IFAE, Pavia,
19 Aprile 2006

Cosmologia e neutrini, con massa fissa e variabile

Marco Cirelli
(Yale)

reviews:
Lesgourgues, Pastor astro-ph/0603494,
Giunti et al., Phys.Rept.379 hep-ph/0211462
Dolgov, Phys.Rept.370 hep-ph/0202122

MaVaNs:
Fardon, Nelson, Weiner JCAP 0410 (2004)
Cirelli, Gonzalez-Garcia, Pena-Garay NPB 2005
+ many others

OUTLINE

Part (1): Neutrino masses and cosmology: bird's eye view

- current bounds
- future sensitivities

Part (2): Mass Varying Neutrinos:

- the basic idea
- constraints from solar neutrino physics
- future developments

Conclusions

Light, Standard Model

Neutrinos in cosmology

are significant because:

- neutrinos are a lot (as abundant as photons)

- neutrinos are hot

  main component of the rel energy density
  that sets the expansion rate of the Universe

- but not so hot, they have a mass

  they cool down at an interesting time

- undergo matter effects in the primordial plasma

- determine neutron/proton in BBN,

  i.e. primordial composition of the Universe

- have energy density similar to Dark Energy

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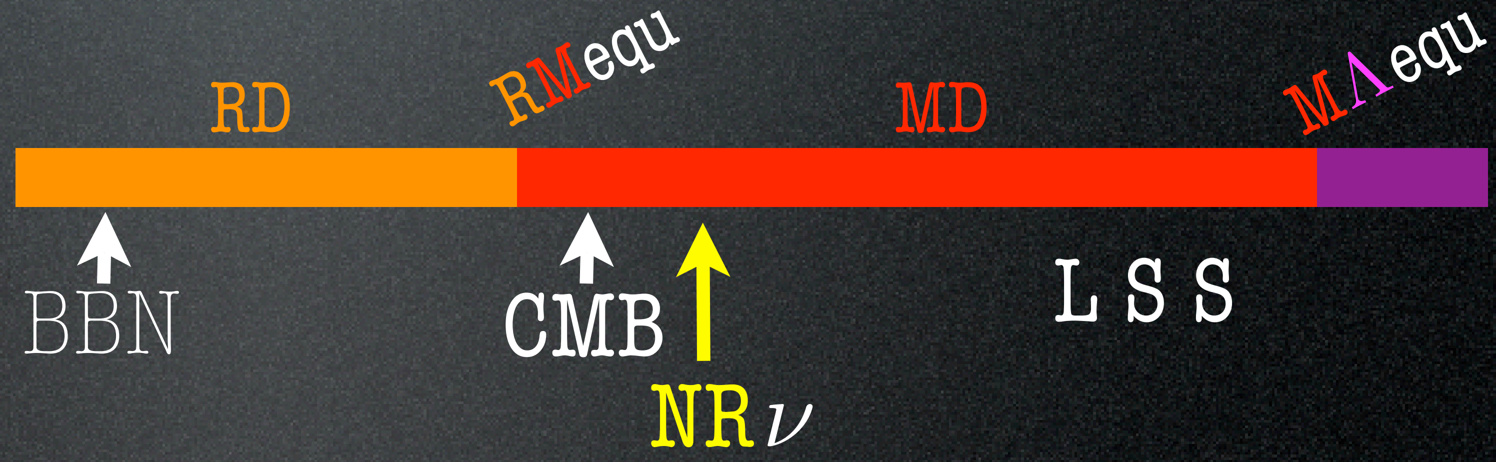
m_ν affects CMB and matter spectra

- Neutrinos become NR at $z \sim \dfrac{m_\nu c^2}{3\,k\,T_{\nu,0}} \sim 2 \cdot 10^3 \left(\dfrac{m_\nu}{\mathrm{eV}}\right)$

(CMB: $z \sim 1100$)

Since $m_\nu < 0.5$ eV $\left(\sum_i m_{\nu_i} < 1.5 \text{ eV}\right)$,

neutrinos became NR after CMB last scattering:



- indirect effect on CMB
- (indirect and) direct effect on LSS and later stuff

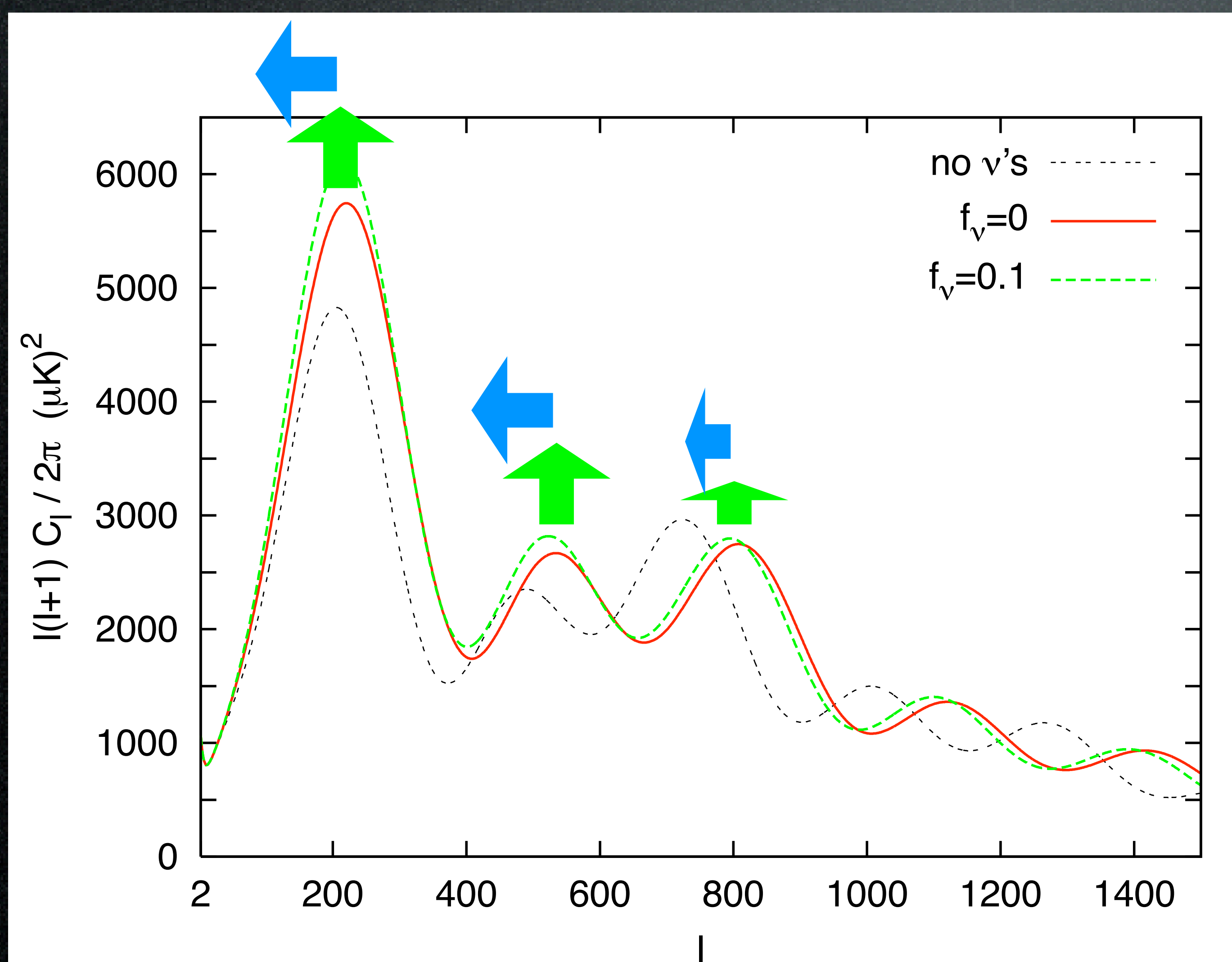
m_ν affects CMB and matter spectra

- On CMB power spectrum:

Contribution of neutrinos to the total energy density today

$\Omega_\nu h^2 = \frac{\sum m_{\nu_i}}{93 \text{ eV}}$ at the expenses of other components, e.g. $\Omega_{\rm CDM}$

E.g. m_ν ◢, Ω_ν ◢, $\Omega_{\rm CDM}$ ◣, rel energy ◢, RM equ delayed.



