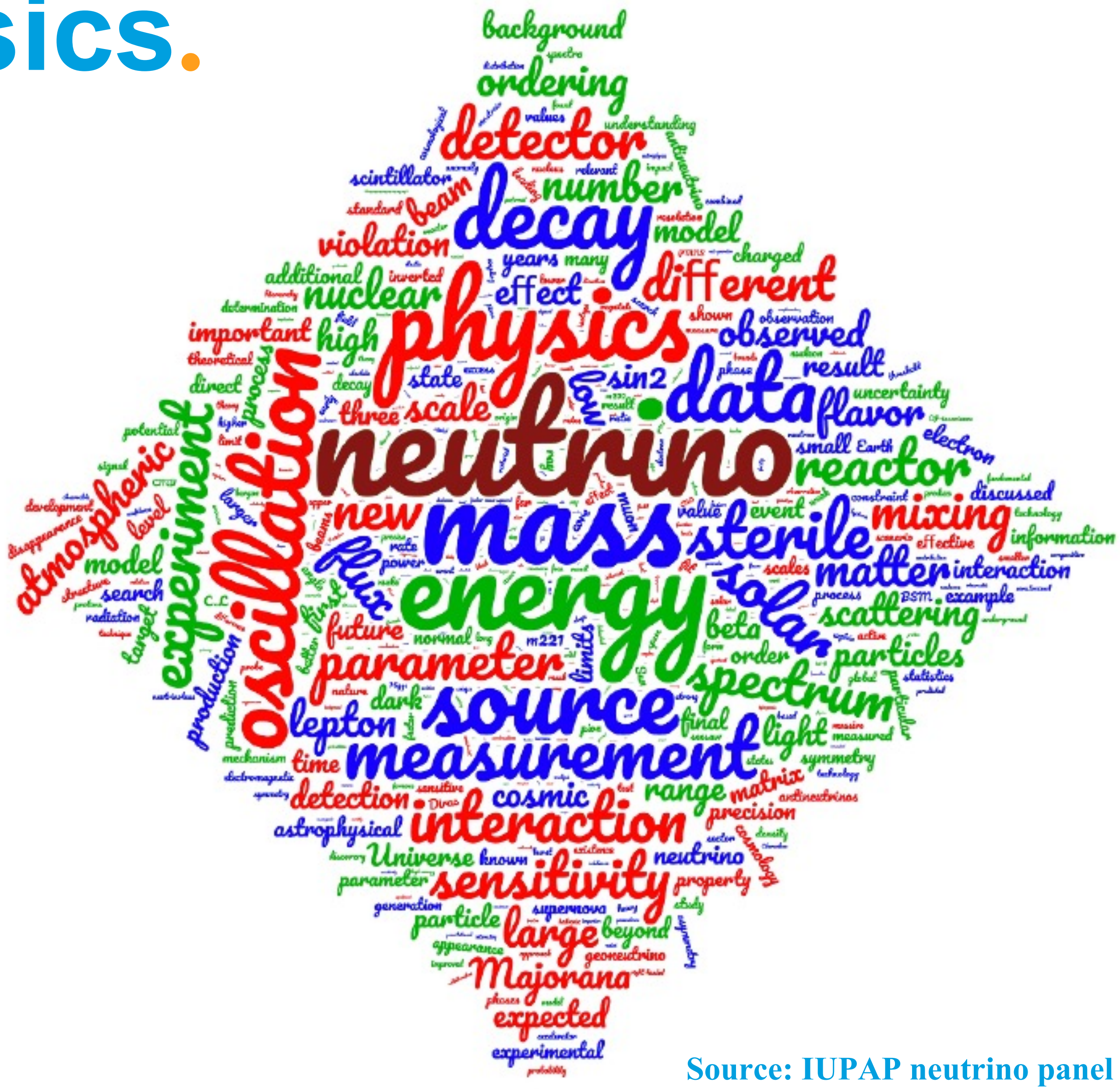
Neutrino physics.



Source: IUPAP neutrino panel

Walter Winter
DESY, Zeuthen, Germany

DESY summer student lecture program
August 2025

Contents

Lecture 1: Neutrino physics
Lecture 2: High-energy neutrino astrophysics

Lecture 1:

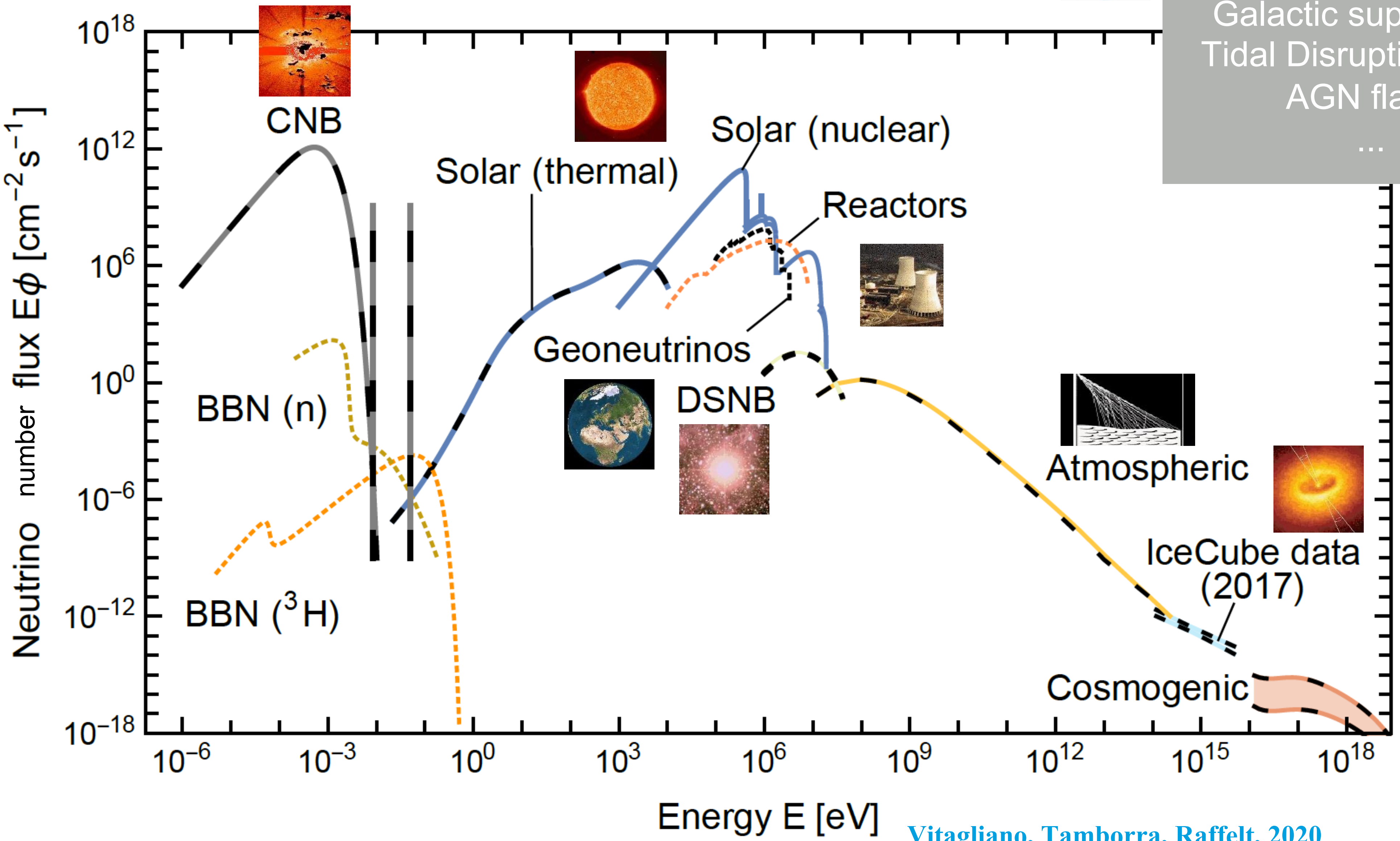
- Introduction
- What is neutrino physics?
- Neutrino oscillations: Introduction
- Current knowledge on neutrino oscillations
- Is neutrino mass evidence for physics beyond the Standard Model?
- Summary

Where do the neutrinos come from?

Diffuse neutrino background (number flux)

Plus "transient" fluxes:
Neutrino beams (pulsed)
Galactic supernova?
Tidal Disruption Event
AGN flares
...

* 0.5 m² ~ 10^{14} s^{-1} through a human being



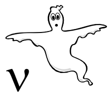
Vitagliano, Tamborra, Raffelt, 2020

Who “invented“ the neutrino?

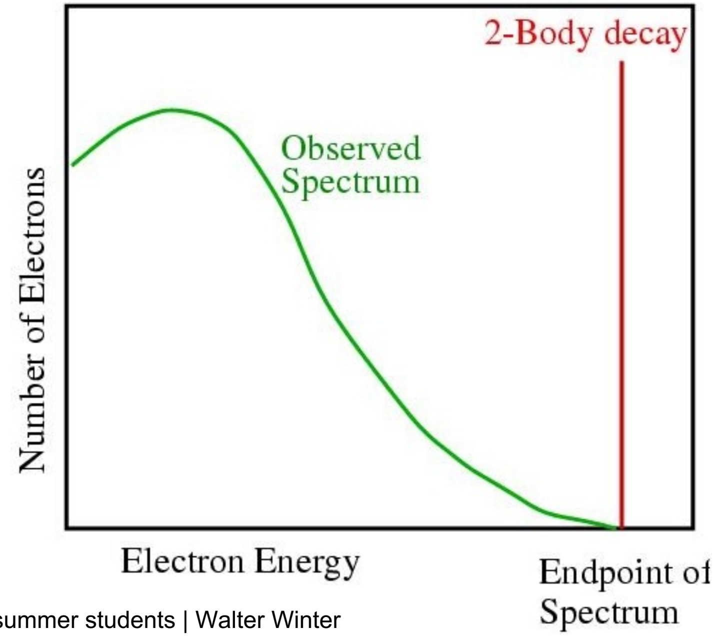
From energy and momentum conservation, we have for the decay into N particles:

- N=2: have particular, discrete energies
- N>2: have continuous spectra

$(N,Z) \rightarrow (N-1,Z+1) + e + \bar{\nu}$



$(N,Z) \rightarrow (N-1,Z+1) + e$



Wolfgang Pauli

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

Abschrift

Physikalisches Institut
der Eidg. Technischen Hochschule
Zürich

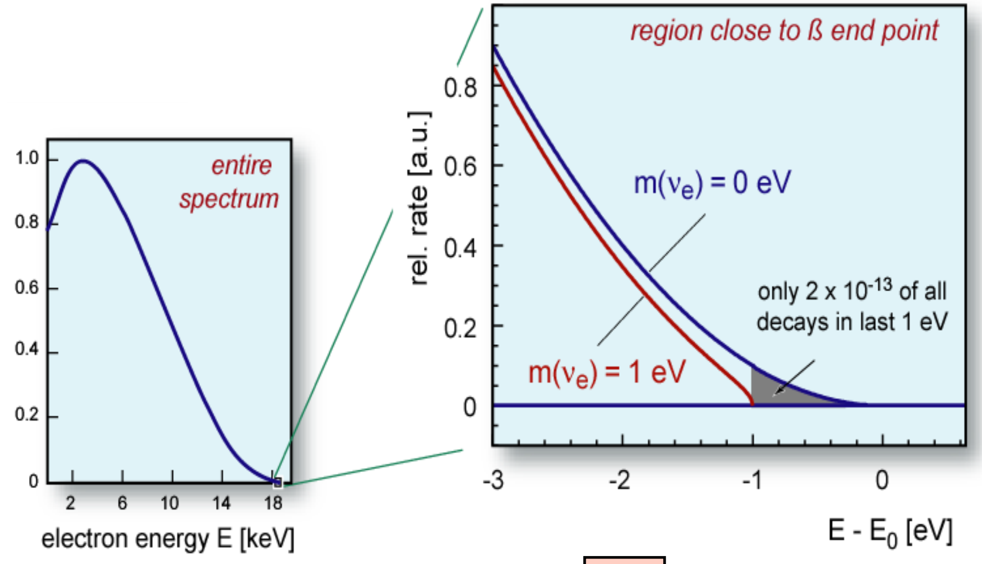
Zürich, 4. Dez. 1930
Gloriastrasse

Liebe Radioaktive Damen und Herren,

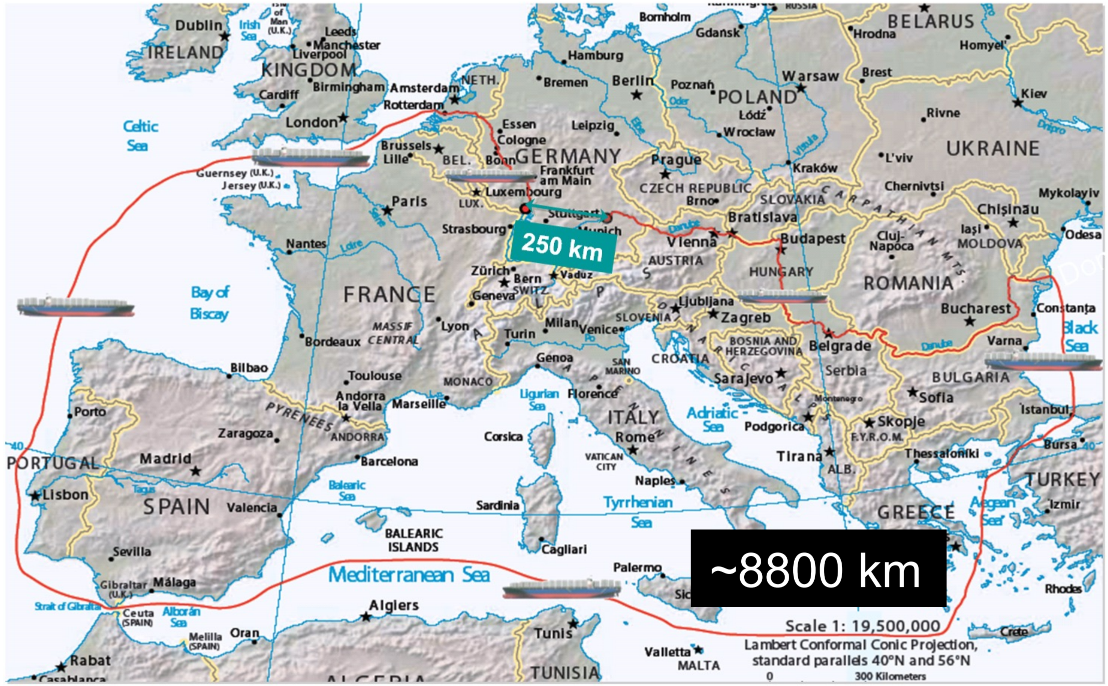
Wie der Ueberbringer dieser Zeilen, den ich huldvollst anzuhören bitte, Ihnen des näheren auseinandersetzen wird, bin ich angesichts der "falschen" Statistik der N- und Li-6 Kerne, sowie des kontinuierlichen beta-Spektrums auf einen verzweifelten Ausweg verfallen um den "Wechselsatz" (1) der Statistik 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 Grossenordnung 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.

