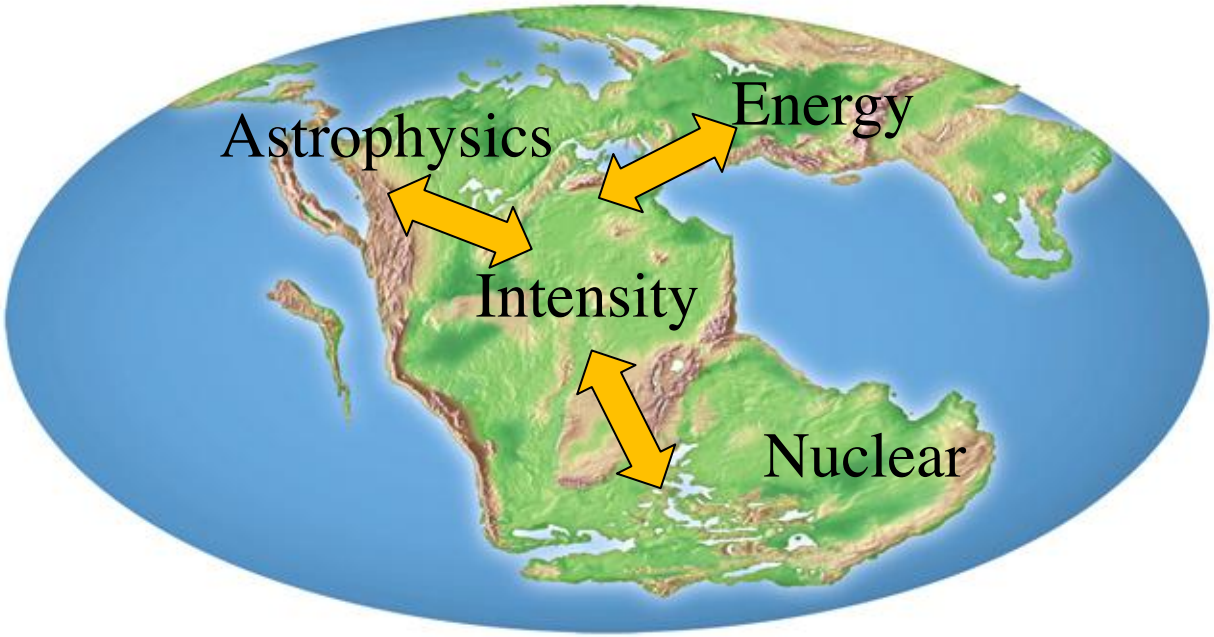
ν Experiments at the Intensity Frontier

Janet Conrad, MIT
PANIC 2014

In the spirit of the PANIC Conference



Neutrinos Without Borders!

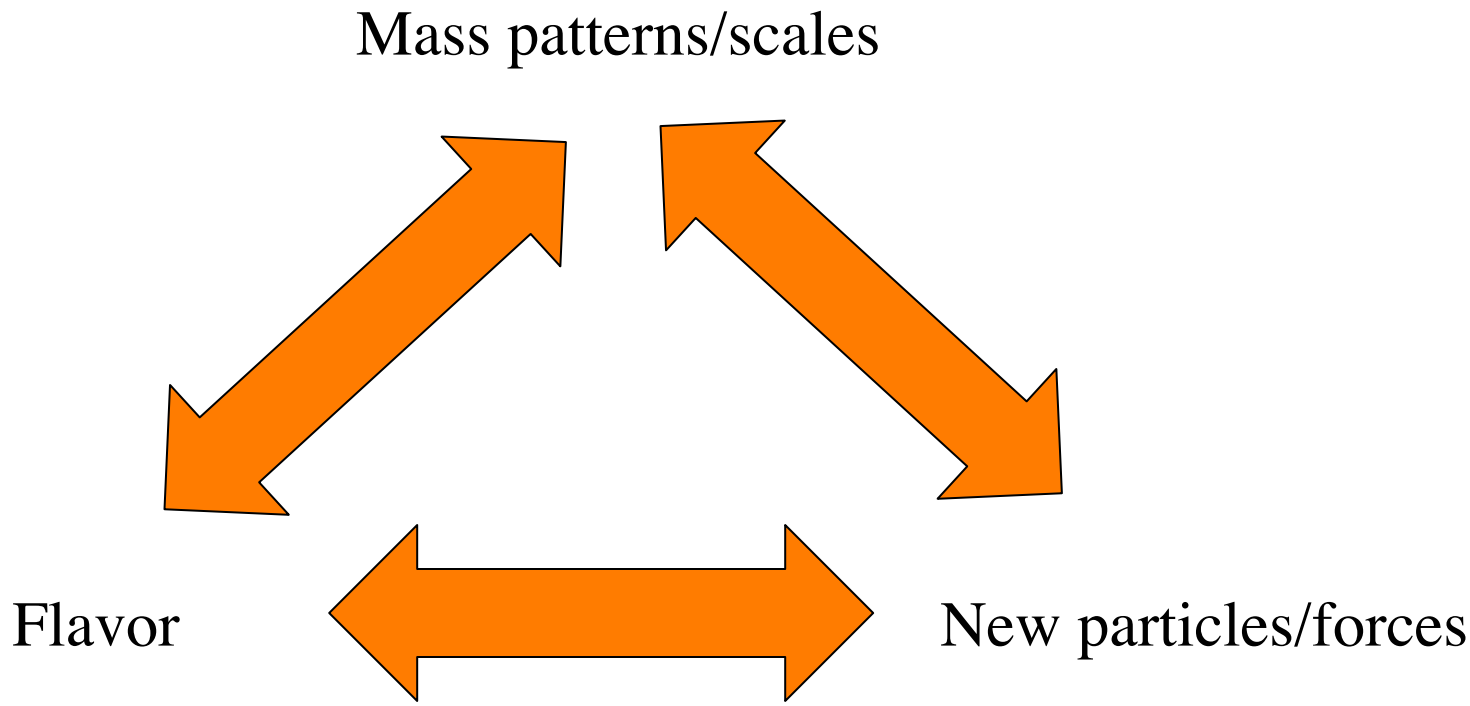
Questions that Unite Us:

What is the origin of the scale/pattern of masses?

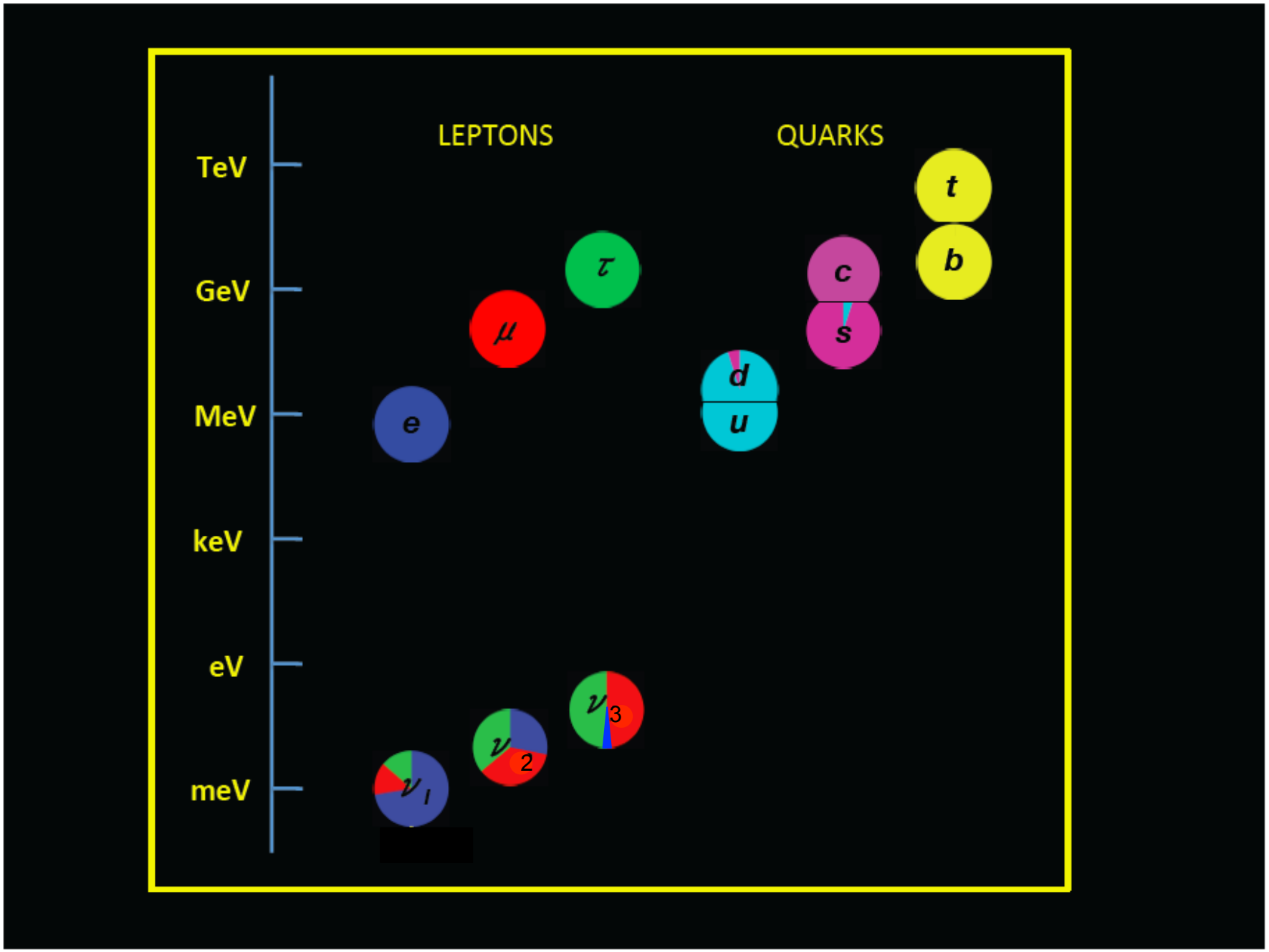
How do we understand flavor?

Are there new particles or forces?

In neutrino physics these questions are highly related

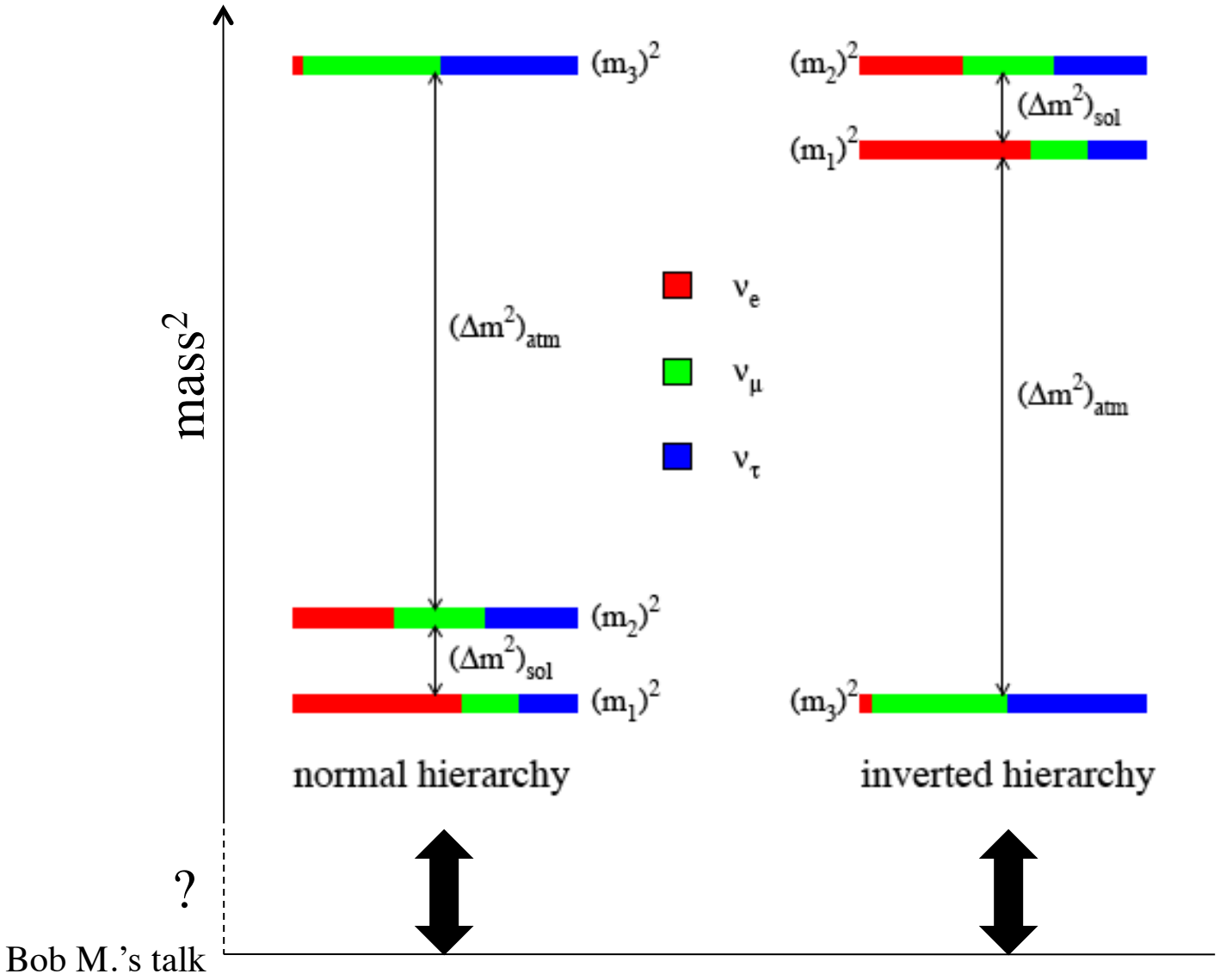


With neutrinos, everything's interconnected.



