© picture-alliance/dpa/Karaba

Reactor $\bar{\nu}_e$ flux predictions for CEvNS experiments

Anthony Onillon

(CEA/IRFU/DPHP now TUM)

Other contributors to this talk:
L. Perissé, M. Vivier, X. Mougeot

Magnificient CEvNS workshop
6–7 oct. 2021

I. Reactor experiments

CEvNS at nuclear reactors

- Pure $\bar{\nu}_e$ flux, on/off measurement
- low energy: $E_{\bar{\nu}_e}$ < 10 MeV
  - → fully coherent regime, low recoil energy ≲ 1 keV
- High flux & high cross-section:
  - → small detectors suitable

⇒ **CEvNS cross-section measurement**

⇒ **Standard model probe, search for new physics at low energy**

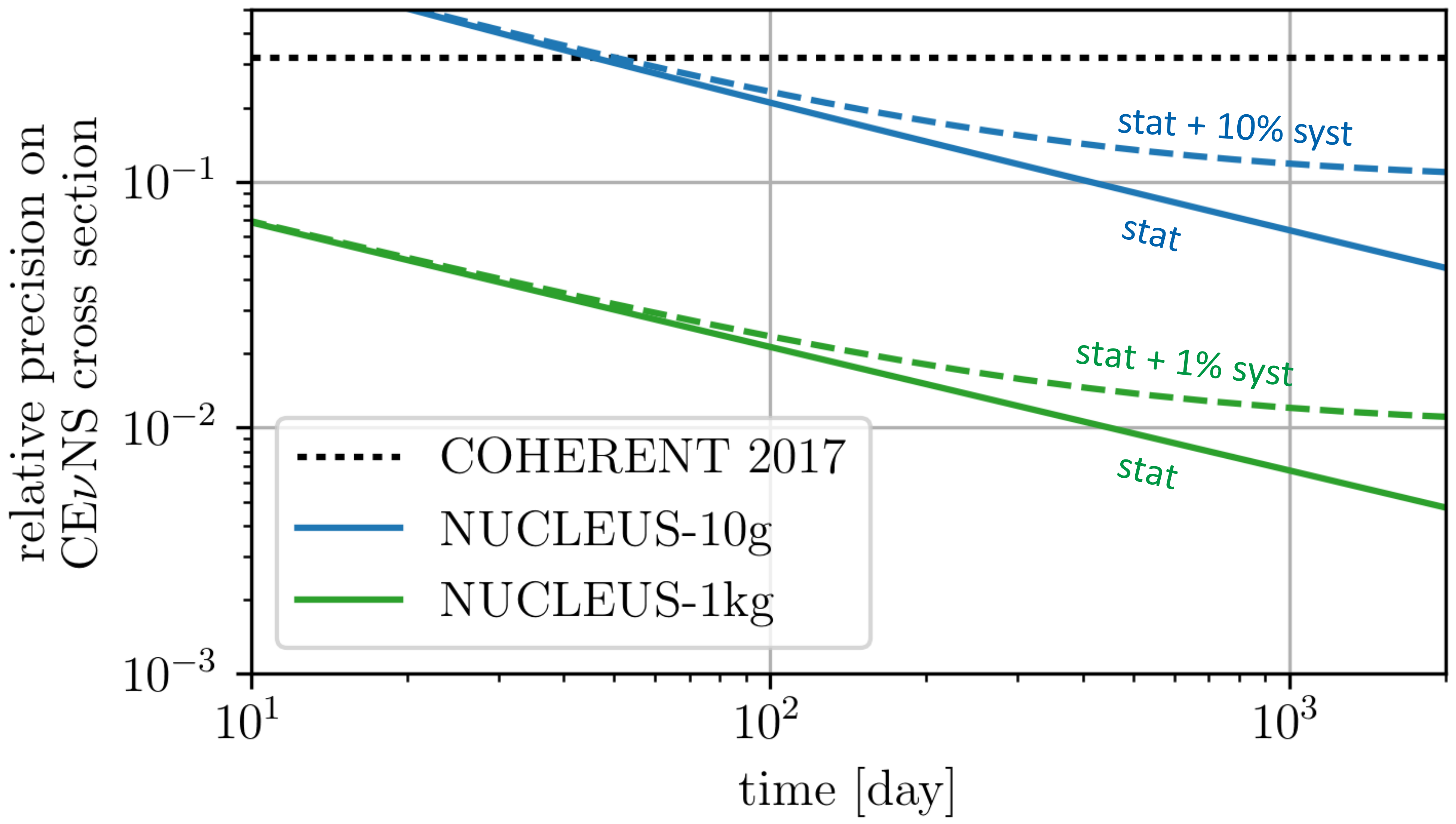
⇒ **Power monitoring & spent fuel contents verification**

Experiment	Power [MWth]	Baseline [m]	Overburden	Technology	Payload	T_{thr} [eV]
NUCLEUS	2 × 4250	59	3	Al_2O_3 /$CaWO_4$ cryo. det.	0.01	20 (nr)
				Ge/Si cryo. det.	1	20 (nr)
Ricochet	58	8	~ 10	Ge/Zn cryo. det.	1.3-10	50 (nr)
MINER	1	1 ↔ 3	15	Ge/Si cryo. det.	O(10)	100 (nr)
CONUS	3900	17	15 → 45	HPGe PC	3.7	300 (ee)
νGeN	3100	11 ↔ 12	50	HPGe PC	1.6	350 (ee)
TEXONO	2900	28	30	HPGe PC	1.5	200 (ee)
CONNIE	3800	30	Surface	Si CCD	~ 0.1	40 → 7 (ee)
NEON	2800	24	20	NaI[Tl]	15	200 (ee)
RED-100	3000	19	65	Dual-phase liquid Xe	160	250 (ee)

Overview of on-going experimental efforts to detect CEvNS at nuclear reactors

$$\phi_{\bar{\nu}_e} \sim 10^{12} - 10^{13}\ \mathrm{cm^{-2}.s^{-1}}$$

[Eur.Phys.J.C 79 (2019) 12, 1018]



With high payload and high exposure, achievable precision can be limited by the reactor $\bar{\nu}_e$ flux knowledge

⇒ **Need for precise & accurate prediction**

II. Reactor antineutrinos

$$\phi_{\bar{\nu}_e} = \underbrace{\phi_{fission}}_{\sim 0\text{-}10\ MeV} + \underbrace{\phi_{activation} + \phi_{spent\ fuel}}_{\sim 0\text{-}3\ MeV}$$

- **Fission:** uranium + plutonium
- **Neutron activated material:** fuel + structural material
- **Spent fuel:** burnt assemblies in storage pools

Commercial reactors

- Lowly enriched UO_2: **3-5% ^{235}U**

Very close reactor design & fuel contents for all PWR reactors
$\Rightarrow$ close $\bar{\nu}_e$ flux/spectrum expected for different reactors

Fuel activation

$$\underset{\searrow\text{fission}}{{}^{238}_{92}U} \xrightarrow{(n,\gamma)} \boxed{{}^{239}_{92}U \xrightarrow[23.45\text{ mn}]{\beta^-}} \boxed{{}^{239}_{93}Np \xrightarrow[2.35\text{ d}]{\beta^-}} \underset{\searrow\text{fission}}{{}^{239}_{94}Pu} \xrightarrow{(n,\gamma)} {}^{240}_{94}Pu \xrightarrow{(n,\gamma)} \underset{\searrow\text{fission}}{{}^{241}_{94}Pu}$$

PWR @Chooz
($E_{235U} \sim 4\%$)
- NUCLEUS

		Flux [$\bar{\nu}_e$.fiss^{-1}]	Rel. Contrib. [%]	
Fission	**^{235}U**	**3.3**	**46.3**	**~83%**
	^{239}Pu	**1.7**	**24.1**	
	^{238}U	0.5	7.3	
	^{241}Pu	0.4	5.1	
Activation	**^{239}U**	0.6	8.6	**~17%**
	^{239}Np	0.6	8.6	
Total		**7.2**		

Research reactors

- Higher enrichment: **^{235}U > 5%** *(High-Assay Low-Enriched Uranium 5-20%, Highly enriched uranium > 20%)*

Wide array of designs & fuel contents for research reactors
$\Rightarrow$ $\bar{\nu}_e$ flux/spectrum specific to the considered reactor

Structure activation

^{27}Al, ^{55}Mn, ^{9}Be, ^{51}V…

HFR @ILL
($E_{235U} \sim 93\%$)
- Ricochet

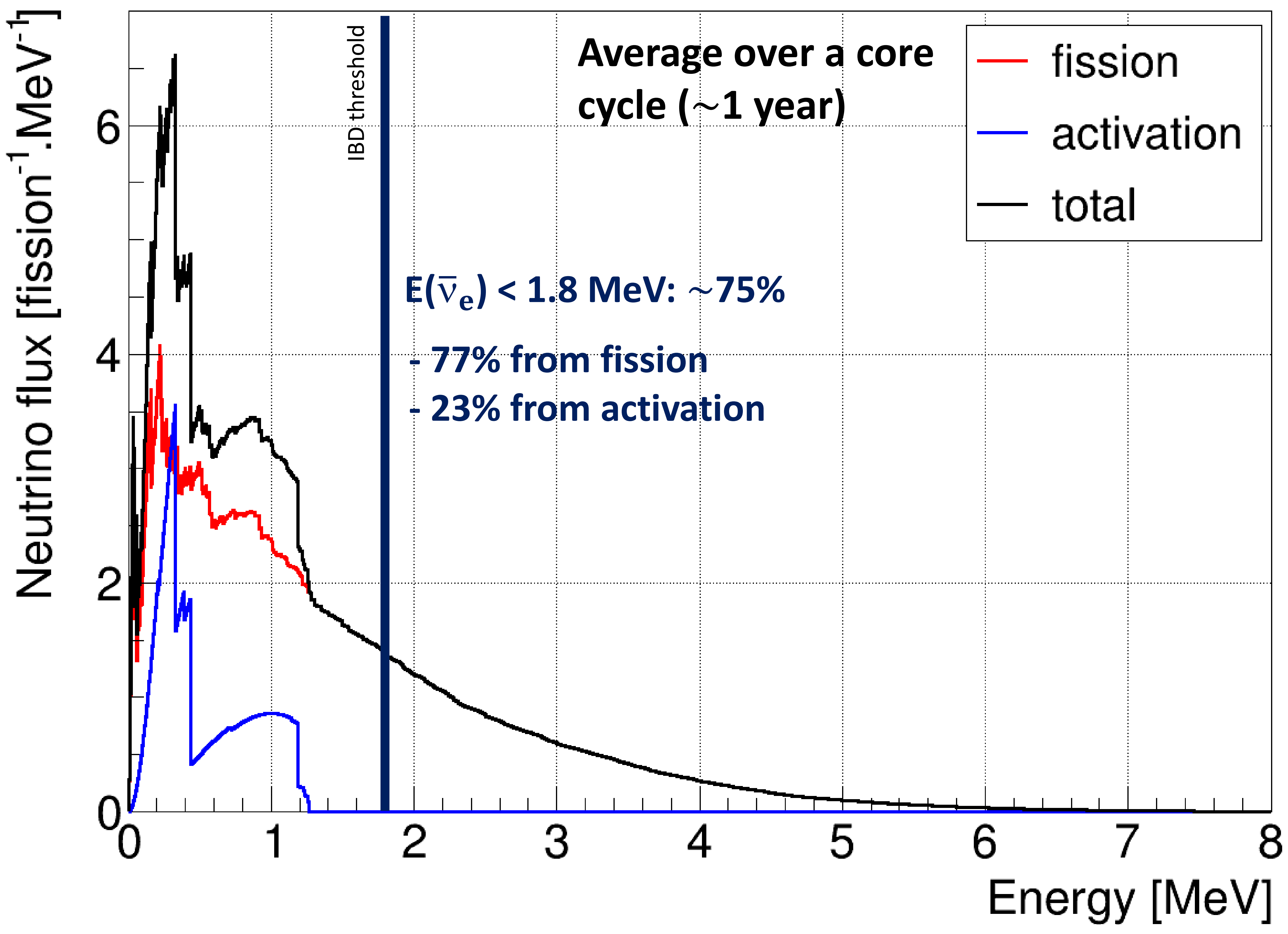
		Flux [$\bar{\nu}_e$.fiss^{-1}]	Rel. Contrib. [%]	
Fission	**^{235}U**	**6.1**	**93.0**	**~93%**
	^{239}Pu	<0.1	0.3	
Activation	**^{239}U**	<0.1	0.2	**~7%**
	^{239}Np	<0.1	0.2	
	^{28}Al	**0.4**	**5.4**	
	^{56}Mn	0.1	0.9	
Total		**6.5**		

