Nuclear Physics School 2013

Scuola
di Fisica Nucleare
Raimondo Anni

Neutrino Physics

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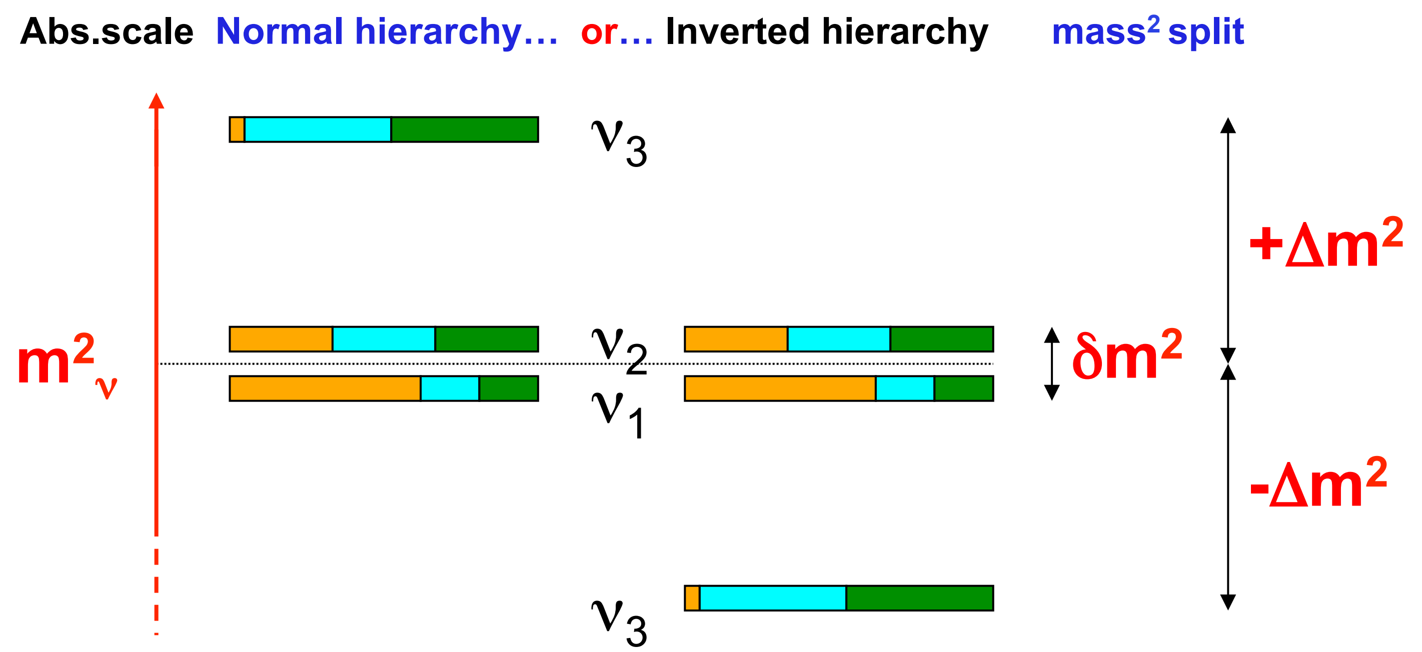
Part Three: Neutrino mass Phenomenology

Notice: I again strongly acknowledge Eligio Lisi for allowing me to use part of his presentations done in CHIPP PhD Winter School, Jan. 2013, Grindelwald, Switzerland

Recap: 3ν framework in just one slide (1 digit accuracy)

Flavors = e μ τ



Knowns:

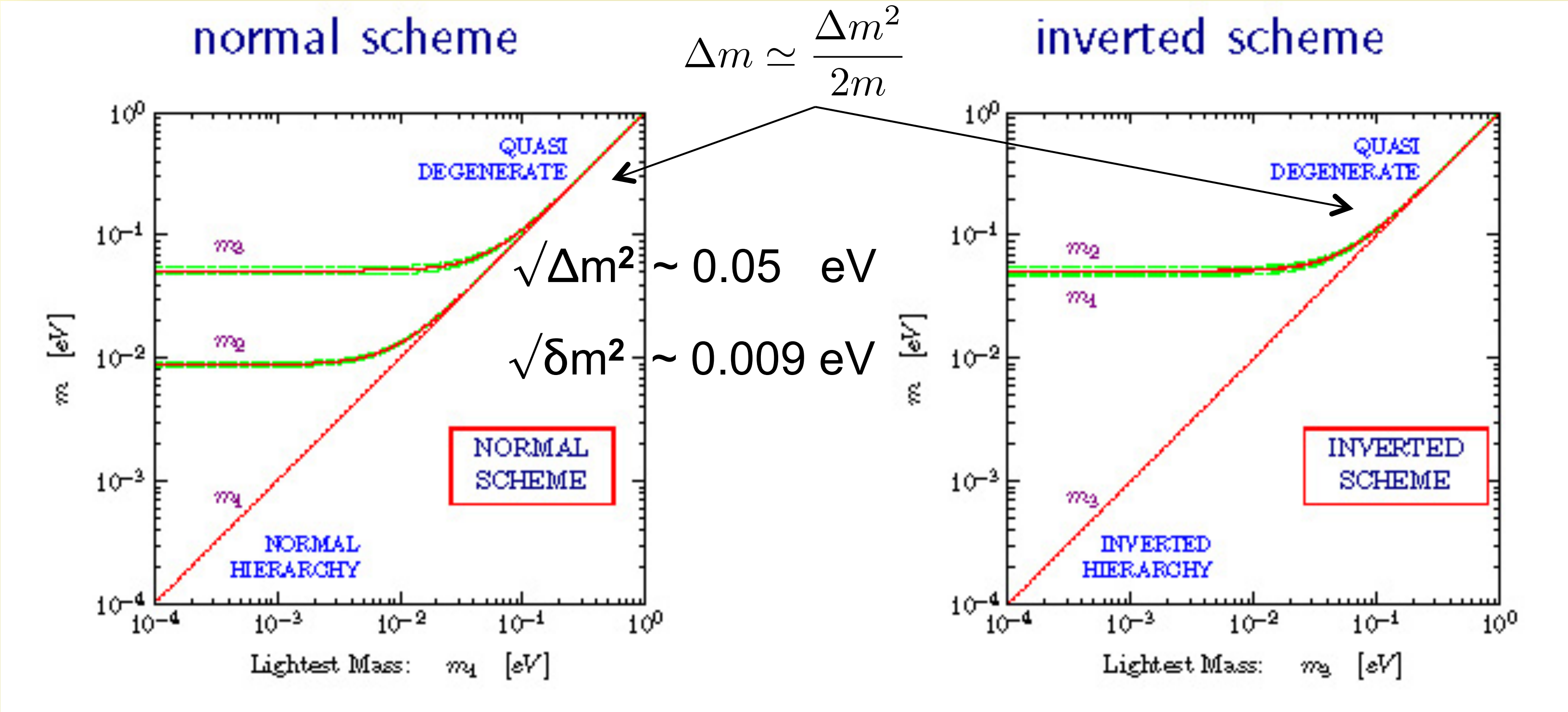
$\delta m^2 \sim 8 \times 10^{-5}$ eV^2
$\Delta m^2 \sim 2 \times 10^{-3}$ eV^2
$\sin^2\theta_{12} \sim 0.3$
$\sin^2\theta_{23} \sim 0.4$
$\sin^2\theta_{13} \sim 0.02$

Unkowns:

δ (CP)
sign(Δm^2)
octant($\sin^2\theta_{23}$)
absolute mass scale
Dirac/Majorana nature

Oscillations constrain neutrino mixings and mass splittings but not the absolute mass scale.

E.g., can take the lightest neutrino mass as free parameter:



$$\Delta m \simeq \frac{\Delta m^2}{2m}$$

$\sqrt{\Delta m^2} \sim 0.05$ eV

$\sqrt{\delta m^2} \sim 0.009$ eV

However, the lightest neutrino mass is not really an “observable”

We know three realistic observables to attack ν masses →

The “weapon”:

One spear:

Three prongs:

ν oscillations

β decay

$0\nu2\beta$ decay

cosmology

The three prongs of the "trident": (m_β, $m_{\beta\beta}$, Σ)

1) **β decay**: $m^2_i \neq 0$ can affect spectrum endpoint. Sensitive to the "effective electron neutrino mass":

$$m_\beta = \left[c^2_{13}c^2_{12}m^2_1 + c^2_{13}s^2_{12}m^2_2 + s^2_{13}m^2_3\right]^{\frac{1}{2}}$$

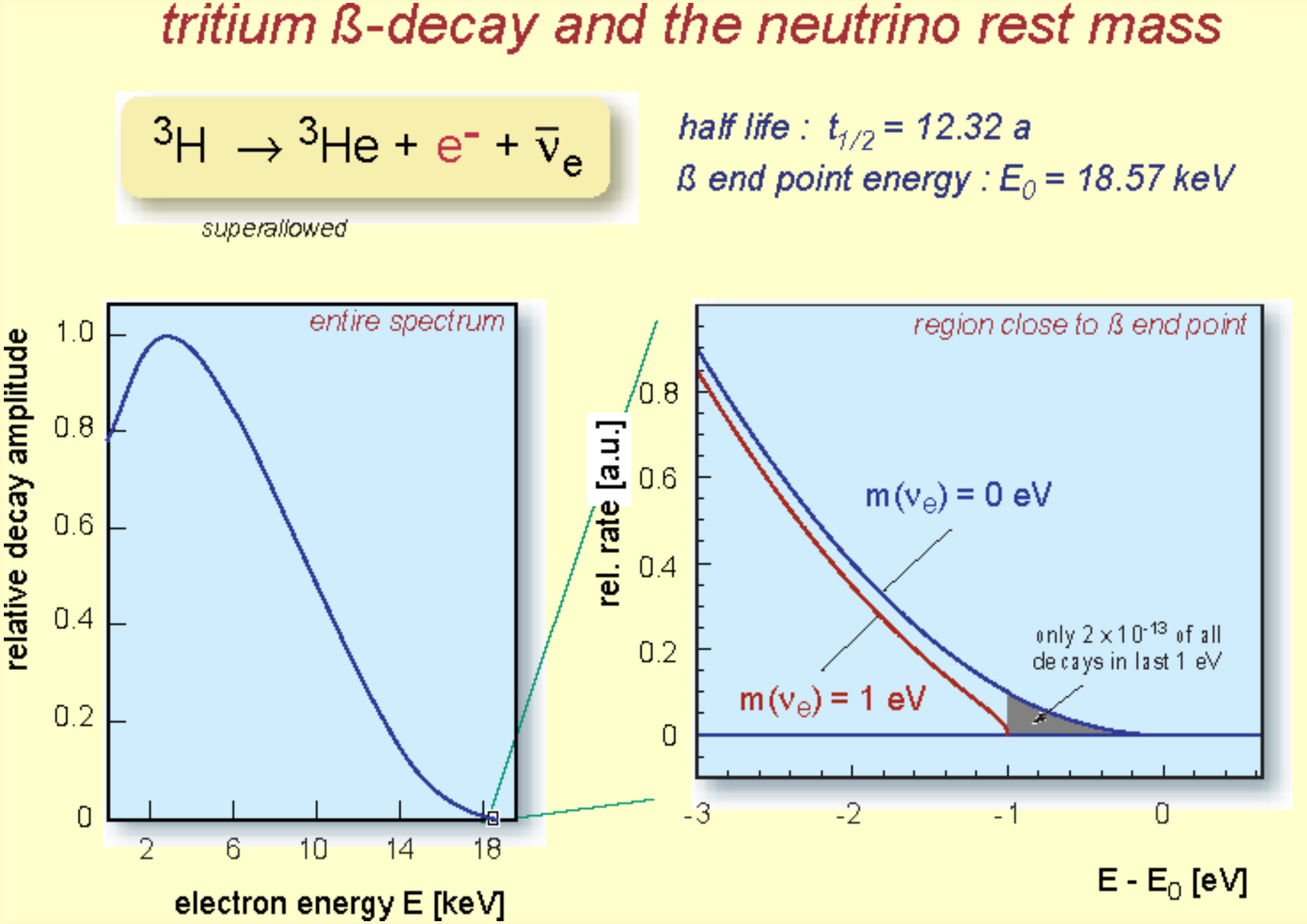
2) **$0\nu\beta\beta$ decay**: Can occur if $m^2_i \neq 0$ and $\nu=\bar{\nu}$ (Majorana, not Dirac) Sensitive to the "effective Majorana mass" (and phases):

$$m_{\beta\beta} = \left|c^2_{13}c^2_{12}m_1 + c^2_{13}s^2_{12}m_2e^{i\phi_2} + s^2_{13}m_3e^{i\phi_3}\right|$$

3) **Cosmology**: $m^2_i \neq 0$ can affect large scale structures in (standard) cosmology constrained by CMB + other data. Sensitive to:

$$\Sigma = m_1 + m_2 + m_3$$

Tritium: low-Q, fast decays



tritium ß-decay and the neutrino rest mass

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

superallowed

half life : $t_{1/2}$ = 12.32 a

ß end point energy : E_0 = 18.57 keV

Need good energy resolution

For just one (electron) neutrino family: sensitivity to $m^2(\nu_e)$ (obsolete)

For three neutrino families ν_i, and individual masses experimentally unresolved in beta decay: sensitivity to the sum of $m^2(\nu_i)$, weighted by squared mixings $|U_{ei}|^2$ with the electron neutrino. Observable:

$$m_\beta = \left[c_{13}^2 c_{12}^2 m_1^2 + c_{13}^2 s_{12}^2 m_2^2 + s_{13}^2 m_3^2\right]^{\frac{1}{2}}$$

(so-called "effective electron neutrino mass")

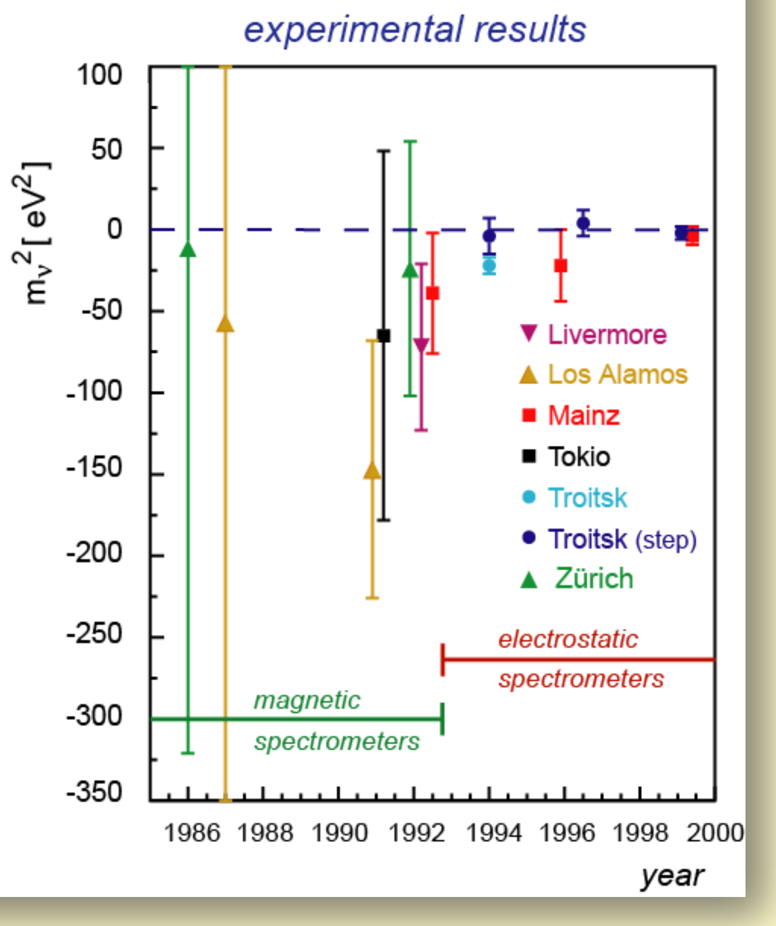
Note: mass state with largest electron flavor component is ν_1:

$$|U_{e1}|^2 \approx \cos^2\theta_{12} \approx 0.7$$

… and we can't exclude that ν_1 is ~massless in normal hierarchy.