How to weigh the neutrino?

- Direct test of neutrino mass by decay kinematics
- Experiment: KATRIN
  (Karlsruhe Tritium Neutrino Experiment)
- Current bound:
  1/500.000 x m_e (0.8 eV) TINY!
- Target: 1/2.500.000 x m_e (0.2 eV)



$$n \longrightarrow p + \boxed{e^-} + \bar{\nu}_e$$

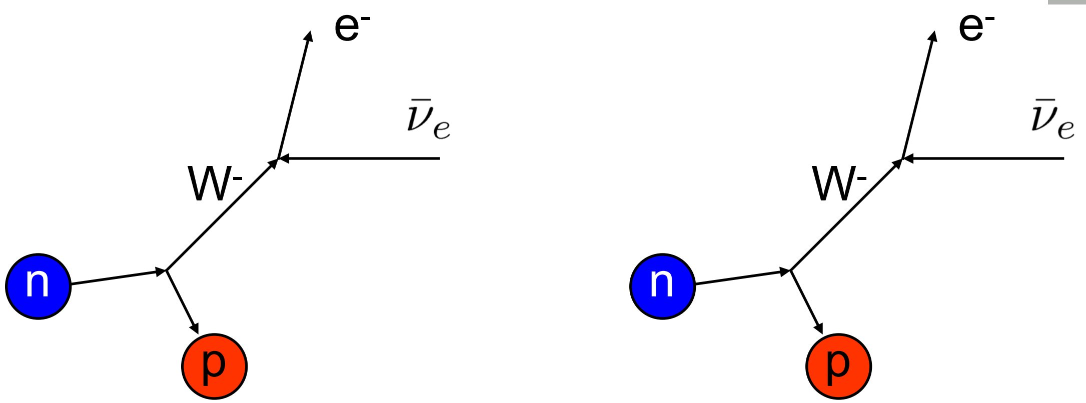


(KATRIN, Nature Phys. 18 (2022) 2, 160)

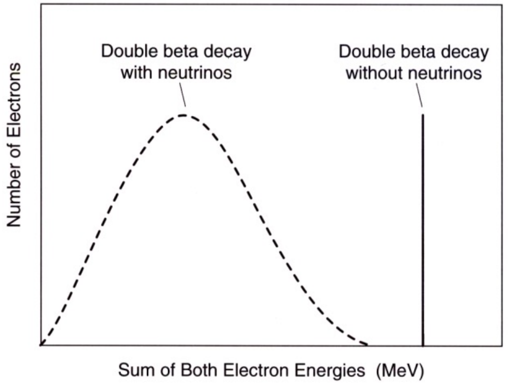
0νββ: Is the neutrino its own anti-particle?

While the non-observation of 0νββ alone cannot exclude the Majorana nature, the detection of 0νββ would be ground-breaking evidence for physics BSM!

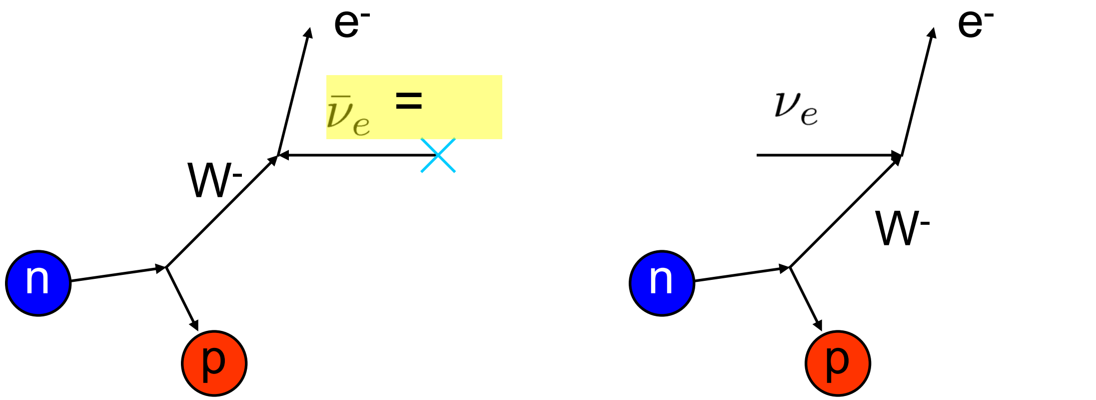
- Two times simple beta decay:



2 x ν
2 x e



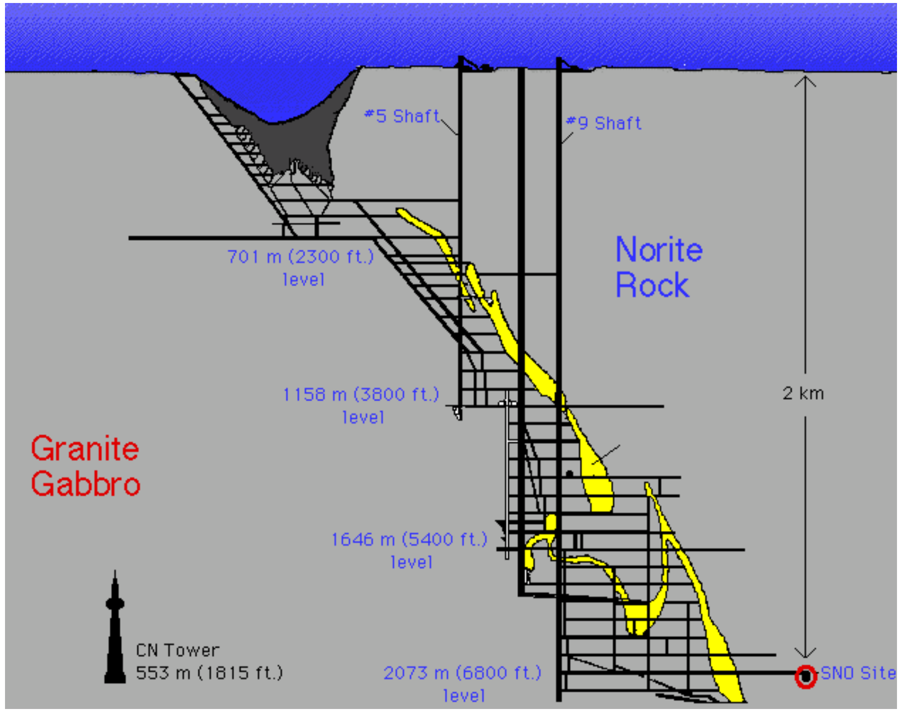
- Neutrinoless double beta decay:

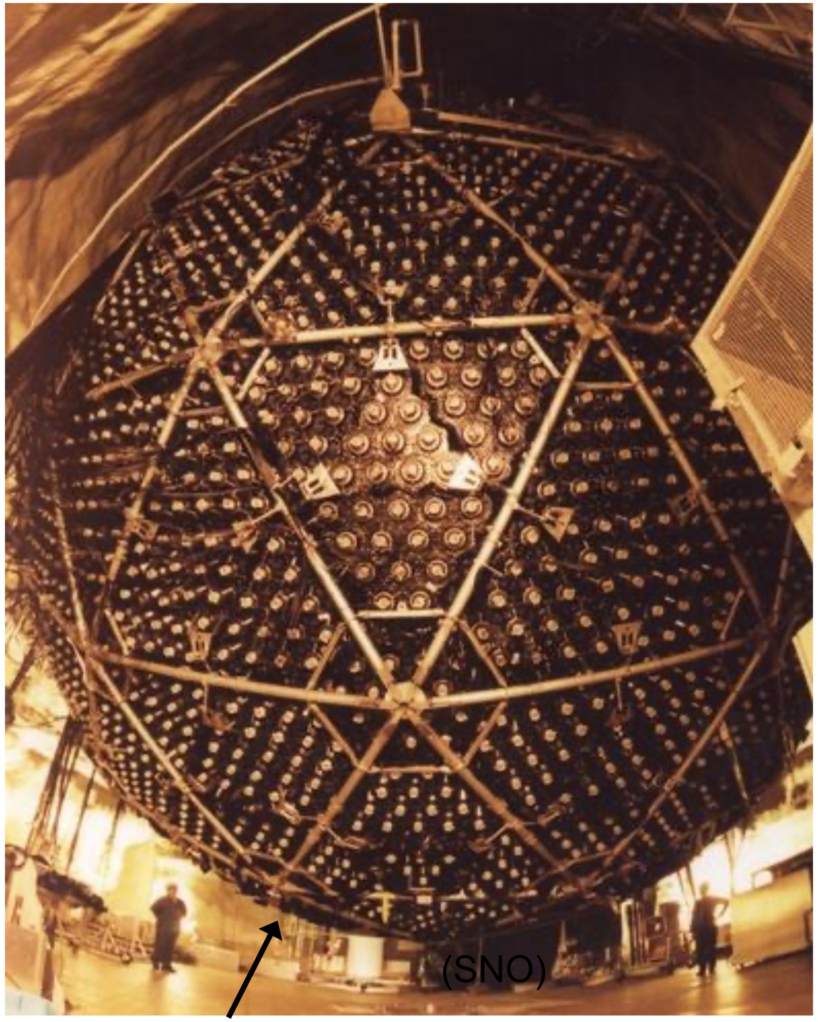


0 x ν
2 x e

How do we observe neutrinos?

- Extremely difficult to catch the neutrinos
- Build huge detectors (O(1000 t)), often deep underground (background reduction!)



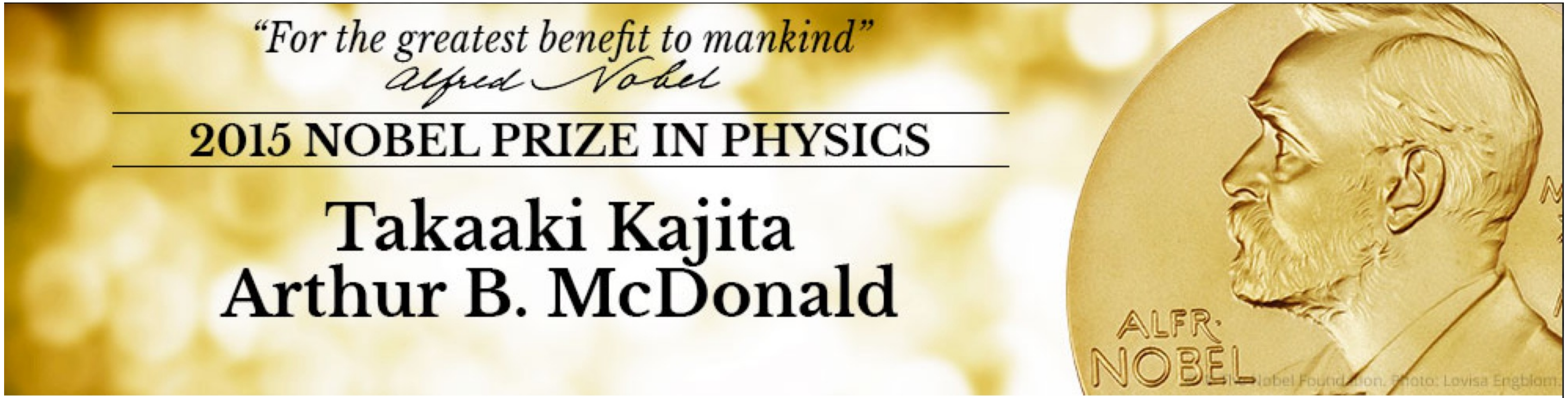


$$N_{\mathrm{obs}} \propto \Phi \times \sigma \times t \times m_{\mathrm{Det}}$$

Flux: extremely large	Cross section: extremely small	Observation time: 1-10 years	Detector mass: matches the product

Nobel prize 2015:

Neutrino oscillations



Ill: N. Elmehed. © Nobel Media 2015

2015 Nobel Prize in Physics

The Nobel Prize in Physics 2015 was awarded jointly to Takaaki Kajita and Arthur B. McDonald "for the discovery of neutrino oscillations, which shows that neutrinos have mass".

→ Read more about the prize

Illustration: © Johan Jarnestad/The Royal Swedish Academy of Sciences

They Solved the Neutrino Puzzle

Takaaki Kajita and Arthur B. McDonald solved the neutrino puzzle and opened a new realm in particle physics. They were key scientists of two large research groups, Super-Kamiokande and Sudbury Neutrino Observatory, which discovered the neutrinos mid-flight metamorphosis.

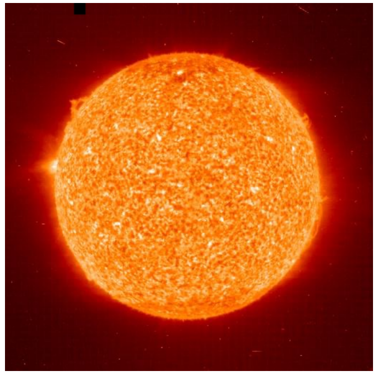
→ Read more (pdf)

"I Gave My Wife a Hug!"

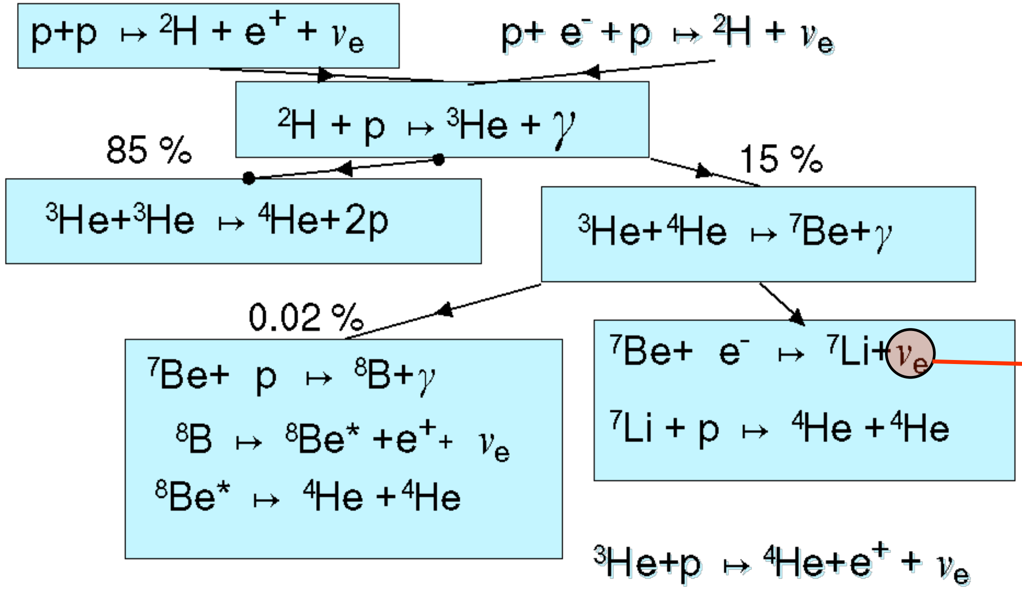
"It's ironic, in order to observe the sun you have to go kilometers under ground. That's not what you would expect." An interview with Arthur B. McDonald, awarded the 2015 Nobel Prize in Physics.