II. Reactor antineutrinos

Plots based on summation calculations

Commercial PWR, LEU

- N4 type Chooz like -



Average over a core cycle (~1 year)

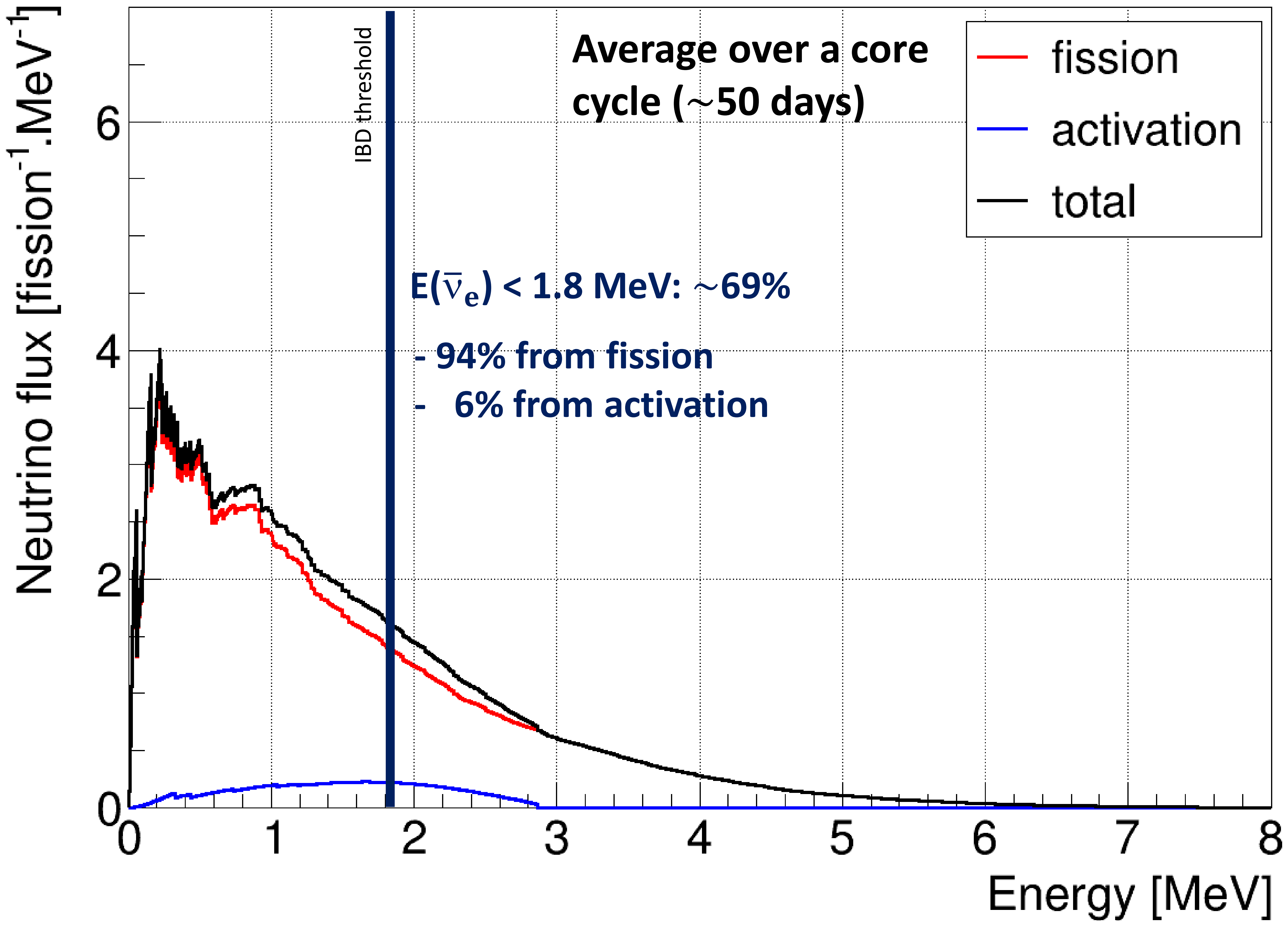
$E(\bar{\nu}_e) < 1.8$ MeV: ~75%

- 77% from fission

- 23% from activation

Research reactor, HEU

- HFR @ILL-



Average over a core cycle (~50 days)

$E(\bar{\nu}_e) < 1.8$ MeV: ~69%

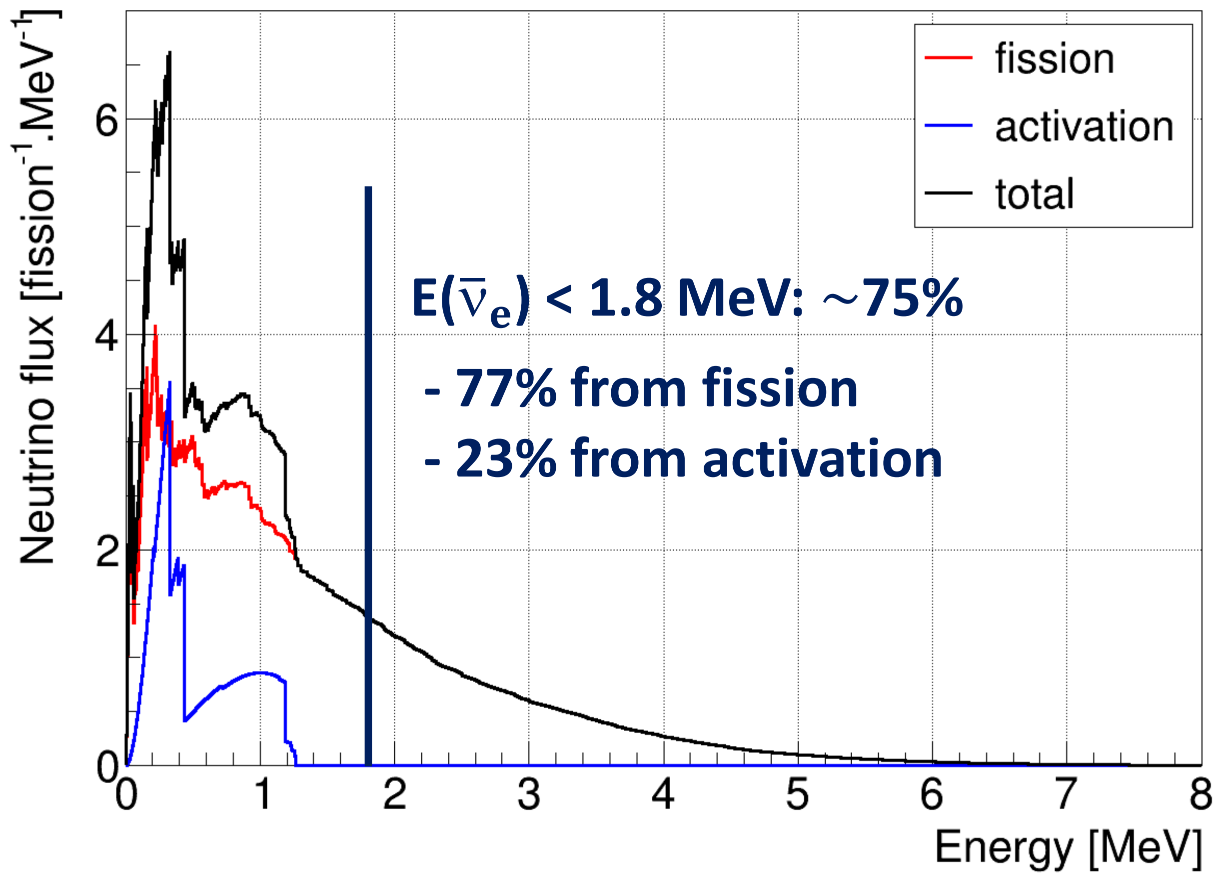
- 94% from fission

- 6% from activation

- CEvNS: thresholdless process ⇒ sensitive to low energy $\bar{\nu}_e$ (fission & activation) below the 1.8 MeV IBD threshold
  ↳ but material + recoil energy threshold dependency