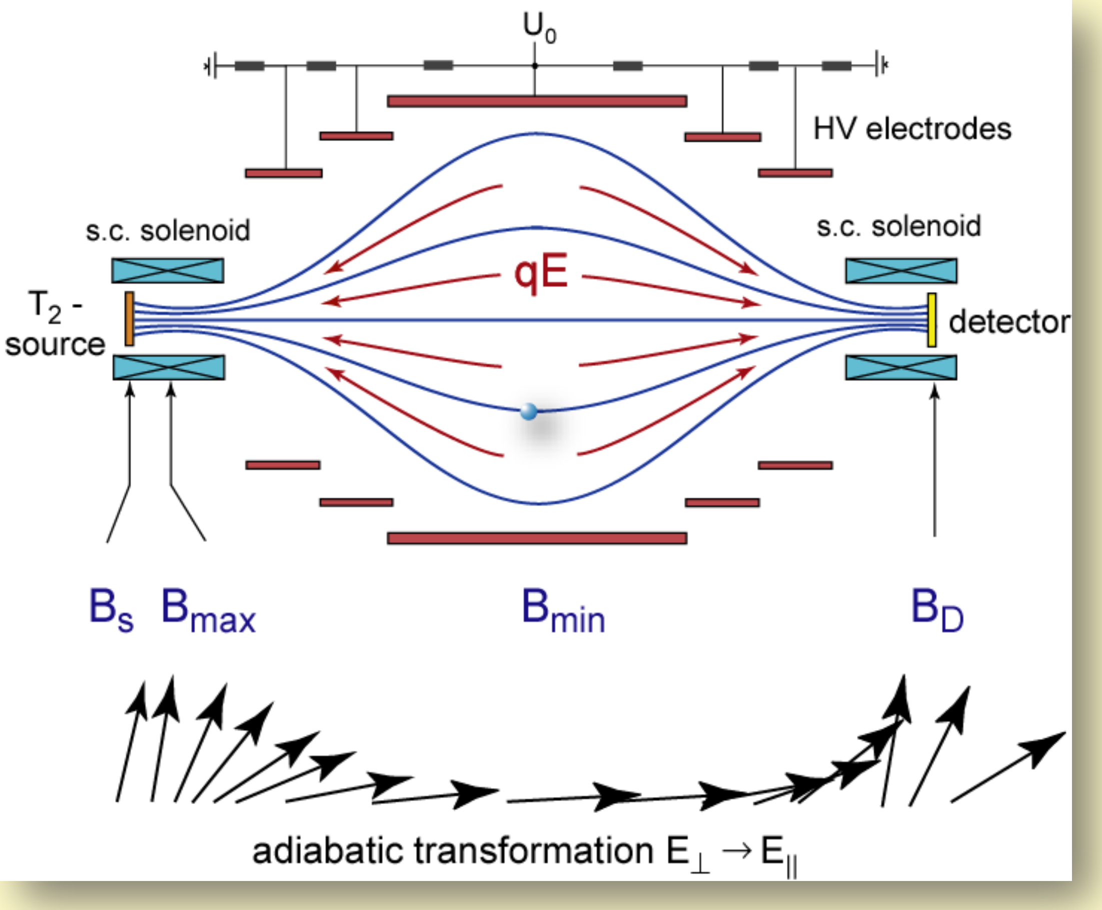
History plot for tritium

	m_ν
ITEP *T_2 in complex molecule* *magn. spectrometer (Tret'yakov)*	17-40 eV
Los Alamos *gaseous T_2 - source* *magn. spectrometer (Tret'yakov)*	< 9.3 eV
Tokio *T - source* *magn. spectrometer (Tret'yakov)*	< 13.1 eV
Livermore *gaseous T_2 - source* *magn. spectrometer (Tret'yakov)*	< 7.0 eV
Zürich *T_2 - source impl. on carrier* *magn. spectrometer (Tret'yakov)*	< 11.7 eV
Troitsk (1994-today) *gaseous T_2 - source* *electrostat. spectrometer*	**< 2.2 eV**
Mainz (1994-today) *frozen T_2 - source* *electrostat. spectrometer*	< 2.3 eV



Latest bounds at the level of ~2 eV

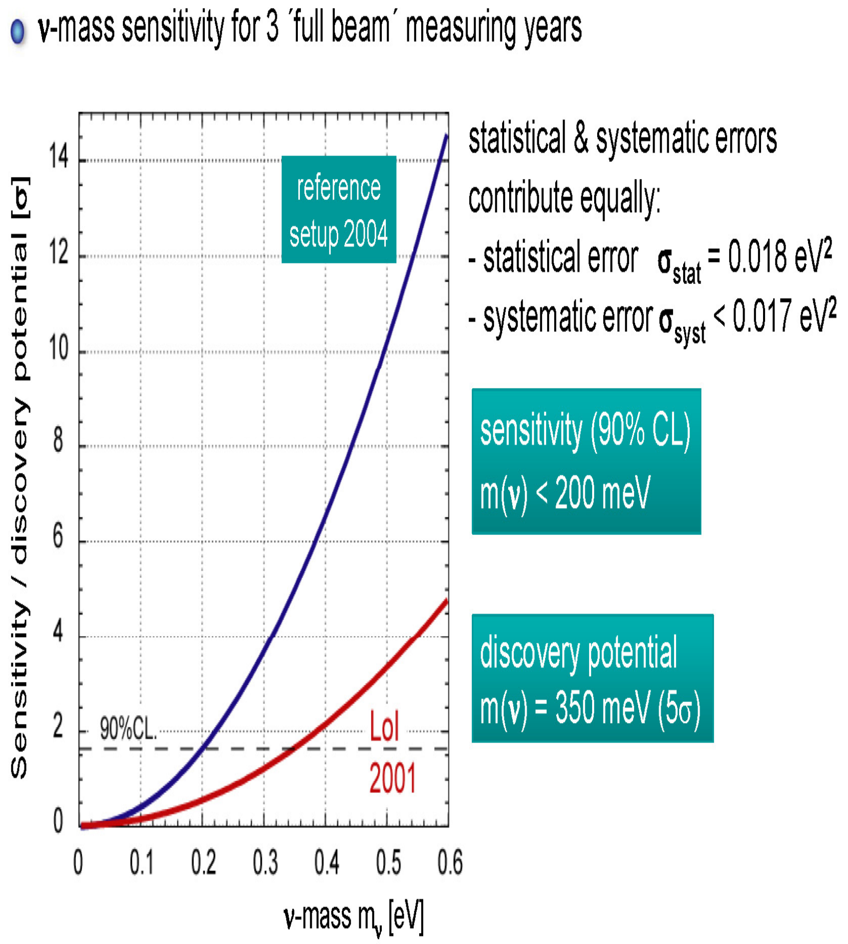
In construction: KATRIN experiment



Magnetic Adiabatic Collimation with an Electrostatic Filter

Probably the "ultimate" spectrometer of this kind….

KATRIN sensitivity



- ν-mass sensitivity for 3 ´full beam´ measuring years

statistical & systematic errors contribute equally:

- statistical error $\sigma_{stat} = 0.018\ \mathrm{eV}^2$
- systematic error $\sigma_{syst} < 0.017\ \mathrm{eV}^2$

sensitivity (90% CL)
m(ν) < 200 meV

discovery potential
m(ν) = 350 meV (5σ)

Mainz + Troitsk: **m_β** < 2 eV

KATRIN: O(10) improvement

Examples of prospective results at KATRIN (±1σ, [eV]):

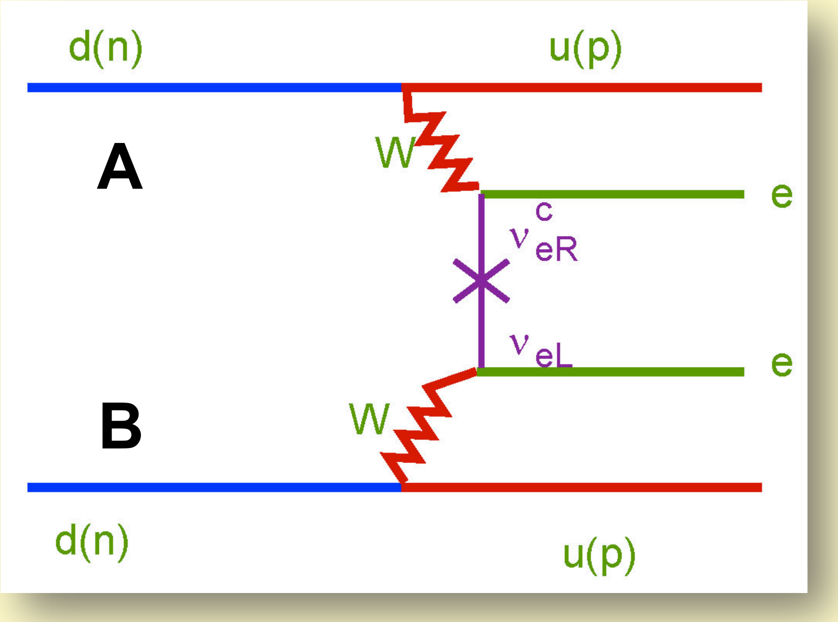
m_β = 0.35±0.07 (5σ discovery)

m_β = 0.30±0.10 (3σ evidence)

m_β = 0 ±0.12 (<0.2 at 90% CL)

[Need new ideas to go below ~0.2 eV]

Neutrinoless double beta decay: (A,Z) → (A,Z+2)+2e

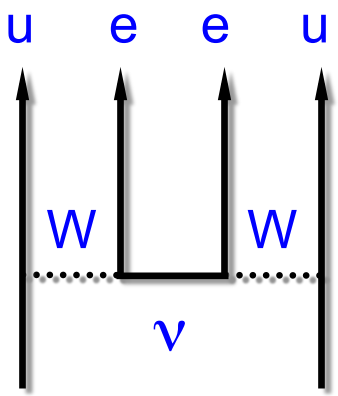


Can occur only for Majorana neutrinos. Intuitive picture:

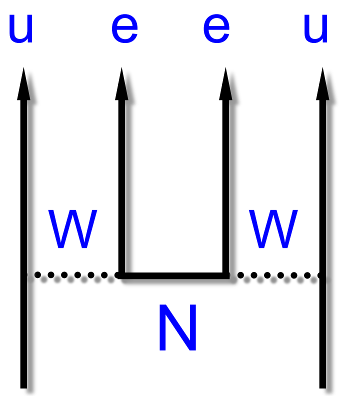
1) A RH antineutrino is emitted at point "**A**" together with an electron
2) If it is massive, at O(m/E) it develops a LH component (not possible if Weyl)
3) If neutrino=antineutrino, this component is a LH neutrino (not possible if Dirac)
4) The LH (Majorana) neutrino is absorbed at "**B**" where a 2nd electron is emitted

[EW part is "simple". Nuclear physics part is rather complicated and uncertain.]

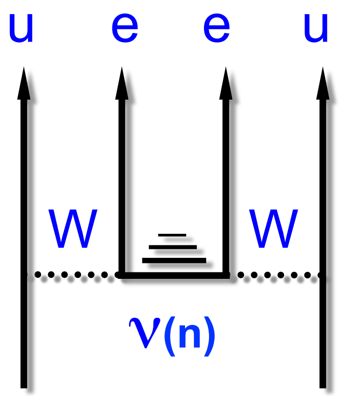
Warning: previous expression invalid for nonstandard $0\nu\beta\beta$ decays



Standard

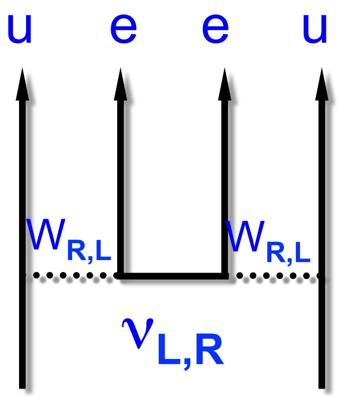


Heavy ν



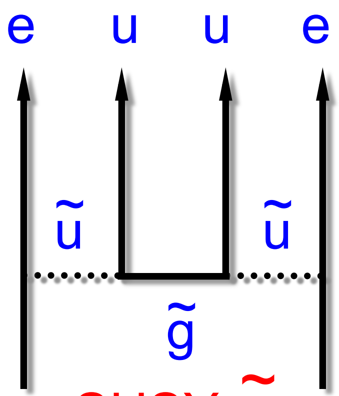
Kaluza-Klein

(KK±1 Brane:a=$10^{\pm1}$/GeV)

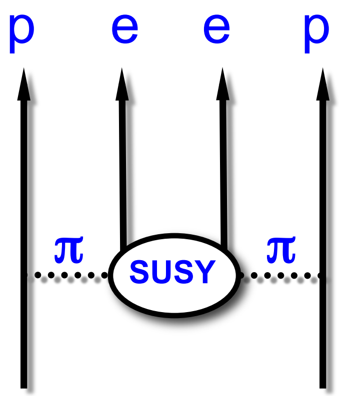


RHC λ,η

λ=RH had, η=LH had



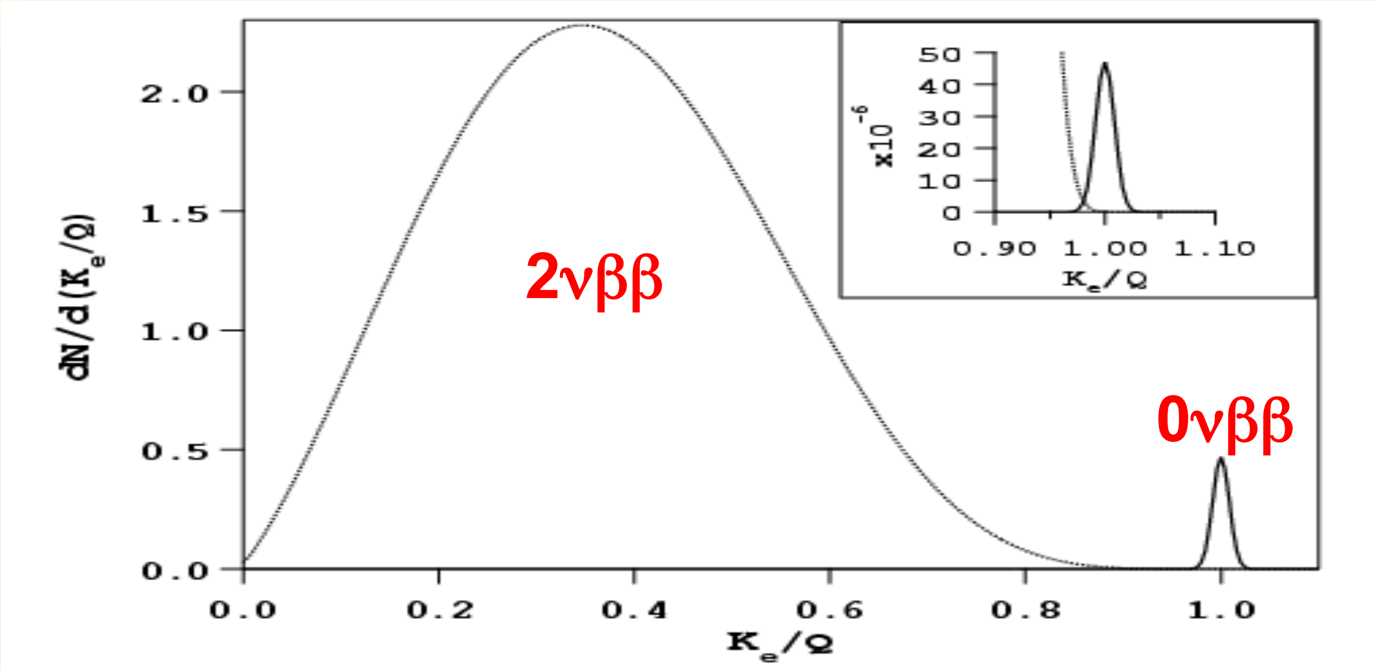
SUSY $\tilde{g}$

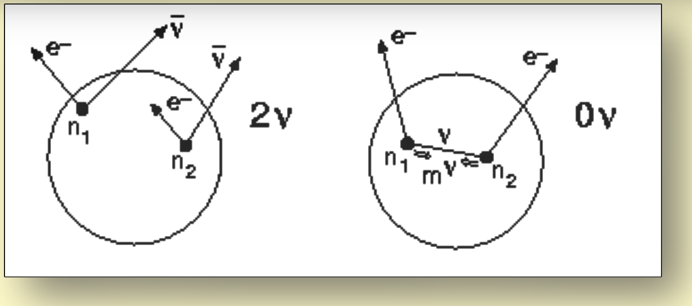


SUSY π

Experimentally: Look at sum energy of both electrons

Need to see the **0νββ** line emerge above bkgd, at endpoint of spectrum from "conventional" **2νββ** decay.





