Residual reactor $\overline{\nu}_e$ measurement with the Double Chooz experiment

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Technical University of Munich

AIEA meeting
January 16, 2023

Summary

I. The Double Chooz experiment

- experimental principle
- analysis highlight and latest results

II. Residual antineutrinos

- modeling
- generality about residual antineutrinos

III. DC off-off periods

- prediction
- preliminary data/prediction comparison

IV. Conclusion

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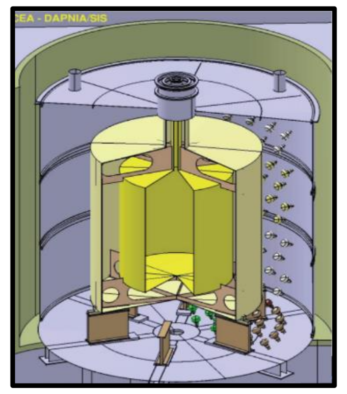
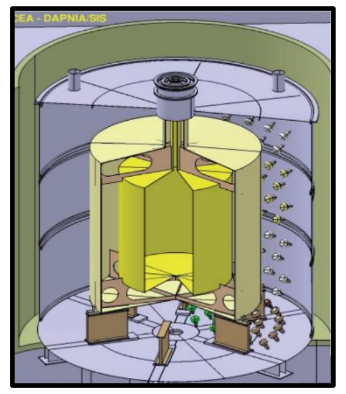
θ_{13} measurement

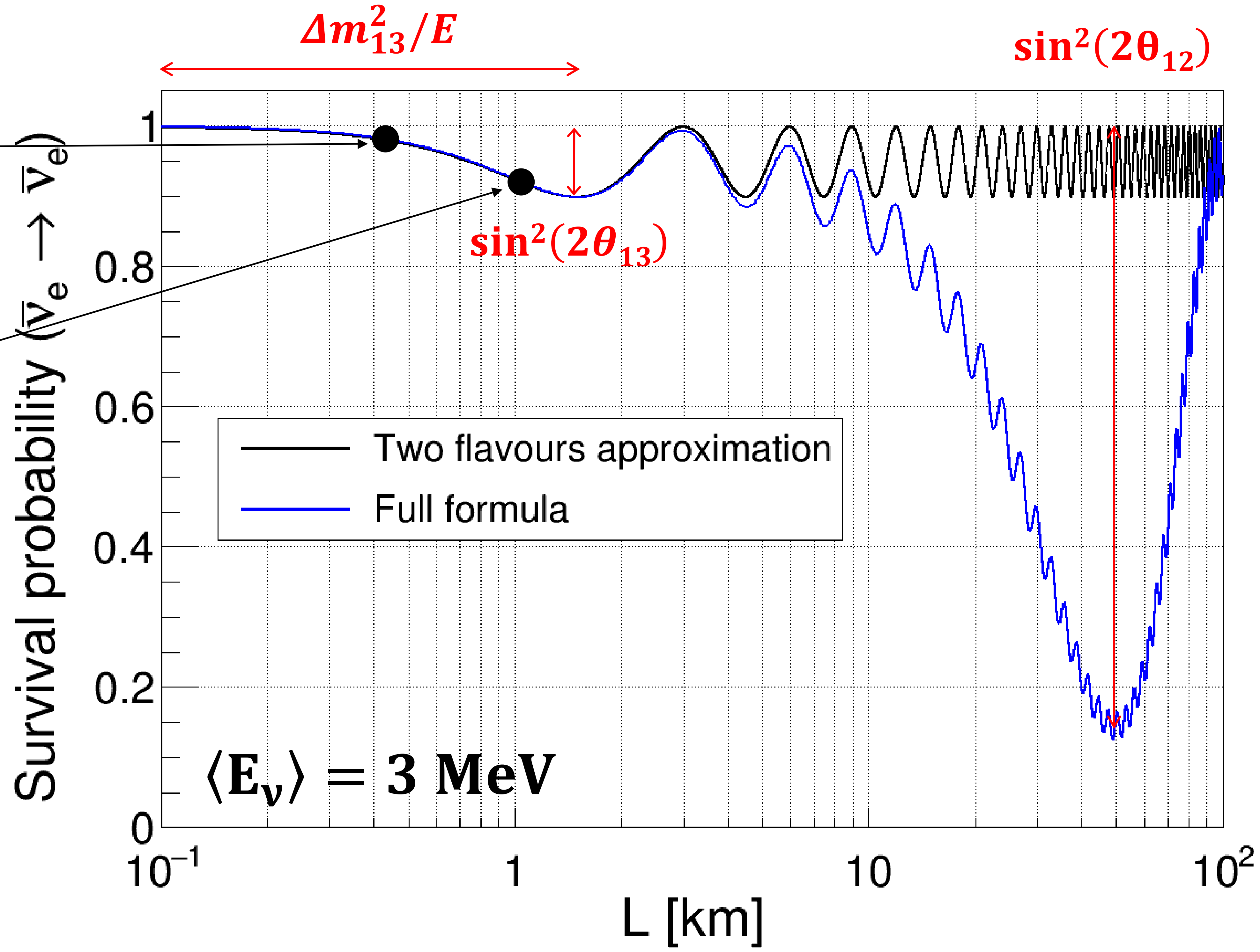
Non oscillation probability:

$$P_{\bar{\nu}_e \to \bar{\nu}_e}(L,E) \simeq 1 - \mathbf{sin^2(2\theta_{13})}\,\sin^2\left(1.267\,\frac{\Delta m_{13}(\mathrm{eV^2})\mathrm{L(m)}}{E(\mathrm{MeV})}\right)$$

(two flavours approximation)


Near detector (ND)


Far detector (FD)

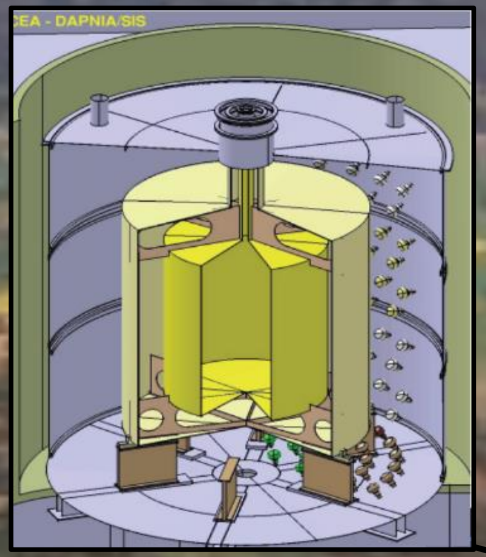


⇒ Systematic uncertainties highly suppressed in multiple detectors configuration at different baselines with identical detectors

Chooz-B Nuclear power plant

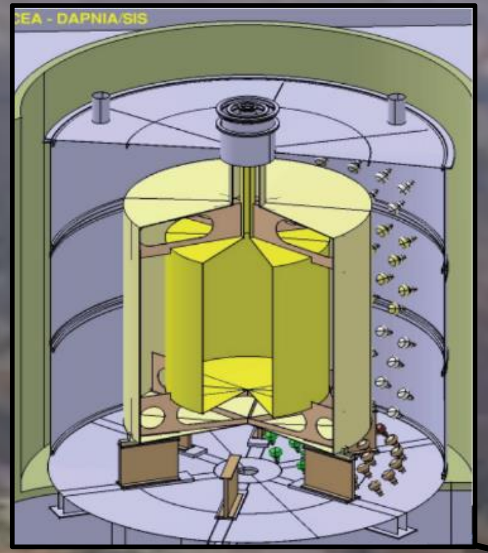
Near Detector

- <L>~400 m
- ~120 mwe
- ~900 IBD$_{\bar{\nu}_e}$/d



Far Detector

- <L>~1050 m
- ~300 mwe
- ~150 IBD$_{\bar{\nu}_e}$/d



B2

B1

N4-PWR
2x4.25 GW$_{th}$
~2.10^{21} $\bar{\nu}_e$/s

Almost iso-flux site configuration
(Same proportion of B1/B2 flux in ND & FD)
⇒ ND is almost a perfect monitor of FD

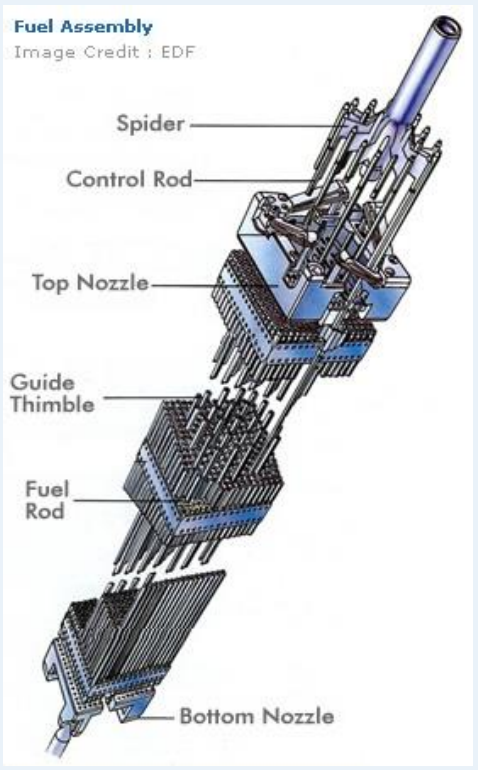
Reactor antineutrinos

Commercial Pressurized Water Reactor

- Fresh fuel : UO_2 (^{238}U + few percent of ^{235}U)
  ↳ Other fissile with fuel depletion

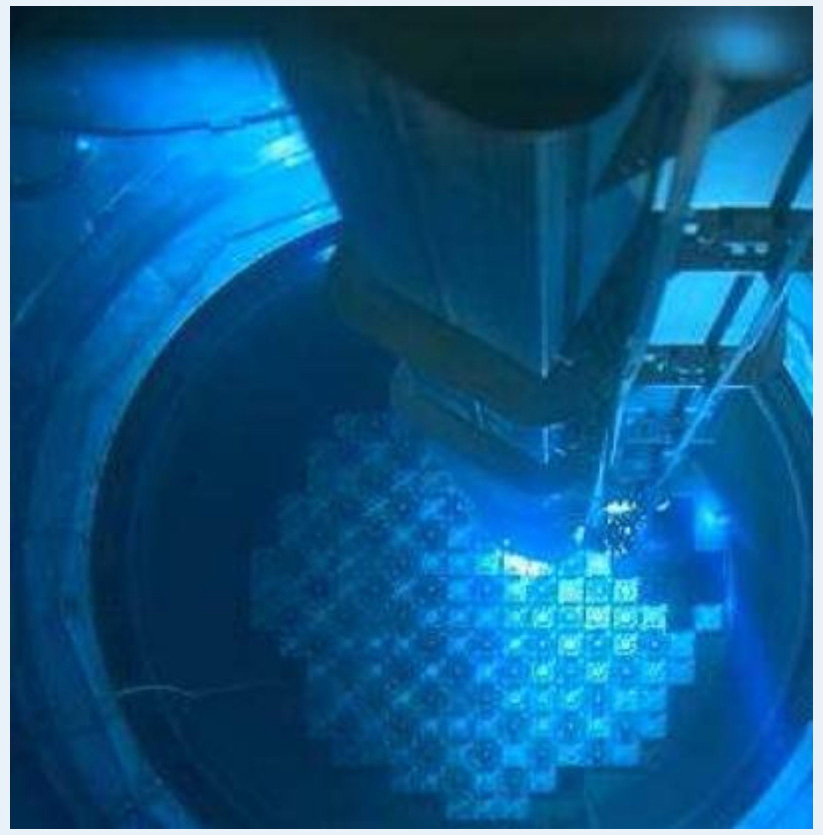
- Thermal power mainly induced by fission of 4 nuclei:

^{235}U, ^{239}Pu, ^{238}U, ^{241}Pu



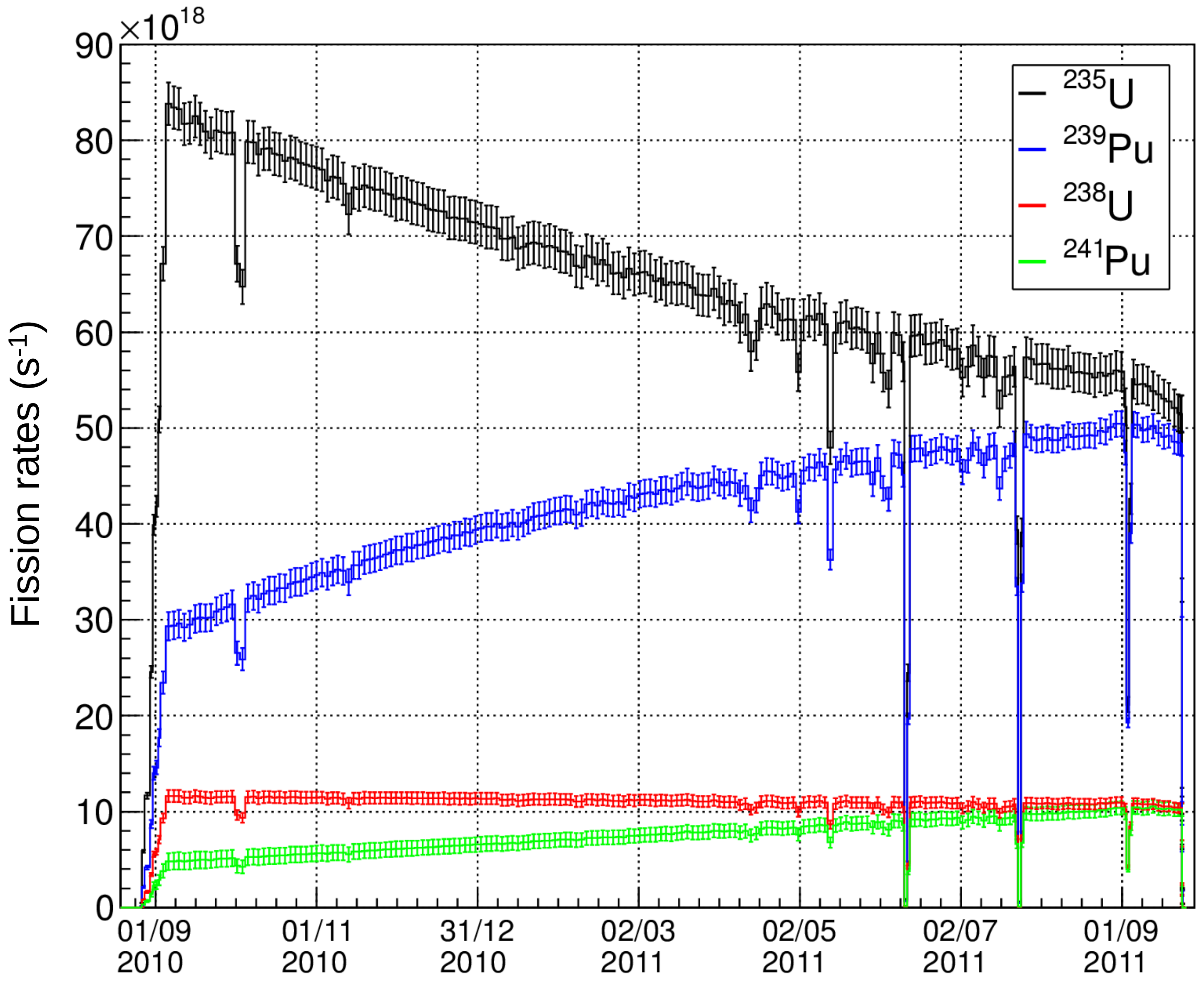
Assembly rods

x 205



N4-PWR reactor core

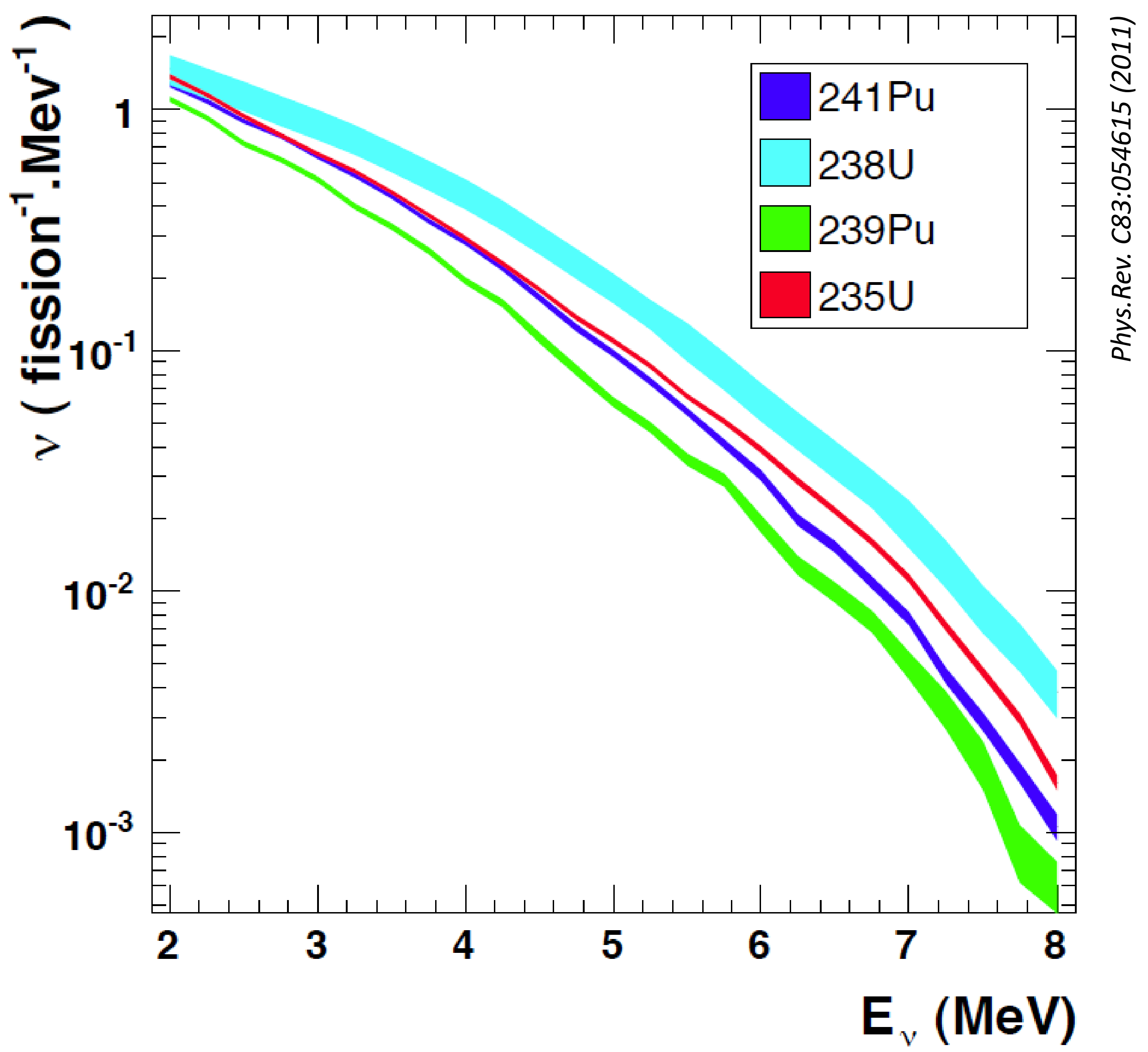
Expected number of IBD events



$$N_{\bar{\nu}_e}^{exp}(E,t) = \sum_{B1,B2} \frac{N_p \epsilon}{4\pi L^2} \times \frac{P_{th}(t)}{\langle E_f \rangle} \times \langle \boldsymbol{\sigma_f} \rangle$$

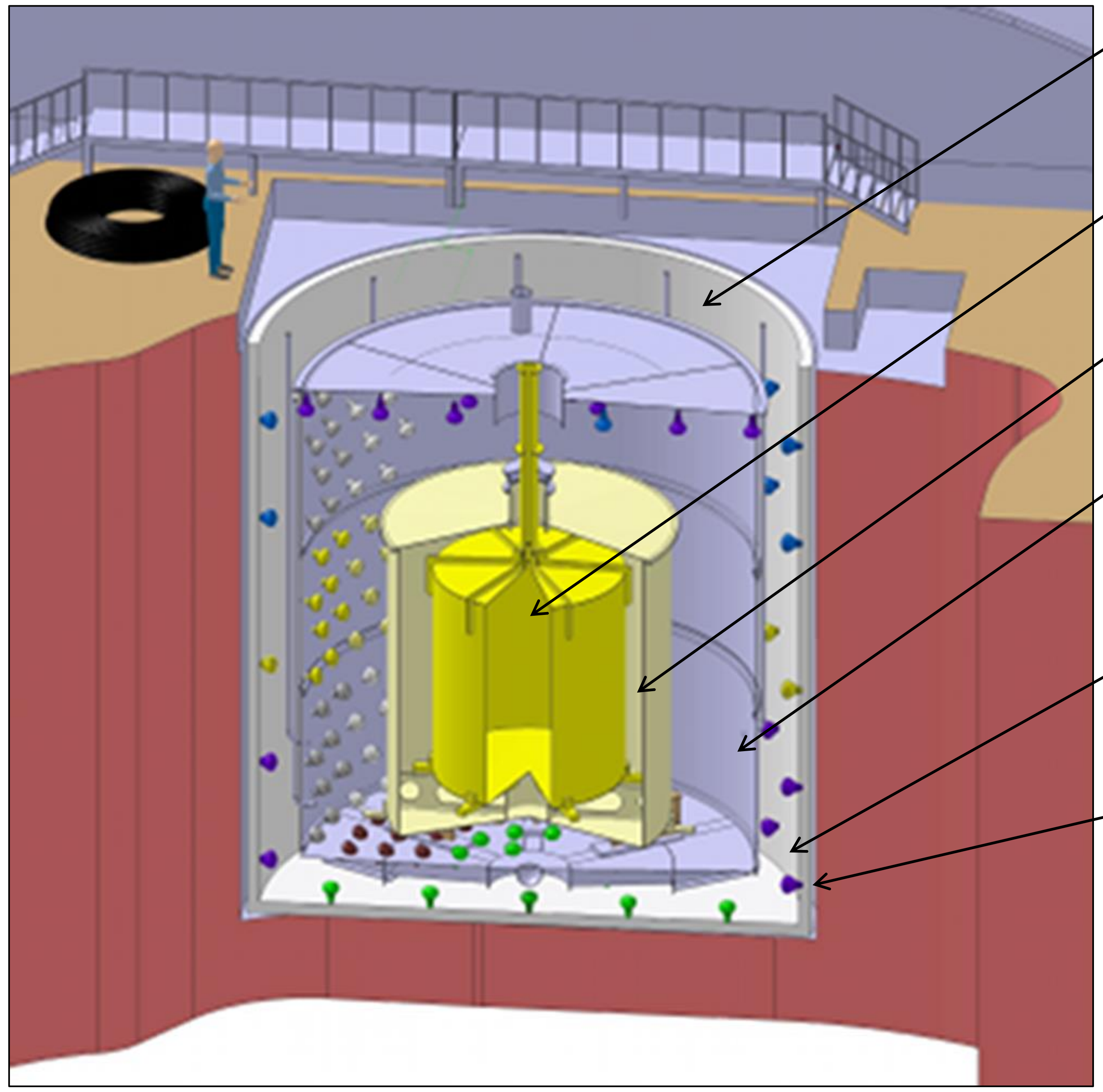
$$\langle \sigma_f \rangle_k = \int_0^x dE \; \boldsymbol{S_k(E)} \; \sigma_{IBD}(E)$$

Fission spectra



Double Chooz detectors

Detector design



Outer Veto: plastic scintillator strips

ν-Target: liquid scintillator doped with 1 g/l of Gd (10.3 m^3)

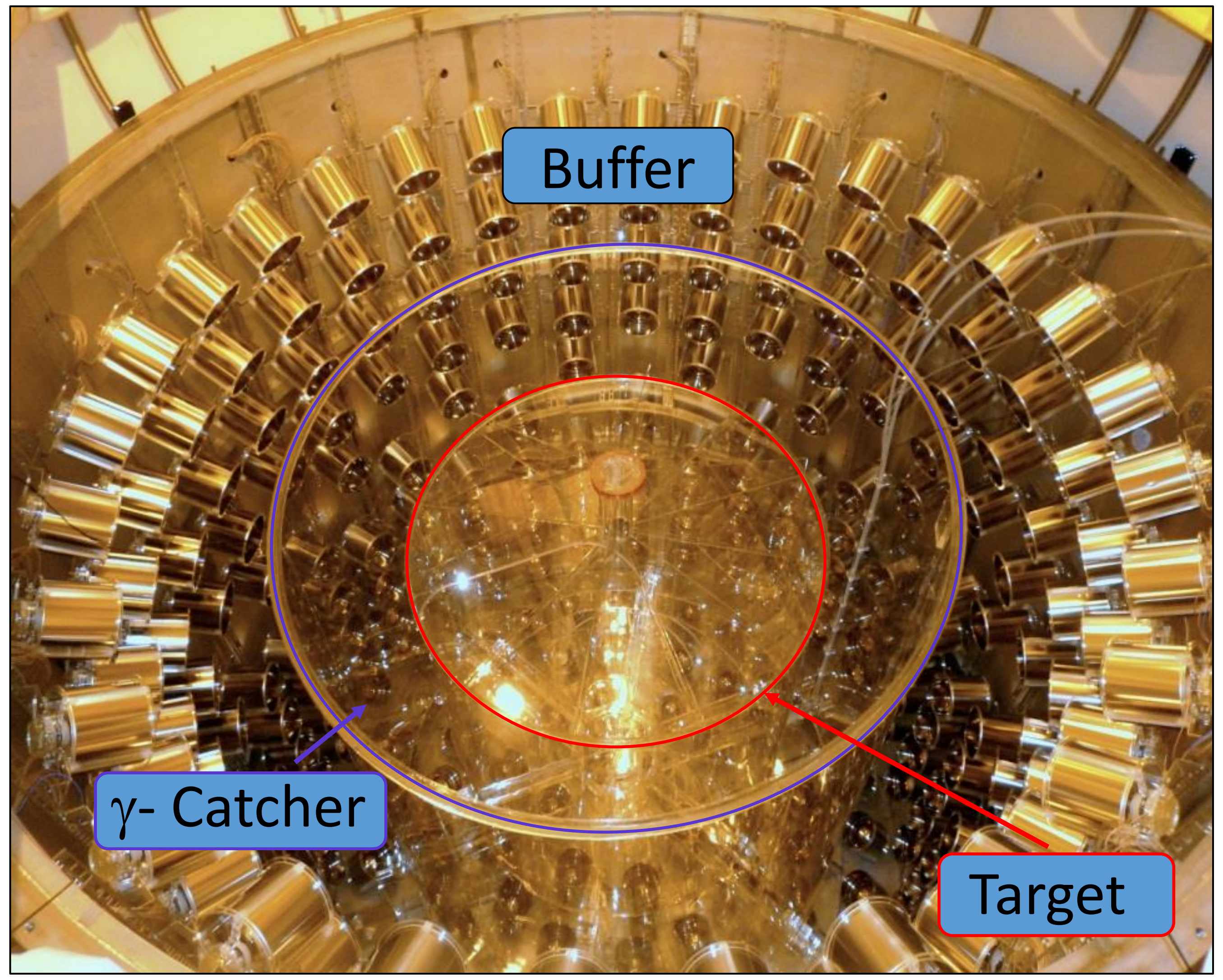
γ-Catcher: liquid scintillator (22.3 m^3)

Buffer: - mineral oil (110 m^3)
- **390 PMTs** (10 inches)

Inner detector

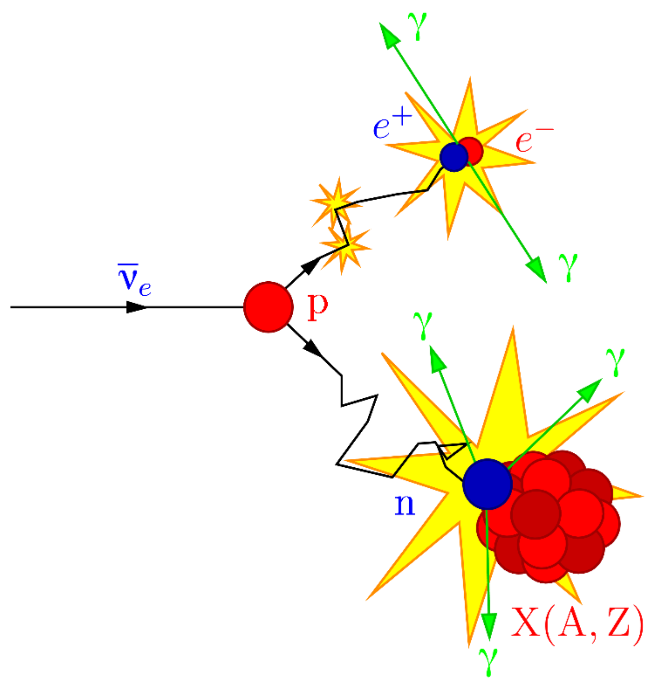
Inner Veto: - liquid scintillator (90m^3)
- 78 PMTs (8 inches)

Shielding: ~250t steel shielding



Two identical detectors
⇒ stable Gd loaded liquid scintillator developped (same batch)

