Annecy Neutrino GDR, 13 March 2007

Sterile Neutrinos

(in all sauces)

Marco Cirelli

(SPhT-CEA/Saclay & INFN)

with:

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based on:

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JCAP 12 (2006) 013, hep-ph/0607086
PRD 74 (2006) 085015, astro-ph/0608206

Why sterile neutrinos

We want to study light sterile neutrinos ν_s.

$\mathcal{O}(\text{eV})$ (why light?)

- spin 1/2 fermions,
- neutral under SM forces,
- mix with active neutrinos.

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pulsar kicks
galactic ionization
solar neutrino modulation...

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r-process nucleosynthesis
pulsar kicks
galactic ionization
solar neutrino modulation...

- predicted in beyond SM models

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

The discovery of a new light particle would be fundamental.

3+1= 4 neutrino mixing

Instead of a limited 2ν formalism $\nu_l \to \cos\theta_s \nu_{l'} + \sin\theta_s \nu_s$

we want a full 4ν formalism, including active-active oscillations.

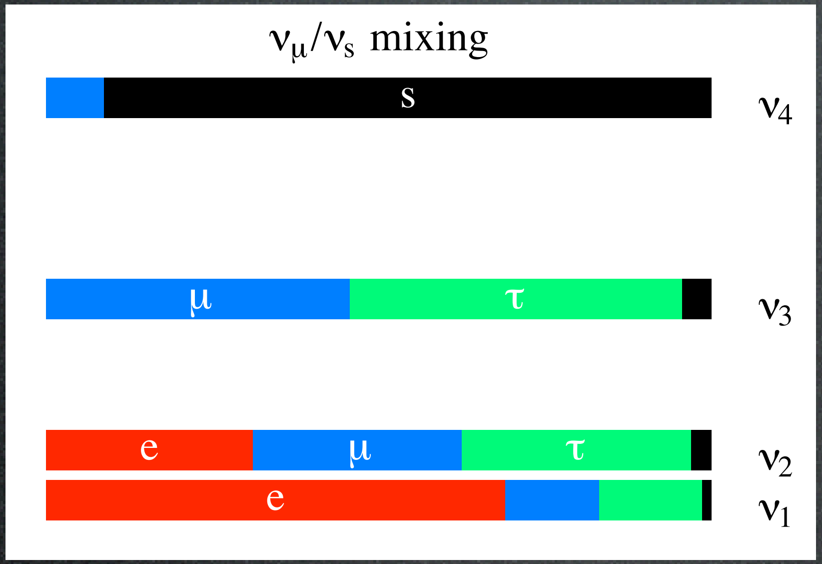
A simple parametrization: unit vector $\vec{n}$ identifies a combination of $\nu_{\rm active}$

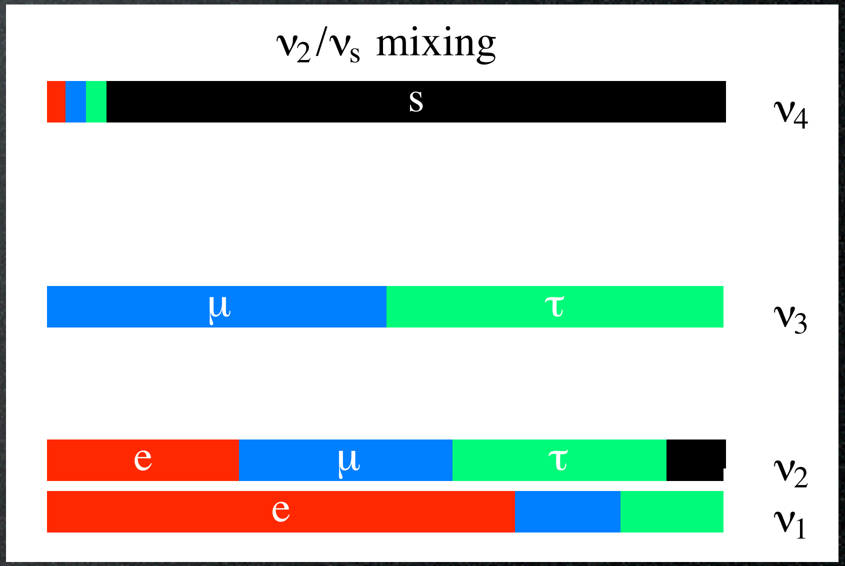
$$\vec{n}\cdot\vec{\nu} = n_e\nu_e + n_\mu\nu_\mu + n_\tau\nu_\tau = n_1\nu_1 + n_2\nu_2 + n_3\nu_3$$

which mixes with ν_s with an angle θ_s,

ν_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 θ_s.

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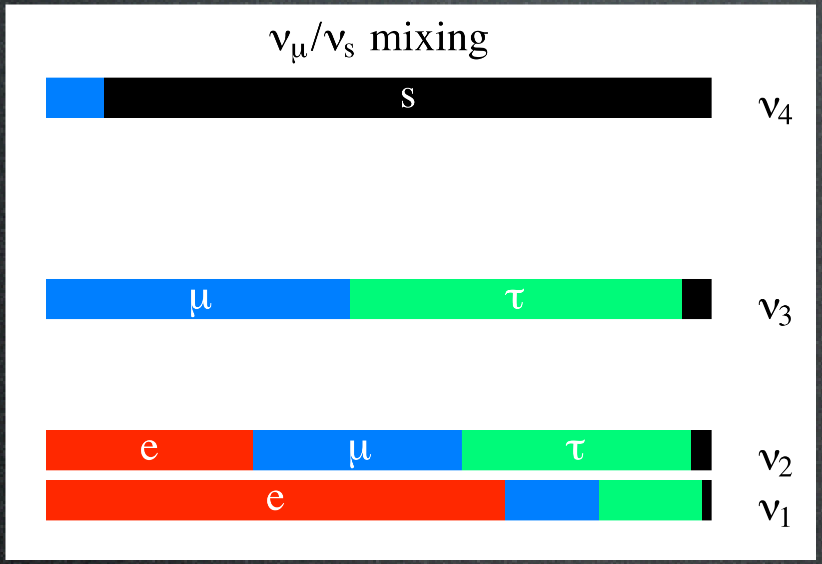
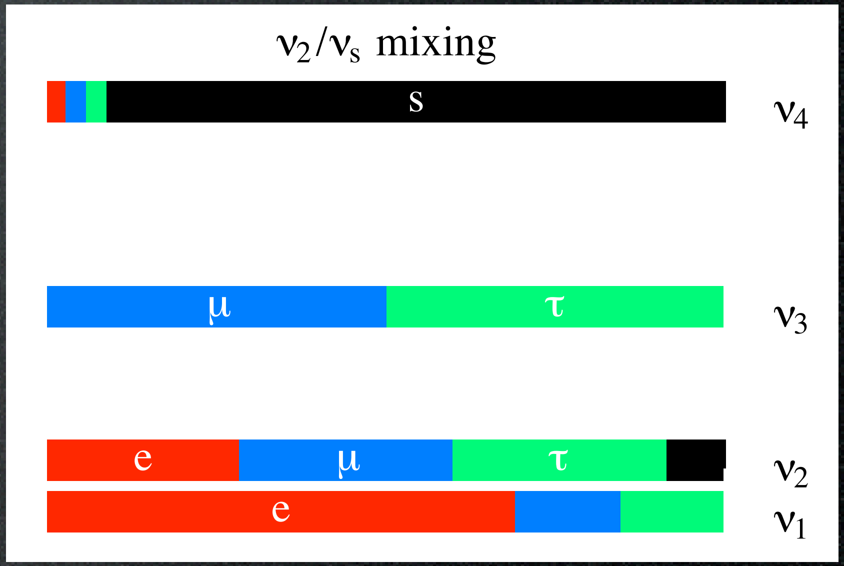
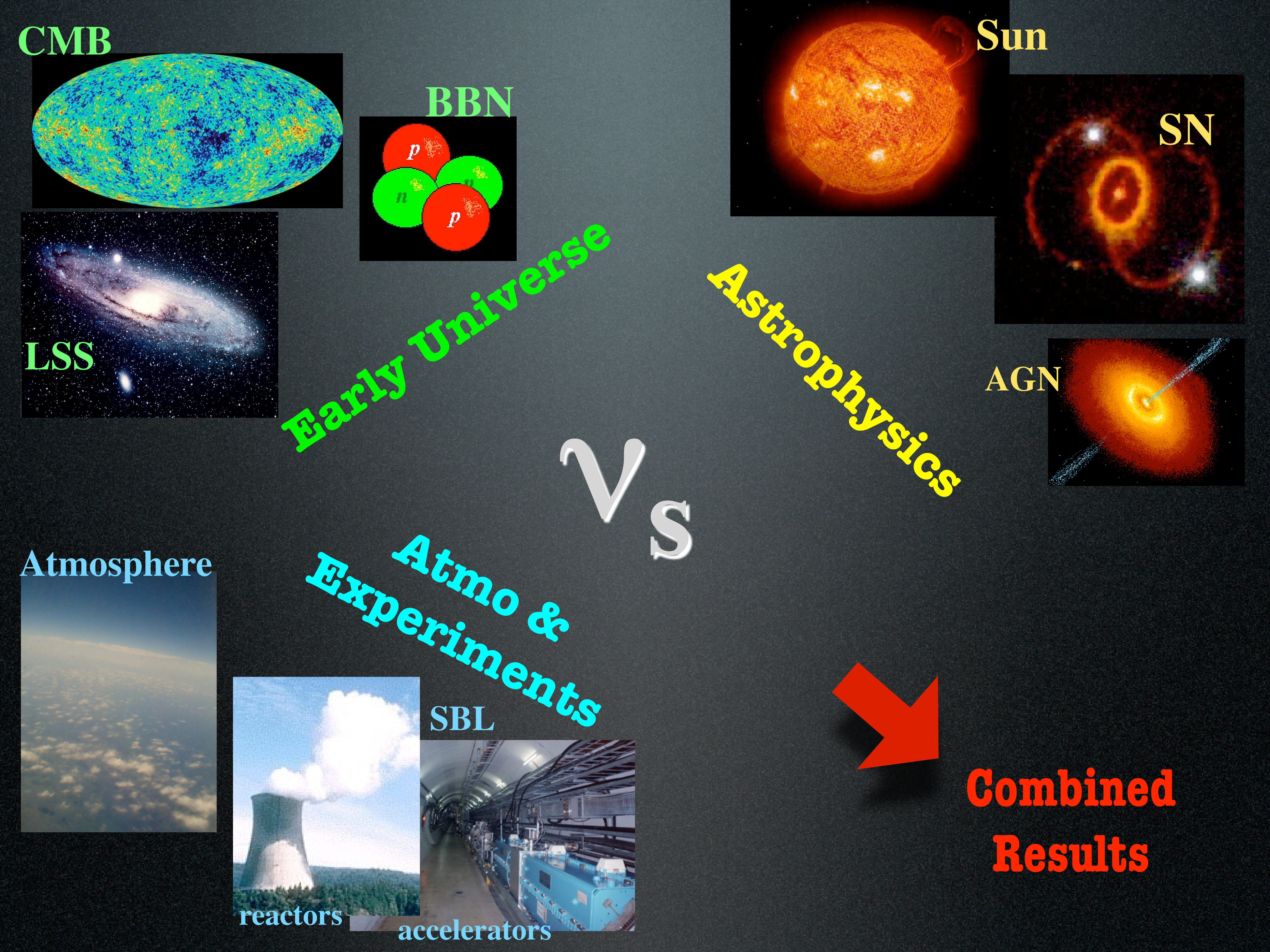




Free parameters: given a case, m_4 and θ_s .

Active parameters: $\Delta m^2_{\rm sun}, \Delta m^2_{\rm atm}, \theta_{12}, \theta_{23}, \theta_{13} \equiv 0$, norm hierarchy.


CMB
BBN
p
n
n
p
Sun
SN
LSS
Early Universe
Astrophysics
AGN
νs
Atmosphere
Atmo &
Experiments
SBL
reactors
accelerators
Combined
Results

Sterile neutrinos in cosmology

Neutrinos are important in the Early Universe because they are:

- a lot (as abundant as photons)
- the main component of the (relativistic) energy density that sets the expansion scale
- shaping the growth of galaxies via their free-streaming

An extra ν_s can make a big difference.

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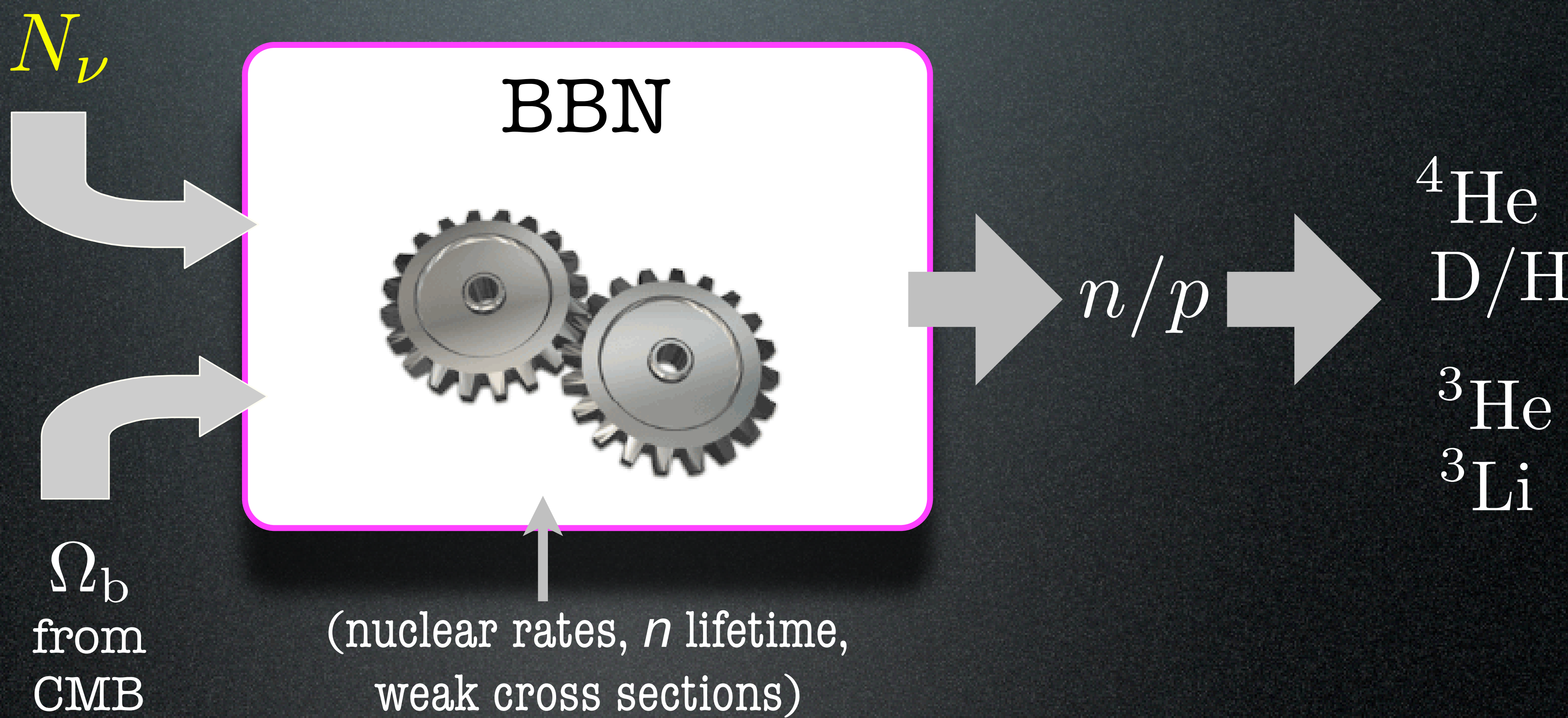
Bounds come: from BBN
- T $\sim$ MeV
- flavor is important
- matter effects in the plasma

Bounds come: from later cosmology (CMB, LSS)
- T $\lesssim$ eV
- m_ν is important

Big Bang Nucleosynthesis



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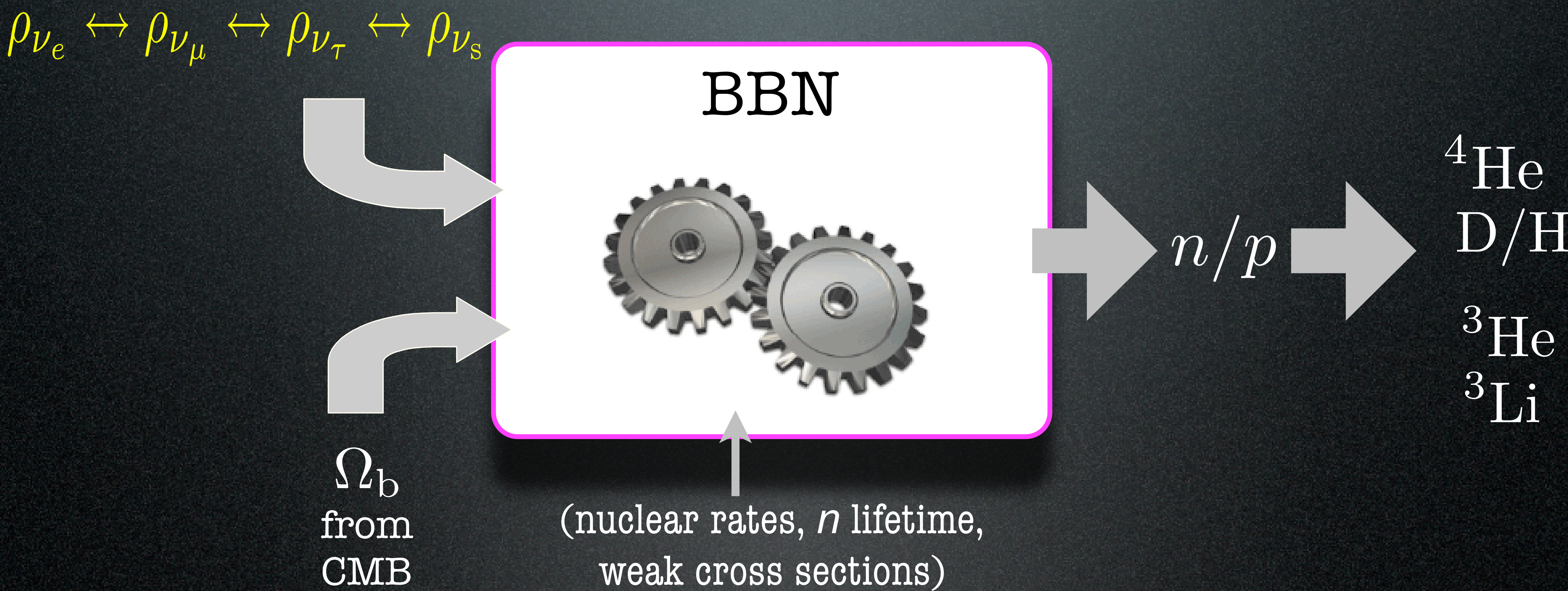

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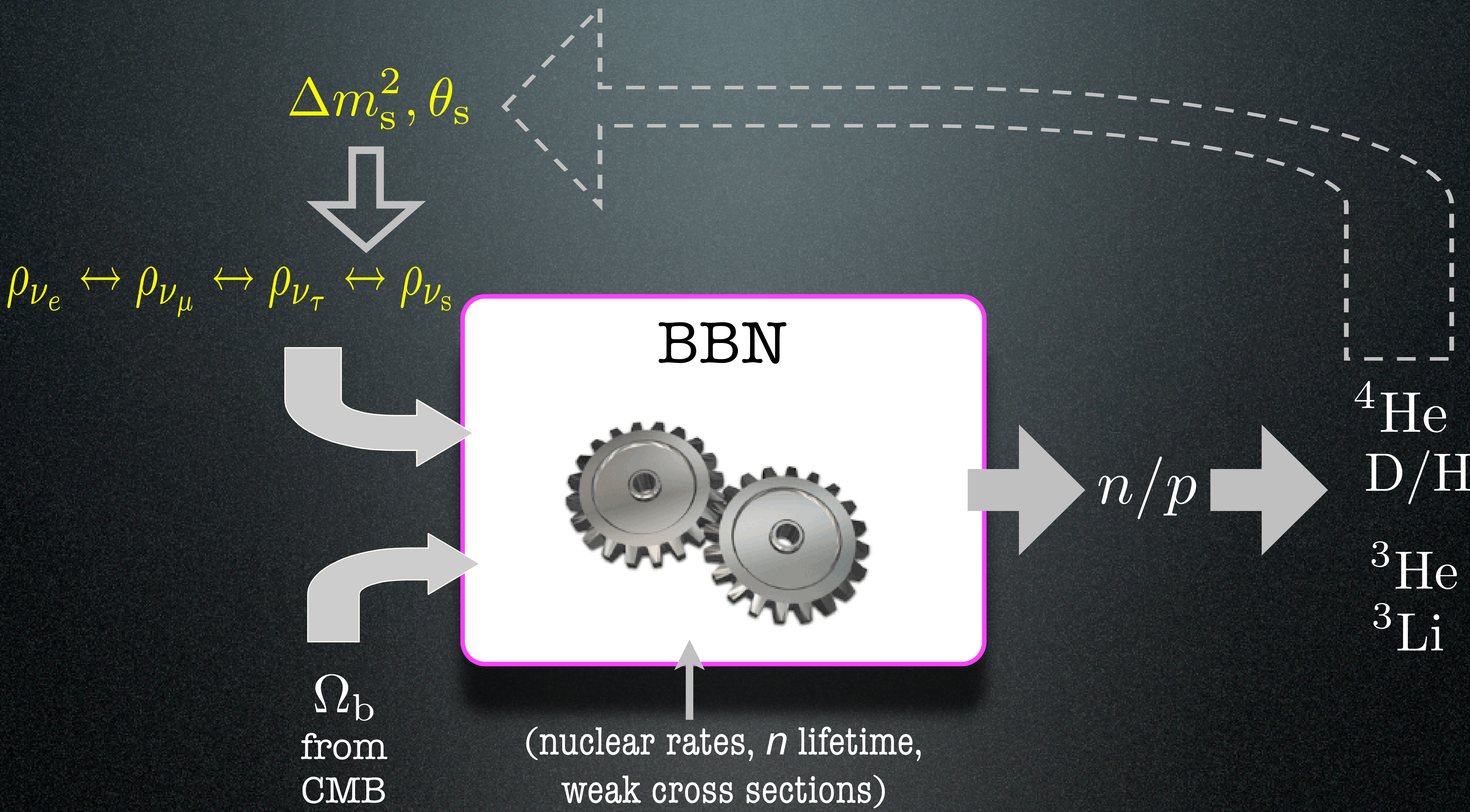


For any choice of $\Delta m_s^2, \theta_s$ a prediction from BBN.

Big Bang Nucleosynthesis

For every choice of $\Delta m_s^2, \theta_s$,
for T $\gg$ MeV $\longrightarrow$ 0.07 MeV
follow:

(BBN ends, les jeux sont faits)

1 kinetic equations for neutrino densities

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

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

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

Assumptions:

- no large lepton asymmetries
- neglect spectral distortions Fuller et al., 2004-2006

Big Bang Nucleosynthesis

1. Neutrino kinetic equations

4x4 neutrino density matrix ρ

3. scatterings and absorptions

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

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

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

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

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

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

$$V_s = 0$$

ν thermal masses

Big Bang Nucleosynthesis

1. Neutrino kinetic equations

What happens qualitatively:

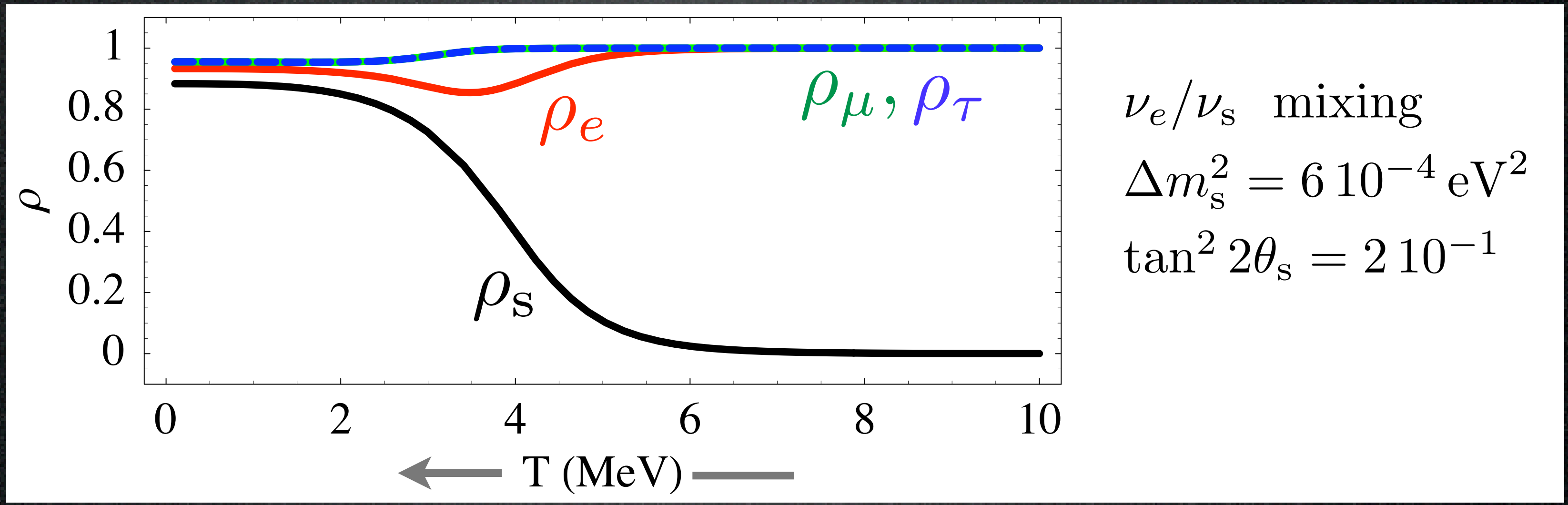
- for $T \gg \text{MeV}$, matter effects suppress mixing $(\rho_{\nu_s} \simeq 0)$

- as T decreases, at a certain point oscillations $\nu_{\rm active} \leftrightarrow \nu_s$ can begin $(\Delta m^2_s, \theta_s)$ $(\rho_{\nu_s} \nearrow)$

- + redistribution $\nu_{\rm active} \leftrightarrow \nu_{\rm active}$

- meanwhile: ν decouple at $T \sim \text{MeV}$, e^+e^- annihilate...

- Output: $\rho_{\nu_e}(T), \rho_{\nu_\mu}(T), \rho_{\nu_\tau}(T), \rho_{\nu_s}(T)$



[back to case with asymmetry]

Big Bang Nucleosynthesis

2. n/p ratio

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

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

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

Big Bang Nucleosynthesis

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So, *where does a* ν_s *enter the game?*

(A) total energy density $\Rightarrow$ expansion parameter

(B) depletion of ν_e density $\Rightarrow$ weak rates

Big Bang Nucleosynthesis

3. Light elements production

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

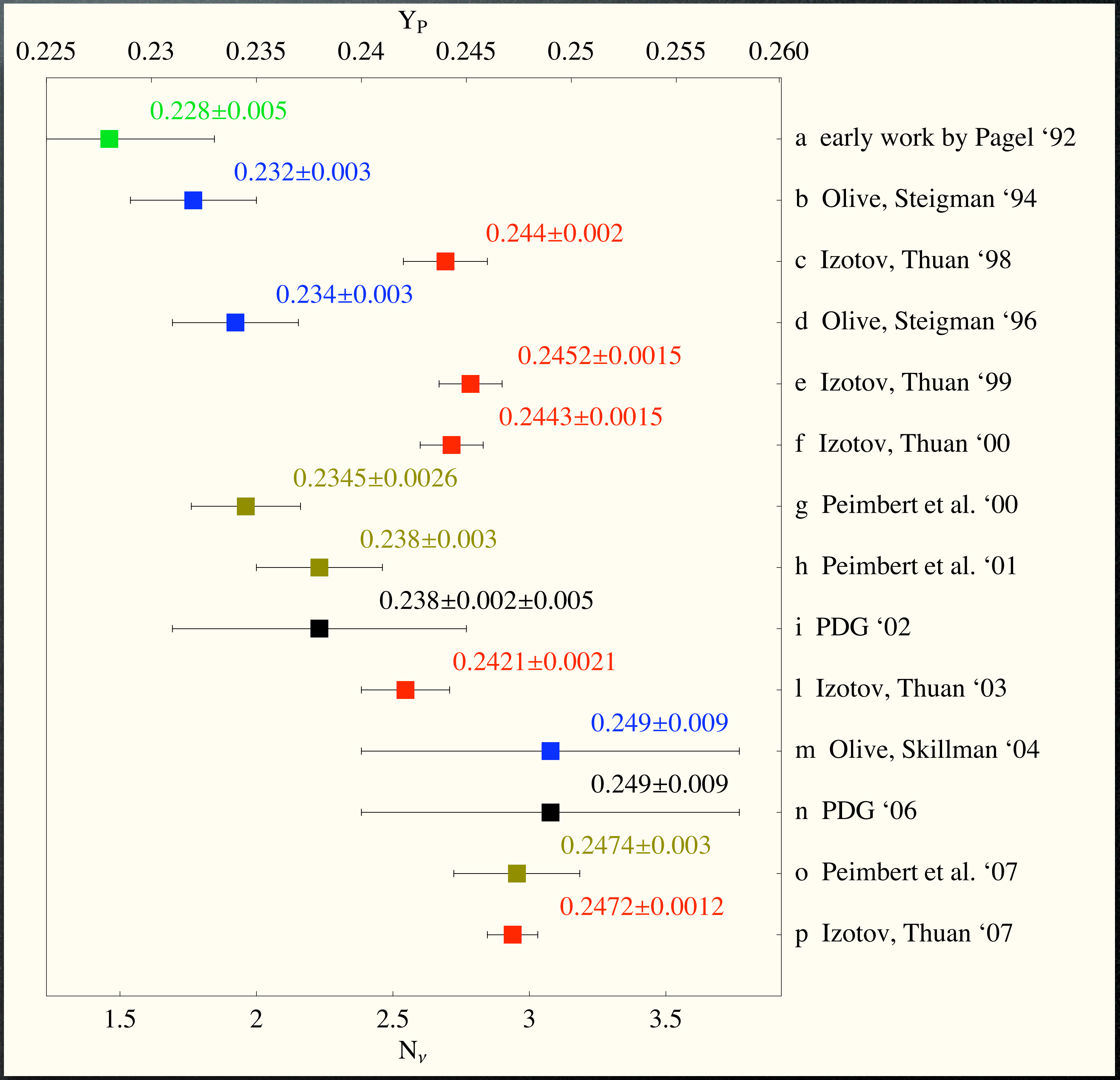
4. Observations

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.)



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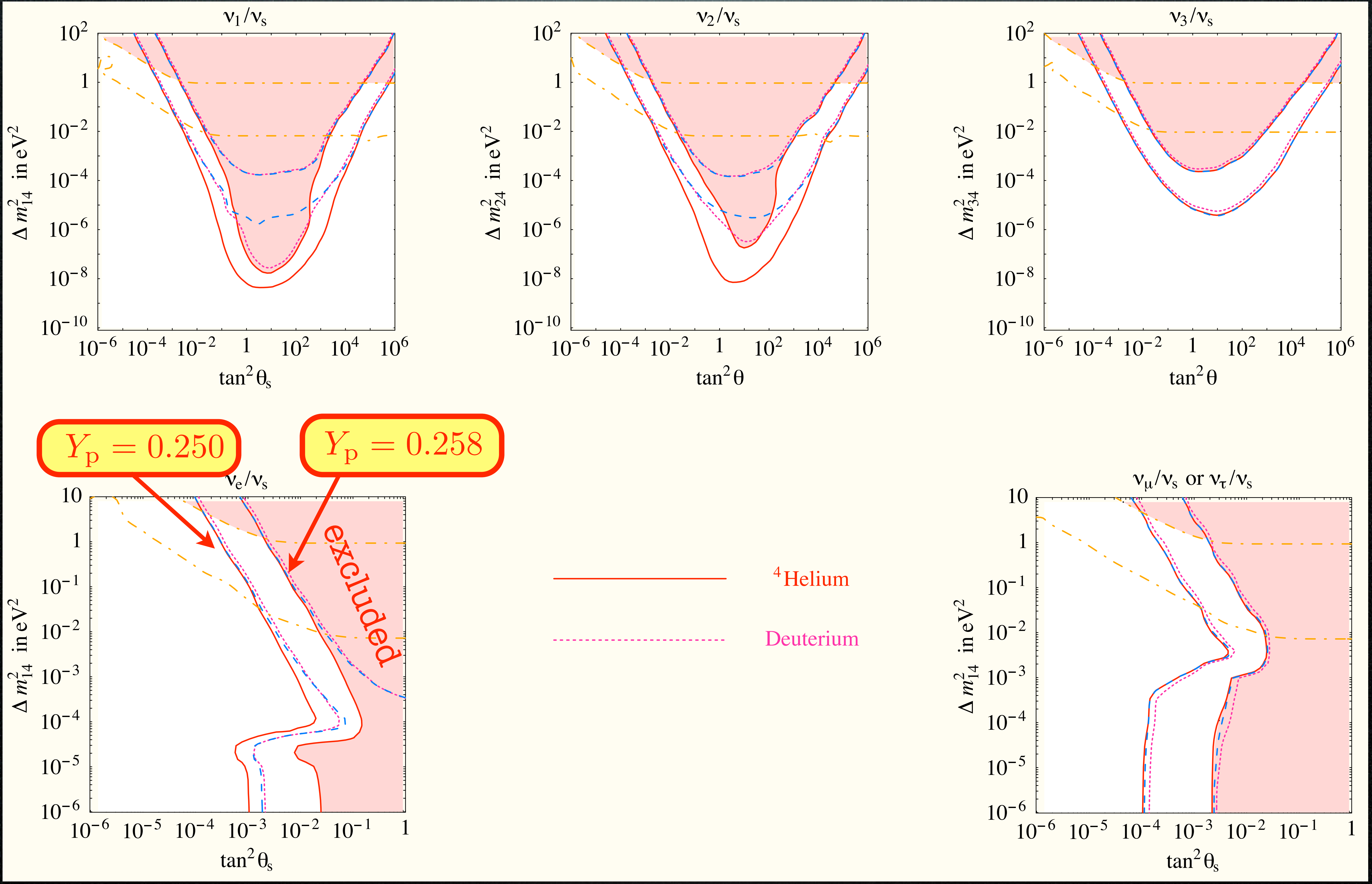


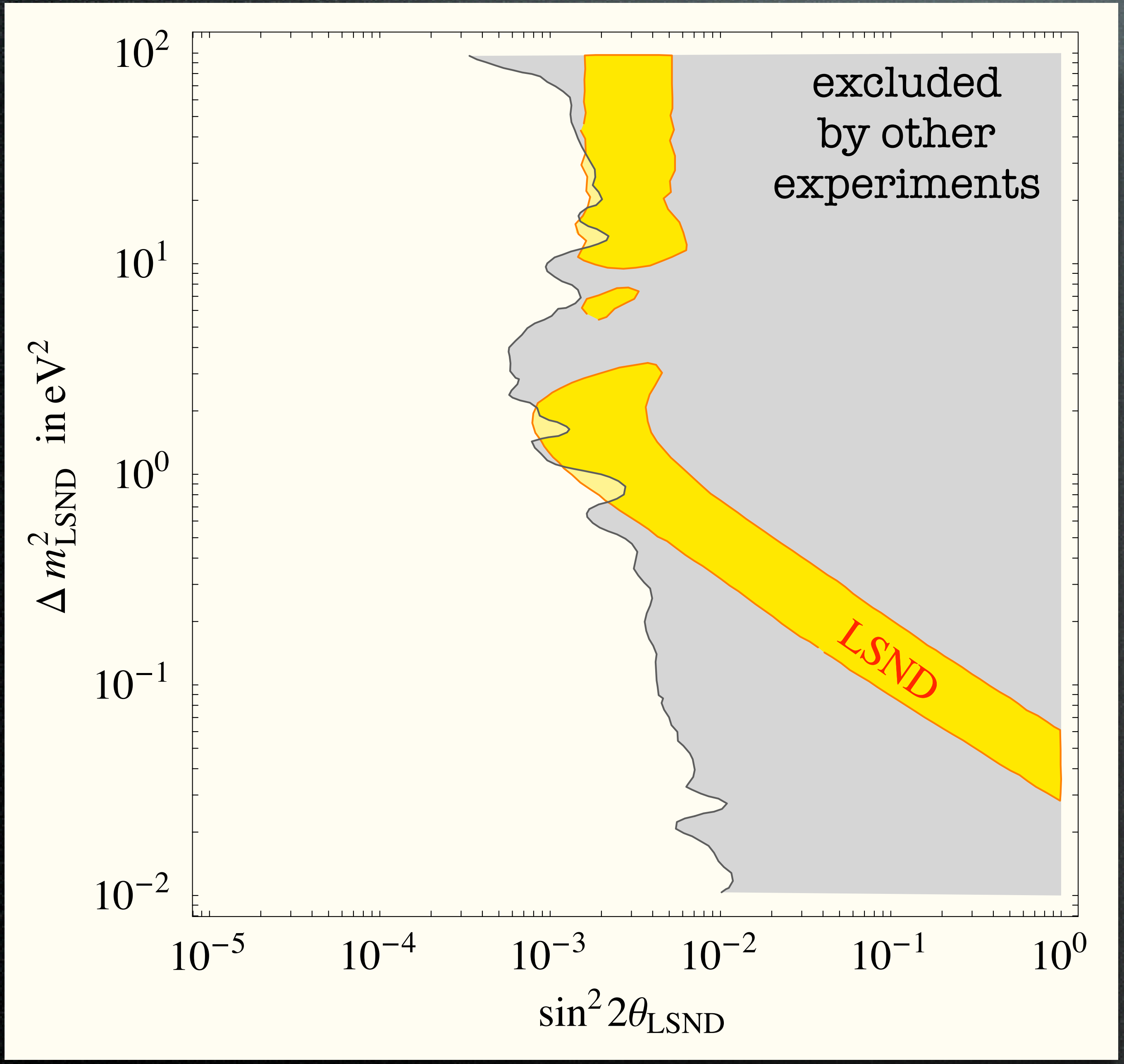
Cirelli, Marandella, Strumia, Vissani 2004

LSND

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

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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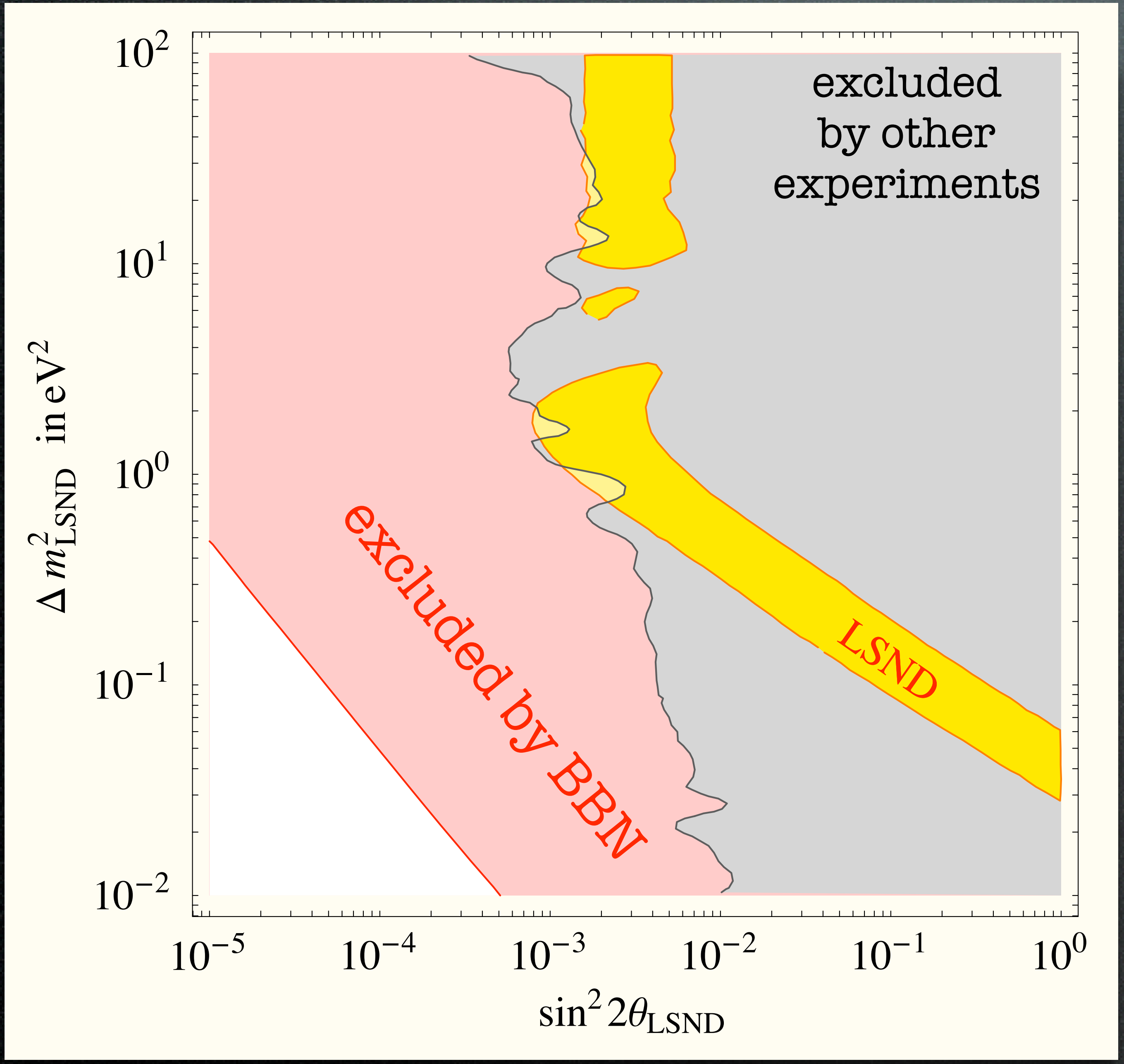

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Cosmological Perturbations

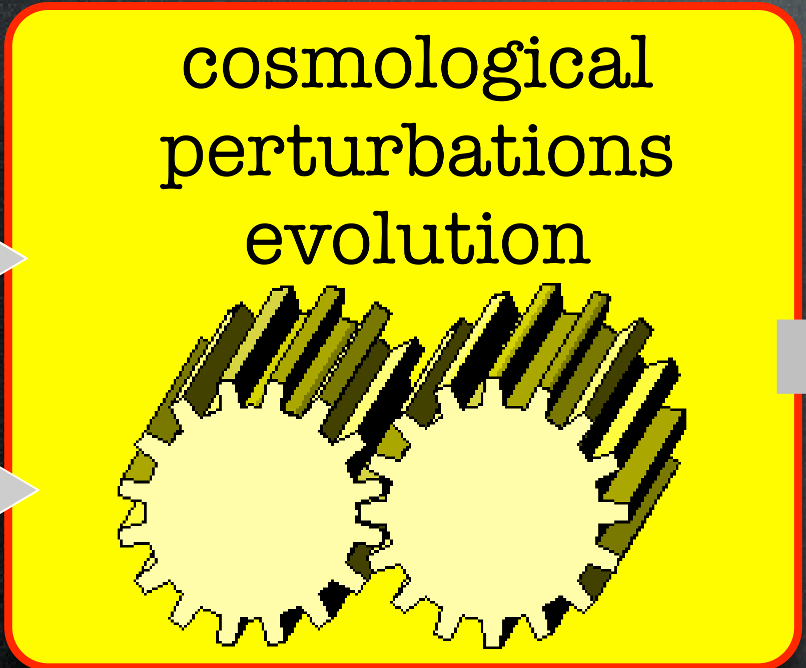
Neutrinos affect cosmological perturbations (CMB, LSS).

