Revisiting Reactor $\bar{\nu}$ 5 MeV Bump with ν-13C Neutral Current Interactions

Min-Gwa Park

Work with Pouya Bakhti, Meshkat Rajaee, Seodong Shin, Chang Sub Shin

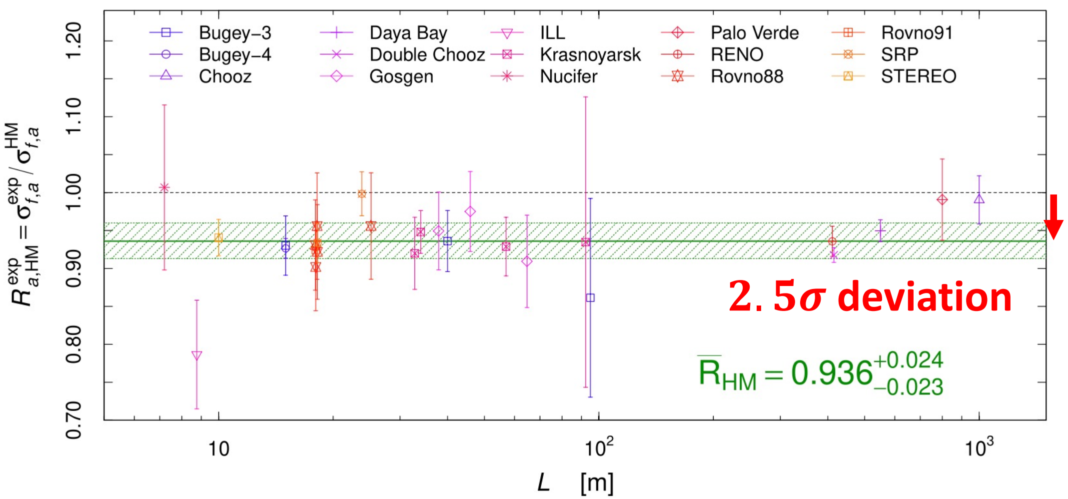
[arXiv : 2405.08724]

Mitchell Conference 2024

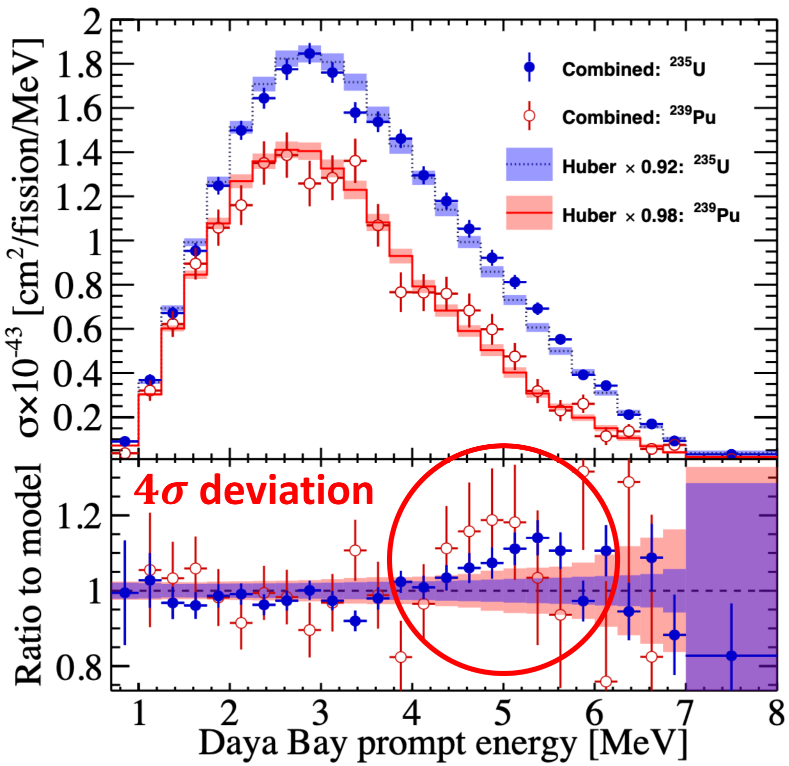
Mitchell Institute, Texas A&M University

May 24, 2024

Anomalies in Reactor Neutrinos



C. Giunti, Y.F. Li, C.A. Ternes, Z. Xin, Phys.Lett.B 829 (2022) 137054



Daya Bay, PROSPECT Collaboration,
Phys. Rev. Lett. 128, 081801

Overall Deficit of Measured $\bar{\nu}_e$ Flux

2011 : Mention et al.

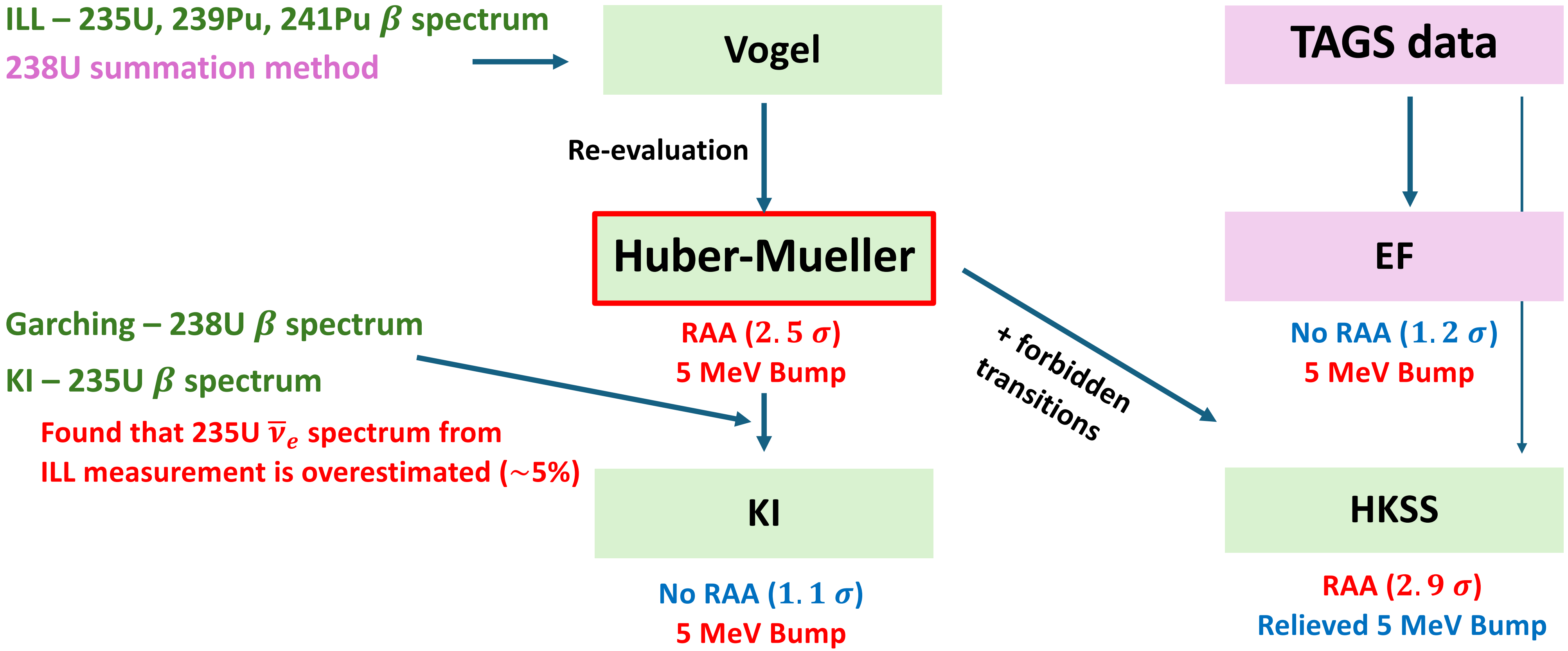
Reactor Antineutrino Anomaly

Local abundance of prompt e^+ energy

2014 : RENO

Shape Anomaly (5 MeV Bump)

C. Giunti, Y.F. Li, C.A. Ternes, Z. Xin, Phys.Lett.B 829 (2022) 137054



2 updated models (KI, EF) resolved RAA, but not 5 MeV Bump.

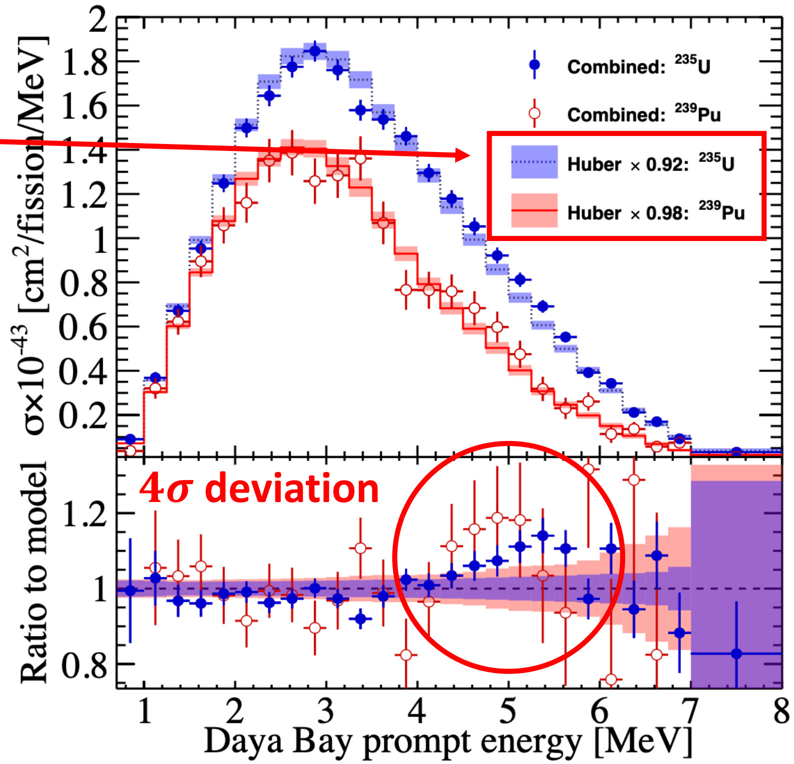
HKSS model relieved 5 MeV Bump, but not RAA.

After the total $\overline{\nu}$ rate normalization
→ 5 MeV Bump

Prior the total $\overline{\nu}$ rate normalization
→ no 5 MeV Bump, deficit below 5 MeV

Where does 5 MeV Bump come from?

- Reactor flux models?
- Unknown systematics with IBD?
- New physics mimicking IBD?



Daya Bay, PROSPECT Collaboration,
Phys. Rev. Lett. 128, 081801

Local abundance of prompt e^+ energy

2014 : RENO

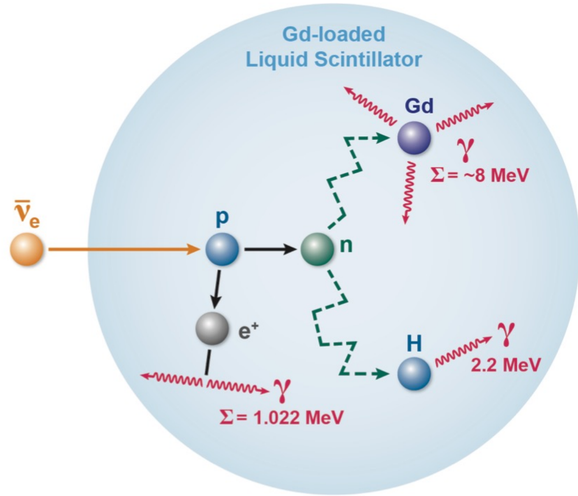
Shape Anomaly (5 MeV Bump)

Detection Channel for Reactor $\bar{\nu}_e$

Xin Qian and Jen-Chieh Peng 2019 *Rep. Prog. Phys.* **82** 036201

Channel	Name	Cross Section (10^{-44} cm^2/ fission)	Threshold (MeV)
$\bar{\nu}_e + p \to e^+ + n$	IBD	63	1.8

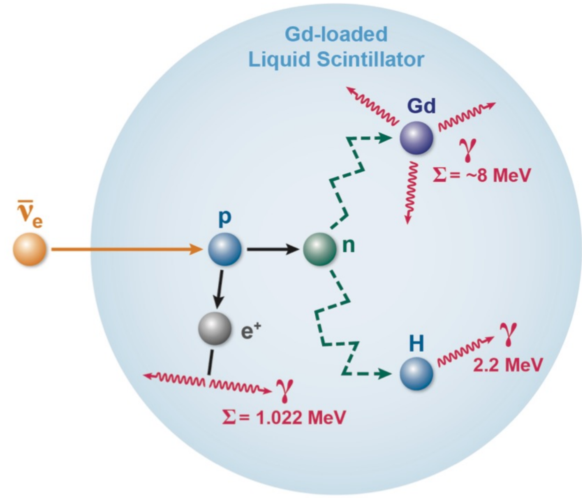
- Large cross section
- Detection of final state e^+, n → can reconstruct E_ν
- Double coincidence signal
- Main detection channel for reactor $\bar{\nu}_e$



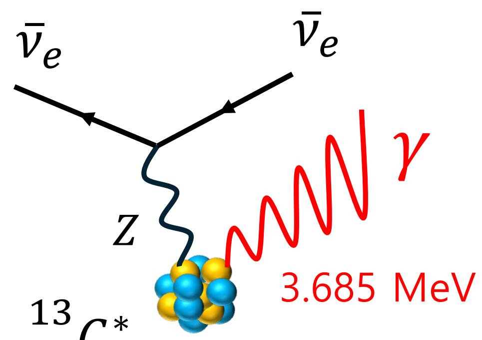
Additional Channel for Reactor $\bar{\nu}_e$?

