Massive Neutrinos in Particle Physics

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1. Leptogenesis

2. Neutrino Mass: where we can see

   passive experiments

   cosmological implications

Baryogenesis

Sakharov (1967): baryon is generated by particle physics

$$\Delta B \neq 0, \quad \Delta C \neq 0, \Delta CP \neq 0, \quad \text{dep. from equil.}$$

'Realistic' -- GUT -- scenario (Yoshimura 1978):

then-standard scenario: leptoquark boson (Higgs) decay

B, L violation is present in standard SU(2)xU(1),

't Hooft (1976): triangle anomaly of $j_B WW, \quad j_L WW$

Christ (1980)

such that $\Delta B \neq 0 \quad \Delta L \neq 0$

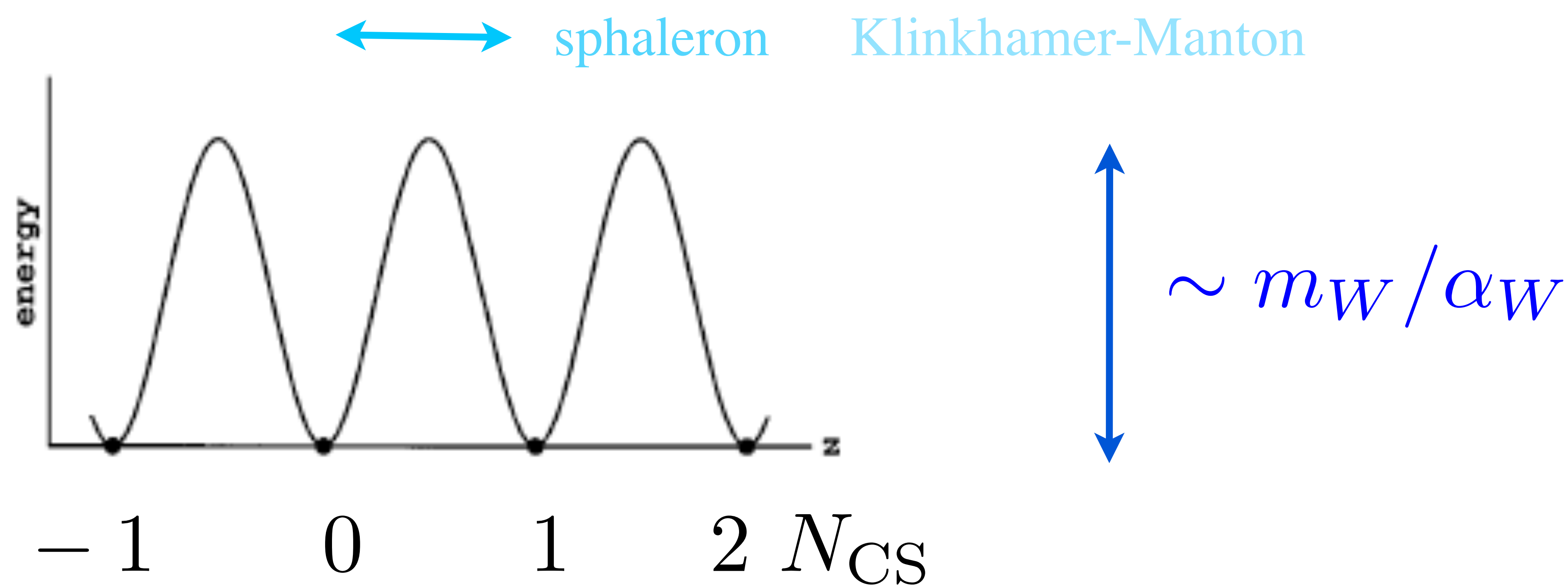
$$\Delta(B-L) = 0$$

Transition rate (at zero temperature): $\Gamma = \exp(-2\pi/\alpha_W)$

Non-perturbative effect (sphaleron) at $T \neq 0$

$$\Gamma = \exp(-\frac{2}{\alpha_W}\frac{M_W}{T}B)$$

non-trivial topology



Kuzmin, Rubakov, Shaposhnikov 1985

$$\Delta B(L) = 3\Delta N_{\rm CS}$$

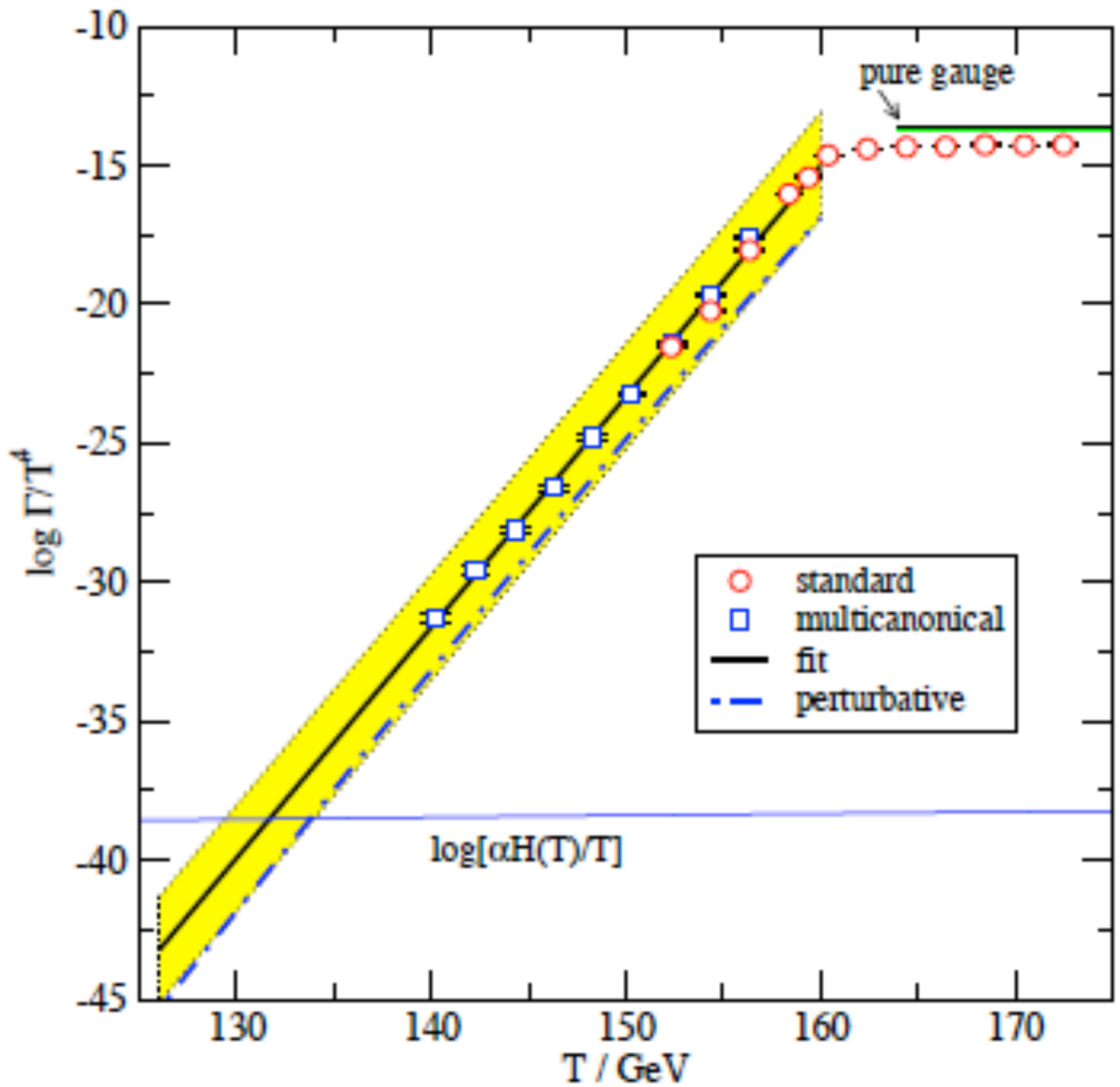
no suppression

$$\Delta B = \Delta L$$

Baryon numbers produced with B=L are washed out at high T

Simulations: Real time, microcanonical since 1988: Grigoriev, Rubakov, Ambjoern, Rummukainen, Shaposhnikov, Moore, Boedeker,...

