Reactor Anti-Neutrinos: Anomalies, Interpretations and new Experiment

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Selected puzzles in particle physics

chaired by Gennaro Corcella (LNF), Giuseppe Degrassi (ROMA3), Barbara Mele (ROMA1), Enrico Nardi (LNF)

from Tuesday, 20 December 2016 at **10:00** to Thursday, 22 December 2016 at **13:00** (Europe/Rome)
at **Laboratori Nazionali di Frascati (High Energy Building, Seminar Room)**

Directions in Neutrino Physics

3 massive ν's only: determine masses and mixings

- oscillations
- absolute mass ←→ how precise should we know?
- Dirac or Majorana

more than 3 neutrinos

- sterile neutrinos
- L-violation ←→ any one of them a major discovery!
- NSIs
- large magnetic moments
- …

methods: **precision** → θ_{ij} , m_1, Δm_{ij}^2, over-constraining

MH, CP → enough precision to extract it

other → 0νββ, coherent scattering, ...

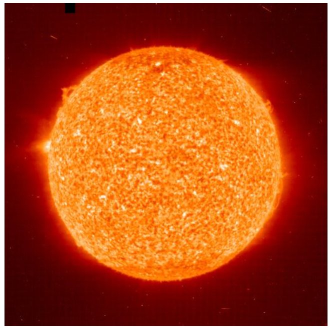
physics goals:

precise flavour information ←→ origin of mass/flavour?

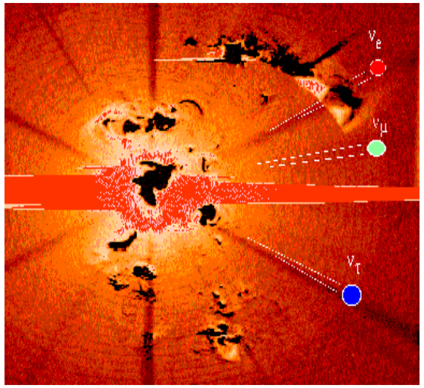
lever arm to other new physics →!

learn about sources →

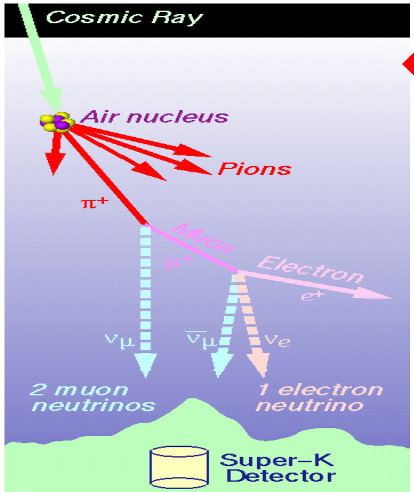
Learning from Neutrino Sources



←Sun



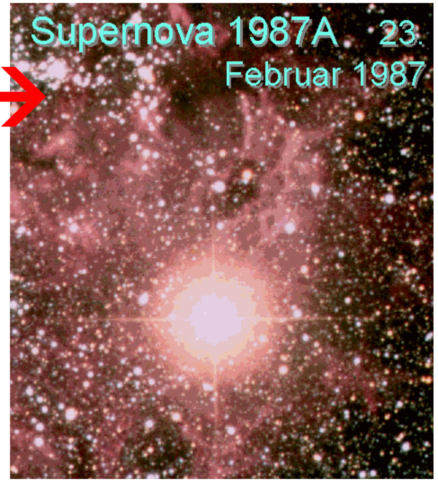
←Cosmology



←Atmosphere

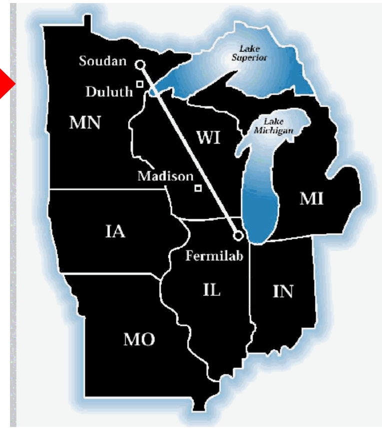
←Earth

Astronomy: →
Supernovae
GRBs
UHE n's

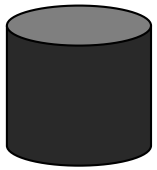


Reactors→

Accelerators→



β-Sources→

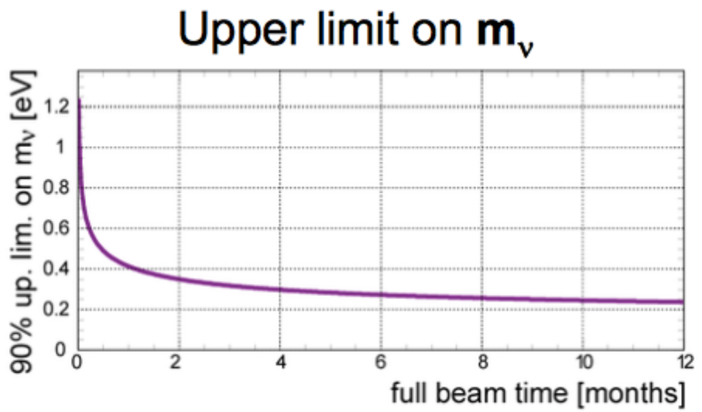


The Status of Neutrino Parameters (3f)

See e.g. Esteban, Gonzalez-Garcia, Maltoni, Martinez-Soler, Schwetz

	Normal Ordering (best fit)		Inverted Ordering ($\Delta\chi^2 = 0.83$)		Any Ordering
	bfp $\pm 1\sigma$	3σ range	bfp $\pm 1\sigma$	3σ range	3σ range
$\sin^2\theta_{12}$	$0.306^{+0.012}_{-0.012}$	$0.271 \to 0.345$	$0.306^{+0.012}_{-0.012}$	$0.271 \to 0.345$	$0.271 \to 0.345$
$\theta_{12}/^\circ$	$33.56^{+0.77}_{-0.75}$	$31.38 \to 35.99$	$33.56^{+0.77}_{-0.75}$	$31.38 \to 35.99$	$31.38 \to 35.99$
$\sin^2\theta_{23}$	$0.441^{+0.027}_{-0.021}$	$0.385 \to 0.635$	$0.587^{+0.020}_{-0.024}$	$0.393 \to 0.640$	$0.385 \to 0.638$
$\theta_{23}/^\circ$	$41.6^{+1.5}_{-1.2}$	$38.4 \to 52.8$	$50.0^{+1.1}_{-1.4}$	$38.8 \to 53.1$	$38.4 \to 53.0$
$\sin^2\theta_{13}$	$0.02166^{+0.00075}_{-0.00075}$	$0.01934 \to 0.02392$	$0.02179^{+0.00076}_{-0.00076}$	$0.01953 \to 0.02408$	$0.01934 \to 0.02397$
$\theta_{13}/^\circ$	$8.46^{+0.15}_{-0.15}$	$7.99 \to 8.90$	$8.49^{+0.15}_{-0.15}$	$8.03 \to 8.93$	$7.99 \to 8.91$
$\delta_{CP}/^\circ$	261^{+51}_{-59}	$0 \to 360$	277^{+40}_{-46}	$145 \to 391$	$0 \to 360$
$\frac{\Delta m^2_{21}}{10^{-5}\ \text{eV}^2}$	$7.50^{+0.19}_{-0.17}$	$7.03 \to 8.09$	$7.50^{+0.19}_{-0.17}$	$7.03 \to 8.09$	$7.03 \to 8.09$
$\frac{\Delta m^2_{3\ell}}{10^{-3}\ \text{eV}^2}$	$+2.524^{+0.039}_{-0.040}$	$+2.407 \to +2.643$	$-2.514^{+0.038}_{-0.041}$	$-2.635 \to -2.399$	$\begin{bmatrix}+2.407 \to +2.643 \\ -2.629 \to -2.405\end{bmatrix}$

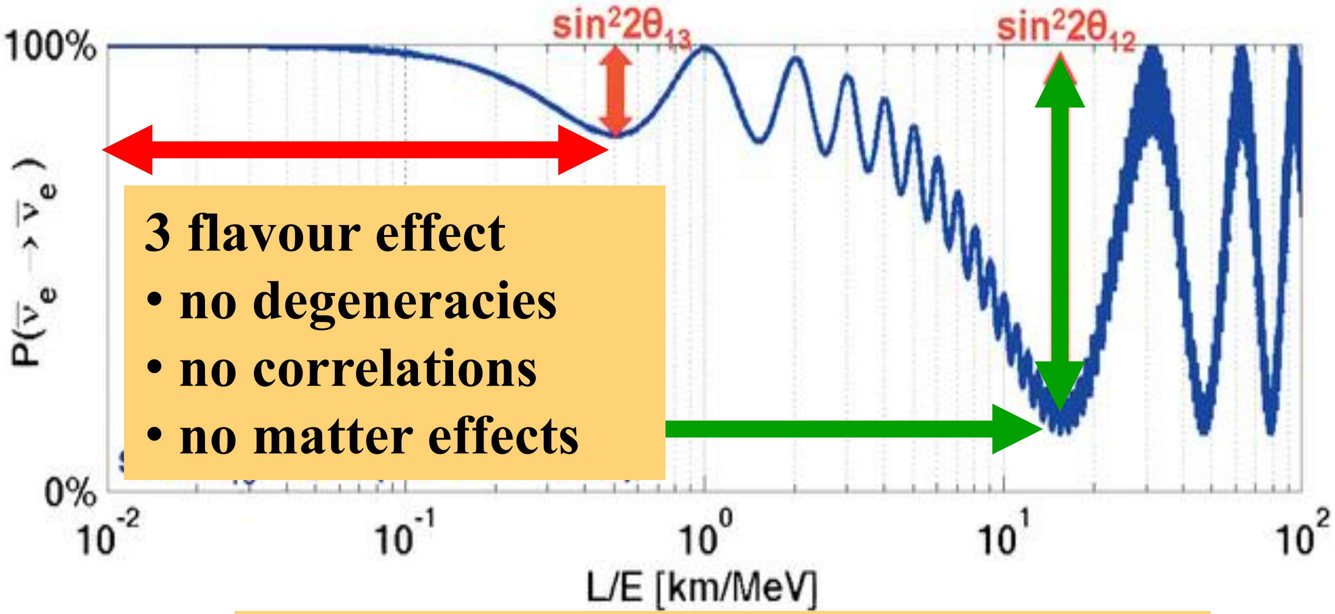
Absolute mass limits from Mainz and Troitsk: $m_1 < 2.2$ eV
Limits from cosmology: 0.17-0.2 eV
Future:
KATRIN ➔ just started operation ➔ 0.2eV
Project8, …



Precision with Reactor Neutrino Experiments

identical detectors ➔ many errors cancel

$$P_{ee} \approx 1 - \sin^2 2\theta_{13} \sin^2 \frac{\Delta m^2_{31} L}{4E_\nu} - \left(\frac{\Delta m^2_{21} L}{4E_\nu}\right)^2 \cos^4 \theta_{13} \sin^2 2\theta_{12}$$



3 flavour effect

- **no degeneracies**
- **no correlations**
- **no matter effects**

E=4MeV ➔ 1km 180km

clean & precise θ_{13} measurments ←→ beams

➔Double Chooz
➔ Daya Bay
➔ Reno

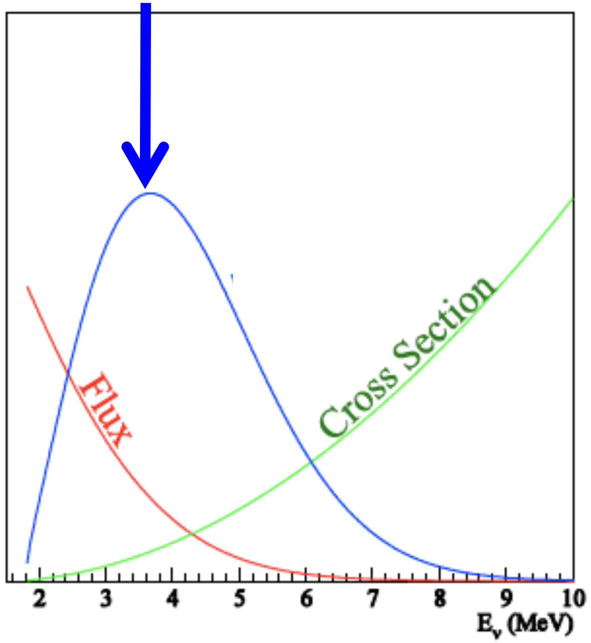
Anti-Neutrino Detection

Oscillations:

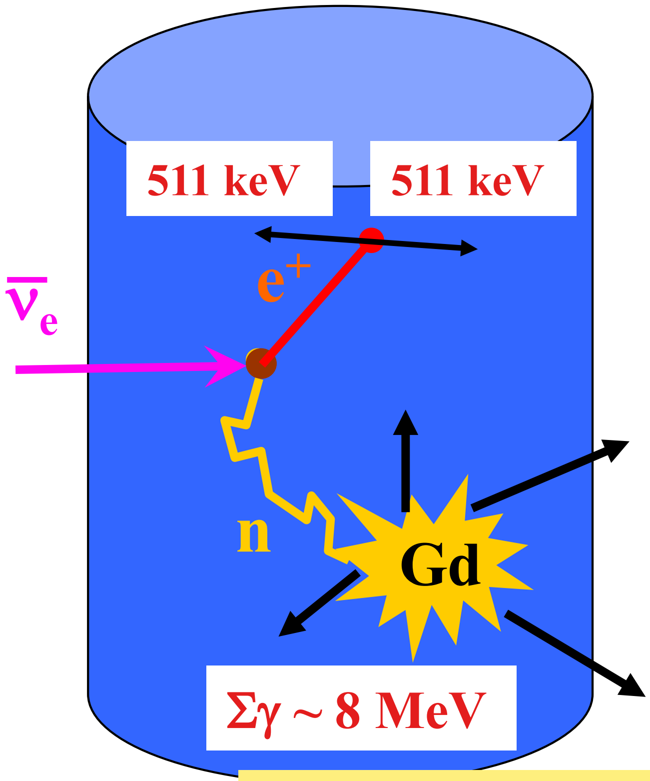
- affect rate & shape

Earlier reactor experiments:

- calculated spectrum
- rate normalized by $P_{thermal}$
- event rate = flux * x-section



- uncertainties in x-sections?



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

prompt e^+ signal

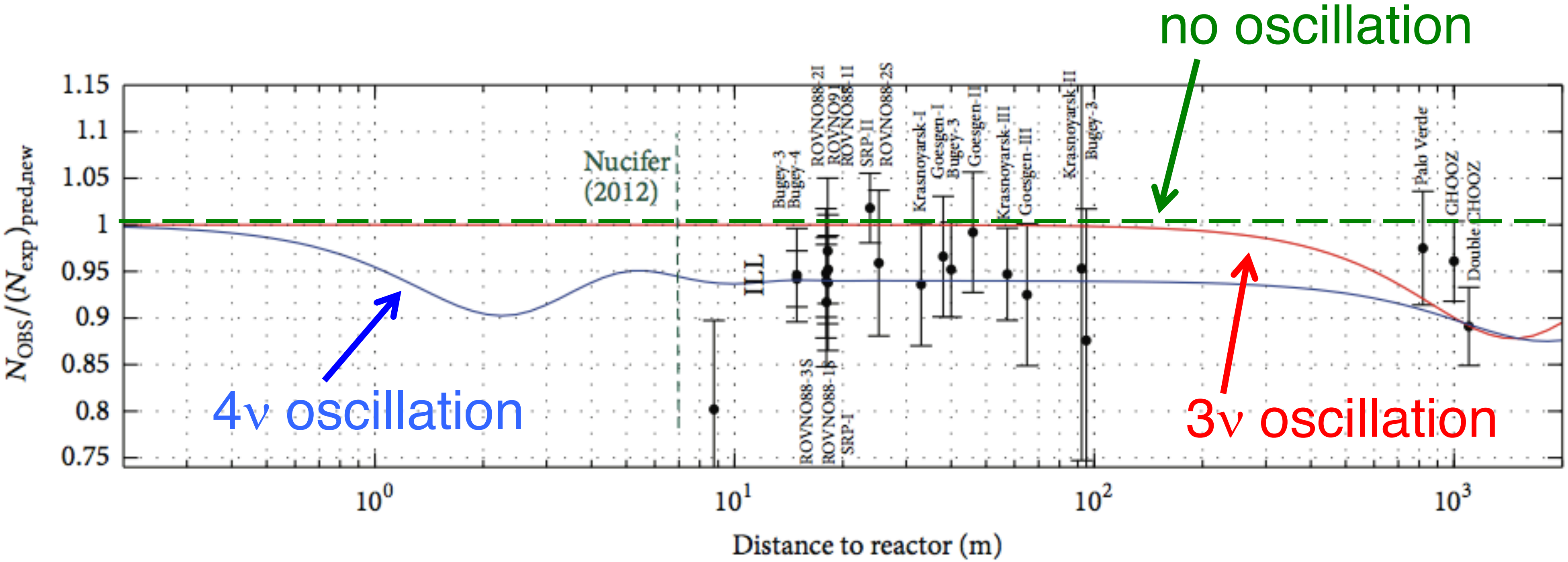
delayed n capture
➔Gd doping
➔delayed γ (30 μs)

- position & time correlation
- delayed energy information
  ➔ background reduction!