Detection



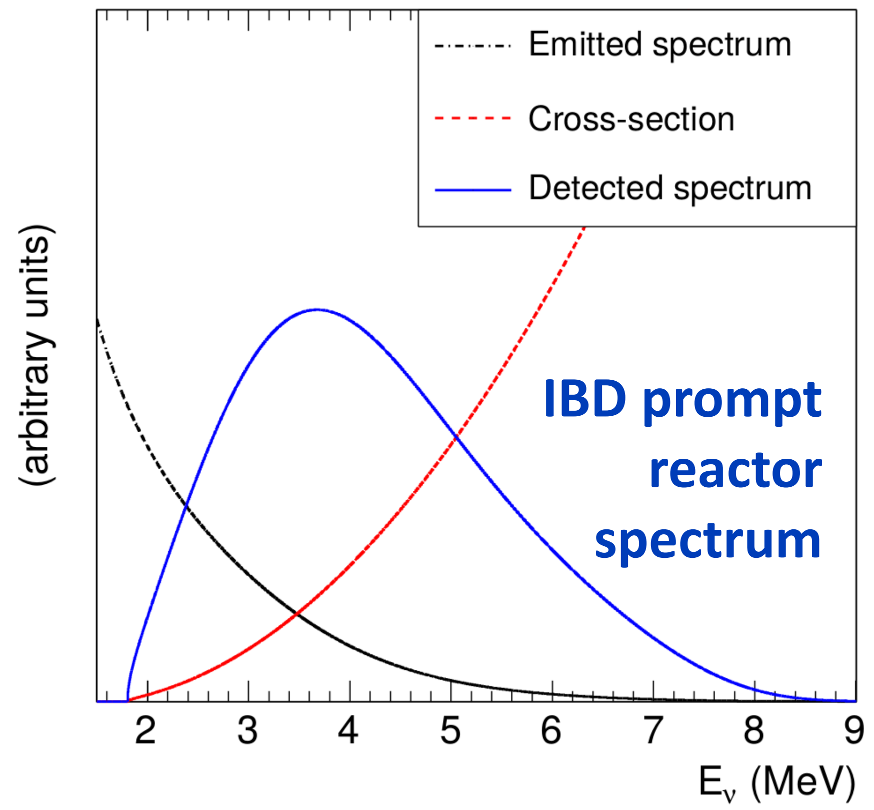
Inverse beta decay reaction (IBD)

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

- **Prompt signal:** ionisation induced by positron + annihilation γ's
- **Delayed signal:** γ's from neutron capture on Gd or/and H

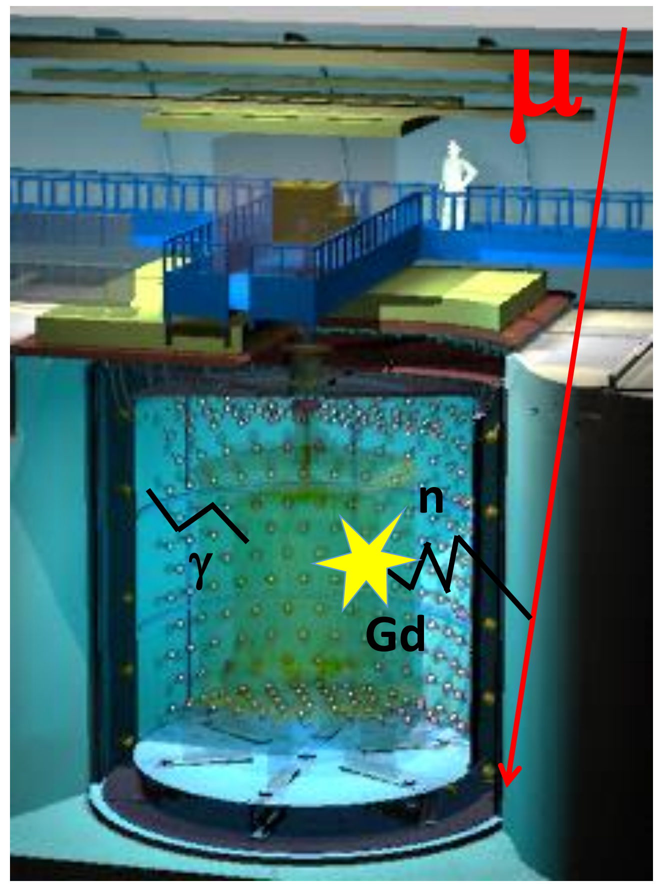
⇒ $\bar{\nu}_e$ **signature:** spatial and temporal correlation prompt/delayed signal

Phys. Rev. C 83, 054615

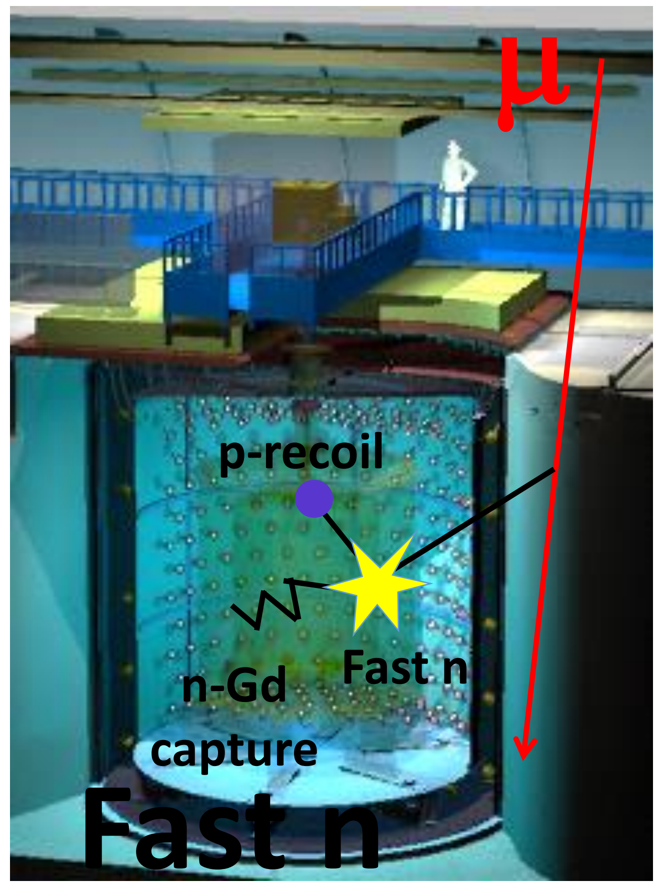


$E_{thresh.}$: 1.8 MeV
$\langle\sigma\rangle \sim 10^{-43}cm^2$

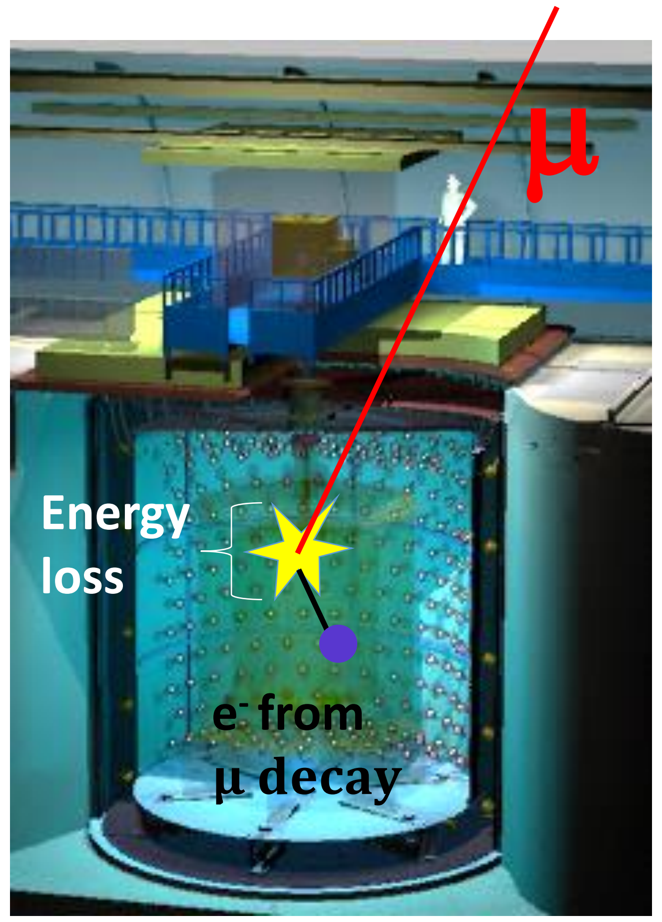
Backgrounds



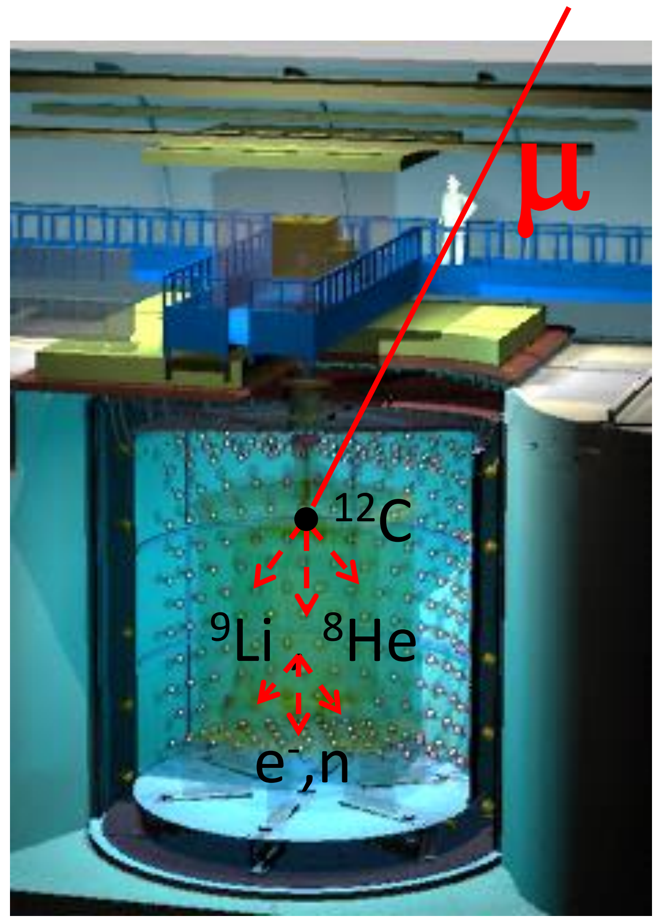
Accidental



Fast neutron



Stopping muon



Cosmogenic β-n

Two types of background

- **Accidental coincidence:**

$$\gamma + \text{spallation } n$$

- **Fast neutron:**

$$n + p \rightarrow p + n$$

- **Stopping muon:**

$$\mu \rightarrow e^- + \nu + \nu$$

- **Cosmogenic β-n emitter:**

$$^{9}Li \rightarrow \alpha + \alpha + e^- + \nu + n$$

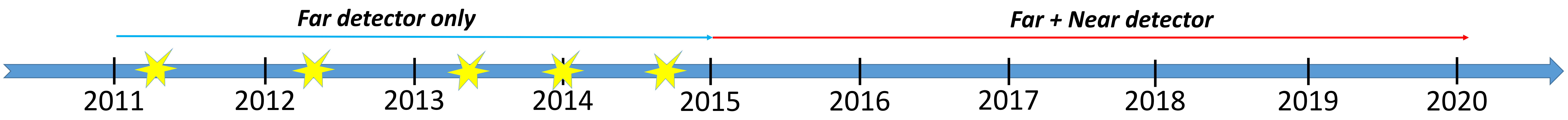
correlated

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

Prompt mimic

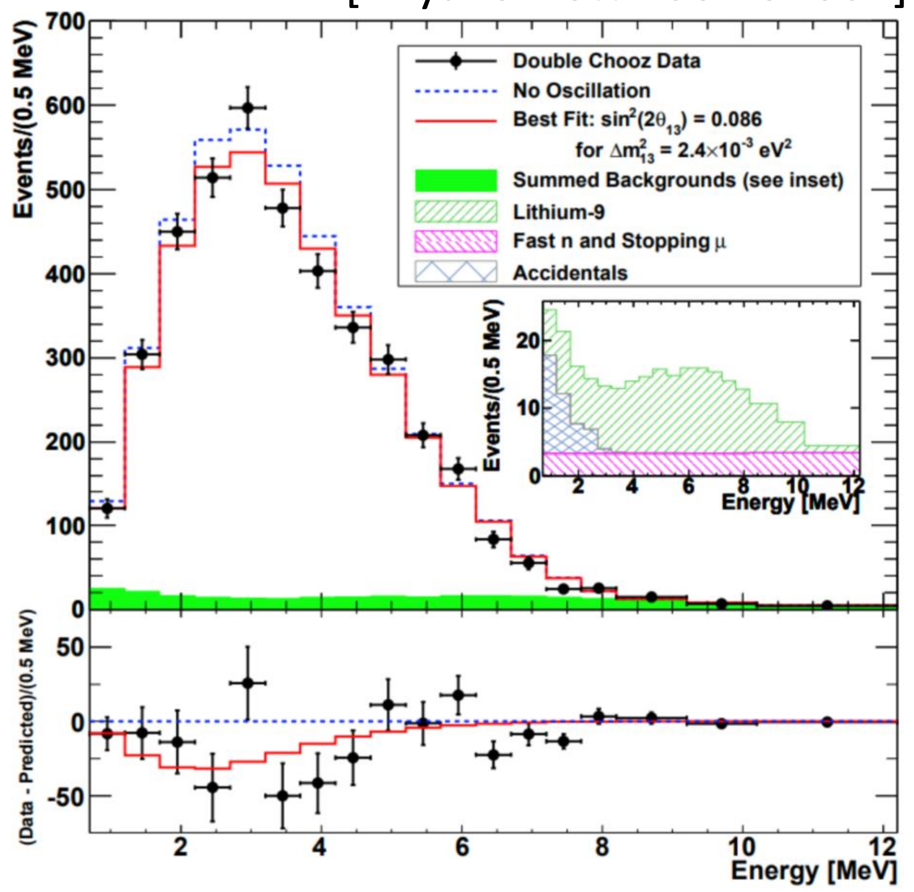
Delayed mimic

Double Chooz timeline



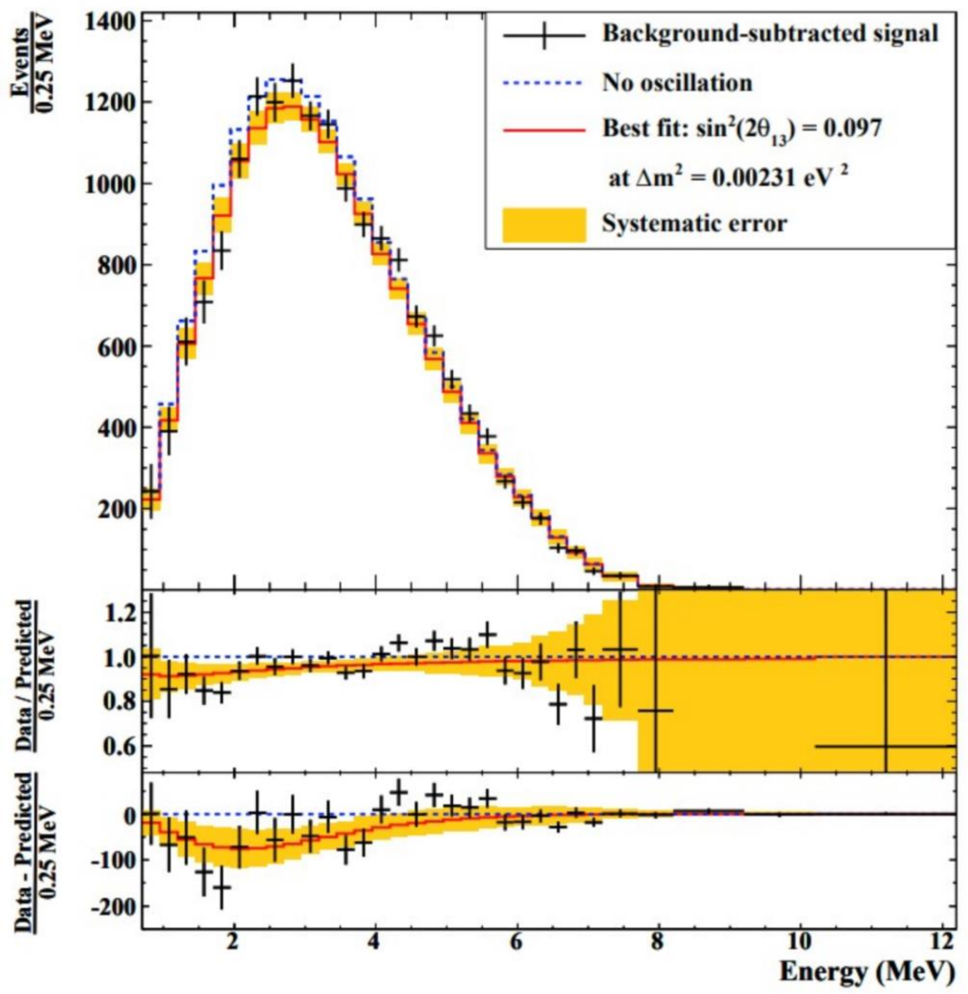
Reactor $\theta_{13} > 0$ (@95% CL)
3σ in combination with T2K

[PhysRevLett.108.131801]



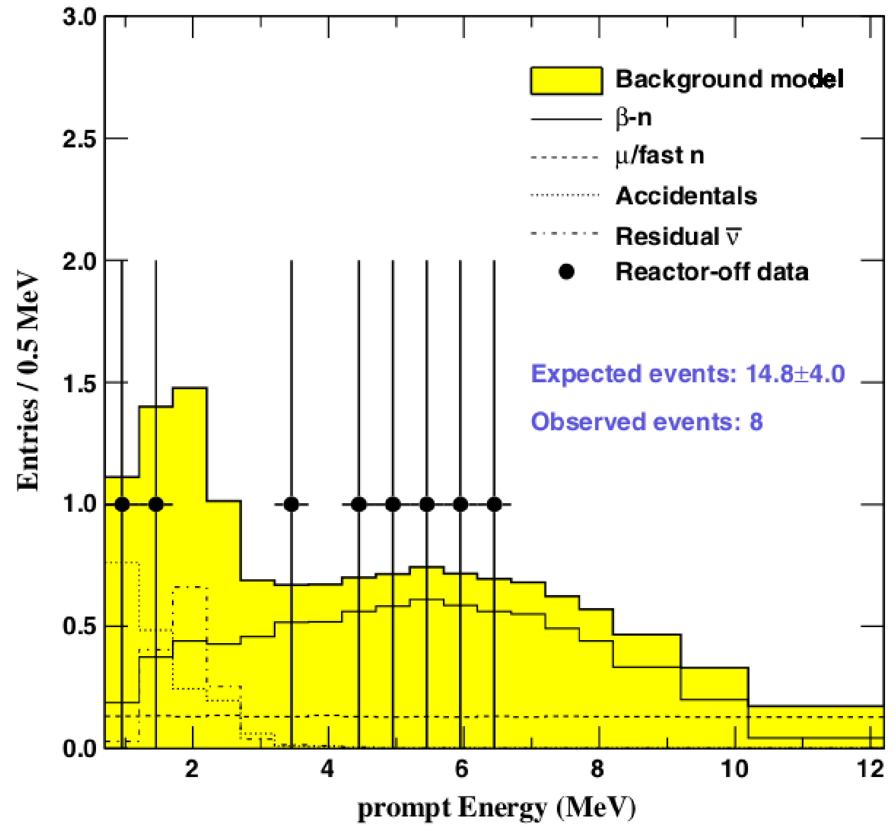
First θ_{13} measurement with n-H captures
thought to be impractical

[j.physletb.2013.04.050]



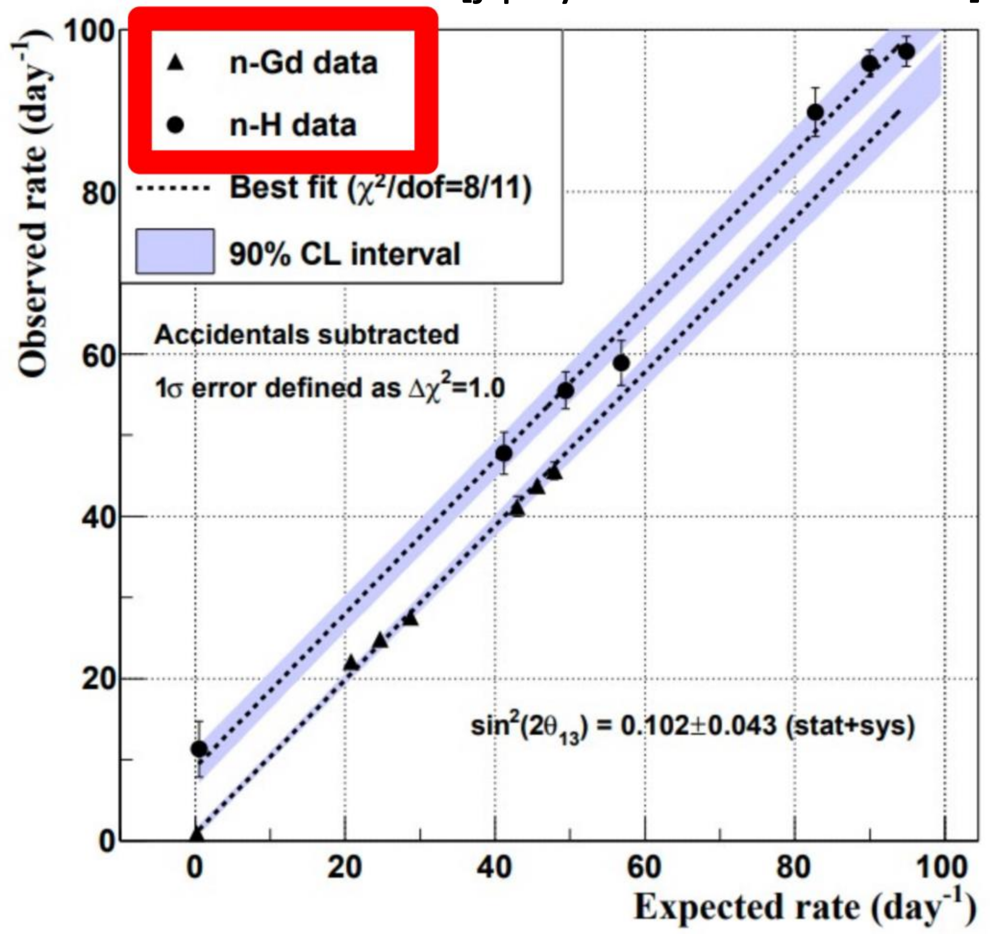
Direct measurement of backgrounds using reactor off data

7.6 days, 1.4 ± 0.6 $\mathrm{IBD}_{\bar{\nu}_e}$ expected, background model validation



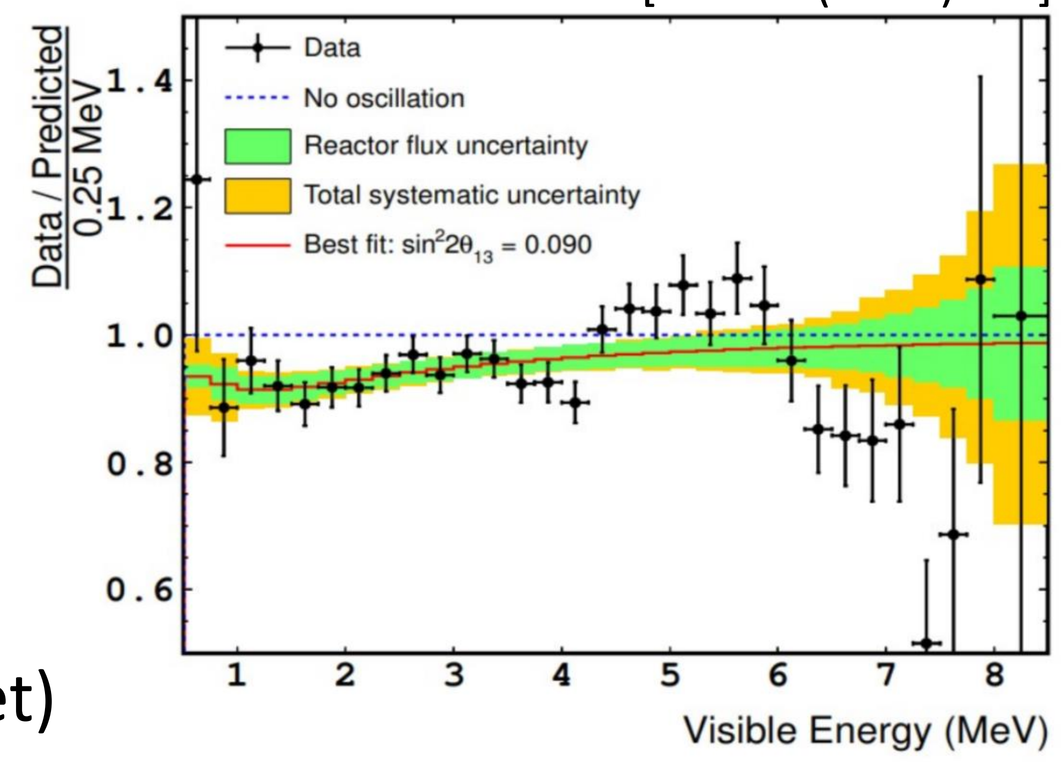
First θ_{13} via Reactor Rate Modulation
n-Gd & n-H (independent dataset)

[j.physletb.2014.04.045]

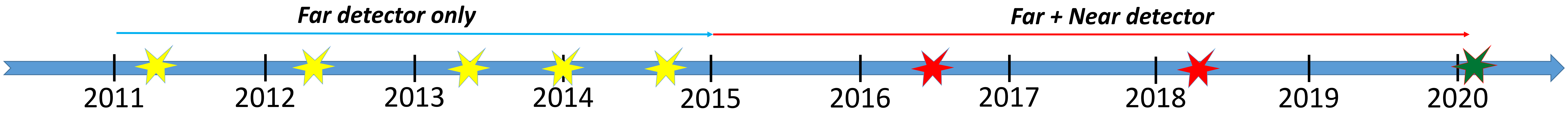


First report on the reactor spectrum distortion
18k IBDs at Far Detector

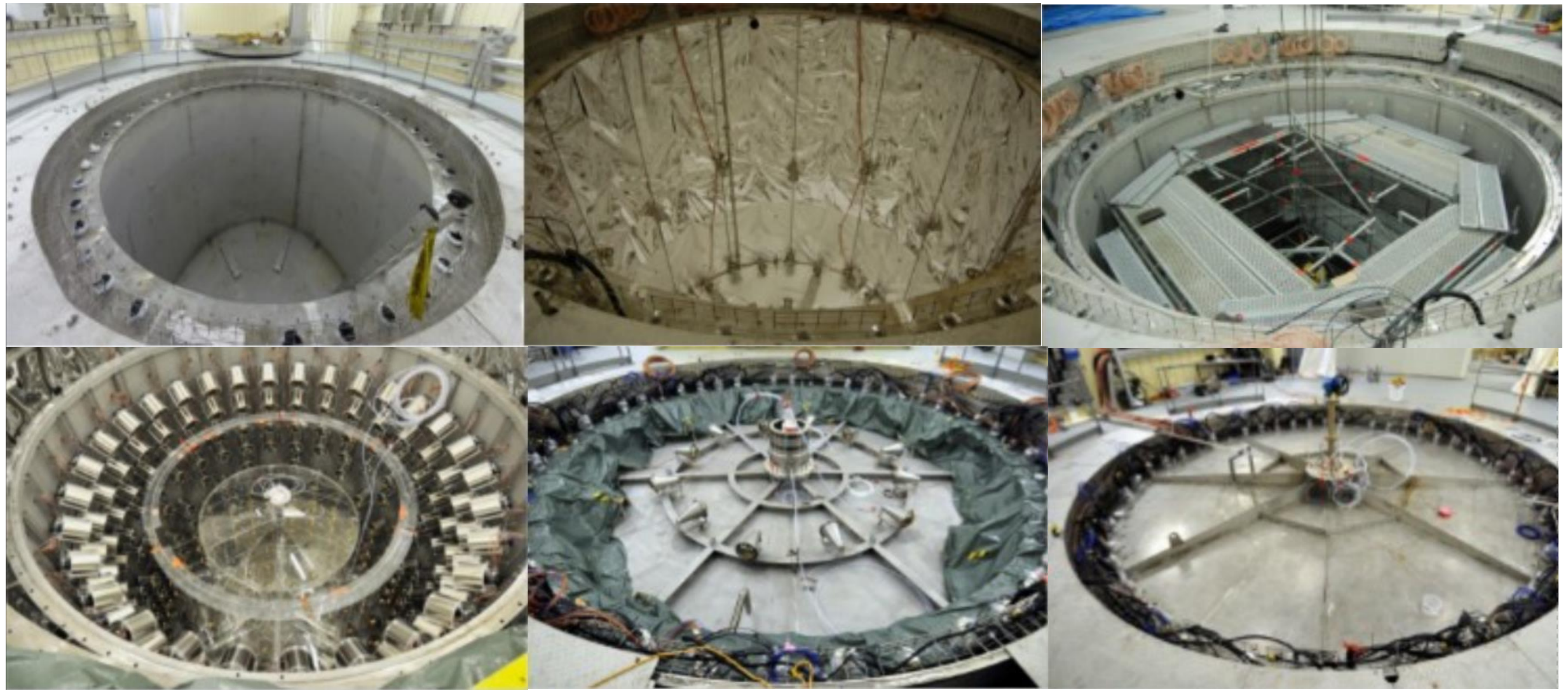
[JHEP10(2014)086]



Double Chooz timeline



2011-2015: near laboratory excavation, detector construction & commissioning



First DC Near + Far Result

- Preliminary @ CERN Seminar
- Officially @ Neutrino 2018
- Published @ Nature Physics - 2020

Hightlight on latest results (1/2)

Nature Physics - 2020

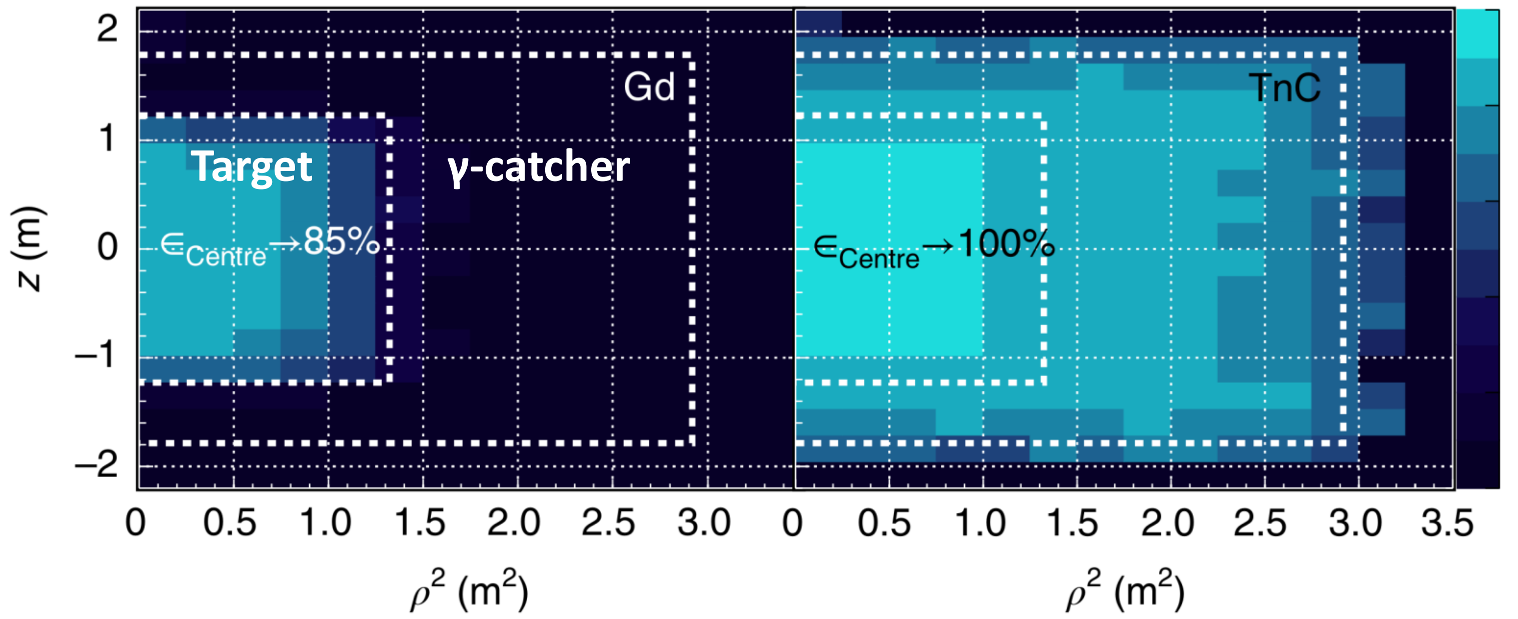
ARTICLES
https://doi.org/10.1038/s41567-020-0831-y
nature physics
Check for updates

Double Chooz θ_{13} measurement via total neutron capture detection

The Double Chooz Collaboration*

Neutrinos were assumed to be massless particles until the discovery of the neutrino oscillation process. This phenomenon indicates that the neutrinos have non-zero masses and the mass eigenstates (ν_1, ν_2, ν_3) are mixtures of their flavour eigenstates (ν_e, ν_μ, ν_τ). The oscillations between different flavour eigenstates are described by three mixing angles ($\theta_{12}, \theta_{23}, \theta_{13}$), two differences of the squared neutrino masses of the ν_2/ν_1 and ν_3/ν_1 pairs and a charge conjugation parity symmetry violating phase δ_{CP}. The Double Chooz experiment, located near the Chooz Electricité de France reactors, measures the oscillation parameter θ_{13} using reactor neutrinos. Here, the Double Chooz collaboration reports the measurement of the mixing angle θ_{13} with the new total neutron capture detection technique from the full data set, yielding $\sin^2(2\theta_{13}) = 0.105 \pm 0.014$. This measurement exploits the multidetector configuration, the isoflux baseline and data recorded when the reactors were switched off. In addition to the neutrino mixing angle measurement, Double Chooz provides a precise measurement of the reactor neutrino flux, given by the mean cross-section per fission $\langle\sigma_f\rangle = (5.71 \pm 0.06) \times 10^{-43}$ cm² per fission, and reports an empirical model of the distortion in the reactor neutrino spectrum.