graphic by H. Robertson

The "νSM extension" -- data driven



Bob M.'s talk

The Flavor Mixing Matrix

Three mixing angles: θ_{12}, θ_{13}, θ_{23}

+ CP violation parameter: δ

$c_{ij}=\cos\theta_{ij}$

$s_{ij}=\sin\theta_{ij}$

$$U = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{pmatrix}$$

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

From Atmospheric and Long Baseline Disappearance Measurements

From Reactor Disappearance Measurements

From Appearance Measurements

From Solar Neutrino Measurements

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From Atmospheric and Long Baseline Disappearance Measurements

From Reactor Disappearance Measurements

From Appearance Measurements

From Solar Neutrino Measurements

See the Neutrino Session parallel talks by T2K (Tuesday) and MINOS(+) today!

The elements of the "PMNS" mixing matrix:

Where we are at today…

$$U_{PMNS}^{2014} = \begin{pmatrix} 0.779\ to\ 0.848 & 0.510\ to\ 0.604 & 0.122\ to\ 0.190 \\ 0.183\ to\ 0.568 & 0.385\ to\ 0.728 & 0.613\ to\ 0.794 \\ 0.200\ to\ 0.576 & 0.408\ to\ 0.742 & 0.589\ to\ 0.775 \end{pmatrix}$$

More or less where the quark sector was in 1995!

$$U_{CKM}^{1995} = \begin{pmatrix} 0.9745\ to\ 0.9757 & 0.219\ to\ 0.224 & 0.002\ to\ 0.005 \\ 0.218\ to\ 0.224 & 0.9736\ to\ 0.9750 & 0.036\ to\ 0.046 \\ 0.004\ to\ 0.014 & 0.034\ to\ 0.046 & 0.9989\ to\ 0.9993 \end{pmatrix}$$

Quark sector is lucky – at least you get strong production!
Weak production + weak interaction is *a hard way to make a living!*

There is a driving the need for

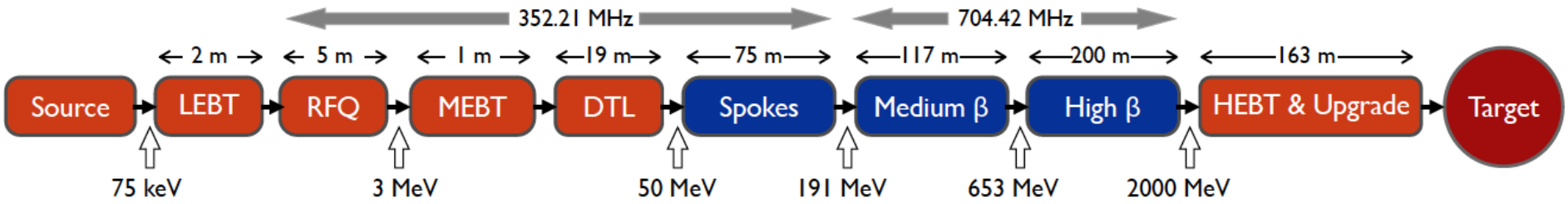
- More intense sources
- More flavor-pure fluxes
- Large detectors that can better discriminate between flavors

A lot of innovative technology is being developed
in neutrino physics,
including in the "Intensity Frontier"

More intense neutrino sources:

- Upgrade the beams we have! FNAL, CERN, JPARC…
- Make innovative use of other "very hot" beamlines

e.g. The ESS proton linac (start date 2023)

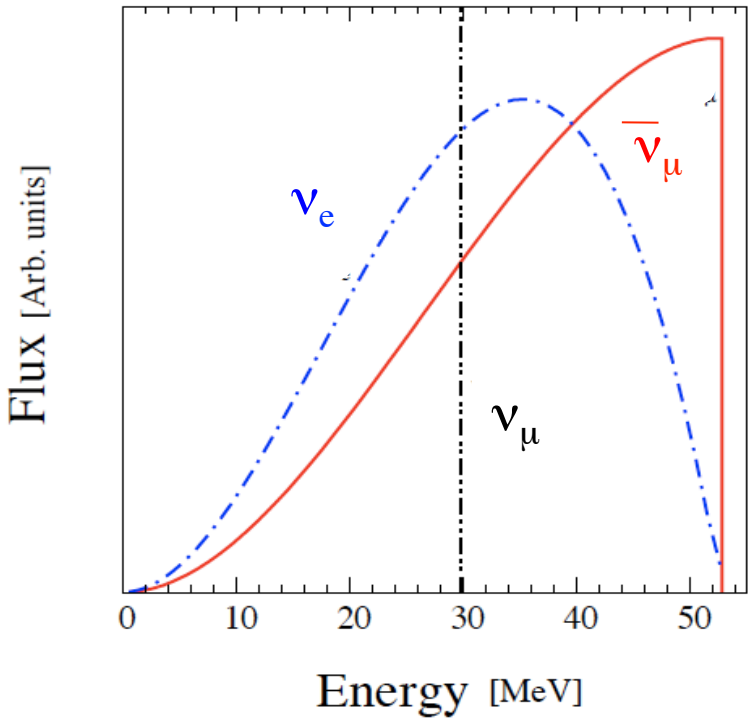


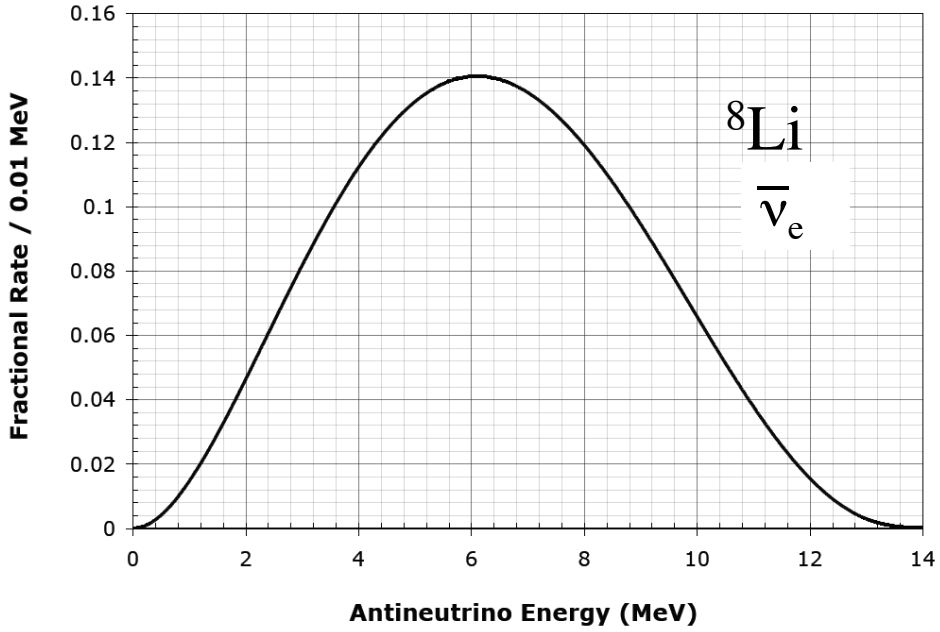
- 5 MW average beam power
- 125 MW peak power
- 14 Hz repetition rate (2.86 ms pulse duration, 10^{15} protons)
- 2.0 GeV protons (up to 3.5 GeV with linac upgrades)
- **$>2.7 \times 10^{23}$ p.o.t/year**

There is a proposal to add a neutrino facility!

Innovative ideas for purer flavor:

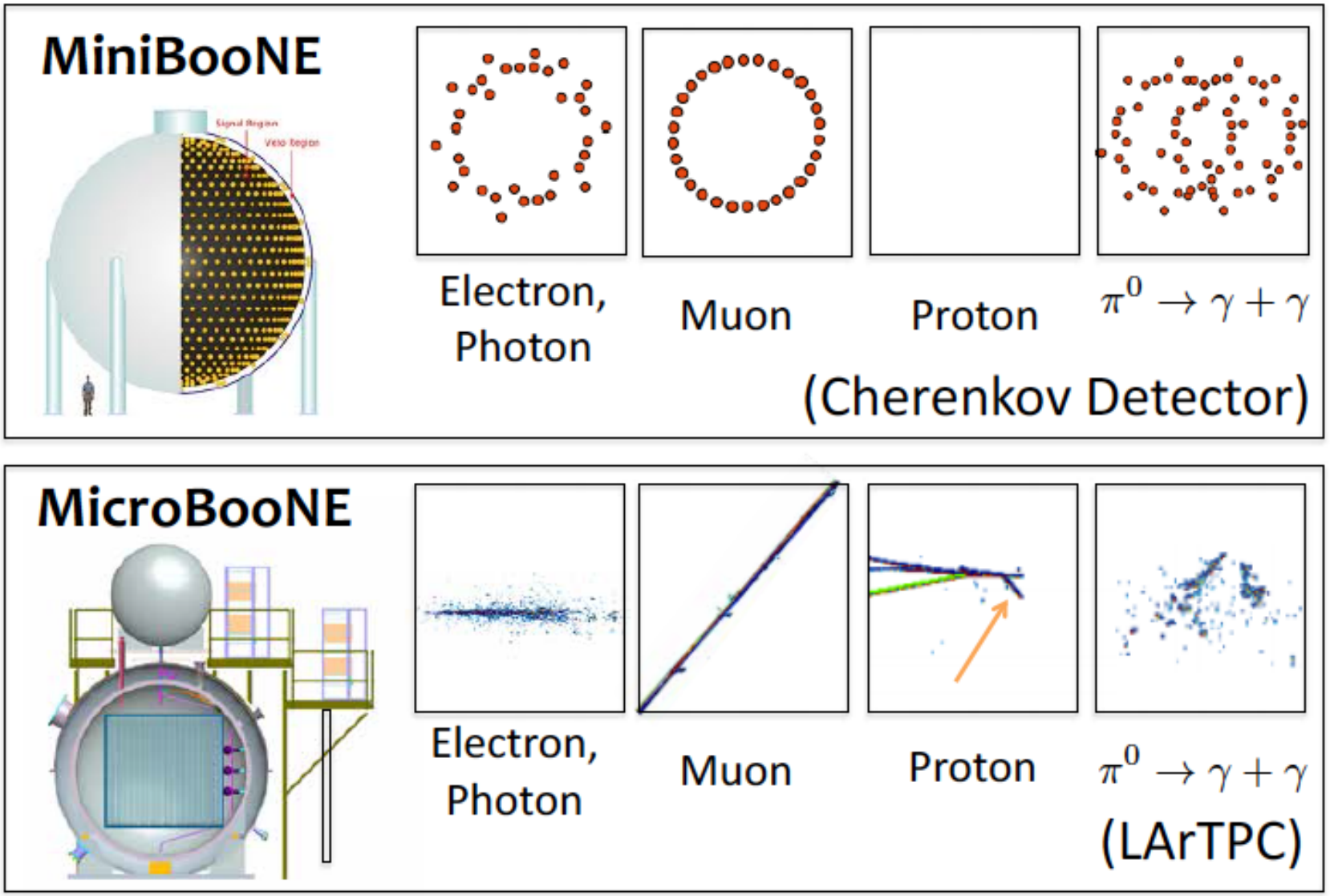
New "decay-at-rest" programs throughout the world:
OscSNS, ν@MLF, DAEδALUS, IsoDAR





See the Tuesday's Neutrino Session IsoDAR/DAEδALUS talk!

