Neutrino **E**xperiment for **O**scillation at **S**hort Baseline

21 Sep 2017 / The 39th ISNP @ Erice, Sicily

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Center for Underground Physics

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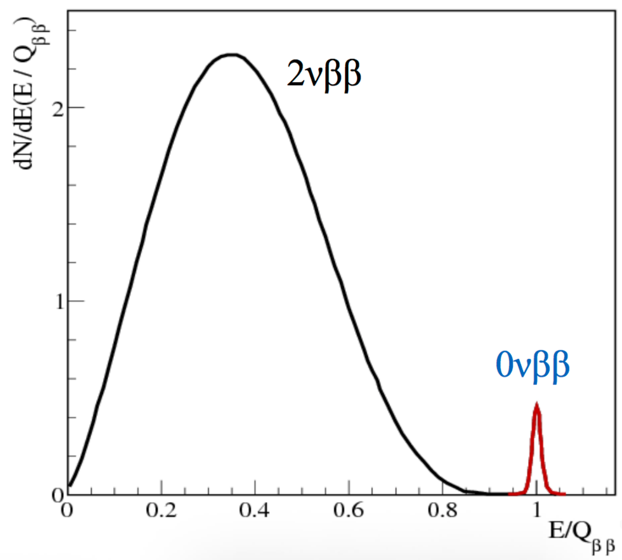
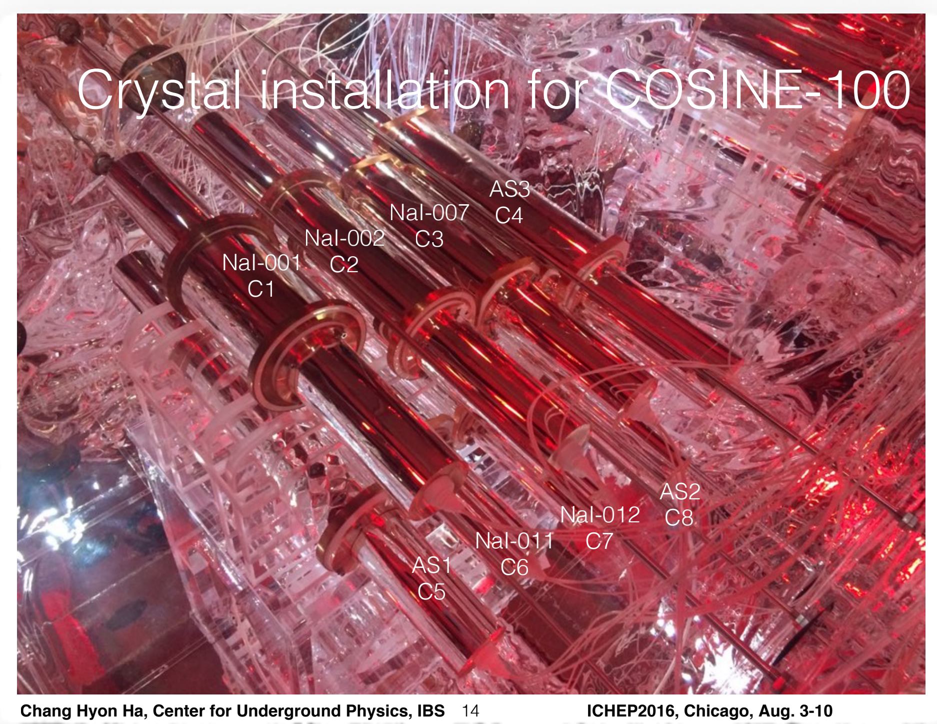
Dark
Matter





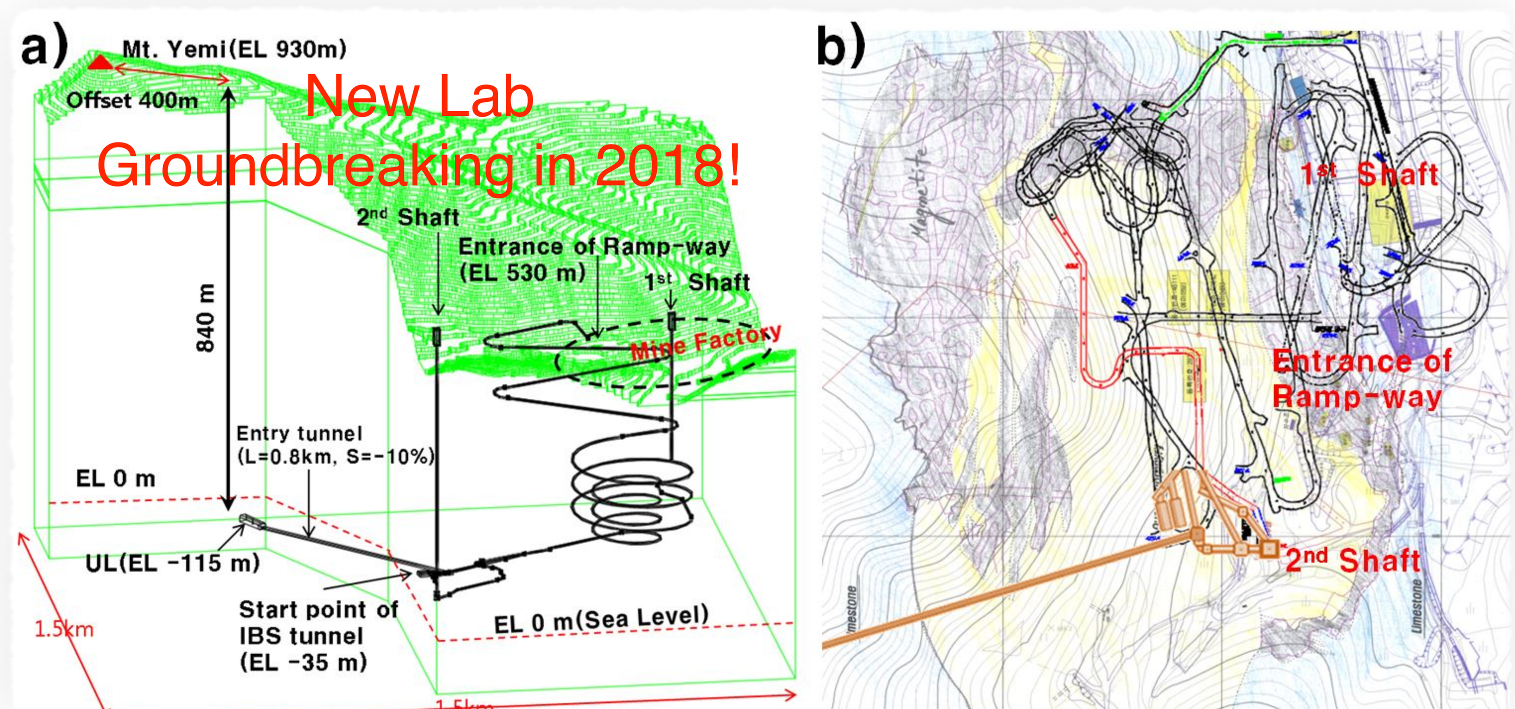
- Rare event search at low background environment
  - WIMP annual modulation (COSINE)
  - neutrinoless double beta decay (AMoRE)
  - HPGe measurement
- new / ν physics
- crystal growing, material purification

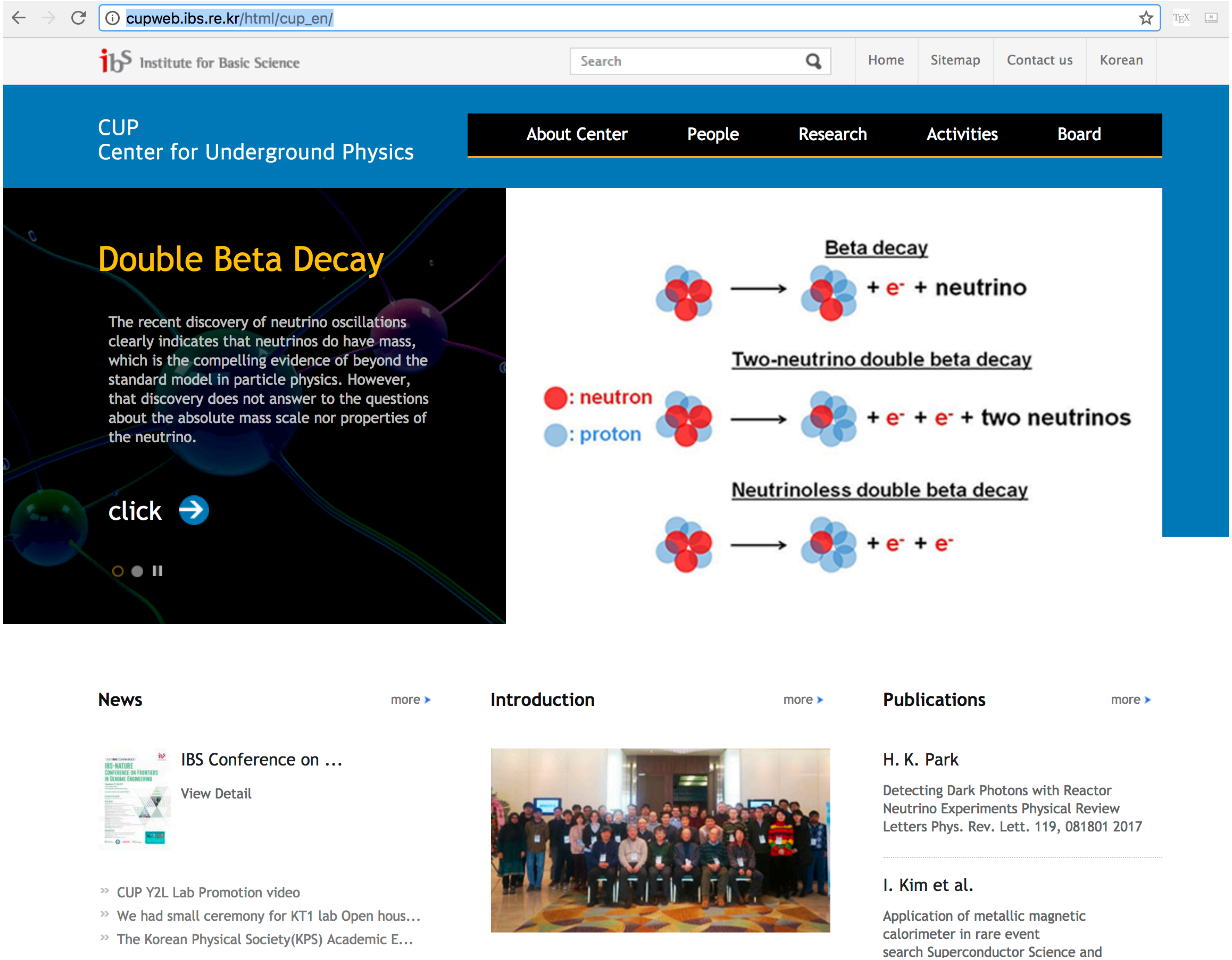
Center for Underground Physics

Underground lab

Y2L

- Minimum depth: 700 m
- Access by car (~2 km)
- Experiments:
  - COSINE (DM)
  - AMoRE (0νββ)

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Double Beta Decay
The recent discovery of neutrino oscillations clearly indicates that neutrinos do have mass, which is the compelling evidence of beyond the standard model in particle physics. However, that discovery does not answer to the questions about the absolute mass scale nor properties of the neutrino.
click
Beta decay
+ e⁻ + neutrino
Two-neutrino double beta decay
: neutron
: proton
+ e⁻ + e⁻ + two neutrinos
Neutrinoless double beta decay
+ e⁻ + e⁻
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IBS Conference on ...
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CUP Y2L Lab Promotion video
We had small ceremony for KT1 lab Open hous...
The Korean Physical Society(KPS) Academic E...
Introduction
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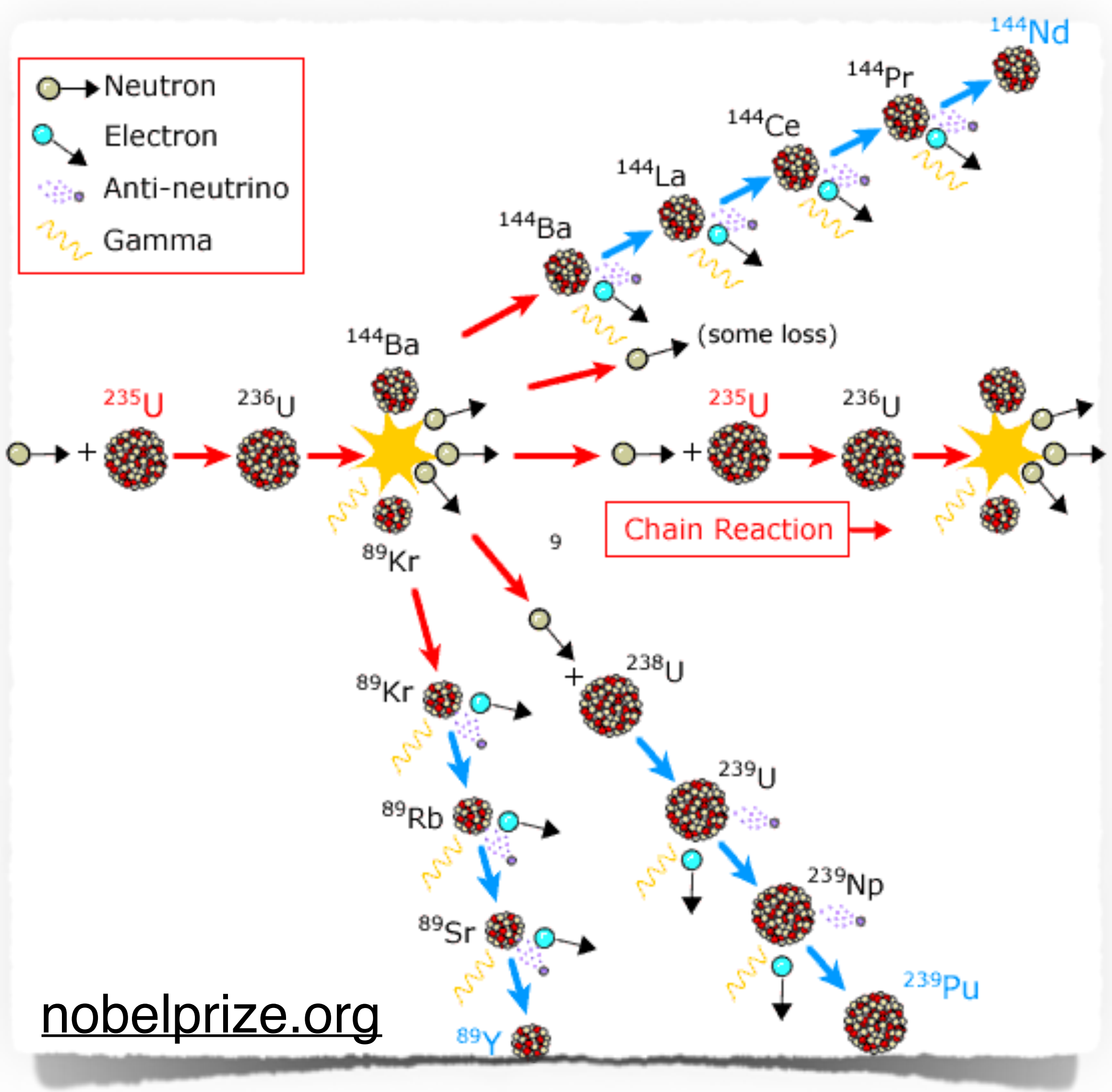
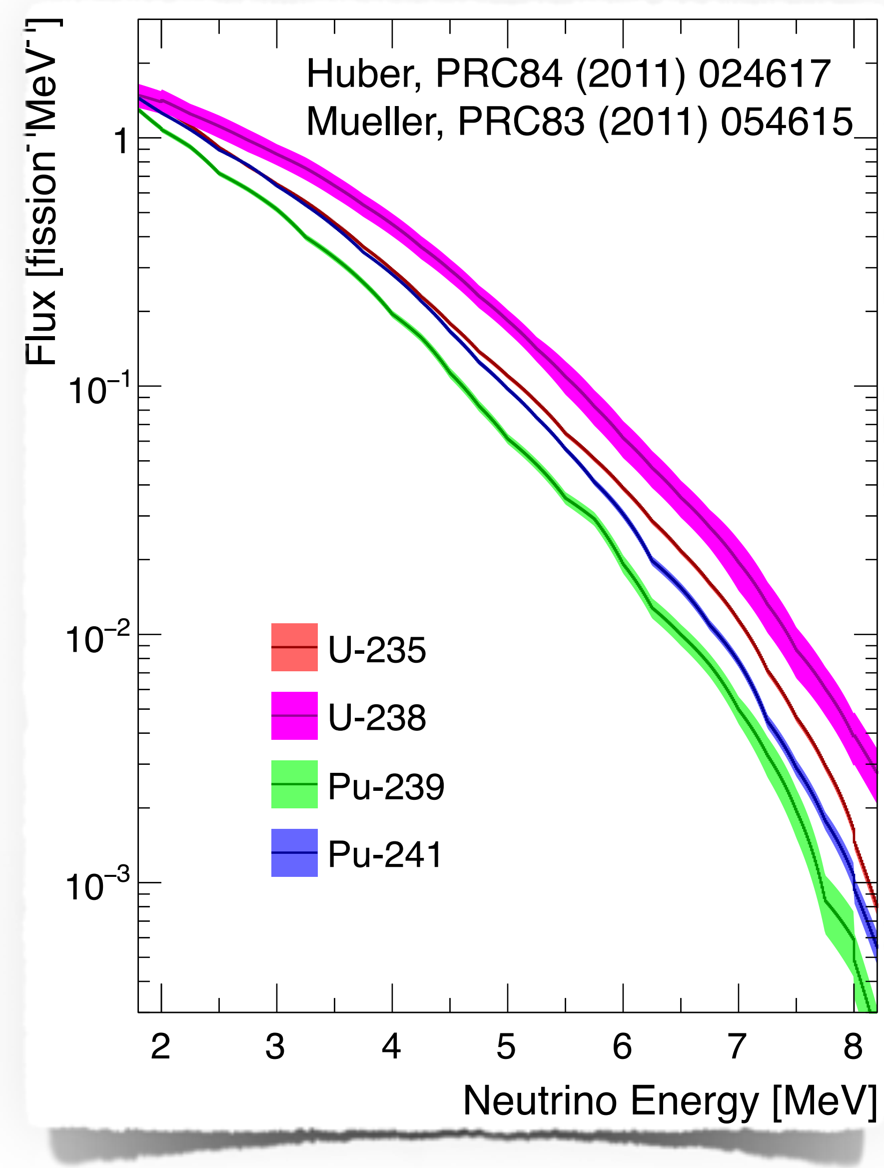
H. K. Park
Detecting Dark Photons with Reactor Neutrino Experiments Physical Review Letters Phys. Rev. Lett. 119, 081801 2017
I. Kim et al.
Application of metallic magnetic calorimeter in rare event search Superconductor Science and

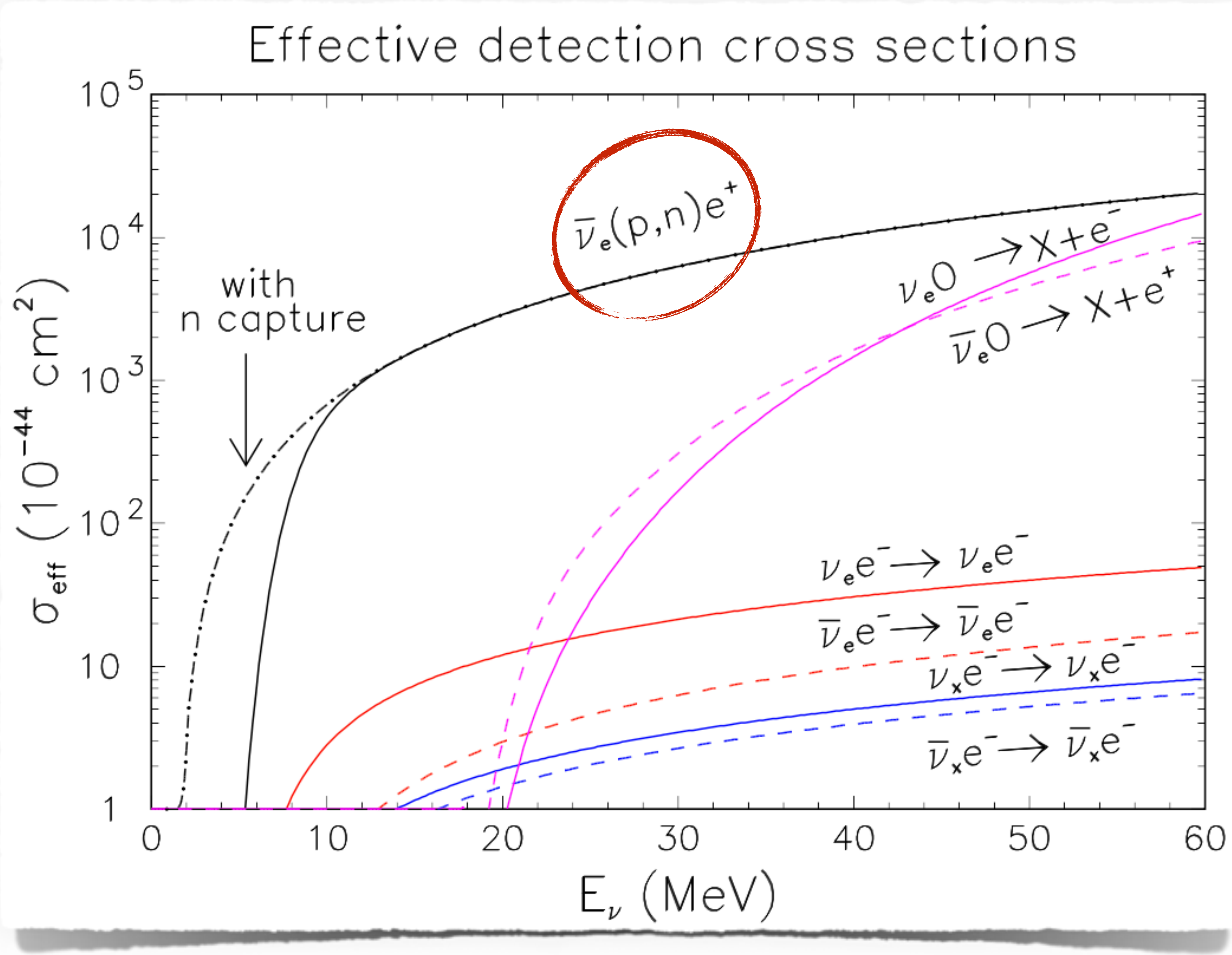
Reactor electron-antineutrino





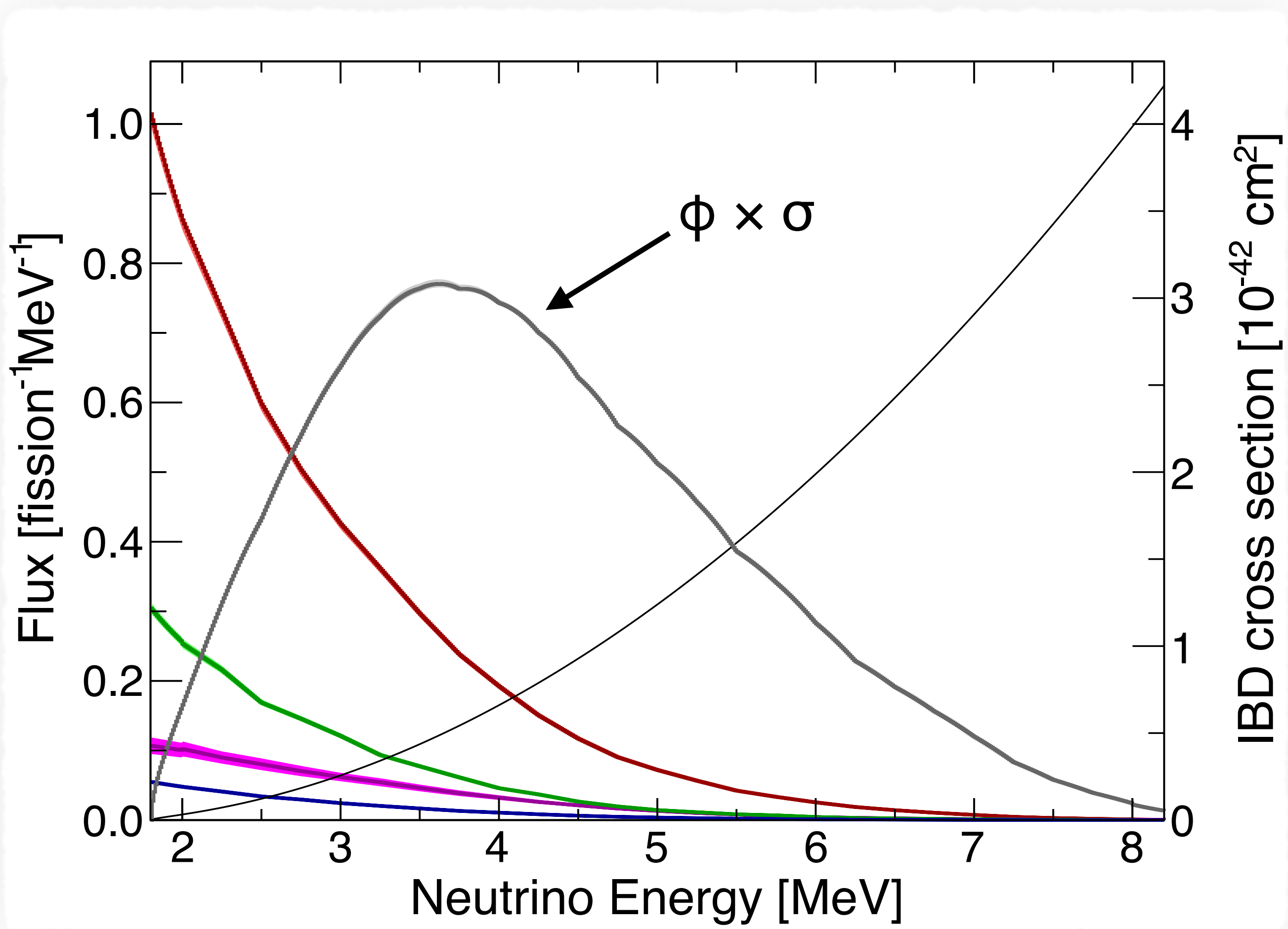
- $\bar{\nu}_e$ from fissile elements in reactor core: U-235, U-238, Pu-239, Pu-241
- ~2×10^{20} $\bar{\nu}_e$/s from 1 GW thermal power reactor
  — commercial: 100 ~ a few GW / research: up to ~100 MW

