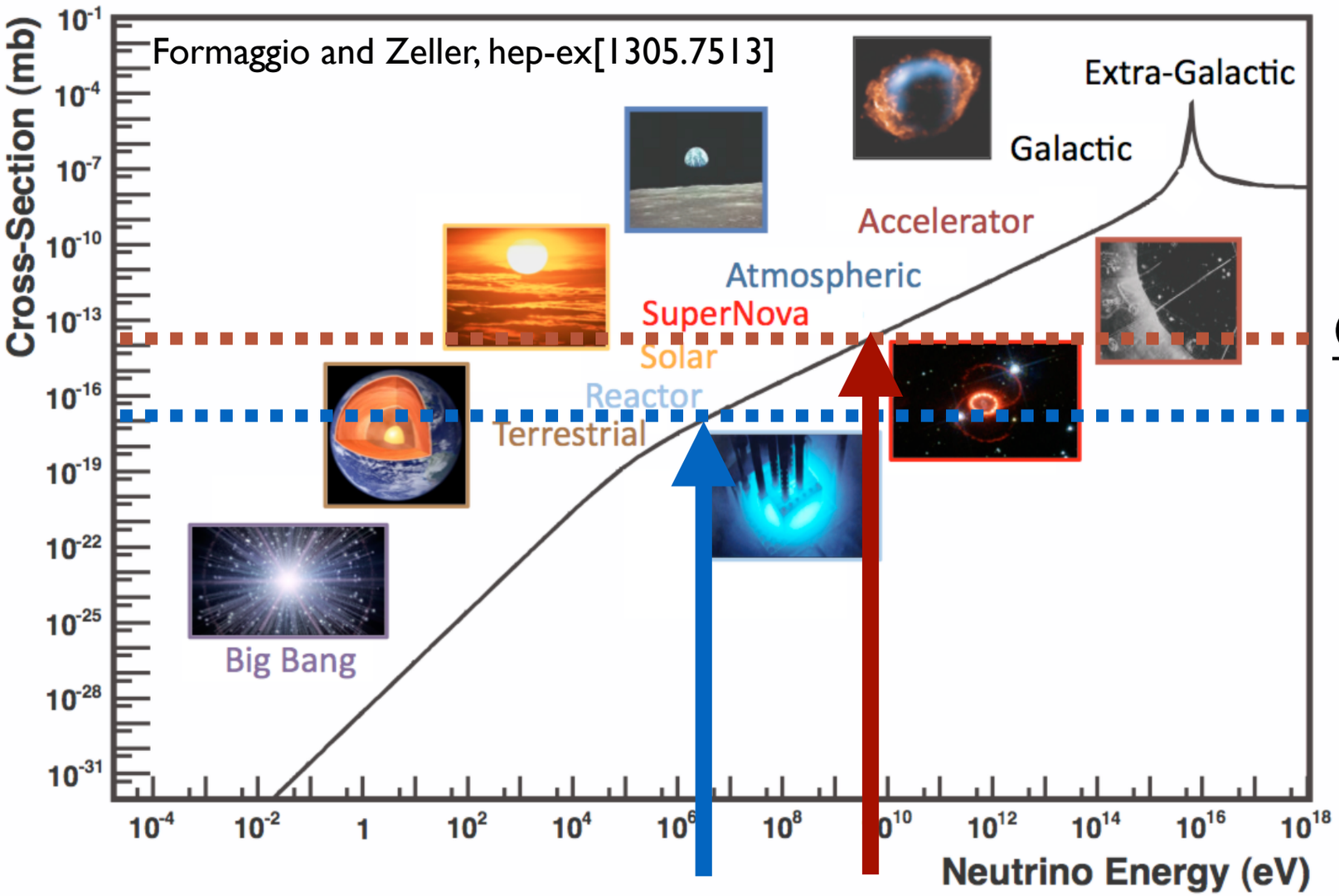
Solar and Reactor Neutrino Experiments

August 7, 2019

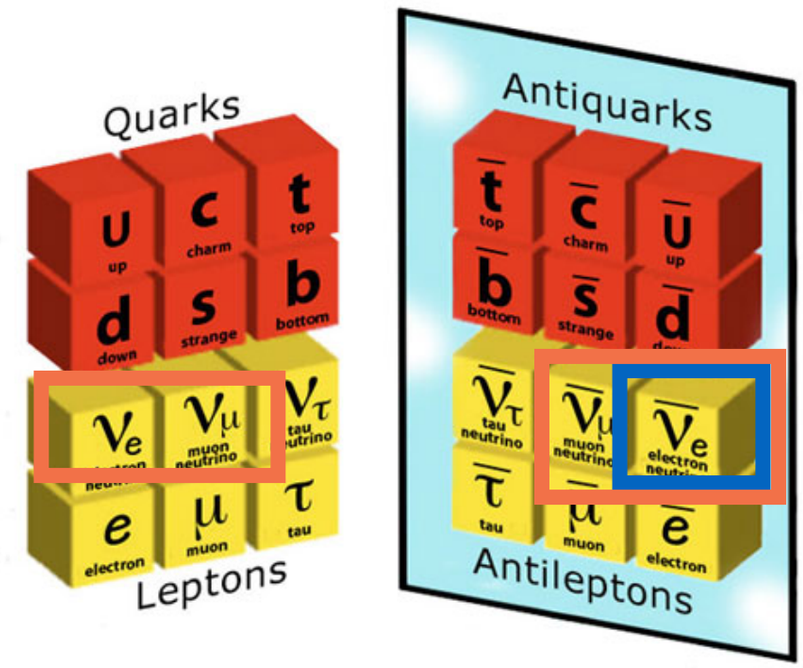
Bryce Littlejohn
Illinois Institute of Technology

Reactor Neutrinos

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



Cross-Sections: much lower!



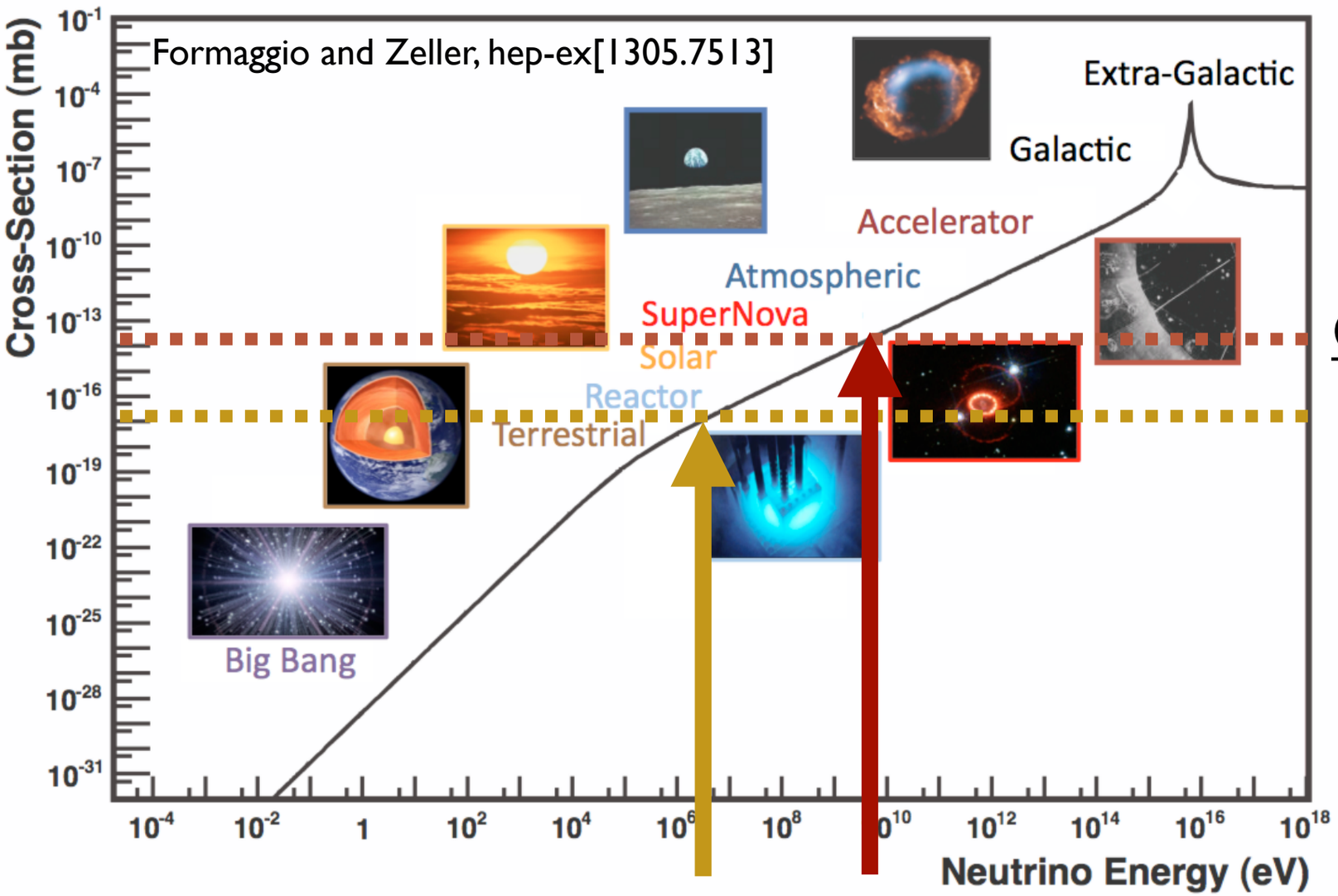
Energy: 0-10 MeV, not 0-10 GeV

Intensity: In 1 minute, a 1GW core makes more ν than all NUMI+BNB ν produced in 2018
(yes, both DAR and DIF ν)

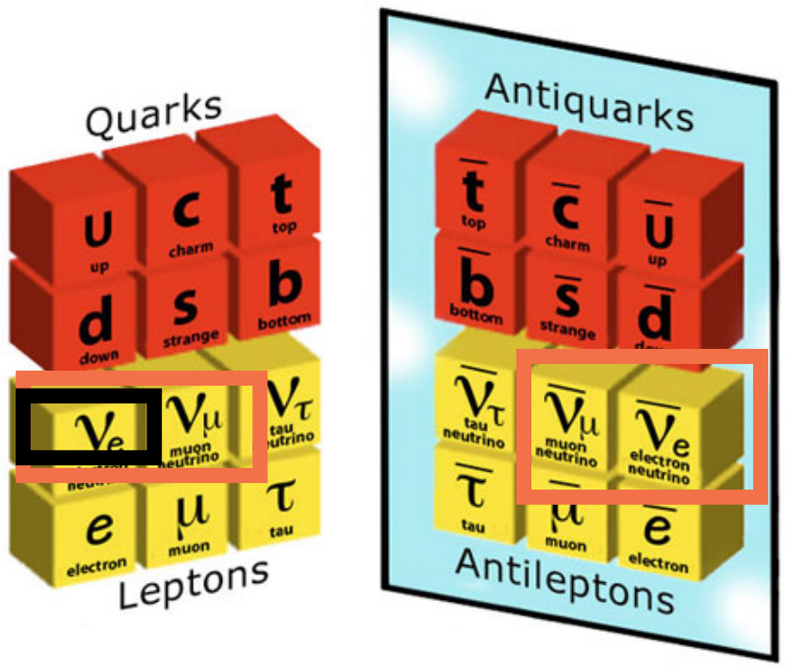
Flavor: $\bar{\nu}_e$ only, not ν_e, ν_μ, $\bar{\nu}_e$, $\bar{\nu}_\mu$

Solar Neutrinos

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



Cross-Sections: much lower!



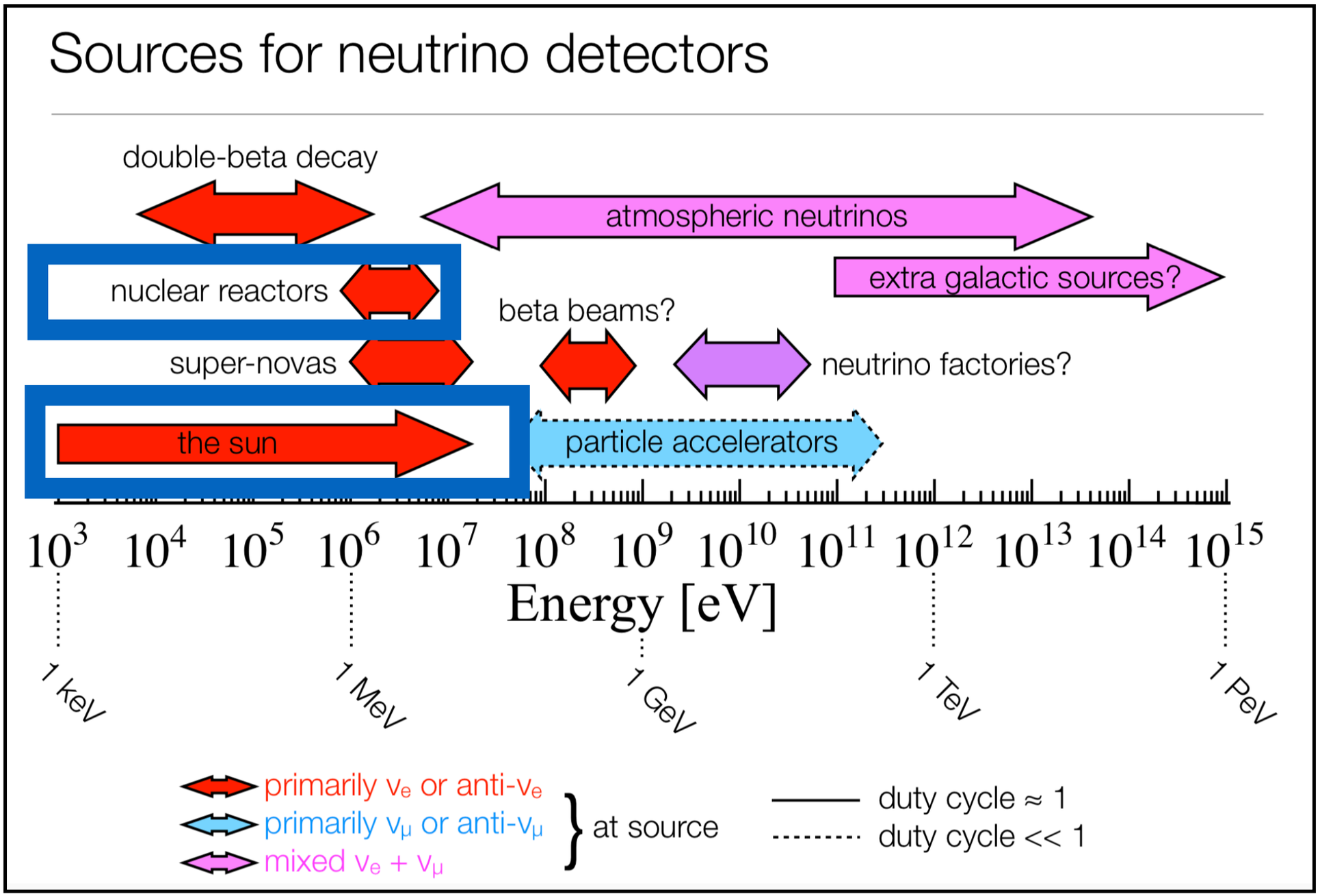
Energy: 0-20 MeV, not 0-10 GeV

Intensity: In 1 femtosecond, THE SUN ν than all NUMI+BNB ν produced in 2018
(yes, both DAR and DIF ν)

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

Solar and Reactor Neutrinos

- From Prof. Messier's slides: talking similar energies here
  - Solar neutrino flux goes to slightly higher energies: ~20, not ~10 MeV



Solar/Reactor Detection

- From Prof. Messier's slides (for an accelerator experimentalist!)

Facts of life for the neutrino experimenter...

Numerical example for typical accelerator-based experiment

$$N_{\rm obs} = \left[\int \mathcal{F}(E_\nu)\sigma(E_\nu,...)\epsilon(E_\nu,...)dE_\nu d...\right]\frac{M}{A\ m_N}T$$

N_{obs}	:	number of neutrino events recorded
$\mathcal{F}$	:	Flux of neutrinos (#/cm^2/s)
σ	:	neutrino cross section per nucleon $\simeq 0.7\frac{E_\nu}{[\mathrm{GeV}]}\times 10^{-38}\mathrm{cm}^2$
ϵ	:	detection efficiency
M	:	total detector mass
A	:	effective atomic number of detector
m_N	:	nucleon mass
T	:	exposure time

typical "super-beam" flux at 1000 km

typical accelerator up time in one year

$$N_{\rm obs} = \left[\frac{1}{\mathrm{cm}^2\mathrm{s}}\right]\left[0.7\times 10^{-38}\frac{E_\nu}{\mathrm{GeV}}\mathrm{cm}^2\right][\epsilon]\,[1\ \mathrm{GeV}]\left[\frac{M}{20\cdot 1.67\times 10^{-27}\ \mathrm{kg}}\right][2\times 10^7\ \mathrm{s}]$$

$$N_{\rm obs} = 4\times 10^{-6}\frac{E_\nu}{[\mathrm{GeV}]}\epsilon\frac{M}{\mathrm{kg}}$$

need detector masses of 10^6 kg = 1 kton to get in the game

work at high energies if you can

push this as high as you can

Challenge to the experimentalist: maximize efficiency and detector mass while minimizing cost

Solar/Reactor Detection

- Comparables for a solar and reactor experimentalist:

Facts of life for the neutrino experimenter...

Numerical example for typical **reactor** *-based experiment*

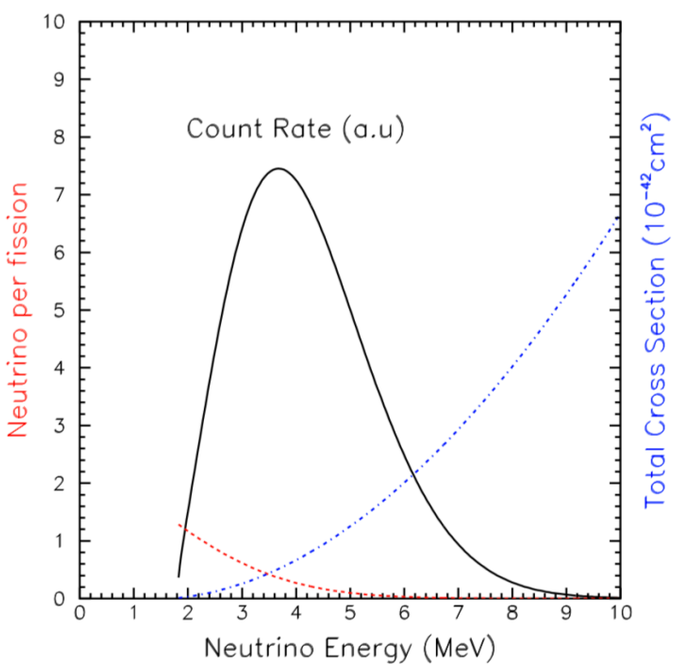
$$\frac{d^2N(E_\nu,t)}{dE_\nu dt} = N_p\sigma(E_\nu)\varepsilon\frac{P(E_\nu,L)}{4\pi L^2}\left(\frac{d^2\phi_r(E_\nu,t)}{dE_\nu dt}\right)$$

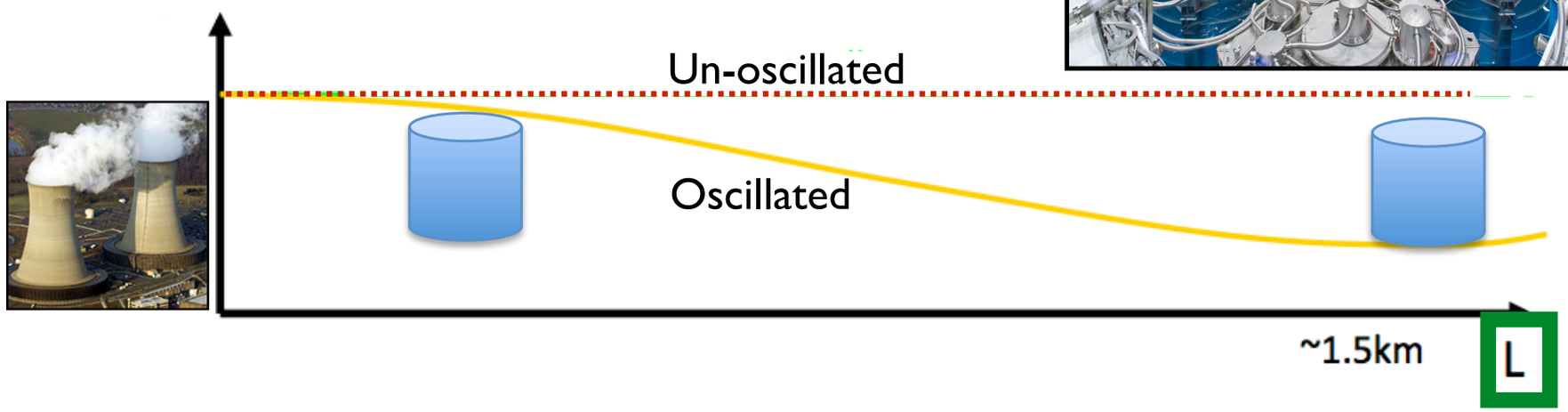
Solar/Reactor Detection

- Detected neutrinos described as:

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

- L: source-detector distance (isotropic emission)
  - Standard sun-earth distance for solar nus…



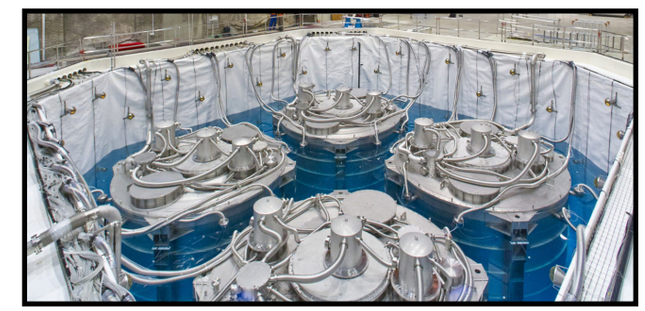


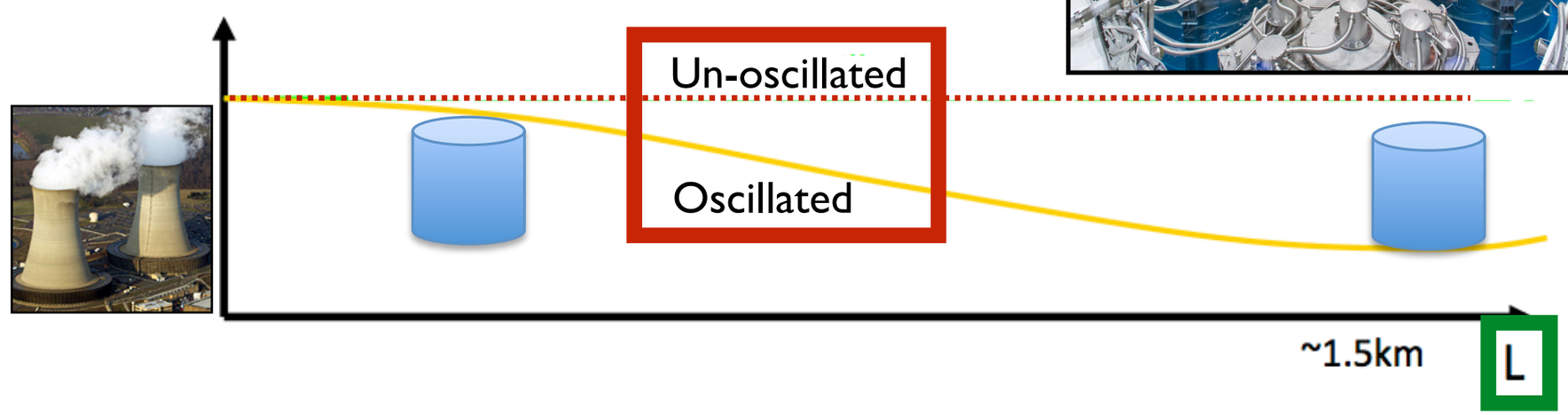
Solar/Reactor Detection

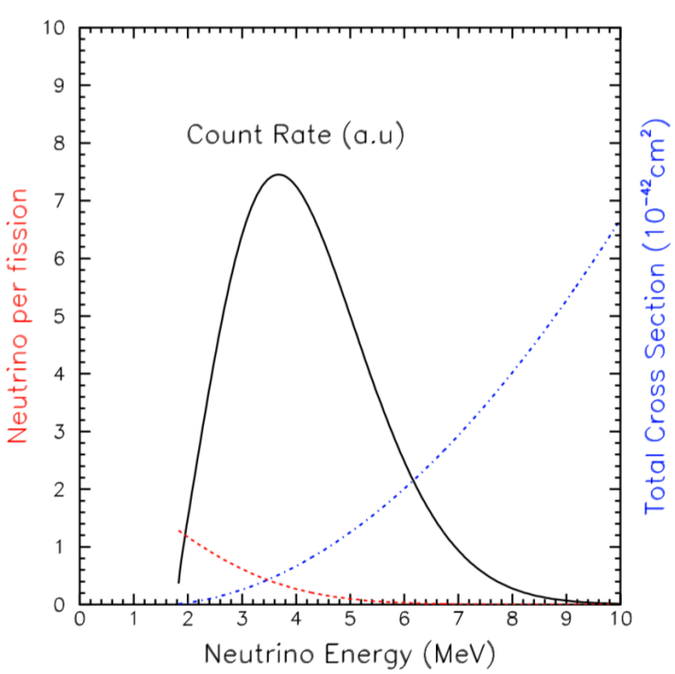
- Detected neutrinos described as:

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

- P: antineutrino disappearance probability





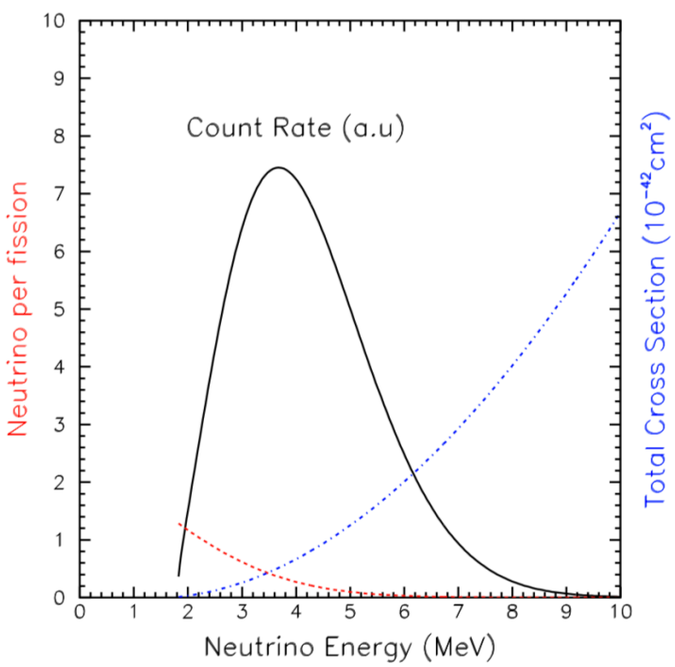


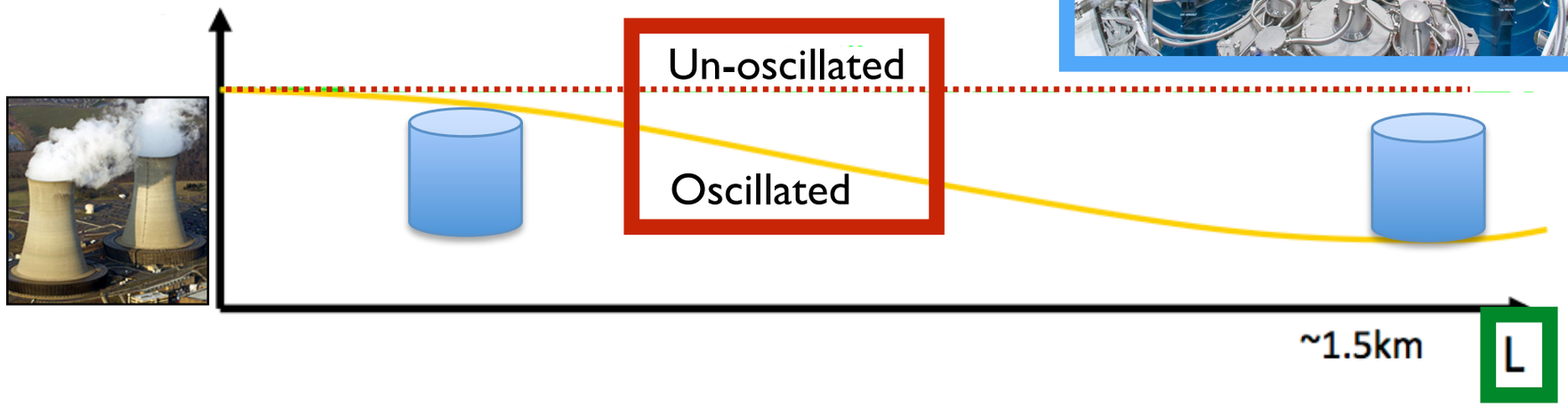
Solar/Reactor Detection

- Detected neutrinos described as:

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

- Proton number and interaction detection efficiency





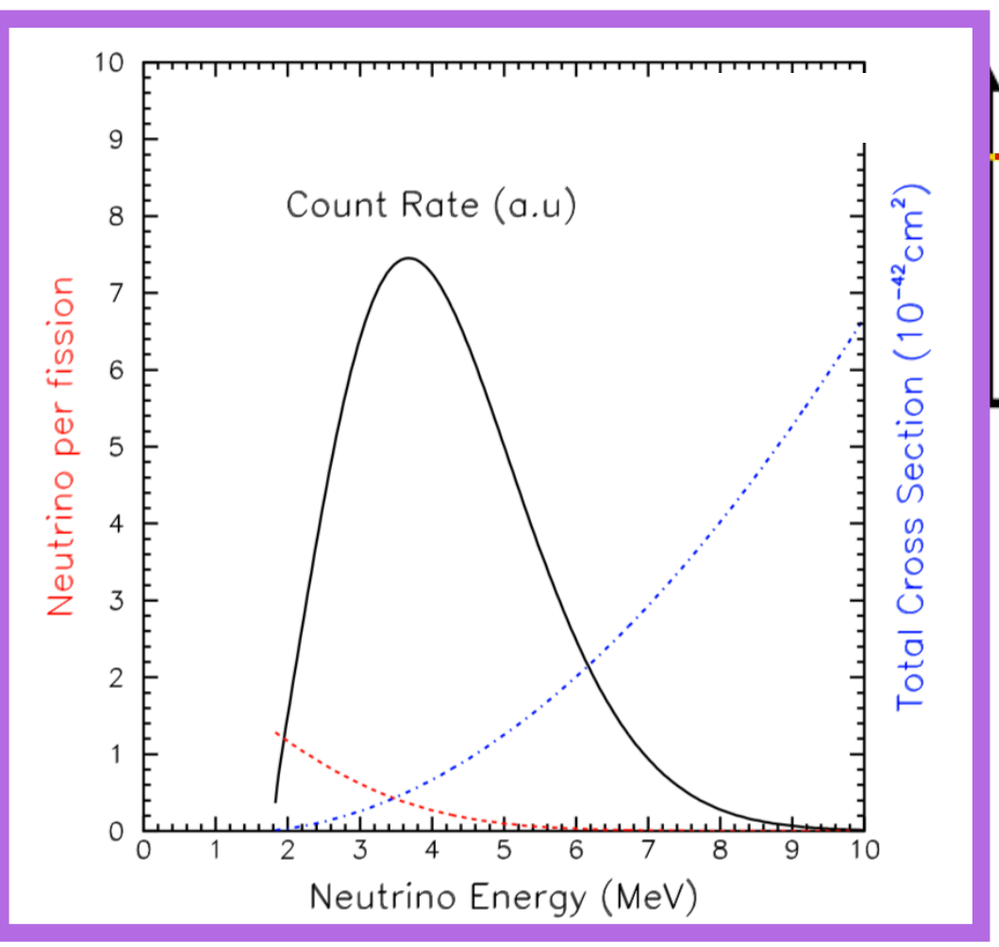
Solar/Reactor Detection

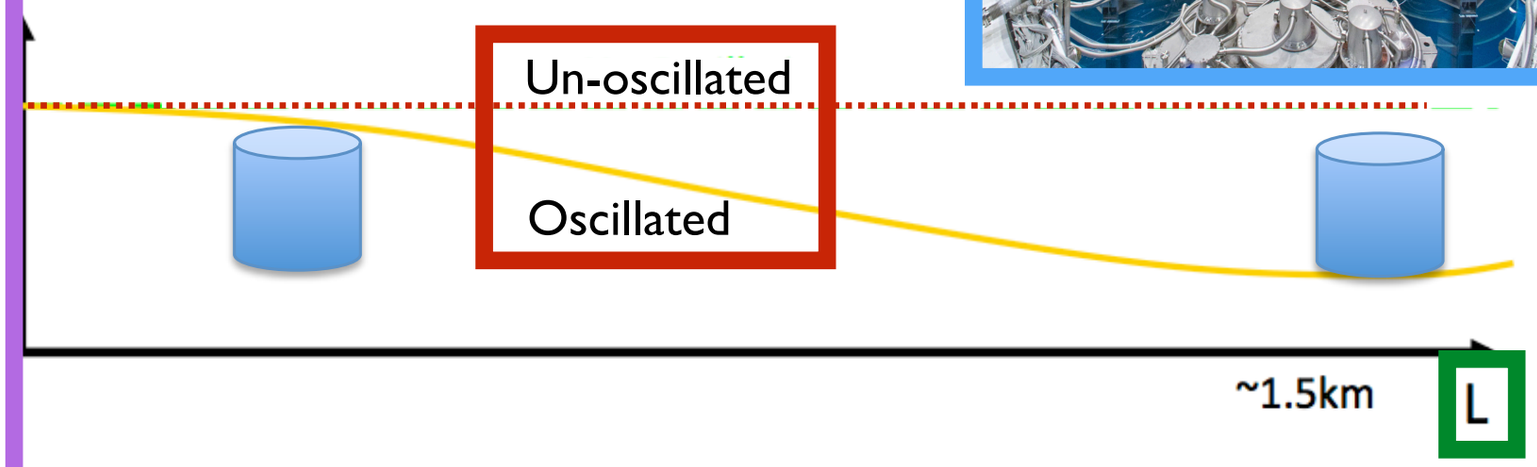
- Detected neutrinos described as:

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

- Production rate and interaction cross-section

Daya Bay, hep-ex[0701029]



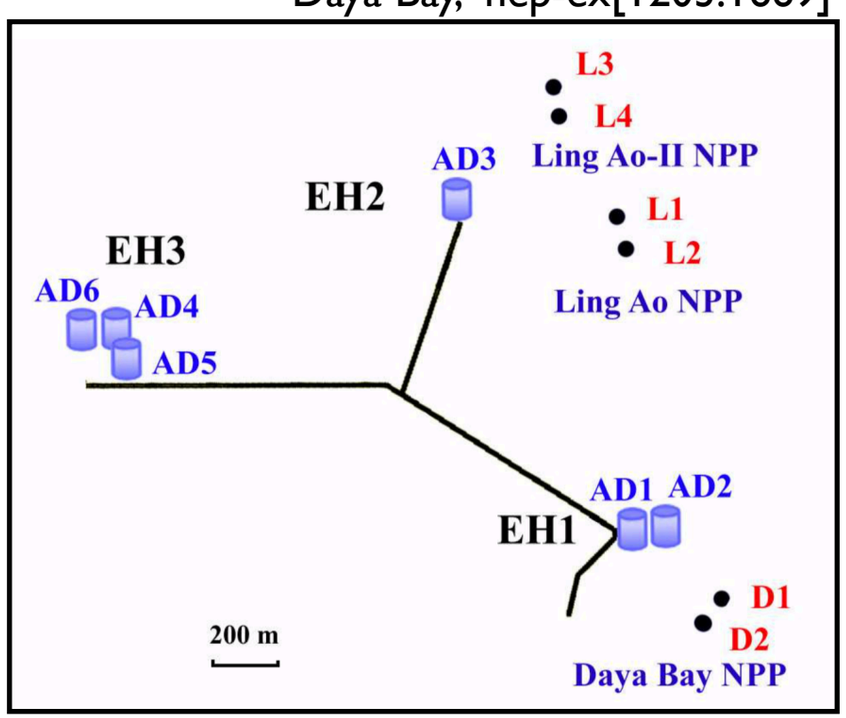


Comparisons: Solar versus Reactor

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

	Solar	Reactor (DYB case)
Production	10^{38}/sec	10^{21}/sec
Baseline	10^{8} km	1 km
Flux		

Daya Bay, hep-ex[1203.1669]



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	~10^{11} nu/sec	~10^{10} nu/sec

WHA???

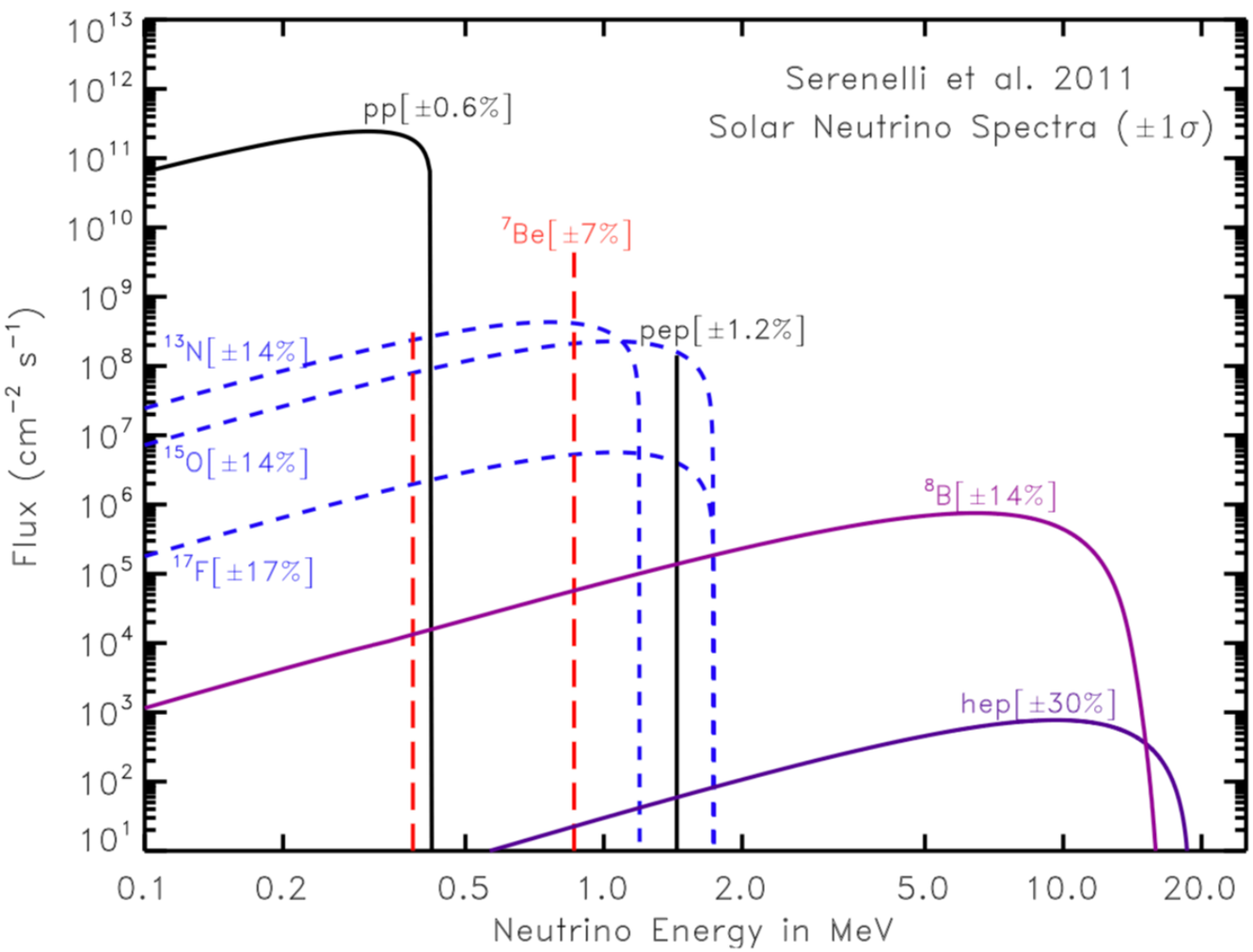
Solar nu flux is higher at Daya Bay than reactor flux?

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

A: Energies, Flavors, and Cross-Sections

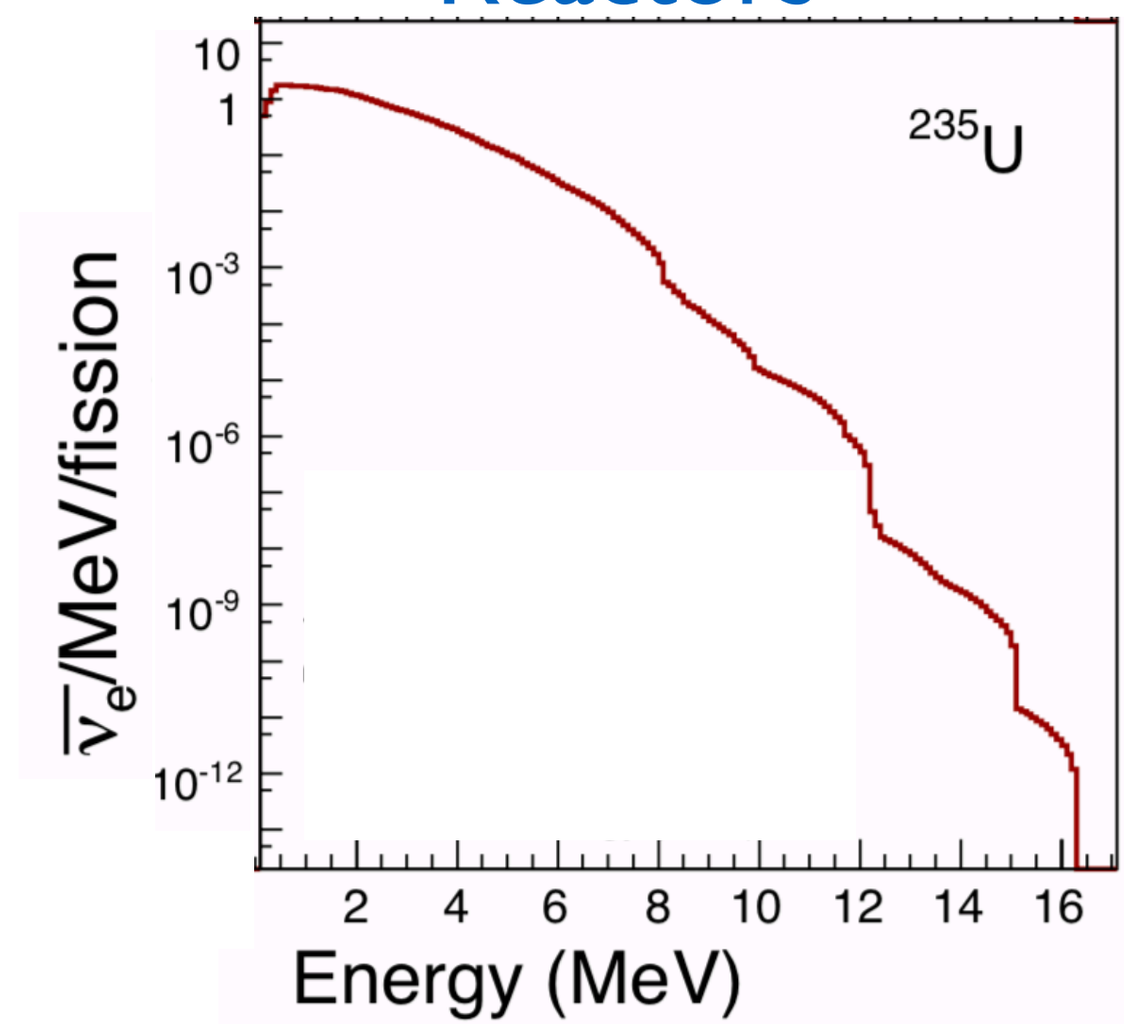
- Interaction methods!
  - Differ for neutrinos versus antineutrinos
  - Differ based on neutrino energy

The Sun



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

Reactors

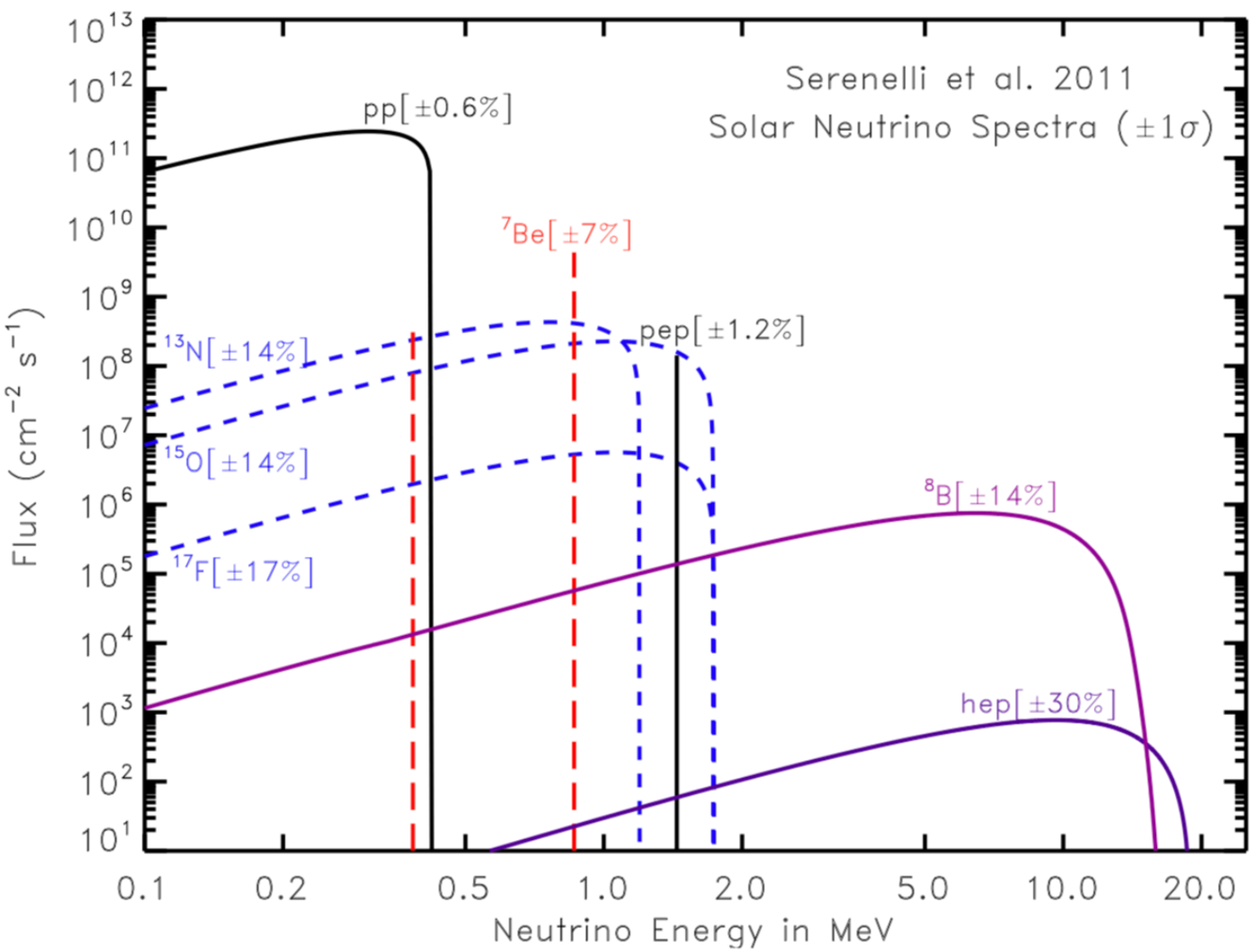


Fallot, et al, nucl-ex[1208.3877]

A: Energies, Flavors, and Cross-Sections

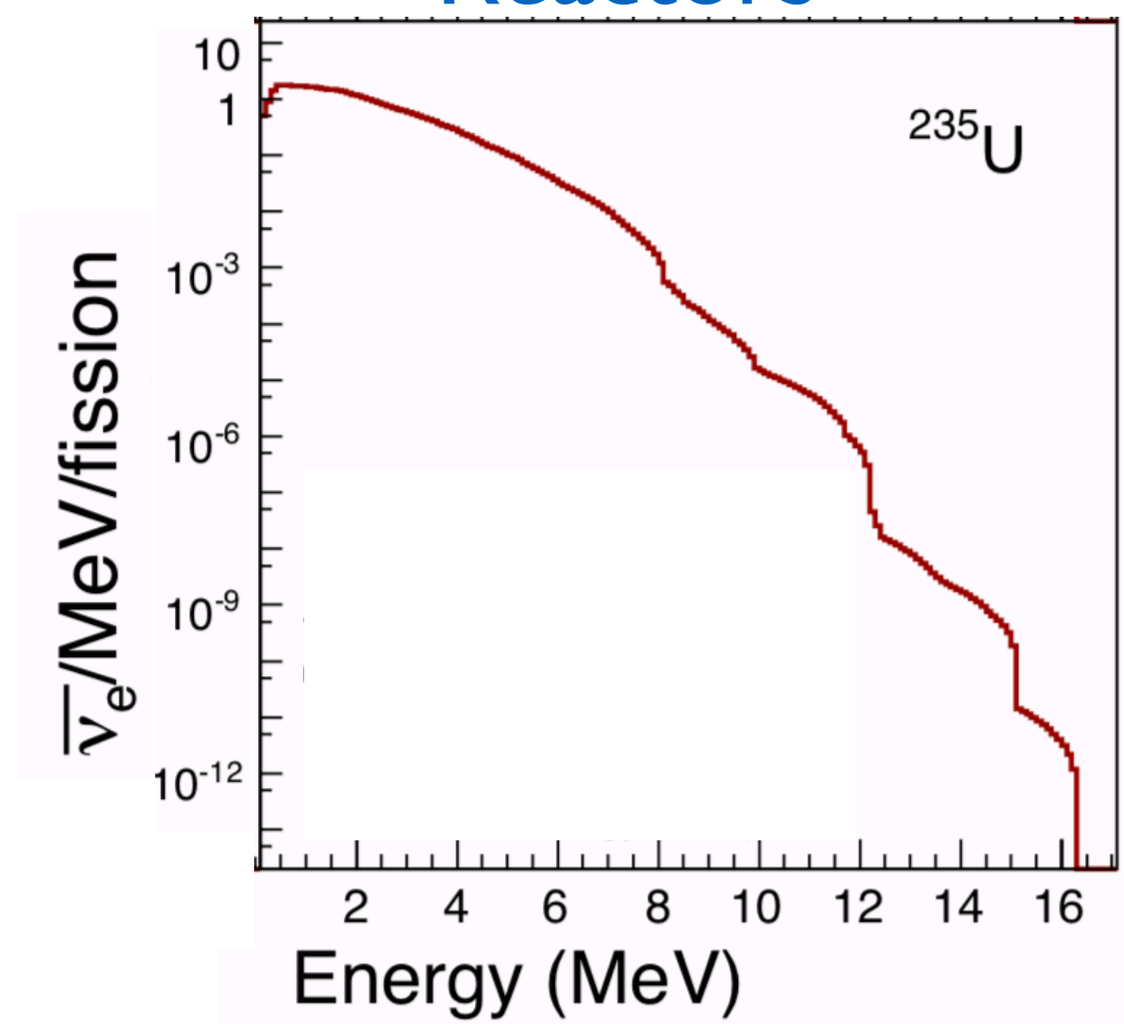
- **Interaction methods!**
  - Differ for neutrinos versus antineutrinos
  - Differ based on neutrino energy

The Sun



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

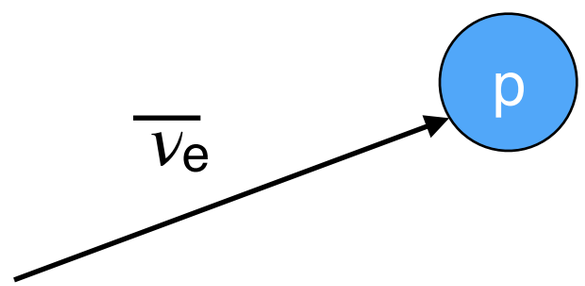
Reactors



Fallot, et al, nucl-ex[1208.3877]