Lesgourgues, Pastor review

the universe "was larger" at recombination because there was more RD

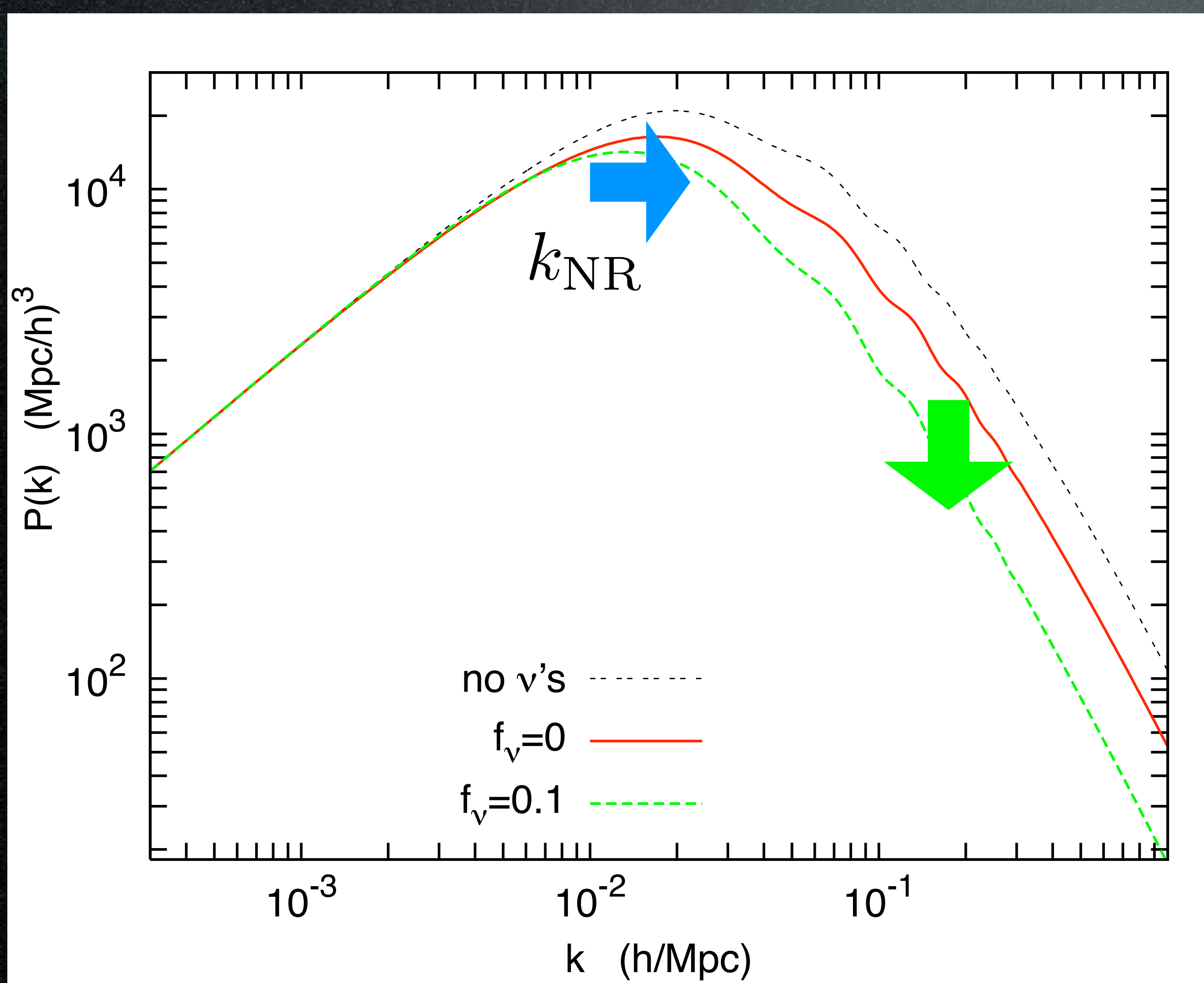
less ISW effect right after recombination because grav wells decay more

Bottom line:
CMB spectrum is (mildly) sensitive to $\sum m_{\nu_i}$.

m_ν affects CMB and matter spectra

- On matter power spectrum:

  neutrinos are not trapped (free stream), counteracting the clustering of galactic structures.
  Massive neutrinos become NR and travel $\lambda_{\rm FS} <$ Hubble radius.
  Small scales are affected.



Lesgourgues, Pastor review

m_ν determines 2 things:

➡ time (↔ scale) of NR:

$$k_{\rm NR} = 0.03 \left(\frac{m_\nu}{1{\rm eV}}\right)^{1/2} \Omega_m^{1/2} h\,{\rm Mpc}^{-1}$$

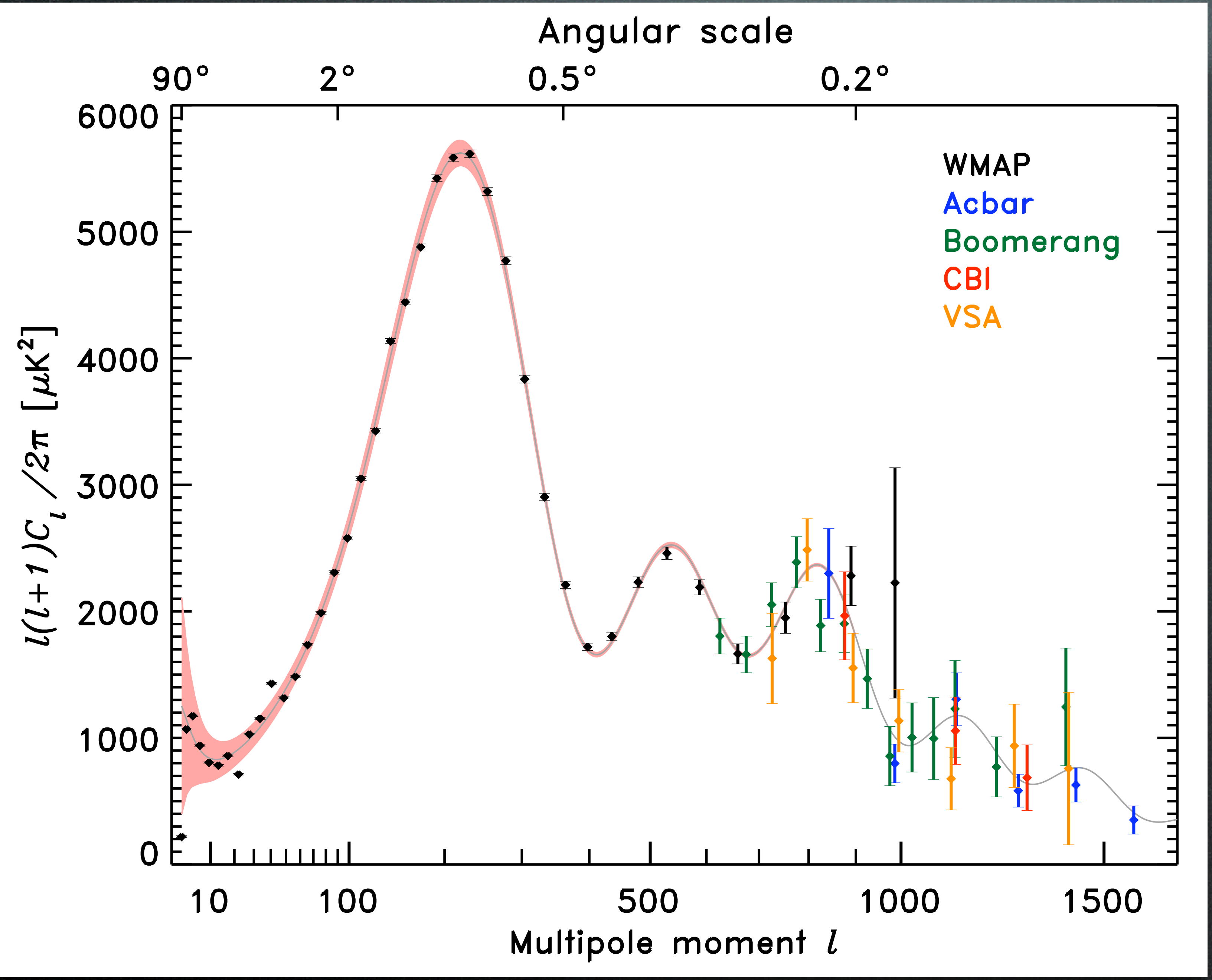
m_ν ◢ , "slowed down" earlier, could reach smaller scales

⬇ amount of suppression:

$$\frac{\Delta P(k)}{P(k)} = -8\frac{\Omega_\nu}{\Omega_m} \qquad \Omega_\nu h^2 = \frac{\sum m_{\nu_i}}{93\ {\rm eV}}$$

m_ν ◢ , Ω_ν ◢ , suppression ◢

1.CMB alone



Hinshaw et al, WMAP 3yr (WMAP Science team)

Ichikawa et al. 2004

$$\sum m_{\nu_i} < 2.0 \text{ eV}$$ (95% c.l.)

(WMAP 1yr + others)

WMAP 3yr, Spergel et al. 2006

$$\sum m_{\nu_i} < 2.11 \text{ eV}$$

(WMAP 3yr only)

Future:

e.g. Lesgourgues, Pastor 2004

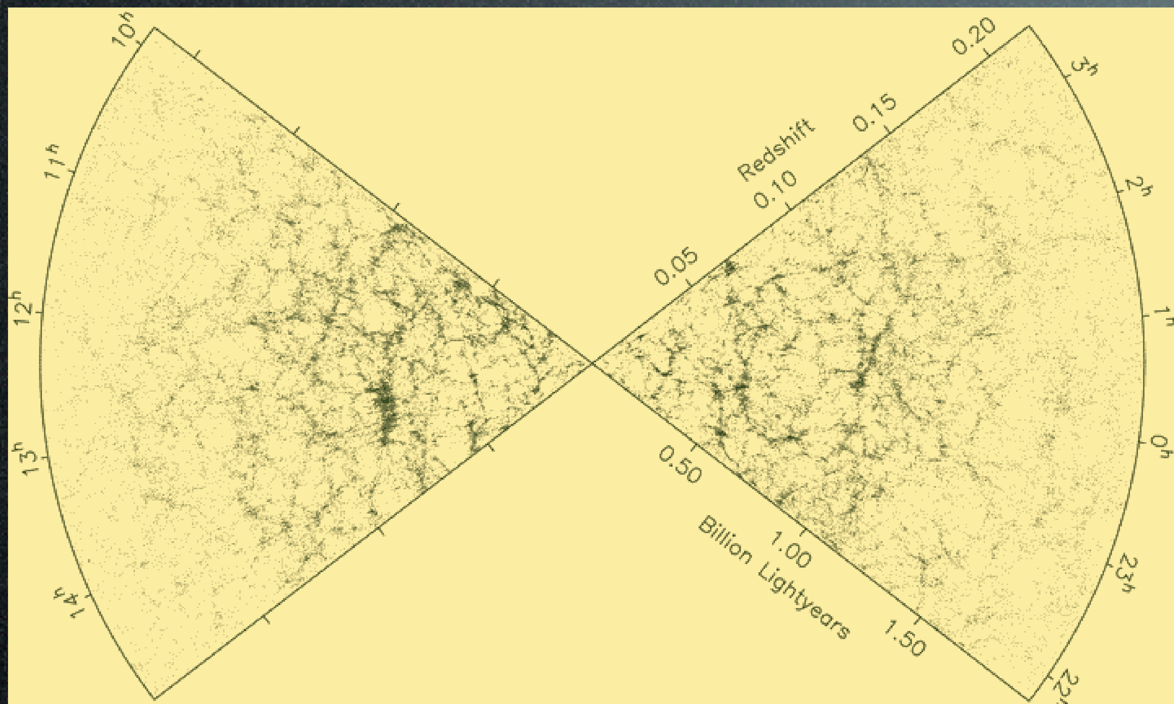
$$\sum m_{\nu_i} \simeq \begin{pmatrix} 1.0 \\ 0.45 \\ 0.15 \end{pmatrix} \text{ eV} \quad (1\sigma)$$