Detecting neutrinos

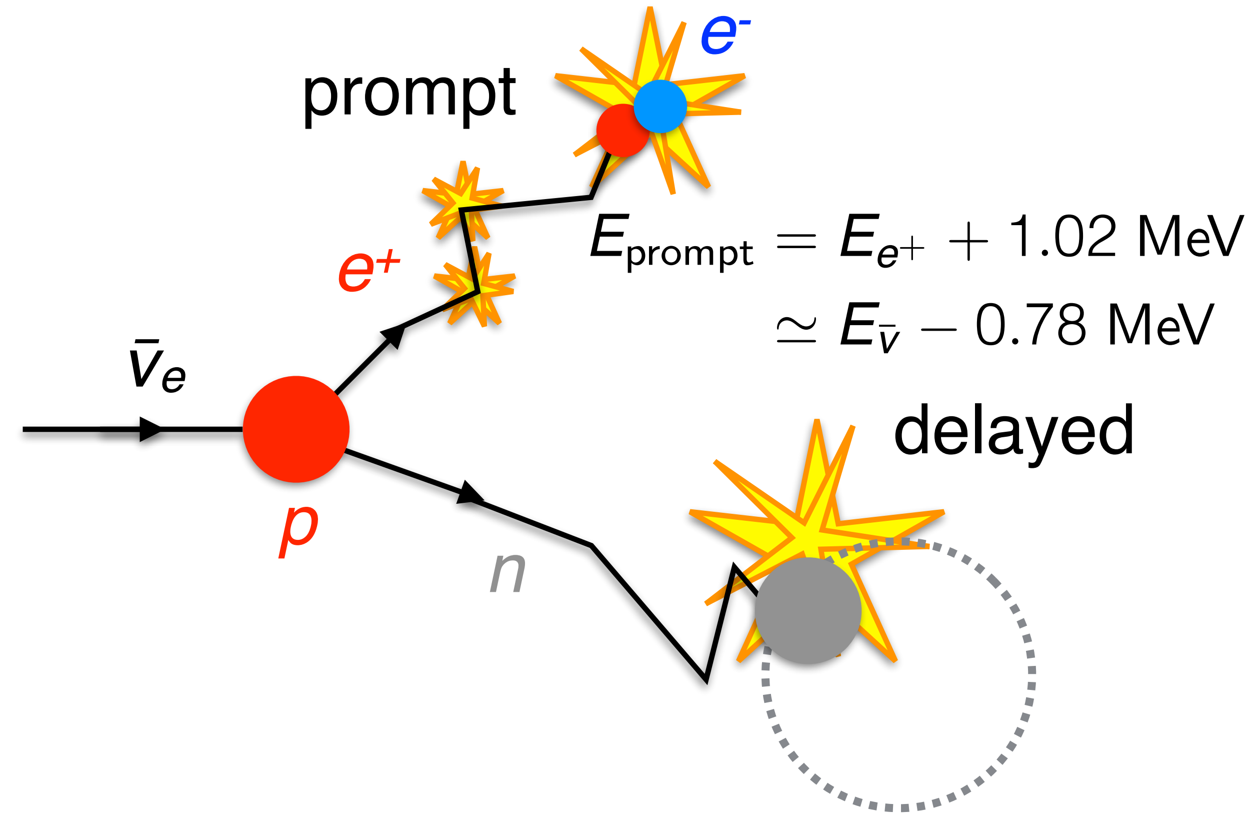


Fogli, JCAP 04 (2005) 002

Reactor $\bar{\nu}_e$ & inverse beta decay



flux by Huber / Mueller (2011)
cross section by Vogel, PRD60 (1999) 053003

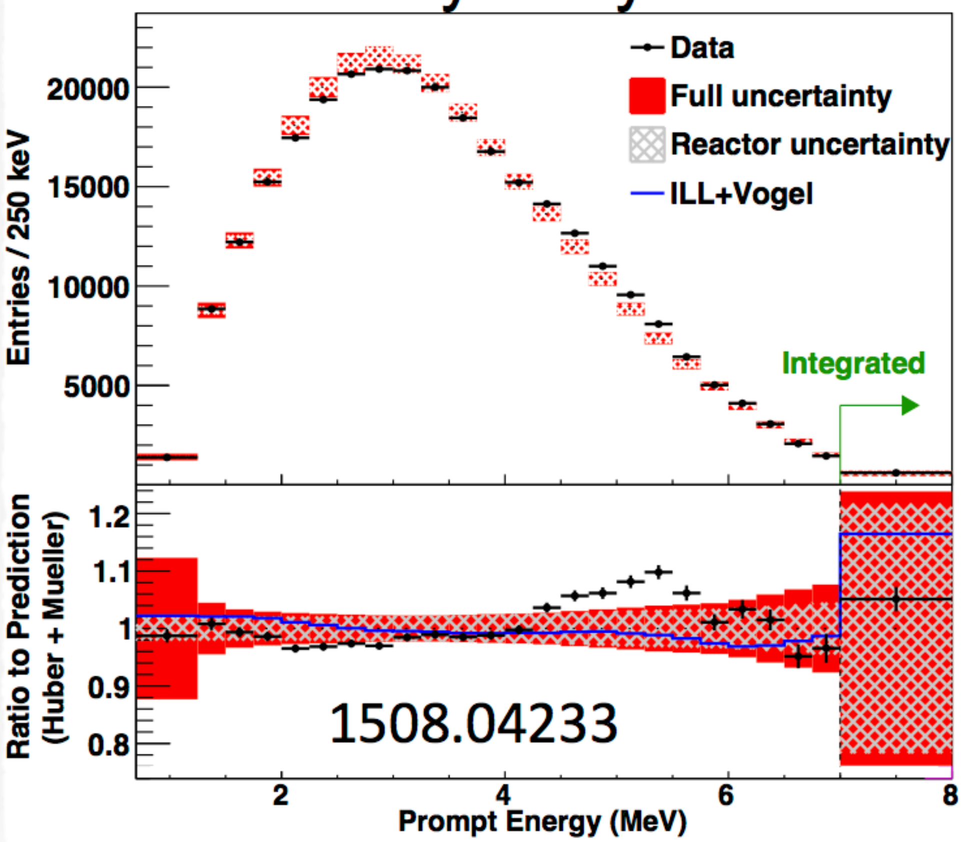


n-capture by
(H, Gd, ^{6}Li, ^{10}B, …)

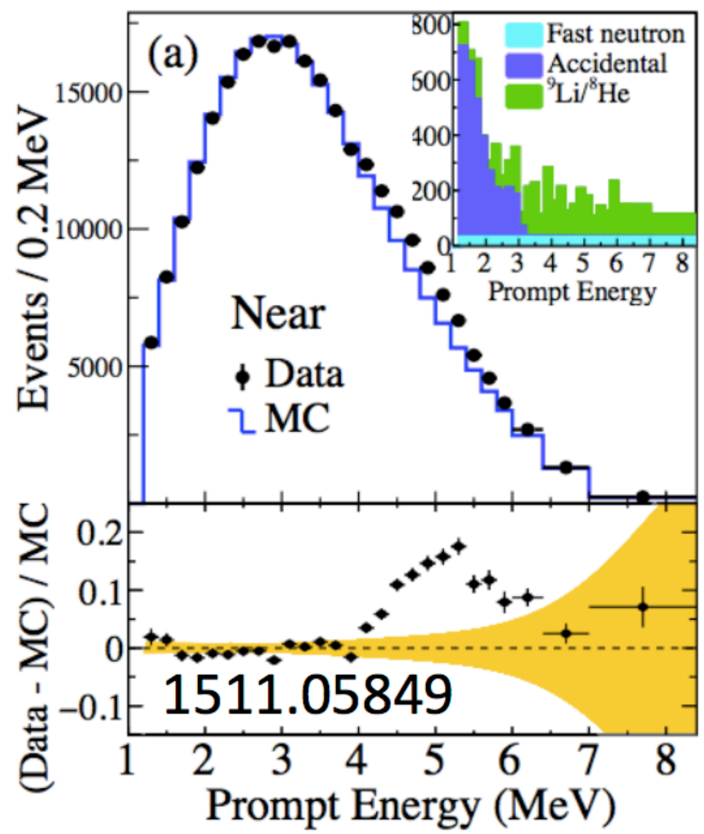
- Tremendous background rejection by selecting *prompt+delayed* pair events.

Reactor neutrino experiments

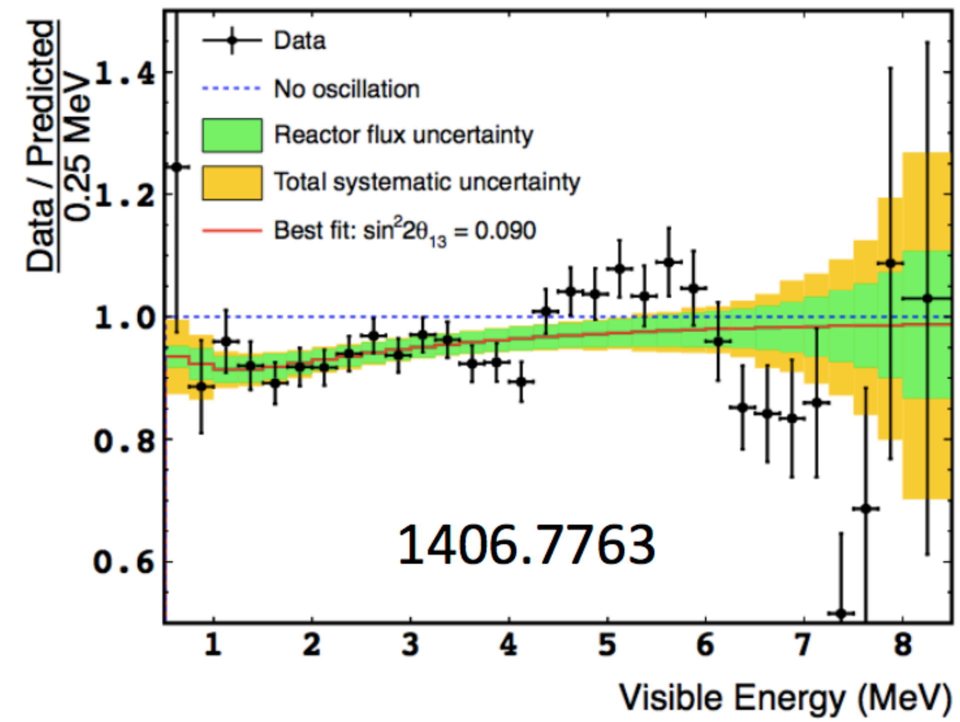
Daya Bay



RENO

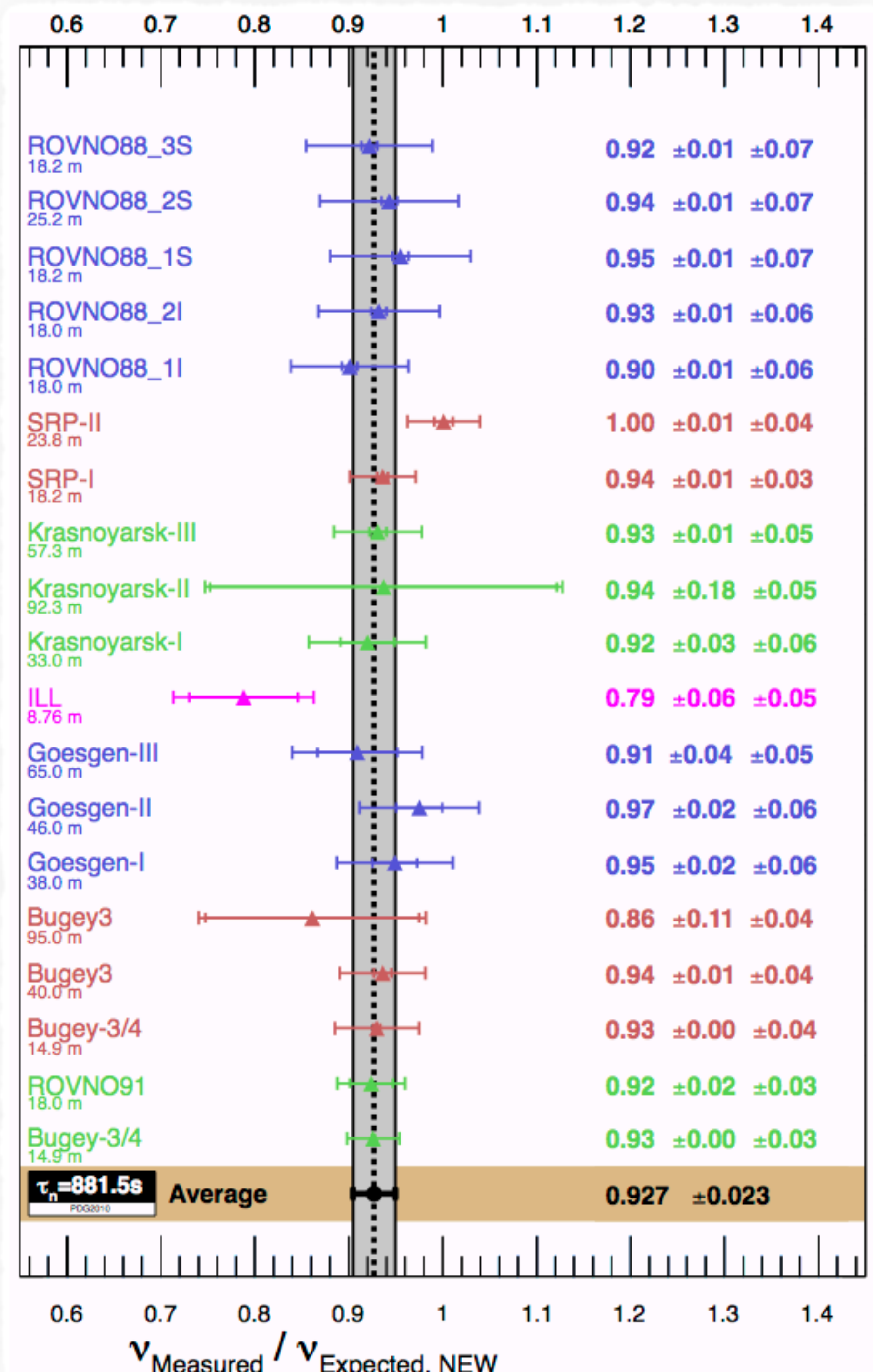


Double Chooz

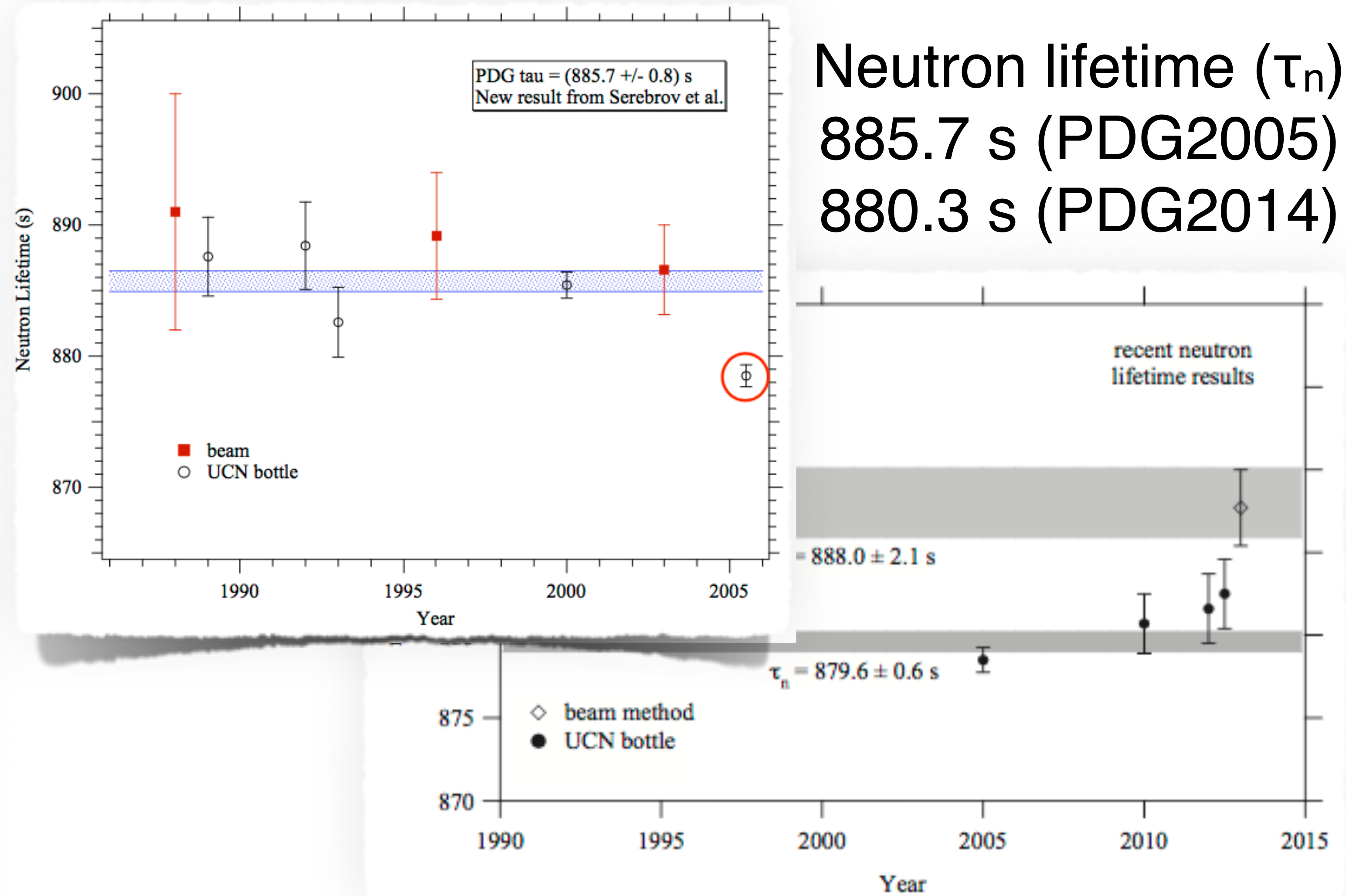


- Observation of mixing angle θ_{13} at several hundred meters ~ 2 km
- Multi-identical-detector experiments: almost free from large flux uncertainties
- Spectral anomaly at around 5 MeV prompt energy, “bump”
  > Questions on existing flux models and reactor anomaly.