Xin Qian and Jen-Chieh Peng 2019 *Rep. Prog. Phys.* **82** 036201

Channel	Name	Cross Section ($10^{-44}\ cm^2$/ fission)	Threshold (MeV)
$\bar{\nu}_e + p \rightarrow e^+ + n$	IBD	63	1.8
$\bar{\nu}_\alpha + 13C \rightarrow \bar{\nu}_\alpha + 13C^*$	ν-13C NC	0.65	3.685



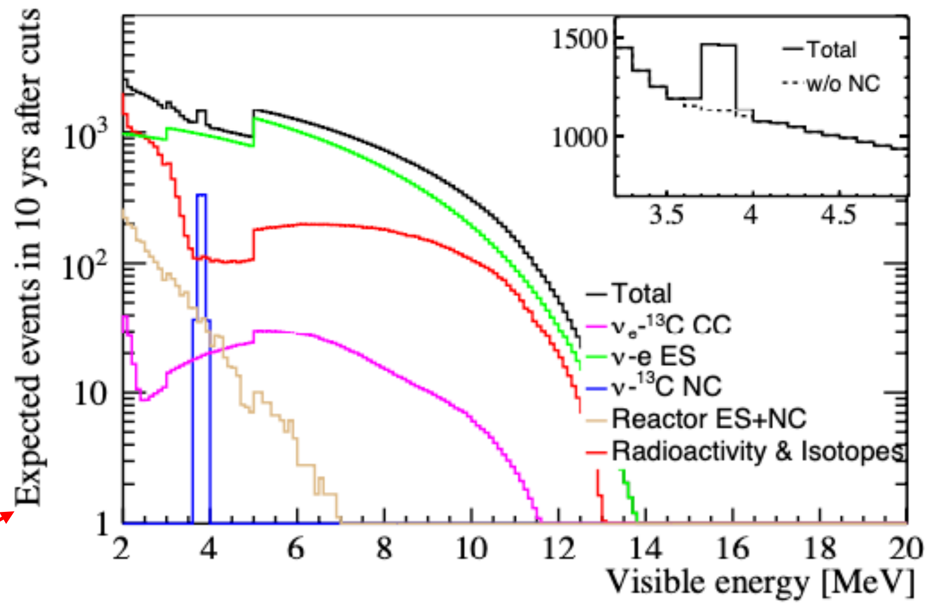
Excitation & de-excitation of ^{13}C



~**1.1% natural abundance** → $^{13}C^*$

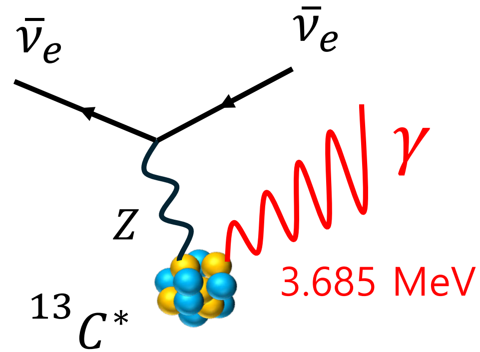
Additional Channel for Reactor $\bar{\nu}_e$?

J. Zhao *et al,* 2024 *ApJ* 965 122 (JUNO solar ν)



- Flavor neutral
- $\sim 4.5\times10^{26}$ in 1 t LS
- Accessible to reactor & solar neutrinos

$\bar{\nu}_\alpha + 13C \rightarrow \bar{\nu}_\alpha + 13C^*$	ν-13C NC	0.65	3.685



$\sim$**1.1% natural abundance** $\rightarrow$ $^{13}C^*$

Additional Channel for Reactor $\bar{\nu}_e$?

Xin Qian and Jen-Chieh Peng 2019 *Rep. Prog. Phys.* **82** 036201

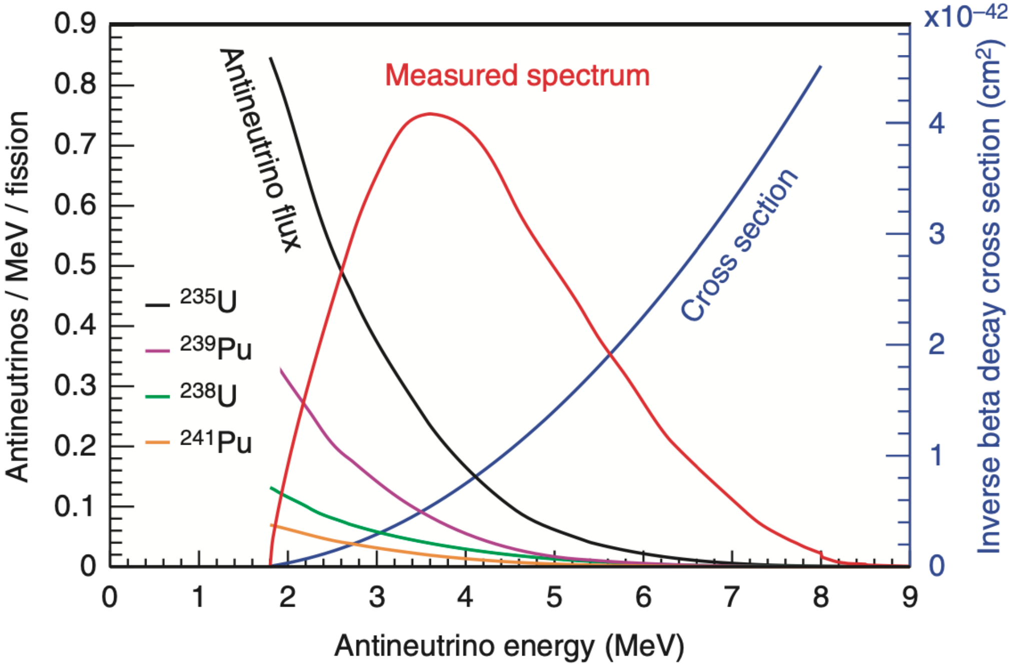
Channel	Name	Cross Section ($10^{-44}\ cm^2$/ fission)	Threshold (MeV)
$\bar{\nu}_e + p \rightarrow e^+ + n$	IBD	63	1.8
$\bar{\nu}_e + e^- \rightarrow \bar{\nu}_e + e^-$	νES	$0.4 \cdot Z$	-
$\bar{\nu}_\alpha + A \rightarrow \bar{\nu}_\alpha + A$	CEνNS	$9.2 \cdot N^2$	-
$\bar{\nu}_e + d \rightarrow n + n + e^+$	ν-d CC	1.1	4.0
$\bar{\nu}_\alpha + d \rightarrow n + p + \bar{\nu}_\alpha$	ν-d NC	3.1	2.2
$\bar{\nu}_\alpha + 13C \rightarrow \bar{\nu}_\alpha + 13C^*$	ν-13C NC	0.65	3.685

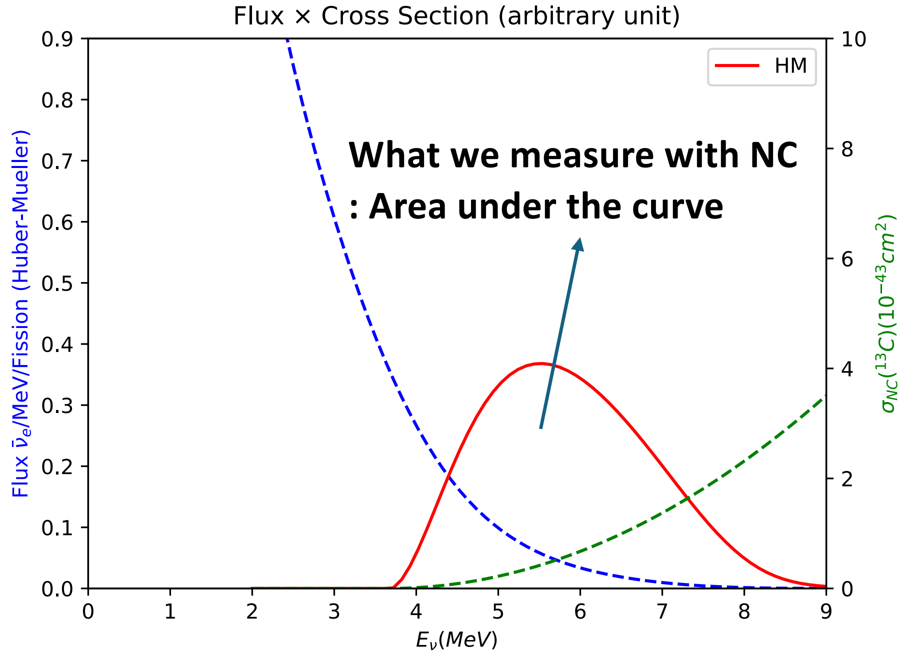
Used for $\sin\theta_W$, NSI.

Challenging but of much interest.

Hard to get large amount.

Vogel, P., Wen, L. & Zhang, C. Nat Commun 6, 6935 (2015).





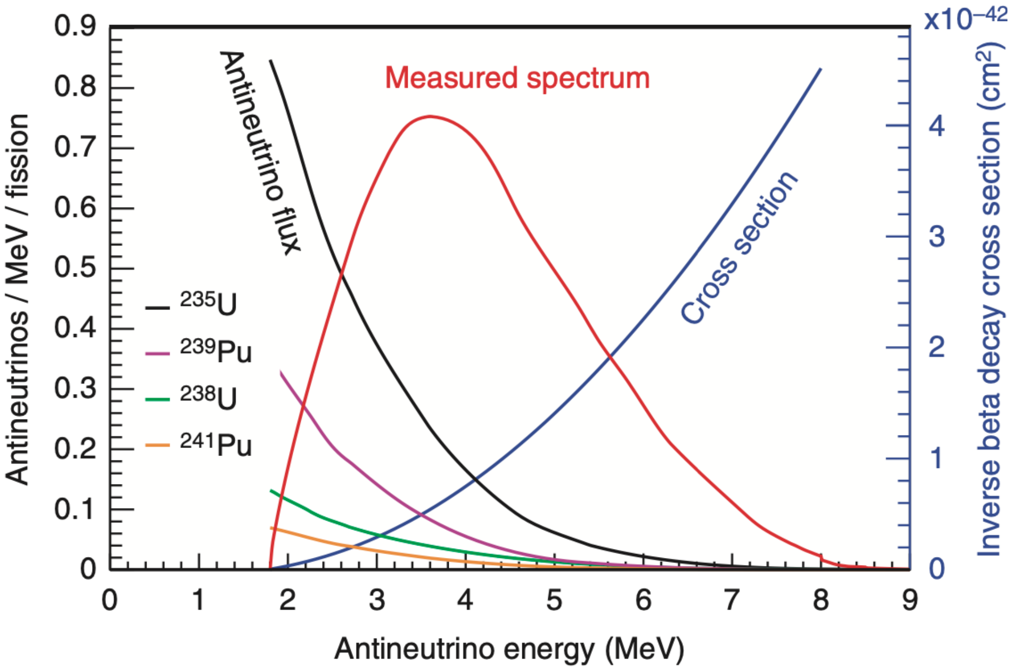
IBD

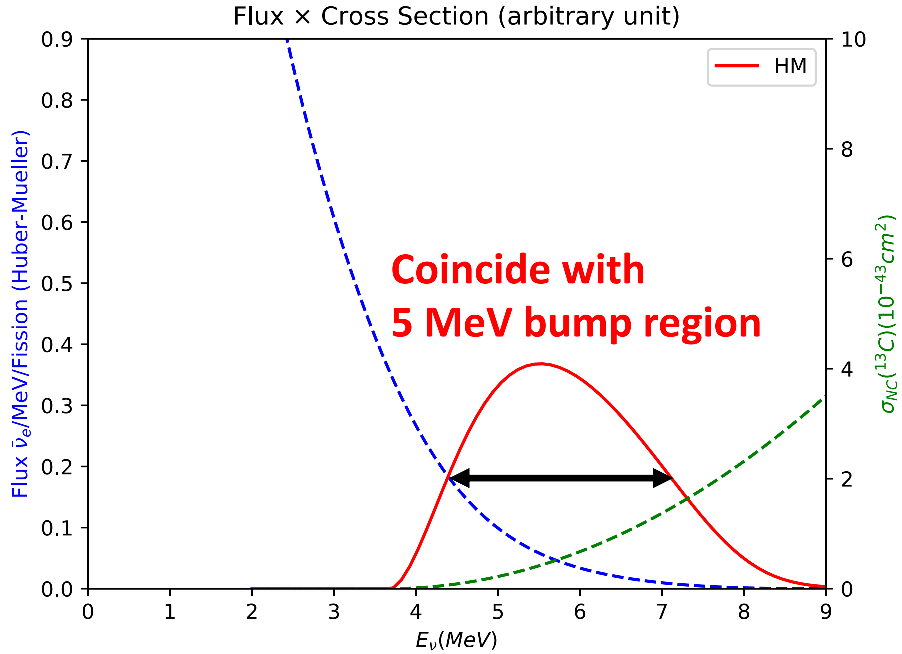
- Much larger cross section
- Detection of final state e^+
- Double coincidence signal
- Main detection channel for reactor $\bar{\nu}_e$

$\nu - 13C$ NC

- Flavor neutral
- Accessible to solar & reactor neutrinos

Vogel, P., Wen, L. & Zhang, C. Nat Commun 6, 6935 (2015).





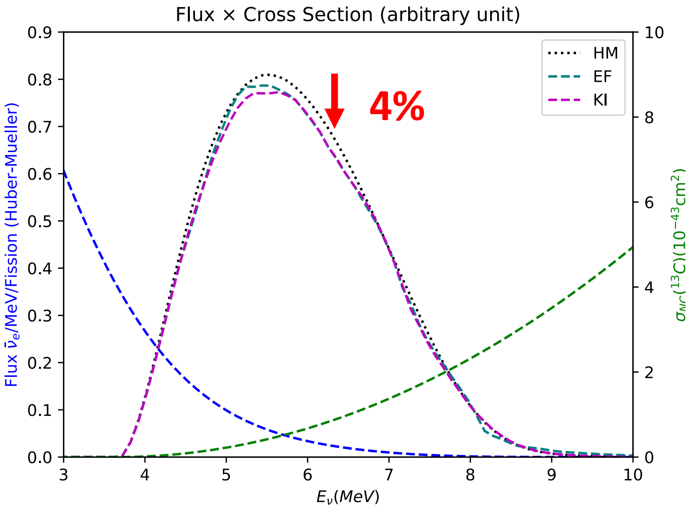
IBD

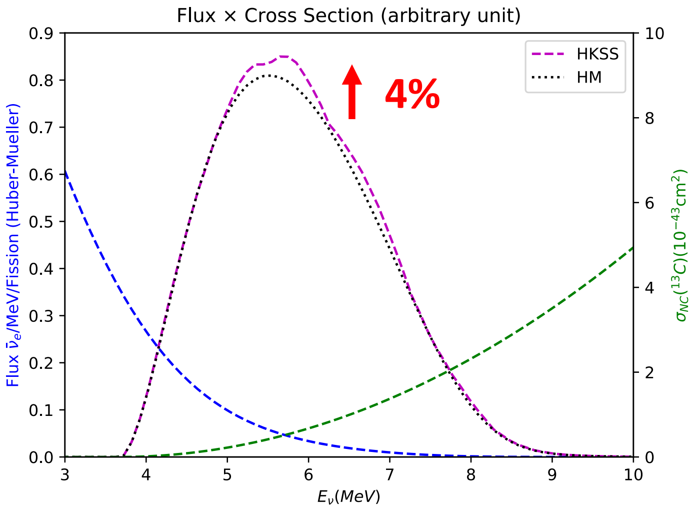
- Much larger cross section
- Detection of final state e^+
- Double coincidence signal
- Main detection channel for reactor $\bar{\nu}_e$

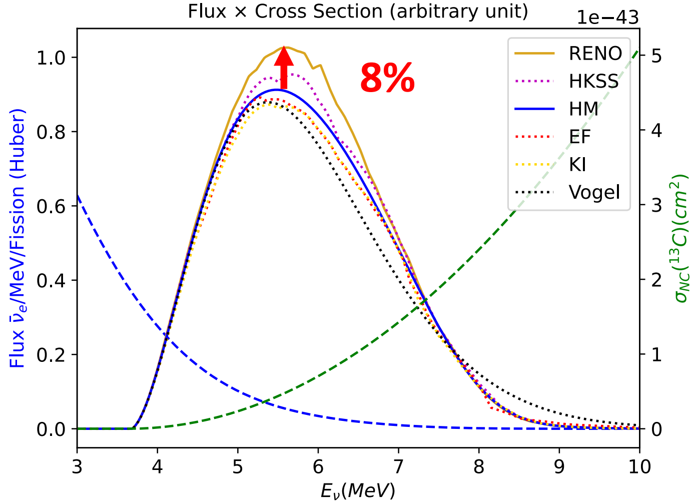
$\nu - 13C$ NC

- Flavor neutral
- Accessible to solar & reactor neutrinos
- Alternative way to test reactor models

Flux Model Comparison







Each models show 4~8% deviation from Huber-Mueller Model.