(future ground exp
Planck
CV limited)

Hannestad 2002

$$\sum m_{\nu_i} \simeq 0.07 \text{ eV}$$

2.LSS galaxy surveys



2dF GRS

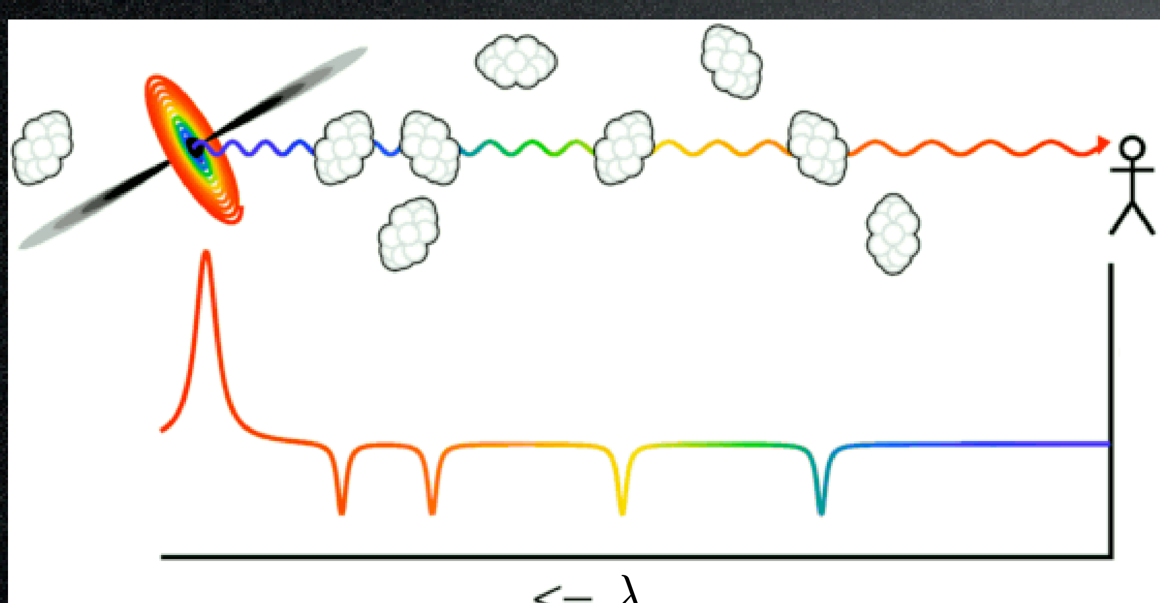
2dF: completed, 222.000 galaxies
SDSS: on going, 5th data release, 1M galaxies

Redshift survey of galaxies allows to reconstruct matter distribution.

Bias parameter b:
how well does light of (non-lin evolved) galaxies trace matter distribution?

Simulations and direct measurements say scale-indep and $b \approx 1.0 \pm 0.1$ Seljak et al., SDSS, astro-ph/0406594

2b.Lyman-alpha forest

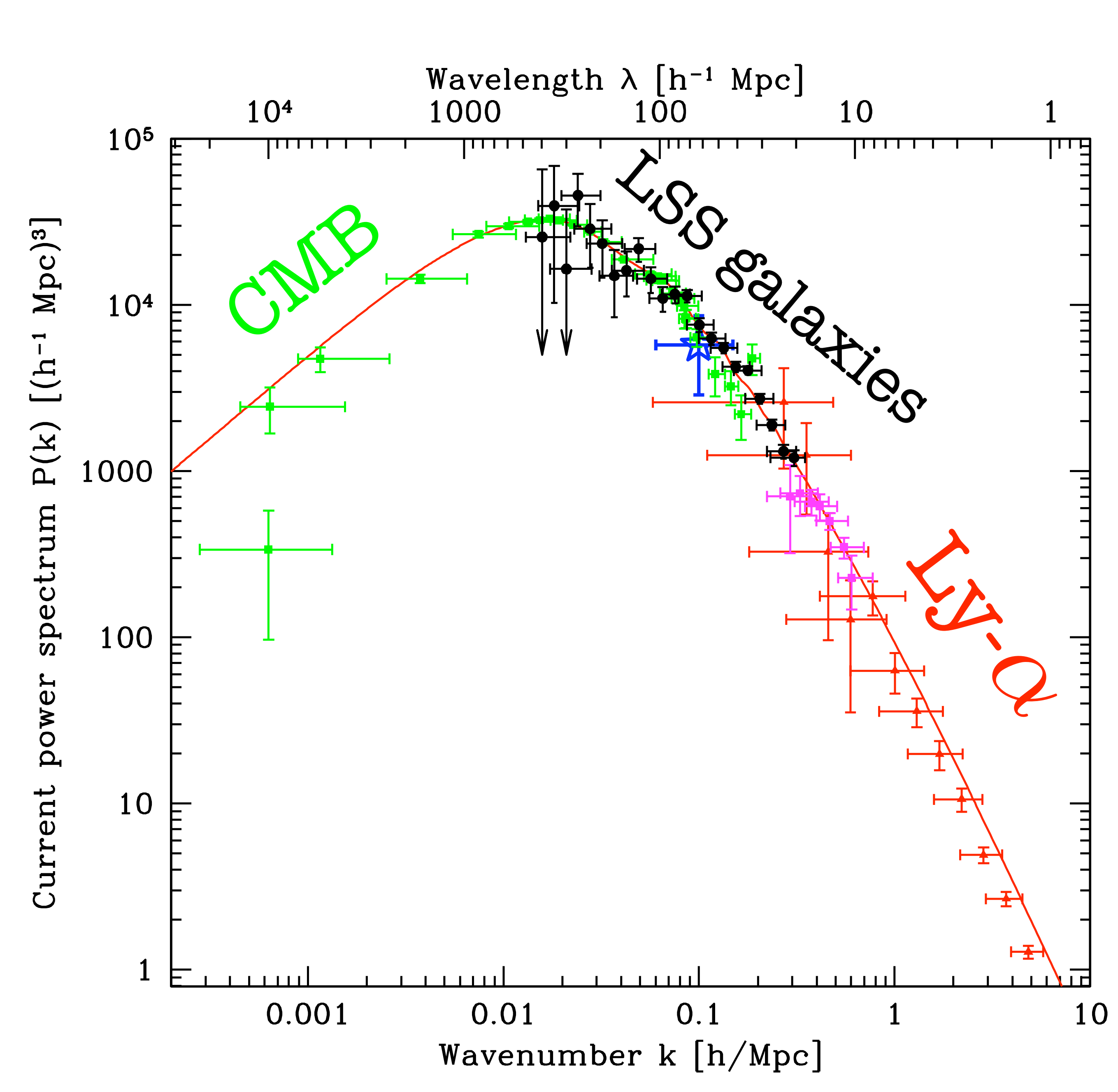


E.Wright, UCLA

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

But: systematics and uncertainties

SDSS 2003



Issue (1): bias

Boomerang coll. 2005

$\sum m_{\nu_i} < 1.2$ eV

no prior on b

$\sum m_{\nu_i} < 0.48$ eV

$b = 1.0 \pm 0.1$

Issue (2): Ly-α or not Ly-α ?

Fogli, Lisi et al. 2004

$\sum m_{\nu_i} < 1.4$ eV

no Ly-α

$\sum m_{\nu_i} < 0.47$ eV

with Ly-α

Issue (3): degeneracies/other data HST, SNIa...

WMAP 3yr, Spergel et al. 2006

$$\sum m_{\nu_i} < 0.68 \text{ eV}$$

(WMAP 3yr + SDSS ($b = 1.03 \pm 0.15$) + 2dF (b margi'ed), **no Ly-a**)

Seljak et al. astro-ph/0604335

$$\sum m_{\nu_i} < 0.17 \text{ eV}$$

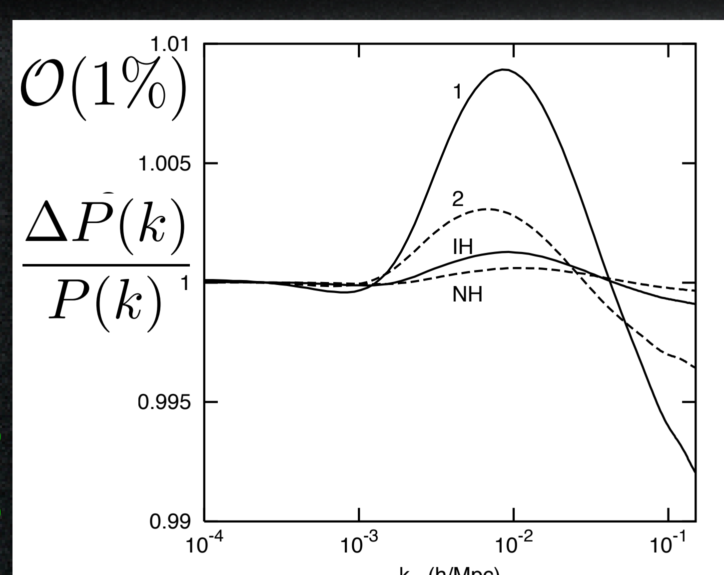
(WMAP 3yr + CMBall + SDSS + 2dF (free b) + SNIa **+ Ly-a**)

