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# Cosmological bounds on light sterile neutrinos

## (and ways around them)

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# Why sterile neutrinos

We want to study light sterile neutrinos $\nu_{\rm s}$.

$\mathcal{O}(\mathrm{eV})$

- spin 1/2 fermions,
- neutral under SM forces,
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r-process nucleosynthesis
pulsar kicks
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- LSND/MiniBooNE
- invoked in phenomenology

r-process nucleosynthesis
pulsar kicks
galactic ionization...

- predicted in beyond SM models

right-handed neutrino
goldstino
majorino
axino
dilatino
branino
familino
modulino
mirror fermion...

The discovery of a new light particle would be fundamental.

# Bounds on $\nu_s$ from cosmology

**Part 1**: bounds from BBN

- T $\sim$ MeV
- flavor is important
- matter effects in the plasma

**Part 2**: bounds from later cosmology

- T $\lesssim$ eV
- $m_\nu$ is important

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# 4 neutrino mixing

Instead of a limited 2$\nu$ formalism $\nu_l \longrightarrow \cos\theta_{\rm s}\nu_{l'} + \sin\theta_{\rm s}\nu_{\rm s}$

we want a full 4$\nu$ formalism.

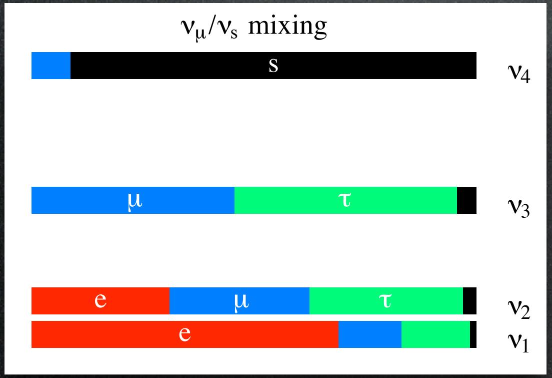
A simple parametrization: define a unit vector $\vec{n}$, which identifies a combination of active neutrinos

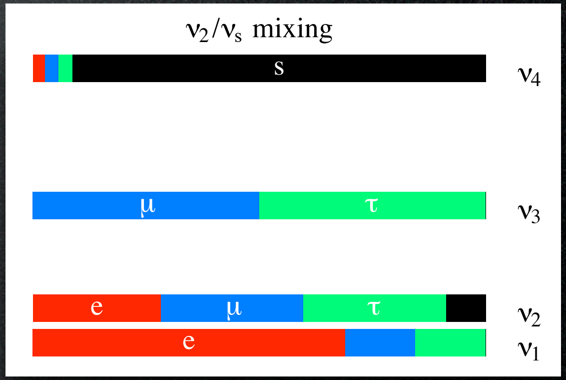
$$\vec{n}\cdot\vec{\nu} = n_e\nu_e + n_\mu\nu_\mu + n_\tau\nu_\tau = n_1\nu_1 + n_2\nu_2 + n_3\nu_3$$

which mixes with $\nu_{\rm s}$ with an angle $\theta_{\rm s}$ ,

$\nu_{\rm s}$ has a mass $m_4$ .

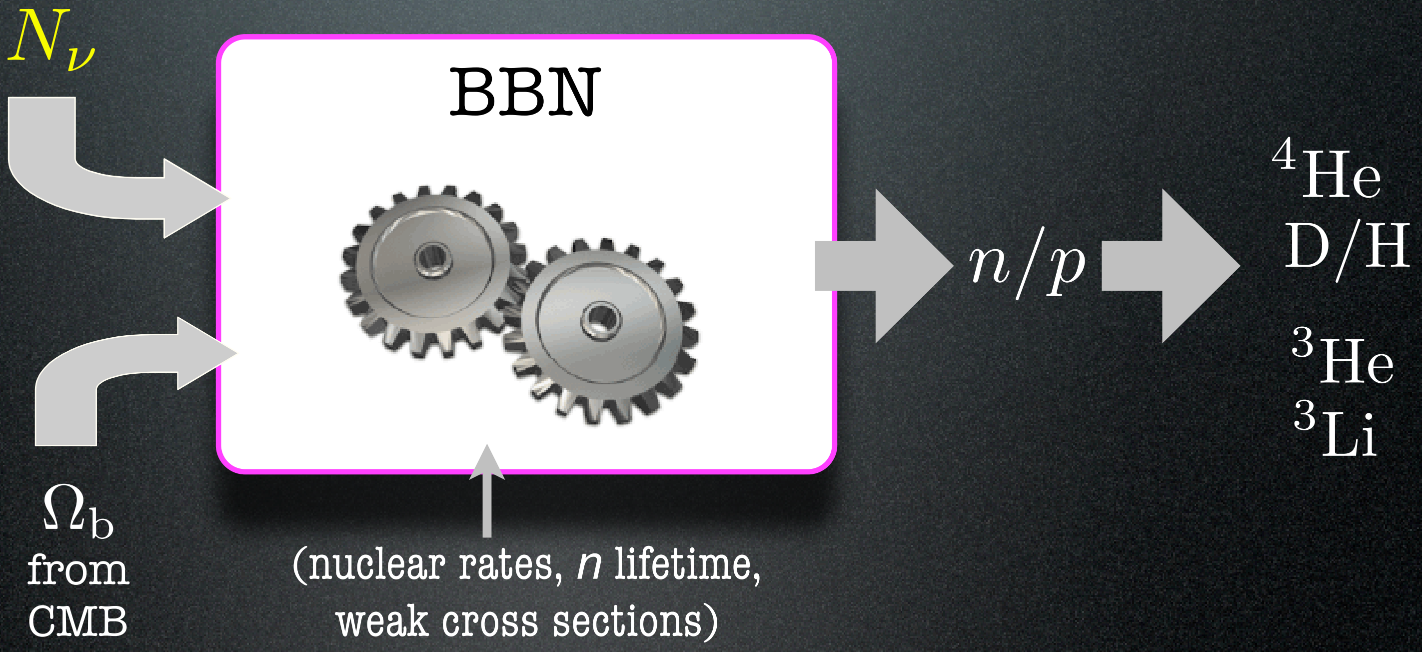
Basic cases: mixing with a flavor eigenstate, or a mass eigenstate





Free parameters: given a case, $m_4$ and $\theta_{\rm s}$ .

# Big Bang Nucleosynthesis



$N_\nu$

BBN

$\Omega_{\rm b}$
from
CMB

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

$n/p$

$^4$He
D/H
$^3$He
$^3$Li

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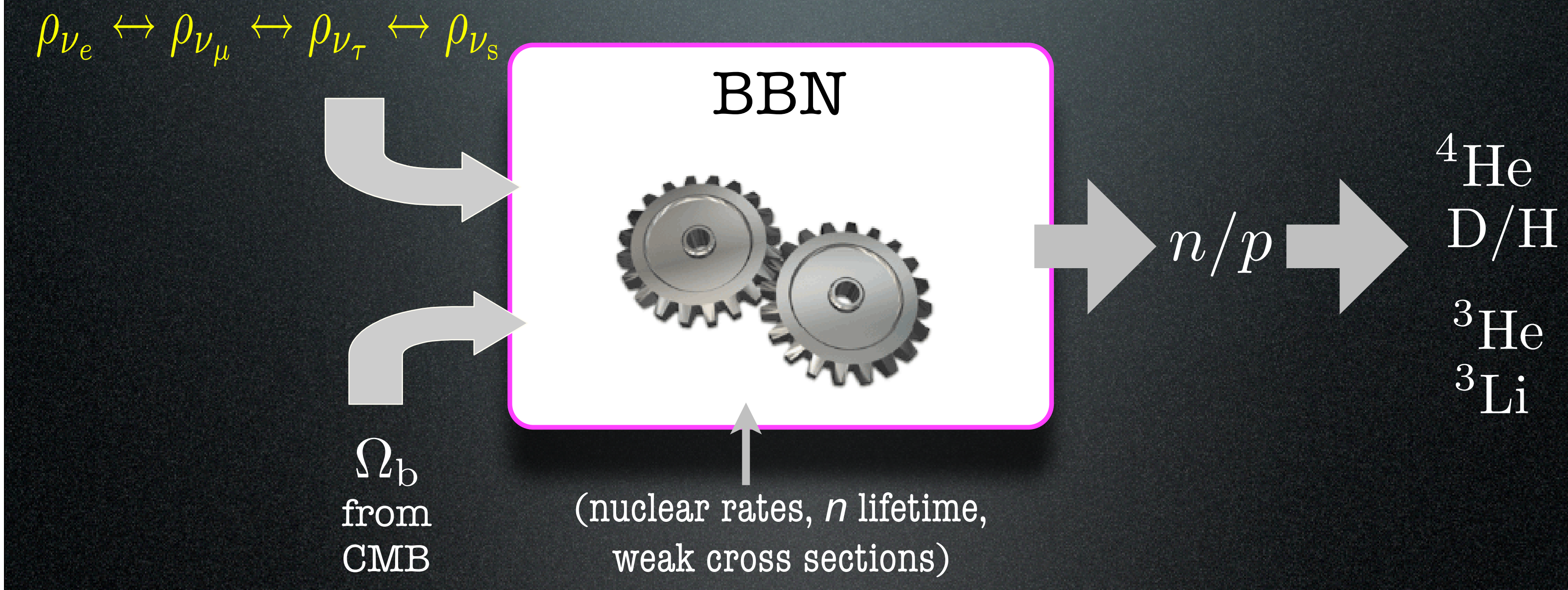

$\rho_{\nu_e} \leftrightarrow \rho_{\nu_\mu} \leftrightarrow \rho_{\nu_\tau} \leftrightarrow \rho_{\nu_s}$

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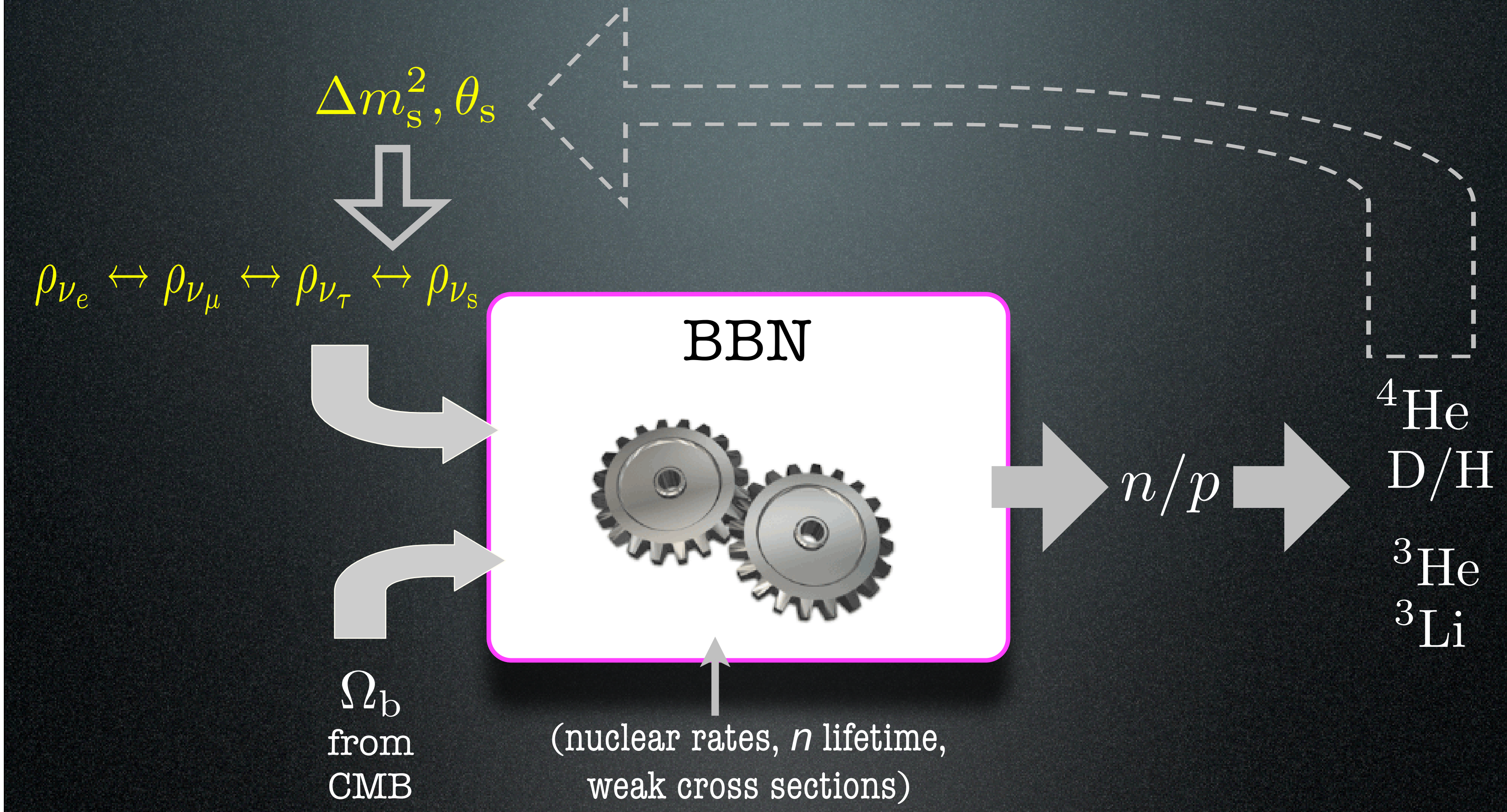

$\Delta m_{\rm s}^2, \theta_{\rm s}$

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For any choice of $\Delta m_{\rm s}^2, \theta_{\rm s}$ a prediction from BBN.

