Neutrino physics.

Theory.
(… in lecture 1 a promise, in lecture 2 a threat …)

Walter Winter
DESY

Summer school on Symmetries and Fundamental Interactions

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Abtei Frauenwörth, Germany

Neutrino physics?!

	Particle physics	Astrophysics	Other disciplines
The established	Missing energy Neutrino oscillations	Stellar burning Stellar evolution	Tests of nuclear theory Reactor ν flux measurements
The emerging	CP violation Sterile neutrinos	Origin of cosmic rays Measurement of ν mass	Geo-chemistry Nuclear monitoring
The fantastic	Physics beyond SM Relic νs ν-theory of everything (baryogenesis, dark matter, dark energy)		Earth tomography

Contents

- Introduction
- Neutrino oscillations:
  - Theory of neutrino oscillations
  - Current knowledge
  - The measurement of δ_{CP}
  - Matter effects in neutrino oscillations
  - Neutrino tomography?
- Theory of neutrino masses and mixings
- Cosmic neutrinos:
  - Particle physics of cosmic neutrino sources
  - Fundamental physics tests with cosmic neutrinos

Lecture 1

Particle phenomenology

@Mainz: Joachim Kopp

Lecture 2

Particle theory

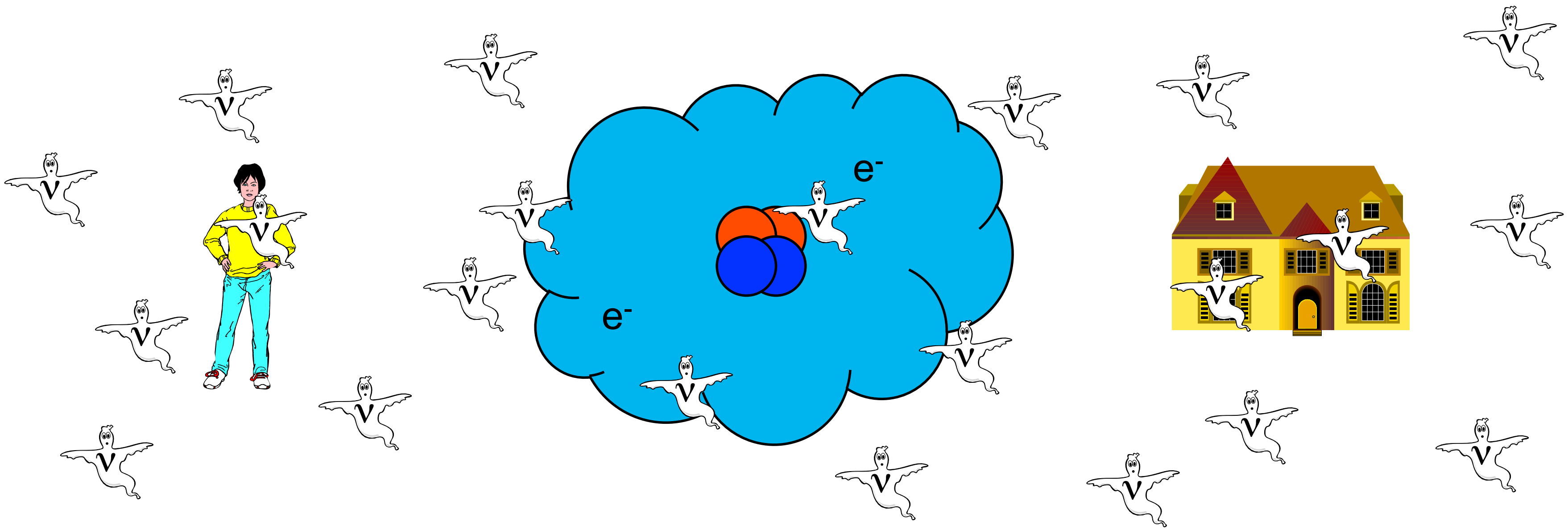
@Mainz (for effective field theory): Matthias Neubert

Astroparticle physics

@Mainz: Lutz Köpke

What are neutrinos?

- Ordinary matter consists of protons, neutrons, and electrons

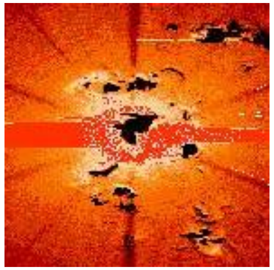


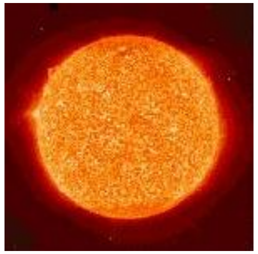
- But that‘s not all. There are many other particles …

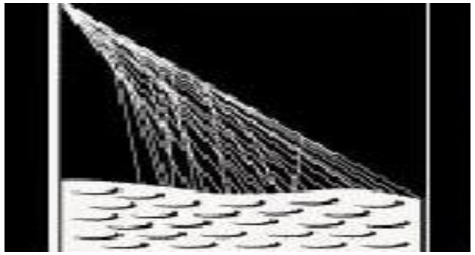
  For instance, for each of the above, there are about **1.000.000.000** (1 billion) neutrinos in the universe
  = **almost massless particles without electric charge**

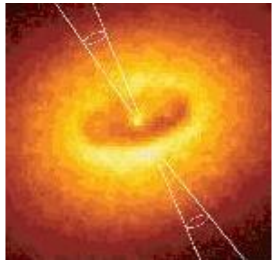
Where do the neutrinos come from?

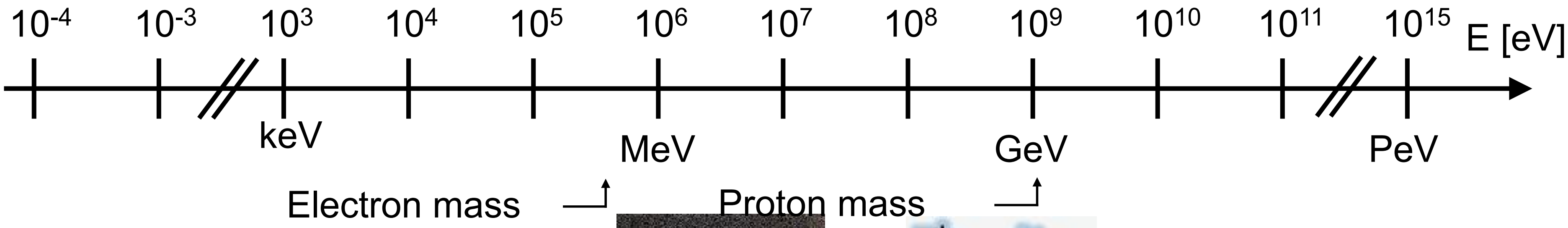
Natural sources



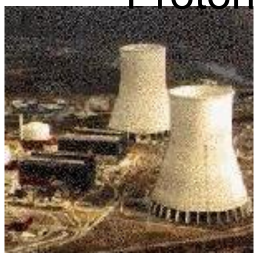




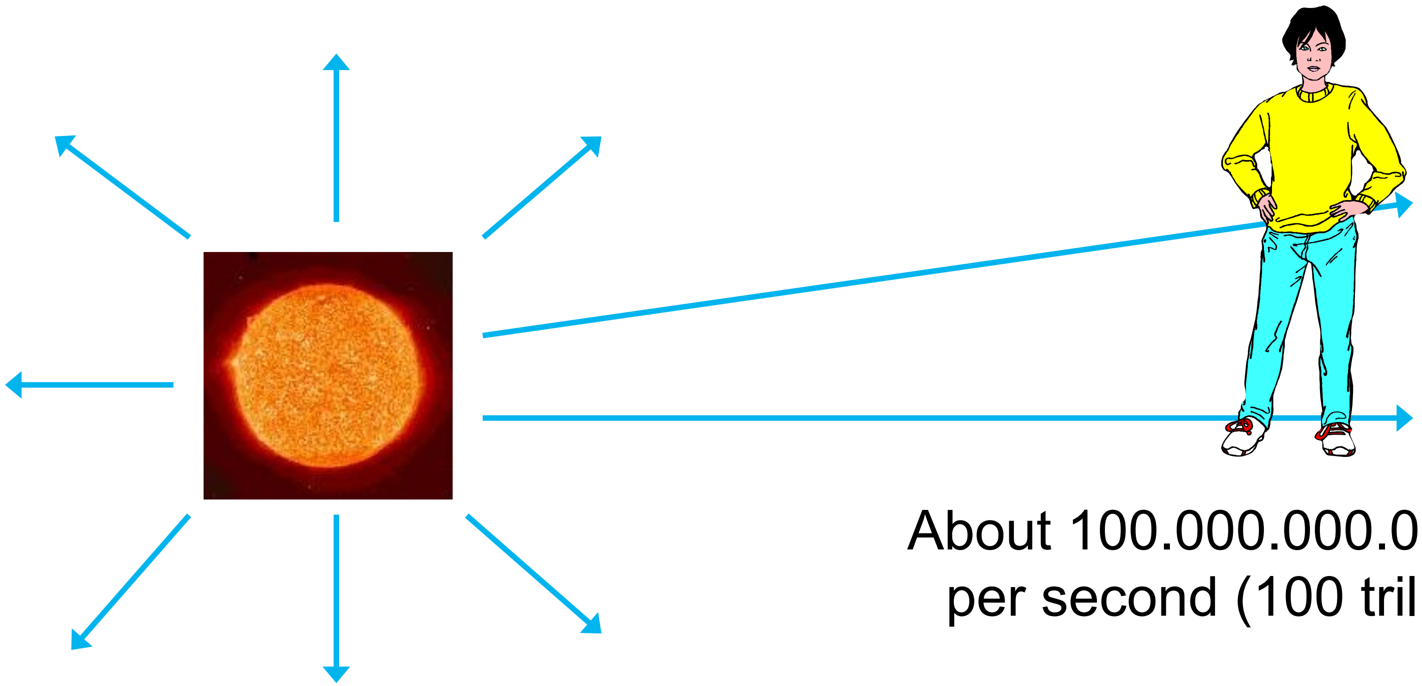




Man-made sources



How many neutrinos are there?



About 100.000.000.000.000
per second (100 trillions)

- So, why don‘t we care?
- Neutrinos interact **extremely weakly**
- Neutrinos escape even from very dense environments (e.g. stars, nuclear reactor, …)
- Neutrinos can be used as messengers!

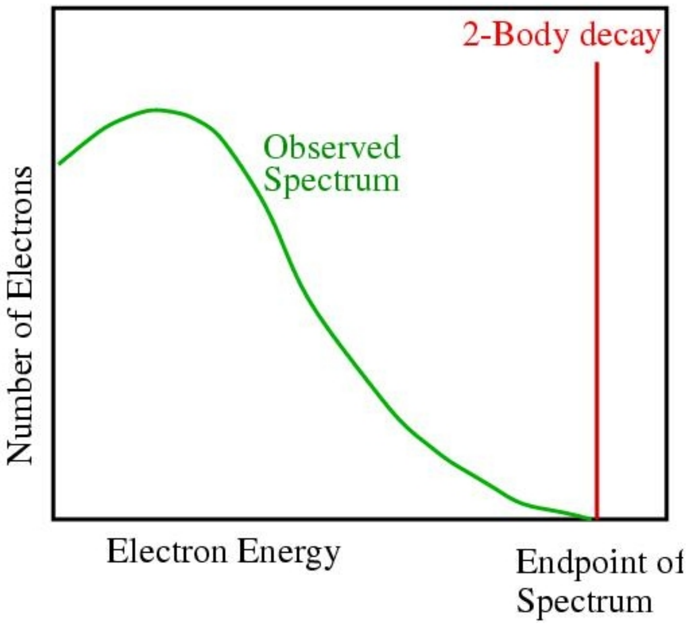
Who “invented“ the neutrino?

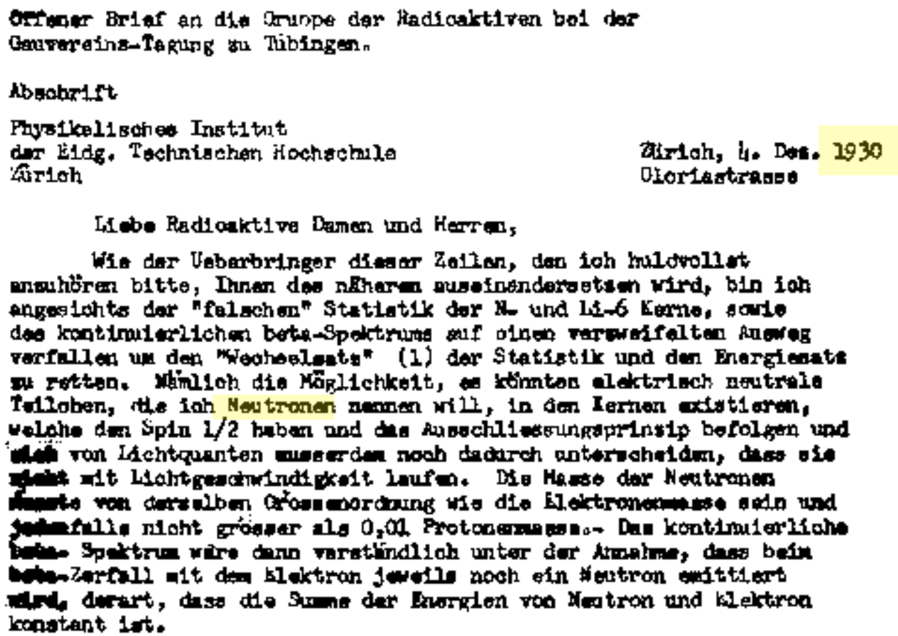
Wolfgang Pauli

- From energy and momentum conservation, we have for the decay into N particles:
  - N=2: have particular, discrete energies
  - N>2: have continuous spectra

$$(N,Z) \to (N-1,Z+1) + e + \nu$$

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





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

Abschrift

Physikalisches Institut
der Eidg. Technischen Hochschule
Zürich

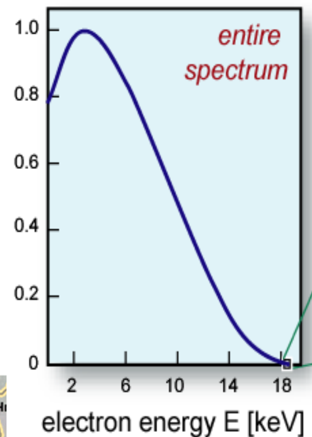
Zürich, 4. Dez. 1930
Gloriastrasse

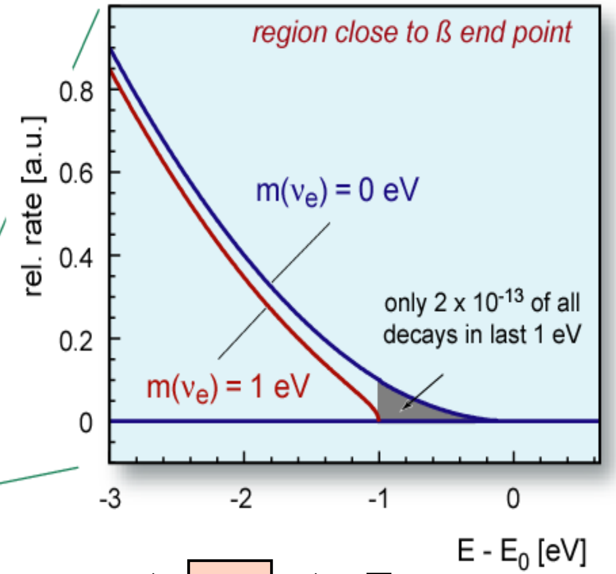
Liebe Radioaktive Damen und Herren,

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.

What masses do the neutrinos have?

- Direct test of neutrino mass by decay kinematics
- Current bound:
  1/250.000 x m_e (2 eV) TINY!
- Future experiment:
  KATRIN
  (Karlsruhe Tritium Neutrino Experiment)
  1/2.500.000 x m_e (0.2 eV)





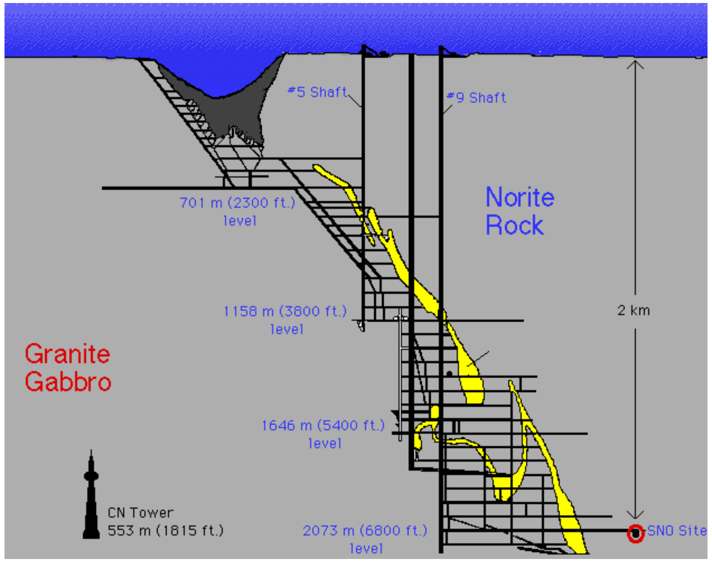
$$n \to p + \boxed{e^-} + \bar{\nu}_e$$

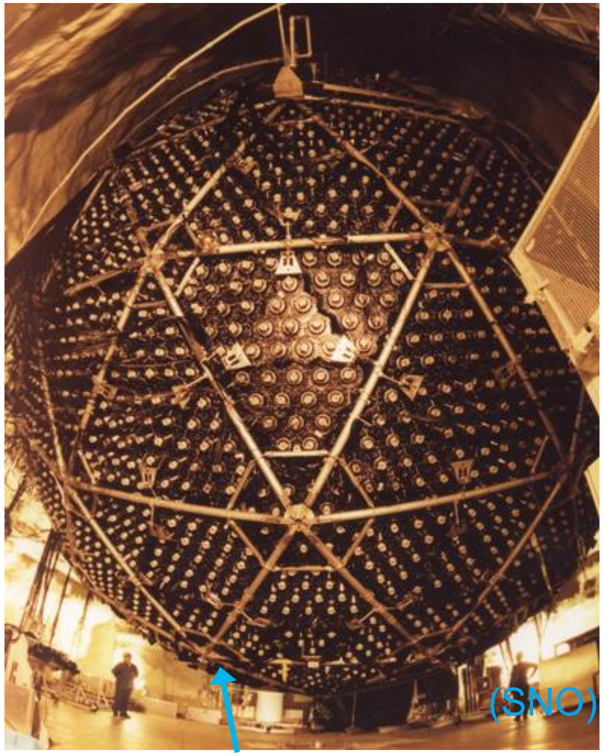
(KATRIN)

DESY

How to observe the neutrino?

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

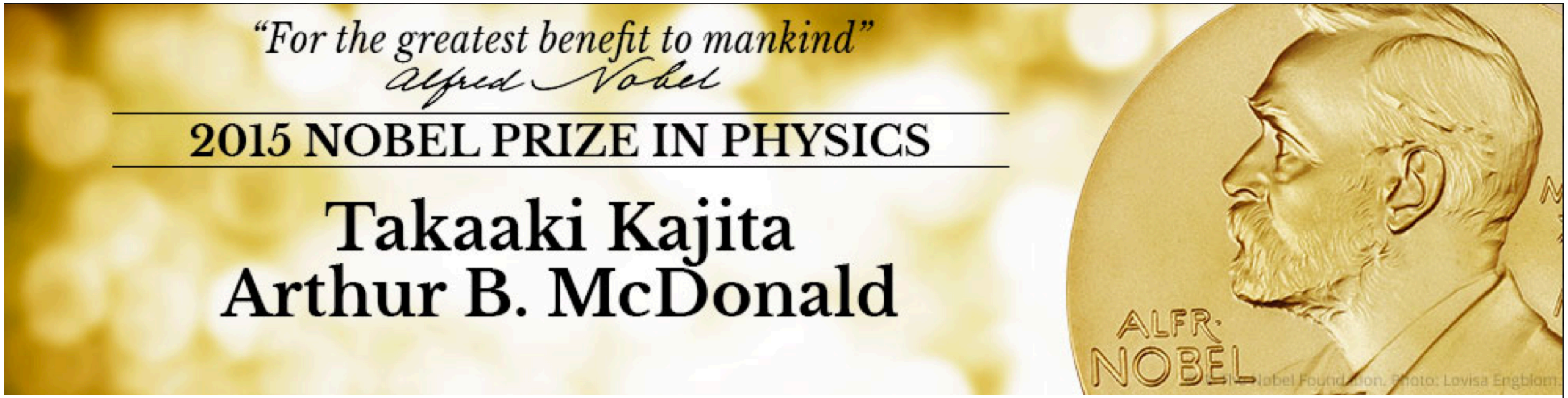



(SNO)

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

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.

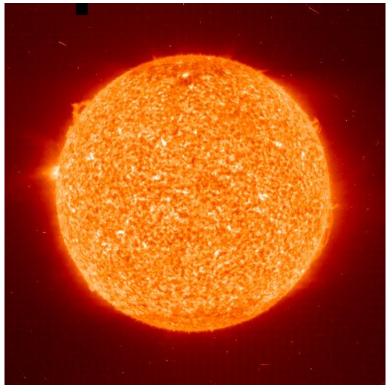
→ Read more (pdf)

"I Gave My Wife a Hug!"

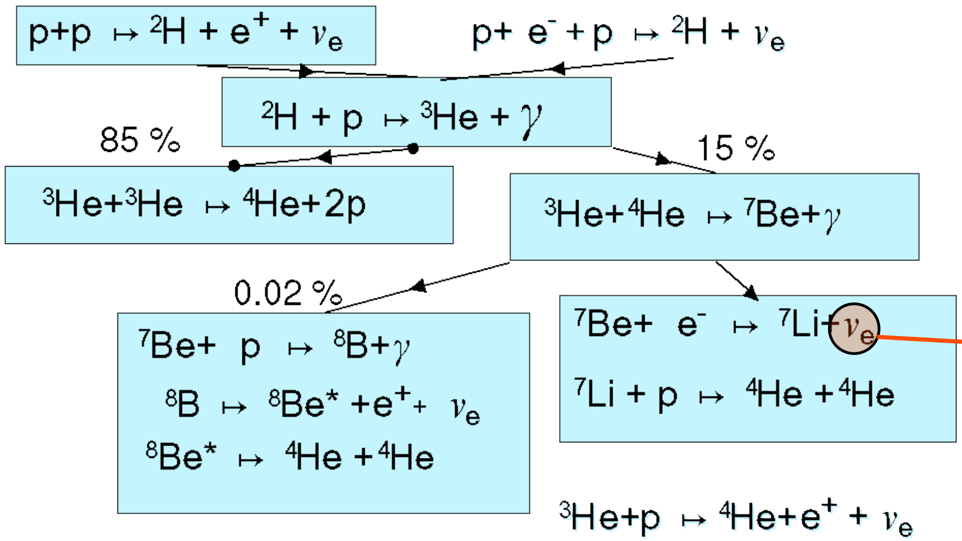
"It's ironic, in order to observe the sun you have to go kilometers under ground. That's not what you would expect." An interview with Arthur B. McDonald, awarded the 2015 Nobel Prize in Physics.

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

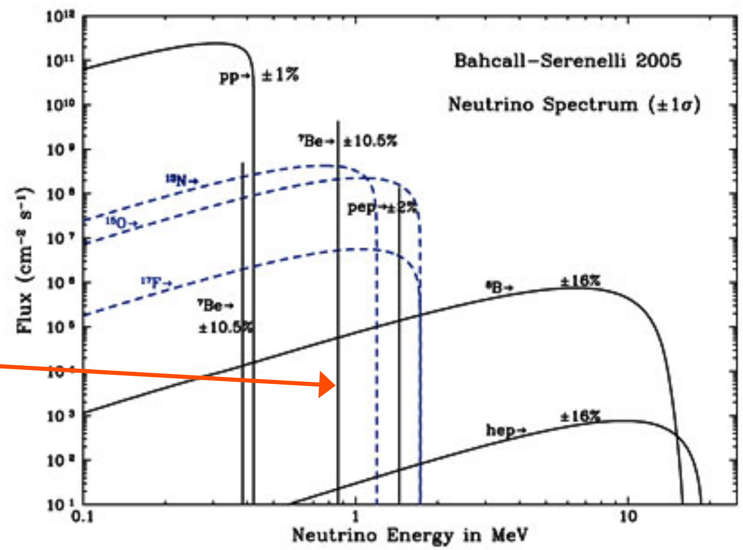
The mystery of the missing neutrinos



- 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)

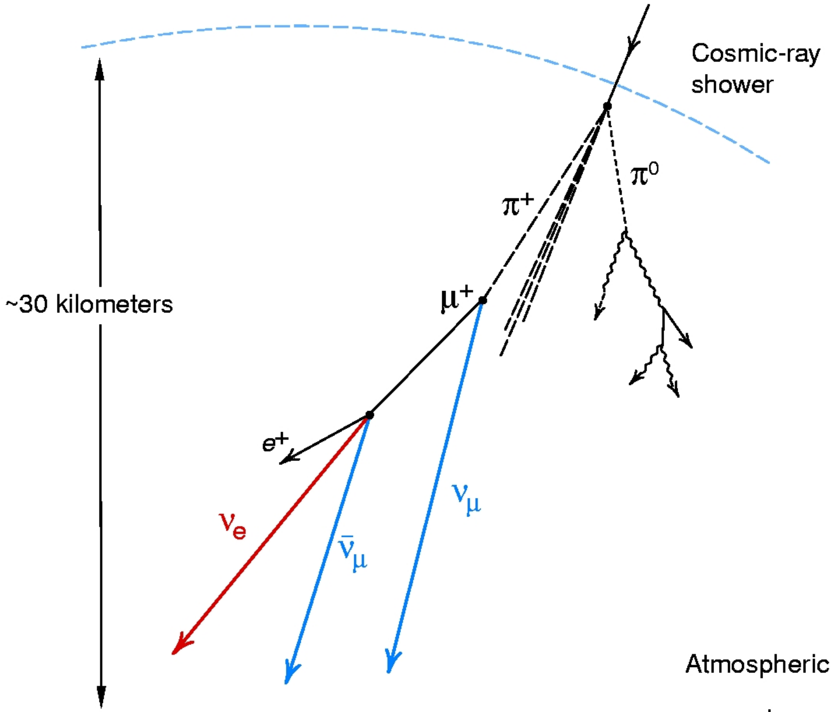


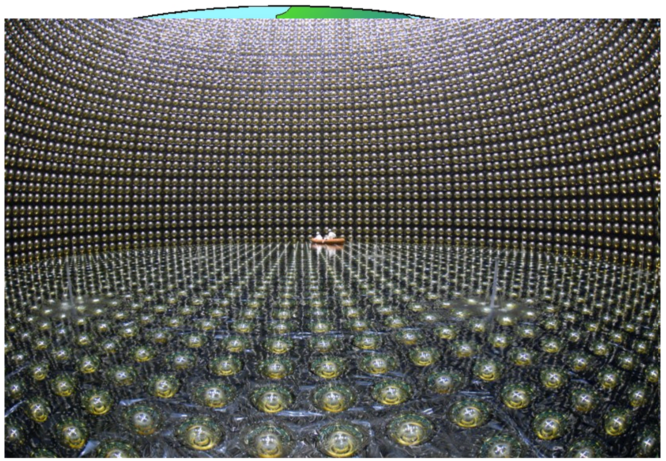
pp-fusion chain



Neutrino spectra

Neutrinos from the atmosphere





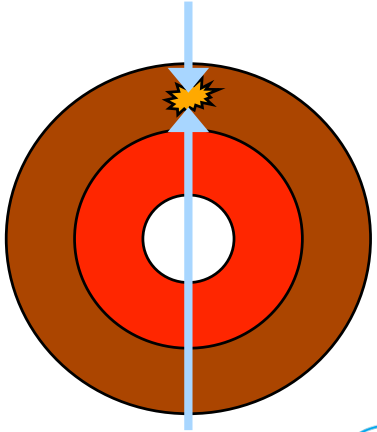
Atmospheric neutrino source

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

Super-Kamiokande
Kajita: Nobel prize 2015

- 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)



Resolving the solar neutrino puzzle

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

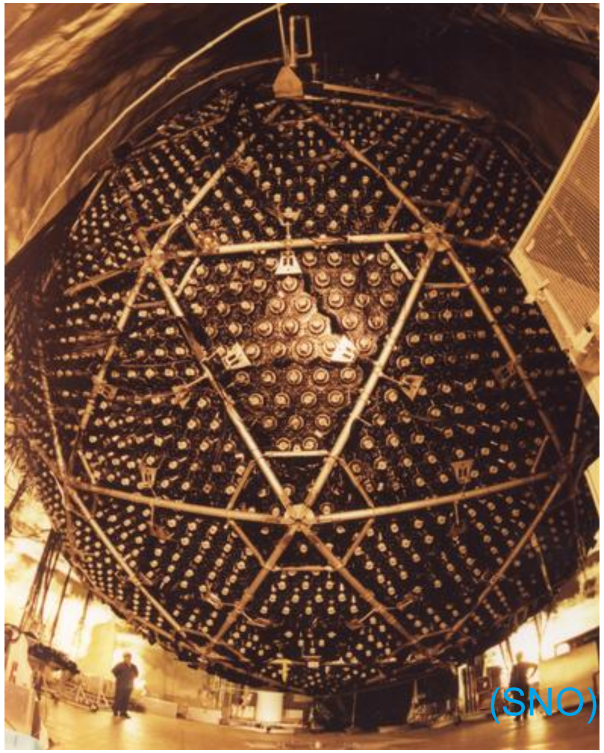
$$\nu_e + {}^2H \to e^- + p + p \quad \text{(CC)}$$

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

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

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

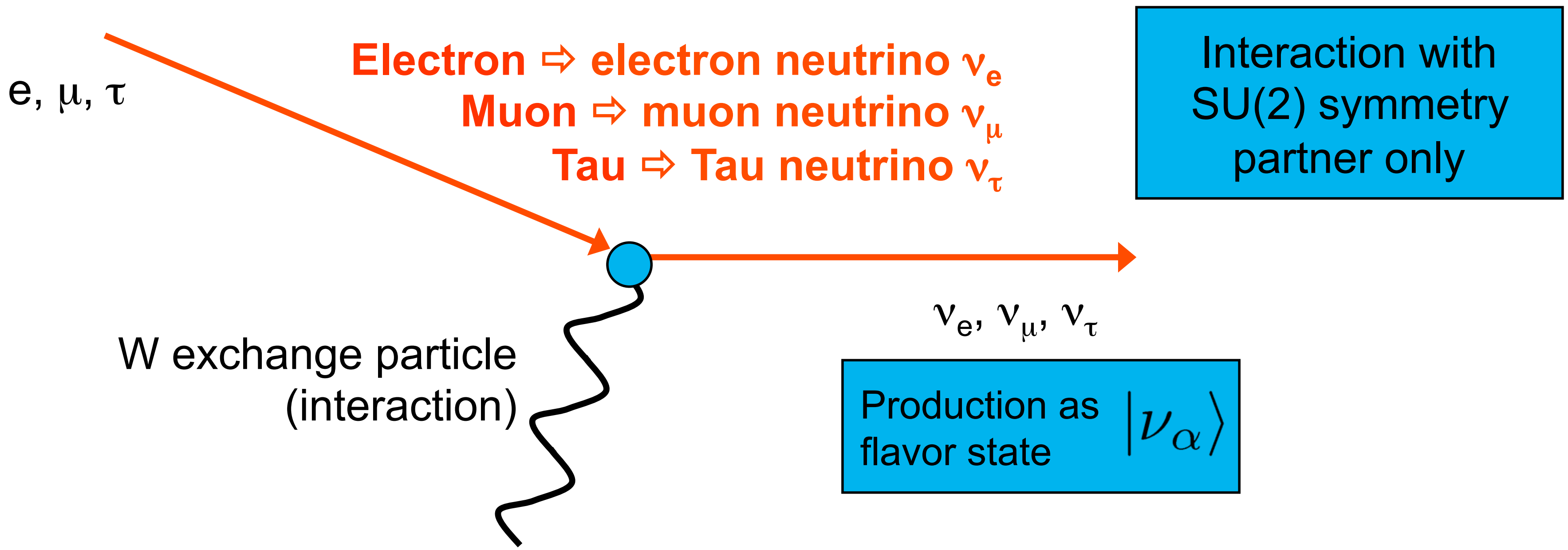
(SNO, McDonald Nobel prize 2015)



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!

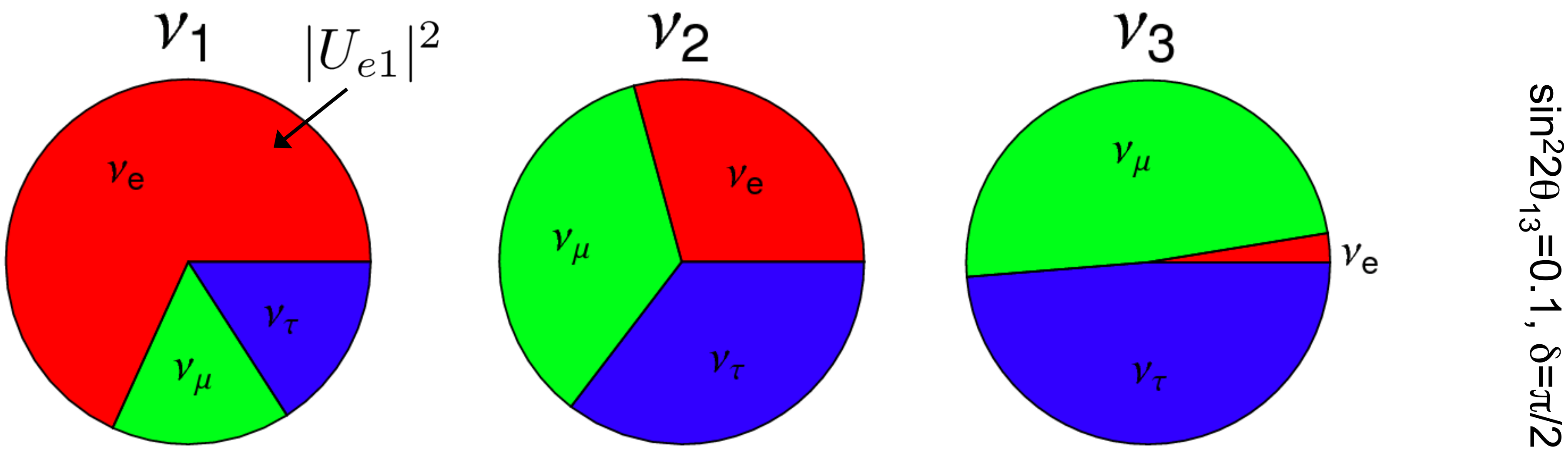
Which mass do the neutrinos have?