Future: $\sum m_{\nu_i} \simeq 0.10$ eV

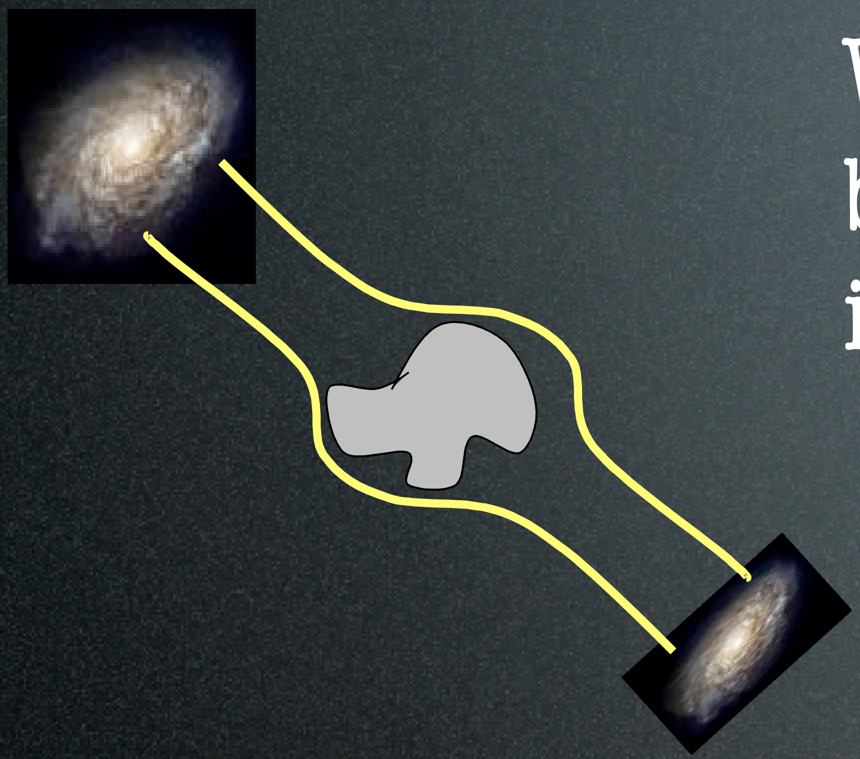
Eisenstein,Hu,Tegmark 1998, (Planck + SDSS)
Lesgourgues,Pastor 2004 (CVlim + SDSS)

Footnote:
is LSS sensitive to Δm^2 ?
No, too small.

Lesgourgues et al. 2004



3.galaxy weak lensing



Weak lensing "ellipticizes" the image of background galaxies, allows to reconstruct intervening matter distribution.

Cooray, astro-ph/9904246

Future: $\sum m_{\nu_i} \simeq 0.1$ eV

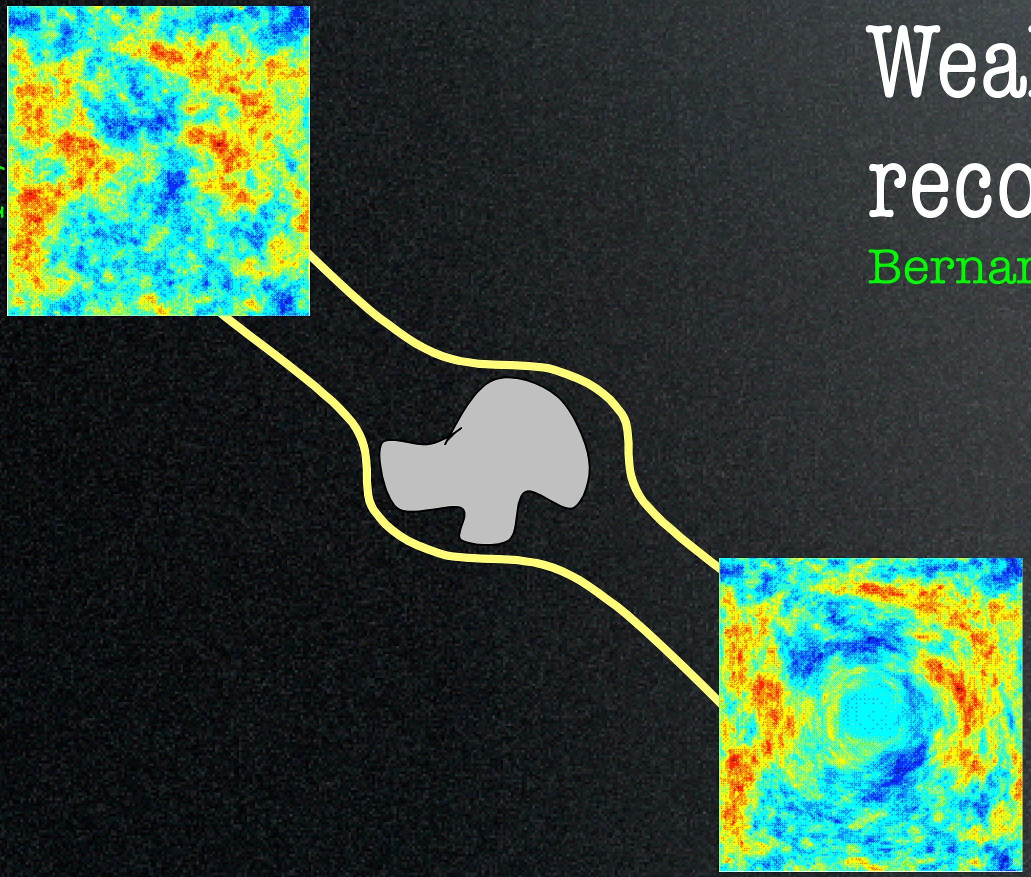
$\sum m_{\nu_i} \simeq 0.03$ eV

Song, Knox 2003

future lensing surveys:
DES, SNAP...

3.CMB weak lensing

astro-ph/9810257



Weak lensing "distorts" the CMB, allows to reconstruct intervening matter distribution.

Bernardeau, astro-ph/9611012, Seljak, Zaldarriaga, astro-ph/9810257

Future: $\sum m_{\nu_i} \simeq 0.4$ eV (ground)

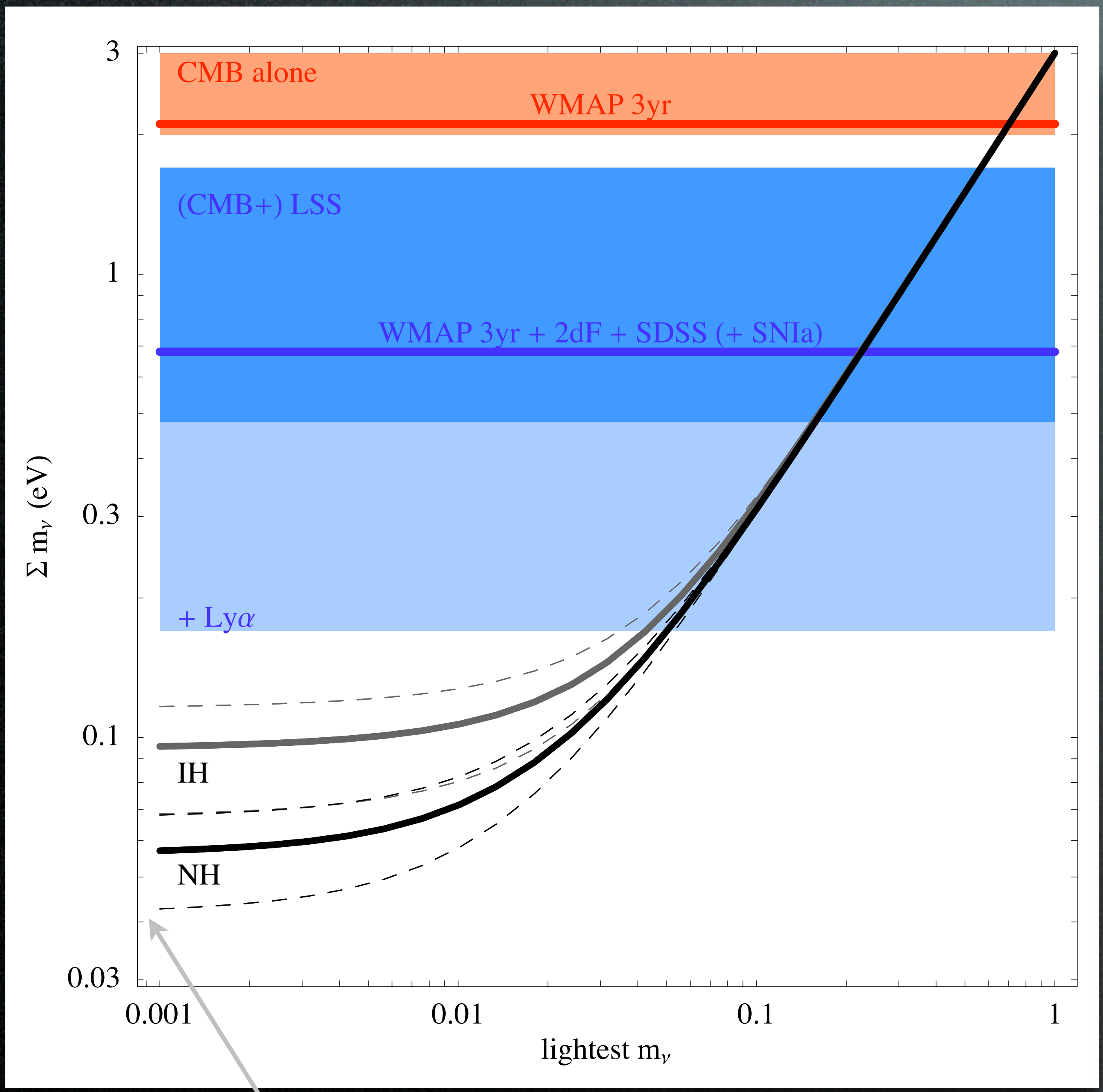
$\sum m_{\nu_i} \simeq 0.15$ eV (Planck)

$\sum m_{\nu_i} \simeq 0.044$ eV (CV limited)