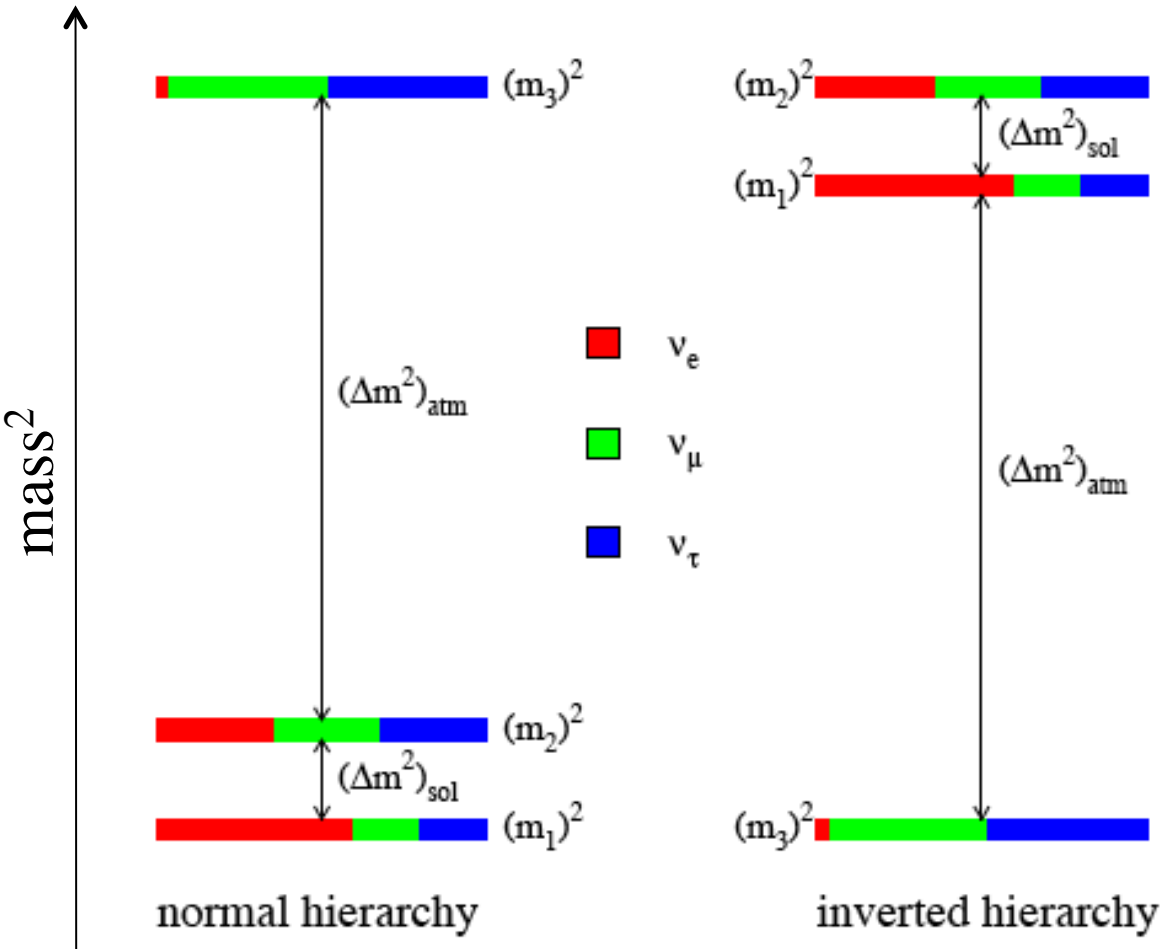
Scalable detectors with better flavor discrimination



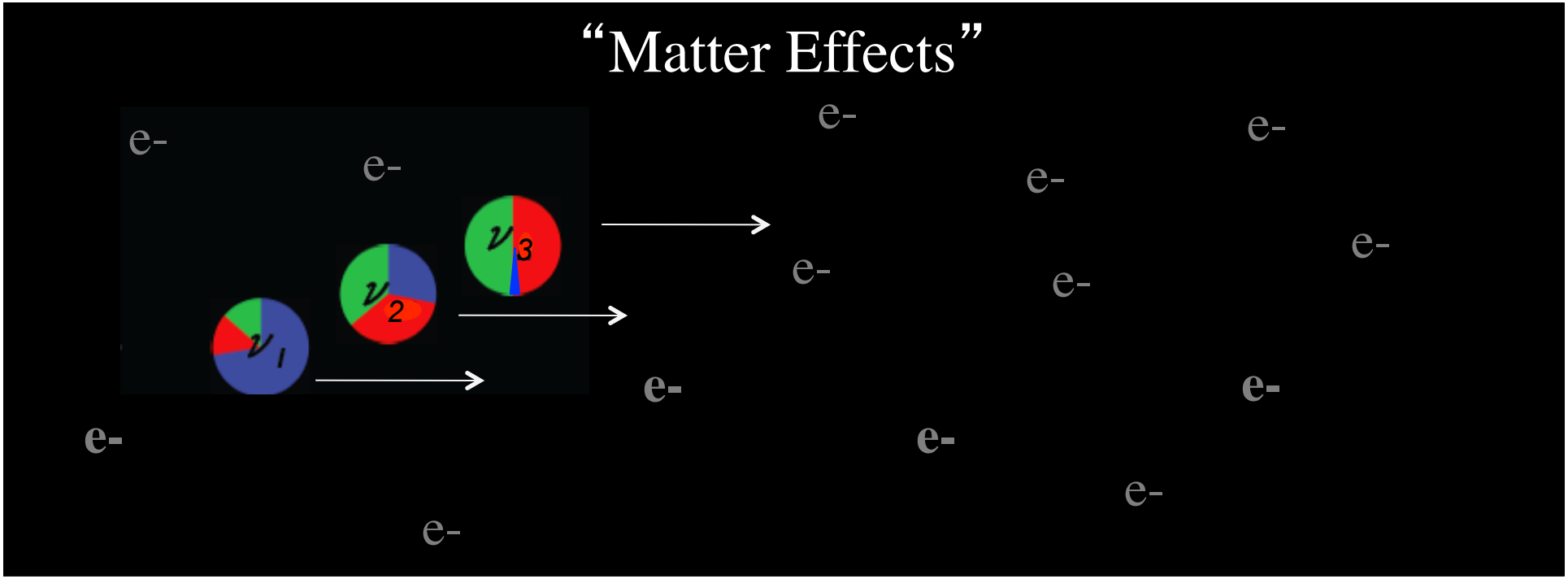
graphic from A. Ereditsto

See today's Neutrino Session MicroBooNE talk!

This will give us more precision on the flavor content,
But what about the hierarchy?



Find the Hierarchy Through



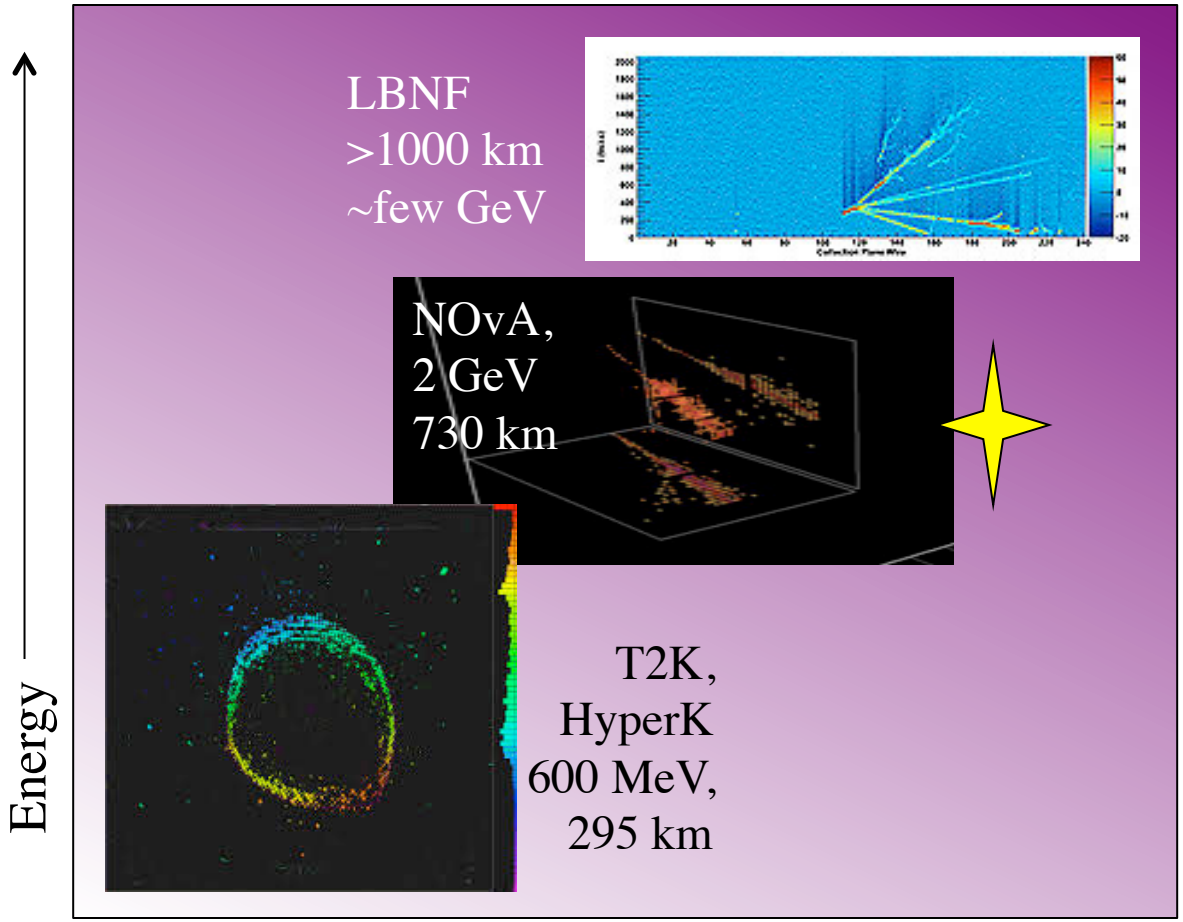
- Electrons in the earth produce a "weak-interaction potential"
- Effect is opposite sign for neutrinos and antineutrinos and
- Depends upon the ν flavor content

At high energies and long distances, oscillations will be affected:

$P(\nu) \neq P(\bar{\nu})$

$\nu_\mu \rightarrow \nu_e$ Appearance

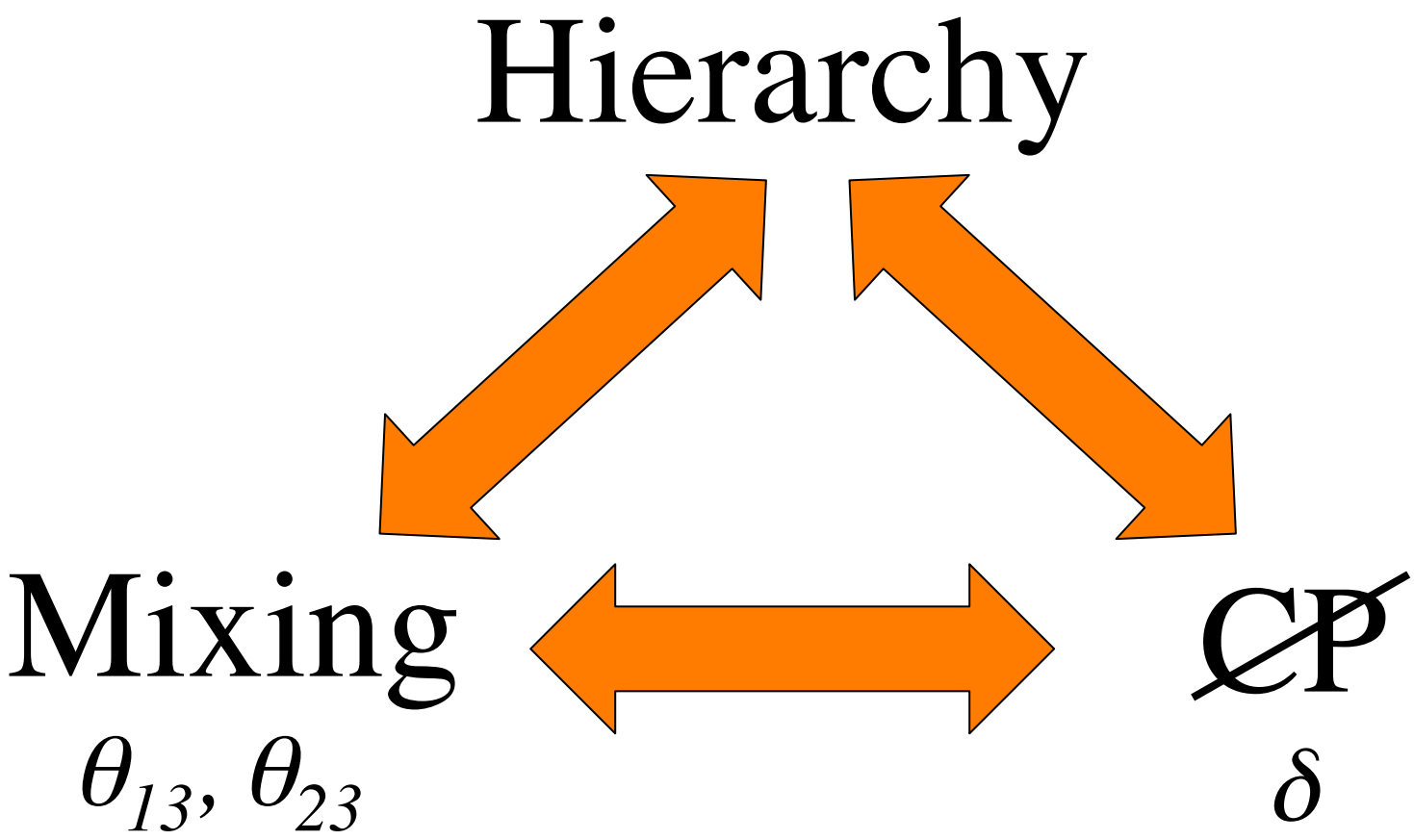
High matter effects



Low matter effects

See today's Neutrino Session NOνA talk!

