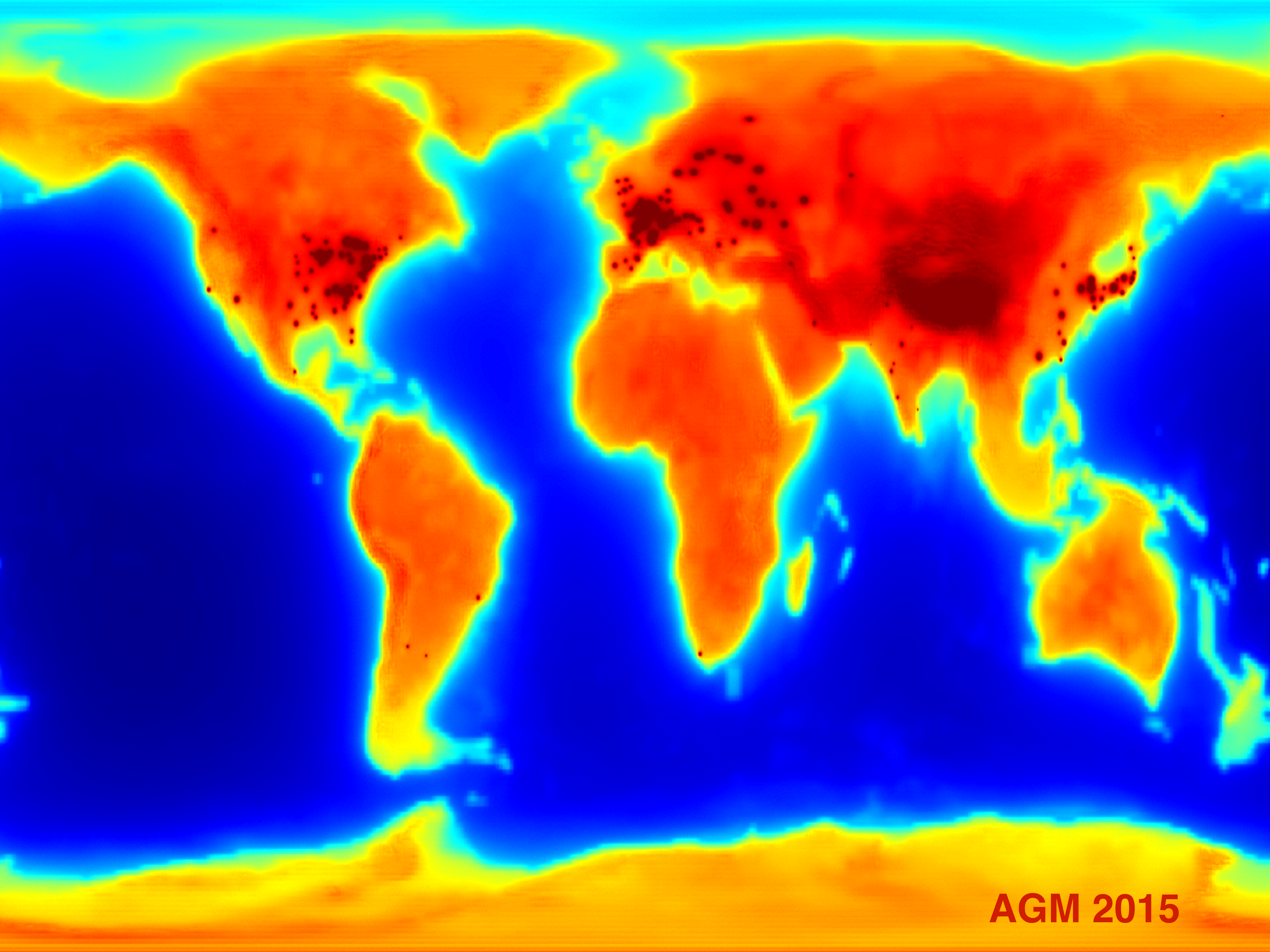
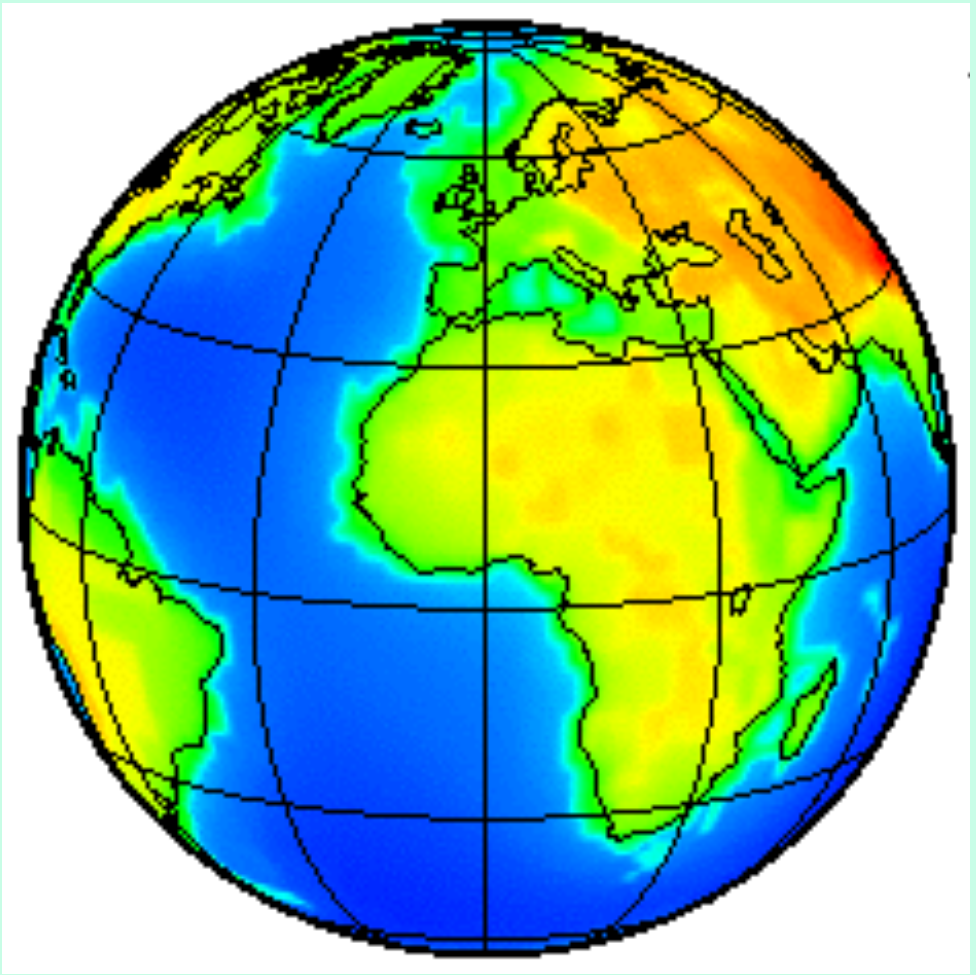
Neutrino geoscience and reactor monitoring with direction-sensitive detectors