Reactor Antineutrino Interactions

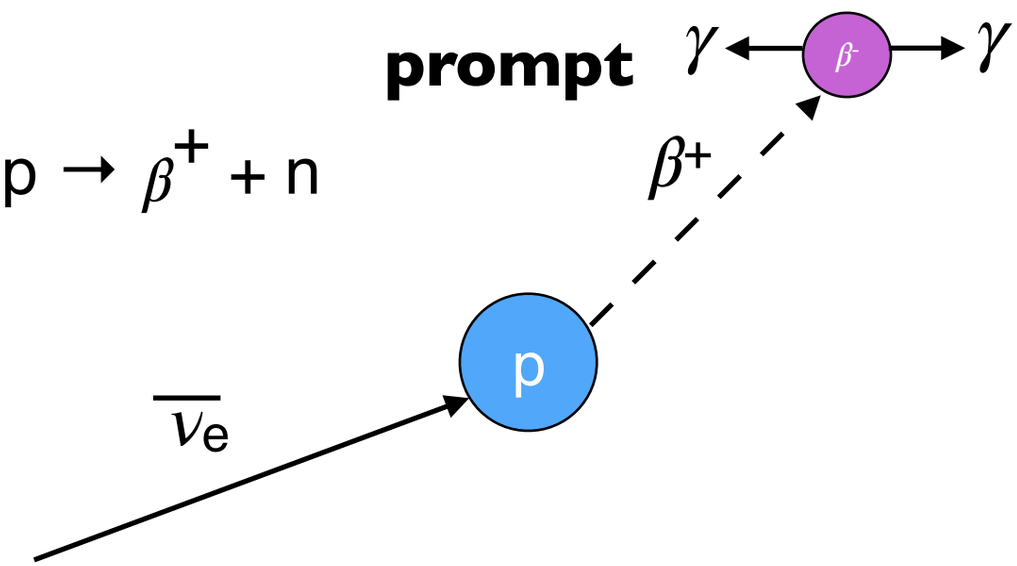
IBD: $\overline{\nu}_e + p \rightarrow \beta^+ + n$



- For reactors: might have heard how we do it in most cases: **inverse beta decay (IBD)**

Reactor Antineutrino Interactions

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

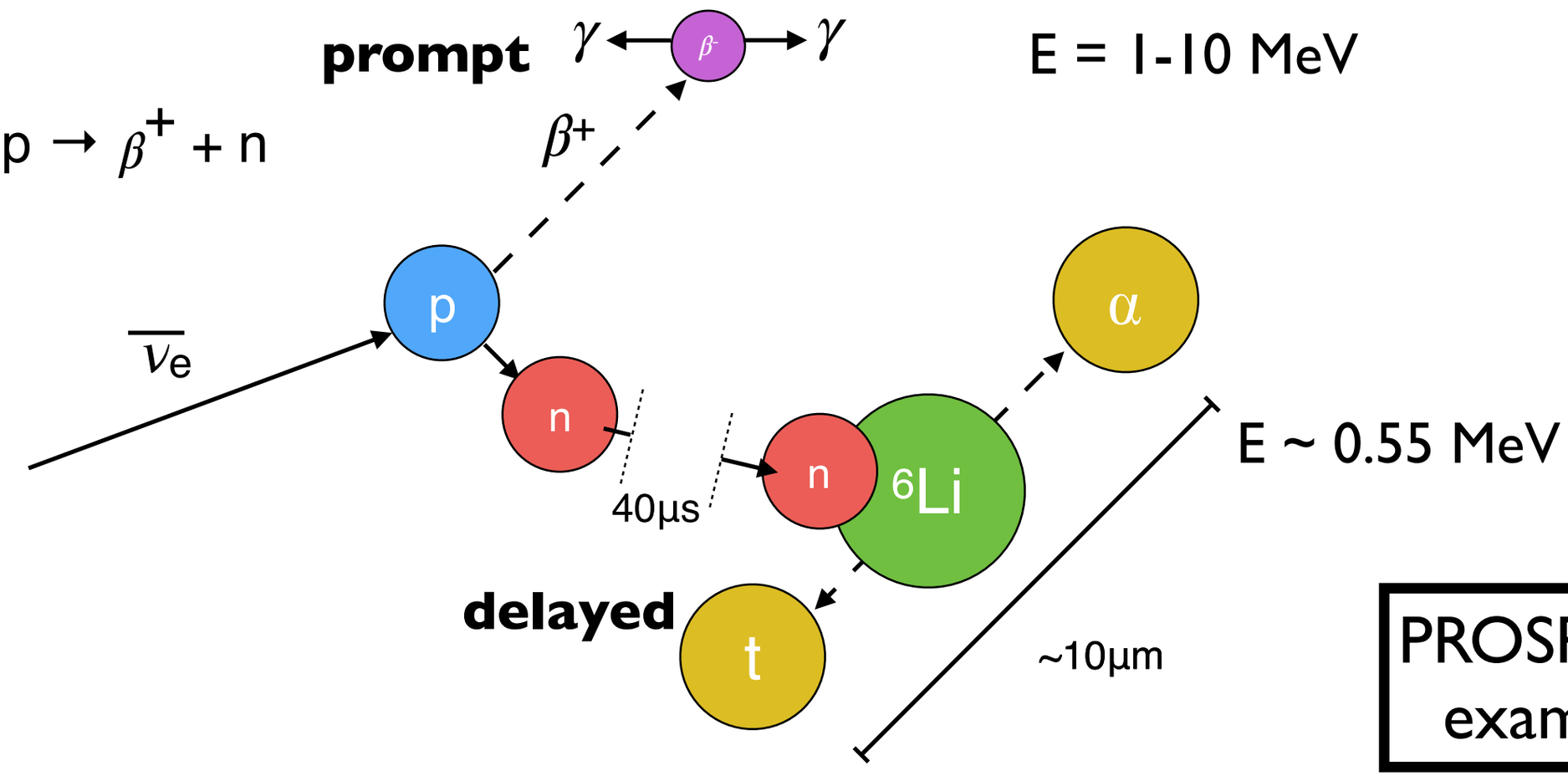


E = 1-10 MeV

- For reactors: might have heard how we do it in most cases: **inverse beta decay (IBD)**

IBD Detection in ^{6}Li-doped LS

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

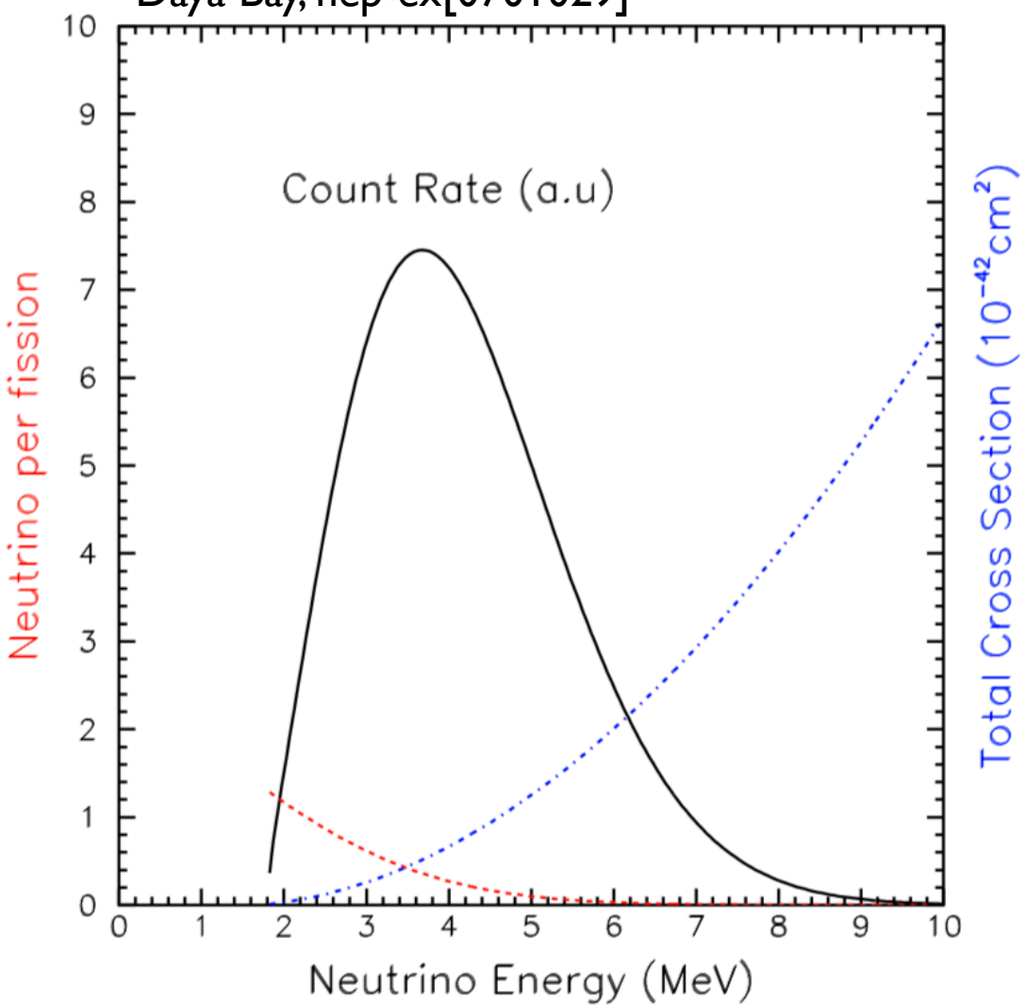


PROSPECT example

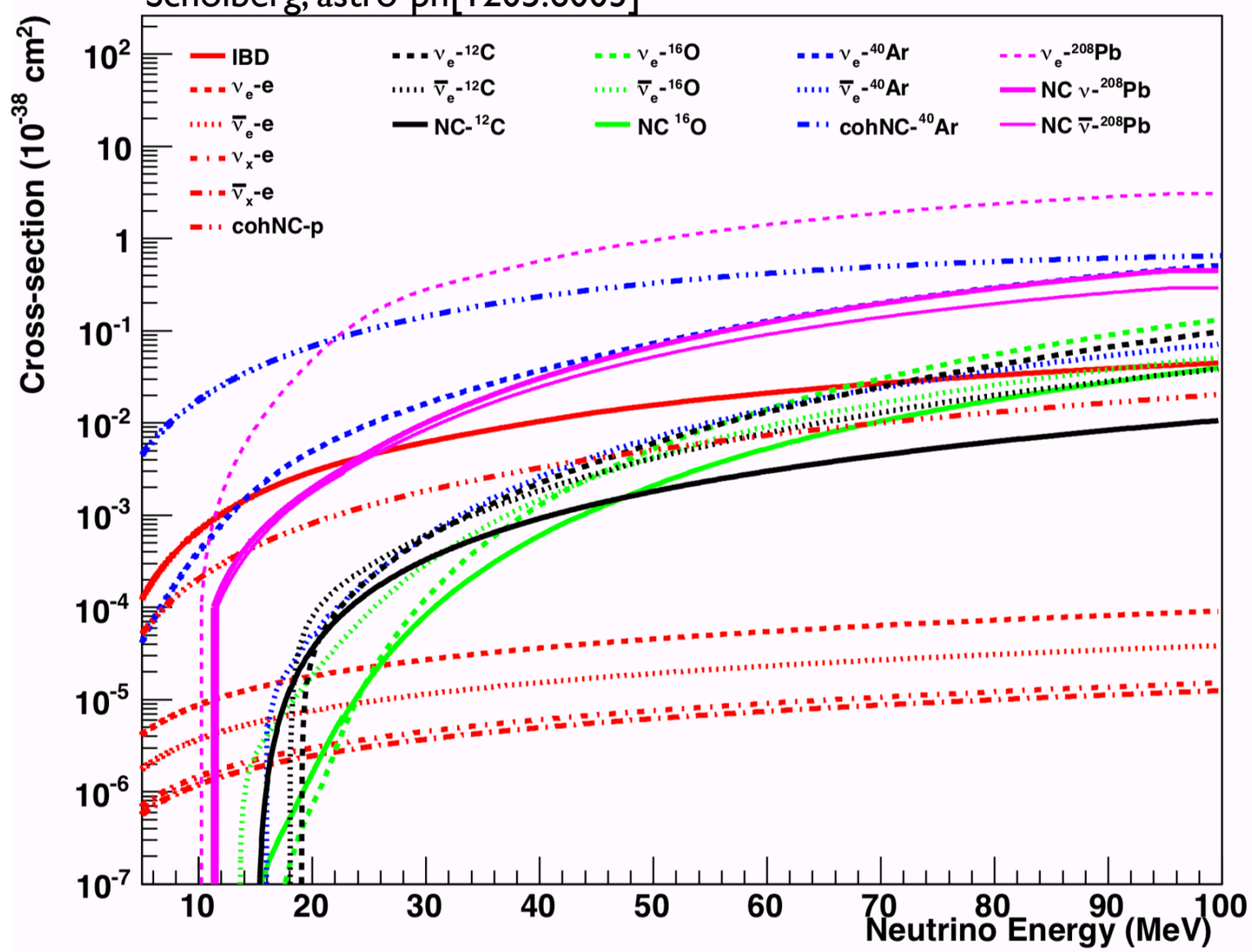
- For reactors: might have heard how we do it in most cases: **inverse beta decay (IBD)**

Reactor Antineutrino Interactions

Daya Bay, hep-ex[0701029]



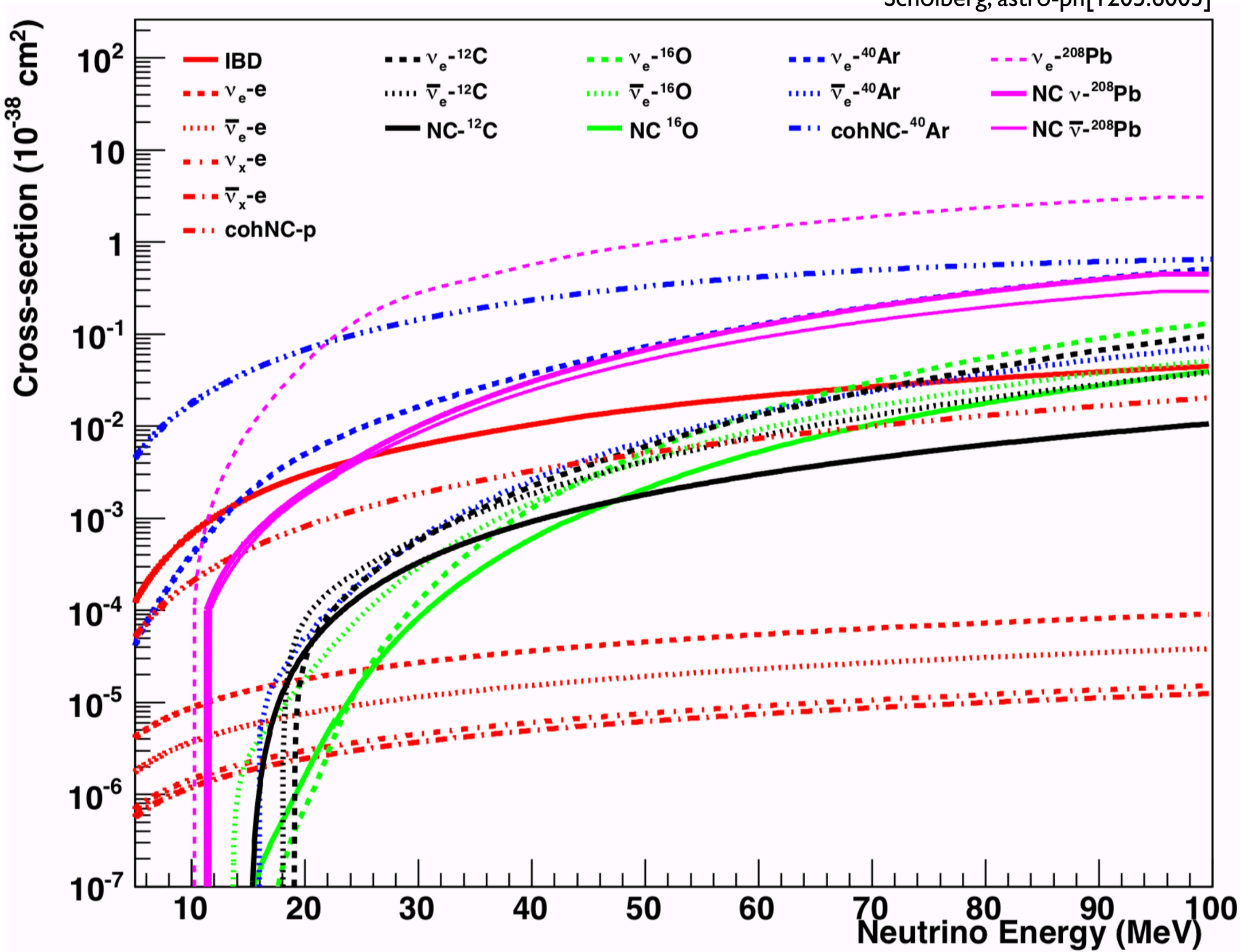
Scholberg, astro-ph[1205.6003]



- For reactors: might have heard how we do it in most cases: inverse beta decay (IBD)
- IBD Cross-section is about 6×10^{-43} cm^2
- **Quite high compared to others at these energies**

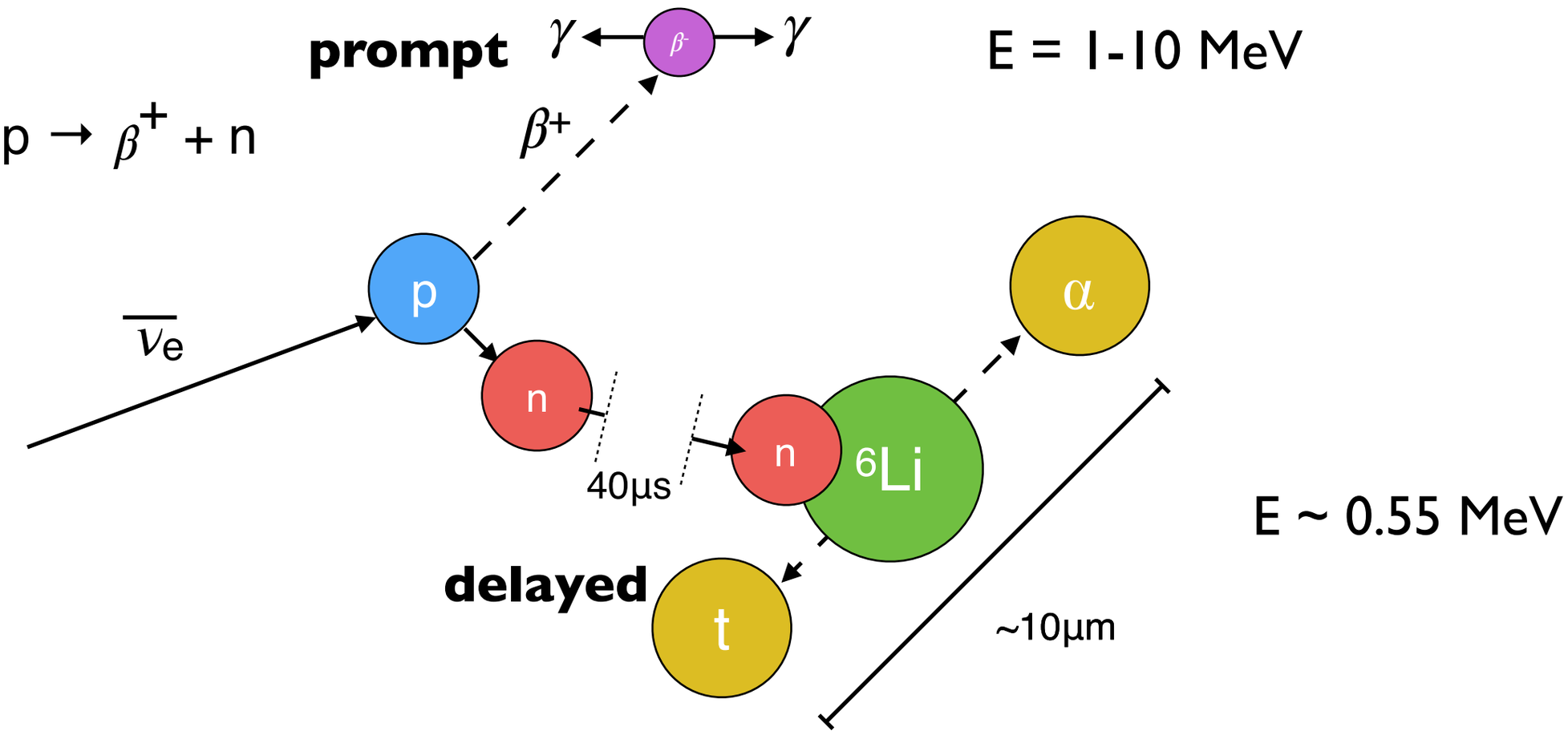
Reactor Antineutrino Interactions

Scholberg, astro-ph[1205.6003]



Reactor Antineutrino Interactions

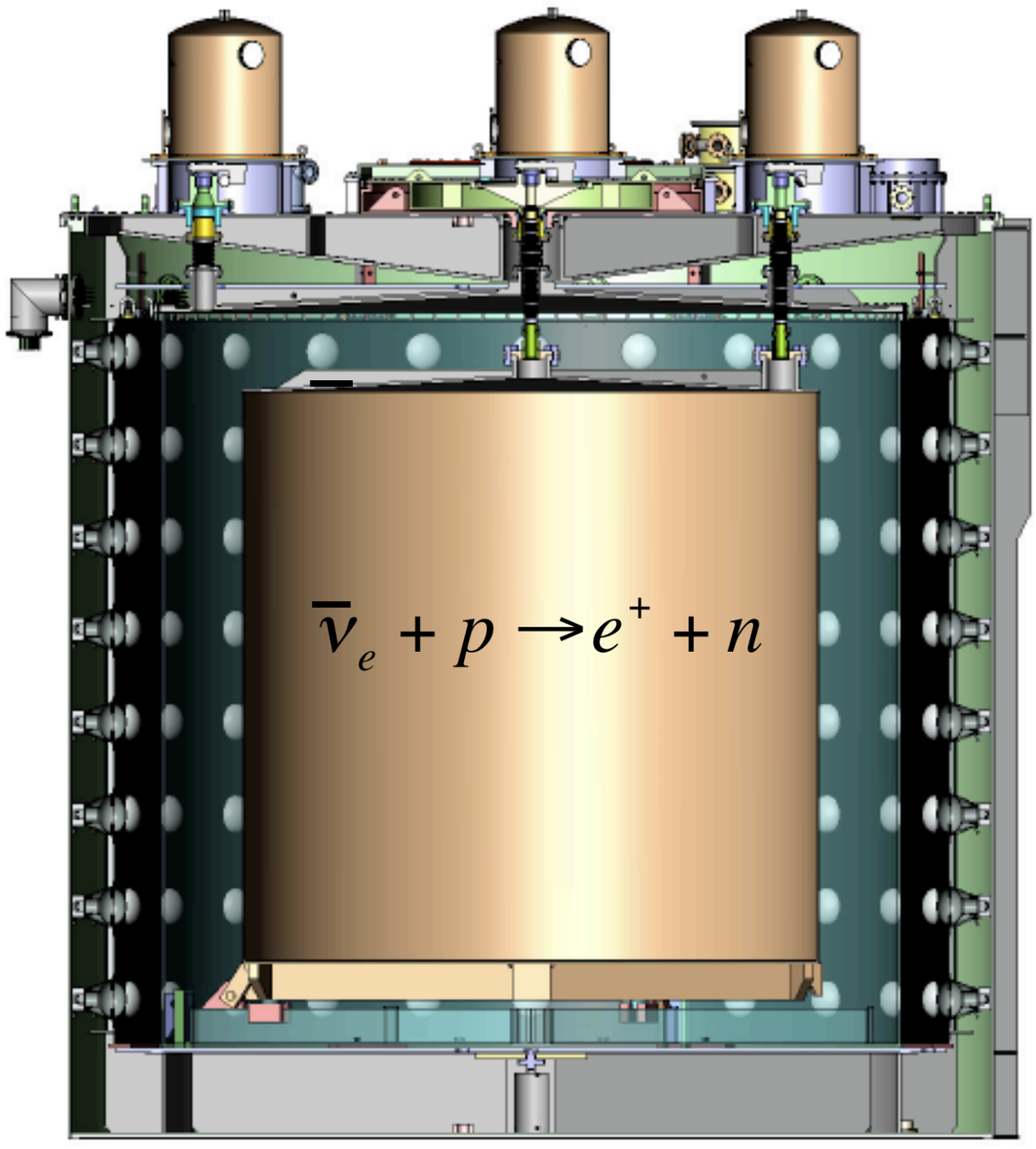
IBD: $\overline{\nu}_e + p \rightarrow \beta^+ + n$



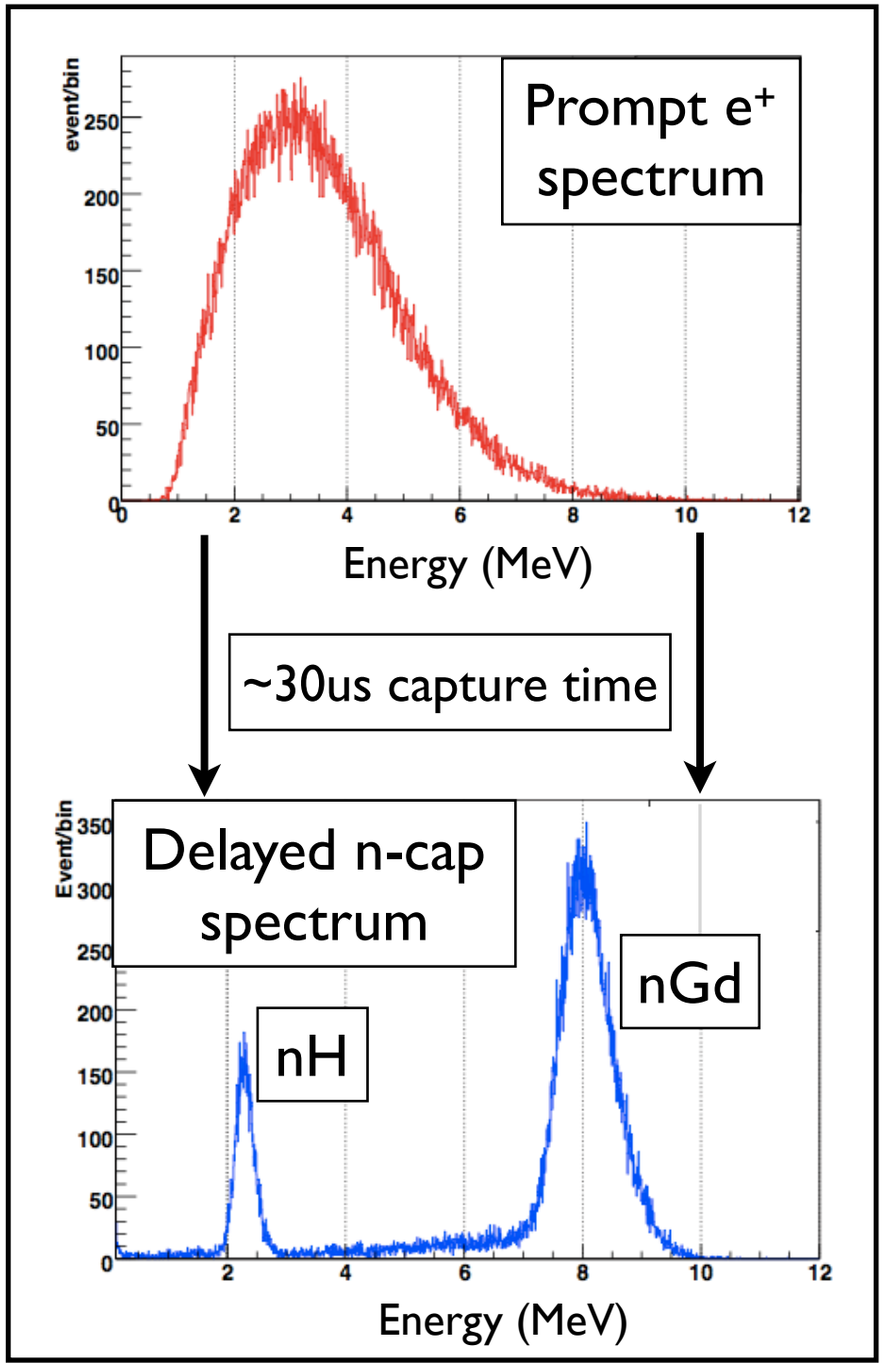
- For reactors: might have heard how we do it in most cases: inverse beta decay (IBD)
- **Two final-state products: positron and neutron**
- So, an IBD detector is also basically a <u>neutron detector</u>

Reactor Antineutrino Detection

- Detect inverse beta decay with organic scintillator and PMTs
  - IBD e+ is direct proxy for antineutrino energy



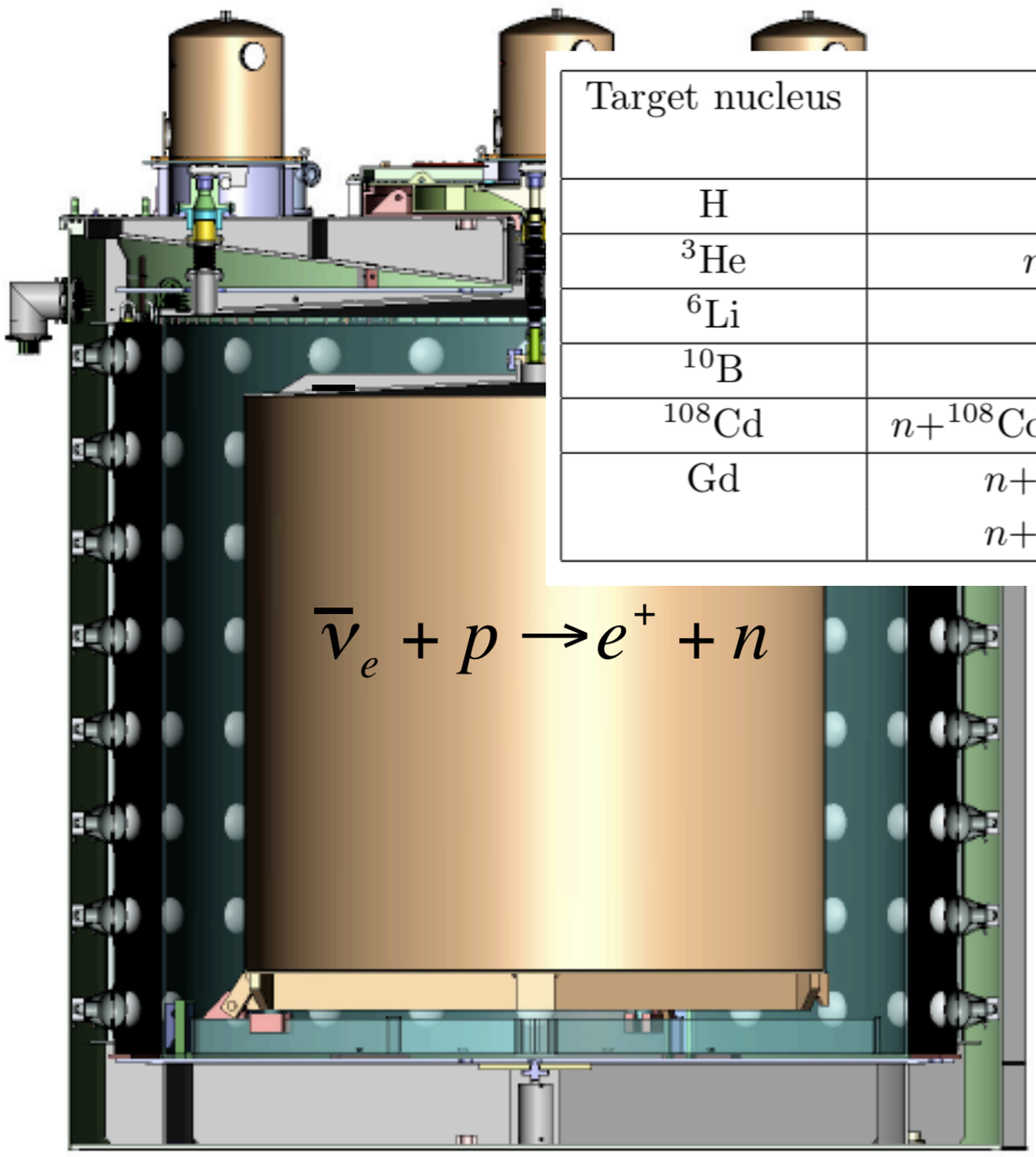
Example: Daya Bay Detector



Daya Bay Monte Carlo Data

Reactor Antineutrino Detection

- Detect inverse beta decay with organic scintillator and PMTs
  - IBD e+ is direct proxy for antineutrino energy



Qian and Peng, hep-ex[1801.05386]

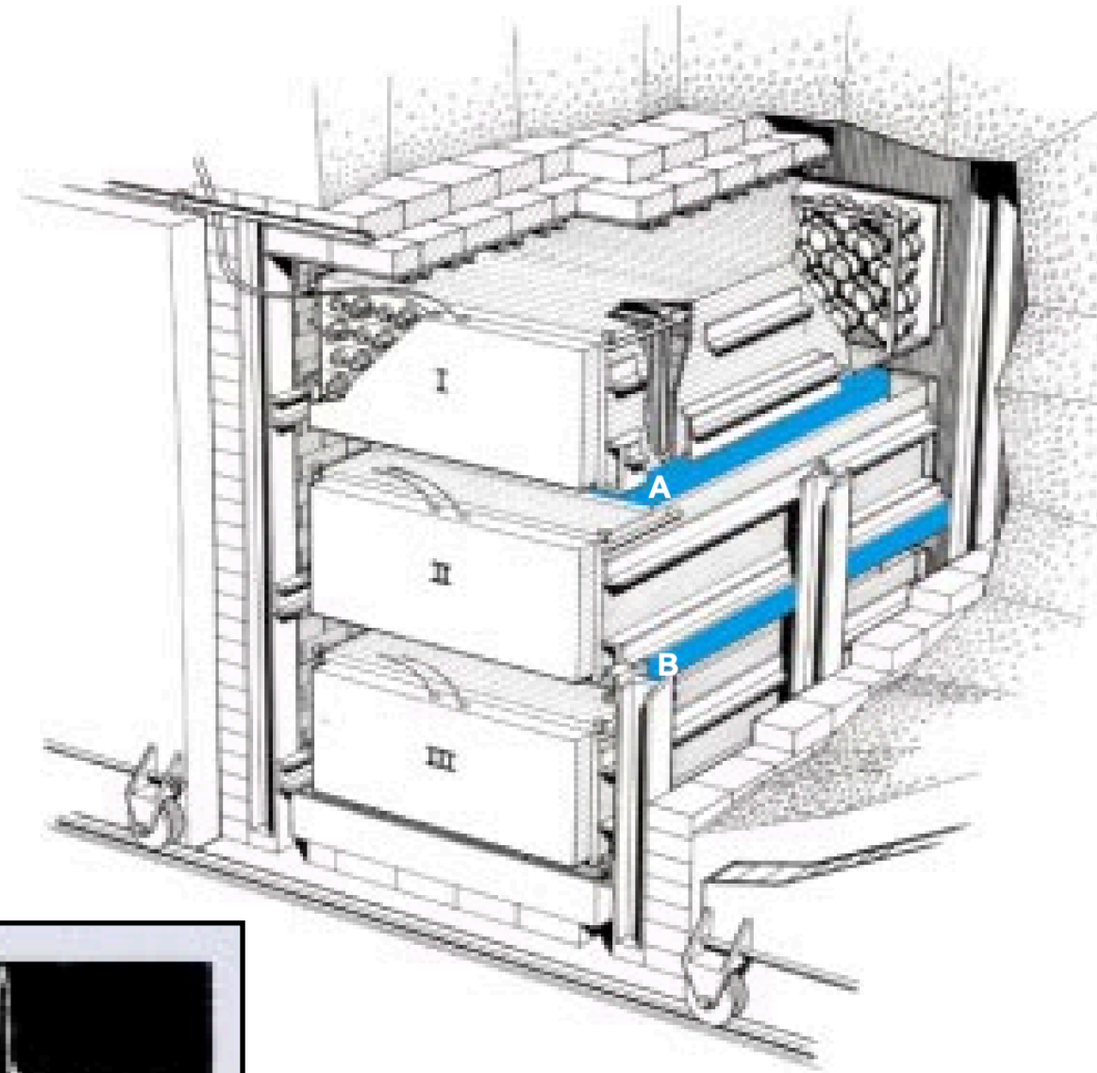
Target nucleus	process	cross section (barn) for thermal neutron
H	$n + p \rightarrow d + \gamma$ (2.2 MeV)	~0.33
^{3}He	$n + ^3\text{He} \rightarrow p + ^3\text{H} + 0.764$ MeV	~5300
^{6}Li	$n + ^6\text{Li} \rightarrow \alpha + ^3\text{H} + 4.6$ MeV	~950
^{10}B	$n + ^{10}\text{B} \rightarrow \alpha + ^7\text{Li} + 6.2$ MeV	~3,860
^{108}Cd	$n + ^{108}\text{Cd} \rightarrow ^{109m}\text{Cd} \rightarrow ^{109}\text{Cd}$ (~9MeV)	~1000 ‖
Gd	$n + ^{155}\text{Gd} \rightarrow ^{156}\text{Gd} + \gamma s$ (8.5 MeV) $n + ^{157}\text{Gd} \rightarrow ^{158}\text{Gd} + \gamma s$ (7.9 MeV)	~61,000 ~256,000

Choose your own neutron adventure

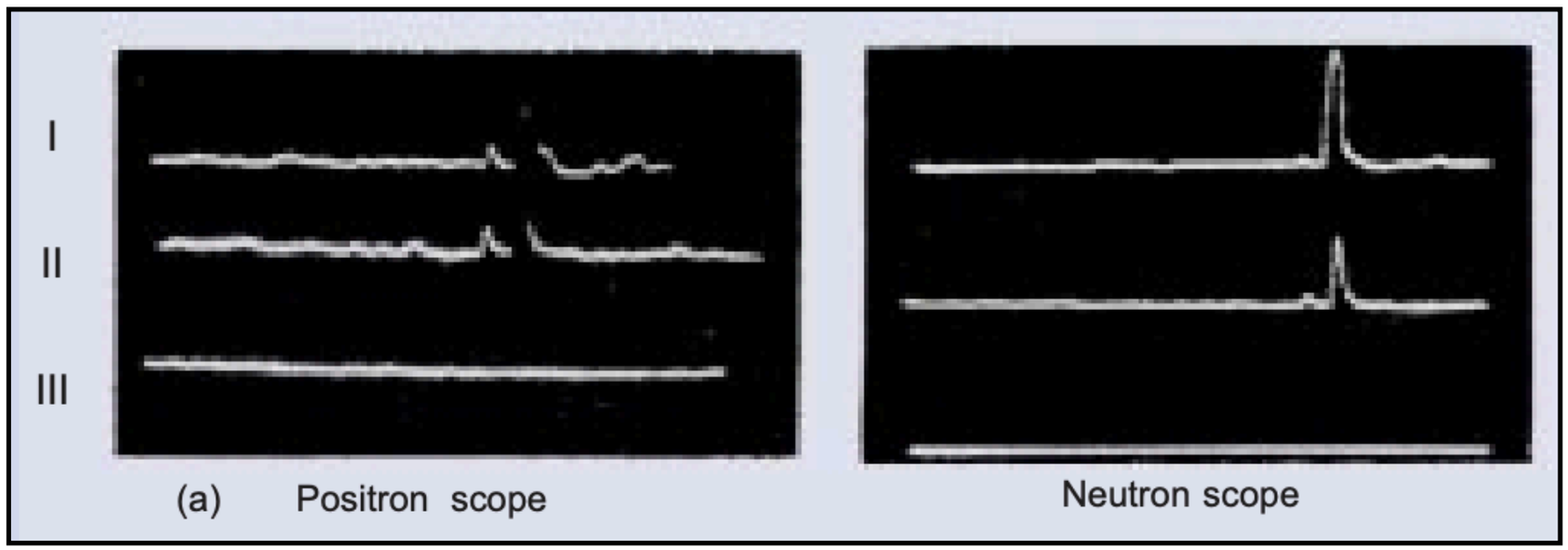
Example: Daya Bay Detector

Example: Savannah River

- Nice illustration provided by first neutrino detection
  - IBD in Cd-doped water tanks (A and B)
  - Liquid scintillator, PMTs in I, II, and III
  - Require:
    - Signals in 2 LS regions (not a cosmic ray)
    - Time-coincident PMT pulses for both LS regions
- Same idea continues today, except LS is now the antineutrino target



Los Alamos Science 25
'Celebrating the Neutrino'

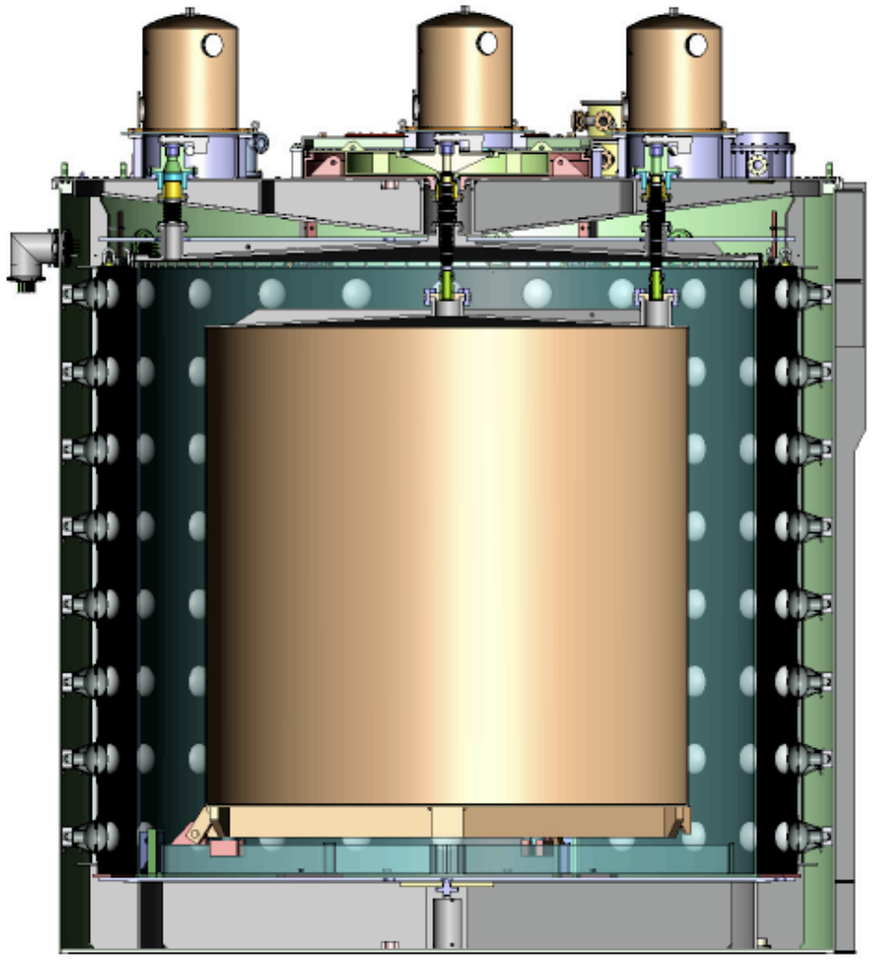


Reactor Antineutrino Detection Rates

- So, how many antineutrinos per day will we see?

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

- Flux: ~10^{10} nuebar/s/cm^2 at 1km
- Cross-section: ~6×10^{-43} cm^2
- Proton number: ~10^{30} protons in a 20 ton scintillator vat
- Detection efficiency: ~70%
- Oscillation probability: ~10%



Reactor Antineutrino Detection Rates

- So, how many antineutrinos per day will we see?

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

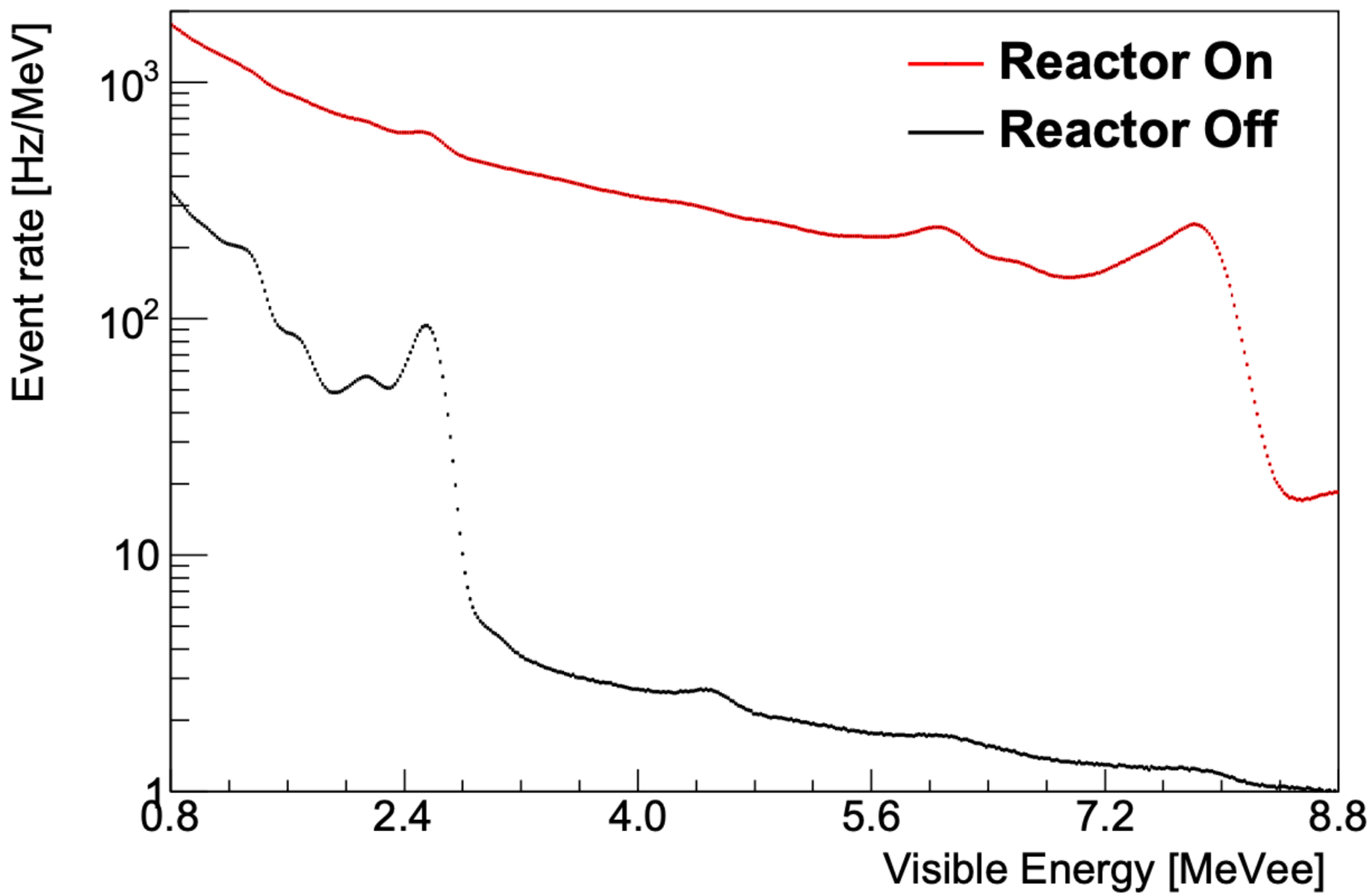
  - Flux: ~10^{10} nuebar/s/cm^2 at 1km
  - Cross-section: ~6×10^{-43} cm^2
  - Proton number: ~10^{30} protons in a 20 ton scintillator vat
  - Detection efficiency: ~70%
  - Oscillation probability: ~10%
- ~4 mHz, or ~300/day
  - In reality, ~100/day: not too far off with back-of-the-envelope calc!

Remember That Neutron

- Why does that neutron matter so much???

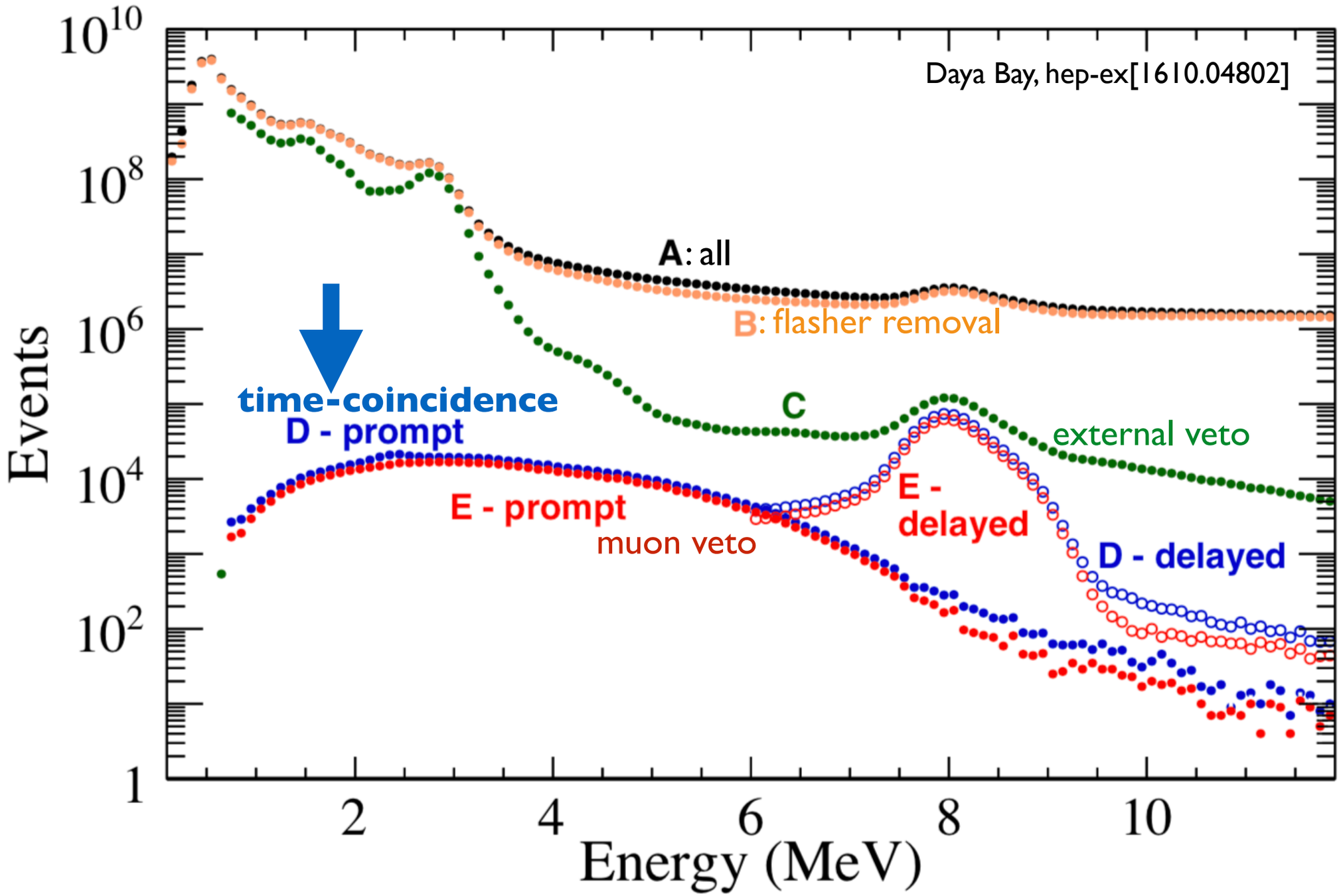
Remember That Neutron

- Why does that neutron matter so much???
- Example: PROSPECT trigger rates
  - Compare this to our <1000/day expectation for IBDs. YIKES.