Kaplinghat et al. 2003,
Lesgourgues, Pastor 2006

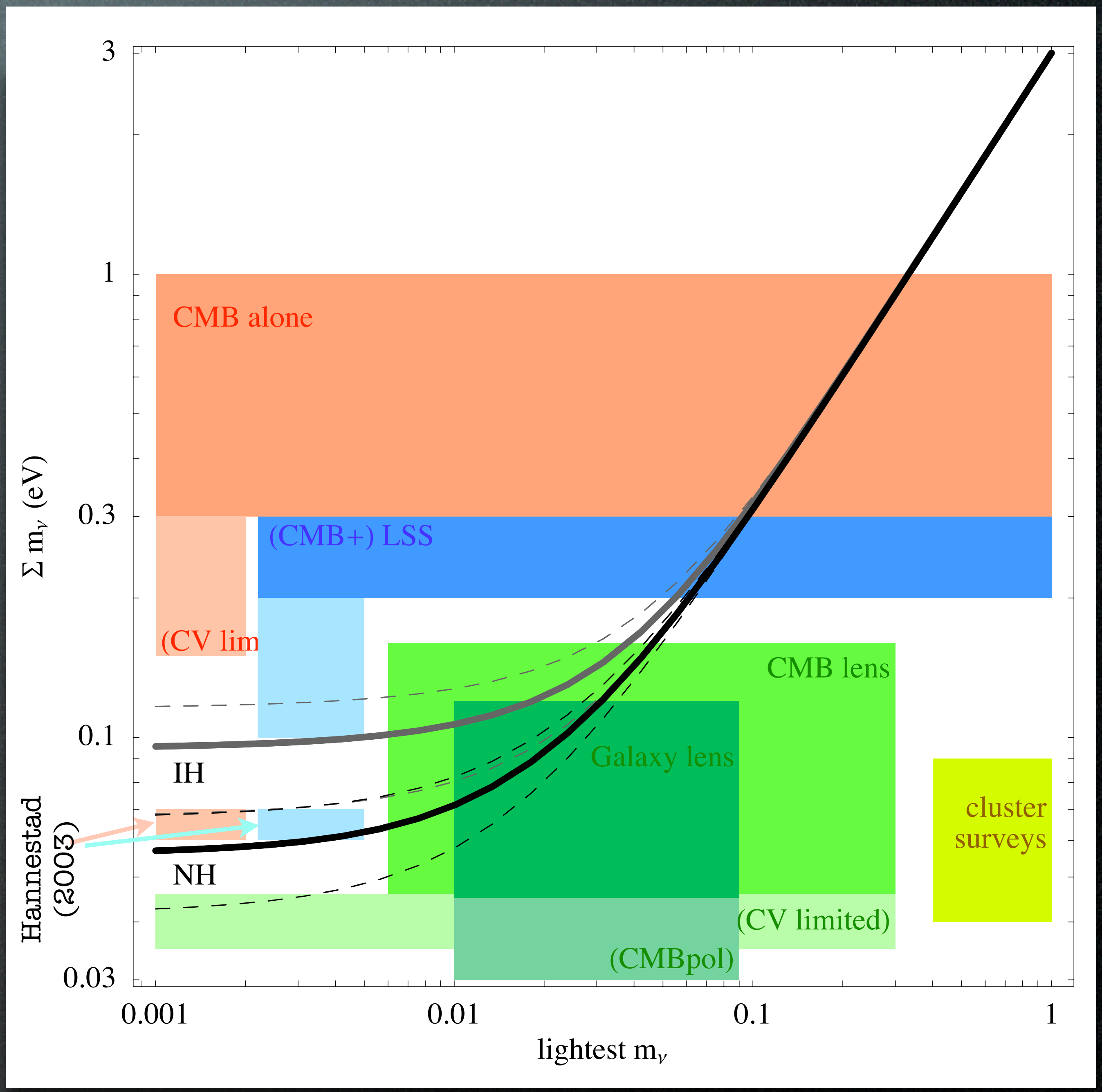
Summary

present bounds



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

future sensitivities



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

Mass Varying Neutrinos

Fardon, Nelson, Weiner JCAP 0410 (2004)
Kaplan, Nelson, Weiner PRL93 (2004)

Zurek 2004
Peccei 2005
Bi, Feng, Gu, Li, Wang, Zhang 2003-4
Cirelli, Gonzalez-Garcia, Pena-Garay 2005
Horvat 2005
Afshordi, Zaldarriaga, Kohri 2005
Takahashi, Tanimoto 2005
Fardon, Nelson, Weiner 2005
Barger, Marfatia, Whisnant 2005
Weiner, Zurek 2005
Honda, Takahashi, Tanimoto 2005
Zhang 2005
Ichikawa, Takahashi 2005
Gu, Bi, Zhang 2005
Gonzalez-Garcia, de Holanda, Funchal 2005
Schwetz, Winter 2005
Gu, Bi, Feng, Young, Zhang 2005
Brookfield, van de Bruck, Mota, Tocchini-Valentini 2005

Mass Varying Neutrinos

Inspiration:

Fardon, Nelson, Weiner, JCAP 2004

- we don't understand Dark Energy, but it's there
  we don't understand neutrino mass, but it's there
- they have a similar value and
  they have a similar value today

$$\Omega_\Lambda = \frac{\rho_{de}}{\rho_c} \simeq 70\% \quad \Rightarrow \quad \rho_{de} \simeq 3\ 10^{-11}\ \mathrm{eV}^4 \quad \Rightarrow \quad \sqrt[4]{\rho_{de}} \simeq 2\ 10^{-3}\ \mathrm{eV}$$

$$m_\nu \simeq \sqrt{\Delta m^2_{atm}} = \sqrt{2\ 10^{-3}\ \mathrm{eV}^2} = 5\ 10^{-2}\ \mathrm{eV}$$
$$m_\nu \simeq \sqrt{\Delta m^2_{sun}} = \sqrt{7\ 10^{-5}\ \mathrm{eV}^2} = 8\ 10^{-3}\ \mathrm{eV}$$

$$\rho_{\nu,0} \simeq \sum m_{\nu_i}\ n_{c\nu b,i} \simeq \text{few}\ 10^{-14}\ \mathrm{eV}^4$$

$$n_{c\nu b,i} = \frac{3}{4}\frac{\zeta(3)}{\pi^2} g_\nu T^3_{\nu,0} = 8\ 10^{-13}\ \mathrm{eV}^3 \simeq 112\mathrm{cm}^{-3}$$

- maybe they are related
  maybe they "track" each other

(A different approach:
Barbieri, Hall, Oliver, Strumia, 2005)

The framework:

Fardon, Nelson, Weiner, JCAP 2004

Ingredients ν_l $\mathcal{A}$ N_r

$$\mathcal{L} = m_D \nu_l N_r + M(\mathcal{A}) N_r N_r + V_{tot}(\mathcal{A})$$

~~$+\frac{\lambda_M}{M_{Pl}} \rho_M \mathcal{A}$~~

Barger et al. hep-ph/0502196

$$m_\nu(\mathcal{A}) = \frac{m_D^2}{M(\mathcal{A})}$$ ("see-saw")

$$\mathcal{L} = m_\nu(\mathcal{A})\ \nu_l \nu_l + V_{de} + V_{c\nu b} + V_{\nu,\mathrm{medium}}$$

$$V_{de} = V_{de}\big(m_\nu(\mathcal{A})\big)$$

$$V_{c\nu b} = m_\nu(\mathcal{A})\ n_{c\nu b}$$

$$V_{\nu,\mathrm{medium}} = \int \frac{d^3k}{(2\pi)^3} \sqrt{k^2 + m_\nu^2}\ f(k)$$

neutrino energy

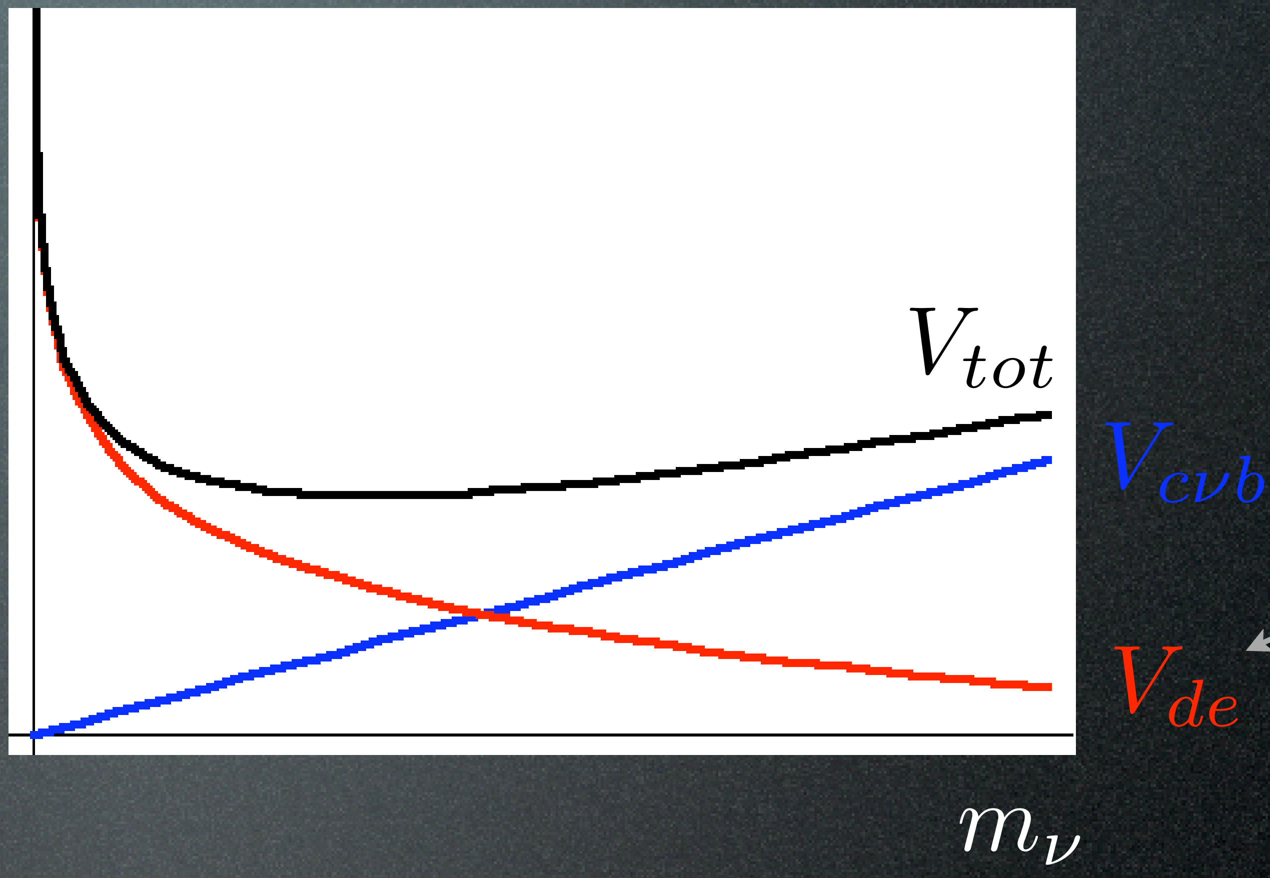
neutrino distribution fnct

In the "vacuum":