Michael Leyton*,
Stephen Dye, Jocelyn Monroe

Dec. 2, 2016

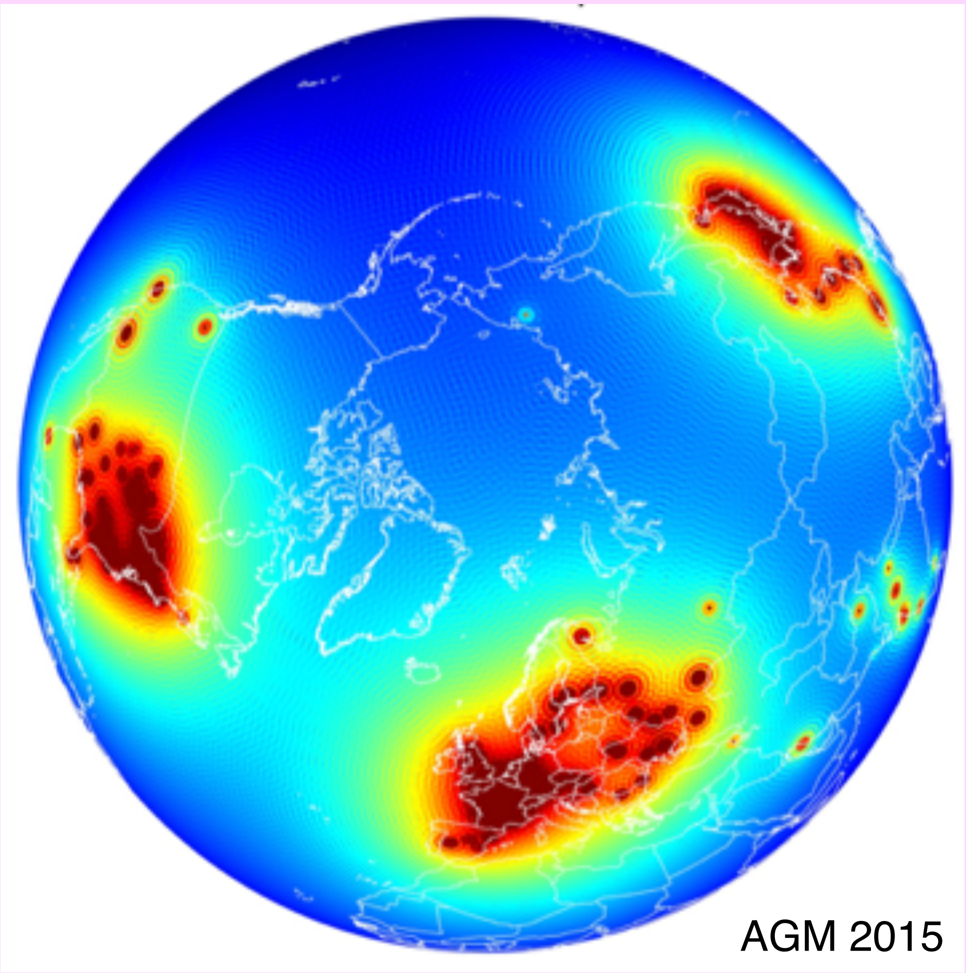

AGM 2015

Geo-ν's



- Produced by β^- decays of radiogenic isotopes in the Earth's crust and mantle (U, Th and K)
- Generate 15±10 TW of radiogenic heating (17-64% of Earth's total heat flow)

Reactor ν's



- Produced by man-made nuclear reactors
- 1-4% of Earth's total ν luminosity
- 439 reactor cores generating 870 GW_{th}

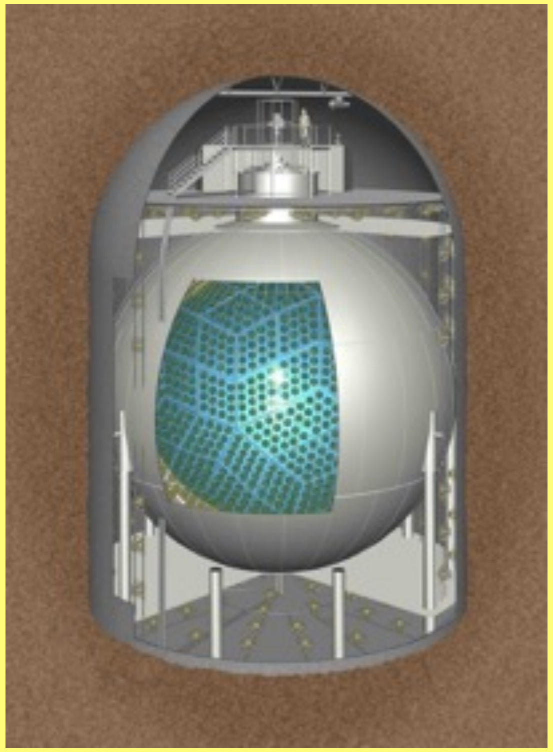
Geo-ν's give us clues about:

- composition of the Earth's interior
- size and sources of radiogenic heat flow
- origin, formation and thermal evolution of our planet
- ‘missing’ source of heat for geo-dynamo

Geo-ν measurements

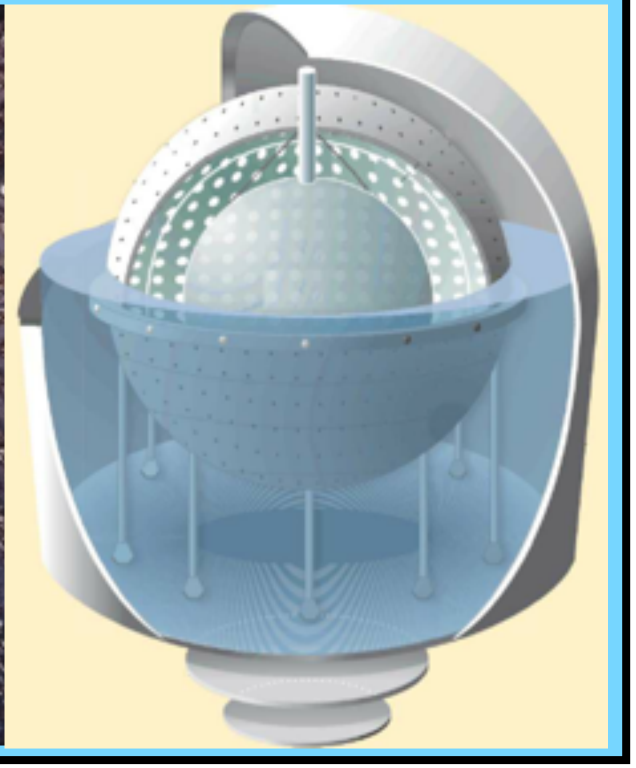
KamLAND, Kamioka, Japan

- 1 kt LS, 1800 PMTs, 34% solid angle
- First observation in 2005 (2 kt-yrs)
- Followed by publications in 2011 (5.8 kt-yrs) and 2013 (6.9 kt-yrs)
- $\langle P_{ee} \rangle = 0.551 \pm 0.015$
- $\Phi(U+Th) = 3.4 \pm 0.08 \times 10^6$ /cm²/s
- 116^{+28}_{-27} geo-ν events



Borexino, LNGS, Italy

- 0.278 kt LS, 2200 PMTs, 30% solid angle
- Most recent paper from 2015 (1.6 kt-yrs)
- $\Phi(U+Th) = 5.0 \pm 1.3 \times 10^6$ /cm²/s
- $23.7^{+6.6}_{-5.7}$ geo-ν events