D'Onofrio, Rummukainen, Tranberg 2014



$$\Gamma > \dot{a}/a$$

$$\text{for} \quad T > 132\text{MeV}$$

$$(\text{high T}: \; T < 10^{12}\text{GeV})$$

$$T_c(\text{EW}) = 159 \pm 1\text{GeV}$$

$$\text{cross over if} \quad m_\phi > 79 \text{ GeV}$$

$$\Gamma/V = (25 \pm 2)\alpha_W^5 T^4$$

B and L get quickly into equilibrium

Accounting for chemical potential with B-L conserved

$$\Delta B = \frac{8N_f + 4N_H}{22N_f + 13N_H}\Delta(B-L)$$
$$= \frac{28}{79}\Delta(B-L) \qquad N_f = 3, \quad N_H = 1$$

Baryon number remains if started with $\Delta(B-L) \neq 0$

GUT: $\Delta(B-L) = 0$

Majorana neutrino: $\Delta L \neq 0$

Leptogenesis

MF, Yanagida 1986

$$\mathcal{L} = h\bar{\ell}_L \nu_R \phi + \frac{1}{2} M \bar{\nu}_R^c \nu_R + \mathcal{L}_{WS}$$

$$m_\nu = -m_D \frac{1}{M} m_D^T$$

$$\mathrm{If\ M = 10^{15} GeV,\ m_D \simeq 100 GeV,} \qquad \mathrm{then\ m_\nu = 0.01 eV}$$

Minkowski 1978; Yanagida 1979; Gell-Mann et al. 1979

lepton number production per decay of M

$$\varepsilon = \frac{3}{16\pi} \frac{M_1}{\langle\phi\rangle^2} \frac{\Delta m_i^2}{m_i} \frac{\mathrm{Im}\ h_{i1}^2}{(h^\dagger h)_{11}} \sim 0.05 \frac{M_1}{M_3}$$

Solve Boltzmann equation for $\frac{dN_1}{dT}$ and $\frac{dN_{B-L}}{dT}$

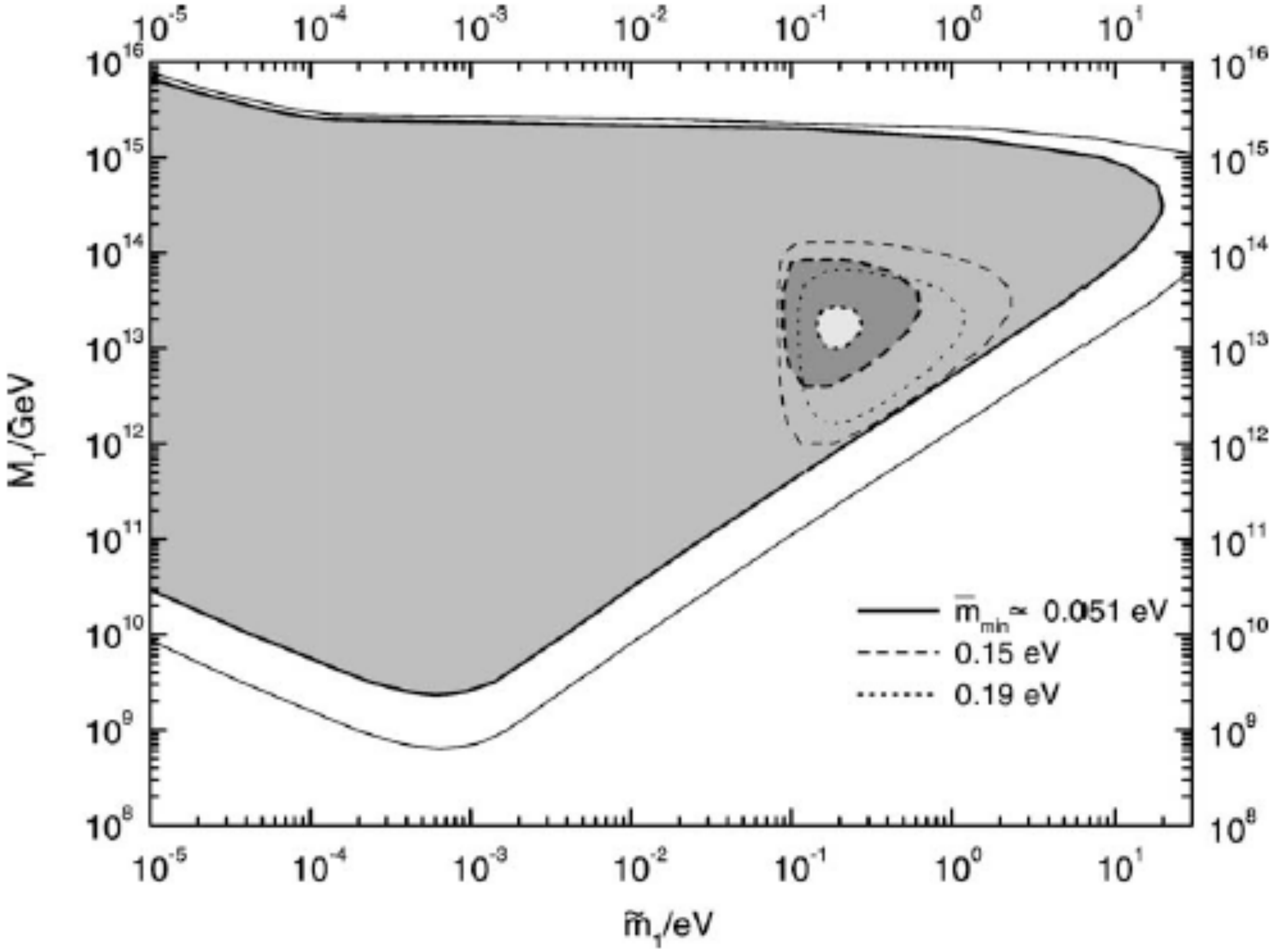
Luty 1992; Buchmueller et al. 2002+

$$\frac{dN_1}{dT} = -[\Gamma(\mathrm{decay}) + \Gamma(\mathrm{scatt})](N_1 - N_1^{\mathrm{eq}})$$

$$\frac{dN_{B-L}}{dT} = -\varepsilon\Gamma(\mathrm{decay})(N_1 - N_1^{\mathrm{eq}}) - \Gamma(\mathrm{erase})N_{B-L}$$

to give $n_B/n_\gamma = 6 \times 10^{-10}$

Buchmueller, di Bari, Pluemacher 2003



$$\bar{m} \leq 0.2\text{eV} \qquad (\bar{m} \geq 0.05\text{eV})$$

$$\text{to wash out initial memory}: \; m > 10^{-3}\ \text{eV}$$

$$M_1 = 10^{10} - 10^{15}\ \text{GeV}$$

Thermal leptogenesis:

$$T > 10^9 \mathrm{GeV}$$

if no SUSY: no problems

if SUSY, the problem of overproduction of gravitinos

One solution: ‘pure’ gravity-mediated SUSY breaking

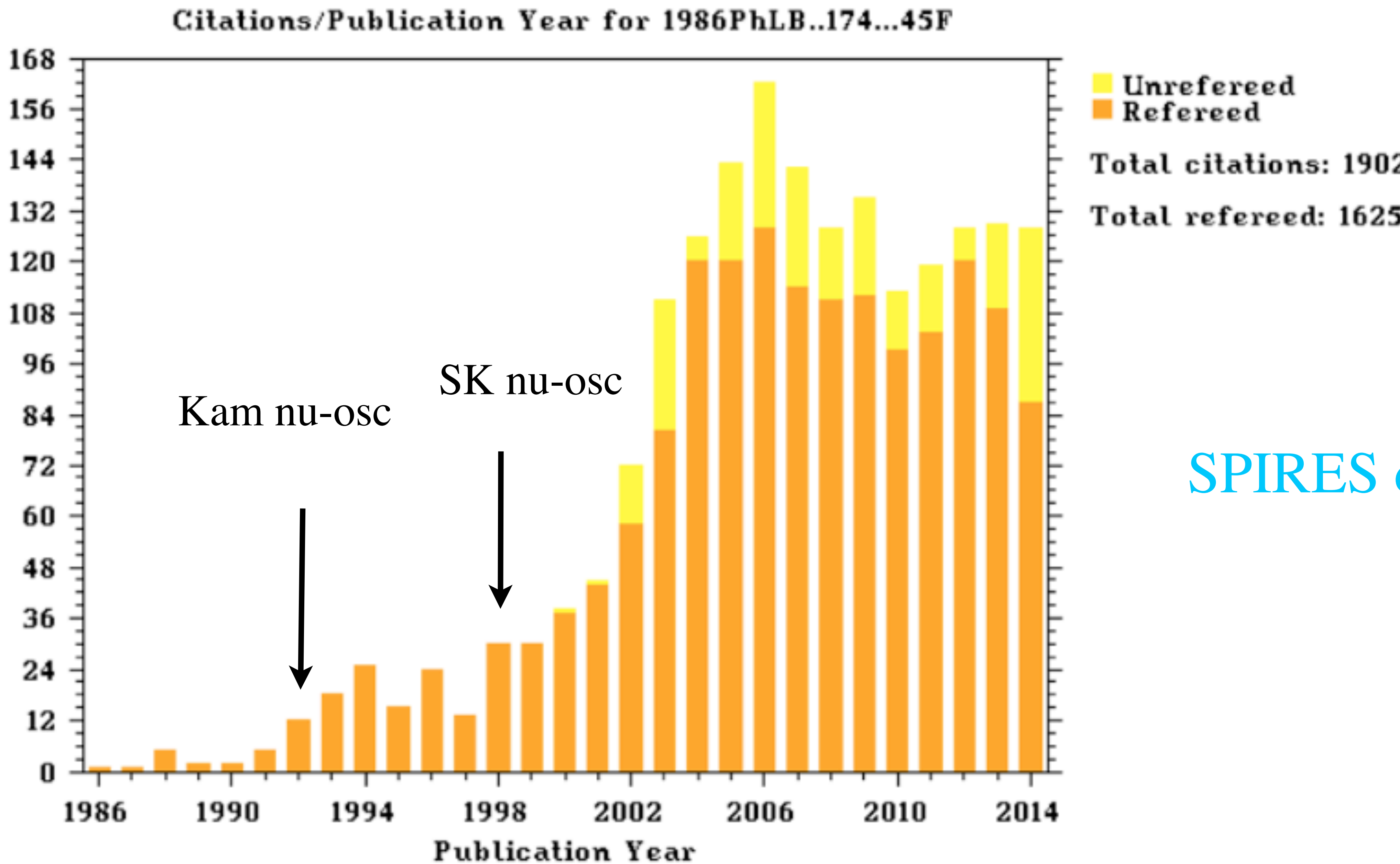
gravitino mass $\sim O(100 \text{ TeV})$ decays fast