# Big Bang Nucleosynthesis

For every choice of $\Delta m_{\rm s}^2, \theta_{\rm s}$,
for T $\gg$ MeV $\longrightarrow$ 0.07 MeV
follow:

(BBN ends, les jeux sont faits)

1 kinetic equations for neutrino densities

$$\rho_{\nu_e}, \rho_{\nu_\mu}, \rho_{\nu_\tau}, \rho_{\nu_{\rm s}}$$

2 equation for ***n/p***

3 equations of light nuclei ($^4$He , D) production

Assumptions:

- no large lepton asymmetries
- neglect spectral distortions

# Big Bang Nucleosynthesis

## 1. Neutrino kinetic equations

4x4 neutrino density matrix $\rho$

3. scatterings and absorptions

$$\frac{d\rho}{dt} \equiv \frac{dT}{dt}\frac{d\rho}{dT} = -i\left[\mathcal{H}_m, \rho\right] - \{\Gamma, (\rho - \rho^{\mathrm{eq}})\}$$

Dolgov, 1981
Barbieri, Dolgov 1990

diag(1,1,1,0)

2. oscillations

$$\mathcal{H}_m = \frac{1}{2E_\nu}\left[V \mathrm{diag}(m_1^2, m_2^2, m_3^2, m_4^2)V^\dagger + E_\nu \mathrm{diag}(V_e, V_\mu, V_\tau, 0)\right]$$

1.expansion

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

Active/sterile
mixing parameters

Hubble parameter
depends on
$\rho_{\nu_e} + \rho_{\nu_\mu} + \rho_{\nu_\tau} + \rho_{\nu_s}$

$$H = (8\pi/3\ G_N\ \rho_{\mathrm{tot}})^{1/2}$$

$$V_e = -\frac{199\sqrt{2}\pi^2}{180}\frac{\zeta(4)}{\zeta(3)}G_{\mathrm{F}}\frac{T}{M_W^2}\left(T^4 + \frac{1}{2}T_\nu^4 \cos\theta_W \rho_{ee}\right)$$

$$V_\mu = -\frac{199\sqrt{2}\pi^2}{180}\frac{\zeta(4)}{\zeta(3)}G_{\mathrm{F}}\frac{TT_\nu^4}{M_W^2}\left(\frac{1}{2}T_\nu^4 \cos\theta_W \rho_{\mu\mu}\right)$$

$$V_\tau = -\frac{199\sqrt{2}\pi^2}{180}\frac{\zeta(4)}{\zeta(3)}G_{\mathrm{F}}\frac{TT_\nu^4}{M_W^2}\left(\frac{1}{2}T_\nu^4 \cos\theta_W \rho_{\tau\tau}\right)$$

$$V_s = 0$$

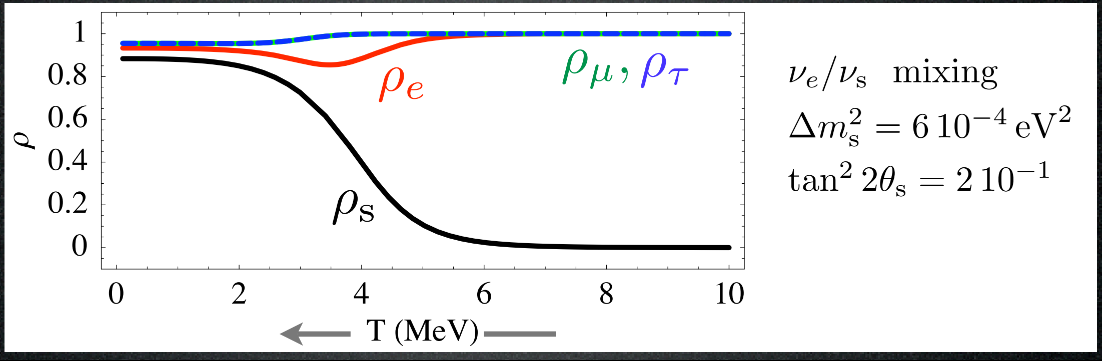
ν thermal masses

# Big Bang Nucleosynthesis

## 1. Neutrino kinetic equations

What happens qualitatively:

- for $T \gg \mathrm{MeV}$, matter effects suppress mixing $(\rho_{\nu_{\rm s}} \simeq 0)$
- as $T$ decreases, at a certain point oscillations $\nu_{\rm active} \leftrightarrow \nu_{\rm s}$ can begin $(\Delta m^2_{\rm s}, \theta_{\rm s})$ $(\rho_{\nu_{\rm s}} \nearrow)$
- + redistribution $\nu_{\rm active} \leftrightarrow \nu_{\rm active}$
- meanwhile: $\nu$ decouple at $T \sim \mathrm{MeV}$, $e^+e^-$ annihilate...
- Output: $\rho_{\nu_e}(T), \rho_{\nu_\mu}(T), \rho_{\nu_\tau}(T), \rho_{\nu_{\rm s}}(T)$



$\nu_e/\nu_{\rm s}$ mixing

$\Delta m^2_{\rm s} = 6\,10^{-4}\,\mathrm{eV}^2$

$\tan^2 2\theta_{\rm s} = 2\,10^{-1}$

[back to case with asymmetry]

# Big Bang Nucleosynthesis

## 2. n/p ratio

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

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

Hubble parameter depends on $\rho_{\nu_e} + \rho_{\nu_\mu} + \rho_{\nu_\tau} + \rho_{\nu_s}$

weak interactions

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

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

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

depend on $\rho_{\nu_e}, \rho_{\bar{\nu}_e}$

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depend on $\rho_{\nu_e}, \rho_{\bar{\nu}_e}$

So, *where does a* $\nu_s$ *enter the game?*

(A) total energy density ⇒ expansion parameter
(B) depletion of $\nu_e$ density ⇒ weak rates

# Big Bang Nucleosynthesis

## 3. Light elements production

A network of Boltzmann equations with up-to-date nuclear rates...

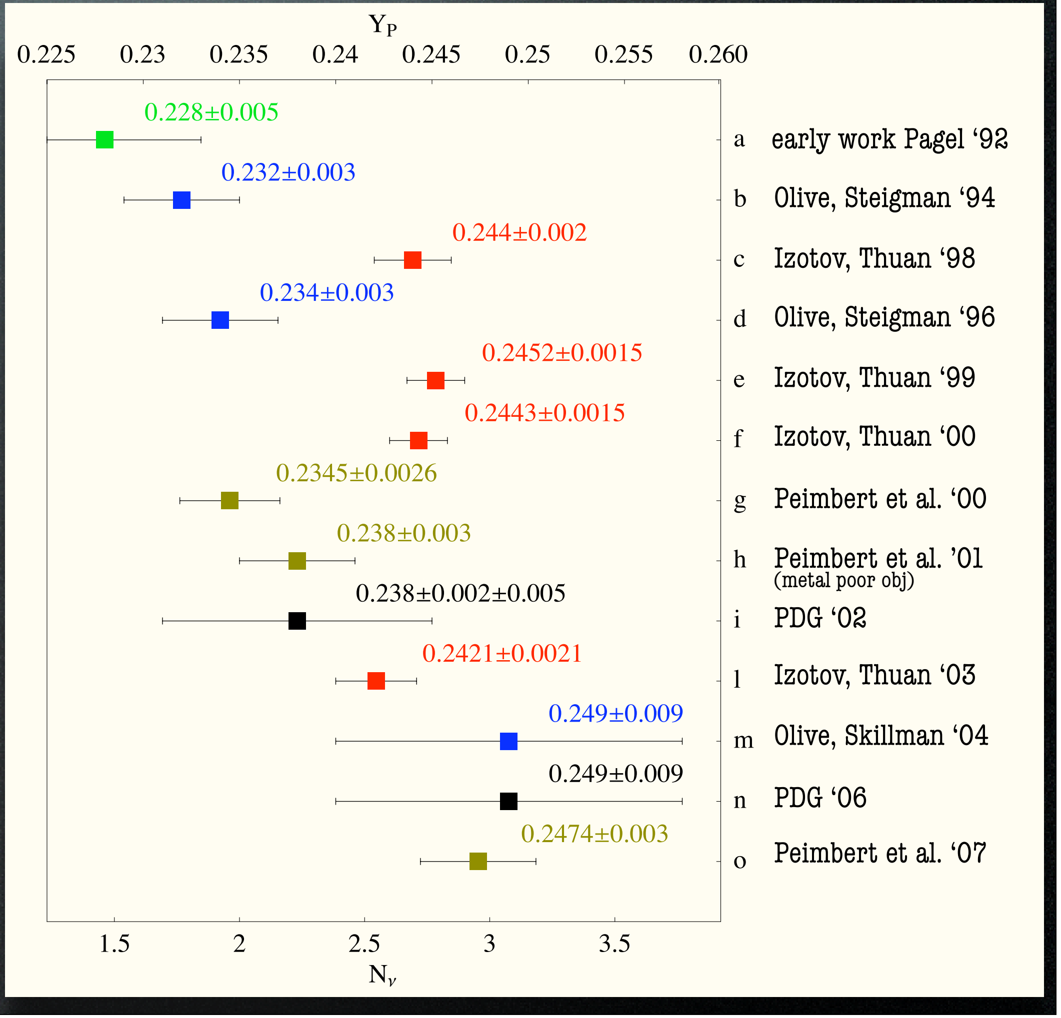
## 4. Observations

Determinations of primordial $^4$He are somehow controversial.

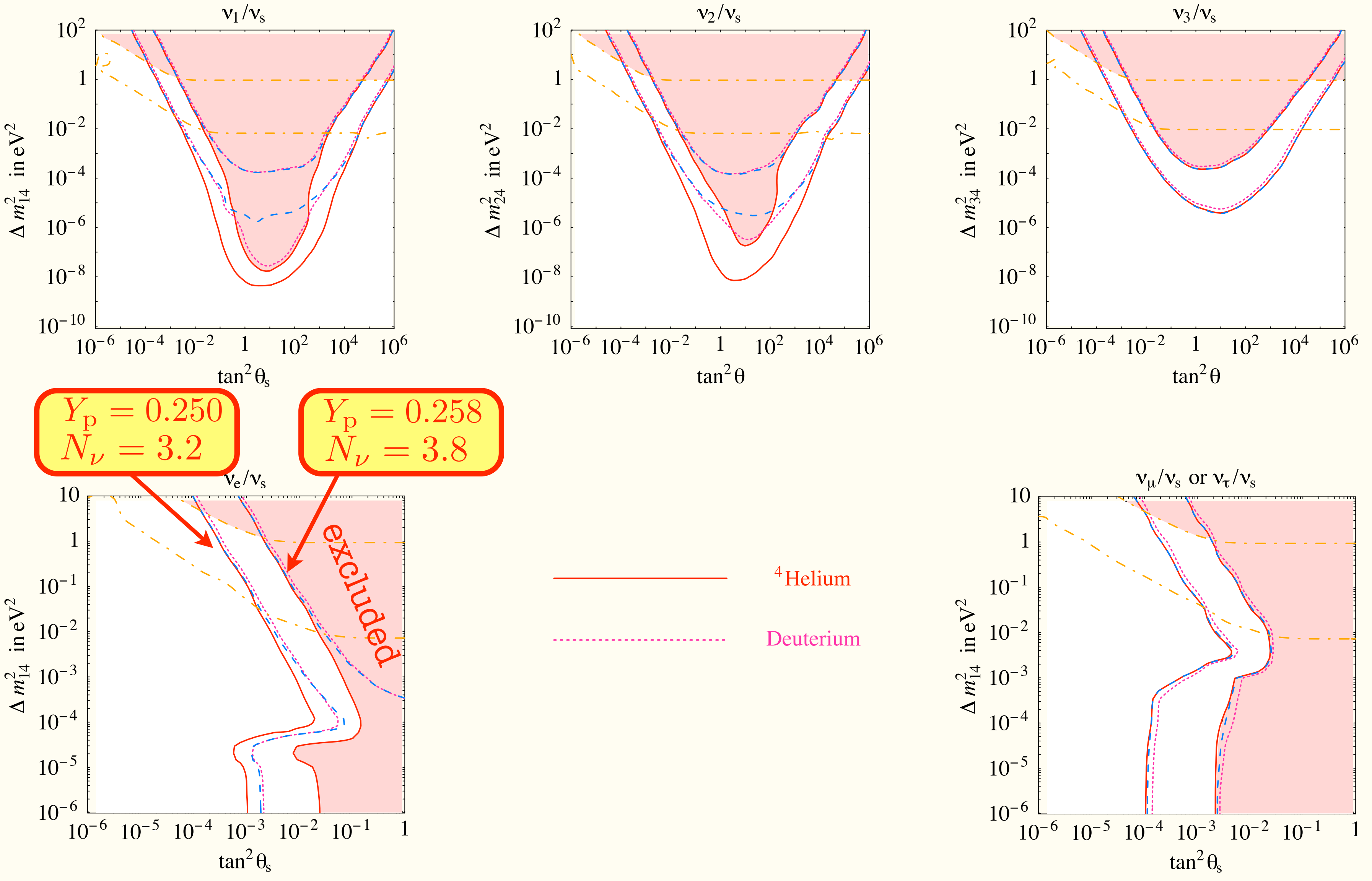
Conservatively, take

$Y_p = 0.249 \pm 0.009$

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



# Big Bang Nucleosynthesis



$Y_p = 0.250$
$N_\nu = 3.2$

$Y_p = 0.258$
$N_\nu = 3.8$

Cirelli, Marandella, Strumia, Vissani 2004

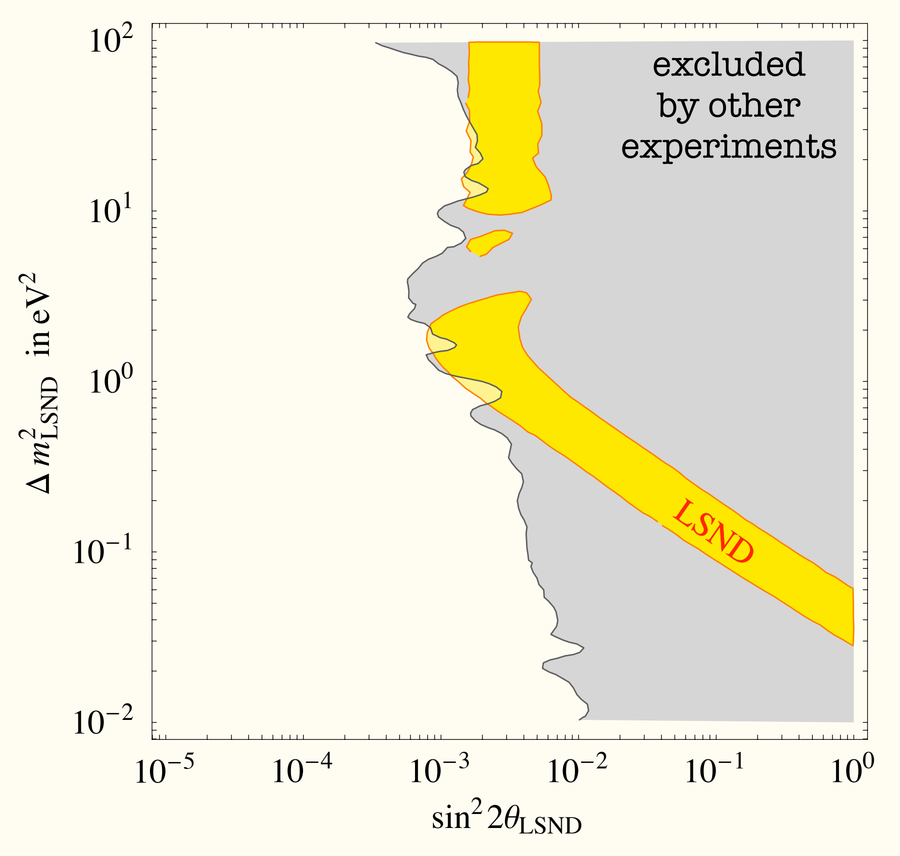
# LSND

LSND claims evidence for $\bar{\nu}_\mu \to \bar{\nu}_e$ with $\Delta m^2 \neq \Delta m^2_{\substack{\text{sun,}\\ \text{atm}}}$