In an appearance experiment measurement….

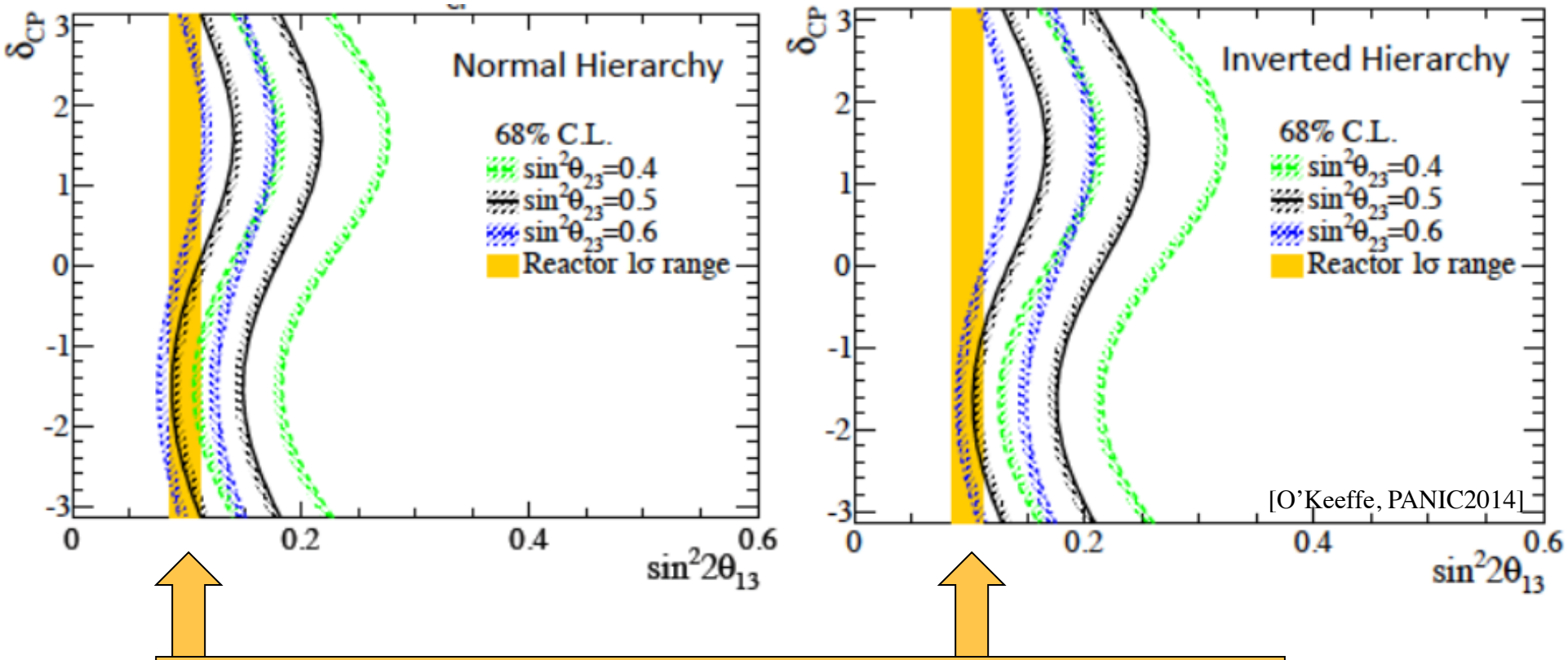


With neutrinos, everything's interconnected.

The new T2K appearance results (a 7σ observation!) …

How to show results depending on 4 variables at once!

- 2 plots – one for each hierarchy
- Each plot shows δ *vs.* $sin^2 2\theta_{13}$
- Use **black**, **blue**, **green** bands to show θ_{23} dependence



Compare to the ~1 km-baseline reactor disappearance results, which have only θ_{13} dependence

Let's design experiments that are primarily sensitive to only one of the variables!

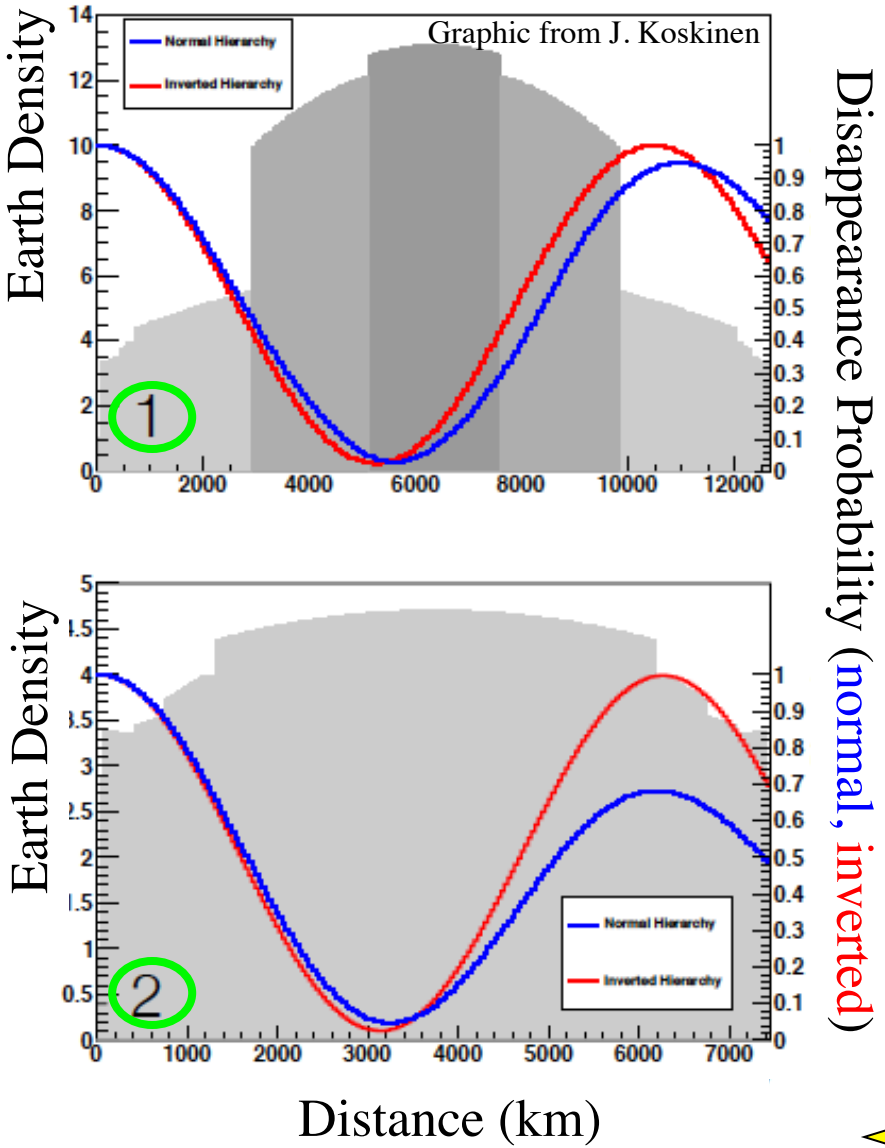
e.g., use long baseline disappearance
to find hierarchy
(no CP violation!)

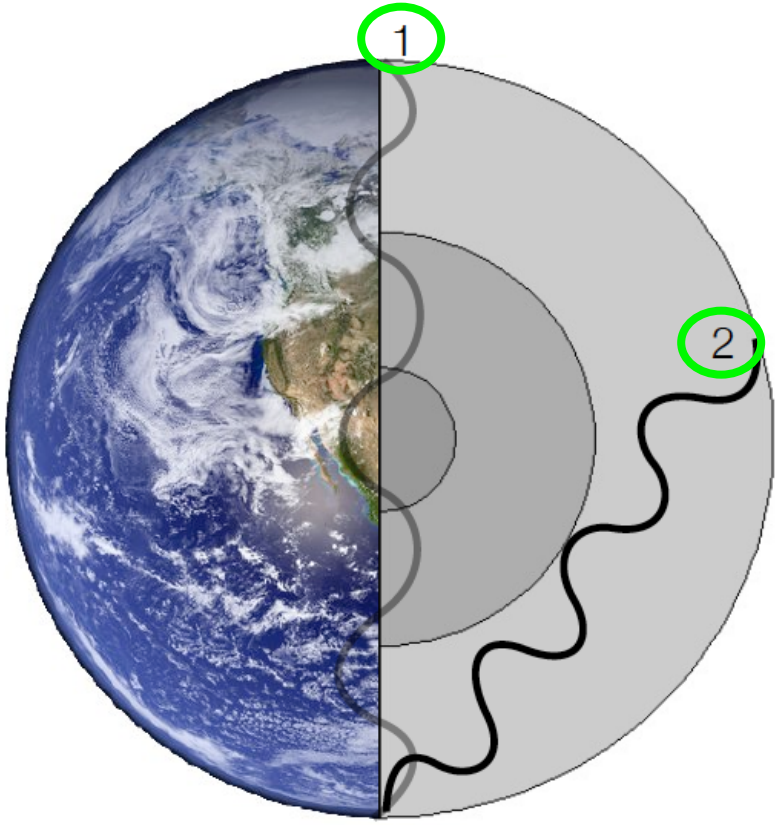
ν_e disappearance: JUNO (see Bob M's talk), HK atmospheric
ν_μ disappearance: **PINGU,** INO [arXiv:1109.3262]

e.g., use very short baseline appearance
to find CP violation
(no matter effects!)

