Neutrino Theory

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Gran Sasso HANDS-ON 2023 PhD Autumn School – 26/09/2023 , LNGS (room Bruno Pontecorvo)

Neutrino Theory

Organizers' request: give a theory/pheno introduction to
ν physics + ν–related experiments in this School, such as:

LEGEND, CUORE/CUPID, PTOLEMY, RES-NOVA, AUGER …

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Learning about neutrinos
(ν properties)

Learning from neutrinos
(ν sources)

For further exploration, browse the very complete and updated neutrino website: www.nu.to.infn.it

Outline:

- Prologue: ν basic properties
- (Un)knowns in neutrino oscillations
- Non-oscillation ν observables
- Learning from neutrinos
- Epilogue: What's in a name?

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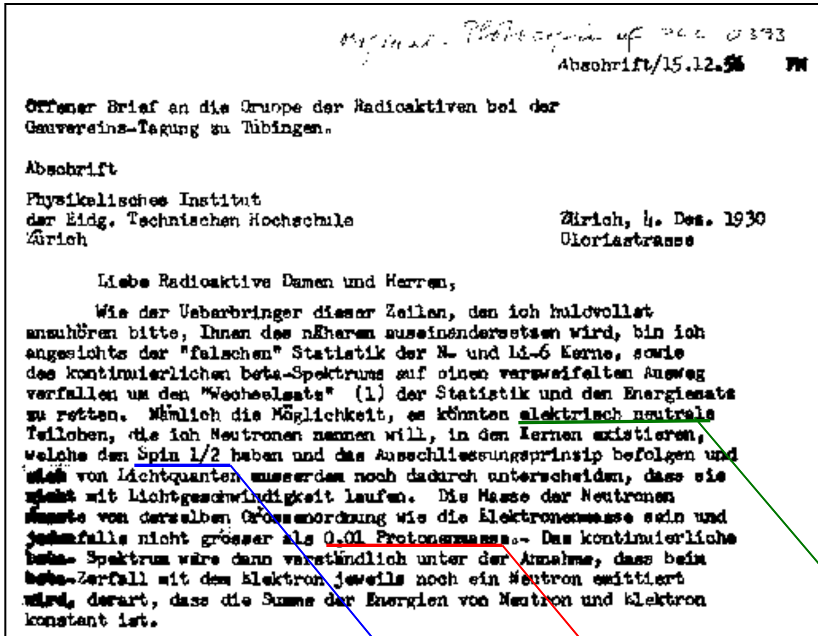
1930: ν hypothesis and first kinematical properties

Solving β-decay paradoxes: A famous letter by Wolfgang Pauli



Abschrift/15.12.56 PM

Offener Brief an die Gruppe der Radioaktiven bei der Gauvereins-Tagung zu Tübingen.

Abschrift

Physikalisches Institut
der Eidg. Technischen Hochschule
Zürich

Zürich, 4. Dez. 1930
Gloriastrasse

Liebe Radioaktive Damen und Herren,

Wie der Ueberbringer dieser Zeilen, den ich huldvollst anzuhören bitte, Ihnen des näheren auseinandersetzen wird, bin ich angesichts der "falschen" Statistik der N- und Li-6 Kerne, sowie des kontinuierlichen beta-Spektrums auf einen verzweifelten Ausweg verfallen um den "Wechselsatz" (1) der Statistik und den Energiesatz zu retten. Nämlich die Möglichkeit, es könnten elektrisch neutrale Teilchen, die ich Neutronen nennen will, in den Kernen existieren, welche den Spin 1/2 haben und das Ausschliessungsprinzip befolgen und sich von Lichtquanten ausserdem noch dadurch unterscheiden, dass sie nicht mit Lichtgeschwindigkeit laufen. Die Masse der Neutronen müsste von derselben Grössenordnung wie die Elektronenmasse sein und jedenfalls nicht grösser als 0,01 Protonenmasse.- Das kontinuierliche beta- Spektrum wäre dann verständlich unter der Annahme, dass beim beta-Zerfall mit dem Elektron jeweils noch ein Neutron emittiert wird, derart, dass die Summe der Energien von Neutron und Elektron konstant ist.

spin 1/2, **tiny mass**, **zero electric harge**

1930: $m_\nu < 0.01$ GeV

Today: $m_\nu < 0.1 - 1$ eV

Three years later: ν name and first dynamical properties

Neutrinos & QFT: A famous paper by Enrico Fermi


ANNO IV · VOL. II · N. 12 QUINDICINALE 31 DICEMBRE 1933 · XII

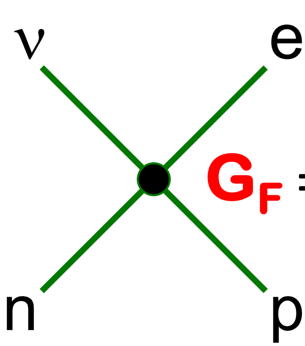
LA RICERCA SCIENTIFICA

ED IL PROGRESSO TECNICO NELL'ECONOMIA NAZIONALE

Tentativo di una teoria dell'emissione dei raggi "beta"

Nota del prof. ENRICO FERMI

Riassunto: Teoria della emissione dei raggi β delle sostanze radioattive, fondata sull'ipotesi che gli elettroni emessi dai nuclei non esistano prima della disintegrazione ma vengano formati, insieme ad un neutrino, in modo analogo alla formazione di un quanto di luce che accompagna un salto quantico di un atomo. Confronto della teoria con l'esperienza.

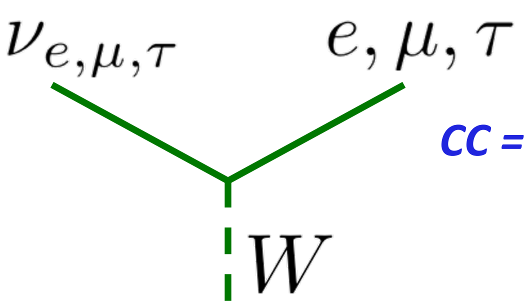


$G_F = 1.166 \times 10^{-5}\ \text{GeV}^{-2}$ → Sets the energy scale $\sqrt{(1/G_F)} \sim O(\text{few } 10^2)$ GeV of weak interactions

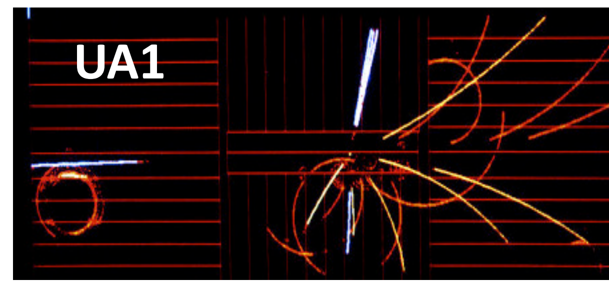
Many decades of research have revealed other ν properties: There are
3 different **ν** "flavors" **e μ τ**

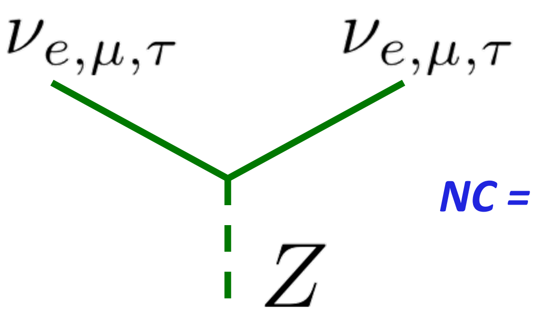
$$\begin{pmatrix} \nu_e \\ e \end{pmatrix} \begin{pmatrix} \nu_\mu \\ \mu \end{pmatrix} \begin{pmatrix} \nu_\tau \\ \tau \end{pmatrix} \quad \begin{matrix} \leftarrow & q = 0 \\ \leftarrow & q = -1 \end{matrix} \quad (\Delta q = 1)$$

and their Fermi **interactions** are mediated by a charged vector boson W, with a neutral counterpart, the Z boson



CC = Charged Current (Δq=1)



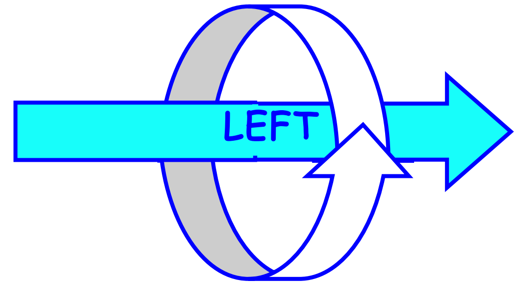


NC = Neutral Current (Δq=0)

Such interactions are chiral (= not mirror-symmetric):

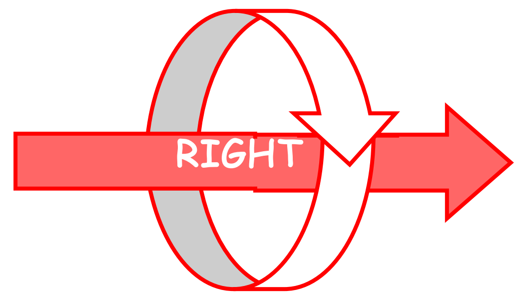
Neutrinos are created in
a left-handed (LH) state

ν



Anti-nus are created in
a right-handed (RH) state

$\overline{\nu}$



P parity symmetry is violated. *Nature is fundamentally chiral!*

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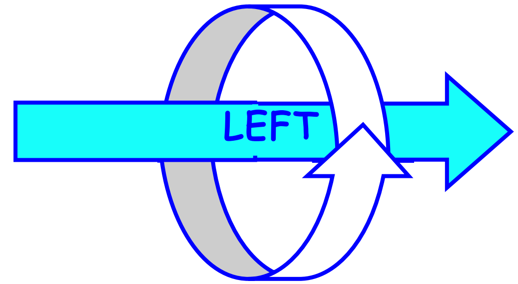

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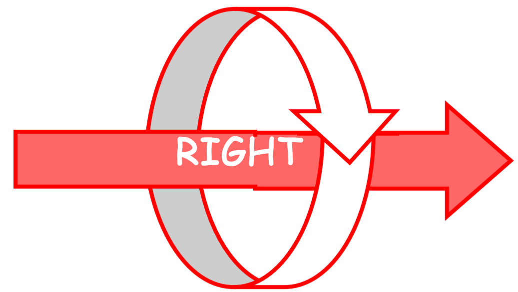


P parity symmetry is violated. *Nature is fundamentally chiral!*

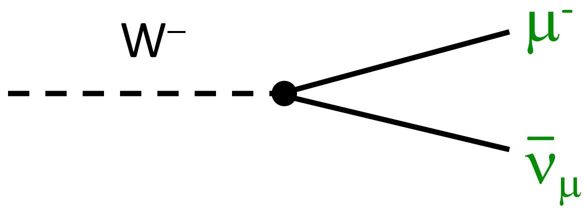
Other discrete symmetries in particle physics:

C charge conjugation (particle-antiparticle exchange)

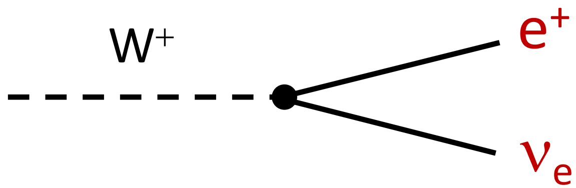
T time reversal (change arrow of time)

Combined **CPT** *conserved in QFT.* **CP** *violation required for baryogenesis.*

CC processes at **production** provide an operative definition of ν flavor, via the corresponding charged (anti)lepton. E.g., in leptonic decays:

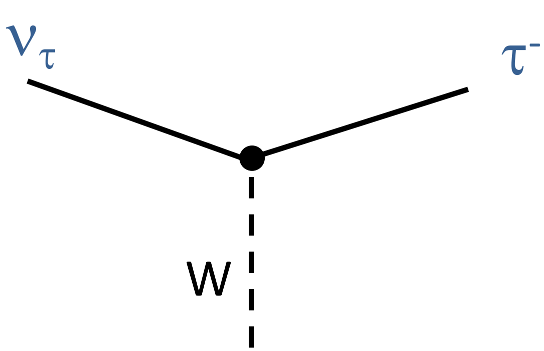


Creation of a muon antineutrino (RH)



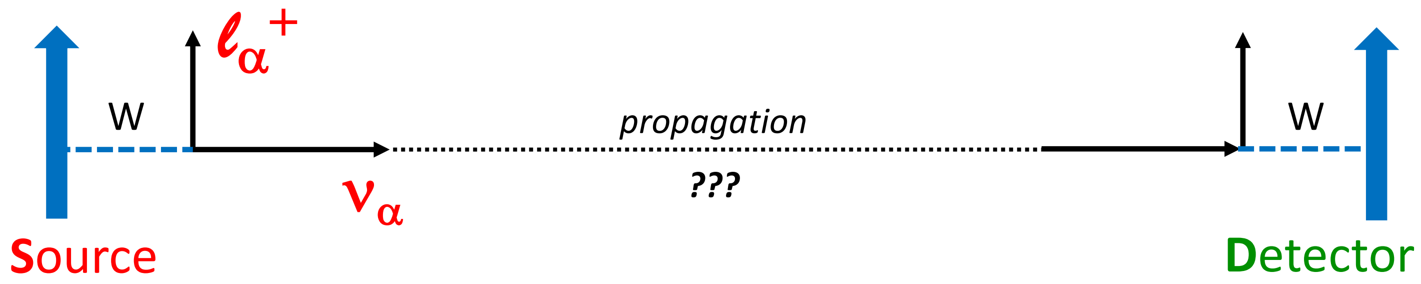
Creation of an electron neutrino (LH)

Similarly at **detection**, e.g.:



Absorption of a tau neutrino (LH)

But… what happens in between?



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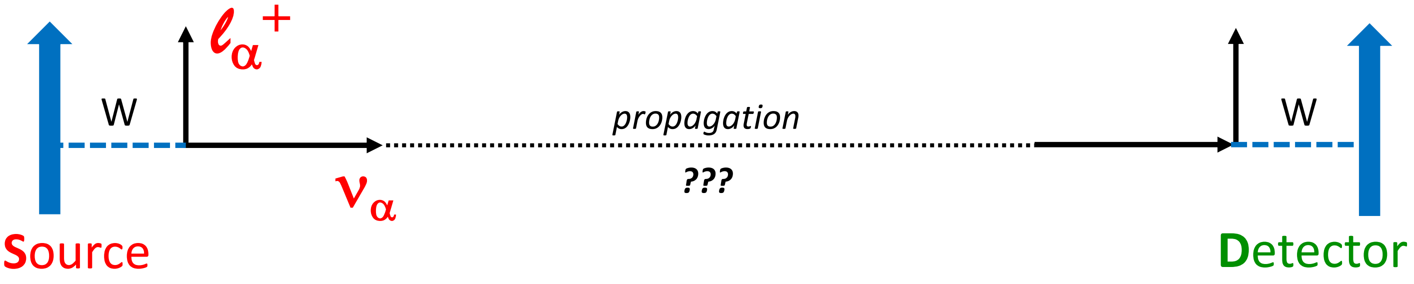


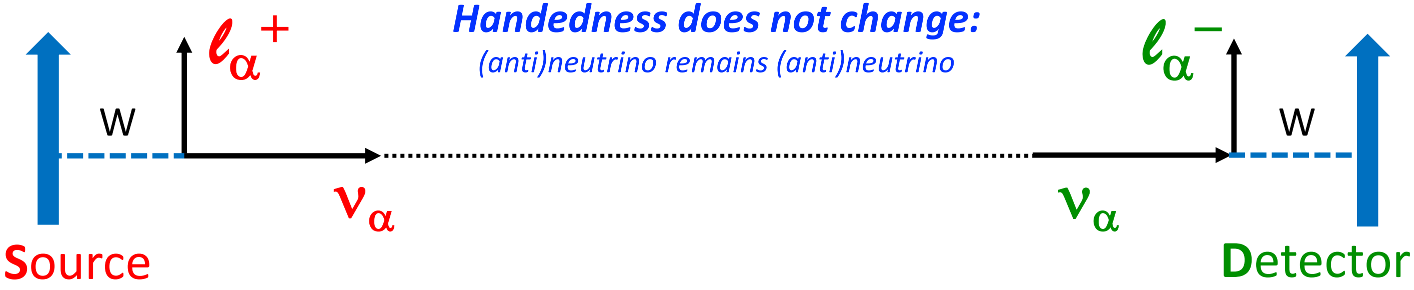
If neutrinos are massless: *v=c* → "clock" is frozen → no change!

Flavor does not change.

neutrino-α remains neutrino-α

Handedness does not change:

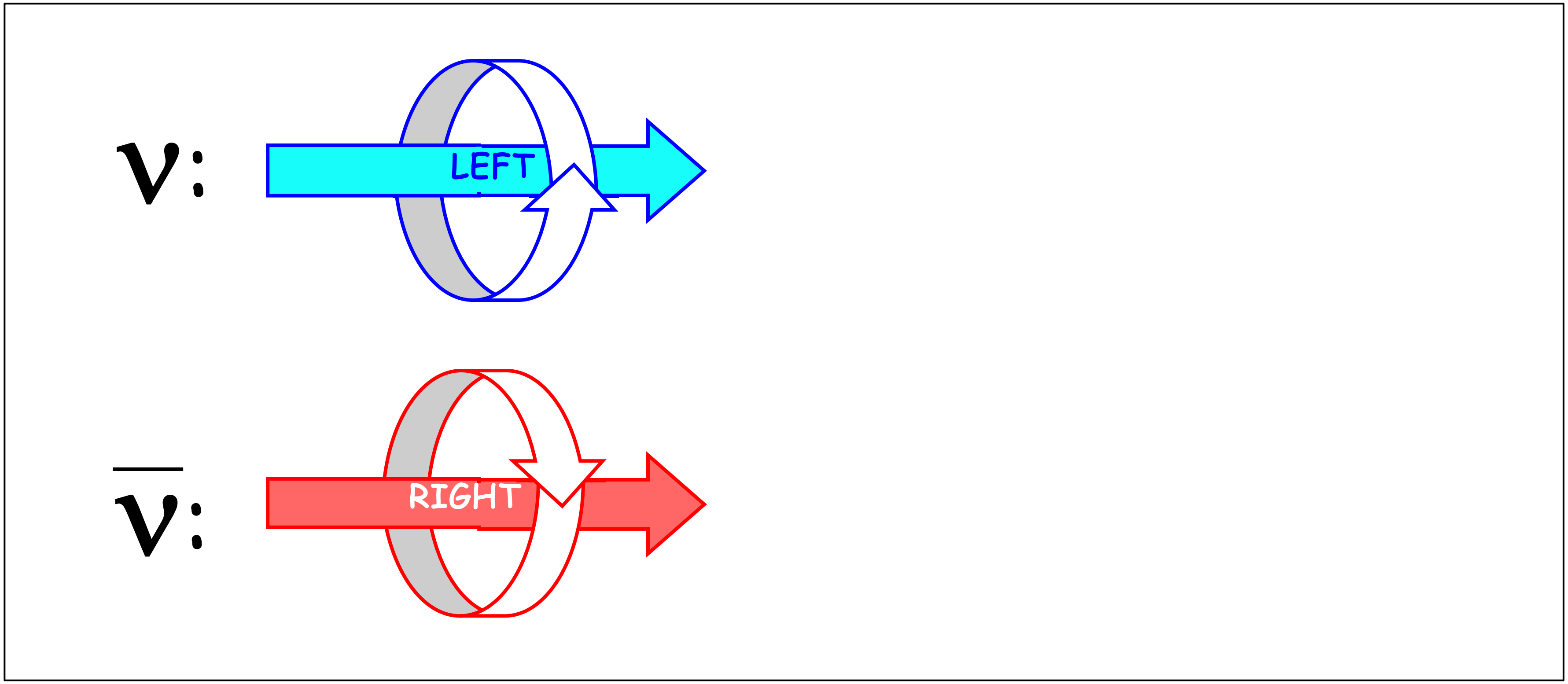
(anti)neutrino remains (anti)neutrino



However, If ν have mass, interesting things may happen to handedness and flavor…

Handedness: is a constant of motion for massless neutrinos

[You would see handedness reversal if you could travel faster… but you can't (v=c)!]

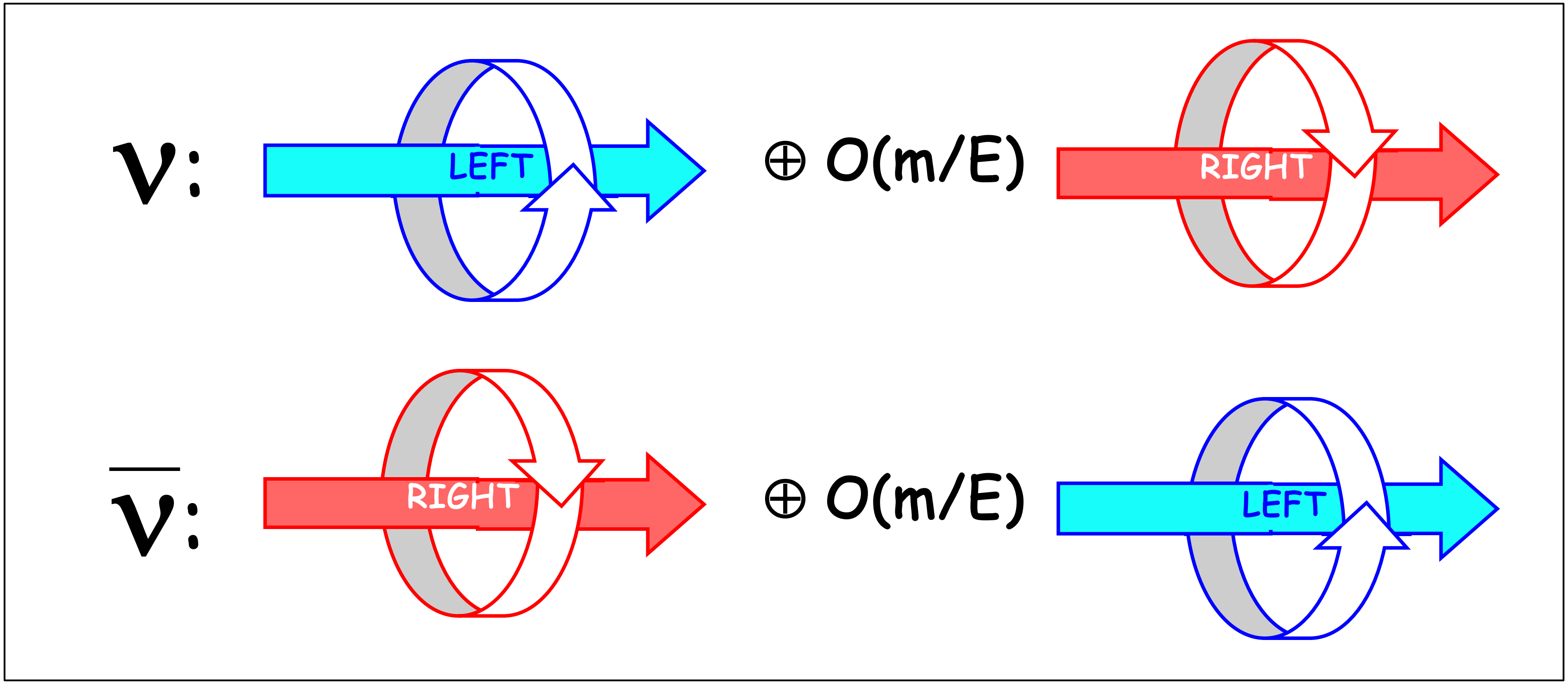


This is a massless "Weyl" two-spinor with 2 independent d.o.f

[And this was also the theoretical prejudice in the construction of the Standard Model]

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

E= neutrino energy; the Dirac equation couples RH and LH states for $m \neq 0$

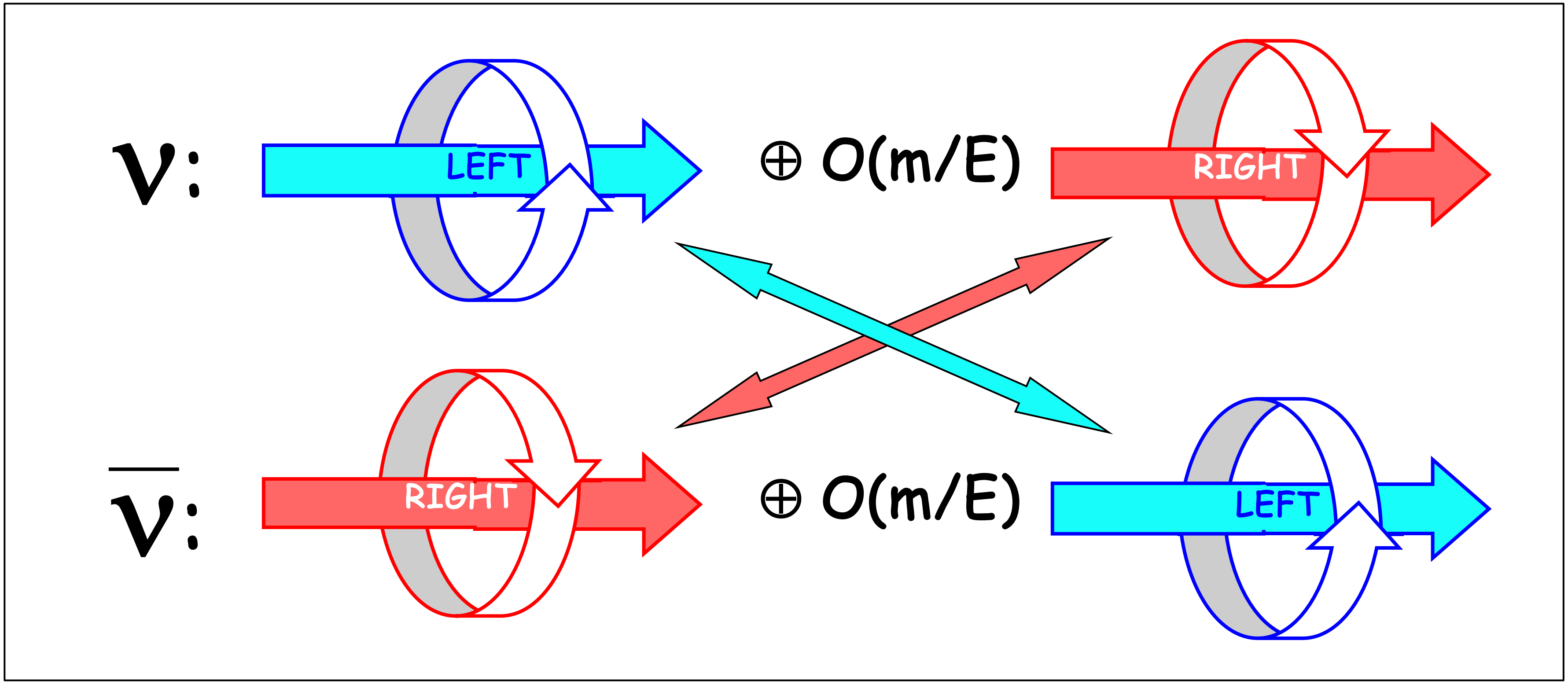


If these 4 d.o.f. are independent: massive "Dirac" four-spinor

Nu and anti-nu are different, just as the charged fermions are different.
Can define a conserved charge, the **"lepton number"** (+1 for leptons, -1 for antileptons)

But, for neutral fermions, two components might be identical !