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

$$|\nu_i\rangle$$

- Mixture of flavor states:

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



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

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“

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

$\Delta m_{kj}^2 \equiv m_k^2 - m_j^2$ “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!

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

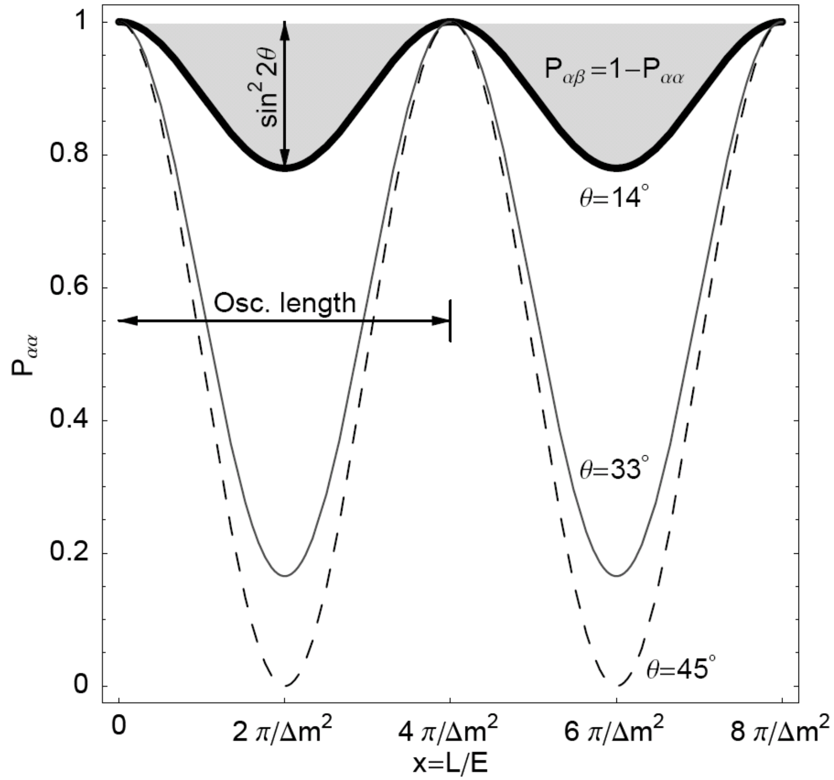
- From the master formula:

Disappearance or
survival probability

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

Appearance probability

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



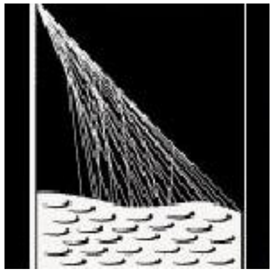
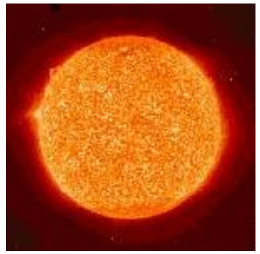
Three flavors: Mixings

- Use same parameterization as for CKM matrix

Potential CP violation ~ θ_{13}

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

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

= () 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

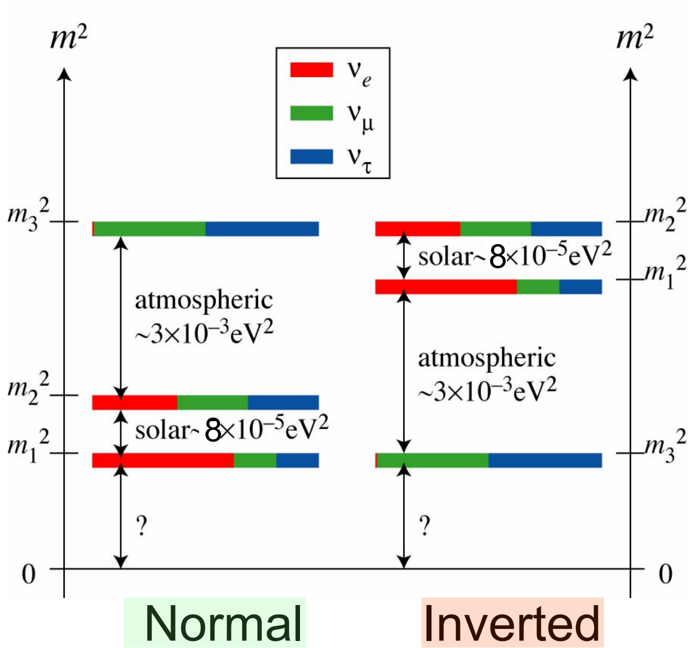
Three active flavors: Masses

- Two independent mass squared splittings, typically
  Δm^2_{21} (solar) Δm^2_{31} (atmospheric)

  Will be relevant for neutrino oscillations!

- The third is given by
  $\Delta m^2_{32} = \Delta m^2_{31} - \Delta m^2_{21}$

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



- The absolute neutrino mass scale is unknown (< eV)

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?

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

- 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: $\Delta_{31} \sim \pi/2$ ⇨ $\Delta_{21} \ll 1$

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

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

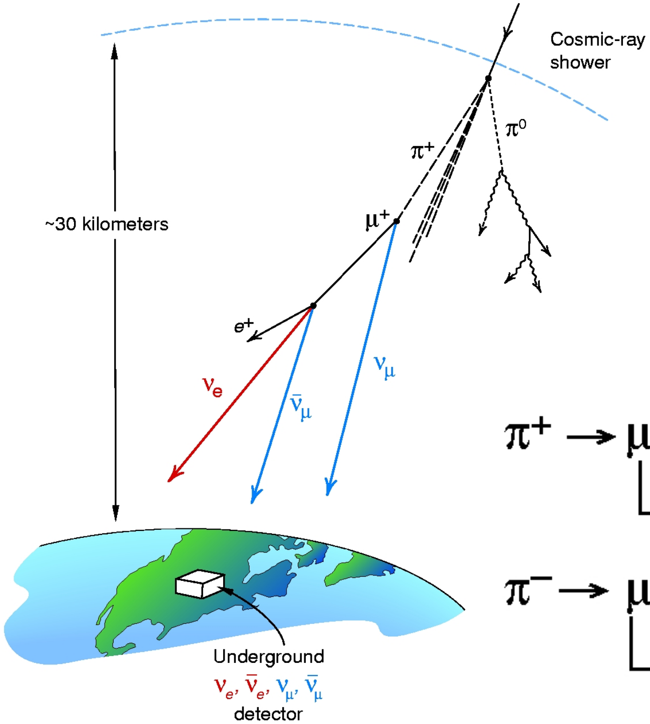
$$P_{\alpha\beta} = \delta_{\alpha\beta} - 4\left(J_{31}^{\alpha\beta} + J_{32}^{\alpha\beta}\right)\boxed{\sin^2\Delta_{31}} - 4\,J_{21}^{\alpha\beta}\sin^2\Delta_{21}$$

averages out

0.5

Select sensitive term by choice of L/E!

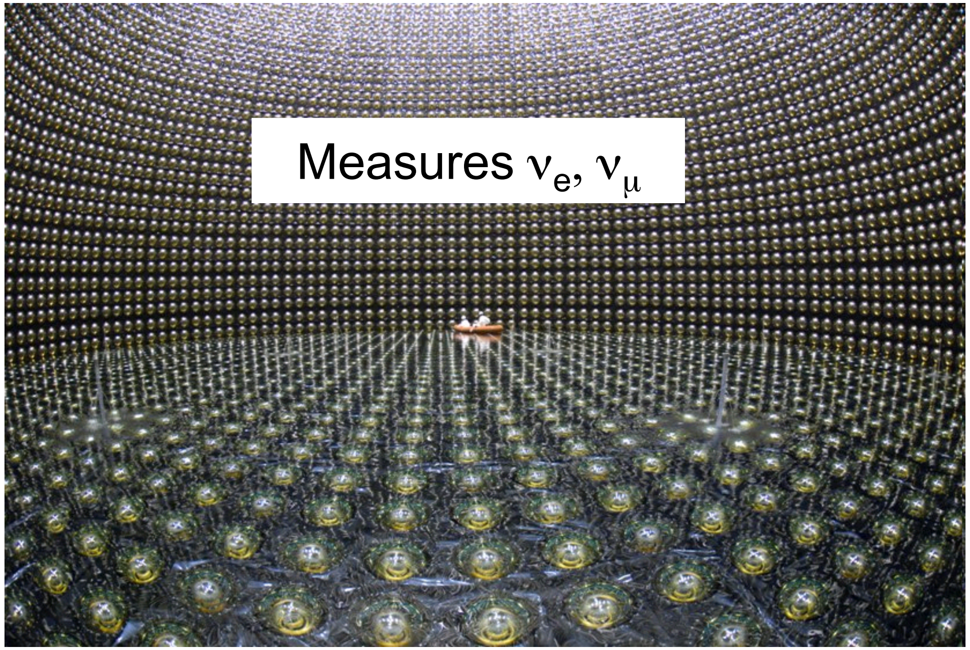
Atmospheric neutrinos



$\pi^+ \to \mu^+ + \nu_\mu$, $\mu^+ \to e^+ + \nu_e + \bar{\nu}_\mu$

$\pi^- \to \mu^- + \bar{\nu}_\mu$, $\mu^- \to e^- + \bar{\nu}_e + \nu_\mu$

Super-Kamiokande



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

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

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

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

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

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

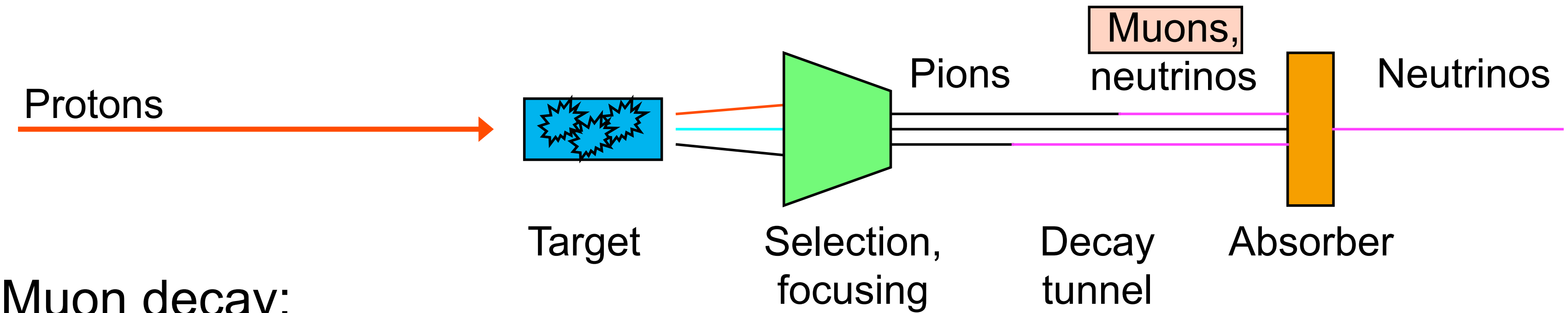
Man-made neutrino sources

There are three possibilities to artificially produce neutrinos

- <u>Beta decay</u>:
  - Example: Nuclear reactors $n \longrightarrow p + e^- + \bar{\nu}_e$

- <u>Pion decay</u>:
  - From accelerators:

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



- <u>Muon decay</u>:
  - Muons produced by pion decays!

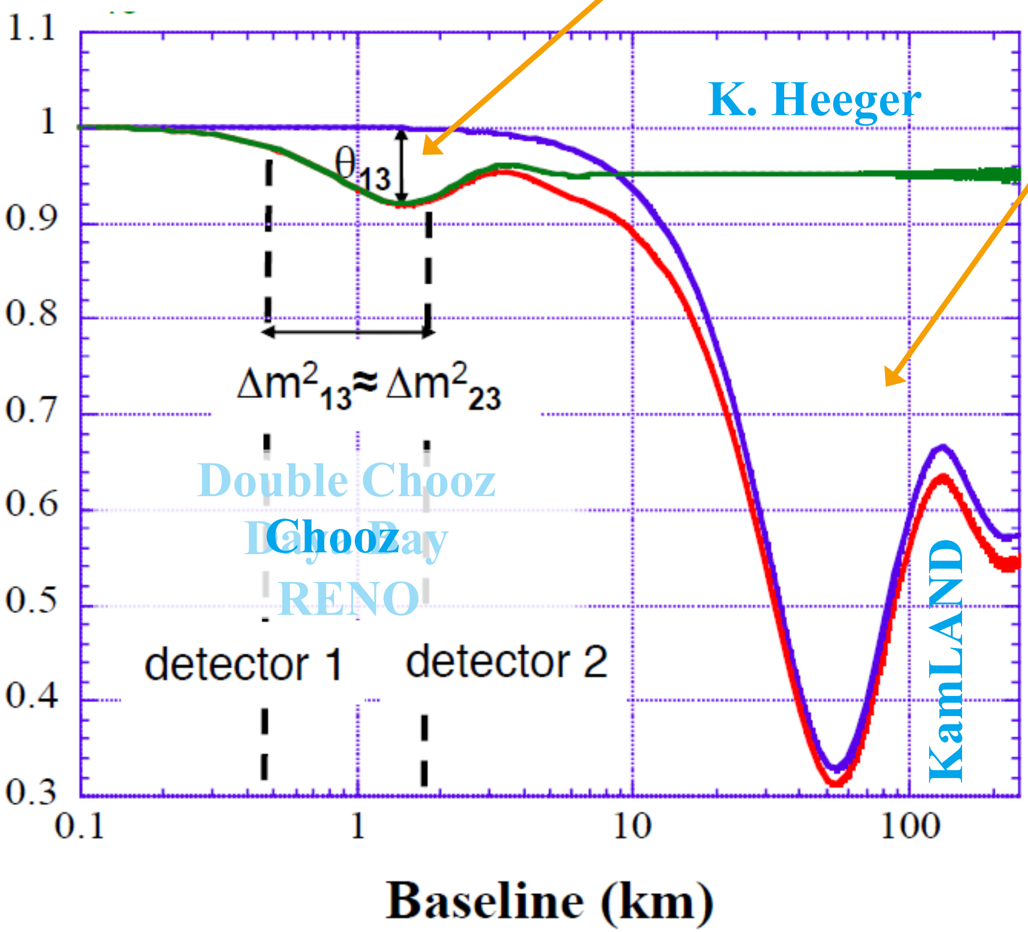
$$\boxed{\mu^-} \longrightarrow e^- + \nu_\mu + \bar{\nu}_e$$

Reactor neutrinos

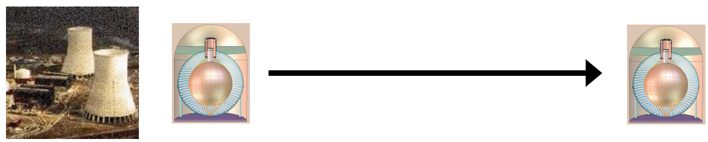
- In the presence of θ_{13} and solar effects:

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

atmospheric solar



New concept:



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

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

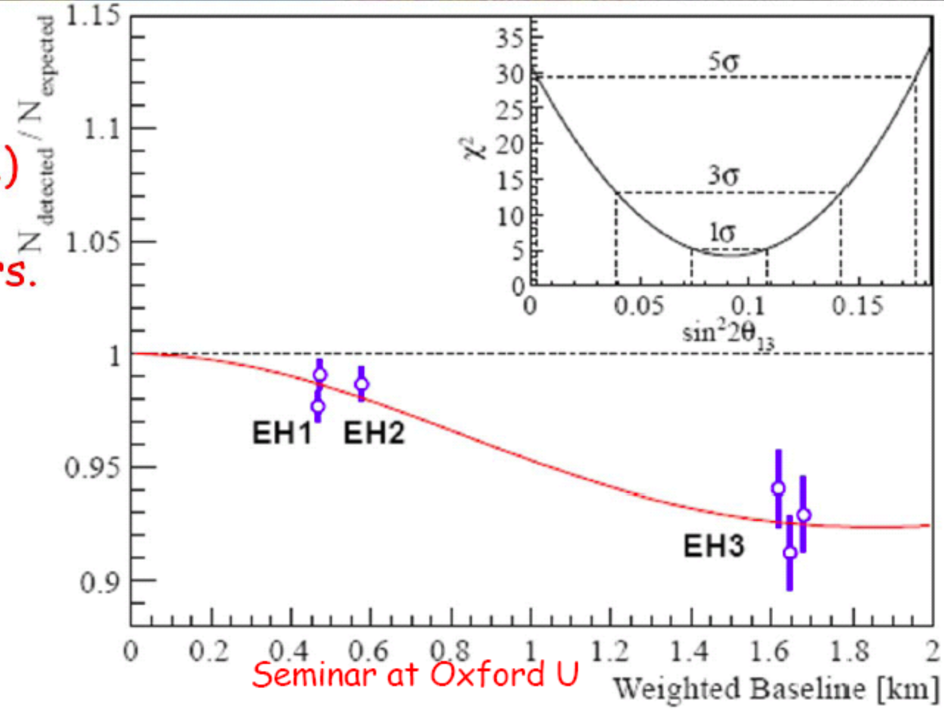
$$P_{\bar{e}\bar{e}} \simeq 1 - \sin^2(2\theta_{13})\,\sin^2\Delta_{31}$$

(short distance)

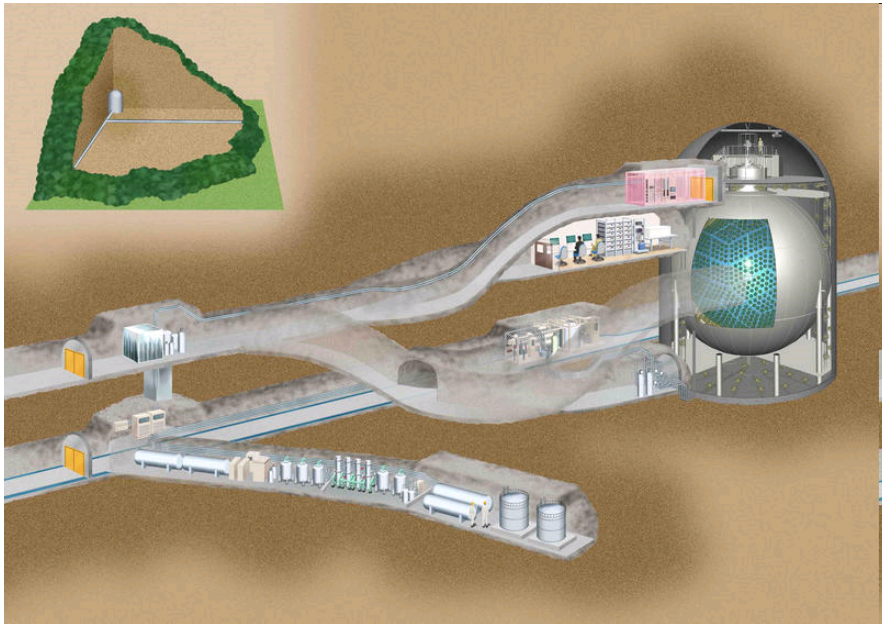
We observe that
$\sin^2 2\theta_{13}$ = 0.092 ± 0.016 (stat.) ± 0.005 (syst.)
after 55 days of operation with 6 detectors
at 3 sites close to 3 pairs of ~ 3 GW reactors.

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

(also: T2K, Double Chooz, RENO)



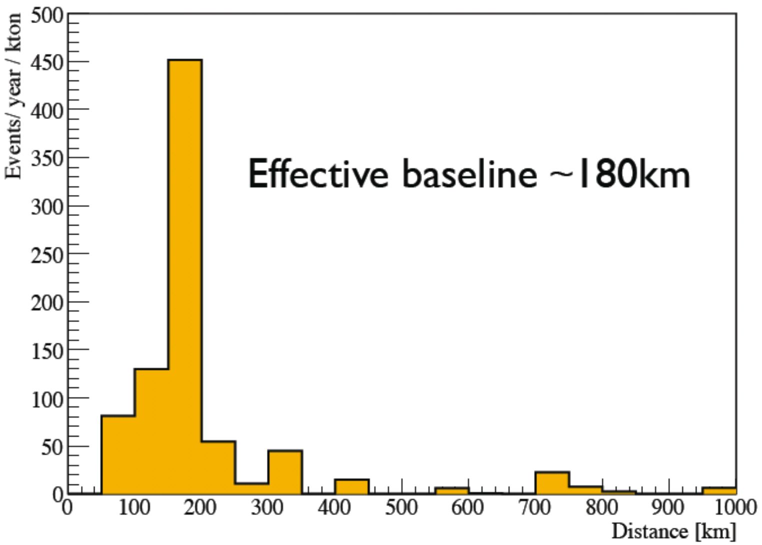
Reactor neutrinos: Solar frequency



KamLAND

Detection by inverse beta decay

$\bar{\nu}_e$



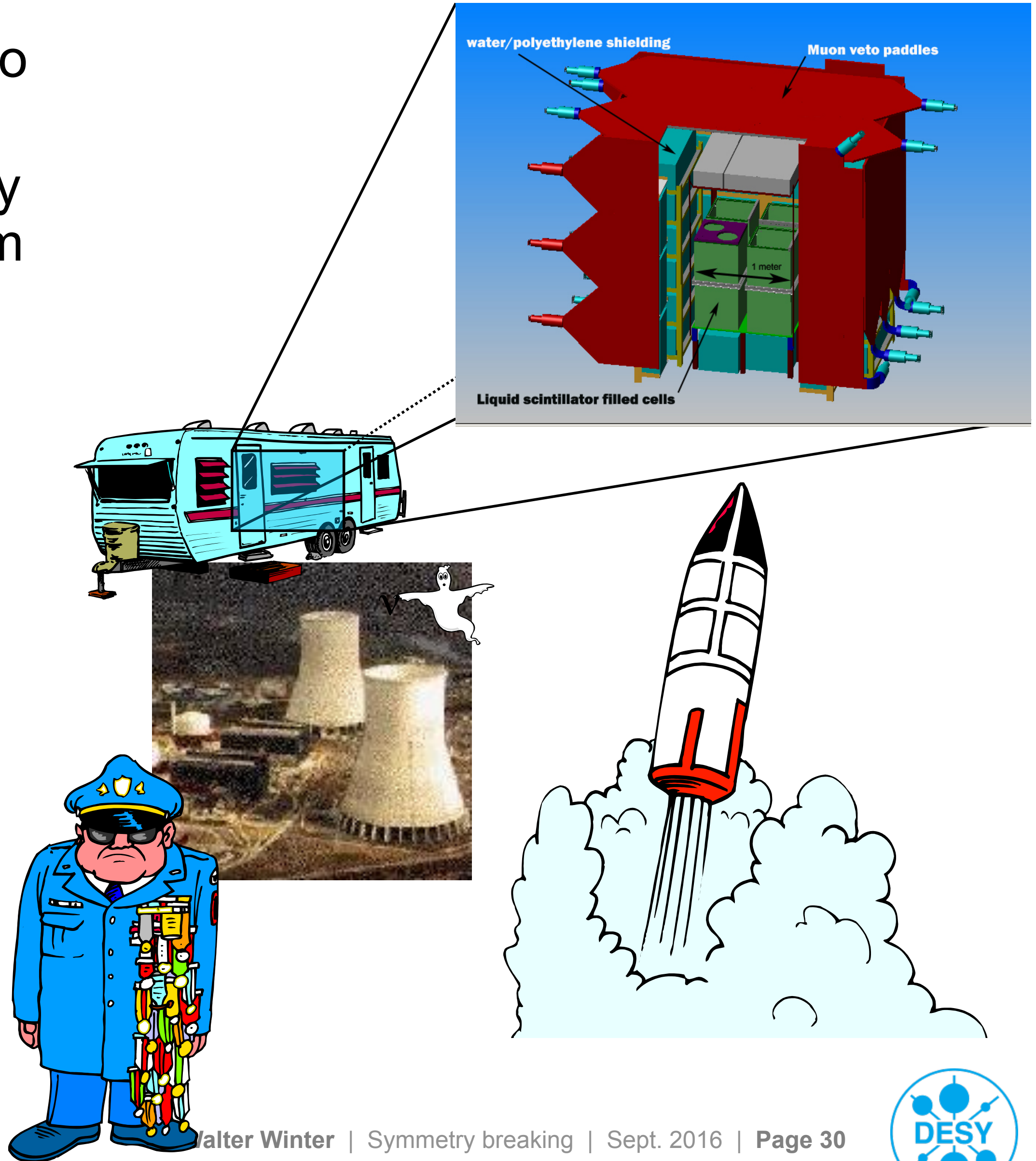
$$P_{\bar{e}\bar{e}} \simeq 1 - \sin^2(2\theta_{12}) \sin^2 \Delta_{21}$$

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

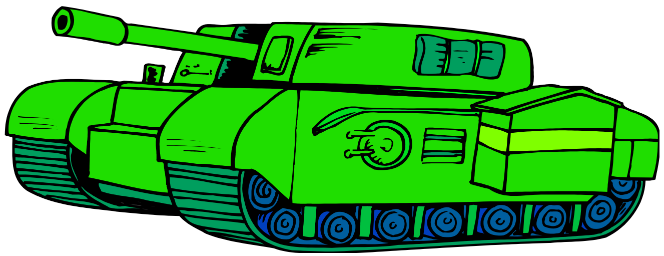
Spin-off: Nuclear monitoring?

- Idea: The event rate N close to the reactor is high, $N \sim 1/R^2$
  - ➢ A few thousand events/day for "small" detector ~ 25 m away from reactor core

- Target precision: ~ O(10) kg for extraction of radioactive material

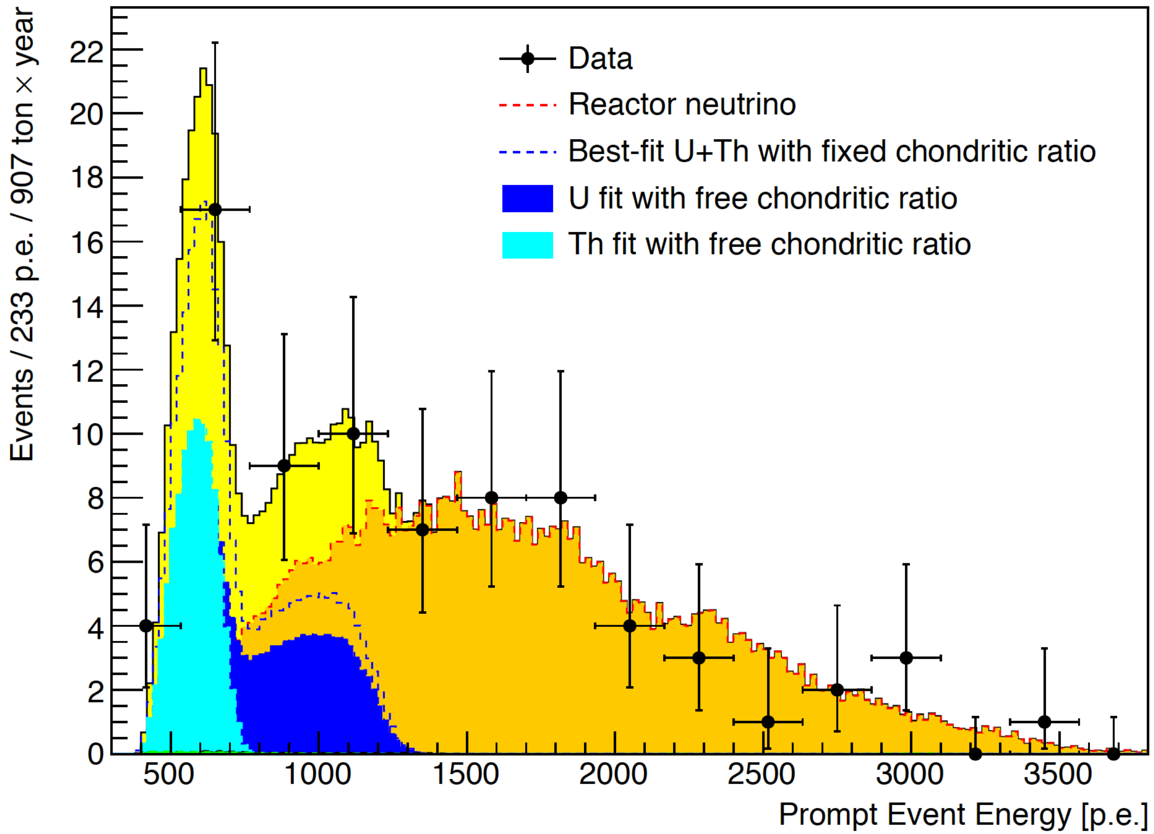


(Adam Bernstein, LLNL)



Spin-off: Neutrino geochemistry

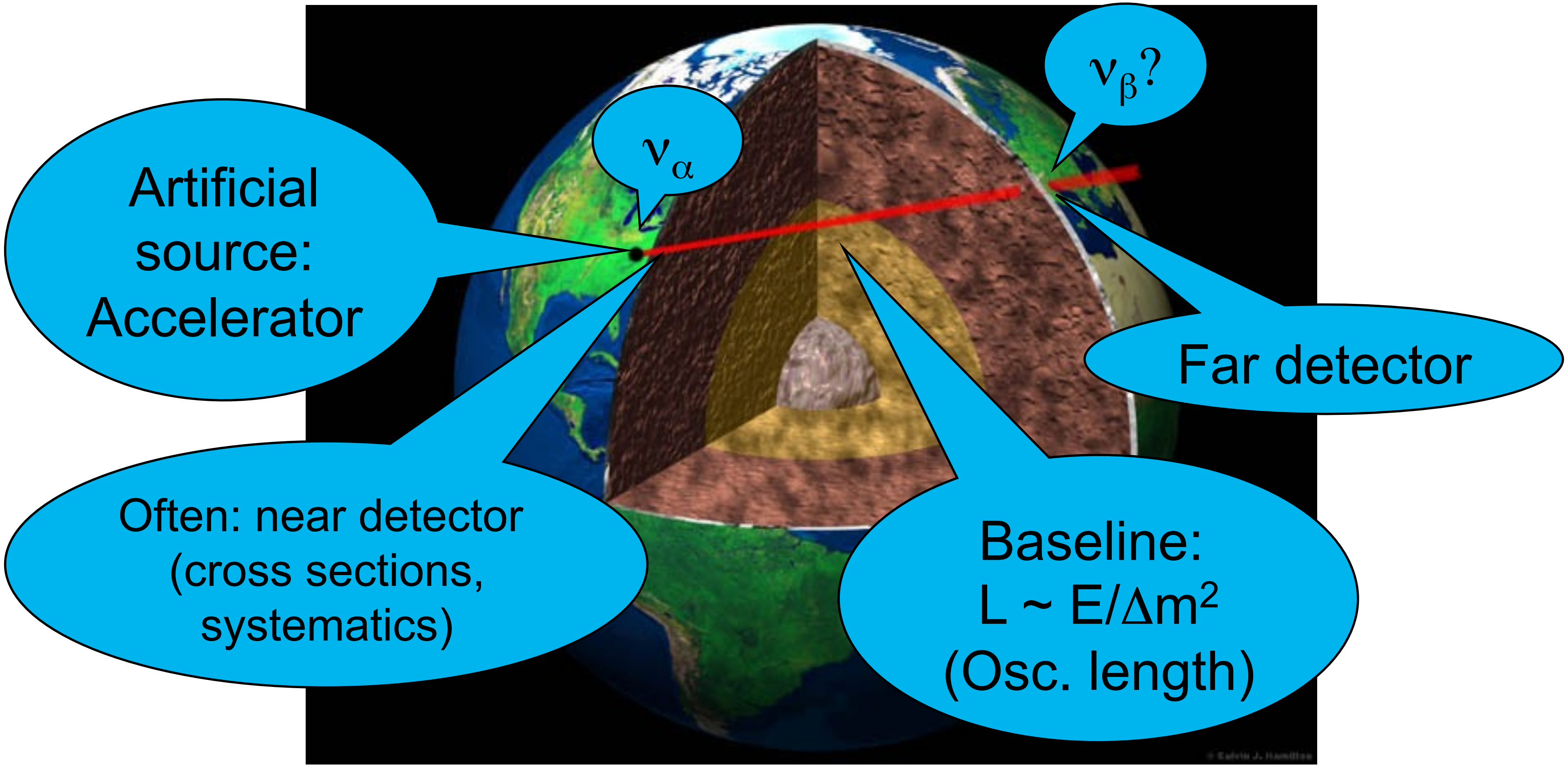
- Neutrinos from ^{238}U and ^{232}Th decays are above the inverse beta decay detection thresholds of experiments such as KamLAND or Borexino



(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)

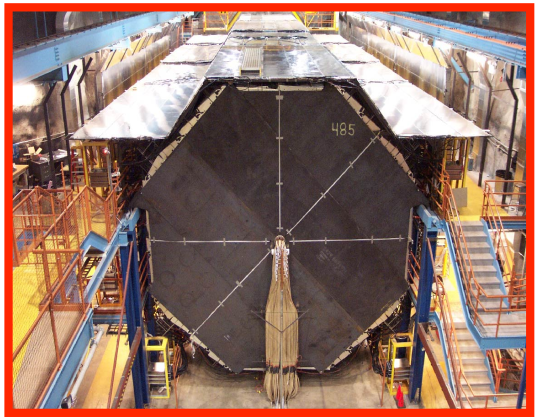
Neutrino beam experiment: Example MINOS

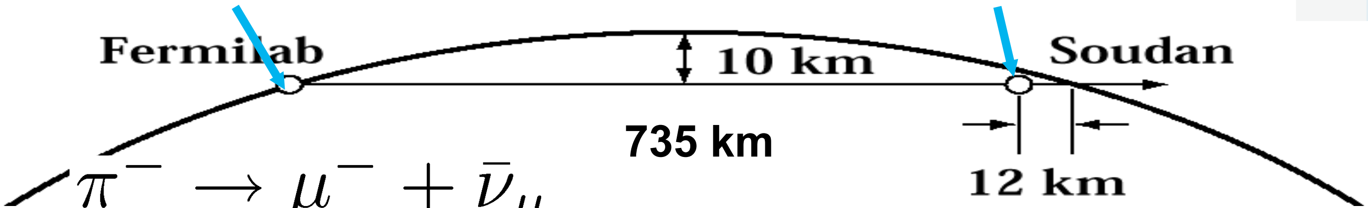
Source: MINOS

> Running experiment in the US for the precision measurement of atmospheric parameters

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


Beam line (Protons)

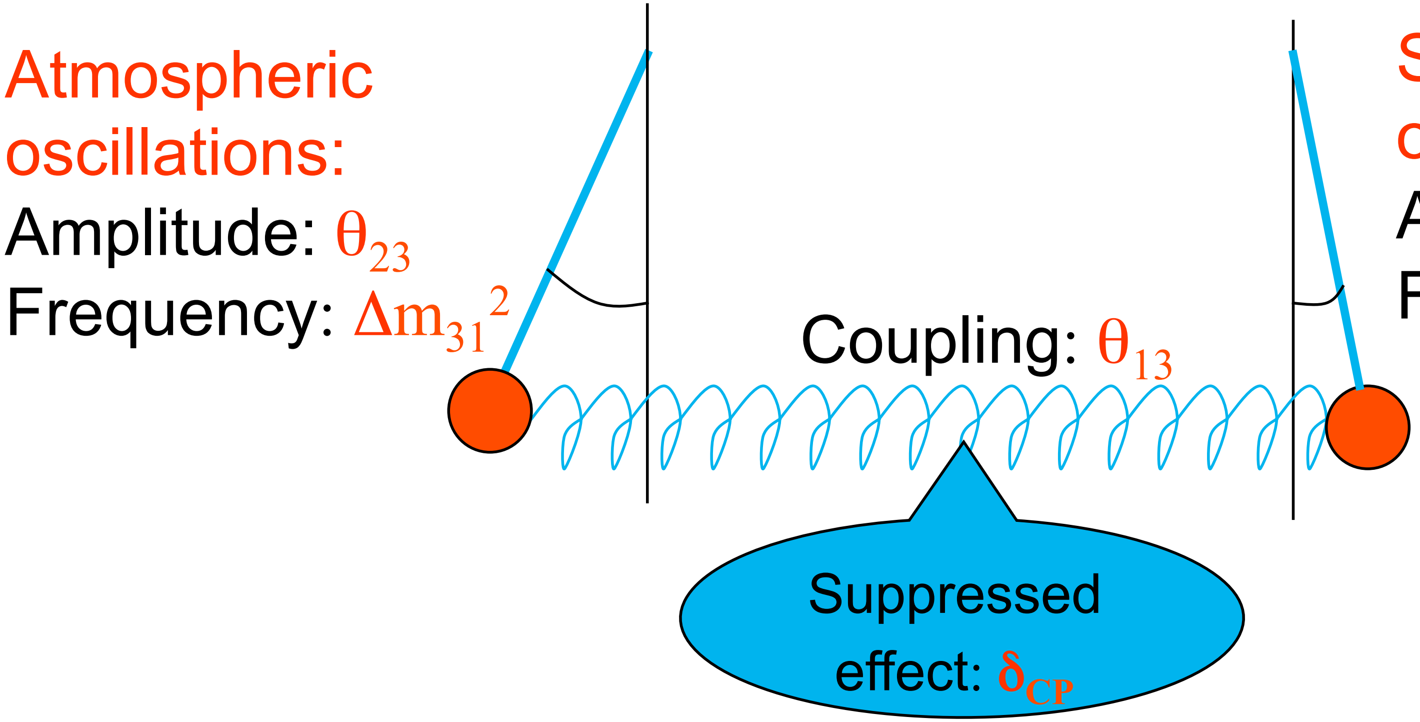




$$\pi^- \rightarrow \mu^- + \bar{\nu}_\mu$$

Three flavors: Summary

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



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

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

Precision of parameters?