$\nu_\mu \rightarrow \nu_e$: DAEδALUS, ESS

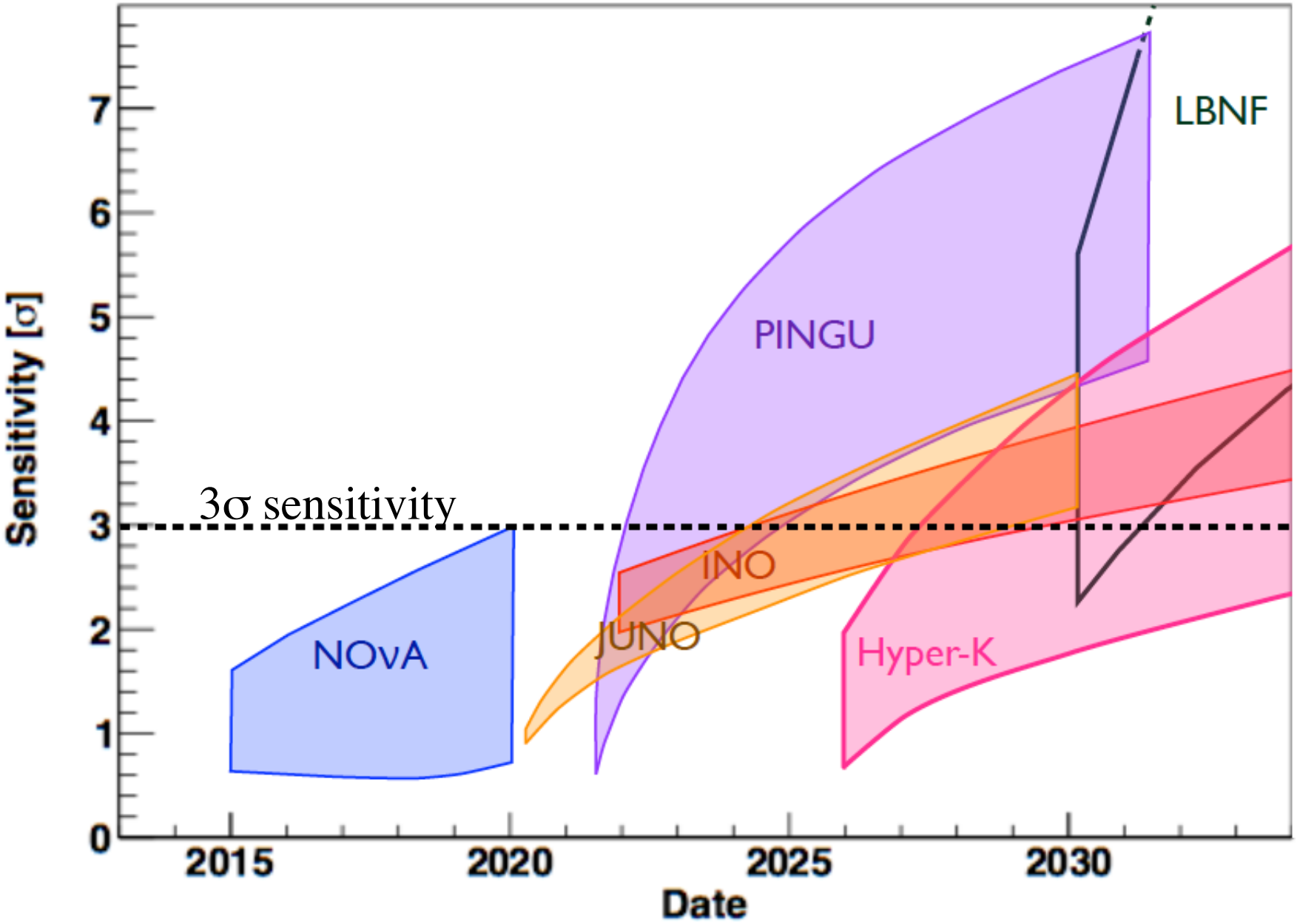
The Idea of PINGU





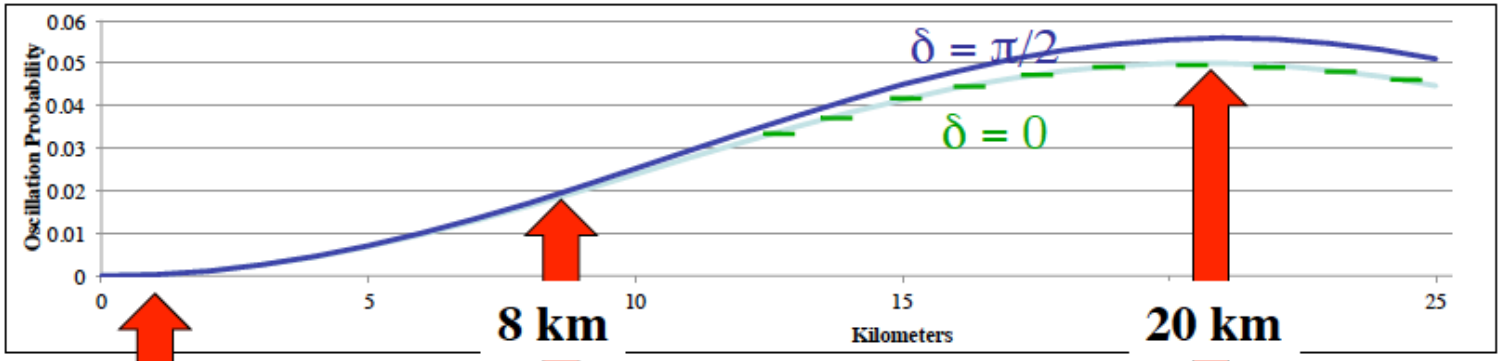
See today's Neutrino Session PINGU talk!

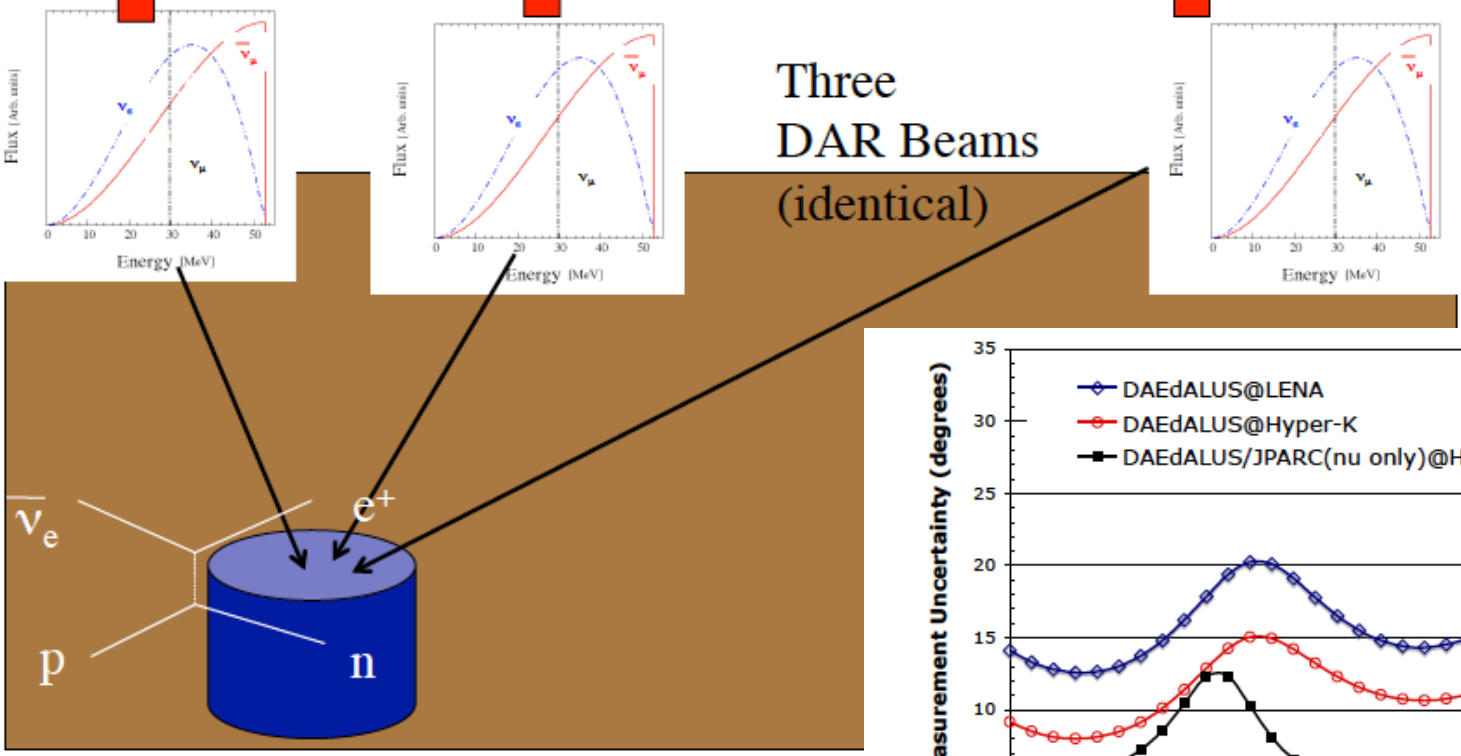
How long until we know the mass hierarchy?

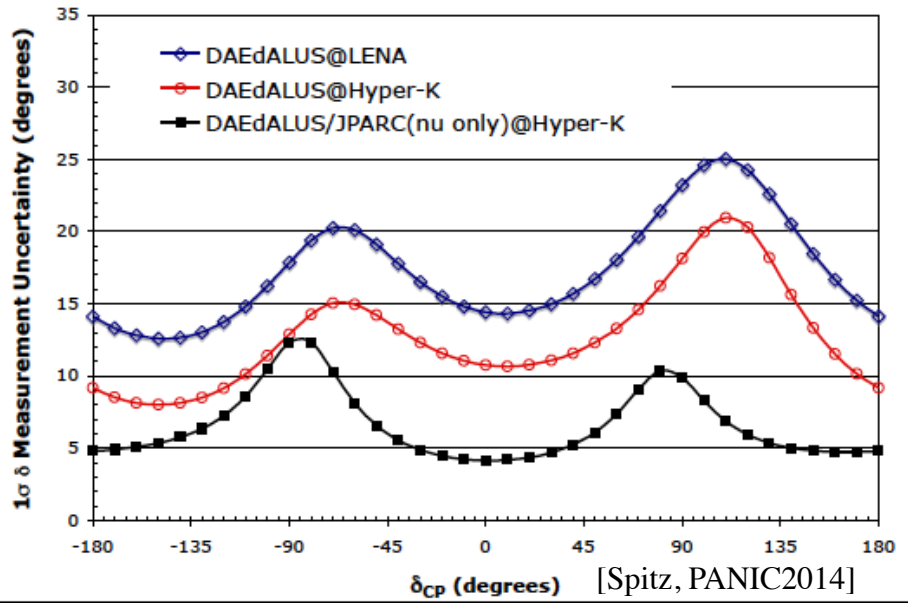


Graphic from D. Grant

Precision experiments sensitive to only δ, e.g.: DAEδALUS







[Spitz, PANIC2014]

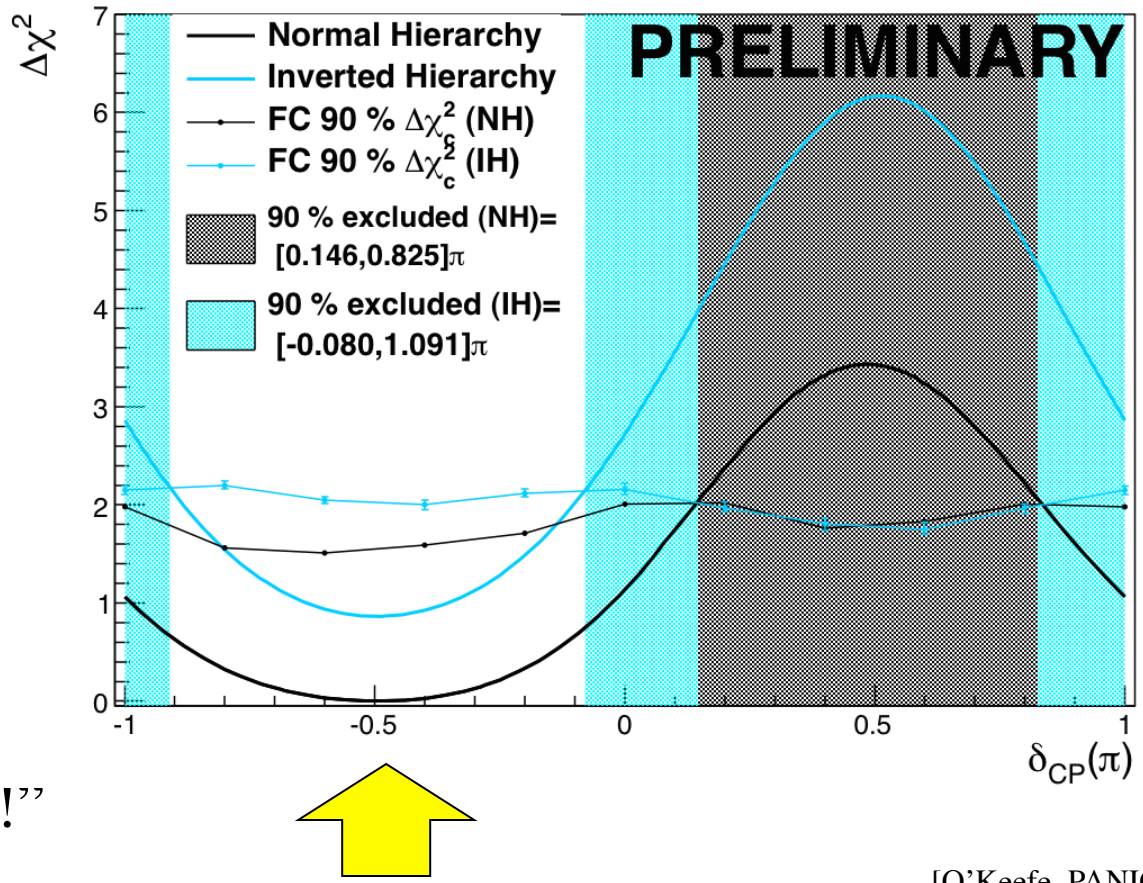
A measurement of δ to ±5 degrees

"What can you learn from a precise measurement of δ_{cp} ?"

$$\text{If} \quad |\sin\theta_{13}\sin\delta| > 0.11$$

You can have successful leptogenesis with
CP violation in only the mixing matrix!