What sets the uncertainty of $m_{\beta\beta}$?

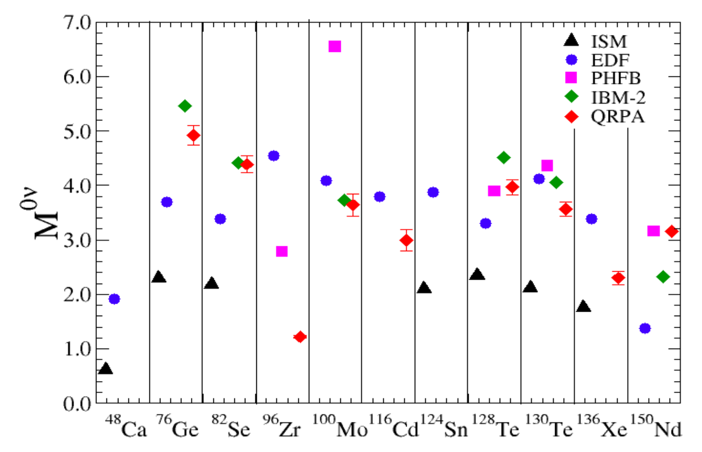
In case of positive signal, a major concern is the accuracy of the **nuclear matrix element |M|**, rather than the expt. uncertainty on the decay half life:

$$T_i^{-1} = G_i \, |M_i'|^2 \, m_{\beta\beta}^2$$

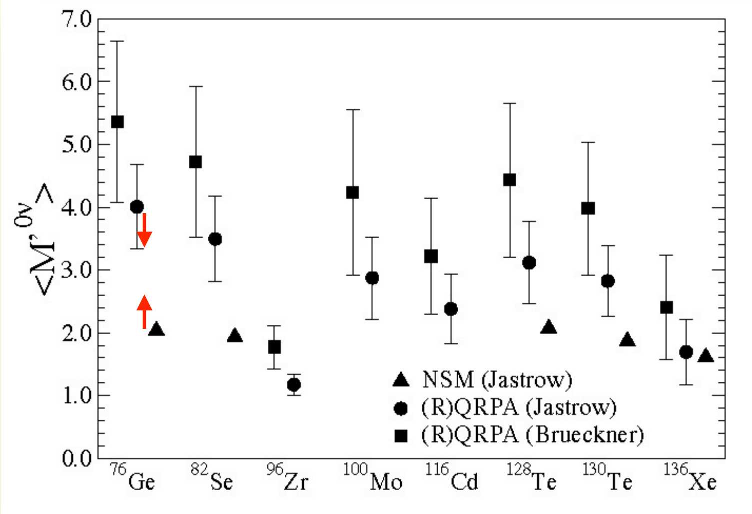
Half-life

Phase space

Matrix element



Luckily, independent nuclear physics models converge better than it could be hoped only a few years ago …



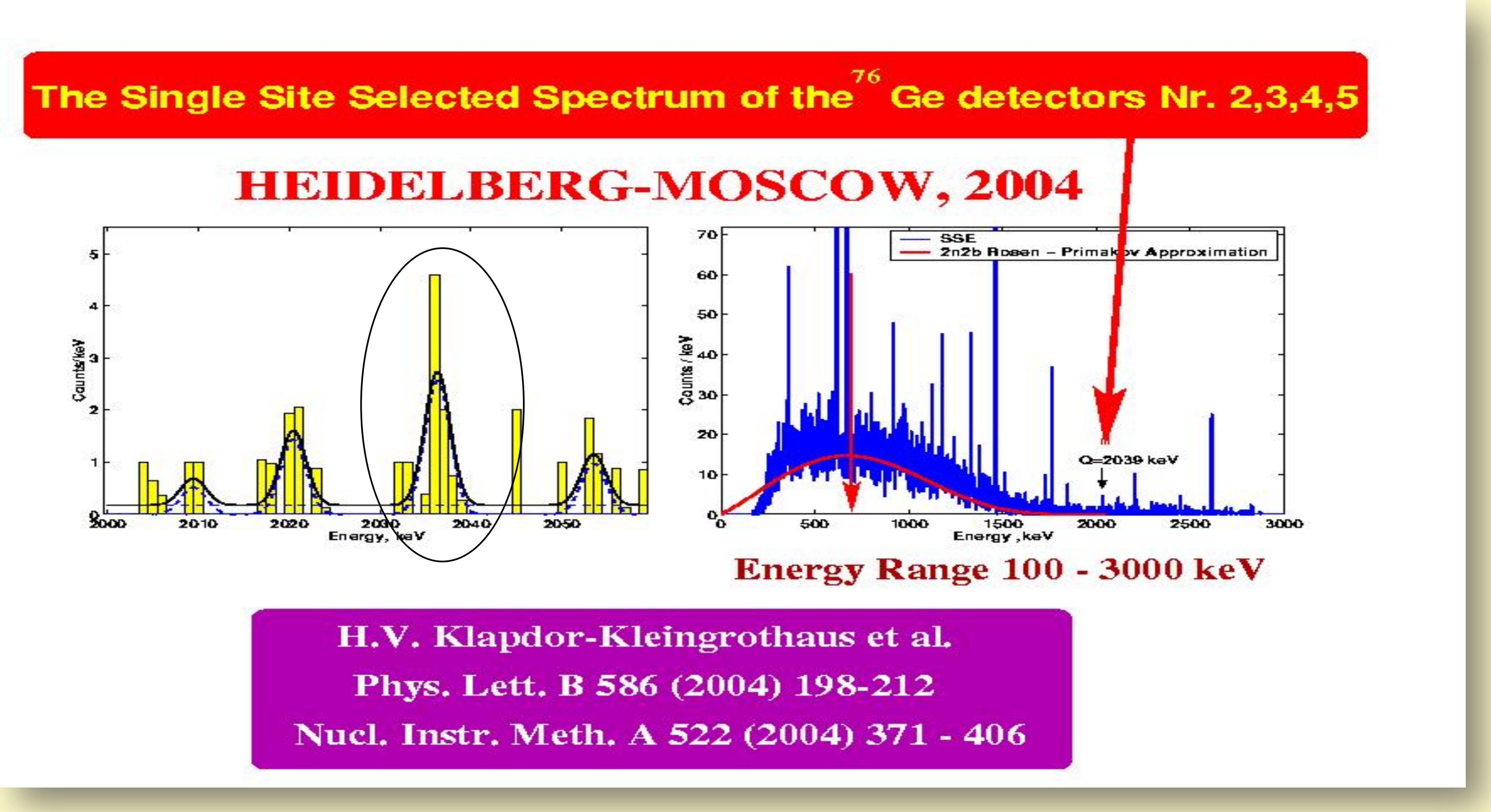
from: Simkovic

… especially when using the same theo. inputs for comparison (e.g, same description of short range nucleon repulsion) and exploiting additional data

BUT: errors remain large for each candidate nucleus.

CUORICINO *Completed*	NEMO at the Frejus Underground Laboratory *Completed*	Heidelberg-Moscow Ge Experiment *Completed*	IGEX *Completed*
XMASS *Taking Data*	EXO 200 *Taking Data* EXO 1000 *Under Construction*	COBRA *Taking data*	KamLAND-Zen *Taking Data*
MOON *Taking Data*	DCBA *Taking Data*	LUCIFER *Taking Data*	AMoRE *Taking Data*
SuperNEMO *Proposal*	CANDLES *Proposal*	NEXT *Proposal*	Gotthard *R&D*
SNO+ *Under Construction*	Majorana *Under Construction*	CUORE *Under construction*	GERDA *Under Construction at LNGS*

$0\nu\beta\beta$ search: No signal observed so far, except in the most sensitive experiment to date (Heidelberg-Moscow): 6σ signal claimed by (part of) the experimental collaboration. Still hotly debated.



The Single Site Selected Spectrum of the ^{76}Ge detectors Nr. 2,3,4,5

HEIDELBERG-MOSCOW, 2004

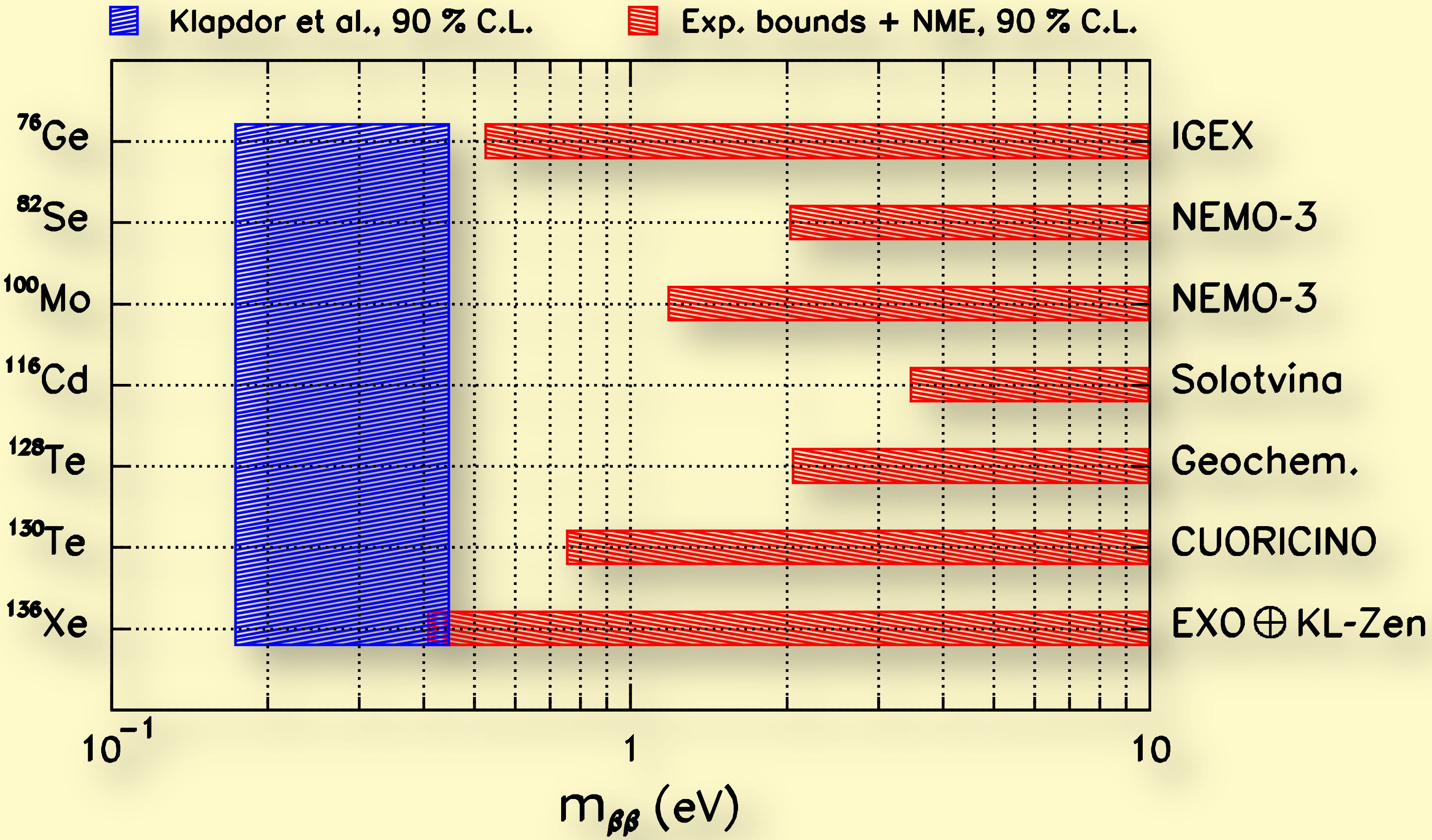
Energy Range 100 - 3000 keV

H.V. Klapdor-Kleingrothaus et al.