Reactor antineutrino anomaly (RAA)



arXiv:1204.5379

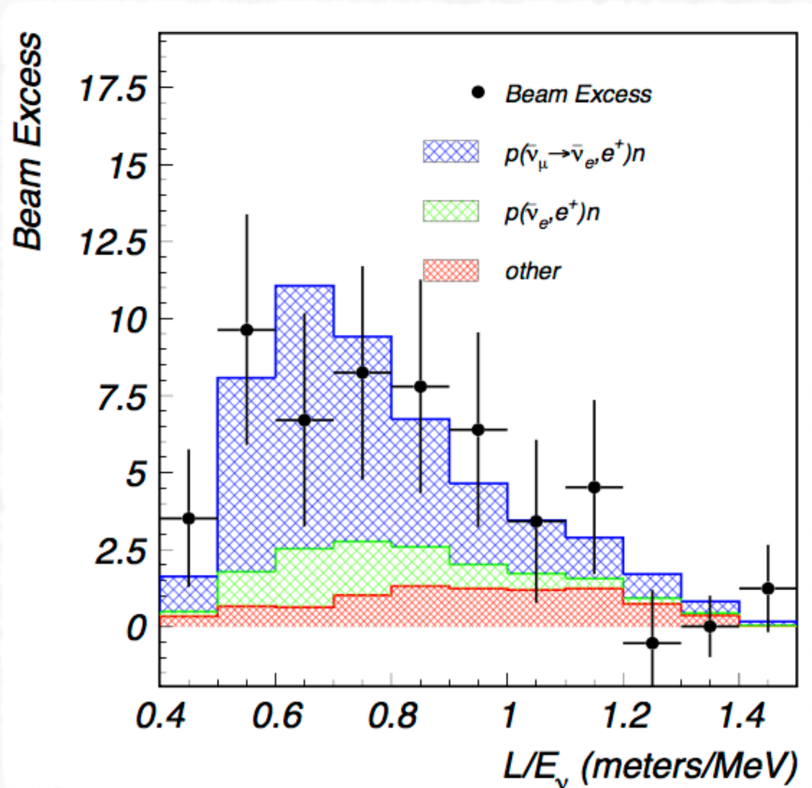


Neutron lifetime (τ_n)
885.7 s (PDG2005)
880.3 s (PDG2014)

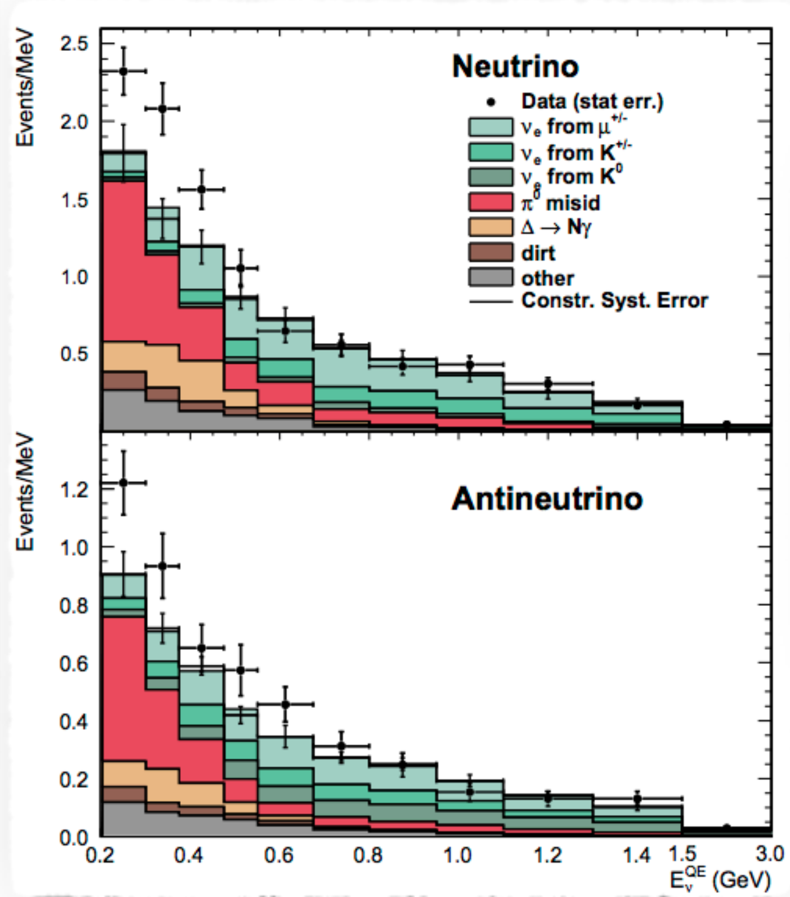
$$\sigma_{\mathrm{V-A}}(E_e)[\mathrm{cm}^2] = \frac{857 \times 10^{-43}}{\tau_n[\mathrm{s}]} p_e[\mathrm{MeV}]\, E_e[\mathrm{MeV}]\,(1 + \delta_{rec} + \delta_{wm} + \delta_{rad}),$$

- Neutron lifetime, IBD cross section
- New flux prediction (Huber-Mueller)
- Measured / Prediction ~ 0.927±0.023

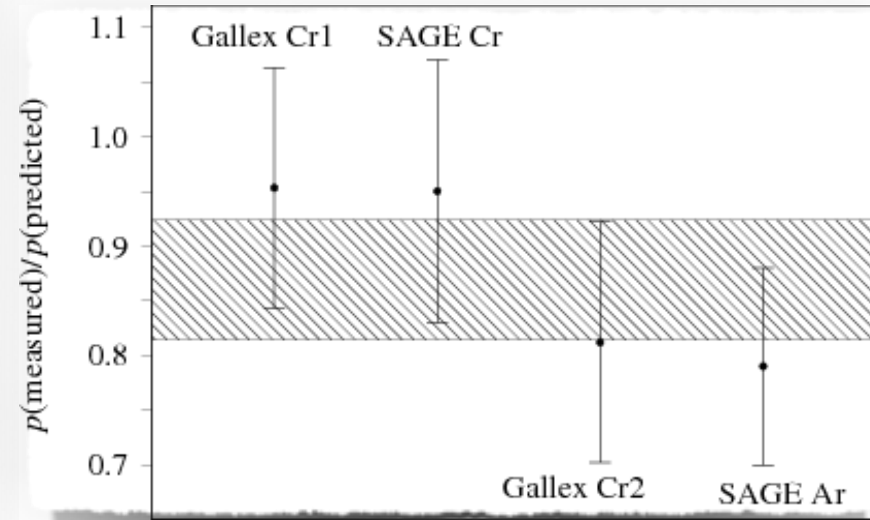
Other anomalies / conflicts



PRD 64 (2001) 112007



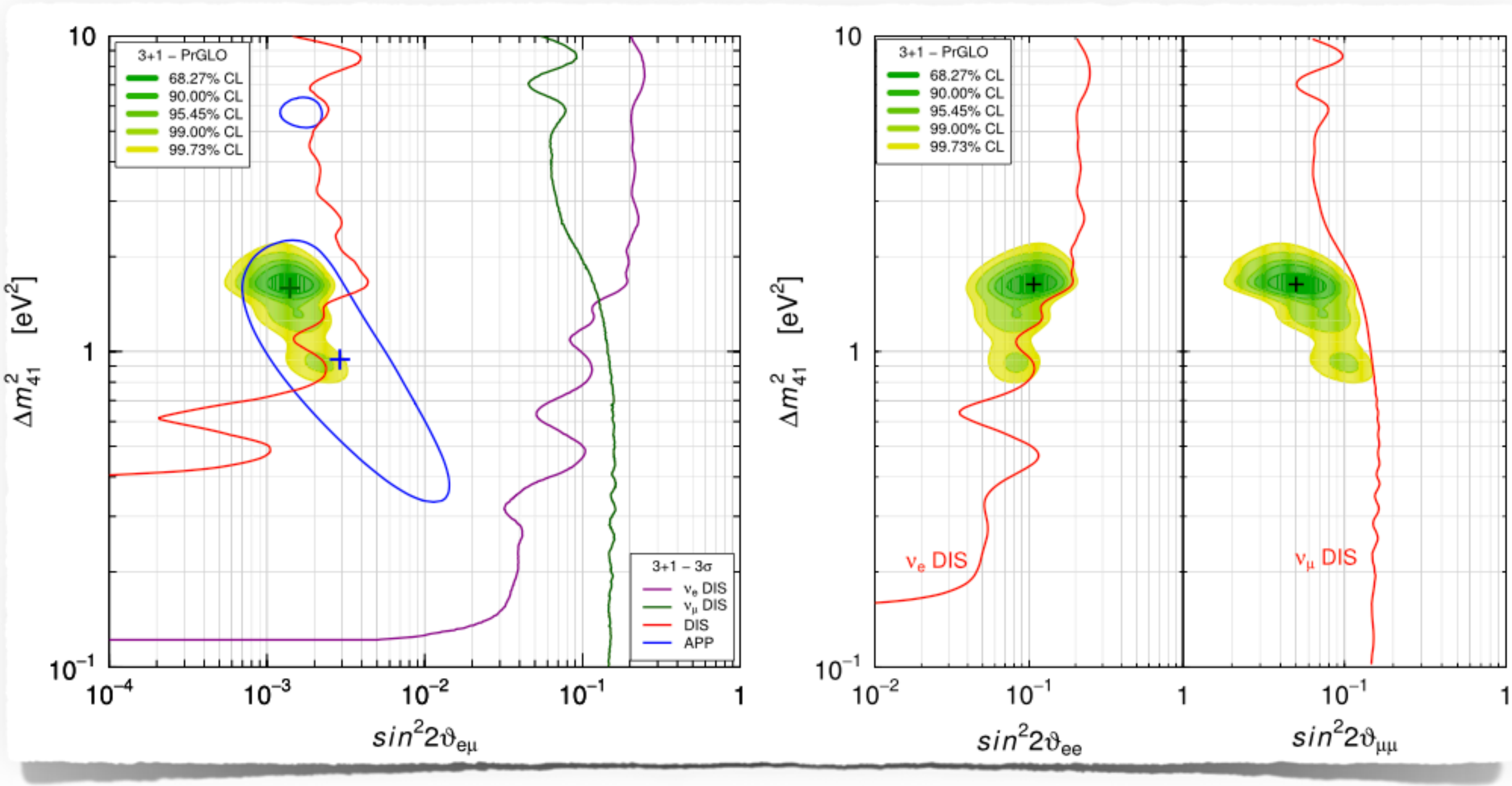
PRL 110 (2013) 161801



PRC 80 (2009) 015807

- LSND: $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ appearance event excess with $\Delta m^2 > 0.2$ eV^2 (>3σ)
- MiniBooNE: ν mode disfavors / $\bar{\nu}$ mode consistent with LSND result $\Delta m^2 \sim 1$ eV^2
- GALLEX / SAGE: 2.9σ deficit from expected
- KARMEN, MINOS, IceCube, … : negative results

Combined



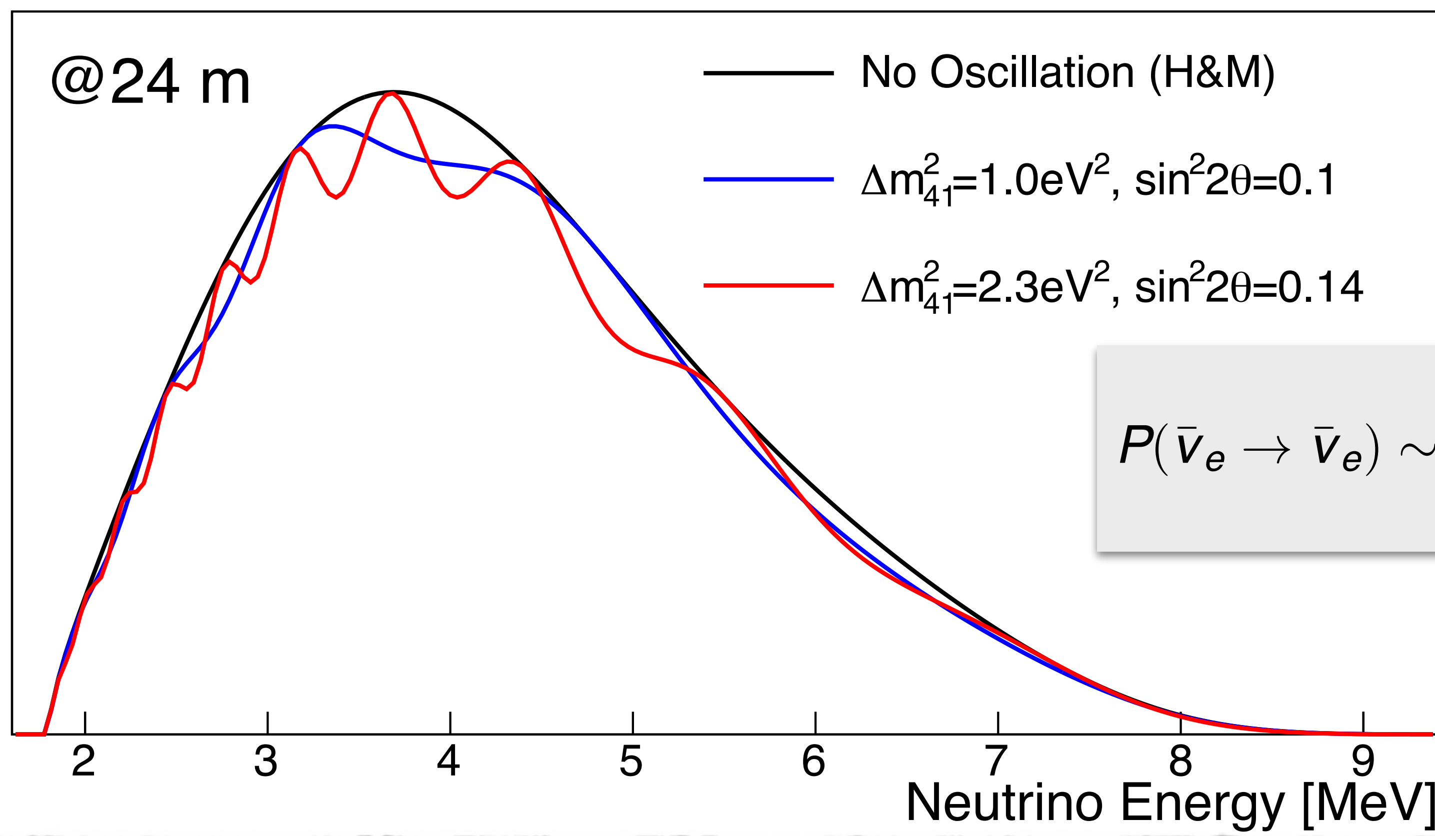
Gariazzo et al., JPG 43 (2016) 033001

- All point toward ~1 eV mass state?!

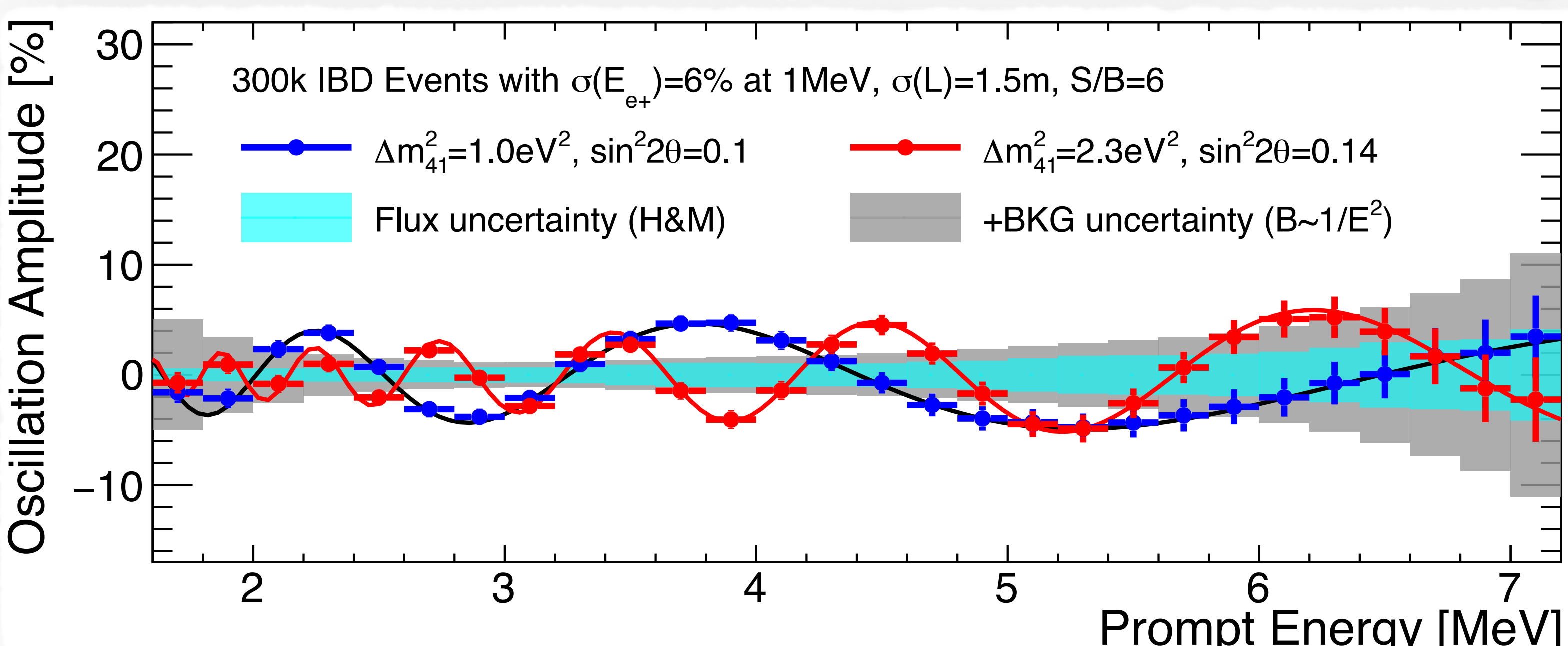
Sterile ν

- Not constrained by the number of active neutrinos (3) from *Z* boson decay-width measurements: "*sterile*"
- Active neutrino's right handed partner
- Gravitational interaction: dark matter
- Possibly sub- eV to 10^{15} GeV
  — experimental evidences pointing ~1 eV
- Possibly one or many
  — Planck satellite measurement:
  N_ν^{eff} = 3.7 (95%C.L.), excluding the existence of 1 eV sterile neutrino fully thermalized in early universe
  — Large lepton asymmetry, neutrino self-interaction

3+1 ν and SBL oscillation



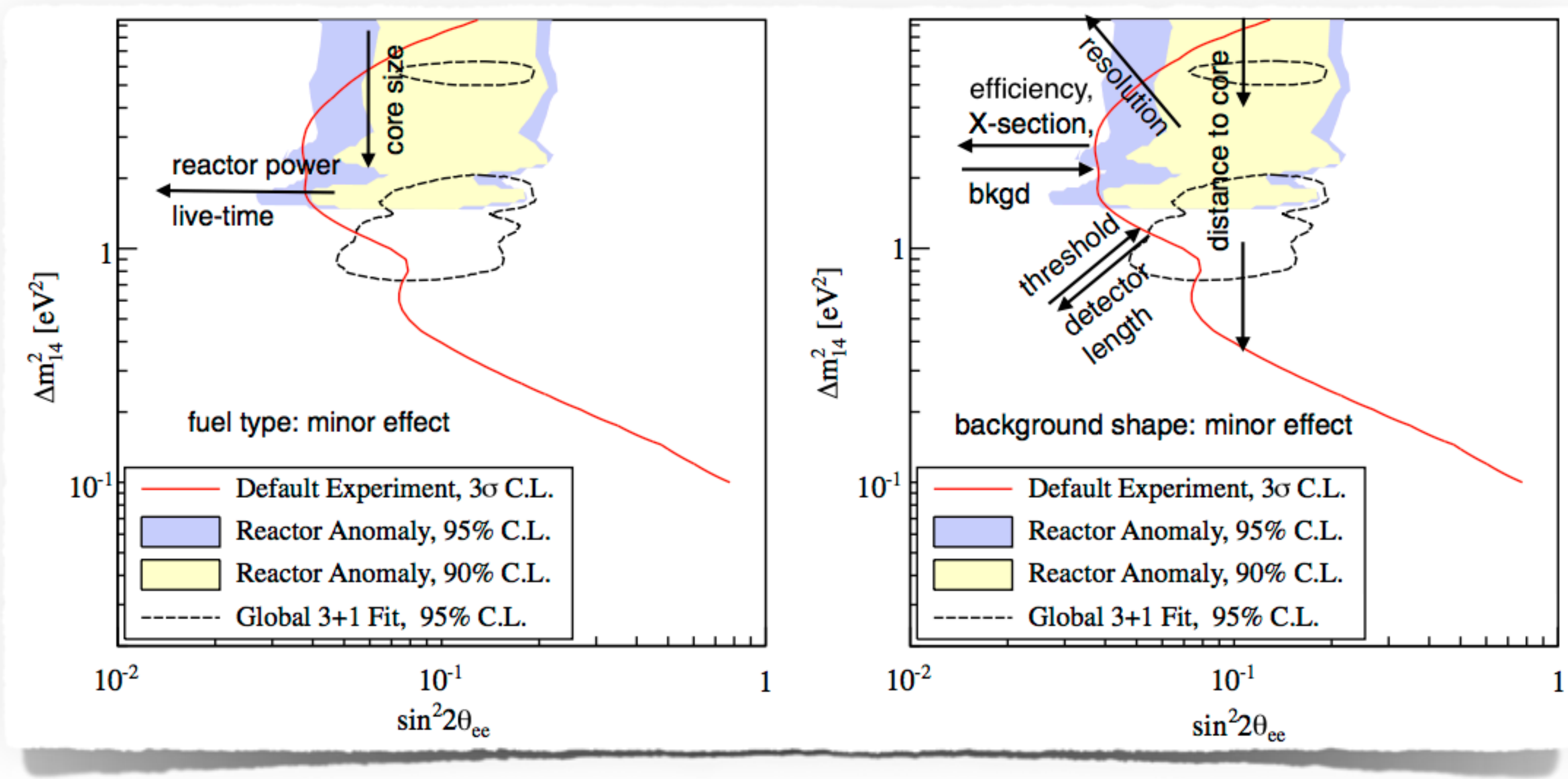
$$P(\bar{\nu}_e \rightarrow \bar{\nu}_e) \sim 1 - \sin^2 2\theta_{14} \sin^2\left(1.27 \frac{\Delta m^2 L}{E_\nu}\left[\frac{\mathrm{eV}^2 \cdot \mathrm{m}}{\mathrm{MeV}}\right]\right)$$



- Oscillation pattern washed out in the measured prompt energy spectrum.
  - — Baseline (L)
    reactor/detector size
  - — Energy (E)
    energy loss/resolution
  - — Systematic errors
  - — Background

Reactor SBL experiments

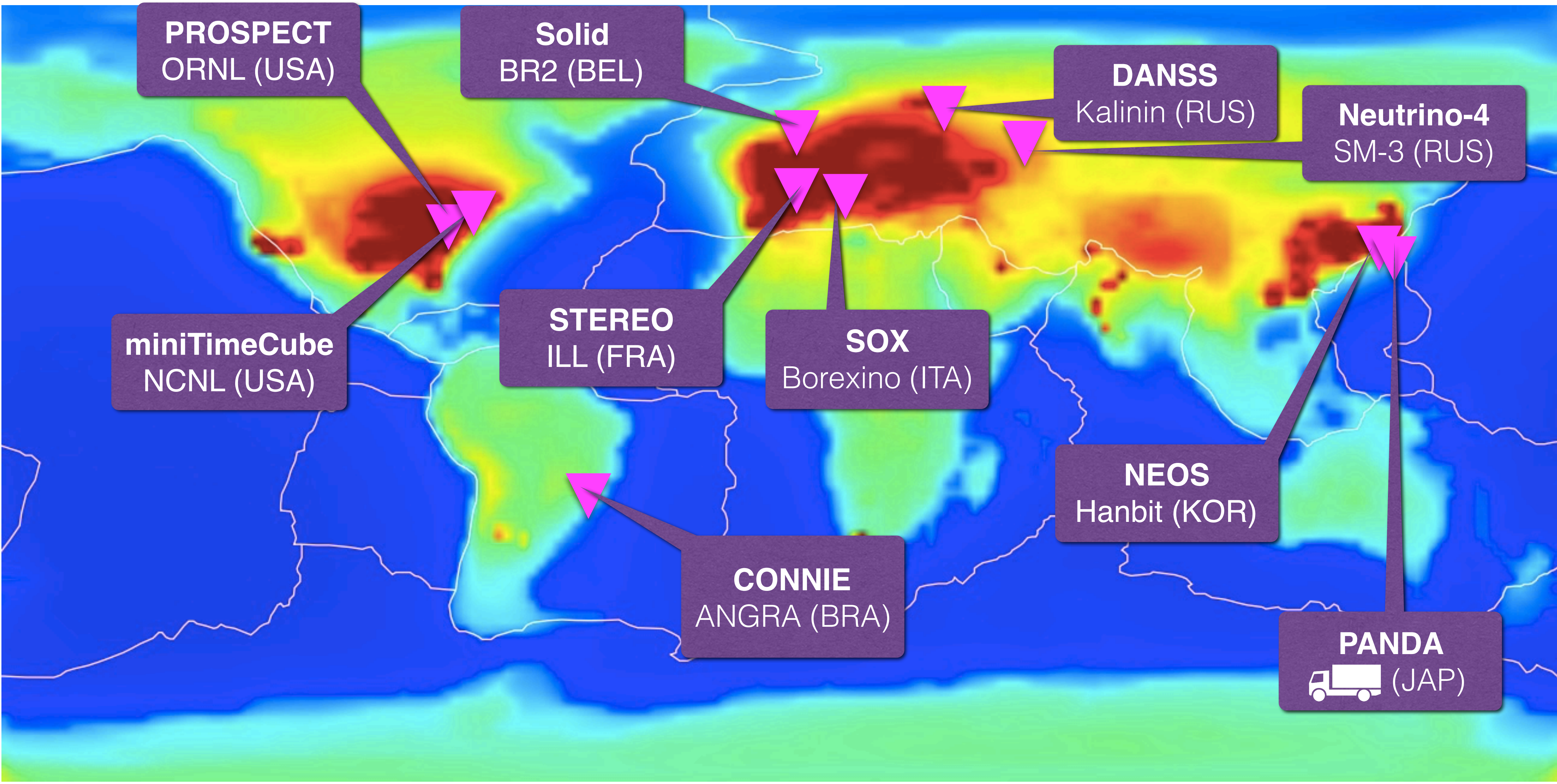
$$P(\bar{\nu}_e \to \bar{\nu}_e) \sim 1 - \sin^2 2\theta_{14} \sin^2\left(1.27 \frac{\Delta m^2 L}{E_\nu}\left[\frac{\mathrm{eV}^2 \cdot \mathrm{m}}{\mathrm{MeV}}\right]\right)$$