Geo-ν measurements

✔ Total of 140 ^{238}U, ^{232}Th geo-ν events …

✘ but no ^{40}K geo-ν events

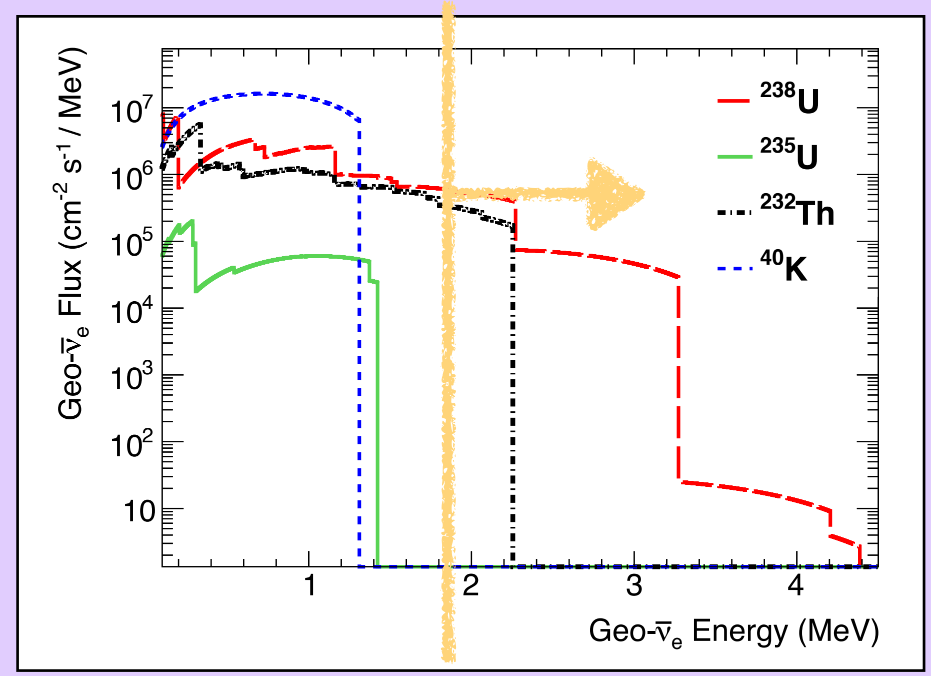
✔ Rate and energy measured …

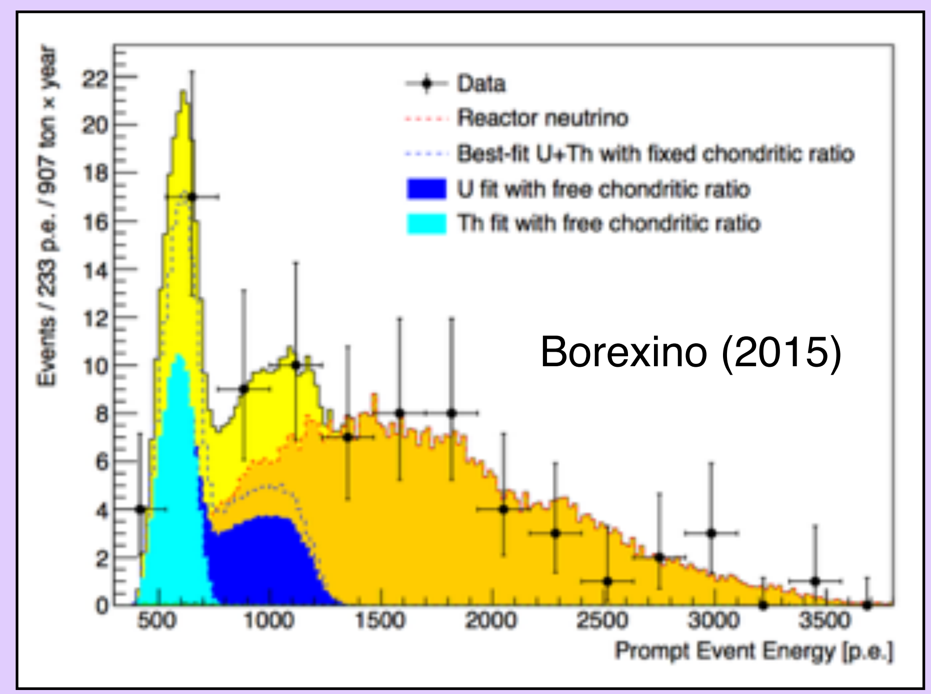
✘ but not direction

✔ Measured signals are consistent …

✘ but large uncertainties (±20-25%)

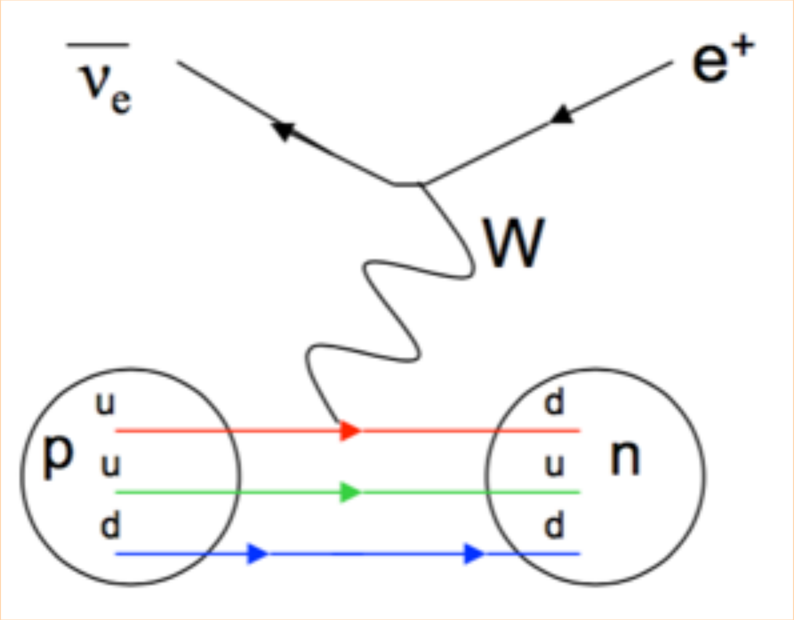
➜ Model-dependent assumptions required for interpreting results





Inverse beta decay

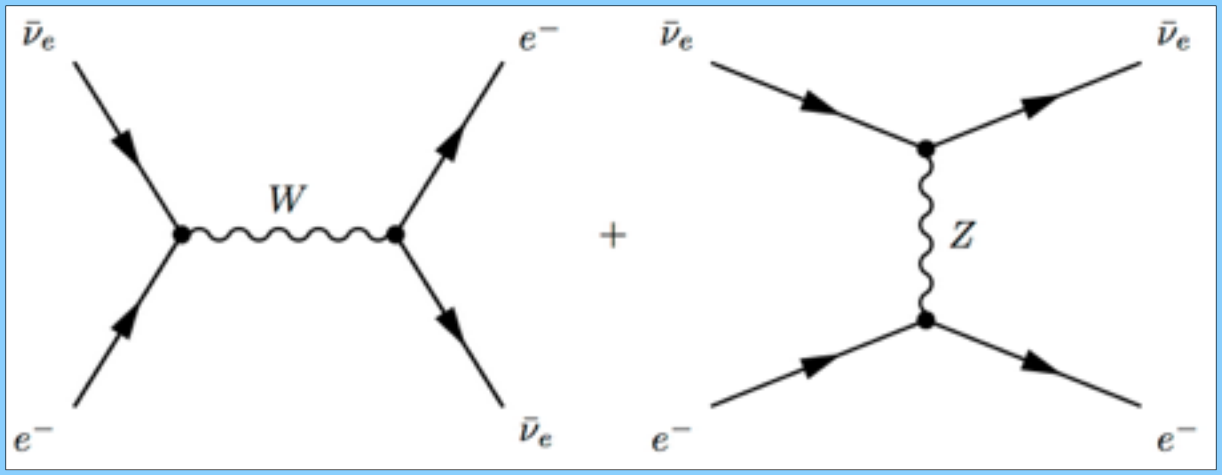
$$\overline{\nu}_e + p^+ \rightarrow e^+ + n$$



- Proton target, $E_{thresh} \approx 1.8$ MeV
- $\sigma(E_\nu) \approx 9.5\text{x}10^{-44} (E_\nu - 1.3 \text{ MeV})^2 \text{ cm}^2$
- No directional information on event-by-event basis