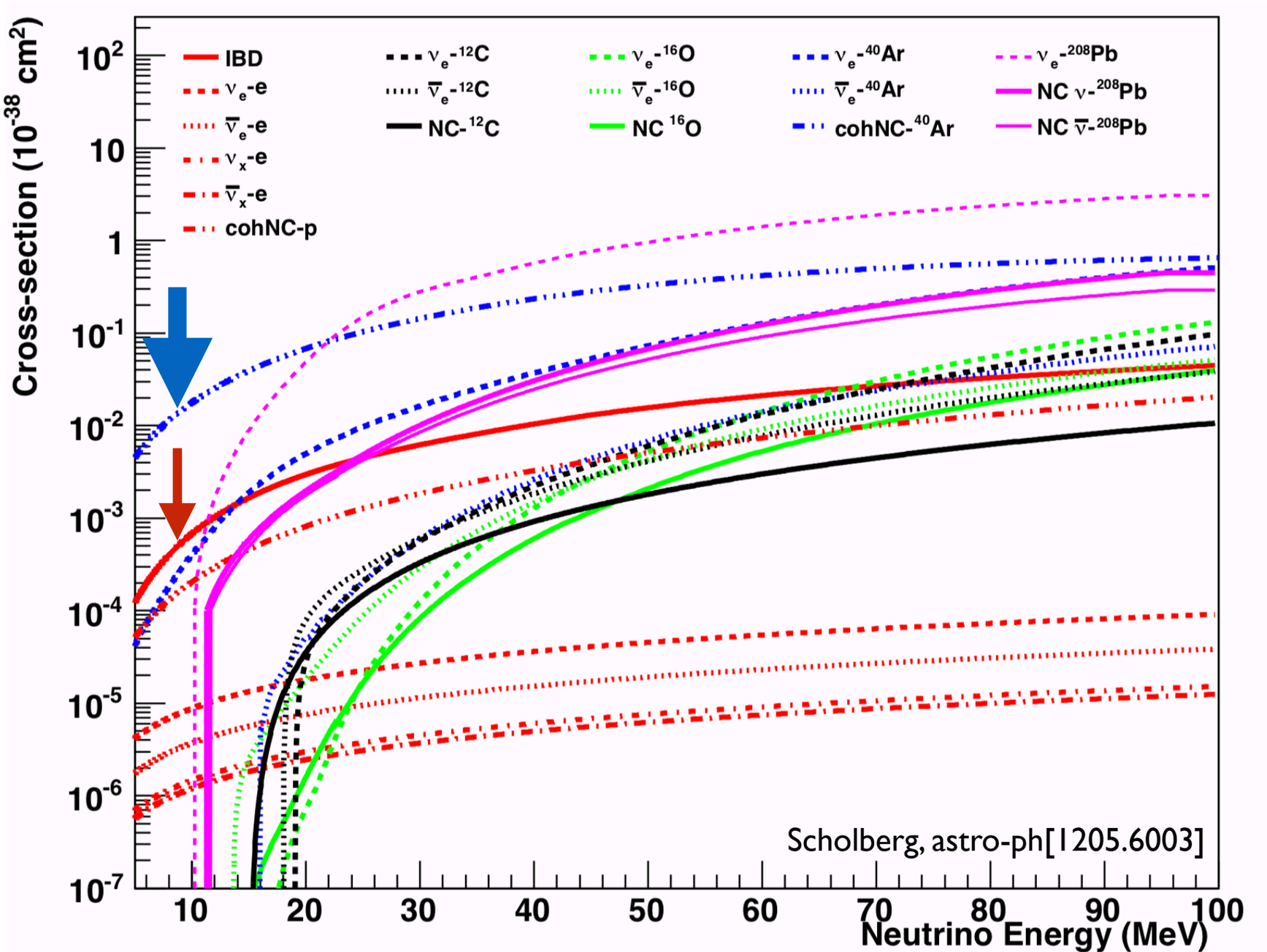
Remember That Neutron

- Why does that neutron matter so much???
- Example: Daya Bay antineutrino selection:



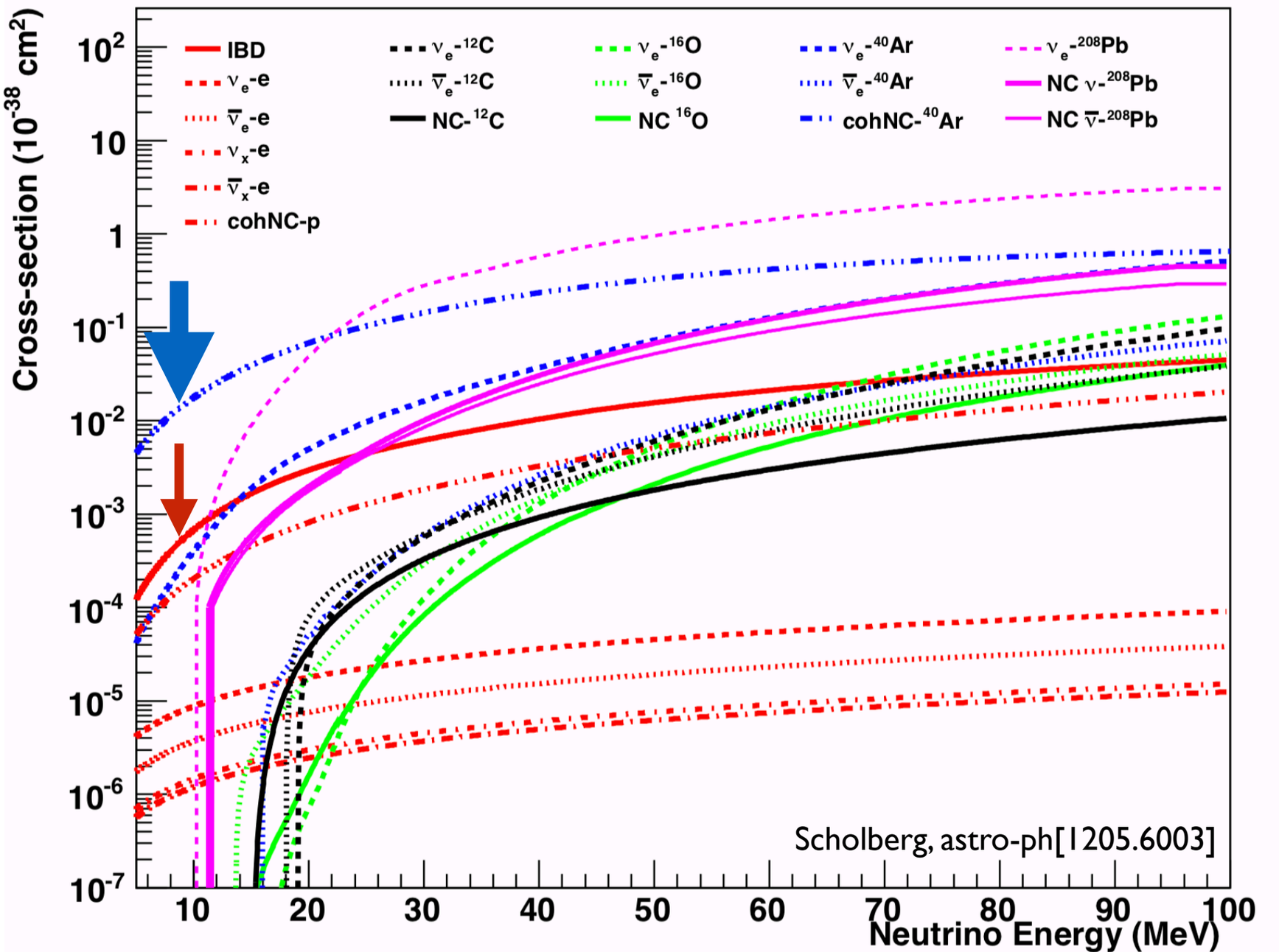
Why Not A Different Channel?

- Coherent scattering detection on LAr?



Why Not A Different Method?

- Coherent scattering detection on LAr?
  - No time-coincident signature… so lots of backgrounds
  - Also other reasons which we won't really address here…



Other Reactor Detection Methods

- IBD rules, but other channels **<u>have</u>** been successfully probed

Qian and Peng, hep-ex[1801.05386]

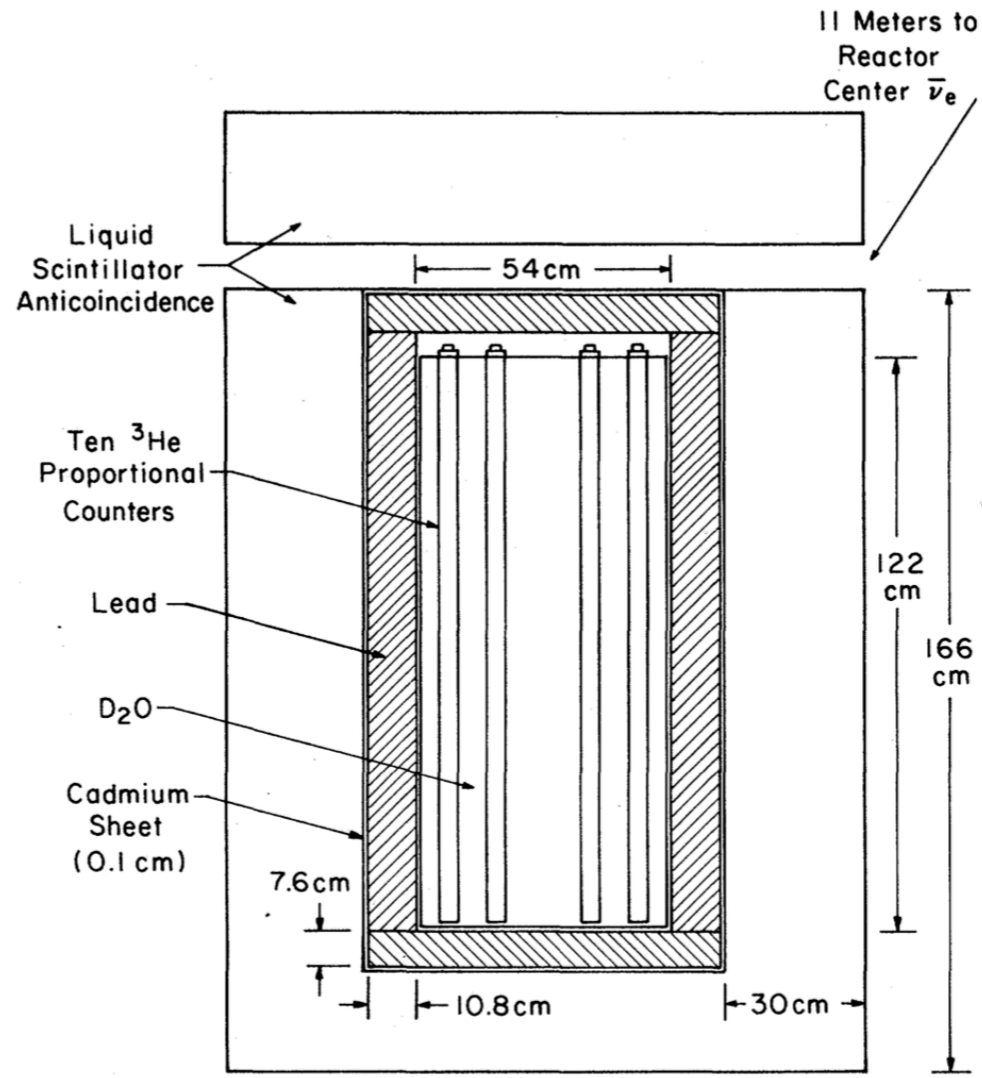
Channel	Interaction Type	Cross Section (10^{-44} cm^2/fission)	Threshold (MeV)
$\bar{\nu}_e + p \rightarrow e^+ + n$	CC	~63	1.8
$\bar{\nu}_e + d \rightarrow n + n + e^+$	CC	~1.1	4.0
$\bar{\nu}_e + d \rightarrow n + p + \bar{\nu}_e$	NC	~3.1	2.2
$\bar{\nu}_e + e^- \rightarrow \bar{\nu}_e + e^-$	CC/NC	~0.4	0
$\bar{\nu}_e + A \rightarrow \bar{\nu}_e + A$	NC	$\sim 9.2 \times N^2$	0

Other Channels: Deuterated Detectors

Detection of Weak Neutral Current Using Fission $\bar{\nu}_e$ on Deuterons

E. Pasierb, H. S. Gurr,[a] J. Lathrop,[b] F. Reines, and H. W. Sobel
Department of Physics, University of California at Irvine, Irvine, California 92717
(Received 27 March 1979)

Number of neutrons	Reactor "ON" (events per day)	Reactor "OFF" (events per day)	"ON" − "OFF" (events per day) (reactor associated)
		Set *A*	
	52.3 days live	38.3 days live	
1	799±9	729±8	70±12
2	71±1	66±1	5±1.4
3	13.7±0.5	12.8±0.6	0.9±0.8



Qian and Peng, hep-ex[1801.05386]

Channel	Interaction Type	Cross Section (10^{-44} cm^2/fission)	Threshold (MeV)
$\bar{\nu}_e + p \to e^+ + n$	CC	~63	1.8
$\bar{\nu}_e + d \to n + n + e^+$	CC	~1.1	4.0
$\bar{\nu}_e + d \to n + p + \bar{\nu}_e$	NC	~3.1	2.2
$\bar{\nu}_e + e^- \to \bar{\nu}_e + e^-$	CC/NC	~0.4	0
$\bar{\nu}_e + A \to \bar{\nu}_e + A$	NC	$\sim 9.2 \times N^2$	0

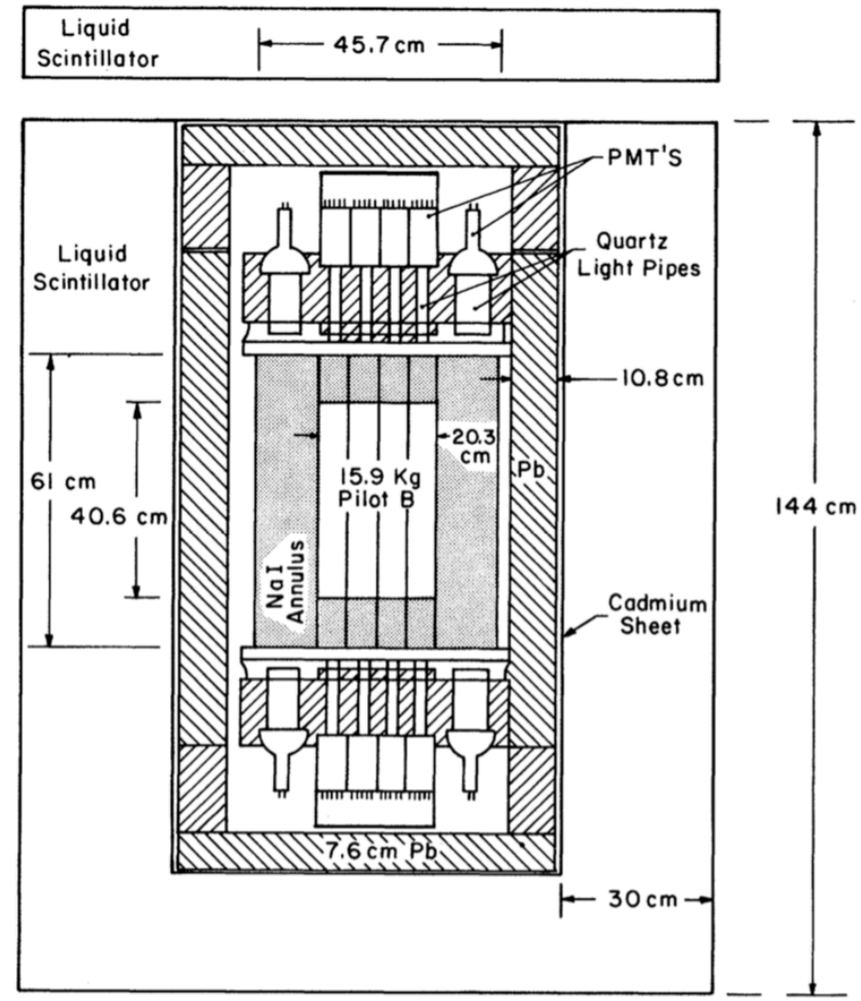
Other Channels: Electron Scattering

Detection of $\bar{\nu}_e$-e Scattering*

F. Reines, H. S. Gurr, and H. W. Sobel
Department of Physics, University of California, Irvine, California 92717
(Received 27 May 1976)

TABLE I. Summary of elastic scattering data (events/day).

Energy bin (MeV)	Reactor on	Reactor off	Stability error	Reactor associated rate	Standard deviations from zero
1.5 – 2.0	30.6 ± 0.8	26.9 ± 0.7	± 0.60	3.7 ± 1.3	2.8
2.0 – 2.5	10.5 ± 0.5	9.1 ± 0.4	0.38	1.4 ± 0.8	1.8
2.5 – 3	4.0 ± 0.2	3.2 ± 0.2	0.17	0.8 ± 0.4	2.2
3.0 – 3.5	1.5 ± 0.2	0.6 ± 0.1	0.08	0.9 ± 0.2	4.3
3.5 – 4	0.54 ± 0.09	0.35 ± 0.08	0.03	0.2 ± 0.1	1.6
4.0 – 4.5	0.40 ± 0.08	0.21 ± 0.06	0.01	0.2 ± 0.1	1.6
1.5 – 3	45.1 ± 1.0	39.2 ± 0.9	± 0.60	5.9 ± 1.4	4.1
3 – 4.5	2.4 ± 0.19	1.2 ± 0.14	0.08	1.2 ± 0.25	4.8
	(64.6 day live time)	(60.7 day live time)			

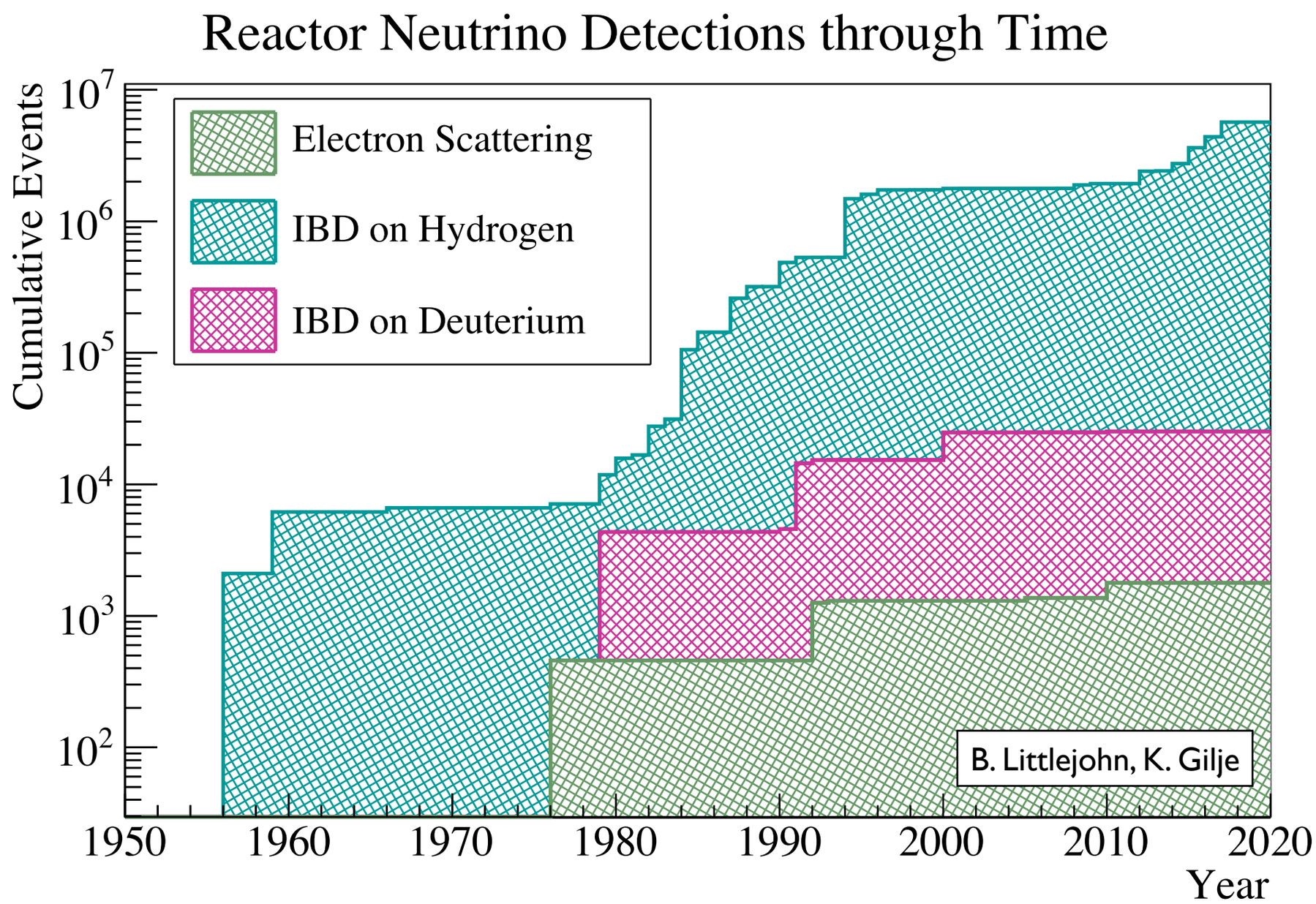


Qian and Peng, hep-ex[1801.05386]

Channel	Interaction Type	Cross Section (10^{-44} cm^2/fission)	Threshold (MeV)
$\bar{\nu}_e + p \to e^+ + n$	CC	~63	1.8
$\bar{\nu}_e + d \to n + n + e^+$	CC	~1.1	4.0
$\bar{\nu}_e + d \to n + p + \bar{\nu}_e$	NC	~3.1	2.2
$\bar{\nu}_e + e^- \to \bar{\nu}_e + e^-$	CC/NC	~0.4	0
$\bar{\nu}_e + A \to \bar{\nu}_e + A$	NC	$\sim 9.2 \times N^2$	0

Reactor Antineutrino Detection Methods

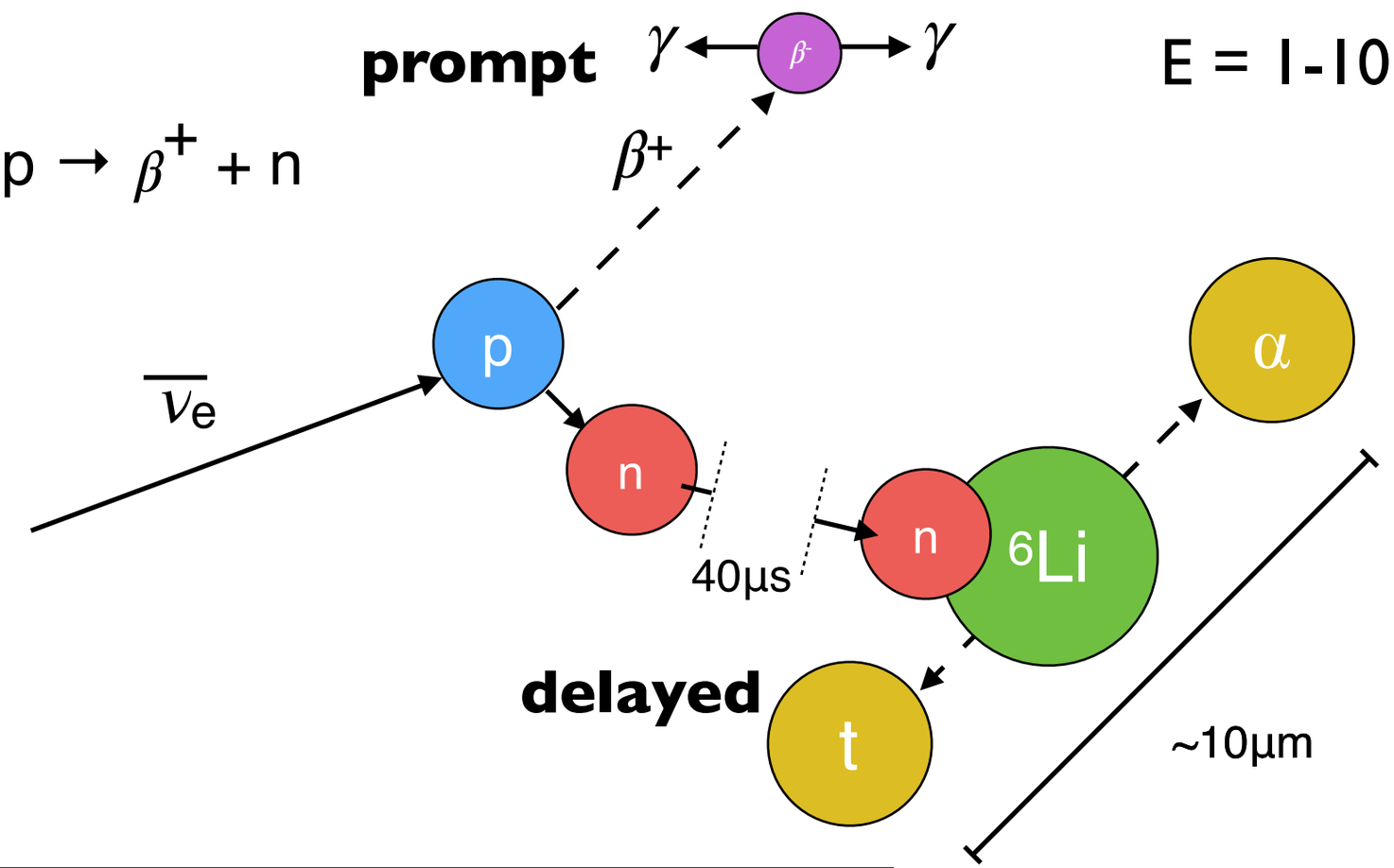
- Clearly IBD is easiest and most common choice
  - Only use non-IBD when necessary to probe the physics: neutrino magnetic moments, SM cross-section tests, etc. etc.



Reactor Antineutrino Backgrounds

- Q: What else might look like an IBD?

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

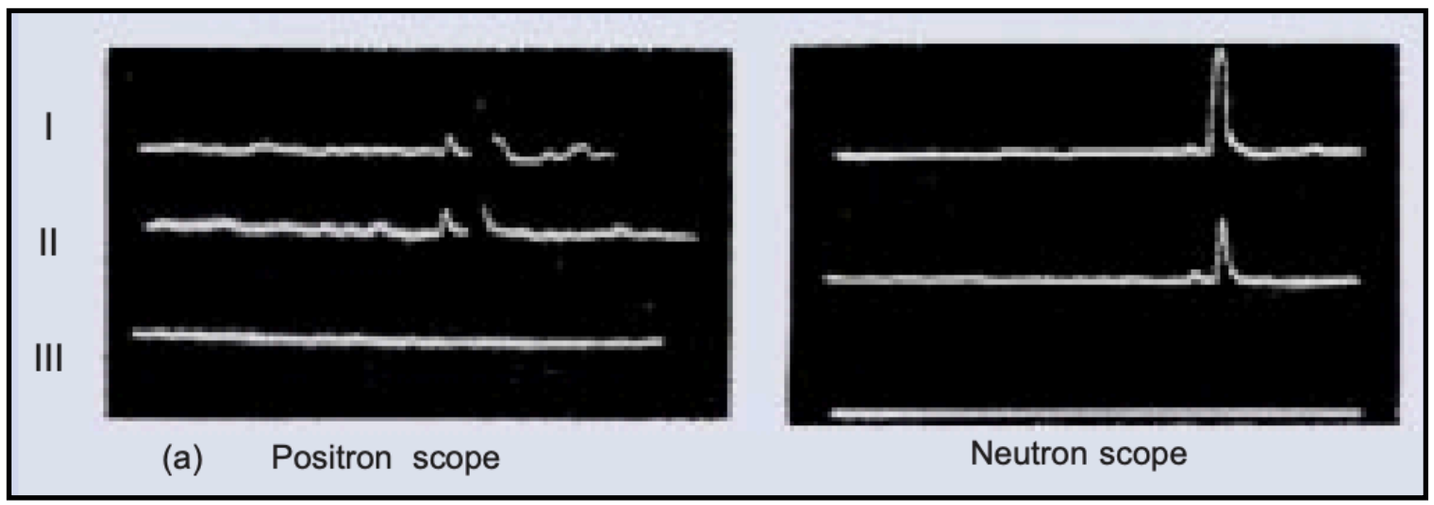


E = 1-10 MeV

E ~ 0.55 MeV

PROSPECT example

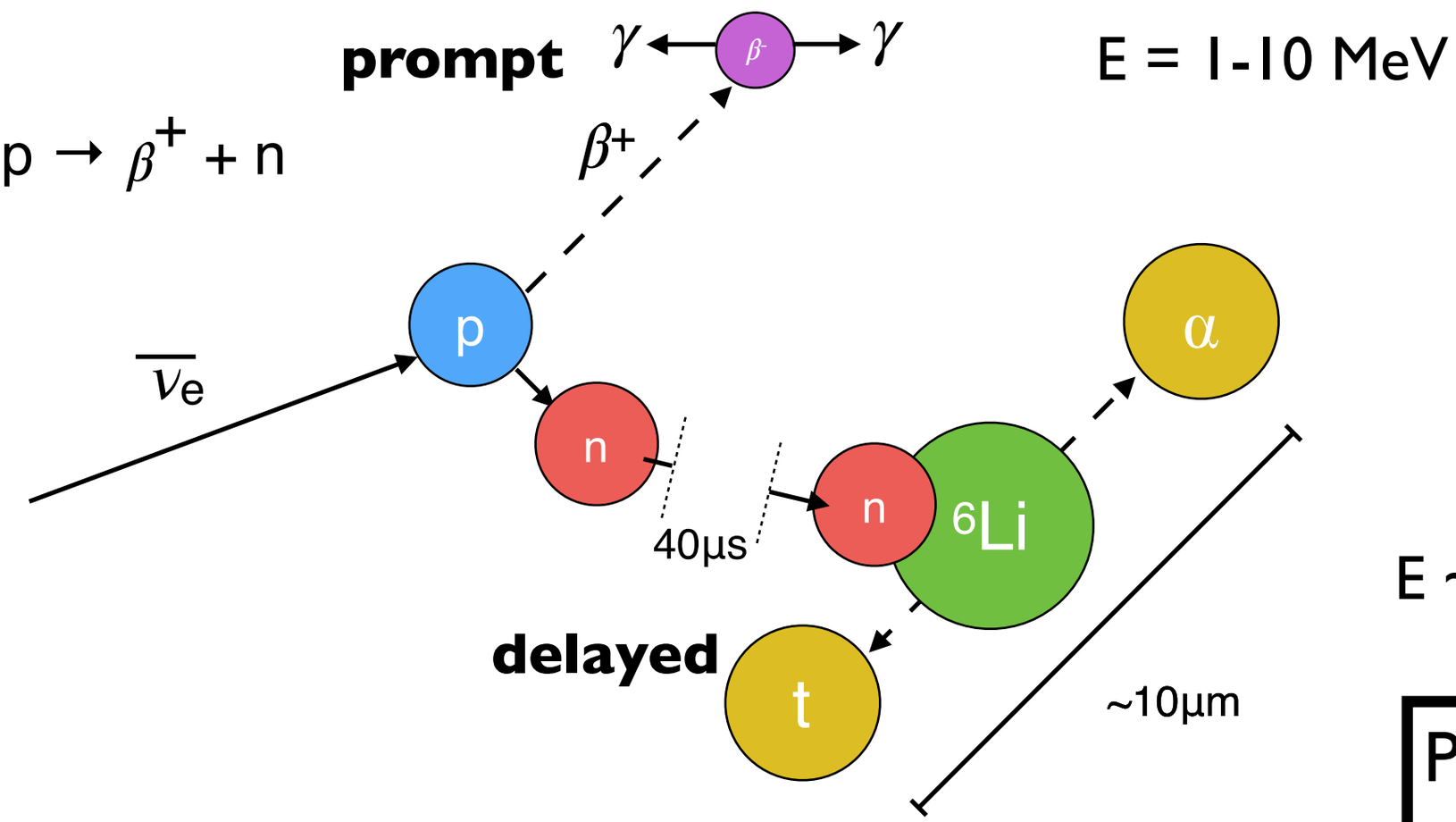
Los Alamos Science 25



Reactor Antineutrino Backgrounds

- Q: What else might look like an IBD?

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



E = 1-10 MeV

E ~ 0.55 MeV

PROSPECT example

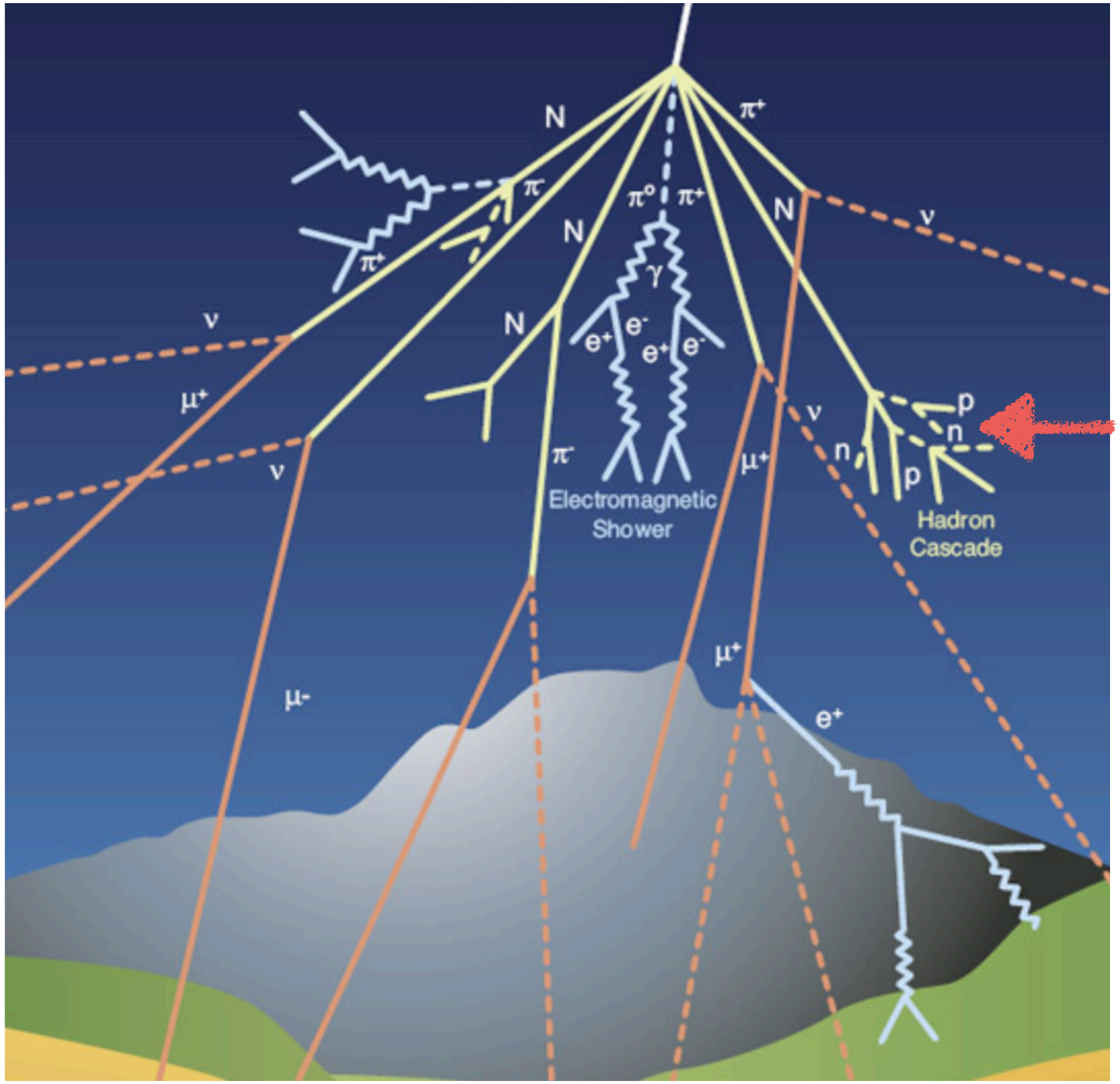
- A: Anything that makes a neutron-like signature.
  - Neutrons have us-scale associated interaction timescales that are quite unique in particle physics (that and Michel electrons…)

Neutrons

- Where do neutrons come from?

Cosmic Neutrons

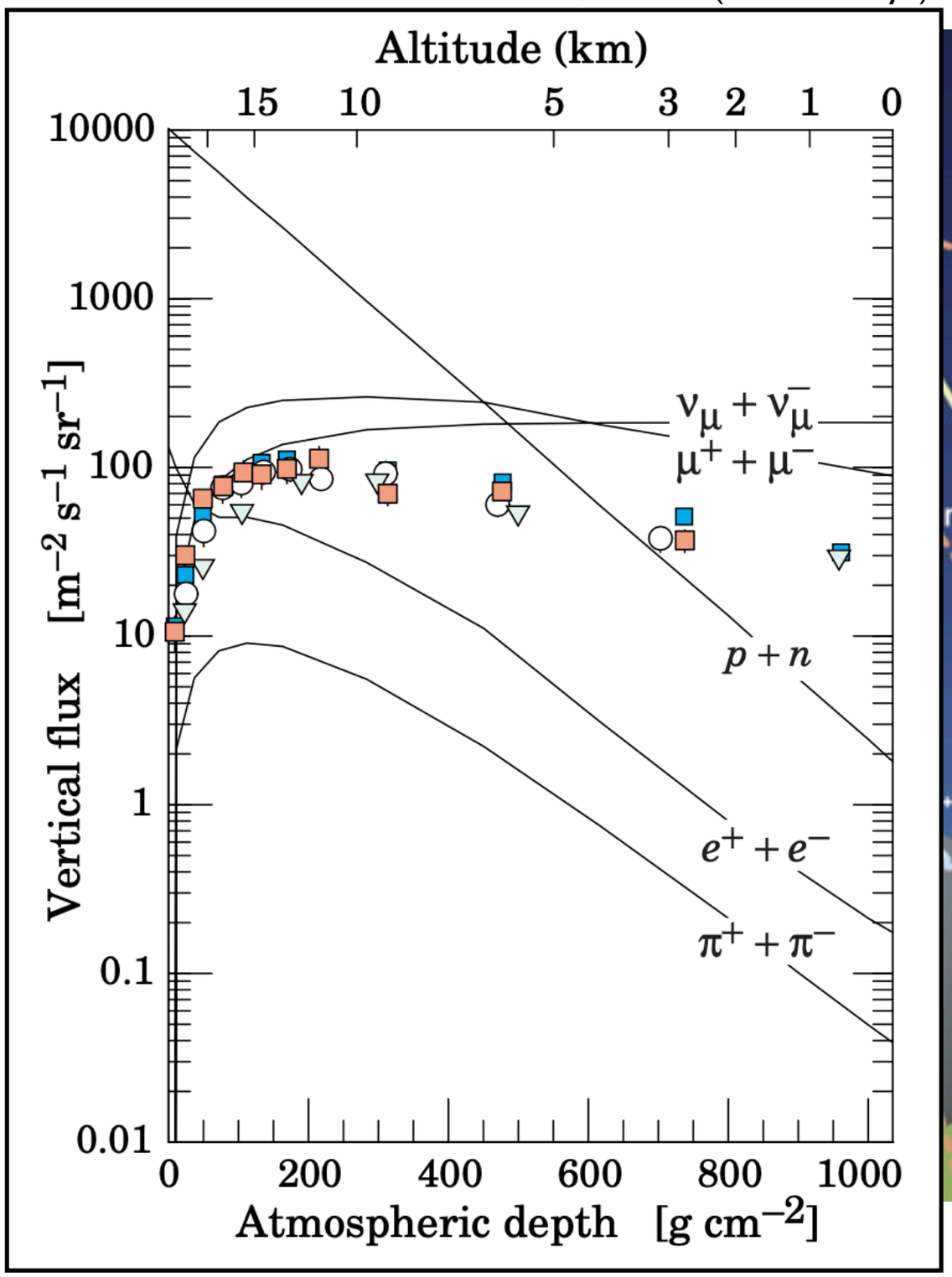
- Where do neutrons come from?
- Cosmogenic radiation
  - 'primary neutrons'
    - Not necessarily cosmic; some produced in atmosphere too

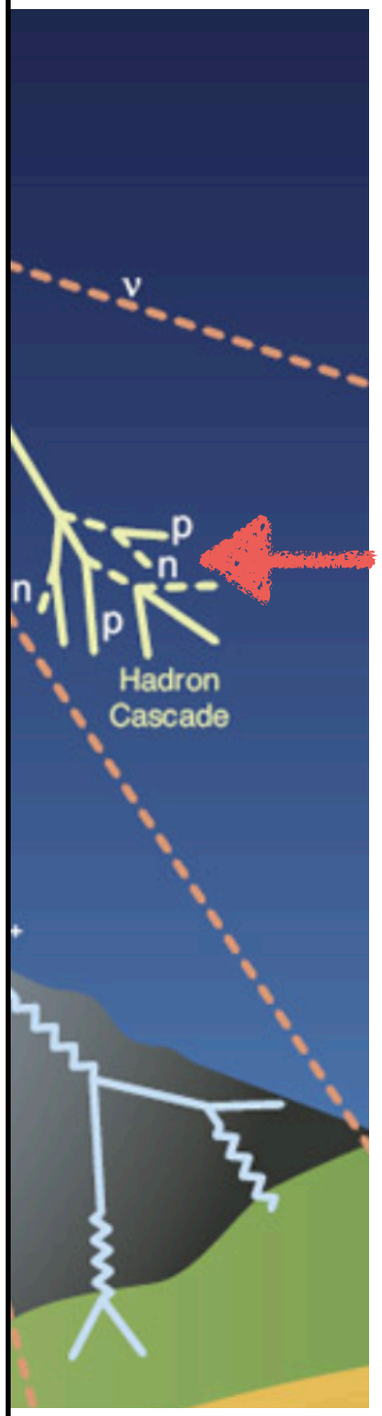


Cosmic Neutrons

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

From PDG, Sec. 30 (Cosmic Rays)

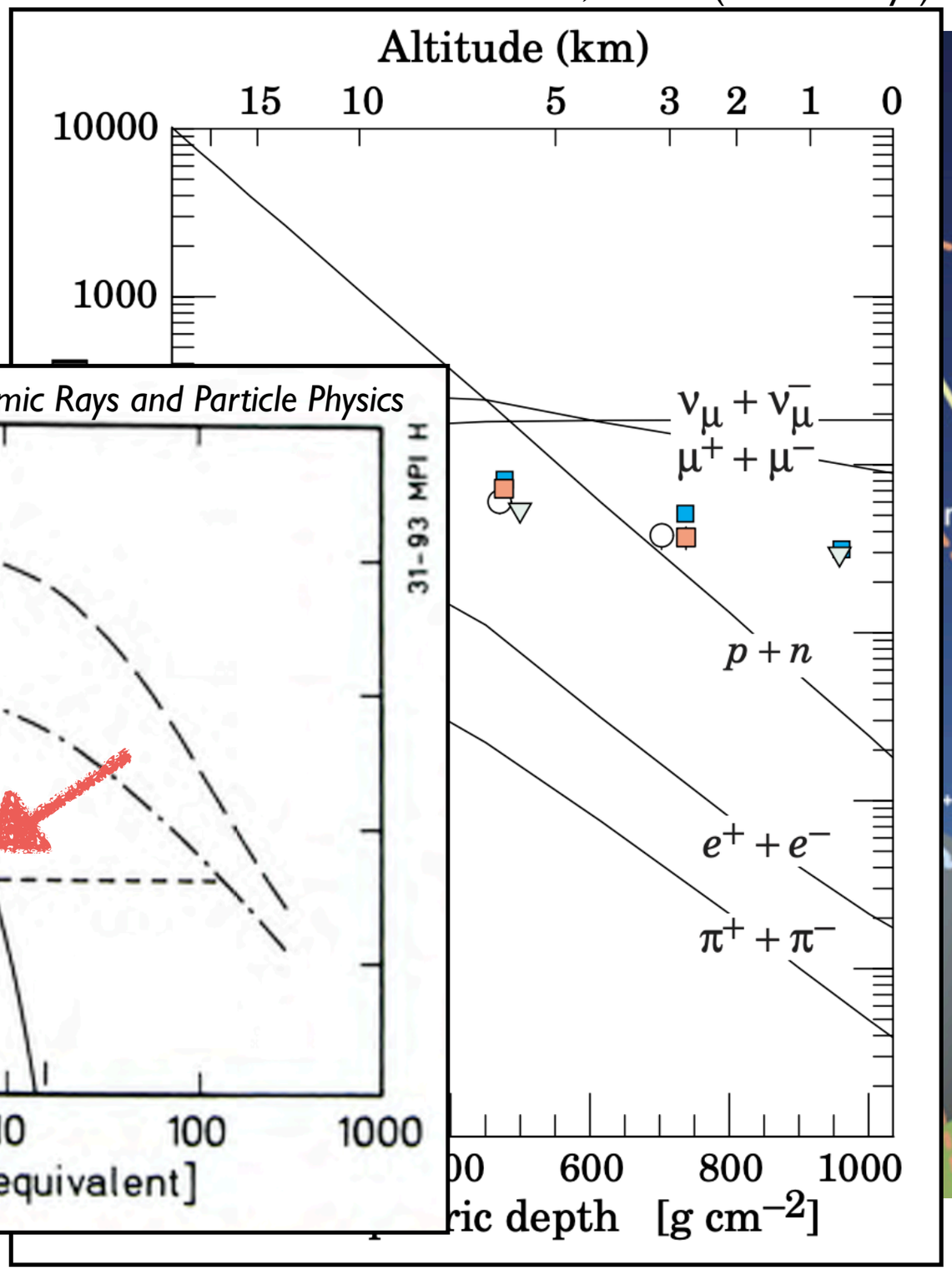




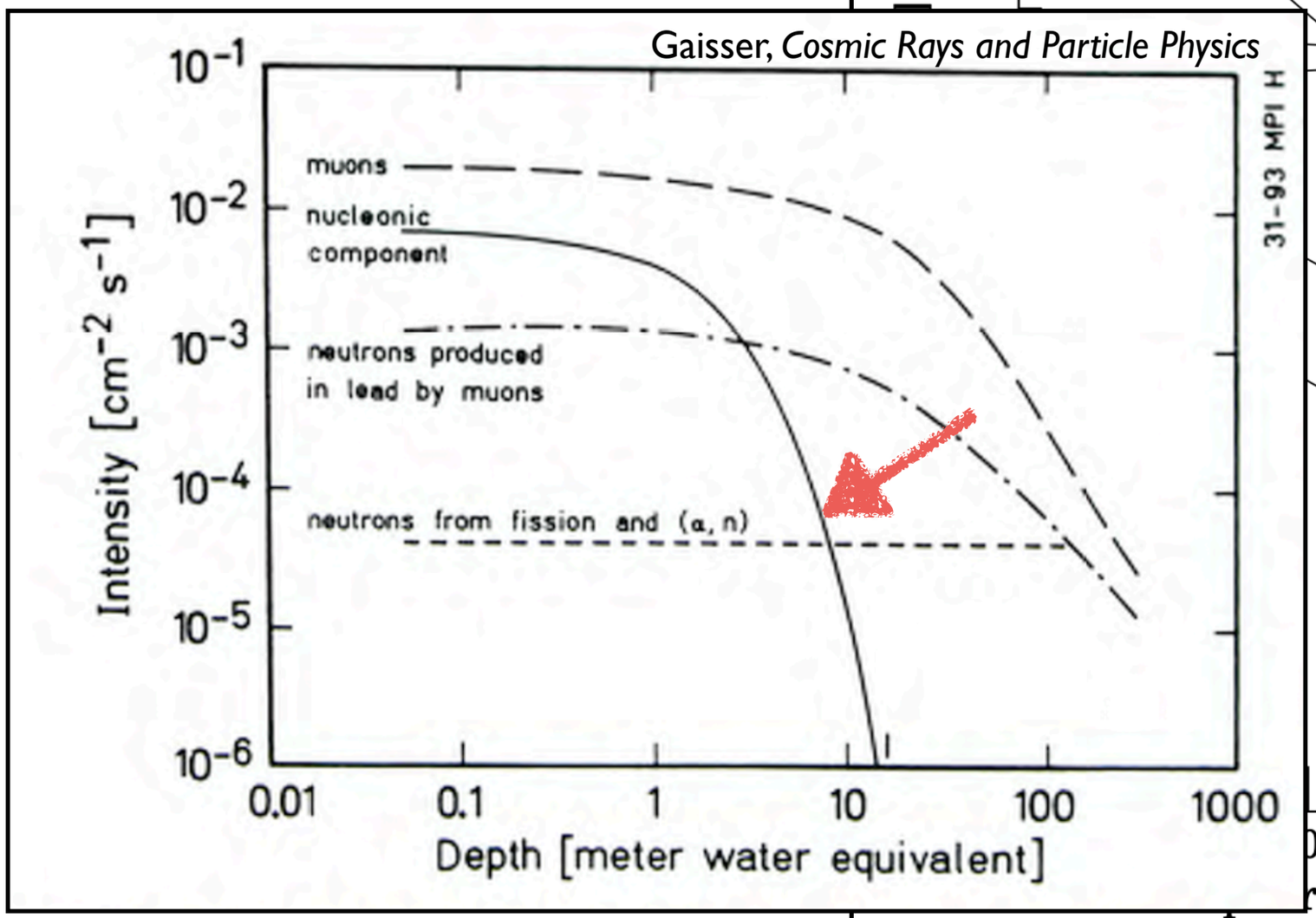
Cosmic Neutrons

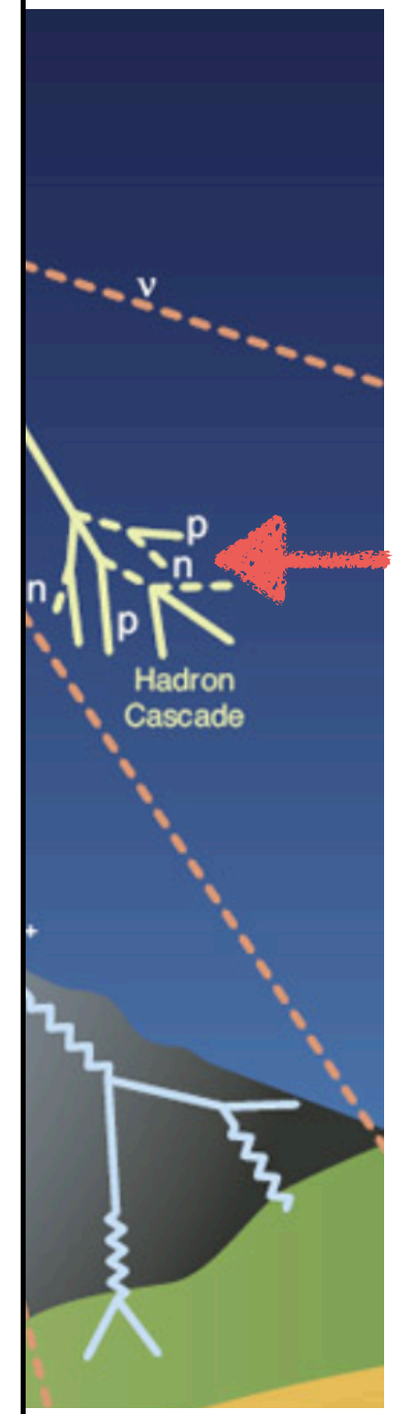
- Where do neutrons come from?
- Cosmogenic radiation
  - 'primary neutrons'
    - 'Very easily' shielded: just add a few meters of concrete…

From PDG, Sec. 30 (Cosmic Rays)



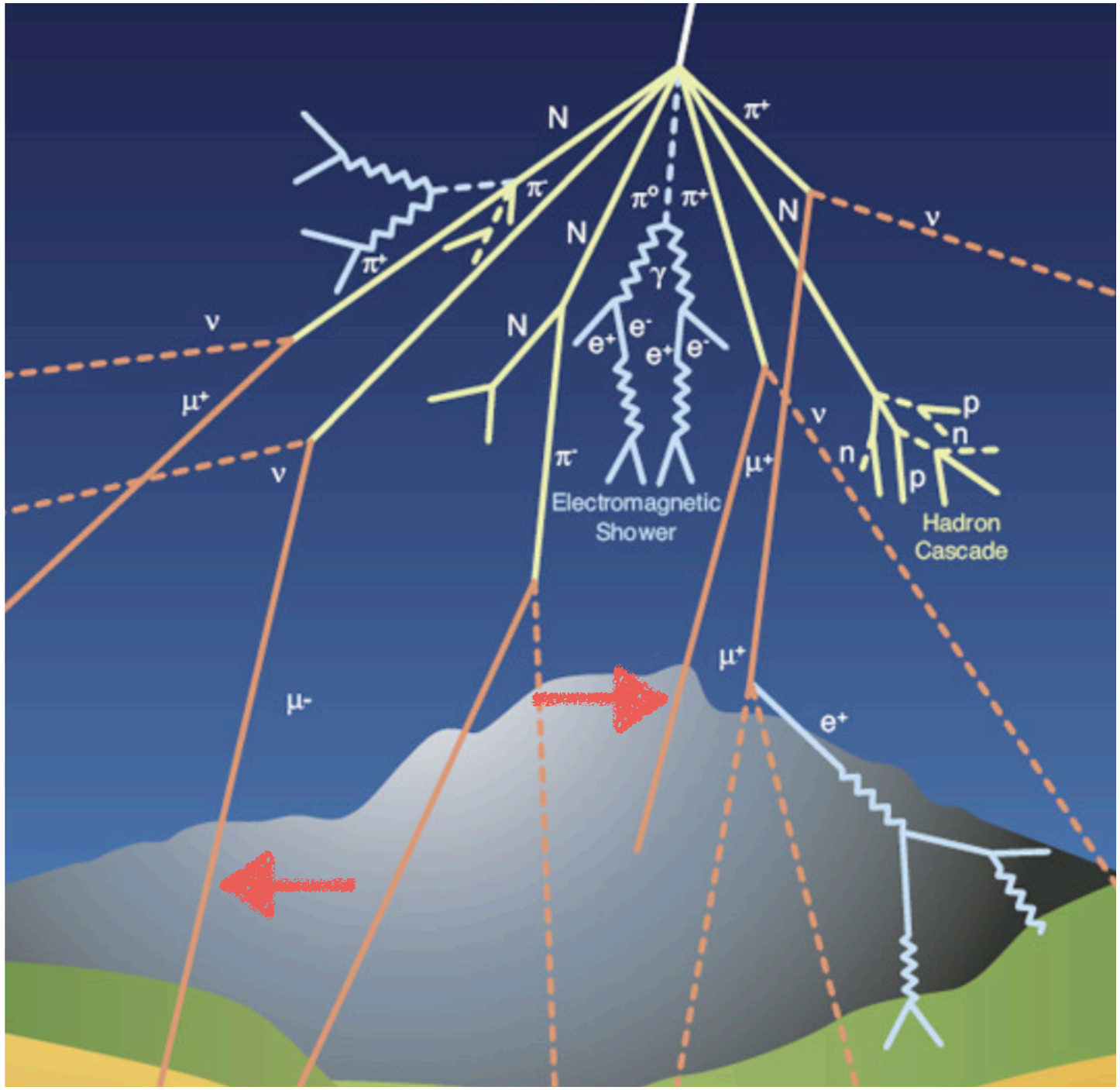
Gaisser, *Cosmic Rays and Particle Physics*





