An Introduction to Reactor Neutrinos

July 19, 2023

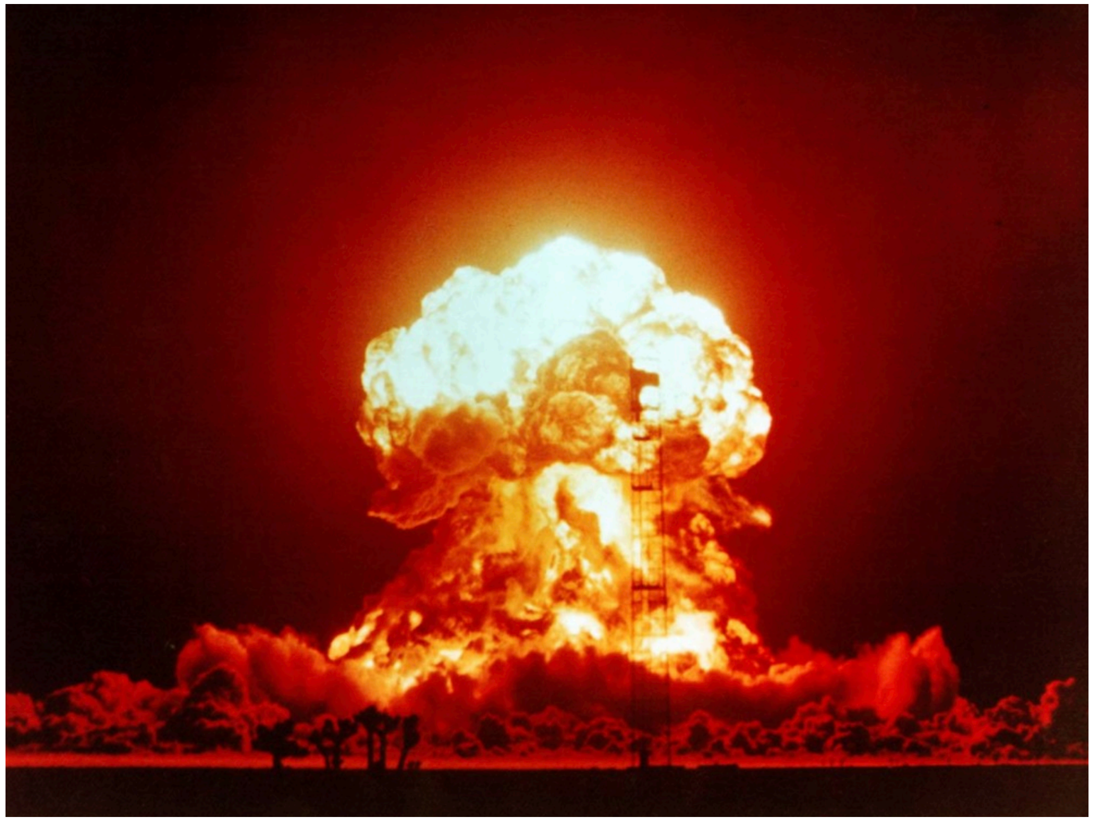
Bryce Littlejohn
Illinois Institute of Technology

What Do Nuclear Reactors Do?

What Do Nuclear Reactors Do?

Generate electric power:

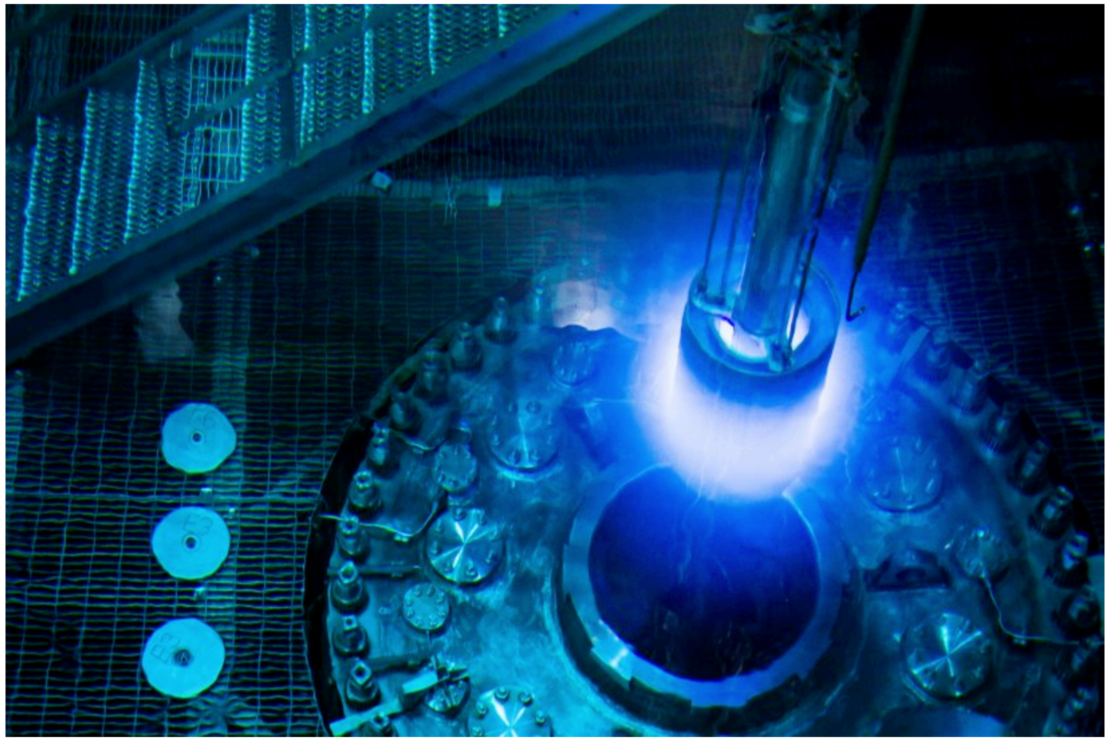
April 2023, in Georgia, USA: new 3.4GW Vogtle 3 reactor connected to the power grid



Make fissile materials:

Hanford, USA:
First-ever atomic test fueled by reactor-bred ^{239}Pu. North Korea follows this same strategy today.

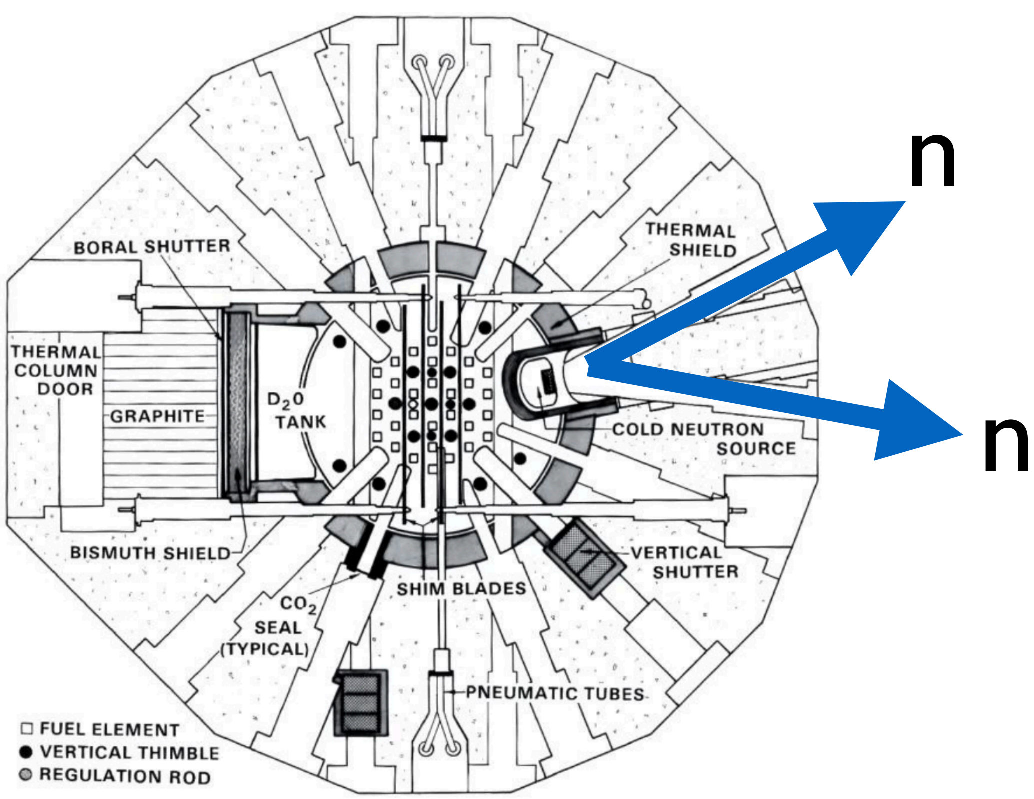
What Do Nuclear Reactors Do?



Make rare isotopes:

Tennessee, USA:

HFIR is USA's only supplier of Cf-252 (assaying mining ores, cancer therapy, etc. etc. etc.), Pu-238 (powering spaceships).



Make neutrons:

Maryland, USA:

NIST's NBSR is used to measure the lifetime of free neutrons, and many other things.

What Do Nuclear Reactors Do?

HFIR
is
behind
this
wall!

Make… neutrinos!!!

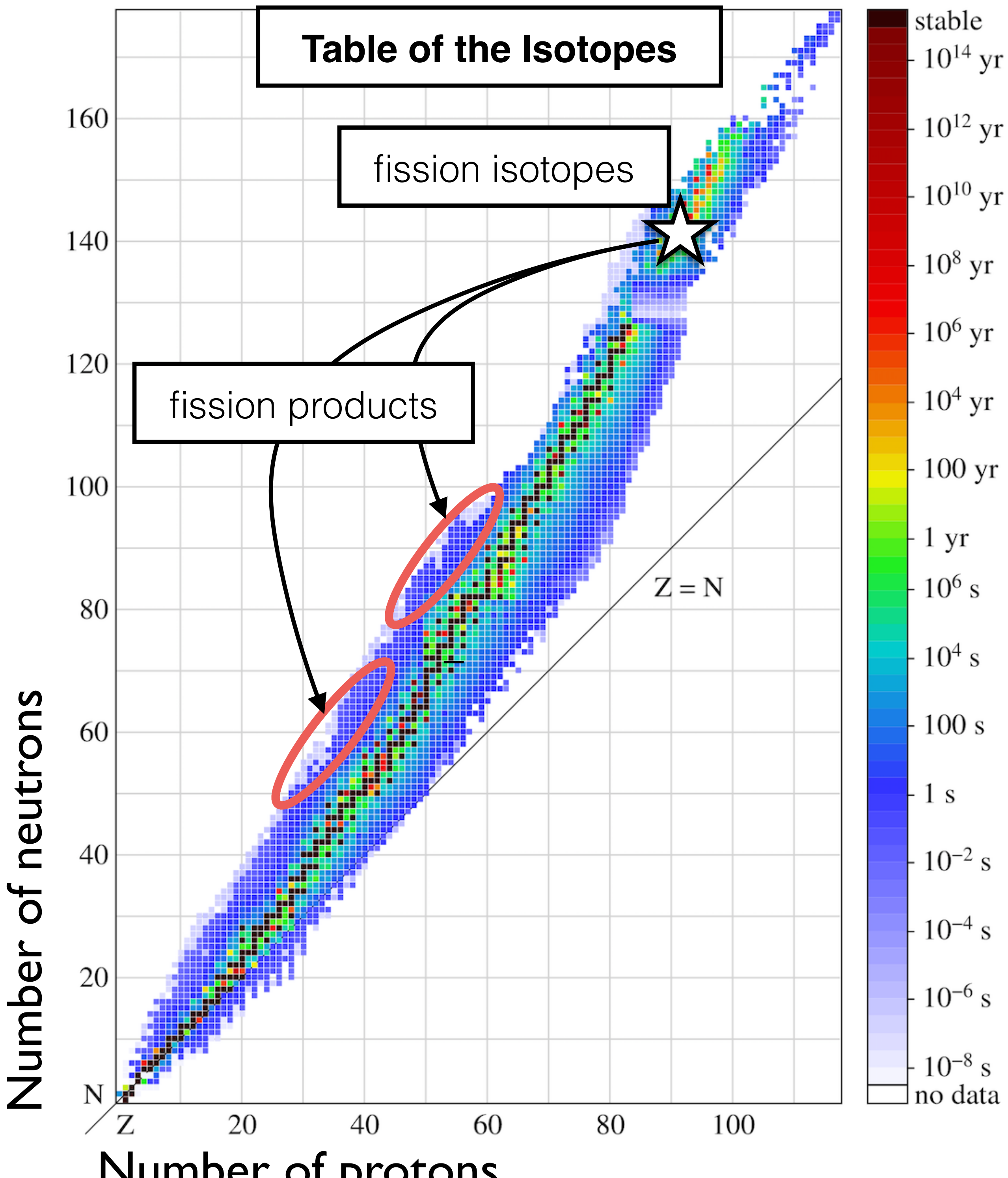
Tennessee, USA:
HFIR is also the host for PROSPECT, a DOE-funded reactor neutrino experiment

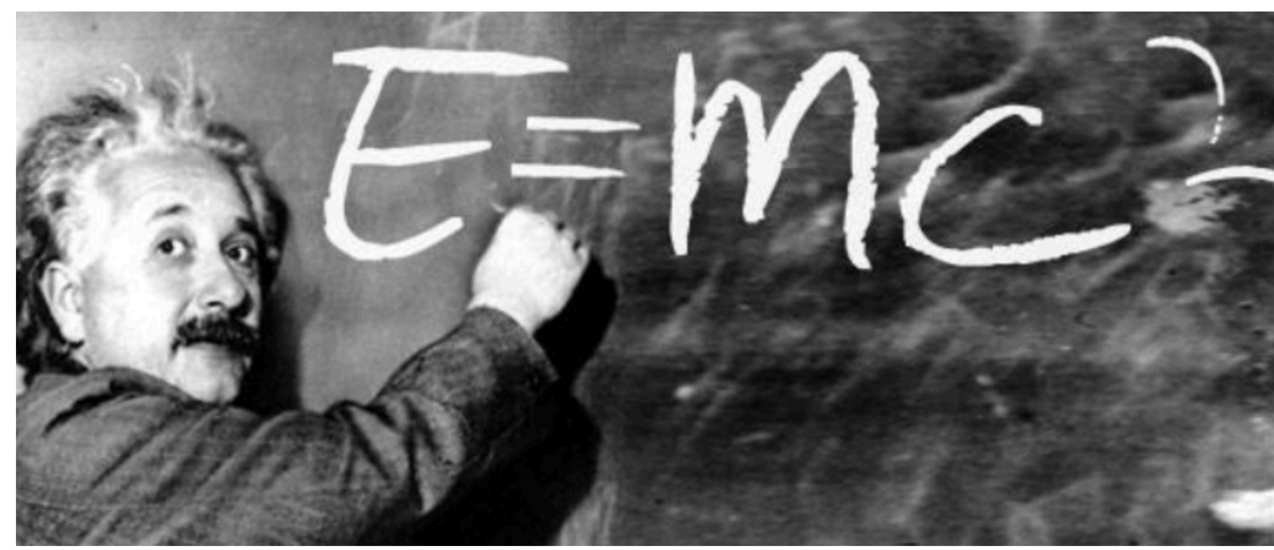
Reactor facilities host many stakeholders from many fields

How Do Nuclear Reactors Work?

Reactors: Nuclear Fission

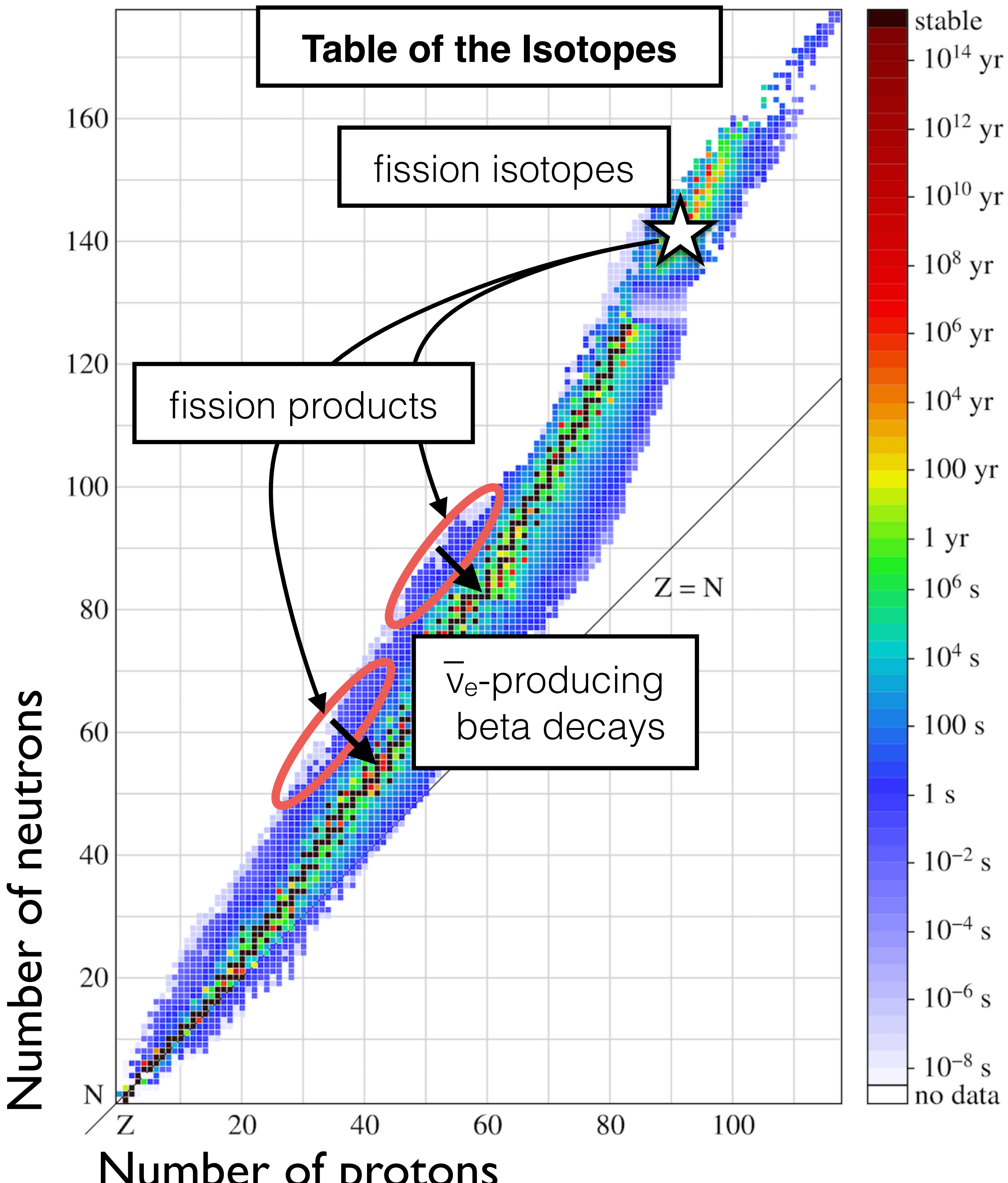
- Heavy nuclei fission to make lighter nuclei plus extra energy
  - Roughly 200 MeV of excess rest mass energy per fission

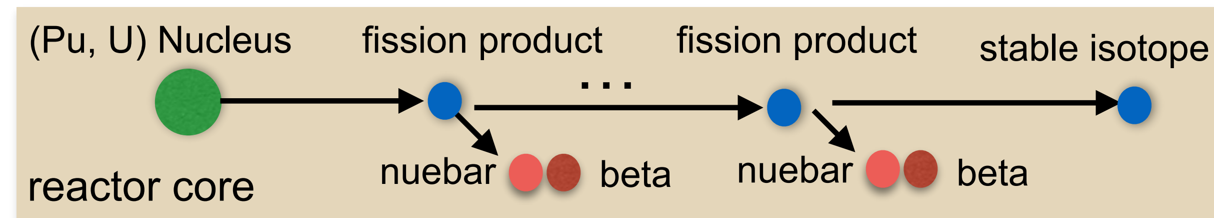


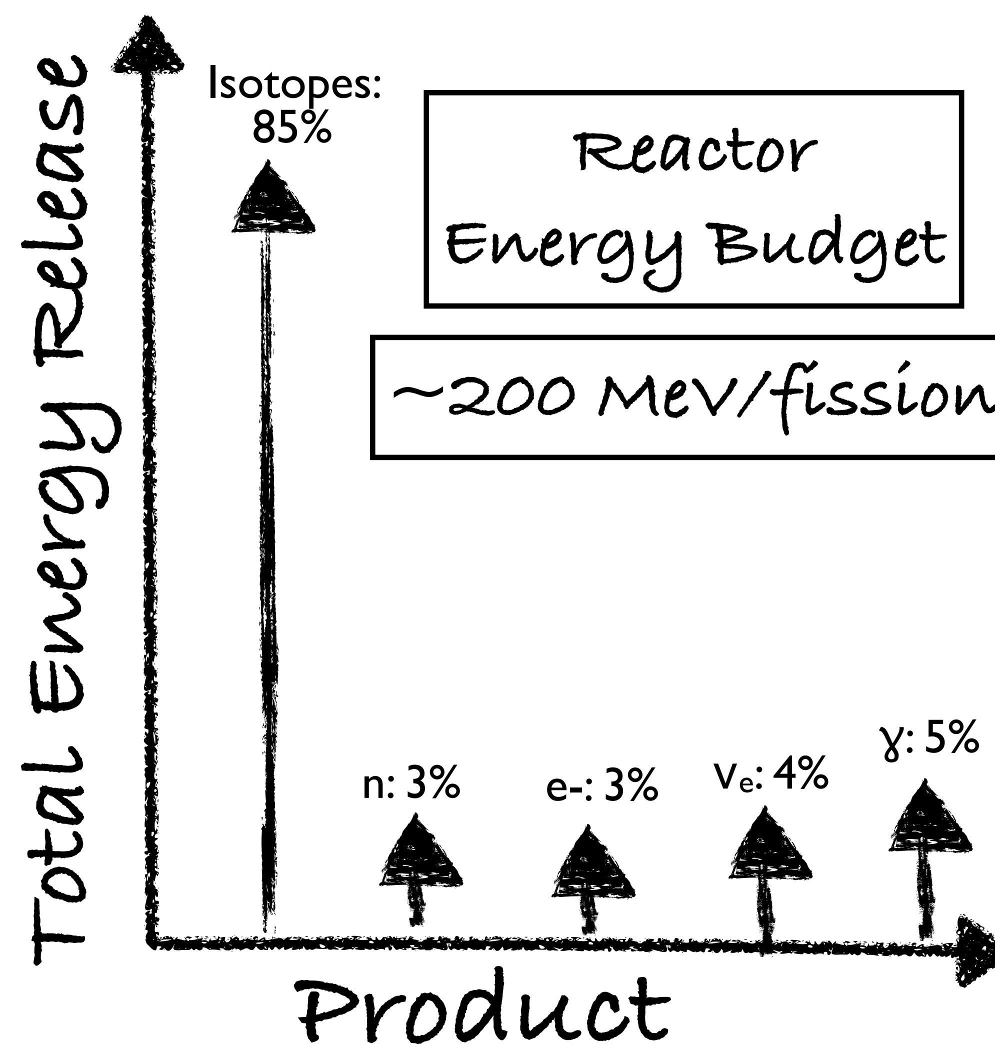


Reactors: Fission Byproducts

- Heavy nuclei fission to make lighter nuclei plus extra energy… **AND** neutrons, neutrinos, betas, and gammas!

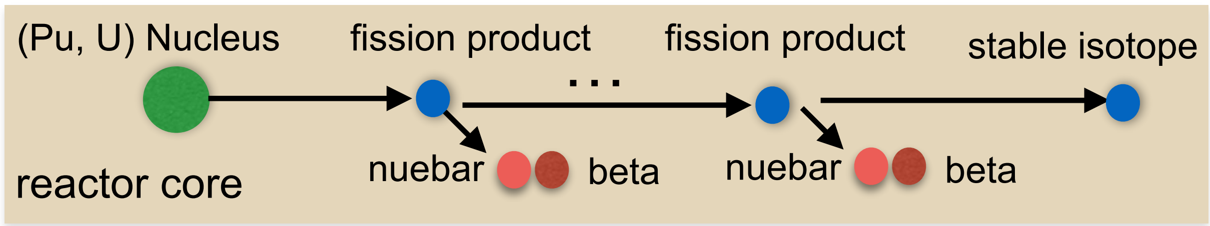


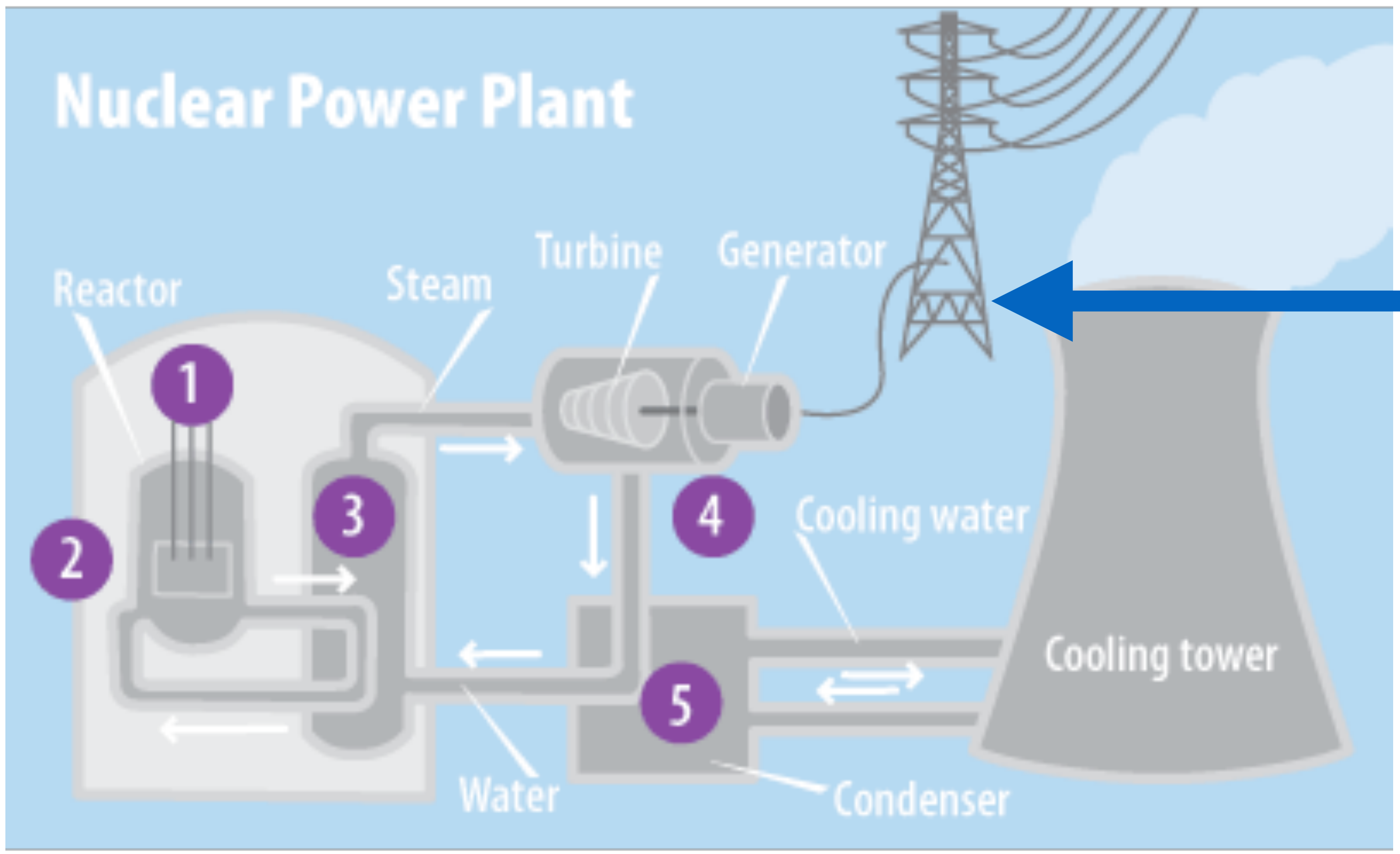


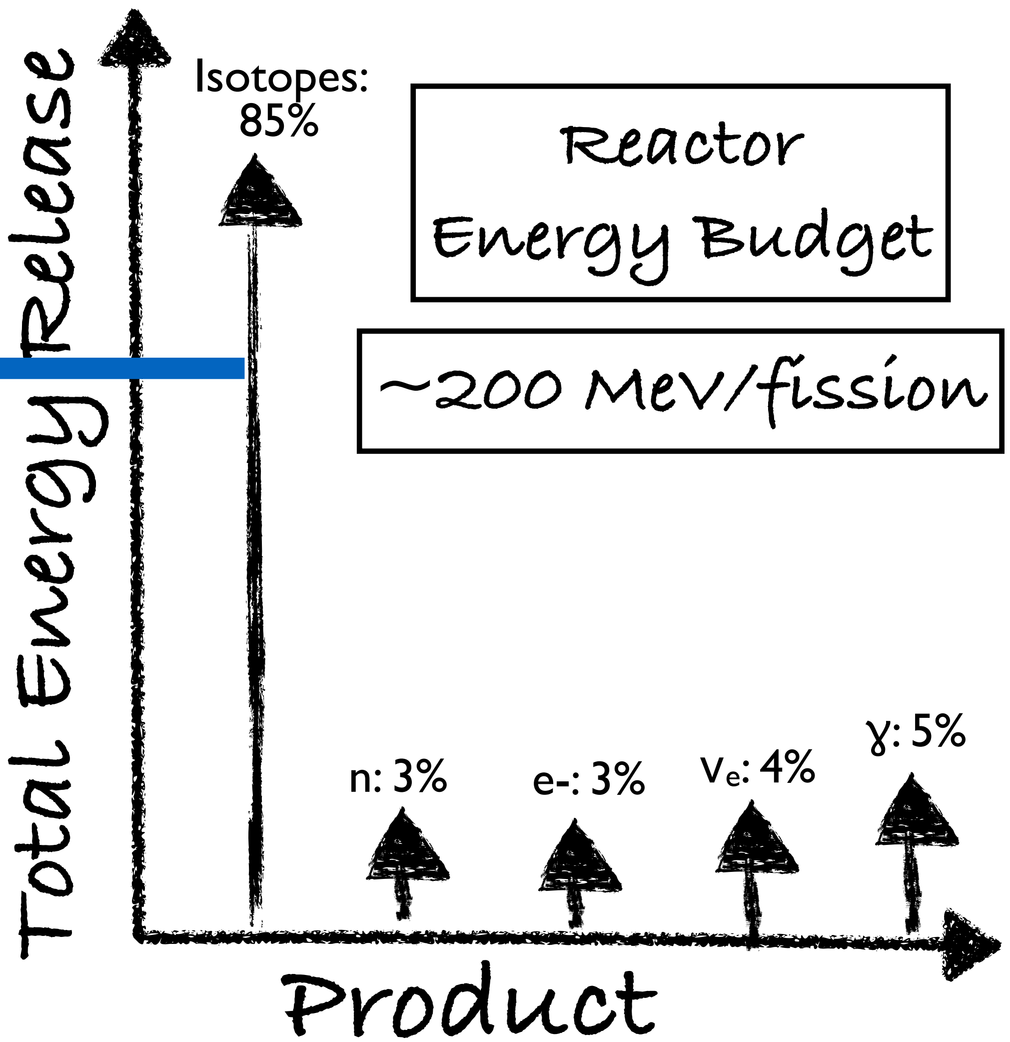


Reactors: Energy Production

- Heavy nuclei fission to make lighter nuclei plus extra energy… **AND** neutrons, neutrinos, betas, and gammas!

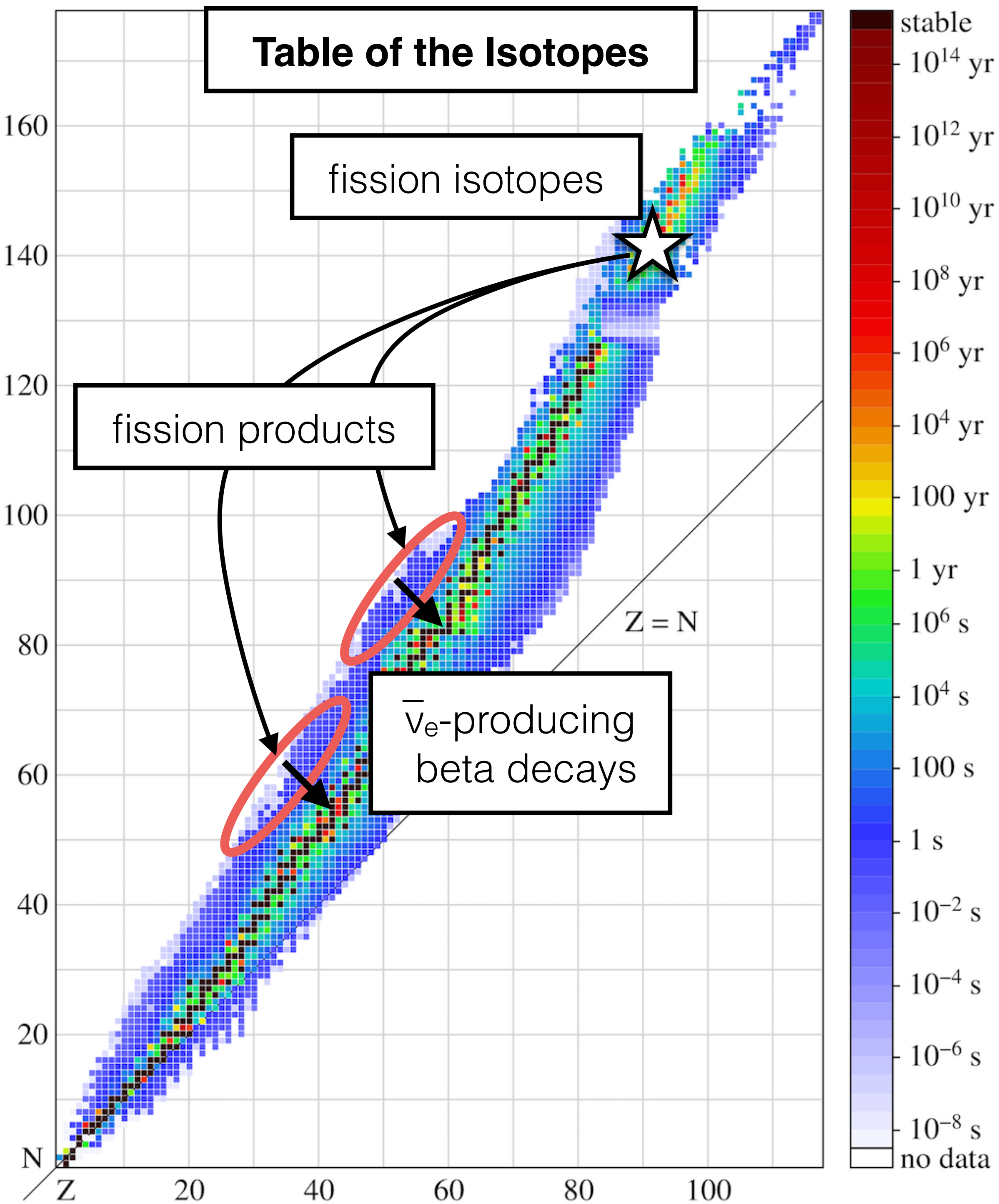


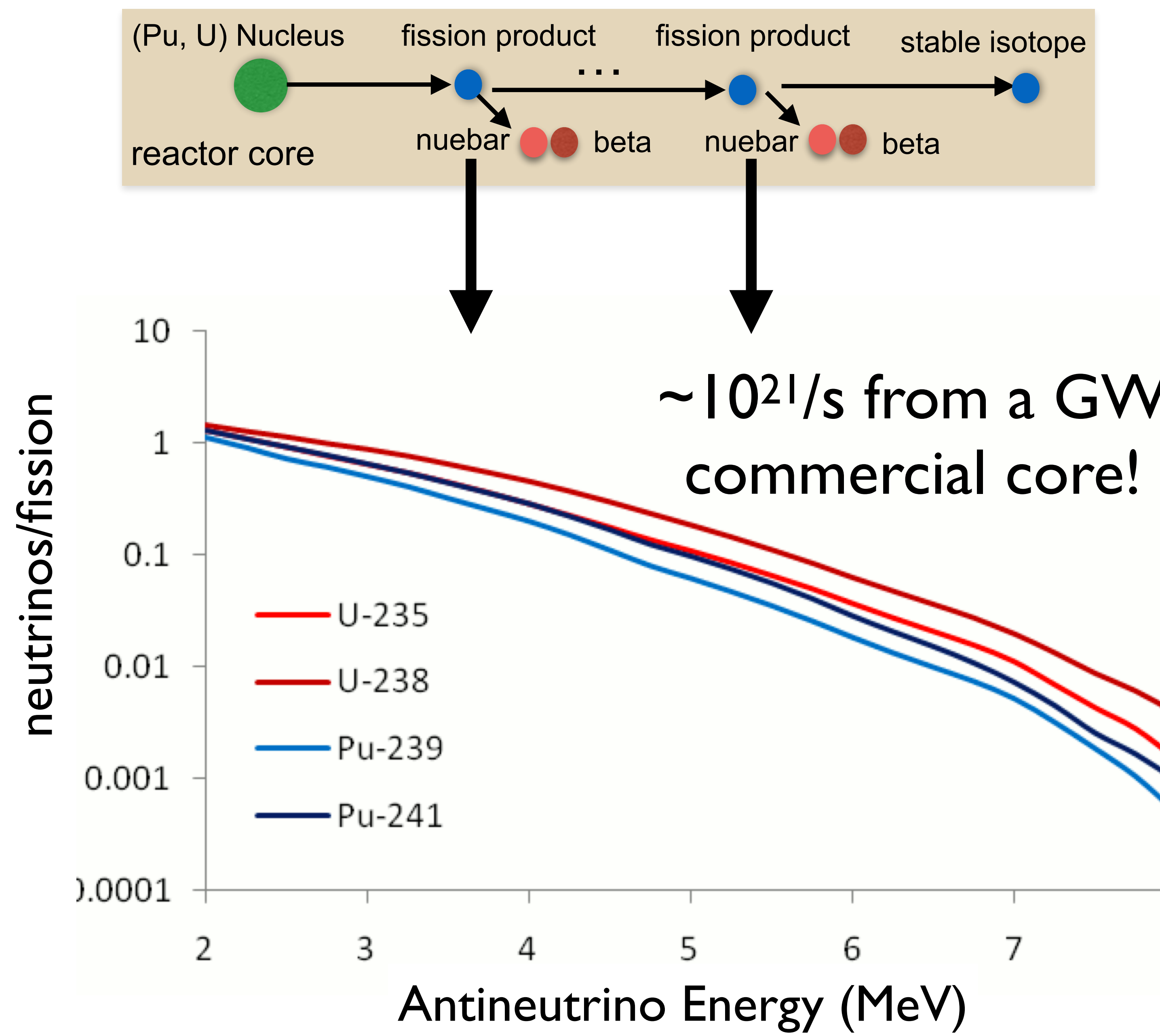




Reactors: Neutrino Production

- Heavy nuclei fission to make lighter nuclei plus extra energy… **AND** neutrons, neutrinos, betas, and gammas!
  - Different fission isotopes yield different products, different fluxes of neutrinos.