Arxiv:hep-ph/0611338

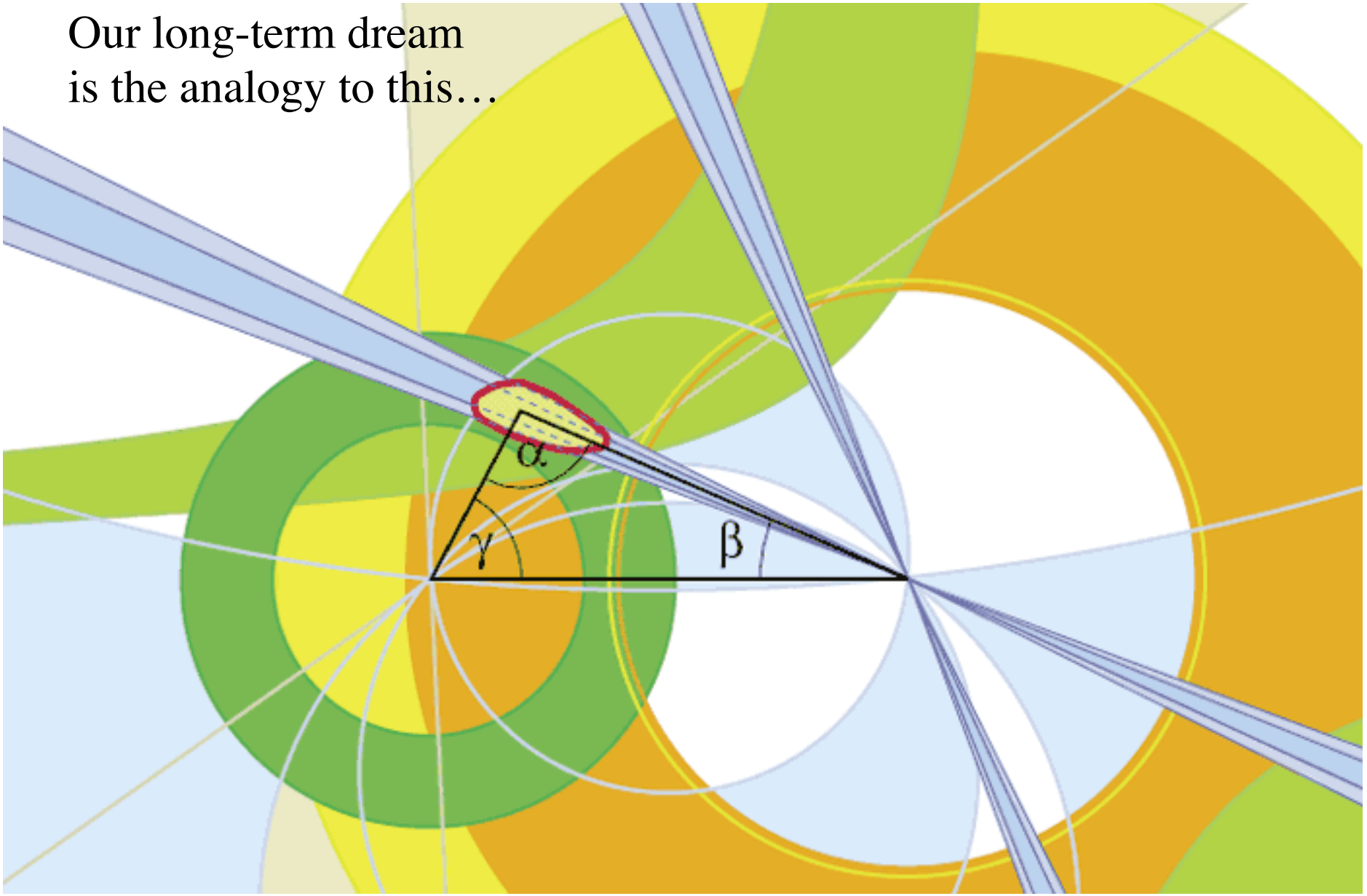


Just for fun, note:

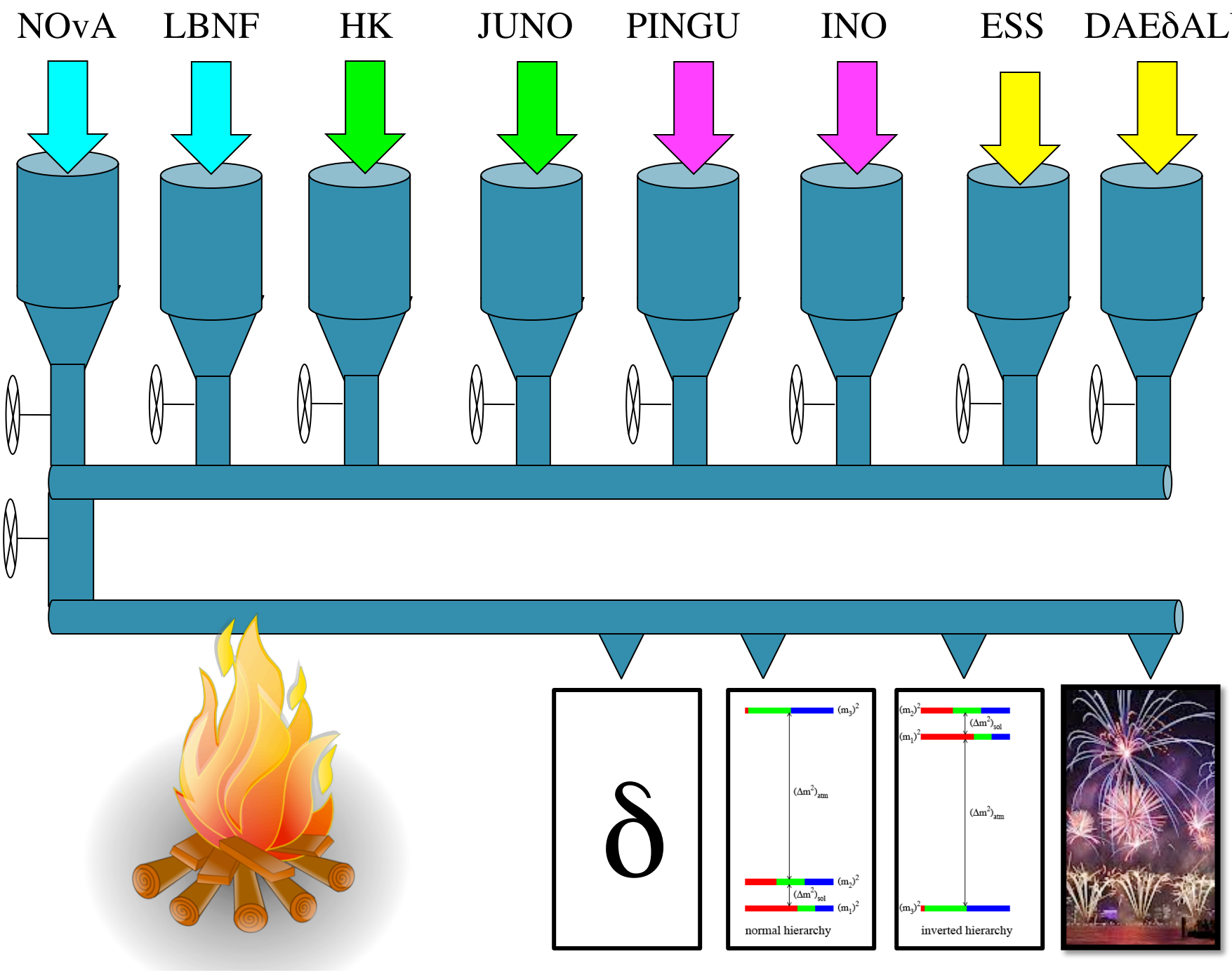
The best fit from T2K
is at that "golden spot!"

[O'Keefe, PANIC2014]

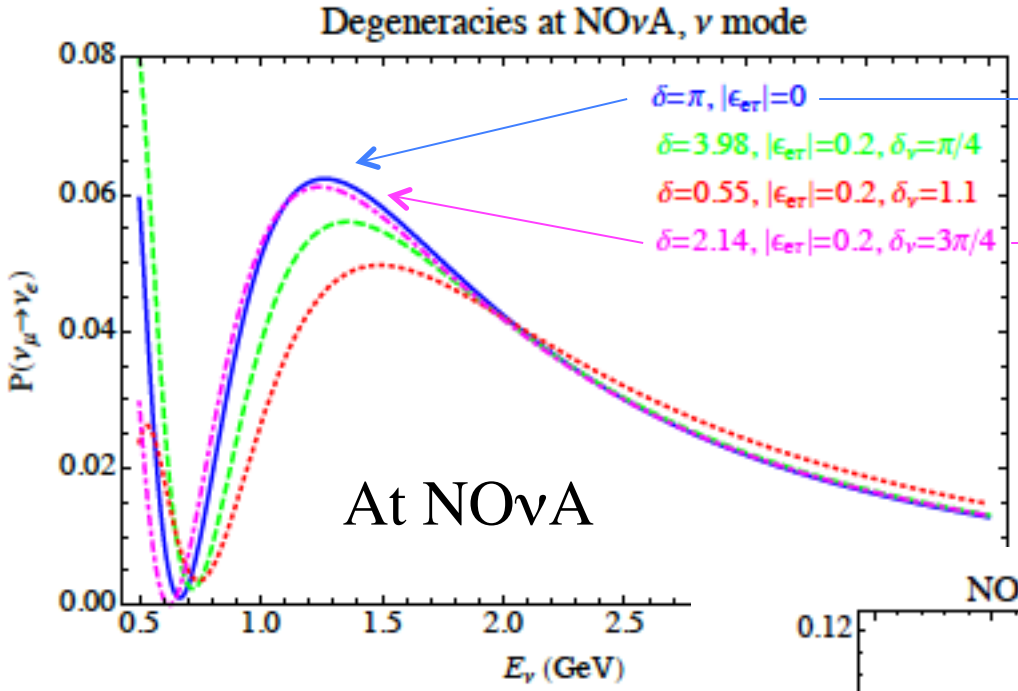
Our long-term dream
is the analogy to this…



graphic from CERN


NOvA
LBNF
HK
JUNO
PINGU
INO
ESS
DAEδALUS
δ
normal hierarchy
inverted hierarchy

New Non-Standard Interactions

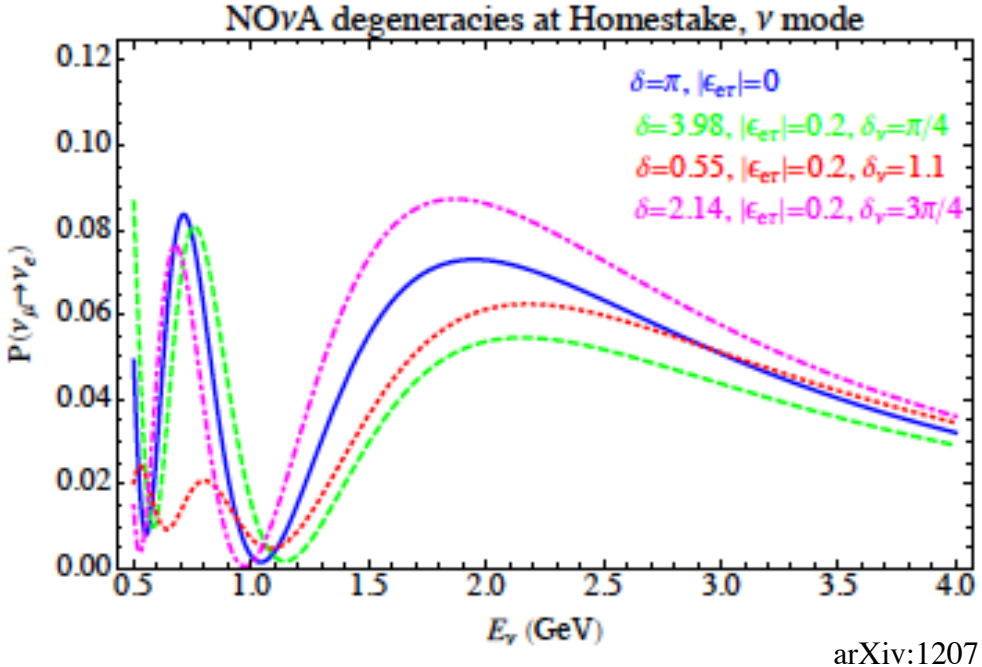


At NOνA

A "νSM" possibility

A different "νSM" possibility combined with NSI!