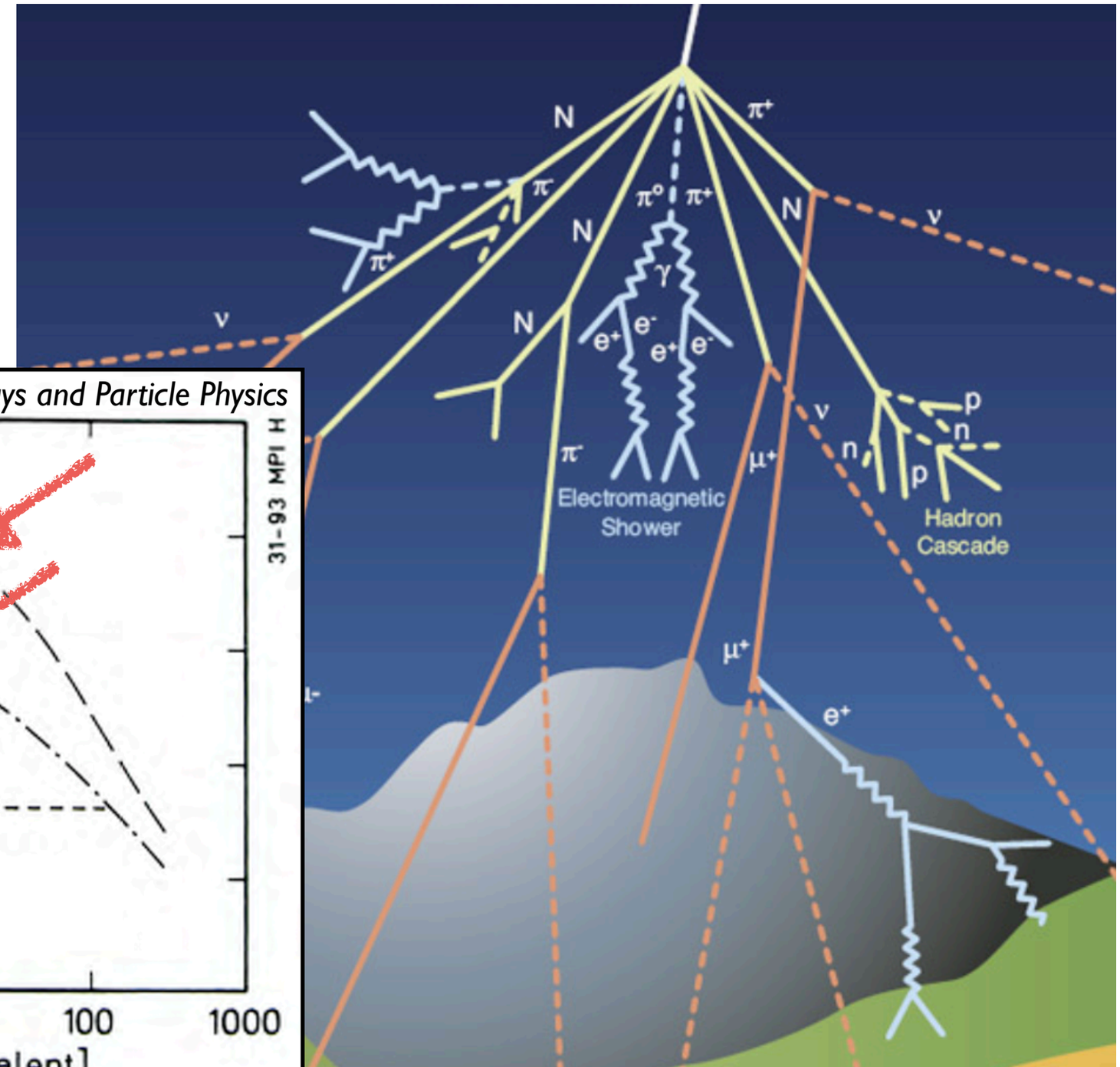
Cosmic Neutrons

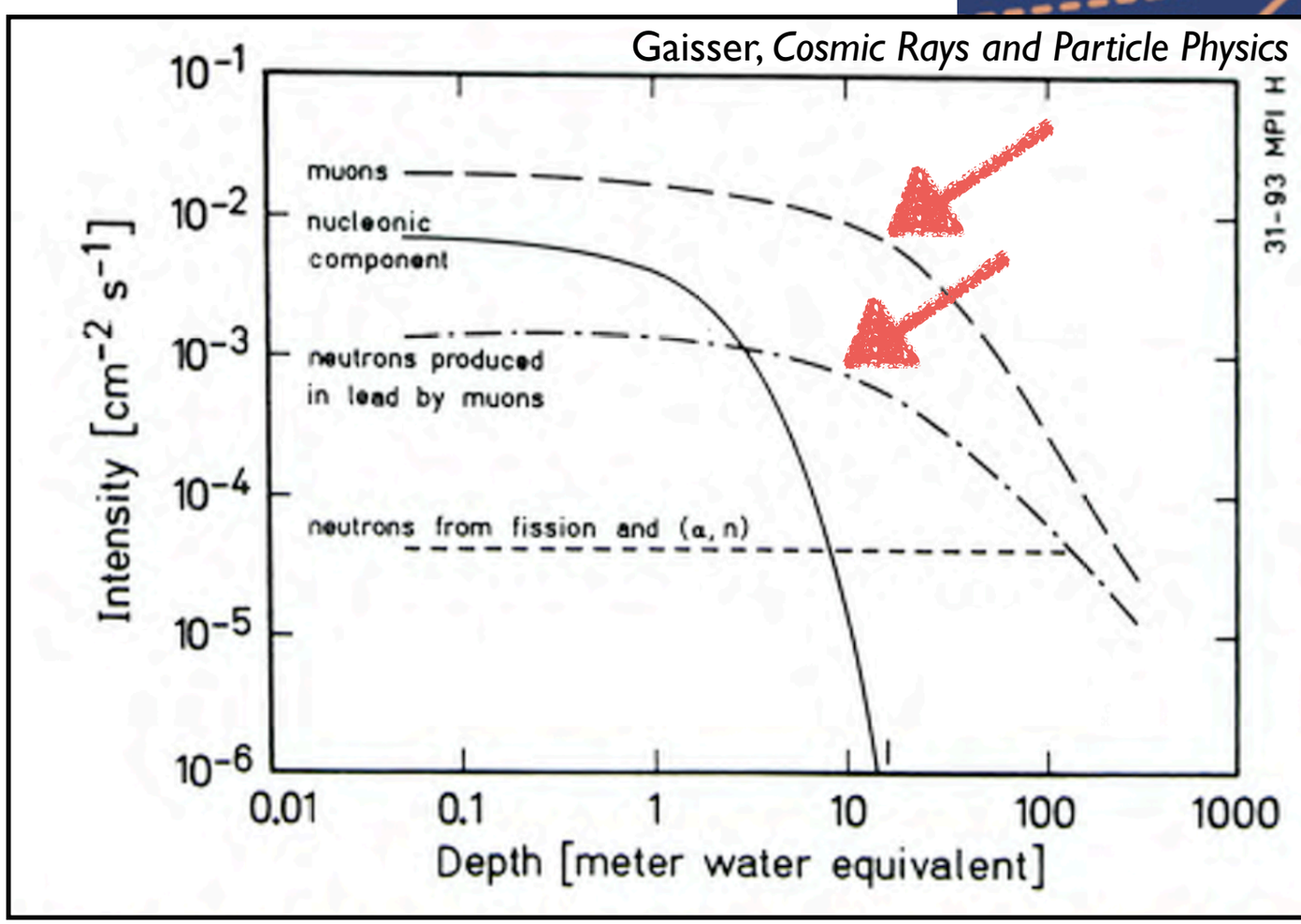
- Where do neutrons come from?
- Cosmogenic radiation
  - 'primary neutrons'
  - 'spallation neutrons' from penetrating cosmic muons



Cosmic Neutrons

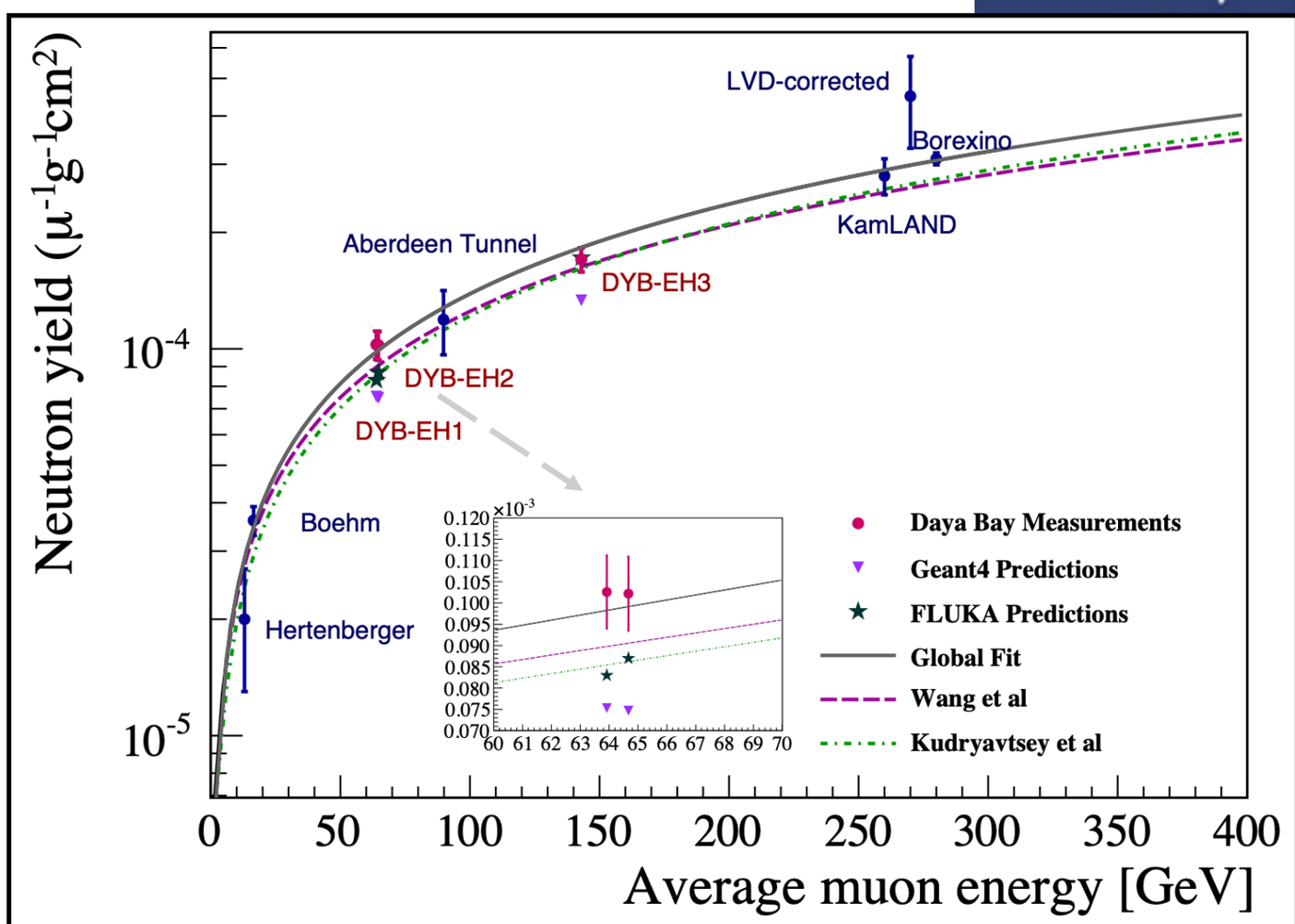
- Where do neutrons come from?
- Cosmogenic radiation
  - 'primary neutrons'
  - 'spallation neutrons' from penetrating cosmic muons

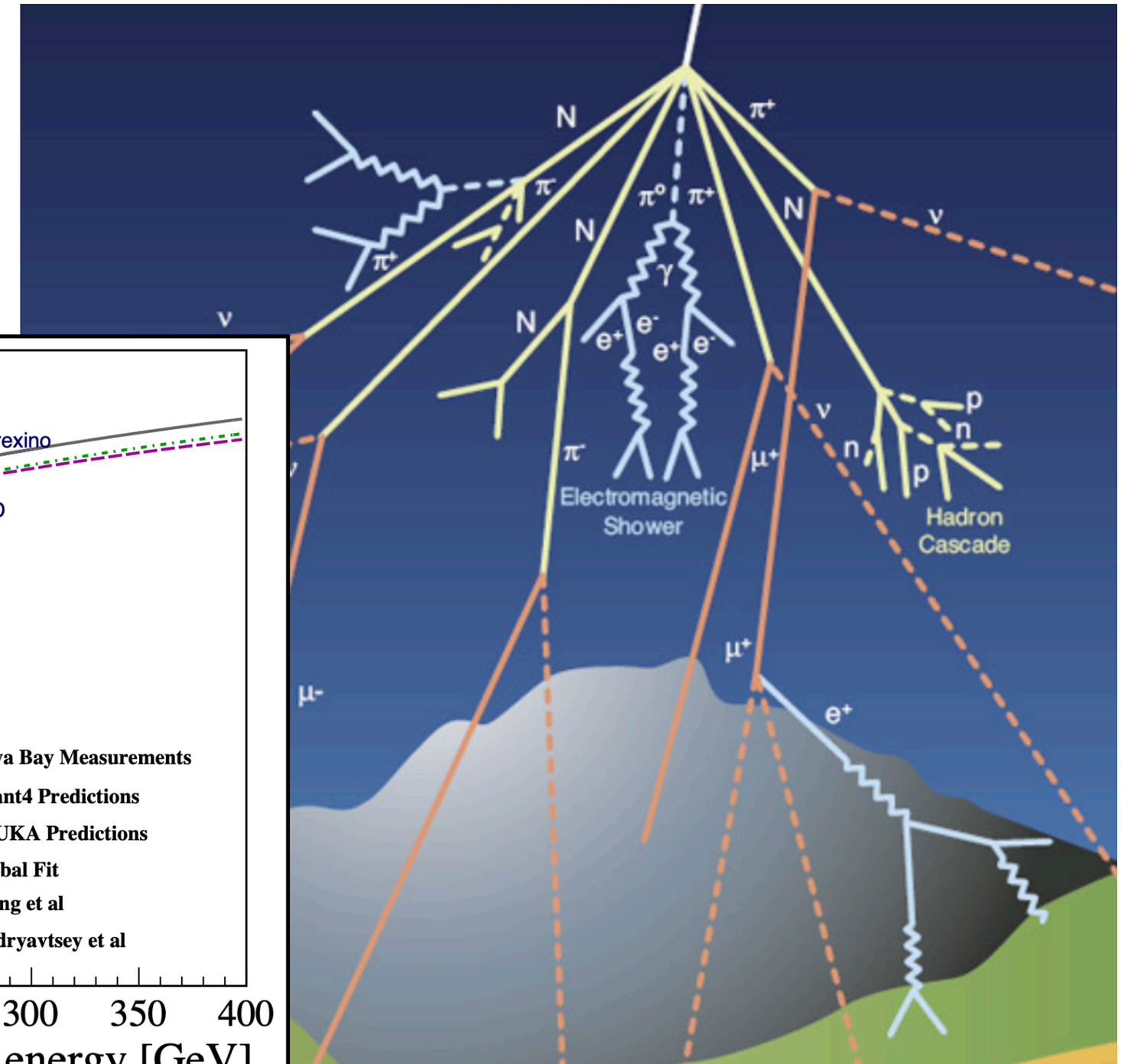




Cosmic Neutrons

- Where do neutrons come from?
- Cosmogenic radiation
  - 'primary neutrons'
  - 'spallation neutrons' from penetrating cosmic muons





Daya Bay, hep-ex[1711.00588]

Cosmogenic Isotopes

- Muon collisions make crazy stuff, which hit C to make crazy isotopes
- Crazy isotope decays, sometimes releasing a neutron
- Example: Li-9 made by C12(pi,^{3}He), sometimes (βn) decays

KamLAND, hep-ex[0907.0066]

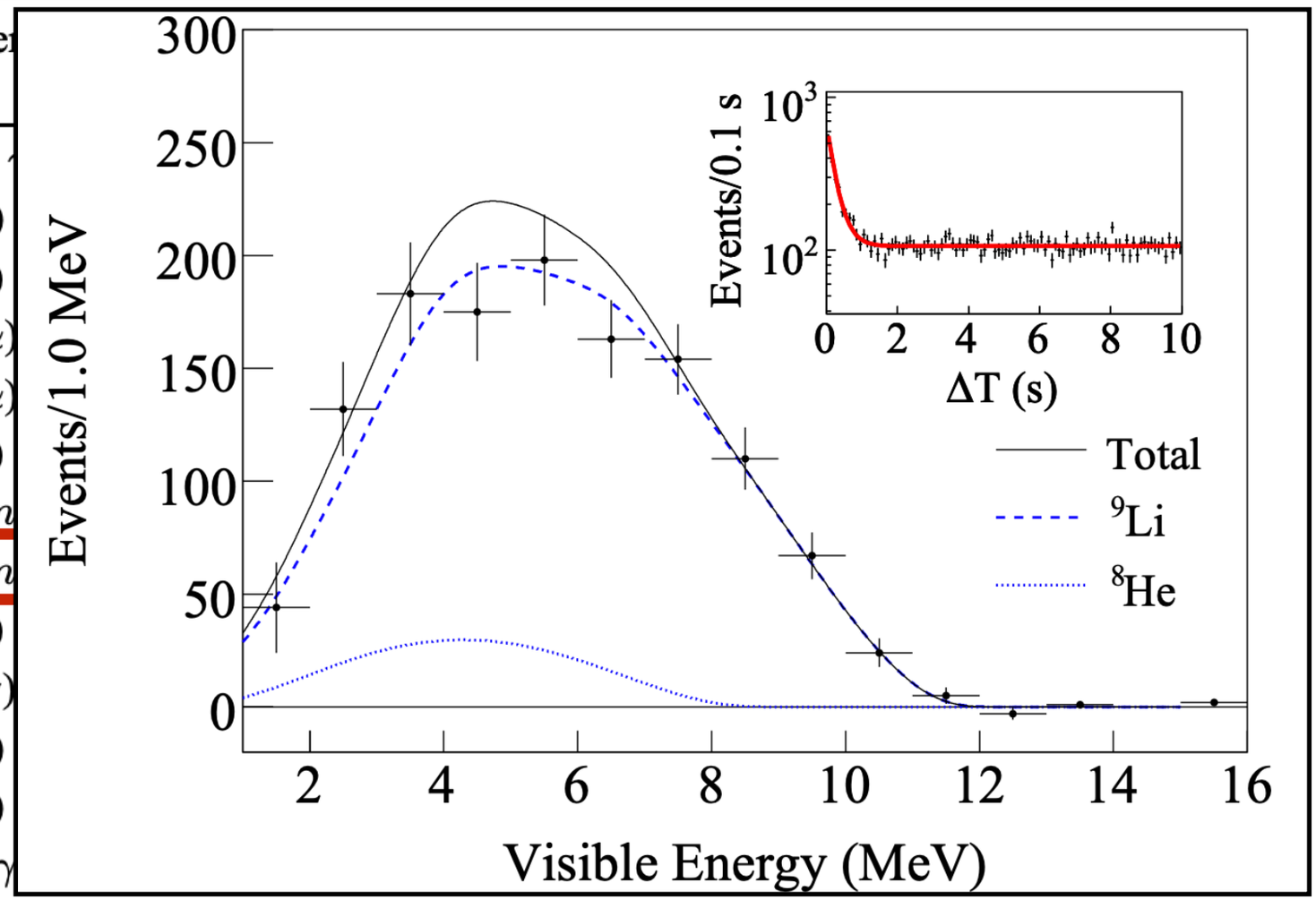
	Lifetime in KamLAND LS	Radiation energy (MeV)	Yield ($\times 10^{-7}\mu^{-1}\mathrm{g}^{-1}\mathrm{cm}^2$) Ref. [10]	FLUKA calc.	This measurement
n	207.5 μs	2.225 (capt. γ)	—	2097 ± 13	2787 ± 311
^{12}B	29.1 ms	13.4 (β^-)	—	27.8 ± 1.9	42.9 ± 3.3
^{12}N	15.9 ms	17.3 (β^+)	—	0.77 ± 0.08	1.8 ± 0.4
^{8}Li	1.21 s	16.0 ($\beta^-\alpha$)	1.9 ± 0.8	21.1 ± 1.4	12.2 ± 2.6
^{8}B	1.11 s	18.0 ($\beta^+\alpha$)	3.3 ± 1.0	5.77 ± 0.42	8.4 ± 2.4
^{9}C	182.5 ms	16.5 (β^+)	2.3 ± 0.9	1.35 ± 0.12	3.0 ± 1.2
^{8}He	171.7 ms	10.7 ($\beta^-\gamma n$)	1.0 ± 0.3	0.32 ± 0.05	0.7 ± 0.4
^{9}Li	257.2 ms	13.6 ($\beta^-\gamma n$)		3.16 ± 0.25	2.2 ± 0.2
^{11}C	29.4 min	1.98 (β^+)	421 ± 68	416 ± 27	866 ± 153
^{10}C	27.8 s	3.65 ($\beta^+\gamma$)	54 ± 12	19.1 ± 1.3	16.5 ± 1.9
^{11}Be	19.9 s	11.5 (β^-)	< 1.1	0.84 ± 0.09	1.1 ± 0.2
^{6}He	1.16 s	3.51 (β^-)	7.5 ± 1.5	12.08 ± 0.83	—
^{7}Be	76.9 day	0.478 (EC γ)	107 ± 21	105.3 ± 6.9	—

Cosmogenic Isotopes

- Muon collisions make crazy stuff, which hit C to make crazy isotopes
- Crazy isotope decays, sometimes releasing a neutron
- Example: Li-9 made by C12(pi,^{3}He), sometimes (βn) decays

KamLAND, hep-ex[0907.0066]

	Lifetime in KamLAND LS	Radiation ener (MeV)
n	207.5 μs	2.225 (capt.
^{12}B	29.1 ms	13.4 (β^-)
^{12}N	15.9 ms	17.3 (β^+)
^{8}Li	1.21 s	16.0 ($\beta^-\alpha$)
^{8}B	1.11 s	18.0 ($\beta^+\alpha$)
^{9}C	182.5 ms	16.5 (β^+)
^{8}He	171.7 ms	10.7 ($\beta^-\gamma n$
^{9}Li	257.2 ms	13.6 ($\beta^-\gamma n$
^{11}C	29.4 min	1.98 (β^+)
^{10}C	27.8 s	3.65 ($\beta^+\gamma$)
^{11}Be	19.9 s	11.5 (β^-)
^{6}He	1.16 s	3.51 (β^-)
^{7}Be	76.9 day	0.478 (EC γ



Aside: Everyone Cares About Neutrons!

- NOTE: final-state n from weak GeV-scale $\underline{\mu}$-A interactions!
- Hmmm… what about weak GeV-scale $\underline{\nu_\mu}$-A interactions?

KamLAND, hep-ex[0907.0066]

	Simulated production yield	Ratio of Simulated Production Yields for		Power-law exp.	Primary process
	$(\times 10^{-7}\mu^{-1}\mathrm{g}^{-1}\mathrm{cm}^2)$	μ^+/μ^-	Spectrum/monoenergetic		
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	${}^{12}\mathrm{C}(n, 2p)$

Aside: Everyone Cares About Neutrons!

- NOTE: final-state n from weak GeV-scale $\underline{\mu}$-A interactions!
- Hmmm… what about weak GeV-scale $\underline{\nu_\mu}$-A interactions?
- So it's not just reactor nu folks who should care about how we detect neutrons!

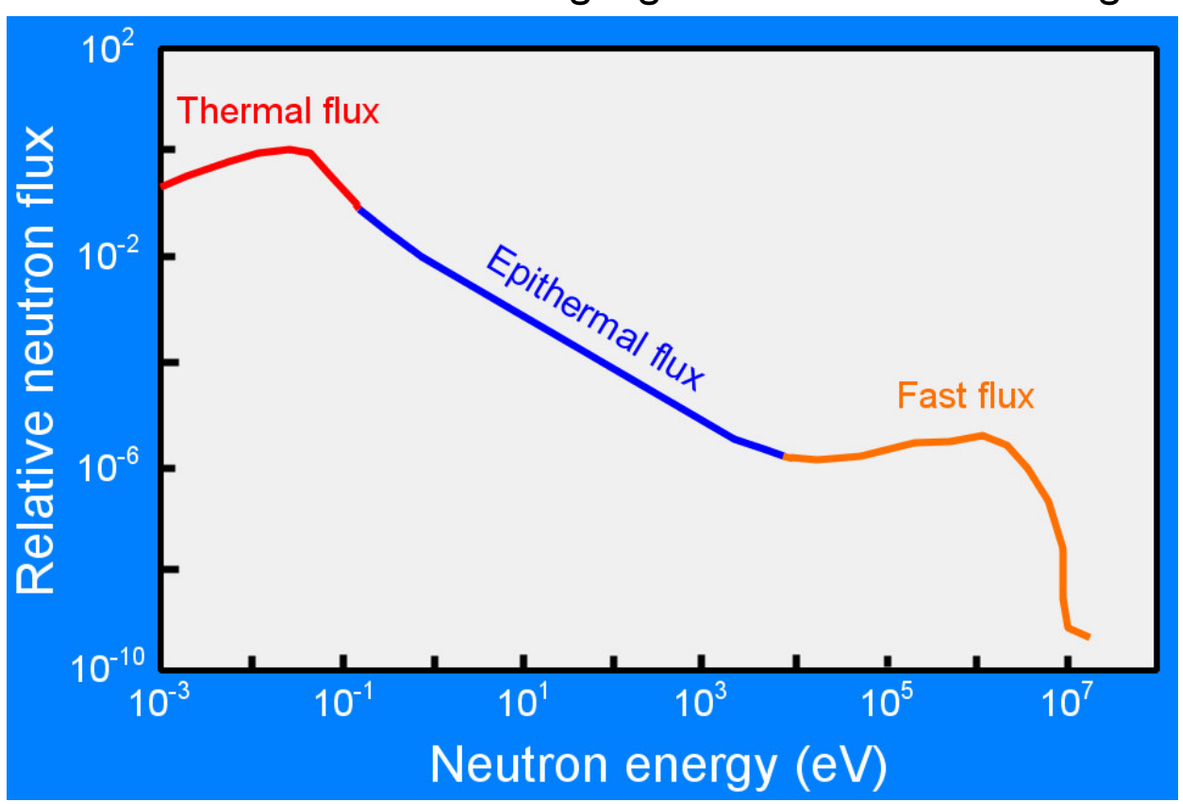
ArgoNeuT, hep-ex[1810.06502] MINERvA, hep-ex[1901.04892]
NOvA, hep-ex[1906.04907]
KamLAND, hep-ex[0907.0066]

	Simulated production yield	Ratio of Simulated Production Yields for		Power-law exp.	Primary process
	$(\times 10^{-7}\mu^{-1}\mathrm{g}^{-1}\mathrm{cm}^2)$	μ^+/μ^-	Spectrum/monoenergetic		
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	${}^{12}\mathrm{C}(n, 2p)$

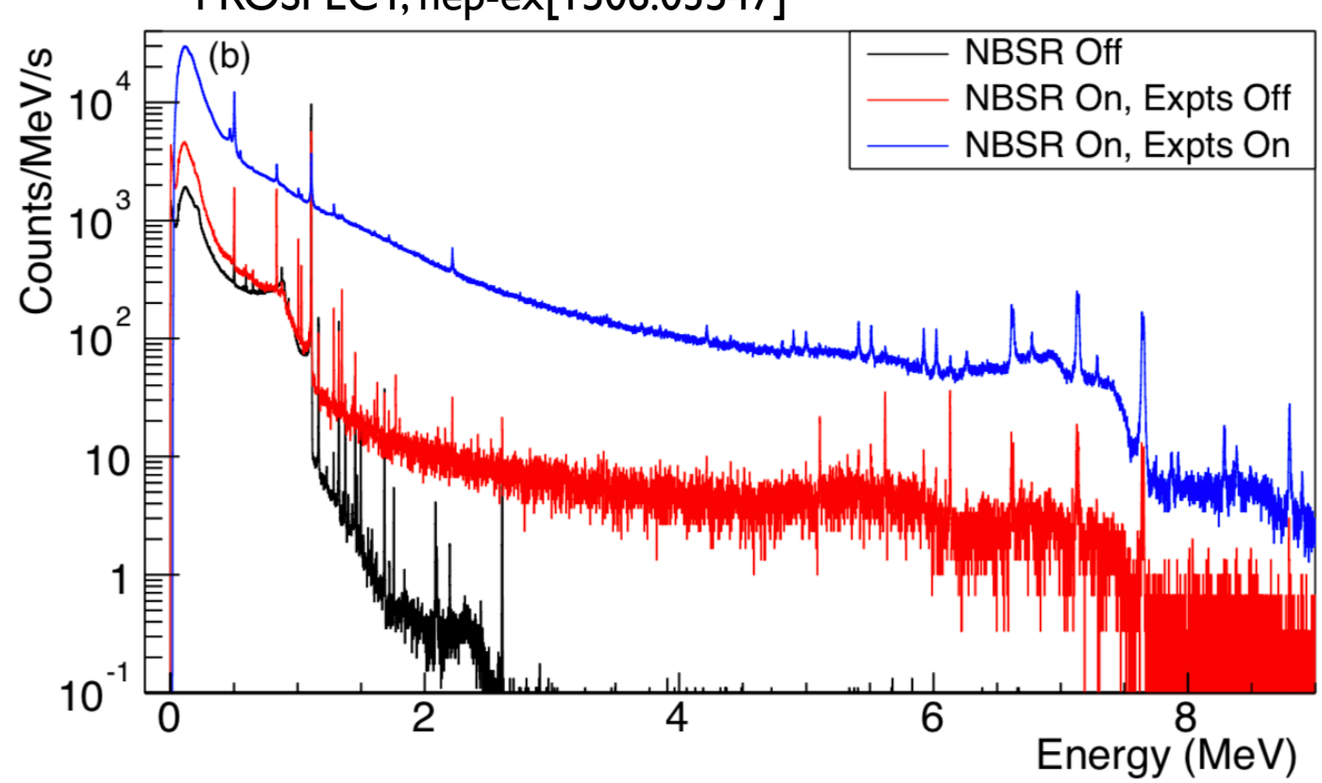
Reactor Neutrons

- 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 **can** produce CRAZY high gamma fluxes, though!

google 'reactor neutron energies'



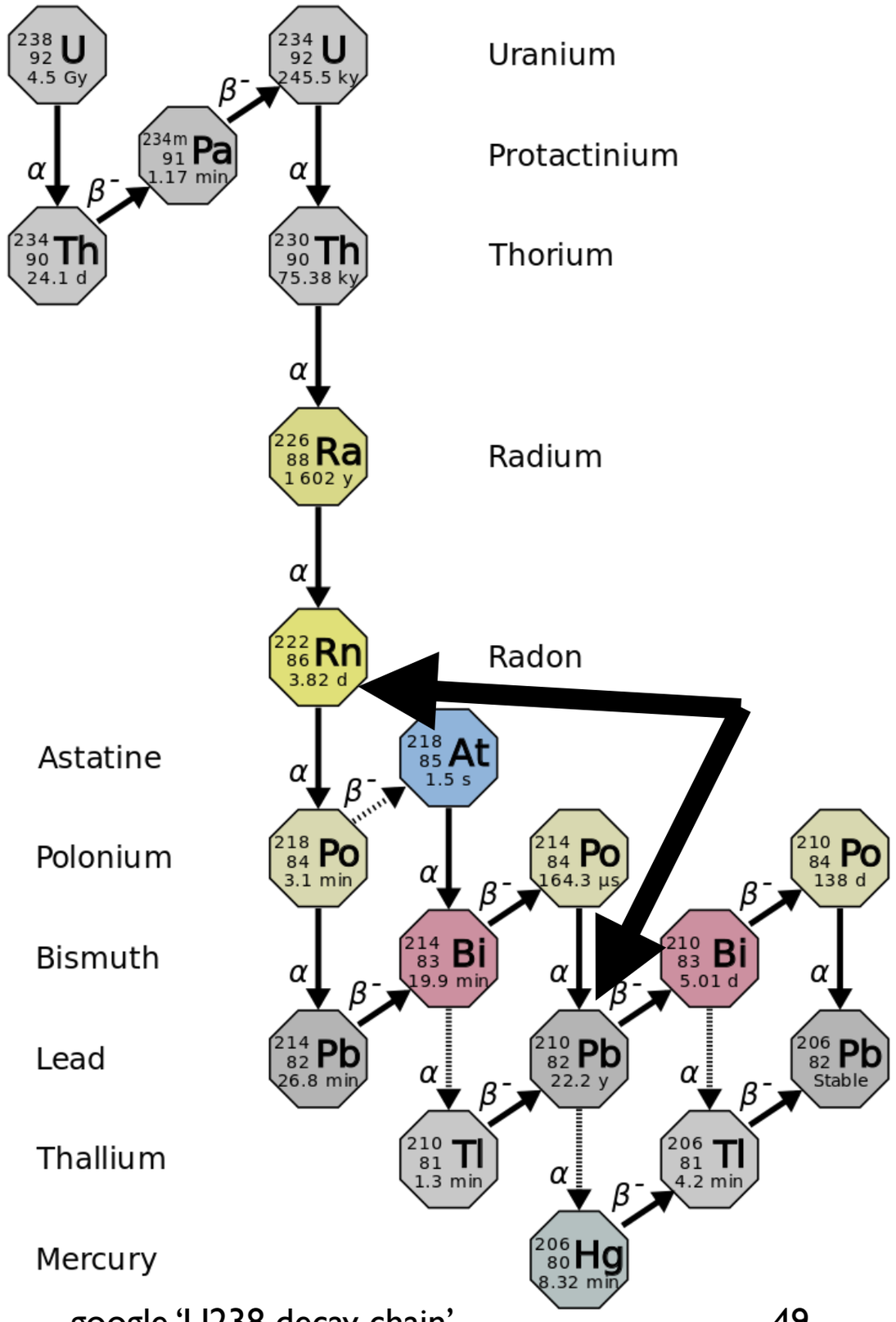
PROSPECT, hep-ex[1506.03547]



https://bit.ly/2Zxm0pm

Radiogenics

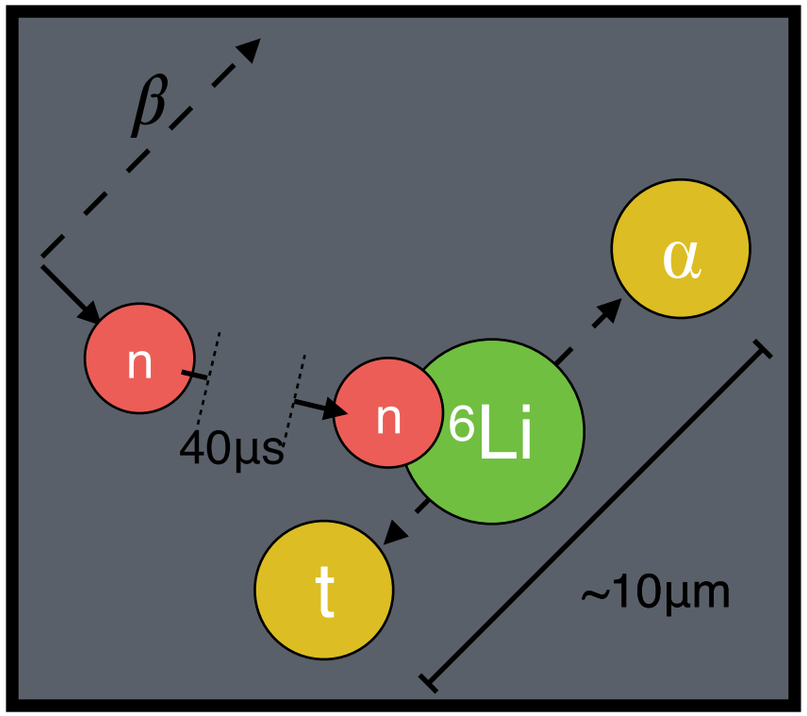
- Few very heavy stable isotopes
  - They get into stuff, thus do their products
    - (Blame the radon, in particular)
  - Some of these products alpha decay and give (α,n) interactions in scintillator
  - Usually a low-rate process: only matters much for low-rate experiments
    - Solar neutrinos
    - Long-baseline reactor
    - Geoneutrinos
    - Dark matter
    - 0nubb

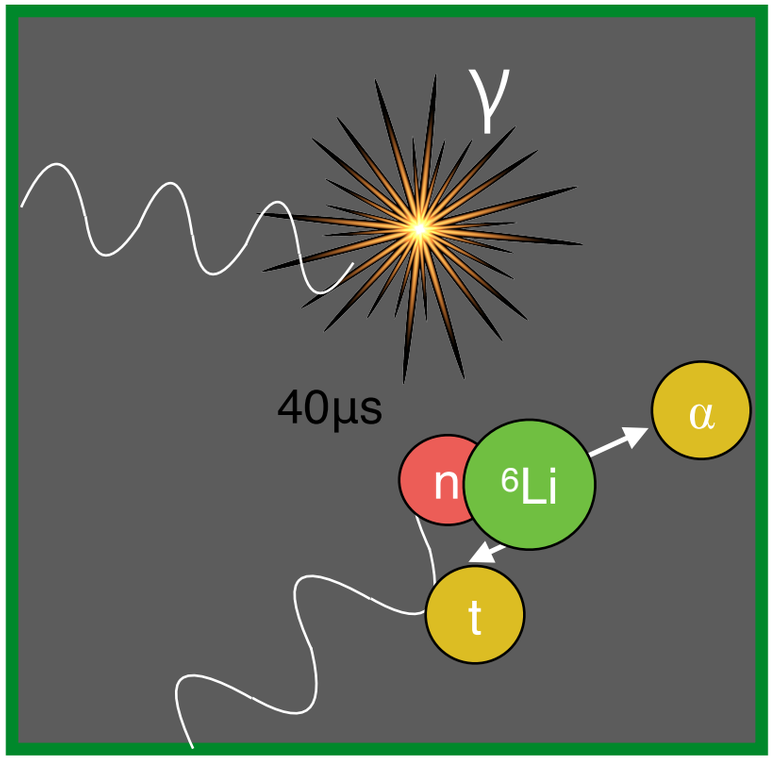


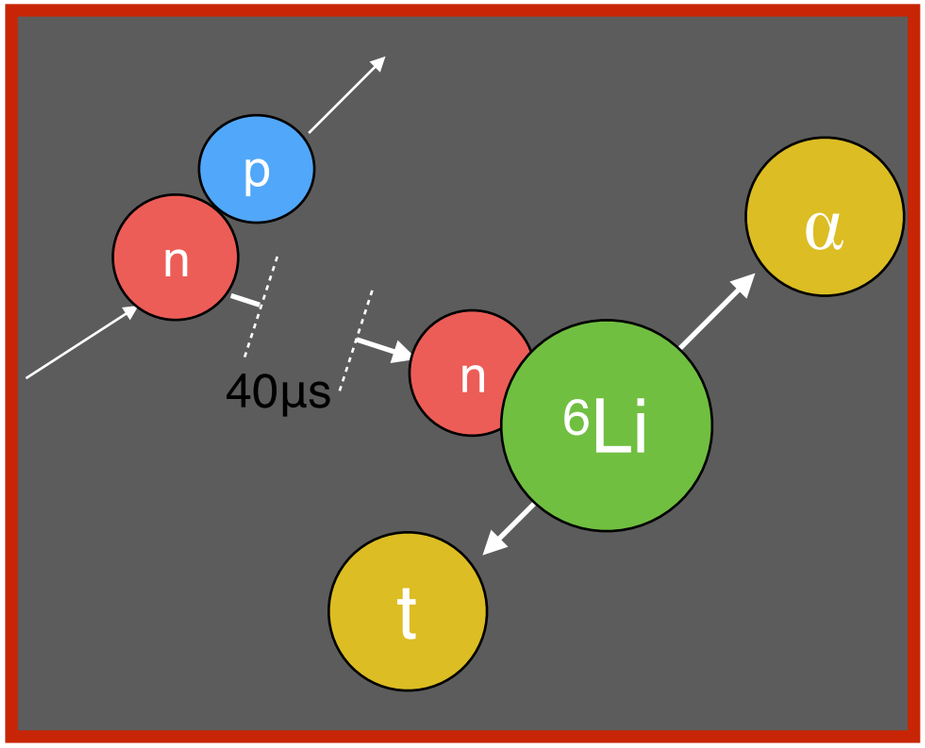
google 'U238 decay chain'

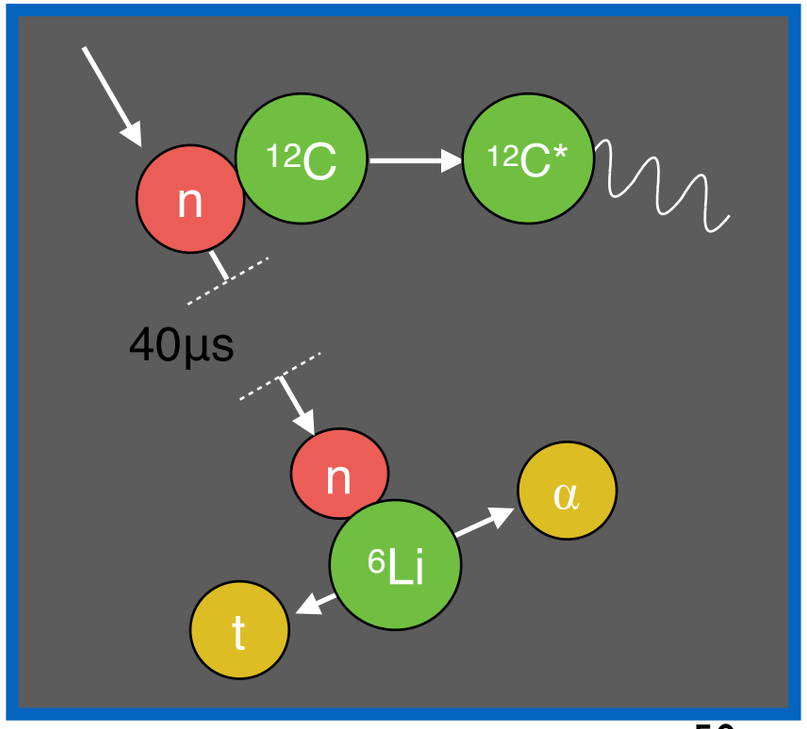
Neutron Background Possibilities

- 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)



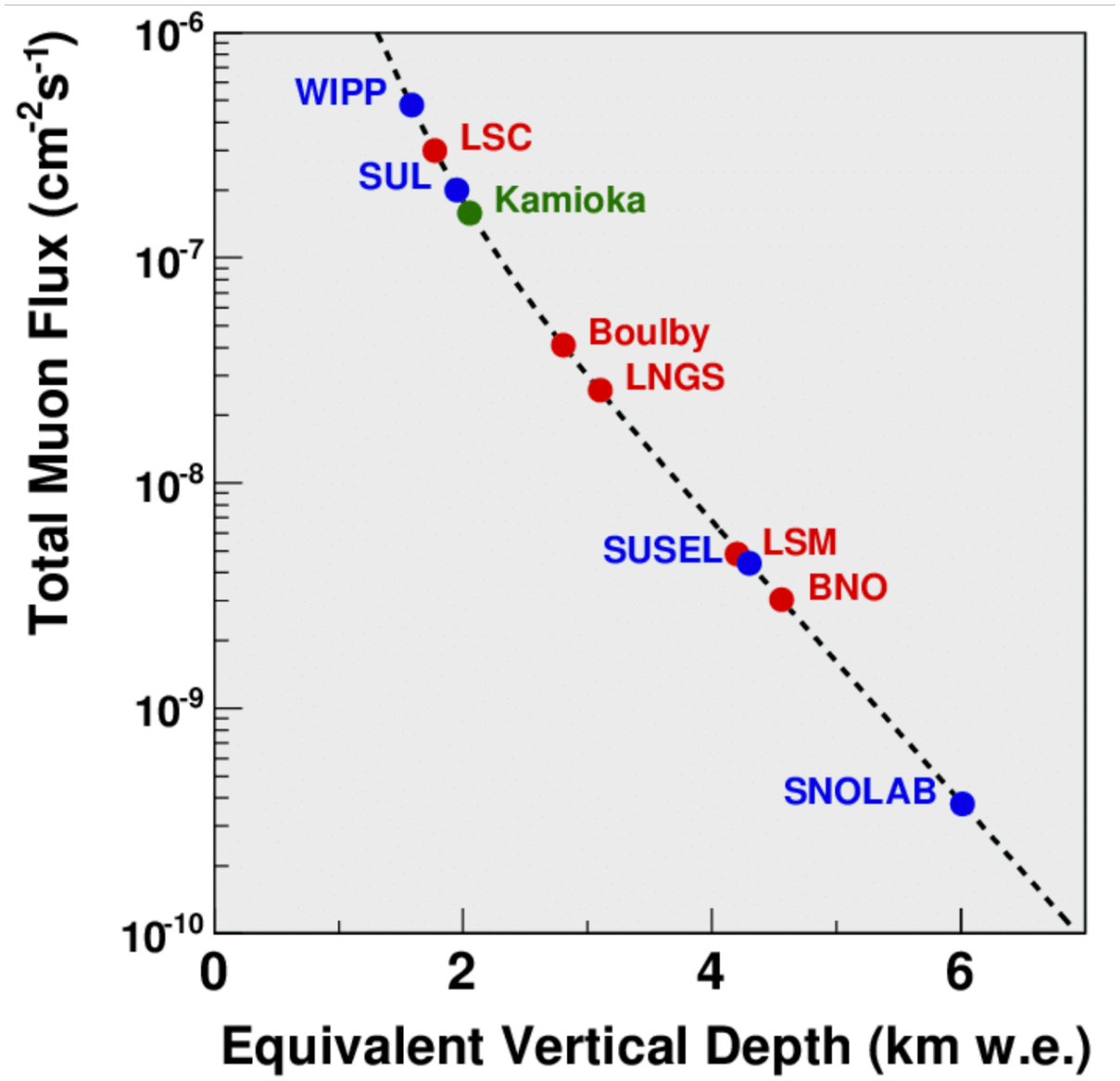






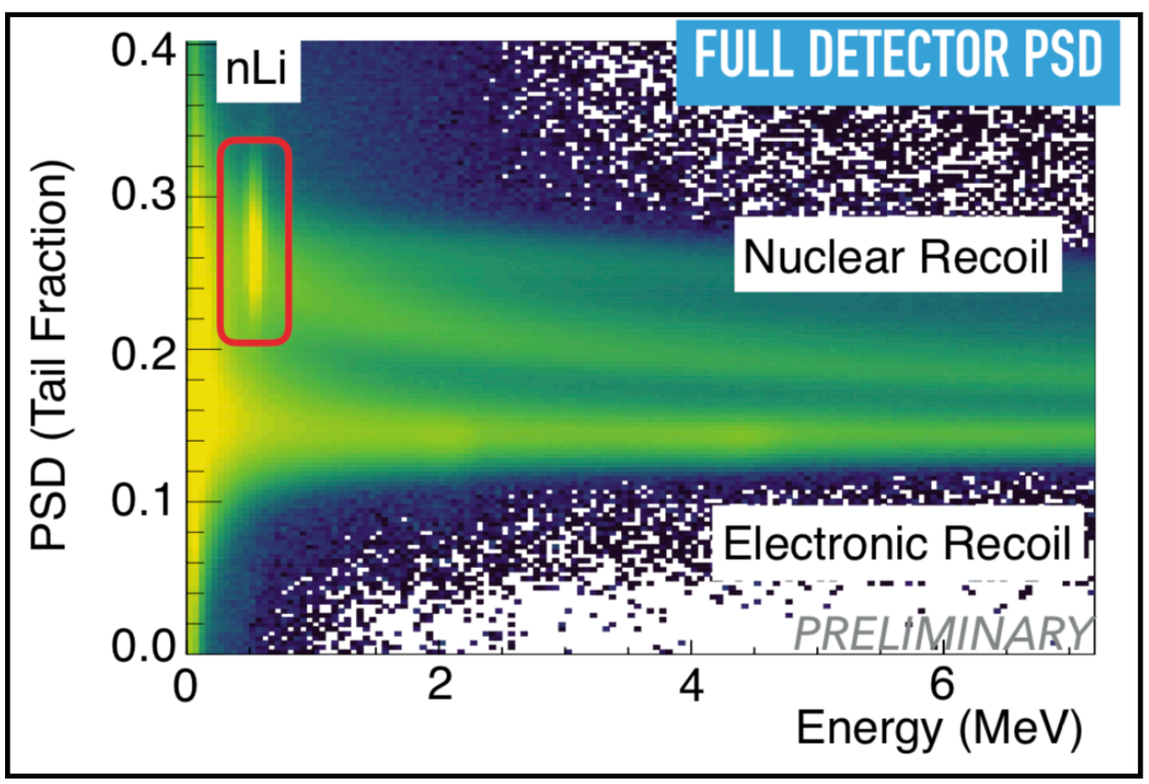
How do we remove these guys?

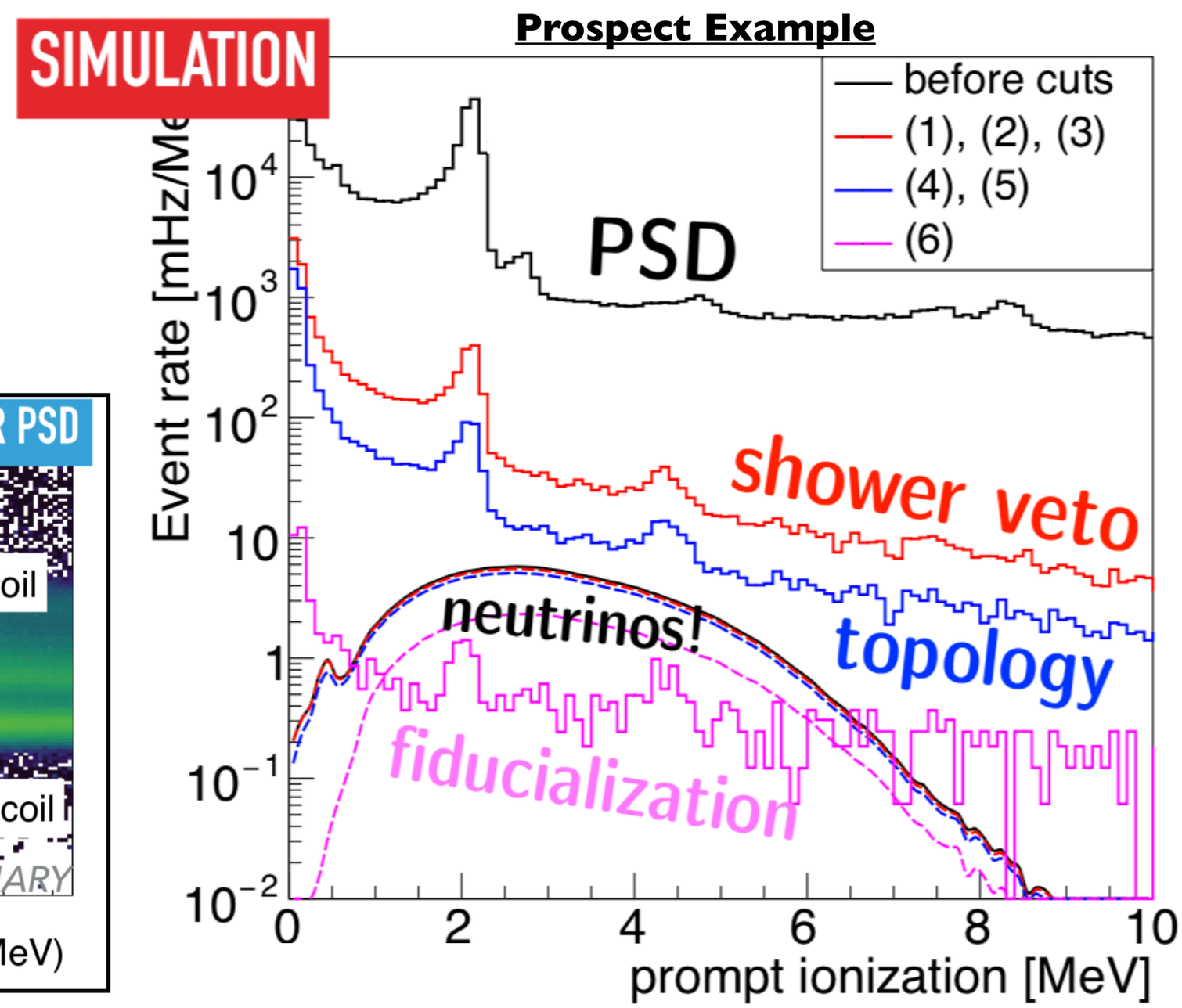
- GO DEEPER
- Byebye, primary cosmic neutron backgrounds
- Muon-produced stuff: exponential suppression!



How do we remove these guys?