Requires a new (sterile) neutrino: $\bar{\nu}_\mu \longrightarrow \bar{\nu}_{\rm s} \longrightarrow \bar{\nu}_e$

(if oscillations)

LSND collaboration - Strumia PLB 539 (2002)



with mixing $\vec{n} \simeq (\frac{1}{\sqrt{2}}, \frac{1}{\sqrt{2}}, 0)$

i.e. $\theta_{es}\theta_{\mu s} \simeq \theta_{\rm LSND}$

$\Delta m^2_{\rm LSND} \simeq 1 \text{ eV}^2$

$\sin^2 2\theta_{\rm LSND} \simeq 10^{-3}$

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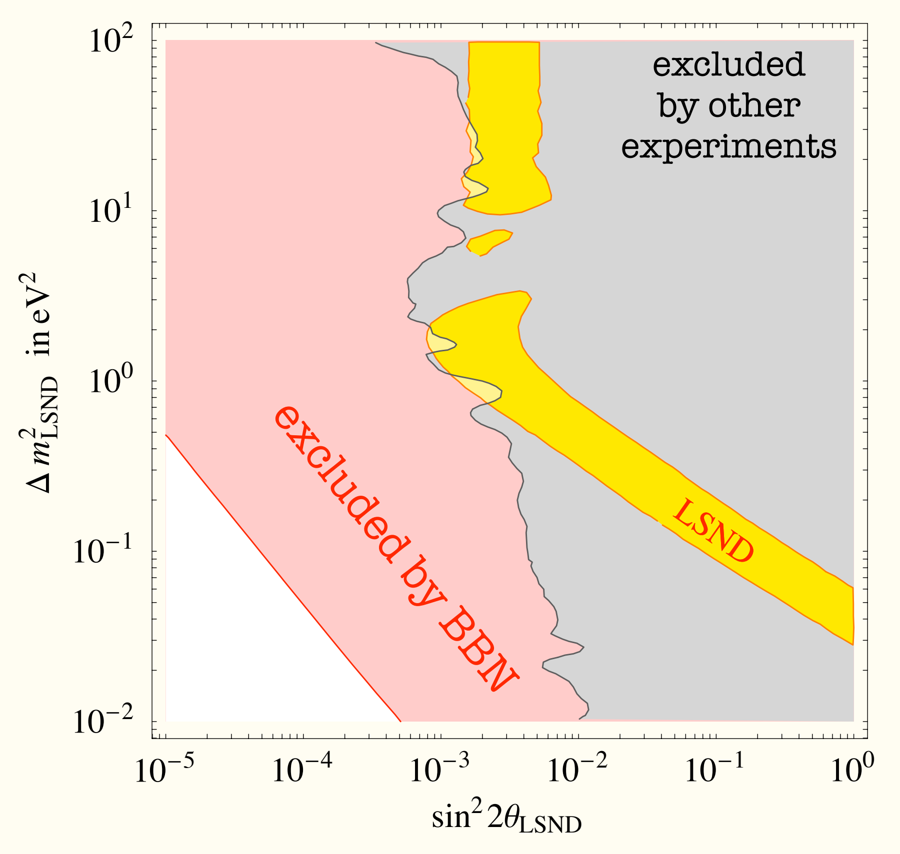

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Bottom Line:

BBN excludes the LSND $\nu_s$

(too much cosmo expansion)

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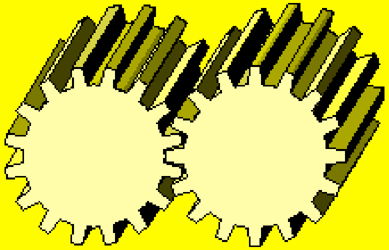
Neutrinos affect cosmological perturbations (CMB, LSS).

$N_\nu$

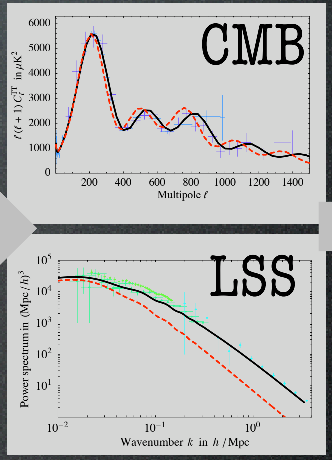
$\sum m_\nu$

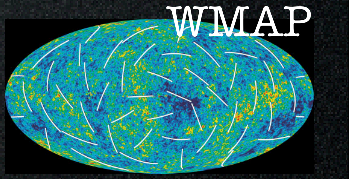
cosmological perturbations evolution

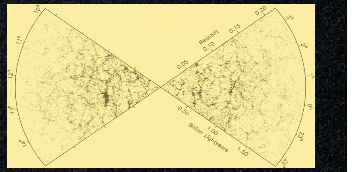


$\Omega_\mathrm{b}, \Omega_\mathrm{DM}, \tau,$

$A_s, H_0, n_s$







2dF, SDSS, Ly-A

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$\Delta m_{\rm s}^2, \theta_{\rm s}$

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$\sum m_\nu$

cosmological
perturbations
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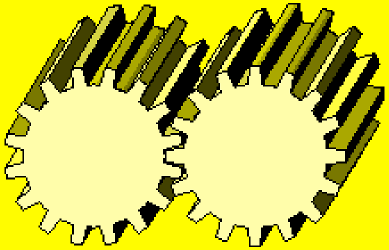

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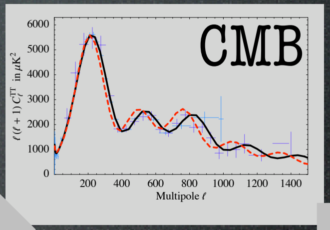

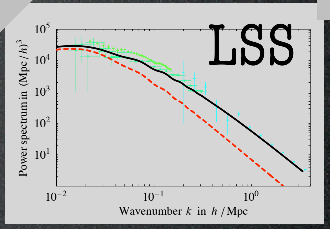

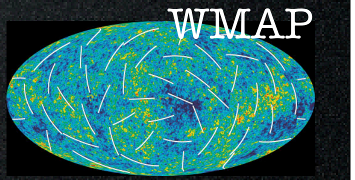

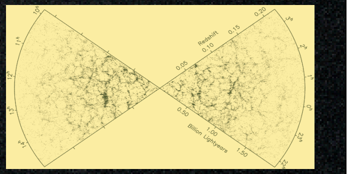

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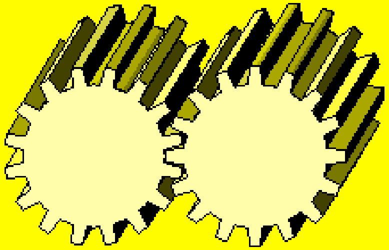
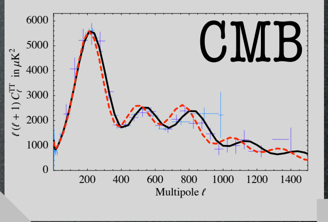
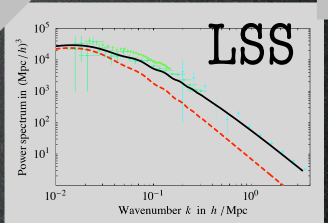
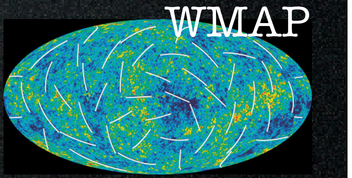
**cosmological perturbations evolution**

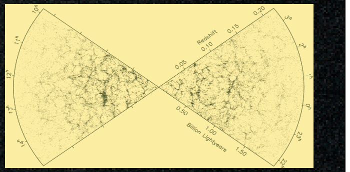


CMBfast/CAMB









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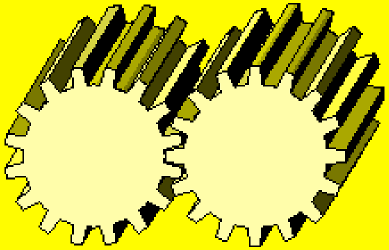

our code

WOLFRAMRESEARCH MATHEMATICA 5.2

Cirelli, Strumia, 2006

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

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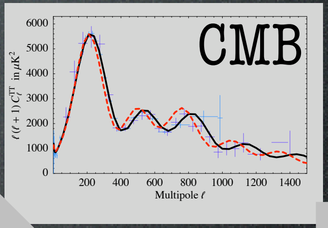
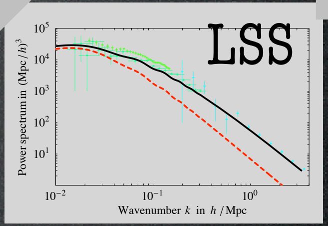
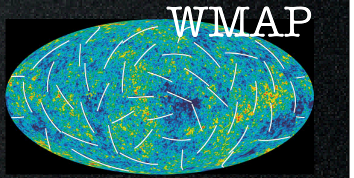
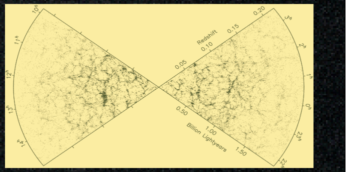








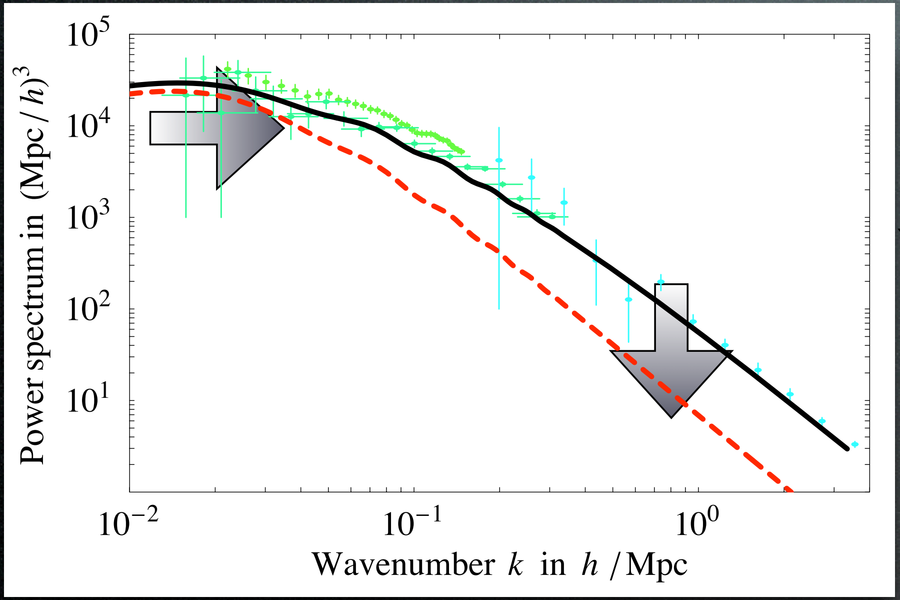
2dF, SDSS, Ly-A

# Cosmological Perturbations

Neutrinos affect cosmological perturbations (CMB, LSS).

Neutrino free-streaming suppresses the growth of LSS on small scales:

(more precisely: massive neutrinos contribute to the energy density of the Universe during MD but they don't source in the Newton equation for $\delta_{\rm dm}$ )



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

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

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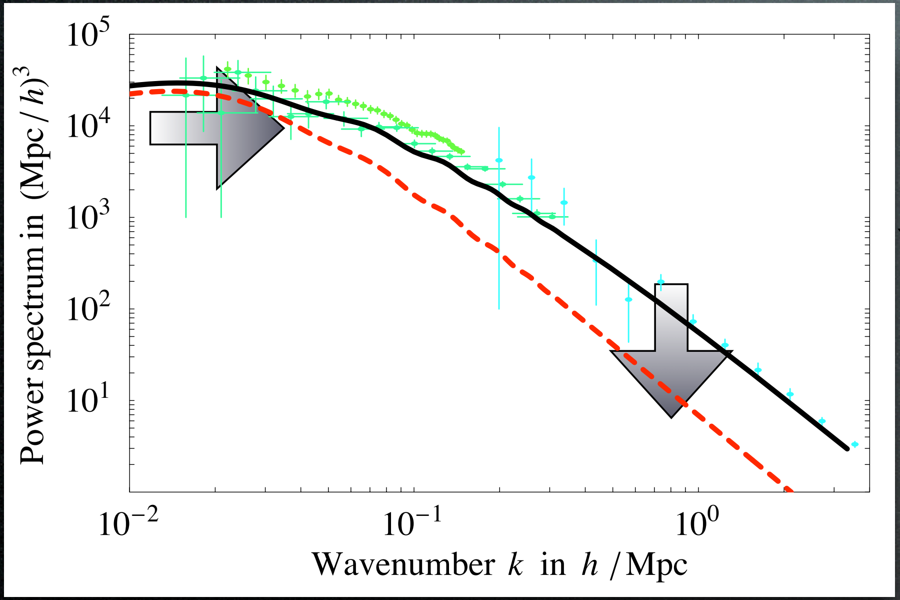

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$$\Downarrow$$

a bound on $\sum m_\nu$ :

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

(@ 99.9% C.L., global fit)

Cirelli, Strumia 2006

in presence of $\rho_{\nu_e}, \rho_{\nu_\mu}, \rho_{\nu_\tau}, \rho_{\nu_s}$: $\sum m_i \rho_i < 0.40$ eV