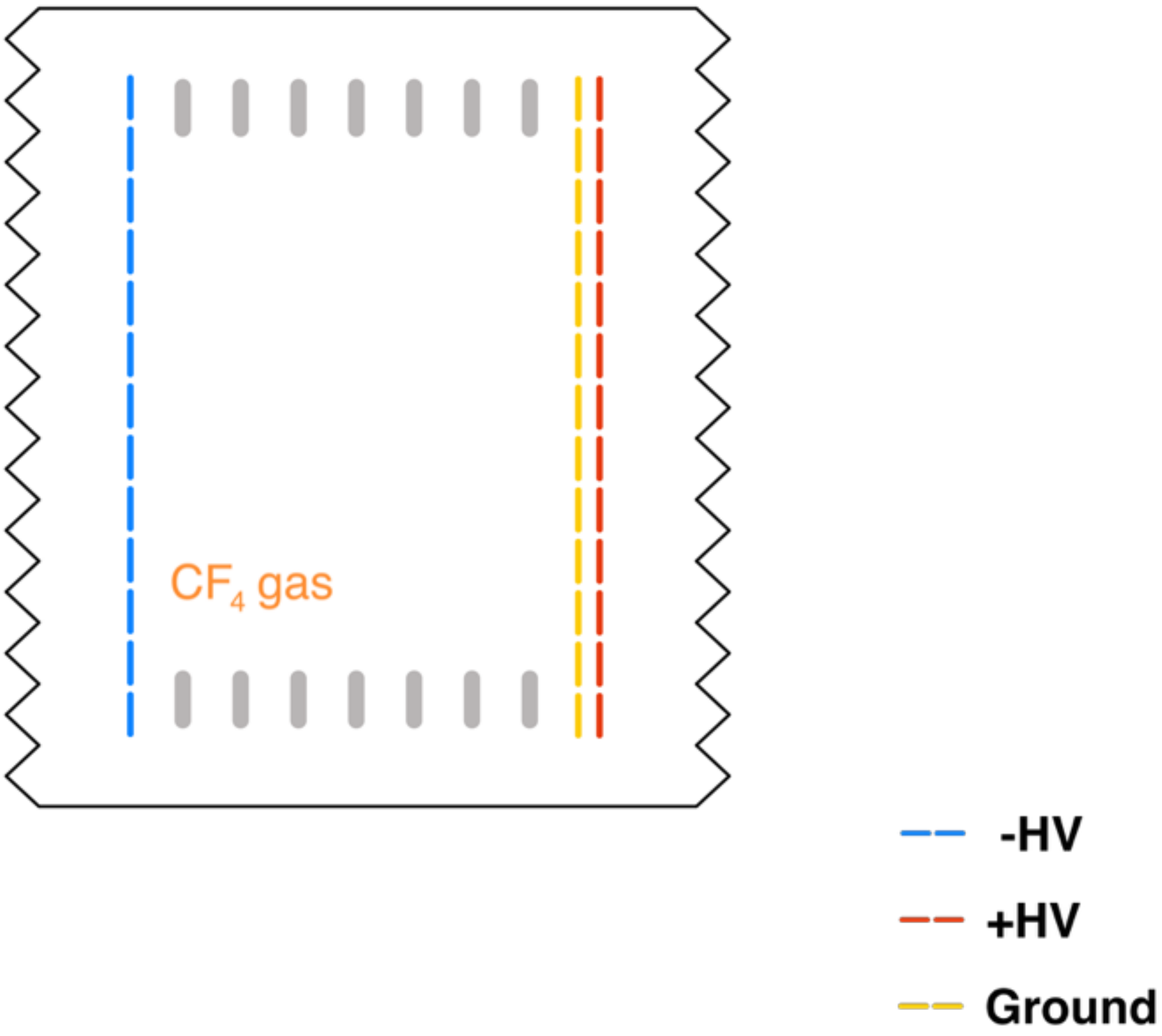
Elastic scattering

$$\overline{\nu}_e + e^- \rightarrow \overline{\nu}_e + e^-$$

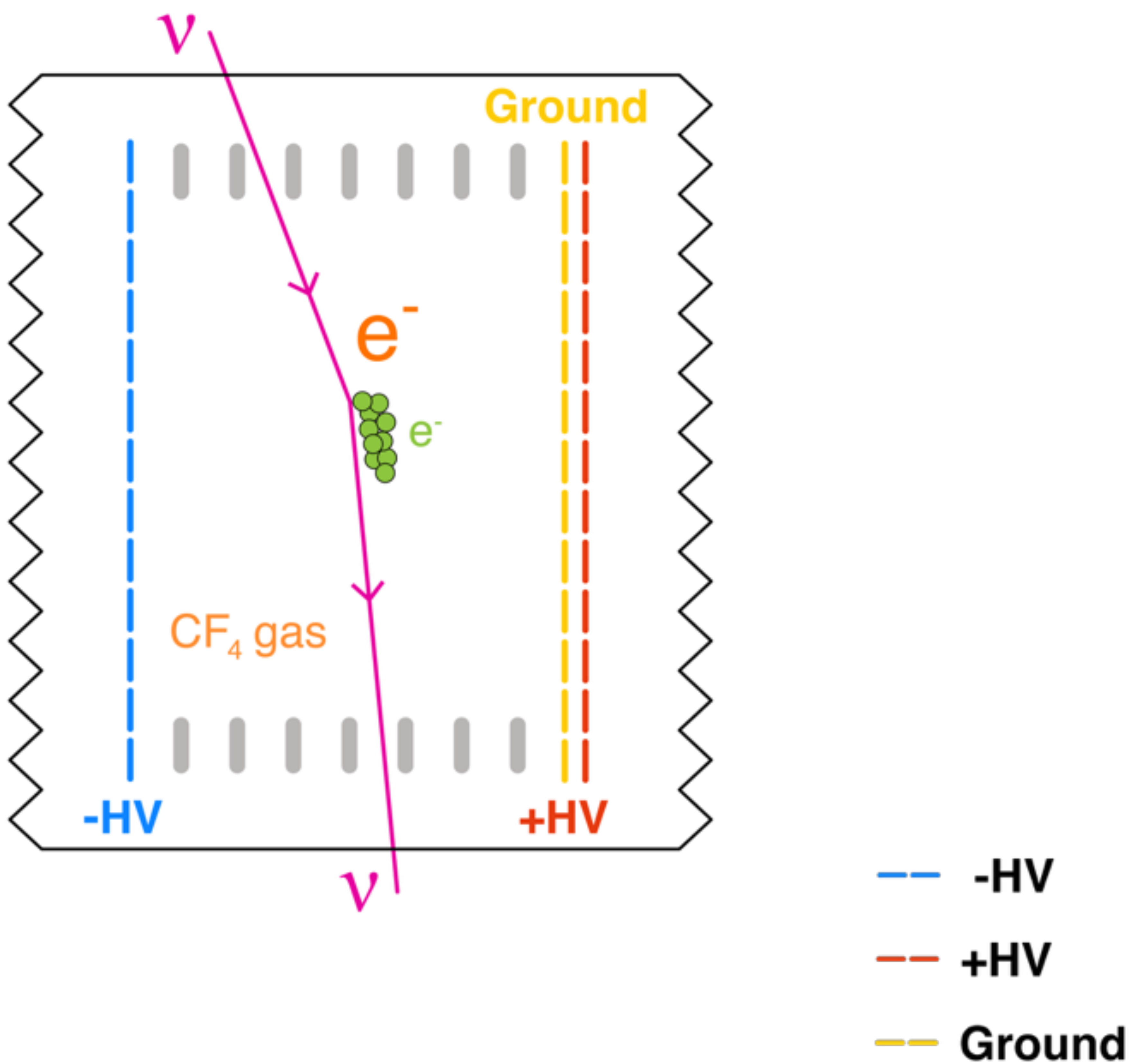


- Electron target, no energy threshold
- $\sigma(E_\nu) \approx 4.0\text{x}10^{-45} (E_\nu) \text{ cm}^2$
- Direction of outgoing e^- closely correlated to direction of incoming ν

