Neutrino Properties

Eligio Lisi, INFN, Bari

Status and Prospects of Astroparticle Physics – Sapienza U. of Rome, 25 Jan. 2023

Outline:

- Pedagogical introduction
- Neutrino oscillations & their parameters
- Neutrino absolute mass observables
- [Neutrino properties in a wider picture]

Pedagogical introduction

Questions about fundamental ν properties (mass, spinor d.o.f., charges, families) asked in the last century:

1. How small is the neutrino mass?
(Pauli, Fermi, ‘30s)

2. Is the neutrino its own antiparticle?
(Majorana, ‘30s)

3. Do ν of different flavors trasform (“oscillate”) among them?
(Pontecorvo, Maki-Nakagawa-Sakata, ‘60s)

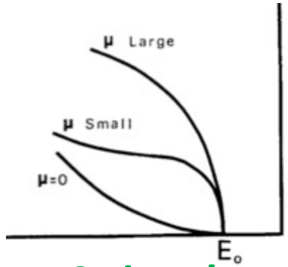
Short answers →

1

Fermi: In β–decay, when the β energy is near its max, the ν energy is near its minimum (nonrelativistic ν),

$$\mathbf{E} \sim \mathbf{m} + p^2/2m$$

→ the β energy spectrum tail kinematically probes **m**.



Dynamically: **m** is a source of gravity → cosmology. **No m>0 signal yet.**

1

Fermi: In β–decay, when the β energy is near its max, the ν energy is near its minimum (nonrelativistic ν),

$$\mathbf{E} \sim \mathbf{m} + p^2/2m$$

→ the β energy spectrum tail kinematically probes **m**.

Dynamically: **m** is a source of gravity → cosmology. **No m>0 signal yet.**

2

More often one deals with ν in the opposite limit (ultrarelativistic ν)

$$\mathbf{E} \sim \mathbf{p} + m^2/2E$$

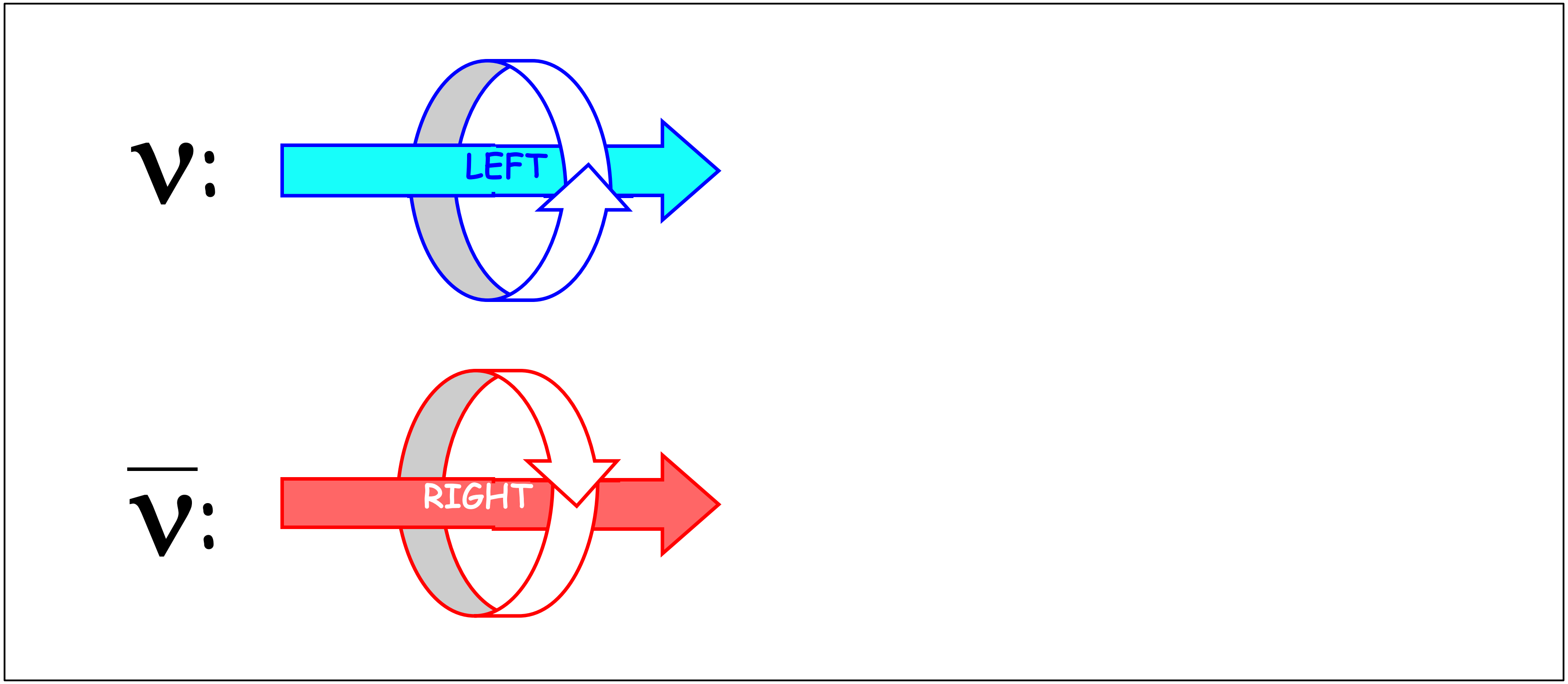
where **Majorana's** hypothesis involves rare flips of handedness

$$\mathbf{LH} \leftrightarrow \mathbf{RH} \sim O(m/E)$$

that may allow an otherwise forbidden decay ($0\nu\beta\beta$). **No decay signal yet.**

→

Spinor d.o.f. for massless ν: handedness is a constant of motion

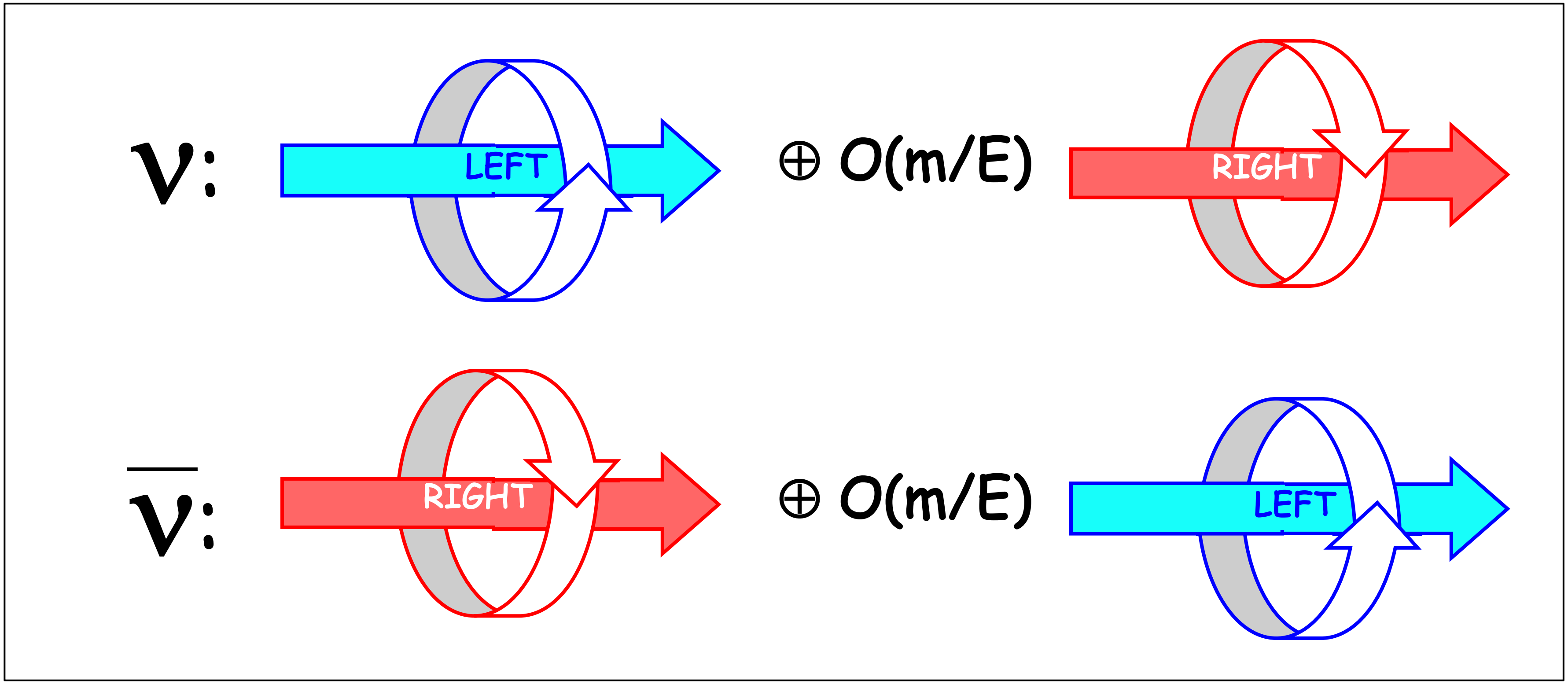


2 independent d.o.f.: massless ("Weyl") 2-spinor

→ Weyl nu / antinu are different

Massive ν can develop the "wrong" handedness at O(m/E)

(Dirac equation mixes RH and LH states for m≠0):

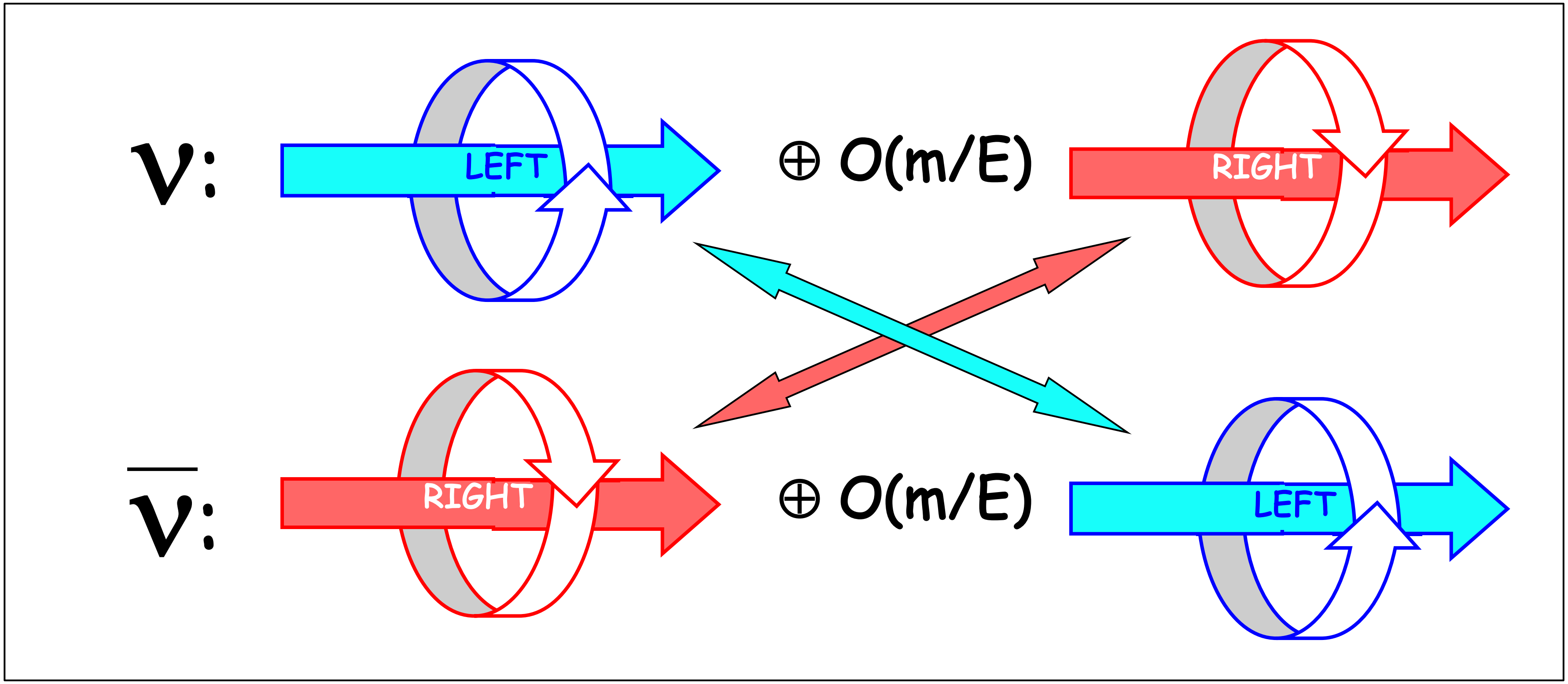


If these 4 d.o.f. are independent: massive ("Dirac") 4-spinor

→ Dirac nu / antinu are different, just as charged fermions.

→ Can define a neutrino charge: their "lepton number"

Majorana: for neutral fermions, components might be paired!



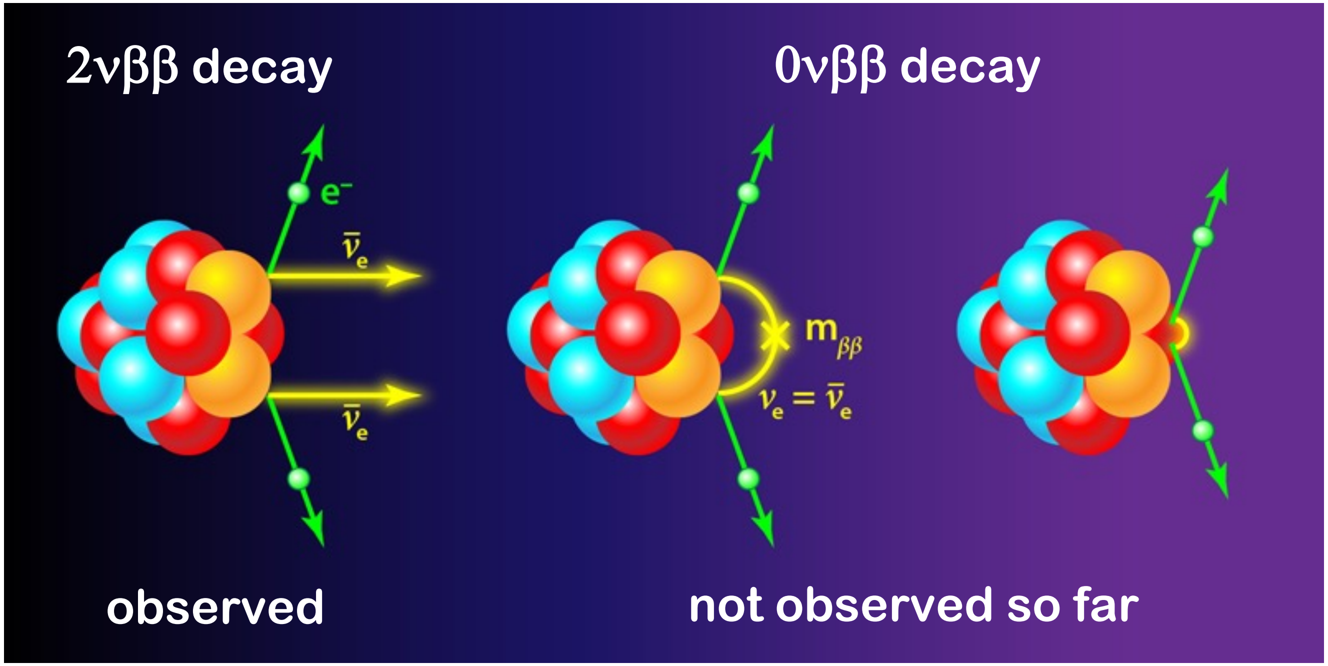
Massive ("Majorana") 4-spinor with 2 independent d.o.f.

the **simplest massive fermion field**, with no charge(s) at all

→ Fundamentally: nu = antinu (up to a phase). Cannot define a lepton number

→ nu and antinu remain "shorthand" for usual ultrarelativ. LH and RH ν states

Only known realistic way to probe this option: $0\nu\beta\beta$ decay
(occurring if and only if ν are Majorana)



A very rare (weak^2) process that violates leptonic number and "creates matter" (*)
Worldwide searches in several candidate nuclei

(*) see the review 2202.01787

1

Fermi: In β–decay, when the β energy is near its max, the ν energy is near its minimum (nonrelativistic ν),

$$\mathbf{E} \sim \mathbf{m} + p^2/2m$$

→ the β energy spectrum tail kinematically probes **m**.

Dynamically: **m** is a source of gravity → cosmology. **No m>0 signal yet.**

2

More often one deals with ν in the opposite limit (ultrarelativistic ν)

$$\mathbf{E} \sim \mathbf{p} + m^2/2E$$

where **Majorana's** hypothesis involves rare flips of handedness

$$\mathbf{LH} \leftrightarrow \mathbf{RH} \sim O(m/E)$$

that may allow an otherwise forbidden decay (0νββ). **No decay signal yet.**

3

Ultrarelativistic ν of different mass accumulate phase differences over L

$$\Delta \mathbf{E} \cdot L \sim (\Delta \mathbf{m^2}/2E) \cdot L$$

that induce $\nu_\alpha \rightarrow \nu_\beta$ oscillations if flavor and mass states are mixed

$$\nu_\alpha = \mathbf{U}\, \nu_i$$

Sensitive to bkgd matter (**MSW**). **Oscillation signals in vac. & matter (>1998)**

The standard 3ν framework & oscillation parameters

Mixing matrix: **CKM→ PMNS** [Pontecorvo-Maki-Nakagawa-Sakata]

$$U_{\alpha i} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{bmatrix} \begin{bmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{bmatrix} \begin{bmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} 1 & 0 & 0 \\ 0 & e^{i\alpha/2} & 0 \\ 0 & 0 & e^{i\beta/2} \end{bmatrix}$$

2-3 rotation

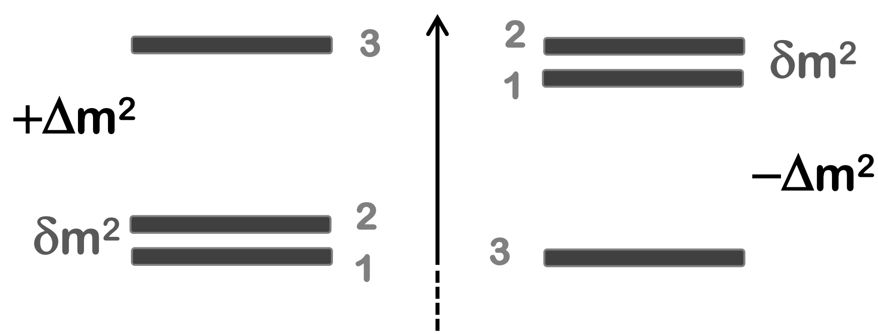
1-3 rotation
+ CPV "Dirac" phase
U(ν) → U*($\overline{\nu}$)

1-2 rotation

Extra CPV phases
[if Majorana]
not tested in oscillat.