Ibe, Yanagida 2014

parameters (heavy sector, Dirac mass) unknown

some work done, but without heavy sectors

ADS

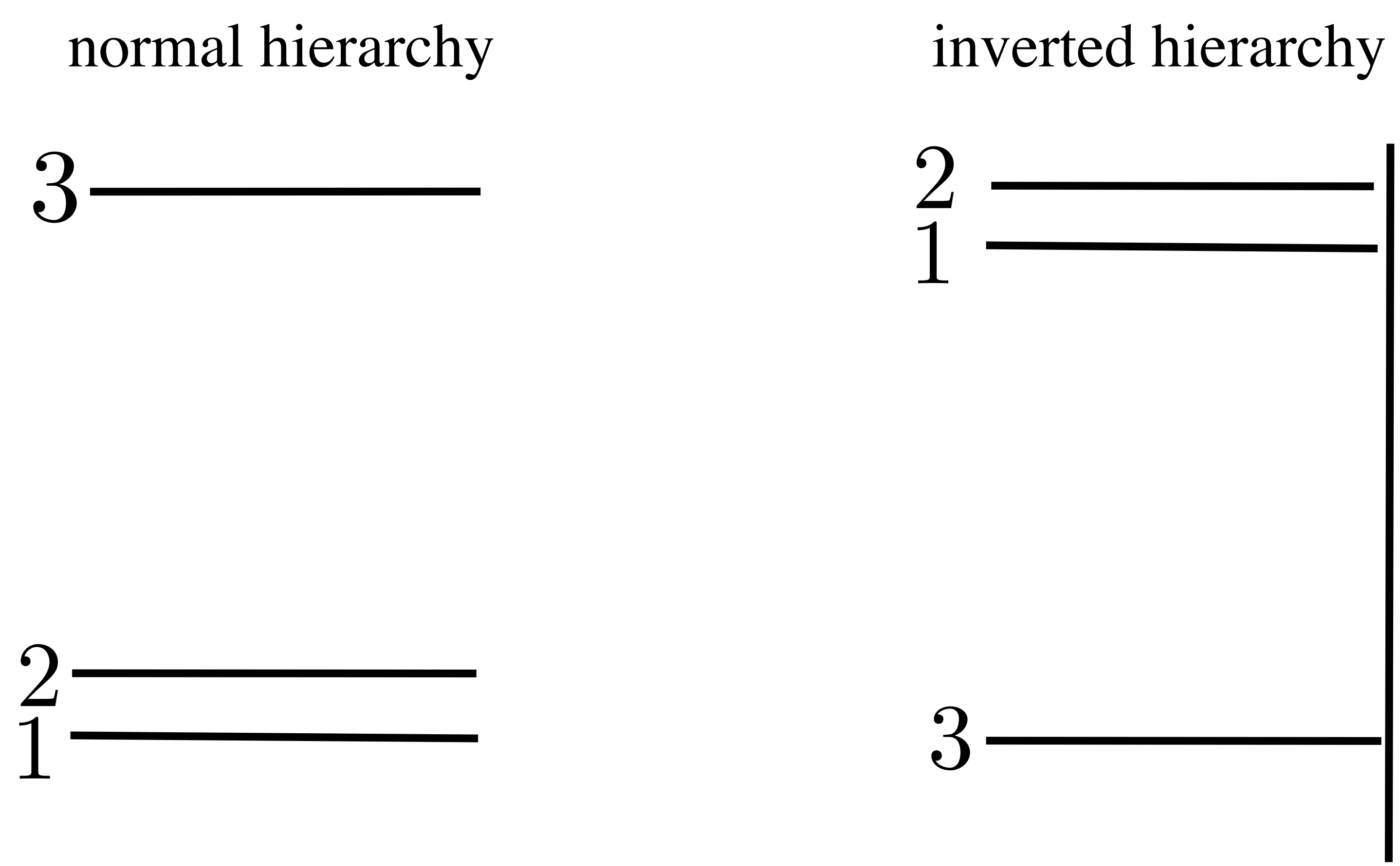


SPIRES cts 2240

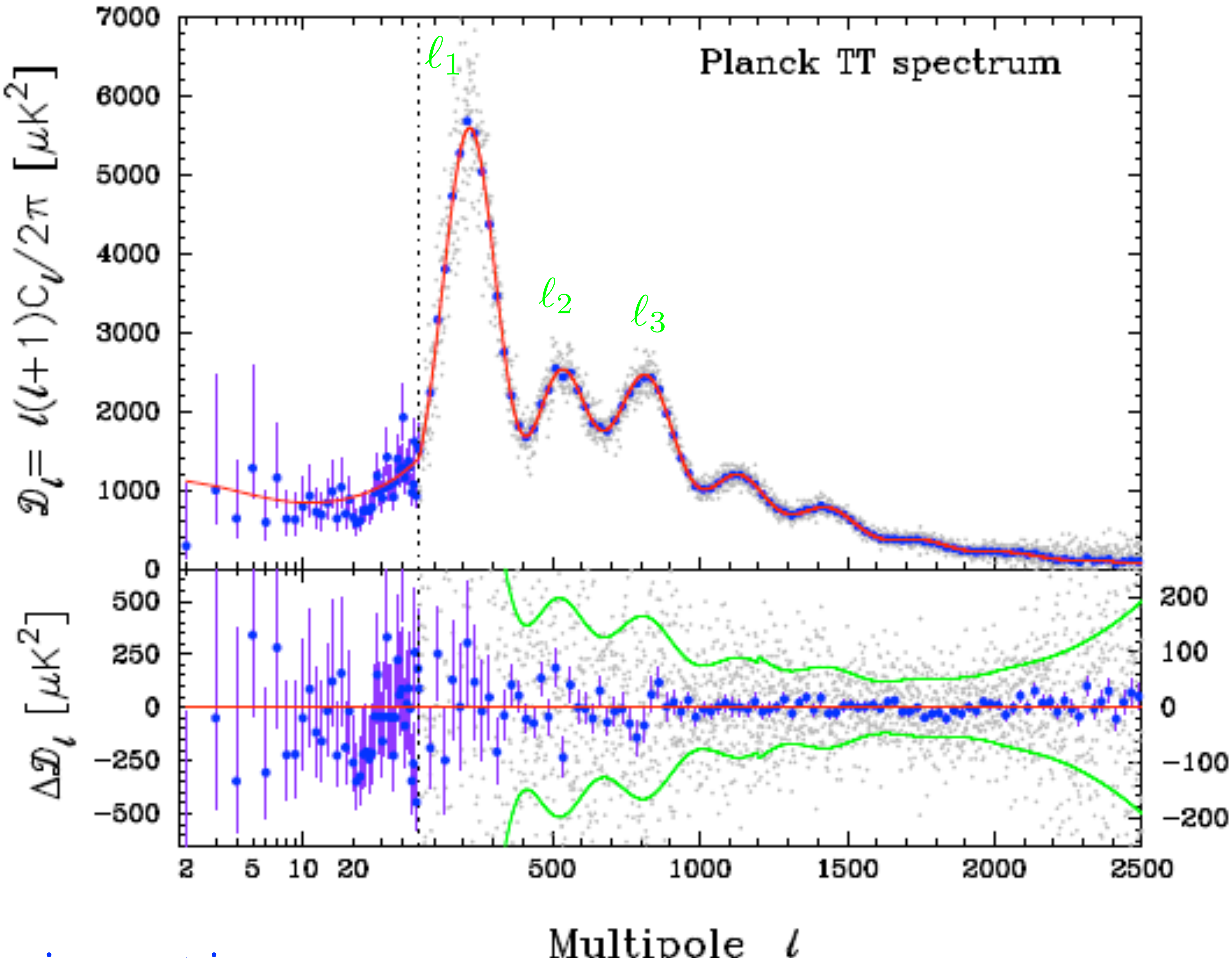
Neutrino mass

$$\sqrt{\Delta m^2_{21}} = 8.7 \pm 0.1 \text{ meV} \qquad \text{solar } \nu; \quad \text{KamLAND}$$

$$\sqrt{|\Delta m^2_{32}|} = 48 \pm 1 \text{ meV} \qquad \text{atmosph } \nu; \quad \text{T2K}$$