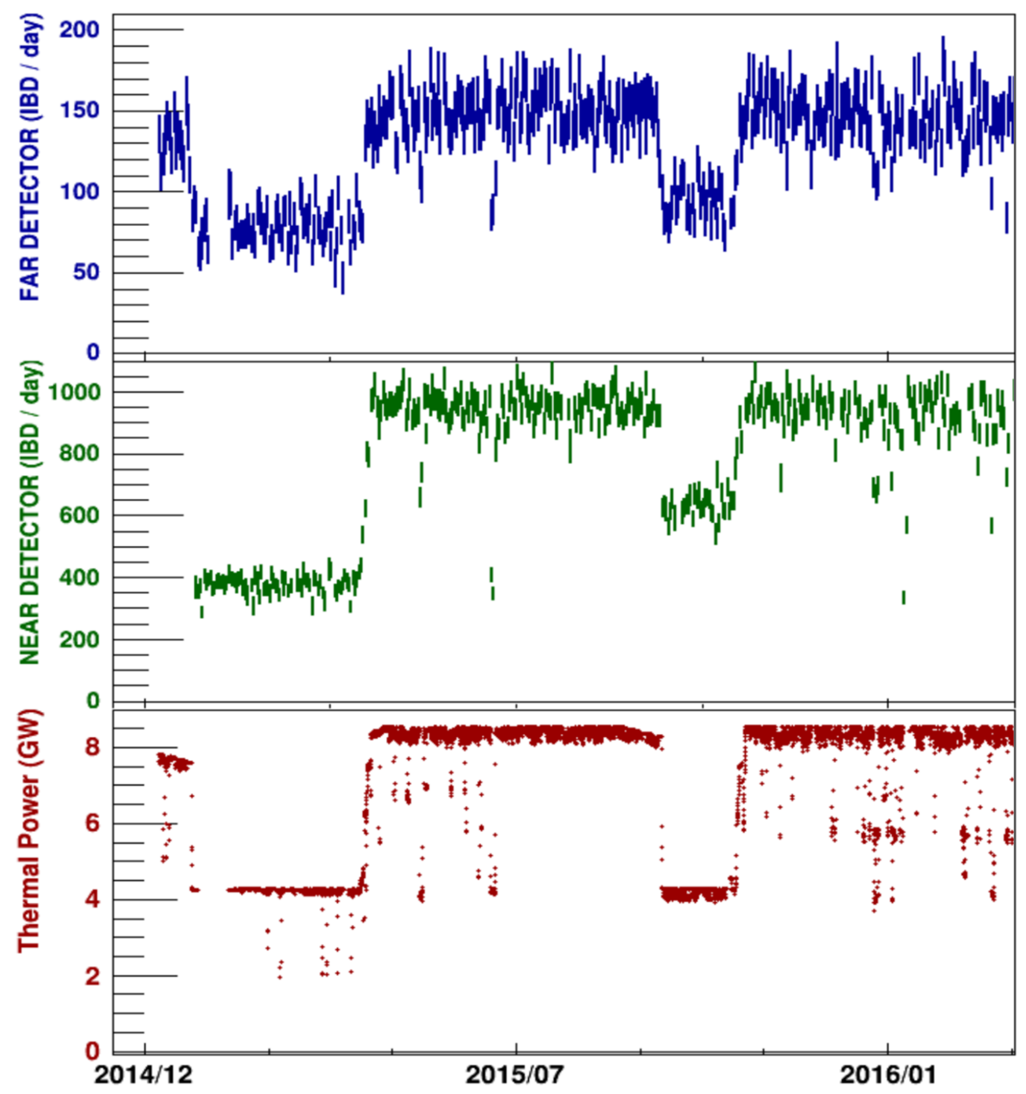
- First θ_{13} analysis with both detectors
  ⇒ strong flux systematics cancellation
- IBD with Total Neutron Capture (Gd + H + C)
  ⇒ x2.5 statistics

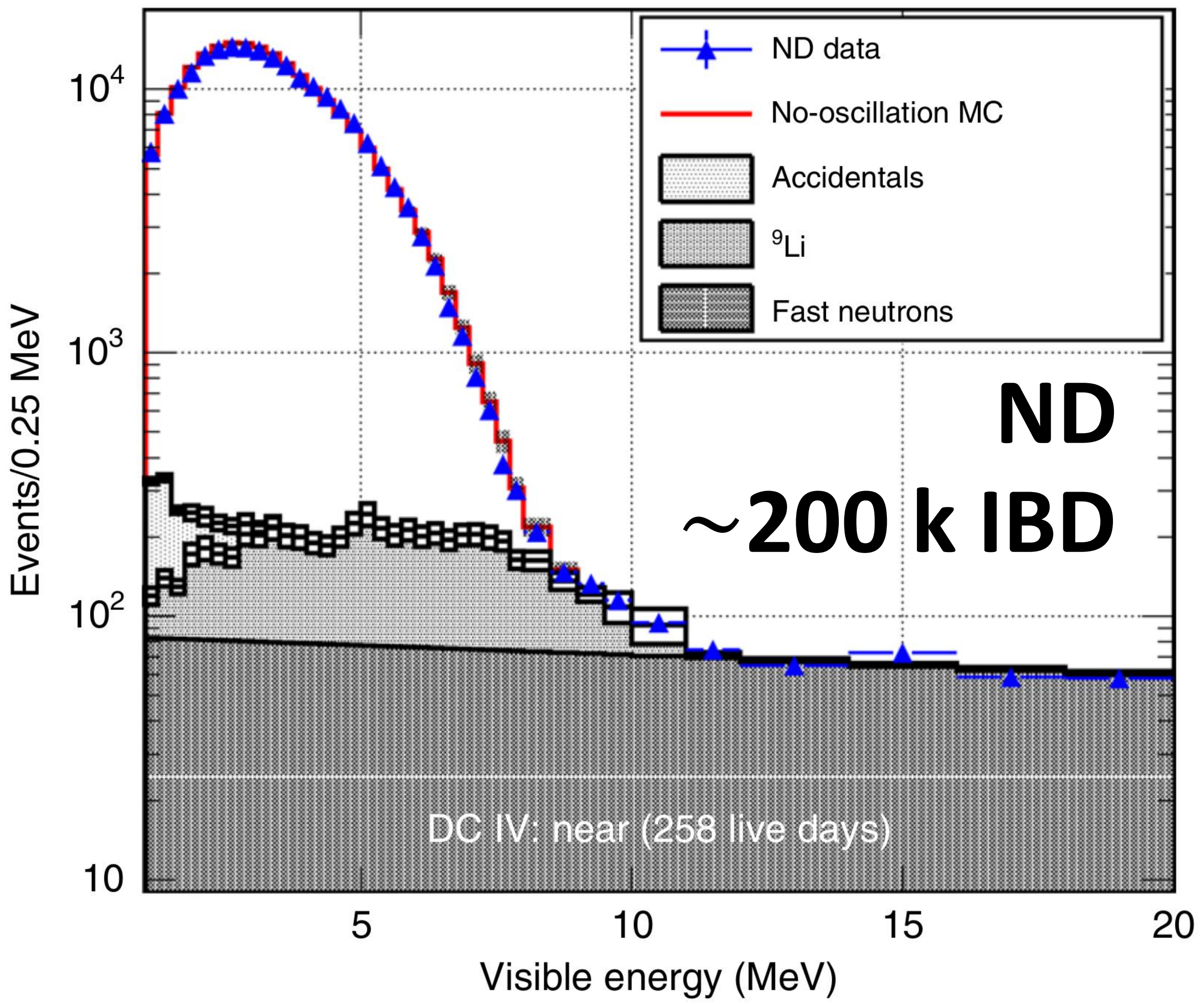


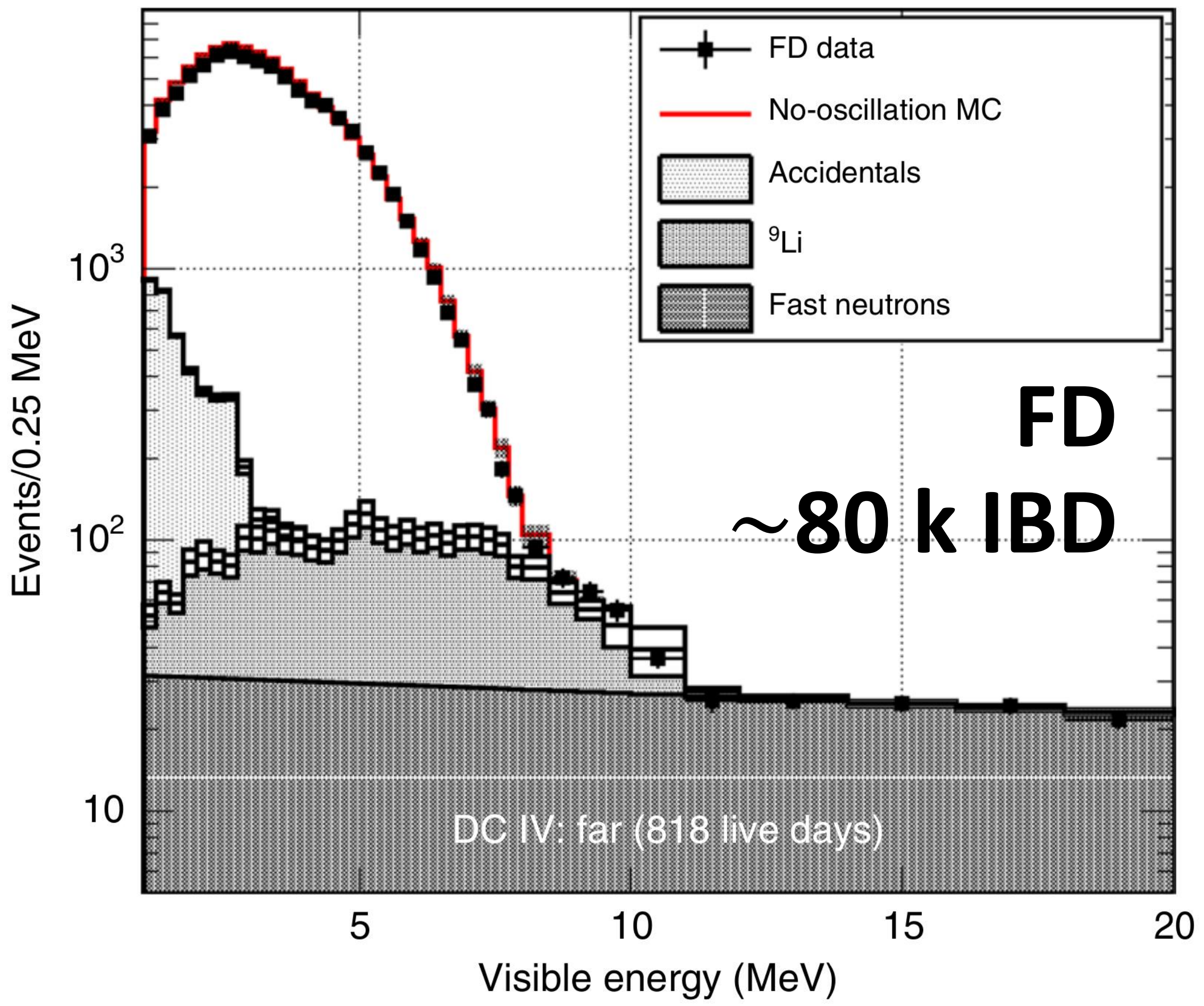
livetime:

- ND+FD: 258 days
- FD: 818 days

ND + FD



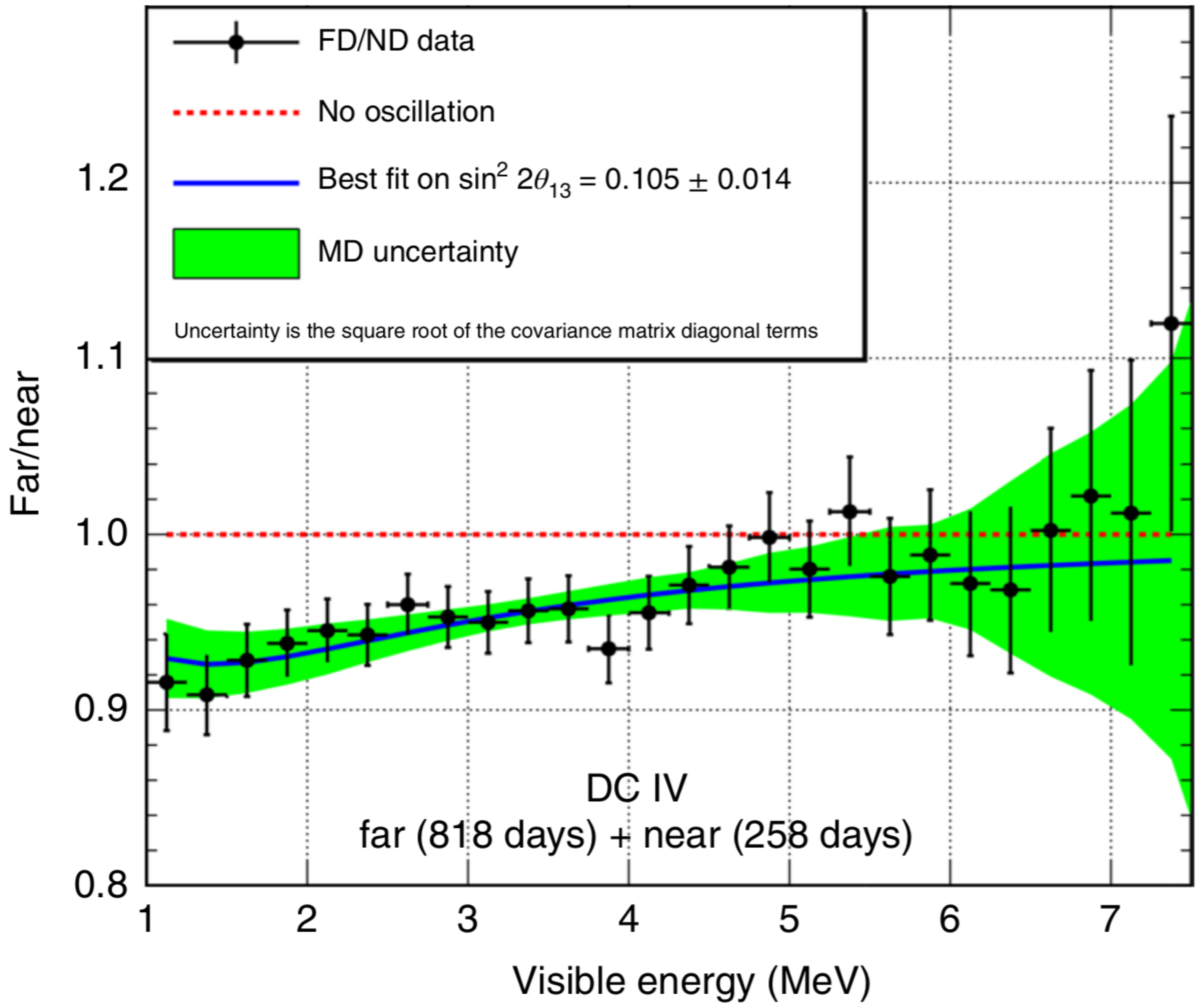




Hightlight on latest results (2/2)

Nature Physics - 2020

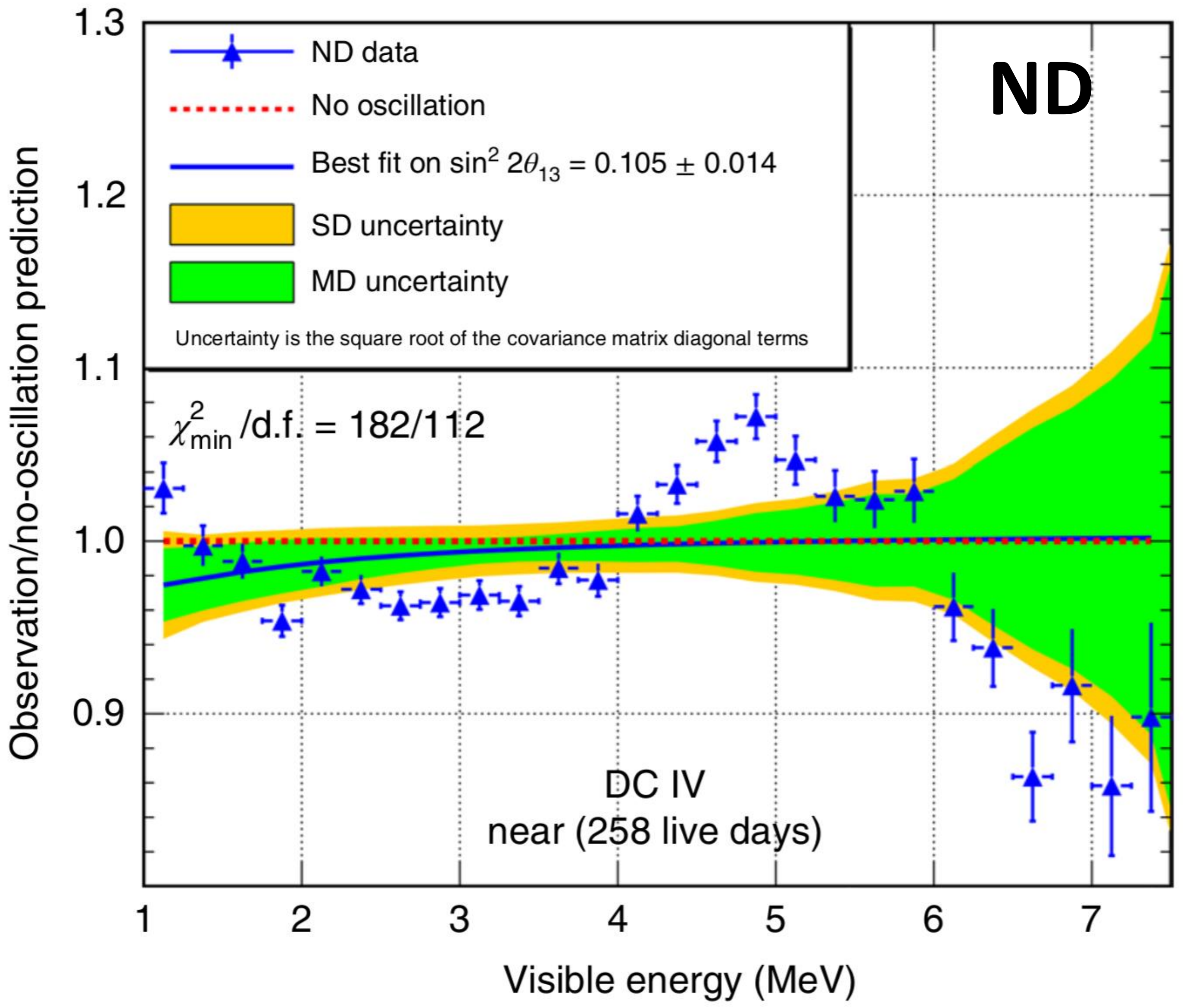
$\sin^2 2\theta_{13}$



$$\sin^2(2\theta_{13}) = 0.102 \pm 0.011\,(\text{syst.}) + 0.04\,(\text{stat.})$$

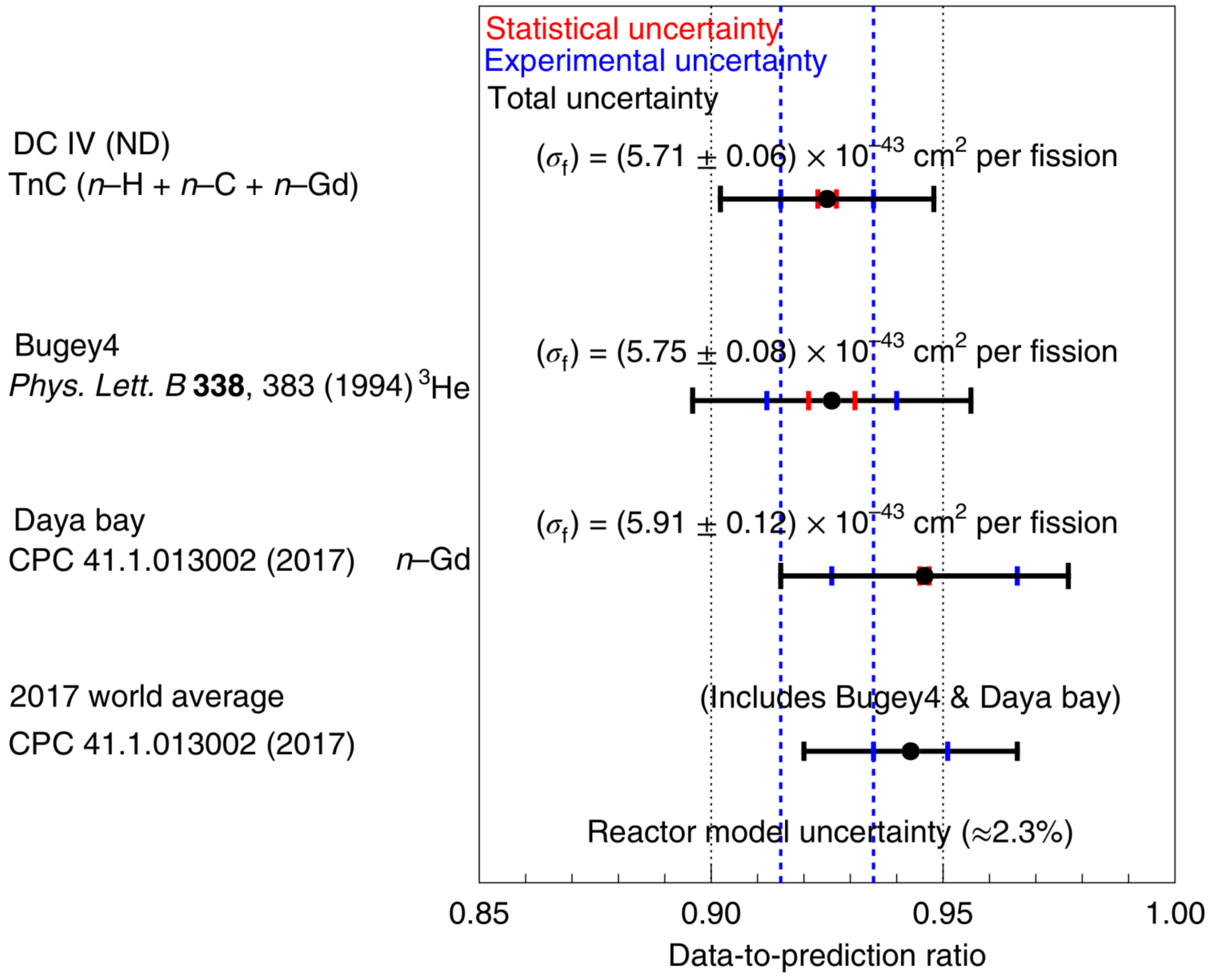
- Unambigious ND/FD deficit and distortion due to θ_{13}
- Good agrement with other experiments

Spectral distortion



- Huber/Muller prediction
- Data/MC shape incompatibility

Mean cross-section per fission



$$\langle\sigma_f\rangle = (5.75 \pm 0.06) \times 10^{-43}\ \text{cm}^2$$

- Very accurate measurement ($\sigma = 1\%$)
- Data/MC deficit in agreement with other experiments

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   - generality about residual antineutrinos

III. **DC off-off periods**
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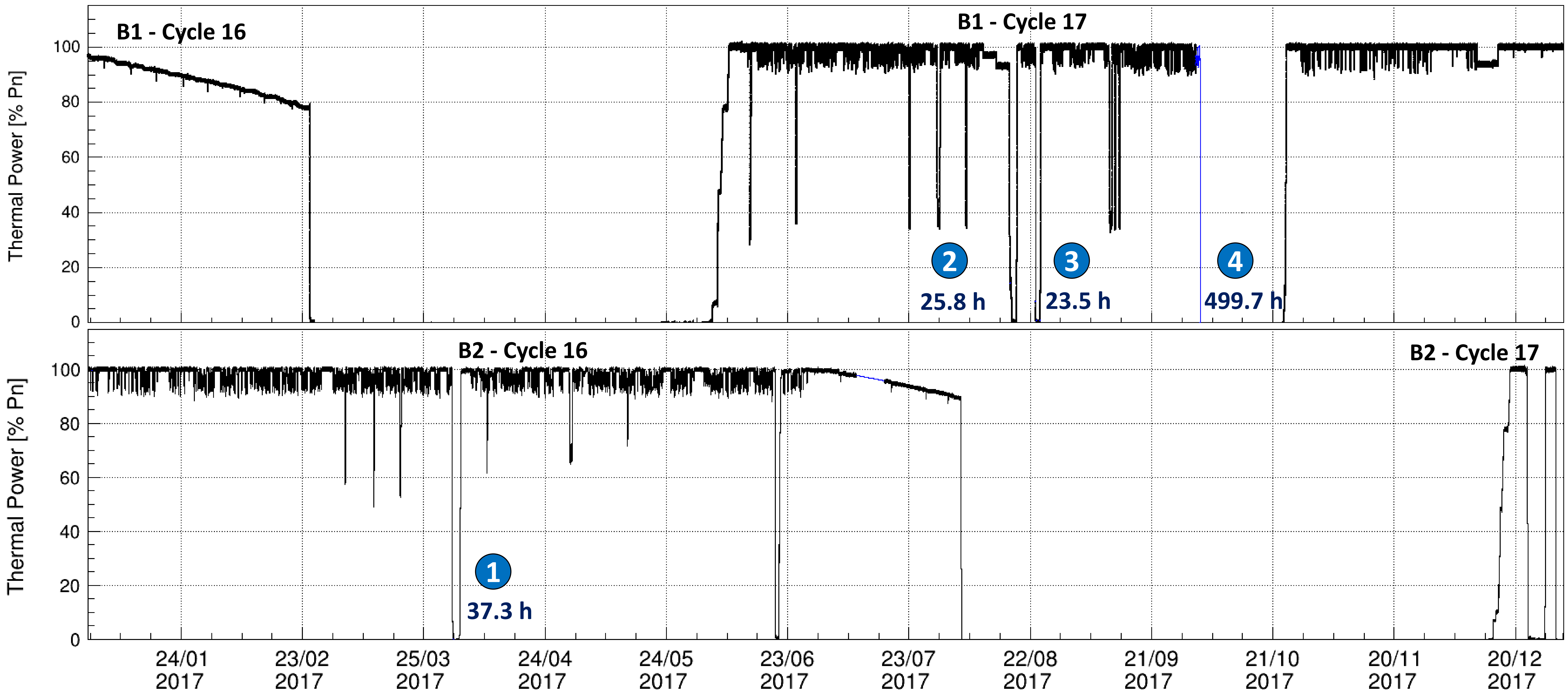
   - preliminary data/prediction comparison