Mass [squared] spectrum)

"Normal" Ordering
N.O.



"Inverted" Ordering
I.O.

$$\delta m^2 = \Delta m^2_{21}, \quad \Delta m^2 = (\Delta m^2_{32} + \Delta m^2_{31})/2$$

+ interaction energy in matter → ~ $G_F \cdot$ density (MSW effect, observed)
[Absolute ν mass scale not tested in oscillations]

Sketchy 3ν overview

5 knowns:

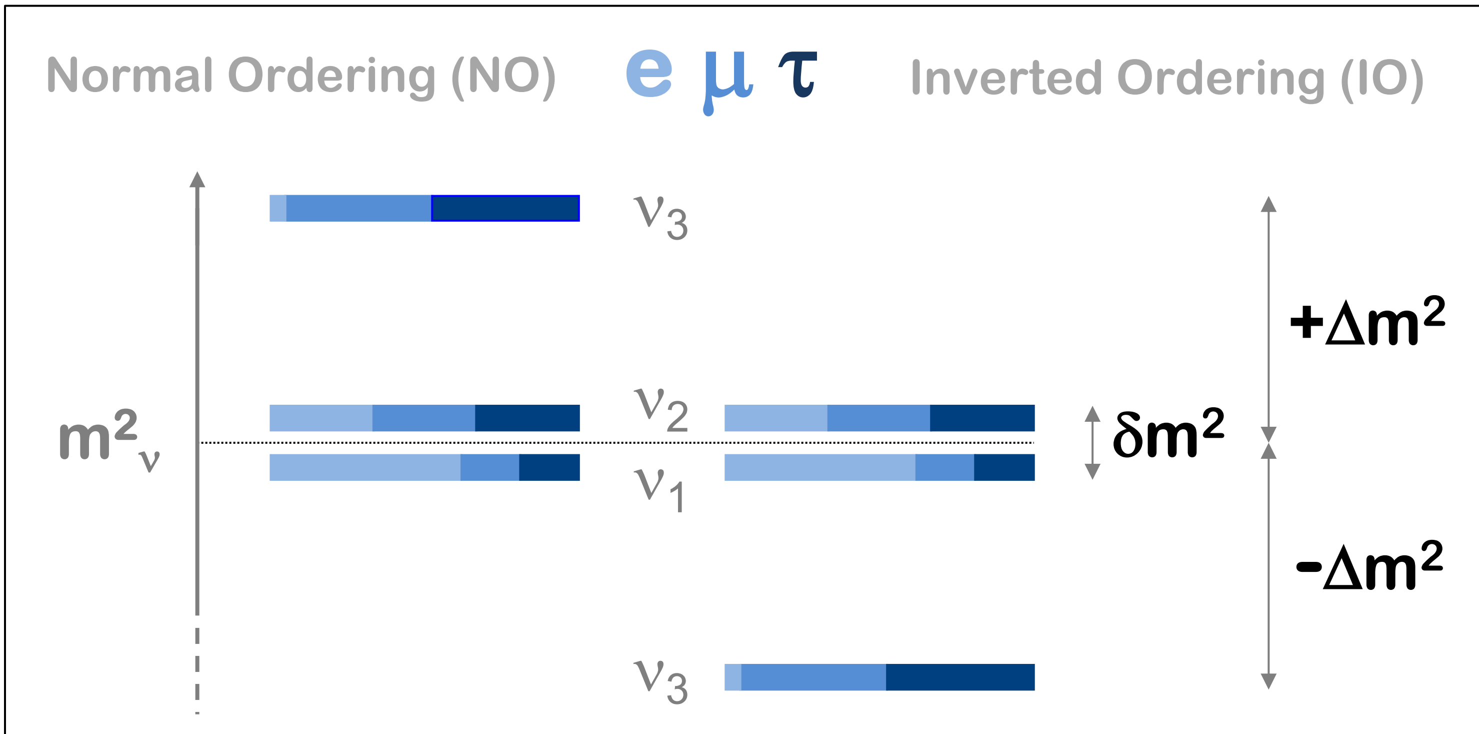
- $\delta m^2 \sim 8 \times 10^{-5}\ eV^2$
- $|\Delta m^2| \sim 2 \times 10^{-3}\ eV^2$
- $\sin^2\theta_{12} \sim 0.3$
- $\sin^2\theta_{23} \sim 0.5$
- $\sin^2\theta_{13} \sim 0.02$

Oscillations

Non-oscillat.

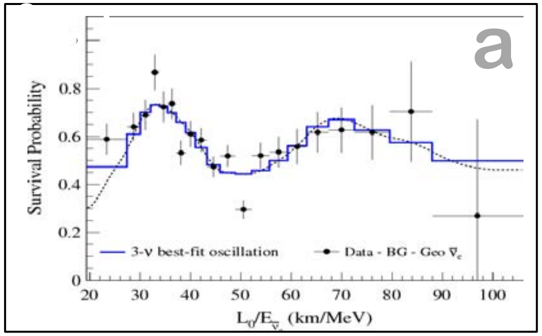
5 unknowns:

- *Oscillations:*
  - δ **CPV** Dirac phase
  - **sign(Δm^2)** → NO/IO
  - θ_{23} **octant** degeneracy
- *Non-oscillat.:*
  - **absolute mass** scale
  - **Dirac/Majorana** nature

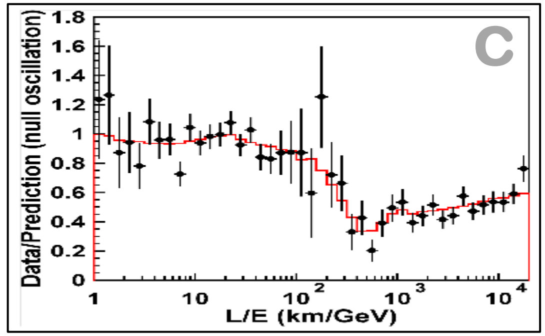


3ν oscillations probed by many experiments in different flavor channels…

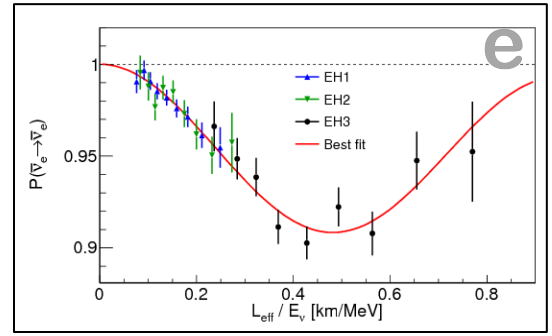
e→e (KamLAND, KL)



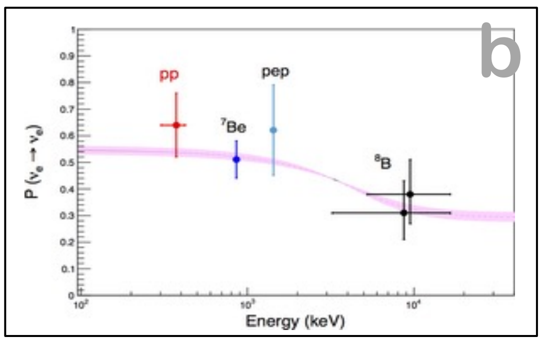
μ→μ (Atmospheric)



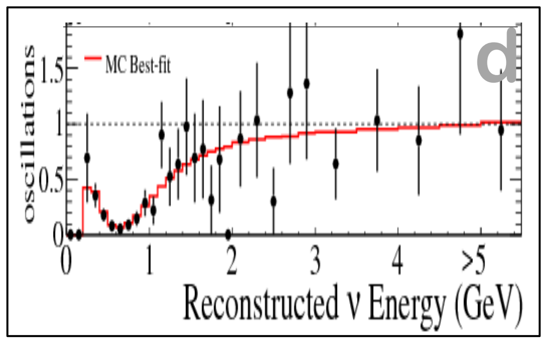
e→e (SBL Reac.)



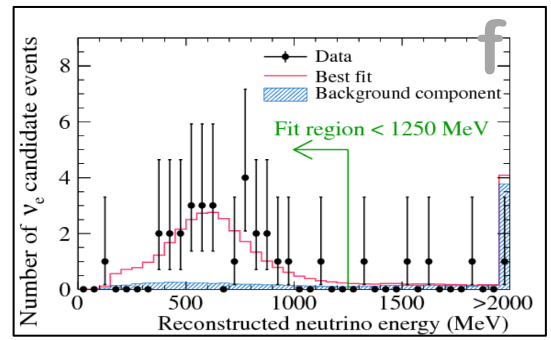
e→e (Solar)



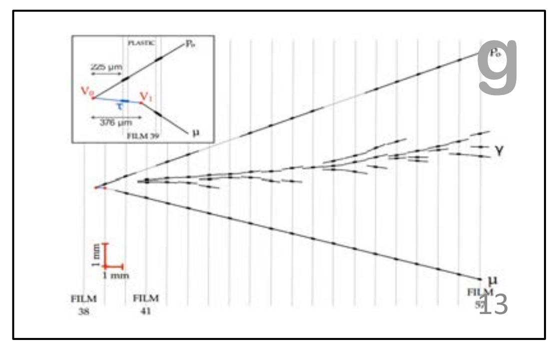
μ→μ (LBL Accel)



μ→e (LBL Accel)



μ→τ (OPERA, SK, DC)

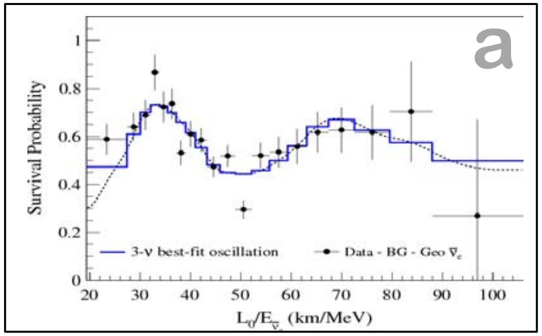


LBL = Long baseline (few x 100 km); **SBL = short baseline** (~1 km)

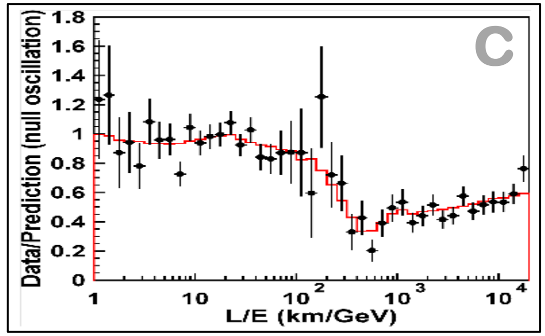
(a) KamLAND reactor [plot]; (b) Borexino [plot], Homestake, Super-K, SAGE, GALLEX/GNO, SNO; (c) Super-K atmosph. [plot], DeepCore, MACRO, MINOS etc.; (d) T2K (plot), NOvA, MINOS, K2K LBL accel.; (e) Daya Bay [plot], RENO, Double Chooz SBL reactor; (f) T2K [plot], MINOS, NOvA LBL accel.; (g) OPERA [plot] LBL accel., Super-K and IC-CD atmospheric.

… with amplitude and frequency governed by 2 (or 3) leading parameters

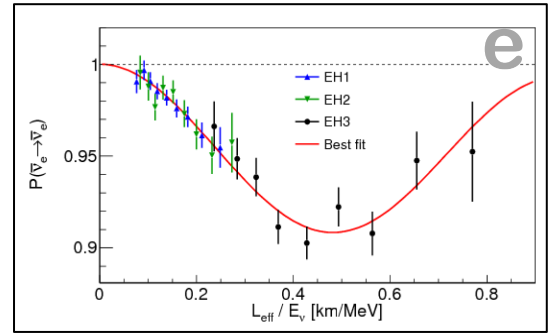
$e \rightarrow e$ (δm^2 , θ_{12})



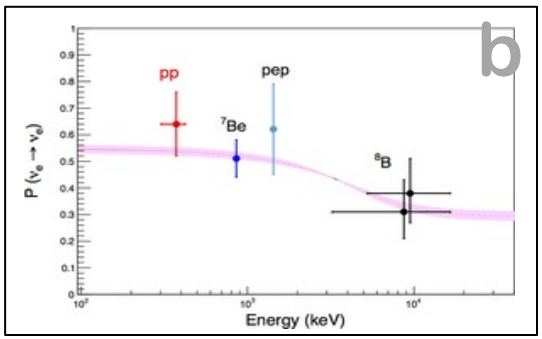
$\mu \rightarrow \mu$ (Δm^2 , θ_{23})



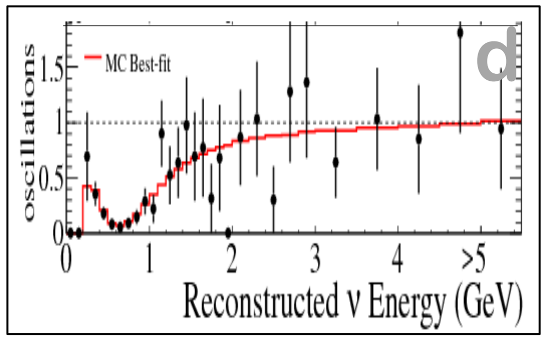
$e \rightarrow e$ (Δm^2 , θ_{13})



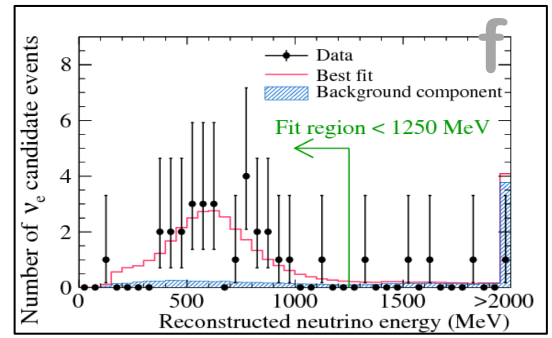
$e \rightarrow e$ (δm^2 , θ_{12})



$\mu \rightarrow \mu$ (Δm^2 , θ_{23})



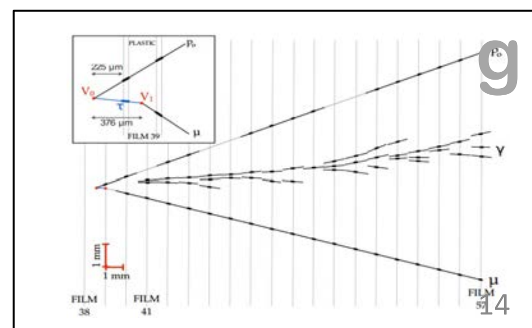
$\mu \rightarrow e$ (Δm^2 , θ_{13} , θ_{23})



5 param.'s known & (over)constrained → consistency

Currently: focus on unknown par. & subleading effects,
especially CPV via $\nu_\mu \rightarrow \nu_e$ in LBL accel. and atmos. expts
and NO/IO mass spectrum via reactor + accel + atmos.

$\mu \rightarrow \tau$ (Δm^2 , θ_{23})



How do $\nu_\mu \rightarrow \nu_e$ oscillation searches probe CPV?

Volume 72B, number 3 PHYSICS LETTERS 2 January 1978

TIME REVERSAL VIOLATION IN NEUTRINO OSCILLATION

Nicola CABIBBO*
*Laboratoire de Physique Théorique et Hautes Energies, Paris, France***

Received 11 October 1977

We discuss the possibility of CP or T violation in neutrino oscillation CP requires $\nu_\mu \leftrightarrow \nu_e$ and $\bar{\nu}_\mu \leftrightarrow \bar{\nu}_e$ oscillations to be equal Time reversal invariance requires the oscillation probability to be an even function of time Both conditions can be violated, even drastically, if more than two neutrinos exist

For two neutrinos, no CPV:

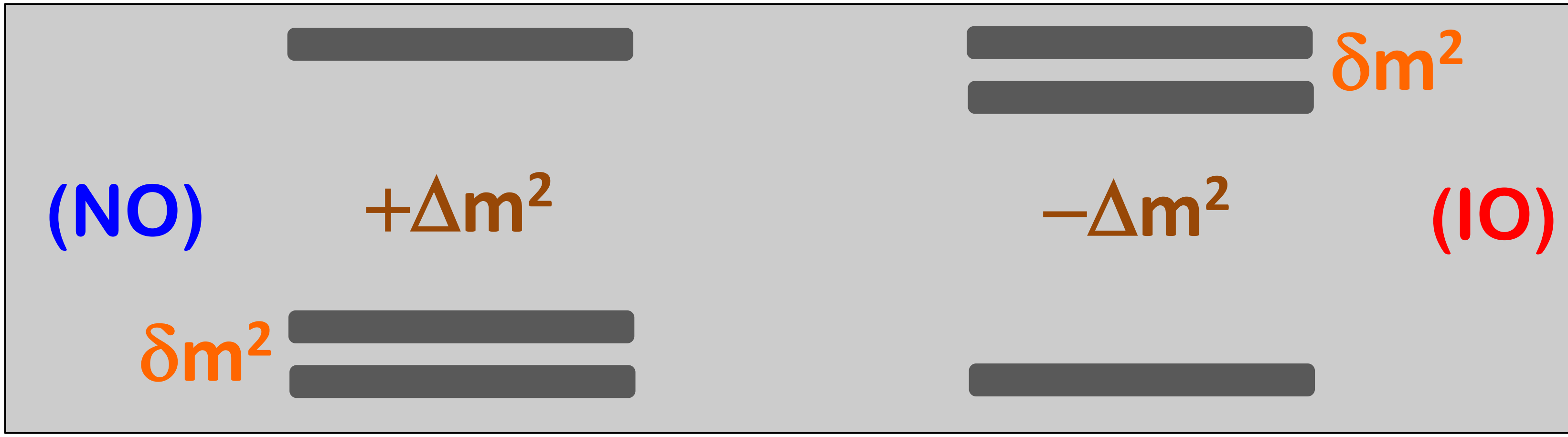
$$\overset{(-)}{\nu}_e = \cos\theta_{12}\,\nu_1 + \sin\theta_{12}\,\nu_2$$

For three neutrinos: possible CPV phase δ, tested via ν versus $\bar{\nu}$

$$\overset{(-)}{\nu}_e = \cos\theta_{13}\,(\cos\theta_{12}\,\nu_1 + \sin\theta_{12}\,\nu_2) + e^{\pm i\delta}\sin\theta_{13}\,\nu_3$$

CPV is a genuine 3ν effect $\rightarrow$
all oscillation parameters (known & unknown) are involved/entangled
(currently tested in T2K, NOvA, Atmosph.)