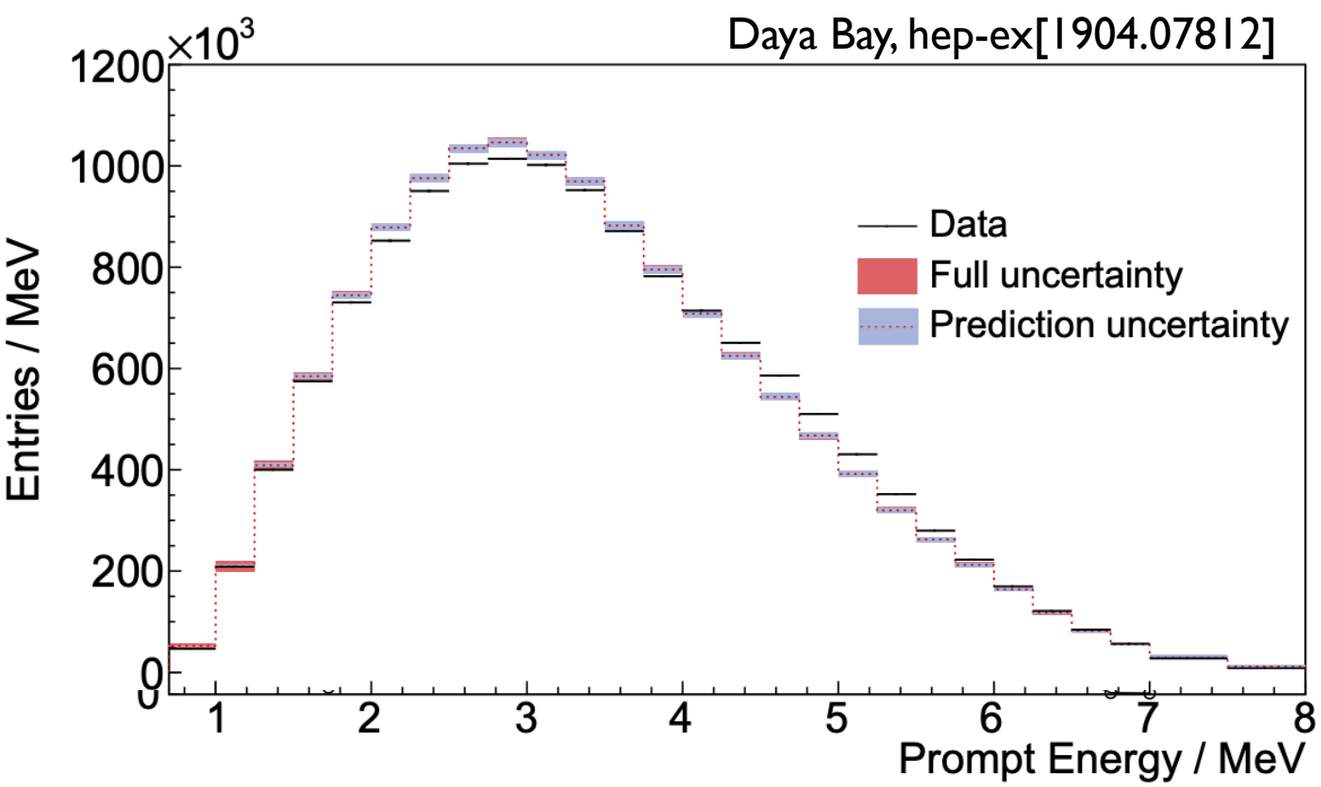
- Coincidence time (accidental coincidences)
- After-muon or after-neutron veto (cosmogenic stuff)
- Spatial topology (all categories)
- PSD (all categories)

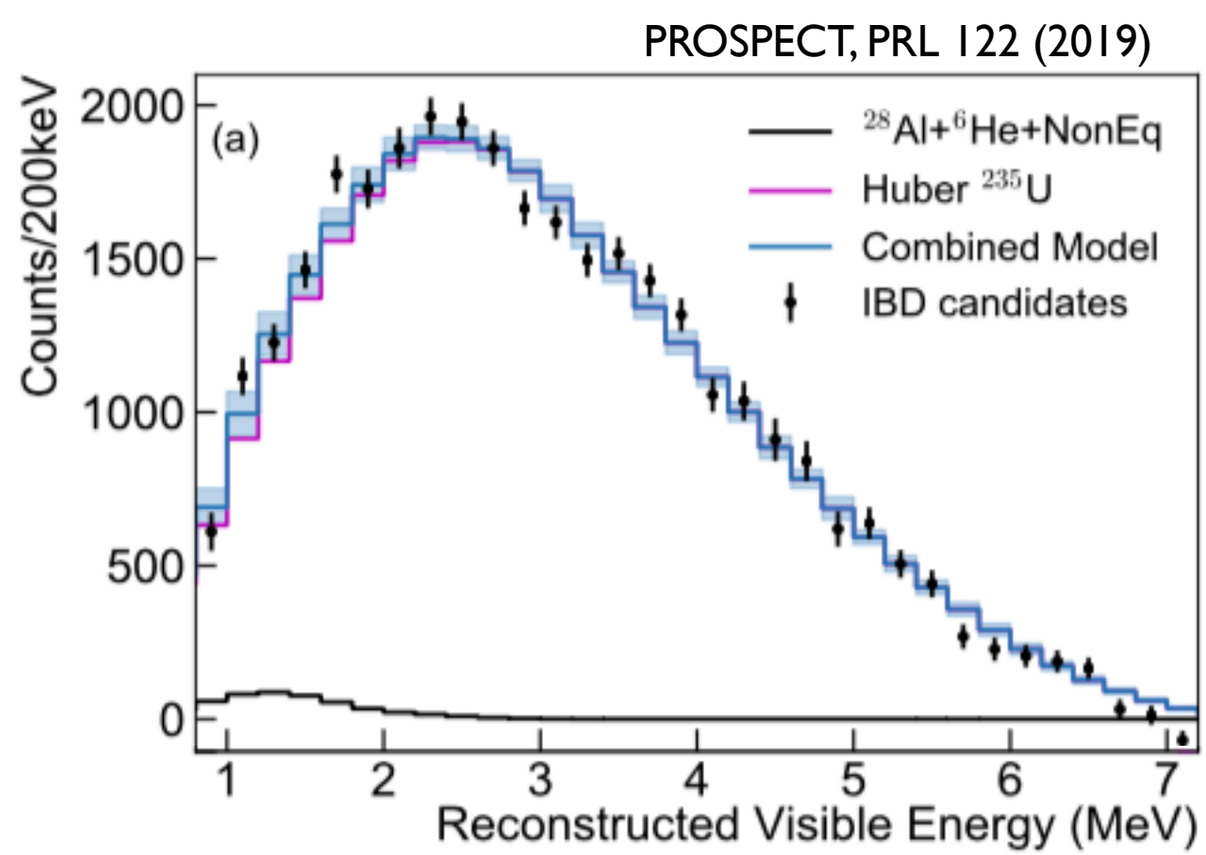




Rx Nuebar: What success looks like.

- Do all this, and you'll see your IBDs!
  - Stuff I did not discuss that's also important in getting to this point:
    - Calibration: conversion from 'light detected' to 'MeV'
    - Systematics: where to those 'prediction' error bars come from?





Questions?

Now: What about ~~anti~~neutrinos?

- Let's go back to SOLAR neutrinos
- How do we detect these?
- Let's go back to our interactions list for antineutrinos.

Xian and Peng, hep-ex[1801.05386]

Channel	Interaction Type	Cross Section (10^{-44} cm^2/fission)	Threshold (MeV)
$\bar{\nu}_e + p \rightarrow e^+ + n$	CC	~63	1.8
$\bar{\nu}_e + d \rightarrow n + n + e^+$	CC	~1.1	4.0
$\bar{\nu}_e + d \rightarrow n + p + \bar{\nu}_e$	NC	~3.1	2.2
$\bar{\nu}_e + e^- \rightarrow \bar{\nu}_e + e^-$	CC/NC	~0.4	0
$\bar{\nu}_e + A \rightarrow \bar{\nu}_e + A$	NC	$\sim 9.2 \times N^2$	0

- How can we flip these around to work for <u>neutrinos</u>?

Now: What about ~~anti~~neutrinos?

- Let's go back to SOLAR neutrinos
- How do we detect these?
- Let's go back to our interactions list for antineutrinos.

Xian and Peng, hep-ex[1801.05386]

Channel	Interaction Type	Cross Section (10^{-44} cm^2/fission)	Threshold (MeV)
$\bar{\nu}_e + p \rightarrow e^+ + n$	CC	~63	1.8
$\bar{\nu}_e + d \rightarrow n + n + e^+$	CC	~1.1	4.0
$\bar{\nu}_e + d \rightarrow n + p + \bar{\nu}_e$	NC	~3.1	2.2
$\bar{\nu}_e + e^- \rightarrow \bar{\nu}_e + e^-$	CC/NC	~0.4	0
$\bar{\nu}_e + A \rightarrow \bar{\nu}_e + A$	NC	~9.2×N^2	0

- How can we flip these around to work for <u>neutrinos</u>?
  - Deuterium: can tell apart NC and CC!
  - Electron scattering too?

$$\nu_e + \mathrm{d} \rightarrow \mathrm{p} + \mathrm{p} + e^-$$

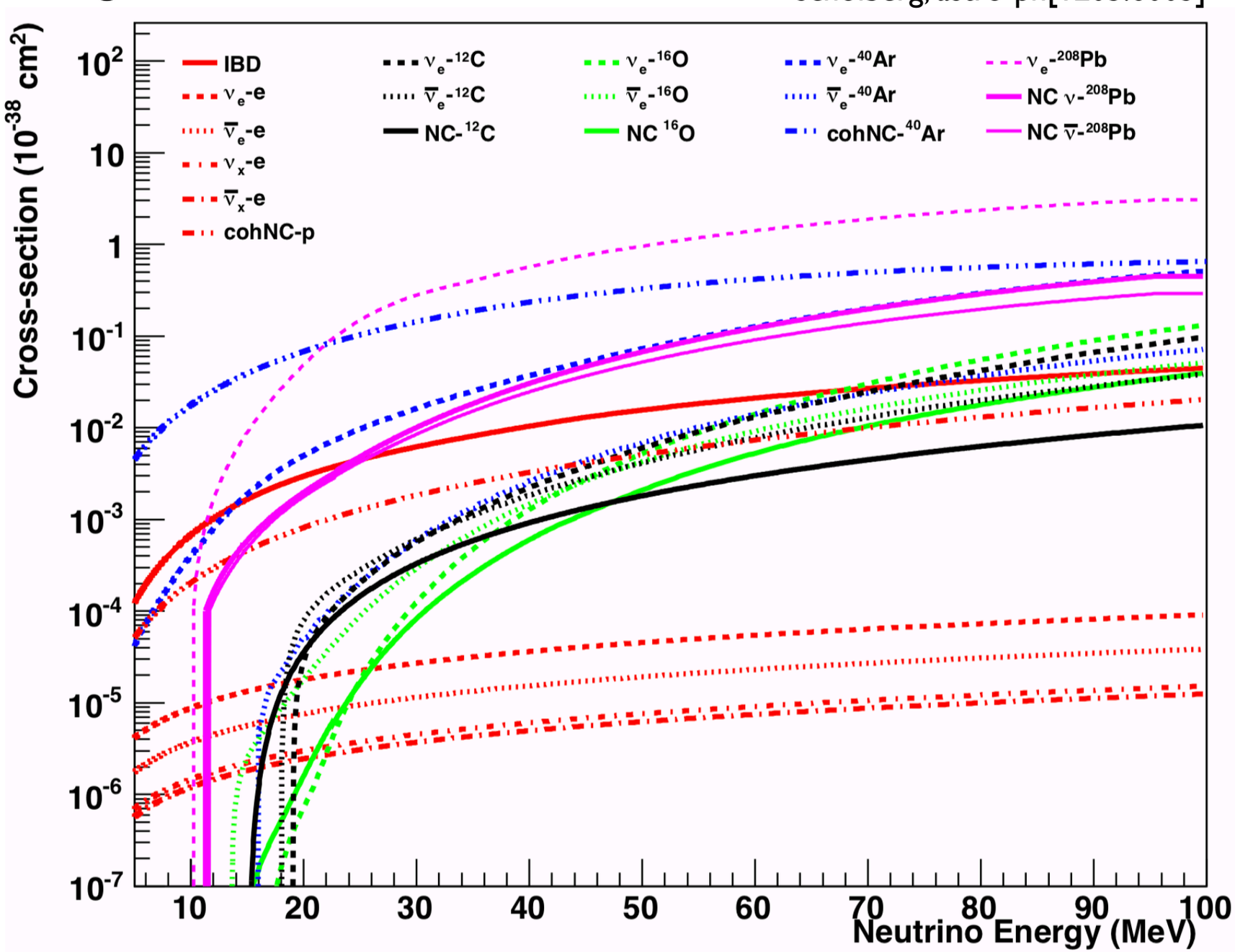
$$\nu_x + e^- \rightarrow \nu_x + e^-$$

$$\nu_x + \mathrm{d} \rightarrow \mathrm{n} + \mathrm{p} + \nu_x$$

Now: What about ~~anti~~neutrinos?

- How can we flip these around to work for <u>neutrinos</u>?
  - Deuterium: can tell apart NC and CC!
  - Electron scattering too?

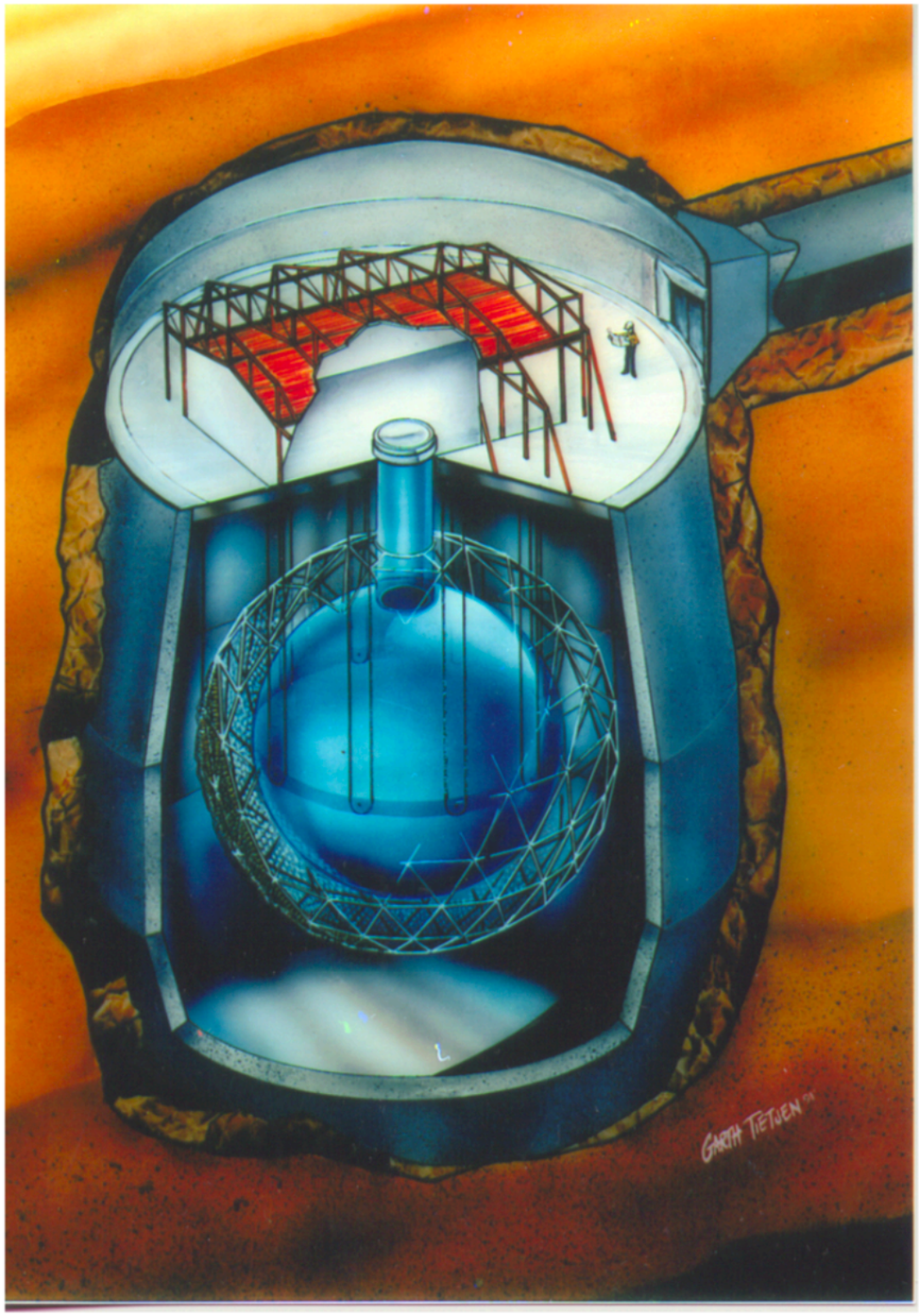
Scholberg, astro-ph[1205.6003]



SNO

- Deuterium: LET'S DO IT
- HOW does this work?
  - Q: Are we making kilotons of deuterated organic scintillator?
  - A: HECK NO.
- Let's just use what exists: 1kT heavy water stockpile
  - Why do these exist? Read up! (https://amzn.to/2YgPR43)
- Looks like we're building a Cerenkov detector.
  - 1kT heavy water sphere; 6 meters across!
  - 9,600 PMTs!

A. Bellerive et al, nucl-ex[1602.02469]



SNO

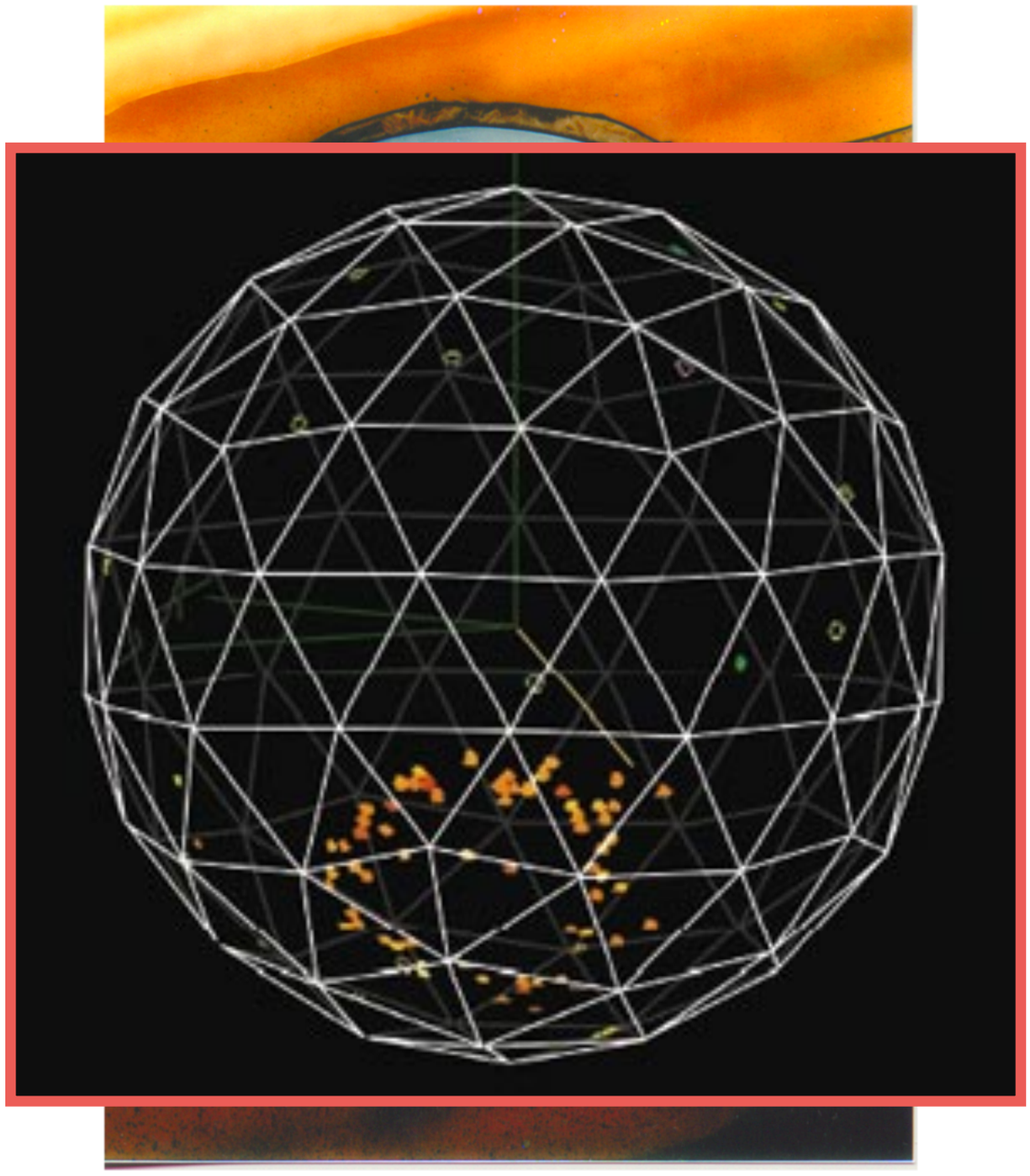
- Deuterium: LET'S DO IT
- HOW does this work?
  - Q: Are we making kilotons of deuterated organic scintillator?
  - A: HECK NO.
- Let's just use what exists: 1kT heavy water stockpile
  - Why do these exist? Read up! (https://amzn.to/2YgPR43)
- Looks like we're building a Cerenkov detector.

$$\nu_e + \mathrm{d} \rightarrow \cancel{\mathrm{p}} + \cancel{\mathrm{p}} + e^-$$

$$\nu_x + e^- \rightarrow \nu_x + e^-$$

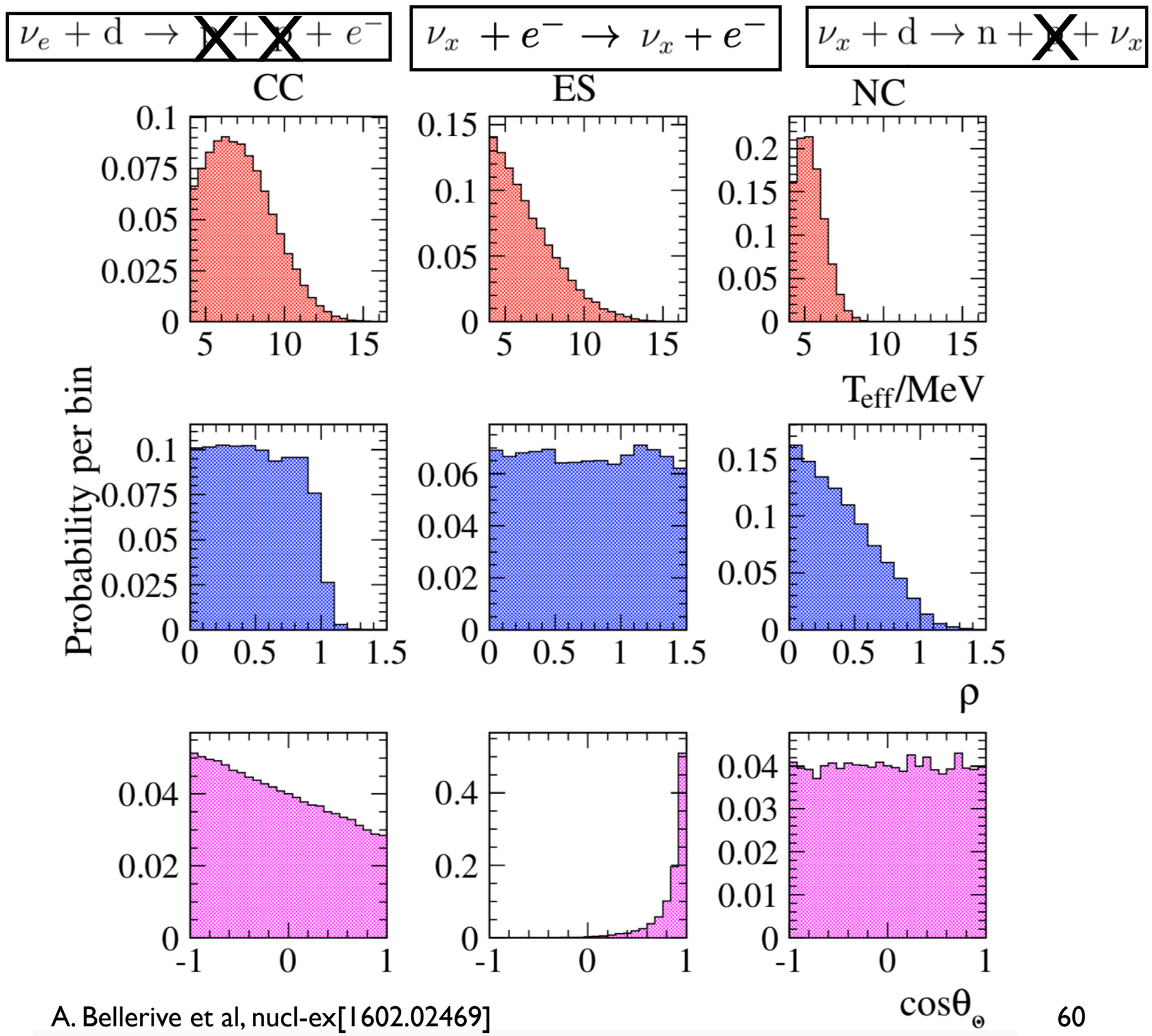
$$\nu_x + \mathrm{d} \rightarrow \mathrm{n} + \cancel{\mathrm{p}} + \nu_x$$

A. Bellerive et al, nucl-ex[1602.02469]



SNO Heavy Water

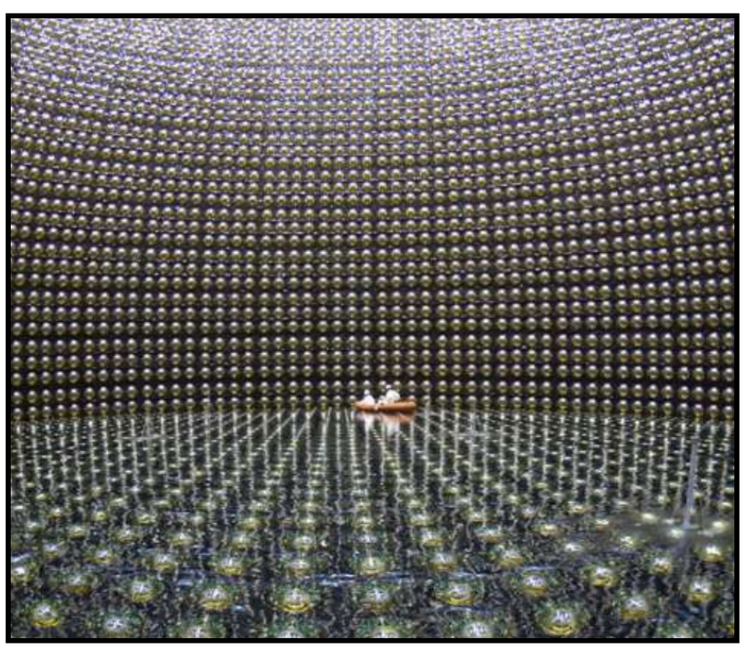
- What the signal looks like:



A. Bellerive et al, nucl-ex[1602.02469]

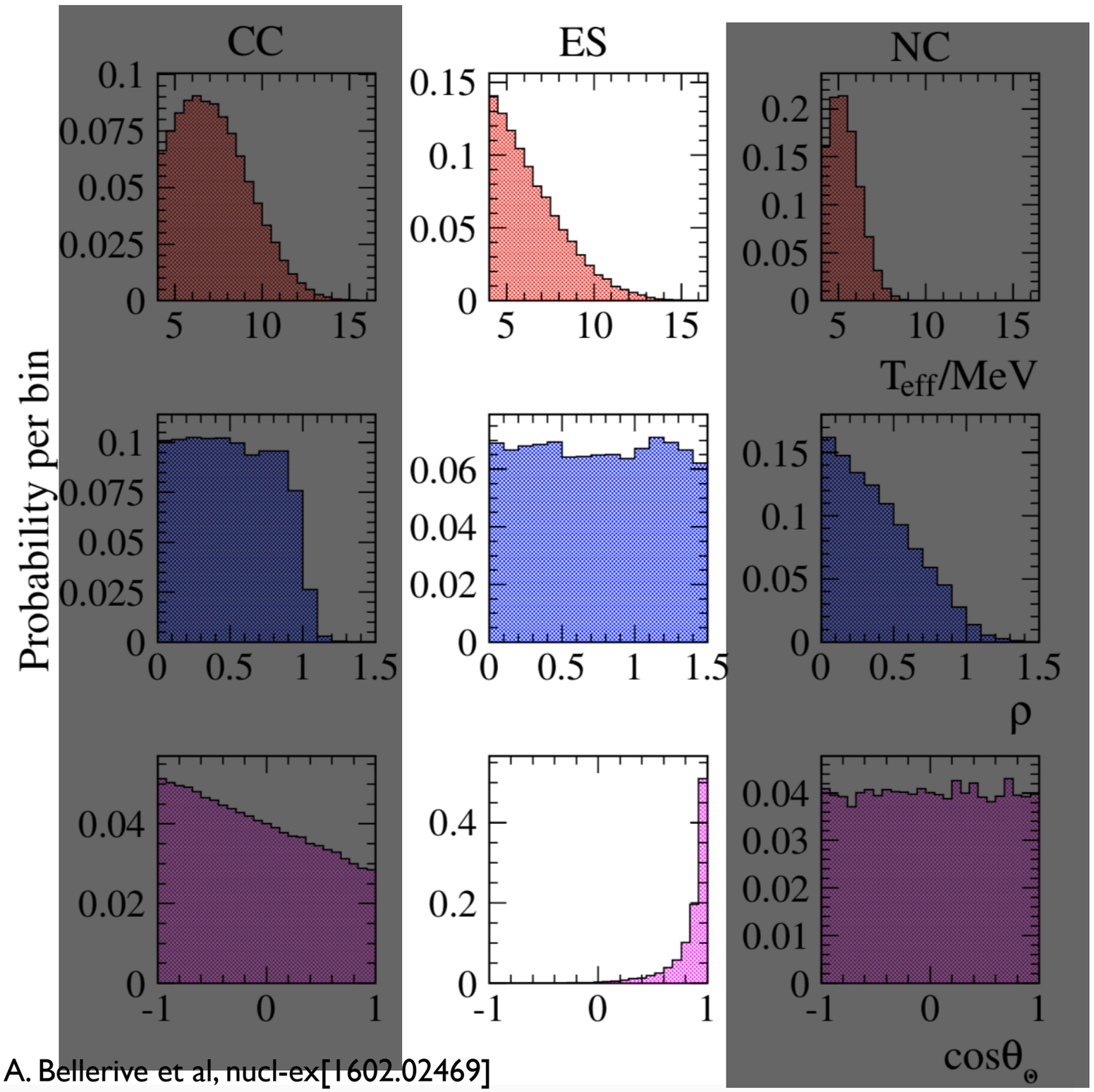
SuperK Light Water

- OK, what if we use light water (normal H)?
- SuperK
  - 22.5 kT
  - 13,000 PMTs
- Fewer channels, more events



No CC!

No neutron!



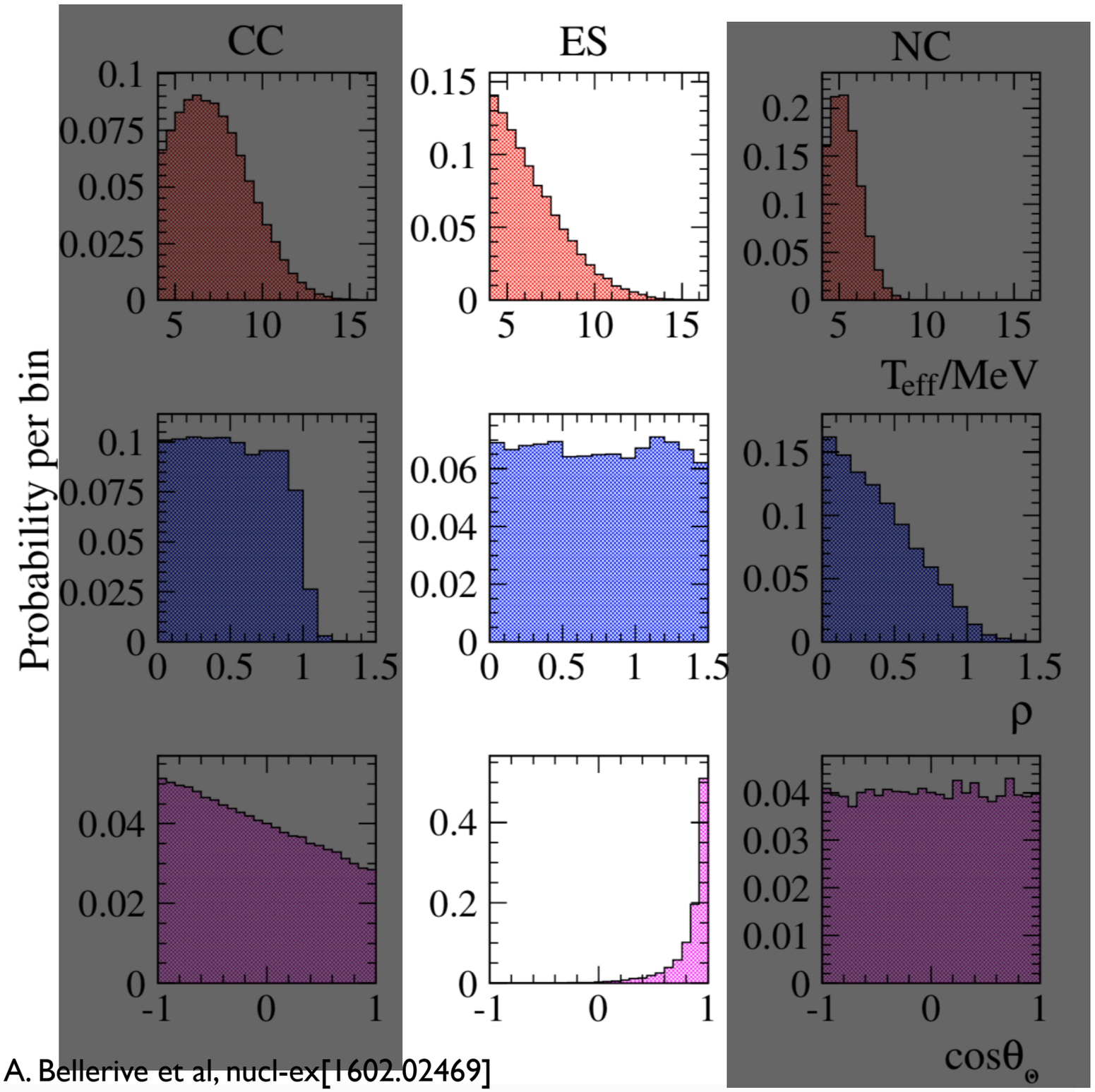
A. Bellerive et al, nucl-ex[1602.02469]

Scintillator Solar Nus

- OK, what if we use scintillator (normal H)?

No CC!

No neutron!



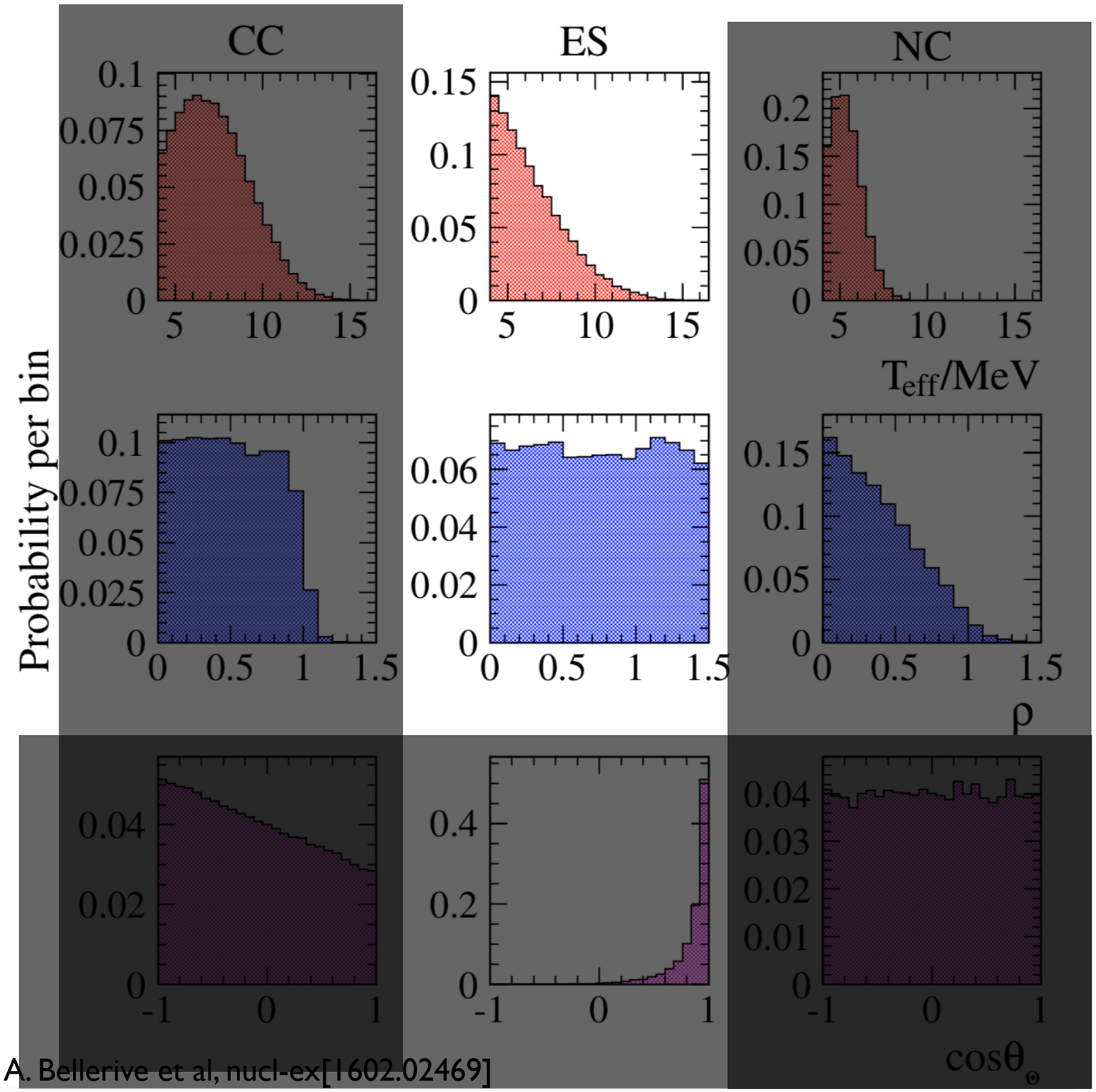
A. Bellerive et al, nucl-ex[1602.02469]

Scintillator Solar Nus

- OK, what if we use scintillator (normal H)?

No CC!

No neutron!

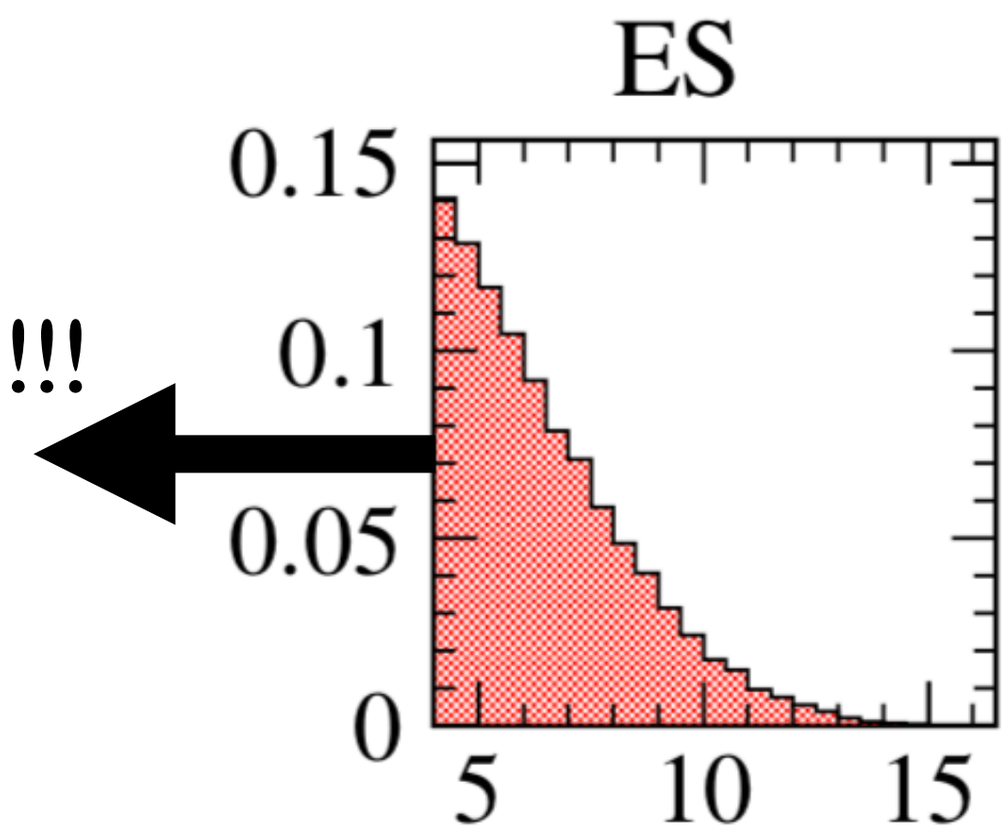


scintillation: no pointing!

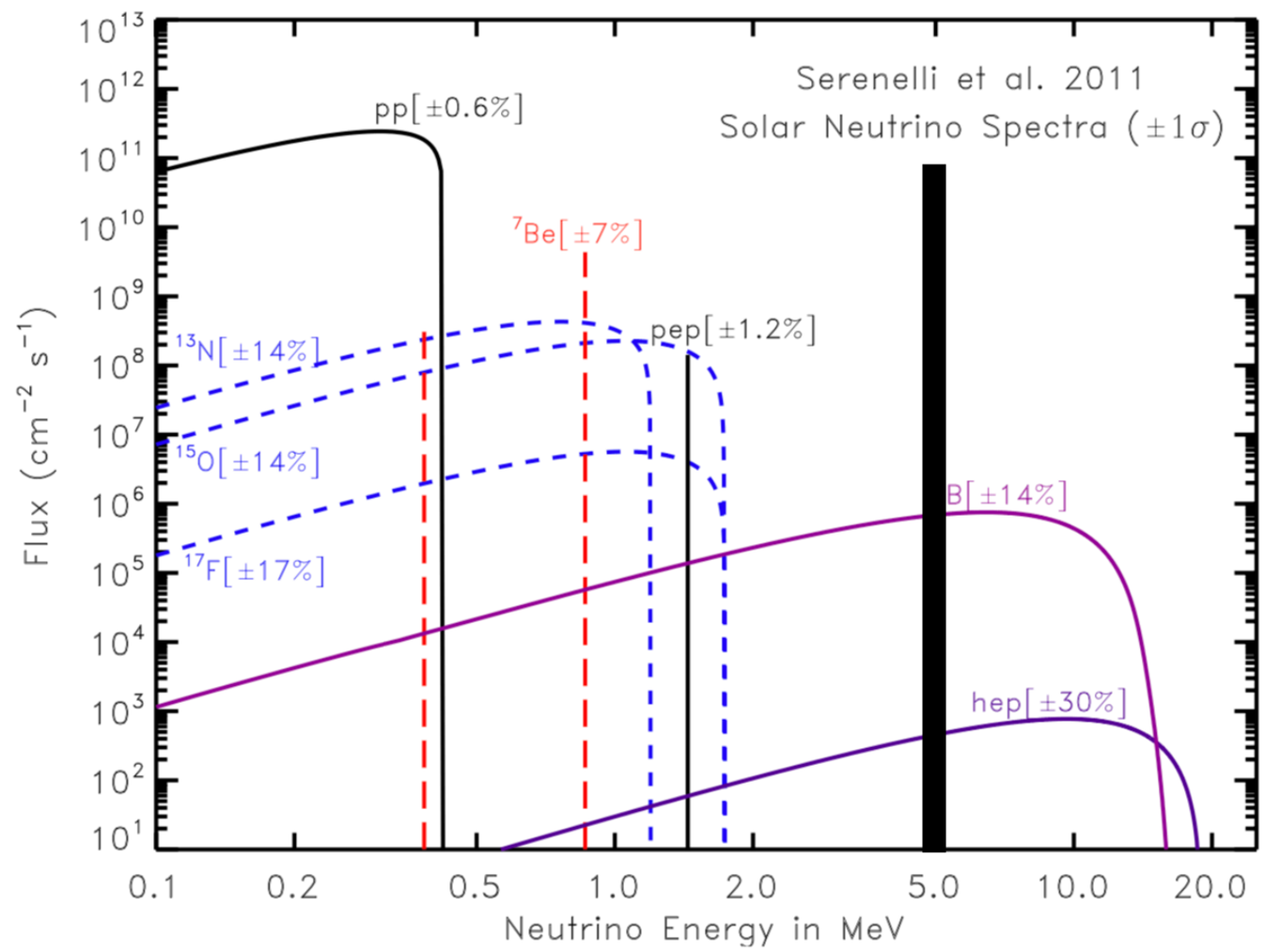
A. Bellerive et al, nucl-ex[1602.02469]

Scintillator Solar Nus

- OK, what if we use scintillator (i.e. with light water)
- Light yield: higher yield = lower energy threshold!
  - SNO (heavy water cerenkov): 10 hit PMTs per MeV gives 5 MeV threshold
  - SNO+ (LS): 500 hit PMTs per MeV gives <0.5 MeV threshold!



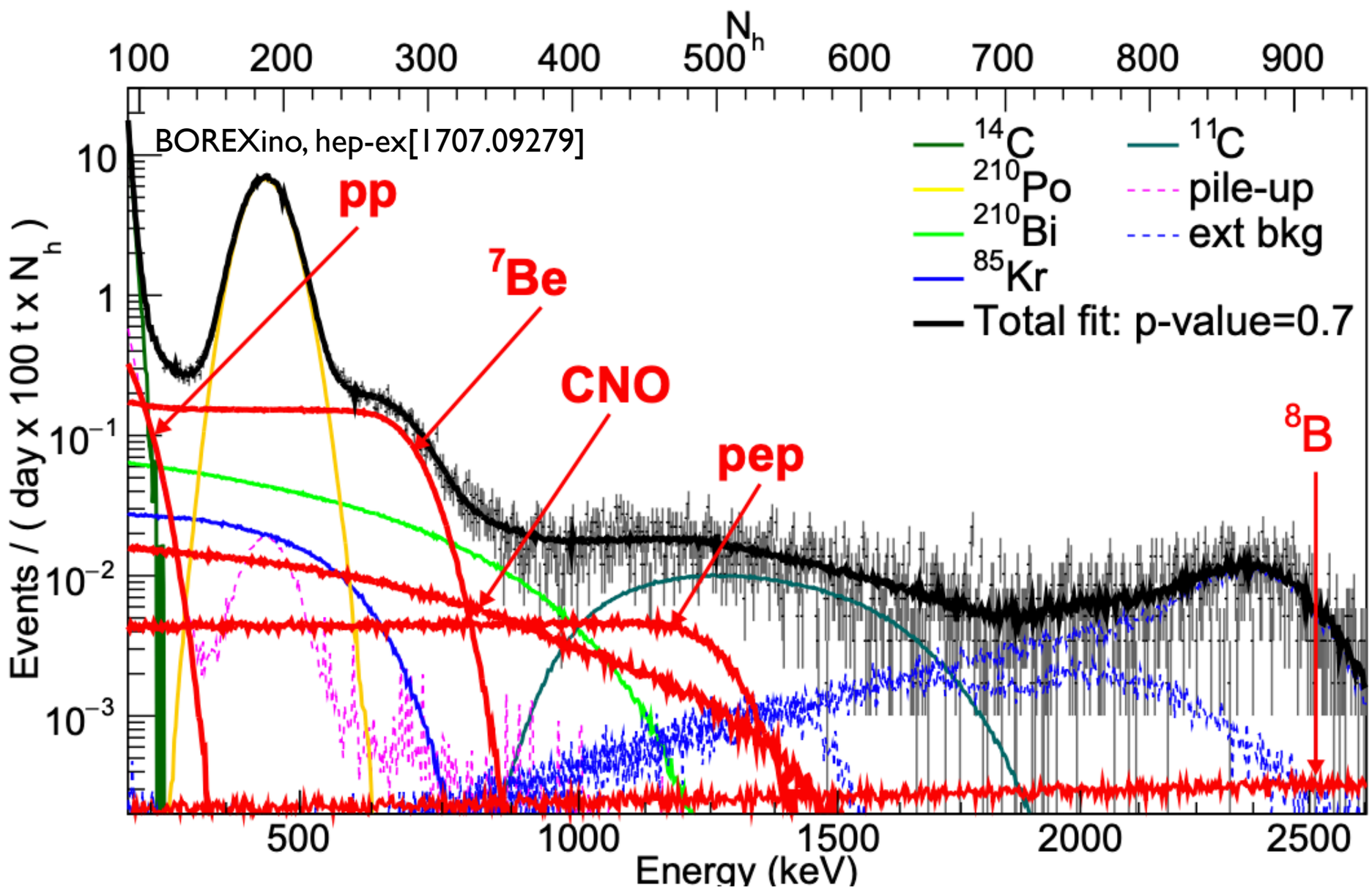
A. Bellerive et al, nucl-ex[1602.02469]



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

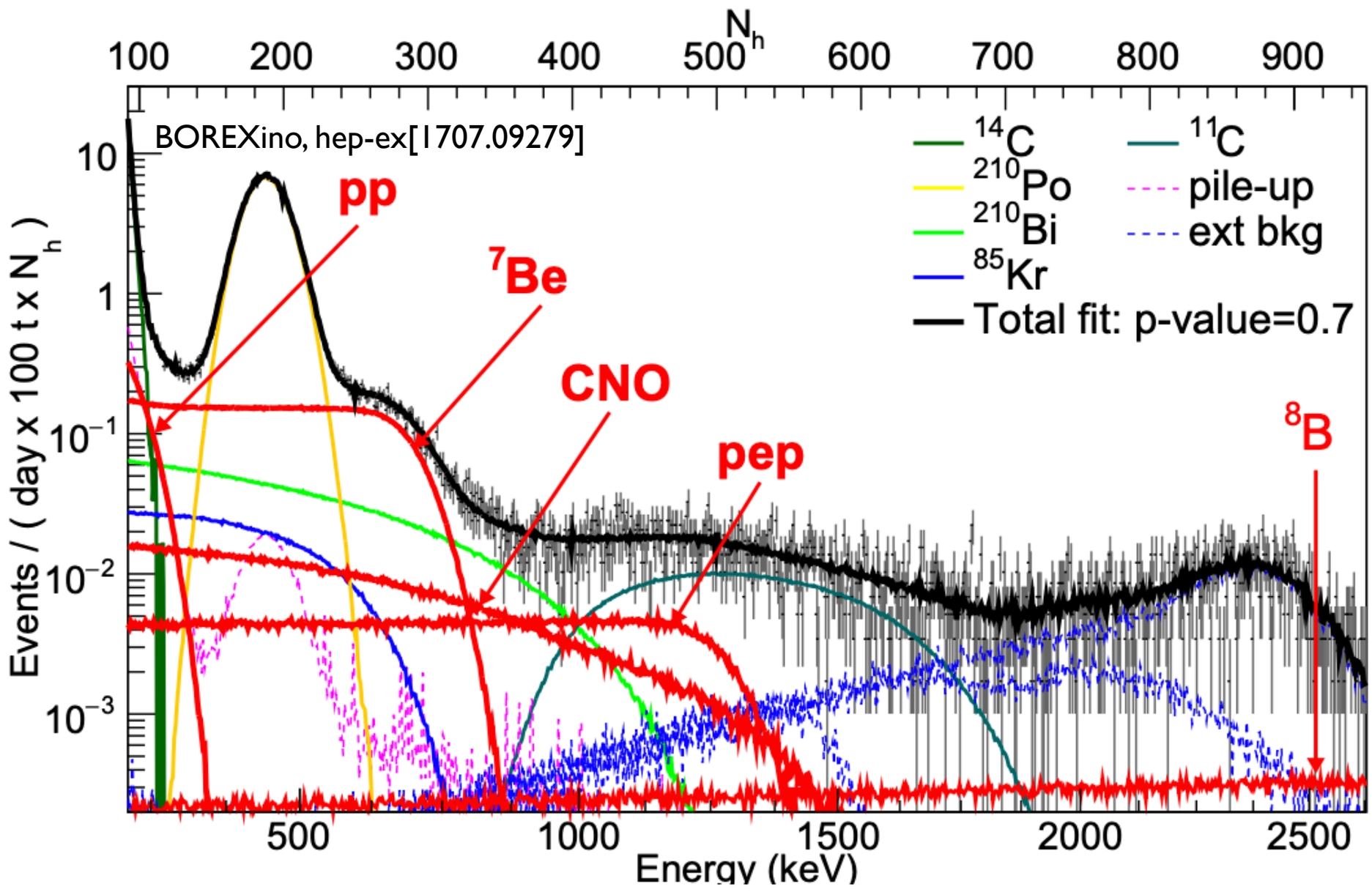
Scintillator Solar Nus

- What does a signal looks like?
- Borexino: 0.1 kT 500 PE/MeV ultrapure liquid scintillator, underground at Gran Sasso