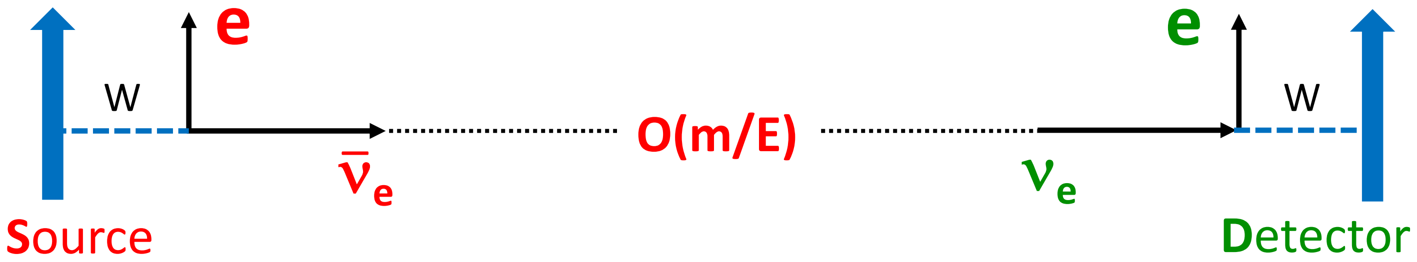
[Pairing components between electron and positron is forbidden: violates electric charge.]



Only 2 independent d.o.f.: Massive "Majorana" four-spinor

No fundamental distinction between nu / antinu, up to a possible **"Majorana phase":**
A *very* neutral particle with no charge at all: **no electric charge, no lepton number …**

If neutrinos are Majorana, expect $\bar{\nu} \rightarrow \nu$ transition:



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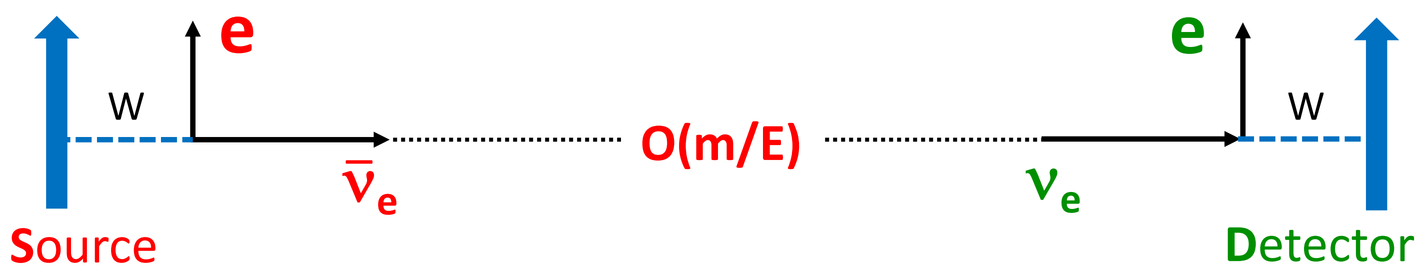

But, we have never seen anything like that so far!

E.g., the inverse beta-decay (IBD) reaction has been observed using reactor anti-ν_e ($E \sim$ few MeV) with a statistics of $O(10^7)$ events:

$$\bar{\nu}_e + p \rightarrow e^+ + n \quad \checkmark \text{ (IBD, observed)}$$

… but no event has ever been observed for the reaction:

$$\nu_e + p \rightarrow e^+ + n \quad \text{✗ (not observed)}$$

Does this imply that neutrinos are not Majorana?

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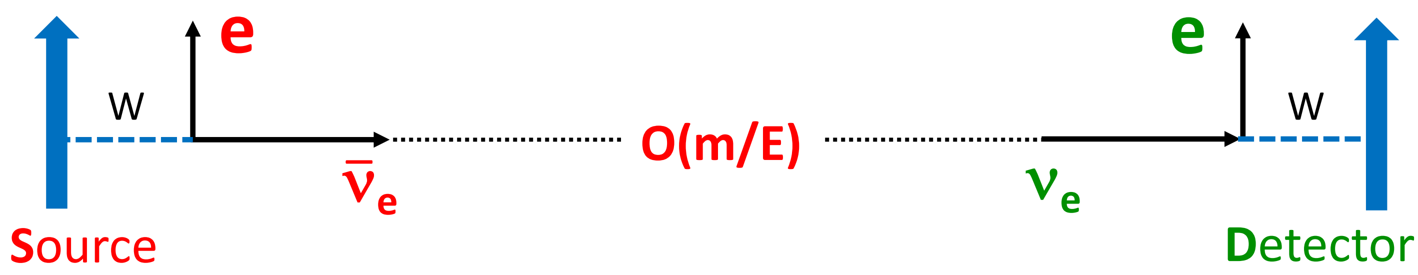

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Does this imply that neutrinos are not Majorana? NO! Still two valid options:

1) ν 's are Dirac: the 2nd reaction is strictly forbidden

2) ν 's are Majorana: the 2nd reaction is allowed… but suppressed by *$m/E<10^{-7}$*!

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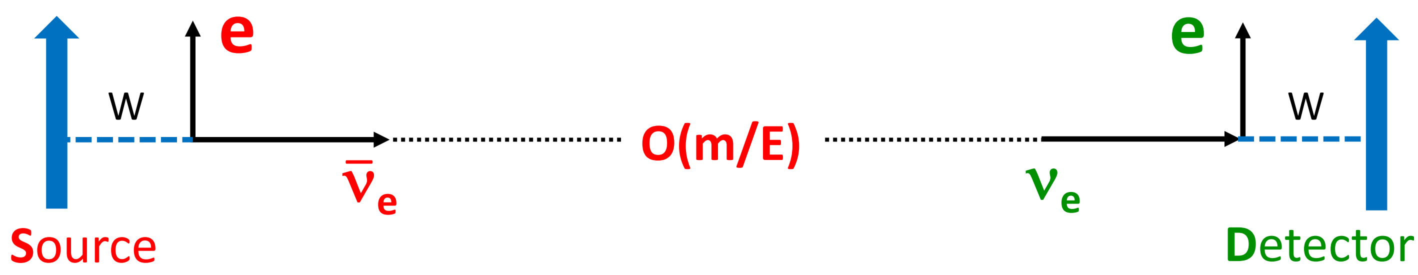

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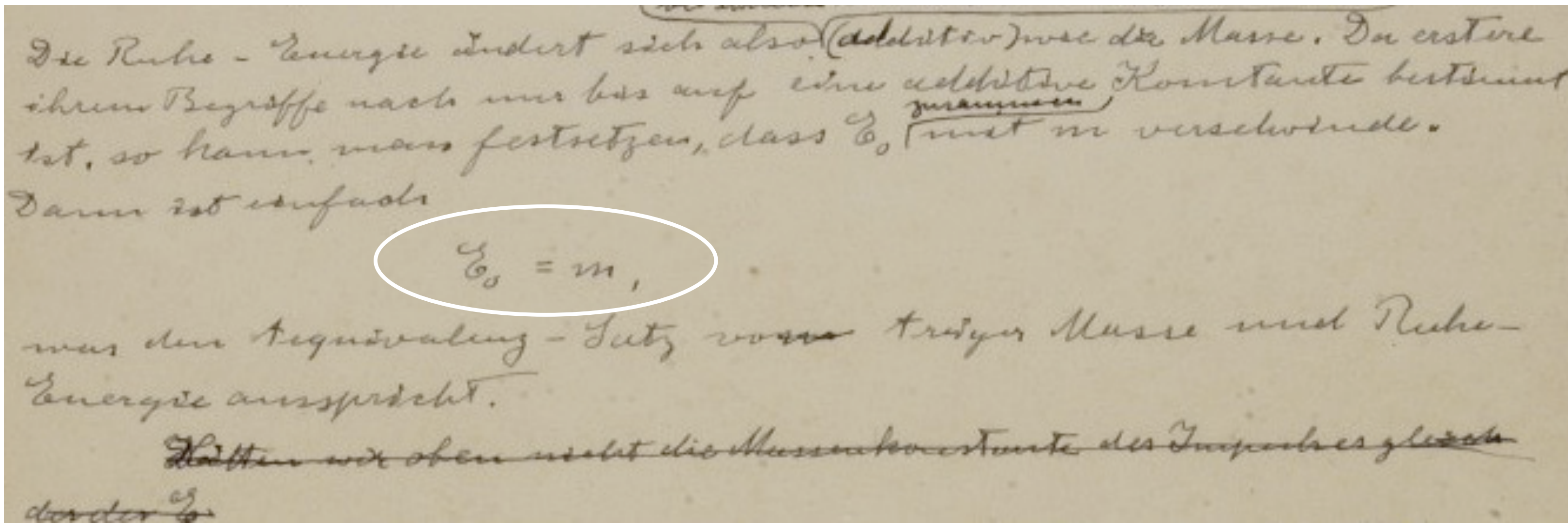
Lesson: to search for Majorana ν, better compare O(1) event to ~0 than to 10^N !

Neutrino flavor oscillations

Proof that ν are massive: not found (yet) via chirality flips but via **flavor change,** involving macroscopic distances x=L and observable when $O(m^2L/E) \sim O(1)$:

Let's start from a celebrated equation, already handwritten in natural units:


Die Ruhe-Energie ändert sich also (additiv) wie die Masse. Da erstere ihrem Begriffe nach nur bis auf eine additive Konstante bestimmt ist, so kann man festsetzen, dass $\mathcal{E}_0$ mit m zusammen verschwinde. Dann ist einfach

$$\mathcal{E}_0 = m,$$

was den Äquivalenz-Satz von träger Masse und Ruhe-Energie ausspricht.

… namely, for p≠0:

$$E = \sqrt{m^2 + p^2}$$

Expand at small *p/m* or *m/p* →

Our ordinary experience takes place in the limit: $p \ll m$

$$E \simeq m + \frac{p^2}{2m}$$

mass

kinetic energy

Our ordinary experience takes place in the limit: $p \ll m$

$$E \simeq m + \frac{p^2}{2m}$$

… while ν often experience the opposite limit: $p \gg m$

$$E \simeq p + \frac{m^2}{2p}$$

Energy difference between two neutrinos ν_i e ν_j with mass m_i e m_j in the same beam $(p_i = p_j \simeq E)$:

$$\Delta E \simeq \frac{\Delta m_{ij}^2}{2E}$$

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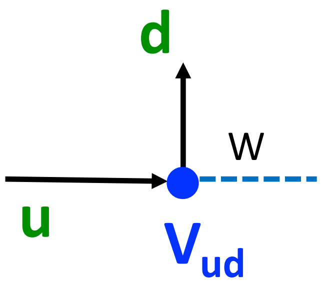
$$\Delta E \simeq \frac{\Delta m^2_{ij}}{2E}$$

Tiny ΔE → Probed at large (macroscopic) x=L~Δt from uncertainty relation:

$$1 \sim \Delta E \Delta t \simeq \frac{m_i^2 - m_j^2}{2E} L$$

Besides (different) neutrino masses, a second important ingredient of neutrino oscillations is **mixing.** In the Standard Model, **mixing matrices** arise in CC interaction vertices involving massive fermions:

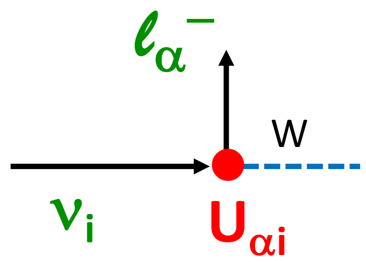
Quarks:



● = CC strength
∝ V element
with $VV^{\dagger}=1$

CKM = Cabibbo-Kobayashi-Maskawa

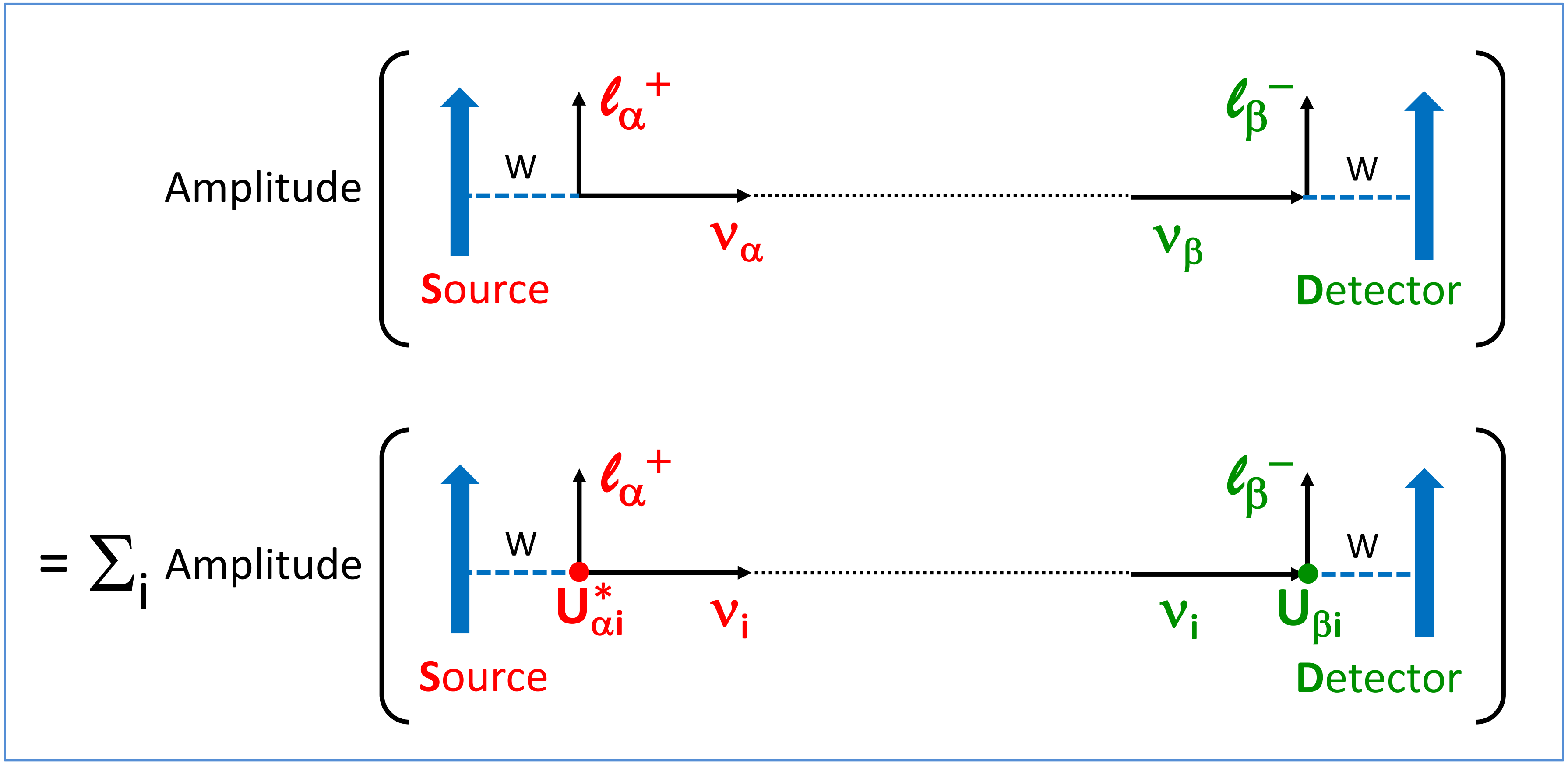
Leptons:



● = CC strength
∝ U element
with $UU^{\dagger}=1$

PMNS = Pontecorvo-Maki-Nakagawa-Sakata

With both ingredients… **flavor may change from α (production) to β (detection)!**



$\nu_\beta = U_{\beta i} \nu_i$

$\nu_i = U^*_{\alpha i} \nu_\alpha$

Oscill. probability = |Amplitude|^2

Note: for $\bar{\nu}$

$\ell_\alpha^\pm \rightarrow \ell_\alpha^\mp$

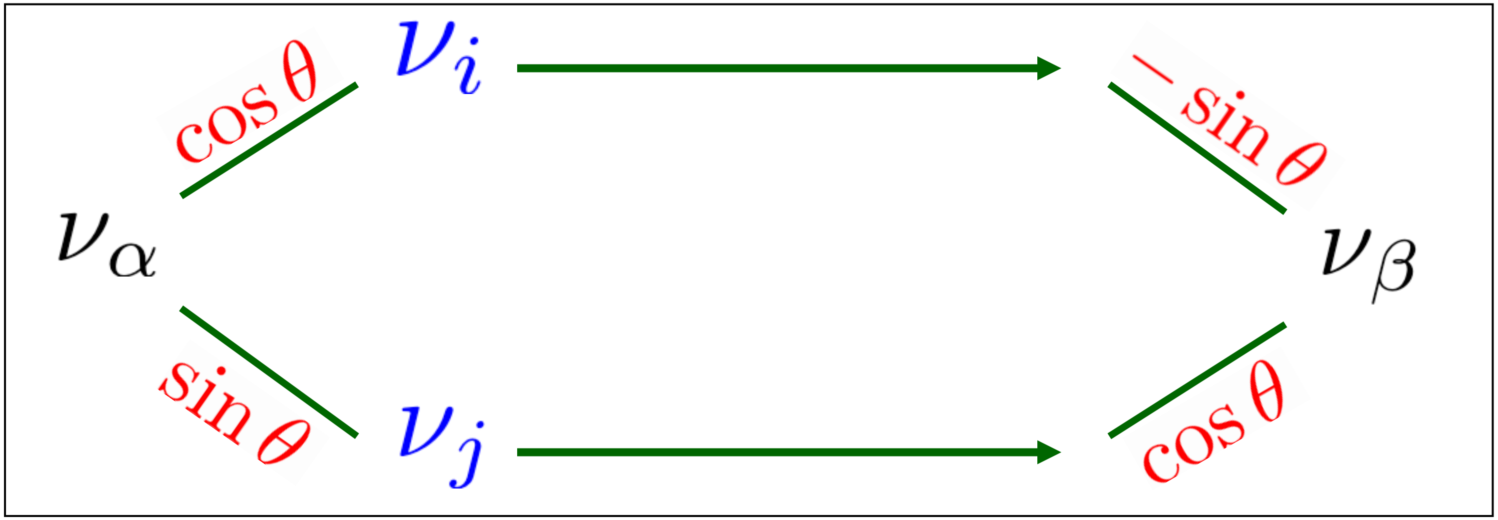
$U \rightarrow U^*$

The simplest oscillations: two neutrinos evolving in vacuum

(flavors α and β, masses m_i and m_j, U = θ-rotation)

$$\begin{bmatrix} \nu_\alpha \\ \nu_\beta \end{bmatrix} = \begin{bmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{bmatrix} \begin{bmatrix} \nu_i \\ \nu_j \end{bmatrix}$$

Analogy with a double-slit interference experiment:

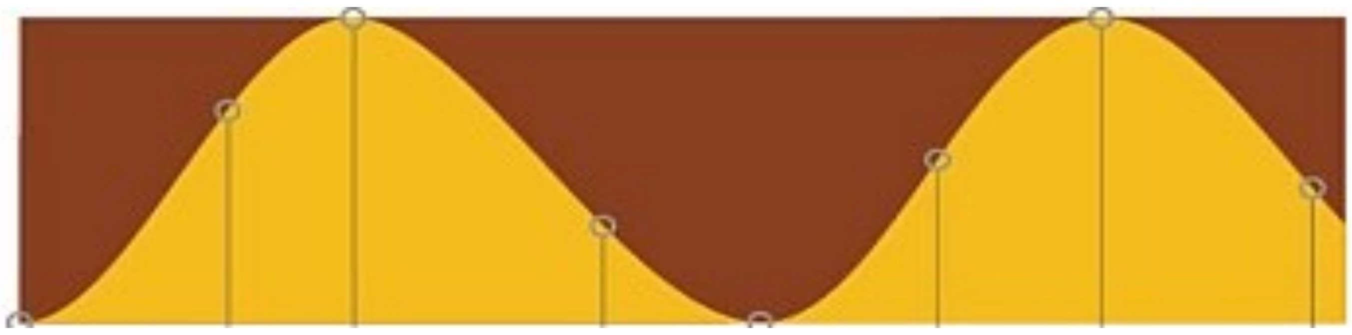


$$\Delta(\text{phase factor}) = e^{-i\Delta E \cdot x} = \exp\left(-i\frac{\Delta m_{ij}^2 x}{2E}\right)$$

Pontecorvo's 2ν oscillation probability:

$$P_{\alpha\beta} = \sin^2(2\theta)\sin^2\left(\frac{\Delta m^2 x}{2E}\right)$$

Mixing angles govern osc. intensity, squared mass differences govern osc. frequency



Intensity → θ

Frequency → Δm^2

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Mixing angles govern osc. intensity, squared mass differences govern osc. frequency

Change from natural units:

$$\frac{\Delta m^2 x}{4E} = 1.267\left(\frac{\Delta m^2}{\mathrm{eV}^2}\right)\left(\frac{x}{\mathrm{m}}\right)\left(\frac{\mathrm{MeV}}{E}\right)$$

In many textbooks: $1.267 \simeq 1.27$, no longer adequate in subpercent precision expts!

Brief recap

If neutrinos are massless: "clock" is frozen, no change in propagation

Flavor does not change.
Handedness does not change.

ν_α → ν_α

If neutrinos are massive, the other handedness develops at $O(m/E) \ll 1$

Iff neutrinos are Majorana:

ν → $\bar{\nu}$

If ν are massive and mixed, other flavors develop at $O(\Delta m^2 L/E)$

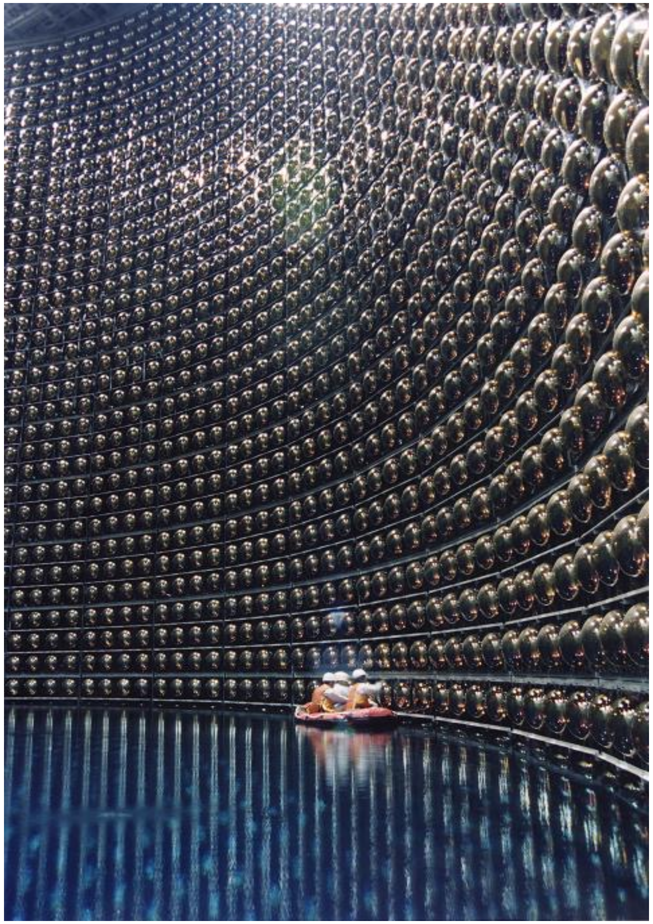
Flavor oscillations / transitions:

ν_α → ν_β

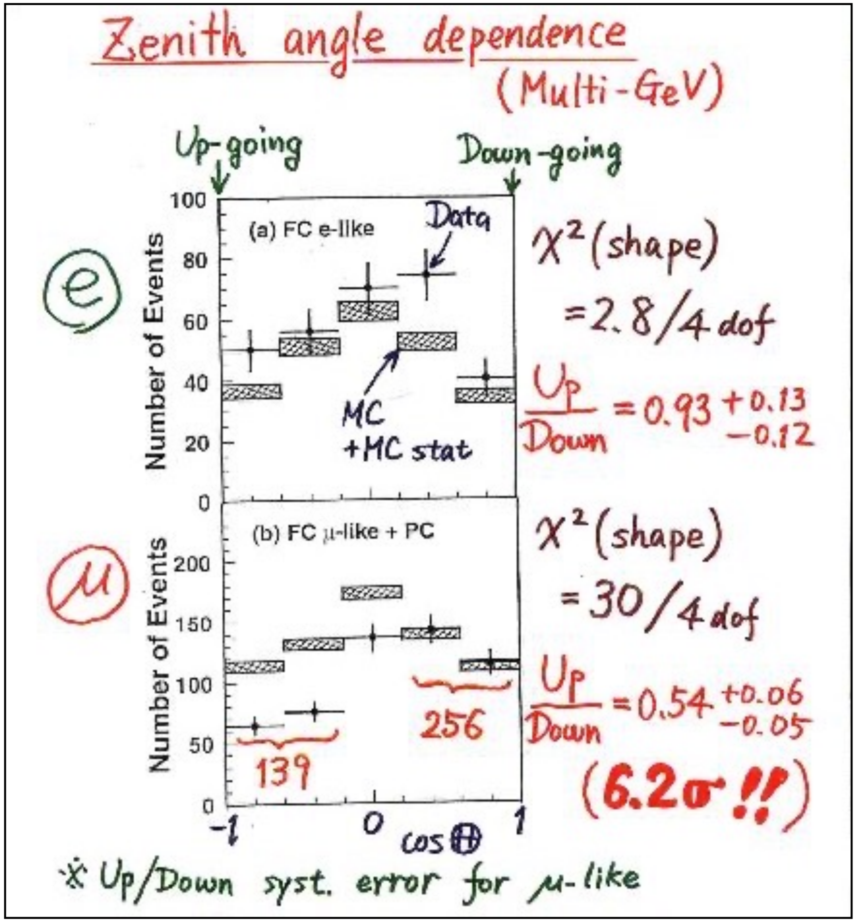
Outline:

- Prologue: ν basic properties
- **(Un)knowns in neutrino oscillations**
- Non-oscillation ν observables
- Learning from neutrinos
- Epilogue: What's in a name?