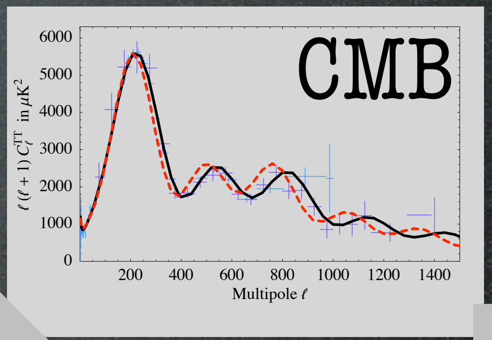
N_ν

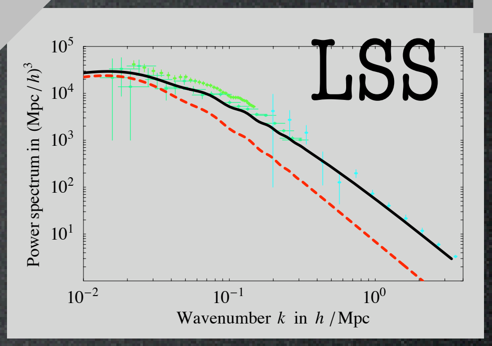
$\sum m_\nu$

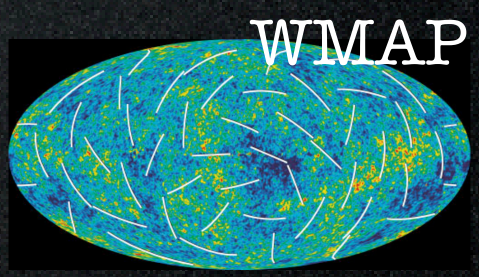
$\Omega_{\rm b}, \Omega_{\rm DM}, \tau,$

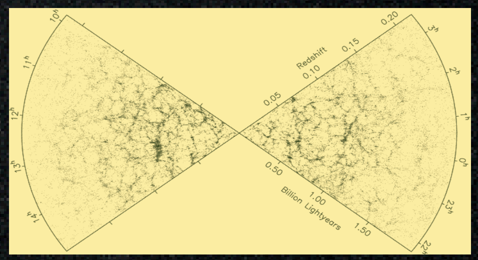
A_s, H_0, n_s











2dF, SDSS, Ly-A

Cosmological Perturbations

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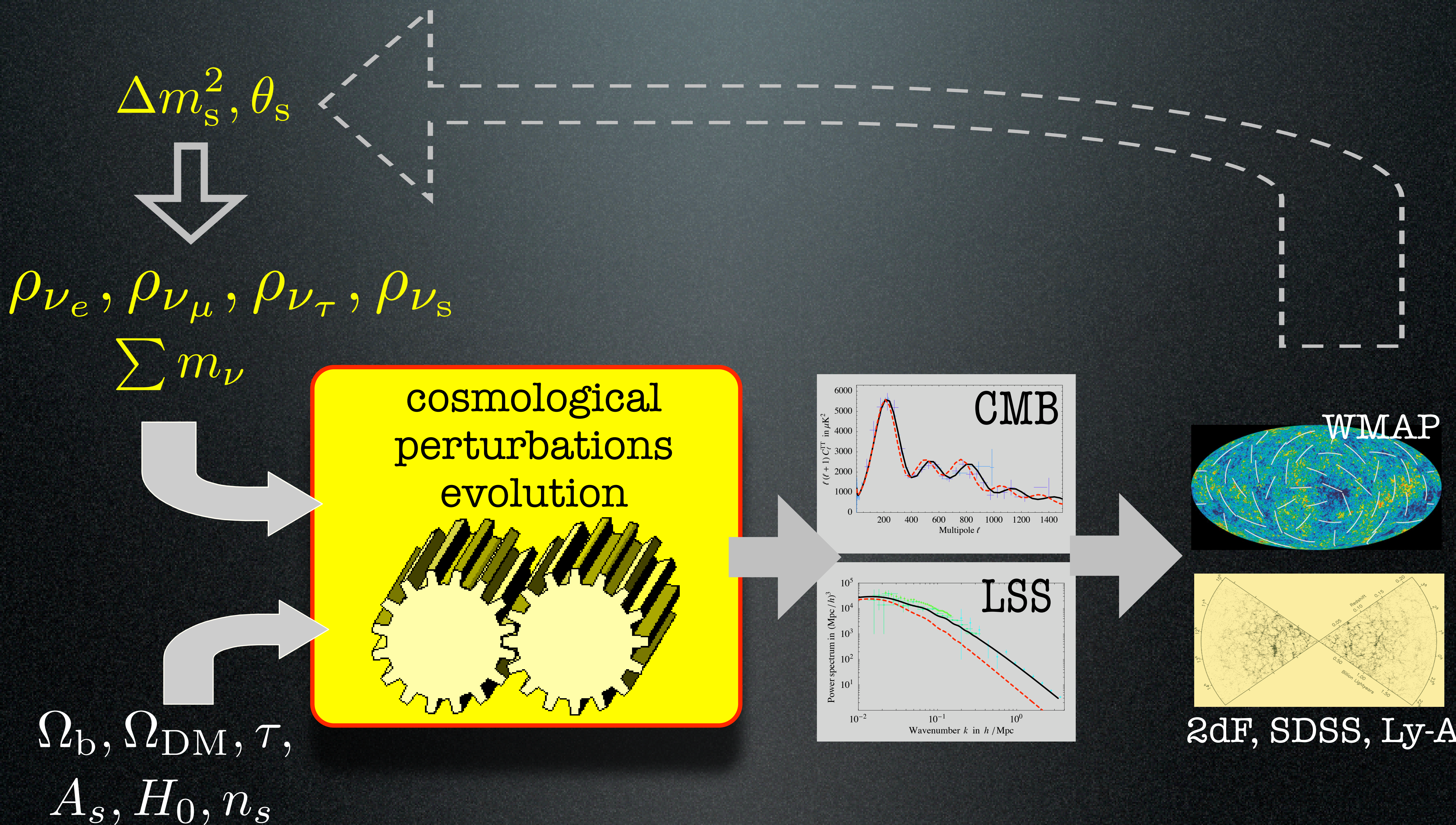

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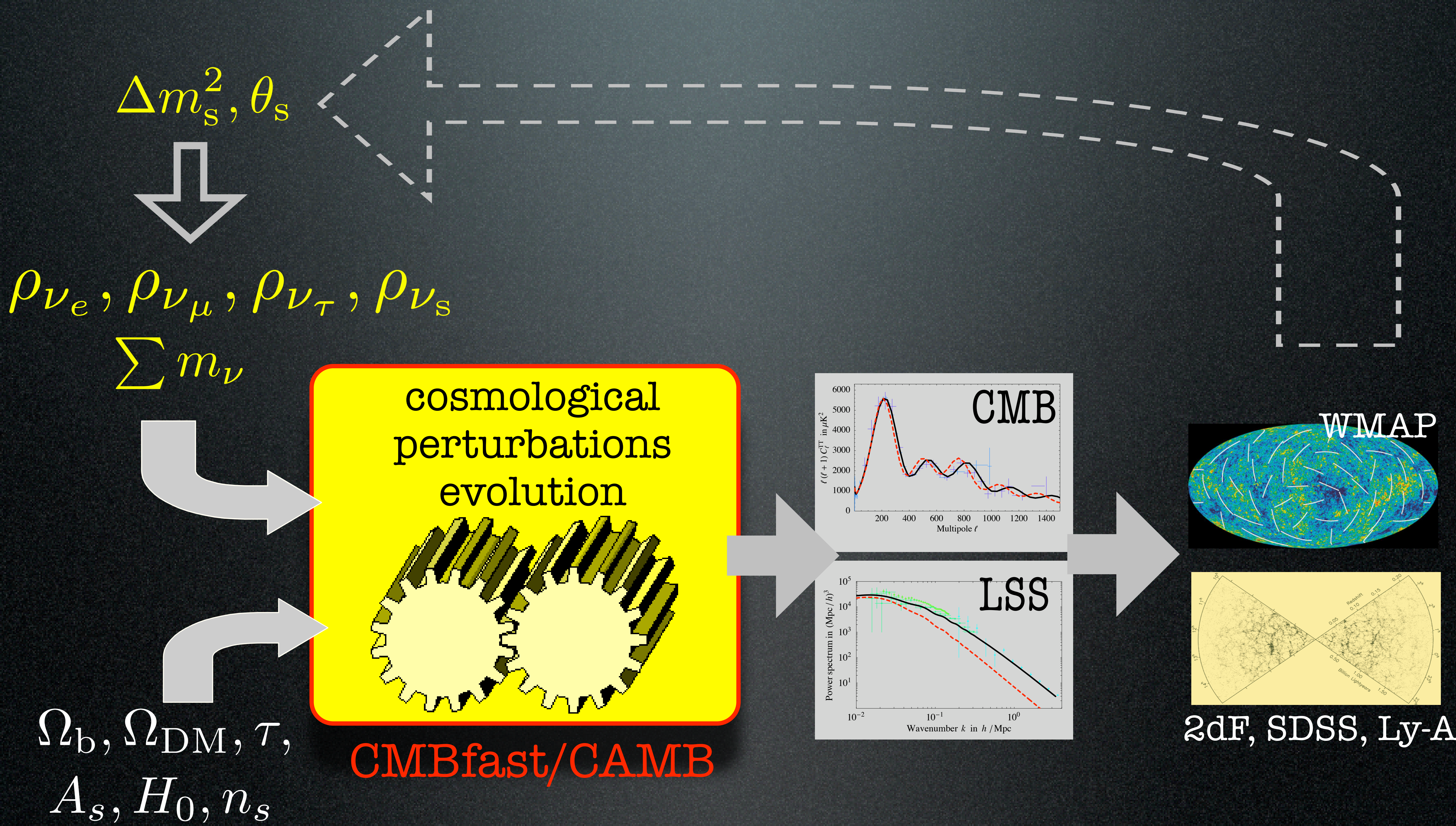

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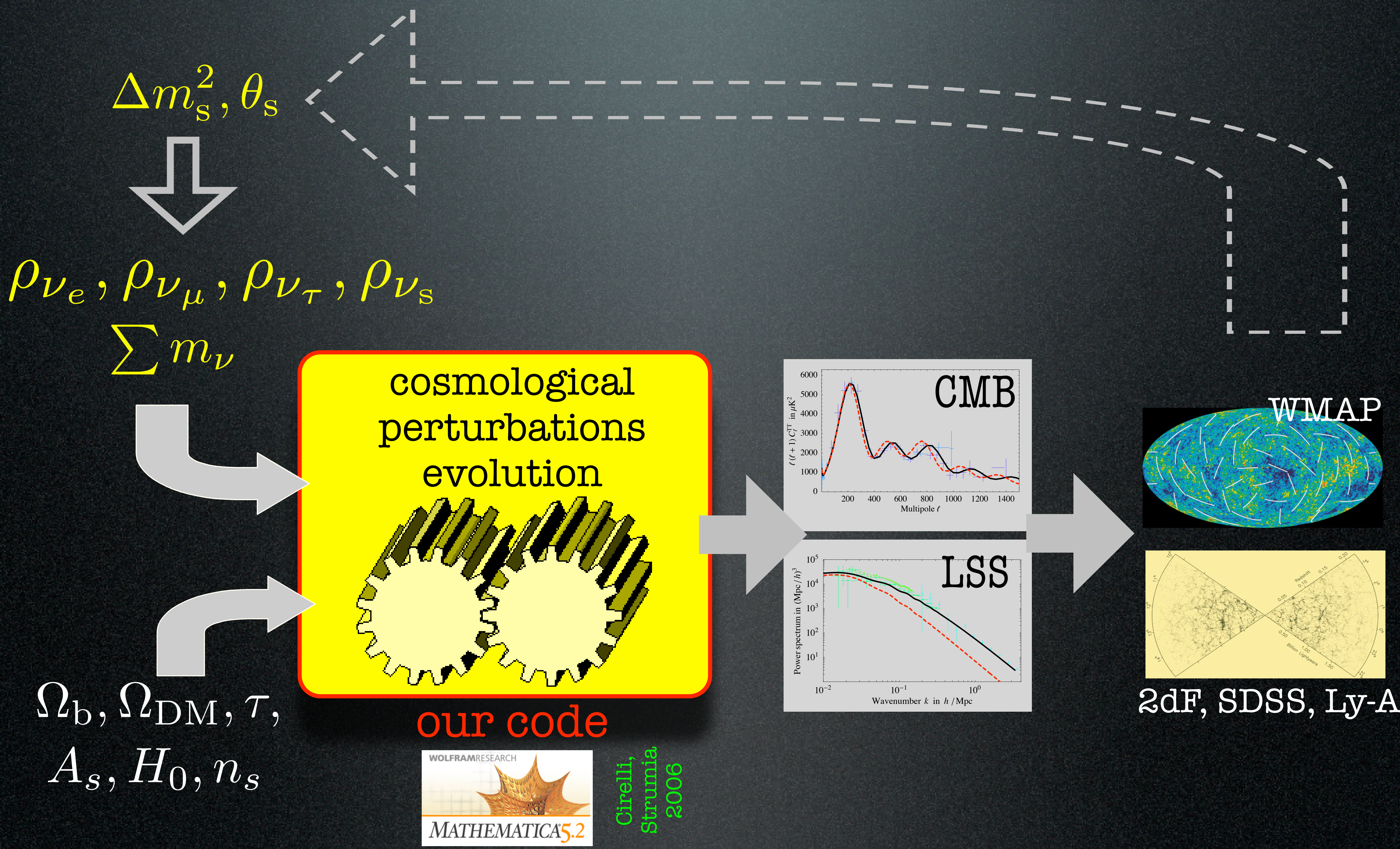
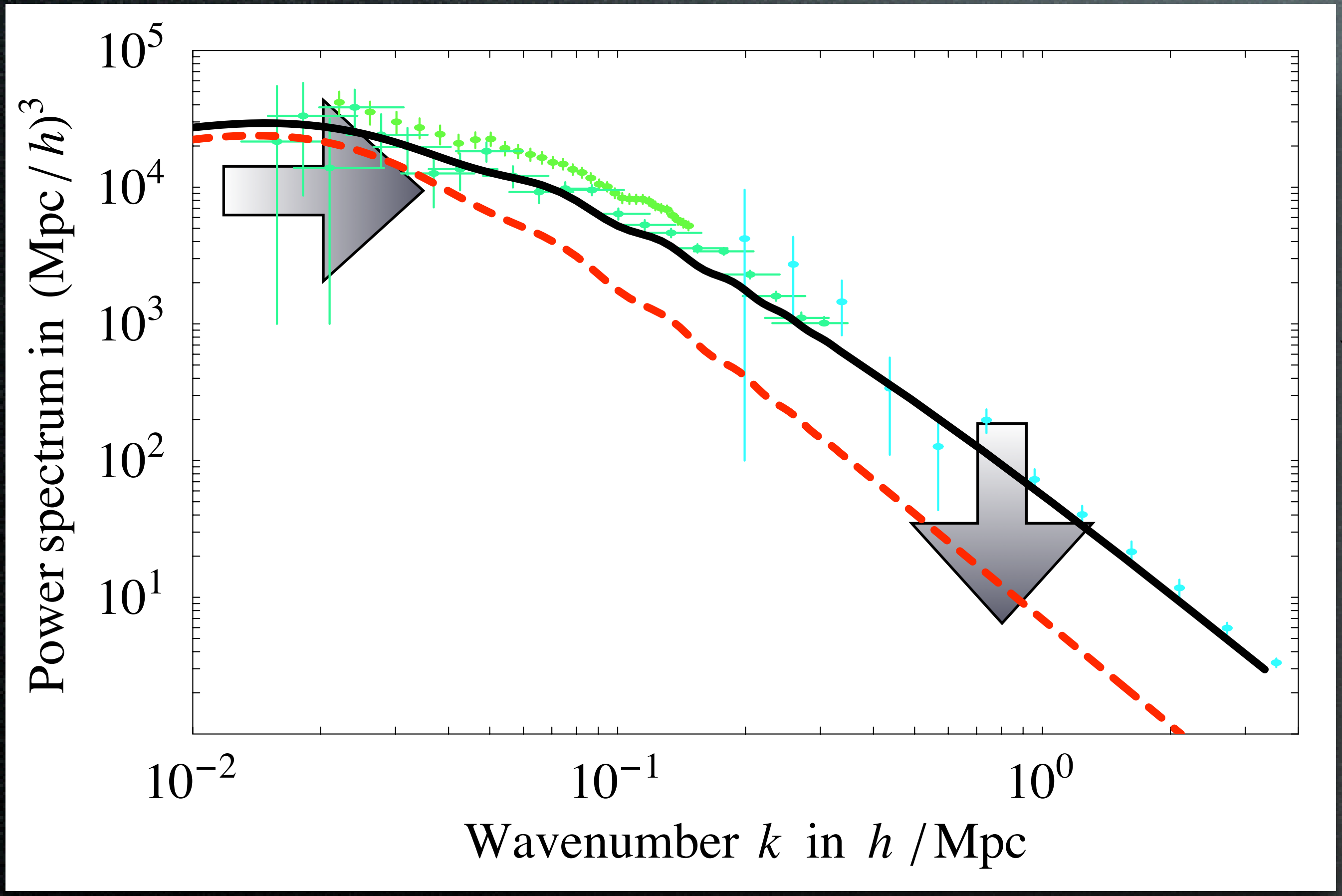


Cosmological Perturbations

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 $\delta_{\rm dm}$)



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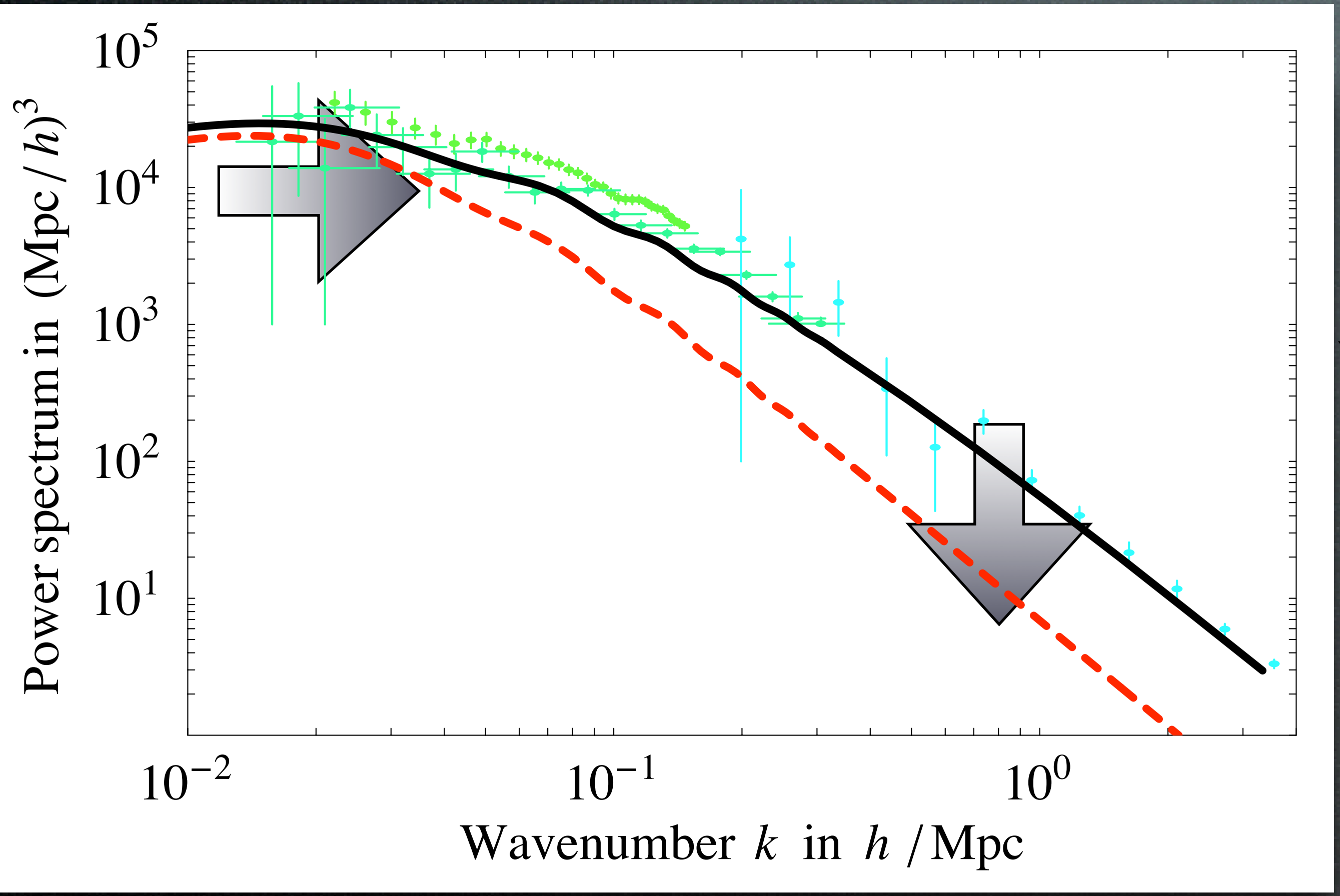

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$$\Downarrow$$

a bound on $\sum m_\nu$:

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

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

Cirelli, Strumia 2006 (others also)

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

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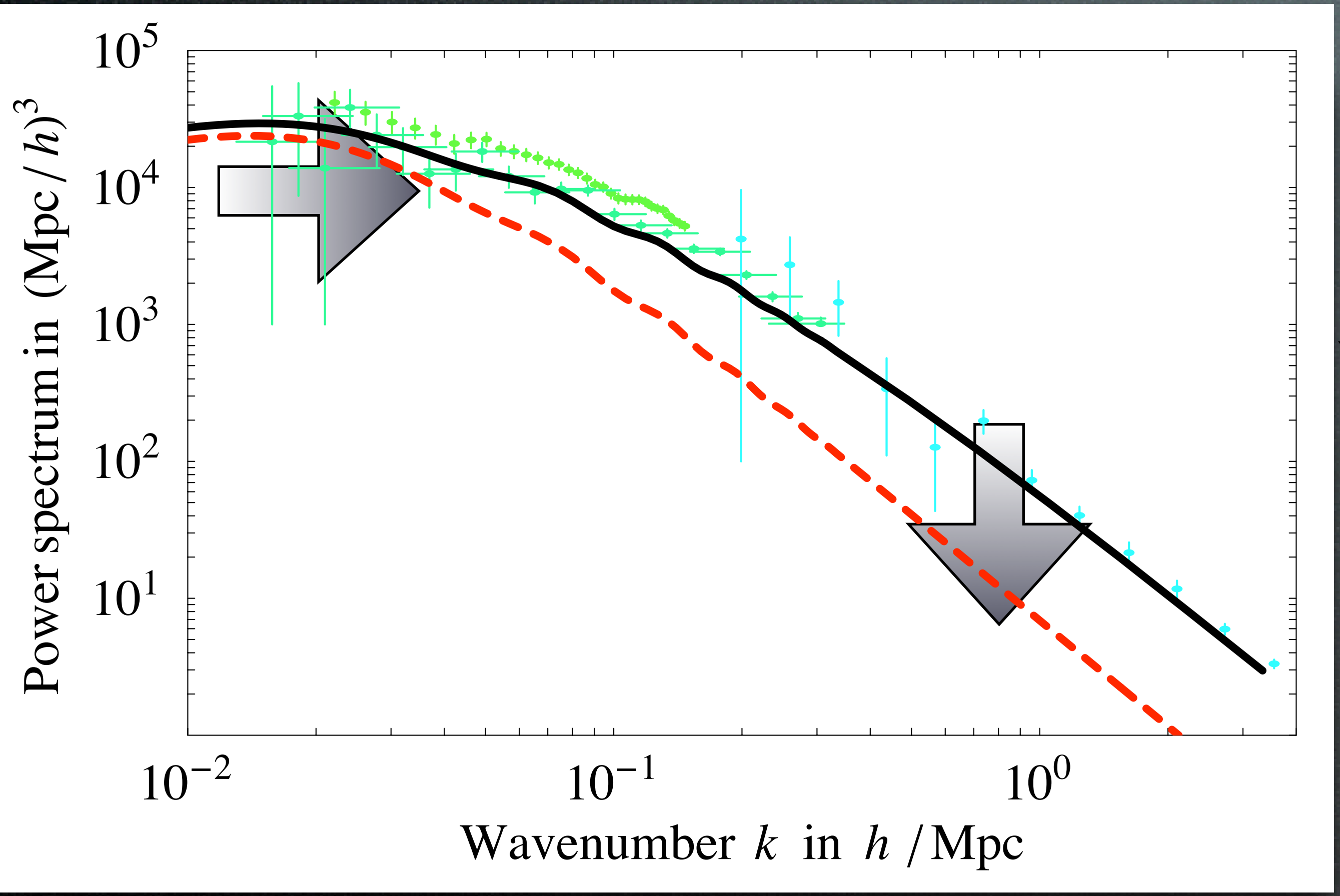

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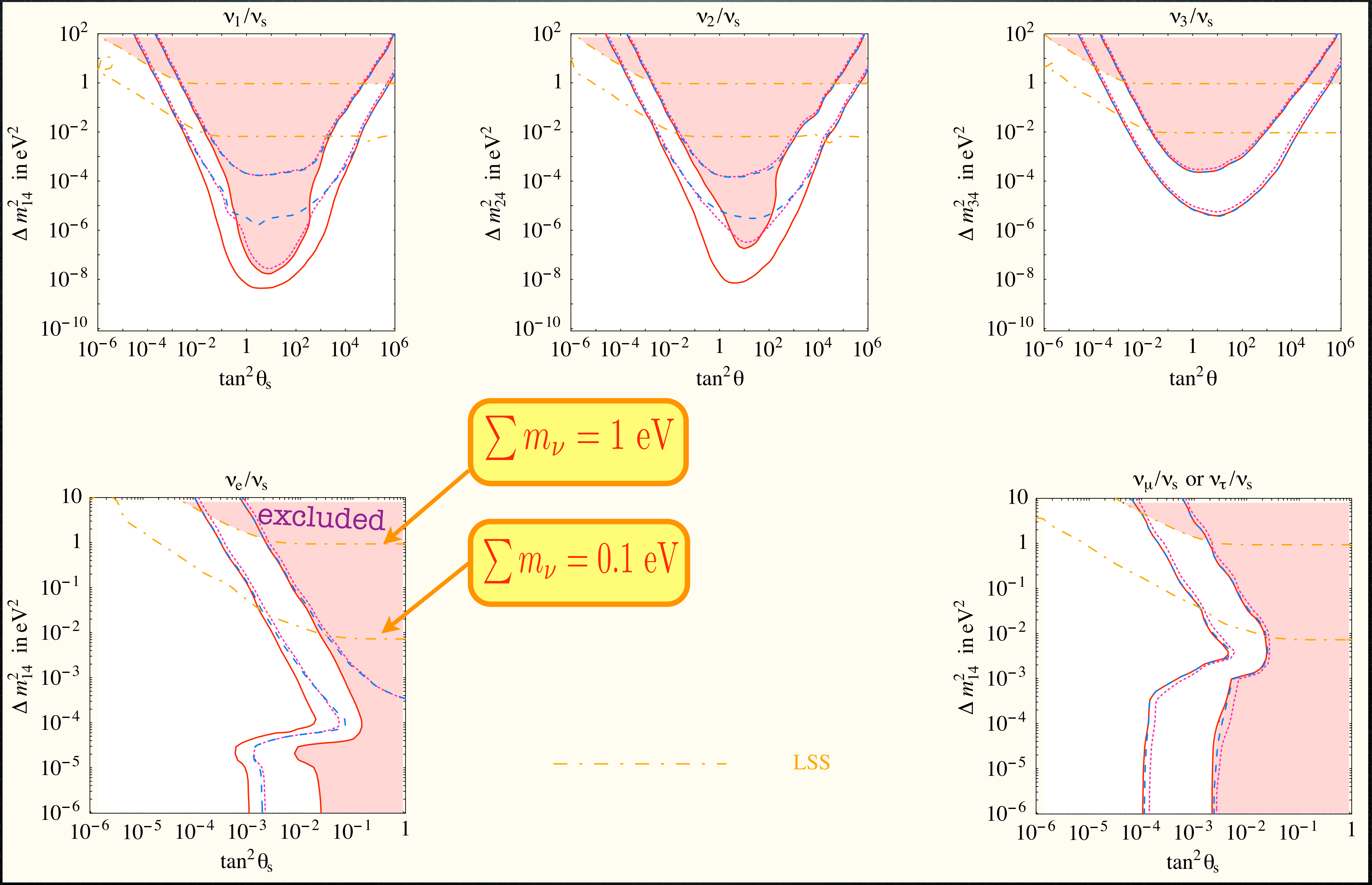
$\nu_{\rm s}$ contribute to $\sum m_\nu$ $\Rightarrow$ a bound on m_4 i.e. $\Delta m^2_{\rm s}$

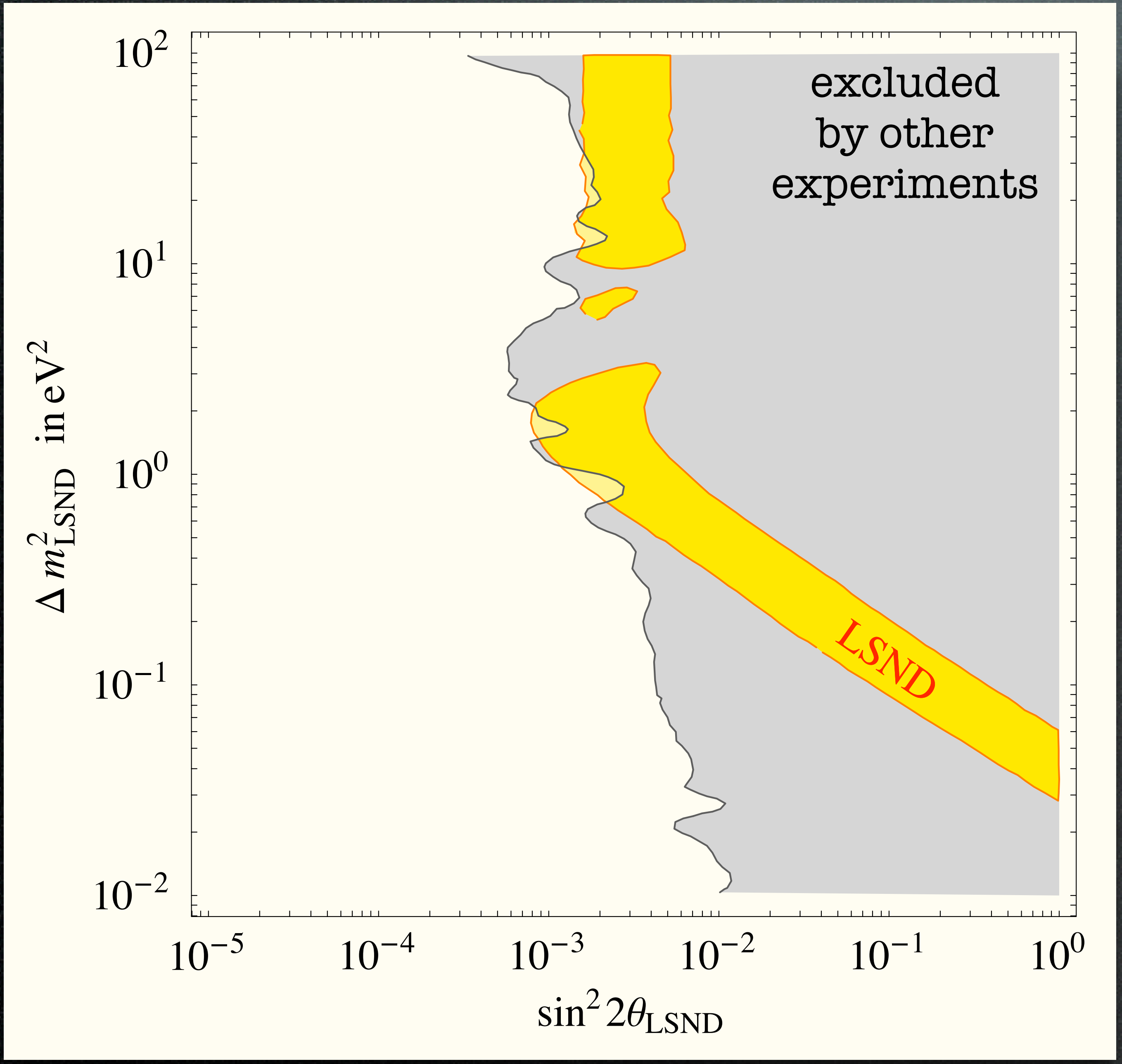
Cosmological Perturbations



Cirelli, Marandella, Strumia, Vissani 2004

LSND

LSND collaboration - Strumia, PLB 539 (2002)