To reach 1σ model separation with ν-13C NC signals,
at least $4-8\%$ sensitivity is required.

Assumptions on Backgrounds

ROI = $3.685 \pm 0.1\ MeV$ (FWHM for 5% $/\sqrt{E(MeV)}$ resolution)

J. M. Conrad, J. M. Link, and M. H. Shaevitz, Phys. Rev. D 71, 073013 → on reactor $\bar{\nu}$ single-flash **ES signals** in 3~5 MeV

Backgrounds for the single-flash 3.685 MeV gamma

After 99.9% rejection with additional fiducial volume cut

↓

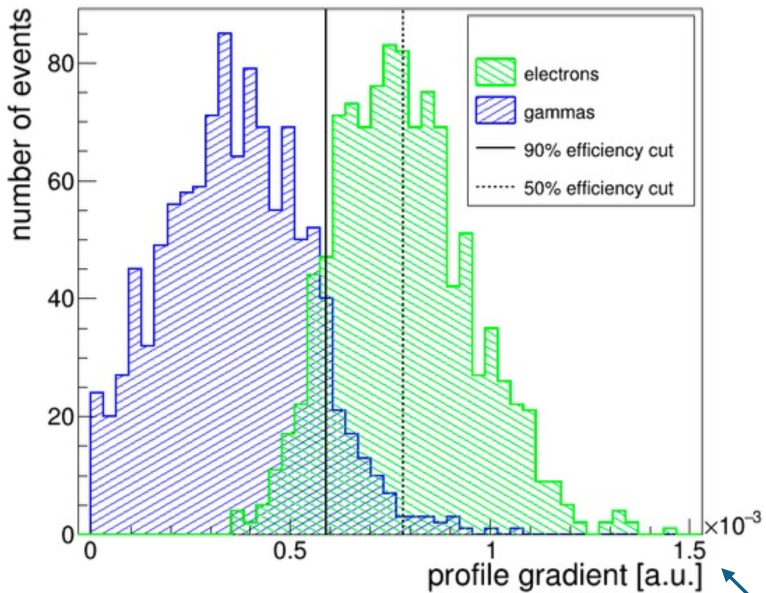
- **ES + mis-IBD : ~6 times of signals -> helped by β/γ discrimination (PID)**
- **Internal radiation (208Tl decay) -> high purity of LS + 232Th chain tagging**
- **Cosmic muon spallation -> overburden (300m.w.e.), muon veto, fiducial volume cut**
- **External radiation -> fiducial volume cut**
- **Solar ν events : dominant if** $\frac{Power(GW)}{(Baseline(km))^2} \ll 1$

Reactor $\bar{\nu}NC \approx 22 \times \frac{Power(GW) \cdot kt \cdot year}{(Baseline(km))^2}$

Solar $\nu NC \approx 15 \cdot kt \cdot year$

↪ **JUNO : Solar ν-13C detector**

H. Rebber *et al*, 2021 *JINST* **16** P01016



JUNO
: Topological Reconstruction

Discrimination of γ/β
using spatial information

for 1.25 – 1.75 MeV, 90% discrimination
→ expect higher level of discrimination for higher E!

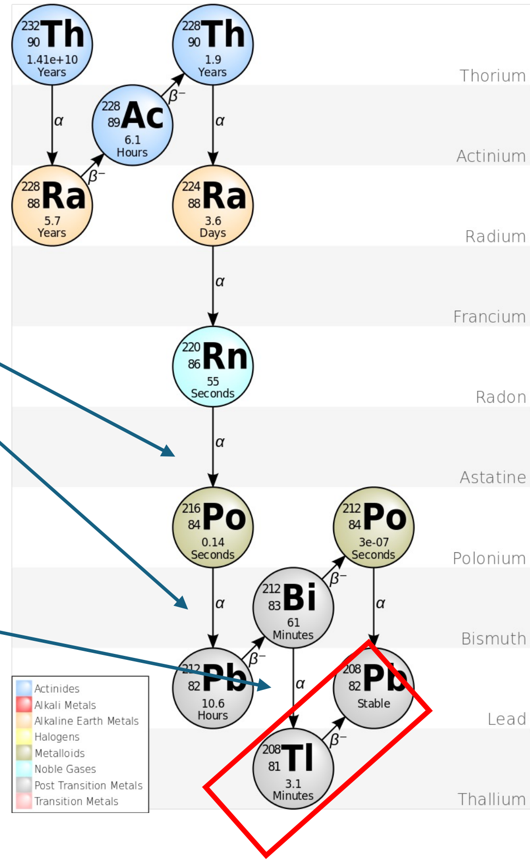
Takahiko Hachiya and for the KamLAND Collaboration
2020 J. Phys.: Conf. Ser. 1468 012257

$^{220}Rn + {}^{216}Po$ tagging :
80% reduction of ^{208}Tl

232Th chain tagging

Angel Abusleme *et al* 2021 *Chinese Phys. C* **45** 023004

$212Bi$ tagging :
99% reduction of ^{208}Tl



Assumption

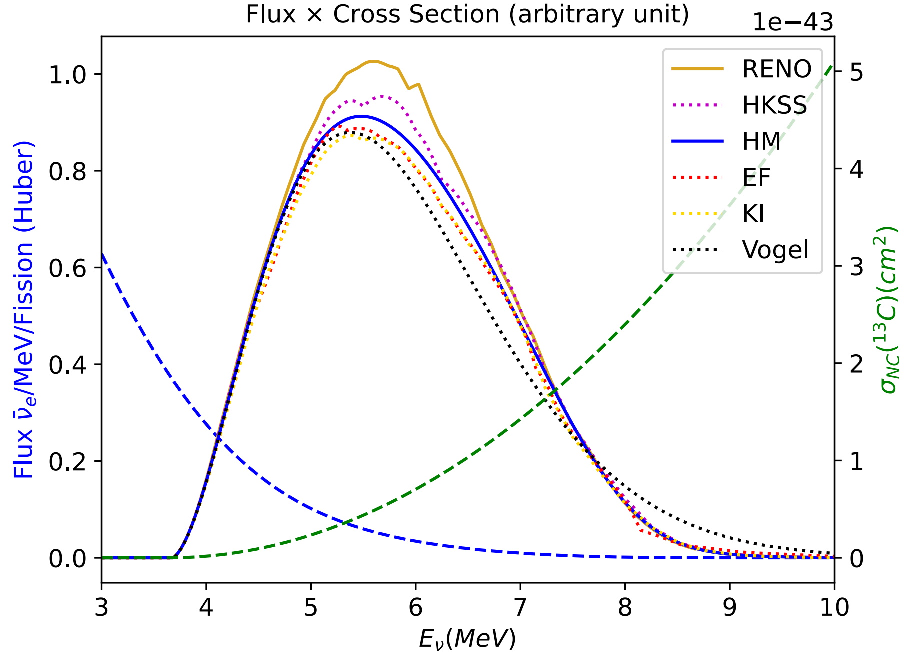
95% of ES, mis-IBD, μ spallation background reduction &
5×10^{-17}g/g ^{232}Th contamination + 80% ^{208}Tl background reduction

Solar ν LS level purity
(level of KamLAND)

Flux Model Comparison

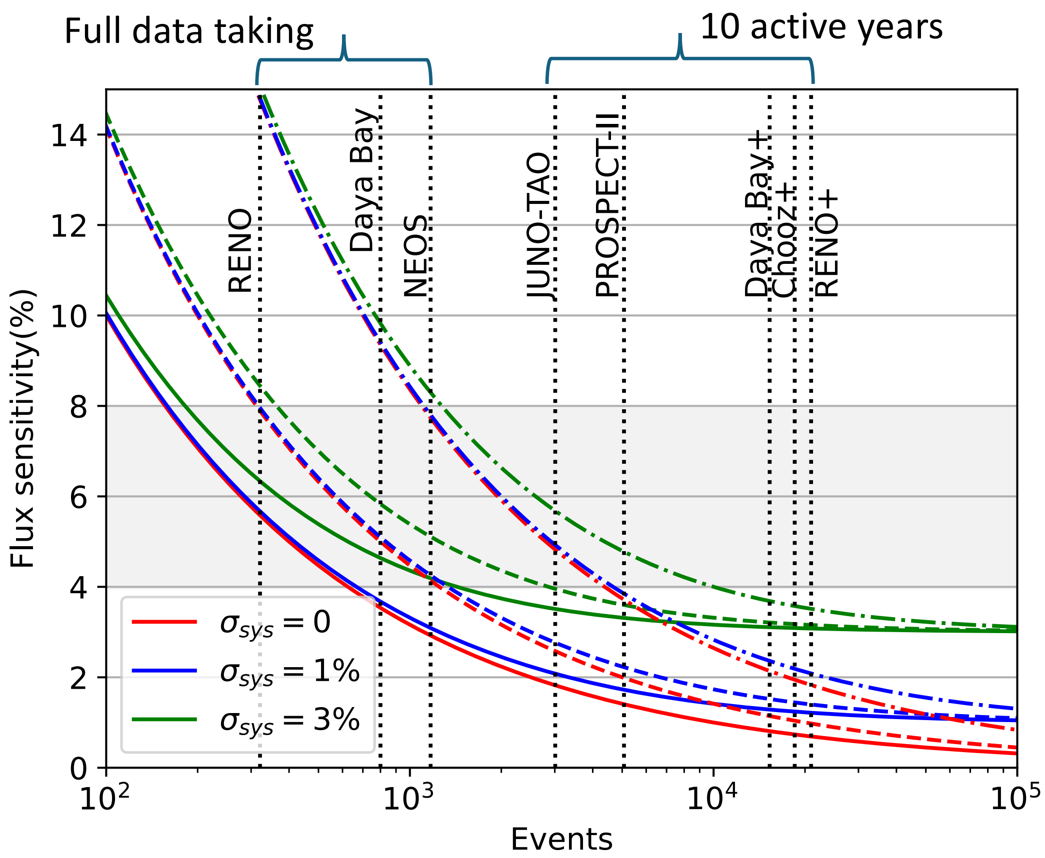
Scenarios
1. **Daya Bay+ (near hall of Daya Bay)**
2. **RENO+ (near hall of RENO)**
3. **Chooz+ (far hall of SuperChooz)**

→ 10 years of data taking



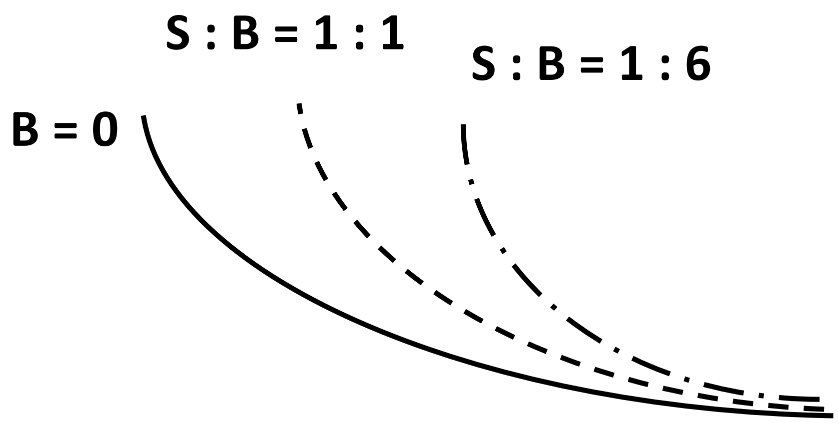
Experiments	Power (GW)	Baseline (m)	Mass (kt)	events	ES+IBD	Muon spallation	^{208}Tl
Daya Bay+ (near hall)	17.4	500	1	1530	460	180	72
RENO+ (near hall)	16.8	420	1	2095	610	900	72
Chooz+ (far hall)	8.4	1000	10	1850	550	900	720