First evidence of oscillations in 1998 boosted neutrino physics…



Super-Kamiokande

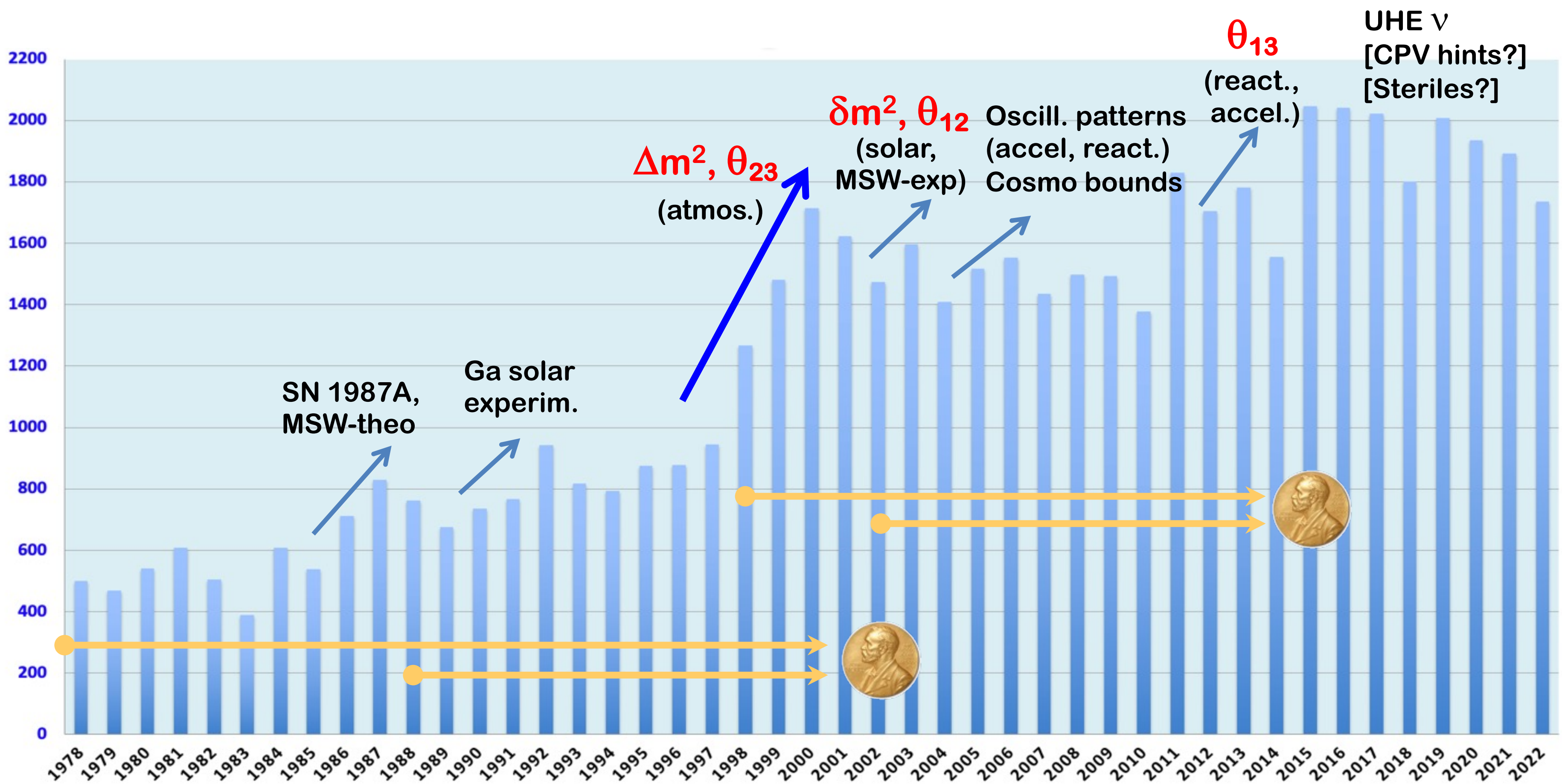


(T. Kajita at Neutrino’98, Takayama)

Also confirmed by the MACRO atmospheric ν expt at LNGS

First evidence of oscillations in 1998 boosted neutrino physics…

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



… and further results established a "standard 3ν framework"

The standard 3ν framework & mass-mixing 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*($\overline{\nu}$)

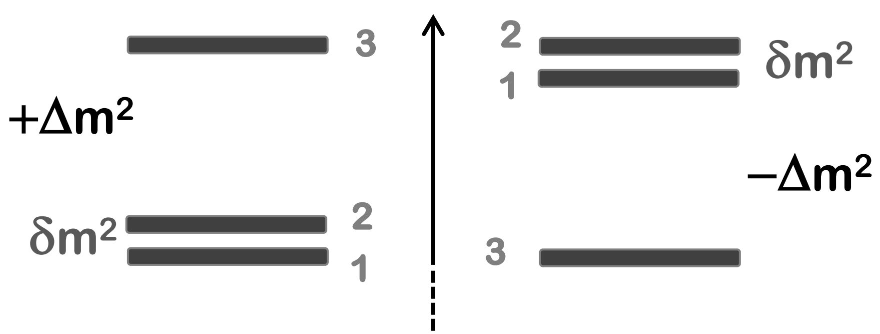
1-2 rotation

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

c=cos, s=sin

Mass [squared] spectrum)

"Normal" Ordering
N.O.



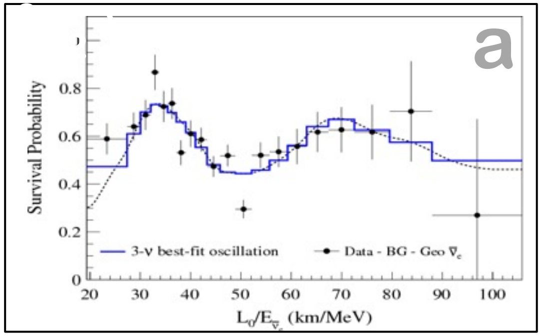
"Inverted" Ordering
I.O.

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

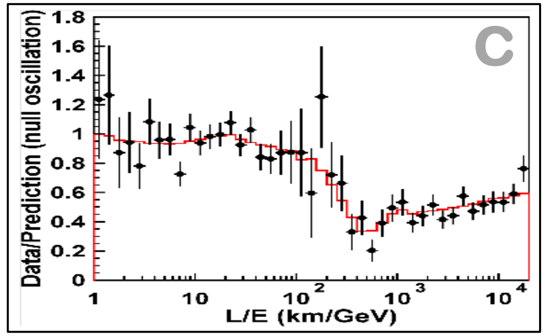
[Absolute ν mass scale not tested in oscillations]

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

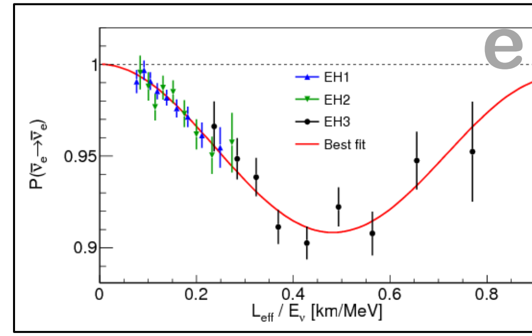
e→e (KamLAND, KL)



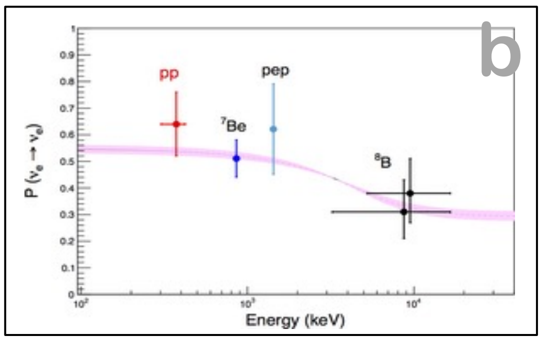
μ→μ (Atmospheric)



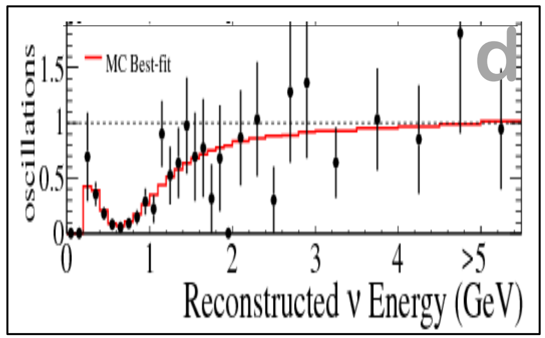
e→e (SBL Reac.)



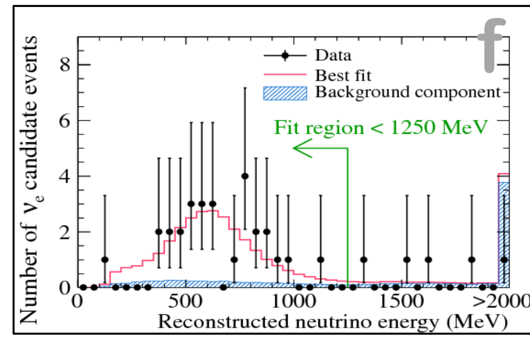
e→e (Solar)



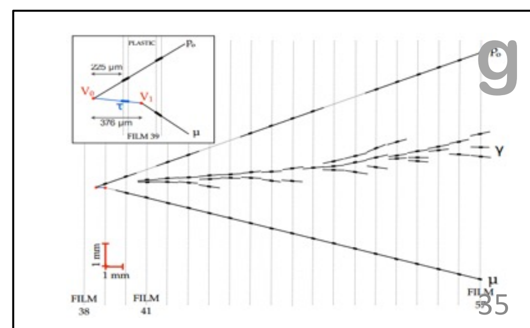
μ→μ (LBL Accel)



μ→e (LBL Accel)



μ→τ (OPERA, SK, DC)

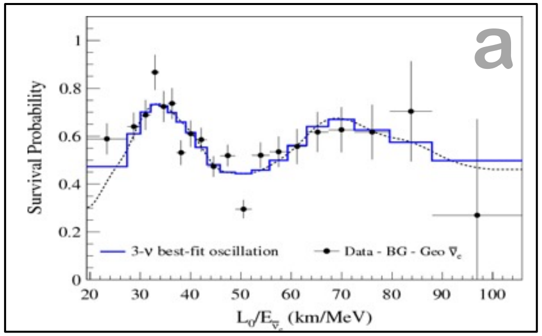


LBL = Long baseline (few x 100 km); **SBL = short baseline** (~1 km)

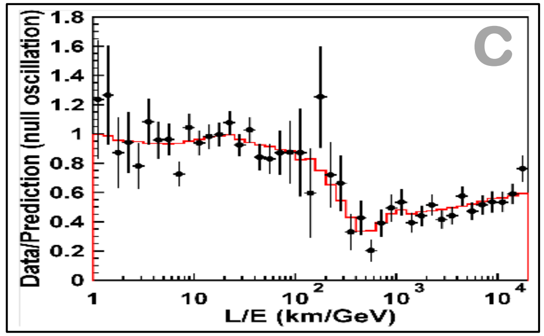
(a) KamLAND reactor [plot]; (b) Borexino [plot], Homestake, Super-K, SAGE, GALLEX/GNO, SNO; (c) Super-K atmosph. [plot], DeepCore, MACRO, MINOS etc.; (d) T2K (plot), NOvA, MINOS, K2K LBL accel.; (e) Daya Bay [plot], RENO, Double Chooz SBL reactor; (f) T2K [plot], MINOS, NOvA LBL accel.; (g) OPERA [plot]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

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

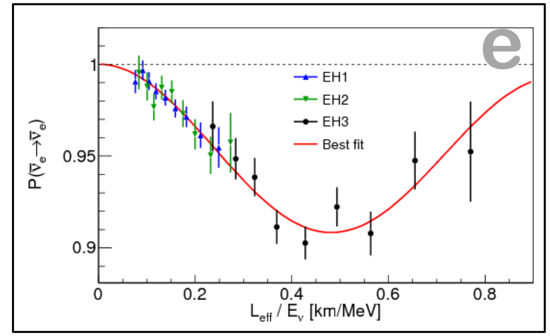
e→e (δm^2 , θ_{12})



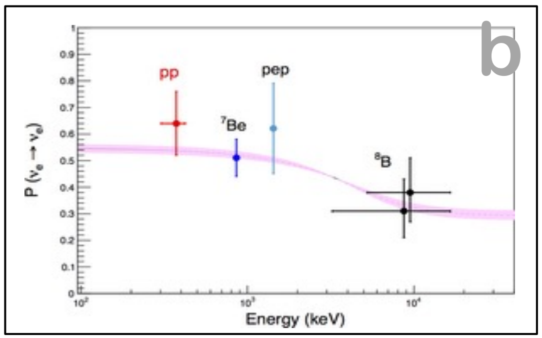
μ→μ (Δm^2 , θ_{23})



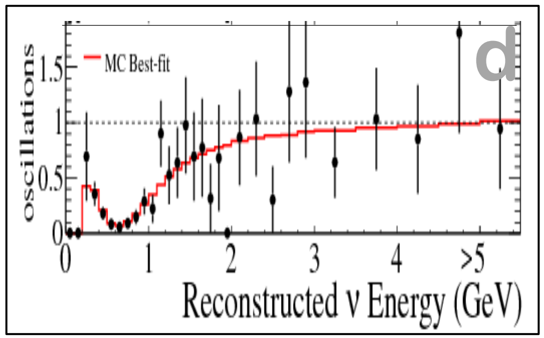
e→e (Δm^2 , θ_{13})



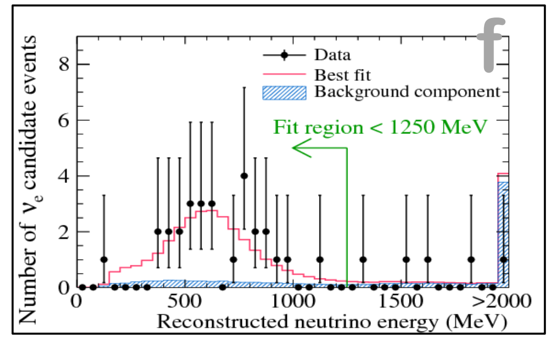
e→e (δm^2 , θ_{12})



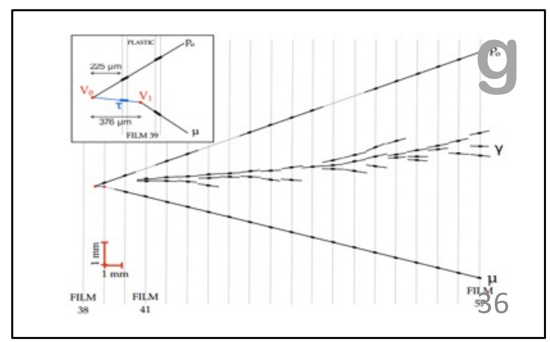
μ→μ (Δm^2 , θ_{23})



μ→e (Δm^2 , θ_{13} , θ_{23})



μ→τ (Δm^2 , θ_{23})



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

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

Sketchy 3ν overview (see pdg.lbl.gov review for details)

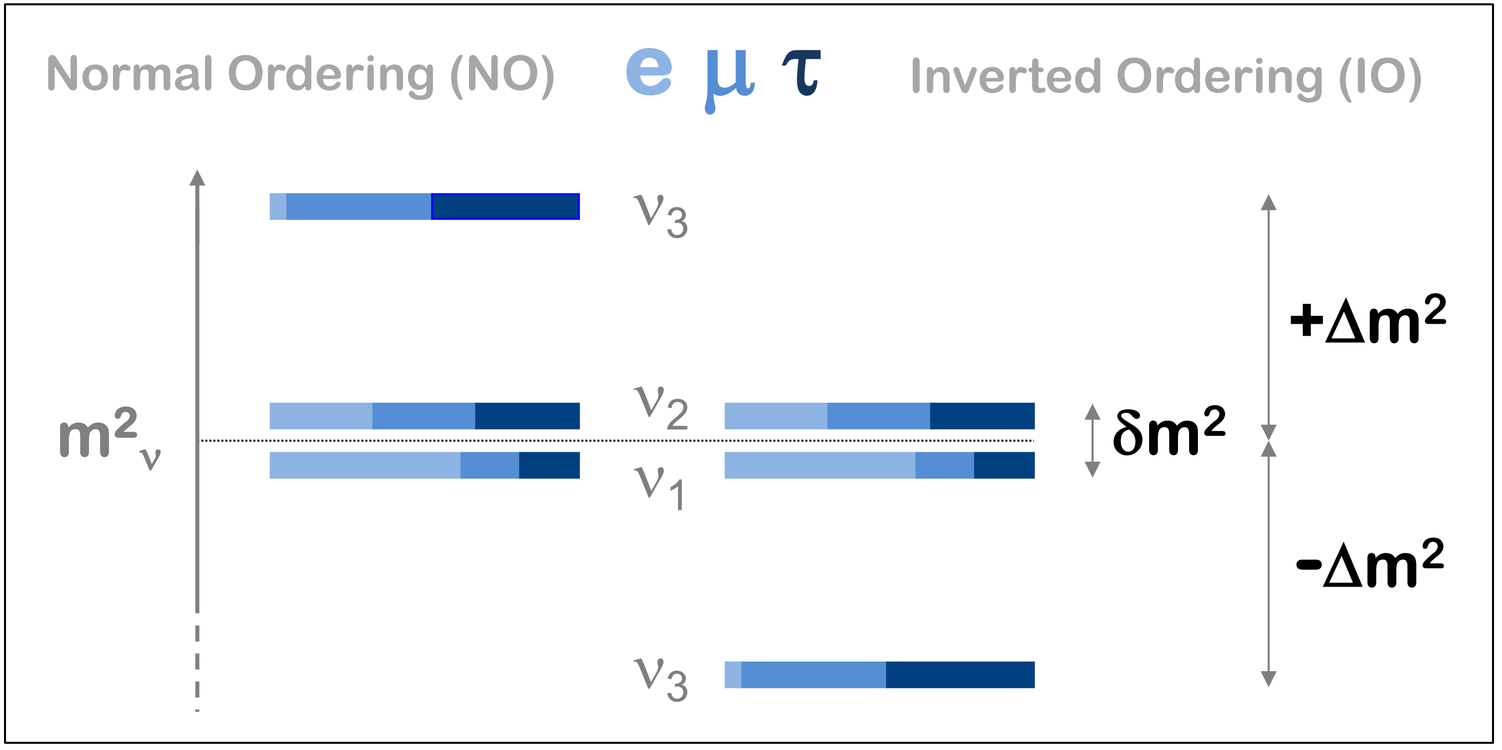
5 knowns:	
δm^2	~ 8 x 10^{-5} eV^2
$\lvert\Delta m^2\rvert$	~ 2 x 10^{-3} eV^2
$\sin^2\theta_{12}$	~ 0.3
$\sin^2\theta_{23}$	~ 0.5
$\sin^2\theta_{13}$	~ 0.02

Oscillations

Non-oscillat.

5 unknowns:

- Oscillations:
  - δ **CPV** Dirac phase
  - **sign(Δm^2)** → NO/IO
  - θ_{23} **octant** (> or < $\pi/4$?)
- Non-oscillat.:
  - **absolute mass** scale
  - **Dirac/Majorana** nature



How do $\nu_\mu \rightarrow \nu_e$ oscillation searches probe CP (T) violation?

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:

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

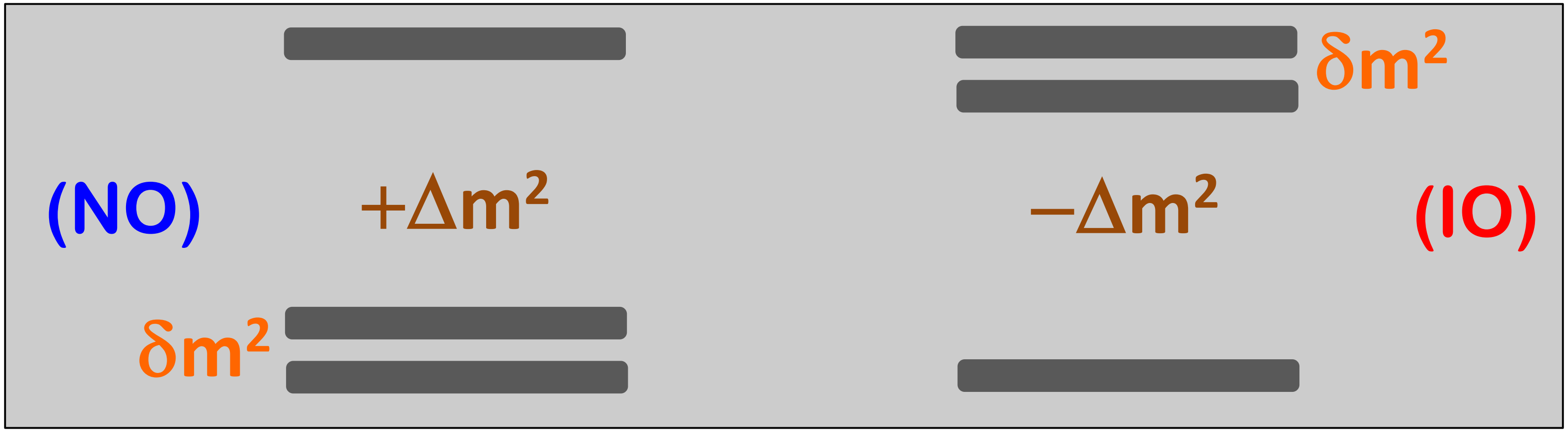
For three neutrinos: possible CPV phase δ, tested via ν versus $\bar{\nu}$

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

Question: $\nu_\mu \rightarrow \nu_e \neq \bar{\nu}_\mu \rightarrow \bar{\nu}_e$?

Currently: hints at ~2σ from T2K (NOvA?)

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 ~ δm^2	medium-baseline reactors in vacuum (JUNO)
Q ~ e^- density	e^- background effects on oscillations (MSW) →
Q ~ ν density	ν background effects at high density (self-interac.)

Currently: global hints for NO at ~2.5σ level

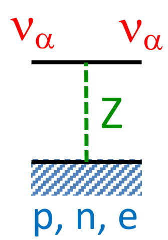
How do ν oscillate in background matter? The MSW effect

(MSW = Mykheev-Smirnov-Wolfenstein)

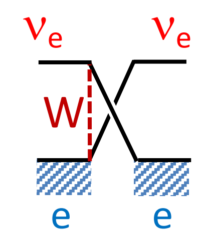
Neutrinos propagating in matter (Earth, Sun, SN…) feel background fermions:
nonzero amplitude that they interact without changing direction

Coherent forward amplitude of $O(G_F)$ - not an absorption process of $O(G_F^2)$!

All ν flavors feel all bkgd fermions via NC…



… but only ν_e feels bkgd electrons via CC…

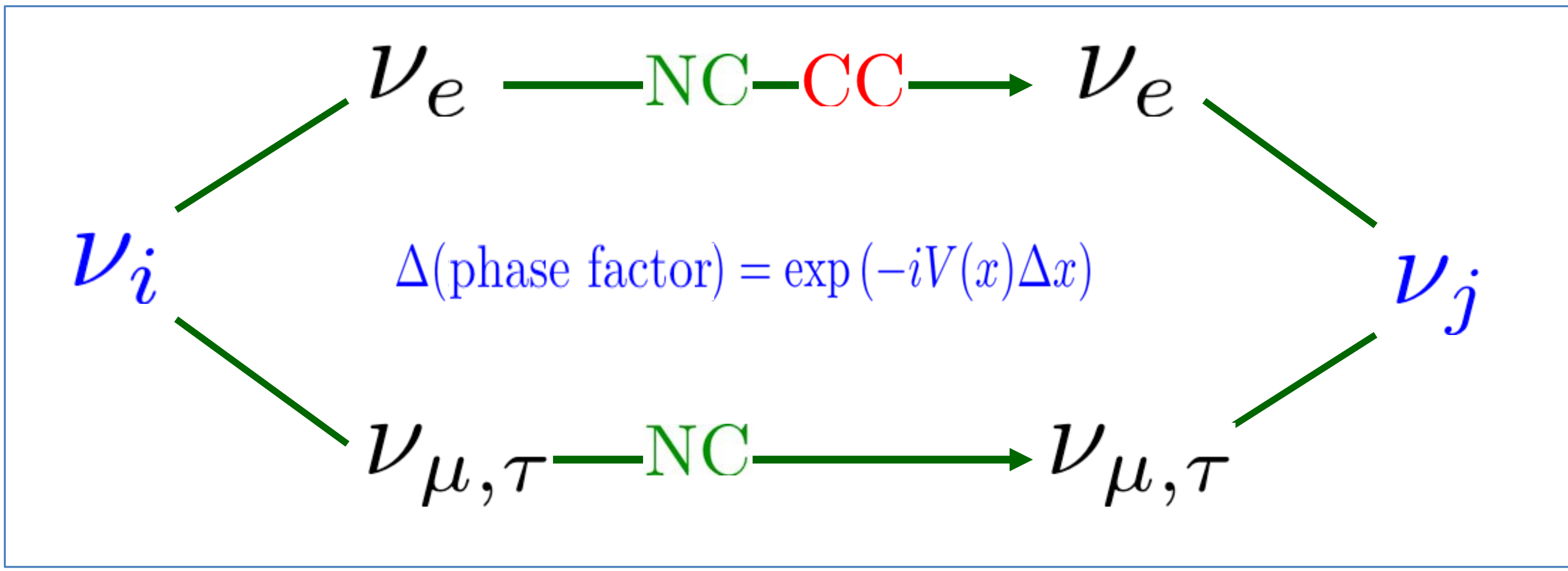


Tiny extra ν_e "interaction energy" or "potential":

$V \propto G_F \cdot E \cdot (e^-$ density)

→ density-dependent change in frequency & intensity

Two-slit analogy: one interferometer arm feels a different refraction index

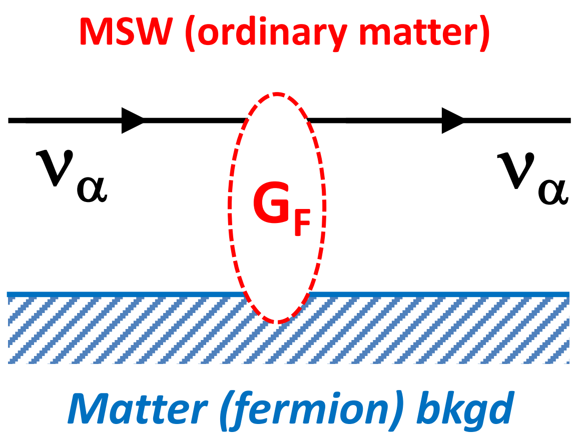


Probability of flavor change may change considerably in matter.