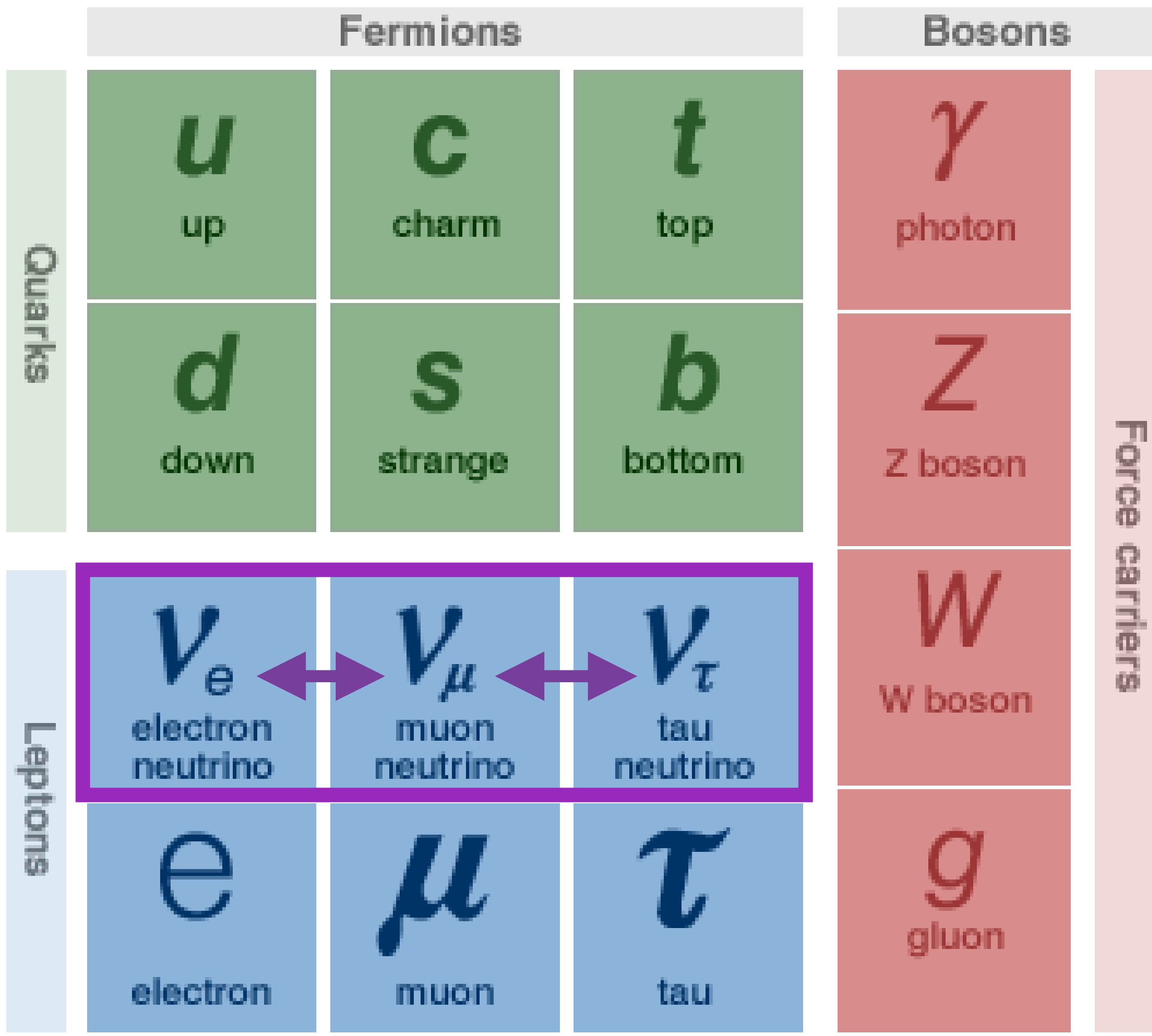




Why Are Reactor Neutrinos Special?

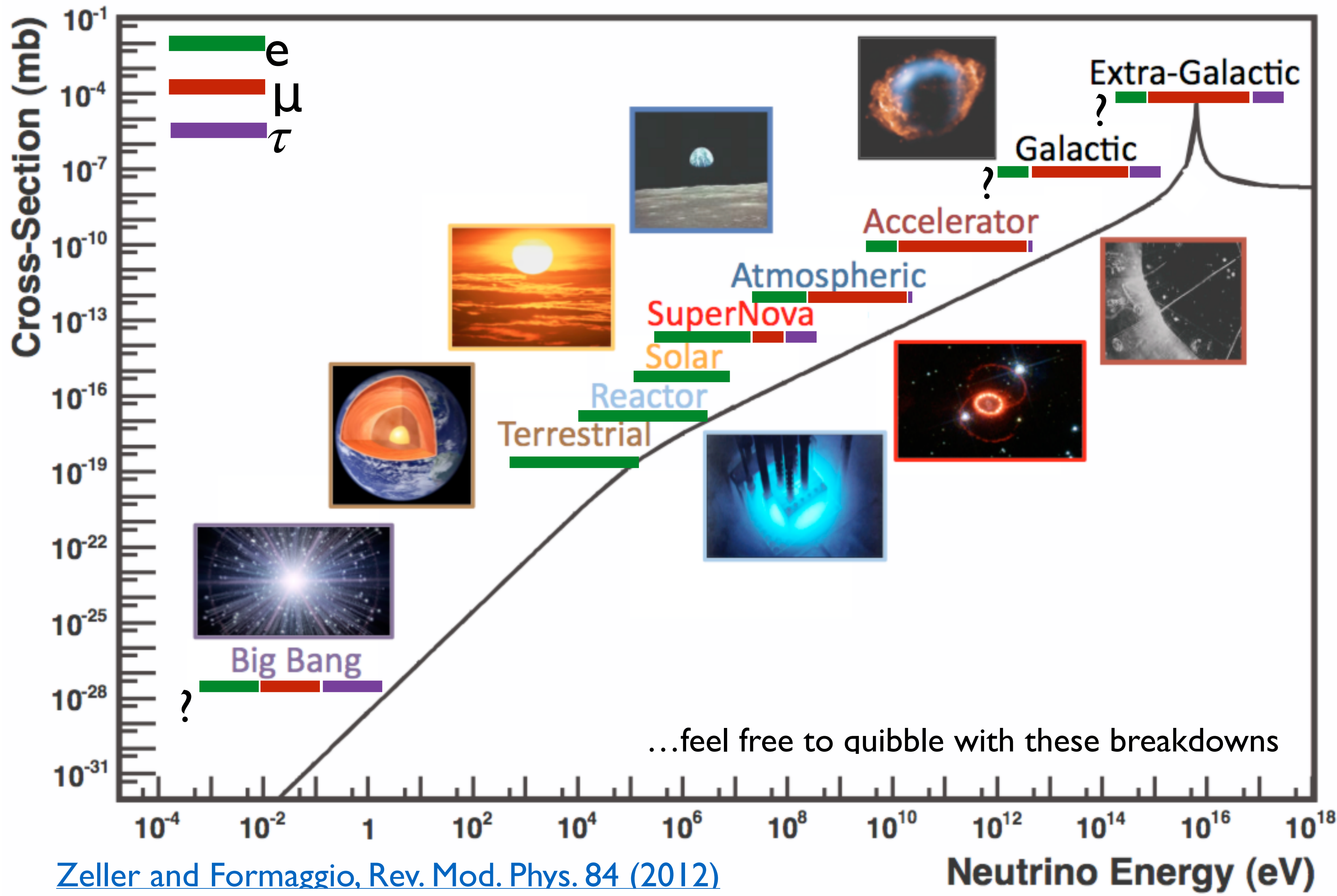
Neutrinos In One Slide

- 2nd-most-common fundamental particle in universe
  - Most were created a second after the Big Bang (before the CMB existed!)
- Only interact weakly
  - No color, and no charge
- Practically no rest mass
  - << eV, most likely.
- Come in 3 flavors that mix
  - Make a mu-flavor; detect e-flavor: it's called 'oscillation'
- Made where weak interactions (like beta radioactive decays) are occurring
  - Sun, supernovae, accelerator, reactors, [bananas](), etc. etc.



How Are Reactor Neutrinos Special?

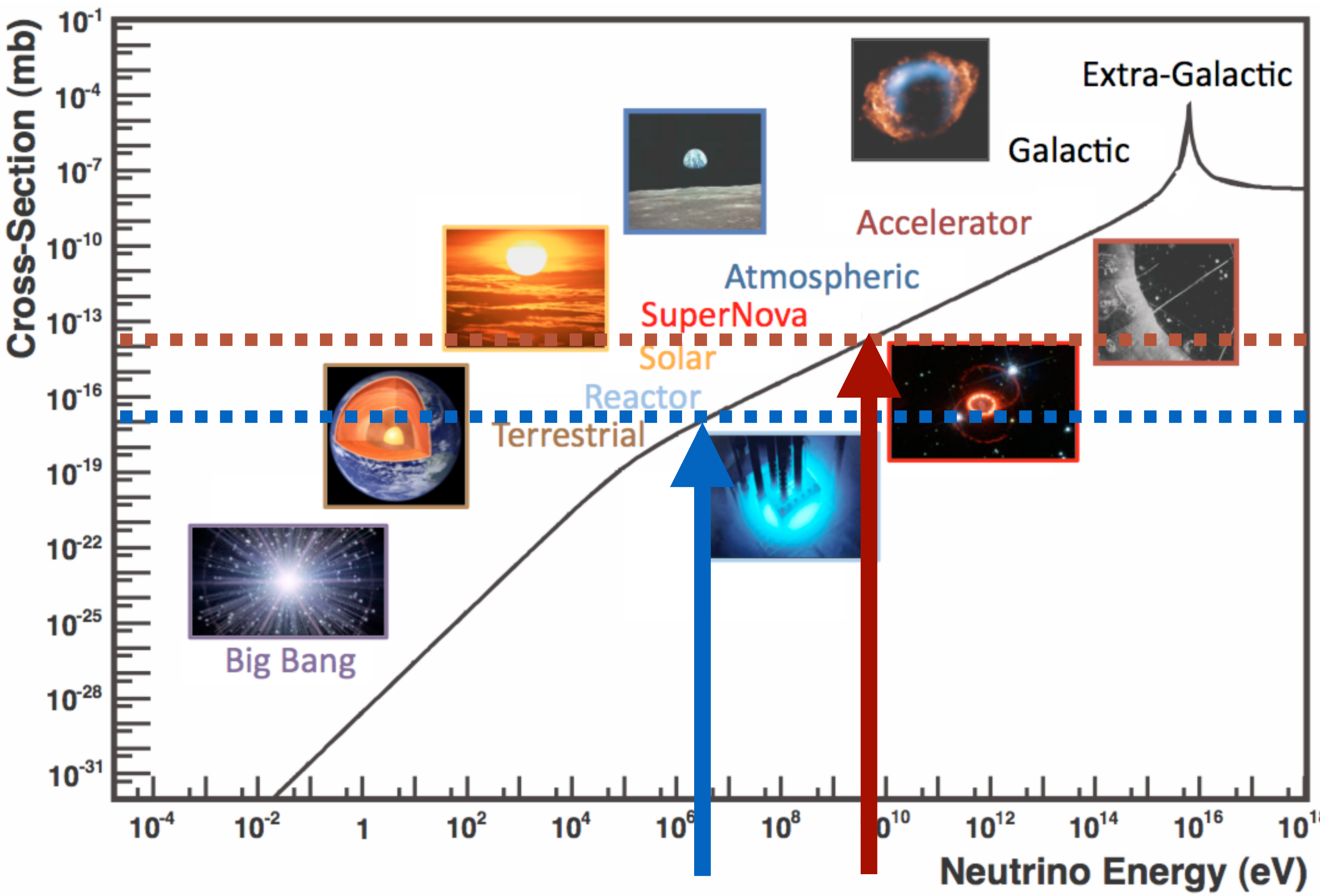
- Energy: MeV-scale, rather than GeV-scale
- Flavor: Pure electron flavor, rather than (mostly) muon flavor
- Operations: terrestrial source operated (paid for) by others
- Attributes belie synergies with accelerator neutrino efforts



Zeller and Formaggio, Rev. Mod. Phys. 84 (2012)

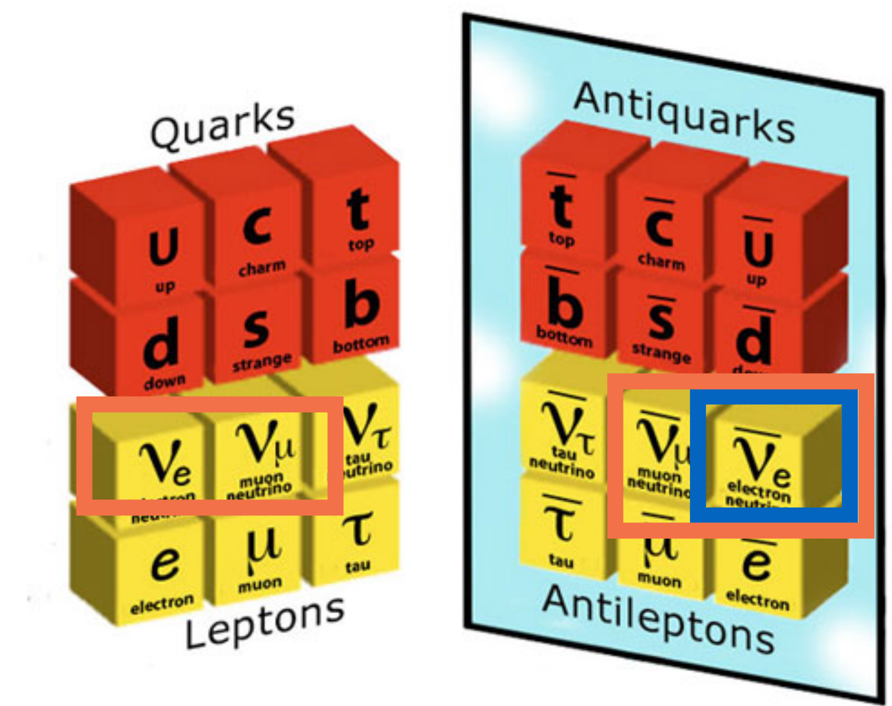
Reactor Nus, Fermilab Nus

- 'I know Fermilab's νs; what's different about reactor νs?'



Energy: 0-10 MeV, not 0-10 GeV

Interaction Probability: quite a bit lower



Intensity: In 1 minute, a 1GW core makes more ν than all NUMI+BNB ν produced in 2018

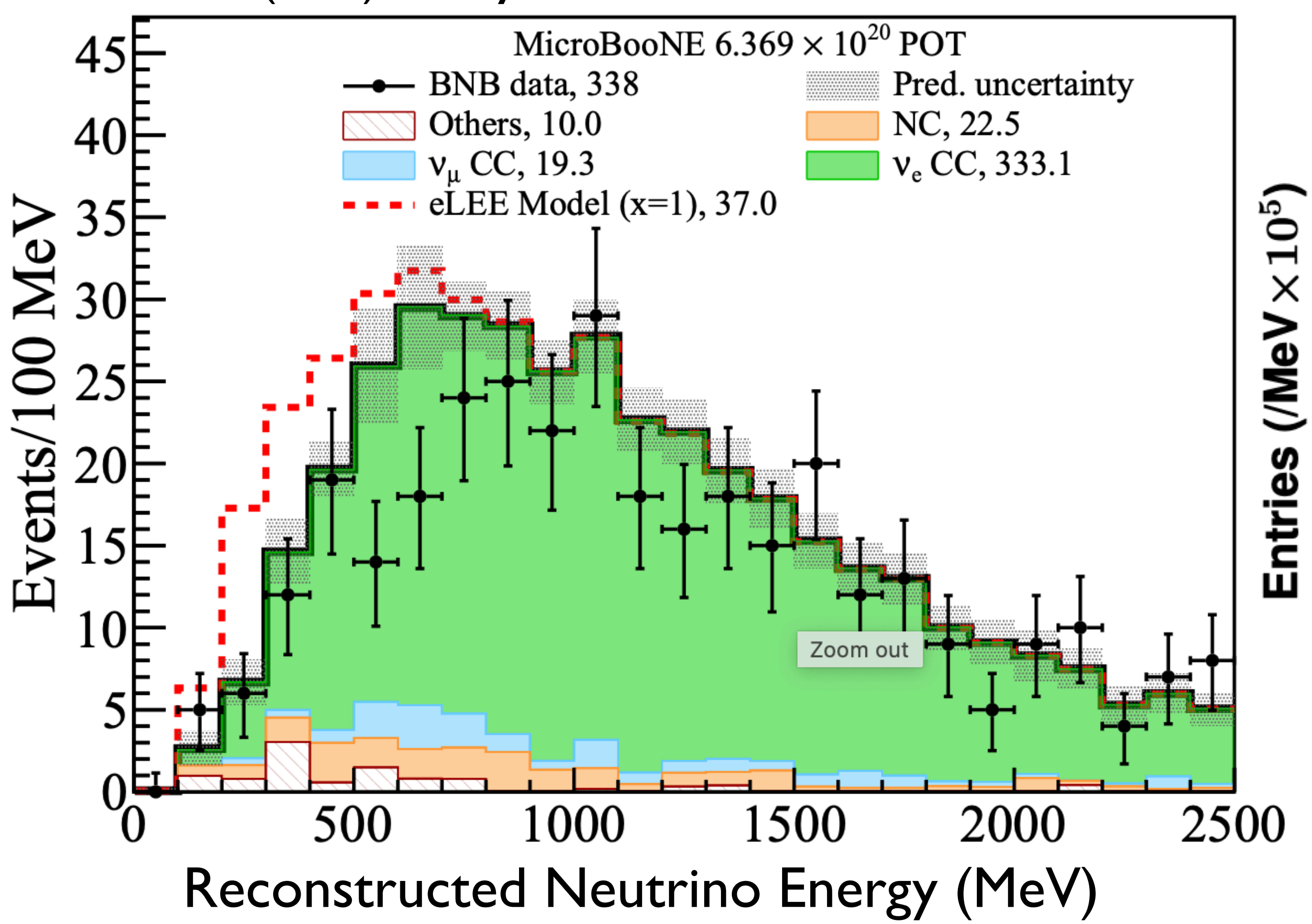
(yes, both DAR and DIF ν)

Flavor: $\bar{\nu}_e$ only, not ν_e, ν_μ, $\bar{\nu}_e$, $\bar{\nu}_\mu$

Electron Flavor Tastes So Good

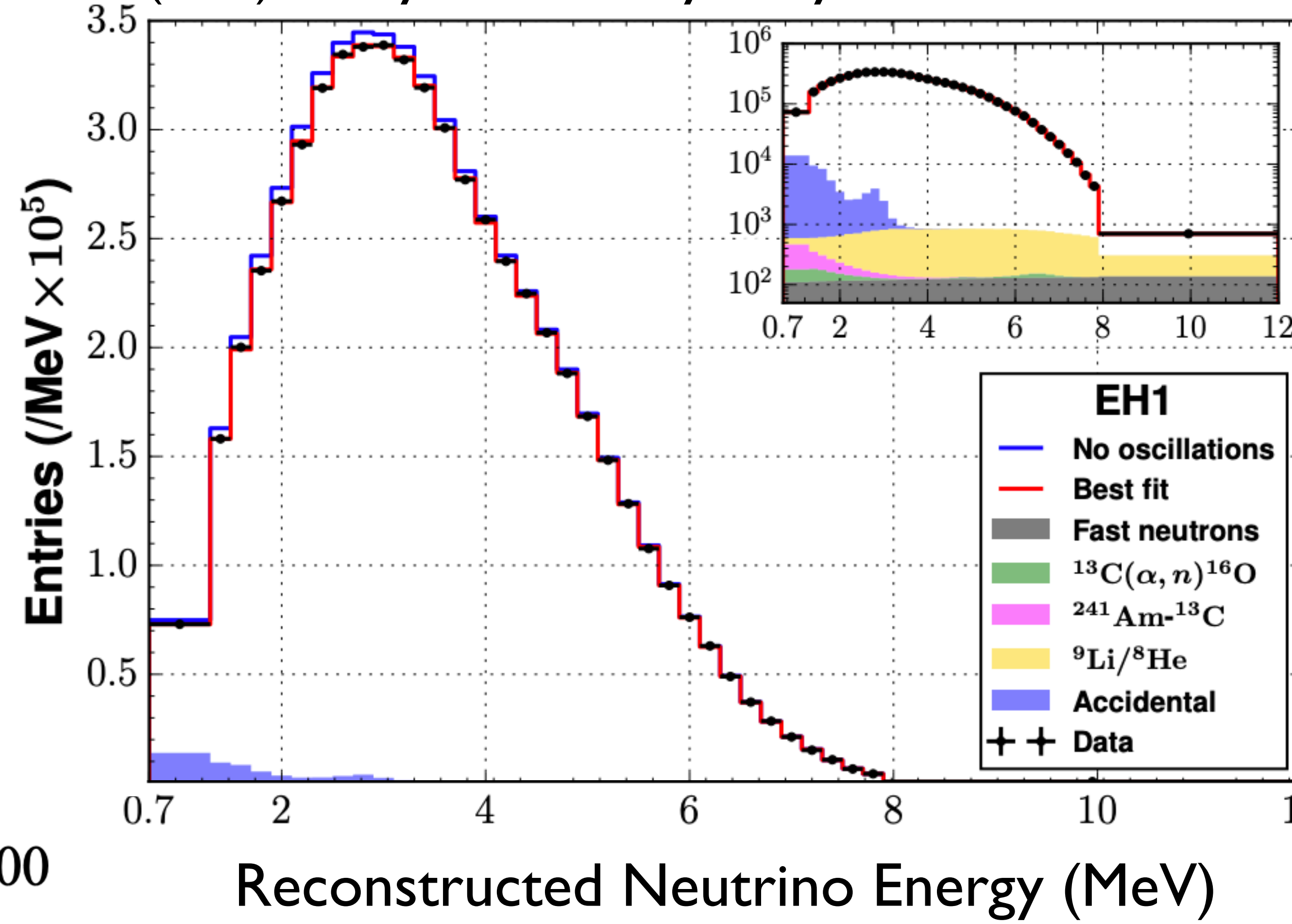
- Reactor neutrinos are the purest, highest-intensity source of electron-flavor neutrinos that we have to work with!
  - This is important to consider if you want to closely study the flavor-changing behavior of all neutrino types

O(100) ton-years at Fermilab: 350 ν_e



[MicroBooNE, hep-ex[2110.14054]](https://arxiv.org/abs/2110.14054)

O(100) ton-years at Daya Bay reactors: 2.5M ν_e



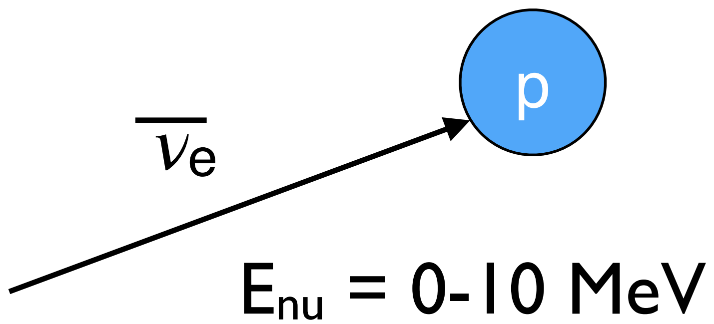
Daya Bay, PRD 95 (2017)

How Do Reactor Neutrino Detector Work?

How Do We Taste Reactor Neutrinos?

- Most reactor experiments look for **inverse beta decays** inside their antineutrino detectors

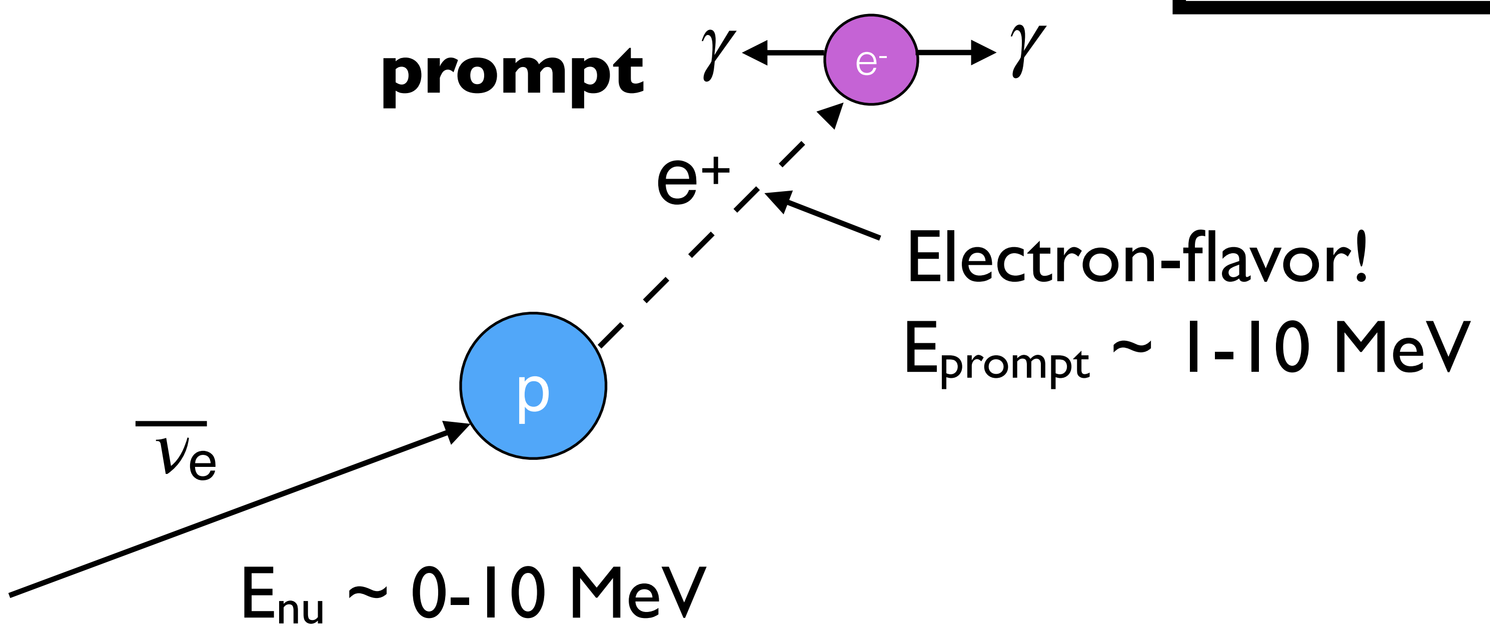
$$\boxed{\text{IBD: } \overline{\nu}_e + p \rightarrow \beta^+ + n}$$



How Do We Taste Reactor Neutrinos?

- Most reactor experiments look for **inverse beta decays** inside their antineutrino detectors

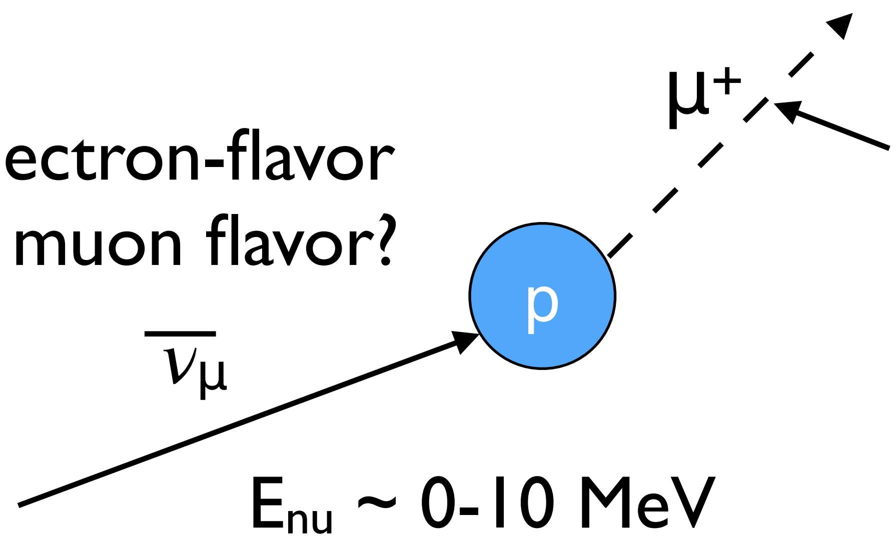
IBD: $\overline{\nu}_e + p \rightarrow \beta^+ + n$



How Do We Taste Reactor Neutrinos?

- Most reactor experiments look for **inverse beta decays** inside their antineutrino detectors

What if our electron-flavor oscillated to a muon flavor?

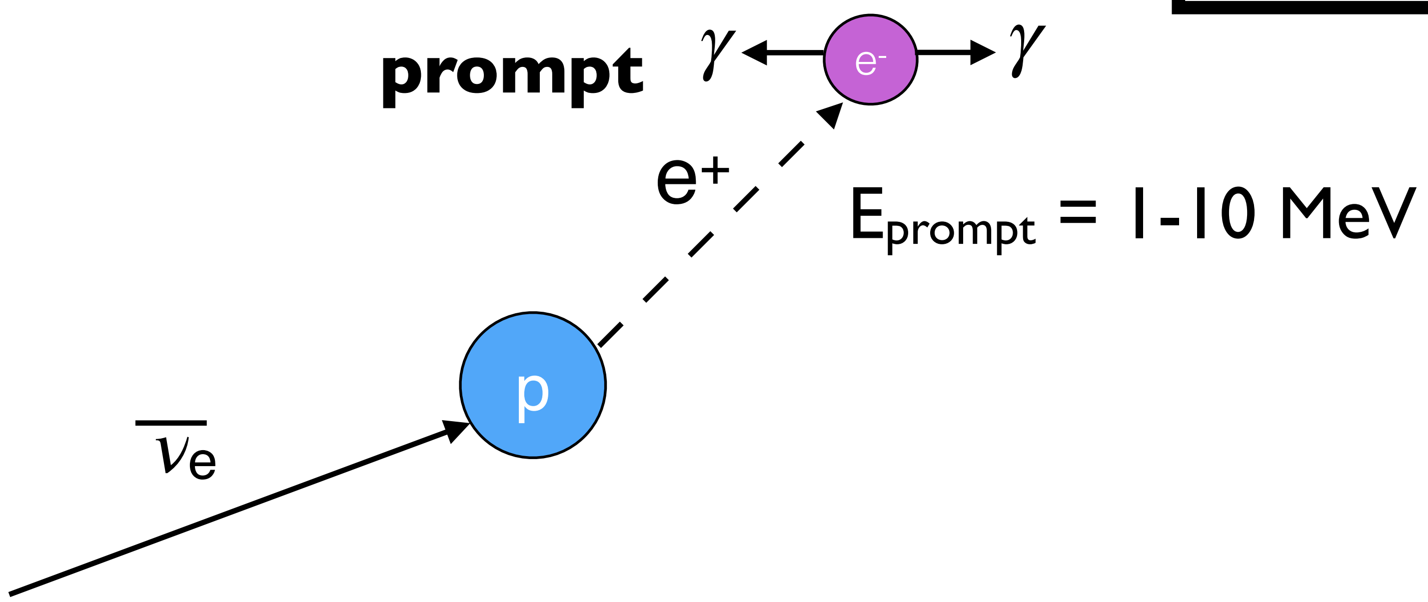


Should we worry about this happening?

Reactor IBD: One Flavor Only

- Most reactor experiments look for **inverse beta decays** inside their antineutrino detectors

$$\text{IBD: } \overline{\nu}_e + p \rightarrow \beta^+ + n$$

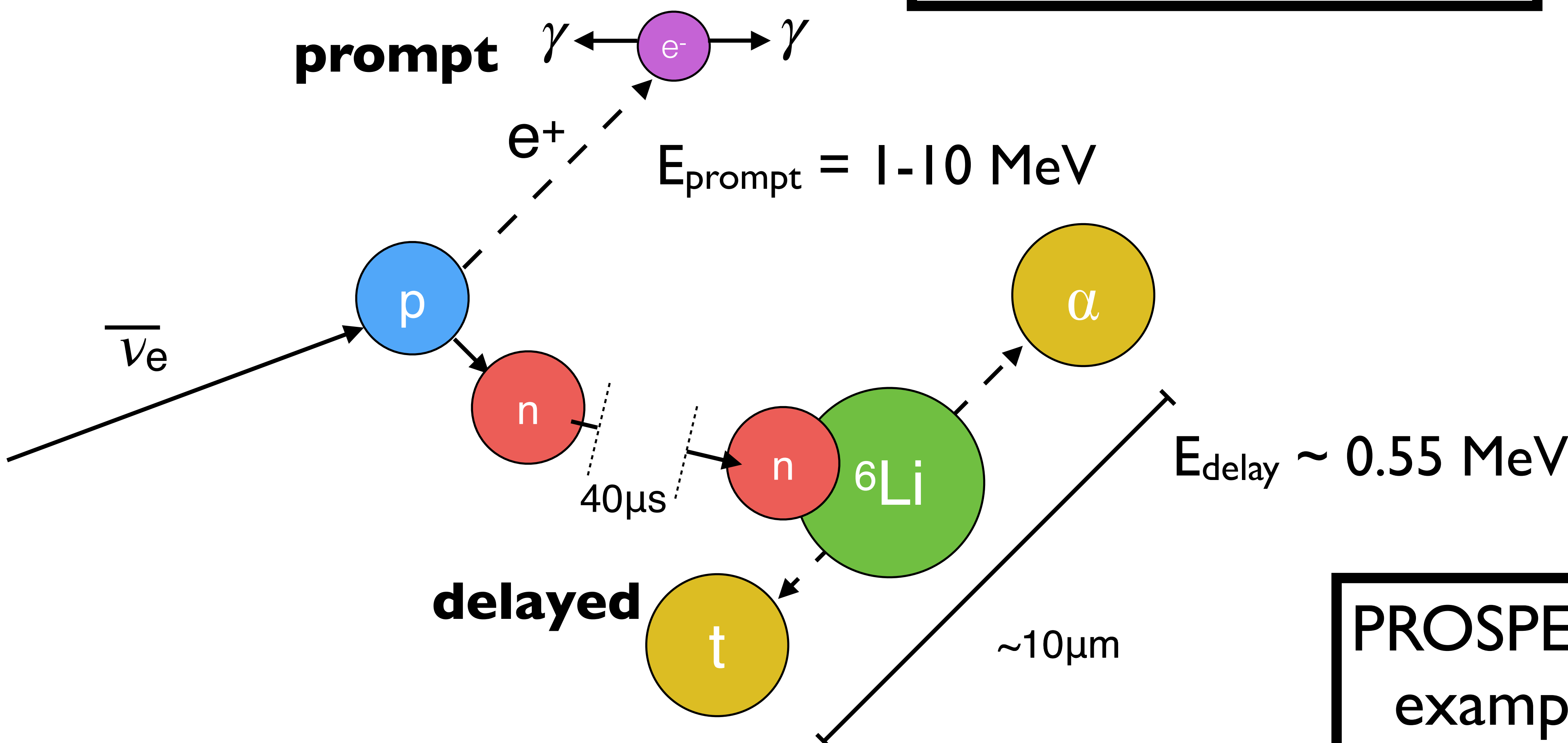


- We can <u>ONLY</u> taste electron flavor at MeV-scale energies.
- Thus, neutrino flavor oscillations will be reflected at reactor experiments as a deficit in IBD interaction rates.