How do oscillation searches probe mass ordering?

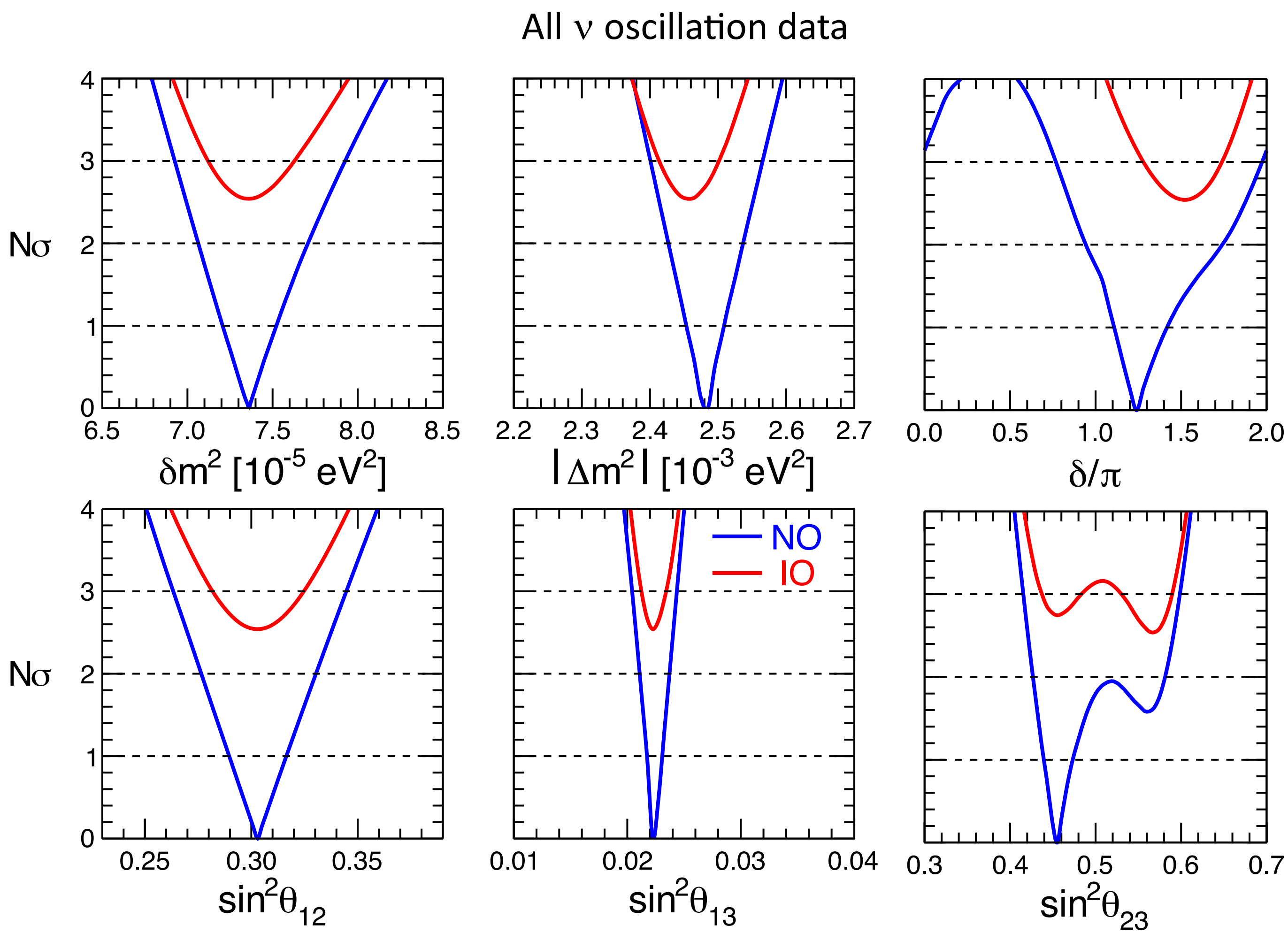


Observe interference effects of oscill. driven by $\pm\Delta m^2$ with oscill. driven by another quantity **Q** with <u>known sign</u>. Options:

$Q \sim \delta m^2$	medium-baseline reactors
$Q \sim G_F N_e E$	atmospheric & LBL accel. expts
[$Q \sim G_F N_\nu E$	core-collapse SN via $\nu-\nu$ collective effects]

Plus: synergy / complementarity of $|\Delta m^2|$ data from different expts
[should converge better in the true ordering than in the wrong one]

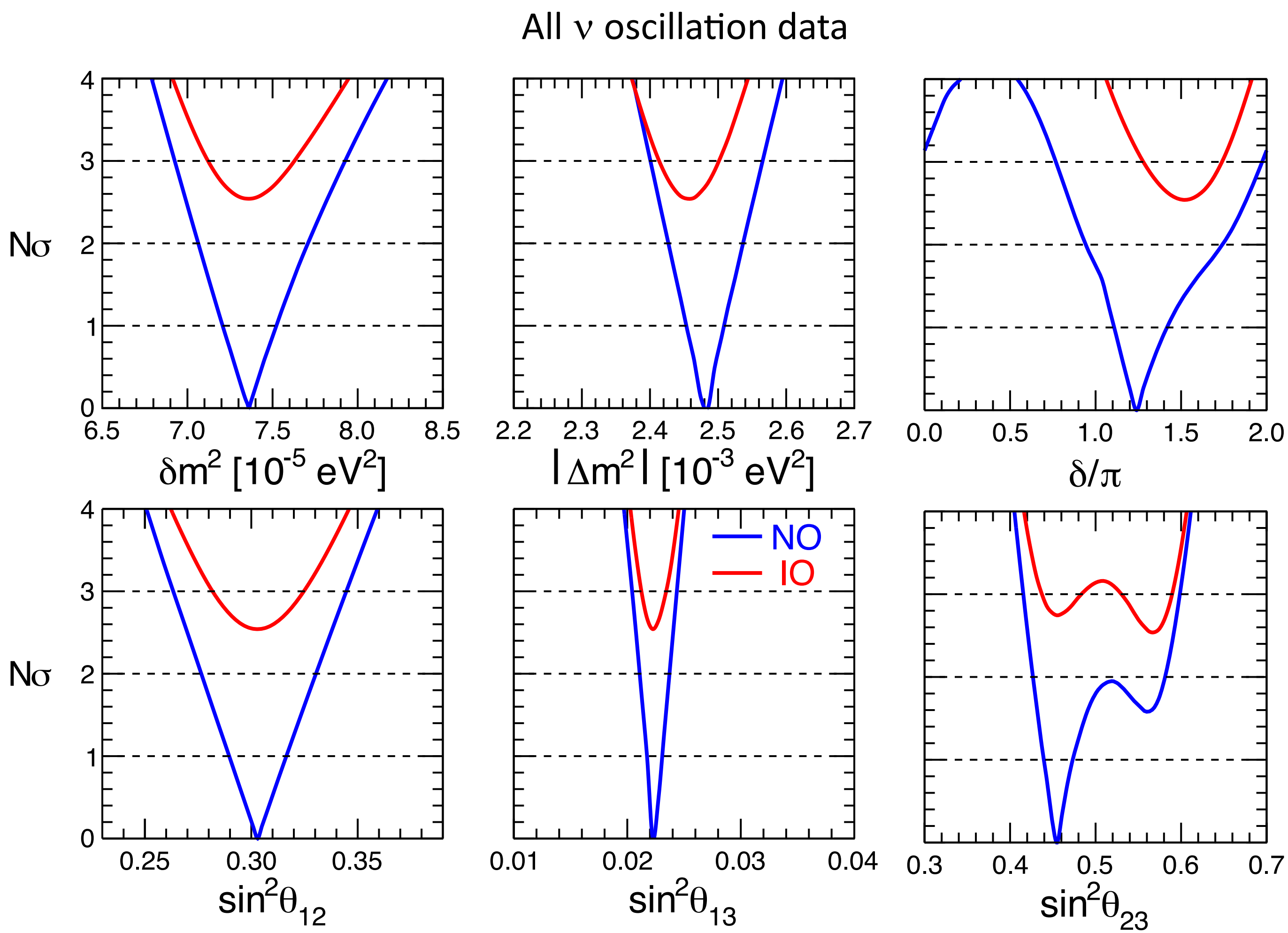
Status of known and unknown 3ν oscillation parameters [from 2107.00532]

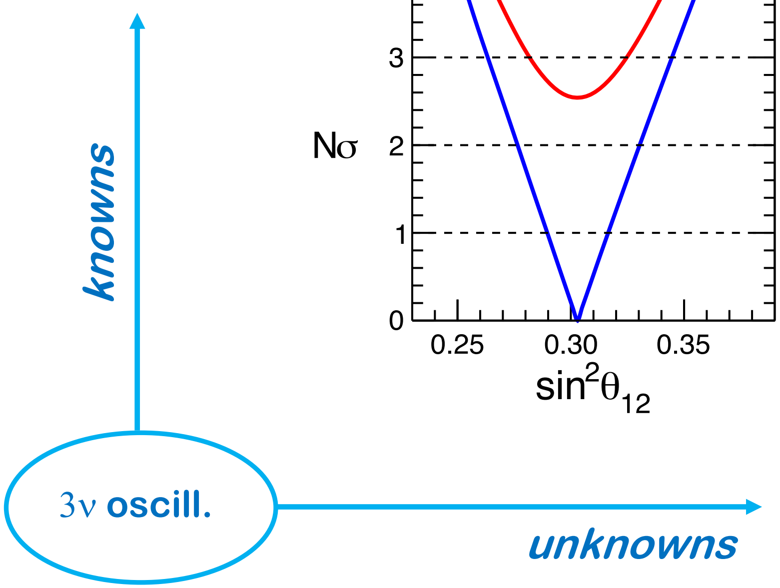


Status of known and unknown 3ν oscillation parameters [from 2107.00532]

1σ error of **known** parameters

$\|\Delta m^2\|$	1.1%
δm^2	2.3%
θ_{13}	3.0%
θ_{12}	4.5%
θ_{23}	~ 6%





Hints on oscillation **unknowns**

NO	~99% CL
$\sin\delta < 0$	~90% CL
$\theta_{23} < \pi/4$	~90% CL*

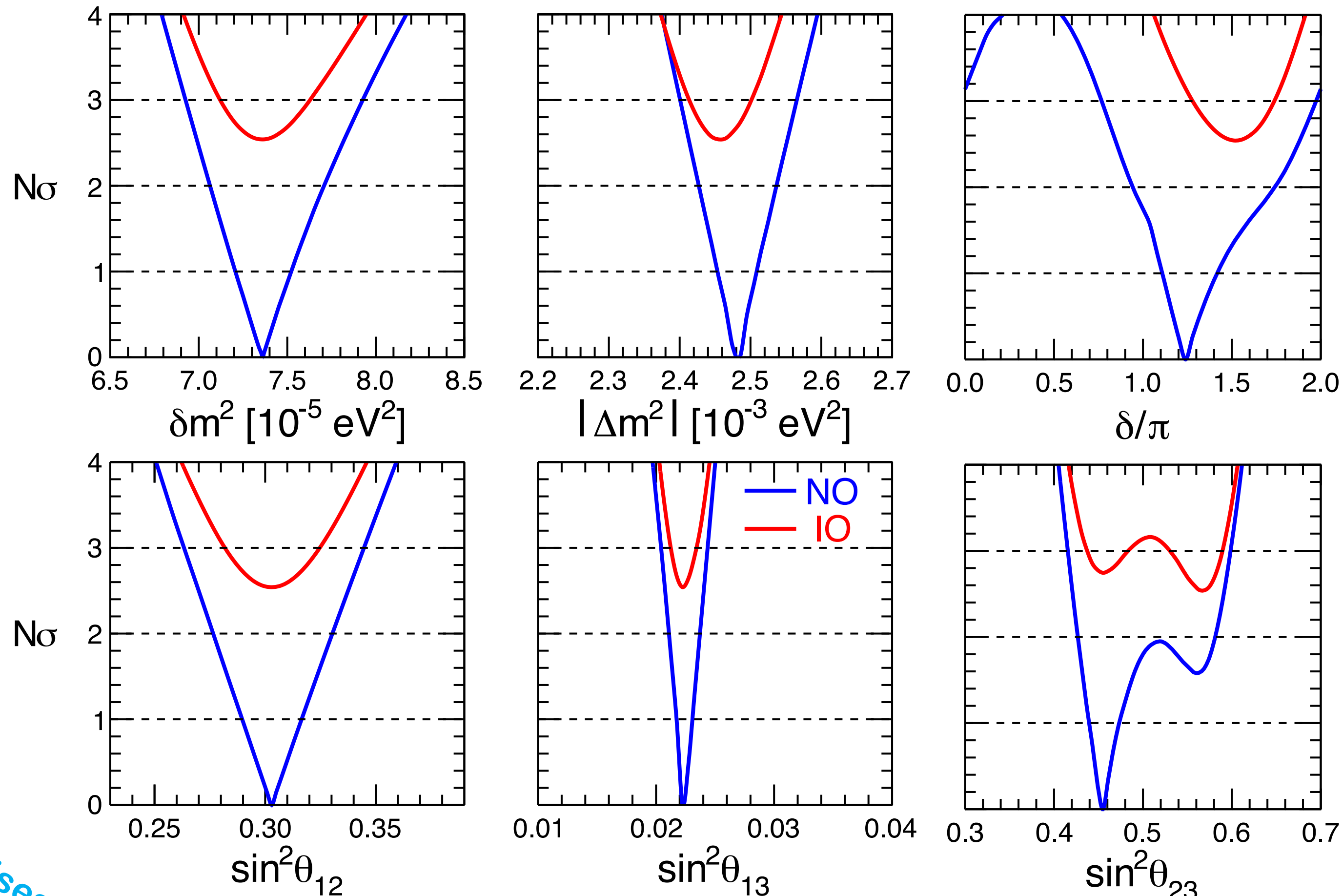
*might flip to 2nd octant with recent data

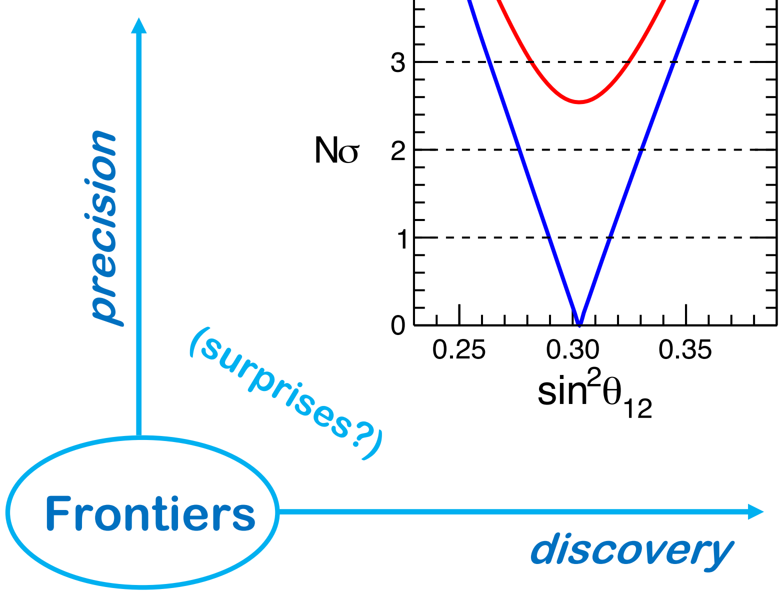
Status of known and unknown 3ν oscillation parameters [from 2107.00532]

1σ error of **known** parameters

$\lvert\Delta m^2\rvert$	1.1%
δm^2	2.3%
θ_{13}	3.0%
θ_{12}	4.5%
θ_{23}	~ 6%

All ν oscillation data





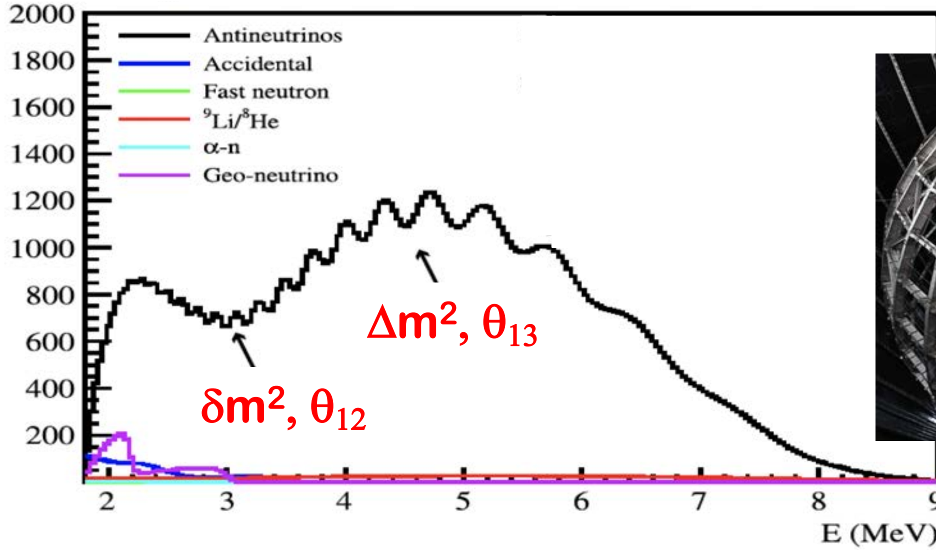
Hints on oscillation **unknowns**

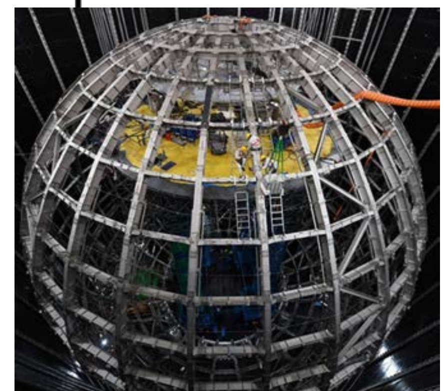
NO	~99% CL
$\sin\delta < 0$	~90% CL
$\theta_{23} < \pi/4$	~90% CL

E.g.: Frontiers for the JUNO reactor experiment [1507.05613]

At “medium” baseline ~50 km, will probe two oscillations in ~vacuum

Main **discovery** goal: distinguish **NO vs IO at 3-4σ** in 6y.