Planck 2013

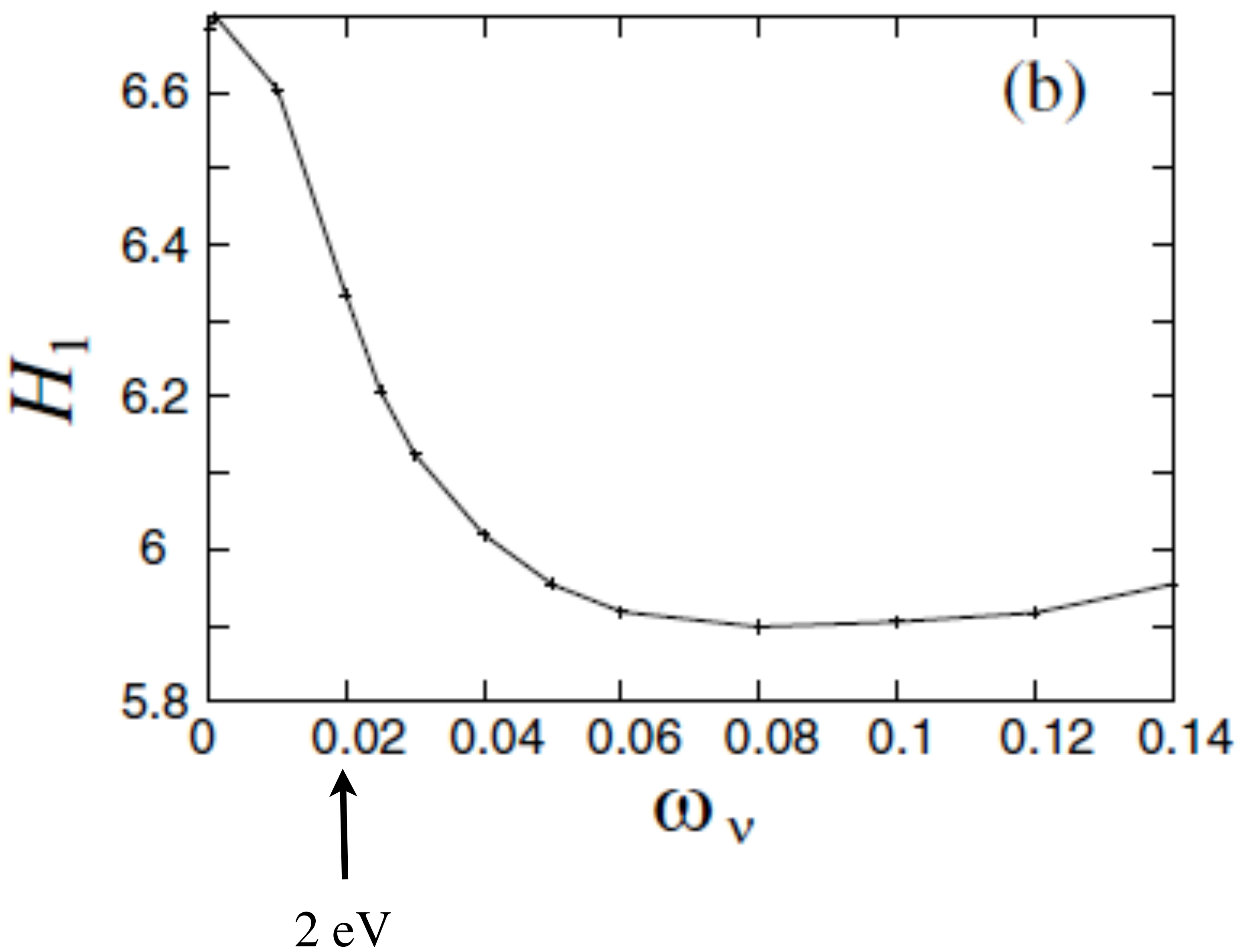


fit w/o massive neutrinos

Any effect that neutrinos get NR before recombination?

$$H_1 = \left(\frac{\Delta T_{\ell_1}}{\Delta T_{\ell=10}} \right)$$

Ichikawa, MF, Kawasaki



Cosmology

CMB only $\sum m_\nu < 1.3 \text{ eV}$ (WMAP9)

$< 1.08 \text{ eV}$ (Planck)

cf. NR before recombination: $m_\nu \simeq 1.6 \text{ eV}$

With weak lensing signal in CMB

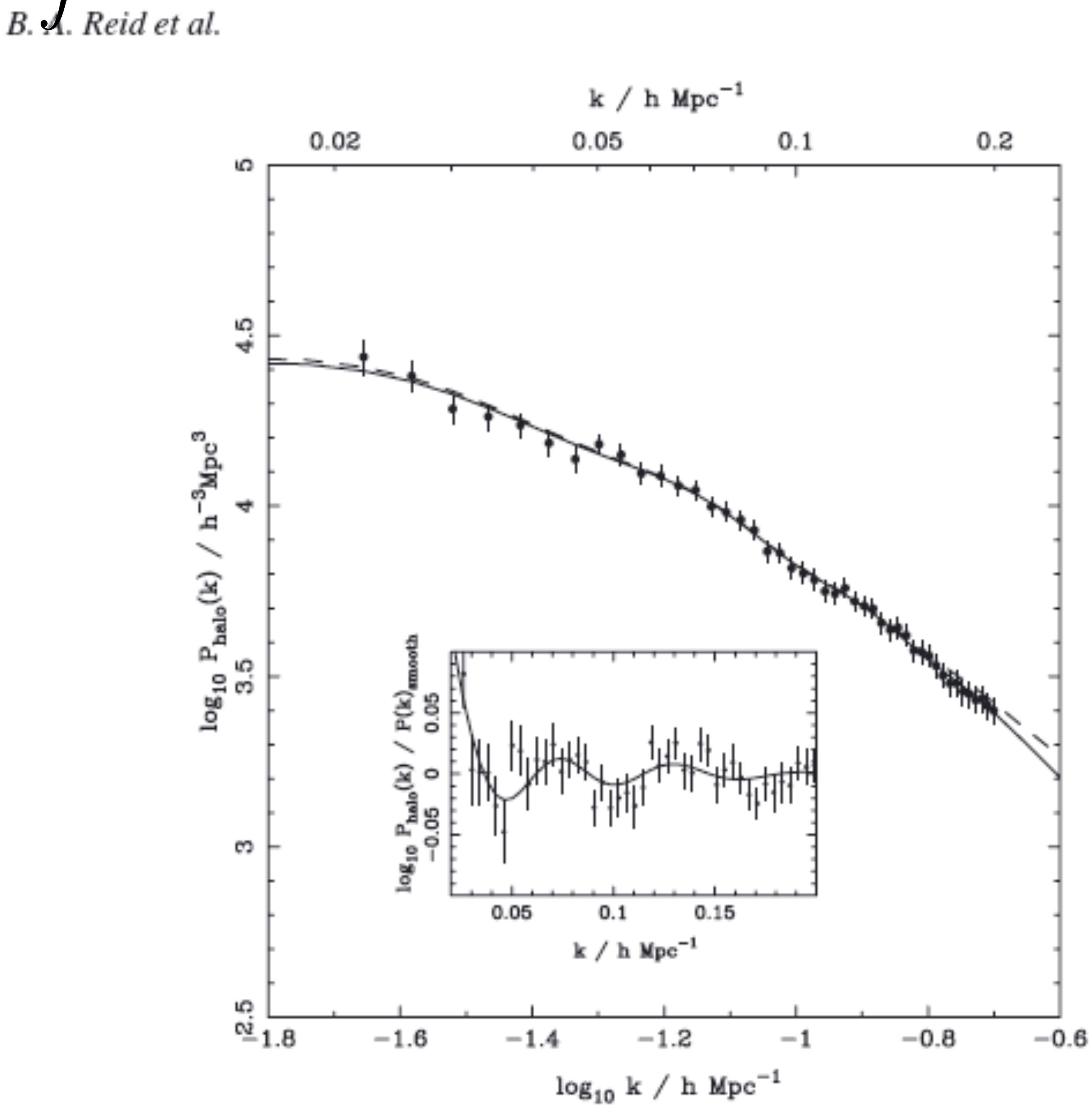
$$\sum m_\nu < 0.66 \text{ eV} \qquad \text{(Planck)}$$