Backgrounds

- You see them clearly here
  - Cosmogenic isotopes
  - U-Th radiogenics



Cosmogenic Isotope Production

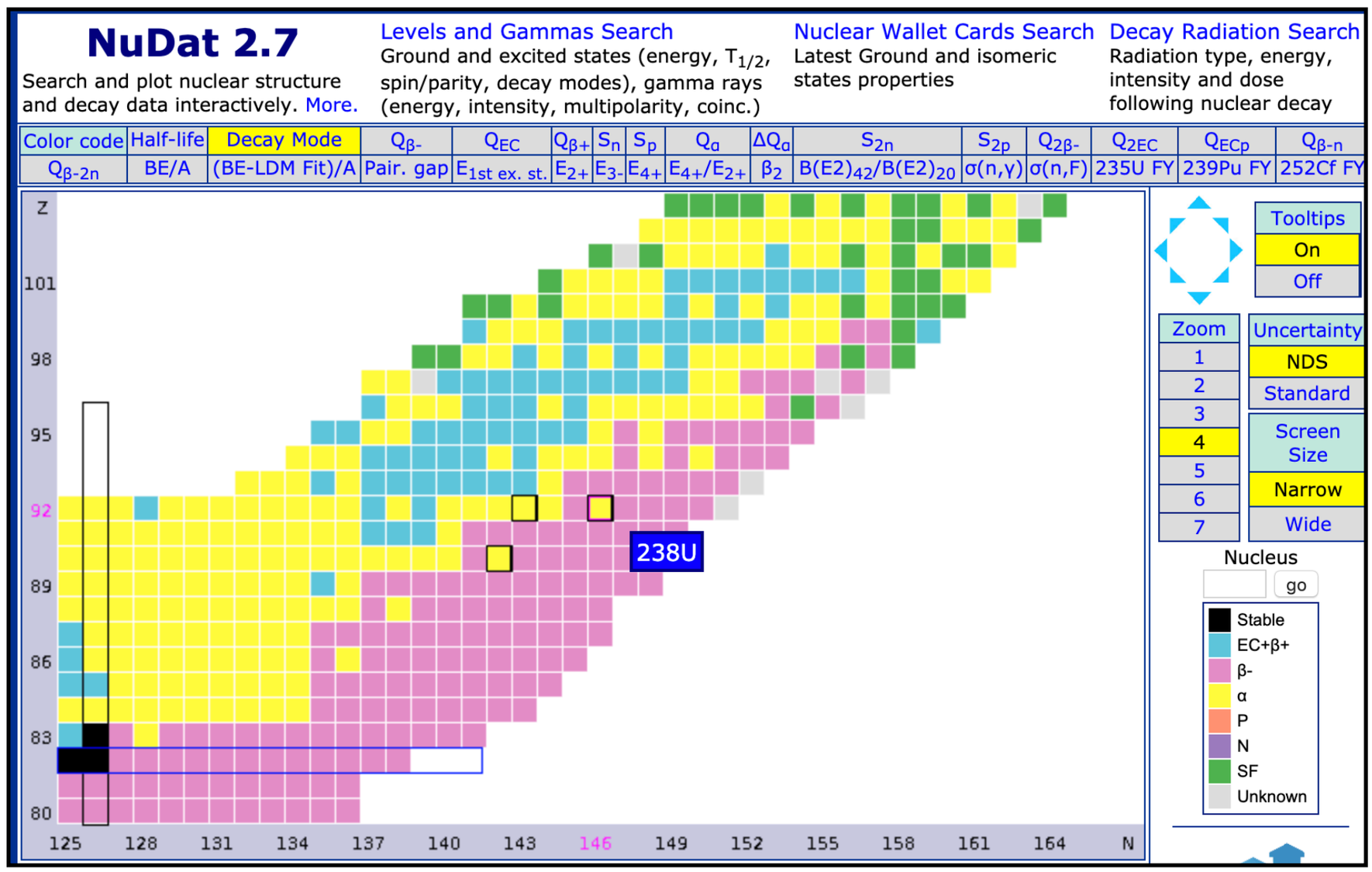
- Muon collisions make crazy stuff, which hit C and O to make crazy isotopes
- Crazy isotope decays, looks like a single electron scatter.
- Example: C-11 produced by C12(γ,n), then beta+ decays

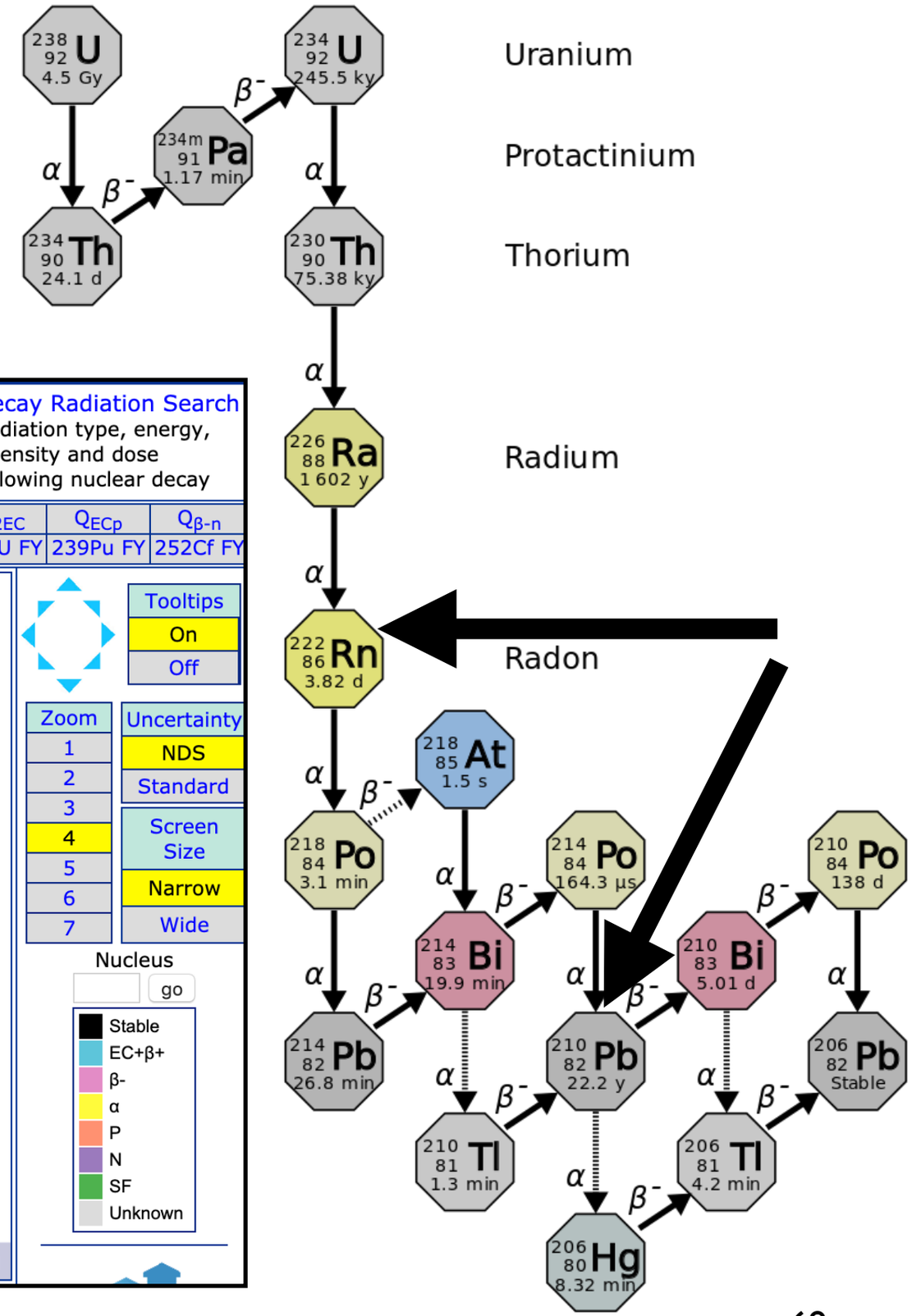
KamLAND, hep-ex[0907.0066]

	Lifetime in KamLAND LS	Radiation energy (MeV)	Yield ($\times 10^{-7}\mu^{-1}\mathrm{g}^{-1}\mathrm{cm}^2$) Ref. [10]	FLUKA calc.	This measurement
n	207.5 μs	2.225 (capt. γ)	—	2097 ± 13	2787 ± 311
^{12}B	29.1 ms	13.4 (β^-)	—	27.8 ± 1.9	42.9 ± 3.3
^{12}N	15.9 ms	17.3 (β^+)	—	0.77 ± 0.08	1.8 ± 0.4
^{8}Li	1.21 s	16.0 ($\beta^-\alpha$)	1.9 ± 0.8	21.1 ± 1.4	12.2 ± 2.6
^{8}B	1.11 s	18.0 ($\beta^+\alpha$)	3.3 ± 1.0	5.77 ± 0.42	8.4 ± 2.4
^{9}C	182.5 ms	16.5 (β^+)	2.3 ± 0.9	1.35 ± 0.12	3.0 ± 1.2
^{8}He	171.7 ms	10.7 ($\beta^-\gamma n$)	1.0 ± 0.3	0.32 ± 0.05	0.7 ± 0.4
^{9}Li	257.2 ms	13.6 ($\beta^-\gamma n$)		3.16 ± 0.25	2.2 ± 0.2
^{11}C	29.4 min	1.98 (β^+)	421 ± 68	416 ± 27	866 ± 153
^{10}C	27.8 s	3.65 ($\beta^+\gamma$)	54 ± 12	19.1 ± 1.3	16.5 ± 1.9
^{11}Be	19.9 s	11.5 (β^-)	< 1.1	0.84 ± 0.09	1.1 ± 0.2
^{6}He	1.16 s	3.51 (β^-)	7.5 ± 1.5	12.08 ± 0.83	—
^{7}Be	76.9 day	0.478 (EC γ)	107 ± 21	105.3 ± 6.9	—

Radiogenics

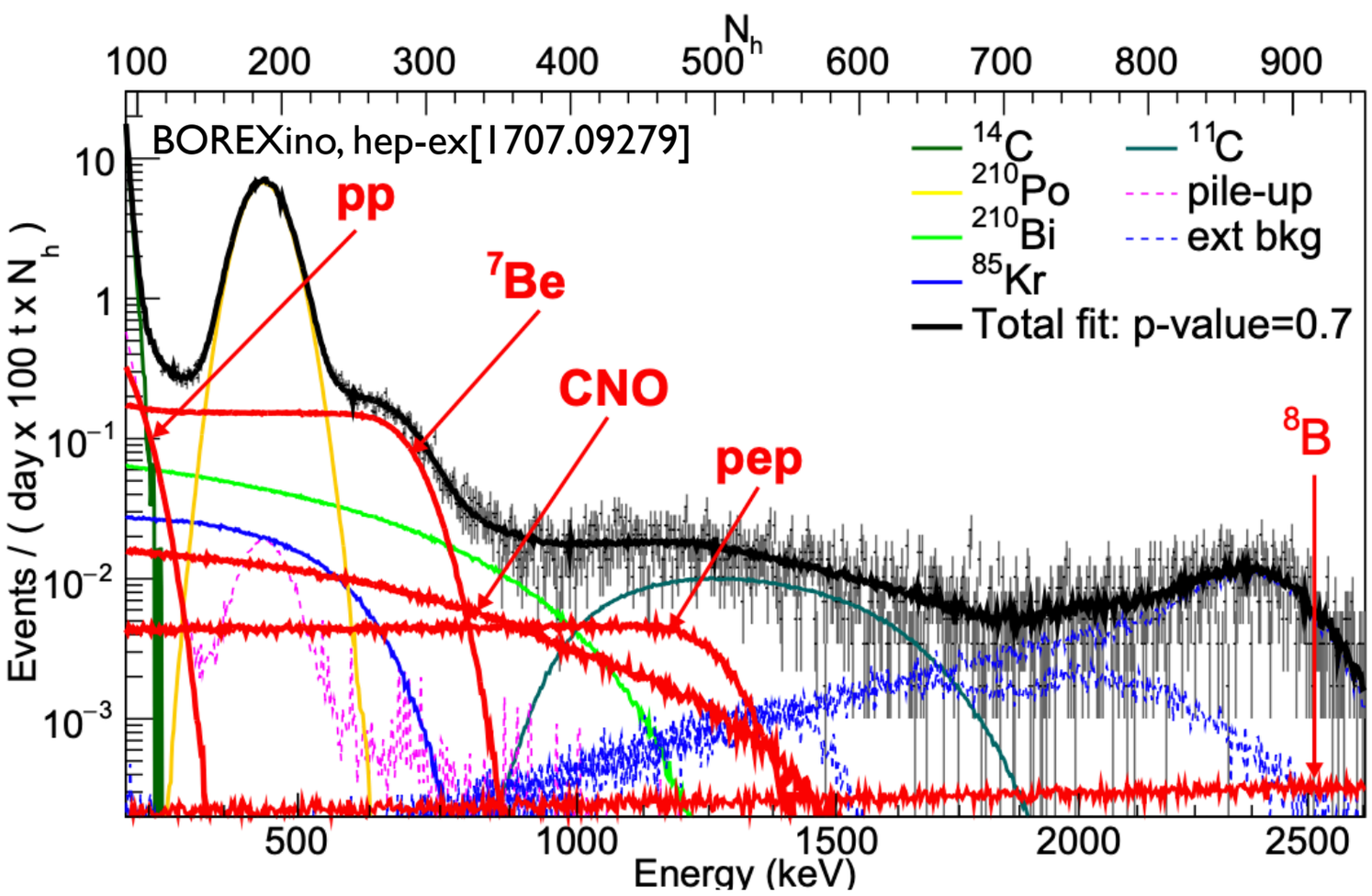
- Only a few very heavy nearly-stable isotopes
  - They get into stuff, thus do their products
  - Blame the radon, in particular



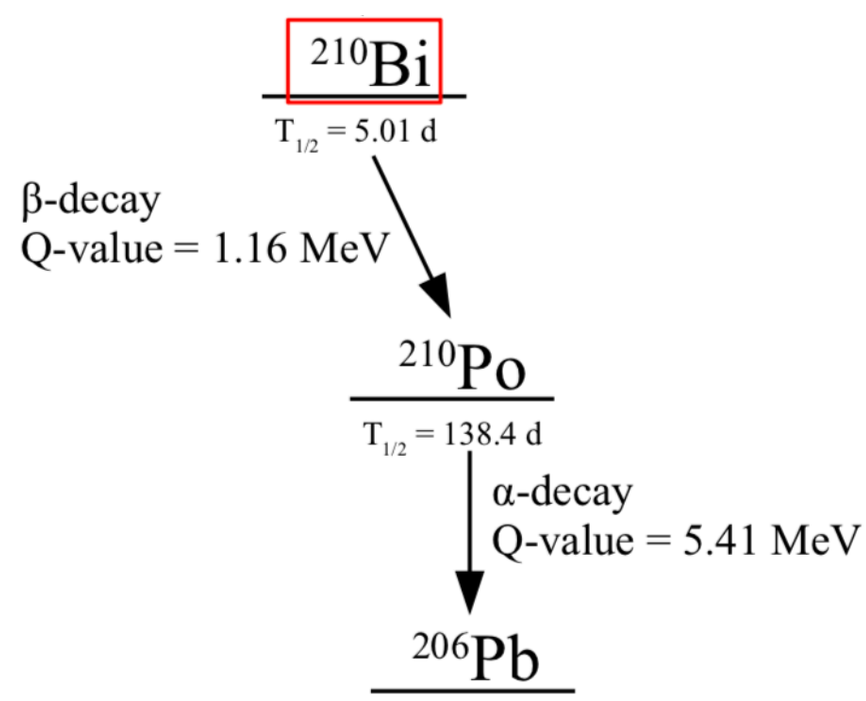


Radiogenics

- Only a few very heavy nearly-stable isotopes
  - They get into stuff, thus do their products
  - Blame the radon, in particular
- Decay products can look like single electron scatters

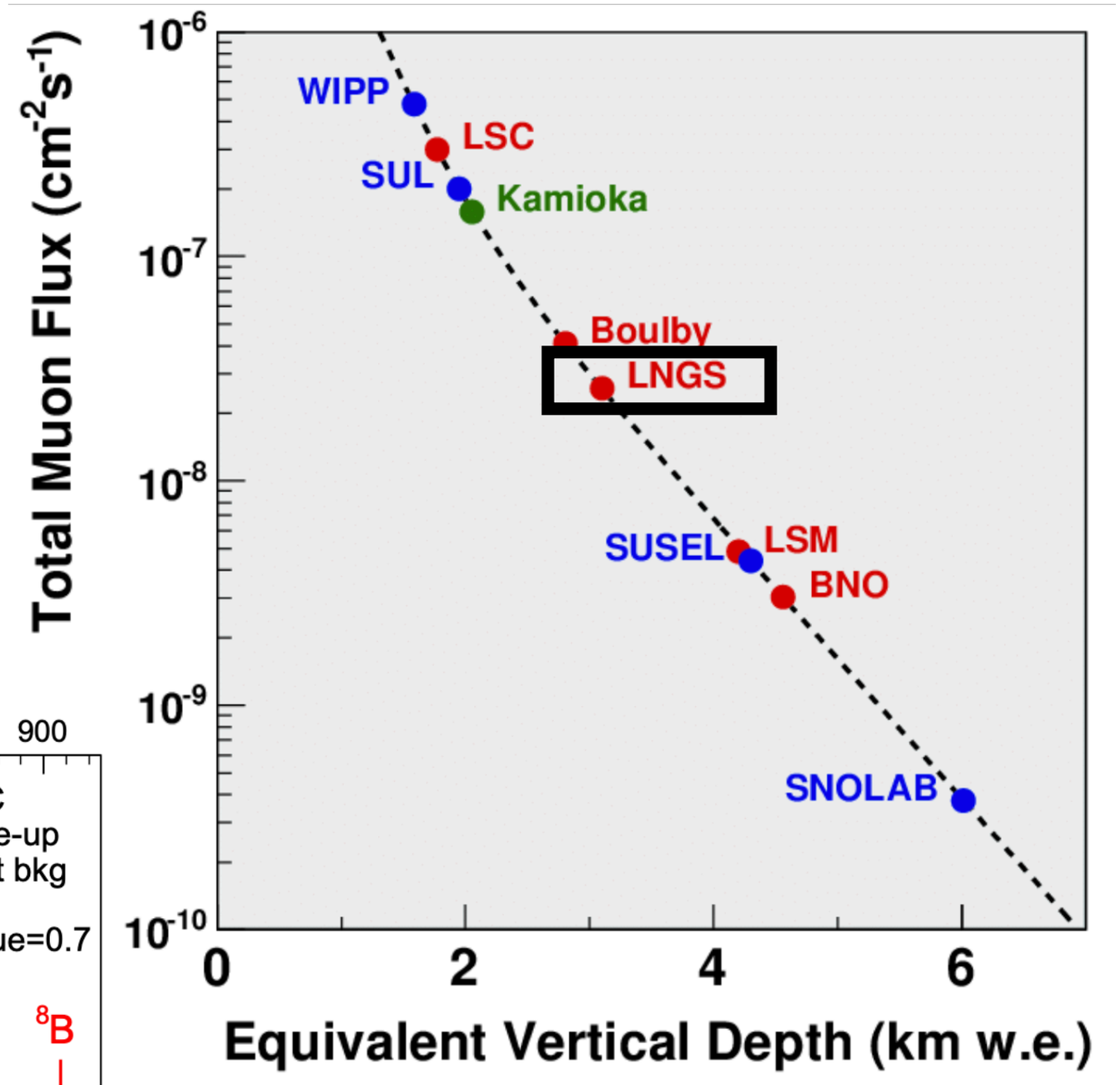


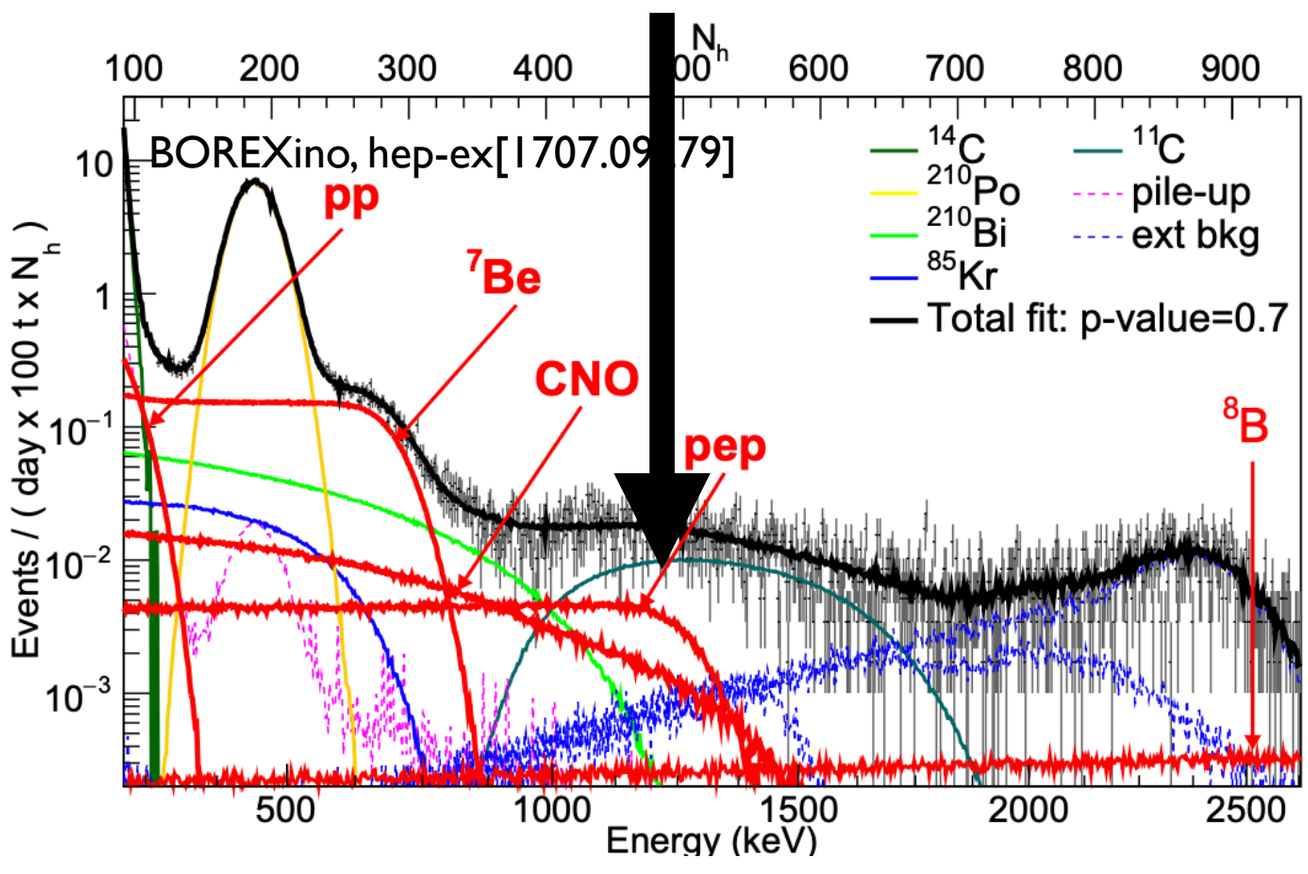
SNO+, hep-ex[707.09279]



Removal Strategy

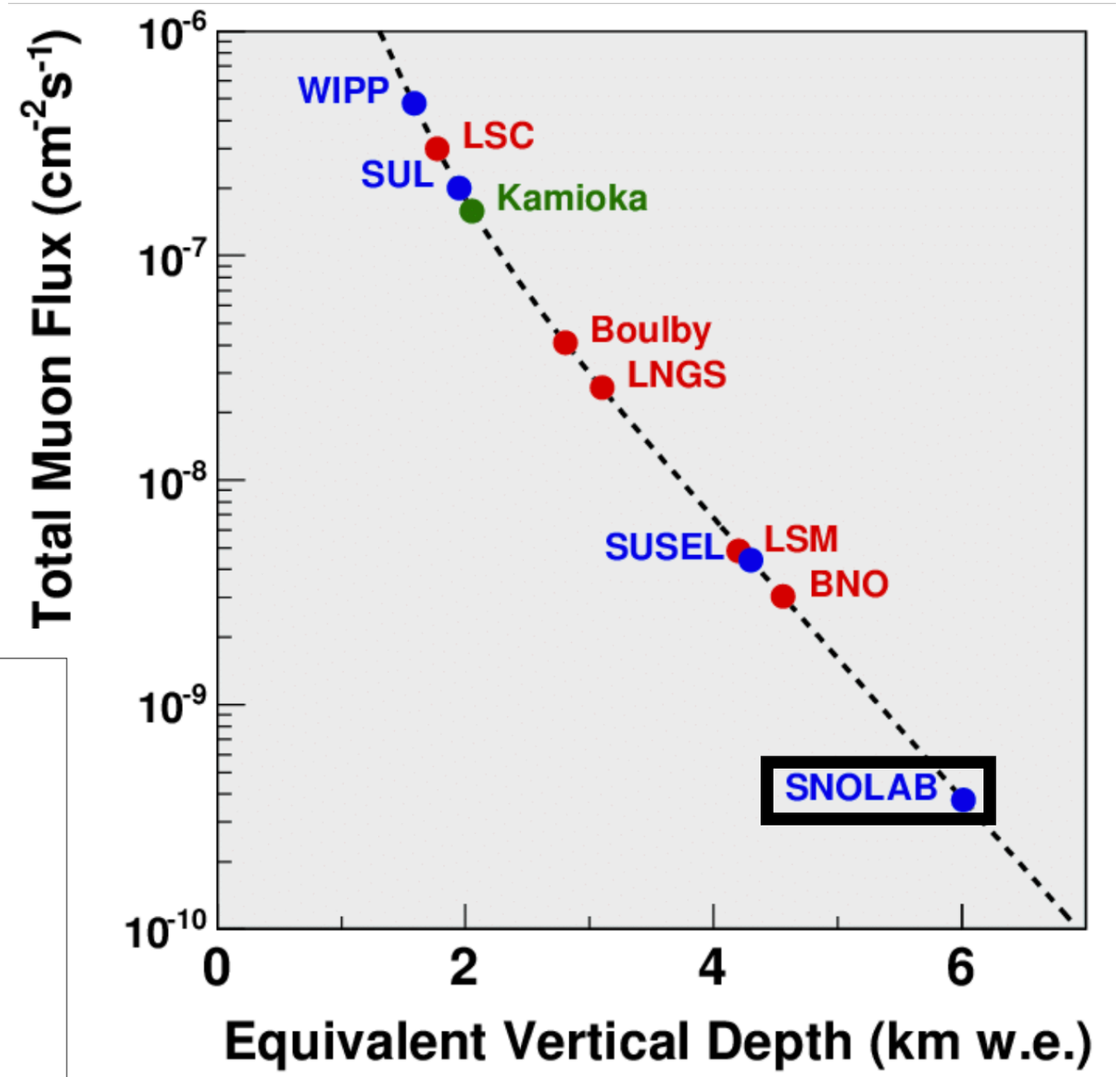
- GO DEEPER!
- For Borexino, C-11 was an issue for CNO, pep neutrinos



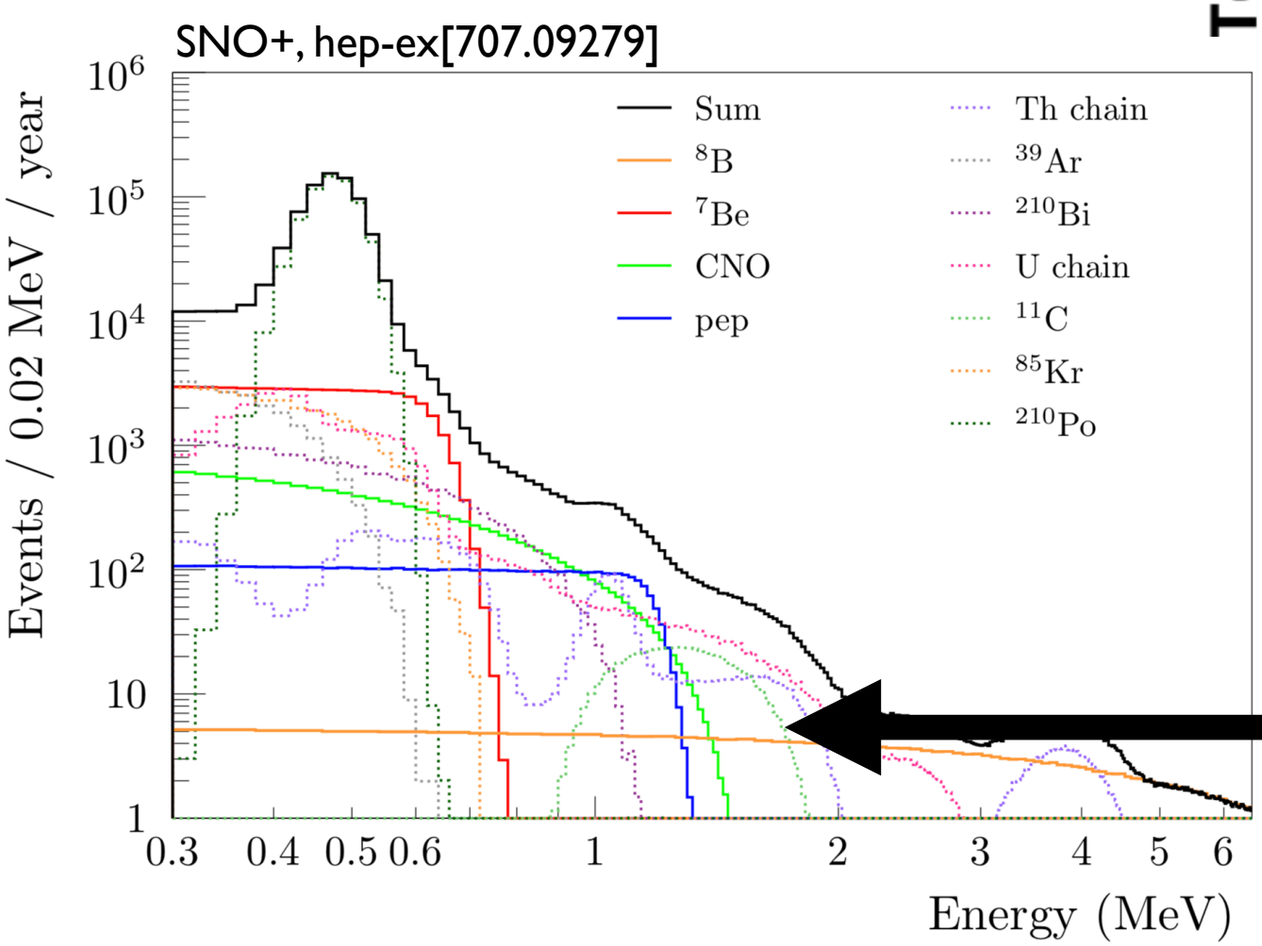


Removal Strategy

- GO DEEPER!
- For SNO+, not so bad: higher overburden = fewer muons and C-11



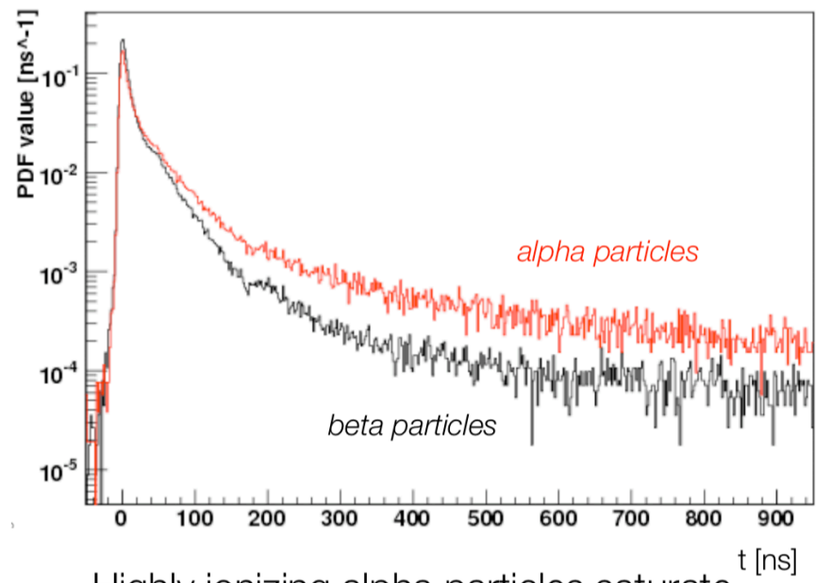
SNO+, hep-ex[707.09279]

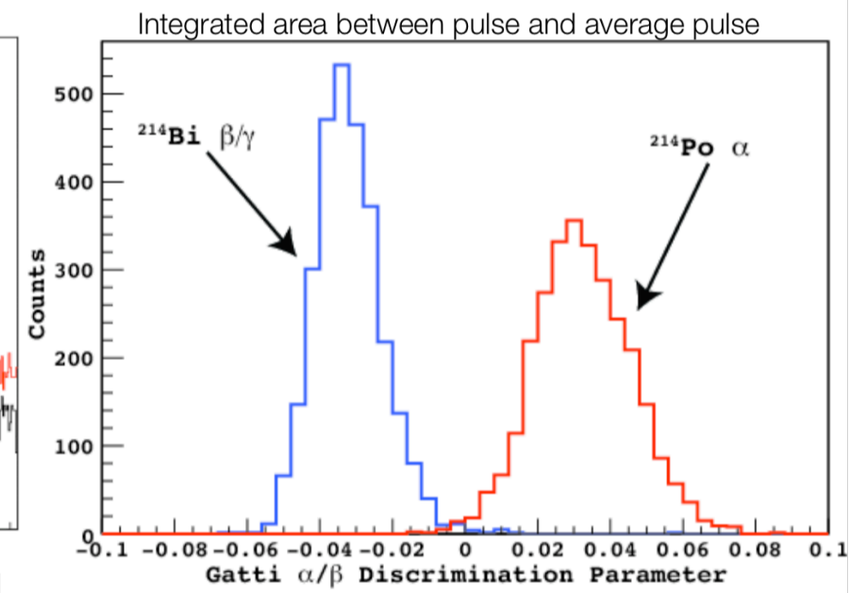


Other Removal Strategies

- PSD
- LONG veto cuts
- Location cuts
- BE CLEAN!

Borexino PSD, from Prof. Messier's slides

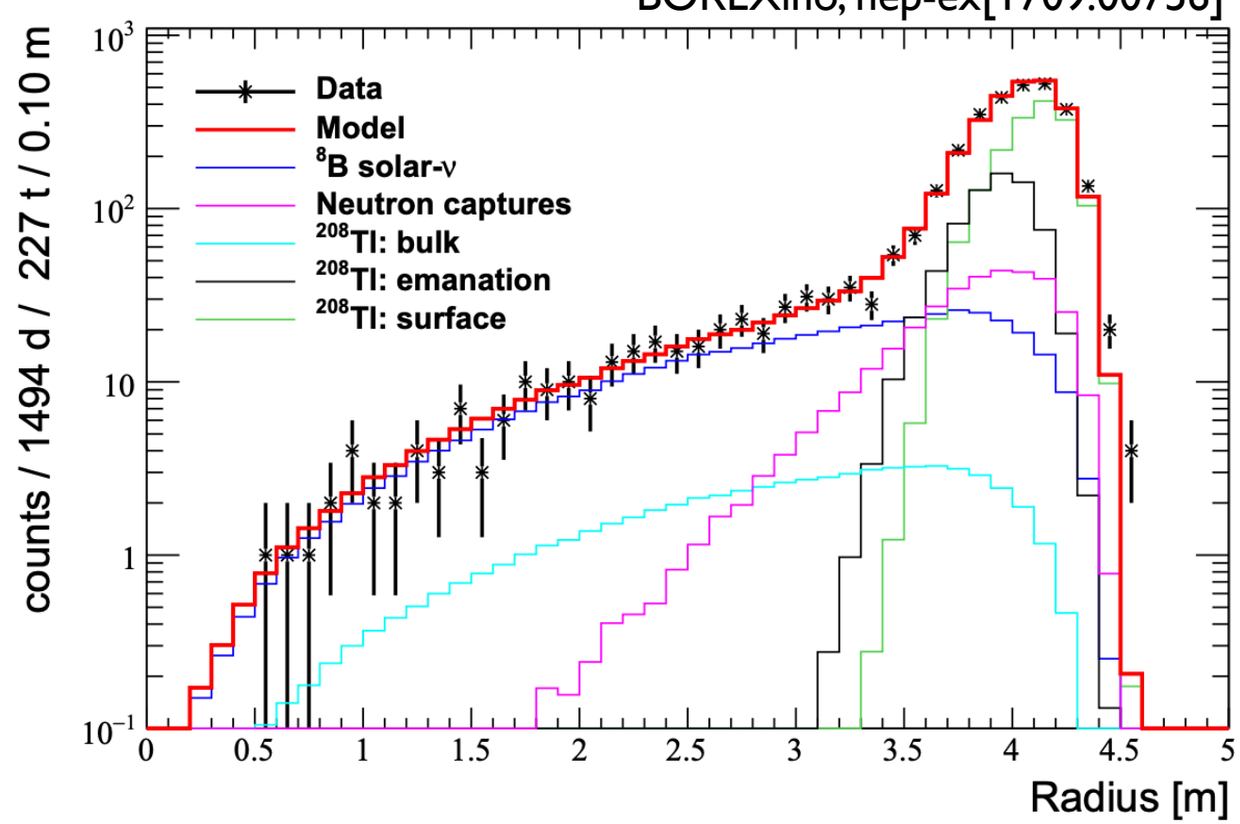




Highly ionizing alpha particles saturate more of the scintillator and excite more of the states with longer lifetimes

Borexino
signal radial distributions

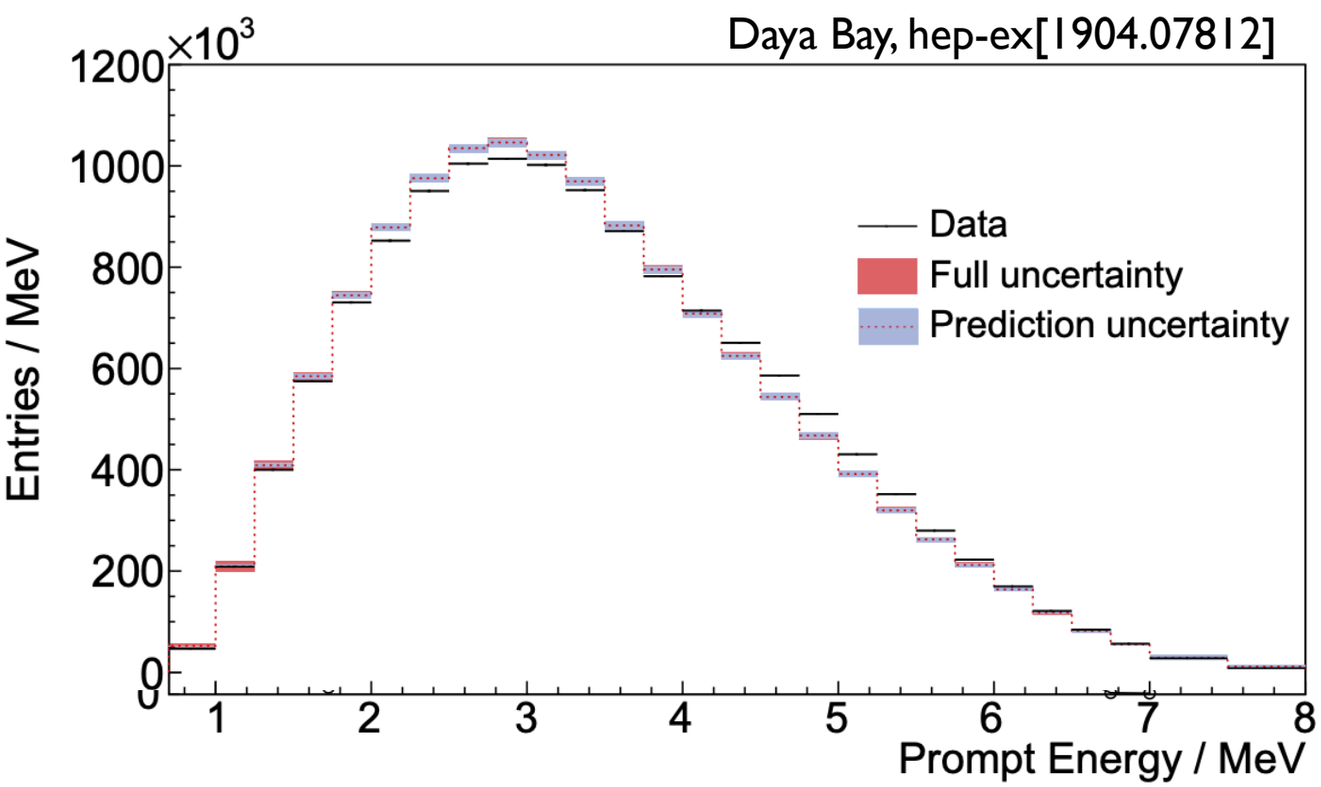
BOREXino, hep-ex[1709.00756]

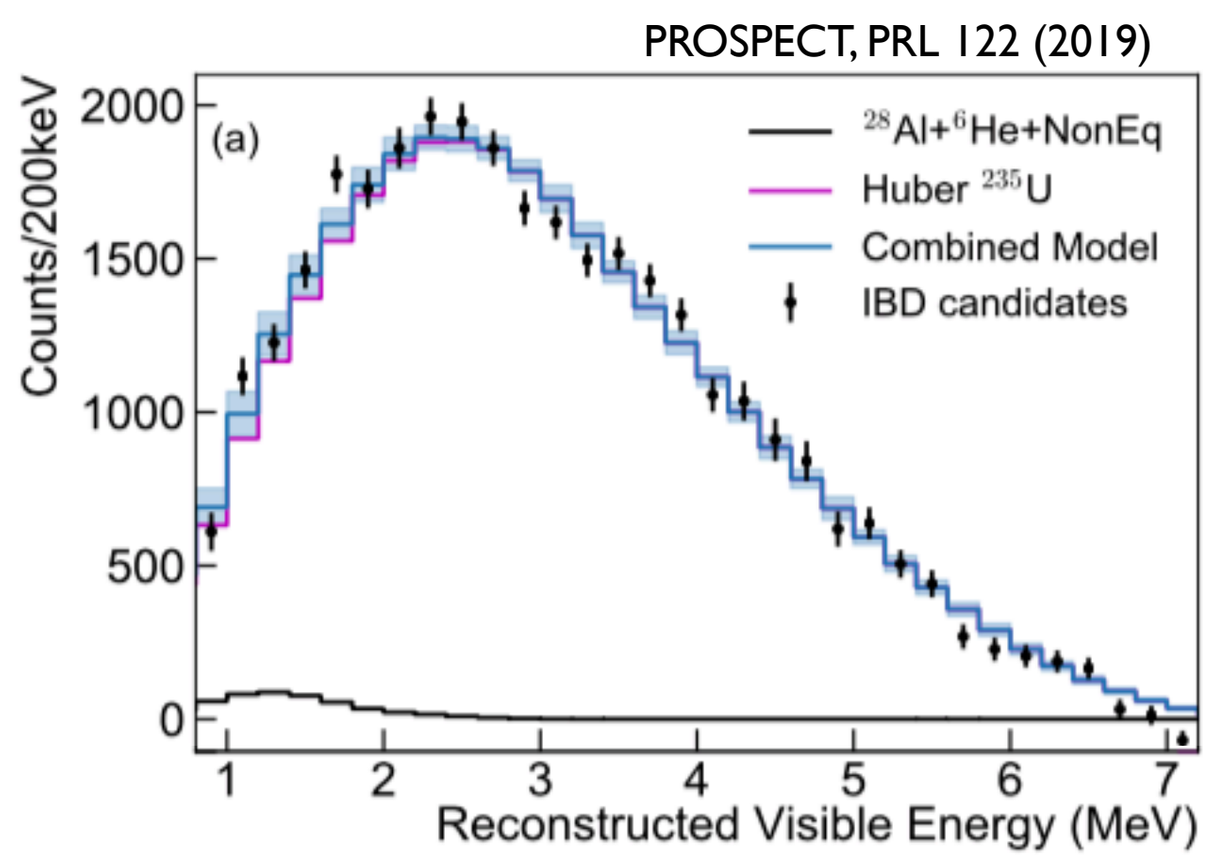


Questions?

Rx Nuebar: What success looks like.

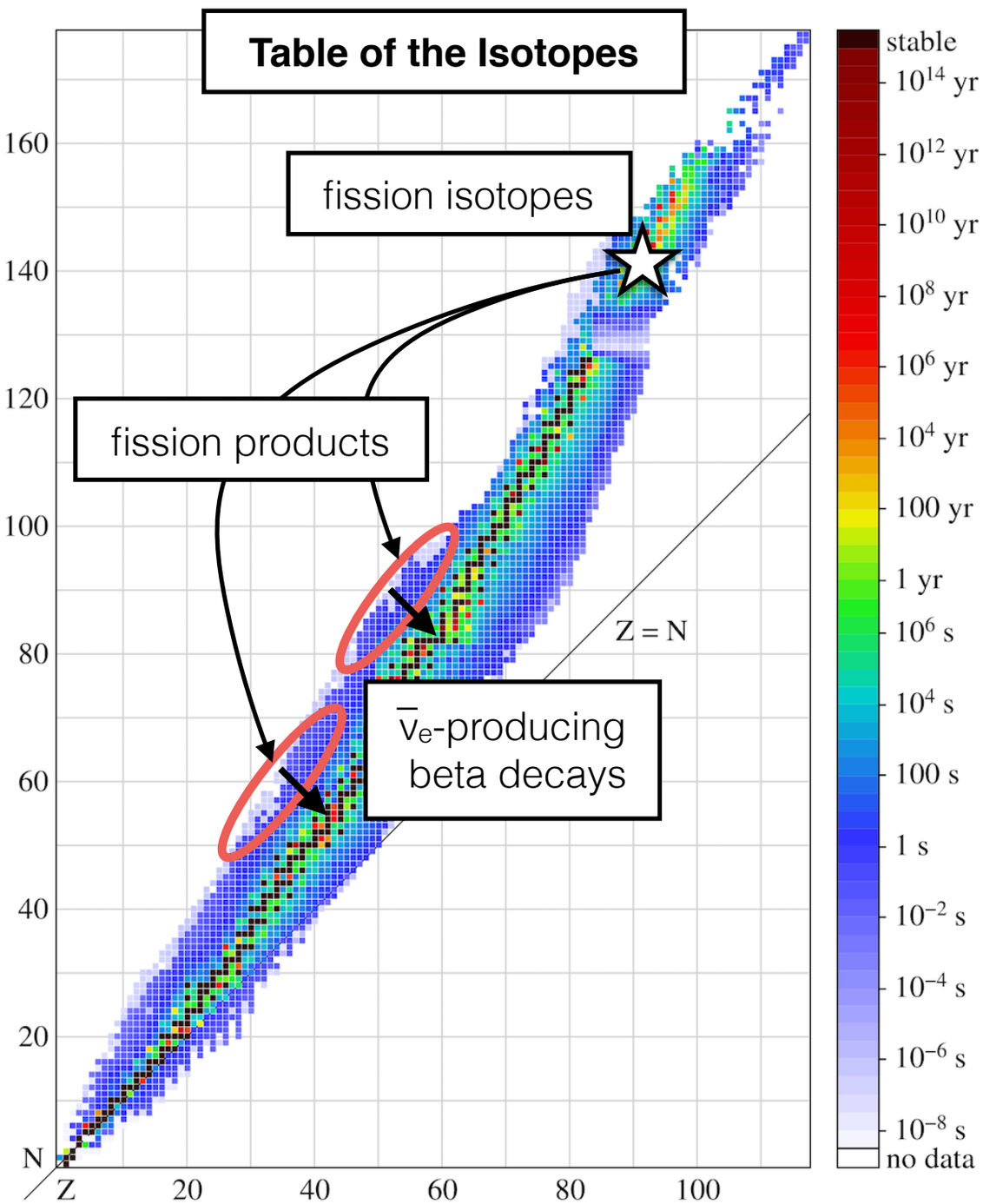
- Do all this, and you'll see your IBDs!
  - Stuff I did not discuss that's also important in getting to this point:
    - Calibration: conversion from 'light detected' to 'MeV'
    - Systematics: where to those 'prediction' error bars come from?

