(In)Direct measurement of neutrino masses

Experimental Evidences of Neutrino Oscillations

Solar $\nu_e \to \nu_\mu, \nu_\tau$ (Homestake, Kamiokande, GALLEX, SAGE, GNO, Super-Kamiokande, SNO)

Reactor $\bar{\nu}_e$ disappearance (KamLAND)

$\Longrightarrow$

$$\Delta m^{2\,\text{best-fit}}_{\text{SUN}} = 6.9 \times 10^{-5}$$

$$5.1 \times 10^{-5} < \Delta m^2_{\text{SUN}} < 9.7 \times 10^{-5}$$

$$1.2 \times 10^{-4} < \Delta m^2_{\text{SUN}} < 1.9 \times 10^{-4}$$

$[\text{eV}^2]$ (99.73% C.L.)

[Maltoni, Schwetz, Valle, PRD 67 (2003) 093003]

Atmospheric $\nu_\mu \to \nu_\tau$ (Kamiokande, IMB, Super-Kamiokande, MACRO, SOUDAN 2)

Accelerator ν_μ disappearance (K2K)

$\Longrightarrow$

$$\Delta m^{2\,\text{best-fit}}_{\text{ATM}} = 2.6 \times 10^{-3}$$

$$1.4 \times 10^{-3} < \Delta m^2_{\text{ATM}} < 5.1 \times 10^{-3}$$

$[\text{eV}^2]$ (99.73% C.L.)

[Fogli, Lisi, Marrone, Montanino, PRD 67 (2003) 093006]

THREE-NEUTRINO MIXING

flavor fields ν_α, $\alpha = e, \mu, \tau$

$$\nu_{\alpha L} = \sum_{k=1}^{3} U_{\alpha k}\, \nu_{kL}$$

massive fields $\nu_k \to m_k$

$$\Delta m^2_{\text{SUN}} = \Delta m^2_{21} \qquad \Delta m^2_{\text{ATM}} \simeq |\Delta m^2_{31}| \simeq |\Delta m^2_{32}|$$

Two features of 3ν mixing

Hierarchy

$$\boxed{\Delta m^2_{21} \ll |\Delta m^2_{31}|}$$

$$\begin{array}{rl} \text{SUN} \rightarrow & U = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \\ & \qquad\qquad\qquad\quad \uparrow \\ & \qquad\qquad\qquad\quad \text{ATM} \end{array}$$

CHOOZ:

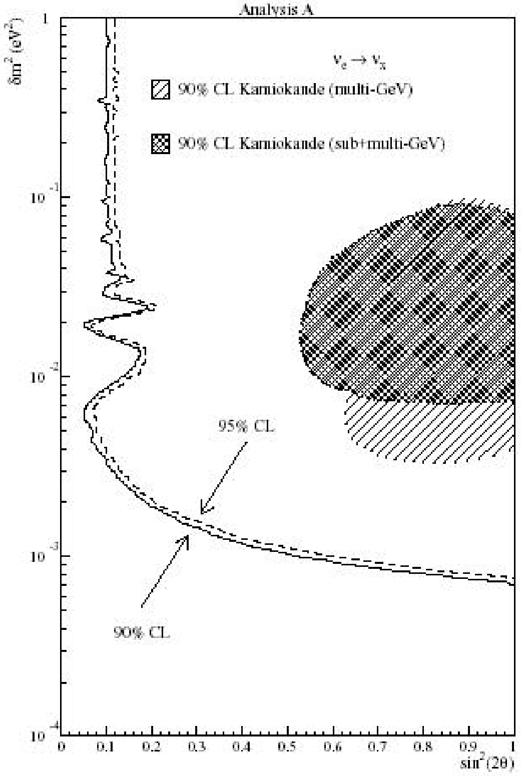
$$\begin{cases} \Delta m^2_{\text{CHOOZ}} = \Delta m^2_{31} = \Delta m^2_{\text{ATM}} \\ \sin^2 2\vartheta_{\text{CHOOZ}} = 4|U_{e3}|^2(1-|U_{e3}|^2) \end{cases}$$

$$\Downarrow$$

Small θ_{13} $\boxed{|U_{e3}|^2 < 5 \times 10^{-2} \ (99.73\% \text{ C.L.})}$ $\approx 13°$

[Fogli et al., PRD 66 (2002) 093008]

SOLAR AND ATMOSPHERIC ν OSCILLATIONS
ARE PRACTICALLY DECOUPLED!



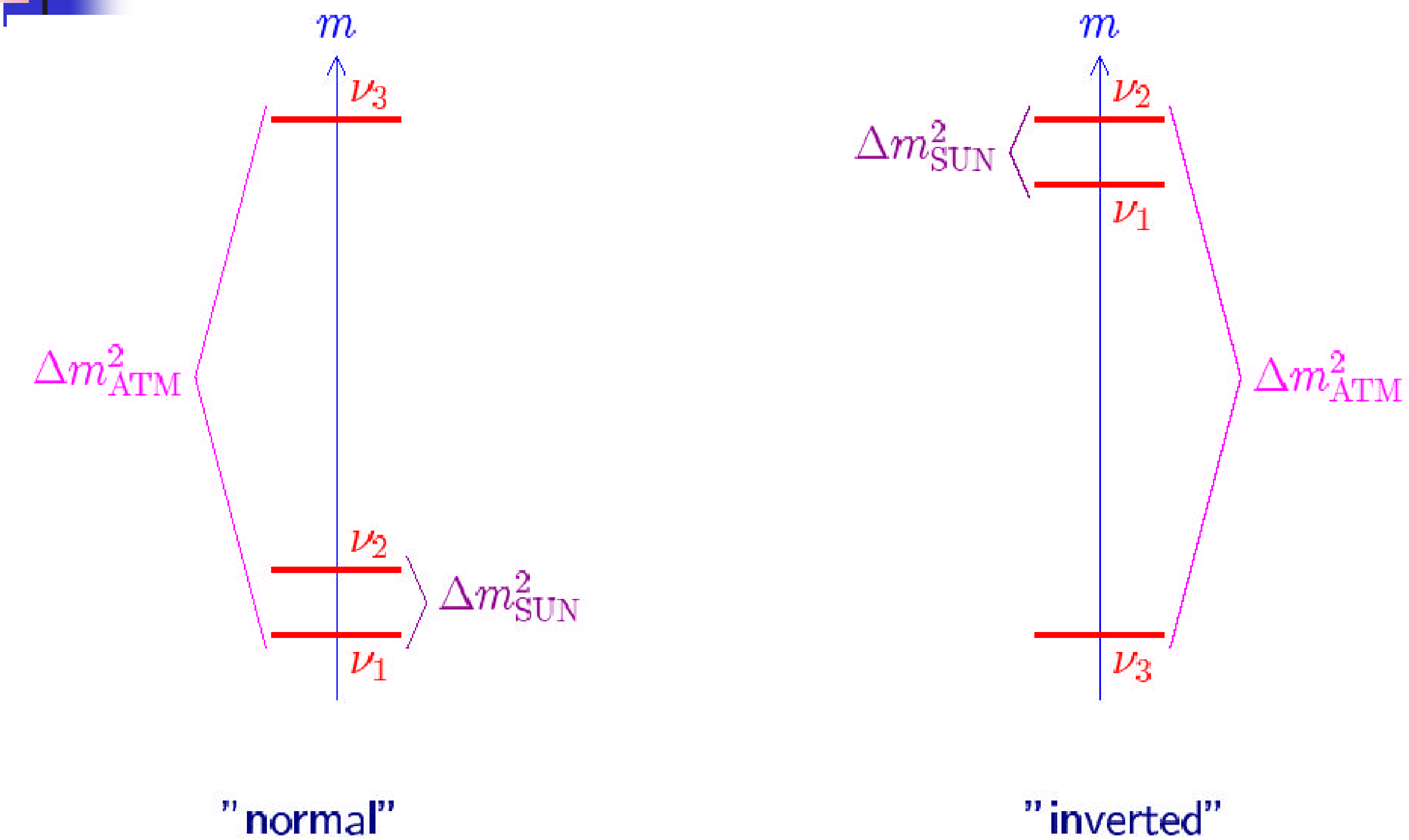
[CHOOZ, PLB 466 (1999) 415]
see also [Palo Verde, PRD 64 (2001) 112001]

TWO-NEUTRINO SOLAR and ATMOSPHERIC ν OSCILLATIONS ARE OK!

$$\sin^2\vartheta_{\text{SUN}} = \frac{|U_{e2}|^2}{1-|U_{e3}|^2} \simeq |U_{e2}|^2 \qquad \sin^2\vartheta_{\text{ATM}} = |U_{\mu 3}|^2$$

[Bilenky, Giunti, PLB 444 (1998) 379]
[Guo, Xing, PRD 67 (2003) 053002]

Allowed three ν schemes



Standard parametrization of mixing matrix

$$U = R_{23} W_{13} R_{12}$$

$$= \underbrace{\begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix}}_{\vartheta_{23} \simeq \vartheta_{\text{ATM}}} \underbrace{\begin{pmatrix} c_{13} & 0 & s_{13} e^{-i\delta_{13}} \\ 0 & 1 & 0 \\ -s_{13} e^{i\delta_{13}} & 0 & c_{13} \end{pmatrix}}_{\vartheta_{13} = \vartheta_{\text{CHOOZ}}} \underbrace{\begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}}_{\vartheta_{12} = \vartheta_{\text{SUN}}}$$

$$= \begin{pmatrix} c_{12} c_{13} & s_{12} c_{13} & s_{13} e^{-i\delta_{13}} \\ -s_{12} c_{23} - c_{12} s_{23} s_{13} e^{i\delta_{13}} & c_{12} c_{23} - s_{12} s_{23} s_{13} e^{i\delta_{13}} & s_{23} c_{13} \\ s_{12} s_{23} - c_{12} c_{23} s_{13} e^{i\delta_{13}} & -c_{12} s_{23} - s_{12} c_{23} s_{13} e^{i\delta_{13}} & c_{23} c_{13} \end{pmatrix}$$

$$\sin^2 \vartheta_{\text{CHOOZ}} = |U_{e3}|^2 = \sin^2 \vartheta_{13}$$

$$\sin^2 \vartheta_{\text{SUN}} = \frac{|U_{e2}|^2}{1 - |U_{e3}|^2} = \frac{s_{12}^2 c_{13}^2}{1 - s_{13}^2} = \sin^2 \vartheta_{12}$$

$$\sin^2 \vartheta_{\text{ATM}} = |U_{\mu 3}|^2 = s_{23}^2 c_{13}^2 \simeq \sin^2 \vartheta_{23}$$

Bilarge mixing

$$|U_{e3}|^2 \ll 1 \;\Rightarrow\; U \simeq \begin{pmatrix} c_{\vartheta_{\rm S}} & s_{\vartheta_{\rm S}} & 0 \\ -s_{\vartheta_{\rm S}} c_{\vartheta_{\rm A}} & c_{\vartheta_{\rm S}} c_{\vartheta_{\rm A}} & s_{\vartheta_{\rm A}} \\ s_{\vartheta_{\rm S}} s_{\vartheta_{\rm A}} & -c_{\vartheta_{\rm S}} s_{\vartheta_{\rm A}} & c_{\vartheta_{\rm A}} \end{pmatrix} \;\Rightarrow\; \left\{ \begin{aligned} \nu_e &= c_{\vartheta_{\rm S}} \nu_1 + s_{\vartheta_{\rm S}} \nu_2 \\ \nu_a^{(\rm S)} &= -s_{\vartheta_{\rm S}} \nu_1 + c_{\vartheta_{\rm S}} \nu_2 \\ &= c_{\vartheta_{\rm A}} \nu_\mu - s_{\vartheta_{\rm A}} \nu_\tau \end{aligned} \right.$$

$$\sin^2 2\vartheta_{\rm A} \simeq 1 \Rightarrow \vartheta_{\rm A} \simeq \frac{\pi}{4} \Rightarrow U \simeq \begin{pmatrix} c_{\vartheta_{\rm S}} & s_{\vartheta_{\rm S}} & 0 \\ -s_{\vartheta_{\rm S}}/\sqrt{2} & c_{\vartheta_{\rm S}}/\sqrt{2} & 1/\sqrt{2} \\ s_{\vartheta_{\rm S}}/\sqrt{2} & -c_{\vartheta_{\rm S}}/\sqrt{2} & 1/\sqrt{2} \end{pmatrix}$$

Solar $\nu_e \to \nu_a^{(\rm S)} \simeq \frac{1}{\sqrt{2}} (\nu_\mu - \nu_\tau)$

$\frac{\Phi_{\rm CC}^{\rm SNO}}{\Phi_{\nu_e}^{\rm SSM}} \simeq \frac{1}{3} \Longrightarrow \Phi_{\nu_e} \simeq \Phi_{\nu_\mu} \simeq \Phi_{\nu_\tau}$ for $E \gtrsim 6\,\rm MeV$

LMA $\Rightarrow \tan^2 \vartheta_{\rm S} \simeq 0.4 \Rightarrow \vartheta_{\rm S} \simeq \frac{\pi}{6} \Rightarrow U \simeq \begin{pmatrix} \frac{\sqrt{3}}{2} & \frac{1}{2} & 0 \\ -\frac{1}{2\sqrt{2}} & \frac{\sqrt{3}}{2\sqrt{2}} & \frac{1}{\sqrt{2}} \\ \frac{1}{2\sqrt{2}} & -\frac{\sqrt{3}}{2\sqrt{2}} & \frac{1}{\sqrt{2}} \end{pmatrix}$

Inference of mixing matrix

$$\sin^2\vartheta_{\mathrm{SUN}} = \frac{|U_{e2}|^2}{1-|U_{e3}|^2} \qquad \sin^2\vartheta_{\mathrm{ATM}} = |U_{\mu 3}|^2 \qquad \sin^2\vartheta_{\mathrm{CHOOZ}} = |U_{e3}|^2$$

$\tan^2\vartheta_{\mathrm{SUN}}^{\text{best-fit}} = 0.46$ $\quad 0.29 < \tan^2\vartheta_{\mathrm{SUN}} < 0.86$ (99.73% C.L.) [Maltoni, Schwetz, Valle, PRD 67 (2003) 093003]

$\sin^2 2\vartheta_{\mathrm{ATM}}^{\text{best-fit}} = 1$ $\quad \sin^2 2\vartheta_{\mathrm{ATM}} > 0.86$ (99.73% C.L.) [Fogli, Lisi, Marrone, Montanino, PRD 67 (2003) 093006]

$\sin^2 2\vartheta_{\mathrm{CHOOZ}}^{\text{best-fit}} = 0$ $\quad \sin^2 2\vartheta_{\mathrm{CHOOZ}} < 5\times 10^{-2}$ (99.73% C.L.) [Fogli et al., PRD 66 (2002) 093008]

$$|U|_{\text{b-f}} \simeq \begin{pmatrix} 0.83 & 0.56 & 0.00 \\ 0.40 & 0.59 & 0.71 \\ 0.40 & 0.59 & 0.71 \end{pmatrix}$$

$$|U| \simeq \begin{pmatrix} 0.71-0.88 & 0.46-0.68 & 0.00-0.22 \\ 0.08-0.66 & 0.26-0.79 & 0.55-0.85 \\ 0.10-0.66 & 0.28-0.80 & 0.51-0.83 \end{pmatrix}$$

Global Analysis

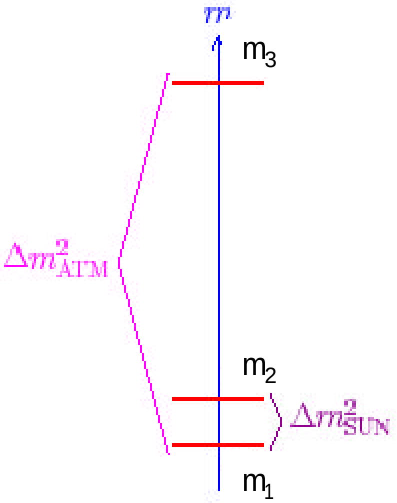
[Gonzalez-Garcia, Pena-Garay, hep-ph/0306001]

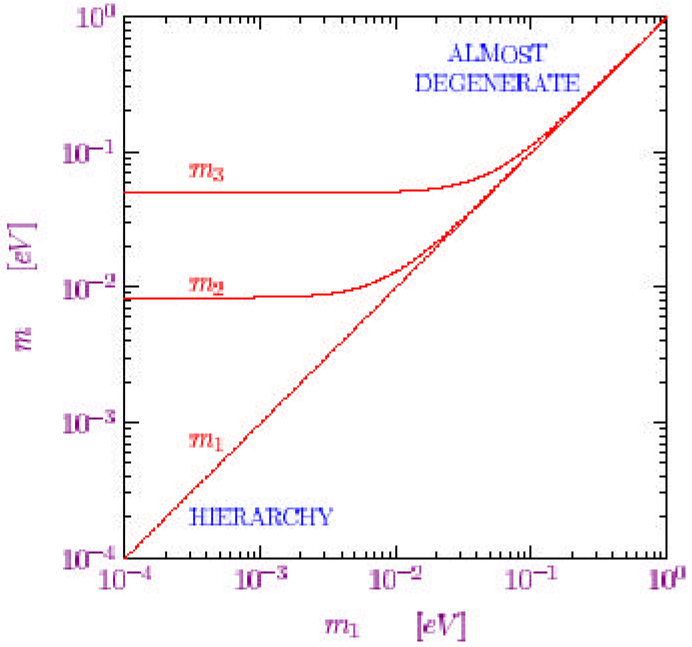
$$|U|_{\text{b-f}} \simeq \begin{pmatrix} 0.83 & 0.55 & 0.09 \\ 0.34-0.45 & 0.55-0.62 & 0.70 \\ 0.34-0.45 & 0.55-0.62 & 0.70 \end{pmatrix}$$

$$|U| \simeq \begin{pmatrix} 0.73-0.88 & 0.47-0.67 & 0.00-0.23 \\ 0.17-0.57 & 0.37-0.73 & 0.56-0.84 \\ 0.20-0.58 & 0.40-0.75 & 0.54-0.82 \end{pmatrix}$$

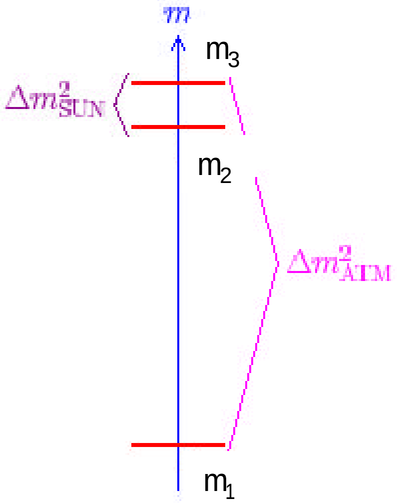
Absolute scale of neutrino masses

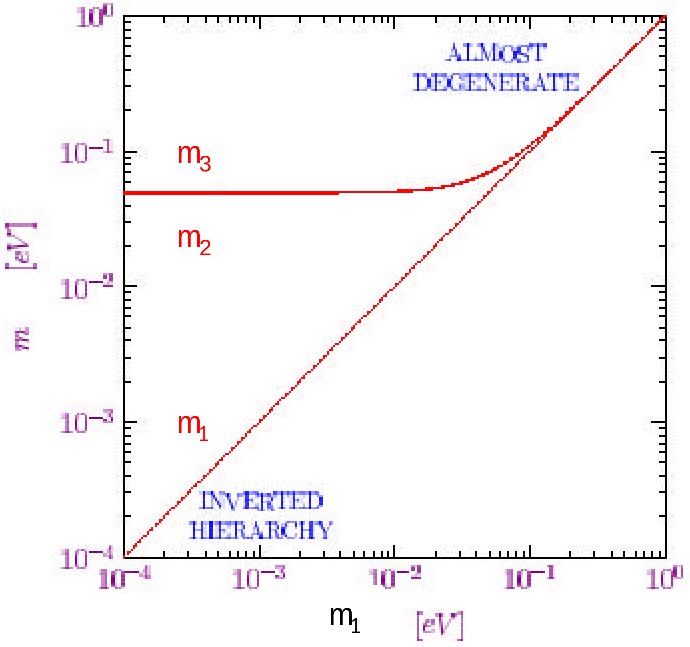
normal

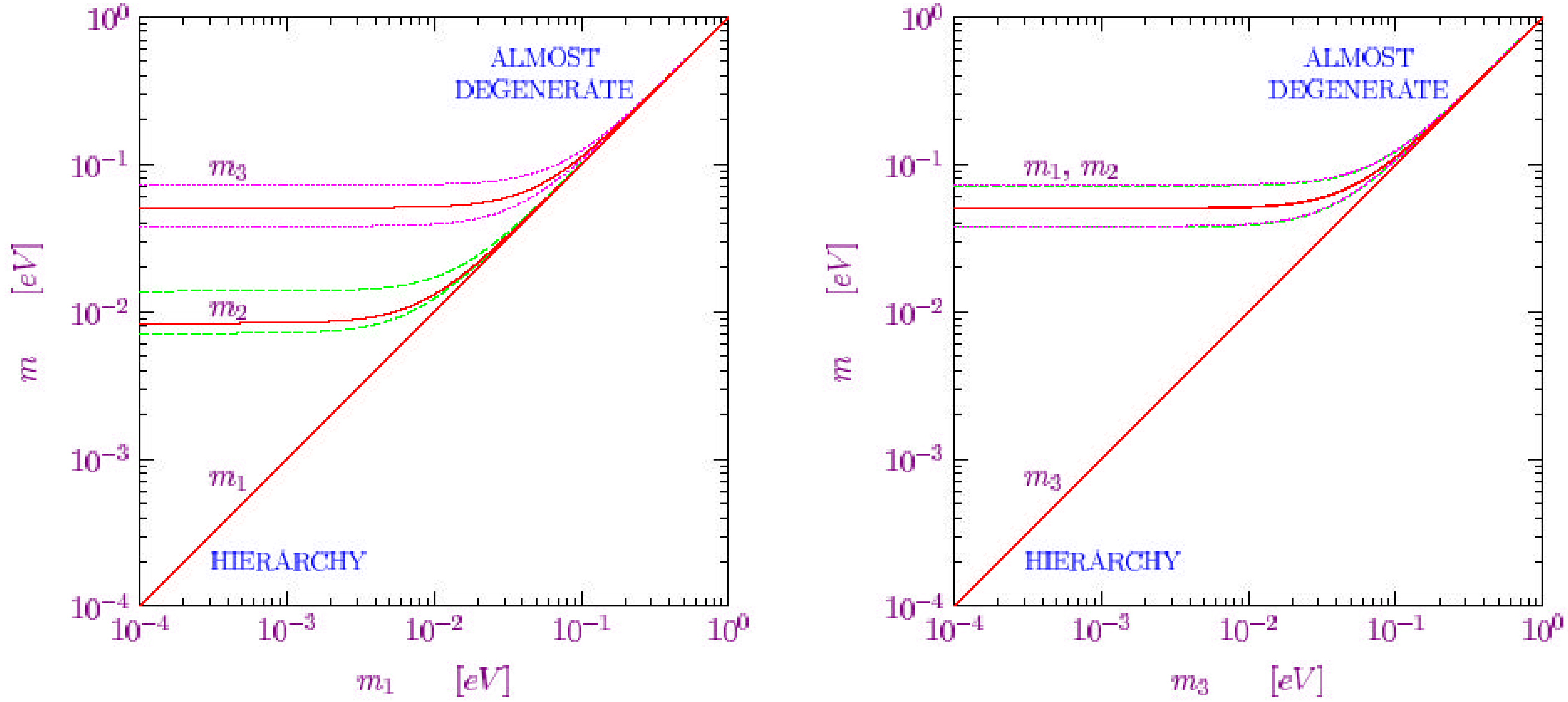




inverted







normal scheme

inverted scheme

Dashed and dotted lines represent, respectively, the limits for m_2 and m_3 from solar and atmospheric neutrino data

Comments

- ✓ Previous considerations hold under the hypothesis that the LSND results are wrong: if MiniBOONE confirms then
  1. One of the evidence is not due to neutrino oscillations
  2. The 3ν family scheme does not work ⇒ at least 4ν are needed
- ✓ From neutrino oscillation experiments we can obtain information only on the neutrino mass-squared differences

⇒ for the understanding of the neutrino masses and neutrino mixing the knowledge of the absolute values of neutrino masses are required

Searches for massive neutrinos

- ✓ Direct mass determination

  No further requirements, except neutral, spin 1/2

  - Beta-decay end-point spectrum analysis (Kurie plot)
  - Pion decay
  - Multi-body τ decay
  - TOF measurements with ν from supernovae

- ✓ Indirect searches

  Search for effects, which can only exist, if $m(\nu)\neq 0$

  - Double beta-decay
  - Galaxy surveys

Note that oscillations may occur only if neutrinos have mass and are not degenerate

Neutrino mass from β-decay exps

- ✓ The method of measurement of m_ν through the detailed investigation of the high-energy part of the b-spectrum was proposed in 1934 by E. Fermi
- ✓ The first results on the measurement of the neutrino mass with this method were obtained by B. Pontecorvo in 1948
- ✓ Nowadays, m_ν is measured through the measurement of the high-energy part of the b-spectrum of tritium

$$^{3}H \rightarrow {}^{3}He + e^{-} + \text{anti-}\nu_e$$

Why the tritium?

Advantages of tritium

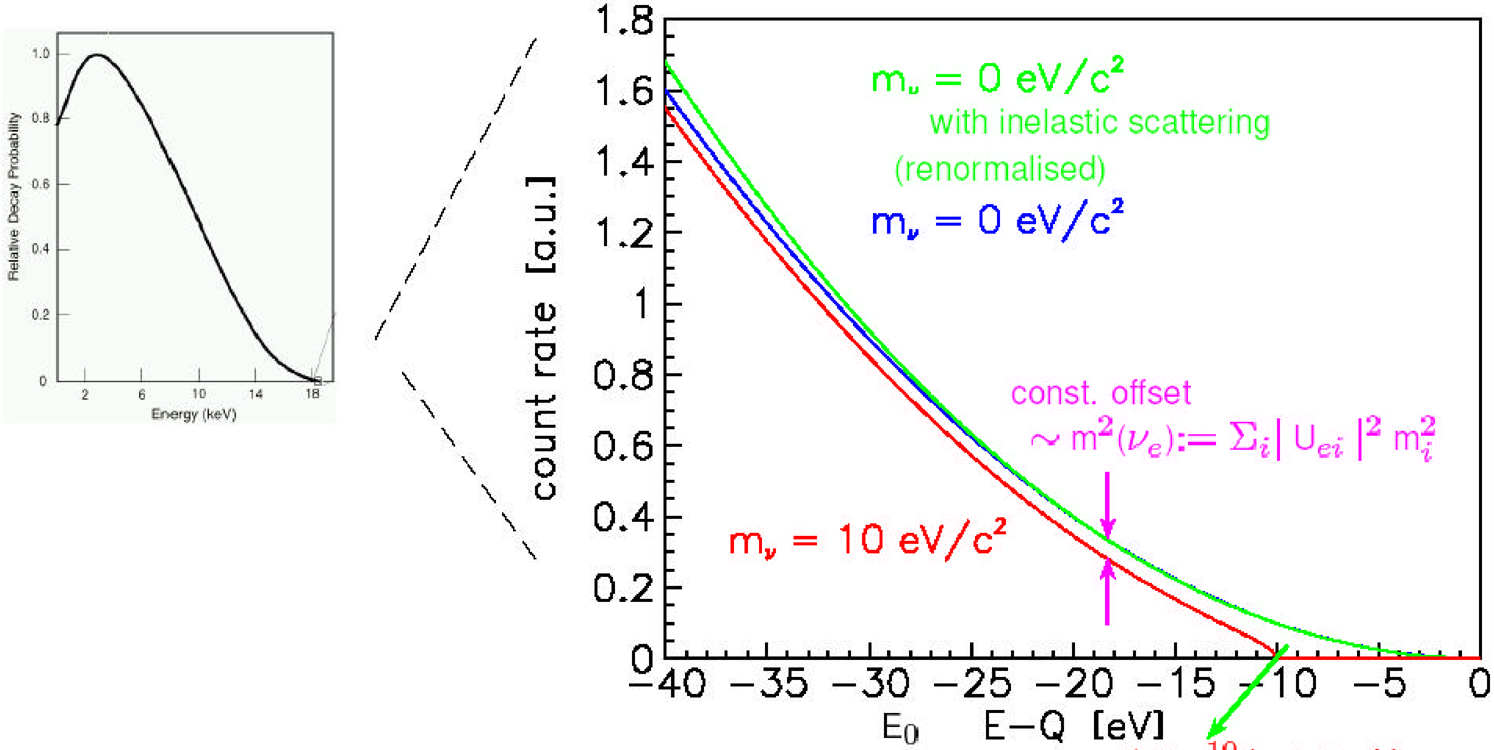
$$T_2 \rightarrow (T^3He)^+ + e^- + \bar{\nu}_e$$

advantages: low endpoint energy: $E_0 = 18.6$ keV

reasonable half: $T_{1/2} = 12.3$ a

molecular states calculable

superallowed



$\sim 2{*}10^{-10}$ last 10 eV

$\sim 10^{-12}$ last 2 eV

$\sim 10^{-15}$ last 0.3 eV

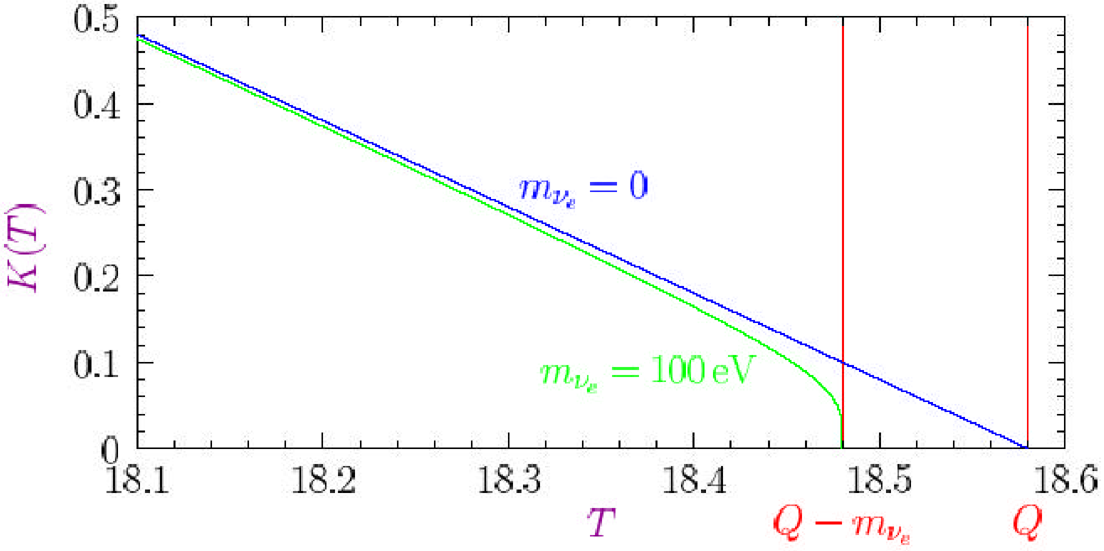
$\sim 10^{-18}$ last 0.03 eV

Tritium β Decay: ${}^3\mathrm{H} \to {}^3\mathrm{He} + e^- + \bar{\nu}_e$

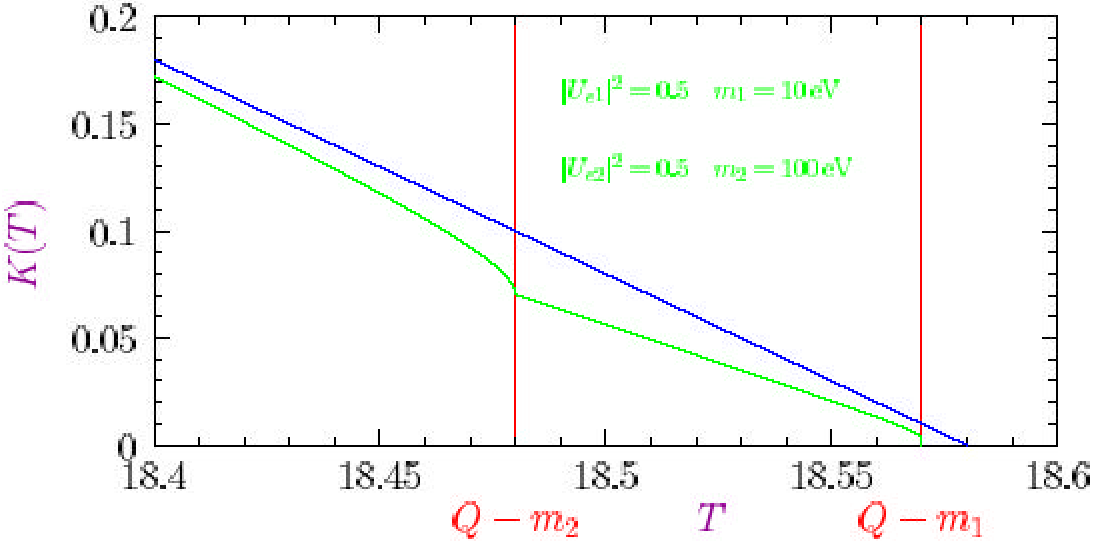
$$\frac{\mathrm{d}\Gamma}{\mathrm{d}T} = \frac{(\cos\vartheta_C G_F)^2}{2\pi^3} |\mathcal{M}|^2 F(E)\, pE\, (Q-T) \sqrt{(Q-T)^2 - m_{\nu_e}^2}$$

$$Q = M_{^3\mathrm{H}} - M_{^3\mathrm{He}} - m_e = 18.58\,\mathrm{keV}$$

Kurie plot: $K(T) = \sqrt{\dfrac{\mathrm{d}\Gamma/\mathrm{d}T}{\dfrac{(\cos\vartheta_C G_F)^2}{2\pi^3} |\mathcal{M}|^2 F(E)\, pE}} = \left[(Q-T)\sqrt{(Q-T)^2 - m_{\nu_e}^2}\right]^{1/2}$



