\Omega_{\rm m}}$ $\Rightarrow$ $a \propto (1+f_\nu)^{\frac{1}{3}} t^{2/3}$

$\Omega_\nu = \sum m_{\nu_i}/93\,{\rm eV}$

but $\delta_\nu = 0$ because neutrinos don't cluster (at $k \gg k_{\rm NR}$, see below)

i.e. massive neutrinos contribute to the energy density of the Universe during MD

but they don't source in the Newton equation for $\delta_{\rm dm}$!

thus $\delta''_{\rm dm} + \frac{4}{3}\frac{1}{t}\delta'_{\rm dm} - \frac{2}{3}(1-f_\nu)\frac{1}{t^2}\delta_{\rm dm} = 0 \Rightarrow \delta_{\rm dm} \propto t^{\frac{-1+\sqrt{25-24f_\nu}}{6}} \propto a^{1-\frac{3}{5}f_\nu}$

An application:

the effect of neutrino mass on the Matter Power Spectrum

- let's follow $\delta_{\rm dm}$ during MD (matter perturbations don't grow during RD)

$$\ddot\delta_{\rm dm} + \frac{\dot a}{a}\dot\delta_{\rm dm} \simeq 4\pi G_N a^2 \rho_{\rm m}\delta_{\rm m}$$ (Newton eq. for $\delta_{\rm dm}$) $\left(\dot{} = \frac{d}{d\eta}\right)$

- with massless neutrinos:

FRW eq. $H^2 = \frac{8}{3}\pi G_N \rho_{\rm m}$ with $\rho_{\rm m} = (\rho_{\rm dm} + \rho_{\rm b}) \propto a^{-3}$ $\Rightarrow$ $a \propto t^{2/3}$

so $\delta''_{\rm dm} + \frac{4}{3}\frac{1}{t}\delta'_{\rm dm} - \frac{2}{3}\frac{1}{t^2}\delta_{\rm dm} = 0$ $\Rightarrow$ growing solution $\delta_{\rm dm} \propto t^{\frac{2}{3}} \propto a$

- with massive neutrinos:

FRW eq. with $\rho_{\rm m} = (\rho_{\rm dm} + \rho_{\rm b} + \rho_\nu) = \rho_{\rm m}(1+f_\nu)$, $f_\nu = \dfrac{\Omega_\nu}{\Omega_{\rm m}}$ $\Rightarrow$ $a \propto (1+f_\nu)^{\frac{1}{3}} t^{2/3}$

$$\Omega_\nu = \sum m_{\nu_i}/93\,{\rm eV}$$

but $\delta_\nu = 0$ because neutrinos don't cluster (at $k \gg k_{\rm NR}$, see below)

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- so effective suppression of the growth is: $\dfrac{\delta_{\rm dm}^{(m_\nu\neq 0)}}{\delta_{\rm dm}^{(m_\nu=0)}} \simeq (a_{\rm NR})^{\frac{3}{5}f_\nu}$ ($a_{\rm NR}$ because at that point massless and massive coincide)

or in terms of $P(k) \propto \langle\delta_{\rm dm}\rangle^2$: $\dfrac{P^{(m_\nu\neq 0)}(k)}{P^{(m_\nu=0)}(k)} \simeq (a_{\rm NR})^{\frac{6}{5}f_\nu}$ modeled by $\boxed{\dfrac{\Delta P}{P} \simeq -8f_\nu}$

An application:
the effect of neutrino mass on the Matter Power Spectrum

- at what scales is the effect relevant?

The free streaming scale is the distance traveled by a neutrino in a Hubble time

$$\lambda_{\rm FS}(t) \simeq \frac{v(t)}{H(t)}$$ ← thermal velocity in units of c

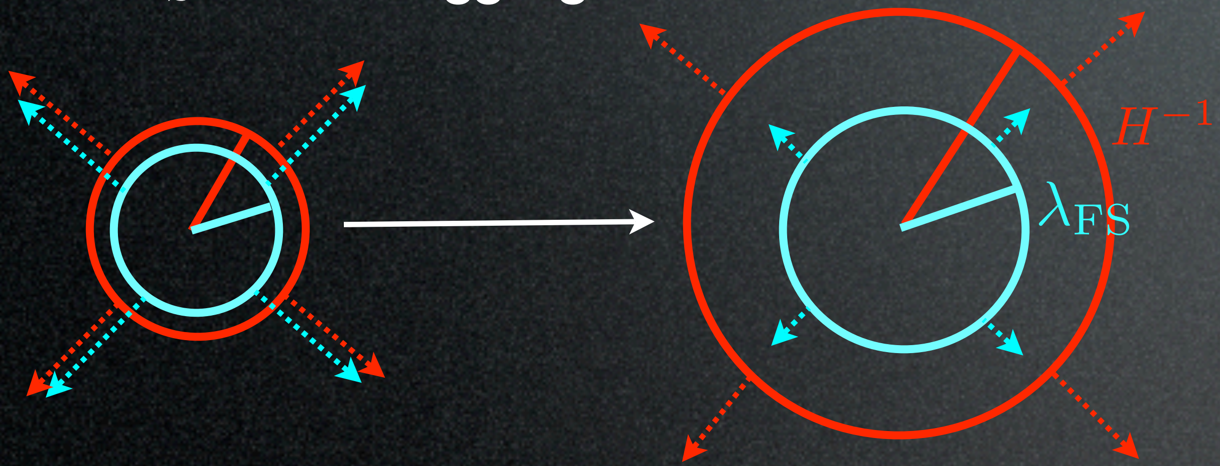
For massive neutrinos $v(t) \simeq \frac{3T_\nu}{m_\nu} \propto \frac{1}{a}\left(\frac{1\,{\rm eV}}{m_\nu}\right)\frac{\rm km}{\rm sec}$

so that $\lambda_{\rm FS} \propto \frac{a^{-1}}{\sqrt{\Omega_{\rm m} a^{-3}}}\left(\frac{1\,{\rm eV}}{m_\nu}\right)\frac{\rm km}{\rm sec} \propto a^{1/2}$

but the size of the Universe scales as $\frac{1}{H(t)} \propto a^{3/2}$

so $\lambda_{\rm FS}$ starts lagging behind H^{-1} when ν become NR, at $a_{\rm NR}^{-1} \simeq 2.1\,10^3\,\frac{m_\nu}{\rm eV}$

(ie m_ν becomes relevant)



The effect of free streaming affects comoving scales inside $\frac{\lambda_{\rm NR}}{a} = \frac{\lambda_{\rm FS}}{a_{\rm NR}}$

or in terms of $k_{\rm NR} = 2\pi\left(\frac{\lambda_{\rm NR}}{a}\right)^{-1}$ at

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

An application:

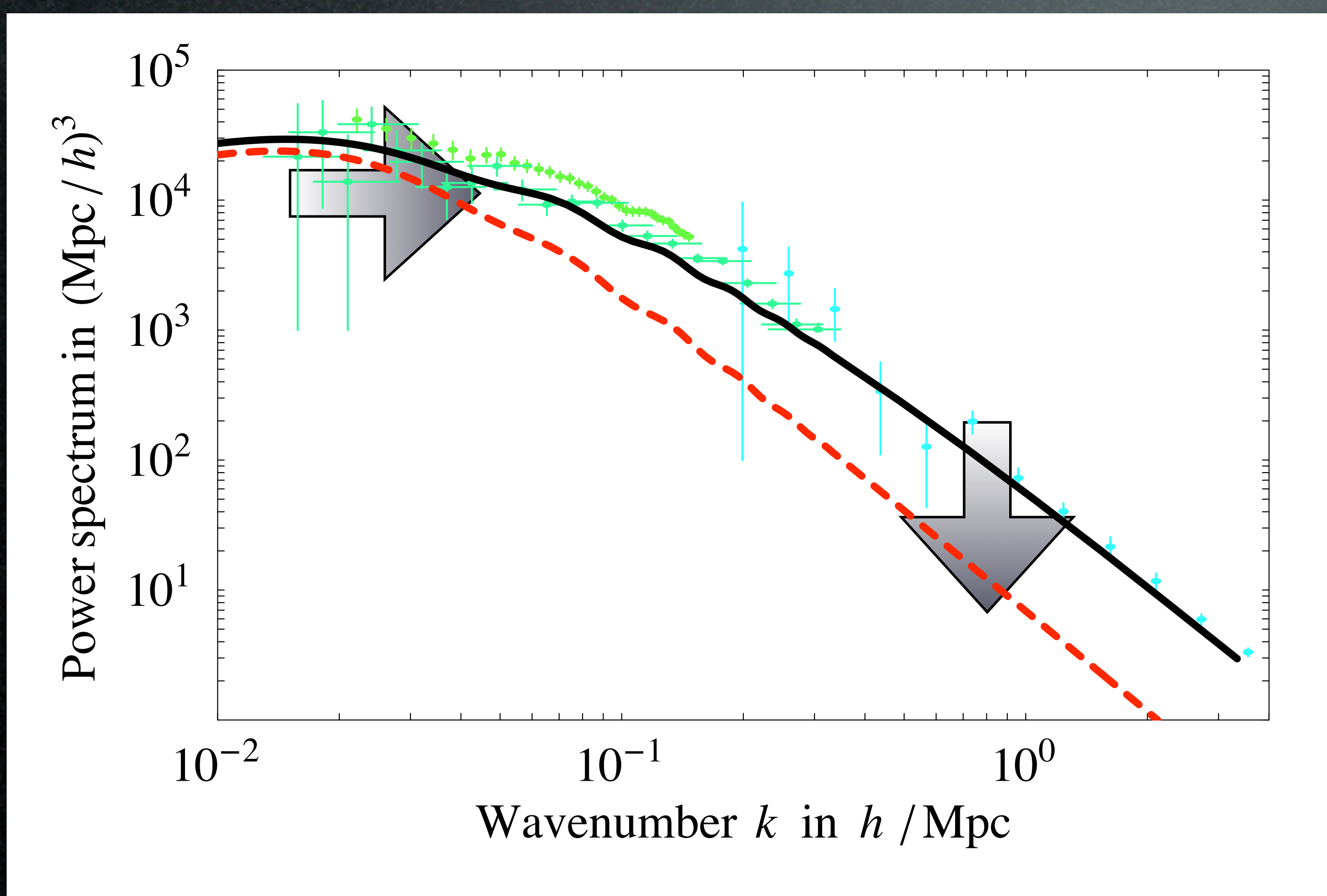
the effect of neutrino mass on the Matter Power Spectrum

In summary

Caveat: plots for illustrative purposes only, all parameters except m_ν are held fixed.

$m_\nu = 0$ (solid black line)

$m_\nu = 2\,\mathrm{eV}$ (dashed red line)



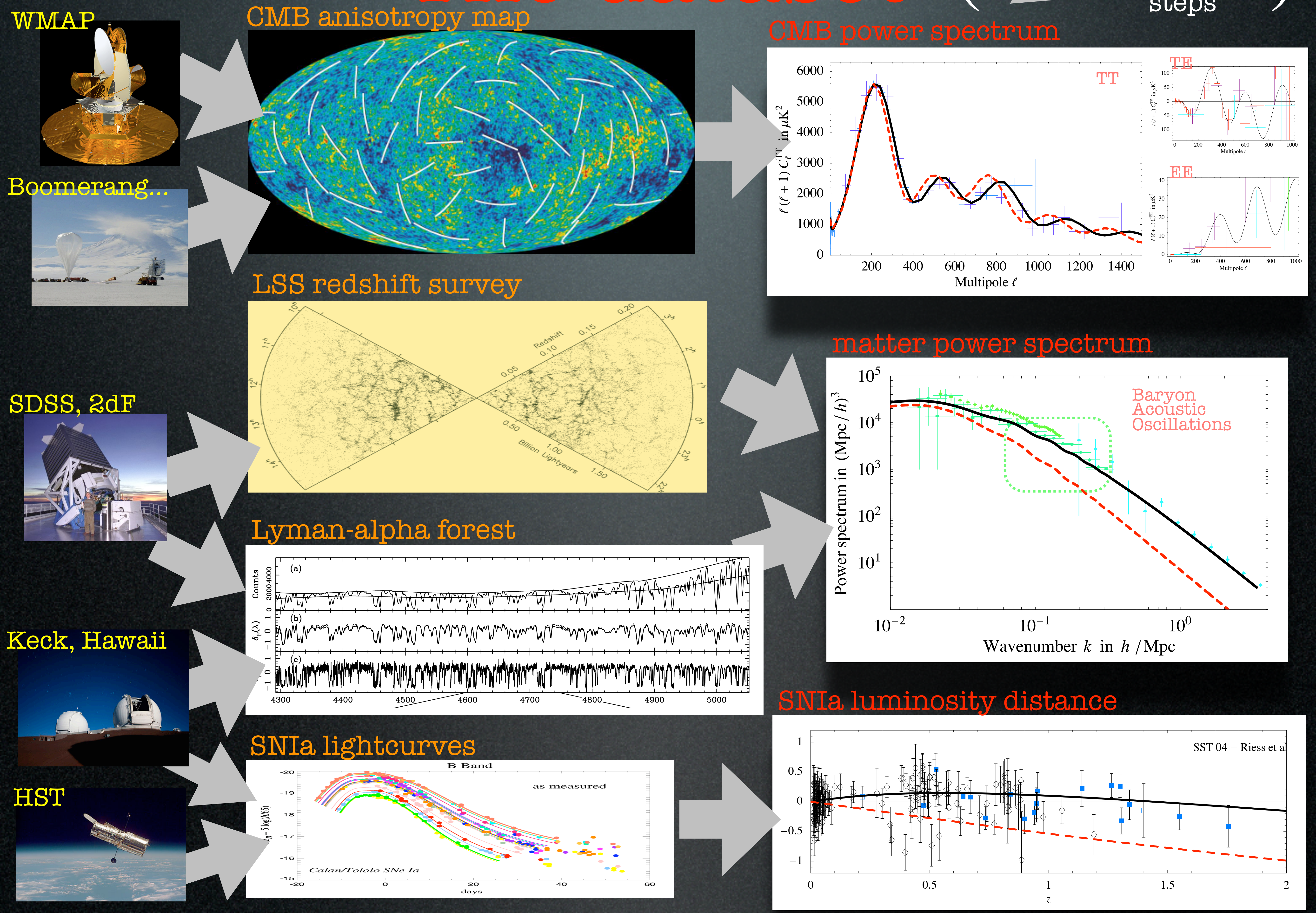
$$k_{\mathrm{NR}} = 0.018\,\Omega_{\mathrm{m}}^{-1/2}\left(\frac{m_\nu}{\mathrm{eV}}\right)^{1/2} h_0\,\mathrm{Mpc}^{-1}$$

$$\frac{\Delta P}{P} \simeq -8 f_\nu \qquad \left(f_\nu = \frac{\sum m_{\nu_i}/93\,\mathrm{eV}}{\Omega_{\mathrm{m}}}\right)$$

We have the formalism to compute
the effect on cosmological observables.

Let's compare quantitatively
with cosmological data.

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
matter power spectrum
SNIa luminosity distance
TT
TE
EE
Multipole ℓ
Baryon Acoustic Oscillations
Power spectrum in (Mpc / h)^3
Wavenumber k in h / Mpc
SST 04 – Riess et al
B Band
as measured
Calan/Tololo SNe Ia
days
Redshift
Billion Lightyears

The dataset

CMB Temperature and Polarization:

- **WMAP 3-years** (TT, TE, EE spectra) WMAP Science Team, astro-ph/0603449 →
- Boomerang 2003 (TT, TE, EE) Boomerang Coll., astro-ph/0507494, astro-ph/0507507, astro-ph/0507514
- ACBAR (TT) Kuo et al., astro-ph/0212289 →
- CAPMAP (EE) Barkats et al., astro-ph/0409380
- CBI (TT, EE) Readhead et al., astro-ph/0402359, astro-ph/0409569, Sievers at al., astro-ph/0509203 →
- DASI (TE, EE) Leitch et al., astro-ph/0409357
- VSA (TT) Grainge et al., astro-ph/0212495

LSS galaxy redshift surveys:

dealing with bias and non-linearities as

$$P_{\rm gal}(k) = b^2 \frac{1+Q\ k^2}{1+A\ k} P(k)$$

- SDSS SDSS Coll., astro-ph/0310725 →
- 2dF 2dF Coll., astro-ph/0501174

Baryon Acoustic Oscillations:

Eisenstein et al., astro-ph/0501171

in terms of a measurement of

$$A = \left(\frac{D_{\rm A}^2 cz}{H(z)}\right)^{1/3} \frac{\sqrt{\Omega_{\rm matter} H_0^2}}{0.35\ c}$$

Lyman-α Forest:

- Croft Croft et al., astro-ph/0012324
- SDSS SDSS Coll., astro-ph/0407377

Type Ia Supernovae:

- SST Gold sample Riess et al., astro-ph/0402512 →
- SNLS Astier et al., astro-ph/0510447 →

Hubble constant:

HST Project, Freedman et al., astro-ph/0012376

$$h = 0.72 \pm 0.08 \qquad H_0 = 100h\ {\rm km/sec/Mpc}$$

The computational tool

We use **our own code** in MATHEMATICA 5.2 to — *as opposed to:*

- evolve cosmological perturbations, — CMBfast/CAMB
- compute spectra and — CMBfast/CAMB
- run statistical comparisons with data. — CosmoMC

Line-of-sight approach, Newtonian gauge.