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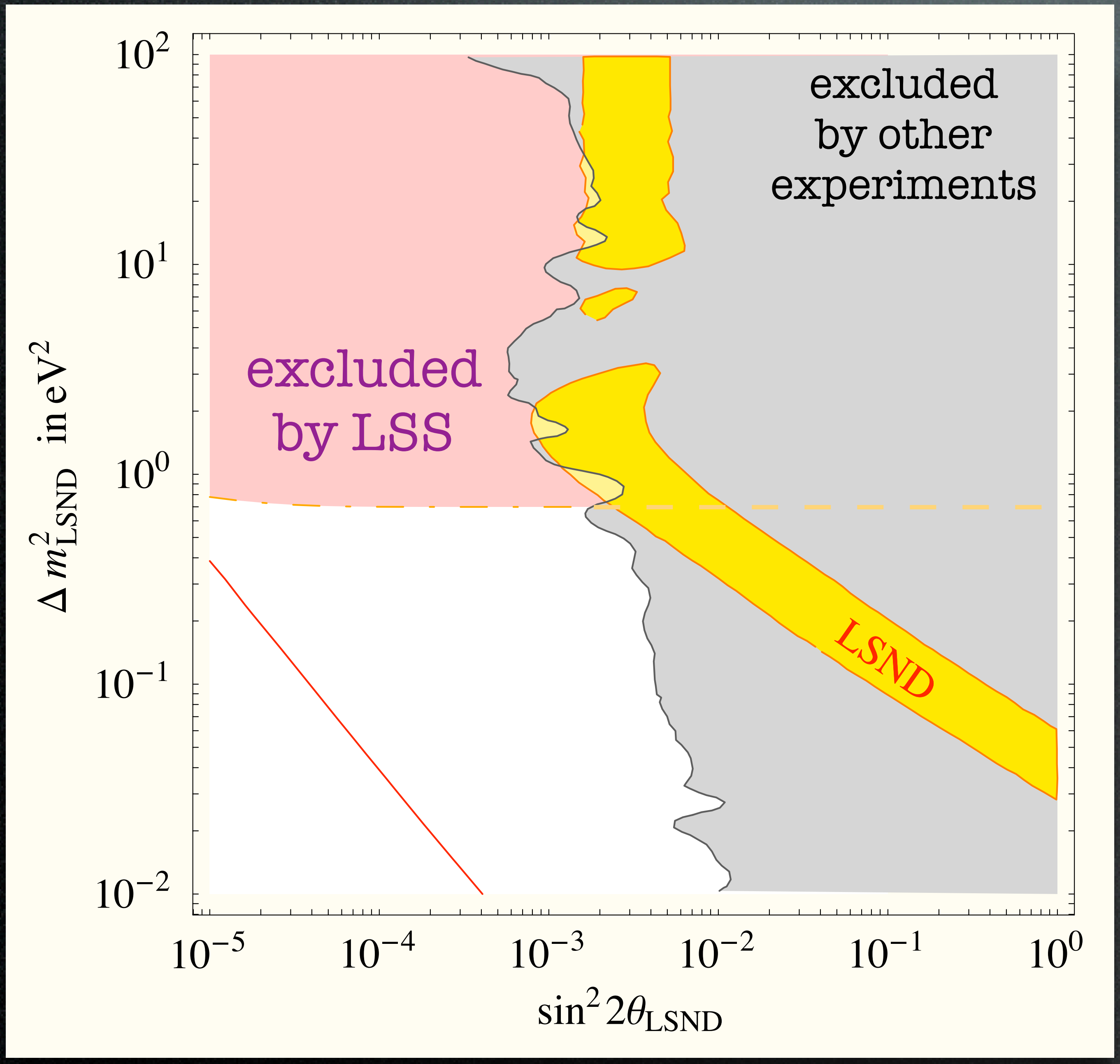

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LSS excludes the LSND $\nu_{\rm s}$
(too much $\sum m_\nu$)

(Open a parenthesis:

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What if there is 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,

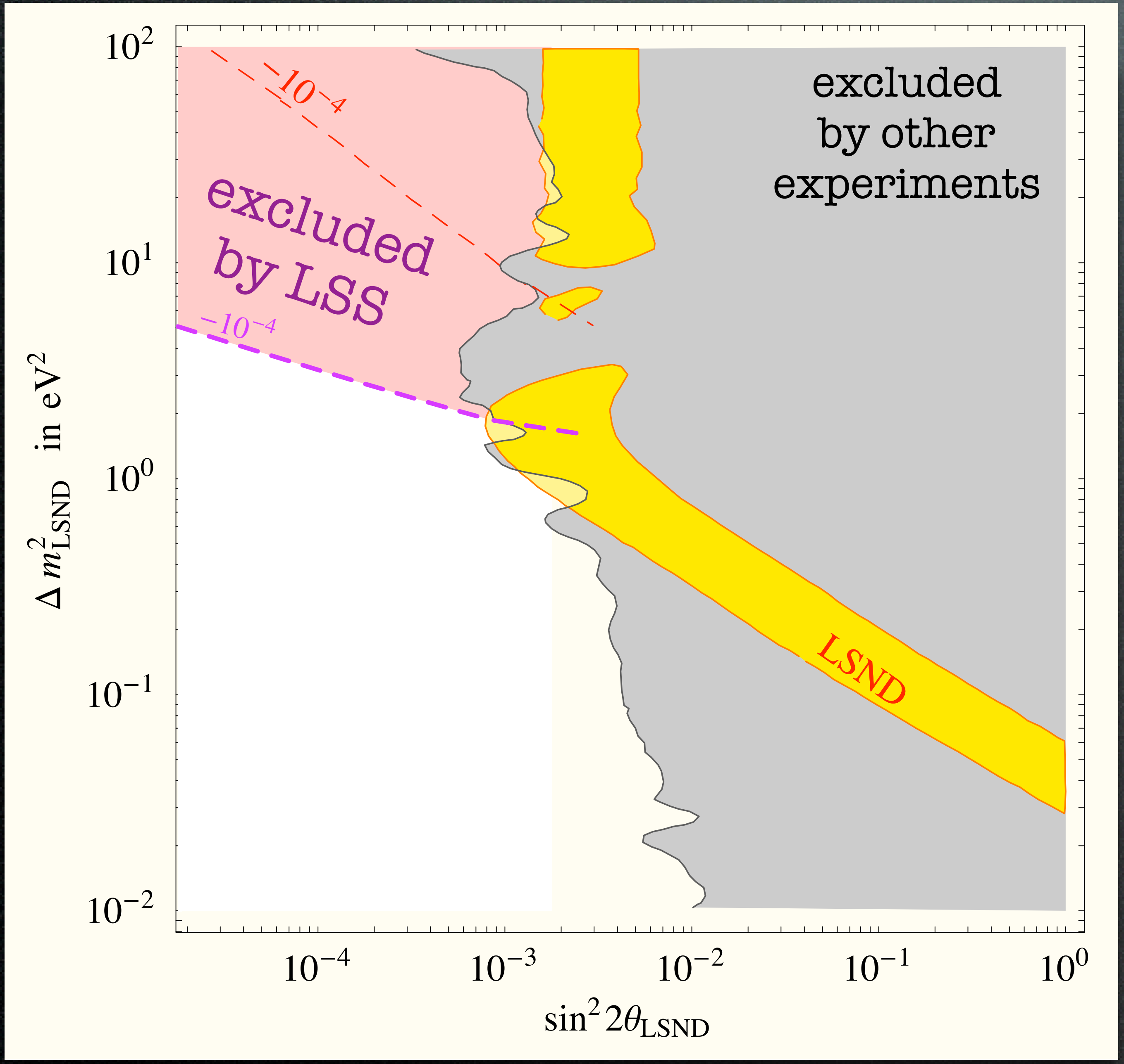
but a priori $L_\nu \sim \mathcal{O}(10^{-2})$ is possible.

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

LSND with lepton asymmetry

Due to matter effects, ν_s are less efficiently produced.

Portions of the parameter space are reopened:



Chu, Cirelli 2006

[Full discussion]

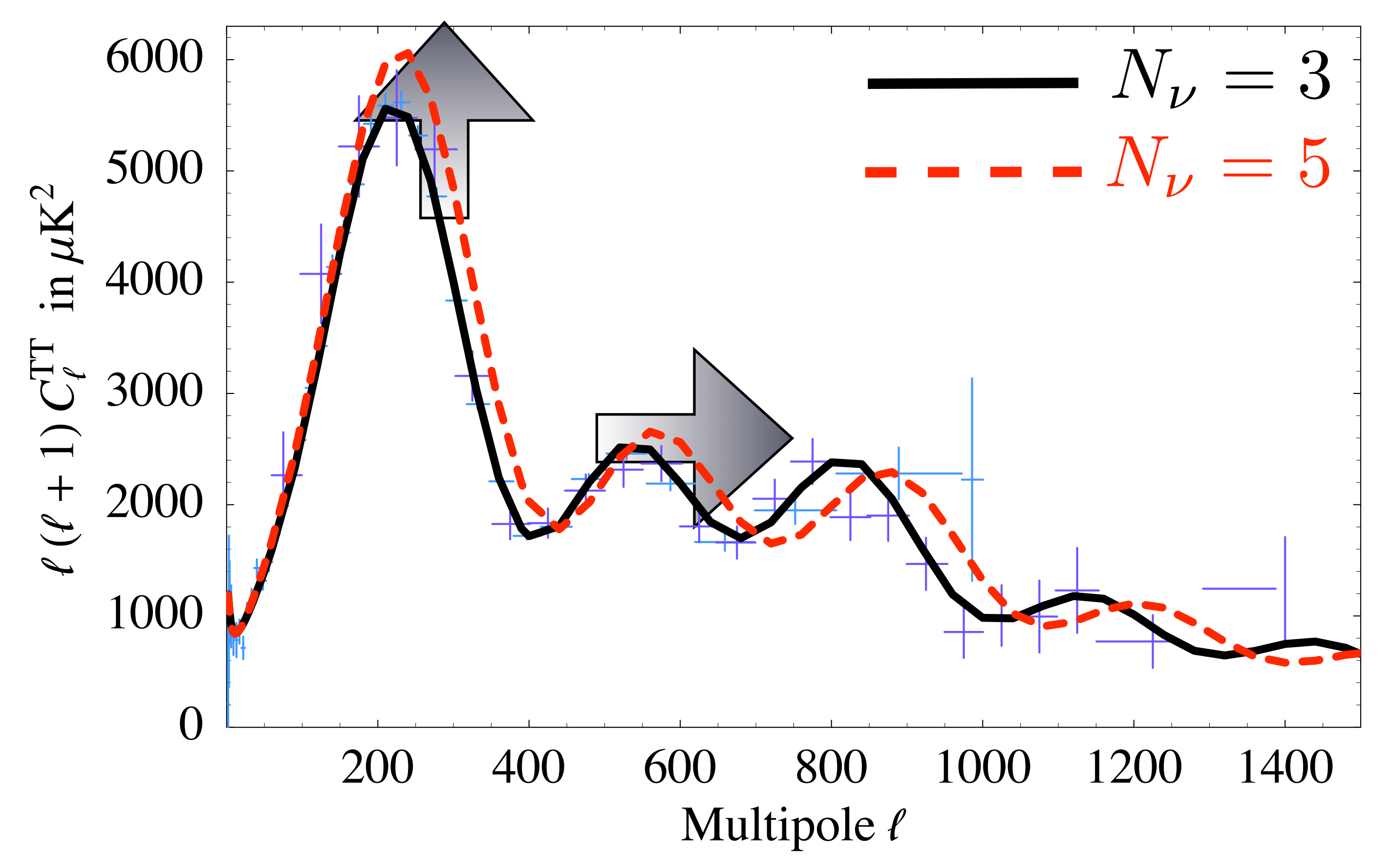
postulating a primordial asymmetry $L_\nu \simeq -10^{-4}$ reconciles LSND and cosmology

Back to standard cosmology.

Cosmological Perturbations

Neutrinos affect cosmological perturbations (CMB, LSS).

$N_\nu = \rho_{\nu_e} + \rho_{\nu_\mu} + \rho_{\nu_\tau} + \rho_{\nu_s}$ sets the total relativistic energy content and affects the peaks of CMB and LSS spectra:



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

$\Downarrow$

a bound on N_ν:

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

(@ 95% C.L., global fit)

Cirelli, Strumia 2006
Seljak et al. 2006

BUT dropping Ly-alpha gives back

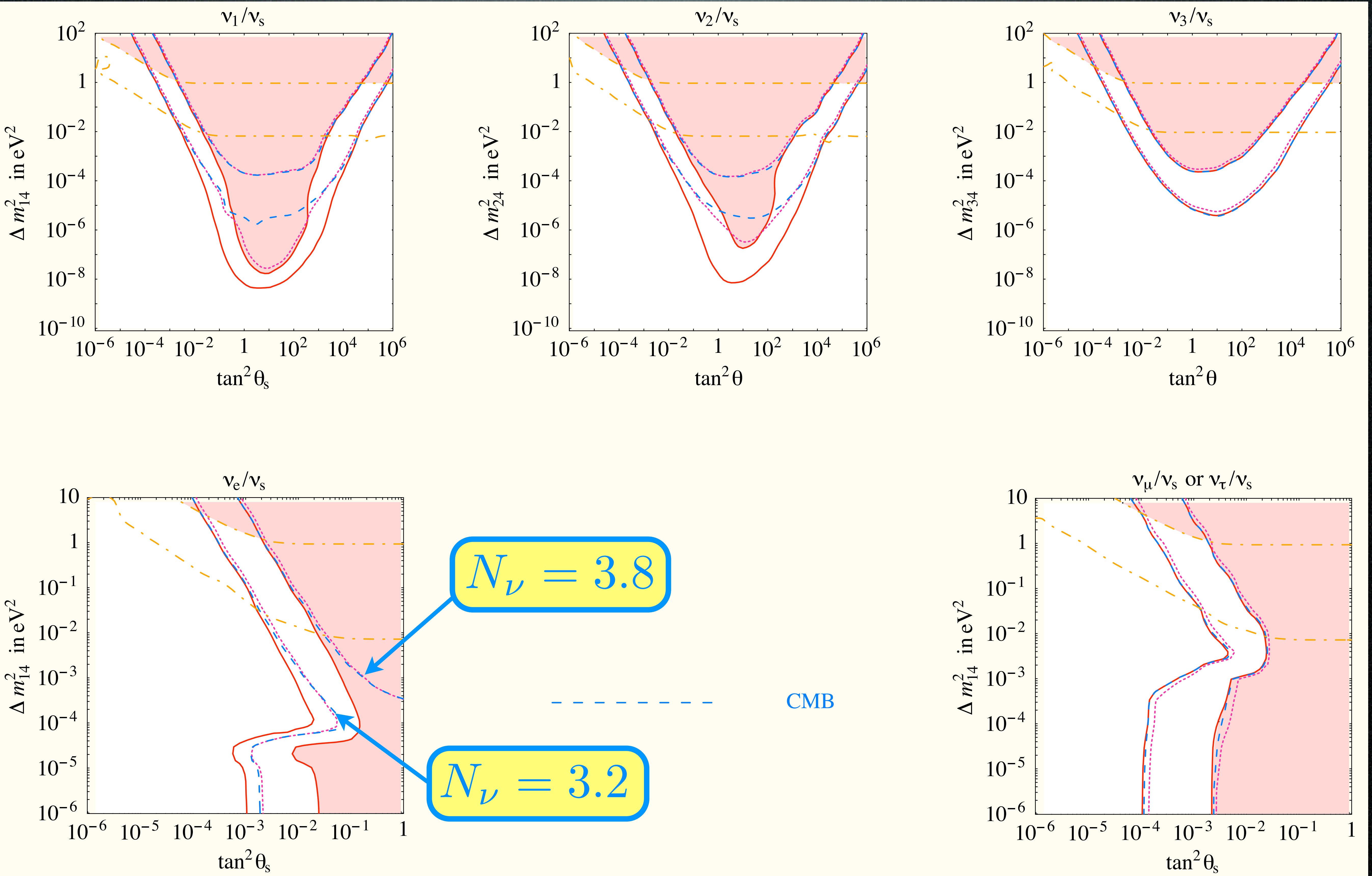
$$N_\nu \simeq 3$$

$\Downarrow$

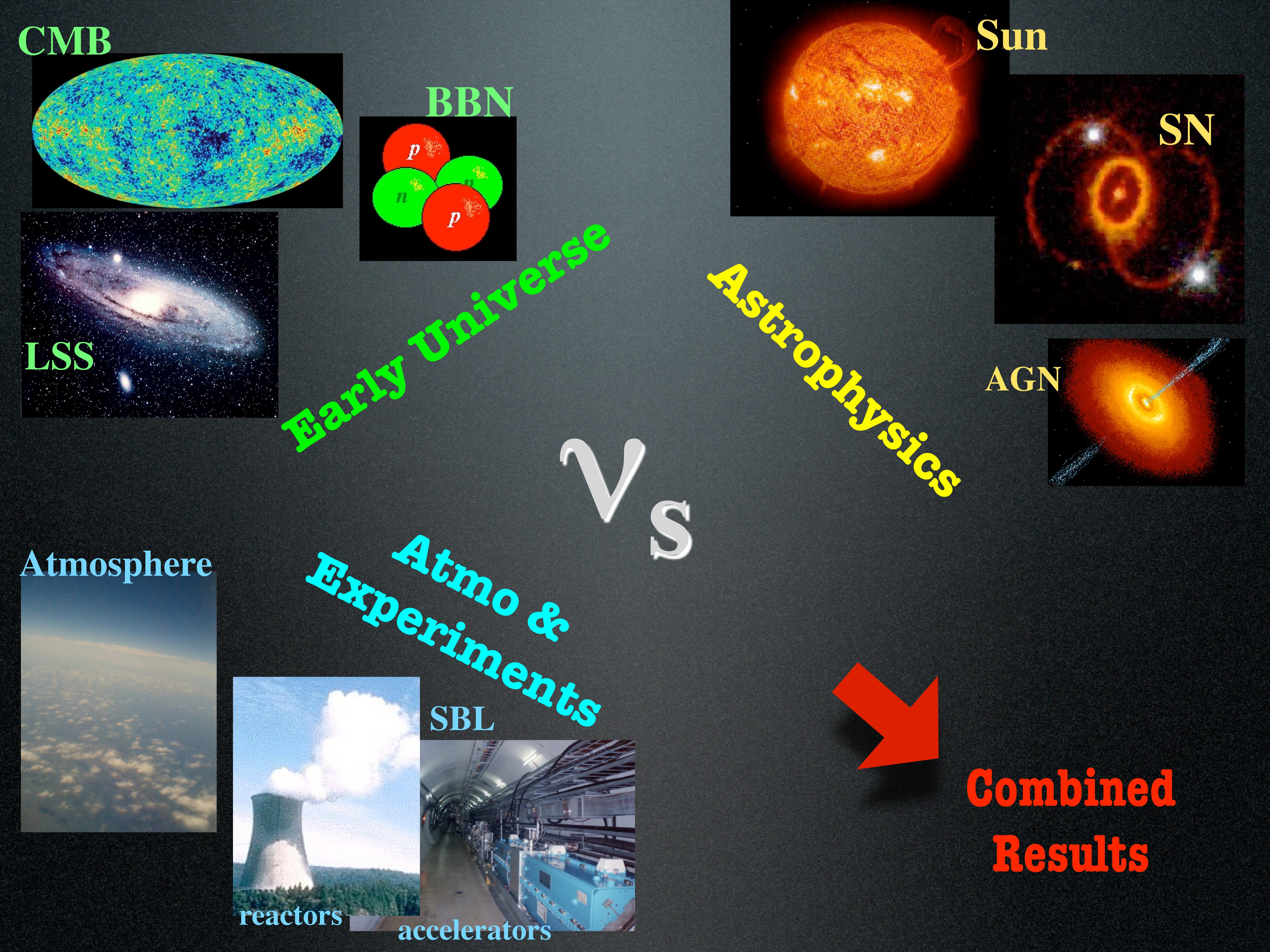
CMB/LSS currently give a weak/unsafe bound on N_ν,

but in the future...

Cosmological Perturbations



Cirelli, Marandella, Strumia, Vissani 2004



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Results

Sterile neutrinos in SNe

Neutrinos from SNe:

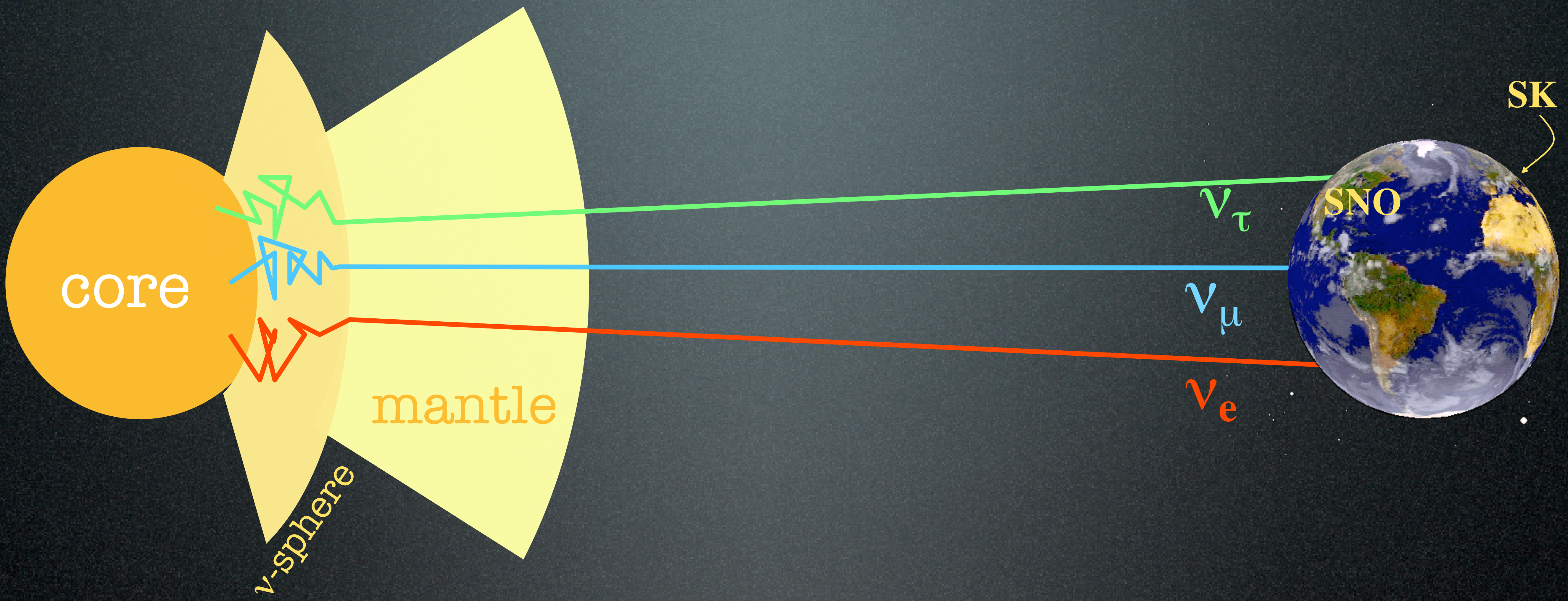
- are a lot (99% of emitted energy)
- undergo “extreme” matter effects
- come from very far away ($\sim$10 kpc)
- have the right energy ($\sim$10 MeV) for present detectors

An extra ν_s can make a big difference.

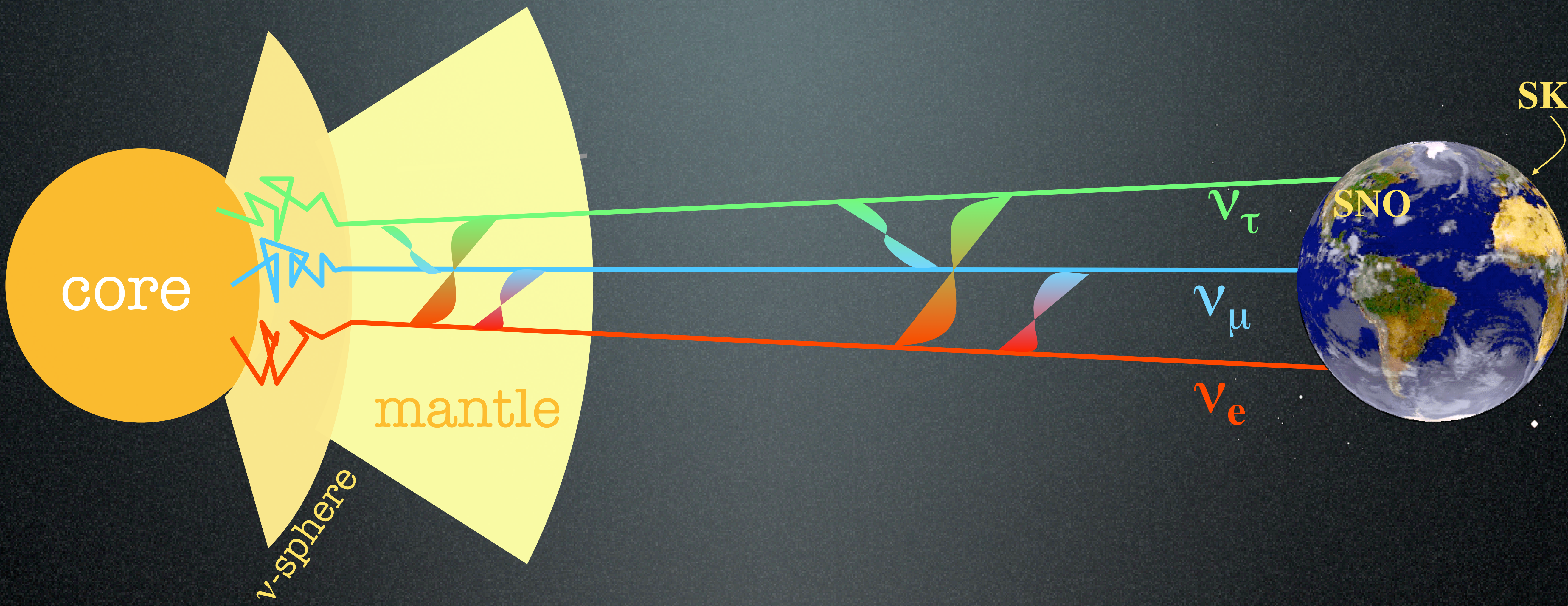
Overall picture confirmed by SN1987a ⇒ Set present bounds

Thousands of events from future SN ⇒ Propose future probes

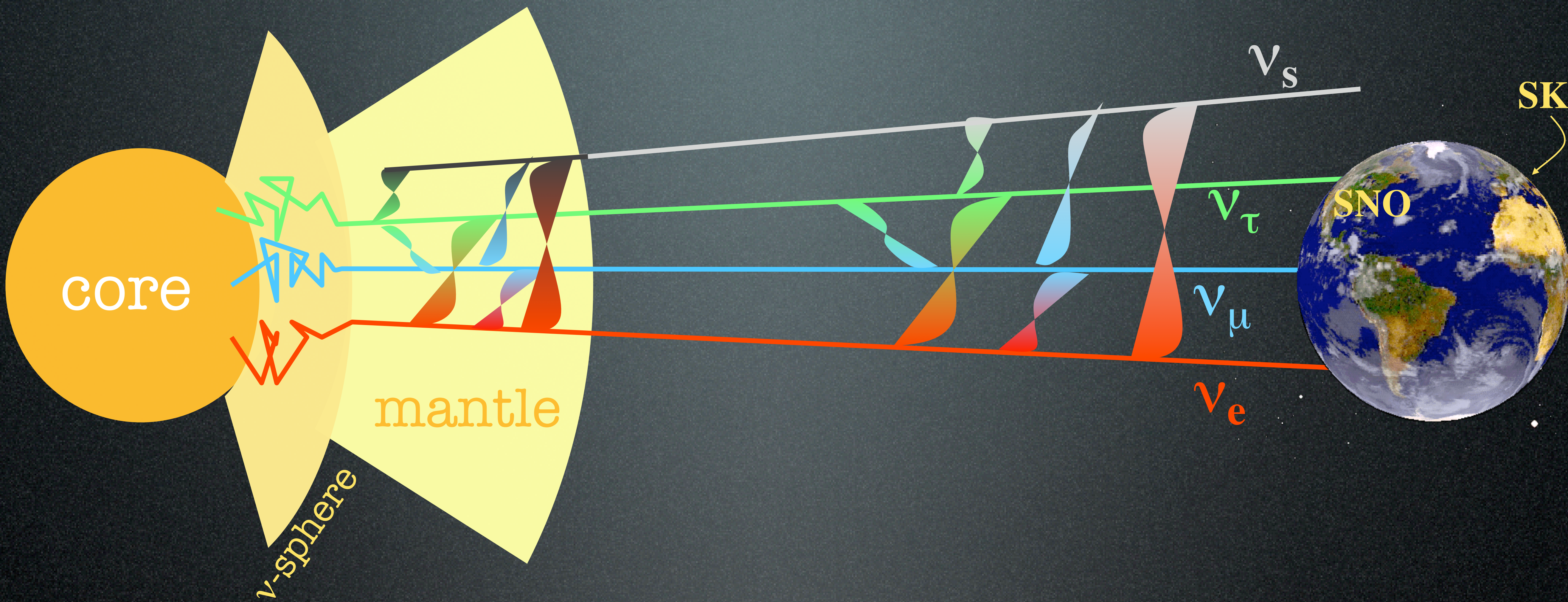
Sterile neutrinos in SNe



Sterile neutrinos in SNe



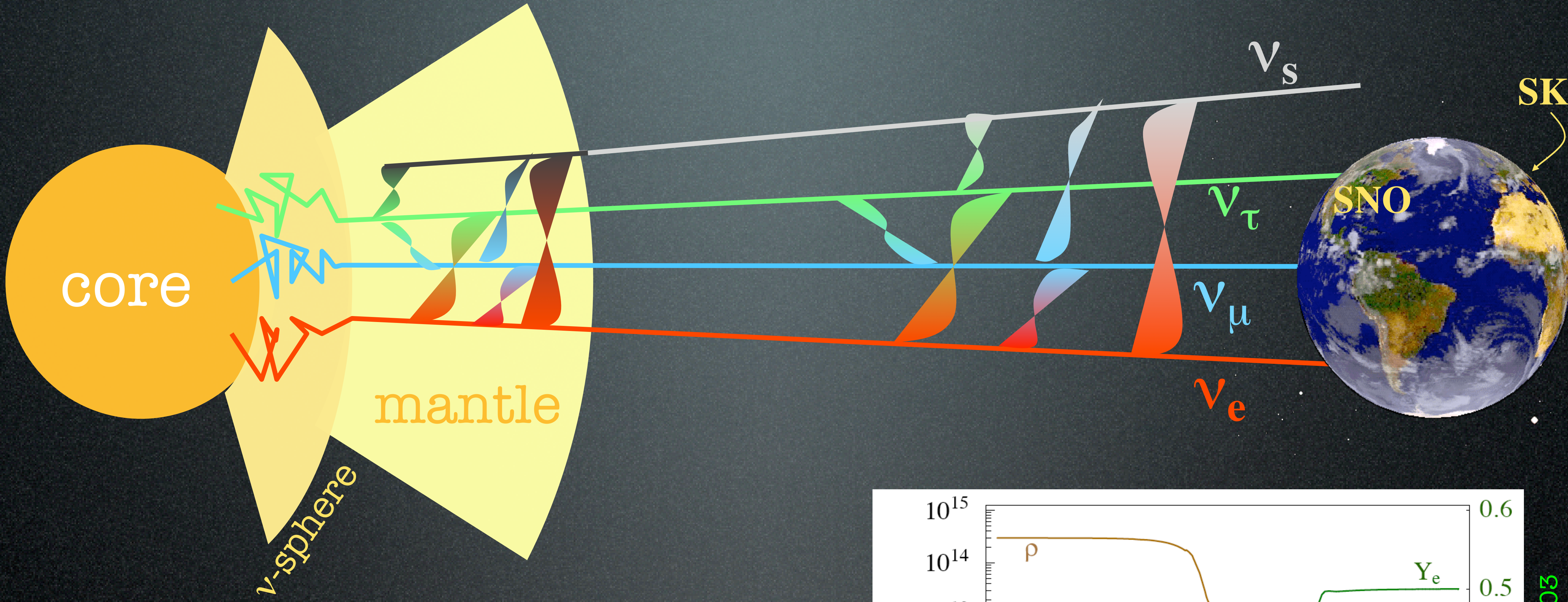
Sterile neutrinos in SNe



Matter oscillations in the star mantle:

$$V_e = \sqrt{2} G_{\mathrm{F}} n_B \left(3Y_e - 1\right)/2, \qquad V_\tau = V_\mu + V_{\mu\tau},$$
$$V_\mu = \sqrt{2} G_{\mathrm{F}} n_B \left(Y_e - 1\right)/2, \qquad V_{\mathrm{s}} = 0,$$

Sterile neutrinos in SNe



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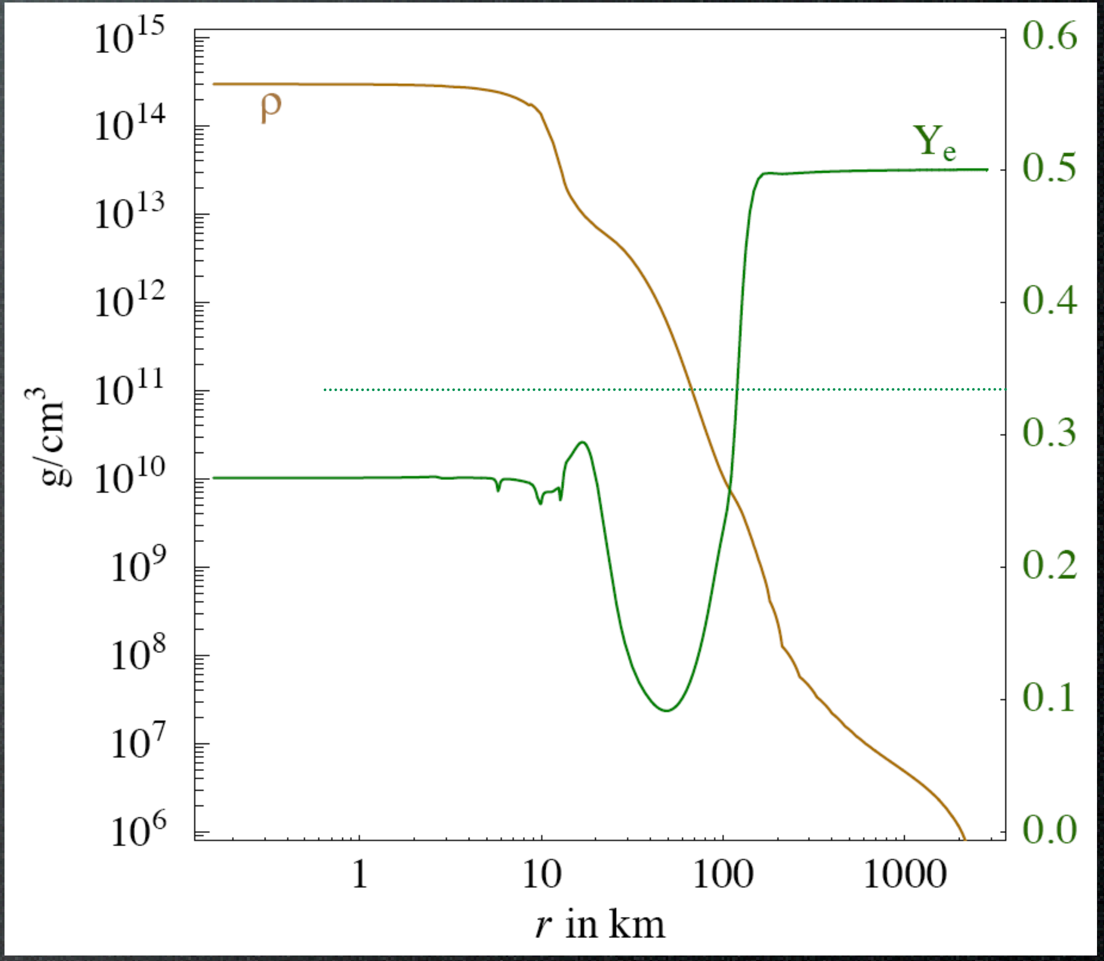
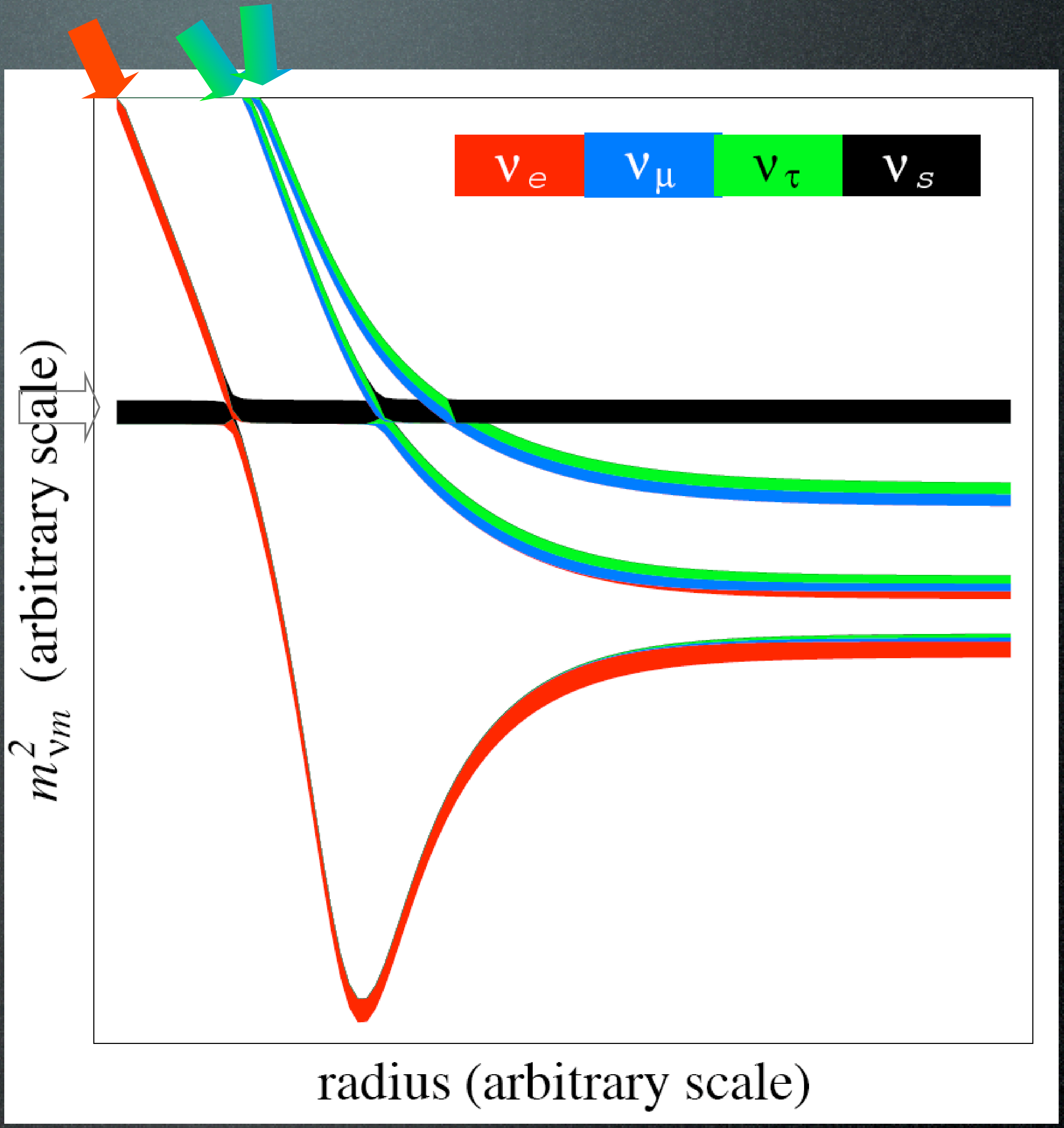