II. Reactor antineutrinos

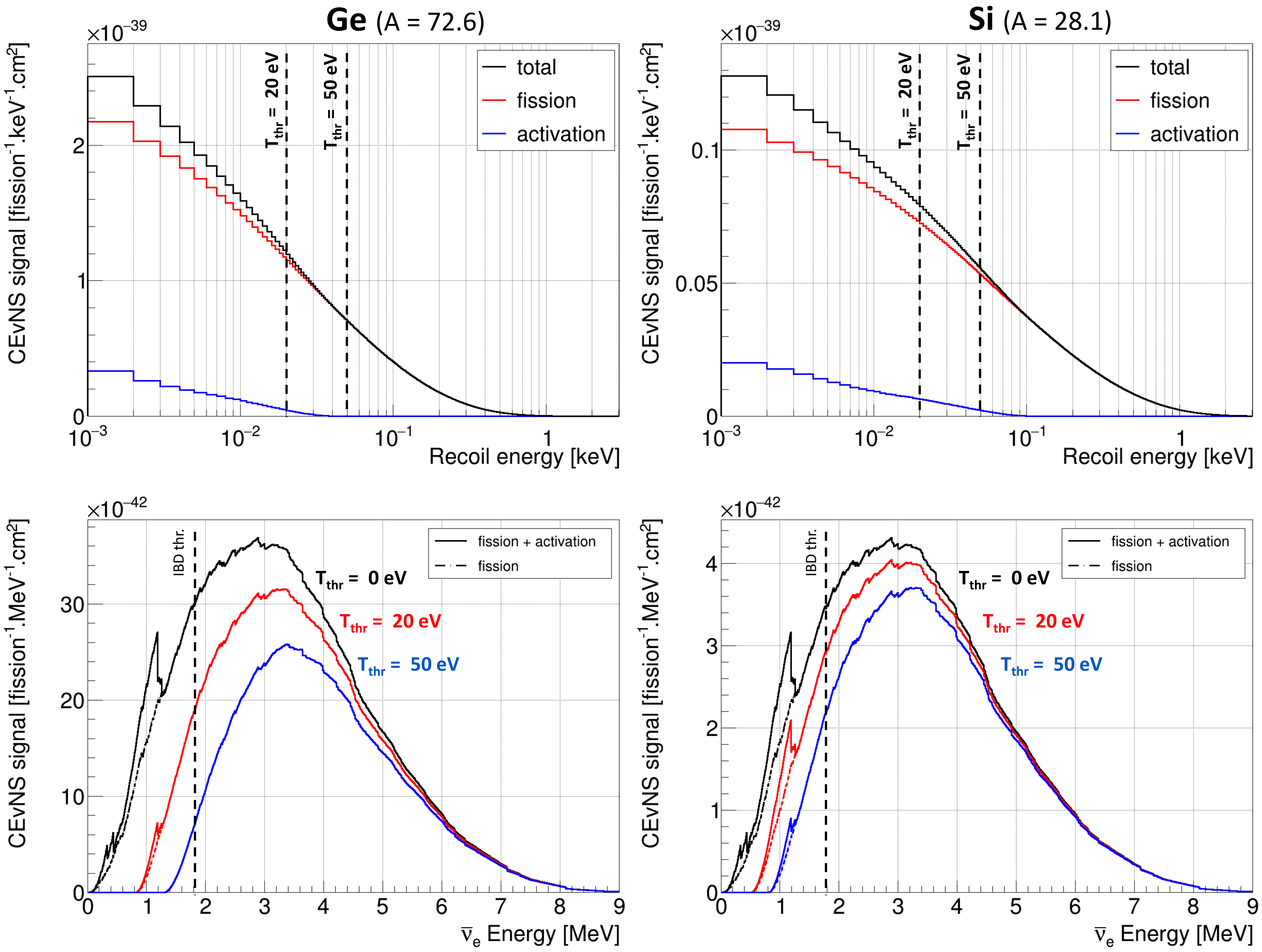
Commercial PWR
- N4 type Chooz like -



$E(\bar{\nu}_e) < 1.8$ MeV: ~75%

- 77% from fission

- 23% from activation

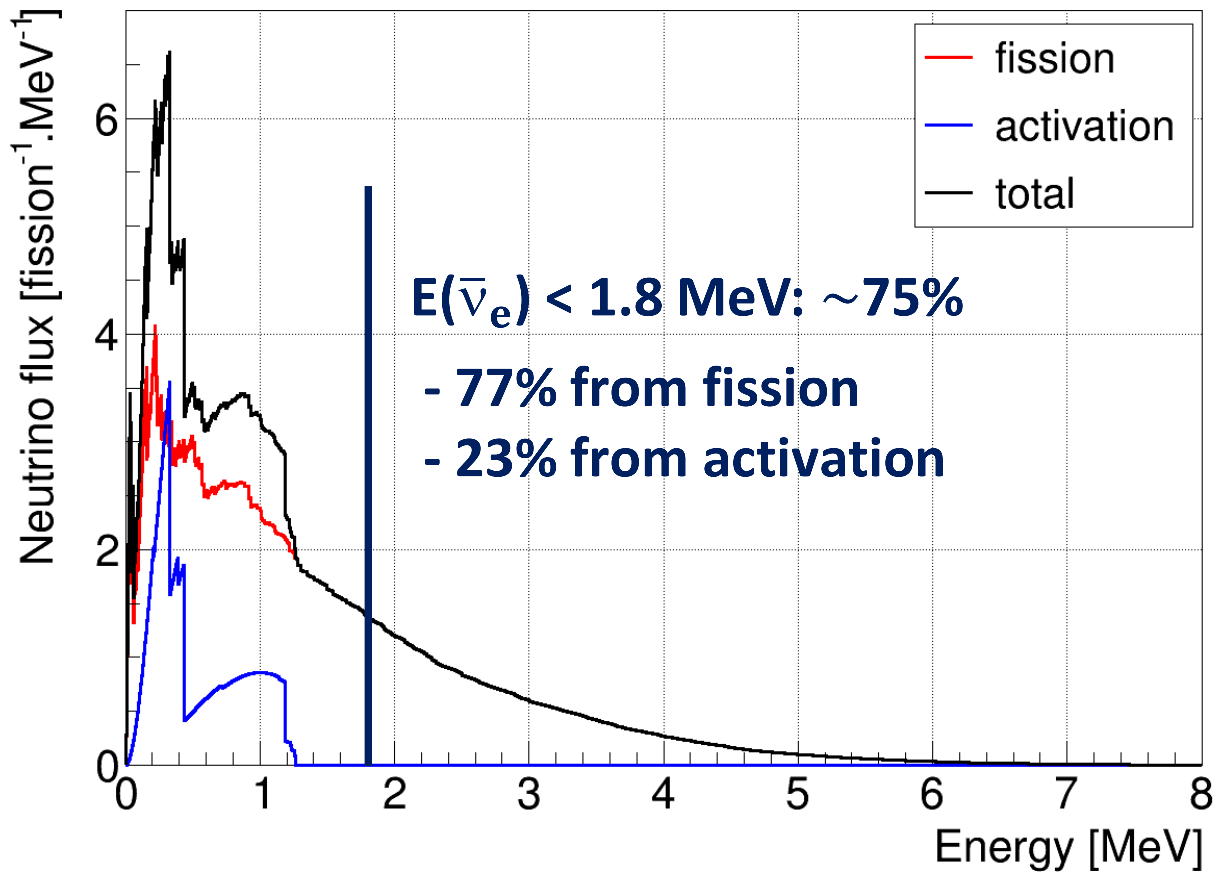


- Max recoil energy T_{max} dependency to M
  ↳ low mass + low recoil energy thresholds required to be sensitive to $\bar{\nu}_e$ with E < 1.8 MeV

$$T_{max} = \frac{2E_\nu^2}{M + 2E_\nu}$$

II. Reactor antineutrinos

Commercial PWR
- N4 type Chooz like -



$E(\bar{\nu}_e) < 1.8$ MeV: ~75%

- 77% from fission
- 23% from activation

- Max recoil energy T_{max} dependency to M
  ↳ low mass + low recoil energy thresholds required to be sensitive to $\bar{\nu}_e$ with E < 1.8 MeV

$$T_{max} = \frac{2E_\nu^2}{M + 2E_\nu}$$

O (A=16.0), Al (A=26.98), Si (A=28.1),
Ca (A=40.1), Zn (A=65.4), Ge (A=72.6) and W (A=183.8)

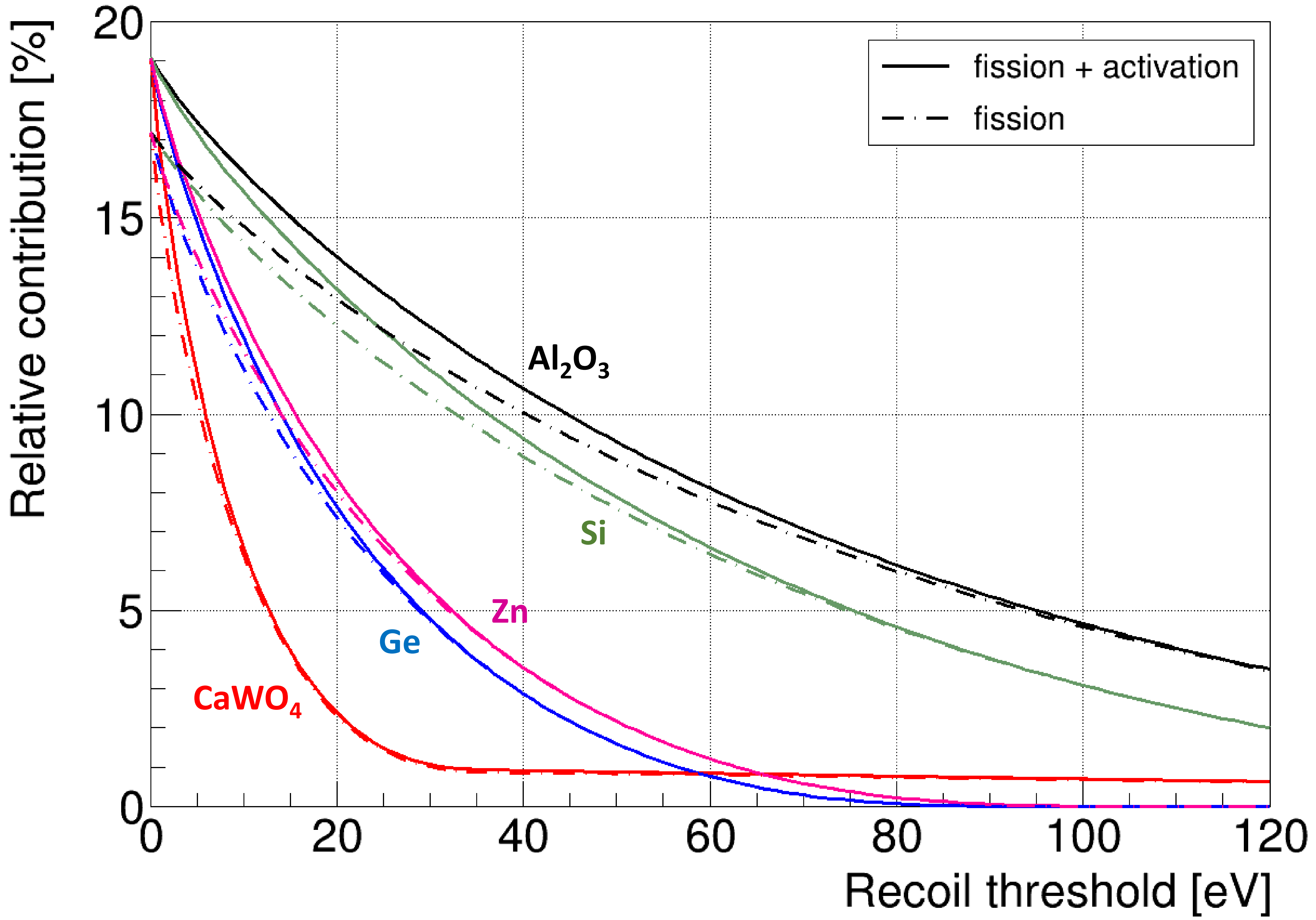


Fig./table Low neutrino energy contribution in percent (E<1.8 MeV) to the total recoil spectrum