Not necessarily periodic: flavor oscillations → flavor transitions

Seen in solar neutrino experiments as Borexino at LNGS

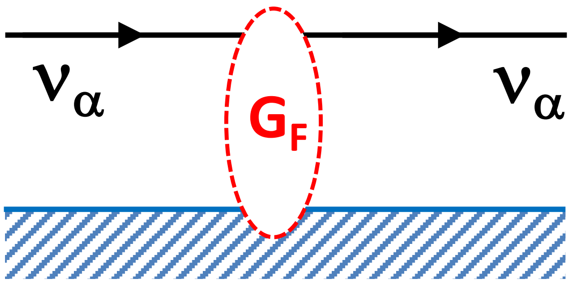
MSW effect: ν's are the beam; (n, p, e) are the background



*Relevant for propagation e.g. in the **Earth**, the **Sun**, Supernovae (**SN**), …*

MSW effect: **ν's are the beam; (n, p, e) are the background**

MSW (ordinary matter)

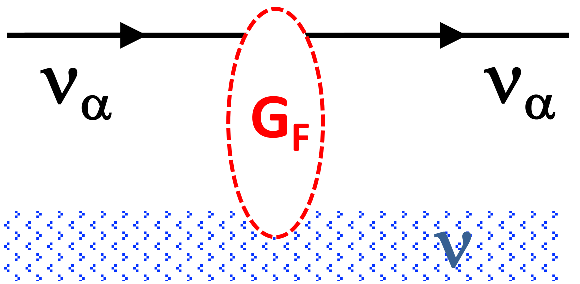


Matter (fermion) bkgd

*Relevant for propagation e.g. in the **Earth**, the **Sun**, Supernovae (**SN**), …*

"Self-interaction" effects: **neutrinos are both the beam and the bkgd!**

Self-interactions (dense ν gas)



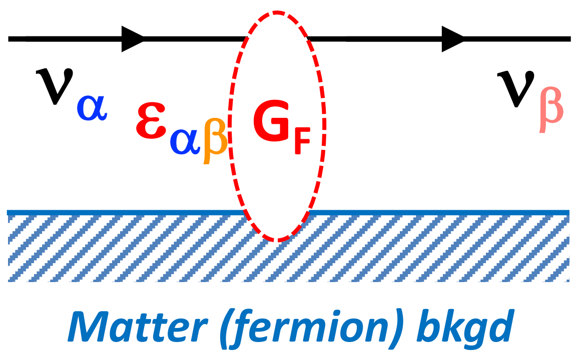
(anti)neutrino bkgd

*Relevant for propagation in very **dense neutrino gas**, e.g. soon after **SN** explosion, compact object mergers…*

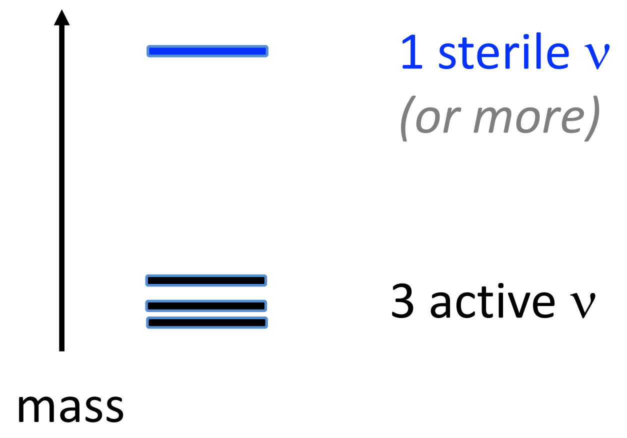
Also called collective effects,
with highly nonlinear evolution.
May be sensitive to NO/IO.
Important but difficult topic!

... Beyond standard oscill.? New interactions? More than 3ν?

Nonstandard interactions (e.g., FCNC)



Mixing with noninteracting (sterile) ν



Possibly suggested by some anomalous (but controversial) results.

In particular, active-sterile oscillations at O(eV) mass scale remain under investigation via muon-electron neutrino flavor oscillations.

Standard 3ν framework: Recap

5 knowns:

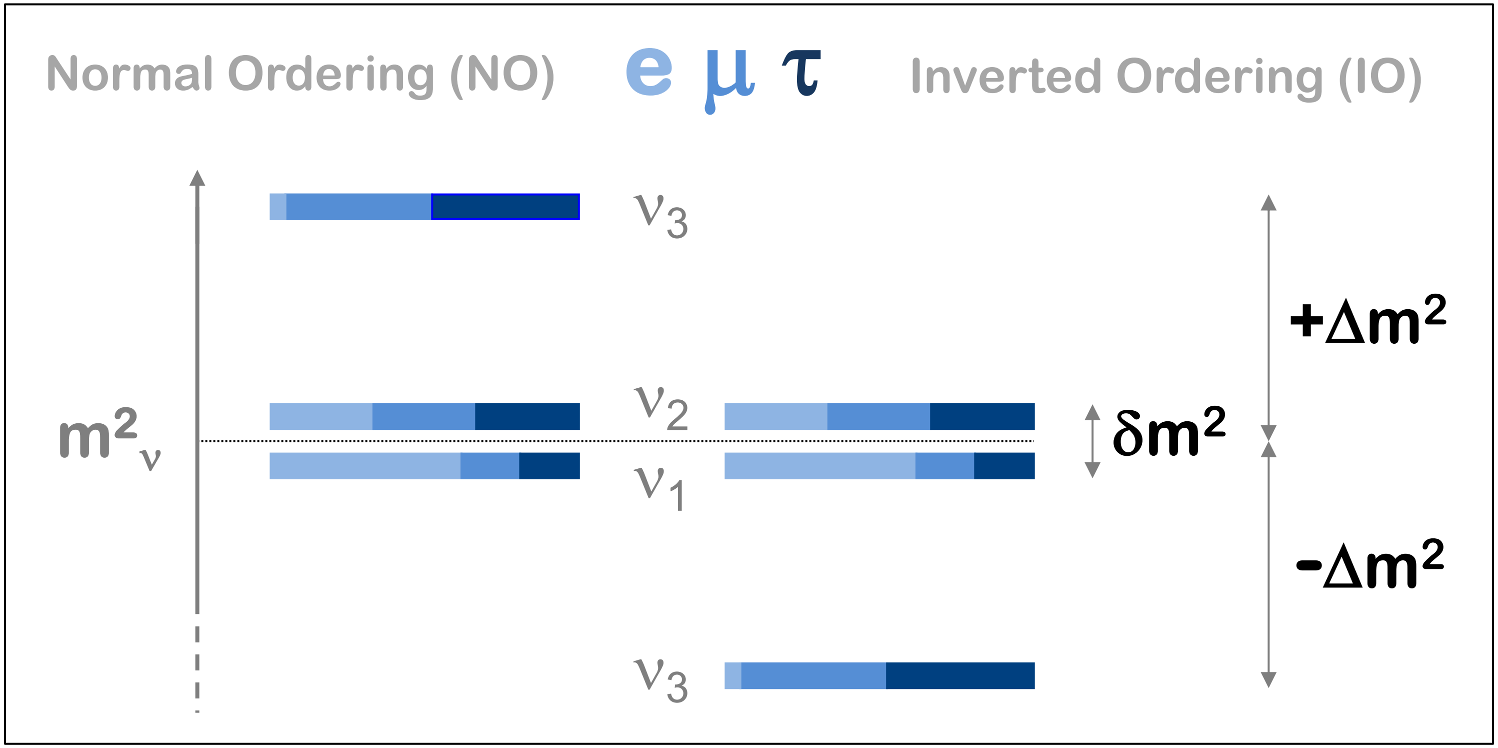
δm^2 ~ 8 x 10^{-5} eV^2
$|\Delta m^2|$ ~ 2 x 10^{-3} eV^2
$\sin^2\theta_{12}$ ~ 0.3
$\sin^2\theta_{23}$ ~ 0.5
$\sin^2\theta_{13}$ ~ 0.02

Oscillations

Non-oscillat.

5 unknowns:

δ **CPV** Dirac phase
sign(Δm^2) → NO/IO
θ_{23} **octant** (> or < π/4 ?)
absolute mass scale
Dirac/Majorana nature



Standard 3ν framework: Recap

5 knowns:			5 unknowns:
$\delta m^2 \sim 8 \times 10^{-5}$ eV^2	Oscillations		δ **CPV** Dirac phase
$\|\Delta m^2\| \sim 2 \times 10^{-3}$ eV^2			**sign(Δm^2)** → NO/IO
$\sin^2\theta_{12} \sim 0.3$			θ_{23} **octant** (> or < π/4 ?)
$\sin^2\theta_{23} \sim 0.5$		*Non-oscillat.*	**absolute mass** scale
$\sin^2\theta_{13} \sim 0.02$			**Dirac/Majorana** nature

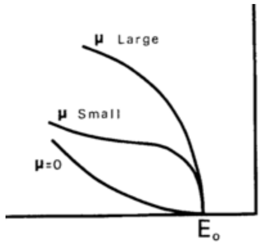
Outline:

- Prologue: ν basic properties
- (Un)knowns in neutrino oscillations
- **Non-oscillation ν observables**
- Learning from neutrinos
- Epilogue: What's in a name?

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

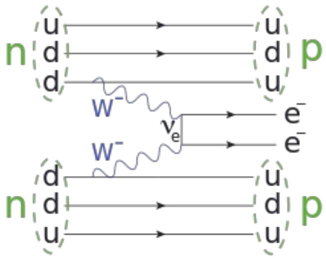
β decay, sensitive to the "effective electron neutrino mass":

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



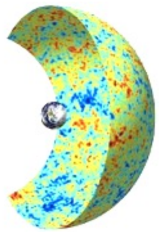
0νββ decay: only if Majorana. "Effective Majorana mass" (+phases):

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



Cosmology: Dominantly sensitive to sum of neutrino masses:

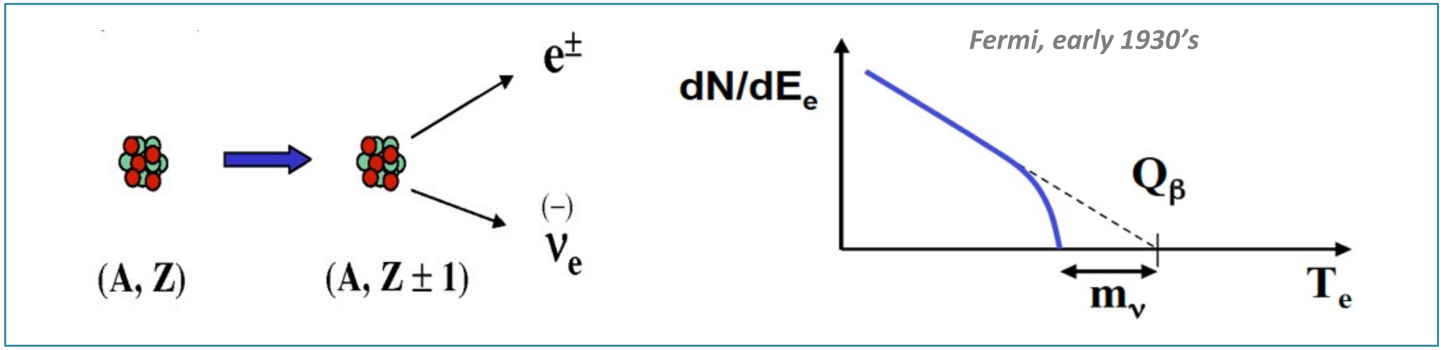
$$\Sigma = m_1 + m_2 + m_3$$



Sensitive to absolute neutrino masses in different ways

May provide additional handles to distinguish NO vs IO

Beta decay: Classic kinematic search for neutrino mass

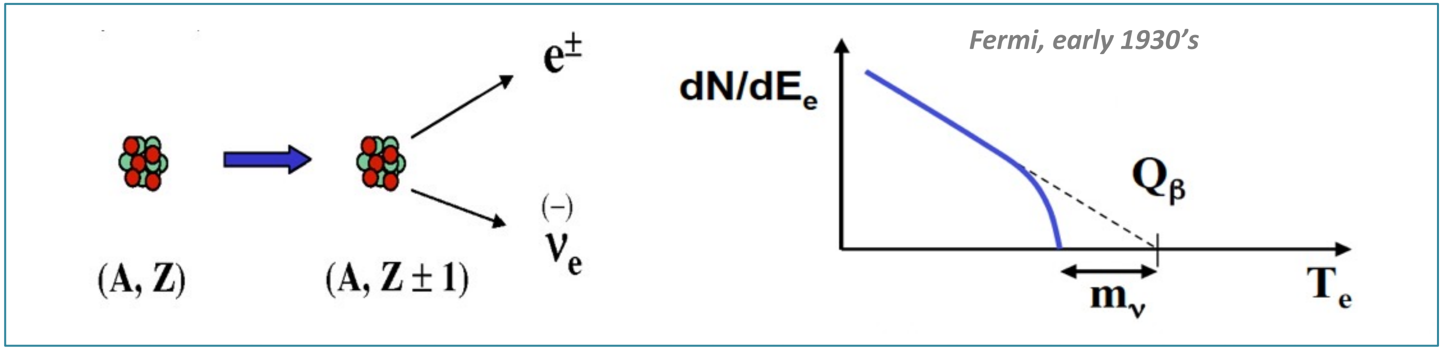


For three families ν_i, and for individual masses m_i experimentally unresolved in beta decay: sensitivity to the sum of $m^2(\nu_i)$, weighted by squared mixings $|U_{ei}|^2$ with the electron neutrino. Observable kink parametrized by:

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

(so-called "effective electron neutrino mass")

Beta decay: Classic kinematic search for neutrino mass



Tritium (^{3}H): low Q and fast decays *(Hanna & Pontecorvo 1949)*

Upper limits on m_β

1949: m_β < 500 eV

2023: m_β < 0.8 eV *KATRIN with O(10^{-4}) g gaseous tritium*

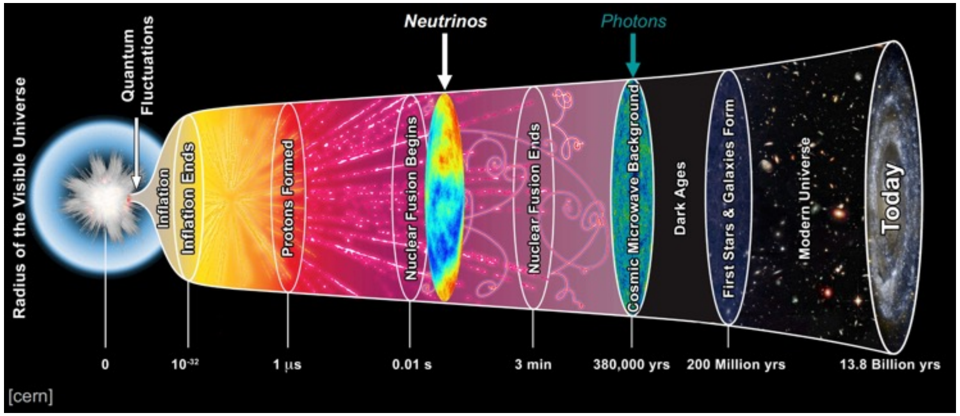
Frontiers:

202X: **m_β < 0.2 eV** *KATRIN final goal*

20XY: m_β ~ O(10^{-2}) eV *Needed to fully explore 3ν expectations…*

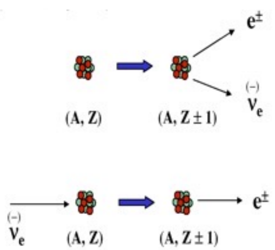
A long-term project aiming at O(10^2) g (!) solid-state Tritium →

P on-
T ecorvo
O bservatory for
L ight,
E arly-universe,
M assive-neutrino
Y ield



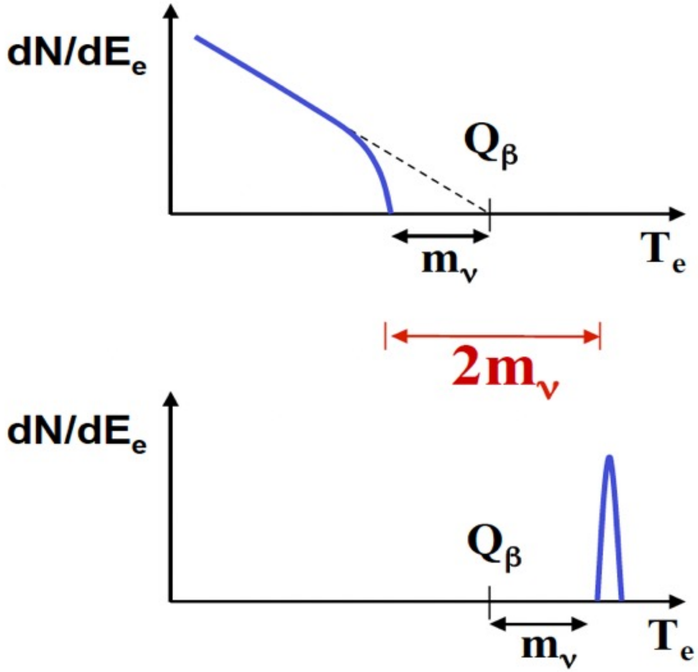
PTOLEMY dream: not just β-decay, but capture big-bang relic ν as "cold" as $T_\nu \sim O(10^{-4})$ eV

Nuclear Beta decay



Neutrino Capture on a Beta Decaying Nucleus

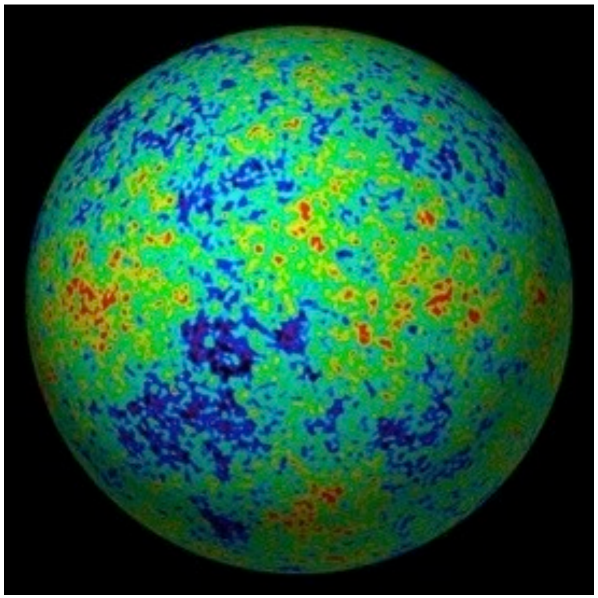
No-threshold reaction!

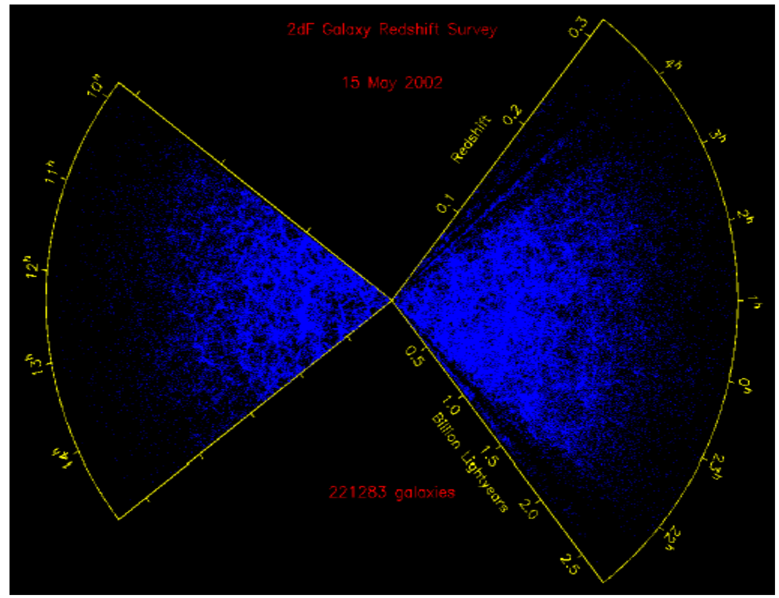


Cosmology: Dynamical effects of ν masses in evolution of the Universe

We can feel relic ν's by their gravit. charge: $\Sigma = m_1 + m_2 + m_3$

Σ slightly affects CMB anisotropies + large scale structures (LSS)





From cosmol. data: Σ < **0.1 - 0.2 eV**

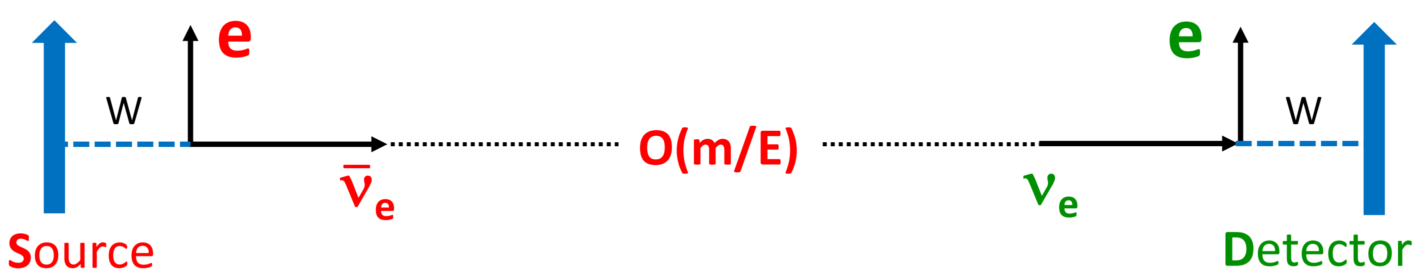
From 3ν oscillations: Σ > 0.06 eV **(NO)**, **>** 0.1 eV **(IO)**

Close to a cosmological discovery of absolute ν mass?

Neutrinoless Double Beta Decay

Reminder:

If neutrinos are Majorana, expect $\bar{\nu} \rightarrow \nu$ transition:



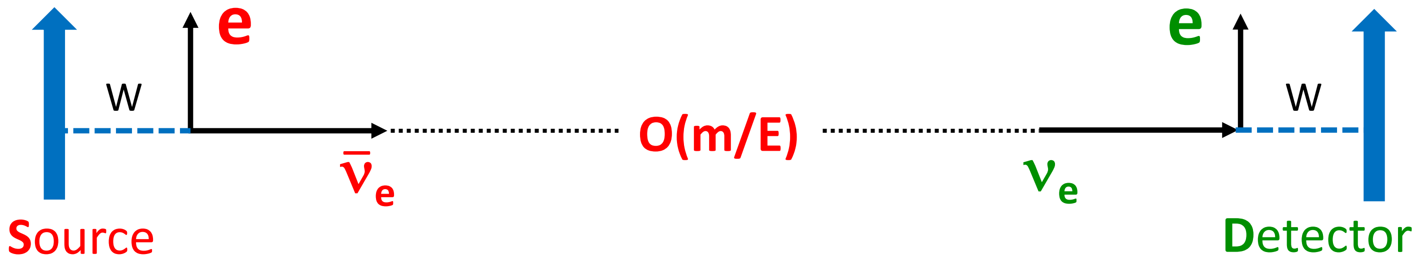
Not found so far, even in the highest-statistics oscill. experiments with 10^7 events

Lesson: to search for Majorana ν, better compare O(1) event to ~0 than to 10^N !

Neutrinoless Double Beta Decay

Reminder:

If neutrinos are Majorana, expect $\bar{\nu} \rightarrow \nu$ transition:

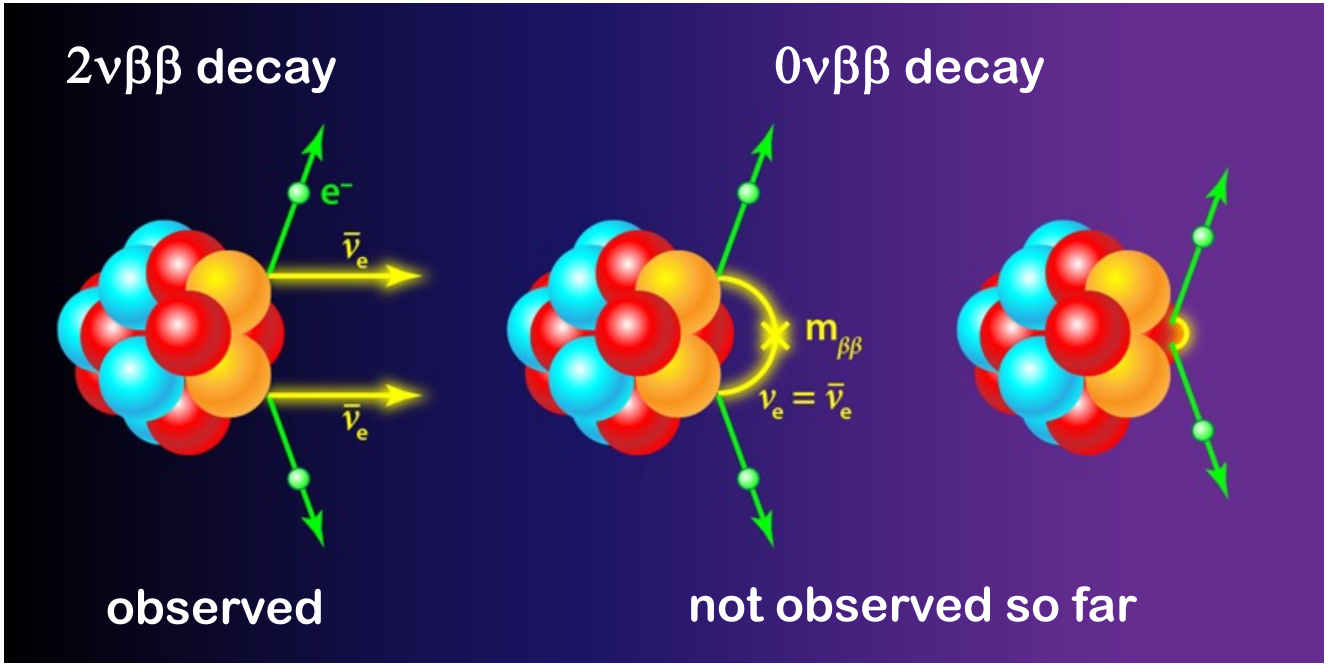


Not found so far, even in the highest-statistics oscill. experiments with 10^7 events

Lesson: to search for Majorana ν, better compare O(1) event to ~0 than to 10^N !

→ Look for rare $\nu \rightarrow \bar{\nu}$ transitions induced by Majorana ν, on top of small or zero bkgd

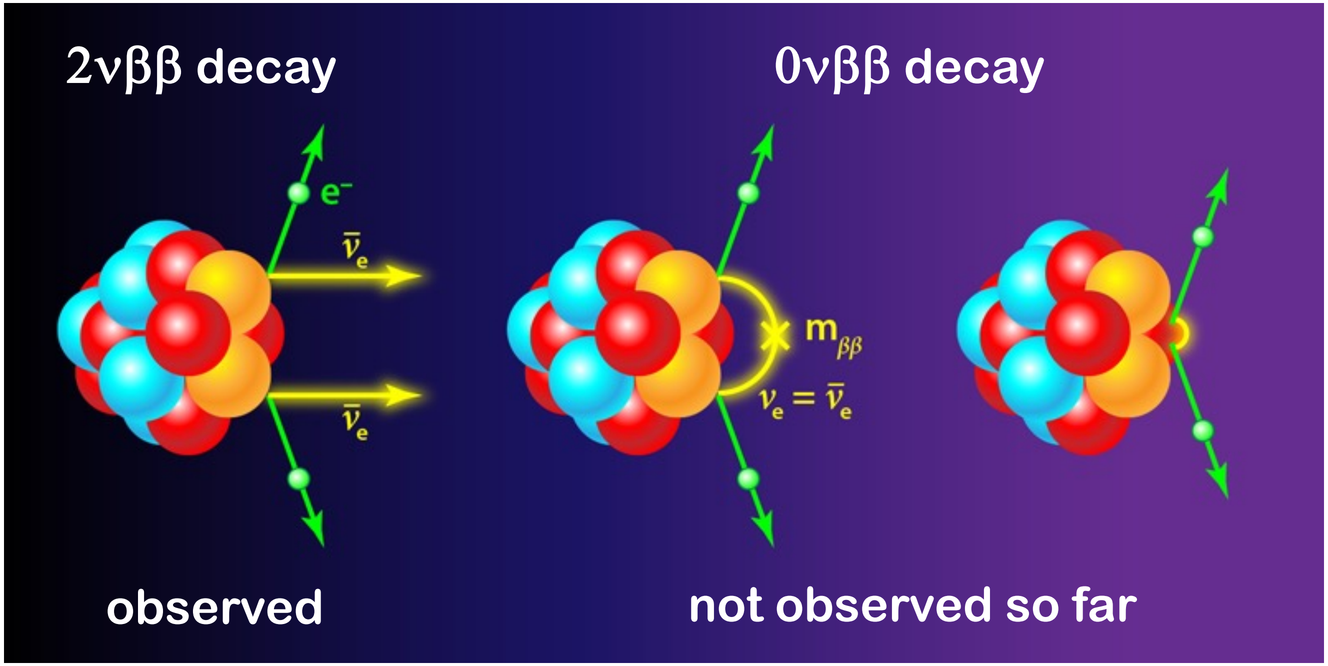
Only known realistic process of this kind:
Neutrinoless double beta decay ($0\nu\beta\beta$)



Very rare: "weak squared" and suppressed by m/E

Possible if and only if neutrinos are Majorana.

