Outlook in Neutrino Physics

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IFIC
INSTITUT DE FISICA CORPUSCULAR

invisibles
neutrinos, dark matter & dark energy physics

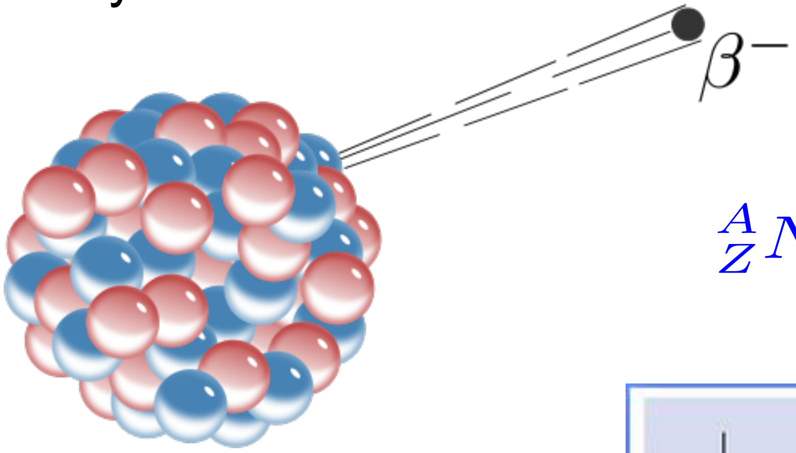
MARIE CURIE ACTIONS

PEOPLE

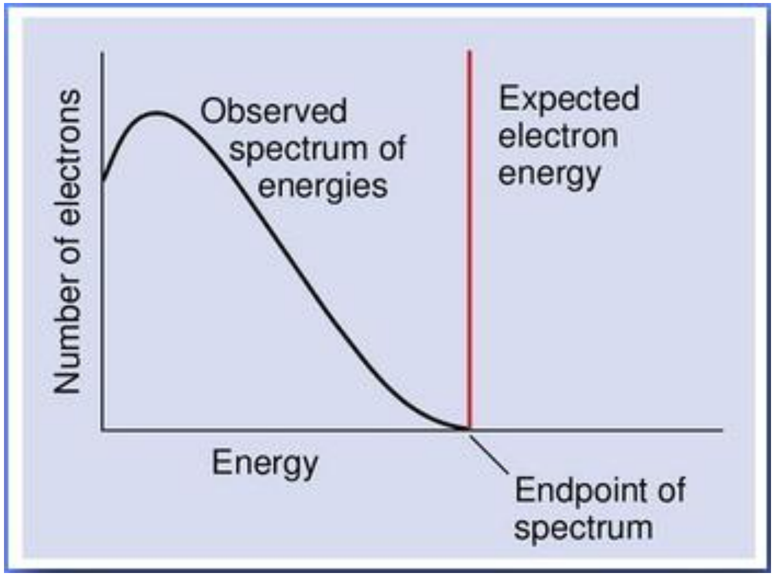
The dark particles

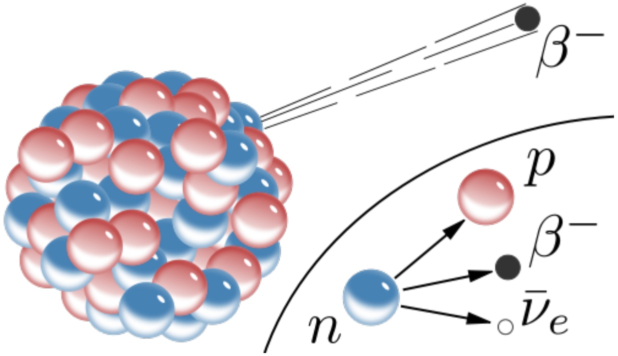
1900 Radioactivity: Becquerel, M & P Curie, Rutherford....

β decay



$$ {}^{A}_{Z}N \rightarrow {}^{A}_{Z+1}N' + e^- $$





1930

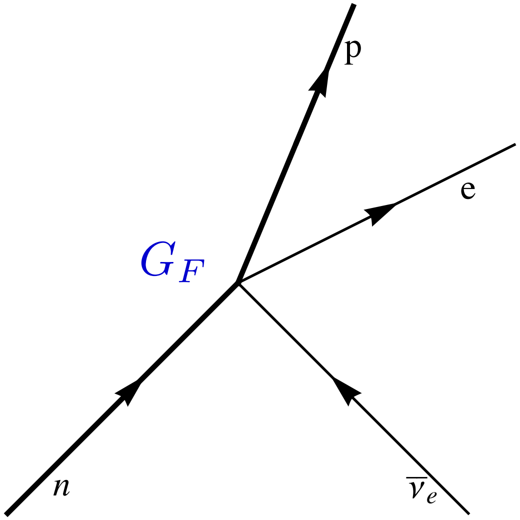
Pauli (Nobel 1945)

Dear Radioactive Ladies and Gentlemen,

As the bearer of these lines, to whom I graciously ask you to listen, will explain to you in more detail, how because of the "wrong" statistics of the N and Li^6 nuclei and the continuous beta spectrum, I have hit upon a desperate remedy to save the "exchange theorem" of statistics and the law of conservation of energy. Namely, the possibility that there could exist in the nuclei electrically neutral particles, that I wish to call neutrons, which have spin 1/2 and obey the exclusion principle, and which further differ from light quanta in that they do not travel with the velocity of light. The mass of the neutrons should be of the same order of magnitude as the electron mass and in any event not larger than 0.01 proton masses. The continuous beta spectrum would then become understandable by the assumption that in beta decay a neutron is emitted in addition to the electron such that the sum of the energies of the neutron and the electron is constant...

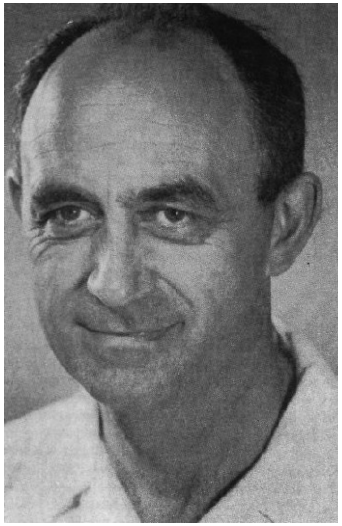
Unfortunately, I cannot personally appear in Tübingen since I am indispensable here in Zürich because of a ball on the night from December 6 to 7....

1934: Theory of beta decay



$$n + \nu \rightarrow p + e^-$$

$$p + \bar{\nu} \rightarrow n + e^+$$



E. Fermi
(Nobel 1938)

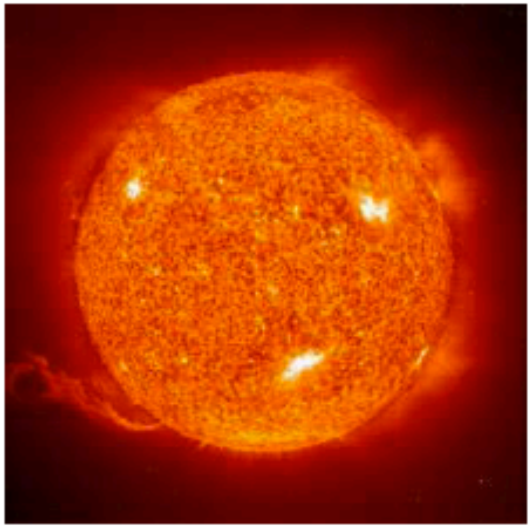
Nature did not publish his article: "contained speculations too remote from reality to be of interest to the reader…"

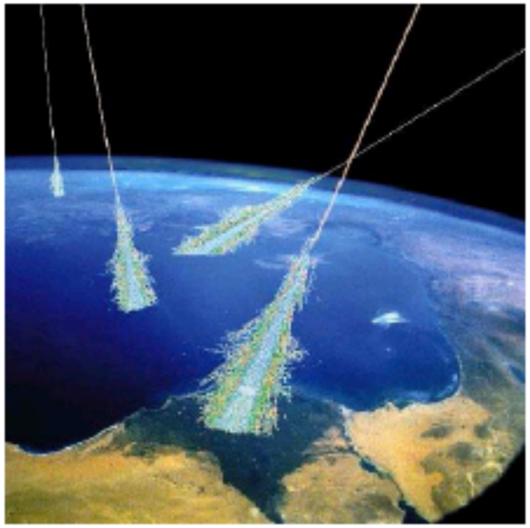
Bethe-Peierls (1934): compute the neutrino cross section using this theory

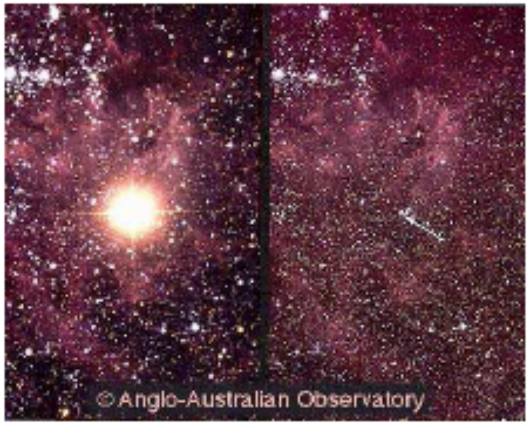
$$\sigma \simeq 10^{-44} cm^2,\ E(\bar{\nu}) = 2\ \mathrm{MeV}$$

"there is not practically possible way of detecting a neutrino"

Revealing Pauli's dark matter was just a question of time and ingenuity...

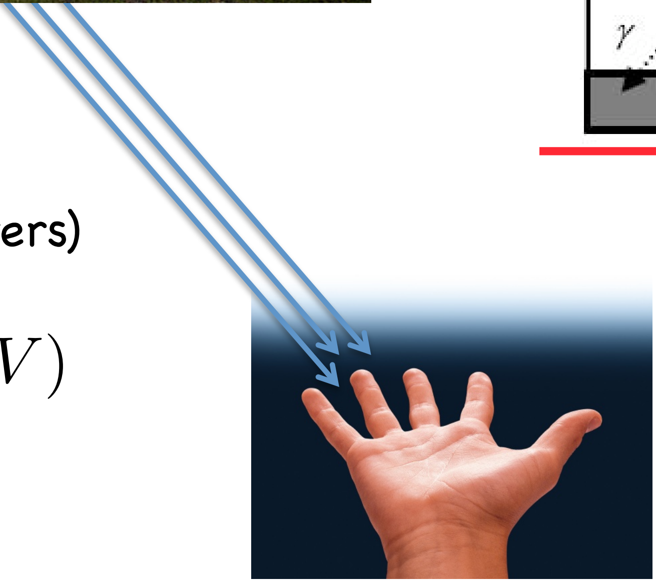






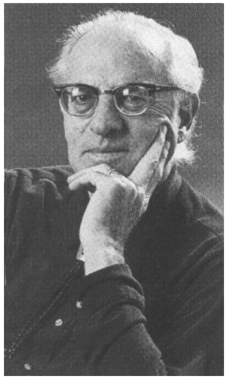
The reactor (anti)-neutrino was hunted...

Reactors: ~ 10^{20}/second!



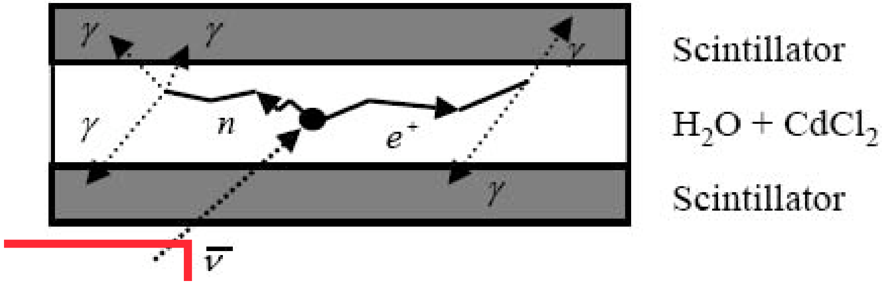
(10^{11}/s@100 meters)

$$E_\nu \sim \mathcal{O}(MeV)$$



Reines Nobel 95

Cowan (died 74)



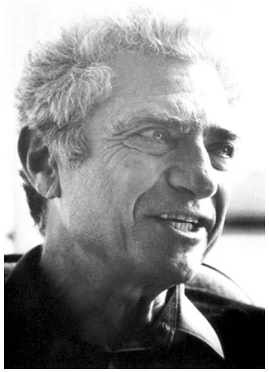
Neutrino Flavour

$$\begin{pmatrix} \nu_e \\ e \end{pmatrix} \begin{pmatrix} \nu_\mu \\ \mu \end{pmatrix}$$

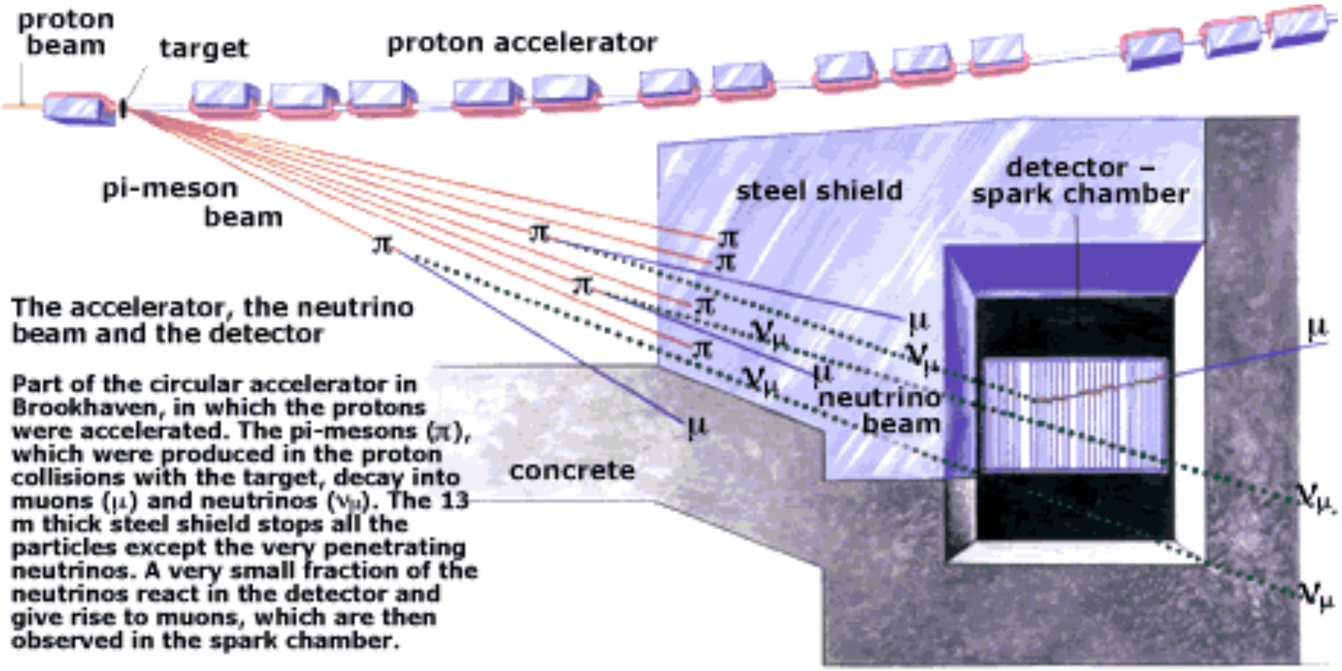
$$E_\nu \sim \mathcal{O}(GeV)$$


Lederman


Schwartz


Steinberger

Nobel 1988



The accelerator, the neutrino beam and the detector

Part of the circular accelerator in Brookhaven, in which the protons were accelerated. The pi-mesons (π), which were produced in the proton collisions with the target, decay into muons (μ) and neutrinos (ν_μ). The 13 m thick steel shield stops all the particles except the very penetrating neutrinos. A very small fraction of the neutrinos react in the detector and give rise to muons, which are then observed in the spark chamber.

Based on a drawing in Scientific American, March 1963.

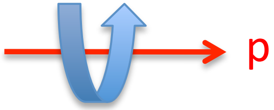
Neutrinos in the Standard Model

$(1,2)_{-\frac{1}{2}}$	$(3,2)_{-\frac{1}{6}}$	$(1,1)_{-1}$	$(3,1)_{-\frac{2}{3}}$	$(3,1)_{-\frac{1}{3}}$
$\begin{pmatrix} \nu_e \\ e \end{pmatrix}_L$	$\begin{pmatrix} u^i \\ d^i \end{pmatrix}_L$	e_R	u^i_R	d^i_R
$\begin{pmatrix} \nu_\mu \\ \mu \end{pmatrix}_L$	$\begin{pmatrix} c^i \\ s^i \end{pmatrix}_L$	μ_R	c^i_R	s^i_R
$\begin{pmatrix} \nu_\tau \\ \tau \end{pmatrix}_L$	$\begin{pmatrix} t^i \\ b^i \end{pmatrix}_L$	τ_R	t^i_R	b^i_R

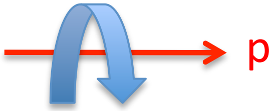
$$\Psi_{L/R} \equiv P_{L/R}\Psi$$

$$P_{L/R} \equiv \frac{1 \mp \gamma_5}{2}$$

Left-handed



Right-handed

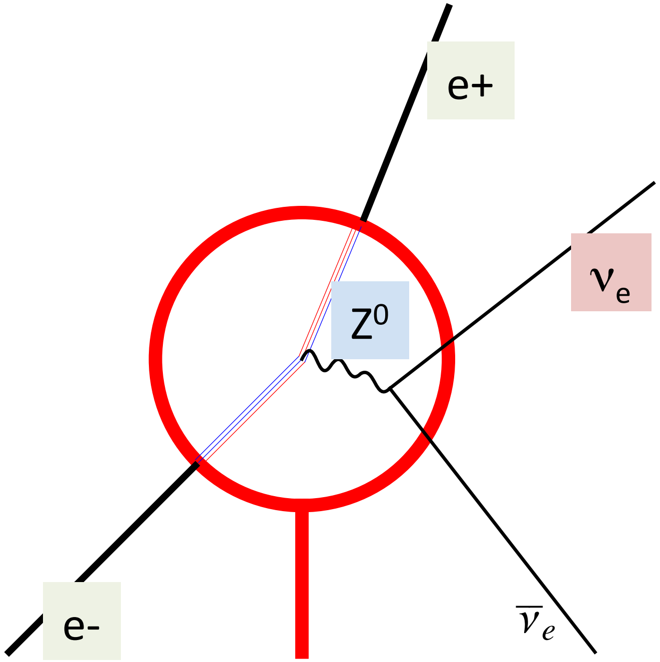


Neutrinos have been key to establishing the two most intringuing features of the SM:

3-fold repetition of family structures

handedness of the weak interactions

Neutrinos in the Standard Model



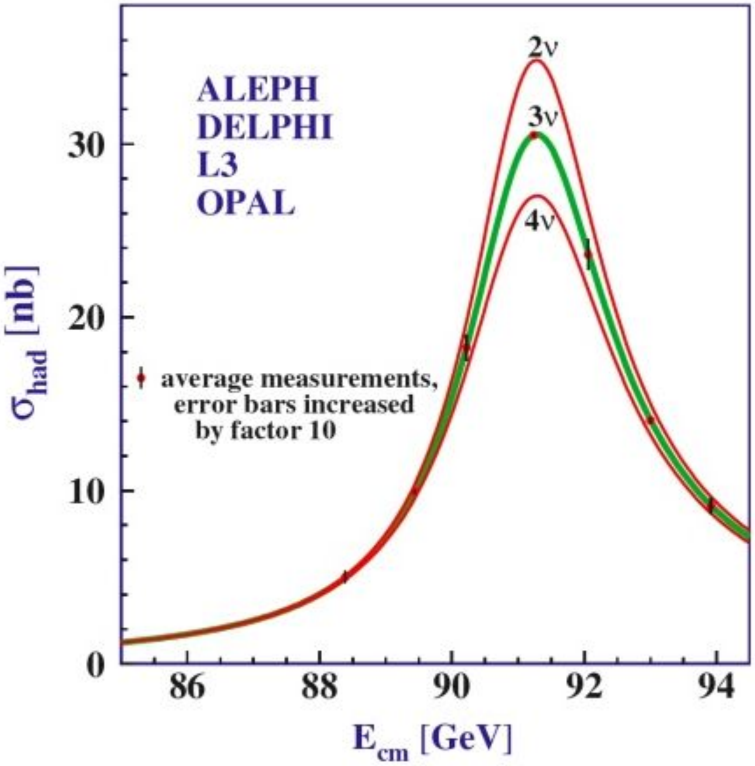
Neutral currents: NC

$$N_\nu = \frac{\Gamma_{\rm inv}}{\Gamma_{\nu\bar{\nu}}} = 2.984 \pm 0.008$$

At LEP:

$$e^+e^- \to Z^0 \to f\bar{f}$$

Only three neutrinos -> three SM families



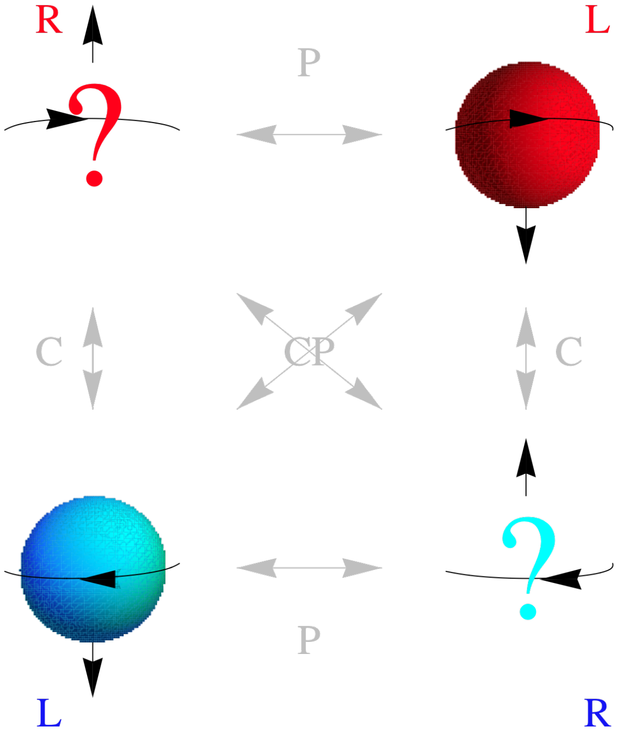
Breaking of C and P

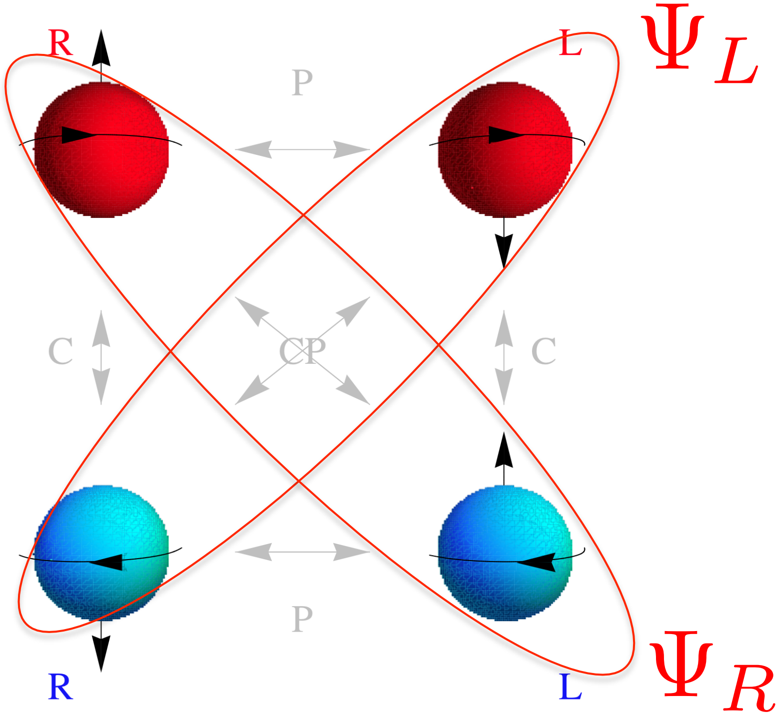
Weyl fermion= 2-component spinor

(Minimal spin ½)