Gd loaded liquid scintillator
  ➔ stability, transparency, WLS, …

DC: 2,1,0 reactors on ➔ bg

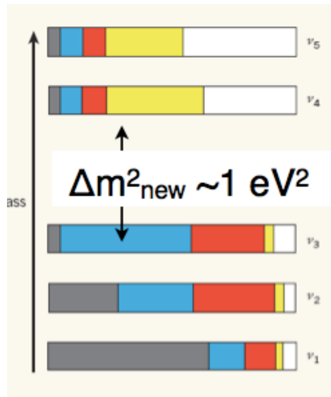
Surprise 1: The Reactor Anomaly



➔ an extra (sterile) neutrino with a small mixing angle and a mass O(eV) or heavier could have oscillated @ 10-100m

averaged out: reduction by ½ * $\sin^2(\theta_s) \simeq 0.06$

⇔ active ν-unitarity tested @ few % ➔ consistent ➔



➔ check with a new experiment at shorter baseline

Surprise 2: A Bump in the Spectrum

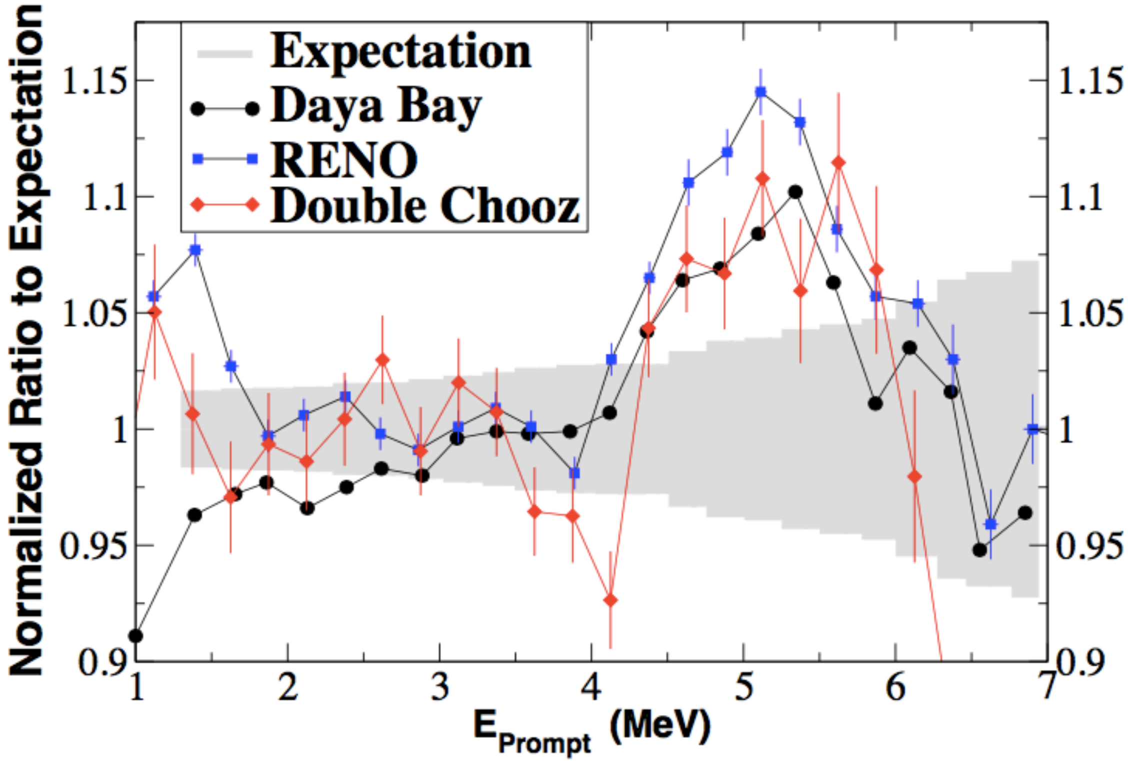
Double Chooz, RENO and Daya Bay:

→ all see unexpected bump in near and far spectrum

→ θ_{13} measurement robust

→ expectations are Huber (235U,239,241Pu) and Mueller (238U)

→ RENO has largest bump



→ Double-Chooz used Huber and Haag (238U) for expected flux

High energy ν's ←→ short lived isotopes …little known

Nuclear theory:

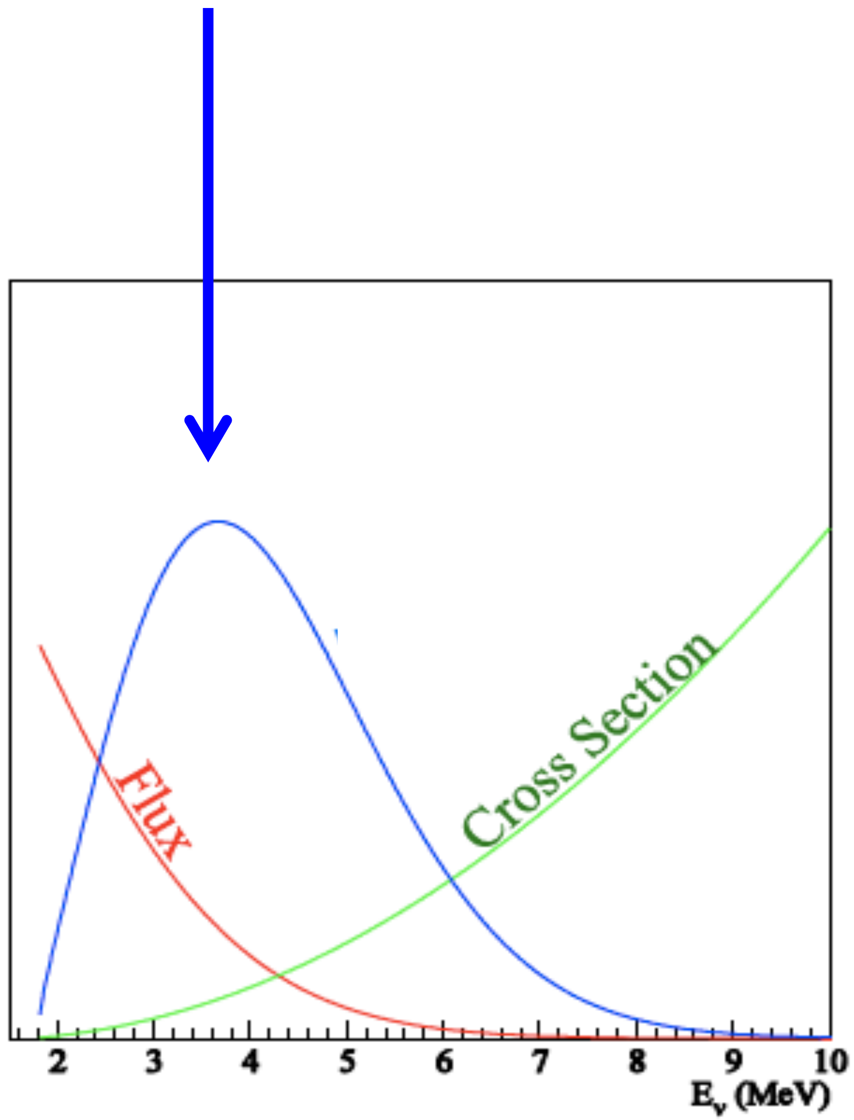
theory errors …maybe explainable…

better ➔ experimental test

Anti-Neutrino Event Rates

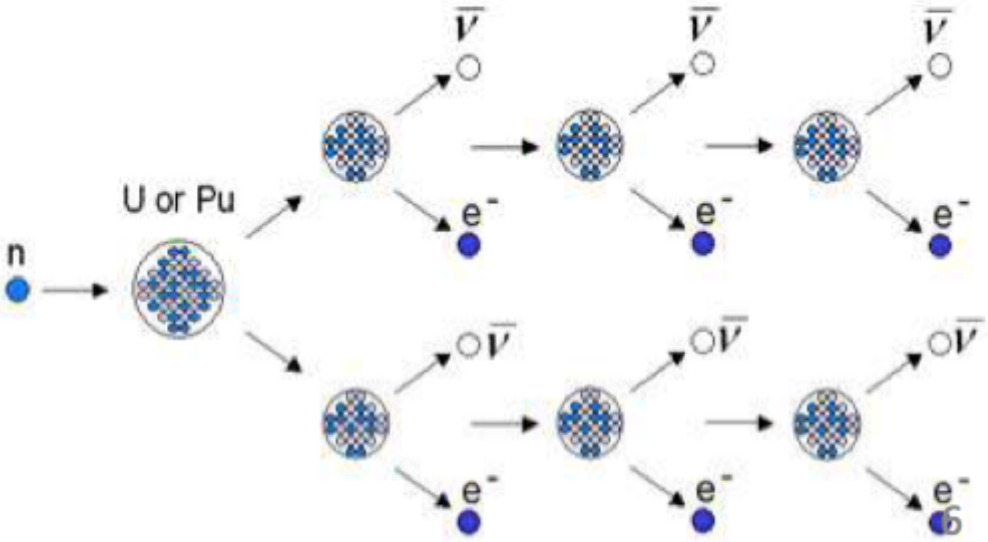
event rates = flux * x-section

- cross-section is safe ~ E^2
- event rate emphasizes medium energies
- uncertainties in ν-flux?
  → HE tail has reduced weight
- BUT: more than 800 nuclides from the fission of ^{235}U and others: ^{238}U, ^{239}Pu, ^{241}Pu, …
  → many instable fission products
  → reactor is during steady operation in a flow equilibrium



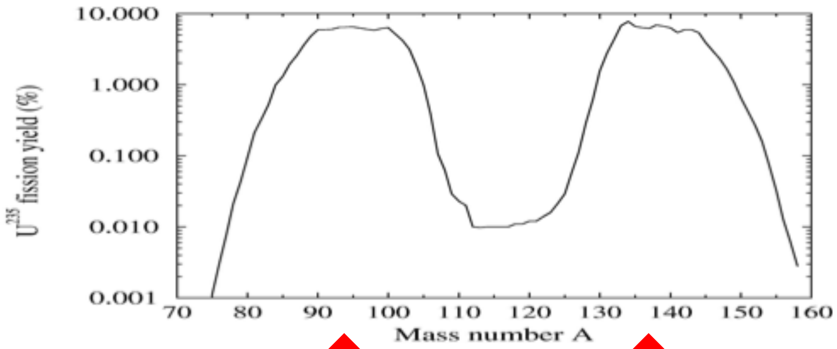
Nuclear Reactors as Antineutrino Source

- **Reactors like Chooz A+B ➔ 8.5 GW_{th}**
- **Few percent of the released energy**
  ➔ escapes with anti-neutrinos
  ➔ $2*10^{21}\bar{\nu}$/s ←→ O(1 kW/m²) @fence



example: fission of U^{235}

$${}^{235}_{92}U + n \to X_1 + X_2 + 2n$$



most likely A

➔ <u>on average:</u>

- 6 neutrons β-decay to 6 protons to reach stable matter
- 1.5 ν_e emitted with E > 1.8 MeV

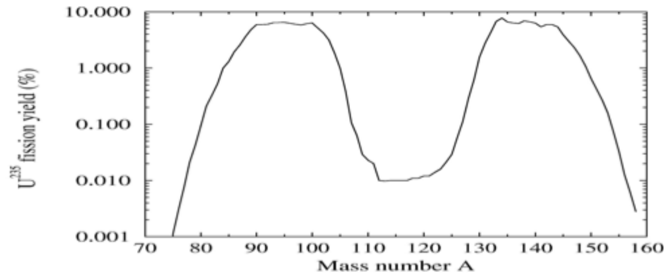
- **measured e⁻ spectrum of U^{235}, Pu^{239}, Pu^{241}**

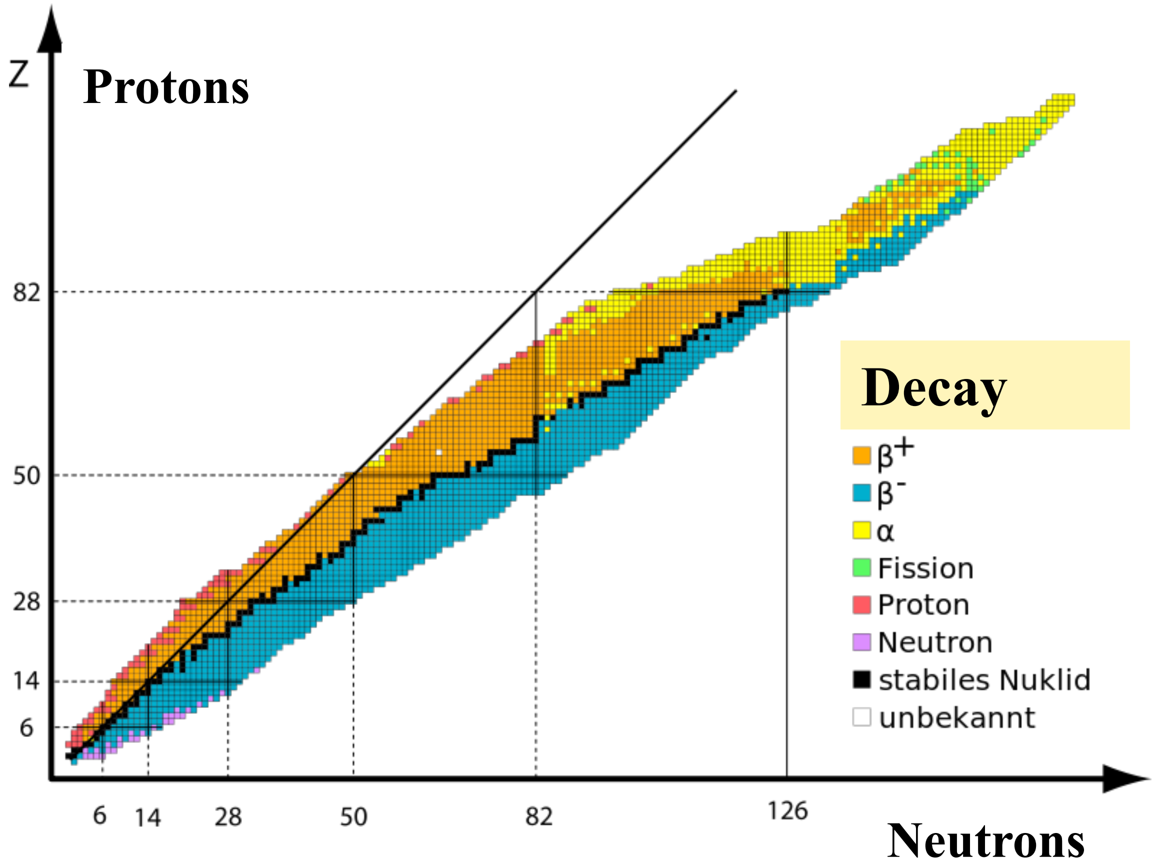
➔ calculate $\bar{\nu}_e$ spectrum ➔ certain precision