A.Burrows et al., 2001, 2002, 2003

Sterile neutrinos in SNe

Matter eigenstates in the mantle:



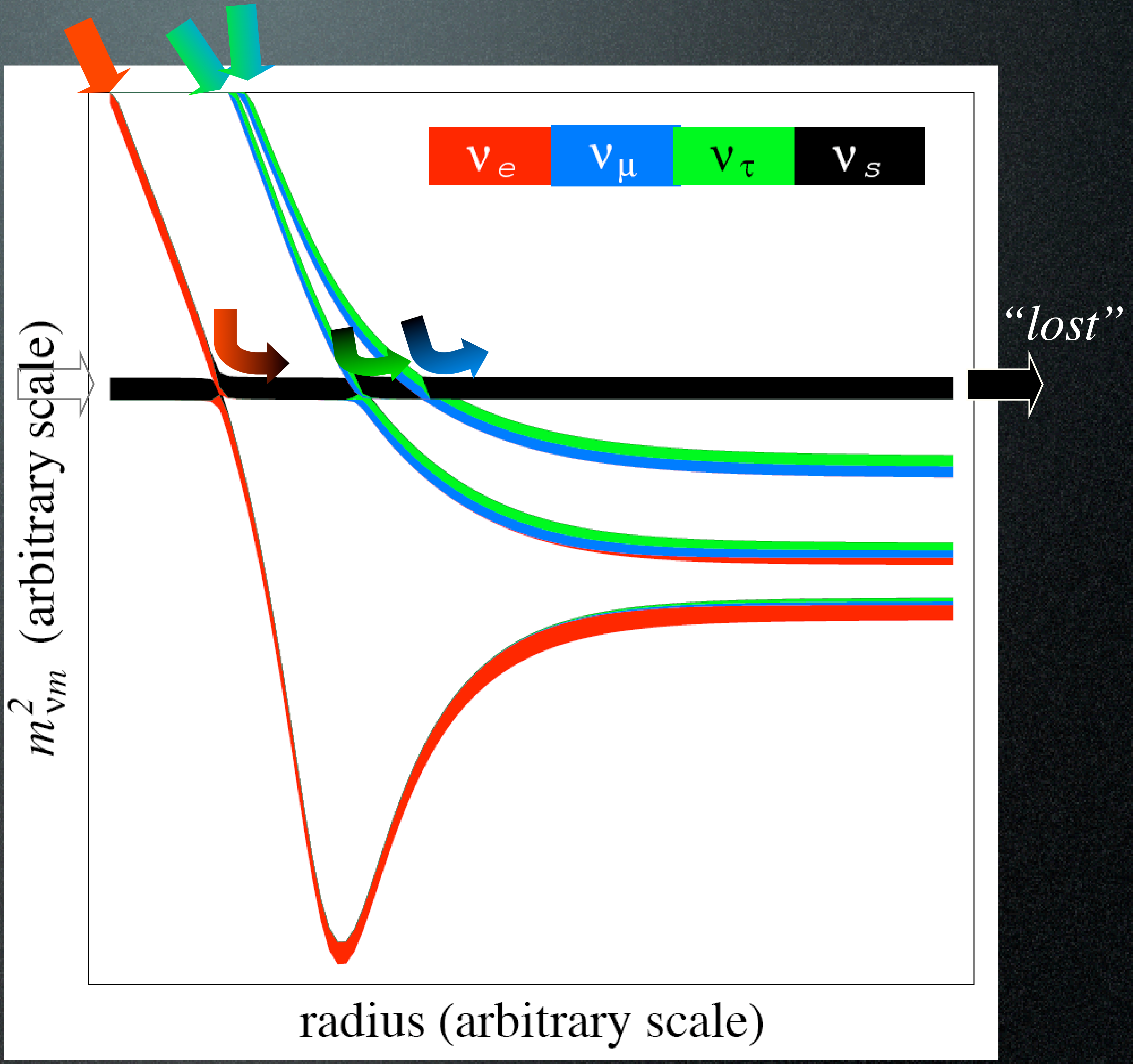
Sterile neutrinos in SNe

Matter eigenstates in the mantle:

At each crossing:
crossing probability

$$P_C = \frac{e^{\tilde{\gamma}\cos^2\theta^m_{as}} - 1}{e^{\tilde{\gamma}} - 1}$$

$$\gamma = \frac{4\mathscr{H}^2_{as}}{dH_a/dr} \equiv \tilde{\gamma} \cdot \frac{\sin^2 2\theta^m_{as}}{2\pi|\cos 2\theta^m_{as}|}$$



Sterile neutrinos in SNe

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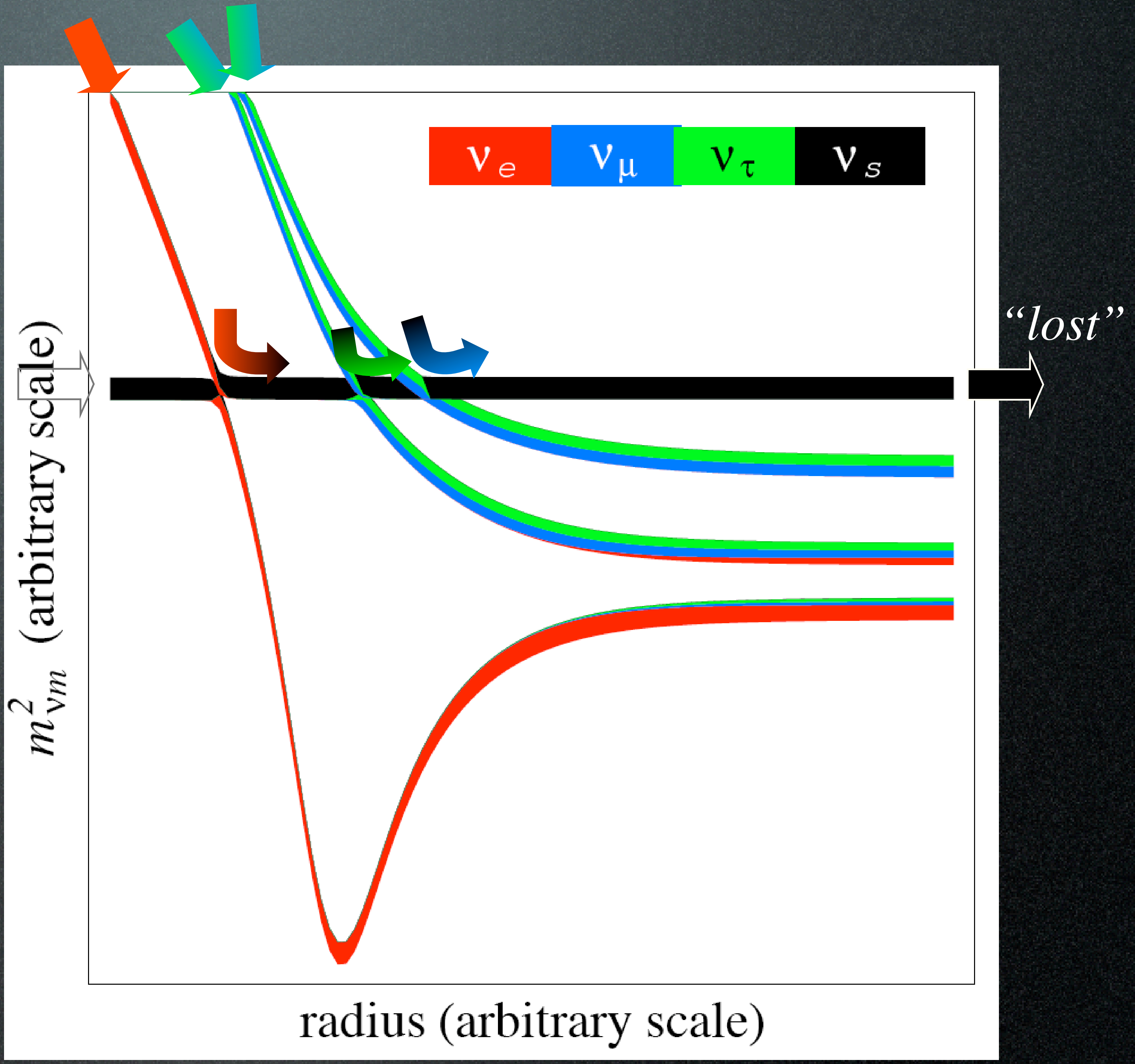


Output: final fluxes of ν_e, ν_μ and ν_τ on Earth .

Sterile neutrinos in SNe

SN1987a neutrinos observed

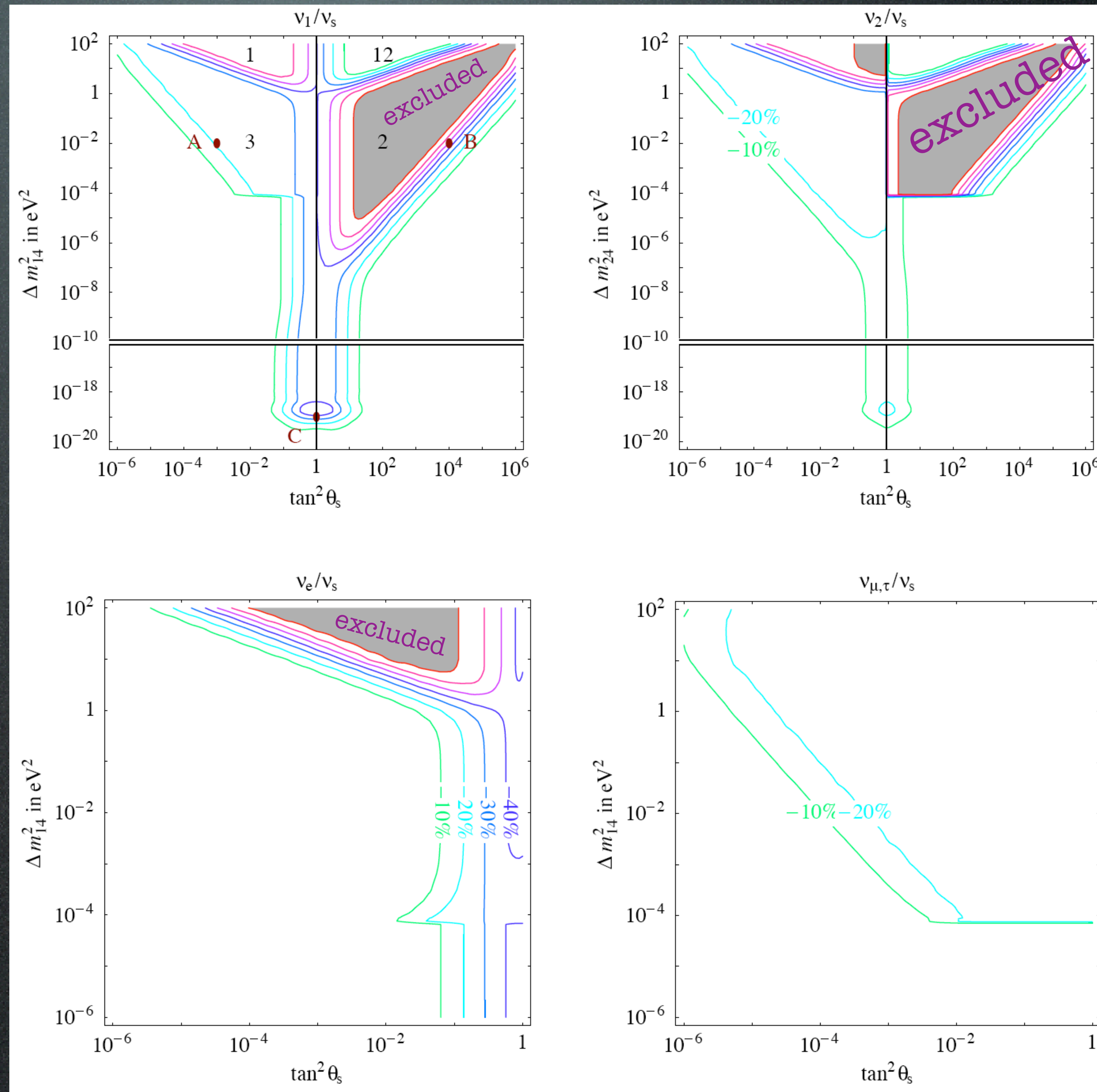
⇓

a bound on the loss of $\bar{\nu}_e$: $\lesssim 70\%$.

$(\bar{\nu}_e p \to n e^+)$

Large portions can be probed.

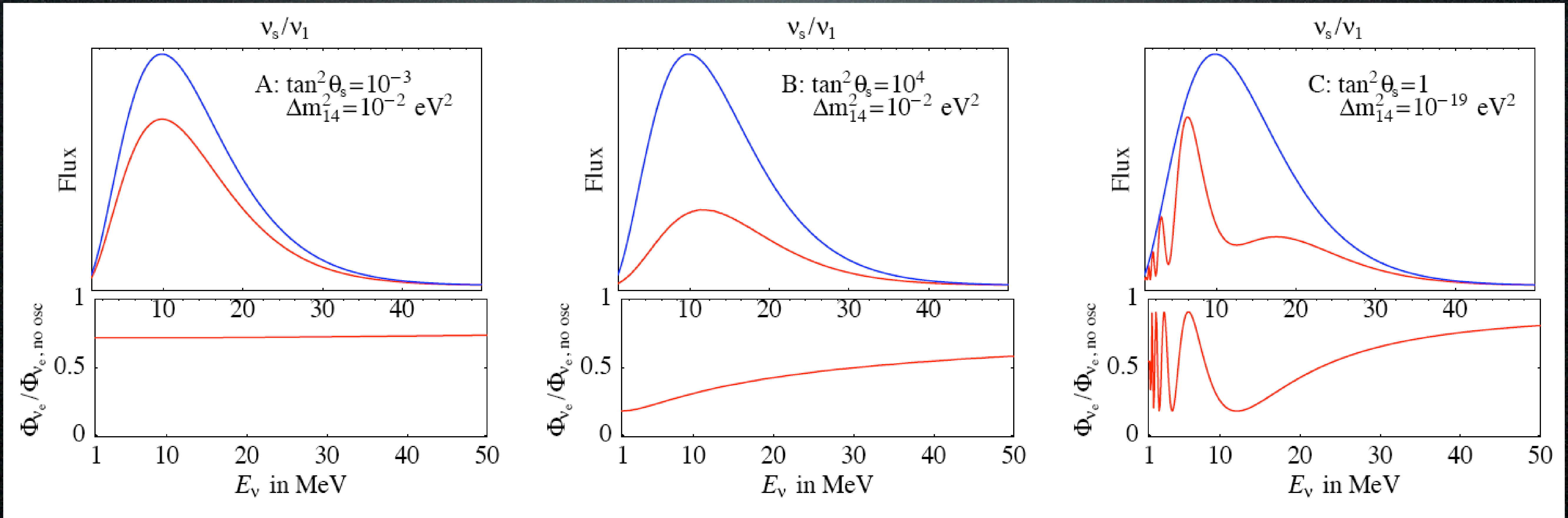
(Beware of theoretical uncertainties...)



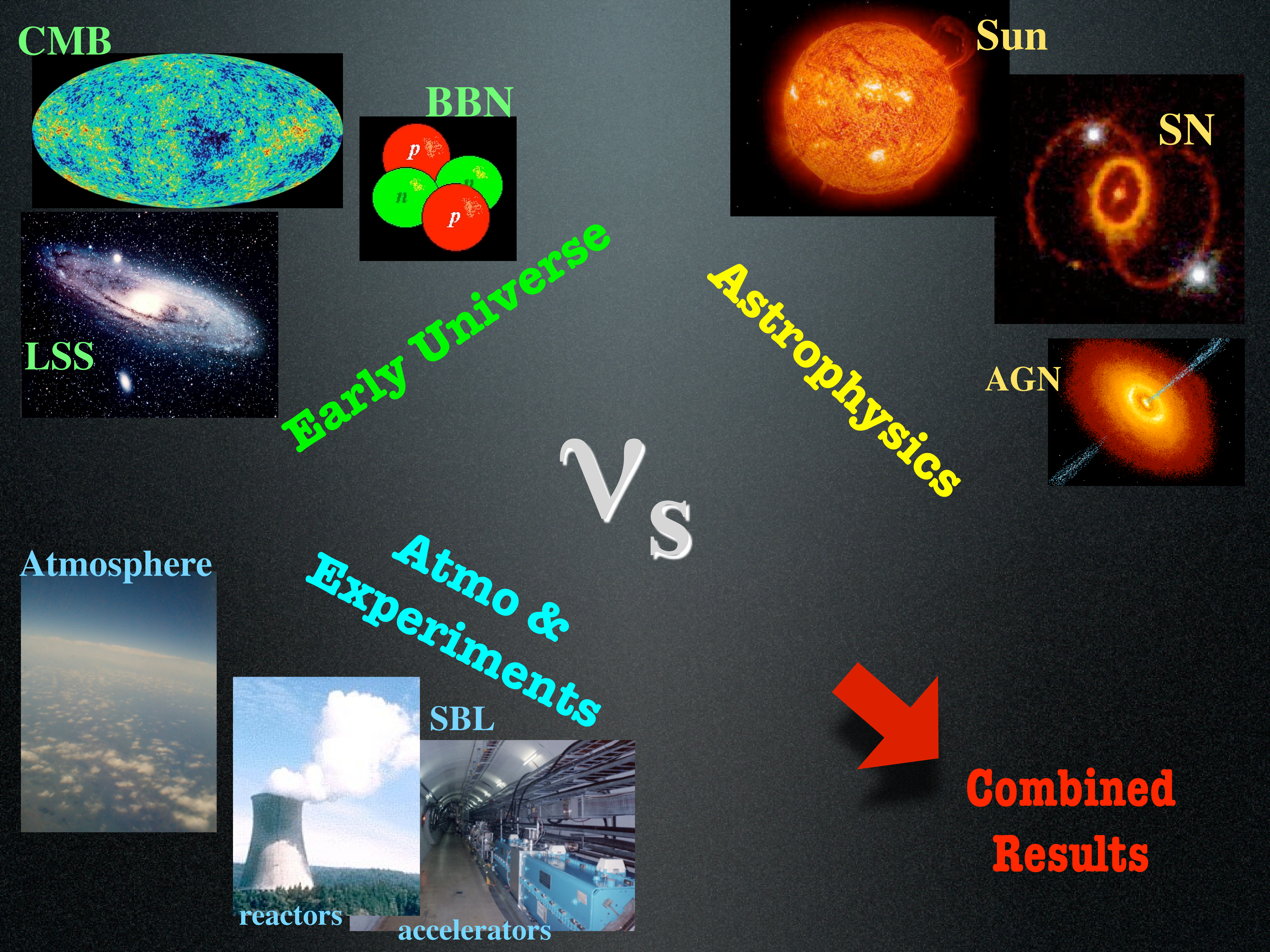
Cirelli, Marandella, Strumia, Vissani 2004

Sterile neutrinos in SNe

The energy dependance of matter/vacuum conversions causes spectral distortions:



Possible very clear feature.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Neutrinos from extragalactic sources

- produced in high-energy astrophysical processes
- expected flavor ratios at production $\nu_e : \nu_\mu : \nu_\tau = 1 : 2 : 0$

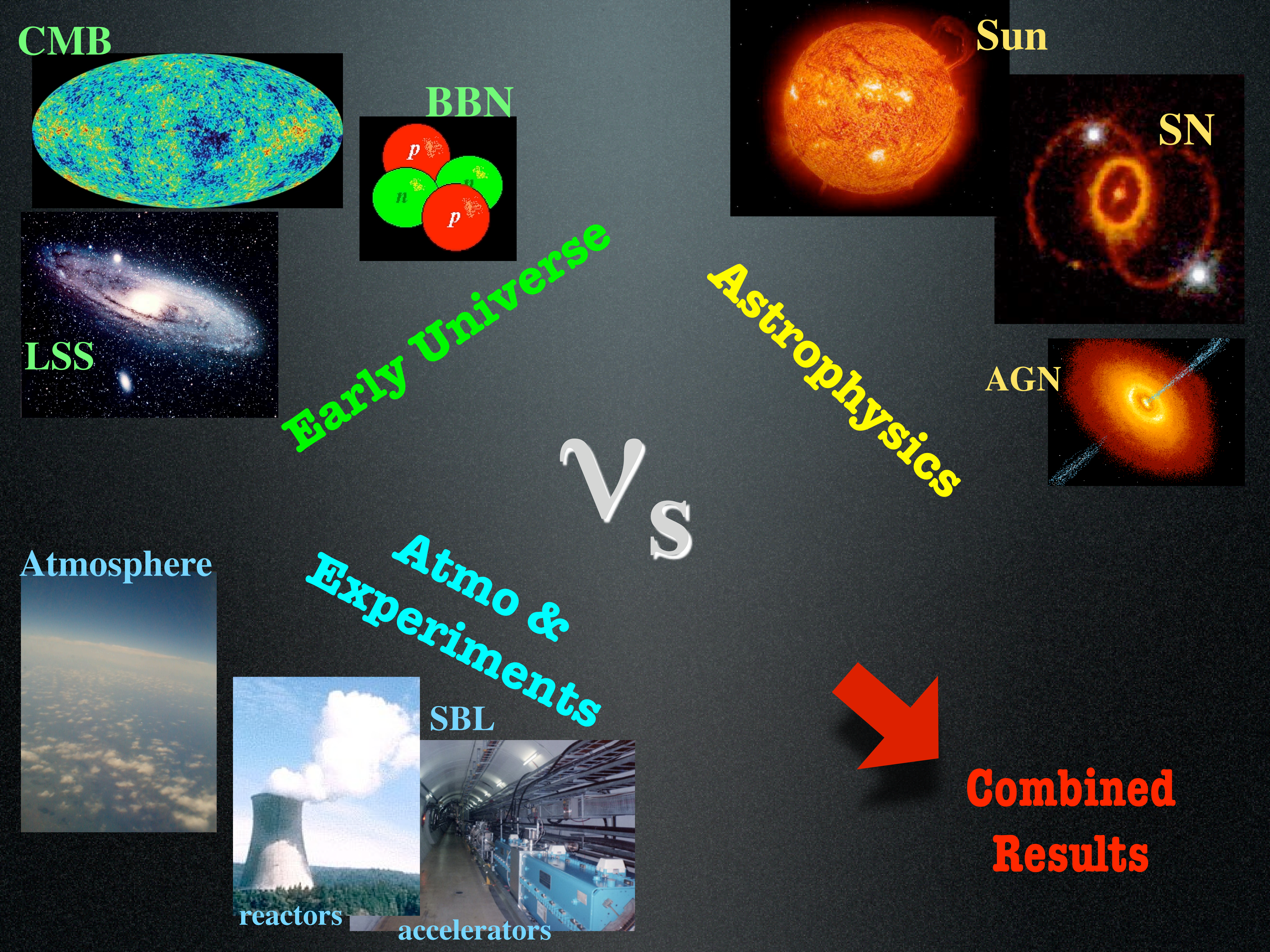
after (active) oscillations $1 : 1 : 1$

An extra $\nu_{\rm s}$ can produce an unbalance.

BUT:
- initial fluxes totally unknown
- sterile effects have to be small
- we tag ν_μ and ν_τ, which balance anyway

⇓

Not a very interesting probe.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Sterile neutrinos in the Sun

Solar neutrinos:

- are a lot, and well studied
- undergo matter effects in the Sun and the Earth
- come from far away ($\sim$150 Mkm)

An extra $\nu_{\rm s}$ can make a difference.

Sterile neutrinos in the Sun

Solar neutrinos:

- are a lot, and well studied
- undergo matter effects in the Sun and the Earth
- come from far away ($\sim$150 Mkm)

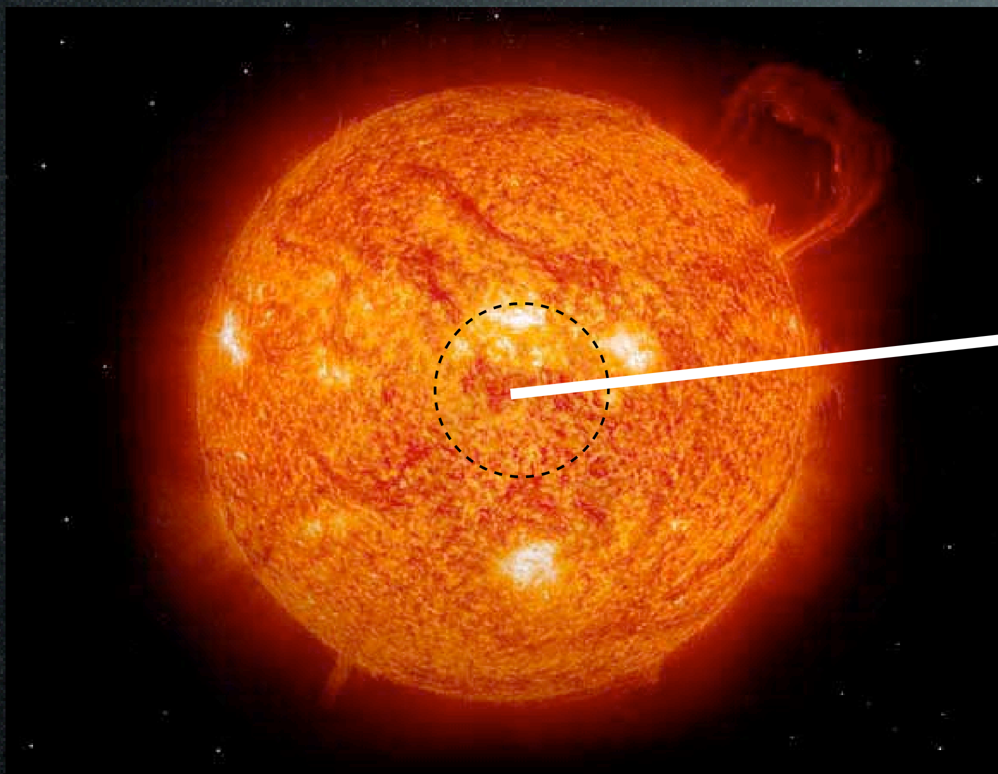
An extra ν_s can make a difference.

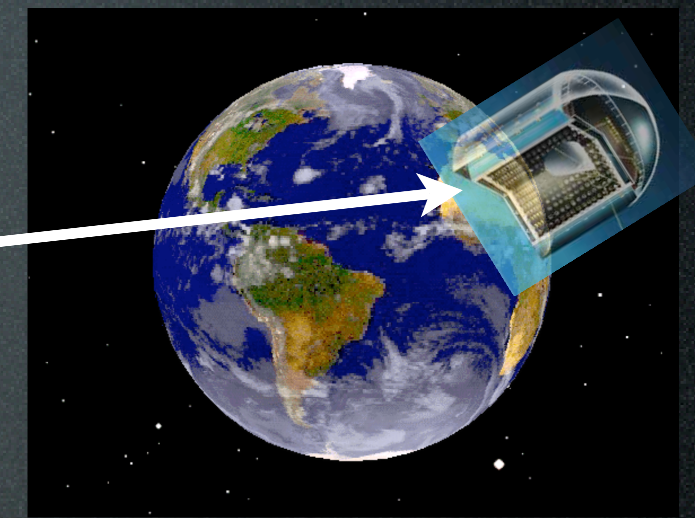
Dominant $\nu_e \longrightarrow \nu_s$ is excluded by SNO (and SK).

Look for subdominant sterile effects,
on top of LMA-MSW $\nu_e \longrightarrow \nu_{\mu,\tau}$.

(i.e. technically, marginalizing over $\Delta m^2_{12} = (8.0 \pm 0.3) \cdot 10^{-5} \mathrm{eV}^2$, $\tan^2 \theta_{12} = 0.45 \pm 0.05$ parameters)

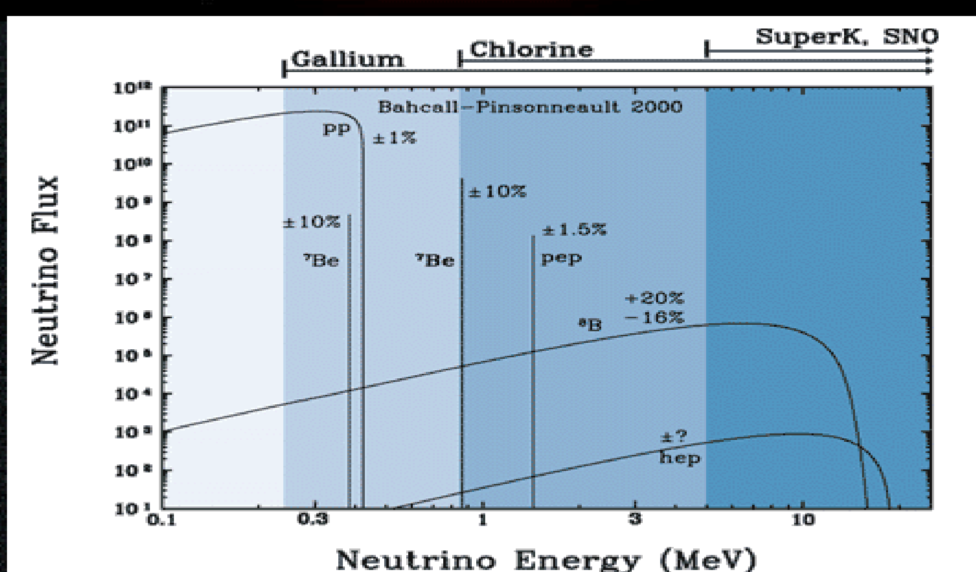
Sterile neutrinos in the Sun



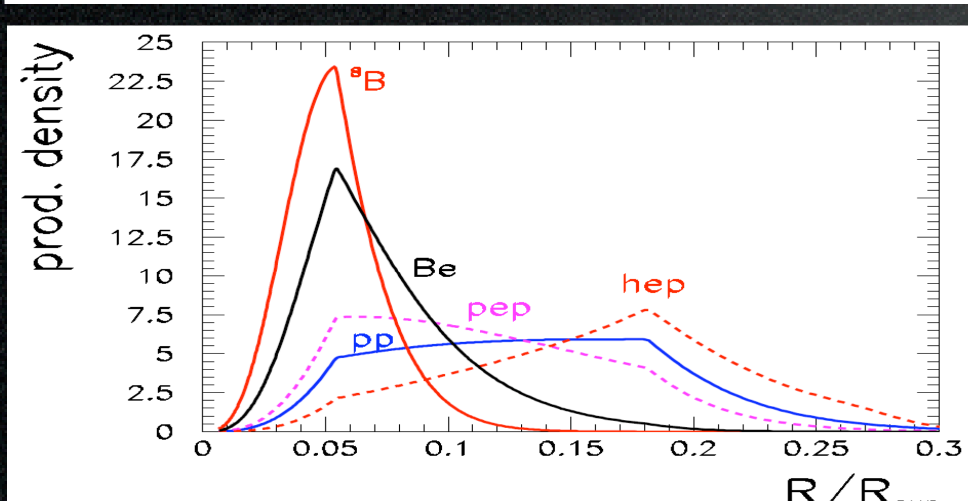


Computation:

- input ν_e fluxes (spectrum, production regions)
- crossings in Sun's matter

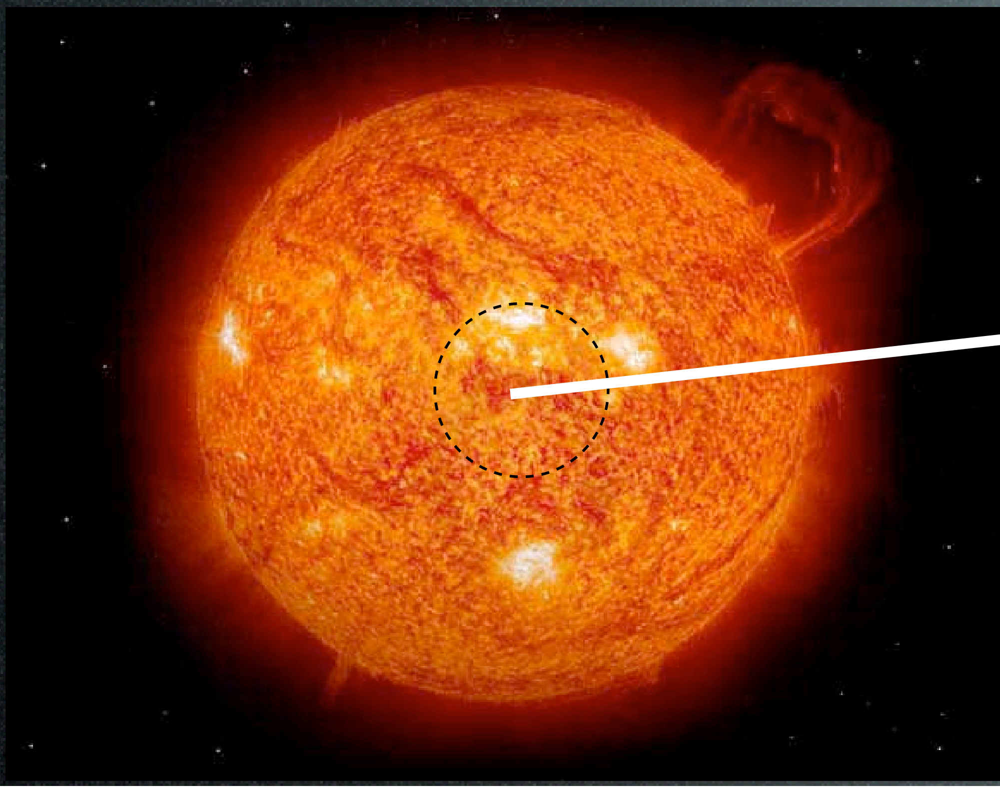


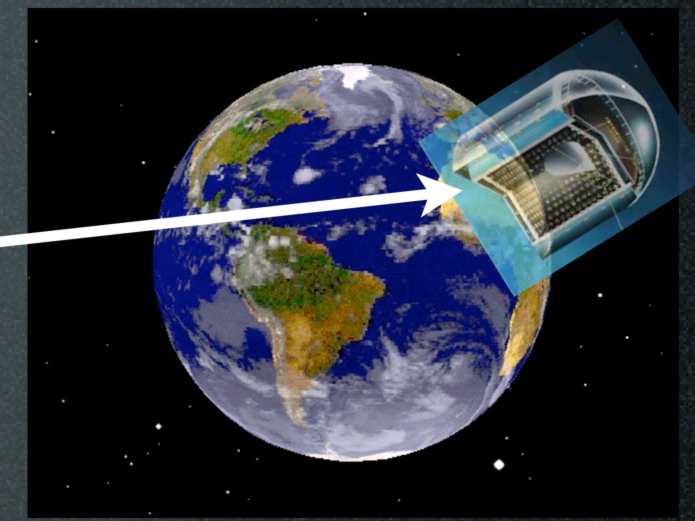
Bahcall, Pinsonneault 2001

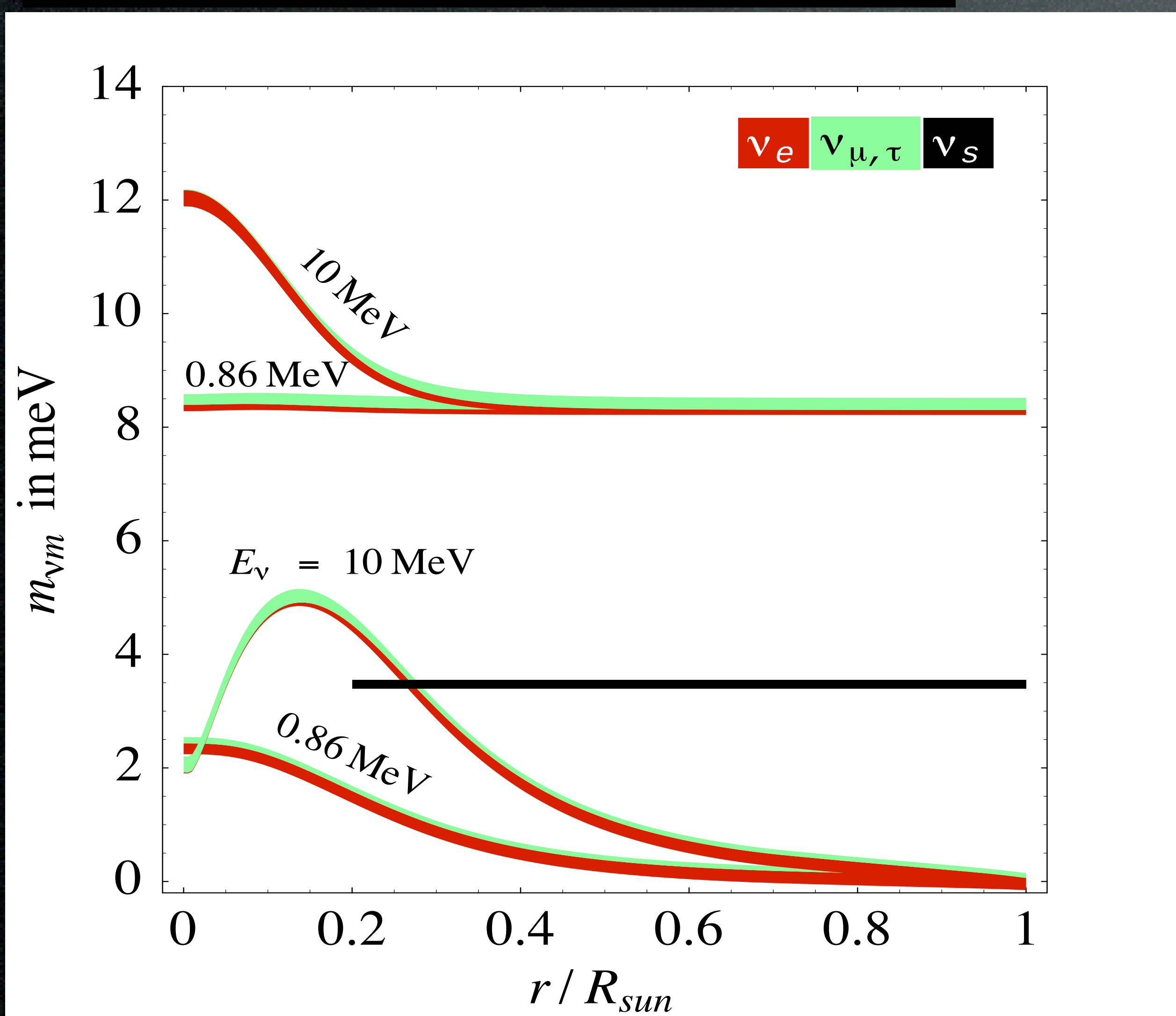


Gonzalez-Garcia, Nir 2002

Sterile neutrinos in the Sun



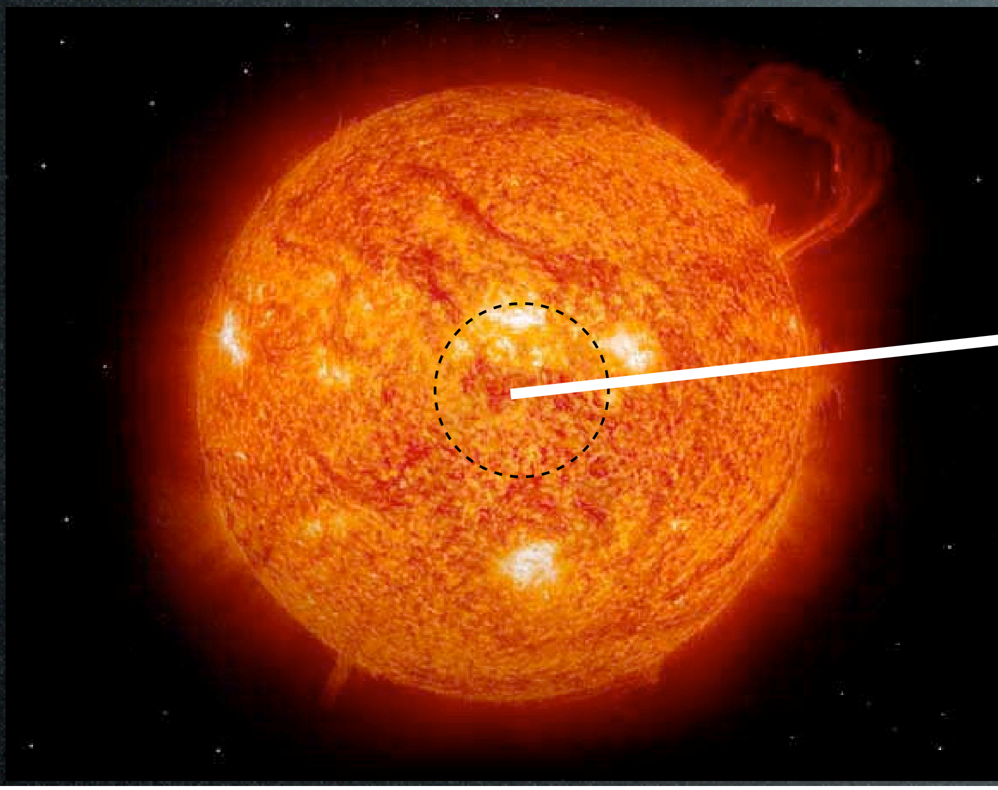


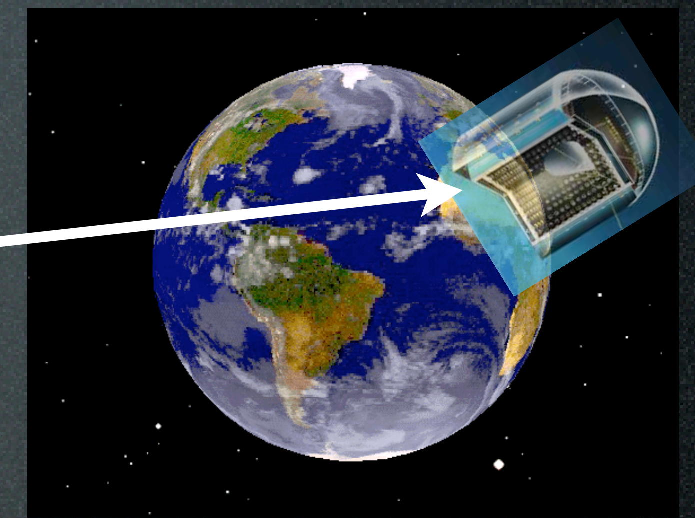


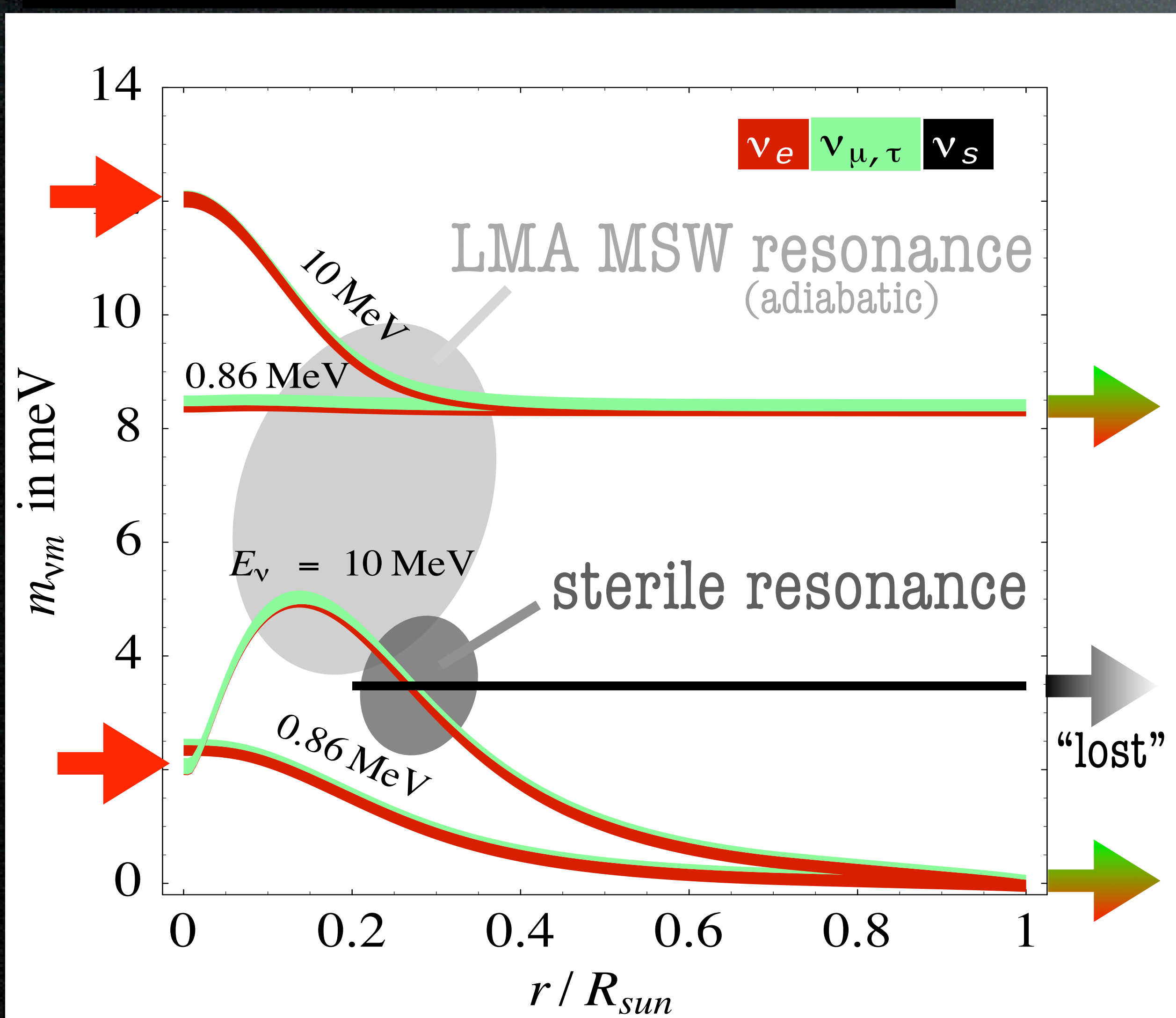
Computation:

- input ν_e fluxes (spectrum, production regions)
- crossings in Sun's matter
- vacuum oscillations
- matter oscillations in Earth
- fit dataset: SNO D_2O (CC, NC, ES d/n spectra)
  SNO salt (CC, NC, ES rates)
  SK (ES spectra w zenith)
  SAGE + Gallex + GNO (Ga)
  Homestake (Cl)
  KamLAND (reactor $\bar{\nu}_e$ spectra)
  SSM prediction for ^8B flux (not critical)

Sterile neutrinos in the Sun







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  KamLAND (reactor $\bar{\nu}_e$ spectra)
  SSM prediction for ^8B flux (not critical)

[technical details] or [skip technical details]

Sterile neutrinos in the Sun

Formalism: evolve the 4x4 neutrino density matrix $\rho(E_\nu, r)$ from production to detection

Production:

ν_e (arrow pointing to the 1 entry)

$$\rho = \begin{pmatrix} 1 & & & \\ & 0 & & \\ & & 0 & \\ & & & 0 \end{pmatrix}$$

Sterile neutrinos in the Sun

Formalism: evolve the 4x4 neutrino density matrix $\rho(E_\nu, r)$ from production to detection

Matter eigenstates:

$$\rho_m = V^\dagger \cdot \begin{pmatrix} 1 & & & \\ & 0 & & \\ & & 0 & \\ & & & 0 \end{pmatrix} \cdot V$$

V 4x4 mixing matrix **in matter**

Sterile neutrinos in the Sun

Formalism: evolve the 4x4 neutrino density matrix $\rho(E_\nu, r)$ from production to detection

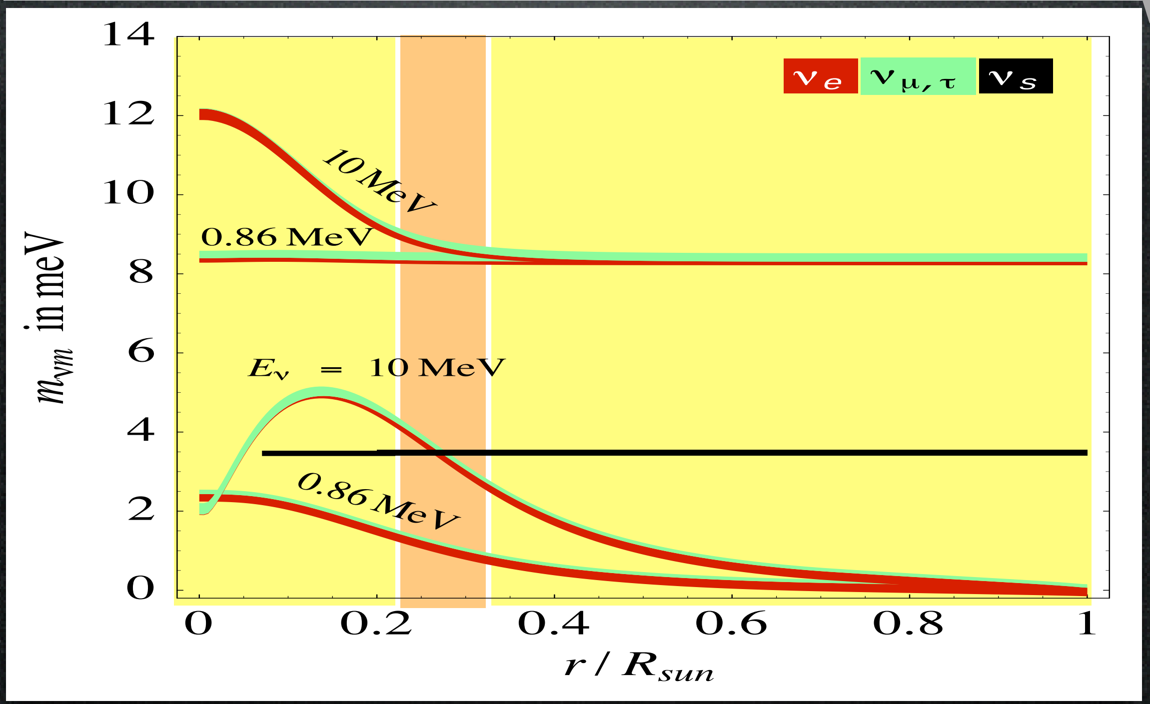
Evolution in the Sun:

$$\rho_{\rm out} = \mathscr{U}_{\rm sun} \cdot V^\dagger \cdot \begin{pmatrix} 1 & & & \\ & 0 & & \\ & & 0 & \\ & & & 0 \end{pmatrix} \cdot V \cdot \mathscr{U}^\dagger_{\rm sun}$$

V 4x4 mixing matrix **in matter**

$$\mathscr{U}^\dagger_{\rm sun} = {\rm diag}\, \exp\left(i \int_0^{r_*} dr \frac{m^2_{\nu_i}}{2E_\nu}\right) \cdot U_{\rm cross} \cdot {\rm diag}\, \exp\left(i \int_{r_*}^{R_\odot} dr \frac{m^2_{\nu_i}}{2E_\nu}\right)$$

point-by-point mass eigenstates **in matter**



a rotation of

$$\tan^2\alpha = \frac{P_{\rm cross}}{1 - P_{\rm cross}}$$

with

$$P_{\rm cross} = \frac{e^{\tilde\gamma \cos^2\theta^m_{as}} - 1}{e^{\tilde\gamma} - 1}$$

$$\gamma = \tilde\gamma \frac{\sin^2 2\theta^m_{as}}{2\pi |\cos 2\theta^m_{as}|}$$

Sterile neutrinos in the Sun

Formalism: evolve the 4x4 neutrino density matrix $\rho(E_\nu, r)$ from production to detection

Evolution in vacuum:

$$\rho_{\rm surf} = \mathscr{U}_{\rm vac}\mathscr{U}_{\rm sun} \cdot V^\dagger \cdot \begin{pmatrix} 1 & & & \\ & 0 & & \\ & & 0 & \\ & & & 0 \end{pmatrix} \cdot V \cdot \mathscr{U}^\dagger_{\rm sun}\mathscr{U}^\dagger_{\rm vac}$$

V 4x4 mixing matrix **in matter**

$$\mathscr{U}^\dagger_{\rm sun} = {\rm diag}\ \exp(i\int_0^{r_*} dr \frac{m^2_{\nu_i}}{2E_\nu}) \cdot U_{\rm cross} \cdot {\rm diag}\ \exp(i\int_{r_*}^{R_\odot} dr \frac{m^2_{\nu_i}}{2E_\nu})$$

$$\mathscr{U}_{\rm vac} = {\rm diag}\ \exp(-\frac{iLm^2_{\nu_i}}{2E_\nu})$$

Sterile neutrinos in the Sun

Formalism: evolve the 4x4 neutrino density matrix $\rho(E_\nu, r)$ from production to detection

Evolution in the Earth:

$$\rho_{\rm det} = \mathscr{U}_{\rm earth}\mathscr{U}_{\rm vac}\mathscr{U}_{\rm sun} \cdot V^\dagger \cdot \begin{pmatrix} 1 & & & \\ & 0 & & \\ & & 0 & \\ & & & 0 \end{pmatrix} \cdot V \cdot \mathscr{U}^\dagger_{\rm sun}\mathscr{U}^\dagger_{\rm vac}\mathscr{U}^\dagger_{\rm earth}$$

V 4x4 mixing matrix **in matter**

$$\mathscr{U}^\dagger_{\rm sun} = \text{diag } \exp(i\int_0^{r_*} dr \frac{m^2_{\nu_i}}{2E_\nu}) \cdot U_{\rm cross} \cdot \text{diag } \exp(i\int_{r_*}^{R_\odot} dr \frac{m^2_{\nu_i}}{2E_\nu})$$

$$\mathscr{U}_{\rm vac} = \text{diag } \exp(-\frac{iLm^2_{\nu_i}}{2E_\nu})$$

$$\mathscr{U}_{\rm earth} = P \cdot \text{diag } \exp(-iL_{\rm mantle/core}\frac{m^2_{\nu_i}}{2E_\nu}) \cdot P^\dagger$$

non-adiabatic vacuum/mantle transition

Sterile neutrinos in the Sun

Formalism: evolve the 4x4 neutrino density matrix $\rho(E_\nu, r)$ from production to detection

Back to flavor basis:

$$\rho_{\rm fin} = V \cdot \mathscr{U}_{\rm earth}\mathscr{U}_{\rm vac}\mathscr{U}_{\rm sun} \cdot V^\dagger \cdot \begin{pmatrix} 1 & & & \\ & 0 & & \\ & & 0 & \\ & & & 0 \end{pmatrix} \cdot V \cdot \mathscr{U}^\dagger_{\rm sun}\mathscr{U}^\dagger_{\rm vac}\mathscr{U}^\dagger_{\rm earth} \cdot V^\dagger$$

V 4x4 mixing matrix **in matter**

$$\mathscr{U}^\dagger_{\rm sun} = {\rm diag}\ \exp(i\int_0^{r_*} dr\frac{m^2_{\nu_i}}{2E_\nu}) \cdot U_{\rm cross} \cdot {\rm diag}\ \exp(i\int_{r_*}^{R_\odot} dr\frac{m^2_{\nu_i}}{2E_\nu})$$

$$\mathscr{U}_{\rm vac} = {\rm diag}\ \exp(-\frac{iLm^2_{\nu_i}}{2E_\nu})$$

$$\mathscr{U}_{\rm earth} = P \cdot {\rm diag}\ \exp(-iL_{\rm mantle/core}\frac{m^2_{\nu_i}}{2E_\nu}) \cdot P^\dagger$$

From the final, evolved $\rho_{\rm fin}$: oscillation quantities:

$P(\nu_e \to \nu_e) = \rho_{ee}$ $\quad$ $P(\nu_e \to \nu_s) = \rho_{es}$ $\quad$ etc.

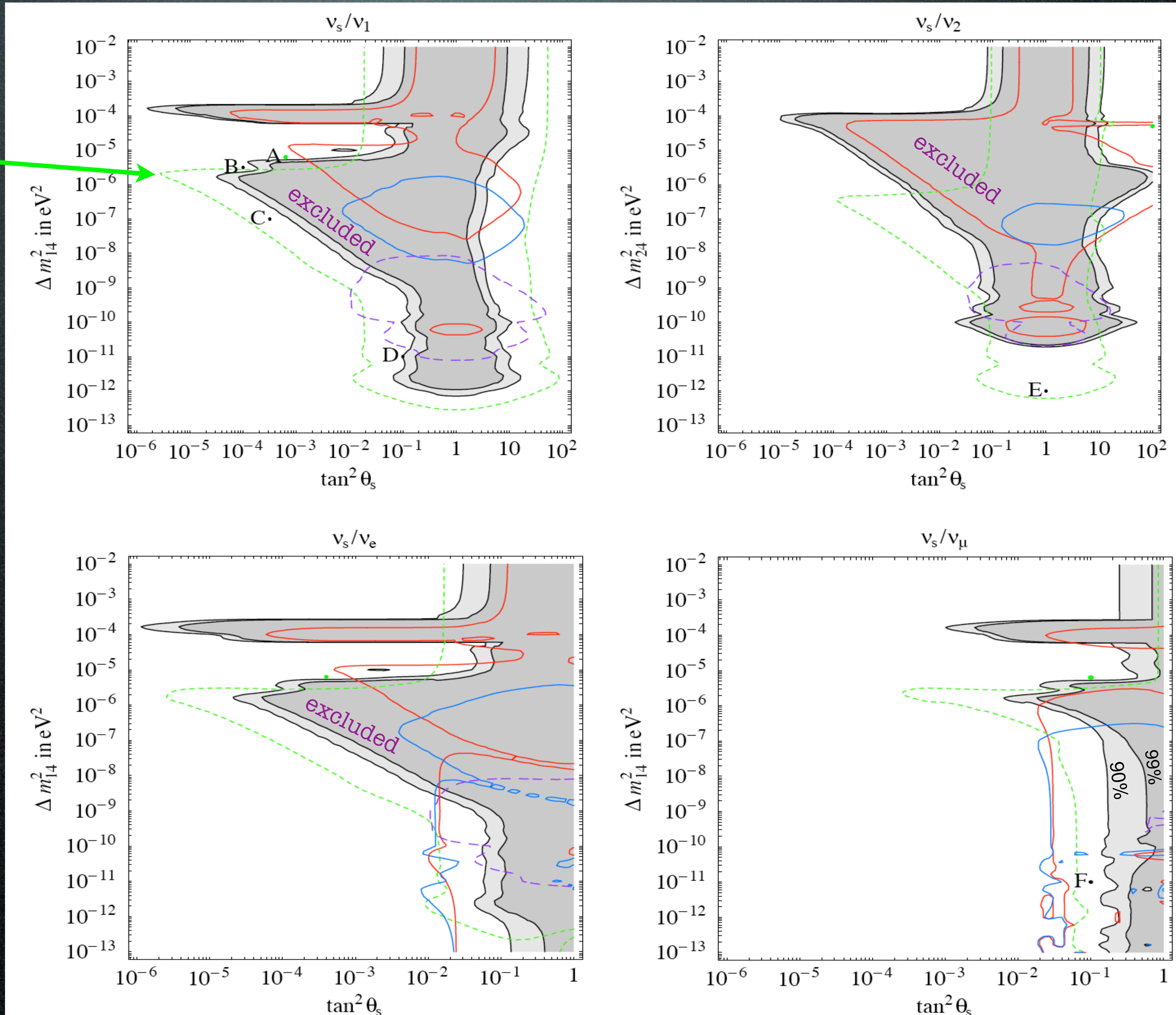
Sterile neutrinos in the Sun

2% deviation from theory of P_{ee} at $E_\nu < \mathrm{MeV}$

1% deviation $A^{\mathrm{ES}}_{\mathrm{d/n}}$
(Mton Water Cerenkov)

2% deviation $A_{\mathrm{d/n}}$
(Borexino? KamLAND?)

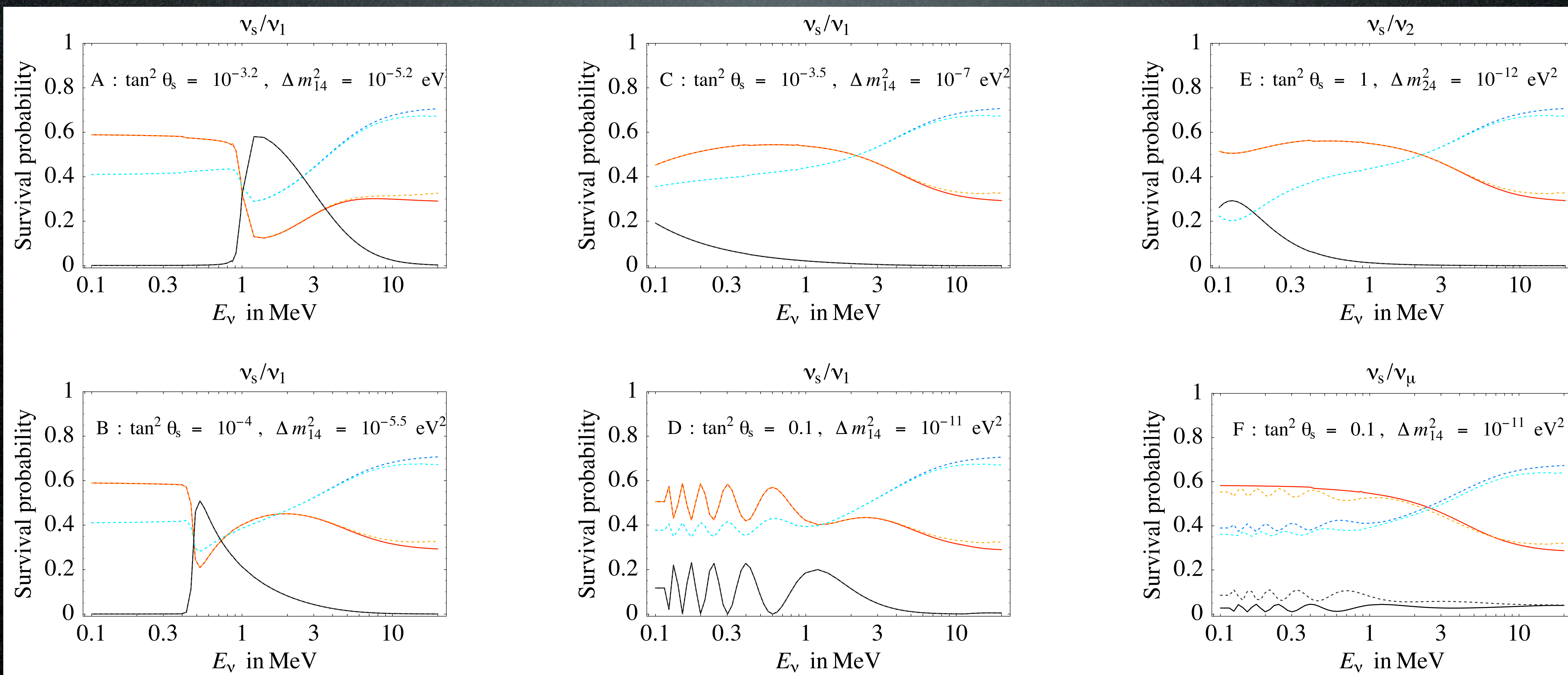
2% deviation $A_{\mathrm{s/w}}$
(Borexino?)



Cirelli, Marandella, Strumia, Vissani 2004

Sterile neutrinos in the Sun

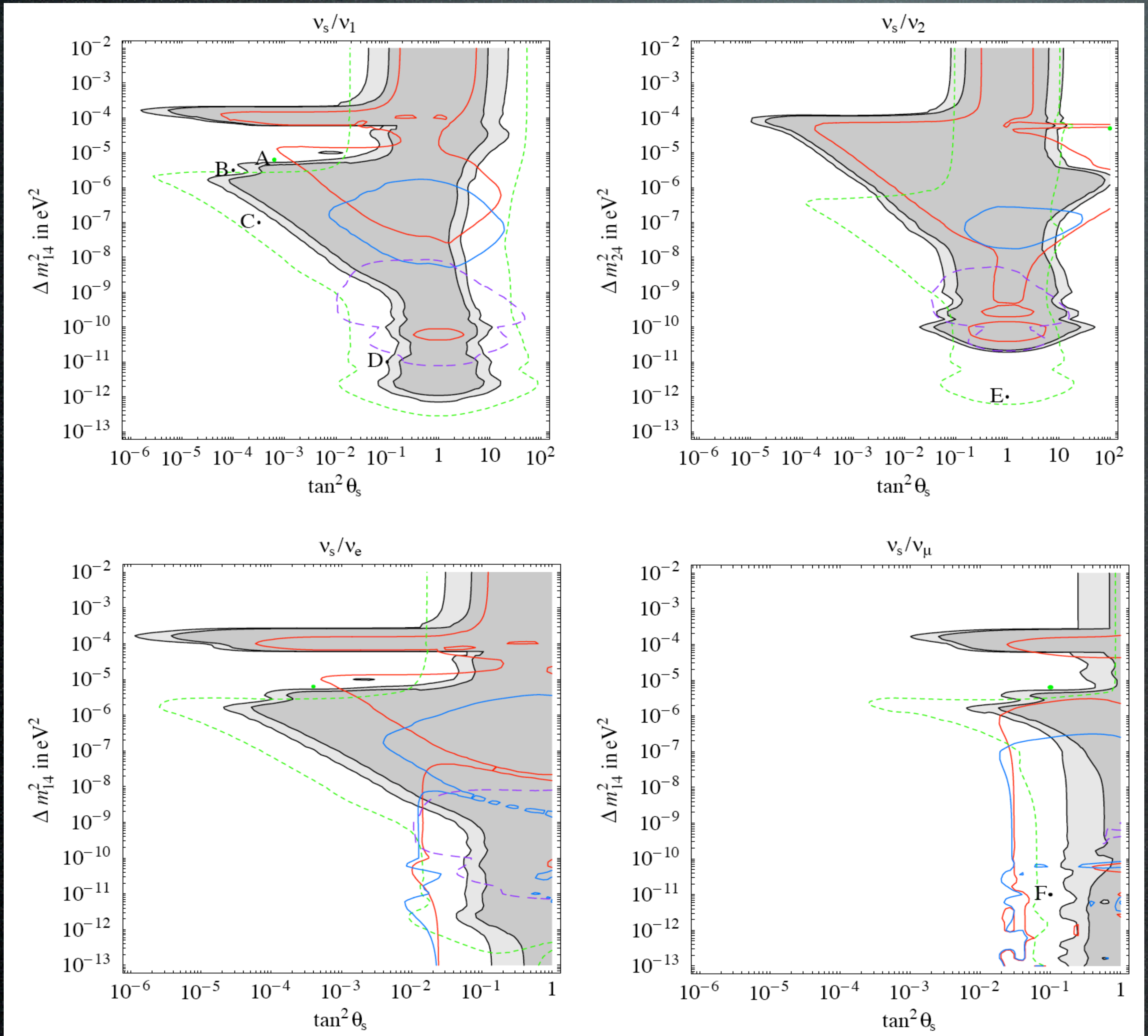
The energy dependance of matter/vacuum conversions causes spectral distortions:



The effects are there at low energy: $E_\nu \lesssim \text{few MeV}$.

Sterile neutrinos in the Sun

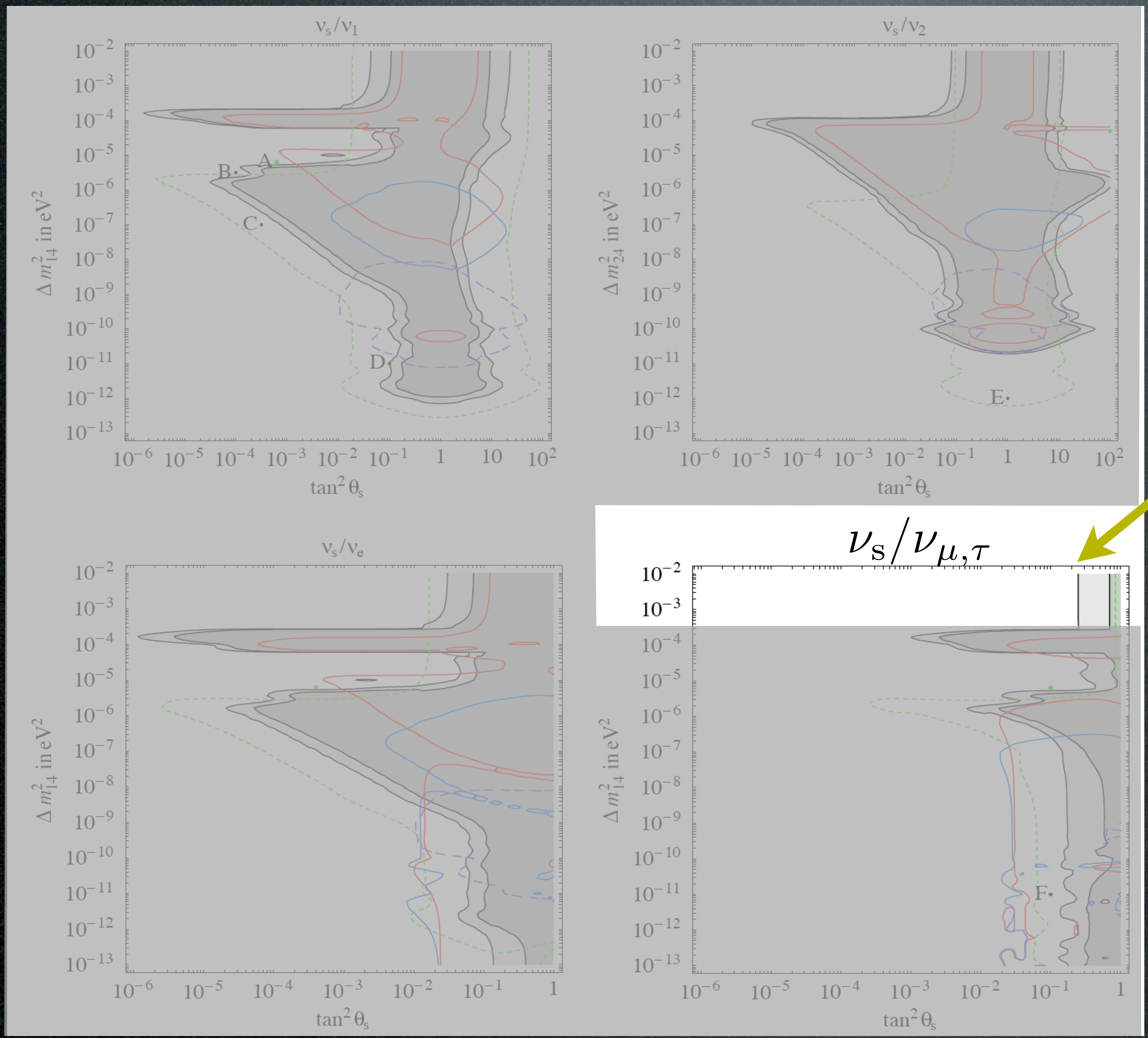
What is the "still allowed component" of sterile in solar neutrinos?



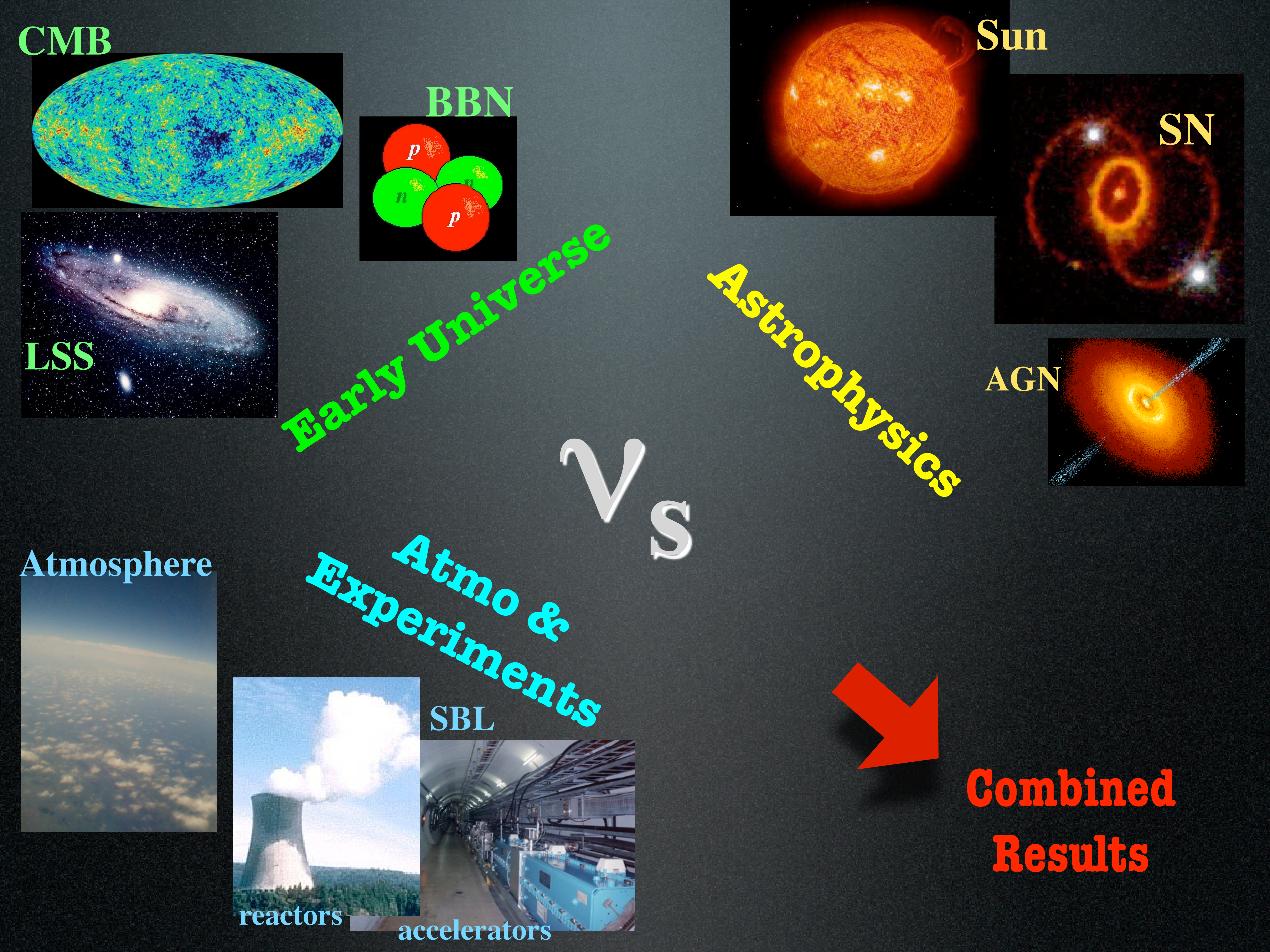
Sterile neutrinos in the Sun

What is the "still allowed component" of sterile in solar neutrinos?