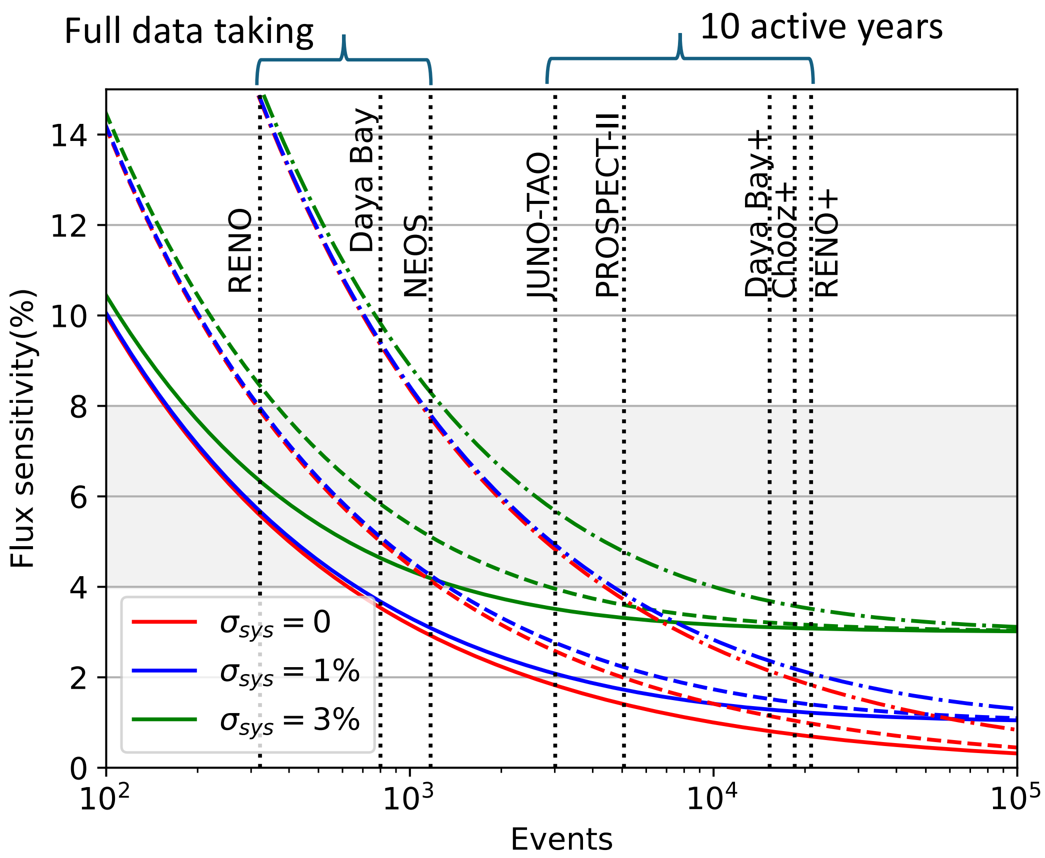
/ active year



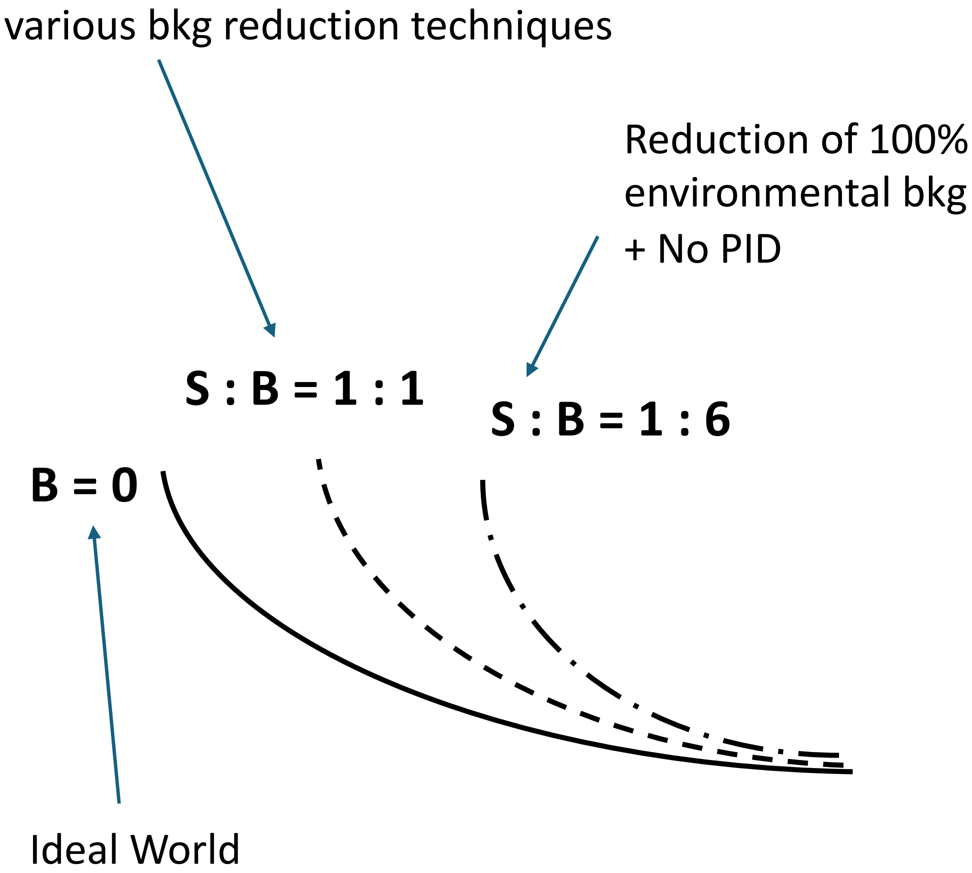
For simplicity, assumed unit signal acceptance

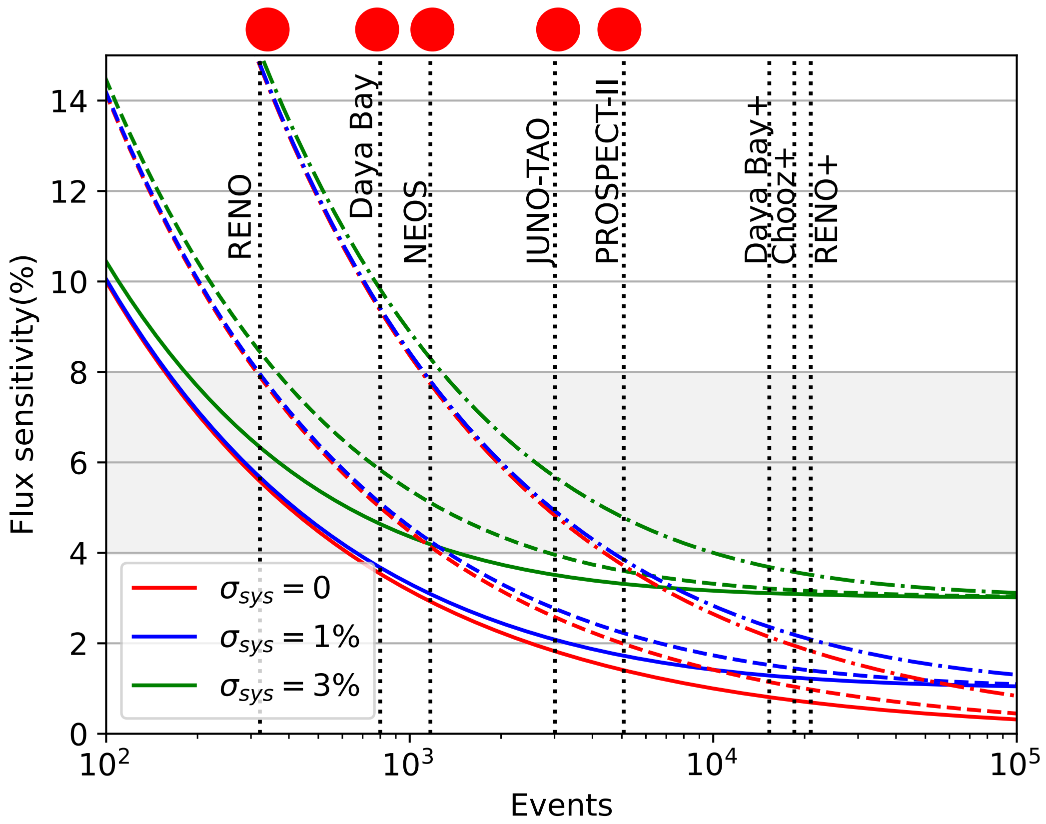
For simplicity, we adopt the three background scenarios:



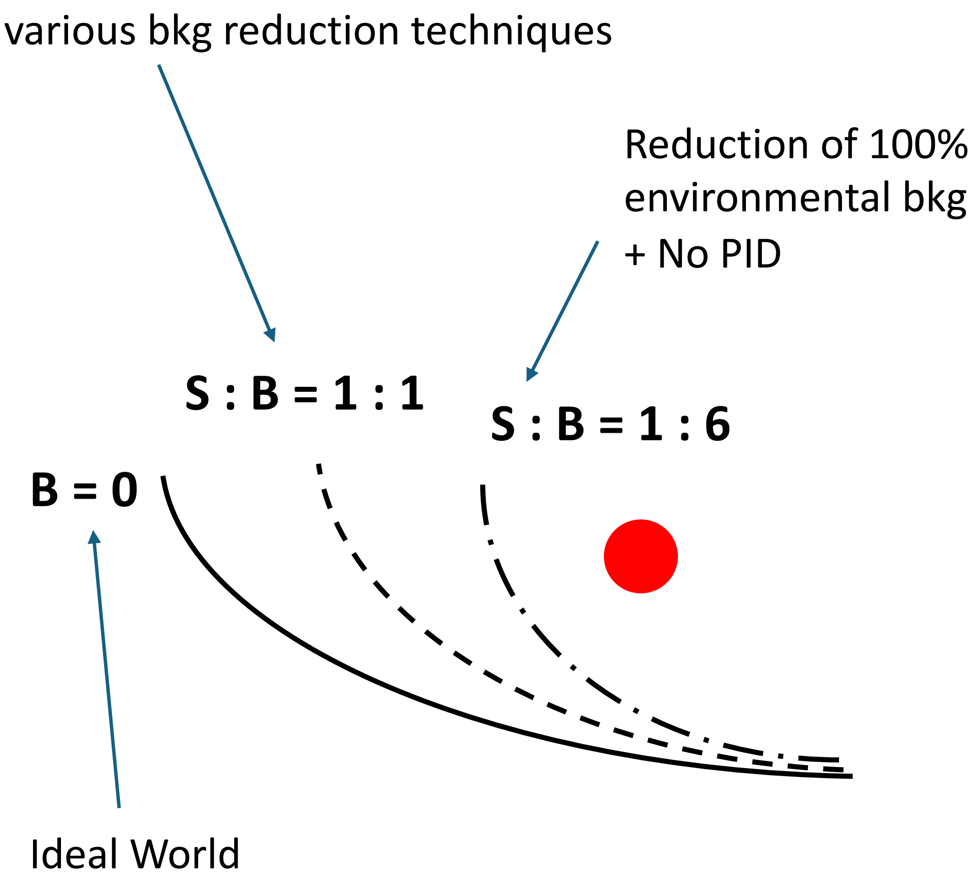


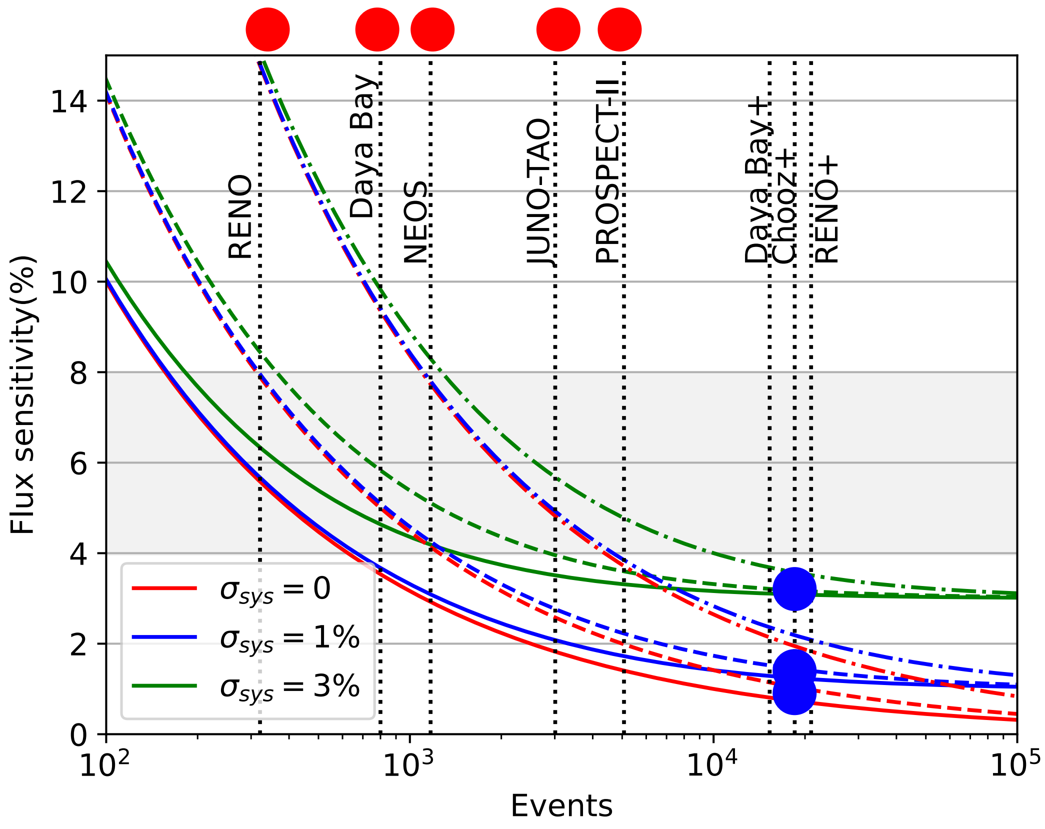
For simplicity, assumed unit signal acceptance