➡ **Modeling effort to be focus above 1.8 MeV**
Target with low nucleus mass and small recoil threshold required to be sensitive to low energy $\bar{\nu}_e$

III. Flux prediction

Expected number of events

$$N_{\bar{\nu}_e}^{exp}(t) = \frac{N_t\epsilon}{4\pi L^2}\frac{P_{th}(t)}{\langle E_f\rangle(t)}\int \sigma(E)\left(\sum_k \alpha_k\phi_k^{fiss}(E,t) + \sum_a y_a\phi_a^{acti}(E,t)\right) \quad + \quad \delta^{res}(t)$$

↑ $\bar{\nu}_e$ from fission

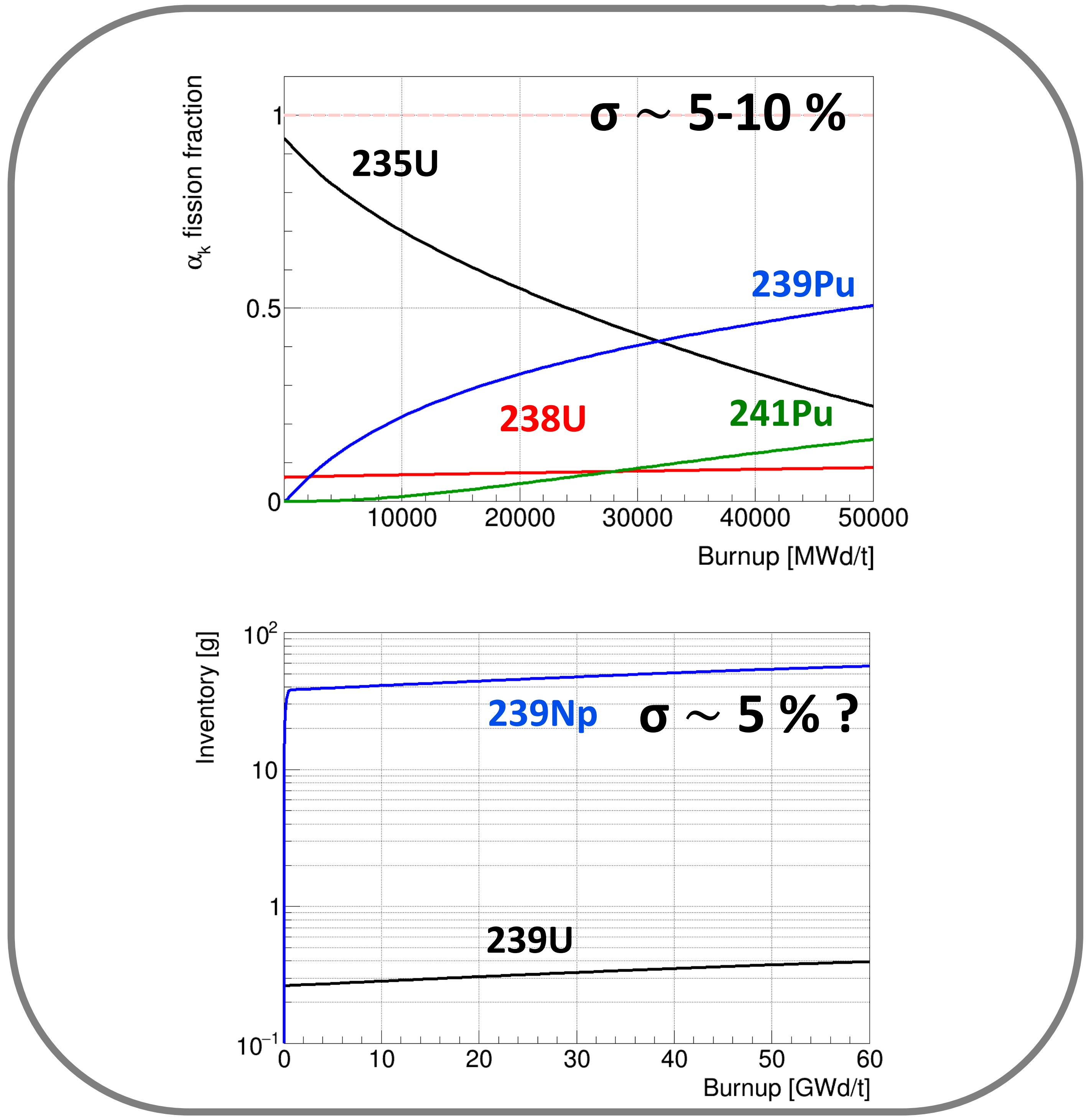
↑ $\bar{\nu}_e$ from activation

↑ residual $\bar{\nu}_e$

- ϵ : detection efficiency
- N_t : number of target isotope
- L : distance reactor-detector
- $\langle E_f\rangle$: mean energy released per fission
- P_{th}: thermal power
- $\sigma(E)$: CEvNS cross-section
- α_k, y_a: fission fraction, activation rate

Key inputs – illustration for PWR

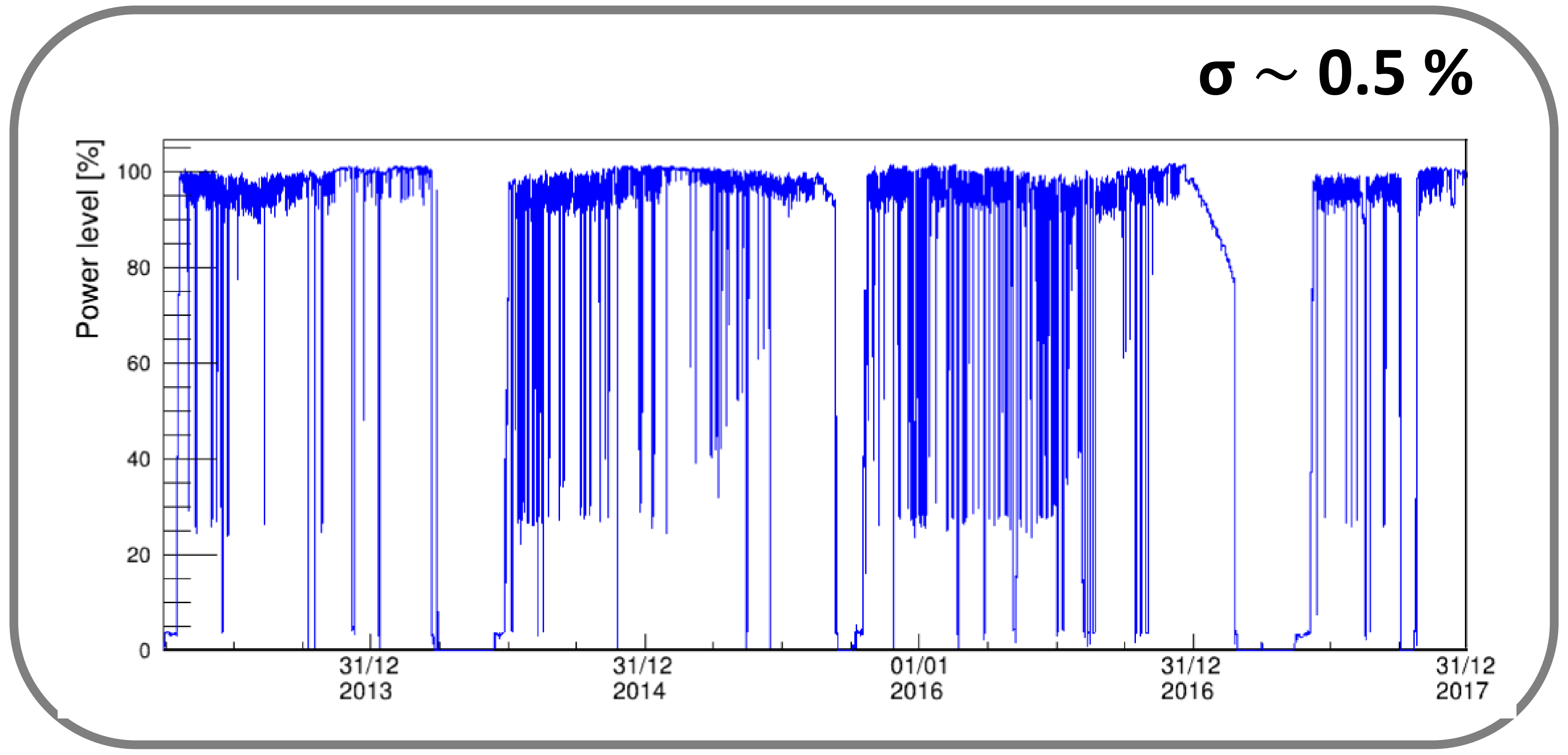
Fission fraction - activated mat. inventories (simulations)



σ ~ 5-10 %

σ ~ 5 % ?