Phys. Lett. B 586 (2004) 198-212

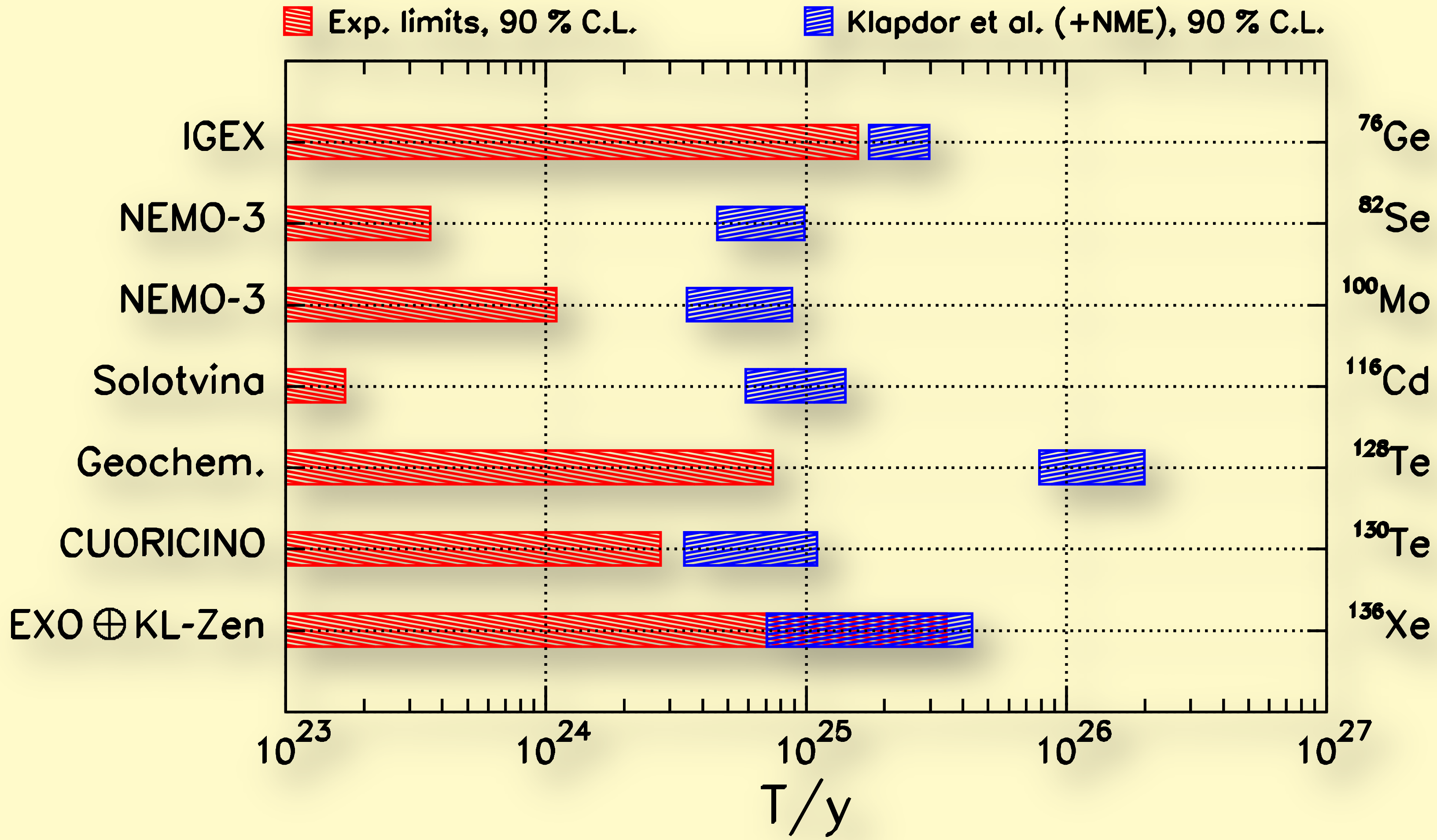
Nucl. Instr. Meth. A 522 (2004) 371 - 406

Claim versus current limits (in terms of Majorana mass)



arXiv:1301.1587

Claim versus current limits (in terms of half-life)



[Claim partly disfavored by EXO + KamLAND-Zen data]

Cosmology: a "modern" probe

Standard big bang cosmology predicts a relic neutrino background with total number density 336/cm^3 and temper. T_ν ~ 2 K ~ 1.7 x 10^{-4} eV << $\sqrt{\delta m^2}$, $\sqrt{\Delta m^2}$.

→At least two relic neutrino species are nonrelativistic today (we can't exclude the lightest to be ~massless)

→Their total mass contributes to the normalized energy density as $\boldsymbol{\Omega_\nu \approx \Sigma / 50}$ **eV**, where

$$\Sigma = m_1 + m_2 + m_3$$

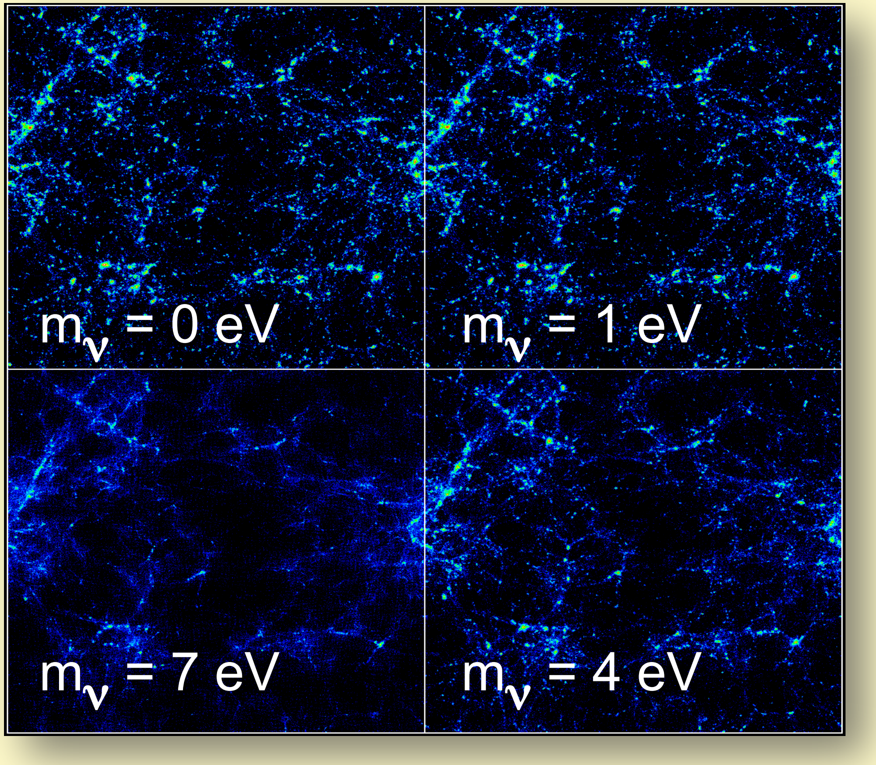
→So, if we just impose that neutrinos do not saturate the total matter density, $\boldsymbol{\Omega_\nu < \Omega_m \approx 0.25}$**,** we get

m_i < 4 eV – not bad!

Much better bounds can be derived from neutrino effects on structure formation.

Massive neutrinos are difficult to cluster because of their relatively high velocities: they suppress matter fluctuations on scales smaller than their mass-dependent free-streaming scale.

→ Get mass-dependent suppression of small-scale structures



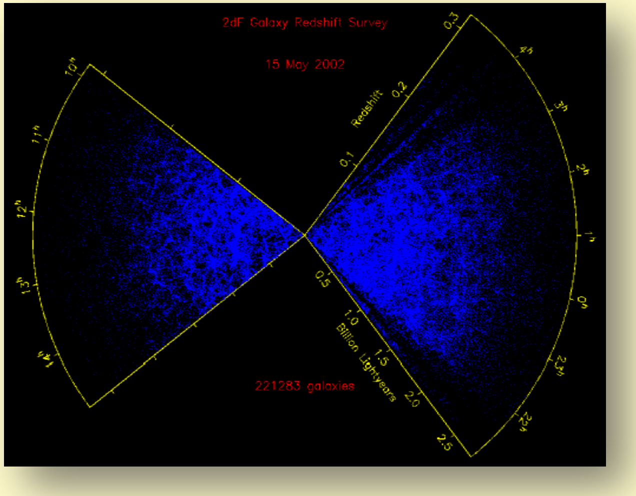
(E..g., Ma 1996)

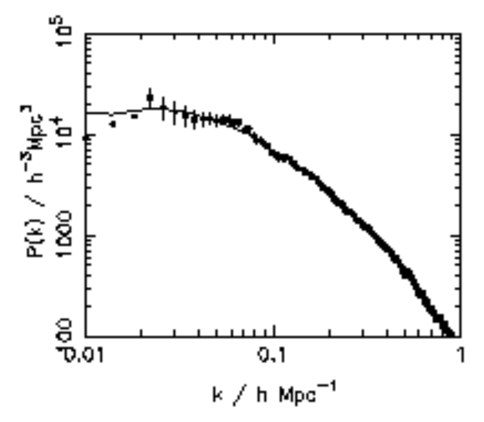
Constraints from CMB also help removing degeneracies.

Observations:

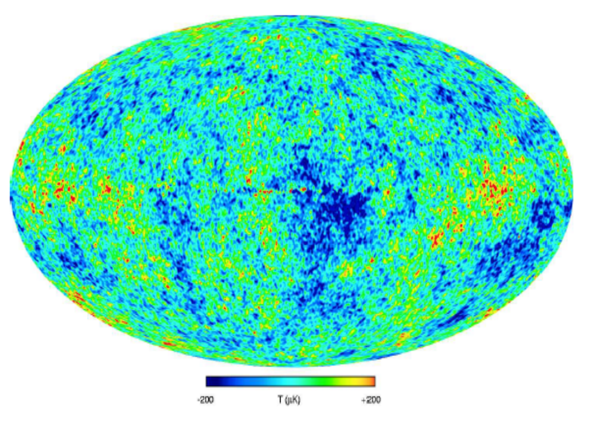
Spectra:

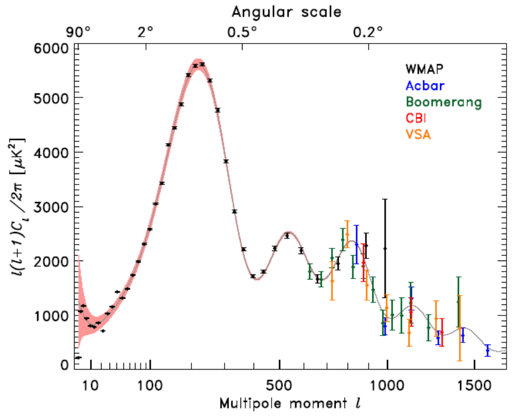
LSS



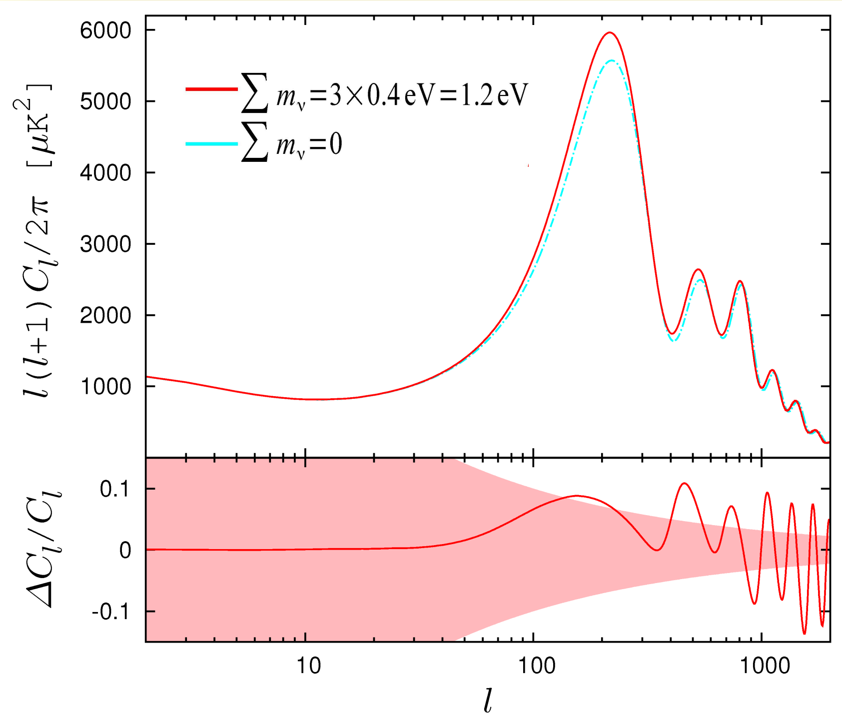


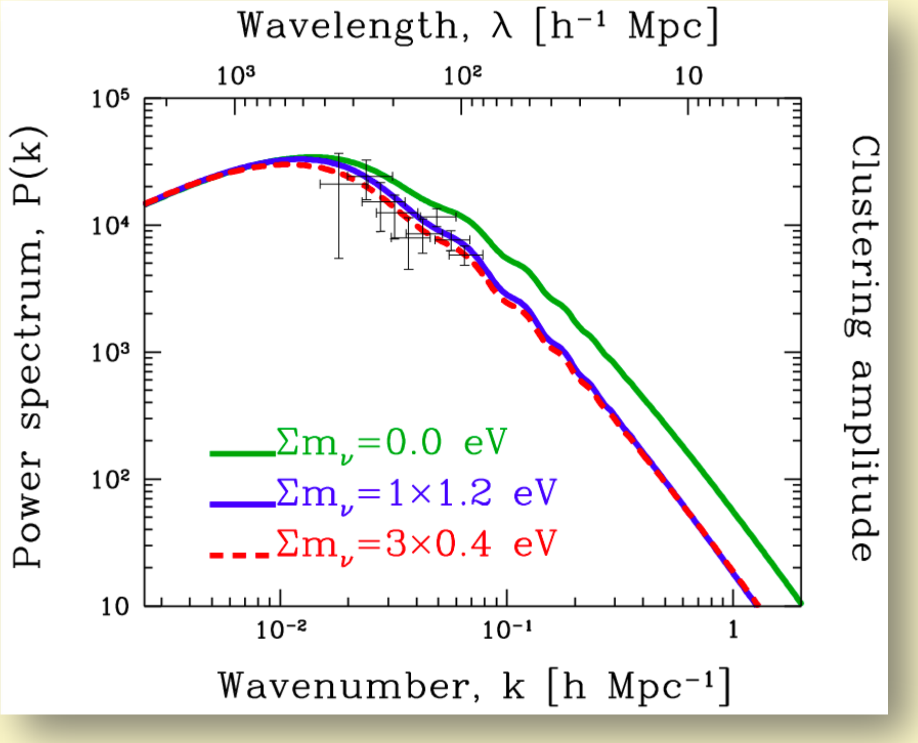
CMB





Spectral effect of massive neutrinos (e.g., from Y.Y.Y. Wong)





Significant progress after WMAP and recent galaxy surveys

Just an example of recent limits on the sum of ν masses from various data sets (assuming the "flat ΛCDM model"):

[from latest WMAP-9y data release, dec. 2012]

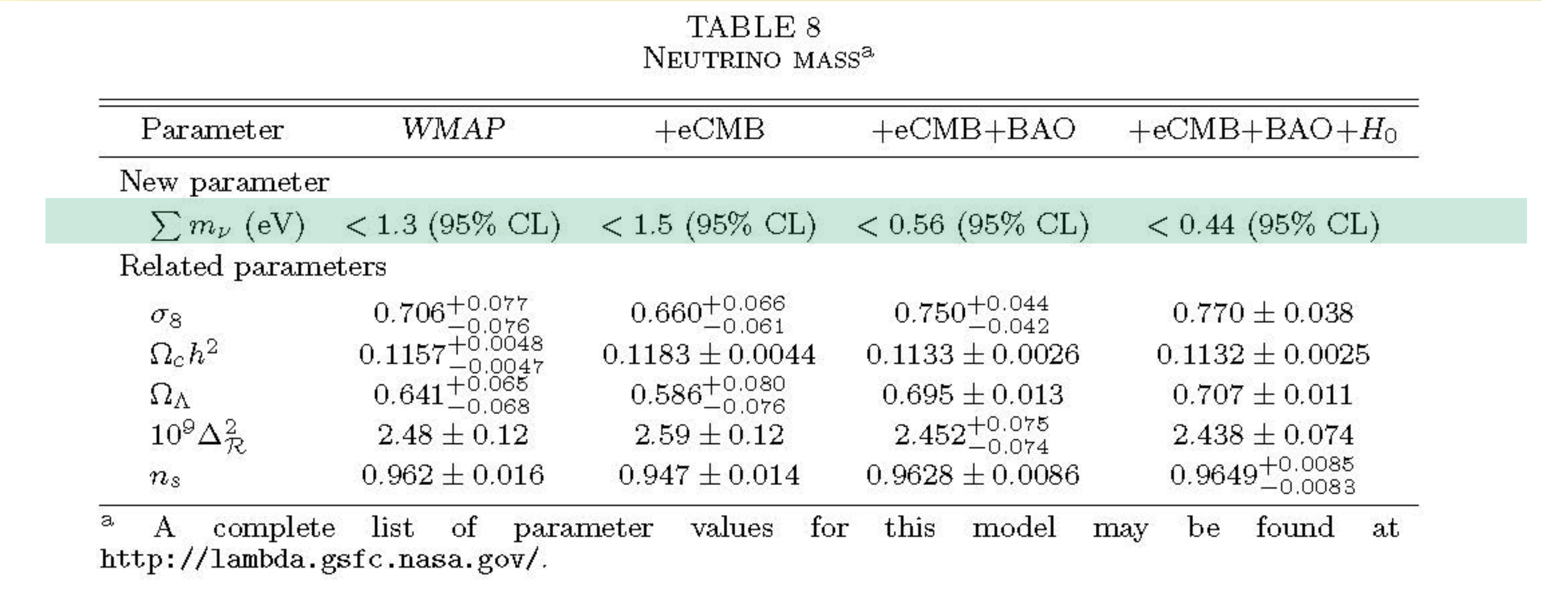


TABLE 8
NEUTRINO MASS[a]