Dirac fermion= 4-component spinor

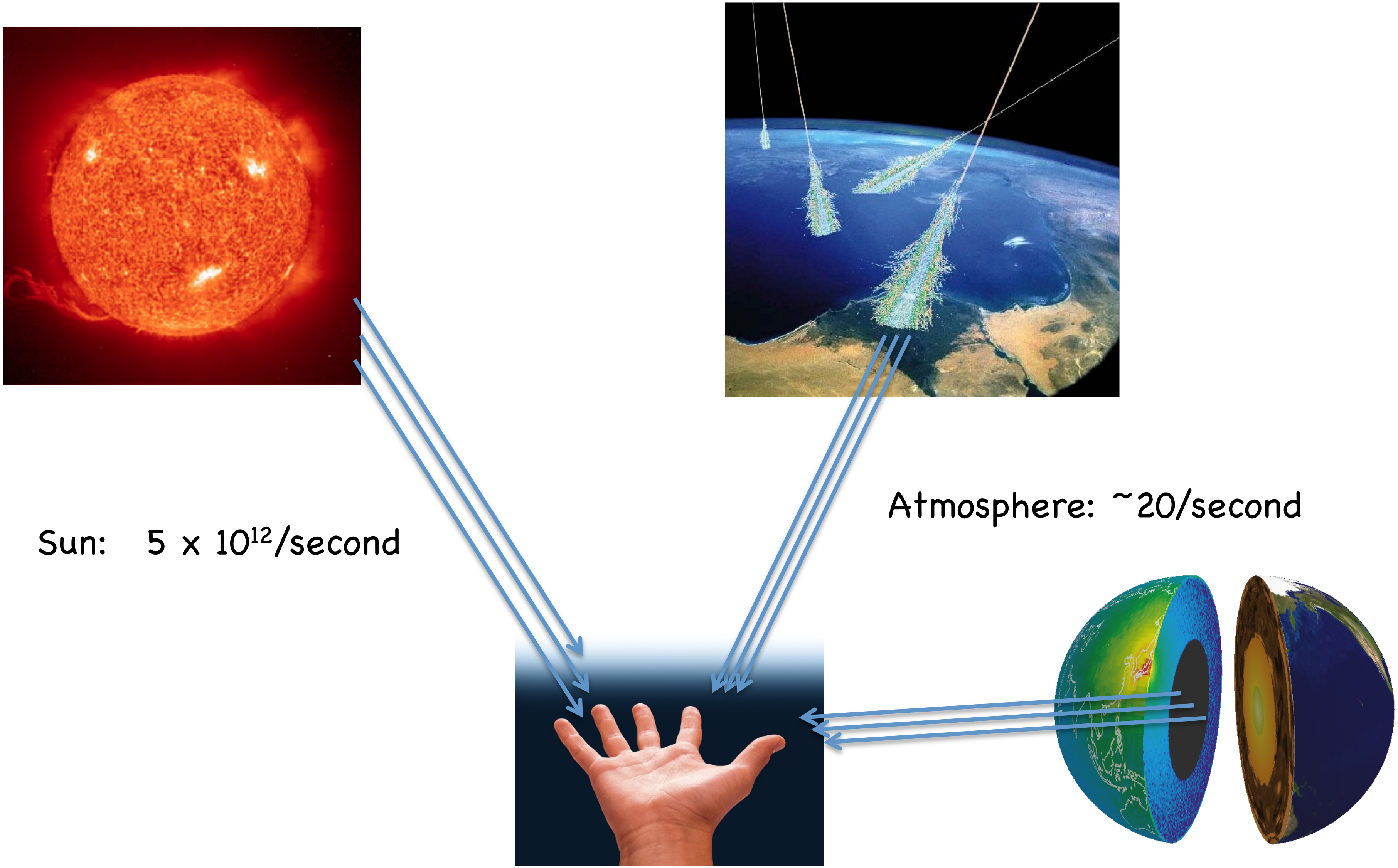
(Minimal spin ½ + Parity)





Ubiquitous Neutrinos

They are everywhere…

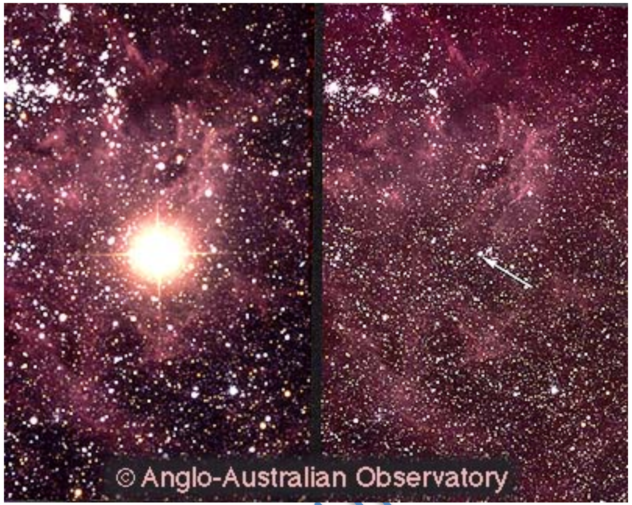


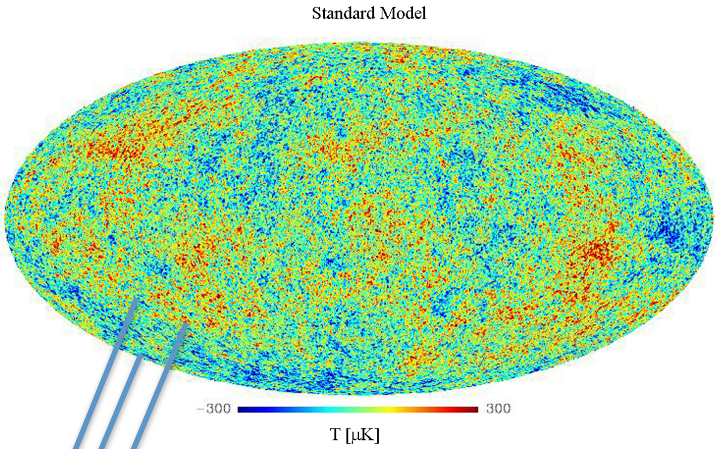
Sun: 5 x 10^{12}/second

Atmosphere: ~20/second

Earth: ~10^{9}/second

Ubiquitous Neutrinos



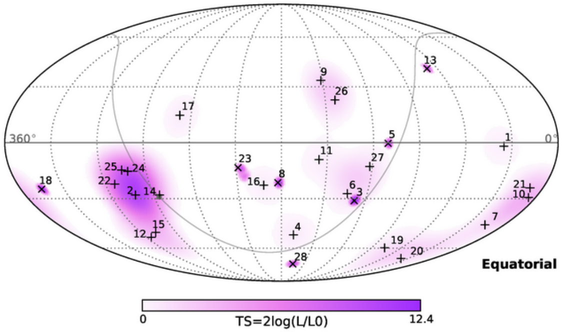


Simulation showing the distribution on the sky of temperature fluctuations in the Cosmic Microwave Background with neutrinos as in the Standard Model.

Big Bang: ~2 x 10^{12}/second

Supernova 1987: ~10^{12}/second

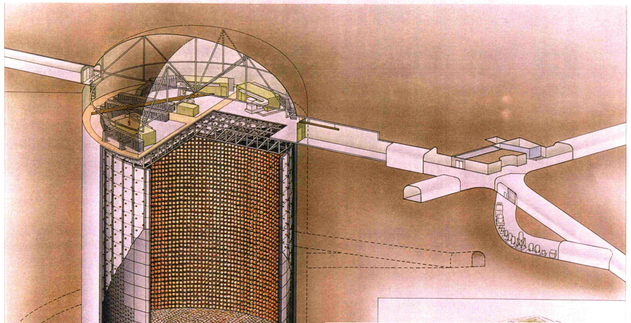
@168000 Light years!
10^{8} farther from Earth

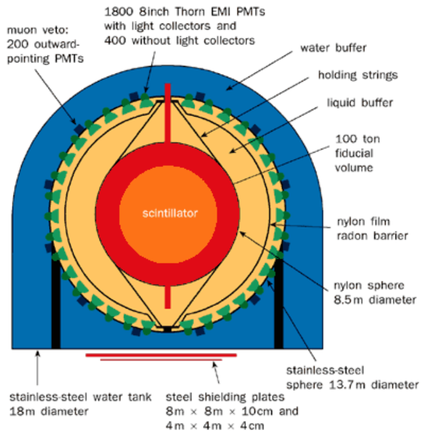


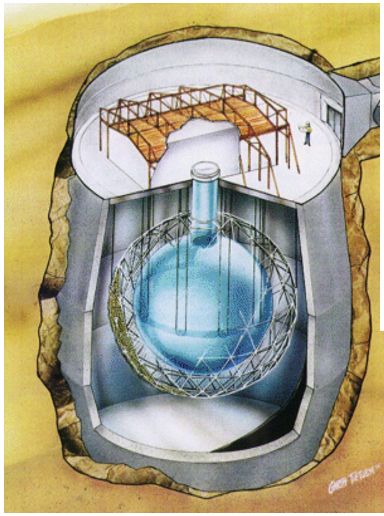
Icecube PeV events

A decade of revolutionary neutrino experiments have revealed a new flavour sector, which does not quite fit in the Standard Model

SuperKamiokande





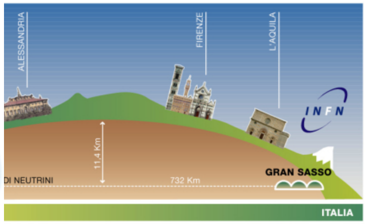


SNO

Borexino

KamLAND
Kamioka Liquid scintillator Anti-Neutrino Detector

MINOS, Opera



T2K

NOvA

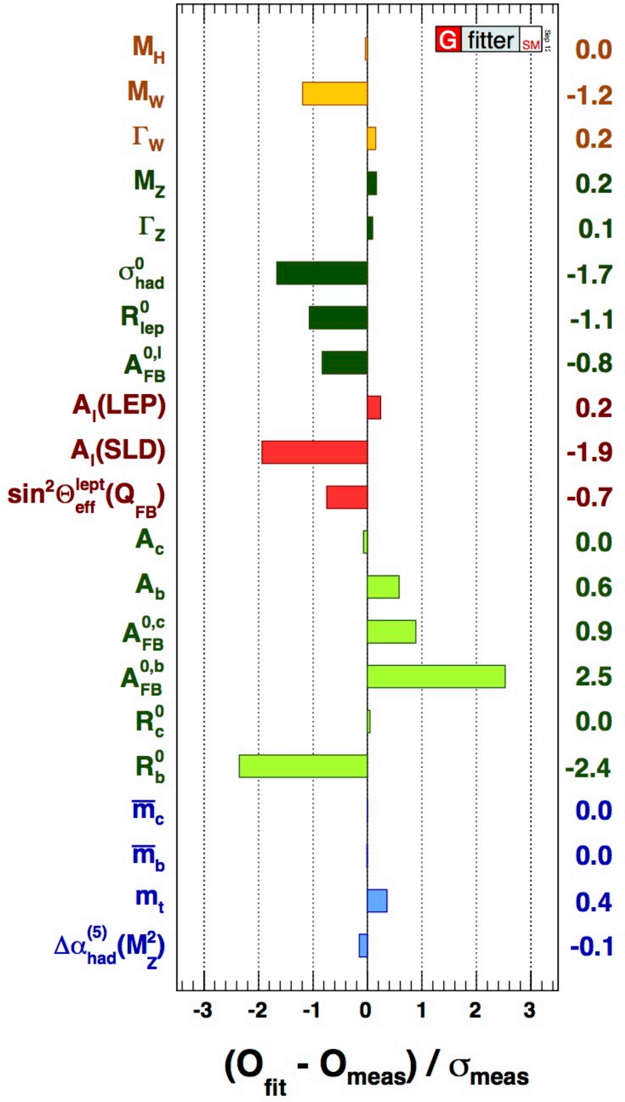
DOUBLE

Daya Bay
θ13

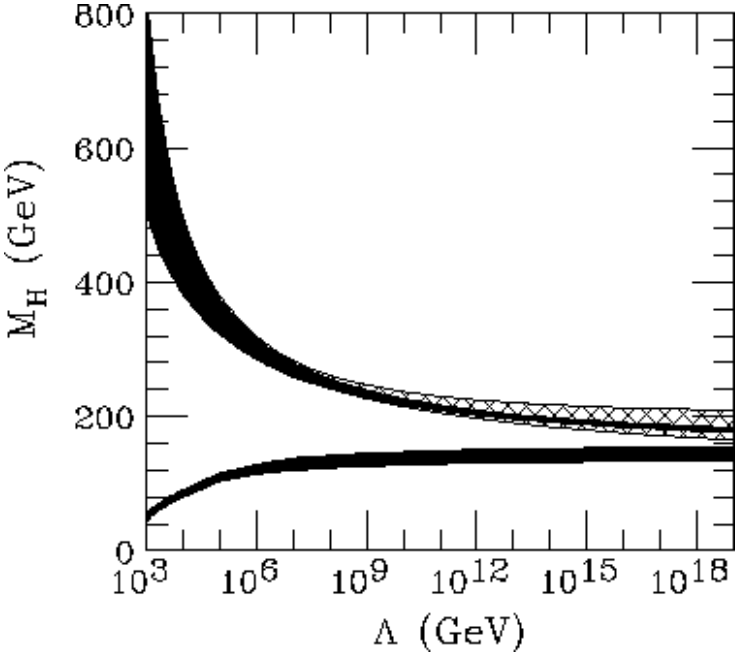
RENO
ν θ13

...and more

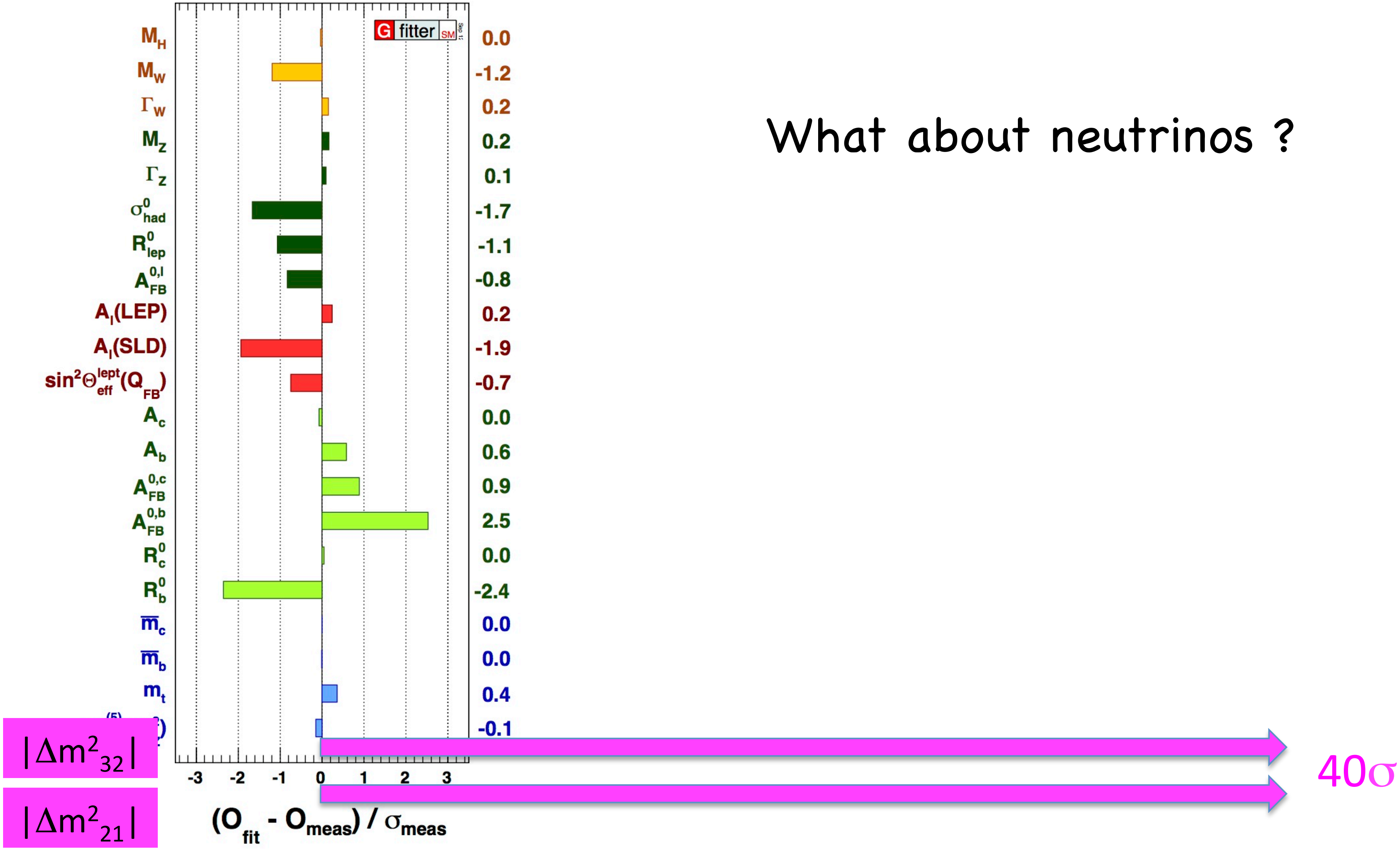
After the discover the Brout-Englert-Higgs particle



Standard Model as healthy as ever...



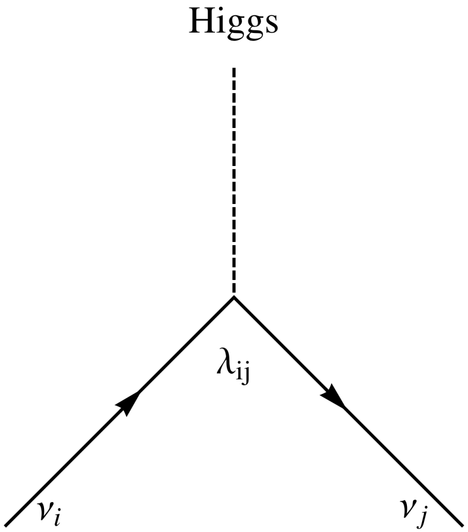
What about neutrinos ?



New dofs needed !

Neutrinos are massive -> there must be new dofs in the SM

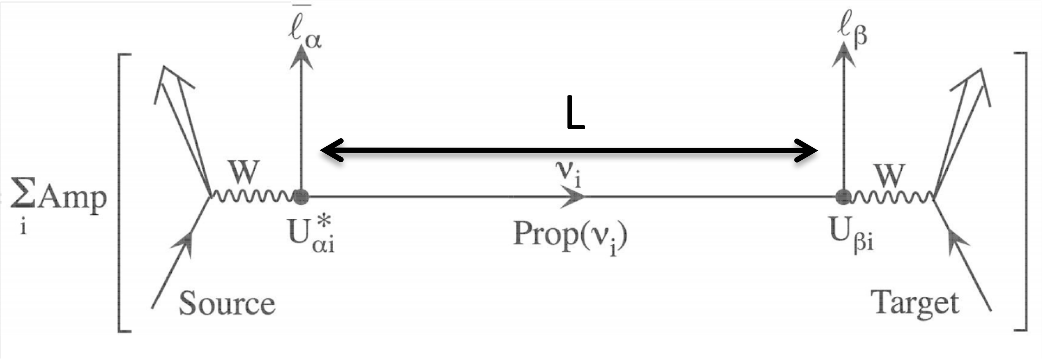
$$-\mathcal{L}_{\rm Dirac} = \bar{\nu}_L m_\nu \nu_R + h.c. \;\; \leftrightarrow \bar{L}\tilde{\Phi}\lambda\nu_R + h.c.$$



$$m_\nu \sim \lambda v$$

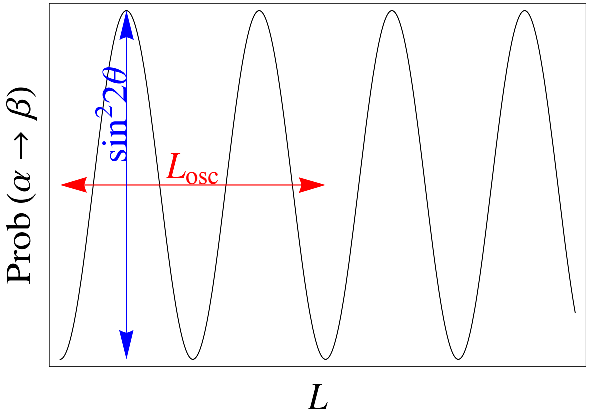
$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = U_{PMNS}(\theta_{12}, \theta_{23}, \theta_{13}, \delta, \ldots) \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

Neutrino Interferometry



Бруно Понтекорво

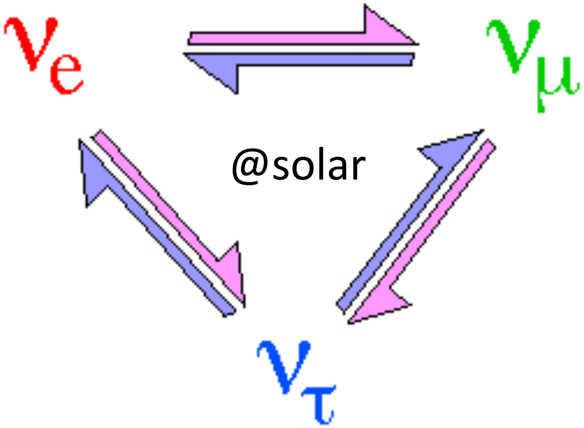
A neutrino experiment is an interferometer in flavour space, because neutrinos are so weakly interacting that can keep coherence over very long distances !



$$P(\nu_\alpha \to \nu_\beta) = \sum_{ij} U_{\alpha i} U^*_{\beta i} U^*_{\alpha j} U_{\beta j} e^{-i \frac{(m_i^2 - m_j^2) L}{2E}}$$

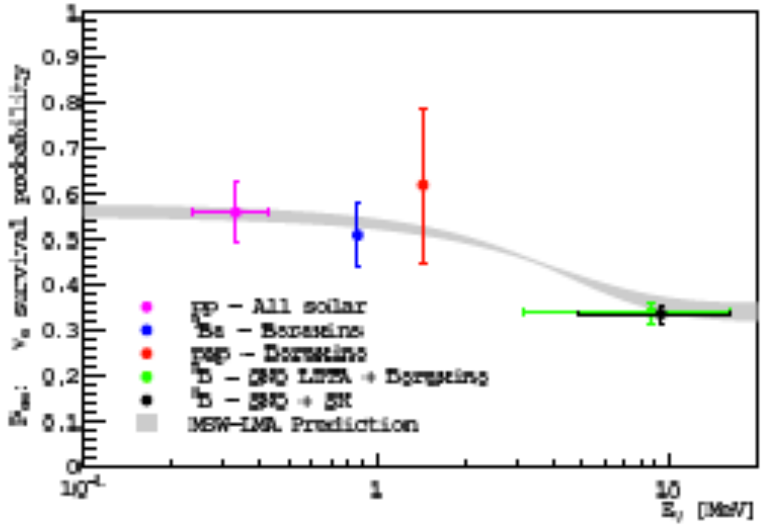
$$L_{osc} \sim \frac{E}{m_i^2 - m_j^2}$$

Solar oscillation of ν_e

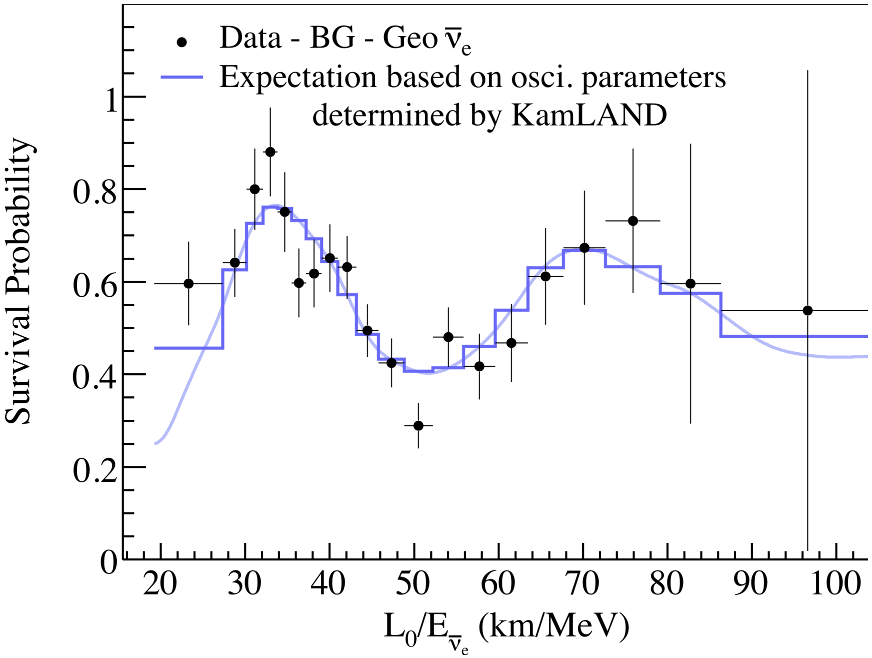


$$|\Delta m^2| \simeq 8 \times 10^{-5}\mathrm{eV}^2 \sim \frac{\mathcal{O}(\mathrm{MeV})}{\mathcal{O}(100\mathrm{km})}$$