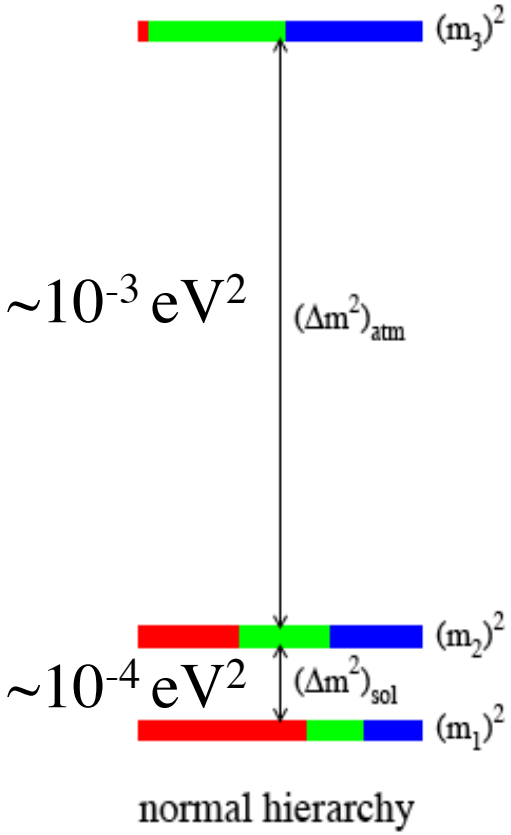
But LBNF has different degeneracies! So what's degenerate at NOνA may be resolvable at LBNF



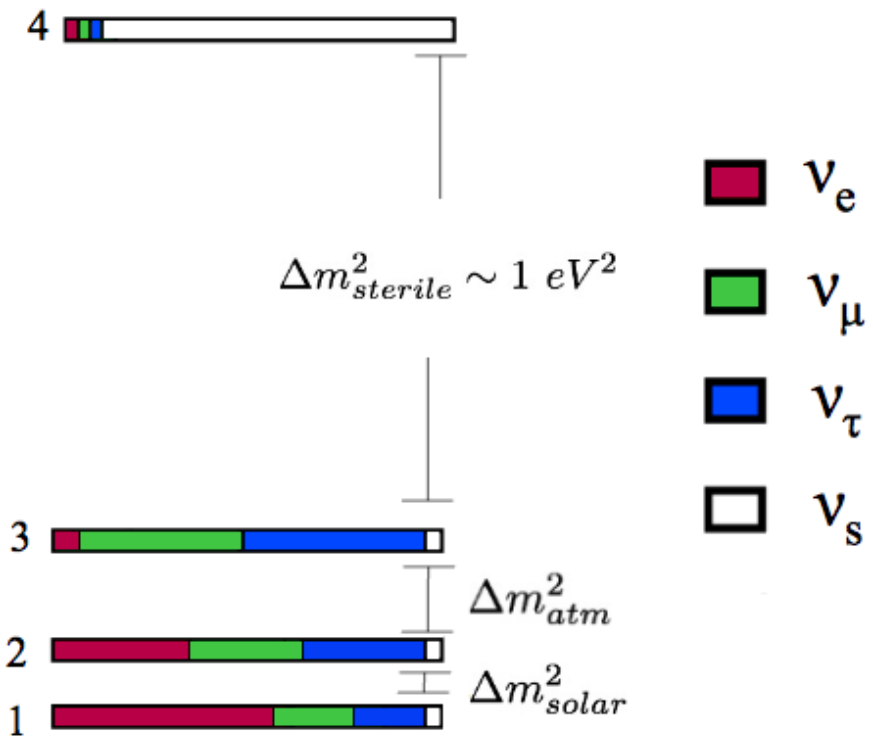
arXiv:1207.6642

New particles: sterile neutrinos?

There is a collection of data that doesn't fit this model:

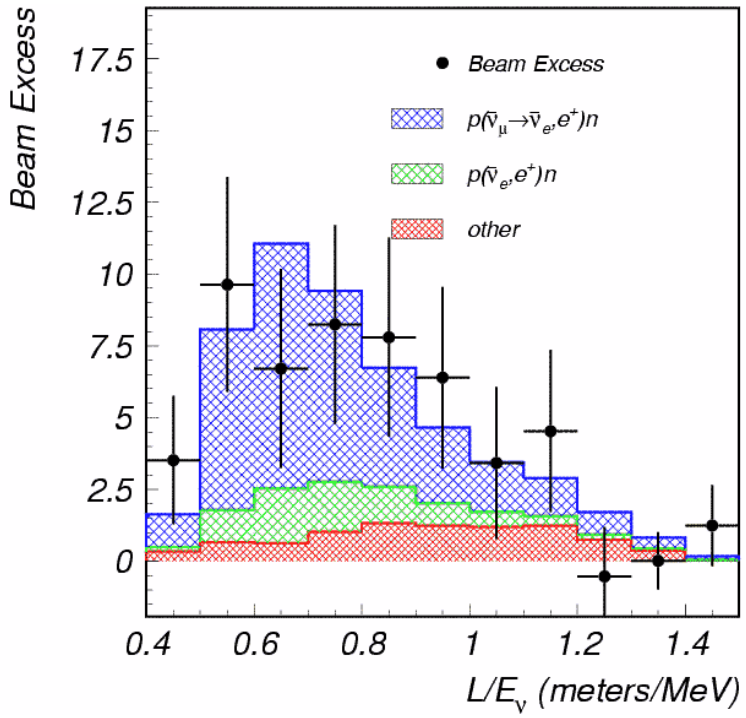


Data sets indicate a high Δm^2
Can be fit by introducing a new ν,
…but it must be non-interacting!



These signals are at the 2-4σ level

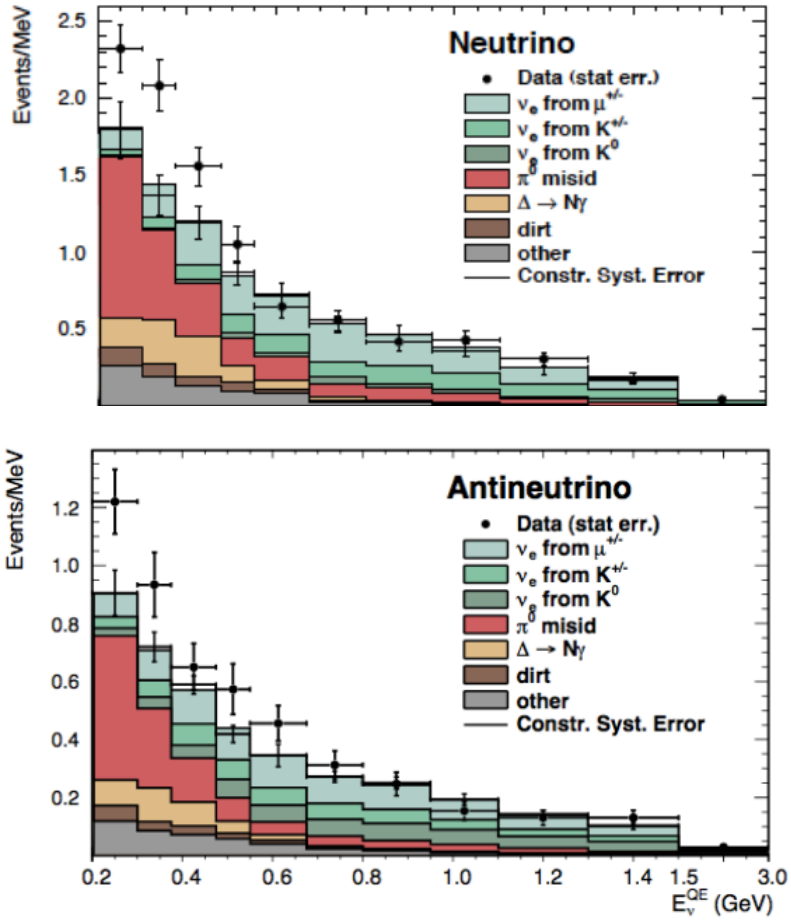
$\nu_\mu \rightarrow \nu_e$ Appearance



Unexpected excess in LSND,
$\bar{\nu}_\mu \rightarrow \bar{\nu}_e$

$\Delta m^2 \sim 1\ eV^2$ shown in blue

[hep-ex/0104049]

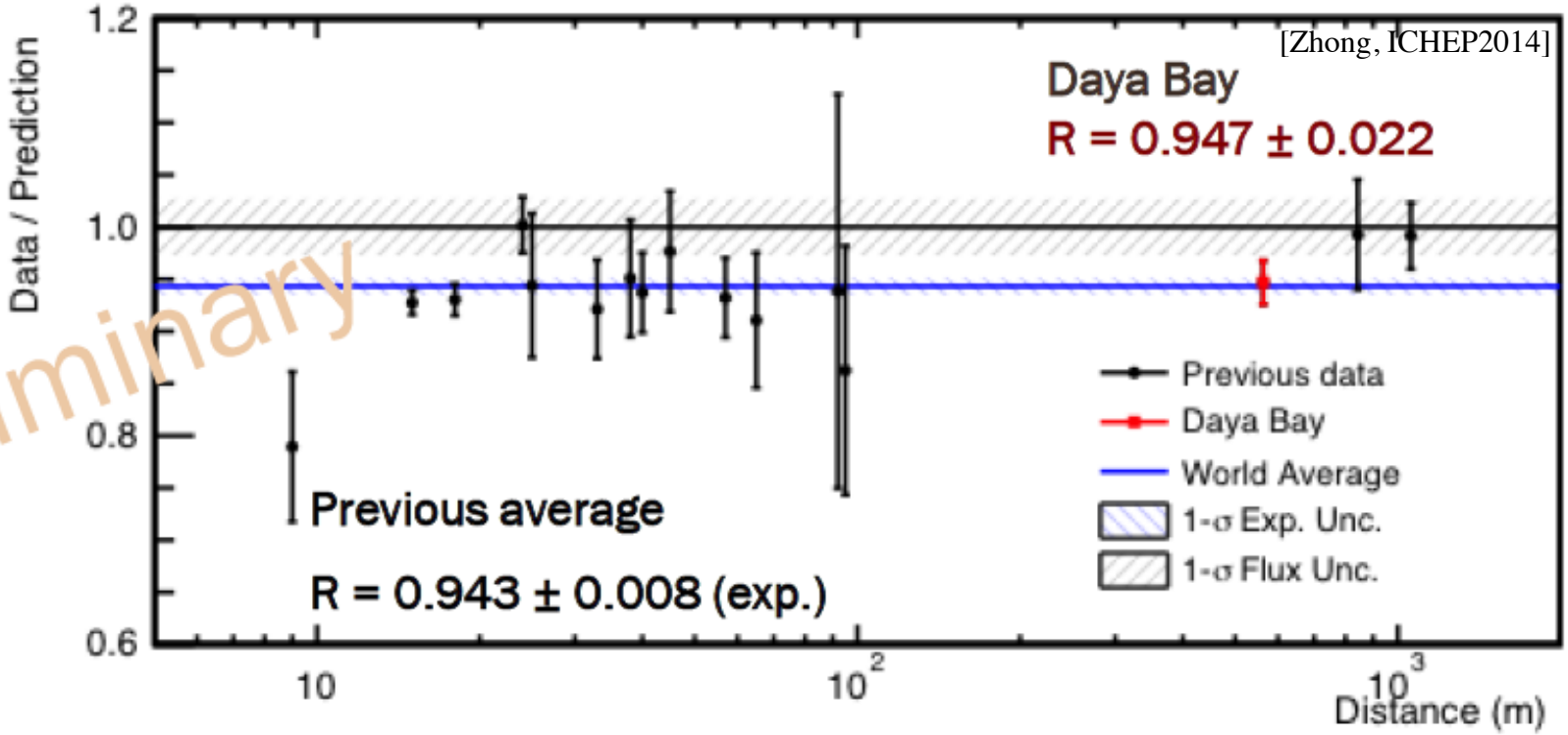


Excesses also seen by MiniBooNE
$\nu_\mu \rightarrow \nu_e$ and $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$

[arXiv:1303.2588]