Neutrino Mixing $\Longrightarrow K(T) = \left[(Q-T) \sum_k |U_{ek}|^2 \sqrt{(Q-T)^2 - m_k^2} \right]^{1/2}$



analysis of data is different from the no-mixing case: $2N-1$ parameters

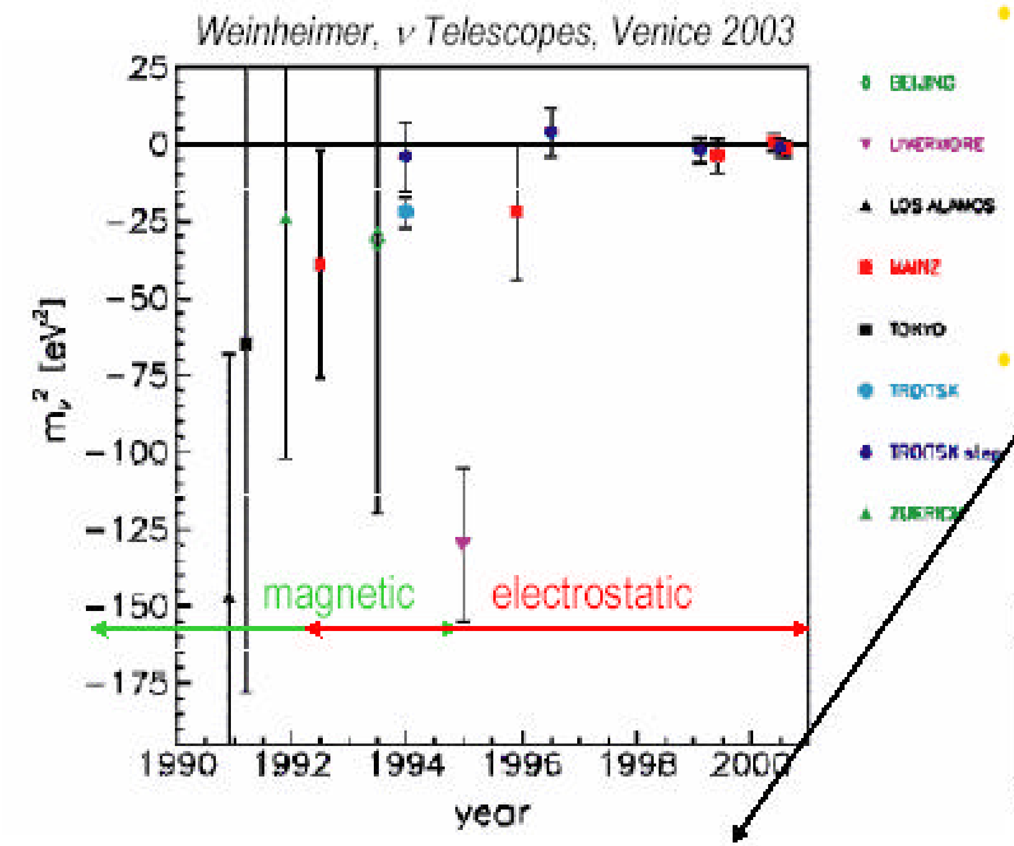
$$\left(\sum_k |U_{ek}|^2 = 1 \right)$$

if experiment is not sensitive to masses $(m_k \ll Q - T)$ $\Longrightarrow$ effective mass

$$\boxed{m_\beta^2 = \sum_k |U_{ek}|^2 m_k^2}$$

$$\begin{aligned} K^2 &= (Q-T)^2 \sum_k |U_{ek}|^2 \sqrt{1 - \frac{m_k^2}{(Q-T)^2}} \simeq (Q-T)^2 \sum_k |U_{ek}|^2 \left[1 - \frac{1}{2} \frac{m_k^2}{(Q-T)^2} \right] \\ &= (Q-T)^2 \left[1 - \frac{1}{2} \frac{m_\beta^2}{(Q-T)^2} \right] \simeq (Q-T) \sqrt{(Q-T)^2 - m_\beta^2} \end{aligned}$$

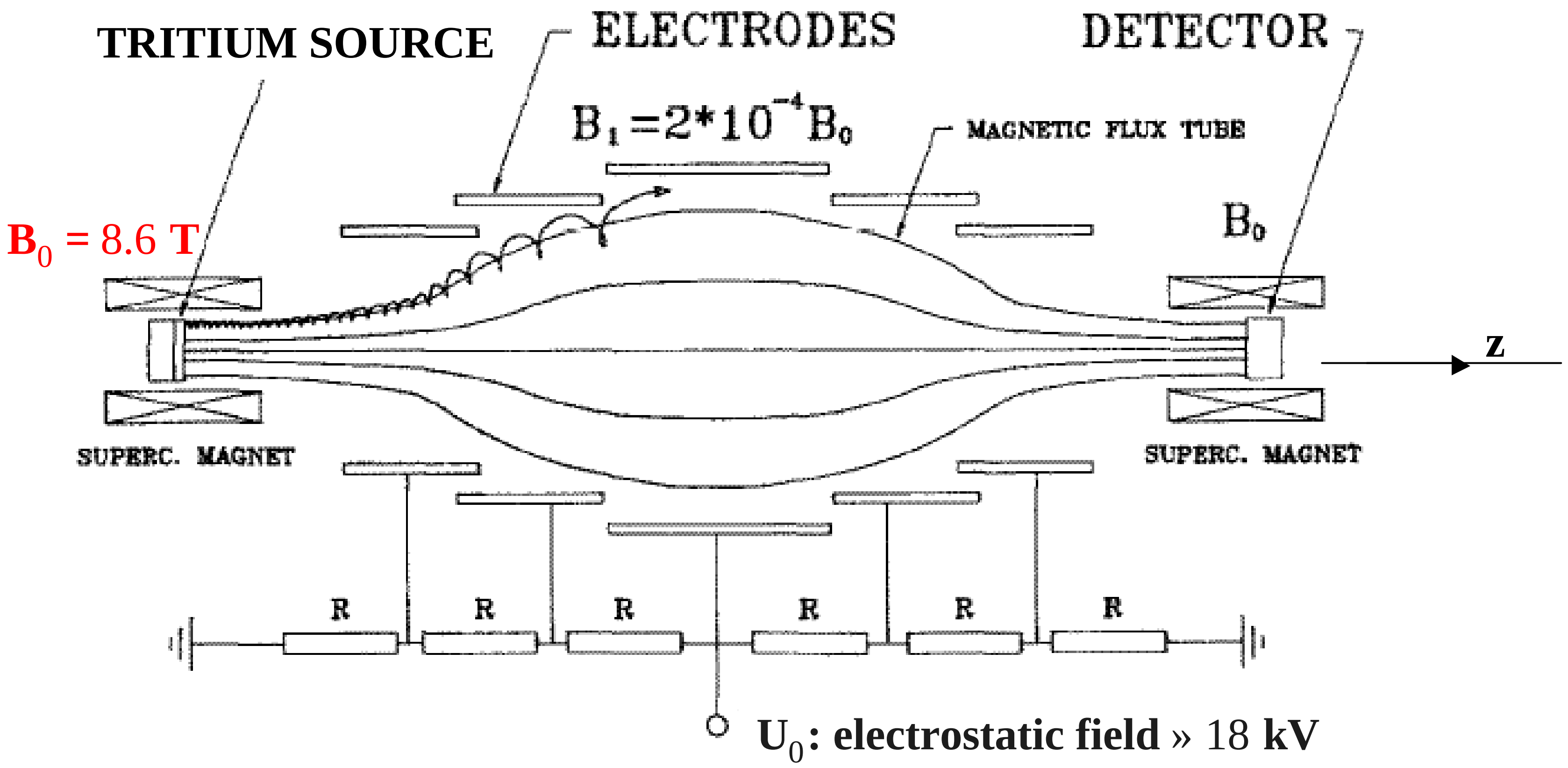
High β resolution spectrometers



can result in negative m^2

- Require high statistics at the β end-point ($dN/N \approx 2(dE/E)^3$)
  - ^{3}H low-Q transition (18.6 keV)
  - Intense source activity
  - Large spectrometer acceptance
- Systematic effects
  - Knowledge of resolution function
  - Source self-absorption and inelastic scattering
  - Initial and final state excitations
  - Background
  - Minimized in the last portion of the β spectrum

The Mainz high β resolution spectrometer



Description of v_e in the field B_0:

$v_z > 0$ (component parallel to the z axis)

$$v_n = \omega r = \frac{eB}{m_e} r$$

(component perpendicular to the z axis;
r : curvature radius (few μm)

Electron energy:
(in a constant magnetic field)

$$E = \frac{1}{2} m_e v^2 = \frac{1}{2} m_e v_z{}^2 + \frac{1}{2} m_e v_n{}^2 = E_z + E_n$$

"Adiabatic" transition from B_0 a B_1

"Adiabatic": component $B_n \ll B_z$ (div B = 0 ⇒ $B_n \neq 0$)

Lorentz force with respect to the z axis is 0

→ $m_e\, v_n\, r$ (electron angular momentum with respect to the z) = costant

$$E_n = \frac{1}{2} m_e v_n{}^2 = \frac{1}{2} m_e v_n r \omega$$

proportional to B ($\omega = eB/m_e$)

☐ E_n is reduced by a factor $B_1/B_0 \approx 2\mathrm{x}10^{-4}$ in the region with weak field B_1

☐ Electron trajectories become almost parallel to the z axis

In order to have electrons going through the electrostatic potential barrier U_0:

$$E_z(B_1) = E - \frac{B_1}{B_0} E_n(B_0) = E - 2\times10^{-4} E_n(B_0) \geq eU_0 \equiv E_{\min}$$

At the source $0 \leq E_n(B_0) \leq E$

➡ The uncertainty on the energy of the electrons going through U_0 is

$$\boxed{\Delta E = 2\times10^{-4} E_{\min}}$$

Electron trajectories are simmetric with respect to the potential barrier

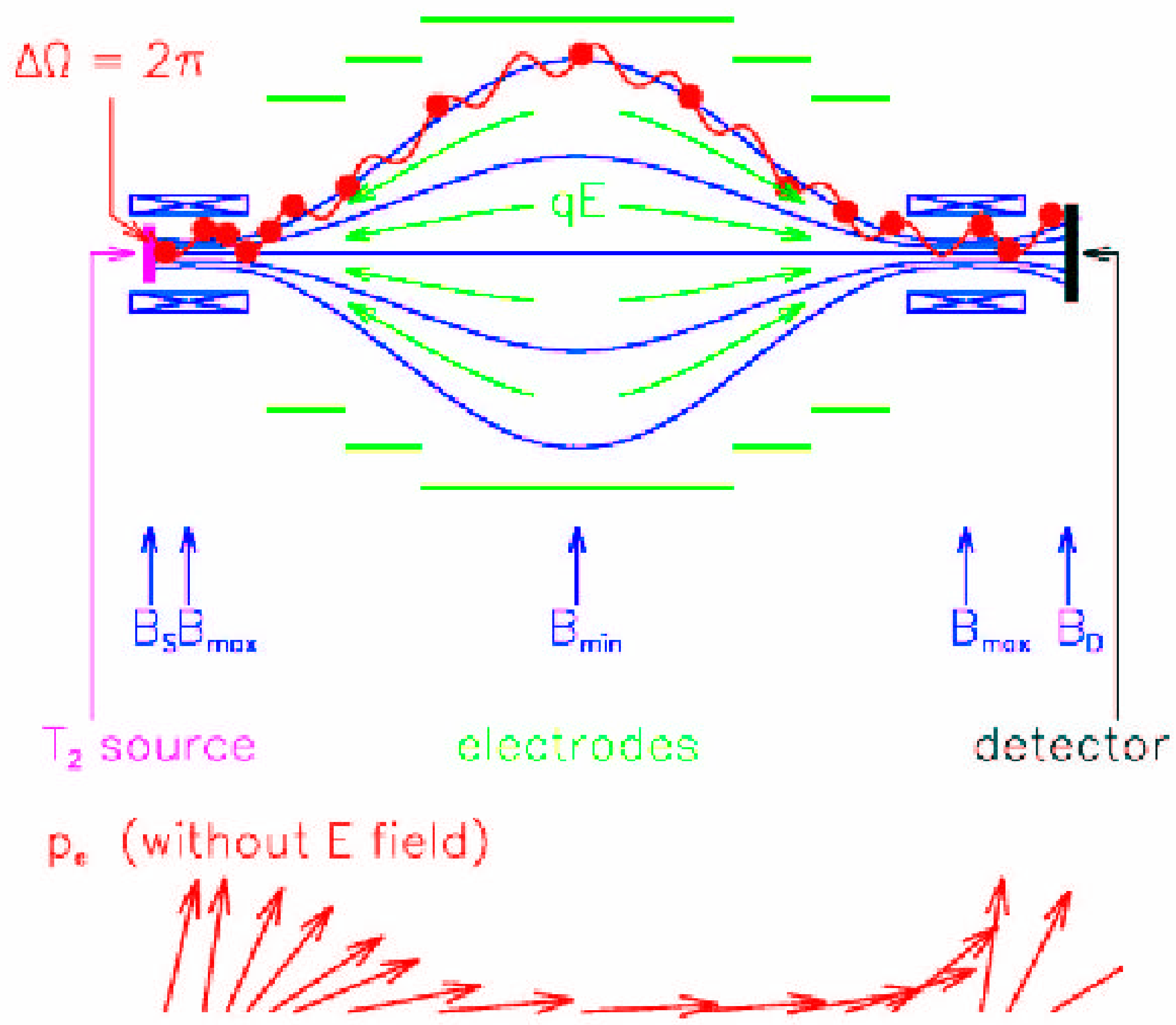
The rate is measured through a solid state :

$$N(E_{\min}) = \int_{E_{\min}} \frac{dn}{dE} dE$$

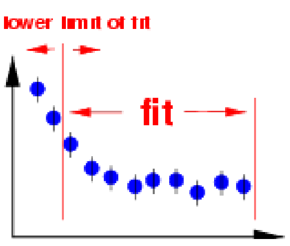
Measuring $N(E_{\min})$ as a function of $E_{\min}$

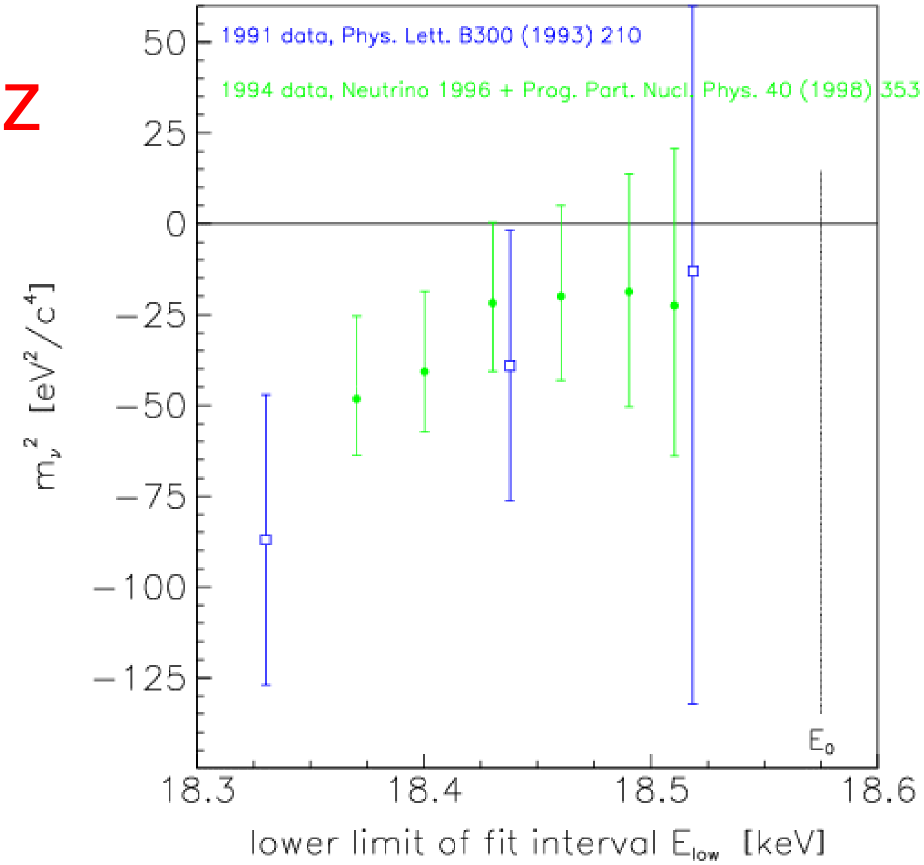
⇒ spectrum measurement

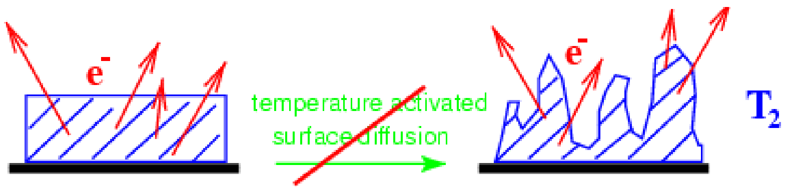
- excellent energy resolution (ΔE = 3.6 eV for $E_{\min}$ = 18 keV)
- large angular aperture (0° ≤ θ ≤ 90°, $\Delta\phi = 2\pi$)


$\Delta\Omega = 2\pi$
qE
B_S B_{max}
B_{min}
B_{max}
B_D
T_2 source
electrodes
detector
p_e (without E field)

Former problem of negative m^2_ν at Mainz







(larger energy losses)

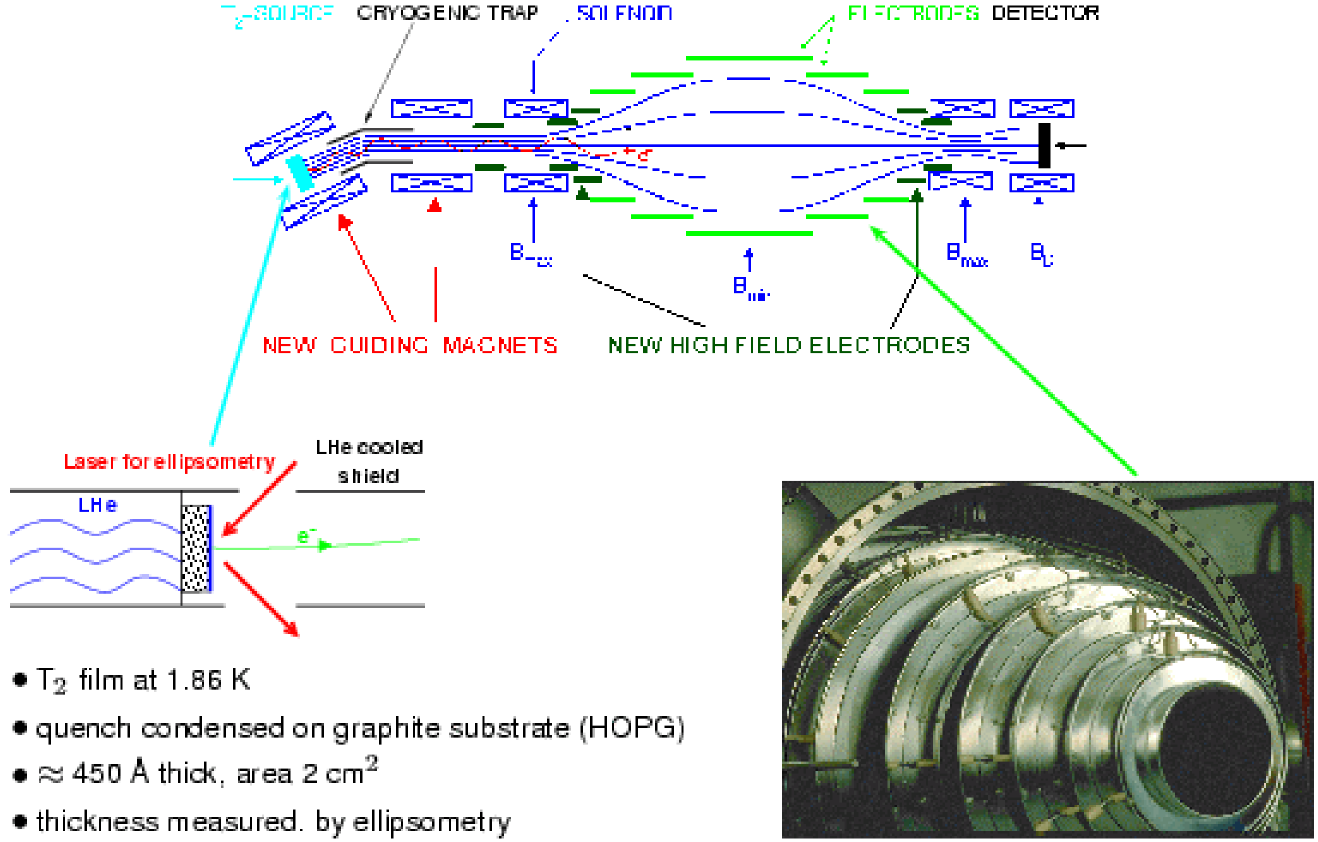
(problems of 1991 and 1994)

(→ negative m_ν^2 value problem)

⇒ Problem of missing energy loss was caused by roughening transition

⇒ should be solved by much lower T_2 temperatures

The Mainz setup since 1997



- T_2 film at 1.86 K
- quench condensed on graphite substrate (HOPG)
- ≈ 450 Å thick, area 2 cm^2
- thickness measured. by ellipsometry

Main features of the 1998-1999 data taking

6 Runs (labelled Q3–Q8),
7 months measurement time in total:

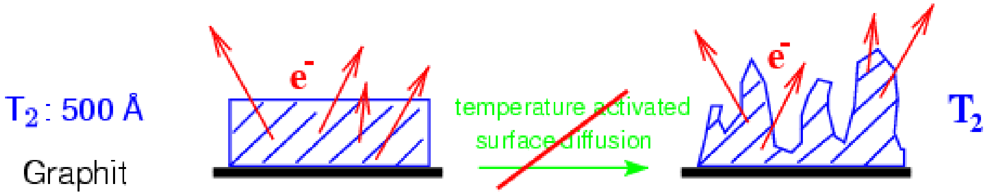
(possible due to automation of apparatus)

- Increasing of signal by a factor of 5

  Decreasing of background by a factor of 2

  → 10× better signal/background

- Lower T_2 film temperature: T = 1.86 K (instead of $\geq$ 3 K)



(larger energy losses)

(problems of 1991 and 1994)

(→ negative m_ν^2 value problem)

L. Fleischmann *et al.*, J. Low Temp Phys. **119** (2000) 615,

L. Fleischmann *et al.*, Eur. Phys. J. **B16** (2000) 521

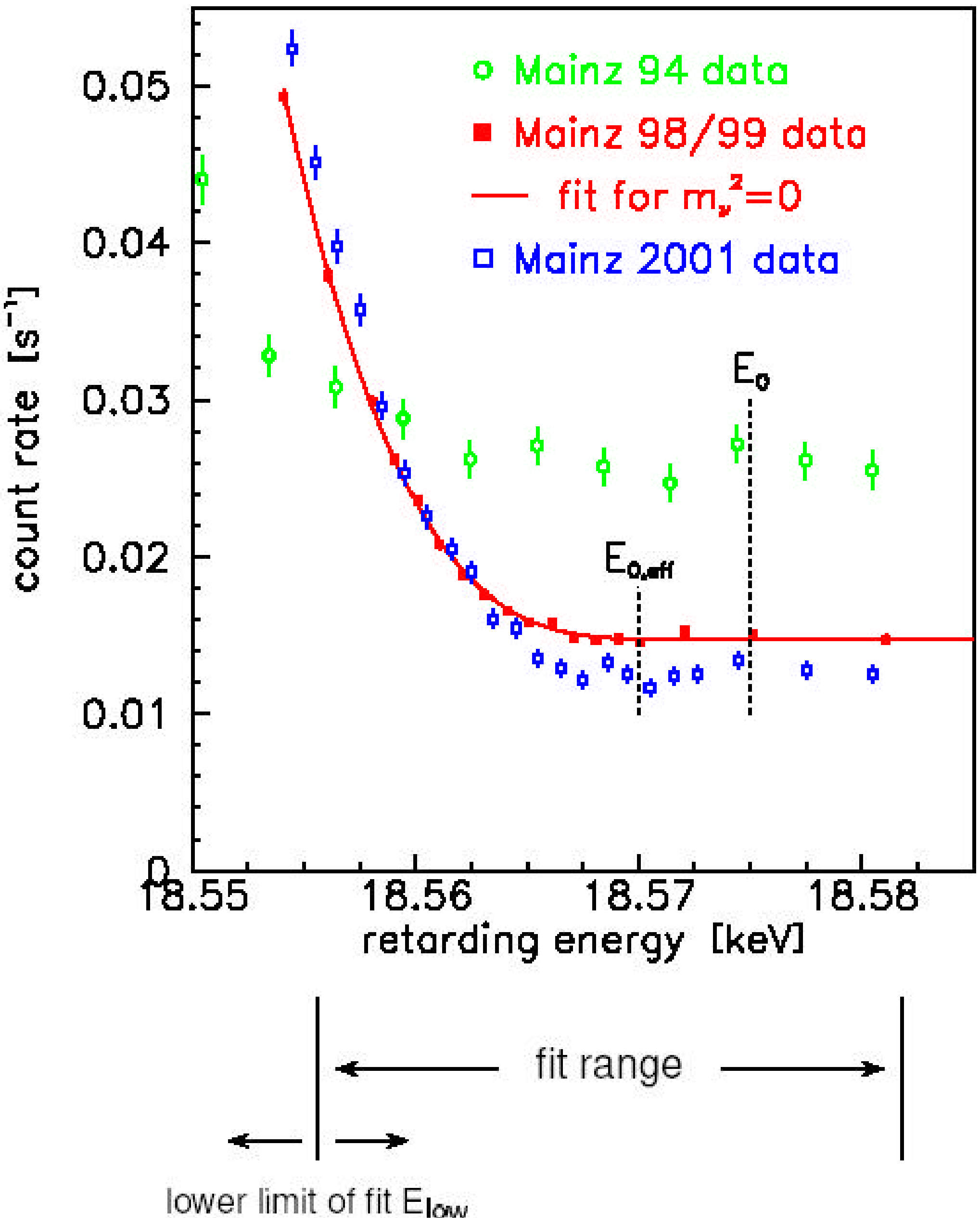
- Better spectrometer resolution: ΔE = 4.8 eV

  (instead of 6.5 eV)

- More stable background:

  HF pulsing on electrodes inbetween measurements from Q5 on

Mainz 1998+1999
measurements: Q3-Q8
Mainz 2001
Measurements: Q11-Q12

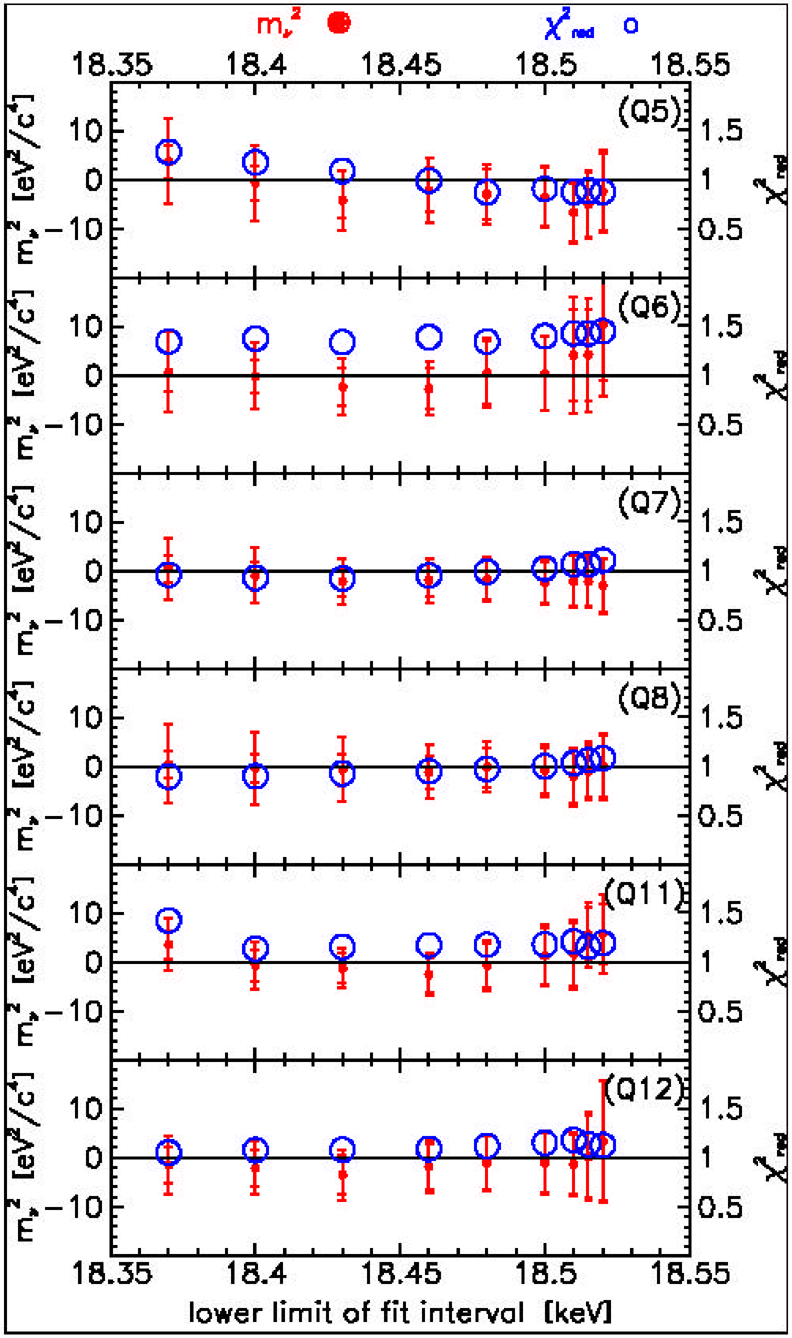


(15 weeks)

(5.5 weeks)

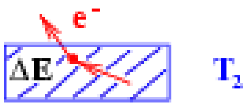
2001: lower background rate, more stable

Results of the measurements 98/99/2001



Systematic uncertainties

- **Inelastic Scattering** (37 %)



thickness measurement: $\Delta d = 3 - 9$ ML (d = 130 ML)

$\lambda_{free} = 363 +/- 19$ ML (Aseev et al., Eur. Phys. J. D10 (2000) 39)

shape of energy loss function

→ some differences to gaseous T_2

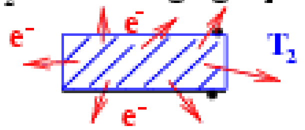
- **Final states** (effects due to solid state) (35 %)

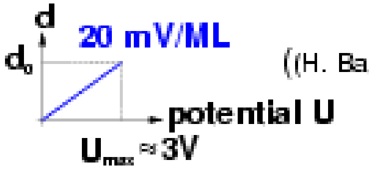
  spectator excitation

  changes of excited states energy levels

  (take full correction as systematic uncertainty into account)

- **T_2 film charging up** (7 %)

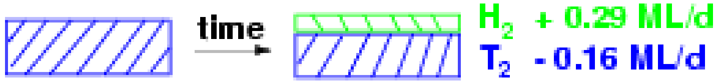




((H. Barth et al., Prog. Part. Nucl. Phys. 40 (1998) 353)

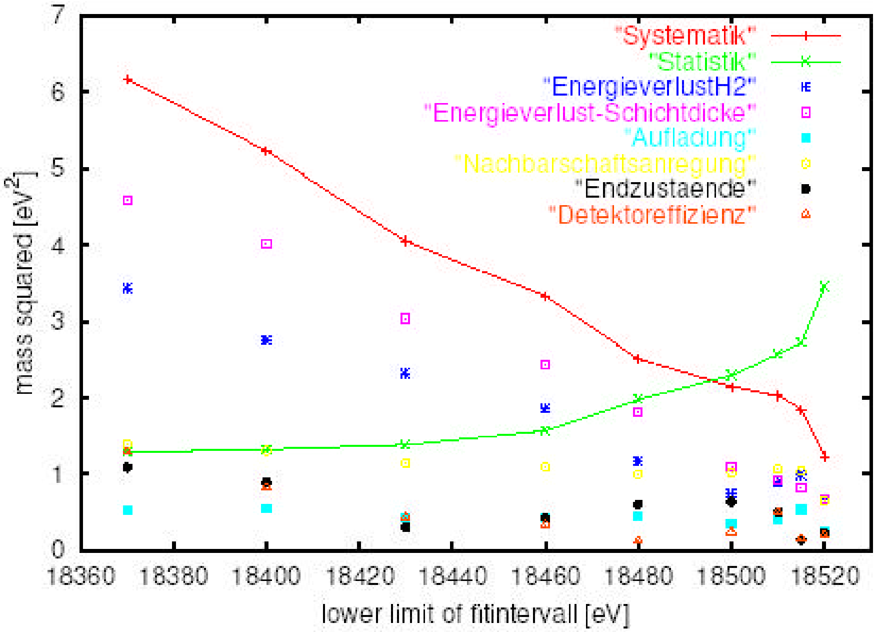
(take 20% of effect as systematic uncertainty into account)

- **T_2 film loss, H_2 coverage** new (21 %)



(take full correction as systematic uncertainty into account)

Systematic uncertainties



- total systematic uncertainty
- total statistical uncertainty
- energy loss due to H_2 on top
- energy loss due to thickness
- self charging
- neighbour excitation
  (decay of T_2 can excite a neighbour molecule)
- final states
- detector efficiency

Results on m_ν with the standard analysis

- m_ν^2 behaviour:

  m_ν^2 is stable against variation of fit range

  m_ν^2 is compatible with physically allowed range

  → no indication for any residual problem in Mainz 1999 and 2001 data!