NuFIT 1.2 (2013)

	bfp $\pm 1\sigma$	3σ range
$\sin^2\theta_{12}$	$0.306^{+0.012}_{-0.012}$	$0.271 \to 0.346$
$\theta_{12}/^\circ$	$33.57^{+0.77}_{-0.75}$	$31.38 \to 36.01$
$\sin^2\theta_{23}$	$0.446^{+0.007}_{-0.007} \oplus 0.587^{+0.032}_{-0.037}$	$0.366 \to 0.663$
$\theta_{23}/^\circ$	$41.9^{+0.4}_{-0.4} \oplus 50.0^{+1.9}_{-2.2}$	$37.2 \to 54.5$
$\sin^2\theta_{13}$	$0.0229^{+0.0020}_{-0.0019}$	$0.0170 \to 0.0288$
$\theta_{13}/^\circ$	$8.71^{+0.37}_{-0.38}$	$7.50 \to 9.78$
$\delta_{CP}/^\circ$	265^{+56}_{-61}	$0 \to 360$
$\frac{\Delta m^2_{21}}{10^{-5}\ \mathrm{eV}^2}$	$7.45^{+0.19}_{-0.16}$	$6.98 \to 8.05$
$\frac{\Delta m^2_{31}}{10^{-3}\ \mathrm{eV}^2}$ (N)	$+2.417^{+0.013}_{-0.013}$	$+2.247 \to +2.623$
$\frac{\Delta m^2_{32}}{10^{-3}\ \mathrm{eV}^2}$ (I)	$-2.410^{+0.062}_{-0.062}$	$-2.602 \to -2.226$

± 2%

± 4% (or better)

± 4%

± 3%

± 3%

Age of the
precision flavor physics of the lepton sector

Open issues:
- **Degeneracies (mass ordering, octant)**
- **CP phase**

Gonzalez-Garcia, Maltoni, Salvado, Schwetz, JHEP 1212 (2012) 123

The future: measurement of δ_{CP}

What is CP violation?

- C stands for “Charge conjugation“
- P stands for “Parity“
- “CP“ corresponds to **particle – anti-particle interchange**
- Do particles and anti-particles behave the same?

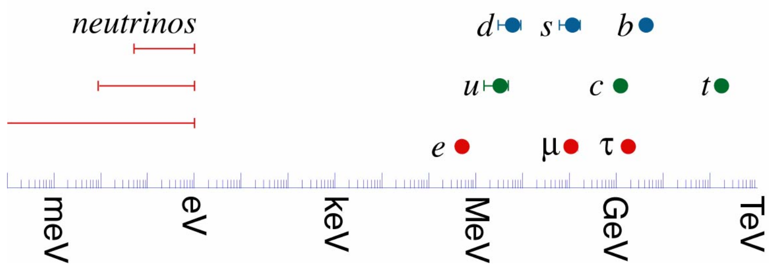
- Why is “C“ (charge conjugation) not sufficient?
- Peculiarity of the Standard Model: couplings to left-handed particles and right-handed anti-particles (V-A interactions)
- Need to flip parity as well to go from left-handed particle to right-handed anti-particle

Why would one care about CP violation?

- Baryogenesis = dynamical mechanism to create the matter-anti-matter asymmetry in the early universe from a symmetric state
- Three necessary conditions (Sakharov conditions):
  1) B violation (need to violate baryon number)
     Need to create net baryon number
  2) Out-of-equilibrium processes
     Otherwise any created asymmetry will be washed out again
  3) **C and CP violation**
     Particles and anti-particles need to “behave“ differently
     Critical: the Standard Model does not have enough CP violation for that!
     Requires physics beyond the Standard Model (BSM)
- There are many theories for baryogenesis, e.g. electroweak baryogenesis, thermal leptogenesis, GUT baryogenesis etc
- Addendum to 1): Can also come from lepton sector (sphalerons!)

Related question: Why is the neutrino mass so small?

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



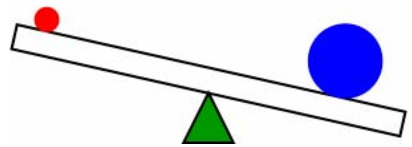
  - Cannot be described in simple extensions of the Standard Model

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

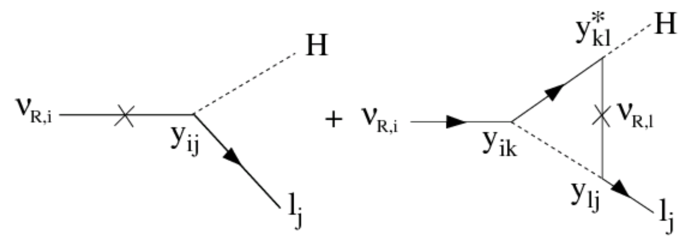
$$m_\nu = \frac{m_D^2}{M_R}$$

← Other SM particles

← Heavy partner



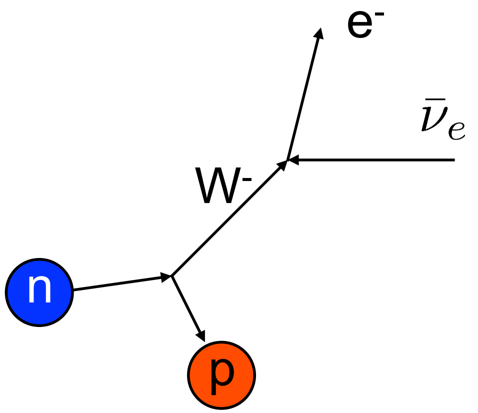
  - Decay of (thermally produced) M_R origin of matter-antimatter-asymmetry? **Thermal leptogenesis** →

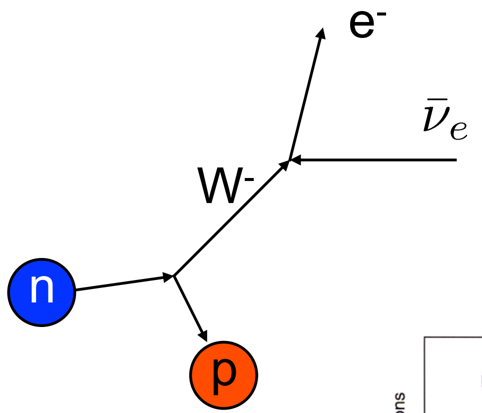


  - CP violation? Test in neutrino oscillations!
  - Requires Majorana nature of neutrino! Test in neutrinoless double beta decay ($0\nu\beta\beta$)

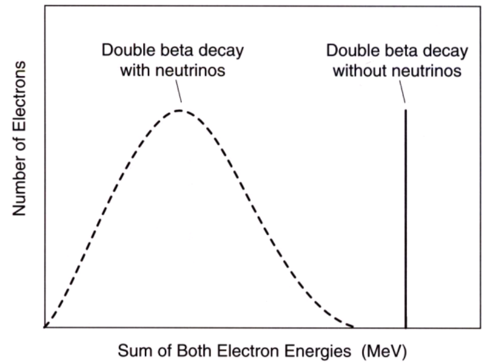
0νββ: Is the neutrino its own anti-particle?

- Two times simple beta decay:

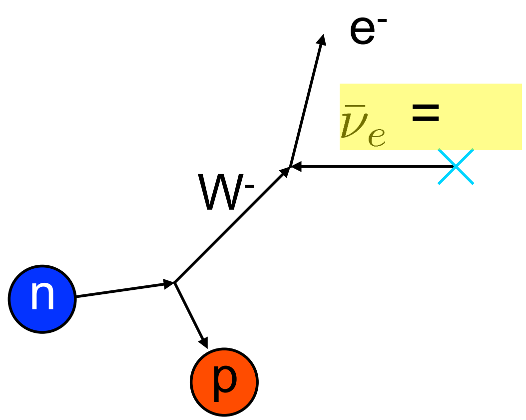


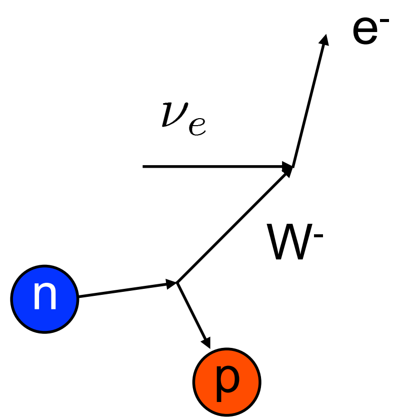


2 x ν
2 x e



- Neutrinoless double beta decay:





0 x ν
2 x e

Necessary conditions for the observation of CP violation
(neutrino oscillations)

- Since
$$\left\langle \sin\left(\frac{\Delta m_{kj}^2 L}{2E}\right)\right\rangle_{L/E} = 0$$
⇨ need spectral info!

- Since for α=β
$$J_{kj}^{\alpha\alpha} = |U_{\alpha k}|^2 \, |U_{\alpha j}|^2$$
⇨ need to observe flavor transitions

~ Jarlskog invariant

$$\underbrace{\cdot\, 2 \sum_{k>j} \boxed{\mathrm{Im} J_{kj}^{\alpha\beta}} \sin\left(\frac{\Delta m_{kj}^2 L}{2\,E}\right)}_{\text{CP violating}}$$

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

- Need (at least) three flavors
(actually conclusion in quark sector by
Kobayashi, Maskawa, Nobel Prize 2008)
⇨ No CP violation in two flavor subspaces!
⇨ Need to be sensitive to (at least) two mass squared splittings at the same time!

Neutrino oscillations with three flavor effects

$$P_{e\mu} \simeq \sin^2 2\theta_{13} \boxed{\begin{matrix}\cos^2\theta_{23} \\ \sin^2\theta_{23}\end{matrix}} \frac{\sin^2[(1 \pm \hat{A})\Delta]}{(1 \pm \hat{A})^2} \qquad \alpha \equiv \frac{\Delta m_{21}^2}{\Delta m_{31}^2},\ \Delta \equiv \frac{\Delta m_{31}^2 L}{4E},\ \hat{A} \equiv \frac{2\sqrt{2} G_F n_e E}{\Delta m_{31}^2}$$

$$\begin{matrix} = \\ \equiv \\ + \end{matrix}\ \alpha \sin 2\theta_{13} \sin 2\theta_{12} \sin 2\theta_{23} \sin\delta_{\mathrm{CP}} \sin(\Delta) \frac{\sin(\hat{A}\Delta)}{\hat{A}} \frac{\sin[(1 \pm \hat{A})\Delta]}{(1 \pm \hat{A})}$$

$$\mp\ \alpha \sin 2\theta_{13} \sin 2\theta_{12} \sin 2\theta_{23} \cos\delta_{\mathrm{CP}} \cos(\Delta) \frac{\sin(\hat{A}\Delta)}{\hat{A}} \frac{\sin[(1 \pm \hat{A})\Delta]}{(1 \pm \hat{A})}$$

$$+\ \alpha^2 \boxed{\begin{matrix}\sin^2\theta_{23} \\ \cos^2\theta_{23}\end{matrix}} \sin^2 2\theta_{12} \frac{\sin^2(\hat{A}\Delta)}{\hat{A}^2}$$

- Antineutrinos: $P_{\bar{e}\bar{\mu}} = P_{e\mu}(\delta_{\mathrm{CP}}, \rightarrow -\delta_{\mathrm{CP}}, \hat{A} \rightarrow -\hat{A})$
- Silver: $P_{e\tau} = P_{e\mu}(s_{23}^2 \leftrightarrow c_{23}^2, \sin 2\theta_{23} \rightarrow -\sin 2\theta_{23})$
- Platinum, T-inv.: $P_{\mu e} = P_{e\mu}(\delta_{\mathrm{CP}}, \rightarrow -\delta_{\mathrm{CP}})$

(Cervera et al. 2000; Freund, Huber, Lindner, 2000; Akhmedov et al, 2004)

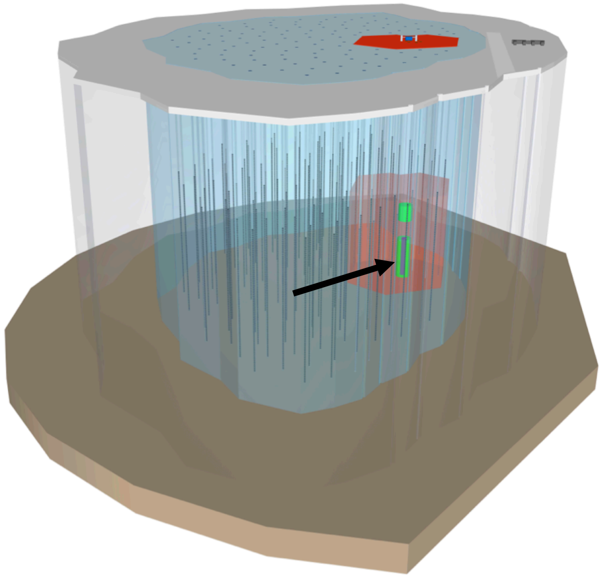
Measurement of CP violation in the laboratory: DUNE
Deep Underground Neutrino Experiment

Bob Wilson @ Neutrino 2014

> Particle Physics Project Prioritization Panel (P5) in the US; Report May ‘14

- The Science Drivers:
  - Use the Higgs boson as a new tool for discovery
  - **Pursue the physics associated with neutrino mass**
  - Identify the new physics of dark matter
  - Understand cosmic acceleration: dark energy and inflation
  - Explore the unknown: new particles, interactions, and physical principles

Recommendation 13: Form a new international collaboration to design and execute a highly capable Long-Baseline Neutrino Facility (LBNF) hosted by the U.S. To proceed, a project plan and identified resources must exist to meet the minimum requirements in the text. LBNF is the highest-priority large project in its timeframe.



Matter effects in neutrino oscillations

... and the neutrino mass ordering

Recap: Neutrino oscillations with two flavors

- Only two parameters:

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

Lower limit for neutrino mass!

$$\Delta m^2_{21} \equiv m^2_2 - m^2_1$$

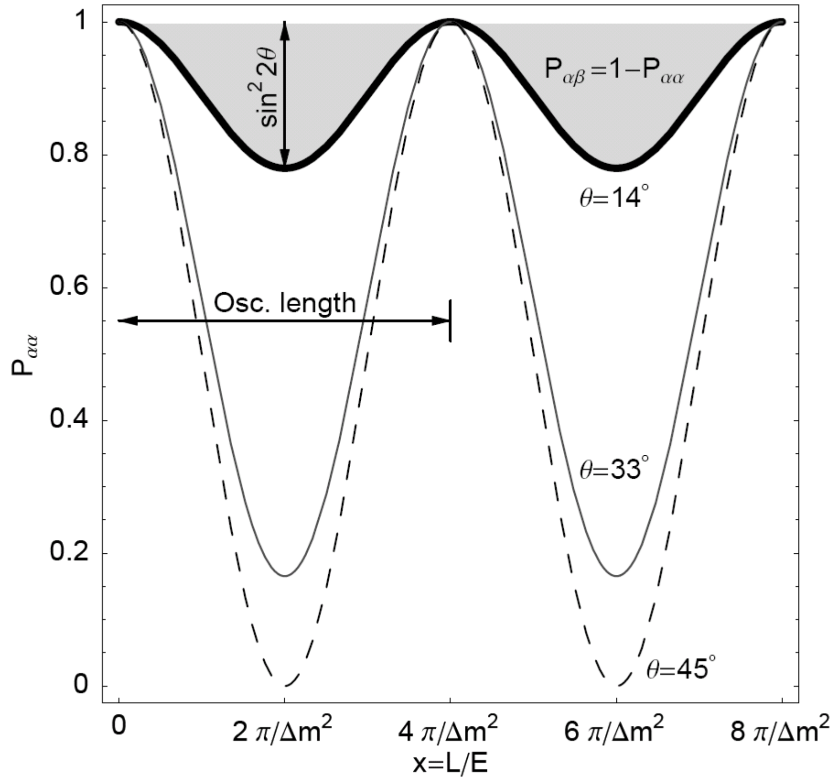
- From the master formula:

Disappearance or
survival probability

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

Appearance probability

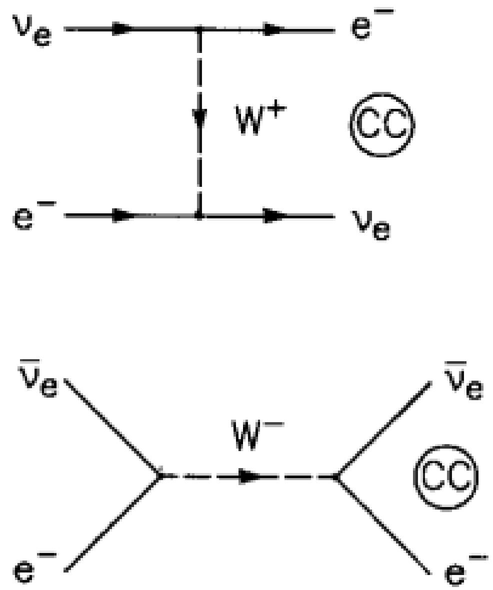
$$P_{\alpha\beta} = \sin^2 2\theta \, \sin^2\left(\frac{\Delta m^2 L}{4E}\right)$$



Matter effects in neutrino oscillations

- Ordinary matter: electrons, but no μ, τ
- Coherent forward scattering in matter: Net effect on electron flavor
- Hamiltonian in matter (matrix form, flavor space):

(Wolfenstein, 1978; Mikheyev, Smirnov, 1985)



$$\mathcal{H}(n_e) = U \begin{pmatrix} 0 & 0 & 0 \\ 0 & \frac{\Delta m_{21}^2}{2E} & 0 \\ 0 & 0 & \frac{\Delta m_{31}^2}{2E} \end{pmatrix} U^\dagger + \begin{pmatrix} V(n_e) & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix}$$

$$V_\nu = +\sqrt{2} G_F n_e, \; V_{\bar{\nu}} = -\sqrt{2} G_F n_e, \; n_e = Y \rho_j / m_N$$

Y: electron fraction ~ 0.5

(electrons per nucleon)

Parameter mapping … for two flavors, constant matter density

Oscillation probabilities in

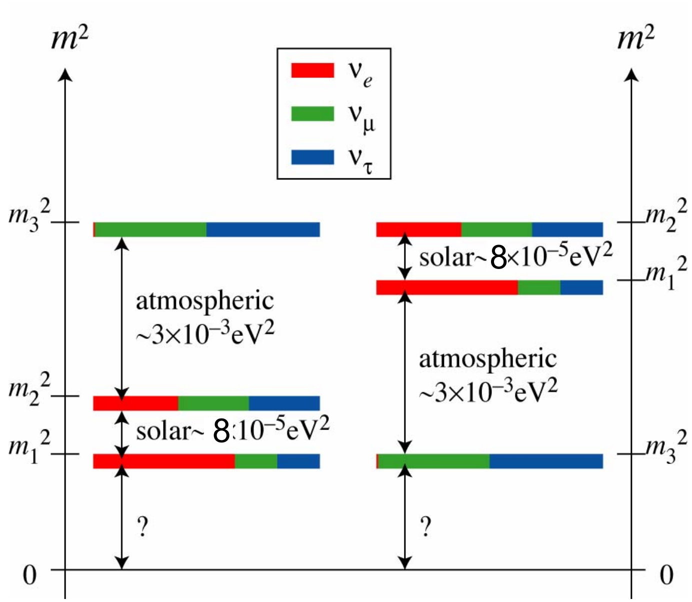
vacuum: $$P_{\alpha\alpha} = 1 - \sin^2 2\theta \sin^2 \frac{\Delta m^2 L}{4E}$$

matter: $$P_{\alpha\alpha} = 1 - \sin^2 2\tilde{\theta} \sin^2 \frac{\Delta \tilde{m}^2 L}{4E}$$

$$\boxed{\Delta\tilde{m}^2 = \xi \cdot \Delta m^2, \quad \sin 2\tilde{\theta} = \frac{\sin 2\theta}{\xi},}$$

$$\xi \equiv \sqrt{\sin^2 2\theta + \left(\cos 2\theta - \hat{A}\right)^2},$$

$$\hat{A} = \frac{2EV}{\Delta m^2} = \frac{\pm 2\sqrt{2} E\, G_F\, n_e}{\Delta m^2}$$



Normal
$\Delta m_{31}^2 > 0$

Inverted
$\Delta m_{31}^2 < 0$

Enhancement condition

$$\cos 2\theta \rightarrow \hat{A}$$

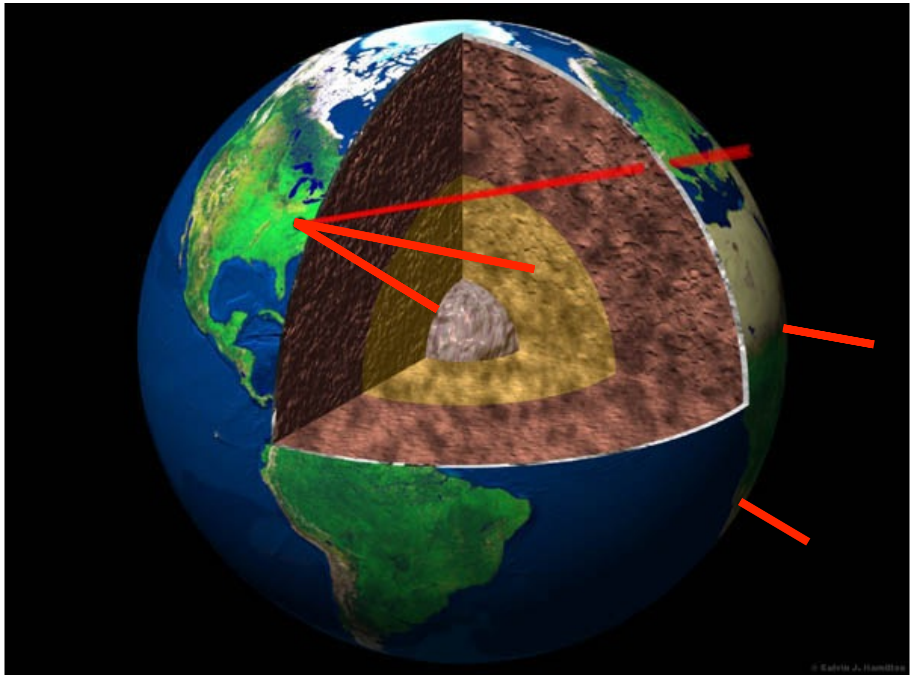
	Normal	**Inverted**
Neutrinos	Resonance	Suppression
Antineutrinos	Suppression	Resonance

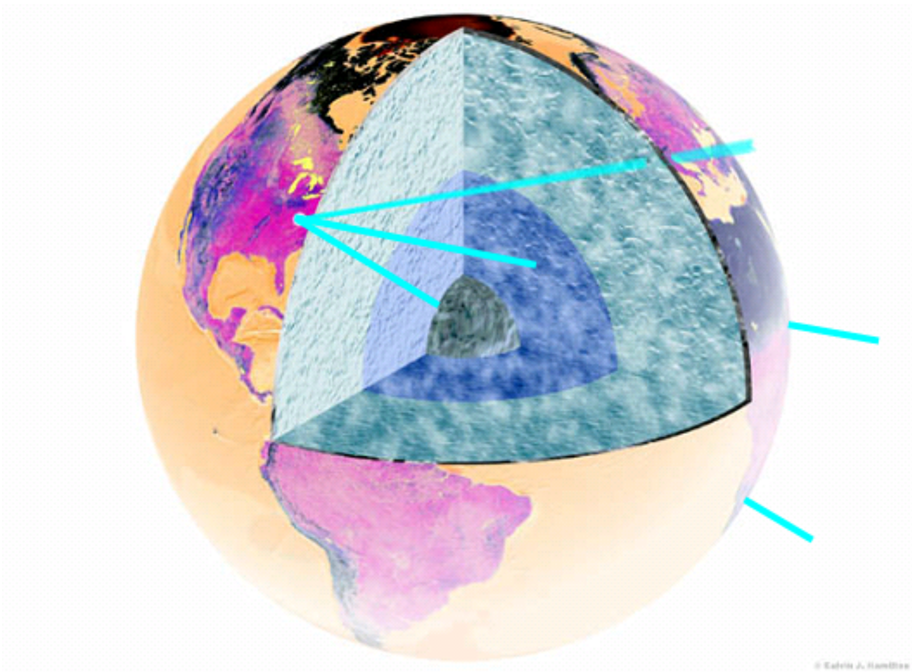
Extrinsic CP violation

- Matter effects violate CP and even CPT “extrinsically“
- Consequence: Obscure extraction of intrinsic CP violation

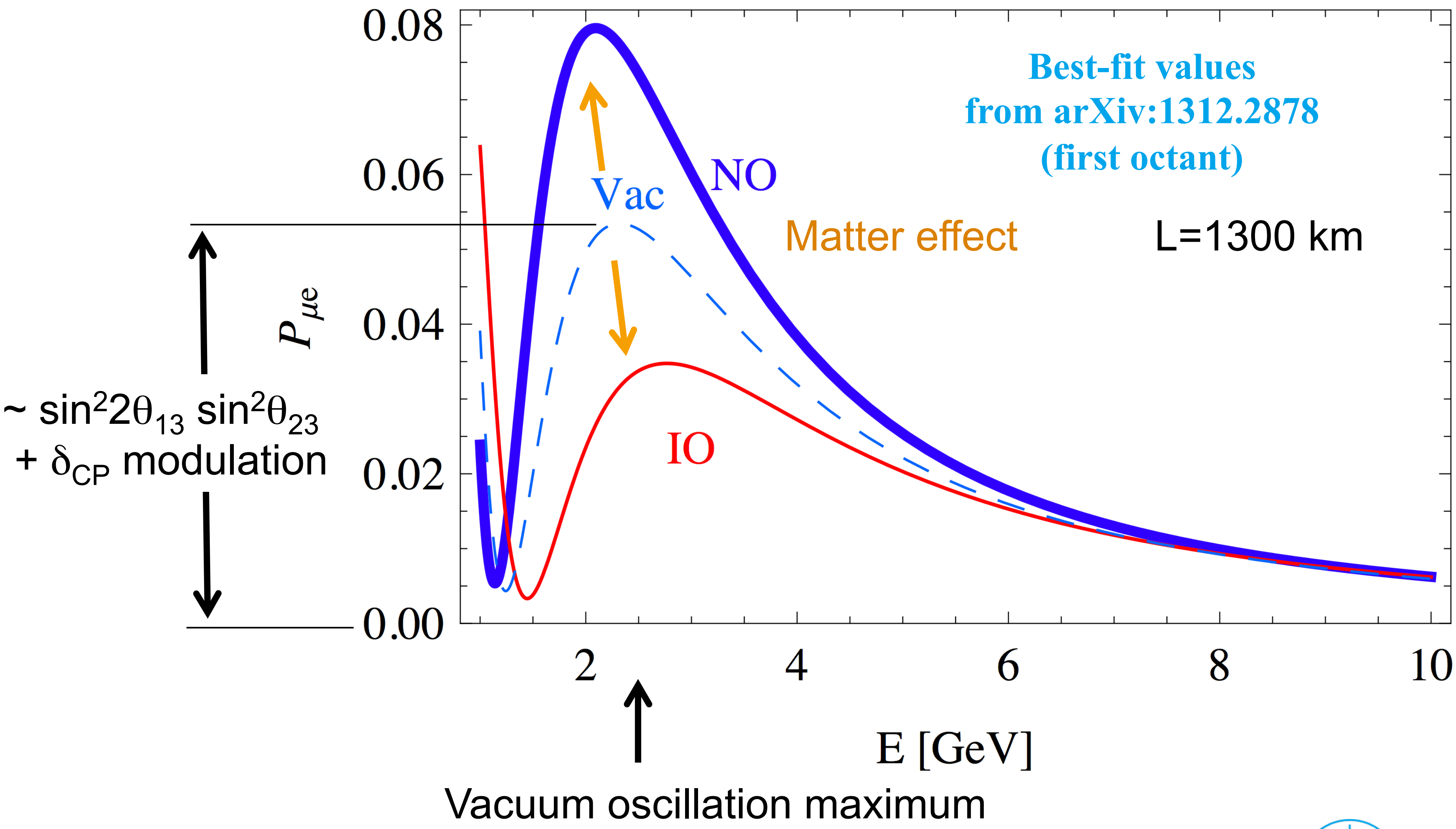
CP

Need an anti-Earth

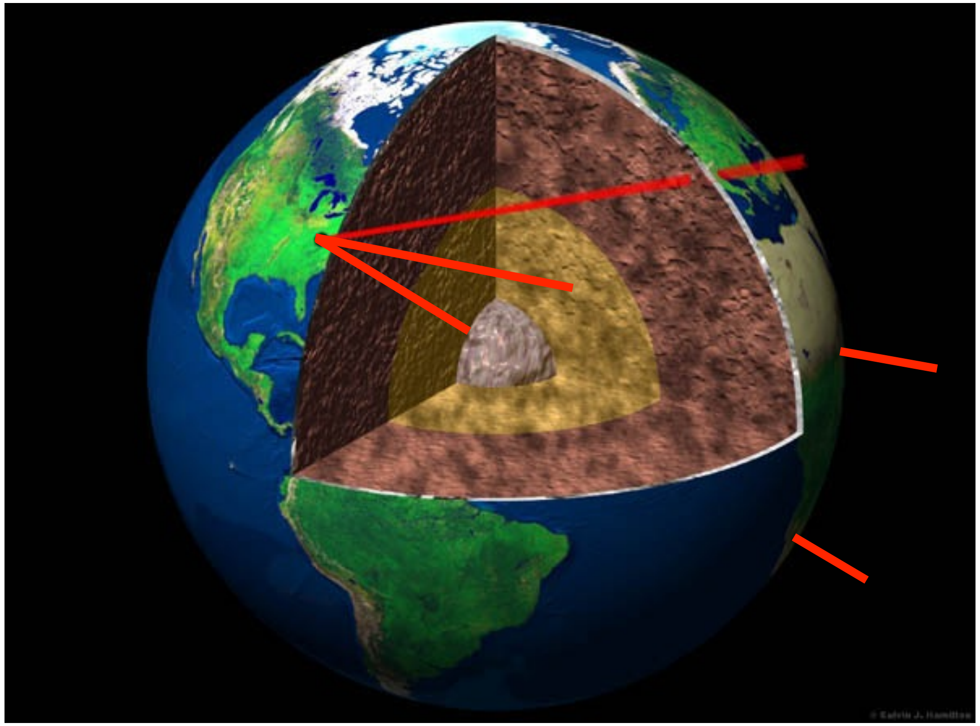


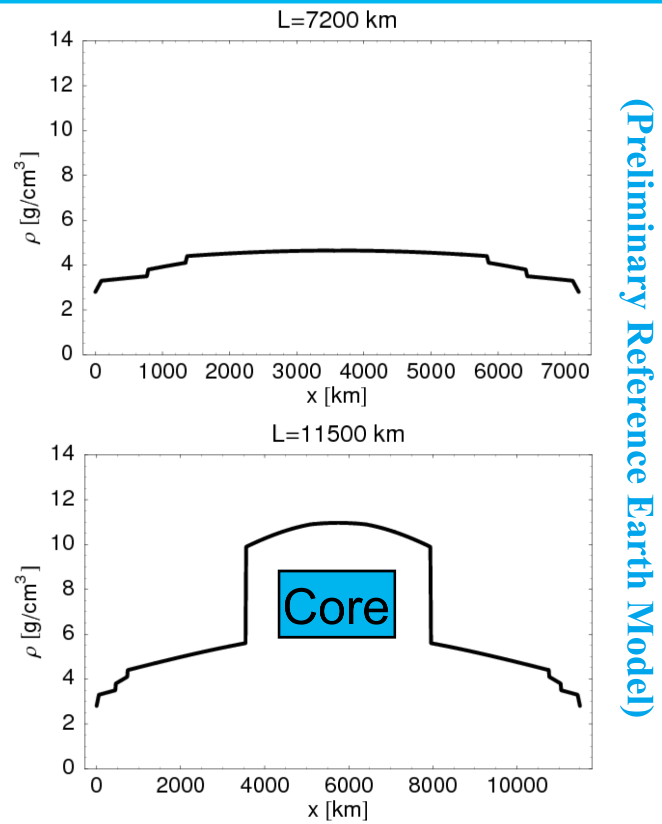


Long baseline experiments (up to first vacuum osc. maximum)