Recombination is implemented calling *recfast*.

SZ background is marginalized over.

We adopt **gaussian** statistics. — MCMC

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Line-of-sight approach, Newtonian gauge.
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We adopt **gaussian** statistics. — MCMC

− slower, not fully optimized,
intrinsic gaussian “systematics”

\+ customizable, analytic computations,
analytic dependance on cosmo parameters

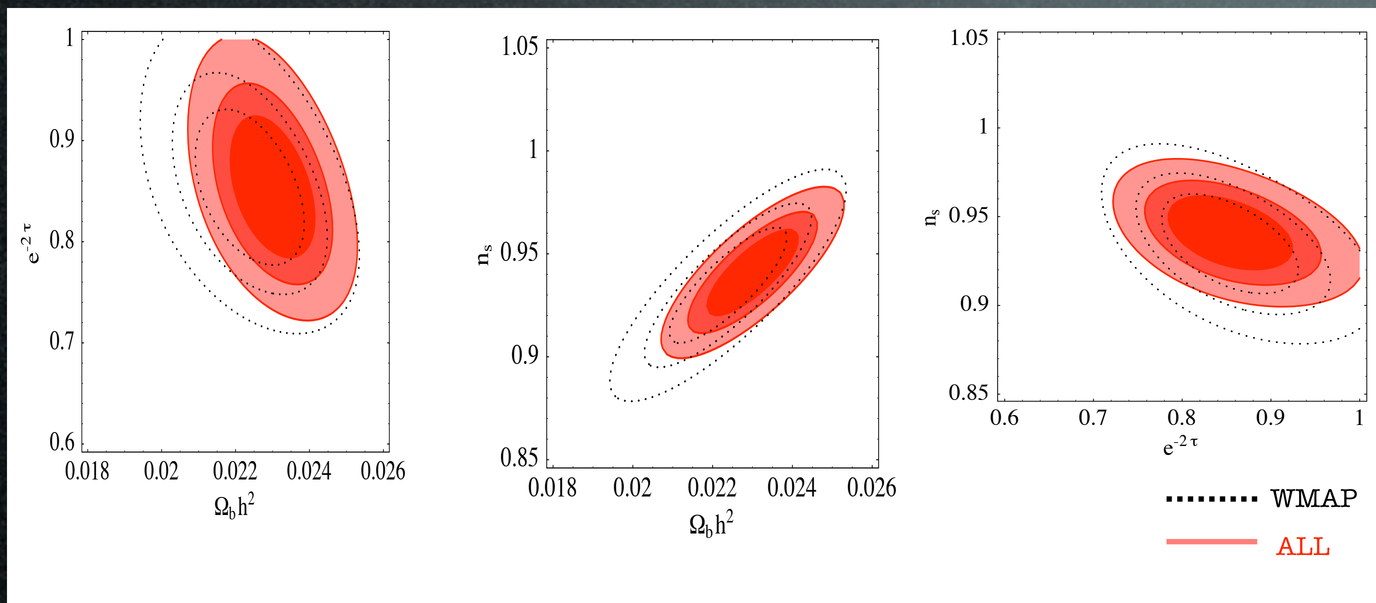
Comparing our code

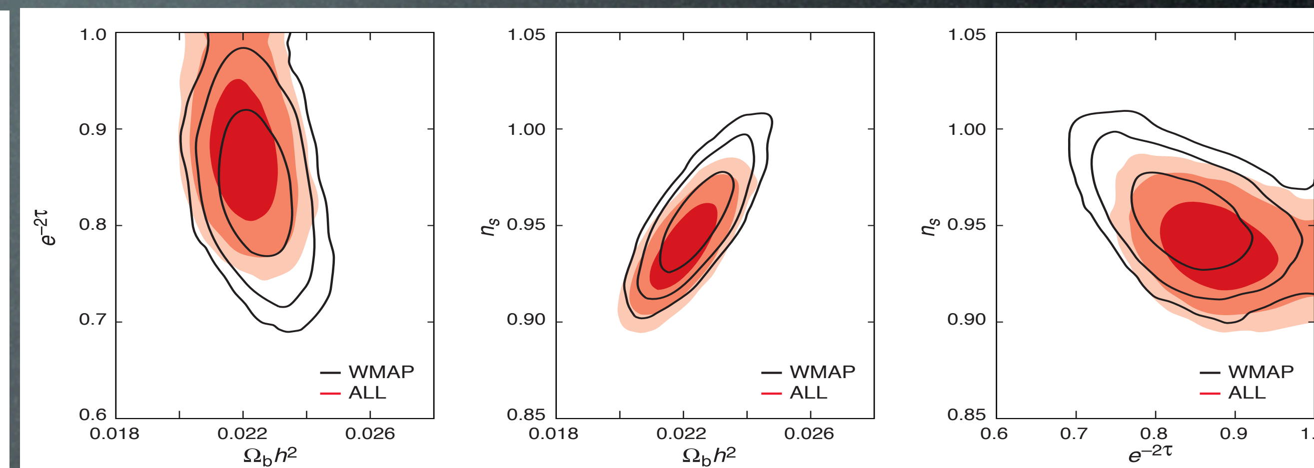
[back]

Our analysis:

MATHEMATICA 5.2

WMAP Science Team analysis:

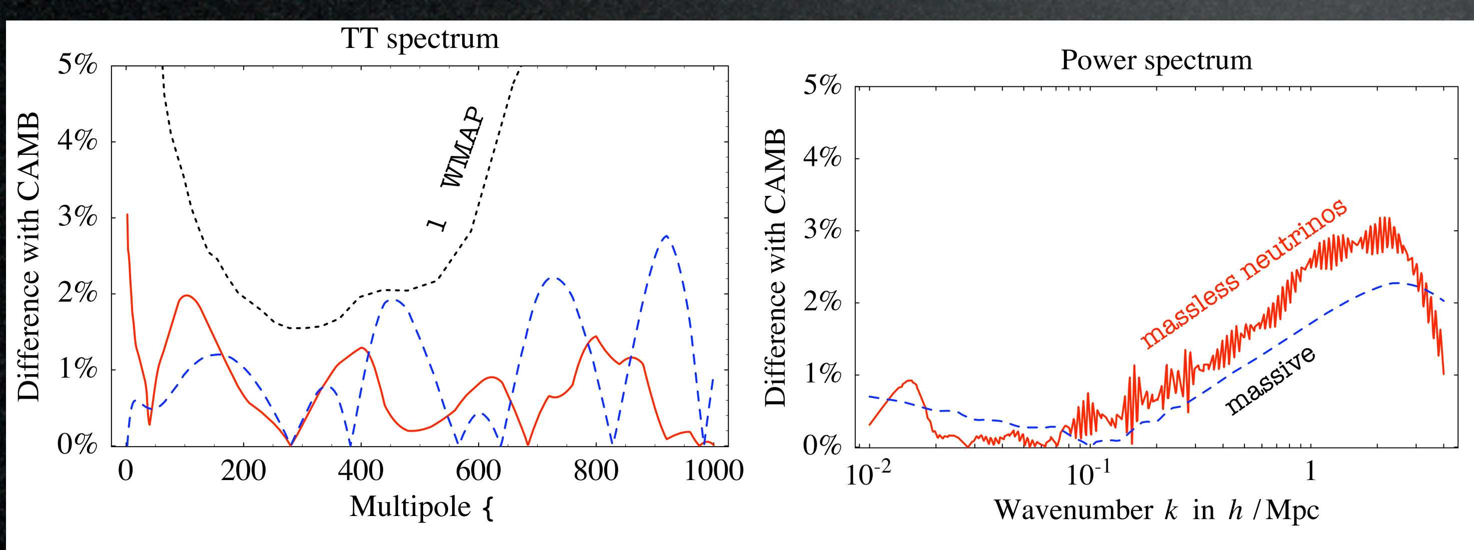




[Spergel et al. WMAP 3yr results '05]

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

Results

(3 massive neutrinos)

How heavy are neutrinos?

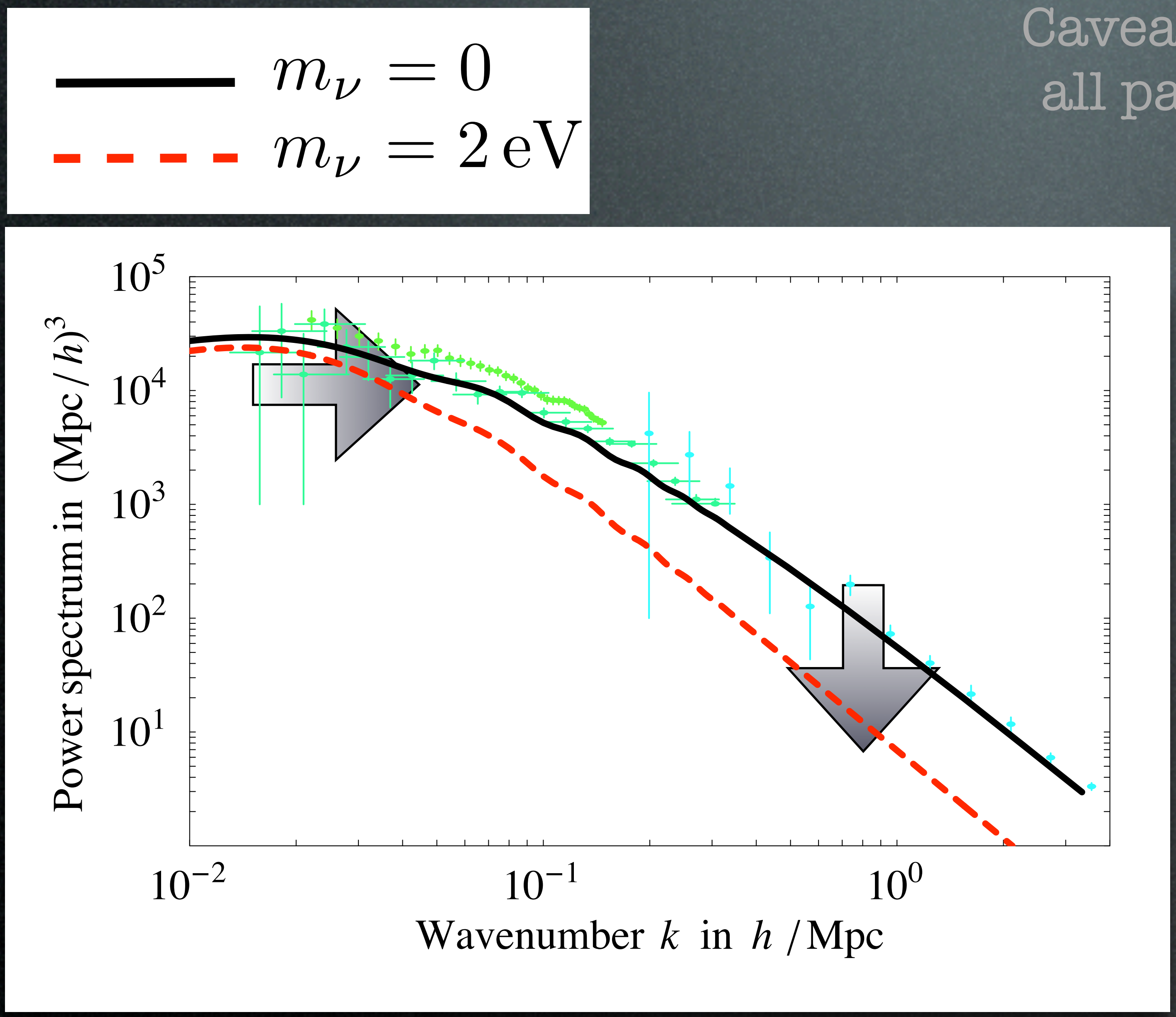
Results

How heavy are neutrinos?

(3 massive neutrinos)

Cosmology probes $\sum m_{\nu_i}$.

Caveat: plots for illustrative purposes only, all parameters except m_ν are held fixed.



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

$$\frac{\Delta P}{P} \simeq -8 f_\nu \qquad \left(f_\nu = \frac{\sum m_{\nu_i}/93\,\text{eV}}{\Omega_{\text{m}}}\right)$$

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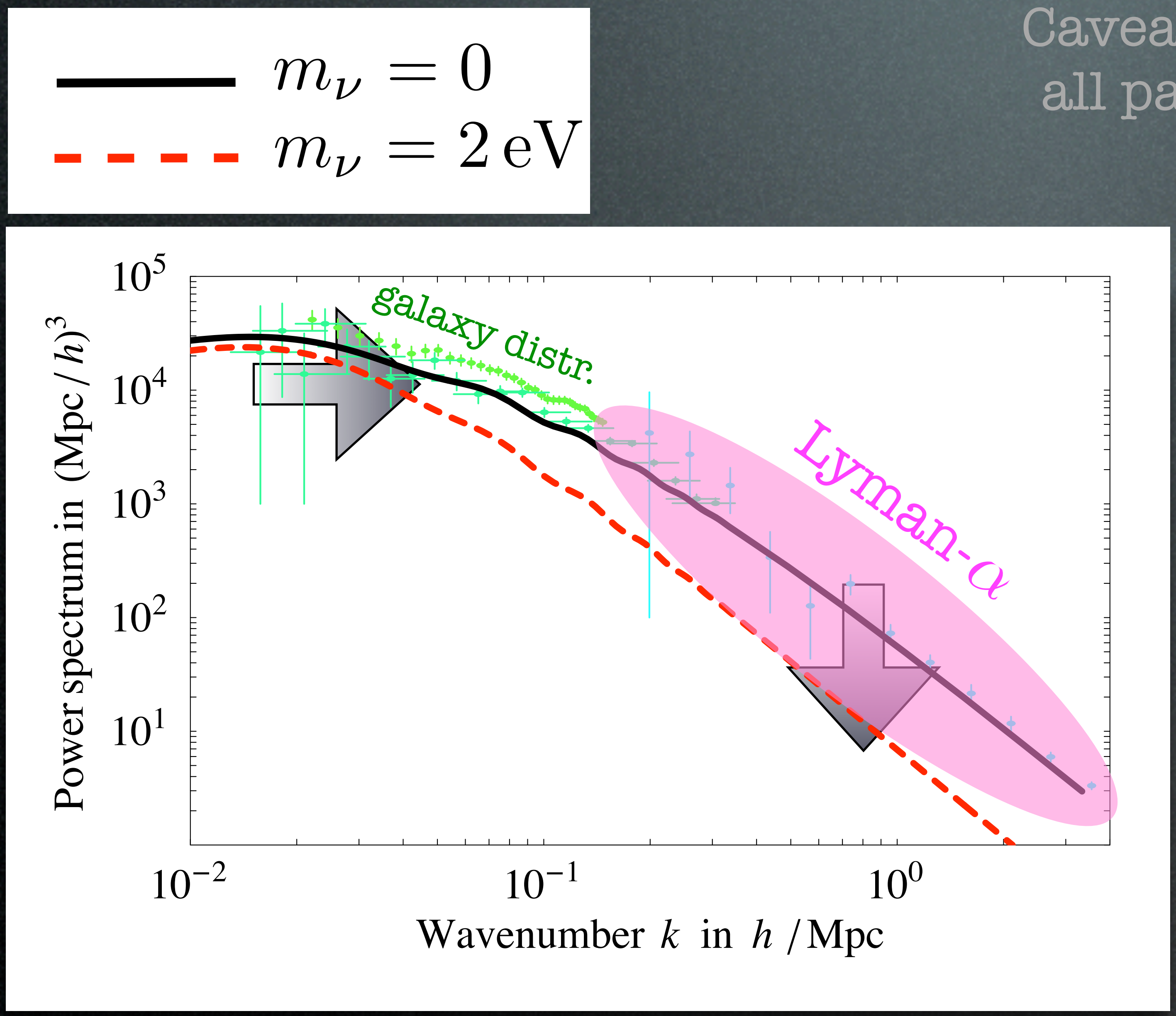