Only known realistic process of this kind:
Neutrinoless double beta decay ($0\nu\beta\beta$)



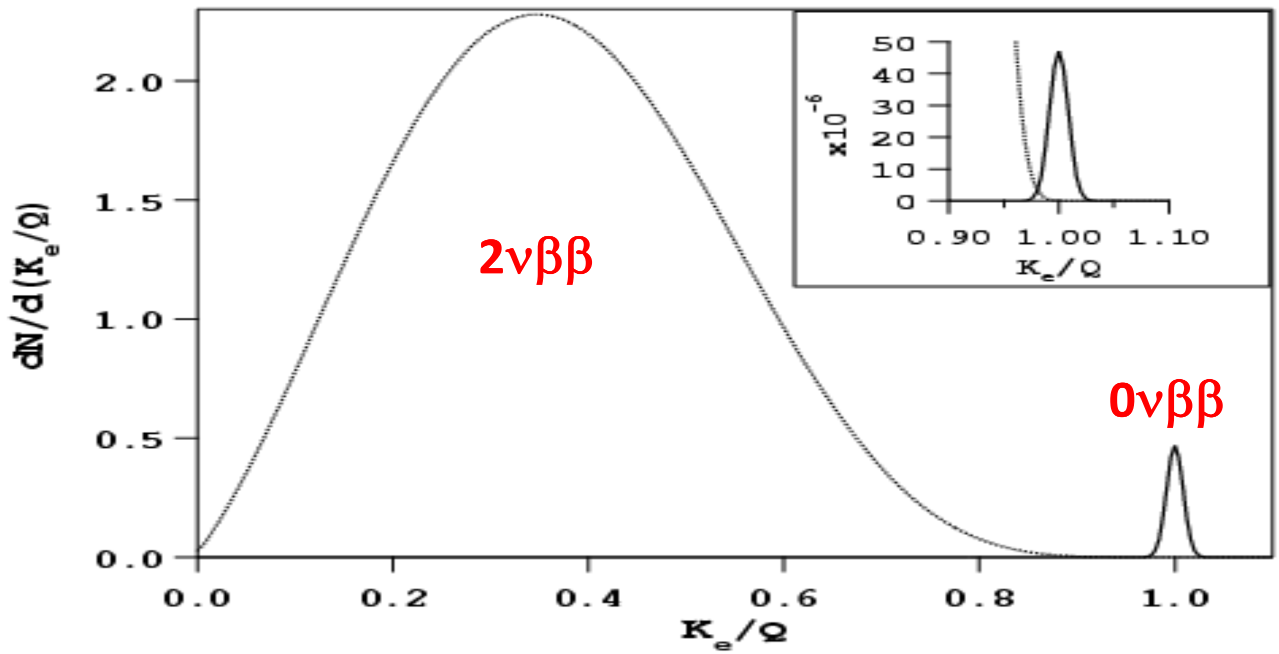
Very rare: "weak squared" and suppressed by m/E

Possible if and only if neutrinos are Majorana.

Discovery of $0\nu\beta\beta$ and Majorana neutrino masses would have profound theoret. implications.
Standard Model (SM): Higgs mechanisms → Dirac fermions. Majorana neutrinos → Beyond SM!
$0\nu\beta\beta$ "creates" charged leptons: theory links with leptogenesis and new (HE) physics scales

Experimentally: Look at sum energy of both electrons

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

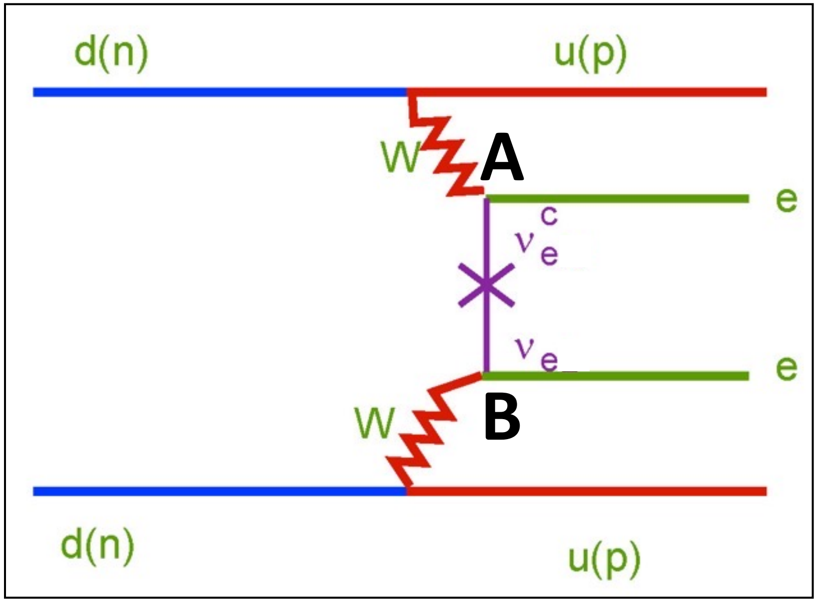


0νββ decay rate ∝ inverse half life (1/T)

Current expt generation probing T ~ O(10^{26}) y.

Ton-scale projects (LEGEND, CUPID, nEXO) aiming at: T ~ O(10^{28}) y

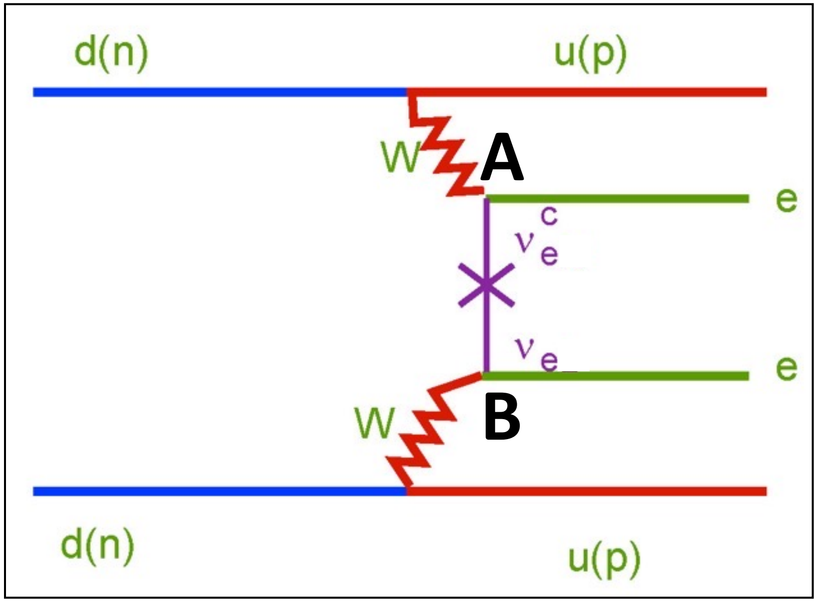
Neutrinoless double beta decay at elementary particle level



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

Neutrinoless double beta decay at elementary particle level



← mixing of ν_e with ν_i

← mass of ν_i [O(m/E)]

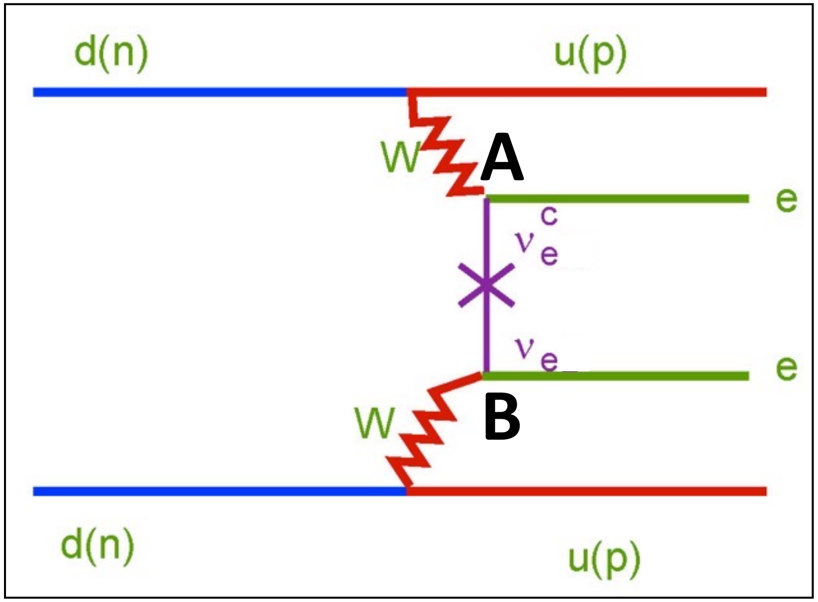
← mixing of ν_i with ν_e

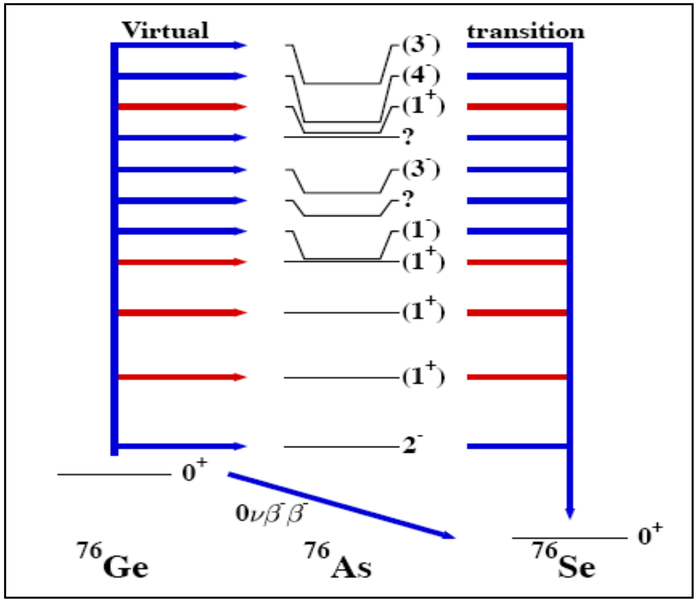
(times an unknown ν_i phase)

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

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

Neutrinoless double beta decay at nuclear level: complicated…



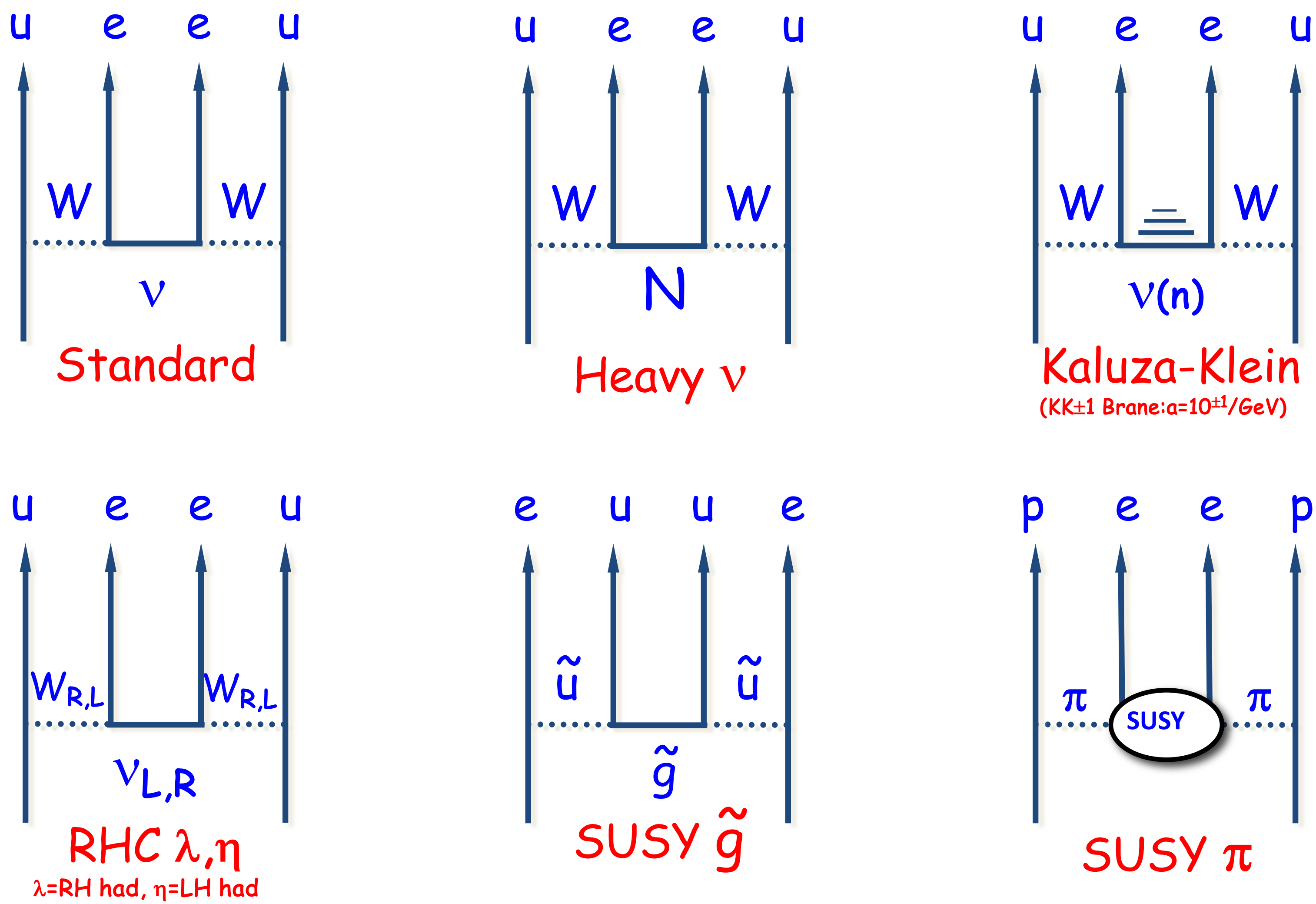


In case of positive decay signal, a major concern is the accuracy of the **nuclear matrix element |M|**, rather than the expt. error on the decay half life:

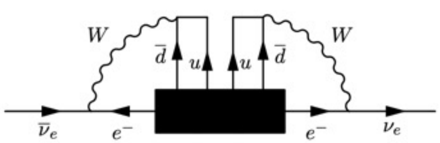
$$T_i^{-1} = G_i \, |M_i'|^2 \, m_{\beta\beta}^2$$

Half-life Phase space Matrix element

Note: 0νββ decays might also be induced by nonstandard physics



In any case, 0νββ decay <u>implies</u> Majorana ν:



Combining 3ν constraints from:

Oscillation data

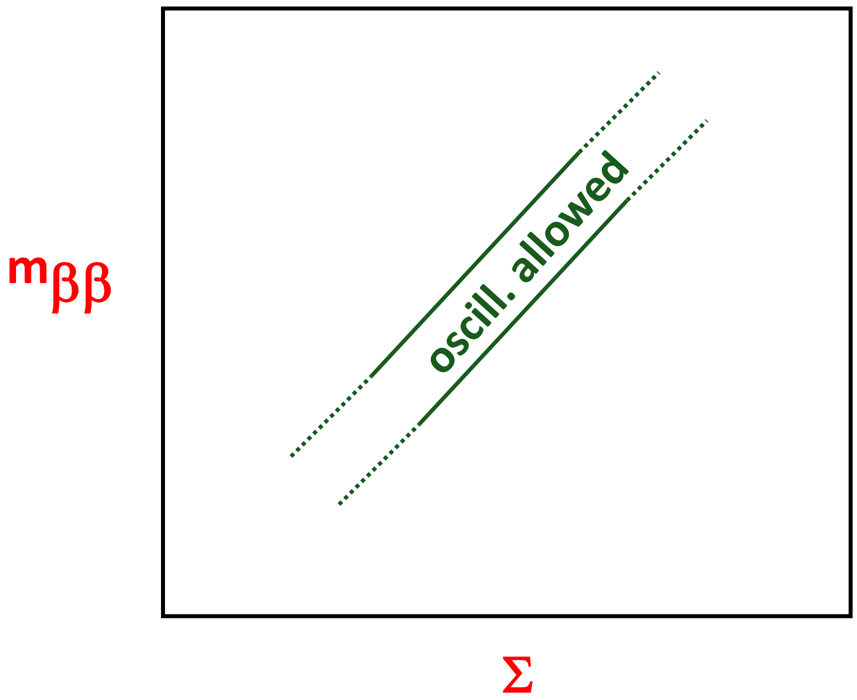
+

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

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

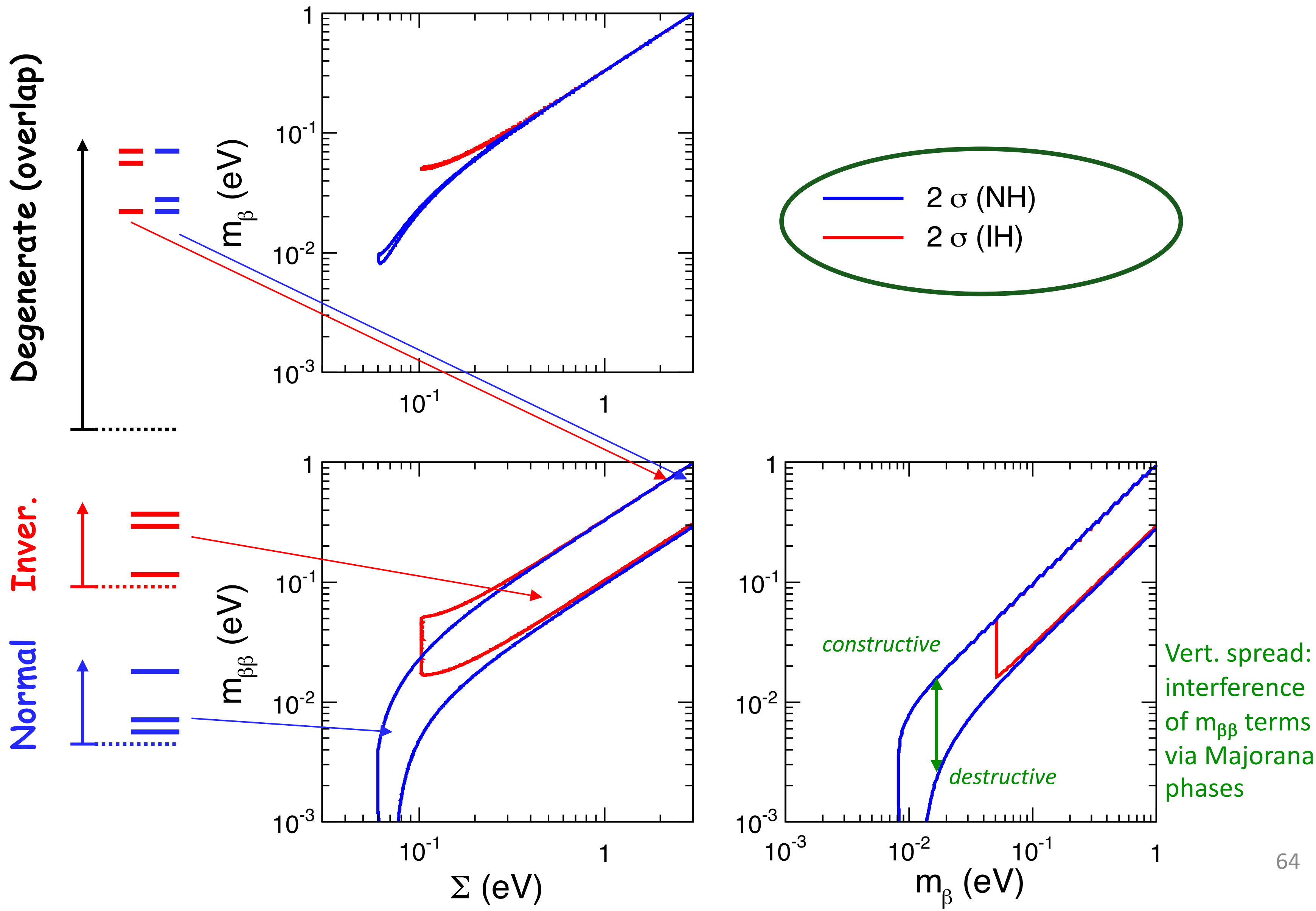
$$\Sigma = m_1 + m_2 + m_3$$

Interplay: **Oscillations** fix the **mass² splittings,** and thus induce **positive correlations** between any pair of the three observables **(m_β, $m_{\beta\beta}$, Σ)**, e.g.:

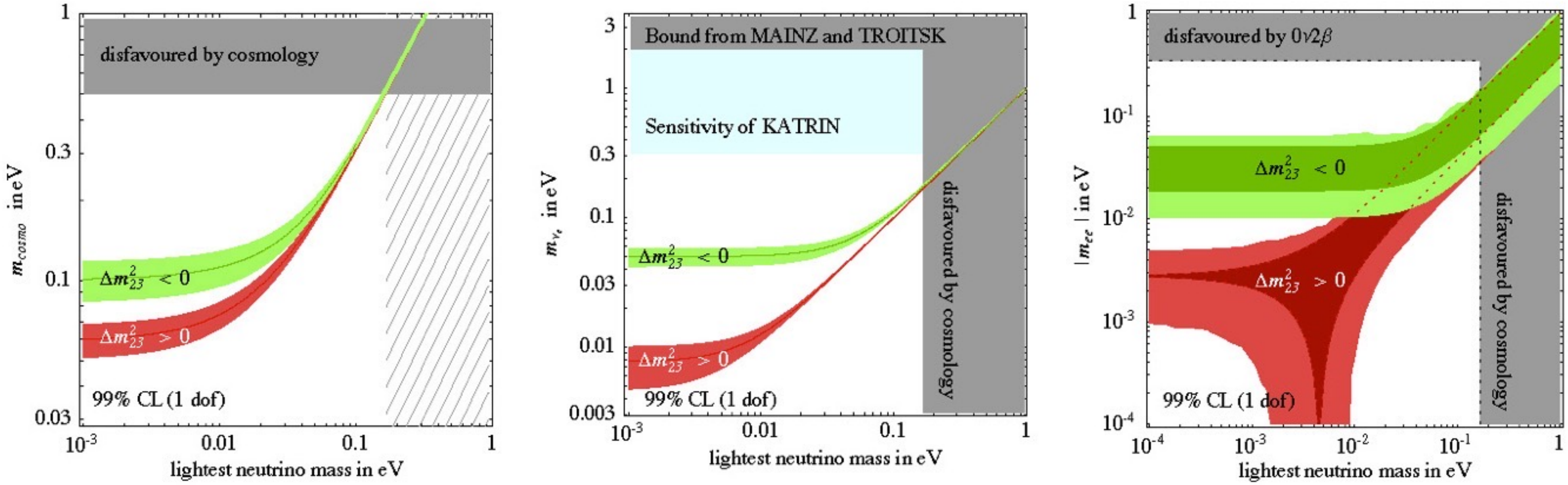


i.e., if one observable increases, the other one (typically) must increase to match mass splitting

Oscillation data constrain the $(m_\beta, m_{\beta\beta}, \Sigma)$ parameters within two bands:

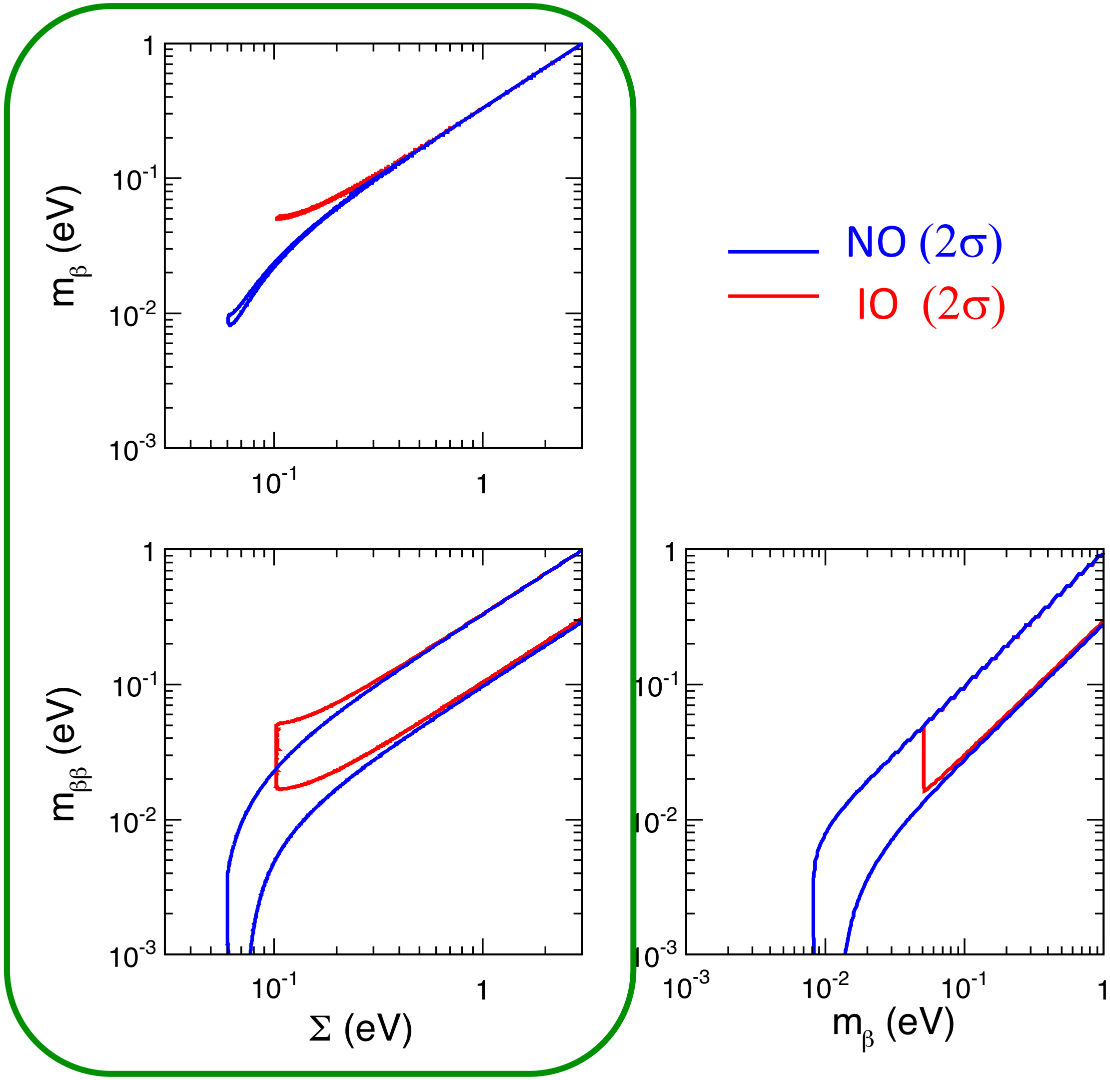


Previous plots project away the "unobservable" lightest neutrino mass from popular graphs like:



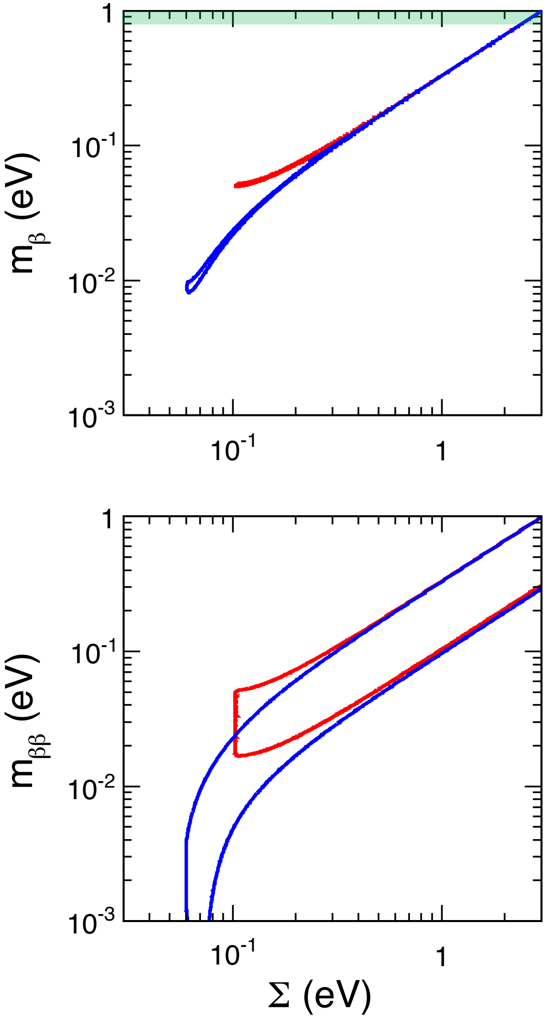
Taken from Strumia and Vissani, 2006

Absolute mass observables: currently, only upper bounds…



Focus on these planes

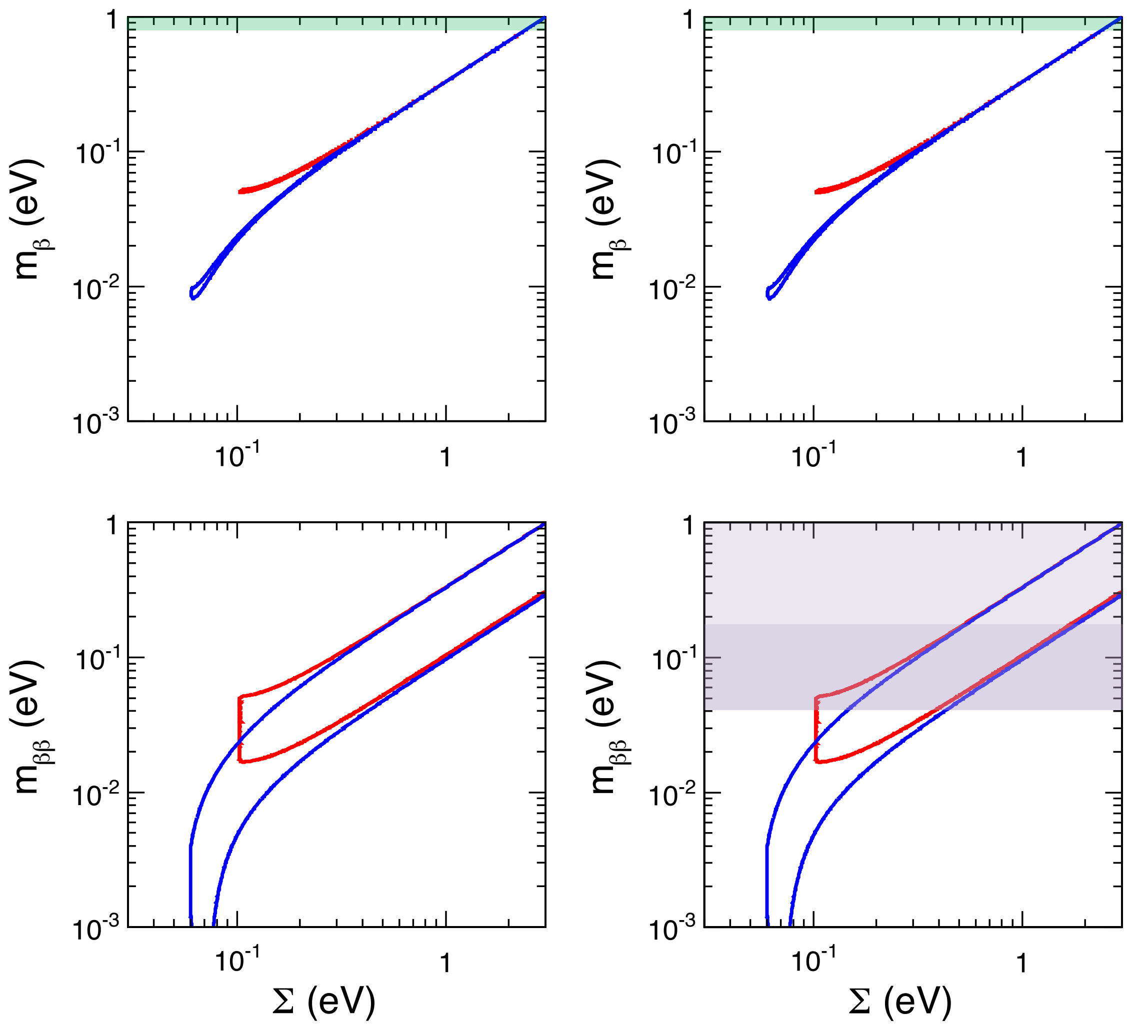
β : KATRIN



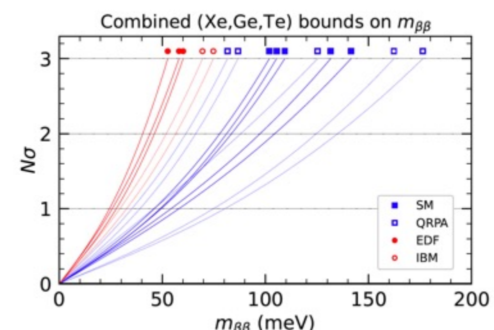
β : KATRIN

$0\nu\beta\beta$: 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



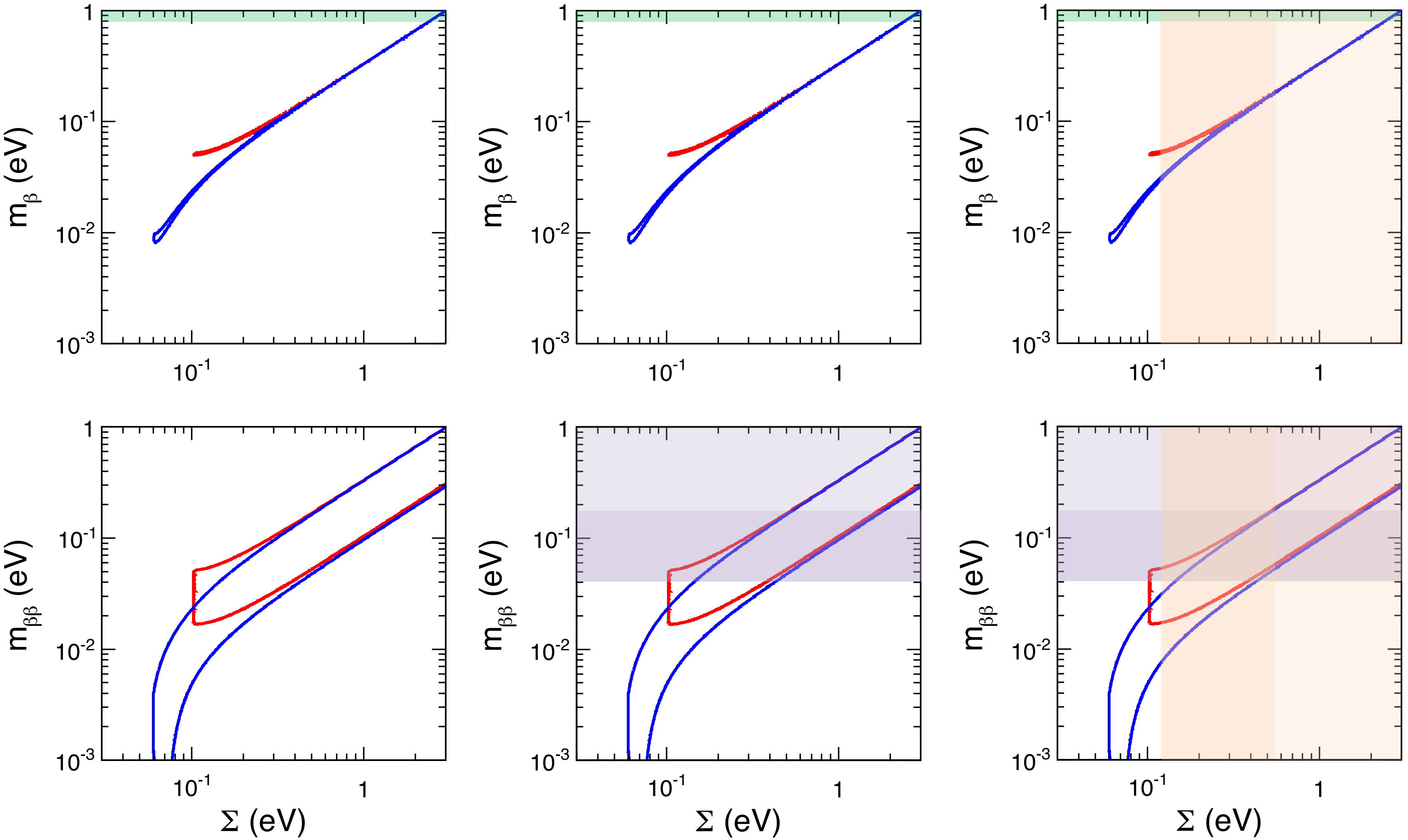
β : KATRIN

0νββ: KL-Zen, Exo, GERDA, Cuore...

[spread: nuclear models]

Σ: Planck, BAO, lensing ...

[spread: cosmo models/data]



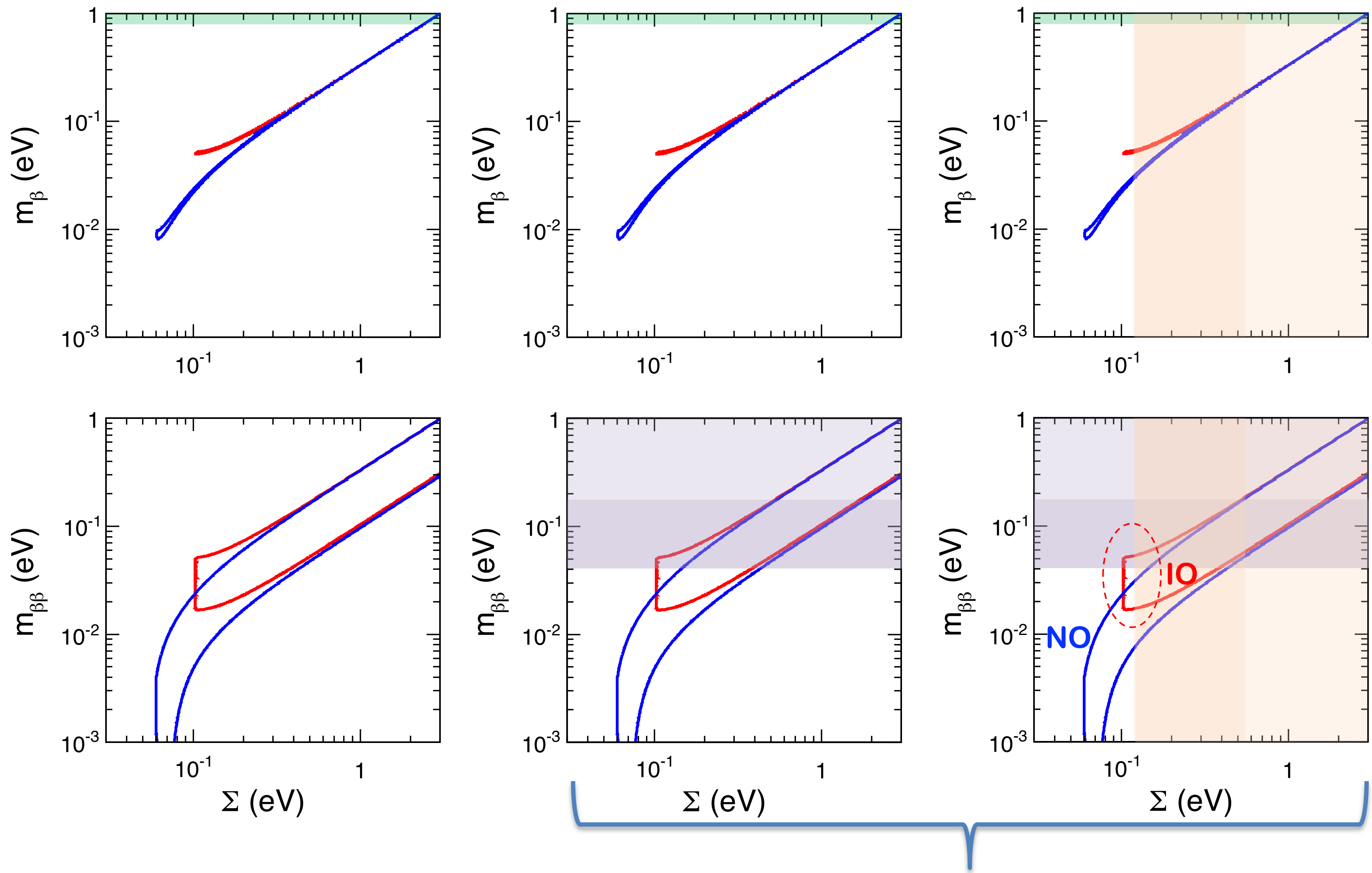
β : KATRIN

0νββ: KL-Zen, Exo, GERDA, Cuore...

[spread: nuclear models]

Σ: Planck, BAO, lensing ...

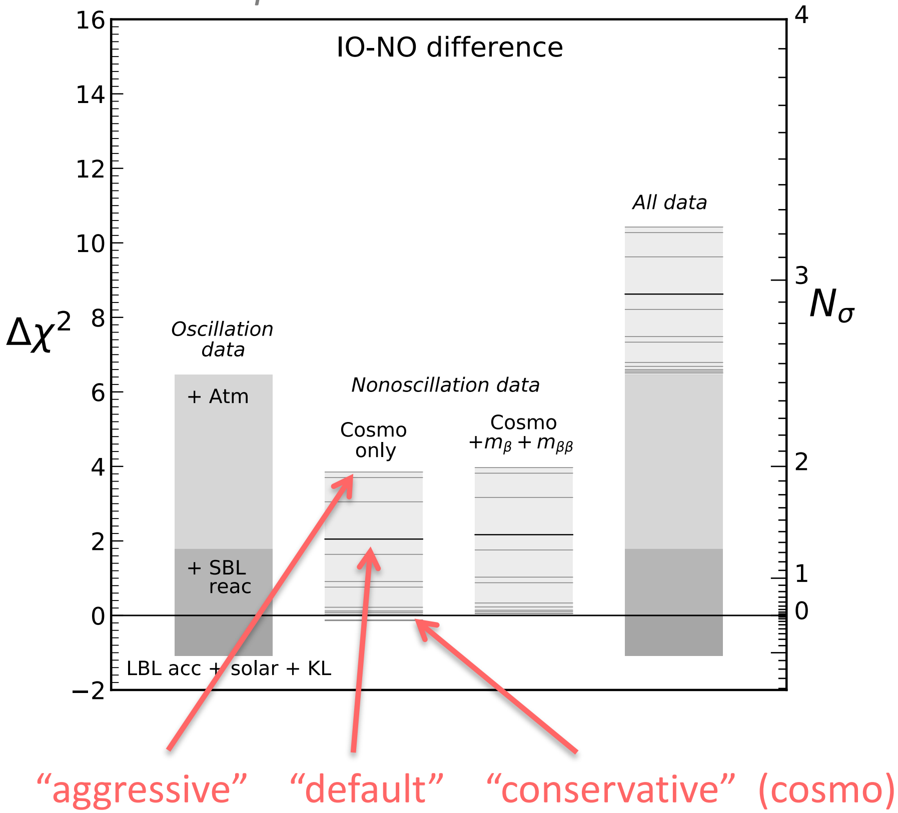
[spread: cosmo models/data]

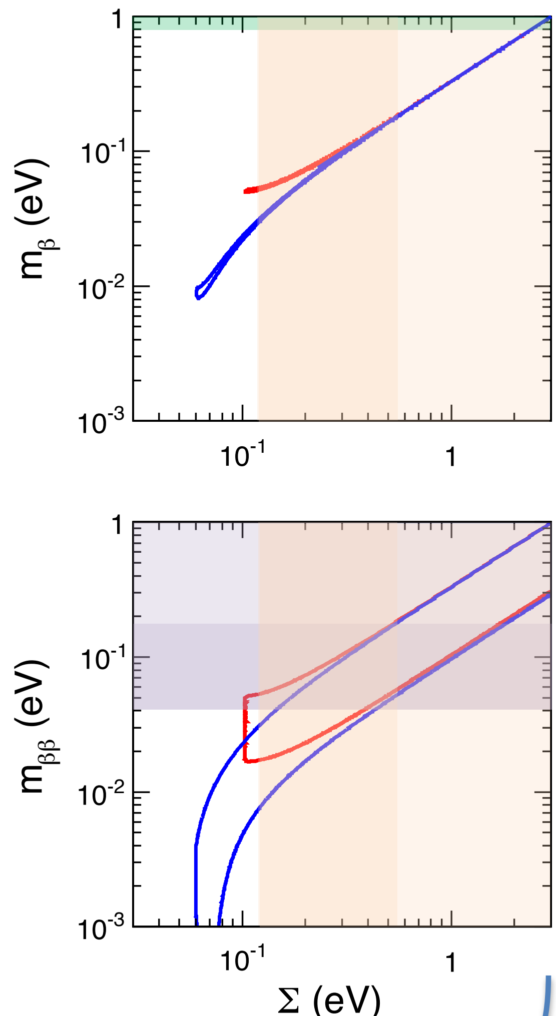


IO "under pressure" but not excluded yet

0νββ expts need to probe IO fully (+ part of NO)

From Capozzi+ 2107.00532



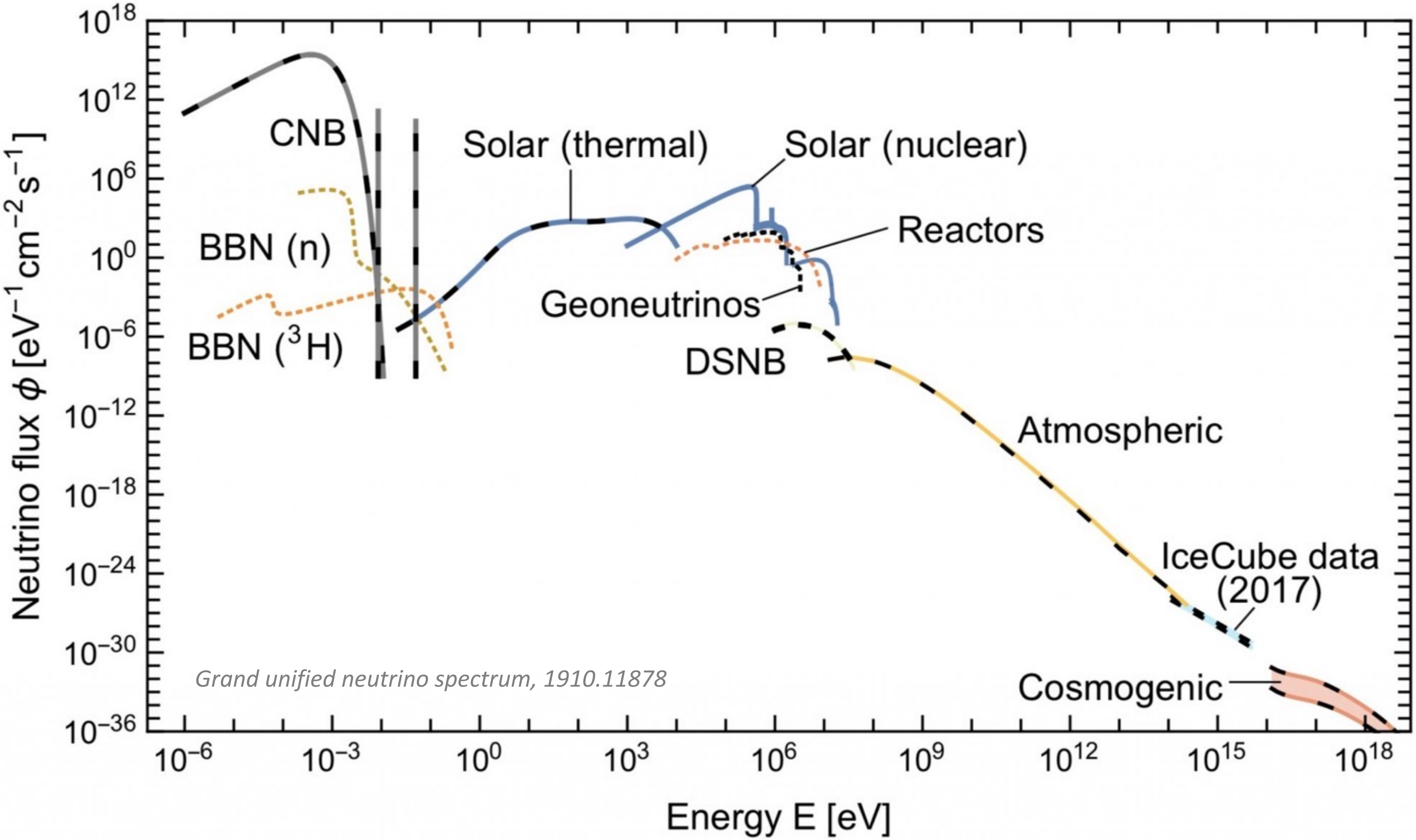


IO currently disfavored at ~3σ by combining oscillation + nonoscillation data

Outline:

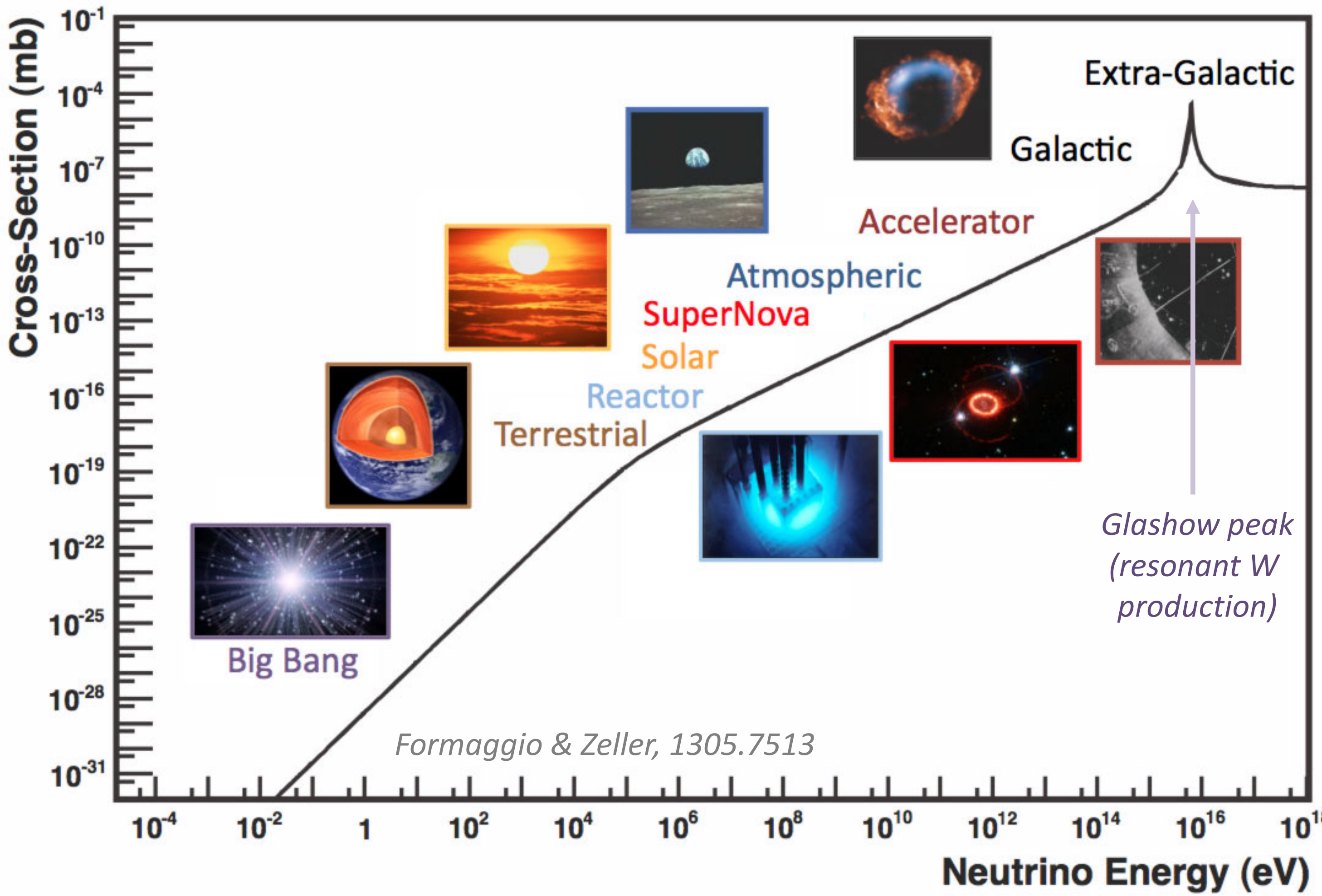
- Prologue: ν basic properties
- (Un)knowns in neutrino oscillations
- Non-oscillation ν observables
- **Learning from neutrinos**
- Epilogue: What's in a name?