IV. **Conclusion**

The 4 off-off periods of Chooz-B in 2017

4 off-off periods in 2017 with both detectors on

- ①: 1 april: ~ 37 h ⇒ Planned shutdown of B2. Maintenance control on reactor building.
- ②: 17 august: ~ 26 h ⇒ Planned shutdown of B1. Maintenance operation in the engine room.
- ③: 23 august: ~ 24 h ⇒ Unplanned automatical shutdown of B1. Unexpected closure of a steam valve
- ④: 3 october: ~ 500 h ⇒ Unplanned shutdown of B1. Unexpected electric grid deconnexion



⇒ Small residual $\bar{\nu}_e$ emission expected after shutdown from accumulation of fission product with long live time

Residual $\bar{\nu}_e$ prediction

Summation method

$$S_{\bar{\nu}_e}(E,t) = \sum_p A_p(t) S^p_{\bar{\nu}_e}(E)$$

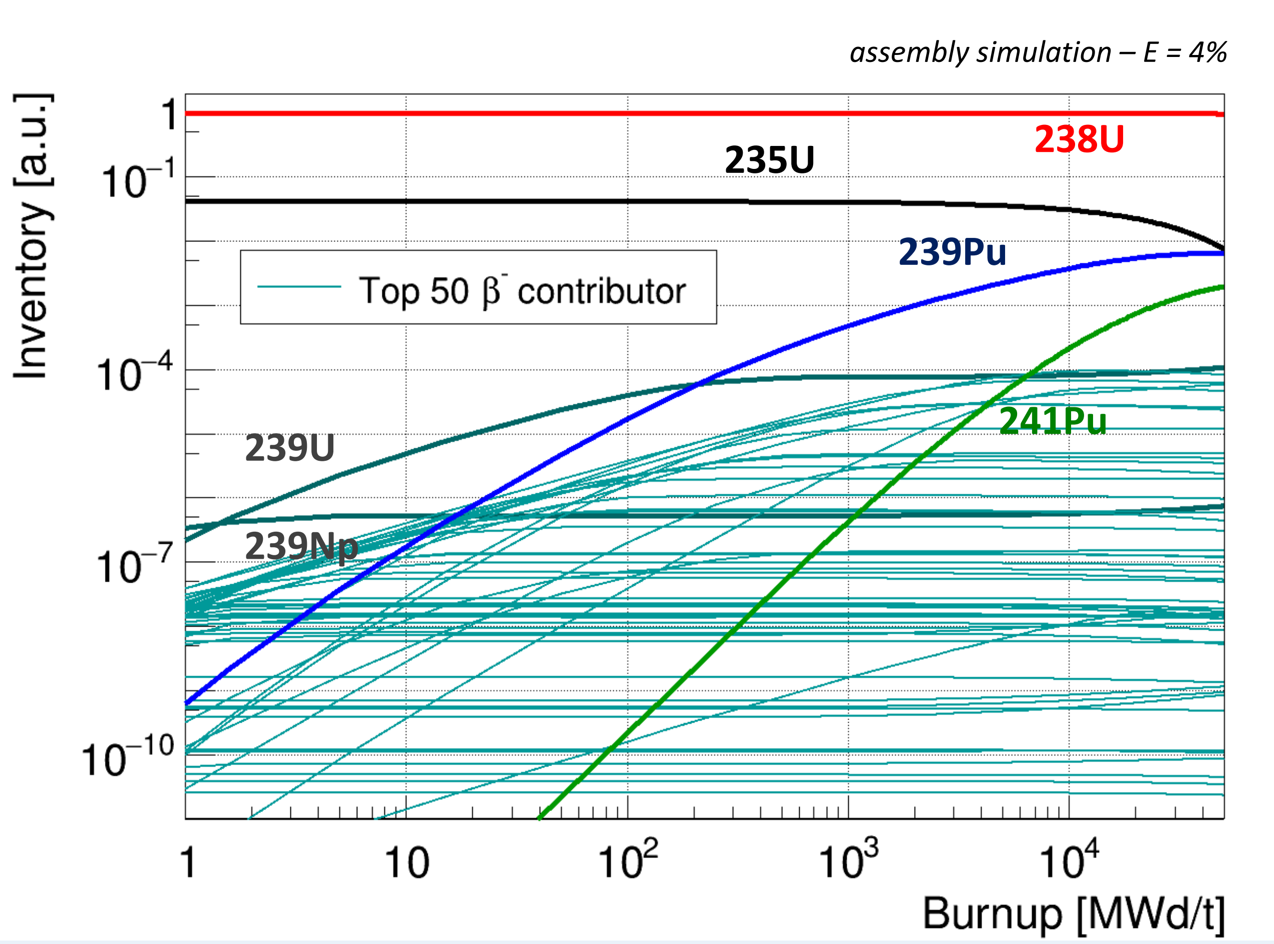
- A_p: activity of the beta decaying isotope p
- $S_{\bar{\nu}_e,p}$: $\bar{\nu}_e$ spectra of the isotope p

$$S_{\bar{\nu}_e}(E,t) = \sum_p \left(\lambda_p N_p(t) \sum_i BR^{p,i} S^{p,i}_{\bar{\nu}_e}(E) \right)$$

- λ_p: decay constant of isotope p
- N_p: number of particule of isotope p
- $S_{\bar{\nu}_e,p}$: $\bar{\nu}_e$ spectra of the branche i of isotope p
- $BR^{p,i}$: branching ratio of the transition i of isotope p

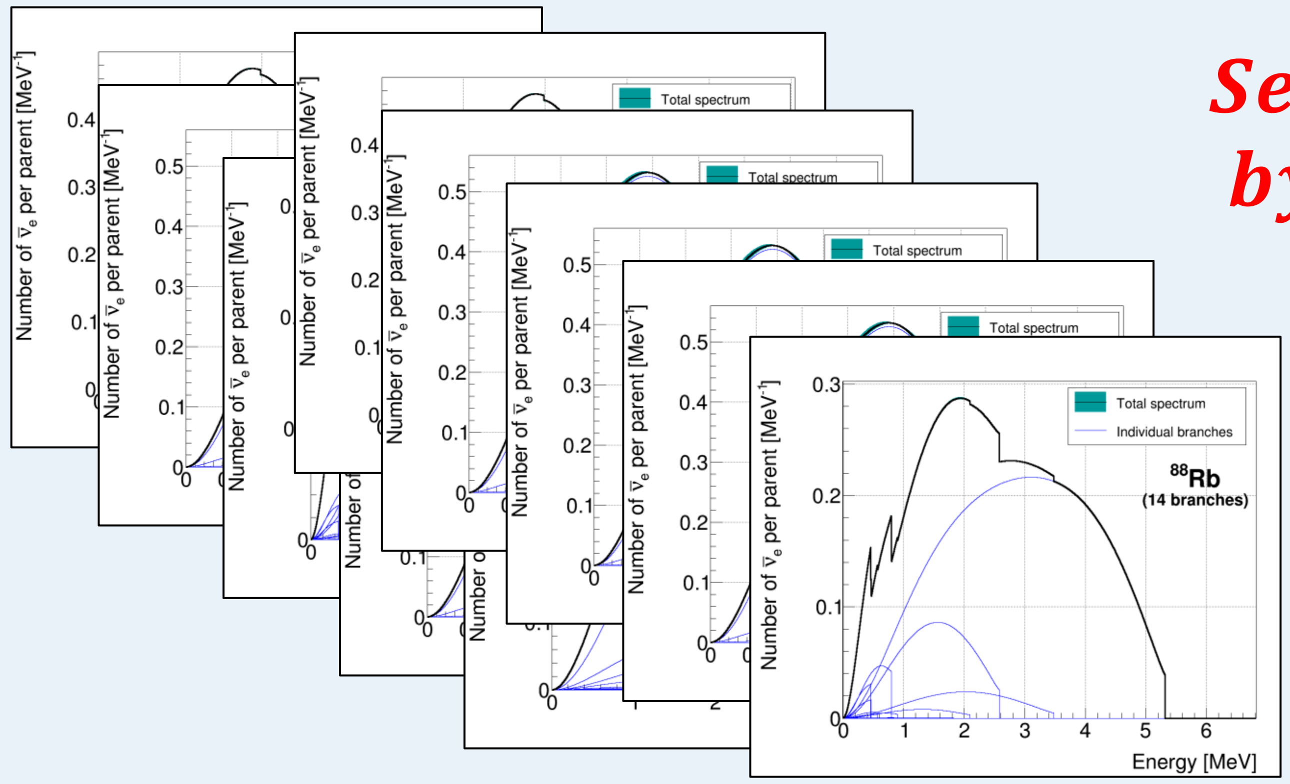
Reactor simulations

- **APOLLO-2.8.4** (deterministic code - Boltzman equation resolution)
- **DARWIN-3** (time evolution - Bateman equation resolution)
  - ⇒ commonly used for residual power estimation
  - ⇒ with evaluated nuclear data: JEFF-3.1.1



$S_{\bar{\nu}_e}$ library

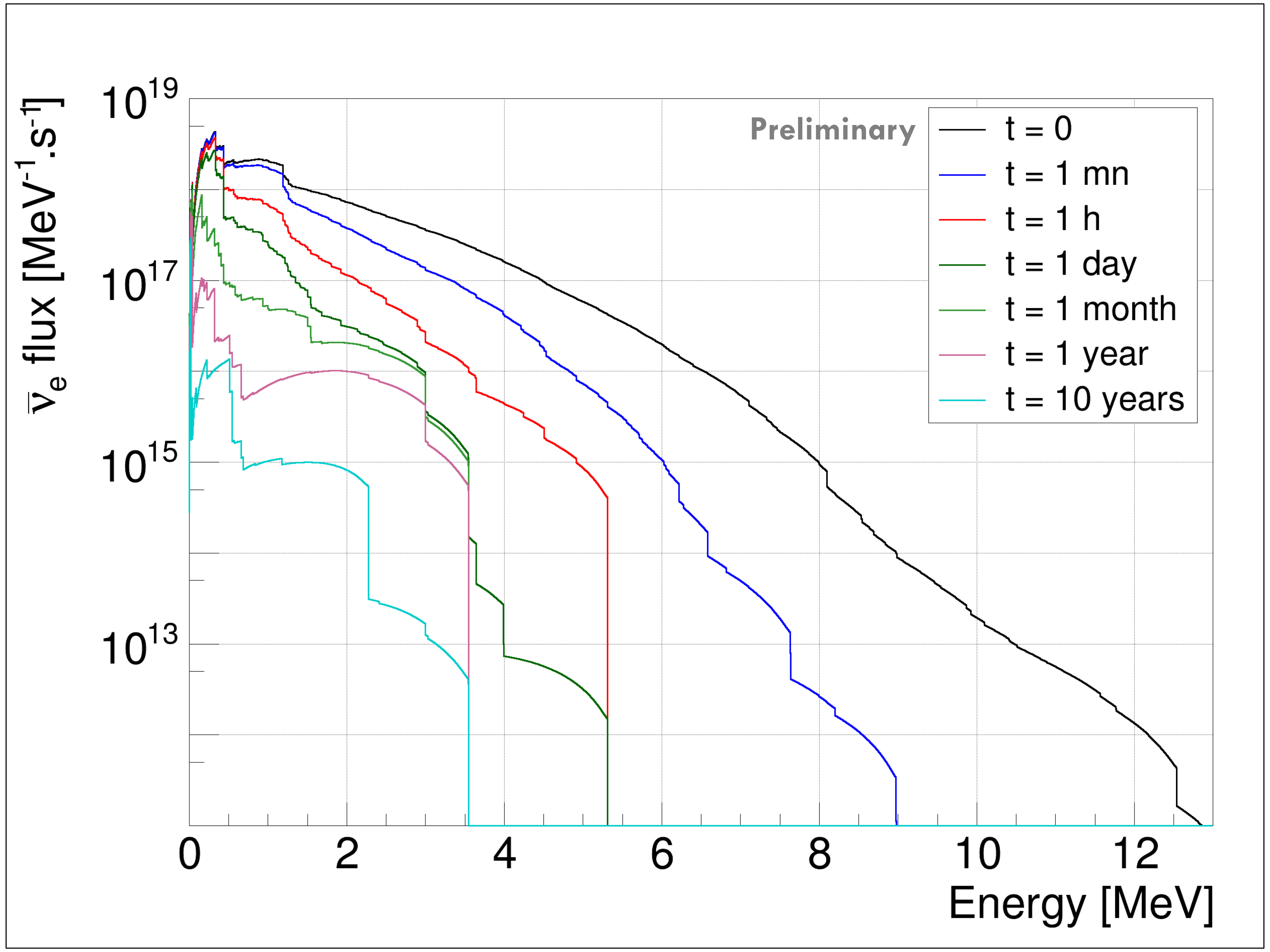
- **BESTIOLE** (see 10.1103/PhysRevC.83.054615) + **advanced modeling with nuclear structure calculation for 1st forbidden non unique transition (X. Mougeot) – ^{144}Pr**
  - ⇒ Evaluated nuclear data: ENSDF, AME, NUBASE



See talk BESTIOLE by Lorenzo Perisse

Residual $\overline{\nu}_e$ & $IBD_{\overline{\nu}_e}$ spectrum

Expected residual $\overline{\nu}_e$ and $IBD_{\overline{\nu}_e}$ spectrum from a discharged assembly



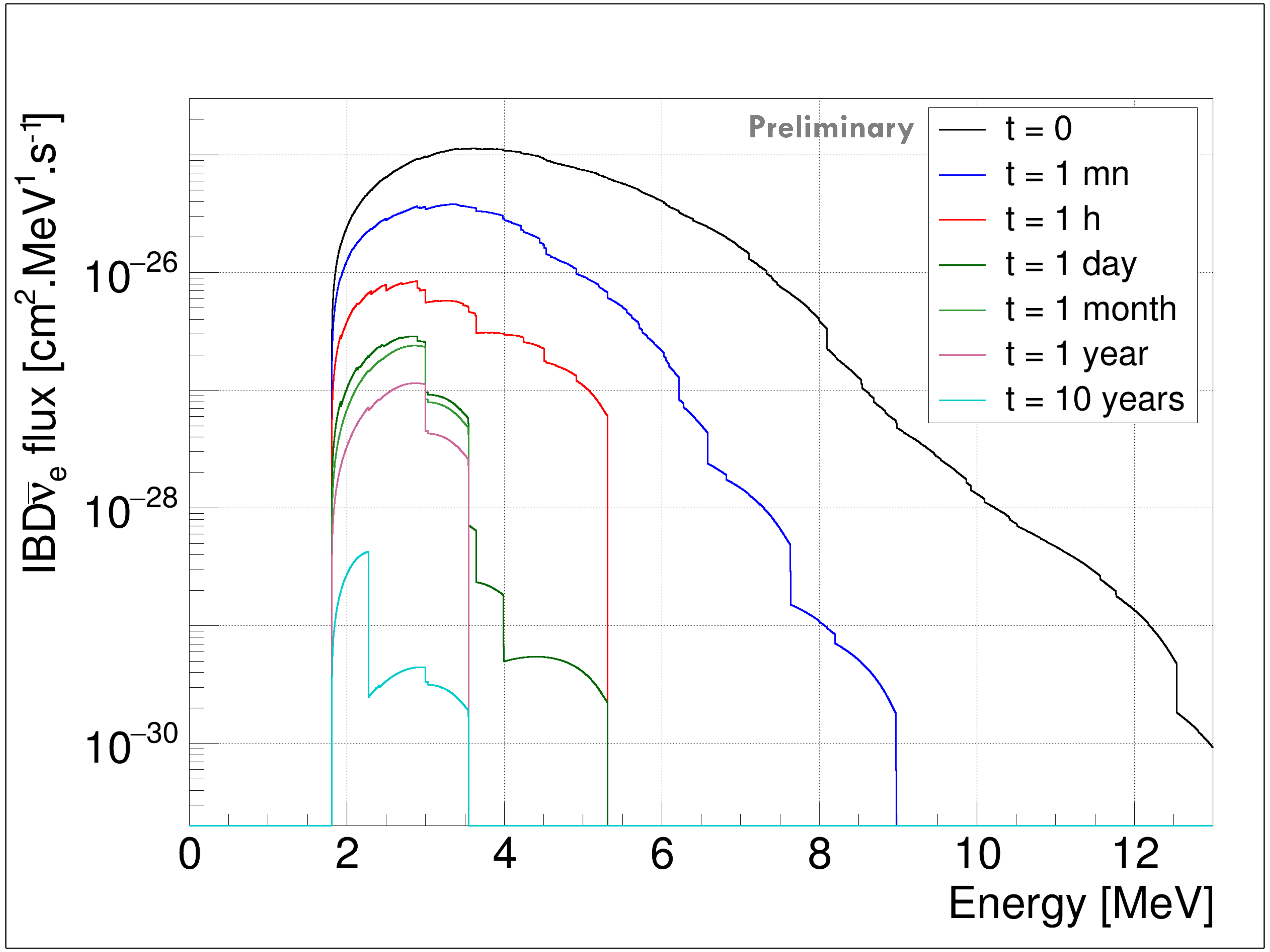


Fig. Typical neutrino spectrum (left) and associated IBD spectrum (right) from a UO_2 (4%) spent fuel assembly irradiated for 45 GWd/t.

Residual $\overline{\nu}_e$ flux (1/2)

Expected residual $\mathrm{IBD}_{\overline{\nu}_e}$ flux from a discharged assembly

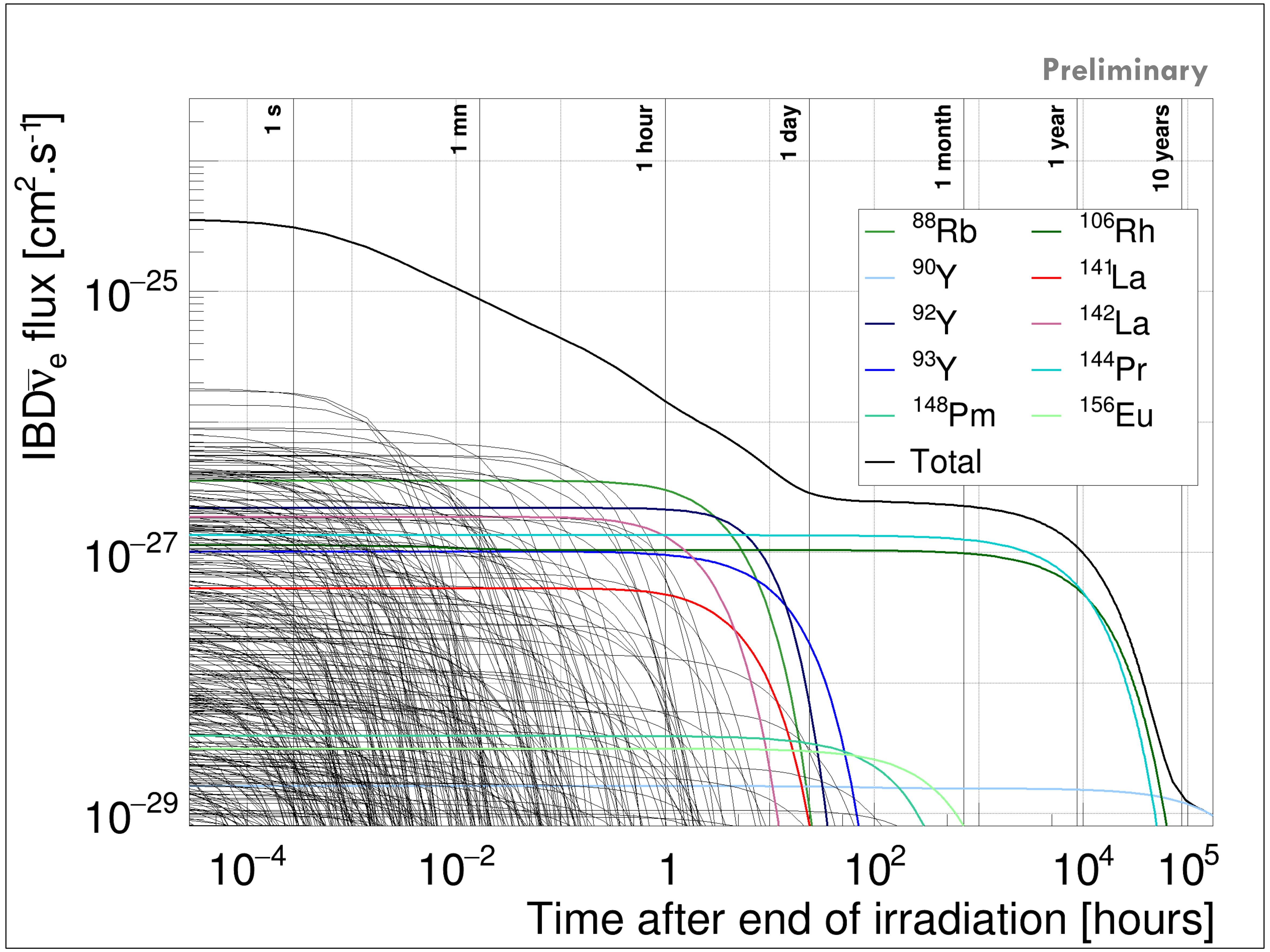


Fig. $\mathrm{IBD}_{\overline{\nu}_e}$ flux from a UO_2 (4%) spent fuel assembly irradiated for 45 GWd/t.

- 1 order of magnitude decrease after ~10 mn
- 2 order of magnitude decrease after ~15 h
- 3 order of magnitude decrease after ~2.5 years

Residual $\bar{\nu}_e$ flux (2/2)

Expected residual $\mathrm{IBD}_{\bar{\nu}_e}$ flux from a discharged assembly

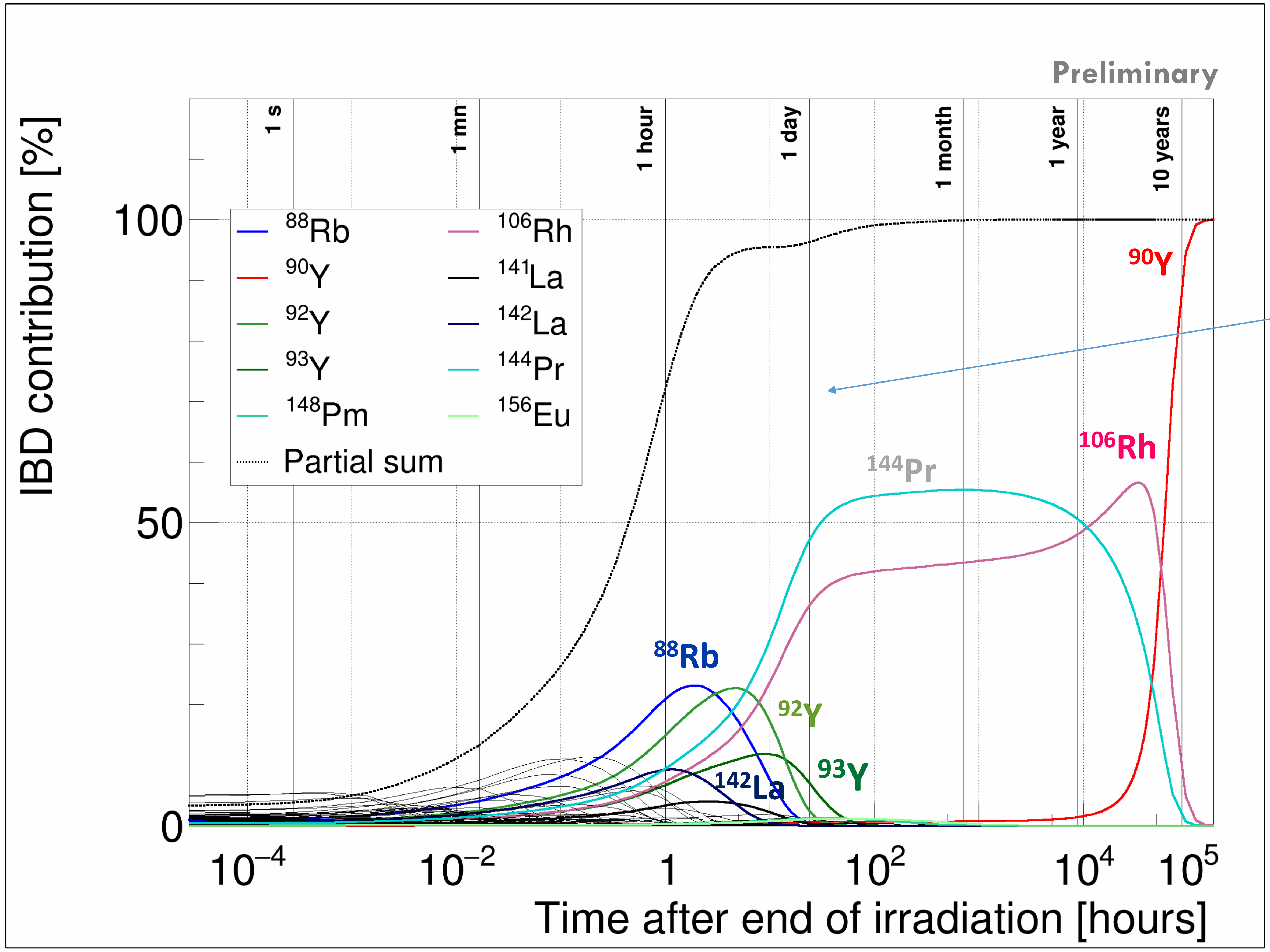


Fig. Relative isotope contribution to the $\mathrm{IBD}_{\bar{\nu}_e}$ flux from a UO_2 (4%) spent fuel assembly irradiated for 45 GWd/t.

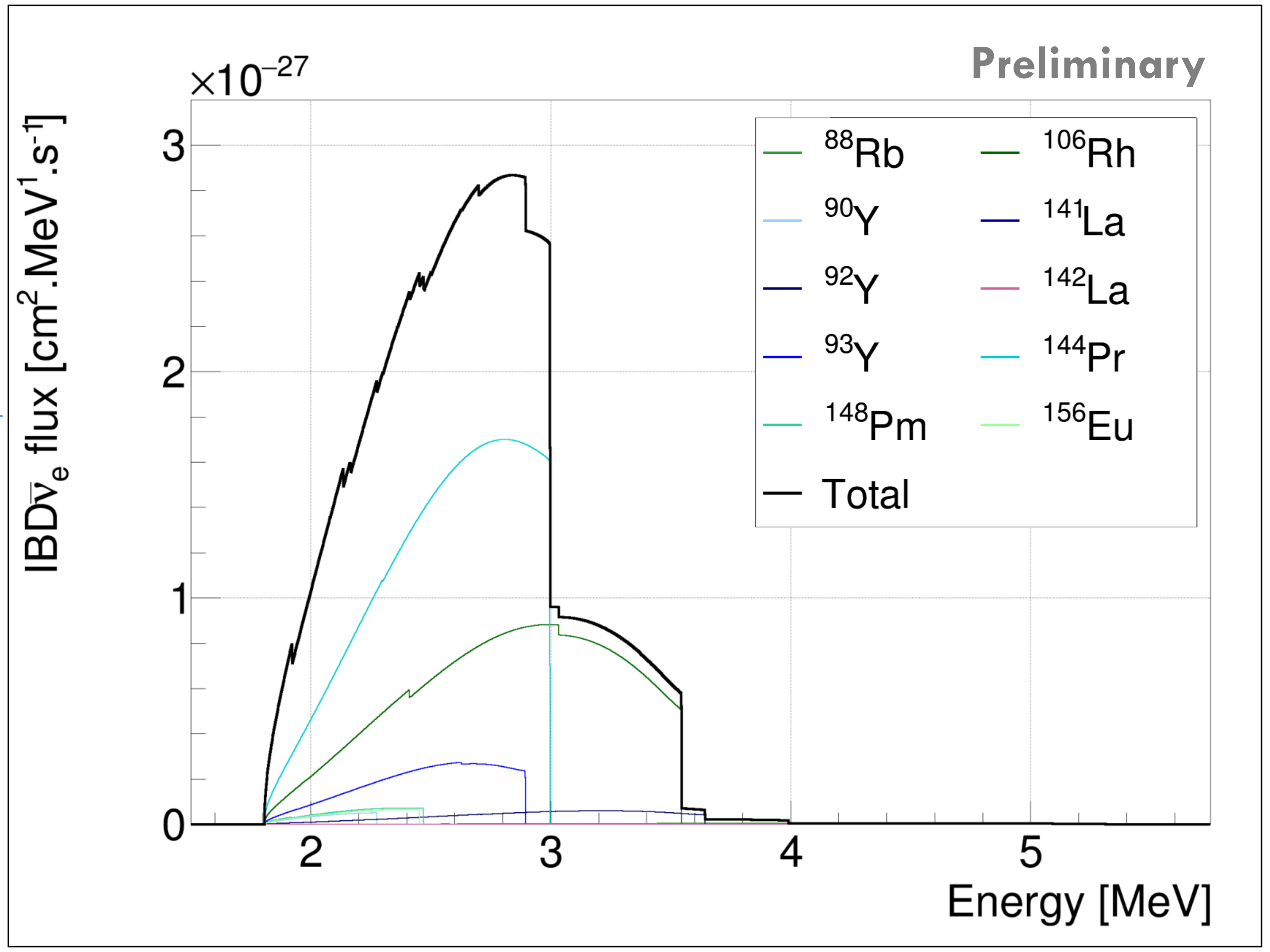


Fig. IBD spectrum after 1 day of cooling

⇒ After few hours of cooling ~6 isotopes are dominating the residual $\bar{\nu}_e$ emission.