PRD 87 (2013) 073008

- High flux at close distance
- Not enough (almost no) overburden > severe background signals originated from cosmic rays / reactor
- Limited space for detector > small detector > energy not fully contained

(Reactor) SBL experiments



geoneutrinos.org

NEOS Collaboration

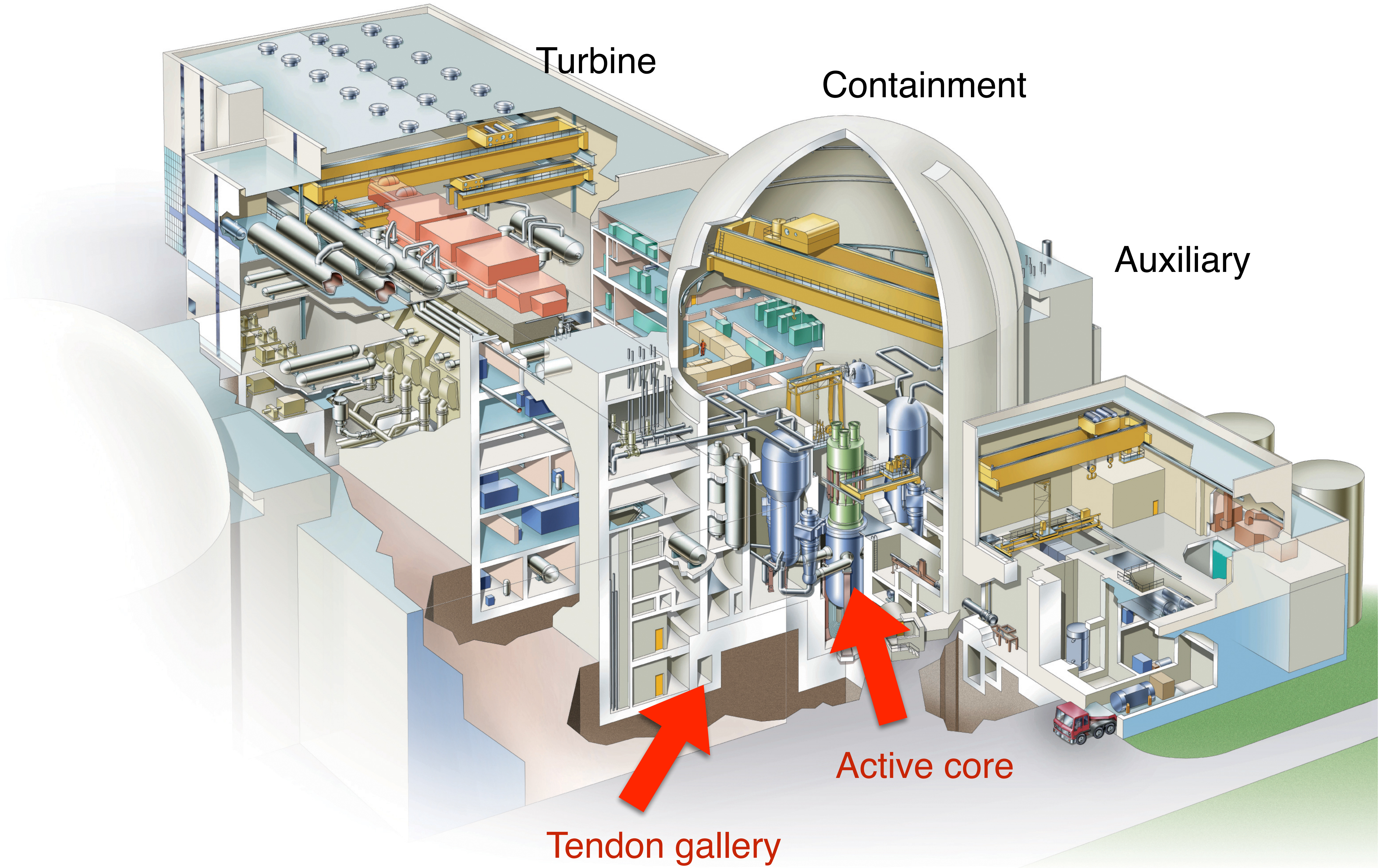
Hongjoo Kim, Jooyoung Lee,
Kyungkwang Joo, Ba Ro Kim,
Changhwan Jang, Siyeon Kim, Youngju Ko,
Kyungmin Seo, Jinyu Kim, Hyunsoo Kim,
Gwang-Min Sun, Boyoung Han,
Hyunseo Park,
Yeongduk Kim, Eun-ju Jeon, Jaison Lee, Moo-hyun Lee,
Yoomin Oh, Hyangkyu Park, Kang-soon Park

- 20 collaborators from 7 institutes in S.Korea
- Project launched in 2012
- Data taking from Summer 2015 to Spring 2016

Experimental site

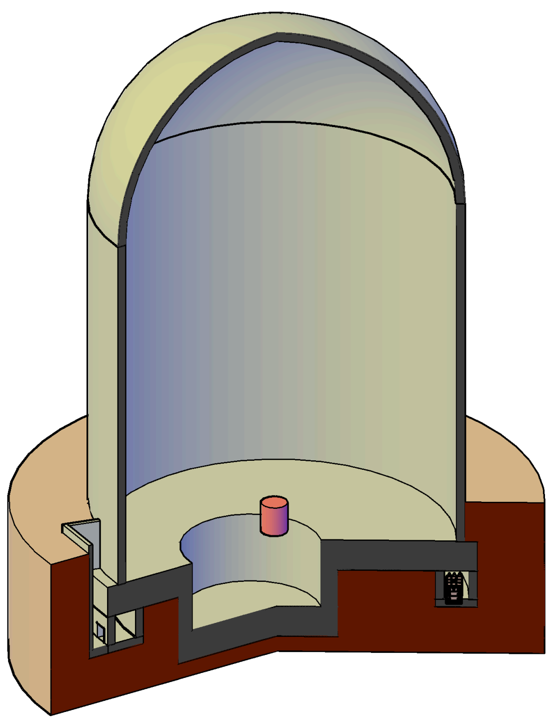
- Reactor Unit 5 in Hanbit Nuclear Power Plant, Yeonggwang, South Korea
- Same reactor complex used for RENO experiment

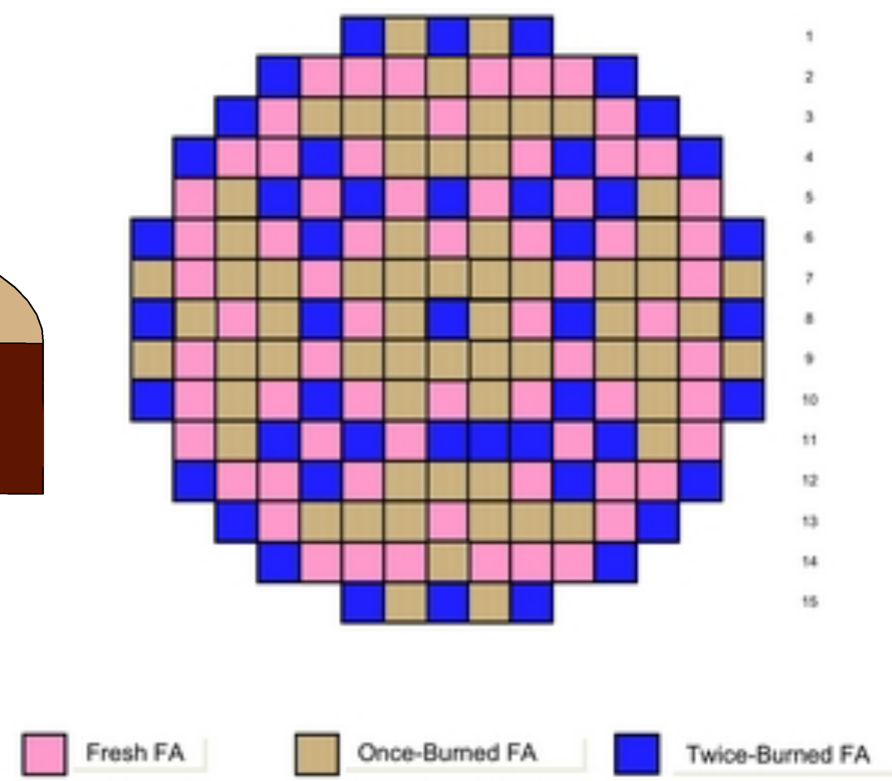
Experimental site

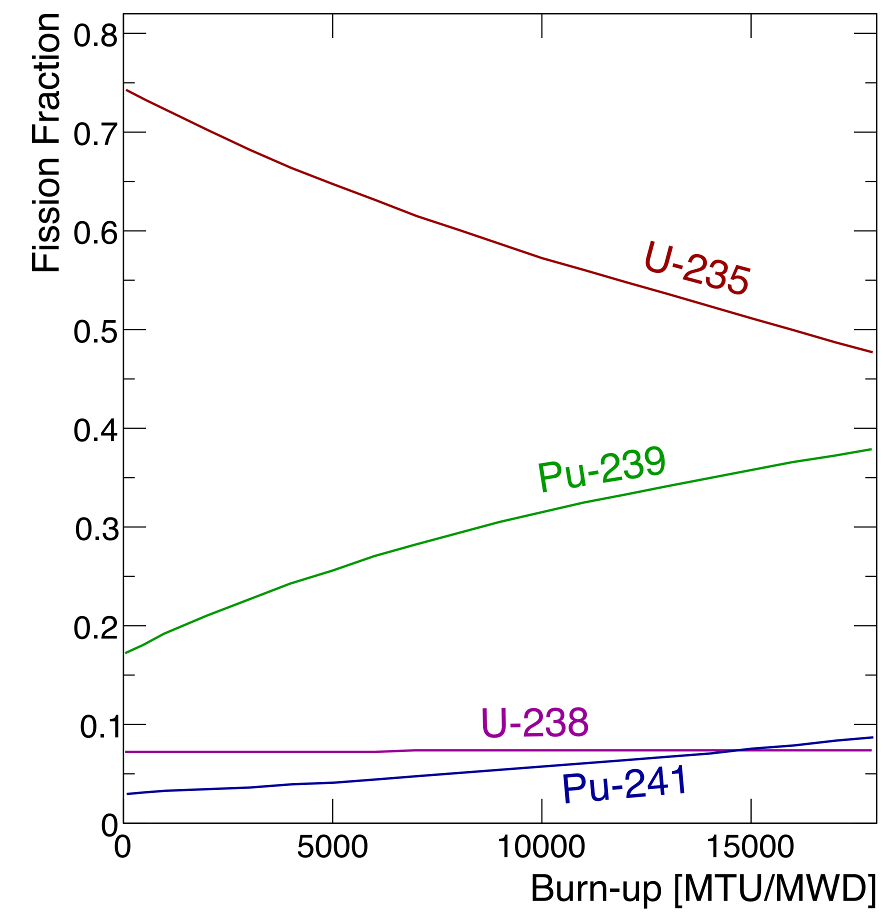


cutaway view of OPR-1000

Active reactor core

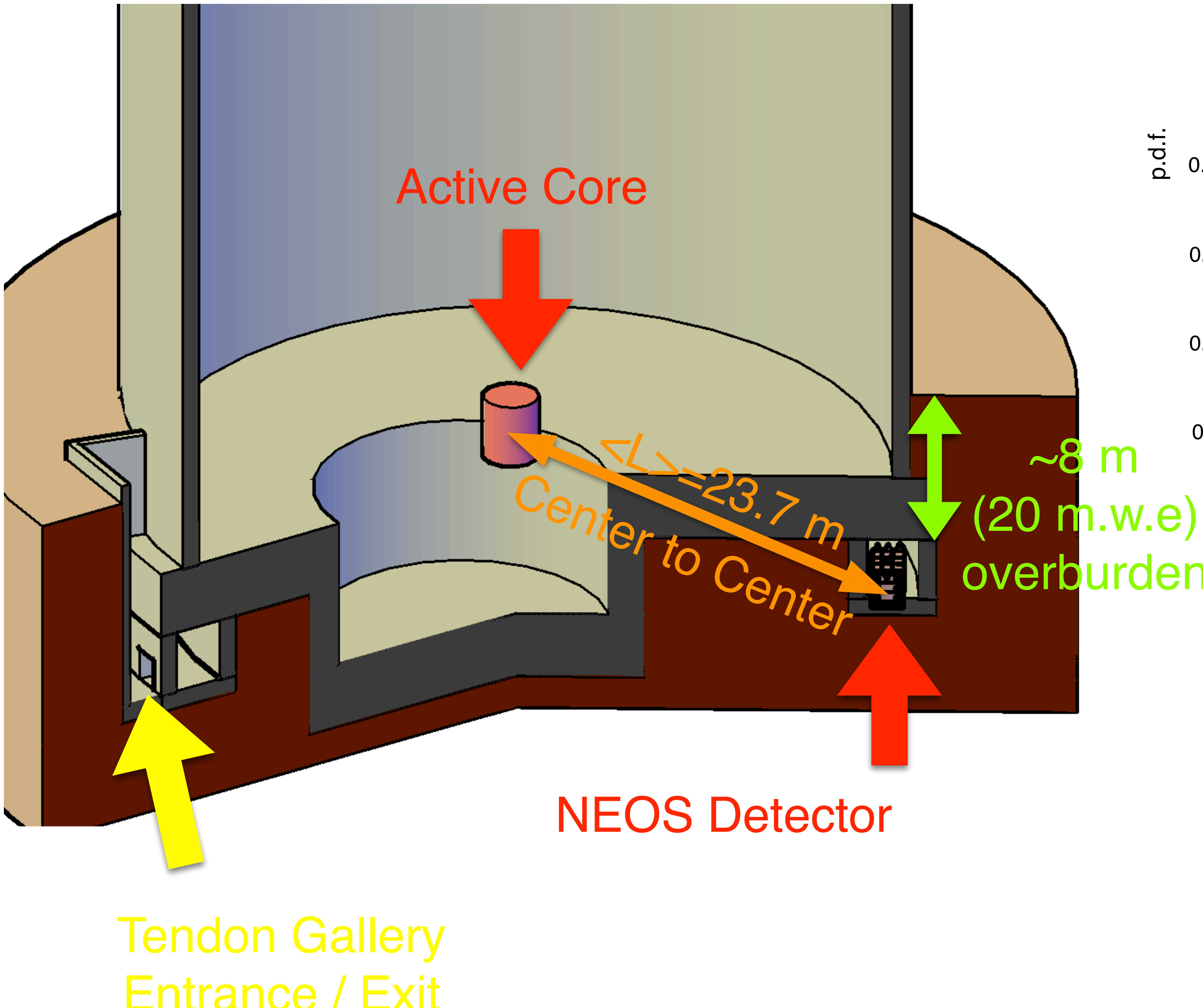


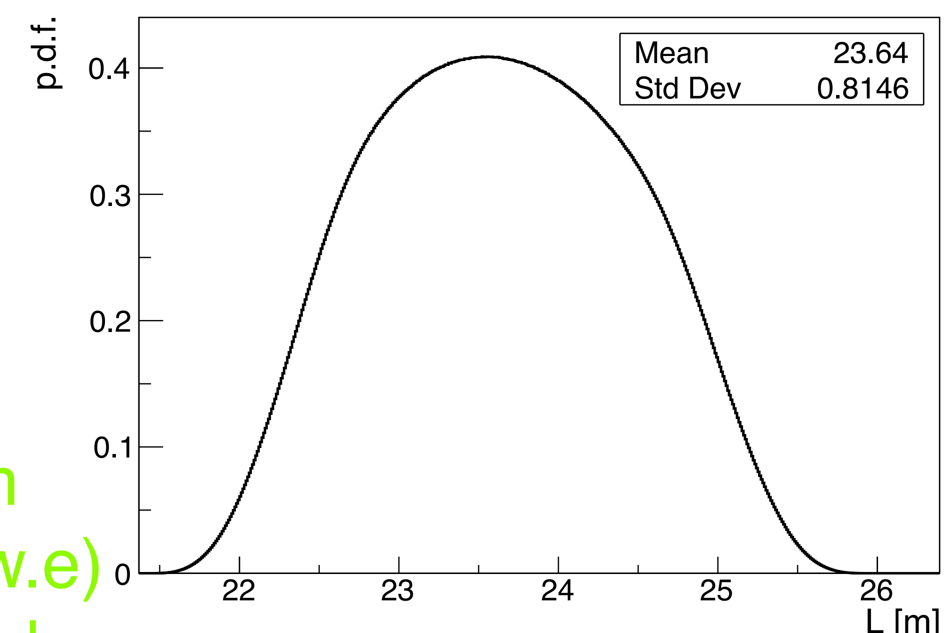




- OPR-1000 reactor, 2815 MWt
- 177 fuel rods, low enriched (4.65%) uranium-235 (LEU) fuel
- Refueling by changing 1/3 of fuel rods for each burn-up cycle (~1.5 year)
- Active core size: 3.1 m (ϕ), 3.8 m (h)

Detector location / baseline

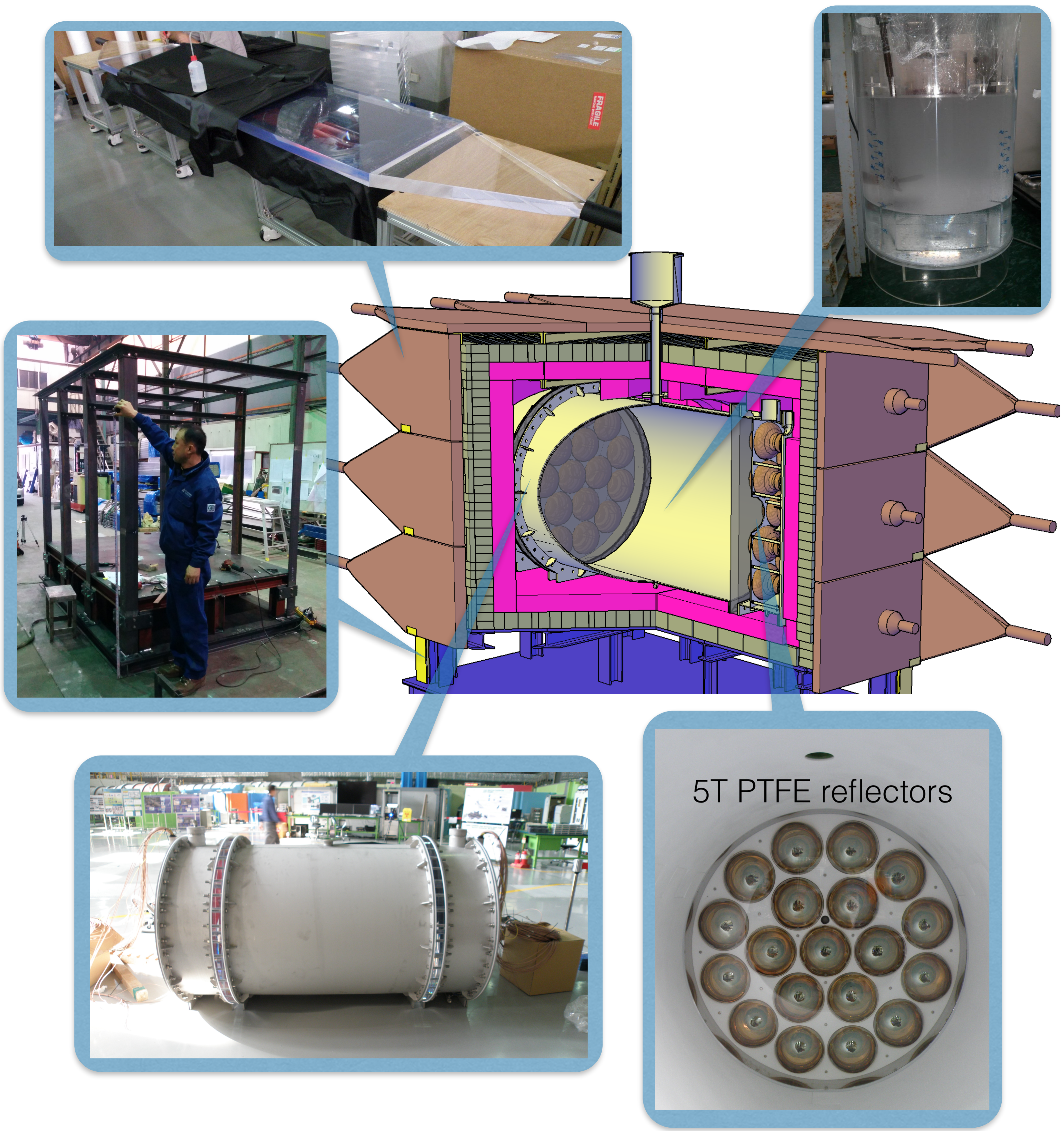


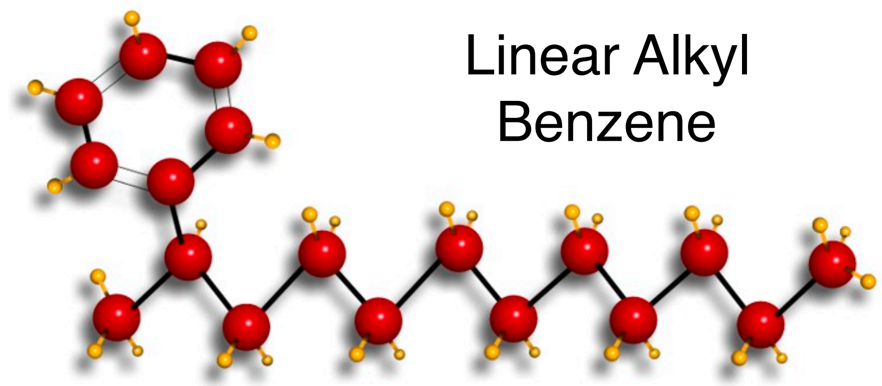


ν travel distance assuming:

— uniformly generated in cylindrical core
— IBD interaction uniformly distributed in target
— $1/L^2$ effect