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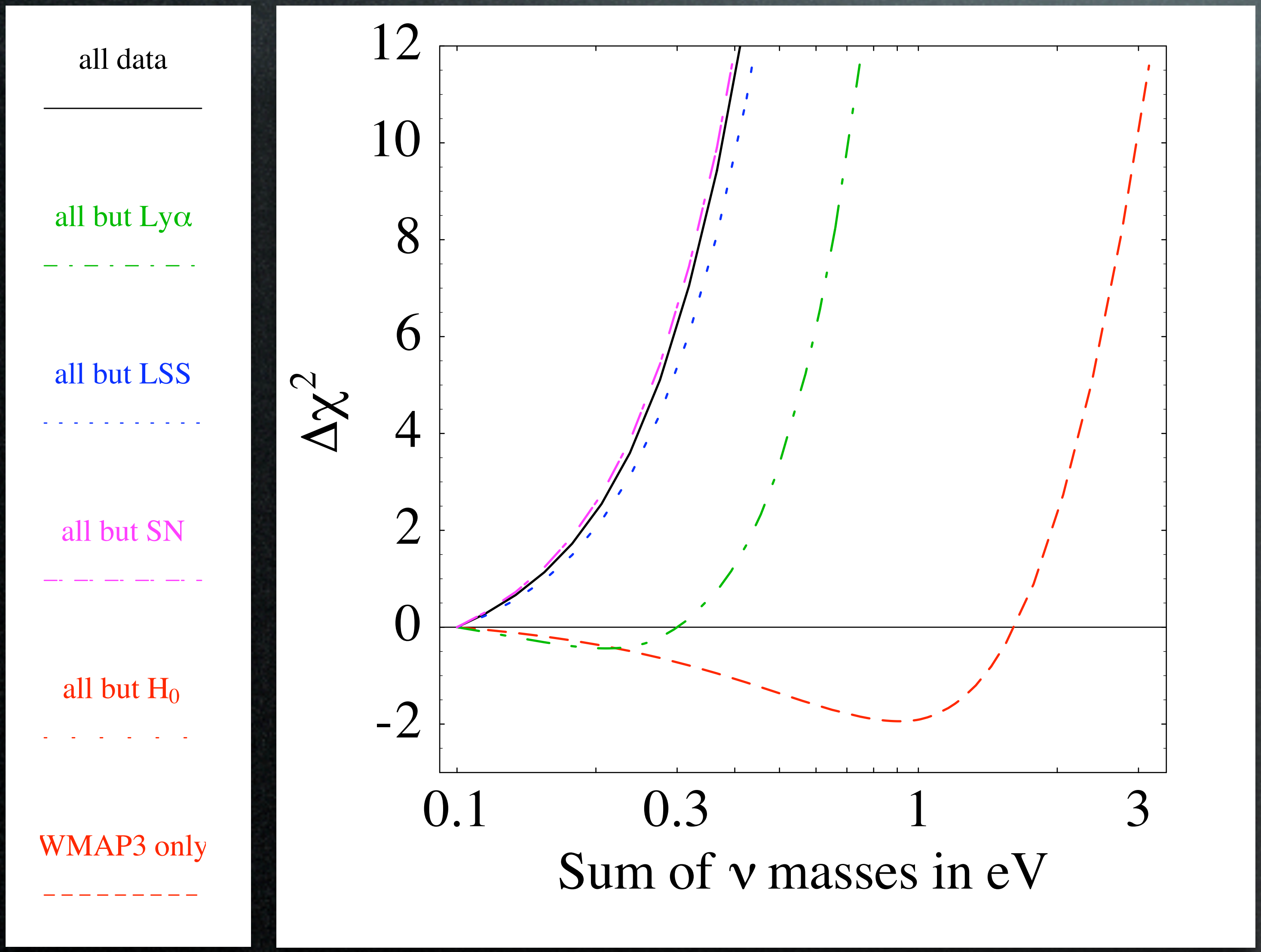


CMB only:

$$\sum m_{\nu_i} < 2.2 \text{ eV}$$ (95% C.L.)

Global fit:

$$\sum m_{\nu_i} < 0.40 \text{ eV}$$ (99.9% C.L.)

dropping Ly-alpha:

$$\sum m_{\nu_i} < 0.73 \text{ eV}$$ (99.9% C.L.)

Bottom Line: Cosmology gives dominant bound on $\sum m_{\nu_i}$;
the bound tightens combining relatively less safe datasets.

Results

New neutrinos?

$3_{.04}$ ΔN_ν

Results

New neutrinos?

$3_{.04}$ ΔN_ν

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

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

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

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

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

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

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

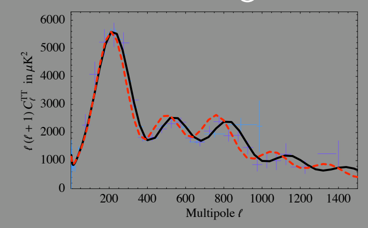
$$k^2\Phi + 3\,\frac{\dot a}{a}\left(\dot\Phi - \Psi\frac{\dot a}{a}\right) = 4\pi G_N a^2\left[\rho_{\rm m}\delta_{\rm m} + 4\rho_{\rm r}\delta_{\rm r}\right]$$

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

metric

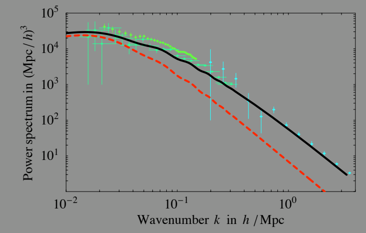
CMB Power spectrum

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



Matter Power spect.

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



Results

New neutrinos?

$3_{.04}$ ΔN_ν

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

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baryons

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neutrinos

all N_ν rel degrees of freedom contribute to the energy density

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

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

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

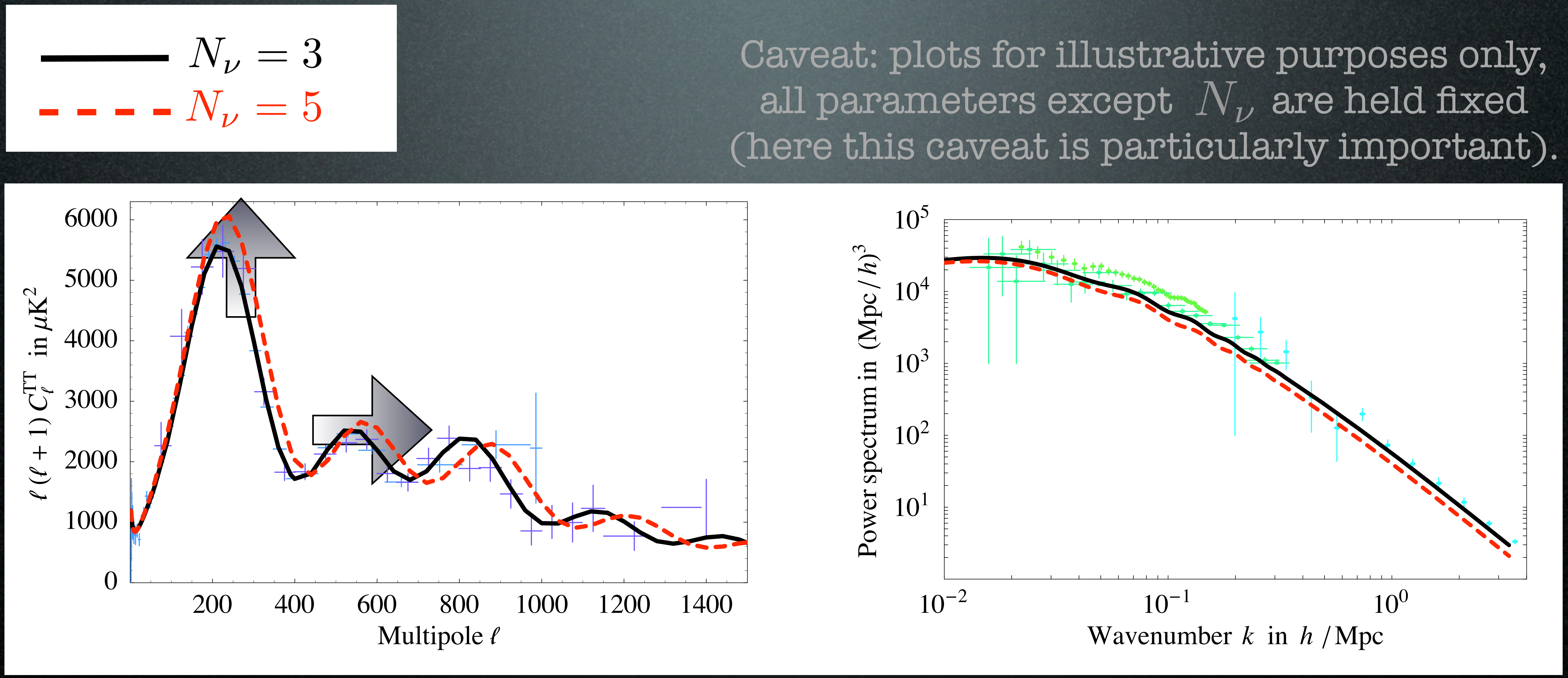
$$k^2(\Phi + \Psi) = -32\pi G_N a^2\rho_{\rm r}\Theta_{\rm r,2}$$

metric

Results

New neutrinos?

Caveat: plots for illustrative purposes only, all parameters except N_ν are held fixed (here this caveat is particularly important).

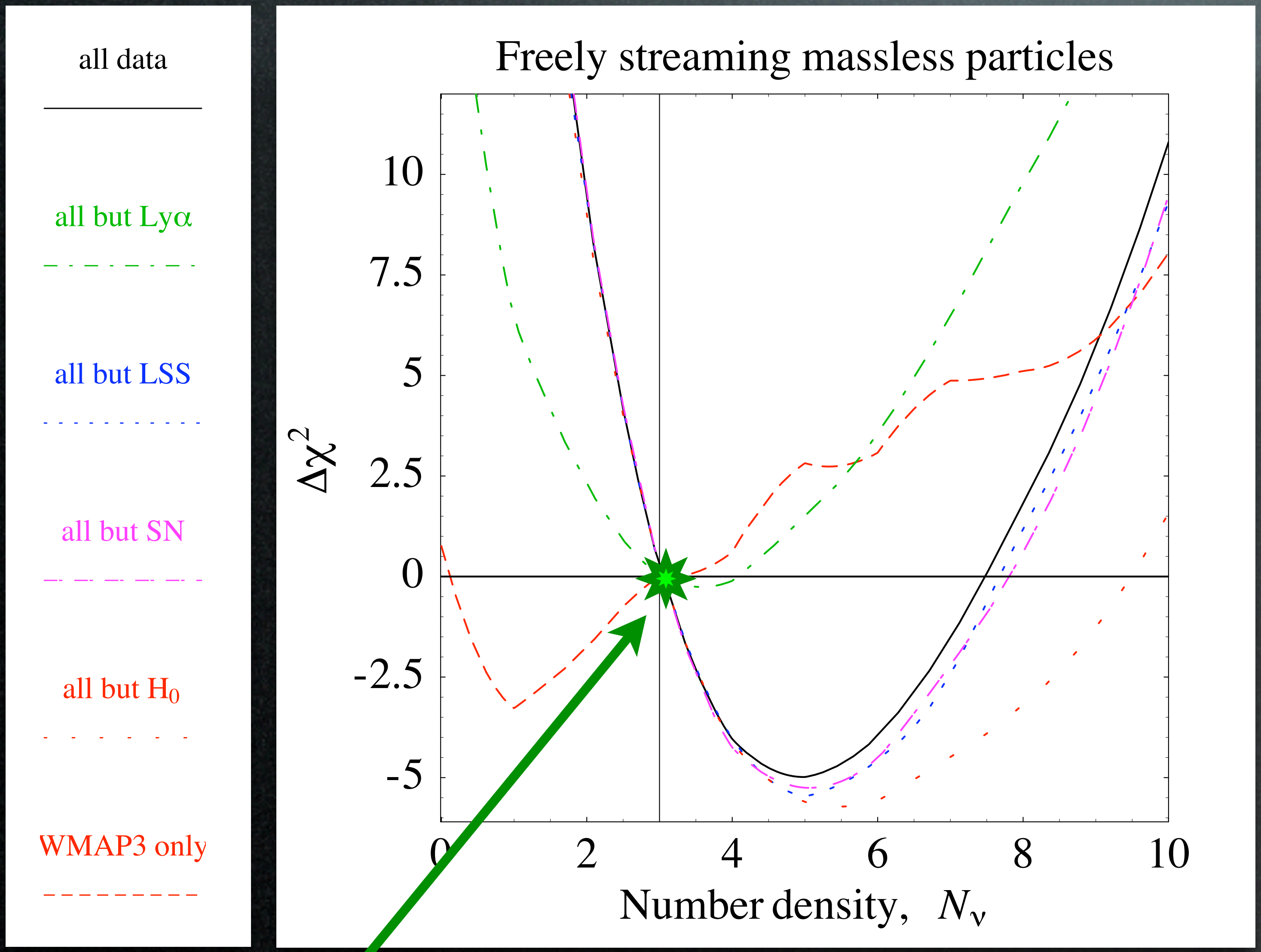


Results

New neutrinos?

$3_{.04}$ ΔN_ν

All N_ν relativistic degrees of freedom contribute to the energy density.



Standard cosmology

Global fit:

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

Cirelli, Strumia 2006
Seljak et al. 2006
Mangano et al. 2006
...

dropping Ly-alpha gives back

$$N_\nu \simeq 3$$

Cirelli, Strumia 2006

Bottom Line: Cosmology seems to suggest **5 neutrinos** (2 extra); but Ly-alpha are mainly driving the suggestion.

Results

New neutrinos?

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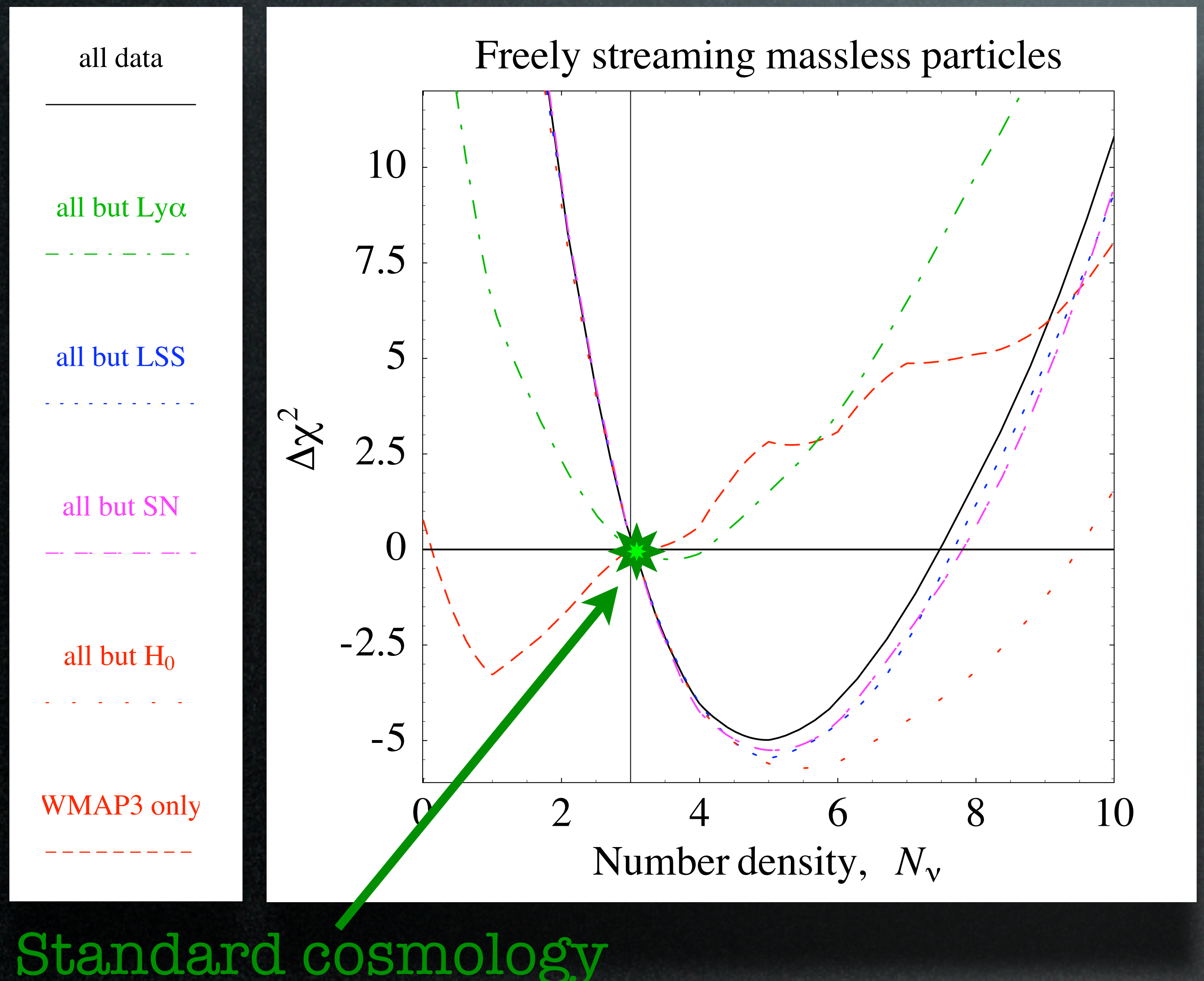

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?