Transition type – review for the main contributors

Transition modeling - top 6 contributors

	Near [%]	I_β [%]	Q_β [MeV]	N_b^{tot}	N_b^{IBD}	Transition type & IBD contribution Allowed / Forb uniq. / 1st forb n-uniq. / nth forb n-uniq.
144Pr	53.0	100	2.9974 (24)	10	2	0 / 1 (0.2%) / **1 (99.8%)** / 0
106Rh	37.1	100	3.5449 (53)	30	6	6 (100%) / 0 / 0 / 0
92Y	2.6	100	3.6425 (91)	12	4	0 / 3 (95.1%) / 1 (4.9%) /0
88Rb	2.1	100	2.9177 (26)	14	4	1 (0.2%) / 1 (98.8%) / 3 (1.0%) / 0
93Y	1.8	100	2.8949 (105)	13	3	1 (0.8%) / 1 (97.8%) / 3 (1.4%) / 0
90Y	0.9	99.9885 (14)	2.2785 (16)	3	1	0 / 1 (97.2%) / 2 (2.3%) / 0
Total	**97.5**					

Tab. Summary of the β^- decay properties of the dominant contributors to the residual IBD flux.

Transition type	Contribution	Shape factor $C(Z,W)$	
Allowed	38.1 %	1	simple modeling
Forb. Unique	7.5 %	polynomial in p_e, p_ν	simple modeling
1st forb. non-unique	0.2 %	ξ-approximation	approximated
	54.3 %	nuclear structure calculation	advanced
nth forb. non−unique	0 %		approximated

Tab. Transition type contribution and modeling

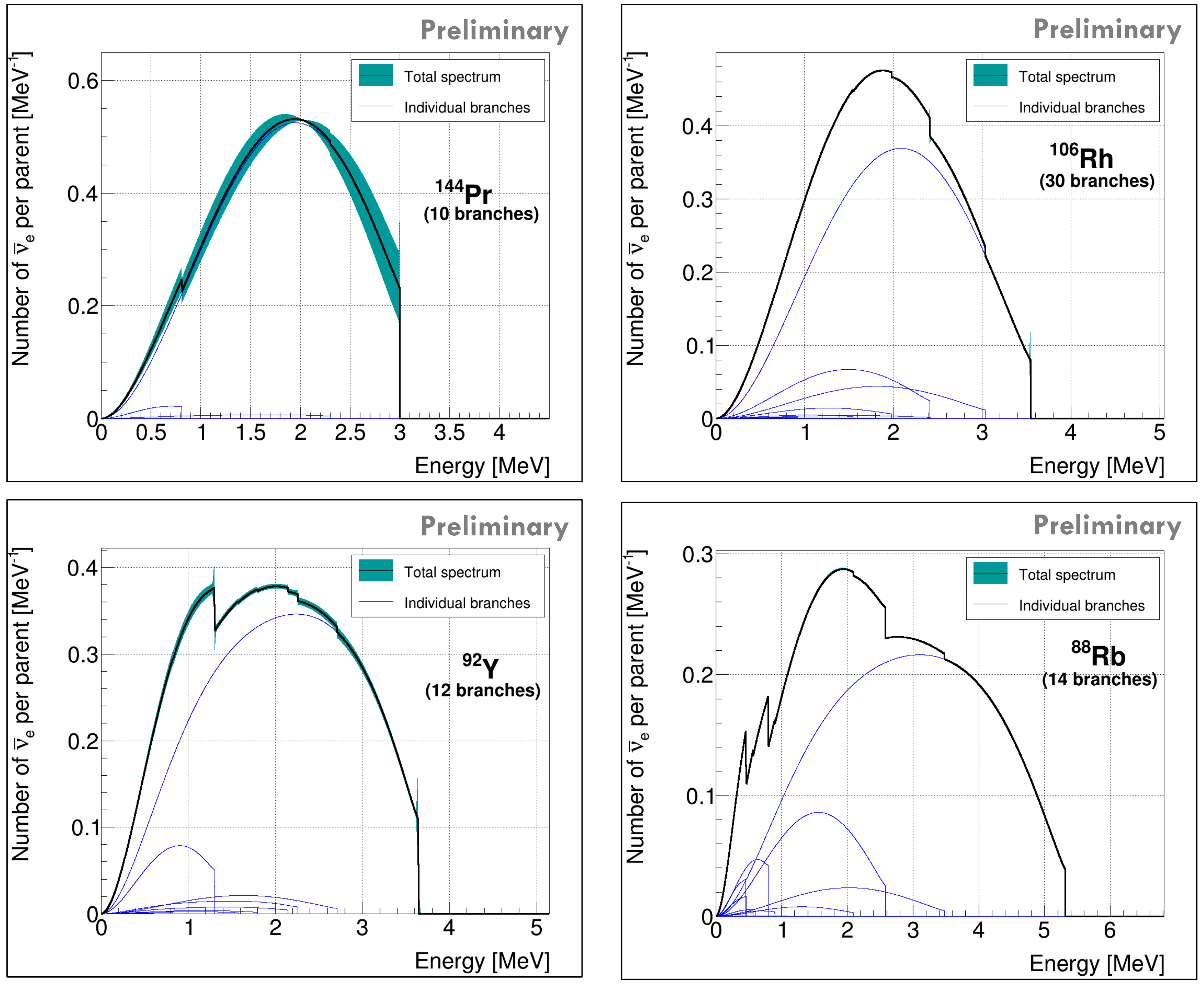
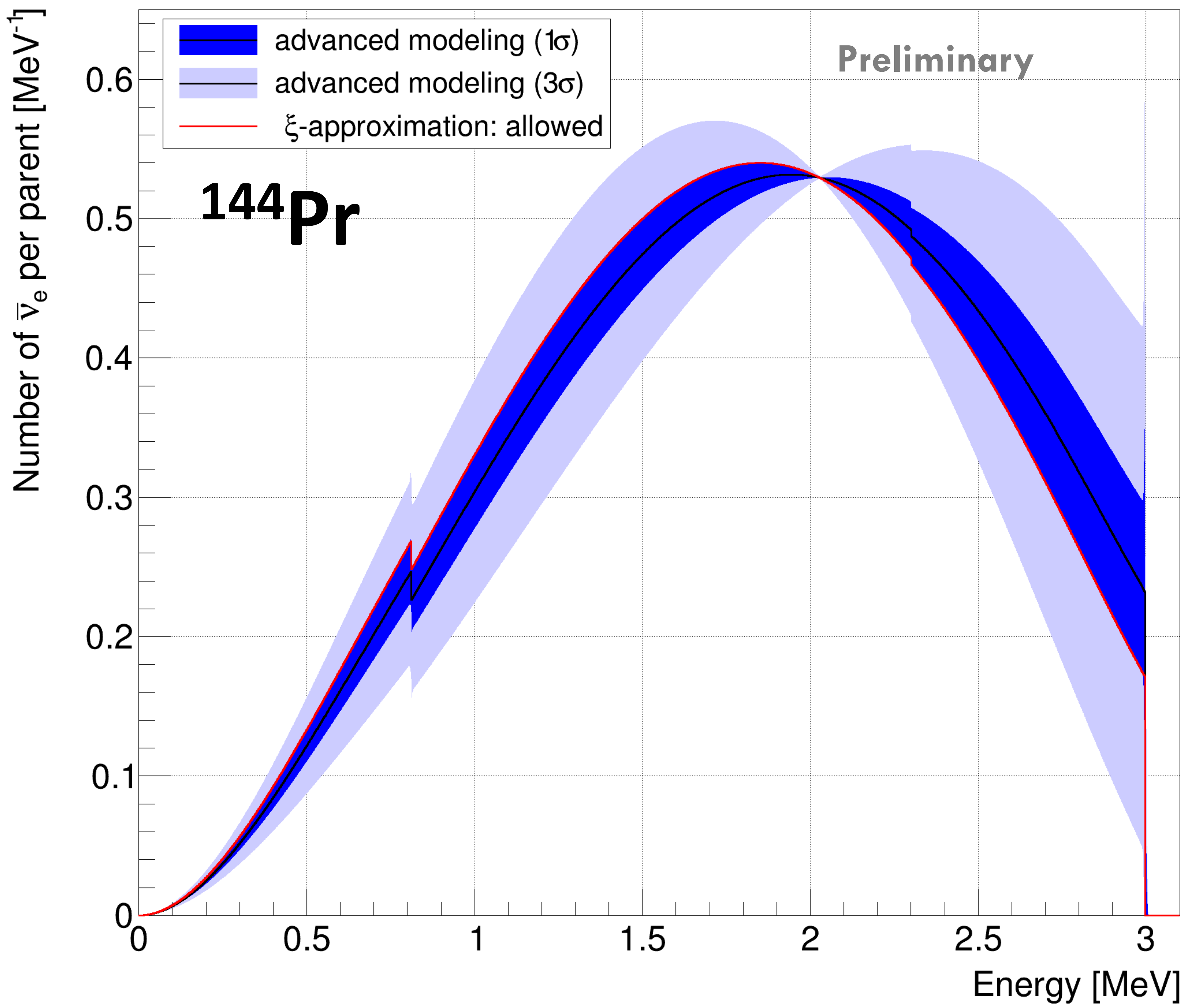
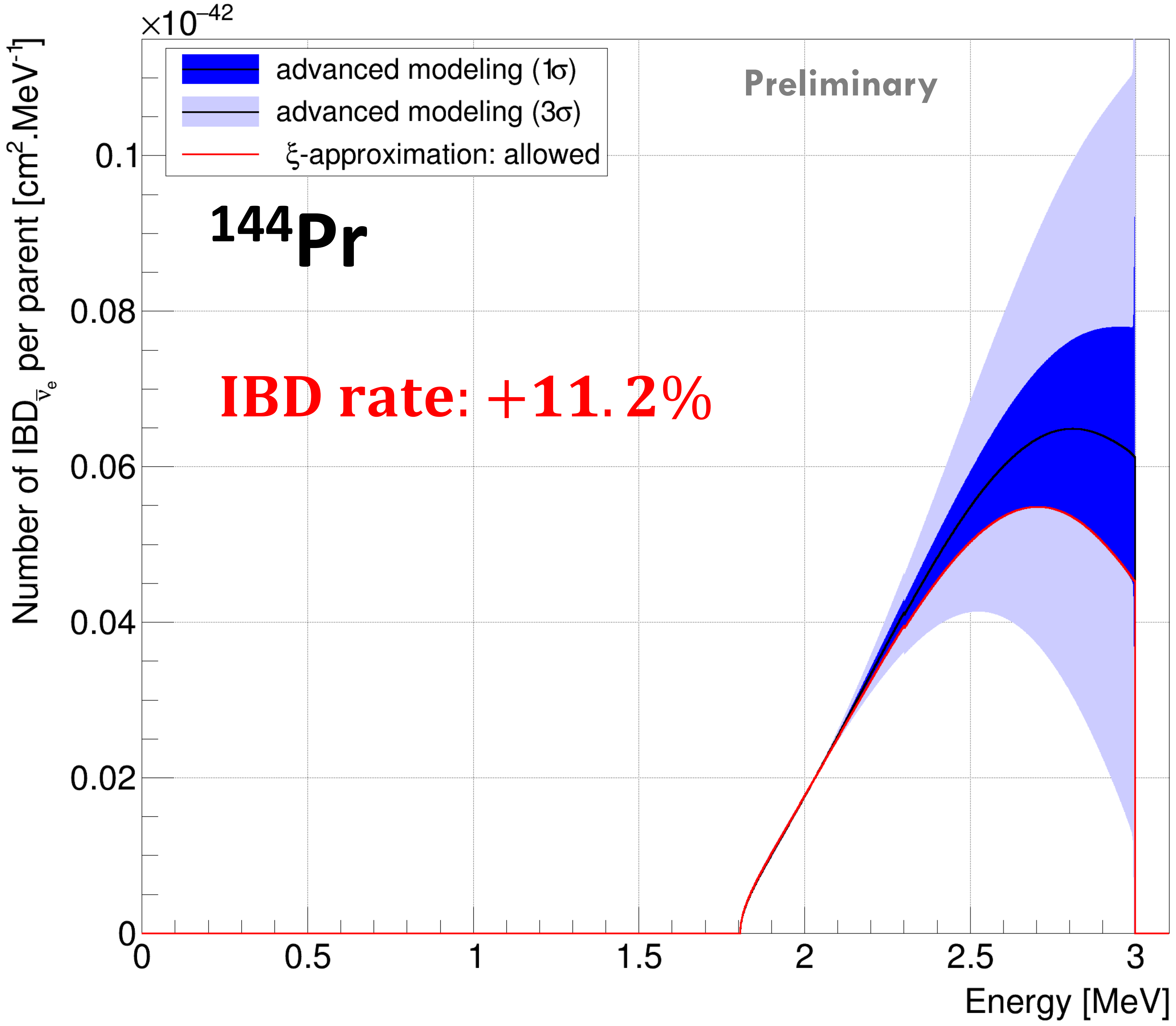


Fig. $\bar{\nu}_e$ spectrum of the 4 dominant residual contributors (97.5% of the flux in ND). Uncertainty from BESTIOLE model.

Dominante transition of ^{144}Pr modeled with advanced nuclear structure calculation (Xavier Mougeot - CEA)
Only 0.2% of the IBD flux of the top 6 residual contributors is modeled using the ξ-approximation

^{144}Pr modeling





Tab. Comparison of ^{144}Pr neutrino (left) and corresponding IBD neutrino spectrum (right) modeled with the ξ-approximation or with nuclear structure calculation

- Advanced modeling of shape factor with nuclear structure calculation (NSC) for the dominante branch of ^{144}Pr
- Difference between calculation with NSC and ξ-approximation used as 1σ uncertainty on the shape factor modeling

Summary

I. **The Double Chooz experiment**
   - experimental principle
   - analysis highlight and latest results

II. **Residual antineutrinos**
   - modeling
   - generality about residual antineutrinos

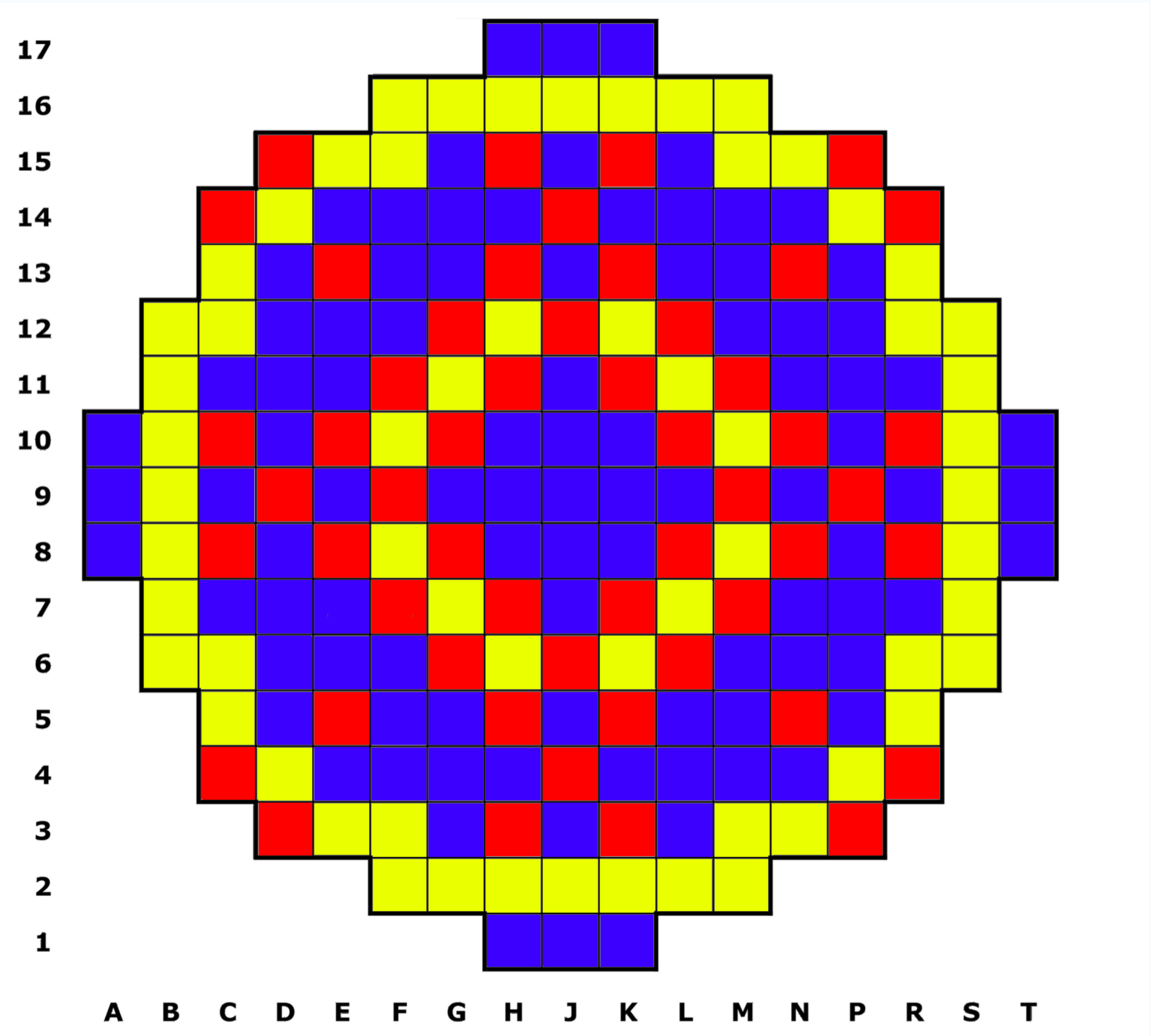
III. **DC off-off periods**
   - prediction
   - preliminary data/prediction comparison

IV. **Conclusion**

Reactor refuelling

Refuelling

- Every ~12-14 months
- 1/3 of burnt fuel assemblies removed
  1/3 of fresh fuel assemblies added
- Operation time: ~6-8 weeks
  ↳ unsynchronized operation between B1 & B2
- Spent assemblies stored in pools for few years before evacuation from the site



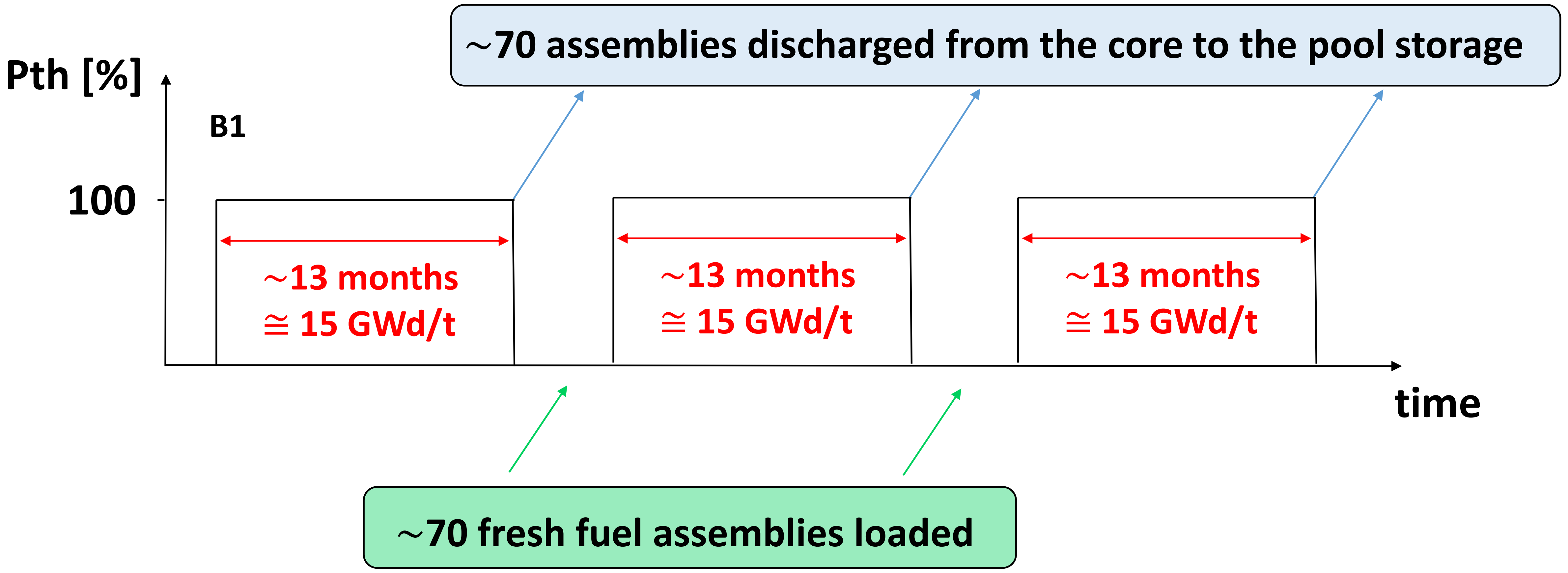
Typical fuel loading map

- 1st irradiation cycle *(fresh fuel, B = 0 MWd/t)*
- 2nd irradiation cycle *(B ~ 15 000 MWd/t)*
- 3rd irradiation cycle *(B ~ 30 000 MWd/t)*

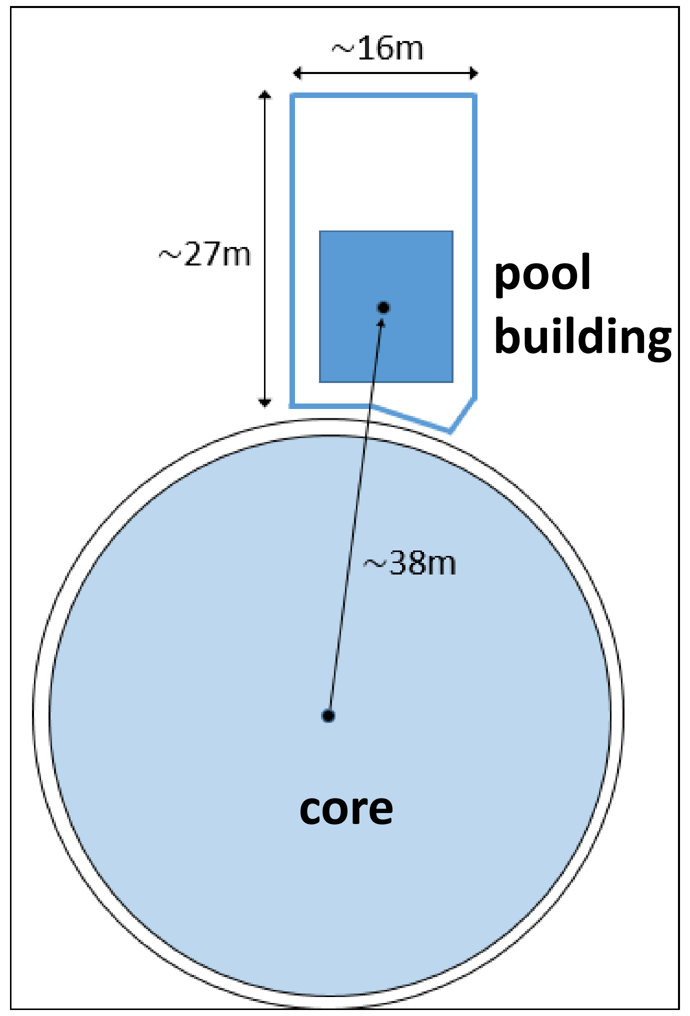
Burnup:

$$B(t)[\mathrm{MWd/t}] = \frac{1}{M_{NL}} \int_0^t \mathrm{P(t')dt'}$$

P(t′) : instantaneous thermal power (MW)
M_{NL}: Initial mass of heavy nucley (ton)



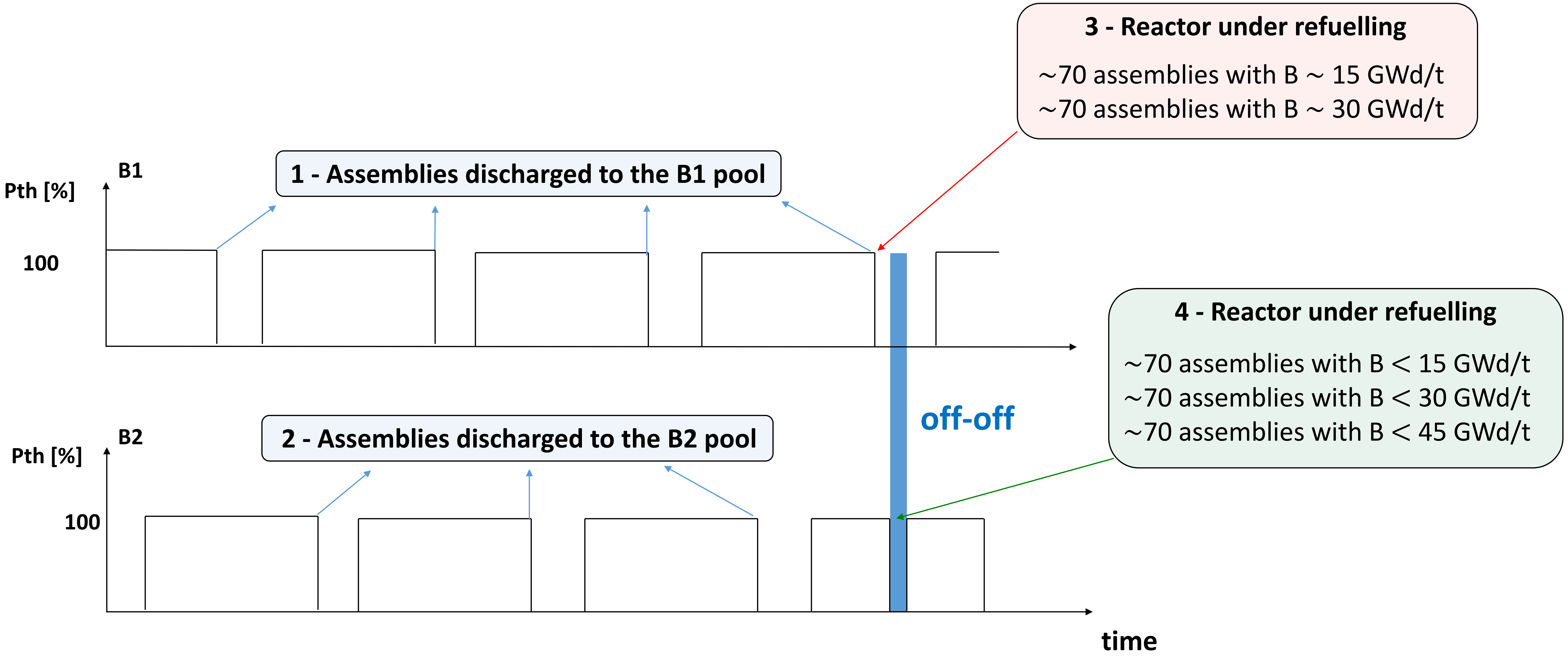
	ND [m]	FD [m]
B1 core	468.8	1114.7
B1 pool	~443	~1135
B2 core	355.4	997.8
B2 pool	~323	~1021



$\bar{\nu}_e$ flux components during a off-off

Power histories illustration for a typical off-off

B1 under refuelling
B2 temporarily shutdown



Four components to the residual $\bar{\nu}_e$ during a off-off

1 - $\bar{\nu}_e$ from spent fuel assemblies stored in B1 pool
2 - $\bar{\nu}_e$ from spent fuel assemblies stored in B2 pool
3 - $\bar{\nu}_e$ from burnt fuel assemblies in the reactor under refuelling and keep for the next irradiation cycle
4 - $\bar{\nu}_e$ from burnt fuel assemblies in the reactor temporarily shutdown