$$V_{tot} = V_{de} + V_{c\nu b}$$

$$V_{c\nu b} = m_\nu(\mathcal{A})\; n_{c\nu b}$$

$$V_{de} = \Lambda^4 \log\left(\frac{\mu}{m_\nu}\right)$$



- $\Lambda \sim 10^{-3}$ eV
- $m_\nu \neq 0 \;\Rightarrow\; V'_{de}(m_\nu) < 0$
- $\omega \approx -1 \;\Rightarrow\; |V'_{de}(m_\nu)| \ll 1$ (flat DE potential) $(\omega = -0.97^{+0.07}_{-0.09})$

WMAP 3yr

minimization of the total potential

$$\frac{dV_{tot}(m_\nu)}{dm_\nu} \equiv 0 \;\Rightarrow\; m_{\nu,0} = \frac{\Lambda^4}{n_{c\nu b}}$$

mass varying!

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$$V_{tot} = V_{de} + V_{c\nu b}$$

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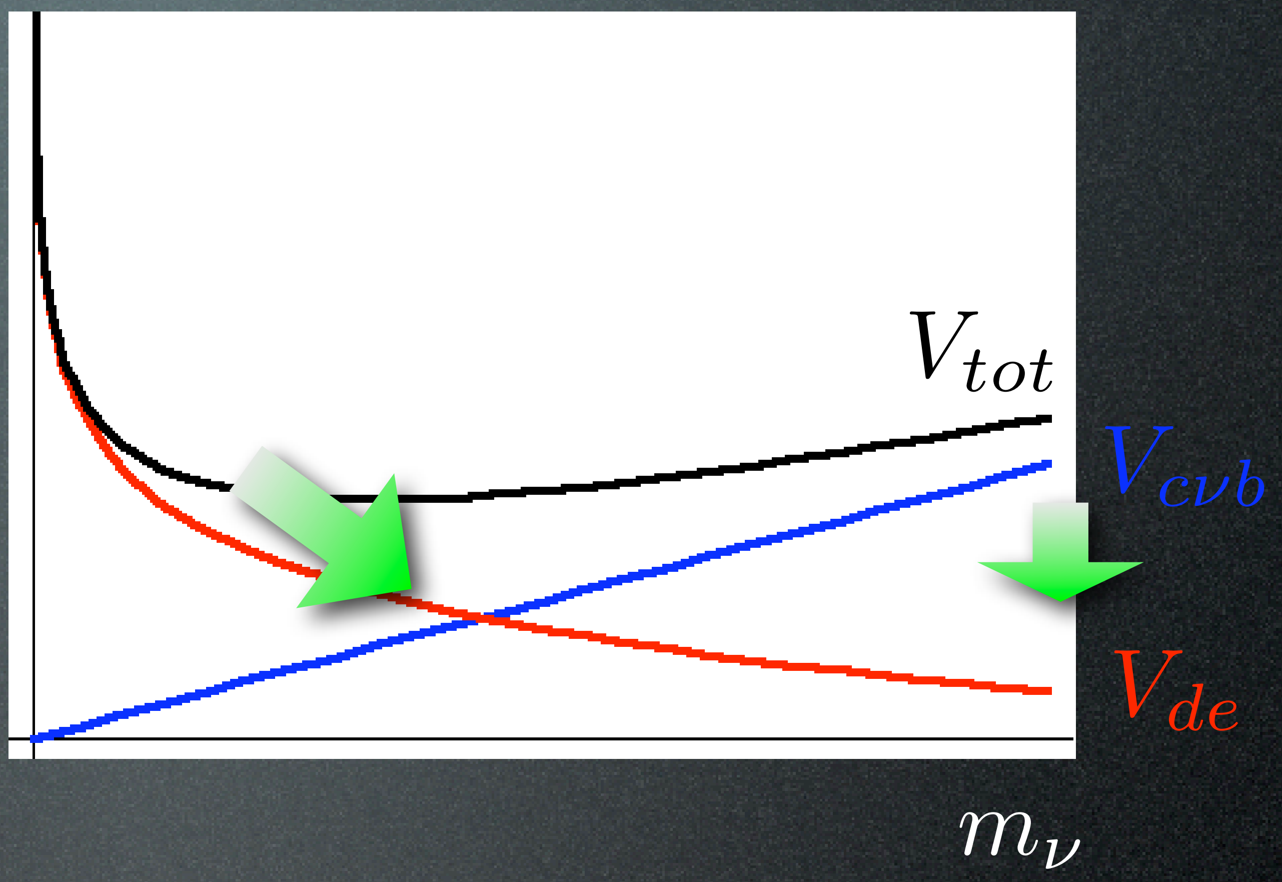

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← mass varying!

In a neutrino rich medium:

Cirelli, Gonzalez-Garcia, Pena-Garay NPB 2005

$$V_{tot} = V_{de} + V_{c\nu b} + V_{\nu,\mathrm{medium}}$$

$$V_{\nu,\mathrm{medium}} = \int \frac{d^3k}{(2\pi)^3}\sqrt{k^2+m_\nu^2}\,f(k)$$

minimization of the total potential

$$\frac{dV_{tot}(m_\nu)}{dm_\nu} \equiv 0 \;\Rightarrow\; V'_{de}(m_\nu) + n_{c\nu b} + m_\nu \int \frac{d^3k}{(2\pi)^3}\frac{1}{\sqrt{k^2+m_\nu^2}}f(k) \equiv 0$$

$$m_\nu = m_{\nu,0} - A\; m_{\nu,0}^2 + \ldots$$

- if $A \to 0$, back to vacuum case
- if $A \sim \mathcal{O}(1)$ ...

$$A = \frac{1}{n_{c\nu b}}\int \frac{d^3k}{(2\pi)^3}\frac{1}{\sqrt{k^2+m_\nu^2}}f(k) \approx \frac{1}{n_{c\nu b}}\frac{n_{\nu,\mathrm{medium}}}{\langle E_\nu\rangle}$$

In the Sun:

given solar ν_e spectrum and prod regions, compute effective Δm^2

$$\begin{aligned}\Delta m^2_{\mathrm{MaVaN}}(x) &= m_2^2(x) - m_1^2(x)\\ &\simeq \Delta m_0^2\left[1 - 3A_2(x)m_{01}\right] + 2\left[A_1(x) - A_2(x)\right]m_{01}^3 + \ldots\end{aligned}$$

effective Δm^2 is a function of m_{01} !

Solar + KamLAND fit: results

Cirelli, Gonzalez-Garcia, Pena-Garay NPB 2005

-fit worsens with m_{01}
(best fit for $m_{01} = 0$)

-Solar only:
-moves to lower $\Delta m^2_{21,0}$
-but D/N asymmetry
-and CC/NC ratio