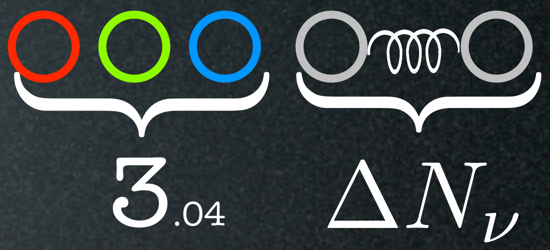
just systematics?
see Hamann, Hannestad, Raffelt, Wong 2007

tension with BBN?
see Ichikawa et al. 2007

Bottom Line: Cosmology seems to suggest **5 neutrinos** (2 extra); but Ly-alpha are mainly driving the suggestion.

Results

New sticky particles?



Results

New sticky particles?

$3_{.04}$ ΔN_ν

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

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

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

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baryons

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neutrinos

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

extra

$$k^2\Phi + 3\,\frac{\dot a}{a}\left(\dot\Phi - \Psi\frac{\dot a}{a}\right) = 4\pi G_N a^2\left[\rho_{\rm m}\delta_{\rm m} + 4\rho_{\rm r}\delta_{\rm r}\right]$$
$$k^2\left(\Phi + \Psi\right) = -32\pi G_N a^2\rho_{\rm r}\Theta_{{\rm r},2}$$

metric

Massless particles, interacting among themselves (i.e.non freely streaming) at the time of CMB formation.

e.g. a scalar φ with $\lambda\varphi^4$

e.g. scalar + fermion with $\lambda'\varphi\nu_{\rm s}^2$

e.g. fermions with $\langle\bar N N\rangle$ ...

⇩

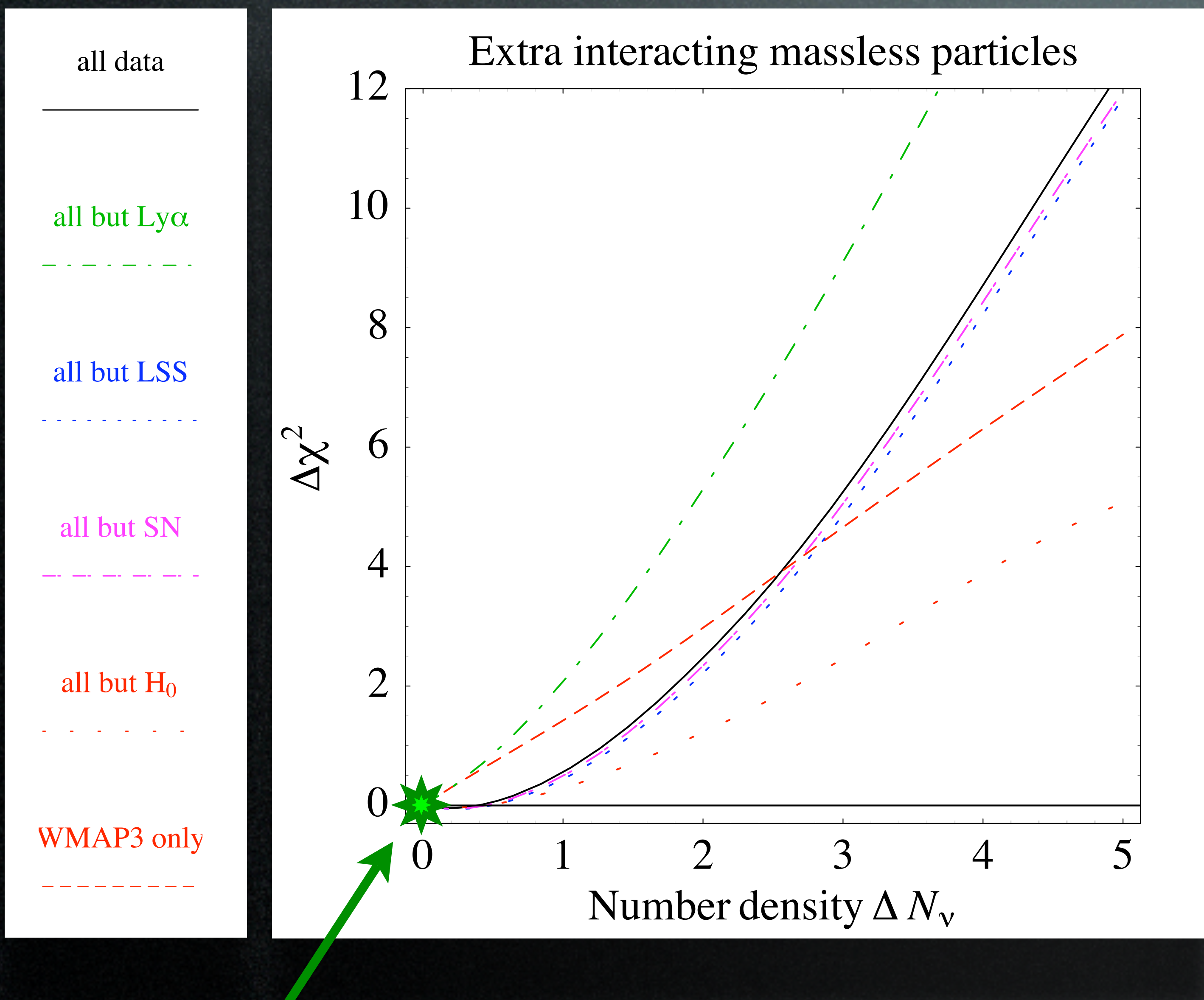
A relativistic fluid: $\delta_{\rm x}, v_{\rm x}$.

Contributes $\Delta N_\nu \cdot \delta_{\rm x}$ to the rel energy density.

Results

New sticky particles?

ΔN_ν extra massless particles interacting among themselves.



Standard cosmology

Global fit:

$$\Delta N_\nu = 0 \pm 1.3$$

Bottom Line: Cosmology **constrains** extra massless sticky particles.

[skip massive nu]

Results

New massive neutrinos?

$\Delta N_\nu, m_s$

Results

New massive neutrinos?

$\Delta N_\nu, m_s$

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

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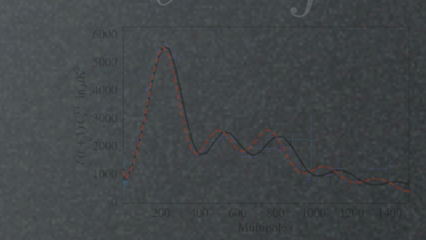
baryons

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

3 standard neutrinos
+
ΔN_ν neutrinos with mass m_s.

Contribute to the Rel/NR energy densities.

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

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

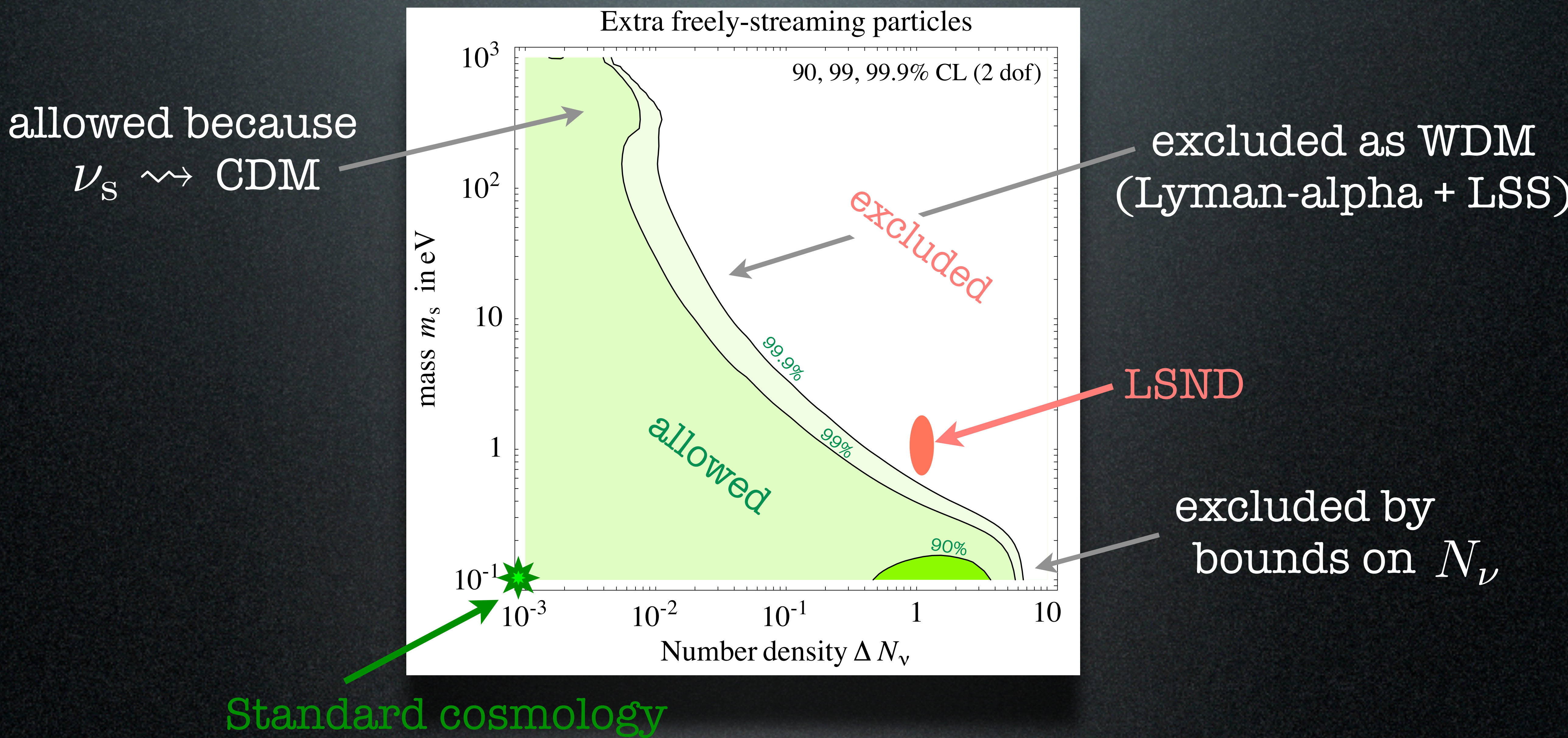
metric

Results

New massive neutrinos?

$\Delta N_\nu, m_s$

3 standard neutrinos + ΔN_ν neutrinos with mass m_s .



Results

$\Delta N_\nu, m_{\rm s}$

New massive, sticky particles?

Results

New massive, sticky particles?

$\Delta N_\nu, m_s$

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

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

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

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

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

neutrinos

$$\dot\delta_x = -(1+w)(3\dot\Phi + ikv_x)$$
$$\dot v_x = -ik\Psi + \frac{\dot a}{a}(1-3w)\,iv_x - \frac{w}{1+w}ik\delta_x$$

extra

$$k^2\Phi + 3\frac{\dot a}{a}\left(\dot\Phi - \Psi\frac{\dot a}{a}\right) = 4\pi G_N a^2\left[\rho_m\delta_m + 4\rho_r\delta_r\right]$$
$$k^2(\Phi + \Psi) = -32\pi G_N a^2\rho_r\Theta_{r,2}$$

metric

CMB Power spectrum

Massive particles, interacting among themselves (i.e.non freely streaming).

A fluid defined by δ_x, v_x,
with $w = 1/3$ when rel,
$w = 0$ when NR.

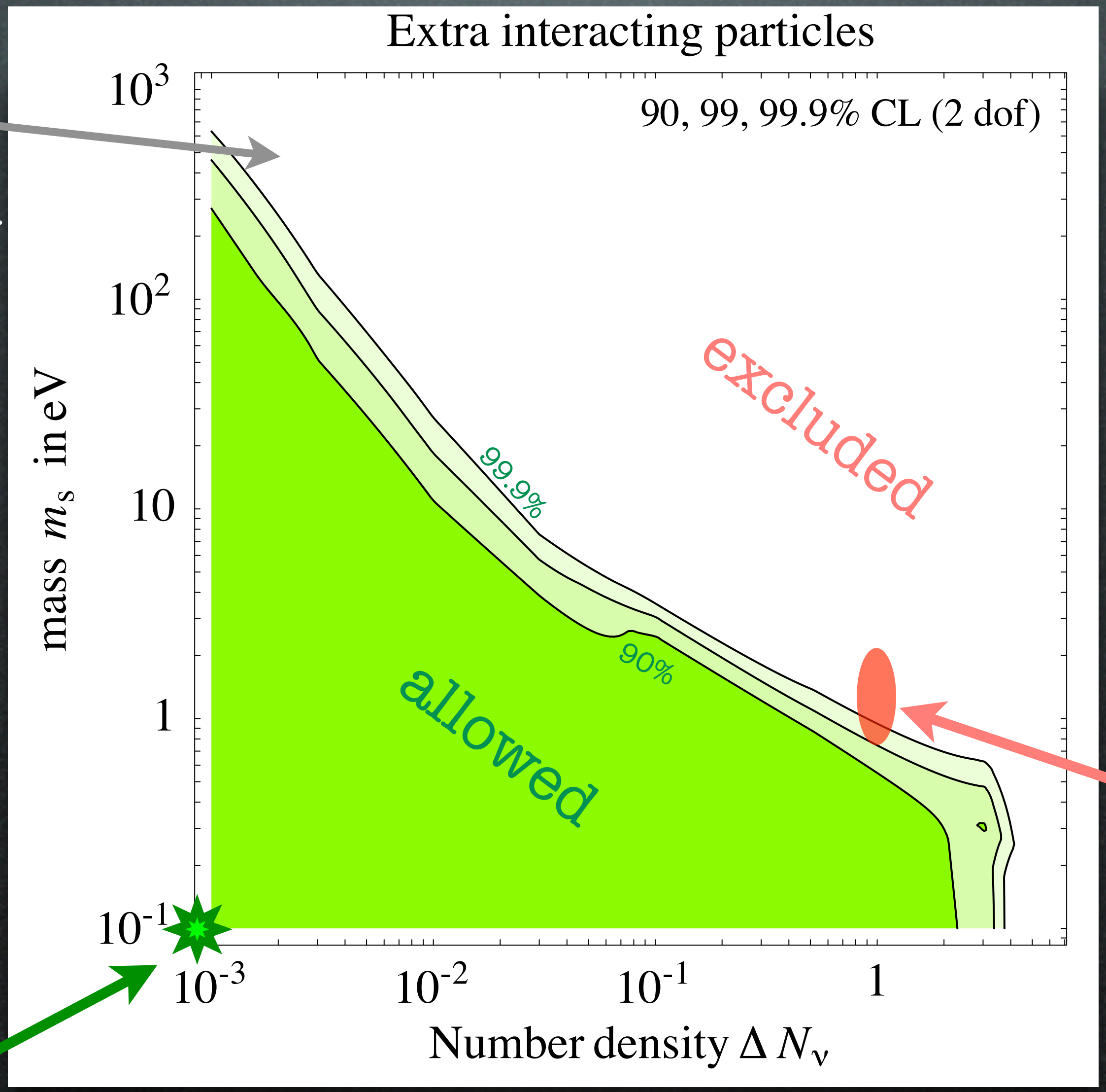
Contribute to the Rel/NR energy densities.

Results

New massive, sticky particles?

3 standard neutrinos + ΔN_ν with mass m_s, interacting among themselves

ν_s as interacting CDM are more constrained



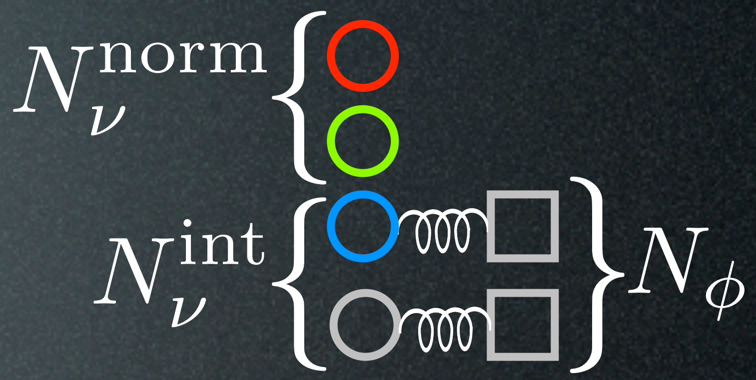
LSND

Standard cosmology

Bottom Line: Cosmology **constrains** extra sterile neutrinos (freely-streaming or interacting): they better be few and light.