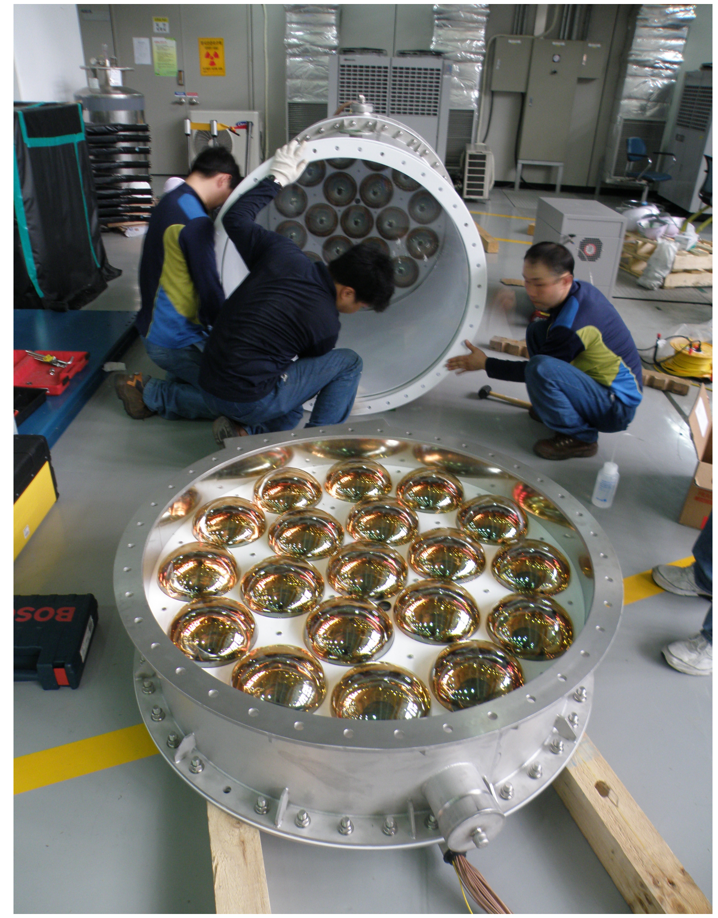
Detector specification





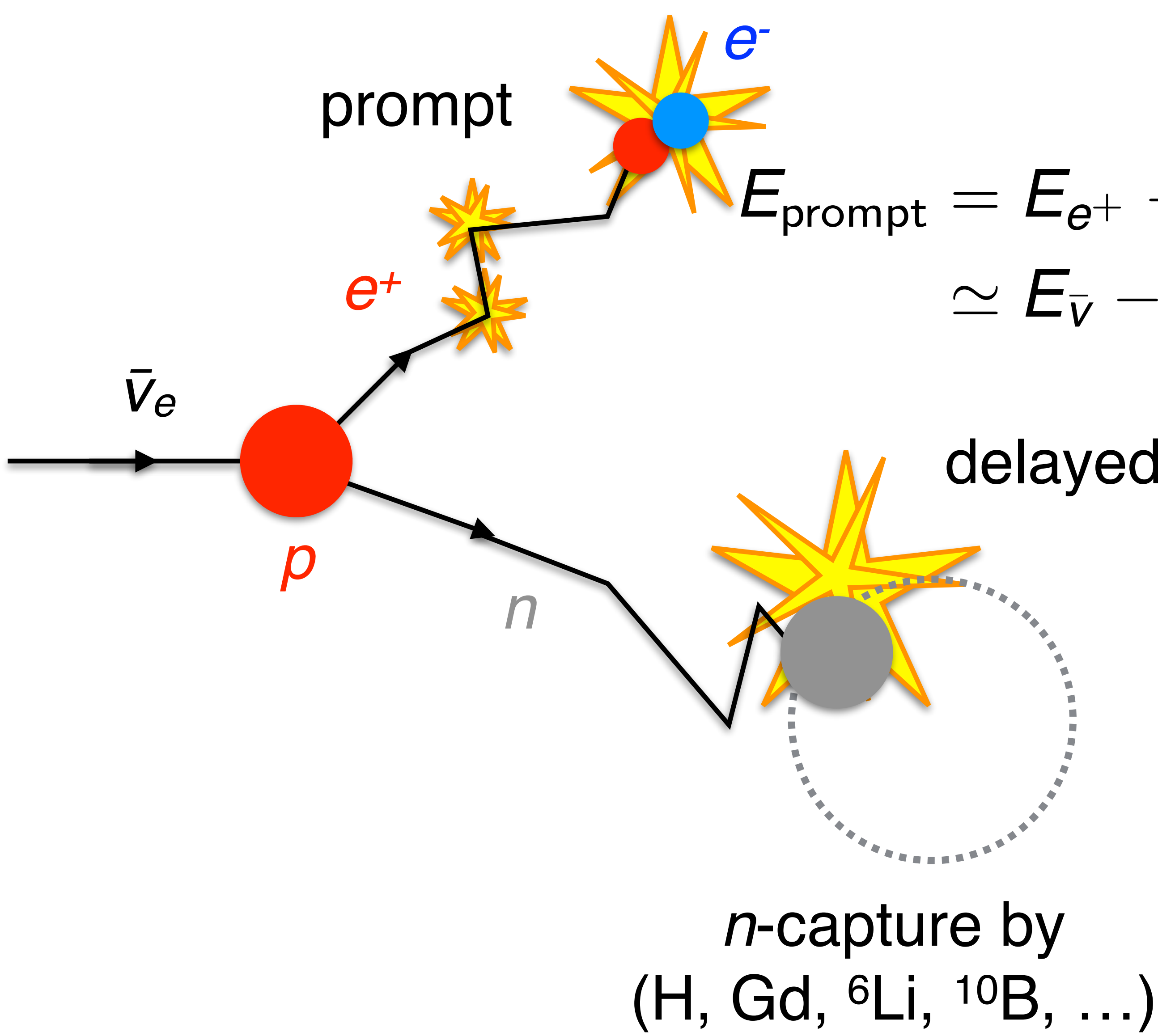
Linear Alkyl Benzene

- Homogeneous LS target
  - — 1008 L volume (R 51.5, L 121) cm
  - — LAB+UG-F (9:1)
  - — 0.5% Gd loaded for high neutron capture efficiency
  - — 38 8″ PMT in mineral oil buffer
- Shieldings
  - — 10 cm B-PE (n), 10 cm Pb (γ)
  - — active muon counter
- Data AcQuisition
  - — 500 MS/s FADC (waveform)
  - — 62.5 MS/s SADC (μ veto)
- Source calibration through chimney



Detector response / calibraiton

$$P(\bar{\nu}_e \rightarrow \bar{\nu}_e) \sim 1 - \sin^2 2\theta_{14} \sin^2\left(1.27 \frac{\Delta m^2 L}{E_\nu}\left[\frac{\text{eV}^2 \cdot \text{m}}{\text{MeV}}\right]\right)$$

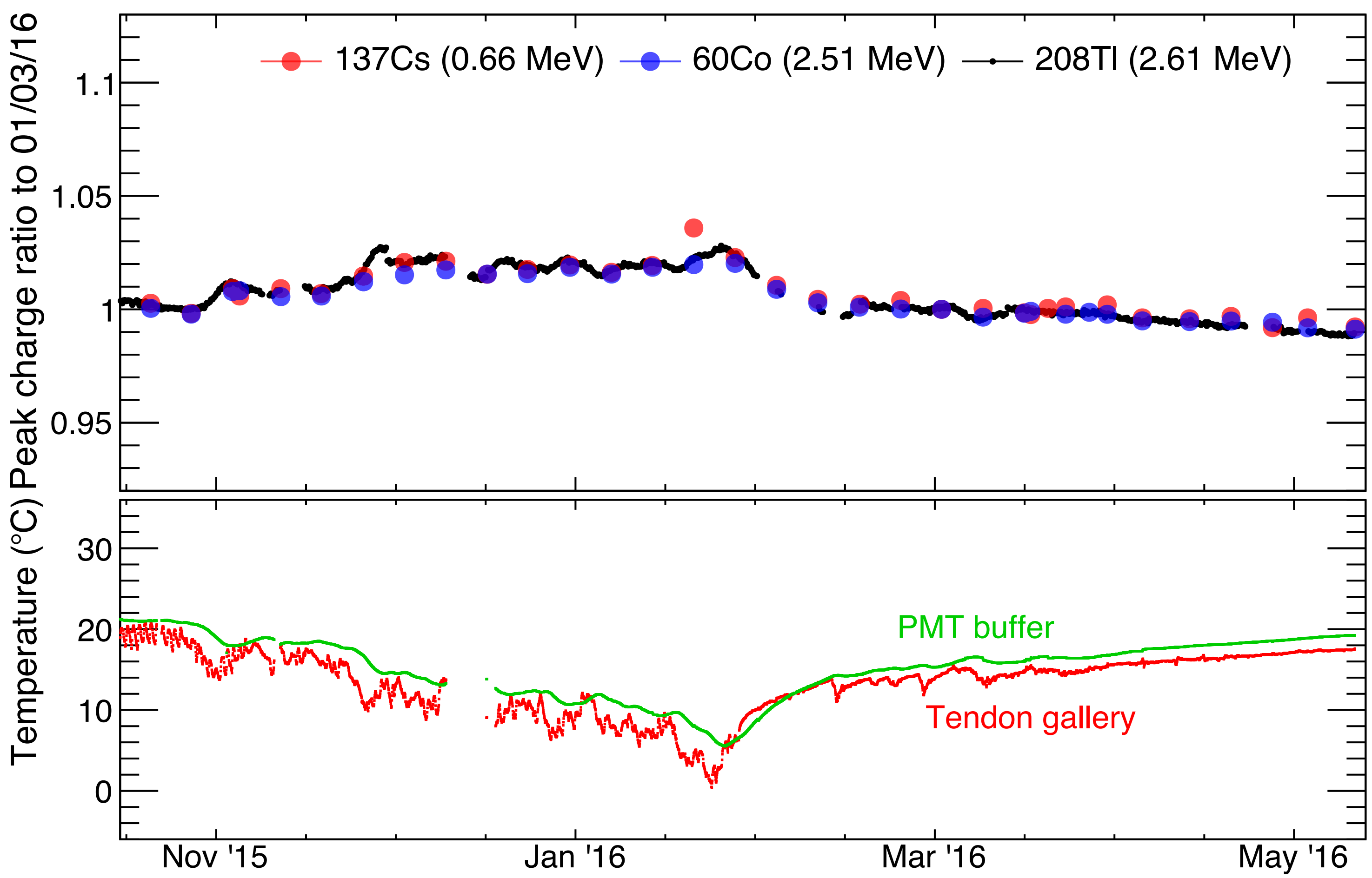


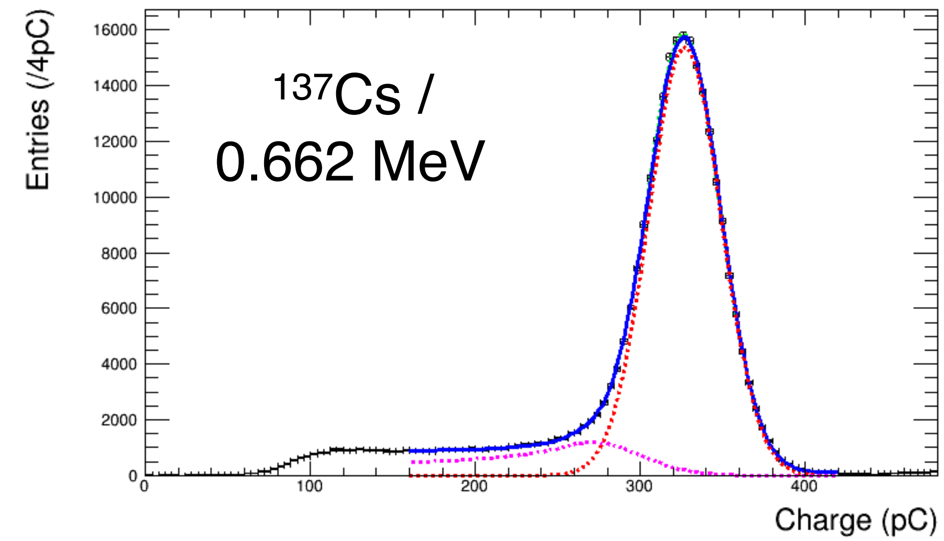
$$E_{prompt} = E_{e^+} + 1.02 \text{ MeV}$$
$$\simeq E_{\bar{\nu}} - 0.78 \text{ MeV}$$

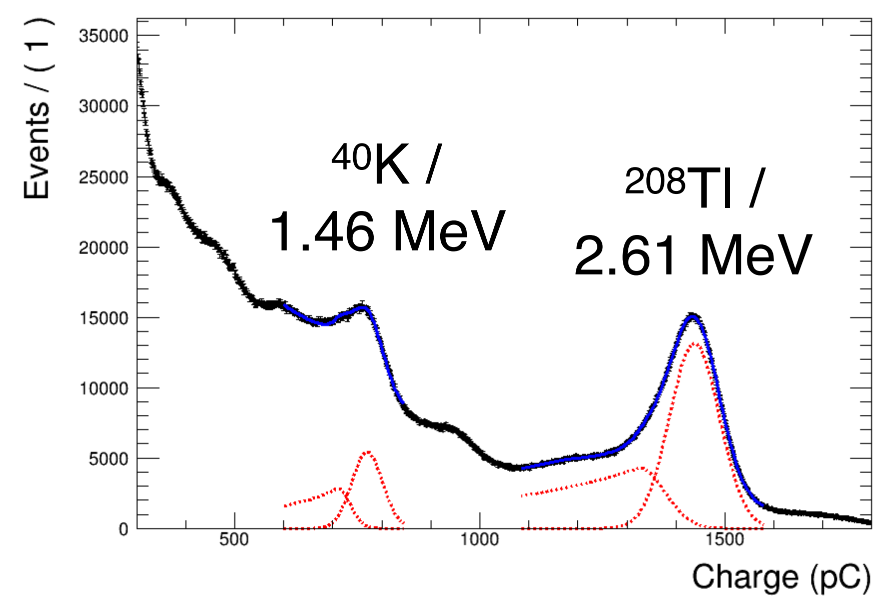
Equation not hold in the detector due to:
- resolution,
- escaping γ,
- non-linearity between energy and light signal

- Radioactive source emitting e+ with kinetic energy in r.o.i?
  ➡e- sources (β- decay), γ sources, and detector simulation

Calibration campaign

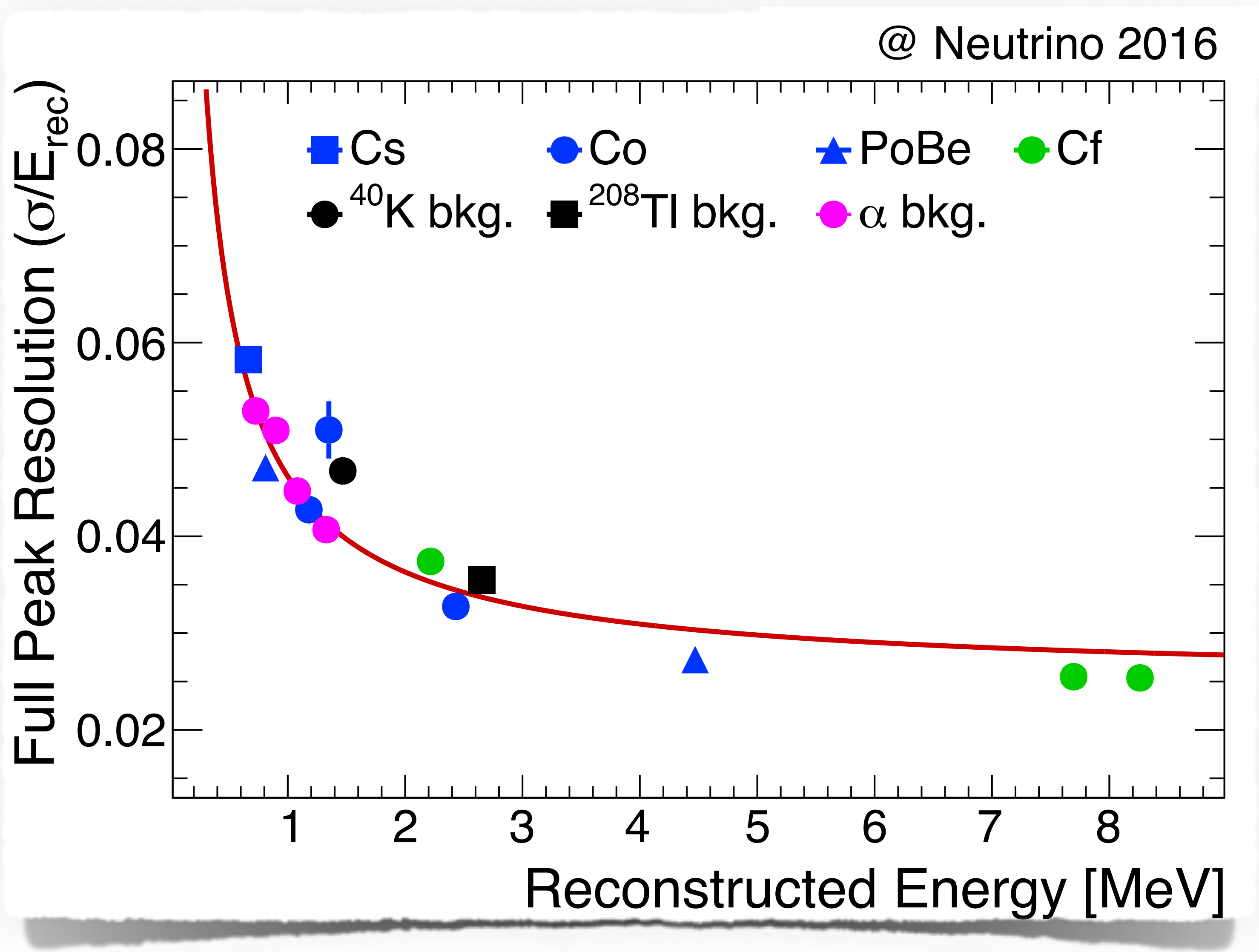


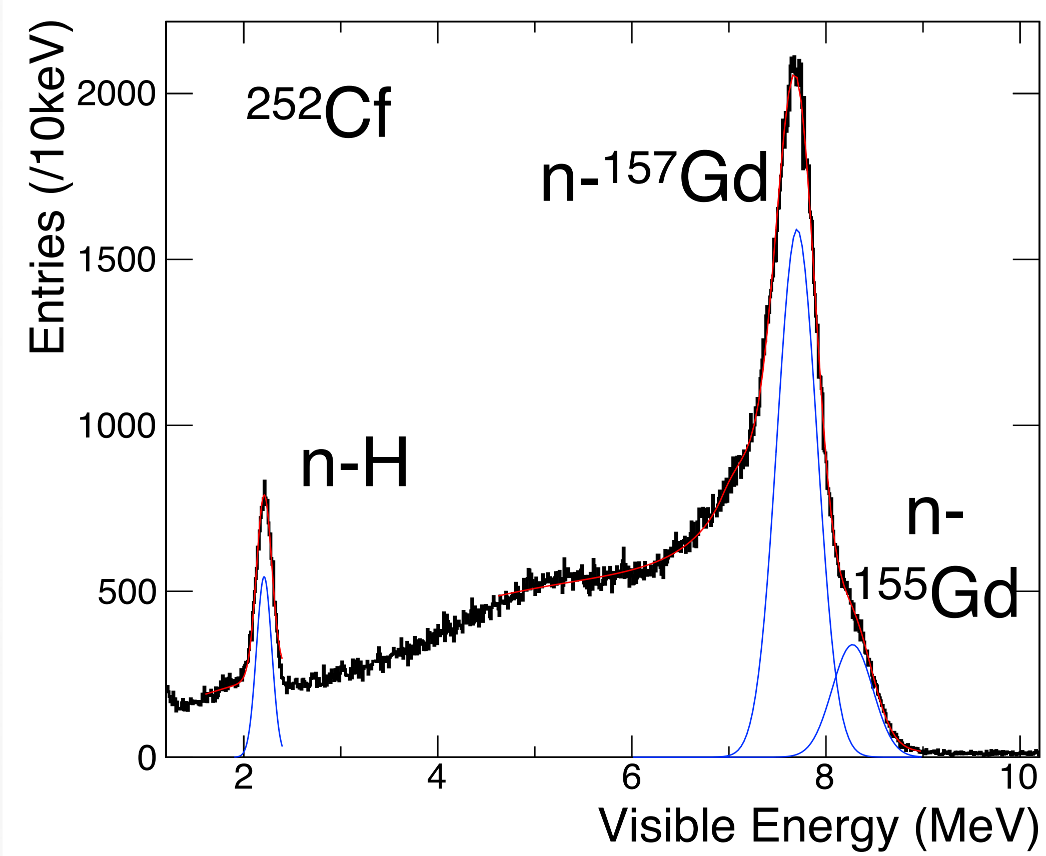




- Once a week with point sources:
  - ^{137}Cs (γ, 0.66 MeV), ^{60}Co (γ, 1.17/1.33 MeV), ^{252}Cf (n, 8 MeV γ from Gd capture), PoBe (n, 4.4 MeV γ)
- Internal/External background (volume sources, continuous):
  - ^{40}K (γ, 1.46 MeV), ^{208}Tl (γ, 2.6 MeV), ^{230}Th > ^{226}Ra > ^{222}Rn > … chain (α, β, γ)
  - used for time / position dependence corrections