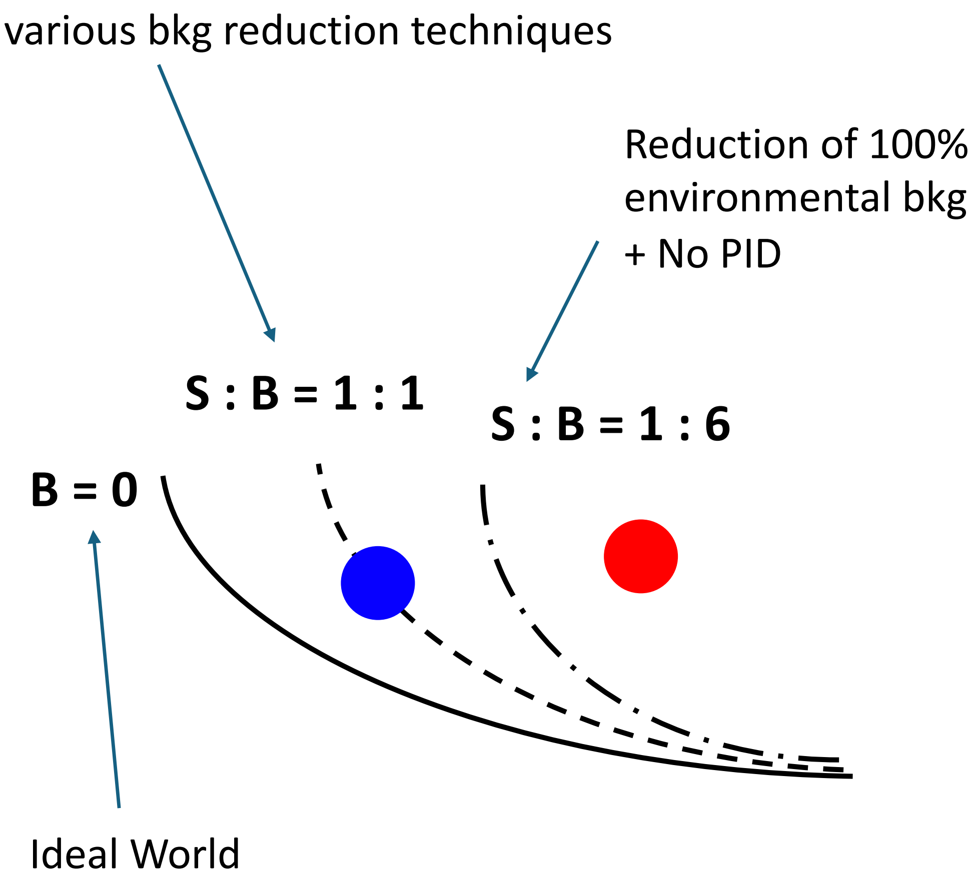


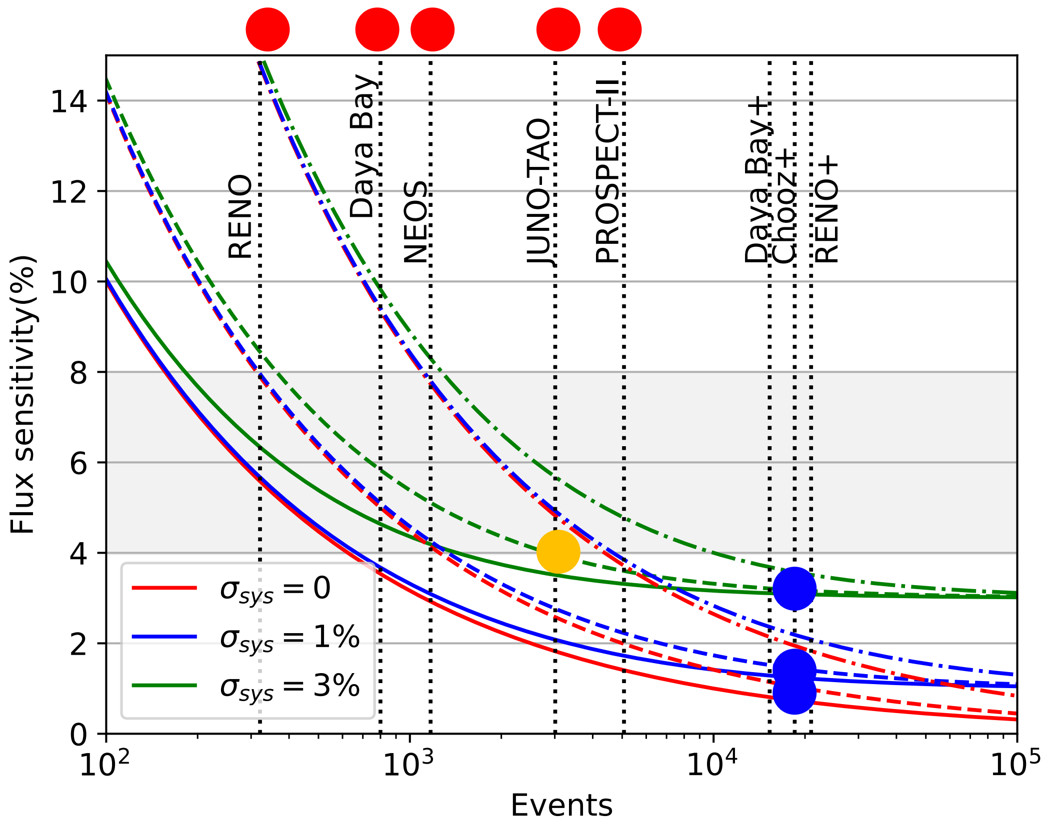
For simplicity, assumed unit signal acceptance



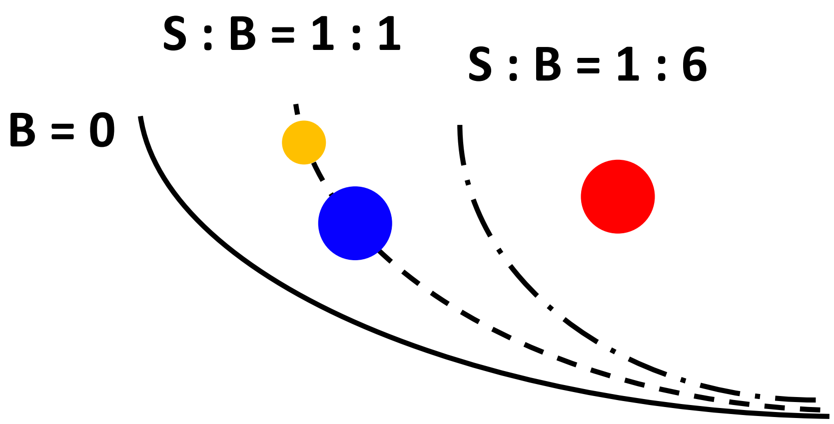


For simplicity, assumed unit signal acceptance





For simplicity, assumed unit signal acceptance

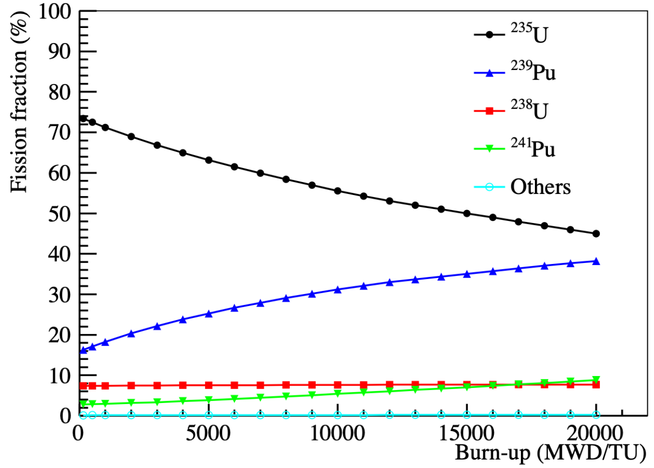


Experiments	events	ES+IBD	Muon spallation	^{208}Tl
RENO+	2095	610	900	72
Daya Bay+	1530	460	180	72
Chooz+	1850	550	900	720

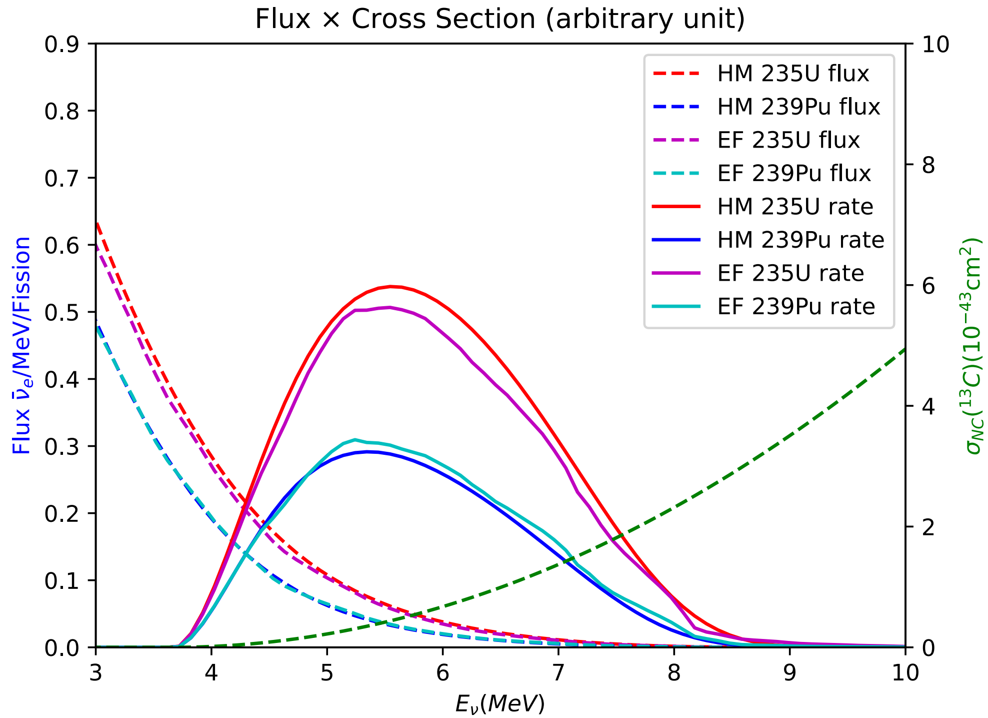
/active year

After 1.5 years data taking of RENO+, we can reach 4% sensitivity

Fuel Evolution

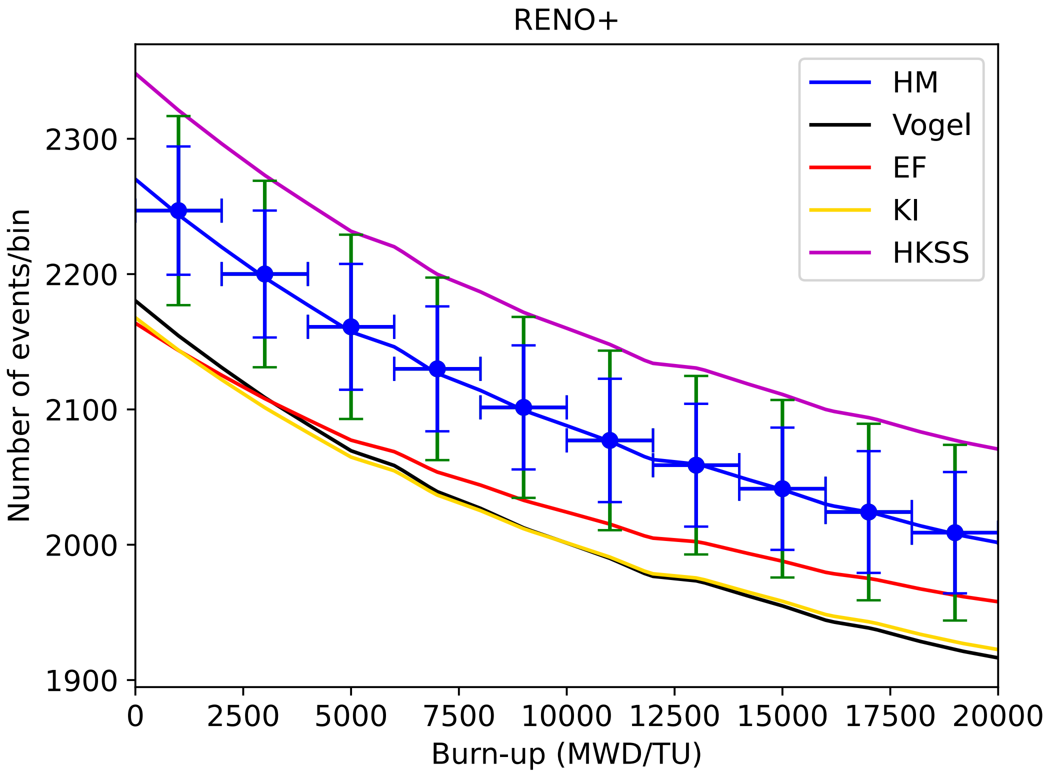


F. P. An et al 2017 Chinese Phys. C 41 013002



$$\frac{\sigma^{HM}_{235U}(\approx 0.72\times 10^{-44}\,cm^2)}{\sigma^{HM}_{239Pu}(\approx 0.37\times 10^{-44}\,cm^2)} \approx 1.93,\quad \frac{\sigma^{EF}_{235U}(\approx 0.67\times 10^{-44}\,cm^2)}{\sigma^{EF}_{239Pu}(\approx 0.39\times 10^{-44}\,cm^2)} \approx 1.70$$

From different $\bar{\nu} - 13C$ yield per fission of different isotopes, we can also observe fuel evolutions with ν-13C NC signals.



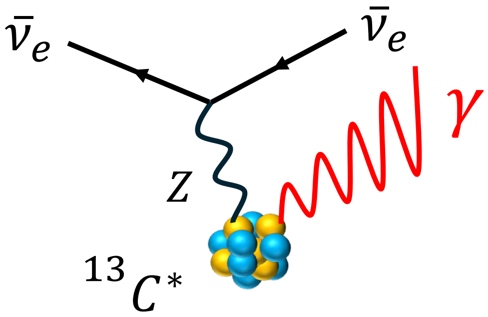
Considering background and 3% (1%) systematics, we can **discriminate models** at

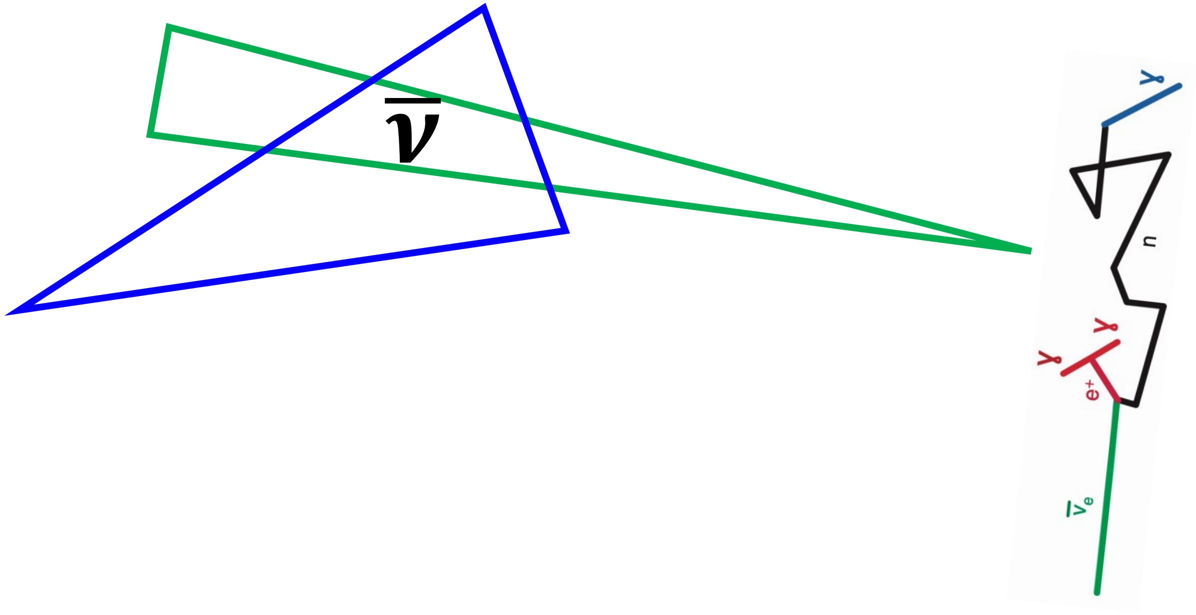
HKSS/KI : 4.5σ (6σ)

HKSS/HM : 2σ (2.5σ)

If we can combine IBD and $\bar{\nu}$-13C neutral current interactions, we can be more accessible to the contribution of the different isotopes to the 5 MeV bump.