Prediction strategy

Expected flux at the near/far detector

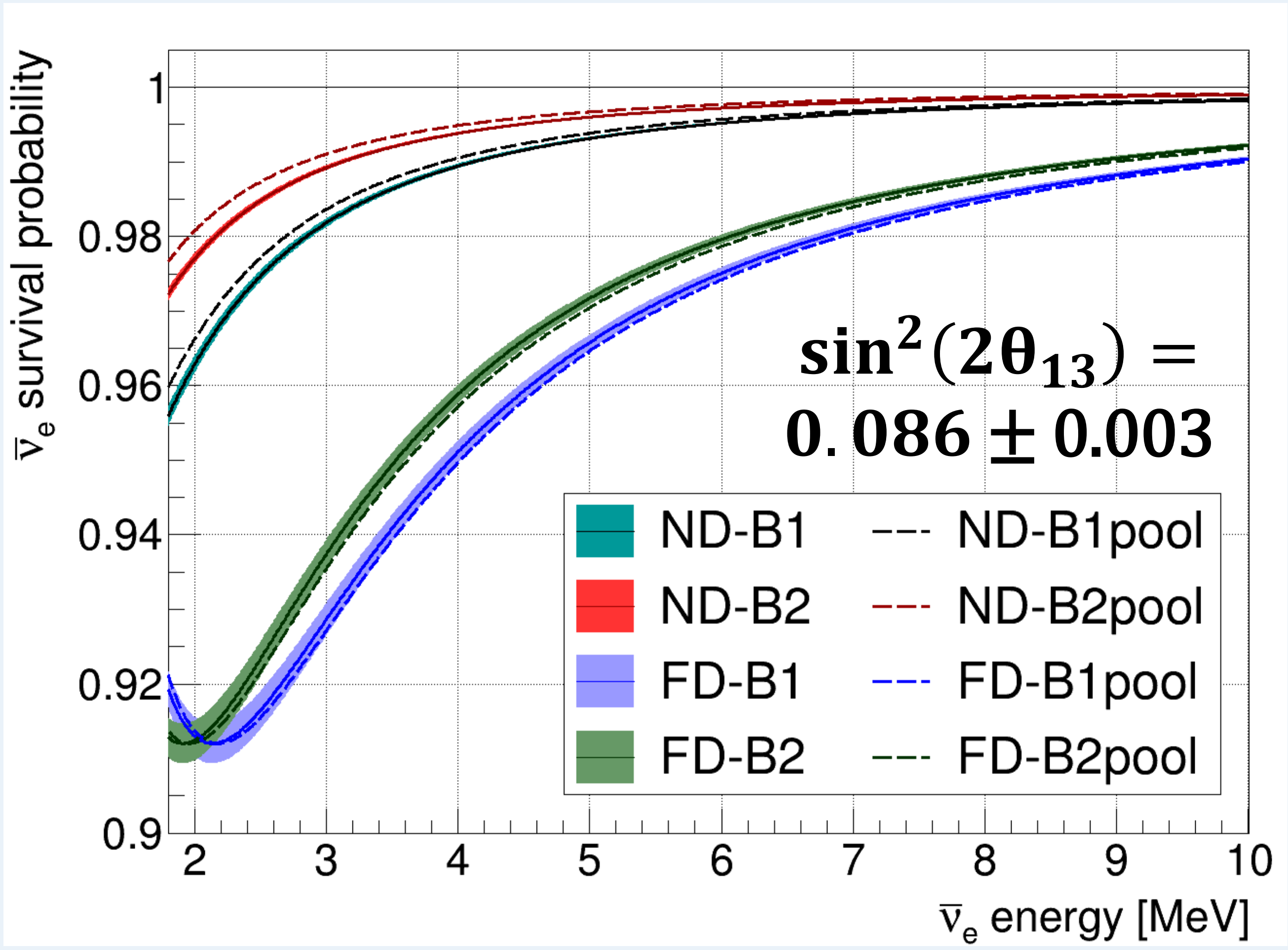
Residual spectrum S(E,t) from summation calculation

$$N_{\bar{\nu}_e} = \frac{N_p \varepsilon P(\bar{\nu}_e \to \bar{\nu}_e)}{4\pi L^2} \int \phi(\boldsymbol{E}) \sigma(E) dE$$

$$\varepsilon P(\bar{\nu}_e \to \bar{\nu}_e) = \frac{\int \varepsilon(E) P(\bar{\nu}_e \to \bar{\nu}_e)(E) \phi(E) dE}{\int \phi(E) dE}$$

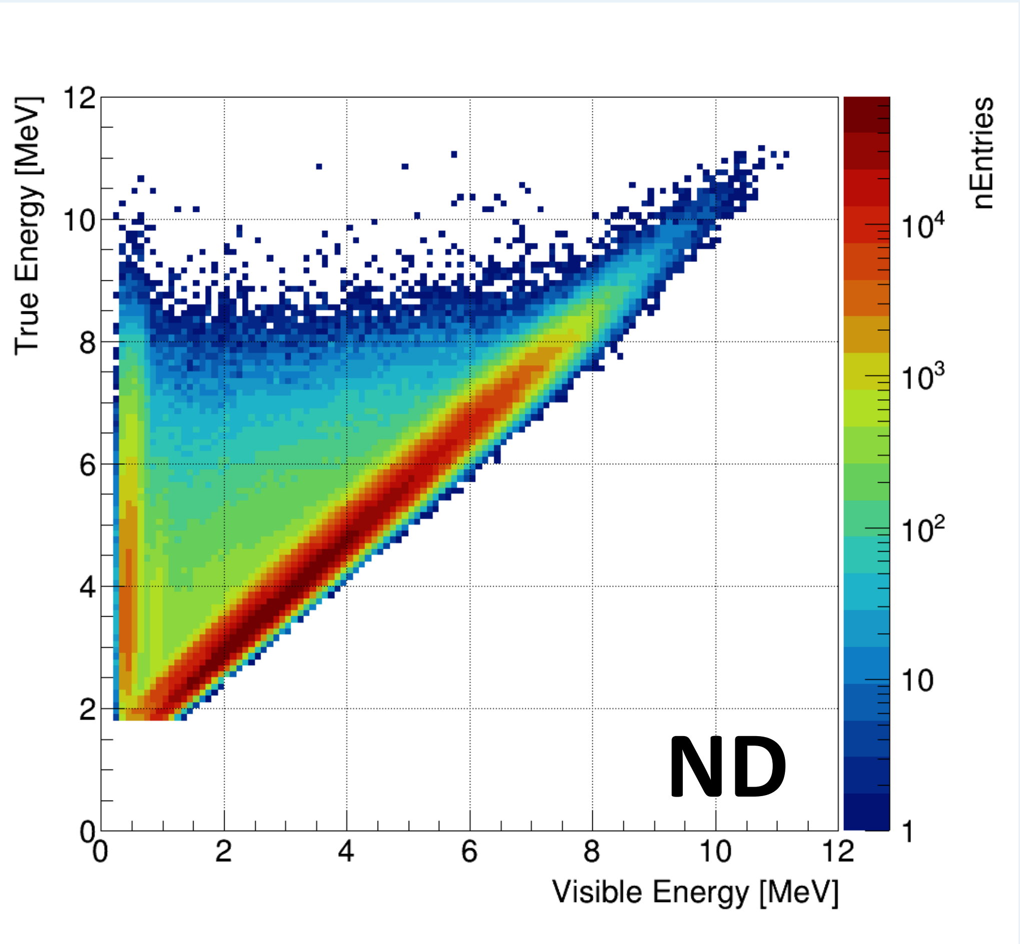
- N_p: proton number
- $\varepsilon(E)$: energy dependant efficiency
- $P(\bar{\nu}_e \to \bar{\nu}_e)$: non oscillation probability
- $\sigma(E)$: IBD cross-section

θ_{13} oscillation (PDG 2022)



Response matrix

IBD[Gd+H+C], all selections but no Ep cut



Absolute efficiency

- Eprompt, Edelay cut
- ΔT, ΔR, ANN
- Escale
- Background vetoes
- Correction factor data-MC (Gd fraction, spill-in out)

Proton number

Target	6.767×10^{29}	6.739×10^{29}
GC	15.80×10^{29}	15.73×10^{29}

IBD$\bar{\nu}_e$ from spent fuel assemblies in the pools (1/2)

Reactor power history used for APOLLO/DARWIN simulation of the discharged assemblies stored in the pools

Asemblies discharged after C12

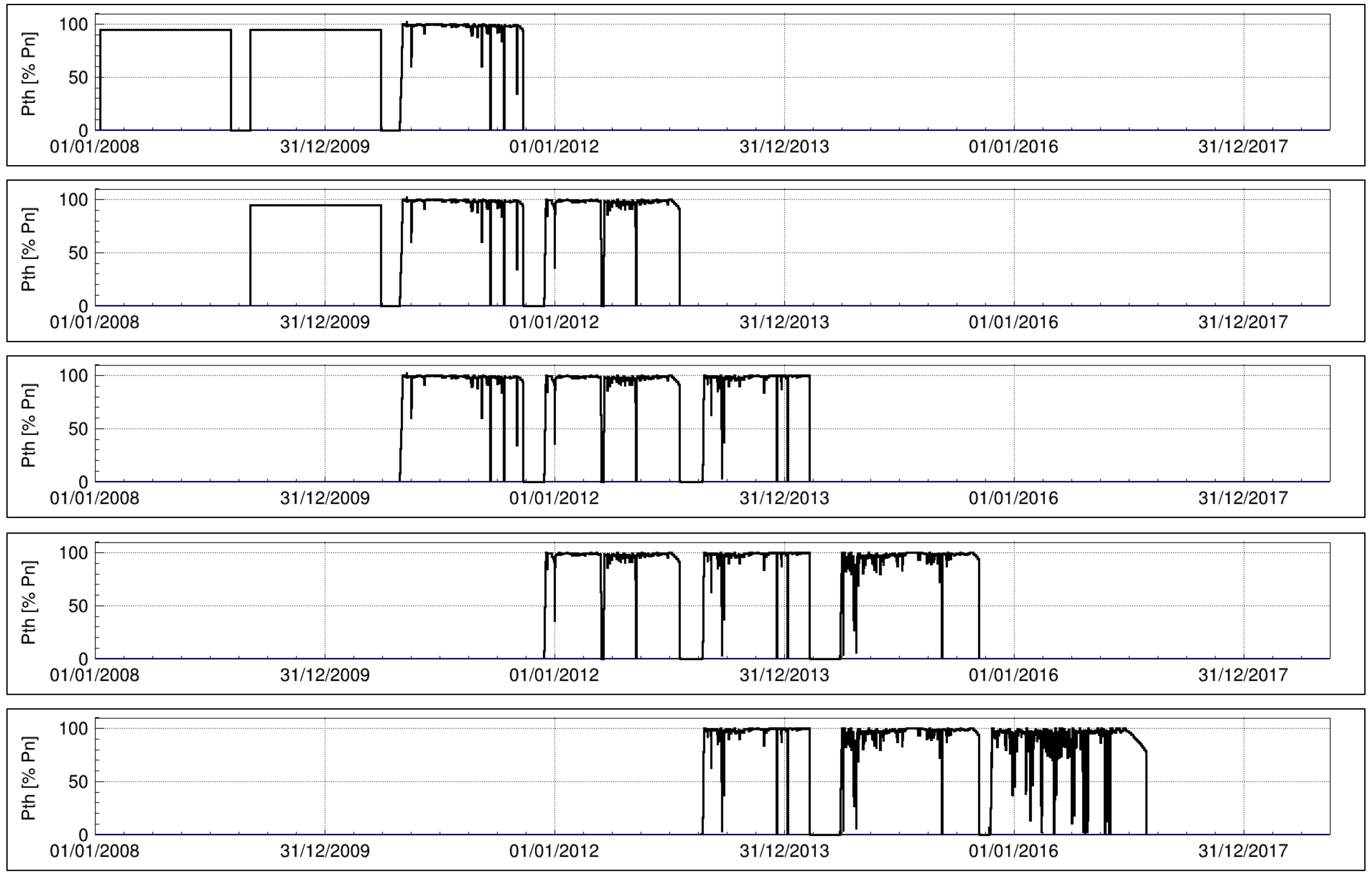
Asemblies discharged after C13

Asemblies discharged after C14

Asemblies discharged after C15

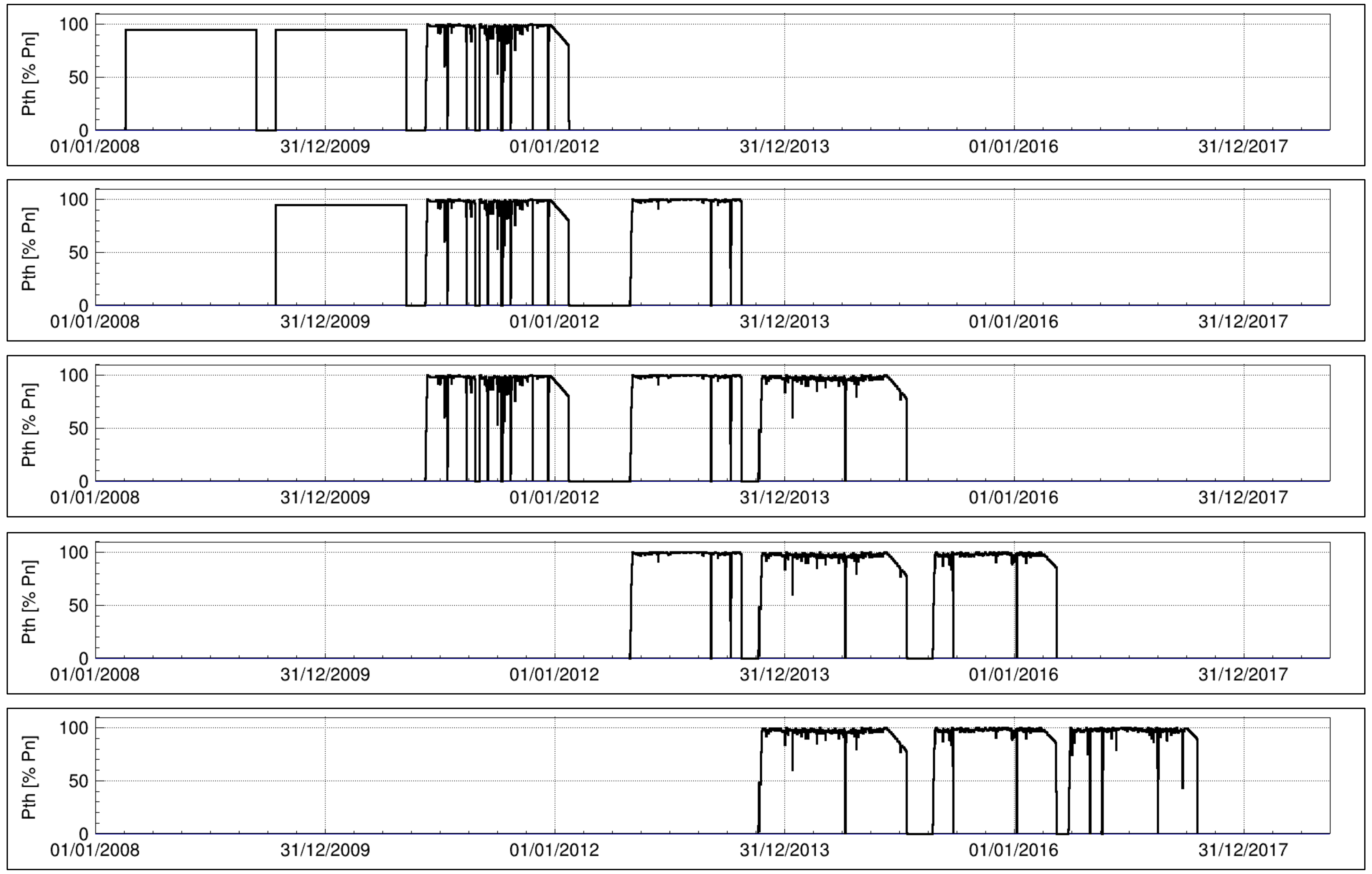
Asemblies discharged after C16

Reactor B1



Cycle 10 Cycle 11 Cycle 12 Cycle 13 Cycle 14 Cycle 15 Cycle 16

Reactor B2



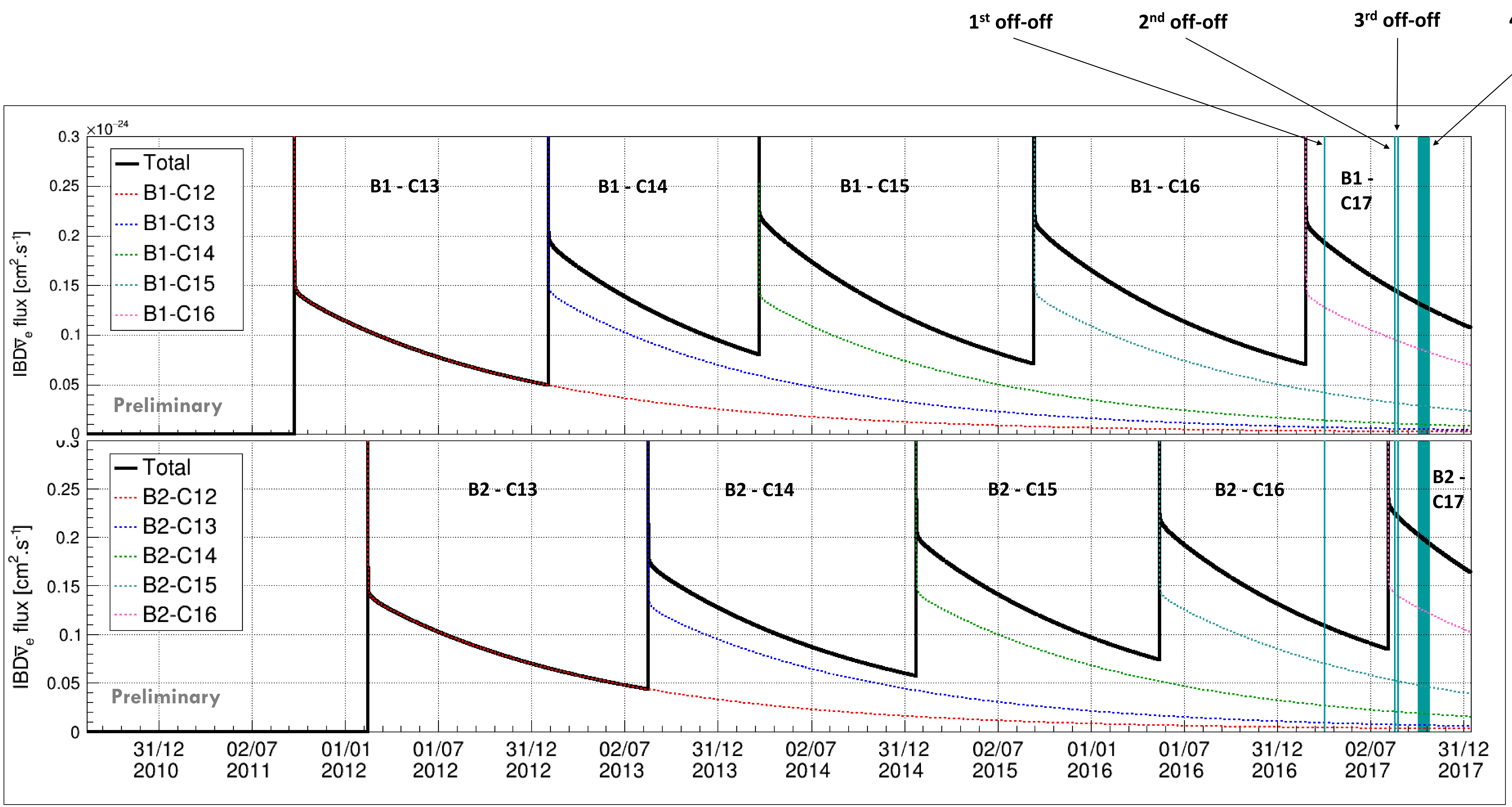
Cycle 10 Cycle 11 Cycle 12 Cycle 13 Cycle 14 Cycle 15 Cycle 16

- Typically 15-17 GWd/t irradiation cycle
- Power history for the simulation: ~1 day time step over the three irradiation cycle + 1 hour time step the day preceding the dischargement

IBD$_{\bar{\nu}_e}$ from spent fuel assemblies in the pools (2/2)

Pool B1

Pool B2



Off-off 4
66 %
21 %
7 %
4 %
2 %

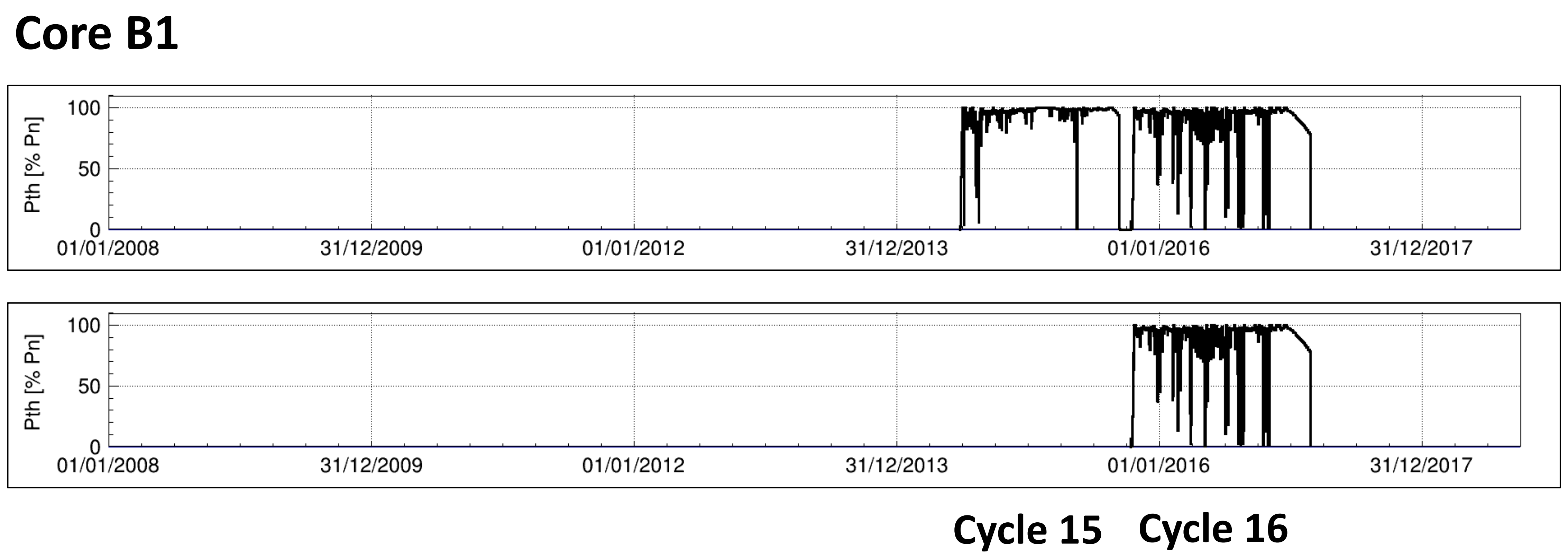
Off-off 4
63 %
24 %
9 %
3 %
1 %

Fig. IBD$_{\bar{\nu}_e}$ flux at the ND by the B1 (top) and B2 (bottom) pools.

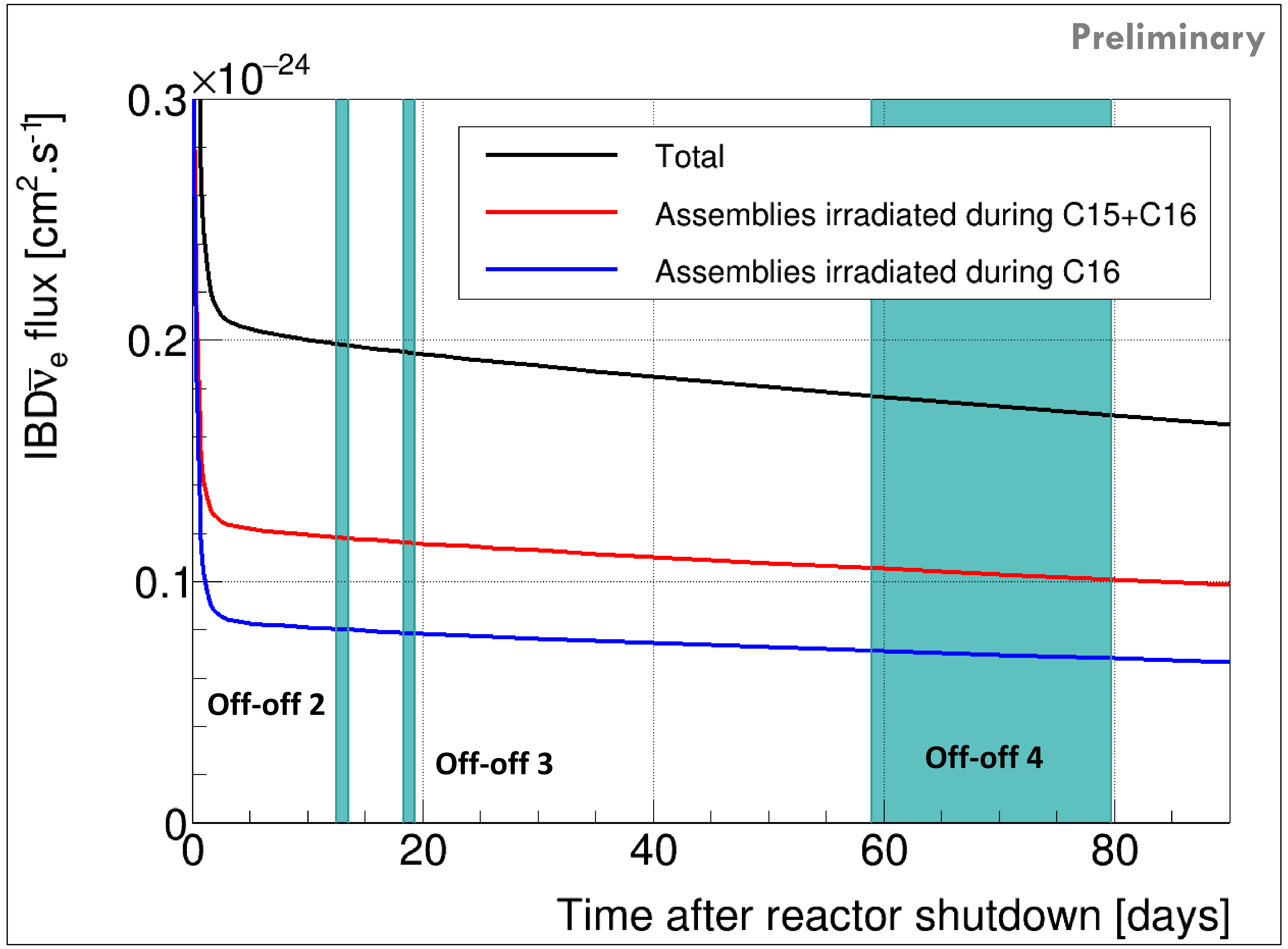
IBD$\bar{\nu}_e$ from the cores under refueling

Exemple for the off-off 2, 3 and 4 (reactor B1 under refuelling)

Reactor power history



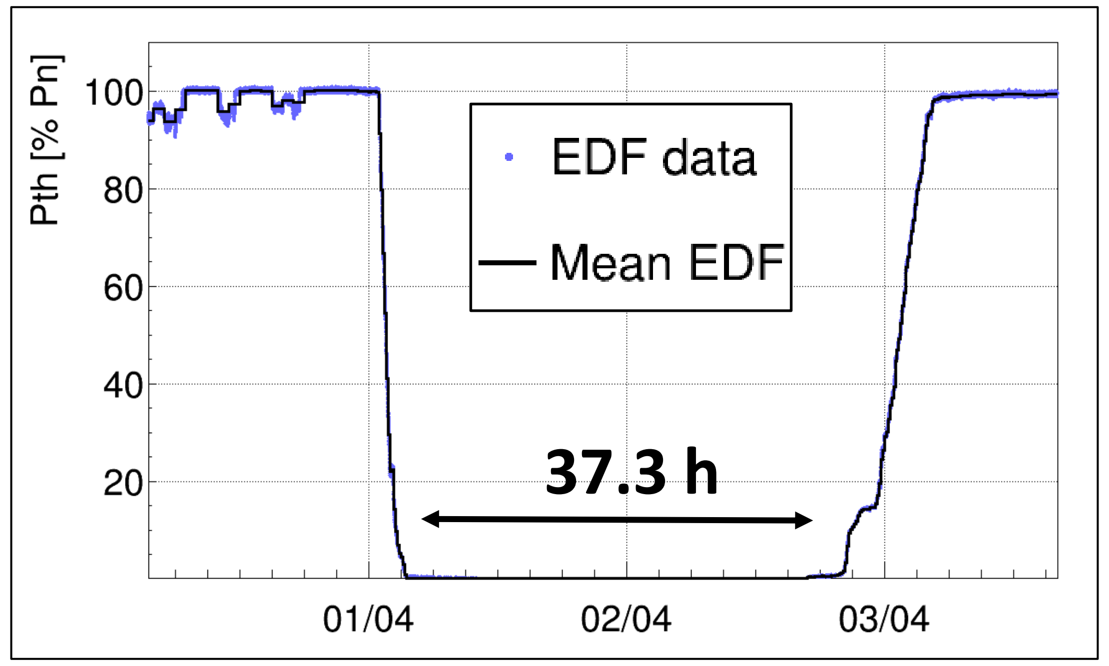
IBD flux - ND



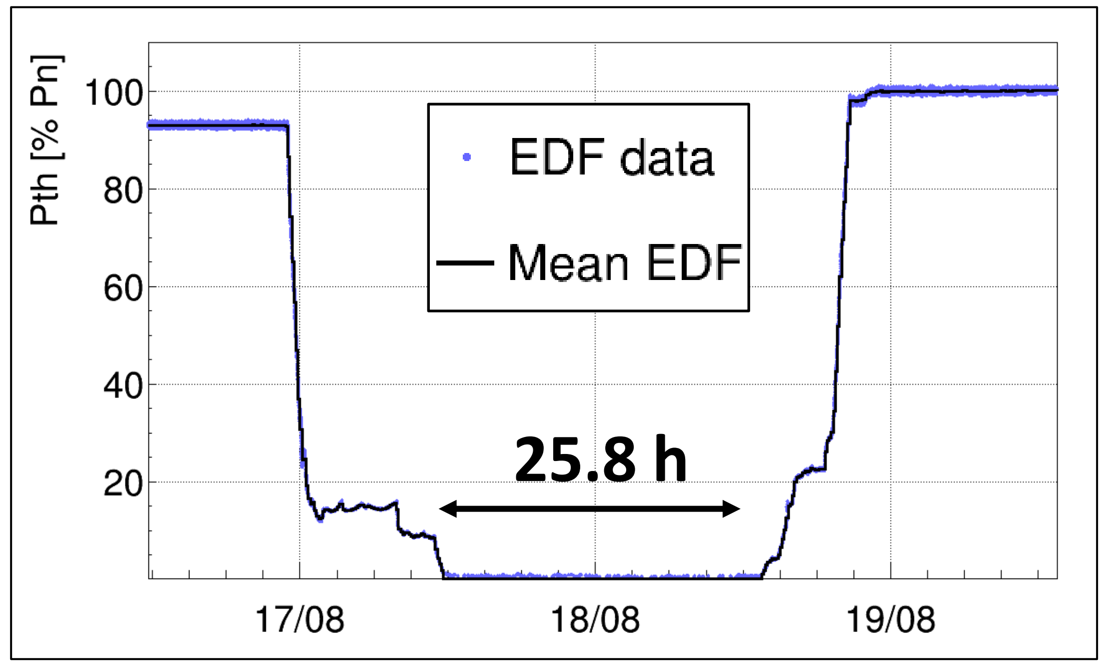
- Detailled power history input for the simulation
- $\bar{\nu}_e$ flux mostly depend of the assemblies burnup