(http://www.nobelprize.org, Oct. 6th, 2015)

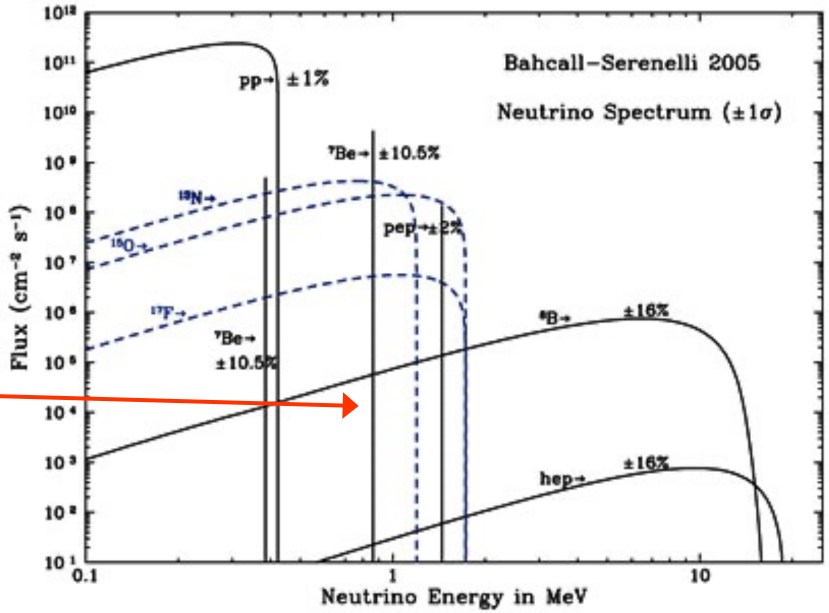
The mystery of the missing neutrinos



- Raymond Davis Jr. (Nobel Prize 2002) found fewer solar neutrinos than predicted by theory (John Bahcall)
- Do the neutrinos disappear?
  Or was the theory wrong?
  Discrepany over 30 years (1960s to 90s)



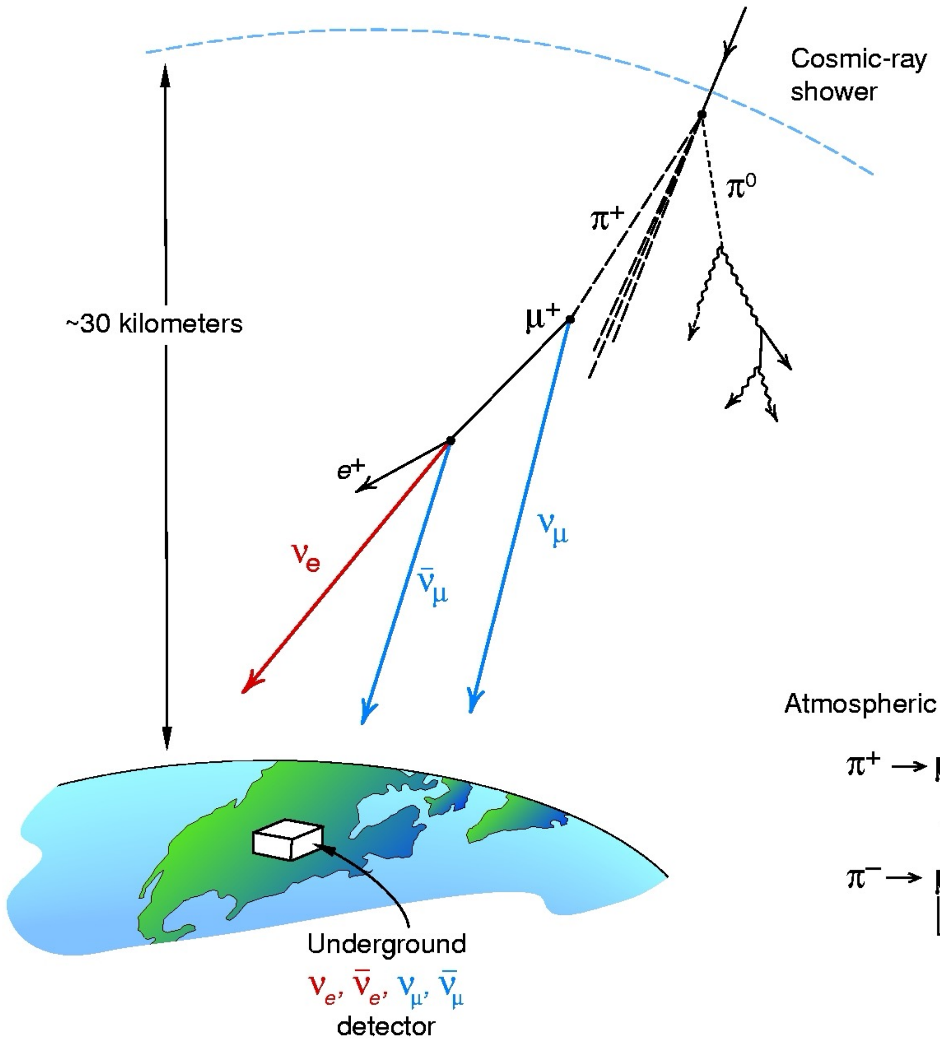
pp-fusion chain



Neutrino spectra

First evidence for CNO neutrinos presented at Neutrino 2020! Nature 587 (2020) 577

Neutrinos from the atmosphere

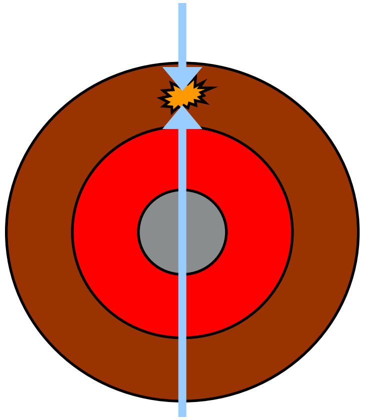


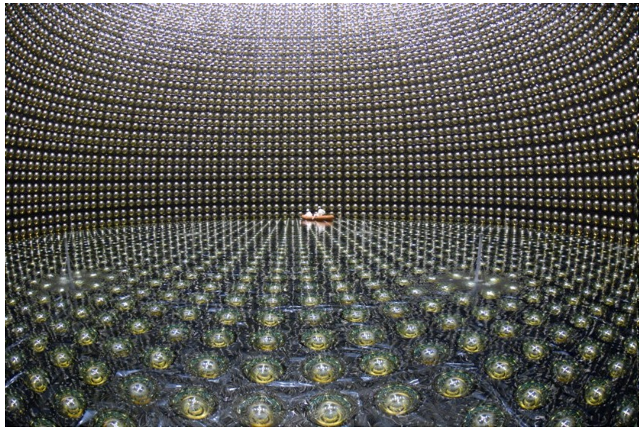
Atmospheric neutrino source

$$\pi^+ \rightarrow \mu^+ + \nu_\mu$$
$$\hookrightarrow e^+ + \nu_e + \bar{\nu}_\mu$$
$$\pi^- \rightarrow \mu^- + \bar{\nu}_\mu$$
$$\hookrightarrow e^- + \bar{\nu}_e + \nu_\mu$$

- The rate of neutrinos should be the same from below and above
- But: About 50% missing from below
- Neutrino change their flavor on the path from production to detection: Neutrino oscillations
- Neutrinos are massive!

(Super-Kamiokande: "Evidence for oscillations of atmospheric neutrinos", 1998)





Super-Kamiokande
Kajita: Nobel prize 2015

Resolving the solar neutrino puzzle

Final test of solar neutrino problem: measure neutral current interactions, sensitive to all flavors (2002)

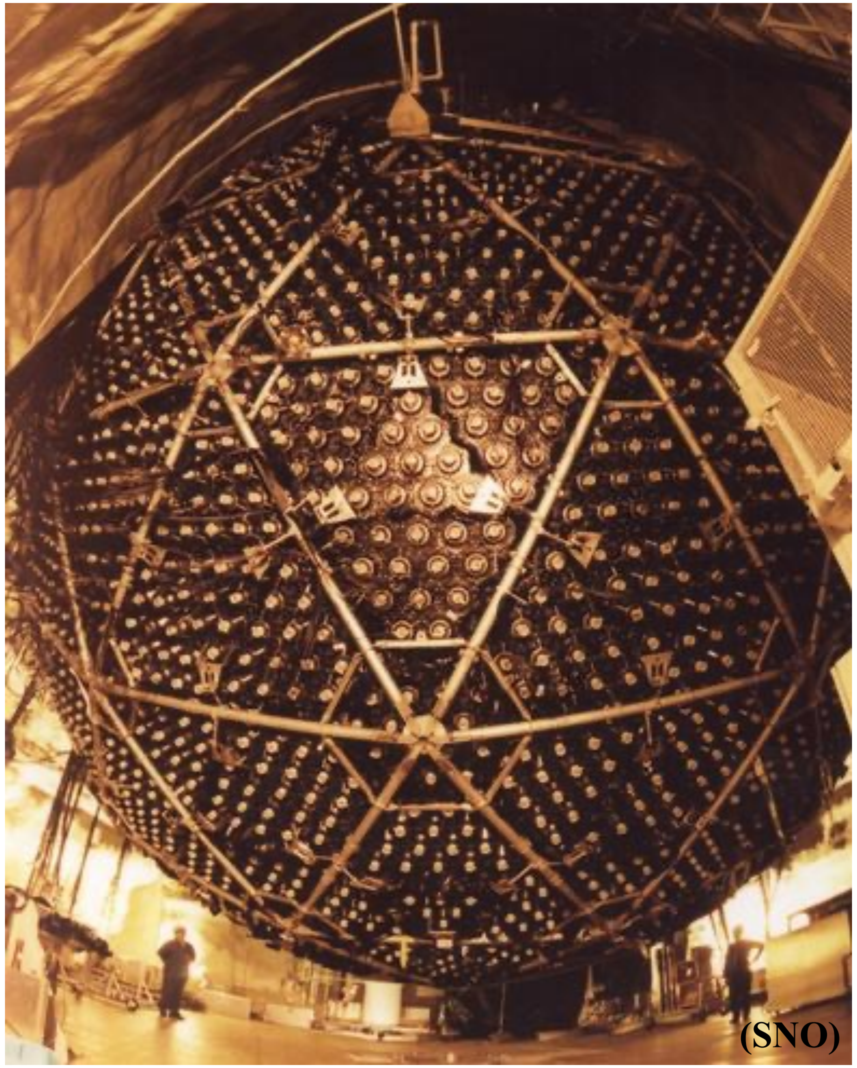
$$\nu_e + {}^2H \rightarrow e^- + p + p \quad \text{(CC)}$$

$$\nu_x + {}^2H \rightarrow \nu_x + p + n \quad \text{(NC)}$$

$$\nu_x + e^- \rightarrow \nu_x + e^- \quad \text{(ES)}$$

- The rate matches the Standard Solar Model
- Neutrinos change flavor in the Sun

(SNO, McDonald Nobel prize 2015)


(SNO)

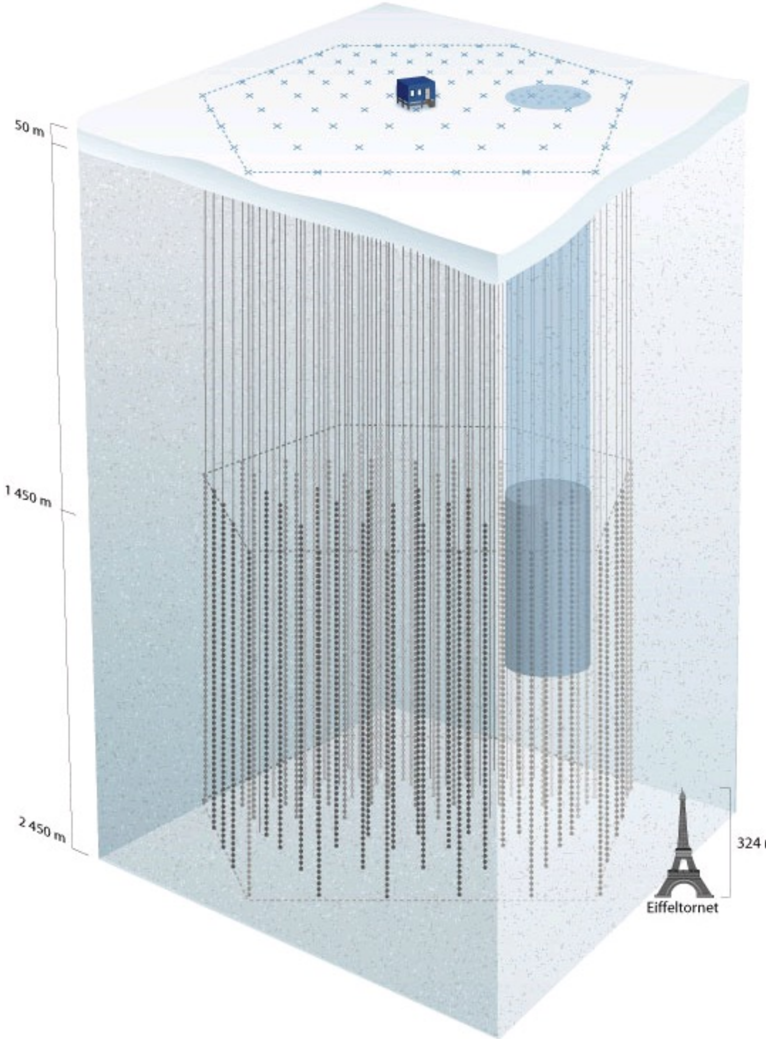
Neutrinos as extragalactic cosmic messengers

- The birth of neutrino astronomy: Feb. 23, 1987 Detection of about twelve neutrinos from an extragalactic supernova explosion (so far, the only one ...); Nobel prize 2002

- The birth of high-energy neutrino astrophysics: The IceCube neutrino telescope of the South Pole sees 28 events in the TeV-PeV range →
  Science 342 (2013) 1242856

  DESY-Zeuthen hosts one of the largest groups in IceCube worldwide!