Matter profile of the Earth … as seen by a neutrino





Resonance energy (from $\hat{A} \rightarrow \cos 2\theta$):

$$E_{\text{res}}\,[\text{GeV}] \sim 13\,200\ \cos 2\theta\, \frac{\Delta m^2\,[\text{eV}^2]}{\rho\,[\text{g/cm}^3]}$$

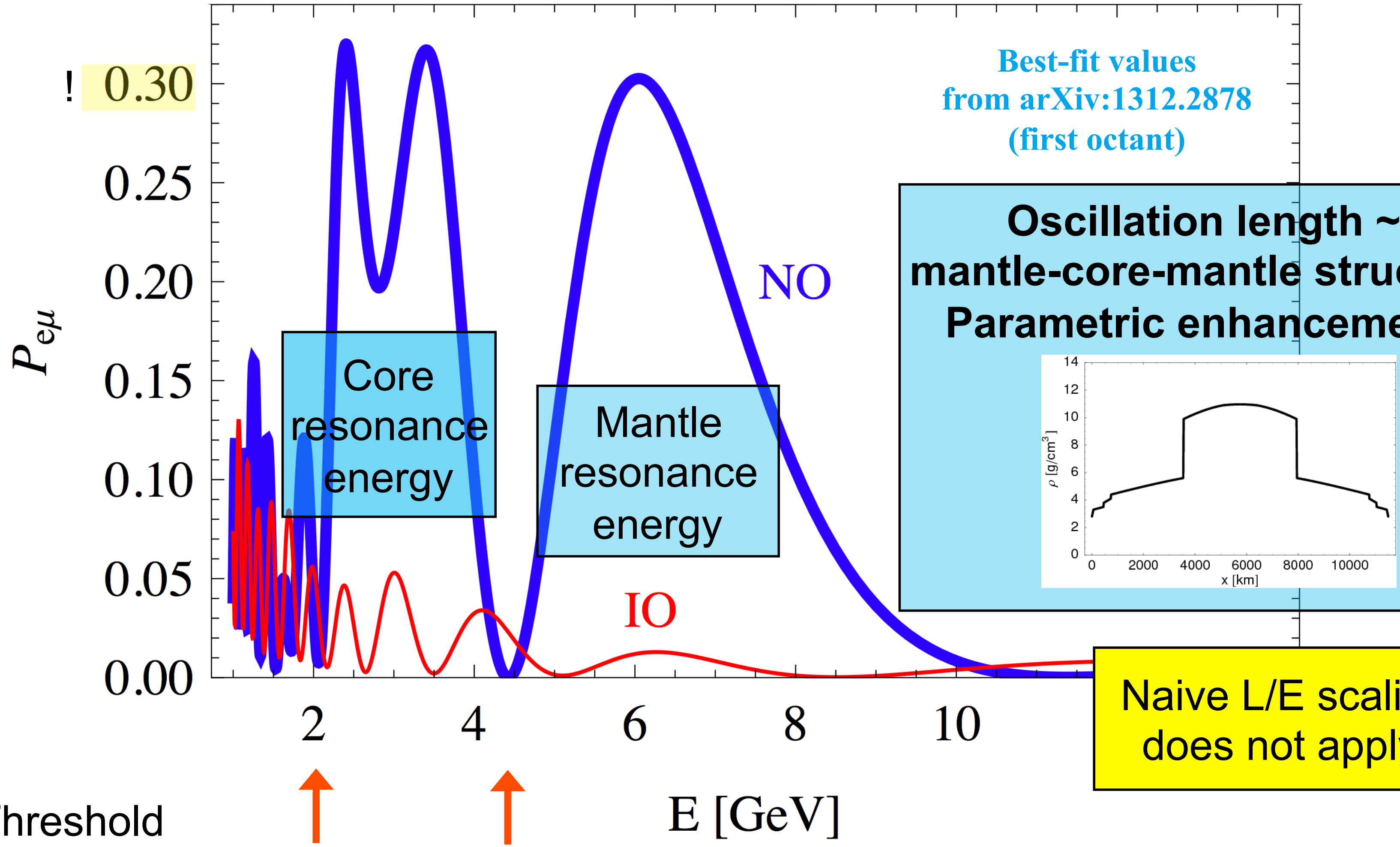
For ν_μ appearance, Δm_{31}^2:

- $\rho \sim 4.7$ g/cm^3 (Earth's mantle): **$E_{res} \sim 6.4$ GeV**
- $\rho \sim 10.8$ g/cm^3 (Earth's outer core): **$E_{res} \sim 2.8$ GeV**

Mantle-core-mantle profile

(Parametric enhancement: Akhmedov, 1998; Akhmedov, Lipari, Smirnov, 1998; Petcov, 1998)

- Probability for L=11810 km



Oscillation length ~ mantle-core-mantle structure Parametric enhancement.

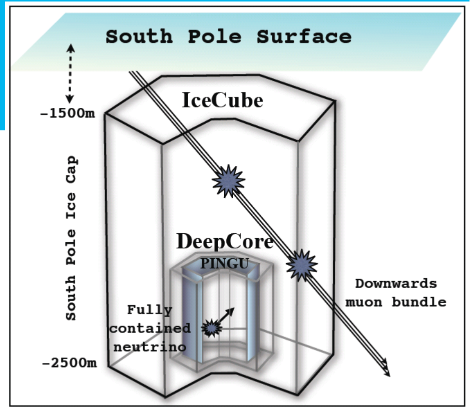
Naive L/E scaling does not apply!

Threshold effects expected at:

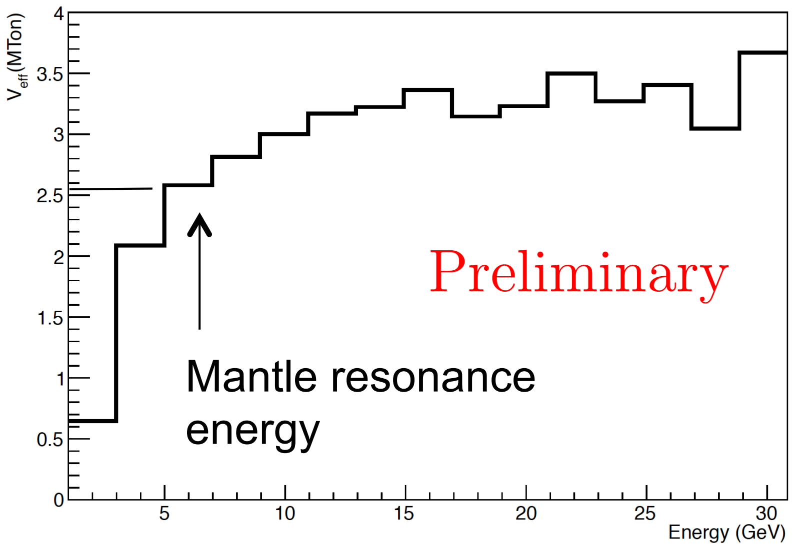
2 GeV

4-5 GeV

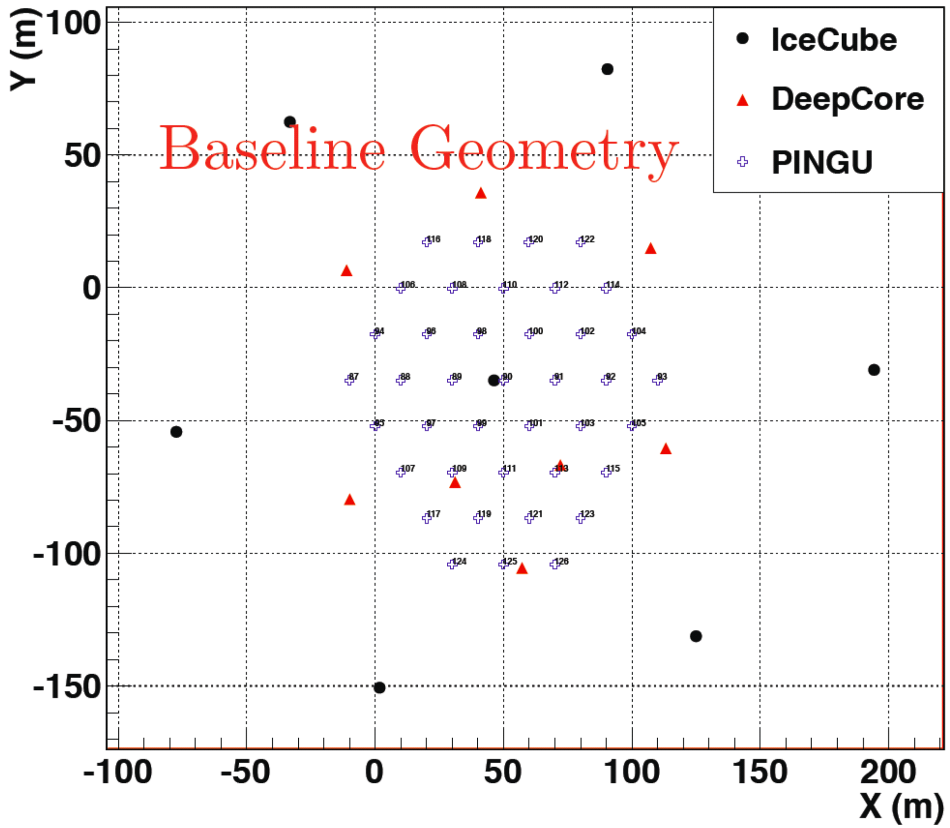
Emerging technologies: Atmospheric νs



- Example: PINGU
  (“Precision IceCube Next Generation Upgrade“)
- 40 additional strings, 60 optical modules each
- Lower threshold, few Mtons at a few GeV
- ORCA, INO: similar methods



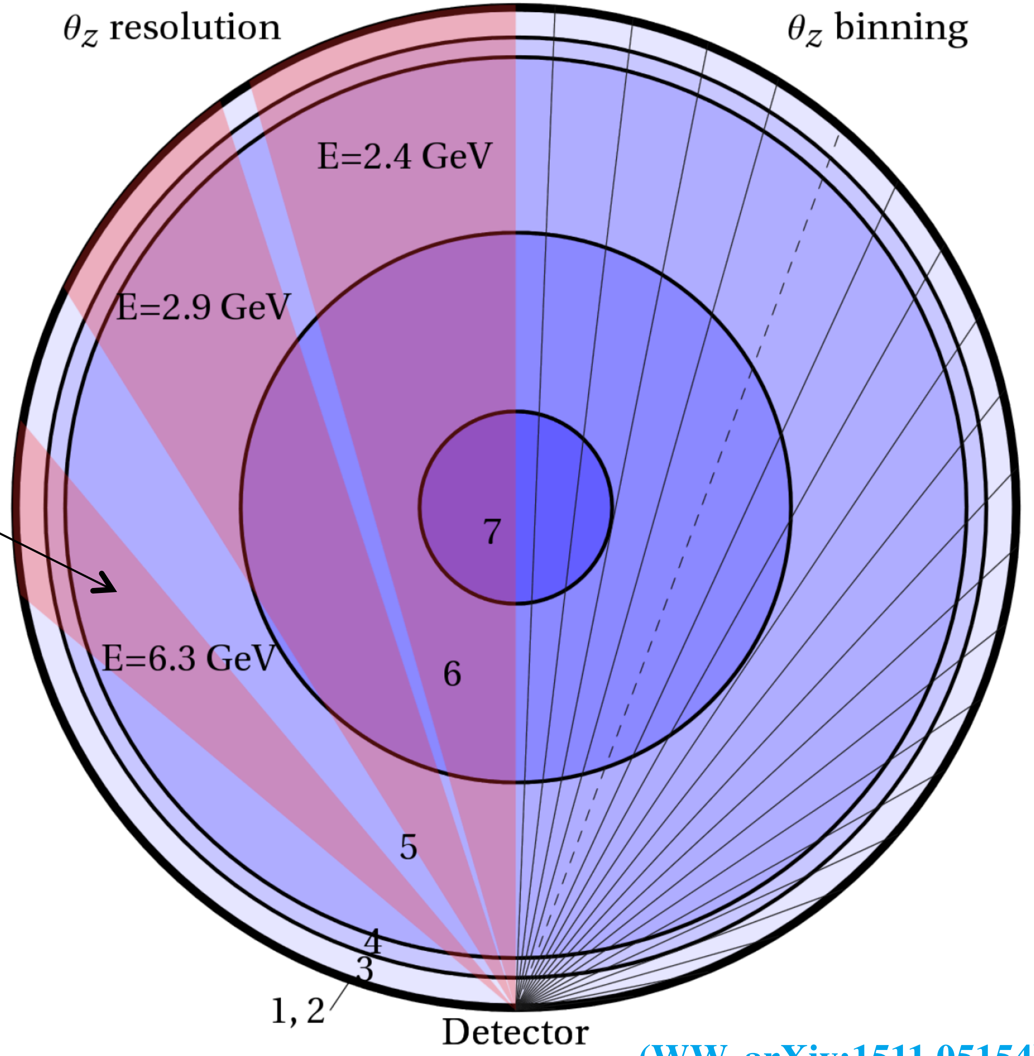
(a) $V_{\mathrm{eff}}(\nu_\mu)$



(PINGU LOI, arXiv:1401.2046)

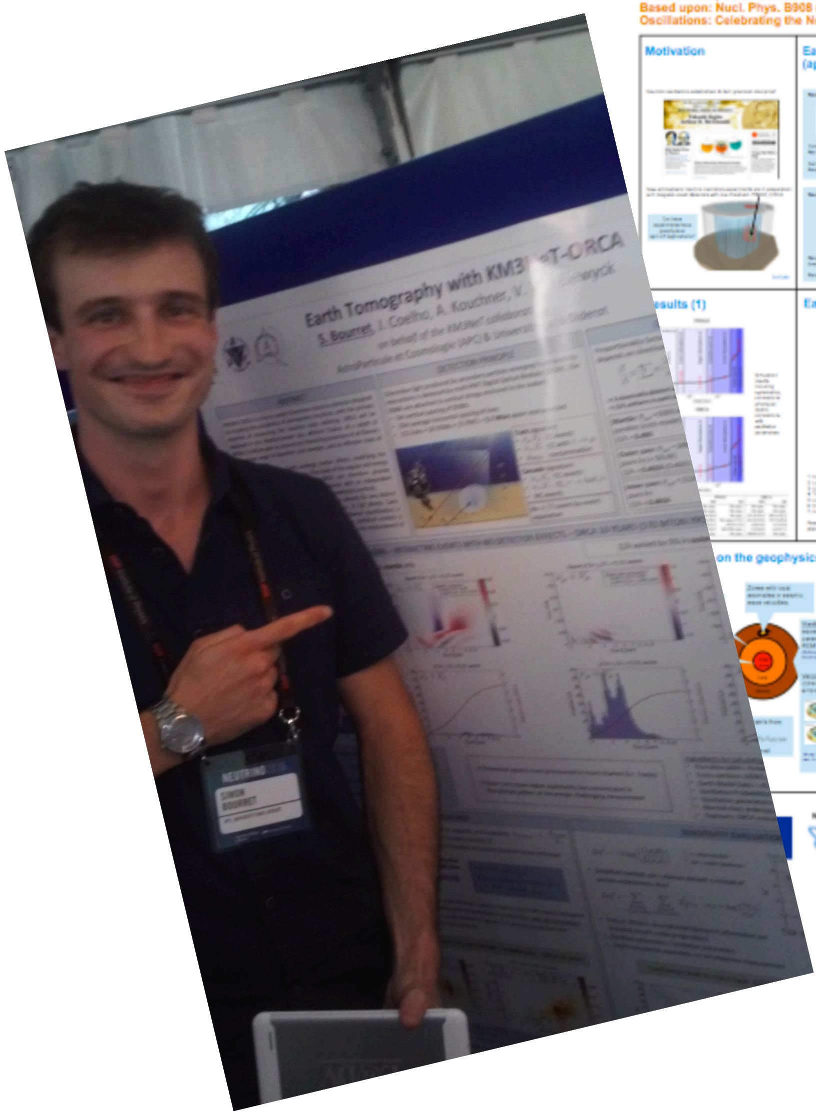
Earth tomography with atmospheric neutrinos

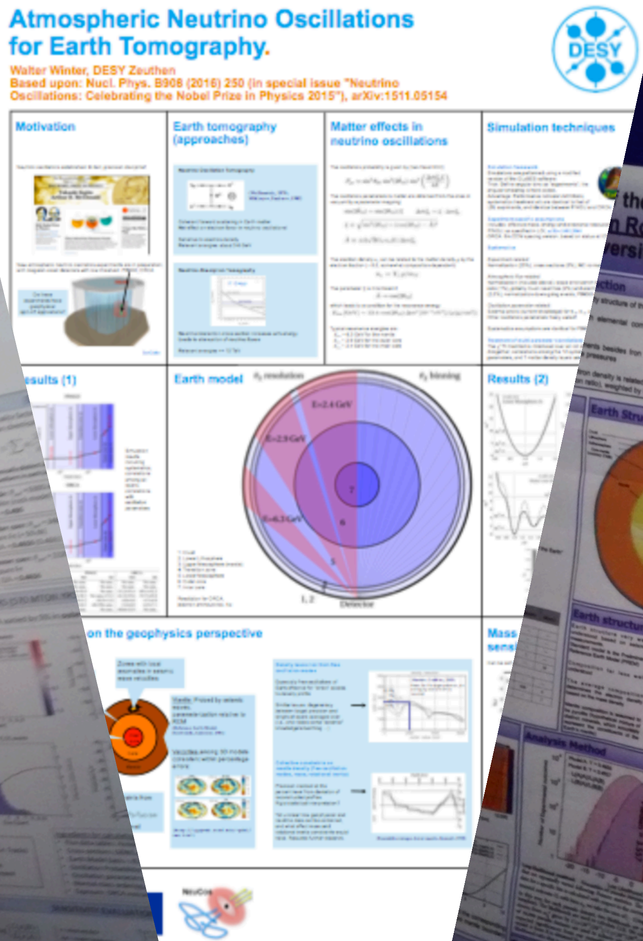
- Re-call that $n_e = Y\ \rho/m_N$
- Measure matter density times composition (Y=Z/A) using *neutrino oscillations* in matter
- Directional resolution potentially good enough in mantle
- Need self-consistent simulation, including systematics, oscillation parameters and matter densities to make this credible

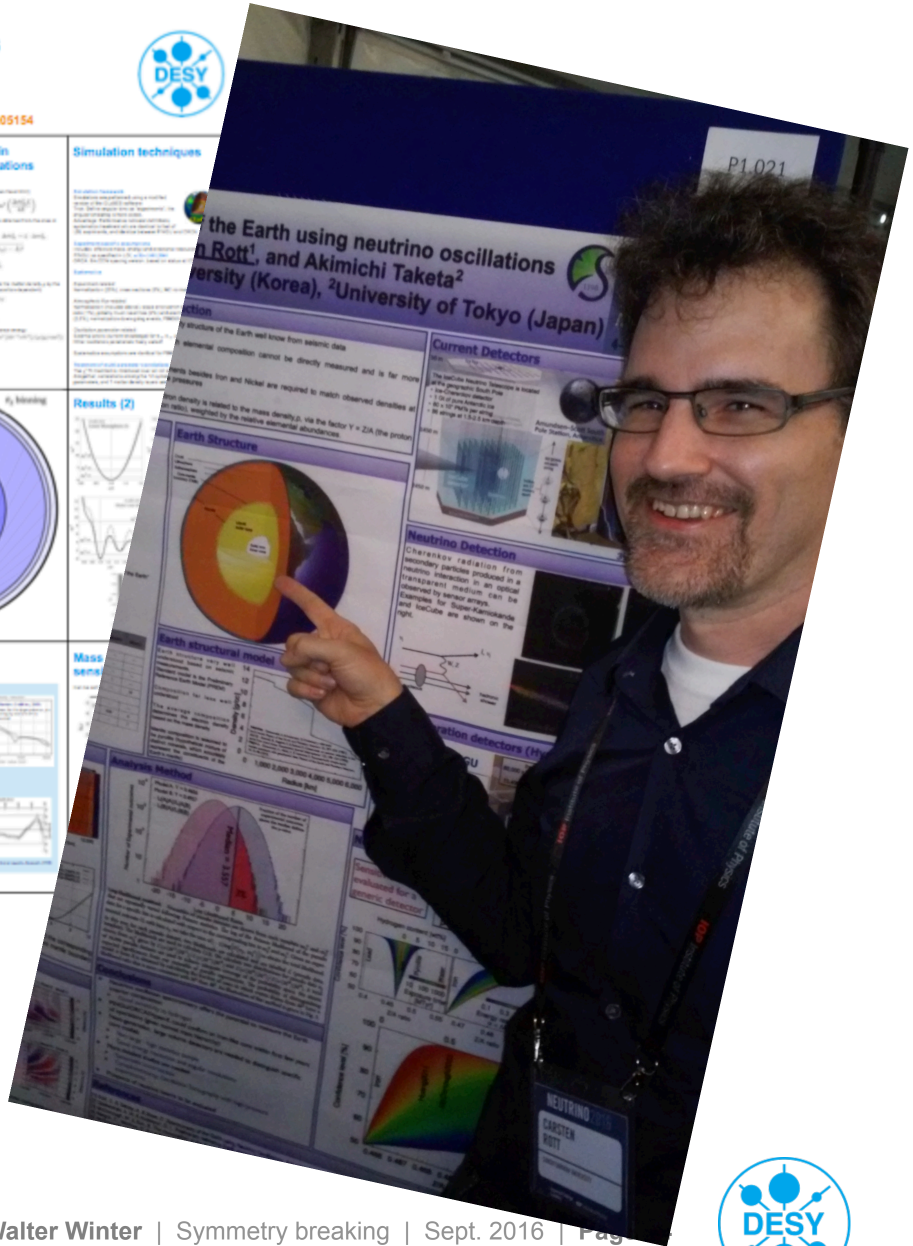


(WW, arXiv:1511.05154)

Impressions from Neutrino 2016





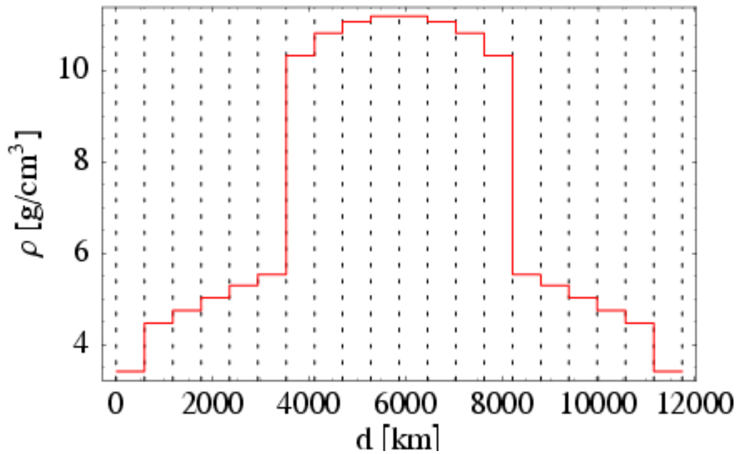


Neutrino oscillations with varying profiles, numerically

- Evolution operator method:

$$\mathcal{V}(x_j, n_j) = e^{-i\mathcal{H}(n_j)x_j}$$

H(n_j): Hamilton operator in constant electron density n_j



- Matter density from $n_j = Y \rho_j / m_N$, Y: electrons per nucleon (~0.5)
- Probability:

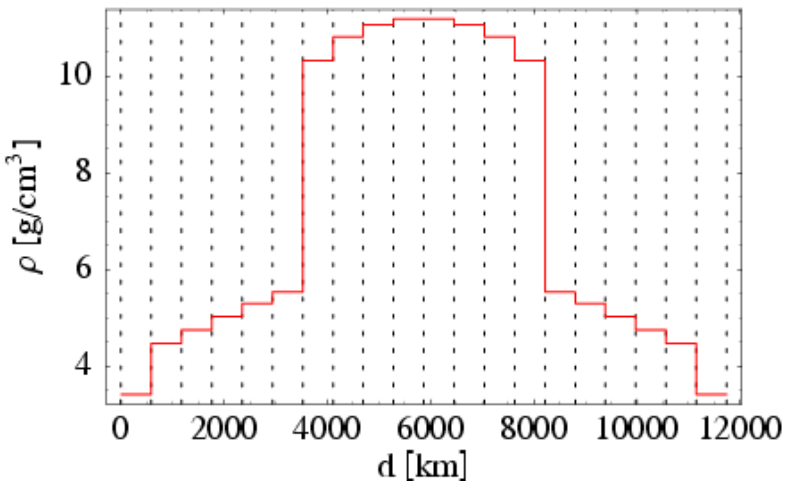
$$P_{\alpha\beta} = \left| \langle \nu_\beta | \mathcal{V}(x_m, n_m) ... \mathcal{V}(x_1, n_1) | \nu_\alpha \rangle \right|^2$$

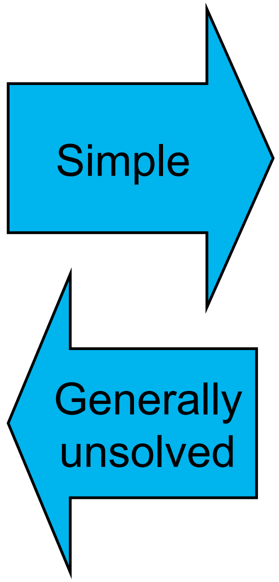
- NB: There is additional information through *interference* compared to absorption tomography because

$$[\mathcal{V}(x_i, n_i), \mathcal{V}(x_j, n_j)] \neq 0 \text{ für } n_i \neq n_j$$

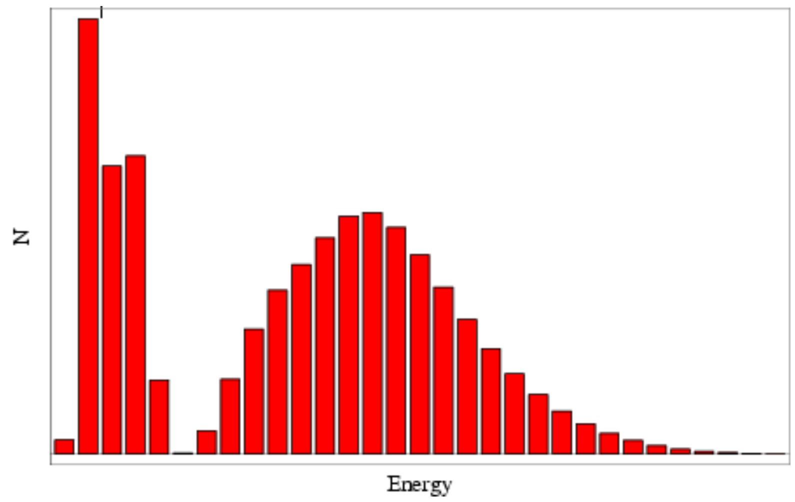
Matter profile inversion problem

Matter profile





Observation

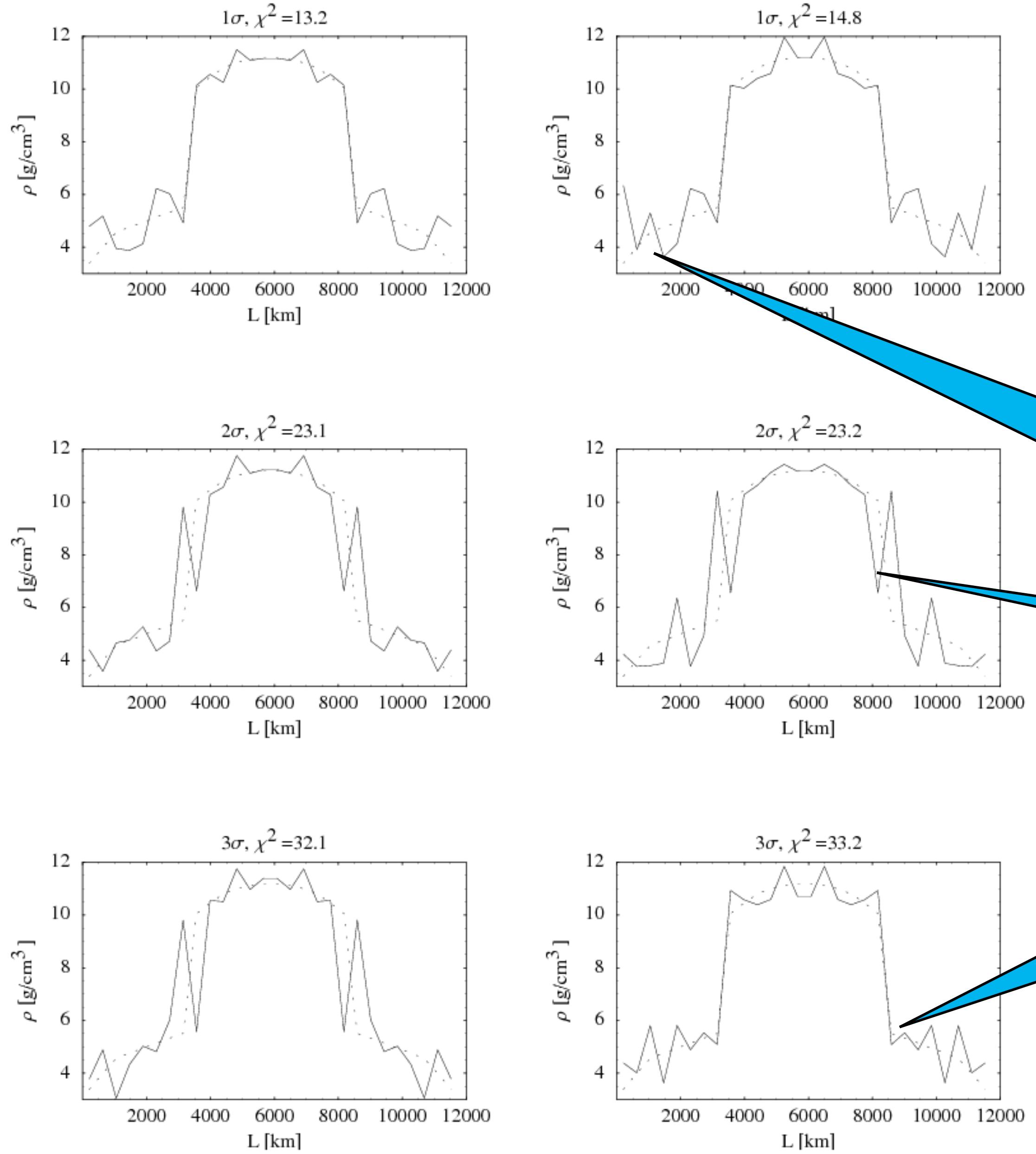


(Ermilova, Tsarev, Chechin, 1988)

<u>Some approaches for direct inversion:</u>

- Simple models, such as one zone (cavity) with density contrast
  (Nicolaidis, 1988; Ohlsson, Winter, 2002; Arguelles, Bustamante, Gago, 2015)
- Linearization for low densities (Akhmedov, Tortola, Valle, 2005)
- Discretization with many (N) parameters:
  Use non-deterministic methods to reconstruct these parameters
  (e. g. genetic algorithm in Ohlsson, Winter, 2001)

Example: structural resolution with a single baseline (11750 km)



Some characteristic examples close to 1σ, 2σ, 3σ (14 d.o.f.)