Reactor IBD: A Beautiful Neutron

- Most reactor experiments look for **inverse beta decays** inside their antineutrino detectors

IBD: $\overline{\nu}_e + p \rightarrow \beta^{+} + n$

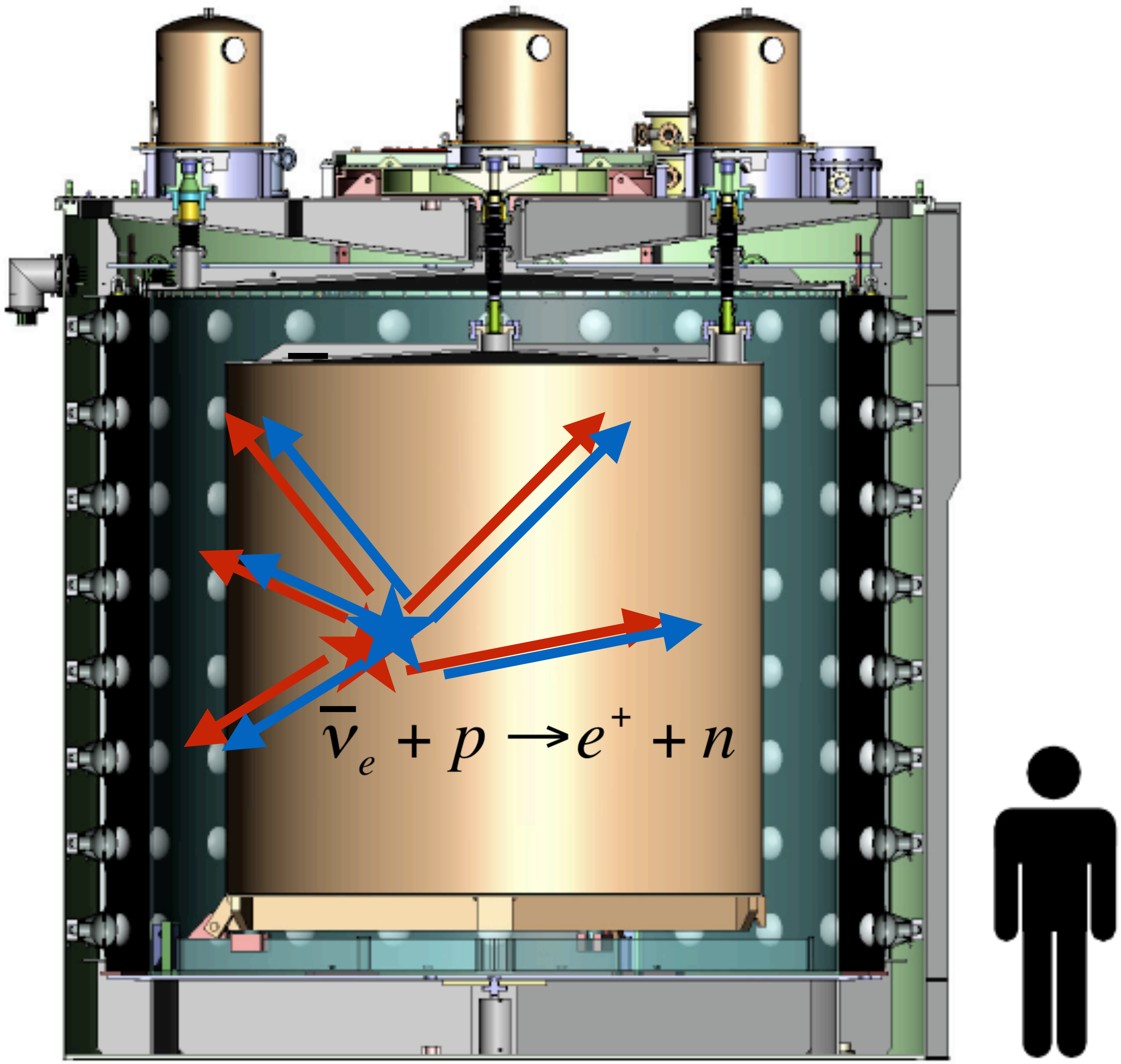


PROSPECT example

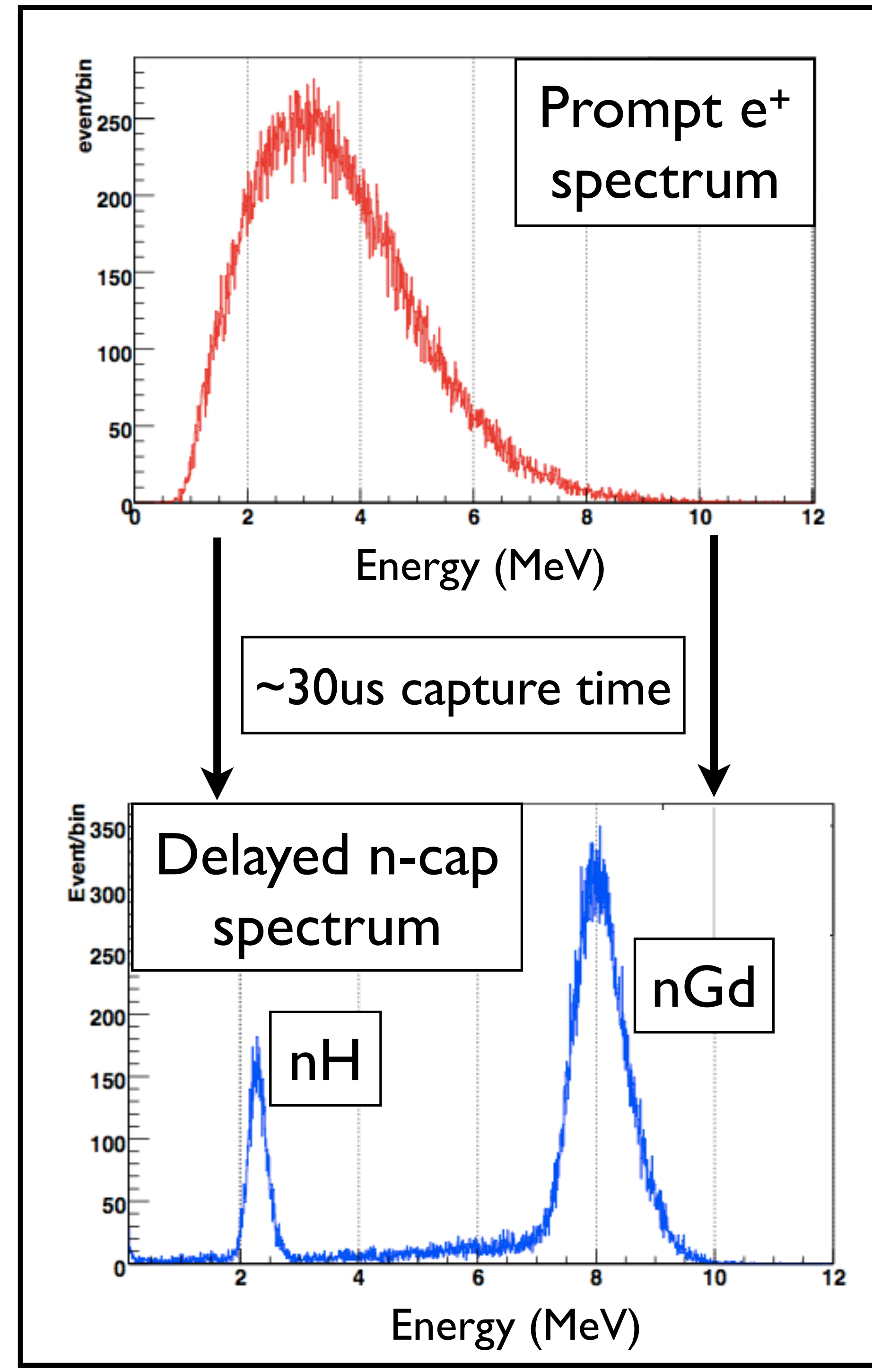
- Time-correlated IBD neutron signal enables major reduction in non-neutrino backgrounds.

Reactor IBD Detection Technology

- Detect IBD products with liquid or solid scintillator, PMTs



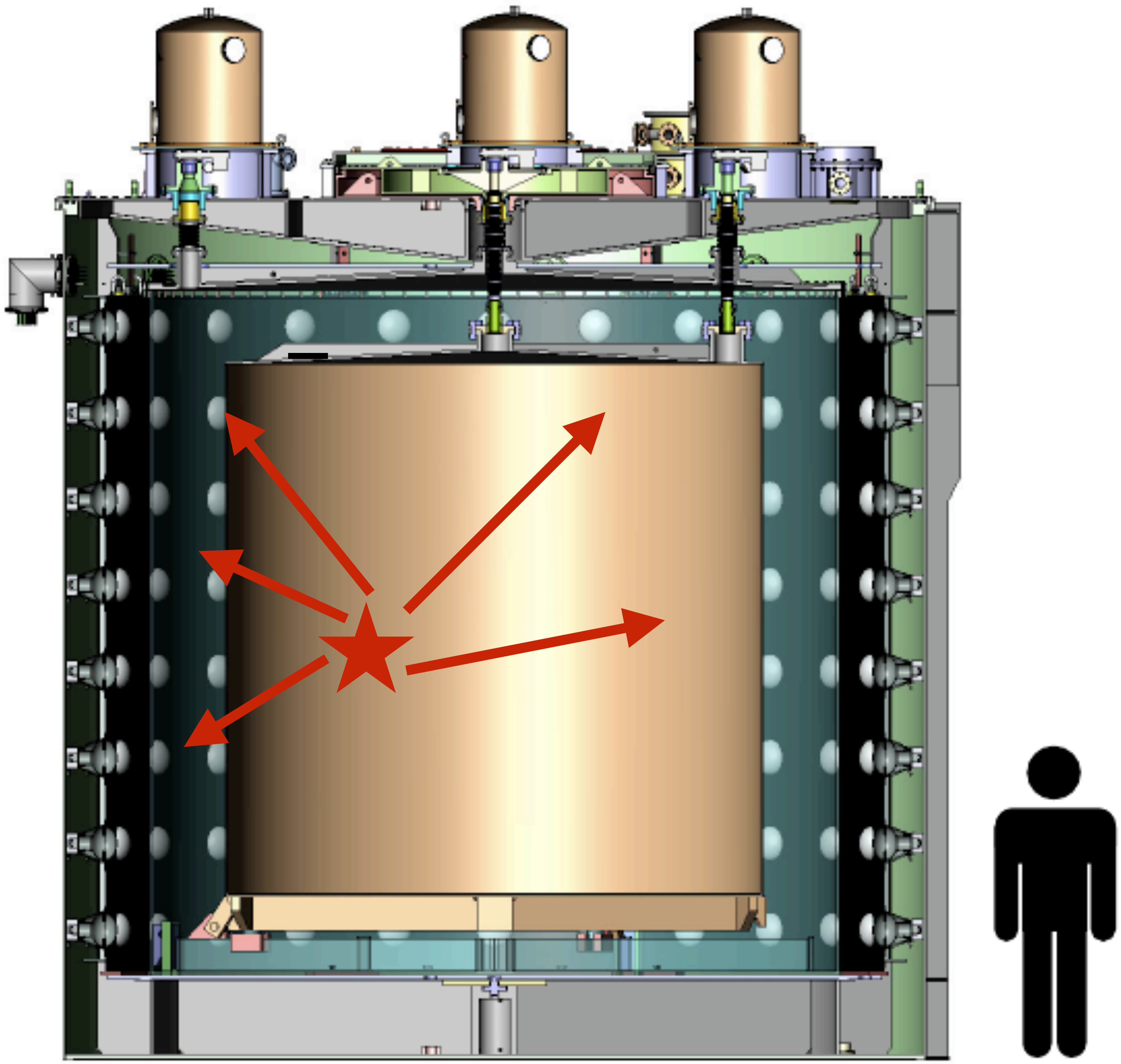
Example: Daya Bay Detector



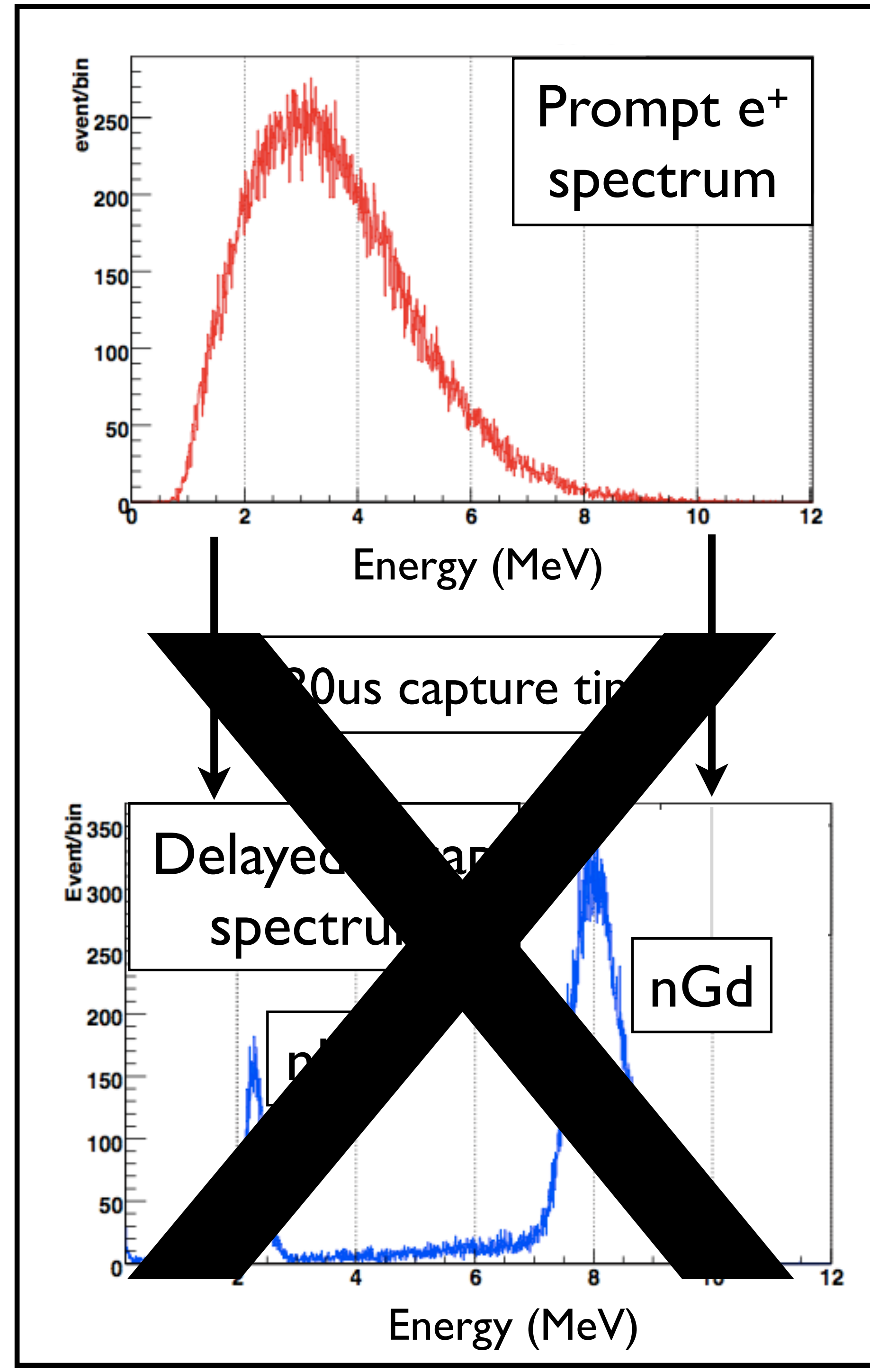
Daya Bay Monte Carlo Data

Reactor IBD Detection Technology

- Gammas from trace radio-impurities: NOT an IBD!



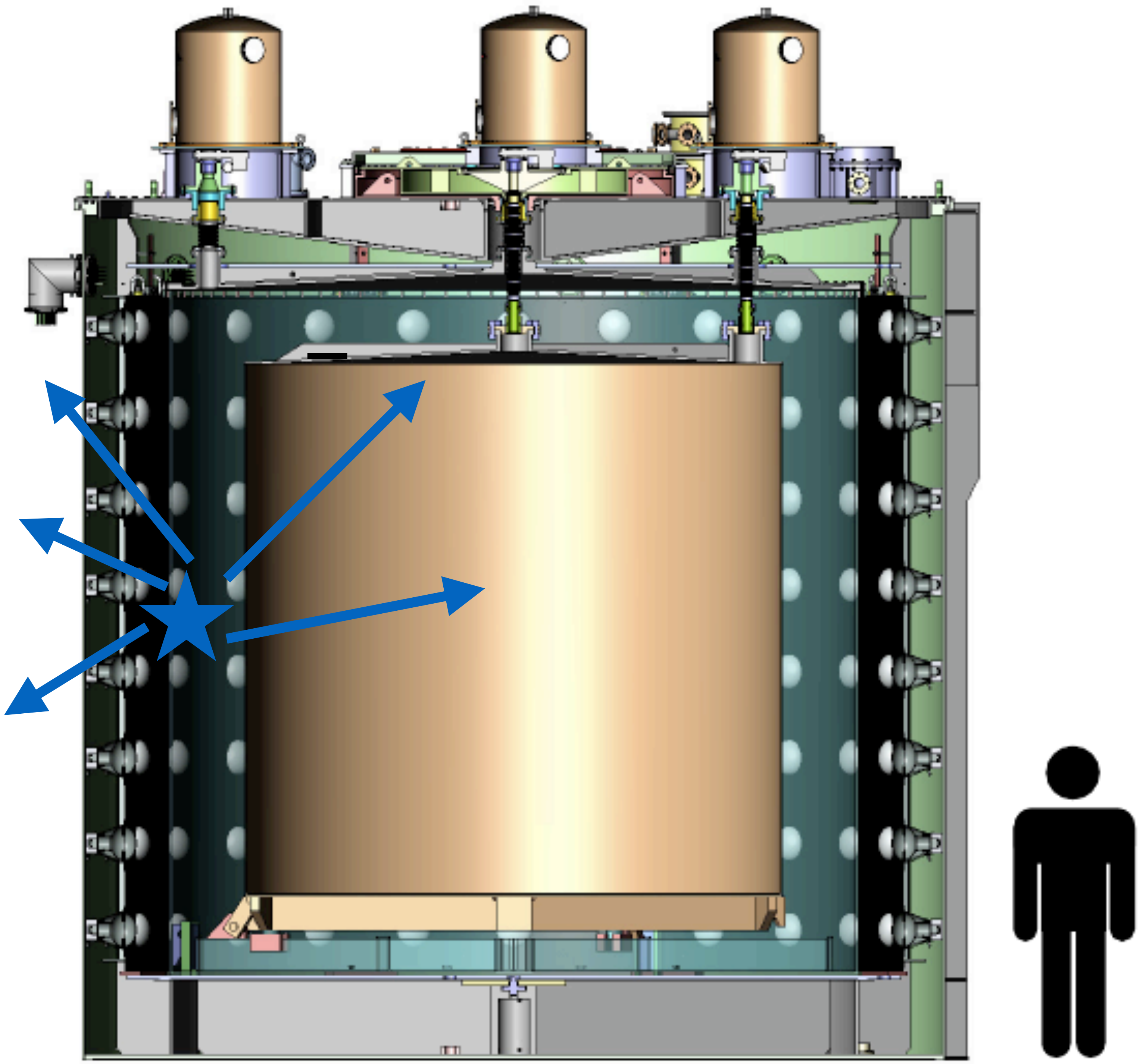
Example: Daya Bay Detector



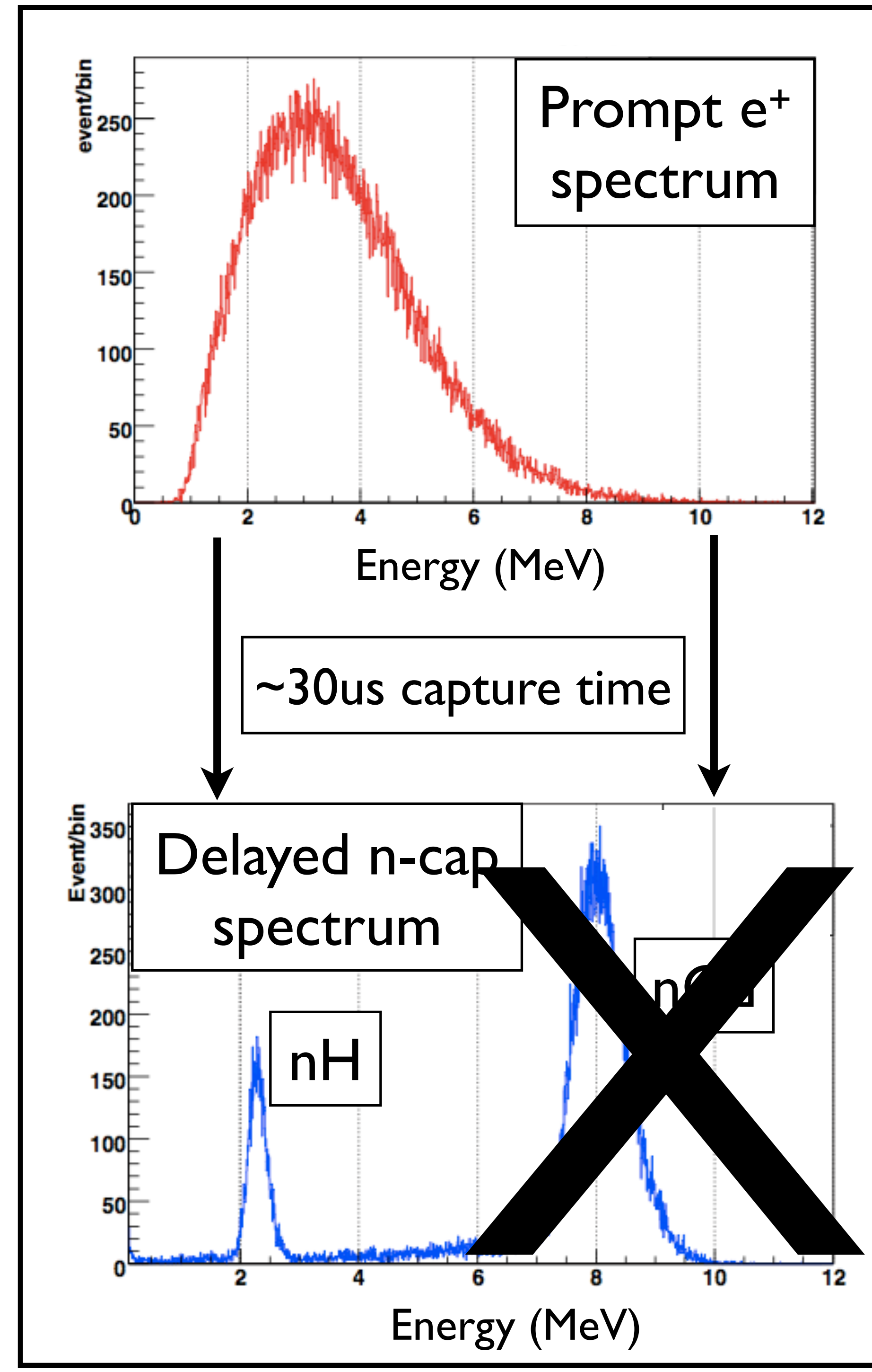
Daya Bay Monte Carlo Data

Reactor IBD Detection Technology

- External neutron created by a cosmic muon: NOT an IBD!
  - EVEN if coincident with a prompt-ish thing!



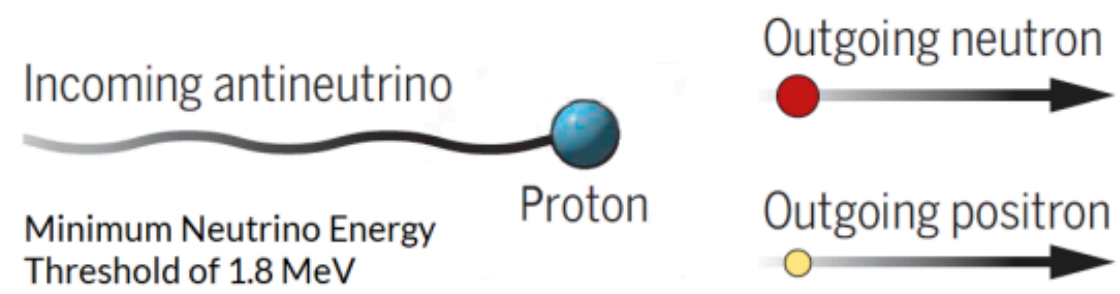
Example: Daya Bay Detector



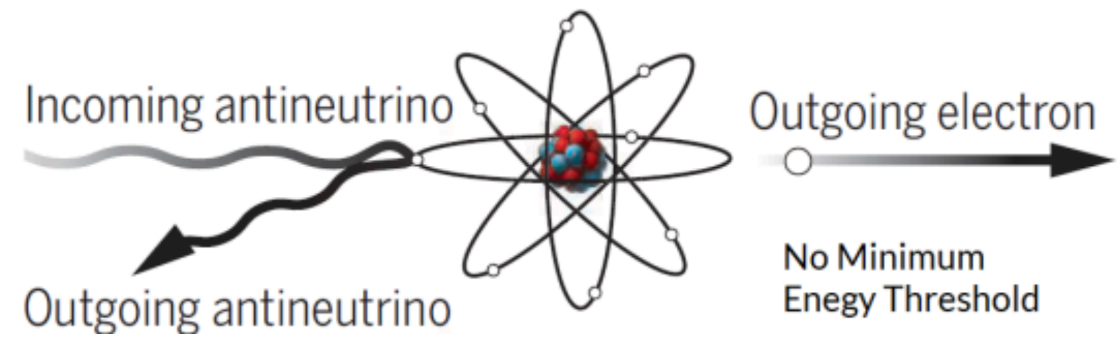
Daya Bay Monte Carlo Data

Other Interaction Methods

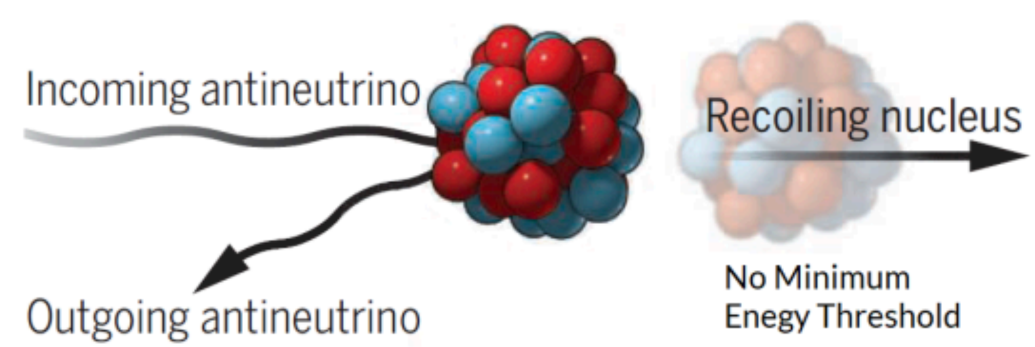
- Inverse beta decay
  - Product: positron AND neutron



- Neutrino-electron scattering
  - Product: a SINGLE electron



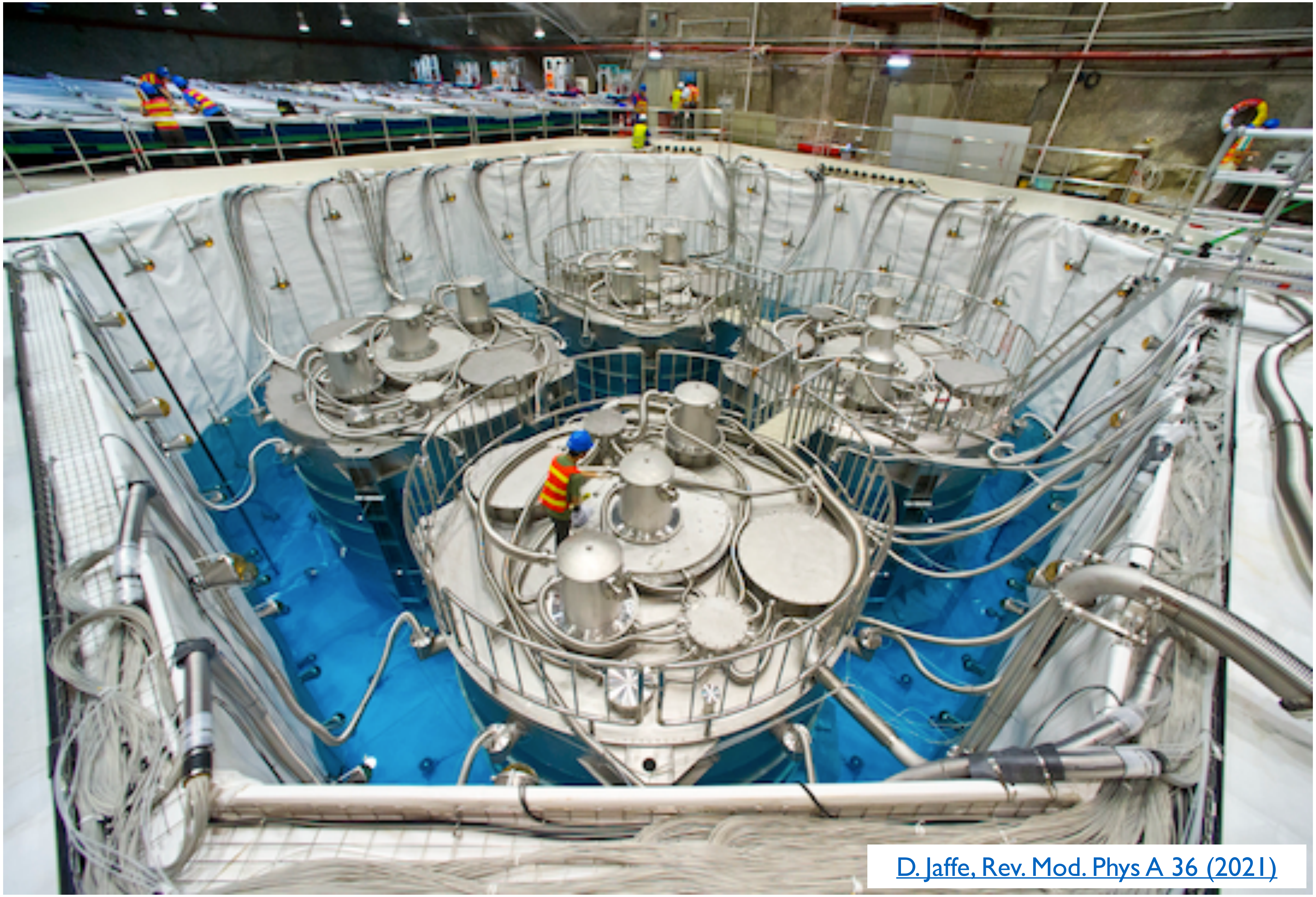
- Coherent neutrino-nucleus scattering
  - Product: a SINGLE recoiling nucleus



[J. Link, "Scattering Neutrinos Caught in the Act"]

Reactor IBD Detector Pix

- Daya Bay (8x20 ton IBD target): 5M IBDs seen in ~8 years



[D. Jaffe, Rev. Mod. Phys A 36 (2021)](#)

Reactor IBD Detector Pix

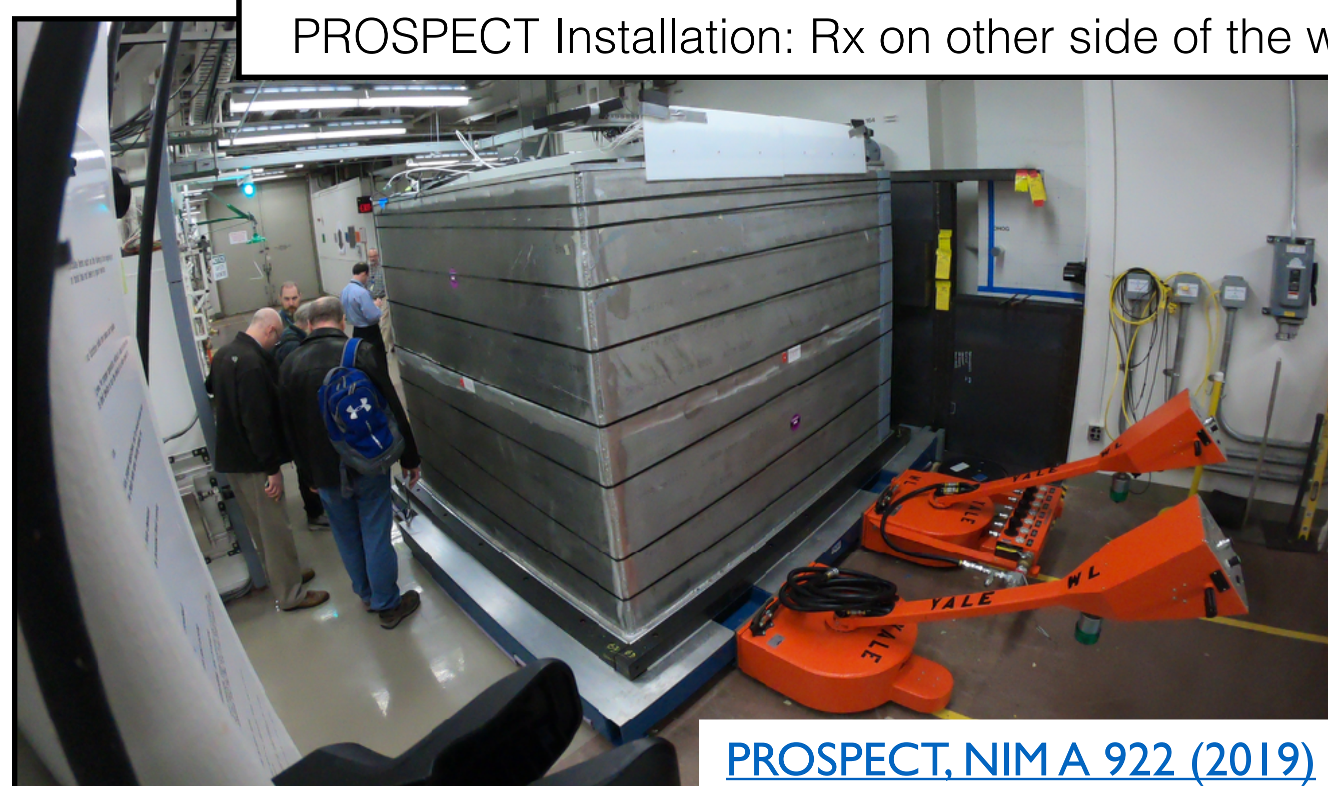
- PROSPECT (1x4 ton IBD target): A different scale altogether!

PROSPECT Assembly: note detector segmentation!

PROSPECT Assembly: adding top row of segments

PROSPECT Shipping: arrival at ORNL

PROSPECT Installation: Rx on other side of the wall!