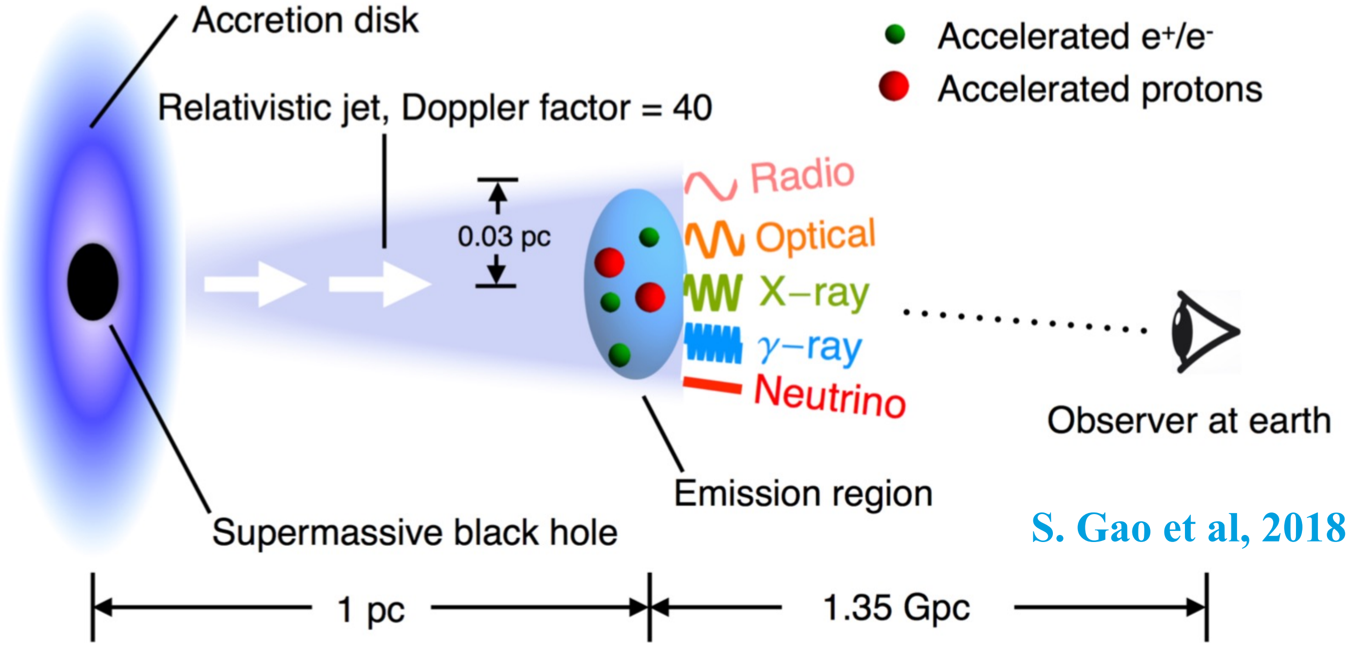
Physics World
Breakthrough of the year 2013



http://icecube.wisc.edu/

Neutrinos from individual sources

Resources (animations/videos):
https://multimessenger.desy.de/
https://www.desy.de/news/news_search/index_eng.html?openDirectAnchor=2030



S. Gao et al, 2018

So what is “neutrino physics”?

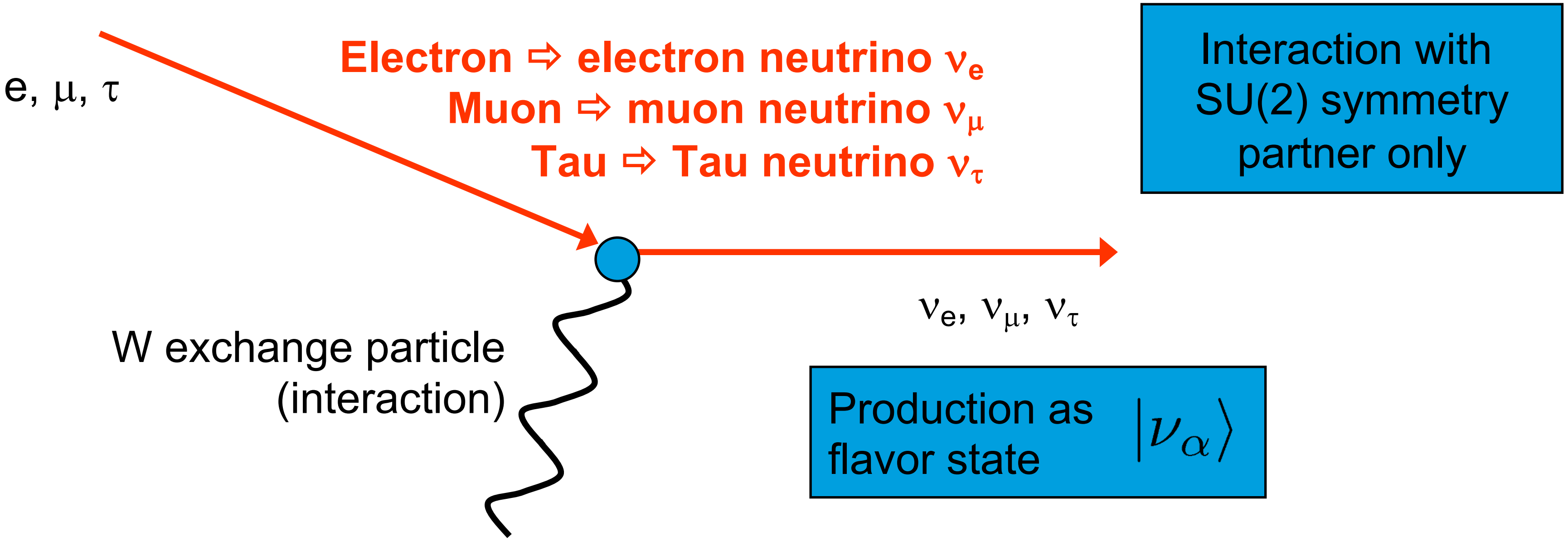
	Particle physics	The Universe	Other disciplines
	Missing energy		
The established	Neutrino oscillations; CP violation, leptogenesis	Cosmology; Stellar burning	Tests of nuclear theory; Reactor ν flux measurements
The emerging	Measurement of ν mass; Sterile neutrinos	Stellar evolution; Origin of cosmic rays	Geo-chemistry; Nuclear monitoring
The fantastic	Physics beyond νSM	Cosmogenic neutrinos; Detection of relic νs	Earth tomography; SETI & Communication
	ν-theory of everything (baryogenesis, dark matter, dark energy)		

For a more differentiated perspective, see the IUPAP neutrino panel report.
Prog. Part. Nucl. Phys. 124 (2022) 103947, arXiv:2111.07586

Introduction to neutrino oscillations

Neutrino production/detection

- Neutrinos are only produced and detected by the weak interaction:



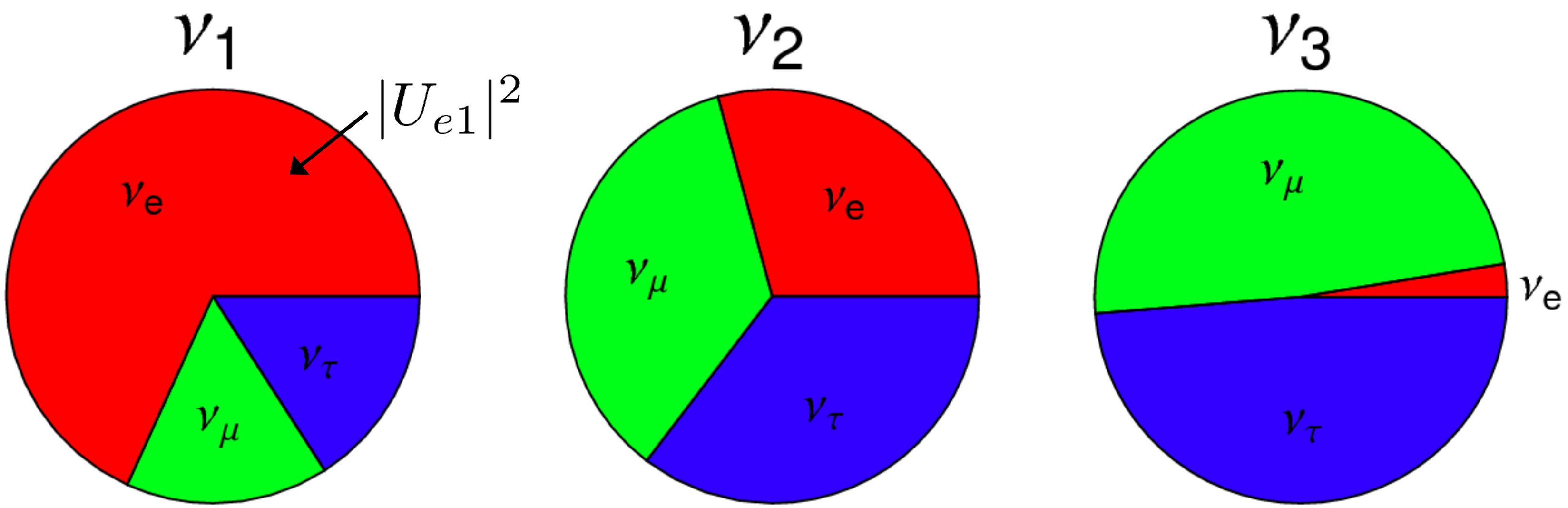
- The dilemma: One cannot assign a mass to the flavor states ν_e, ν_μ, ν_τ!

Which mass do the neutrinos have?

- There is a set of neutrinos ν_1, ν_2, ν_3, for which a mass can be assigned.
- Mixture of flavor states:

$$|\nu_i\rangle$$

$$|\nu_\alpha\rangle = \sum_{k=1}^{3} U^*_{\alpha k} |\nu_k\rangle$$

- 

- Not unusual, know from the Standard Model for quarks
- However, the mixings of the neutrinos are much larger!

$\sin^2 2\theta_{13}=0.1$, $\delta=\pi/2$

Neutrino oscillation probability

Standard derivation N active, S sterile (not weakly interacting) flavors

- Mixing of flavor states
$$|\nu_\alpha\rangle = \sum_{k=1}^{N+S} U^*_{\alpha k} |\nu_k\rangle$$

- Time evolution of mass state $|\nu_k(t)\rangle = \exp(-iE_k t)\,|\nu_k\rangle$

- Transition amplitude
$$A_{\nu_\alpha \to \nu_\beta} \equiv A_{\alpha\beta} = \langle \nu_\beta | \nu_\alpha(t)\rangle = \sum_{k=1}^{N+S} U^*_{\alpha k} U_{\beta k}\, \exp(-iE_k t)$$

- Transition probability
$$P_{\alpha\beta} = A^*_{\alpha\beta} A_{\alpha\beta} = \sum_{k,\,j=1}^{N+S} \underbrace{U^*_{\alpha k} U_{\beta k} U_{\alpha j} U^*_{\beta j}}_{\equiv J^{\alpha\beta}_{kj}} \exp\left(-i(E_k - E_j)t\right)$$

"quartic re-phasing invariant"

Further simplifications

- Ultrarelativistic approximations:

$$E_k = \sqrt{\vec{p}^2 + m_k^2} \simeq E + \frac{m_k^2}{2E}, \qquad t \simeq L$$

  L: baseline (distance source-detector)
- Plus some manipulations: “Master formula“

$$P_{\alpha\beta} = \delta_{\alpha\beta} - 4\underbrace{\sum_{k>j} \mathrm{Re} J_{kj}^{\alpha\beta} \sin^2\left(\frac{\Delta m_{kj}^2 L}{4\,E}\right)}_{\text{CP conserving}} + 2\underbrace{\sum_{k>j} \mathrm{Im} J_{kj}^{\alpha\beta} \sin\left(\frac{\Delta m_{kj}^2 L}{2\,E}\right)}_{\text{CP violating}}$$

$\Delta m_{kj}^2 \equiv m_k^2 - m_j^2$ “mass squared difference“

F(L,E)=L/E “spectral dependence“

- For antineutrinos: U ⇨ U*

Two flavor limit: N=2, S=0

- Only two parameters:

$$U = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix}$$

Lower limit for neutrino mass!

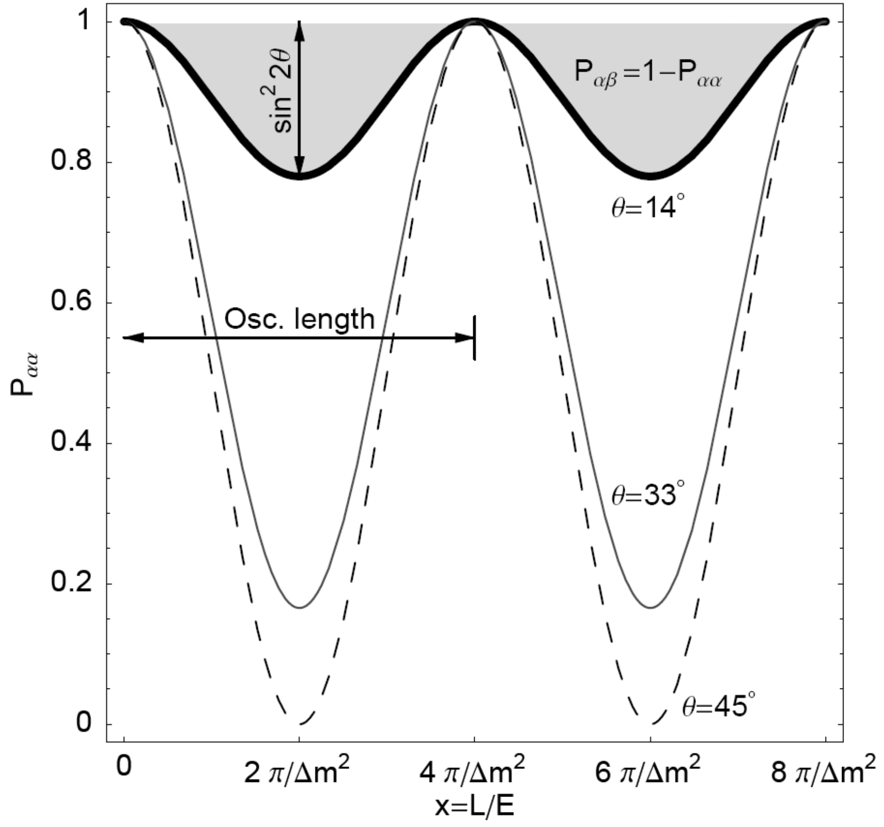
$$\Delta m^2_{21} \equiv m_2^2 - m_1^2$$

- From the master formula:
  Disappearance or **survival** probability

$$P_{\alpha\alpha} = 1 - \sin^2 2\theta \, \sin^2\left(\frac{\Delta m^2 L}{4E}\right)$$

Appearance probability

$$P_{\alpha\beta} = \sin^2 2\theta \, \sin^2\left(\frac{\Delta m^2 L}{4E}\right)$$



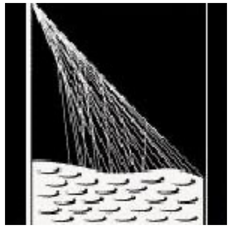
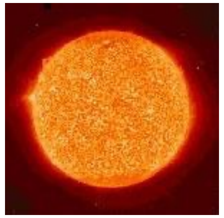
Three flavors: Mixings

- Use same parameterization as for CKM matrix

Potential CP violation ~ θ_{13}

$$U_{\text{PMNS}} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}\,e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}\,e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}.$$