IBD$\bar{\nu}_e$ from the cores temporarily shutdown

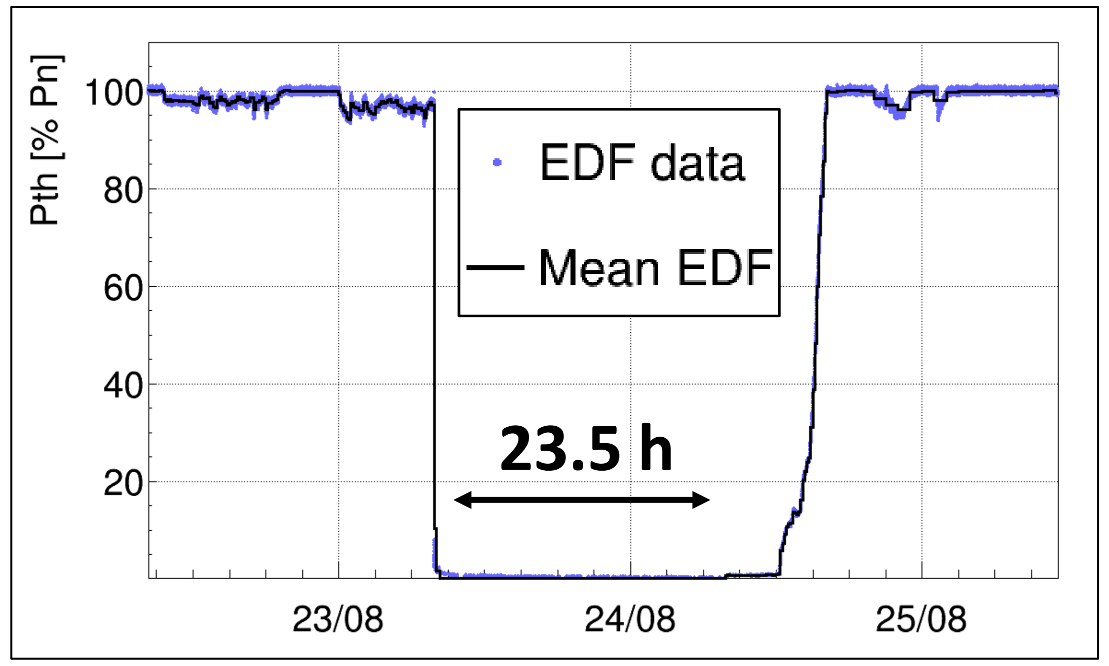
Reactor power history



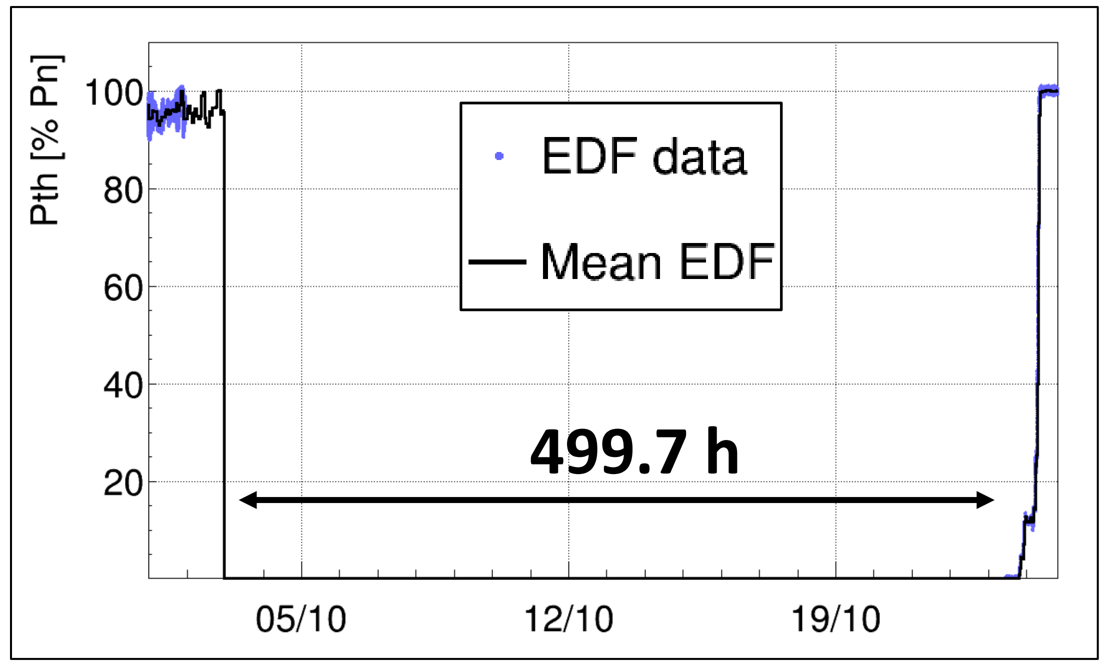
Off-off 1 (B2 stopped)



Off-off 2 (B1 stopped)

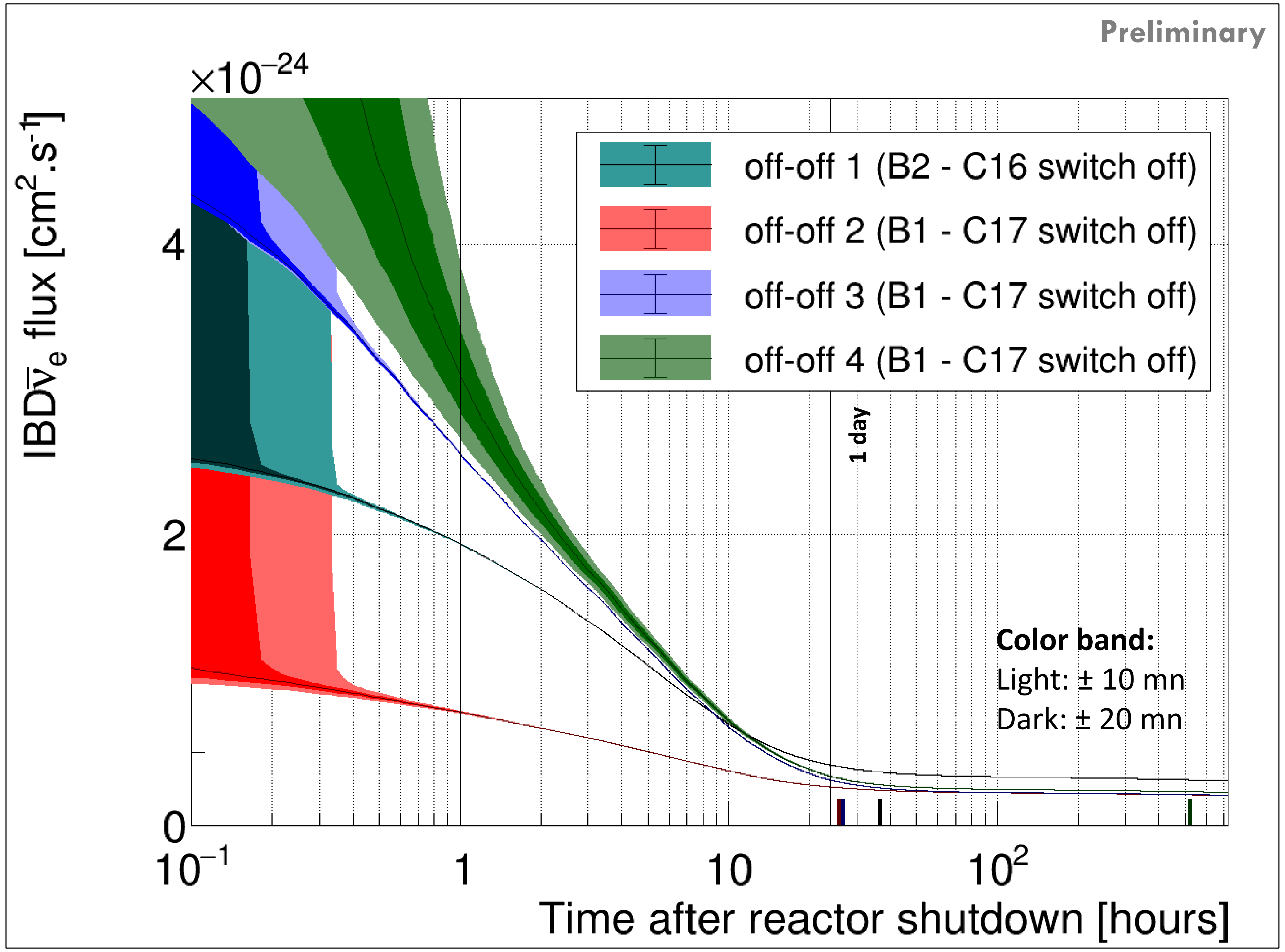


Off-off 3 (B1 stopped)



Off-off 4 (B1 stopped)

IBD flux - ND



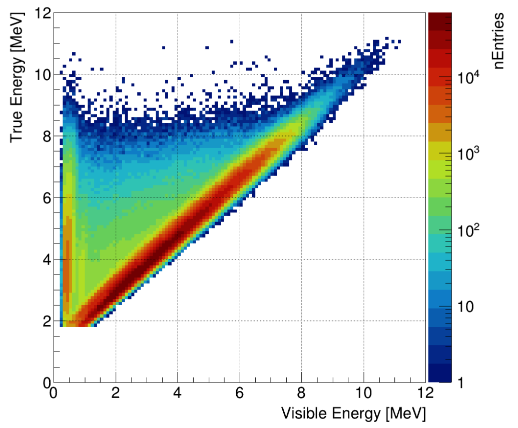
- Detailled power history input for the simulation (down to 10 mn time step the day precedding the off)

- $\bar{\nu}_e$ flux strongly depend of power history for ~1 day following the shutdown
- $\bar{\nu}_e$ flux mostly depend of burnup after 1 day

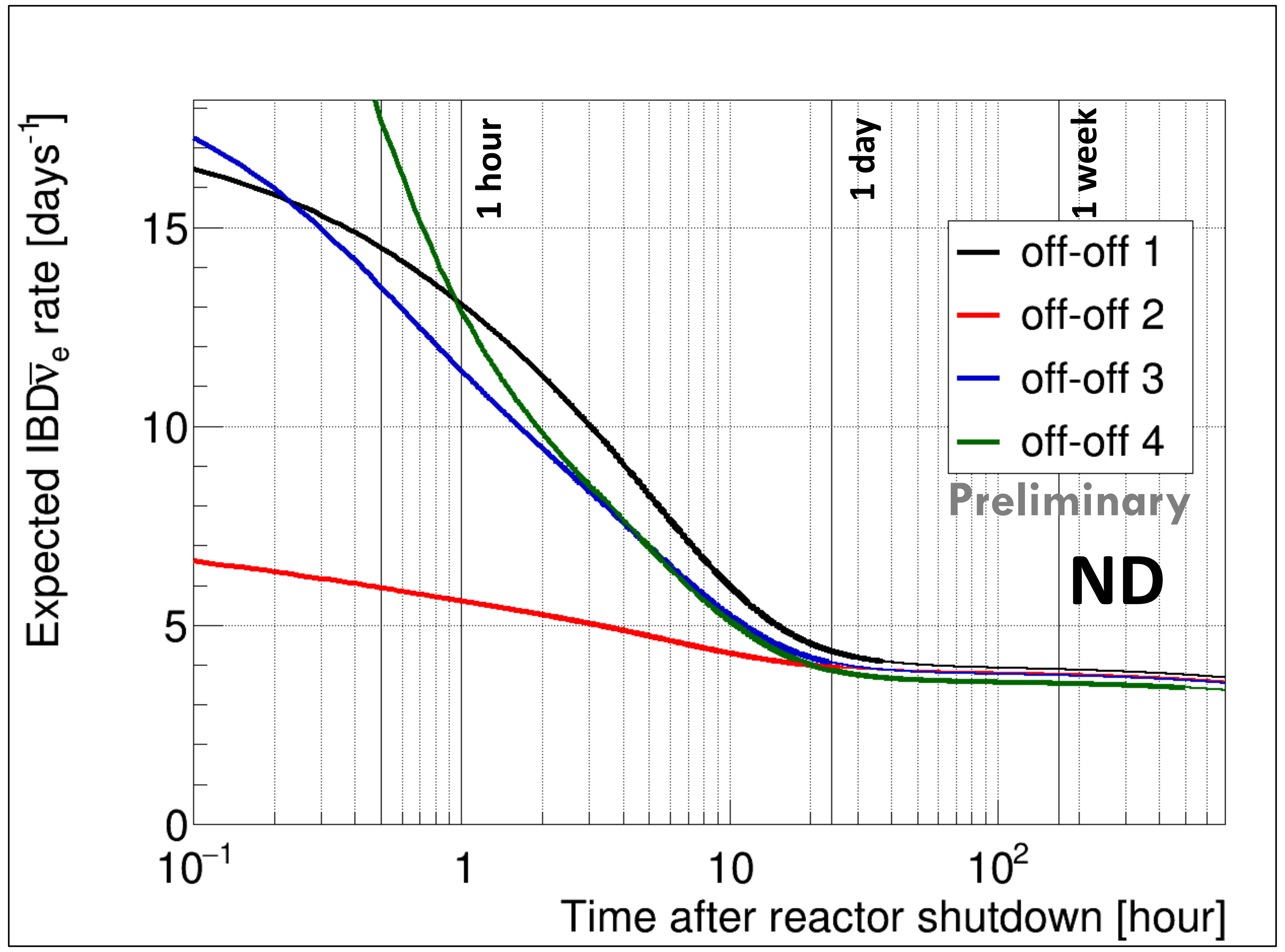
Expected ND rates and spectrum

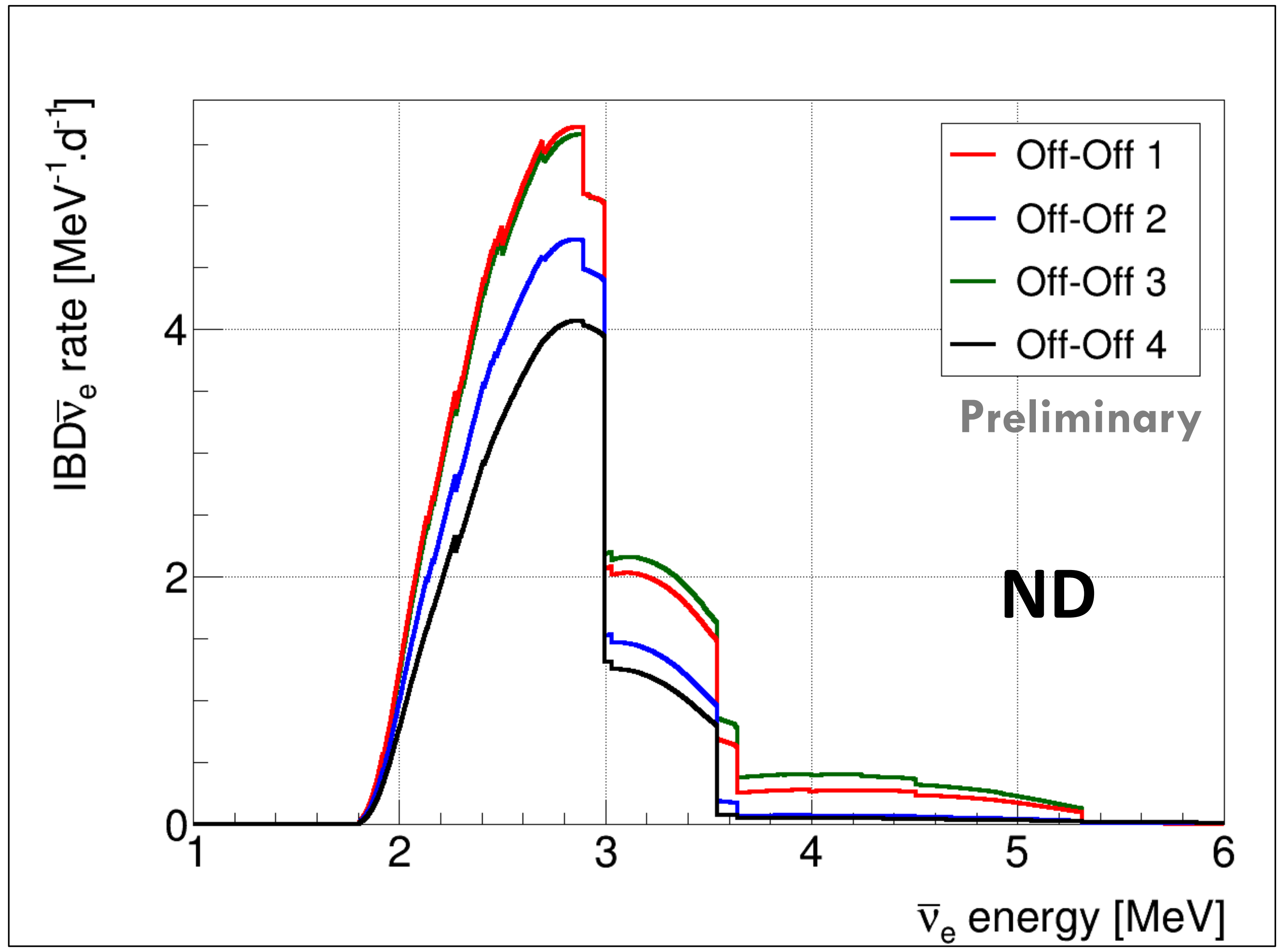
Expected rates and spectra at the ND

- sum of the four flux component



Response matrix





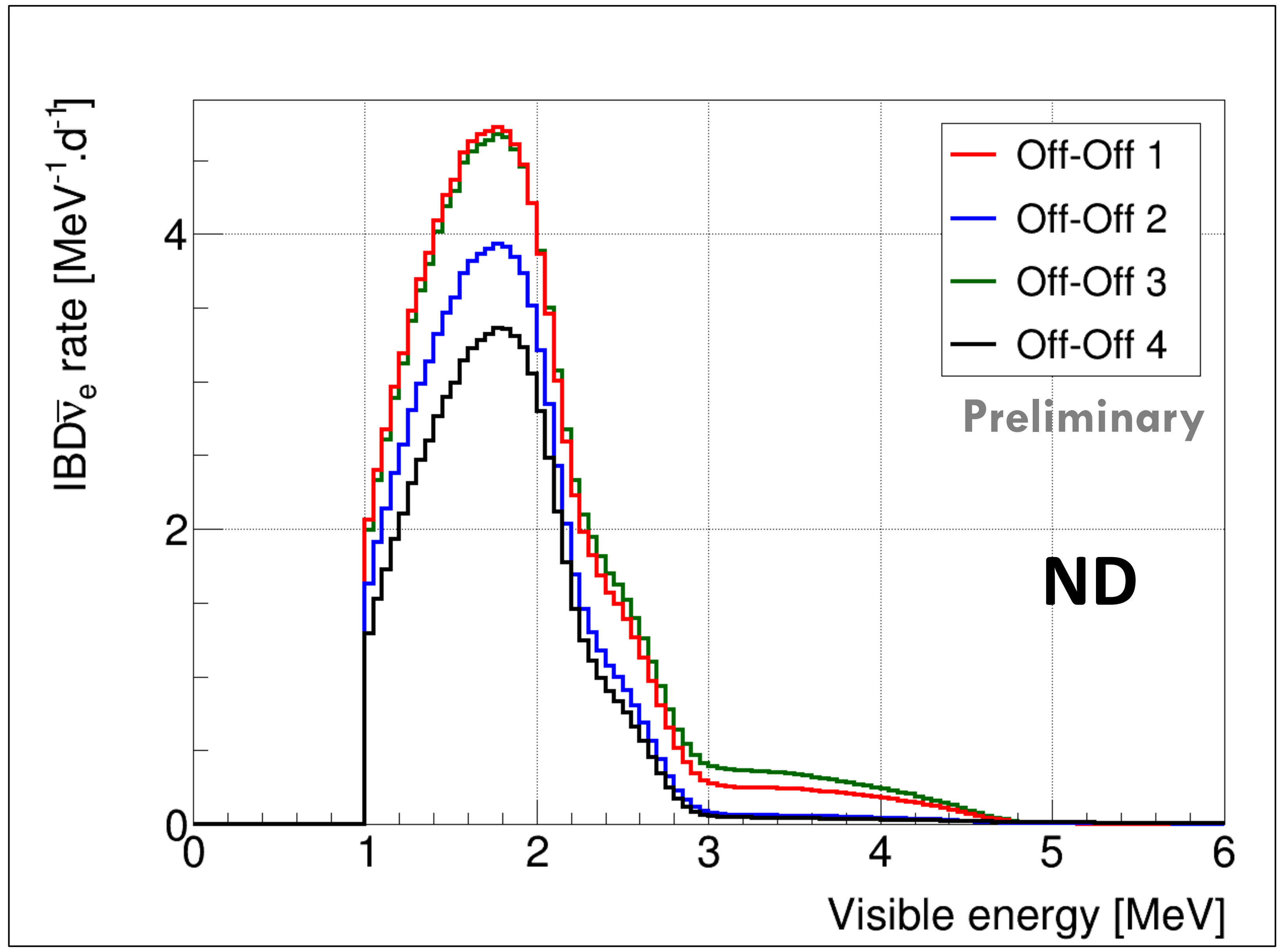


Fig. Expected IBD$\bar{\nu}_e$ rate in the ND for each off-off periods as a function of time

Fig. Expected IBD$\bar{\nu}_e$ spectrum at the ND for each off-off periods as a function of the true (left) and visible (right) energy

- Residual $\bar{\nu}_e$ flux strongly depend of power history for ~1 day following the shutdown
- ~3.5 evts/day expected after the first day of off-off
- Dominant contribution in the 1-3 MeV range in visible energy

Expected IBD events (1/2)

Expected IBD spectra

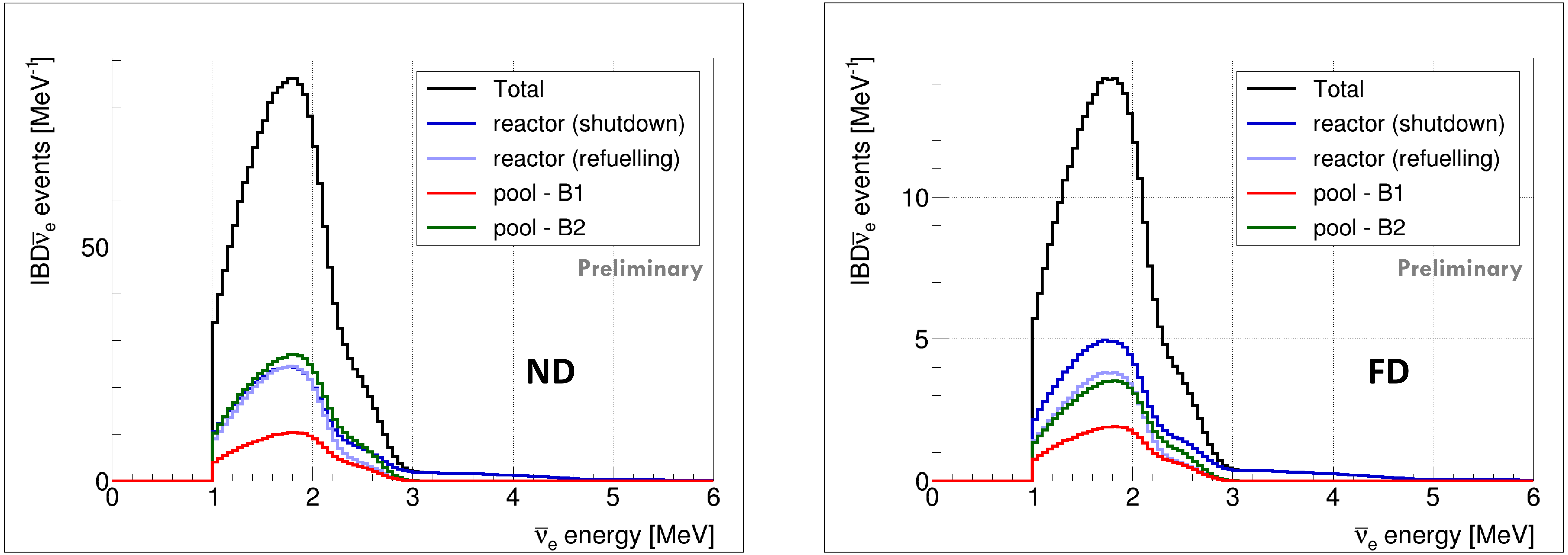


Fig. Expected IBD$\bar{\nu}_e$ spectrum in the ND (left) and FD (right) for all off-off period combined (no runlist).

	Relative contribution [%]	
	Reactors	**Pools**
Near	56.5	43.5
Far	61.7	38.3

Tab. Expected number of IBD$\bar{\nu}_e$ in the ND and FD for all off-off periods combined.