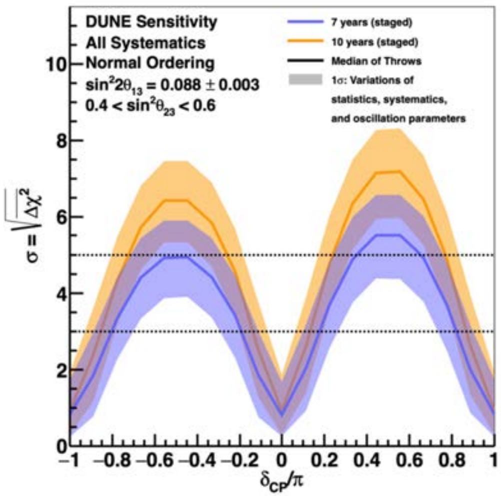
Significant better **precision** expected on 3 out of 4 oscillation parameters:

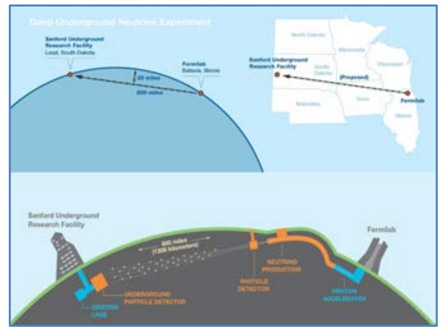
Parameter	1σ, now	JUNO in ~6y
δm^2	2.3 %	0.6 %
$\sin^2\theta_{12}$	4.4 %	0.7 %
Δm^2	1.1 %	0.4 %
$\sin^2\theta_{13}$	3.0 %	comparable

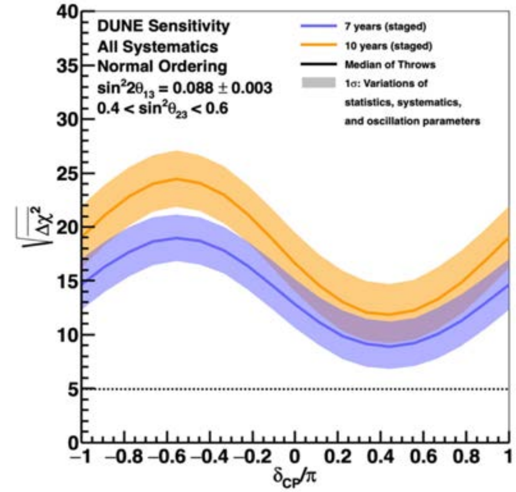
E.g., frontiers for DUNE, LBL acceler. expt [2002.03005]

Disappearance + appearance, nu/antinu mode, matter effects at L~1300 km

CPV ← **Discovery goals** → **NO vs IO**







Precision frontier
↓

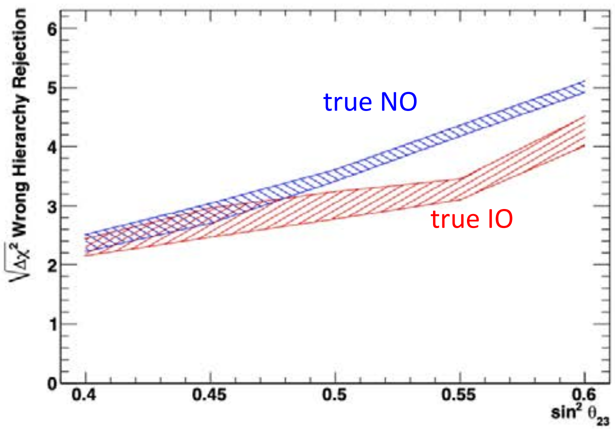
Parameter	1σ, now	DUNE in ~10 y
Δm^2	1.1 %	factor ~1/4 reduction
$\sin^2\theta_{23}$	~ 6 %	factor ~1/4 reduction
$\sin^2\theta_{13}$	3.0 %	comparable

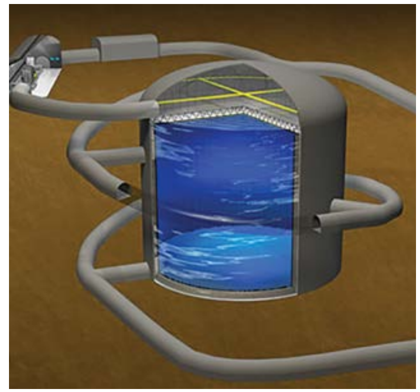
T2HK: same ballpark. DUNE & T2HK will need precise cross sections!

Worldwide activity to better understand **nuclear response to ν probes**

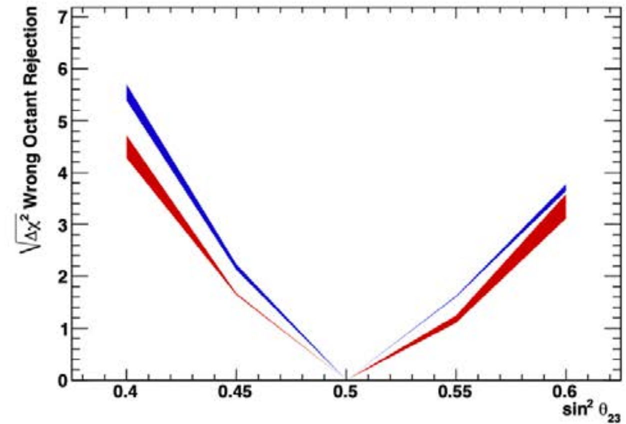
E.g., frontiers for Hyper-Kamiokande atmosph. [2002.03005]

Mass ordering





Octant resolution



...surprises?

While advancing the precision and discovery frontiers, JUNO, DUNE, (T2)HK, ... might either converge on consistent discoveries and precision parameters,
or find anomalous results → new neutrino states, nonstandard interactions?

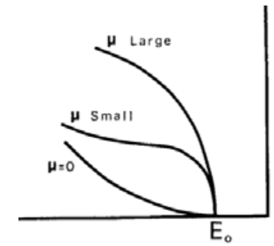
E.g., already in current data:

- **Saga of possible indications of sterile (~RH) neutrino state(s) at O(eV) scale**
- **4-fermion-like interactions ~$\varepsilon_{\alpha\beta}G_F$ weakly preferred by recent SK solar data**

Absolute neutrino mass observables: (m_β , $m_{\beta\beta}$, Σ)

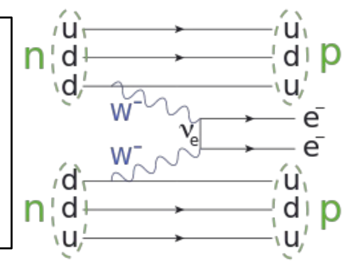
β decay, sensitive to the "effective electron neutrino mass":

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



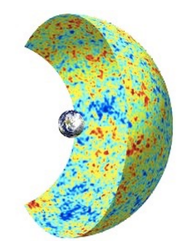
0νββ decay: only if Majorana. "Effective Majorana mass" (+phases):

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



Cosmology: Dominantly sensitive to sum of neutrino masses:

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



Sensitive to absolute neutrino masses in different ways

May provide additional handles to distinguish NO vs IO

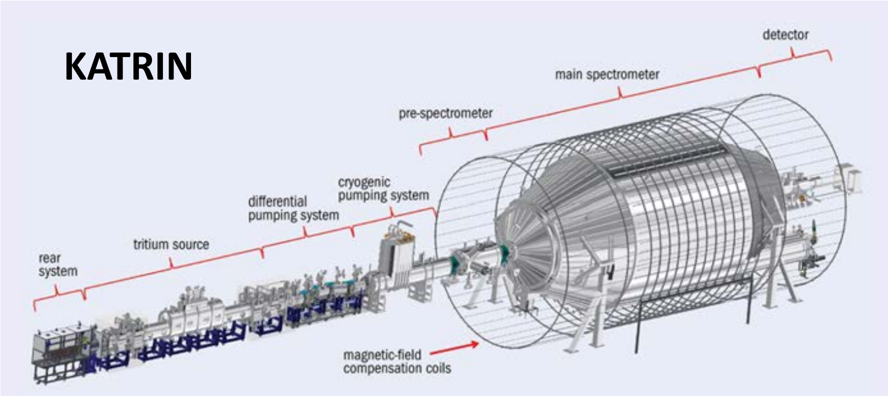
Beta decay

$m^2_i \neq 0$ can affect beta spectrum endpoint. For just one (electron) neutrino family: sensitivity to $m^2(\nu_e)$ (obsolete)

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

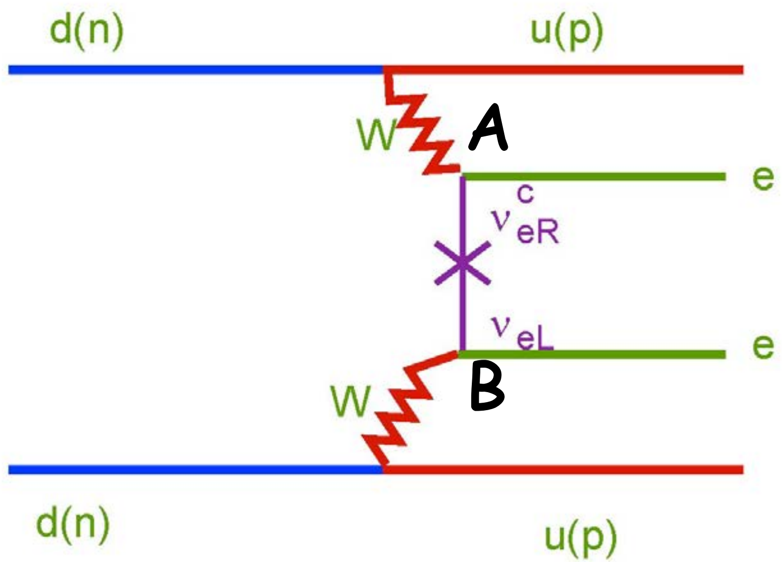
$$m_\beta = \left[c^2_{13}c^2_{12}m^2_1 + c^2_{13}s^2_{12}m^2_2 + s^2_{13}m^2_3\right]^{\frac{1}{2}}$$

(so-called "**effective electron neutrino mass**", $c_{ij} = \cos\theta_{ij}$ etc.)



Neutrinoless Double Beta Decay

Iff the ν_e is a superposition of Majorana mass states $\nu_\mathbf{i}$, then for each state the $0\nu\beta\beta$ decay amplitude is proportional to:



... mixing of $\nu_\mathbf{e}$ with $\nu_\mathbf{i}$

... mass of $\nu_\mathbf{i}$ [O(m/E)]

... mixing of $\nu_\mathbf{i}$ with $\nu_\mathbf{e}$

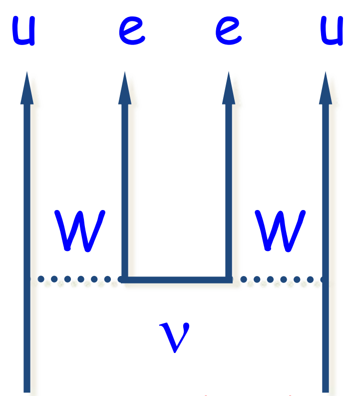
(times an unknown $\nu_\mathbf{i}$ phase)

Summing up for three massive neutrinos: Amplitude ~ **"effective Majorana mass"**

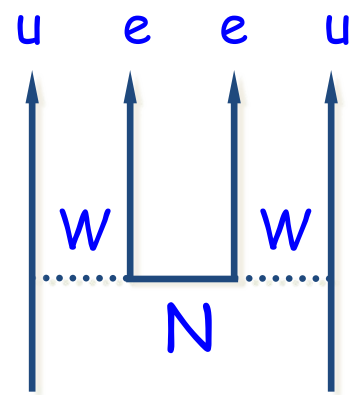
$$m_{\beta\beta} = \left| c_{13}^2 c_{12}^2 m_1 + c_{13}^2 s_{12}^2 m_2 e^{i\phi_2} + s_{13}^2 m_3 e^{i\phi_3} \right|$$

Searched in ^{130}Te (**CUORE**), ^{136}Xe (**KL-Zen, EXO**), ^{76}Ge (**GERDA, MAJORANA**), …
currently probing T ~ O(10^{26}) y

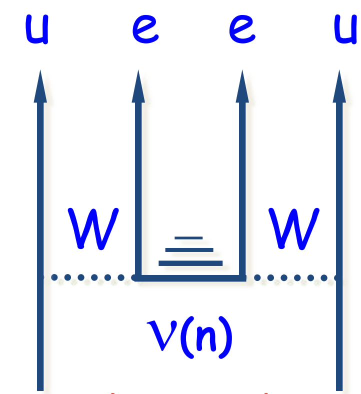
Warning: $0\nu\beta\beta$ decays might also be induced by nonstandard physics



Standard

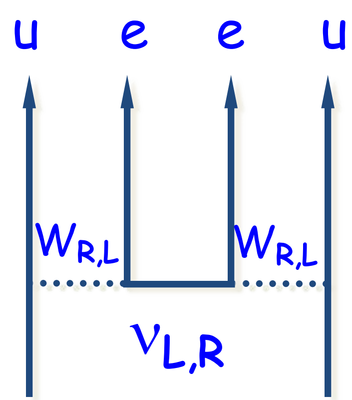


Heavy ν



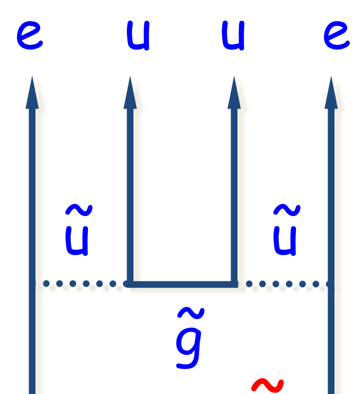
Kaluza-Klein

(KK±1 Brane:a=$10^{\pm1}$/GeV)

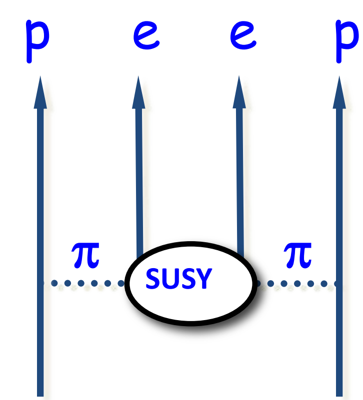


RHC λ,η

λ=RH had, η=LH had

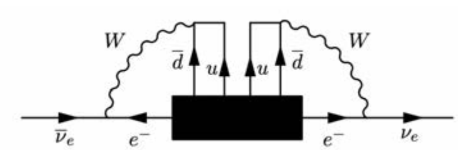


SUSY $\tilde{g}$



SUSY π

In any case, $0\nu\beta\beta$ decay implies Majorana ν:

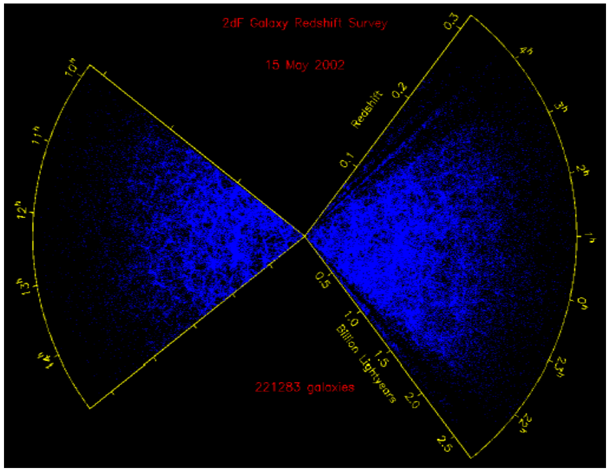


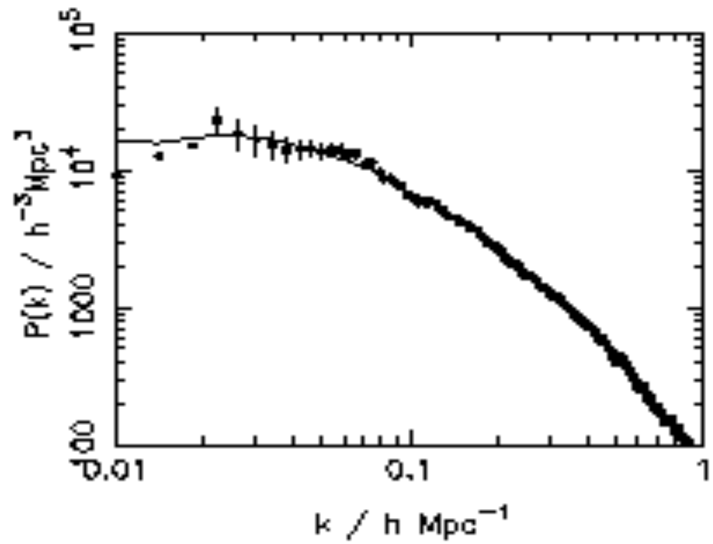
Precision Cosmology

Observations:

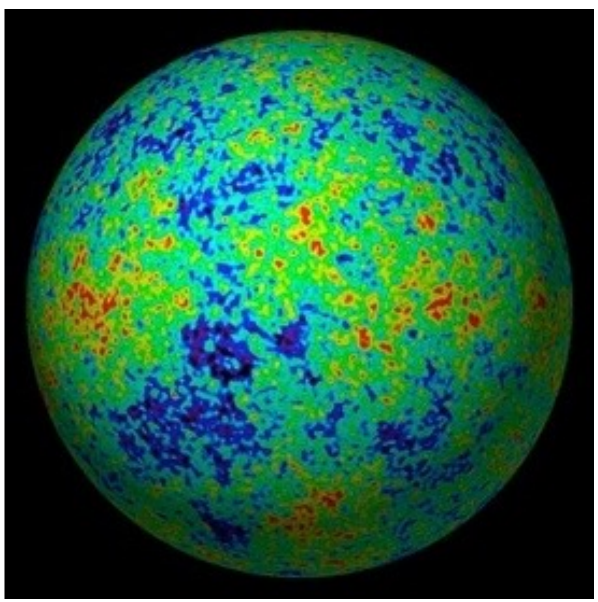
Spectra:

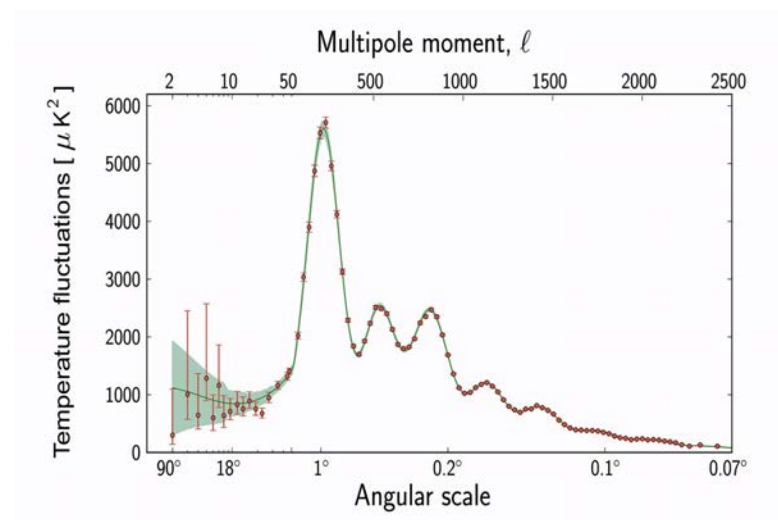
LSS



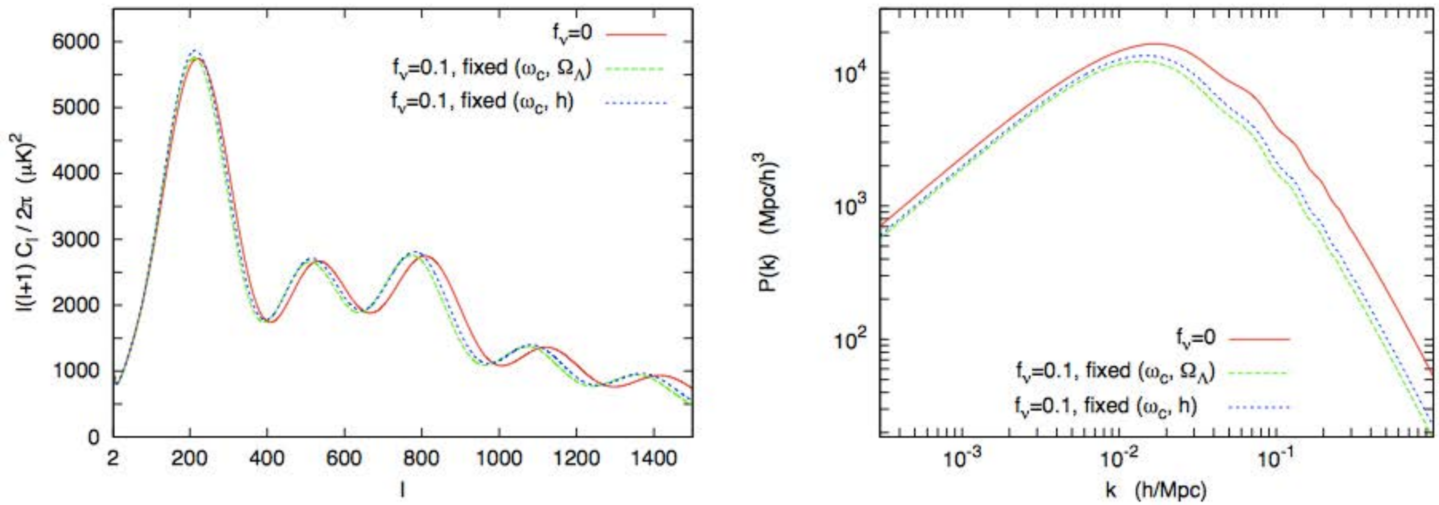


CMB





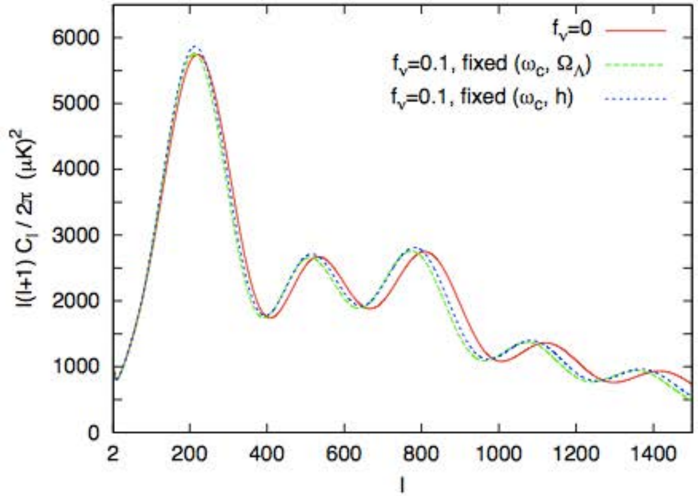
Spectra depend mainly on “total gravit. charge” $\Sigma = m_1 + m_2 + m_3$

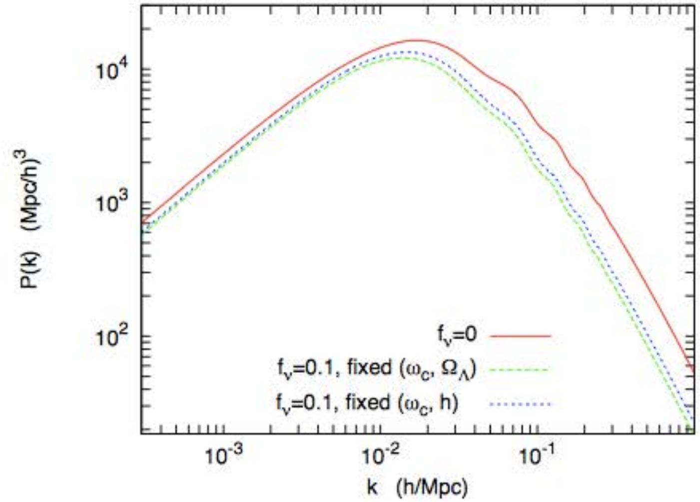


(e.g., from Lesgourgues & Pastor 2006)

Significant progress after Planck & recent galaxy surveys...
Upper bounds on Σ (well) below the eV scale

Spectra depend mainly on “total gravit. charge” $\Sigma = m_1 + m_2 + m_3$



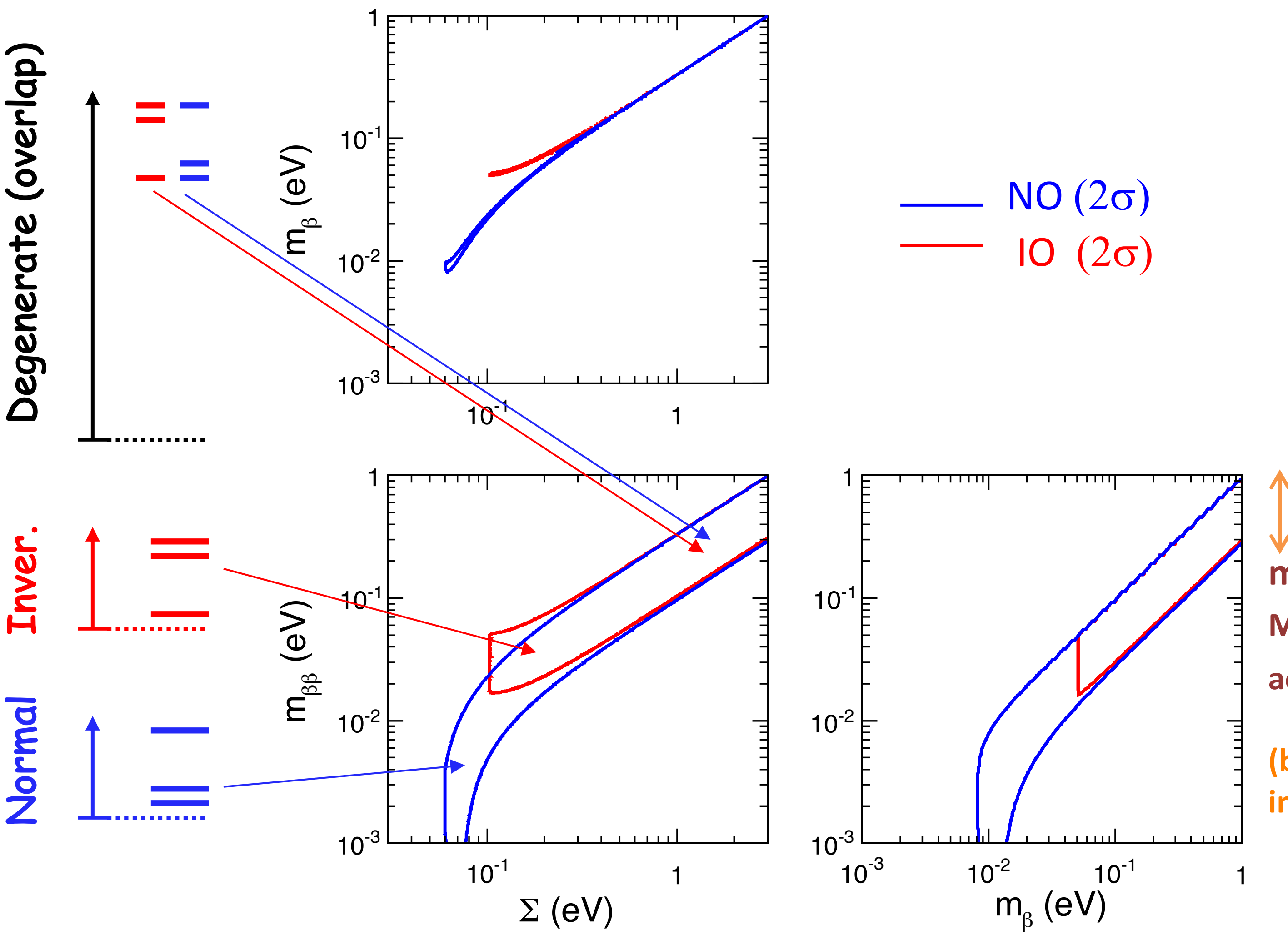


(e.g., from Lesgourgues & Pastor 2006)

Significant progress after Planck & recent galaxy surveys...
Upper bounds on Σ (well) below the eV scale

Overview of (m_β , $m_{\beta\beta}$, Σ) observables →

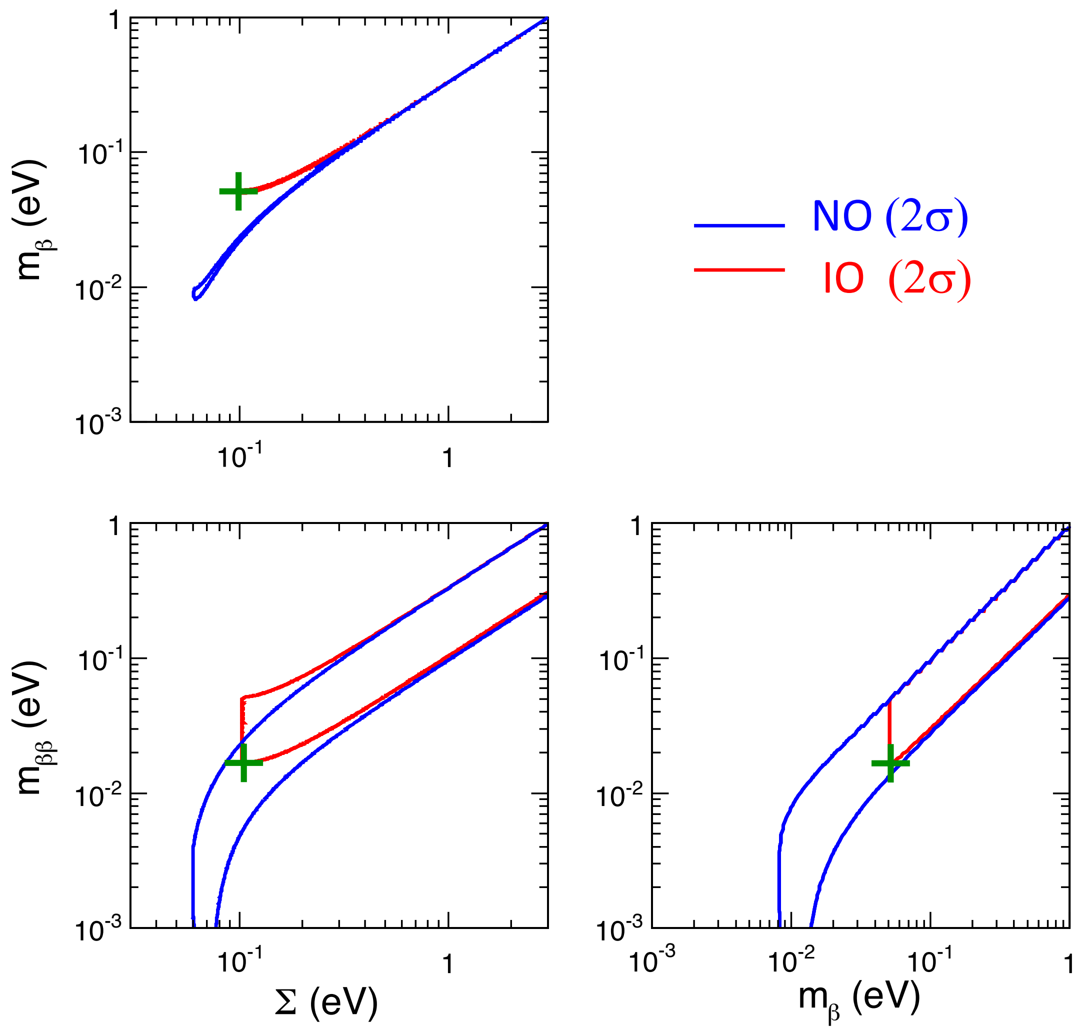
Absolute mass observables: bands allowed by oscillations in NO/IO



$m_{\beta\beta}$ spread due to Majorana CP phase(s): accessible in principle

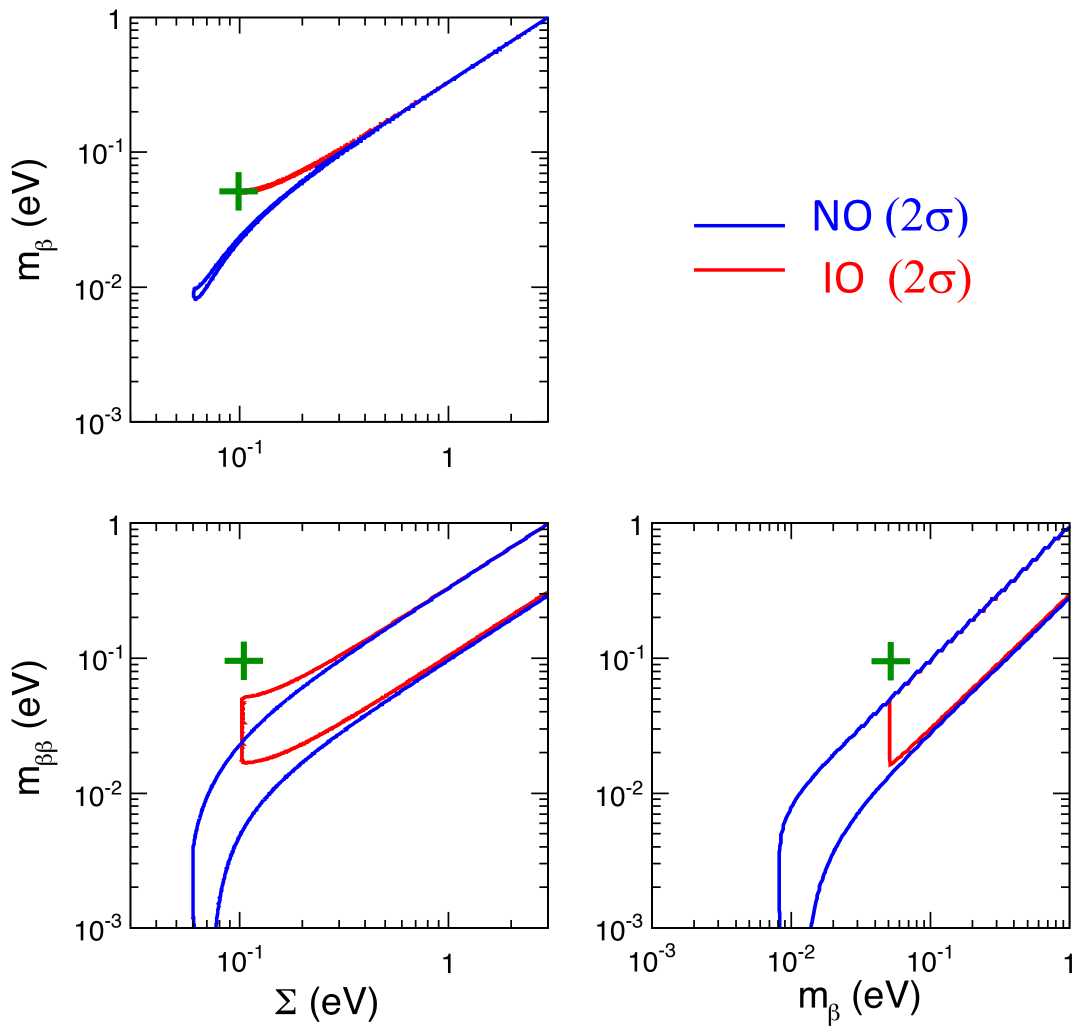
(but: no nuclear uncert. included here!)