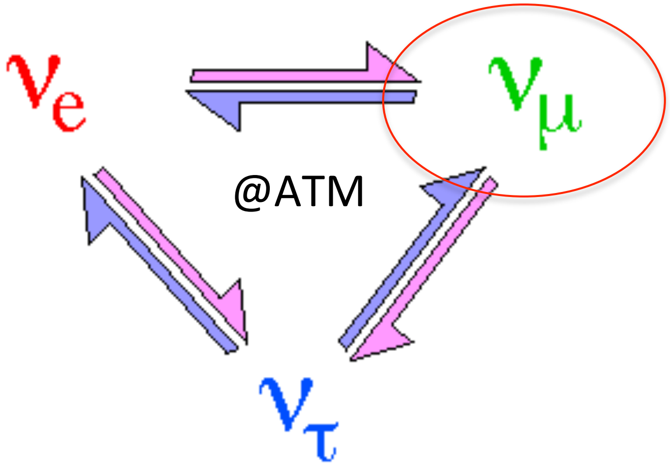
MSW conversion in Sun



KamLAND = Reines&Cowan @170km

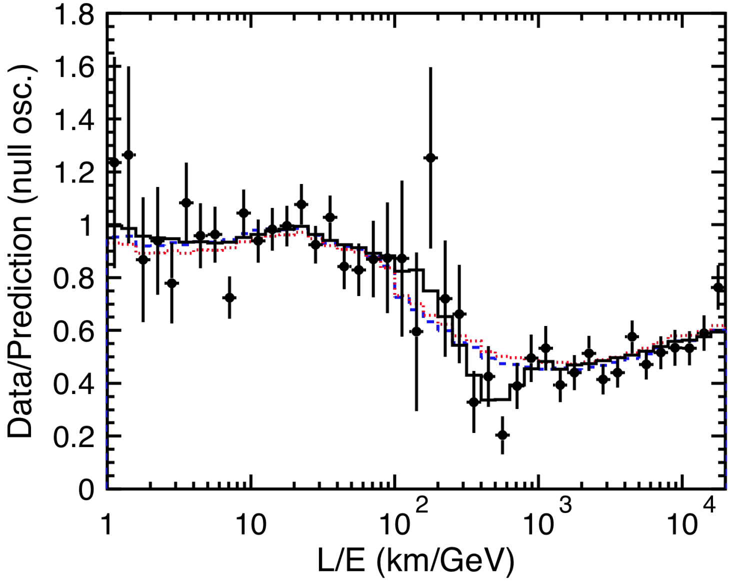


Atmospheric Oscillation of ν_μ



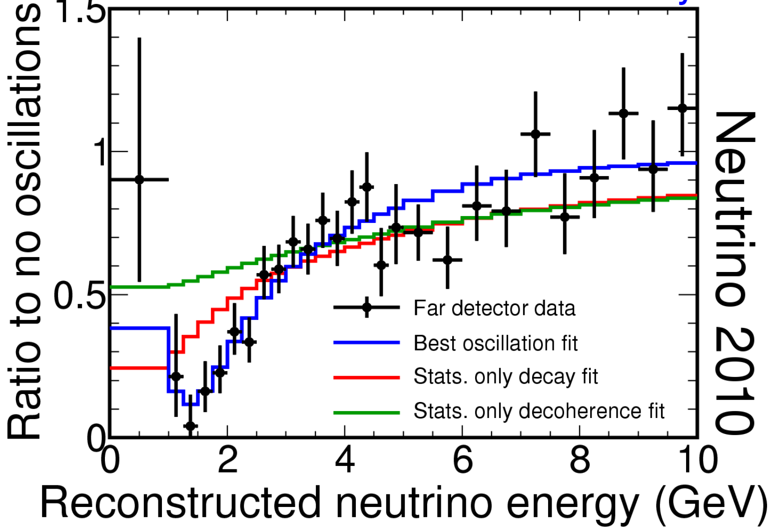
$$|\Delta m^2| \simeq 2.5 \times 10^{-3}\text{eV}^2 \sim \frac{\mathcal{O}(\text{GeV})}{\mathcal{O}(1000\text{ km})} \sim \frac{\mathcal{O}(\text{MeV})}{\mathcal{O}(1\text{ km})}$$

SuperKamiokande

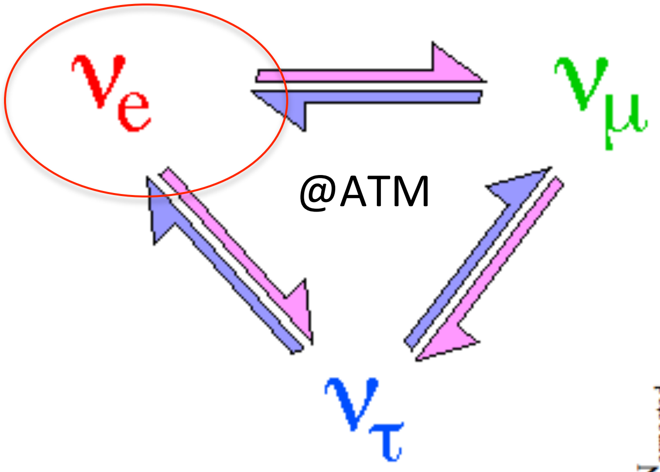


MINOS=LSS experiment @730km

MINOS Preliminary

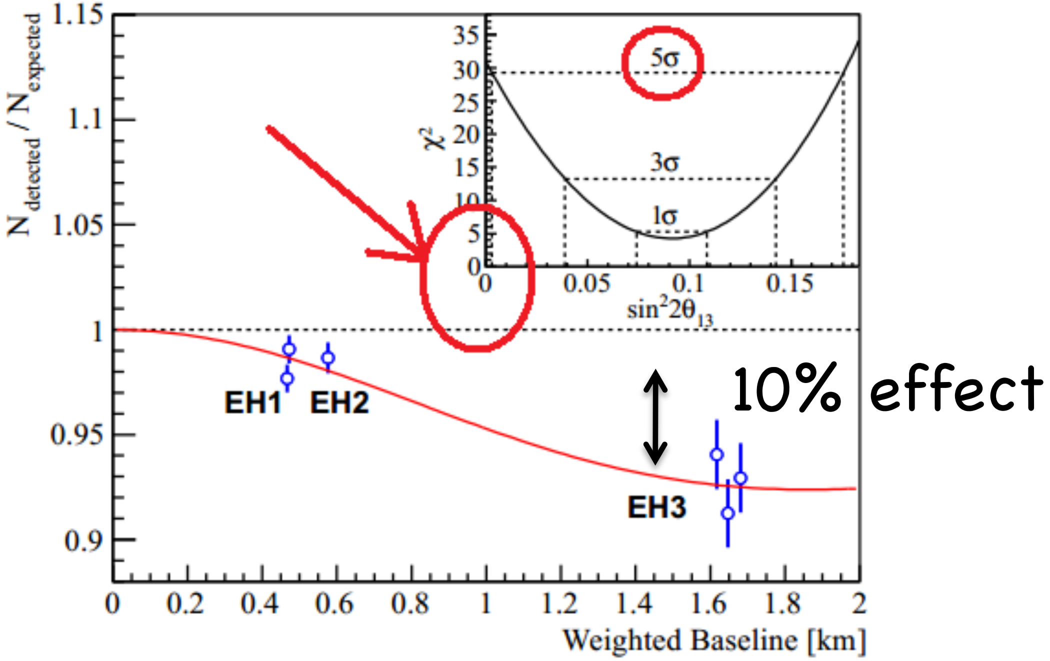


Atmospheric Oscillation of ν_e



$$|\Delta m^2| \simeq 2.5 \times 10^{-3}\text{eV}^2 \sim \frac{\mathcal{O}(\text{GeV})}{\mathcal{O}(1000\text{ km})} \sim \frac{\mathcal{O}(\text{MeV})}{\mathcal{O}(1\text{ km})}$$

Daya Bay= Reines&Cowan @1km



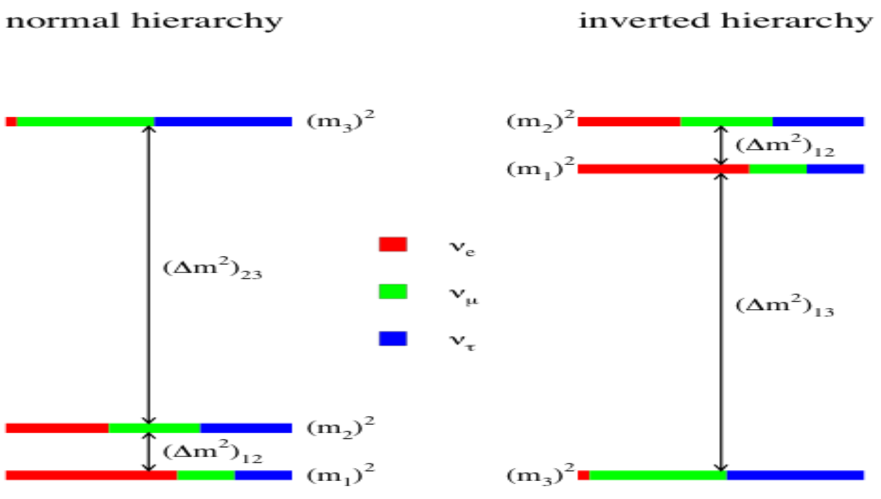
2012

T2K, Double Chooz
Daya Bay, RENO

SM+3 massive neutrinos

www.nu-fit.org

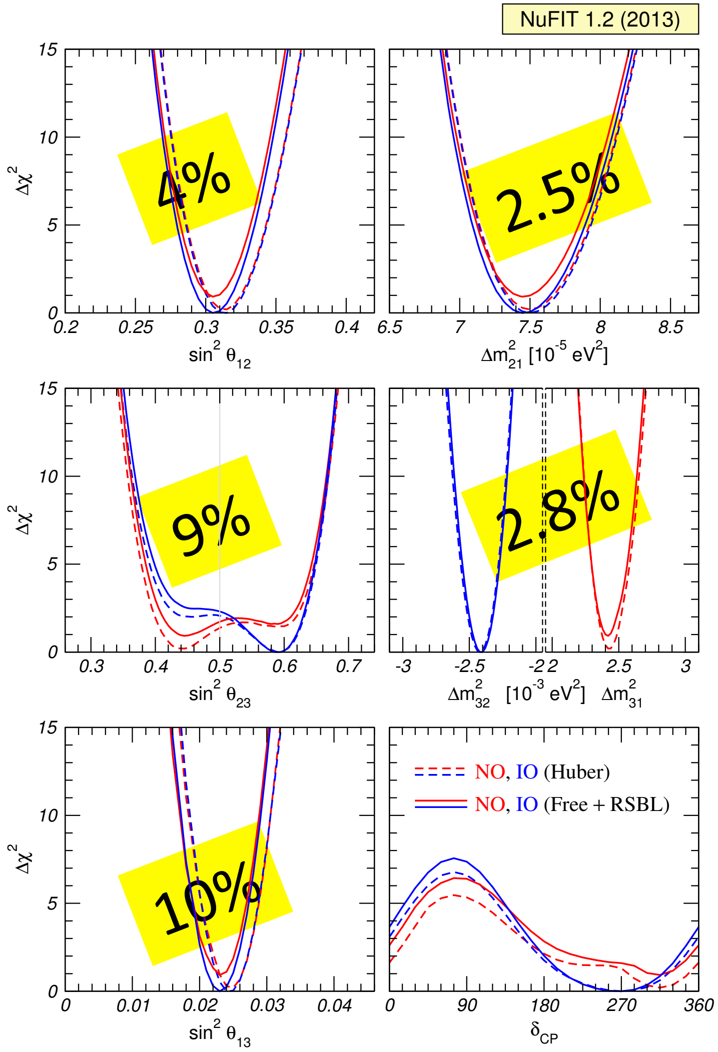
$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = U_{PMNS}(\theta_{12}, \theta_{23}, \theta_{13}, \delta, \ldots) \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$



?

$$\Delta m^2_{13} > 0$$

$$\Delta m^2_{13} < 0$$

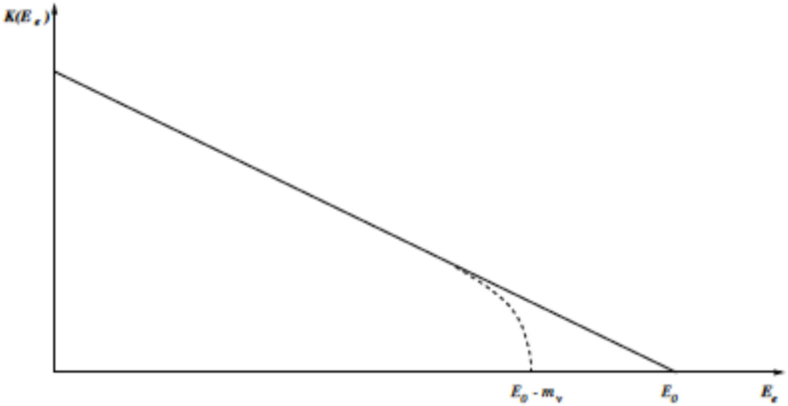


Gonzalez-Garcia et al 1209.3023

Absolute mass scale

Kinematical effects: most stringent from Tritium beta-decay

$$H^3 \rightarrow^3 He + e^- + \bar{\nu}_e$$



$m_{\nu_e} < 2.2\text{eV}$ (Mainz-Troitsk)

$m_{\nu_\mu} < 170\text{keV}$ (PSI: $\pi^+ \to \mu^+ \nu_\mu$)

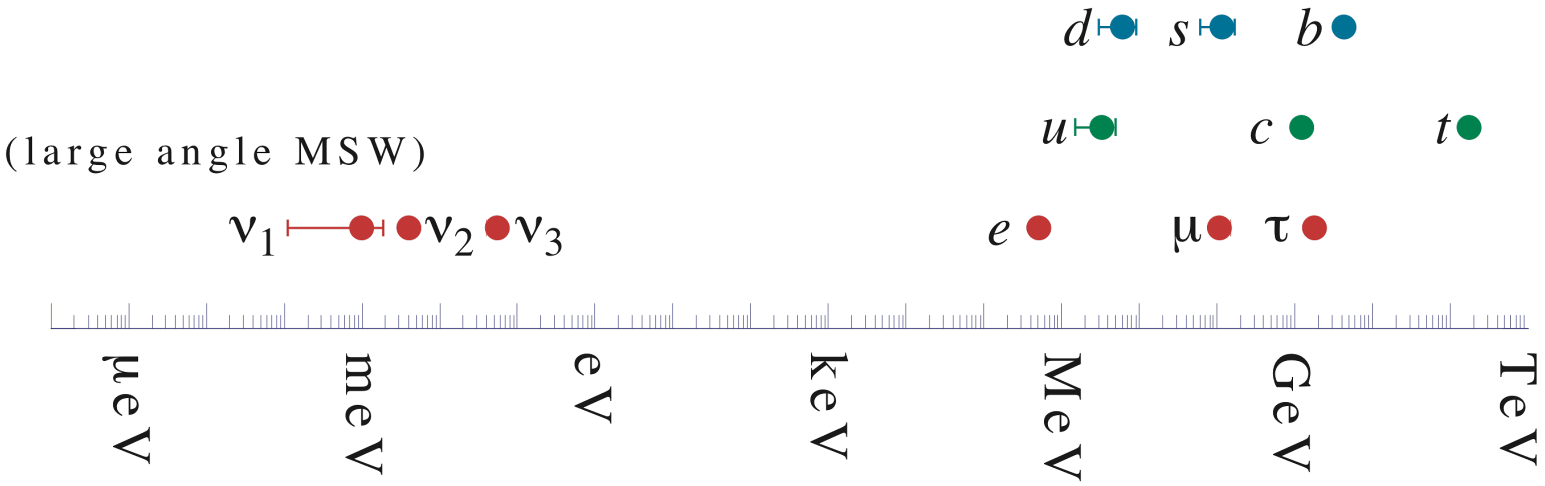
$m_{\nu_\tau} < 18.2\text{MeV}$ (LEP: $\tau^- \to 5\pi\nu_\tau$)

Limits will be soon superseded by Katrin

Gravitational effects: $\sum_i m_i$ from cosmology

Why are neutrinos so much lighter ?

Neutral vs charged hierarchy ?



$m_f \sim \lambda$

Why so different mixing ?

CKM

$$|V|_{\mathrm{CKM}} = \begin{pmatrix} 0.97427 \pm 0.00015 & 0.22534 \pm 0.0065 & (3.51 \pm 0.15) \times 10^{-3} \\ 0.2252 \pm 0.00065 & 0.97344 \pm 0.00016 & (41.2^{+1.1}_{-5}) \times 10^{-3} \\ (8.67^{+0.29}_{-0.31}) \times 10^{-3} & (40.4^{+1.1}_{-0.5}) \times 10^{-3} & 0.999146^{+0.000021}_{-0.000046} \end{pmatrix}$$

PMNS

3σ

$$|U| = \begin{pmatrix} 0.795 \to 0.846 & 0.513 \to 0.585 & 0.126 \to 0,178 \\ 0.205 \to 0.543 & 0.416 \to 0.730 & 0.579 \to 0.808 \\ 0.215 \to 0.548 & 0.409 \to 0.725 & 0.567 \to 0.800 \end{pmatrix}$$

Gonzalez-Garcia, et al 1209.3023

A new physics scale

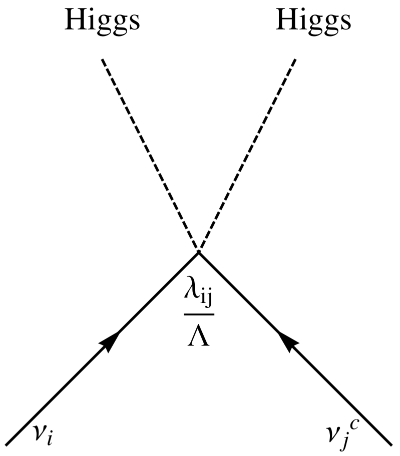
Neutrinos have tiny masses <-> a new physics scale !

$$-\mathcal{L}_{\text{Majorana}} = \bar{\nu}_L m_\nu \nu_L^c + h.c. \;\; \leftrightarrow \bar{L}\tilde{\Phi}\;\alpha\;\tilde{\Phi}L^c + h.c.$$

Weinberg

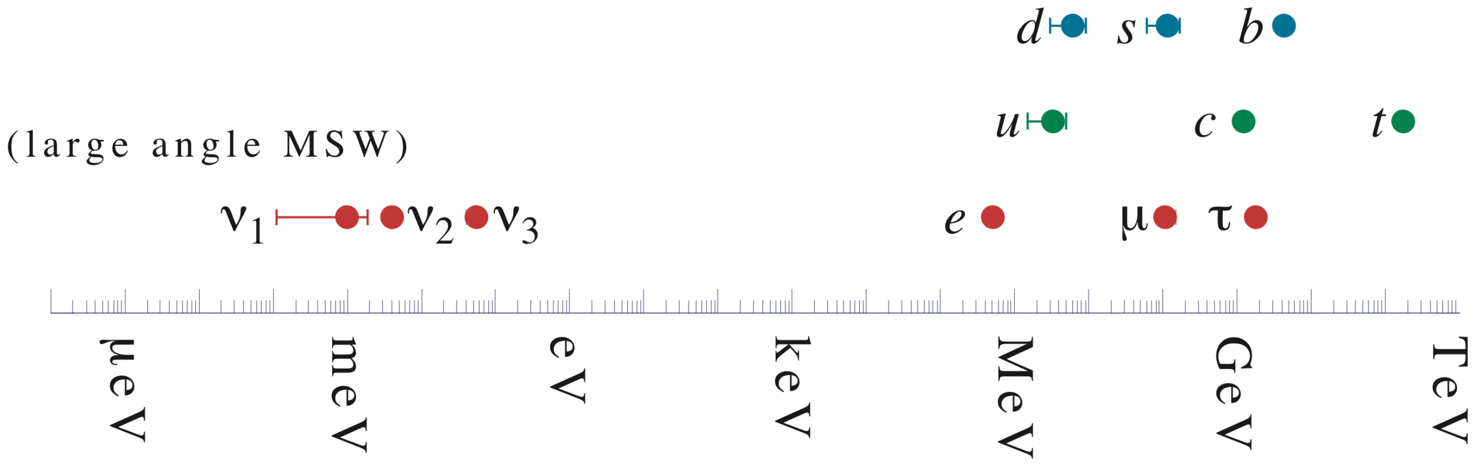
$$[\alpha] = -1$$

$$m_\nu \sim \lambda \frac{v^2}{\Lambda}$$

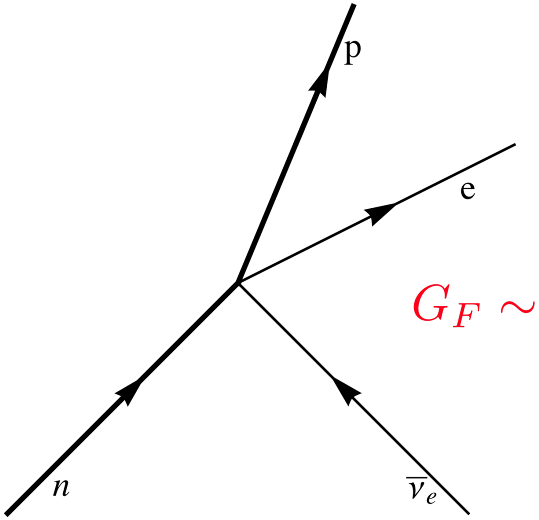


Massive Majorana neutrinos & SSB ?

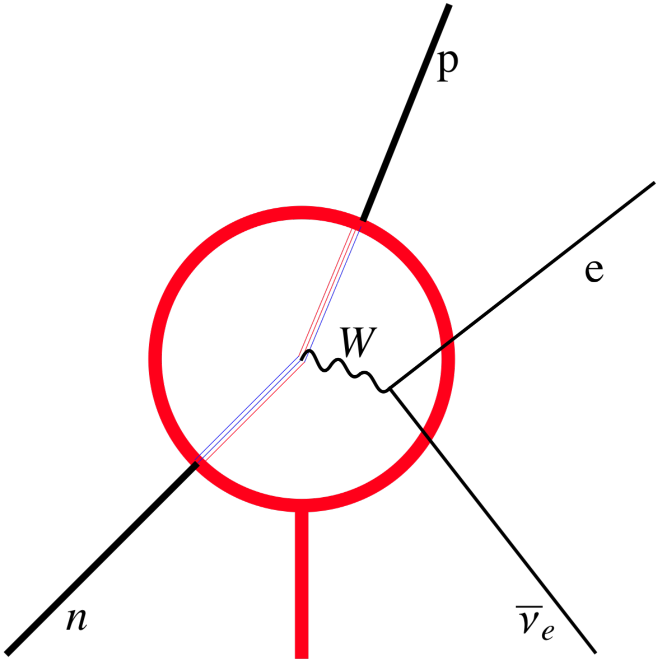
If Λ >> v natural explanation for the smallness of neutrino mass



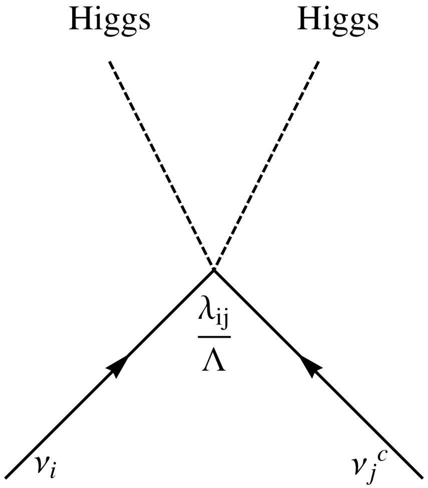
$$m_f(\text{charged}) \sim Y v, \quad m_\nu \sim Y \frac{v^2}{\Lambda} \qquad m_\nu \simeq m_f \frac{v}{\Lambda}$$



$$G_F \sim \frac{1}{M_W^2}$$



SM



→

νSM ?