With the power spectrum of galaxies (systematics difficult)

$$\sum m_\nu < 0.62 \text{ eV (?)} \qquad \text{(SDSS : Reid et al.)}$$

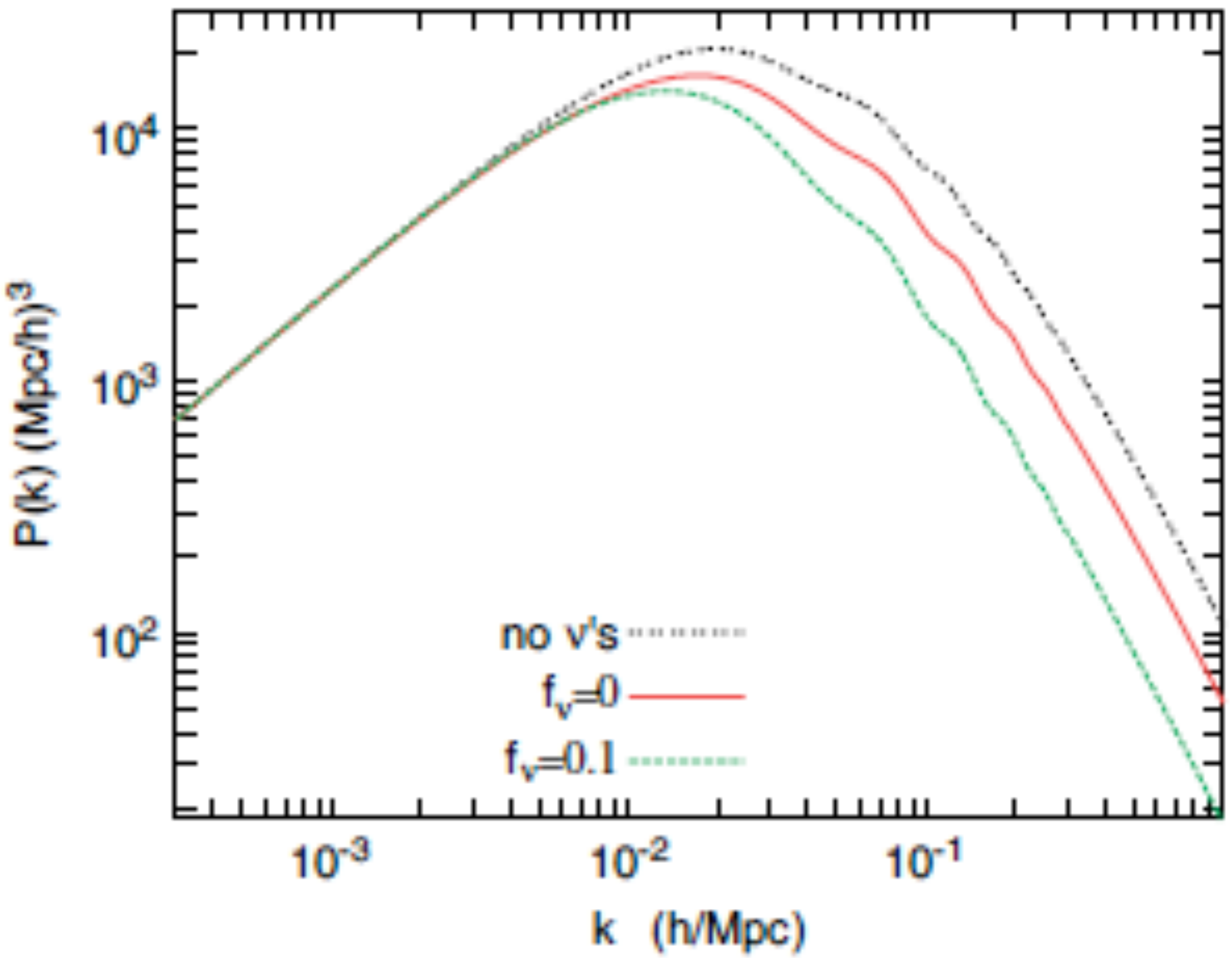
SDSS:Reid et al. 2010

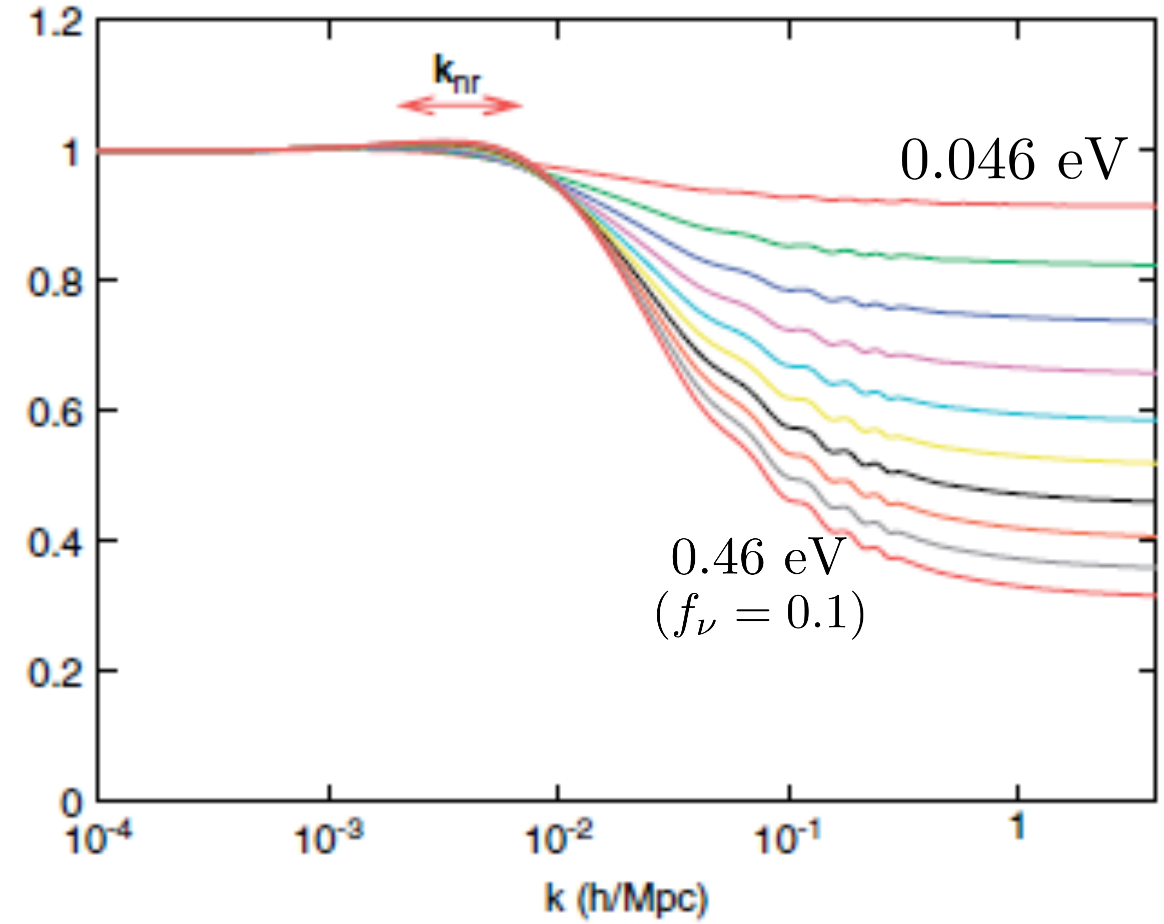
$$P(k) = \int d^3 r \xi(r) e^{ik\cdot r}$$



$\Omega_m = 0.29$

$h = 0.69$





Lesgourgues Pestor 2006

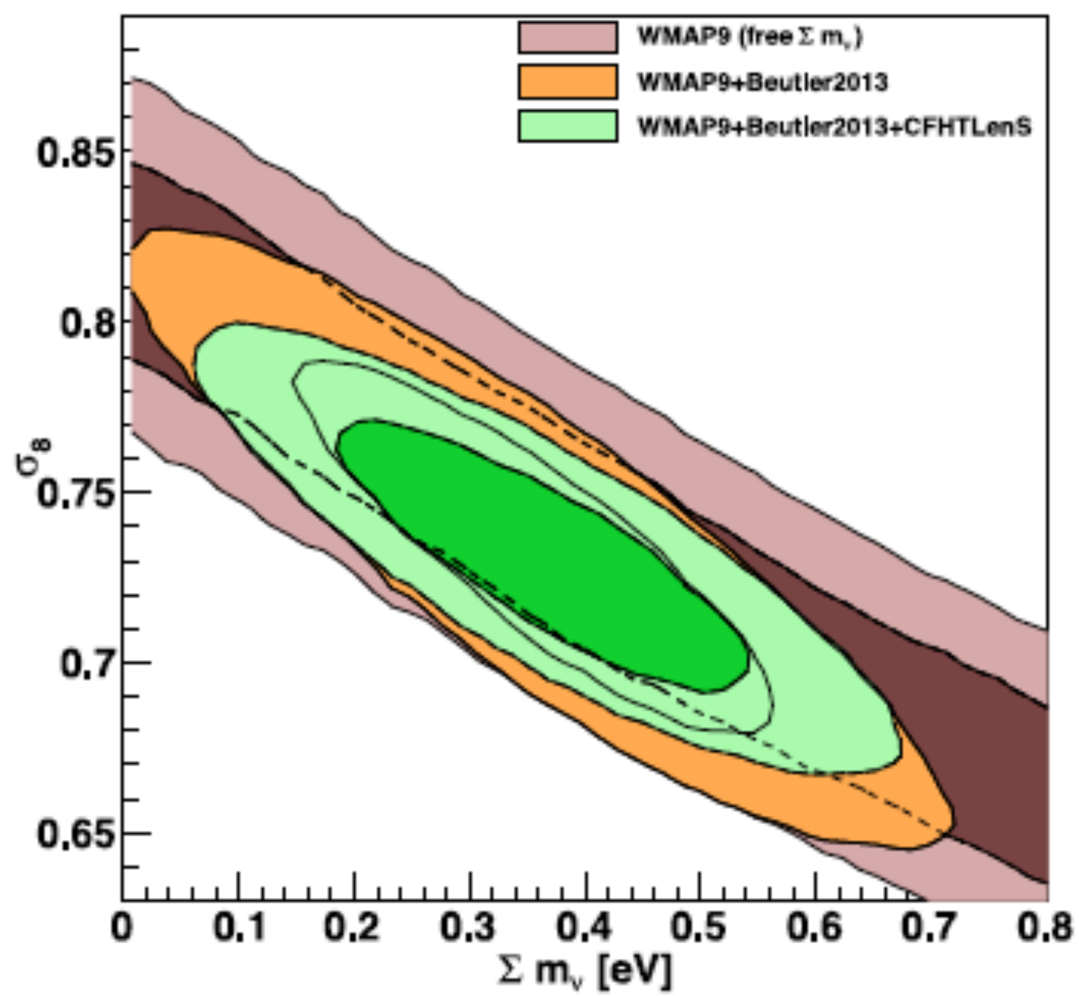
Power spectrum of galaxies (systematics difficult) with CMB