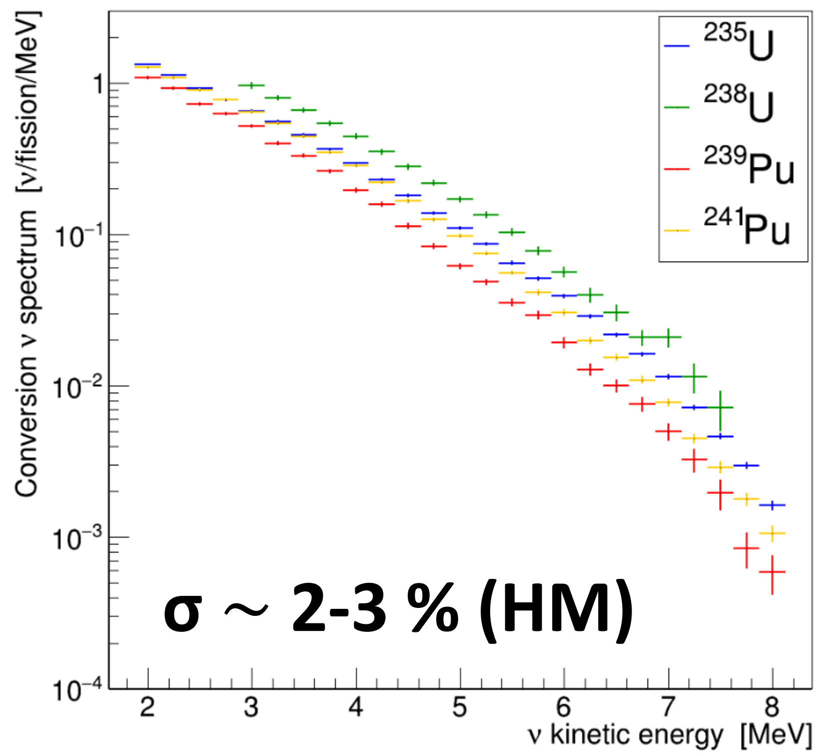
Thermal power (reactor operator)



σ ~ 0.5 %

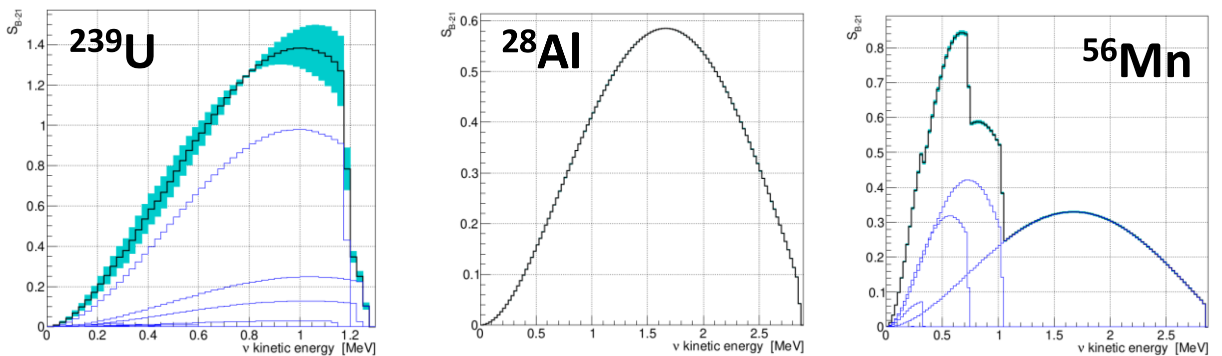
$\bar{\nu}_e$ spectra (fission & activation)

fission



σ ~ 2-3 % (HM)

Activation



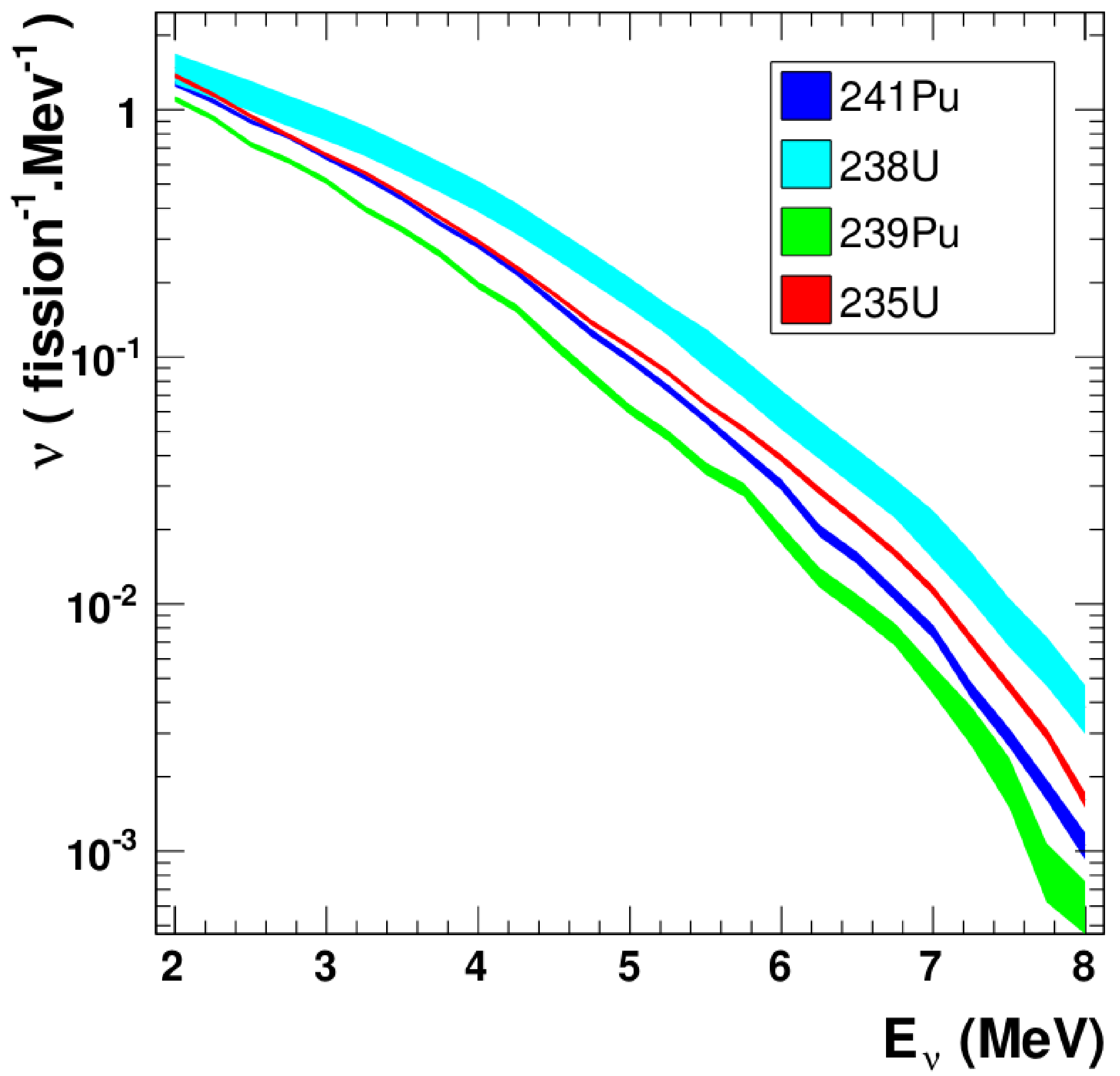
Plots courtesy of L. Perissé

IV. Fission $\bar{\nu}_e$ spectra

Conversion spectra

Inversion of measured β decay spectra from neutron-irradiated targets

- ^{235}U, ^{239}Pu, ^{241}Pu: Schreckenbach & al., HFR reactor @ILL (80's)
- ^{238}U: N. Haags et al., FRM-II reactor @Garching (2013)



[Phys.Rev. C83:054615, 2011]

Huber / Mueller spectra

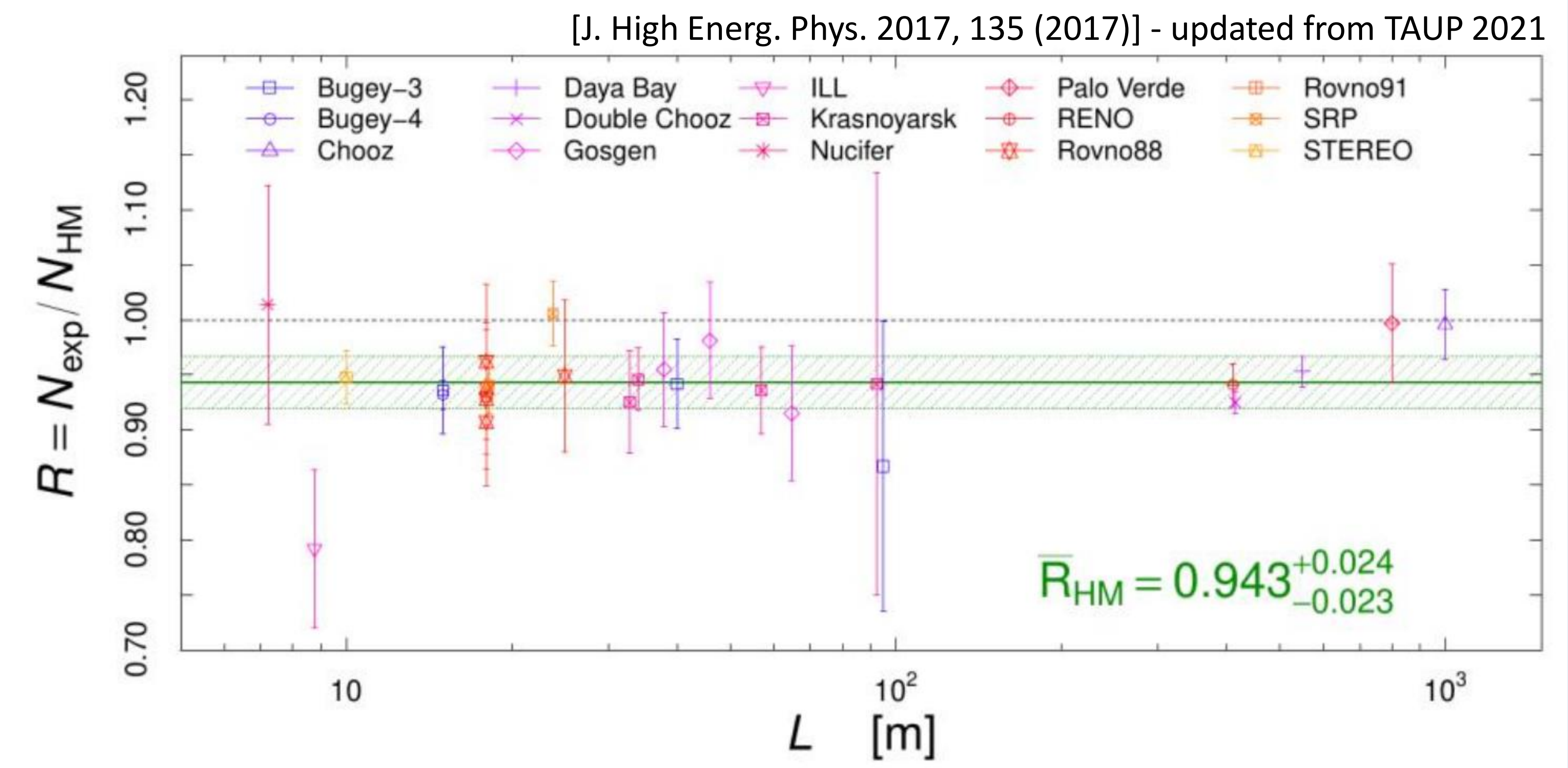
☺ ▪ **data driven, small experimental uncertainties: σ <3%**

😐 ▪ **conversion based on virtual allowed transition, impact hard to assess**
▪ **no prediction below 1.8 MeV / fission only**