Effective Theories of Neutrino Masses

For any $\Lambda >> v$ low-energy effects should be well described by an effective field theory:

$$\mathcal{L} = \mathcal{L}_{SM} + \sum_i \frac{\alpha_i}{\Lambda} O_i^{d=5} + \sum_i \frac{\beta_i}{\Lambda^2} O_i^{d=6} + \ldots$$

Weinberg; Buchmuller, Wyler;...

Only one with d=5: Weinberg's operator or neutrino masses !

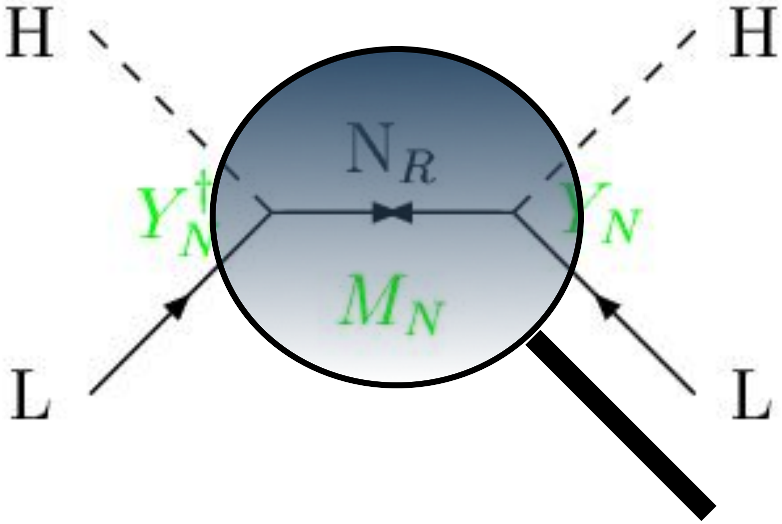
$$O^{d=5} = \bar{L}\tilde{\Phi}C\tilde{\Phi}^T\bar{L}^T + h.c.$$

Data-driven BSM: such that gives the Weinberg operator !

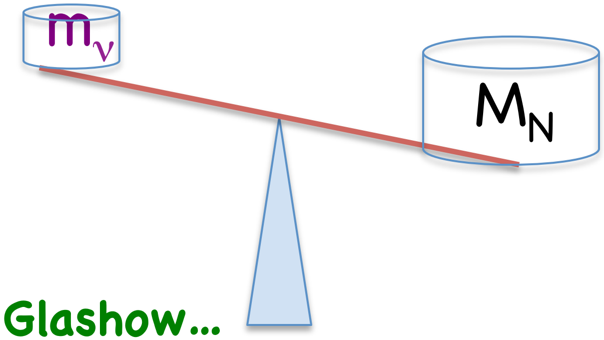
How does the ν scale relates to the EW scale ?

Example: Type I seesaw model

$$\mathcal{L} = \mathcal{L}_{SM} - \sum_{i=1}^{n_R} \bar{l}_L^{\alpha} Y^{\alpha i} \tilde{\Phi} \nu_R^i - \sum_{i,j=1}^{n_R} \frac{1}{2} \bar{\nu}_R^{ic} M_N^{ij} \nu_R^j + h.c.$$



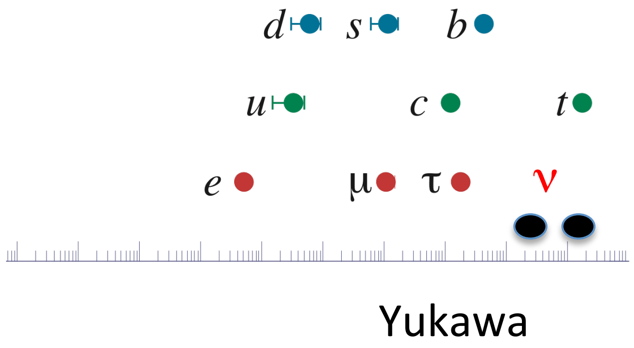
$$m_\nu = \frac{\alpha v^2}{\Lambda} \equiv Y_N^T \frac{v^2}{M_N} Y_N$$



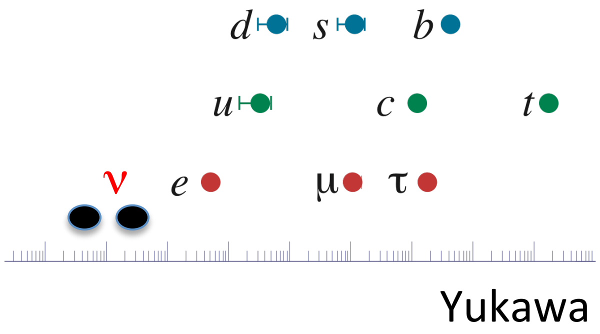
Minkowski; Gell-Mann, Ramond Slansky; Yanagida, Glashow...

Charged/neutral hierarchy in seesaw (I)

M ≤ GUT

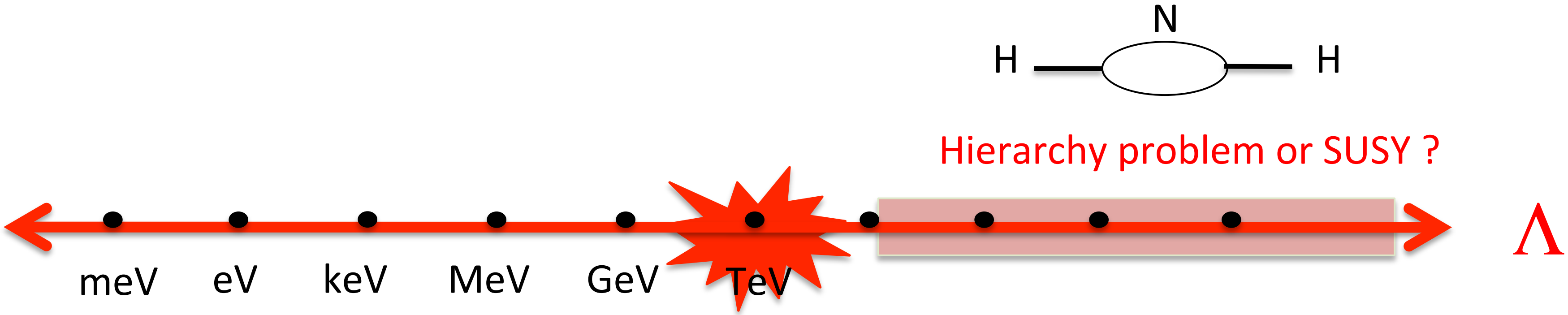


M = TeV



Minkowski; Gell-Mann, Ramond Slansky; Yanagida, Glashow…

Pinning down the New physics scale



Hierarchy problem or SUSY ?

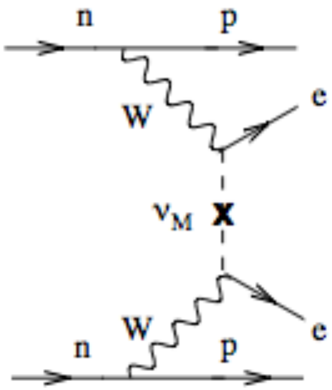
Robust predictions of high (and not so high) scale νSM

there is neutrinoless double beta decay at some level ($\Lambda > 100$MeV)

a matter-antimatter asymmetry if there is CP violation in the lepton sector: leptogenesis

there are other states out there at scale Λ : new physics

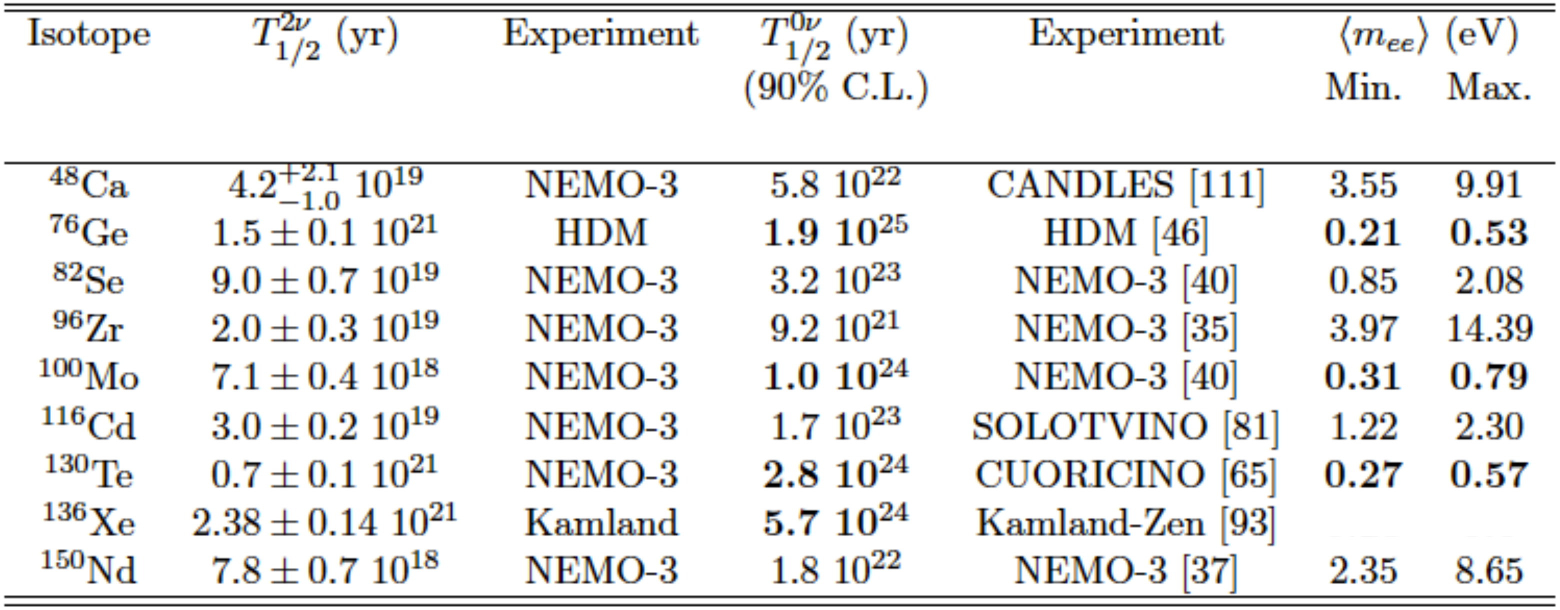
Neutrinoless double-β decay



$$T^{-1}_{2\beta0\nu} \simeq \underbrace{G^{0\nu}}_{\text{Phase}} \underbrace{\left|M^{0\nu}\right|^2}_{\text{Nuclear M.E.}} \underbrace{\left|\sum_i \left(V^{ei}_{MNS}\right)^2 m_i\right|^2}_{|m_{ee}|^2}$$

Present bounds:

Sarazin 2012



Isotope	$T^{2\nu}_{1/2}$ (yr)	Experiment	$T^{0\nu}_{1/2}$ (yr) (90% C.L.)	Experiment	$\langle m_{ee}\rangle$ (eV) Min.	Max.
^{48}Ca	$4.2^{+2.1}_{-1.0}\ 10^{19}$	NEMO-3	$5.8\ 10^{22}$	CANDLES [111]	3.55	9.91
^{76}Ge	$1.5 \pm 0.1\ 10^{21}$	HDM	**$1.9\ 10^{25}$**	HDM [46]	**0.21**	**0.53**
^{82}Se	$9.0 \pm 0.7\ 10^{19}$	NEMO-3	$3.2\ 10^{23}$	NEMO-3 [40]	0.85	2.08
^{96}Zr	$2.0 \pm 0.3\ 10^{19}$	NEMO-3	$9.2\ 10^{21}$	NEMO-3 [35]	3.97	14.39
^{100}Mo	$7.1 \pm 0.4\ 10^{18}$	NEMO-3	**$1.0\ 10^{24}$**	NEMO-3 [40]	**0.31**	**0.79**
^{116}Cd	$3.0 \pm 0.2\ 10^{19}$	NEMO-3	$1.7\ 10^{23}$	SOLOTVINO [81]	1.22	2.30
^{130}Te	$0.7 \pm 0.1\ 10^{21}$	NEMO-3	**$2.8\ 10^{24}$**	CUORICINO [65]	**0.27**	**0.57**
^{136}Xe	$2.38 \pm 0.14\ 10^{21}$	Kamland	**$5.7\ 10^{24}$**	Kamland-Zen [93]		
^{150}Nd	$7.8 \pm 0.7\ 10^{18}$	NEMO-3	$1.8\ 10^{22}$	NEMO-3 [37]	2.35	8.65

^{136}Xe	EXO-Kamland	0.12	0.25
^{76}Ge	GERDA	0.2	

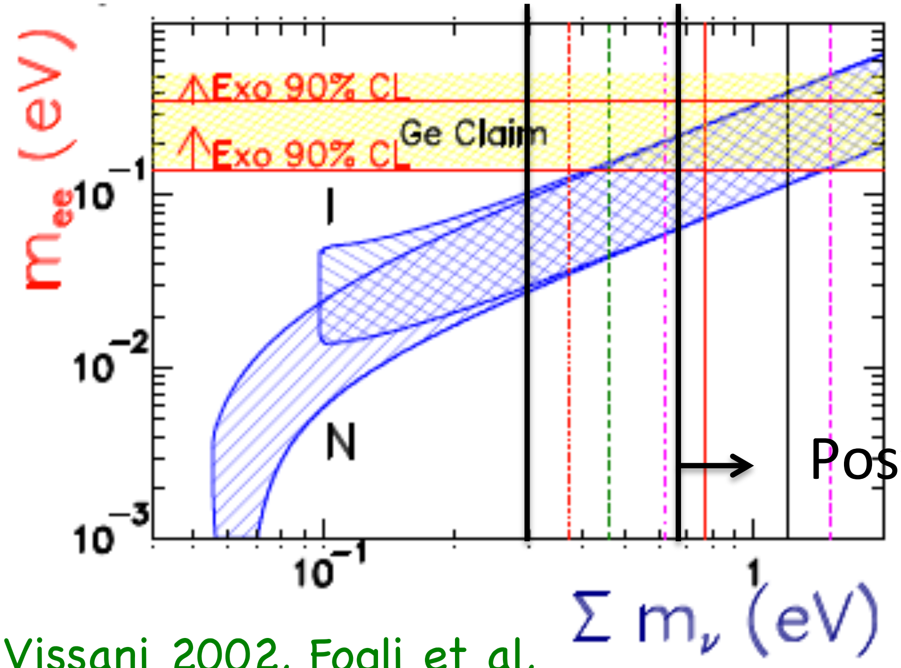
Majorana nature: ββ0ν

Plethora of experiments with different techniques/systematics: EXO, KAMLAND-ZEN, GERDA, CUORE, NEXT, SuperNEMO, LUCIFER…

$$m_{\beta\beta} \equiv |m_{ee}|$$

$$\Sigma \equiv \sum_i m_i$$

If Λ > 100MeV



Post-Planck

Vissani 2002, Fogli et al,

Updated by Gonzalez-Garcia et al, 2012

Leptonic CP violation (in vacuum)

$$
\begin{aligned}
P_{\nu_e\nu_\mu(\bar{\nu}_e\bar{\nu}_\mu)} &= s_{23}^2 \sin^2 2\theta_{13} \sin^2\left(\frac{\Delta_{23}\, L}{2}\right) && \equiv P^{atmos} \\
&+ c_{23}^2 \sin^2 2\theta_{12} \sin^2\left(\frac{\Delta_{12}\, L}{2}\right) && \equiv P^{solar} \\
+\tilde{J} \quad & \cos\left(\pm\delta - \frac{\Delta_{23}\, L}{2}\right) \frac{\Delta_{12}\, L}{2} \sin\left(\frac{\Delta_{23}\, L}{2}\right) && \equiv P^{inter}
\end{aligned}
$$

$$\tilde{J} \equiv c_{13}\ \sin 2\theta_{13}\ \sin 2\theta_{12}\ \sin 2\theta_{23}$$

Best S/N:

$$P^{atmos} \gg P^{solar} \qquad @E/L \sim \Delta_{23}$$

Golden Channel in matter

In matter:

$$P_{\nu_e\nu_\mu(\bar{\nu}_e\bar{\nu}_\mu)} = s_{23}^2 \sin^2 2\theta_{13} \left(\frac{\Delta_{13}}{B_\pm}\right)^2 \sin^2\left(\frac{B_\pm L}{2}\right)$$

$$+c_{23}^2 \sin^2 2\theta_{12} \left(\frac{\Delta_{12}}{A}\right)^2 \sin^2\left(\frac{A\,L}{2}\right)$$

$$+\tilde{J}\,\frac{\Delta_{12}}{A}\,\sin(\frac{AL}{2})\,\frac{\Delta_{13}}{B_\pm}\,\sin\left(\frac{B_\pm L}{2}\right)\,\cos\left(\pm\delta - \frac{\Delta_{13}\,L}{2}\right)$$

$$\tilde{J} \equiv c_{13}\;\sin 2\theta_{13}\;\sin 2\theta_{12}\;\sin 2\theta_{23} \qquad B_\pm \equiv \sqrt{2}G_F n_e \pm \Delta_{13}$$

Cervera et al, 2000

Golden Channel in matter

Octant dependence

Hierarchy dependence

In matter:

$$P_{\nu_e\nu_\mu(\bar{\nu}_e\bar{\nu}_\mu)} = s_{23}^2 \sin^2 2\theta_{13} \left(\frac{\Delta_{13}}{B_\pm}\right)^2 \sin^2\left(\frac{B_\pm L}{2}\right)$$
$$+c_{23}^2 \sin^2 2\theta_{12} \left(\frac{\Delta_{12}}{A}\right)^2 \sin^2\left(\frac{AL}{2}\right)$$
$$+\tilde{J}\,\frac{\Delta_{12}}{A}\,\sin(\frac{AL}{2})\,\frac{\Delta_{13}}{B_\pm}\,\sin\left(\frac{B_\pm L}{2}\right)\,\cos\left(\pm\delta - \frac{\Delta_{13}L}{2}\right)$$

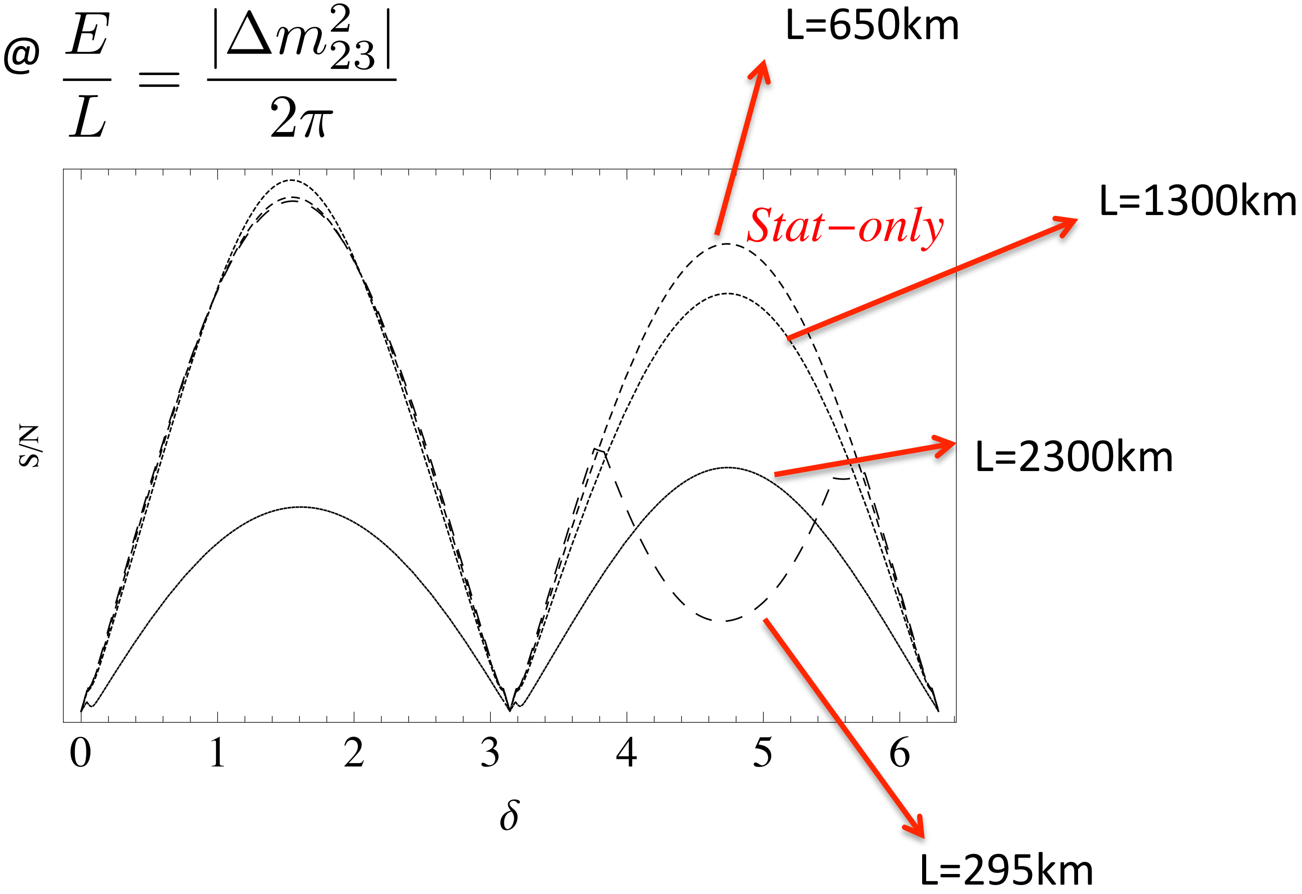
$\tilde{J} \equiv c_{13}\ \sin 2\theta_{13}\ \sin 2\theta_{12}\ \sin 2\theta_{23}$ $\quad$ $B_\pm \equiv \sqrt{2}G_F n_e \pm \Delta_{13}$