Absolute mass observables: ...dreaming of far-future data ... +



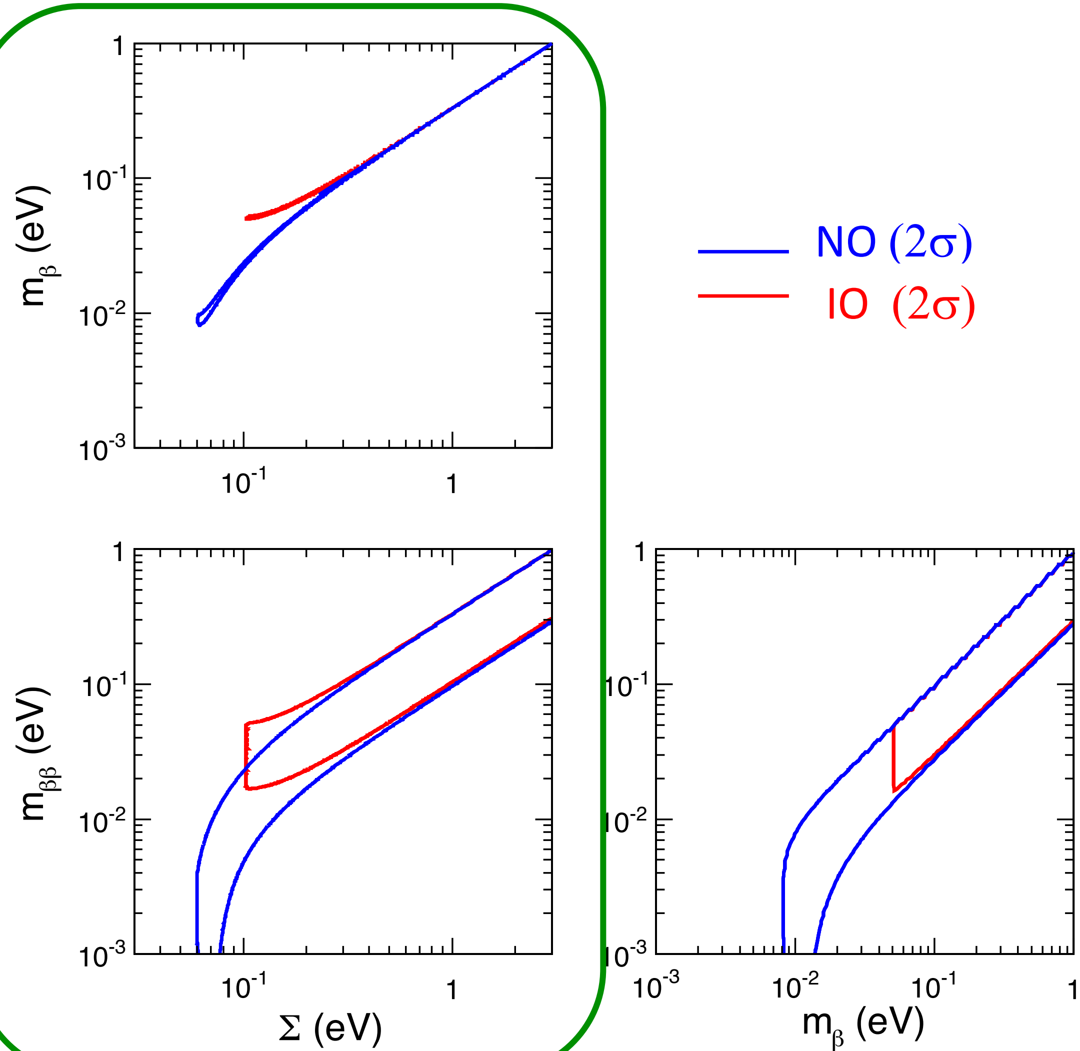
→ confirming the 3ν framework & discovering (some) current unknowns

Absolute mass observables: … finding some surprises ? …



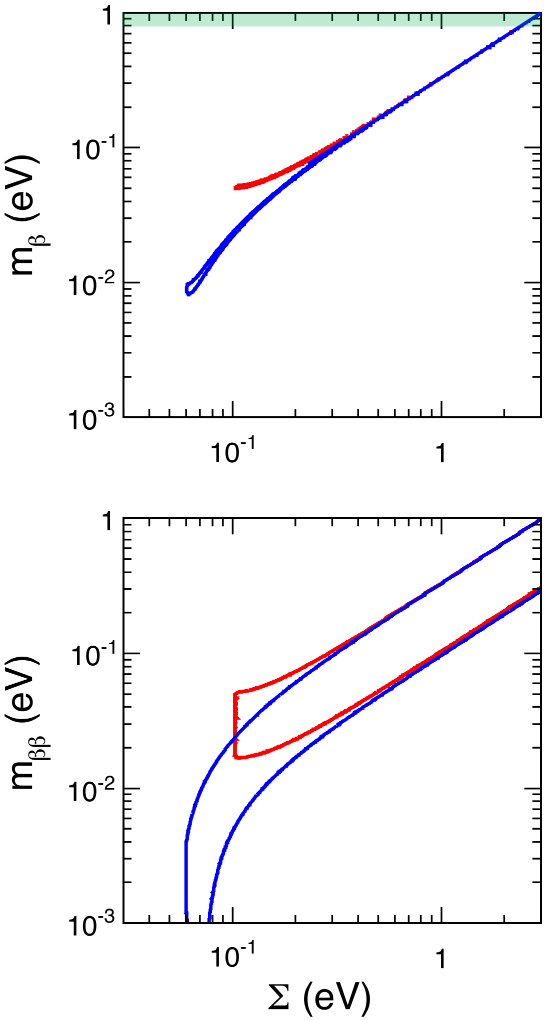
→ lack of convergence indicating new physics? (e.g., nonstandard $0\nu\beta\beta$)

Absolute mass observables: currently, only upper bounds!



Focus on these planes

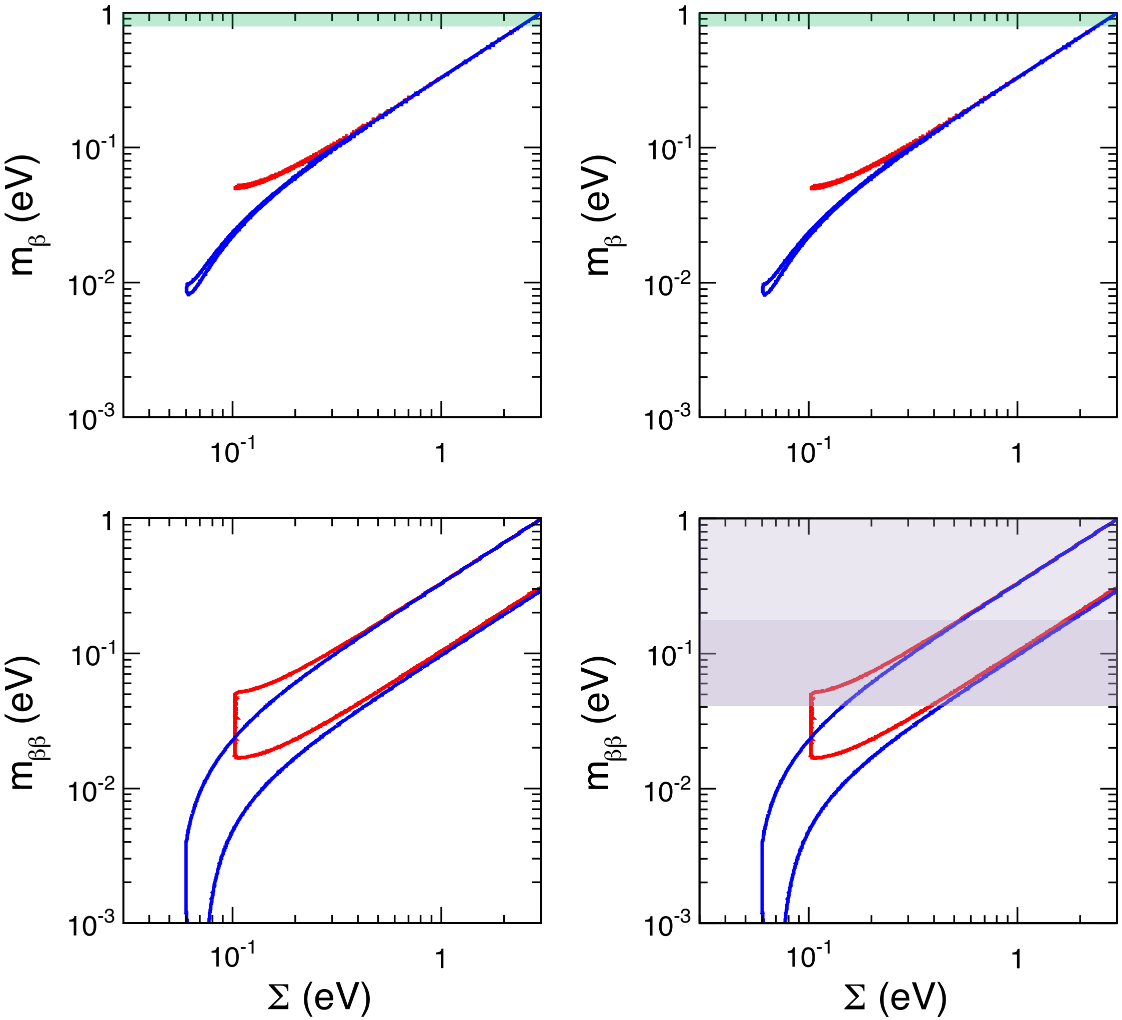
β : KATRIN



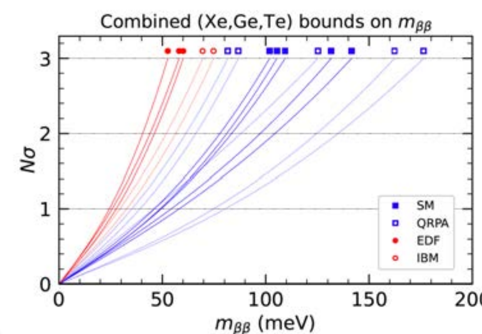
β : KATRIN

0νββ : KL-Zen, Exo, GERDA, Cuore...

[spread: nuclear models]



E.g., spread of upper bounds from Xe+Ge+Te data by using 15 nuclear matrix elements from 4 classes of nucl. models. e-print 2204.09569



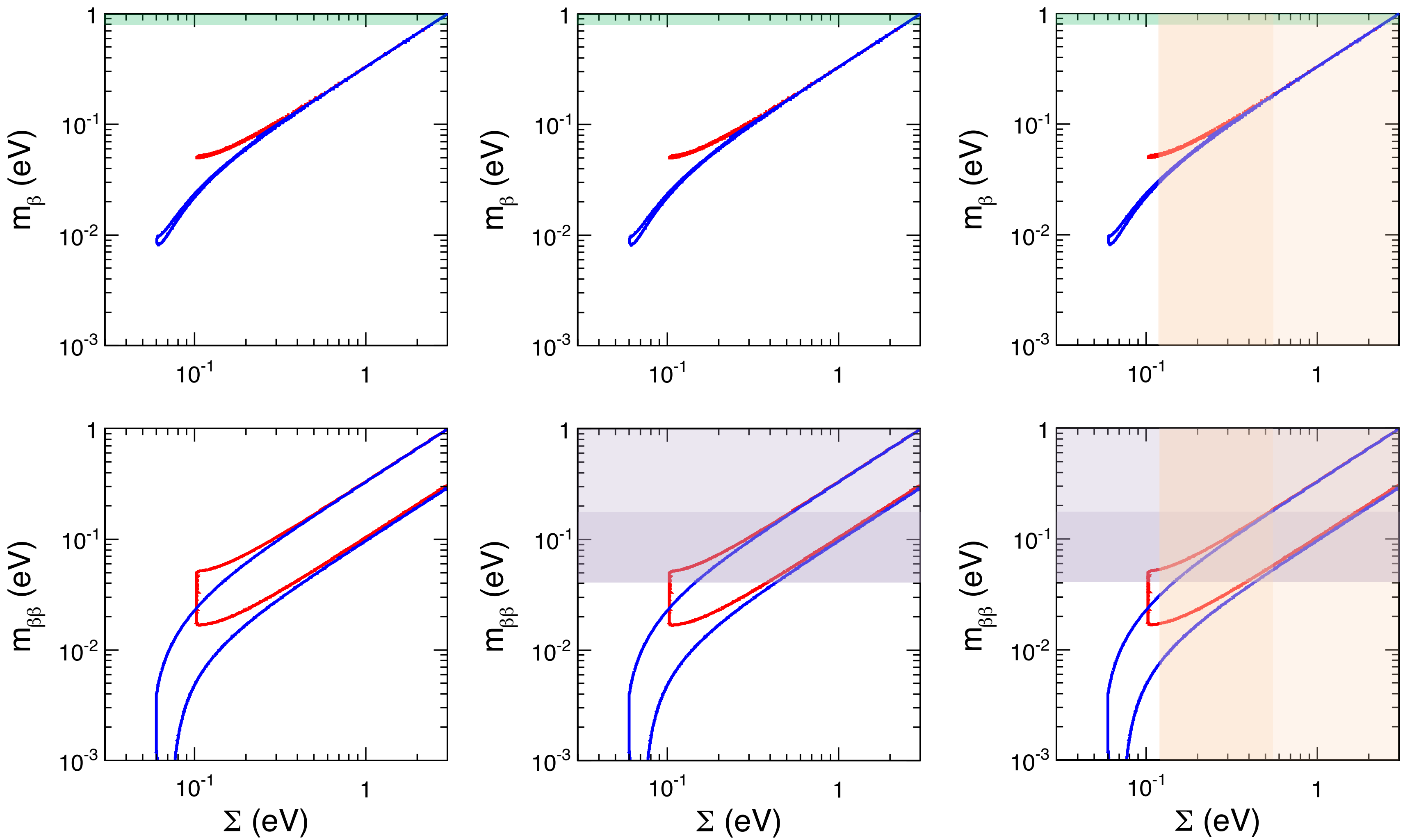
β : KATRIN

0νββ : KL-Zen, Exo, GERDA, Cuore...

[spread: nuclear models]

Σ: Planck, BAO, lensing ...

[spread: cosmo models/data]



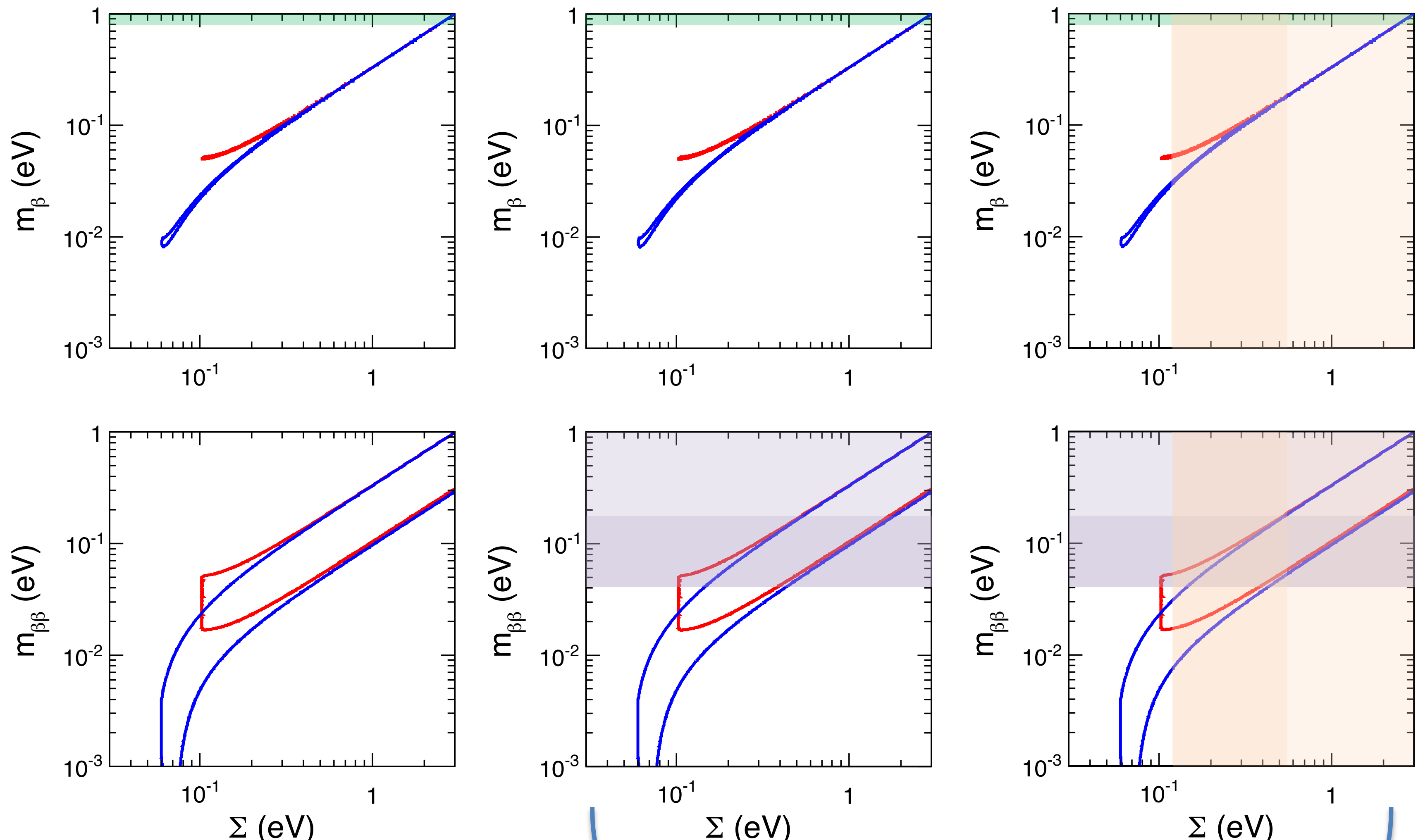
β : KATRIN

0νββ : KL-Zen, Exo, GERDA, Cuore...

Σ: Planck, BAO, lensing ...