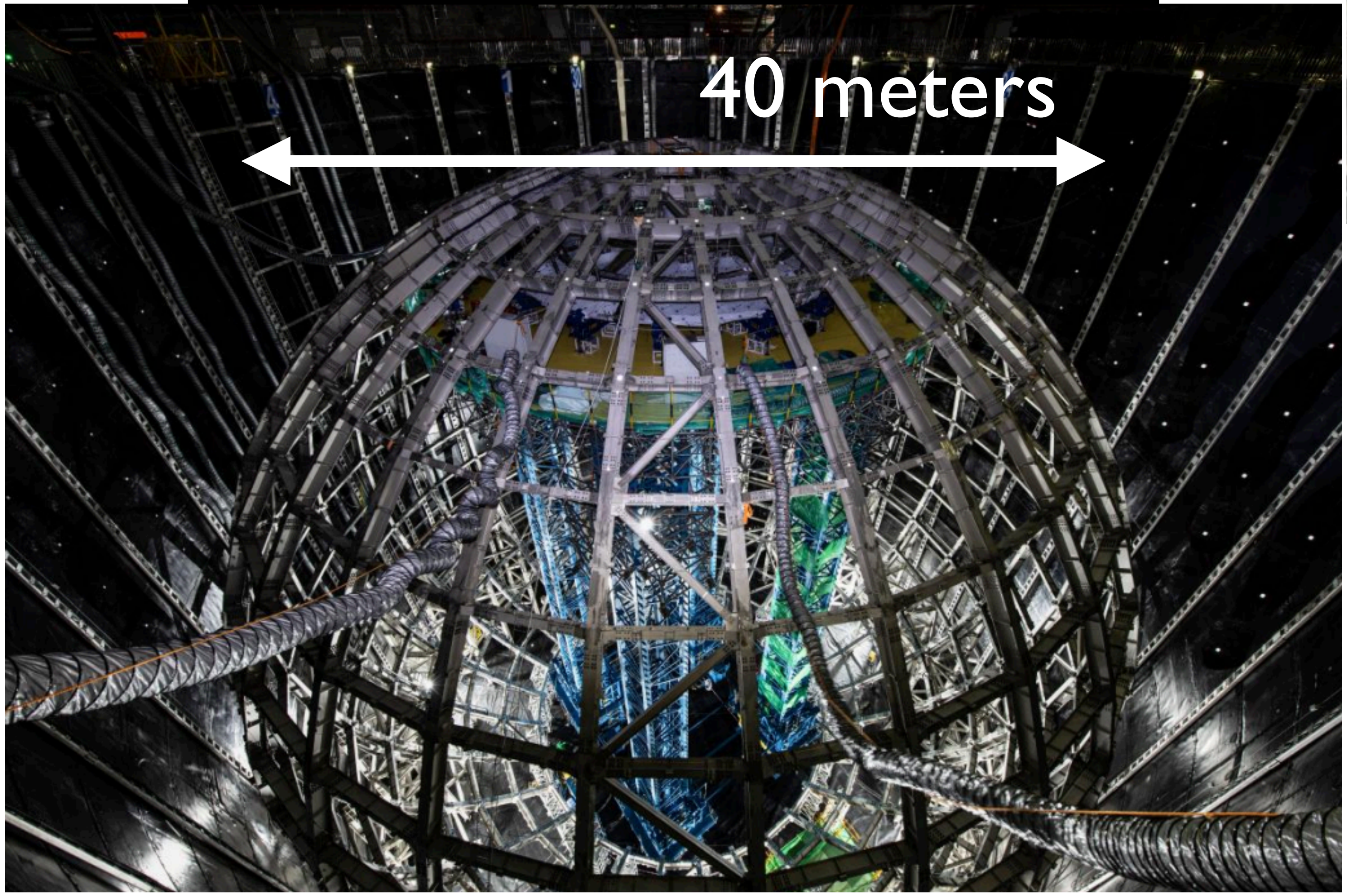


PROSPECT, NIM A 922 (2019)

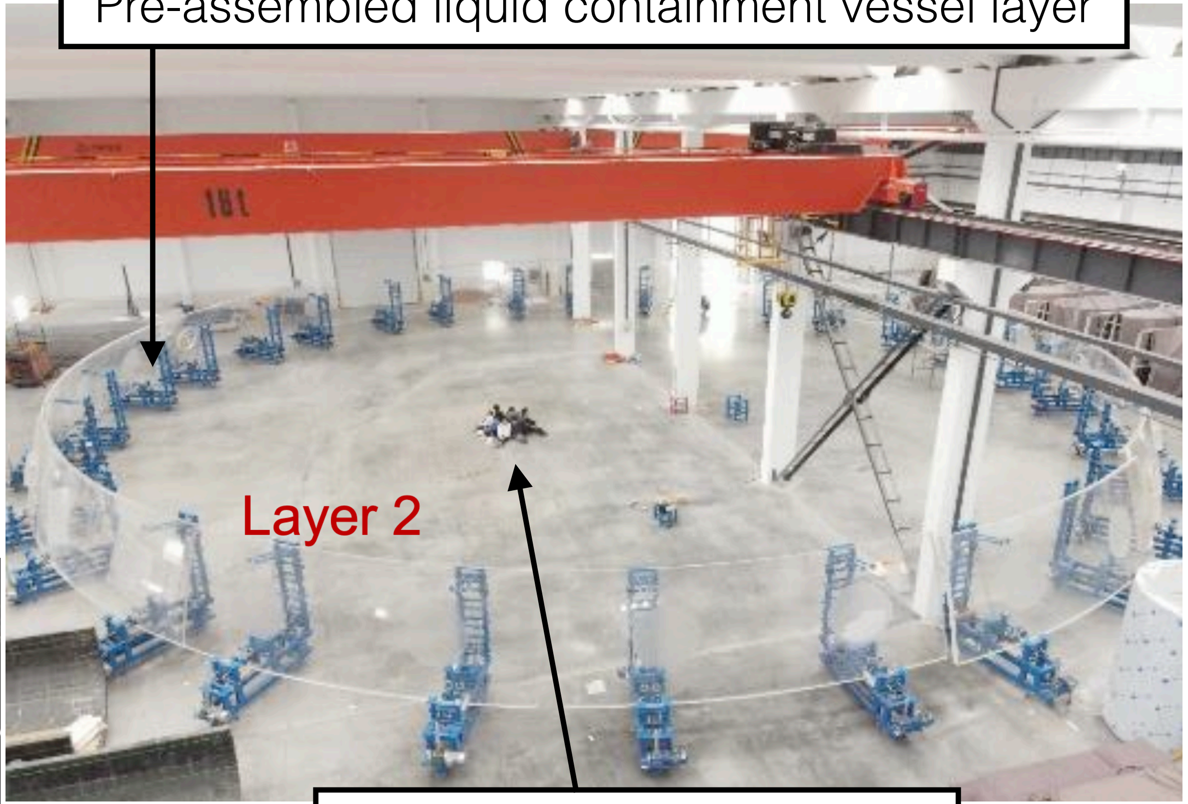
Reactor IBD Detector Pix

- JUNO (1x20000 ton target): A different scale altogether!
  - Super-Kamiokande in scale
  - 45,000 vacuum PMTs: 4x SuperK!

Liquid containment vessel support system



Pre-assembled liquid containment vessel layer



Grad students hard at work!

[JUNO, Prog. Nucl. Part. Phys. 123 (2022)](#)

What Neutrino Physics
Do Reactor Experiments Do?

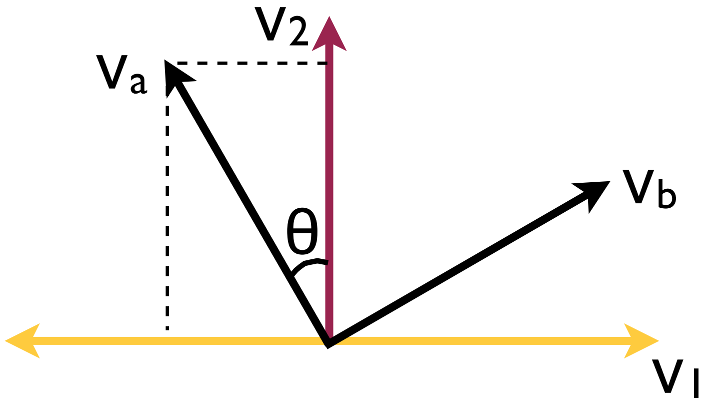
A: Measure Neutrino Oscillations.*

*<u>MANY</u> other things, too many to describe here…
plz check https://arxiv.org/abs/2203.07214

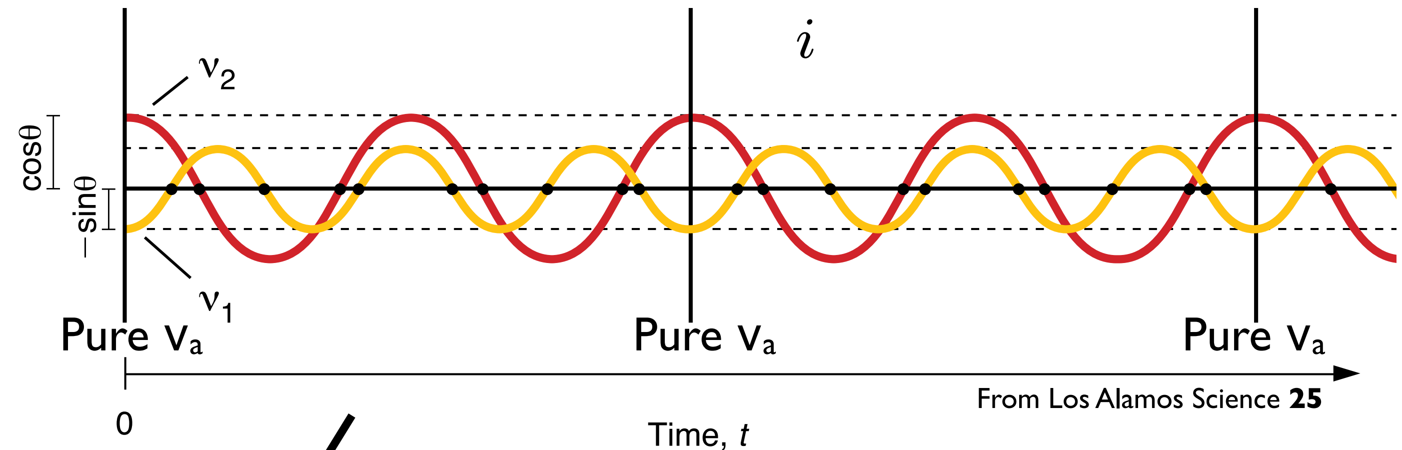
Neutrino Flavor Oscillation in One Slide

- Neutrinos can transform from one flavor to another
  - A quantum mechanical outcome of differing neutrino flavor and mass states

$$\begin{pmatrix} \nu_b \\ \nu_a \end{pmatrix} = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \end{pmatrix}$$



$$\Psi_{\nu_a}(x,t) = f(x,t) \sum_i U_{ai} e^{-i(m_i t/2E)}$$



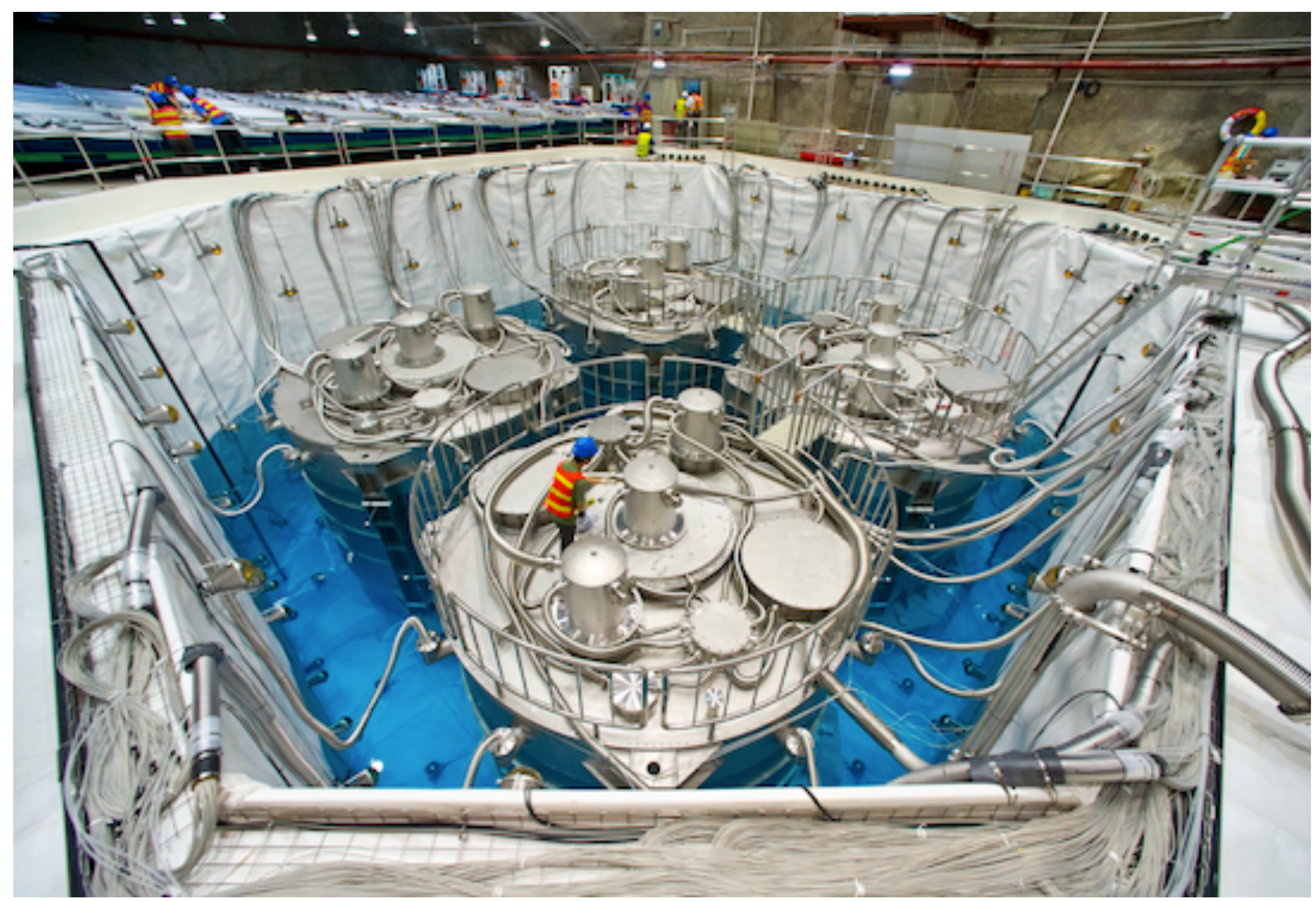
$$P(\nu_a \rightarrow \nu_b) = \sin^2 2\boxed{\theta} \sin^2 \left[1.27 \boxed{\Delta m^2} (eV^2) \frac{L(km)}{E_\nu(GeV)} \right]$$

- Important quantities:
  - θ: Oscillation amplitude
  - Δm²: Oscillation frequency
  - L/E: Experimental parameter

One Quick Illustration: Daya Bay

A simple recipe for measuring neutrino oscillations:

1. Make reactor ν_e, emit them isotropically
2. Detect ν_e at 0.5 and 2 km distances



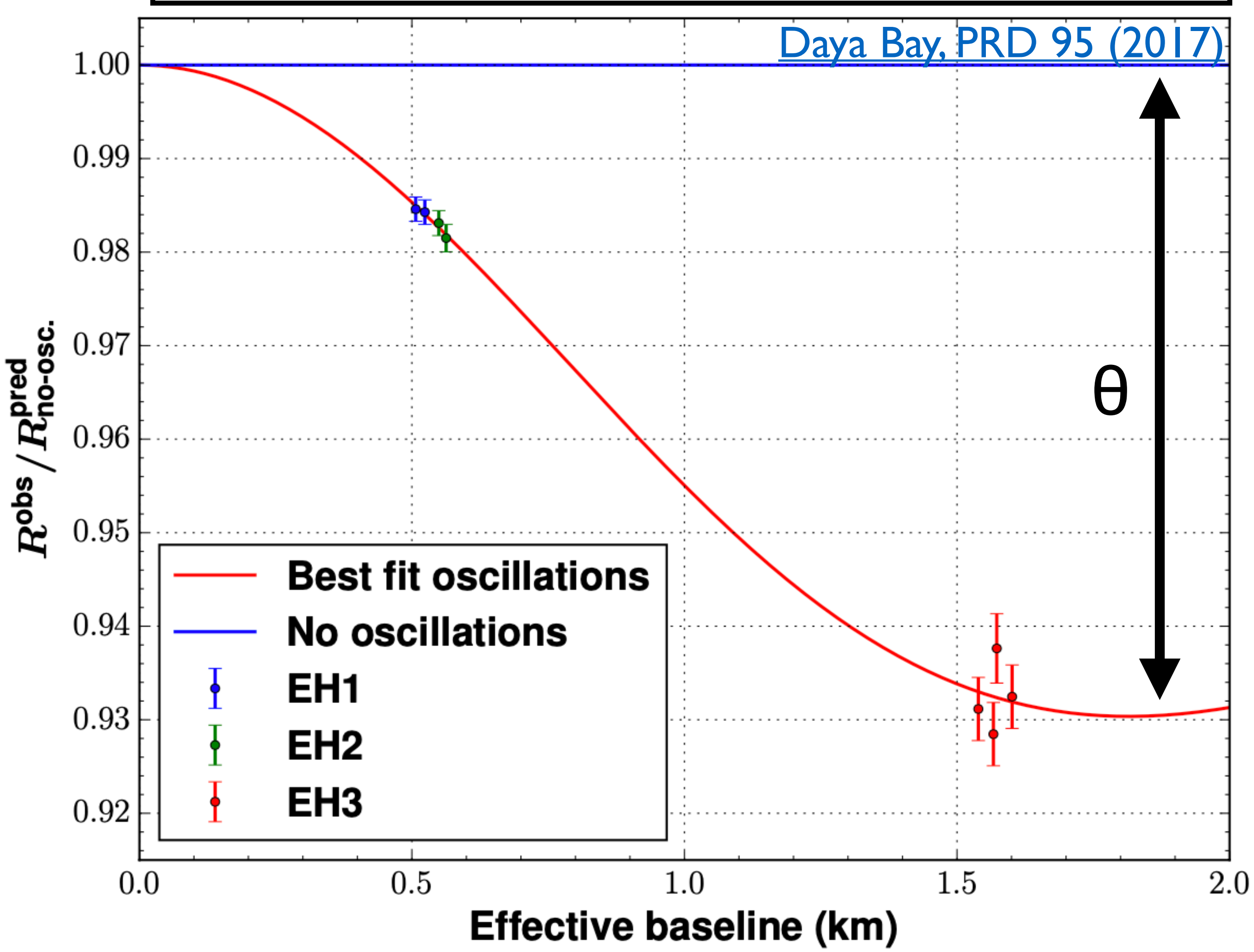
One Quick Illustration: Daya Bay

A simple recipe for measuring neutrino oscillations:

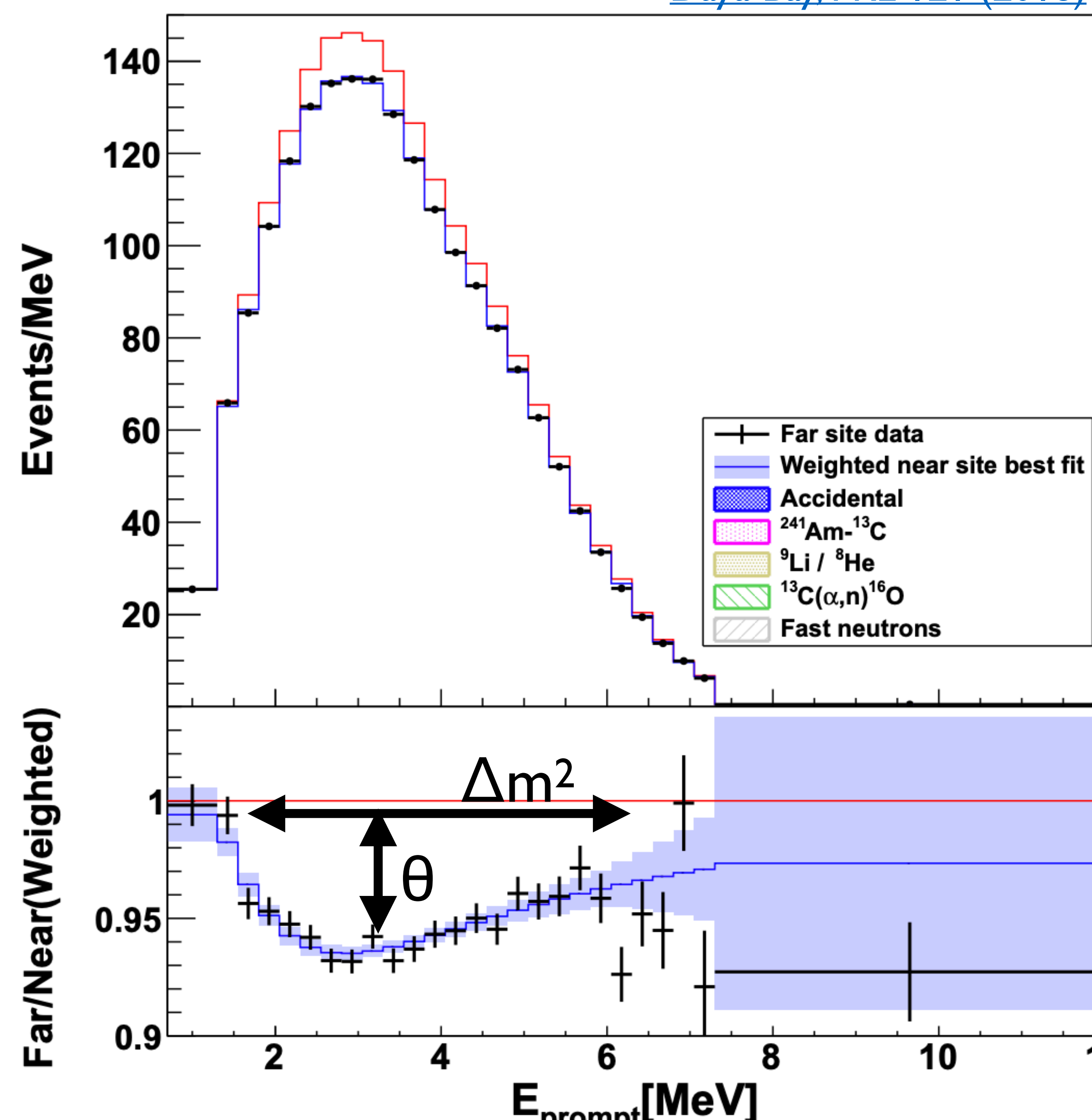
1. Make reactor ν_e, emit them isotropically
2. Detect ν_e at 0.5 and 2 km distances
3. Look for L-dependent deficit
4. Look for E-dependent deficit

$$P(\nu_a \rightarrow \nu_b) = \sin^2 2\theta \sin^2 \left[1.27\Delta m^2(eV^2)\frac{L(km)}{E_\nu(GeV)}\right]$$

Daya Bay, PRD 95 (2017)



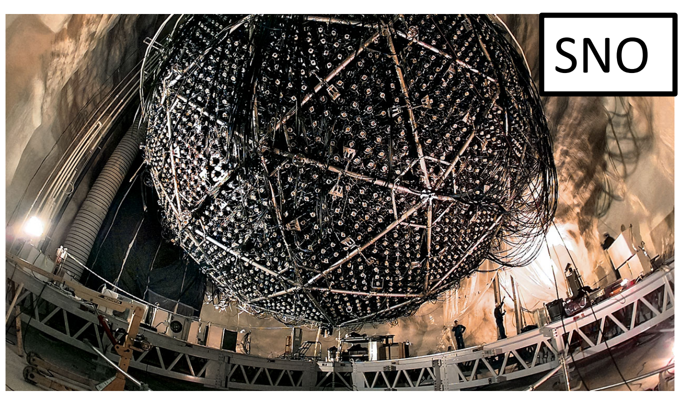
Daya Bay, PRL 121 (2018)

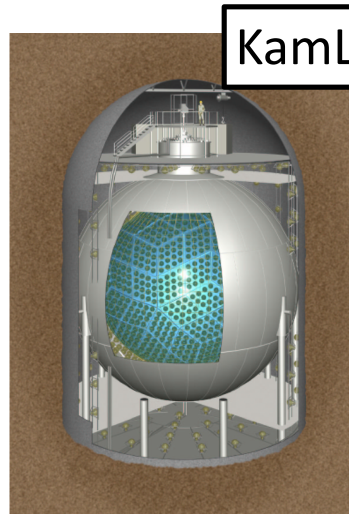


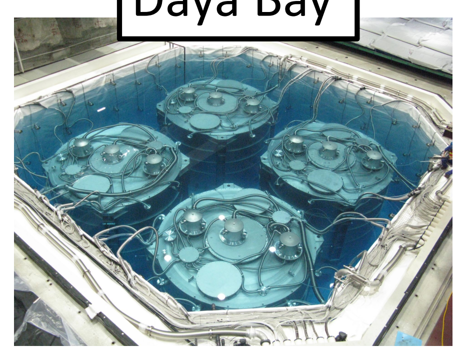
Standard Model Neutrino Oscillations

- Have a beautiful picture of three oscillating Standard Model neutrinos coming into focus
  - Three angles, three mass differences to describe a 3D neutrino space
- Reactor experiments are key to elucidating this picture

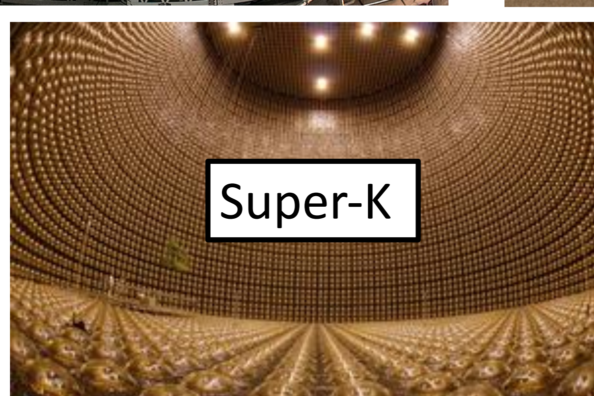
2016 Breakthrough Prize

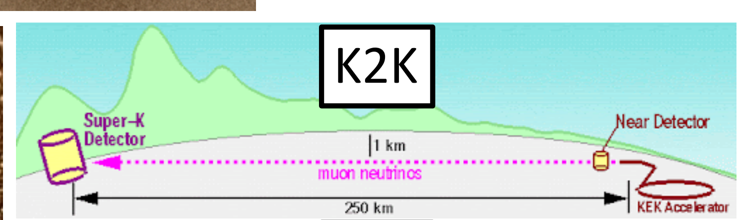


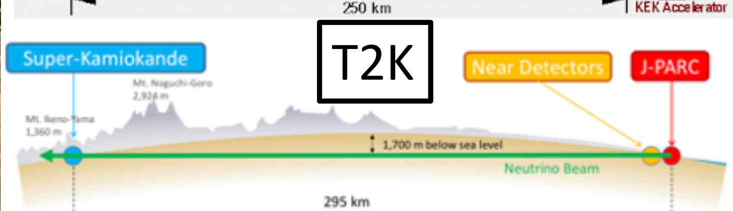


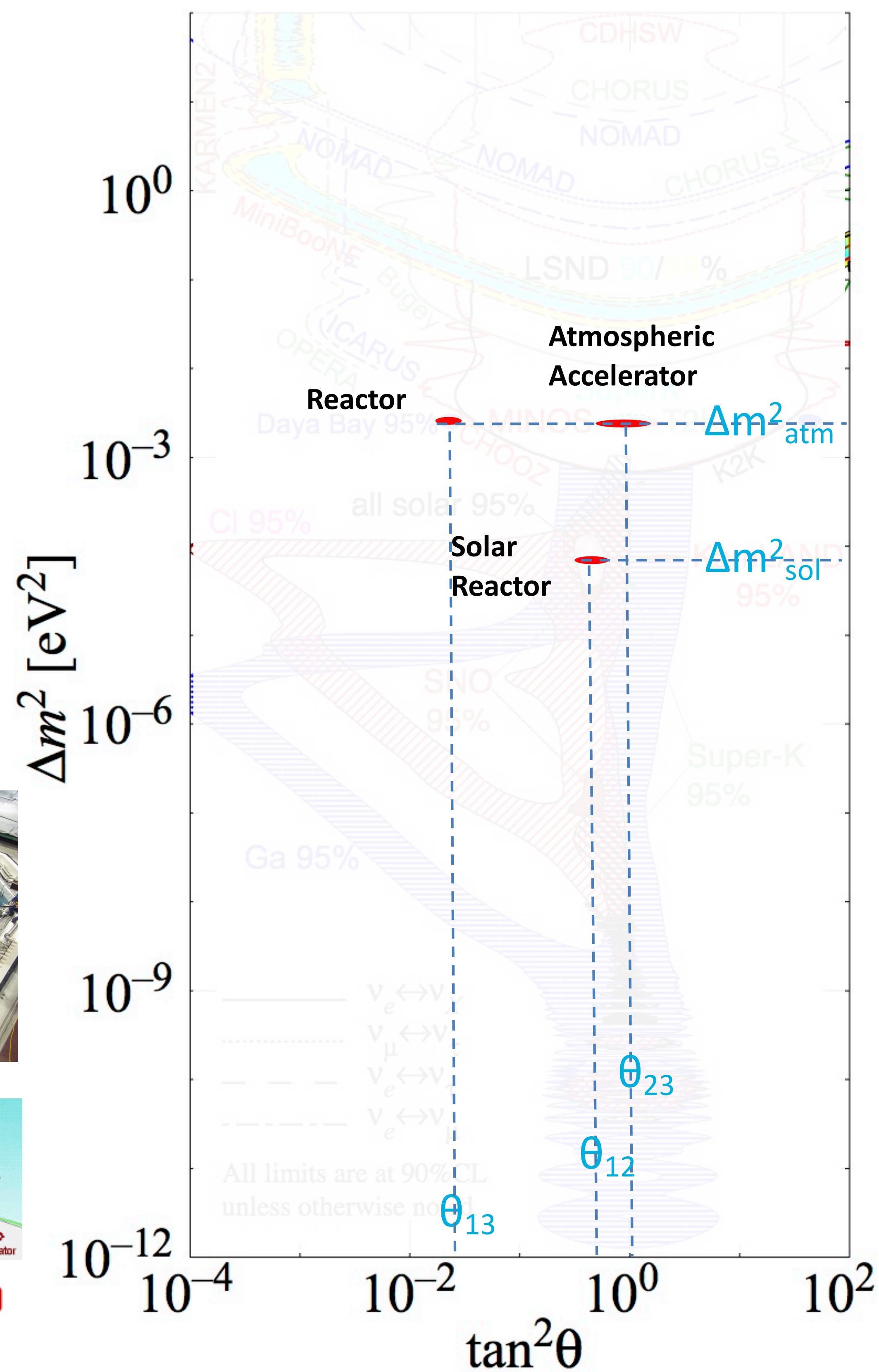


2015 Nobel Prize
Takaaki Kajita & Arthur B. McDonald





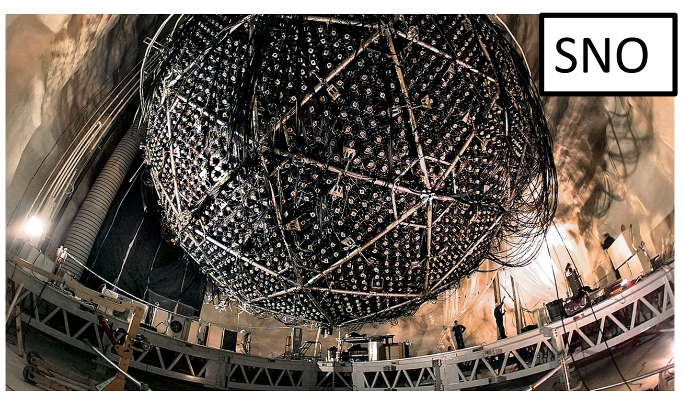


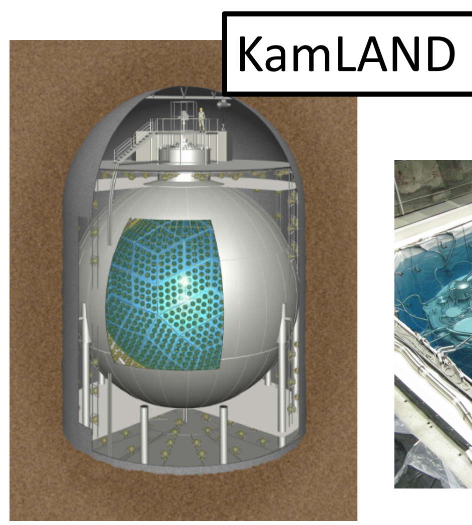


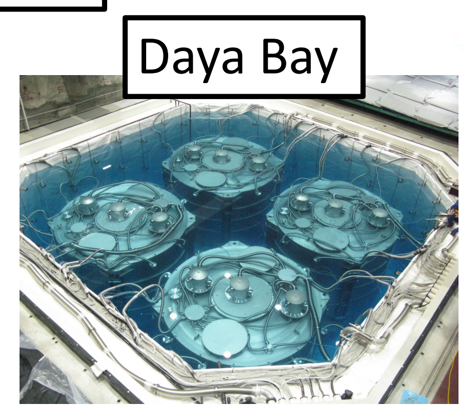
Standard Model Neutrino Oscillations

- Have a beautiful picture of three oscillating Standard Model neutrinos coming into focus
  - Three angles, three mass differences to describe a 3D neutrino space
- Reactor experiments are key to elucidating this picture

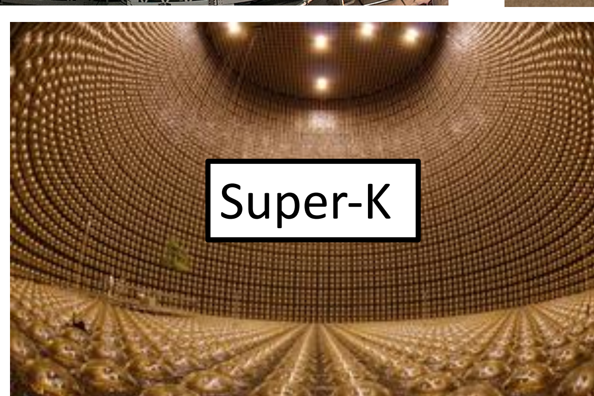
2016 Breakthrough Prize

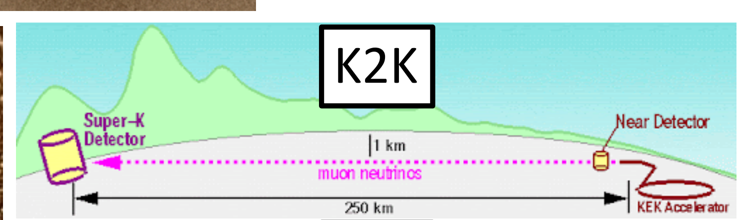


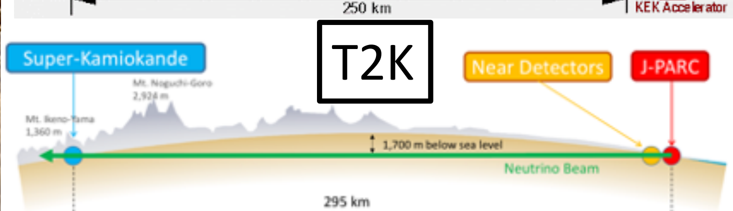


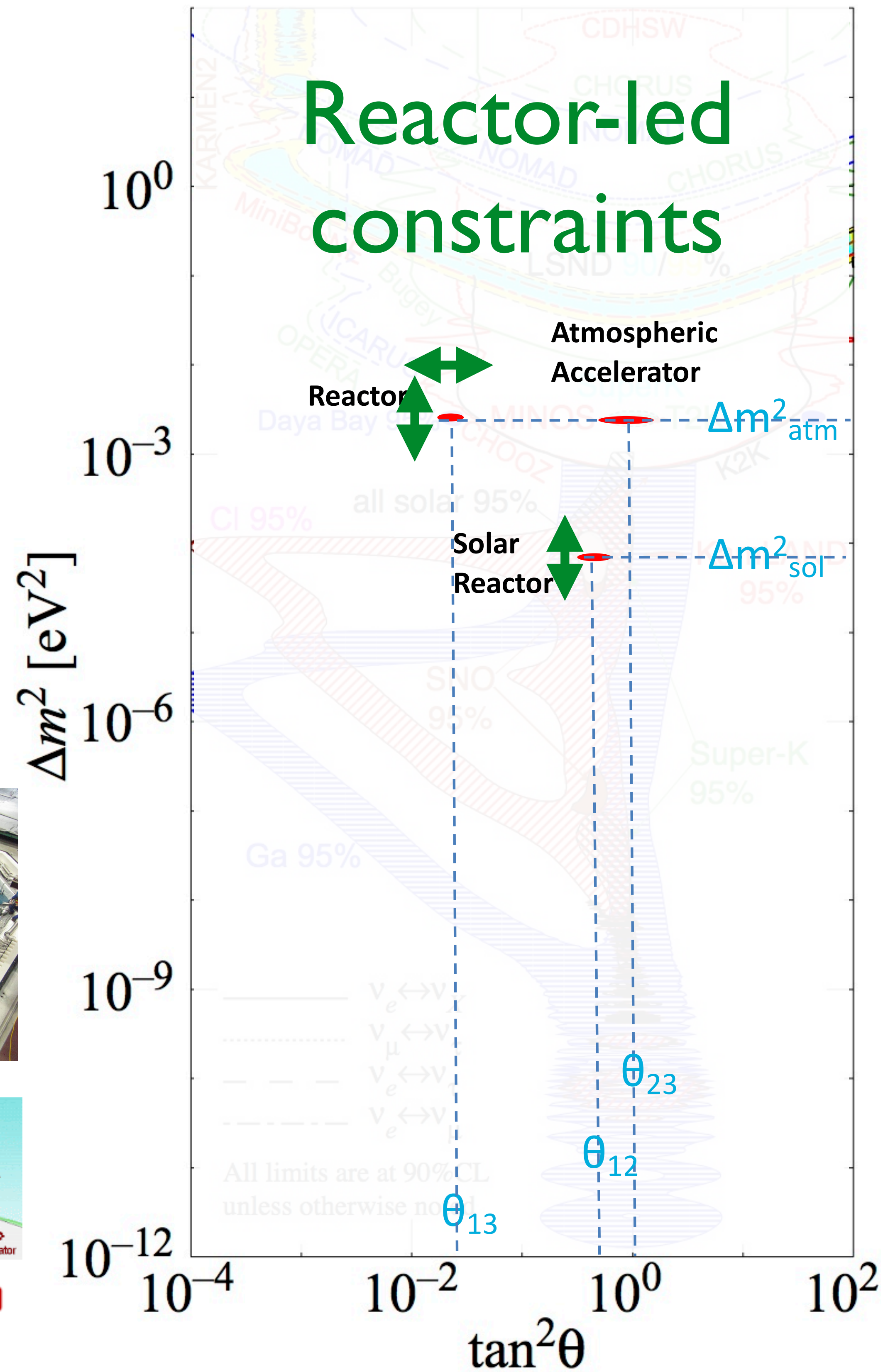


2015 Nobel Prize
Takaaki Kajita & Arthur B. McDonald





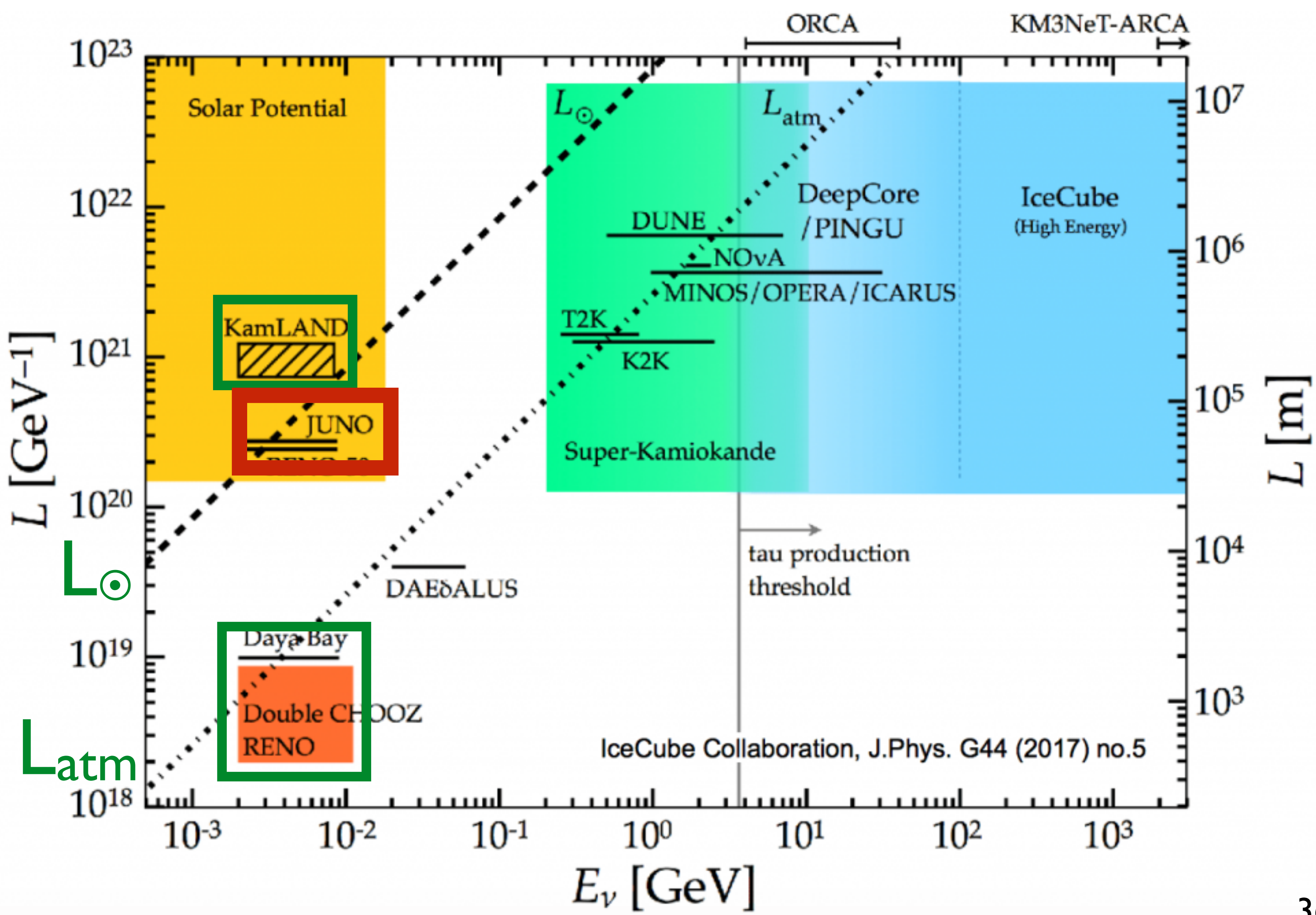




Neutrino Oscillations: L and E

- Reactor experiments are key to elucidating 3-neutrino oscillation picture: in the recent past and in the **future**