Conclusion





$\bar{\nu}$-13C NC interactions can

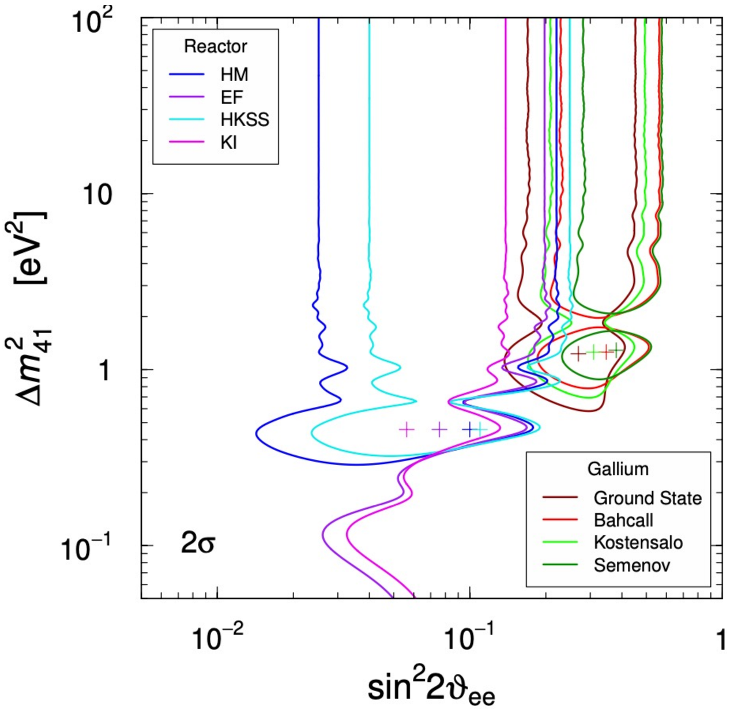
- be complementary channel to **IBD.**
- achieve sensitivity to **distinguish reactor models** with realizable background reduction techniques (PID, LS purity, overburden).
- observe **fuel evolution** and help understanding the contribution of each isotopes.
- be a tool to identifying the origin of the **5 MeV bump**

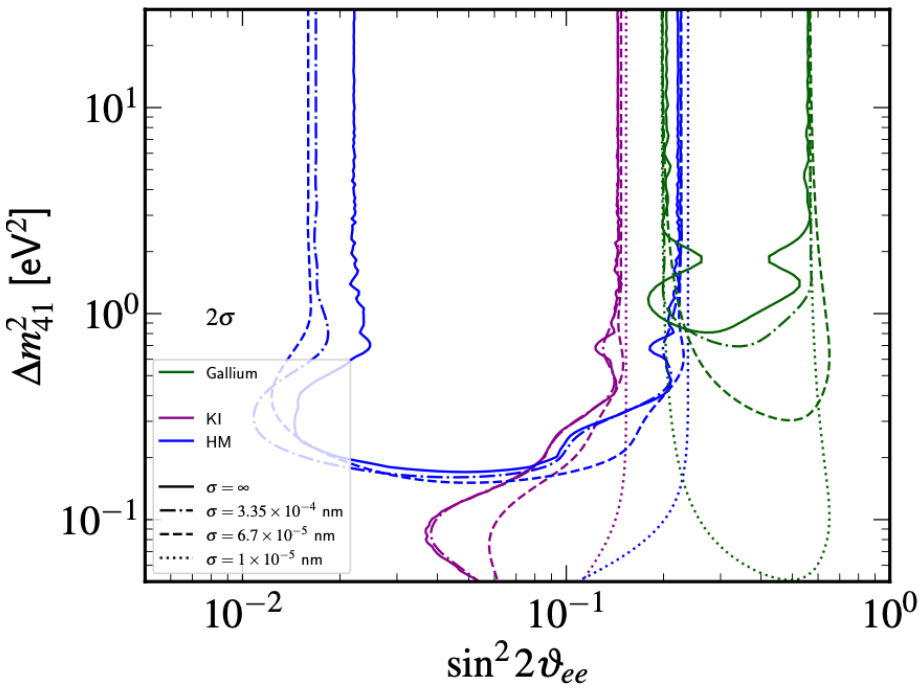
Thank You!

Back up

Reactor Model Dependence of Reactor-Gallium Tension

C. Giunti, Y. F. Li, C. A. Ternes, O. Tyagi, Z. Xin *J. High Energ. Phys.* **2022**, 164 (2022).
C. Giunti, C. A. Ternes. Phys.Lett.B 849 (2024) 138436





3 + 1

G. Mention, M. Fechner, Th. Lasserre, Th. A. Mueller,

D. Lhuillier, M. Cribier, A. Letourneau. Phys. Rev. D 83, 073006

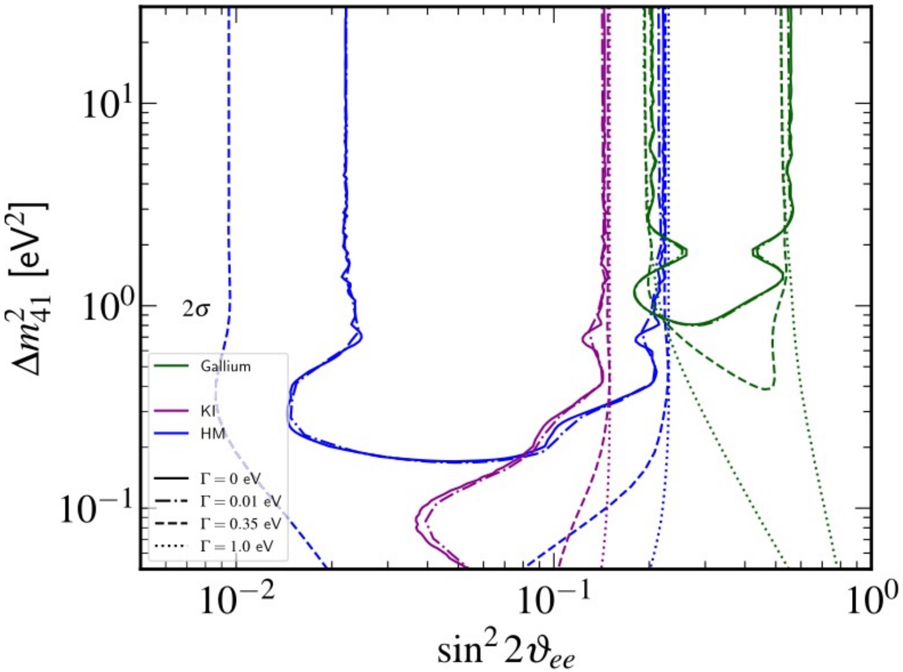
Wave Packet

C. A. Argüelles, T. Bertólez-Martínez, J. Salvado

Phys. Rev. D 107, 036004

Reactor Model Dependence of Reactor-Gallium Tension

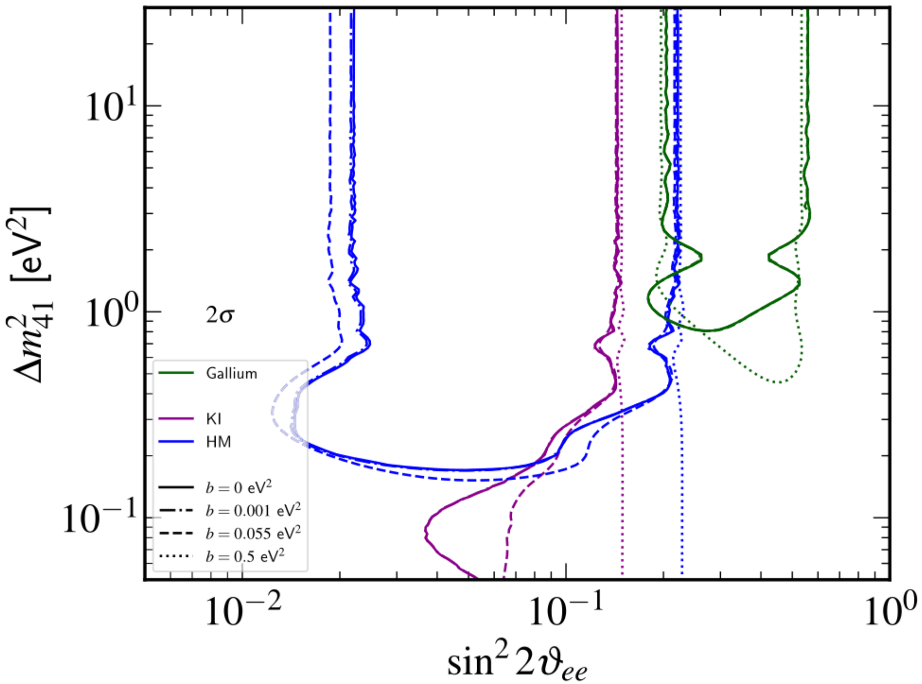
C. Giunti, C. A. Ternes. Phys.Lett.B 849 (2024) 138436



3 + 1 (Decay)

J.M. Hardin, I. Martinez-Soler, A. Diaz, M. Jin, M.W. Kamp, C.A. Arguelles, J.M. Conrad, M.H. Shaevitz.

J. High Energy Phys. 09 (11, 2023) 058



Broad ν_s mass

H. Banks, K.J. Kelly, M. McCullough, T. Zhou

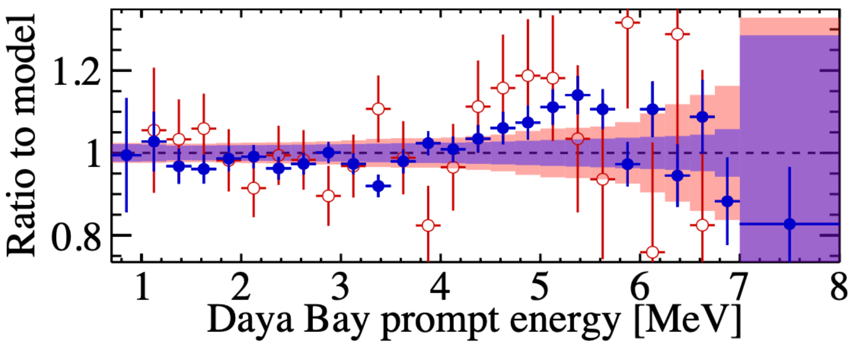
J. High Energy Phys. **2024**, 96 (2024)

New Physics mimicking IBD

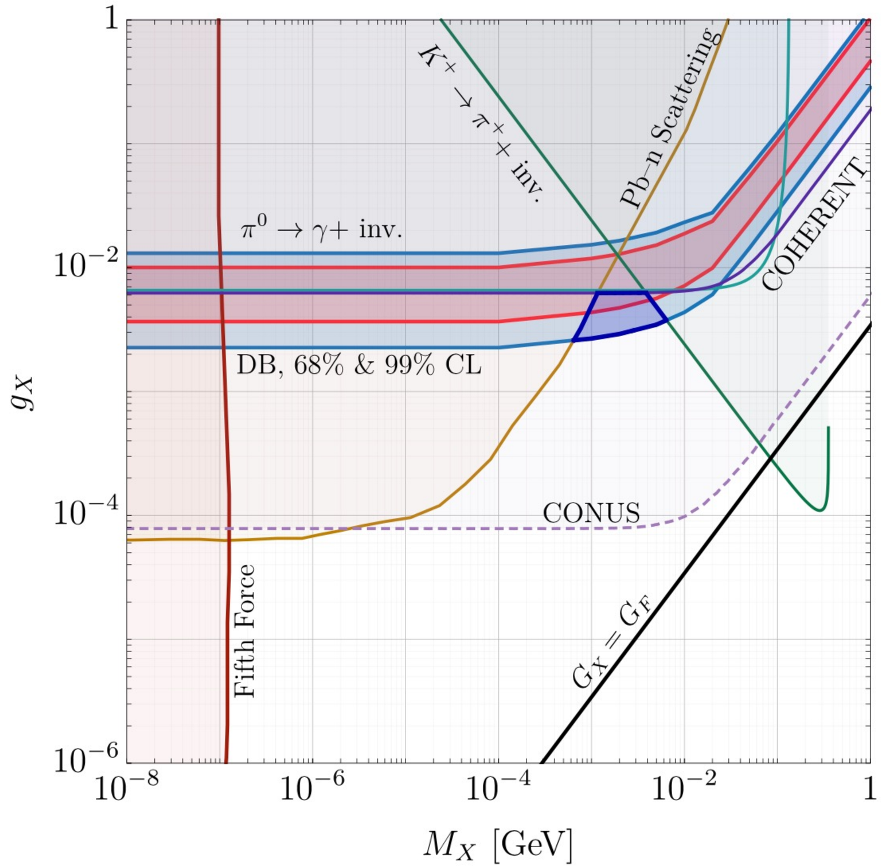
J.M. Berryman, V. Brdar, P. Huber, PHYS. REV. D 99, 055045 (2019)

$$\bar{\nu}_e \xrightarrow{oscillation} \nu_s + {}^{13}C \xrightarrow{\text{NSI}} \nu_s + n + {}^{12}C^* \rightarrow \gamma(4.44\ MeV)$$

Recoil energy deposit to LS

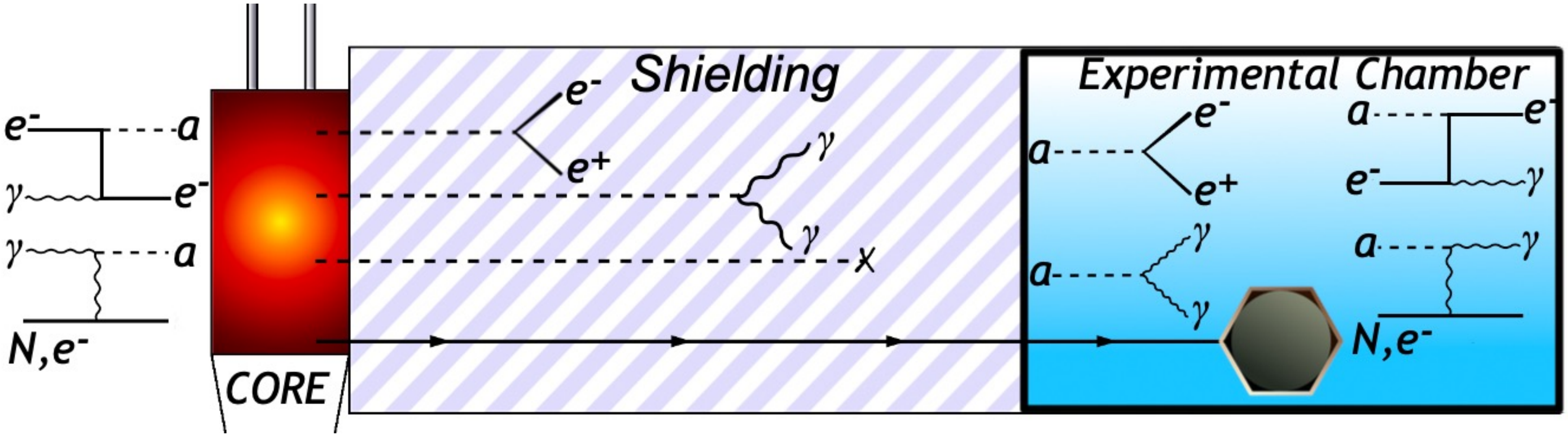


Mimicking IBD is hard…
Can we find other scenarios?