You mean the limit case $\nu_e \to \cos\theta_s\ \nu_{\mu,\tau} + \sin\theta_s\ \nu_s$ (with large Δm^2_s, energy-indep. oscillations)



$\sin^2\theta_s < 0.2$ (99% C.L.)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Sterile neutrinos in atmo+LBL

Atmospheric neutrinos:

- are a lot, and well studied
- may undergo matter effects in Earth (but no resonances)
- are detected via NC and CC

An extra $\nu_{\rm s}$ can make a difference.

Sterile neutrinos in atmo+LBL

Atmospheric neutrinos:

- are a lot, and well studied
- may undergo matter effects in Earth (but no resonances)
- are detected via NC and CC

An extra ν_s can make a difference.

Dominant $\nu_\mu \to \nu_s$ is excluded. [details]

Look for subdominant sterile effects, on top of $\nu_\mu \to \nu_\tau$.

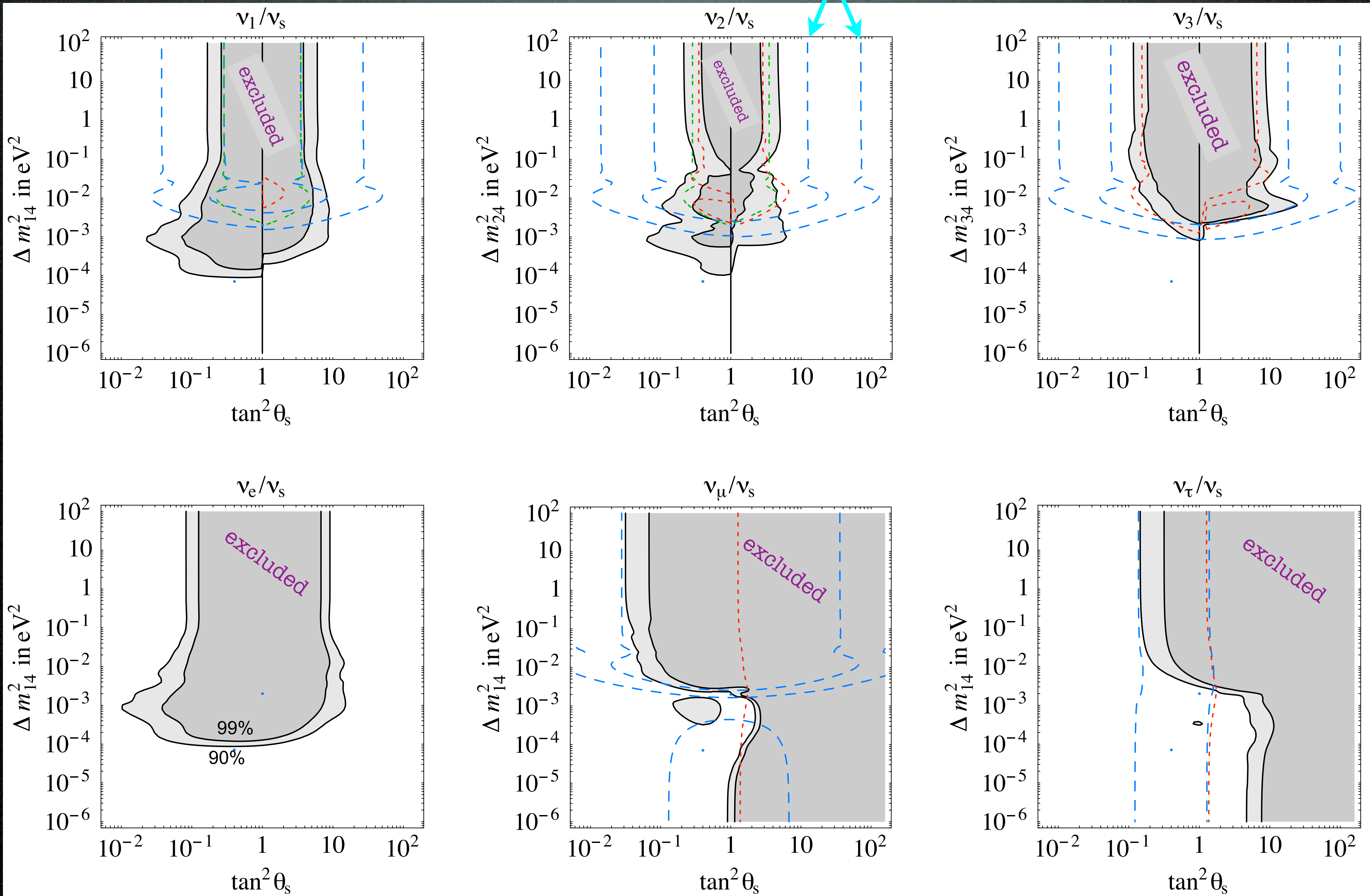
$\Rightarrow$ None found. Exclusion regions.

Dataset: SK + Macro + K2K.

(i.e. technically, marginalizing over $\Delta m^2_{23} = (2.5 \pm 0.2) \cdot 10^{-3}\ \mathrm{eV}^2$, $\sin^2 2\theta_{23} = 1.02 \pm 0.04$ parameters)

Sterile neutrinos in atmo+LBL

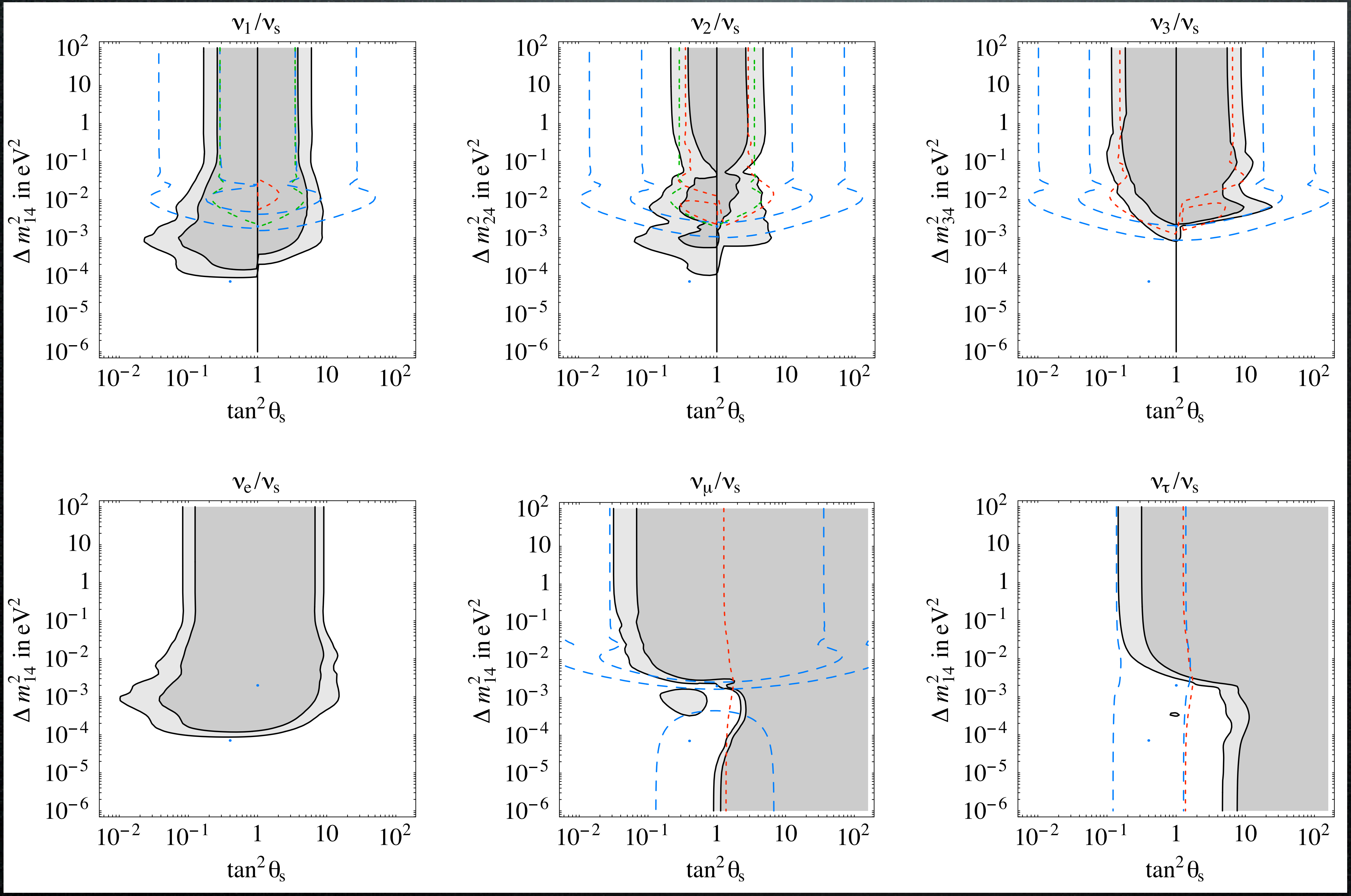
1%, 5% anomaly in NC at MINOS



Cirelli, Marandella, Strumia, Vissani 2004

Sterile neutrinos in atmo+LBL

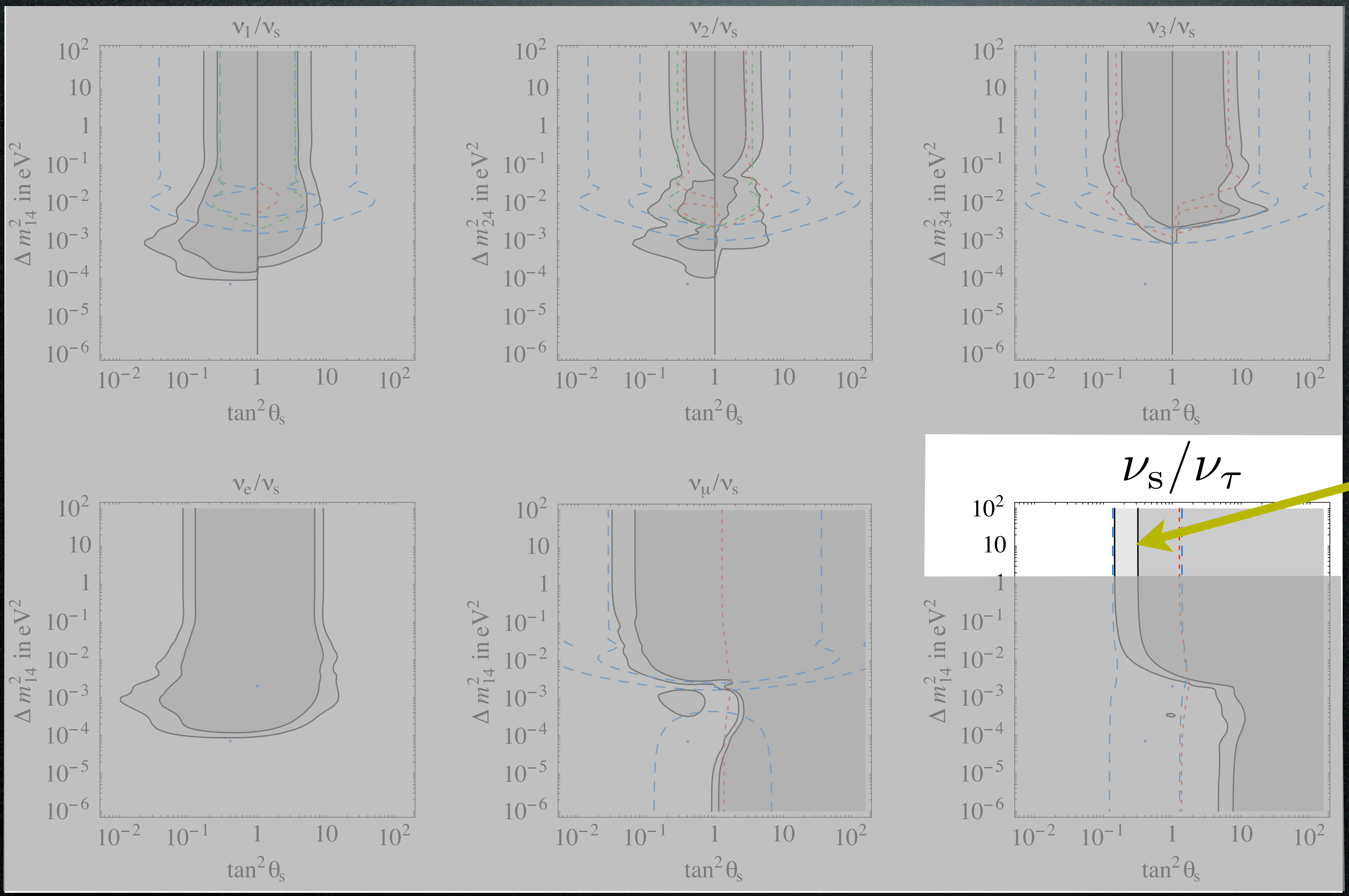
What is the "still allowed component" of sterile in atmospheric nus?



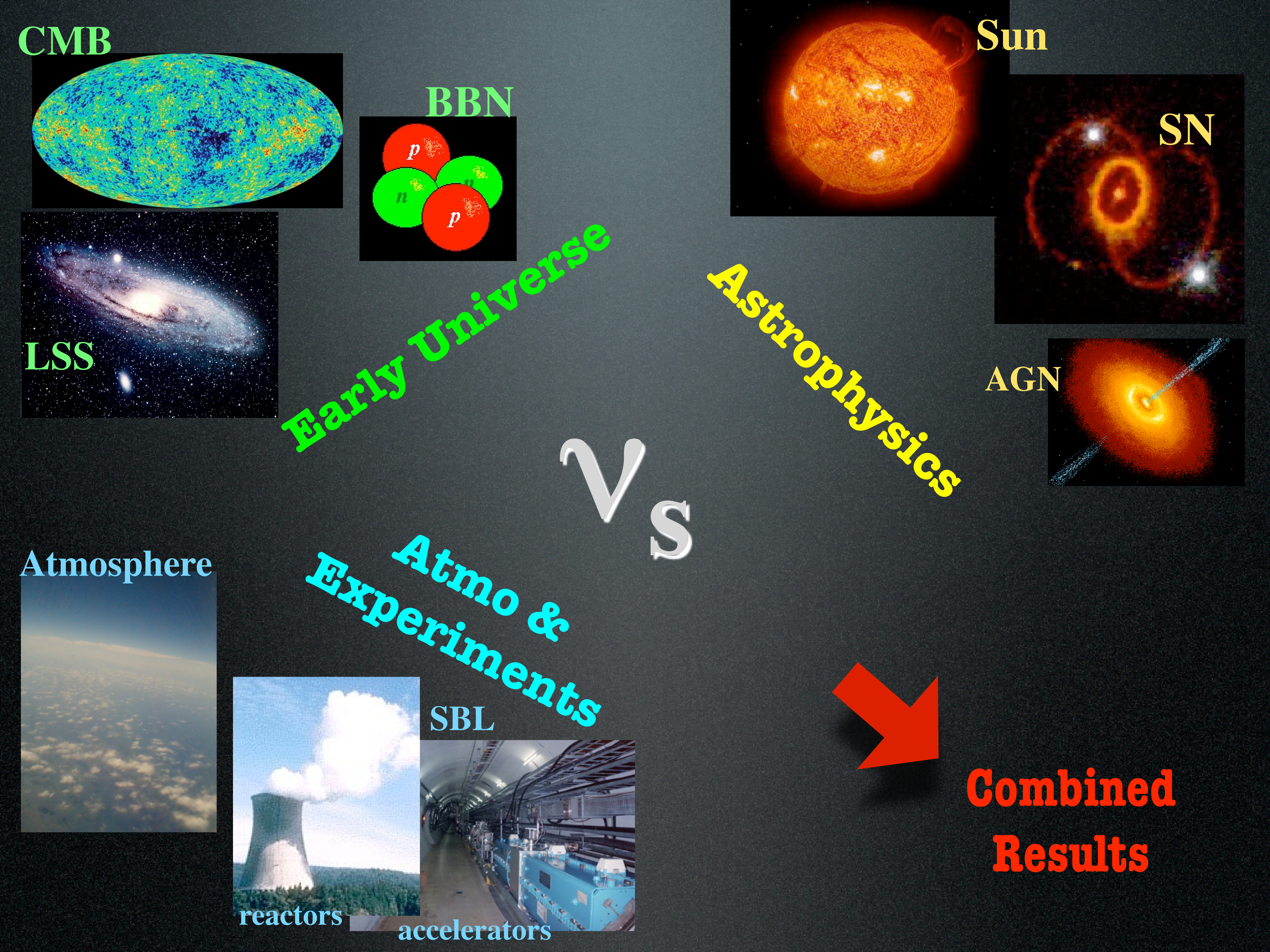
Sterile neutrinos in atmo+LBL

What is the "still allowed component" of sterile in atmospheric nus?

You mean the limit case $\nu_\mu \to \cos\theta_s \nu_\tau + \sin\theta_s \nu_s$ (with large Δm^2_s, energy-indep. oscillations)



$\sin^2\theta_s < 0.23$
(99% C.L.)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Sterile neutrinos in SBL exp.s

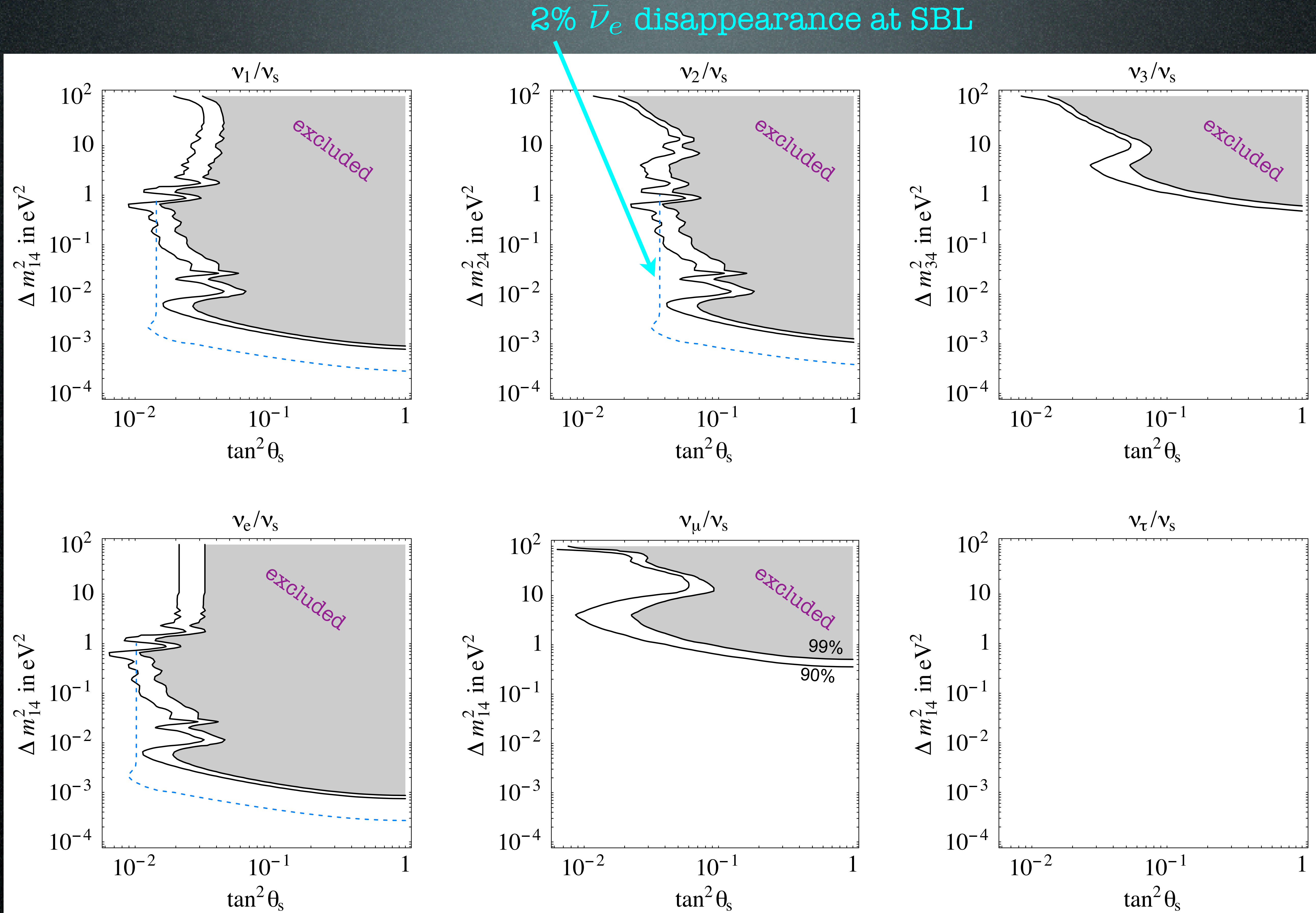
Many reactor/beam experiments looked for $\bar{\nu}_e/\nu_\mu \to \nu_{\rm s}$
disappearance in neutrino fluxes/beams.
$\Rightarrow$ Null results. Exclusion regions.

Dataset:
- Chooz, Bugey ($\bar{\nu}_e$ disappearance)
- CDHS, CCFR ($\bar{\nu}_\mu, \nu_\mu$ disappearance)
- Karmen (null $\bar{\nu}_\mu \to \bar{\nu}_e$)
- Nomad, Chorus (null $\nu_{\mu,e} \to \nu_\tau$ and $\nu_\mu \to \nu_e$)
-- LSND does not fit

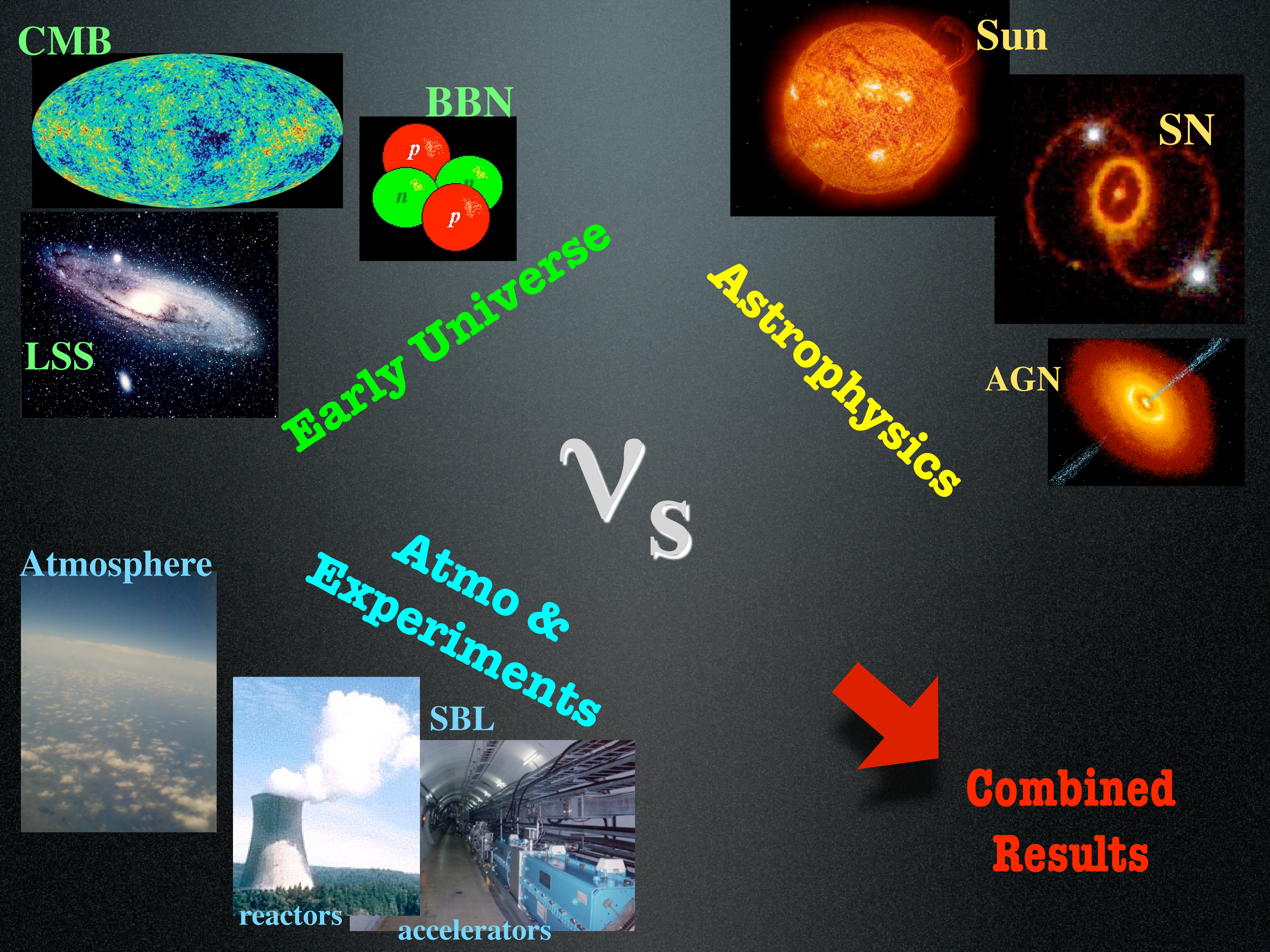
Method: simply vacuum oscillations, with $\Delta m^2_{\rm s} \gg \Delta m^2_{\rm atm,\ sun}$

$$P(\nu_\ell \to \nu_{\ell'}) = \begin{cases} 1 - 4|V^2_{\ell 4}|(1-|V^2_{\ell 4}|)\sin^2(\Delta m^2_{14} L/4E_\nu) & \text{for } \ell = \ell' \\ 4|V^2_{\ell 4}||V^2_{\ell' 4}|\sin^2(\Delta m^2_{14} L/4E_\nu) & \text{for } \ell \neq \ell' \end{cases}$$

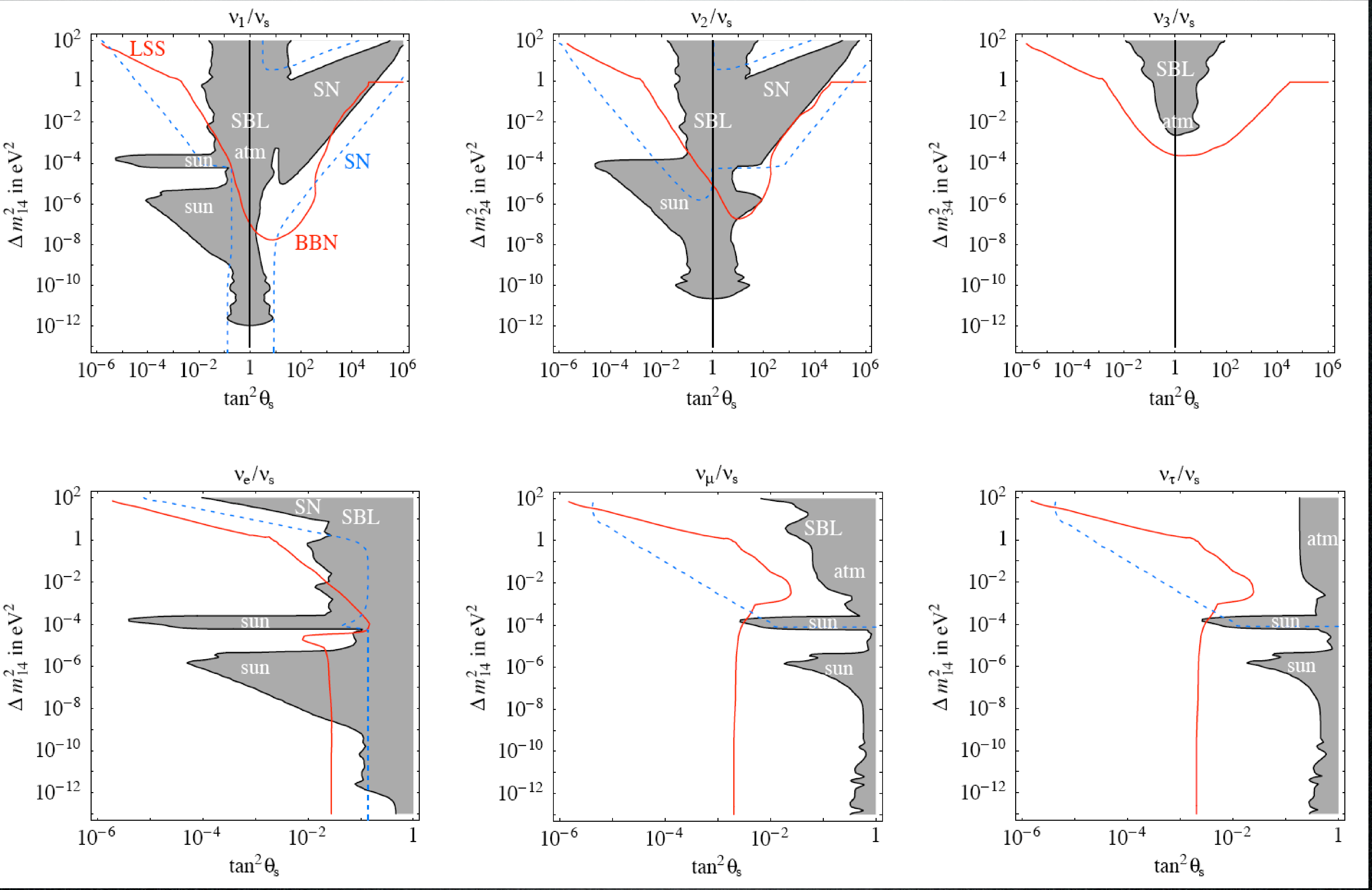
Sterile neutrinos in SBL exp.s



Cirelli, Marandella, Strumia, Vissani 2004

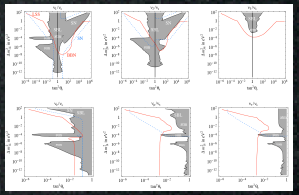

CMB
BBN
p
n
n
p
LSS
Early Universe
Sun
SN
AGN
Astrophysics
ν_s
Atmosphere
Atmo &
Experiments
SBL
reactors
accelerators
Combined
Results

Combined Results



Conclusions

- the direct/easy ways for sterile neutrinos are now closed
- look for subdominant effects, refine analysis, include all sources
- no significant evidence found, powerful bounds imposed

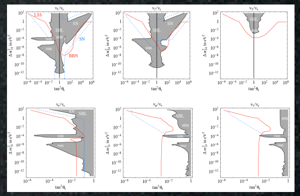


in particular:
LSND excluded by std cosmology,
reallowed if large asymmetry

- **cosmo, astro, ν exps probe different, complementary scenarios**

Conclusions & Executive Summary

- ☑ the direct/easy ways for sterile neutrinos are now closed
- ☑ look for subdominant effects, refine analysis, include all sources
- ☑ no significant evidence found, powerful bounds imposed



in particular:
LSND excluded by std cosmology,
reallowed if large asymmetry

- ☑ **cosmo, astro, ν exps probe different, complementary scenarios**

- ☐ MiniBooNE?
- ☐ cosmology: measure He and D better,
  next CMB, LSS will be decisive
- ☐ low energy solar neutrinos
- ☐ brace for the next SN: 10^4 events (but improve theory)

- ☐ **combine data from different fields**

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

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

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

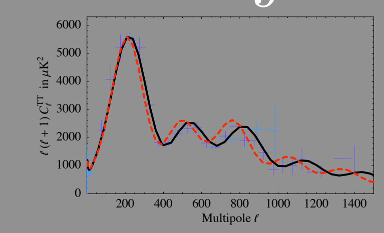
baryons

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

neutrinos

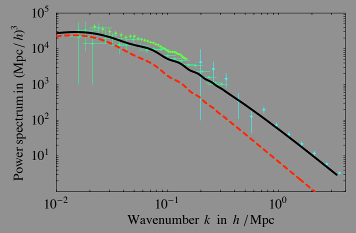
CMB Power spectrum

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



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

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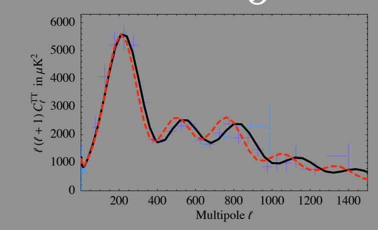
metric

CMB Power spectrum

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



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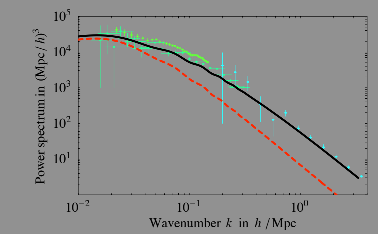

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photons

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

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

dark matter

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

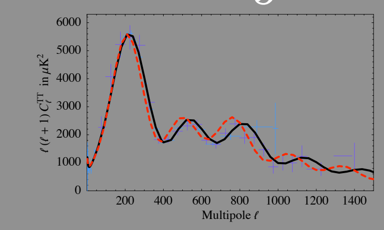
and velocity $v_{\rm dm}$

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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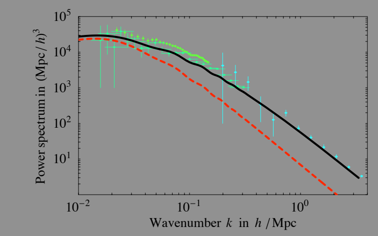

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metric

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

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

baryons

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

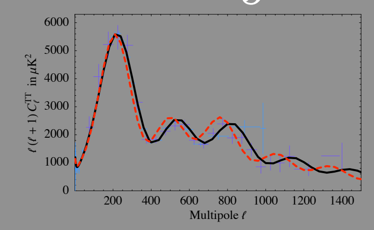
$v_{\rm b}(k,\eta)$

Thomson scattering

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

CMB Power spectrum

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



Matter Power spect.

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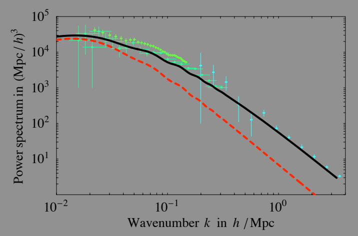

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$$\dot{\delta}_{\rm dm} + ikv_{\rm dm} = -3\dot{\Phi}$$

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

dark matter

$\dot{\delta}_{\rm b}$ …

$\dot{v}_{\rm b}$ …

$\dot{\mathcal{N}}$ …

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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metric

CMB Power spectrum

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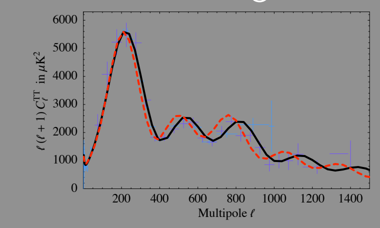

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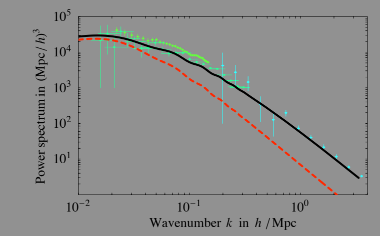

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baryons

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

neutrinos

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

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

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

metric

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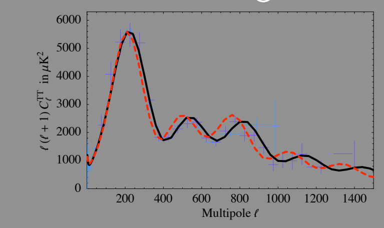

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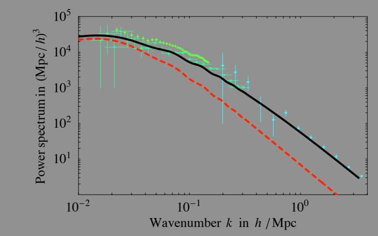

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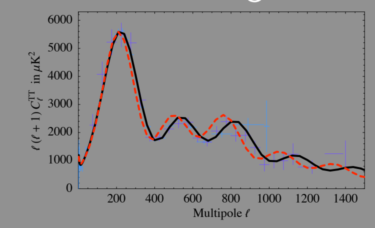

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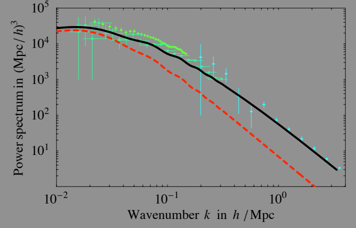

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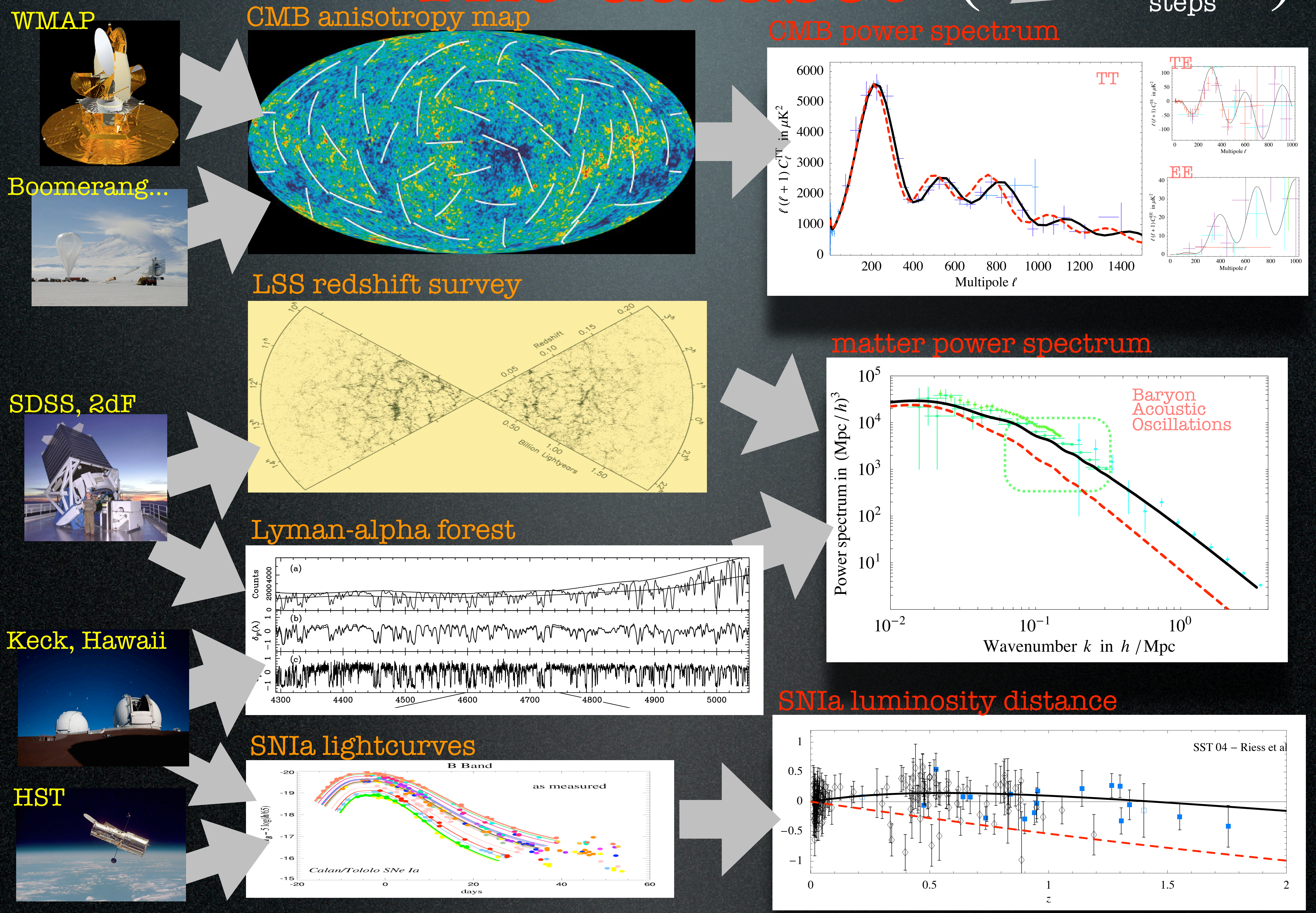
metric

The dataset

(= some highly non trivial steps)



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

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

[back]

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.