Parameter	*WMAP*	+eCMB	+eCMB+BAO	+eCMB+BAO+H_0
New parameter				
$\sum m_\nu$ (eV)	< 1.3 (95% CL)	< 1.5 (95% CL)	< 0.56 (95% CL)	< 0.44 (95% CL)
Related parameters				
σ_8	$0.706^{+0.077}_{-0.076}$	$0.660^{+0.066}_{-0.061}$	$0.750^{+0.044}_{-0.042}$	0.770 ± 0.038
$\Omega_c h^2$	$0.1157^{+0.0048}_{-0.0047}$	0.1183 ± 0.0044	0.1133 ± 0.0026	0.1132 ± 0.0025
Ω_Λ	$0.641^{+0.065}_{-0.068}$	$0.586^{+0.080}_{-0.076}$	0.695 ± 0.013	0.707 ± 0.011
$10^9\Delta^2_{\mathcal{R}}$	2.48 ± 0.12	2.59 ± 0.12	$2.452^{+0.075}_{-0.074}$	2.438 ± 0.074
n_s	0.962 ± 0.016	0.947 ± 0.014	0.9628 ± 0.0086	$0.9649^{+0.0085}_{-0.0083}$

[a] A complete list of parameter values for this model may be found at `http://lambda.gsfc.nasa.gov/`.

In general, upper limits range

from: "conservative" (only CMB data, dominated by WMAP 9y), **<1.2 eV**

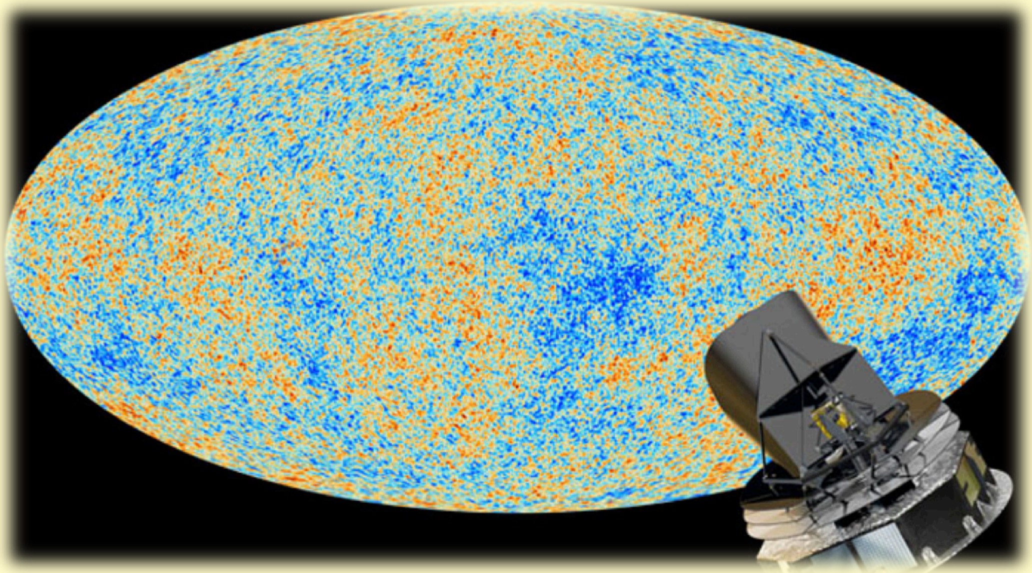
to: "aggressive" (all relevant cosmological data), **<0.2 eV**

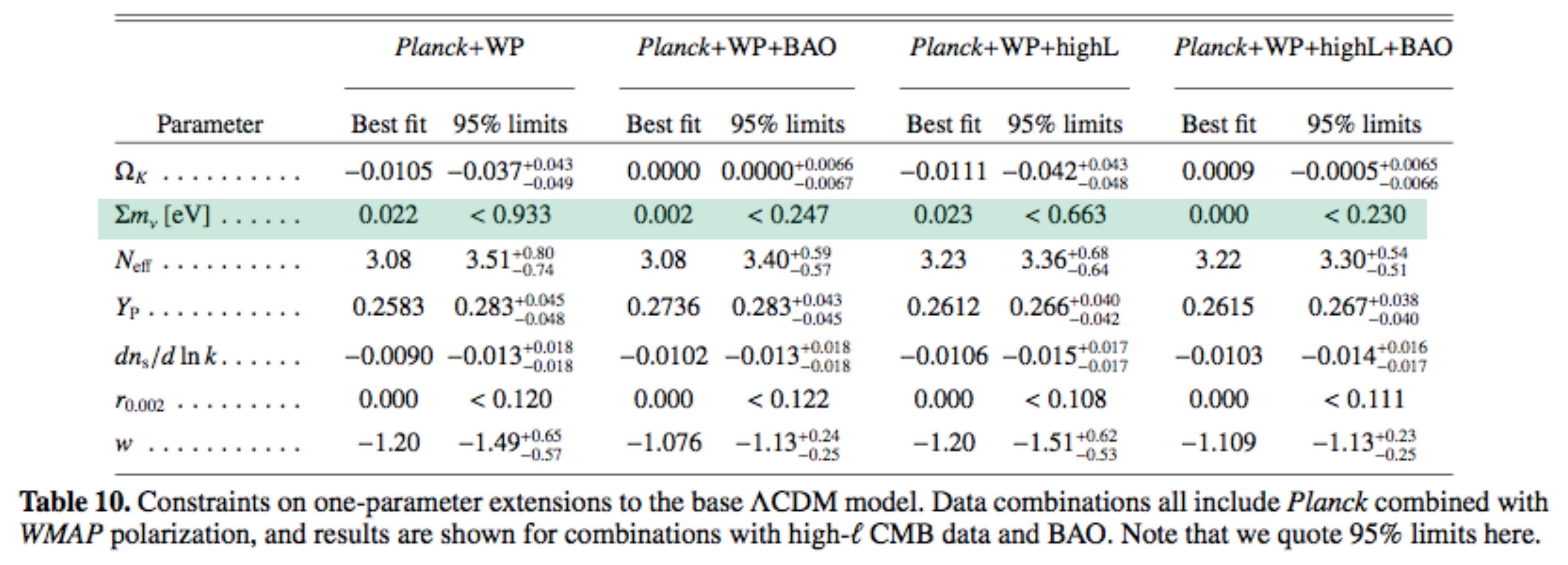
Intermediate upper limits around $\Sigma < 0.6$ eV have gained large consensus.

More stringent limits require more "faith" in current control of syst.'s.

After Planck (march 2013)

arXiv:1303.5076





	Planck+WP		*Planck*+WP+BAO		*Planck*+WP+highL		*Planck*+WP+highL+BAO	
Parameter	Best fit	95% limits	Best fit	95% limits	Best fit	95% limits	Best fit	95% limits
Ω_K	-0.0105	$-0.037^{+0.043}_{-0.049}$	0.0000	$0.0000^{+0.0066}_{-0.0067}$	-0.0111	$-0.042^{+0.043}_{-0.048}$	0.0009	$-0.0005^{+0.0065}_{-0.0066}$
Σm_ν [eV]	0.022	< 0.933	0.002	< 0.247	0.023	< 0.663	0.000	< 0.230
$N_{\rm eff}$	3.08	$3.51^{+0.80}_{-0.74}$	3.08	$3.40^{+0.59}_{-0.57}$	3.23	$3.36^{+0.68}_{-0.64}$	3.22	$3.30^{+0.54}_{-0.51}$
$Y_{\rm P}$	0.2583	$0.283^{+0.045}_{-0.048}$	0.2736	$0.283^{+0.043}_{-0.045}$	0.2612	$0.266^{+0.040}_{-0.042}$	0.2615	$0.267^{+0.038}_{-0.040}$
$dn_s/d\ln k$	-0.0090	$-0.013^{+0.018}_{-0.018}$	-0.0102	$-0.013^{+0.018}_{-0.018}$	-0.0106	$-0.015^{+0.017}_{-0.017}$	-0.0103	$-0.014^{+0.016}_{-0.017}$
$r_{0.002}$	0.000	< 0.120	0.000	< 0.122	0.000	< 0.108	0.000	< 0.111
w	-1.20	$-1.49^{+0.65}_{-0.57}$	-1.076	$-1.13^{+0.24}_{-0.25}$	-1.20	$-1.51^{+0.62}_{-0.53}$	-1.109	$-1.13^{+0.23}_{-0.25}$

Table 10. Constraints on one-parameter extensions to the base ΛCDM model. Data combinations all include *Planck* combined with *WMAP* polarization, and results are shown for combinations with high-ℓ CMB data and BAO. Note that we quote 95% limits here.

The trident… in action

ν oscillations

β decay

0ν2β decay

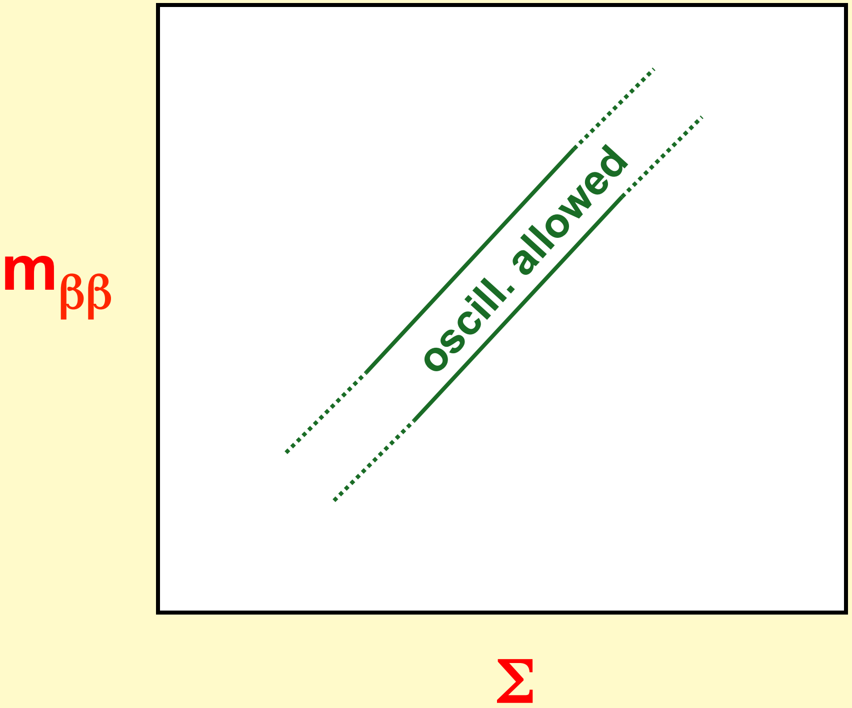
cosmology

$$m_\beta = \left[c_{13}^2 c_{12}^2 m_1^2 + c_{13}^2 s_{12}^2 m_2^2 + s_{13}^2 m_3^2\right]^{\frac{1}{2}}$$

$$m_{\beta\beta} = \left|c_{13}^2 c_{12}^2 m_1 + c_{13}^2 s_{12}^2 m_2 e^{i\phi_2} + s_{13}^2 m_3 e^{i\phi_3}\right|$$

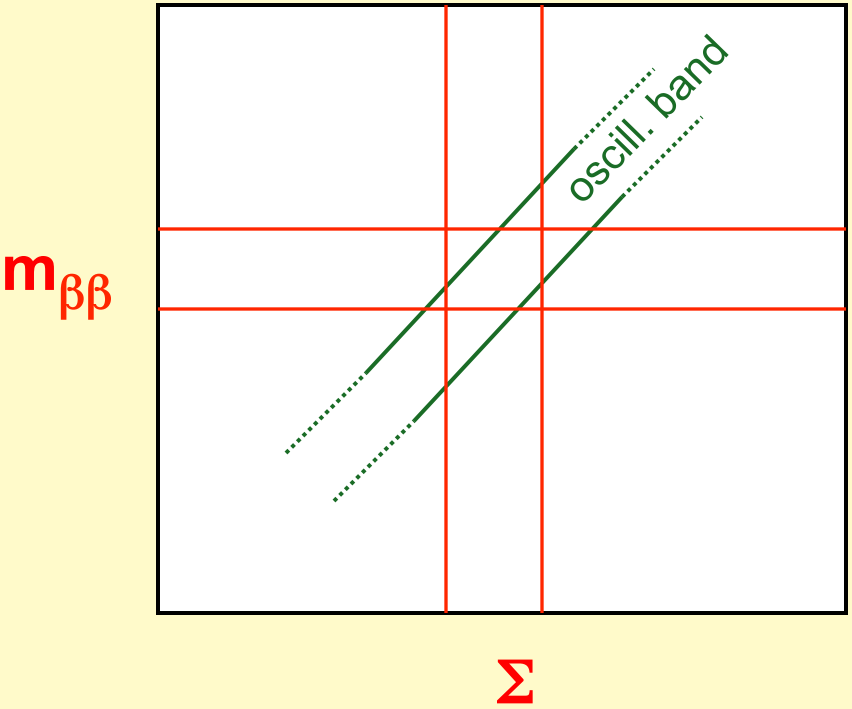
$$\Sigma = m_1 + m_2 + m_3$$

Interplay: **Oscillations** fix the **mass^2 splittings,** and thus induce **positive correlations** between any pair of the three observables **(m_β, $m_{\beta\beta}$, Σ)**, e.g.:



i.e., if one observable increases, the other one (typically) must increase to match mass splitting