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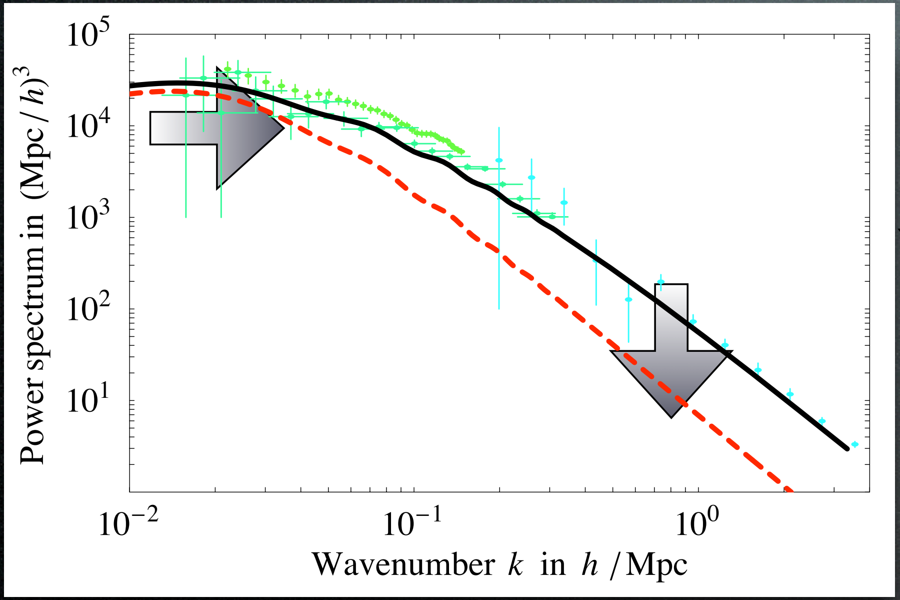

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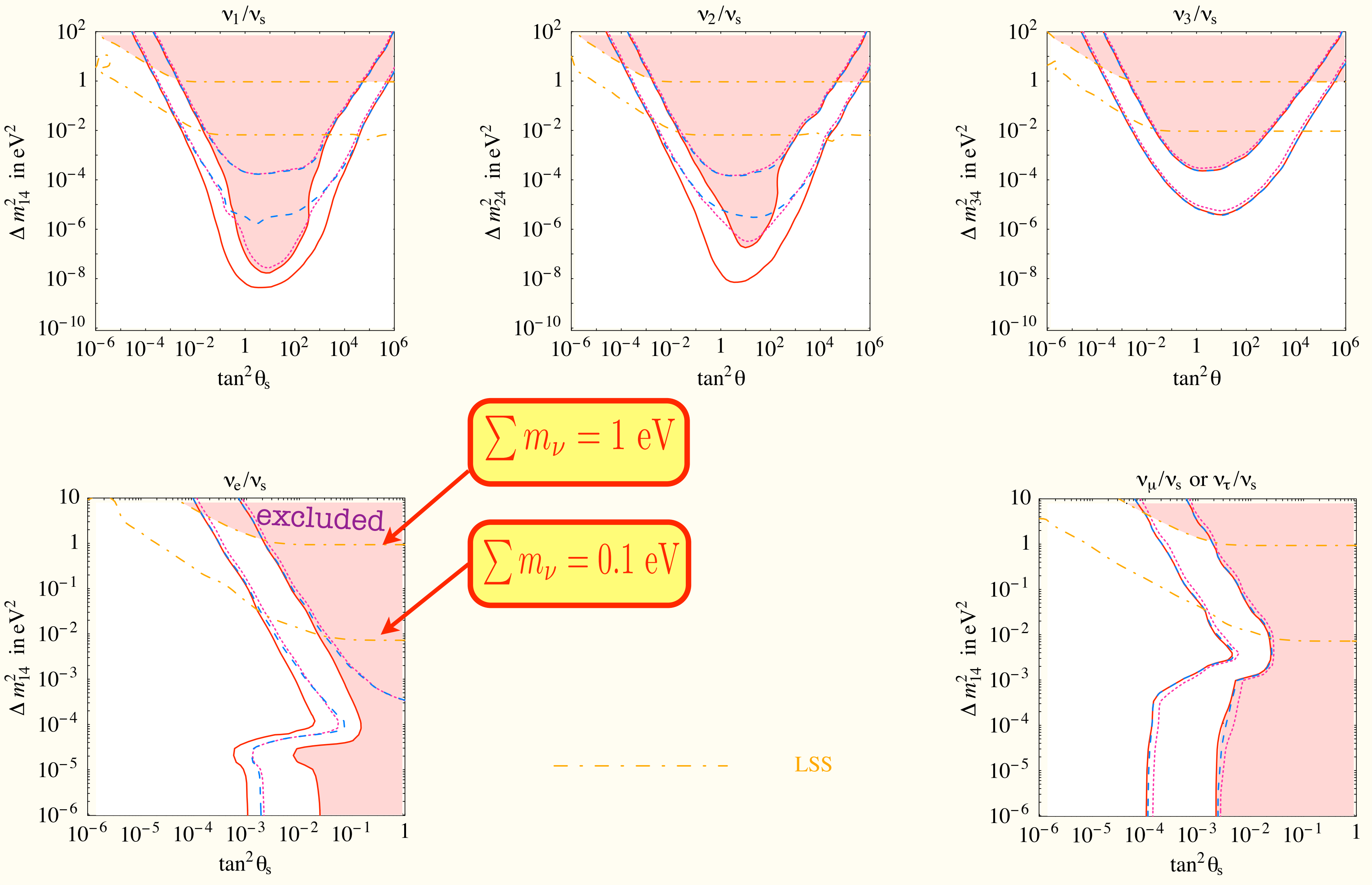
$\nu_{\rm s}$ contribute to $\sum m_\nu$ $\Rightarrow$ a bound on $m_4$ i.e. $\Delta m^2_{\rm s}$

# Cosmological Perturbations

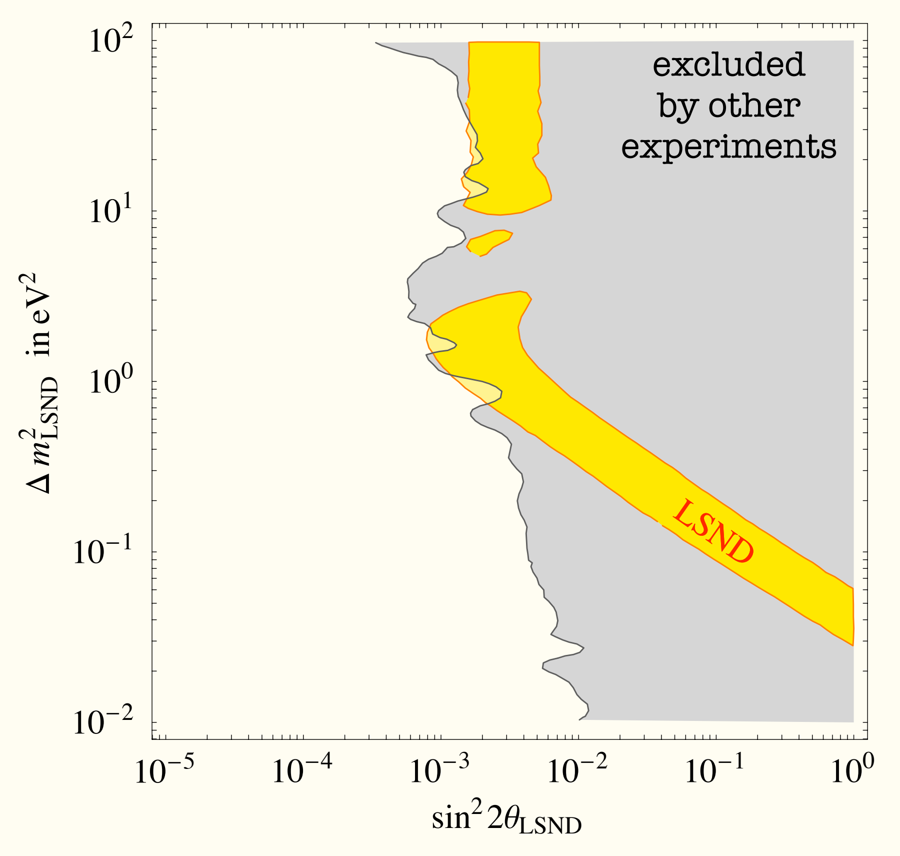


$\sum m_\nu = 1$ eV

$\sum m_\nu = 0.1$ eV

Cirelli, Marandella, Strumia, Vissani 2004

# LSND



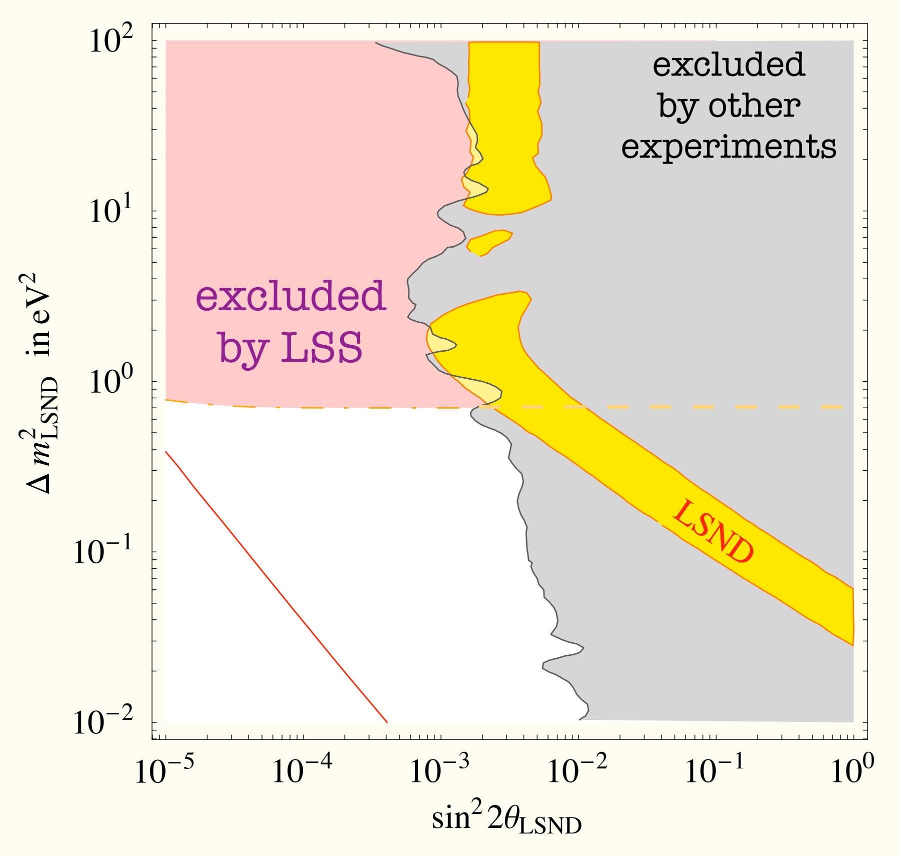
LSND collaboration - Strumia PLB 539 (2002)

$$\Delta m^2_{\rm LSND} \simeq 1 \text{ eV}^2$$

$$\sin^2 2\theta_{\rm LSND} \simeq 10^{-3}$$

# LSND

Cirelli, Marandella, Strumia, Vissani 2004



$$\Delta m^2_{\rm LSND} \simeq 1\ {\rm eV}^2$$

$$\sin^2 2\theta_{\rm LSND} \simeq 10^{-3}$$

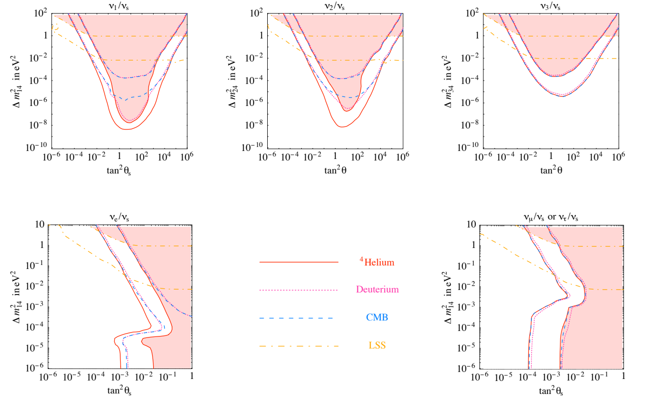
Bottom Line:

LSS excludes the LSND $\nu_{\rm s}$

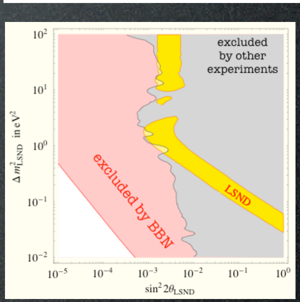
(too much $\sum m_\nu$)

# Recap

- Cosmology gives some of the **most stringent bounds on $\nu_s$**:
  - BBN constraints the total $N_\nu$ and
  the depletion of $\nu_e, \bar{\nu}_e$,
  - LSS constraints $\sum m_\nu$ .



- BBN and LSS **reject the LSND $\nu_s$**:



# Non-standard modifications

A. a large primordial lepton asymmetry

B. neutrino interactions with new light particles

C. low reheating temperature

D. ...

[skip to conclusions]

# Non-standard modifications

A. a large primordial lepton asymmetry

$$L_\nu = \frac{n_\nu - n_{\bar{\nu}}}{n_\gamma}$$

Foot, Volkas PRL 75 (1995)
P.Di Bari (2002, 2003)
V.Barger et al., PLB 569 (2003)
...