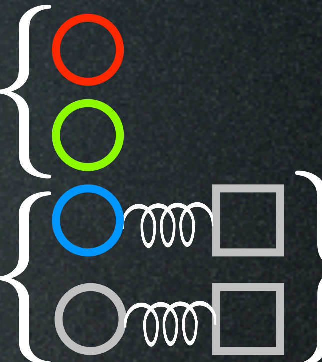
Results

Can some neutrinos be sticky?



Results

Can some neutrinos be sticky?



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

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

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

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

$$\dot\delta_{\rm b} + ikv_{\rm b} = -3\dot\Phi \qquad R = 3\rho_{\rm b}^0/4\rho_\gamma^0$$
$$\dot v_{\rm b} + \frac{\dot a}{a} v_{\rm b} = -ik\Psi + \frac{\dot\tau}{R}\left[v_{\rm b} + 3i\Theta_1\right]$$

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

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

extra

$$k^2\Phi + 3\,\frac{\dot a}{a}\left(\dot\Phi - \Psi\frac{\dot a}{a}\right) = 4\pi G_N a^2\left[\rho_{\rm m}\delta_{\rm m} + 4\rho_{\rm r}\delta_{\rm r}\right]$$
$$k^2\left(\Phi + \Psi\right) = -32\pi G_N a^2 \rho_{\rm r}\Theta_{{\rm r},2}$$

metric

Neutrinos interacting with extra particles such that free-streaming is prevented.

e.g. effective couplings $g\,\nu\nu\varphi$

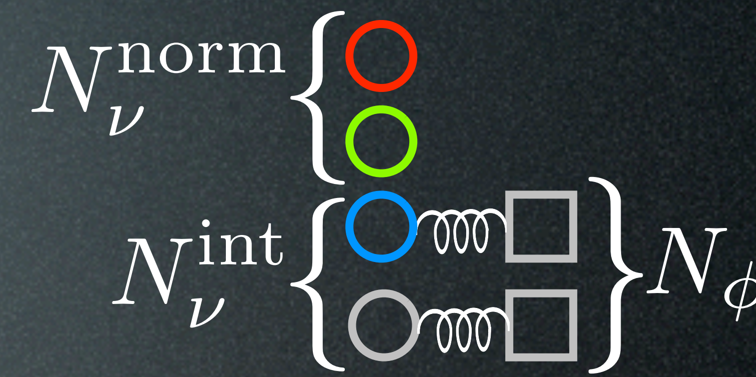
$g'\,\nu\nu_{\rm s}\varphi$

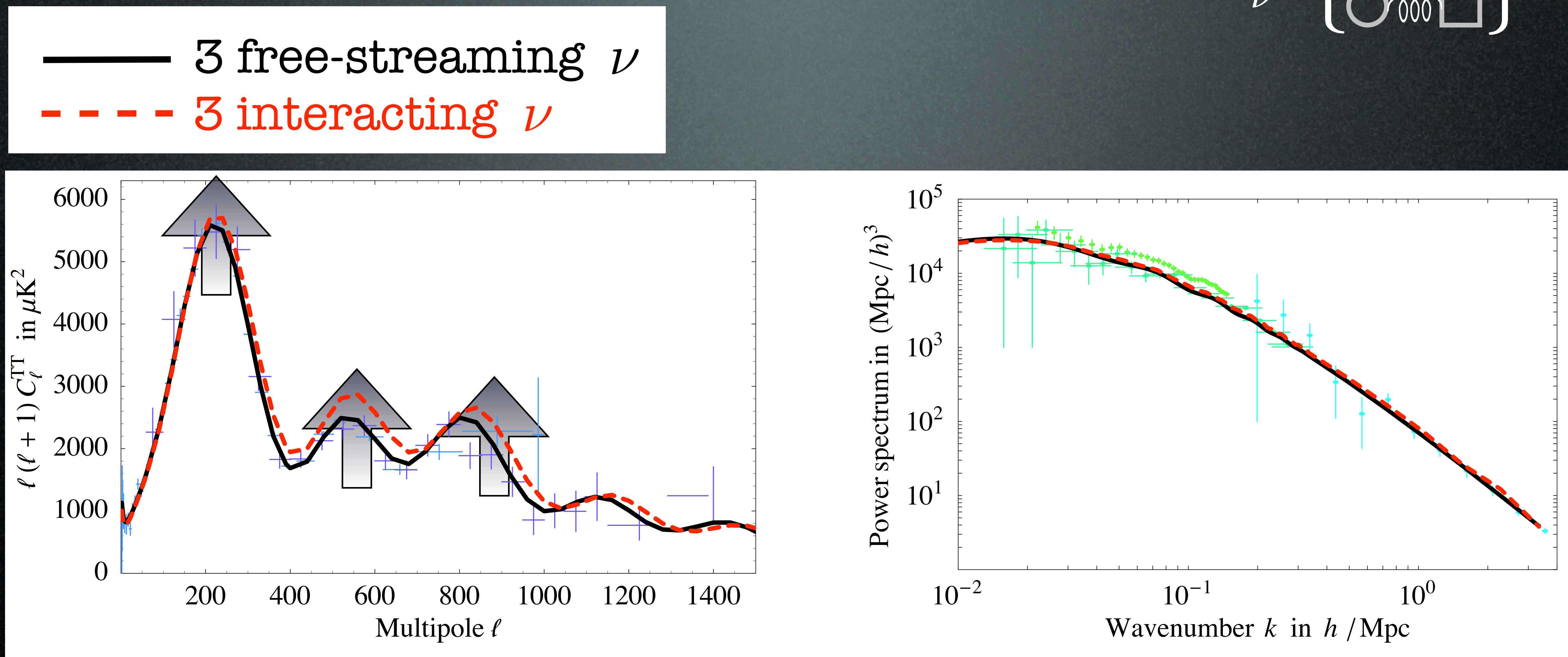
$N_\nu^{\rm norm}$ freely-streaming neutrinos

$N_\nu^{\rm int} + \frac{4}{7}N_\phi$ interacting particles contribute to Rel energy density.

Results

Can some neutrinos be sticky?





Sticky neutrinos don't stream out of gravitational wells: contribute power to CMB.
For massless neutrinos the effect on P(k) is minor.

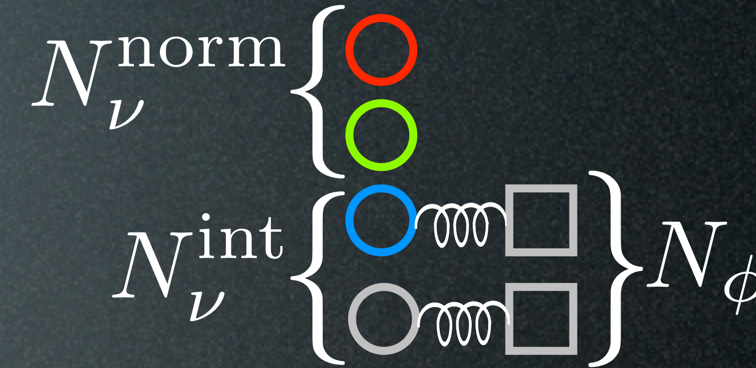
Quantitatively: (Friedland et al. 2007)

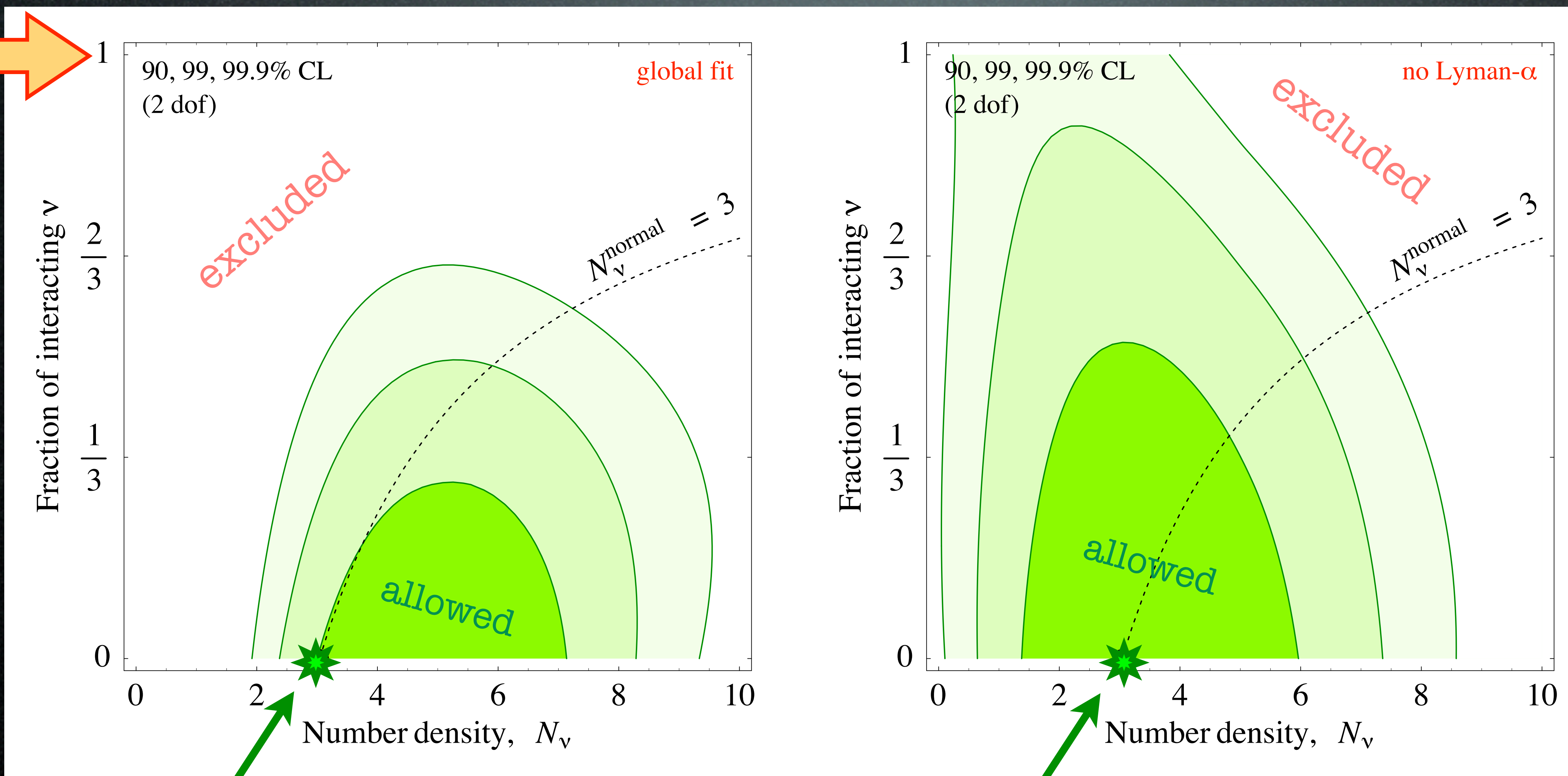
$$\left\{\frac{\Delta C_\ell}{C_\ell}, \Delta\ell\right\} \approx -\{0.53, 57\}\,\frac{\rho_{\rm free}}{\rho_{\rm free}+\rho_{\rm sticky}+\rho_\gamma}$$

[Hannestad, JCAP 2005]
[Bell, Pierpaoli, Sigurdson, PRD73 (2006)]

Results

Can some neutrinos be sticky?





Standard cosmology

Standard cosmology

[see also Bell, Pierpaoli, Sigurdson, PRD73 (2006)]

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

3 sticky ν excluded (at 5σ)

PLANCK will greatly improve
(will test 1 sticky at 4)

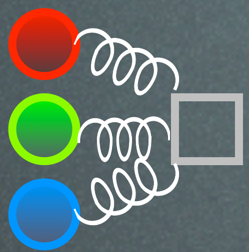
[Friedland, Zurek, Bashinsky(2007)]

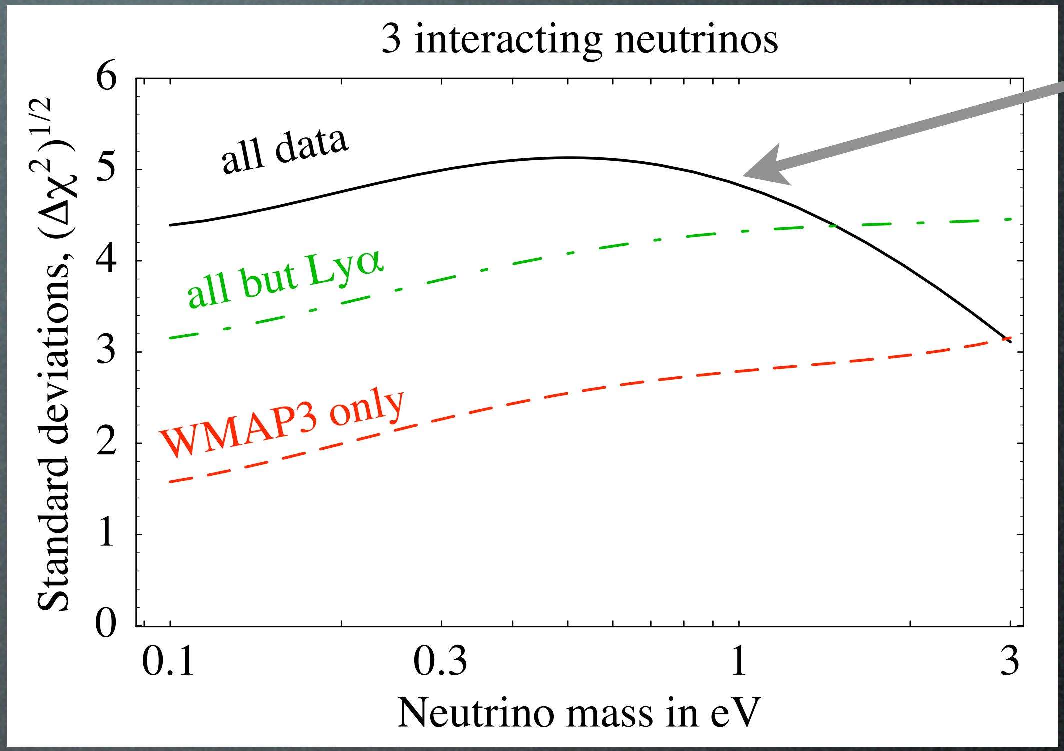
Results

[plots]

Can all neutrinos be sticky?

Massive neutrinos and massless boson:





disfavored at 3 to 5 σ

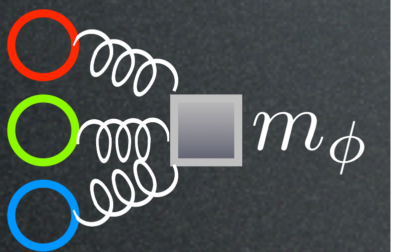
[see also Hannestad, JCAP 2004]

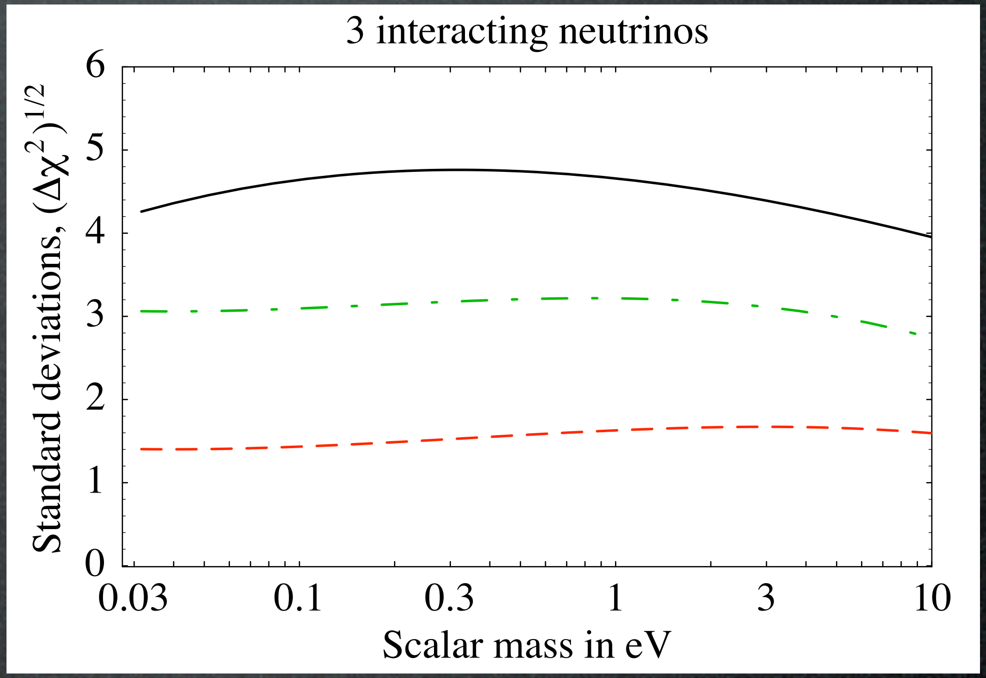
e.g. Neutrinoless Universe [Beacom et al. PRL '04]

e.g. Mass Varying Neutrinos, [Fardon et al. JCAP '04]

Late Neutrino mass models [Chacko et al. PRD '04]

Massless neutrinos and massive boson:





Bottom Line: Cosmology **strongly disfavors** fully interacting (non-freely streaming) neutrinos.