- No indication for a non-zero neutrino mass:

- analysis of last 70 eV below endpoint (take data points > 18.5 keV)

  Q5,Q6,Q7,Q8,Q11,Q12 $m_\nu^2 c^4 = -1.2 \pm 2.2_{stat} \pm 2.1_{sys}\ eV^2$ $\chi^2/\text{d.o.f.} = 208/193$

  $\rightarrow m_\nu c^2 \leq 2.2\ eV$ (95% C.L., unif. appr.)

  sensitivity = 2.4 eV (95% C.L., unif. appr. for $m_\nu c^2 = 0\ eV$)

Mainz setup is modified for systematic investigations to prepare KATRIN

results for m_ν^2 in [eV^2], single runs

Q5	Q6	Q7	Q8	Q11	Q12
-3.46	+0.38	-2.44	-0.91	+1.32	-1.01

Common analysis – fitting neighbour excitation amplitude from data

problem: neighb. excitation taken by only one calculation (gaseous)

(W. Kolos et. al., Phys. Rev. **A37**, 1988)

$\Rightarrow$ mean excitation energy ϵ = 14.6 eV, amplitude a_{nex} = 5.9%

may have some weak points (mentioned by Troitsk group)

Mainz measurements of energy loss in quench condensed D_2-films

(V.N. Aseev et.al., Eur. Phys. J. D **10**, 2000) $\Rightarrow$ mean free path λ = 1240±80 Å

(σ_{tot} = 2.98*$10^{-18}$$cm^2$)

different mean excitation energy due to solid state and due to vacancies

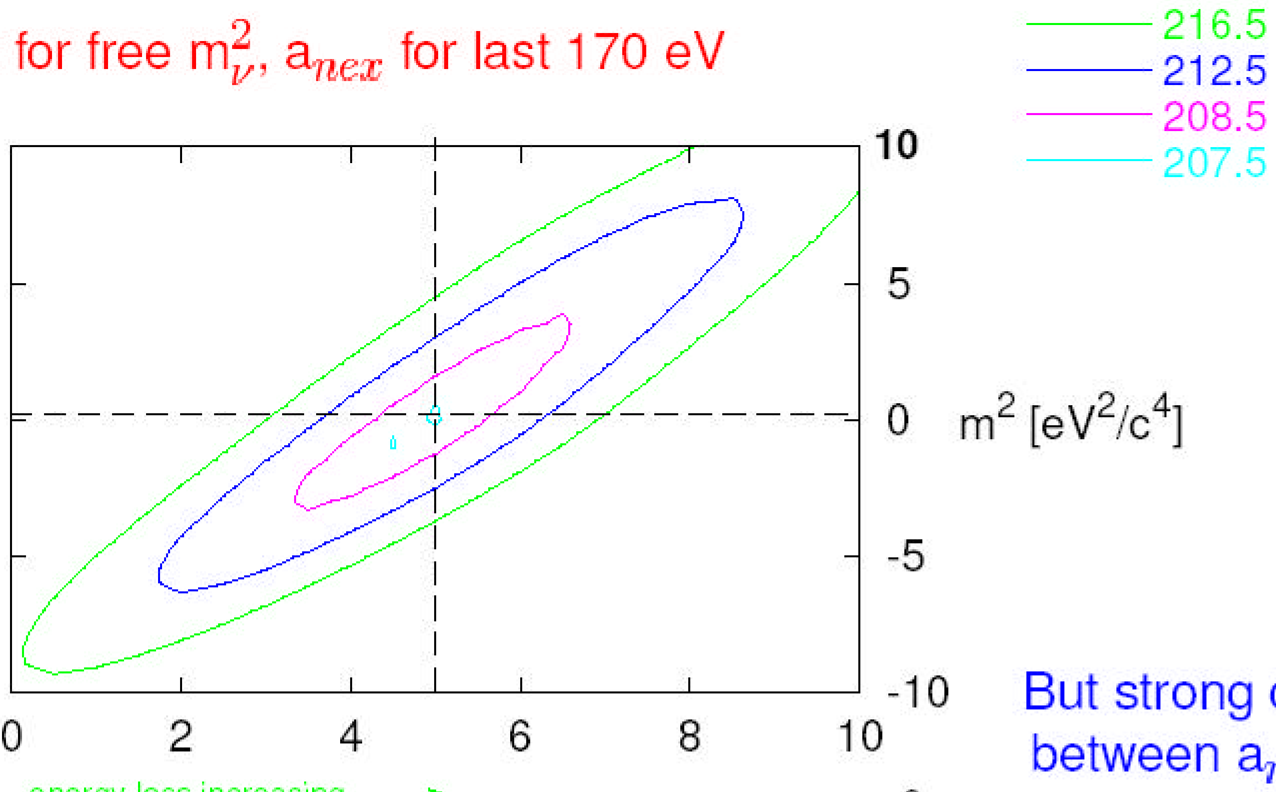
$\Rightarrow$ applied up to now ϵ = 16.1 eV and a_{nex} =4.6%

now: energy levels quite certain $\Rightarrow$ no change for ϵ

amplitude might be uncertain $\Rightarrow$ fit a_{nex}

$\Rightarrow$ fitting with data from 1998,1999 and 2001 (enough statistic)

fit for free m_ν^2, a_{nex} for last 170 eV



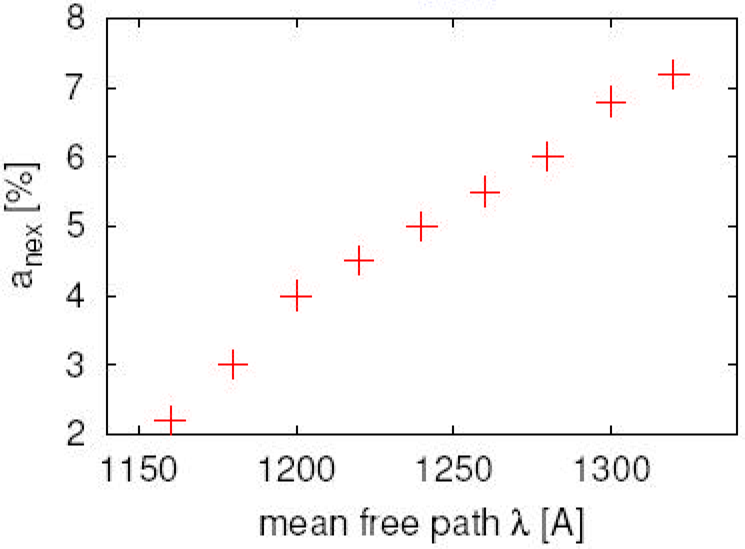
But additional systemematic uncertainty due to uncertainty of λ

$\Rightarrow a_{nex} = 5 \pm 1.6 \pm 2.2\%$

standard analysis (calculation):

$a_{nex} = 4.6 \pm 1.3\%$

But strong correlation between a_{nex} and λ:



Mainz results

calculation by W.Kolos et.al. in good agreement with our data

Use fitted a_{nex} value and correlation to λ for standard analysis interval (last 70 eV)

Q5,Q6,Q7,Q8,Q11,Q12 $m_\nu^2 c^4 = -0.7 \pm 2.2_{stat} \pm 2.1_{sys}$ eV^2

$\rightarrow m_\nu c^2 \leq 2.3$ eV (95% C.L., unif. appr.) preliminary!!

compared to standard analysis:

Q5,Q6,Q7,Q8,Q11,Q12 $m_\nu^2 c^4 = -1.2 \pm 2.2_{stat} \pm 2.1_{sys}$ eV^2 $\chi^2/\text{d.o.f.} = 208/193$

$\rightarrow m_\nu c^2 \leq 2.2$ eV

May we predict m_β?(I)

The minimal neutrino mass m_1 and the character ("normal" or "inverted", hierarchical or almost degenerate) of the neutrino mass spectrum are unknown at present

On the other hand neutrino oscillation exps can only determine the neutrino mass-squared differences Δm^2_{21} and Δm^2_{32}

$$m_2 = \sqrt{m_1^2 + \Delta m_{21}^2} \qquad m_3 = \sqrt{m_1^2 + \Delta m_{21}^2 + \Delta m_{32}^2}$$

In the "normal" three neutrino scheme

$$m_b^2 = m_1^2 + \left(\sin^2 q_{sol} + \cos^2 q_{sol} \left|U_{e3}\right|^2\right)\Delta m_{sol}^2 + \left|U_{e3}\right|^2 \Delta m_{atm}^2$$

May we predict m_β?(II)

In the case of hierarchical mass spectrum we have

$$m_2 \approx \sqrt{\Delta m^2_{sol}} \approx 7\times10^{-3}\ \text{eV} \qquad m_3 \approx \sqrt{\Delta m^2_{atm}} \approx 5\times10^{-2}\ \text{eV}$$

The heaviest neutrino mass enters into m_β with a weight given by $|U_{e3}|^2$ for which we have only an upper bound given by CHOOZ

$$m_b = \sqrt{\sin^2 q_{sol} \Delta m^2_{sol} + \left|U_{e3}\right|^2 \Delta m^2_{atm}} \le 1.2\times10^{-2}\ \text{eV}$$

May we predict m_β?(III)

In the case of inverted neutrino scheme we have

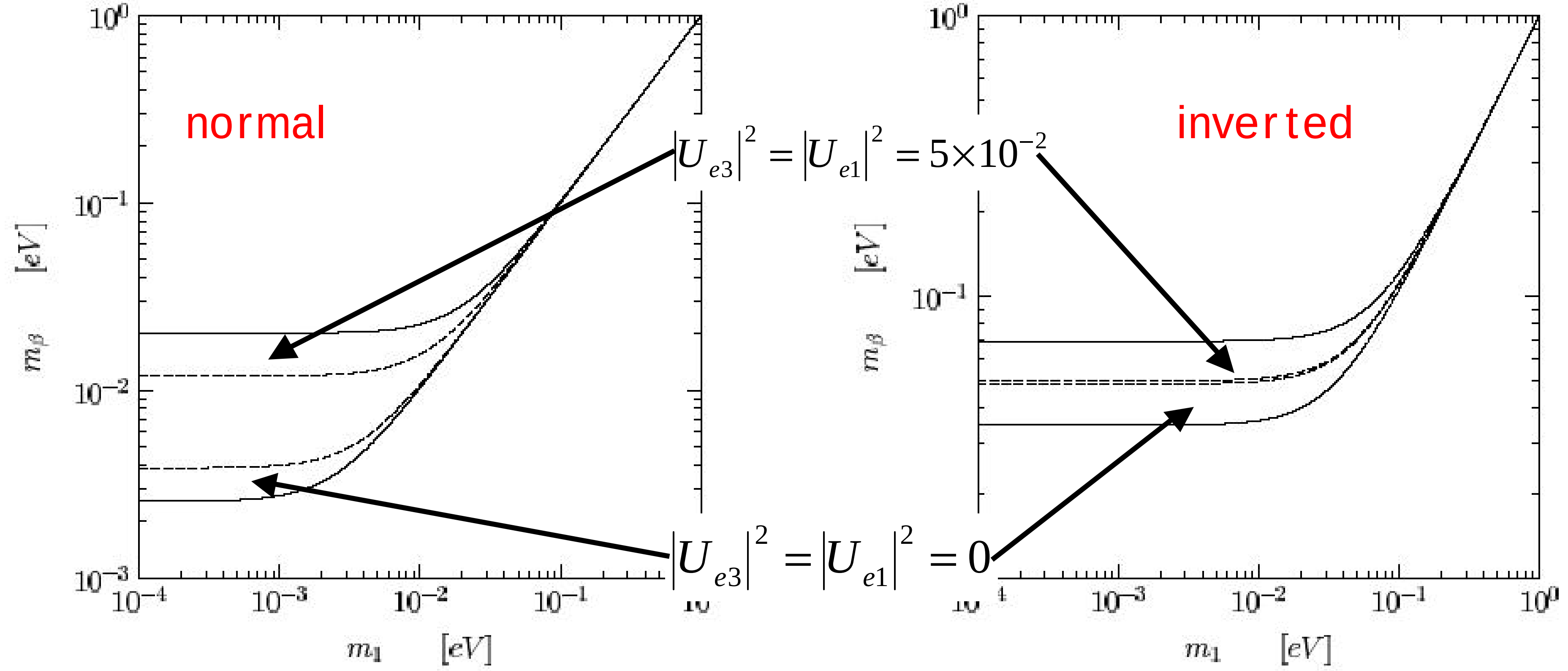
$$m_b^2 = m_1^2 + \left(1 - |U_{e1}|^2\right)\left(\sin^2 q_{sol} \Delta m_{sol}^2 + \Delta m_{atm}^2\right)$$

The heaviest neutrino mass enters into m_β with a weight given by $|U_{e1}|^2$ for which we have only an upper bound given by CHOOZ

$$m_b = \sqrt{\Delta m_{atm}^2} \leq 5 \times 10^{-2} \text{ eV}$$

May we predict m_β?(IV)

The solid lines show the lower and upper bounds on m_β taking into account all available information on solar, atmospheric and reactor neutrino oscillation exps



$$|U_{e3}|^2 = |U_{e1}|^2 = 5\times10^{-2}$$

$$|U_{e3}|^2 = |U_{e1}|^2 = 0$$

Comments

- ✓ Mainz and Troitsk are by far above the region where experimental indications point for the value of m_β
- ✓ Of course the previous consideration holds only in the three family neutrino scheme. In the case LSND is confirmed by MiniBOONE we have the following contraints on m_β

$$0.45 \le m_b \le 1.4 \text{ eV}$$

- ✓ A next generation experiment (KATRIN) whose aim is to perform high resolution and high statistics measurement of ß-spectrum close to 18.6 keV endpoint of T_2 is in preparation

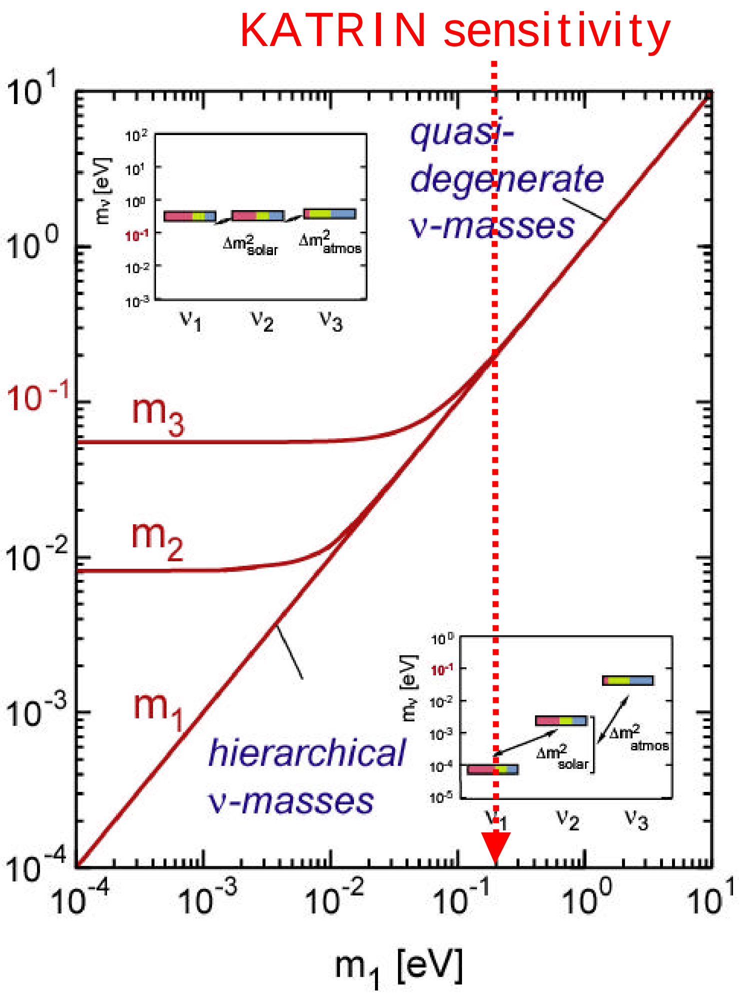
Science objectives of KATRIN

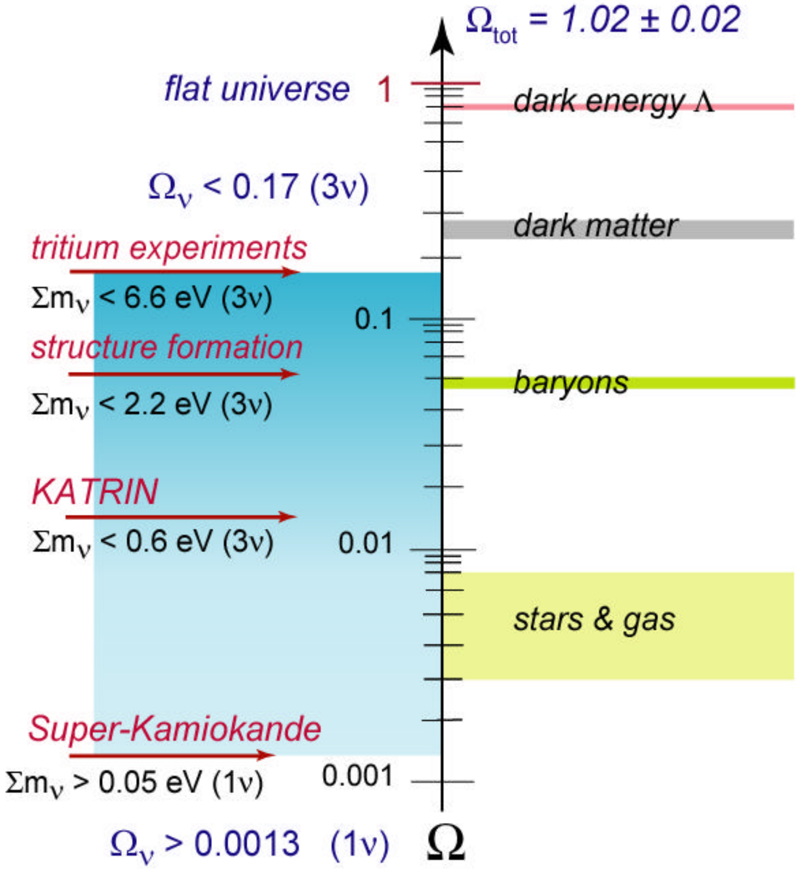
Motivation I : particle physics

valididate or largely rule out models
w. quasi-degenerate mass eigenstates

Motivation II : cosmology

role of ν's as hot dark matter –
fix or constrain m_ν (Ω_ν)

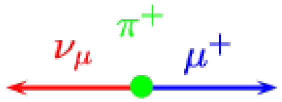




Determination of m(ν_μ) from pion decay

$$\pi^+ \rightarrow \mu^+ + \nu_\mu$$ (Two body decay)

Decay at rest:



$$|\vec{p}_\nu| = |\vec{p}_\mu|$$

$$m_\pi = E_\nu + E_\mu$$

$$\rightarrow \mathrm{m}_\nu^2 = \mathrm{m}_\pi^2 + \mathrm{m}_\mu^2 - 2 \cdot \mathrm{m}_\pi \cdot \sqrt{\mathrm{m}_\mu^2 + \mathrm{p}_\mu^2}$$

3 different Experiments:

Values from PDG2000

Pionic atoms:	$\mathrm{m}_\pi = 139.570180(350)$ MeV
Myonium:	$\mathrm{m}_\mu = 105.658357(5)$ MeV
Magnetic spektrometer (PSI):	$\mathrm{p}_\mu = 29.791998(110)$ MeV

$\Rightarrow \mathrm{m}(\nu_\mu) < 170\mathrm{keV/c^2}$ $(95\%\ \mathrm{c.l.})$ (K. Assamagan *et al.*, Phys. Rev. D53 (1996) 6065)

PDG2000: $\mathrm{m}(\nu_\mu) < 190\mathrm{keV/c^2}$ $(95\%\ \mathrm{c.l.})$

Improvements expected: Factor 3 by new m_π measurement (PSI)
Factor 20 by $\pi^+ \rightarrow \mu^+\nu_\mu$ in flight (g-2, BNL)

Determination of $m(\nu_\tau)$ from multi body τ decay

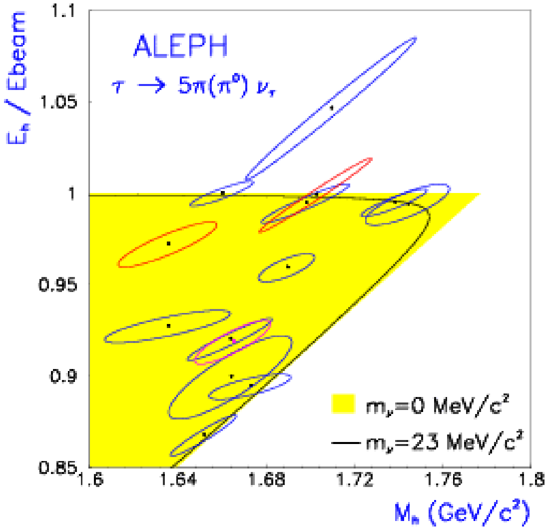
Collider experiments: $e^+e^- \rightarrow \tau^+\tau^-$

Search for rare subsequent τ decays:

$$\tau \rightarrow 5\pi\ (+\pi^o) + \nu_\tau \qquad (BR = 10^{-3})$$

"Observable": invariant mass of the 5(6) π's

$$M_h{}^2 = (\sum E_i,\ \sum \vec{p}_i)^2 \leq (m_\tau - m_\nu)^2$$



Lowest present limit:

$m_{\nu_\tau} < 18.2$ MeV/c^2

(ALEPH)

also limits from OPAL, CLEO

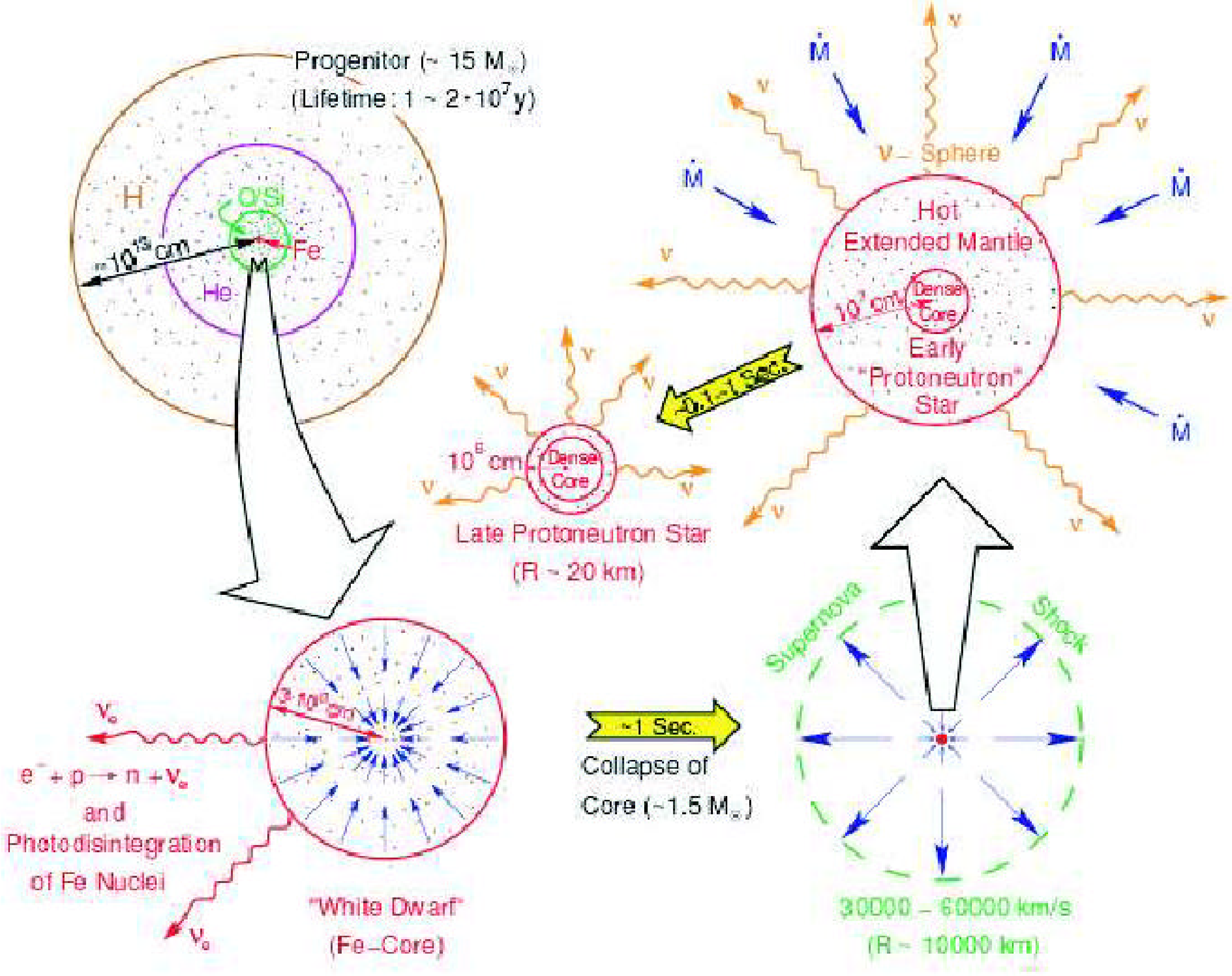
Future perspectives:

- Sensitivity of 3 MeV/c^2 expected from BABAR and BELLE
  → close small cosmological window
- Further significant improvement by nearby Supernova possible!