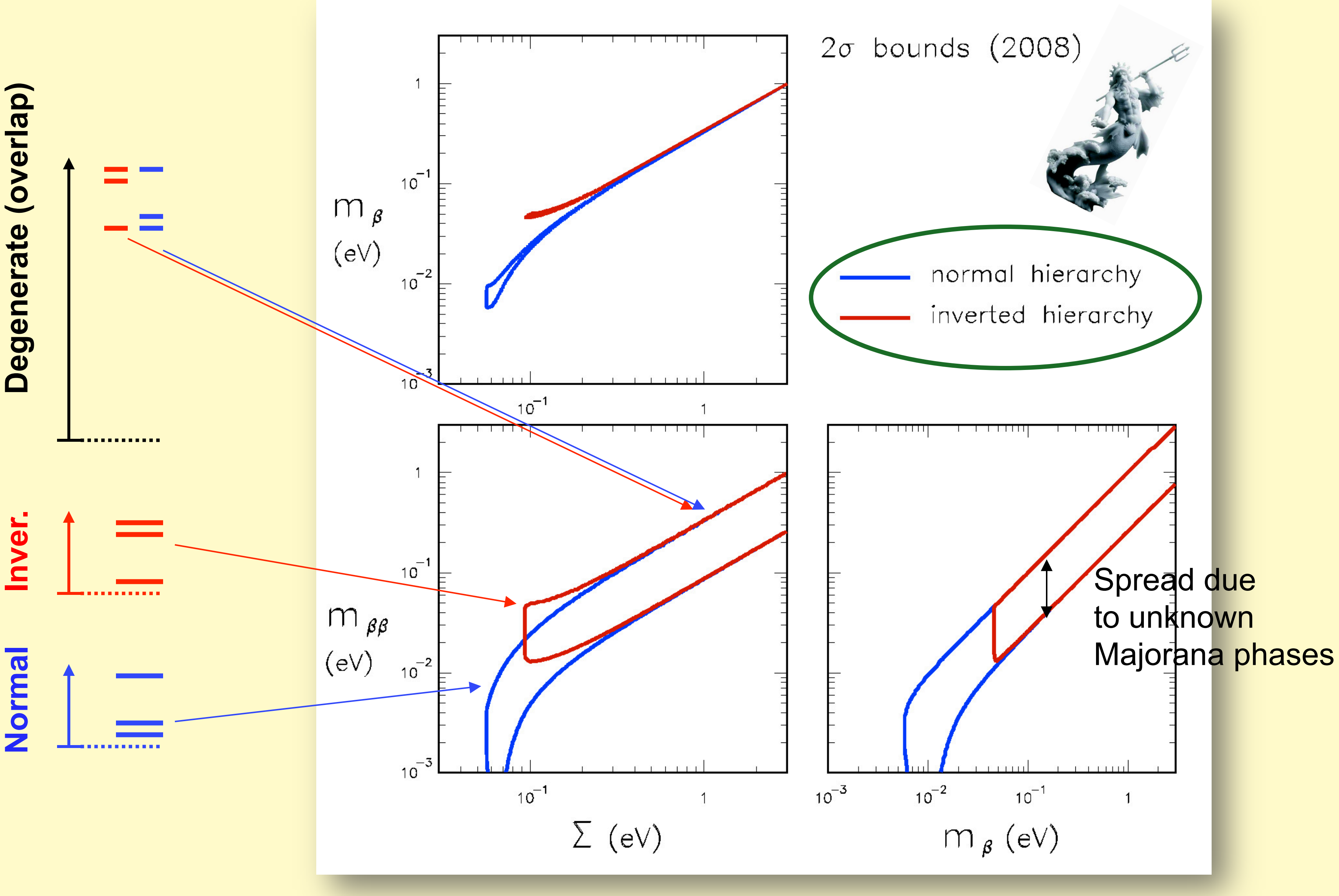
Generic expectations: **In the absence of new physics** (beyond 3ν masses and mixing), **any two data** among **(m_β, $m_{\beta\beta}$, Σ)** are expected to **cross the oscillation band**



This requirement provides either an important consistency check or, if not realized, an indication for new physics (barring expt mistakes)

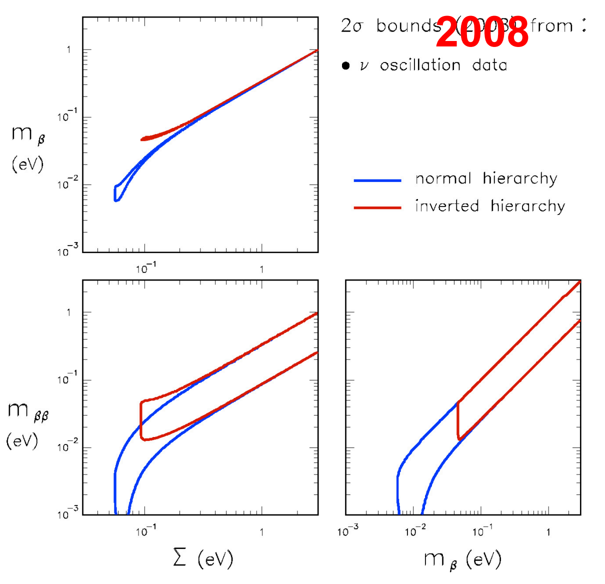
⇒ **Data accuracy/reliability/redundance are crucial**

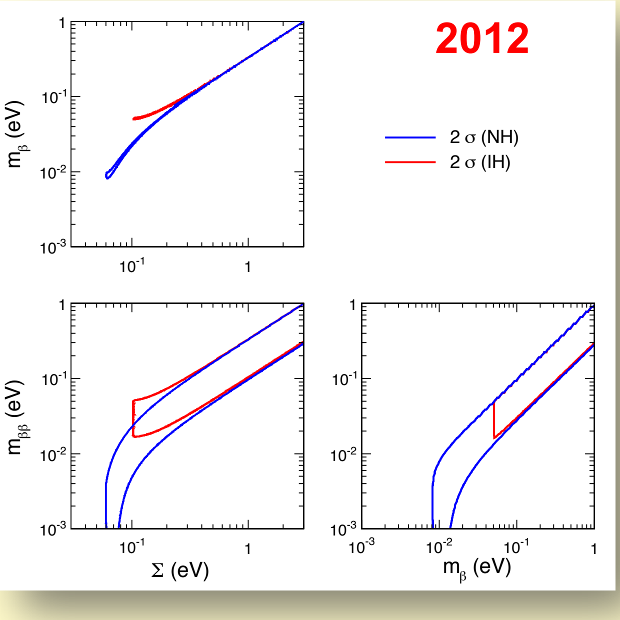
The “spear” (oscill. data) sets the “hunting direction” in the **$(m_\beta, m_{\beta\beta}, \Sigma)$** parameter space:



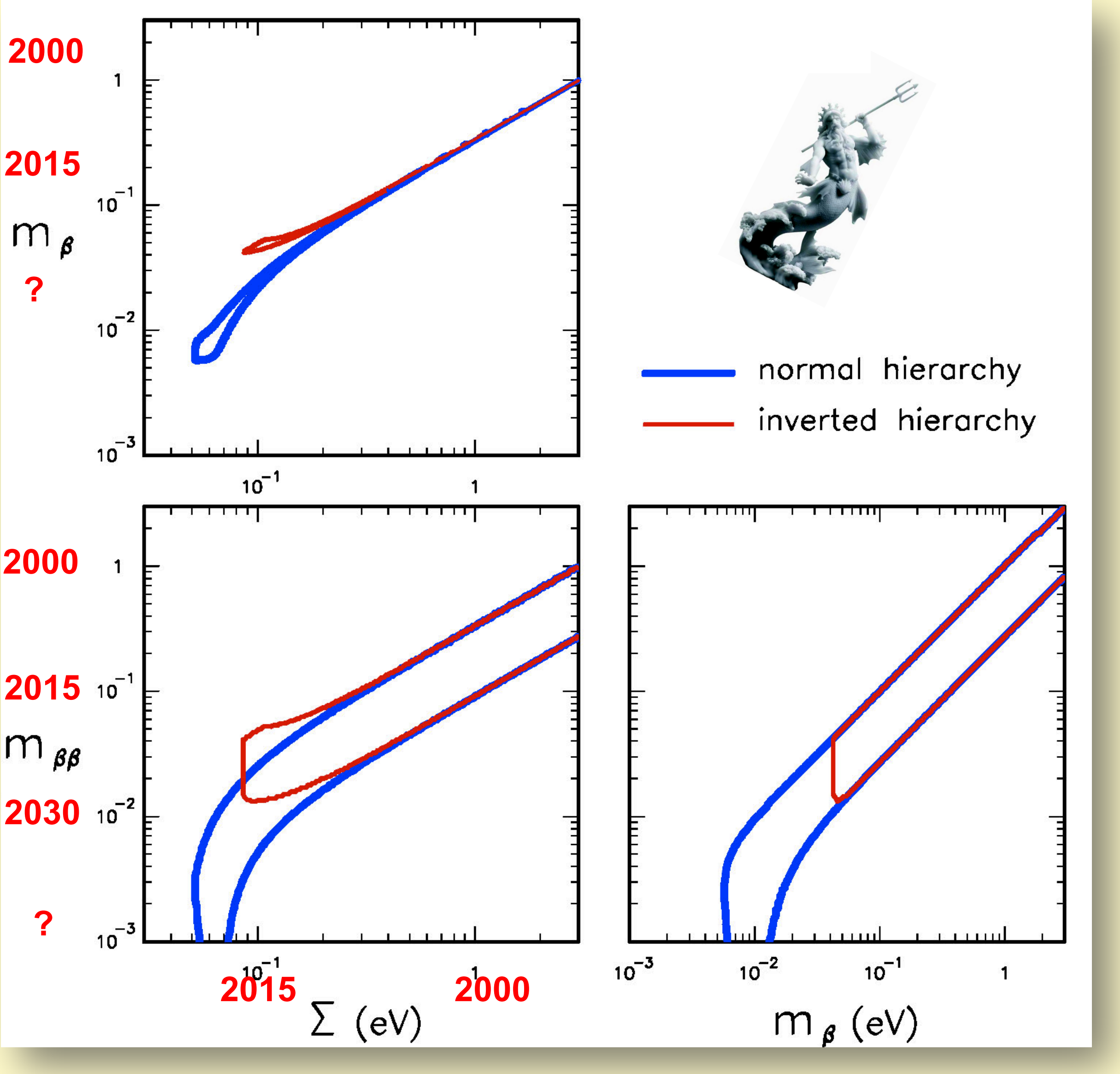
Spread due to unknown Majorana phases

Footnote 1 - Slightly thinner bands in recent years (progress in oscillation parameters). Majorana phase uncertainty remains dominant in sub-plots with $m_{\beta\beta}$.





“Moore’s law” in this field: factor of ~10 improvement every ~15 years



Such “logarithmic progress” seems to be:

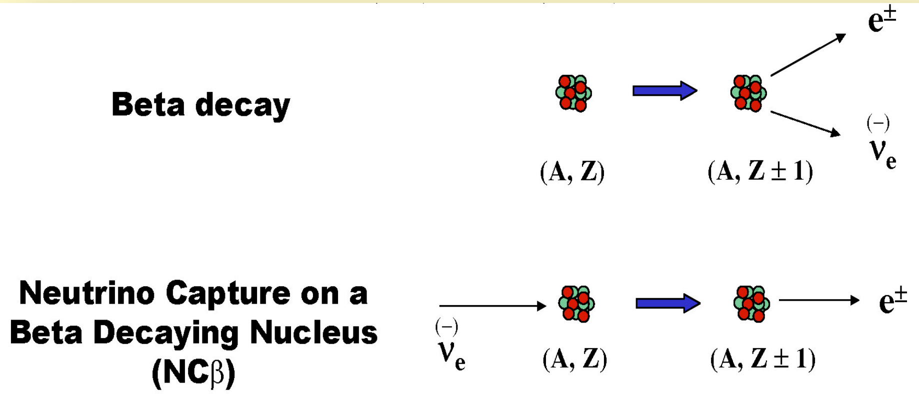
- maybe slowing for β decay (after KATRIN)

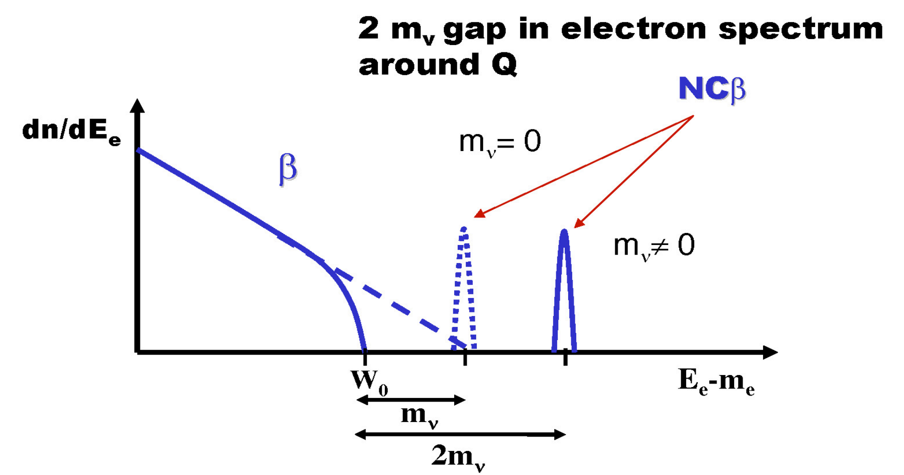
- continuing for $0\nu2\beta$ decay

- “accelerating” for cosmology: the only probe where the ultimate goal ($\Sigma_{min} = \sqrt{\Delta m^2} \approx 0.05$ eV) is claimed to be reachable

You have good chances to see first successful results within your career!

β decay: need new ideas to go beyond KATRIN (calorimetry?). Very far future … a possible observation of the relic neutrino bkgd ?





(Cocco, Mangano & Messina)

Double-beta decay:
Progress expected from many experiments in the next decade:

(from Rodejohann 2012)

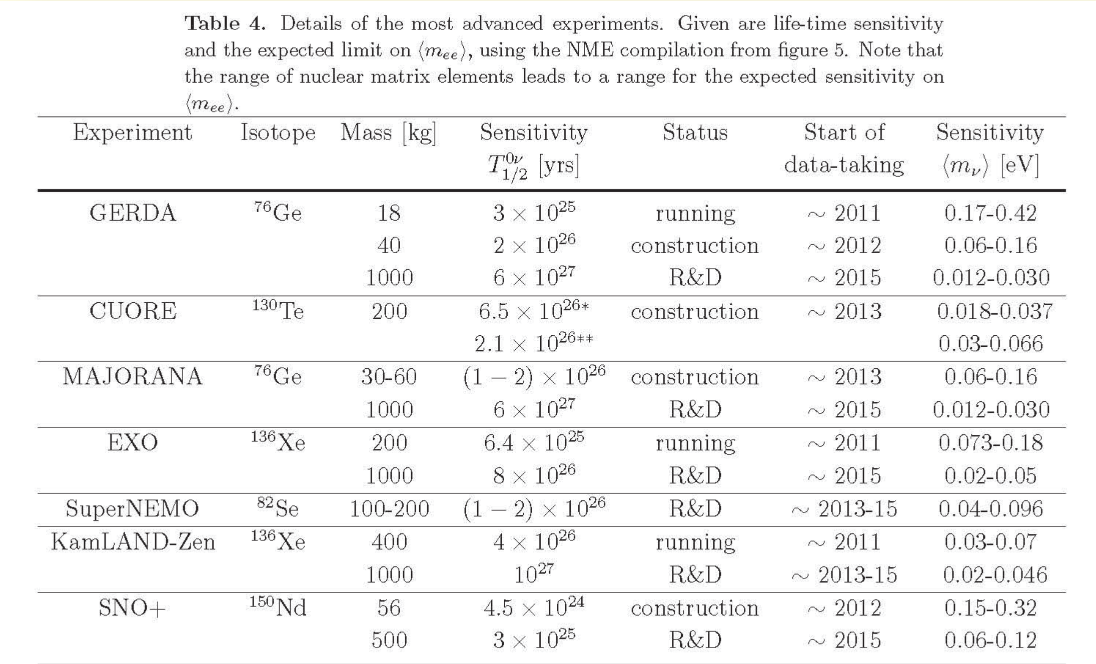
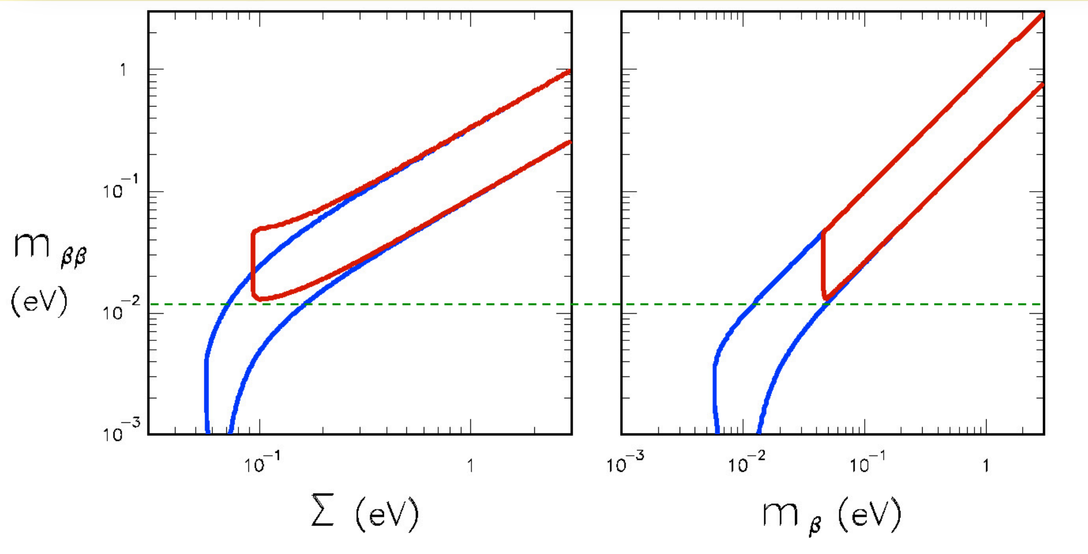