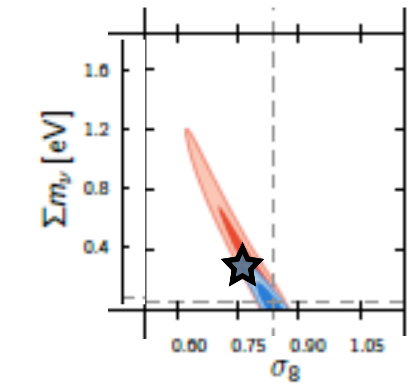
$$\sum m_\nu < 0.62 \text{ eV} \qquad \text{(SDSS : Reid et al.)}$$

?

PLANCK2013

Beutler et al. 2014 (SDSS-III/BOSS)





double beta decay

$$\langle m_{ee}\rangle = \sum_i m_{\nu_i}\eta_i |U_{ei}|^2 \qquad\qquad (\eta = \pm 1)$$

$$\simeq m_{\nu_e}\cos^2\theta_{12} \pm m_{\nu_\mu}\sin^2\theta_{12} \pm m_{\nu_\tau}\sin^2\theta_{13}$$

$\sim 30 - 40 \text{ meV}$ for inverted

$\sim 5 - 10 \text{ meV}$ for normal

Many experiments:

e.g. KamLAND-ZEN $\langle m_{ee}\rangle = 120 - 250 \text{ meV}$

$T^{0\nu} = 1.9 \times 10^{25}\text{yr}$ $\quad {}^{136}\text{Xe } 89.5 \text{ kg}\cdot\text{yr}$

also GERDA, CUORE, EXO

Attempt at mass matrix

Assuming symmetry ad hoc + breaking ad hoc

Assuming mass matrix ad hoc

e.g., bi-maximal, ... +breaking

e.g., off-diagonal

Weinberg to account for the Cabibbo angle

$$\theta = \sqrt{m_d/m_s}$$

extension to 3x3 (Fritzsch)

large neutrino mixing (MF, Tanimoto, Yanagida 1993)

If Majorana $\theta =^4 \sqrt{m_2/m_1}$

All mixing angles come out right

charged lepton nu-Dirac

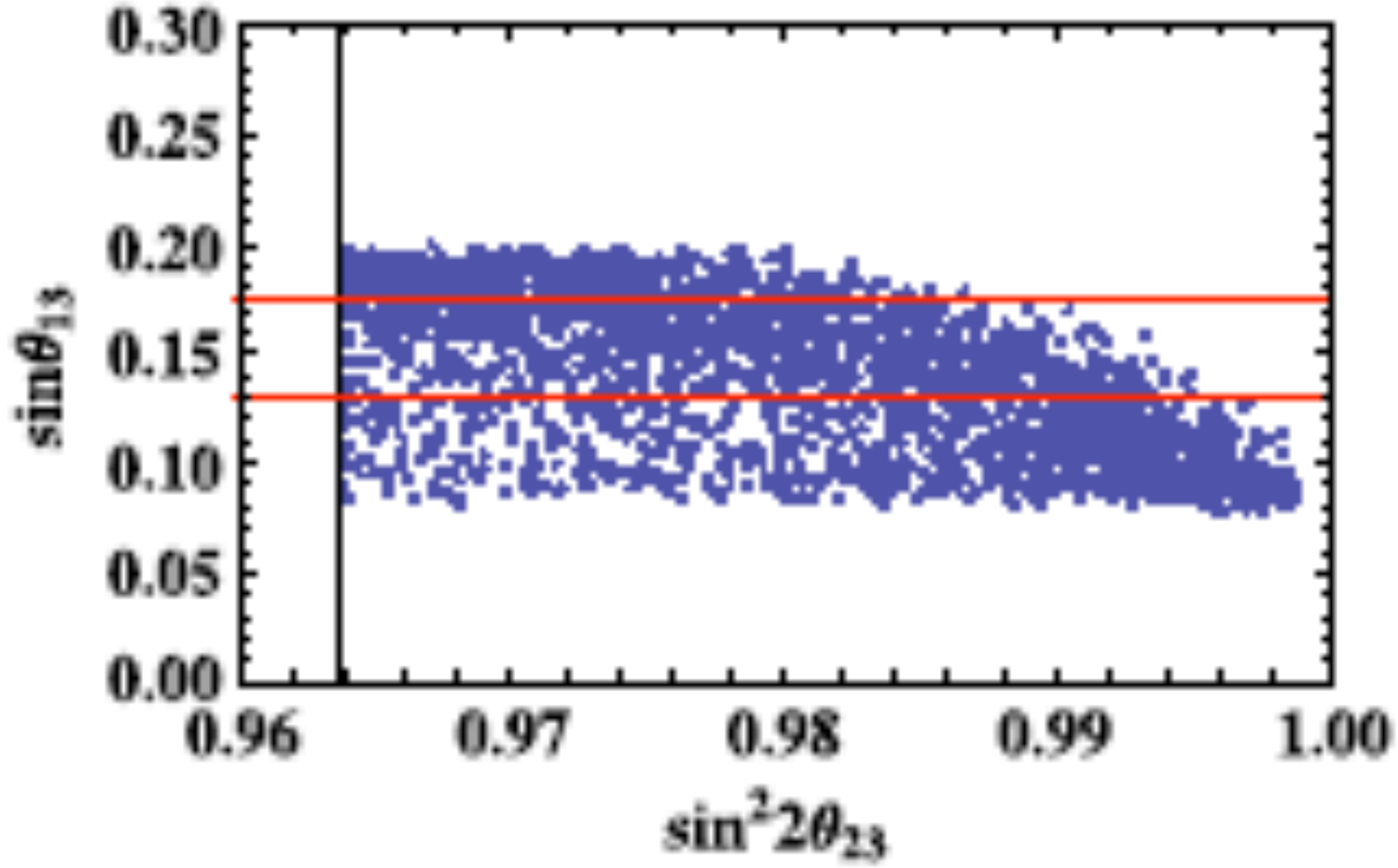
$$m_E = \begin{pmatrix} 0 & A_\ell & 0 \\ A_\ell & 0 & B_\ell \\ 0 & B_\ell & C_\ell \end{pmatrix}, \qquad m_{\nu D} = \begin{pmatrix} 0 & A_\nu & 0 \\ A_\nu & 0 & B_\nu \\ 0 & B_\nu & C_\nu \end{pmatrix},$$

$$M_i = (M_1, M_2, M_3)$$

All Δm^2 and $\sin^2\theta_{12}, \sin^2\theta_{23}$ are accounted for at a good accuracy: tests $\sin^2\theta_{13}$ (and ϕ)

Consistent only with normal hierarchy

θ_{13} test (prediction) MF, Shimizu, Tanimoto, Yanagida 2012



$$m_{ee} = 3.7 - 5.6 \text{ meV}$$

$$\sum m_\nu = 59 - 63 \text{ meV}$$

$$(1 \text{ meV}) < \quad \bar{m} = 48 - 53 \text{ meV} \quad (< 200 \text{ meV})$$

Problems

Is neutrino Dirac or Majorana?