Cervera et al 00

Parameter degeneracies (eg. neutrino hierarchy, octant) compromise δ sensitivity

Burguet et al; Minakata, Nunokawa;
Barger, Marfatia, Whisnant
Minakata, Parke

@ $$\frac{E}{L} = \frac{|\Delta m^2_{23}|}{2\pi}$$



L=650km

L=1300km

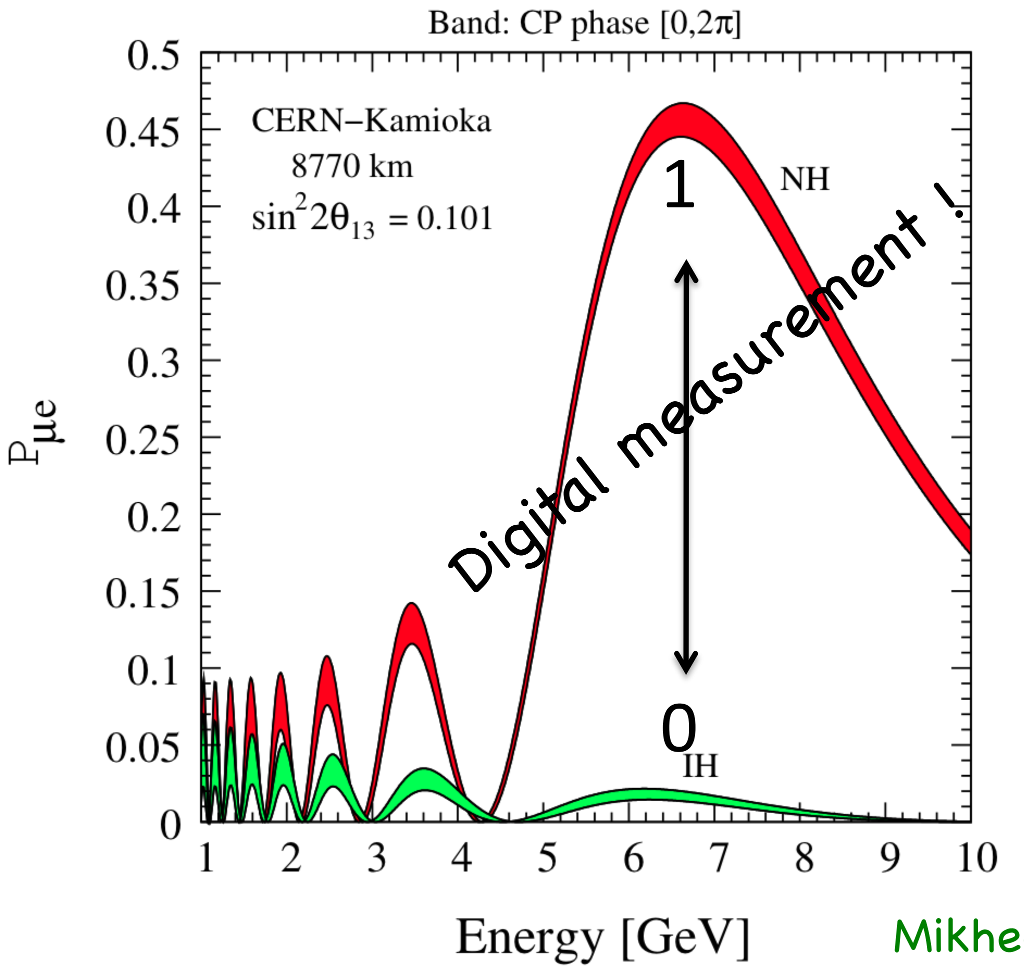
L=2300km

L=295km

Naive scaling of S/N assuming statistical errors dominate …

To maximize sensitivity to CP violation don't go too far

Hierarchy through MSW @Earth



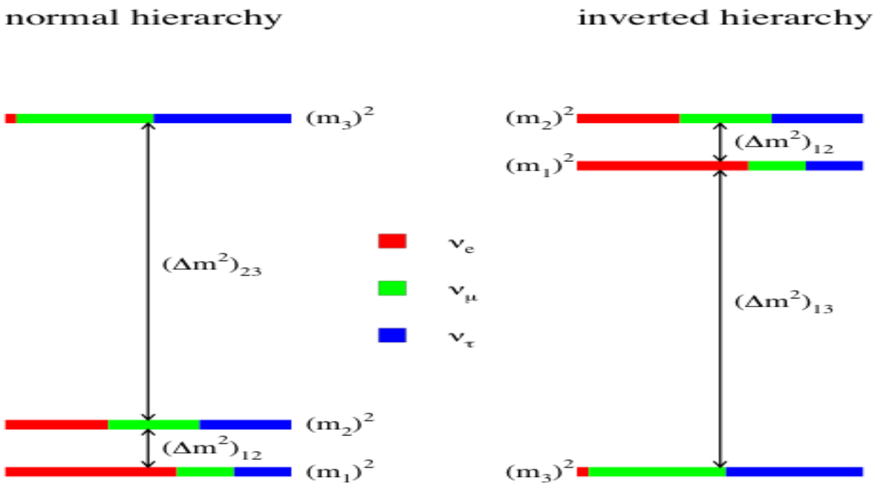
$$E_{\rm res} \equiv \frac{\Delta m^2_{31}\cos 2\theta_{13}}{2\sqrt{2}G_F n_e},$$

$$n_e(L)L|_{L_{\max}} = \frac{\pi}{\sqrt{2}G_F\tan 2\theta_{13}}$$

Mikheev, Smirnov; Wolfenstein

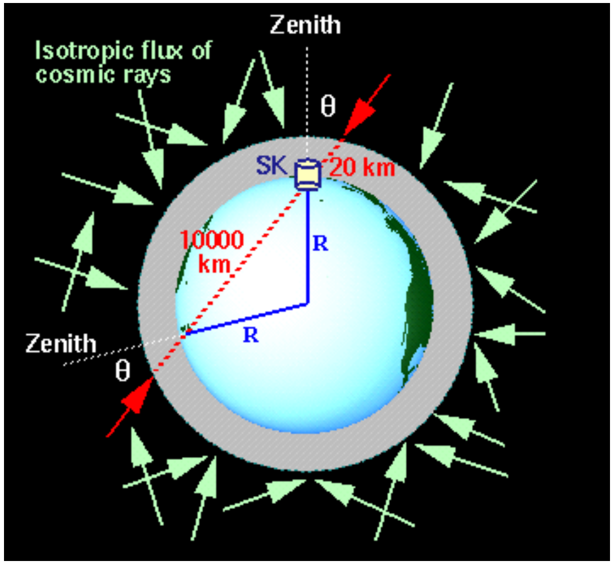
Spectacular MSW effect at O(6GeV) and very long baselines: no need for spectral info nor two channels

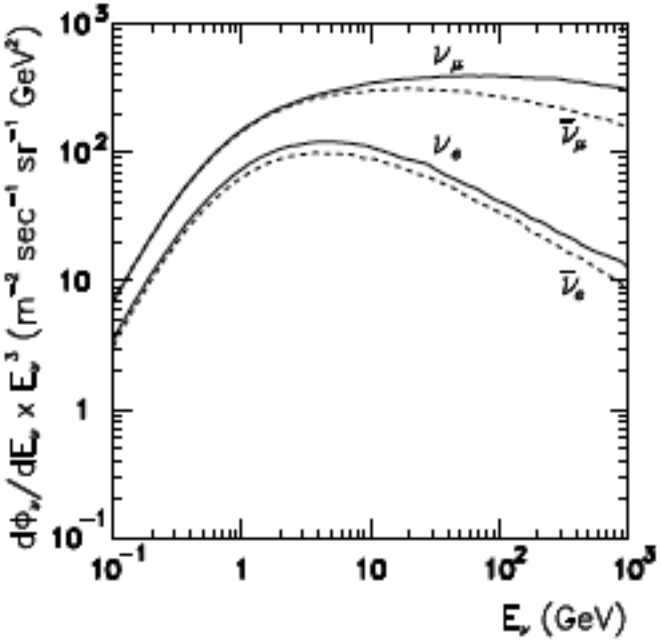
Can we measure the hierarchy with existing neutrino sources ?



Hierarchy from atmospherics ? the hard way…

$\nu_e, \bar{\nu}_e, \nu_\mu, \bar{\nu}_\mu$



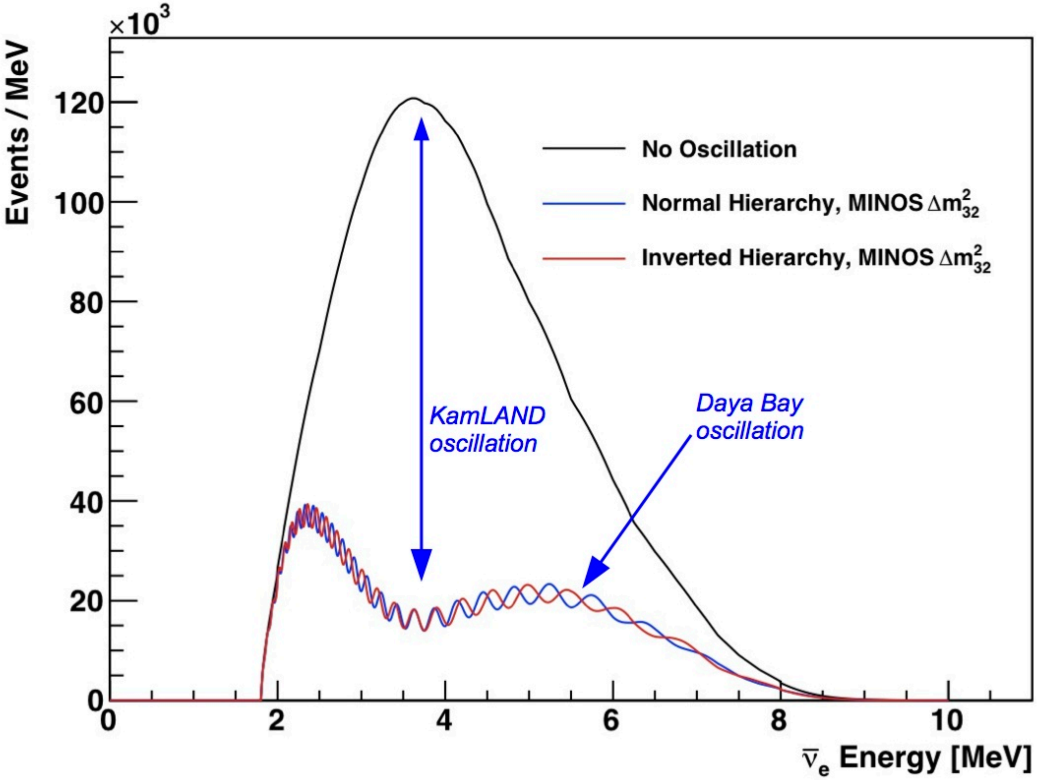


Atmospheric data contain the golden signal but hard to dig…
neutrino telescopes (PINGU, ORCA) or improved atmospheric detectors (HyperK, INO)

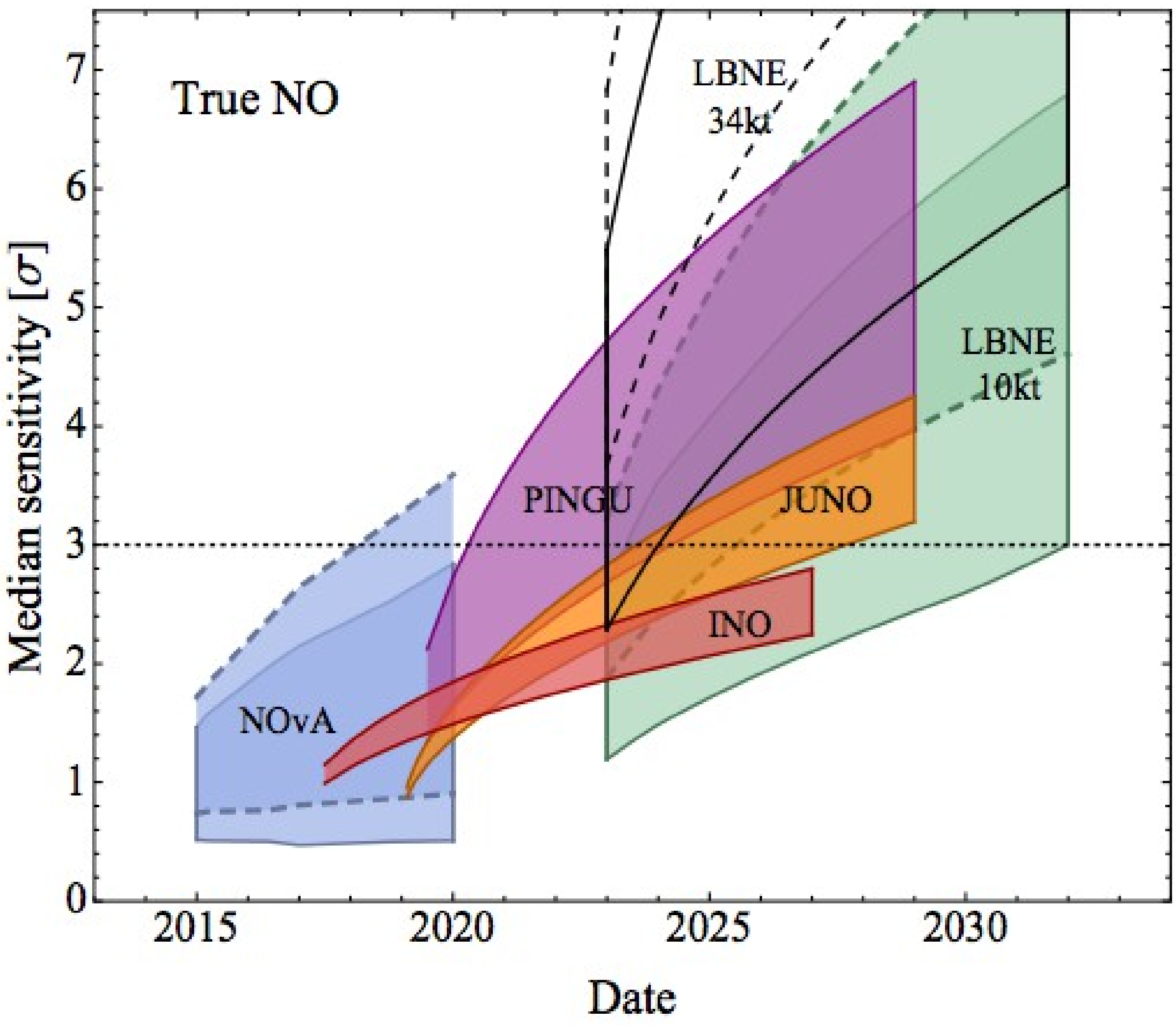
Hierarchy from reactor ν's

Petcov, Piai; Choubey et al; Learned et al

L = 50 km

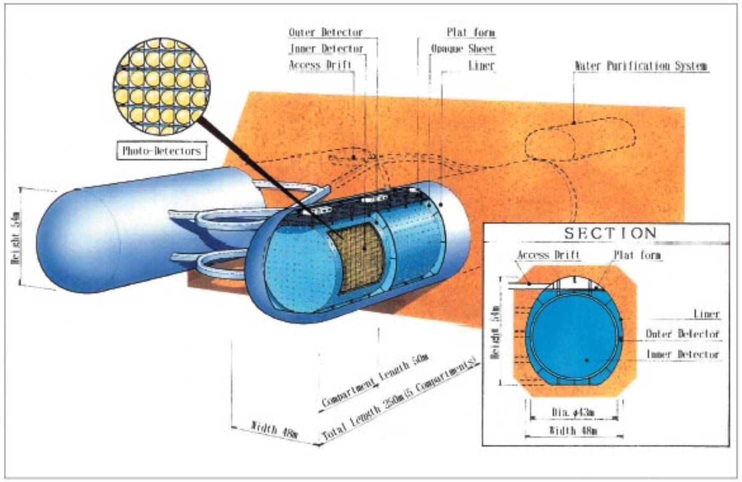


Hierarchy propects

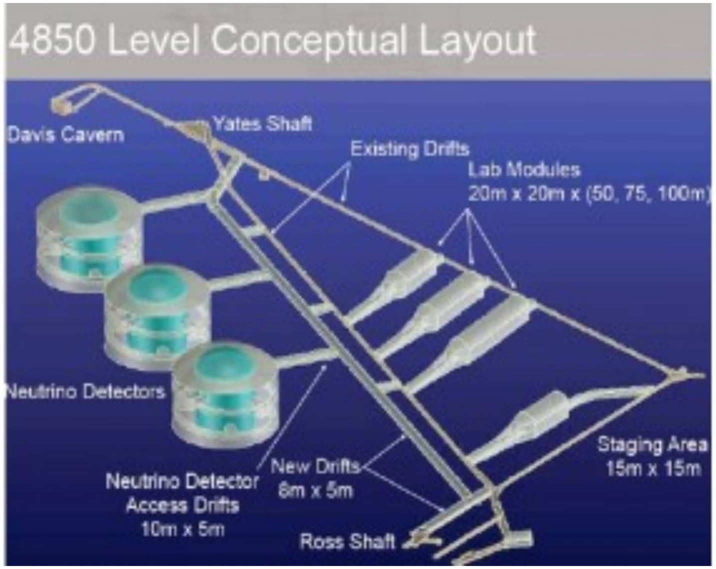


Blennow, Coloma, Huber, Schwetz 1311.1822

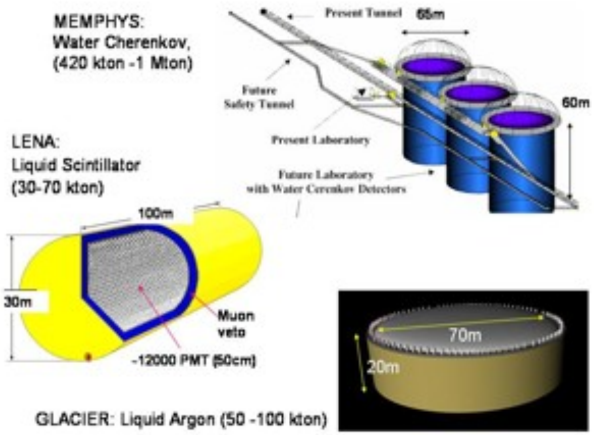
Hierarchy + CP in one go... superbeams+superdectectors



HK: 230km

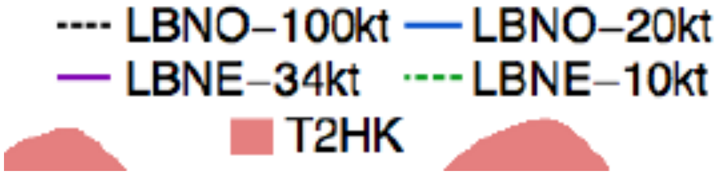


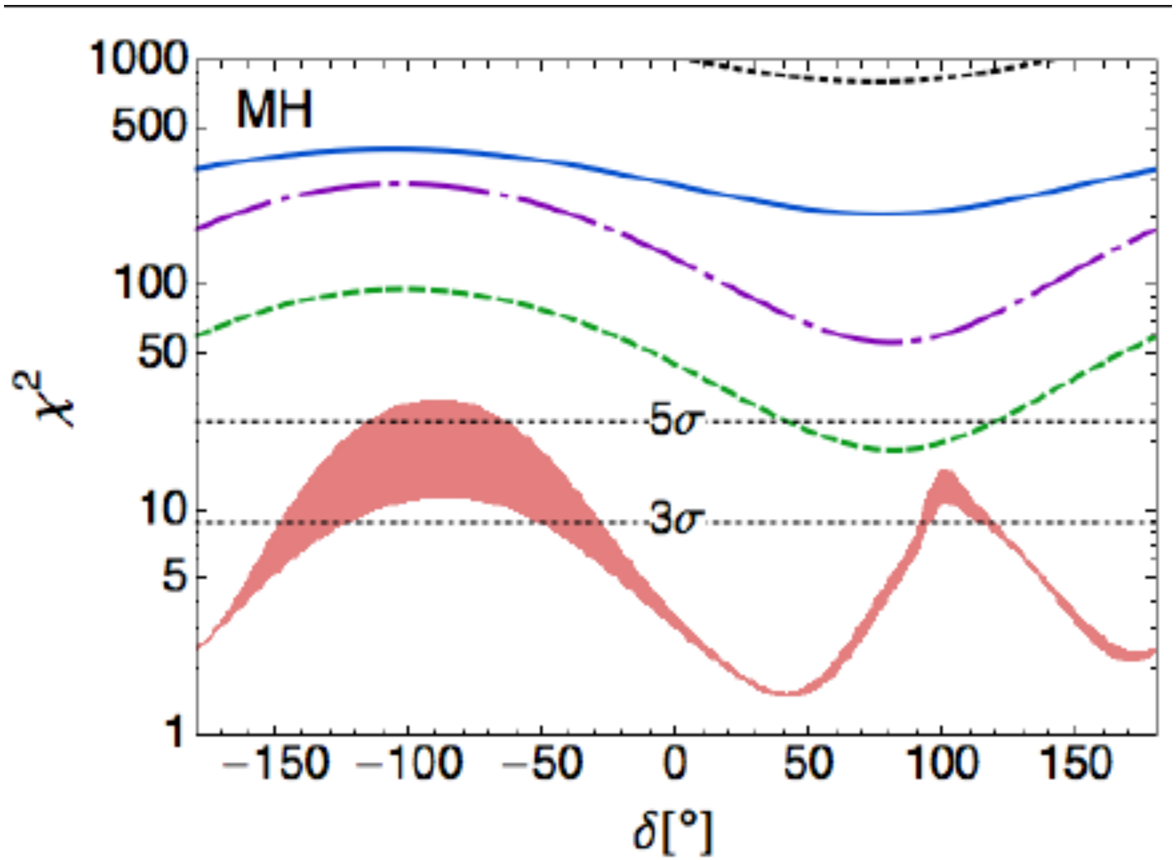
LBNE: 1300km



LBNO: 2300km

In 20 years from now with conventional beams…



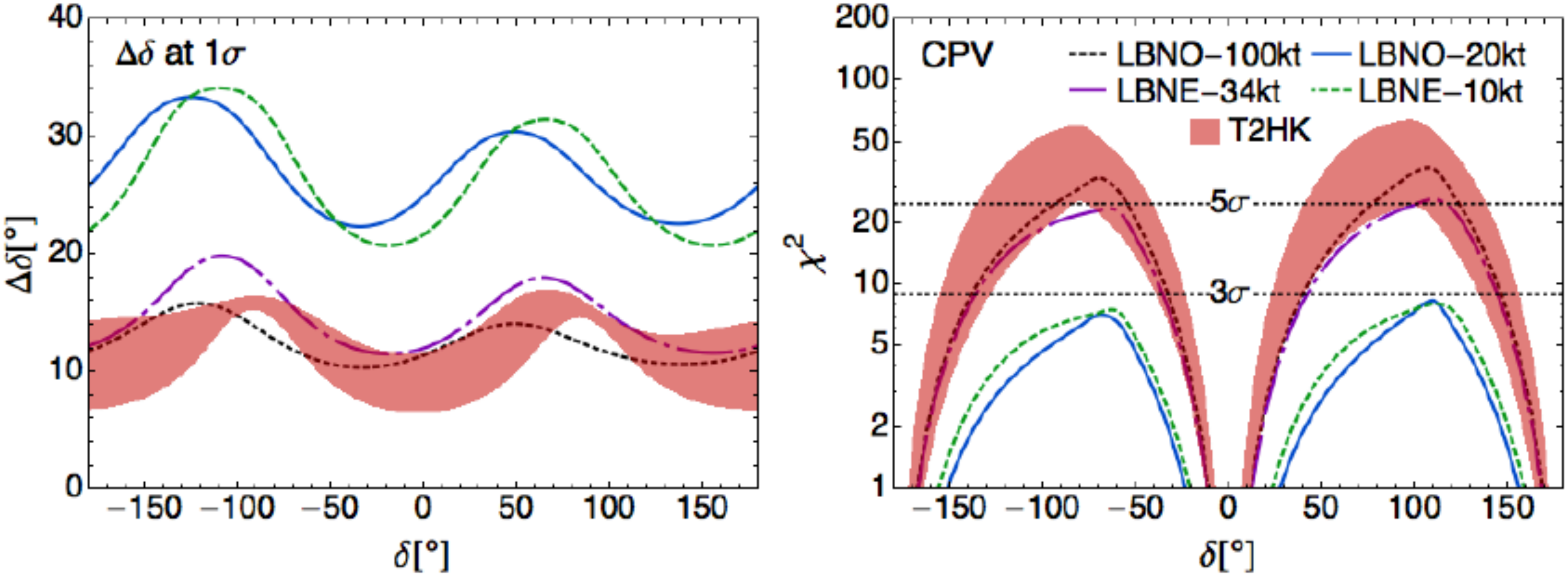


Compiled by P. Coloma

O(10kton) LAr can do the job easily

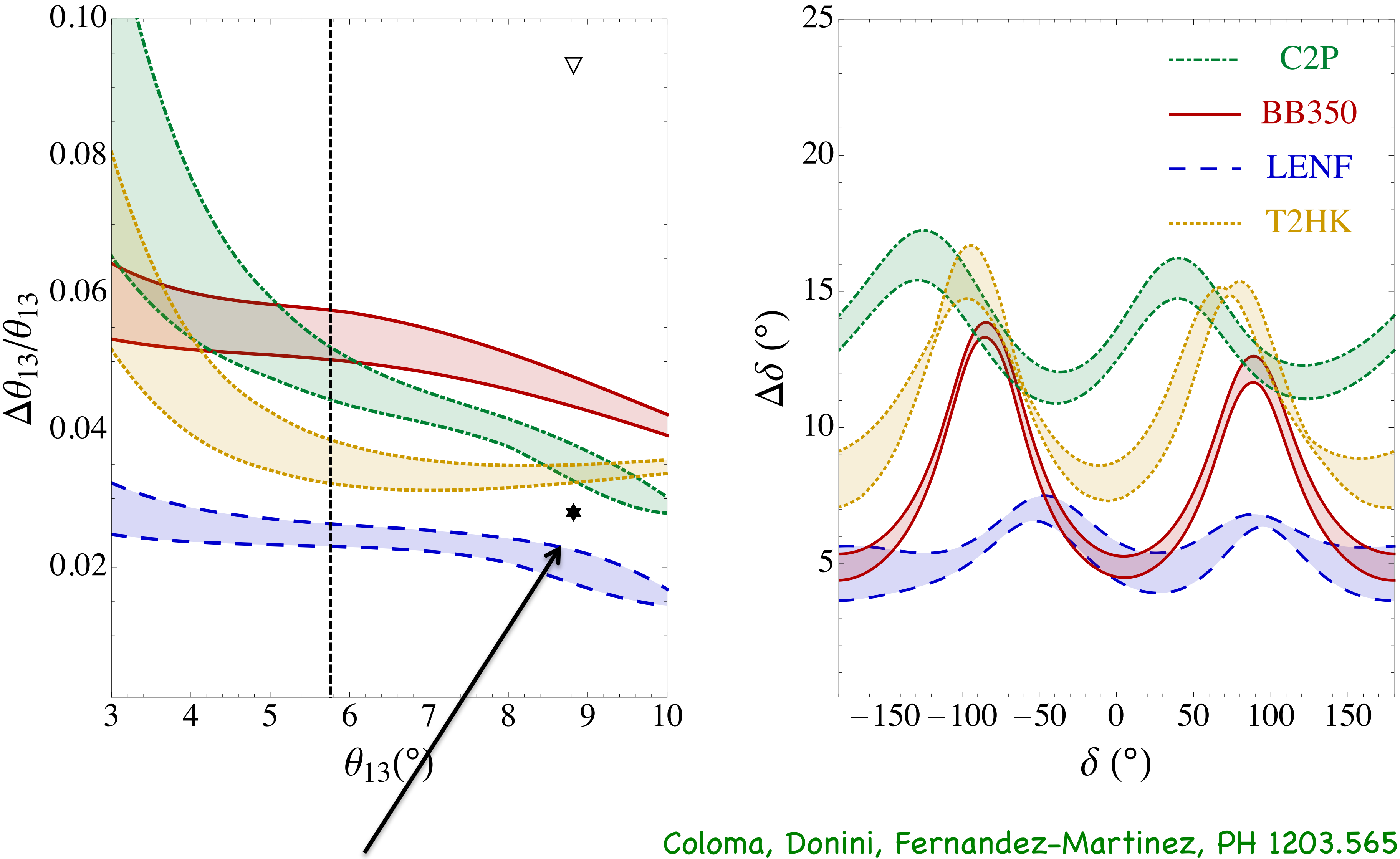
In 20 years from now with conventional beams…

Hierarchy known



Compiled by P. Coloma

With better beams (eg NUFACT) in XX years...