Neutrino mass from SN

1. Neutrino production from SN
2. The SN1987A observation
3. Limit on neutrino mass

Neutrino production from SuperNovae



SN1987A

- ✓ On 24 February 1987 a supernova, called SN1987A, was discovered in the Large Magellanic Cloud at a distance of about 50 kpc from the solar system
- ✓ Four underground experiments potentially sensitive to SN neutrinos were in operation: Kamiokande, IMB, Baksan and LSD
- ✓ In the numerous analyses of SN1987A data LSD is not included, being its signal recorded about five hours before those of other detectors

SN1987A data sample

- ✓ Kamiokande
  - 16 events have been observed, although only 7 are unambiguously induced by SN neutrinos
- ✓ IMB
  - 8 events have been observed with negligible background
- ✓ Baksan
  - 5 events observed, but only after Kamiokande and IMB gave the evidence for SN neutrino detection

Many authors performed a fit of these data, but the more recent and accurate (with the background included) had been performed by Loredo and Lamb (Phys.Rev. D65 063002)

How to extract m_ν from SN?(I)

An extremely relativistic neutrino with mass m<<E has velocity

$$\mathrm{v} = \frac{p}{E} = \sqrt{1 - \frac{m^2}{E^2}} \approx 1 - \frac{m^2}{2E^2}$$

If the neutrino is emitted at a distance D, the TOF delay of a massive neutrino wrt to a massless particle is

$$\Delta t = \frac{D}{\mathrm{v}} - D \approx \frac{m^2}{2E^2} D = 2.57 \left(\frac{m}{eV} \right)^2 \left(\frac{E}{MeV} \right)^{-2} \frac{D}{50kpc} \sec.$$

How to extract m_ν from SN?(II)

- ❑ If ν are emitted in a burst with intrinsic duration ΔT_0, the observation of events separated by a time interval larger than ΔT_0 would provide a direct measurement of the neutrino mass (assuming D known and E measurable)
- ❑ If the ν energy spectrum has mean value E and width ΔE, ν's produced at the same time with different energies would reach a detector at a distance D in the time interval

$$\Delta T \approx \frac{m^2}{E^2} D \frac{\Delta E}{E}$$

The model independent sensitivity to m_ν is found by requiring

$$\Delta T < \Delta T_0 \le \Delta T_{obs}$$

Results

Since the time duration of the neutrino signal is compatible with theoretical expectations, only an upper limiti on m_ν can be derived

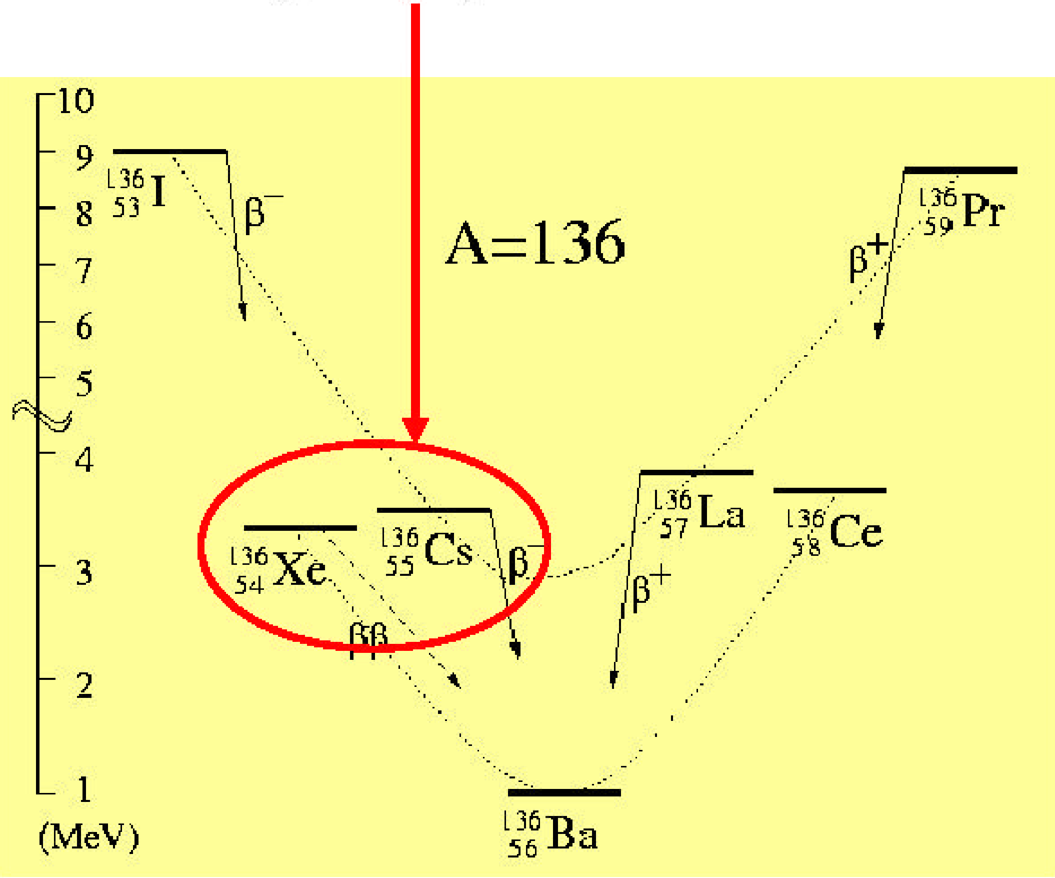
$$m \leq E\sqrt{\frac{E}{\Delta E}\frac{\Delta T_{obs}}{D}} \approx 14\text{eV}\left(\frac{E}{10\text{MeV}}\right)\sqrt{\frac{E}{\Delta E}}\sqrt{\frac{\Delta T_{obs}}{10\sec}}\sqrt{\frac{50kpc}{D}}$$

In the recent analysis of Loredo and Lamb the following upper limit was obtained

$$m \leq 5.7 \text{ eV (at 95\% C.L.)}$$

Double-beta decay:

a second-order process only detectable if first order beta decay is energetically forbidden



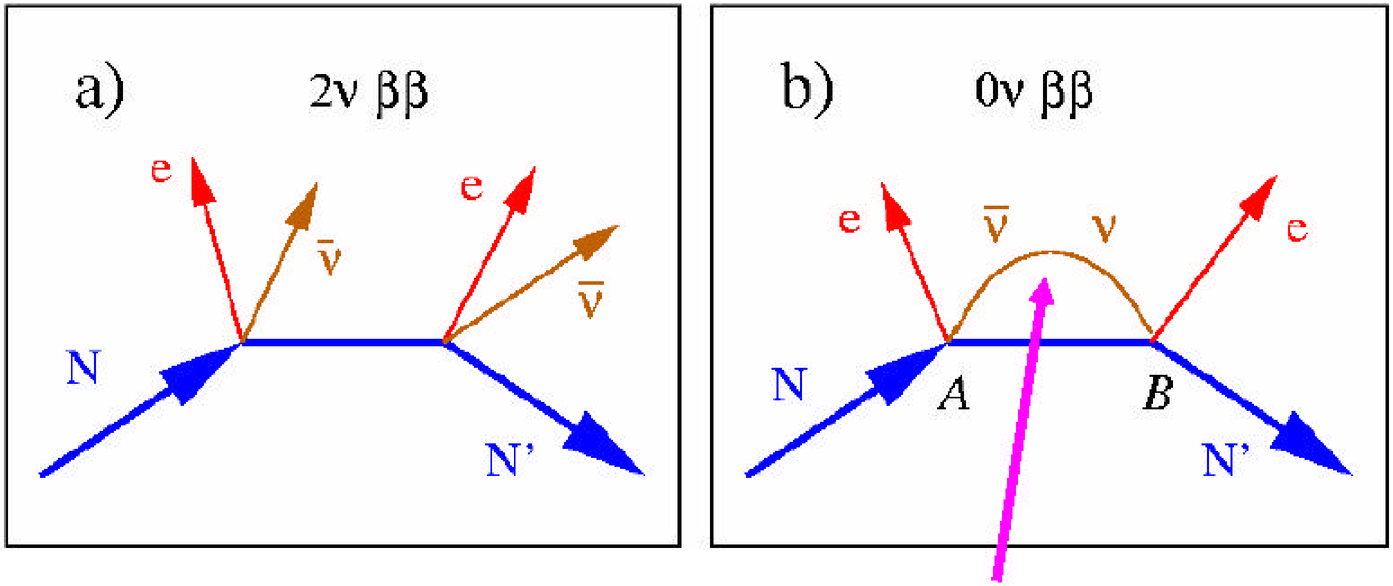
Candidate nuclei with Q>2 MeV

Candidate	Q (MeV)	Abund. (%)
$^{48}Ca \rightarrow {}^{48}Ti$	4.271	0.187
$^{76}Ge \rightarrow {}^{76}Se$	2.040	7.8
$^{82}Se \rightarrow {}^{82}Kr$	2.995	9.2
$^{96}Zr \rightarrow {}^{96}Mo$	3.350	2.8
$^{100}Mo \rightarrow {}^{100}Ru$	3.034	9.6
$^{110}Pd \rightarrow {}^{110}Cd$	2.013	11.8
$^{116}Cd \rightarrow {}^{116}Sn$	2.802	7.5
$^{124}Sn \rightarrow {}^{124}Te$	2.228	5.64
$^{130}Te \rightarrow {}^{130}Xe$	2.533	34.5
$^{136}Xe \rightarrow {}^{136}Ba$	2.479	8.9
$^{150}Nd \rightarrow {}^{150}Sm$	3.367	5.6

2ν mode: a conventional
2nd order process
in nuclear physics

0ν mode: a hypothetical
process can happen
only if:

- $M_\nu \neq 0$ Since helicity has to "flip"
- $\nu = \bar{\nu}$



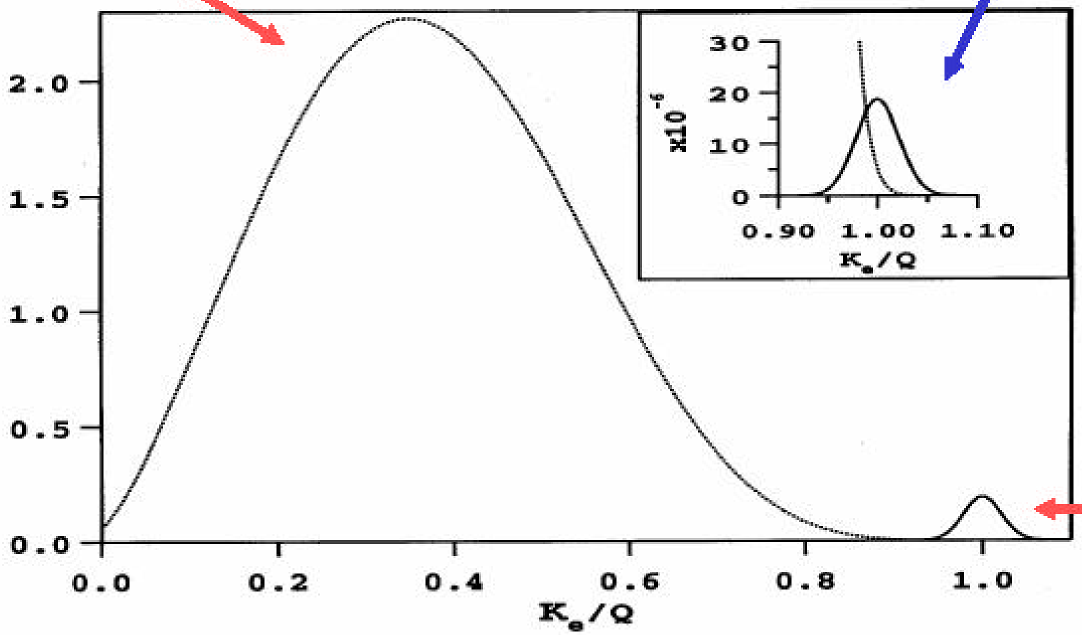
Several new particles can take
the place of the virtual ν

But 0νββ decay always implies new physics

$(A, Z) \rightarrow (A, Z+2) + e^- + e^- + \bar{\nu}_e + \bar{\nu}_e$

$(A, Z) \rightarrow (A, Z+2) + e^- + e^-$

Background due to the Standard Model $2\nu\beta\beta$ decay



$2\nu\beta\beta$ spectrum (normalized to 1)

$0\nu\beta\beta$ peak (5% FWHM) (normalized to 10^{-6})

$0\nu\beta\beta$ peak (5% FWHM) (normalized to 10^{-2})

Summed electron energy in units of the kinematic endpoint (Q)

from S.R. Elliott and P. Vogel, Ann.Rev.Nucl.Part.Sci. **52** (2002) 115.

The only effective tool here is energy resolution

$\beta\beta$ decay experiments are at the leading edge of "low background" techniques

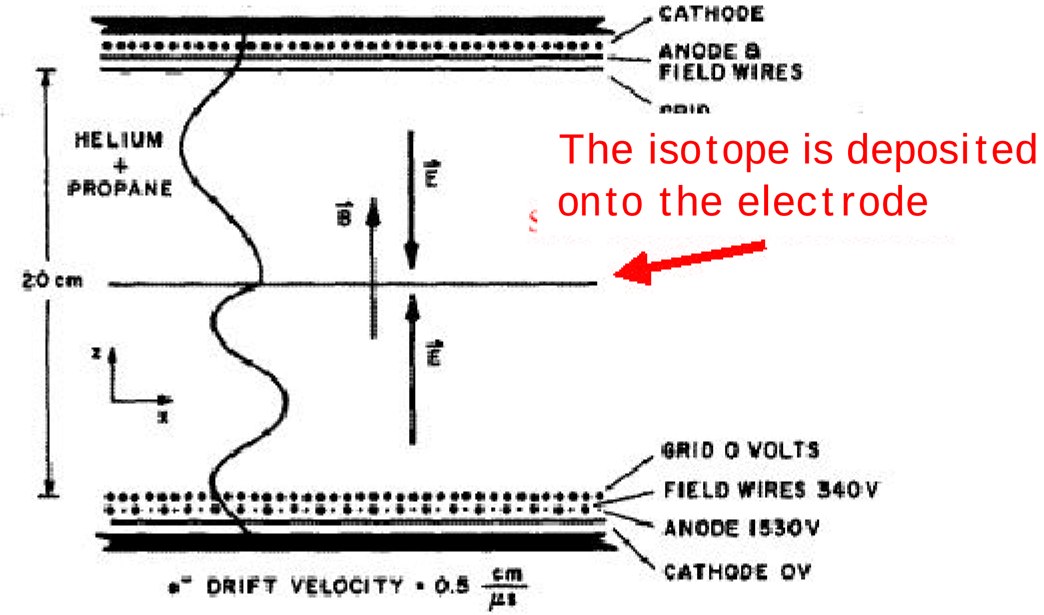
- Final state ID: 1) "Geochemical": search for an abnormal abundance of (A,Z+2) in a material containing (A,Z)
  2) "Radiochemical": store in a mine some material (A,Z) and after some time try to find (A,Z+2) in it
  - \+ Very specific signature
  - \+ Large live times (particularly for 1)
  - \+ Large masses
  - \- Possible only for a few isotopes (in the case of 1)
  - \- No distinction between 0ν, 2ν or other modes
- "Real time": ionization or scintillation is detected in the decay
  a) "Homogeneous": source=detector
  b) "Heterogeneous": source≠detector
  - \+ Energy/some tracking available (can distinguish modes)
  - \+ In principle universal (b)
  - \- Many γ backgrounds can fake signature
  - \- Exposure is limited by human patience

Real time is needed to discover ν masses, final state ID would be a nice complement !

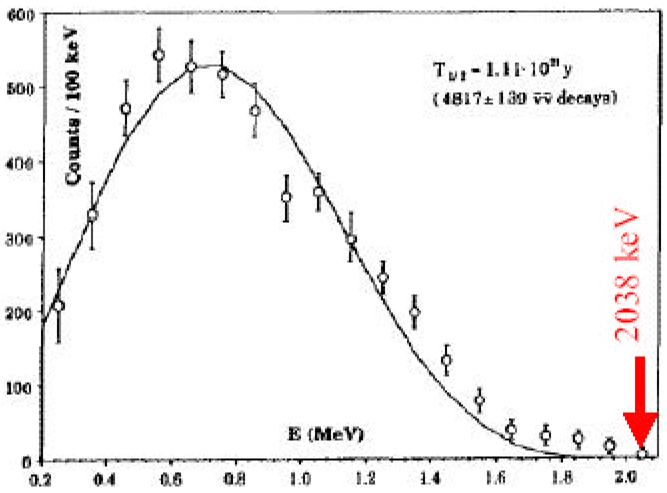
The 2ν ββ decay

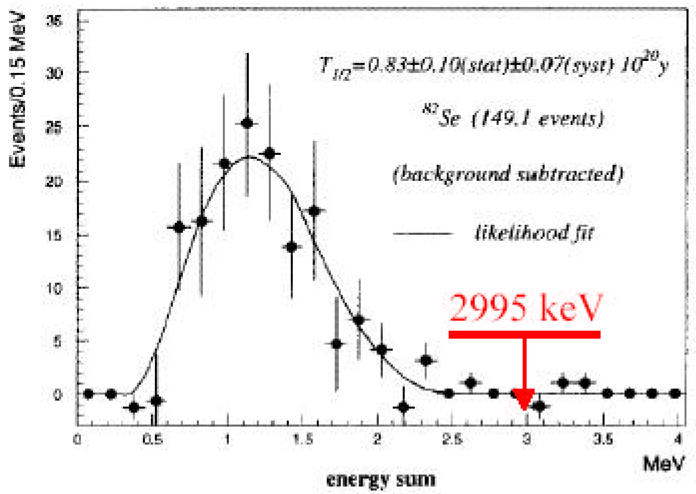
This process has been observed by many exps

The two electron tracks have to detected
I.e. TPC detector



The isotope is deposited onto the electrode





$$^{82}Se_{34} \rightarrow {}^{82}Kr_{36} + e^{-} + e^{-} + \bar{\nu}_e + \bar{\nu}_e$$

Isotope	$T_{1/2}^{2\nu}$ (yr)
^{48}Ca	$(4.3\pm2.2)\cdot10^{19}$
^{76}Ge	$(1.77\pm0.12)\cdot10^{21}$
^{82}Se	$(8.3\pm1.2)\cdot10^{19}$
$^{96}\text{Zr}^{\dagger}$	$(9.4\pm3.2)\cdot10^{18}$ § $(2.1\pm0.6)\cdot10^{19}$ $(3.9\pm0.9)\cdot10^{19}$ §
^{100}Mo	$(9.5\pm1.0)\cdot10^{18}$
^{116}Cd	$(2.6\pm0.6)\cdot10^{19}$
^{128}Te	$(7.2\pm0.4)\cdot10^{24}$ §
$^{130}\text{Te}^{\dagger}$	$(2.7\pm0.1)\cdot10^{21}$ § $(7.9\pm1.0)\cdot10^{20}$ § $(6.1\pm3.5)\cdot10^{20}$
$^{136}\text{Xe}^{\$}$	$>1.1\cdot10^{22}$ 90% CL
^{150}Nd	$(6.7+0.8)\cdot10^{18}$
^{238}U	$(2.0\pm0.6)\cdot10^{21}$ *

The Standard Model 2νββ decay has been observed in many isotopes

Table arbitrarily simplified from PDG 2003

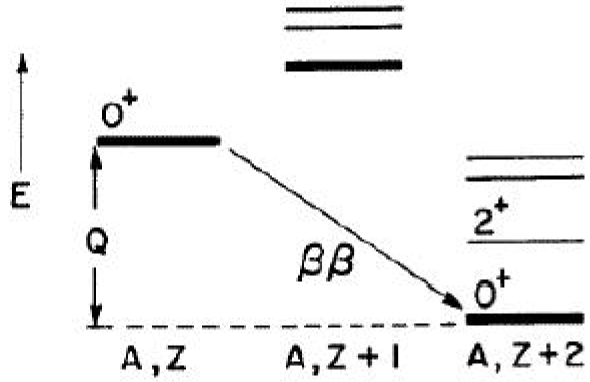
†Results not in good agreement
§Geochemical experiment
*Radiochemical experiment
$^{\$}$Decay NOT observed, lower limit reported

The 0ν ββ decay

- ✓ Sensitive to neutrino mass
- ✓ Sensitive to the neutrino nature (Dirac or Majorana?)

NB the results obtained by studying this process are valid only if the neutrino is a Majorana particle

Choice of the nucleus



$$(\mathrm{A}, \mathrm{Z}) \rightarrow (\mathrm{A}, \mathrm{Z}+1) + \mathrm{e}^- + \overline{\nu}_\mathrm{e}$$

should be energetically forbidden

$$\mathrm{Q} > 2m_\mathrm{e}\mathrm{c}^2$$

If $0\nu\beta\beta$ is due to light ν Majorana masses

$$\langle m_\nu \rangle^2 = \left(T_{1/2}^{0\nu\beta\beta} \; G^{0\nu\beta\beta}(E_0, Z) \left| M_{GT}^{0\nu\beta\beta} - \frac{g_V^2}{g_A^2} M_F^{0\nu\beta\beta} \right|^2 \right)^{-1}$$

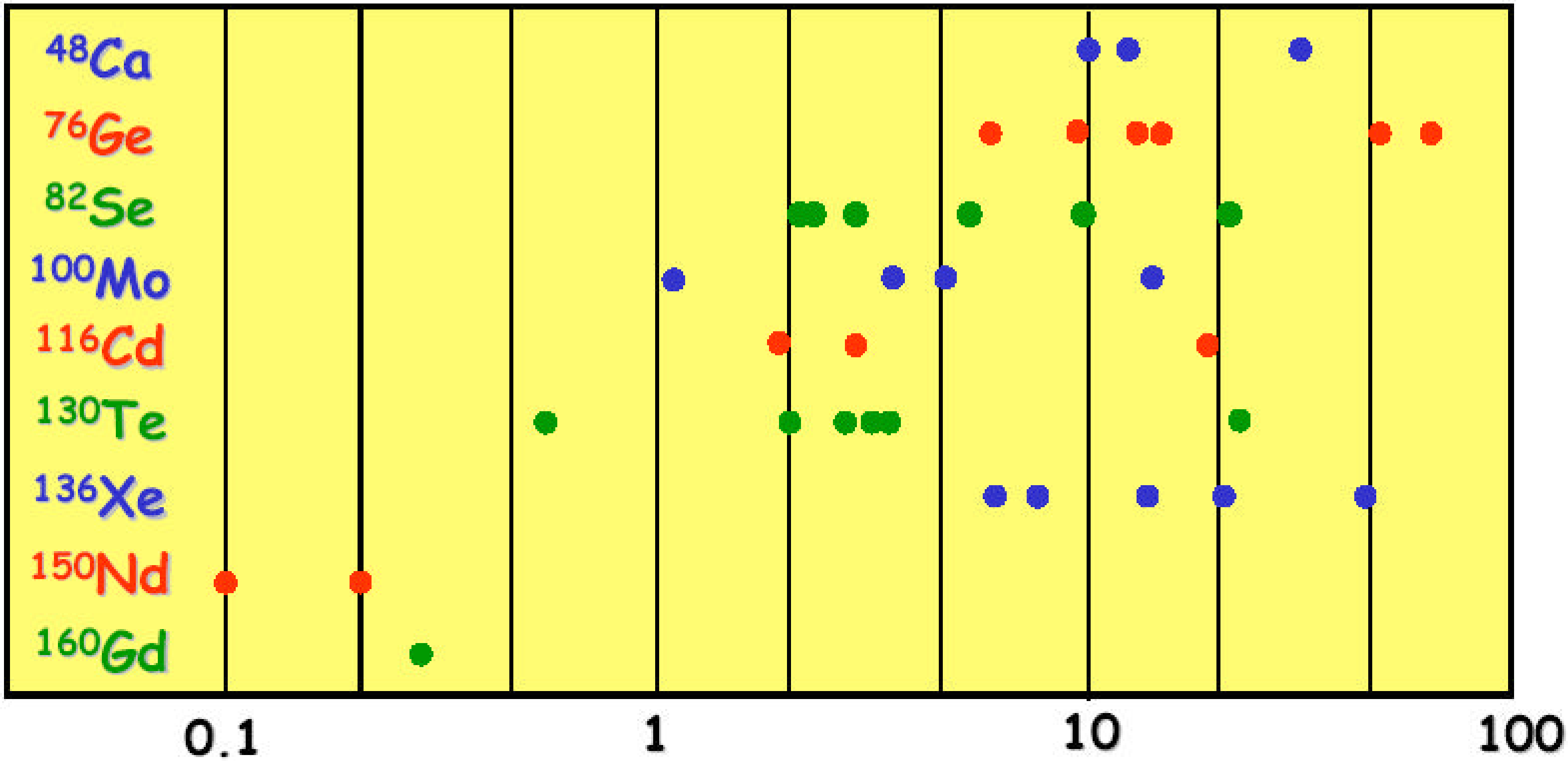
$M_F^{0\nu\beta\beta}$ and $M_{GT}^{0\nu\beta\beta}$	can be calculated within particular nuclear models
$G^{0\nu\beta\beta}$	a known phasespace factor
$T_{1/2}^{0\nu\beta\beta}$	is the quantity to be measured

$$\langle m_\nu \rangle = \left| \sum_{i=1}^{3} U_{e,i}^2 m_i \; \varepsilon_i \right|$$

effective Majorana ν mass
($\varepsilon_i = \pm 1$ if CP is conserved)

Cancellations are possible...

0νββ decay half lives in 10^{26} yr units for $\langle m_\nu \rangle$ = 50 meV according to different nuclear matrix element calculations



[adapted from S.R.Elliott & P.Vogel Ann. Rev. Nucl. Part. Sci. 52 (2002) 115]

Unfortunately it is not trivial to use the 2ν matrix element to normalize the 0ν one:

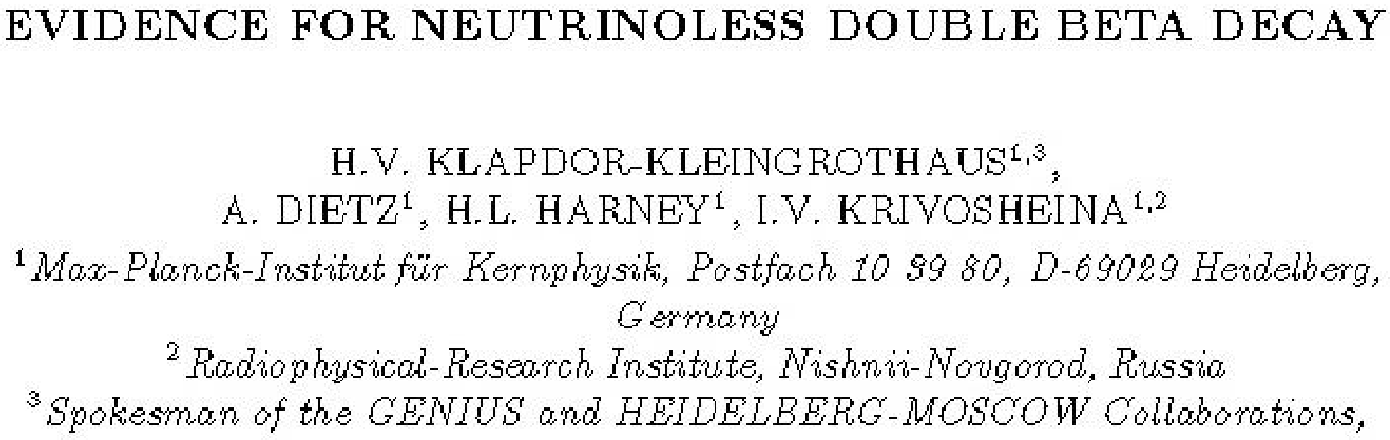
- $|M_{2\nu}|$ - has stronger dependence on intermediate states
- $|M_{0\nu}|$ - all multipoles contribute
  - ν propagator results in long range potential

Present Limits for 0ν double beta decay

Candidate nucleus	Detector type	(kg yr)	Present $T_{1/2}^{0\nu\beta\beta}$ (yr)	<m> (eV)
^{48}Ca			$>9.5*10^{21}$ (76%CL)	
^{76}Ge	Ge diode	~30	$>1.9*10^{25}$ (90%CL)	$<0.39^{+0.17}_{-0.28}$
^{82}Se			$>9.5*10^{21}$ (90%CL)	
^{100}Mo			$>5.5*10^{22}$ (90%CL)	
^{116}Cd			$>7.0*10^{22}$ (90%CL)	
^{128}Te	TeO$_2$ cryo	~3	$>1.1*10^{23}$ (90%CL)	
^{130}Te	TeO$_2$ cryo	~3	$>2.1*10^{23}$ (90%CL)	$<1.1 - 2.6$
^{136}Xe	Xe scint	~10	$>1.2*10^{24}$ (90%CL)	<2.9
^{150}Nd			$>1.2*10^{21}$ (90%CL)	
^{160}Gd			$>1.3*10^{21}$ (90%CL)	

Adapted from the Particle Data Group 2003

Has $0\nu\beta\beta$ decay been already discovered ??



EVIDENCE FOR NEUTRINOLESS DOUBLE BETA DECAY

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A. DIETZ[1], H.L. HARNEY[1], I.V. KRIVOSHEINA[1,2]

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[3] *Spokesman of the GENIUS and HEIDELBERG-MOSCOW Collaborations,*

(Part of the Heidelberg-Moscow collaboration)

Mod. Phys Lett. A27 (2001) 2409

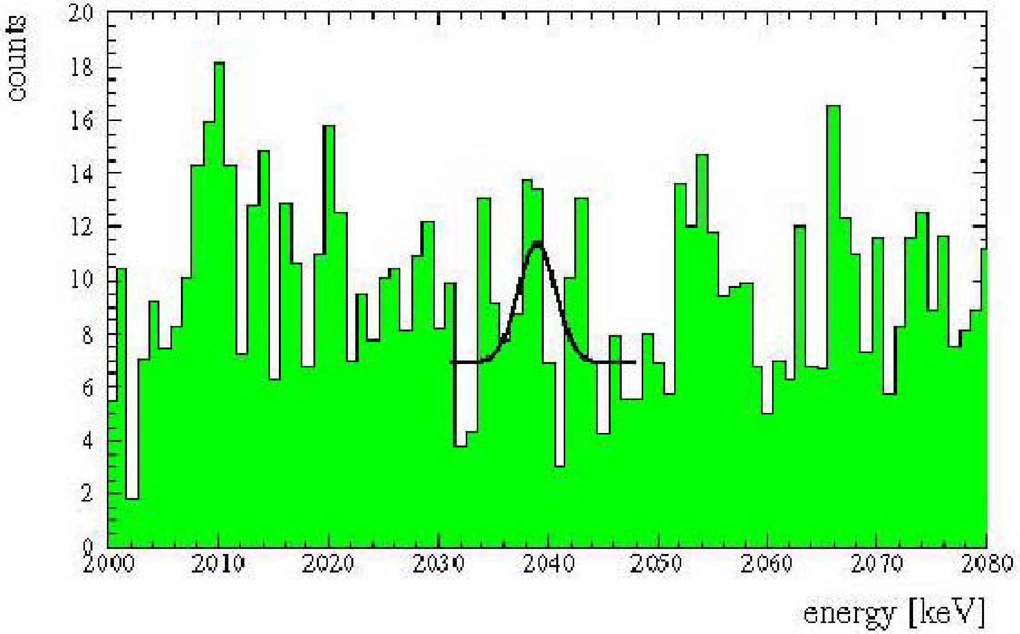
...most likely not

...see details in

C.A.Aalseth Mod. Phys. Lett. A17 (2002) 1475
F.Feruglio et al. Nucl.Phys. B637 (2002) 345-377
Addendum-ibid. B659 (2003) 359-362
Yu.Zdesenko et al. Phys.Lett. B 546 (2002) 206
H.L.Harney Mod.Phys.Lett. A16 (2001) 2409
H.V.Klapdor-Kleingrouthaus hep-ph/0205228
A.M.Bakalyarov et al. ("Moscow" of Heidelberg-Moscow) to appear in proceedings of NANP 2003, June 2003, Dubna, Russia

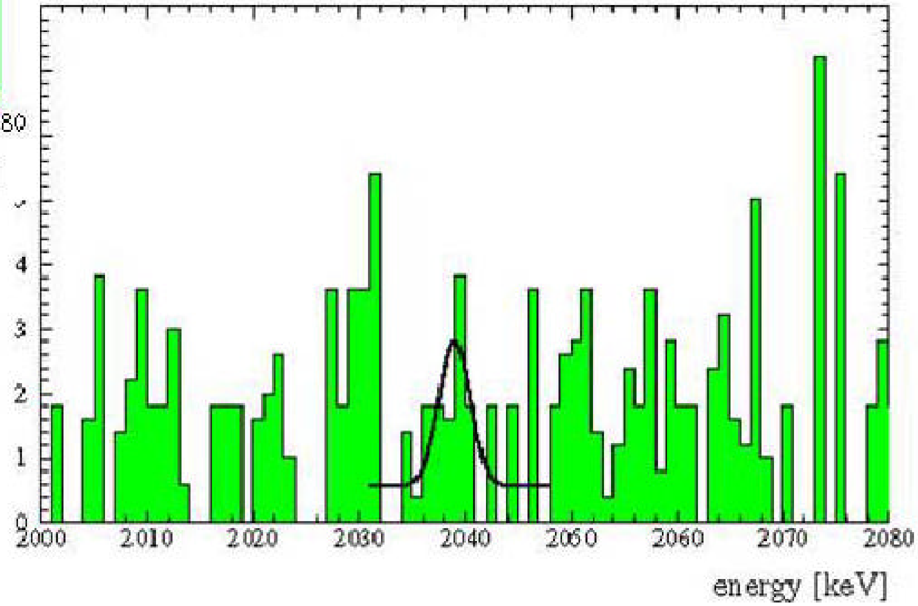
Paper's bottom line is $T_{1/2}$ = [0.8 - 18.3] · 10^{25} yr at 95% CL
best value is $T_{1/2}$ = 1.5 · 10^{25} yr corresponding to 0.39 eV

Allegedly this is a 2 to 3 sigma effect depending on the analysis



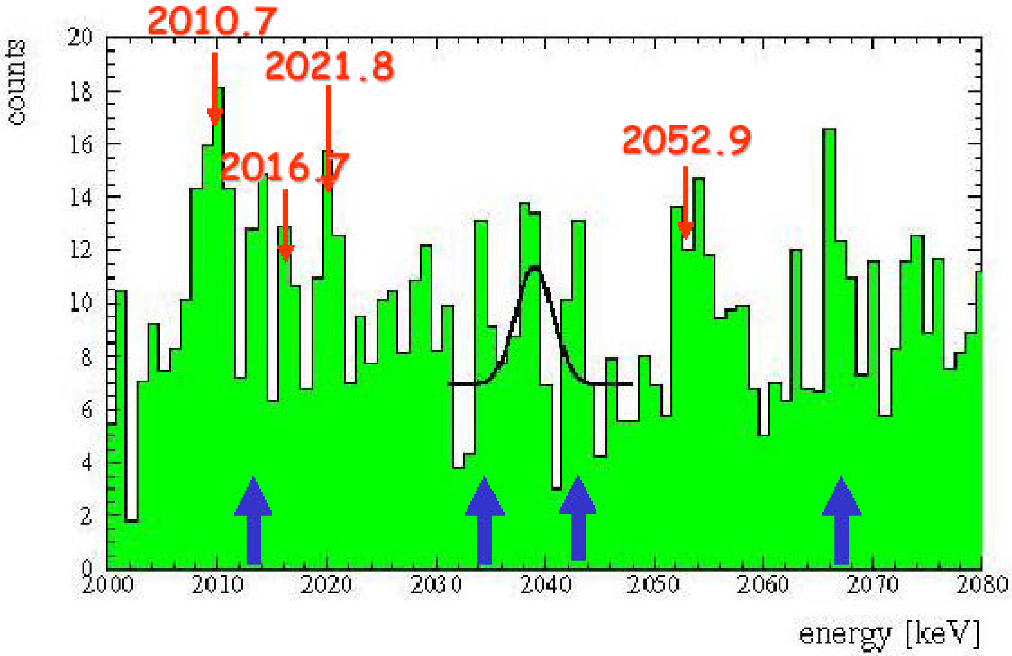
"Evidence" from the search of a peak in the energy spectrum observed in a set of low activity Ge detectors inside the Gran Sasso Lab.