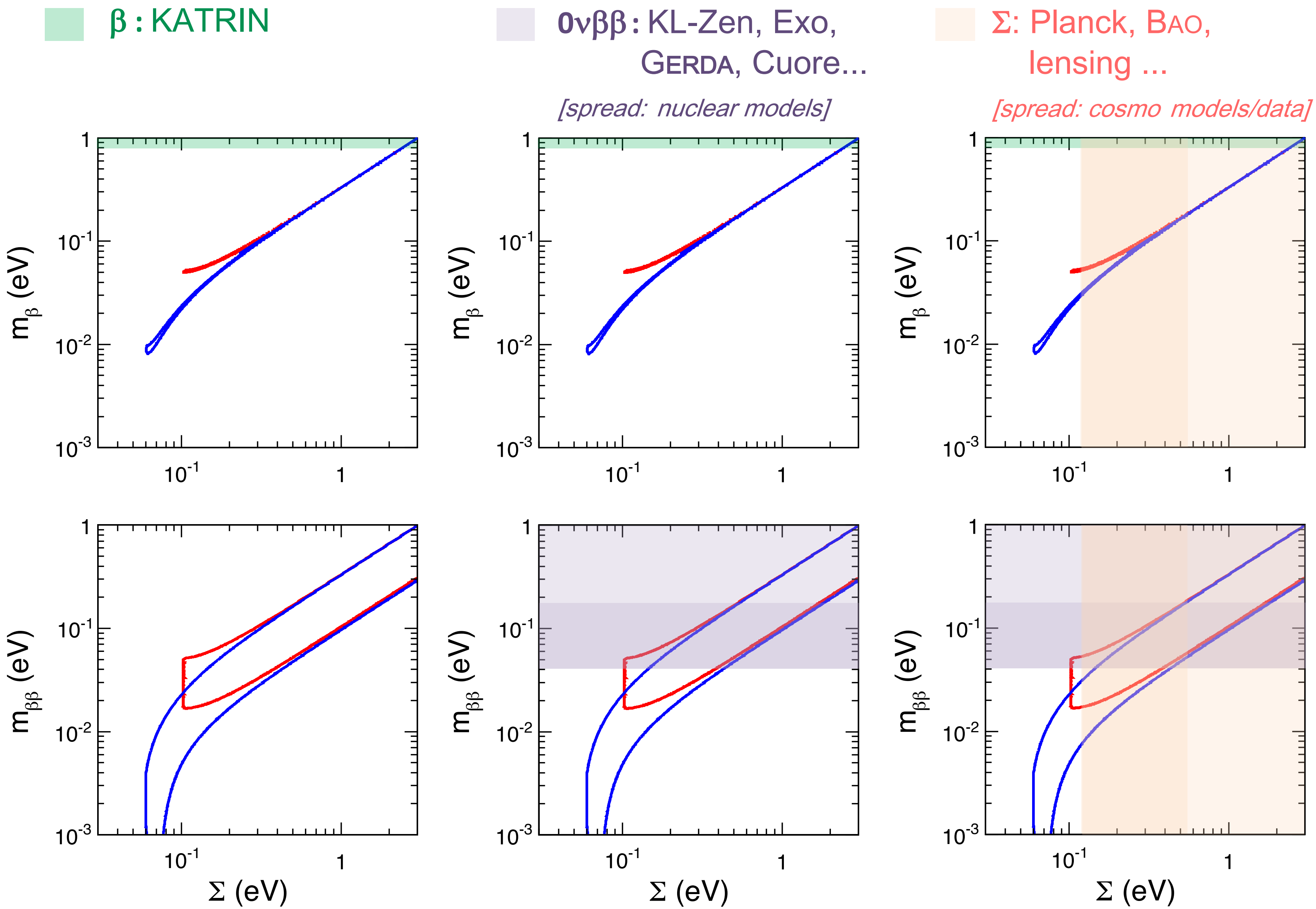
[spread: nuclear models]

[spread: cosmo models/data]



IO “under pressure” but not excluded yet

[IO disfavored at ~3σ by osc+nonosc data]

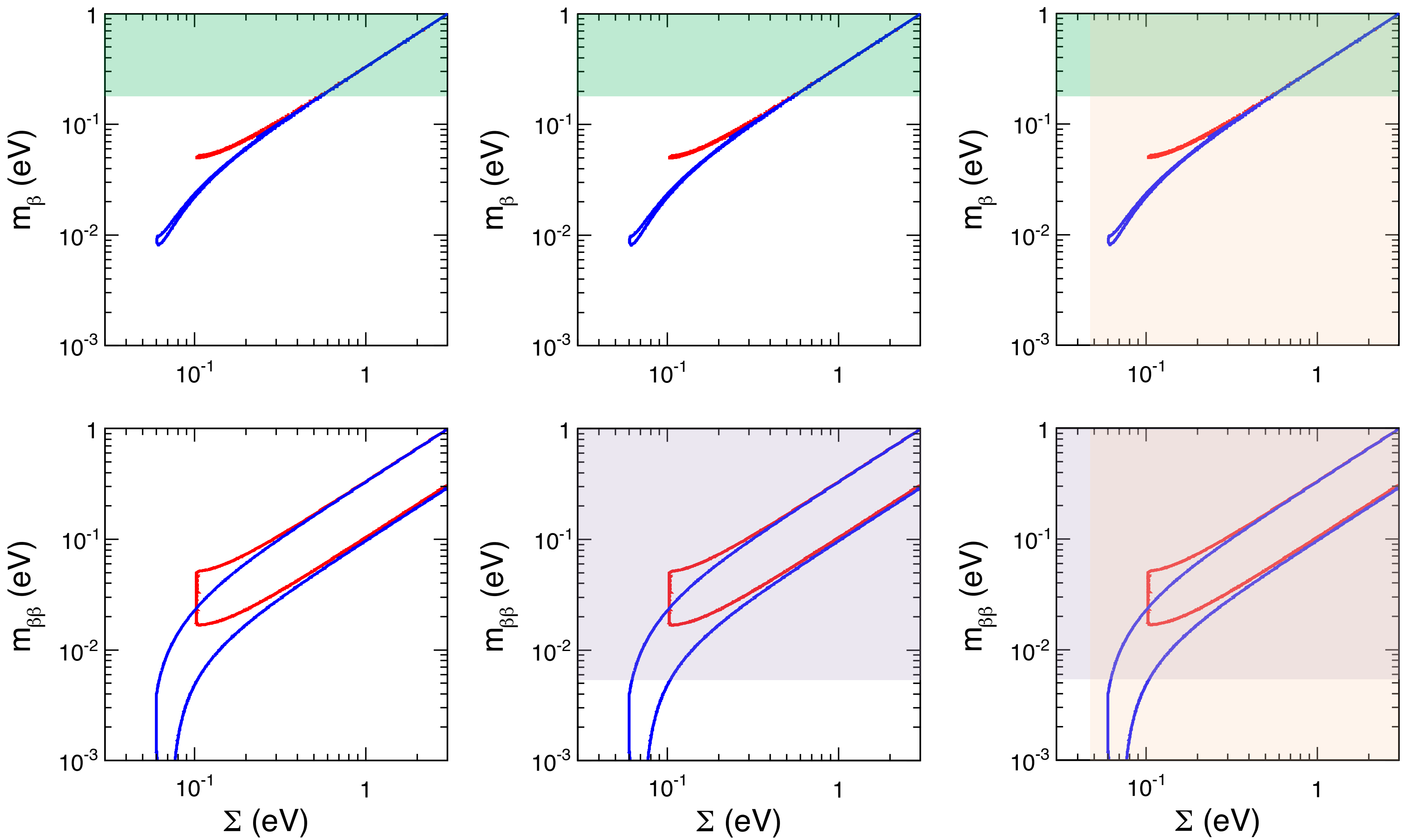


Frontiers for the next ~10-20 yrs →

β: ~0.2 eV sensitivity (difficult to go beyond KATRIN afterwards)

0νββ: Well below IO limit at ton scale (LEGEND, NEXO, CUPID…) w/ improved NME

Σ: complete covering seems possible if cosmo model globally confirmed.



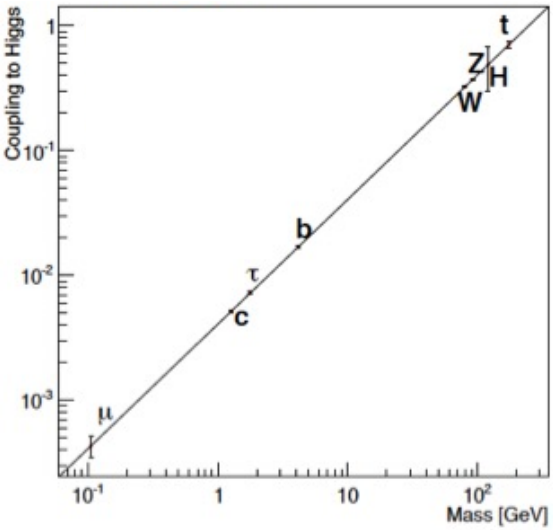
See e.g. review talks at Neutrino 2022 and NOW 2022 + Snowmass 2022 Reports

Large phase space for possible signal discoveries

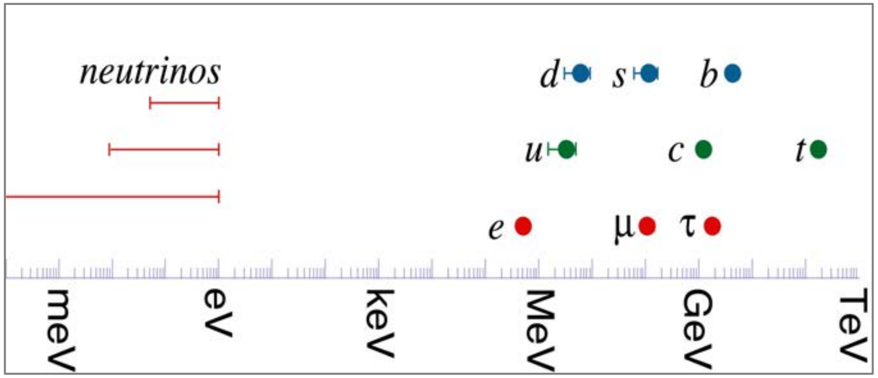
First claims about absolute neutrino mass are likely to come from cosmology!

Neutrino mass and Dirac/Majorana nature: Linking two research programs

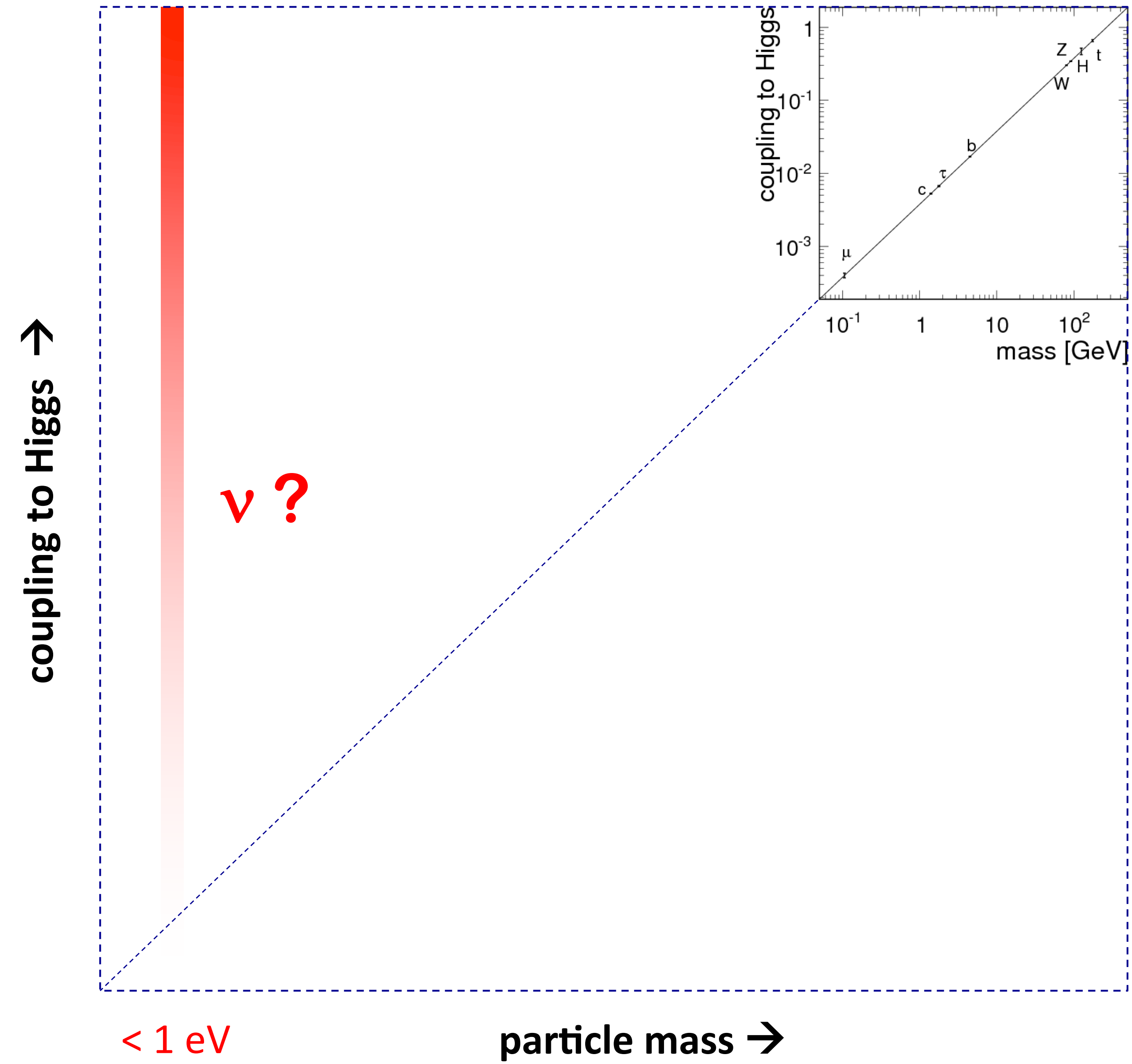
1. Test Higgs sector



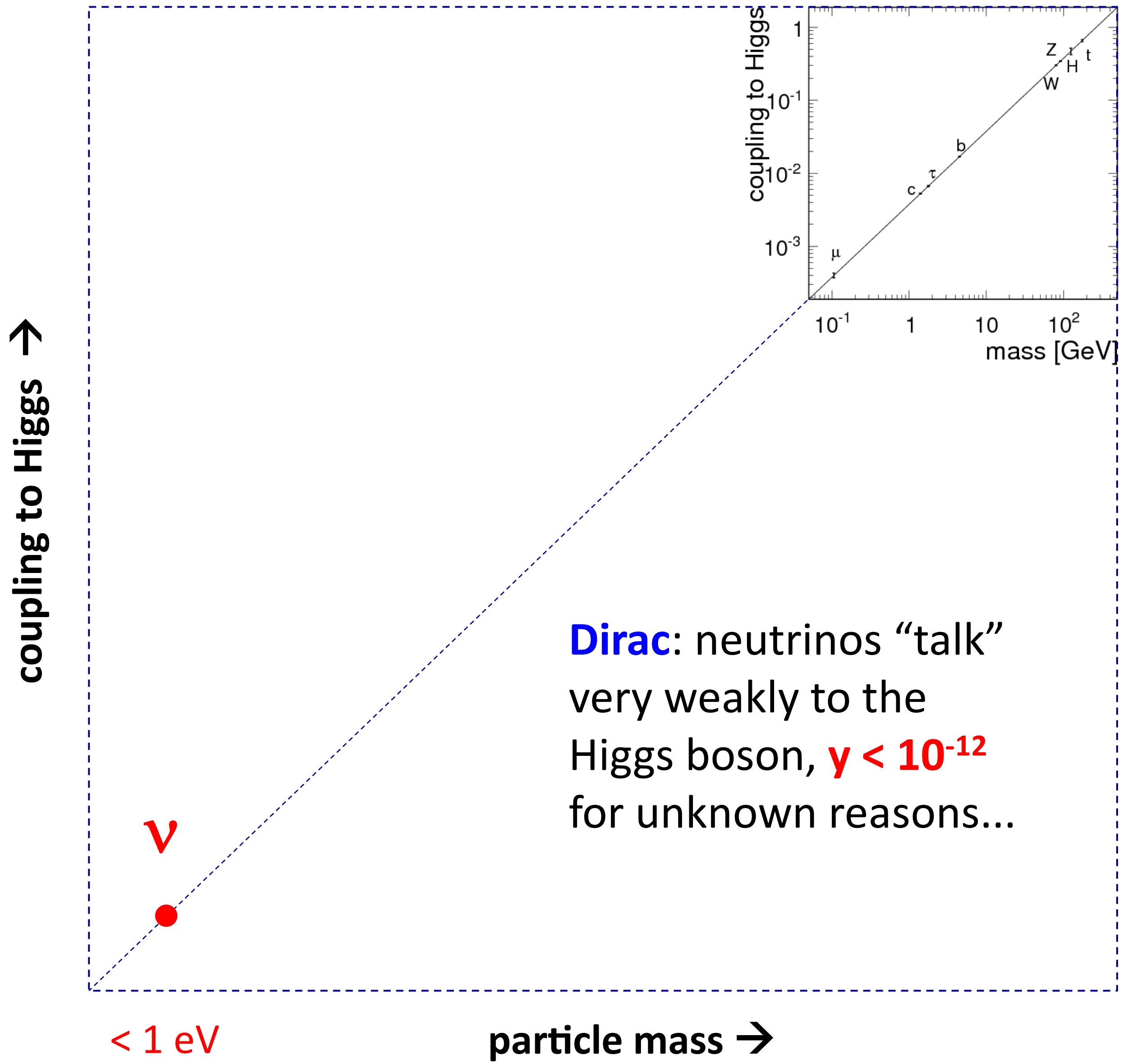
2. Find ν masses



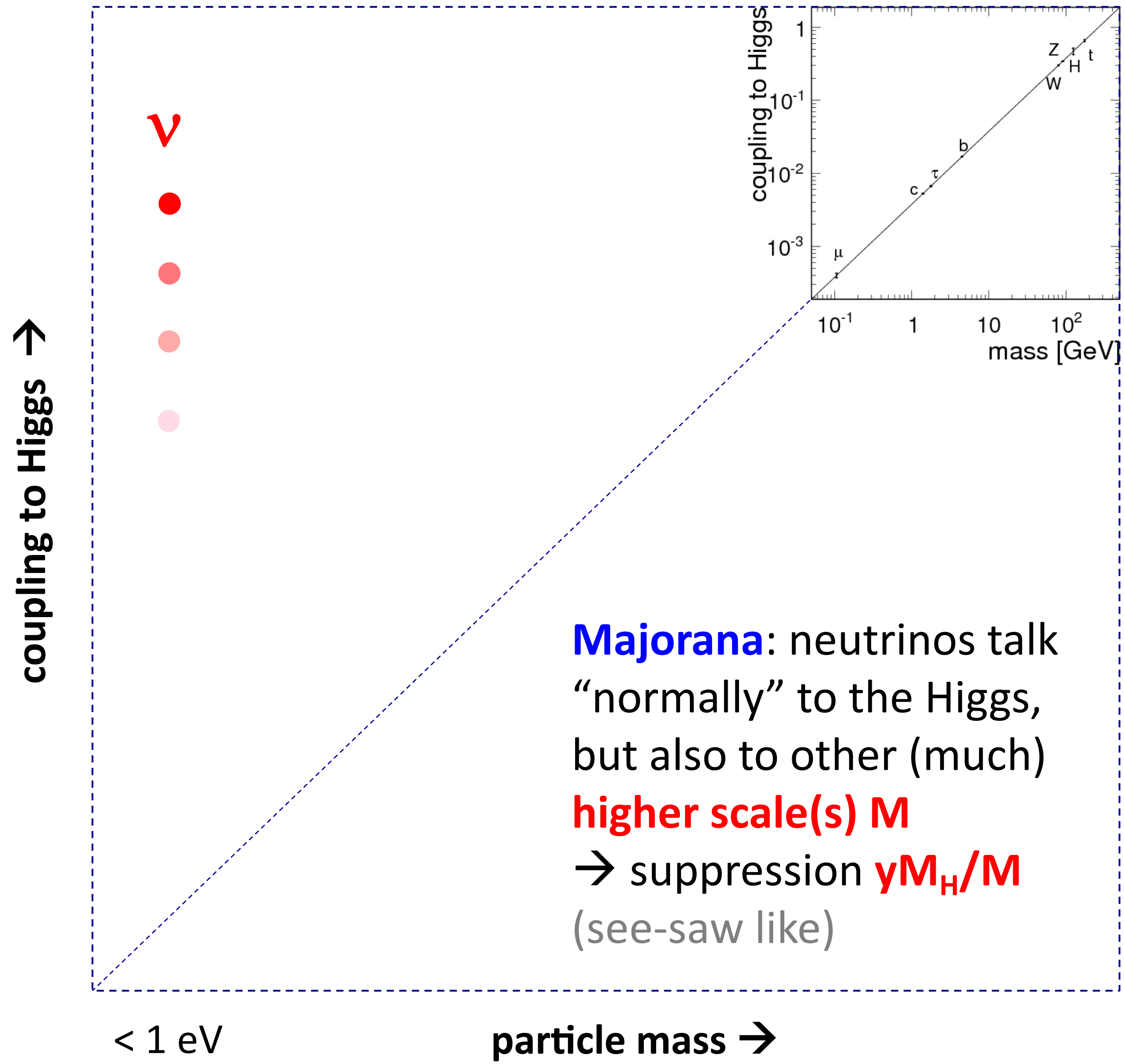
1 + 2 Where are the ν's on this plot? Why are they so light?