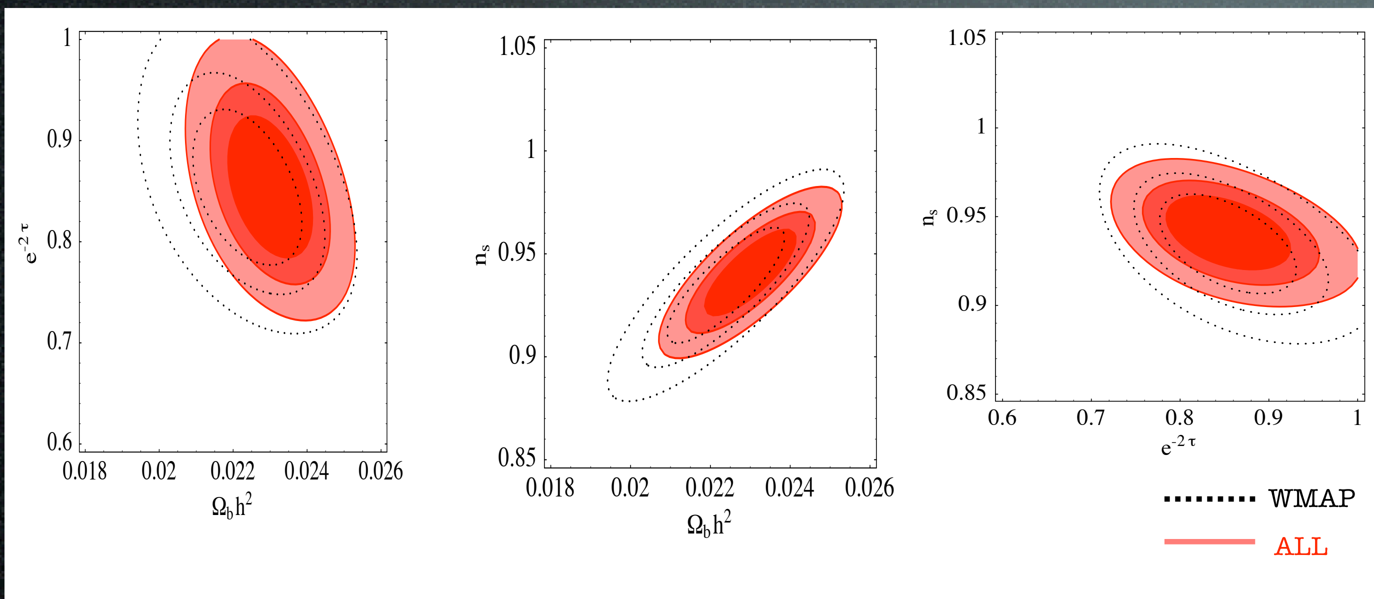
For Standard Cosmology we obtain:

fit	A_s	h	n_s	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

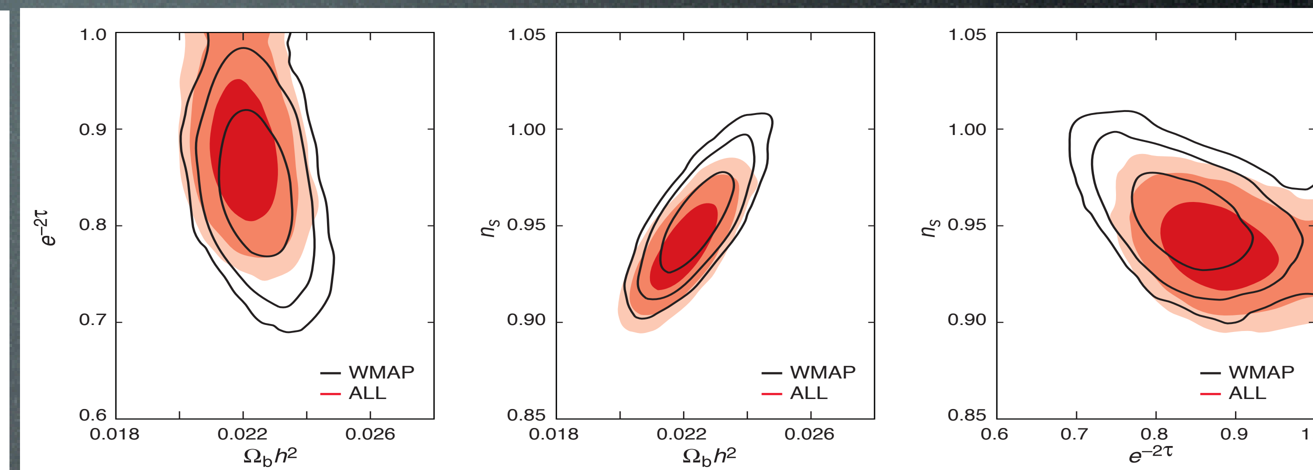
(assumes $3_{.04}$ massless, freely-streaming neutrinos).

Comparing our code

Our analysis:



WMAP Science Team analysis:



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

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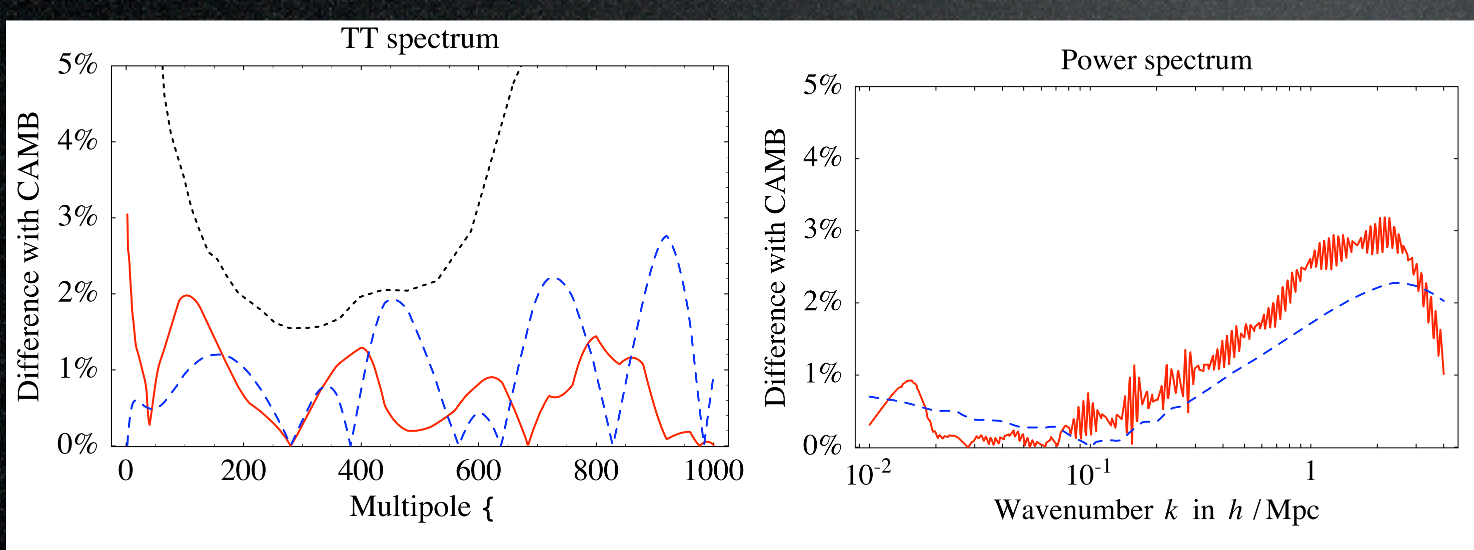
Global	0.84 ± 0.04	0.729 ± 0.013	0.951 ± 0.012	0.121 ± 0.025	2.36 ± 0.07	0.117 ± 0.003

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

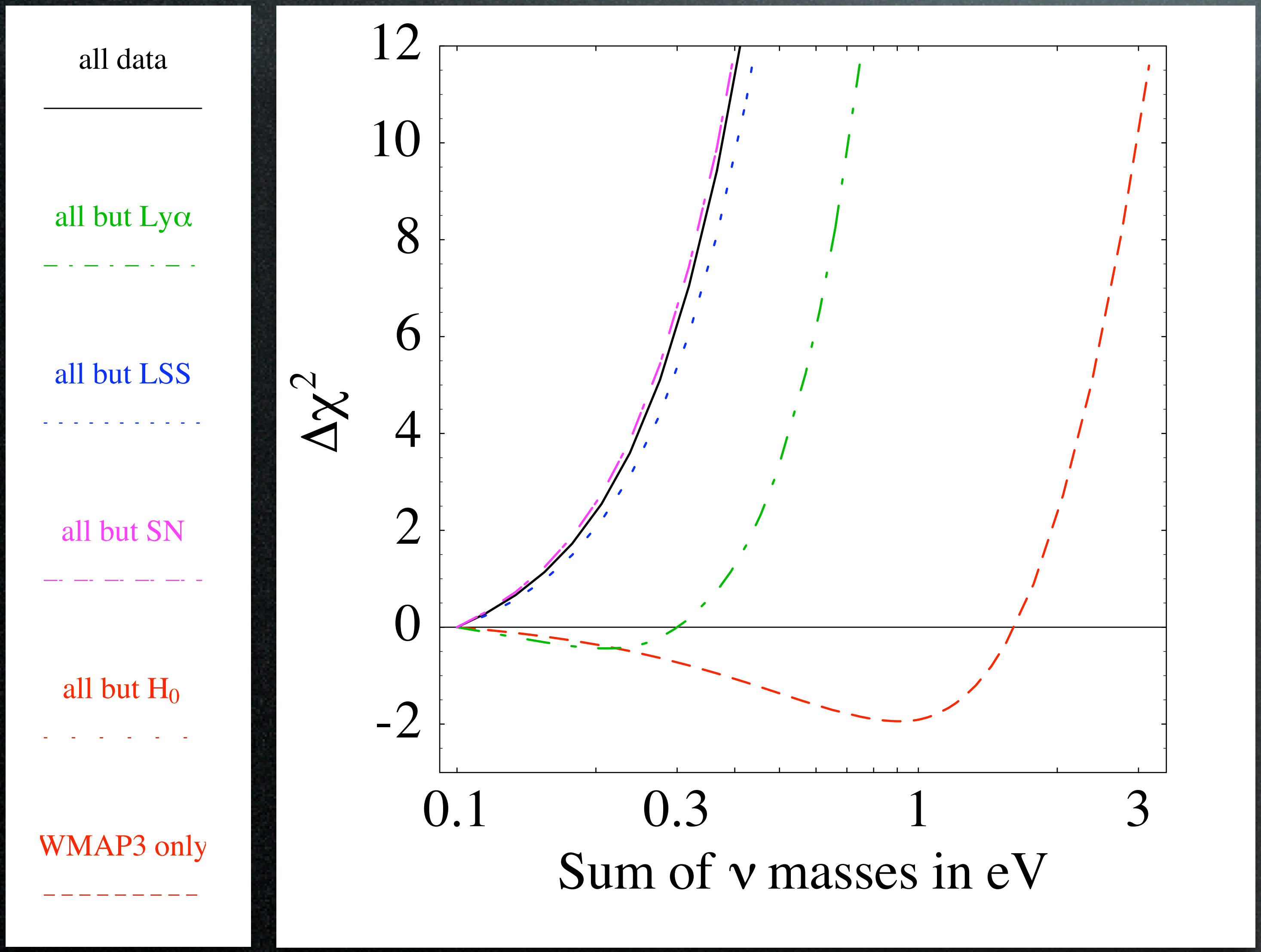
[back]

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.

[back]

Neutrino mass bounds

Particle Data Book 2008

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	

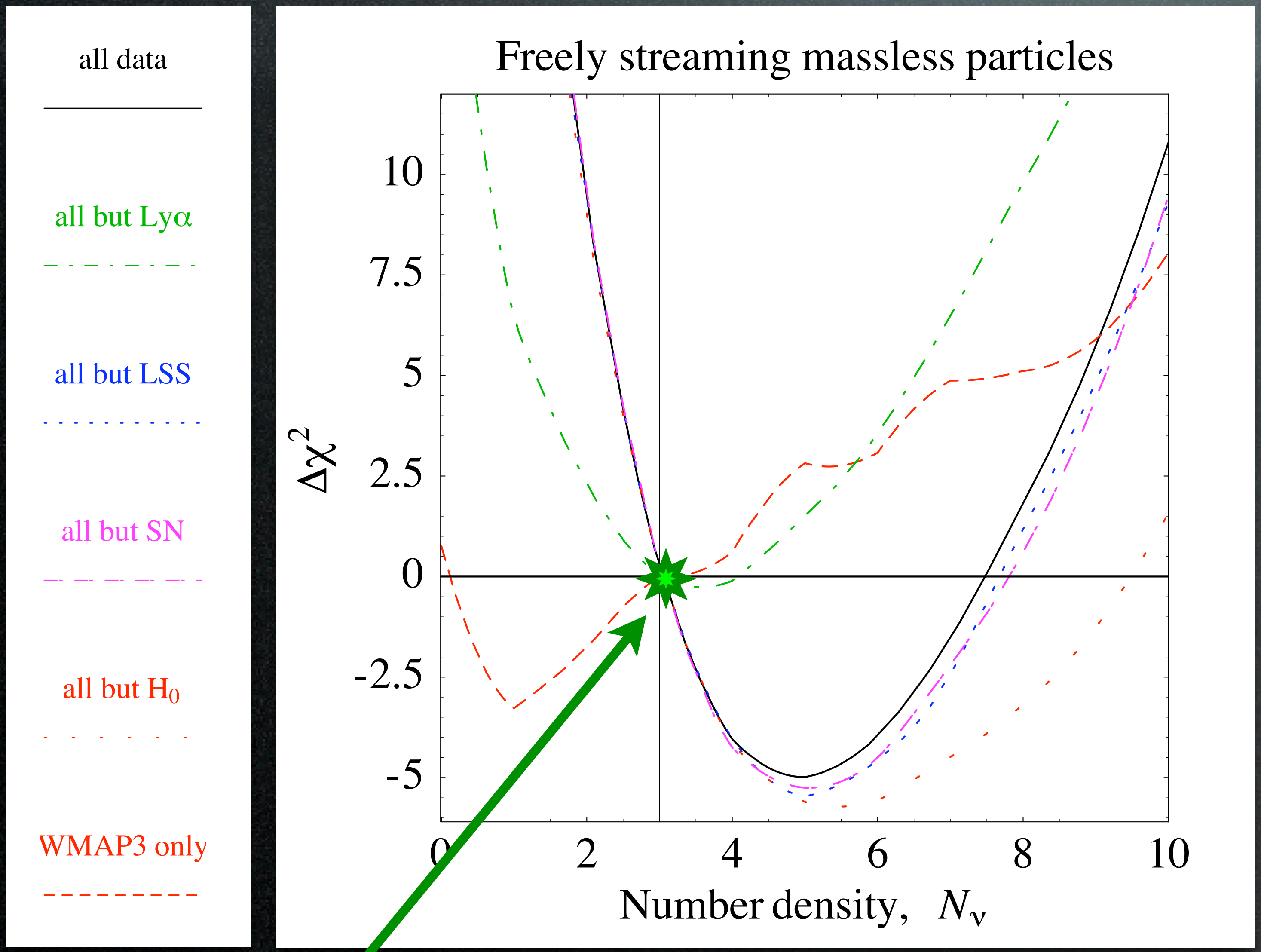
[back]

Results

New neutrinos?

$3_{.04}$ ΔN_ν

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



Standard cosmology

Global fit:

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

dropping Ly-alpha gives back

$$N_\nu \simeq 3$$

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

Neutrino number bounds

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; ≥ 3 massless ν
< 3.3		WALKER	91		Cosmology

[back]

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.

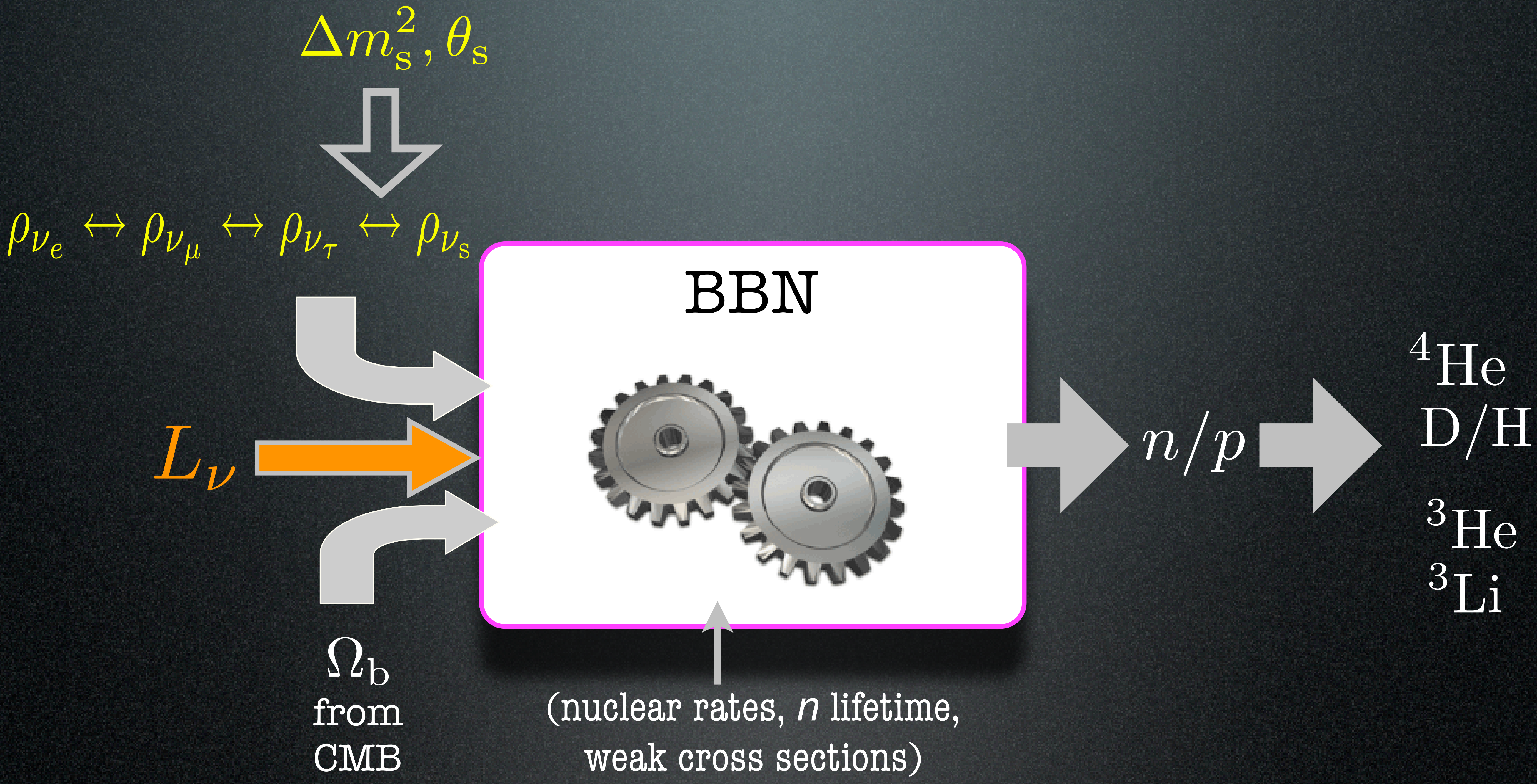
Dolgov,..., Semikoz (2002)
Abazajian, Beacom, Bell (2002)
Cuoco,..., Serpico (2004)
Serpico, Raffelt (2005)

B. neutrino interactions with new light particles

C. low reheating temperature

D. ...

BBN with lepton asymmetry



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

BBN with lepton asymmetry

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

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

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

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

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

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

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

$$V_s = 0$$

ν thermal masses

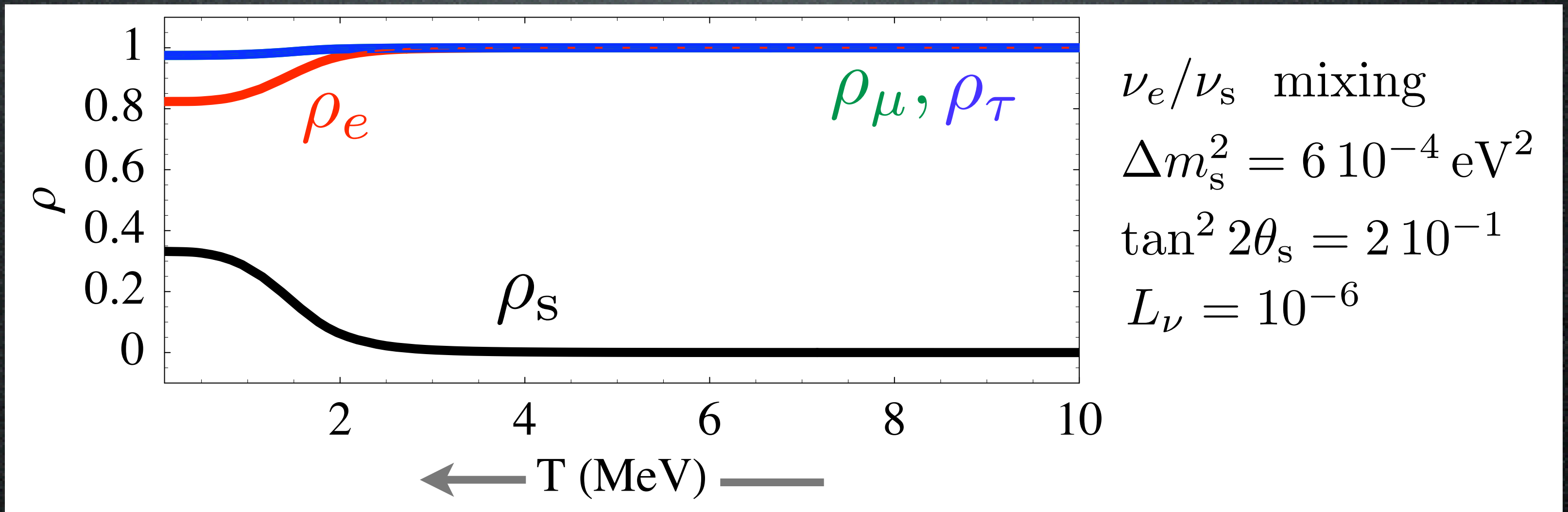
BBN with lepton asymmetry

What happens qualitatively:

- for $T \gg \mathrm{MeV}$, matter effects suppress mixing $(\rho_{\nu_s} \simeq 0)$
- despite T decreasing, the asymmetry term inhibits $\nu_{\rm active} \leftrightarrow \nu_s$ oscillations

⬇

- ν_s are less efficiently produced (or not at all) $(\rho_{\nu_s} \ll 1)$



[comparison with standard case]

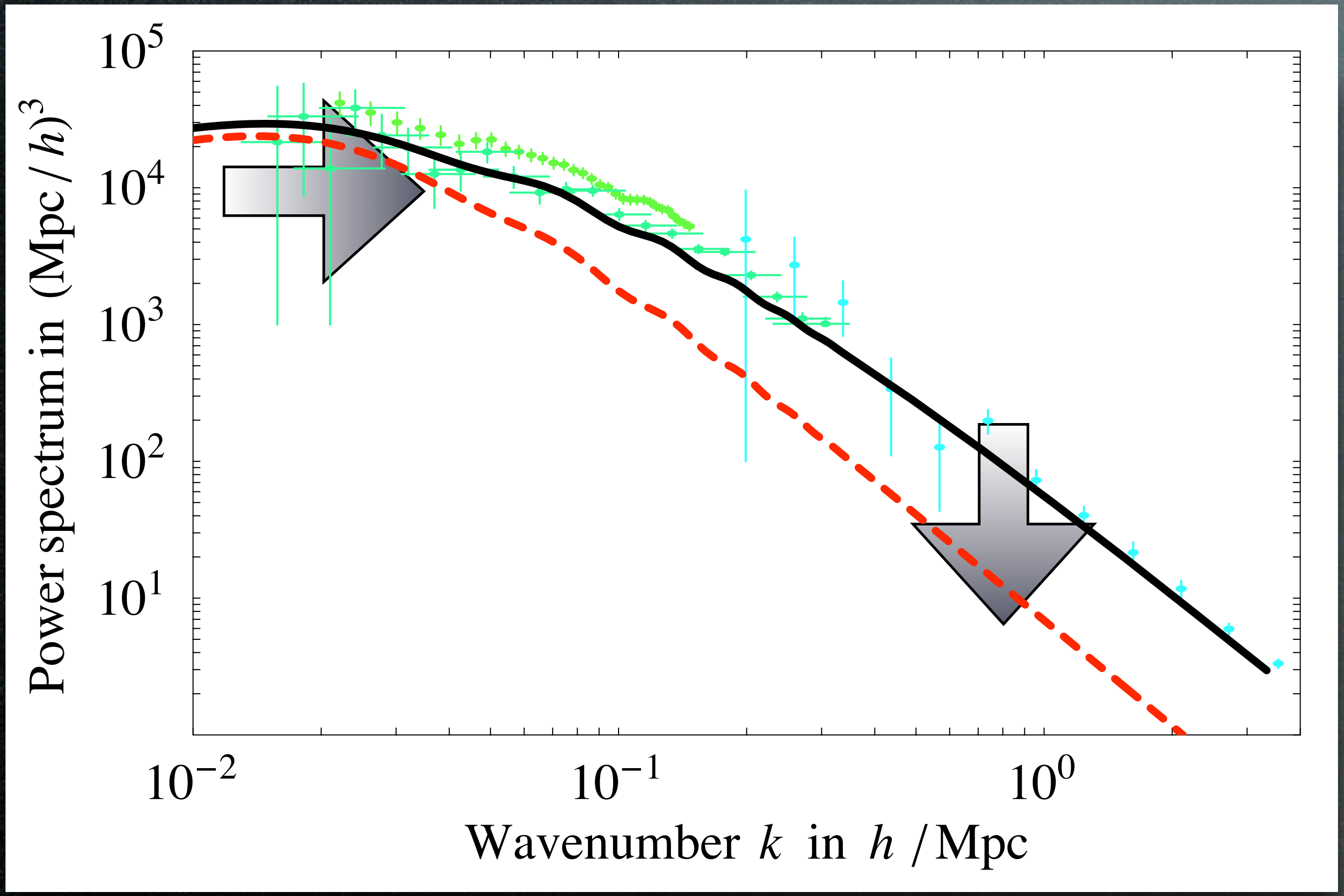
- (also: n/p weak rates affected by $\rho_{\nu_e} \neq \bar{\rho}_{\nu_e}$)

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

Fuller et al., 2004-2006

LSS with lepton asymmetry

Recall that



$\Rightarrow$ $\sum m_{\nu_i} < 0.40$ eV (@ 99.9% C.L., global fit)

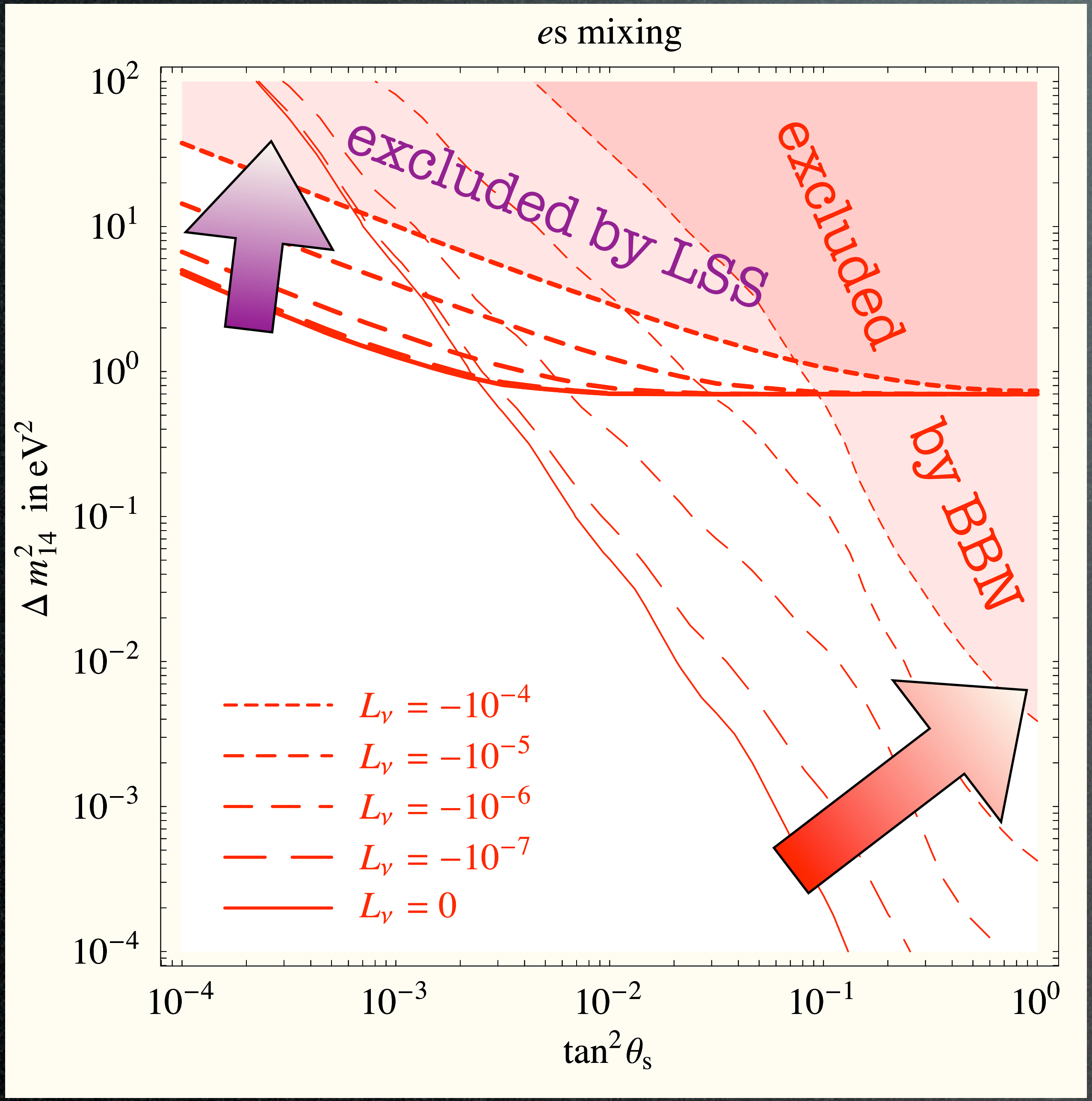
or better

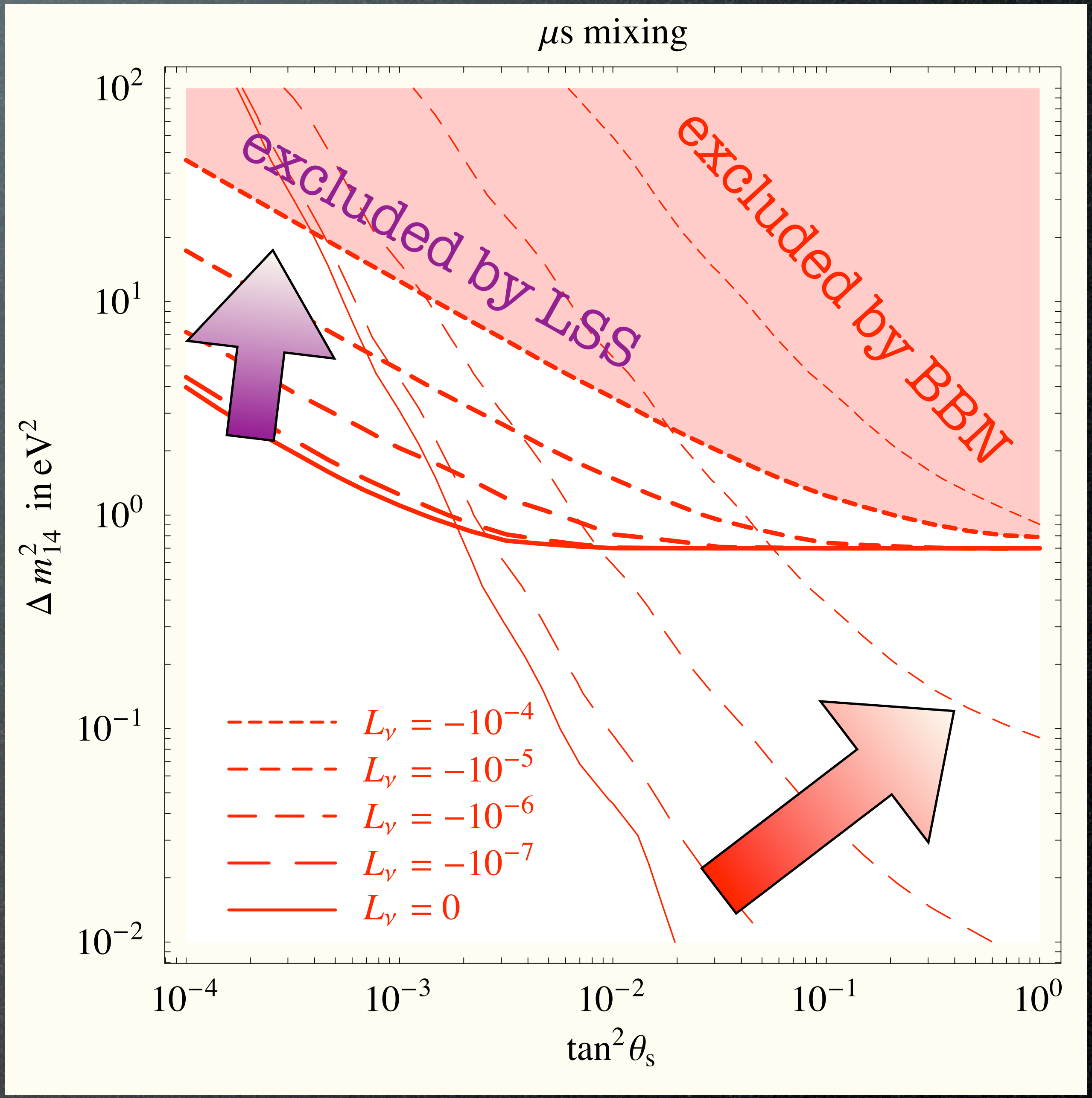
$\sum m_i \rho_i < 0.40$ eV

L_ν suppresses ν_s production $(\rho_{\nu_s} \ll 1)$:
the bound on m_4 i.e. Δm_s^2 is **relaxed**.

with lepton asymmetry

Portions of the parameter space are reopened:

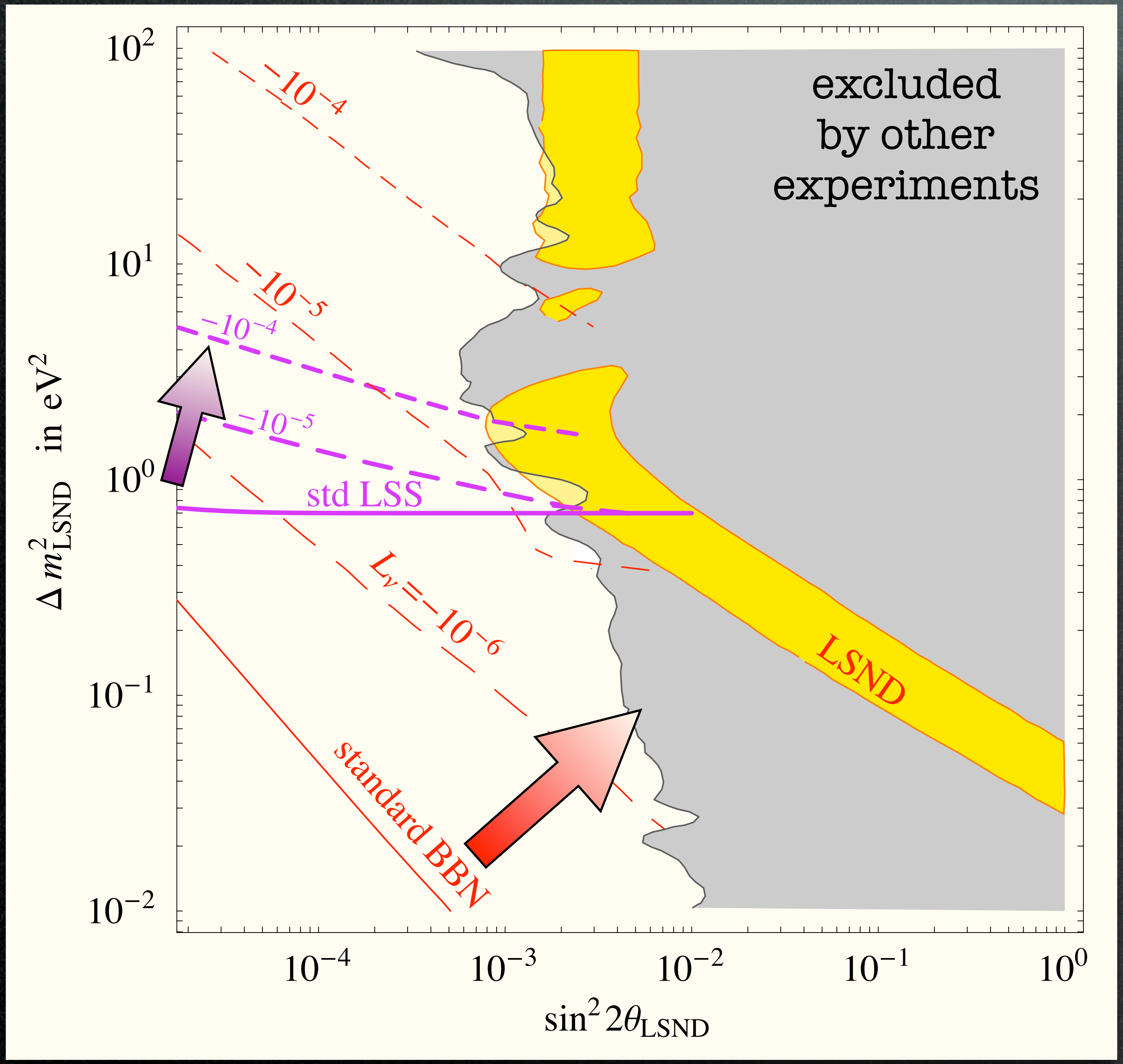




Chu, Cirelli 2006

LSND with lepton asymmetry

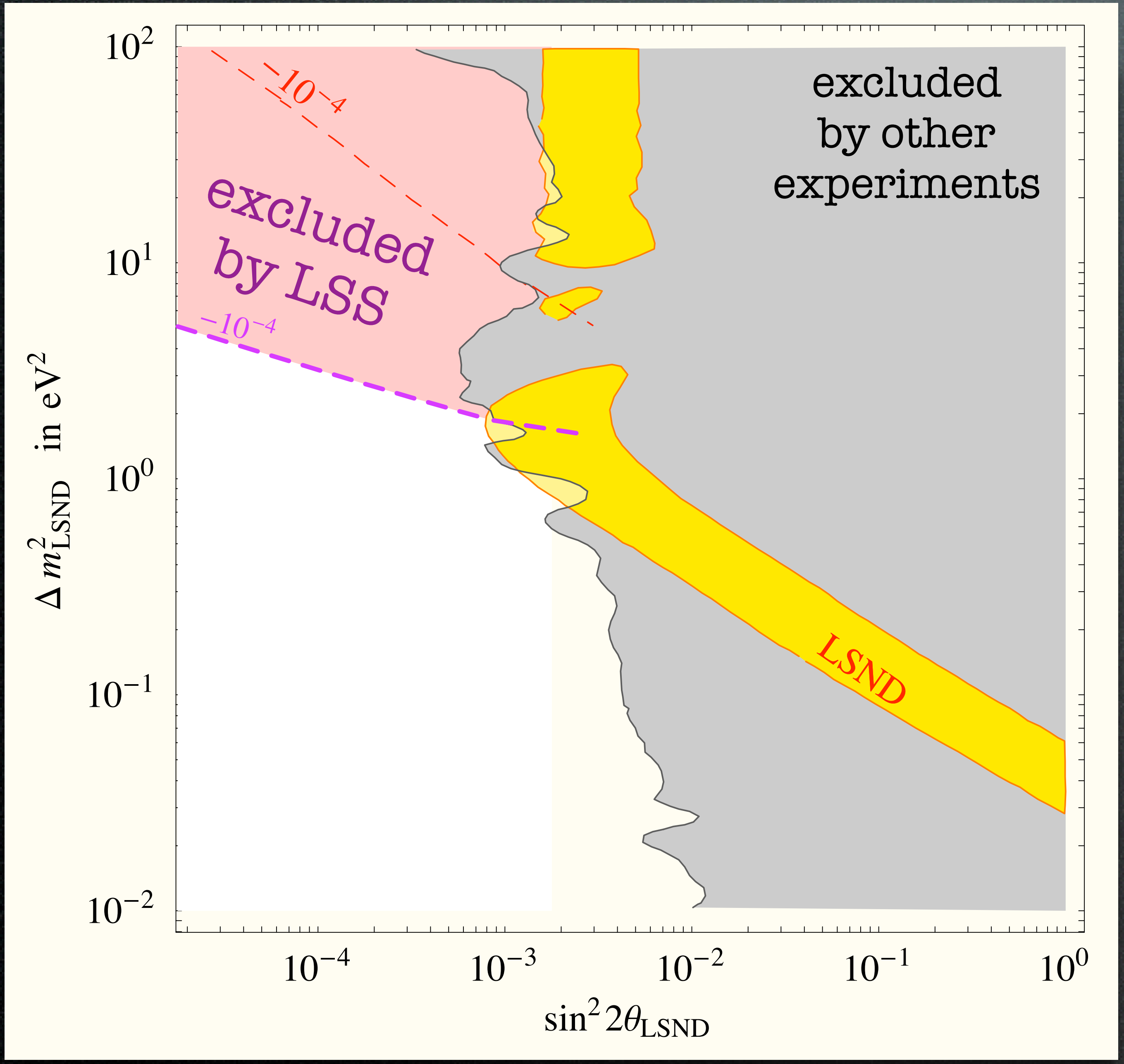
Portions of the parameter space are reopened:



Chu, Cirelli 2006

LSND with lepton asymmetry

Portions of the parameter space are reopened:



Chu, Cirelli 2006

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

[back]

Non-standard modifications

A. a large primordial lepton asymmetry

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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 $g\,\nu_{\mathrm{s}}\bar{\nu}\phi$

"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

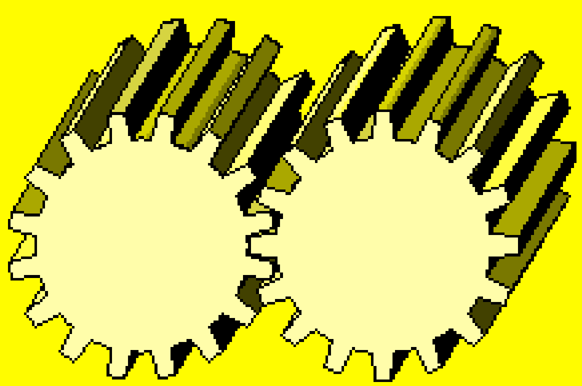
$N_\nu^{\rm norm}, N_\nu^{\rm int}, N_\phi, m_\nu, m_\phi$

⇩

Boltzmann eqs for tightly coupled fluid + standard ν eqs

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

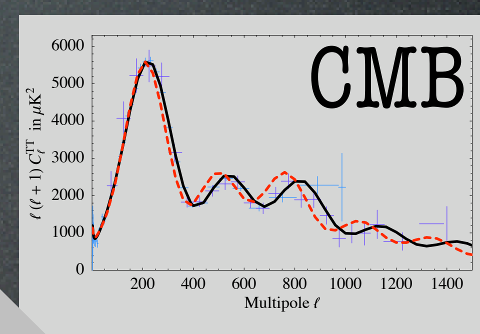
cosmological perturbations evolution

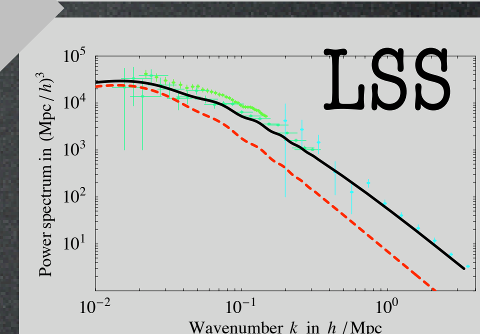


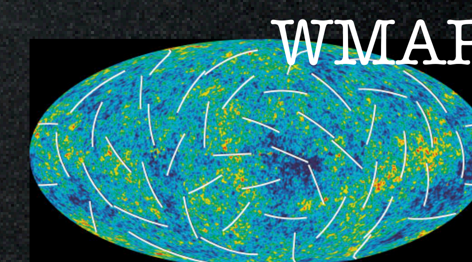
our code

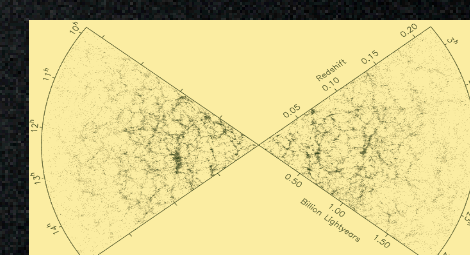
MATHEMATICA 5.2

Cirelli, Strumia, 2006





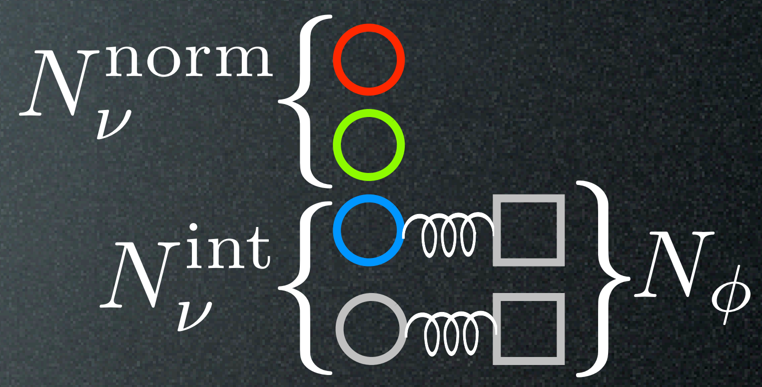


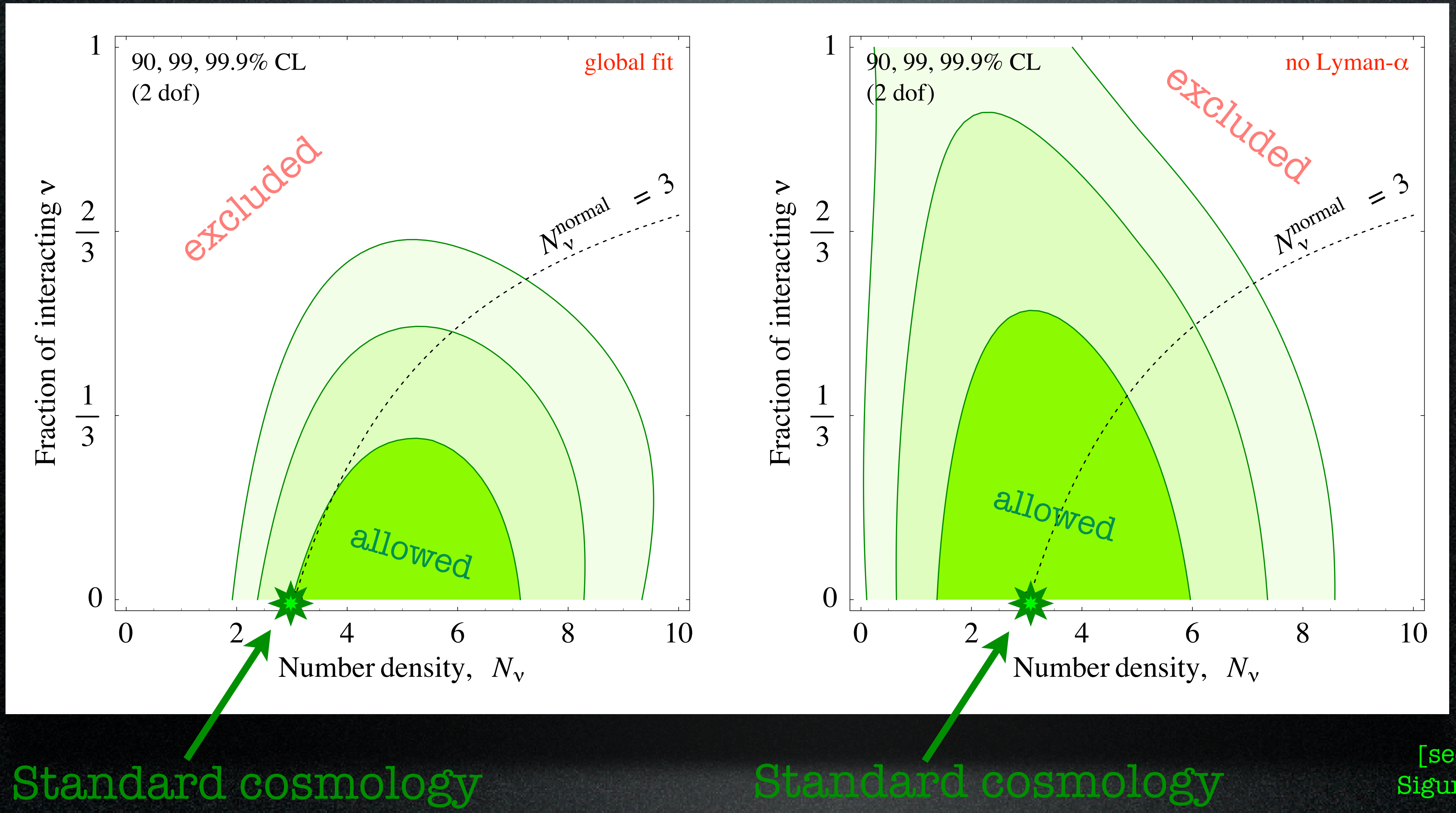


2dF, SDSS, Ly-A

Cosmology with sticky neutrinos

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



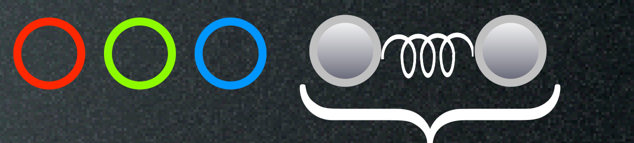


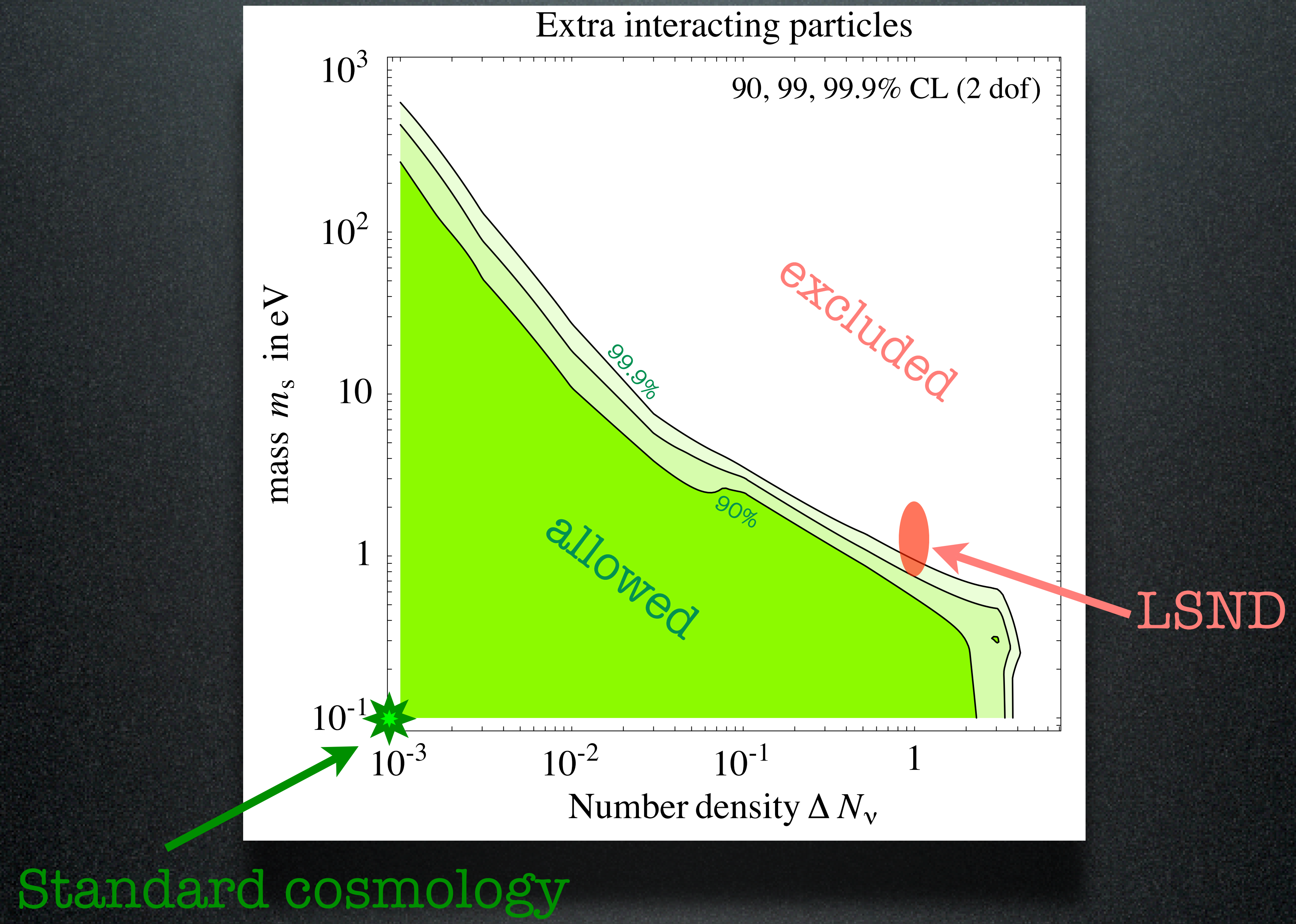
Cirelli, Strumia (2006)

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

Cosmology with sticky neutrinos

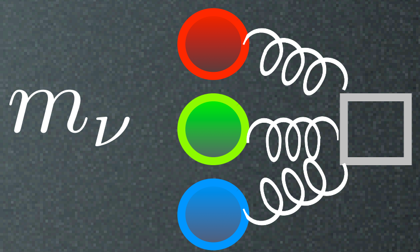
Case: three standard neutrinos (massless), ΔN_ν interacting sterile neutrinos, with mass m_s.

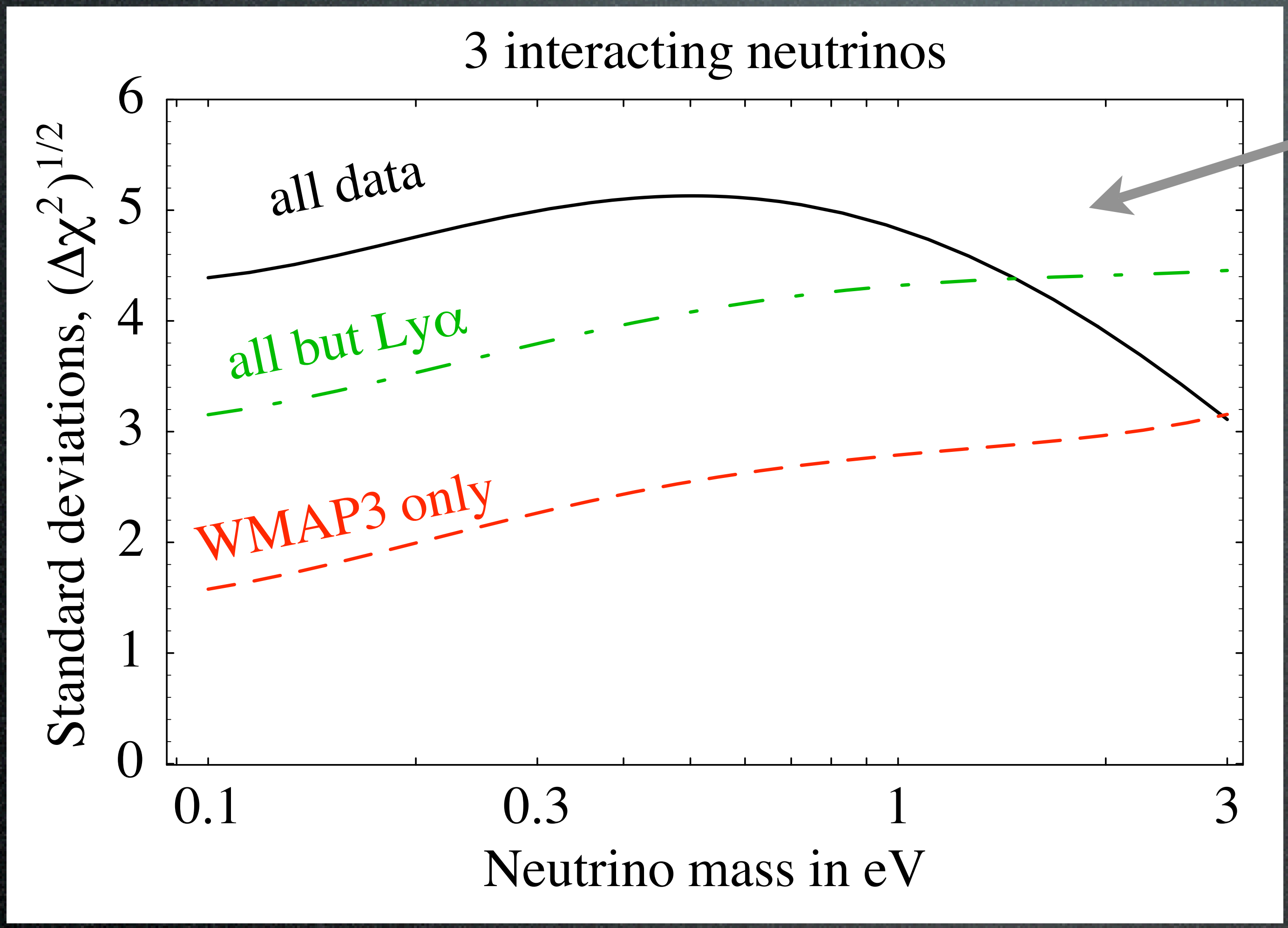




Cosmology with sticky neutrinos

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





disfavored at
3 to 5 σ.

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

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

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

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

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

} extra

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

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

} metric

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

⇩

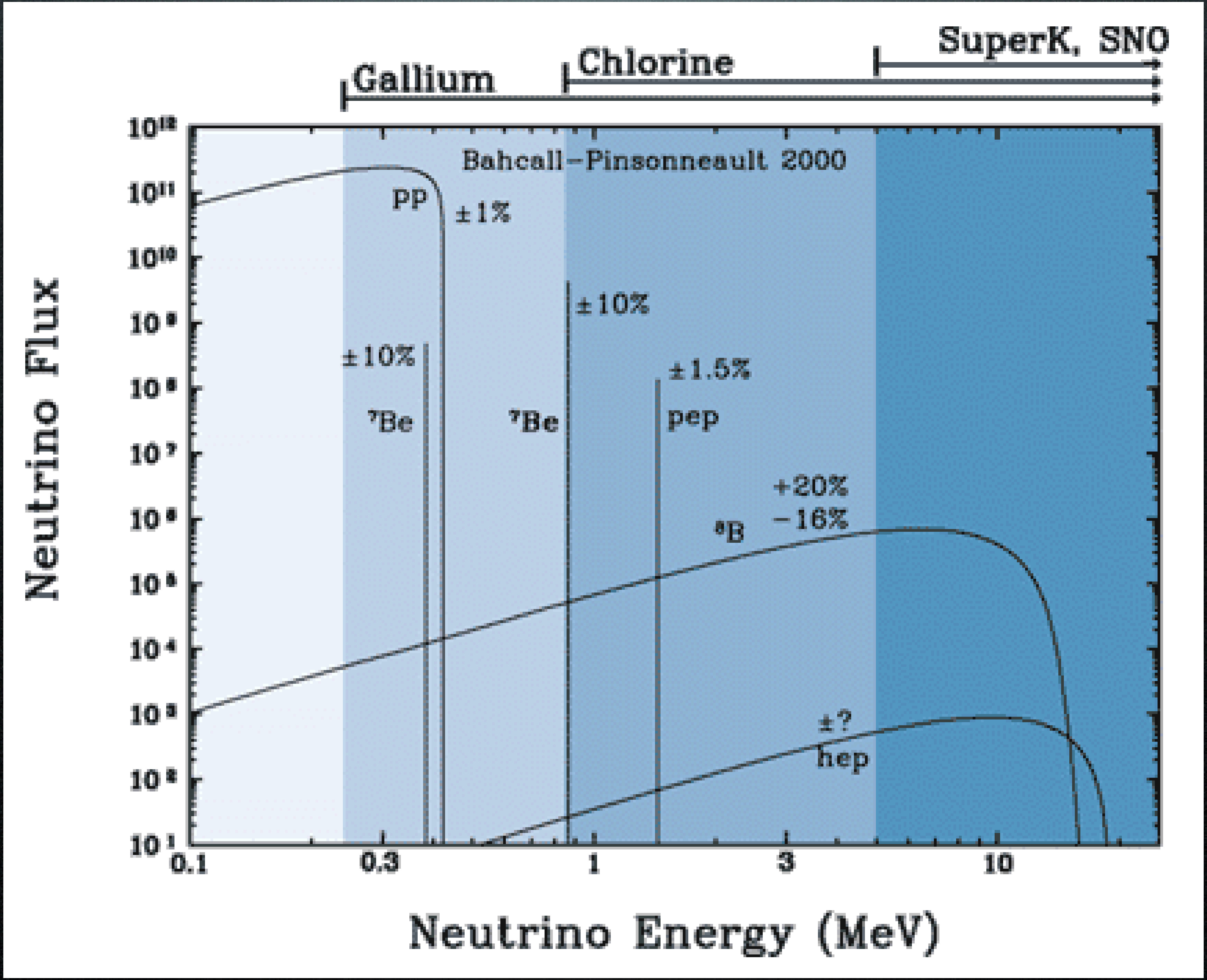
A fluid defined by $\delta_{\rm x}$, $v_{\rm x}$,
with $w = 1/3$ when rel,
$w = 0$ when NR.

Contribute to the Rel/NR energy densities.

[back]

Solar neutrino spectrum

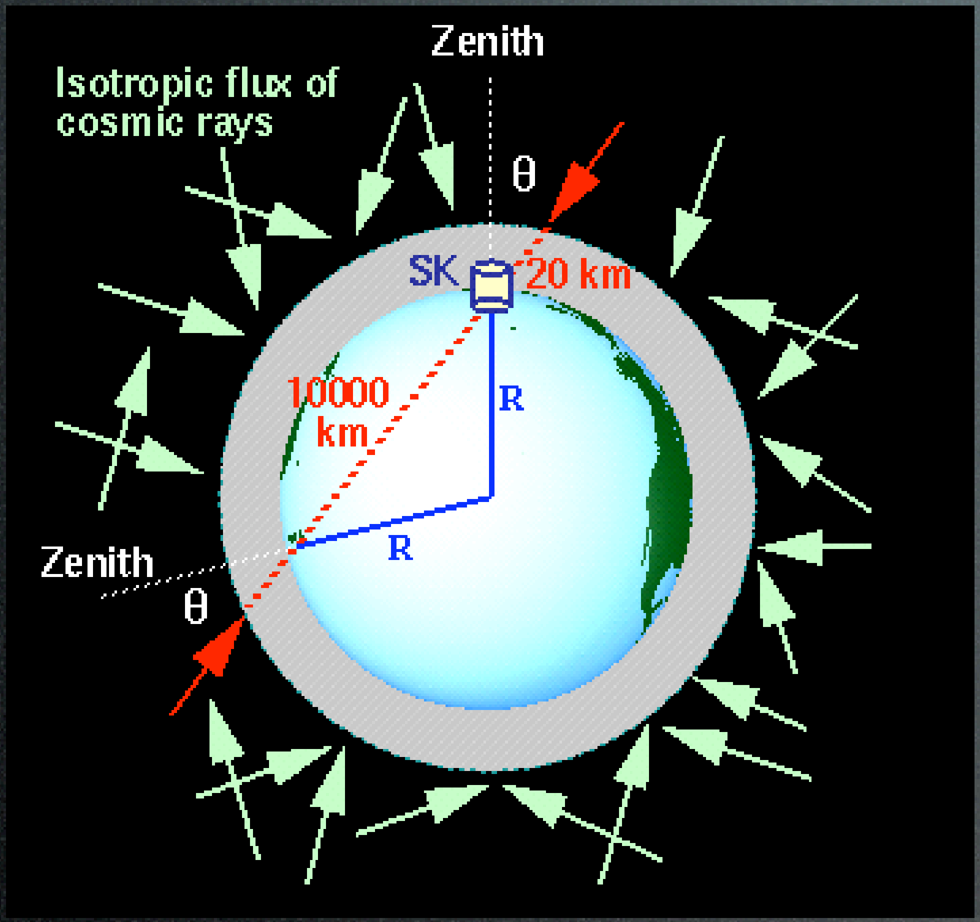
Bahcall, Pinsonneault 2001

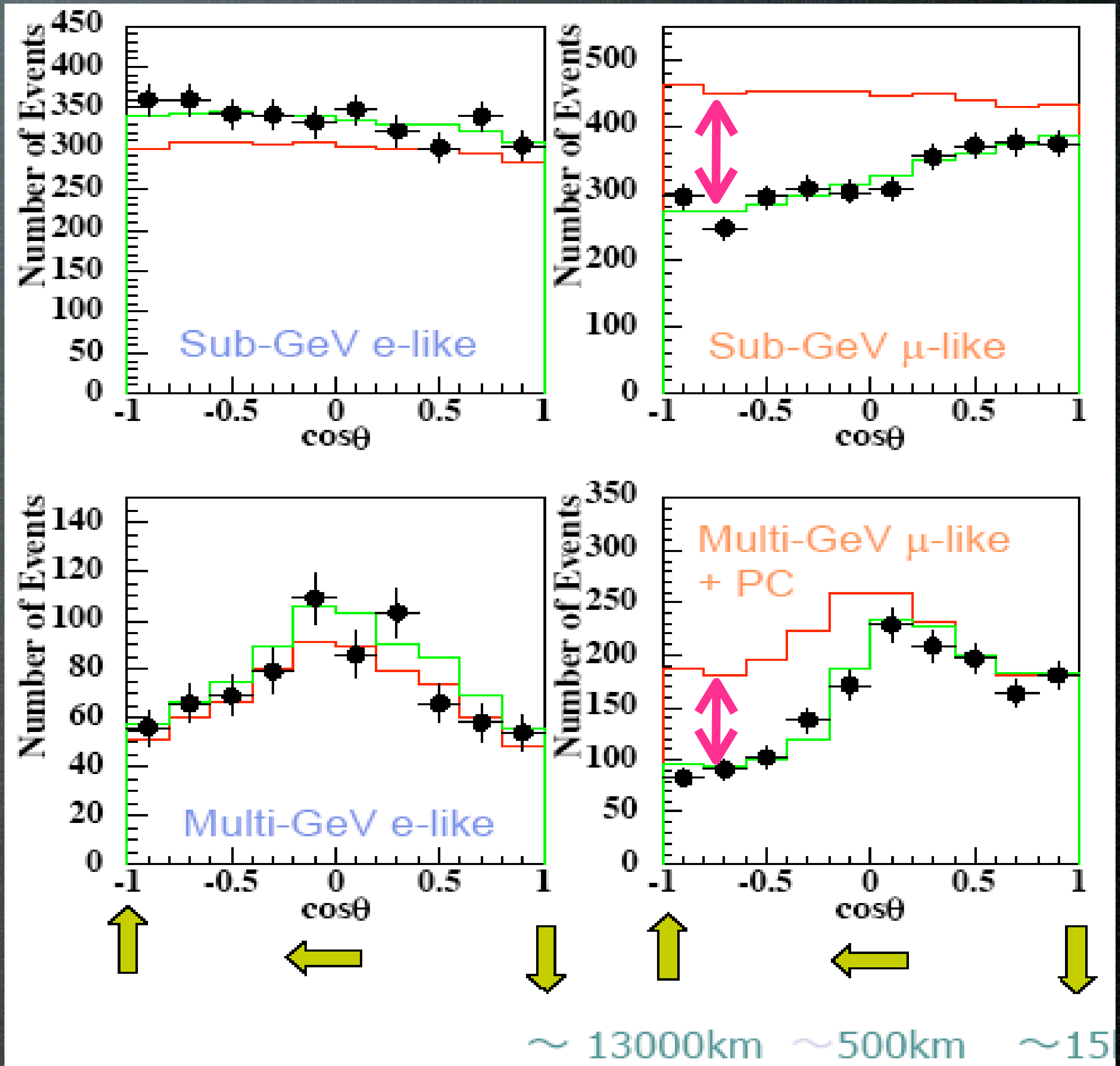


[back]

Sterile neutrinos in atmo+LBL

Basics: evidence for oscillations is disappearance of ν_μ from below

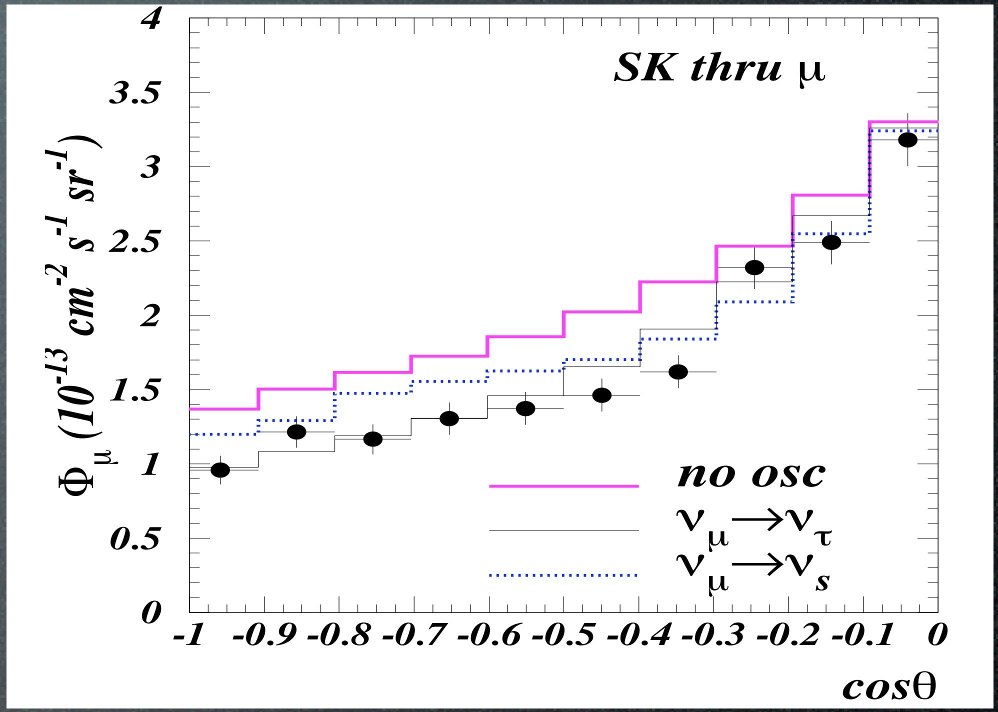




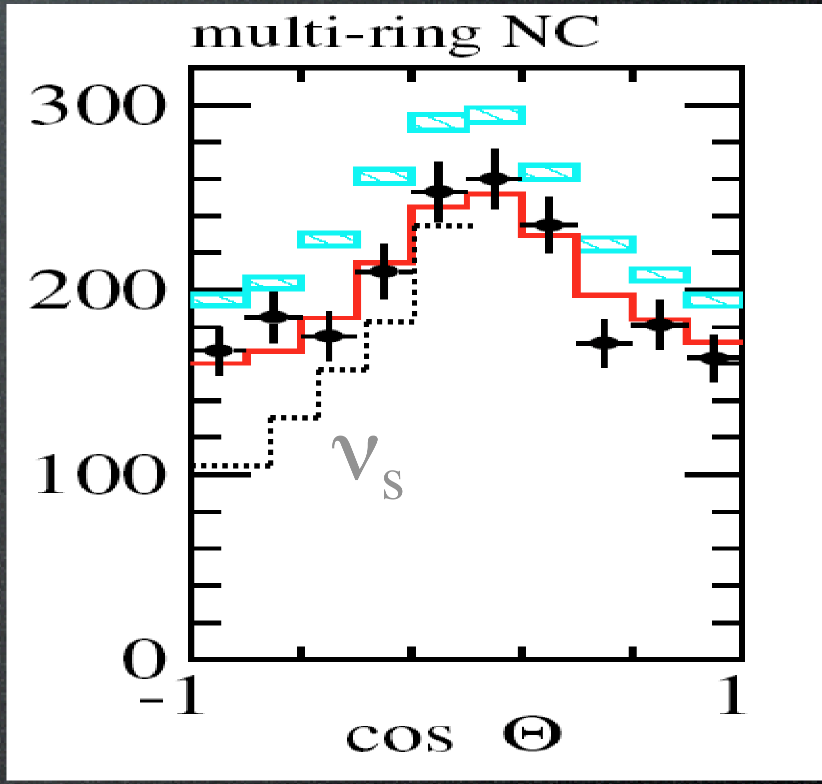
[back to atmo]

Sterile neutrinos in atmo+LBL

	$\nu_\mu \to \nu_\tau$	$\nu_\mu \to \nu_s$
(1)	no matter effects ($V_\mu = V_\tau$)	matter effects ($V_\mu \neq V_s = 0$) enhanced thru-μ and PC-μ
(2)	ν_τ makes NC	ν_s gives no signal reduced NC
(3)	ν_τ appearance	no ν_τ appearance



Gonzalez-Garcia, Nir 2002



Kearns 2002 (adapted)

(still poor statistics)

[back to atmo]