Can reconstruct mantle-core-mantle profile

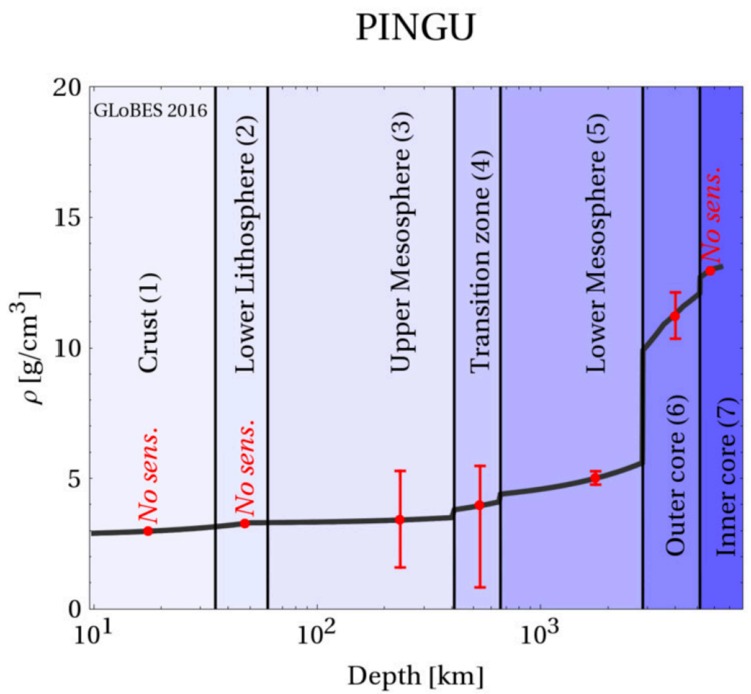
Fluctuations on short scales (<< L^{osc}) cannot be resolved

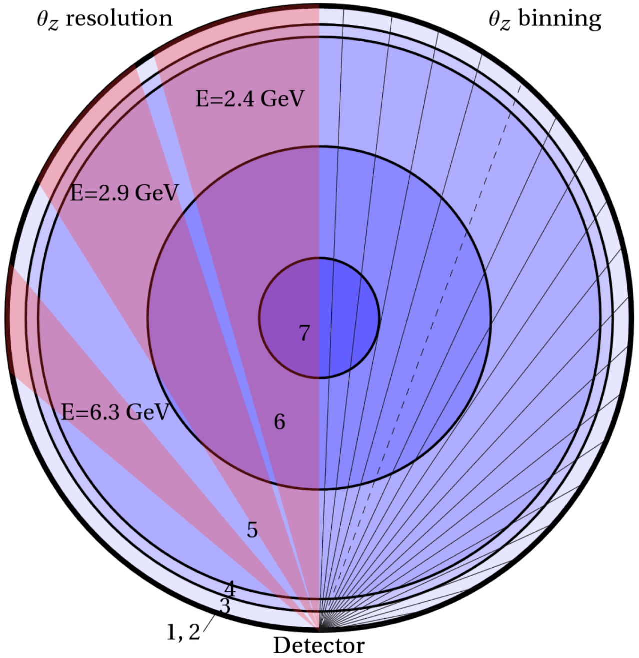
Cannot localize mantle-core-boundary

Cannot resolve very small density contrasts

(Ohlsson, Winter, Phys. Lett. B512 (2001) 357)

… back to tomography using atmospheric neutrinos





(NO, 10 yr)

Layer	PINGU		ORCA	
	NO	IO	NO	IO
Crust (1)	No sens.	No sens.	No sens.	No sens.
Lower Lithosphere (2)	No sens.	No sens.	No sens.	No sens.
Upper Mesosphere (3)	$-53.4/+55.0$	No sens.	$-51.2/+53.4$	$-69.1/+52.2$
Transition zone (4)	$-79.2/+38.3$	No sens./$+72.2$	$-61.2/+35.6$	$-52.7/+45.8$
Lower Mesosphere (5)	$-5.0/+5.2$	$-10.5/+11.6$	$-4.0/+4.0$	$-4.7/+4.8$
Outer core (6)	$-7.6/+8.2$	-40.2/No sens.	$-5.4/+6.0$	$-6.5/+7.1$
Inner core (7)	No sens.	No sens.	$-60.8/+32.9$	No sens.

WW, special issue "Neutrino Oscillations: Celebrating the Nobel Prize in Physics 2015", Nucl. Phys. B908, 2016, 250; Review on neutrino tomography: WW, Earth Moon Planets 99 (2006) 285

Theory of neutrino masses and mixings

What it is:

- The unadorned truth about neutrinos and physics BSM
- A generic view, supported by a biased selection of models (always if you let a theorist talk about that topic …)

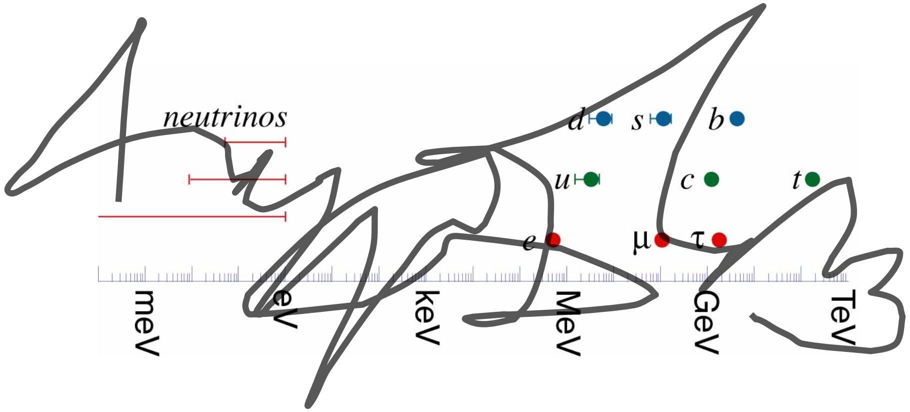
What it is *not*:

- A comprehensive review or coverage of topics
- An homage to flavor models

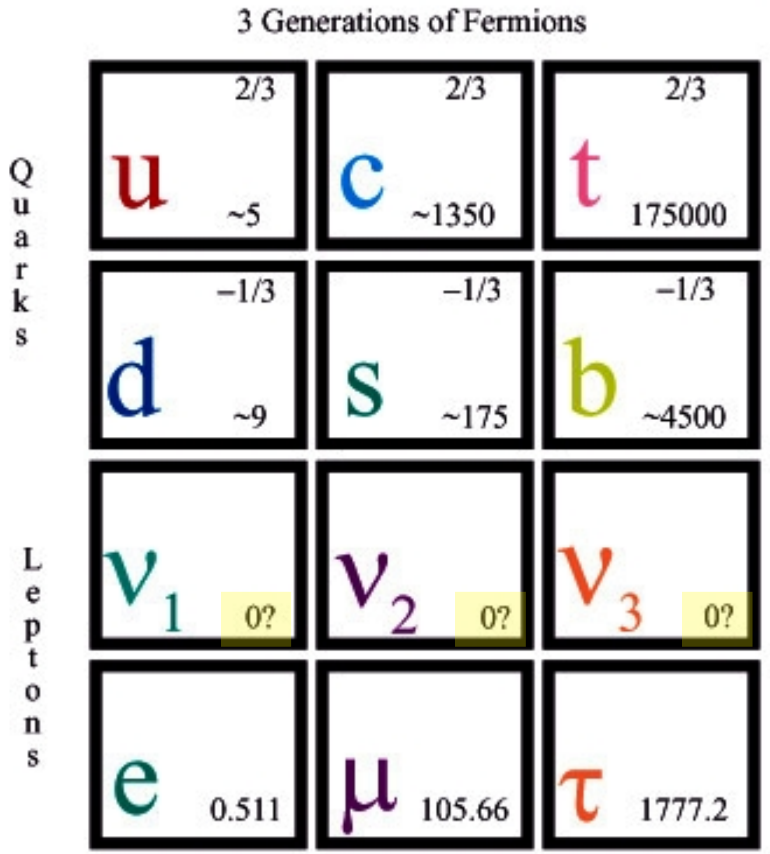
Are massive neutrinos physics beyond the Standard Model?

- Neutrinos in the Standard Model are massless
- So what?

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



Problem fixed!!!!!?



Masses are in MeV

Caveat: Neutrinos are electrically neutral …

- **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 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
- [FAQ: Why not write a light Majorana mass term $m_L \nu \nu$ directly?]
- <u>Problem solution (1):</u> get rid off this Majorana mass term
- **Reminder from "model building 101", rule 2:**
  If I want to forbid some interactions, I introduce/invent a (new) discrete 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 beyond the Standard Model

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

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

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

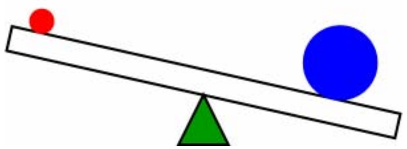
Block diag. $\Rightarrow$ $M_{\text{eff}}^{\text{Maj}} = -M_D M_R^{-1} M_D^T$

- Fixes another problem: smallness of neutrino mass (seesaw, type-I)

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

$\leftarrow$ Other SM particles

$\leftarrow$ Heavy partner



Generation of fermion mixings: Standard theory

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

Model-dependent: there are other possibilities to generate effective light Majorana neutrino masses

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

Block diag.

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

Charged lepton mass terms

Eff. neutrino mass terms

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

Rotates left-handed fields

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

cf., charged current

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

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):

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

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) 0νββ decay!

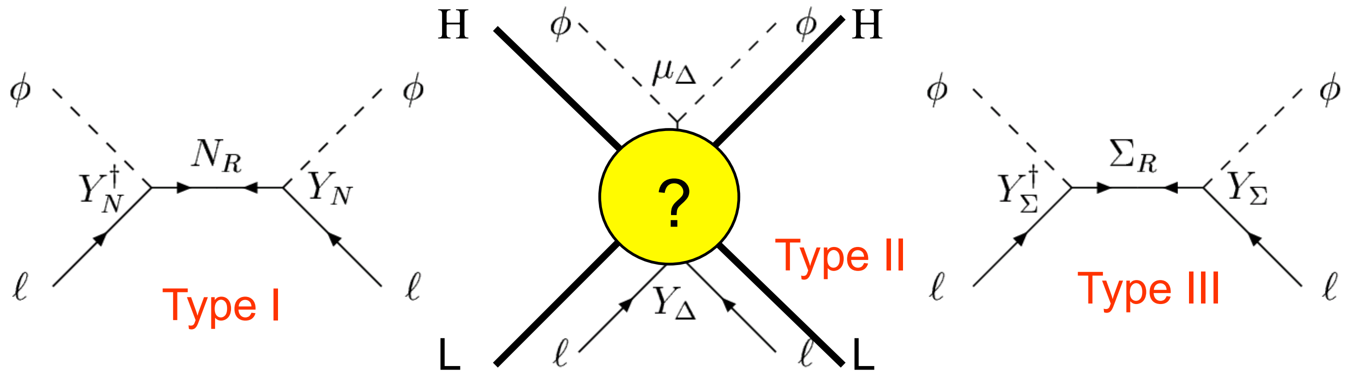
Lepton flavor violation (LFV)

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}
  - Interactions difficult to observe at the LHC
  - Couplings “unnaturally“ small? Fine-tuning?

Neutrino masses at the TeV scale?

> **Goals:**

- New physics scale “naturally“ at TeV scale
  (i.e., TeV scale not put in by hand)
  ⇨ Testable at the LHC?
- Yukawa couplings of order one

> Requires additional suppression mechanisms. The typical ones:

1) Radiative generation of neutrino mass (n loops)
2) Neutrino mass from higher than d=5 eff.operator
3) Small lepton number violating contribution ε
   (e.g. **inverse see-saw**, RPV SUSY models, …)

Model building 101, rule 3:
If I restore a symmetry by switching off a term, I would expect that this term is small **(‘t Hooft)**

$$m_\nu \propto \frac{\langle H^0 \rangle^2}{\Lambda} \times \left(\frac{1}{16\pi^2} \right)^n \times \epsilon \times \left(\frac{\langle H^0 \rangle}{\Lambda} \right)^{d-5}$$

Neutrino mass from higher dimensional or loop models

Loop suppression, controlled by 1/(16 π^2)

Type I, II, II seesaw

Depends on mediators/int.

2-loop

$$\mathscr{L}_{\text{eff}} = \mathscr{L}_{\text{SM}} + \frac{1}{\Lambda_{\text{NP}}}\left[\mathscr{L}^{(0)}_{d=5} + \delta\mathscr{L}^{(1)}_{d=5} + \delta\mathscr{L}^{(2)}_{d=5} + \cdots\right]$$

d=5

Discrete symmetry to forbid d=5?

$$+ \frac{1}{\Lambda^3_{\text{NP}}}\left[\mathscr{L}^{(0)}_{d=7} + \cdots\right]$$

Depends on scale: Λ > 4πv ~ 3 TeV?

d=7

$$+ \frac{1}{\Lambda^5_{\text{NP}}}\left[\mathscr{L}^{(0)}_{d=9} + \delta\mathscr{L}^{(1)}_{d=9} + \delta\mathscr{L}^{(2)}_{d=9} + \cdots\right]$$

d=8

$$+ \frac{1}{\Lambda^7_{\text{NP}}}\left[\mathscr{L}^{(0)}_{d=11} + \delta\mathscr{L}^{(1)}_{d=11} + \delta\mathscr{L}^{(2)}_{d=11} + \cdots\right]$$

d=11

$$+ \cdots$$

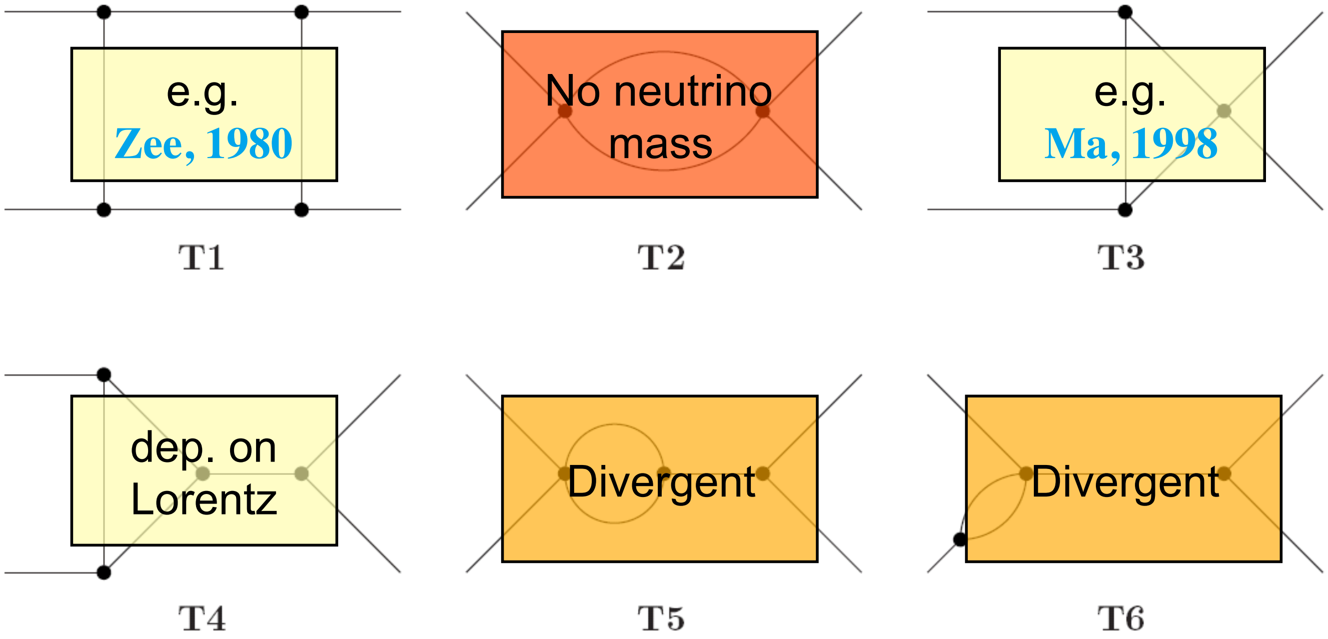
Suppression by d, controlled by 1/Λ^2

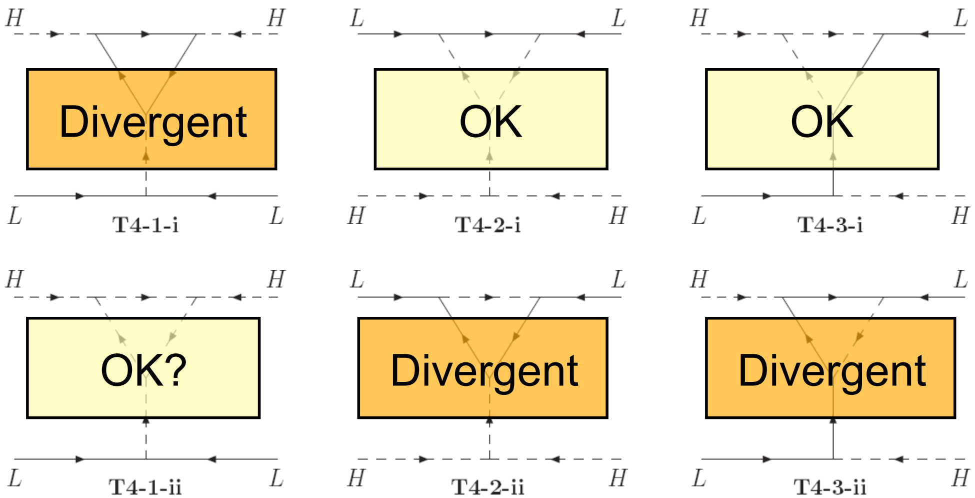
How can I make sure that no lower order operators are generated?

One loop models (d=5, complete list)

$$\begin{aligned}
\mathscr{L}_{\rm eff} = \mathscr{L}_{\rm SM} &+ \frac{1}{\Lambda_{\rm NP}}\left[\mathscr{L}^{(0)}_{d=5} + \delta\mathscr{L}^{(1)}_{d=5} + \delta\mathscr{L}^{(2)}_{d=5} + \cdots\right] \\
&+ \frac{1}{\Lambda^3_{\rm NP}}\left[\mathscr{L}^{(0)}_{d=7} + \delta\mathscr{L}^{(1)}_{d=7} + \delta\mathscr{L}^{(2)}_{d=7} + \cdots\right] \\
&+ \frac{1}{\Lambda^5_{\rm NP}}\left[\mathscr{L}^{(0)}_{d=9} + \delta\mathscr{L}^{(1)}_{d=9} + \delta\mathscr{L}^{(2)}_{d=9} + \cdots\right] \\
&+ \frac{1}{\Lambda^7_{\rm NP}}\left[\mathscr{L}^{(0)}_{d=11} + \delta\mathscr{L}^{(1)}_{d=11} + \delta\mathscr{L}^{(2)}_{d=11} + \cdots\right] \\
&+ \cdots
\end{aligned}$$

Topologies from FeynArts:





Bonnet, Hirsch, Ota, Winter, 2012

Neutrino mass from higher dimensional operators

- Approach: Use higher dimensional operators, e.g.

$$\begin{aligned} \mathcal{O}^5 &= \mathcal{O}_W = LLHH \\ \mathcal{O}^7 &= (LLHH)(H^\dagger H) \\ \mathcal{O}^9 &= (LLHH)(H^\dagger H)(H^\dagger H) \end{aligned}$$

- Leads to

$$m_\nu \sim v \left(\frac{v}{\Lambda_{\mathrm{NP}}} \right)^{d-4}$$

- Estimate: for Λ ~ 1 – 10 TeV and m_ν linear in Yukawas (worst case):
  - d = 9 sufficient if no other suppression mechanism
  - d = 7 sufficient if Yukawas ~ m_e/v ~ 10^{-6} allowed

Forbid lower dimensional operators

- Define *genuine* d=D operator as leading contribution to neutrino mass with all operators d<D forbidden
- Use new U(1) or discrete symmetry (“matter parity“)
- Problem: H^+H can never be charged under the new symmetry!
  ⇨ **Need new fields, such as SU(2) singlet S or doublet H**
- The simplest possibilities are

$$\mathscr{L}_{\text{eff}}^{d=n+5} = \frac{1}{\Lambda_{\text{NP}}^{d-4}} (LLHH)(S)^n \,, \quad n = 1, 2, 3, \ldots$$

(e.g. Chen, de Gouvea, Dobrescu, hep-ph/0612017; Godoladze, Okada, Shafi, arXiv:0809.0703; Bonnet at al, arXiv:0907.3143)

$$\mathscr{L}_{\text{eff}}^{d=2n+5} = \frac{1}{\Lambda_{\text{NP}}^{d-4}} (LLH_uH_u)(H_dH_u)^n \,, \quad n = 1, 2, 3, \ldots$$

(e.g. Babu, Nandi, hep-ph/9907213; Giudice, Lebedec, arXiv:0804.1753; Bonnet at al, arXiv:0907.3143)

Towards TeV seesaws with O(1) couplings

Bonnet, Hernandez, Ota, Winter, JHEP 10 (2009) 076

Loop suppression, controlled by 1/(16 π^2)

Tree | 1-loop | 2-loop

Suppression by d, controlled by 1/Λ^2

$$\mathscr{L}_{\rm eff} = \mathscr{L}_{\rm SM} + \ldots$$

Switched off by discrete symmetry — d=5

$+ \ldots$ — d=7

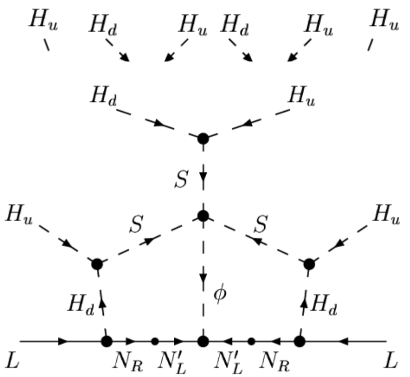
To be avoided

for Λ < 3 TeV

$$+ \frac{1}{\Lambda^5_{\rm NP}} \left[\mathscr{L}^{(0)}_{d=9} + \delta\mathscr{L}^{(1)}_{d=9} + \delta\mathscr{L}^{(2)}_{d=9} + \cdots \right]$$ — d=8

$$+ \frac{1}{\Lambda^7_{\rm NP}} \left[\mathscr{L}^{(0)}_{d=11} + \delta\mathscr{L}^{(1)}_{d=11} + \delta\mathscr{L}^{(2)}_{d=11} + \cdots \right]$$ — d=11

$$+ \cdots$$



Physics at TeV scale with O(1) couplings

Example 1: d=9 at tree level

Example 2: d=7 at two loop ⇨ **Suppression mechanisms 1), 2), and 3)**

Different scales for the “heavy” sterile neutrinos?

Sterile neutrinos are good for manys scales and problems:

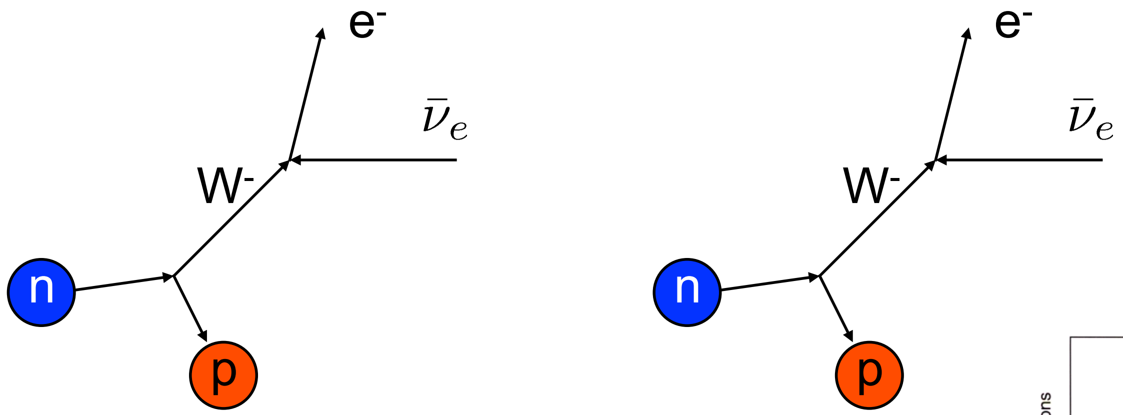
- eV-scale: neutrino anomalies (LSND)
  Tests in short-baseline neutrino oscillations
- keV-scale: candidates for warm dark matter
  Tests in X-ray astronomy,e.g. 3.5 keV line (XMM-Newton)
- GeV-scale: candidates for low-E seesaws, leptogenesis
  Tests in beam-dump experiments (SHiP) and future colliders
- ✔ TeV-scale: see-saw models, physics BSM (hierarchy problem)
  Tests at the LHC
- ✔ (below) GUT scale: natural O(1) couplings, leptogenesis
  Test by exclusion principle (no direct test)

νMSM
aka
νTOE

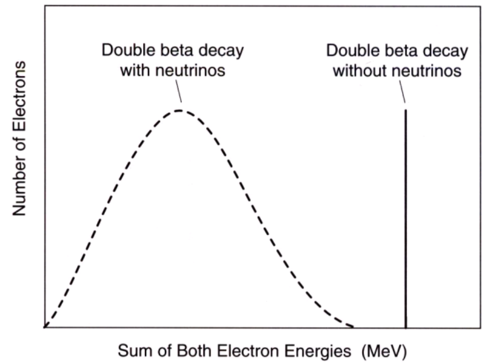
Solve all outstanding BSM questions? Use e.g. three extra sterile neutrinos, two at GeV scale (leptogenesis), one at keV scale (dark matter) [requires some fine-tuning of the masses for leptogenesis …]
Canetti, Drewes, Shaposhnikov, 2012

Signature of the Majorana nature: $0\nu\beta\beta$

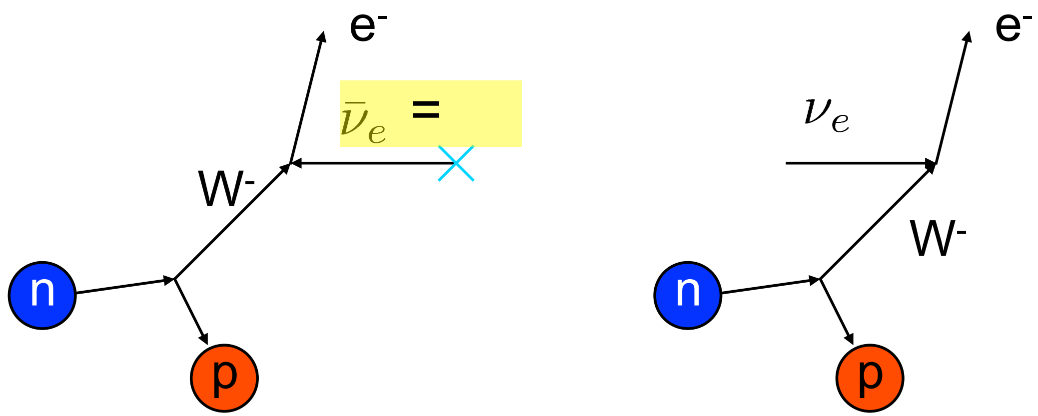
> Two times simple beta decay:



$\Rightarrow$ $2 \times \nu$
$2 \times e$



> Neutrinoless double beta decay:



$\Rightarrow$ $0 \times \nu$
$2 \times e$

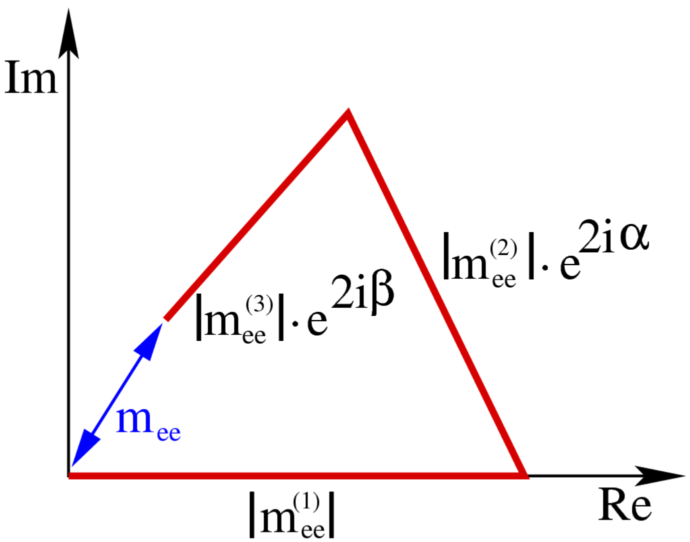
$0\nu\beta\beta$ phenomenology

- Rate ~ $|m_{ee}|^2$ x |nucl. matrix element|

$$|m_{ee}| \equiv \left| \sum_i m_i U_{ei}^2 \right|$$

$$m_{ee} = |m_{ee}^{(1)}| + |m_{ee}^{(2)}|\, e^{2i\alpha} + |m_{ee}^{(3)}|\, e^{2i\beta}$$

Majorana phases



(Lindner, Merle, Rodejohann, 2005)

$$\begin{aligned} |m_{ee}^{(1)}| &= m_1\,|U_{e1}|^2 = m_1\, c_{12}^2\, c_{13}^2 \;, \\ |m_{ee}^{(2)}| &= m_2\,|U_{e2}|^2 = m_2\, s_{12}^2\, c_{13}^2 \;, \\ |m_{ee}^{(3)}| &= m_3\,|U_{e3}|^2 = m_3\, s_{13}^2 \;. \end{aligned}$$

0νββ phenomenology (2)

- **Normal ordering**: Lightest mass is m_1

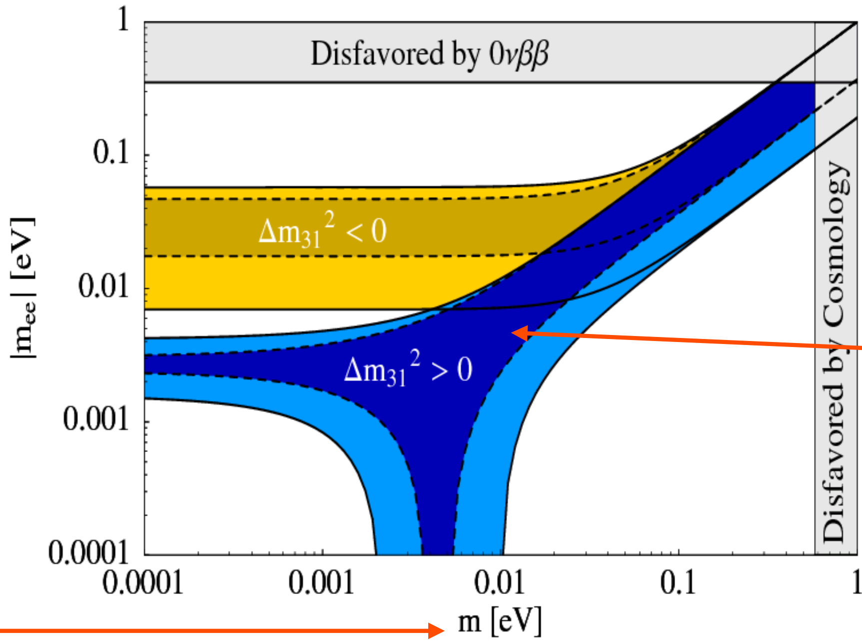
$$m_{ee}^{\rm nor} = m_1\, c_{12}^2\, c_{13}^2 + \sqrt{m_1^2 + \Delta m_\odot^2}\, s_{12}^2\, c_{13}^2\, e^{2i\alpha} + \sqrt{m_1^2 + \Delta m_{\rm A}^2}\, s_{13}^2\, e^{2i\beta}$$

Potentially small parameters: cancellation possible

- **Inverted ordering**: Lightest mass is m_3

$$m_{ee}^{\rm inv} = \sqrt{m_3^2 + \Delta m_{\rm A}^2}\, c_{12}^2\, c_{13}^2 + \sqrt{m_3^2 + \Delta m_\odot^2 + \Delta m_{\rm A}^2}\, s_{12}^2\, c_{13}^2\, e^{2i\alpha} + m_3\, s_{13}^2\, e^{2i\beta}$$

Always largest term, no cancellations



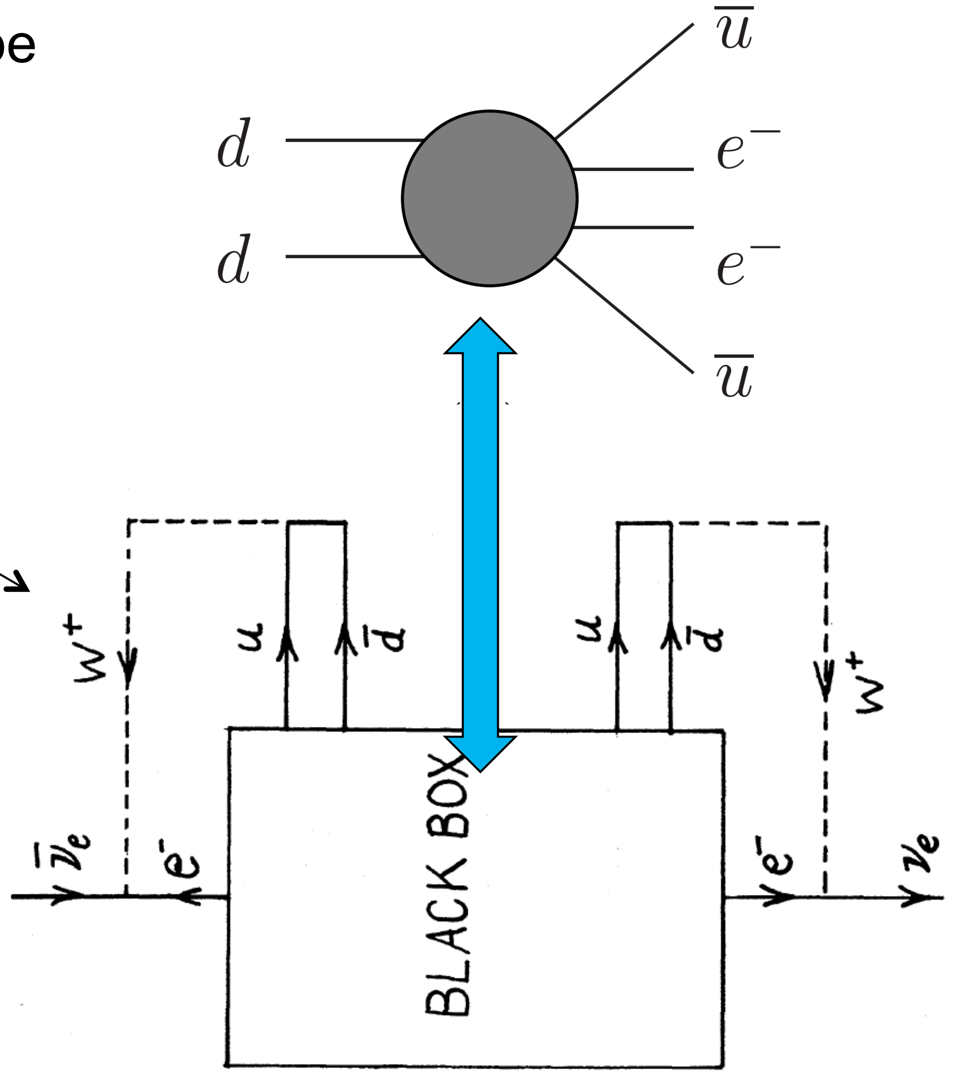
Bands: Impact of phases/ current knowledge

(Lindner, Merle, Rodejohann, 2005)

Lightest mass m_1 or m_3

Relationship to neutrino mass? Effective field theory!