($s_{ij} = \sin\theta_{ij}$ $c_{ij} = \cos\theta_{ij}$)

= () x () x ()

Pontecorvo-Maki-Nakagawa-Sakata matrix

- Neutrinos ⇨ Anti-neutrinos: **U ⇨ U*** (neutrino oscillations)
- If neutrinos are their own anti-particles (Majorana neutrinos):
  U ⇨ U diag($1,e^{i\alpha},e^{i\beta}$) - do enter $0\nu\beta\beta$, but not neutrino oscillations

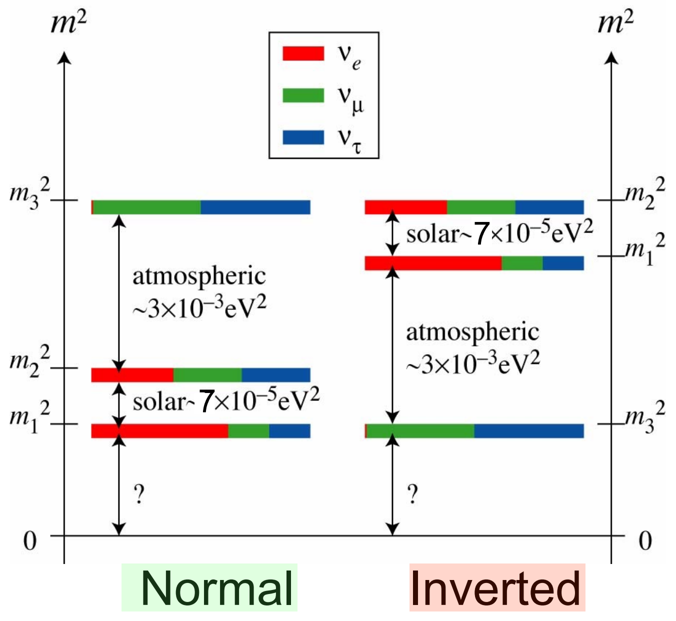
Three flavors: Neutrino masses. Ordering vs. hierarchy

- The (atmospheric) mass **ordering** is unknown →
  (normal or inverted)

- The absolute neutrino mass scale is unknown (< eV).
  Often parameterized by lightest neutrino mass: m_1 or m_3

- In theory: three cases
  - Normal **hierarchy**: $m_1 < (\Delta m_{21}^2)^{0.5}$ (**ordering**: normal)
  - Inverted **hierarchy**: $m_3 \ll |\Delta m_{31}^2|^{0.5}$ (**ordering**: inverted)
  - (Quasi-)**Degenerate**: $m_1 \sim m_2 \sim m_3 \gg |\Delta m_{31}^2|^{0.5}$
    (**ordering**: normal or inverted)

- Lower bound on neutrino neutrino masses from $\Delta m_{31}^2 \sim 0.0024\ eV^2$:
  Normal hierarchy: $m_3 \sim 0.05$ eV
  Inverted hierarchy: $m_1, m_2 \sim 0.1$ eV



$$\Delta m_{ij}^2 = m_i^2 - m_j^2$$

Current knowledge of neutrino oscillations

Three flavors: Simplified

- What we know (qualitatively):
  - Hierarchy of mass splittings $$\Delta m^2_{21} \ll |\Delta m^2_{31}| \simeq |\Delta m^2_{32}|$$
  - Two mixing angles large, one (θ_{13}) small ~ 0?

$$U^{\theta_{13}\to 0}_{\text{PMNS}} = \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12}\, c_{23} & c_{12}\, c_{23} & s_{23} \\ s_{12}\, s_{23} & -c_{12}\, s_{23} & c_{23} \end{pmatrix}$$

- From the “master formula“, we have

$$P_{\alpha\beta} = \delta_{\alpha\beta} - 4\left(J^{\alpha\beta}_{31} + J^{\alpha\beta}_{32}\right)\sin^2\Delta_{31} - 4\, J^{\alpha\beta}_{21}\sin^2\Delta_{21}$$

$$J^{\alpha\beta}_{kj} = U^*_{\alpha k} U_{\beta k} U_{\alpha j} U^*_{\beta j} \qquad \Delta_{ij} \equiv \Delta m^2_{ij}\, L/(4E)$$

Two flavor limits

$$P_{\alpha\beta} = \delta_{\alpha\beta} - 4\left(J_{31}^{\alpha\beta} + J_{32}^{\alpha\beta}\right)\sin^2\Delta_{31} - 4\,J_{21}^{\alpha\beta}\sin^2\Delta_{21}$$

$$\Delta_{ij} \equiv \Delta m_{ij}^2\, L/(4E)$$

Two flavor limits by selection of frequency:

- Atmospheric frequency: $\Delta_{31} \sim \pi/2$ ⇨ $\Delta_{21} << 1$

$$P_{\alpha\beta} = \delta_{\alpha\beta} - 4\left(J_{31}^{\alpha\beta} + J_{32}^{\alpha\beta}\right)\sin^2\Delta_{31} - 4\,J_{21}^{\alpha\beta}\sin^2\Delta_{21}$$

- Solar frequency: $\Delta_{21} \sim \pi/2$ ⇨ $\Delta_{31} >> 1$

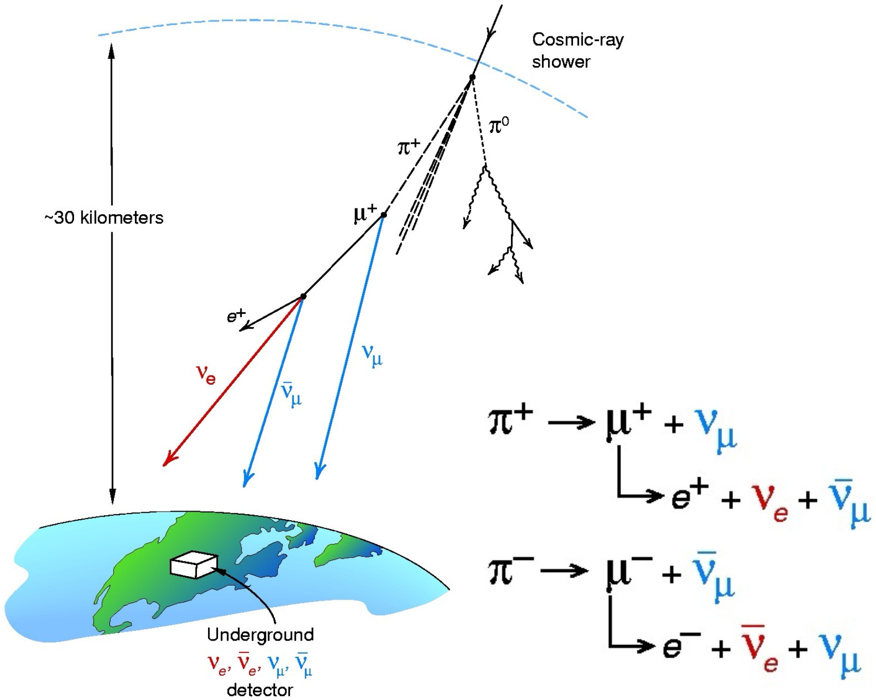
$$P_{\alpha\beta} = \delta_{\alpha\beta} - 4\left(J_{31}^{\alpha\beta} + J_{32}^{\alpha\beta}\right)\sin^2\Delta_{31} - 4\,J_{21}^{\alpha\beta}\sin^2\Delta_{21}$$

averages out

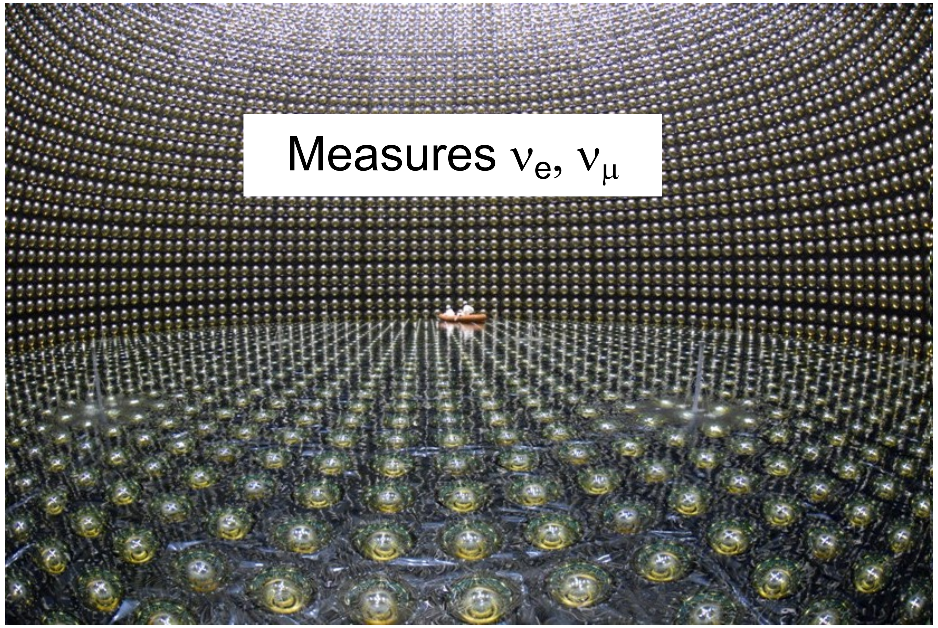
0.5

Select sensitive term by choice of L/E!

Atmospheric neutrinos



Super-Kamiokande



From $P_{\alpha\beta} = \delta_{\alpha\beta} - 4\left(J_{31}^{\alpha\beta} + J_{32}^{\alpha\beta}\right)\sin^2\Delta_{31}$

and θ_{13} small, we have: $P_{ee} \sim 1$, $P_{e\mu} \sim P_{\mu e} \sim 0$ and

$$P_{\mu\mu} \simeq 1 - \sin^2(2\theta_{23})\sin^2\Delta_{31}$$

$$U_{\rm PMNS}^{\theta_{13}\to 0} = \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12}\,c_{23} & c_{12}\,c_{23} & s_{23} \\ s_{12}\,s_{23} & -c_{12}\,s_{23} & c_{23} \end{pmatrix}$$

$$J_{kj}^{\alpha\beta} = U_{\alpha k}^* U_{\beta k} U_{\alpha j} U_{\beta j}^*$$

⇨ Two flavor limit with particular parameters θ_{23}, Δm^2_{31}

Man-made neutrino sources

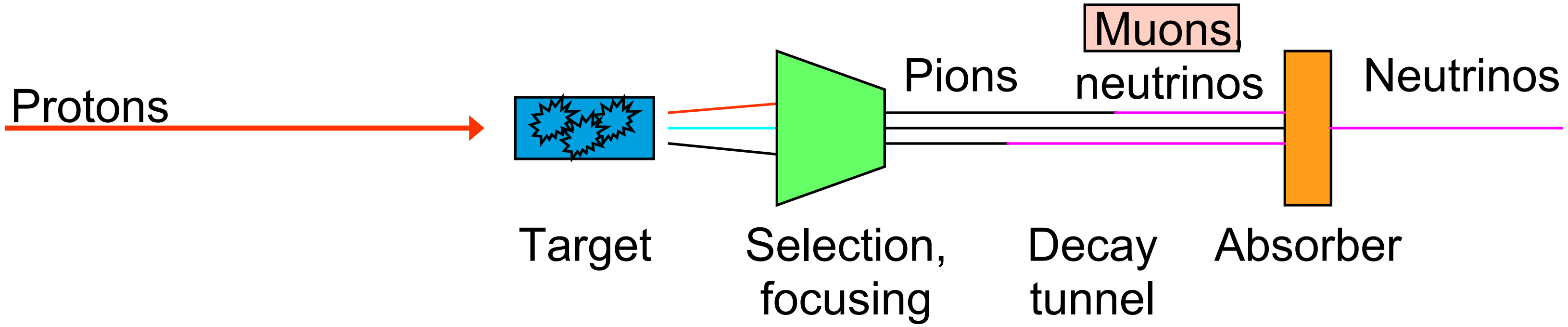
There are three possibilities to artificially produce neutrinos

- Beta decay:
  - Example: Nuclear reactors

$$n \longrightarrow p + e^- + \bar{\nu}_e$$

- Pion decay:
  - From accelerators:

$$\pi^- \longrightarrow \mu^- + \bar{\nu}_\mu$$



- Muon decay:
  - Muons produced by pion decays!

$$\mu^- \longrightarrow e^- + \nu_\mu + \bar{\nu}_e$$

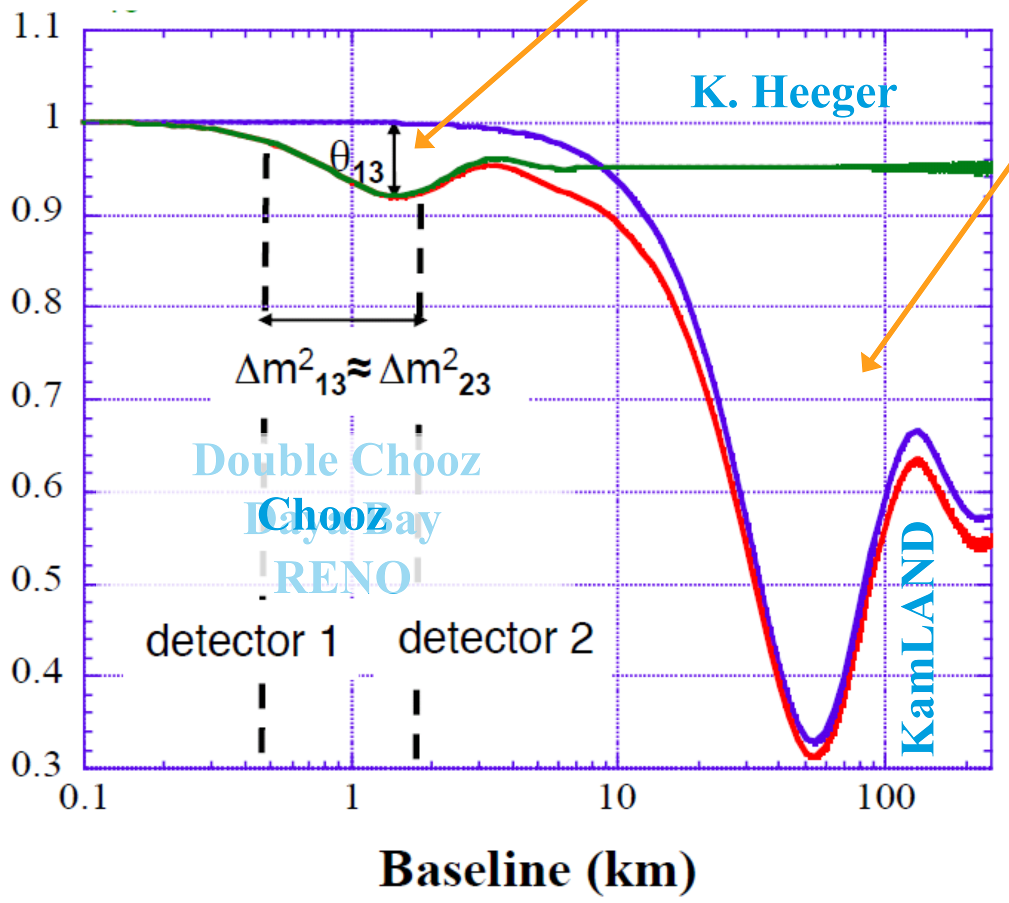
Reactor neutrinos

- In the presence of θ_{13} and solar effects:

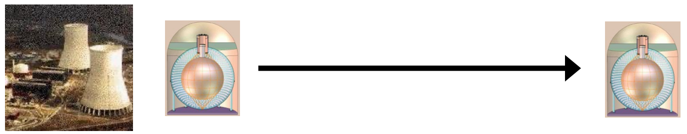
$$P_{\bar{e}\bar{e}} \simeq 1 - \sin^2(2\theta_{13}) \sin^2 \Delta_{31} - \cos^4 \theta_{13} \sin^2(2\theta_{12}) \sin^2 \Delta_{21}$$

atmospheric

solar



New idea:



Identical detectors, L ~ 1-2 km
to control systematics

(Minakata, Sugiyama, Yasuda, Inoue, Suekane, 2003;
Huber, Lindner, Schwetz, Winter, 2003)

Observation of Mixing Angle θ_{13}

in the Daya Bay Reactor Antineutrino Experiment

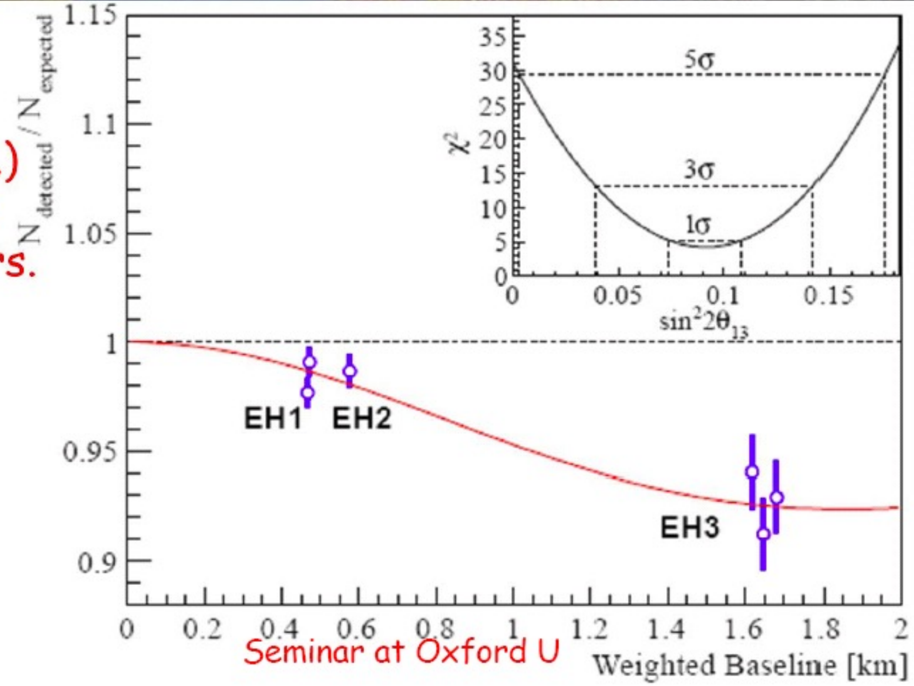
$$P_{\bar{e}\bar{e}} \simeq 1 - \sin^2(2\theta_{13})\sin^2\Delta_{31}$$

(short distance)

Kirk T McDonald
Princeton U
(April 24, 2012)
on behalf of the Daya Bay Collaboration

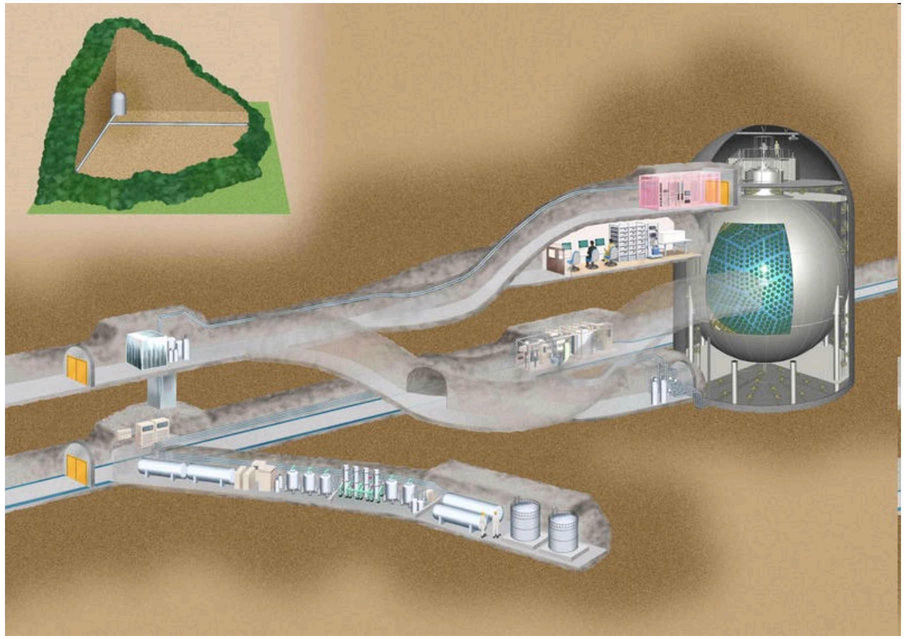
We observe that
$\sin^2 2\theta_{13}$ = 0.092 ± 0.016 (stat.) ± 0.005 (syst.)
after 55 days of operation with 6 detectors
at 3 sites close to 3 pairs of ~ 3 GW reactors.

F.P. Ahn *et al.*
Phys. Rev. Lett. **108**, 171803 (2012).



(also: T2K, Double Chooz, RENO)

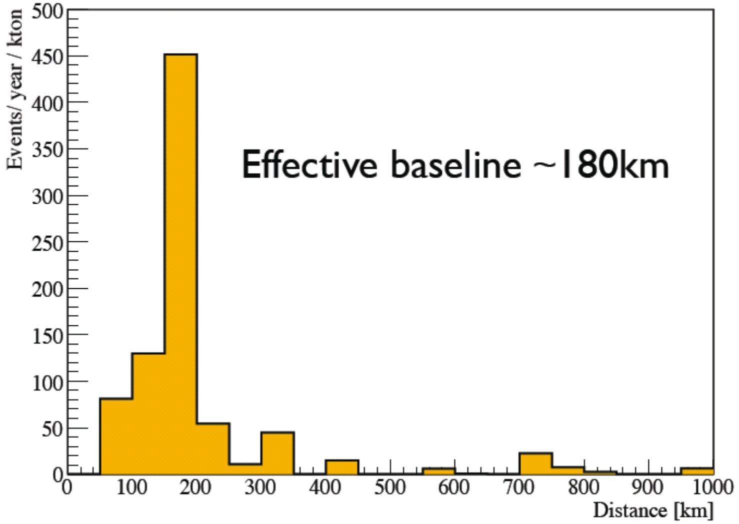
Reactor neutrinos: Solar frequency



KamLAND

Detection by inverse beta decay

$\bar{\nu}_e$

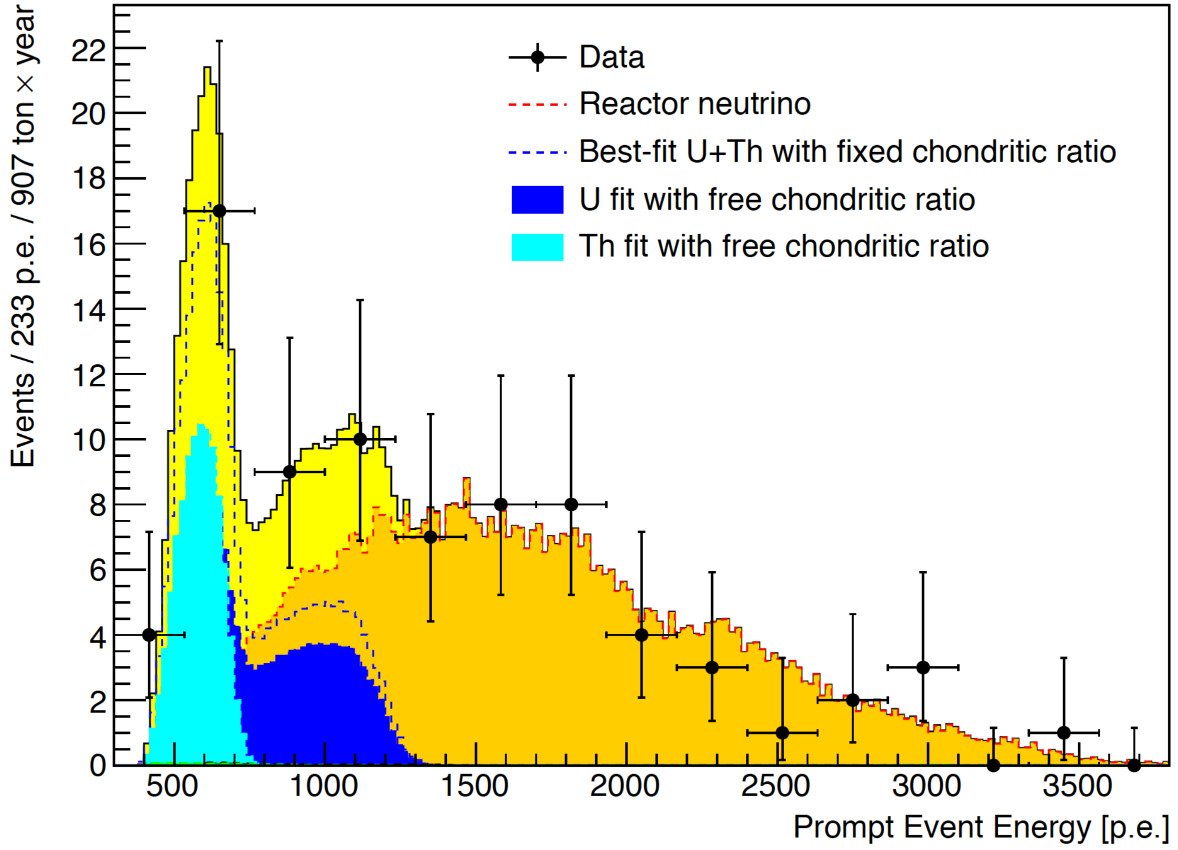


$$P_{\bar{e}\bar{e}} \simeq 1 - \sin^2(2\theta_{12}) \sin^2 \Delta_{21}$$

Two flavor (small θ_{13}) limit with a different set of parameters: θ_{12}, Δm^2_{21}

Spin-off: Neutrino geochemistry

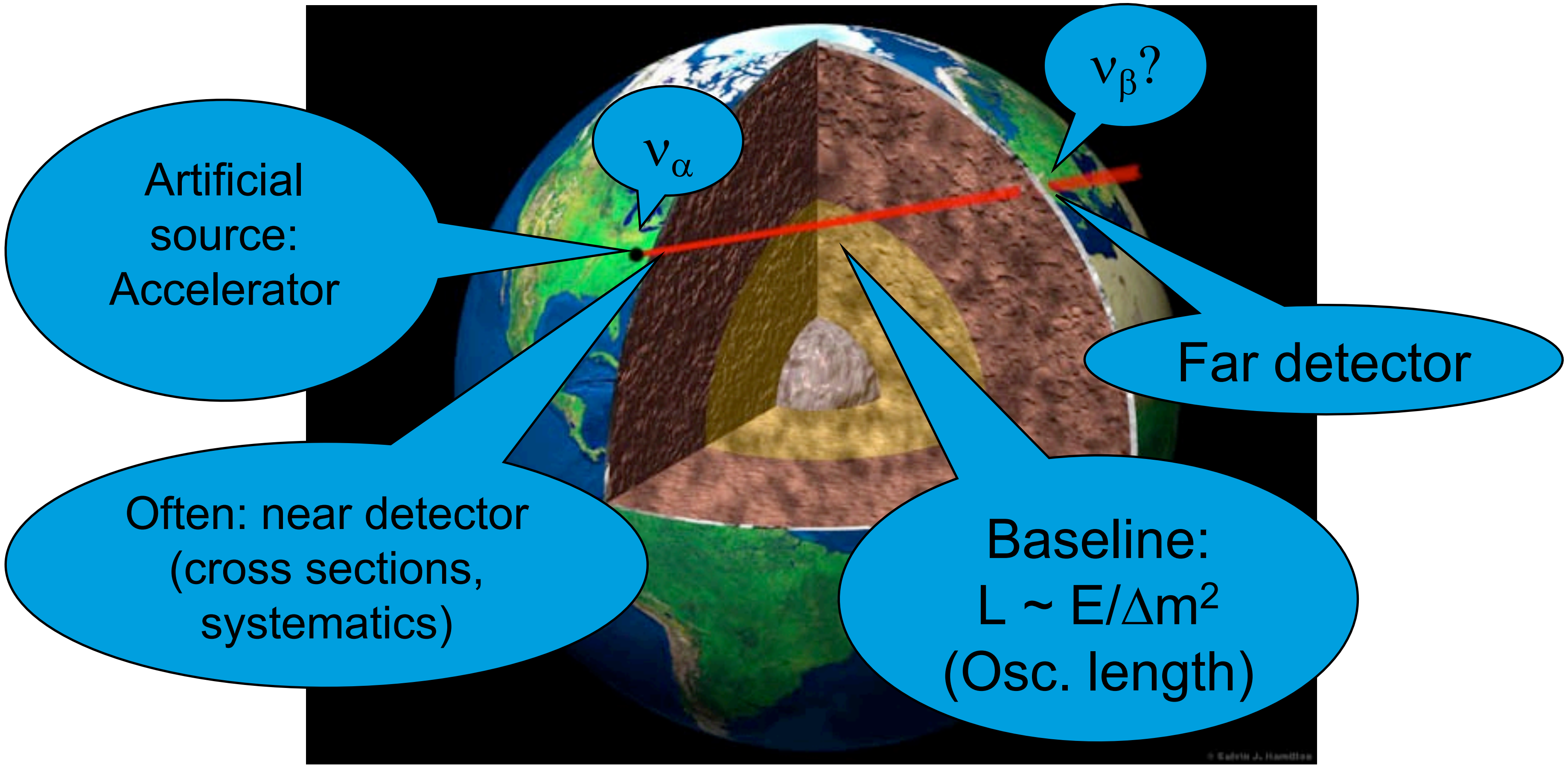
Neutrinos from ^{238}U and ^{232}Th decays are above the inverse beta decay detection thresholds of experiments such as KamLAND or Borexino



(figure from Borexino, Phys. Rev. D92 (2015) 031101; see also Nature 436 (2005) 495)

So far, consistent with expectations; higher precision needed for conclusions about chondritic model and age of the earth

Neutrino beams



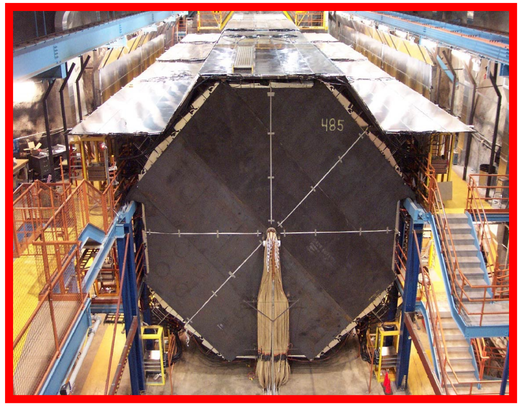
Examples:
NuMI beam (MINOS, NOvA), CNGS beam (OPERA, ICARUS), J-PARC beam (T2K), ...