An asymmetry $L_\nu \approx \eta = 6\ 10^{-10}$ (baryon asym.) would be natural,

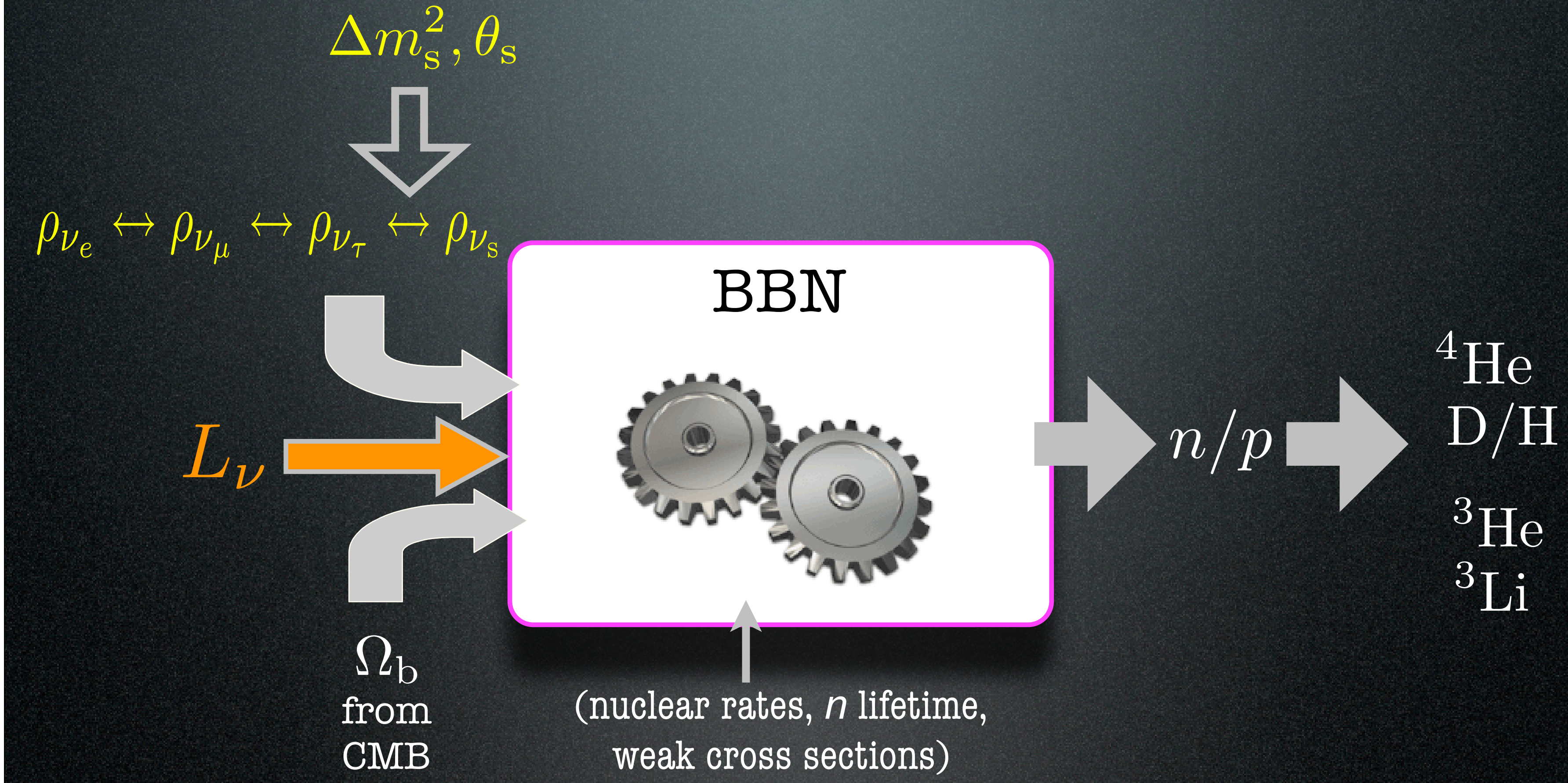
but a priori $L_\nu \sim \mathcal{O}(10^{-2})$ is possible.

Dolgov,..., Semikoz (2002)
Abazajian, Beacom, Bell (2002)
Cuoco,..., Serpico (2004)
Serpico, Raffelt (2005)

B. neutrino interactions with new light particles

C. low reheating temperature
D. ...

# BBN with lepton asymmetry



$\Delta m_s^2, \theta_s$

$\rho_{\nu_e} \leftrightarrow \rho_{\nu_\mu} \leftrightarrow \rho_{\nu_\tau} \leftrightarrow \rho_{\nu_s}$

$L_\nu$

$\Omega_b$
from
CMB

BBN

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

$n/p$

$^4$He
D/H
$^3$He
$^3$Li

For any choice of $\Delta m_s^2, \theta_s, L_\nu$ a prediction from BBN.

# BBN with lepton asymmetry

- follow separately $\rho$ and $\bar{\rho}$
- an extra term in the neutrino matter potentials

$$\frac{d\rho}{dt} \equiv \frac{dT}{dt}\frac{d\rho}{dT} = -i\left[\mathcal{H}_m, \rho\right] - \left\{\Gamma, (\rho - \rho^{\mathrm{eq}})\right\}$$

3. scatterings and absorptions

2. oscillations

$$\mathcal{H}_m = \frac{1}{2E_\nu}\left[V \mathrm{diag}(m_1^2, m_2^2, m_3^2, m_4^2) V^\dagger + E_\nu \mathrm{diag}(V_e, V_\mu, V_\tau, 0)\right]$$

1.expansion

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

$$V_e \simeq \boxed{\pm\sqrt{2} G_F n_\gamma \left[\frac{1}{2}\eta + 2L_{\nu_e} + L_{\nu_\mu} + L_{\nu_\tau}\right]} - \frac{199\sqrt{2}\pi^2}{180}\frac{\zeta(4)}{\zeta(3)} G_F \frac{T_\nu}{M_W^2}\left[T^4 + \frac{1}{4}T_\nu^4 \cos^2\theta_w (\rho_{ee} + \bar{\rho}_{ee})\right]$$

$$V_\mu \simeq \boxed{\pm\sqrt{2} G_F n_\gamma \left[\frac{1}{2}\eta + L_{\nu_e} + 2L_{\nu_\mu} + L_{\nu_\tau}\right]} - \frac{199\sqrt{2}\pi^2}{180}\frac{\zeta(4)}{\zeta(3)} G_F \frac{T_\nu T^4}{M_W^2}\left[\frac{1}{4}T_\nu^4 \cos^2\theta_w (\rho_{\mu\mu} + \bar{\rho}_{\mu\mu})\right]$$

$$V_\tau \simeq \boxed{\pm\sqrt{2} G_F n_\gamma \left[\frac{1}{2}\eta + L_{\nu_e} + L_{\nu_\mu} + 2L_{\nu_\tau}\right]} - \frac{199\sqrt{2}\pi^2}{180}\frac{\zeta(4)}{\zeta(3)} G_F \frac{T_\nu T^4}{M_W^2}\left[\frac{1}{4}T_\nu^4 \cos^2\theta_w (\rho_{\tau\tau} + \bar{\rho}_{\tau\tau})\right]$$

$$V_{\mathrm{s}} = 0$$

ν thermal masses

# BBN with lepton asymmetry

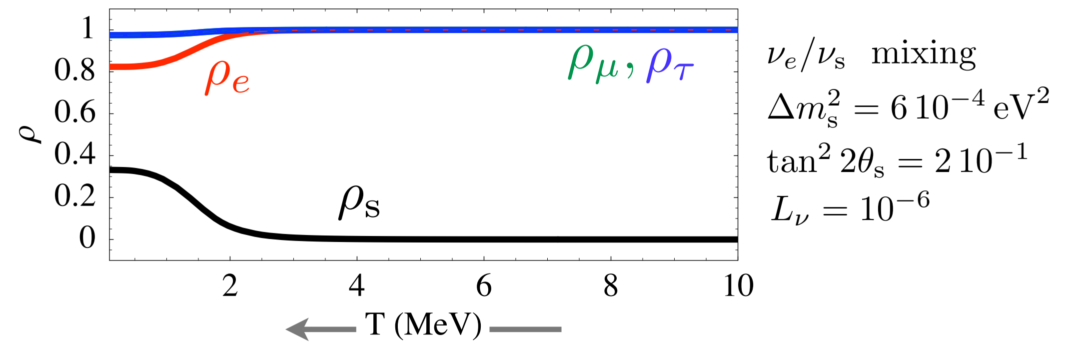
What happens qualitatively:

- for $T \gg \text{MeV}$, matter effects suppress mixing $(\rho_{\nu_\text{s}} \simeq 0)$

- despite $T$ decreasing, the asymmetry term inhibits $\nu_\text{active} \leftrightarrow \nu_\text{s}$ oscillations

⇓

- $\nu_\text{s}$ are less efficiently produced (or not at all) $(\rho_{\nu_\text{s}} \ll 1)$



[comparison with standard case]

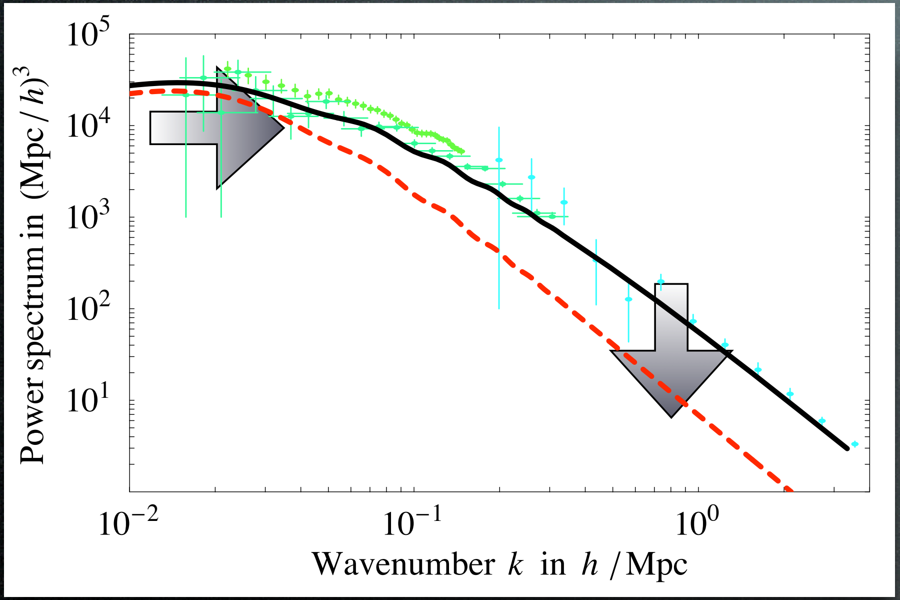
- (also: n/p weak rates affected by $\rho_{\nu_e} \neq \bar{\rho}_{\nu_e}$)

Assumptions:

- $L_{\nu_e} = L_{\nu_\mu} = L_{\nu_\tau}$ for simplicity
- non-dynamical $L_\nu$
- neglect spectral distortions

# LSS with lepton asymmetry

Recall that



$$\Rightarrow \boxed{\sum m_{\nu_i} < 0.40 \text{ eV}}$$

(@ 99.9% C.L.,
global fit)

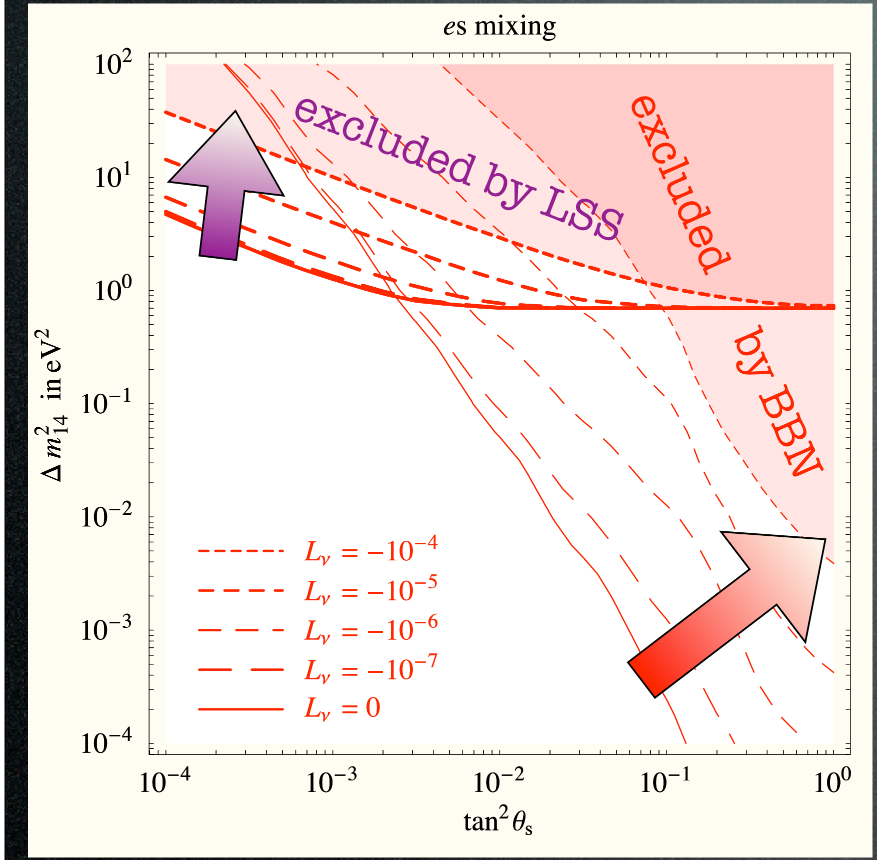
or better

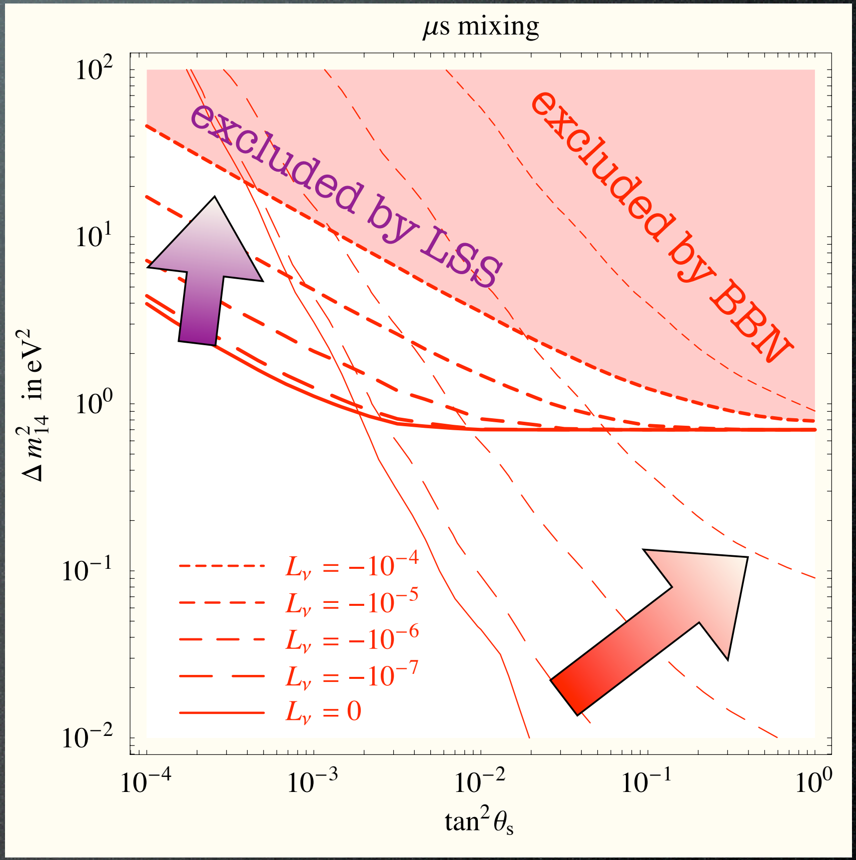
$$\sum m_i \rho_i < 0.40 \text{ eV}$$

$L_\nu$ suppresses $\nu_{\rm s}$ production $(\rho_{\nu_{\rm s}} \ll 1)$:
the bound on $m_4$ i.e. $\Delta m^2_{\rm s}$ is relaxed.