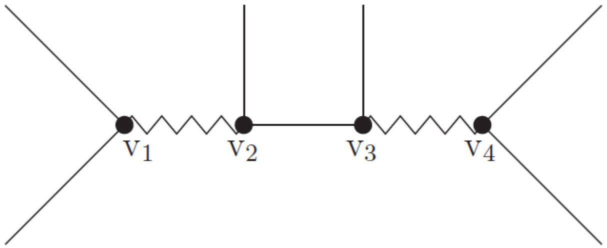
- Neutrinoless double beta decay can be treated as effective d=9 operator:



- This leads to loop-generated Majorana masses
  Schechter, Valle, 1982
- The contribution to neutrino mass may, however, be small
  Dürr, Lindner, Merle, 2012
- Is neutrino mass the leading mechanism for 0νββ?

$0\nu\beta\beta$ mechanisms

- There exists a long list of BSM tree-level models which can lead to $0\nu\beta\beta$
  Bonnet, Hirsch, Ota, Winter JHEP 1303 (2013) 055



- The observation of $0\nu\beta\beta$ is a smoking gun signature for physics BSM, not (necessarily) for neutrino mass!

#	Decomposition	Long Range?	Mediator $(U(1)_{\rm em}, SU(3)_c)$ S or V_ρ	ψ	S' or V'_ρ	Models/Refs./Comments
1-i	$(\bar{u}d)(\bar{e})(\bar{e})(\bar{u}d)$	(a)	$(+1,\mathbf{1})$	$(0,\mathbf{1})$	$(-1,\mathbf{1})$	Mass mechan., RPV [58–60], LR-symmetric models [39], Mass mechanism with ν_S [61], TeV scale seesaw, e.g., [62, 63]
			$(+1,\mathbf{8})$	$(0,\mathbf{8})$	$(-1,\mathbf{8})$	[64]
1-ii-a	$(\bar{u}d)(\bar{u})(d)(\bar{e}\bar{e})$		$(+1,\mathbf{1})$	$(+5/3,\mathbf{3})$	$(+2,\mathbf{1})$	
			$(+1,\mathbf{8})$	$(+5/3,\mathbf{3})$	$(+2,\mathbf{1})$	
1-ii-b	$(\bar{u}d)(d)(\bar{u})(\bar{e}\bar{e})$		$(+1,\mathbf{1})$	$(+4/3,\overline{\mathbf{3}})$	$(+2,\mathbf{1})$	
			$(+1,\mathbf{8})$	$(+4/3,\overline{\mathbf{3}})$	$(+2,\mathbf{1})$	
2-i-a	$(\bar{u}d)(d)(\bar{e})(\bar{u}\bar{e})$		$(+1,\mathbf{1})$	$(+4/3,\overline{\mathbf{3}})$	$(+1/3,\overline{\mathbf{3}})$	
			$(+1,\mathbf{8})$	$(+4/3,\overline{\mathbf{3}})$	$(+1/3,\overline{\mathbf{3}})$	
2-i-b	$(\bar{u}d)(\bar{e})(d)(\bar{u}\bar{e})$	(b)	$(+1,\mathbf{1})$	$(0,\mathbf{1})$	$(+1/3,\overline{\mathbf{3}})$	RPV [58–60], LQ [65, 66]
			$(+1,\mathbf{8})$	$(0,\mathbf{8})$	$(+1/3,\overline{\mathbf{3}})$	
2-ii-a	$(\bar{u}d)(\bar{u})(\bar{e})(d\bar{e})$		$(+1,\mathbf{1})$	$(+5/3,\mathbf{3})$	$(+2/3,\mathbf{3})$	
			$(+1,\mathbf{8})$	$(+5/3,\mathbf{3})$	$(+2/3,\mathbf{3})$	
2-ii-b	$(\bar{u}d)(\bar{e})(\bar{u})(d\bar{e})$	(b)	$(+1,\mathbf{1})$	$(0,\mathbf{1})$	$(+2/3,\mathbf{3})$	RPV [58–60], LQ [65, 66]
			$(+1,\mathbf{8})$	$(0,\mathbf{8})$	$(+2/3,\mathbf{3})$	
2-iii-a	$(d\bar{e})(\bar{u})(d)(\bar{u}\bar{e})$	(c)	$(-2/3,\overline{\mathbf{3}})$	$(0,\mathbf{1})$	$(+1/3,\overline{\mathbf{3}})$	RPV [58–60]
			$(-2/3,\overline{\mathbf{3}})$	$(0,\mathbf{8})$	$(+1/3,\overline{\mathbf{3}})$	RPV [58–60]
2-iii-b	$(d\bar{e})(d)(\bar{u})(\bar{u}\bar{e})$		$(-2/3,\overline{\mathbf{3}})$	$(-1/3,\mathbf{3})$	$(+1/3,\overline{\mathbf{3}})$	
			$(-2/3,\overline{\mathbf{3}})$	$(-1/3,\overline{\mathbf{6}})$	$(+1/3,\overline{\mathbf{3}})$	
3-i	$(\bar{u}\bar{u})(\bar{e})(\bar{e})(dd)$		$(+4/3,\overline{\mathbf{3}})$	$(+1/3,\overline{\mathbf{3}})$	$(-2/3,\overline{\mathbf{3}})$	only with V_ρ and V'_ρ
			$(+4/3,\mathbf{6})$	$(+1/3,\mathbf{6})$	$(-2/3,\mathbf{6})$	
3-ii	$(\bar{u}\bar{u})(d)(d)(\bar{e}\bar{e})$		$(+4/3,\overline{\mathbf{3}})$	$(+5/3,\mathbf{3})$	$(+2,\mathbf{1})$	only with V_ρ
			$(+4/3,\mathbf{6})$	$(+5/3,\mathbf{3})$	$(+2,\mathbf{1})$	
3-iii	$(dd)(\bar{u})(\bar{u})(\bar{e}\bar{e})$		$(+2/3,\mathbf{3})$	$(+4/3,\overline{\mathbf{3}})$	$(+2,\mathbf{1})$	only with V_ρ
			$(+2/3,\overline{\mathbf{6}})$	$(+4/3,\overline{\mathbf{3}})$	$(+2,\mathbf{1})$	
4-i	$(d\bar{e})(\bar{u})(\bar{u})(d\bar{e})$	(c)	$(-2/3,\overline{\mathbf{3}})$	$(0,\mathbf{1})$	$(+2/3,\mathbf{3})$	RPV [58–60]
			$(-2/3,\overline{\mathbf{3}})$	$(0,\mathbf{8})$	$(+2/3,\mathbf{3})$	RPV [58–60]
4-ii-a	$(\bar{u}\bar{u})(d)(\bar{e})(d\bar{e})$		$(+4/3,\overline{\mathbf{3}})$	$(+5/3,\mathbf{3})$	$(+2/3,\mathbf{3})$	only with V_ρ
			$(+4/3,\mathbf{6})$	$(+5/3,\mathbf{3})$	$(+2/3,\mathbf{3})$	see Sec. 4 (this work)
4-ii-b	$(\bar{u}\bar{u})(\bar{e})(d)(d\bar{e})$		$(+4/3,\overline{\mathbf{3}})$	$(+1/3,\overline{\mathbf{3}})$	$(+2/3,\mathbf{3})$	only with V_ρ
			$(+4/3,\mathbf{6})$	$(+1/3,\mathbf{6})$	$(+2/3,\mathbf{3})$	
5-i	$(\bar{u}\bar{e})(d)(d)(\bar{u}\bar{e})$	(c)	$(-1/3,\mathbf{3})$	$(0,\mathbf{1})$	$(+1/3,\overline{\mathbf{3}})$	RPV [58–60]
			$(-1/3,\mathbf{3})$	$(0,\mathbf{8})$	$(+1/3,\overline{\mathbf{3}})$	RPV [58–60]
5-ii-a	$(\bar{u}\bar{e})(\bar{u})(\bar{e})(dd)$		$(-1/3,\mathbf{3})$	$(+1/3,\overline{\mathbf{3}})$	$(-2/3,\overline{\mathbf{3}})$	only with V'_ρ
			$(-1/3,\mathbf{3})$	$(+1/3,\mathbf{6})$	$(-2/3,\mathbf{6})$	
5-ii-b	$(\bar{u}\bar{e})(\bar{e})(\bar{u})(dd)$		$(-1/3,\mathbf{3})$	$(-4/3,\mathbf{3})$	$(-2/3,\overline{\mathbf{3}})$	only with V'_ρ
			$(-1/3,\mathbf{3})$	$(-4/3,\mathbf{3})$	$(-2/3,\mathbf{6})$	

A few comments on a theory of flavor: The θ_{13} challenge

"Flavor symmetry model" = acronym for breaking the symmetry among different flavors by introducing flavor-dependent properties

very small — θ_{13} — very large

Structure:
flavor symmetry
A_4, S_4, TBM, …

vs.

Anarchy:
Random draw?

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

Corrections?
CL sector?
RGR running?

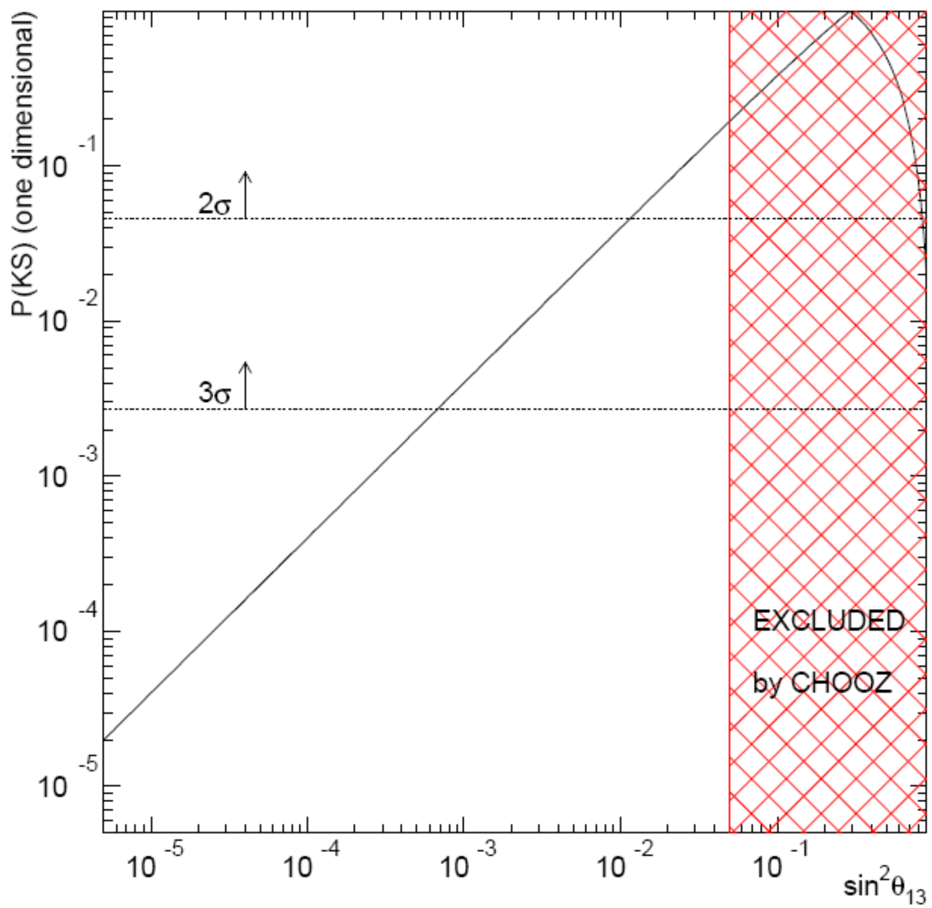
Generic structure
+ random
O(1) coefficients?

e.g. $\theta_{12} = 35° + \theta_{13}$ **cosδ**
(Antusch, King, Masina, ...)

Different ad-hoc flavor symmetry?

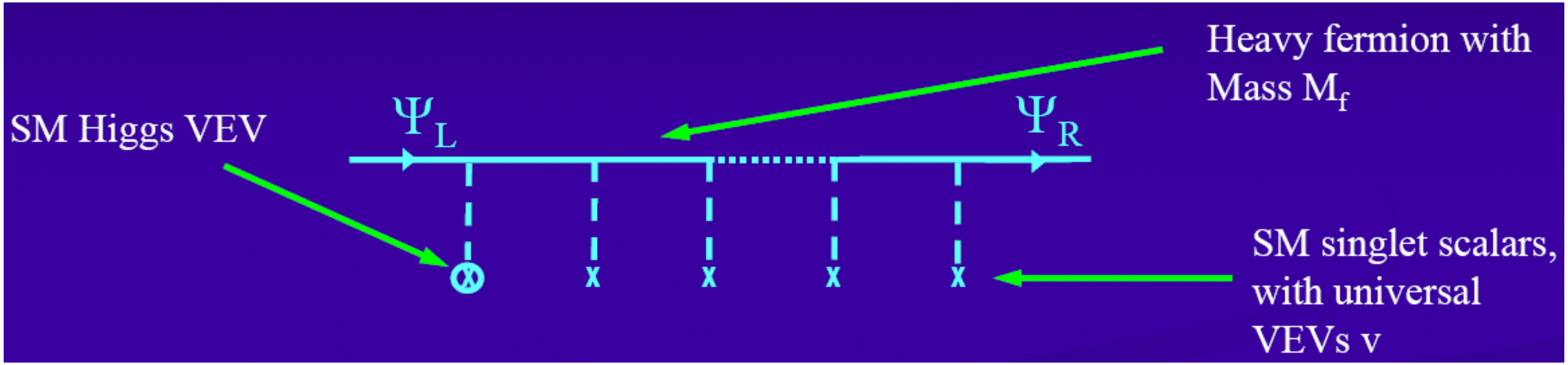
Anarchy: The flavor model builder‘s antichrist

- Idea: perhaps the mixing parameters are a “random draw“?
- Challenge: define “basis-independent“ measure for mixing angles
- Result: large θ_{13} “natural“, no magic needed
- Challenges: Justify small mixings in the quark sector? Predictions for masses?



(Hall, Murayama, Weiner, 2000; de Gouvea, Murayama, 2003, 2012)

Simple flavor models: Froggatt Nielsen



- $\Psi_{L/R}$ are SM fermions
- Integrate out the heavy fermions: spontaneously break flavor symmetry

$$\mathcal{L}_{\text{eff}} \sim K \, \langle H \rangle \varepsilon^n \bar{\Psi}_L \Psi_R \, , \quad \varepsilon = \frac{v}{M_f}$$

- Integer power n is controlled by the (generation/flavor-dependent) quantum numbers of the fermions under the flavor symmetry

Example:

- K: (complex) generation dependent (random) order one coefficients
- Well-suited to describe hierarchies among masses, and small mixings

$$M_l \sim \begin{pmatrix} \epsilon^4 & \epsilon^3 & \epsilon \\ 0 & \epsilon^2 & \epsilon^2 \\ 0 & \epsilon^4 & 1 \end{pmatrix}$$

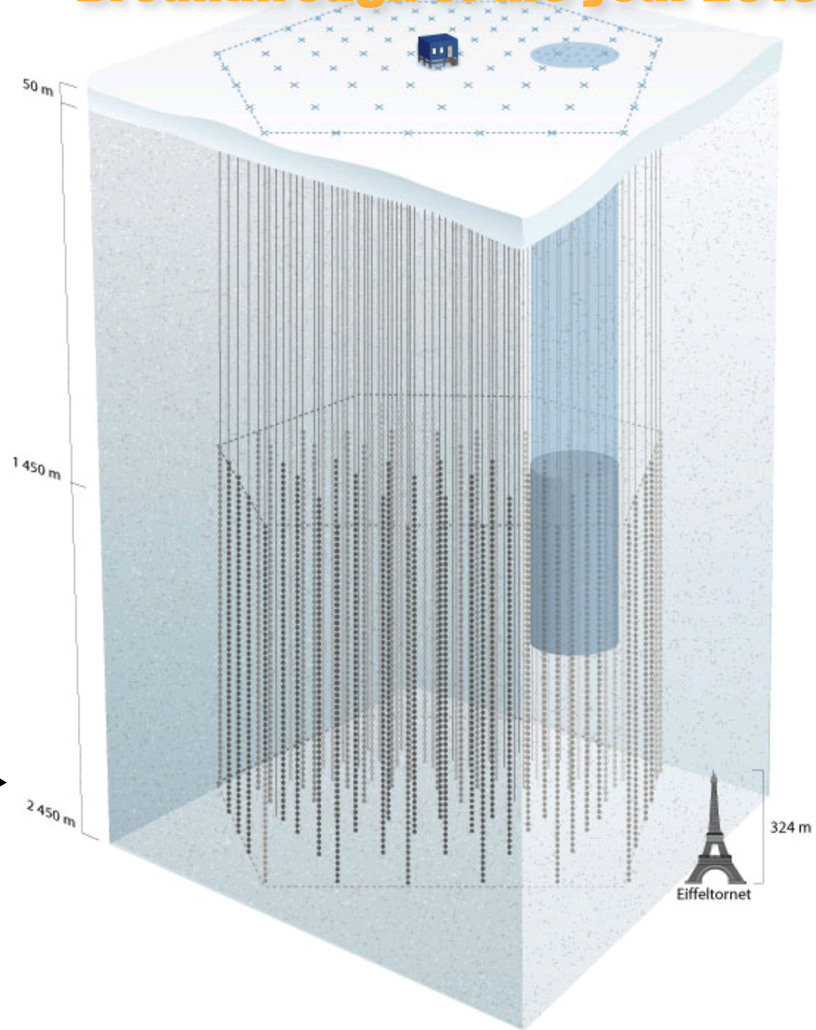
Particle physics of cosmic neutrino sources

Neutrinos as extragalatic cosmic messengers

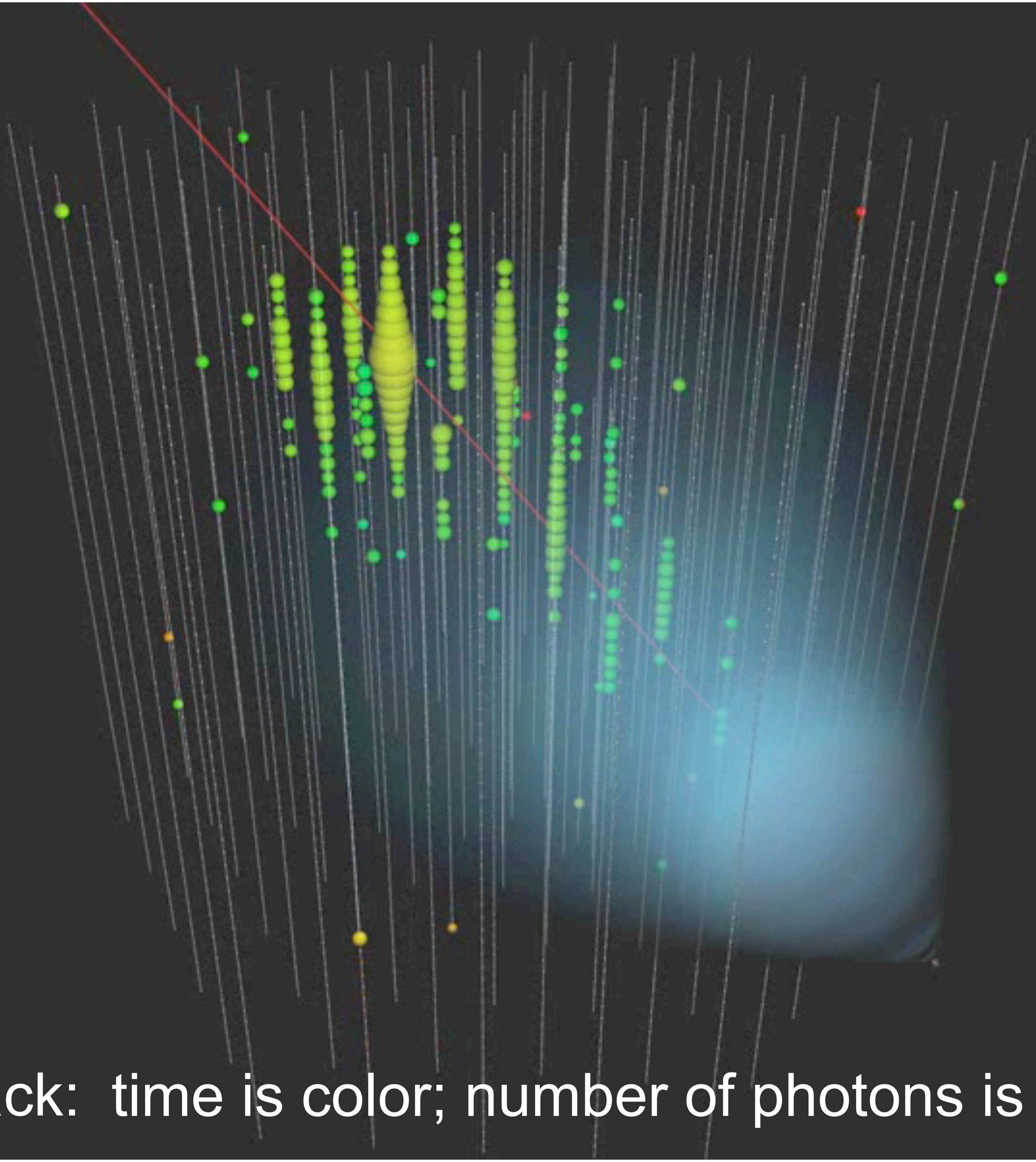
- The birth of neutrino astronomy: Feb. 23, 1987 Detection of twelve neutrinos from an extragalactic supernova explosion in Kamiokande (so far, the only one ...); Nobel prize 2002

- 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

Physics World
Breakthrough of the year 2013



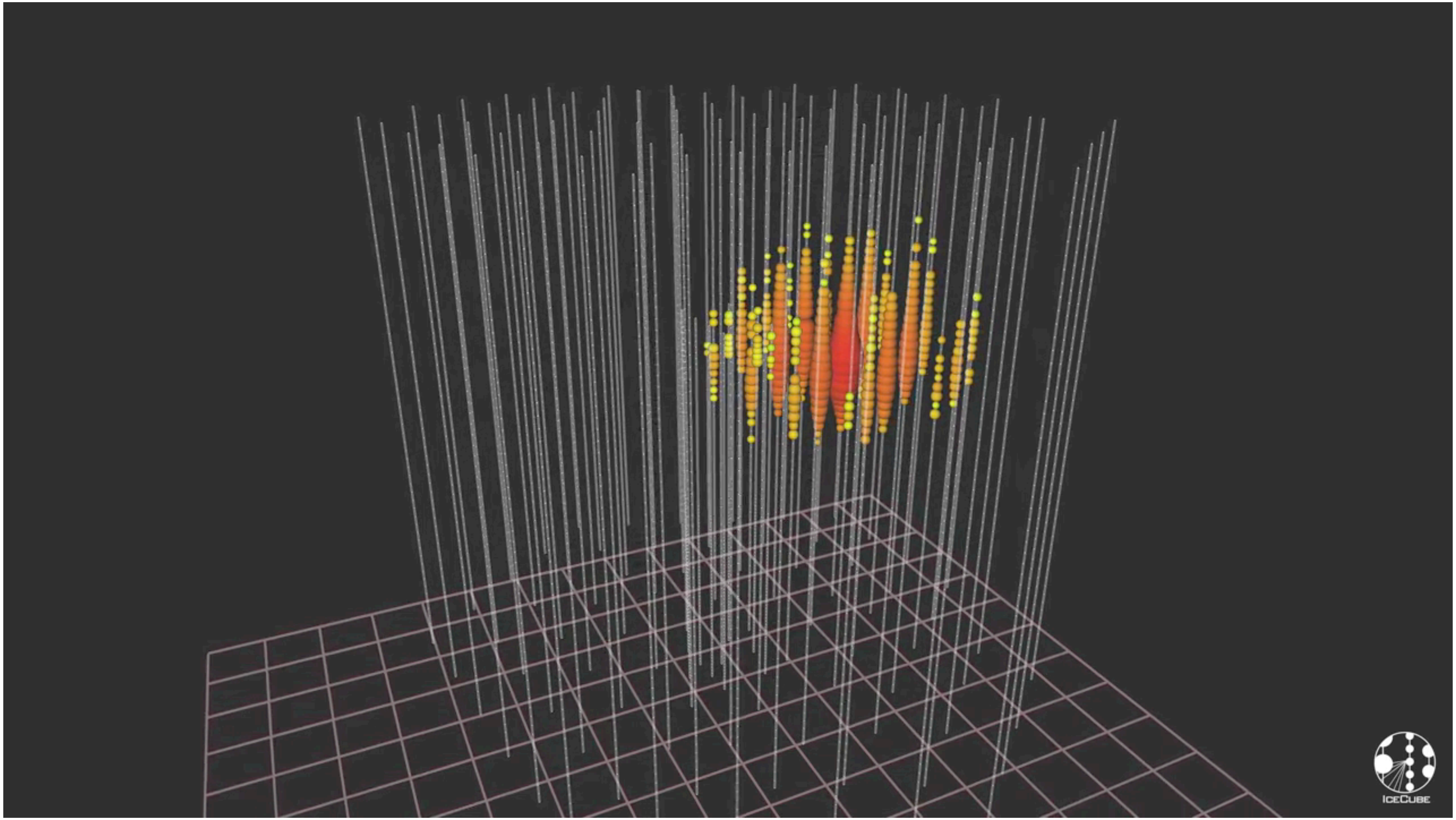
http://icecube.wisc.edu/



IceCube (Halzen at WIN'15)

muon track: time is color; number of photons is energy

Cascades: Neutrinos with > 1 PeV

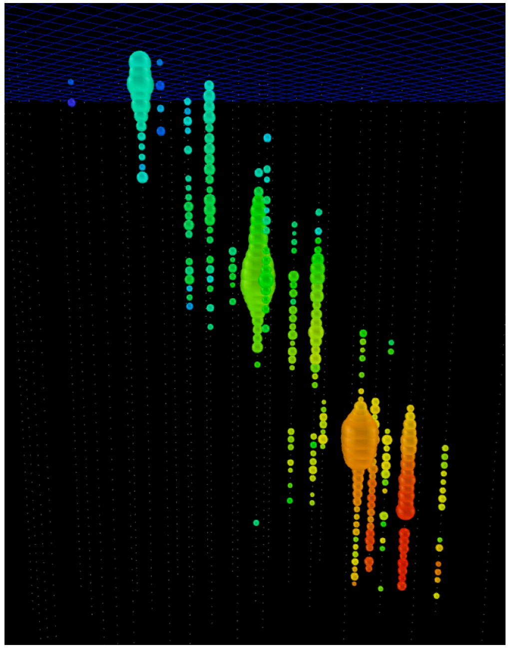


IceCube (Halzen at WIN'15)

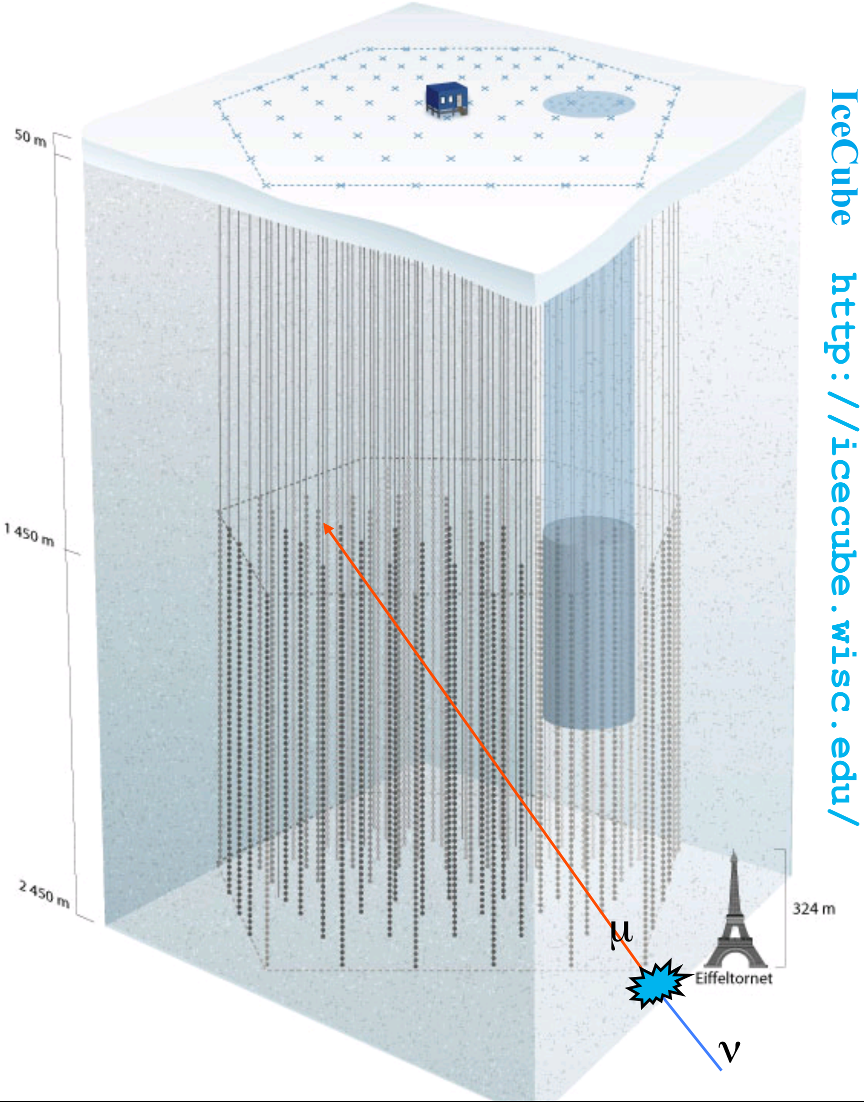
IceCube: Event topologies?