Reactor models as input for BSM searches

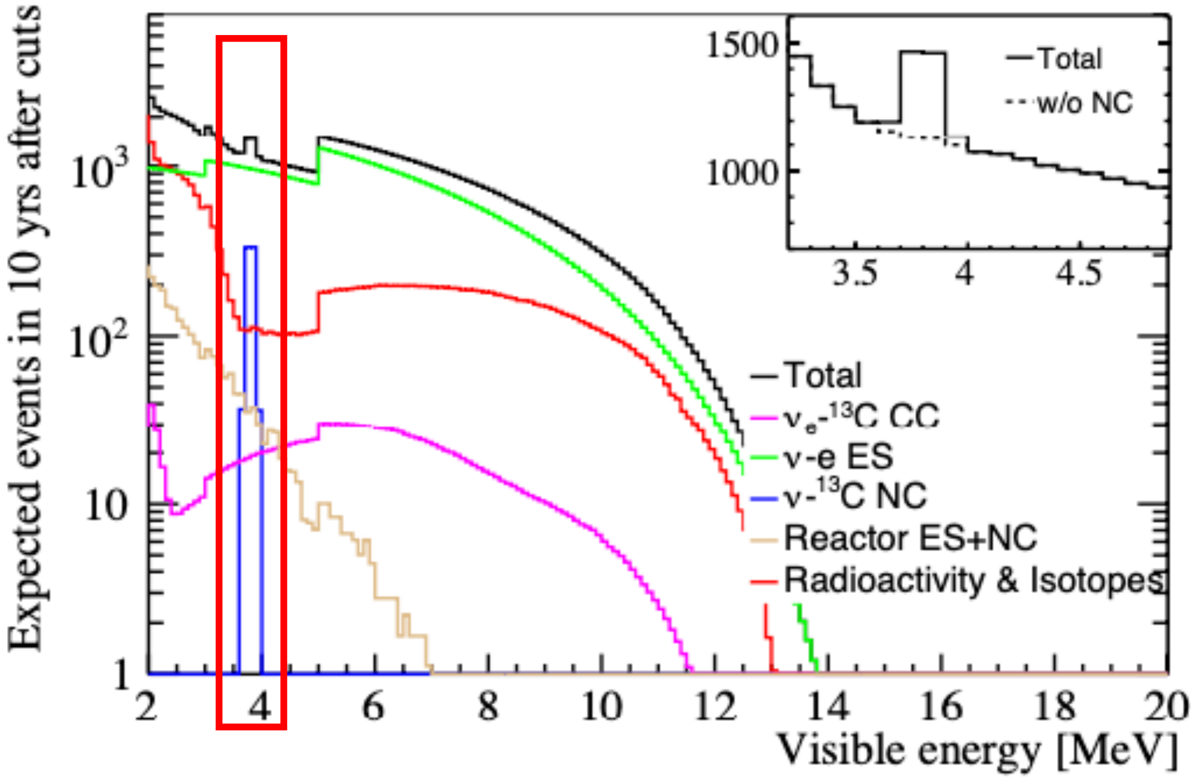
H. K. Park. Phys. Rev. Lett. 119, 081801 (2017)
M. Danilov, S. Demidov, D. Gorbunov. Phys. Rev. Lett. 122, 041801 (2019)
J. B. Dent, B. Dutta, D. Kim, S. Liao, R. Mahapatra, K. Sinha, and A. Thompson. Phys. Rev. Lett. 124, 211804 (2020)
D. Aristizabal Sierra, V. De Romeri, L. J. Flores, D. K. Papoulias. J. High Energ. Phys. 2021, 294 (2021)
F. Arias-Aragón, V. Brdar, and J. Quevillon. Phys. Rev. Lett. 132, 211802 (2024)

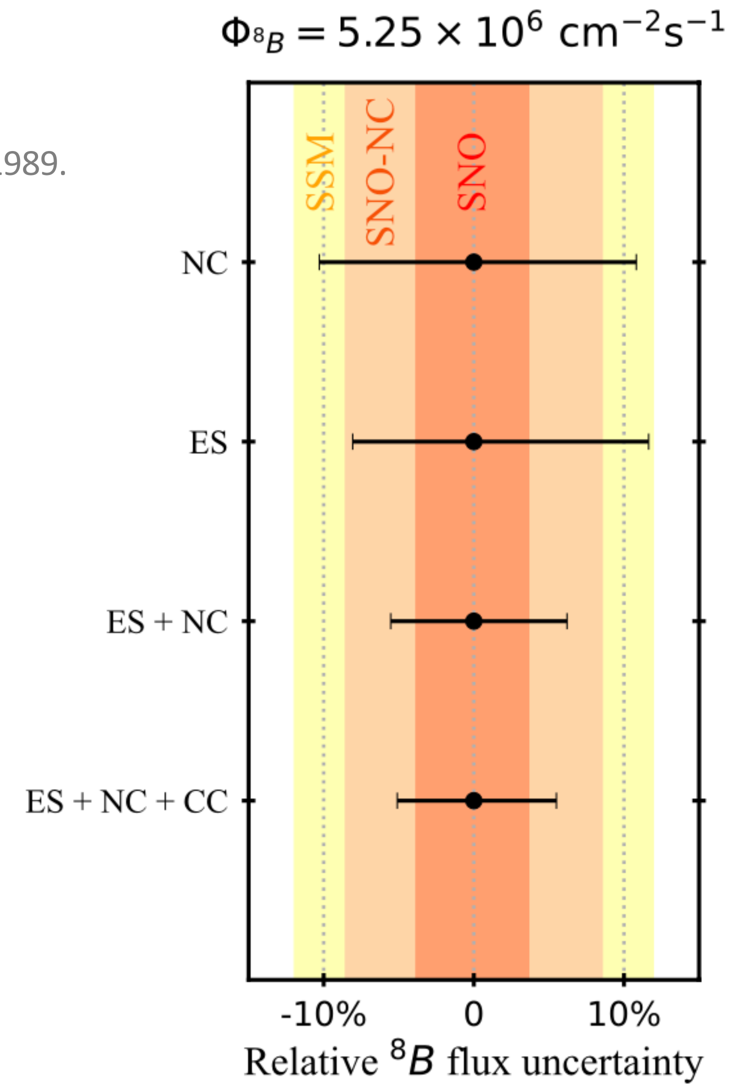


We are not in the precision era of such scenarios...
But better understanding of reactor can be important if we detect something.

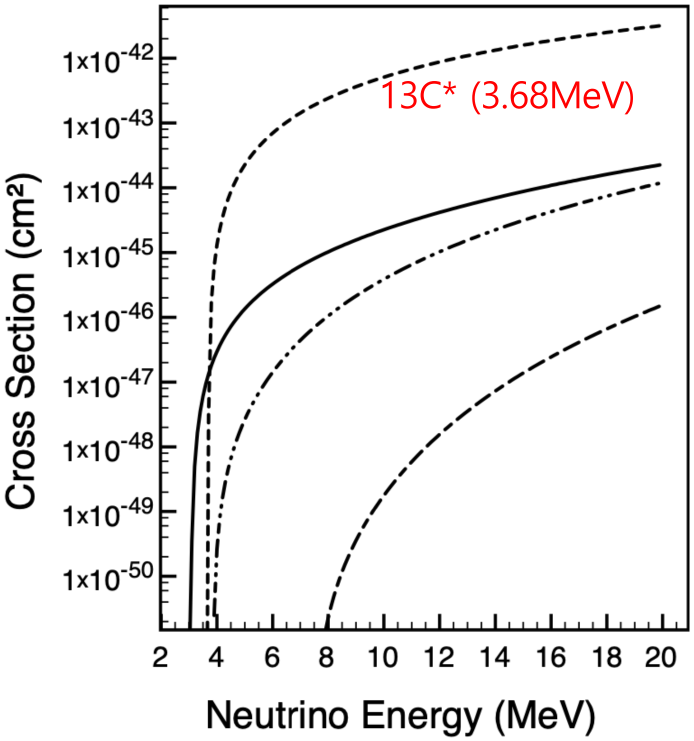
13C as a Solar ν Detector

J. Arafune, M. Fukugita, Y. Kohyama, K. Kubodera, Physics Letters B, Volume 217, Issues 1–2, 1989.
A. Ianni, D. Montanino, F.L. Villante, Physics Letters B, Volume 627, Issues 1-4, 2005.
J. Zhao *et al*, 2024 *ApJ* 965 122 ← **JUNO**





ν-13C Neutral Current Cross Section



M. Fukugita, Y. Kohyama, K. Kubodera, and T. Kuramoto, Phys. Rev. C 41, 1359 (1990)
M. Pourkaviani and S. L. Mintz, J. Phys. G G 17, 1139 (1991)
S. L. Mintz, Nucl. Phys. A 672, 503 (2000).
T. Suzuki, A. B. Balantekin, and T. Kajino, Phys. Rev. C 86, 015502 (2012).

$$\sigma = [a_1(E_\nu - Q) + a_2(E_\nu - Q)^2 + a_3(E_\nu - Q)^3]\times 10^{-44}\ cm^2$$

$13C\ (\bar{\nu}, \bar{\nu}')\ 13C^*$ ***Q***

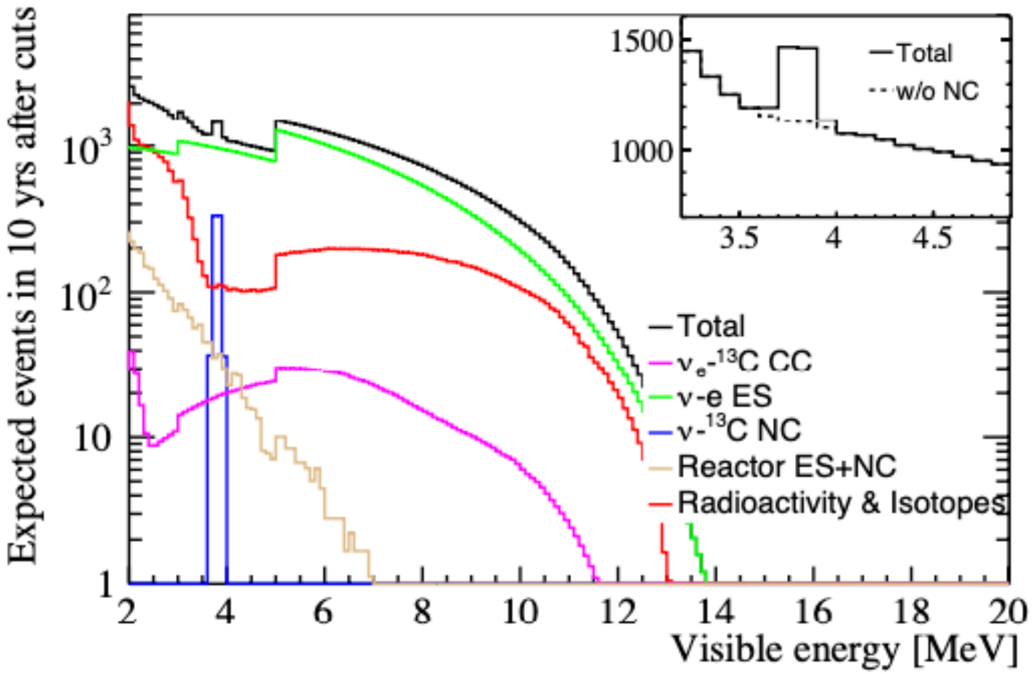
State	E_x (MeV)	a_1 (MeV^{-1})	a_2 (MeV^{-2})	a_3 (MeV^{-3})
$1/2^+$	3.089	6.80×10^{-3}	8.80×10^{-4}	4.00×10^{-4}
$3/2^-$	3.685	0.122	1.26	0
$5/2^+$	3.854	9.83×10^{-3}	-3.38×10^{-3}	4.54×10^{-4}
$5/2^-$	7.547	0.596	-0.56	0.1

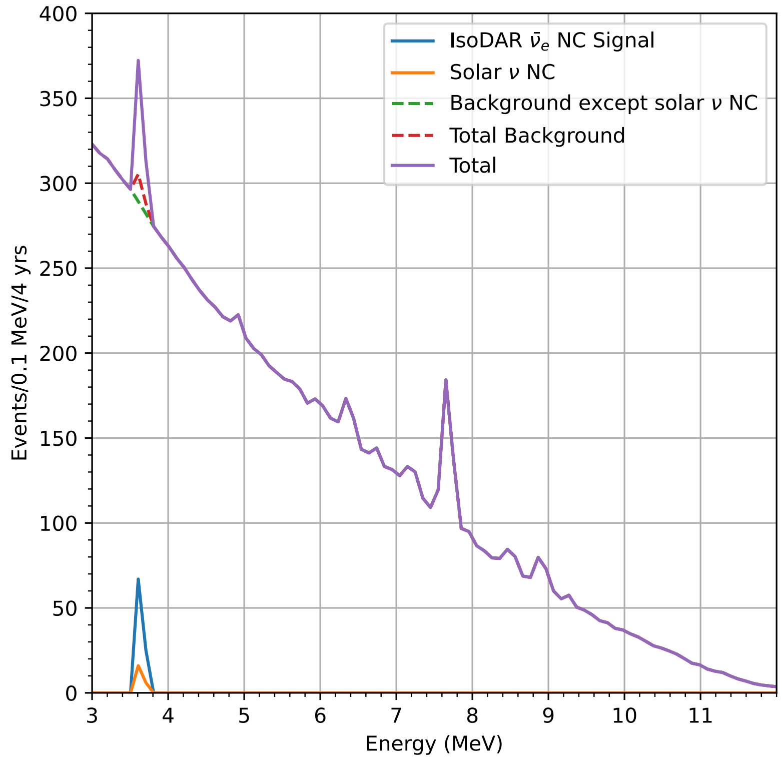
$13C\ (\nu, \nu')\ 13C^*$

$3/2^-$	3.685	0.123	1.28	7.56×10^{-3}

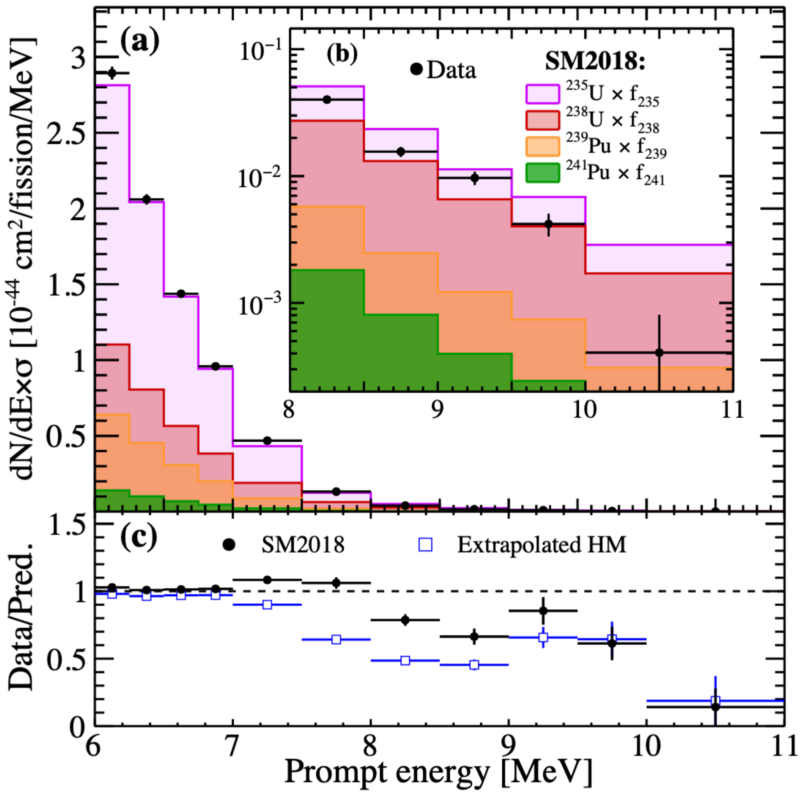
ν-13C Neutral Current Cross Section

B. R. Barrett, P. Navratil, and J. P. Vary, Prog. Part. Nucl. Phys. 69, 131 (2013). ← Ab initio no core shell model calculation
J. Zhao *et al*, 2024 *ApJ* 965 122 ← JUNO
J. Alonso et al. – Neutrino Physics Opportunities with the IsoDAR Source at Yemilab (2111.09480) ← IsoDAR