-Solar + KamLAND:
-KamLAND nails $\Delta m^2_{21,0}$ high

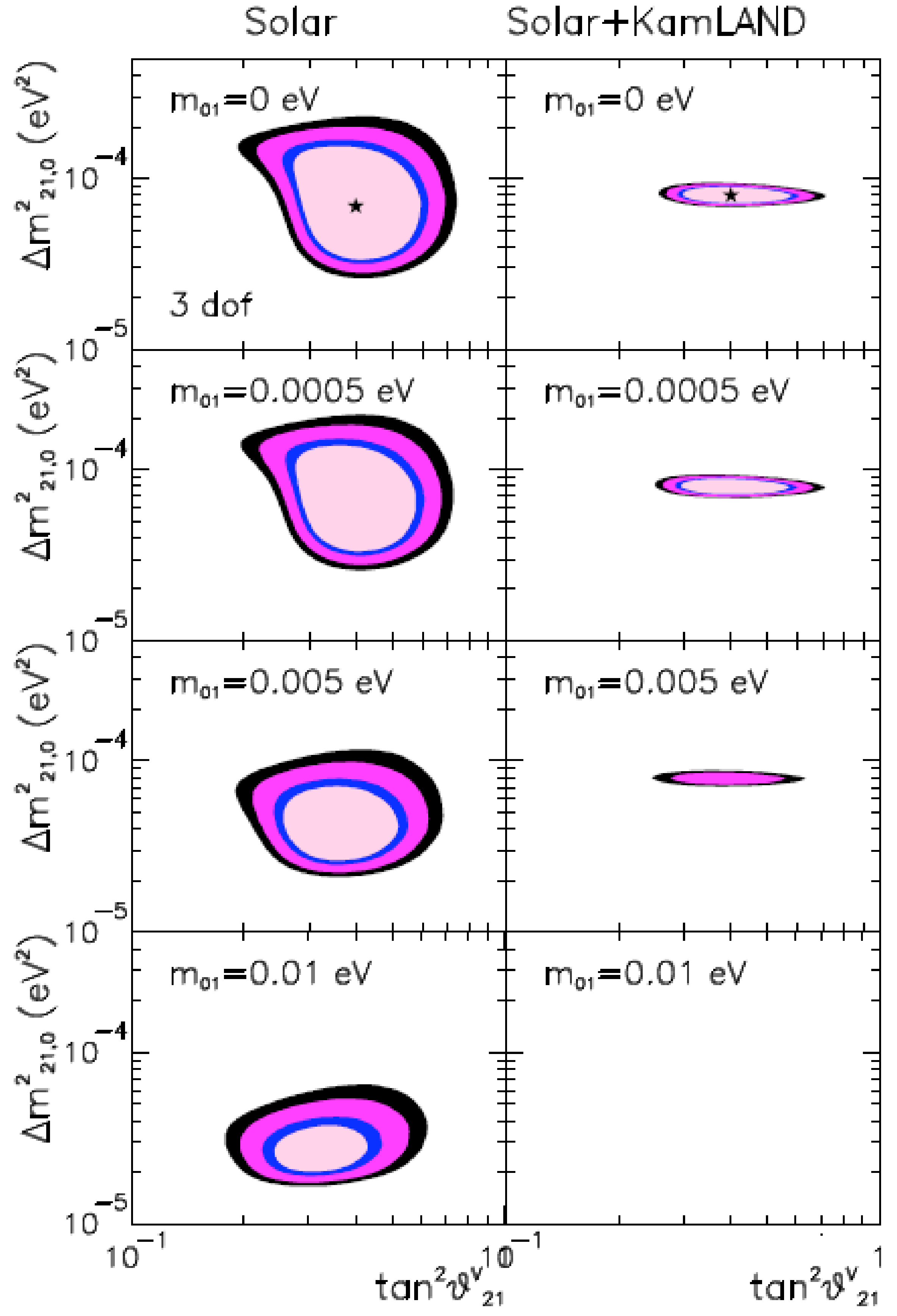
upper bound on m_{01} :

solar only

$m_{01} \lesssim 0.05$ eV

solar + KamLAND

$m_{01} \lesssim 0.01$ eV



[more results]

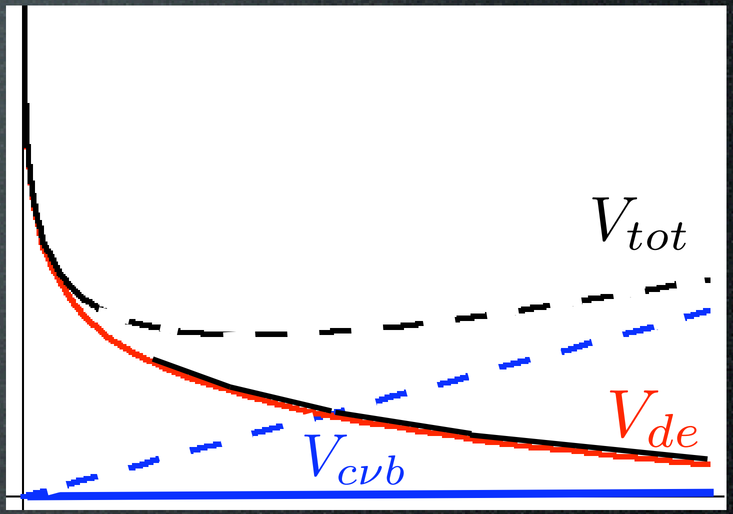
Outlook:

MaVaNs clustering:

Afshordi, Zaldarriaga, Kohri 2005

when ν become NR, instabilities collapse, neutrino CDM-like nuggets form.

- connection with m_ν^{today} lost
- DE disappears (SNIa data uproar)

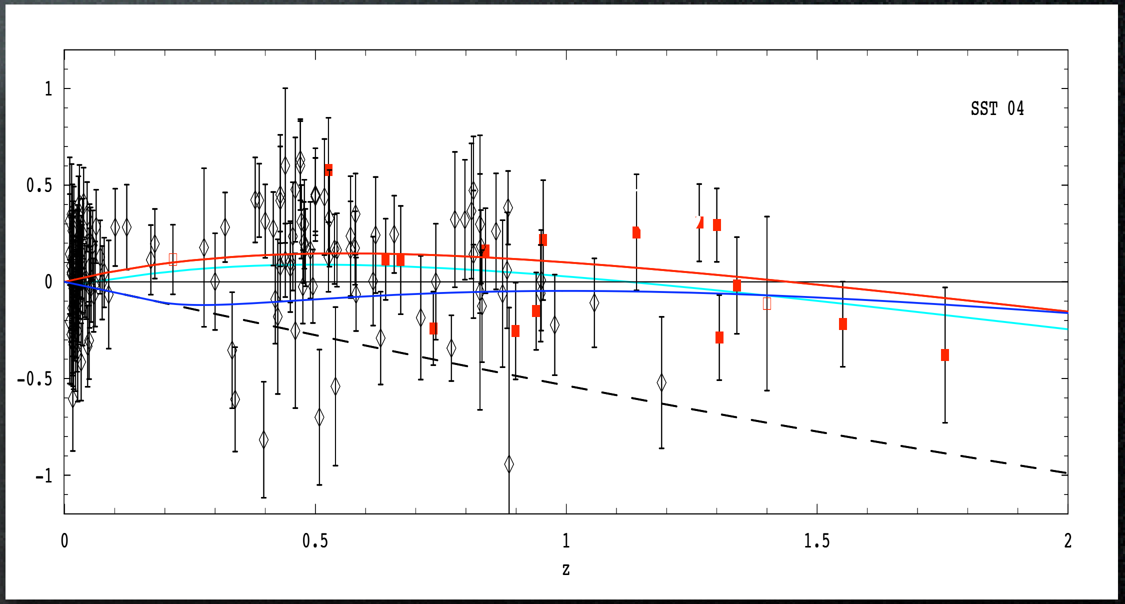


alternatively:

-only the lightest neutrino, still R, is coupled to DE?

Fardon, Nelson, Weiner 2005

-clustering occurred yesterday? (indistinguishable from Λ ?)



Couple to ordinary matter, environmental mass:

- does *not* reconcile LSND
- effects on solar and reactor and accelerator neutrinos...

Conclusions

- the bound from cosmology is the dominant bound on m_ν:

CMB only	(CMB +) LSS	+ Ly-α
$\sum m_{\nu_i} < 2.11$ eV	$\sum m_{\nu_i} < 0.68$ eV	$\sum m_{\nu_i} < 0.17$ eV

(status on 19 april 2006)

- future improvements likely "guarantee" positive detection (e.g. lensing surveys)

- Mass Varying Neutrinos models aim to link fruitfully neutrinos and DE: work in progress