Muon track:

- From ν_μ (mostly)

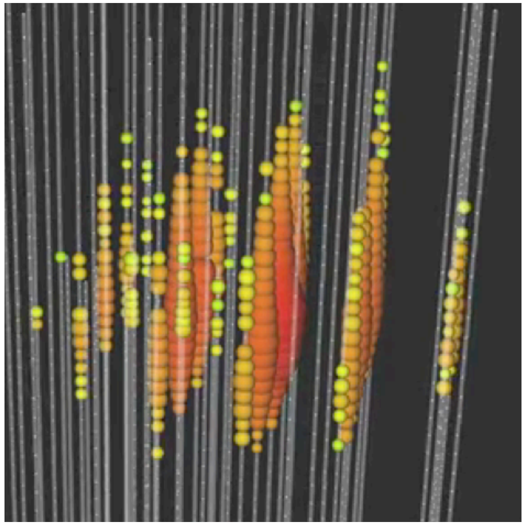


Better directional info



Cascade (shower):

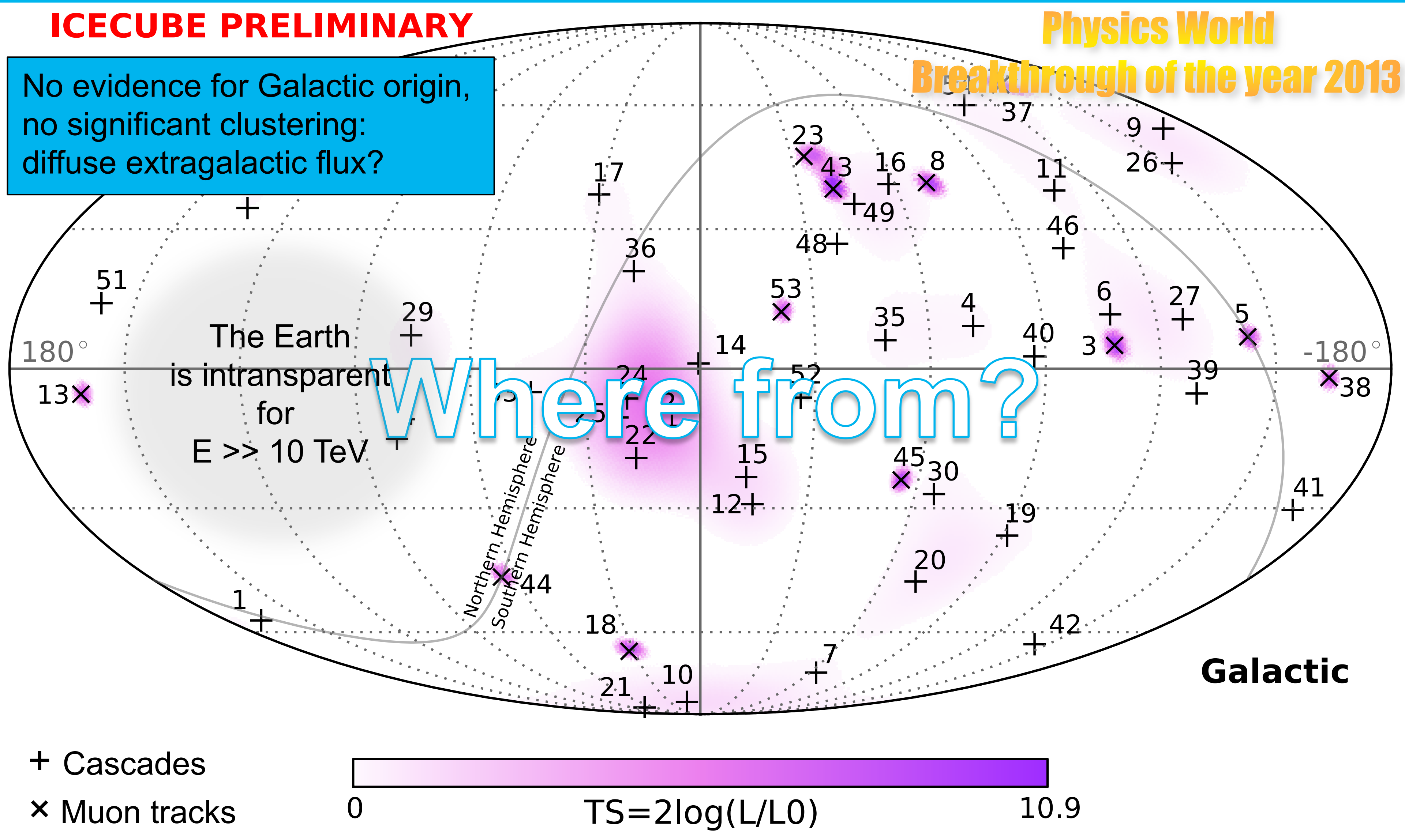
- From ν_e
- From ν_τ
- [From ν_e, ν_μ, ν_τ neutral current interactions]



Better energy info

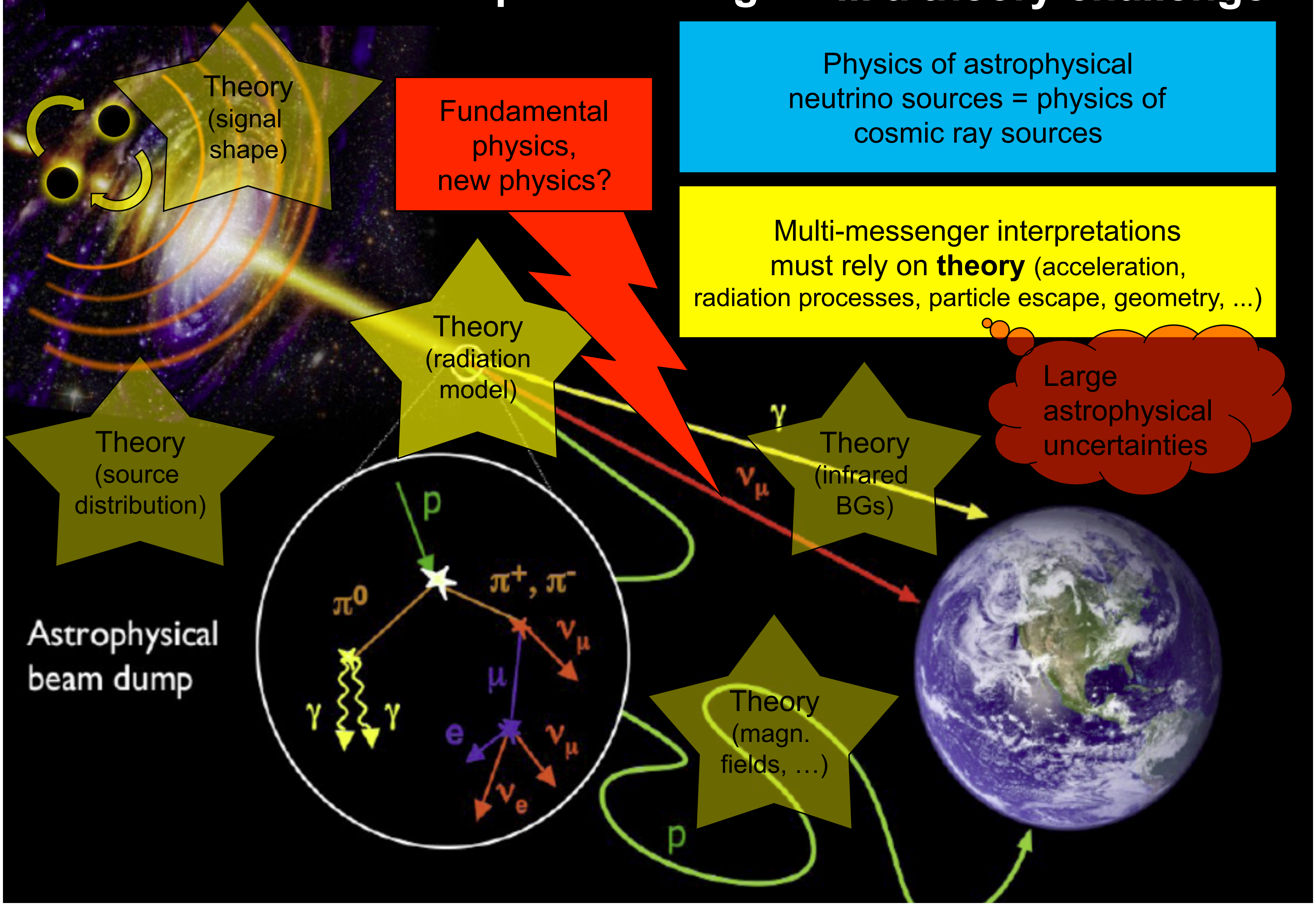
The ratio between muon tracks and showers ~ $\nu_\mu/(\nu_e+\nu_\tau)$, roughly

2015: 54 high energy cosmic neutrinos



IceCube: Science 342 (2013) 1242856; Phys. Rev. Lett. 113, 101101 (2014); Halzen at WIN 2015

The universe in multiple messengers ... a theory challenge



A simple toy model for the source

If neutrons can escape:
Source of cosmic rays

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

Neutrinos produced in ratio (ν_e:ν_μ:ν_τ)=(1:2:0)

$$\pi^+ \rightarrow \mu^+ + \nu_\mu ,$$
$$\mu^+ \rightarrow e^+ + \nu_e + \bar{\nu}_\mu$$

Delta resonance approximation:

$$p + \gamma \longrightarrow \Delta^+ \longrightarrow \begin{cases} n + \pi^+ & 1/3 \text{ of all cases} \\ p + \pi^0 & 2/3 \text{ of all cases} \end{cases}$$

$$\pi^0 \longrightarrow \gamma + \gamma$$

High energetic gamma-rays;
typically cascade down to lower E
Additional constraints!

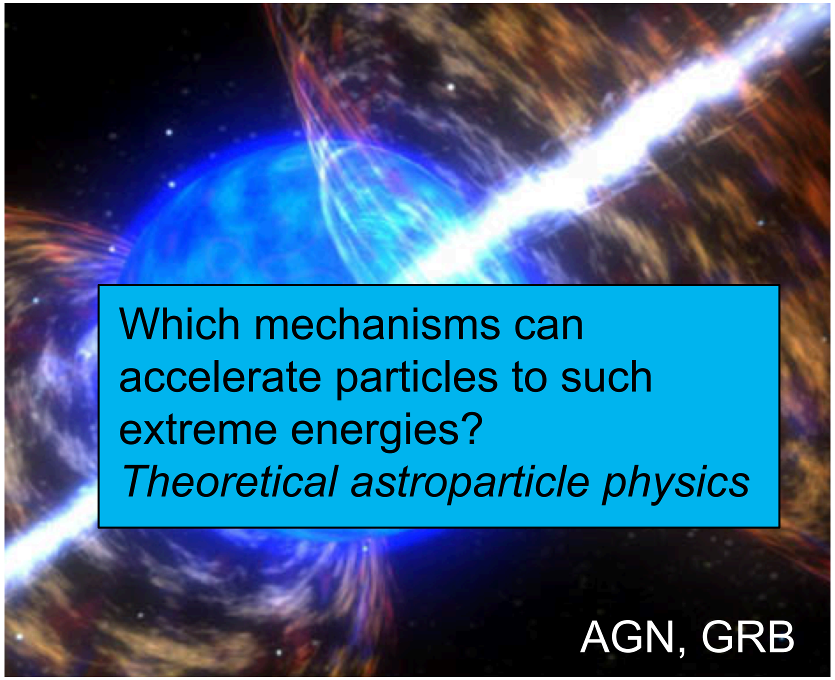
Cosmic messengers

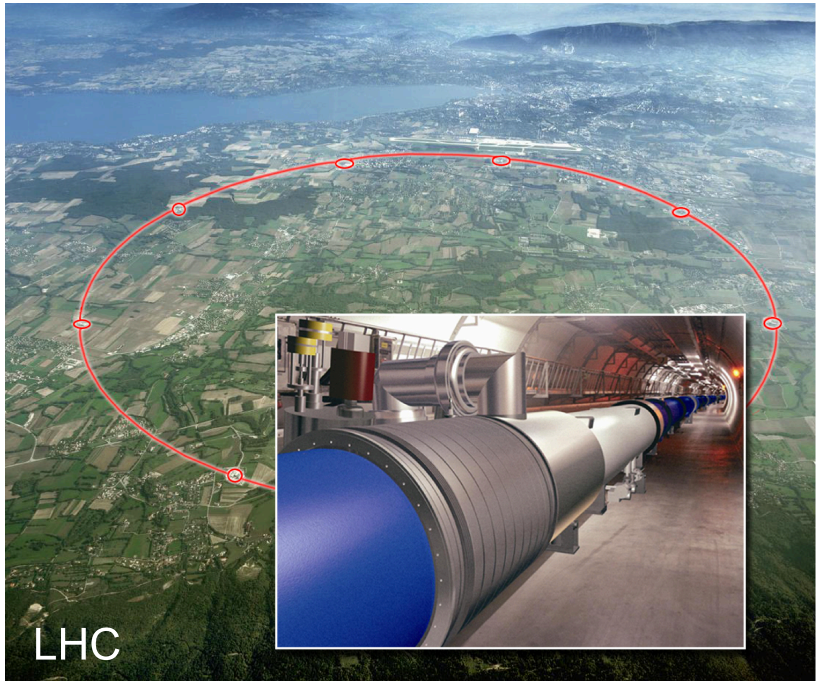
Cosmic vs. terrestrial particle accelerators

Lorentz force = centrifugal force ➔ $E_{max} \sim q\,B\,R$

- E_{max} ~ **300,000,000 TeV**
- B ~ 1 mT – 1 T
- R ~ 100,000 – 10,000,000,000 km

- E_{max} ~ 7 TeV
- B ~ 8 T
- R ~ 4.3 km

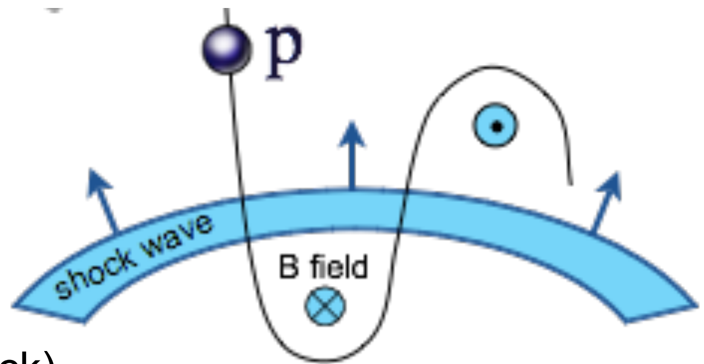




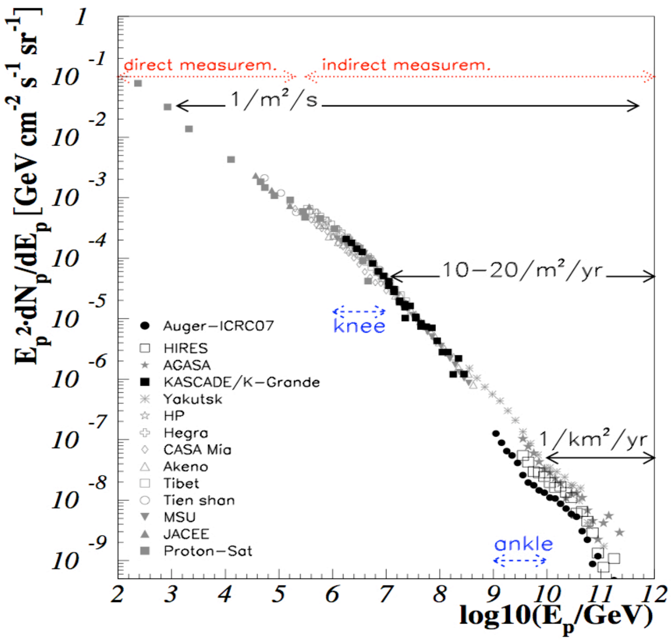
Acceleration of primaries (protons, nuclei)

Example: Fermi shock acceleration

- Energy gain per cycle: $E \rightarrow \eta E$
- Escape probability per cycle: P_{esc}
- Yields a **power law** spectrum ~ $E^{\frac{\ln P_{\mathrm{esc}}}{\ln \eta} - 1}$
- $\ln P_{esc}/\ln \eta \sim -1$ (from compression ratio of a strong shock), and $\mathbf{E^{-2}}$ is the typical "textbook" spectrum

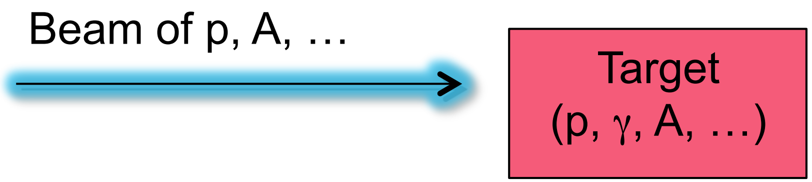


- Although theory of acceleration at relativistic shocks challenging, we **do observe** power law spectra in Nature →
- For neutrino production: adopt pragmatic point of view! *(we know that it works, somehow ...)*

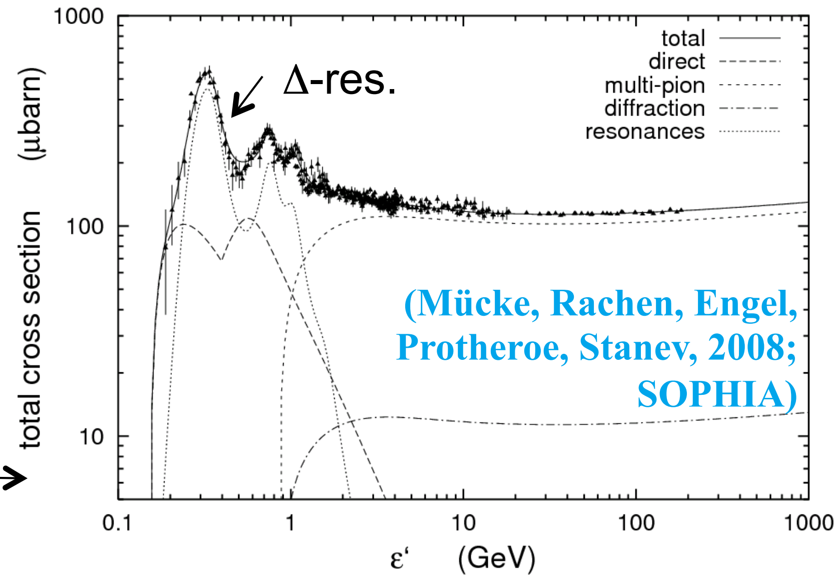


Secondary production: Particle physics 101

- Beam dump picture (particle physics)



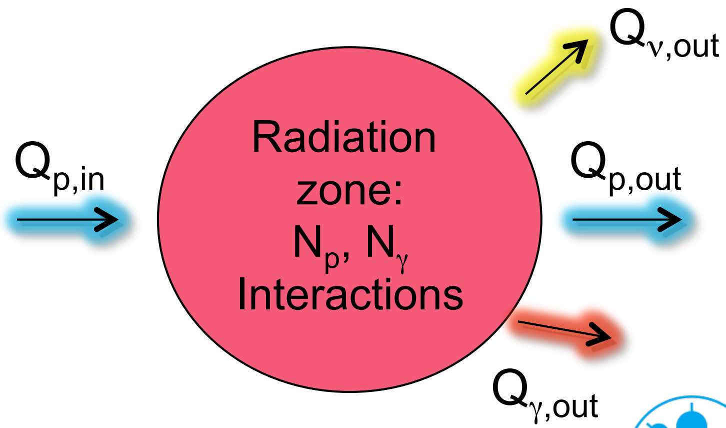
- Interaction rate $\Gamma \sim c\ \ N\ [cm^{-3}]\ \ \sigma\ [cm^2]$



(Photon energy in nucleon rest frame)

Target density (e.g. N_γ) critical for ν production!

- Astrophysical challenges:
  - Feedback between beam and target (e.g. photons from π^0 decays); need self-consistent description called **radiation model**
  - *What you see is*, in general, **not** *what you get* in the source



Kinetic equations for self-consistent treatment (steady state)

- Treat energy losses/escape in continuous limit in radiation zone:

$$Q(E) = \frac{\partial}{\partial E}\left(b(E)\, N(E)\right) + \frac{N(E)}{t_{\mathrm{esc}}}$$

Injection | Energy losses | Escape

One equation for each particle species!

$b(E)=-E\, t^{-1}_{loss}$
$Q(E,t)$ [GeV^{-1} cm^{-3} s^{-1}] injection per time frame (e. g. from acc. zone)
$N(E,t)$ [GeV^{-1} cm^{-3}] particle spectrum including spectral effects

Need N(E) to compute particle interactions

- Simple case: No energy losses b=0: $N(E) = Q(E)\, t_{\mathrm{esc}}$
- Special case: t_{esc} ~ R/c (free-streaming, aka “leaky box“)

In the presence of strong B: Secondary cooling

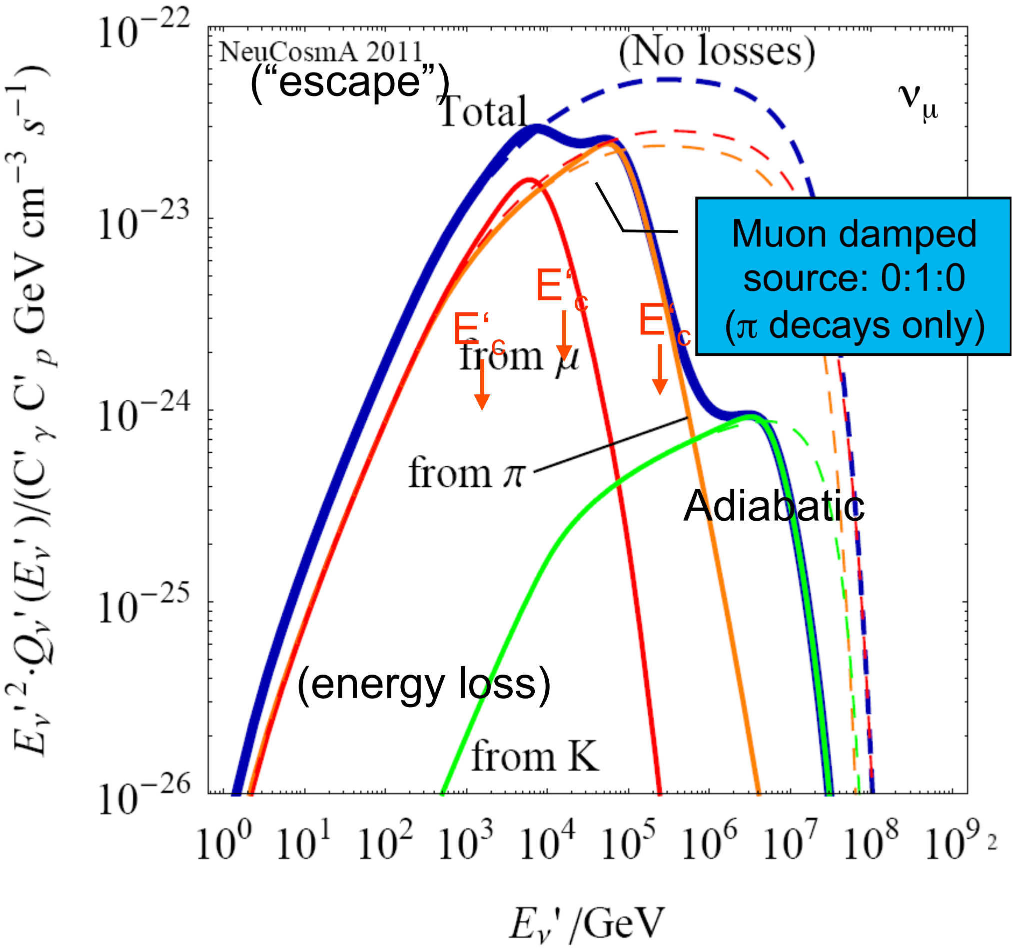
Example: GRB

Secondary spectra (μ, π, K) loss-steepend above critical energy

$$E'_c = \sqrt{\frac{9\pi\epsilon_0 m^5 c^7}{\tau_0 e^4 B'^2}}$$

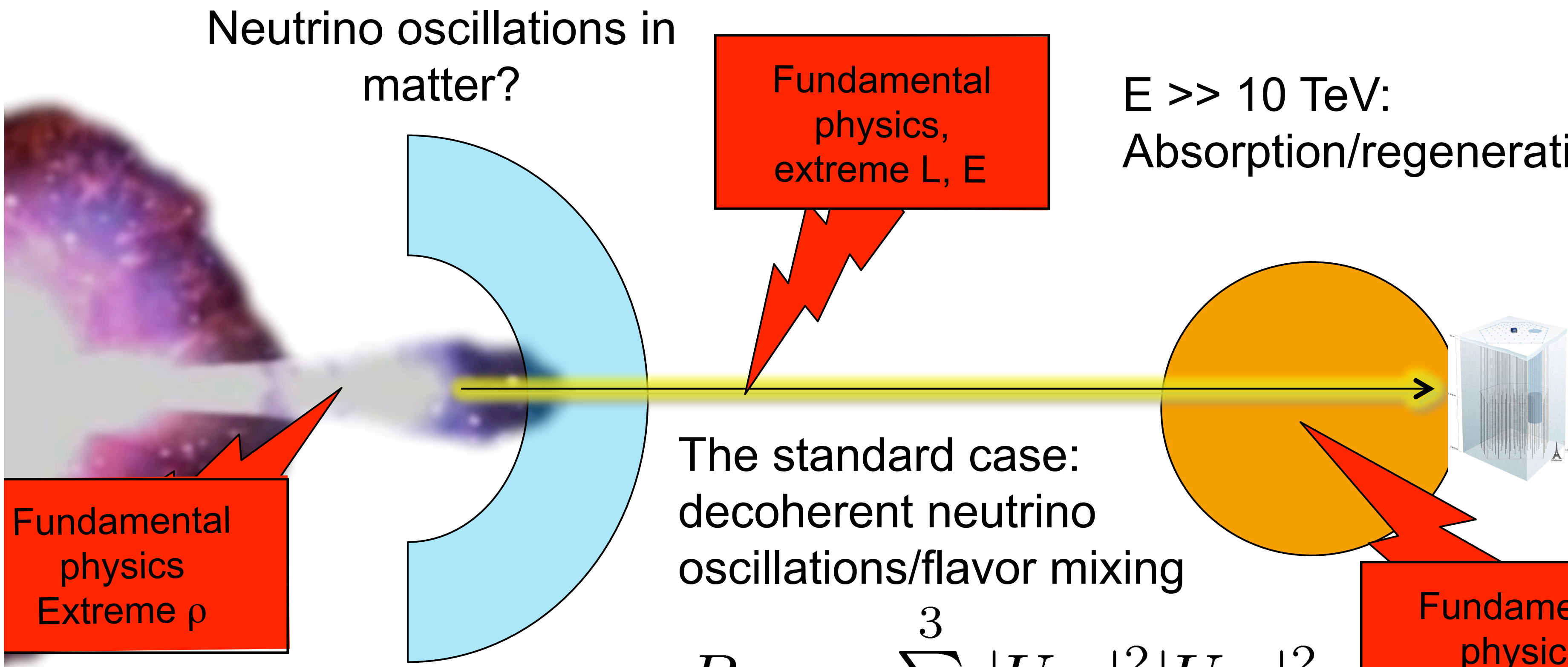
- E'_c depends on particle physics only (m, τ_0), and **B'**
- Leads to characteristic flavor composition and shape

Decay/cooling: charged μ, π, K



Baerwald, Hümmer, Winter, Astropart. Phys. 35 (2012) 508; also: Kashti, Waxman, 2005; Lipari et al, 2007; ...

Neutrino propagation: From source to detector



The standard case: decoherent neutrino oscillations/flavor mixing

$$P_{\alpha\beta} = \sum_{i=1}^{3} |U_{\alpha i}|^2 |U_{\beta i}|^2$$

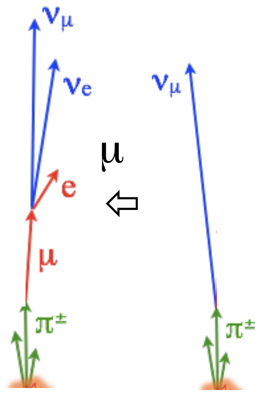
Source $\nu_e:\nu_\mu:\nu_\tau$ = 1:2:0 ➔ Detector 1:1:1
+ redshift of energy if cosmological distance

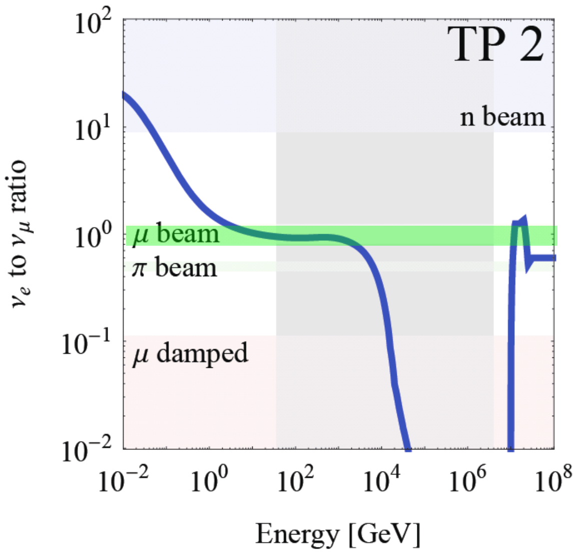
Neutrino flavor and the test of fundamental physics

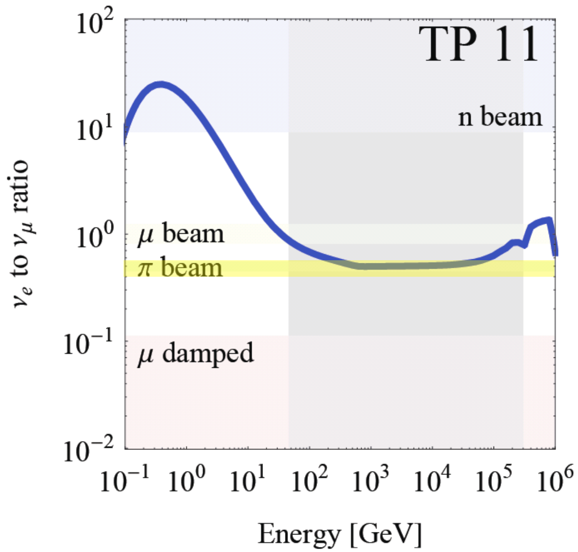
Flavor composition at source from numerical simulations

Example: pγ, target photons from synchrotron emission of co-accelerated electrons

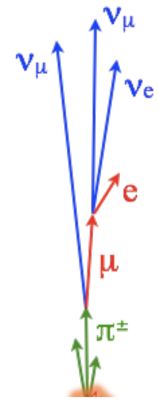
Muon beam
- muon damped





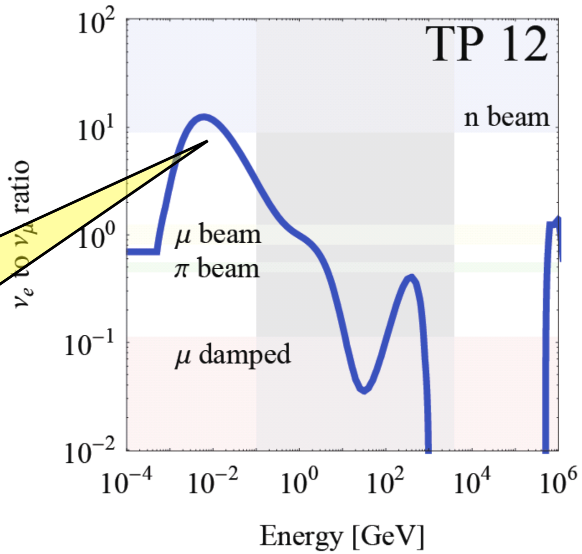


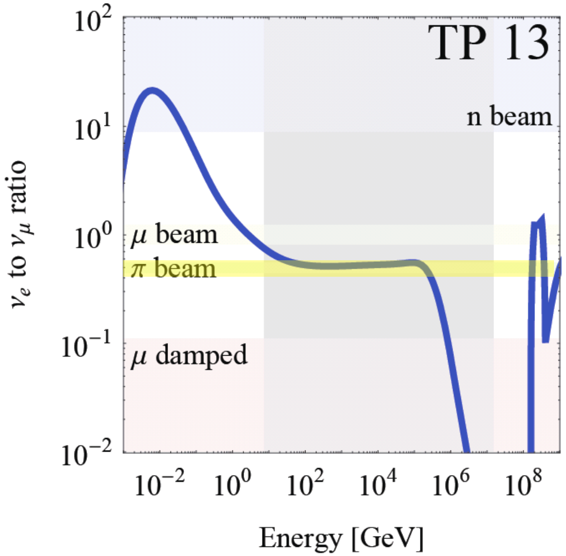
Pion beam
$(\nu_e:\nu_\mu:\nu_\tau)=(1:2:0)$



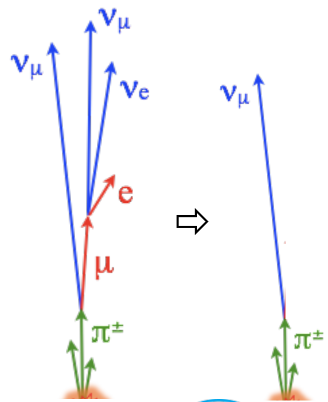
Undefined
(mixed source)

Typically
n beam
for low E
(from pγ)





Pion beam
⇨ muon damped

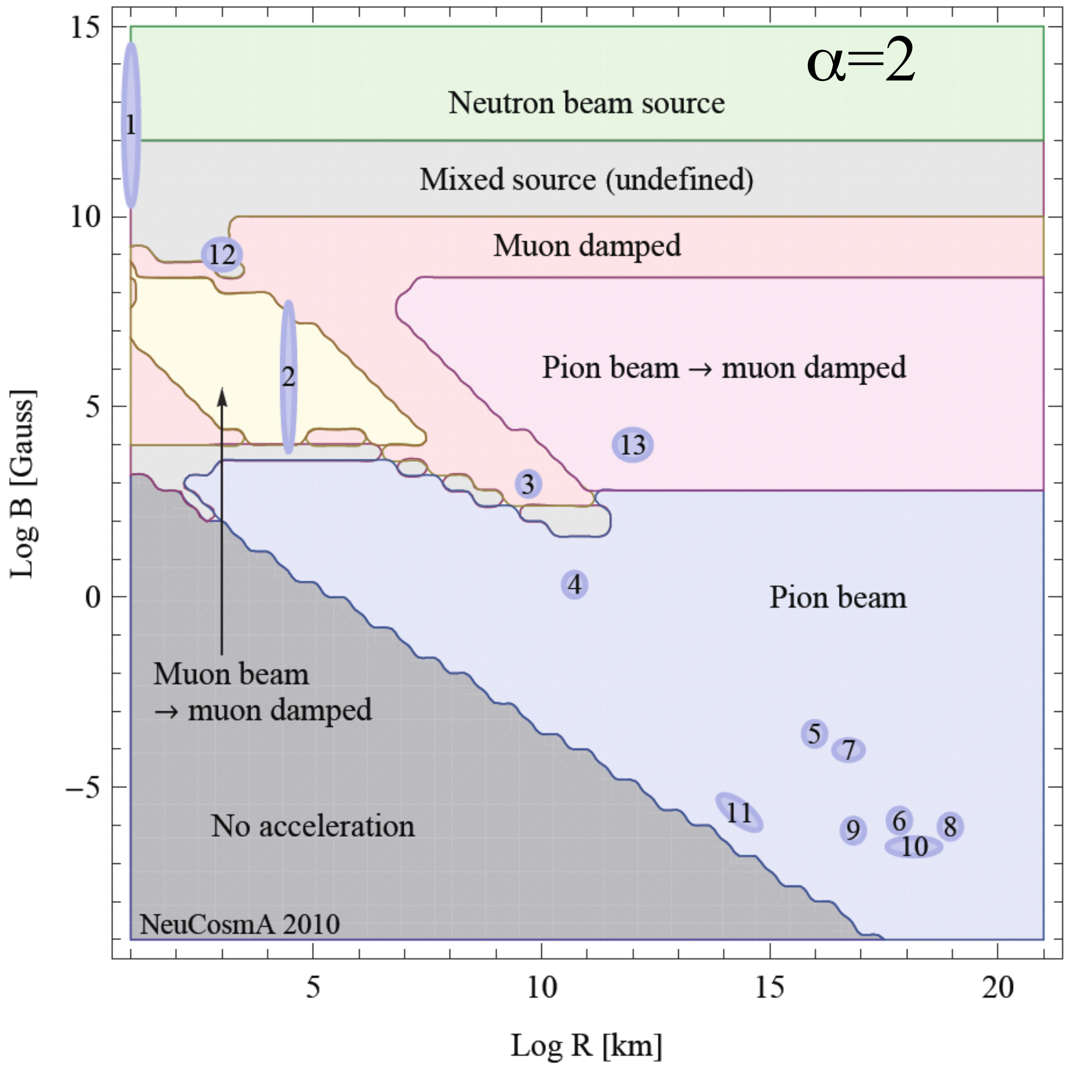


(from Hümmer, Maltoni, Winter, Yaguna, Astropart. Phys. 34 (2010) 205)