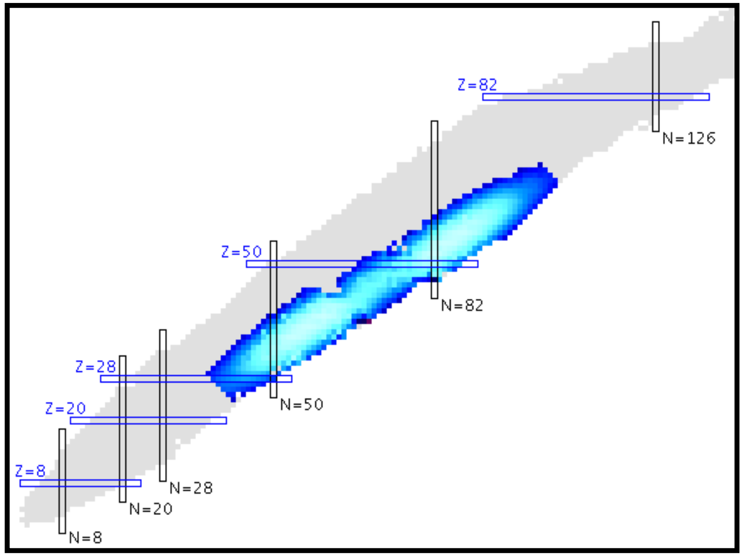
➔ two "identical" detectors…

Calculating Reactor Neutrino Spectra

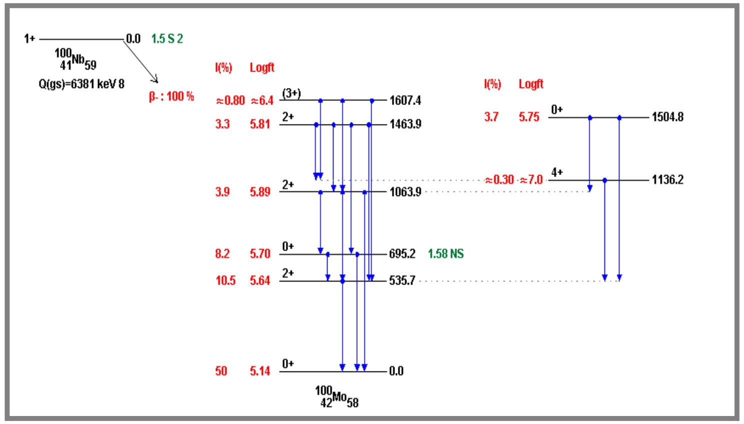
$$^{235}_{92}U + n \rightarrow X_1 + X_2 + 2n$$





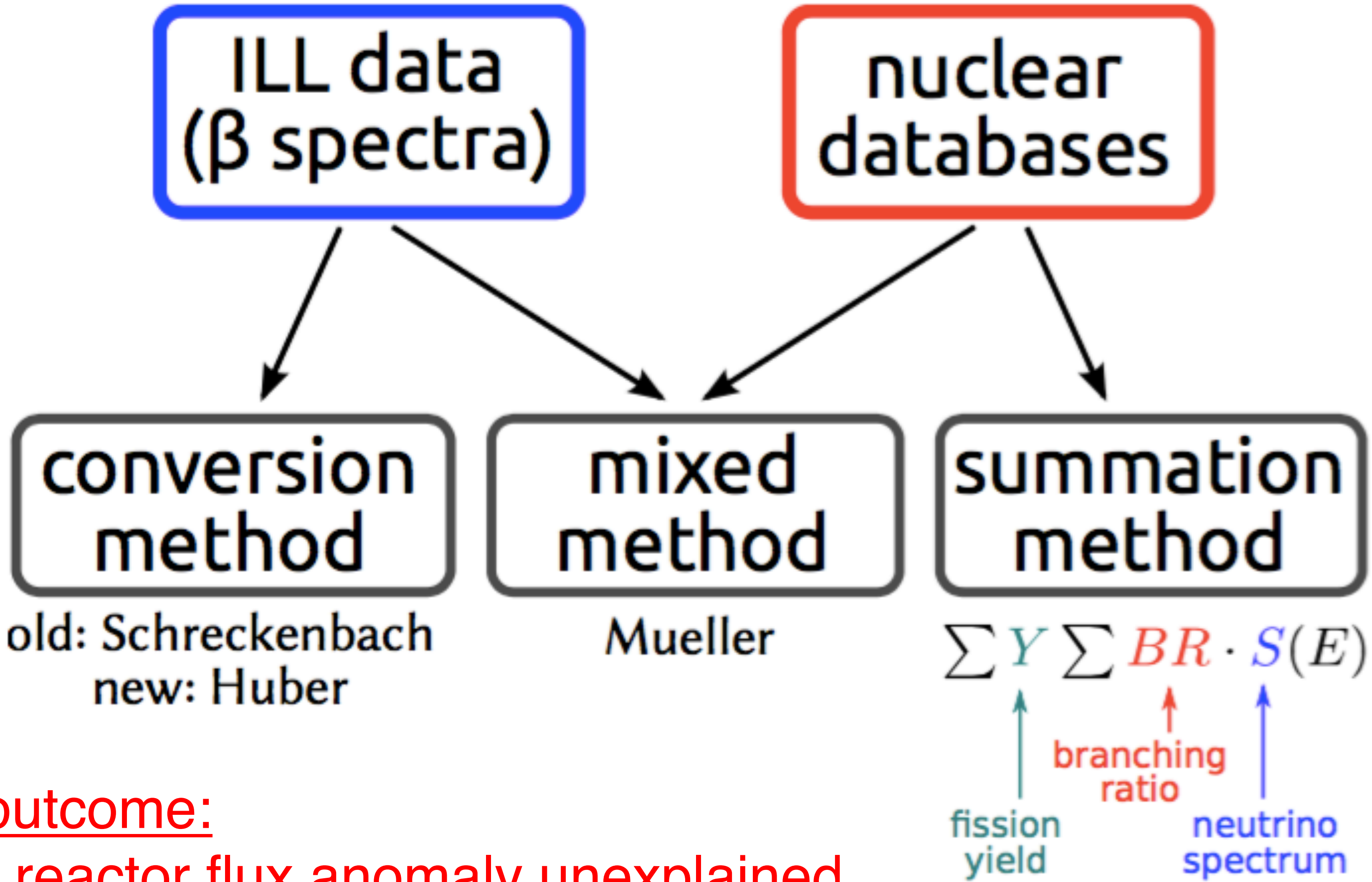


involves poorly known β-emitters



short lived ←→ high energy
→ spectral uncertainties?

Reactor Spectrum Predictions



<u>outcome:</u>

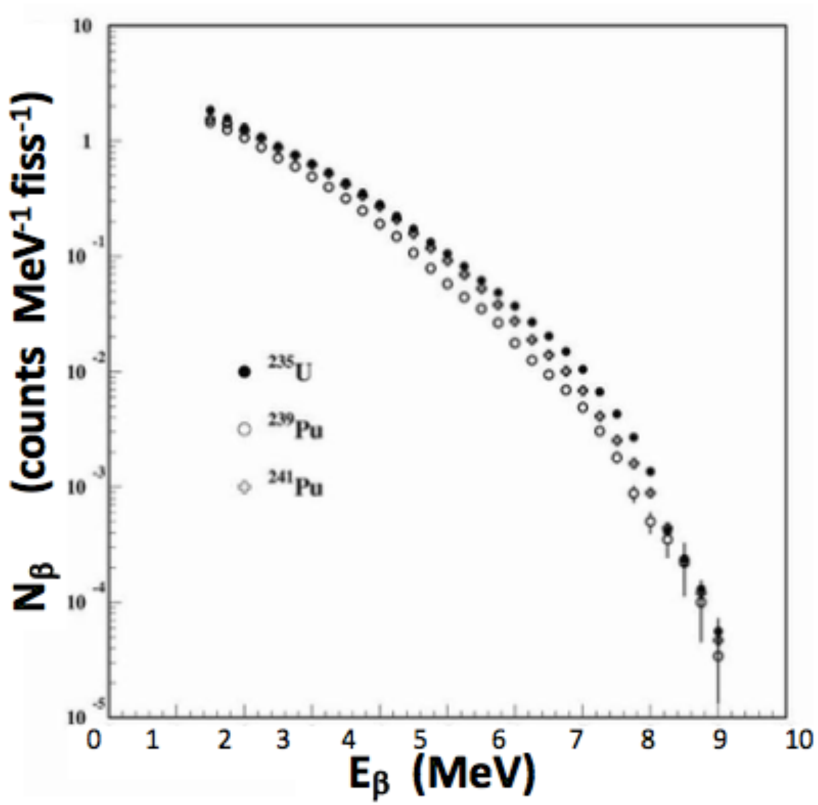
- reactor flux anomaly unexplained
- most impressive proof of existence of dark sectors
  $P = 4 GW_{th}$ @15m from core ➔ 150kW/m^2 in anti-neutrinos

The ILL β-Spectra

Expected ν-fluxes originally determined from measurements of electrons (β-spectra) at ILL
→ inversion: ν-spectra from β-decays

- ILL fission β-spectra for ^{235}U, ^{239}Pu, ^{241}Pu
- converted to antineutrino β-spectra by fitting to 30 end-point energies
- originally, used ENDF nuclear database

→ beware of uncertainties…



K. Schreckenbach et al. PLB118, 162 (1985)

FIT

$$S_\beta(E) = \sum_{i=1,30} a_i \, S^i(E, E_o^i)$$

Z→ Z_{eff} and δ are parametrizations!

$$S^i(E, E_0^i) = E_\beta p_\beta (E_0^i - E_\beta)^2 F(E, Z)(1 + \delta_{corrections})$$

Conversion of ILL β-Spectra requires Input

$$S^i(E,E_0^i) = E_\beta p_\beta (E_0^i - E_\beta)^2 F(E, Z)(1+ \delta_{corrections})$$

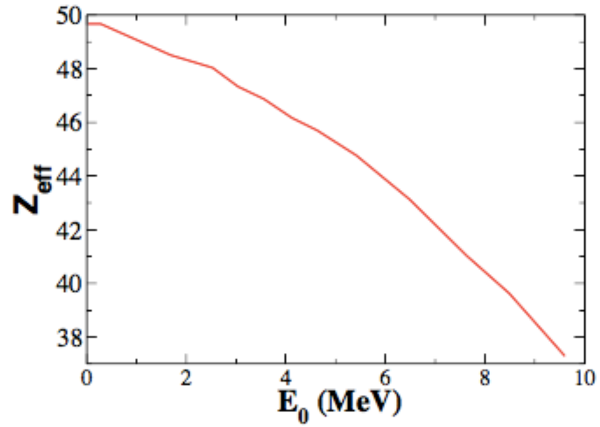
1) Z of the fission fragments

→ Z_{eff} which determines the Fermi function →

$$Z_{eff} \sim a + b\, E_0 + c\, E_0^2$$

On average, higher end-point energy correlates with lower Z

←→ different nuclear binding energies



2) sub-dominant corrections $\delta_{corrections}$

$$\delta_{correction}(E_e,Z,A) = \delta_{FS} + \delta_{WM} + \delta_R + \delta_{rad}$$

δ_{FS} = Finite size correction to Fermi functi

δ_{WM} = Weak magnetism

δ_R = Recoil correction

δ_{rad} = Radiative correction

3) Contributing β-branches: 30 → ?

Finite Size and Weak Magnetism Corrections

$$S(E_e,Z,A)=\frac{G_F^2}{2\pi^3}p_eE_e(E_0-E_e)^2F(E_e,Z,A)(1+\delta_{corr}(E_e,Z,A))$$

δ_{FS} = Finite size correction to Fermi function

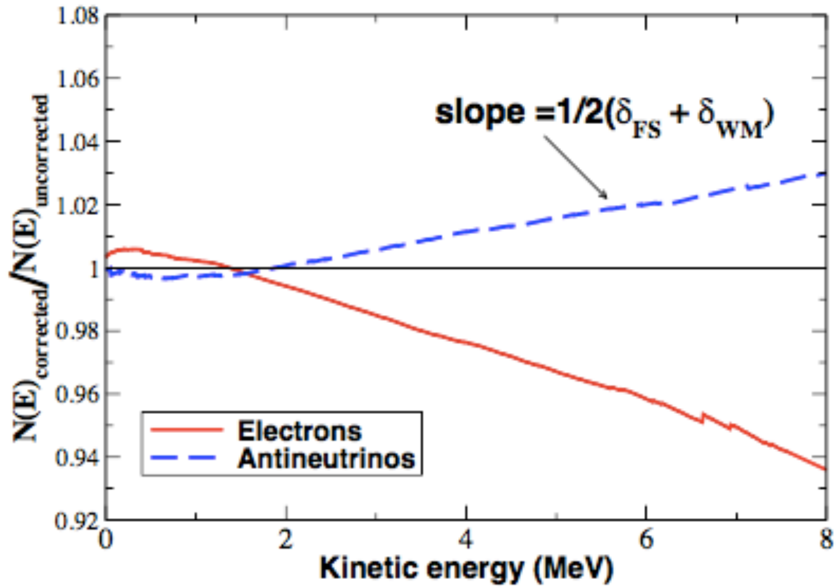
δ_{WM} = Weak magnetism

Original approximation by parametrization: $\delta_{FS}+\delta_{WM}=0.0065(E_\nu-4MeV))$

In the updated spectra, both corrections were applied on a state-by-state basis
An approximation was used for each:

$$\delta_{FS}=-\frac{10Z\alpha R}{9\hbar c}E_\beta;\ R=1.2A^{1/3}$$

$$\delta_{WM}=+\frac{4(\mu_V-1/2)}{3M_n}2E_\beta$$



➔ leads to a systematic increase of in the antineutrino flux above 2 MeV
➔ might account for half of the anomaly…

Forbidden Transitions

Forbidden transitions introduce a shape factor C(E):

$$S(E_e,Z,A)=\frac{G_F^2}{2\pi^3}p_eE_e(E_0-E_e)^2\underline{C(E)}F(E_e,Z,A)(1+\delta_{corr}(E_e,Z,A))$$

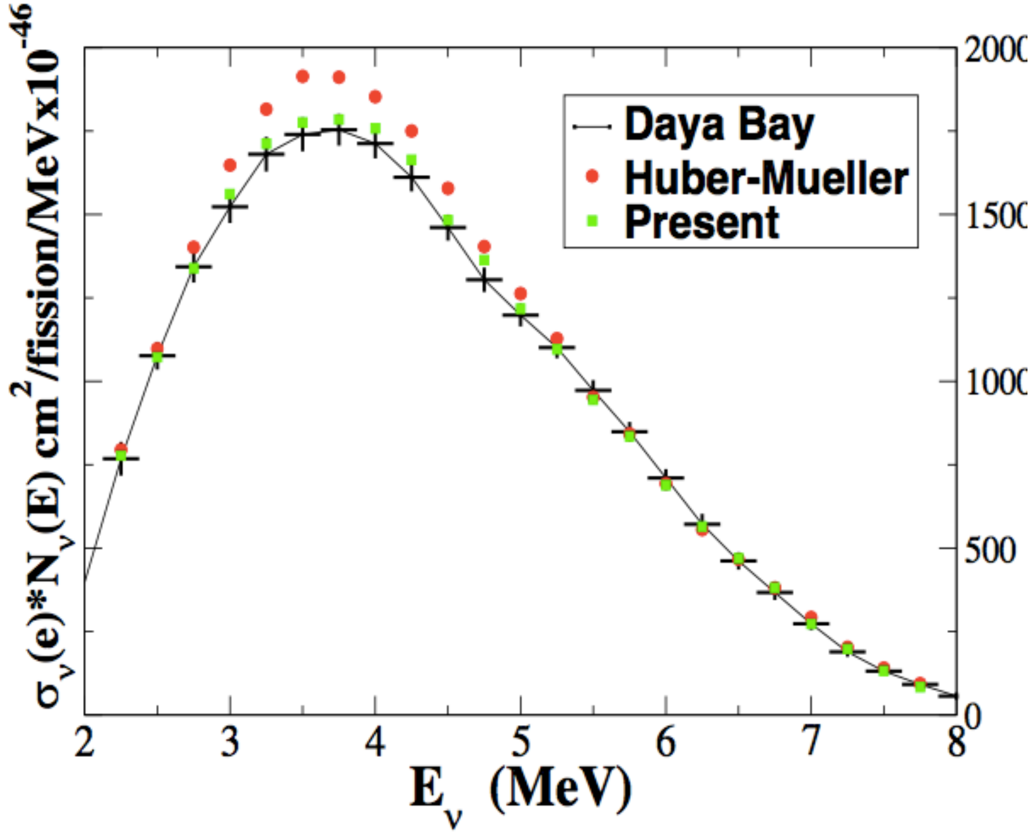
Corrections for forbidden transitions: uncertainties or unknown