# with lepton asymmetry

Portions of the parameter space are reopened:

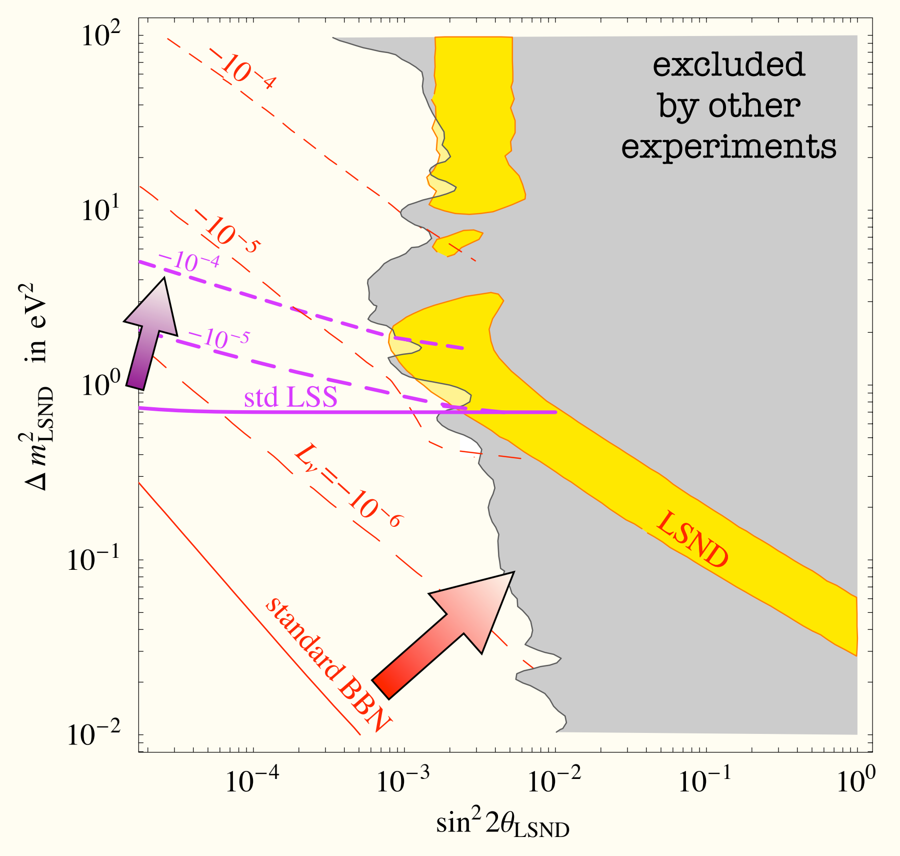




Chu, Cirelli 2006

# LSND with lepton asymmetry

Portions of the parameter space are reopened:



Chu, Cirelli 2006

# LSND with lepton asymmetry

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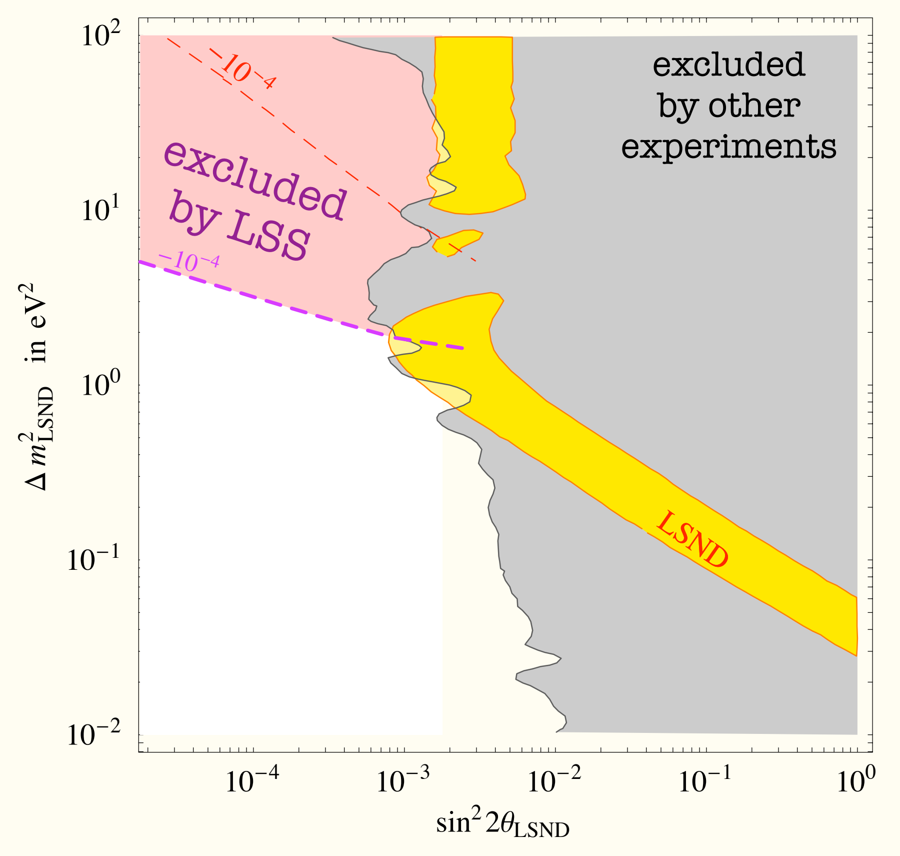


Chu, Cirelli 2006

Bottom Line:

postulating a primordial asymmetry $L_\nu \simeq -10^{-4}$ reconciles LSND and cosmology

# Non-standard modifications

A. a large primordial lepton asymmetry

B. neutrino interactions with new light particles

C. low reheating temperature

D. ...

[skip to conclusions]

# Non-standard modifications

A. a large primordial lepton asymmetry

B. neutrino interactions with new light particles

couplings $g\,\nu\bar{\nu}\phi$ mediate neutrino decay at late times:

neutrinos disappear $\Rightarrow$ not subject to cosmo bounds

"Neutrinoless Universe", Beacom, Bell, Dodelson (2004)

also for sterile neutrinos $g\,\nu_s\bar{\nu}\phi$ "LSND", Palomares-Ruiz, Pascoli, Schwetz (2005)

in general, interacting neutrinos pop up often

"MaVaNs", Fardon, Nelson, Weiner (2004)
"Late-time masses", Chacko, Hall et al., (2004)

C. low reheating temperature

D. ...

# Cosmology with sticky neutrinos

$\nu \leftrightarrow \phi$ couplings imply a tightly coupled fluid at recombination for $g > 10^{-8}, 10^{-14}$ (decay, scattering) Hannestad, Raffelt (2005)

$\Rightarrow$ neutrino free streaming is obstructed

# Cosmology with sticky neutrinos

$\nu \leftrightarrow \phi$ couplings imply a tightly coupled fluid at recombination
for $g > 10^{-8}, 10^{-14}$ (decay, scattering) Hannestad, Raffelt (2005)
$\Rightarrow$ neutrino free streaming is obstructed

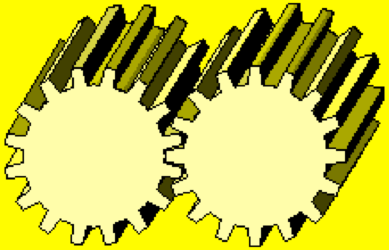
$N_\nu^{\rm norm}, N_\nu^{\rm int}, N_\phi, m_\nu, m_\phi$

$\Downarrow$

Boltzmann eqs for
tightly coupled fluid
+
standard $\nu$ eqs

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

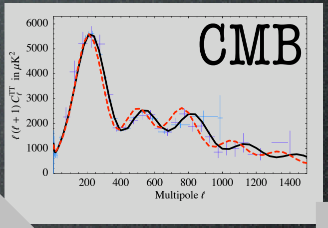
cosmological
perturbations
evolution



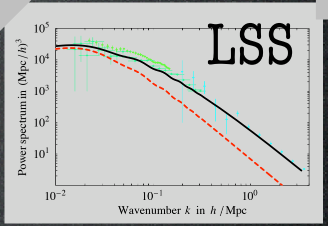
our code

Cirelli, Strumia, 2006

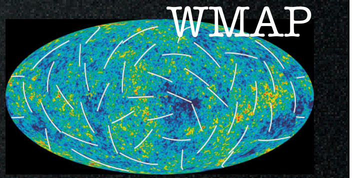
CMB

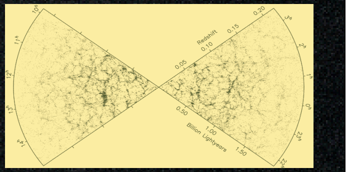


LSS



WMAP

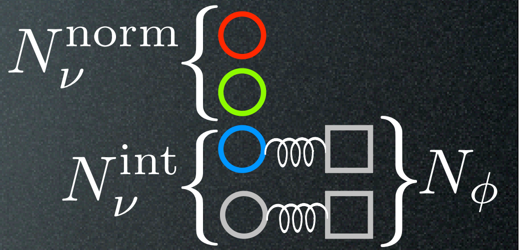


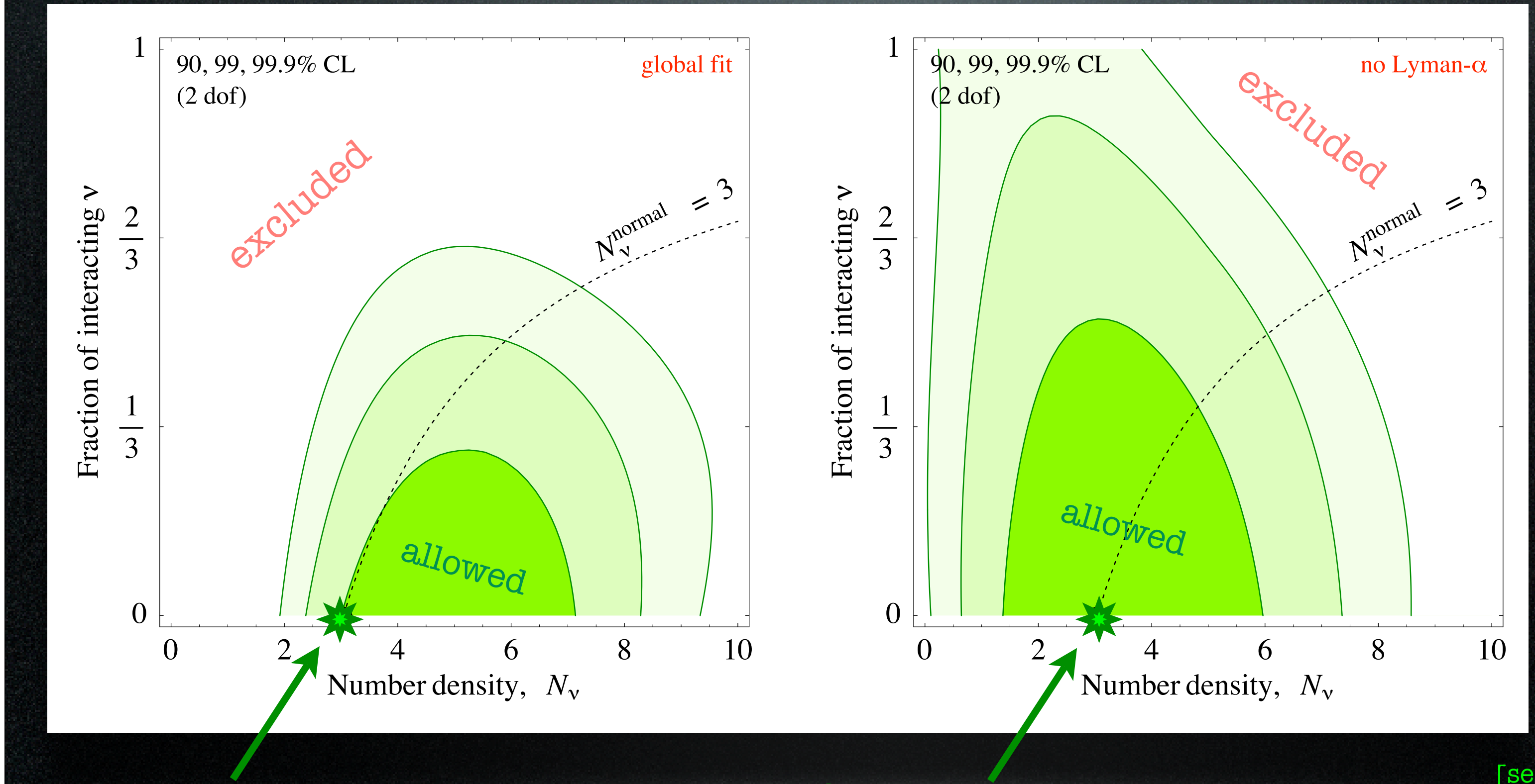


2dF, SDSS, Ly-A

# Cosmology with sticky neutrinos

Case: $N_\nu^{\text{norm}}$ standard neutrinos,
$N_\nu^{\text{int}}$ interacting with $N_\phi$ scalars,
everything massless.





Standard cosmology

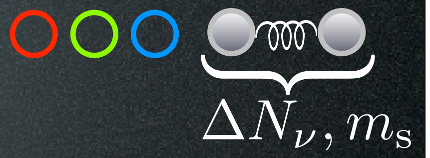
Standard cosmology

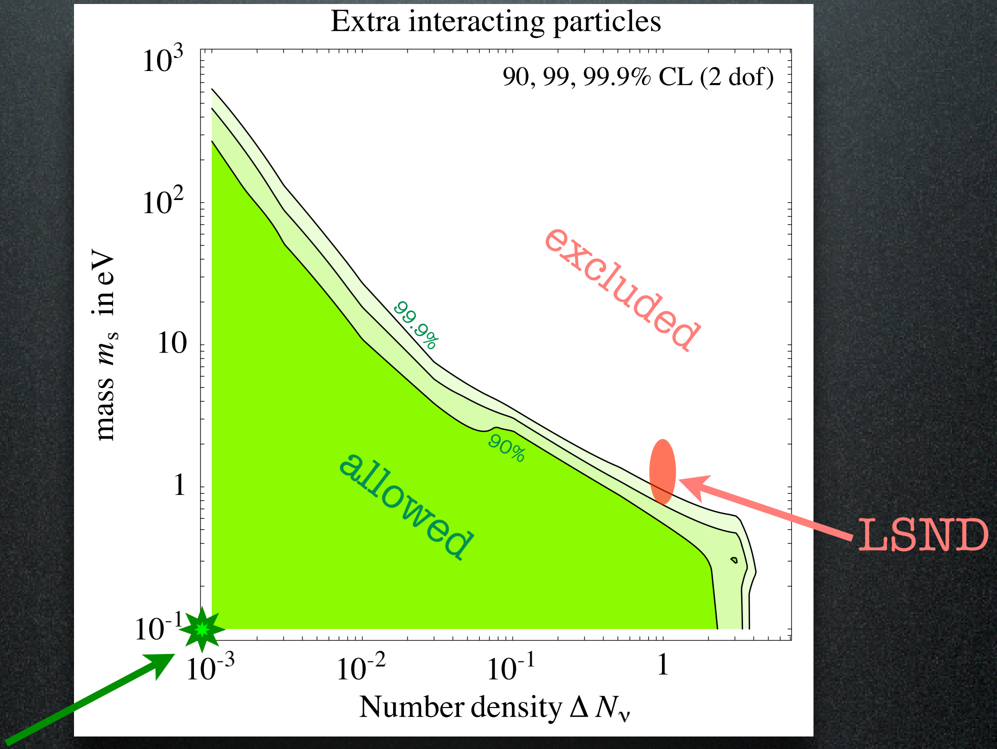
Cirelli, Strumia (2006)

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

# Cosmology with sticky neutrinos

Case: three standard neutrinos (massless),
$\Delta N_\nu$ interacting sterile neutrinos,
with mass $m_{\rm s}$.