Parameter space scan of Hillas plot

- Flavor composition is, in all realistic cases, a function of energy!
- “Test points“:

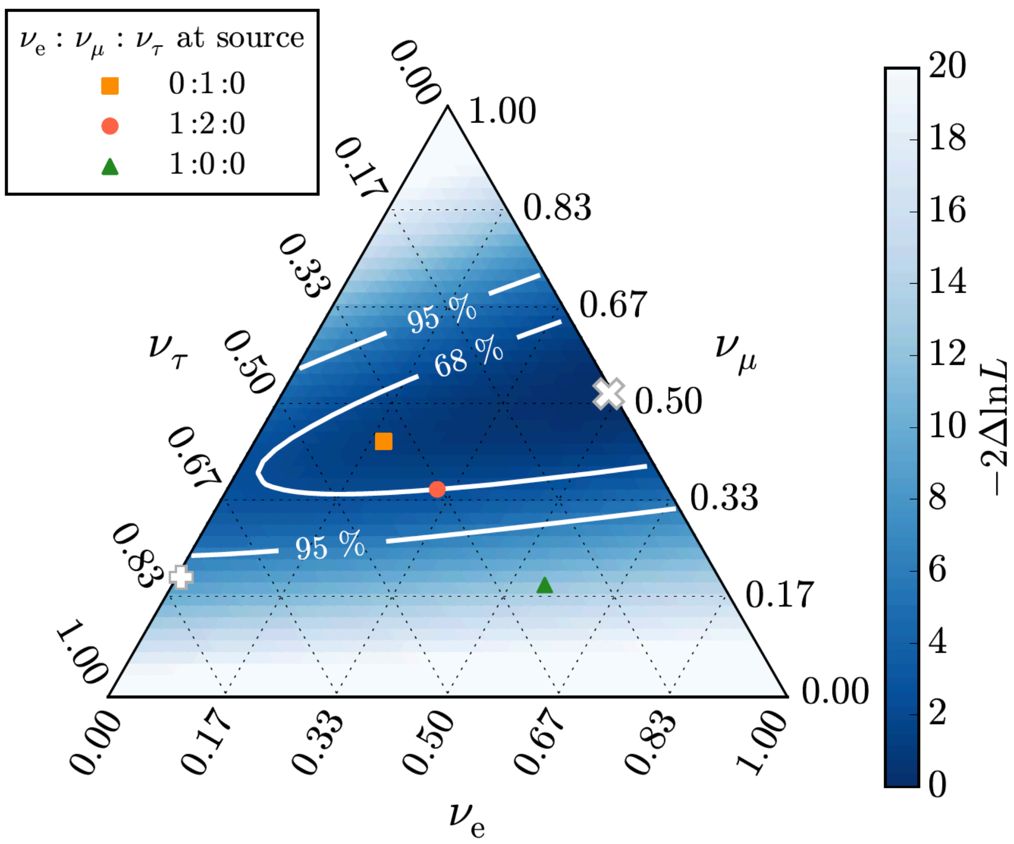
1 Neutron stars
2 White dwarfs
Active galaxies:
 3 nuclei
 4 jets
 5 hot–spots
 6 lobes
7 Colliding galaxies
8 Clusters
9 Galactic disk
10 Galactic halo
11 SNRs



Hümmer, Maltoni, Winter, Yaguna, Astropart. Phys. 34 (2010) 205

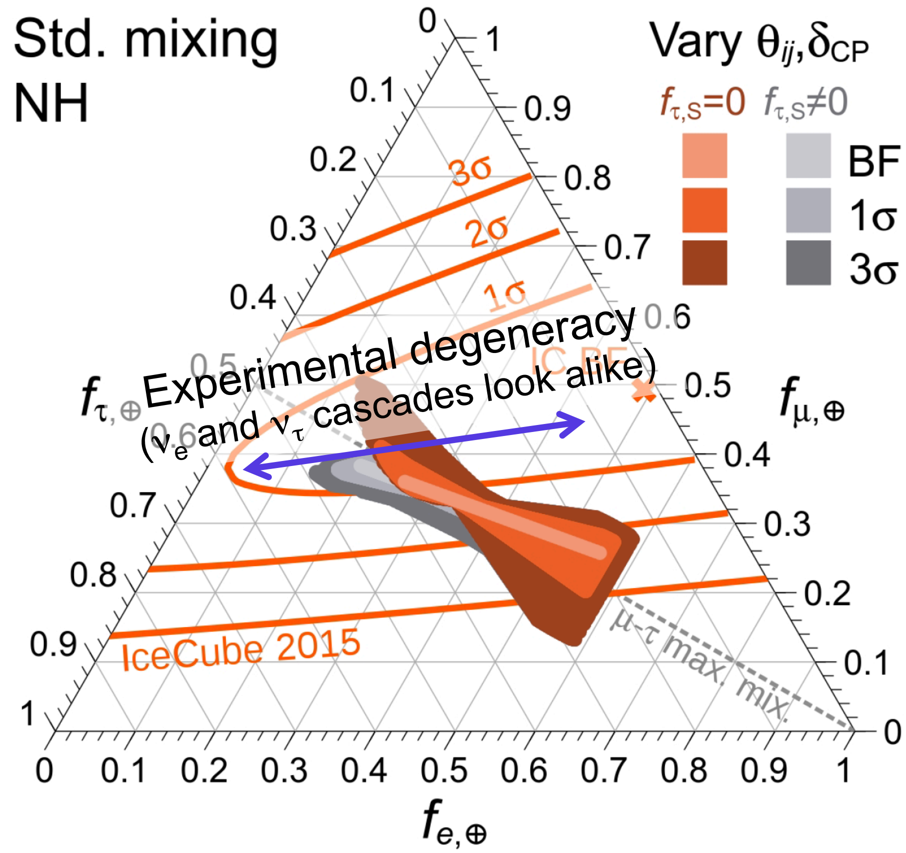
Flavor composition at detector?

> **Measurement**



IceCube measurement
Astrophys. J. 809 (2015) 1, 98

> **Standard Model expectation**

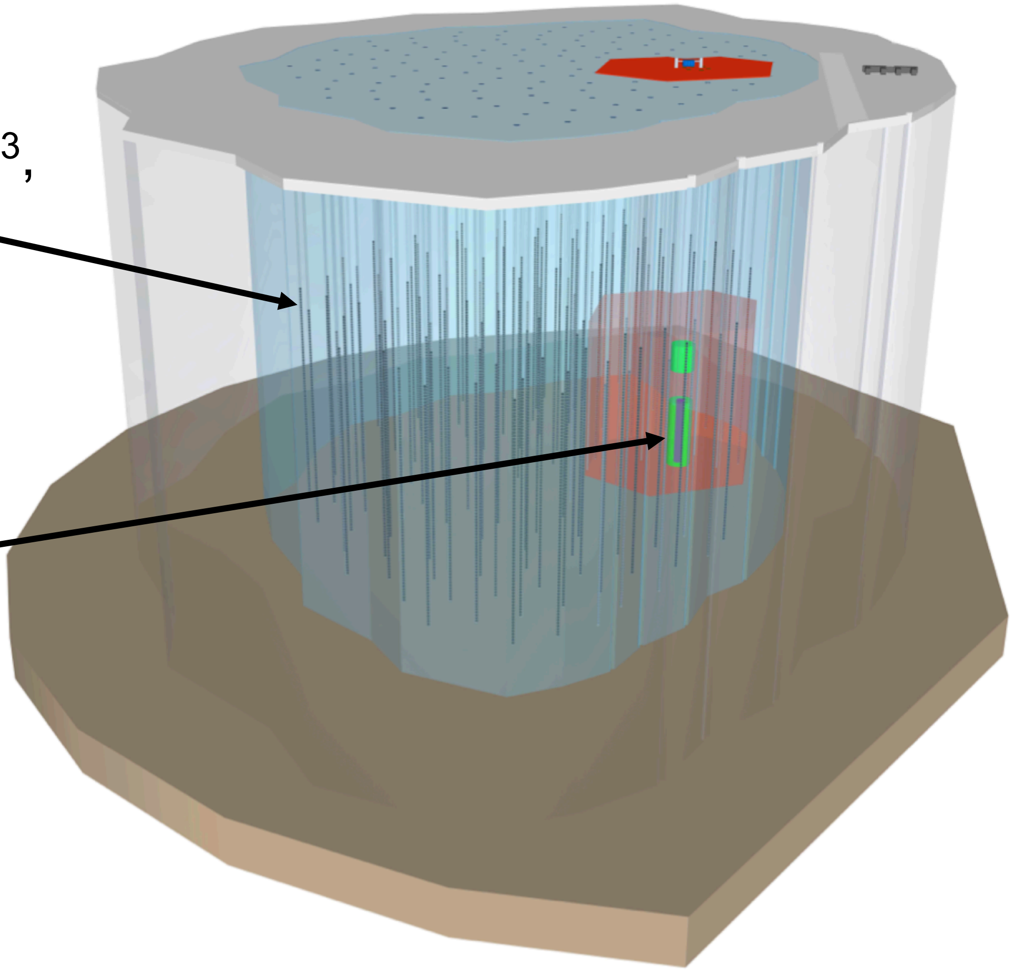


Bustamante, Beacom, Winter,
PRL 115 (2015) 16, 161302

(there is a marginal tension …)

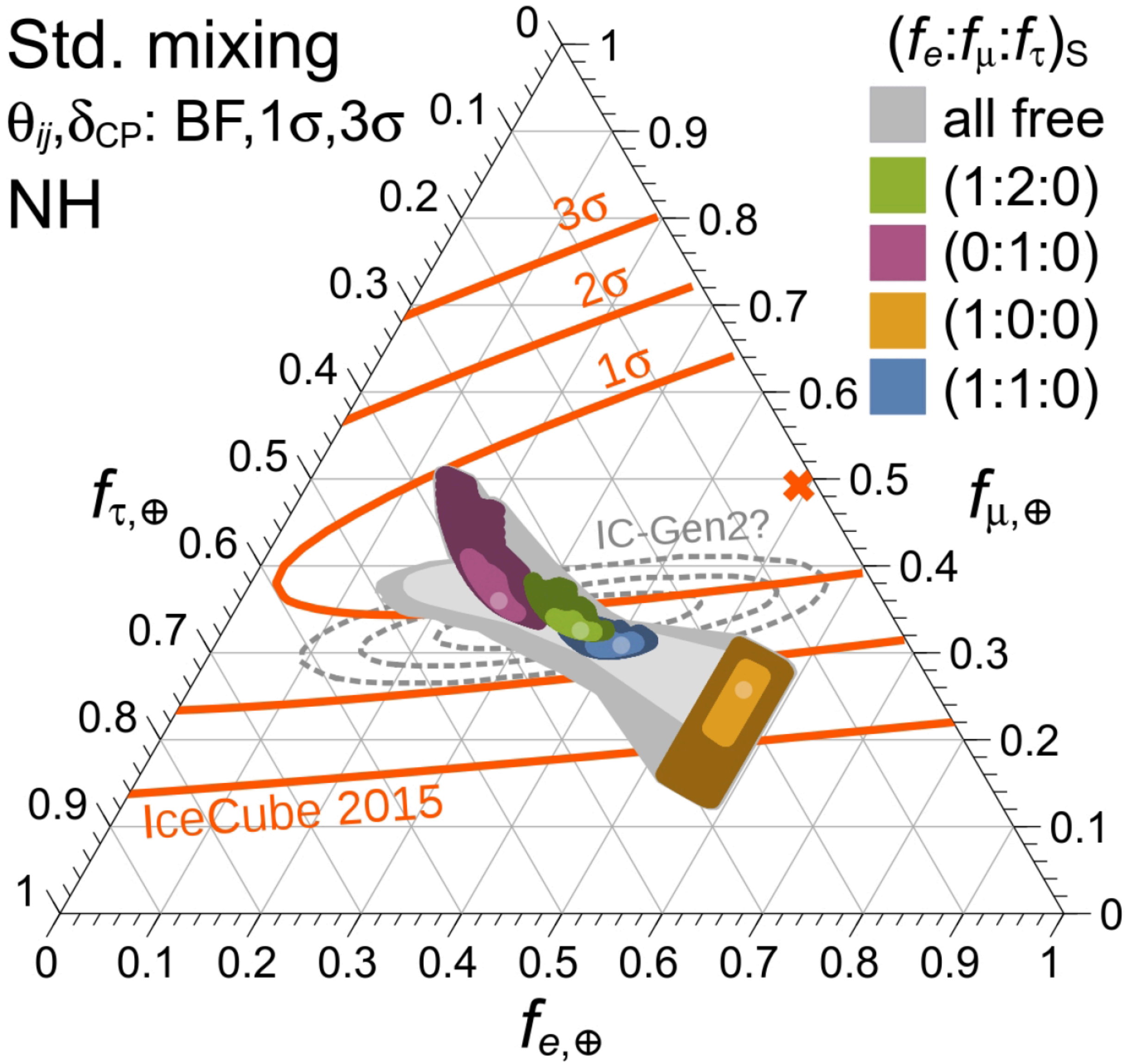
IceCube – Generation Two?

- Plans for upgrade of IceCube experiment
- Instrumented volume O(10) km^3, string spacing 240-300m
- Purpose: “deliver substantial increases in the astrophysical neutrino sample for all flavors”
- PINGU-infill for oscillation physics (about 40 strings for lower threshold in DeepCore region).
  Neutrino mass ordering!
- Similar ideas in sea water (KM3NeT, ORCA)



(arXiv:1401.2046, arXiv:1412.5106)

The future: SM expectations vs. measurement?



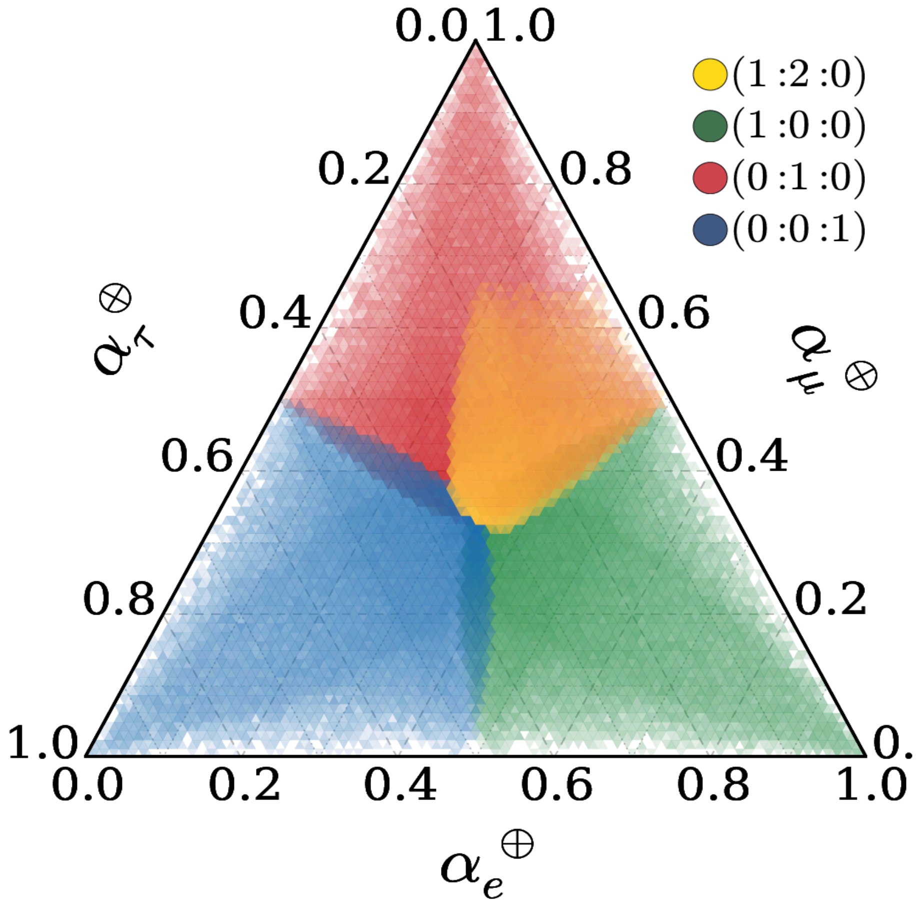
(shaded regions: current 3σ range for mixing params)

Bustamante, Beacom, Winter, PRL 115 (2015) 16, 161302

- Start to constrain specific flavor compositions at source

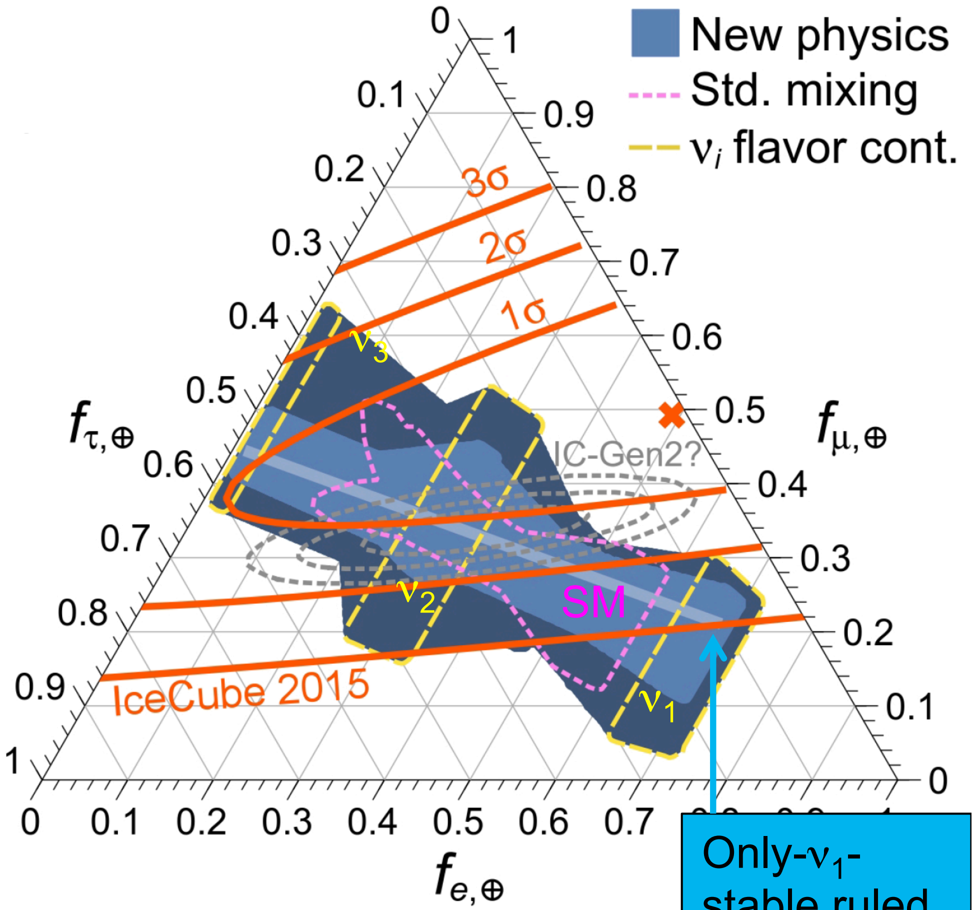
What if there is physics beyond the Standard Model?

Effective operators (CPT violation) changing Hamiltonian at high E



Arguelles, Katori, Salvado,
PRL 115 (2015) 161303

"Known models" (e.g. neutrino decays over cosmological distances)



Only-ν_1-stable ruled out at 2σ

Bustamante, Beacom, Winter,
PRL 115 (2015) 161302

Propagation effects over cosmological distances

Example: Neutrino lifetime
… but generic thoughts apply to other classes of new physics as well …

Neutrino lifetime: Basics

- If neutrino mass eigenstates decay: Decay rate $\lambda_i = 1/(\tau_{0,i}\ \gamma)=m_i/(\tau_{0,i}\ E)$
- Rest frame lifetime τ_0 cannot be measured. Describe by

$$\kappa^{-1} \left[\frac{\mathrm{s}}{\mathrm{eV}} \right] \equiv \frac{\tau\,[\mathrm{s}]}{m\,[\mathrm{eV}]} \simeq 10^2 \frac{L\,[\mathrm{Mpc}]}{E\,[\mathrm{TeV}]}$$

  (last term: estimate for sensitive L/E-range)
- Naively: need long distances and low energies to test decay!
- Best bounds from SN 1987A neutrinos: $\tau/m > 10^5$ s/eV
  Caveat: large uncertainty in neutrino flux normalization and only electron flavor measured; bound must apply to either m_1 or m_2 (or both)
- Can one obtain better bounds over cosmological distances, such as from high-z gamma-ray burst neutrinos (GRBs)?
- Have to face subtleties of new physics over cosmological distances!

Propagation effects over cosmologial distances

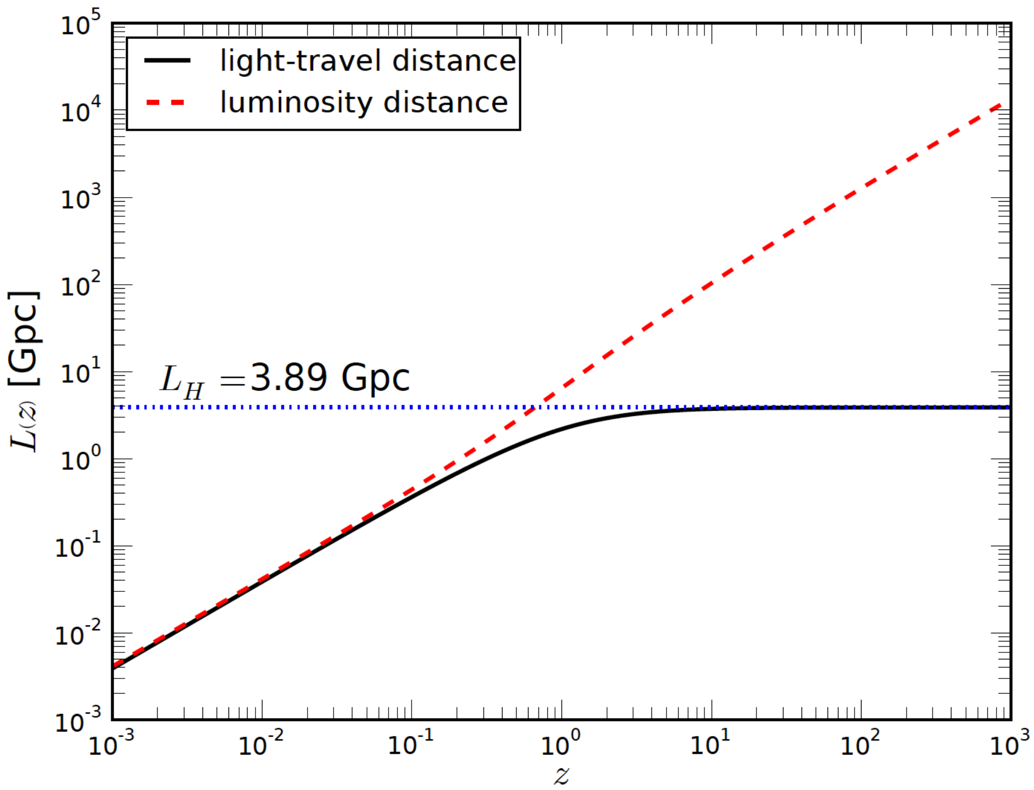
- What is the "clock" for the decay of the neutrinos? **Light-travel distance**

$$L(z) = L_H \int_0^z \frac{dz'}{(1+z')\,h(z')}$$

$$h(z) \equiv H(z)/H_0 \qquad H(z) \equiv H_0 \sqrt{\Omega_m (1+z)^3 + \Omega_\Lambda}$$

- The light-travel distance is limited by the Hubble length
- Consequence: Time/distance dependent new physics effects in the propagation (including oscillations) cannot be tested for arbitrarily large distances!

e. g. Weiler, Simmons, Pakvasa, Learned, 1994; Wagner, Weiler, 1997; Beacom et al., 2004; Esmaili, Farzan, 2012; Baerwald, Bustamante, Winter, 2012



A stability paradox

- Invisible decays

$$P_{\alpha\beta}(E_0, z) = \sum_i |U_{\alpha i}|^2 \, |U_{\beta i}|^2 \, \frac{N_i(E_0, z)}{\hat{N}_i(E_0)} = \sum_i |U_{\alpha i}|^2 \, |U_{\beta i}|^2 \; D_i(E_0, z) \, ;$$

Damping factor

- Ansatz for decays: $N_i(z) = \hat{N}_i \, e^{-\lambda_i L(z)}$
- Correct decay rate for redshift: $\lambda_i = \lambda_i\,(z) = \dfrac{\kappa_i}{E_0\,(1+z)}$
- Damping factor $D_i(E_0, z) = \exp\left(-\dfrac{\kappa_i}{E_0}\,\dfrac{L\,(z)}{(1+z)}\right)$
- Re-write as $D_i(E_0, z) = \left[\mathcal{Z}_1\,(z)\right]^{-\frac{\kappa_i L_H}{E_0}}$

$$\mathcal{Z}_1\,(z) \equiv \exp\left(\frac{L(z)}{L_H \cdot (1+z)}\right)$$

For $z \rightarrow \infty$: $L \rightarrow L_H$ and $Z_1 \rightarrow 1$
Thus: $D \rightarrow 1$ and neutrinos from extremely high z are stable! Stability paradox! What is wrong?

Baerwald, Bustamante, Winter, JCAP 1210 (2012) 020

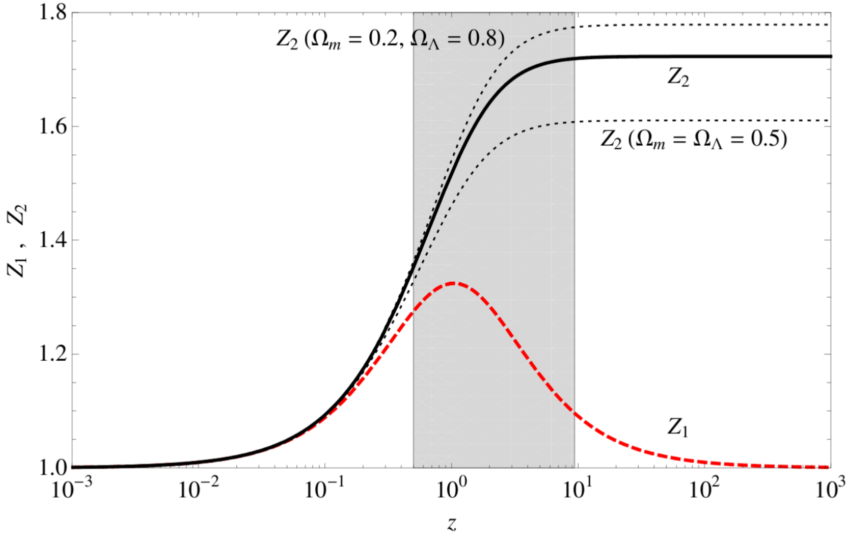
Proper solution

- Start with differential equation, re-written in terms of redshift

$$\frac{dN_i(E_0,z)}{dz} = -\frac{\kappa_i}{E_0}\frac{dL}{dz}\frac{N_i(E_0,z)}{1+z}$$

- Result

$$D_i(E_0,z) = \exp\left(-\frac{\kappa L_H}{E_0}\int_0^z \frac{dz'}{(1+z')^2\, h(z')}\right) = \left[\mathcal{Z}_2(z)\right]^{-\frac{\kappa L_H}{E_0}}$$



Neutrinos from high z decay now!

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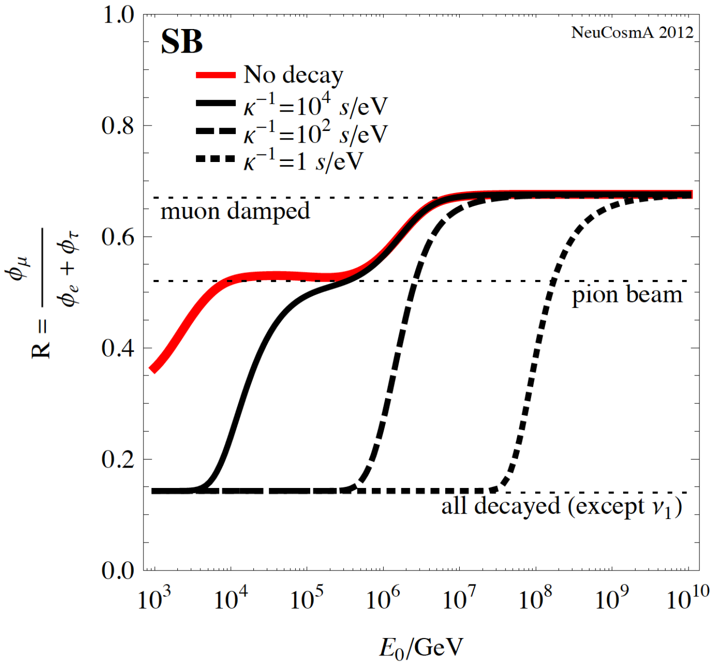
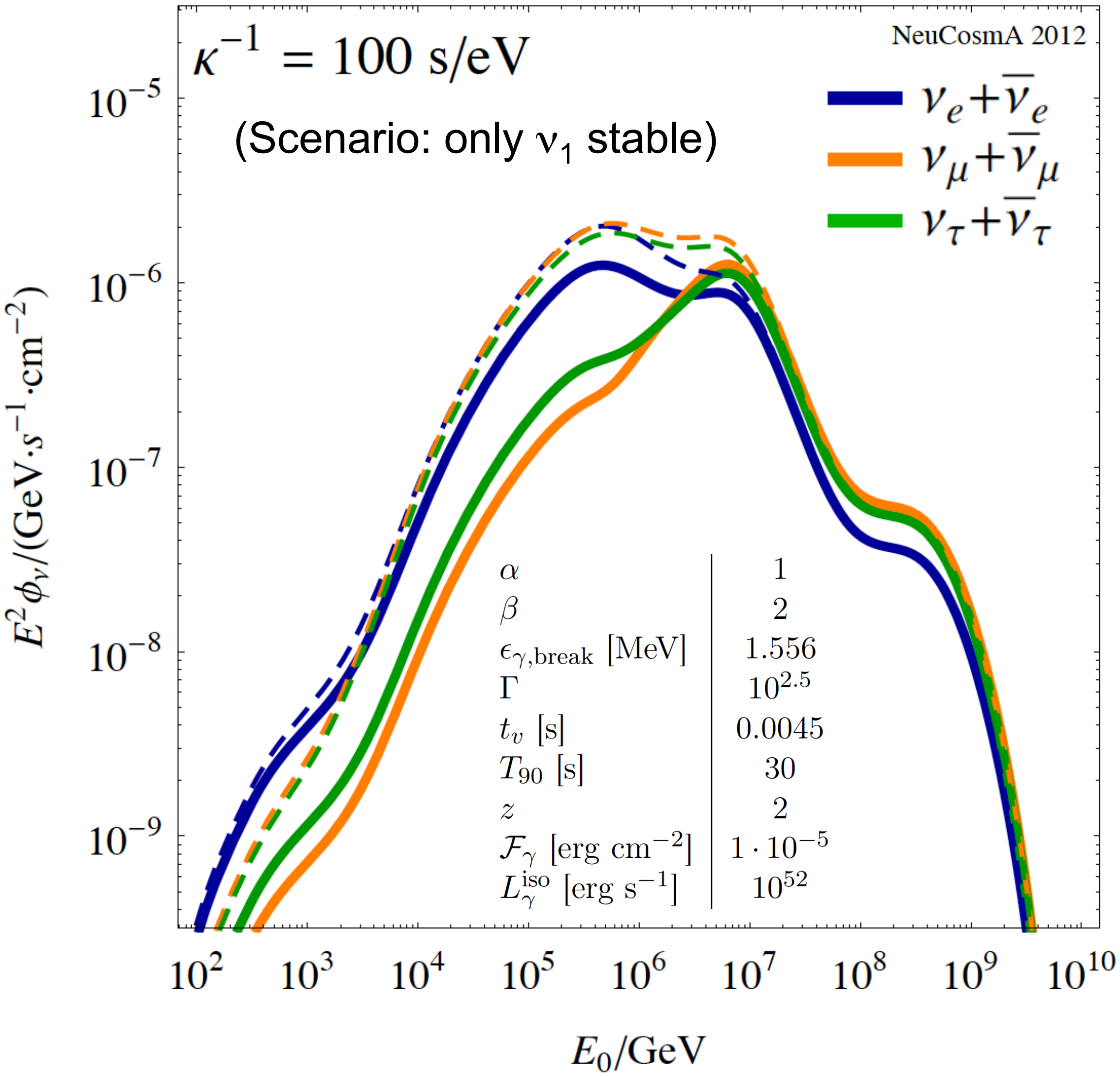
Decays of GRB neutrinos?

Interesting implications:

- ν_μ from GRBs may be suppressed (current stacking analyses based on ν_μ!). Need GRB-cascade searches
- Flavor composition depends on energy





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Neutrino physics?!

The established

The emerging

The fantastic

Particle physics

- Missing energy
- Neutrino oscillations
- CP violation
- Sterile neutrinos
- Physics beyond SM
- Relic νs
- ν-theory of everything (baryogenesis, dark matter, dark energy)

Astrophysics

- Stellar burning
- Stellar evolution
- Origin of cosmic rays
- Measurement of ν mass

Other disciplines

- Tests of nuclear theory
- Reactor ν flux measurements
- Geo-chemistry
- Nuclear monitoring
- Earth tomography