Spectrum can be somewhat cleaned-up by applying pulseshape discrimination to remove γ ray events …still lots of peaks besides the 2039 keV



The fit to the "signal" peak at 2039.006 keV is done *AFTER* the subtraction of 4 peaks that are claimed to be *UNDERSTOOD* background from *IDENTIFIED* lines of ^{214}Bi

Without this subtraction the significance of the 2039 peak is even less than 2 sigma, as it is evident by just staring at the spectrum



But then, what about the other peaks !
There are more that are
not understood !

Note that the data used is the same that was earlier interpreted as an upper limit
$T_{1/2} > 1.9 \cdot 10^{25}$ eV at 90% CL

"The claim of discovery…is considered critically and firm conclusion about, at least, prematurely of such claim is derived on the basis of simple statistical analysis…"

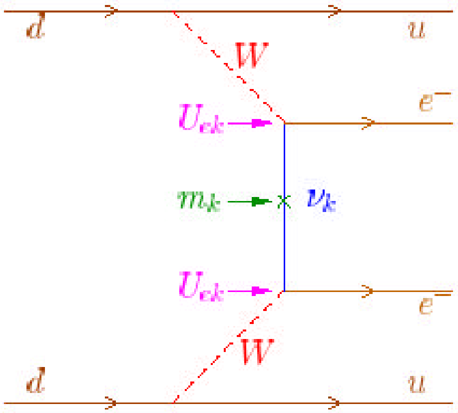
Yu.Zdesenko et al. Phys Lett B546 (2002) 206

A (probably incomplete) list of the different ideas discussed by various groups

Experiment	Nucleus	Detector	$T^{0\nu}$ (y)	$< m_\nu >$ eV
CUORE	^{130}Te	.77 t of TeO_2 bolometers (nat)	7×10^{26}	.014-.091
EXO	^{136}Xe	10 t Xe TPC + Ba tagging	1×10^{28}	.013-.037
GENIUS	^{76}Ge	1 t Ge diodes in LN	1×10^{28}	.013-.050
Majorana	^{76}Ge	1 t Ge diodes	4×10^{27}	.021-.070
MOON	^{100}Mo	34 t nat.Mo sheets/plastic sc.	1×10^{27}	.014-.057
DCBA	^{150}Nd	20 kg Nd-tracking	2×10^{25}	.035-.055
CAMEO	^{116}Cd	1 t $CdWO_4$ in liquid scintillator	$> 10^{26}$	.053-.24
COBRA	^{116}Cd, ^{130}Te	10 kg of CdTe semiconductors	1×10^{24}	.5-2.
Candles	^{48}Ca	Tons of CaF_2 in liq. scint.	1×10^{26}	.15-.26
GSO	^{116}Cd	2 t Gd_2SiO_5:Ce scint in liq scint	2×10^{26}	.038-.172
Xmass	^{136}Xe	1 t of liquid Xe	3×10^{26}	.086-.252

Note that the sensitivity numbers are somewhat arbitrary, as they depend on the author's guesstimate of the background levels they will achieve

MAJORANA NEUTRINOS? $\Longleftrightarrow$ $\beta\beta_{0\nu}$ decay



$$\mathcal{N}(A,Z) \to \mathcal{N}(A,Z+2) + e^- + e^-$$

effective Majorana mass $$|\langle m \rangle| = \left| \sum_k U_{ek}^2 m_k \right|$$

complex U_{ek} $\Rightarrow$ possible cancellations among m_1, m_2, m_3 contributions

$$|\langle m \rangle| = \left| |U_{e1}|^2 m_1 + |U_{e2}|^2 e^{i\alpha_{21}} m_2 + |U_{e3}|^2 e^{i\alpha_{31}} m_3 \right|$$

conserved CP

$\alpha_{21} = 0, \pi$ $\quad$ $\alpha_{31} = 0, \pi$

$\eta_{kj} = e^{i\alpha_{kj}}$ relative CP parity

Heidelberg-Moscow (^{76}Ge) $|\langle m \rangle|_{\text{exp}} < 0.35\,\text{eV}$ (90% C.L.) [EPJA 12 (2001) 147]

IGEX (^{76}Ge) $|\langle m \rangle|_{\text{exp}} < 0.33 - 1.35\,\text{eV}$ (90% C.L.) [PRD 65 (2002) 092007]

catch: about factor 3 theoretical uncertainty on nuclear matrix element!

Neutrino Oscillations Implications for $\beta\beta_{0\nu}$ decay

$$|\langle m\rangle| = \left||U_{e1}|^2 m_1 + |U_{e2}|^2 e^{i\alpha_{21}} m_2 + |U_{e3}|^2 e^{i\alpha_{31}} m_3\right|$$

mass hierarchy without fine-tuned cancellations among m_1, m_2, m_3 contributions

[Giunti, PRD 61 (2000) 036002]

$$|\langle m\rangle| \simeq \max_k |\langle m\rangle|_k \qquad |\langle m\rangle|_k \equiv |U_{ek}|^2 m_k$$

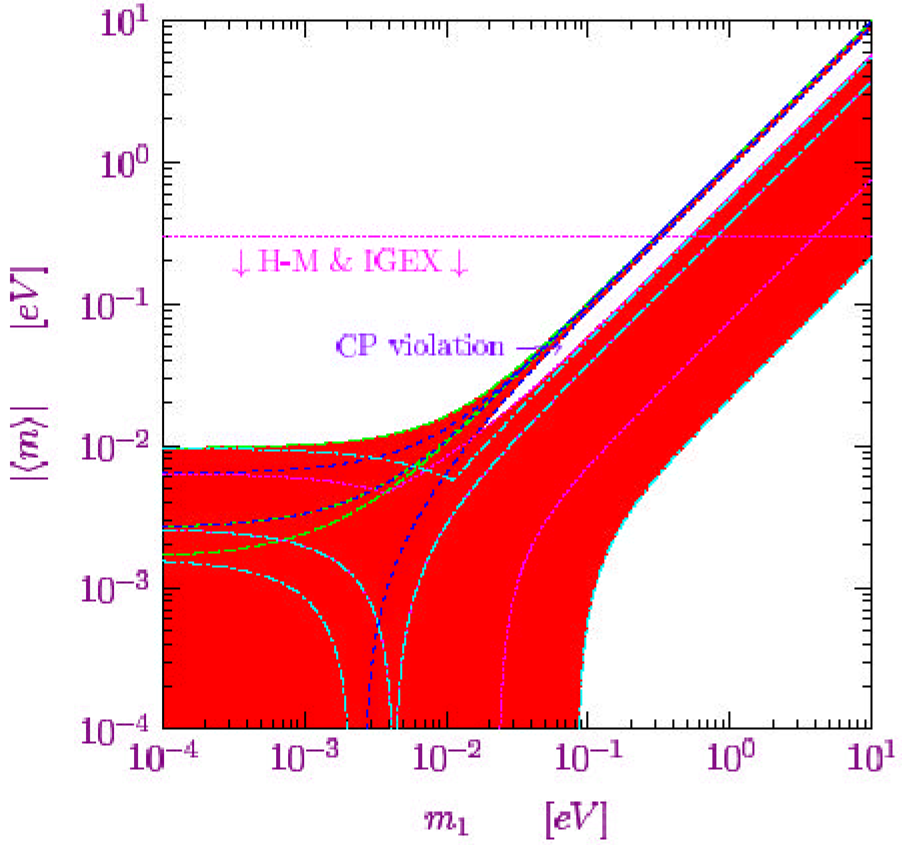
$$|U_{e2}|^2 \simeq \sin^2\vartheta_{\text{SUN}},\; m_2 \simeq \sqrt{\Delta m^2_{\text{SUN}}} \qquad |U_{e3}|^2 \simeq \sin^2\vartheta_{\text{CHOOZ}},\; m_3 \simeq \sqrt{\Delta m^2_{\text{ATM}}}$$

$$\left.\begin{array}{c} \Delta m^{2\,\text{best-fit}}_{\text{SUN}} = 6.9\times10^{-5}, \quad |U_{e2}|_{\text{best-fit}} = 0.56 \\ 5.1\times10^{-5} \lesssim \Delta m^2_{\text{SUN}} \lesssim 1.9\times10^{-4} \\ 0.46 \lesssim |U_{e2}| \lesssim 0.68 \end{array}\right\} \Longrightarrow \left\{\begin{array}{c} |\langle m\rangle|_2^{\text{best-fit}} = 2.6\times10^{-3} \\ 1.5\times10^{-3} \lesssim |\langle m\rangle|_2 \lesssim 6.4\times10^{-3} \end{array}\right.$$

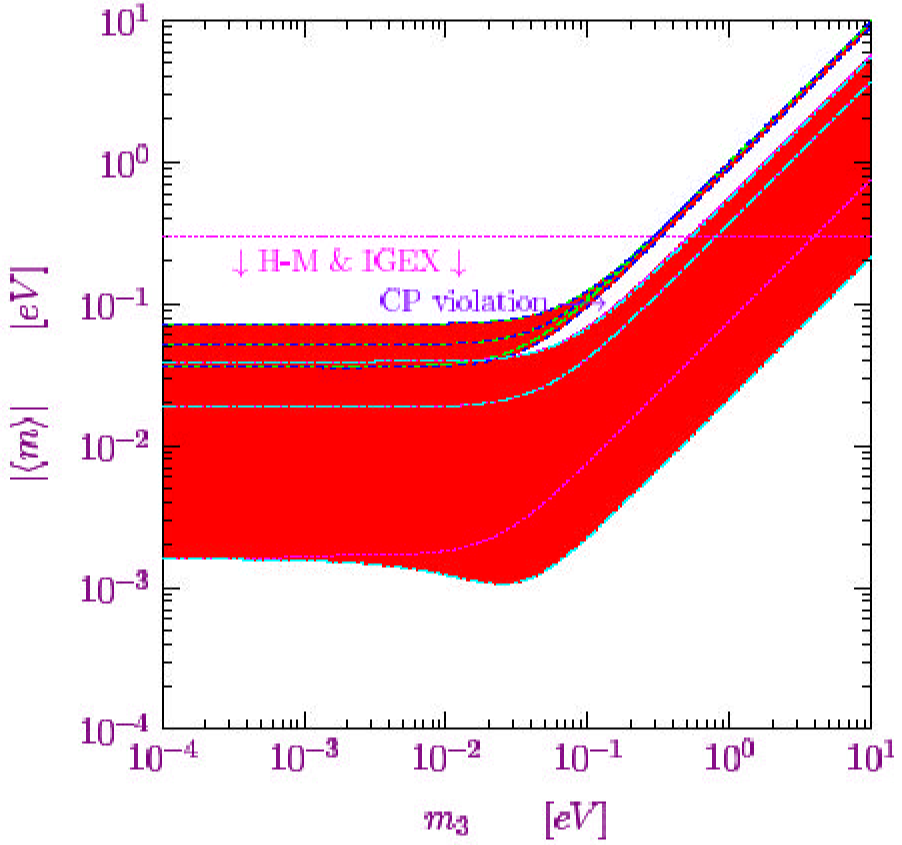
$$\left.\begin{array}{c} \Delta m^{2\,\text{best-fit}}_{\text{ATM}} = 2.6\times10^{-3}, \quad |U_{e3}|_{\text{best-fit}} = 0 \\ 1.4\times10^{-3} \lesssim \Delta m^2_{\text{ATM}} \lesssim 5.1\times10^{-3} \\ |U_{e2}| \lesssim 0.22 \end{array}\right\} \Longrightarrow \left\{\begin{array}{c} |\langle m\rangle|_3^{\text{best-fit}} = 0 \\ |\langle m\rangle|_3 \lesssim 3.5\times10^{-3} \end{array}\right.$$

m_2 contribution $|\langle m\rangle|_2$ may be dominant! (lower limit for $|\langle m\rangle|$)

General Neutrino Oscillations Bounds for $\beta\beta_{0\nu}$ decay



"normal" scheme

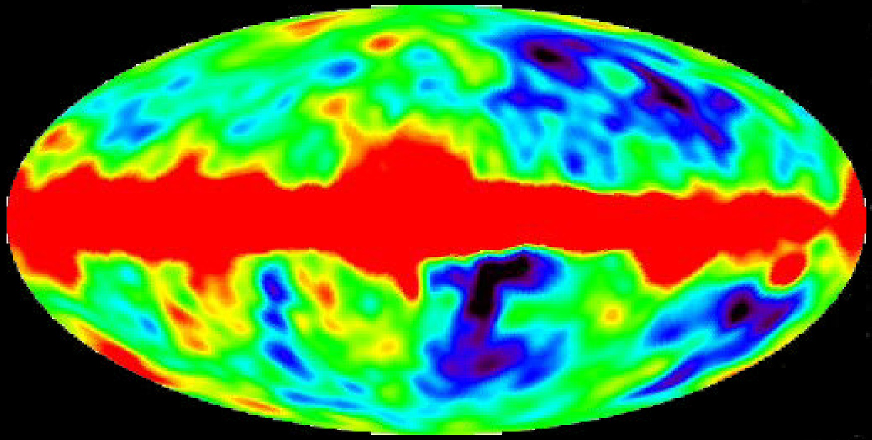


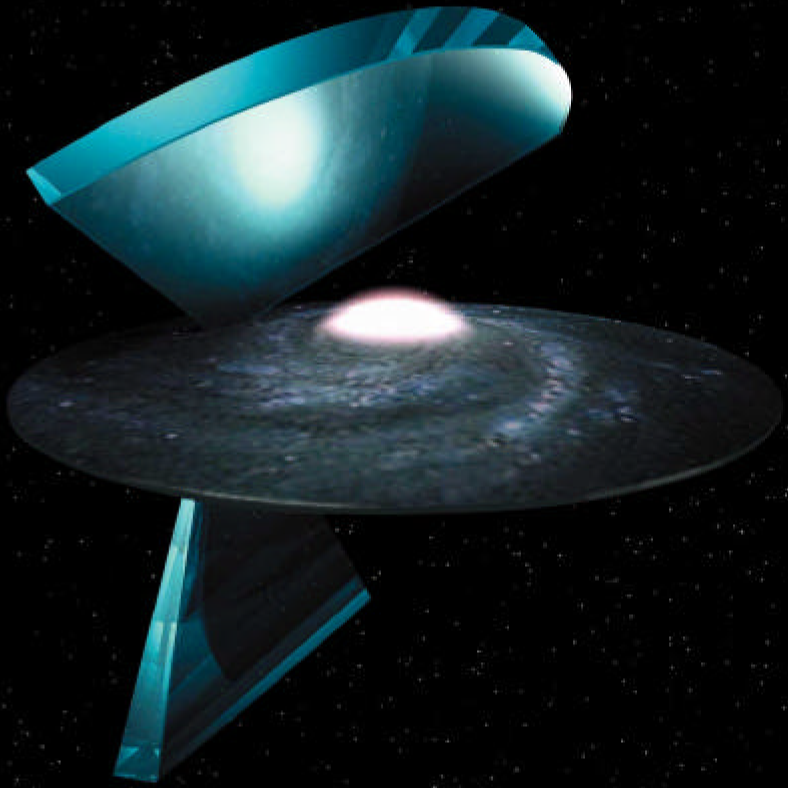
"inverted" scheme

FUTURE: NEMO3, CAMEO, Majorana, CUORICINO, XMASS ($|\langle m \rangle| \sim 10^{-1}\,\mathrm{eV}$)
GENIUS, CUORE, EXO, MOON, GEM ($|\langle m \rangle| \sim 10^{-2}\,\mathrm{eV}$)

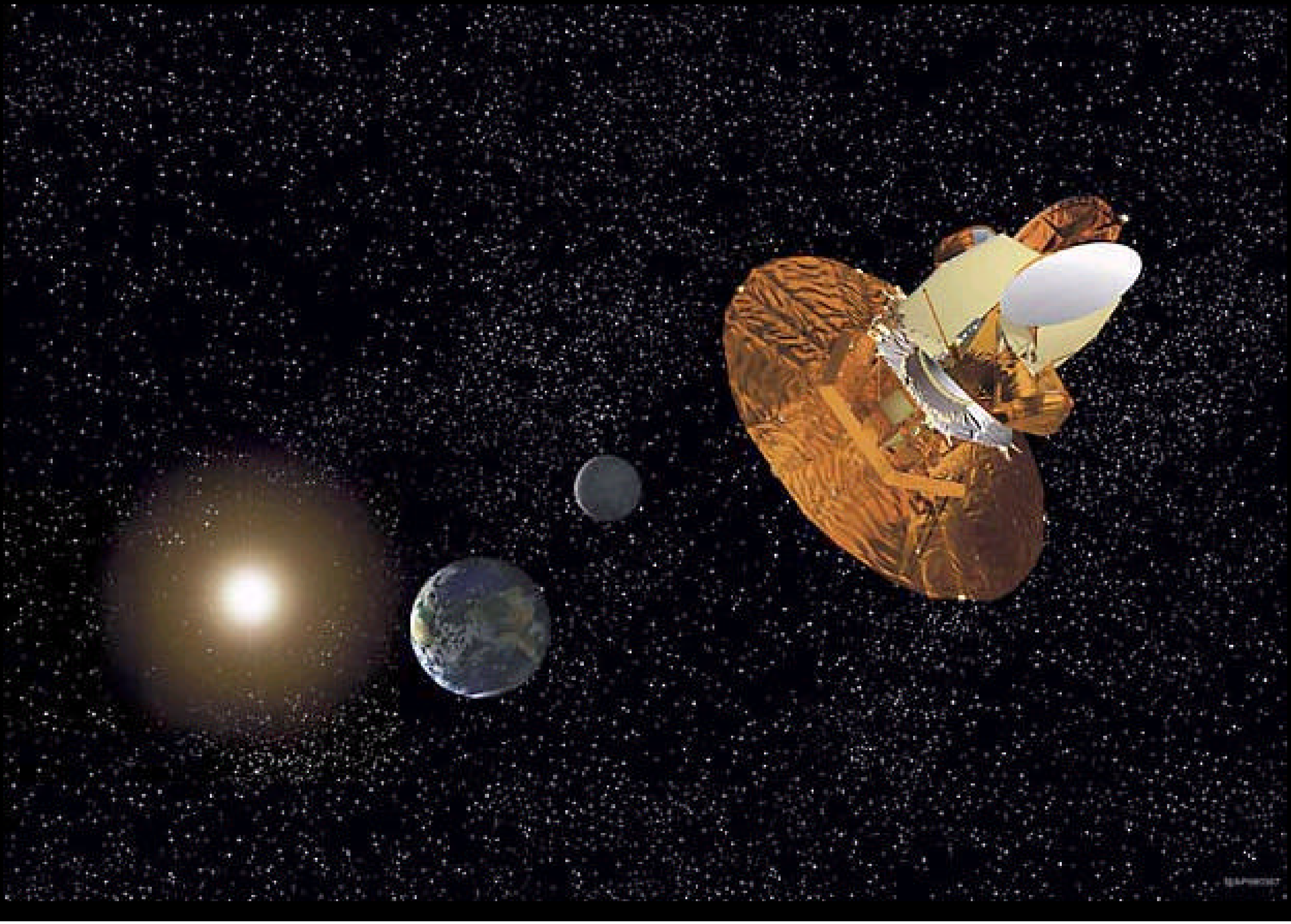
VERY FAR FUTURE: IF $|\langle m \rangle| < 10^{-3}\,\mathrm{eV} \Longrightarrow$ NORMAL HIERARCHY

NEUTRINOS, THE MICROWAVE BACKGROUND AND LARGE SCALE STRUCTURE





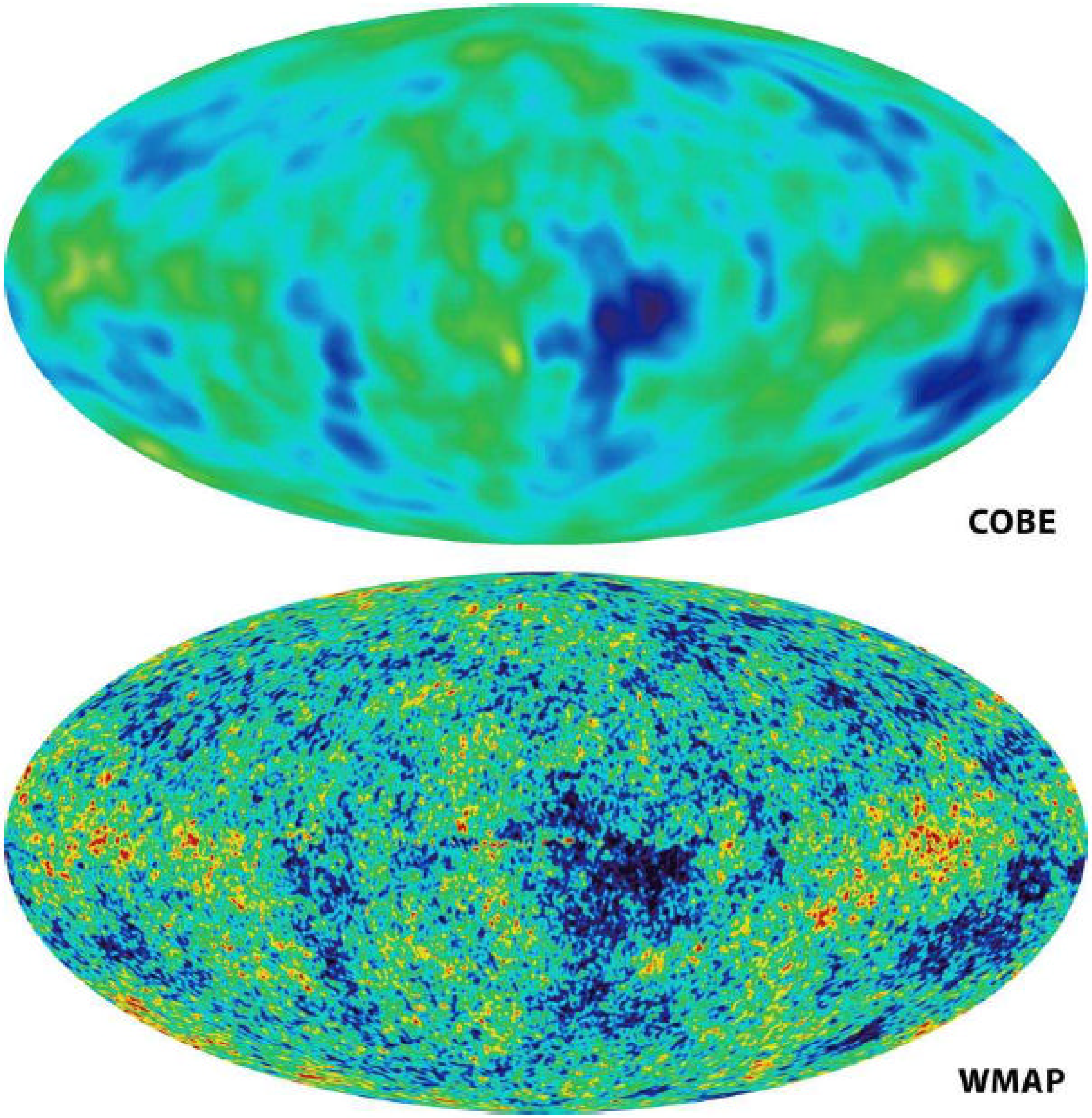
WMAP PROJECT, PUBLISHED RESULTS FEBRUARY 2003



Cosmic Microwave Background Anysotropies

- ✓ The CMB was discovered in the ’50 and it was found to follow an almost perfect black-body spectrum at T_0=2.73 K
- ✓ The homogeneity was checked at the level of 10^{-5}!
- ✓ However, the Universe is highly inhomogeneous today ⇒ in the past it should have been sufficiently inhomogeneous in the past in order that structures could grow via gravitational instability
- ✓ Therefore, density inhomogeneities should give rise to temperature inhomogeneities in the sky
- ✓ These inhomogeneities were observed at the aforementioned 10^{-5} level by COBE

Wilkinson Microwave Anisotropy Probe



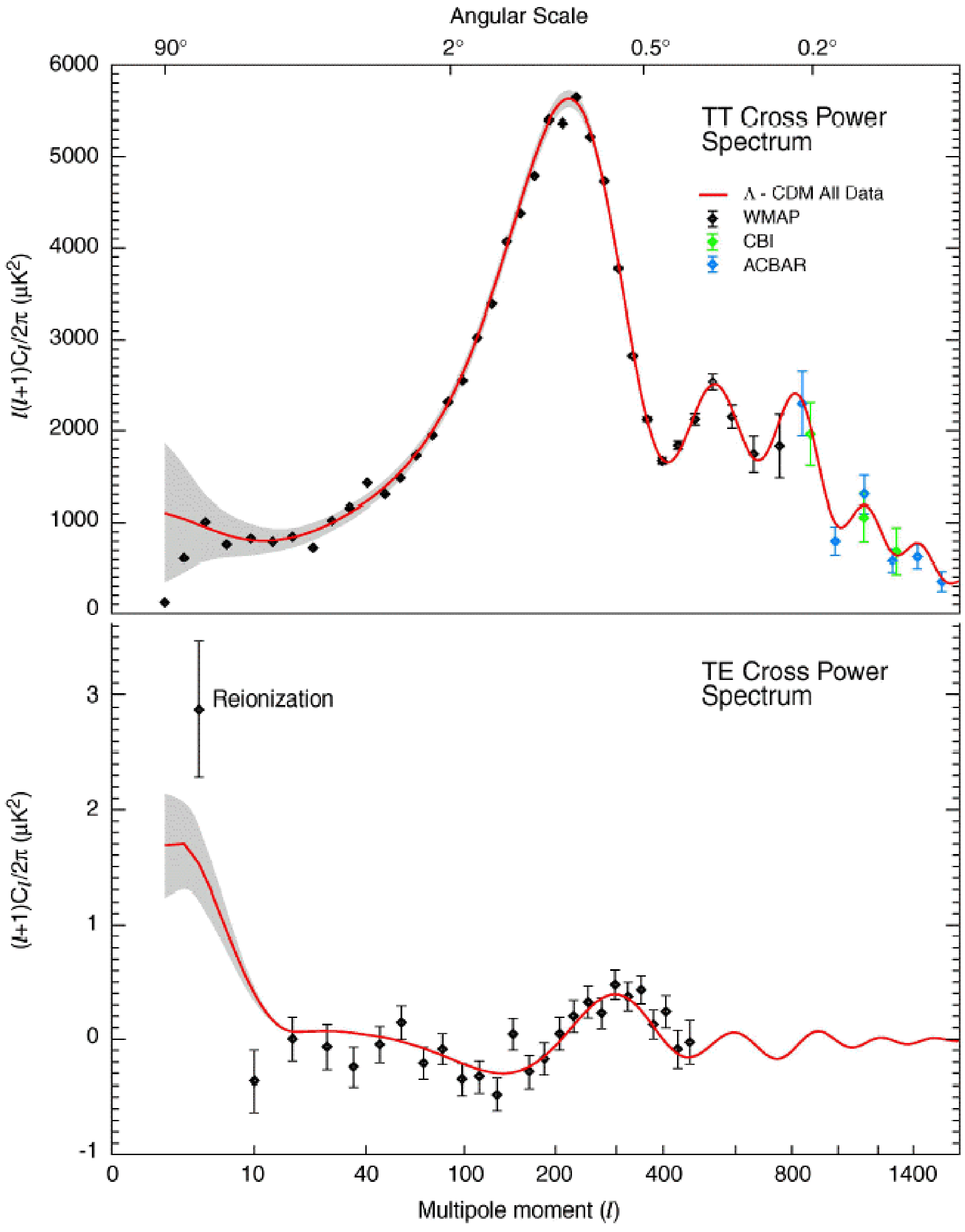
[WMAP, `http://map.gsfc.nasa.gov`]

$$\frac{\Delta T}{T} = \sum_{l \geq 2} a_{lm} Y_{lm} (J, j\ )$$

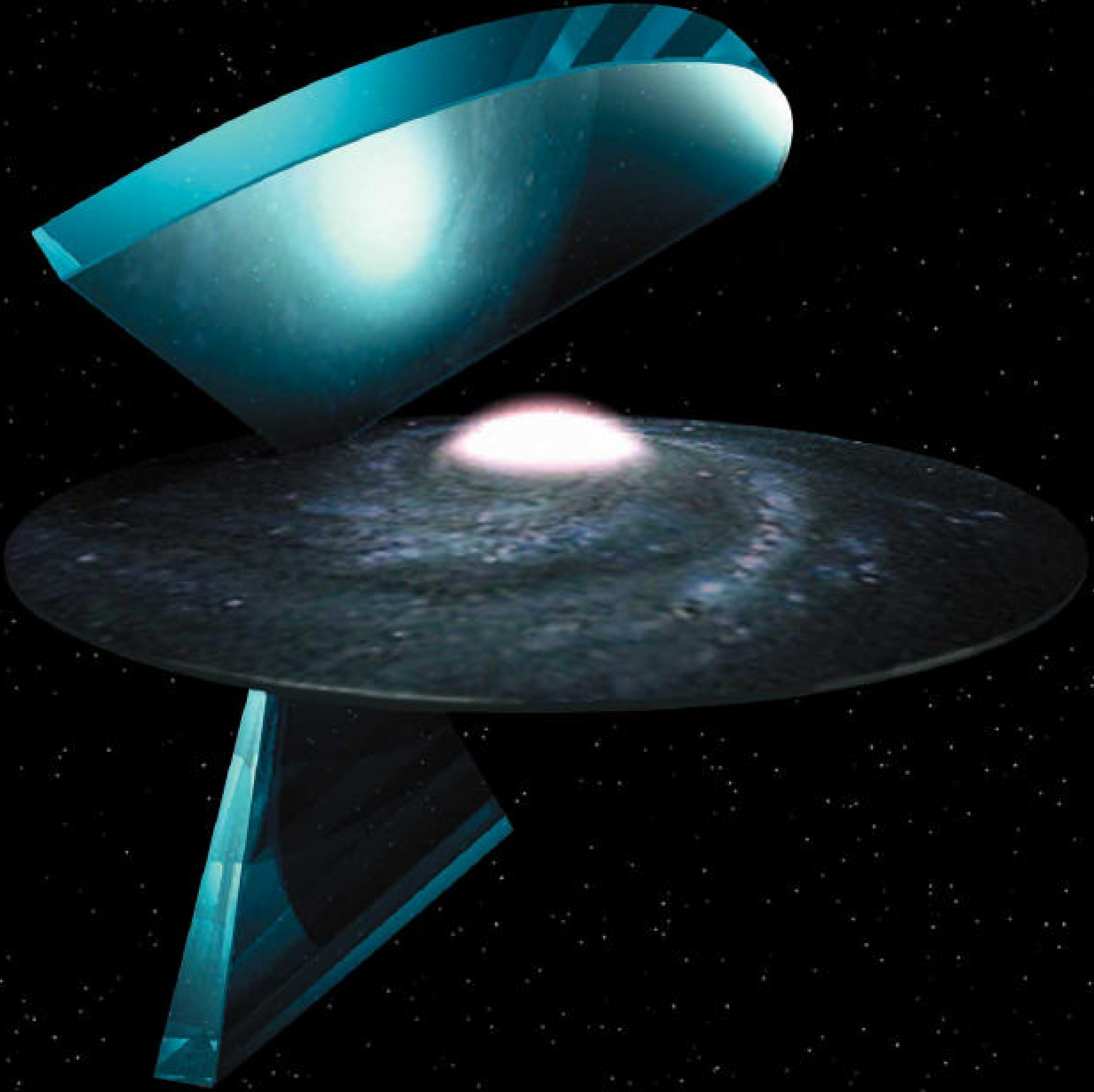
Mean $\langle a_{lm} \rangle = 0$

Variance $\langle a^{*}_{lm} a_{l'm'} \rangle = C_l d_{ll'} d_{mm'}$

C_l's form the angular power spectrum and it is convetionally used to show CMB results