Neutrino beam experiment: Example MINOS

Source: MINOS

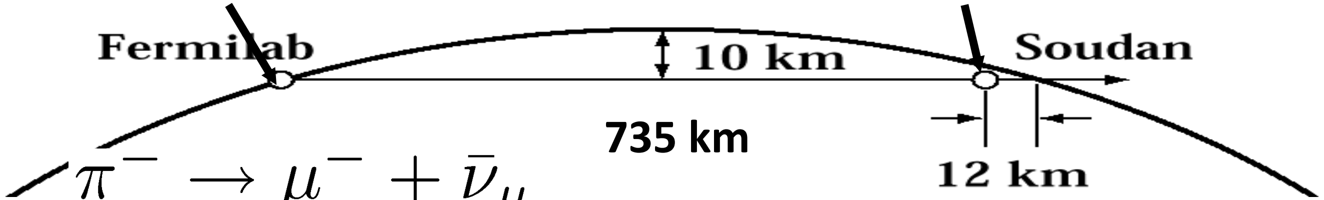
Experiment in the US for the precision measurement of atmospheric parameters

$$P_{\mu\mu} \simeq 1 - \sin^2(2\theta_{23})\sin^2\Delta_{31}$$



Near detector: 980 t

Far detector: 5400 t

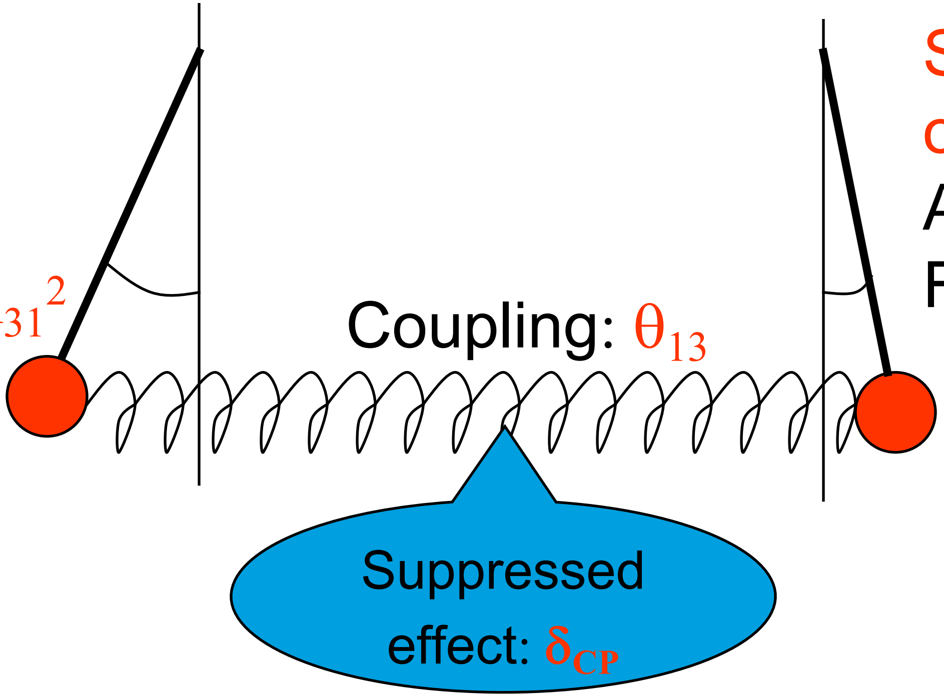


$$\pi^- \rightarrow \mu^- + \bar{\nu}_\mu$$

Three flavors: Summary

Three flavors: 6 params (3 angles, one phase; 2 x Δm^2)

Atmospheric oscillations:
Amplitude: θ_{23}
Frequency: Δm_{31}^2



Solar oscillations:
Amplitude: θ_{12}
Frequency: Δm_{21}^2

(Super-K, 1998; Chooz, 1999; SNO 2001+2002; KamLAND 2002; Daya Bay, RENO 2012; MINOS, T2K, NOvA …)

- Describes solar and atmospheric neutrino anomalies, as well as reactor antineutrino disappearance!

Precision of parameters? Combined fit.

NuFIT 5.0 (2020)

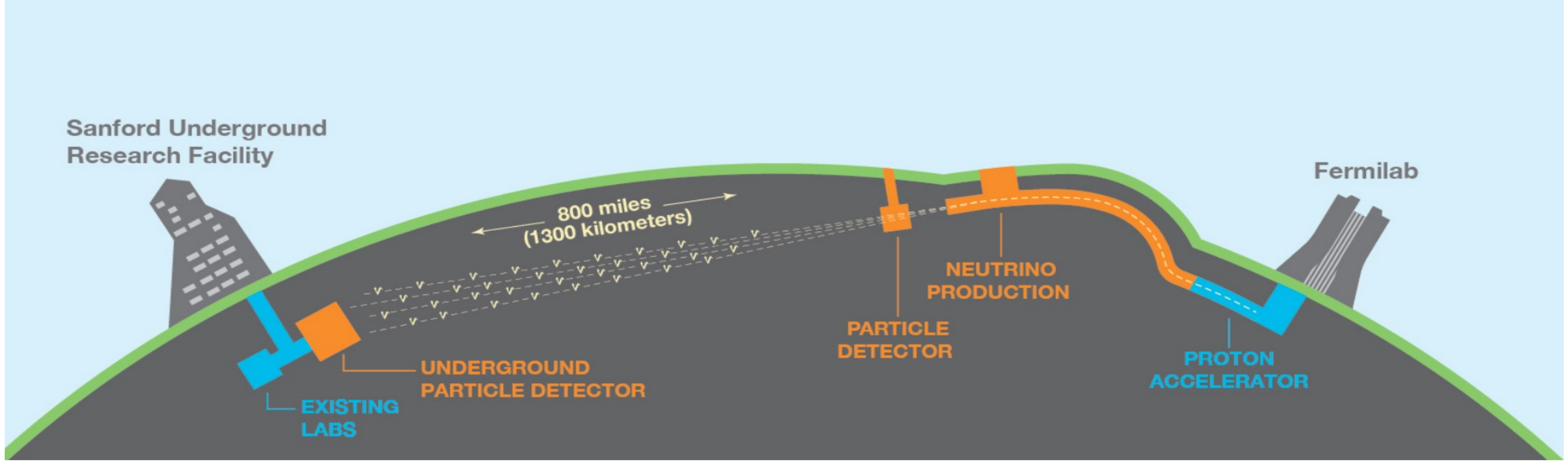
	Normal Ordering (best fit)		Inverted Ordering ($\Delta\chi^2 = 2.7$)		
	bfp $\pm 1\sigma$	3σ range	bfp $\pm 1\sigma$	3σ range	
$\sin^2\theta_{12}$	$0.304^{+0.013}_{-0.012}$	$0.269 \to 0.343$	$0.304^{+0.013}_{-0.012}$	$0.269 \to 0.343$	± 2%
$\theta_{12}/^\circ$	$33.44^{+0.78}_{-0.75}$	$31.27 \to 35.86$	$33.45^{+0.78}_{-0.75}$	$31.27 \to 35.87$	
$\sin^2\theta_{23}$	$0.570^{+0.018}_{-0.024}$	$0.407 \to 0.618$	$0.575^{+0.017}_{-0.021}$	$0.411 \to 0.621$	± 2%
$\theta_{23}/^\circ$	$49.0^{+1.1}_{-1.4}$	$39.6 \to 51.8$	$49.3^{+1.0}_{-1.2}$	$39.9 \to 52.0$	
$\sin^2\theta_{13}$	$0.02221^{+0.00068}_{-0.00062}$	$0.02034 \to 0.02430$	$0.02240^{+0.00062}_{-0.00062}$	$0.02053 \to 0.02436$	± 1%
$\theta_{13}/^\circ$	$8.57^{+0.13}_{-0.12}$	$8.20 \to 8.97$	$8.61^{+0.12}_{-0.12}$	$8.24 \to 8.98$	
$\delta_{CP}/^\circ$	195^{+51}_{-25}	$107 \to 403$	286^{+27}_{-32}	$192 \to 360$	± 15%
$\frac{\Delta m^2_{21}}{10^{-5}\ \mathrm{eV}^2}$	$7.42^{+0.21}_{-0.20}$	$6.82 \to 8.04$	$7.42^{+0.21}_{-0.20}$	$6.82 \to 8.04$	± 3%
$\frac{\Delta m^2_{3\ell}}{10^{-3}\ \mathrm{eV}^2}$	$+2.514^{+0.028}_{-0.027}$	$+2.431 \to +2.598$	$-2.497^{+0.028}_{-0.028}$	$-2.583 \to -2.412$	± 1%

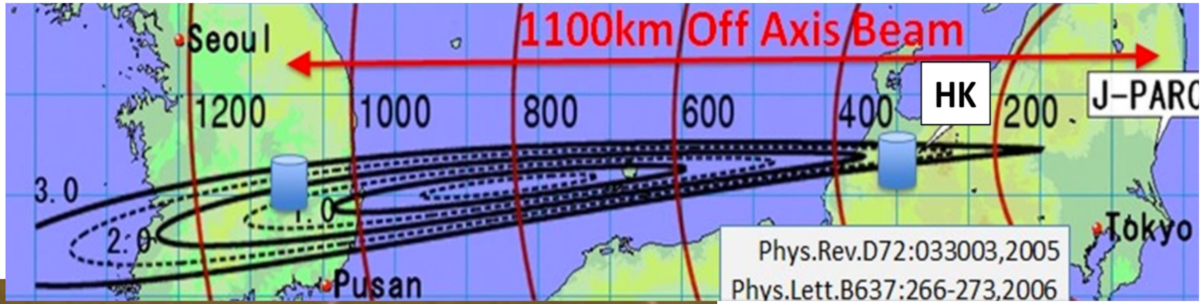
Open/interesting issues:
- **Degeneracies (mass ordering, octant?)**
- **CP phase, CP violation**
- **Short-baseline anomalies (not covered)**

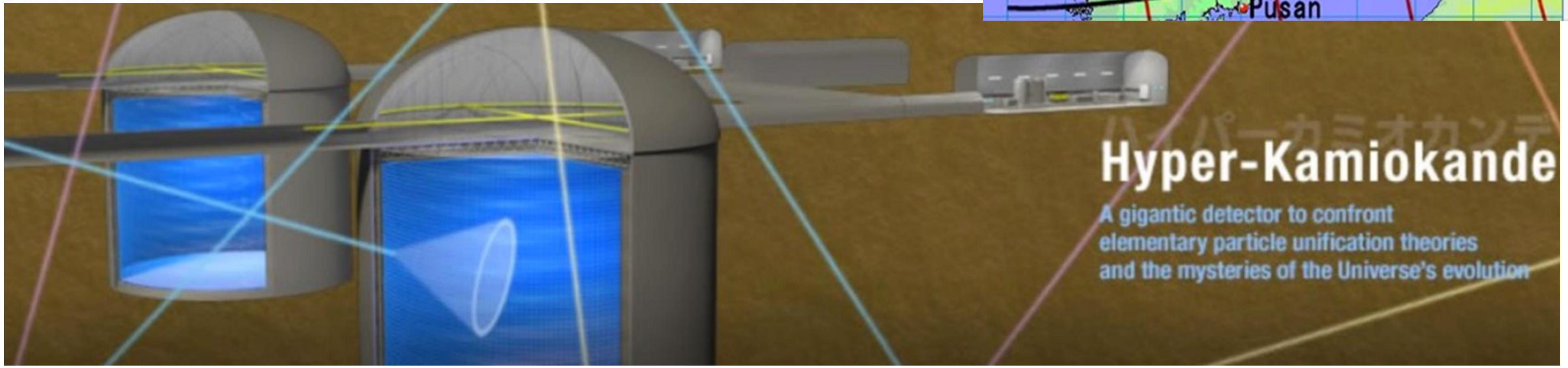
Age of the
precision flavor physics
of the lepton sector

Gonzalez-Garcia, Maltoni, Salvado, Schwetz, JHEP 1212 (2012) 123.
Check for updates at http://www.nu-fit.org

The future: DUNE, T2HK/T2KK







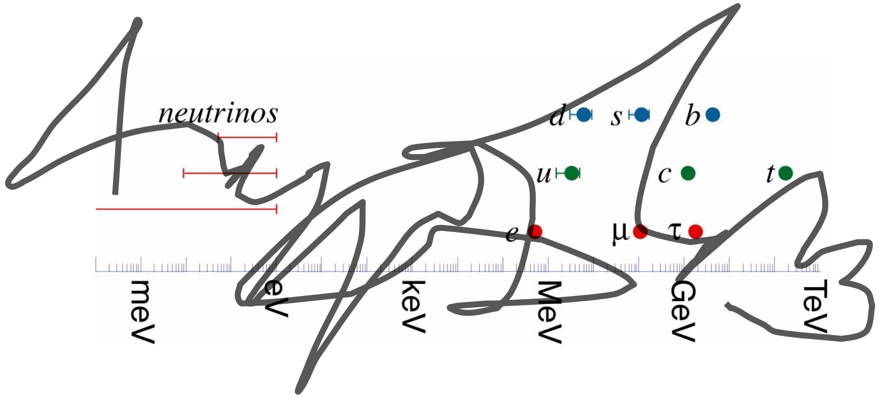
Neutrino mass:
Evidence for physics BSM?