Classification	ΔJ^π	Oper.	Shape Factor $C(E_e)$	Fractional Weak Magnetism Correction $\delta_{WM}(E_e)$
Gamow-Teller:				
Allowed	1^+	$\Sigma\equiv\sigma\tau$	1	$\frac{2}{3}\left[\frac{\mu_v-1/2}{M_N g_A}\right](E_e\beta^2-E_\nu)$
1^{st} F.	0^-	$[\Sigma,r]^{0-}$	$p_e^2+E_\nu^2+2\beta^2E_\nu E_e$	0
1^{st} F. ρ_A	0^-	$[\Sigma,r]^{0-}$	λE_0^2	0
1^{st} F.	1^-	$[\Sigma,r]^{1-}$	$p_e^2+E_\nu^2-\frac{4}{3}\beta^2E_\nu E_e$	$\left[\frac{\mu_v-1/2}{M_N g_A}\right]\left[\frac{(p_e^2+E_\nu^2)(\beta^2E_e-E_\nu)+2\beta^2E_eE_\nu(E_\nu-E_e)/3}{(p_e^2+E_\nu^2-4\beta^2E_\nu E_e/3)}\right]$
Uniq. 1^{st} F.	2^-	$[\Sigma,r]^{2-}$	$p_e^2+E_\nu^2$	$\frac{3}{5}\left[\frac{\mu_v-1/2}{M_N g_A}\right]\left[\frac{(p_e^2+E_\nu^2)(\beta^2E_e-E_\nu)+2\beta^2E_eE_\nu(E_\nu-E_e)/3}{(p_e^2+E_\nu^2)}\right]$
Fermi:				
Allowed	0^+	τ	1	0
1^{st} F.	1^-	$r\tau$	$p_e^2+E_\nu^2+\frac{2}{3}\beta^2E_\nu E_e$	0
1^{st} F. $\vec{J}_V$	1^-	$r\tau$	E_0^2	-

Forbidden transitions are part of the uncertainty in the calculated expected spectrum
➔ Might account for up to 30% increase (while being consistent with ILL β-spectra)

Improvement with optimized Z_{eff}

- Simultaneous fit to Daya Bay and β-spectra, with improved description of Z_{eff} → significantly reduced anomaly
  Hayes, *et al.*



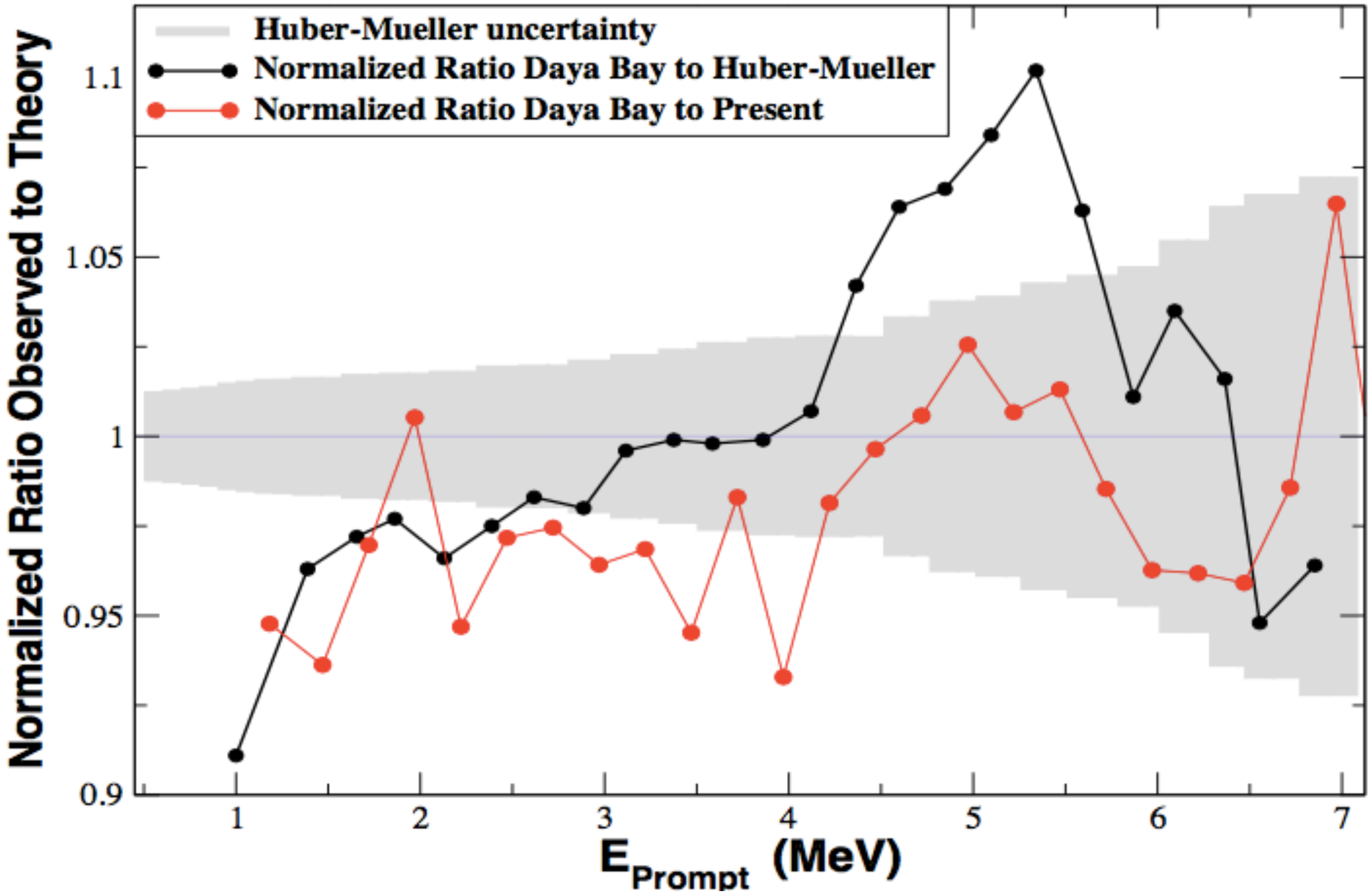
- New fit is within the Daya Bay 1σ error bars

- DC+RENO+DB combined?

The Bump and improved Z_{eff}

what happens to the bump with the optimized Z_{eff} ?

➔ better!



➔ The bump depends on how the 'expected' spectrum was derived

➔ Shape differences partly reflect assumption in the conversion of β-spectra

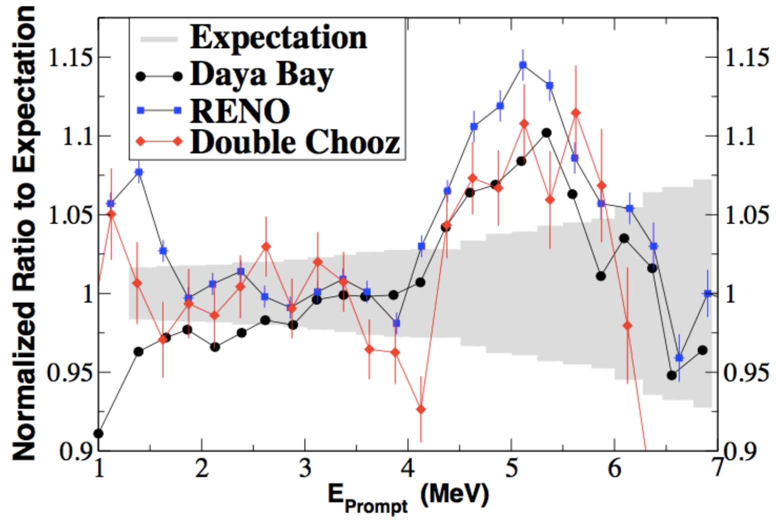
➔ But: Beware of collecting effects that go in the right direction…

Other Directions to explain th the Bump

- **Forbidden transitions** – unlikely; effect ~ < 1%

- **Harder neutron spectrum**
  conceivable, but so far no indication from theory and any data

- **Dominant from ^{238}U**
  conceivable; would fit to the fact that RENO has biggest effect.
  ➔ clarification required

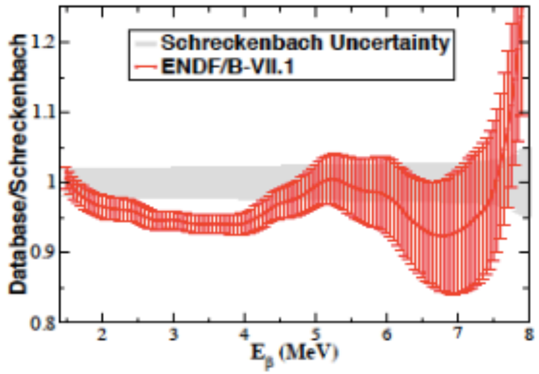


- **Errors in the ILL β-spectrum measurements**
  possible, initially considered likely, now unlikely

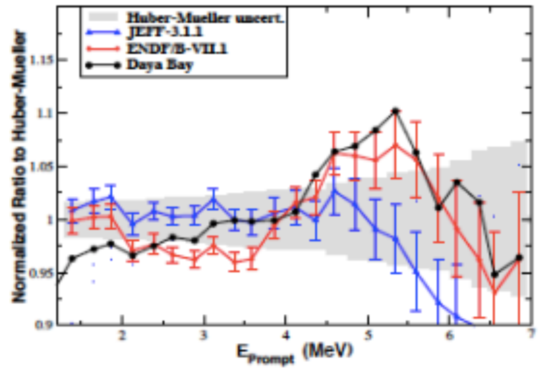
- …?

Why not the ILL Spectra?

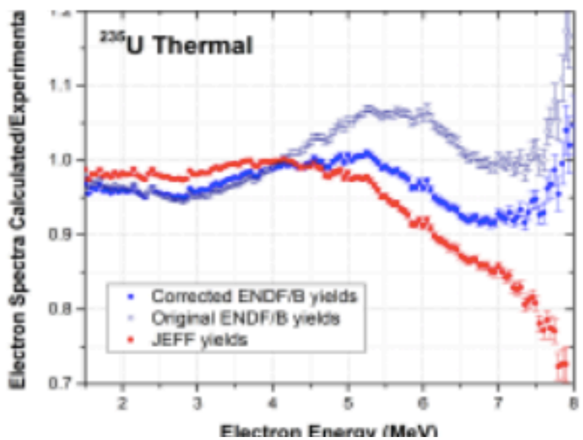
• ENDF database predicts an analogous bump in the beta-spectrum relative to Schreckenbach
Dwyer, Langford, PRL 114, 012502 (2014)



• The European database JEFF does not predict the bump
Hayes, *et al.* PRD, 92, 033015 (2015)



• The bump in ENDF is largeley a mistake in the database for fission yields at mass A=86. Plus other shortcomings of ENDF
Corrected: ENDF no longer predicts a bump
Sonzogni, et al. PRL, March 2016



➔ More experimental Tests needed

Do sterile neutrinos exist?
Understand / explain reactor anomaly
Understand / expplain the bump
➔ use well understood reactor spectra
- improved analysis of experiments
- new experiments…

Sterile Hints & Plans for Tests

Project	neutrino	source	E (MeV)	L (m)	status
SAGE [166]	ν_e	^{51}Cr	0.75	$\lesssim 1$	in preparation
CeSOX [167, 168]	$\bar{\nu}_e$	^{144}Ce	1.8 – 3	5 – 12	in preparation
CrSOX [167]	ν_e	^{51}Cr	0.75	5 – 12	proposal
Daya Bay [169, 170]	$\bar{\nu}_e$	^{144}Ce	1.8 – 3	1.5 – 8	proposal
JUNO [171]	$\bar{\nu}_e$	^{144}Ce	1.8 – 3	$\lesssim 32$	proposal
LENS [172]	$\nu_e, \bar{\nu}_e$	^{51}Cr, ^{6}He	0.75, $\lesssim 3.5$	$\lesssim 3$	abandoned
CeLAND [173]	$\bar{\nu}_e$	^{144}Ce	1.8 – 3	$\lesssim 6$	abandoned
LENA [174]	ν_e	^{51}Cr, ^{37}Ar	0.75, 0.81	$\lesssim 90$	abandoned

Source experiments

tensions with cosmology…
➔ N_{eff} = 3.x < ~ 4
BBN...

Nevertheless:
➔ lab tests important

Also important:
➔ keV sterile ν =WDM..

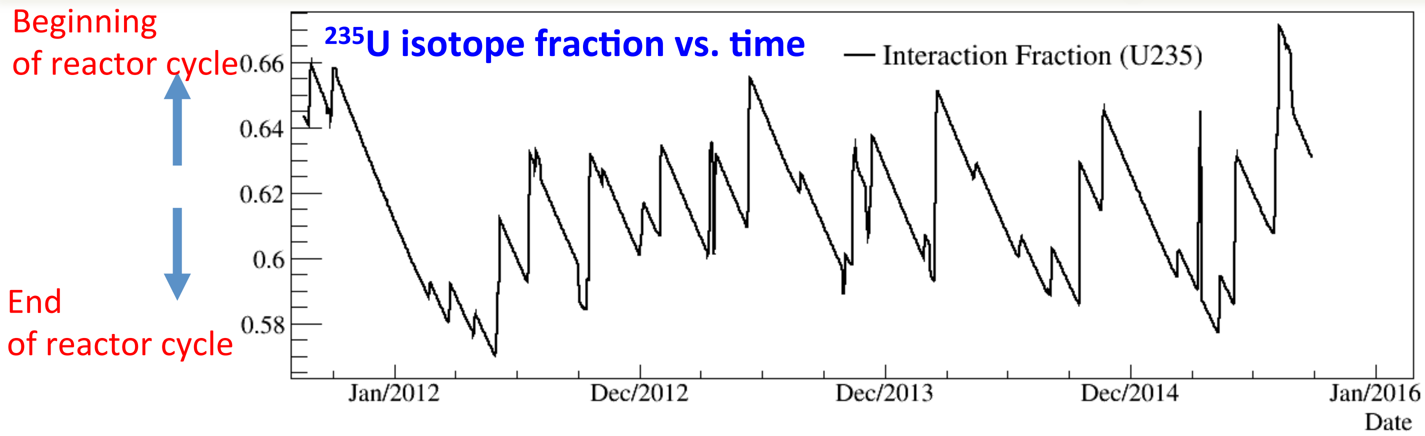
Project	P_{th} (MW)	M_{target} (tons)	L (m)	Depth (m.w.e.)	status
Nucifer (FRA) [175]	70	0.8	7	13	operating
Stereo (FRA) [176]	57	1.75	9 – 12	18	~~in preparation~~ ➔ **running**
DANSS (RUS) [177]	3000	0.9	10 – 12	50	~~in preparation~~ ➔ **running**
SoLid (BEL) [178]	45 – 80	3	6 – 8	10	in preparation
PROSPECT (USA) [179]	85	3, 10	7 – 12, 15 – 19	few	in preparation
NEOS (KOR) [180]	16400	1	25	10 – 23	~~in preparation~~ ➔ **result, withdrawn**
Neutrino-4 (RUS) [181]	100	1.5	6 – 11	10	proposal
Poseidon (RUS) [182]	100	3	5 – 8	15	proposal
Hanaro (KOR) [183]	30	0.5	6	few	proposal
CARR (CHN) [184]	60	~ 1	7, 11	few	proposal