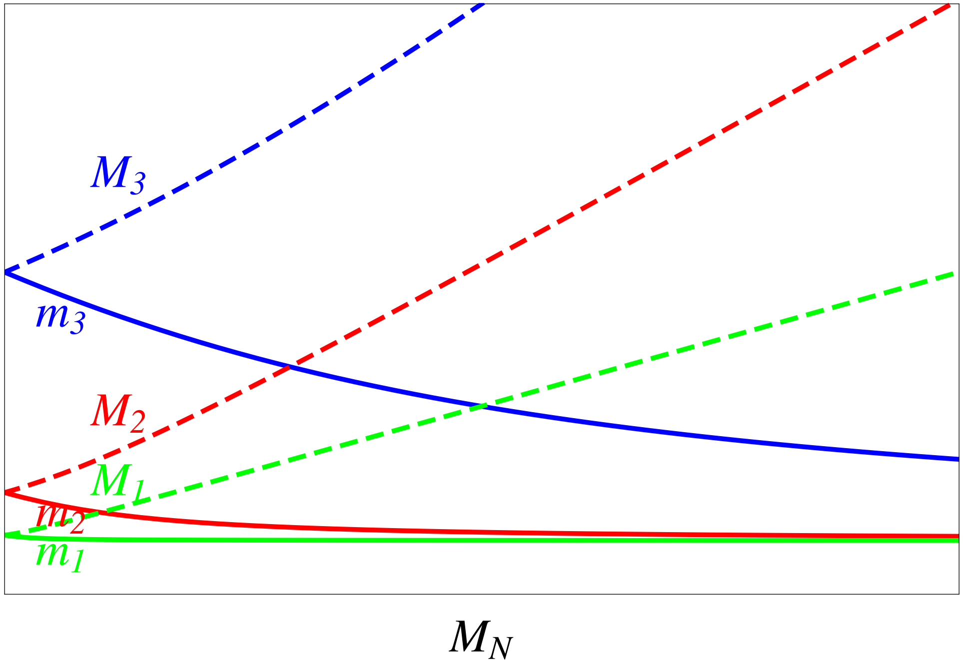


Daya Bay syst only!

Coloma, Donini, Fernandez-Martinez, PH 1203.5651

Other states at Λ...

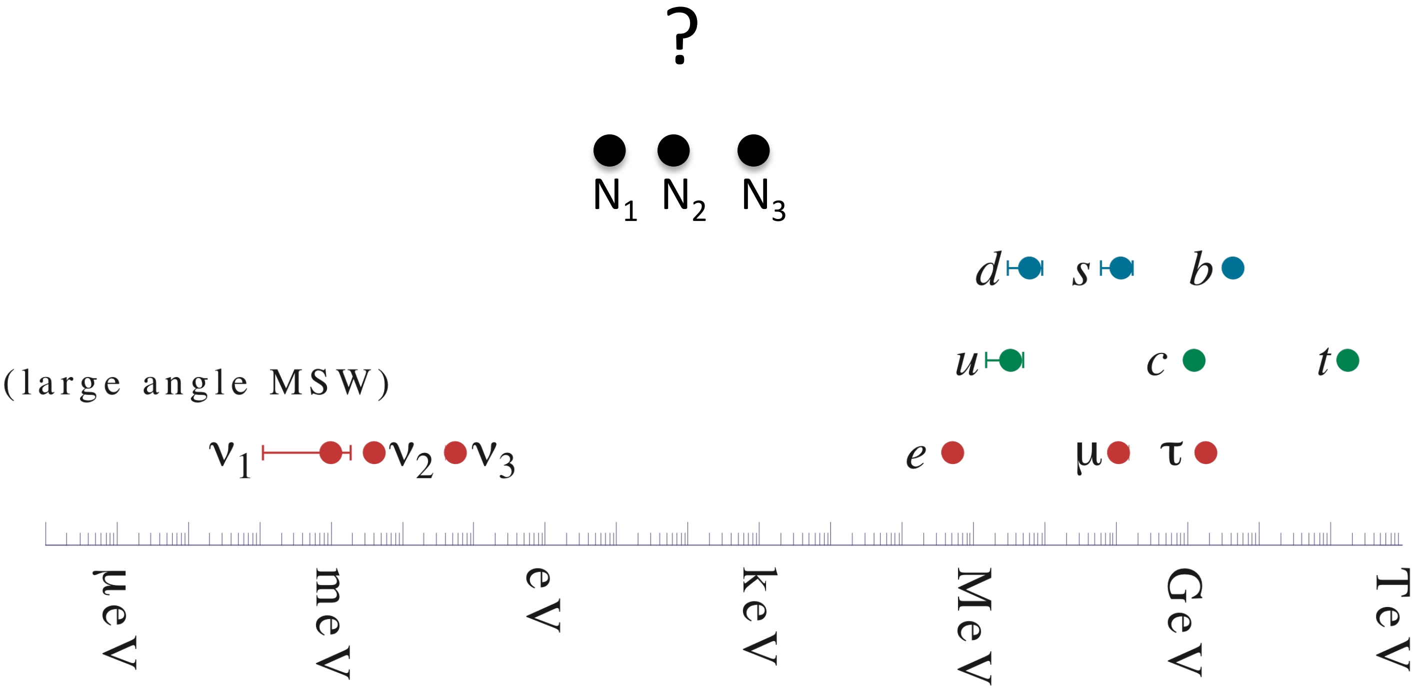
Type I seesaw models



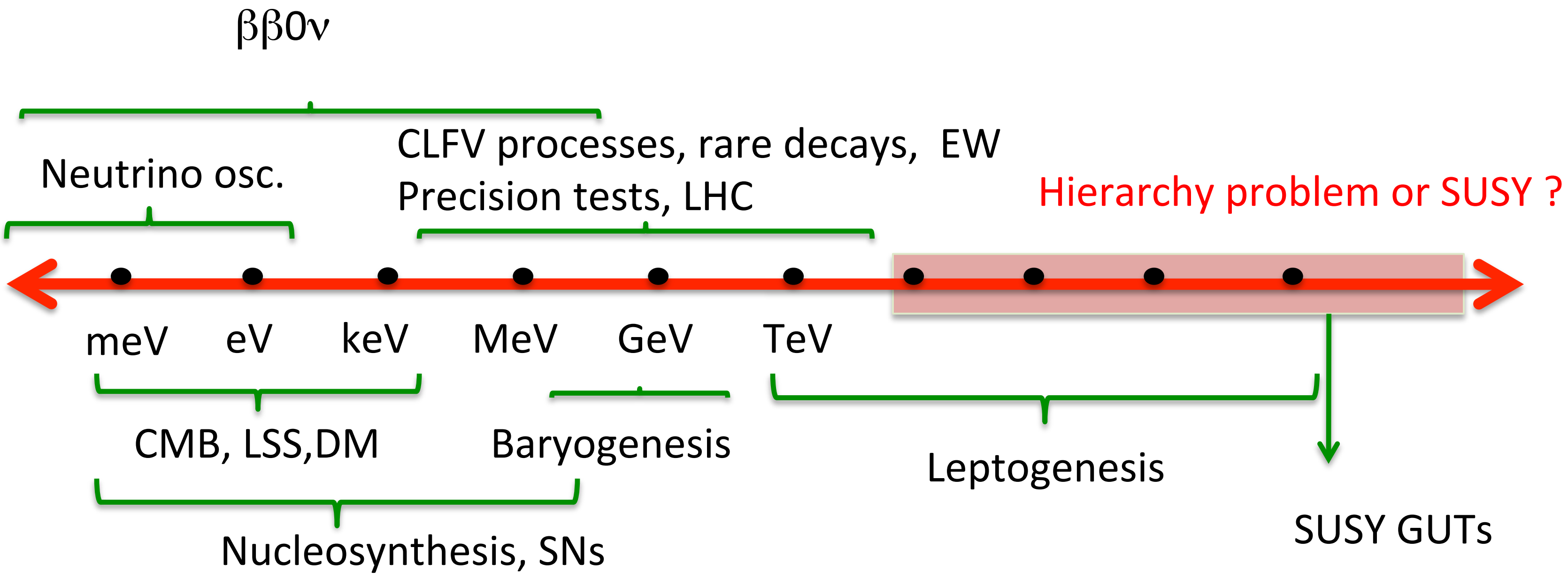
$$|U_{\alpha s_i}|^2 \sim \frac{m_l}{M_i}$$

- kinematically allowed (the lower the mass the better)
- they mix significantly with the rest of the SM
(the lower the mass the better)

Where are they ?



Pinning down the New physics scale



ββ0ν

Neutrino osc.

CLFV processes, rare decays, EW
Precision tests, LHC

Hierarchy problem or SUSY ?

meV eV keV MeV GeV TeV

CMB, LSS,DM

Baryogenesis

Leptogenesis

SUSY GUTs

Nucleosynthesis, SNs

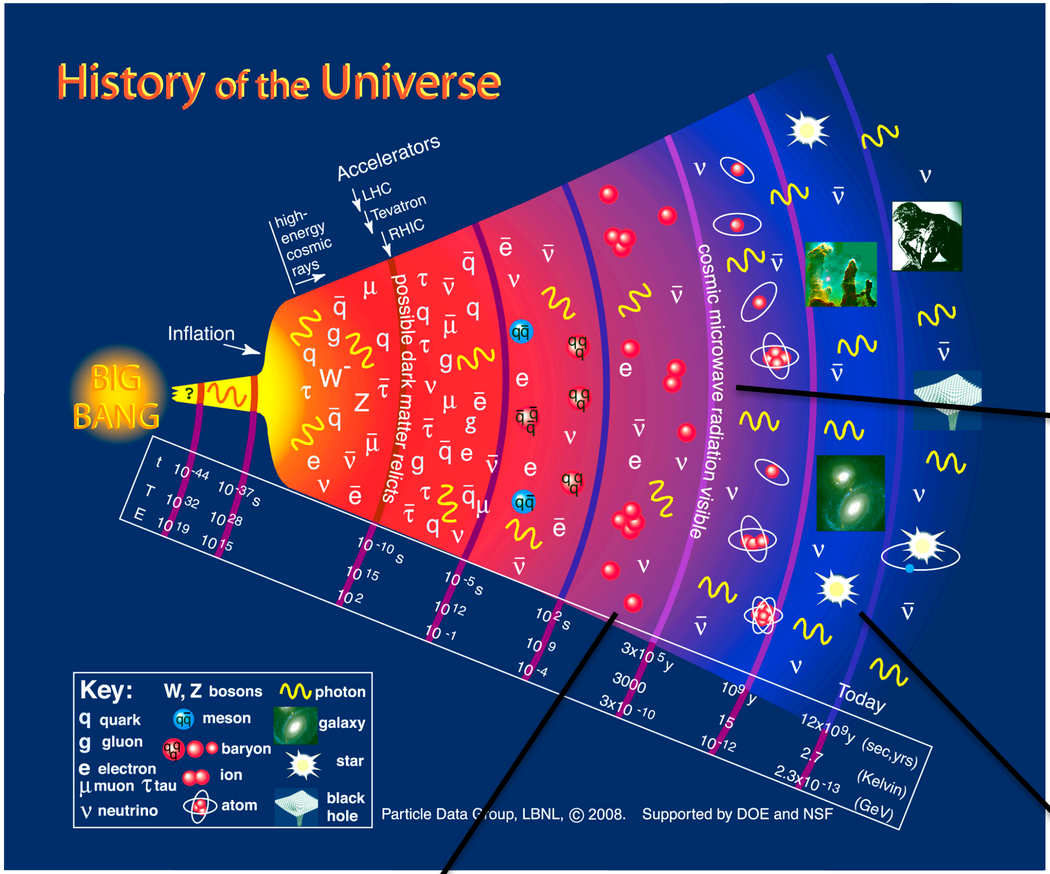
Light Sterile Neutrinos White Paper, Abazajian et al arXiv: 1204.5379 and refs. therein

The measurement of any of these additional observables would give complementary information to that in neutrino masses, making the models much more predictive ...

Cosmological neutrinos

neutrinos have left many traces in the history of the Universe

$$\Omega_{\nu,0}h^2 = \sum_i \frac{m_{\nu_i}}{94eV}$$



Particle Data Group, LBNL, © 2008. Supported by DOE and NSF

CMB <-> N_ν

Galaxy distribution (LSS) <-> $\sum_i m_i$

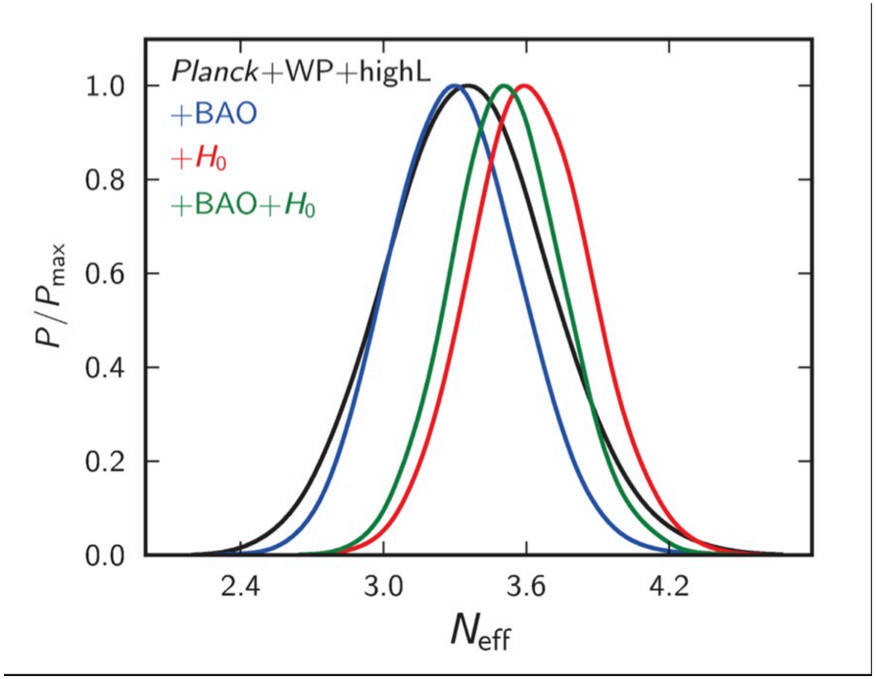
Nucleosynthesis <-> N_ν

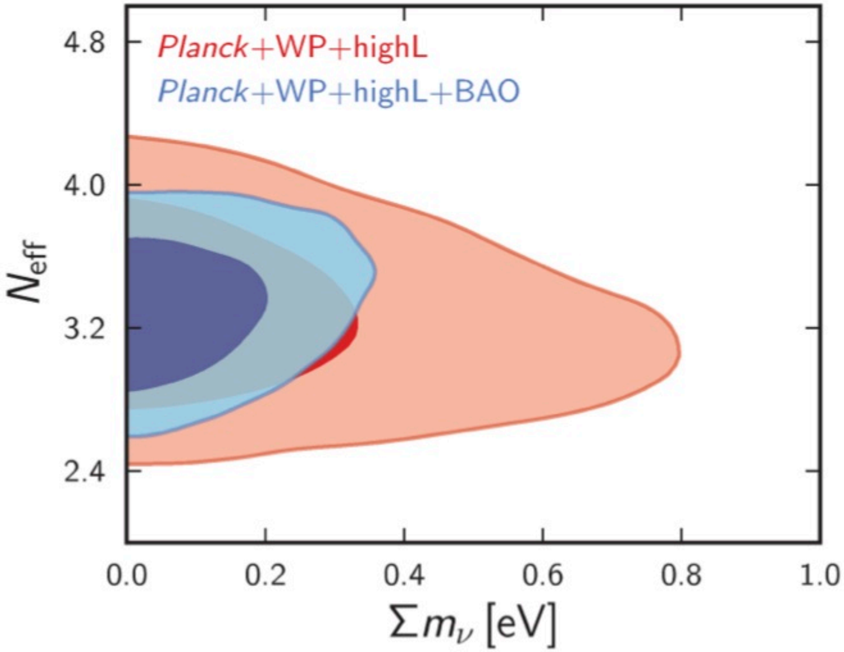
Extra relativistic species might be welcome

Nucleosynthesis: $N_{\rm eff} = 3.50 \pm 0.20$ Cooke et al, 1308.3240

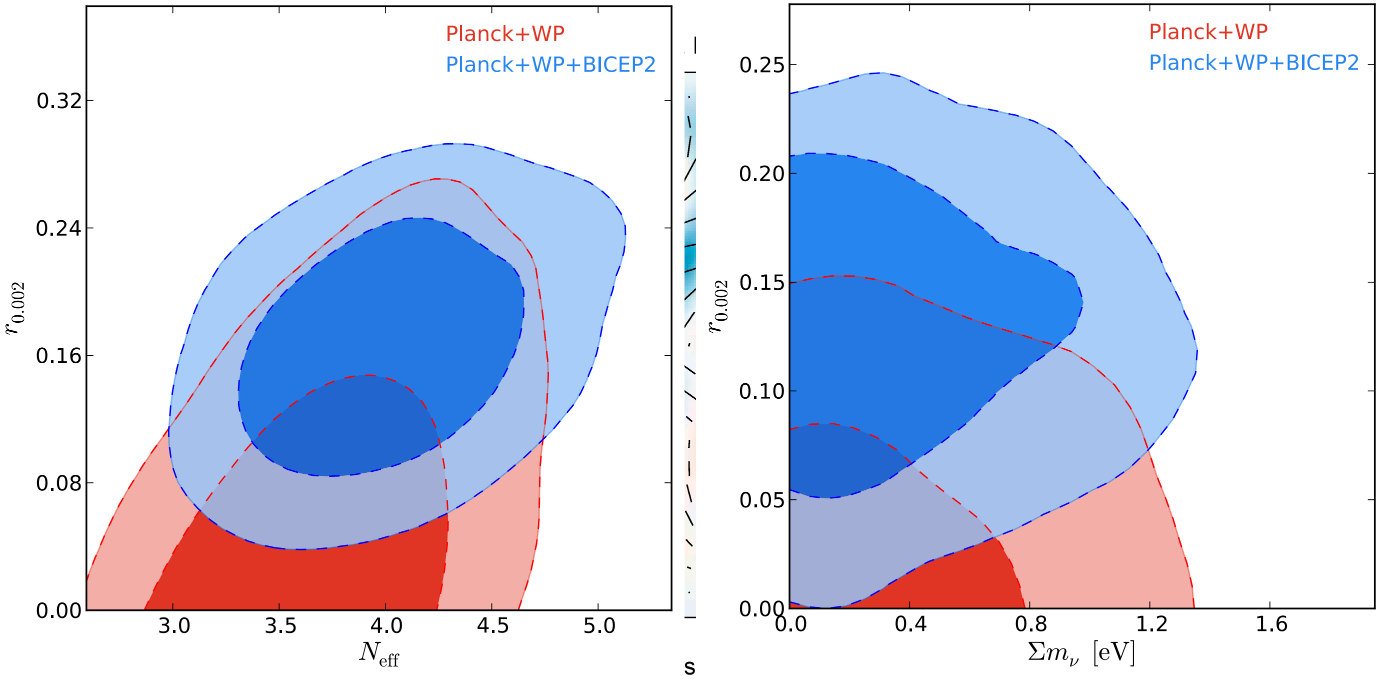
CMB +LSS:

PLANCK col. 2013





Last week: BICEPs earthquake in cosmology…



Giusarma et al, 1403.4852

One extra species OK but still not too heavy…

Seesaw scale @ early Universe

The extra states contribute to the energy density of the Universe: how many of them are there ? $T < T_{EW}$ produced via mixing...

$$\Gamma_{s_i} \simeq \sum_{\alpha} \langle P(\nu_\alpha \to \nu_{s_i}) \rangle \times \Gamma_{\nu_\alpha}$$

Barbieri&Dolgov; Kainulainen

Thermalisation will occur if for any T: $\frac{\Gamma_{s_i}(T)}{H(T)} \geq 1$

Neutrinos propagation is modified by forward scattering on the plasma particles

$$V_\alpha \propto \frac{G_F}{M_W^2} T^5$$

Notzold, Raffelt

Seesaw scale vs cosmology

$\frac{\Gamma_{s_i}(T)}{H(T)}$ reaches a maximum at $T_{\rm max} \sim (M_i^2 M_W^2/G_F)^{1/6}$

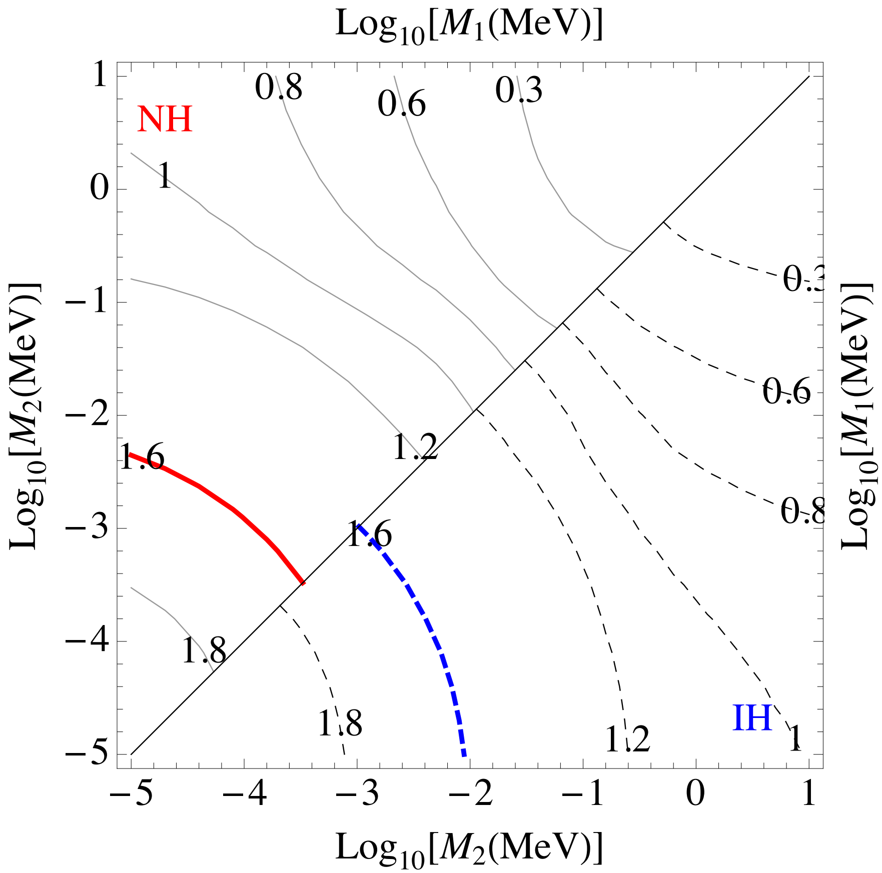
$$\frac{\Gamma_{s_i}(T_{\rm max})}{H(T_{\rm max})} \sim \frac{\sum_\alpha |U_{\alpha s_i}|^2 M_i}{\sqrt{g_*(T_{\rm max})}}$$

With the naive seesaw scaling law $|U_{\alpha s_i}|^2 \sim \frac{m_l}{M_i}$

thermalisation independent of seesaw scale !!