☹ ▪ **several anomalies/discrepancies when compared with measured IBD spectra**
▪ **5% relative tension of S(235U)/S(239Pu) measured at ILL vs new beta spectra measured at KI [Kopeikin et al., Phy. At. Nuc. 84 (2021)]**

IBD anomalies

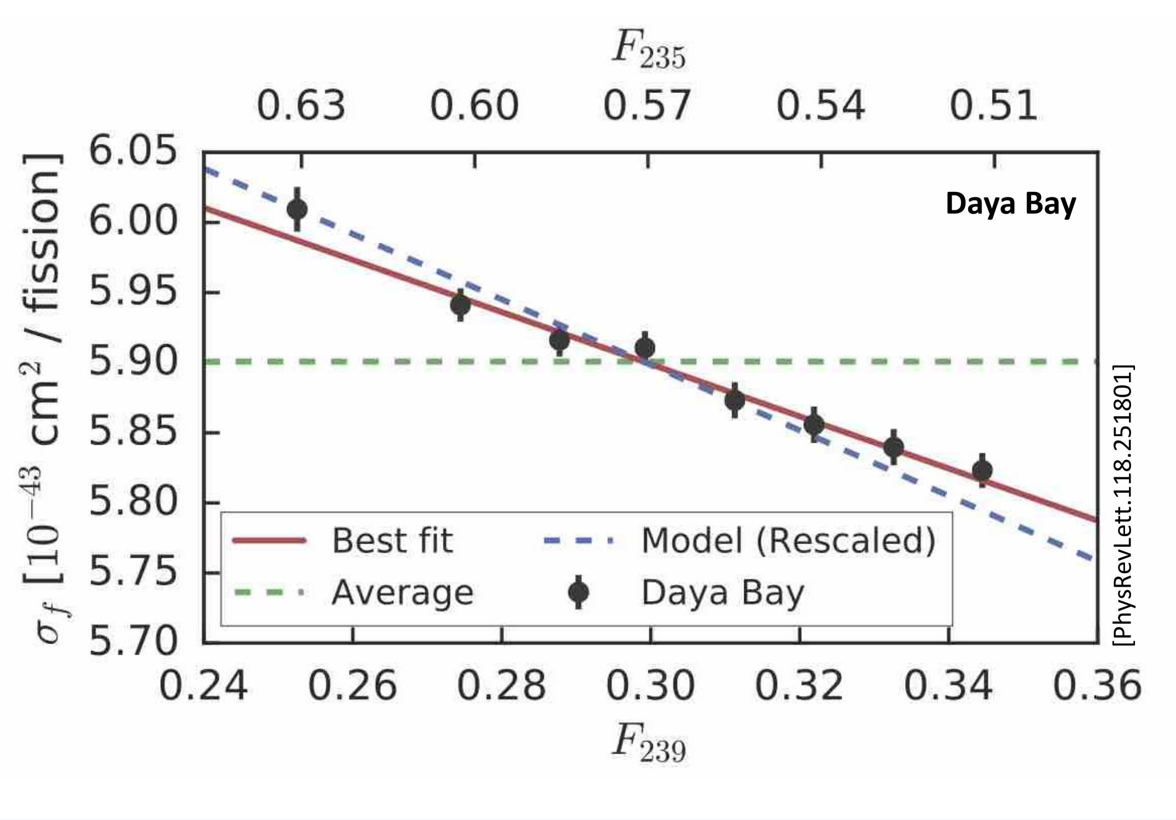
▪ **The « Reactor Antineutrino Anomaly » (RAA) - 2011**



[J. High Energ. Phys. 2017, 135 (2017)] - updated from TAUP 2021

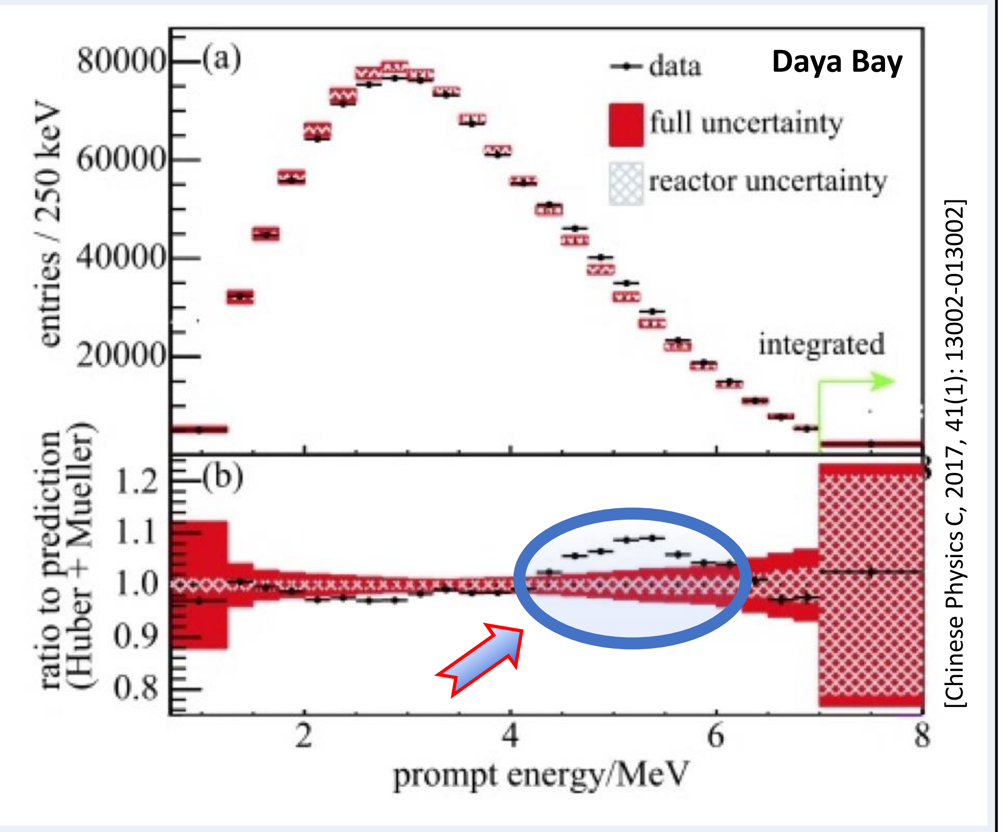
~6% **systematic deficit** of reactor $\bar{\nu}_e$ flux measurements vs predictions of ~20 experiments.

▪ **The fuel evolution anomaly - 2017**



Measured rate correlation with fuel composition incompatible with the prediction

▪ **The « 5 MeV bump » - 2014**



Incompatible measured and expected shape for the estimated uncertainties

IV. Fission $\bar{\nu}_e$ spectra

Spectra from IBD

Several IBD experiments have released unfolded IBD spectra & cov. matrices

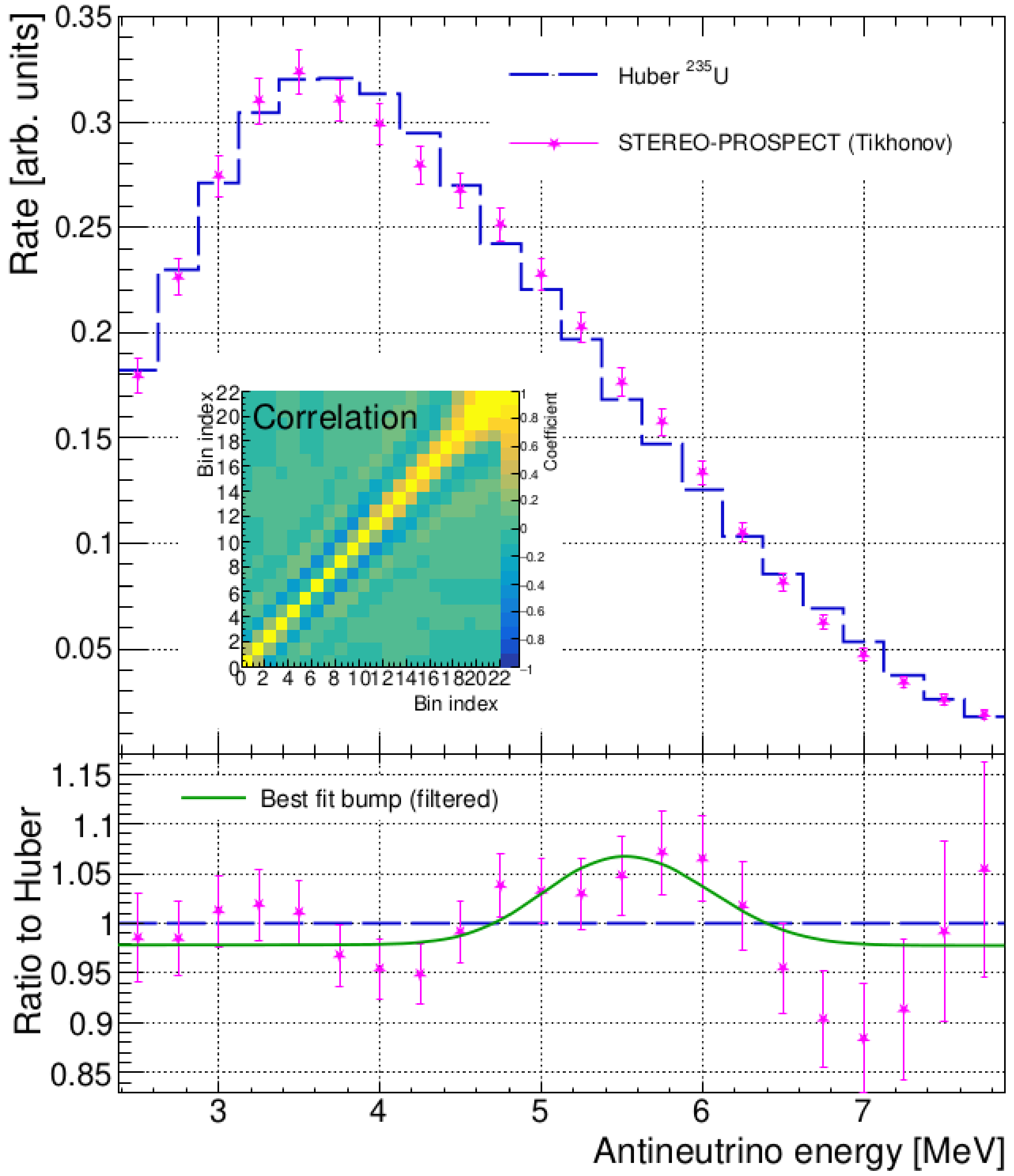
- Mixture U/Pu (PWR): DayaBay / RENO / NEOS
- Pure 235U: STEREO-PROSPECT
- Pu « combo »: DayaBay