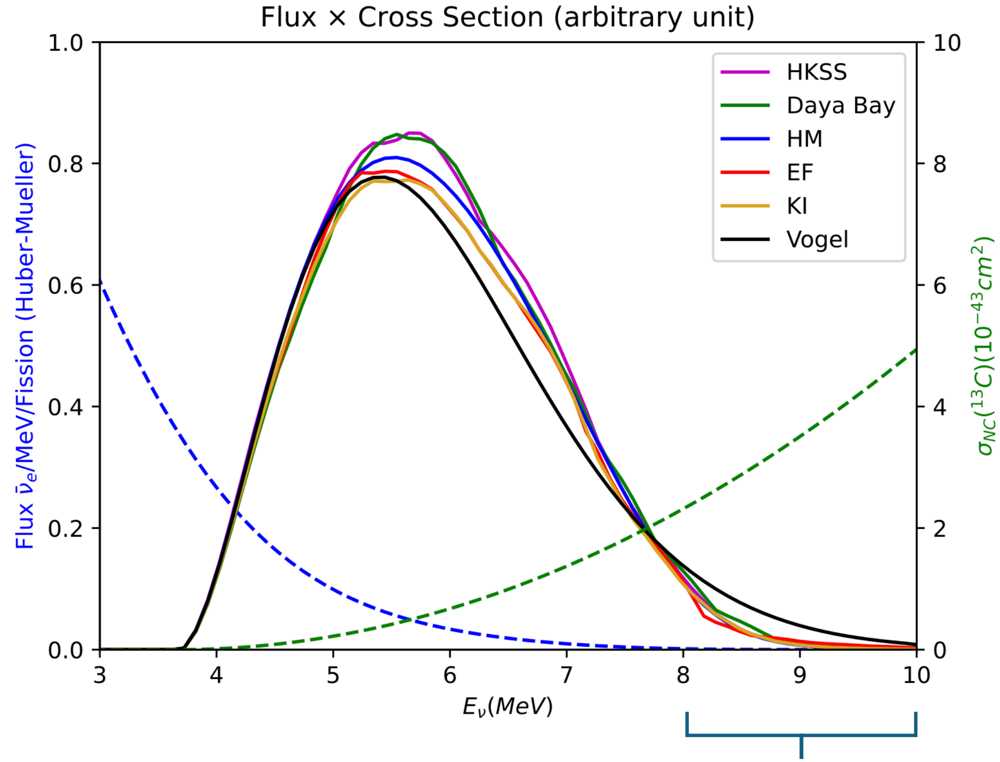




High energy $\bar{\nu}_e$



F. P. An et al. (Daya Bay Collaboration)
Phys. Rev. Lett. 129, 041801



< 2%

In 8~10 MeV region, we assumed extrapolated HM for HKSS and KI.
Inclusion of 8~10 MeV region did not change event rate ratios between flux models much.

Assumptions on Backgrounds

ROI $= 3.685 \pm 0.1\ MeV$ (FWHM for 5% $/\sqrt{E(MeV)}$ resolution)

J. M. Conrad, J. M. Link, and M. H. Shaevitz, Phys. Rev. D 71, 073013 → on reactor $\bar{\nu}$ single-flash ES signals in 3~5 MeV

Backgrounds for the single-flash 3.685 MeV gamma

After 99.9% rejection with additional fiducial volume cut

- **ES + mis-IBD : ~6 times of signals -> helped by β/γ discrimination (PID)**
- **Internal radiation (208Tl decay) -> high purity of LS + 232Th chain tagging**
- **Cosmic muon spallation -> overburden (300m.w.e.), muon veto, fiducial volume cut**
- **External radiation -> fiducial volume cut**

- **Solar ν events : if $\frac{Power(GW)}{(Baseline(km))^2} \ll 1$**

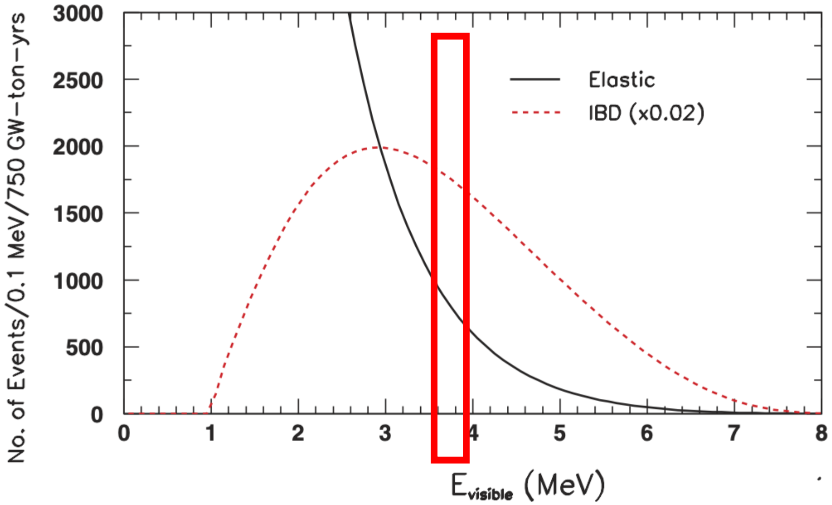
↪ **JUNO : Solar ν-13C detector**

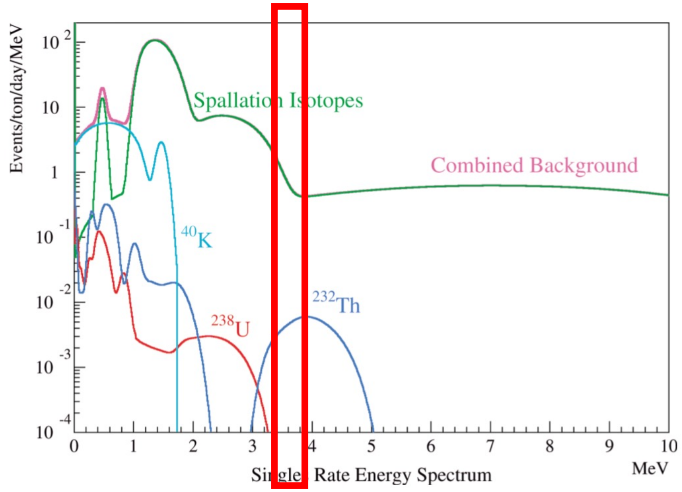
Reactor $\bar{\nu}NC \approx 22\times \frac{Power(GW)\cdot kt\cdot year}{(Baseline(km))^2}$

Solar $\nu NC \approx 15\ kt\cdot year$

Assumptions on Backgrounds

J. M. Conrad, J. M. Link, and M. H. Shaevitz, Phys. Rev. D 71, 073013 → on reactor $\bar{\nu}$ single-flash ES signals in 3~5 MeV

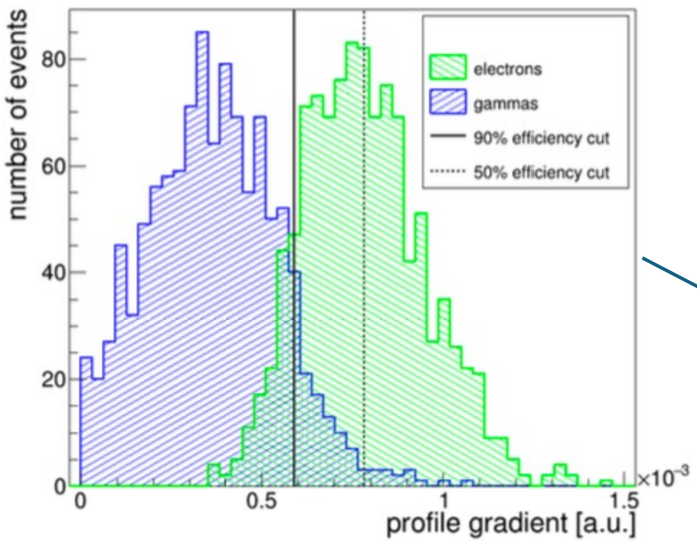




Assumption
: ~ 300 m.w.e. overburden, 5×10^{-17}g/g 232Th contamination
→
~540 times IBD and ~5.5 times ES to 13C NC signals,
1 208Tl events / kt·day, 5 spallation events / kt·day

Particle Identification (TR)

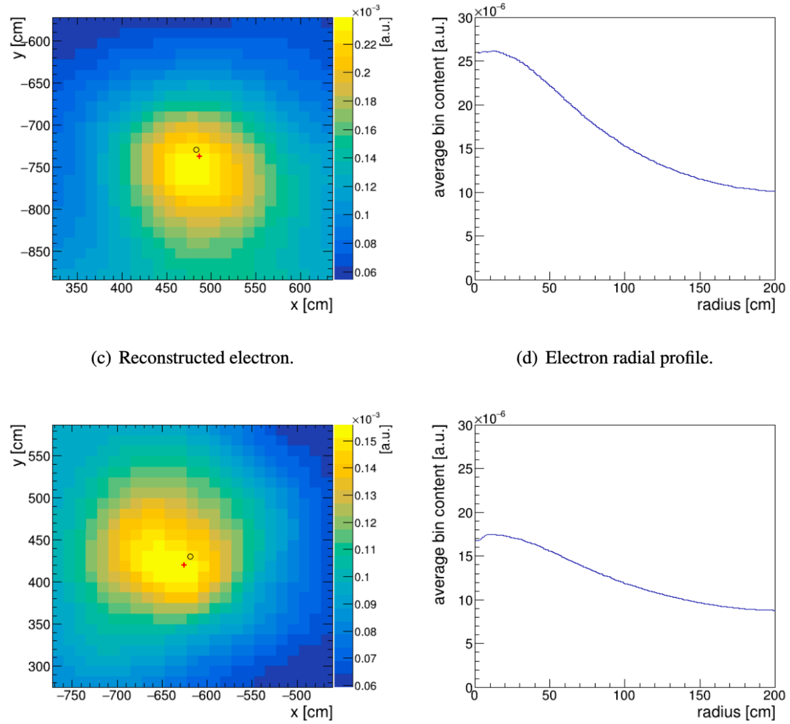
H. Rebber *et al*, 2021 *JINST* **16** P01016
H. Rebber, PhD thesis, University of Hamburg, 11 2019.



(c) TR

for 1.25 – 1.75 MeV

Expecting better efficiency
for **higher energies**!

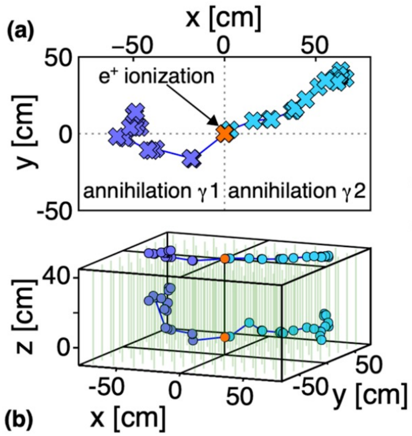


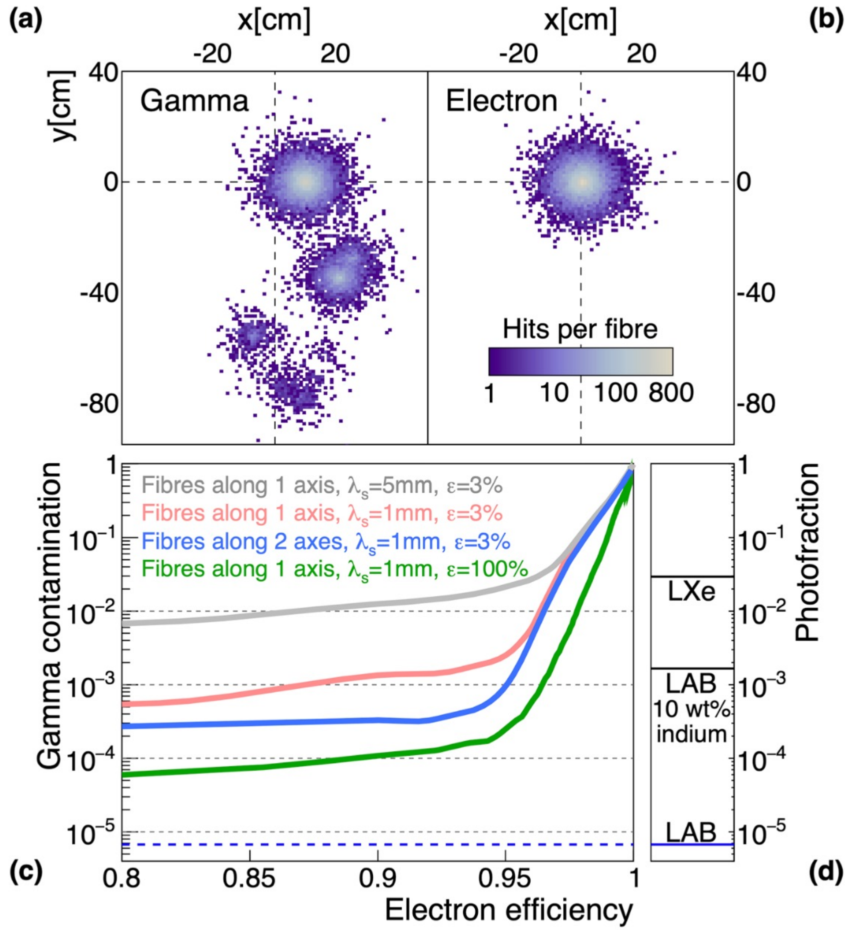
(c) Reconstructed electron. (d) Electron radial profile.
(e) Reconstructed gamma. (f) Gamma radial profile.

Topological Reconstruction
@JUNO

Particle Identification (LiquidO)

LiquidO Consortium. Neutrino physics with an opaque detector. Commun Phys 4, 273 (2021).





LiquidO (opaque LS + optical fiber)
@Super Chooz

232Th chain tagging

Takahiko Hachiya and for the KamLAND Collaboration
2020 J. Phys.: Conf. Ser. 1468 012257

$^{220}Rn + ^{216}Po$ tagging :
80% reduction of ^{208}Tl

KamLAND
firstly tag prompt coincidence (PC) of 220Rn–216Po
+ search for associated 212Bi–212Po pair decay or 208Tl decay
within ~2 day from PC.

Angel Abusleme *et al* 2021 *Chinese Phys. C* **45** 023004

$212Bi$ tagging :
99% reduction of ^{208}Tl

JUNO
With a 22 minutes veto in a spherical volume of radius 1.1 m
around a 212Bi α candidate, 99% 208Tl decays can be removed.