Grand view of the neutrino landscape: flux vs energy



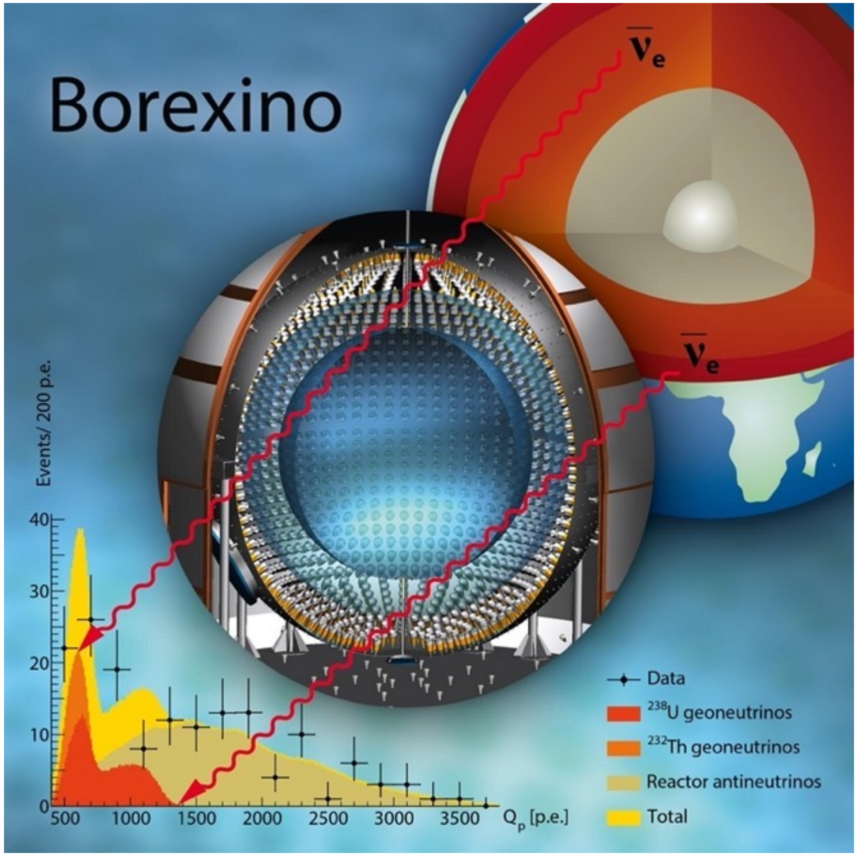
Grand unified neutrino spectrum, 1910.11878

Typical neutrino cross section ($\bar{\nu}_e e^- \rightarrow \bar{\nu}_e e^-$) vs energy



NOTE: ν absorption in Earth (!) relevant >100 TeV & Glashow event @ ~6 PeV: seen in IceCube

Learning from ν about the Earth's interior and heat budget…



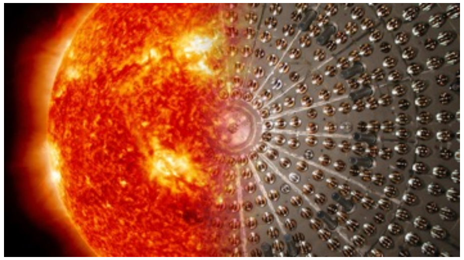
Geoneutrinos from U, Th decays in the Earth observed in KamLAND & Borexino

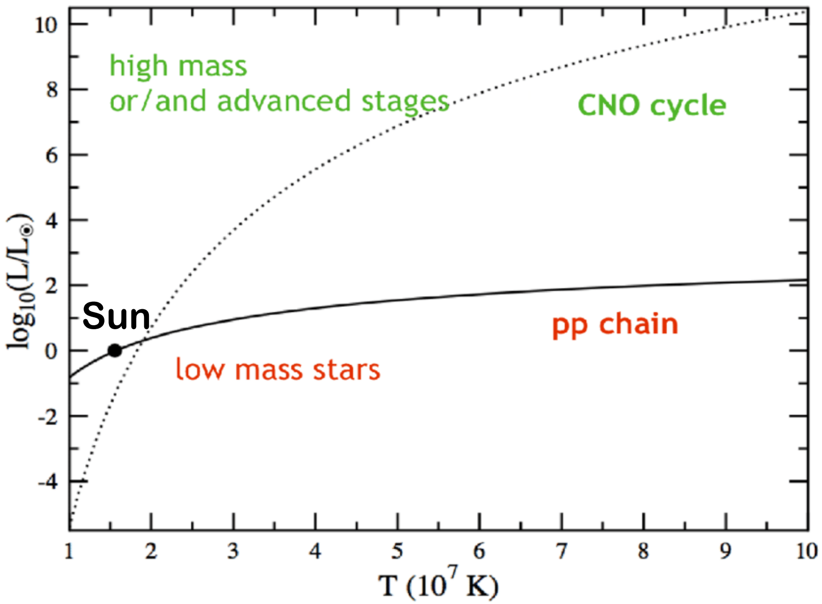
Test global geo-chemical models

Frontiers:
JUNO and other large-volume, low-energy detectors

Co-messengers of elastic waves (seismology)

Learning from ν about the Solar nuclear reaction chains …





CNO neutrinos recently observed in Borexino

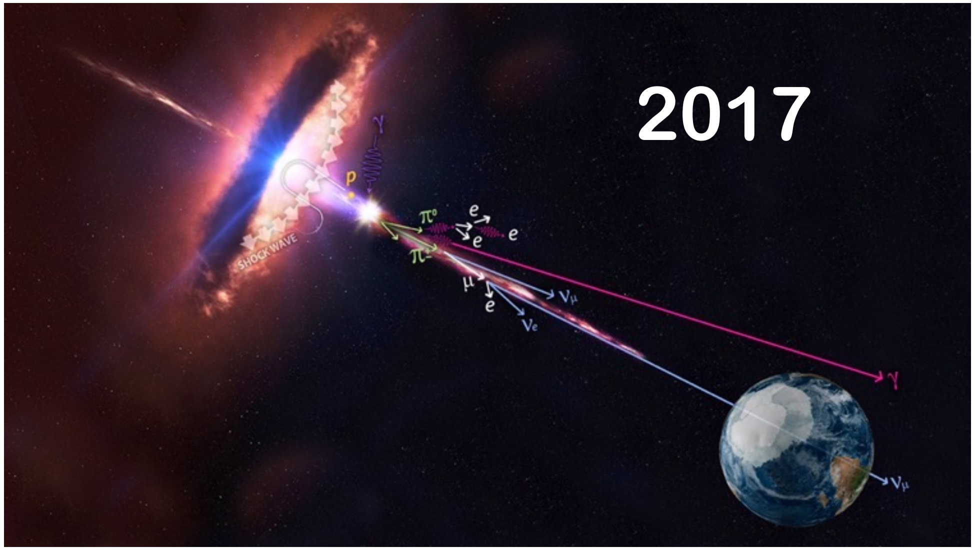
Test solar and stellar evolution models*

Also w/ nuclear astrophysics inputs, e.g., from LUNA expt.

Frontiers:
JUNO, DUNE, HK
and other large-volume, low-energy detectors

Co-messengers of elastic waves (helioseismology)
Co-messengers of photons

Learning from ν about violent “particle accelerator” sources…



Fluorishing field of multimessenger astronomy with neutrino telescopes (IceCube, KM3Net…)

New sources…

RESEARCH ARTICLE | NEUTRINO ASTROPHYSICS

Multimessenger observations of a flaring blazar coincident with high-energy neutrino IceCube-170922A

The IceCube Collaboration, *Fermi*-LAT, MAGIC, *AGILE*, ASAS-SN, HAWC, H.E.S.S., *INTEGRAL*, Kanata, Kiso, Kapteyn, Liverpool Telescope, Subaru, *Swift/NuSTAR*, VERITAS, VLA/17B-403 teams*,†

†Email: analysis@icecube.wisc.edu

* The full lists of participating members for each team and their affiliations are provided in the supplementary materials.
– Hide authors and affiliations

Science 12 Jul 2018:
eaat1378
DOI: 10.1126/science.aat1378

Co-messengers of photons

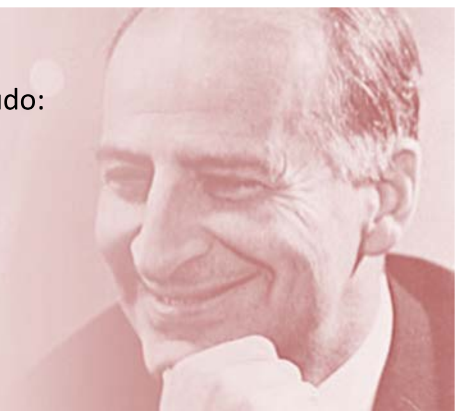
Co-messengers of gravitational waves?… hopefully in the future!

Learning from ν about the death of stars (core-collapse SN)

Rome, 23 feb 1987,
Bruno Pontecorvo to his nephew Ludo:

**"Did you hear
what happened today?
Ten to the fifty-eighth neutrinos!
All in one go!"**

[As quoted by F. Close]



Frontiers:

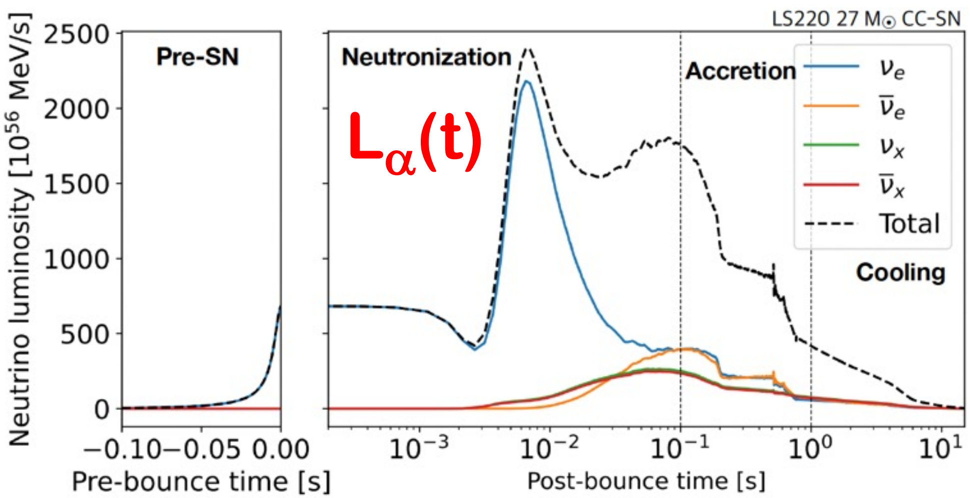
- **Observe diffuse SN ν bkgd flux**
- **Understand collective ν effects**
- **Be ready for next near SN explosion!**

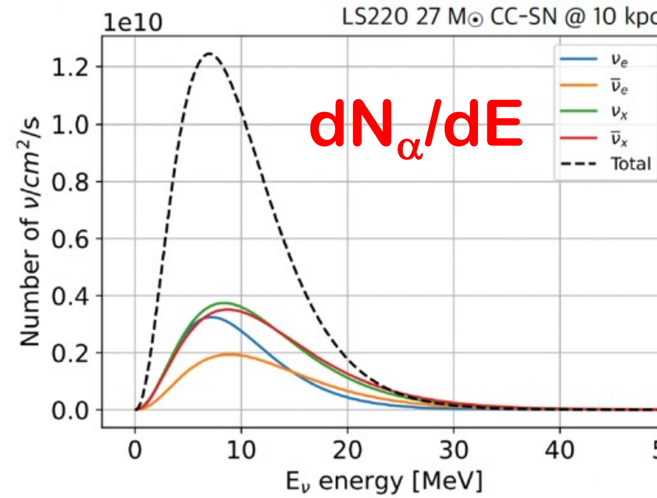
Co-messengers of photons ...as anticipated by B. Pontecorvo, JETP 36, 1625 (1959)

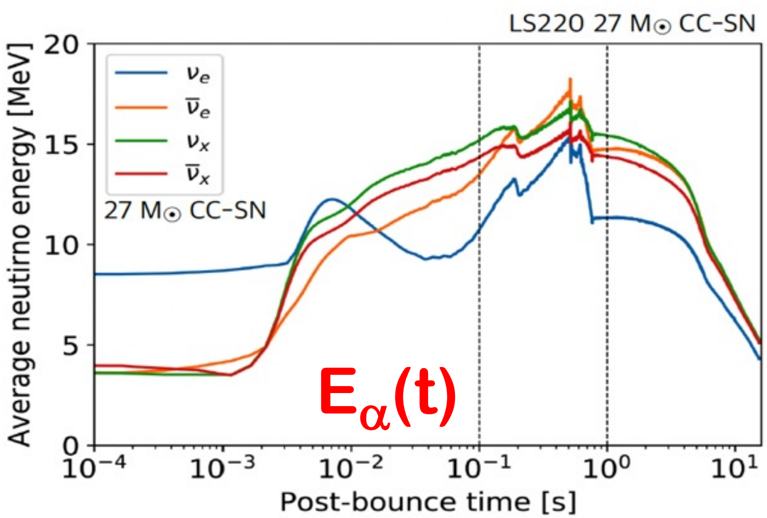
Co-messengers of gravitational waves?... hopefully in the future!

Towards the next SN event: frontiers in ν detection

Typical (simulated, unoscillated) SN neutrino signals for different flavors α:







Flavor transformations re-weight such spectra (and may even alter the SN evolution ← feedback)

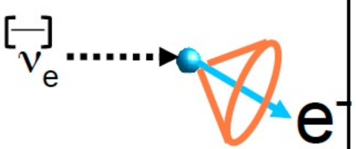
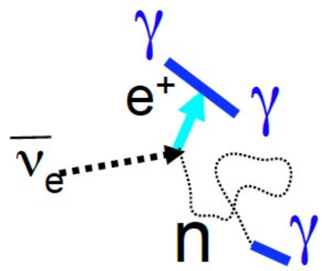
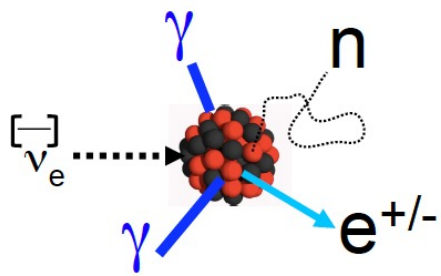
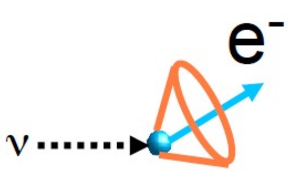
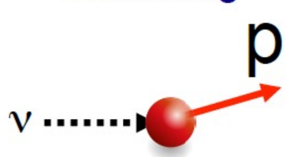
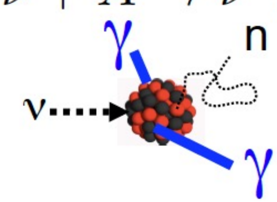
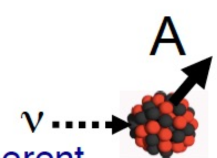
X-sections differ with α →

CC: α = e NC: α = e,μ,τ

Plots from Luca Pattavina @ LNGS SNvD 2023

Neutrino interactions in the ~10 MeV range

Slide from Kate Scholberg

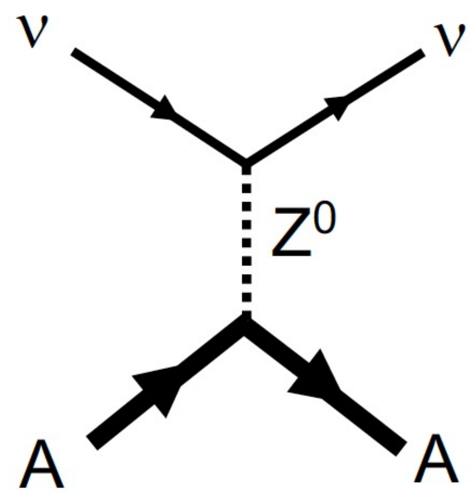
	Electrons	**Protons**	**Nuclei**
Charged current	Elastic scattering $\nu + e^- \to \nu + e^-$ 	Inverse beta decay $\bar{\nu}_e + p \to e^+ + n$ 	$\nu_e + (N, Z) \to e^- + (N-1, Z+1)$ $\bar{\nu}_e + (N, Z) \to e^+ + (N+1, Z-1)$  Various possible ejecta and deexcitation products
Neutral current	 Useful for pointing	Elastic scattering  very low energy recoils	$\nu + A \to \nu + A^*$  $\nu + A \to \nu + A$  Coherent elastic (CEvNS)

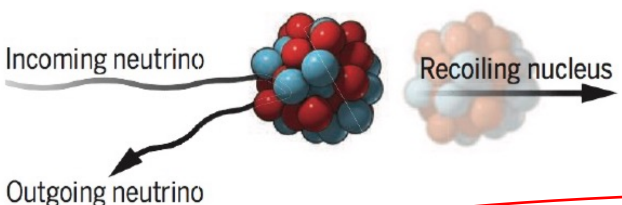
Coherent Elastic neutrino Nucleus Scattering = CEνNS (read: "sevens"): Predicted in 1974, observed in 2017

The gentlest (coherent) interaction of a neutrino with a nucleus…

$$\nu + A \rightarrow \nu + A$$

A neutrino smacks a nucleus via exchange of a Z, and the nucleus recoils as a whole; **coherent** up to $E_\nu \sim 50$ MeV





Nucleon wavefunctions in the target nucleus are **in phase with each other** at low momentum transfer

For $QR << 1$, [total xscn] ~ A^2 * [single constituent xscn]

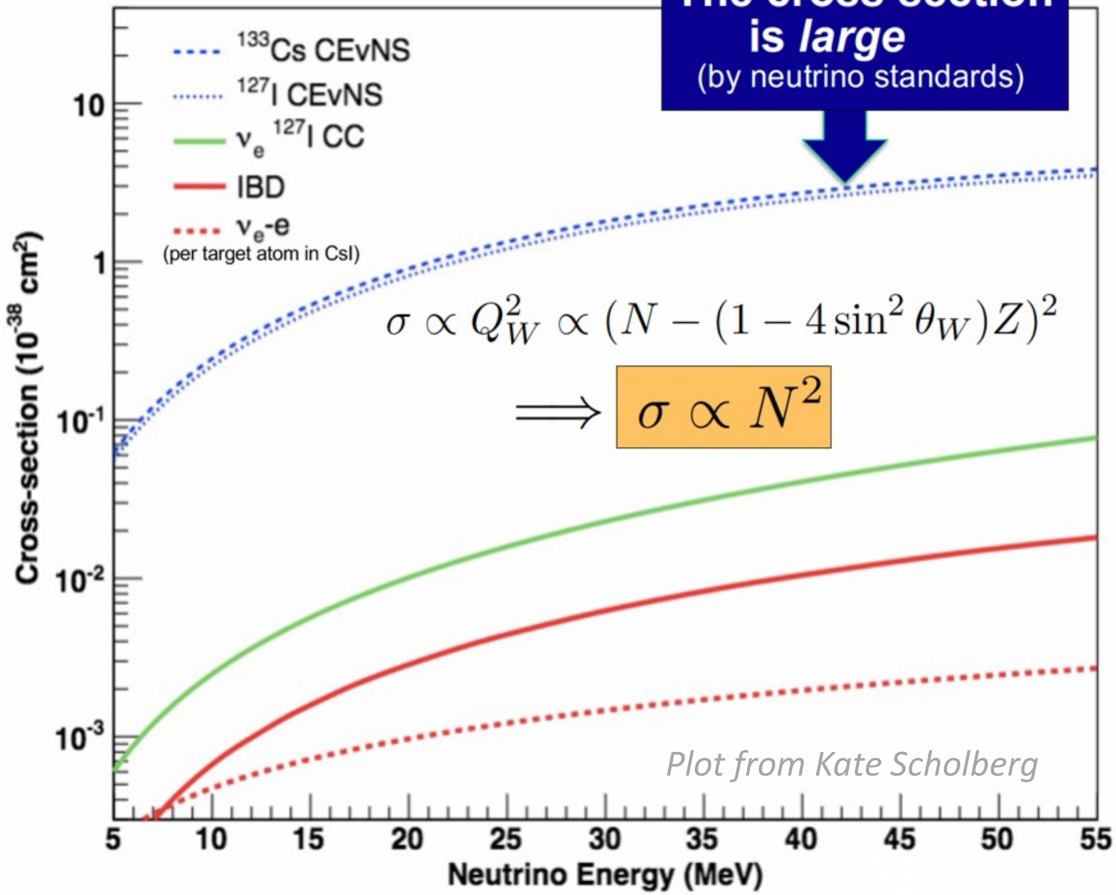
A: no. of constituents

Image: J. Link *Science* Perspectives

Slide from Kate Scholberg

… but with the highest cross section, proportional to N^2 !

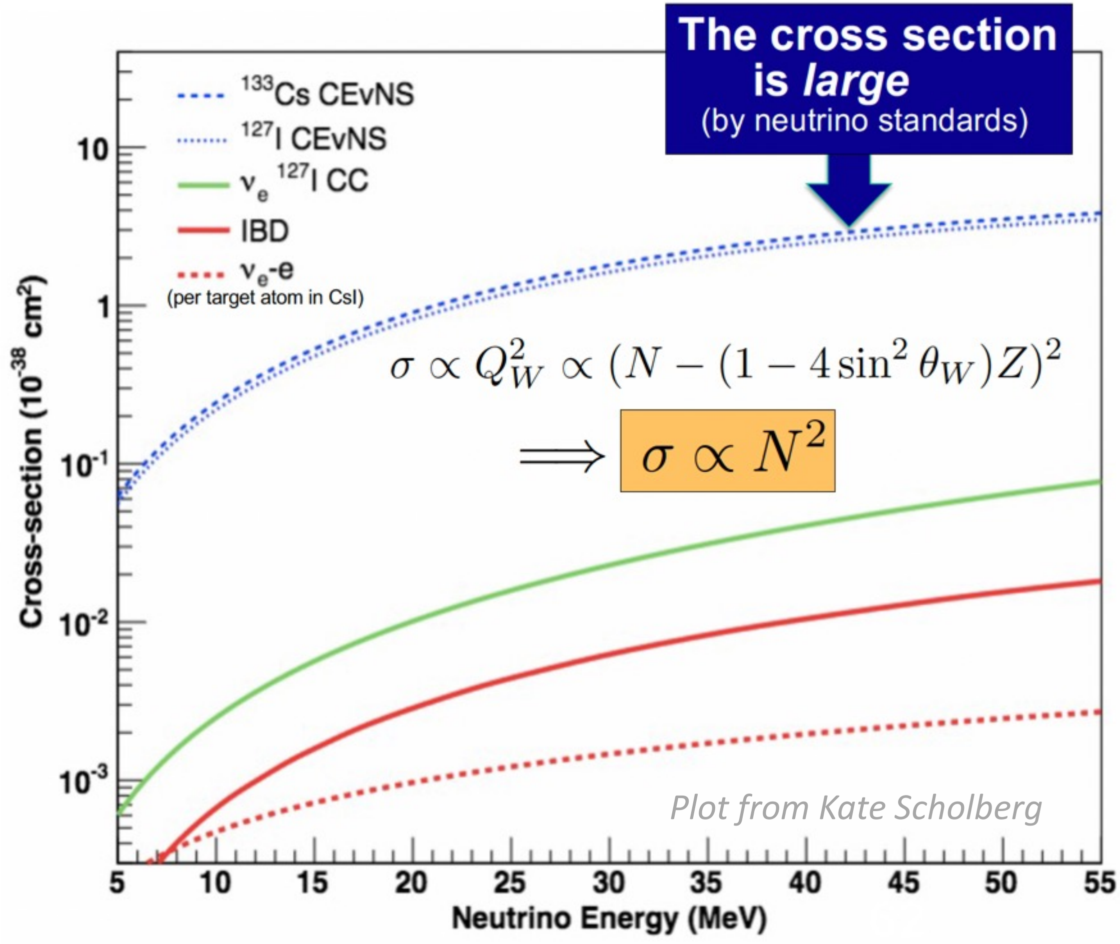
The cross section is *large*
(by neutrino standards)



$$\sigma \propto Q_W^2 \propto (N - (1 - 4\sin^2\theta_W)Z)^2$$

$$\Longrightarrow \boxed{\sigma \propto N^2}$$

Plot from Kate Scholberg

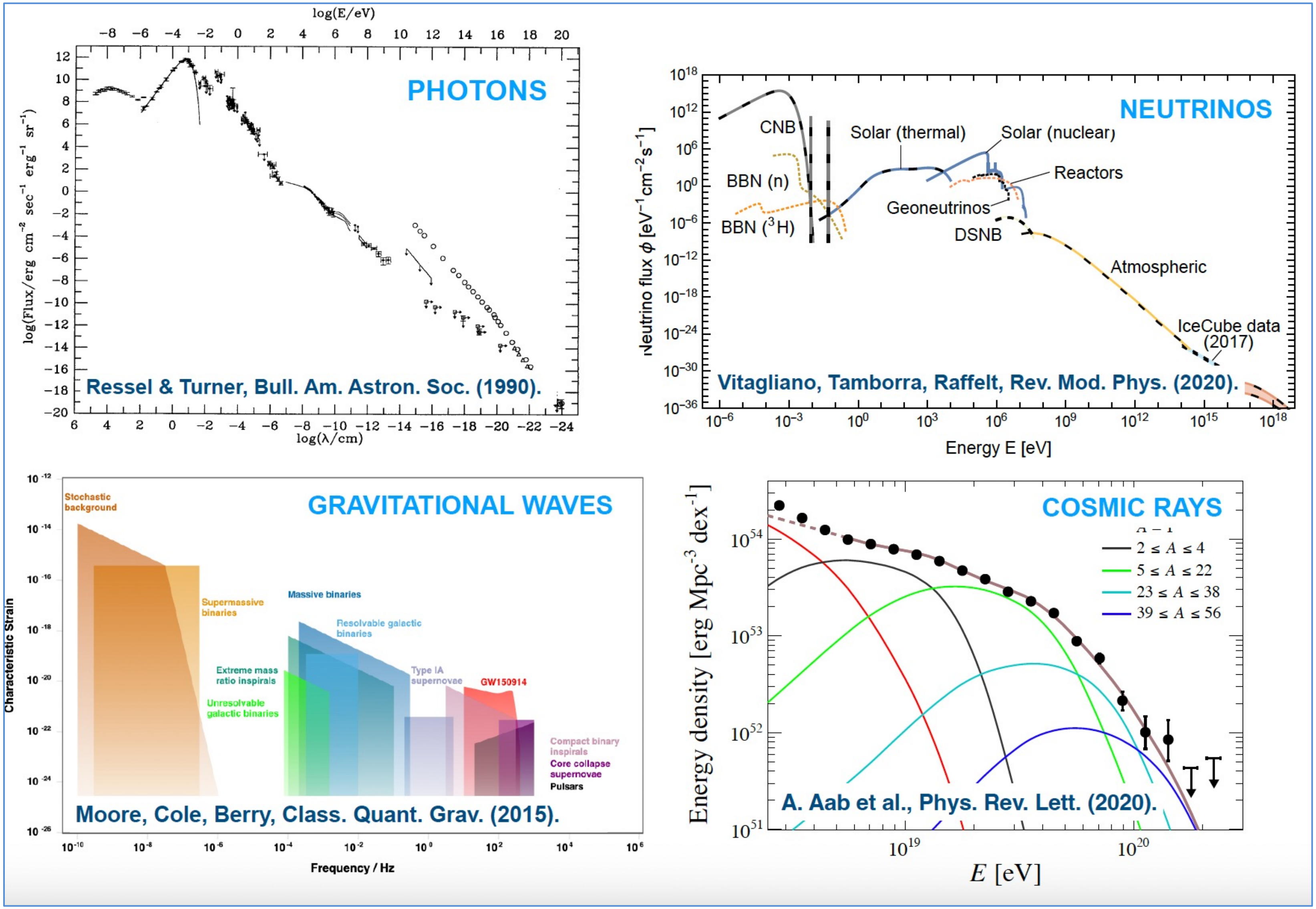


...but recoil energy is O(1-100) keV: small & difficult to measure!