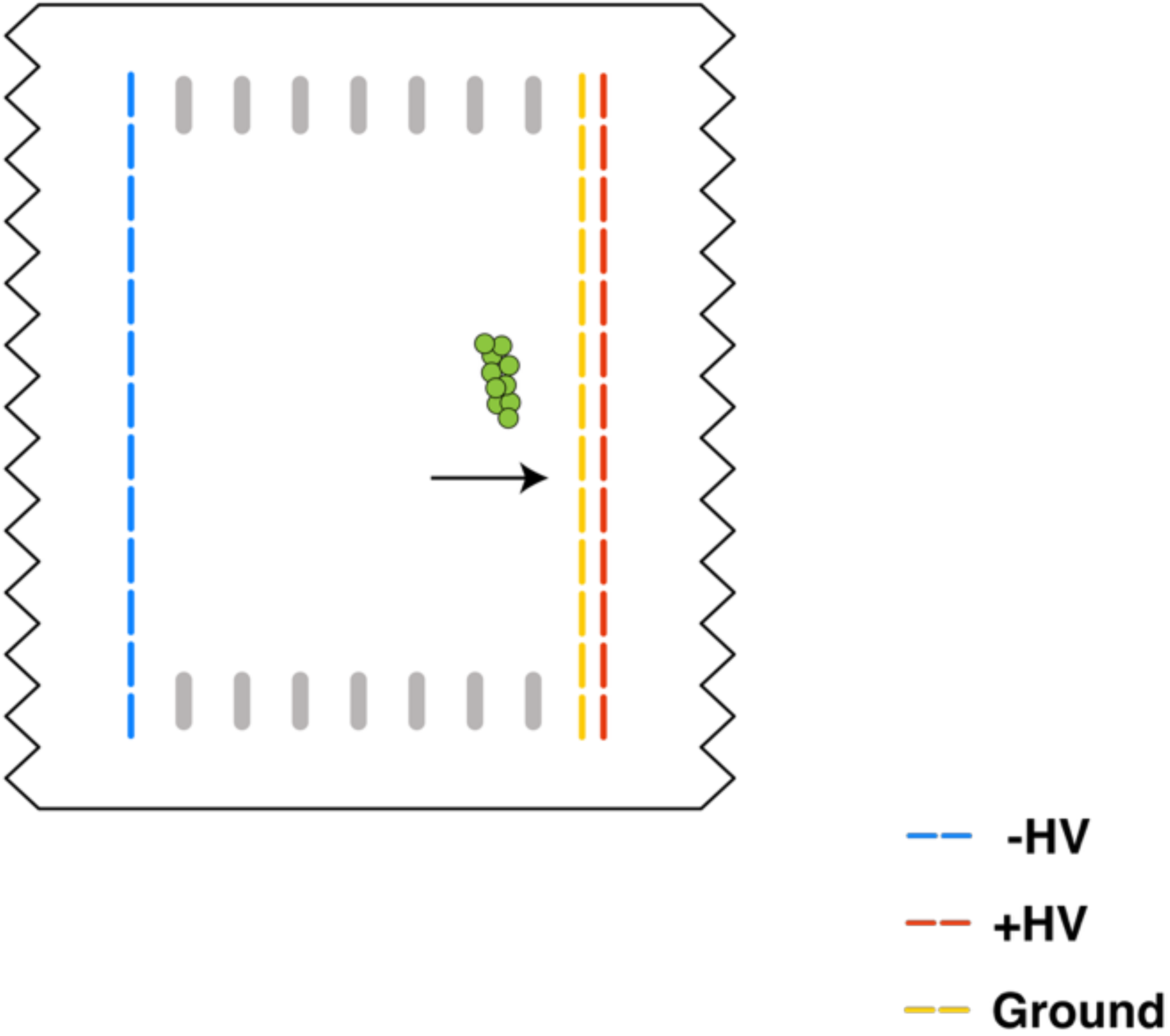
e^- recoils in gas TPCs



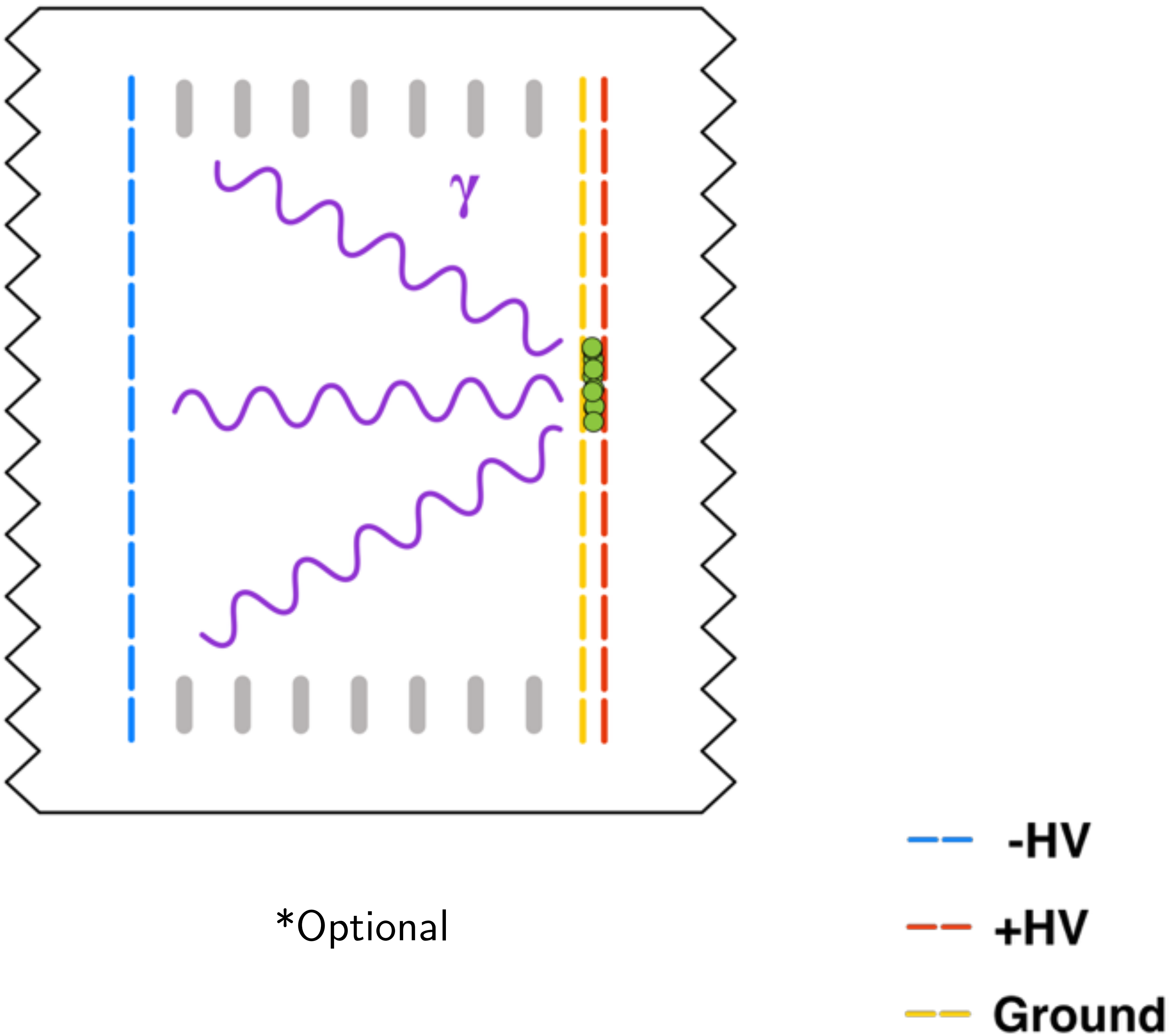
e^- recoils in gas TPCs



e⁻ recoils in gas TPCs



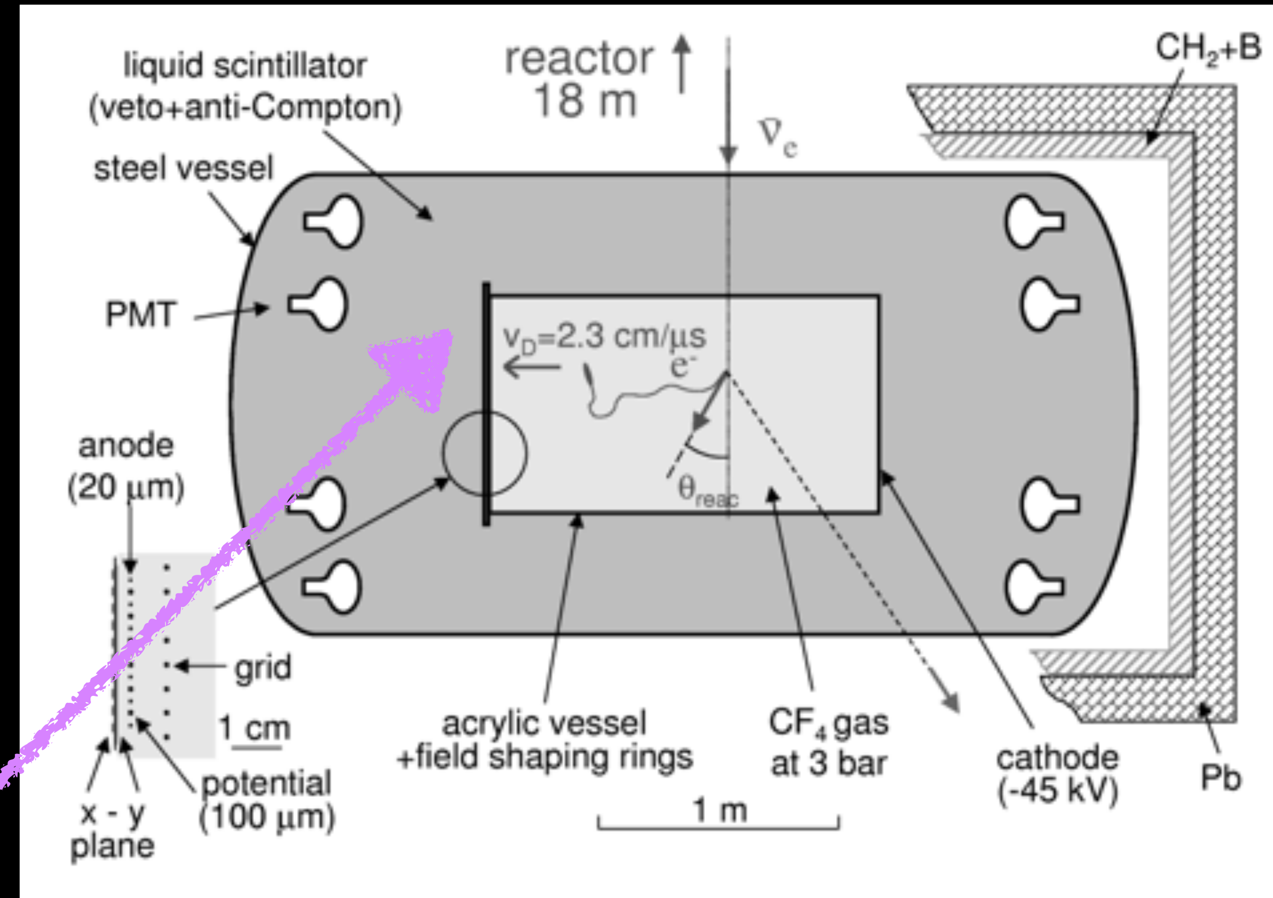
e⁻ recoils in gas TPCs

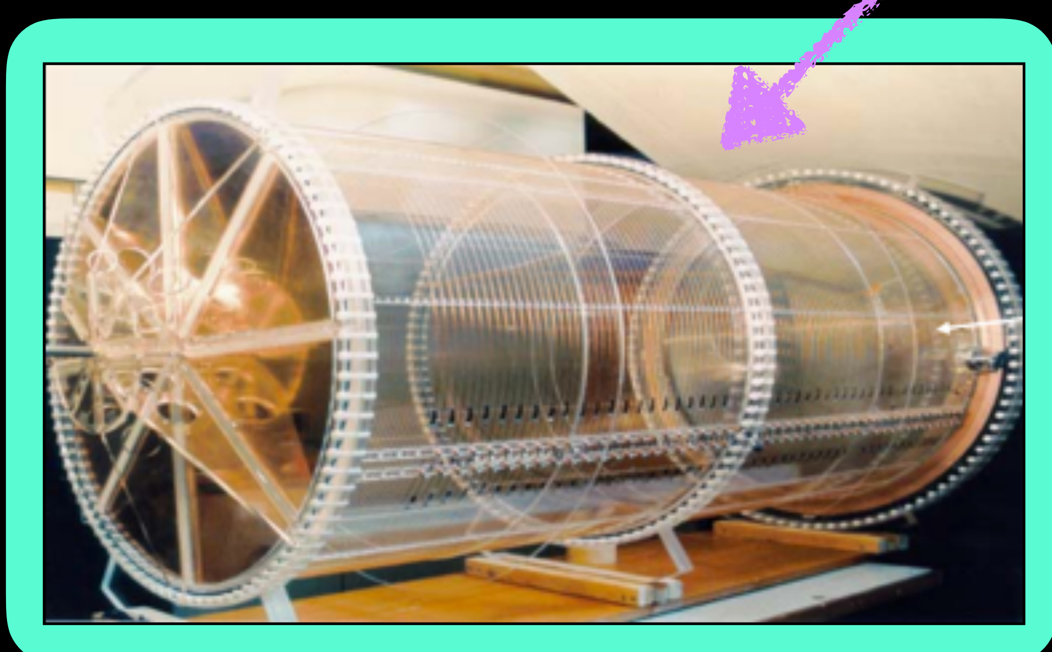


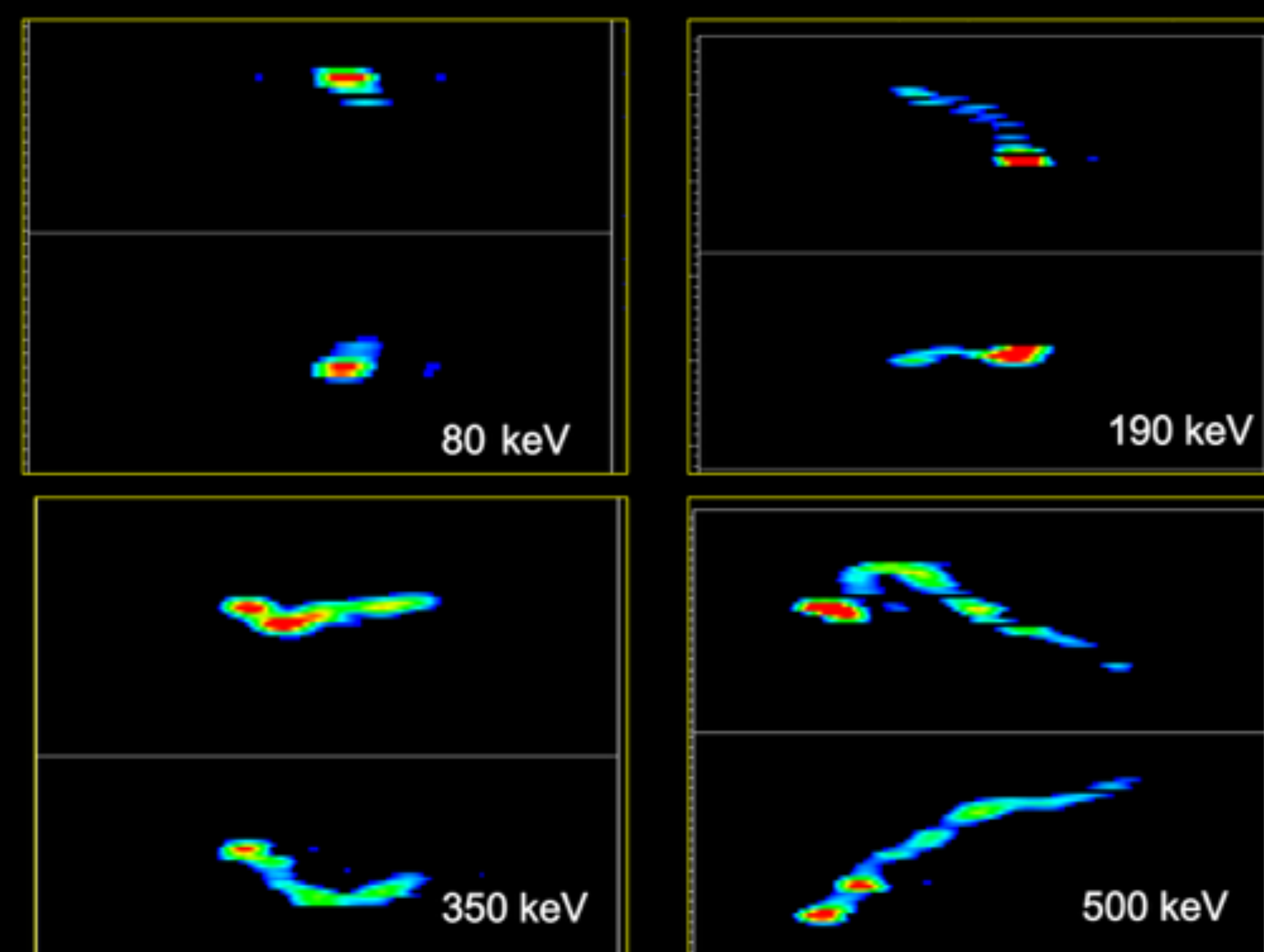
*Optional

e^- recoils in MUNU