Reactor experiments

Giunti 1512.04758

RENO

Correlation of 5 MeV excess with ^{235}U isotope fraction

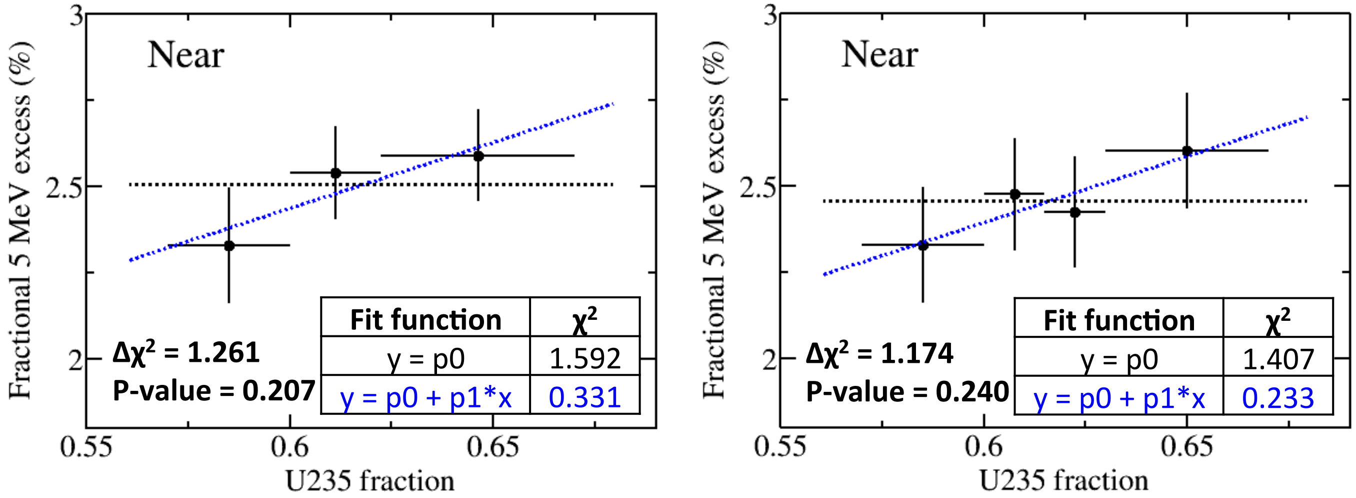


burnup in LEU reactors changes isotope fraction

➔ effect on spectrum?
➔ not yet significant

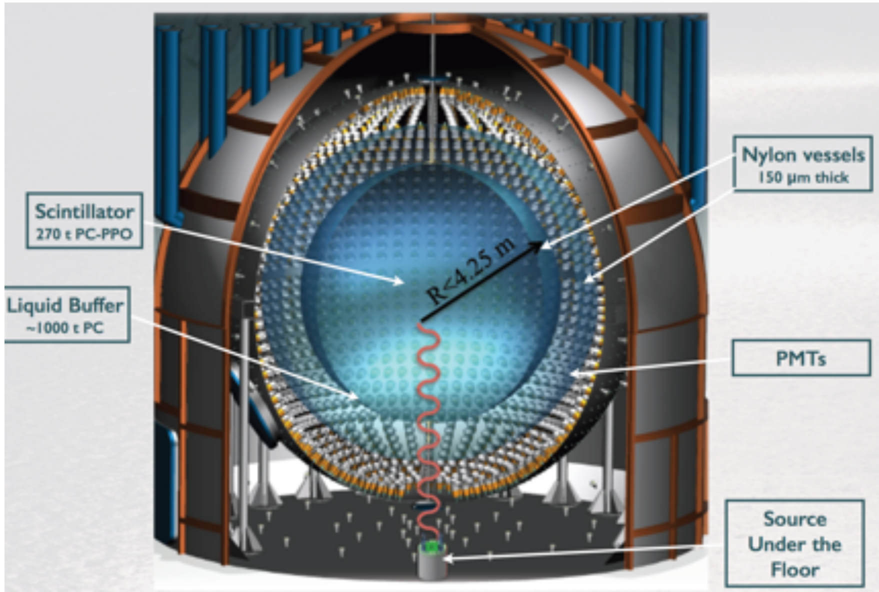
➔ use HEU+LEU

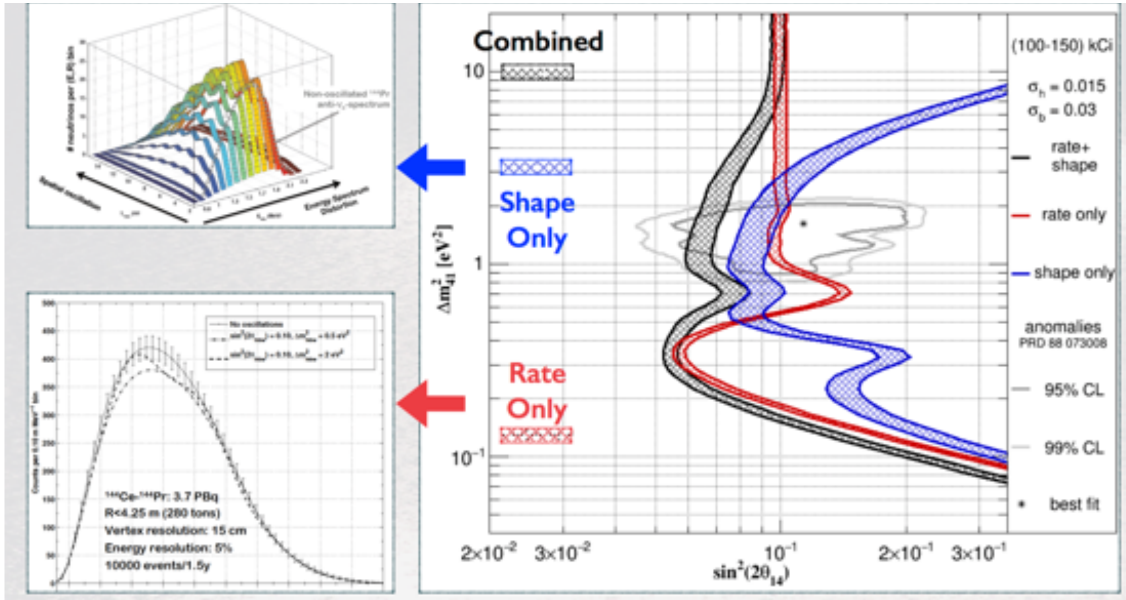
Correlation of 5 MeV excess with ^{235}U fraction



- what if cosmology (N_{eff}) conflicts with sterile ν's?
  - ➔ check assumptions/errors on both sides
  - ➔ or new/extra physics on one side

SOX: Radioactive Source @ BOREXINO





large detector combined with 100-150 kCi Ce-144 source

goal 1% normalization uncertainty → met & ready (TUM)

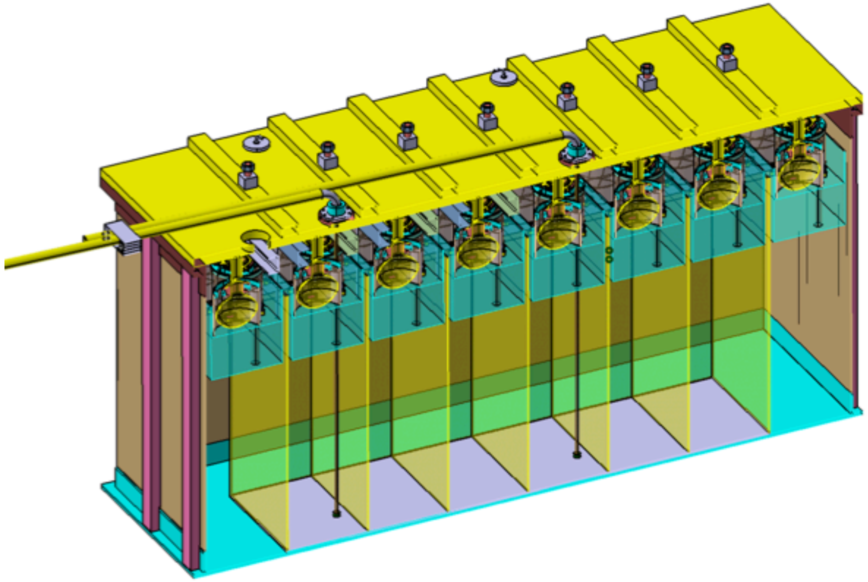
precise shape & rate measurement

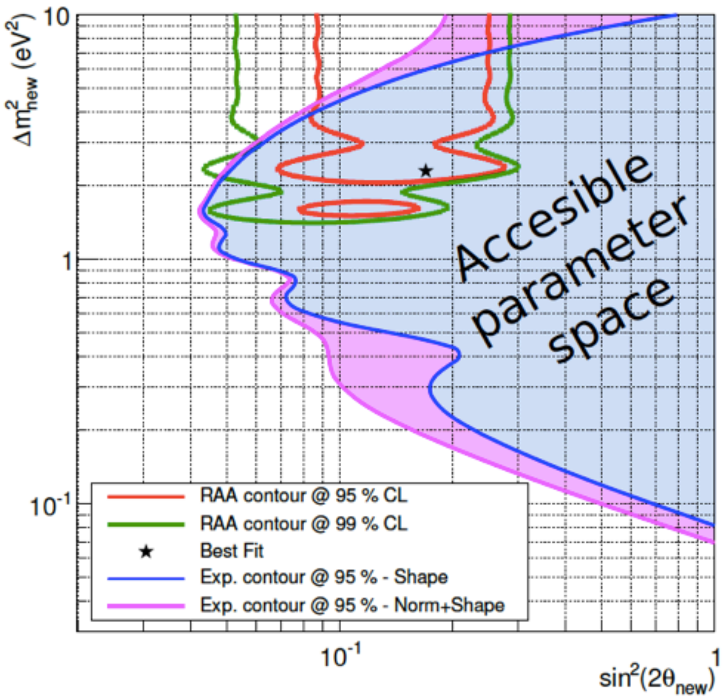
authorizations in Italy OK

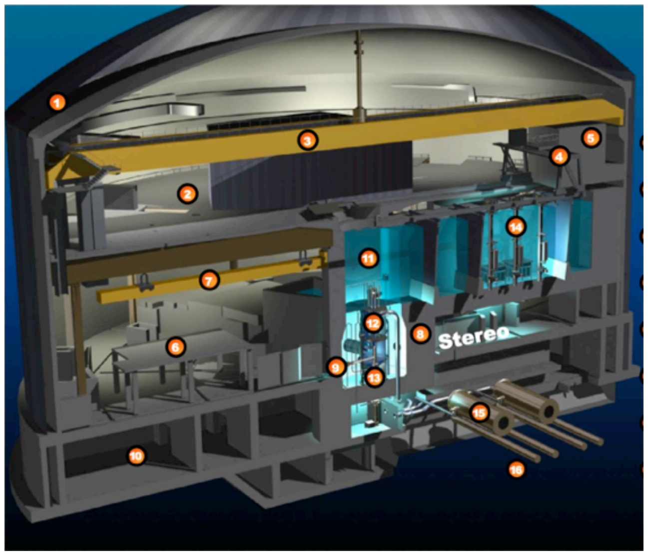
contract between CEA and Mayak settled

→ delivery scheduled for fall/end of next year → data taking

STEREO @ ILL Reactor (HEU)







57 MW, compact core < 1m
~8–11 m from core
15 mwe overburden

Segmented detector with Gd loaded LS

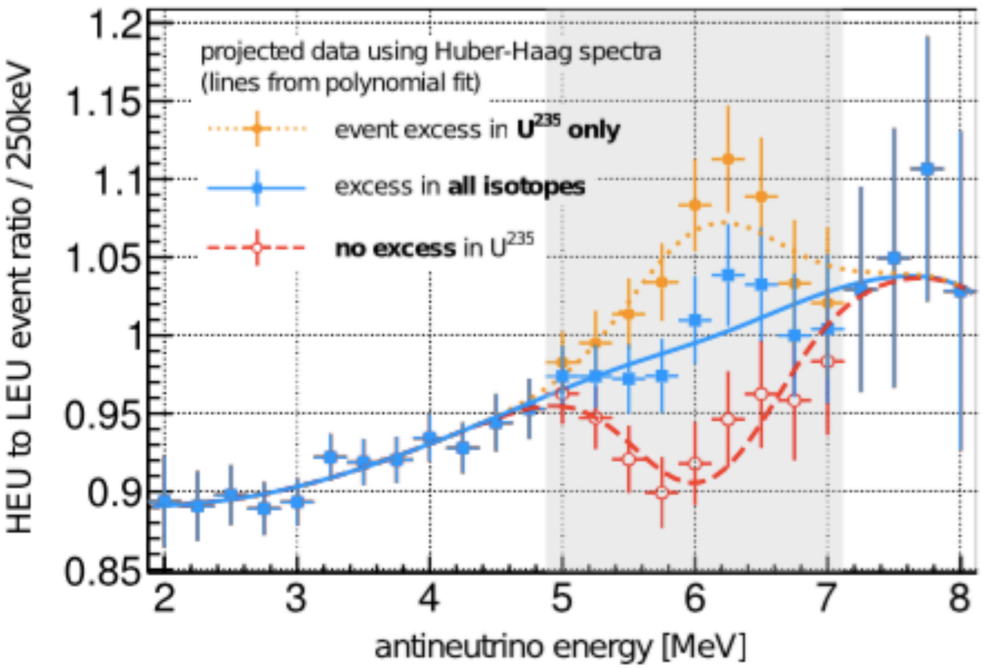
➔ **400 ν per day**
➔ **Spectral distortions in identical cells**

HEU: burn only 235U ➔ compare pwr stations

Comparing different Reactor Fuels

⇒ ratio of HEU to LEU spectrum for different hypotheses

Combine STEREO (HEU) and Double Chooz ND (LEU)

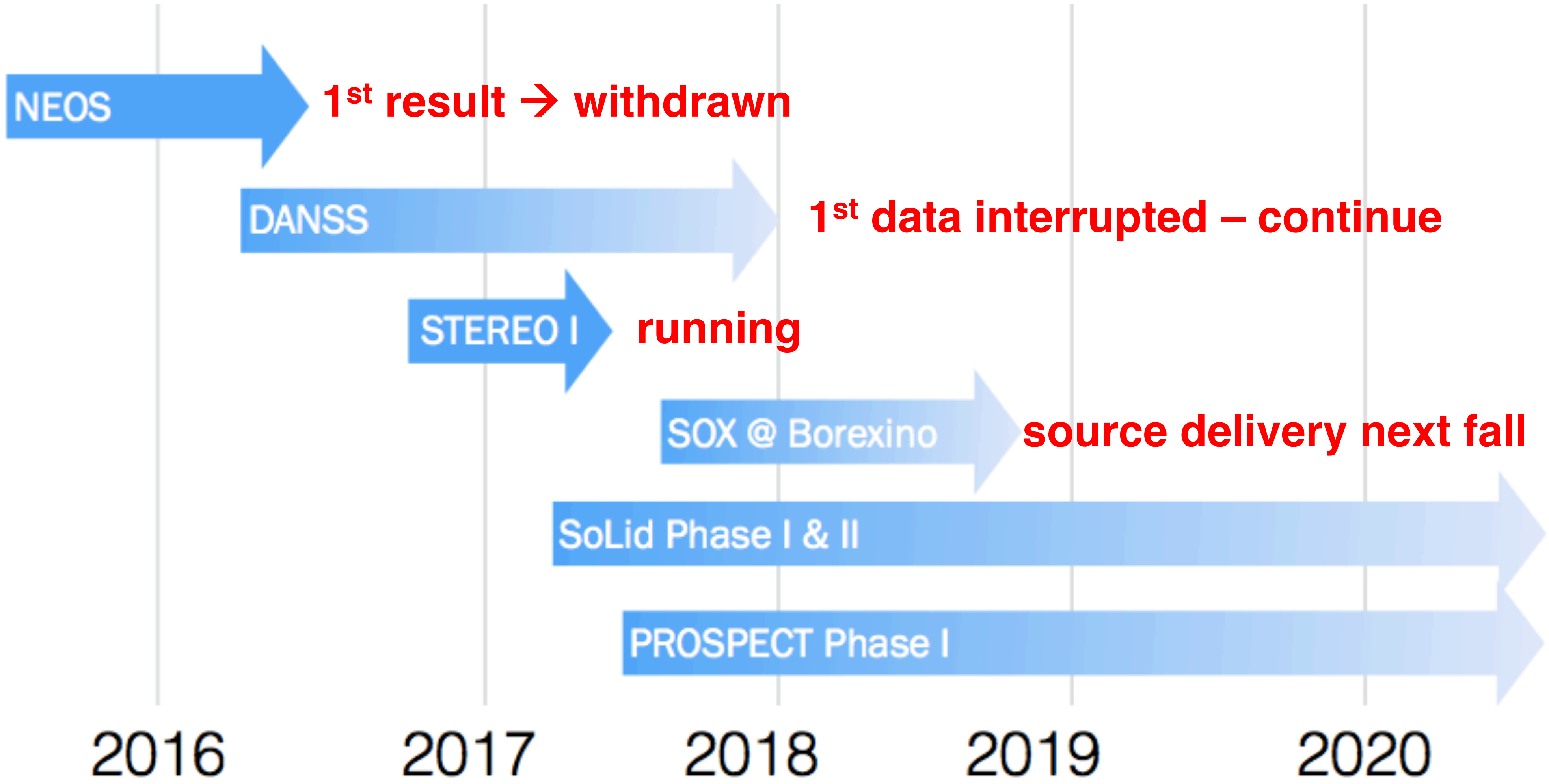


- 2 y runtime
- uncertainties: statistical + reference spectra
- significance of discrepancy [5, 7] MeV:
  - only ^{235}U: 4.2 σ
  - no excess in HEU: 5.5 σ
- significance including energy resolution:
  - only ^{235}U: 3.7 σ
  - no excess in HEU: 4.7 σ