⇒ **can be used as references for CEvNS prediction**

- bypass anomalies observed with H/M spectra, percents level uncertainties
- detailled procedure in [10.1088/1674-1137/abfc38] (with fuel content correction)

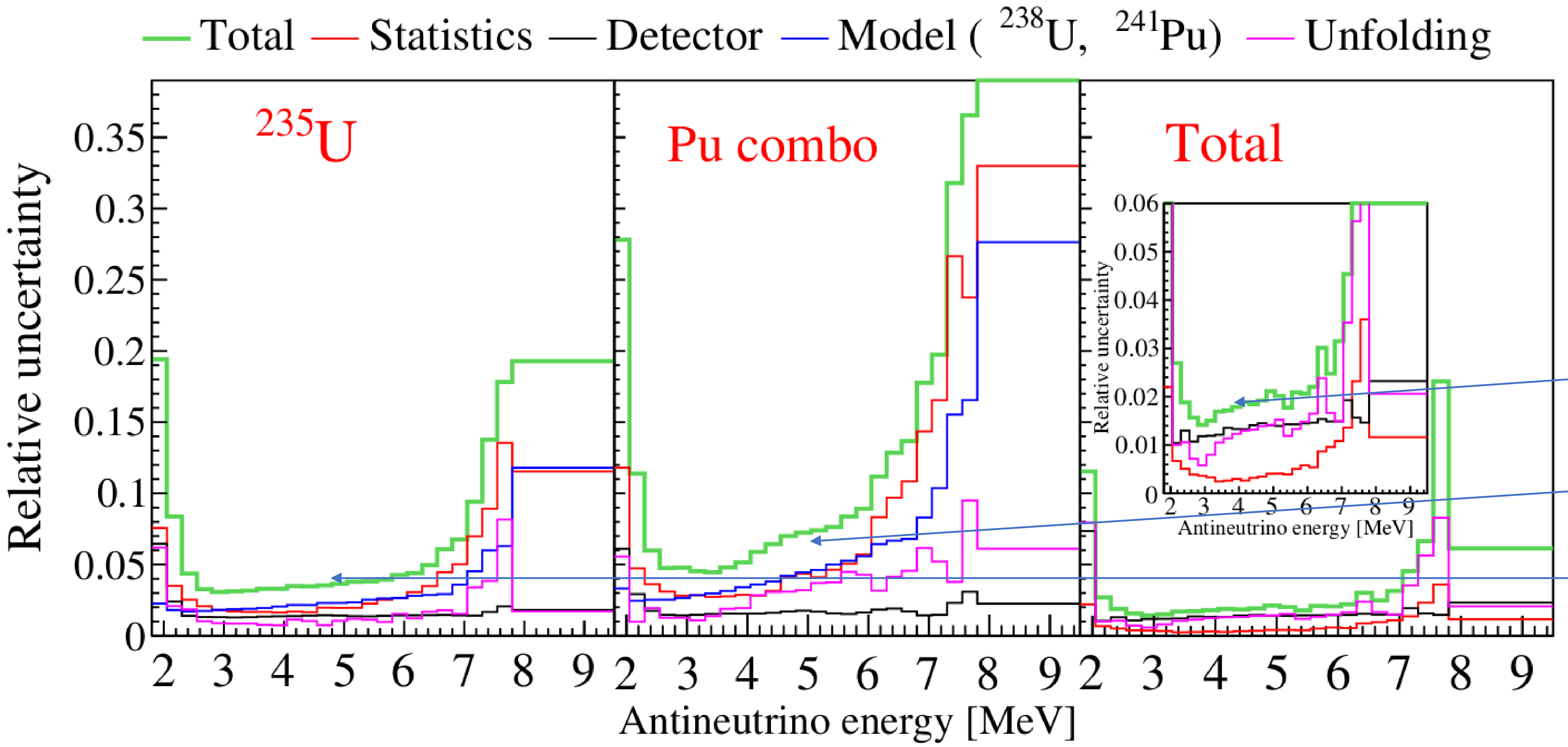
$$\begin{aligned}\boldsymbol{S}_A &= \boldsymbol{S}_{\rm total} + \Delta f_{235}\boldsymbol{S}_{235} + \Delta f_{239}\boldsymbol{S}_{239} + \Delta f_{238}\boldsymbol{S}_{238} + \Delta f_{241}\boldsymbol{S}_{241} \\ &= \boldsymbol{S}_{\rm total} + \Delta f_{235}\boldsymbol{S}_{235} + \Delta f_{239}\boldsymbol{S}_{\rm combo} + \Delta f_{238}\boldsymbol{S}_{238} + (\Delta f_{241} - 0.183 \times \Delta f_{239})\boldsymbol{S}_{241}.\end{aligned}$$

STEREO-PROSPECT



[arXiv:2107.0337]

Daya Bay



[10.1088/1674-1137/abfc38]

Total: $\sigma_{\rm shape}$~2%

Pu combo: $\sigma_{\rm shape}$~$5-8\%$

U235: $\sigma_{\rm shape}$~$3-4\%$

IV. Fission $\bar{\nu}_e$ spectra

IBD mean cross-section per fission

PWR

- DayaBay: (5.91 ± 0.09) × 10^{-43} cm^2/fission (σ=1.5%) [Phys. Rev. Lett. 123, 111801 (2019)]
- Double Chooz: (5.71 ± 0.06) × 10^{-43} cm^2/fission (σ=1.0%) [Nature Phys. 16, 558–564 (2020)]
- RENO: (5.84 ± 0.13) × 10^{-43} cm^2/fission (σ=1.5%) [PhysRevLett.122.232501]

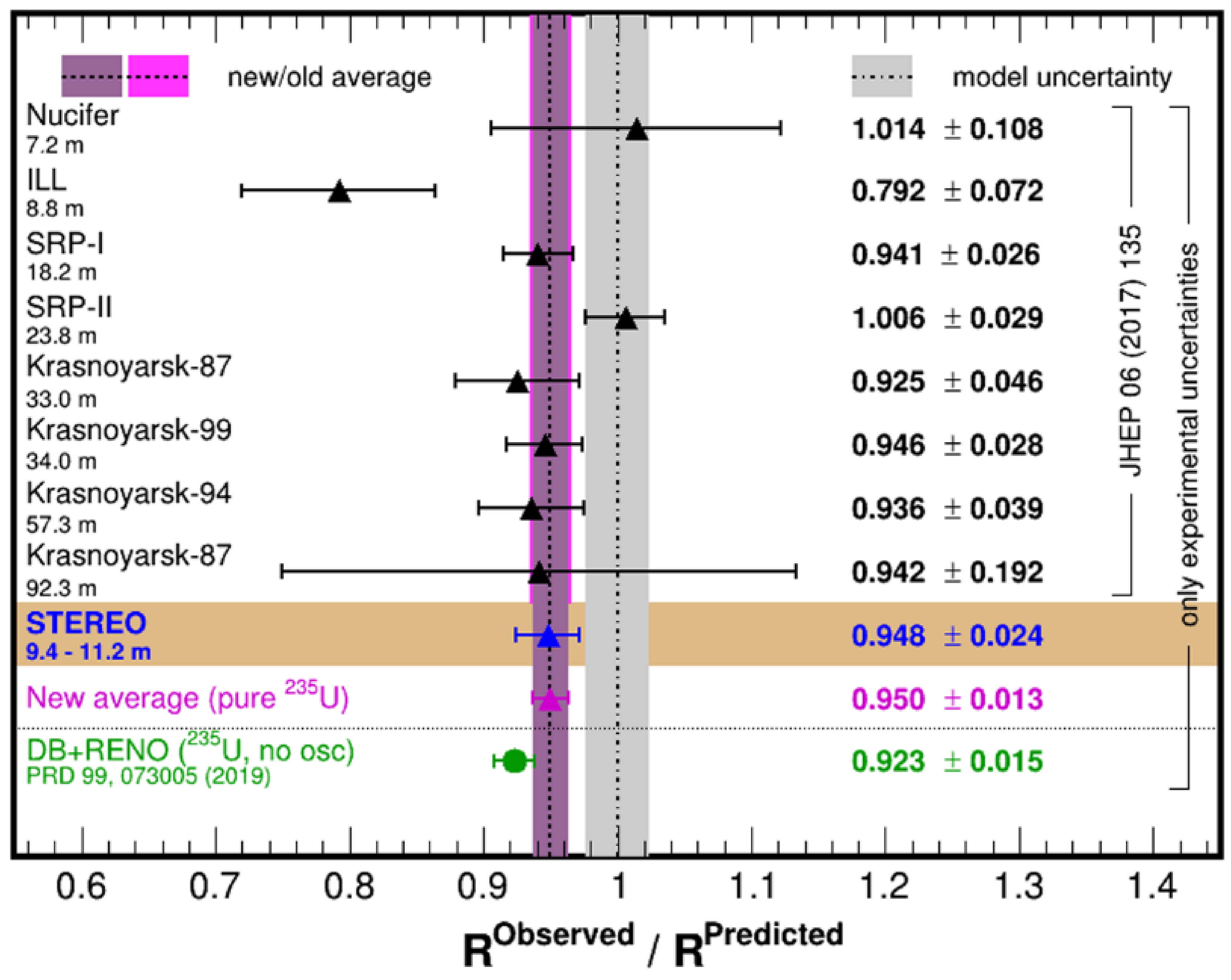
235U:

- DayaBay: (6.10 ± 0.15) × 10^{-43} cm^2/fission (σ=2.5%) [Phys. Rev. Lett. 123, 111801 (2019)]
- RENO: (6.15 ± 0.19) × 10^{-43} cm^2/fission (σ=3.0%) [PhysRevLett.122.232501]
- STEREO: (6.34 ± 0.16) × 10^{-43} cm^2/fission (σ=2.5%) [Phys. Rev. Lett. 125, 201801 (2020)]

239Pu:

- DayaBay: (4.32 ± 0.25) × 10^{-43} cm^2/fission (σ=5.8%) [Phys. Rev. Lett. 123, 111801 (2019)]
- RENO: (4.18 ± 0.26) × 10^{-43} cm^2/fission (σ=6.2%) [PhysRevLett.122.232501]

235U



[10.1103/PhysRevLett.125.201801]

➡ **CEvNS rates (E>1.8 MeV) predictable with a small uncertainty: ~2-3%**

↳ *value depending of the target material, recoil energy threshold & fuel content*