Table 4. Details of the most advanced experiments. Given are life-time sensitivity and the expected limit on $\langle m_{ee} \rangle$, using the NME compilation from figure 5. Note that the range of nuclear matrix elements leads to a range for the expected sensitivity on $\langle m_{ee} \rangle$.

Experiment	Isotope	Mass [kg]	Sensitivity $T^{0\nu}_{1/2}$ [yrs]	Status	Start of data-taking	Sensitivity $\langle m_\nu \rangle$ [eV]
GERDA	^{76}Ge	18	3×10^{25}	running	~ 2011	0.17-0.42
		40	2×10^{26}	construction	~ 2012	0.06-0.16
		1000	6×10^{27}	R&D	~ 2015	0.012-0.030
CUORE	^{130}Te	200	$6.5 \times 10^{26*}$	construction	~ 2013	0.018-0.037
			$2.1 \times 10^{26**}$			0.03-0.066
MAJORANA	^{76}Ge	30-60	$(1-2) \times 10^{26}$	construction	~ 2013	0.06-0.16
		1000	6×10^{27}	R&D	~ 2015	0.012-0.030
EXO	^{136}Xe	200	6.4×10^{25}	running	~ 2011	0.073-0.18
		1000	8×10^{26}	R&D	~ 2015	0.02-0.05
SuperNEMO	^{82}Se	100-200	$(1-2) \times 10^{26}$	R&D	~ 2013-15	0.04-0.096
KamLAND-Zen	^{136}Xe	400	4×10^{26}	running	~ 2011	0.03-0.07
		1000	10^{27}	R&D	~ 2013-15	0.02-0.046
SNO+	^{150}Nd	56	4.5×10^{24}	construction	~ 2012	0.15-0.32
		500	3×10^{25}	R&D	~ 2015	0.06-0.12

... might cover the whole range for inverted hierarchy:



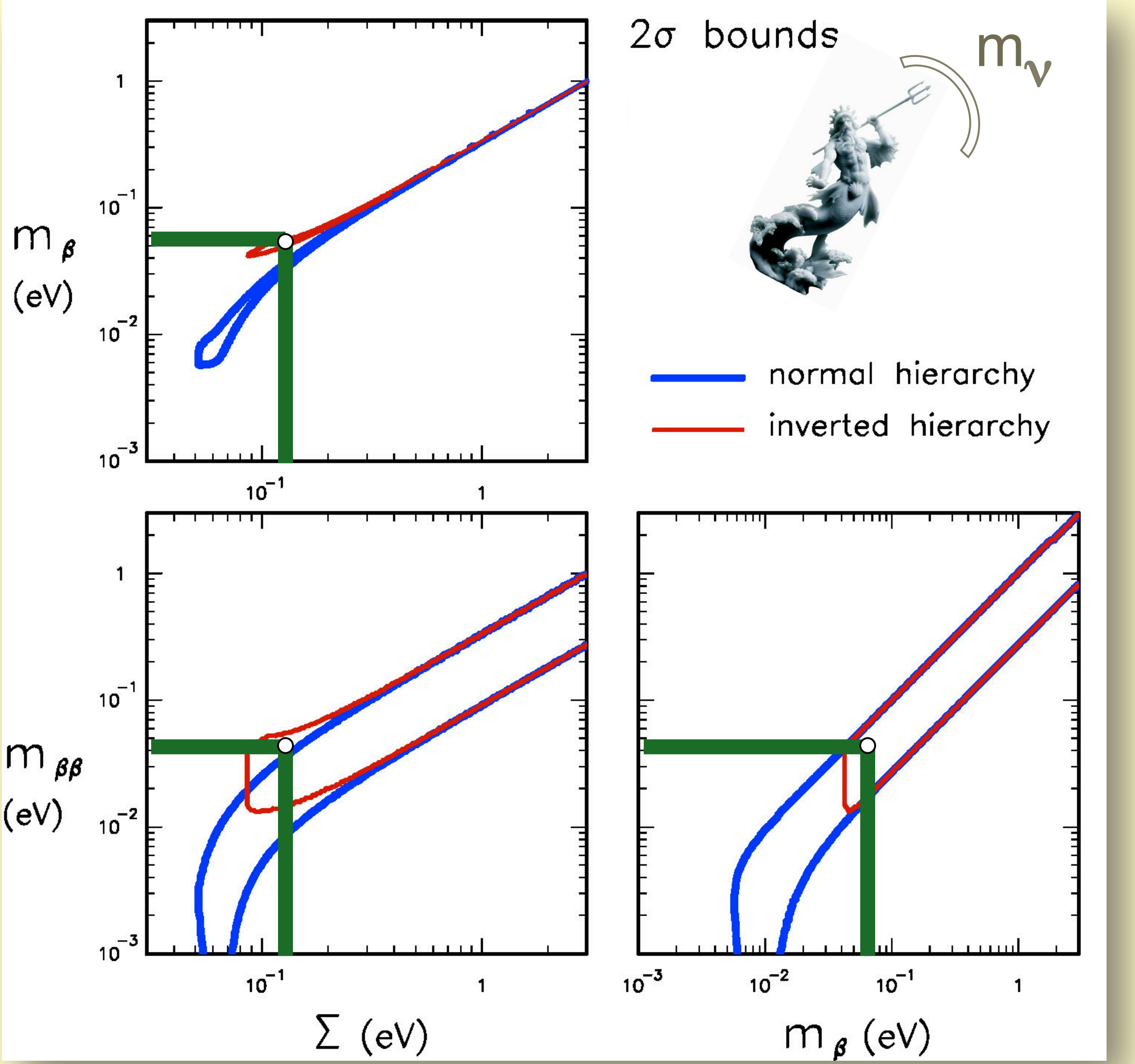
With “dreamlike” data one could, e.g.

Determine the mass scale…

Check 3**ν** consistency …

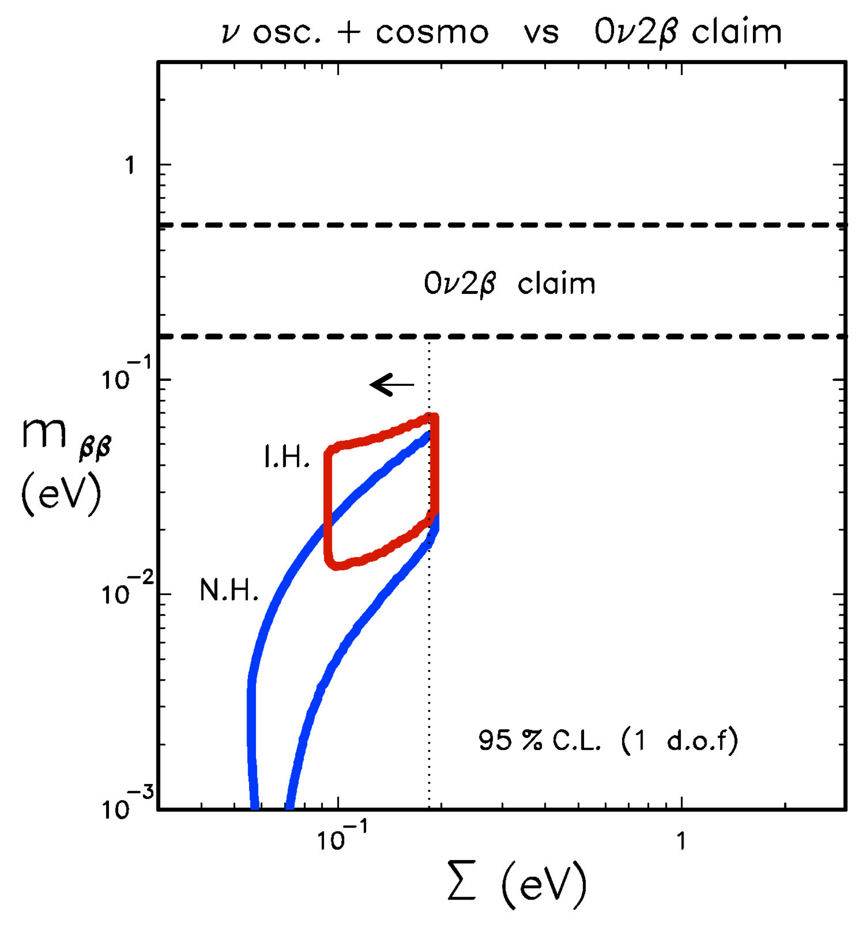
Identify the hierarchy …

Probe the Majorana phase(s) …



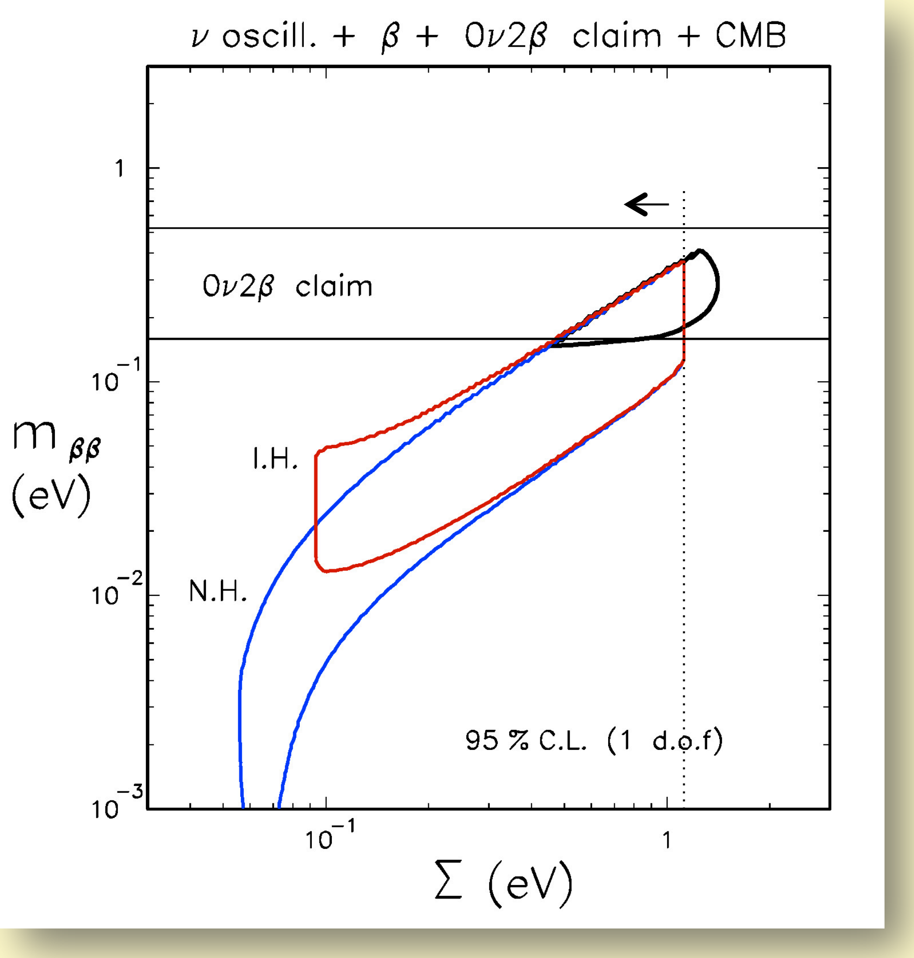
But the available data do not yet lead to definite conclusions.
Beta decay: no yet very constraining. Double beta vs cosmology: different possibilities. E.g.,

Cosmo-“aggressive”



The tighest cosmo bounds are not compatible with Klapdor’s claim. Then, either one of the two is wrong, or there is new physics beyond the standard model (of particle physics and/or of cosmology)

Cosmo-“conservative”



The safest cosmo bounds can be made compatible with Klapdor’s claim, with no new physics required. Then, the combination of data (black wedge) would prefer degenerate neutrino masses, ~few x 10^{-1} eV

Let’s entertain the possibility that the “true” answer is just at or around the corner… For instance, that neutrinos are Majorana, with nearly degenerate and relatively large masses:

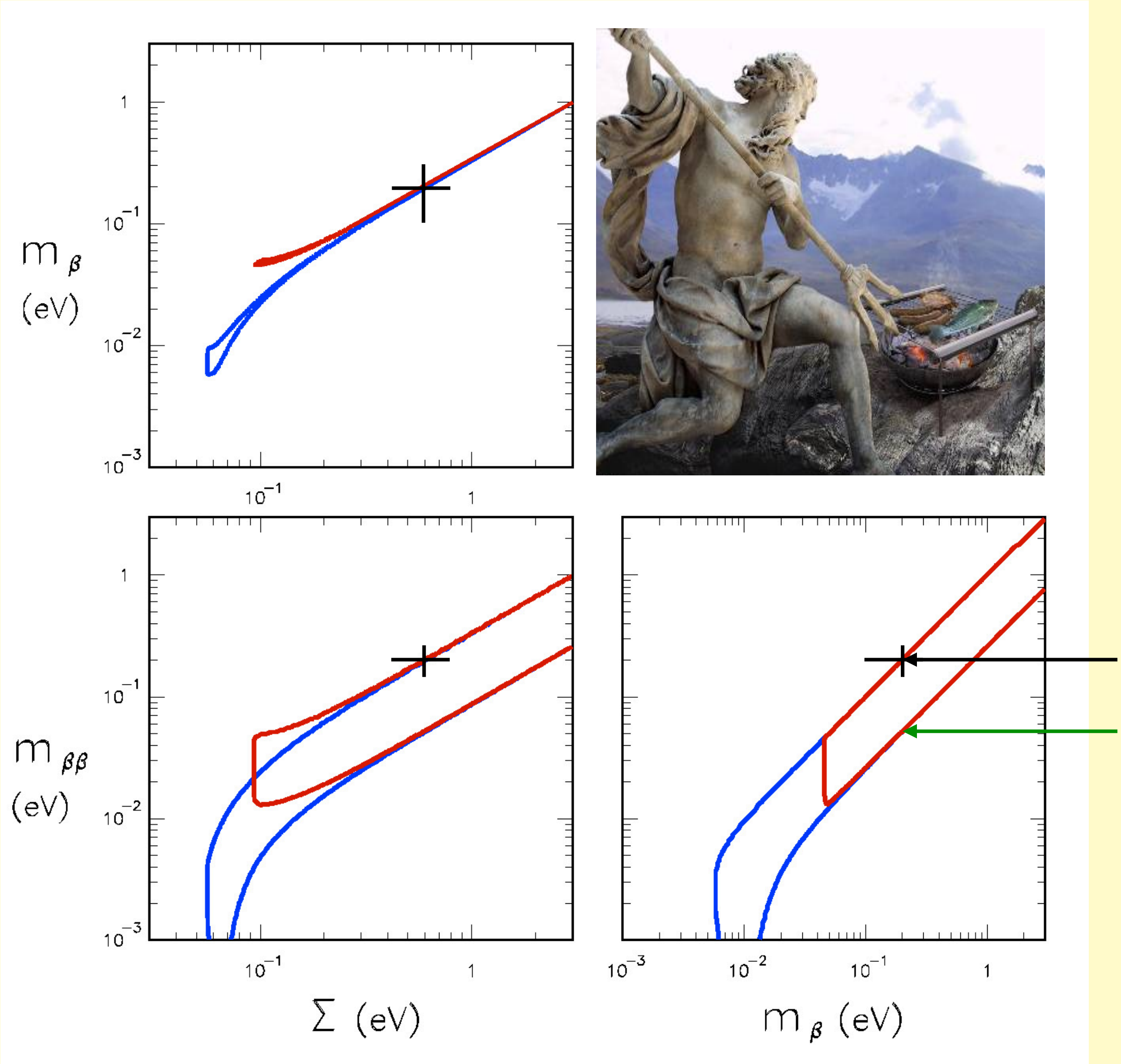
$$m_1 \sim m_2 \sim m_3 \sim 0.2 \text{ eV} \, .$$

Then we might reasonably hope to observe soon all three nonoscillation signals in current/next generation experiments, e.g.,

$$\begin{aligned} m_{\beta\beta} &\simeq 0.2(1 \pm 0.3)\ \mathrm{eV} \\ \Sigma &\simeq 0.6(1 \pm 0.3)\ \mathrm{eV} \\ m_{\beta} &\simeq 0.2(1 \pm 0.5)\ \mathrm{eV} \end{aligned}$$

in which case…

…The absolute neutrino mass would be established within ~25% uncertainty, and one Majorana phase (ϕ_2) would be constrained…

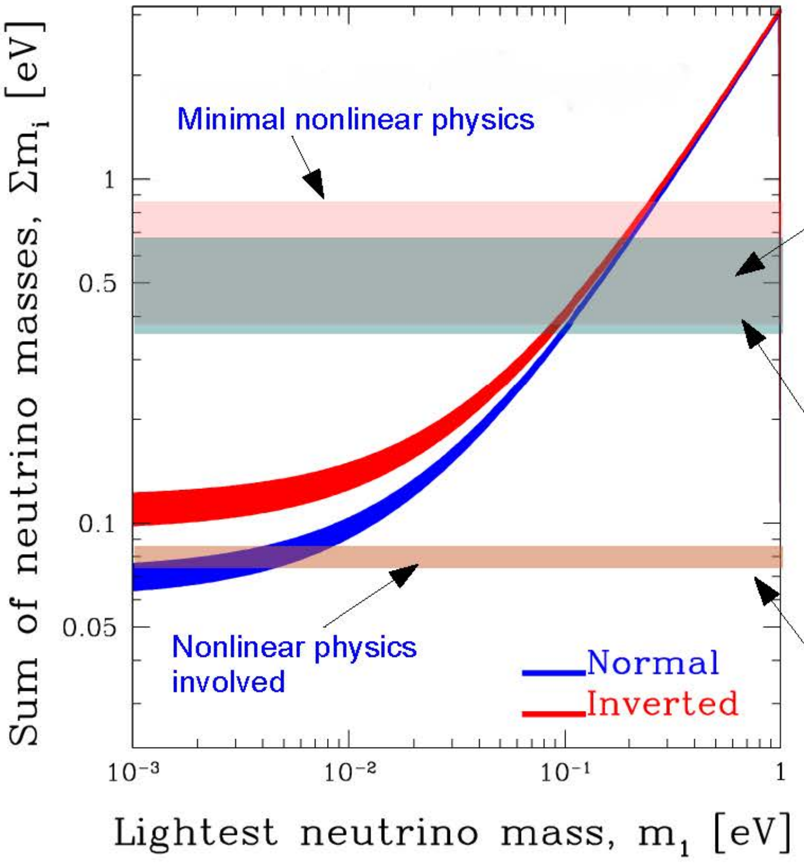


$\exp(i\phi_2) = +1$

$\exp(i\phi_2) = -1$
(disfavored)

Progress expected in **cosmology**: (from Y.Y.Y. Wong)

Present constraints and future sensitivities...



CMB (WMAP7+ACBAR+BICEP+QuaD)
+ LSS (SDSS-HPS)
+ H_0+SNIa

$$\sum m_\nu < 0.36 \rightarrow 0.76\,\mathrm{eV} \quad (95\%\,\mathrm{CI})$$

depending on the model complexity

Hannestad, Mirizzi, Raffelt & Y^3W 2010
Gonzalez-Garcia et al. 2010
de Putter et al. 2011, etc.

Planck alone (1 year) 2013

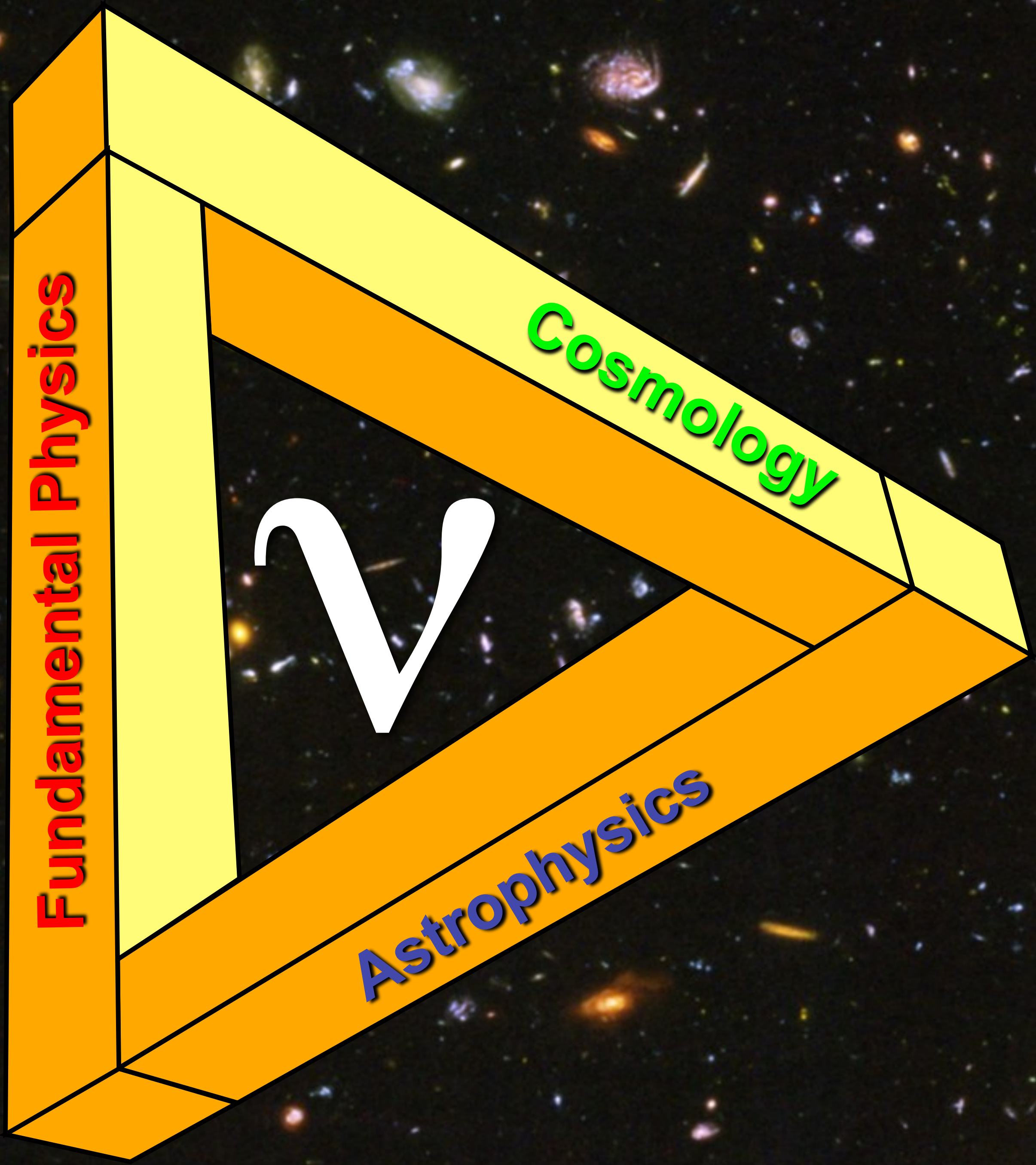
$$\sum m_\nu < 0.38 \rightarrow 0.84\,\mathrm{eV} \quad (95\%\,\mathrm{CI})$$

Perotto et al. 2006

Planck+Weak lensing (**Euclid**) 2020+

$$\sum m_\nu < 0.074 \rightarrow 0.086\,\mathrm{eV} \quad (95\%\,\mathrm{CI})$$

Hannestad, Tu & Y^3W 2006

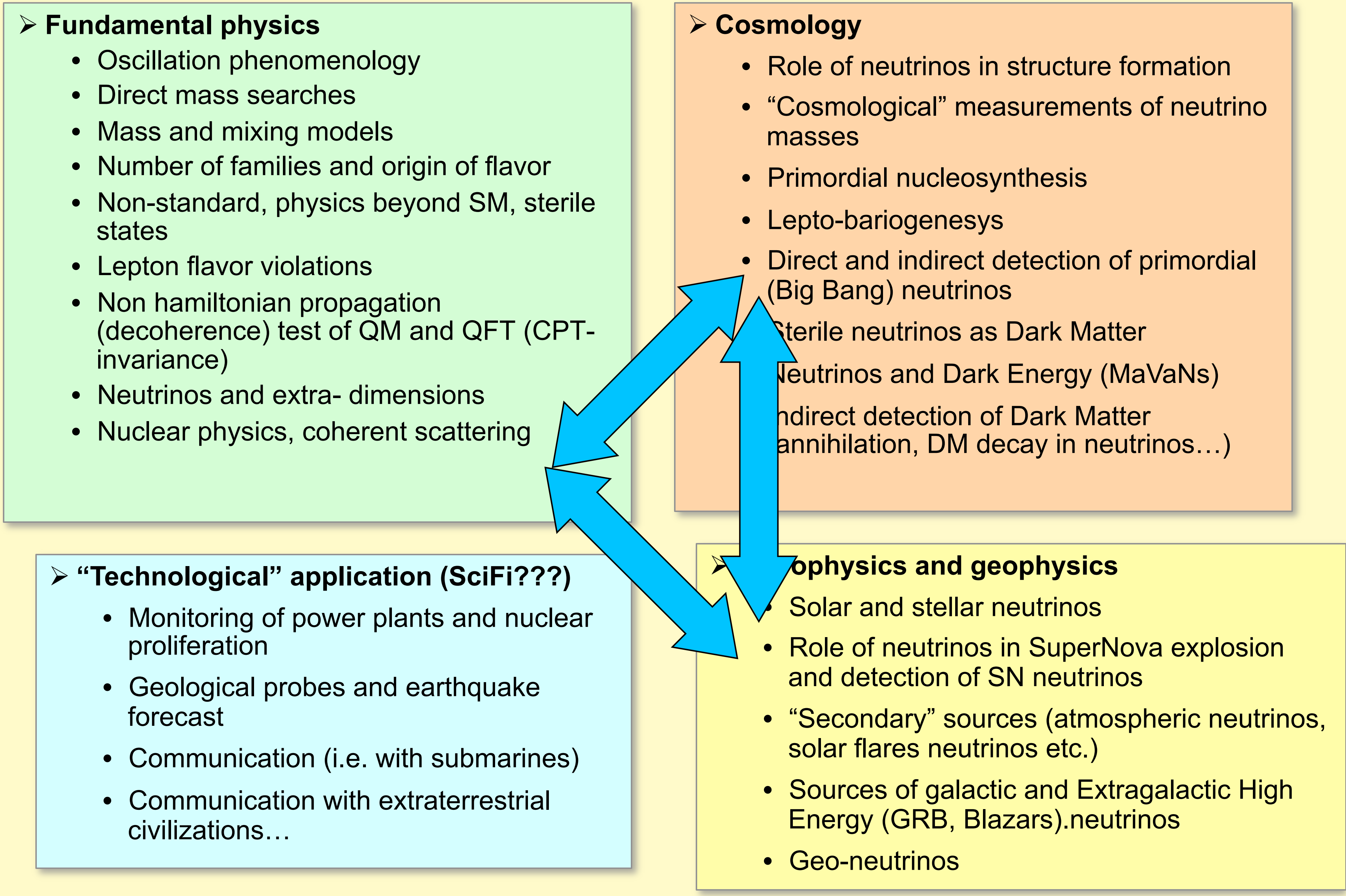


ν

Fundamental Physics

Cosmology

Astrophysics



- **Fundamental physics**
  - Oscillation phenomenology
  - Direct mass searches
  - Mass and mixing models
  - Number of families and origin of flavor
  - Non-standard, physics beyond SM, sterile states
  - Lepton flavor violations
  - Non hamiltonian propagation (decoherence) test of QM and QFT (CPT-invariance)
  - Neutrinos and extra- dimensions
  - Nuclear physics, coherent scattering

- **Cosmology**
  - Role of neutrinos in structure formation
  - "Cosmological" measurements of neutrino masses
  - Primordial nucleosynthesis
  - Lepto-bariogenesys
  - Direct and indirect detection of primordial (Big Bang) neutrinos
  - Sterile neutrinos as Dark Matter
  - Neutrinos and Dark Energy (MaVaNs)
  - ndirect detection of Dark Matter annihilation, DM decay in neutrinos…)

- **"Technological" application (SciFi???)**
  - Monitoring of power plants and nuclear proliferation
  - Geological probes and earthquake forecast
  - Communication (i.e. with submarines)
  - Communication with extraterrestrial civilizations…

- **ophysics and geophysics**
  - Solar and stellar neutrinos
  - Role of neutrinos in SuperNova explosion and detection of SN neutrinos
  - "Secondary" sources (atmospheric neutrinos, solar flares neutrinos etc.)
  - Sources of galactic and Extragalactic High Energy (GRB, Blazars).neutrinos
  - Geo-neutrinos