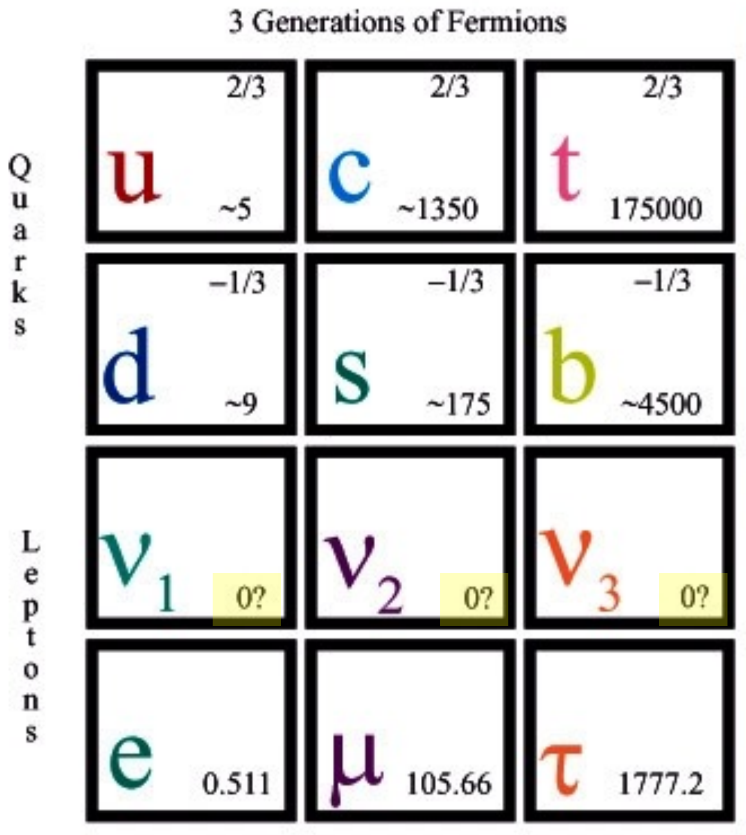
(a flavour of theory …)

Origin of neutrino mass: physics beyond the SM?

- Neutrinos in the Standard Model are massless, but: the charged leptons have masses
- So what?

  Introduce right-handed neutrino field ν^c,
  Yukawa interaction ~ Y l H ν^c
  forget about fine-tuning (Y)





Masses are in MeV

Problem fixed!!!!!?

Caveat: Neutrinos are electrically neutral …

But:
“Naturalness arguments are aesthetic arguments“

Sabine Hossenfelder

- **Reminder from “model building 101”, rule 1:**
  If I introduce new fields, I have to write down all possible interactions allowed by the gauge symmetries given the (new) field content
- I can write a Majorana mass term ~ $M_R \nu^c \nu^c$ with the new field ν^c because the neutrino is electrically neutral
- Violates lepton number by two units

- <u>Problem solution (1):</u> get rid off this Majorana mass term

Scenario “ν-simple”

- **Reminder from “model building 101”, rule 2:**
  If I want to forbid some interactions, I introduce (invent?) a (new) symmetry and charge the fields under it
- Here we have such a symmetry already: lepton number is *accidentally* conserved in the Standard Model
- Promote lepton number from an accidental to a fundamental symmetry?
- Physics BSM (kind of), but no leptogenesis

What if there is a Majorana mass term?

- Problem solution (2): Accept that there is such a mass term
- Lepton number violation, clearly physics beyond the Standard Model
- Lagrangian for fermion masses after EWSB

$$\mathcal{L}_{\text{mass}} = -(M_\ell)_{ij} e_i e^c_j - (M_D)_{ij} \nu_i \nu^c_j - \frac{1}{2} (M_R)_{ij} \nu^c_i \nu^c_j + h.c.$$

Scenario “ν-compact”
aka Type-I seesaw

$$\mathcal{L}_{\text{mass}} \sim (\nu \;\; \nu^c) \begin{pmatrix} & M_D \\ M_D^T & M_R \end{pmatrix} \begin{pmatrix} \nu \\ \nu^c \end{pmatrix}$$

Block diag.

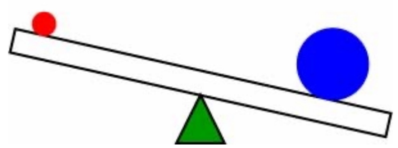
$$M^{\text{Maj}}_{\text{eff}} = -M_D M_R^{-1} M_D^T$$

- Fixes two other problems: smallness of neutrino mass and *leptogenesis*

$$m_\nu = \frac{m_D^2}{M_R}$$

m_D^2 ← Other SM particles

M_R ← Heavy partner



Generation of fermion mixings: Standard theory

$$\mathcal{L}_{\text{mass}} = -(M_\ell)_{ij} e_i e^c_j - (M_D)_{ij} \nu_i \nu^c_j - \frac{1}{2}(M_R)_{ij} \nu^c_i \nu^c_j + h.c.$$

$$\mathcal{L}_{\text{mass}} \sim (\nu \; \nu^c) \begin{pmatrix} & M_D \\ M_D^T & M_R \end{pmatrix} \begin{pmatrix} \nu \\ \nu^c \end{pmatrix}$$

Model-dependent (type-II, III seesaw, radiative generation of neutrino mass, etc)

Block diag.

$$M^{\text{Maj}}_{\text{eff}} = -M_D M_R^{-1} M_D^T$$

Scenario "ν-complex"

Charged lepton mass terms

Eff. neutrino mass terms

$$M_\ell = U_\ell M_\ell^{\text{diag}} (U'_\ell)^\dagger \qquad M^{\text{Maj}}_{\text{eff}} = U_\nu M_\nu^{\text{diag}} U_\nu^T$$

Rotates left-handed fields

$$U_{\text{PMNS}} = U_\ell^\dagger U_\nu$$

cf., charged current

$$J^\mu = \bar{l}_L \gamma^\mu (1-\gamma_5) U_\ell^\dagger U_\nu \nu$$

Origin of MH and CP violation? Leptogenesis?

- Scenario "ν-**simple**"

Structure from flavor model?

Mass hierarchy

CP violation

$$\mathcal{L}_{\text{mass}} = -(M_\ell)_{ij} e_i e_j^c - (M_D)_{ij} \nu_i \nu_j^c$$

$$M_\ell = U_\ell M_\ell^{\text{diag}} (U'_\ell)^\dagger \qquad M_\nu = U_\nu M_\nu^{\text{diag}} (U'_\nu)^\dagger$$

$$U_{\text{PMNS}} = U_\ell^\dagger U_\nu$$

No leptogenesis

- Scenario "ν-**compact**" (aka type-I seesaw)

$$\mathcal{L}_{\text{mass}} = -(M_\ell)_{ij} e_i e_j^c - (M_D)_{ij} \nu_i \nu_j^c - \frac{1}{2}(M_R)_{ij} \nu_i^c \nu_j^c + h.c.$$

… works even if heavy neutrinos at GeV scale, and together with a keV dark matter candidate
Canetti, Drewes, Shaposhnikov, 2012

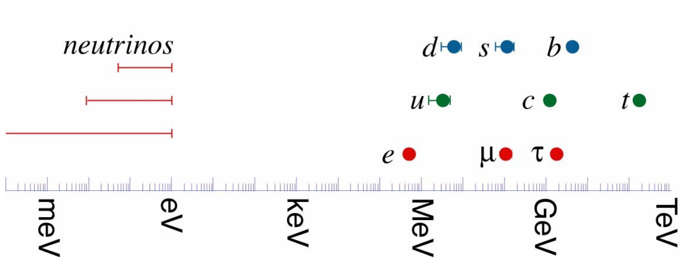
Leptogenesis!

- Scenario "ν-**complex**"
Origin of MH and CP violation depends on specific scenario; no universal discussion of leptogenesis possible

Leptogenesis?

Recap: A simple and self-consistent scenario: "ν-compact"

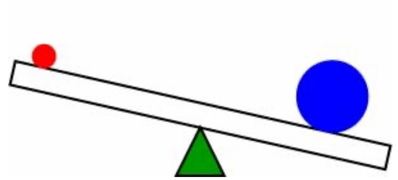
- Why are the neutrinos more than 250.000 times lighter than the electron?



- Seesaw mechanism: Neutrino mass suppressed by heavy partner, which only exists in the early universe?

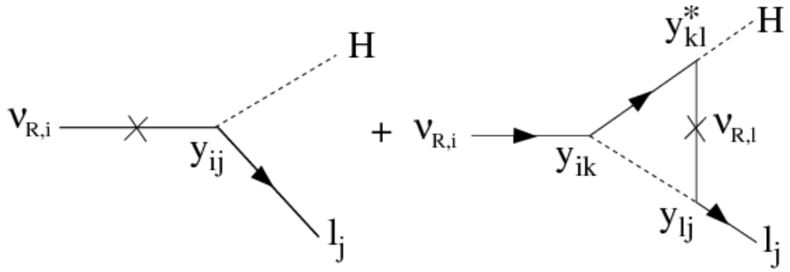
$$m_\nu = \frac{m_D^2}{M_R}$$

← Other SM particles
← Heavy partner



Decay of (thermally produced) M_R origin of matter-antimatter-asymmetry?
Thermal leptogenesis

→



- Often quoted experimental evidence:
  - CP violation? Test in neutrino oscillations
  - Requires Majorana nature of neutrino! Test in neutrinoless double beta decay (0νββ)

How solid is the evidence from such experimental tests?

Do we really test thermal leptogenesis with δ_{CP}?

- The *pessimistic* perspective: There is no general connection

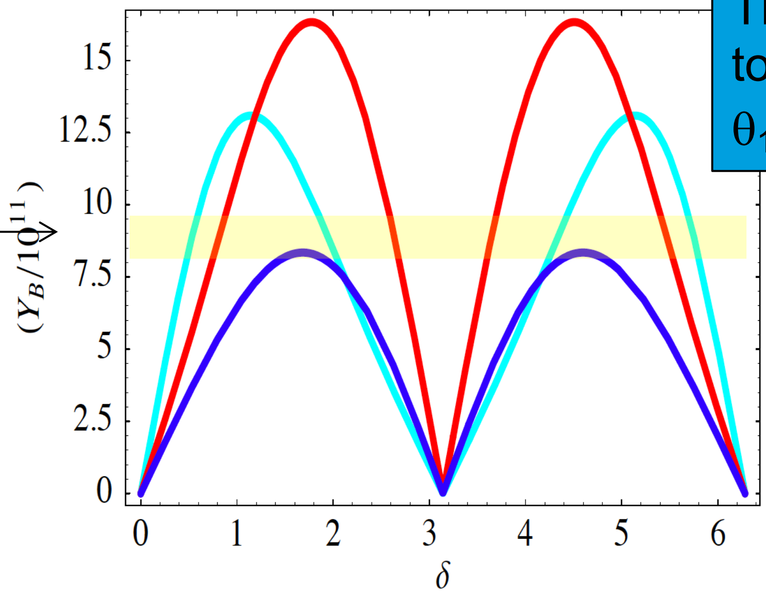
$$y = \frac{1}{v} \sqrt{M_R^{\text{diag}}}\, R \sqrt{M_\nu^{\text{diag}}}\, U_{\text{PMNS}}^\dagger$$

R: arbitrary, $R^T R=1$

Casas, Ibarra, 2001

Leptogenesis = Not accessible x Measurable

- The *minimalistic* perspective:
  One can find parameters for which the CP violation from δ_{CP} is sufficient to generate the baryon asymmetry
  Pascoli, Petcov, Riotto, 2007 + newer papers



Thanks to large θ_{13}!

- The *self-consistent* perspective:
  However, there is so far no (?) convincing model to imply that
- The *agnostic* perspective:
  Why care, we would probably anyways not be able to test that…

A different perspective: Effective field theory

BSM physics described by effective (gauge-invariant) operators in the low-E limit (gauge invariant) in the presence of *heavy* fields (>> EWSB):

$$\mathcal{L} = \mathcal{L}_{\rm SM} + \frac{1}{\Lambda}\mathcal{L}_5 + \frac{1}{\Lambda^2}\mathcal{L}_6 + \ldots$$

Λ: Scale of new physics

$$\mathcal{L}_5 = LLHH$$
$$\mathcal{L}_6 = \bar{L}L\bar{L}L$$
$$\mathcal{L}_7 = (LLHH)(H^\dagger H)$$
$$\mathcal{L}_8 = (\bar{L}L\bar{L}L)(H^\dagger H)$$

Neutrino mass (LNV) $0\nu\beta\beta$ decay!

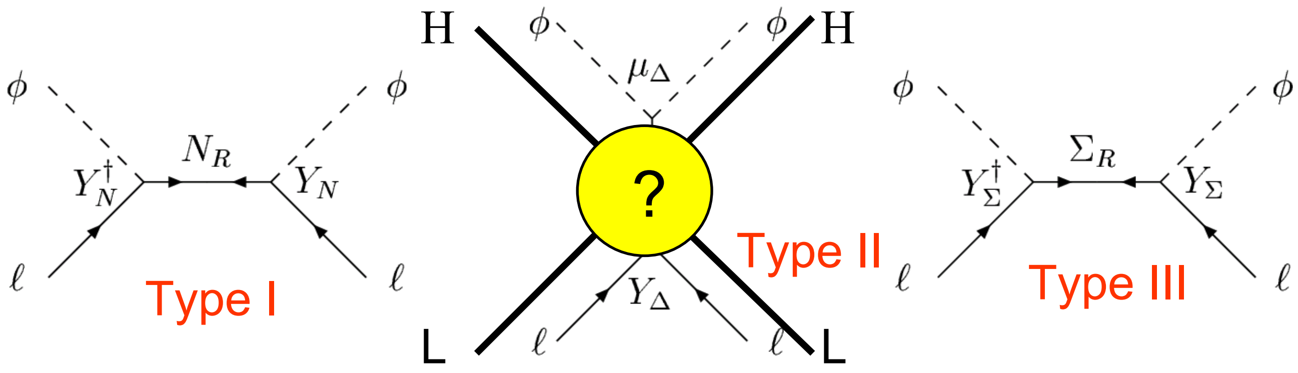
Lepton flavor violation (LFV)

There is only one d=5 operator, the so-called Weinberg operator.
Leads to light effective Majorana masses after EWSB.
Neutrino mass is the lowest order perturbation of physics BSM!

But these are no fundamental theories (so-called "non-renormalizable operators").
Idea: Investigate fundamental theories systematically!

Tree-level decompositions of the Weinberg operator

- Fundamental theories at tree level:



ϕ ~ H, L ~ l

Seesaw

- Neutrino mass ~ $Y^2 v^2/\Lambda$ (type I, III see-saw)
- For Y = O(1), v ~ 100 GeV: Λ ~ GUT scale
- For Λ ~ TeV scale: Y << 10^{-5}

- Additional suppression e.g. from loop-generated neutrino masses.
  For a complete list of one-loop neutrino mass models, see e.g.
  Bonnet, Hirsch, Ota, Winter, 2012 + a lot of follow-up papers …

Summary and conclusions

- Neutrino physics is a very wide field + interdisciplinary
- Neutrino oscillations have been recently established
- Next goals: establish
  - $0\nu\beta\beta$ decay
  - Leptonic CP violation
  - Mass ordering
- Neutrinos may reveal the remaining mysteries of particle physics, such physics beyond the SM
- There are potential spin-off applications, such as nuclear monitoring, Earth tomography, geochemistry, ...

Literature: IUPAP neutrino panel report
Prog. Part. Nucl. Phys. 124 (2022) 103947, arXiv:2111.07586