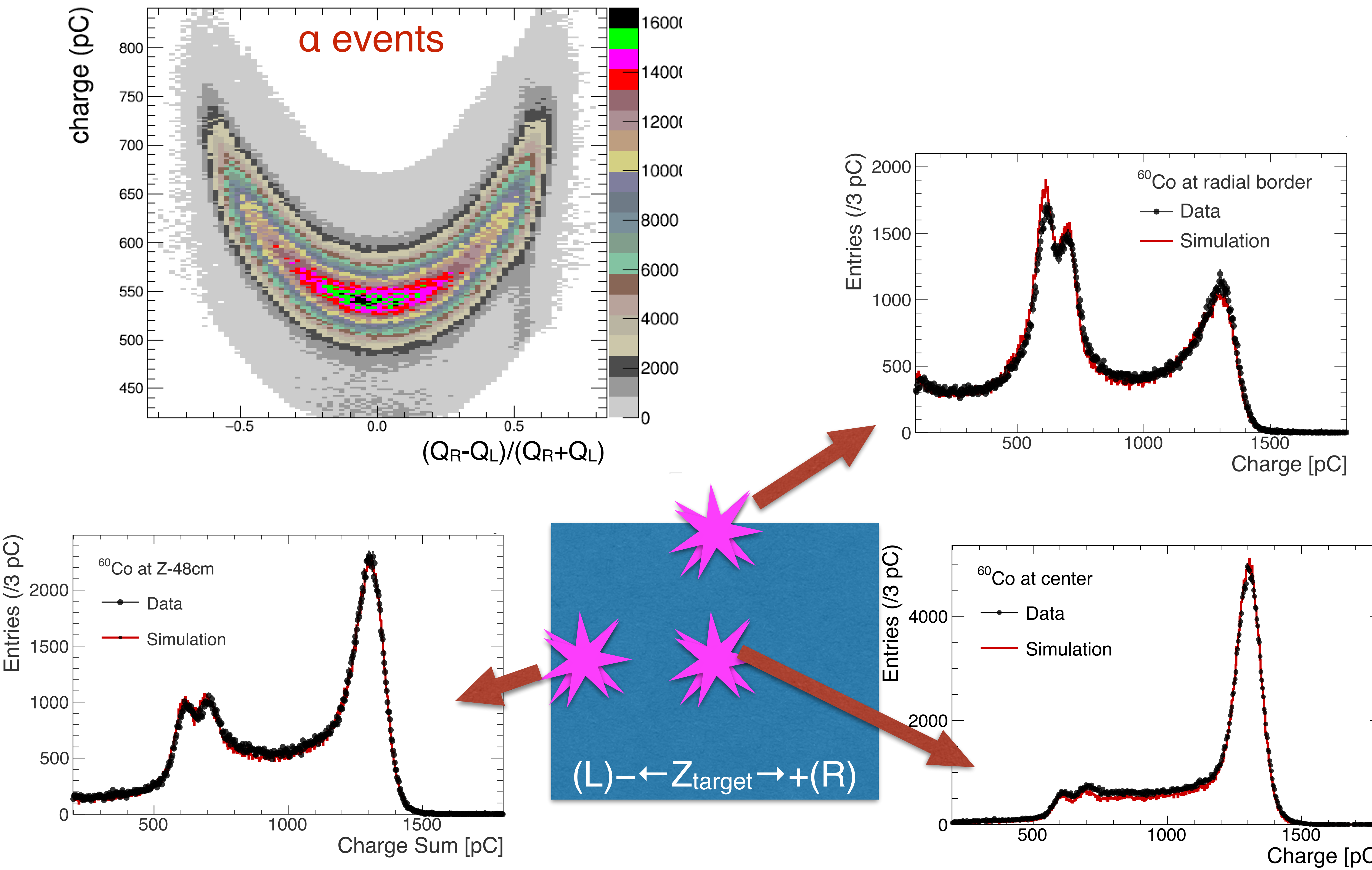
Energy resolution



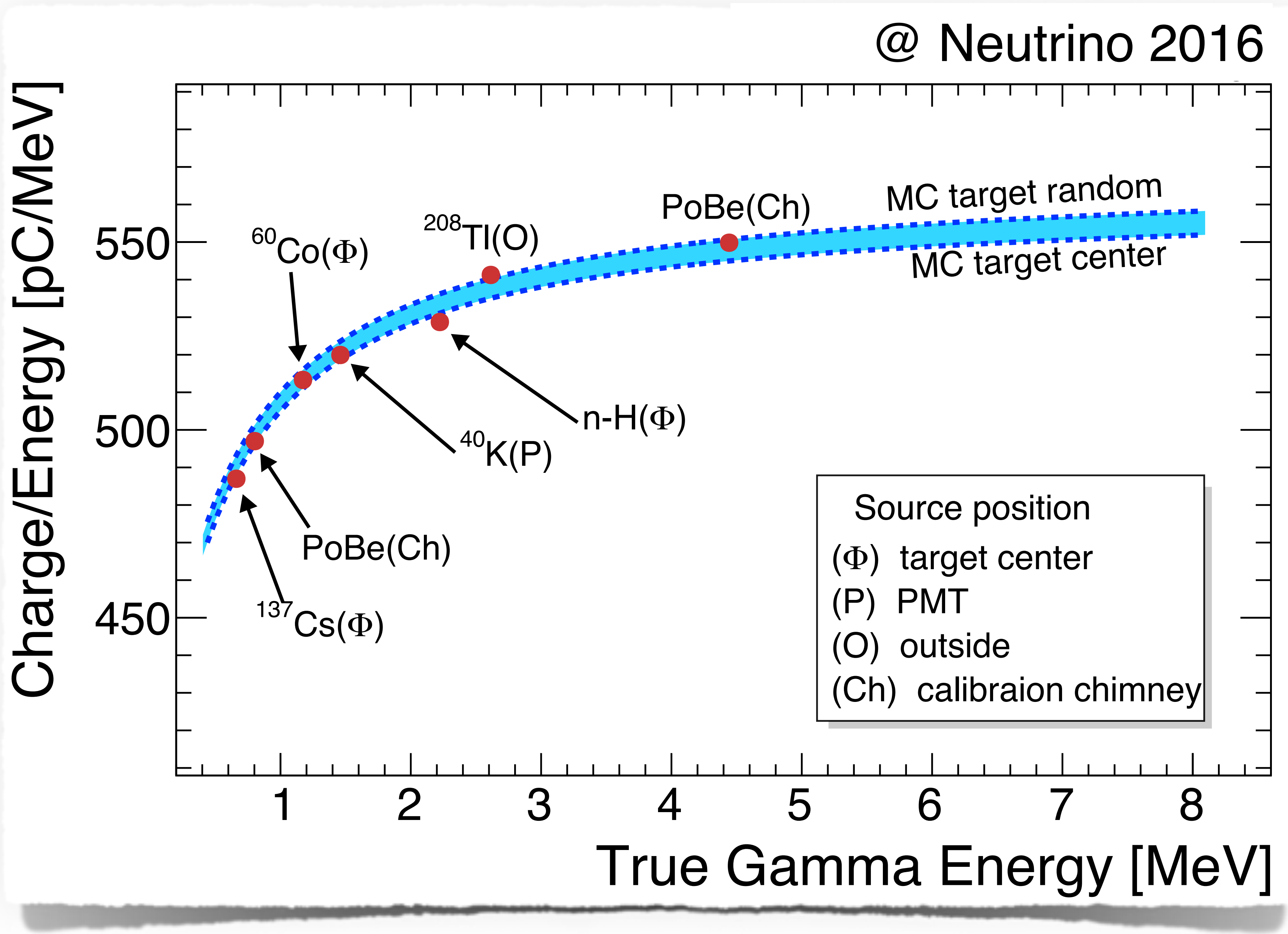


- $\sigma(E) = 5\%\sqrt{E}$ /MeV at 1 MeV for a full peak

Non-uniform response / escaping γ

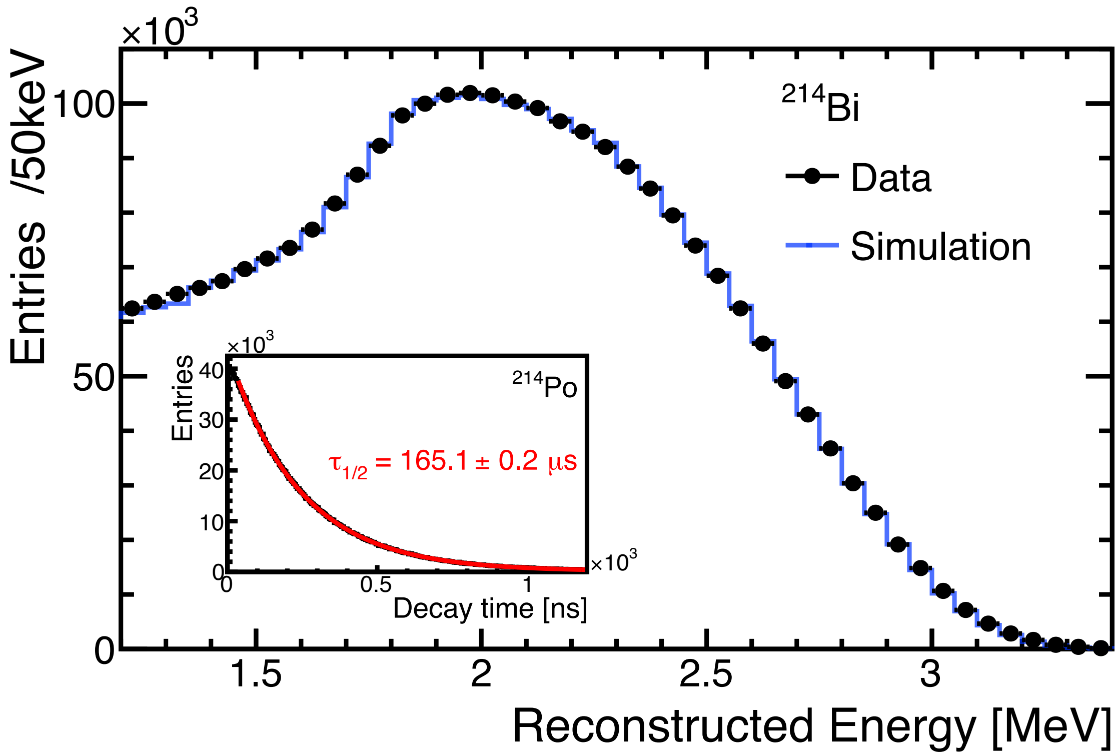


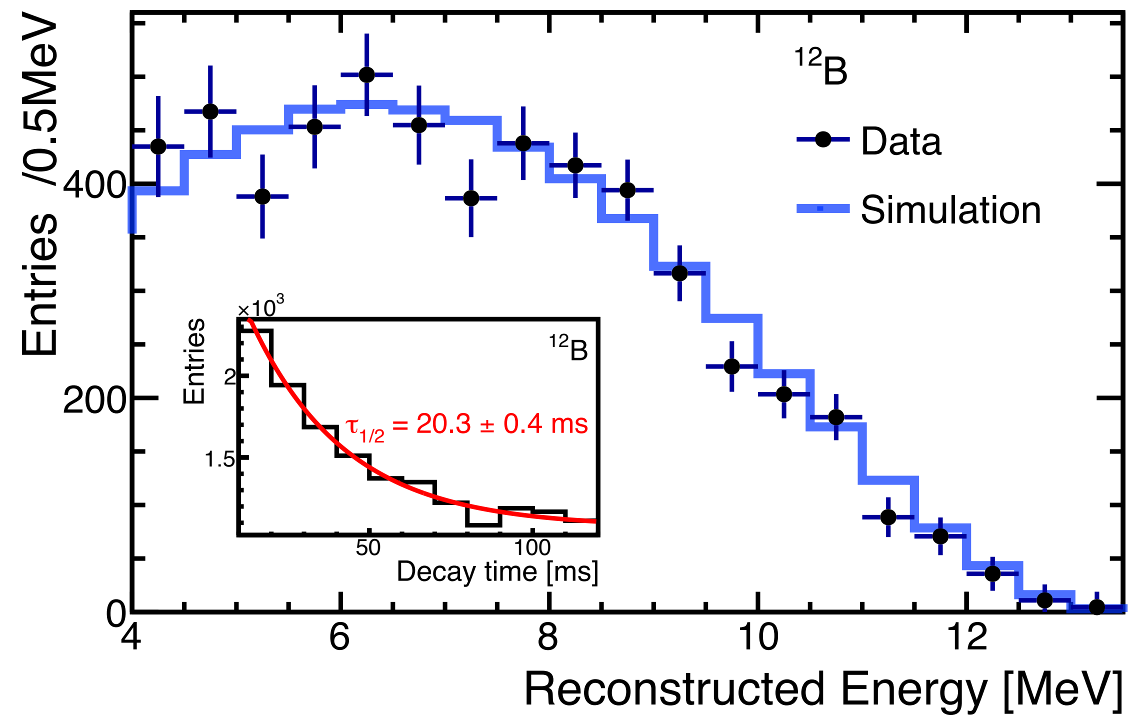
Nonlinear charge response to energy

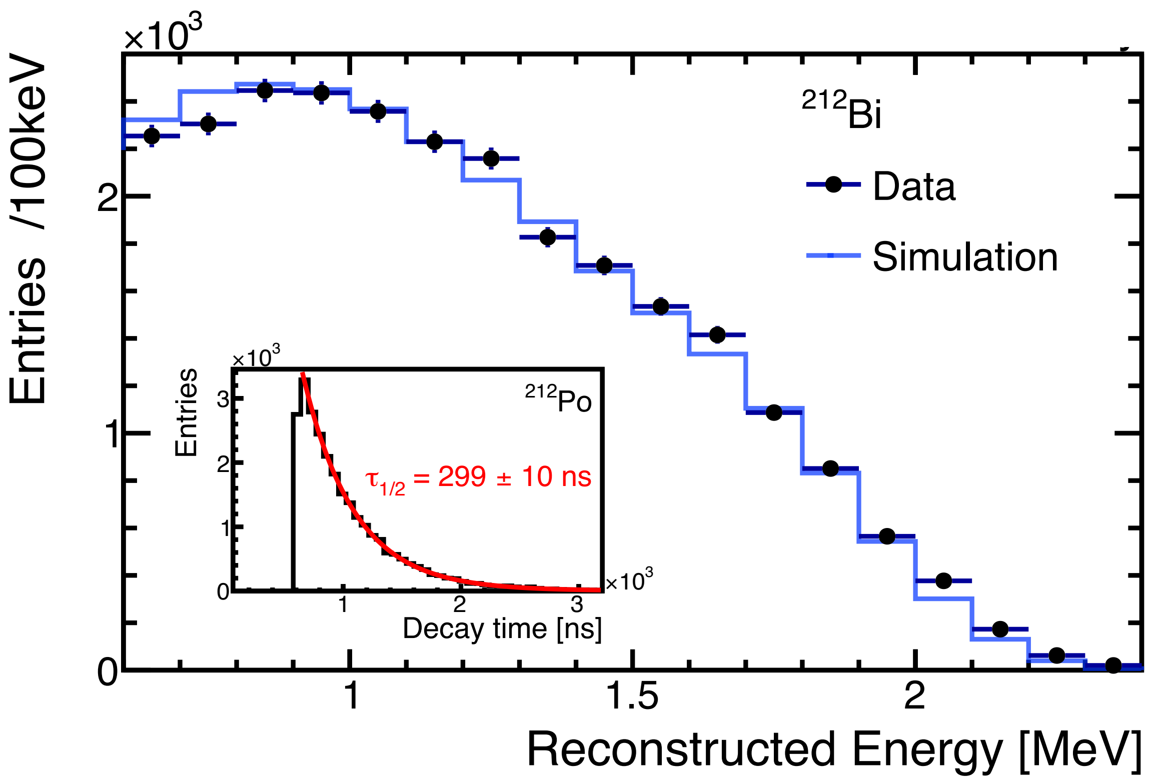


- Signal quenched at low energy
- Cerenkov light important at higher energy

β-decay events and simulation

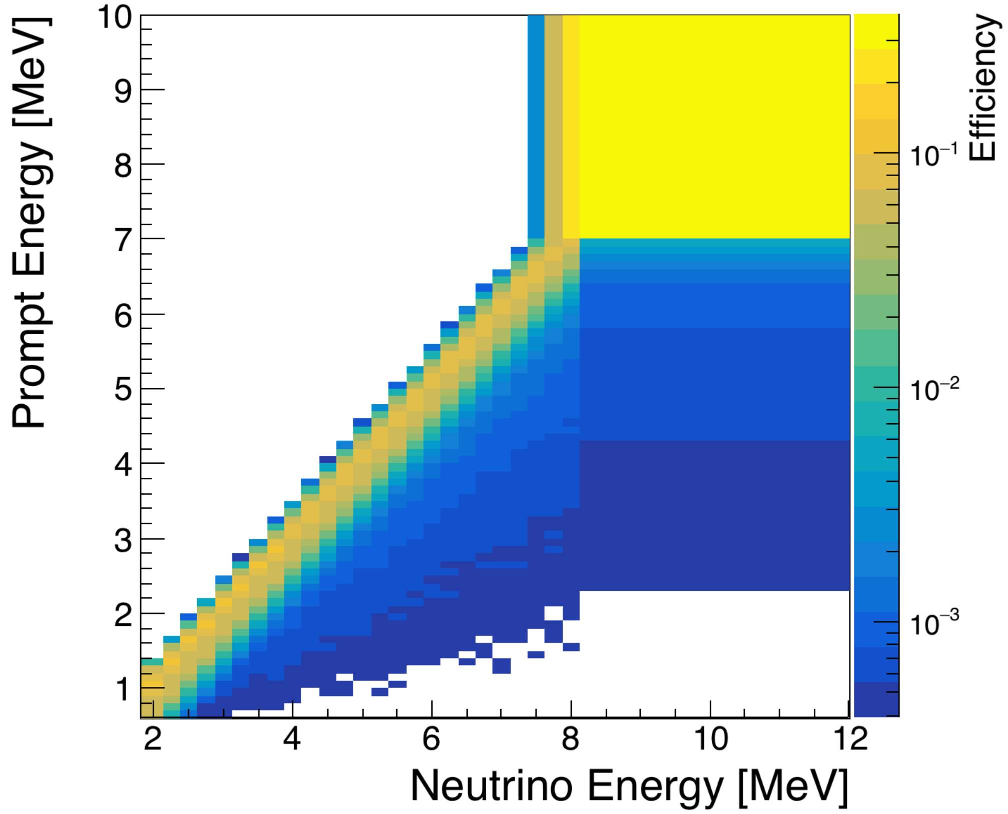




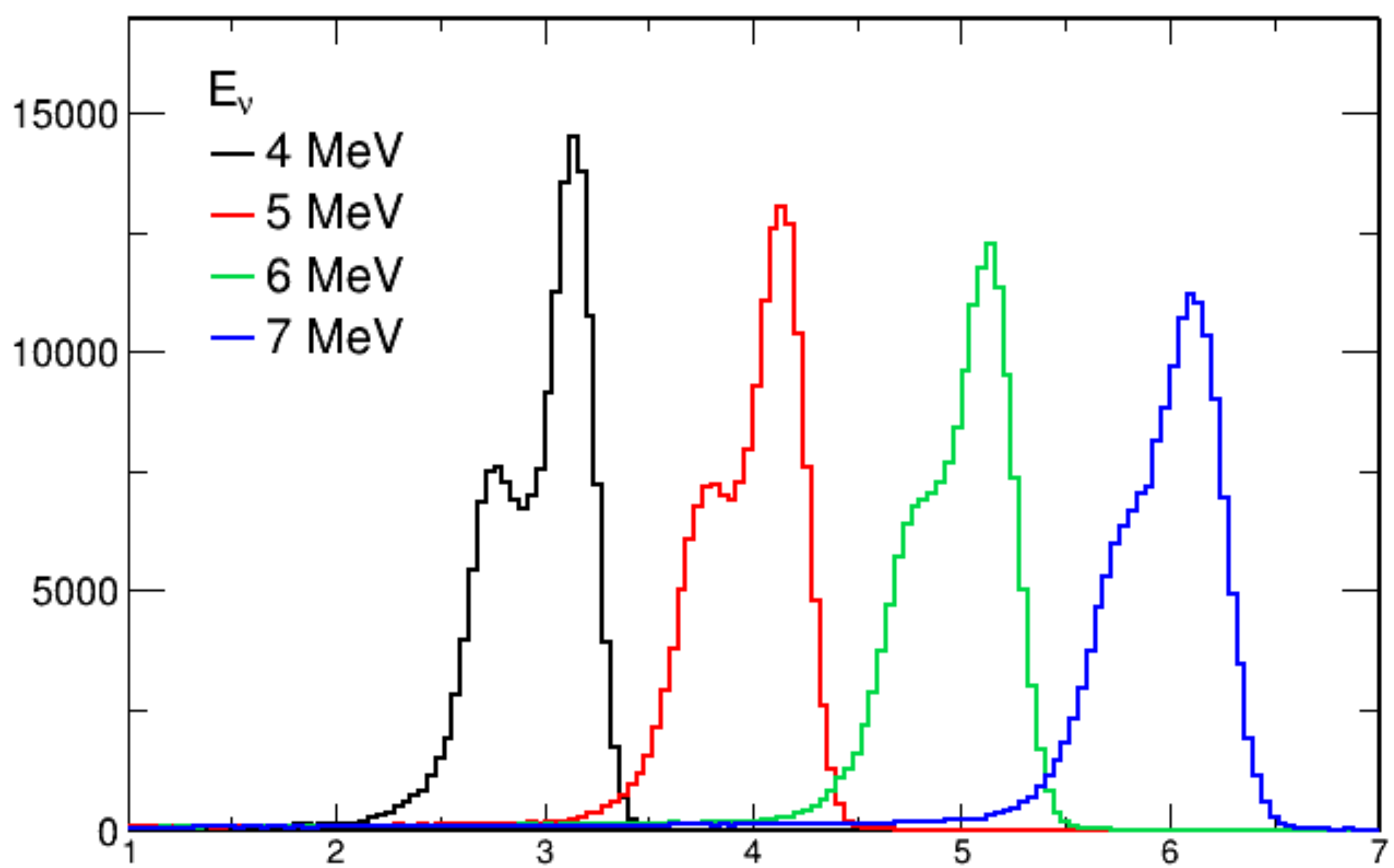


- Geant4 based MC simulation
  — LS, PMT optical properties,
  — full simulation of physics processes including trigger simulation
- Excellent agreement with data in the energy r.o.i:
  — Energy resolution
  — Non-linearity
  — Escaping γ

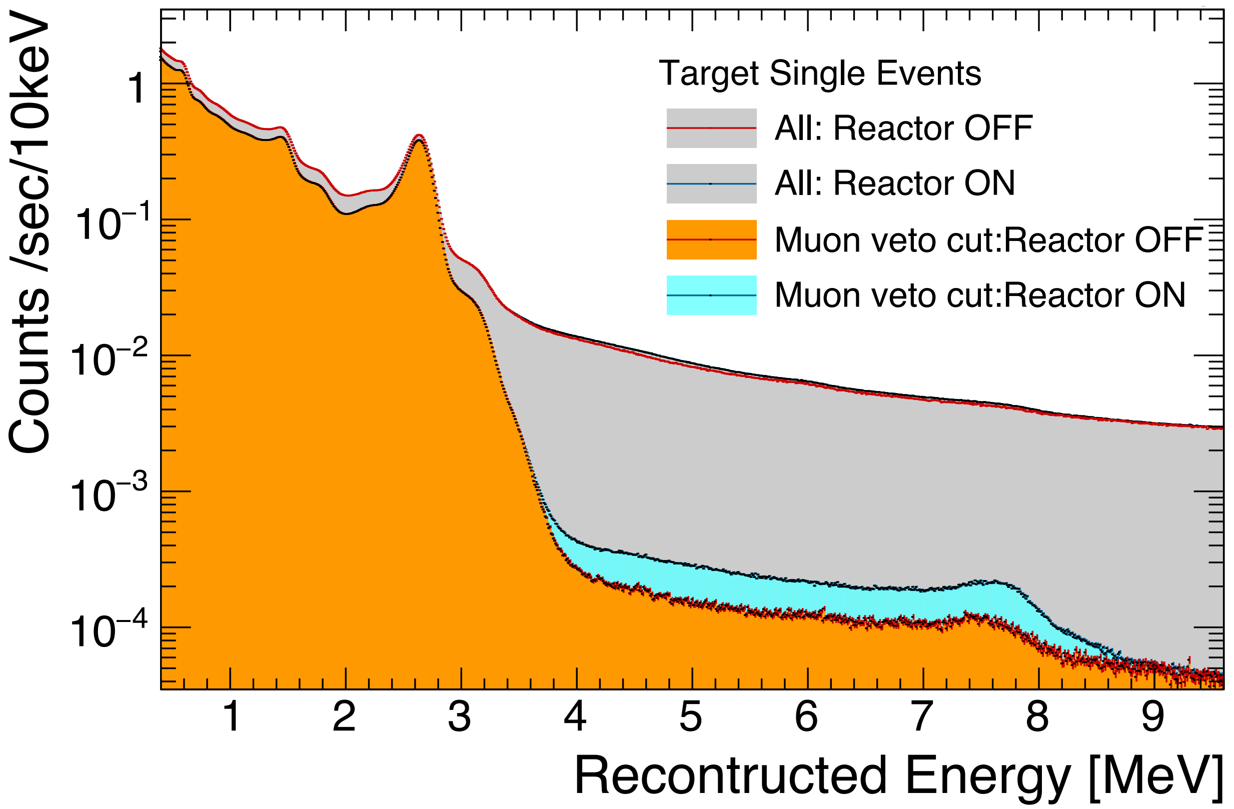
Detector response to $E_{\bar{\nu}}$



Small volume detector suffers from energy loss due to escaping of γ ray(s).