Detection requires:
Low threshold
Low background
High E resolution

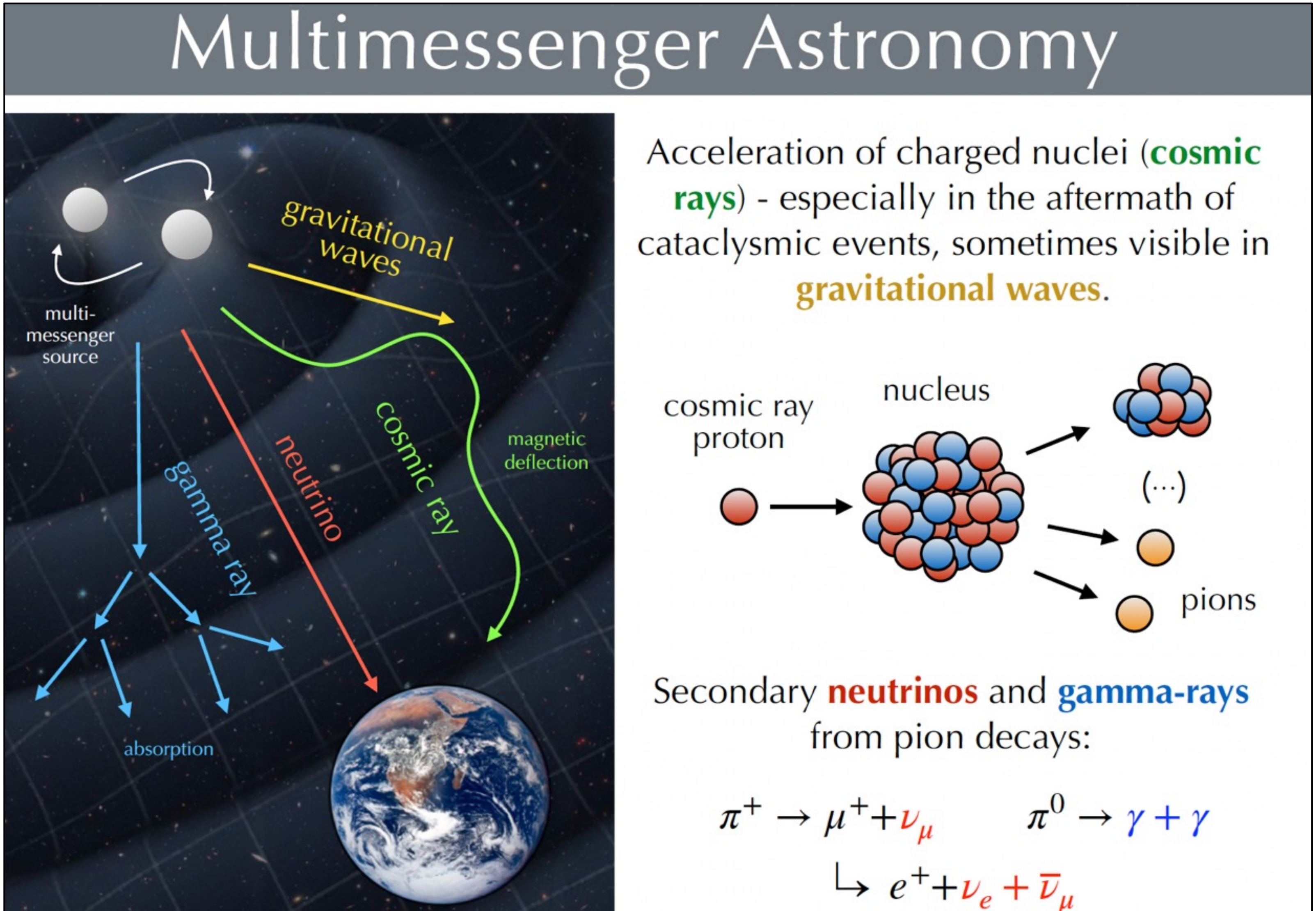
RES-NOVA approach:
Archaeological Pb
& cryogenic detector

Back to neutrinos as (co)messengers of natural sources…



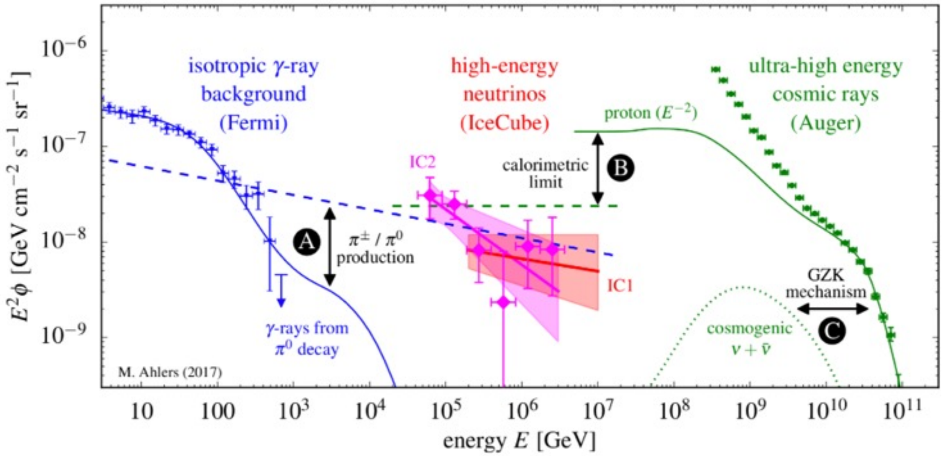
Slide from Irene Tamborra @ TAUP 2023

In general, expect (model-dep.) correlation of messengers from a single source…



Slide from Markus Ahlers @ GGI 2021

… and also at a "statistical" level from diffuse sources



The observed diffuse flux of neutrinos, gamma rays and cosmic rays has been shown to be of comparable magnitude. This apparently shared energy scale is the main motivation behind the search for a common origin between these three messengers.

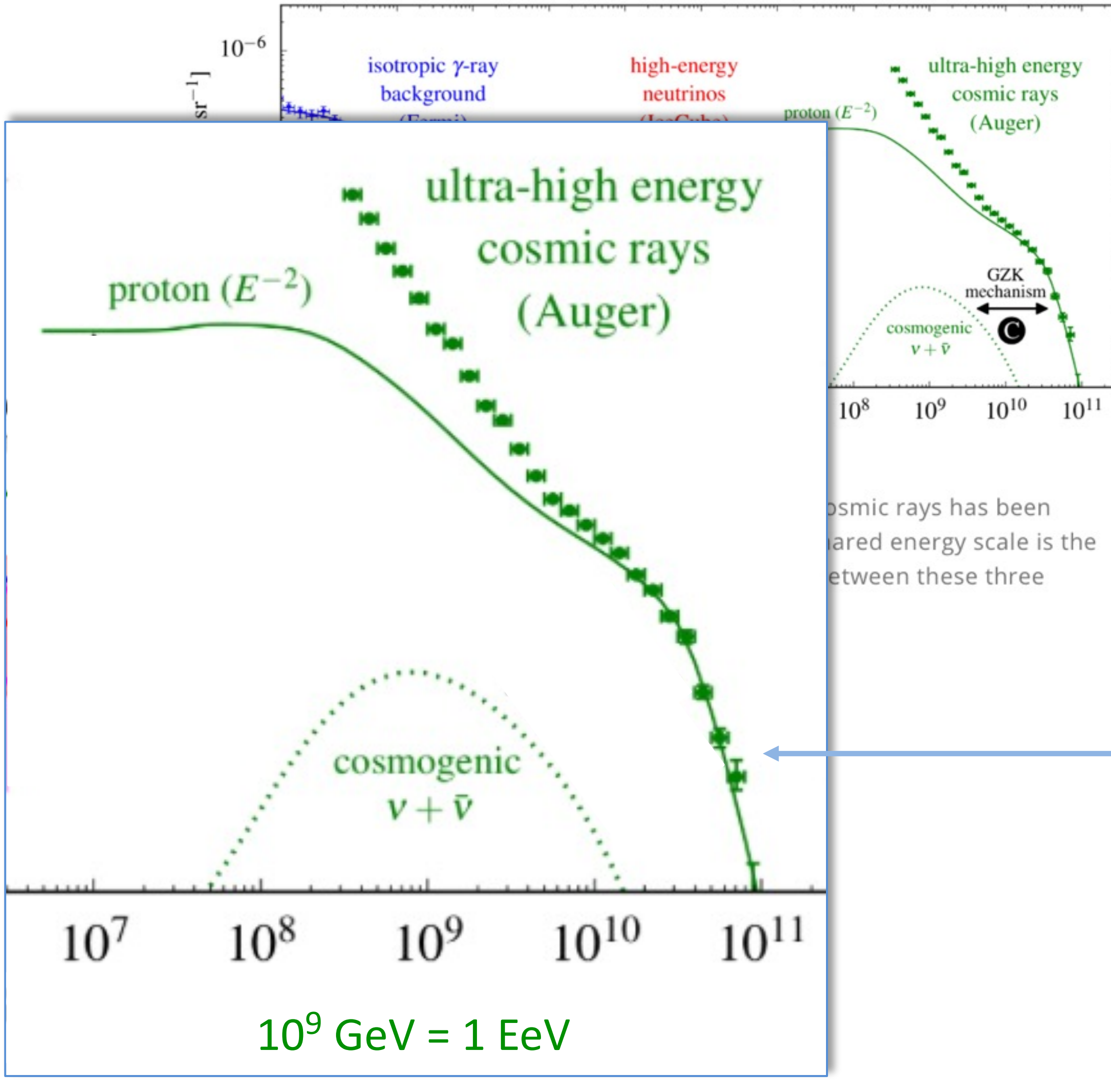
A: The joined production of charged pions and neutral pions in cosmic-ray interactions leads to the emission of neutrinos (dashed blue) and gamma-rays (solid blue), respectively. What does gamma-ray observations tell us about the neutrino emission?

B: Cosmic ray emission models (solid green) of the most energetic cosmic rays imply a maximal flux (calorimetric limit) of neutrinos from the same sources (green dashed). Is there a deep connection between these unknown CR sources and the recent IceCube observation?

C: The same cosmic ray model predicts the emission of cosmogenic neutrinos from the collision with cosmic background photons (GZK mechanism). What are the requirements for future neutrino observatories to reach this low flux of cosmogenic to test the GZK mechanism?

From NBI Copenhagen website

… and also at a “statistical” level from diffuse sources

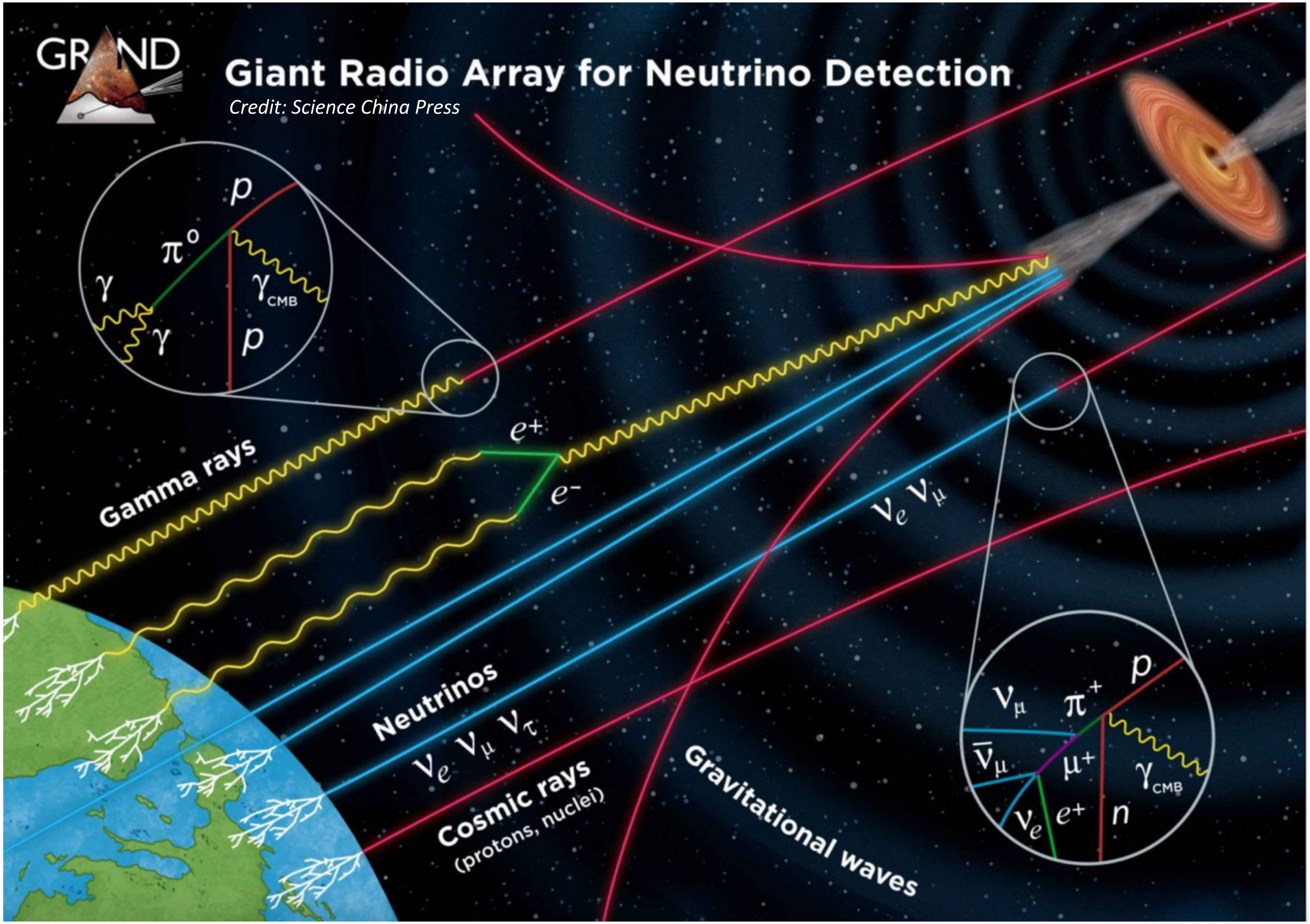


Of interest for this school (AUGER):

Linking the high-energy tails of CR and ν spectra

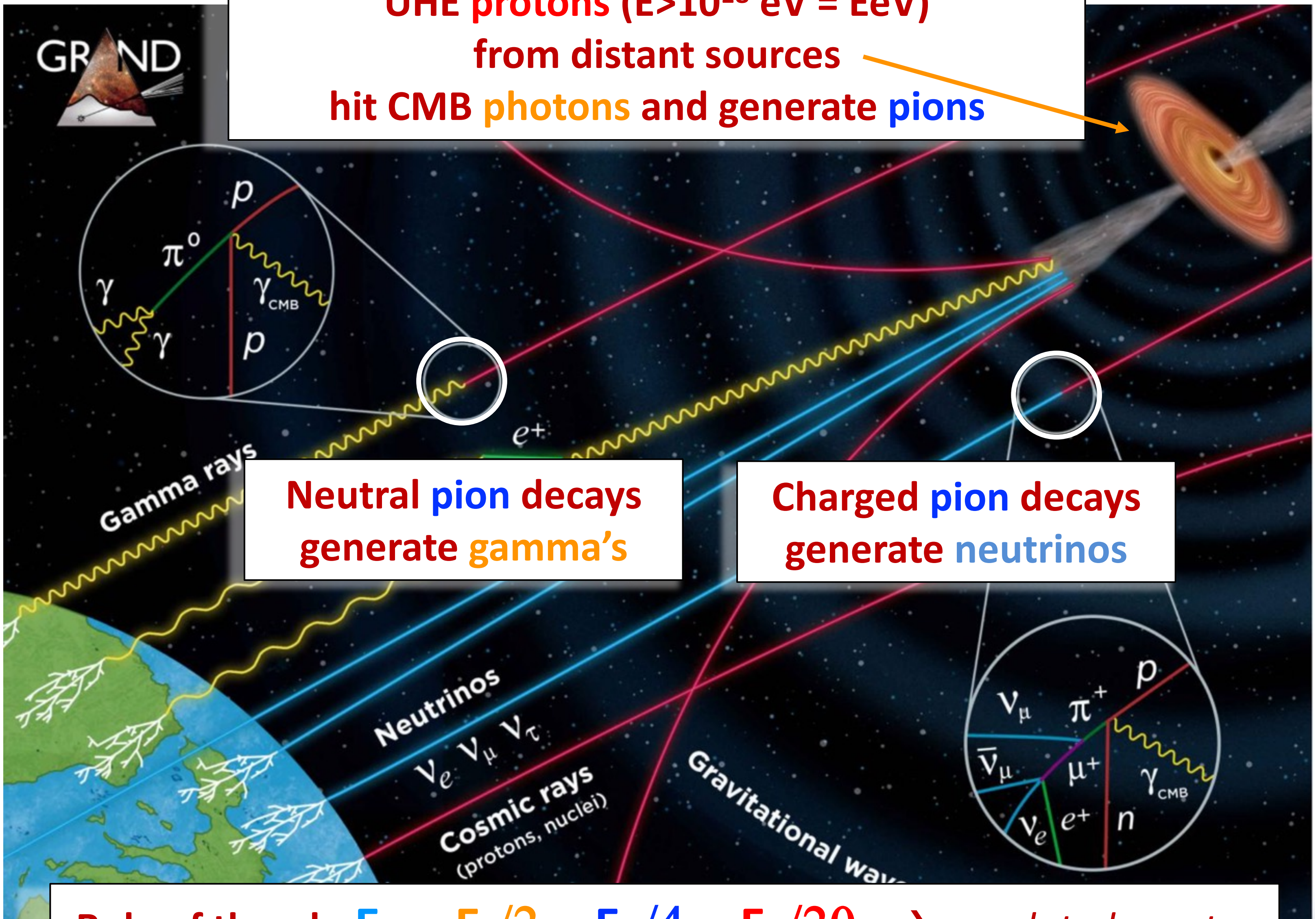
(UHECR & cosmogenic ν)

Creation and propagation of ultra-high energy particles in the Universe



(Above: "standard" processes. Possible UHECR from new physics: heavy dark matter, topological defects, etc.)

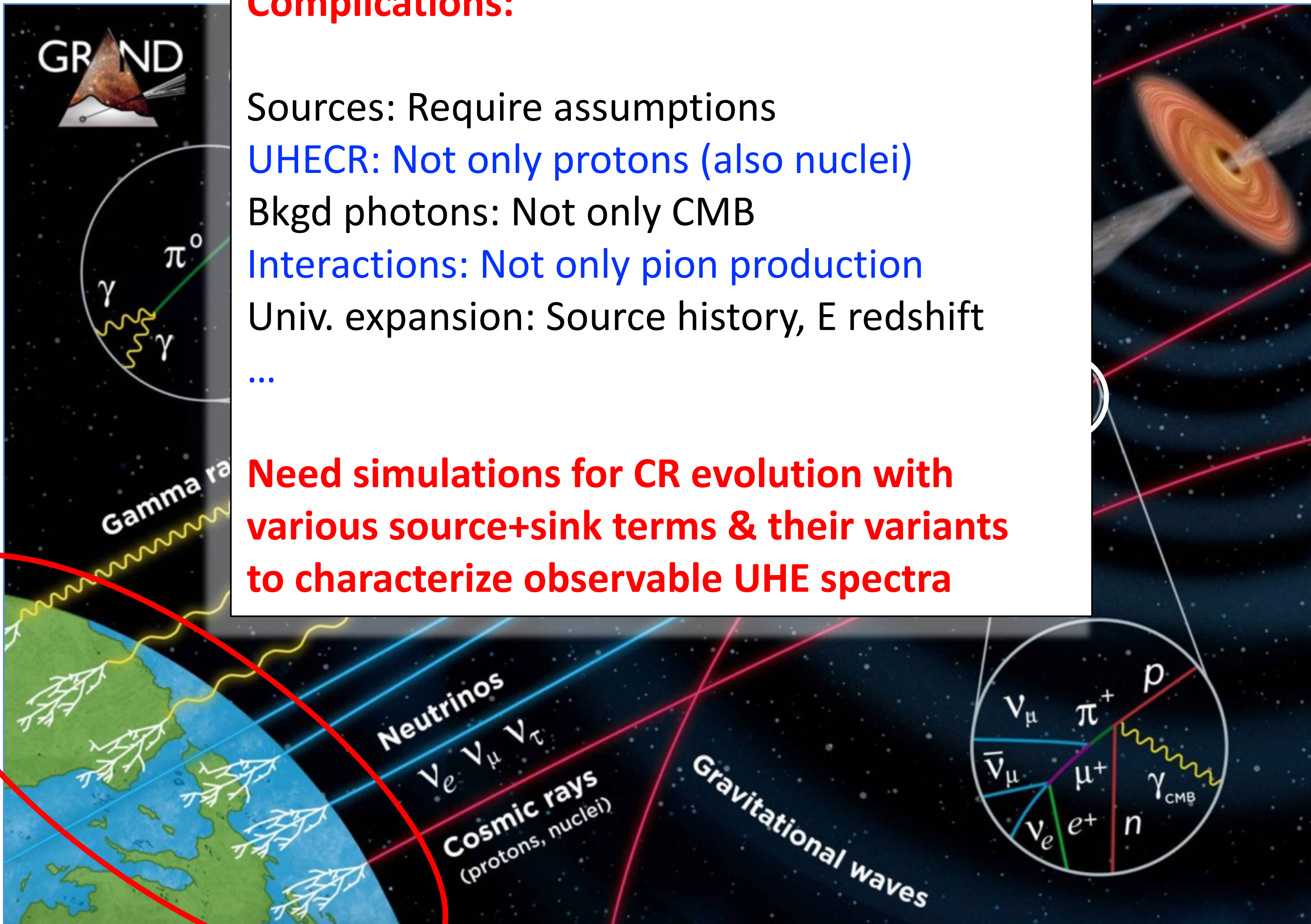
UHE protons ($E>10^{18}$ eV = EeV)
from distant sources
hit CMB photons and generate pions



Neutral pion decays generate gamma's

Charged pion decays generate neutrinos

Rule of thumb: $E_\nu \sim E_\gamma/2 \sim E_\pi/4 \sim E_p/20$ → *correlated spectra*



Complications:

Sources: Require assumptions

UHECR: Not only protons (also nuclei)

Bkgd photons: Not only CMB

Interactions: Not only pion production

Univ. expansion: Source history, E redshift

…

Need simulations for CR evolution with various source+sink terms & their variants to characterize observable UHE spectra

Outline:

- Prologue: ν basic properties
- (Un)knowns in neutrino oscillations
- Non-oscillation ν observables
- Learning from neutrinos
- **Epilogue: What's in a name?**

An old latin dictum:

A name, a destiny…

Neutrino name: which destiny?

Language	Word tree	*…Some branches*	Meaning
Physics (Fermi 1934)	NEUTR-INO		Little neutral one
Italian	NEUTRO		Neutral
Latin	NE-UTER		Not either; neutral
Latin	UTER		Either
Greek	↑	*OUDETEROS*	*Neutral*
Old High German	↑ ↗	*HWEDAR*	*Which of two; whether*
Phonetic change/loss	[K]UOTER[US]		Which of the two?
Ionic Greek	KOTEROS		Which of the two?
Sanskrit	KATARAS		Which of the two?

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Phonetic change/loss	[K]UOTER[US]		Which of the two?
Ionic Greek	KOTEROS		Which of the two?
Sanskrit	KATARAS		Which of the two?
Latin	↑	*QUANTUS*	*How much?*
Sanskrit		*KATAMAS*	*Which out of many?*
Sanskrit		*KATHA*	*How?*
Sanskrit		↗ *KAS*	*Who?*
Indo-European root	KA *or* KWA		Interrogative base

The root of the name [neutrino] … is a [kwa]stion

Language	Word tree	…*Some branches*	Meaning
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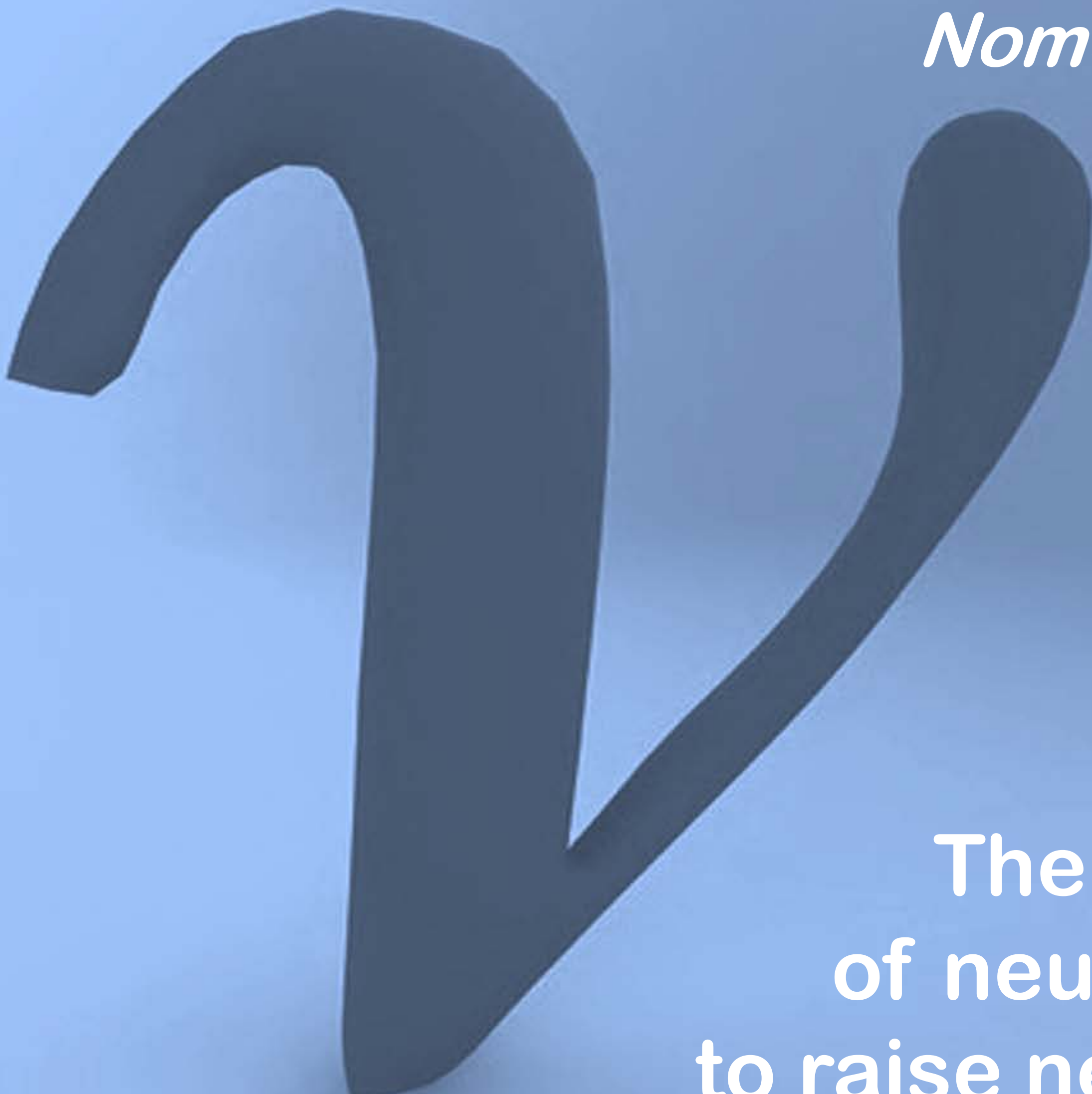
Sanskrit		*KATHA*	*How?*
Sanskrit	↗	*KAS*	*Who?*
Indo-European root	KA *or* KWA		Interrogative base

Nomen Omen…



?

The destiny
of neutrinos is…
to raise new questions!