- 11.4 (3.8) kg CF_4 gas at 3 (1) bar
- Angular resolution: 15° @ 200 keV, 12° @ 400 keV, 10° @ 600 keV
- Energy resolution: 10% @ 200 keV, 6.8% @ 478 keV







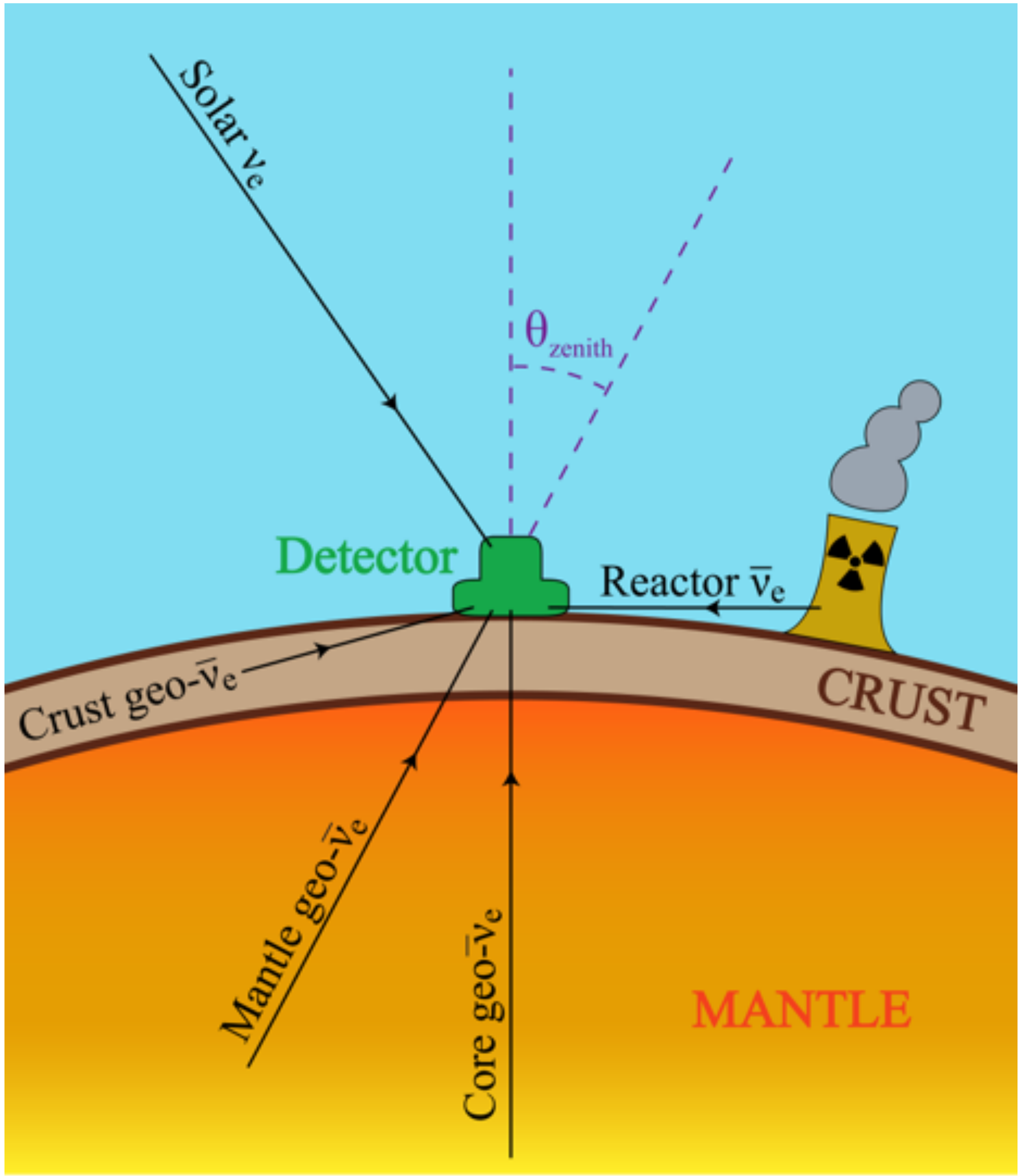
Daraktchieva, NEUTRINO 2006

What is the sensitivity of a directional detector to the flux of geo-ν's from:

- ^{40}K decays?
- the Earth's mantle?
- the Earth's core?