- Baselines (L): >km-scale



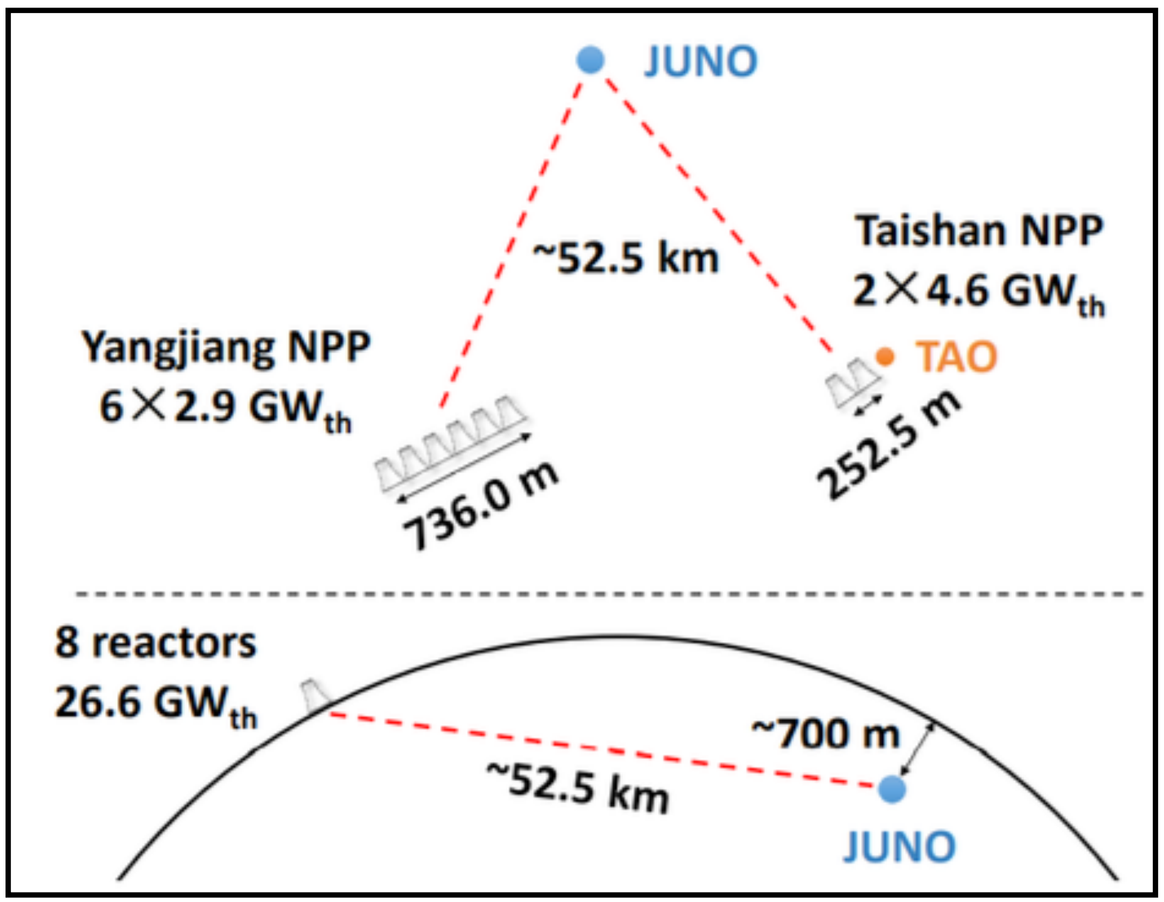
Neutrino Oscillations: JUNO

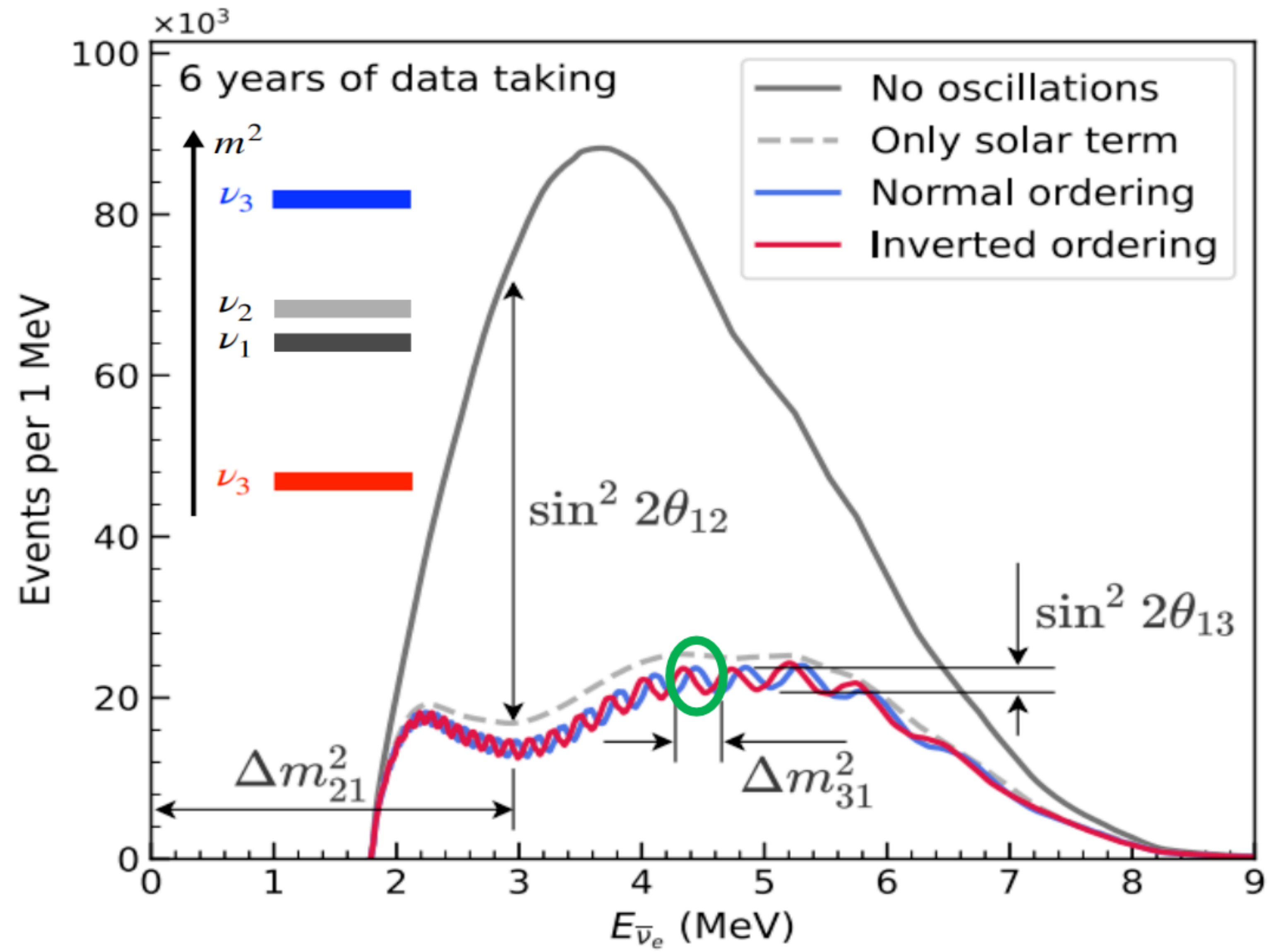
- JUNO will start physics data-taking at L = 52.5 km in ~2024

JUNO, Prog. Nucl. Part. Phys. 123 (2022)

Neutrino Oscillations: JUNO Physics

- Odds are good that a reactor experiment, JUNO, will give first ~3sigma indications of the neutrino mass ordering

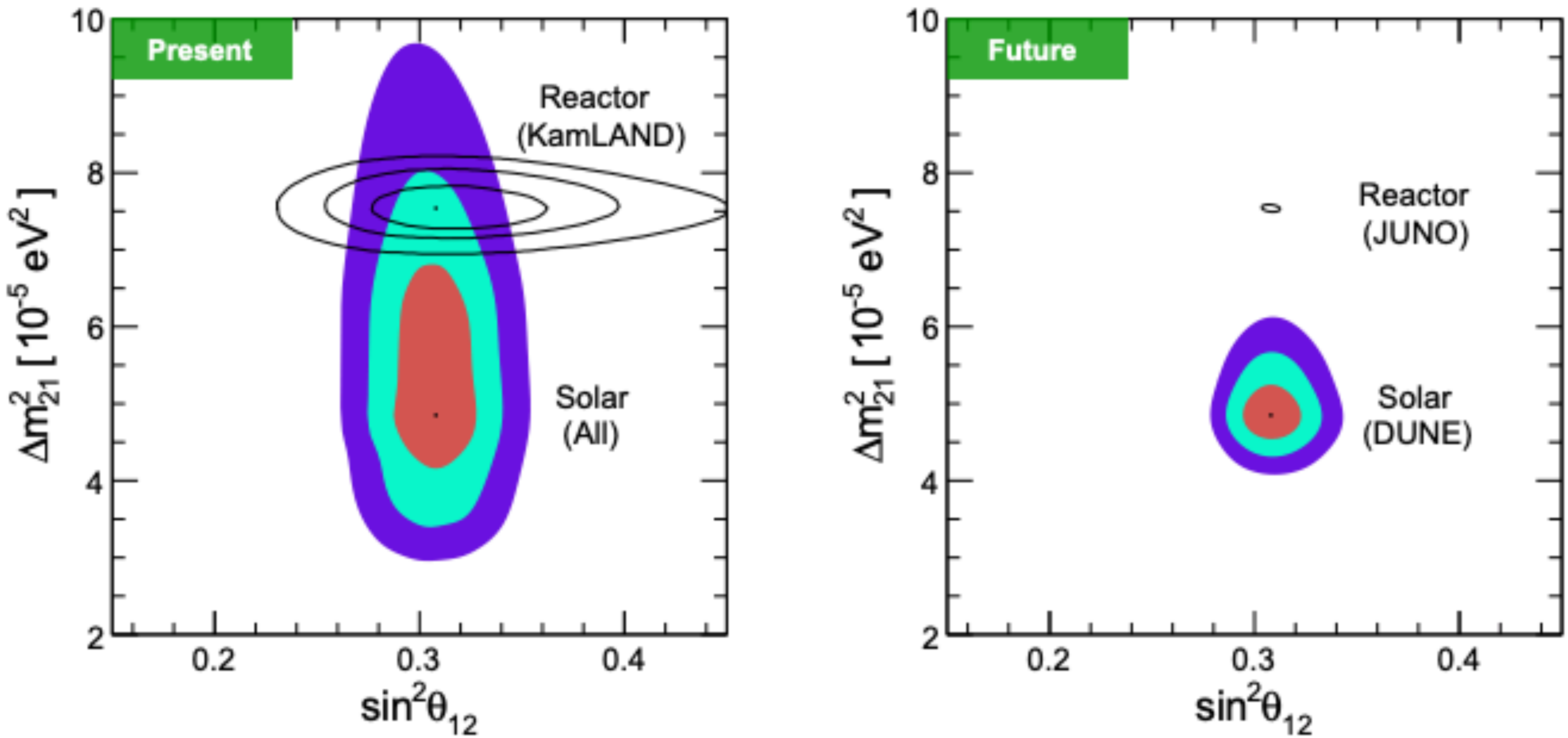




JUNO, Prog. Nucl. Part. Phys. 123 (2022)

Neutrino Oscillations: JUNO Physics

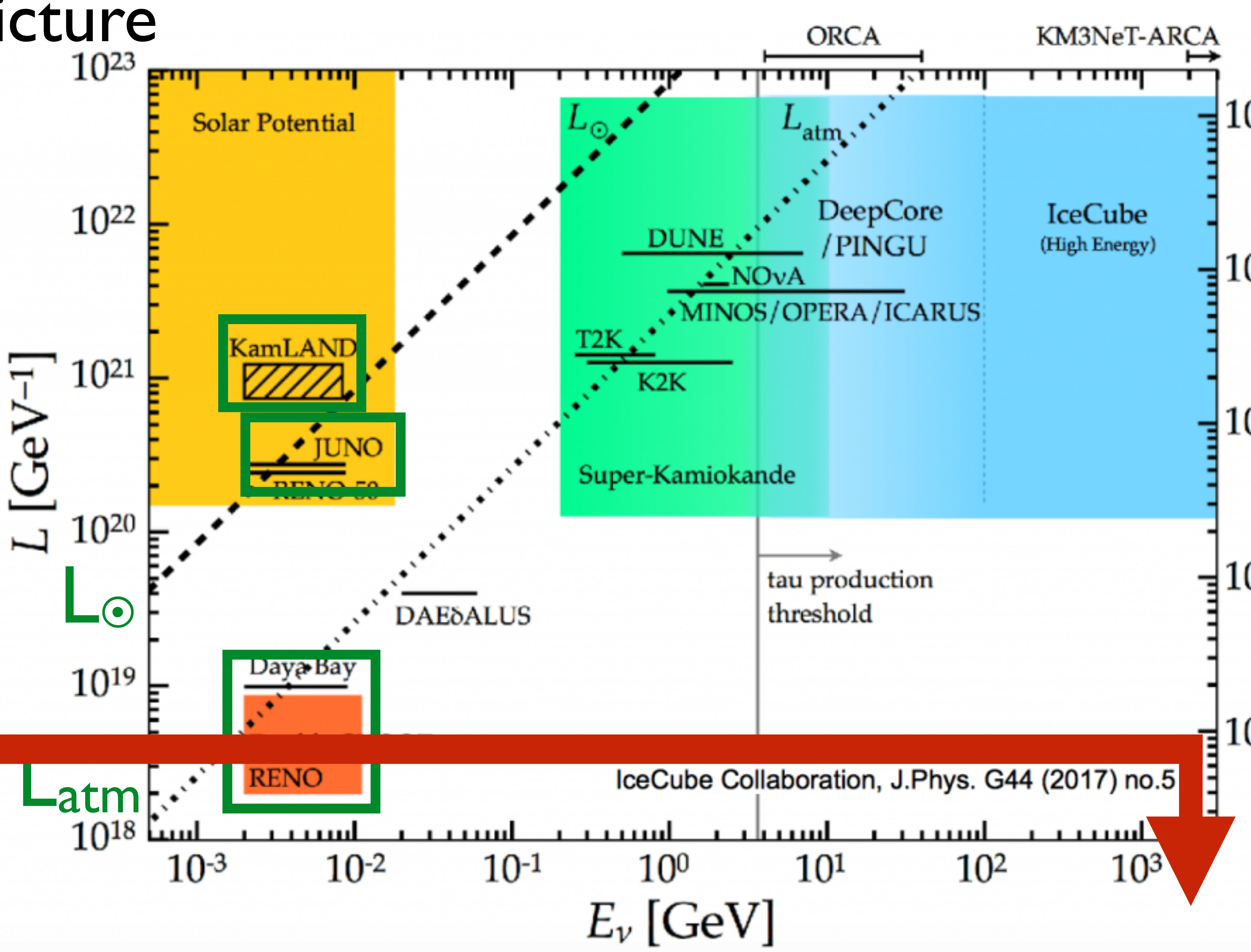
- JUNO will almost immediately set new best limits on other fundamental neutrino parameters: θ_{12} and Δm^2_{21}
  - A DUNE solar neutrino measurement would be very interesting to compare to JUNO's very-high-precision measurement!



Capozzi, et al, PRL 123 (2019)

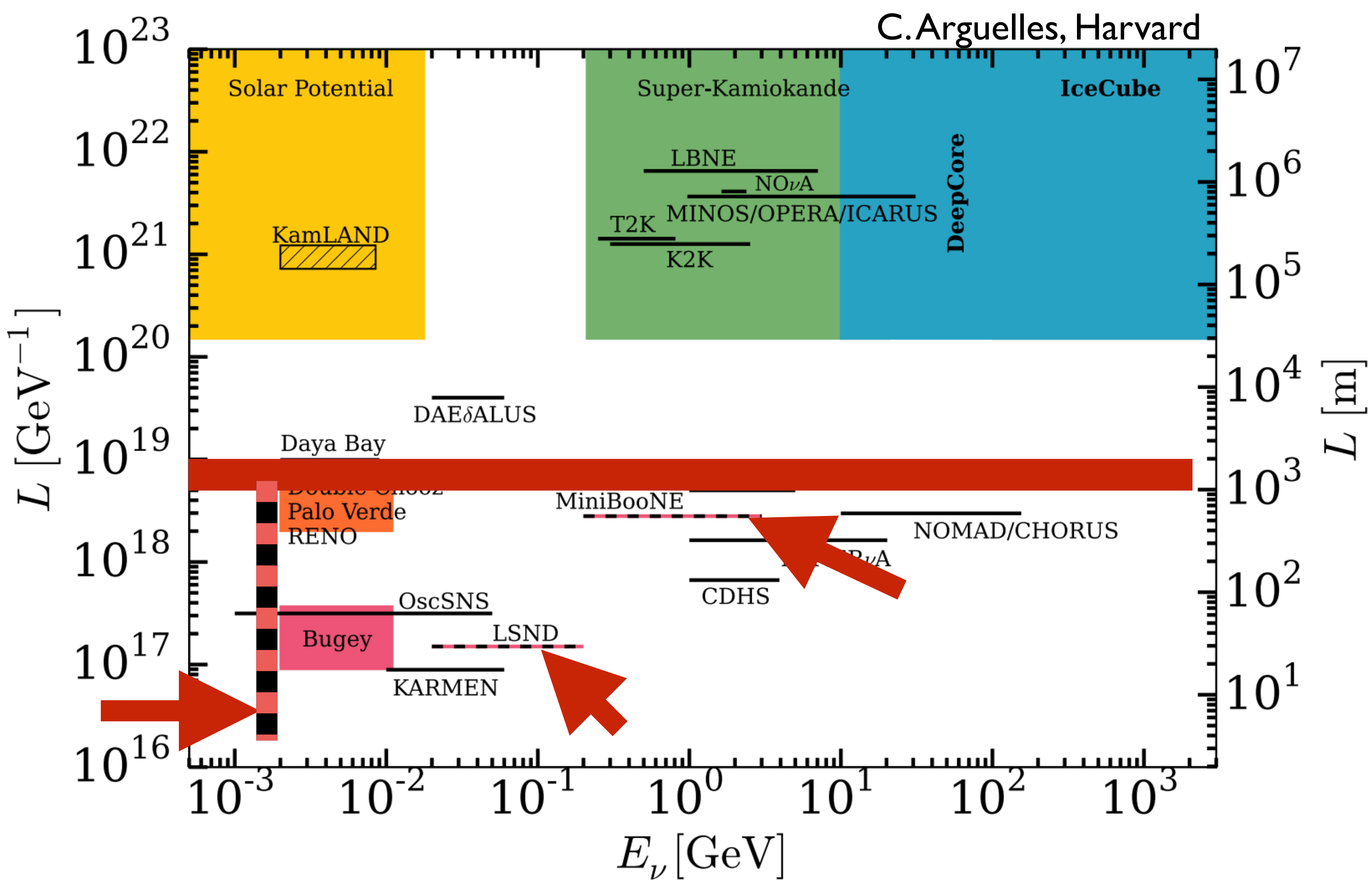
Neutrino Oscillations: L and E

- Have a beautiful picture of three oscillating Standard Model neutrinos coming into focus
- Reactor experiments are key to elucidating this picture
- Baselines (L): >km-scale
- Let's go HERE!
- WHY go here?



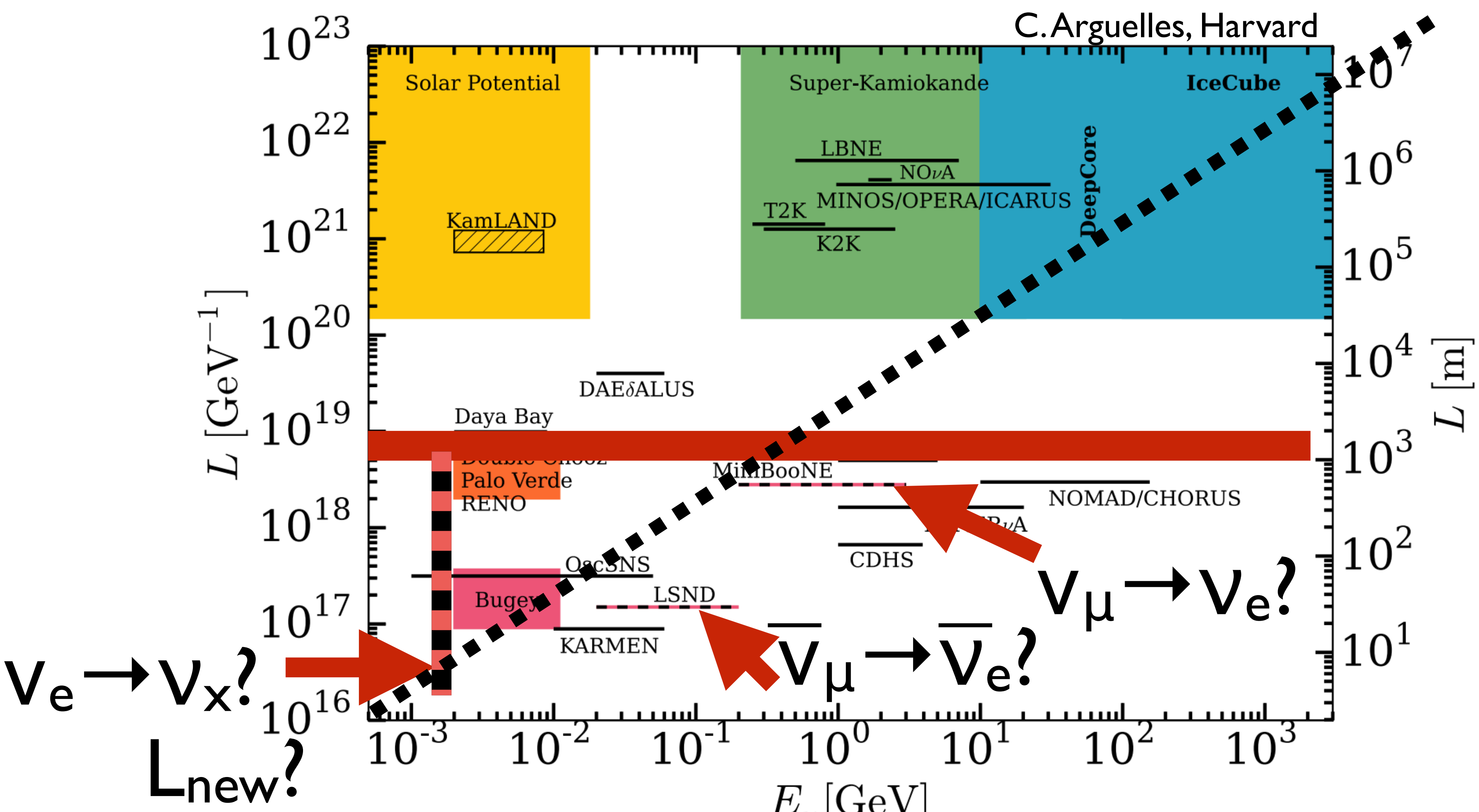
Neutrino Anomalies

- Neutrino fluxes and energies measured at < km disagree with state-of-the-art neutrino predictions
- Indications of new physics beyond 'SM oscillations'?!



New Neutrino Mass States?

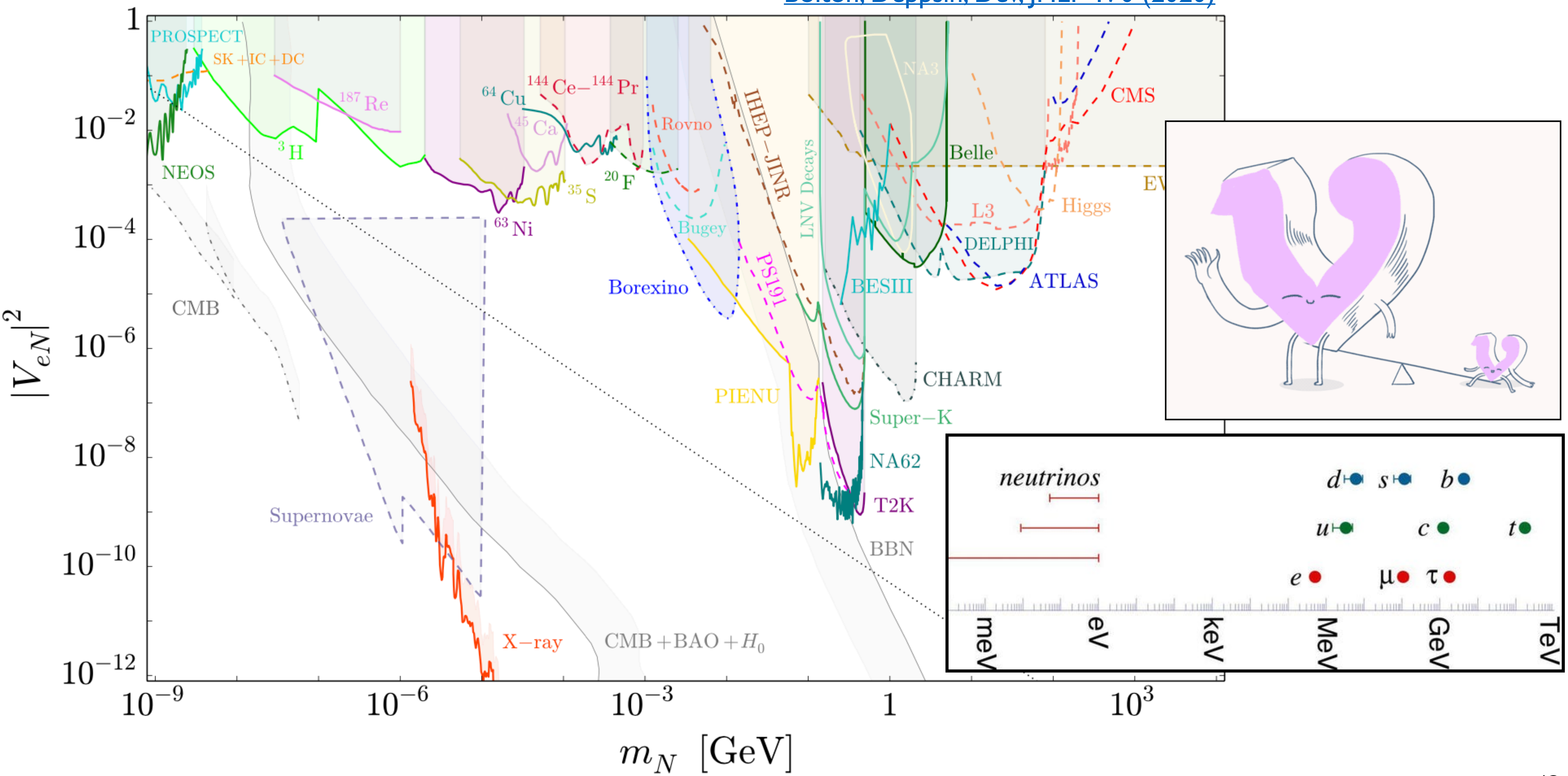
- Neutrino fluxes and energies measured at < km disagree with state-of-the-art neutrino predictions
- Indications of new physics beyond ‘SM oscillations’?!
  - Additional neutrino mass states: **sterile neutrinos?** Other new physics?



New Neutrino Mass States?

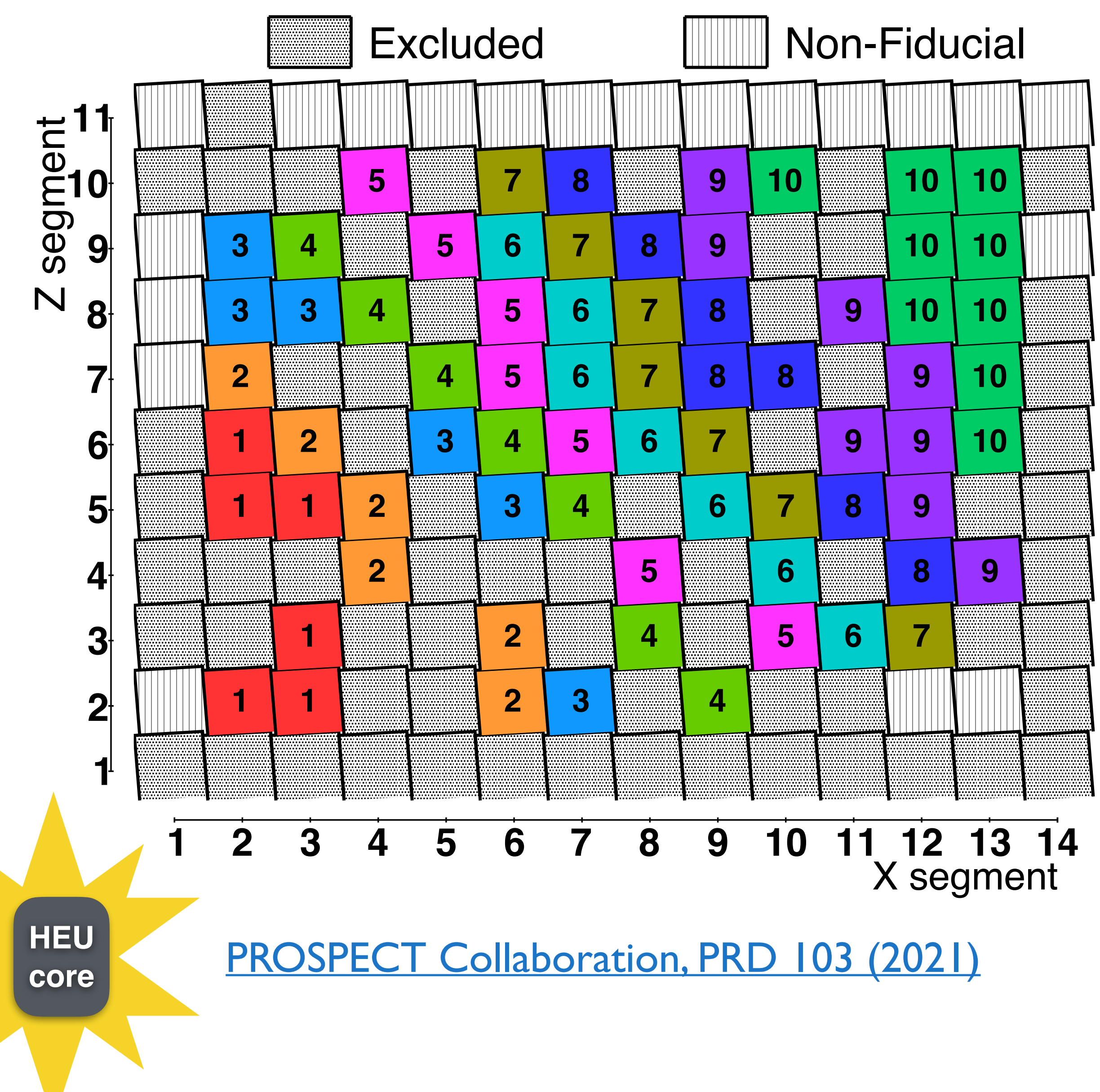
- **Other good reasons to look for new mass states, too**
  - See-saw mechanism: heavier neutral leptons help explain why SM neutrinos are so light?