Buck, Collin, Haser, ML

→ can realistically be done (also with other results)

Timeline for Source and Reactor Experiments

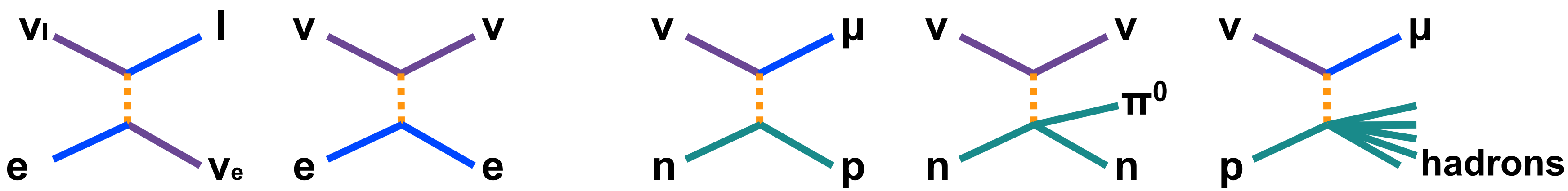


➔ **Very interesting results as of next year**

Coherent Neutrino Scattering

The Standard Model has six different interactions of neutrinos with matter:

- **5 have already been detected**



inverse muon (tau) decay

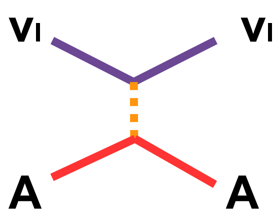
elastic electron scattering

(quasi) - elastic nucleon scattering

nuclear excitation and resonant production

Deep inelastic scattering and jet production

- **1 has so far not been detected:**



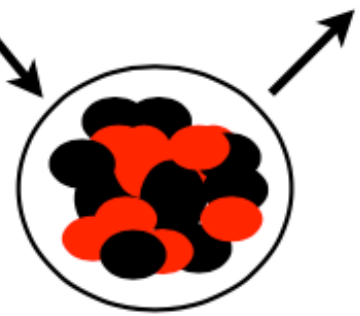
Coherent neutrino-nucleus scattering: CνS

➔ conceptually important
➔ useful method to test new physics

A. Drukier, Leo Stodolsky, Phys.Rev. D30 (1984) 2295 (1984), DOI: 10.1103/PhysRevD.30.2295

Coherent Neutrino Scattering

Z-exchange of a neutrino with nucleus
→ nucleus recoils as a whole
→ coherent up to E_ν~ 50 MeV

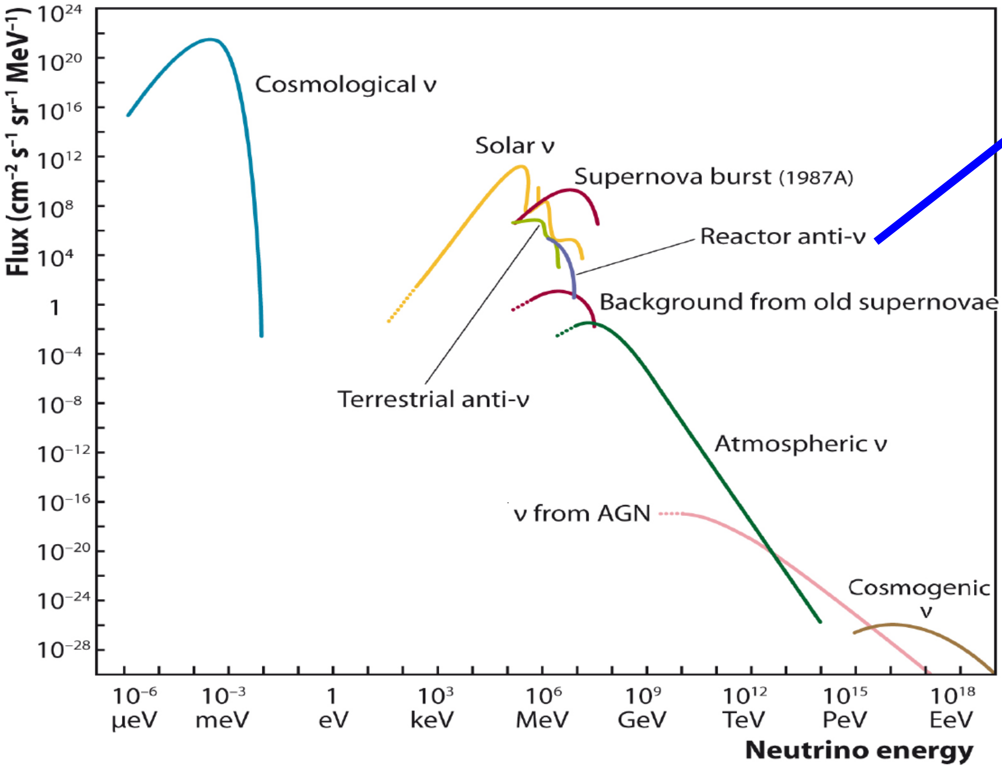


$$Q_w = N - (1 - 4\sin^2\theta_w)Z$$

$$\frac{d\sigma(E_\nu, T)}{dT} = \frac{G_f^2}{4\pi} Q_w^2 M \left(1 - \frac{MT}{2E_\nu^2}\right) F(Q^2)^2$$ **~ N²**

Important: Coherence length ~ 1/E
→ need neutrinos below O(50) MeV for typical nuclei
→ low energy E_ν ←→ lower cross sections ←→ flux!

The Neutrino Spectrum



10 GW at a distance of 150 km

reactor neutrinos:
ca. 4% of the thermal power P
3.9 GW → ca. 150 MW in ν's
dilution by distance R
flux $\Phi \sim P/R^2$
ca. 7kW/m^2 at 15m distance

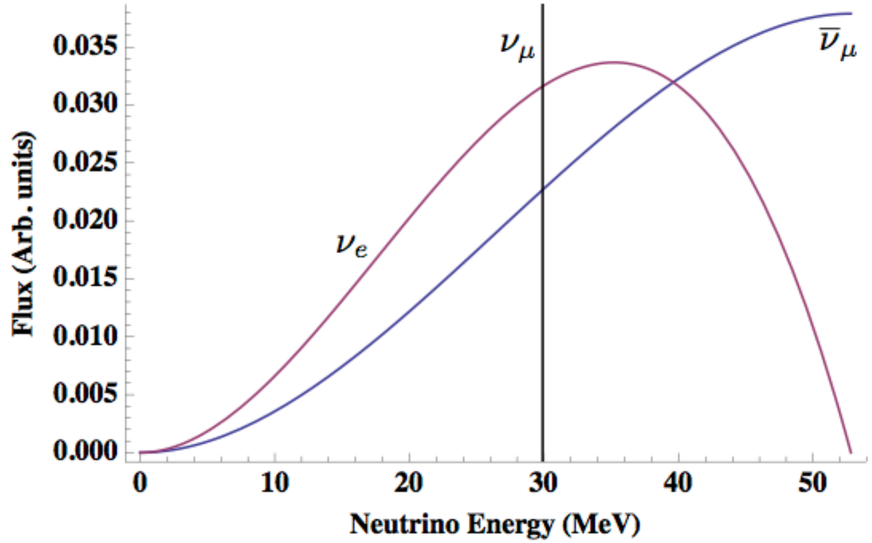
But: Interaction is
- **extremely weak**
- **grows with neutrino energy**

source	flux	
reactor neutrinos (3 GW, at 10m distance)	5 x 10^13	/cm^2/s
solar neutrinos (on Earth)	6 x 10^10	/cm^2/s
supernova (50 kpc Abstand, for O(10) seconds)	~ 10^9	/cm^2/s
geo-neutrinos (on the Earth's continental surface)	6 x 10^6	/cm^2/s

Two main Paths

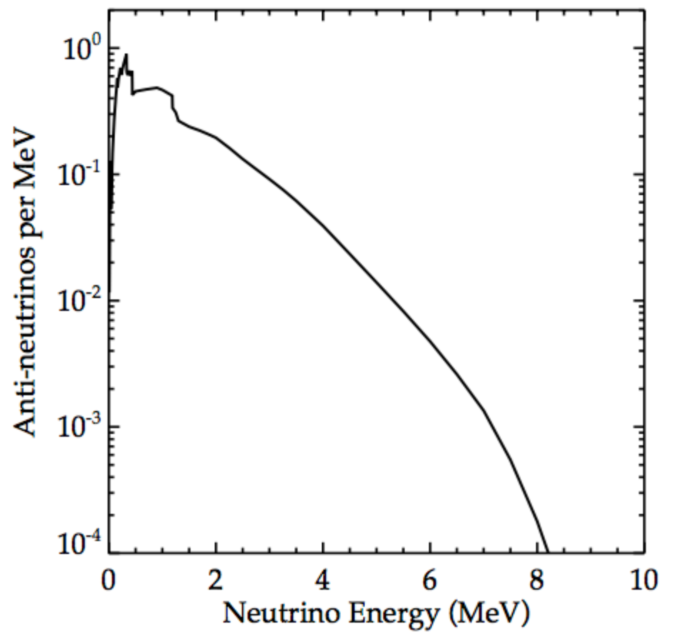
Accelerators:

π-decay-at-rest (DAR) ν source
Different flavors produced
relatively high recoil energies
➔ close to de-coherence
➔ COHERENT project



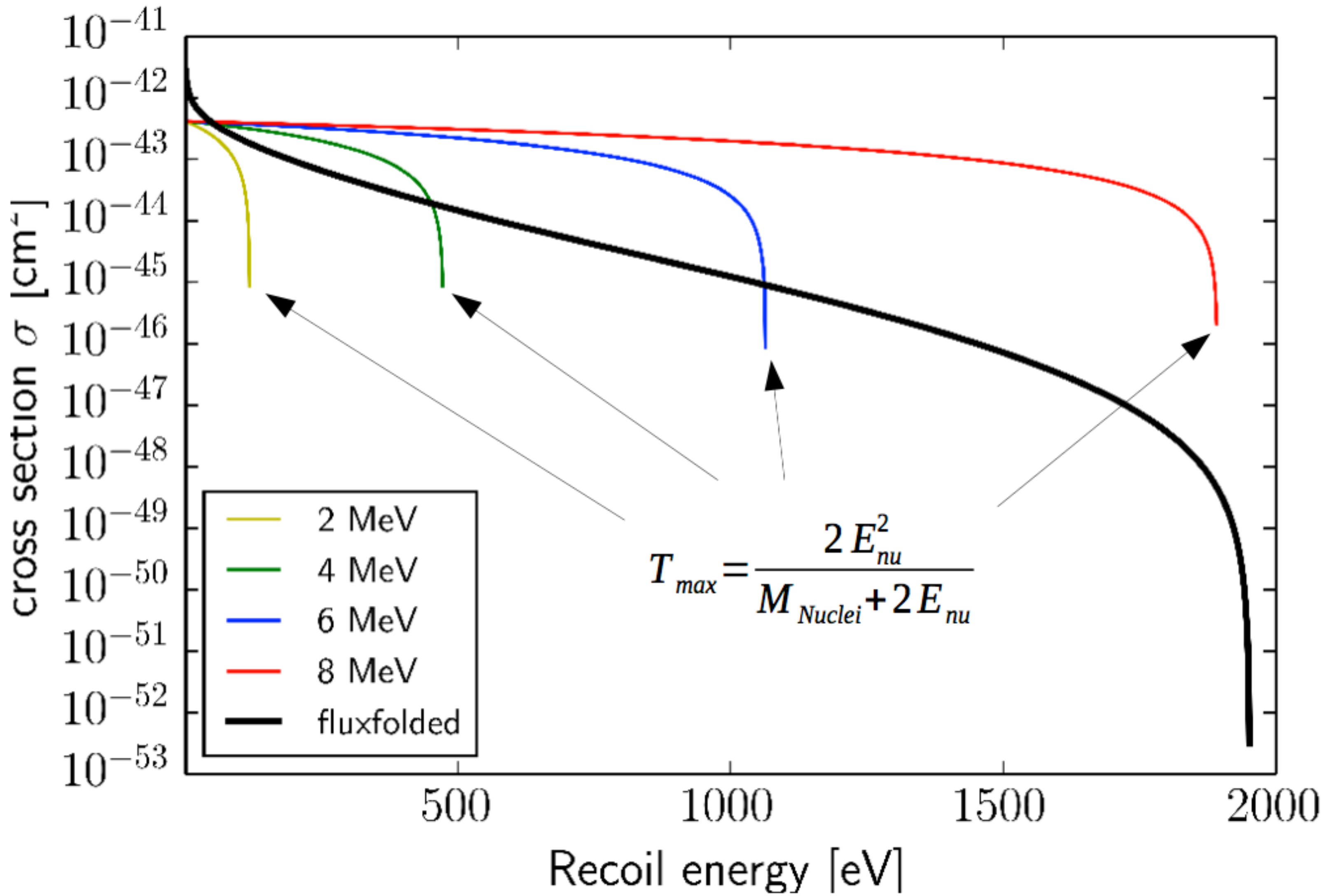
Reactors:

Lower ν energies than accelerators
Lower cross section
Different flavor content
implications for probes of new physics
➔ Will follow this route



Vogel et al. 1981, Kopeikin 2012

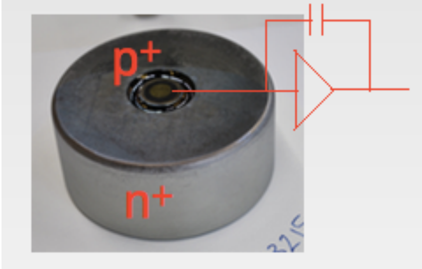
CνS Cross Section at different (reactor) E_ν



➔ **this shows the importance of low thresholds**

Event Rates for a conceivable Experiment

Detector: BEGE or SAGE type germanium diode O(1kg)
Distance D=15m; 3.9GW ←→ flux = 3.12*10^{13}/cm^2/s
For a 1kg detector: Background ~ 1/kg/keV/day
Suitable shielding (not trivial!) a la GIOVE



Pulser/Threshold [eV]	QF = 0.15	QF = best fit	QF = 0.25
60 / 180	971 / 61 / 15.8	2 173 / 85 / 25.6	9 194 / 127 / 72.3
65 / 195	588 / 58 / 10.1	1 488 / 81 / 18.4	6 962 / 123 / 56.4
70 / 210	352 / 55 / 6.4	1 014 / 78 / 13.0	5 272 / 120 / 44/0
75 / 225	207 / 52 / 4.0	686 / 75 / 9.2	3 989 / 117 / 34.2
80 / 240	120 / 49 / 2.5	460 / 71 / 6.5	3 012 / 113 / 26.7
85 / 255	69 / 46 / 1.5	306 / 68 / 4.5	2 269/110/20.7