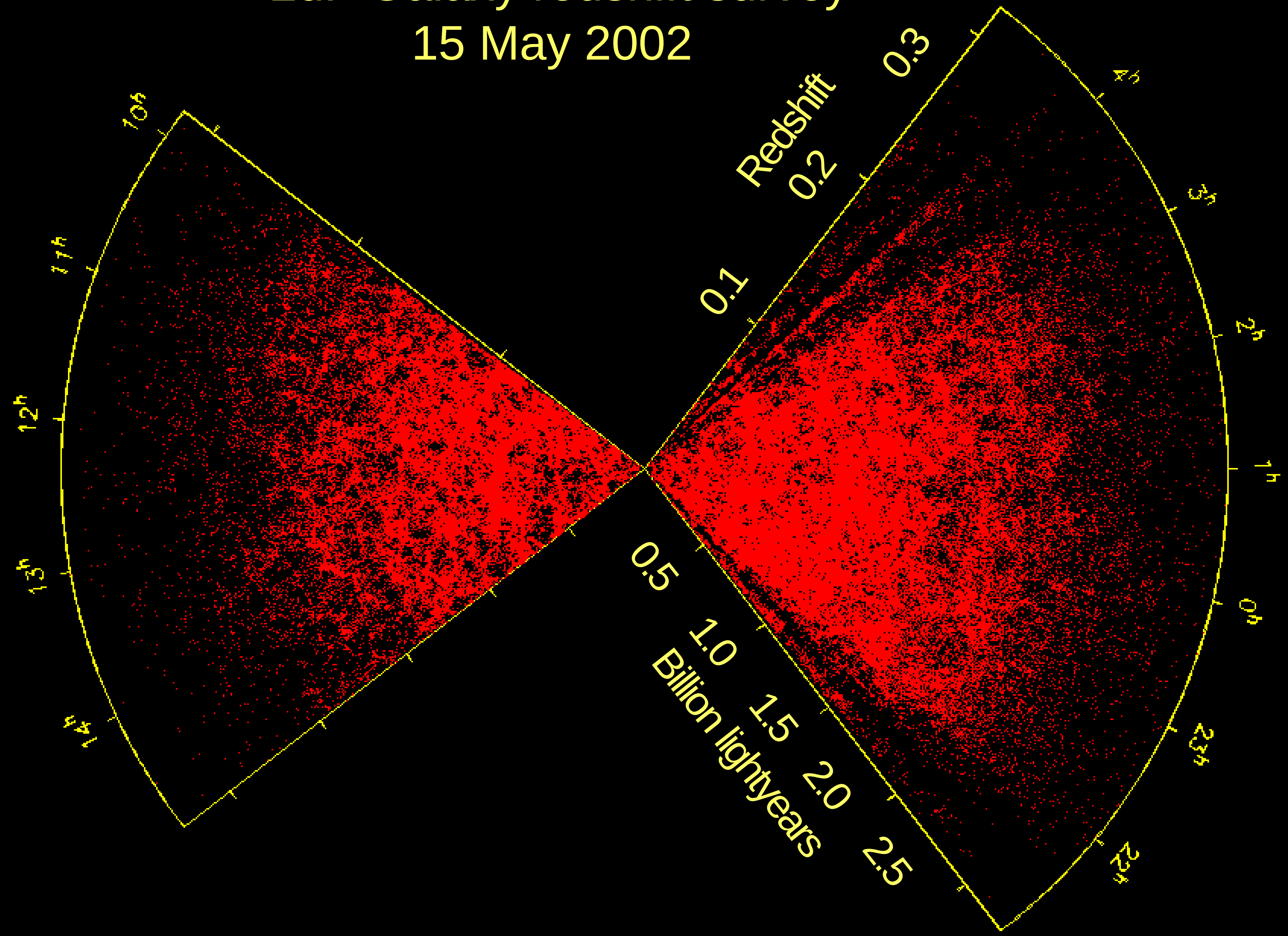
2dF SURVEY

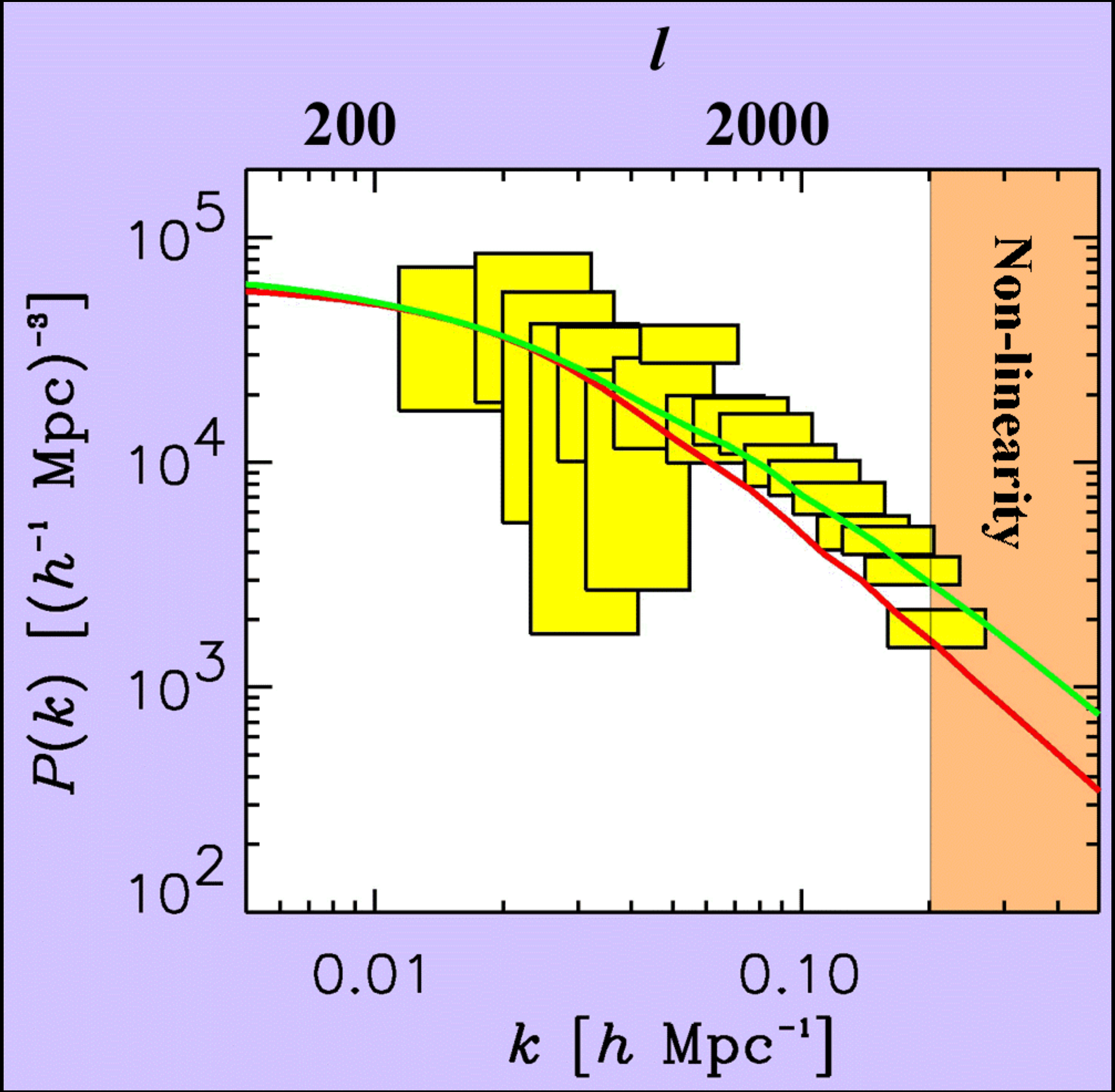


Galaxy Redshift Surveys

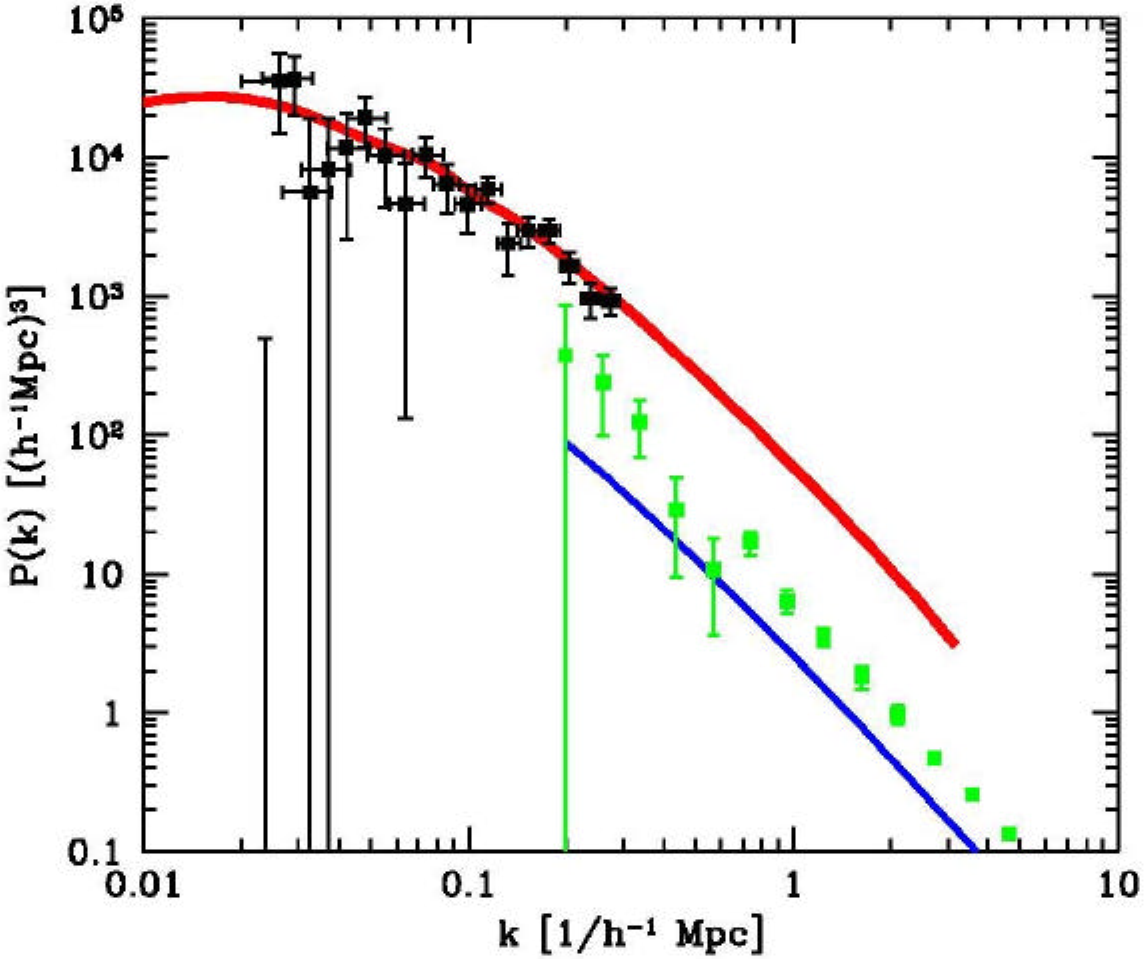
- ✓ The effect of neutrino mass on the angular power spectrum is only marginal
- ✓ However, ii can be used in combination with other astrophysical sources, where the neutrino mass plays a more relevant role, to help reduce the number of uncertainties in the various cosmological parameters
- ✓ Large Scale Structures (LSS) are one of these sources. Neutrino mass affects LSS formation and its effect can be studied via observation of the distribution of the galaxies
- ✓ Since the distribution of galaxies should trace the matter density of the Universe, large samples of galaxy redshifts in surveys such as the 2 degree Field Galaxy Redshift Survey (2dFGRS) provide a tool to study the power spectrum of matter fluctuations with very small random errors

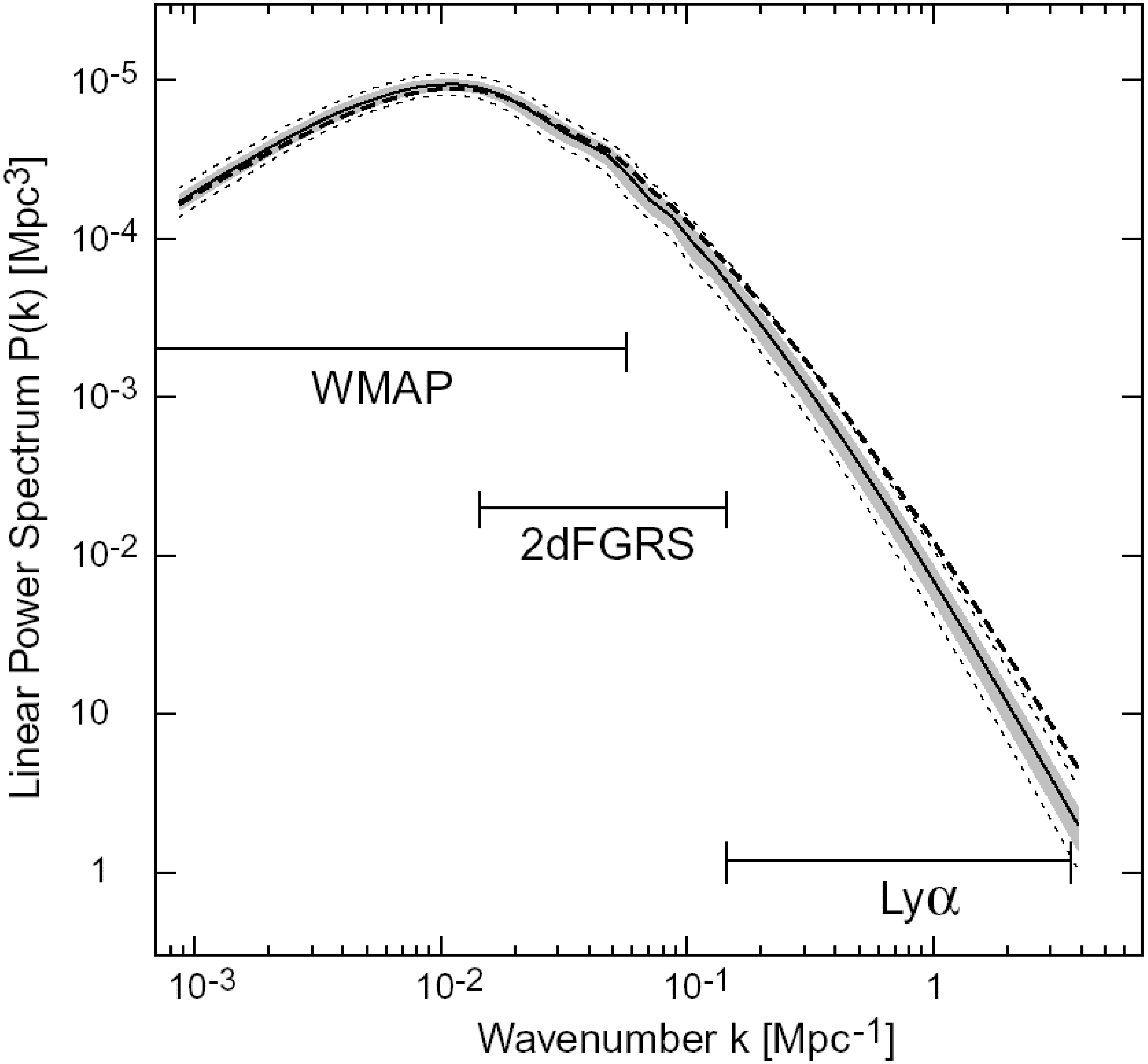
2dF Galaxy redshift survey
15 May 2002




l
200
2000
Non-linearity
10^5
10^4
10^3
10^2
$P(k)$ $[(h^{-1}\ \mathrm{Mpc})^{-3}]$
0.01
0.10
k $[h\ \mathrm{Mpc}^{-1}]$

BU

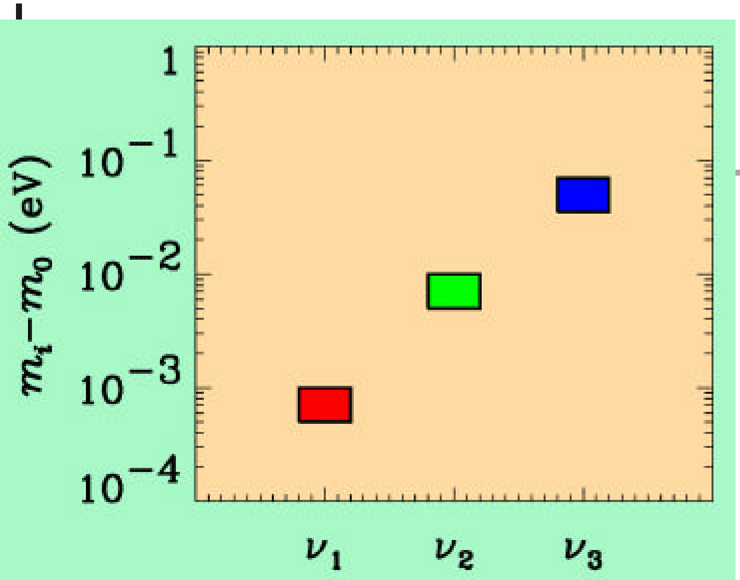


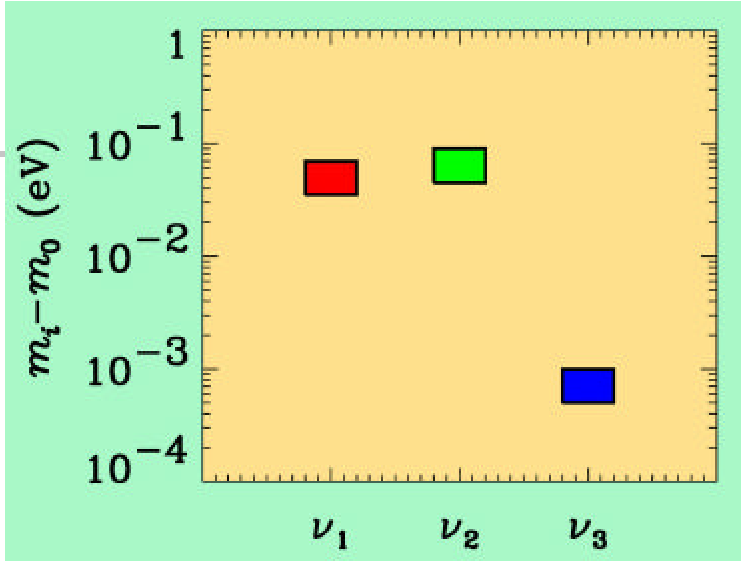

Linear Power Spectrum P(k) [Mpc^3]
10^{-5}
10^{-4}
10^{-3}
10^{-2}
10
1
WMAP
2dFGRS
Lyα
10^{-3}
10^{-2}
10^{-1}
1
Wavenumber k [Mpc^{-1}]

EXPERIMENTAL QUESTIONS FROM NEUTRINO PHYSICS

- NEUTRINO MASS HIERARCHY AND MIXING MATRIX
  - solar & atmospheric neutrinos
  - supernovae
- ABSOLUTE NEUTRINO MASSES
  - cosmology: CMB and large scale structure
  - supernovae
- STERILE NEUTRINOS (LEPTOGENESIS)
  - cosmology, supernovae
- NUMBER OF RELIC NEUTRINOS / RELATIVISTIC ENERGY
  - cosmology

If neutrino masses are hierarchical then oscillation experiments do not give information on the absolute value of neutrino masses





However, if neutrino masses are degenerate

no information can be gained from such experiments.

Experiments which rely on the kinematics of neutrino mass are the most efficient for measuring m_0

Tritium decay endpoint measurements have reached limits on the electron neutrino mass

Bonn et al. 2001 (Mainz experiment)

This translates f the three mass eigenstates

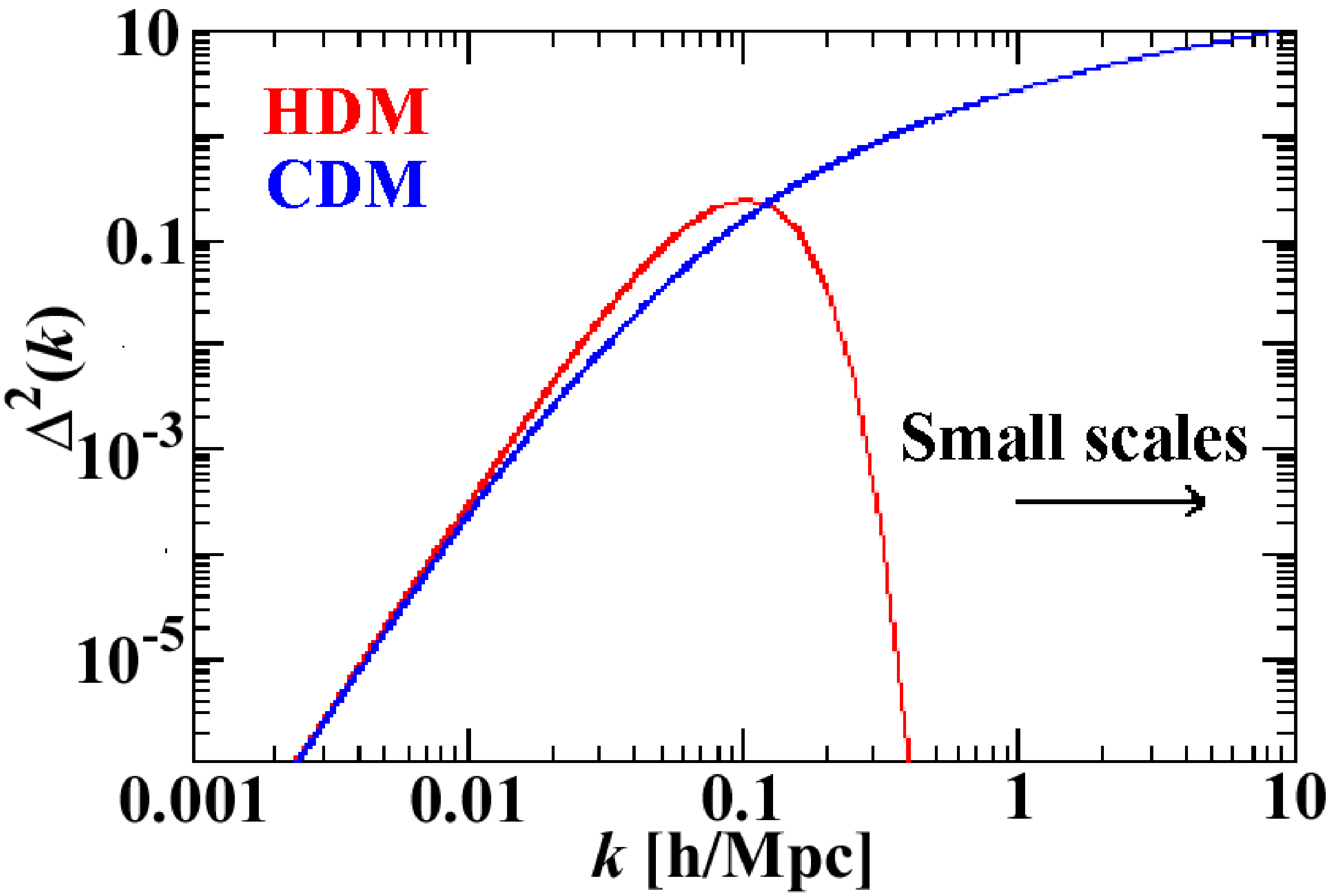
CHRISTINE KRAUS
NEXT TALK

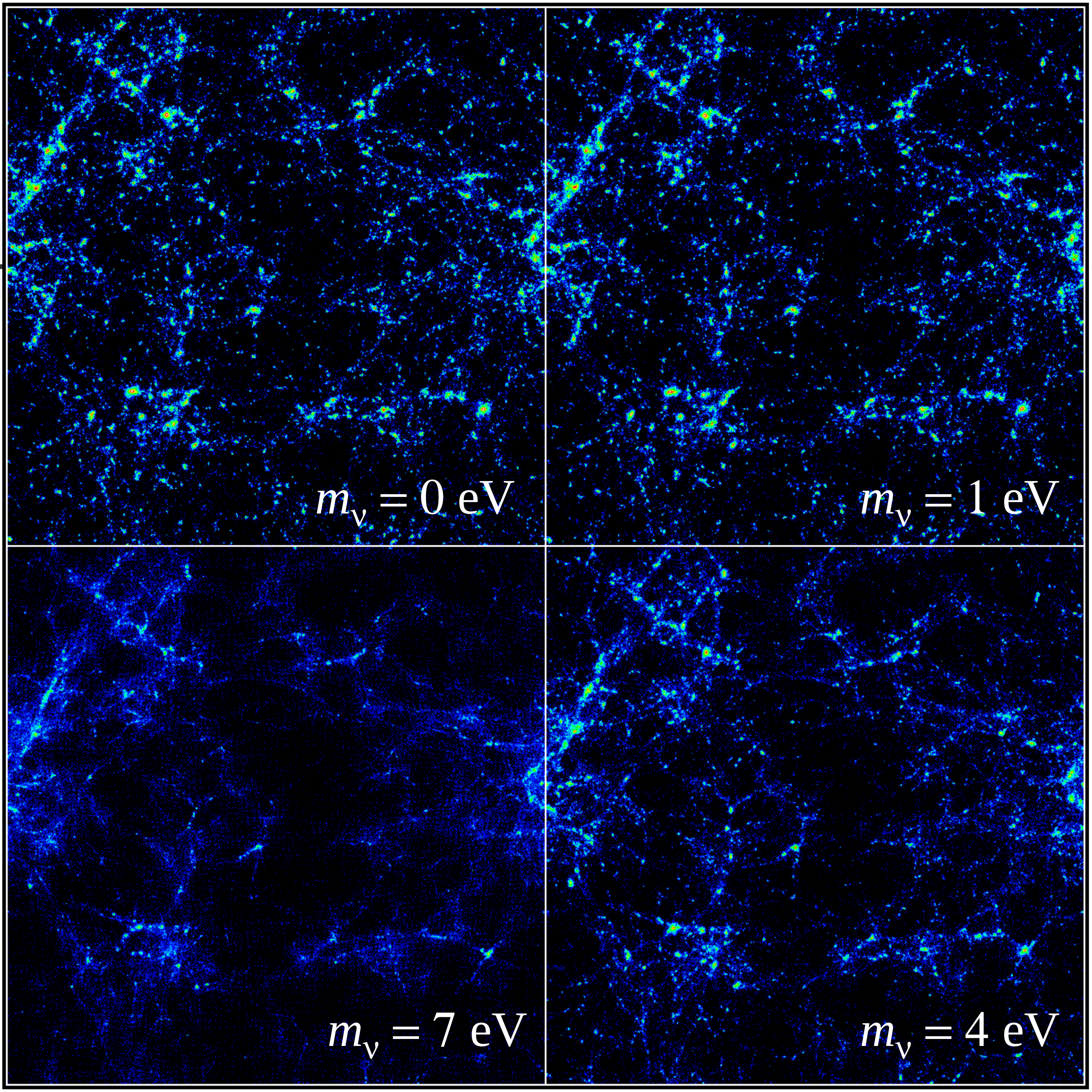
$$\sum m_i \leq 7 \text{ eV}$$

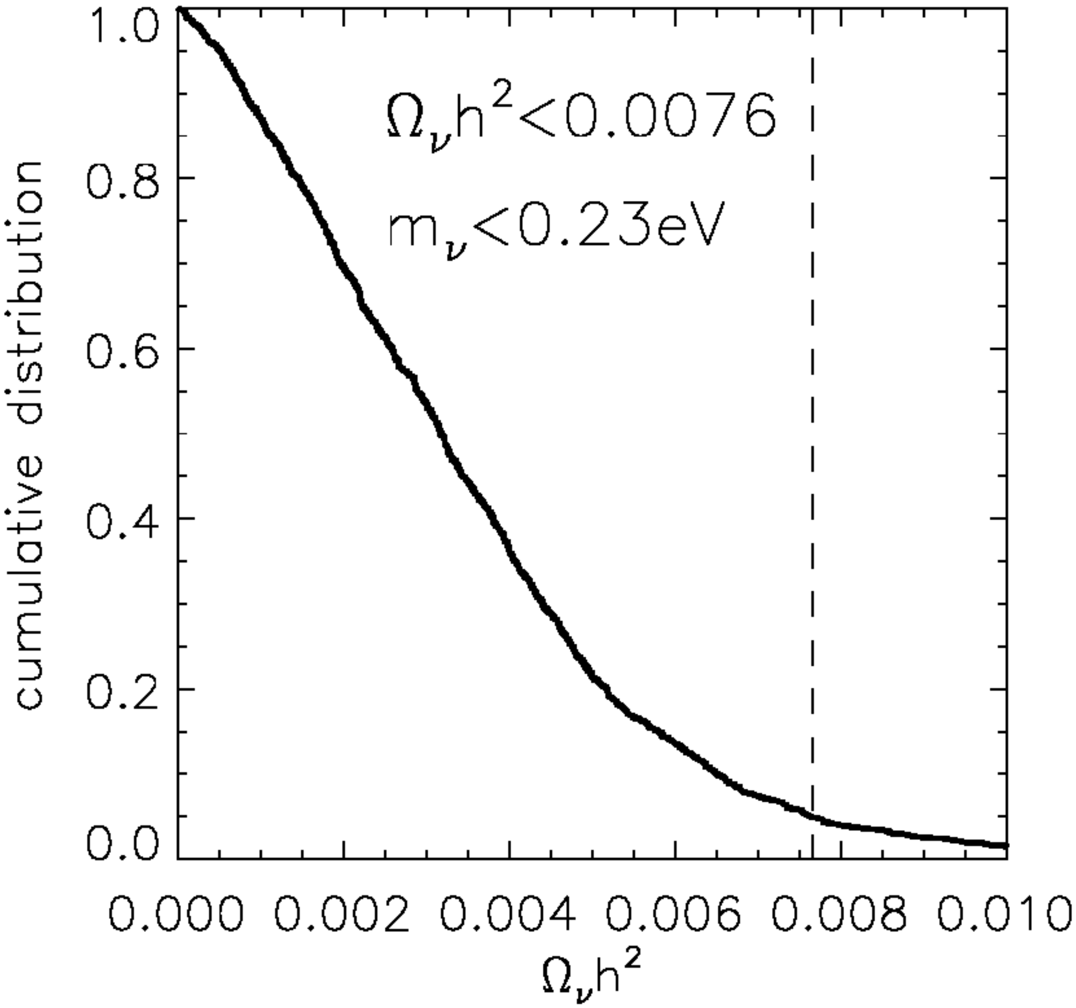
THE ABSOLUTE VALUES OF NEUTRINO MASSES FROM COSMOLOGY

$$d_{\mathrm{FS}} \sim 1200\,\mathrm{Mpc}\; m_{\mathrm{eV}}^{-1}$$

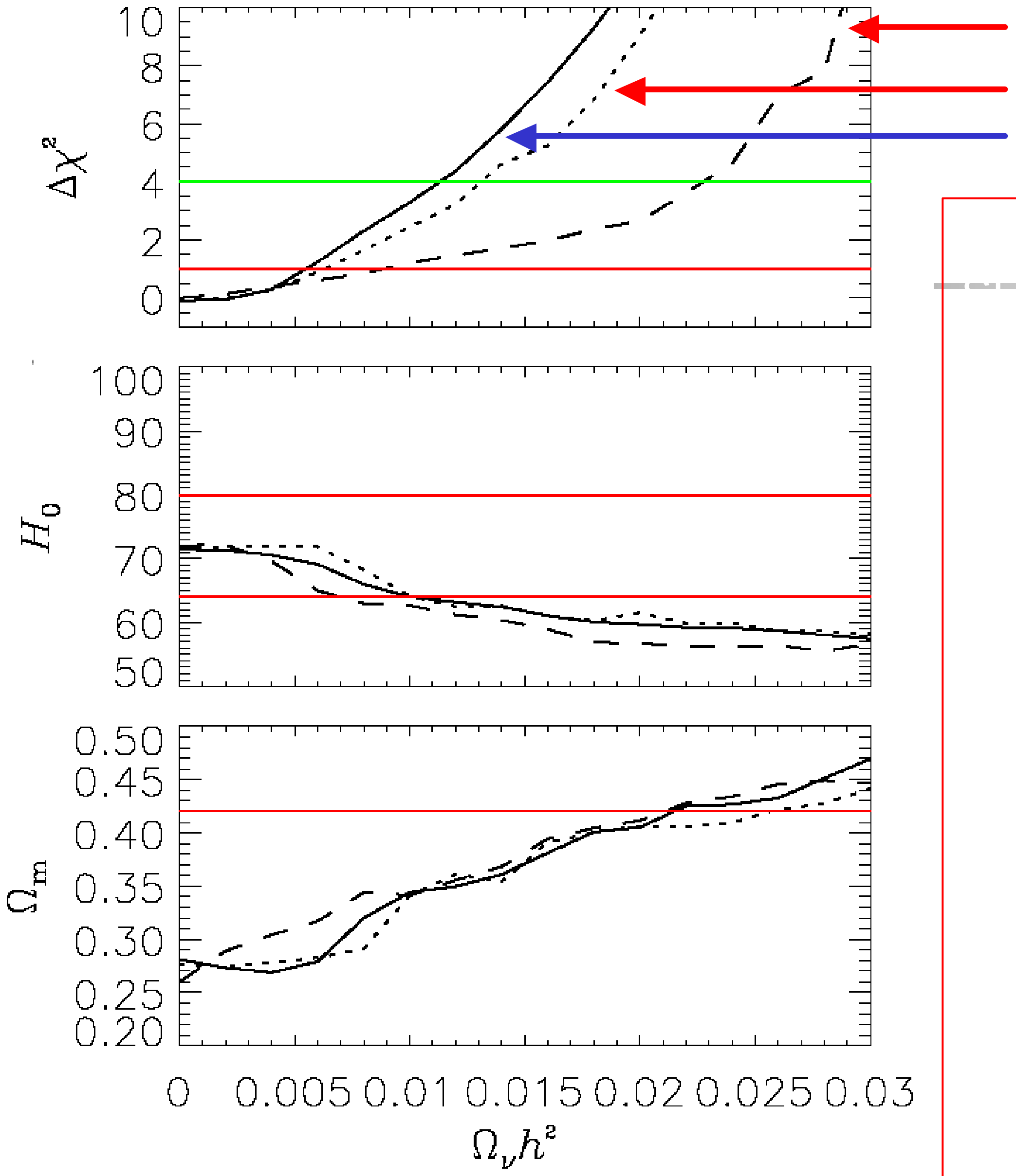
$$\frac{\Delta P}{P} \approx -8\,\frac{\Omega_n}{\Omega_m}$$