[Bolton, Deppsih, Dev, JHEP 170 (2020)]



PROSPECT: Relative IBD Spectrum Ratios

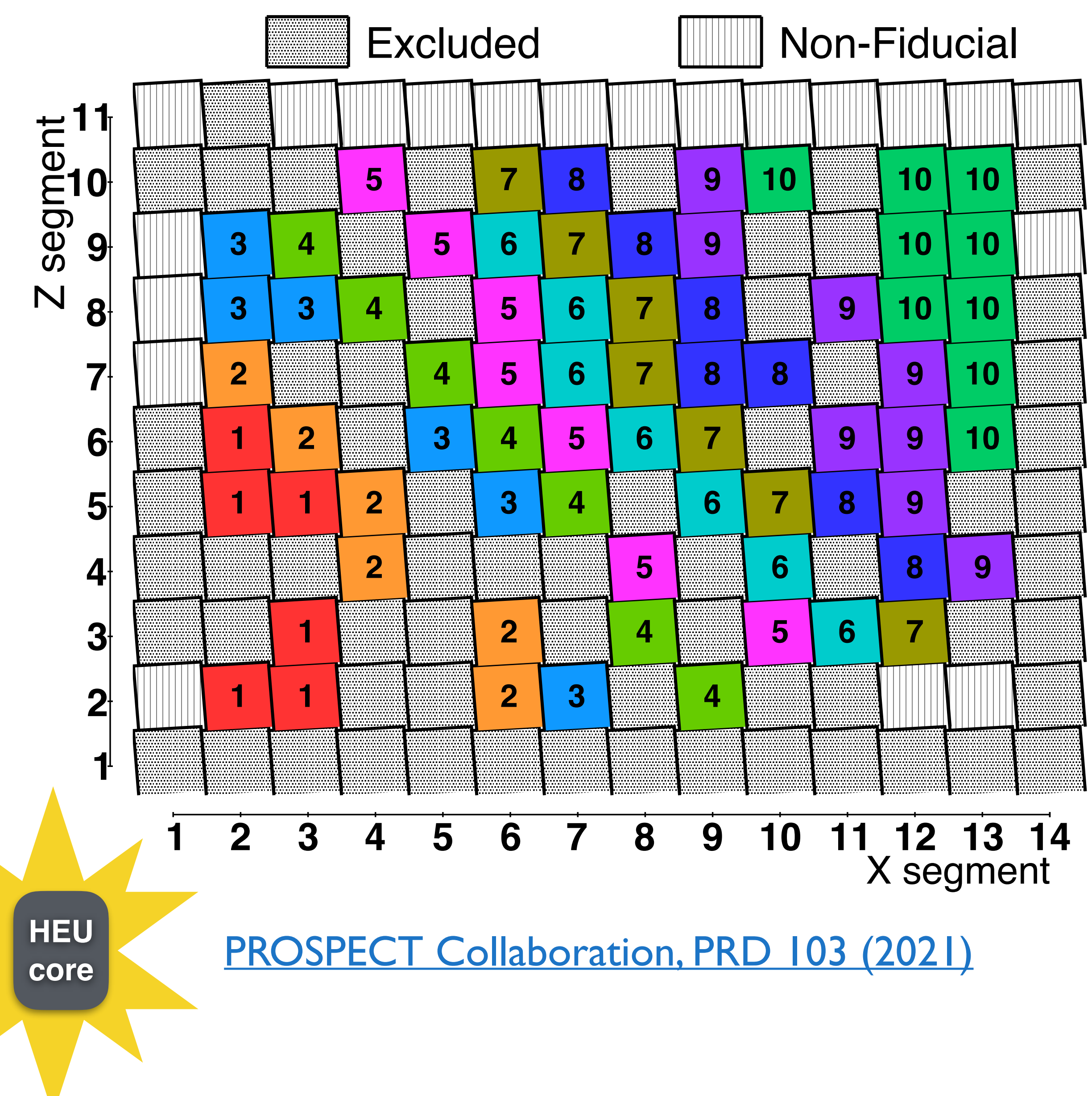
- Look for variations between energy spectra of full detector versus individual baselines
  - Any wiggles in ratio is evidence of L/E nature of sterile neutrino oscillations

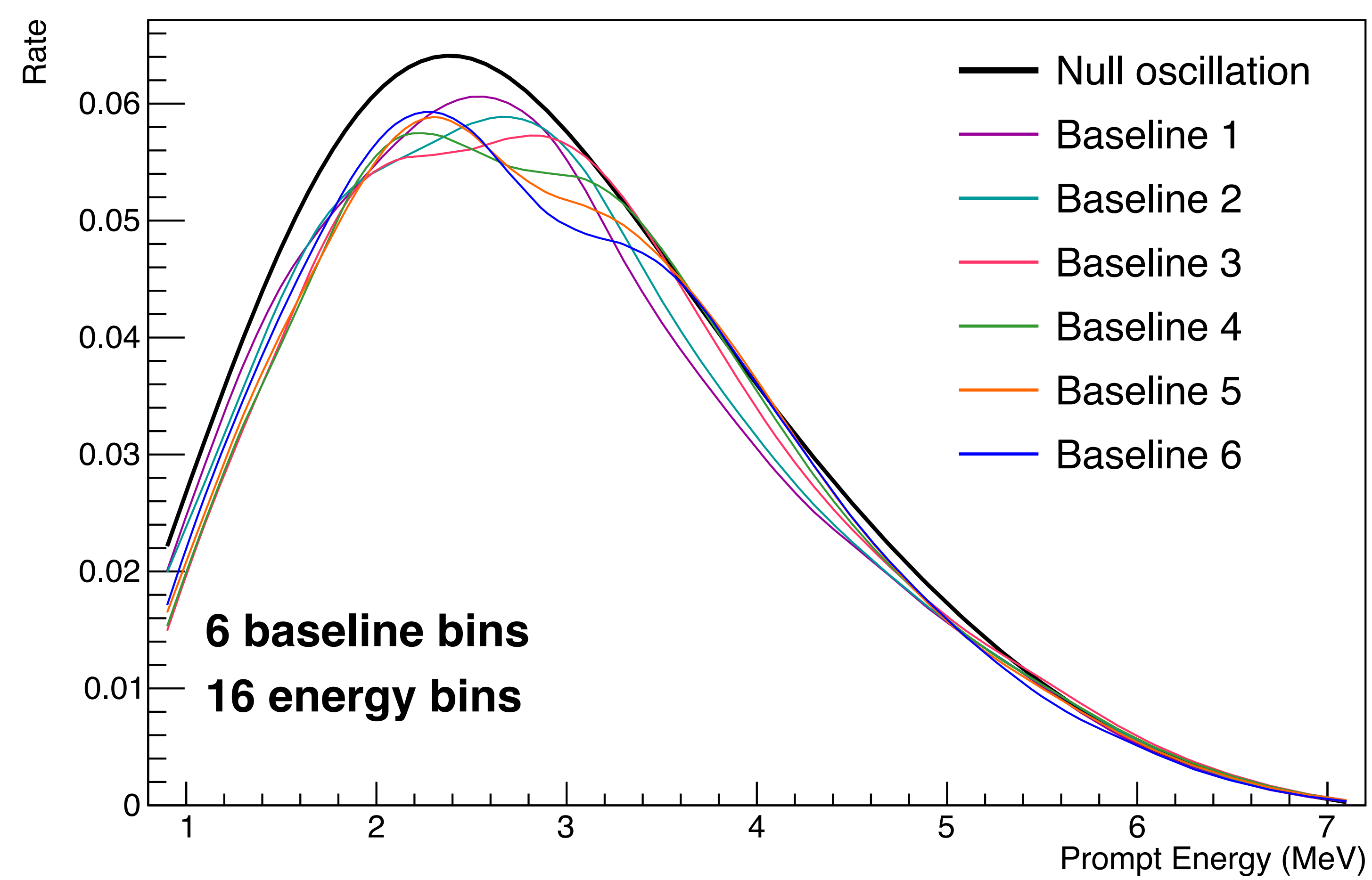


[PROSPECT Collaboration, PRD 103 (2021)]

PROSPECT: Relative IBD Spectrum Ratios

- Look for variations between energy spectra of full detector versus individual baselines
  - Any wiggles in ratio is evidence of L/E nature of sterile neutrino oscillations

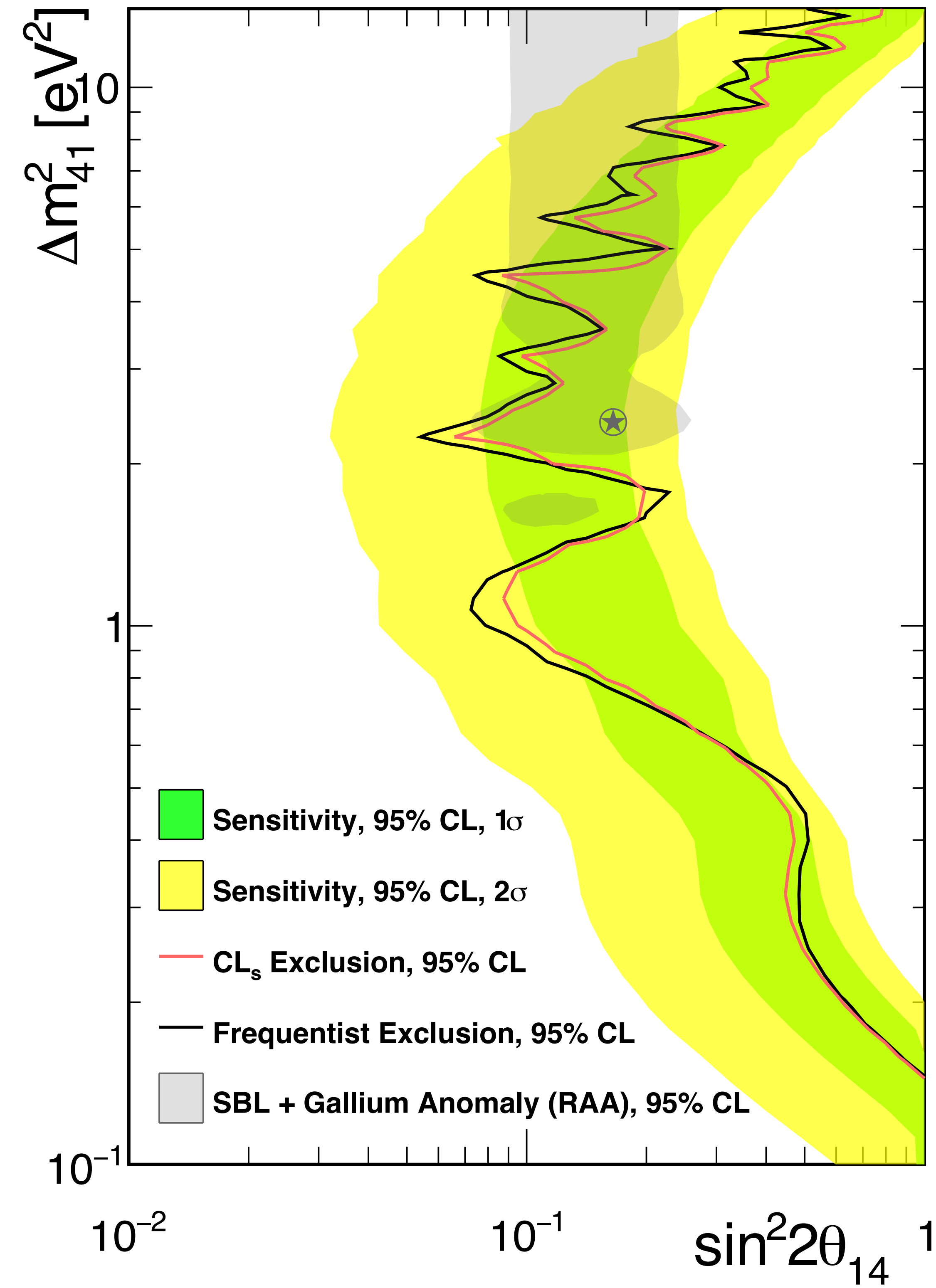




[PROSPECT Collaboration, PRD 103 (2021)]

PROSPECT: Relative IBD Spectrum Ratios

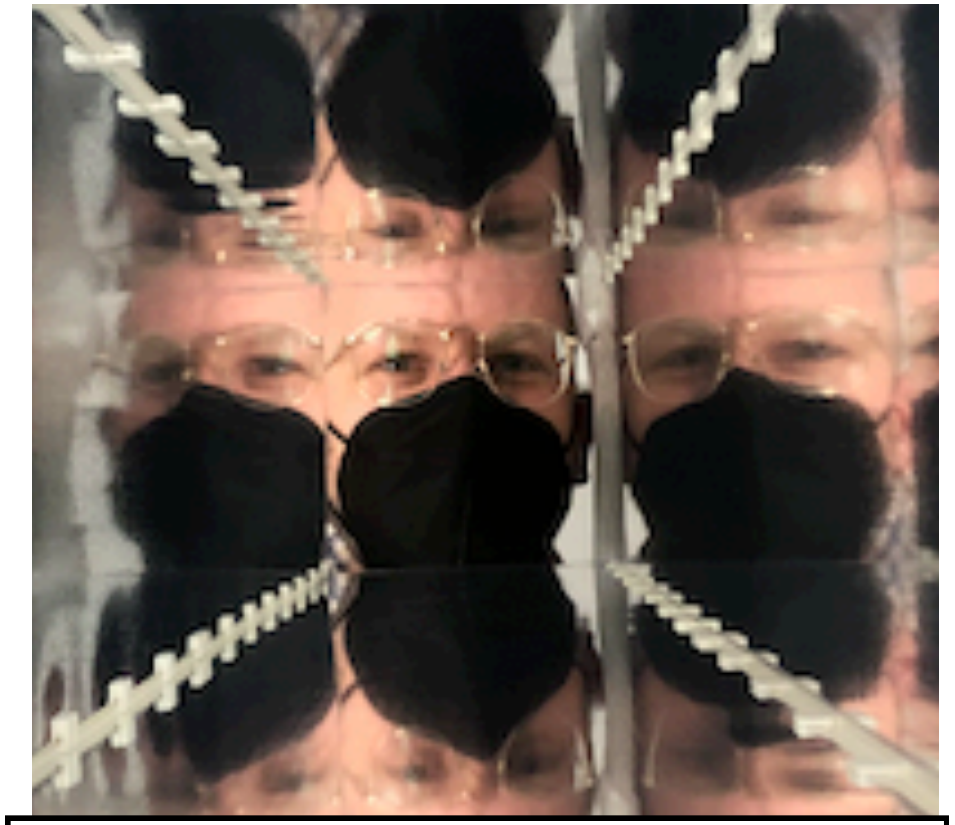
- Look for variations between energy spectra of full detector versus individual baselines
  - Any wiggles in ratio is evidence of L/E nature of sterile neutrino oscillations
- We have not observed any such effect so far, setting new bounds on oscillation at O(1-10) eV^2
- Stay tuned for final PROSPECT-I oscillation results in the next month or two!



PROSPECT Collaboration, PRD 103 (2021)

Conclusion

- Reactors are the world's most intense and flavor-pure sources of electron antineutrinos.
- Reactors play a major role addressing fundamental outstanding questions about particle physics:
  - How different are neutrinos' masses, and which is the heaviest?
  - How flavor-pure are the different neutrino mass states?
  - Are there other mass states besides the three Standard Model ones?



Down the barrel of a PROSPECT segment

Neutrino Alley @ ORNL!

My fave scientists!

Thanks!

Backup

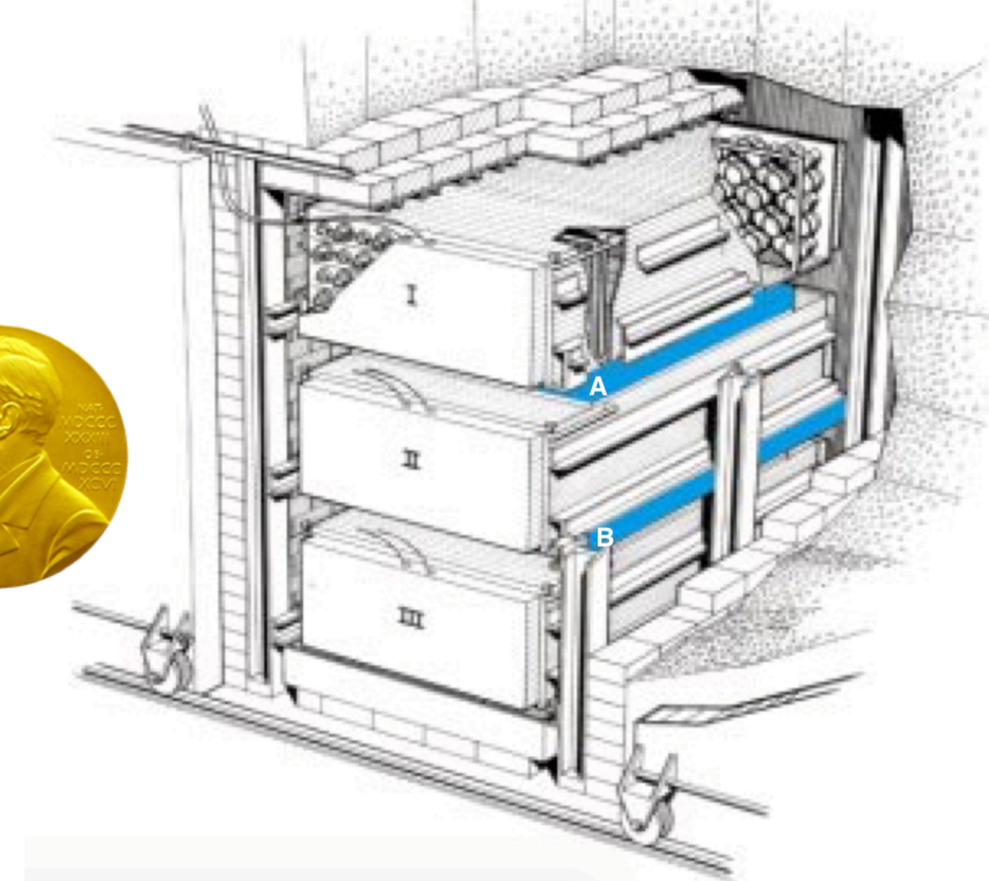
Backup

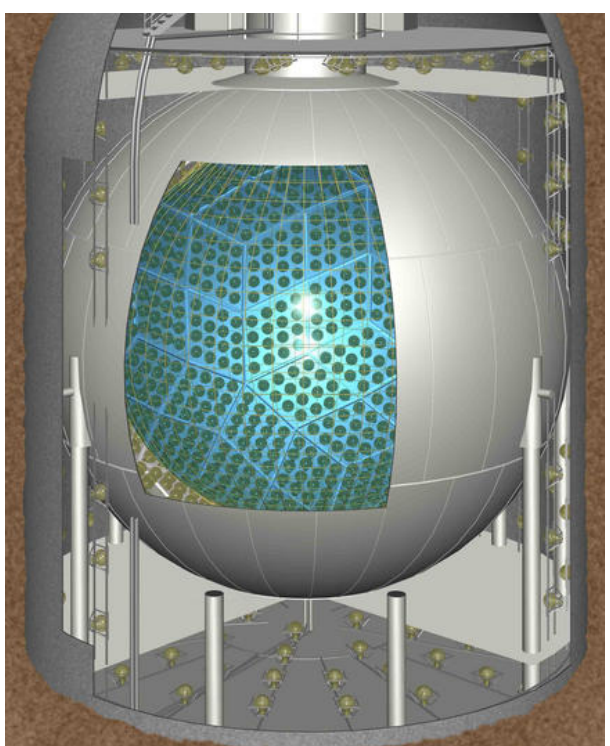
Backup

What's Been Done With Reactor Neutrinos?

- Proved neutrinos' existence (1950s)
- Probed CC/NC cross-sections back when that was new and cool (50s-70s)
- More recently: proving neutrinos have mass, and measuring SM neutrino oscillation parameters
  - Leading or competitive precision for 3 of 6 SM oscillation parameters: θ_{13}, Δm^2_{21}, $|\Delta m^2_{31}|$

Savannah River Neutrino Detector schematic





KamLAND Detector

2016 Breakthrough Prize

Daya Bay Far Site

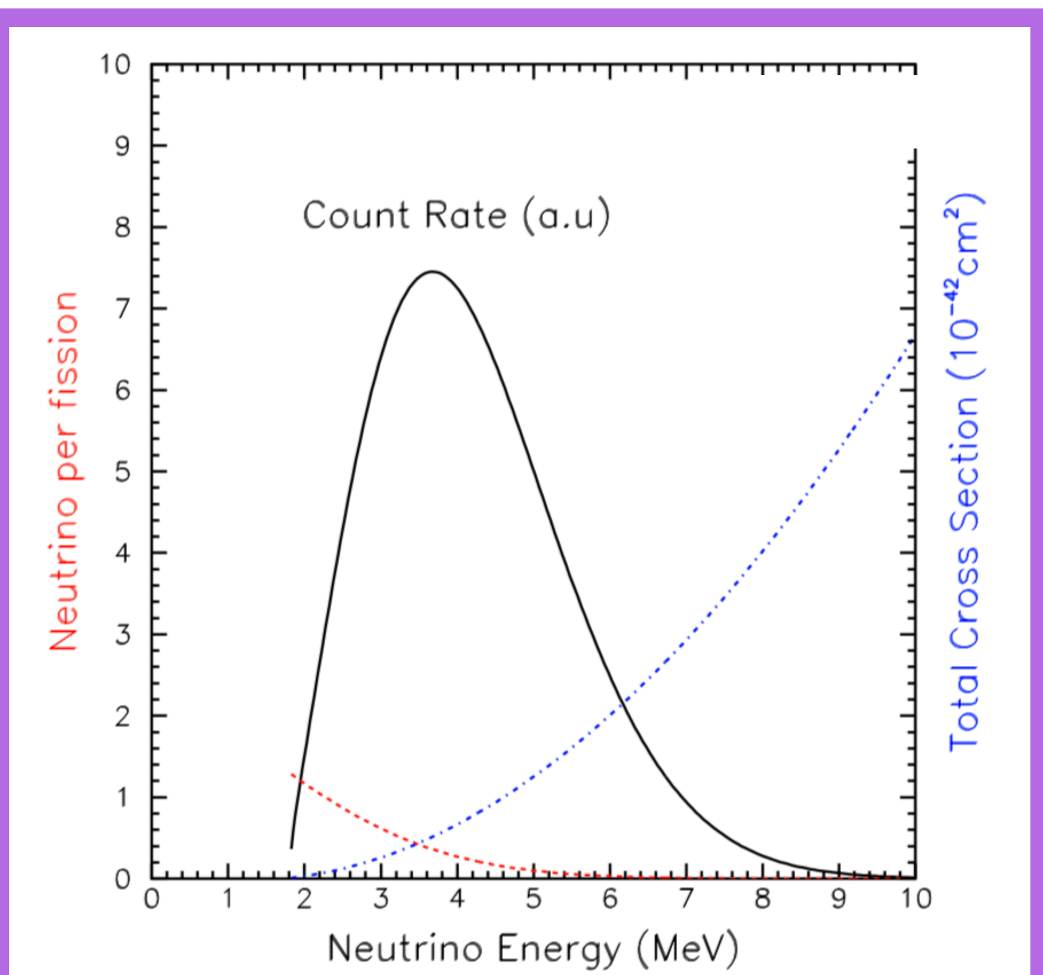
Reactor Prediction Elements

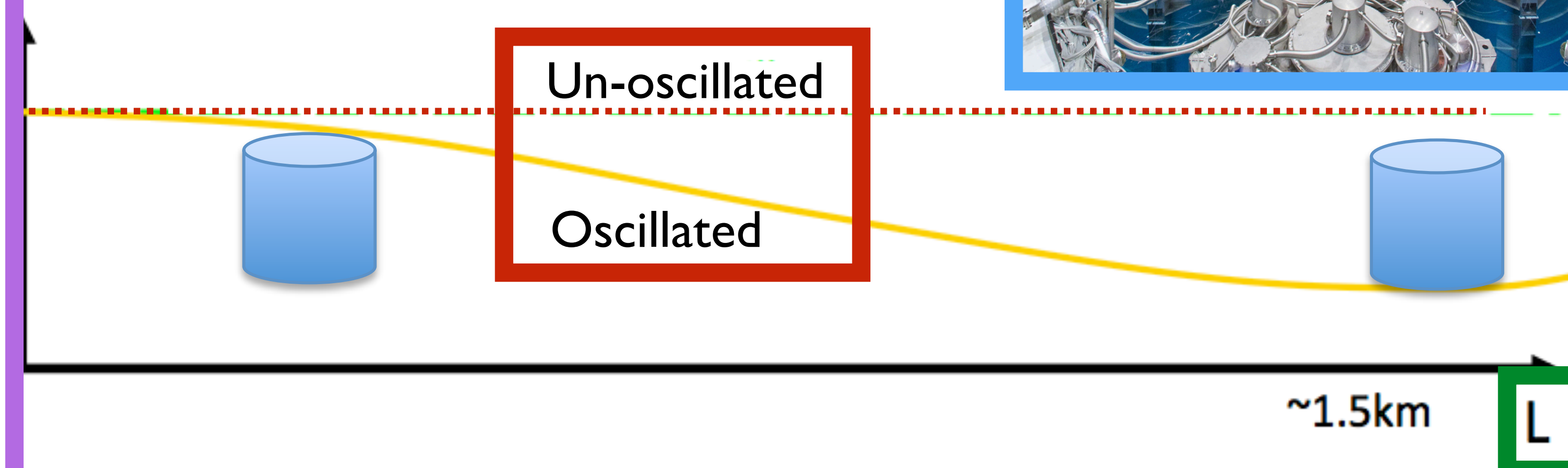
- Detected neutrinos described as:

$$\frac{d^2N(E_\nu,t)}{dE_\nu dt} = \boxed{N_p}\boxed{\sigma}(E_\nu)\boxed{\varepsilon}\frac{\boxed{P(E_\nu,L)}}{\boxed{4\pi L^2}}\left(\boxed{\frac{d^2\phi_r(E_\nu,t)}{dE_\nu dt}}\right)$$

- Production rate and interaction cross-section

Daya Bay, hep-ex[0701029]





Comparisons: Solar versus Reactor

- So: how do solar and reactor fluxes compare on Earth?

	Solar	**Reactor (DYB case)**
Production	10^{38}/sec	10^{21}/sec
Baseline	10^{8} km	1 km
Flux	$\sim 10^{11}$ nu/sec	$\sim 10^{10}$ nu/sec

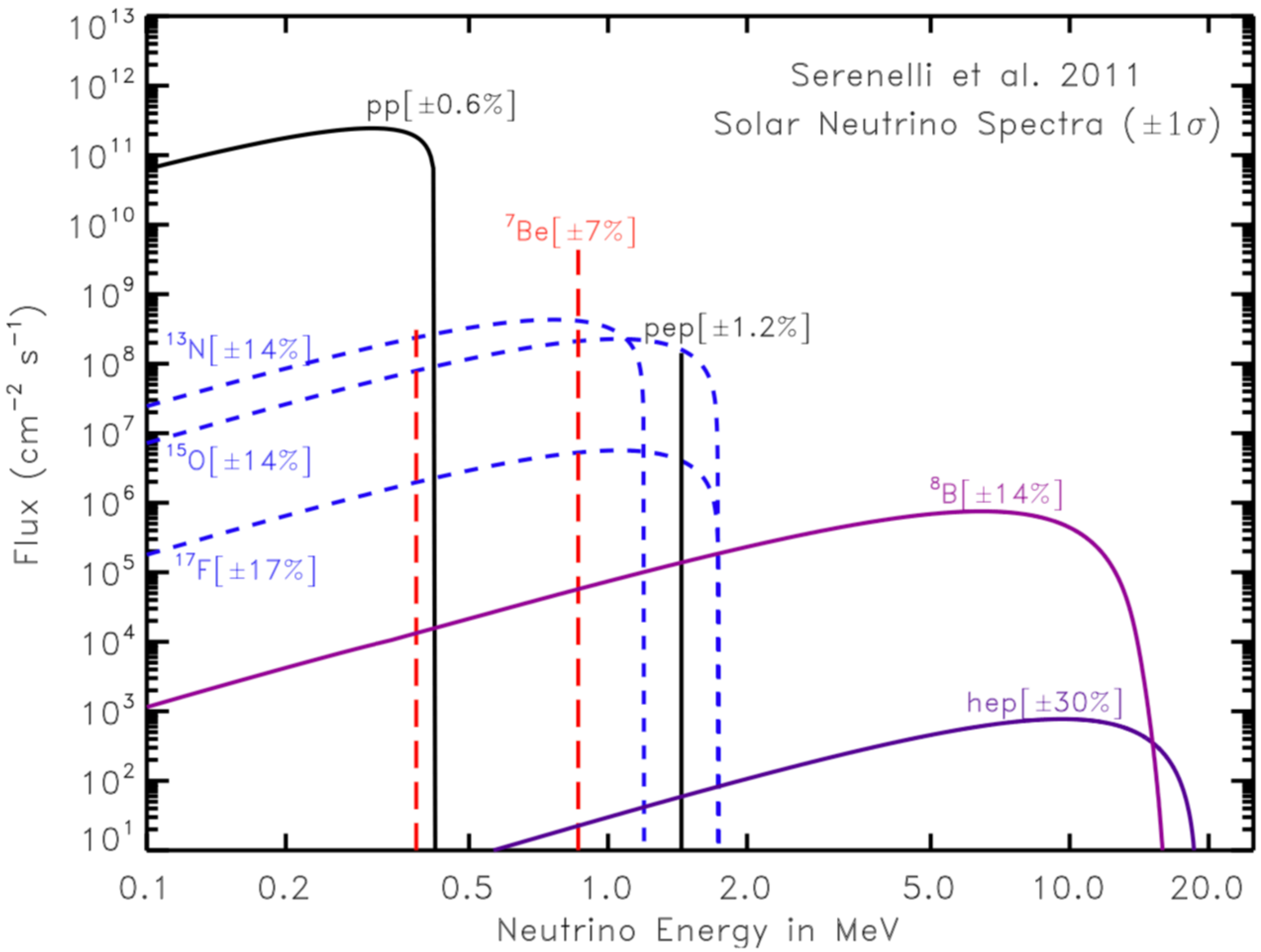
WHA???

Solar nu flux is higher at Daya Bay than reactor flux?

Why doesn't Daya Bay see a bunch of solar neutrinos?

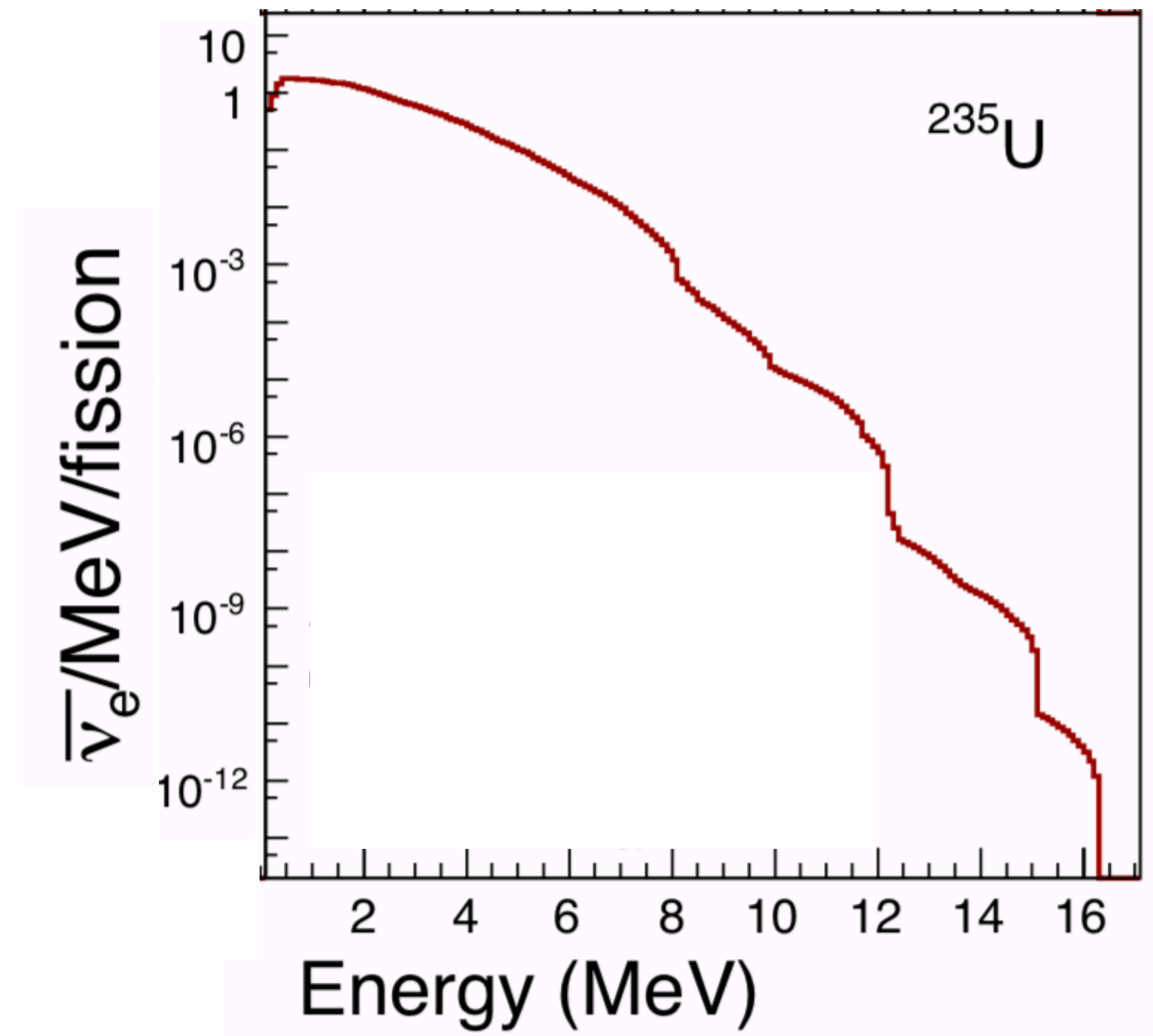
Electron Flavor Energies

The Sun



Haxton, Robertson, Serenelli, astro-ph[1208.5723]

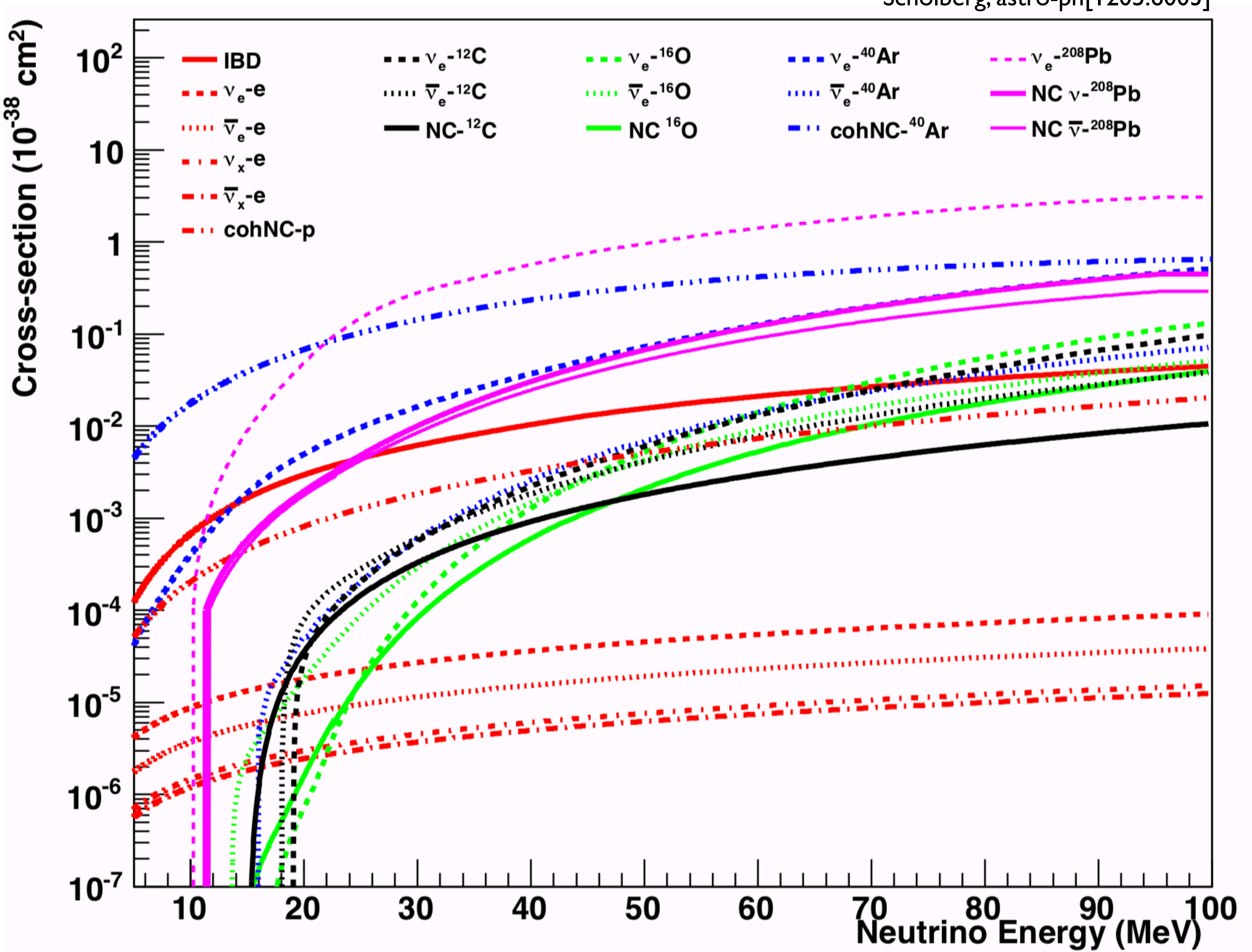
Reactors



Fallot, et al, nucl-ex[1208.3877]

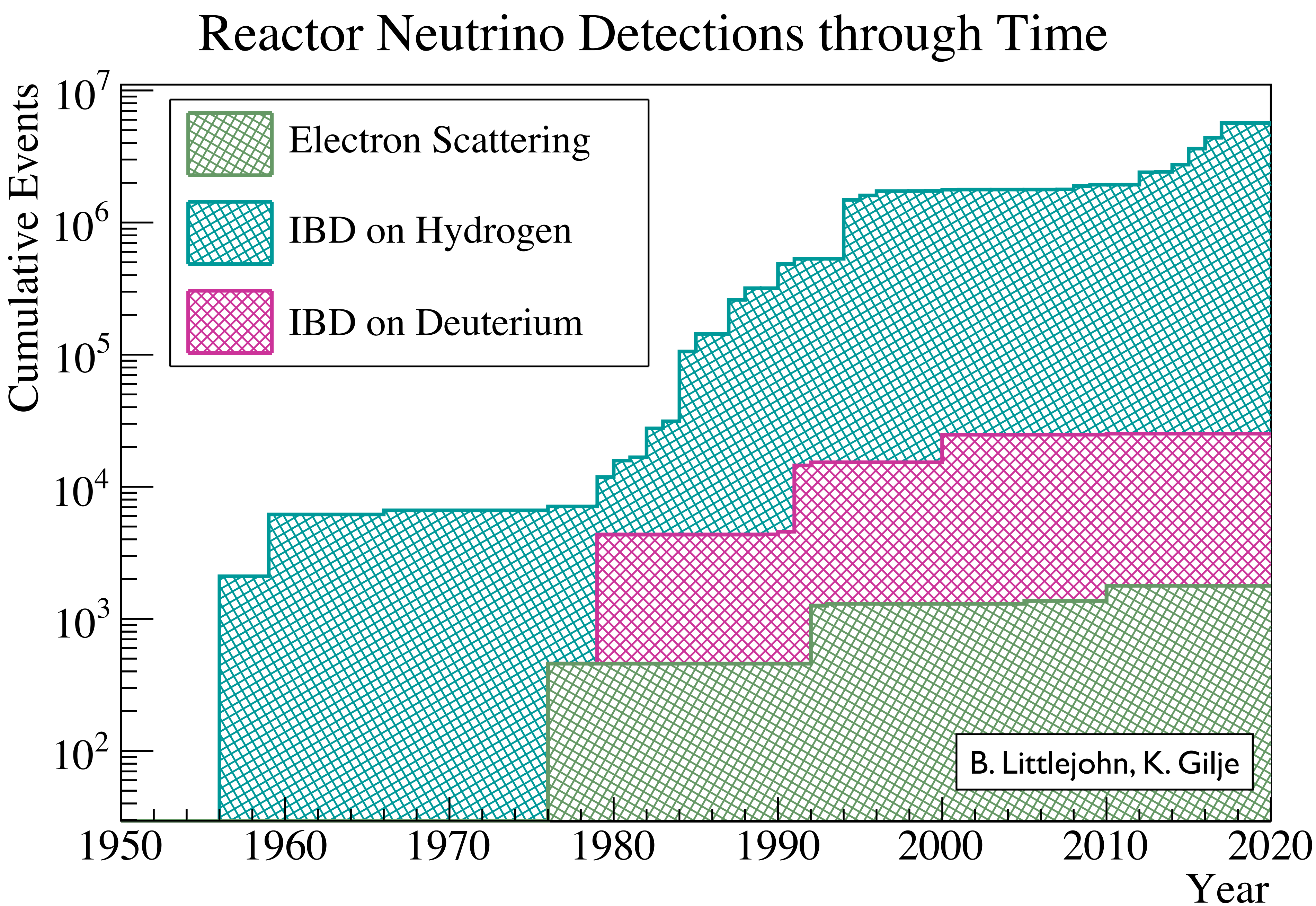
Reactor Antineutrino Interactions

Scholberg, astro-ph[1205.6003]