IV. $\bar{\nu}_e$ spectra – any contributors

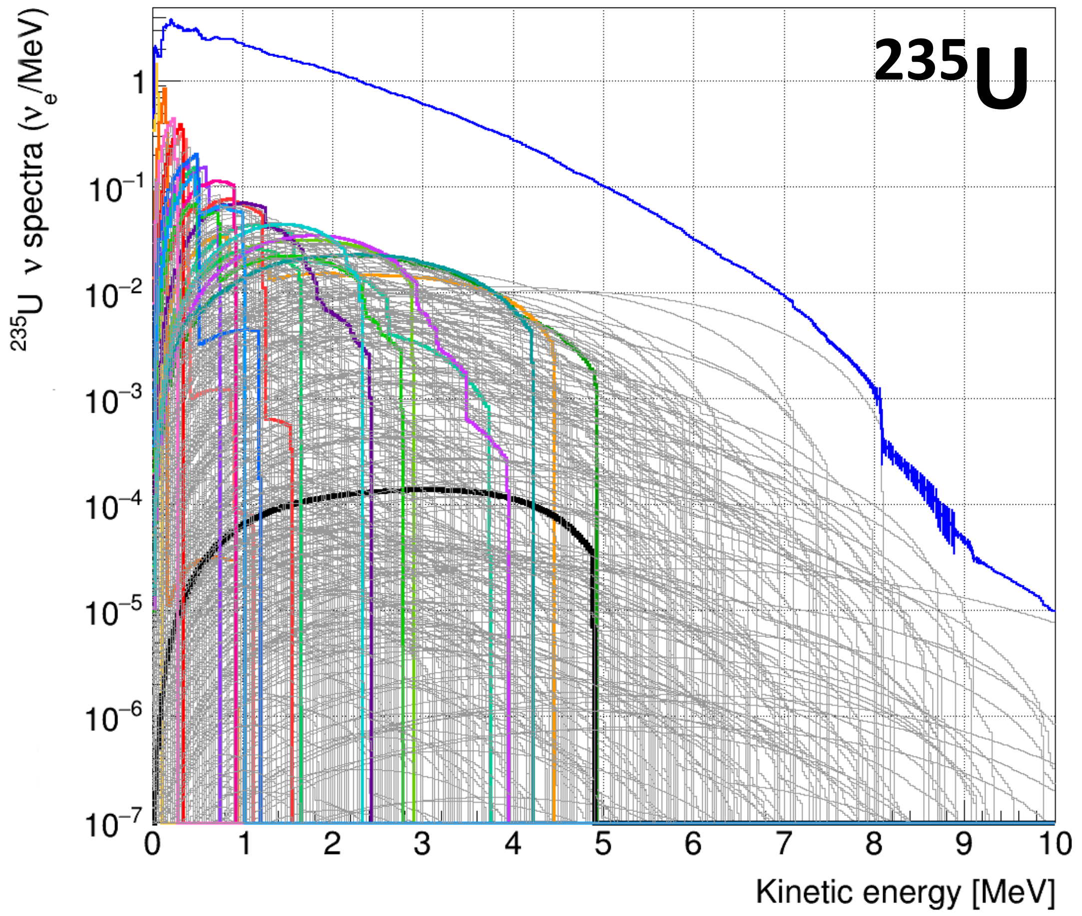
Summation calculation

- V-A theory of the β^- decay

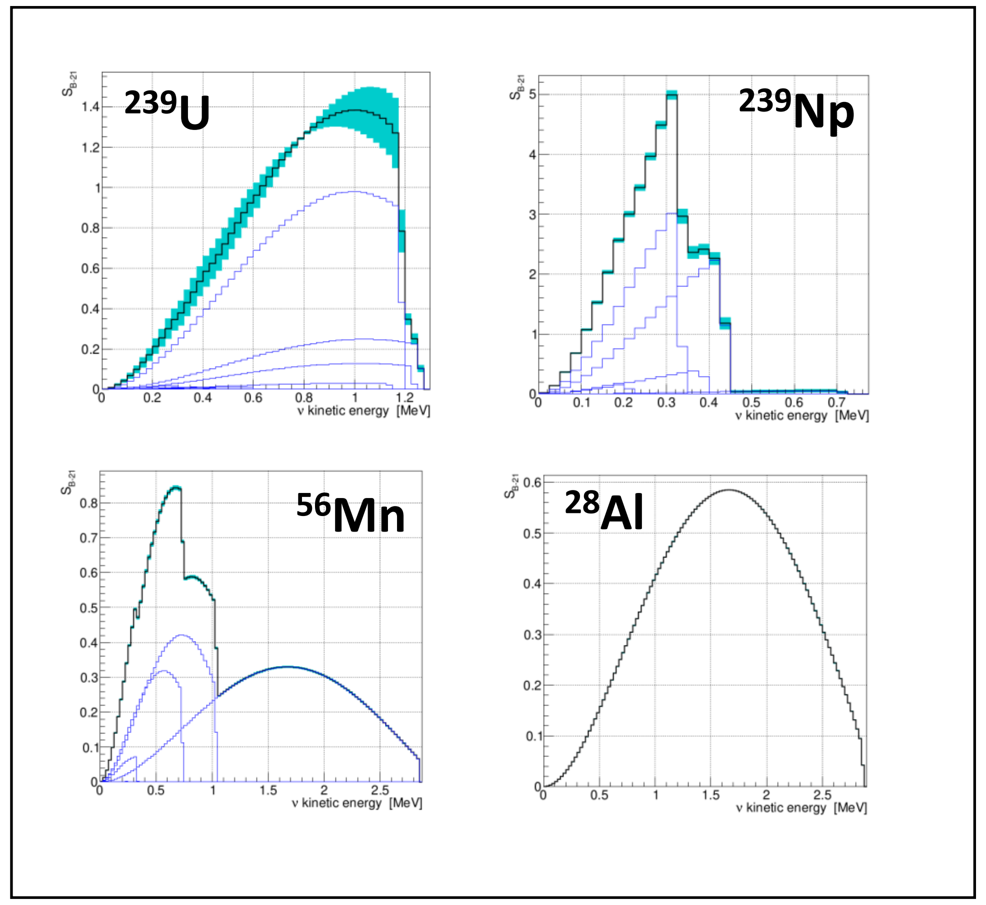
$$S_\beta(W) = KF_0(Z,W)C(Z,W)pW(W_0 - W)^2$$

- Branch by branch modeling of all β^- transitions involved
- S(E): summation over all transitions

Fission spectra



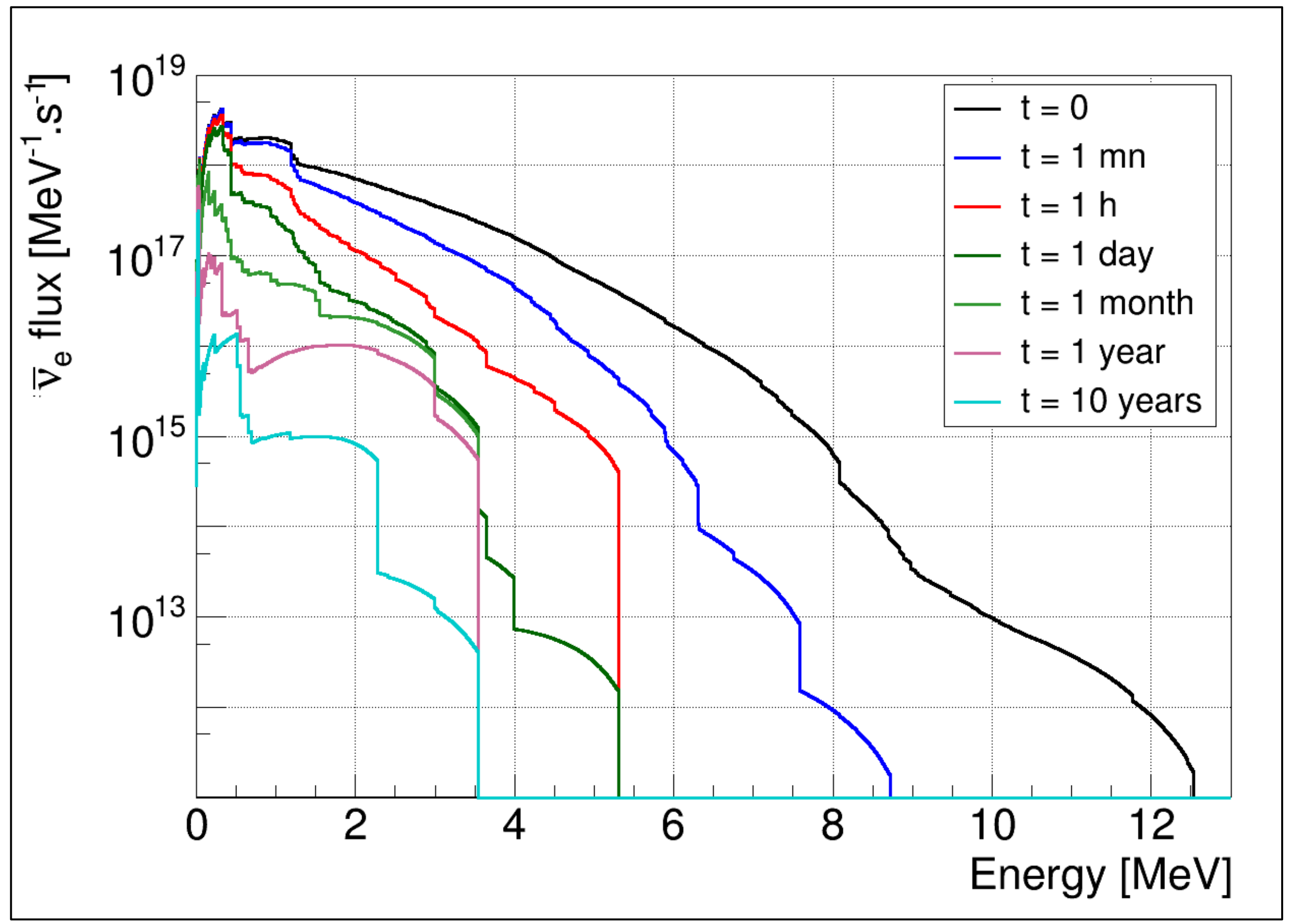
Activated materials



Required for:

- Fission spectra below 1.8 MeV
- $\bar{\nu}_e$ spectra from activated materials
- $\bar{\nu}_e$ from spent fuel

Residual – spent fuel



Main drawback of summation calculation: very difficult to evaluate systematic uncertainties

↳ *On-going effort in the Saclay group at CEA to revised fission, activation and residual $\bar{\nu}_e$ spectra* ***with uncertainty budget*** *in the context of IBD & CEvNS experiments with the BESTIOLE code (L. Perissé et al.)*

Conclusions

- IBD data usable to predict CEvNS rate from $\bar{\nu}_e$ above 1.8 MeV with high precision

$$\Rightarrow \langle \sigma_{CE\nu NS} \rangle^{pred} \sim 2-3\%$$

… and more data to come!

- Low sensitivity of CEvNS experiments to low energy neutrino (E<1.8 MeV)

Requirement
- targets with low nucleus mass
- very low recoil energy threshold

⇒ Predictable with summation calculation