10
0.1
10^{-3}
10^{-5}
$\Delta^2(k)$
HDM
CDM
Small scales
0.001
0.01
0.1
1
10
k [h/Mpc]


$m_\nu = 0$ eV
$m_\nu = 1$ eV
$m_\nu = 7$ eV
$m_\nu = 4$ eV

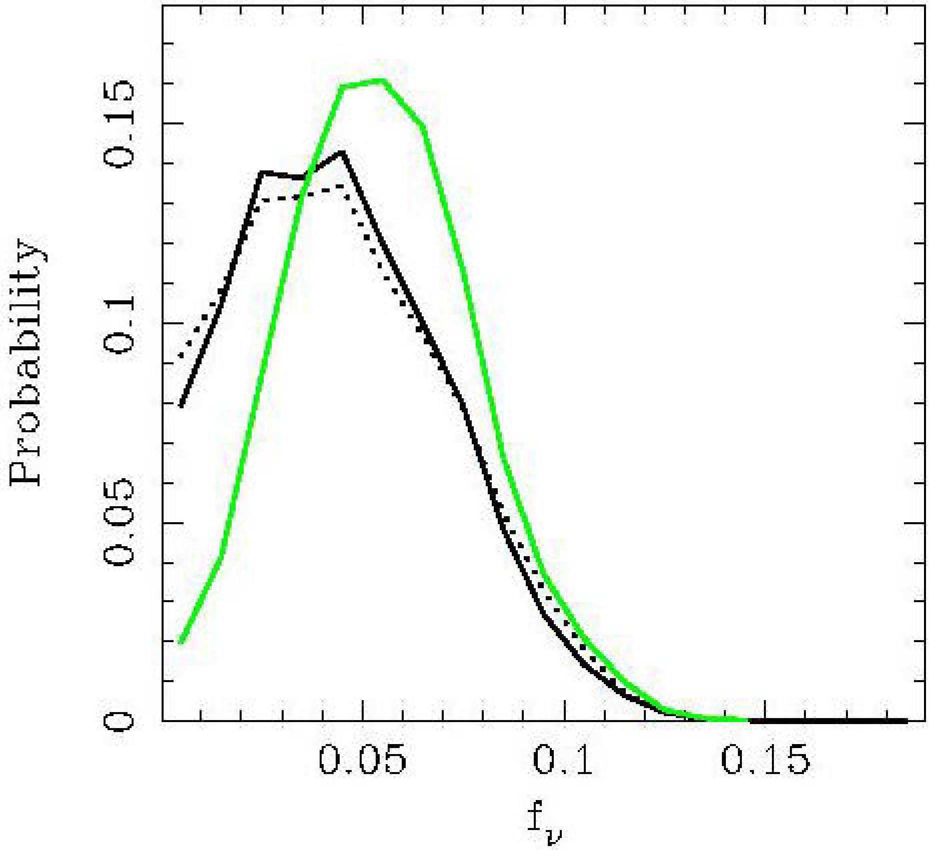


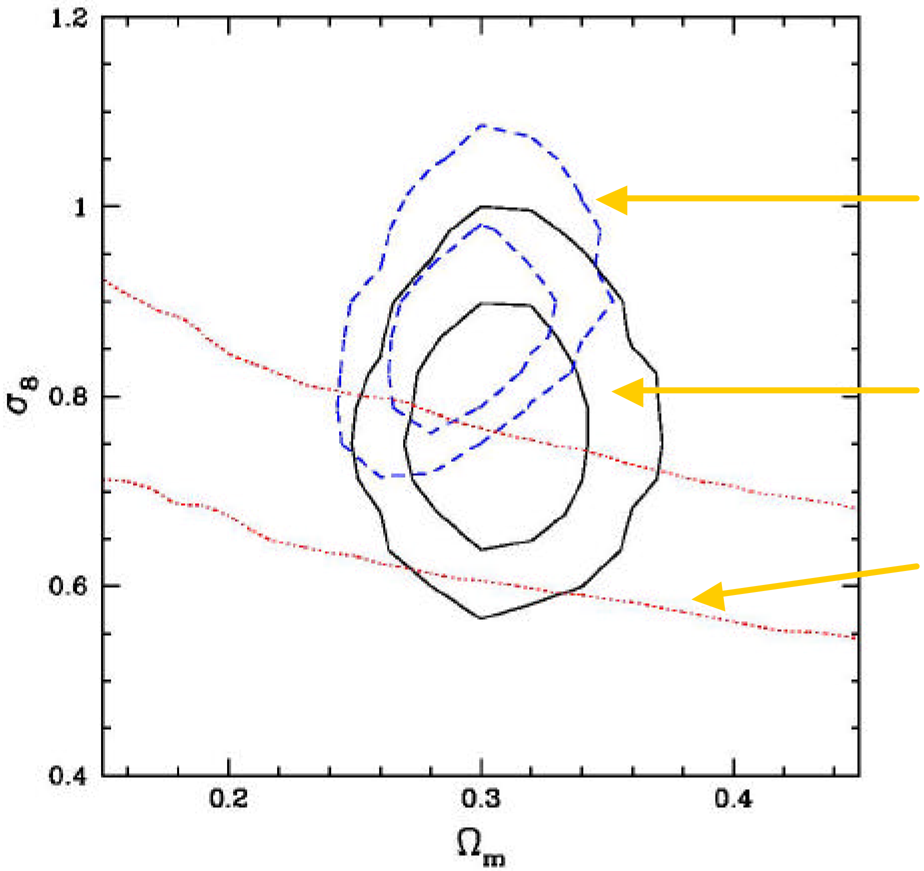
$\Omega_\nu h^2 < 0.0076$
$m_\nu < 0.23$eV
cumulative distribution
1.0
0.8
0.6
0.4
0.2
0.0
0.000
0.002
0.004
0.006
0.008
0.010
$\Omega_\nu h^2$

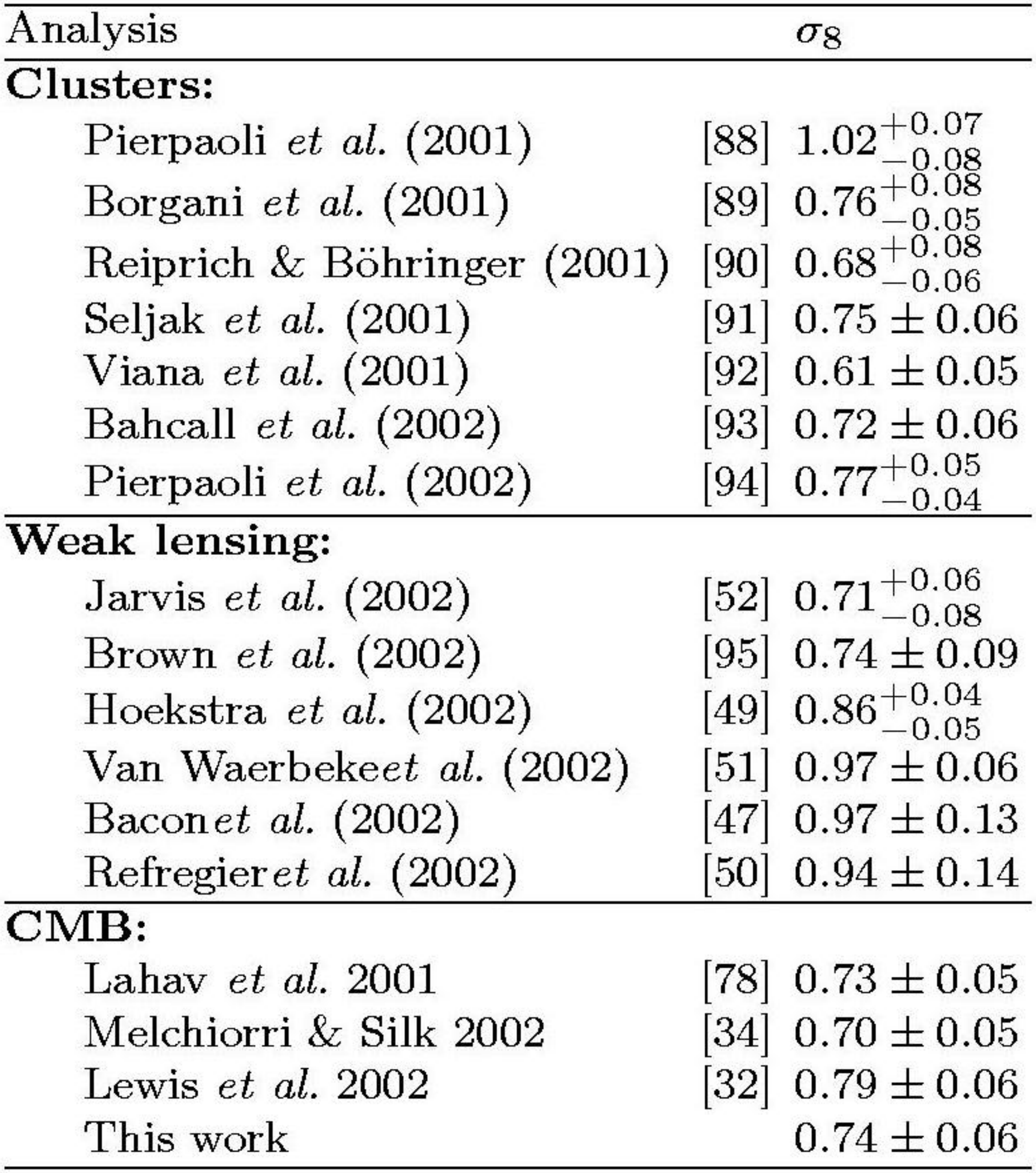

$\Delta\chi^2$
10
8
6
4
2
0
H_0
100
90
80
70
60
50
Ω_m
0.50
0.45
0.40
0.35
0.30
0.25
0.20
0
0.005
0.01
0.015
0.02
0.025
0.03
$\Omega_\nu h^2$

A RUNNING SPECTRAL INDEX CAN LOOK LIKE
A NON-ZERO NEUTRINO MASS

A MODEL WITH BROKEN SCALE-INVARIANCE CAN
ALLOW FOR A HIGH NEUTRINO MASS


Probability
0
0.05
0.1
0.15
0.05
0.1
0.15
f_ν


1.2
1
0.8
0.6
0.4
σ8
0.2
0.3
0.4
Ωm



Analysis		σ_8
Clusters:		
Pierpaoli *et al.* (2001)	[88]	$1.02^{+0.07}_{-0.08}$
Borgani *et al.* (2001)	[89]	$0.76^{+0.08}_{-0.05}$
Reiprich & Böhringer (2001)	[90]	$0.68^{+0.08}_{-0.06}$
Seljak *et al.* (2001)	[91]	0.75 ± 0.06
Viana *et al.* (2001)	[92]	0.61 ± 0.05
Bahcall *et al.* (2002)	[93]	0.72 ± 0.06
Pierpaoli *et al.* (2002)	[94]	$0.77^{+0.05}_{-0.04}$
Weak lensing:		
Jarvis *et al.* (2002)	[52]	$0.71^{+0.06}_{-0.08}$
Brown *et al.* (2002)	[95]	0.74 ± 0.09
Hoekstra *et al.* (2002)	[49]	$0.86^{+0.04}_{-0.05}$
Van Waerbeke*et al.* (2002)	[51]	0.97 ± 0.06
Bacon*et al.* (2002)	[47]	0.97 ± 0.13
Refregier*et al.* (2002)	[50]	0.94 ± 0.14
CMB:		
Lahav *et al.* 2001	[78]	0.73 ± 0.05
Melchiorri & Silk 2002	[34]	0.70 ± 0.05
Lewis *et al.* 2002	[32]	0.79 ± 0.06
This work		0.74 ± 0.06

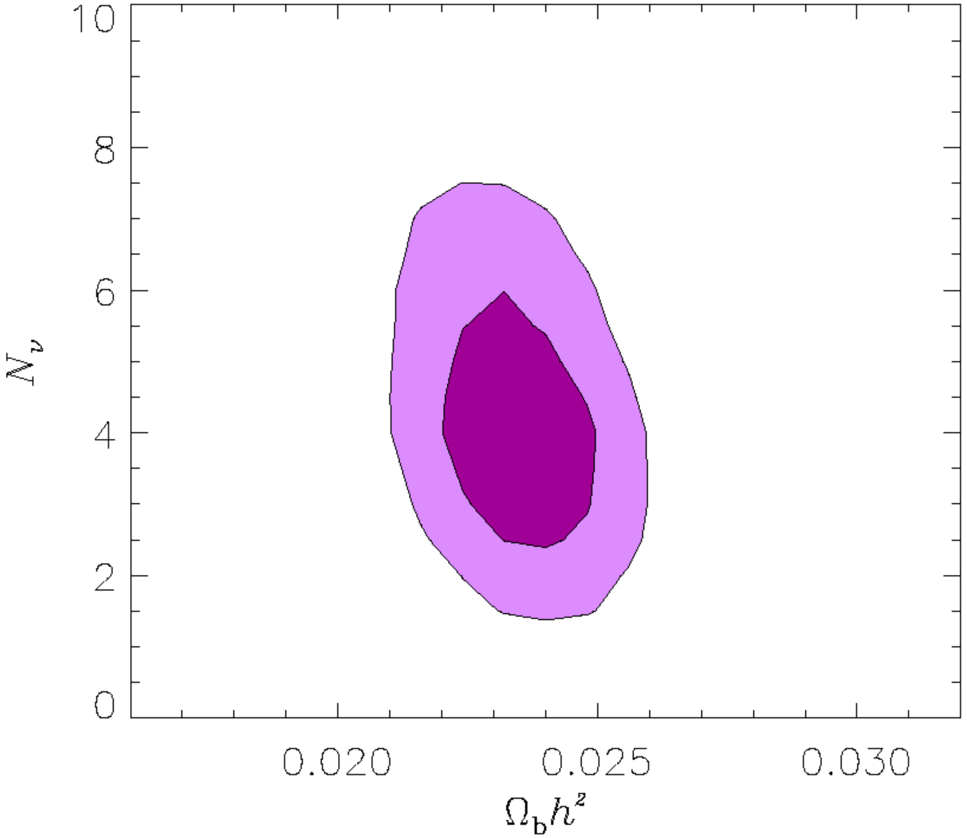
EXPERIMENTAL QUESTIONS FROM NEUTRINO PHYSICS

- NE

- cosmology: CMB and large scale structure

- cosmology

- NUMBER OF RELIC NEUTRINOS / RELATIVISTIC ENERGY
  - cosmology



STH, PRL 85, 4203 (2000)
Crotty et al. PRD 67, 123005 (2003)
Pierpaoli MNRAS 342, L63 (2003)
Barger et al., PLB 566, 8 (2003)

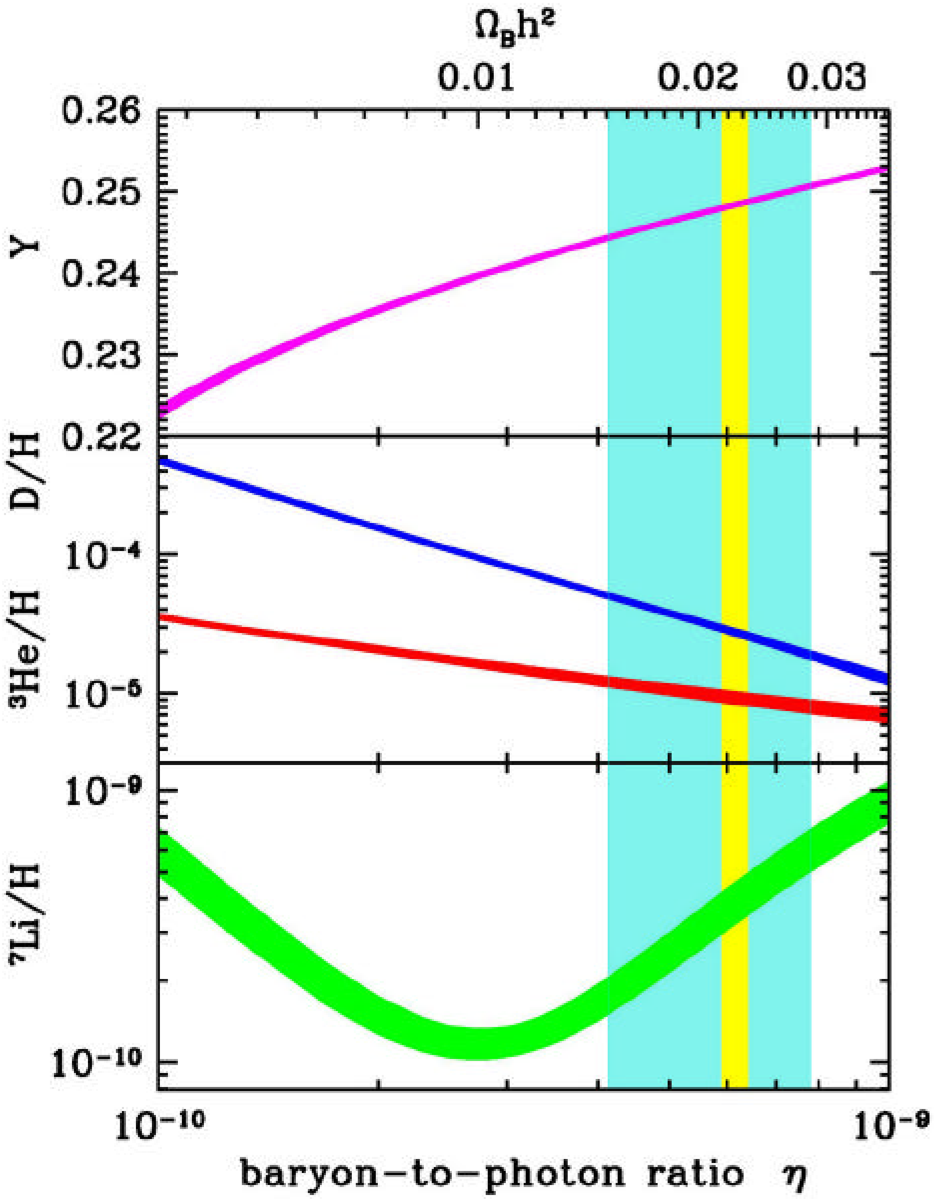
STH 2003 (JCAP 5, 004 (2003))

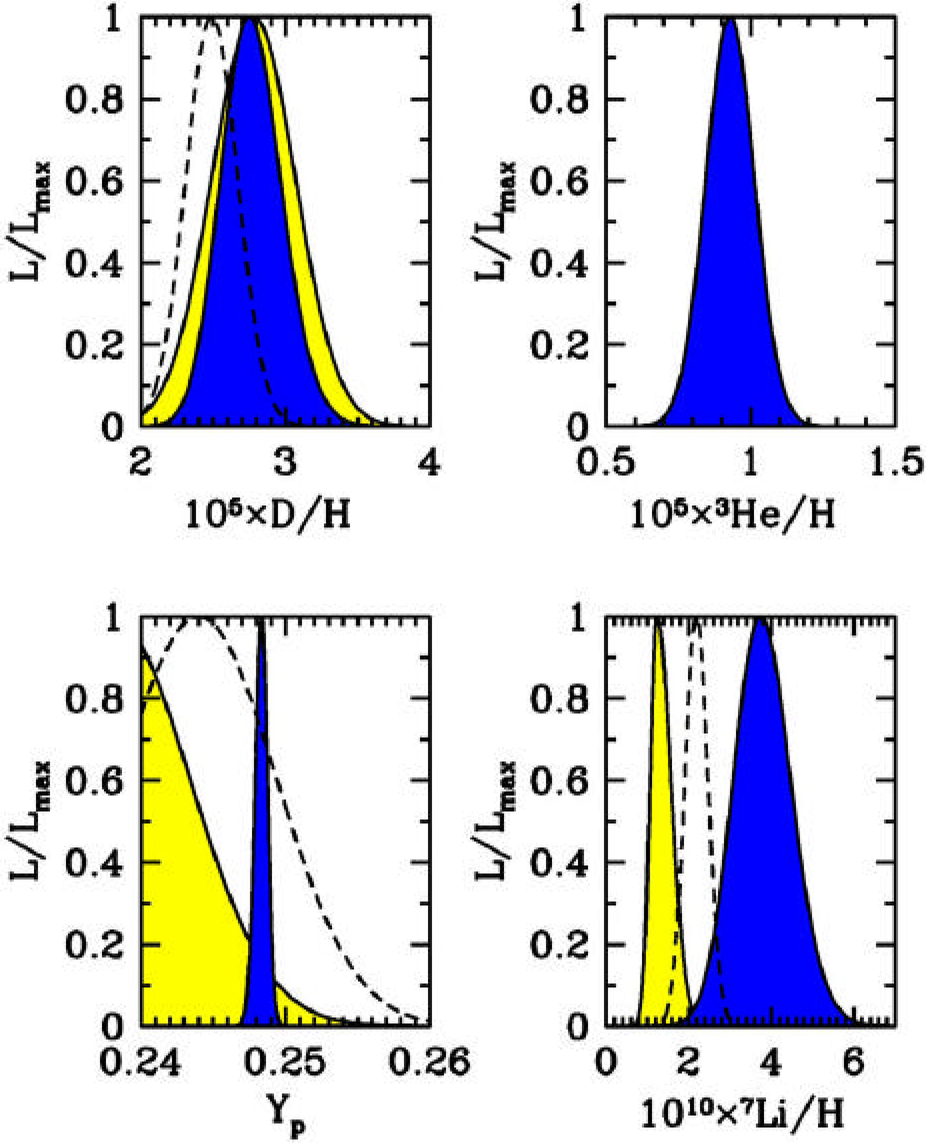
THE

THE

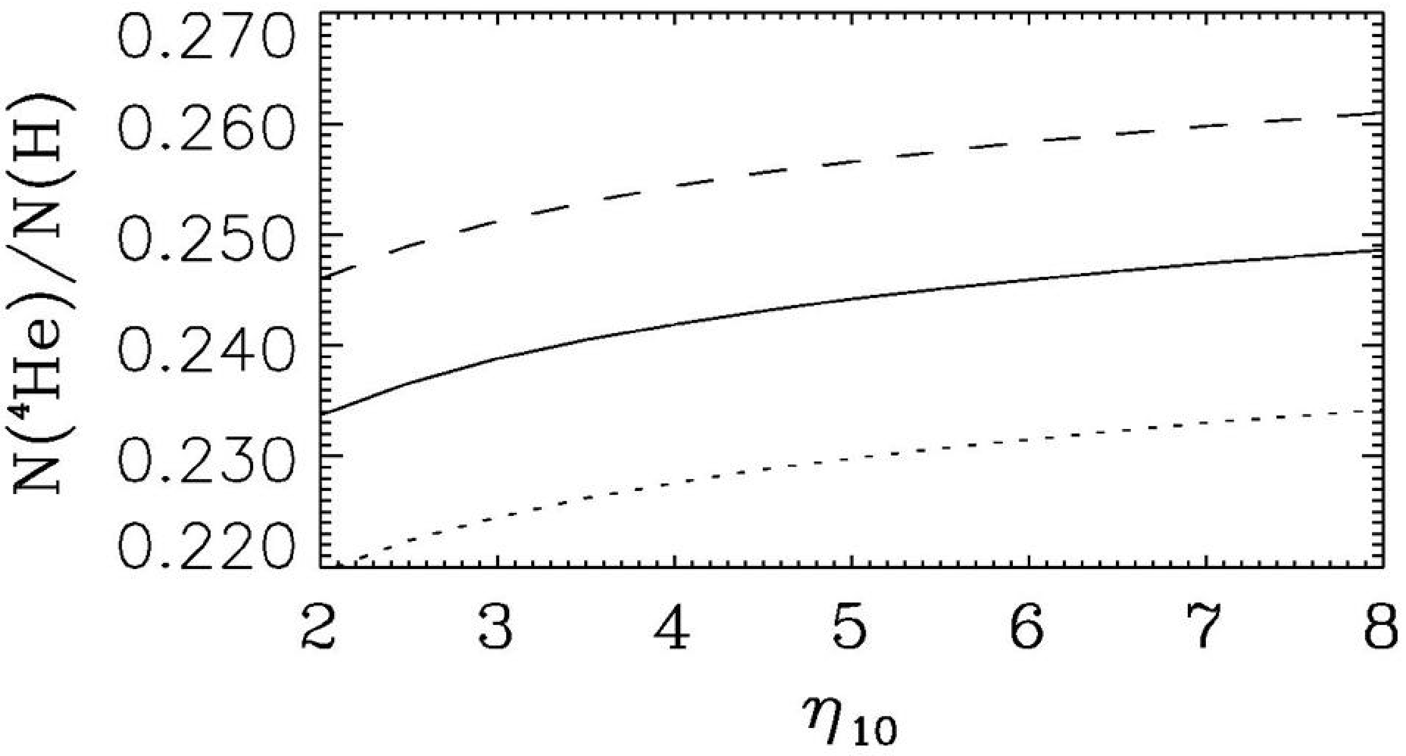
$$\Omega_b h^2 = 0.0226 \pm 0.0008$$

$$\Omega_b h^2 \approx 0.022 \pm 0.006$$

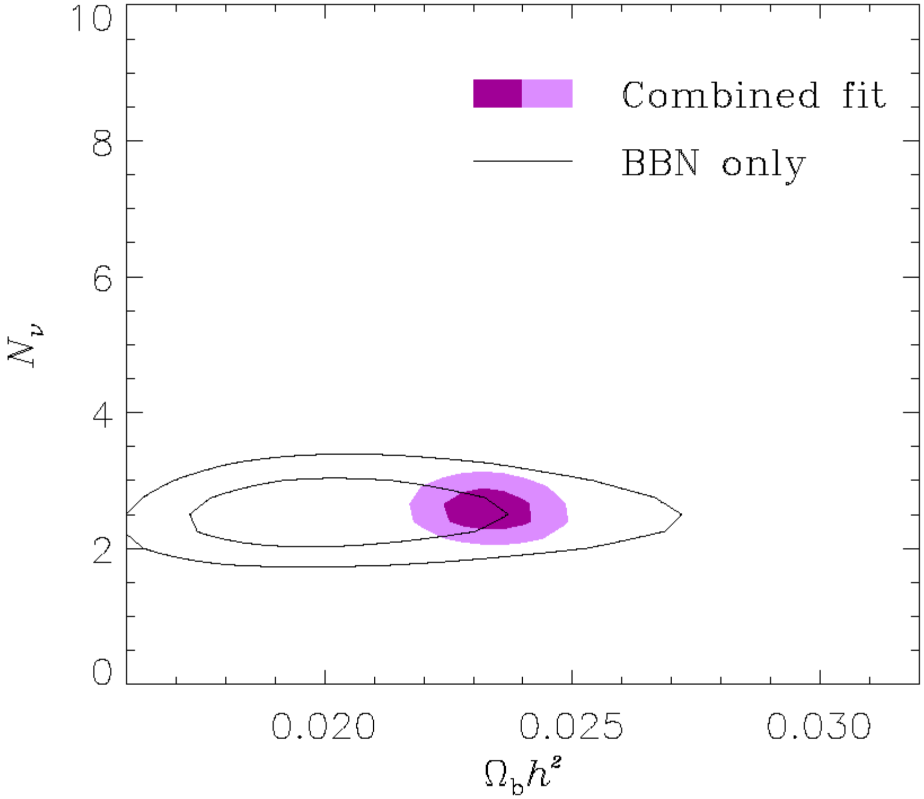


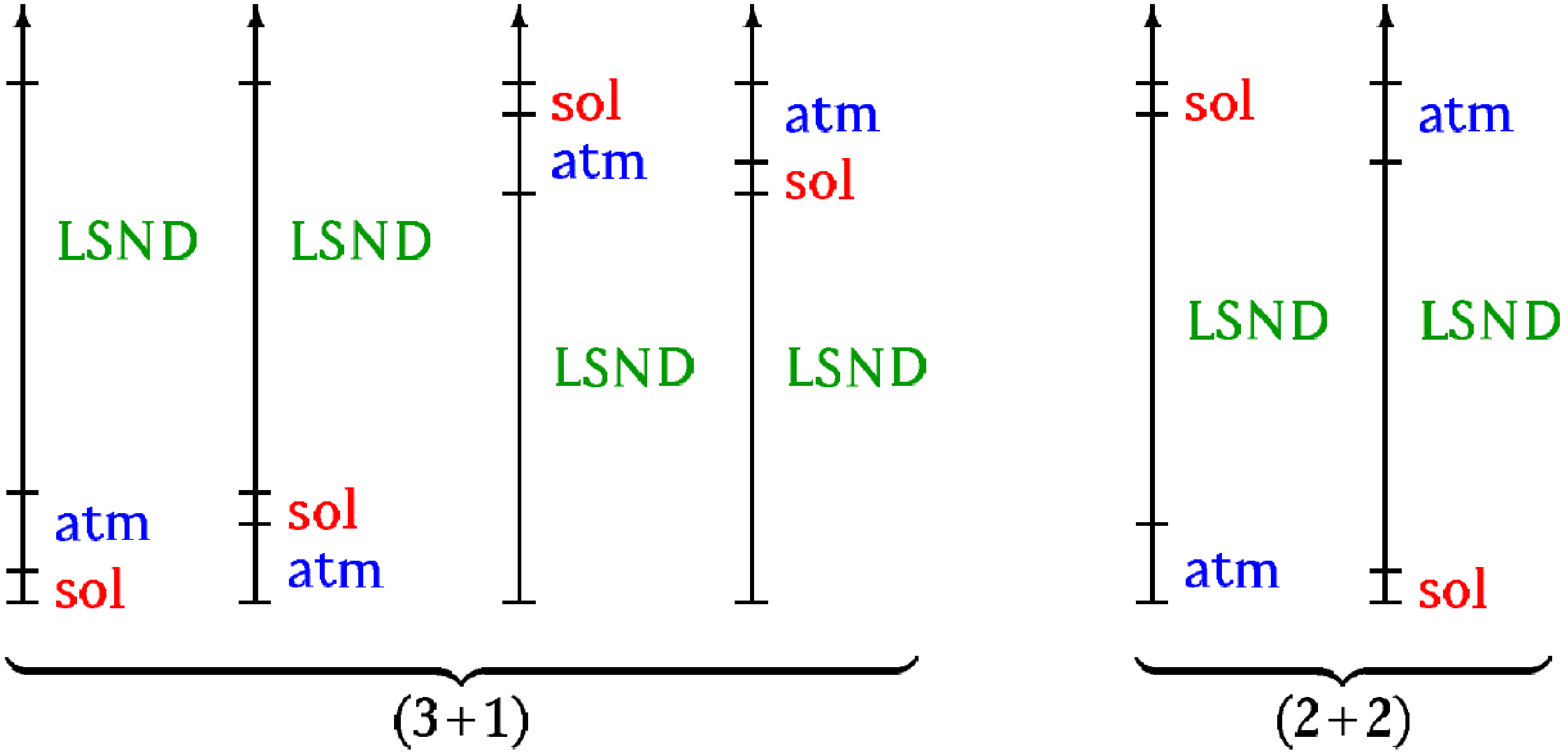

L/L$_{max}$
1
0.8
0.6
0.4
0.2
0
2
3
4
10^5×D/H
0.5
1
1.5
10^5×^{3}He/H
0.24
0.25
0.26
Y$_p$
0
2
4
6
10^{10}×^{7}Li/H