S[1/yr] / B[1/yr] / R=S/B

Maneschg, Rink, Salathe, ML

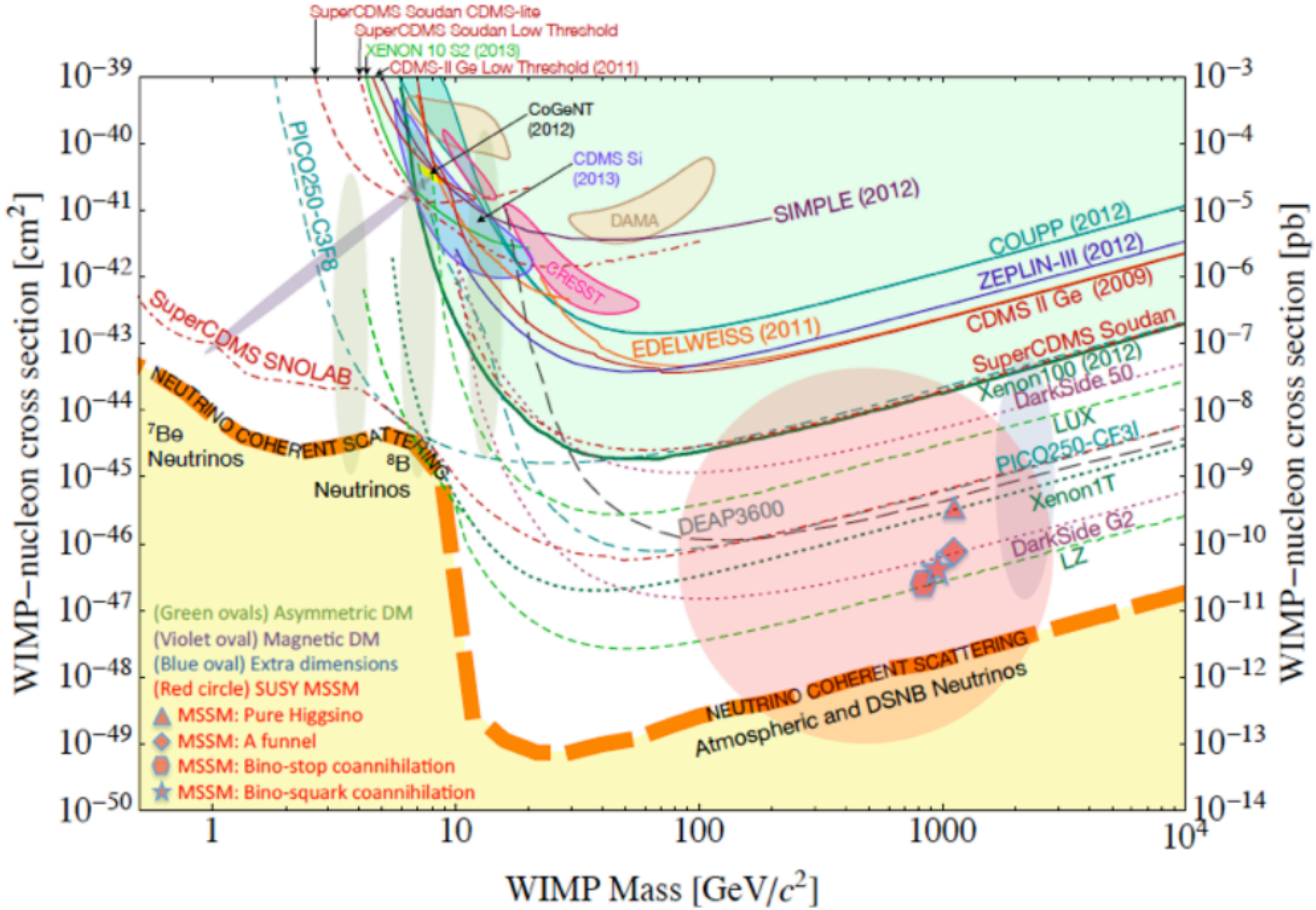
➔ **Not trivial (reactor flux, detector threshold, background reduction) but doable on a short time scale!**

➔ **Even a 1kg detector would see CνS very soon**

➔ **what then?**

Why is CνS interesting: DM connections

1) DM experiments <u>assume</u> coherent DM scattering → test of CνS
2) Neutrino floor of direct DM experiments *IS* due to CνS



Upscaling to 100kg ➔ Interesting Potential

high statistics ➔ precision ➔ various interesting topics…

Maneschg, Rink, Salathe, ML

100kg detector
4GW @ 15m
flux ~3*10^{13}/cm^2/s
background 1/kg/day

BSMsens=ΔS/S

Puler/Thresh [eV]	QF=0.15	**BSMsens**	QF=BF	**BSMsens**	QF=0.25	**BSMsens**
40 / 120	647 474/ 8291 / 78.1	$1*10^{-3}$	965 999/ 10 775/89.7	$1*10^{-3}$	$2.9*10^{6}$/ 15 158 / 189	$6*10^{-4}$
45 / 135	407 092/ 8 036 / 50.7	$2*10^{-3}$	664 316/ 10 519/63.2	$1*10^{-3}$	$2.1*10^{6}$/ 14 866 / 144	$7*10^{-4}$
50 / 150	254 745/ 7780 / 32.7	$2*10^{-3}$	458 072/ 1 0264/44.6	$1*10^{-3}$	$1.6*10^{6}$/ 14 574 / 84.9	$8*10^{-4}$
55 / 165	158 109/ 7 524 / 21.0	$3*10^{-3}$	315 843/ 9 971/31.7	$2*10^{-3}$	$1.2*10^{6}$/ 14 318 / 84.9	$9*10^{-4}$
60 / 180	97 066/ 7 305 / 13.3	$3*10^{-3}$	217 277/ 9 716/22.4	$2*10^{-3}$	919 435/ 13 026 / 65.6	$1*10^{-3}$
65 / 195	58 827/ 7 049 / 8.3	$4*10^{-3}$	148 848/ 9 460/15.7	$3*10^{-3}$	696 196/ 13 770 / 50.6	$1*10^{-3}$
70 / 210	35 154/ 6 830 / 5.1	$5*10^{-3}$	101 386/ 9 204/11.0	$3*10^{-3}$	527 204/ 13 514 / 39.0	$1*10^{-3}$
75 / 225	20 711/ 6 575 / 3.2	$7*10^{-3}$	68 573/ 8 949/7.7	$4*10^{-3}$	398 867/ 13 222 / 30.2	$2*10^{-3}$
80 / 240	12 042/ 6 355 / 1.9	$9*10^{-3}$	46 008/ 8 730/5.27	$5*10^{-3}$	301 231/ 12 966 / 23.2	$2*10^{-3}$
85 / 255	6 924/ 6 136 / 1.1	$1*10^{-2}$	30 598/ 8 474/3.6	$6*10^{-3}$	226 910/ 12 711 / 17.9	$2*10^{-3}$

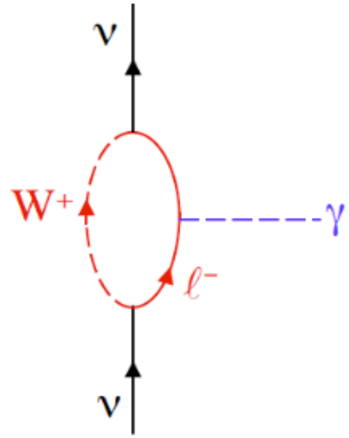
BSMsens=ΔS/S S[1/yr] / B[1/yr] / R=S/B

Searches for new Physics: Magnetic Moments

Magnetic moment for minimal ν masses are very tiny:

Dirac: $$\mu^D_{kk} \backsimeq 3.2 * 10^{-19} \left(\frac{m_k}{\text{eV}}\right) \mu_B$$

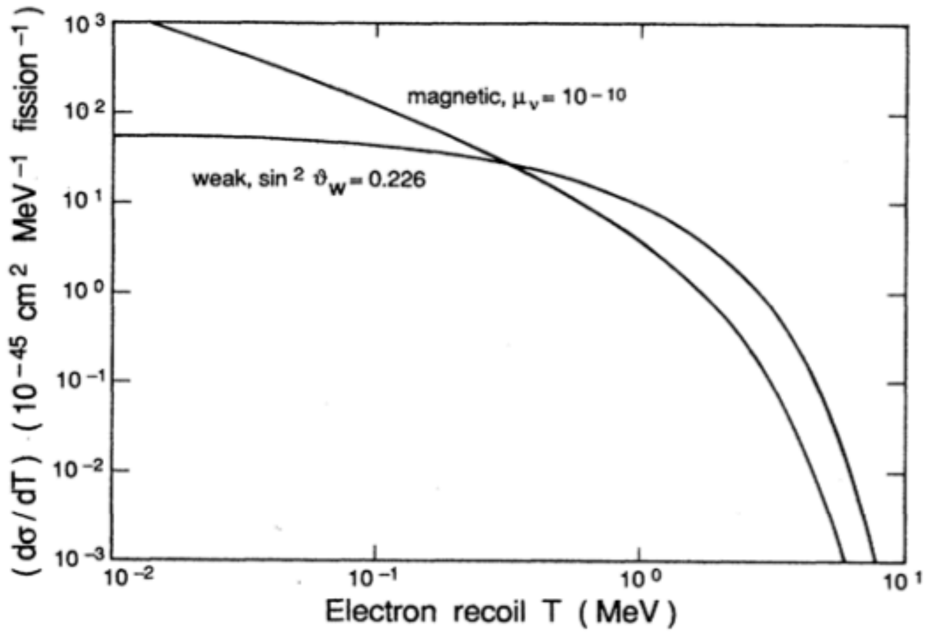
Majorana: $$\mu^M_{ll'} \lesssim 4 * 10^{-9} \mu_B \left(\frac{M^M_{ll'}}{\text{eV}}\right) \left(\frac{\text{TeV}}{\Lambda}\right)^2 \left|\frac{m_\tau^2}{m_l^2 - m_{l'}^2}\right|$$



New physics ➔ detectable enhancements due to new physics:
SUSY, extra dimensions, …

At least new best limits:
e-scattering (GEMMA) and astrophysics:

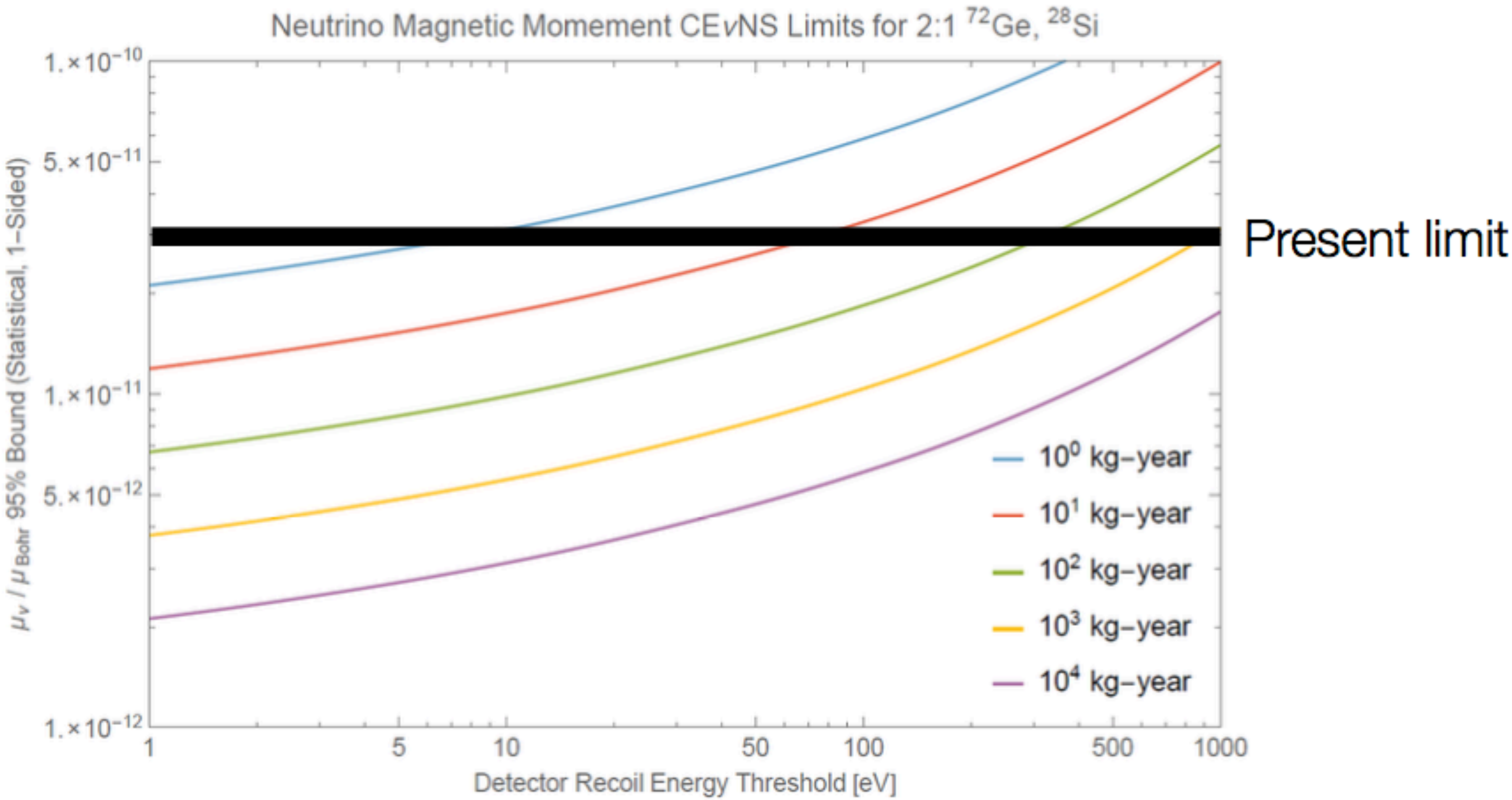
$$\mu_\nu < 3 \times 10^{-11} \mu_b$$



Scattering on protons coherently enhanced: ➔ detectable at low energy (Vogel & Engel 1989)

$$\left.\frac{d\sigma}{dT_R}\right|_{\mu_\nu} = \frac{\pi\alpha^2\mu_\nu^2}{m_e^2}\left[\frac{1 - T_R/E_\nu}{T_R} + \frac{T_R}{4E_\nu^2}\right]$$

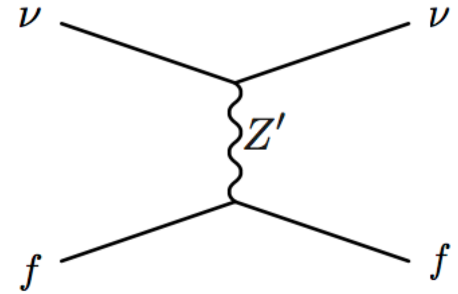
Potential for Magnetic Moments



100kg * 5y = 500 kg-year ; low threshold ➔ one order of magnitude better

Searches for new Physics: NSI's

NSI's ←→ new physics at high scales
Which are integrated out
Z', new scalars, … ➔ ε_{ij}



$$\mathcal{L}_{NSI} \simeq \epsilon_{\alpha\beta} 2\sqrt{2} G_F (\bar{\nu}_{L\beta}\, \gamma^{\rho}\, \nu_{L\alpha})(\bar{f}_L \gamma_\rho f_L)$$

$$\frac{d\sigma}{dT}(E_\nu, T) = \frac{G_F^2 M}{\pi}\left(1 - \frac{MT}{2E_\nu^2}\right) \times \left\{\left[Z(g_V^p + 2\varepsilon_{ee}^{uV} + \varepsilon_{ee}^{dV}) + N(g_V^n + \varepsilon_{ee}^{uV} + 2\varepsilon_{ee}^{dV})\right]^2 + \sum_{\alpha=\mu,\tau}\left[Z(2\varepsilon_{\alpha e}^{uV} + \varepsilon_{\alpha e}^{dV}) + N(\varepsilon_{\alpha e}^{uV} + 2\varepsilon_{\alpha e}^{dV})\right]^2\right\}$$