Options:


coupling to Higgs →
particle mass →
< 1 eV
ν
coupling to Higgs
mass [GeV]
1
10^{-1}
10^{-2}
10^{-3}
10^{-1}
1
10
10^{2}
Z
H
t
W
b
τ
c
μ
Dirac: neutrinos "talk" very weakly to the Higgs boson, **$y < 10^{-12}$** for unknown reasons...

Options:

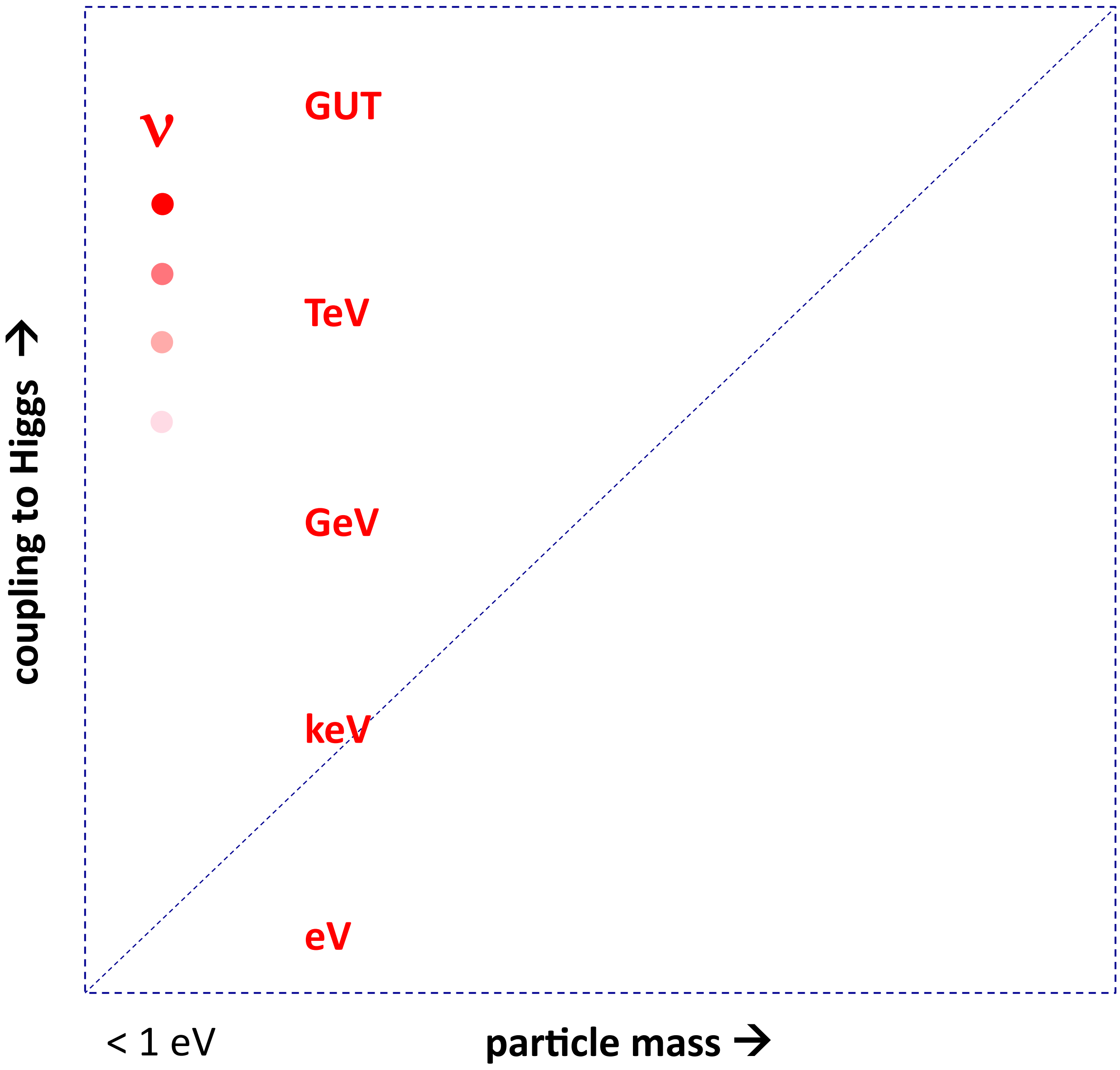


Majorana: neutrinos talk "normally" to the Higgs, but also to other (much) **higher scale(s) M**

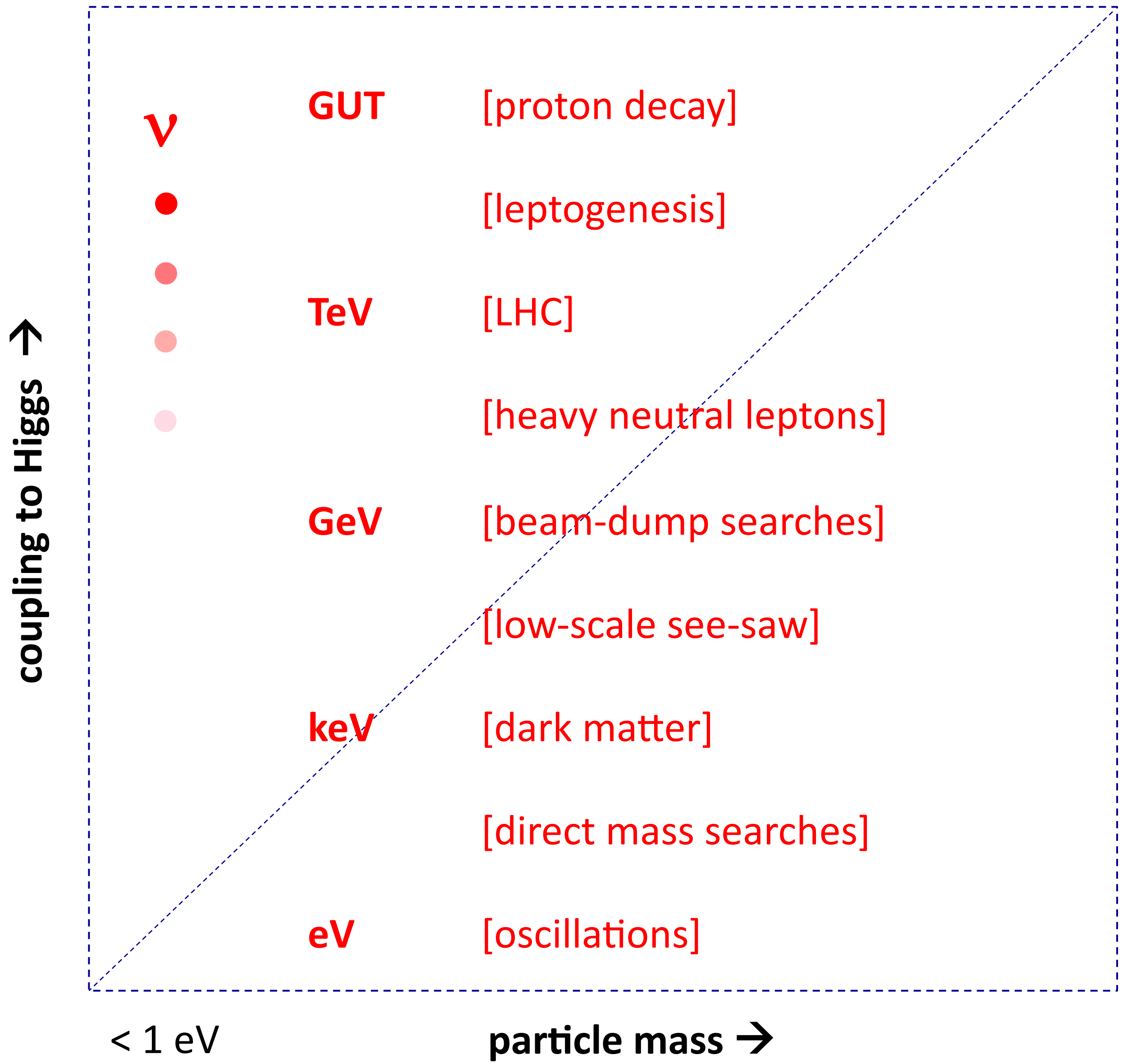
→ suppression **yM_H/M**

(see-saw like)

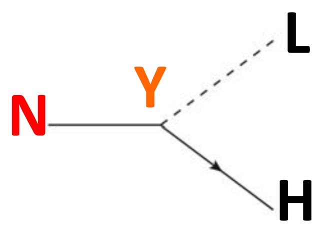
...New ν mass states could emerge at one or more scales ...



… and contribute to a wide research program with HE/LE links…



E.g. Leptogenesis: C, CP, L-violating and out-of-equilib. decays of heavy **N** at **T~M_N** can generate lepton asymmetry **ΔL** → non-perturb. → **ΔB** (BAU)



+ loops

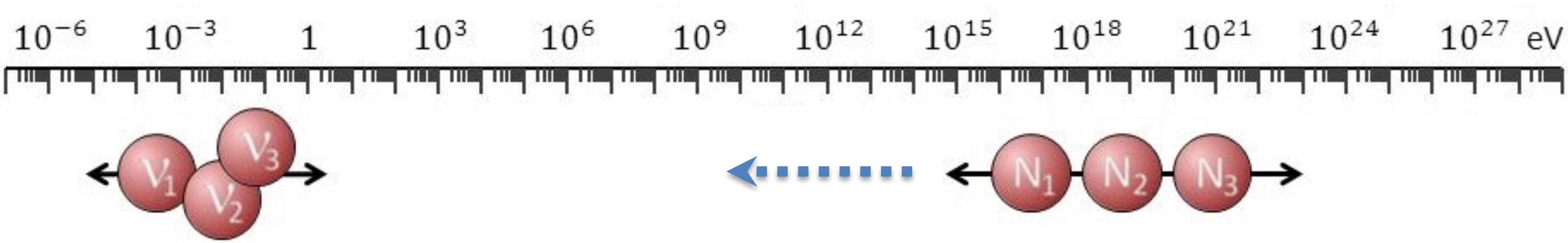
with: $\Gamma(N \rightarrow L) \neq \Gamma(N \rightarrow \bar{L}) \rightarrow \Delta L$

via: $Y \sim U_\nu\, m_\nu^{1/2}\, \frac{1}{v}\, U_N\, M_N^{1/2}$

Involves masses, mixing, phases at both low (ν) and high (N) scales.

Involves (non)equilibrium evolution in an expanding & cooling universe.

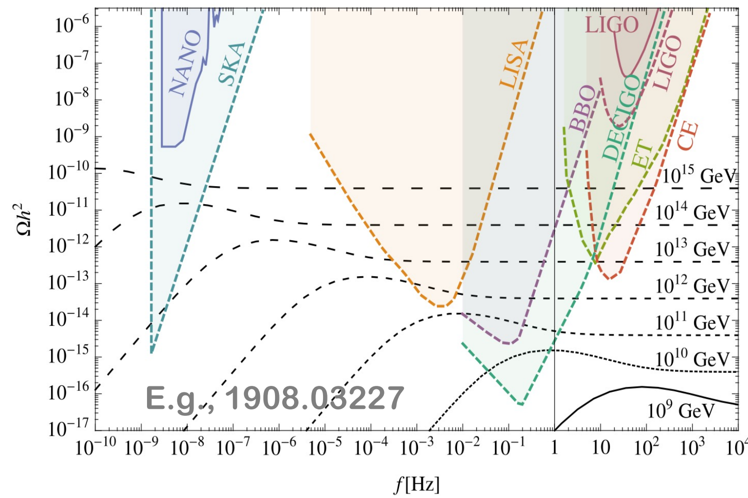
Significant work to assess/extend ranges of M (and T) of successful models



At low scale: contact with low-energy CPV and 0νββ decay

At high scale: contact with heavy N searches and other HE processes

Recent twist: impact of physics at **leptogenesis** scales on primordial **GW background**



ν

GUT

TeV

GeV

keV

eV

coupling to Higgs →

< 1 eV

particle mass →

Summary

Knowns:

δm^2, $|\Delta m^2|$, θ_{13}, θ_{12} and θ_{23} (up to octant) → *worldwide precision physics program*

Unknowns:

NO/IO, CPV, abs. mass, Majorana/Dirac → *ongoing searches aiming at discoveries*

Be open to:

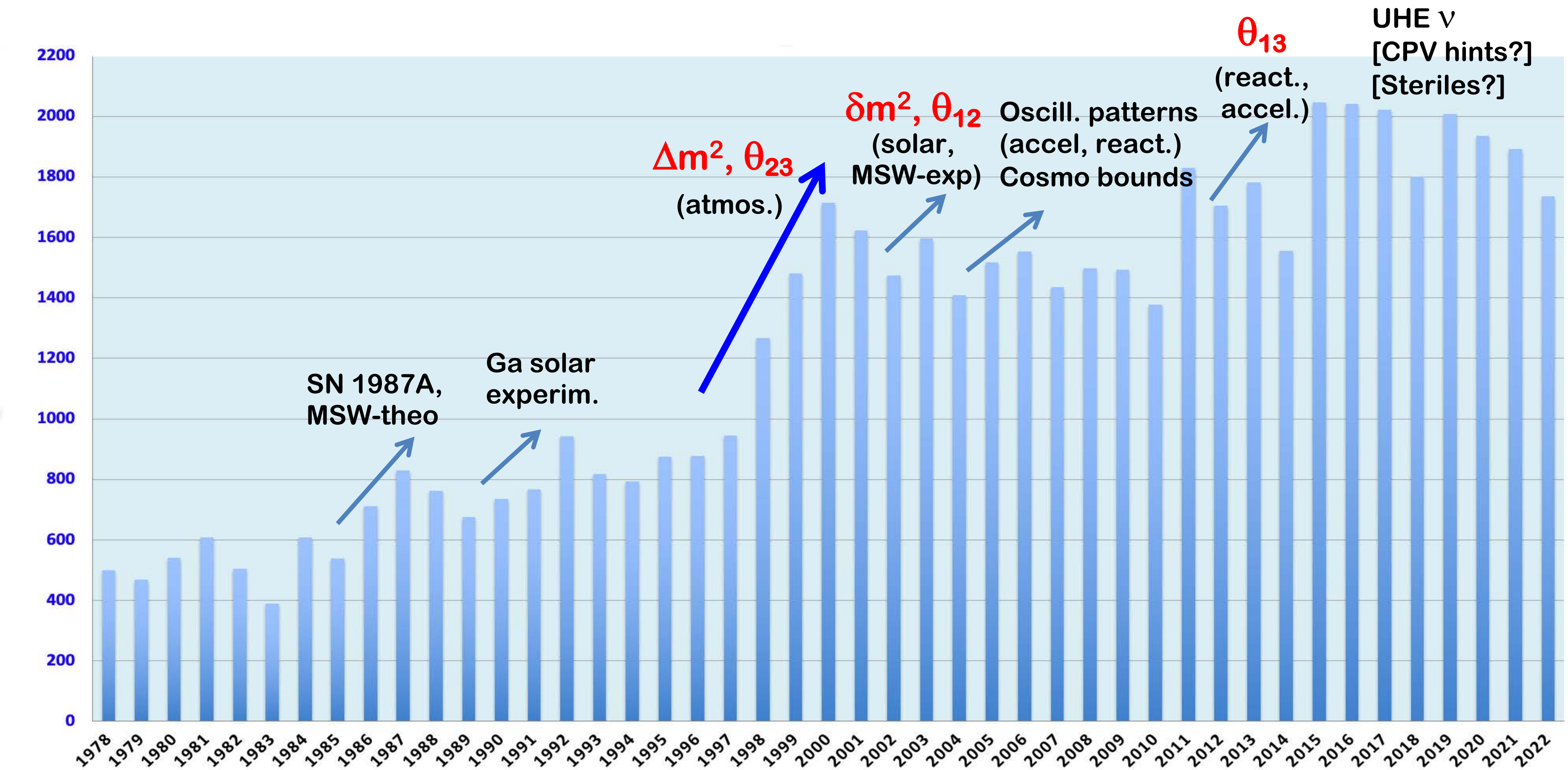
New ν states and interactions, HE/LE links → *diversity of expt/theo approaches*

Be part of this adventure!

While answering old questions… → *new questions will emerge!*

…?

Papers with *neutrino* in the title, yearly trend from iNSPIRE HEP



→ … ?