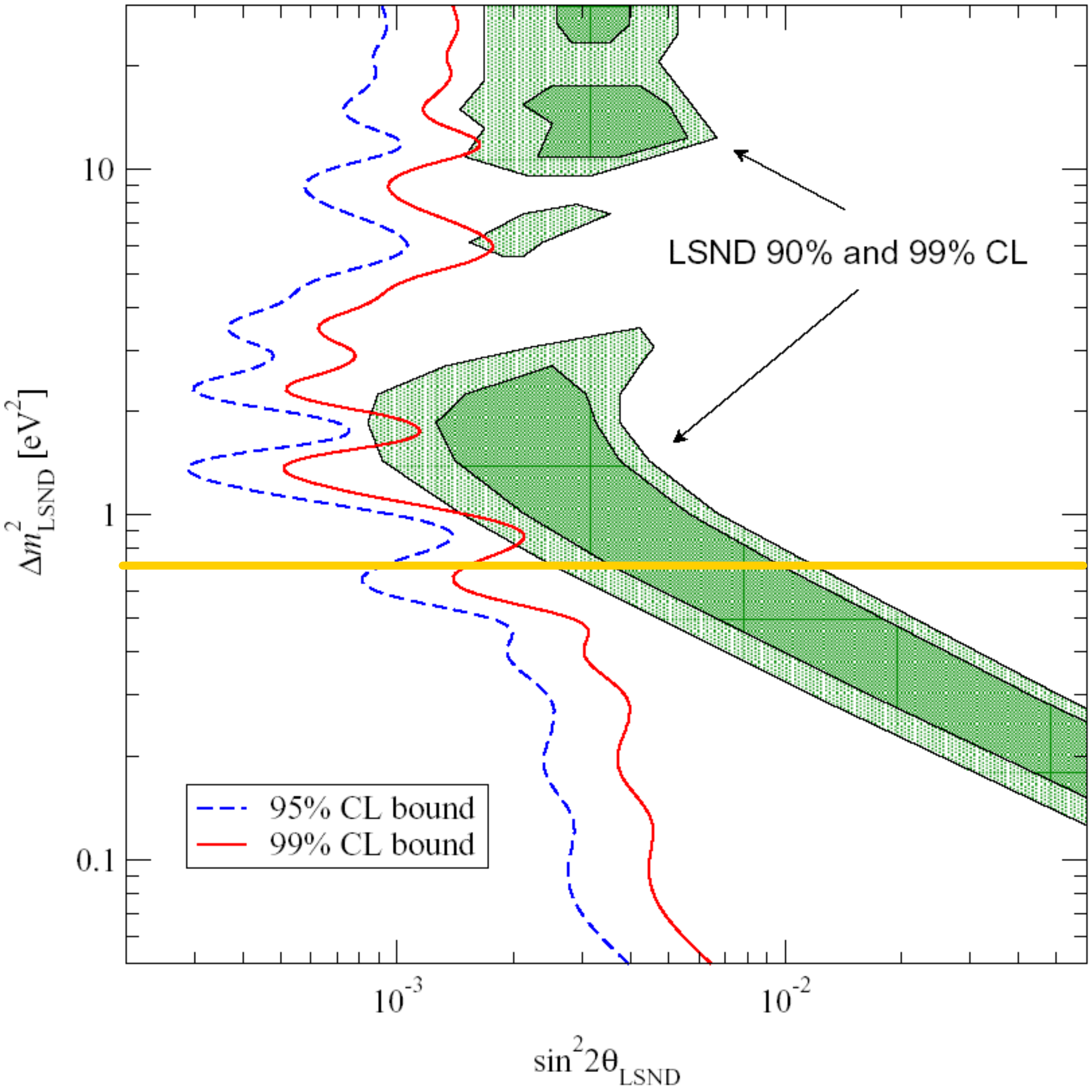
Si heli

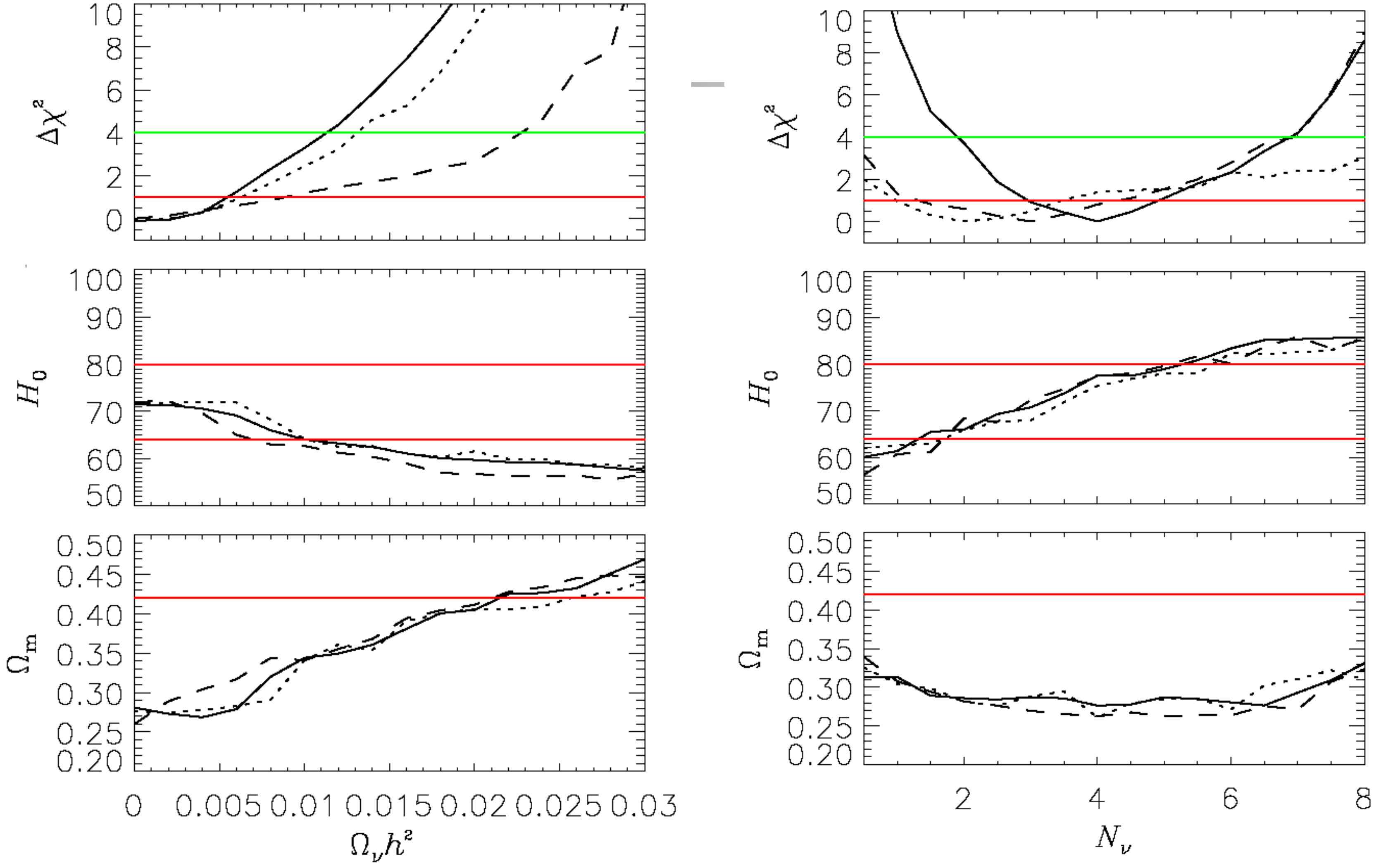


N_n

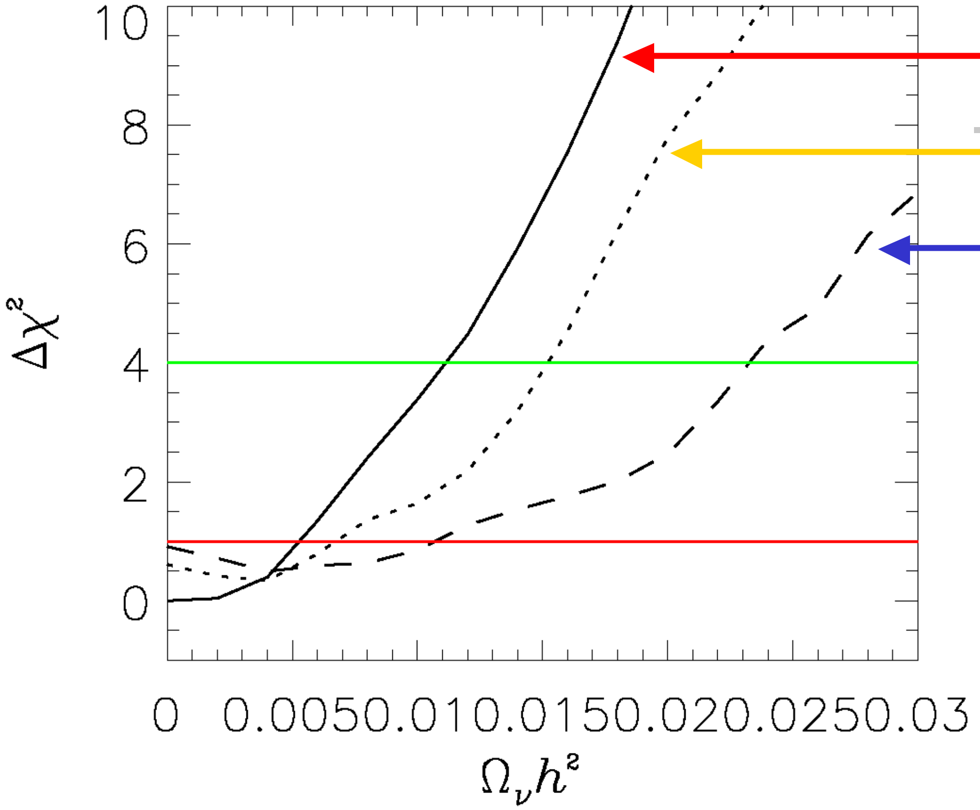



LSND
atm
sol
LSND
sol
atm
sol
atm
LSND
atm
sol
LSND
(3+1)
sol
LSND
atm
atm
LSND
sol
(2+2)

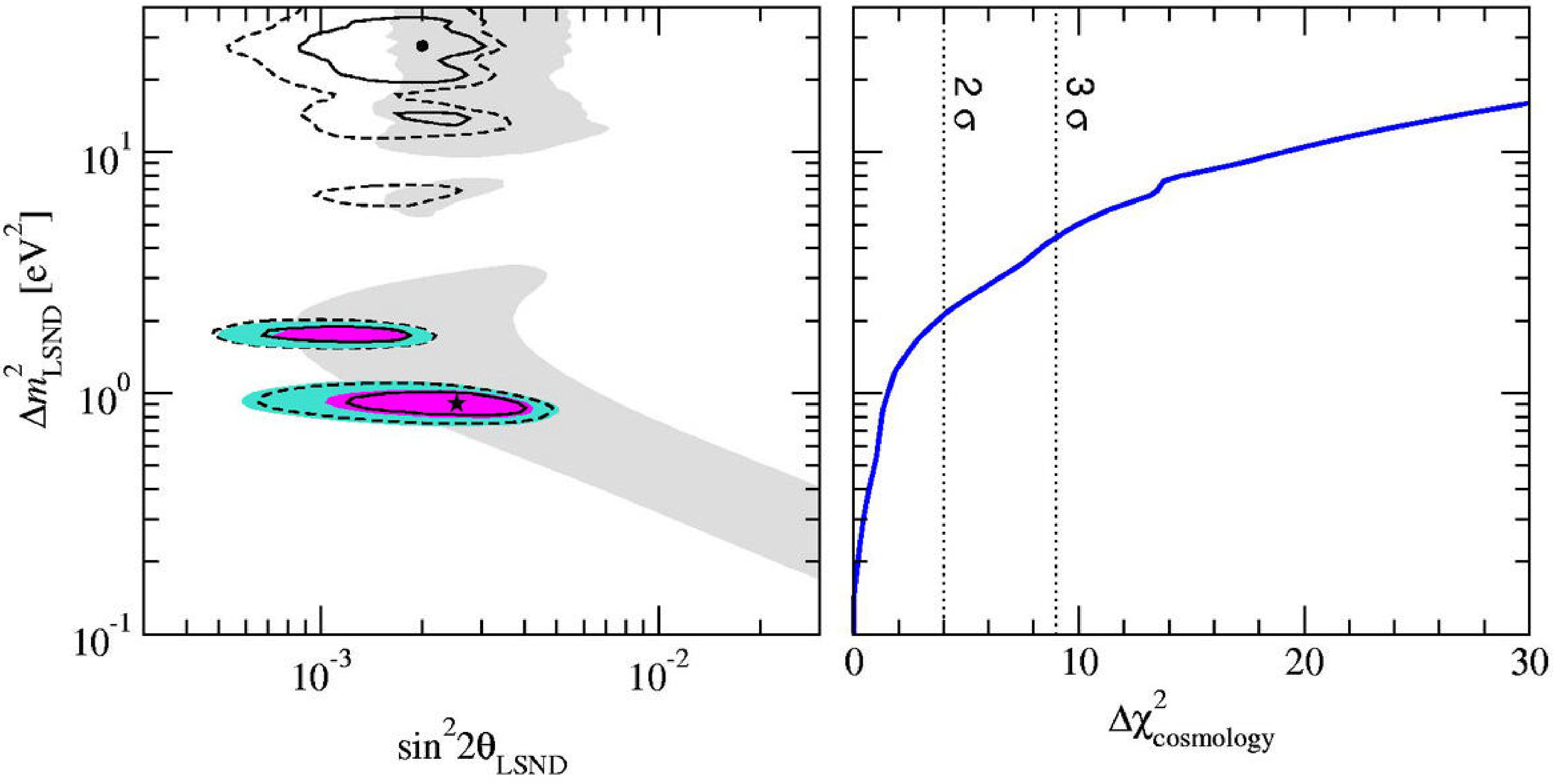

LSND 90% and 99% CL
95% CL bound
99% CL bound
10
1
0.1
10^{-3}
10^{-2}
$\Delta m^2_{\rm LSND}$ [eV^2]
$\sin^2 2\theta_{\rm LSND}$

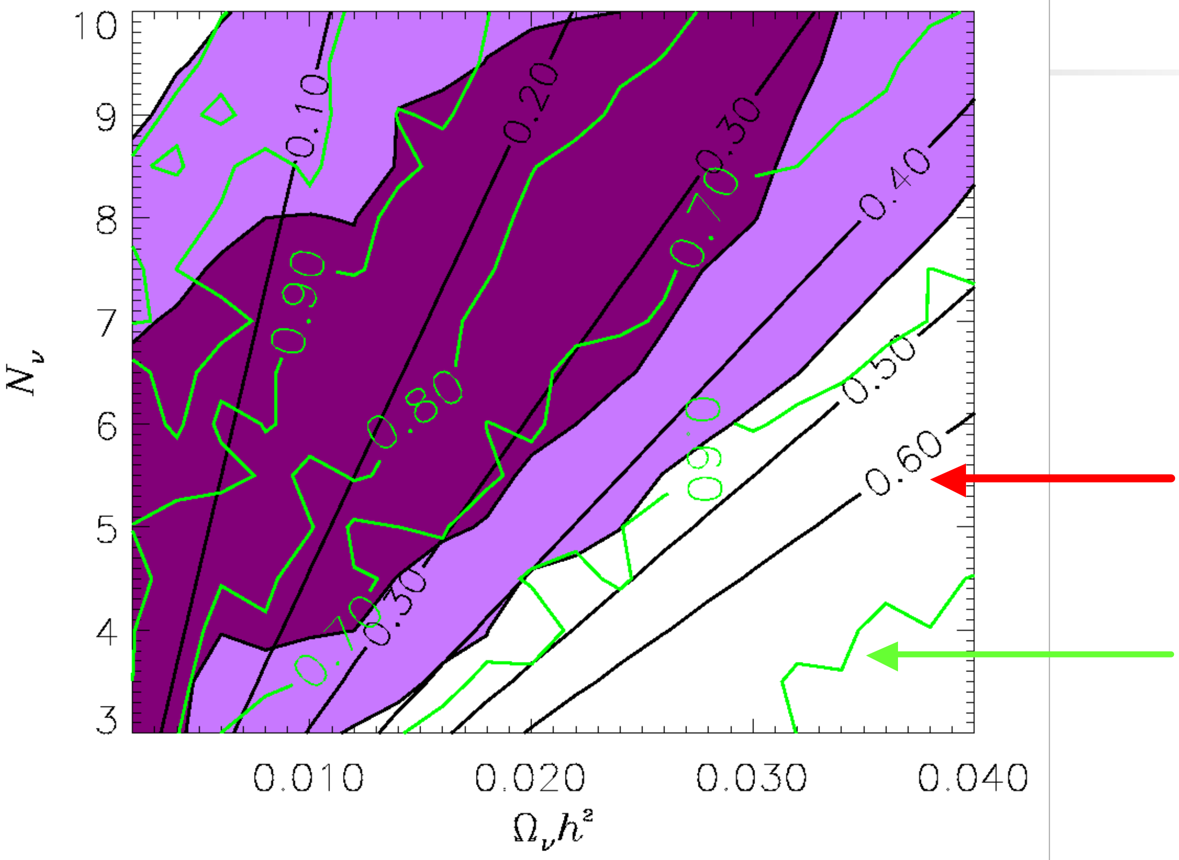


$\Delta\chi^2$
10
8
6
4
2
0
H_0
100
90
80
70
60
50
Ω_m
0.50
0.45
0.40
0.35
0.30
0.25
0.20
0
0.005
0.01
0.015
0.02
0.025
0.03
$\Omega_\nu h^2$
2
4
6
8
N_ν



$N_\nu = 3$


10^{1}
10^{0}
10^{-1}
Δm^2_{LSND} [eV^2]
10^{-3}
10^{-2}
$\sin^2 2\theta_{LSND}$
2 σ
3 σ
0
10
20
30
$\Delta\chi^2_{cosmology}$



10
9
8
7
6
5
4
3
N_ν
0.010
0.020
0.030
0.040
$\Omega_\nu h^2$
0.10
0.20
0.30
0.40
0.50
0.60
0.90
0.80
0.70
0.60
0.50

WHAT IS IN STORE FOR THE FUTURE?

BETTER CMBR TEMPERATURE MEASUREMENTS

MAP (ongoing)
Planck (2007)

Boomerang (ongoing)
TopHat (ongoing)

CBI (ongoing)
DASI (ongoing)

CMBR POLARIZATION MEASUREMENTS

MAP (ongoing)
Planck (2007)

Boomerang (2002-3)

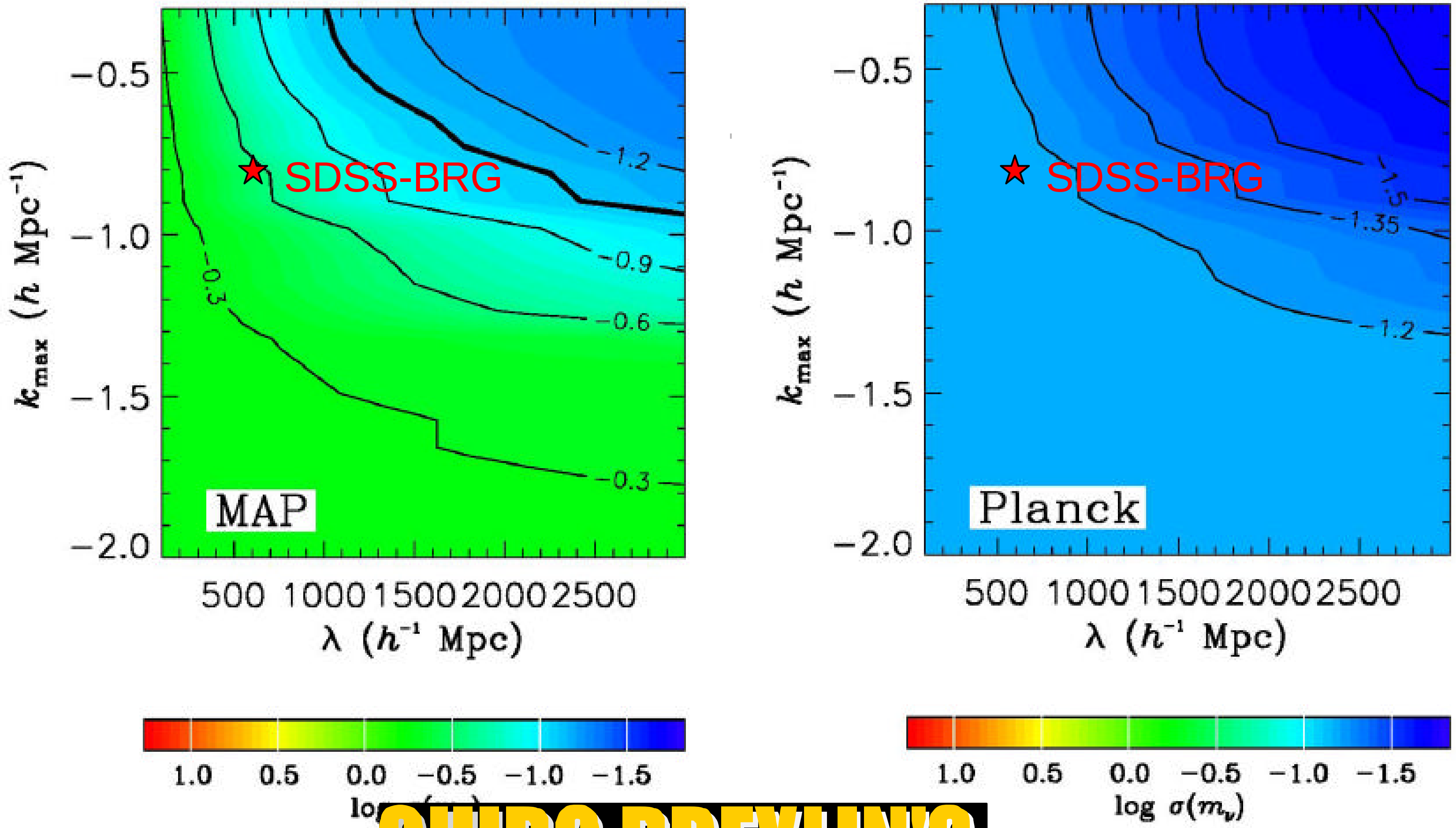
Polatron (ongoing)
DASI

LARGE SCALE STRUCTURE SURVEYS

COSMOLOGICAL SUPERNOVA SURVEYS

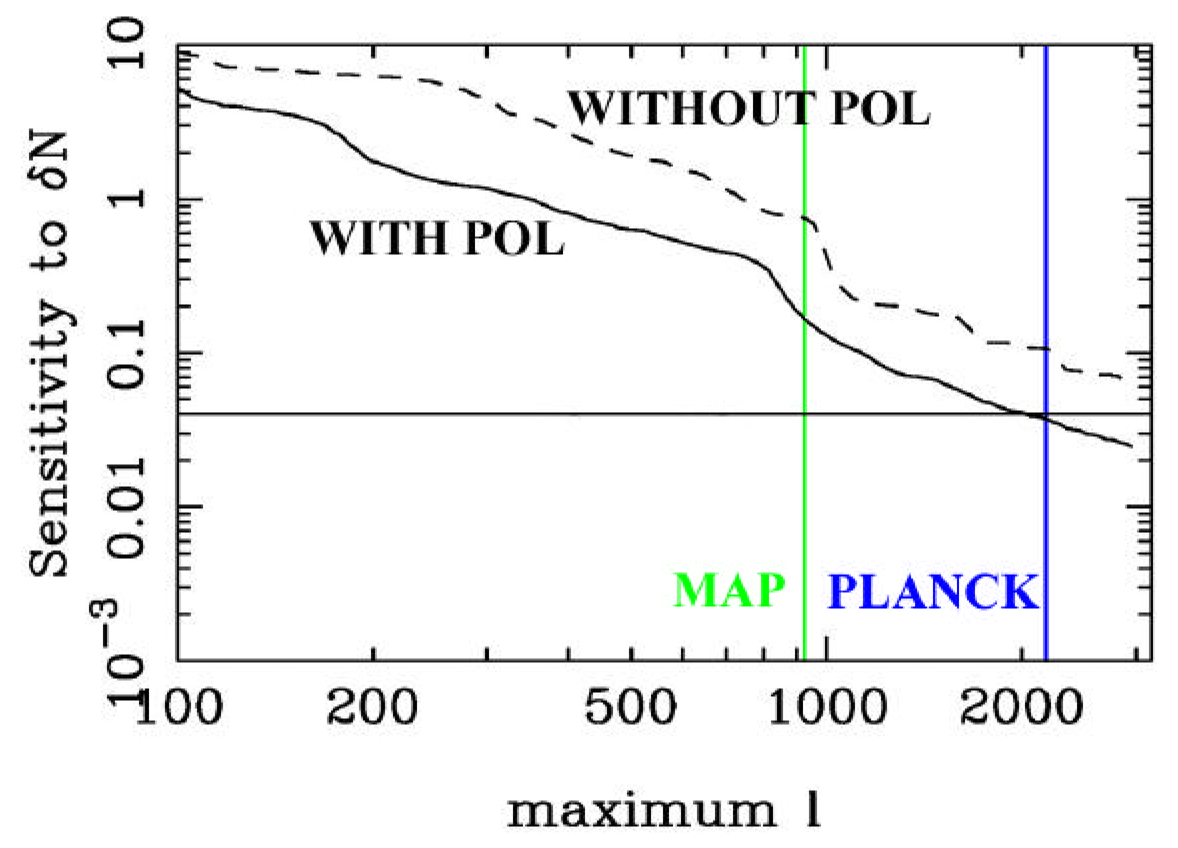
WEAK LENSING SURVEYS

MEASURING m_ν USING CMB+LSS DATA



GUIDO DREXLIN'S TALK ON KATRIN

PROSPECTS FOR FUTURE DETERMINATION OF N_ν



Lopez et al. 1998

Data from Planck may allow for very accurate determination of N_n

Standard model prediction N_n =3.03-3.04 due to heating and finite temperature effect could perhaps be detected

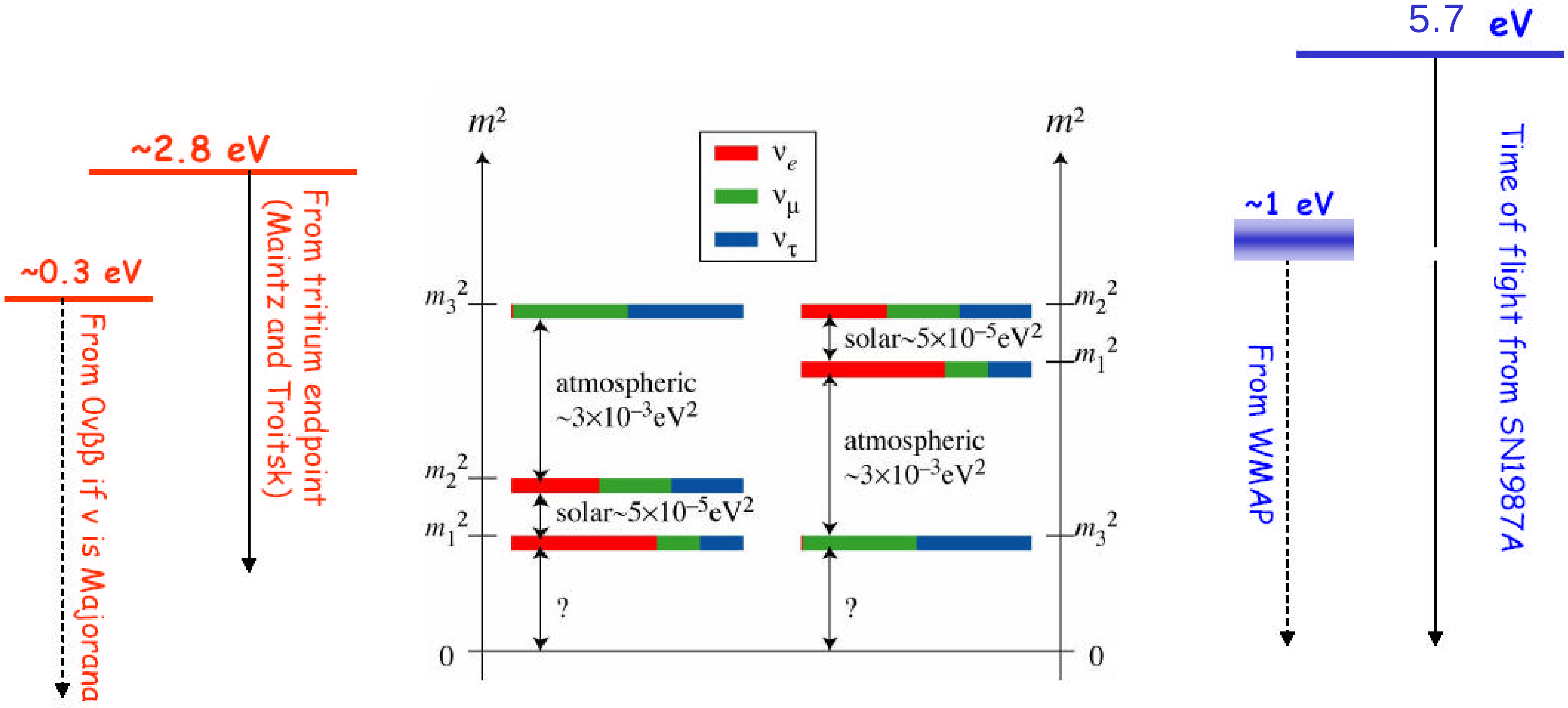
C
POWERFUL PROBE OF NEUTRINO PROPERTIES

- $\sum m_n \le 0.7 - 1.2\ \text{eV depending on priors}$

  $2 \le N_n \le 7$

- IN THE COMING YEARS, TERRESTRIAL EXPERIMENTS ARE LIKELY TO MEASURE SOME OF THE RELEVANT PARAMETERS VERY PRECISELY, BUT COSMOLOGY WILL REMAIN AN EXCELLENT AND COMPLEMENTARY LAB FOR NEUTRINO PHYSICS

Summary



~0.3 eV

From 0νββ if ν is Majorana

~2.8 eV

From tritium endpoint (Maintz and Troitsk)

~1 eV

From WMAP

5.7 eV

Time of flight from SN1987A