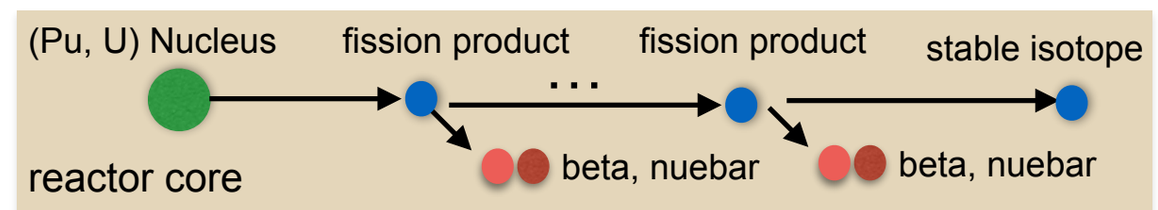


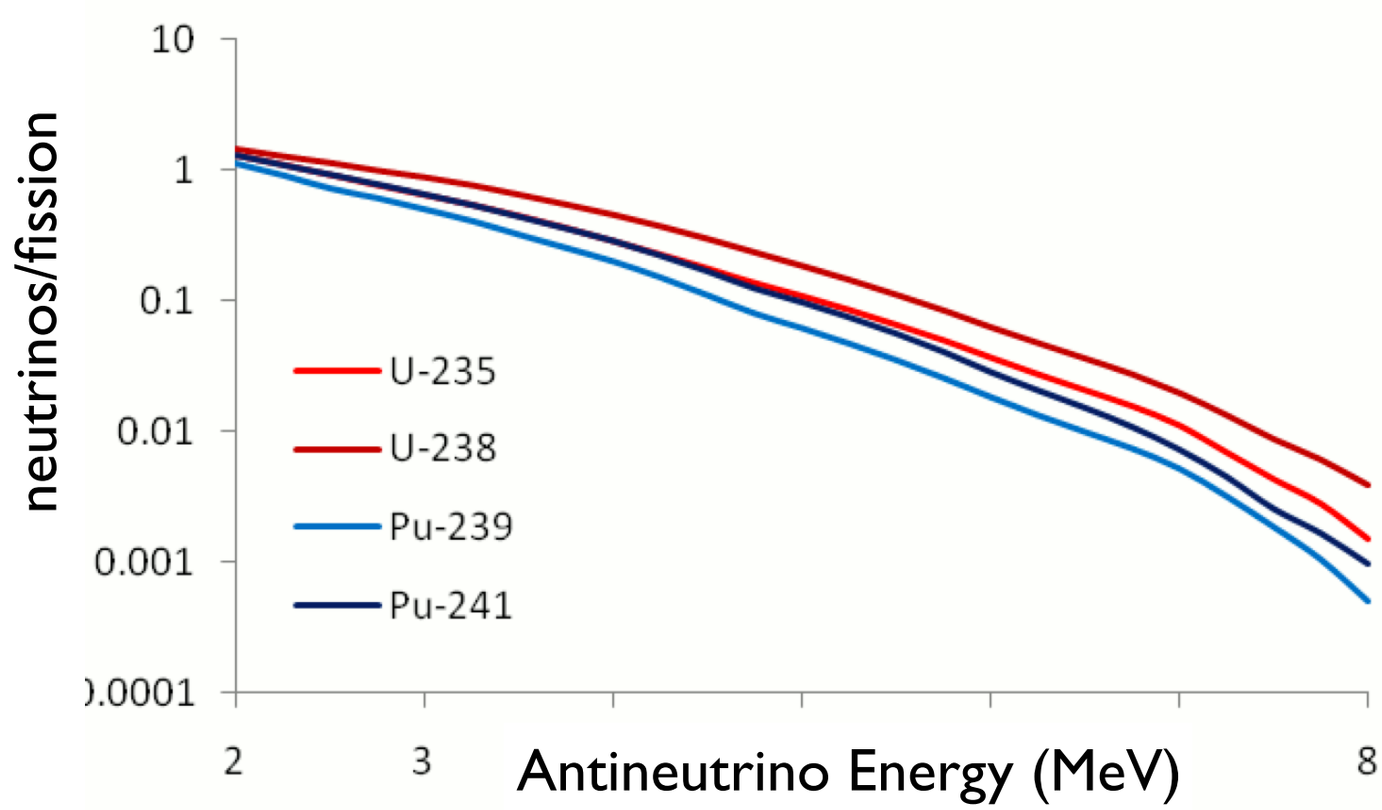


Reactor Antineutrino Production

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

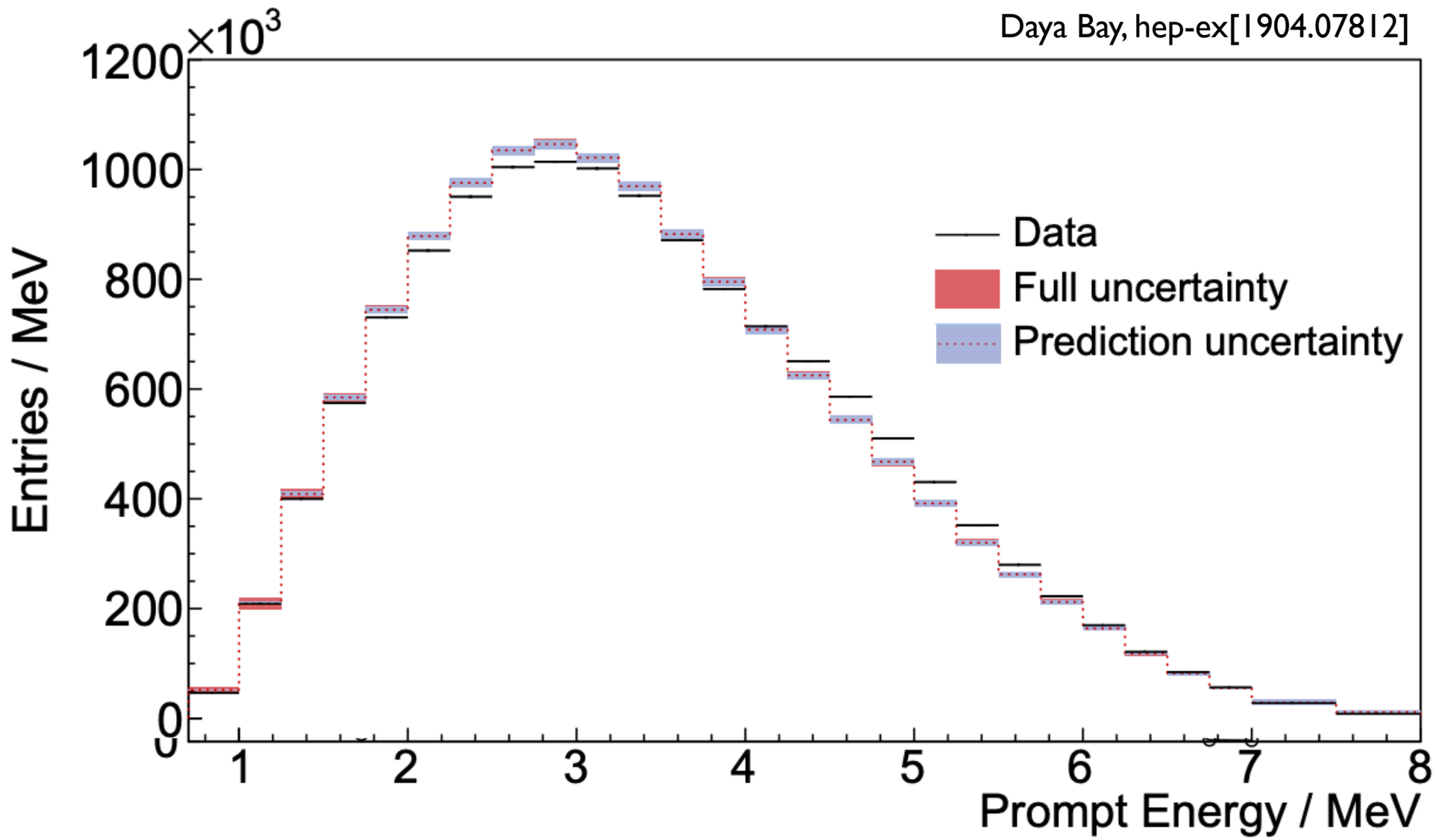






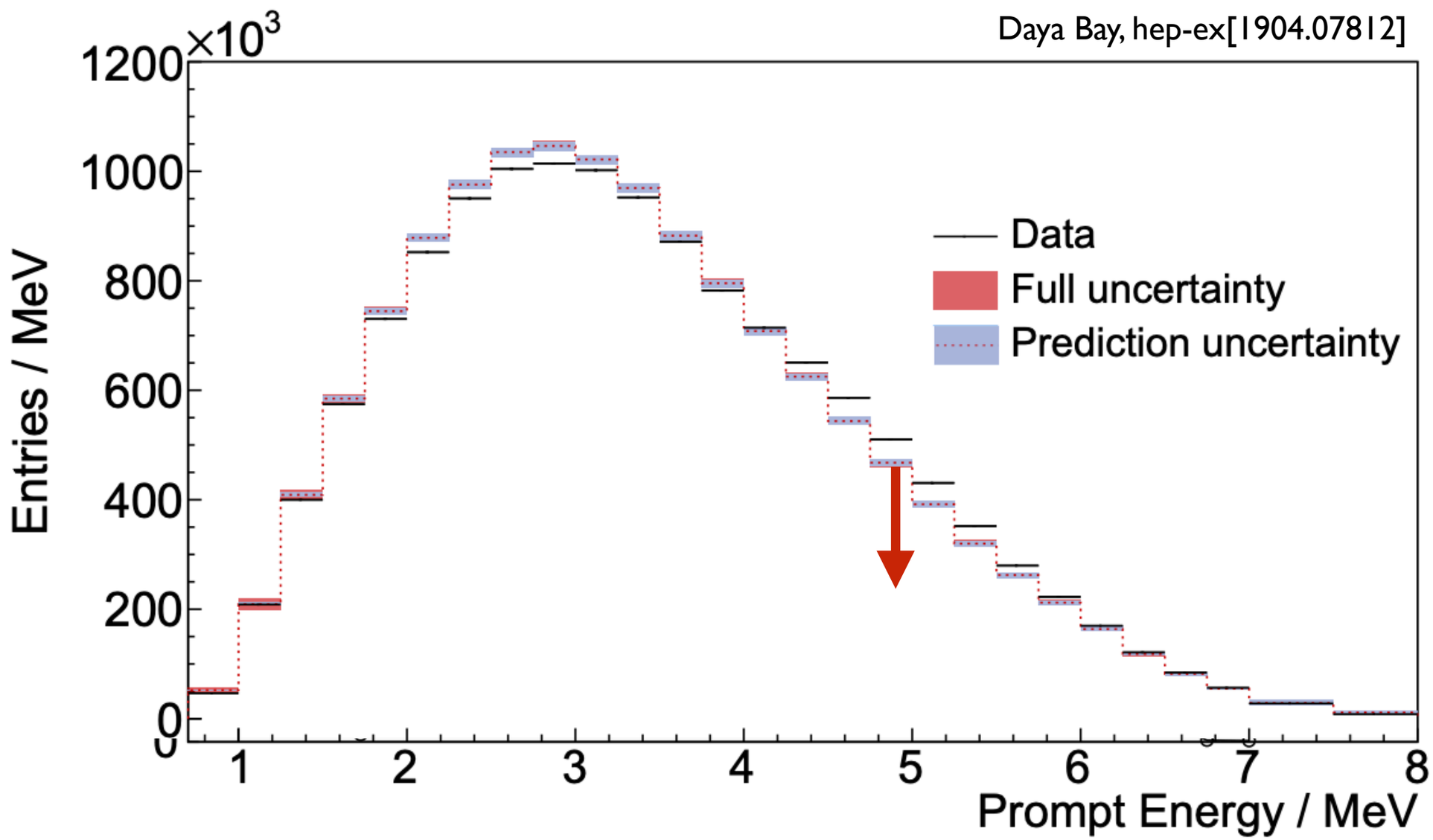
Follow-Up: Uncertainties

- What if our *true* IBD detection efficiency is 60%, instead of our estimated 70%?



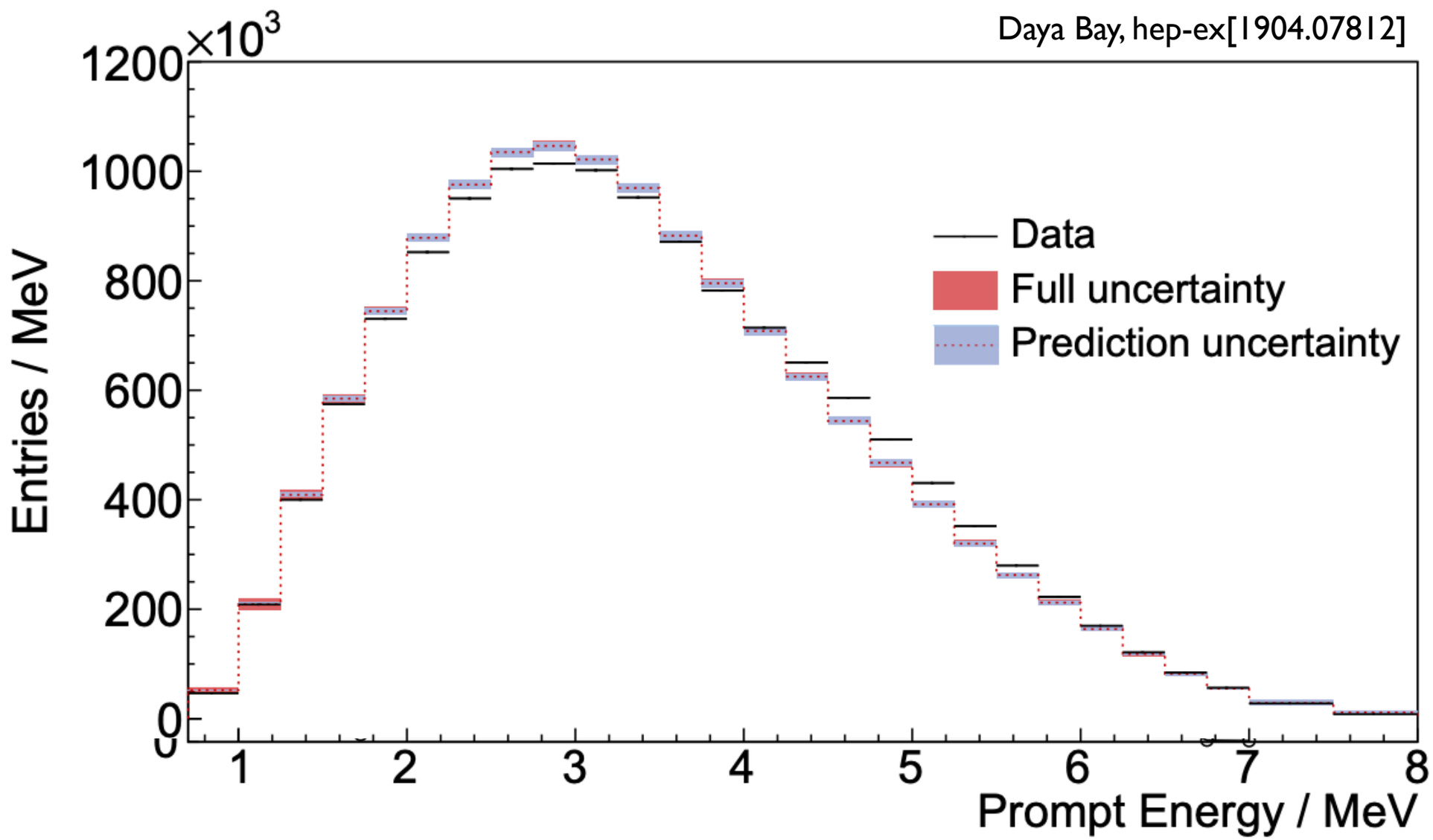
Follow-Up: Uncertainties

- What if our *true* IBD detection efficiency is 60%, instead of our estimated 70%?
  - I guess our current prediction is too high, and should be lowered…
  - In reality, reactor experiments' efficiencies are ~1% uncertain



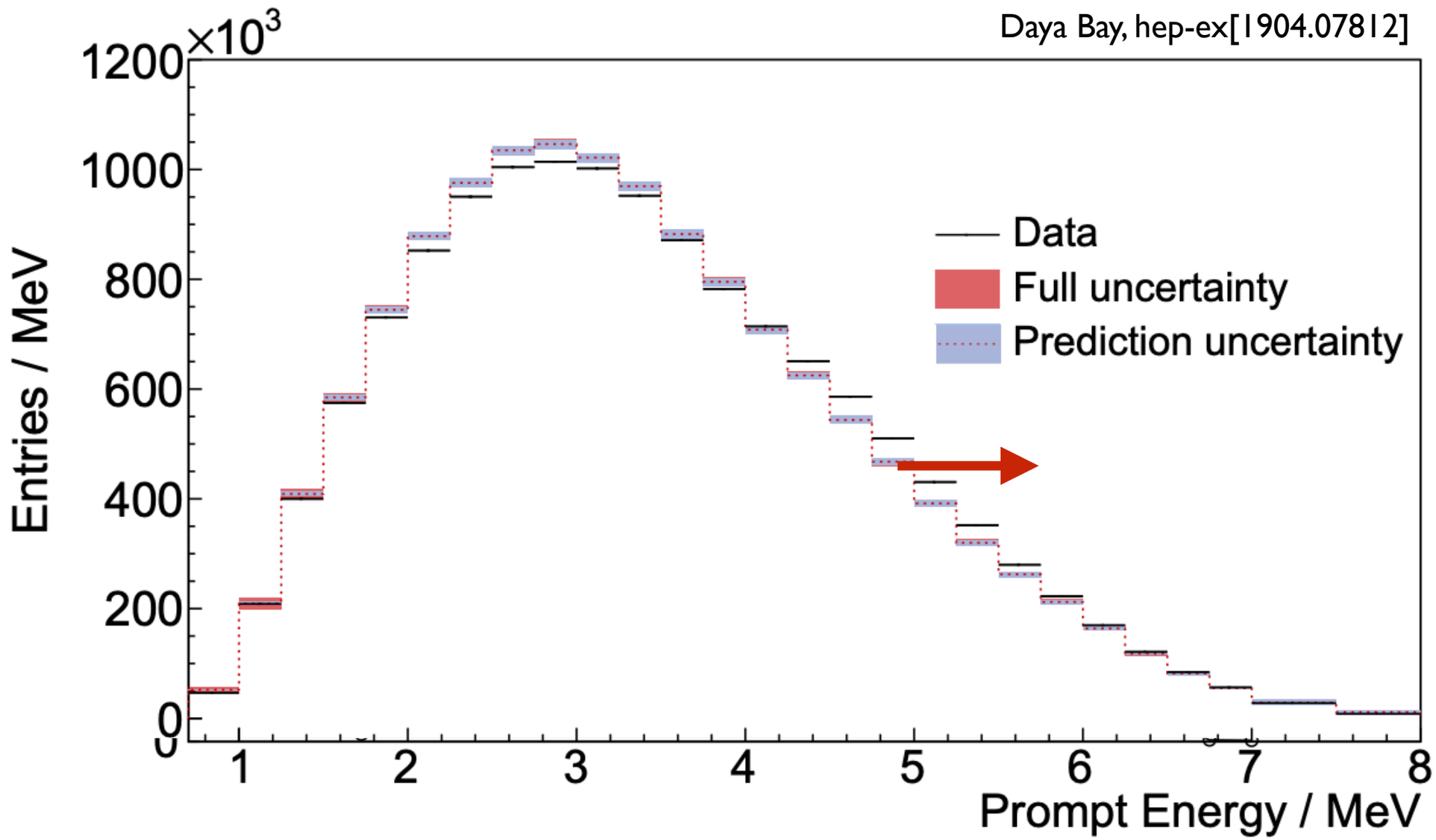
Follow-Up: Uncertainties

- What if our scintillation light collection per MeV estimate is too high by 10%?



Follow-Up: Uncertainties

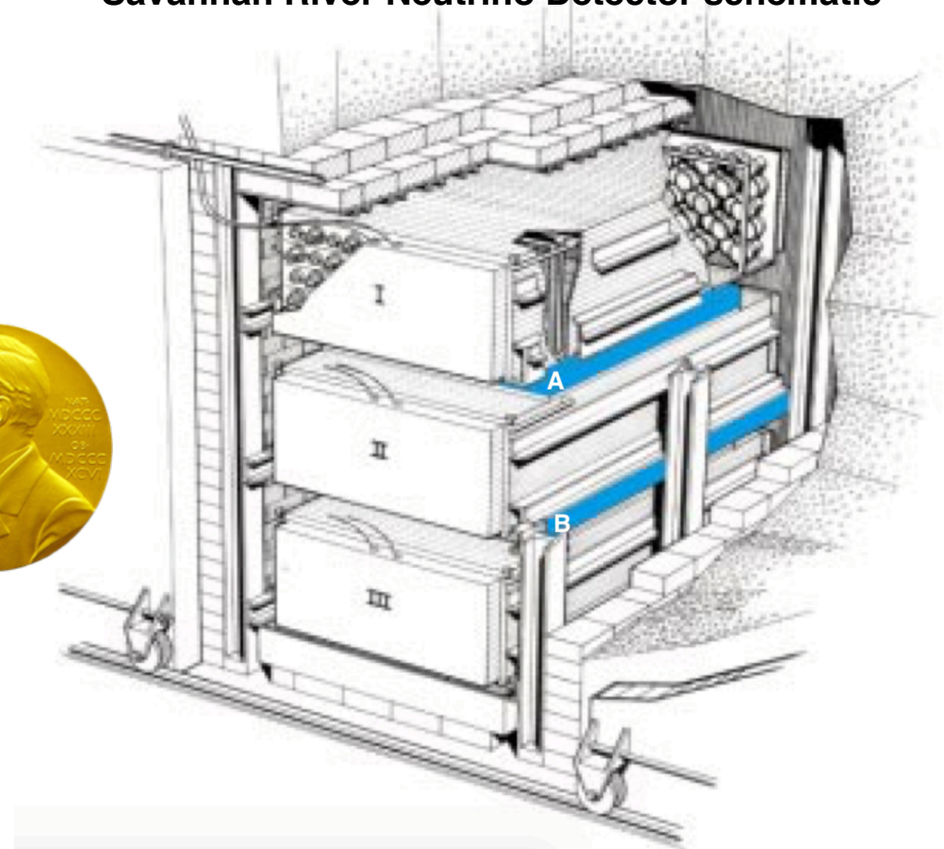
- What if our estimate of scintillation light collection per MeV is too high by 10%?
  - I guess our current prediction will under-estimate energies, so our predicted spectrum should be shifted to the left.
  - In reality, these energy definition uncertainties are of order 1% for Rx exps.

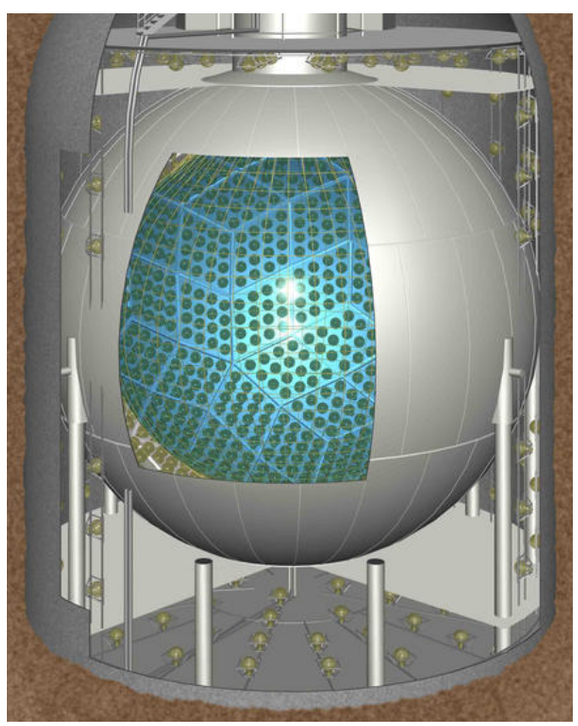


What's Been Done With Reactor Neutrinos?

- 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

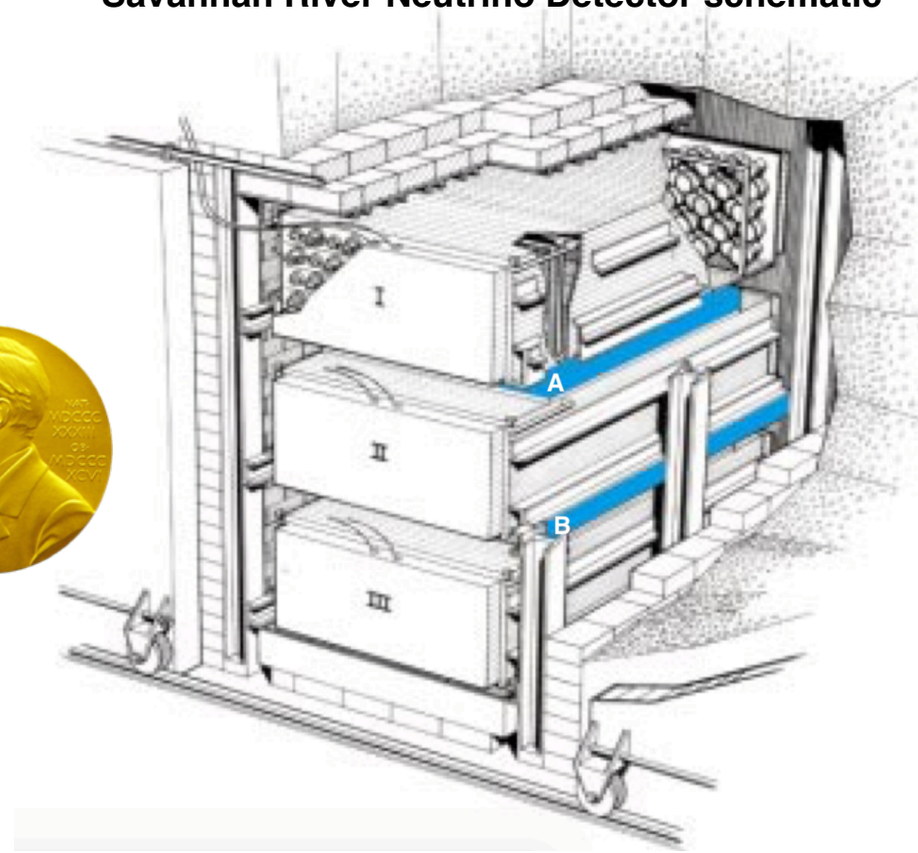
Daya Bay Far Site

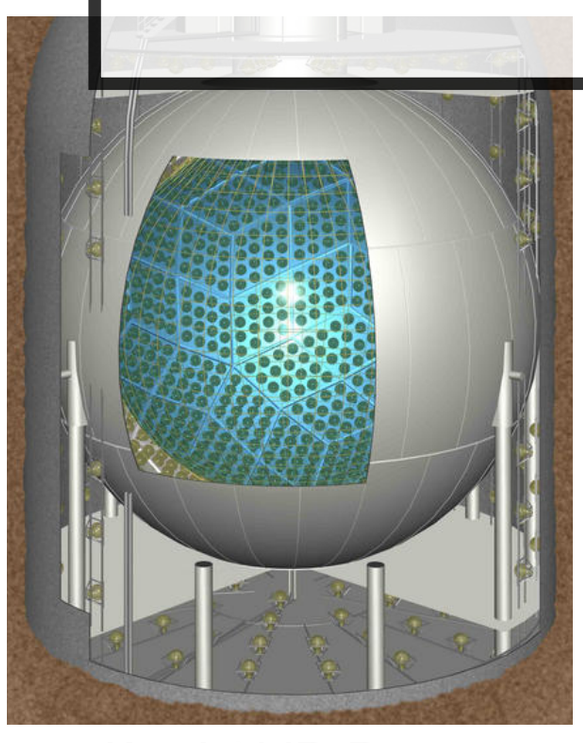
What's Been Done With Reactor Neutrinos?

- 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}, $|\Delta m^2$

HOW?

Savannah River Neutrino Detector schematic





KamLAND Detector

2016 Breakthrough Prize

Daya Bay Far Site

Measuring Osc: KamLAND

Measuring Osc: Theta13

Measuring Osc: JUNO

What We've Been Doing Very Recently

- Important questions remain that have big implications
  - Do we understand reactor neutrino fluxes?
    - Sterile neutrinos?
  - Do we understand reactor neutrino energies?
    - Bad nuclear data; implications for nuclear applications?
    - Mass hierarchy measurements at reactors?

What We've Been Doing Very Recently

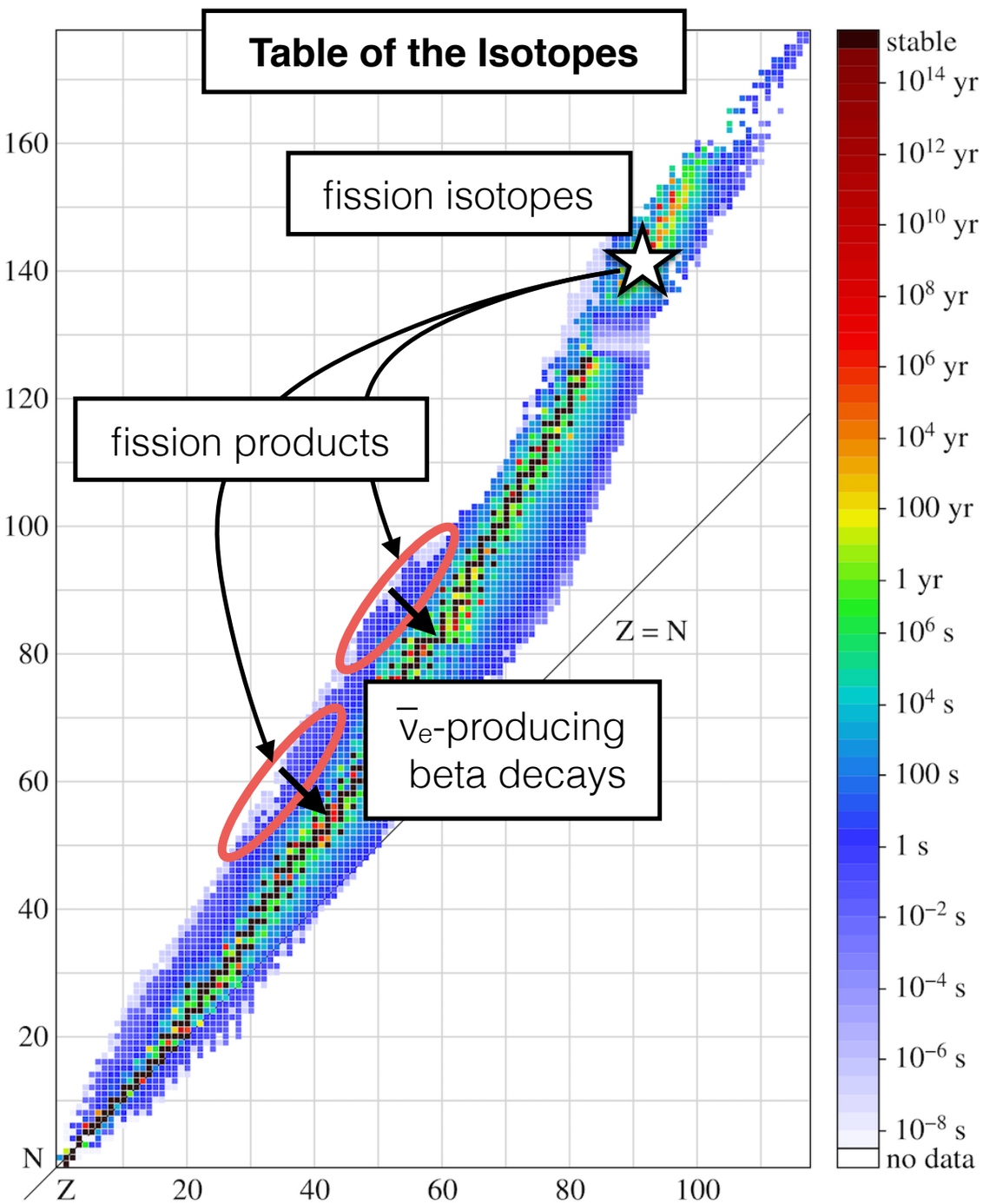
- Important questions remain that have big implications

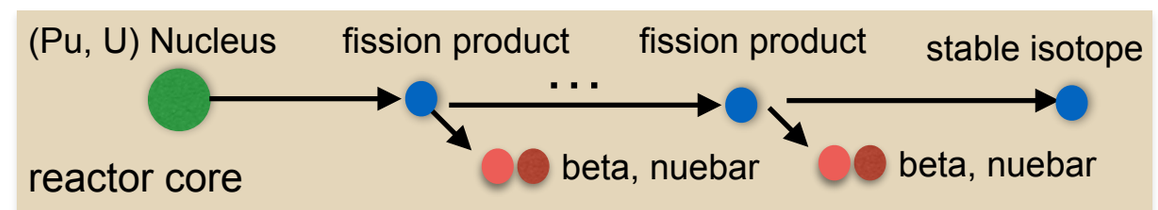
- Do we understand reactor neutrino fluxes?
  - Sterile neutrinos?
- Do we understand reactor neutrino energies?
  - Bad nuclear data; implications for nuclear applications?
  - Mass hierarchy measurements at reactors?

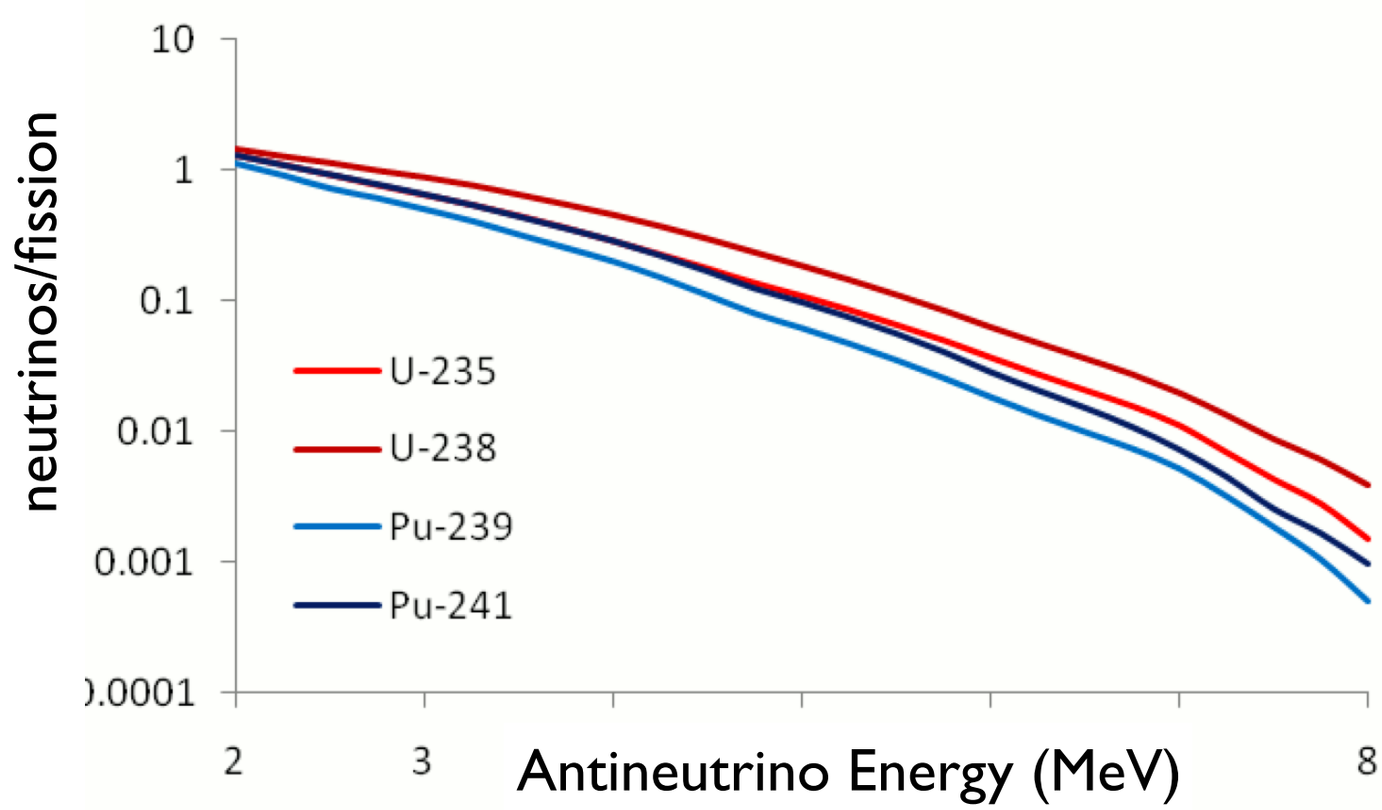
HOW?

Reactor Antineutrino Production

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







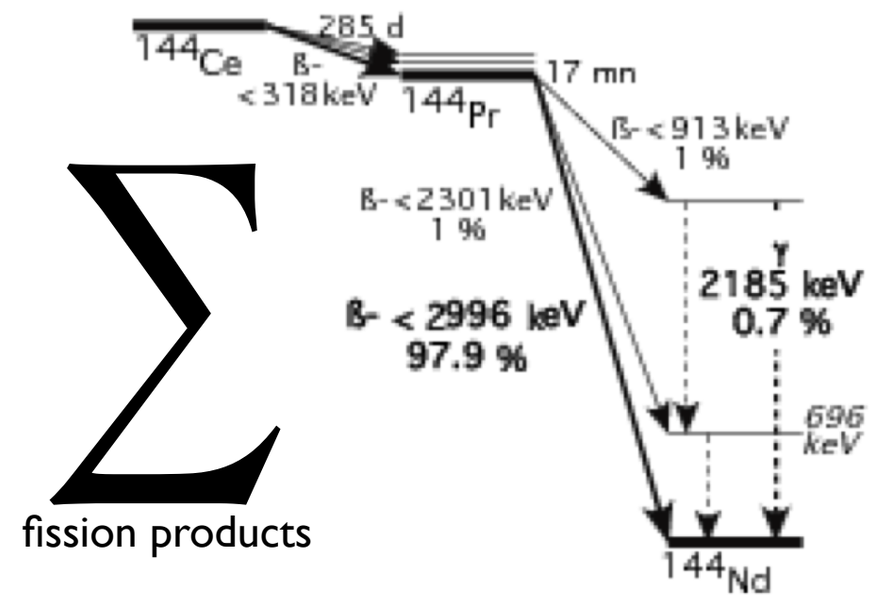
Predicting $S_i(E)$, Neutrinos Per Fission

- Two main methods:

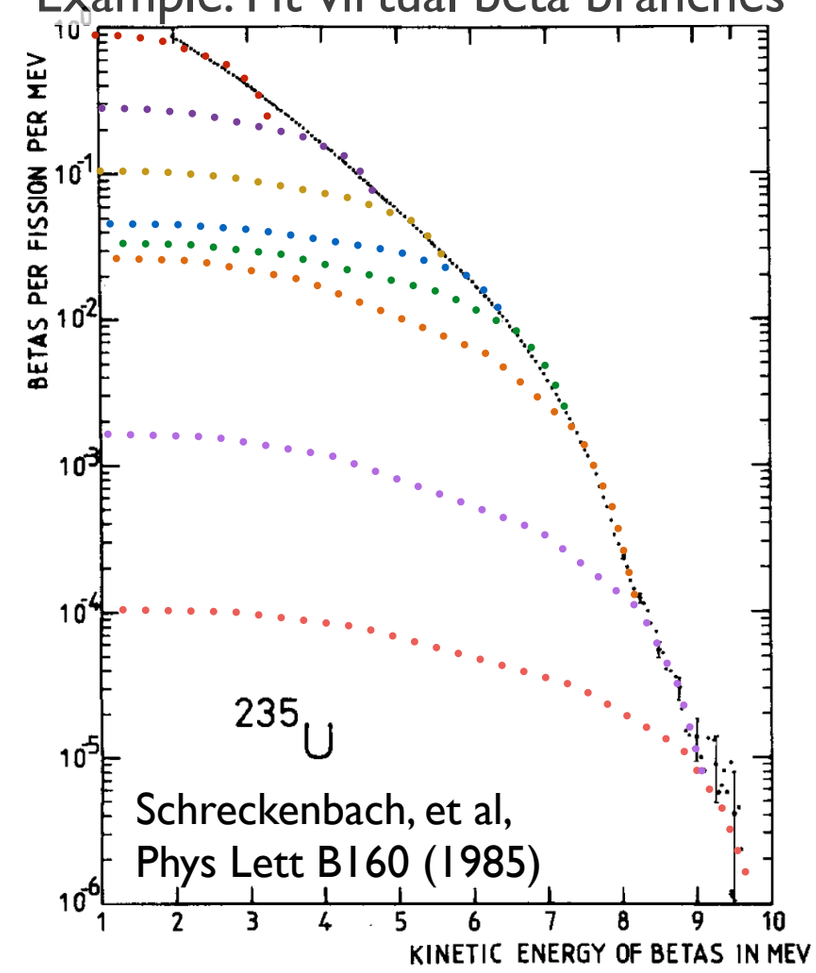
- *Ab Initio* approach:
  - Calculate spectrum branch-by-branch w/ databases: fission yields, decay schemes, …
  - **Problem:** rare isotopes / beta branches: missing, possibly incorrect info…

- Conversion approach
  - Measure beta spectra directly
  - Convert to $\overline{\nu}_e$ 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



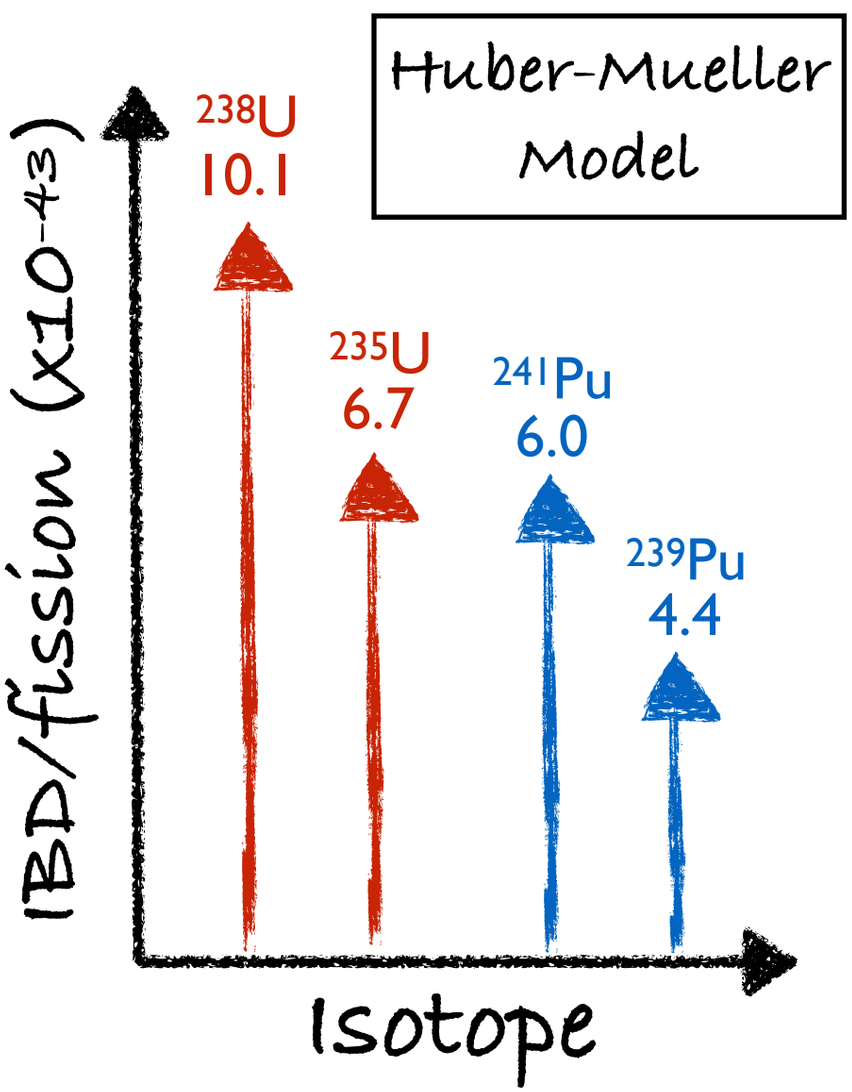
Example: Fit virtual beta branches



Reactor Antineutrino Flux

Reactor Flux Predictions

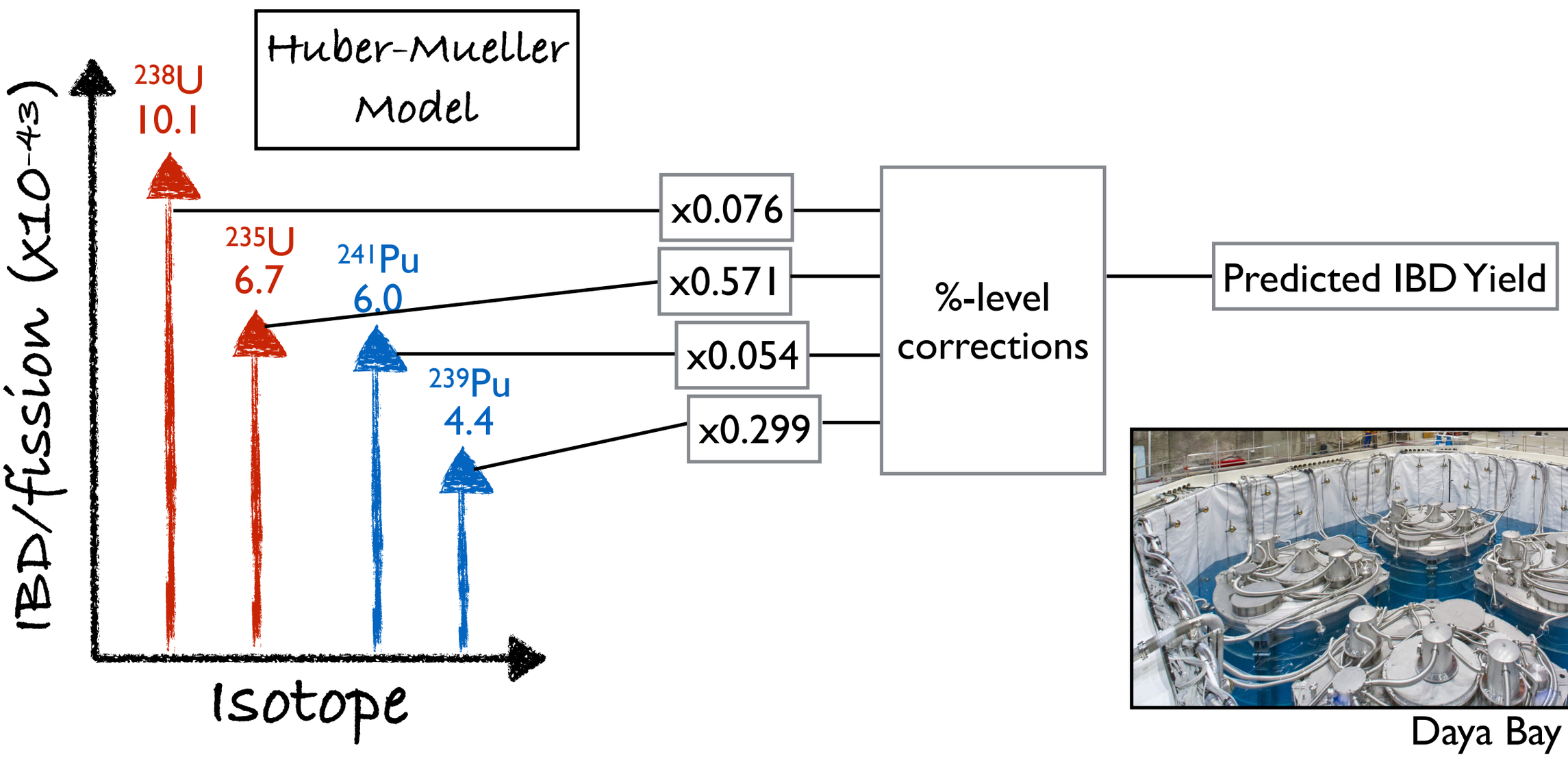
- Three isotopes' $\bar{\nu}_e$ flux predictions re-formulated in 2011
  - Note: 'flux' often cited as IBD per fission, or 'IBD yield': flux * cross-section



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

Reactor IBD Yield Measurements

- Three isotopes' $\bar{\nu}_e$ flux predictions re-formulated in 2011
- To predict one experiment's yield: multiply each isotope's IBD yield by its fission fraction, correct, sum, and you're done.

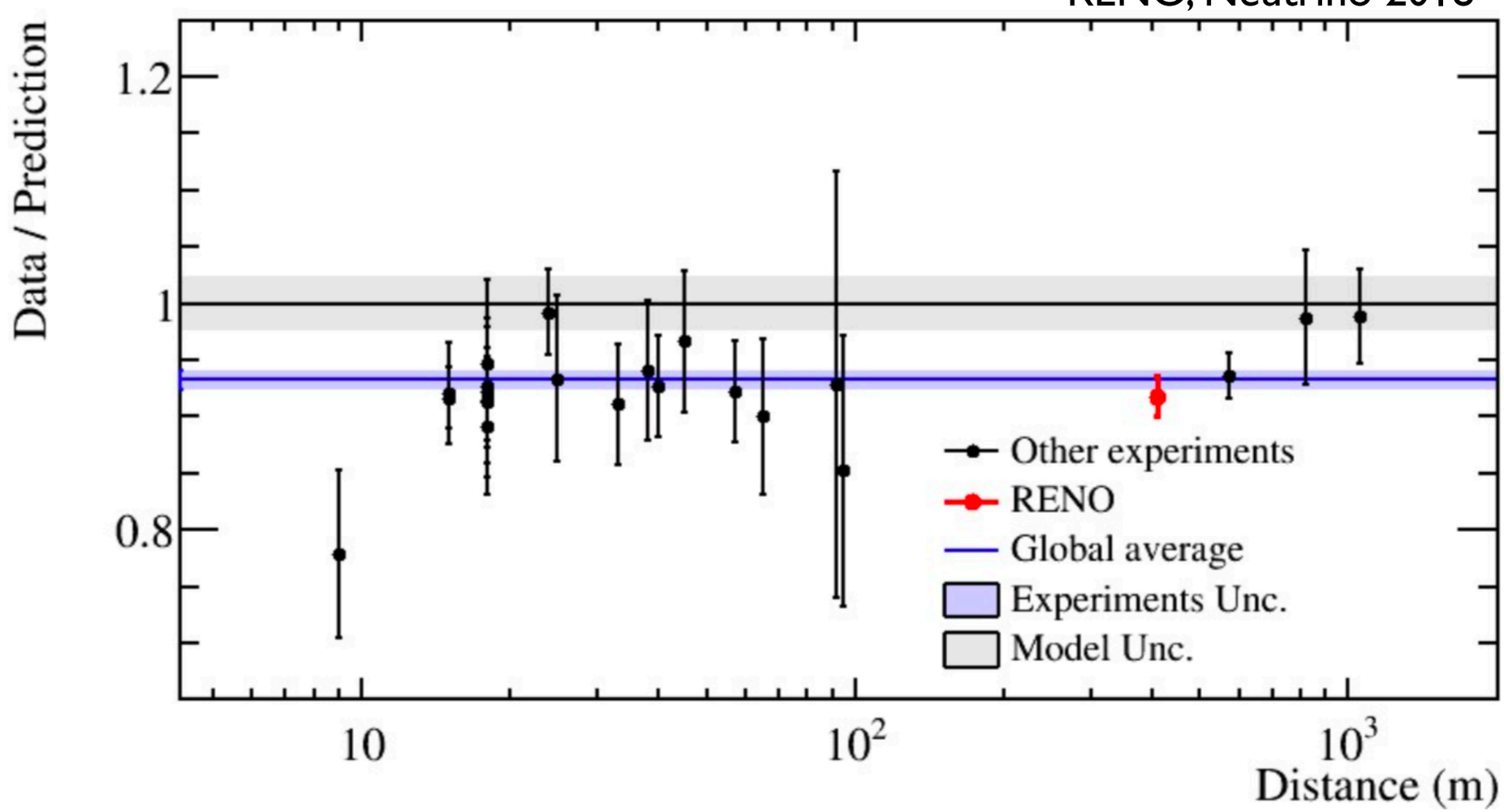


Daya Bay

Reactor Antineutrino Flux Anomaly

- Bad news: these flux predictions don't match the data.
- New precise measurements also do not match predictions: Daya Bay (1.5%), RENO (2%), Double Chooz (~1%?)
- WHY the deficit??

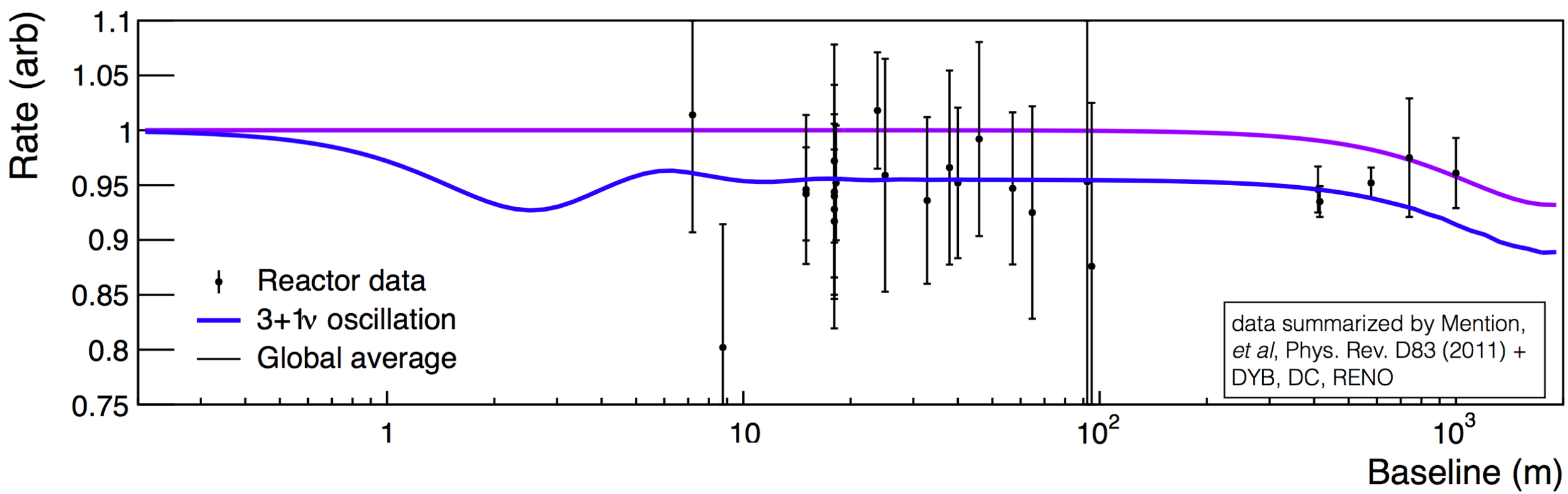
RENO, Neutrino 2018



Sterile Neutrino Oscillations

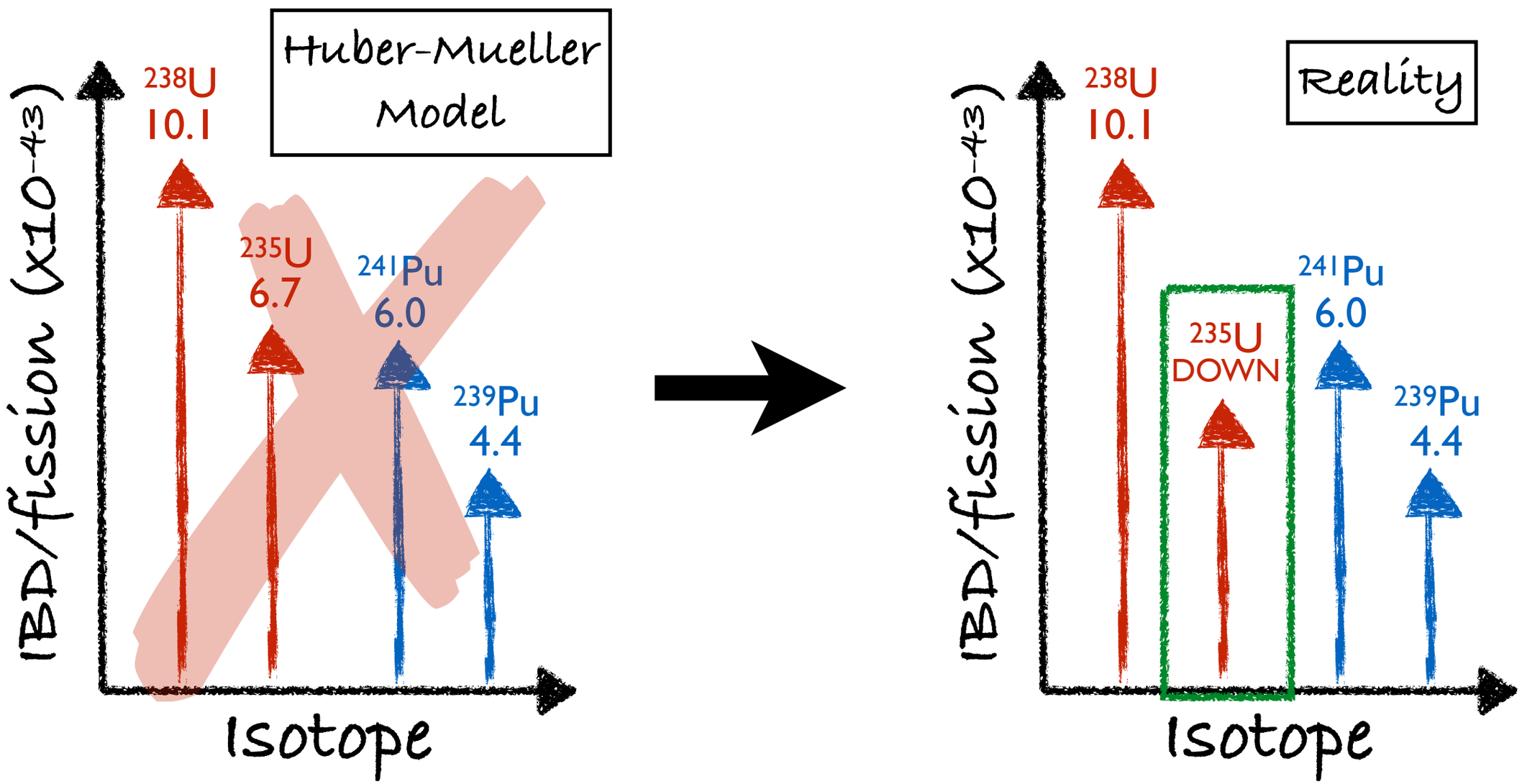
- Hypothesis 1: Some $\bar{\nu}_e$ oscillated to unobservable types
  - This hypothesis indicates a deficit that is <u>baseline-dependent</u>
  - To fit data, need osc maximum at small baselines: large (~eV) mass splitting
  - Only measuring average flux deficit here… not L/E behavior…

$$sin^2(2\theta)sin^2(1.27\Delta m^2\frac{L}{E_\nu})$$



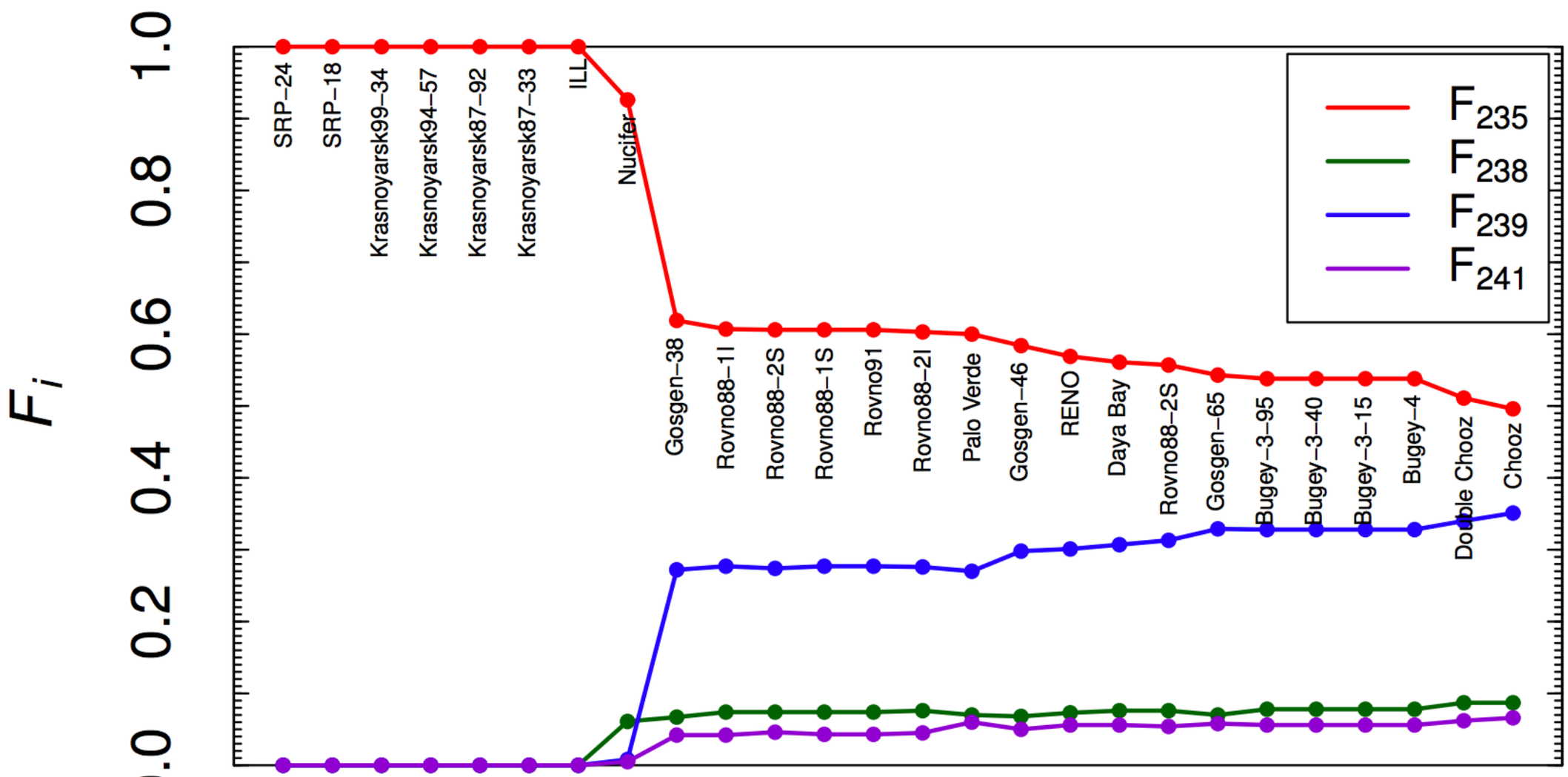
Bad Flux Predictions

- Hypothesis 2: 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.