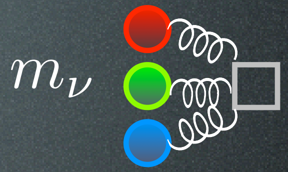


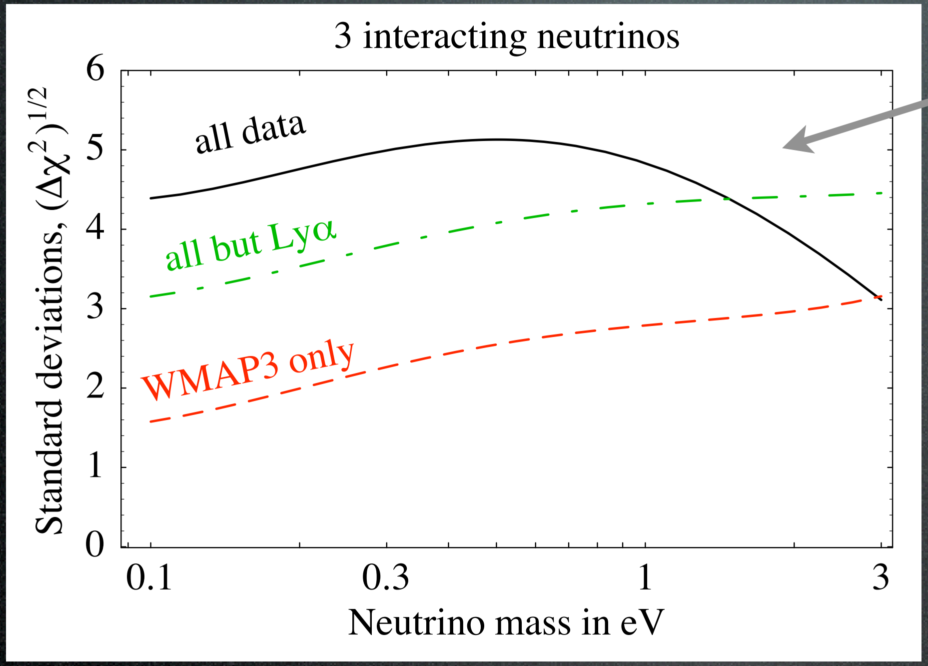


Standard cosmology

# Cosmology with sticky neutrinos

Case: three massive neutrinos,
interacting with a massless scalar.





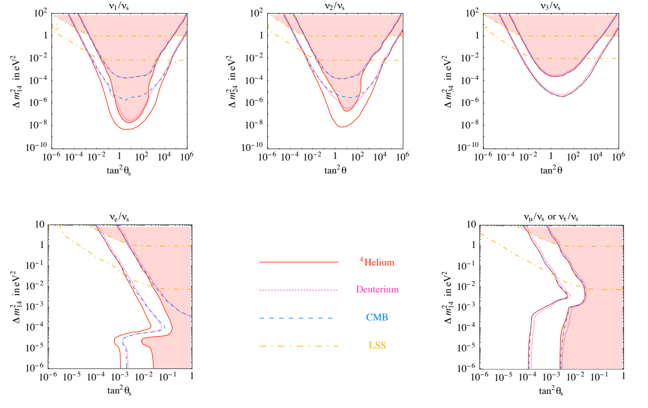
disfavored at
3 to 5 $\sigma$.

Cirelli, Strumia (2006)
[see also Hannestad, JCAP 2004]

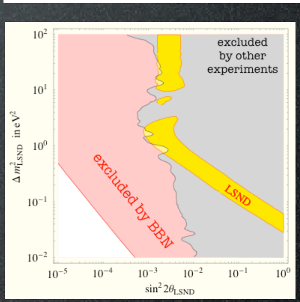
Bottom Line: Cosmology **disfavors**, at various degrees, interacting (non-freely streaming) neutrinos.

# Conclusions

- Cosmology gives some of the **most stringent bounds on $\nu_s$**:
  - BBN constraints the total $N_\nu$ and the depletion of $\nu_e, \bar{\nu}_e$
  - LSS constraints $\sum m_\nu$



- BBN and LSS **reject the LSND $\nu_s$**:



- a **large lepton asymmetry** relaxes BBN and LSS bounds ($L_\nu \simeq -10^{-4}$ to reconcile LSND)
- **interacting neutrinos** may avoid some bounds, but look problematic (lacking free streaming)

# Extra Slides

# Cosmological Perturbations

Dodelson's (Chicago, 2003)
notations

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

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

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

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

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

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

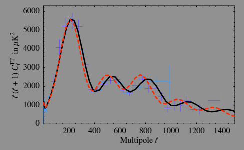
baryons

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

neutrinos

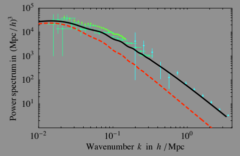
CMB Power spectrum

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



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

# Cosmological Perturbations

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

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

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:

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

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

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

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

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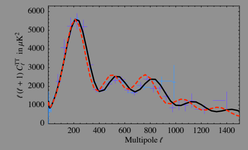
metric

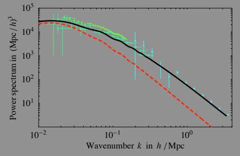
## CMB Power spectrum

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



## Matter Power spect.

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



# Cosmological Perturbations

$$\left.\begin{aligned}
&\dot{\Theta} + ik\mu\Theta = -\dot{\Phi} - ik\mu\Psi - \dot{\tau}\left[\Theta_0 - \Theta + \mu v_{\rm b} - 1/2\,\mathcal{P}_2(\mu)\Pi\right] \\
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&\dot{\Theta}_P + ik\mu\Theta_P = -\dot{\tau}\left[\Theta_P + 1/2\left(1 - \mathcal{P}_2(\mu)\right)\Pi\right]
\end{aligned}\right\}\ \text{photons}$$

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

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

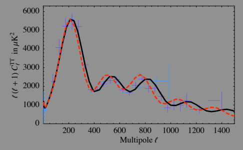
and velocity $v_{\rm dm}$

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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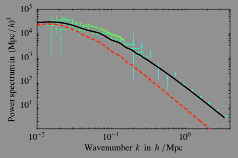

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&k^2\left(\Phi + \Psi\right) = -32\pi G_N a^2\rho_{\rm r}\Theta_{{\rm r},2}
\end{aligned}\right\}\ \text{metric}$$

# Cosmological Perturbations

$$\left.\begin{aligned}
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&\qquad\qquad\qquad \dot{\tau} = d\tau/d\eta = -n_e\sigma_T a \qquad \Pi = \Theta_2 + \Theta_{P2} + \Theta_{P0} \\
&\dot{\Theta}_P + ik\mu\Theta_P = -\dot{\tau}\left[\Theta_P + 1/2\big(1 - \mathcal{P}_2(\mu)\big)\Pi\right]
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\end{aligned}\right\}$$

dark matter

$$\left.\begin{aligned}
&\dot{\delta}_{\mathrm{b}} + ikv_{\mathrm{b}} = -3\dot{\Phi} \qquad\qquad R = 3\rho_{\mathrm{b}}^0/4\rho_\gamma^0 \\
&\dot{v}_{\mathrm{b}} + \frac{\dot{a}}{a}v_{\mathrm{b}} = -ik\Psi + \frac{\dot{\tau}}{R}\left[v_{\mathrm{b}} + 3i\Theta_1\right]
\end{aligned}\right\}$$

baryons

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

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

Thomson scattering

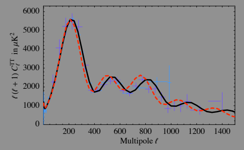
$e^-\gamma \longleftrightarrow e^-\gamma$

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

metric

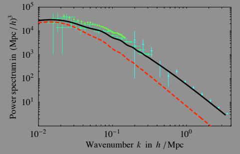
CMB Power spectrum

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



Matter Power spect.

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



# Cosmological Perturbations

$$\left.\begin{array}{l}\dot\Theta + ik\mu\Theta = -\dot\Phi - ik\mu\Psi - \dot\tau\left[\Theta_0 - \Theta + \mu v_{\rm b} - 1/2\,\mathcal{P}_2(\mu)\Pi\right] \\ \qquad\qquad \dot\tau = d\tau/d\eta = -n_e\sigma_T a \qquad \Pi = \Theta_2 + \Theta_{P2} + \Theta_{P0} \\ \dot\Theta_P + ik\mu\Theta_P = -\dot\tau\left[\Theta_P + 1/2\big(1 - \mathcal{P}_2(\mu)\big)\Pi\right]\end{array}\right\}$$

photons

$$\left.\begin{array}{l}\dot\delta_{\rm dm} + ikv_{\rm dm} = -3\dot\Phi \\ \dot v_{\rm dm} + \frac{\dot a}{a}v_{\rm dm} = -ik\Psi\end{array}\right\}$$

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

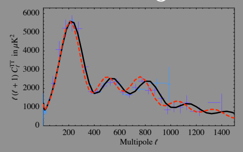
$\Phi(\vec{x},t) \longrightarrow \Phi(k,\eta)$

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

metric

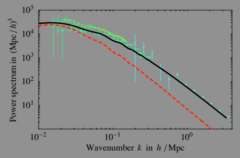
CMB Power spectrum

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



Matter Power spect.

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



# Cosmological Perturbations

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

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

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

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

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

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

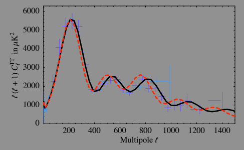
Expand in multipoles: $\mathcal{N}_\ell(k, \mu, \eta)$

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

metric

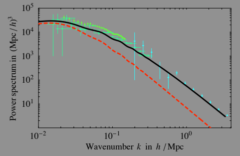
CMB Power spectrum

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



Matter Power spect.

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



# Cosmological Perturbations

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

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

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

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

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

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

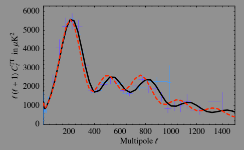
baryons

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

neutrinos

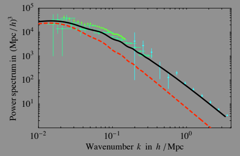
## CMB Power spectrum

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



## Matter Power spect.

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



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

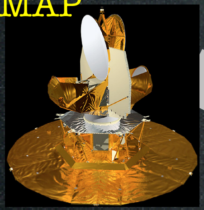
$$k^2\left(\Phi + \Psi\right) = -32\pi G_N a^2\rho_{\rm r}\Theta_{{\rm r},2}$$

metric

# The dataset

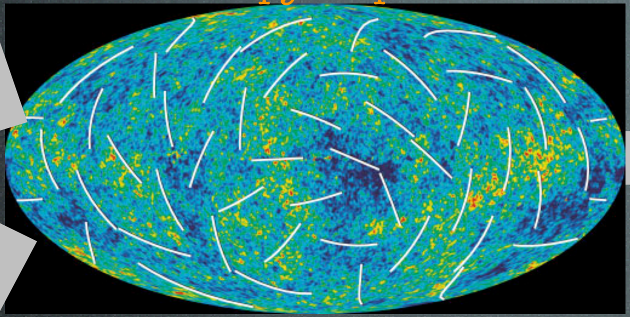
( ↘ = some highly non trivial steps )

WMAP

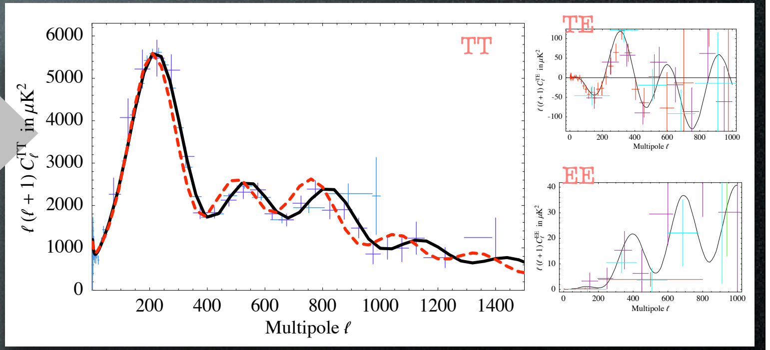


Boomerang...