Barranco et al. 2005

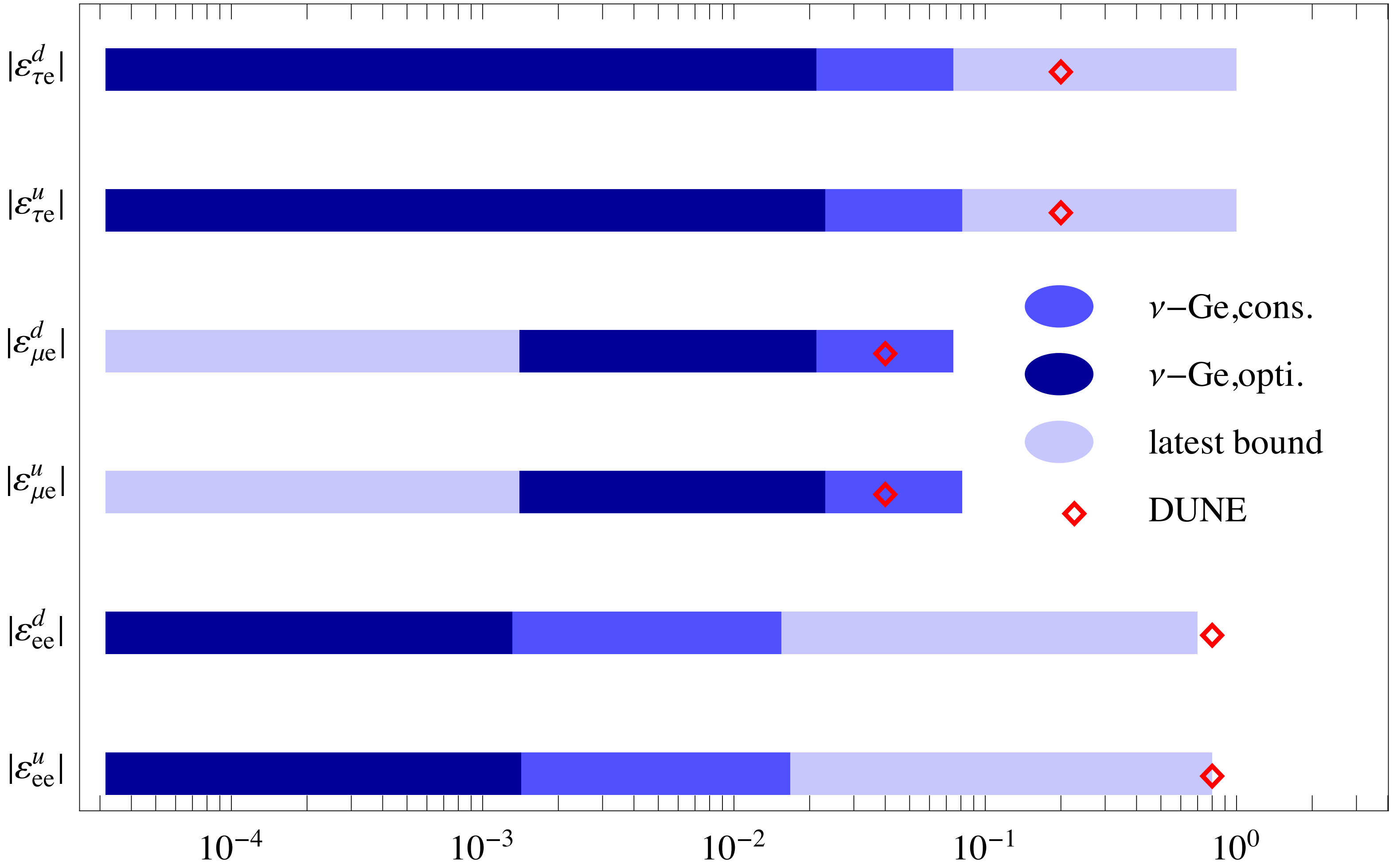
$$|\epsilon| \simeq \frac{M_W^2}{M_{NSI}^2}$$

➔ Competitive method to test TeV scales
ε = 0.01 ←→ TeV scales

NSI-Potential of O(100kg) Detector

100kg detector, 5 years operation @ 4GW

ML, W. Rodejohann, X.Xu



~10 TeV **~TeV**

Searches for new Physics: Sterile ν's

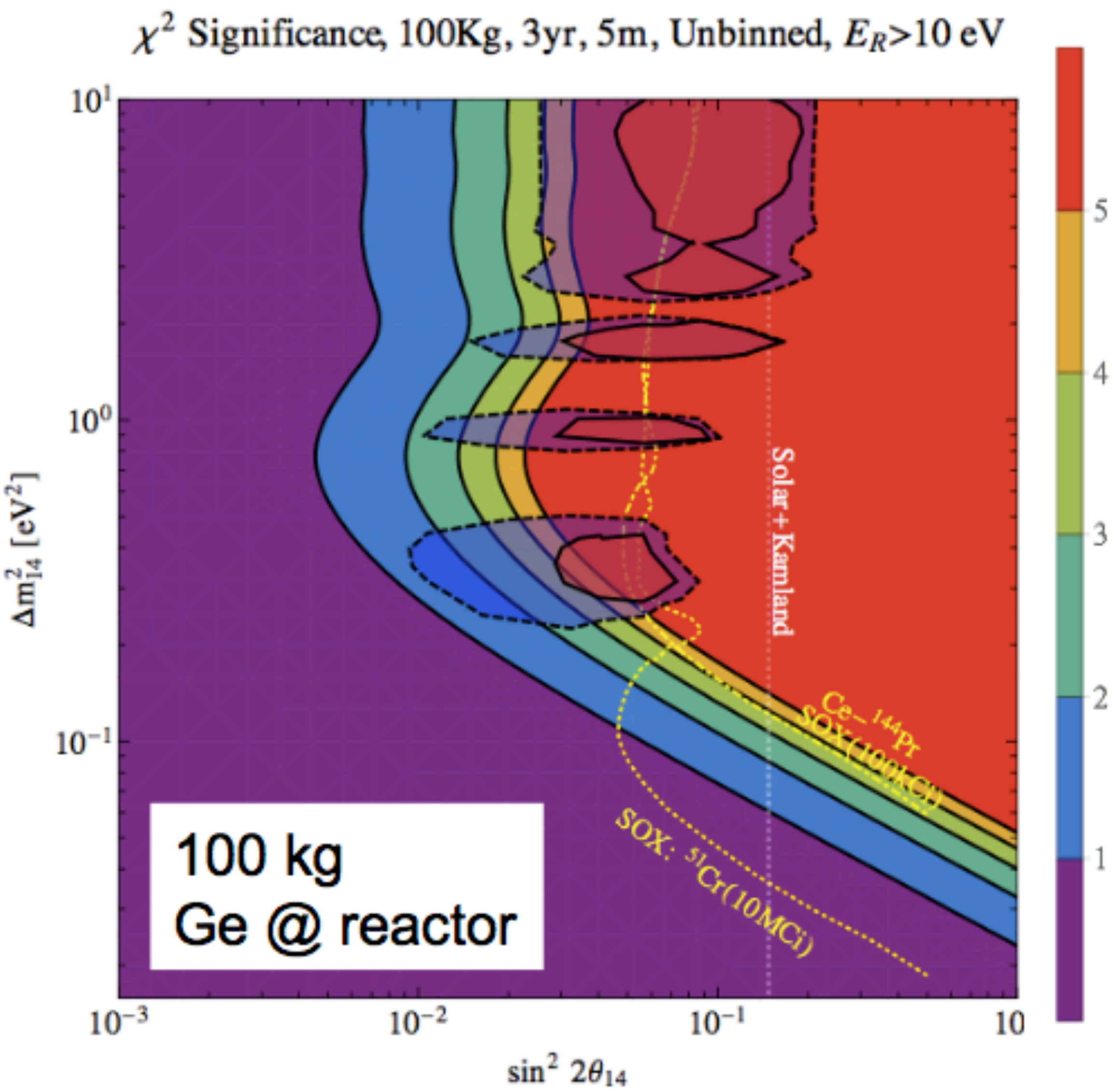
Various indications / hints for steril
tensions with cosmology?

- eV hints with small mixing
- keV warm dark matter
  with tiny mixing ≤ 10^{-8}

➔ Different mass ranges,
but any sterile state
would motivate others

➔ test if flux deviates
from $1/R^2$

➔ time scales compared to other
projects



B. Dutta et al, arXiv:1511.02834

Nuclear Physics with coherent Scattering

Remember: DAR sources close to decoherence ⇔ combine with reactor measurements

we can start to explore nuclear form factors

P. S. Amanik and G. C. McLaughlin, J. Phys. G 36:015105

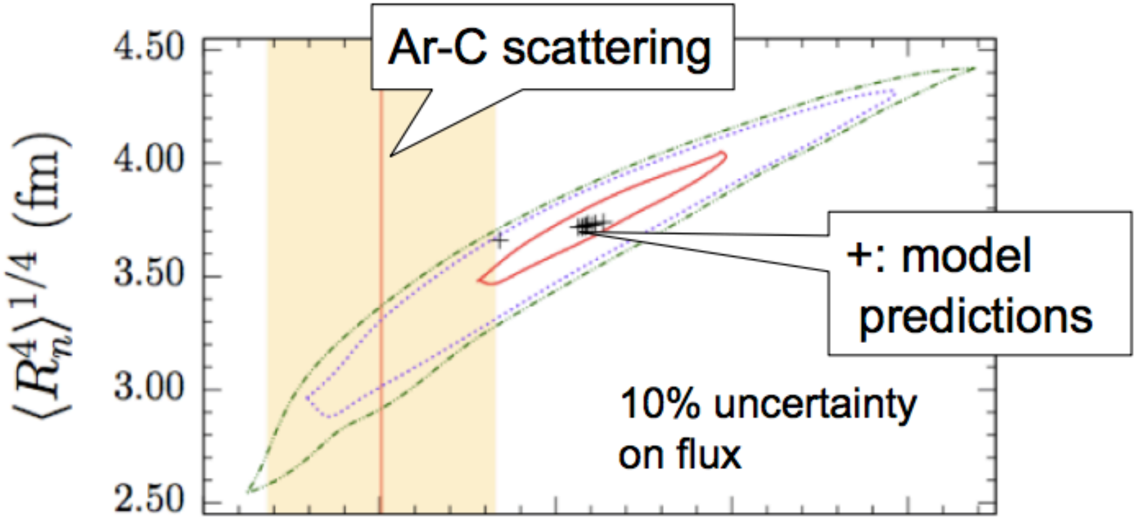
K. Patton et al., PRC86 (2012) 024612

$$\frac{d\sigma}{dT}(E,T) = \frac{G_F^2}{2\pi} M \left[2 - \frac{2T}{E} + \left(\frac{T}{E}\right)^2 - \frac{MT}{E^2}\right] \frac{Q_W^2}{4} F^2(Q^2)$$

Form factor: encodes information about nuclear (primarily neutron) distributions

Fit recoil ***spectral shape*** to determine the $F(Q^2)$ moments
(requires very good energy resolution,good systematics control)

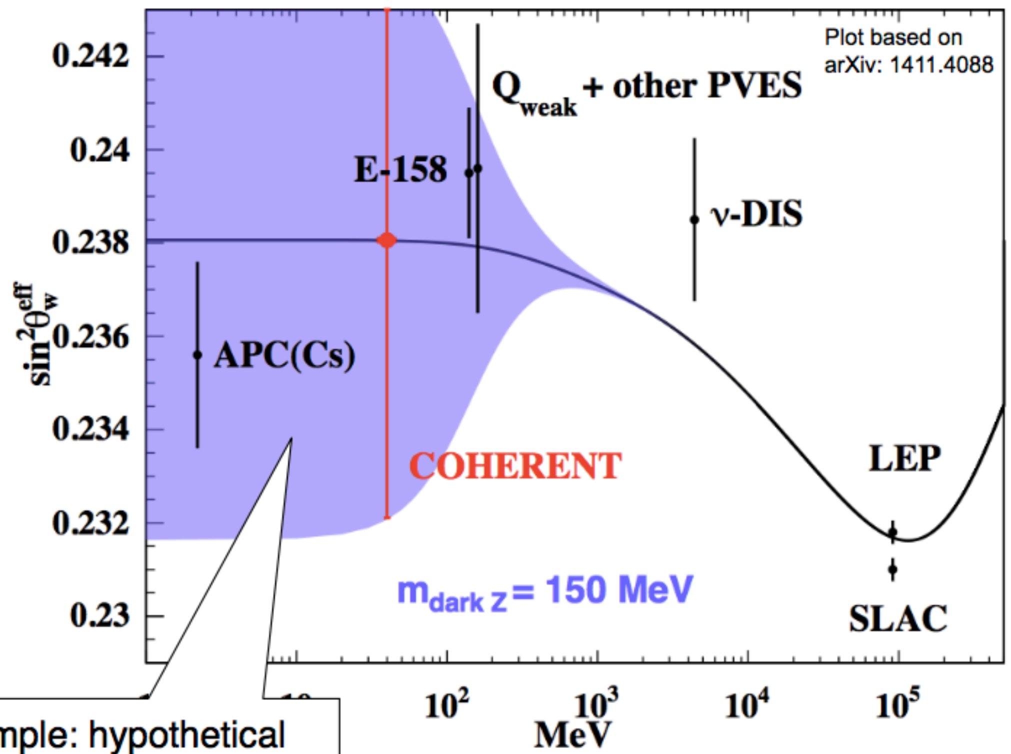
Example:
tonne-scale experiment at πDAR source



Precise Measurement of $\sin^2\theta_W$ at low E

Clean SM prediction for the rate ➔ measure $\sin^2\theta_W$eff ;
deviation probes new physics

$$\sigma \sim \frac{G_f^2 E^2}{4\pi}(N - (1 - 4\sin^2\theta_W)Z)^2$$



Example: hypothetical dark Z mediator (explanation for g-2 anomaly)

BSMsens =
10^{-3} ➔ $\Delta\sin^2\theta_W = 0.006$
10^{-4} ➔ $\Delta\sin^2\theta_W = 0.0006$

CEvNS sensitivity is @ low Q;
need sub-percent precision to compete w/ electron scattering & APV, but **new channel**

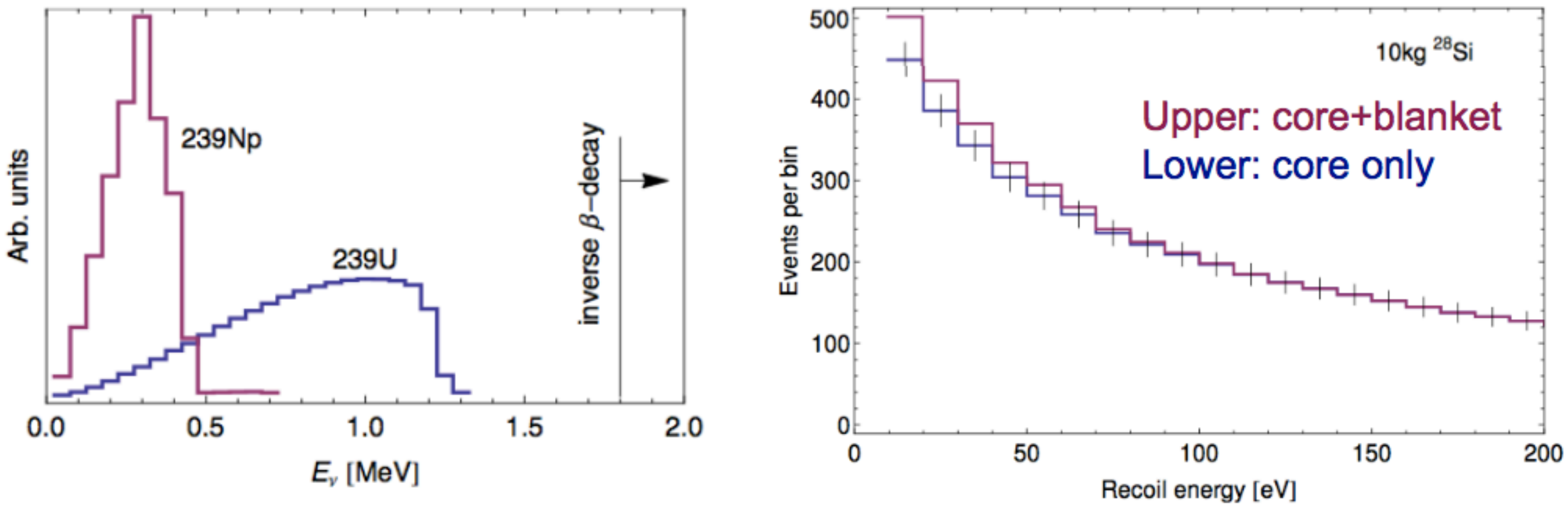
slide adopted from K. Scholberg

Nuclear Safeguarding

P. Huber, talk at NA/NT workshop, Manchester, May 2015

Presence of **plutonium breeder blanket** in a reactor has ν spectral signature

$$^{238}\mathrm{U} + n \rightarrow {}^{239}\mathrm{U} \xrightarrow{\beta} {}^{239}\mathrm{Np} \xrightarrow{\beta} {}^{239}\mathrm{Pu}$$



ν spectrum is below IBD threshold

➔ accessible with CEvNS, but require low recoil energy threshold

a) This is of interest to IAEA

b) Could be used as an extra "sensor" in reactors (close to core ←→ $1/R^2$) ➔ safety, optimal burn-up

Conclusions

- **Neutrino physics was, is and will remain a hot field**
- **Important and unique insights into**
  - fundamental interactions, important consequences: BAU...
- **3 neutrino flavours ➔ precision area**
  - reactor neutrinos + neutrino beams ➔ origin of fermion masses?
- **More than 3 neutrinos**
  - Majorana masses, L-violation, sterile ν's, NSIs, large magnetic moments, ...

  ➔ any one of them would be a major discovery
- **Coherent neutrino scattering will be a new tool**
  - will contribute / make use of better β-spectra
  - will allow new experiments to test
  - coherent ν scattering ←→ DM & WIMP scattering
  - mag. Moments, NSIs, steriles, $\sin^2\theta_W$, $F(q^2)$, safeguarding, ...