Reactor Antineutrino Detection Methods

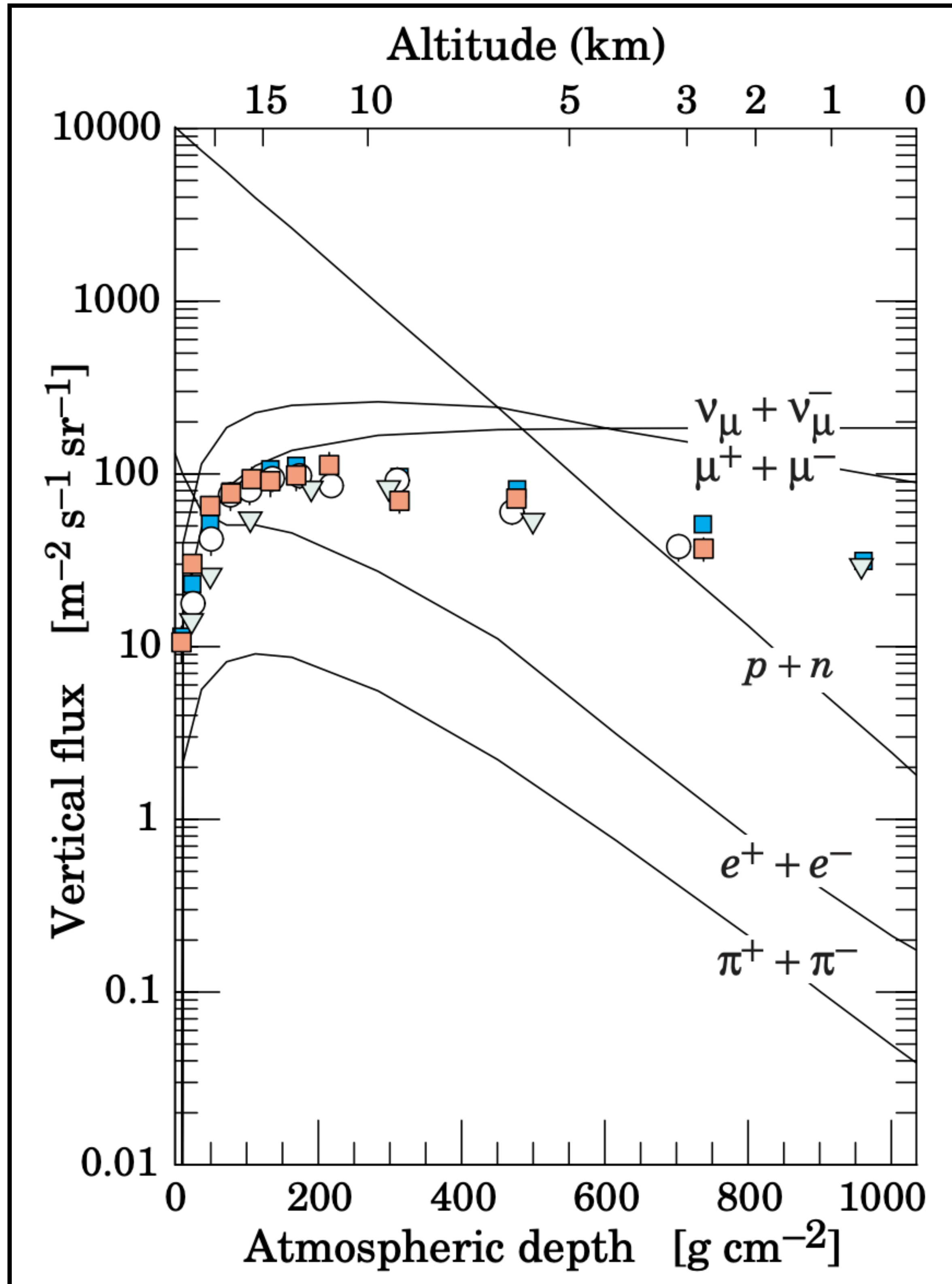
- Clearly IBD is easiest and most common choice
  - Only use non-IBD when necessary to probe the physics: neutrino magnetic moments, SM cross-section tests, etc. etc.



Cosmic Neutrons

- Where do neutrons come from?
- Cosmogenic radiation
  - ‘primary neutrons’
    - Not necessarily cosmic; some produced in atmosphere too

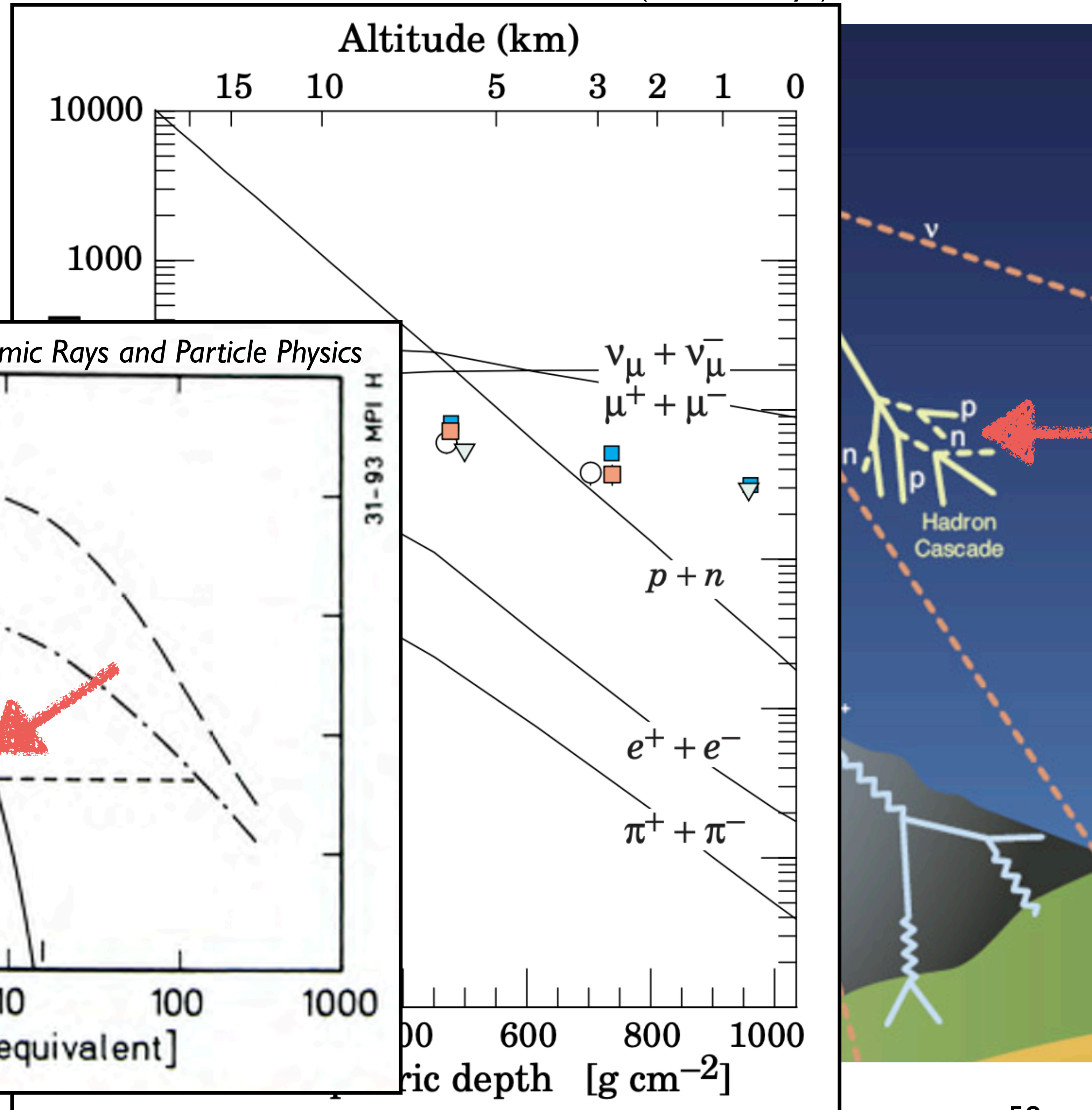
From PDG, Sec. 30 (Cosmic Rays)



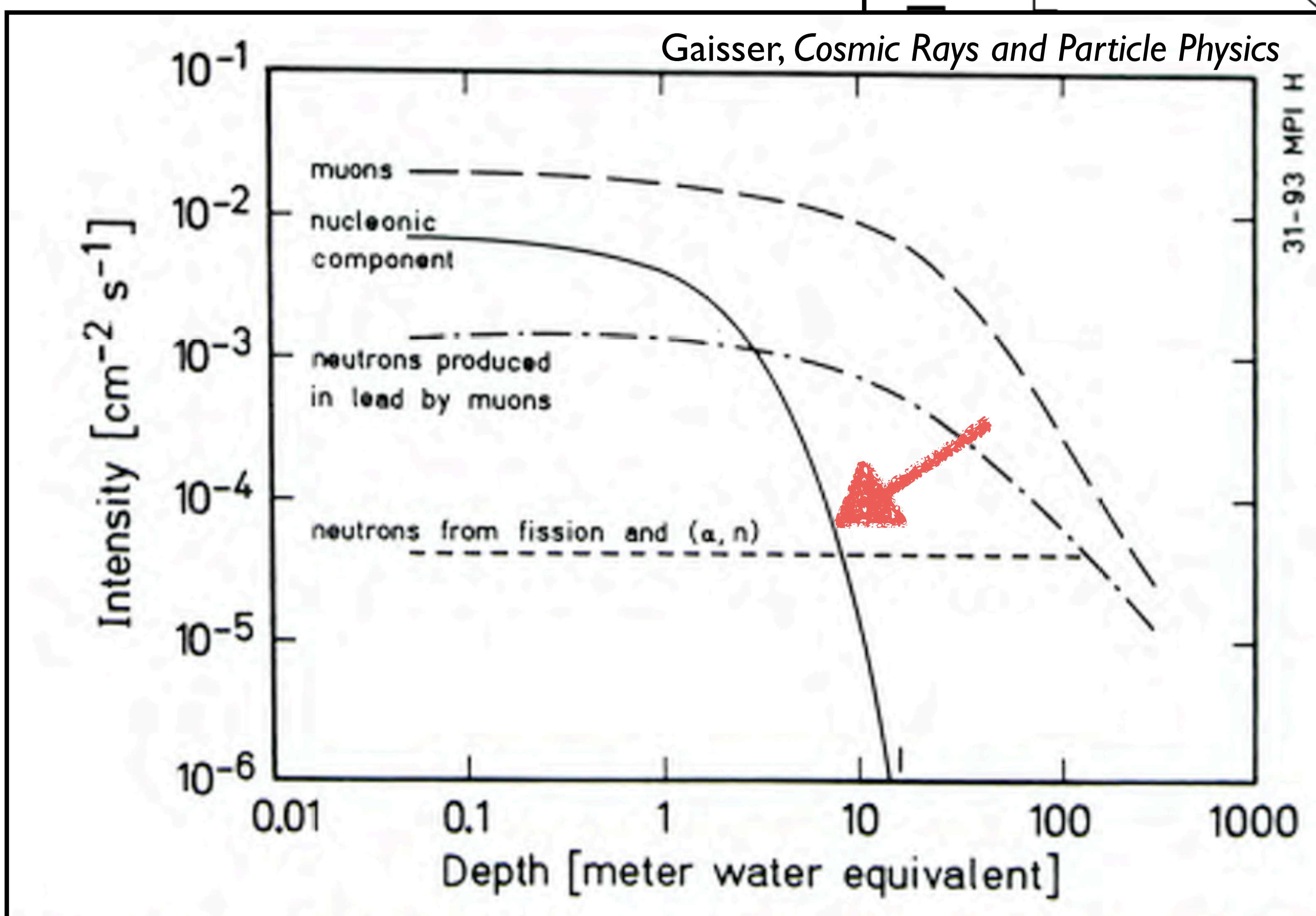
Cosmic Neutrons

- Where do neutrons come from?
- Cosmogenic radiation
  - ‘primary neutrons’
    - 'Very easily’ shielded: just add a few meters of concrete…

From PDG, Sec. 30 (Cosmic Rays)



Gaisser, *Cosmic Rays and Particle Physics*



Aside: Everyone Cares About Neutrons!

- NOTE: final-state n from weak GeV-scale <u>μ</u>-A interactions!
- Hmmm… what about weak GeV-scale <u>ν_μ</u>-A interactions?
- So it's not just reactor nu folks who should care about how we detect neutrons!

ArgoNeuT, hep-ex[1810.06502] MINERvA, hep-ex[1901.04892]

NOvA, hep-ex[1906.04907]

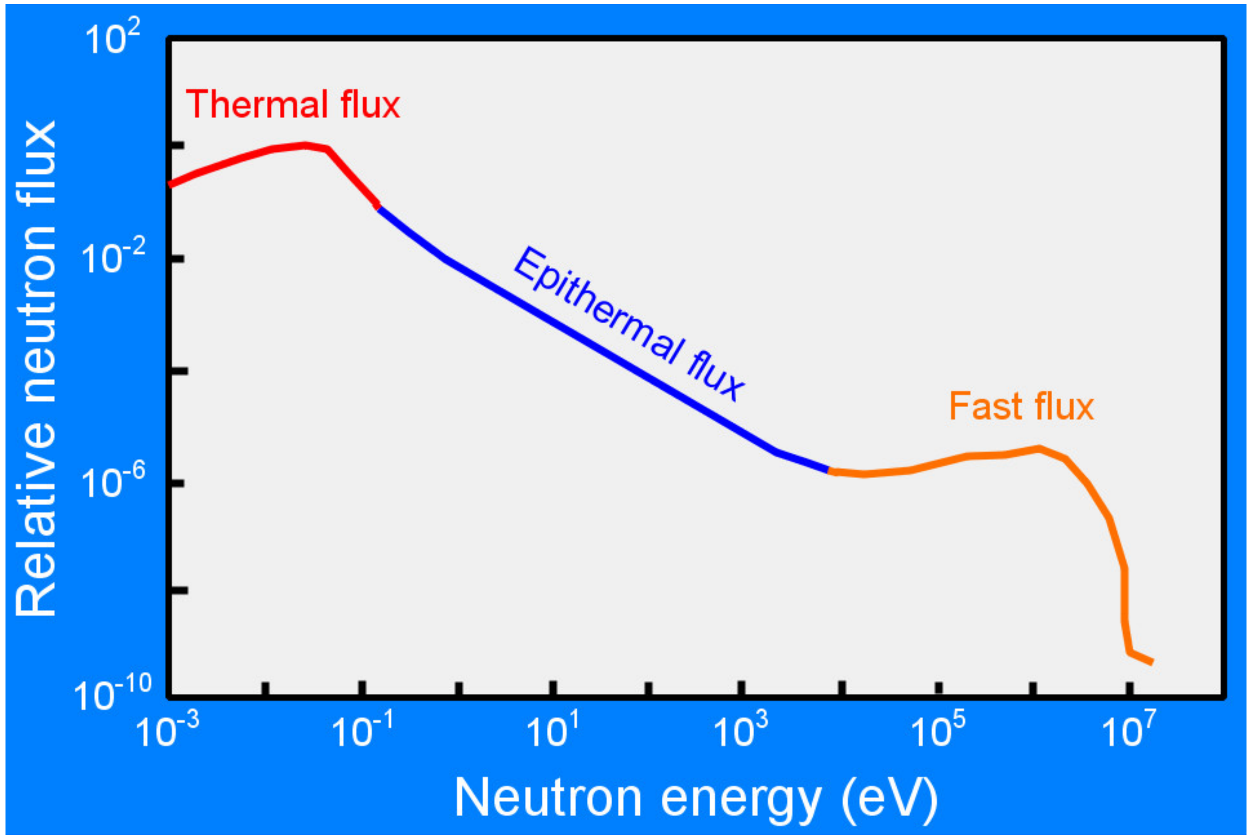
KamLAND, hep-ex[0907.0066]

	Simulated production yield ($\times 10^{-7}\mu^{-1}\mathrm{g}^{-1}\mathrm{cm}^2$)	Ratio of Simulated Production Yields for μ^+/μ^-	Ratio of Simulated Production Yields for Spectrum/monoenergetic	Power-law exp.	Primary process
n	2344 ± 4	0.969 ± 0.002	0.912 ± 0.003	0.779 ± 0.001	$\pi^- + {}^1\mathrm{H}, {}^{12}\mathrm{C}$
${}^{11}\mathrm{C}$	460.8 ± 1.7	0.971 ± 0.005	0.913 ± 0.006	0.703 ± 0.002	${}^{12}\mathrm{C}(\gamma, n)$
${}^{7}\mathrm{Be}$	116.8 ± 0.9	0.986 ± 0.011	0.945 ± 0.011	0.684 ± 0.004	${}^{12}\mathrm{C}(\gamma, n\alpha)$
${}^{10}\mathrm{Be}$	44.63 ± 0.53	0.960 ± 0.018	0.891 ± 0.019	0.825 ± 0.007	${}^{12}\mathrm{C}(n, {}^3\mathrm{He})$
${}^{12}\mathrm{B}$	30.85 ± 0.44	0.970 ± 0.021	0.936 ± 0.022	0.828 ± 0.009	${}^{12}\mathrm{C}(n, p)$
${}^{8}\mathrm{Li}$	23.42 ± 0.39	0.927 ± 0.026	0.936 ± 0.025	0.821 ± 0.010	${}^{12}\mathrm{C}(n, p\alpha)$
${}^{10}\mathrm{C}$	21.13 ± 0.37	0.982 ± 0.025	0.915 ± 0.027	0.810 ± 0.010	${}^{12}\mathrm{C}(\pi^+, np)$
${}^{6}\mathrm{He}$	13.40 ± 0.29	0.916 ± 0.035	0.918 ± 0.035	0.818 ± 0.013	${}^{12}\mathrm{C}(n, 2p{}^3\mathrm{He})$
${}^{8}\mathrm{B}$	6.40 ± 0.20	0.996 ± 0.045	0.915 ± 0.050	0.804 ± 0.019	${}^{12}\mathrm{C}(\pi^+, {}^2\mathrm{H}{}^2\mathrm{H})$
${}^{9}\mathrm{Li}$	3.51 ± 0.15	0.856 ± 0.074	0.842 ± 0.078	0.801 ± 0.026	${}^{12}\mathrm{C}(\pi^-, {}^3\mathrm{He})$
${}^{9}\mathrm{C}$	1.49 ± 0.10	0.850 ± 0.114	0.949 ± 0.102	0.772 ± 0.039	${}^{12}\mathrm{C}(\pi^+, {}^3\mathrm{H})$
${}^{12}\mathrm{N}$	0.86 ± 0.07	0.963 ± 0.128	1.006 ± 0.120	0.921 ± 0.045	${}^{12}\mathrm{C}(p, n)$
${}^{11}\mathrm{Be}$	0.94 ± 0.08	0.842 ± 0.145	0.804 ± 0.161	0.753 ± 0.051	${}^{12}\mathrm{C}(n, 2p)$

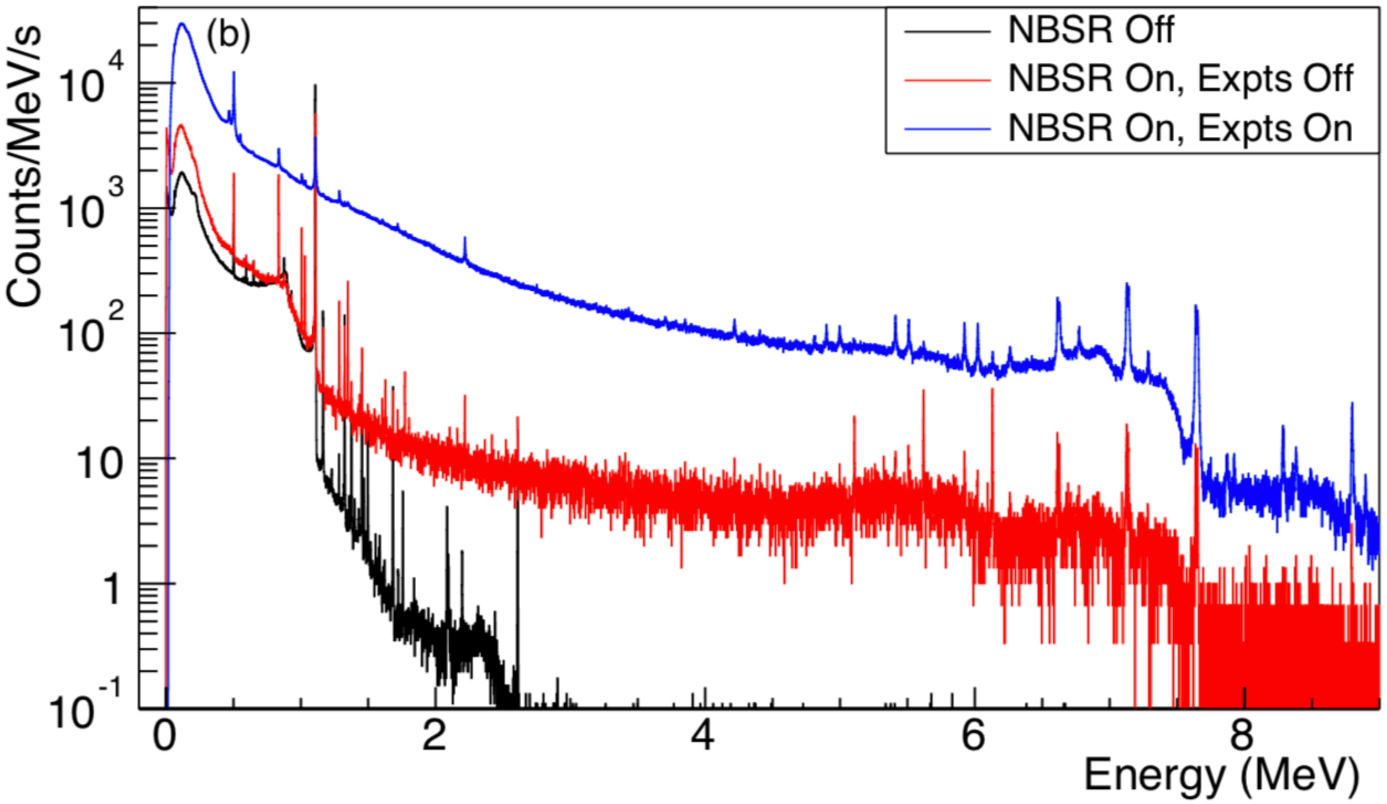
Reactor Neutrons

- Reactors make LOTS of neutrons — it's their job!
  - Practically all are below 10MeV — fairly easy to stop or slow them down
  - Once slow, they just capture on stuff — just a single (non-IBD-like) signal
- So — even for short-baseline Rx experiments, reactor neutrons produce few direct IBD-like signals in a detector
  - Rx neutrons <u>**can**</u> produce CRAZY high gamma fluxes, though!

google 'reactor neutron energies'



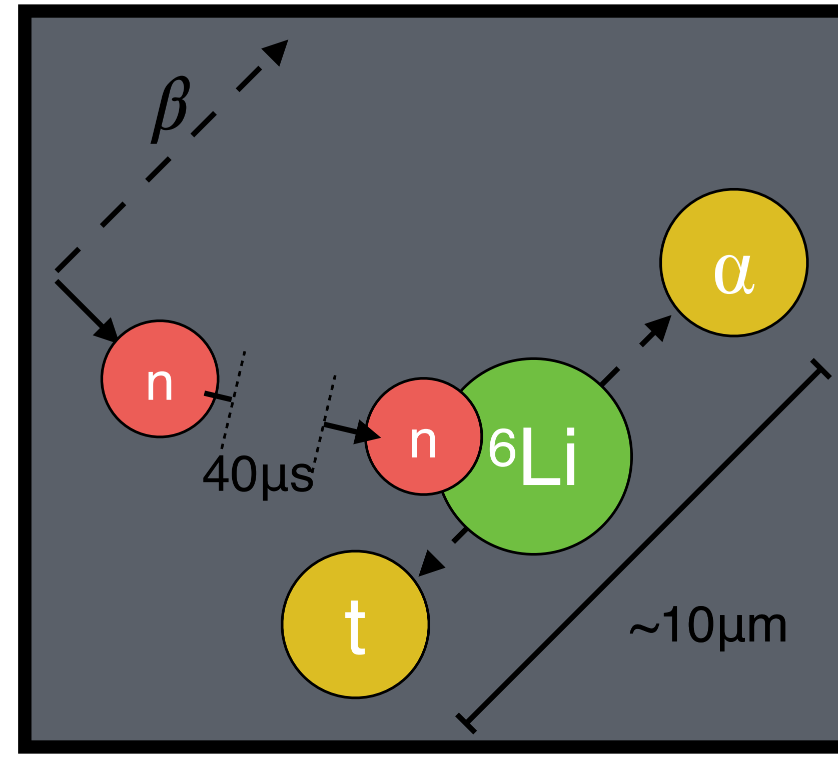
PROSPECT, hep-ex[1506.03547]

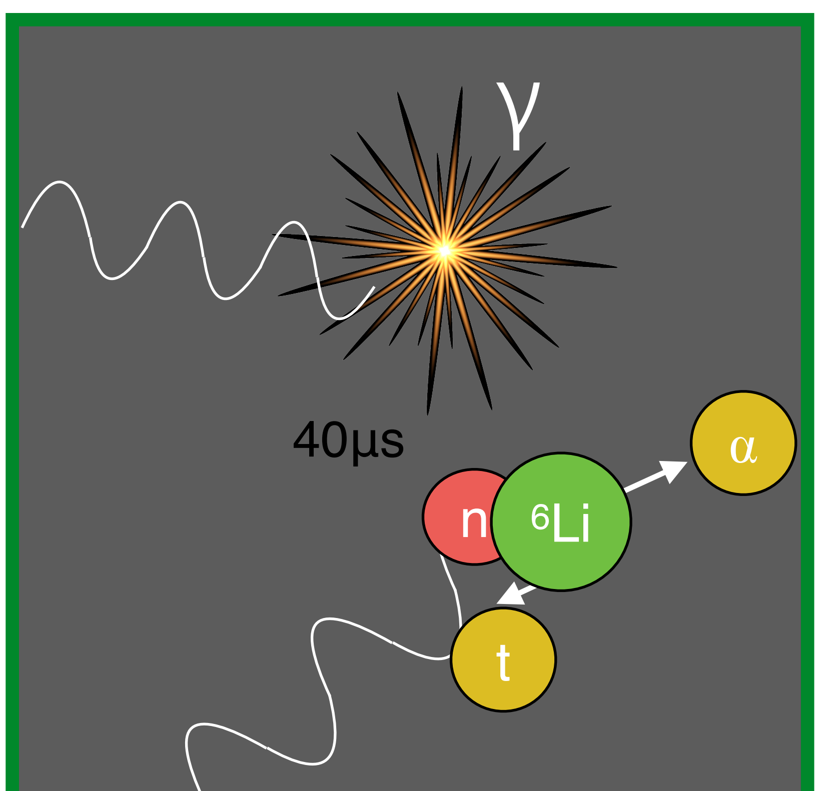


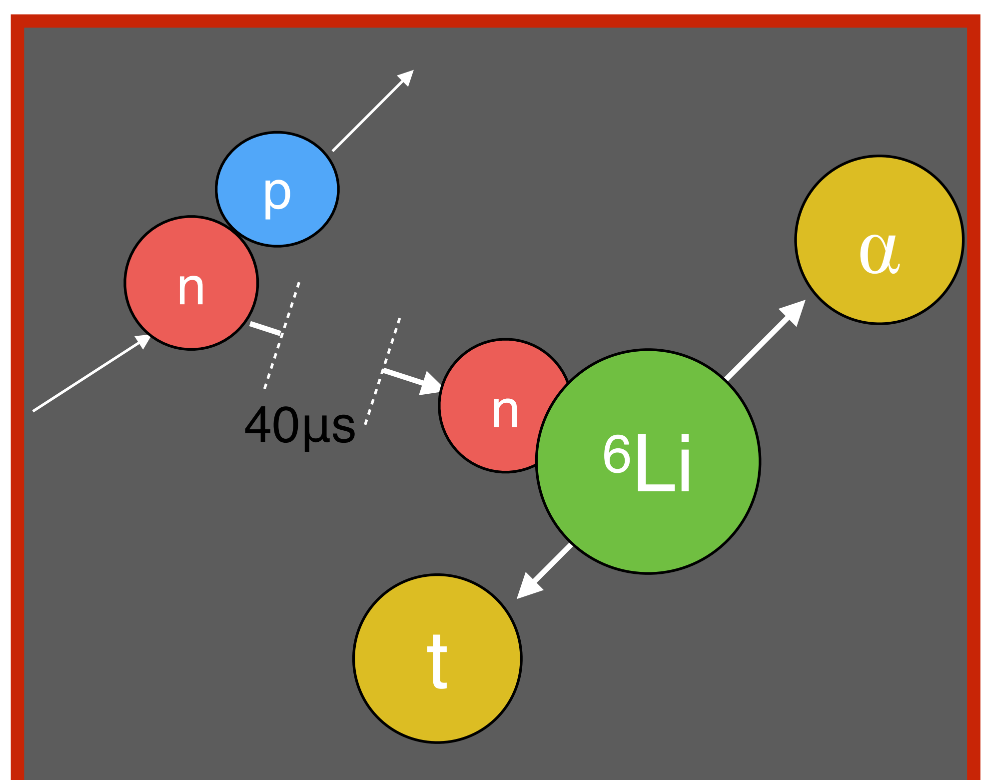
https://bit.ly/2Zxm0pm

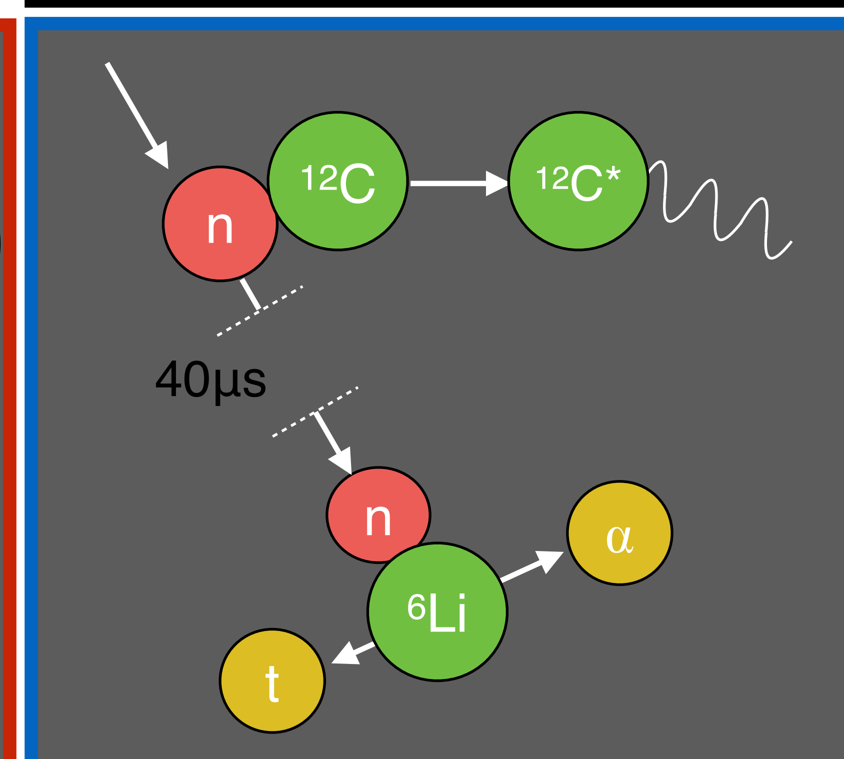
Neutron Background Possibilities

- How to make IBD signal from a neutron?
  - Fast neutrons
  - Inelastic scattering
  - Thermal neutron capture
    - Need something else in coincidence here: gammas!
  - Natural emission of neutrons with other stuff (cosmo isotopes, (α,n) interactions)