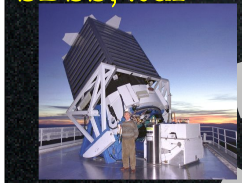
CMB anisotropy map



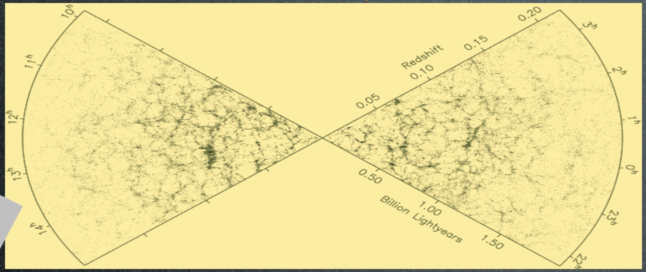
CMB power spectrum



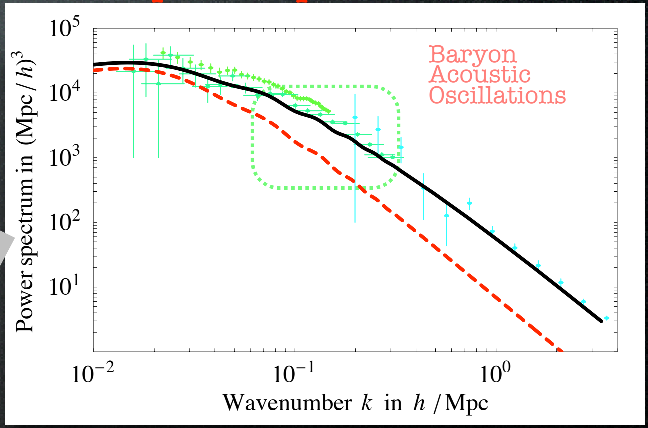
SDSS, 2dF



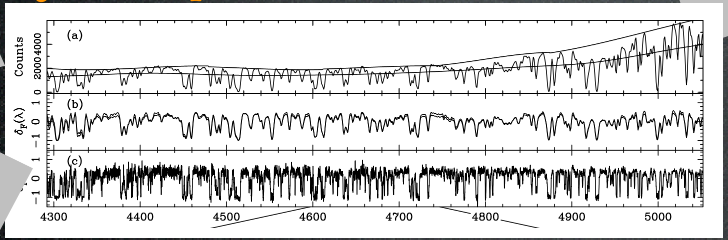
LSS redshift survey



matter power spectrum



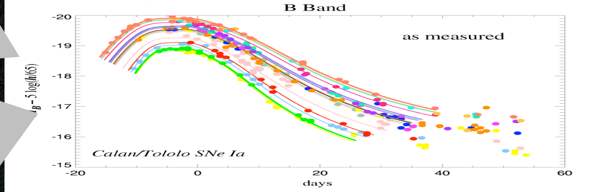
Lyman-alpha forest



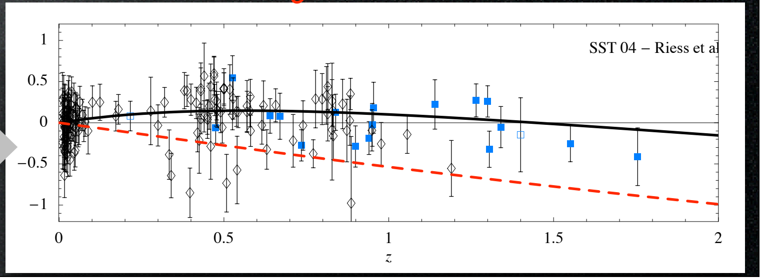
Keck, Hawaii

HST

SNIa lightcurves



SNIa luminosity distance



# 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:

in terms of a measurement of

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

Eisenstein et al., astro-ph/0501171

## Lyman-$\alpha$ 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

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

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# 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 |

(Recombination is implemented calling recfast.)

We adopt **gaussian** statistics.

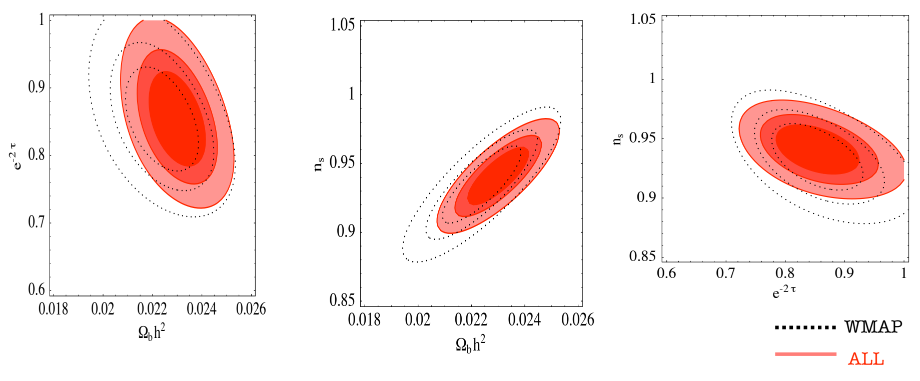
For Standard Cosmology we obtain:

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

(assumes $3_{.04}$ massless, freely-streaming neutrinos).

# Comparing our code

## Our analysis:



| fit | $A_s$ | $h$ | $n_s$ | $\tau$ | $100\Omega_b h^2$ | $\Omega_{\rm DM} h^2$ |
|---|---|---|---|---|---|---|
| WMAP3 | $0.80 \pm 0.05$ | $0.704 \pm 0.033$ | $0.935 \pm 0.019$ | $0.081 \pm 0.030$ | $2.24 \pm 0.10$ | $0.113 \pm 0.010$ |
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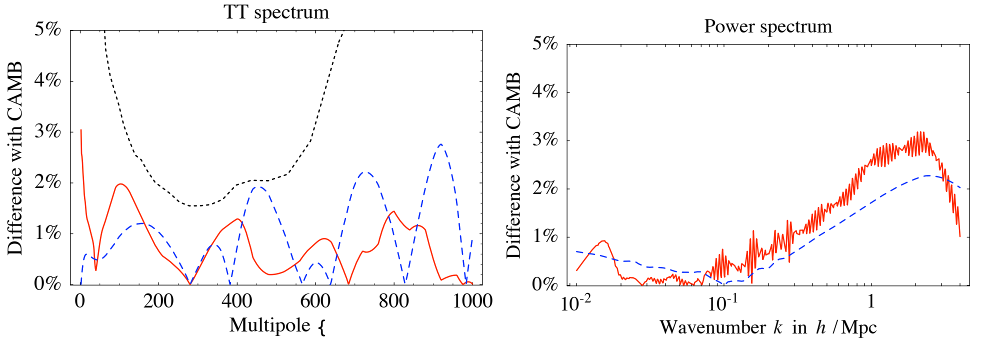
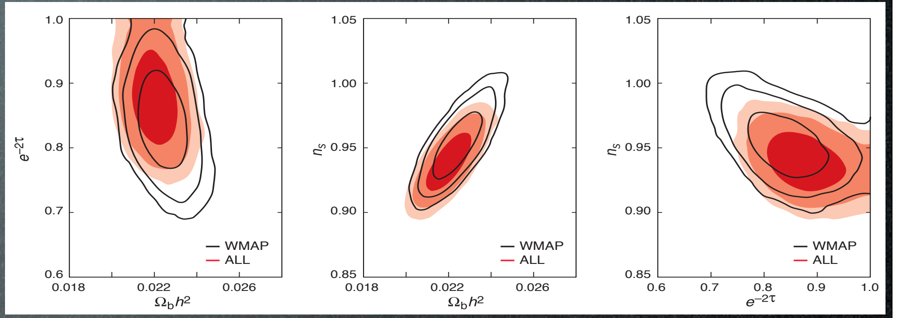


## WMAP Science Team analysis:



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

| Parameter | WMAP Only | WMAP+ SDSS | WMAP+ LRG | WMAP + SN Gold |
|---|---|---|---|---|
| $100\Omega_b h^2$ | $2.233^{+0.072}_{-0.091}$ | $2.233^{+0.062}_{-0.086}$ | $2.242^{+0.062}_{-0.084}$ | $2.227^{+0.065}_{-0.082}$ |
| $\Omega_m h^2$ | $0.1268^{+0.0073}_{-0.0128}$ | $0.1329^{+0.0057}_{-0.0109}$ | $0.1337^{+0.0047}_{-0.0098}$ | $0.1349^{+0.0054}_{-0.0106}$ |
| $h$ | $0.734^{+0.028}_{-0.038}$ | $0.709^{+0.024}_{-0.032}$ | $0.709^{+0.016}_{-0.023}$ | $0.701^{+0.020}_{-0.026}$ |
| $A$ | $0.801^{+0.043}_{-0.054}$ | $0.813^{+0.042}_{-0.052}$ | $0.816^{+0.042}_{-0.049}$ | $0.827^{+0.045}_{-0.053}$ |
| $\tau$ | $0.088^{+0.028}_{-0.034}$ | $0.079^{+0.029}_{-0.032}$ | $0.082^{+0.028}_{-0.033}$ | $0.079^{+0.028}_{-0.034}$ |
| $n_s$ | $0.951^{+0.015}_{-0.019}$ | $0.948^{+0.015}_{-0.018}$ | $0.951^{+0.014}_{-0.018}$ | $0.946^{+0.015}_{-0.019}$ |
| $\sigma_8$ | $0.744^{+0.050}_{-0.060}$ | $0.772^{+0.036}_{-0.048}$ | $0.781^{+0.032}_{-0.045}$ | $0.784^{+0.035}_{-0.049}$ |
| $\Omega_m$ | $0.238^{+0.027}_{-0.045}$ | $0.266^{+0.025}_{-0.040}$ | $0.267^{+0.017}_{-0.029}$ | $0.276^{+0.022}_{-0.036}$ |

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

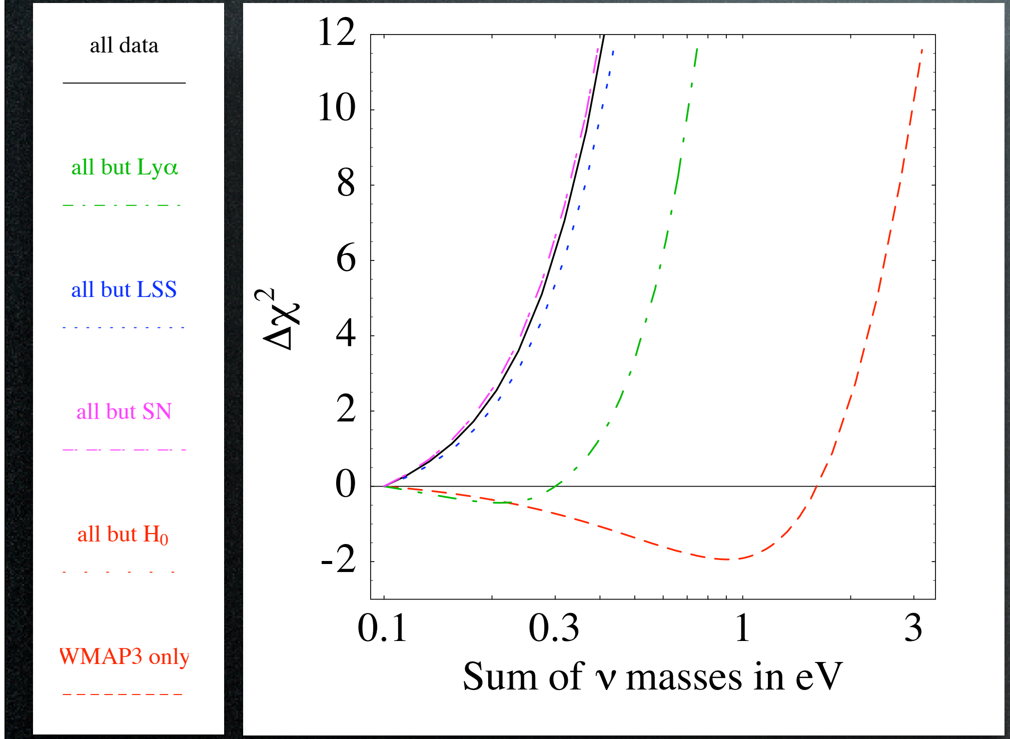
[back]

# Results

## How heavy are neutrinos?

● ● ●
(3 massive neutrinos)

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



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.

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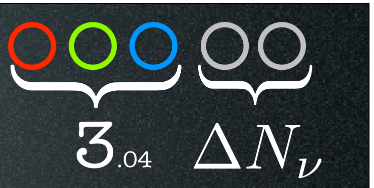
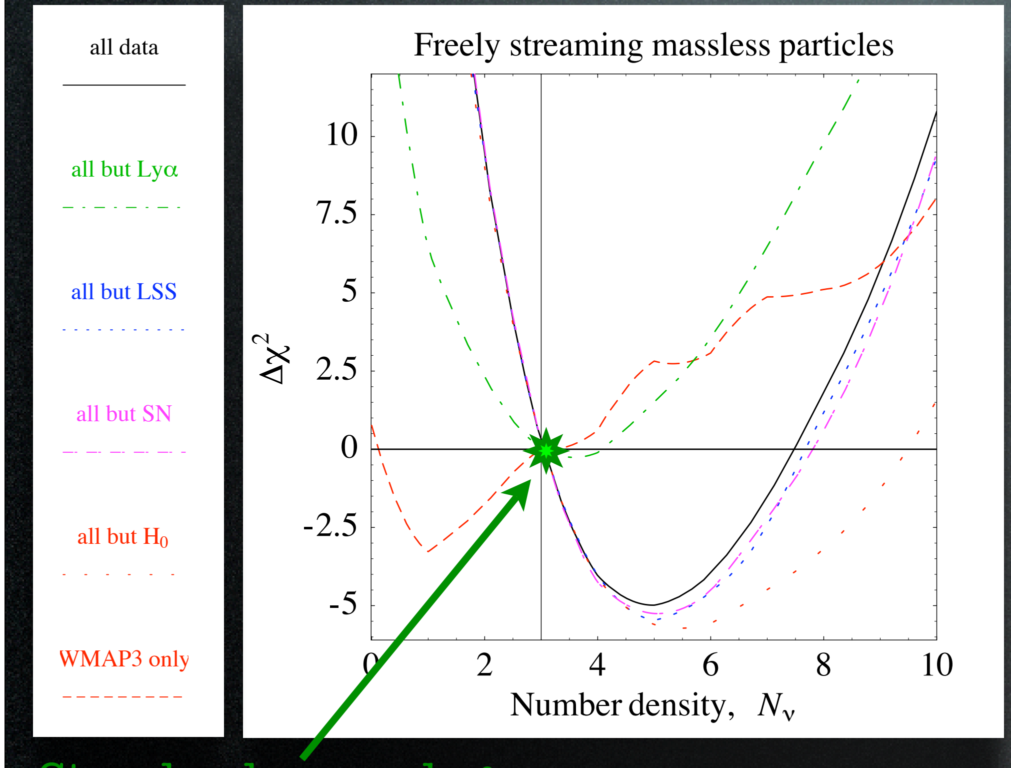
# Results

## New neutrinos?



All $N_\nu$ relativistic degrees of freedom contribute to the energy density.



Standard cosmology

Global fit:

$$\boxed{N_\nu = 5 \pm 1}$$

dropping Ly-alpha gives back

$$\boxed{N_\nu \simeq 3}$$

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

# Cosmological Perturbations

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

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

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

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

$$\dot{\delta}_{\rm x} = -(1+w)(3\dot{\Phi} + ikv_{\rm x})$$

$$\dot{v}_{\rm x} = -ik\Psi + \tfrac{\dot{a}}{a}\,(1-3w)\,iv_{\rm x} - \tfrac{w}{1+w}ik\delta_{\rm x}$$

extra

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

⇩

A fluid defined by $\delta_{\rm x}, v_{\rm x}$,
with $w = 1/3$ when rel,
$w = 0$ when NR.

Contribute to the Rel/NR
energy densities.

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

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

metric

[back]