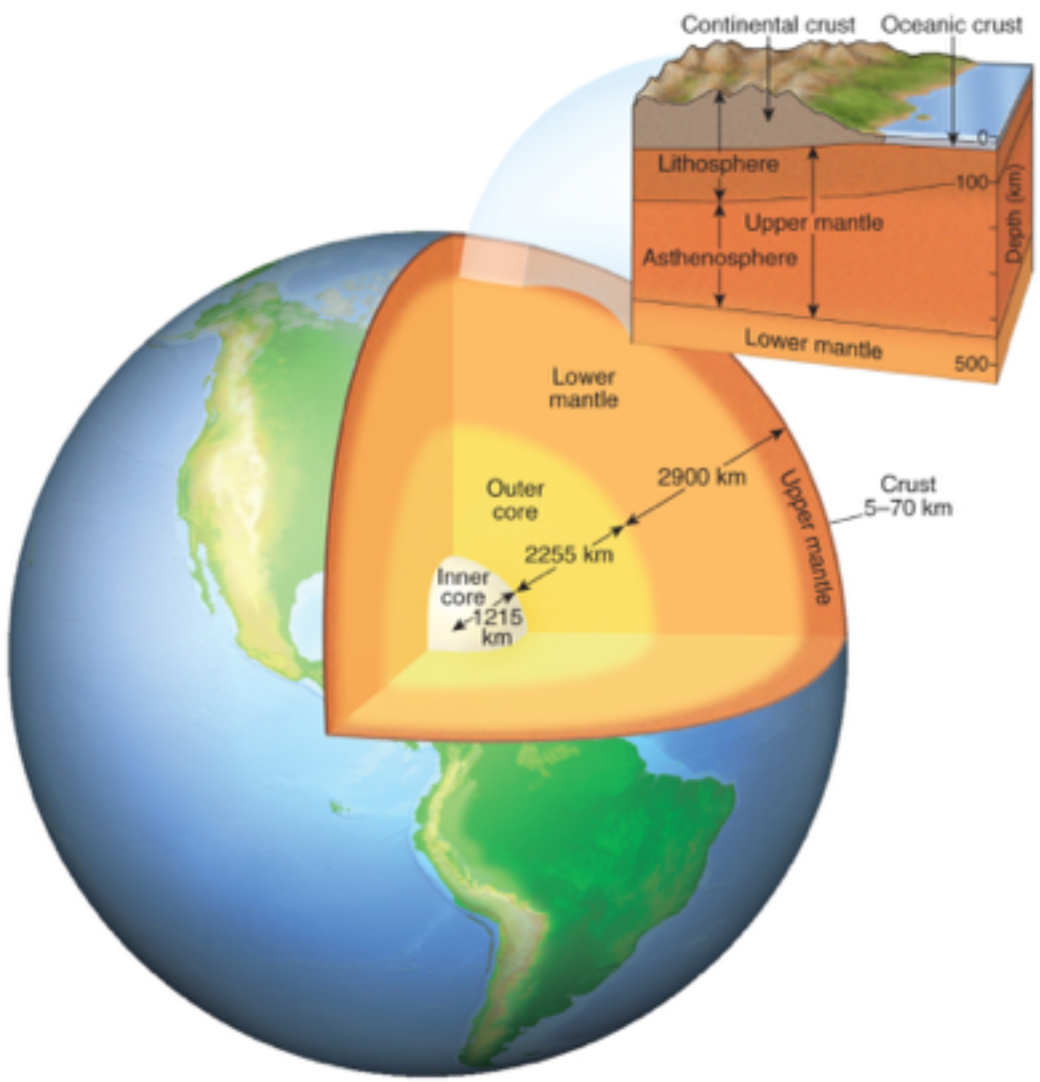
Studied at 3 underground sites:
Gran Sasso*, Kamioka, SNOLAB

Neutrino flux model



Geo-ν model

- Physical structure of crust from seismology:
  - CRUST 1.0: http://igppweb.ucsd.edu/~gabi/crust1.html
  - Supplemented with topographical information
  - U, Th and K element abundances from geochemistry

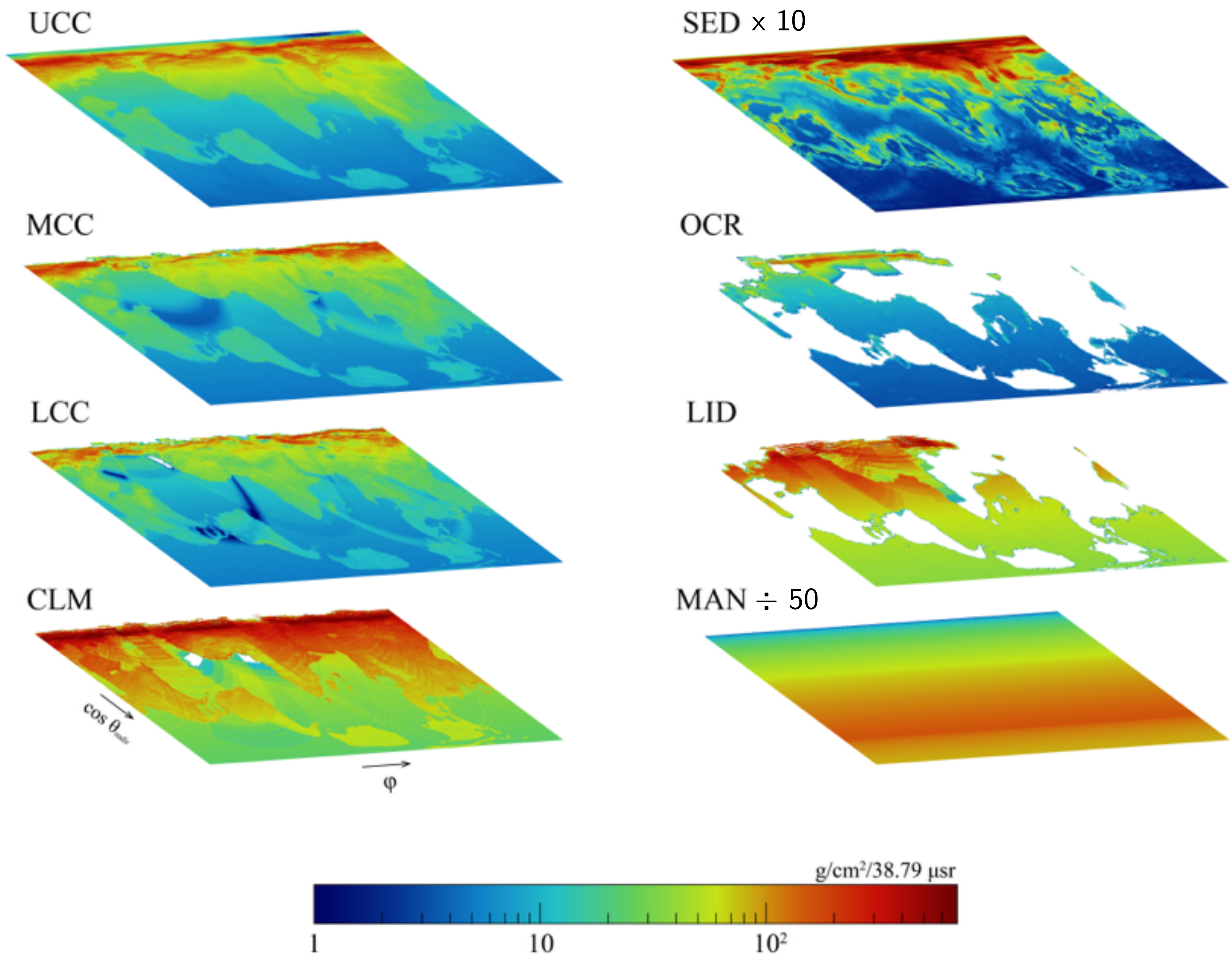


- Mantle modeled as homogeneous spherical shell (with and without radioactivity in core)

$$\Phi_{\text{mantle}} = \frac{\sum_i w^i (\Phi^i_{\text{observed}} - \Phi^i_{\text{crust}})}{\sum_i w^i}$$