Systematic breakdown

Normalization uncertainties summary

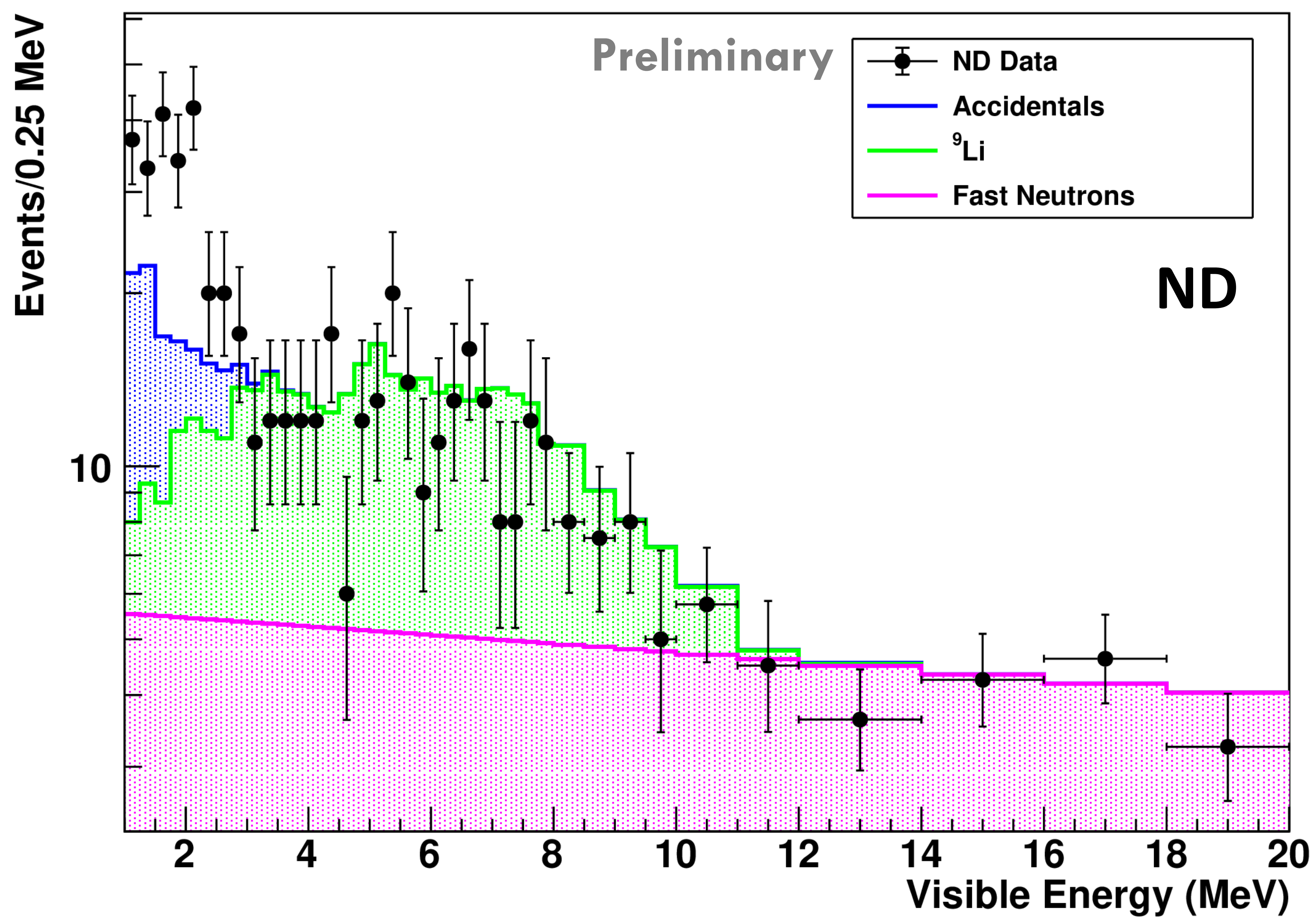
Preliminary

		ND	FD
Chooz site	- Distance assemblies-detectors	**2.9**	**0.9**
	- θ_{13} oscillation	0.1	0.3
Detector	- detection efficiency	0.3	0.4
	- proton number	0.7	0.7
Reactor	- Thermal power	0.5	0.5
	- Reactor stop time	0.2	0.2
	- IBD cross-section	0.1	0.1
	- Fission product inventory	**2.1**	**2.1**
	- Amount of spent fuel in the pool	**2.0**	**1.5**
	- $\bar{\nu}_e$ spectra	**6.0**	**6.0**
	Total	**7.4 %**	**6.7 %**

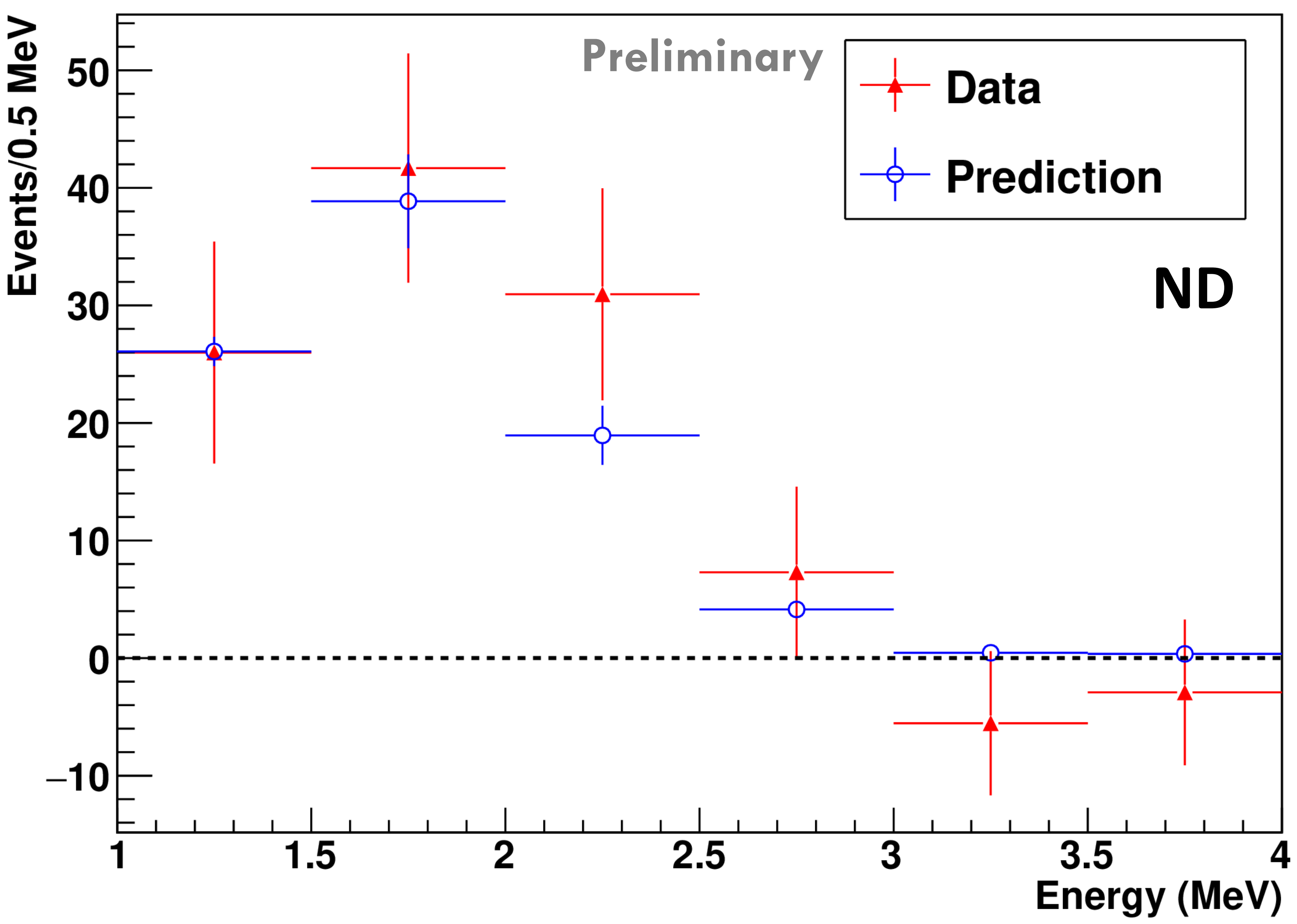
- Total uncertainty dominated by the uncertainty associated to the $\bar{\nu}_e$ spectra modeling (NSC ^{144}Pr)
- Request to EDF to lift approximations associated to the pool dimension and fuel content in the pools
  - Status of spent fuel from old reactor cycle unknown ⇒ treated as systematic

Preliminary data – prediction comparison (1/2)

Off-off data



Data (bckg. substracted) vs prediction

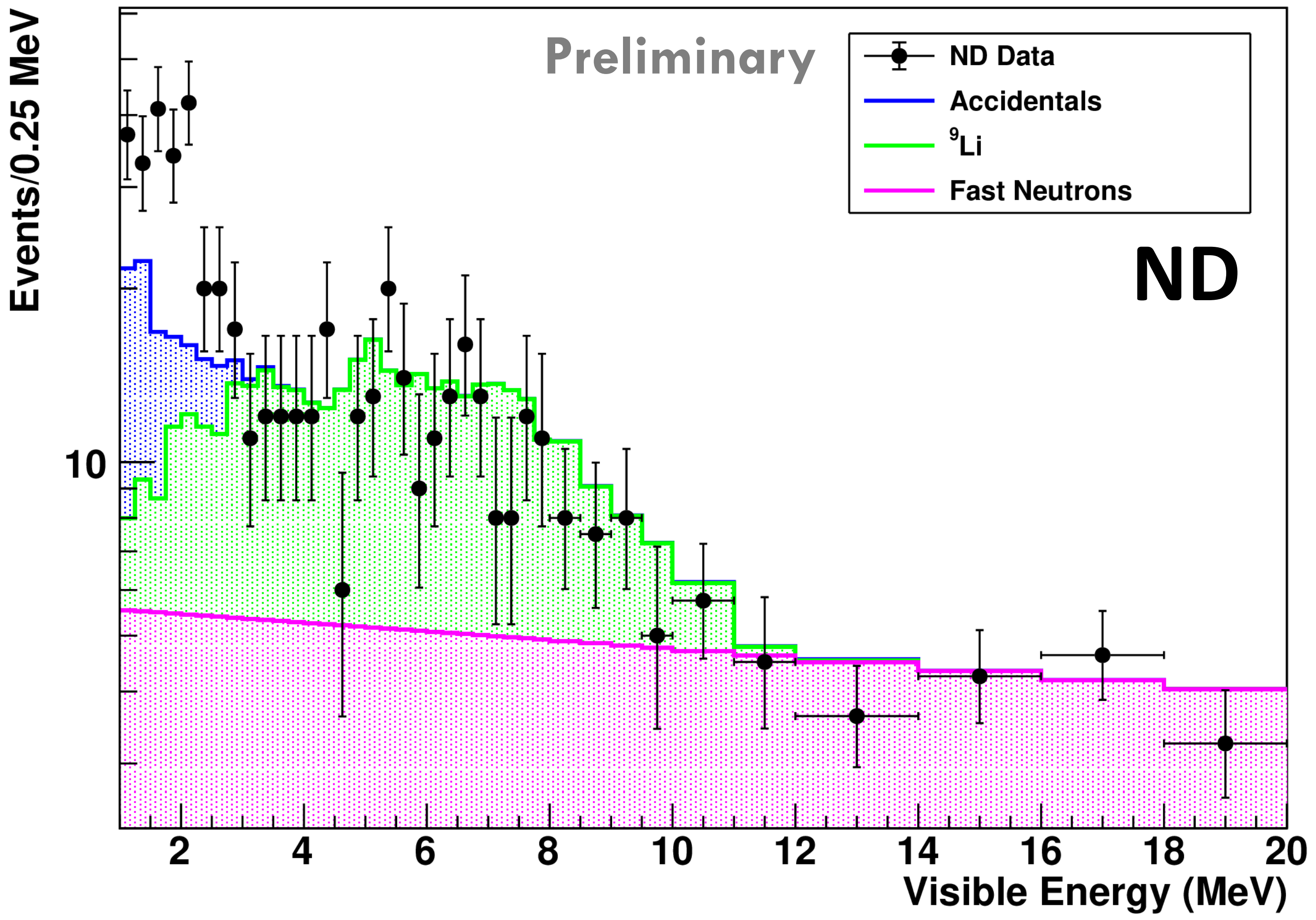


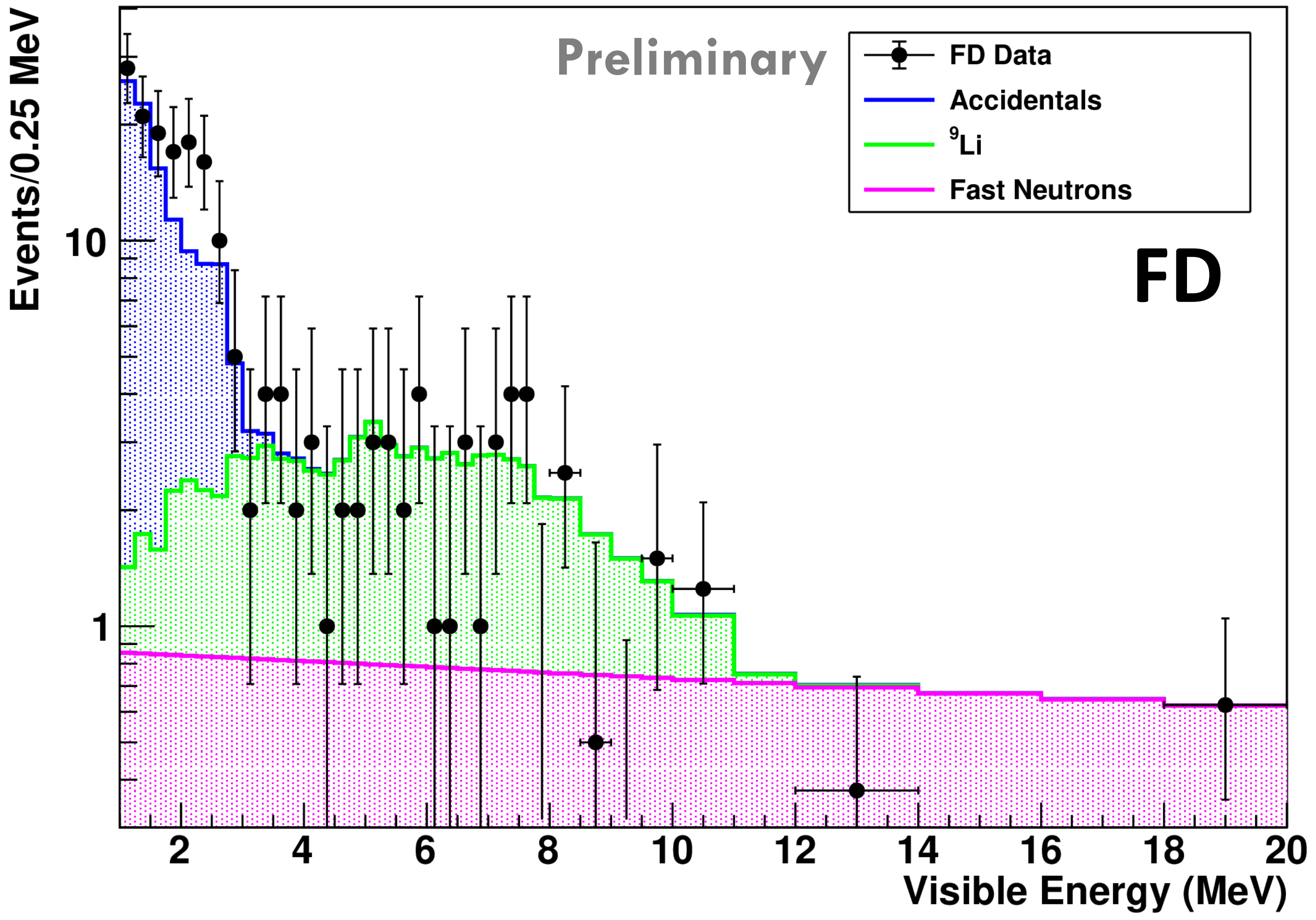
- Reference background model from last analysis (Nature physics)
- Limited statistic: $\sigma_{stat} \sim 15\%$
- Very good preliminary data/prediction agreement

1-3 MeV: $N_{\mathrm{IBD}}^{\mathrm{data}} = 106 \pm 18$ evts
$N_{\mathrm{IBD}}^{\mathrm{pred}} = 88 \pm 6$ evts

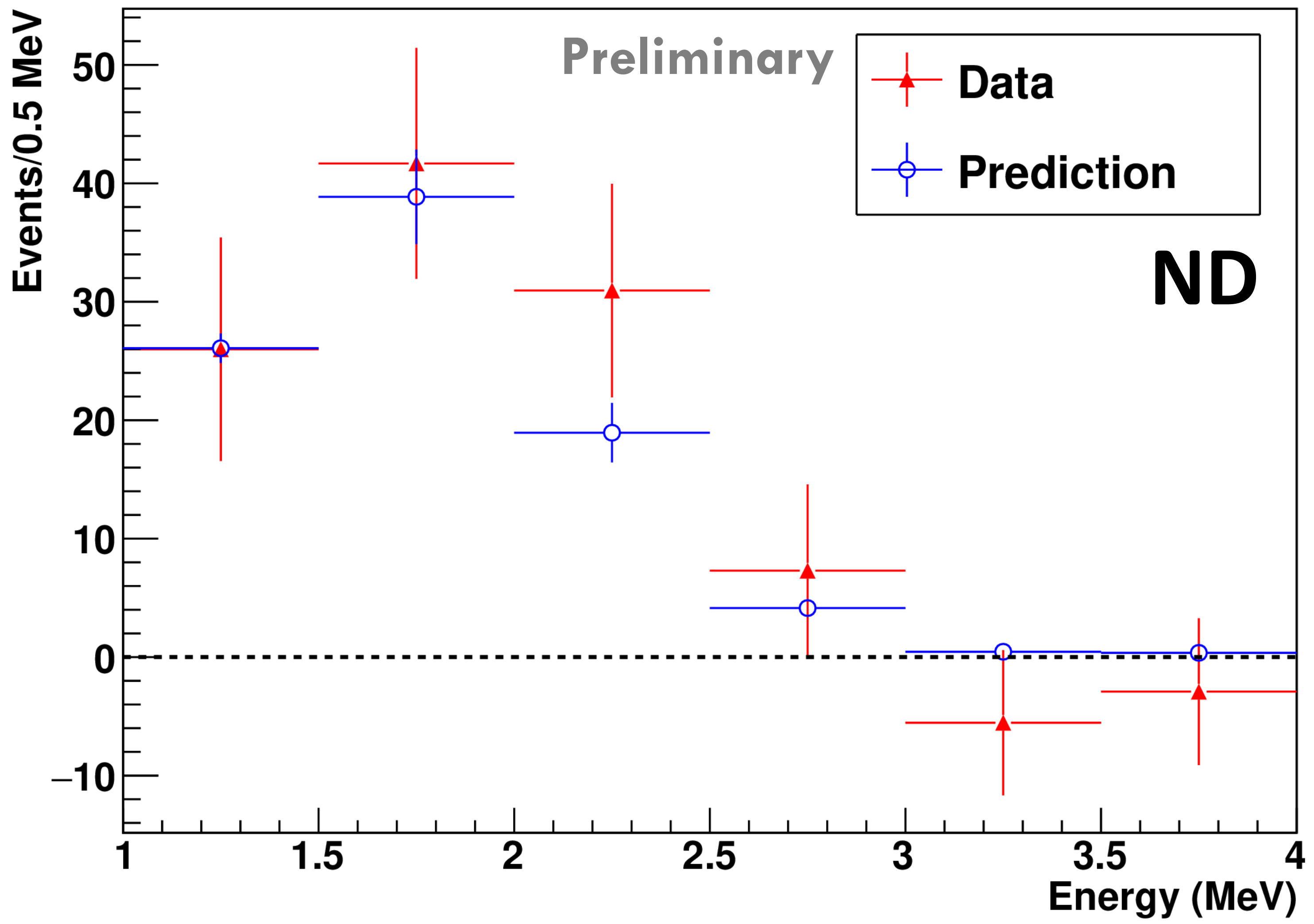
Preliminary data – prediction comparison (2/2)

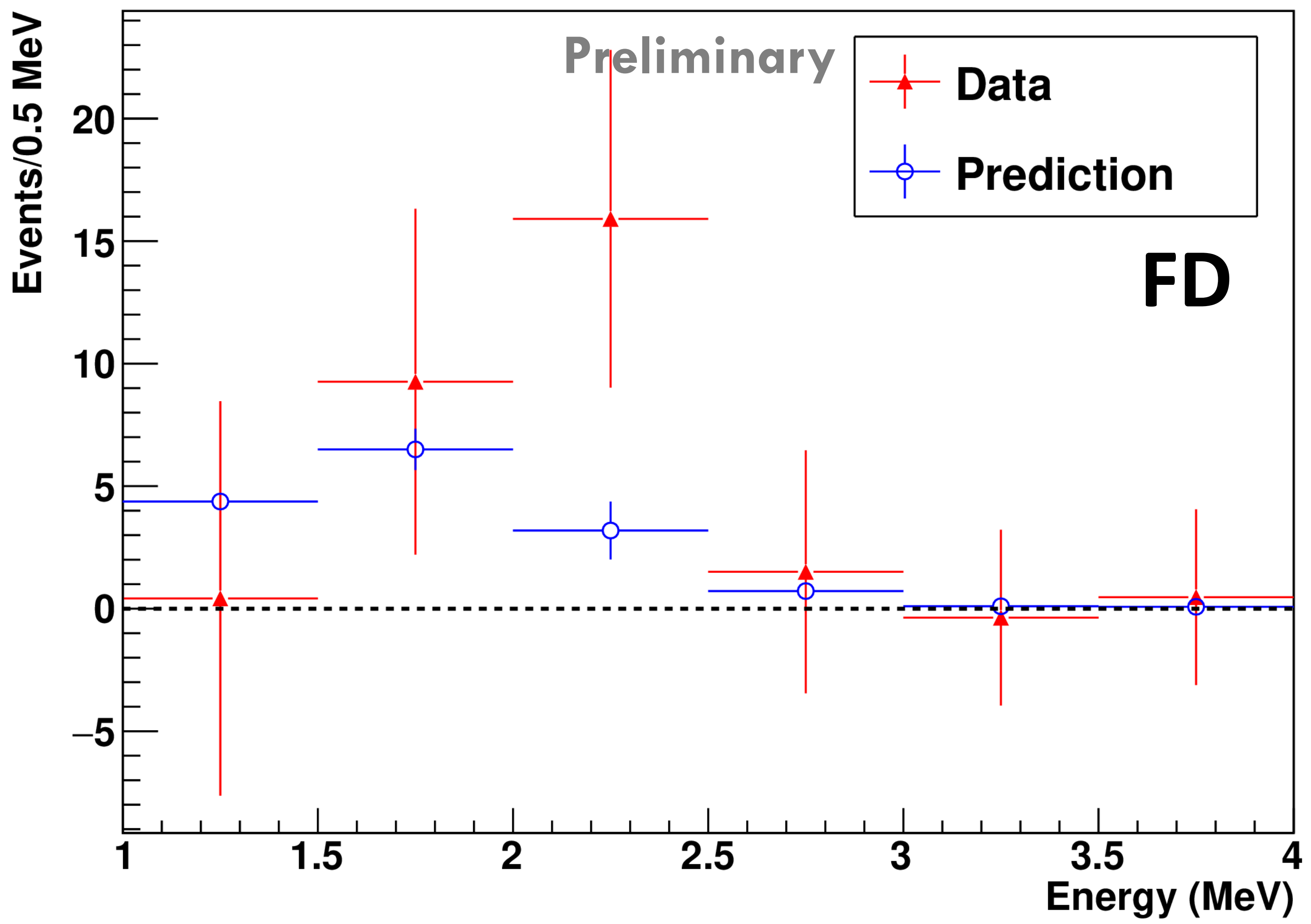
Off-off data





Data (bckg. substracted) vs prediction





$\mathrm{IBD}_{\bar{\nu}_e}$ 1-3 MeV

	Data	Prediction	Difference
ND	106 ± 18	88 ± 6	18 ± 19
FD	27 ± 14	15 ± 1	12 ± 14

Preliminary

- Reference background model from last analysis (Nature Physics)
- Limited statistic: $\sigma_{stat}^{ND} \sim 17\%$, $\sigma_{stat}^{FD} \sim 52\%$
- Very good preliminary data/prediction agreement

I. **The Double Chooz experiment**
   - experimental principle
   - analysis highlight and latest results

II. **Residual antineutrinos**
   - modeling
   - generality about residual antineutrinos

III. **DC off-off periods**
   - prediction
   - preliminary data/prediction comparison

IV. **Conclusion**

VIII. Conclusion

Double Chooz reaching its life-cycle end…

- End of data taking in 2020
- Detectors under dismantlement
- Latest published result: - $\mathbf{\sin^2(2\theta_{13}) = 0.102 \pm 0.011\ (syst.) + 0.04\ (stat.)}$

  - $\boldsymbol{\langle \sigma_f \rangle = (5.75 \pm 0.06) \times 10^{-43}\ cm^2}$

  ⇒ Still room for $\sin^2(2\theta_{13})$ improvement (expected 1σ ≲ 0.01 for the final result)

Off-off measurement

- ~24 days with both reactor off ⇒ very unique data set in the framework of reactor experiments
- Detailled prediction, including nuclear structure calculation for ^{144}Pr isotope
- Dataset for both detector, statistic dominated
- Very good preliminary data/prediction agreement: $\mathbf{N_{IBD,}^{data,ND} = 106 \pm 18}$ **evts measured /** $\mathbf{N_{IBD}^{pred,ND} = 88 \pm 6}$ **evts**

⇒ Demonstrate the great progress in detection and prediction over the last 20 years!

- Analysis under finalisation – publication foreseen soon

Backup

Impact of the neutrino spectrum shape on the survival probability

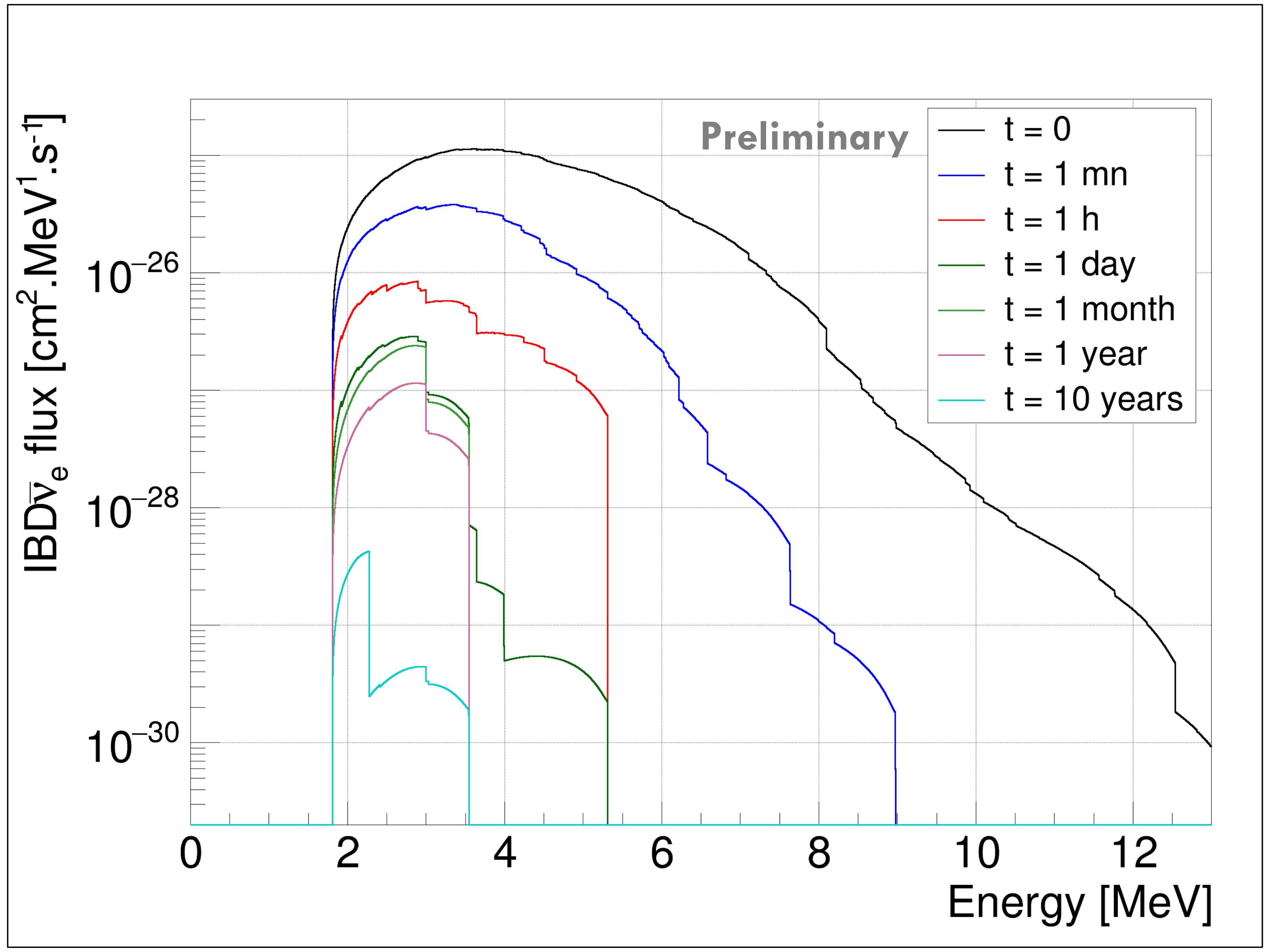


Fig. IBD neutrino spectrum from a UO_2 (4%) spent fuel assembly irradiated for 45 GWd/t.

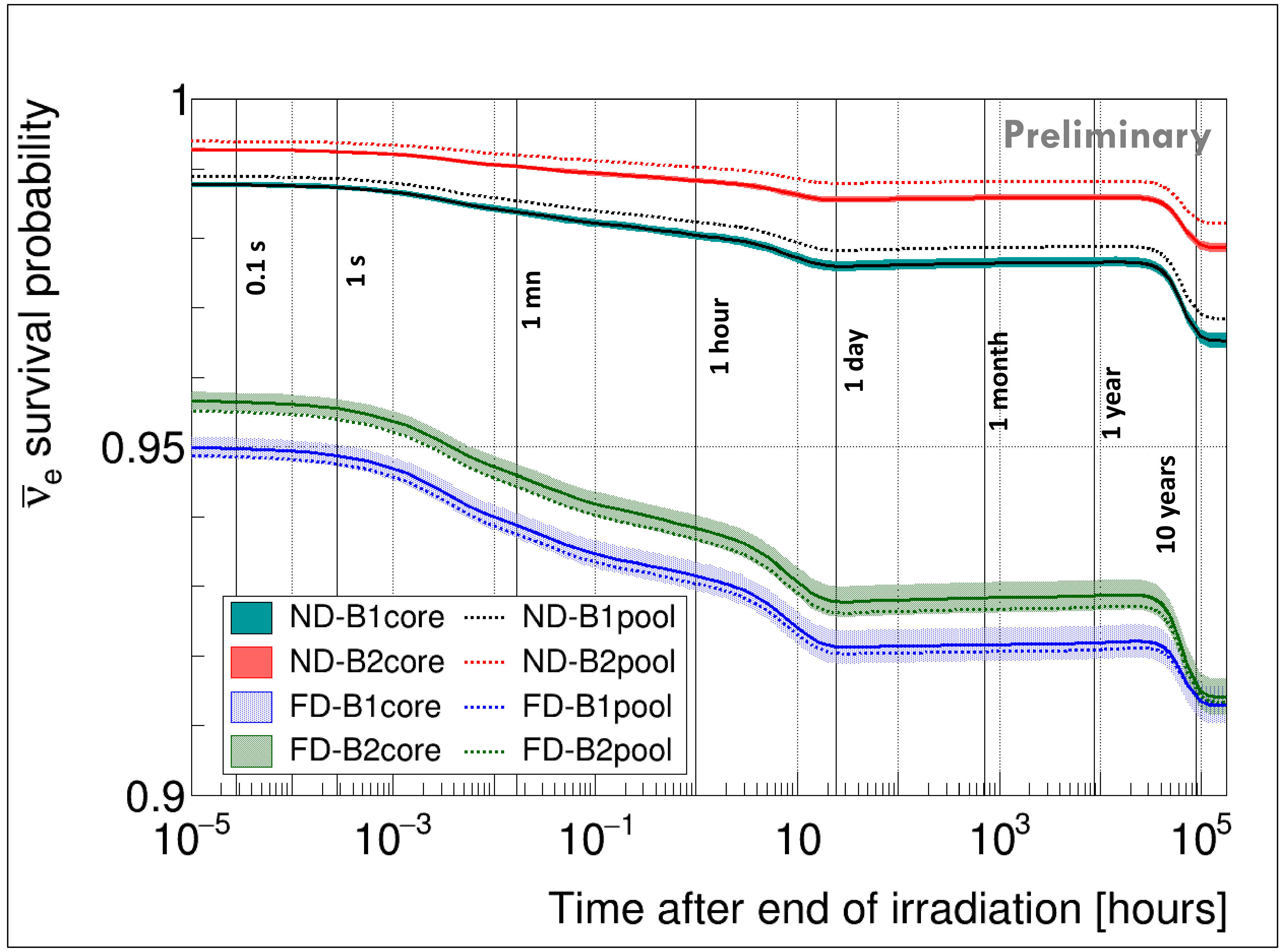


Fig. Oscillation probability for the neutrino spectrum of an assembly irradiated up to 45 GWd/t during its cooling. Colored bands represent the 1σ uncertainty induced by $\sigma_{\theta_{13}}$ (for clarity only display on core cases)