Conclusions & Messages

- Cosmology is a sensitive probe of neutrinos and possible new light particles; let's put at work the formalism (and a new code) for cosmological perturbation to extract the most from the full cosmo dataset.

- Cosmology gives **dominant bound on** $\sum m_{\nu_i}$; $\sum m_{\nu_i} < 0.40$ eV (global fit, 99.9% C.L.)
  the bound tightens combining relatively less safe datasets.

- Cosmology seems to suggest **5 neutrinos** (2 extra);
  but Ly-alpha are mainly driving the suggestion.

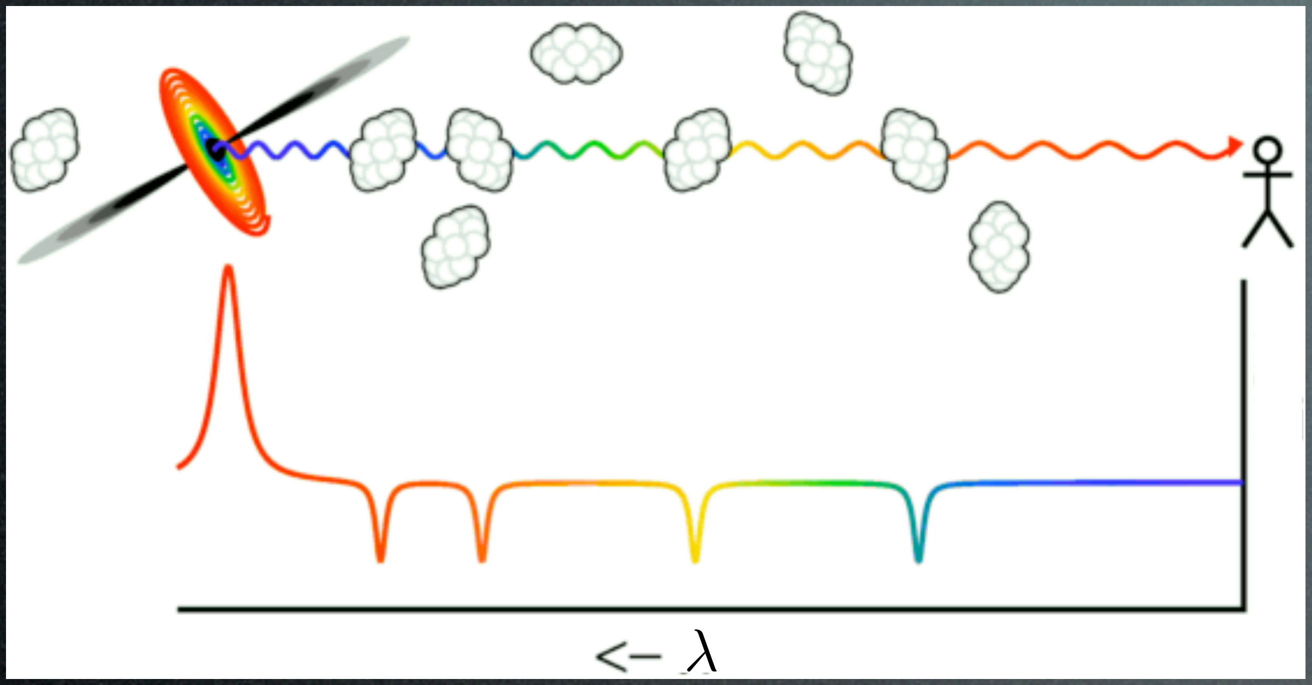
  The massive extra neutrino of **LSND** was already **strongly disfavored**.

- Cosmology disfavors at various degrees neutrino interactions and other light particles: neutrinos **ought to free-stream**.

- Future observations will be powerful probes.

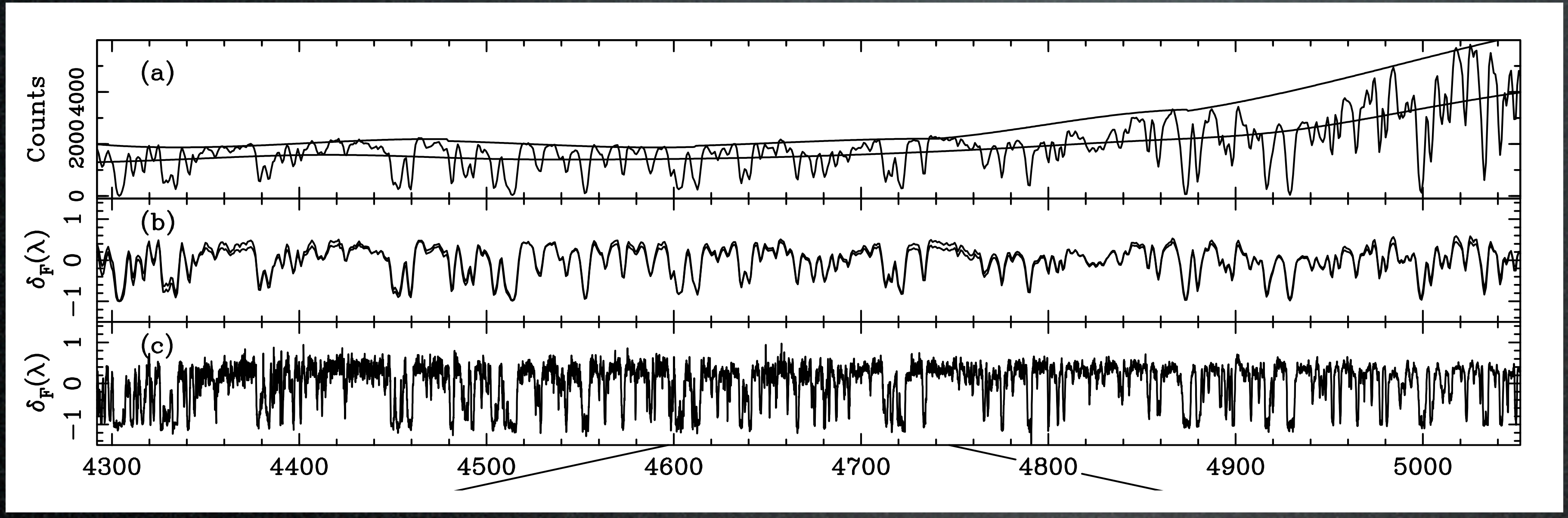
Extra slides

Lyman-alpha forest



E.Wright, UCLA

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



Skepticism on Lyman-α :
- very complicated measurement and analysis (from flux to matter spectra), different groups disagree (even on same data)
- non linearities
- HMD simulations don't include neutrinos

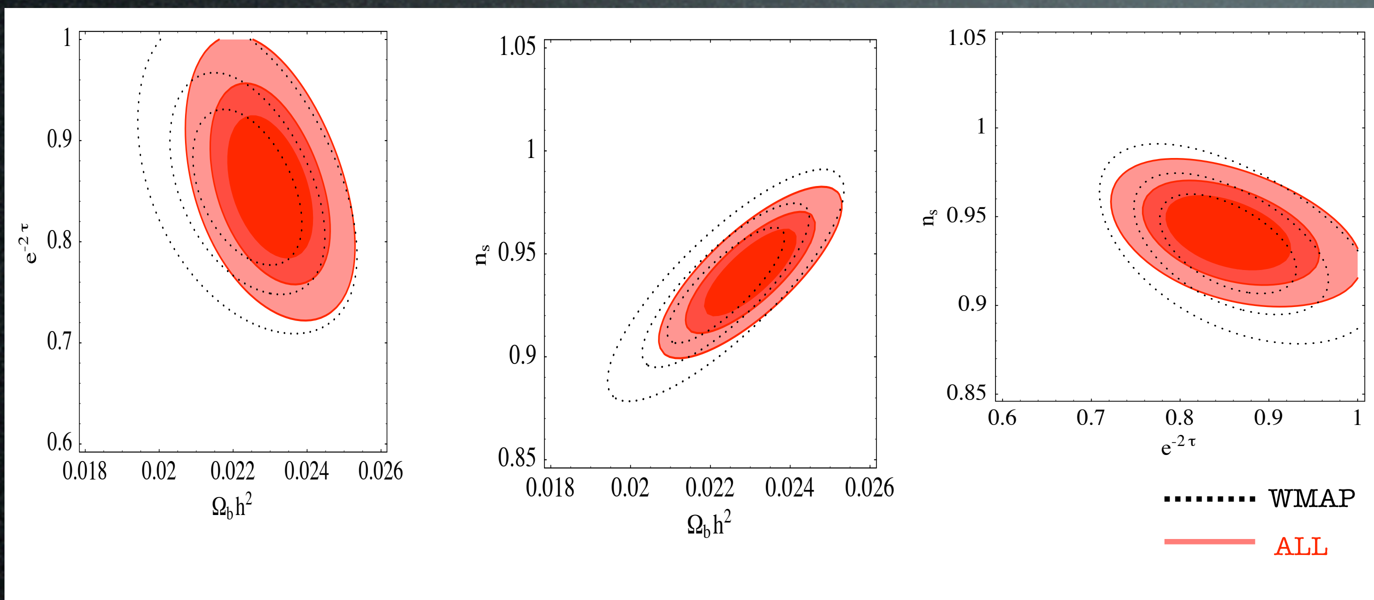
[back]

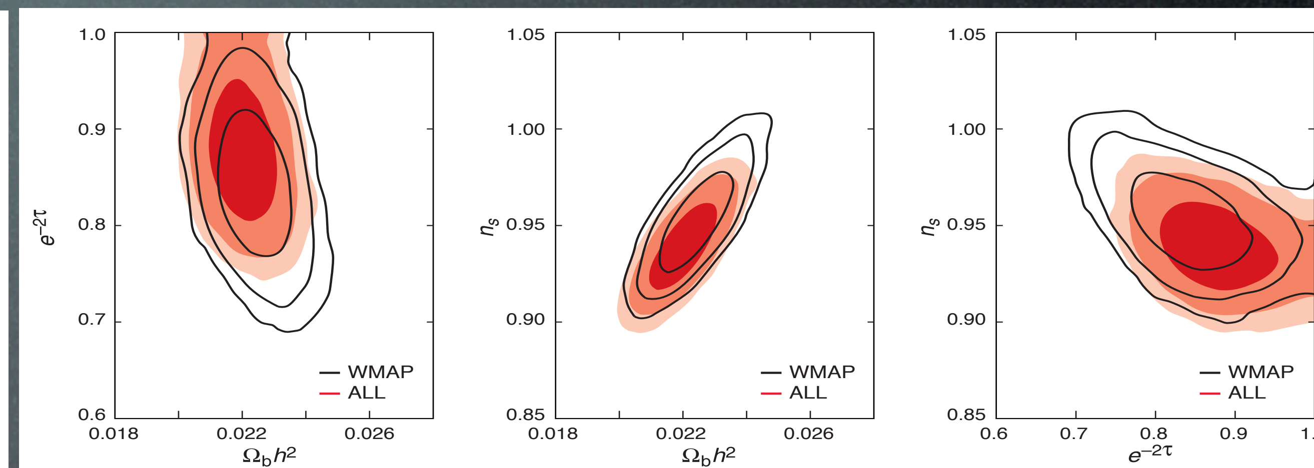
Comparing our code

[back]

Our analysis:

WMAP Science Team analysis:

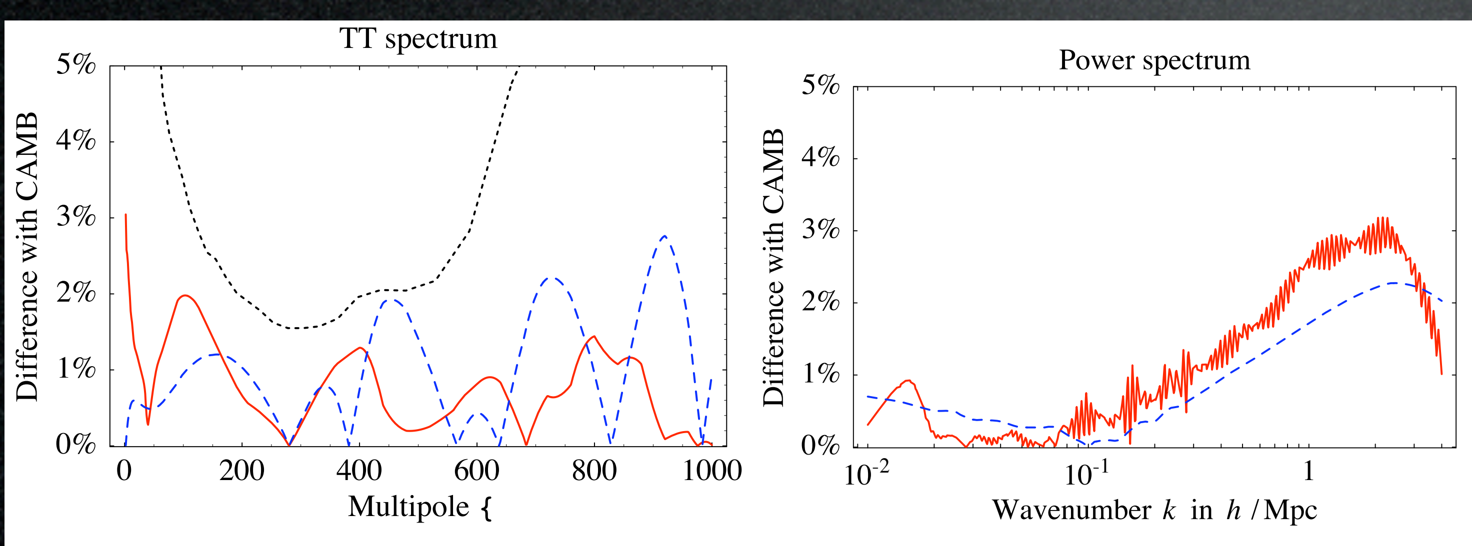




[Spergel et al. WMAP 3yr results '05]

fit	A_s	h	n_s	τ	$100\Omega_b h^2$	$\Omega_{DM} h^2$
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

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	

(from Particle Data Book 2008)