PH, M. Kekic, J. López-Pavon 1311.2614

Minimal model: N =2



Minimizing thermalization over all unknown parameters

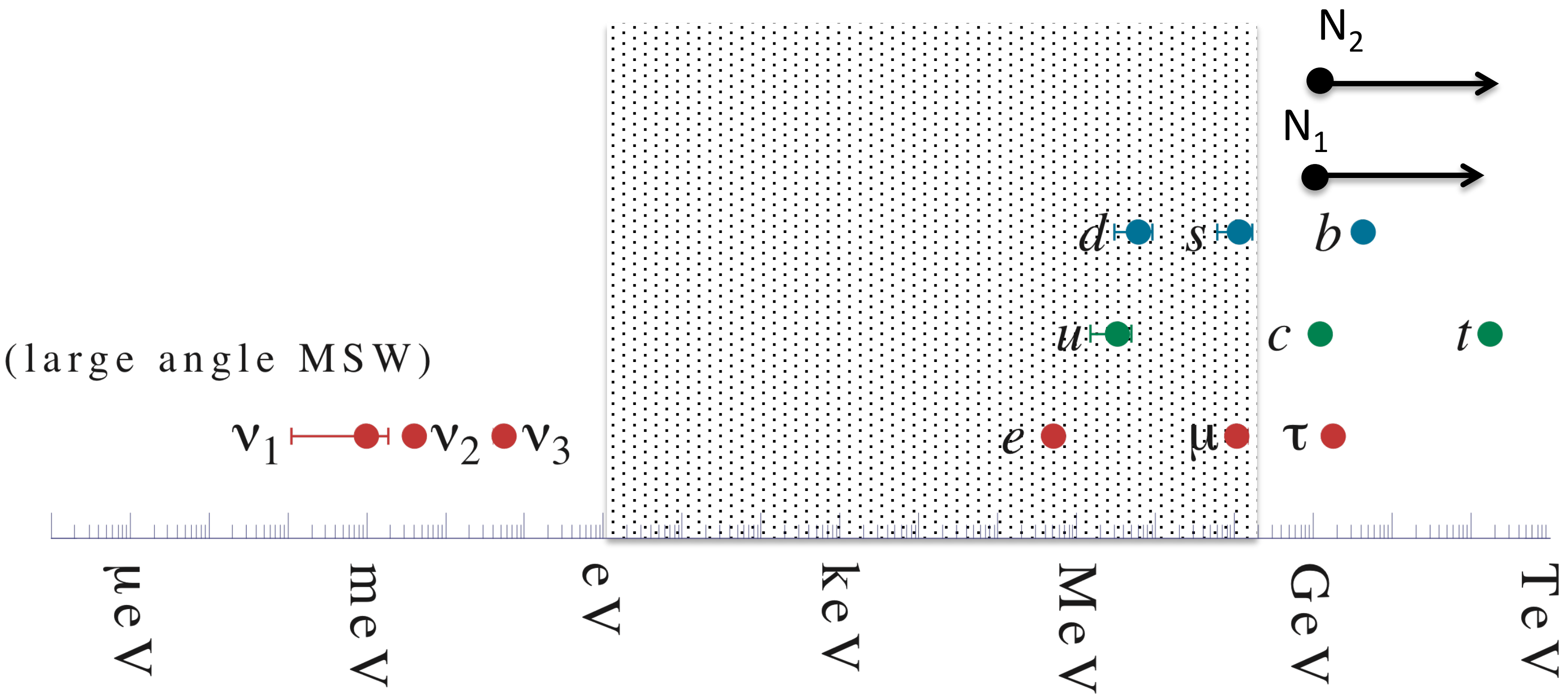
$$\Delta N_{\rm eff}(T_{BBN}) \simeq \underbrace{\left(\frac{g_*(T_{BBN})}{g_*(T_{dec})}\right)^{4/3}}_{\rm dilution} \Delta N_{\rm eff}(T_{dec})$$

PH, M. Kekic, J. López-Pavon

Sterile states M_i < O(100 MeV) thermalise independently of their mass: too large radiation or/and too much dark matter…

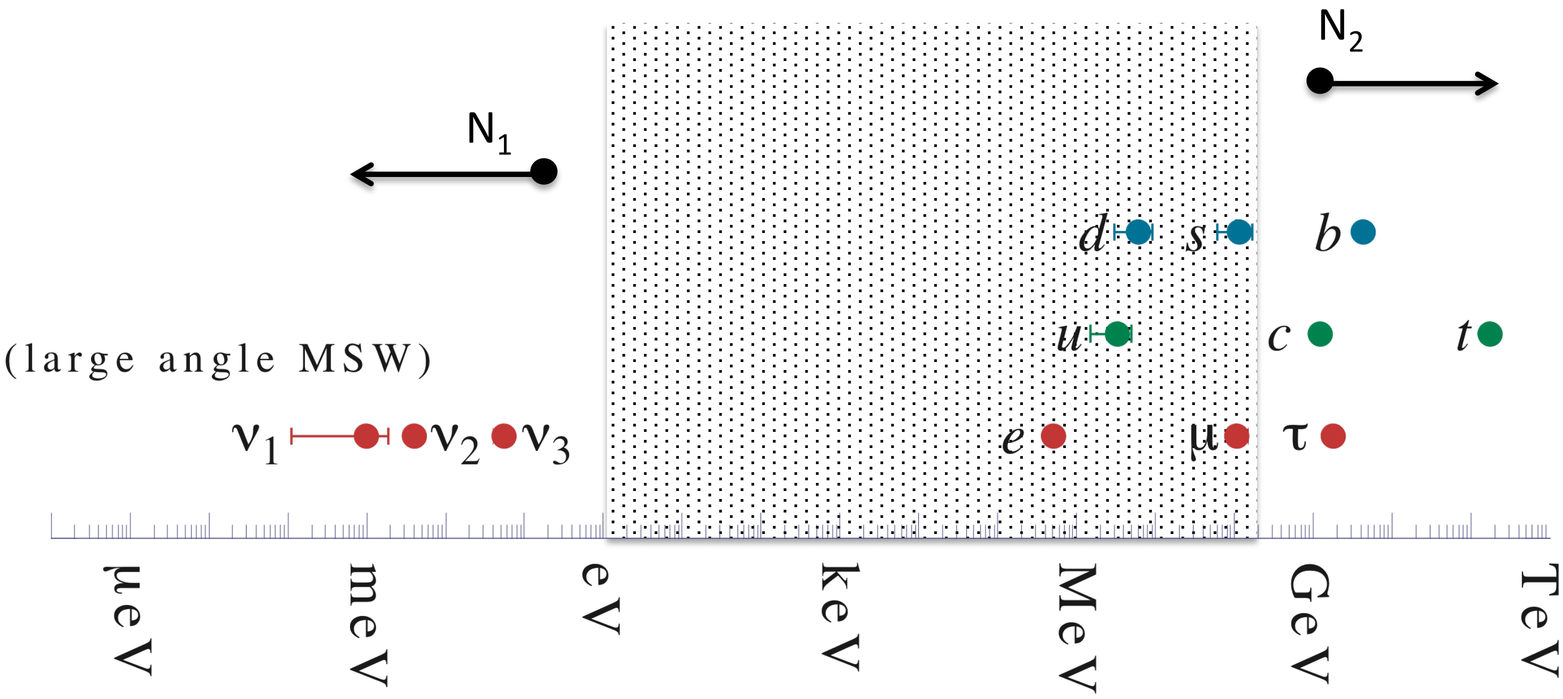
Larger masses OK: decay before BBN or non-relativistic at decoupling

Minimal model: N =2



(Caveat: N=2… N>3 a bit more freedom…work in progress)

Minimal model: N =2

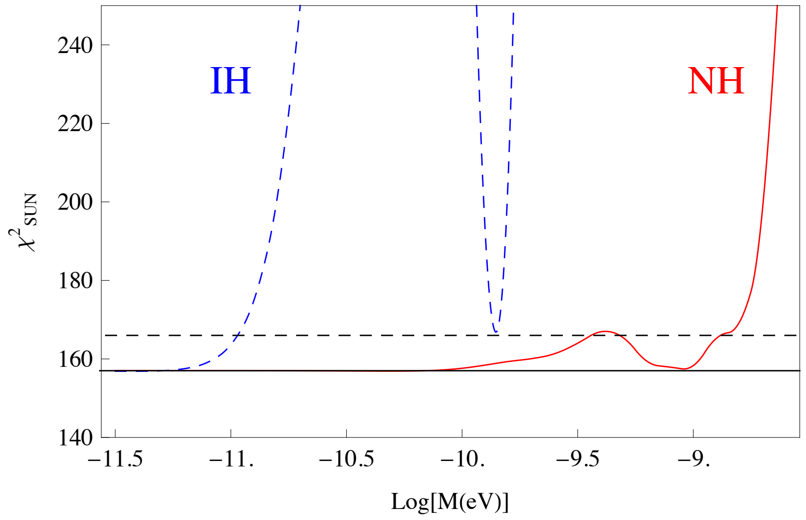


Could explain indications from cosmology of extra radiation

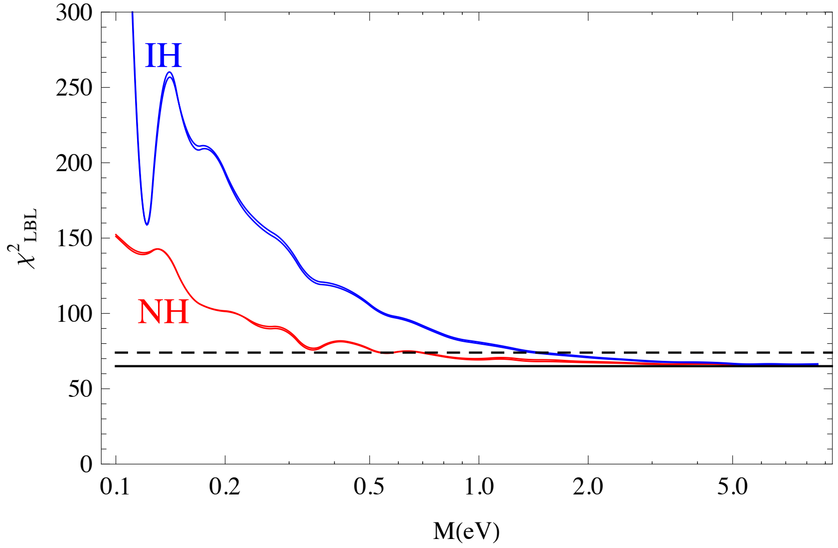
Other states out there ?

Below eV, strong constraints from oscillations...

Solar data

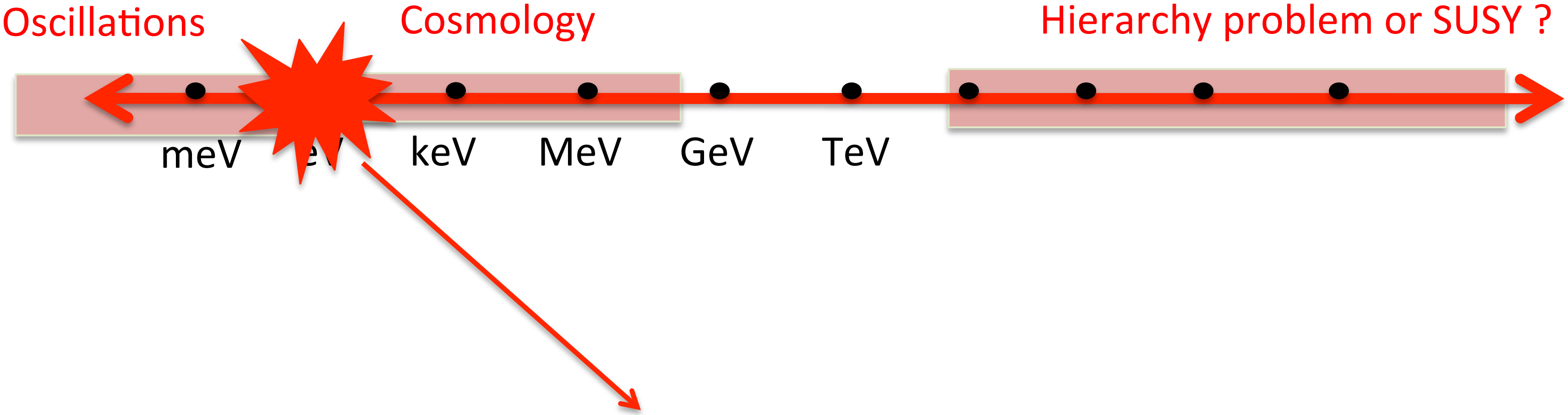


LBL data



Donini, PH, J. López-Pavon, M. Maltoni 1106.0064

Other states out there ?



Oscillations

Cosmology

Hierarchy problem or SUSY ?

meV eV keV MeV GeV TeV

Neutrino anomalies ?

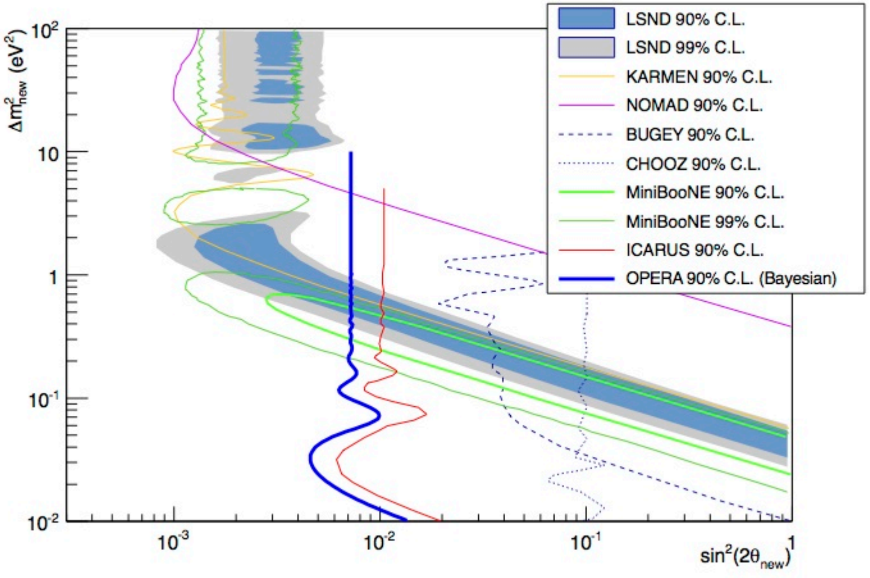
Neutrino anomalies

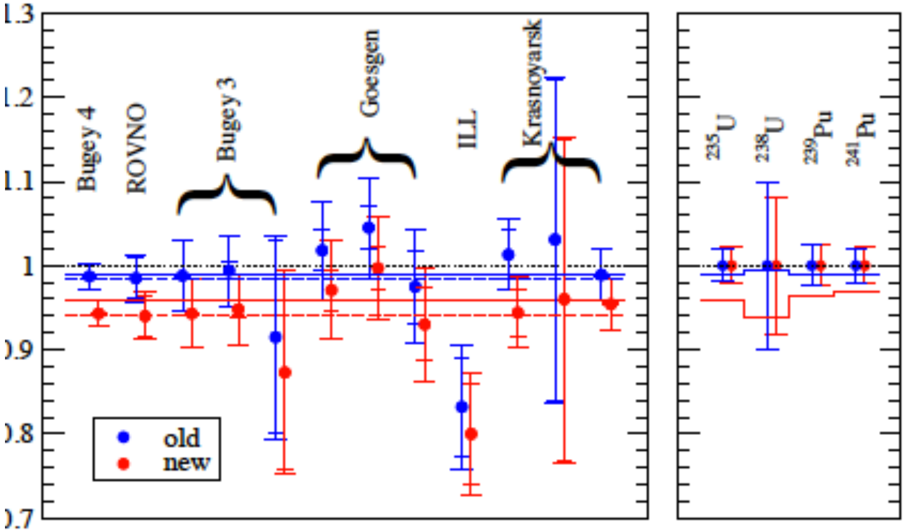
$$|\Delta m^2| \sim \frac{\mathcal{O}(MeV)}{\mathcal{O}(1-10m)} \sim \frac{\mathcal{O}(1GeV)}{\mathcal{O}(1-10km)}$$

LSND

P($\nu_\mu \to \nu_e$) = O($|U_{ei}|^2\ |U_{\mu i}|^2$)

Reactors P($\nu_e \to \nu_e$) = O($|U_{ei}|^2$)





T. A. Mueller et al; P. Huber

+Gallium anomaly+ MiniBOONE low-energy excess…

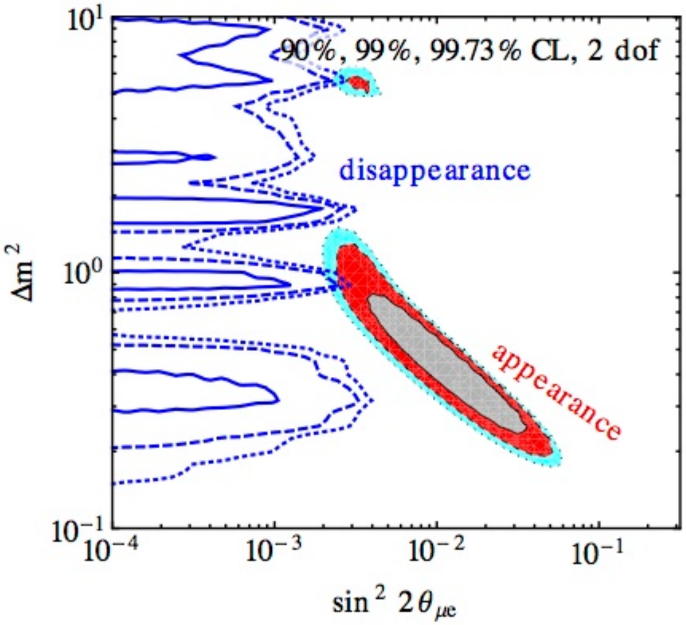
Neutrino anomalies

Smoking gun still not there...

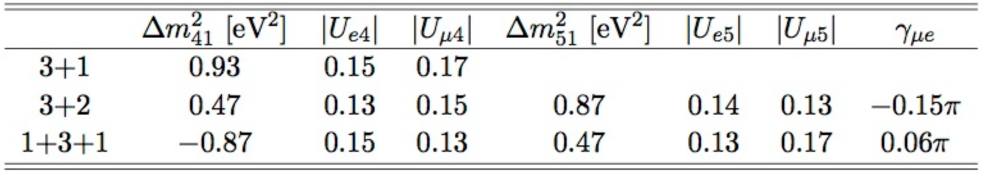
$P(\nu_e -> \nu_\mu) = O(|U_{ei}|^2\ |U_{\mu i}|^2)$ ✔

$P(\nu_e -> \nu_e) = O(|U_{ei}|^2)$ ✔

$P(\nu_\mu -> \nu_\mu) = O(|U_{\mu i}|^2)$ ✗



Kopp et al; Conrad et al, Archidiacono et al



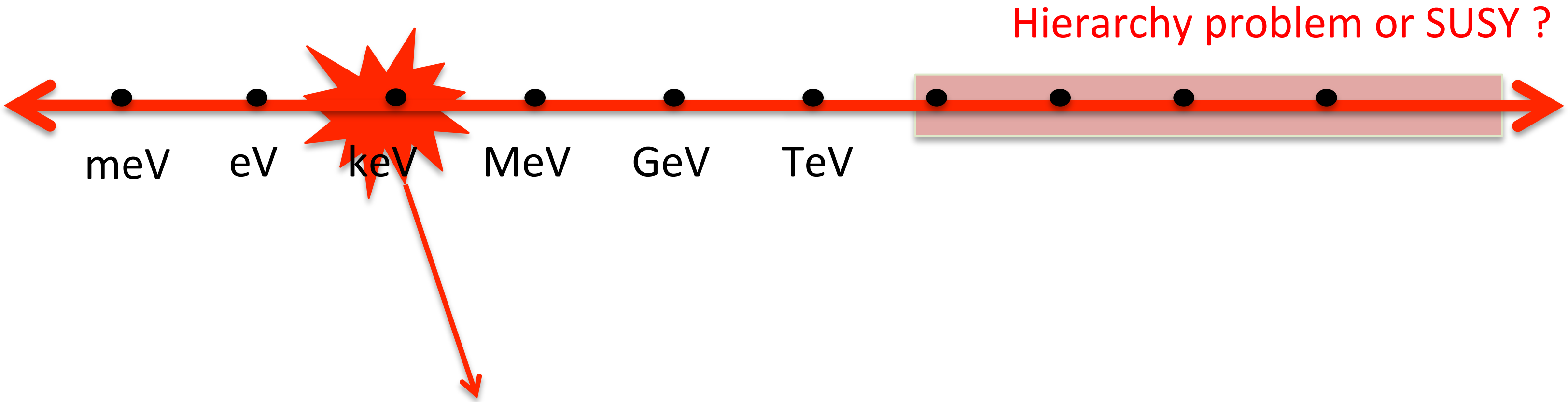
	Δm^2_{41} [eV^2]	$\|U_{e4}\|$	$\|U_{\mu 4}\|$	Δm^2_{51} [eV^2]	$\|U_{e5}\|$	$\|U_{\mu 5}\|$	$\gamma_{\mu e}$
3+1	0.93	0.15	0.17				
3+2	0.47	0.13	0.15	0.87	0.14	0.13	-0.15π
1+3+1	-0.87	0.15	0.13	0.47	0.13	0.17	0.06π

Consistent with $$|U_{\alpha s_i}|^2 \sim \frac{m_l}{M_i}$$

O(1eV) seesaw scale models provide similar fits to the data while being much more constrained

Donini, PH, Lopez-Pavon, Maltoni; Fan, Langacker;

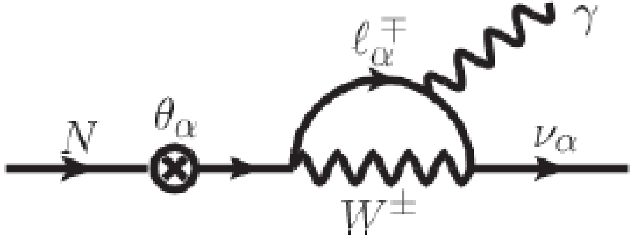
Other states out there ?