Exploration needed down to 5 meV

First milestone to 20 meV

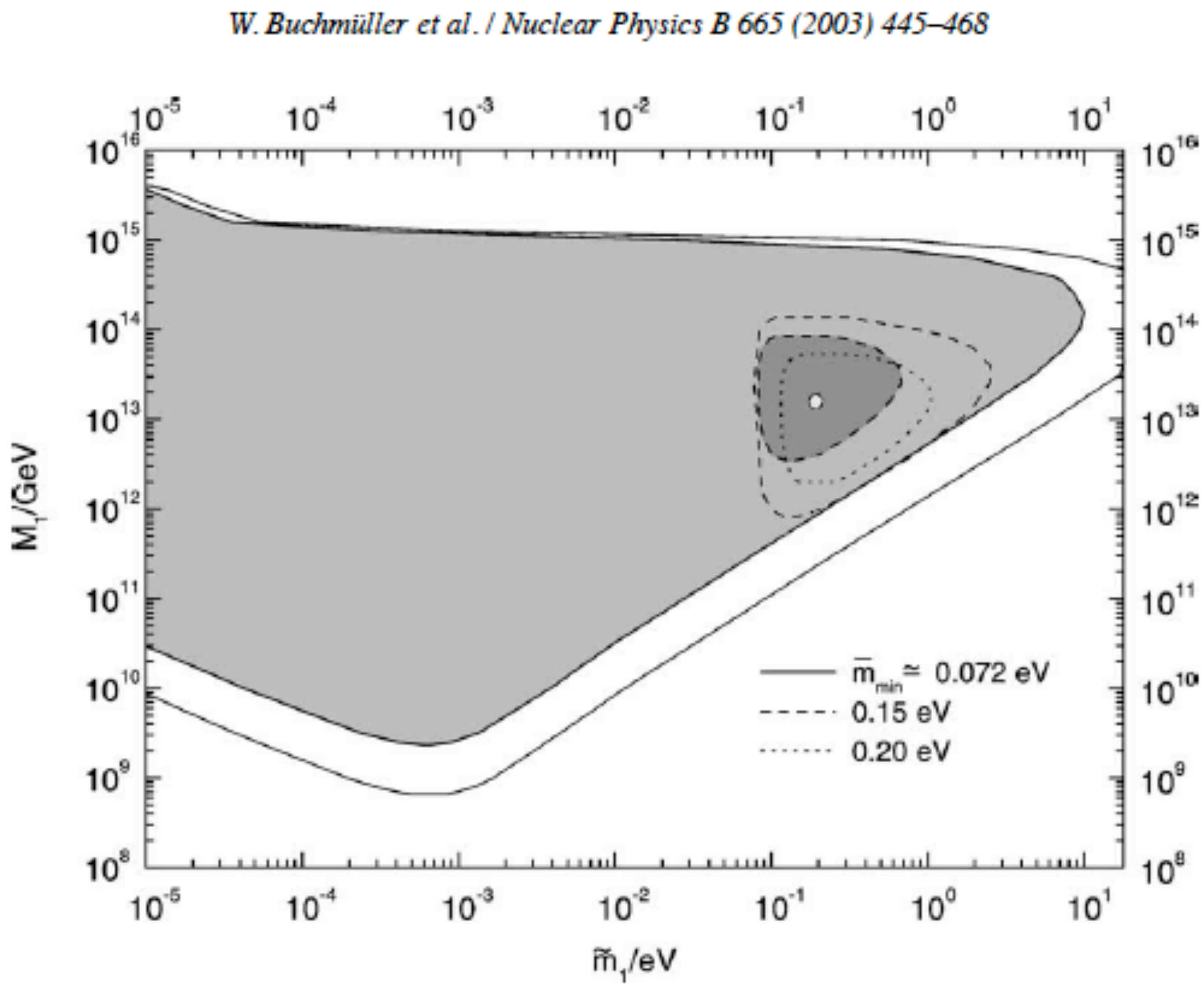
Nuclear matrix element: a measure for reliability?

Where is parallelism between quarks and leptons?

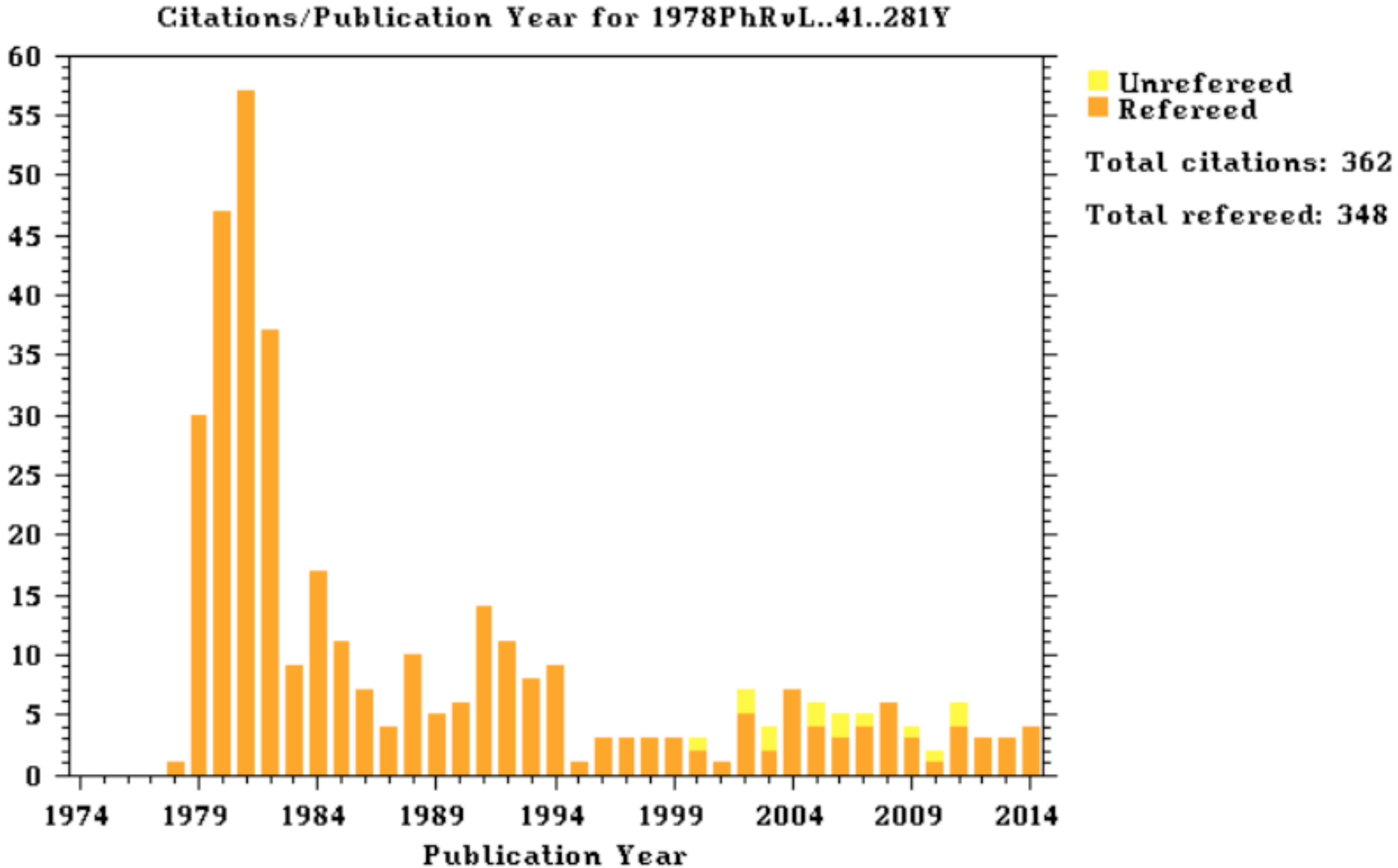
For the moment, none is known

How to get information as to heavy M and Dirac mass?