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

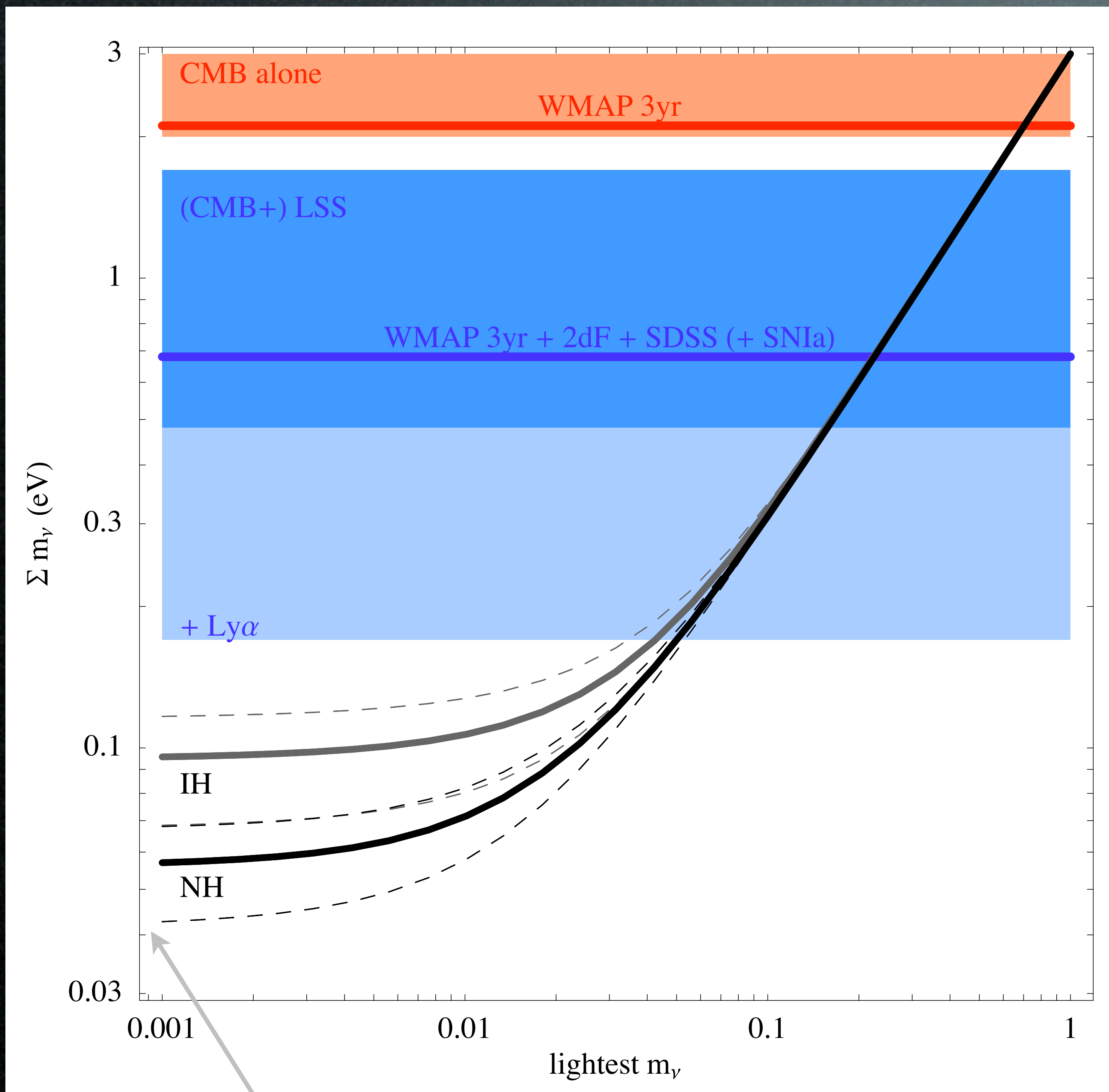
Number of Light ν Types

("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

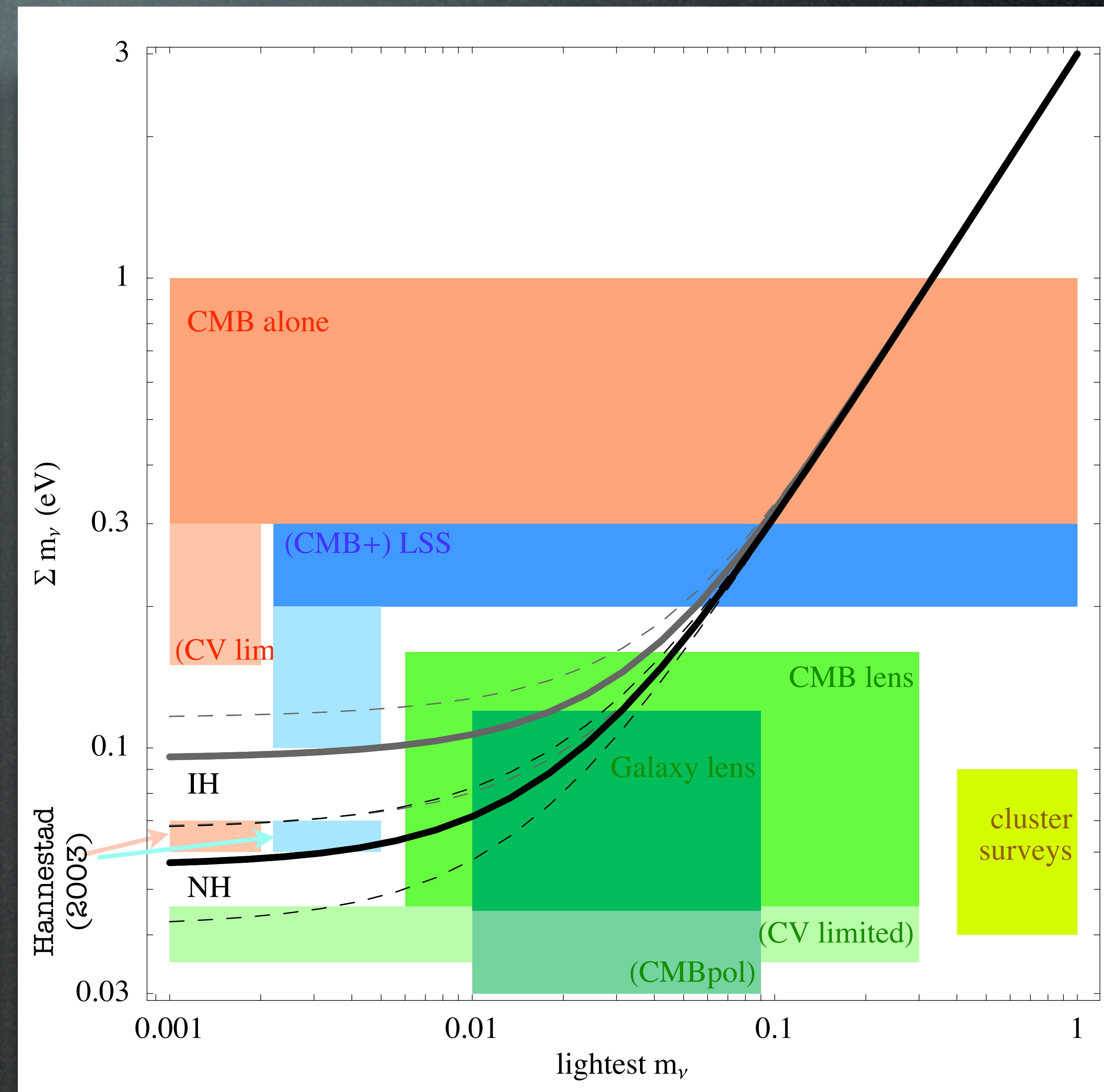
On neutrino masses

present bounds



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

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

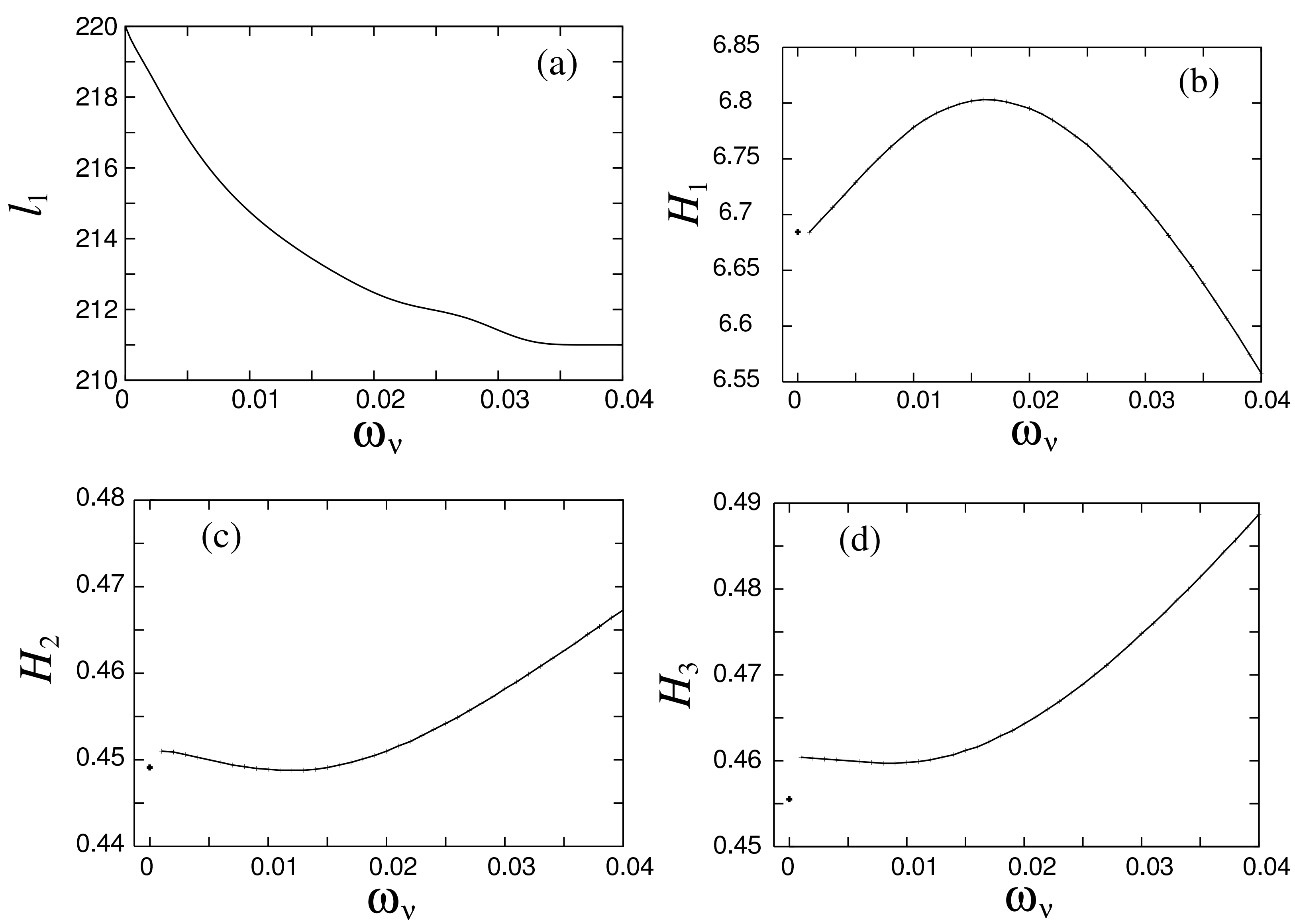


FIG. 5: Response of the four reduced CMB observables to the variation of ω_ν. The isolated points show the values at $\omega_\nu = 0$, which do not connect to the $\omega_\nu \neq 0$ values smoothly.

Ichikawa et al, 2004

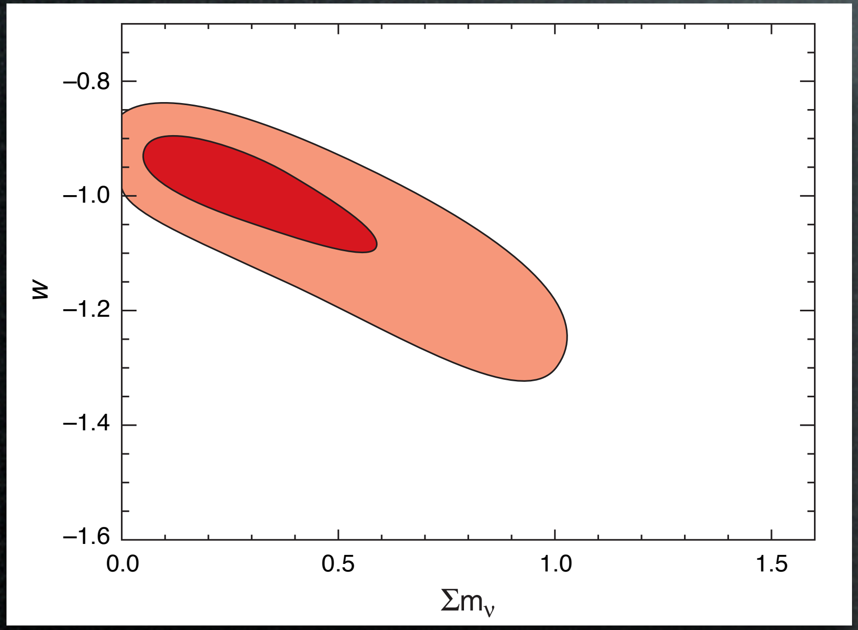
Degeneracies

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

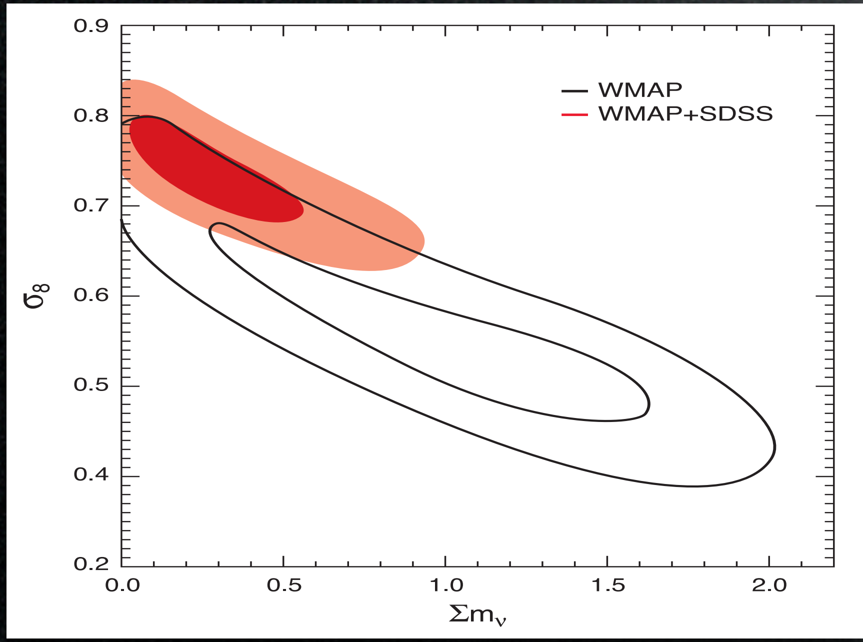
Hannestad, astro-ph/0505551

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

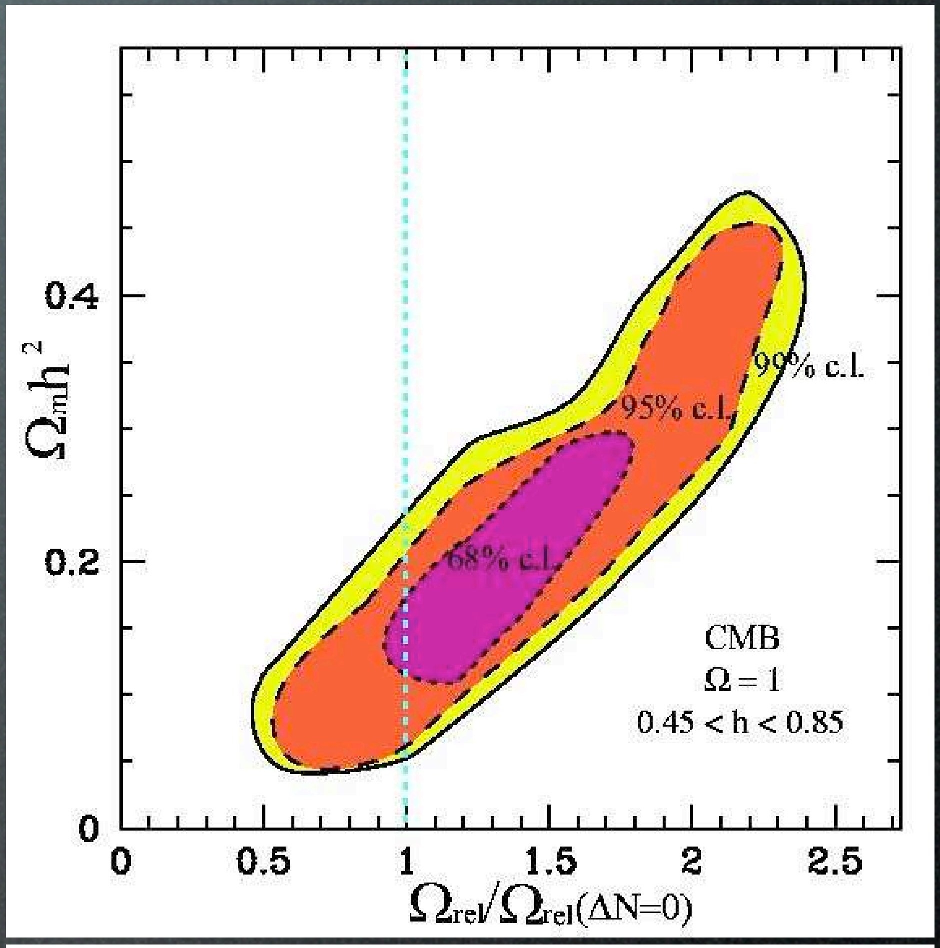
WMAP 3yr, Spergel et al.