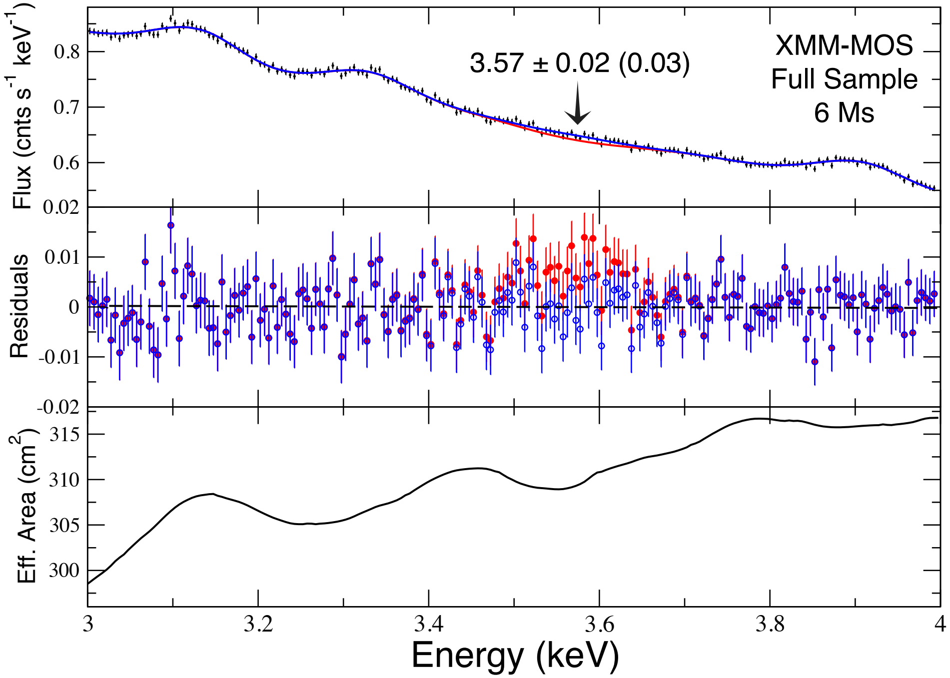
Warm DM (N>2)

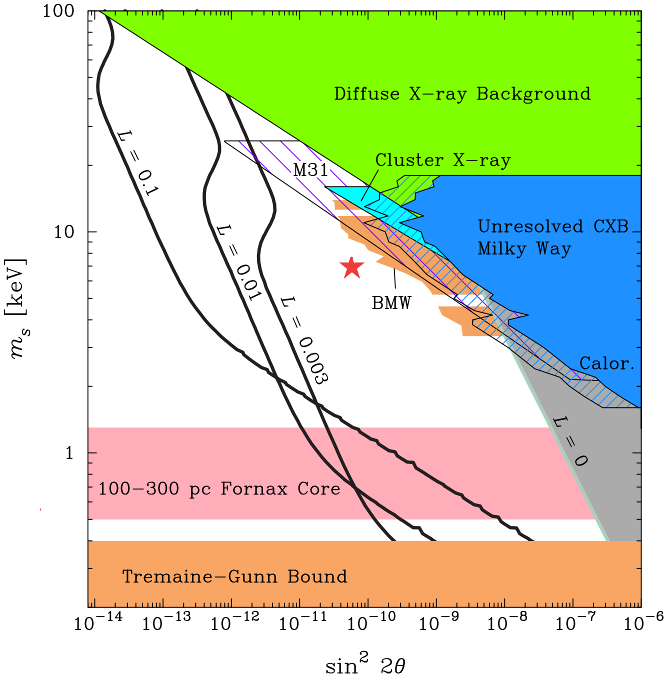
Dodelson, Widrow
Fuller et al

7 keV neutrino ?



Bulbul et al 1402.2301

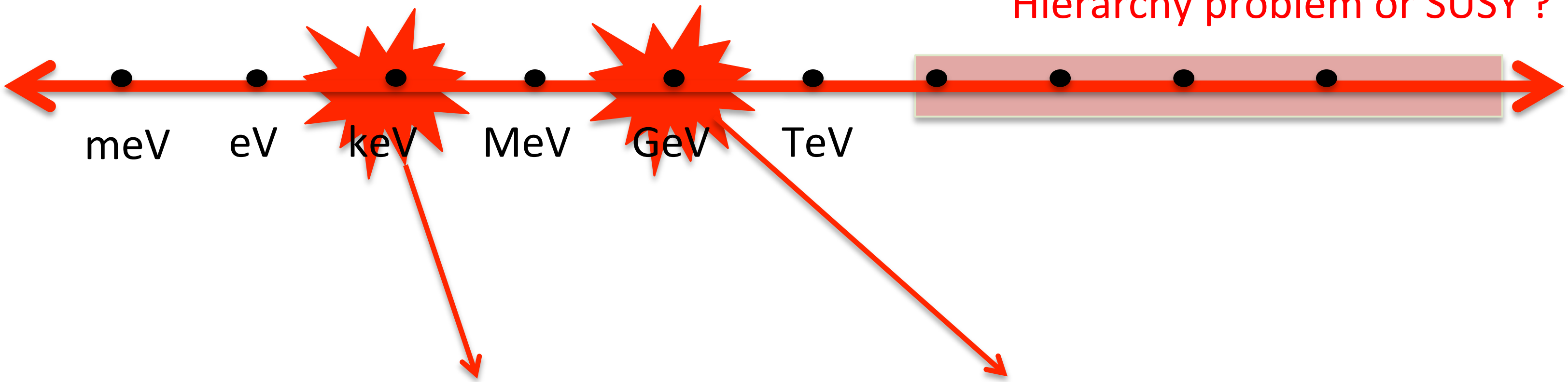




$$M_s \simeq 7\text{keV}, \quad \sin^2 2\theta = 7\times 10^{-11}$$

$$|U_{\alpha s}|^2 \ll \frac{\sqrt{\Delta m^2_{atm}}}{M_s}$$

Other states out there ?



Hierarchy problem or SUSY ?

Warm DM (N>2)

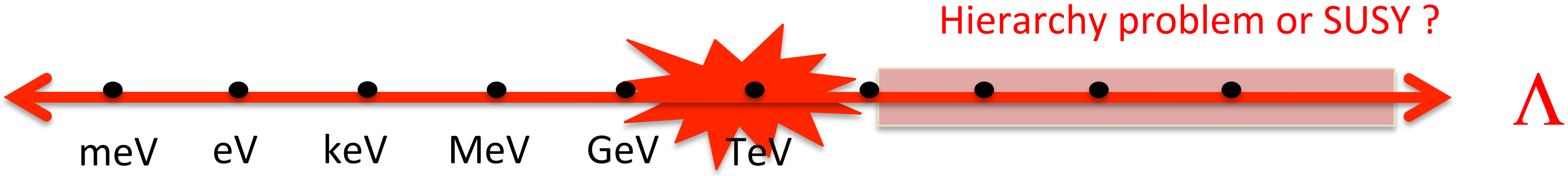
Dodelson, Widrow
Fuller et al

Baryogenesis

Akhmedov, Smirnov;
Shaposnikov et al

Even though there are typically more parameters than those in the neutrino mass, there are strong correlations…

Other states out there EW scale ?



$$|U_{\alpha s_i}|^2 \sim \frac{m_l}{M_i}$$

too small couplings unless....

Two scale see-saw models (approx) Lepton number

Wyler, Wolfenstein; Mohapatra, Valle;
Branco, Grimus, Lavoura, Malinsky, Romao,…

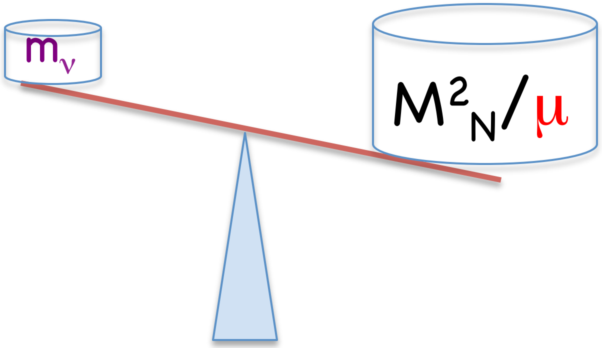
$$\begin{array}{cccc}
 & & \multicolumn{2}{c}{\overbrace{\hspace{4em}}^{n_R}} \\
 & 0 & Yv & 0 \\
 & Yv & 0 & M_N \\
 & 0 & M_N & 0 \\
 & \downarrow & \downarrow & \downarrow \\
L= & +1 & -1 & +1
\end{array}$$

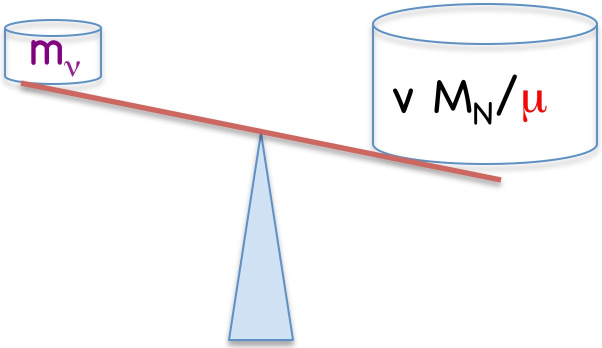
Inverse Seesaw

$$\begin{pmatrix} 0 & Yv & 0 \\ Yv & 0 & M_N \\ 0 & M_N & \mu \end{pmatrix}$$

Direct Seesaw

$$\begin{pmatrix} 0 & Yv & \mu \\ Yv & 0 & M_N \\ \mu & M_N & 0 \end{pmatrix}$$



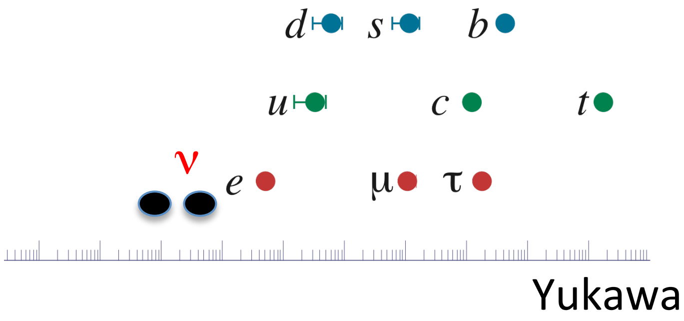


Y unsuppressed: -> LFV effects large μ-> e γ, etc
-> heavier spectrum M_N, Y v, at LHC

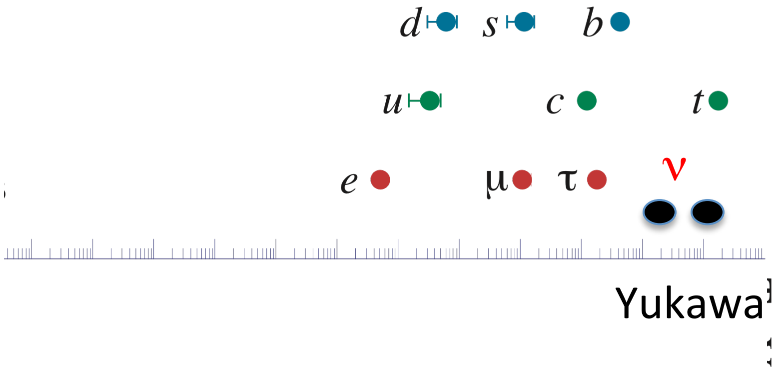
Kersten,Smirnov 07; Abada et al 07; Gavela,et al 09

Charged/neutral hierarchy in seesaw

M = TeV



M ≤ TeV + aprox. $U(1)_L$



Eg: Inverse seesaw/direct seesaw

Other states out there: other constraints ?

Stringent constraints from peak and decay searches, unitarity, EW...

Direct production at LHC of heavy states ? **Keung, Senjanovic;...**

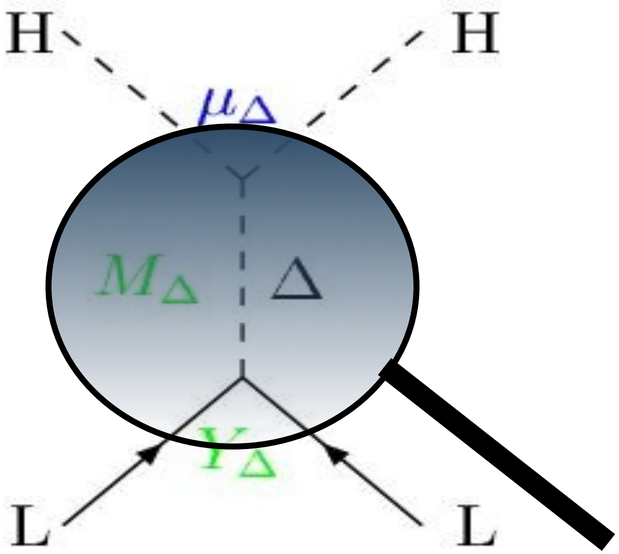
Han et al; Garayoa, Schwetz; Kadastik,et al ; Akeroyd, et al; Fileviez et al, del Aguila et al; Franceschini et al; Aguilar-Saavedra et al;Arhrib et al; Eboli et al...; Tello et al.

Generically it is needed

- Gauge interactions of extra fields for large enough production (ex. type II and type III or type I +W', Z')
- Flavour effects unsuppressed by small Yukawas: approximate $U(1)_L$

How does the ν scale relates to the EW scale ?

Type II see-saw: interchange a heavy triplet scalar

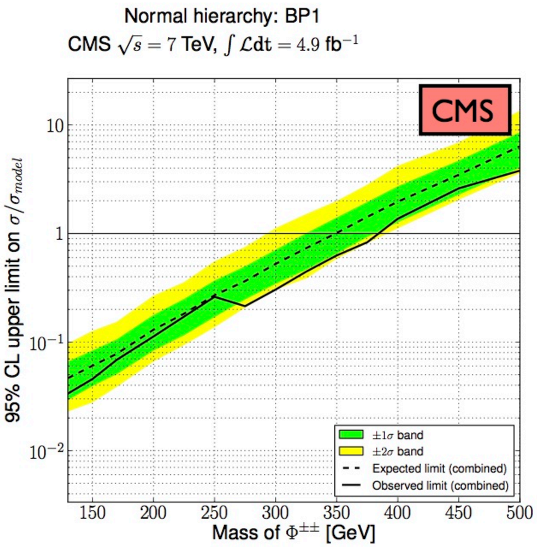


$$m_\nu = \frac{\alpha v^2}{\Lambda} \equiv Y_\Delta \frac{\mu_\Delta}{M_\Delta^2} v^2$$

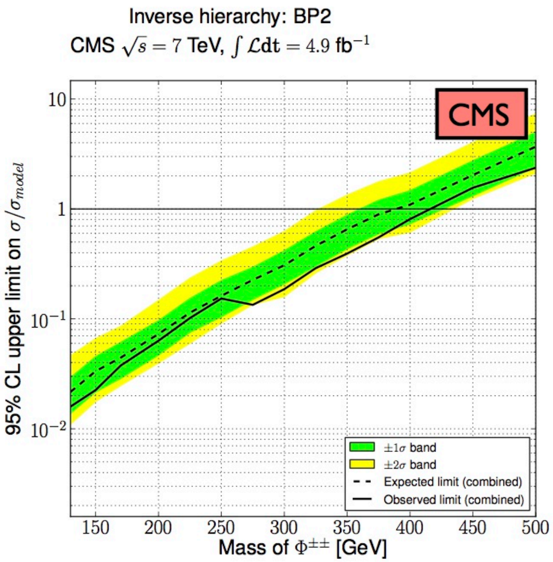
Konetschny, Kummer; Cheng, Li; Lazarides, Shafi, Wetterich ...

pp-> H^{++} H^{--} -> $l^+l^+l^-l^-$

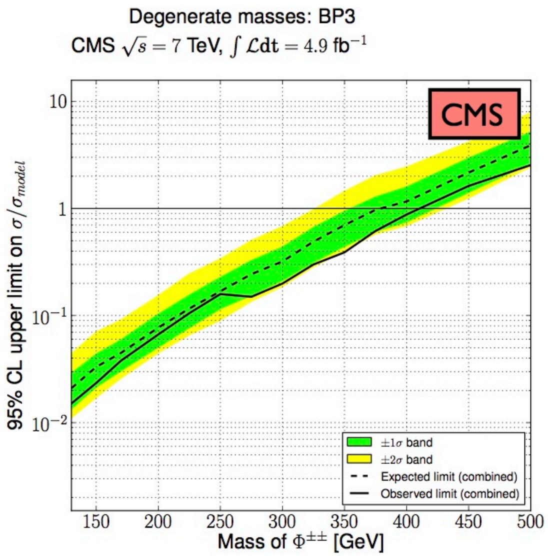
Normal hierarchy



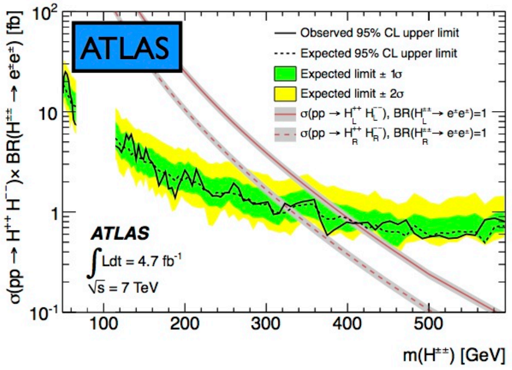
Inverted hierarchy



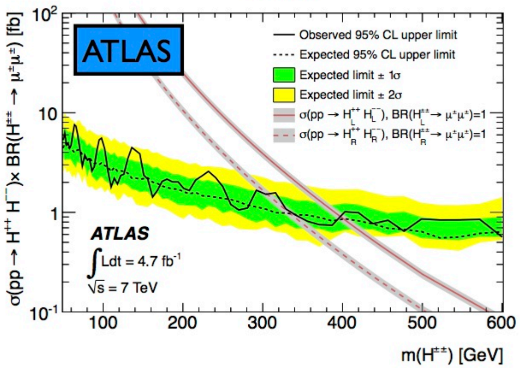
Degenerate ν



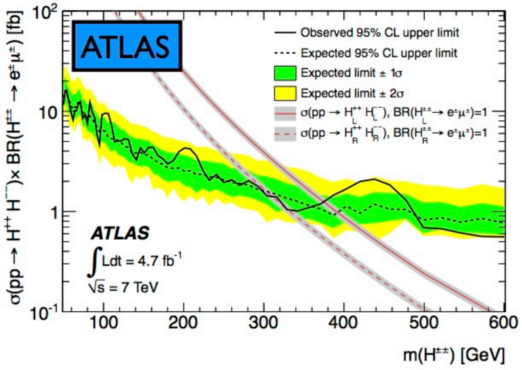
Br(ee)=1



Br(μμ)=1

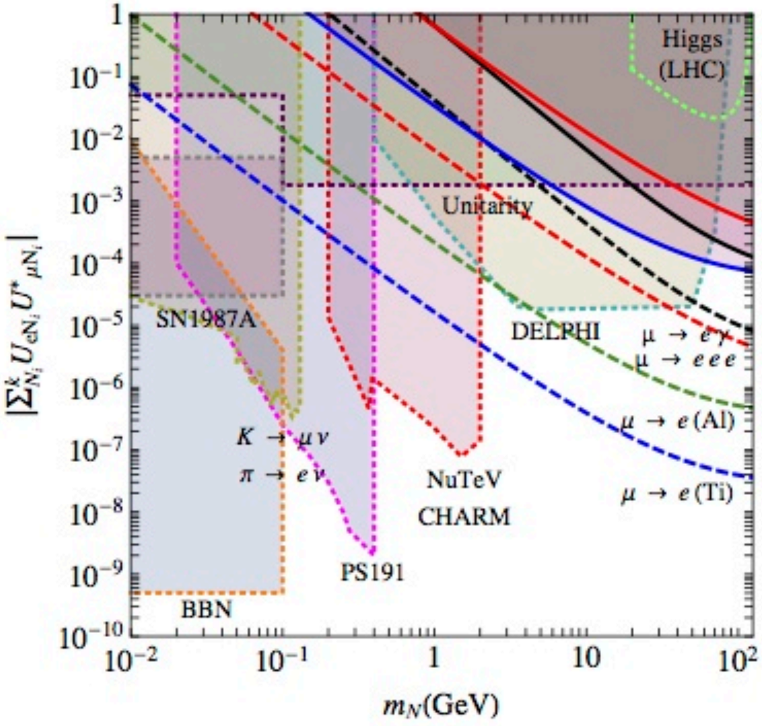


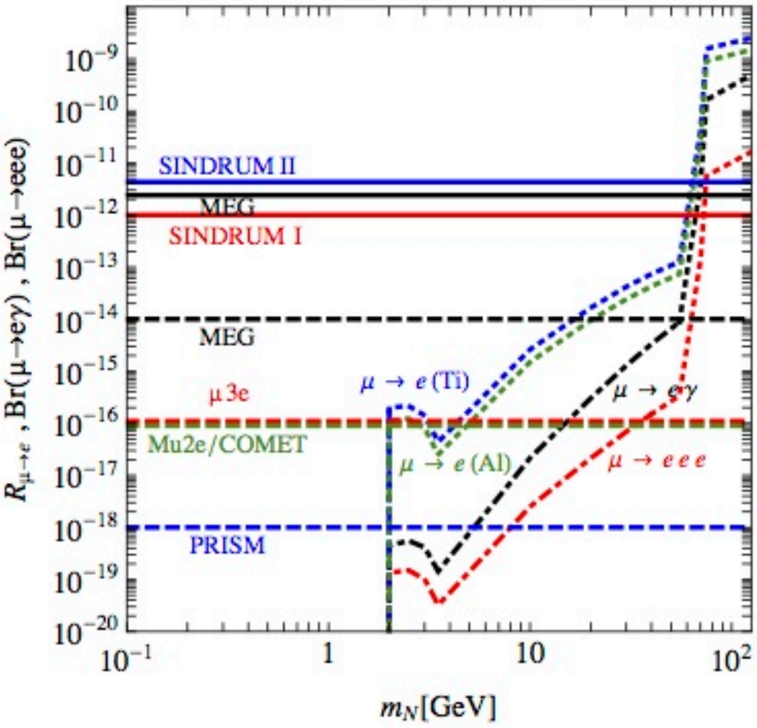
Br(eμ)=1



Rich phenomenology of low-scale models with U(1)

$\mu \to e\,\gamma$ $\mu \to eee$ $\mu \to e$ conversion





recent analysis Alonso et al 2012

Detecting such a signal would be a breakthrough to pin down the new scale

Why so different mixing ?

CKM

$$|V|_{\mathrm{CKM}} = \begin{pmatrix} 0.97427 \pm 0.00015 & 0.22534 \pm 0.0065 & (3.51 \pm 0.15) \times 10^{-3} \\ 0.2252 \pm 0.00065 & 0.97344 \pm 0.00016 & (41.2^{+1.1}_{-5}) \times 10^{-3} \\ (8.67^{+0.29}_{-0.31}) \times 10^{-3} & (40.4^{+1.1}_{-0.5}) \times 10^{-3} & 0.999146^{+0.000021}_{-0.000046} \end{pmatrix}$$

PMNS

3σ

$$|U| = \begin{pmatrix} 0.795 \to 0.846 & 0.513 \to 0.585 & 0.126 \to 0,178 \\ 0.205 \to 0.543 & 0.416 \to 0.730 & 0.579 \to 0.808 \\ 0.215 \to 0.548 & 0.409 \to 0.725 & 0.567 \to 0.800 \end{pmatrix}$$

Gonzalez-Garcia, et al 1209.3023

What about mixing ?

Anarchy for leptons ?

Discrete symmetries (TB mixing)
not particularly motivated with large θ_{13}

Dynamical origin of Yukawas

What about flavour ?

A "natural" landscape ?

R. Alonso, et al, 1306.5927 and 1306.5922

$$V(I_i(\mathcal{Y}_D, \mathcal{Y}_U, \mathcal{Y}_E, \mathcal{Y}_\nu)), i = 1, .., N_{\text{invariants}}$$

Natural/generic extrema <-> those at boundaries (invariance groups)

$$[SU(3)]^5 \otimes O(3)$$

Quarks: (0,0,1) hierarchy + unit CKM

Leptons: degenerate neutrino spectrum
+ large mixings
+ $\pi/2$ Majorana phase

- The results of many beautiful experiments have demonstrated that ν are (for the time-being) the less standard of the SM particles

- Many fundamental questions remain to be answered however:
Majorana nature of neutrinos and scale of new physics? CP violation in the lepton sector? Source of the matter-antimatter asymmetry ?
Lepton vs quark flavour ?

- A rich experimental programme lies ahead where fundamental physics discoveries are very likely (almost warrantied) ...

A galactic message to decipher ?