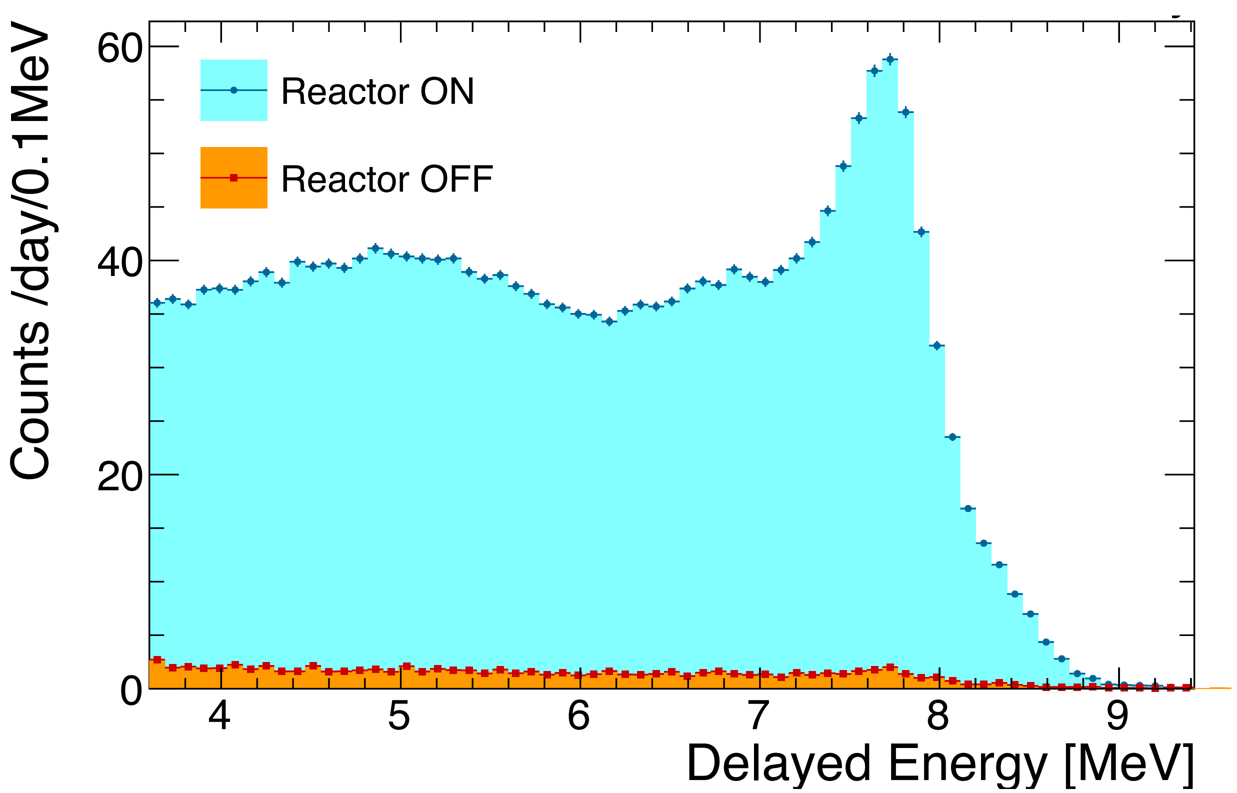


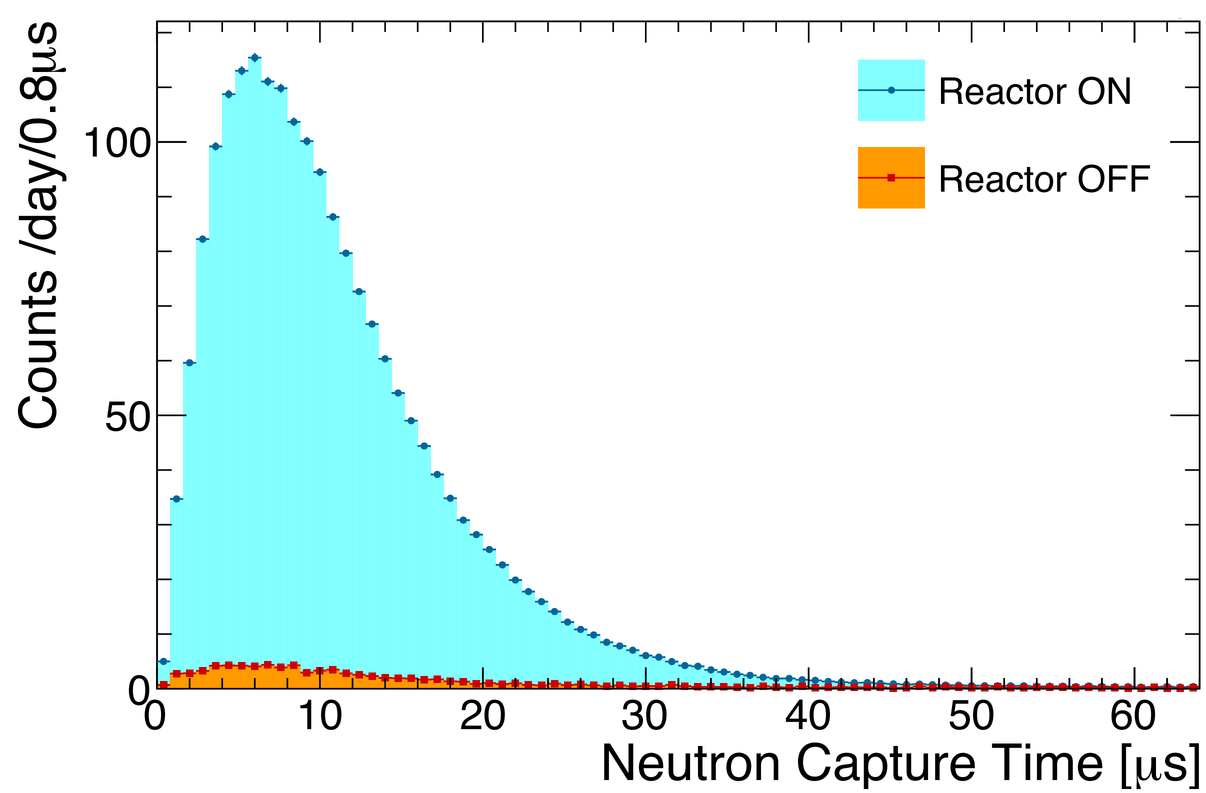
IBD reconstruction



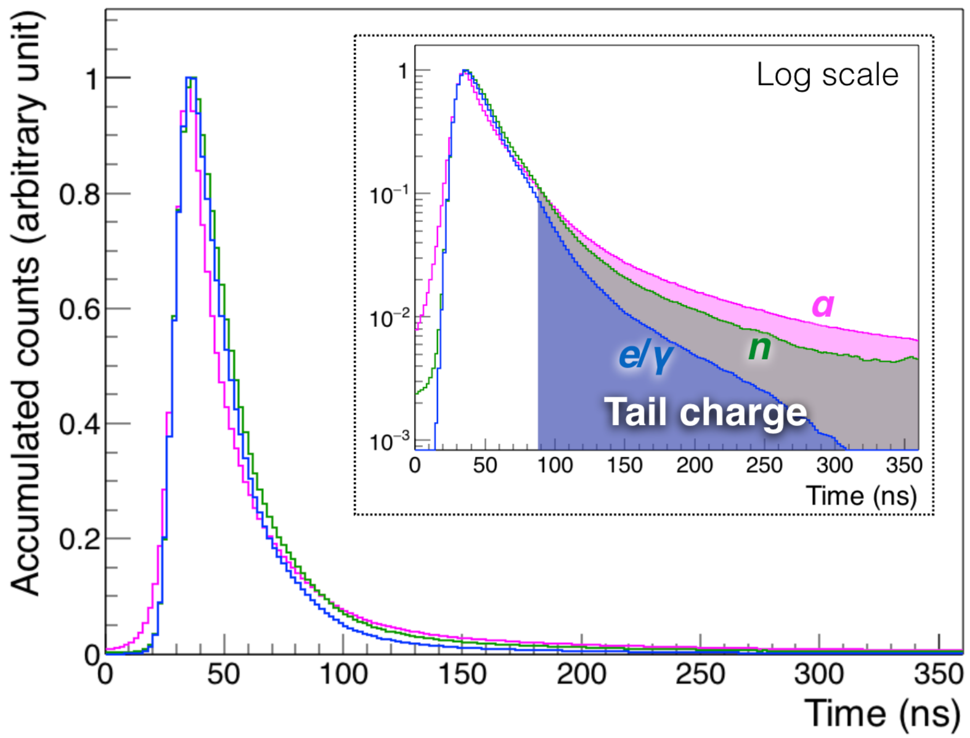
Selection rules developed for best S/N ratio:

- Prompt energy: 1-10 MeV
- Delayed energy: 4-10 MeV
- Time coincidence: 1-30 μs
- Multiplicity: no event before (after) 30 (150) μs from the prompt/delayed pair
- Muon veto: 150 μs
- Pulse shape discrimination





Fast *n* background / pulse shape discrimination



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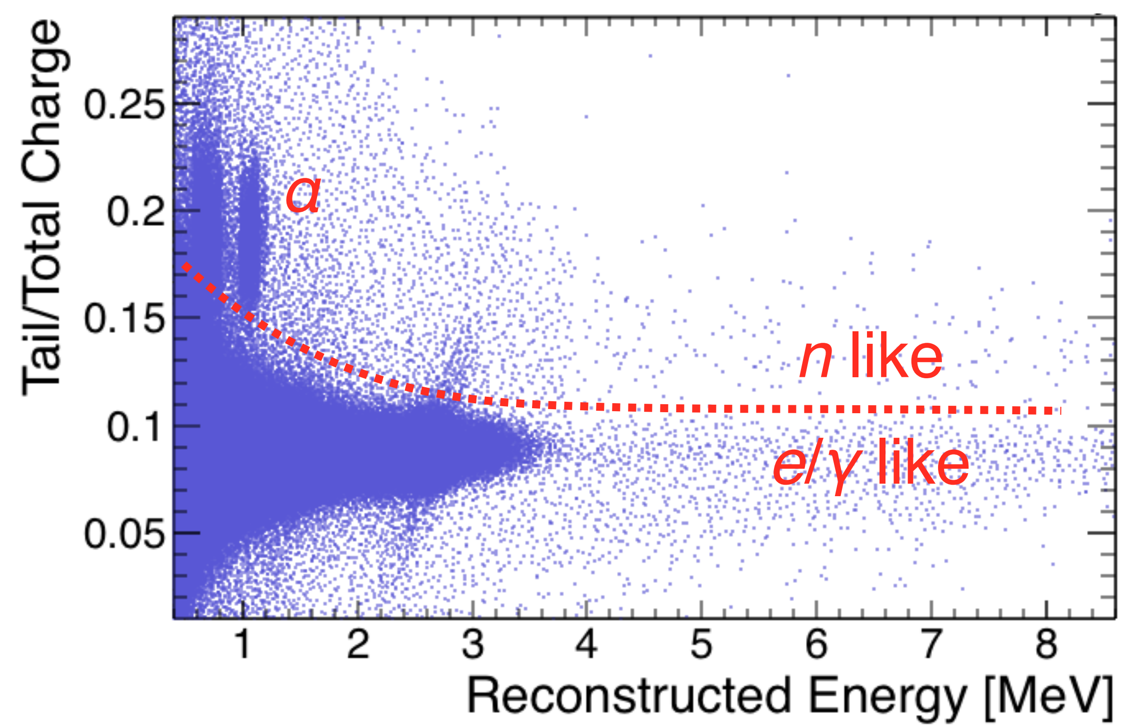
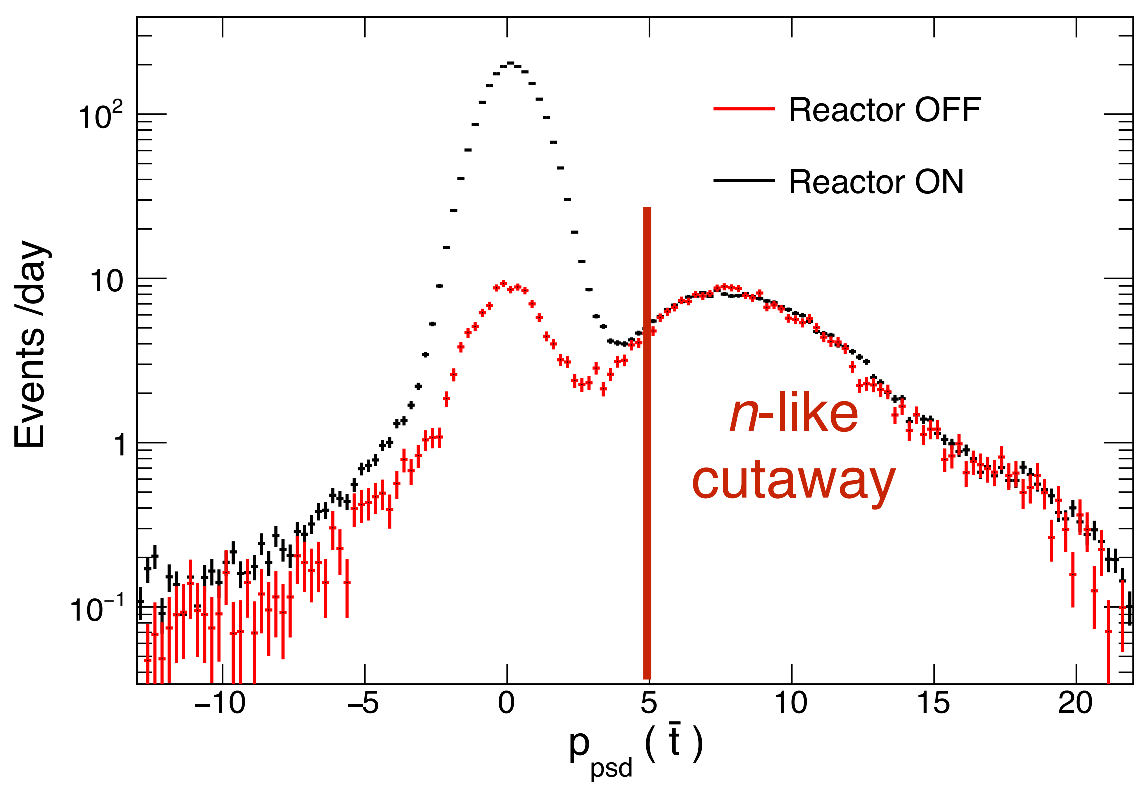
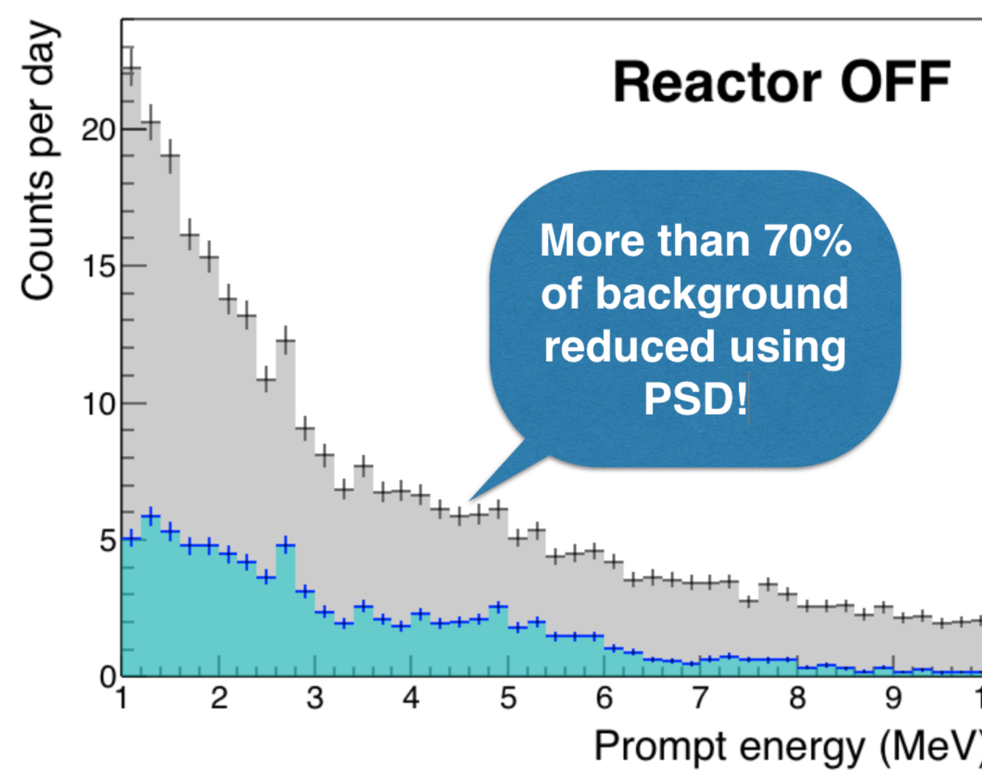
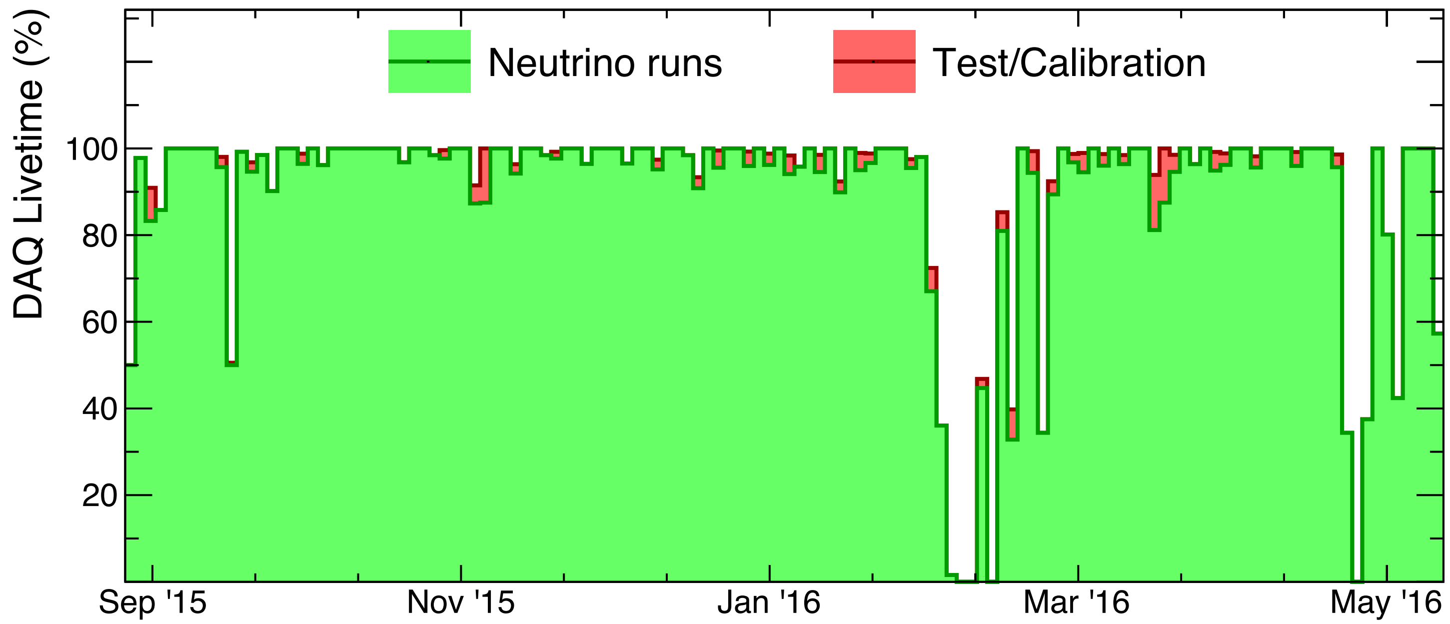
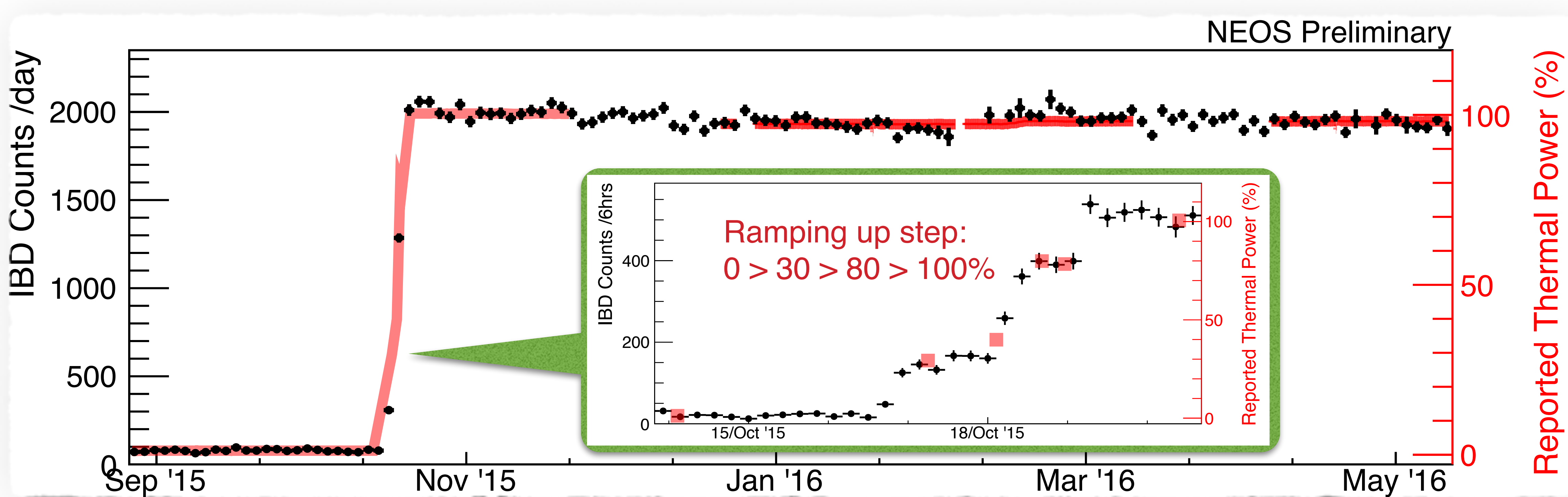