Bad Flux Predictions

- Hypothesis 2: Something is wrong with the flux predictions
  - This hypothesis indicates a deficit that *could be* fuel-content-dependent
  - All isotopes have ~same $\langle E_\nu \rangle$, so oscillations can't mimic this behavior

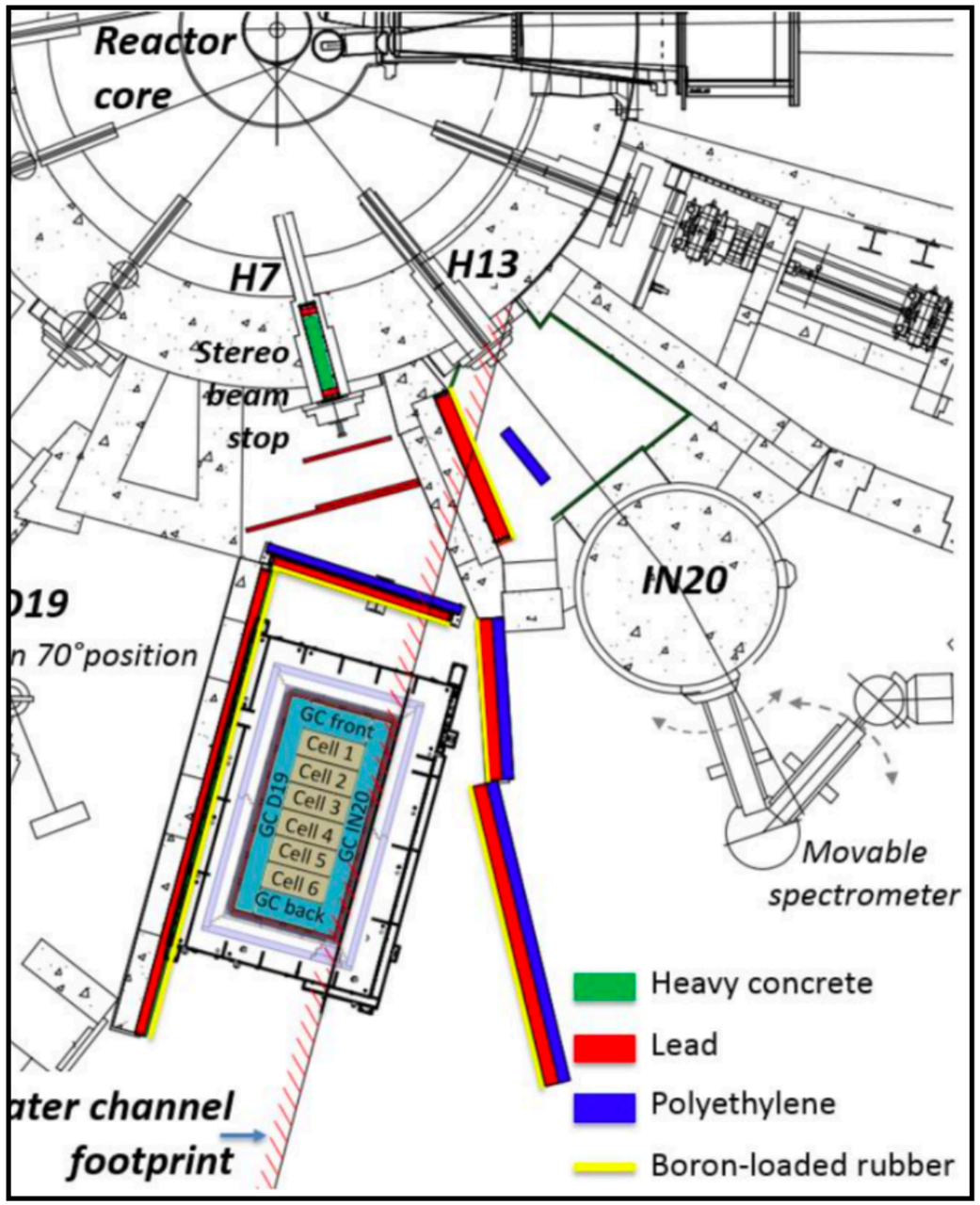


Giunti, et al, JHEP 10:143 (2017)

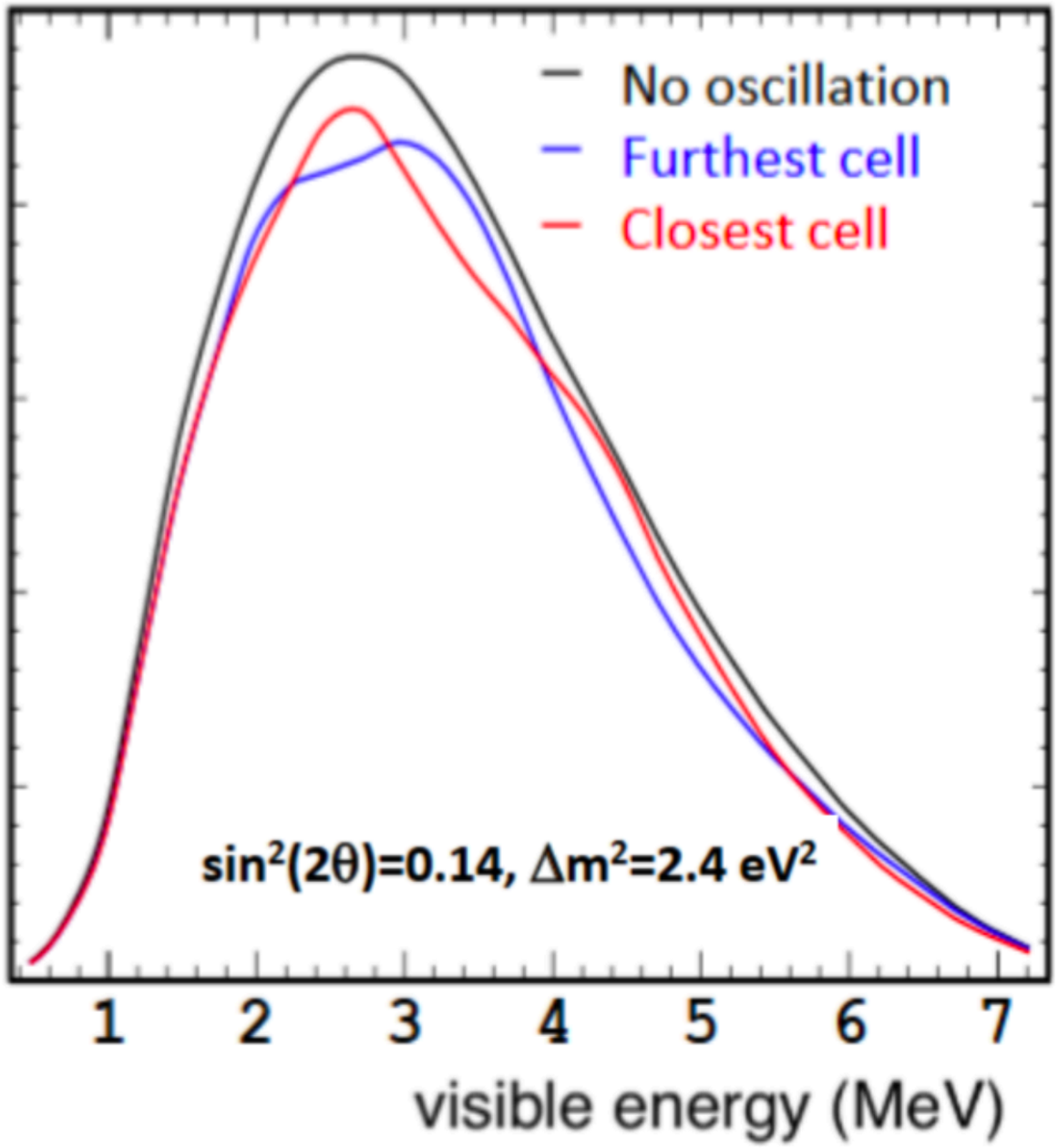
Testing Steriles: Short-Baseline Experiments

- PROSPECT, Soliδ, STEREO, etc: Compare spectra between 'sub-detectors' at different baselines inside a single detector!

STEREO Experimental Layout



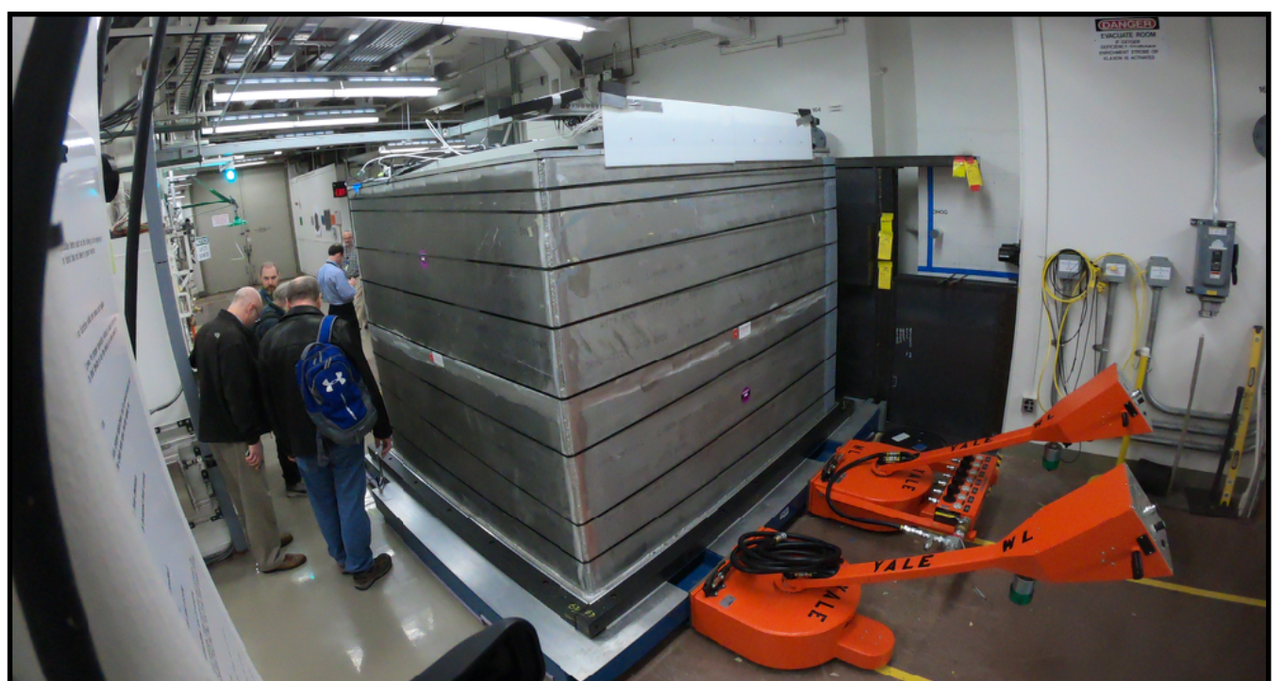
STEREO Toy Prompt Spectra From RAA Best-Fit Osc



Testing Steriles: PROSPECT

- PROSPECT currently deployed at highly-enriched reactor core!

PROSPECT Assembly: note detector segmentation!



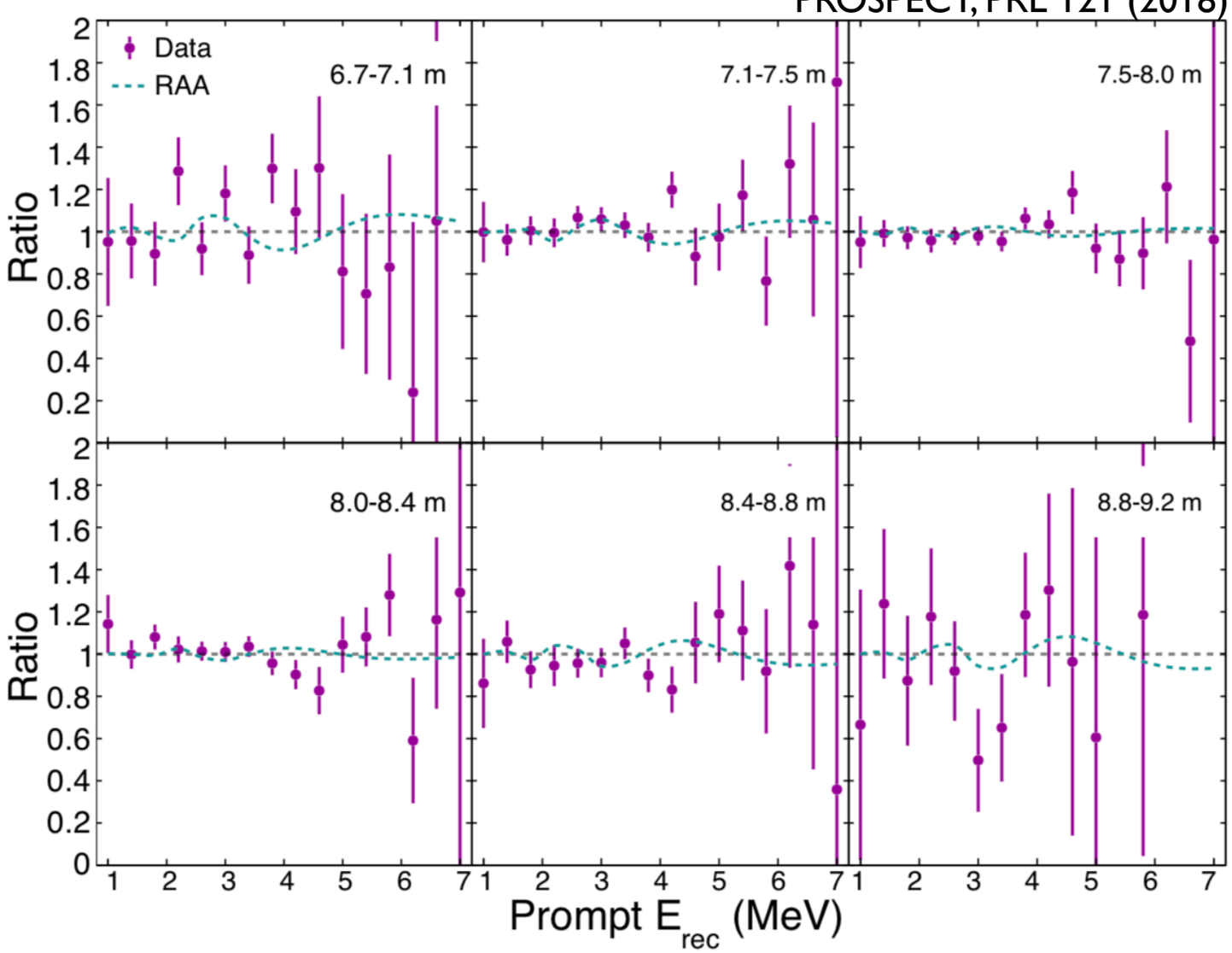
PROSPECT Installation: Rx on other side of the wall!

HFIR reactor core:
Burns <u>only</u> ^{235}U!

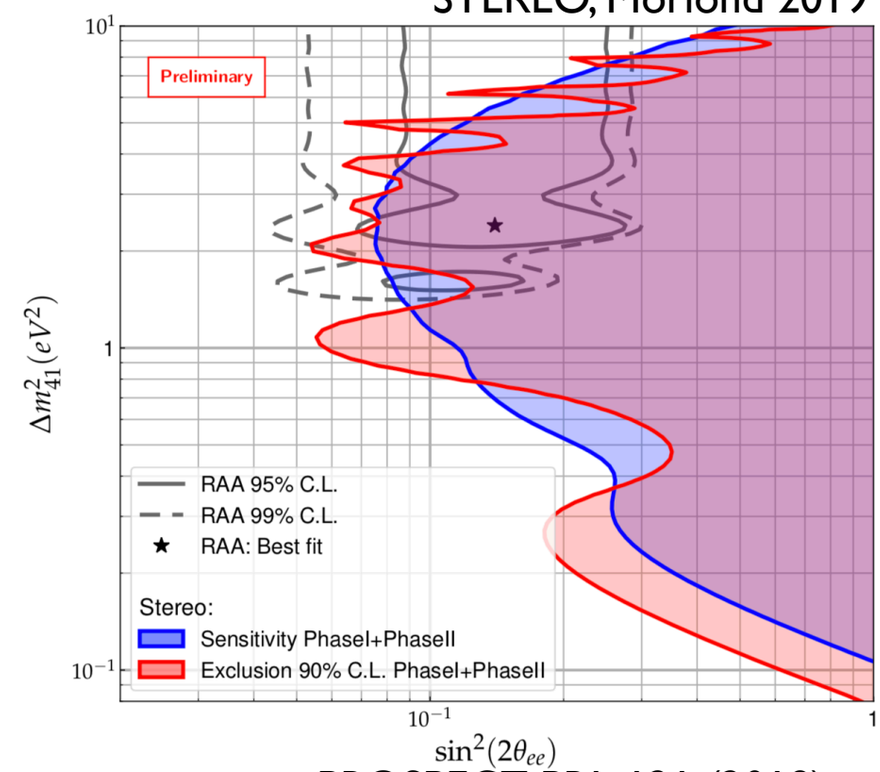
Testing Steriles: PROSPECT and STEREO

- PROSPECT and STEREO: Results are here already!
- No evidence for steriles so far
  - More statistics will bring sensitivity improvements in the coming year

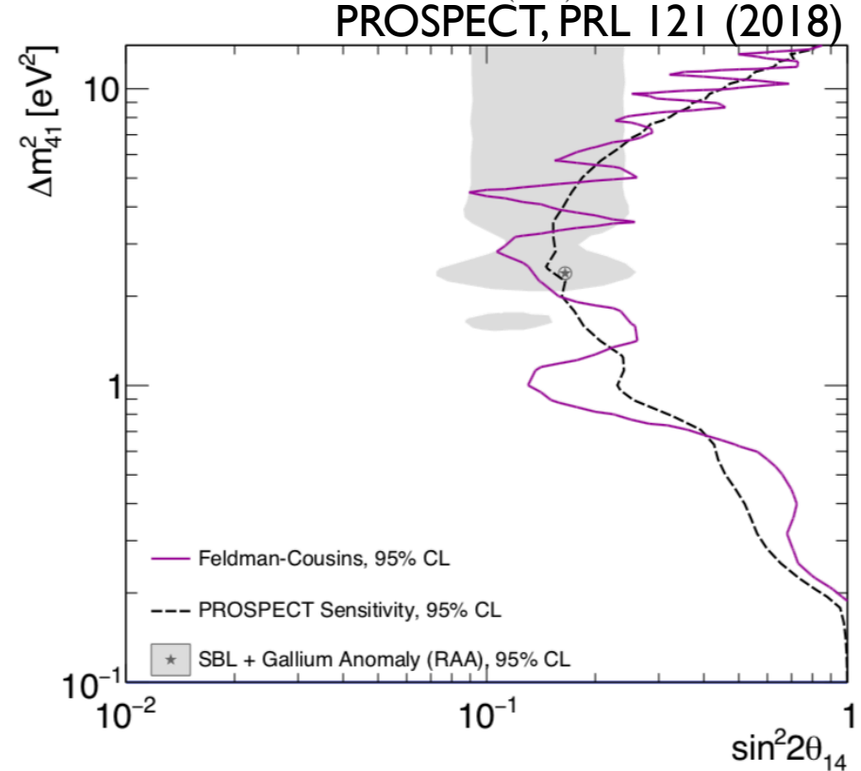
PROSPECT, PRL 121 (2018)



STEREO, Moriond 2019

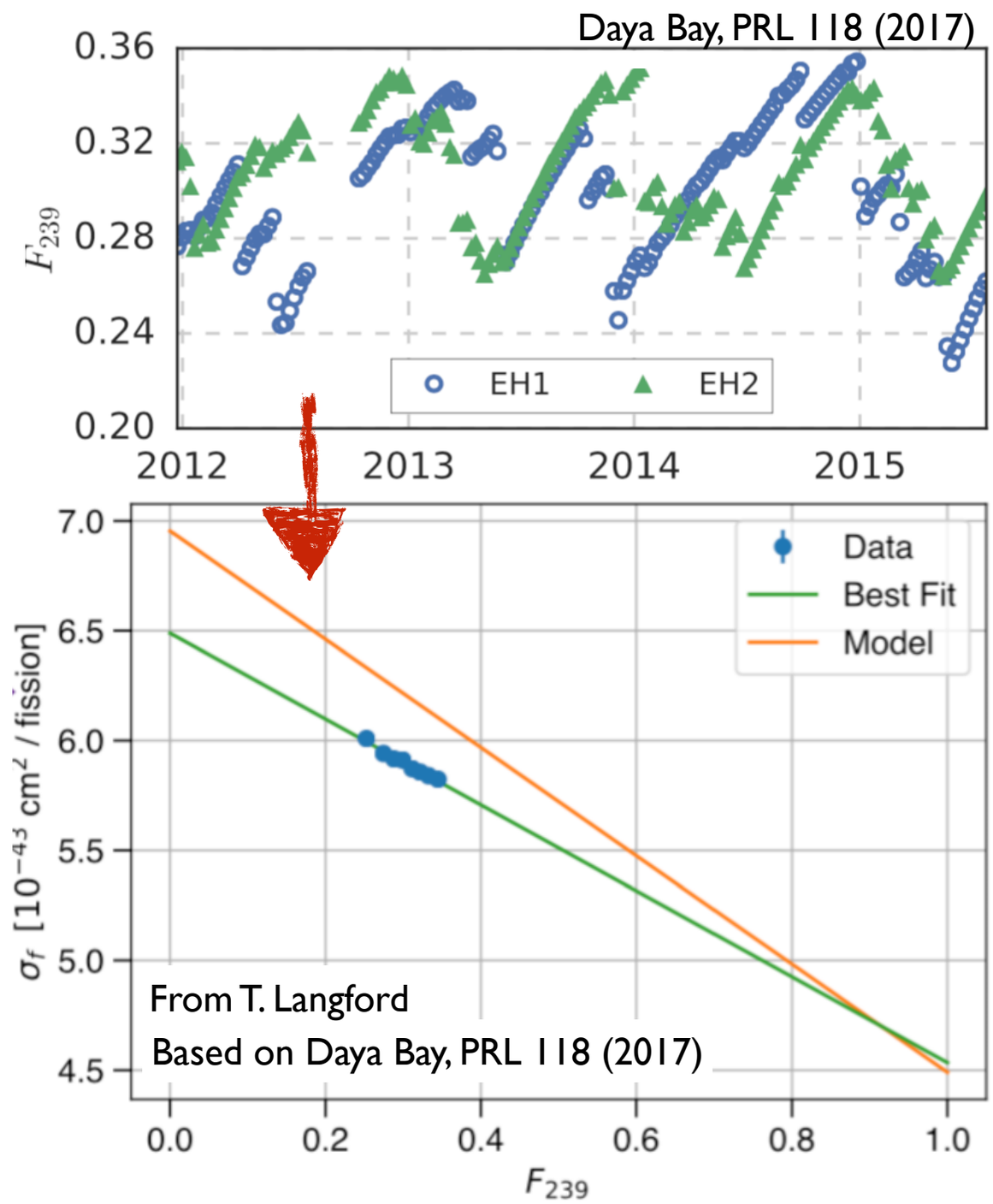


PROSPECT, PRL 121 (2018)



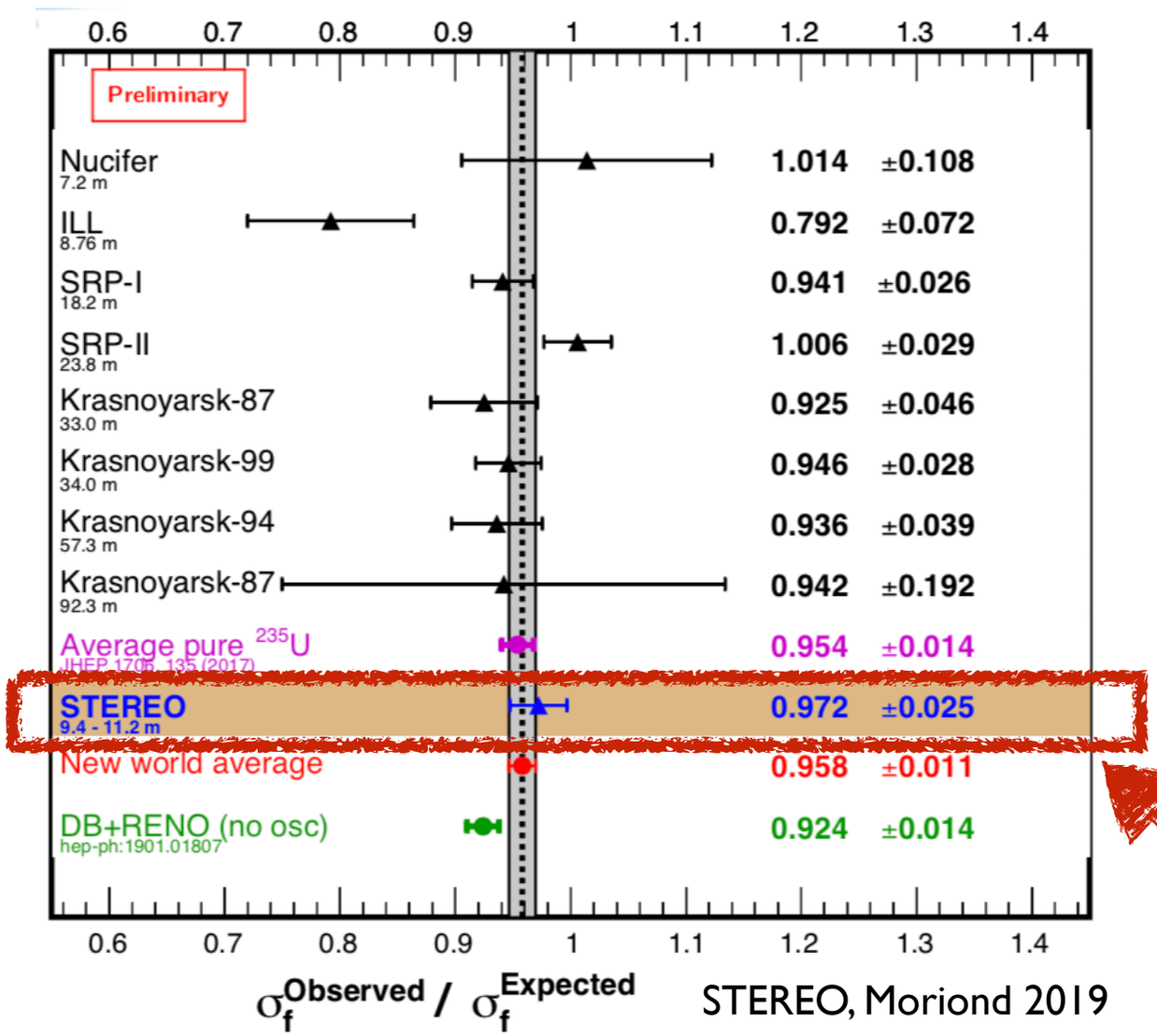
Testing Fluxes: Daya Bay Evolution

- 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

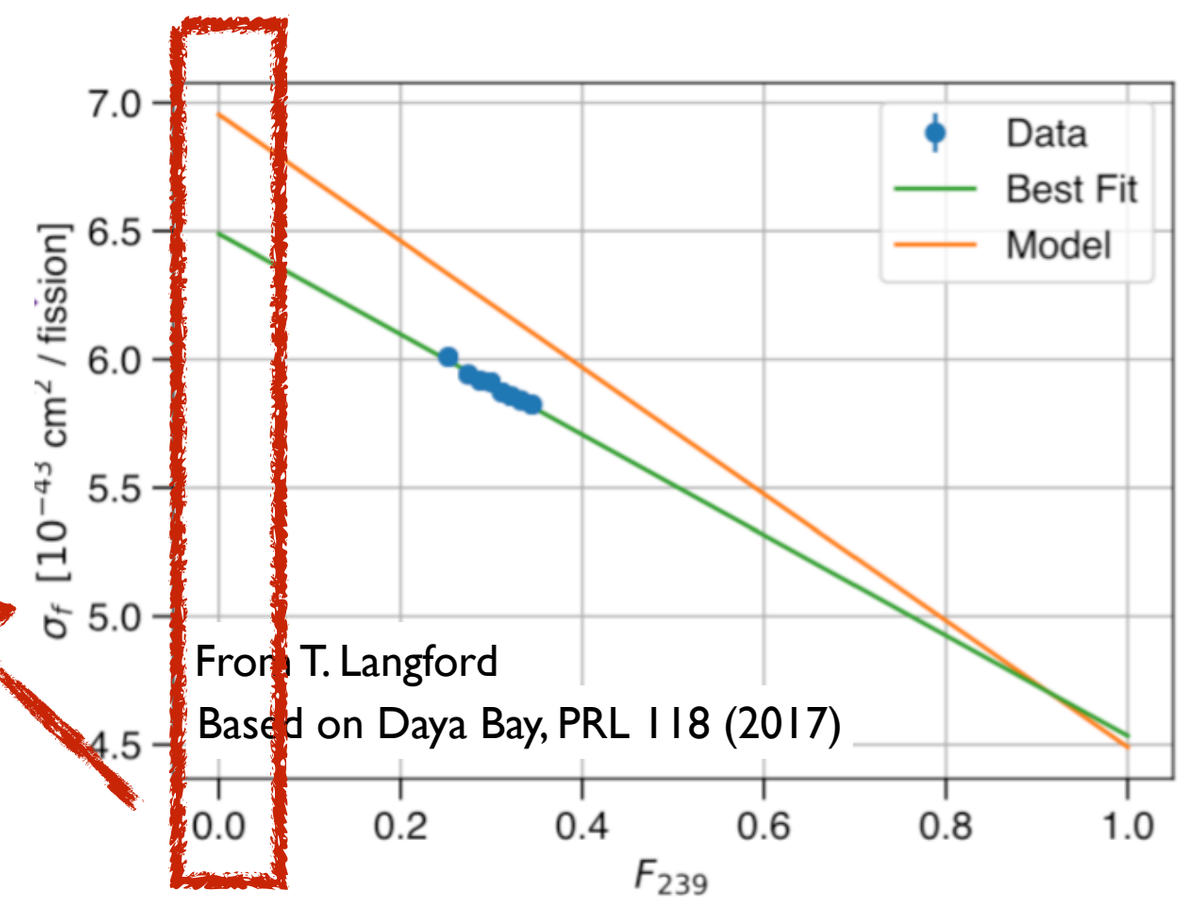


Testing Fluxes: Daya Bay Evolution

- 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



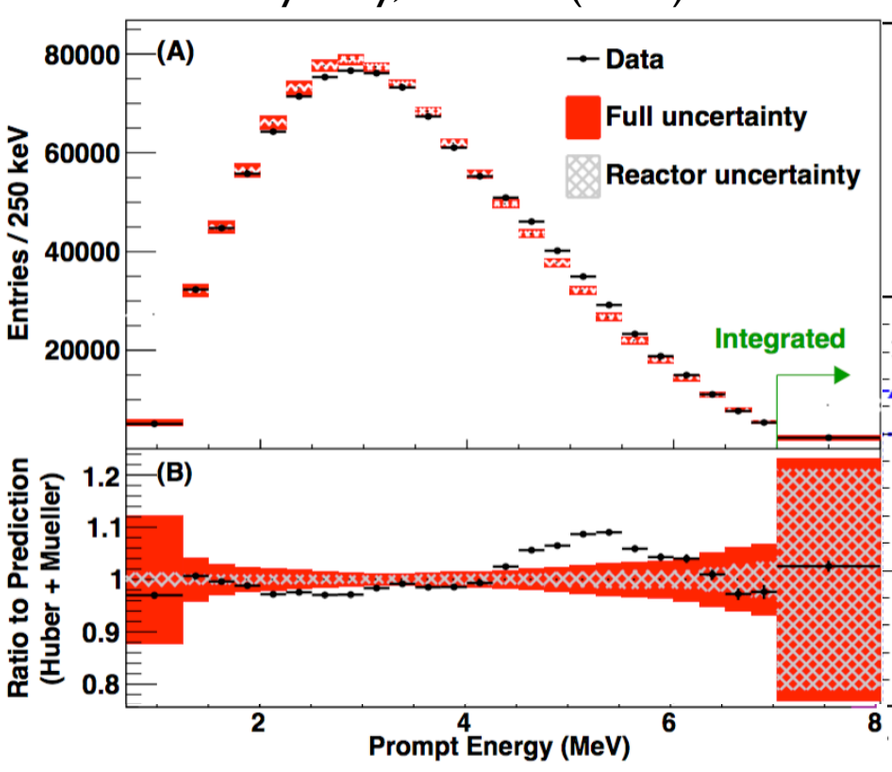
From T. Langford
Based on Daya Bay, PRL 118 (2017)

Reactor Antineutrino Spectrum

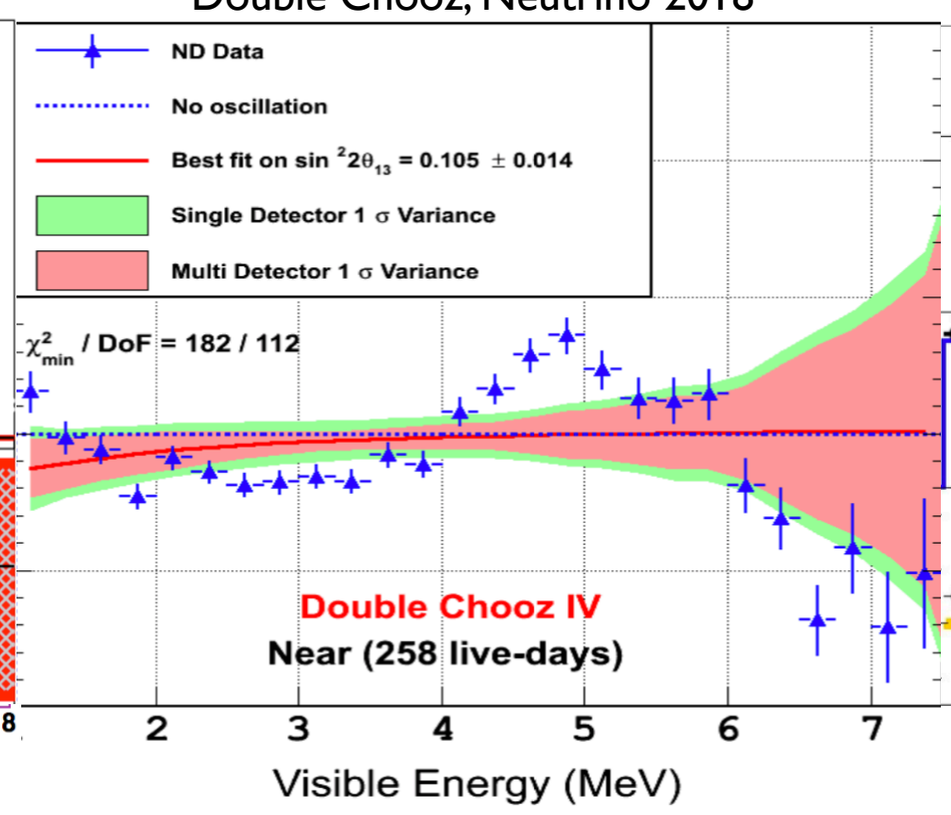
Reactor Spectrum Anomaly

- 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!

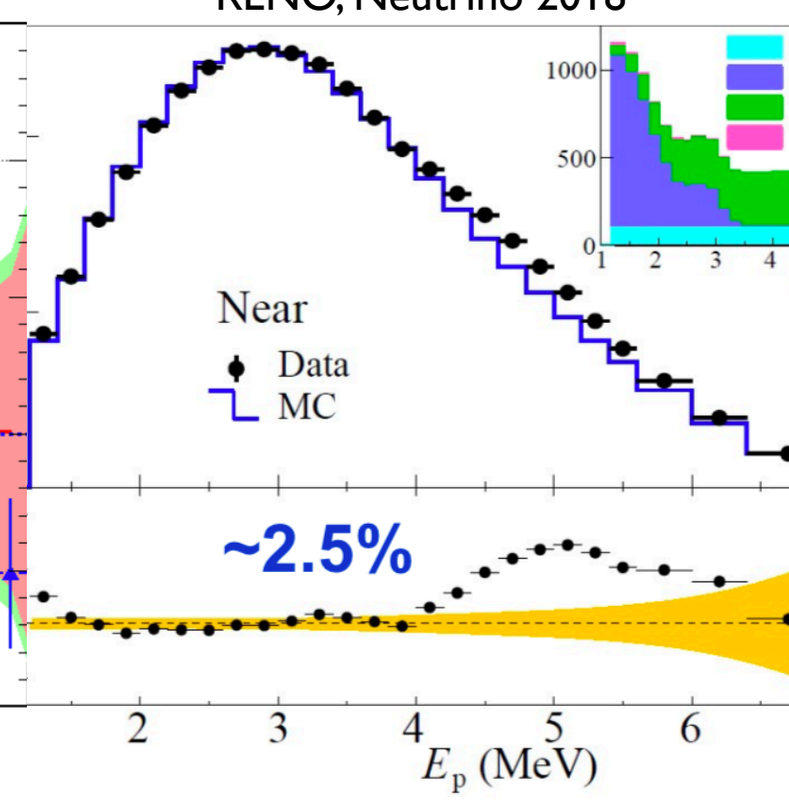
Daya Bay, CPC 41 (2017)



Double Chooz, Neutrino 2018



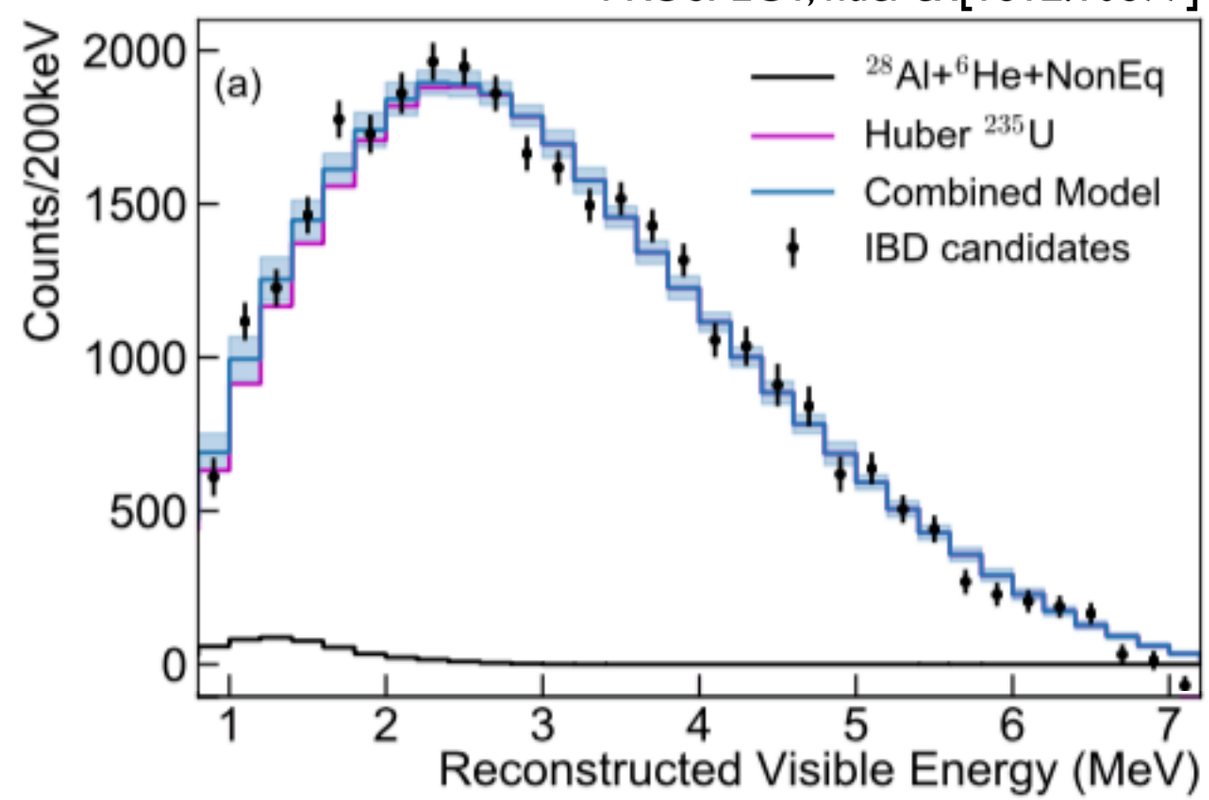
RENO, Neutrino 2018



Isotopic Origins: PROSPECT

- Measure spectrum when burning <u>only</u> ^{235}U
- PROSPECT has done this!

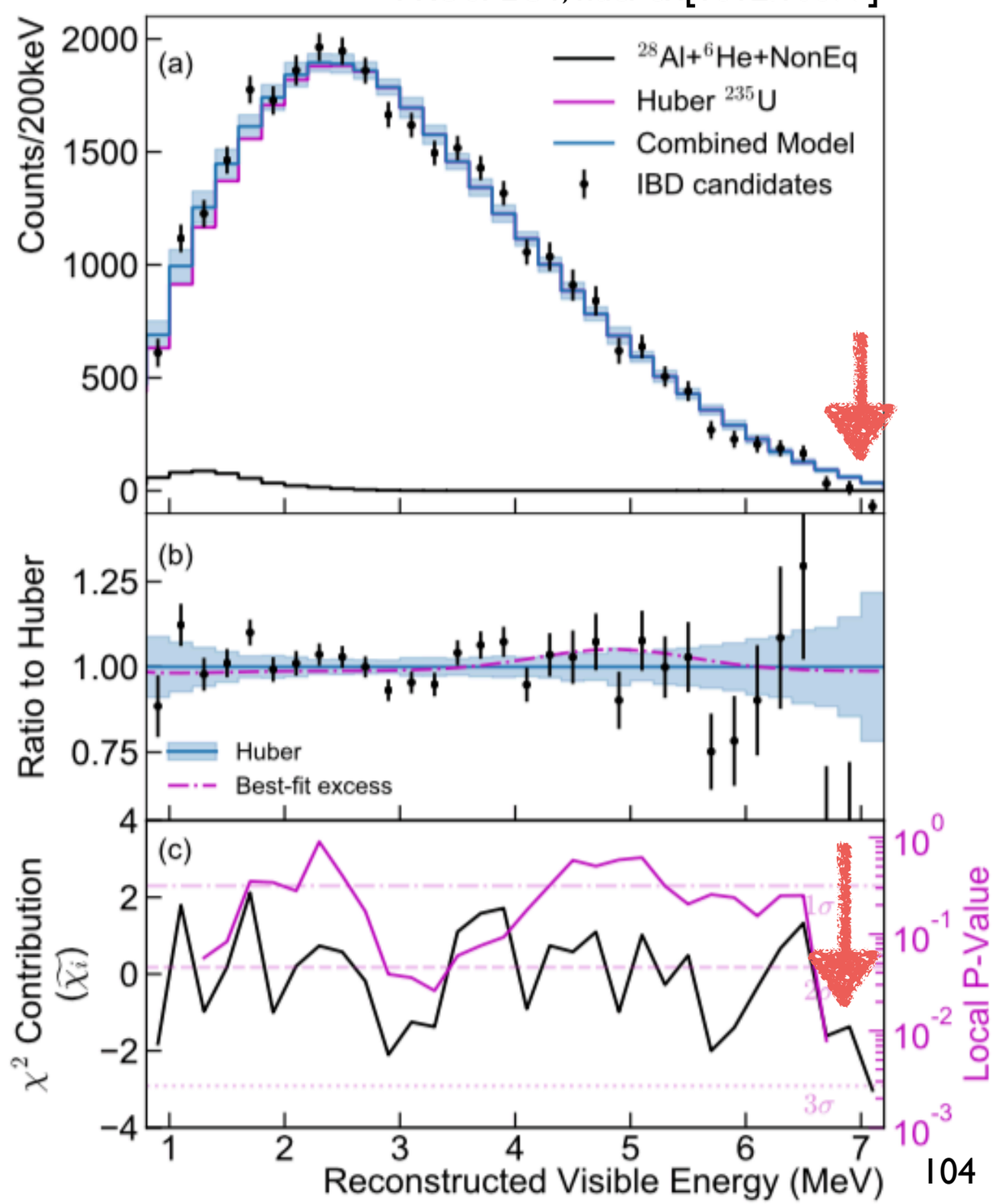
PROSPECT, nucl-ex[1812.10877]



Isotopic Origins: PROSPECT

- Measure spectrum when burning <u>only</u> ^{235}U
- PROSPECT has done this!
- Is PROSPECT consistent with Huber's ^{235}U model?
  - $X^2/ndf = 52.1/31$; p-value = 0.01
  - Huber broadly agrees with PROSPECT, but not a great fit
  - Worst offender: high energy fit is OK otherwise.
    - Bkg issue? Unlucky statistics? Need more stats to know for sure.

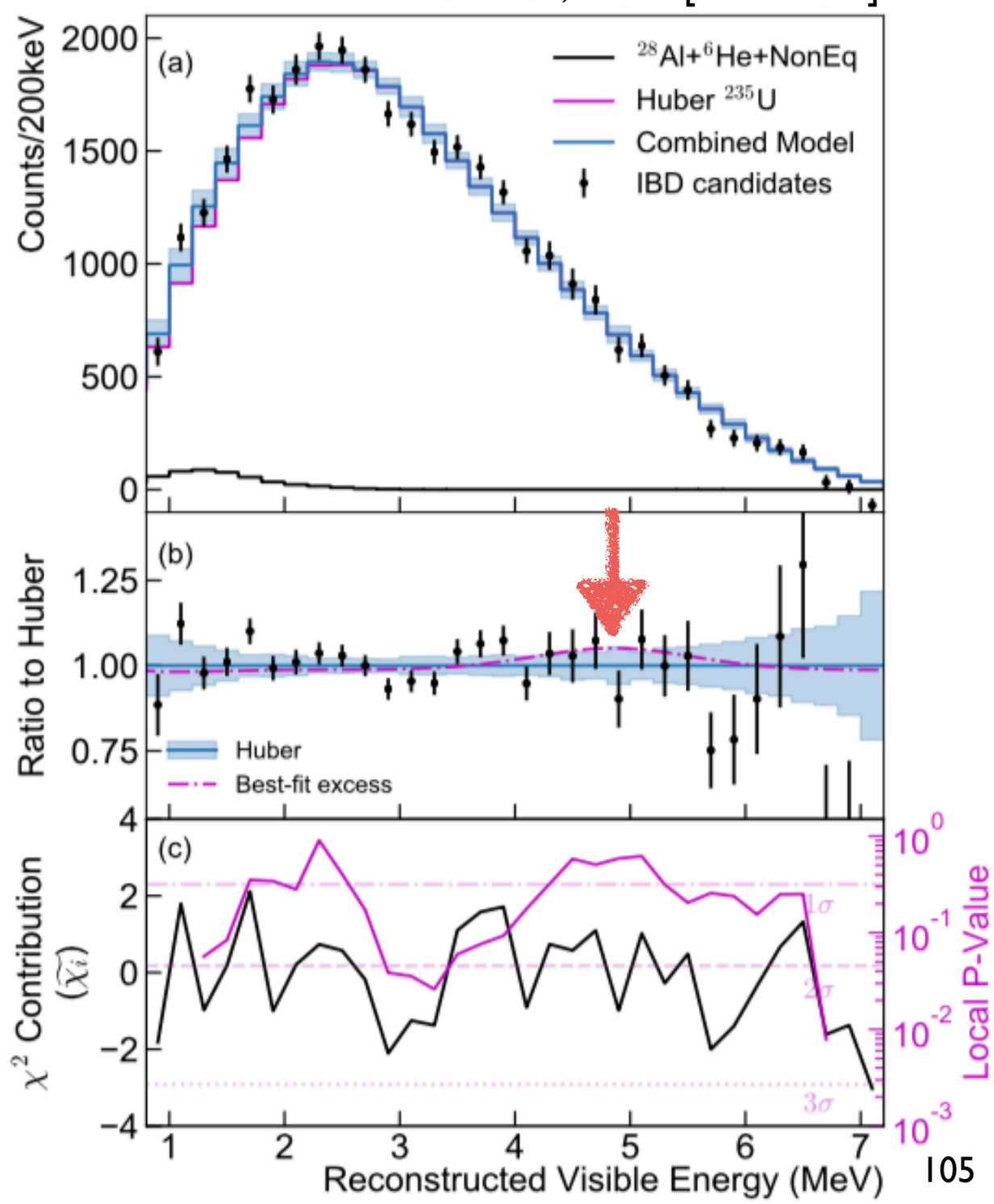
PROSPECT, nucl-ex[1812.10877]



Isotopic Origins: PROSPECT

- Measure spectrum when burning <u>only</u> ^{235}U
- PROSPECT has done this!
- How does PROSPECT compare to 'bump' in θ_{13} experiments?
  - PROSPECT relative bump size WRT to Daya Bay: 69% ± 53%
  - ~consistent with 'no bump' (0%) and 'DYB-sized bump' (100%)
    - Need more stats to differentiate
  - 'Big bump' (178%) if ^{235}U is the sole bump contributor
    - Disfavored at 2.1σ

PROSPECT, nucl-ex[1812.10877]



Thanks!

- Things I didn't even get to mention (quiz me later!)
  - New STEREO HEU spectrum results
  - RENO Spectrum Evolution
  - DANSS and NEOS
  - Reactor IBD-CEνNS complementarity
  - New studies questioning ILL beta spectrum calibration accuracy
  - More theory studies probing inaccuracies in conversion / ab initio methods