Buchmueller et al. : case of inverted hierarchy

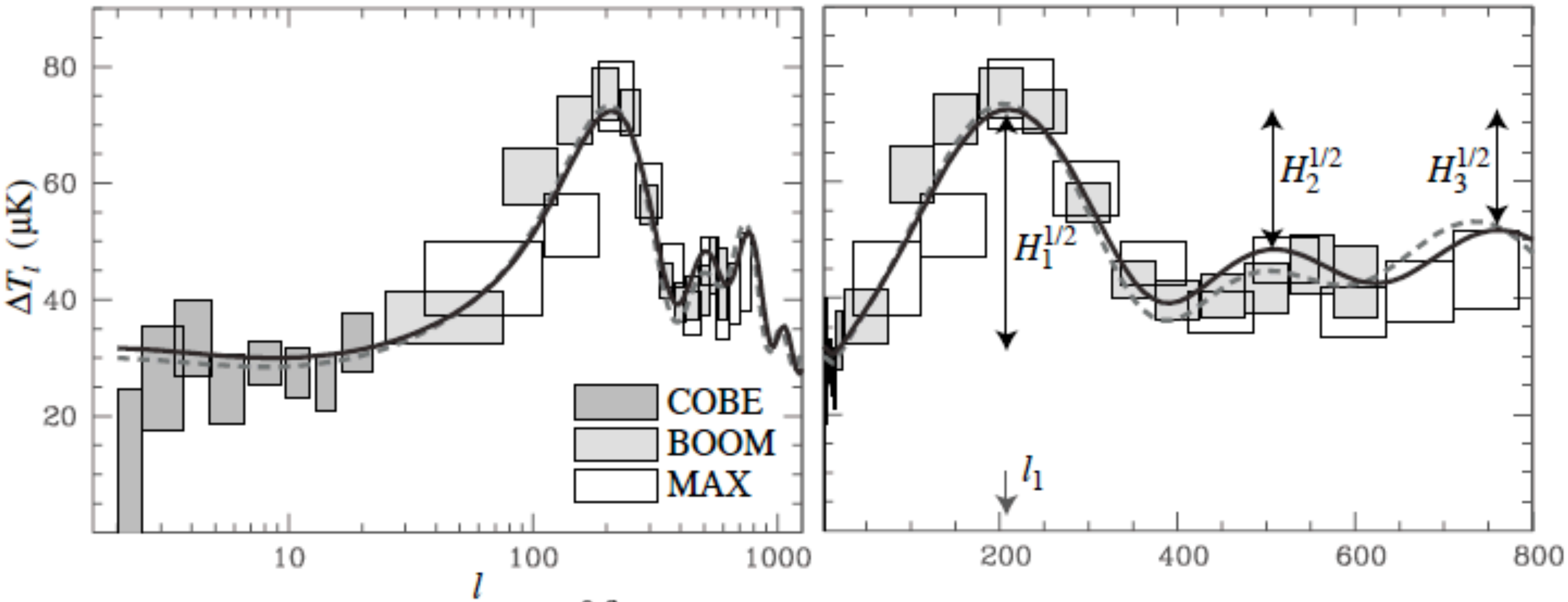


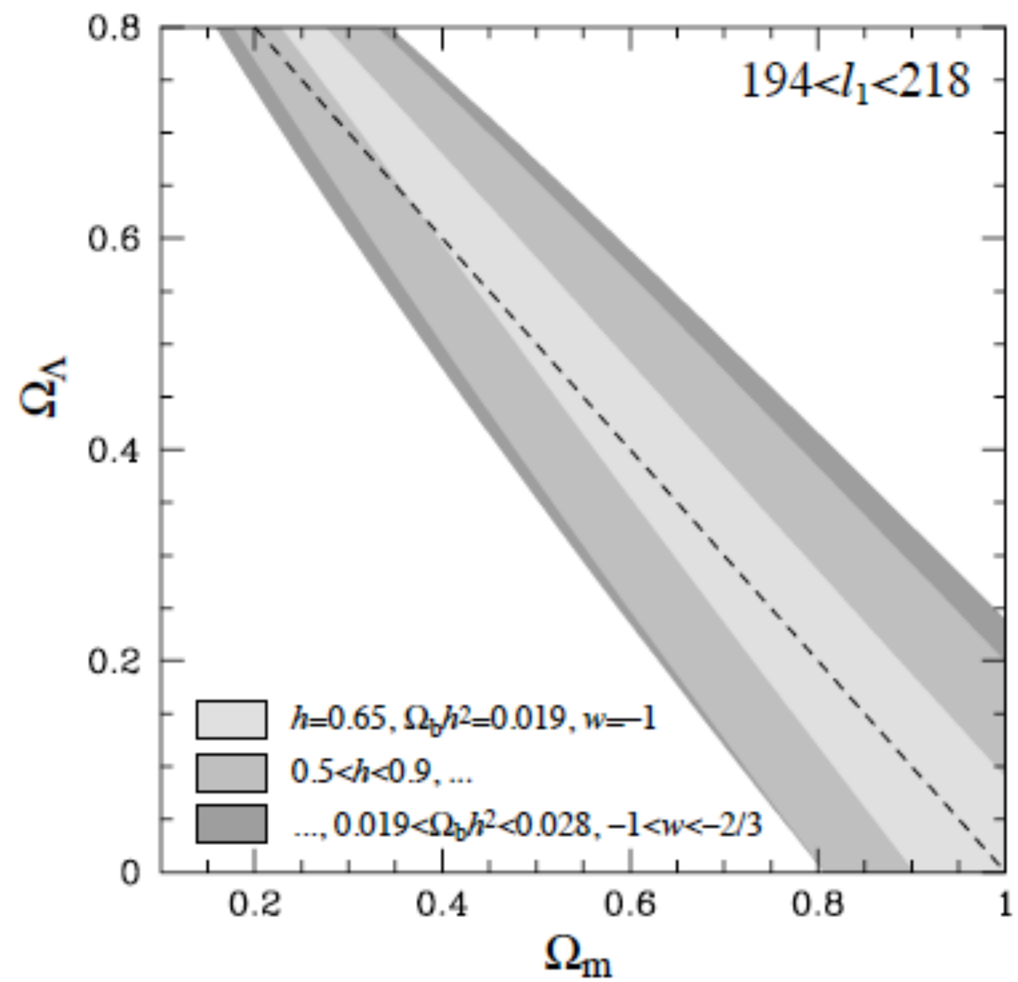
Yoshimura 1978

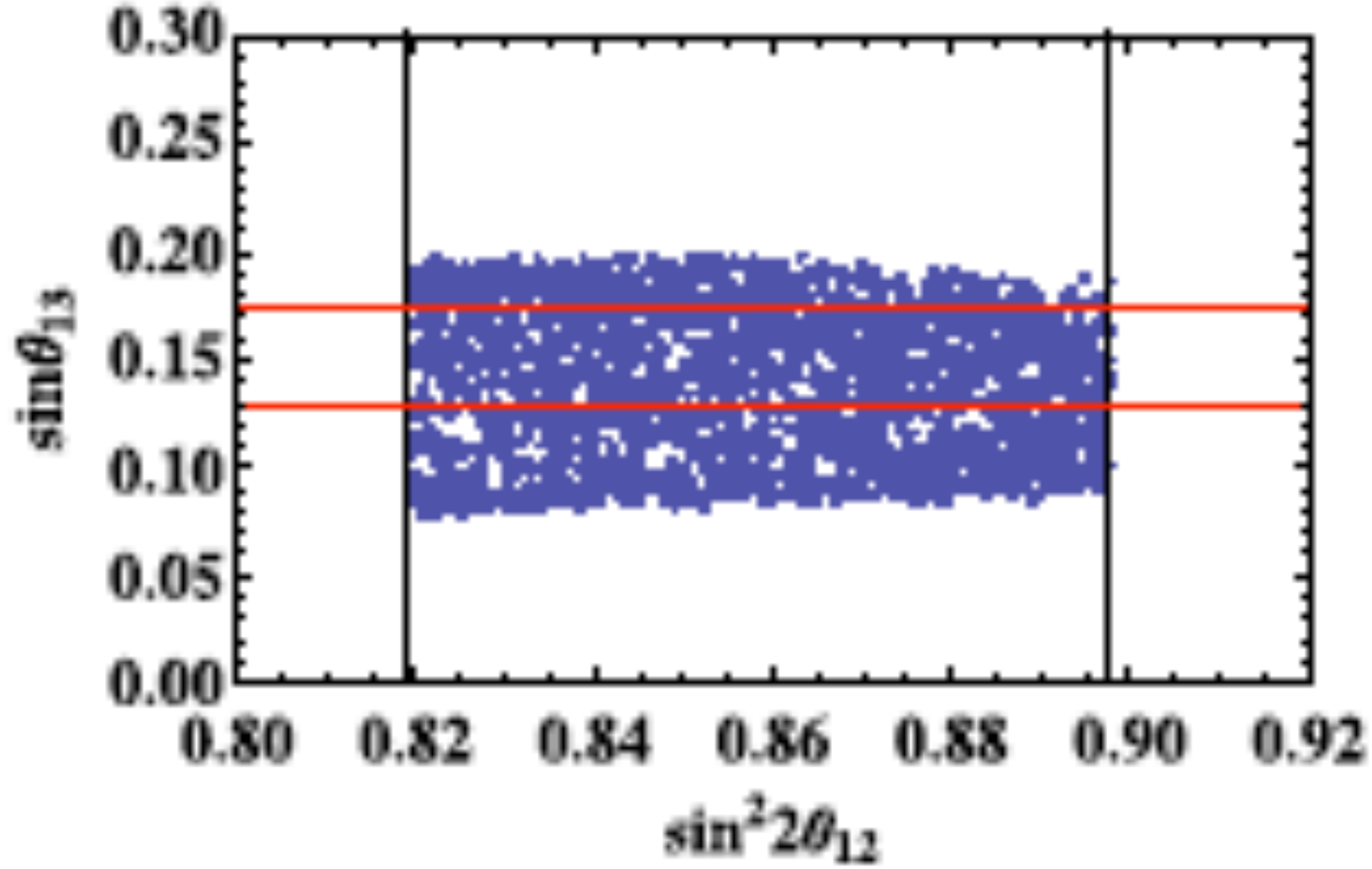


Hu, MF, Zaldarriaga, Tegmark 2001

before WMAP (2000)






0.30
0.25
0.20
0.15
0.10
0.05
0.00
$\sin\theta_{13}$
0.80
0.82
0.84
0.86
0.88
0.90
0.92
$\sin^2 2\theta_{12}$

MF, Shimizu, Tanimoto, Yanagida