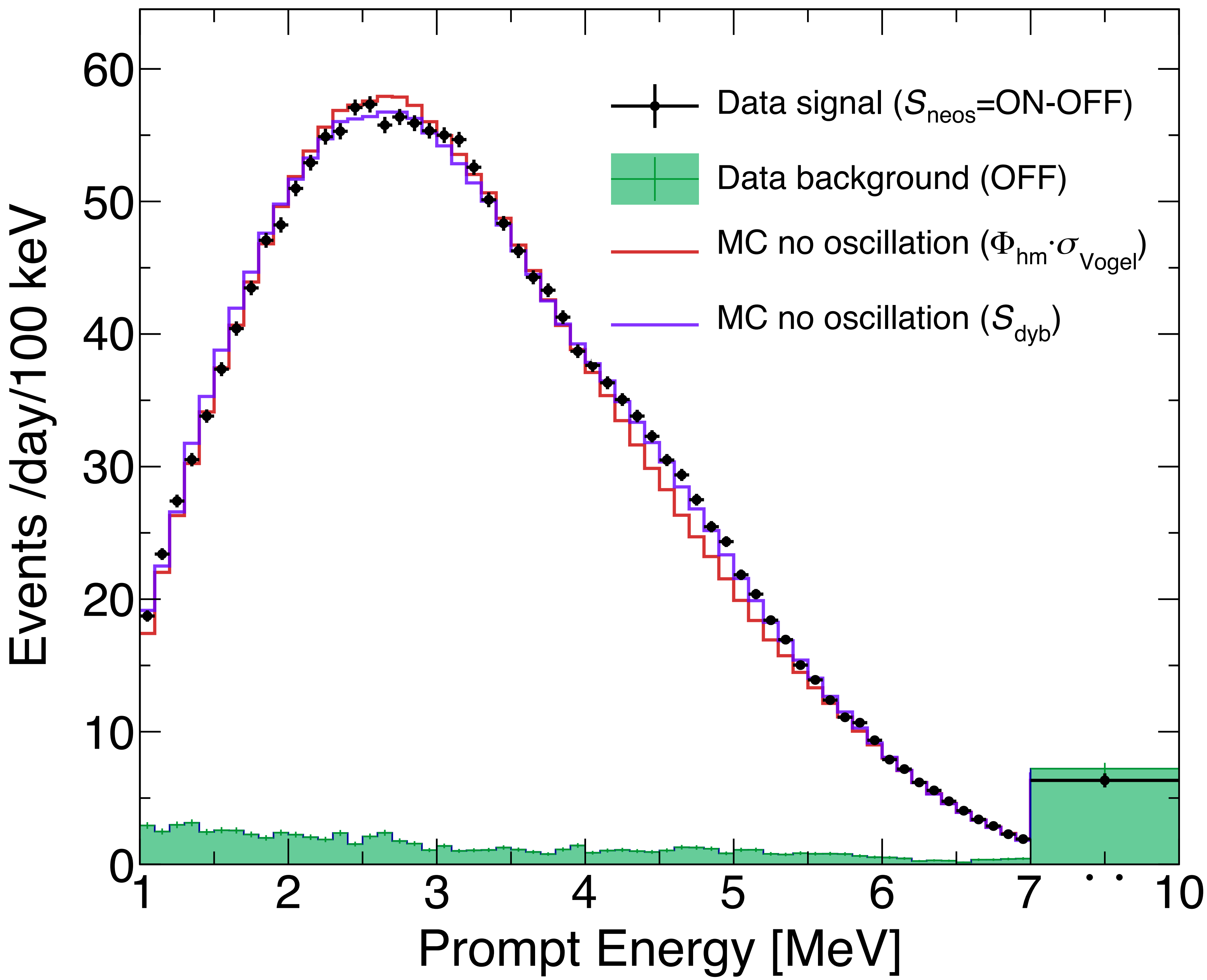
IBD candidates event rate



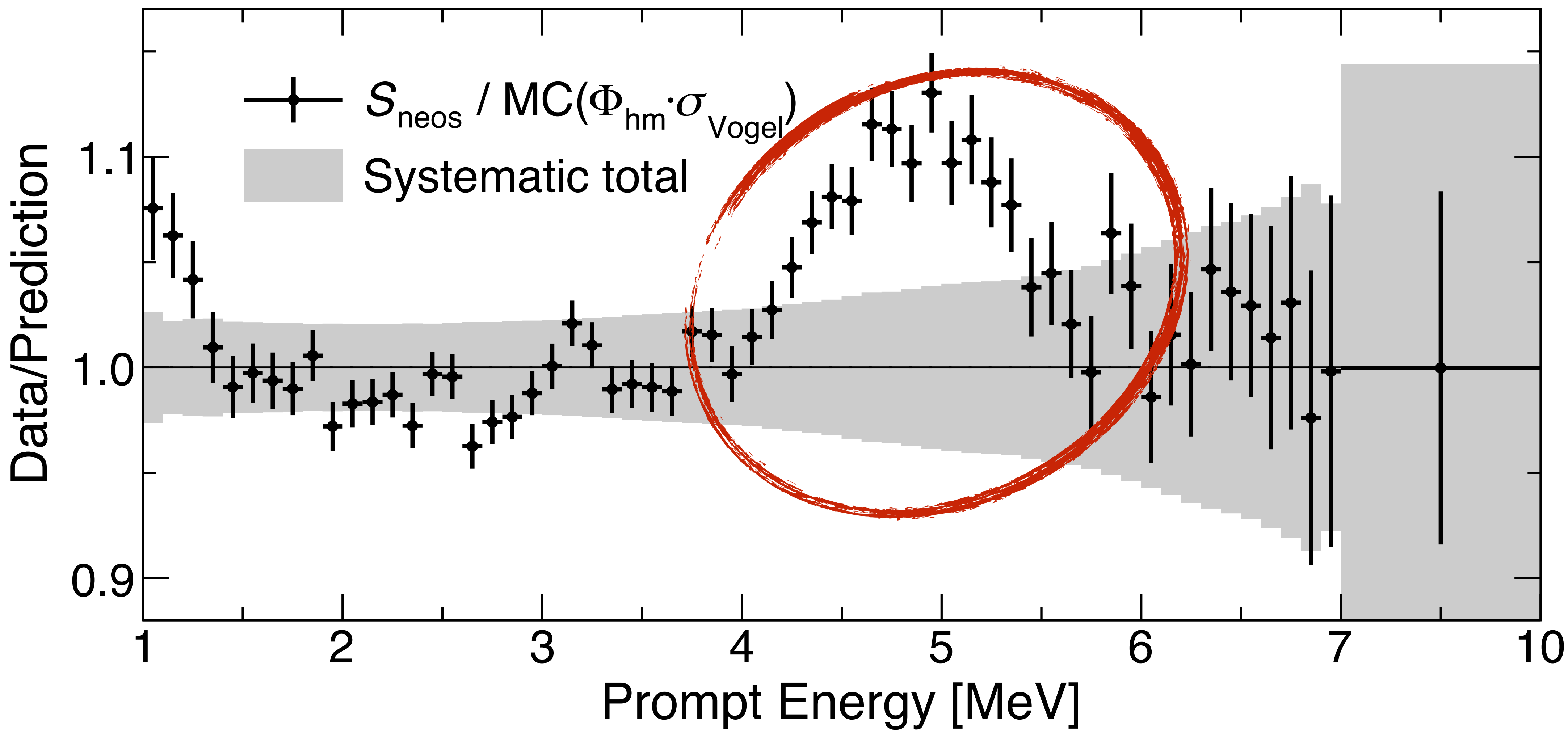


- Signal/background ~23:
  ~2000 (Reactor ON) vs ~80 (OFF) IBD candidates

Prompt energy spectrum

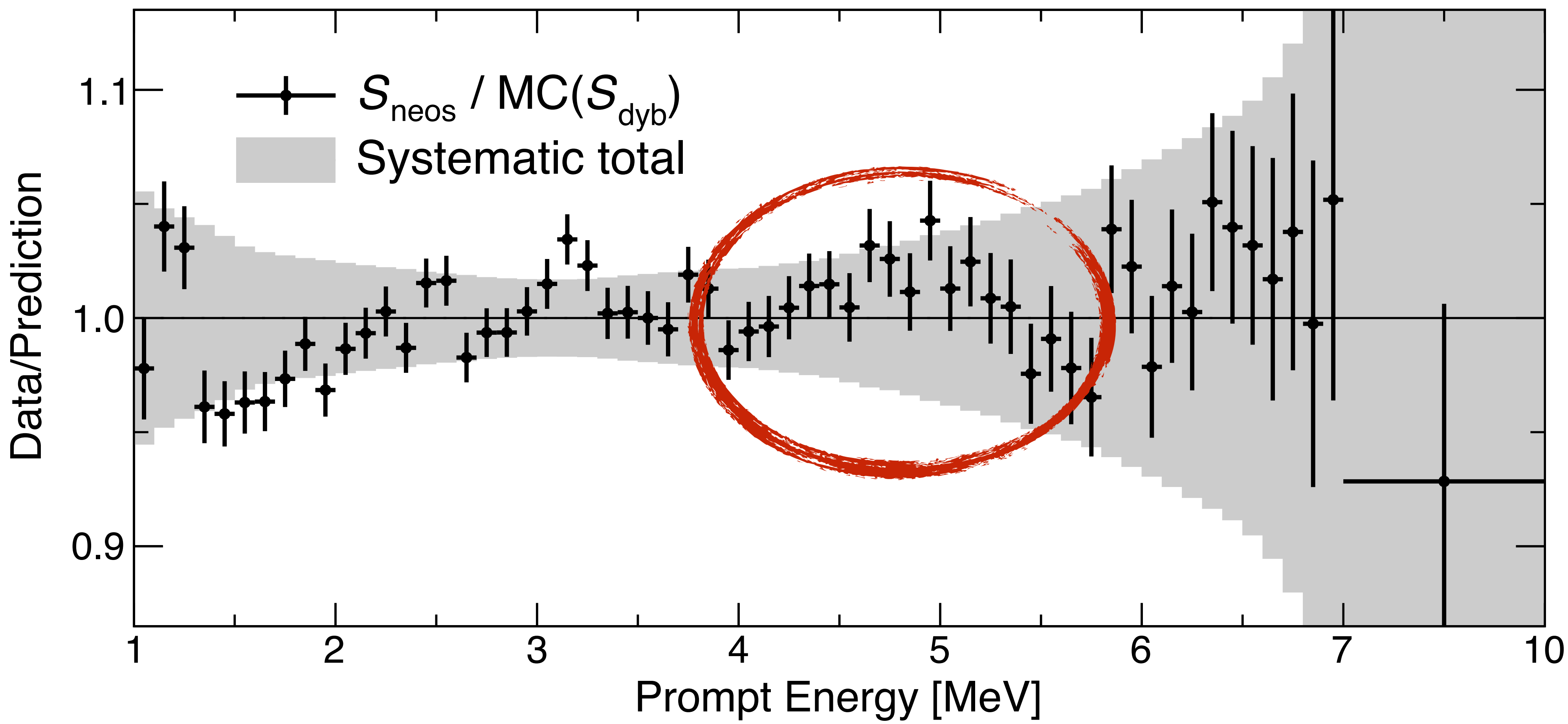


NEOS vs Huber-Mueller × Vogel



- 5 MeV excess is seen (with 2-4 MeV normalization).
- not so practical to do the oscillation analysis

NEOS vs Daya Bay



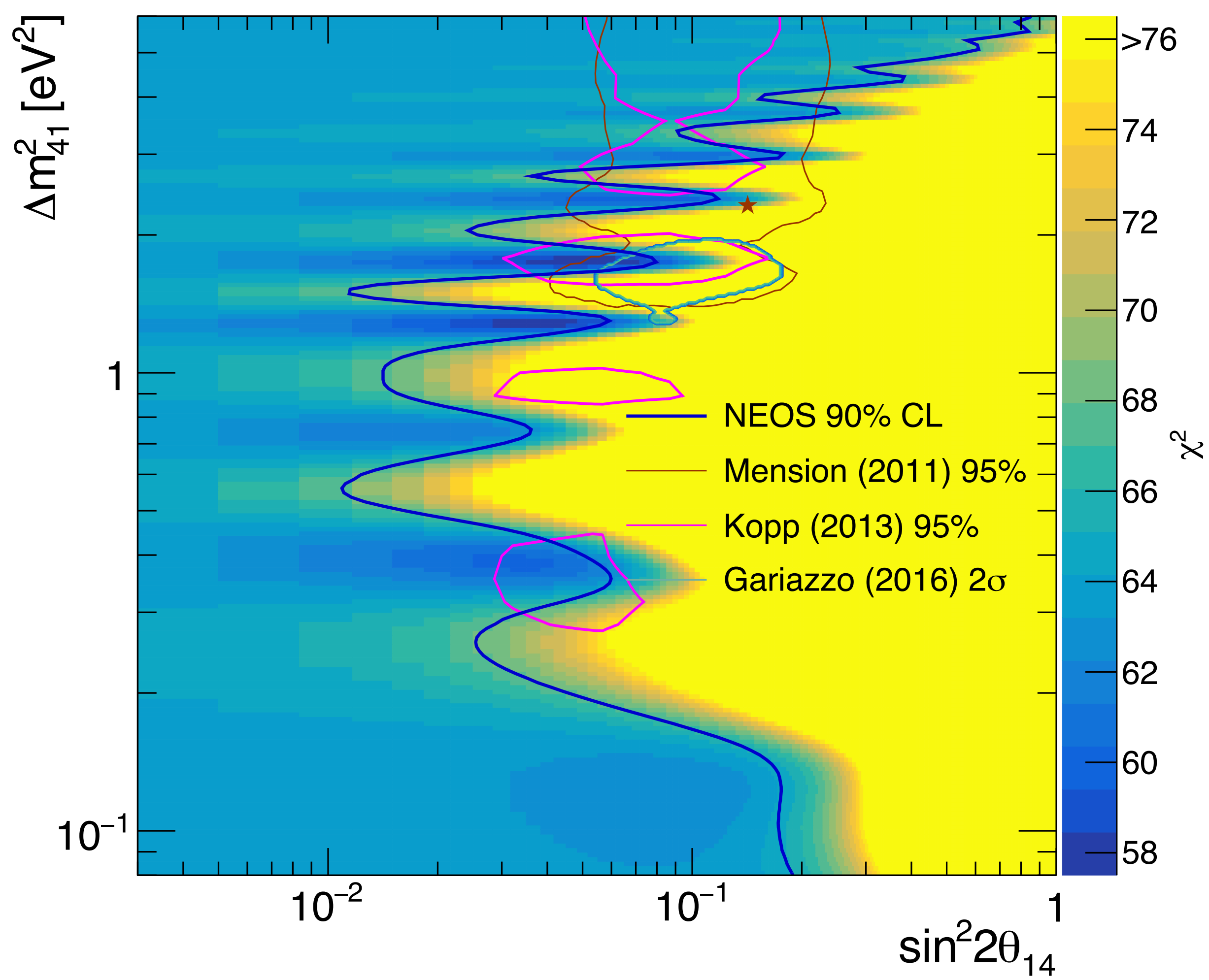
- Bump got much smaller, but still there is a structure:
  > Note average fission fraction differences between two experiments:
  (U-235, U-238, Pu-239, Pu-241)
  NEOS: (0.655, 0.072, 0.235, 0.038), Daya Bay: (0.561, 0.076, 0.307, 0.056)
  — Negligible spectral difference expected in the H&M model.
  > One of the isotopes responsible for the bump?

Search for Oscillation

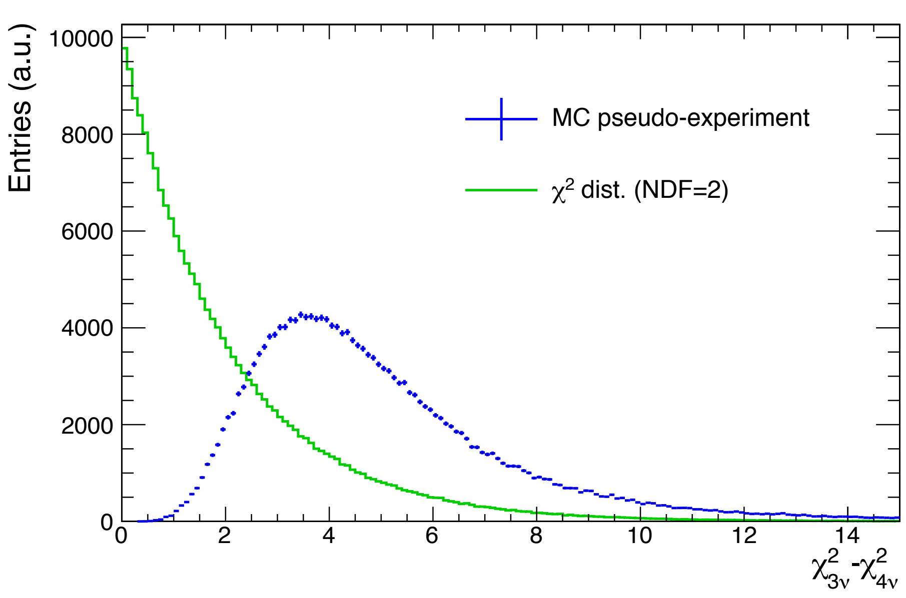
$$\chi^2 = \left(N_i^{\rm on} - (t_{\rm on}/t_{\rm off})N_i^{\rm off} - T_i\right) V_{ij}^{-1} \left(N_j^{\rm on} - (t_{\rm on}/t_{\rm off})N_j^{\rm off} - T_j\right)$$

- $\chi^2 = \chi^2(\Delta m^2, \sin^2 2\theta)$: chi-square for each oscillation parameter set
- N_i^{on} : measured number of event in i th prompt energy bin during reactor on (signal+background)
- N_i^{off} : measrued event number during reactor off (background)
- t_{on} / t_{off} : time period of reactor on/off
- $T_i = T_i(\Delta m^2, \sin^2 2\theta)$: expected spectrum for each oscillation parameter set, generated from model spectrum and convolved with the simulated detector response (Daya Bay spectrum is used so far.)
- V_{ij} : covariance matrix including statistical/systematic uncertainties and their correlation between energy bins

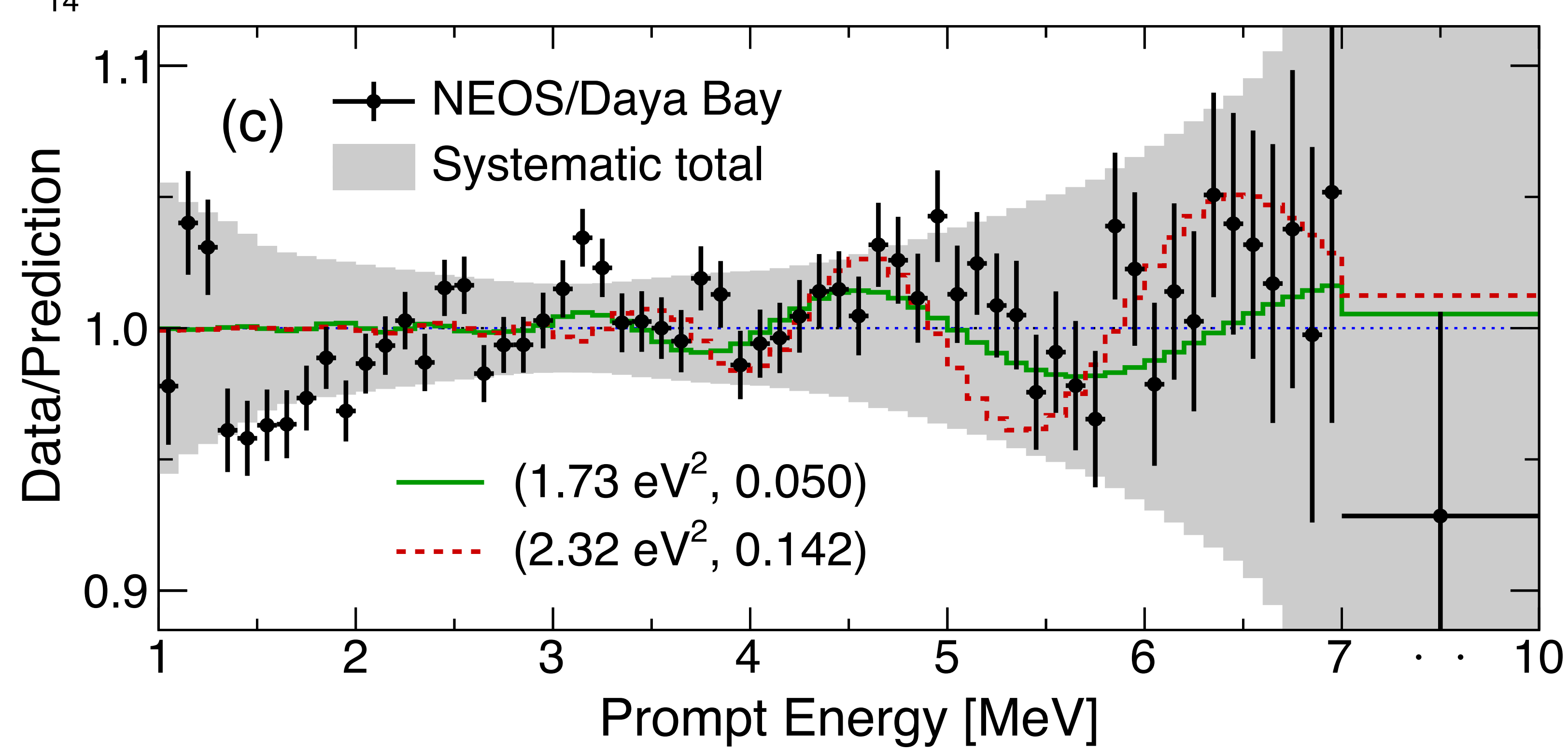
Search for oscillation / limits



- χ^2 minima are found at ($\sin^2 2\theta$, Δm^2)=(0.04, 1.3 eV^2), (0.05, 1.73 eV^2) with $\Delta\chi^2 = \chi^2_{3\nu} - \chi^2_{4\nu} = 6.5$.
- p-value ~ 22%
- No strong sign of 3+1 active-to-sterile ν oscillation.
- Small mixing, similar mass squared difference.



Yoomin Oh / NEOS



Summary & Conclusion

- No strong active-to-sterile mixing seen in the NEOS data for $\Delta m^2 \sim 1\ eV^2$
  — Best fits to smaller mixing. (0.04, 1.3 eV^2) / (0.05, 1.73 eV^2), but not so significant.
  — Analysis highly depends on model spectrum.
- Reactor antineutrino anomaly
  — 5 MeV excess is observed at this short baseline, too.
  — Sizes are different between different reactors
  — Flux prediction should be re-examined, hopefully with experimental effort.

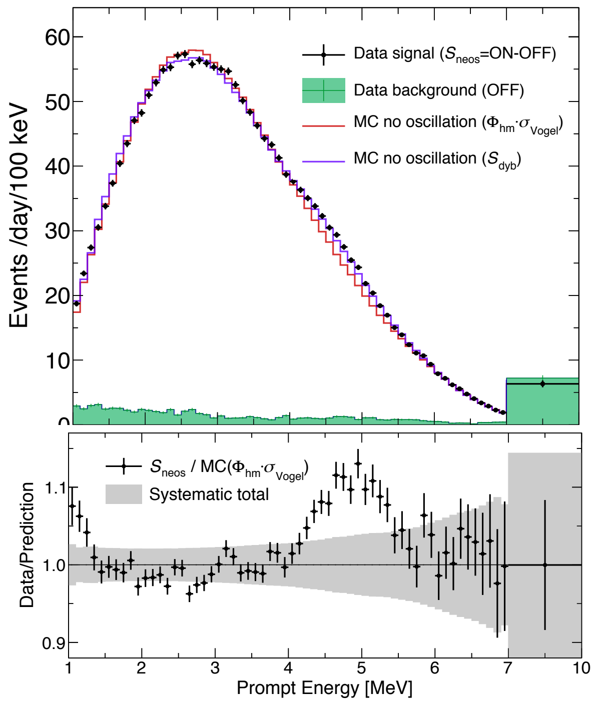
"I came here to tell you how it's going to begin."

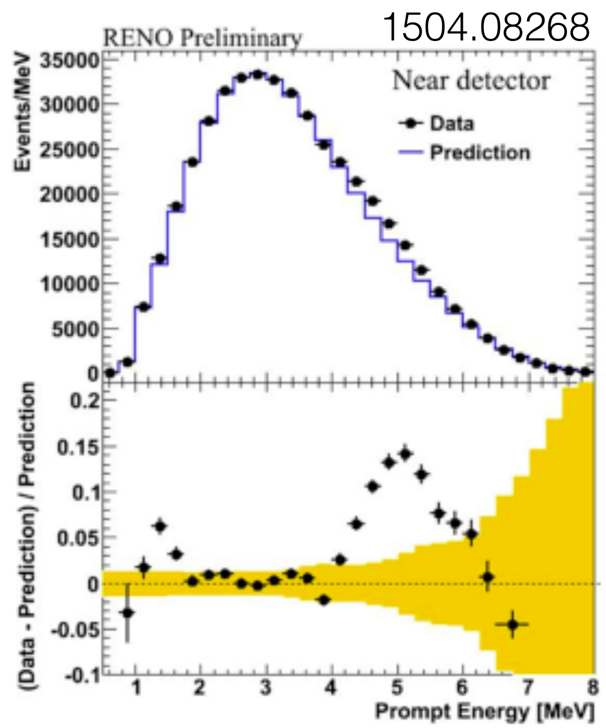
FAQ1. Status and plan

- Data taking over (paused) in May 2016
  - due to regular maintenance of tendon gallery
- Investigating the possible improvement in reactor flux measurement with an additional measurement longer than 1 burnup cycle.
  - Preparing an proposal, including
  - other neutrino measurement (vN)

"We're gonna make them an offer they can't refuse."

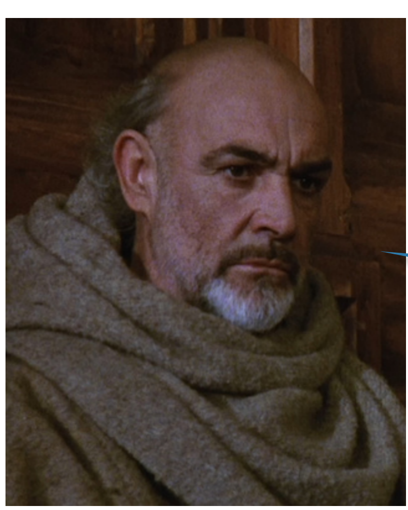
FAQ2. Model spectrum





1. Why don't we use the RENO spectrum as a reference?
   — working on it.
   — a direct comparison between the two prompt (e+) energy spectra is not working, because the detector responses are different.
   — Burnup (or fission fractions) is not the same for the two experiments.

2. How did we deal with the difference between the DYB and the NEOS (i.e. reactors, fission fractions)?
   — current model (H-M) does not provide satisfactory answer.
   — different fuel / long term measurements with a good *E* resolution.



"Nihil sequitur geminis ex particularibus unquam."

FAQ3. Rate analysis

1. Why don't we do rate analysis?
 — Uncertainty in the number of proton in the target LS:
 + Temperature-volume fluctuation
 — Associated γ levels from n-Gd capture in GEANT4 do not describe the delayed spectrum very well for our small volume detector.
 > difficult to estimate the efficiency in the delayed event selection.
 > No particular improvement by rate analysis is expected.