solar + KamLAND physics imply $m_{01} \lesssim 0.01$ eV

Extra slides

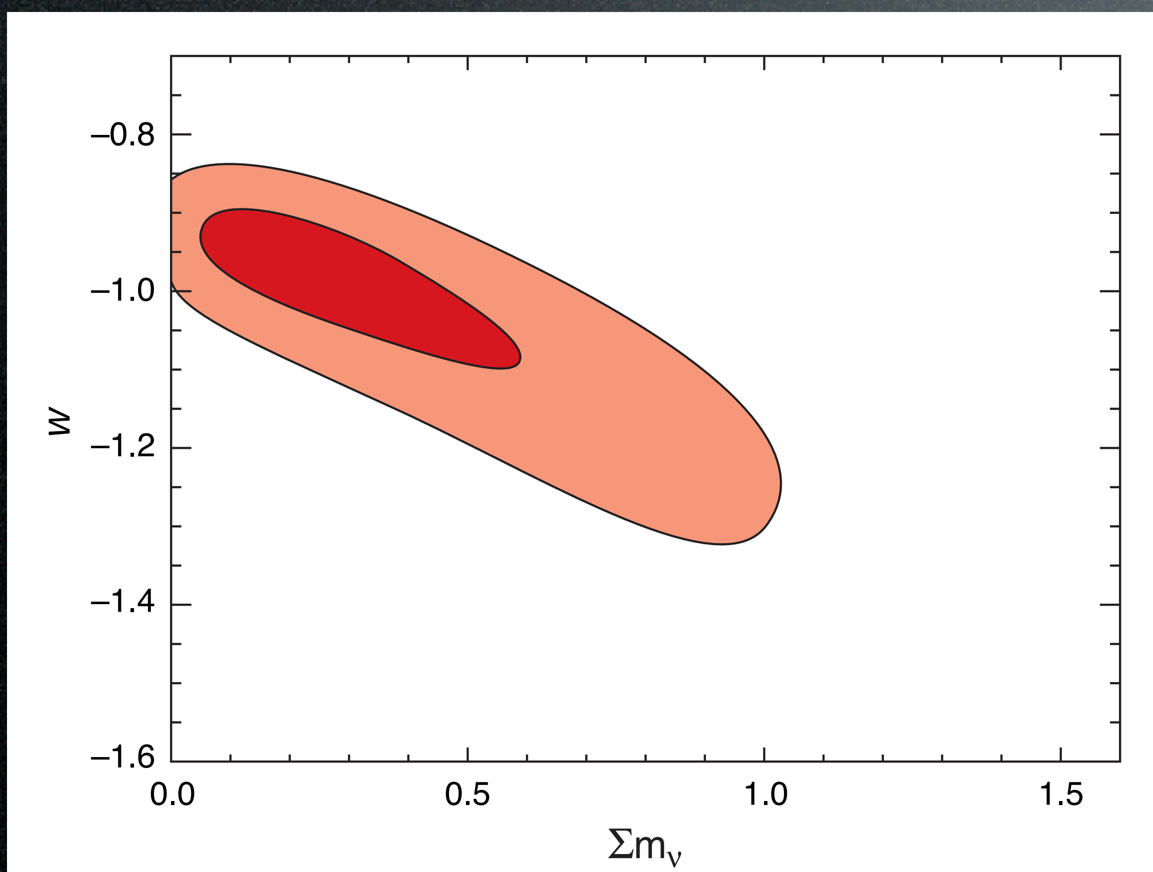
LSS and degeneracies

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

Hannestad, astro-ph/0505551

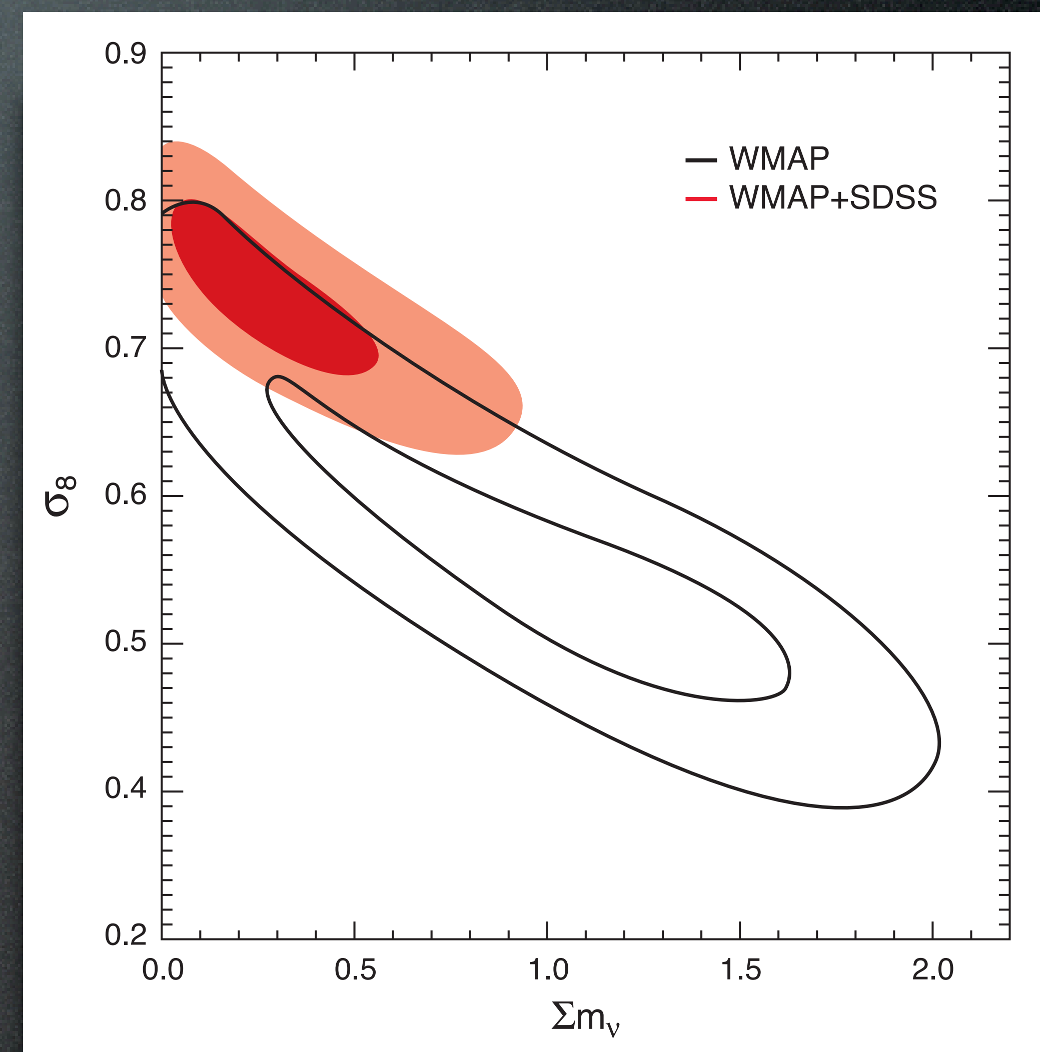
(SNIa data allow less Ω_Λ, hence more Ω_m, if $w < -1$; more Ω_m brings back up the P(k))

WMAP 3yr, Spergel et al.



Still, $\sum m_{\nu_i} \lesssim 1.0$ eV.

m_ν effect can be cancelled by low σ_8.



[back to LSS]

more on MaVaNs results

(in order of boldness)

- upper bound on m_{01}:

solar only

$$m_{01} \lesssim 0.05 \text{ eV}$$

solar + KamLAND

$$m_{01} \lesssim 0.01 \text{ eV}$$

(3σ)

- lower bound on “degeneracy param.” $\dfrac{\Delta m^2_{21,0}}{m^2_{01}}$:

solar only

$$\frac{\Delta m^2_{21,0}}{m^2_{01}} > 2\ 10^{-2}$$

solar + KamLAND

$$\frac{\Delta m^2_{21,0}}{m^2_{01}} > 1$$

(3σ)

i.e. inverse hierarchy not likely $m_{01} \simeq \sqrt{\Delta m^2_{\rm ATM}} \simeq 0.06 \text{ eV}$

- when m_{01} known, $\Delta m^2_{\rm MaVaNs}$ known ➡ proof-test MaVaNs

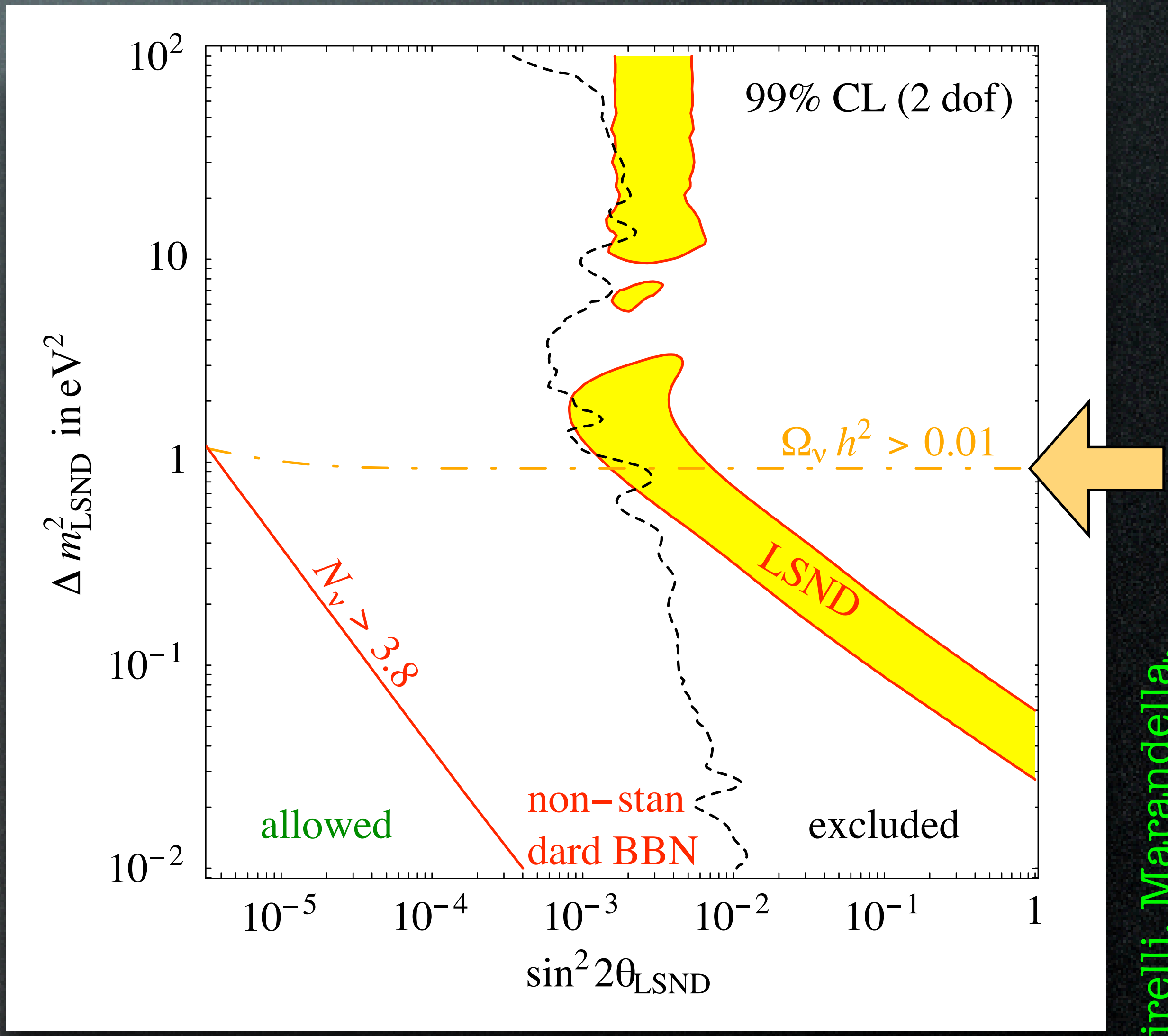
- if $\Delta m^2_{\rm eff,sol} \neq \Delta m^2_{\rm KamLAND}$ ➡ determined m_{01} with oscillation experiments!

LSND sterile and the cosmological mass bound

If a 4th (sterile) neutrino exists, the bound applies:

$$\Omega_\nu h^2 = \frac{\mathrm{Tr}[m \cdot \rho_\nu]}{93\,\mathrm{eV}} \rightarrow \frac{\sum m_{\nu_i}}{93\,\mathrm{eV}}$$

(in the limit of fully thermalized extra state)



Cirelli, Marandella,

LSND neutrino almost excluded.

Neutrinos cosmology in one sentence! Wow...

?? CnuB Sun, SNe

Nature provides for three types of neutrinos, yet scientists know very little about these "ghost particles," which can traverse the entire Earth without interacting with matter. But the abundance of neutrinos in the universe, produced by stars and nuclear processes, may explain how galaxies formed and why antimatter has disappeared. Ultimately, these elusive particles may explain the origin of the neutrons, protons and electrons that make up all the matter in the world around us.

Reactors BBN LSS Leptogenesis

MINOS press release, march 2006