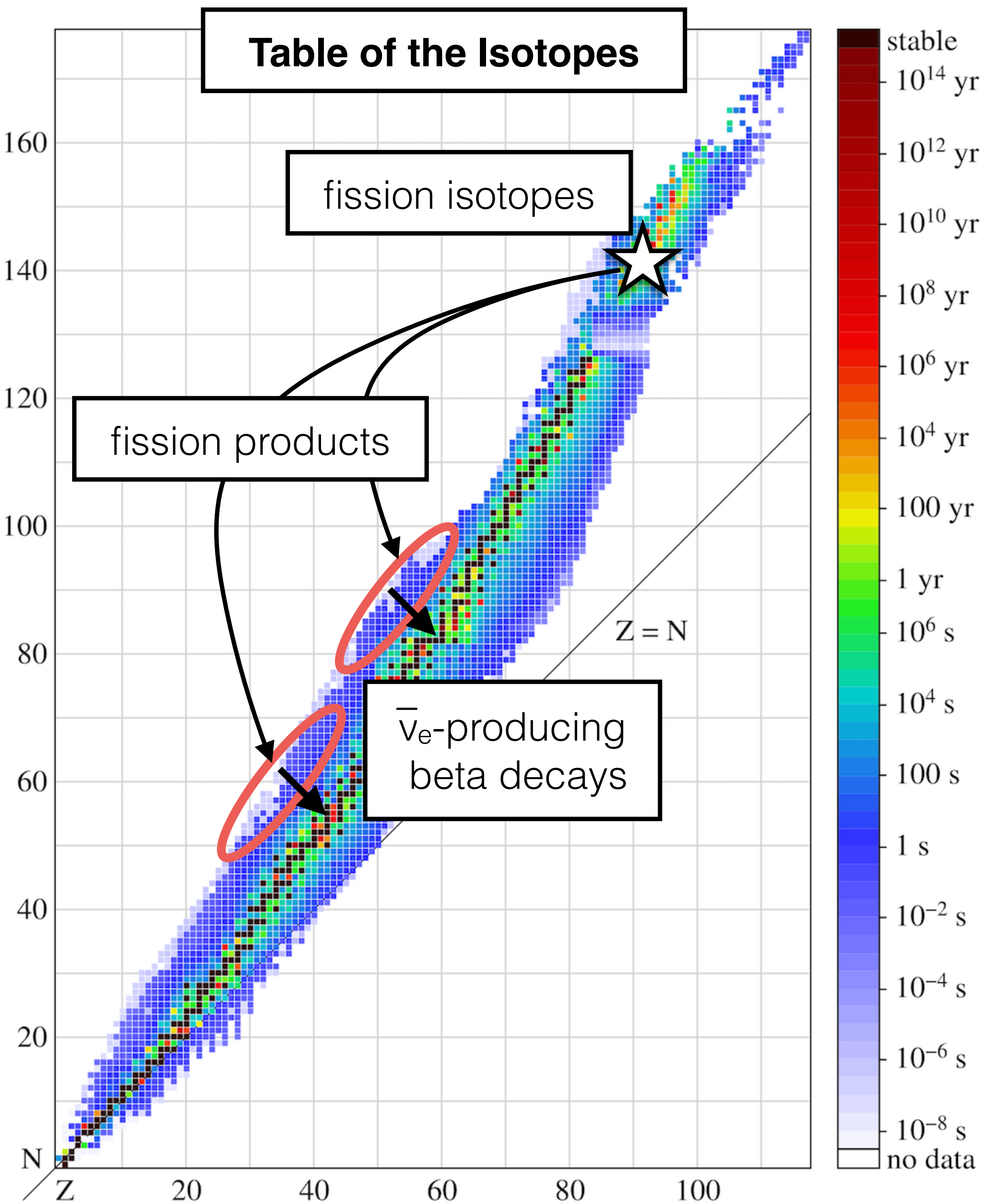


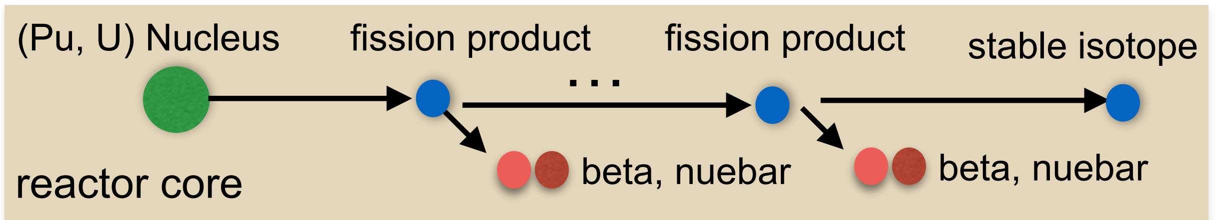


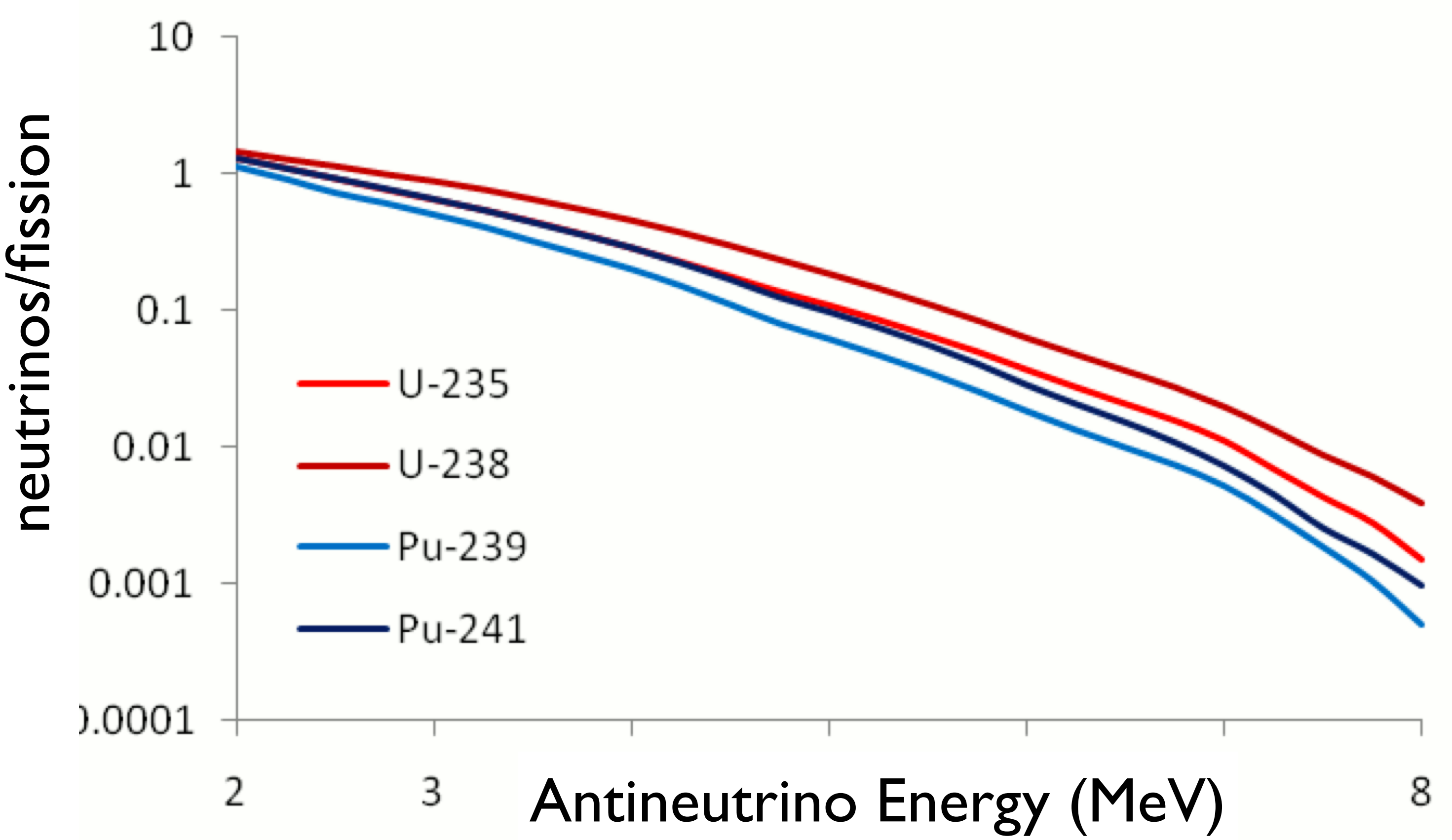


Reactor Antineutrino Production

- Reactor $\bar{\nu}_e$: produced in decay of product beta branches
  - Each isotope: different branches, so different neutrino energies (slightly)







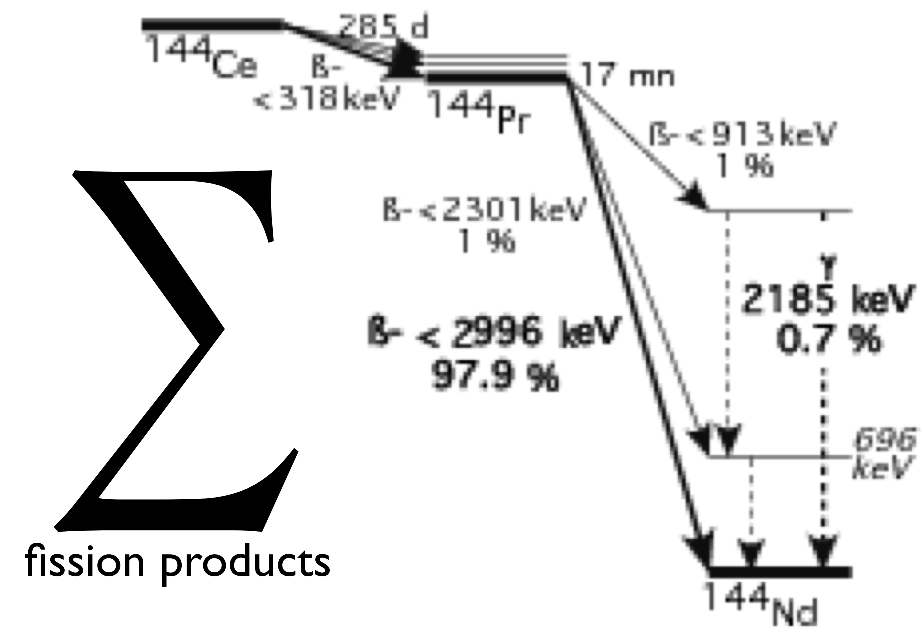
Predicting $S_i(E)$, Neutrinos Per Fission

- Two main methods:

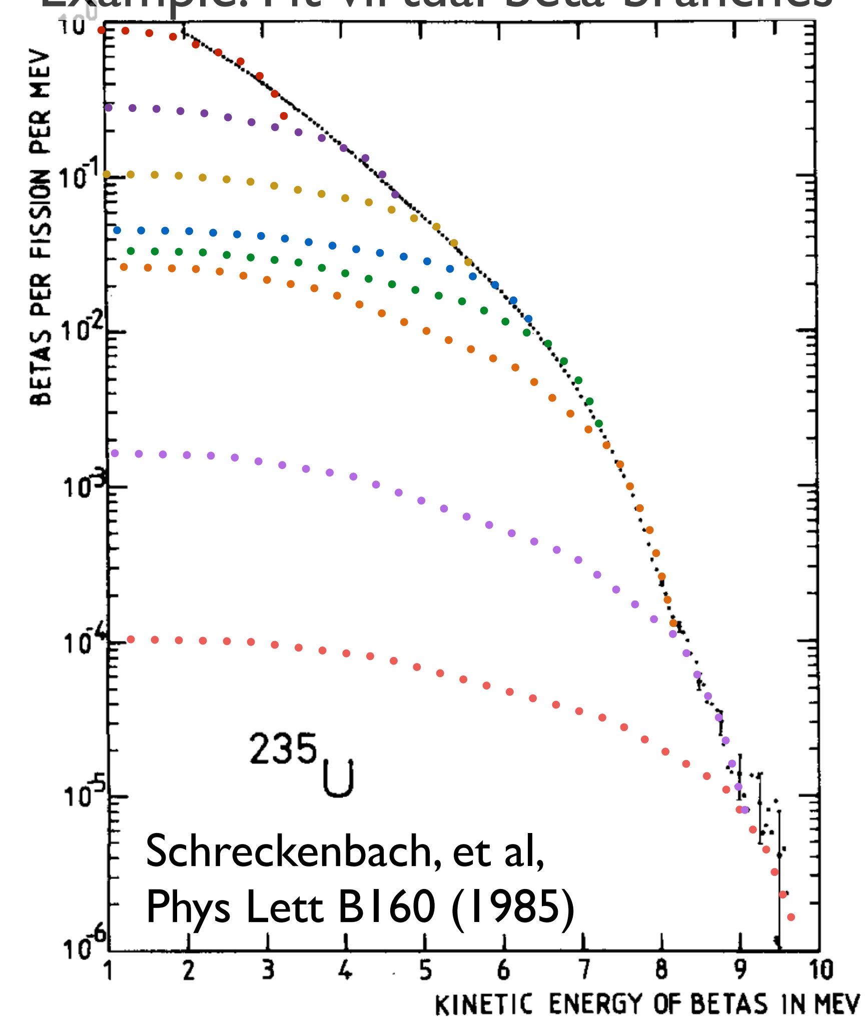
- *Ab Initio* approach:
  - Calculate spectrum branch-by-branch w/ databases: fission yields, decay schemes, …
  - **Problem:** rare isotopes / beta branches: missing, possibly incorrect info…

- Conversion approach
  - Measure beta spectra directly
  - Convert to $\bar{\nu}_e$ using 'virtual beta branches'
  - **Problem:** 'Virtual' spectra not well-defined: what forbiddenness, charge, etc. should they have?
  - 'Preferred' method: smaller error bars

Example: Ce-144 Decay Scheme

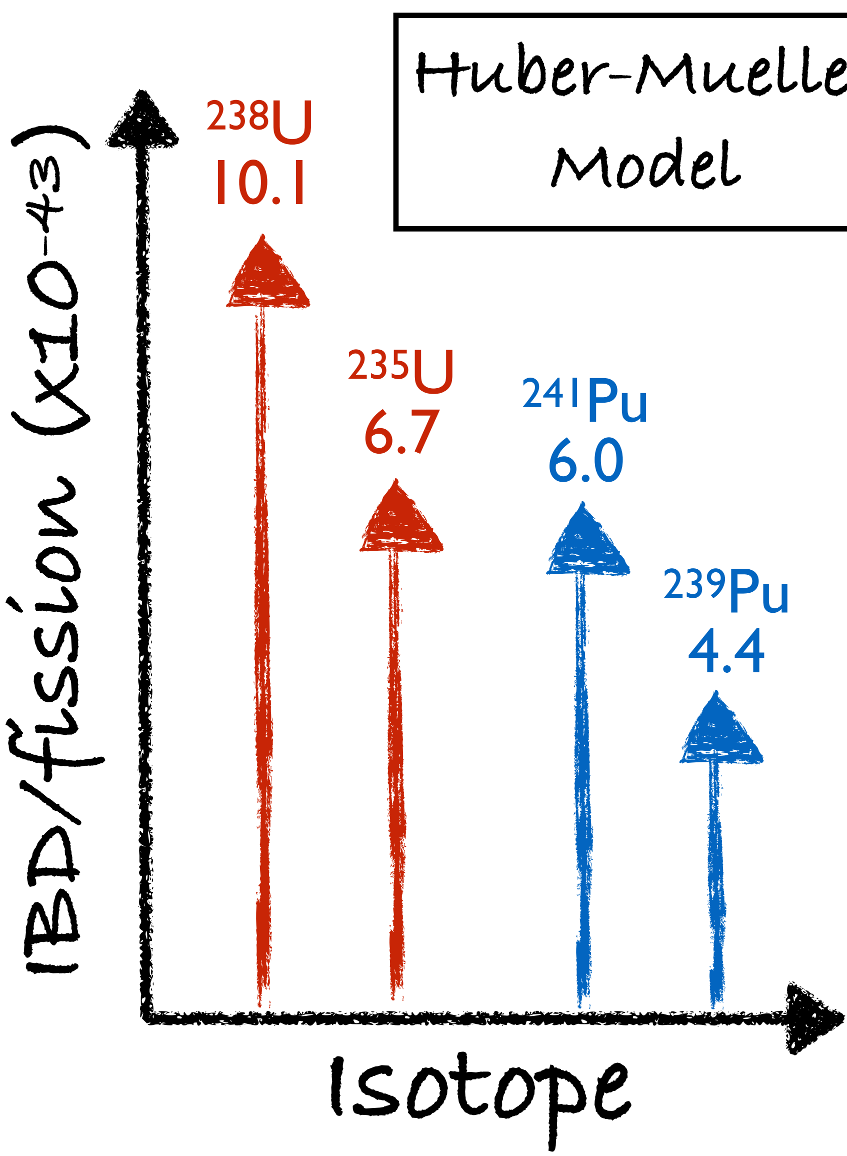


Example: Fit virtual beta branches



Reactor Flux Predictions

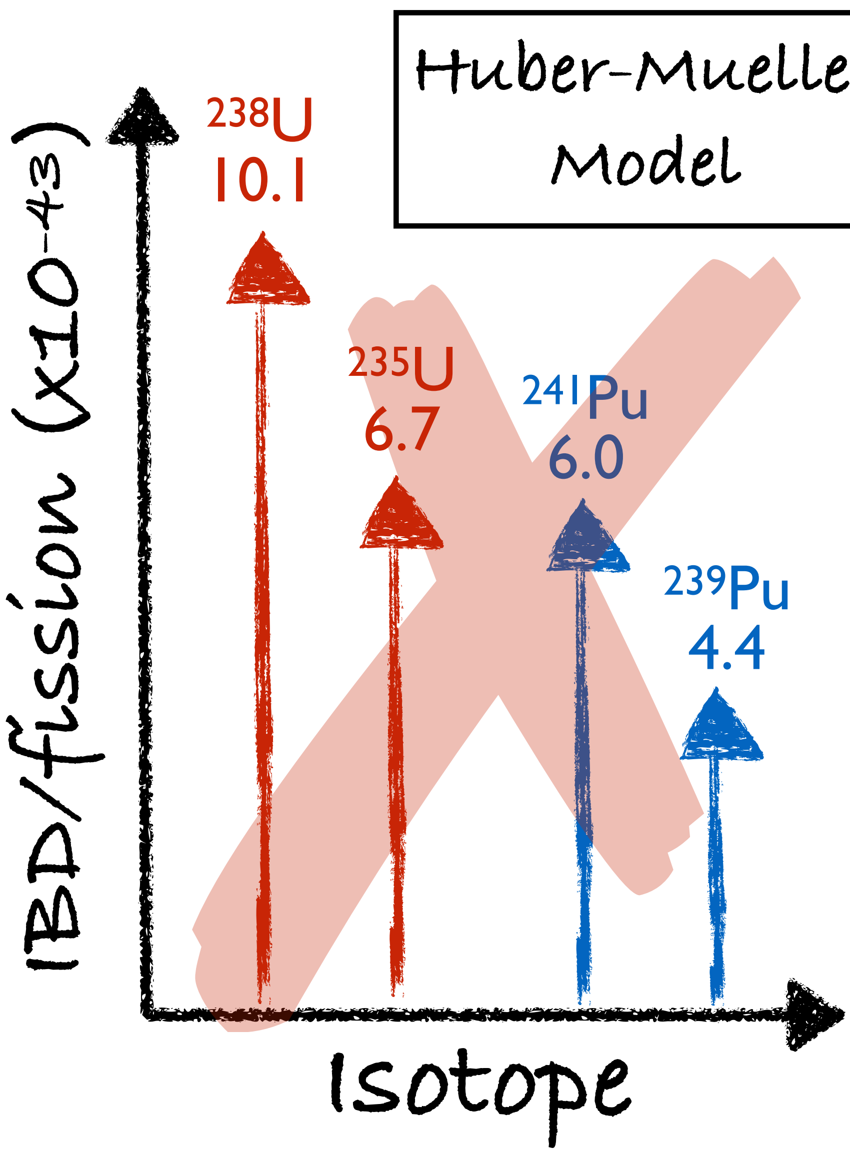
- Three isotopes' $\bar{\nu}_e$ flux predictions re-formulated in 2011
  - Note: 'flux' often cited as IBD per fission, or 'IBD yield': flux * cross-section

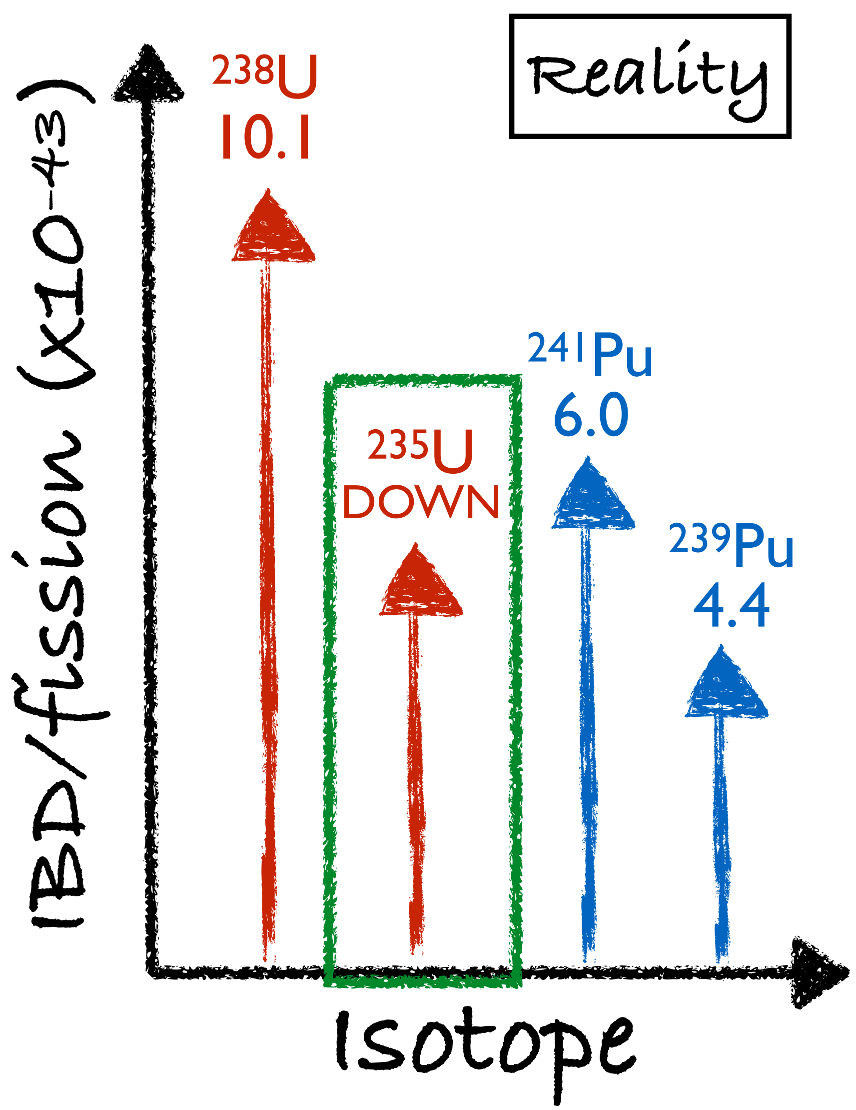


Mueller, *et al*, Phys. Rev. C83 (2011)
Mention, *et al*, Phys. Rev. D83 (2011)
Huber, Phys. Rev. C84 (2011)

Bad Flux Predictions

- Hypothesis: Something is wrong with the flux predictions
  - Theorists have come up with lots of reasons predictions could be bad
  - Could be just <u>one</u> isotope; or could be <u>all</u> isotopes.

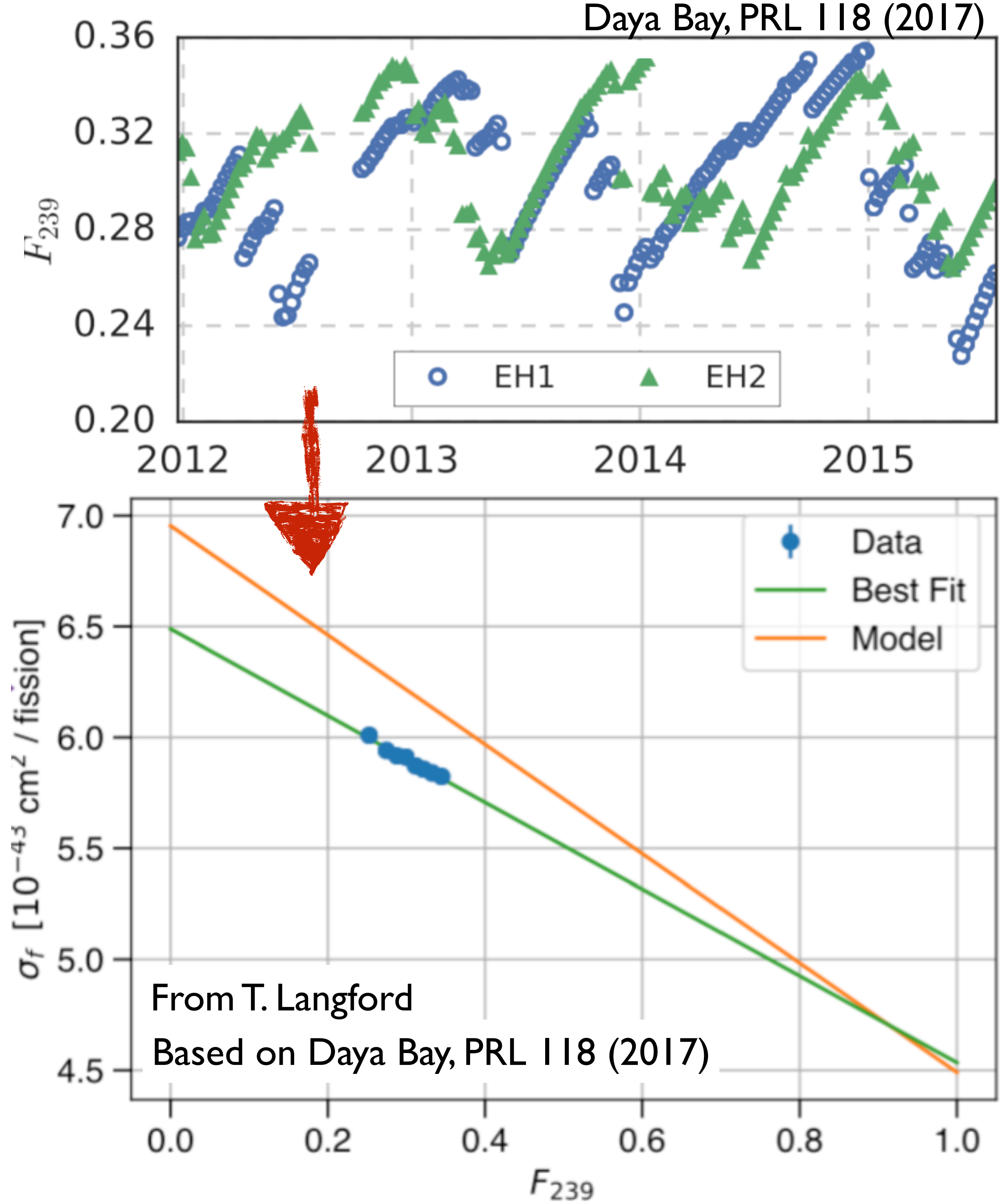




Testing Fluxes: Daya Bay Evolution

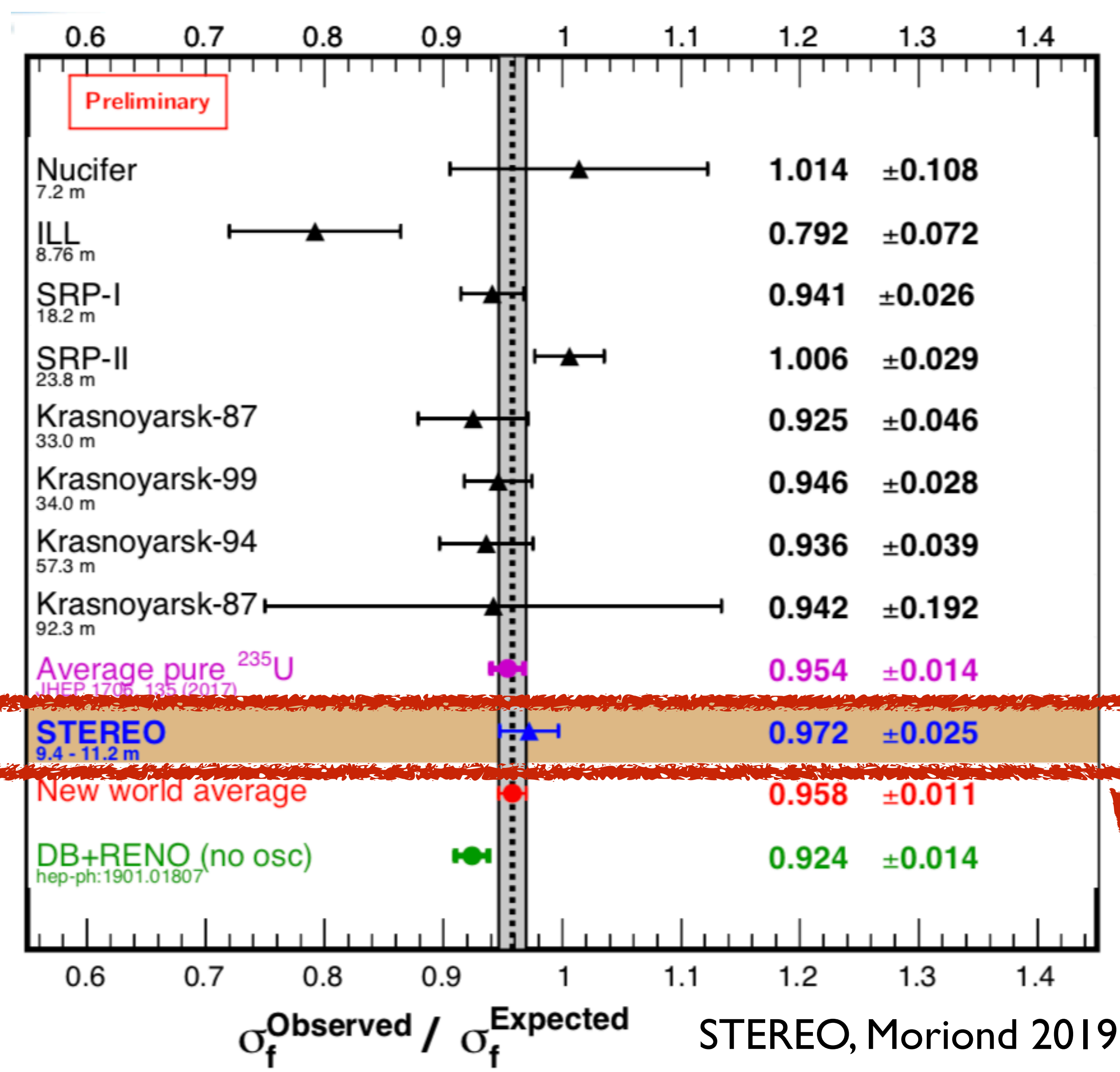
- Measure IBD yields during periods with differing fuel content.
- Flux anomaly's size depends on how much ^{235}U is burning
- Sterile neutrinos cannot explain this result
- Points towards flux problems

Daya Bay, PRL 118 (2017)

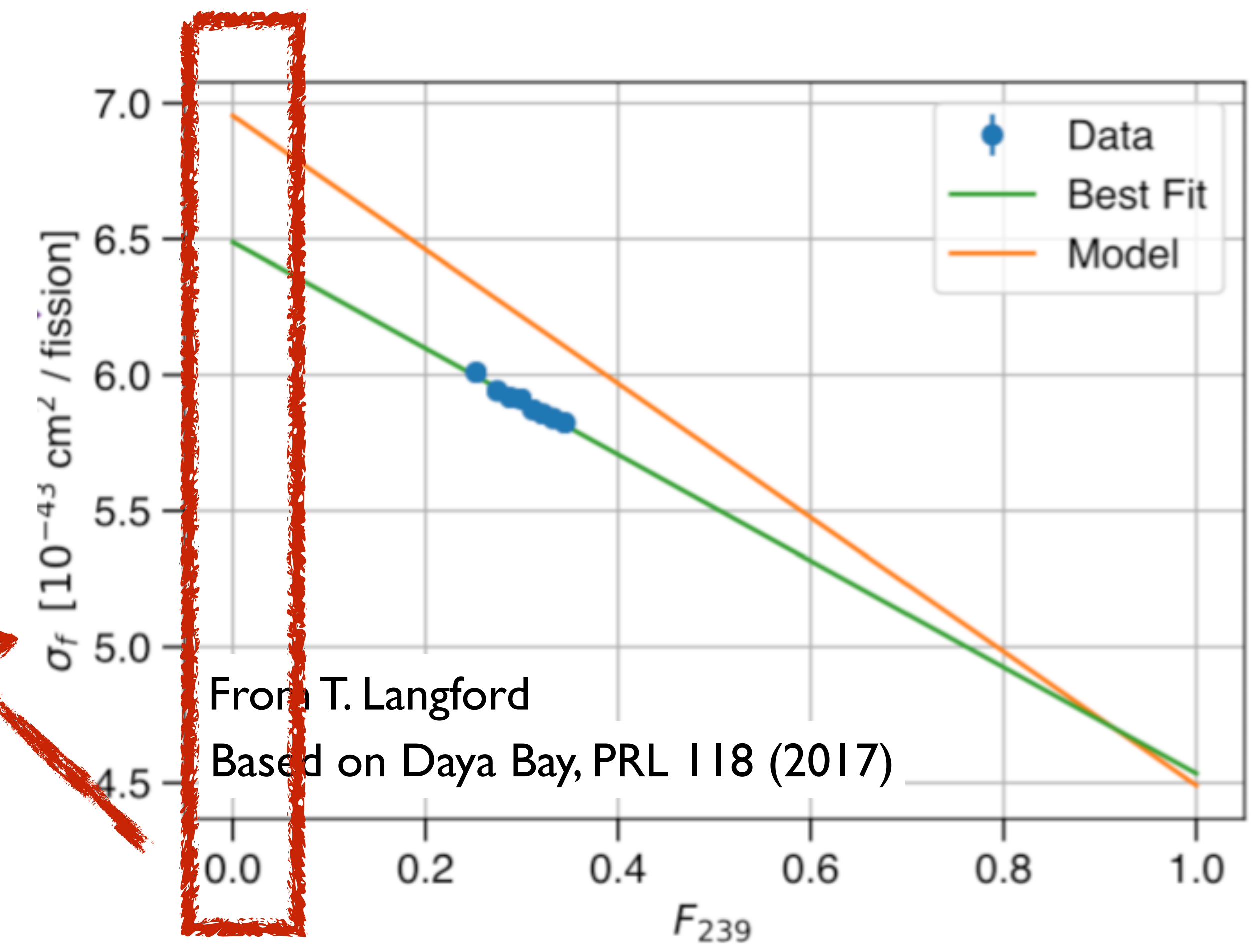


Testing Fluxes: Daya Bay Evolution

- Measure IBD yields during periods with differing fuel content.
- Instead: measure ^{235}U all by itself!
- New STEREO preliminary result: see modest flux deficit
  - Error bars are quite large; still investigating; not published yet…



STEREO, Moriond 2019

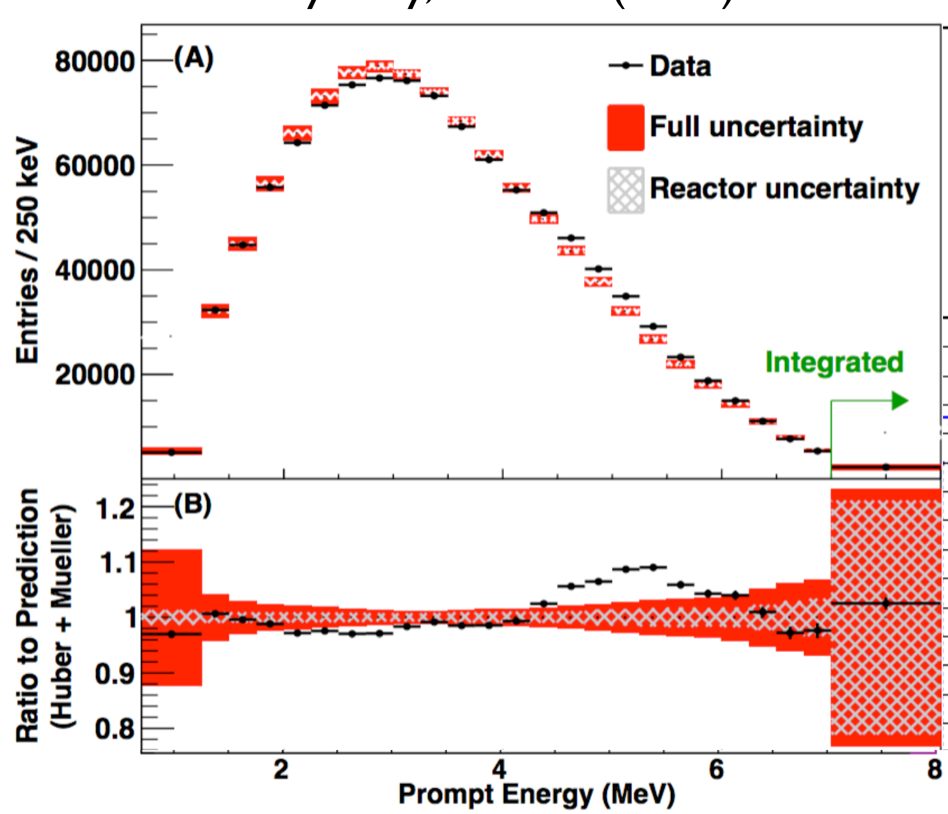


From T. Langford
Based on Daya Bay, PRL 118 (2017)

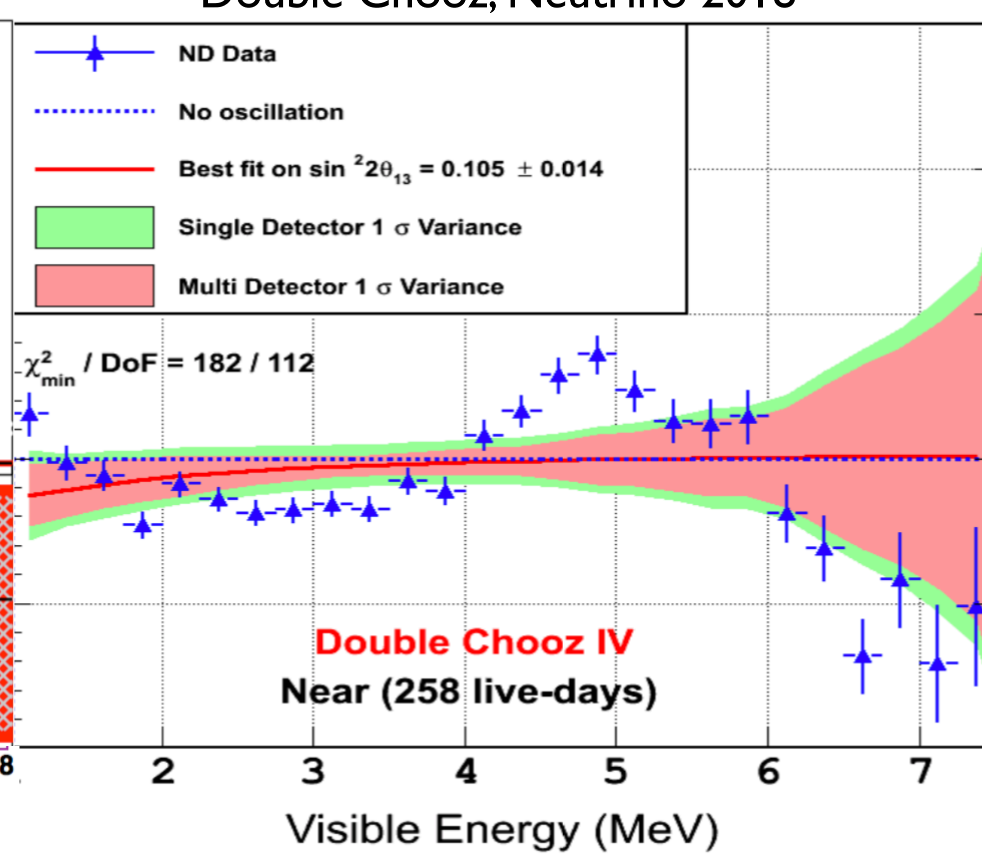
Reactor Spectrum Anomaly

- Bad news: these spectrum predictions don't match the data.
  - Eye is first drawn to the 'bump' in the 4-6 MeV range.
  - Zooming out: kinda just looks bad generally across the entire spectrum…
- HOW is spectrum incorrectly predicted???
  - Like with flux: is <u>one</u> particular isotope to blame (like ^{235}U)? Or <u>all</u>?
  - Looks like short-baseline ^{235}U measurements can also give new info here!

Daya Bay, CPC 41 (2017)



Double Chooz, Neutrino 2018



RENO, Neutrino 2018