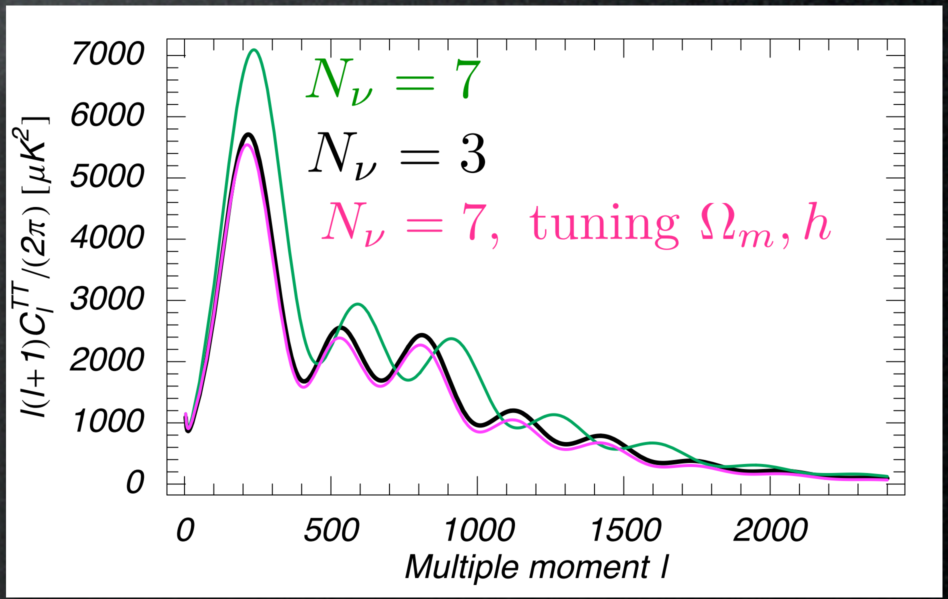
or by low σ_8



Large N_ν can be cancelled by large Ω_m or h



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



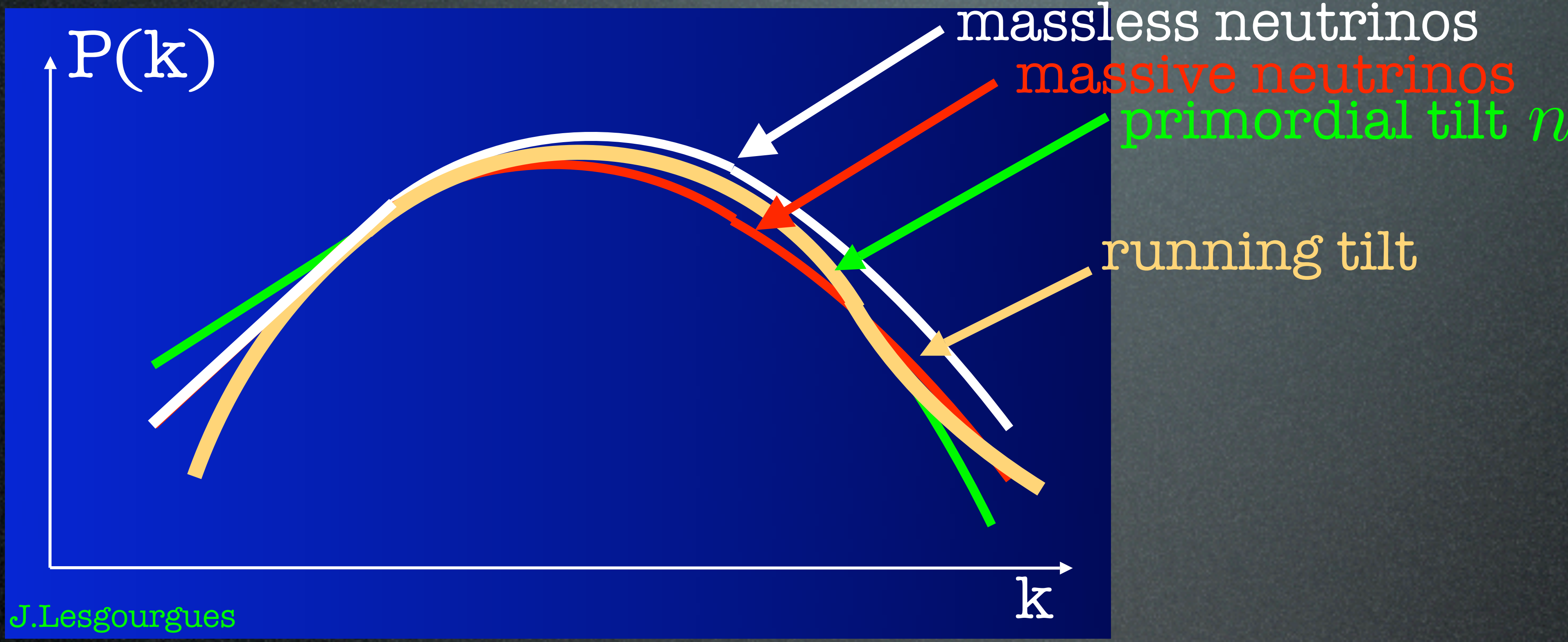
Friedland et al. 2007

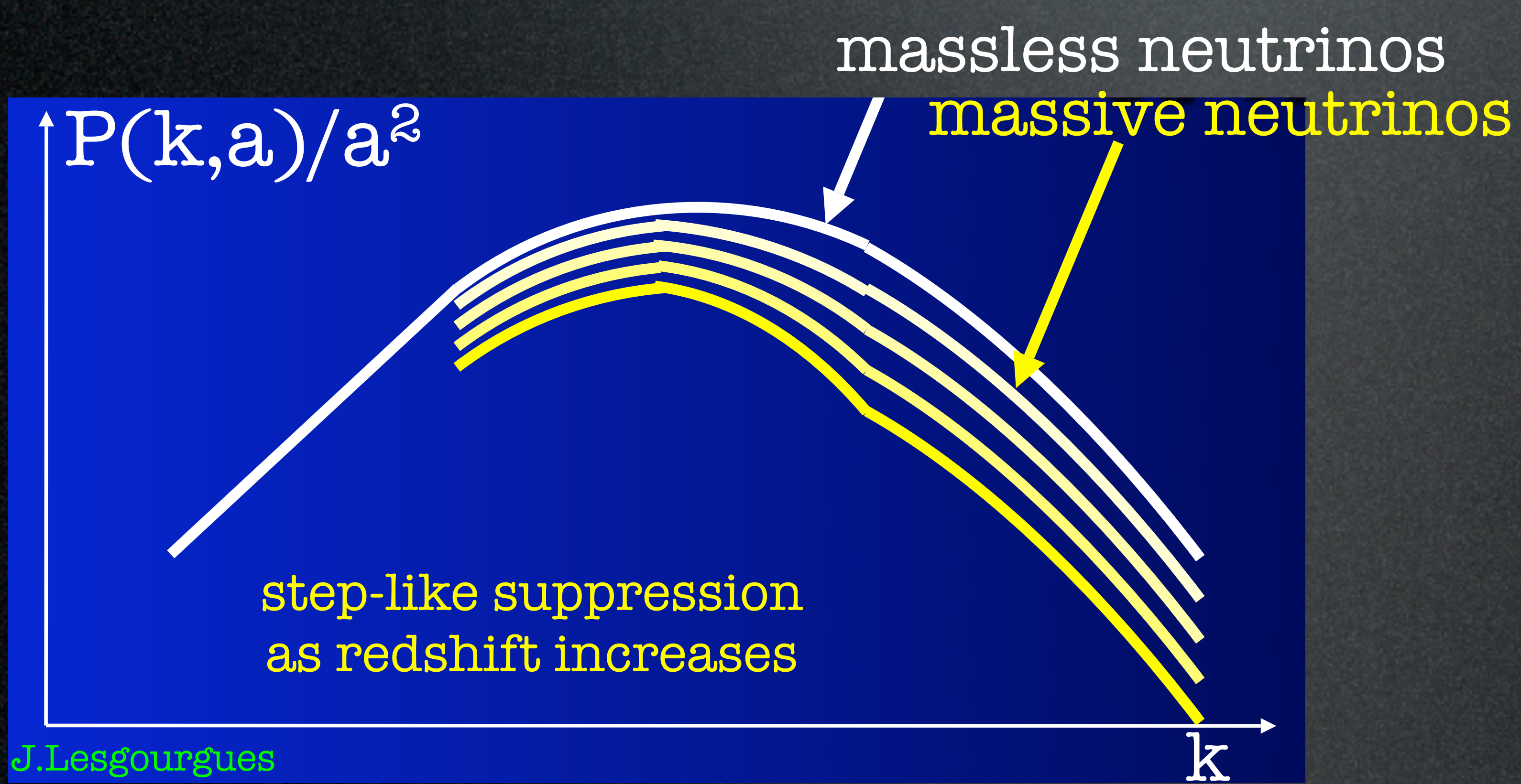
[back to Nnu]

Degeneracies

$\sum m_\nu$ will **not** be forever degenerate with other parameters:

Julien Lesgourgues, talks in 2007



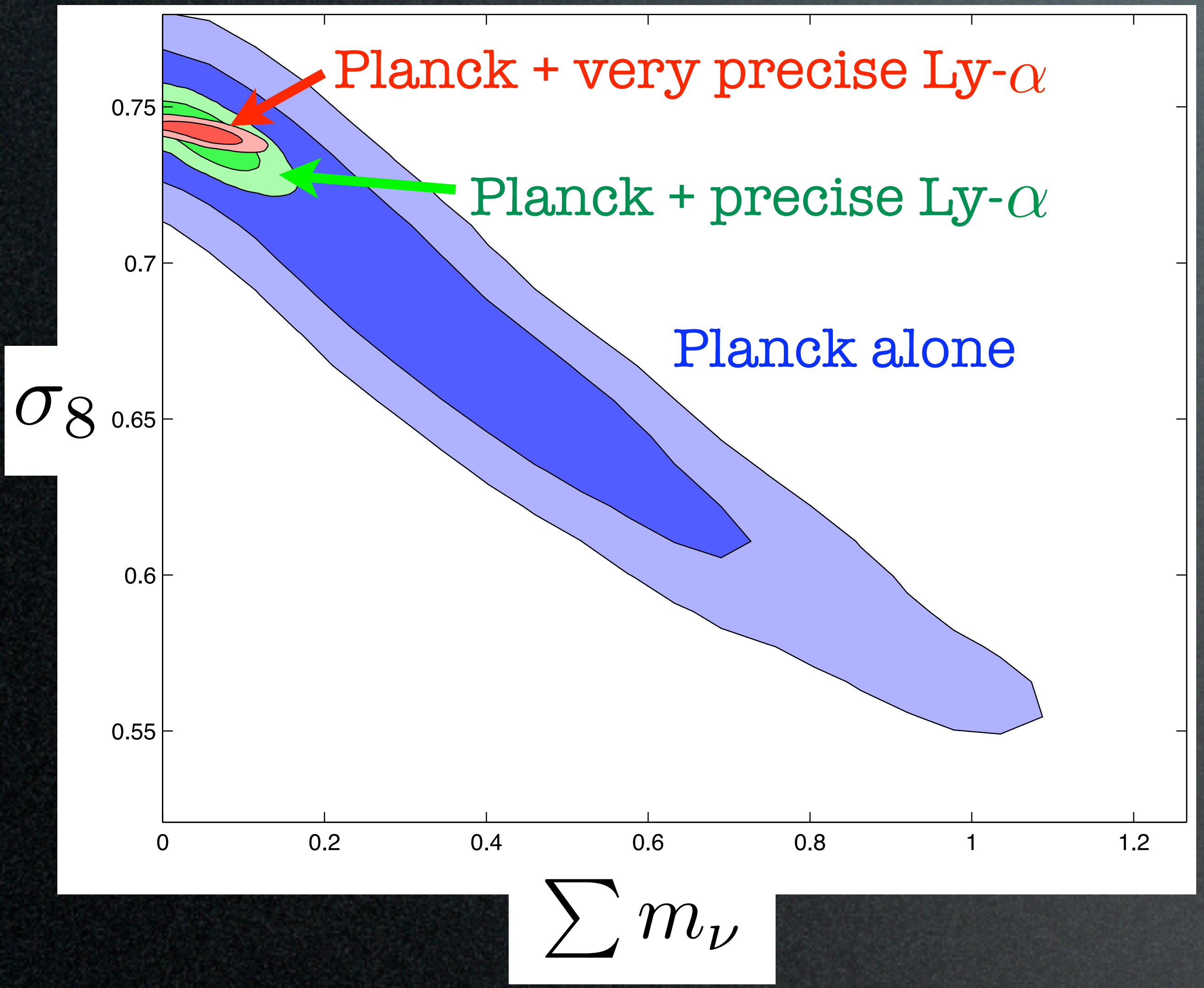


Degeneracies

$\sum m_\nu$ will **not** be forever degenerate with other parameters:

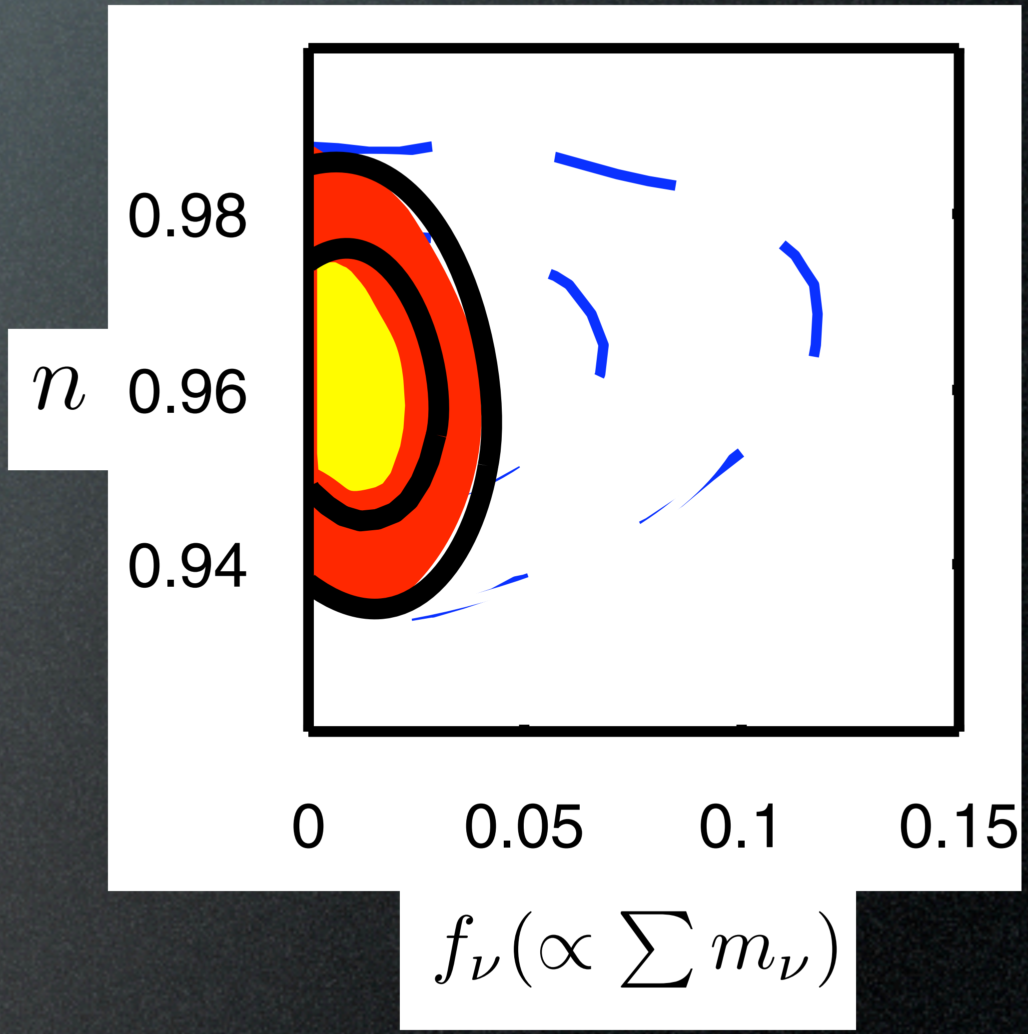
Julien Lesgourgues, talks in 2007

Planck + precision Ly-α:



Gratton, Lewis, Efstathiou 2007

Planck (with lensing extraction):



Perrotto, Lesgourgues et al, 2006