$\bar{\nu}_e$ Disappearance at Reactors

See Bob M's talk



And also…

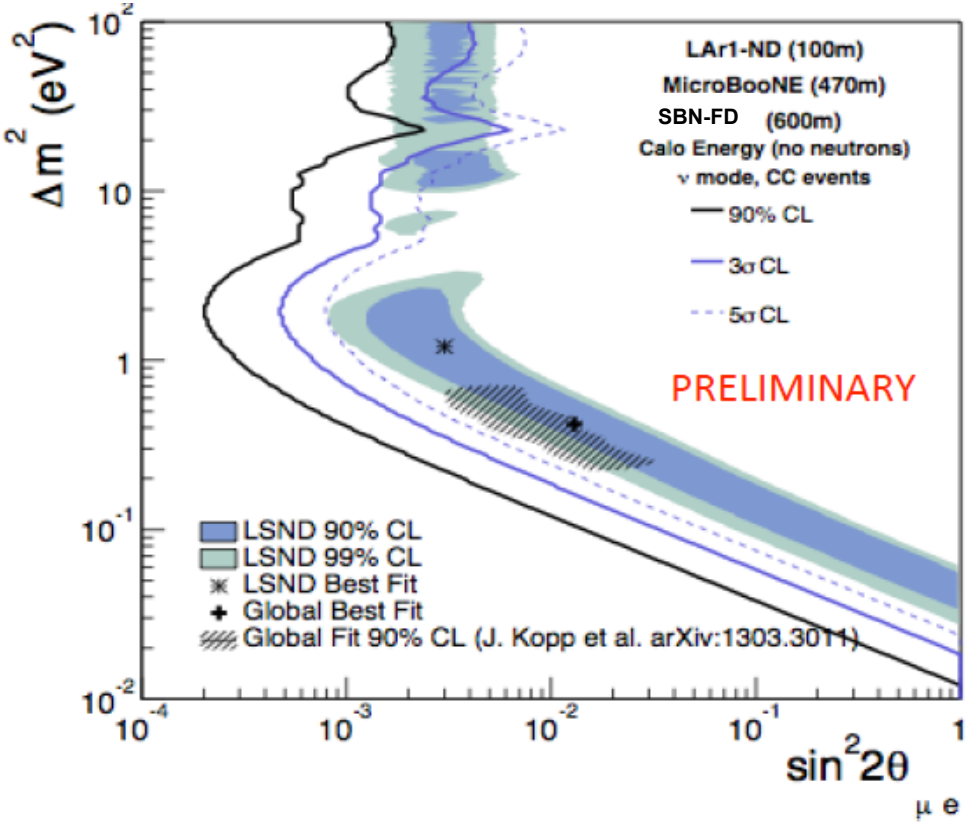
ν_e disappearance is seen at high power source expts. too!

(SAGE, Gallex Calibration data)

How do we answer these questions?

Fermilab LAr SBN Program

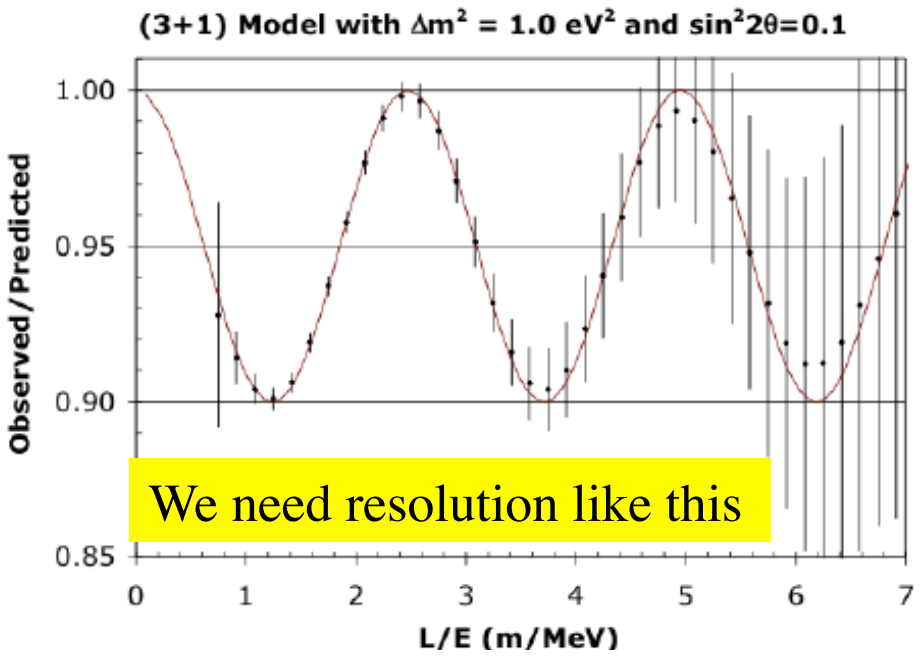
[Fermilab-Proposal-1053]

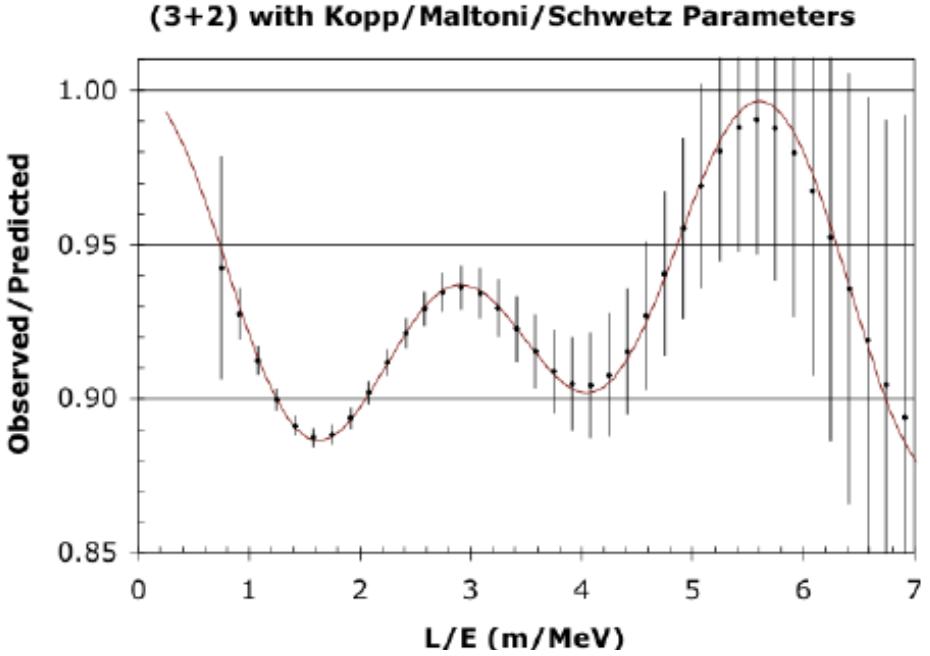


That sensitivity was for a 3+1 model:
3+1 gives a poor fit to existing data (ν *vs.* $\bar{\nu}$ disagreement)
Fits want at least 3+2

[arXiv:1303.3011]
[arxiv: 1207.4765]

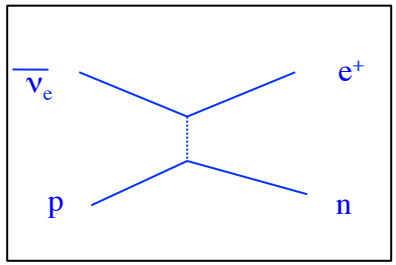
To believe you are seeing sterile neutrinos,
You need to be able to trace the oscillation wave,
Even "messy" 3+2 waves



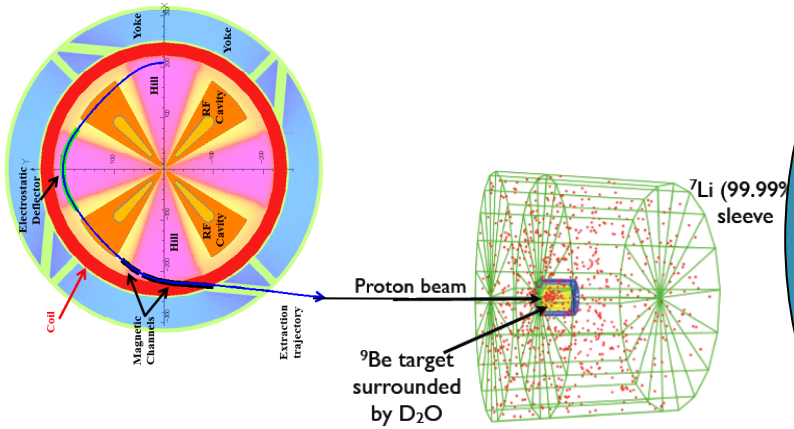


$\bar{\nu}_e$ disappearance without reactors: **IsoDAR**

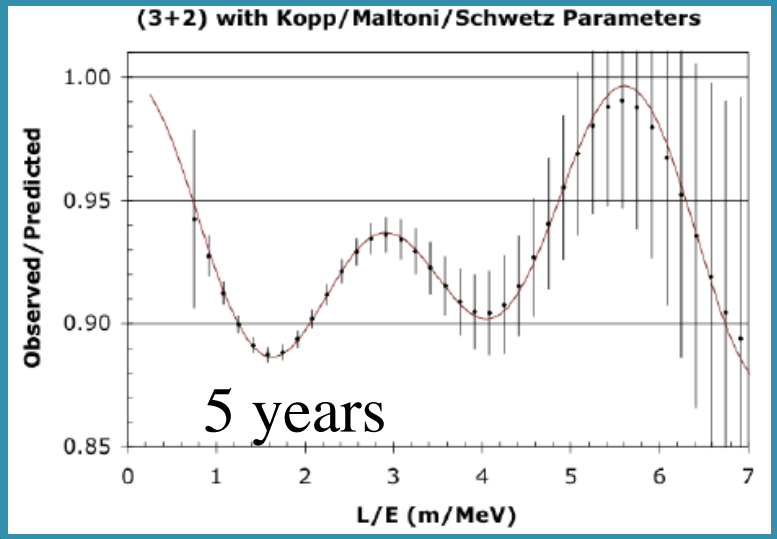
Proton beam → Be → n → captures on ^{7}Li → ^{8}Li → $\bar{\nu}_e$



For example, at KamLAND



1 kton LS detector



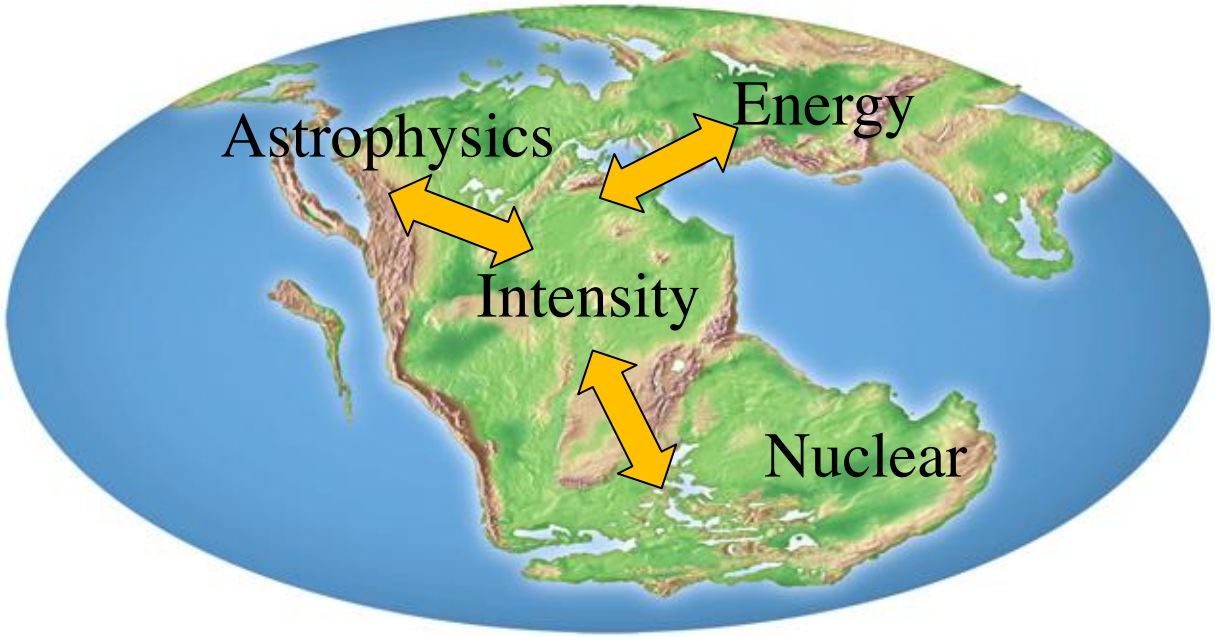
16.5 m

[arXiv:1205.4419]

This program really is "without borders"

…If you consider the entire program,
neutrino physicists work on every continent.

Let's stay interconnected!



Thank you!