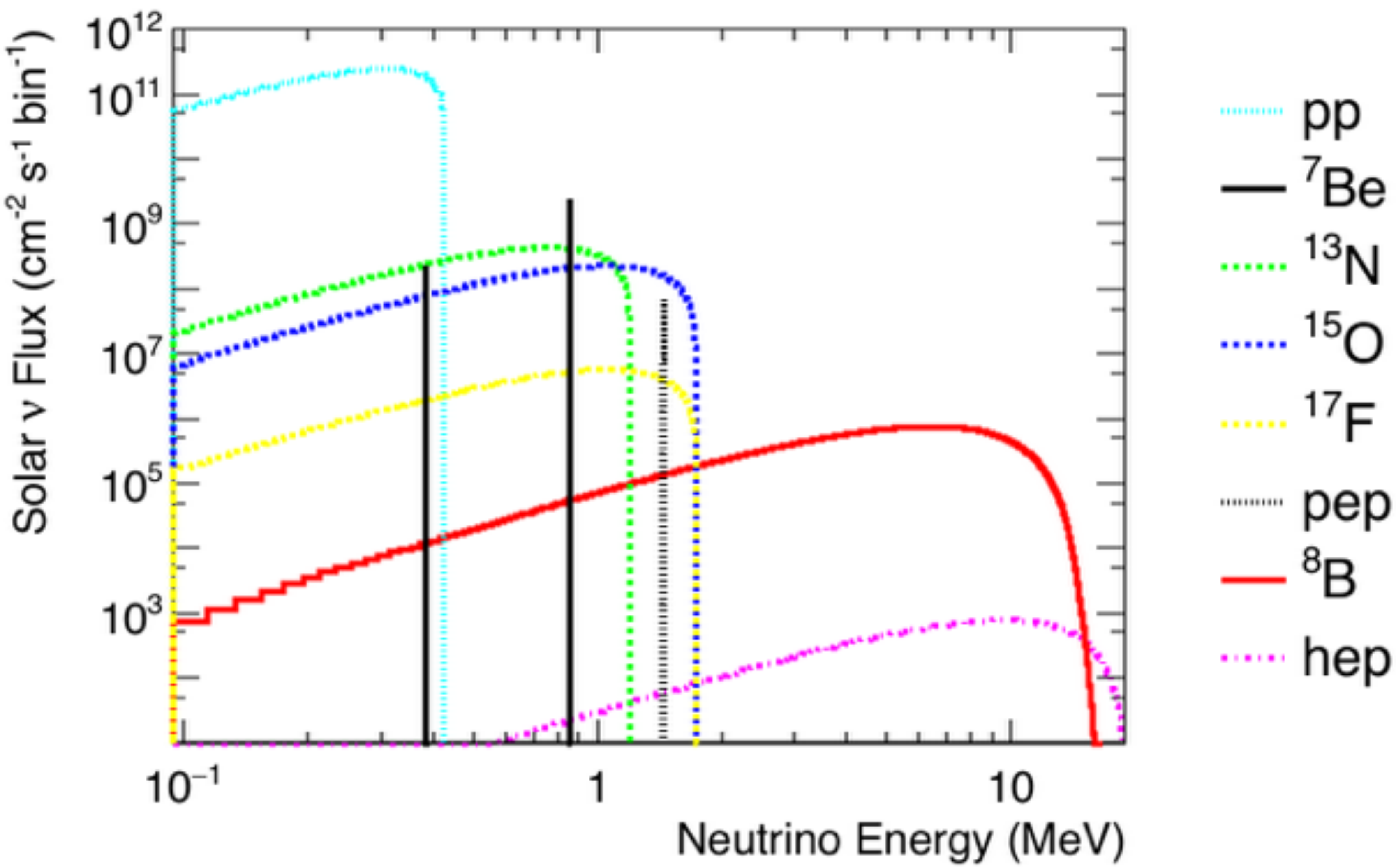
  - Data from Preliminary Reference Earth Model (PREM) and CRUST 1.0

Geophysical response



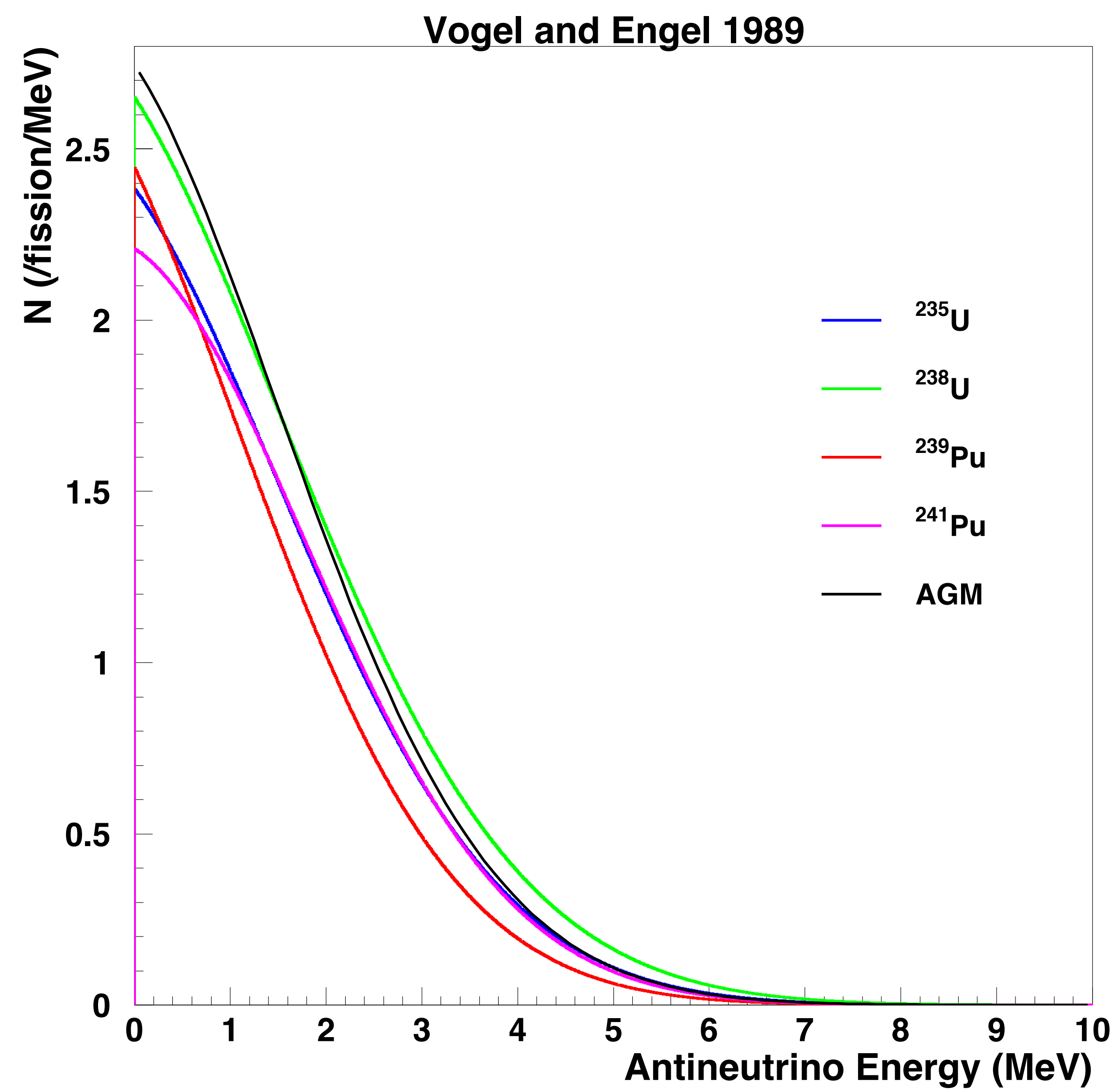
Solar-ν model

- Normalization from Bergstrom et al. *JHEP* 03, 132 (2016)
- +1.5%, -0.8% uncertainty on total flux, but very energy-dependent:
  - Largest (fractional) uncertainties on ^{17}F, ^{13}N, ^{15}O



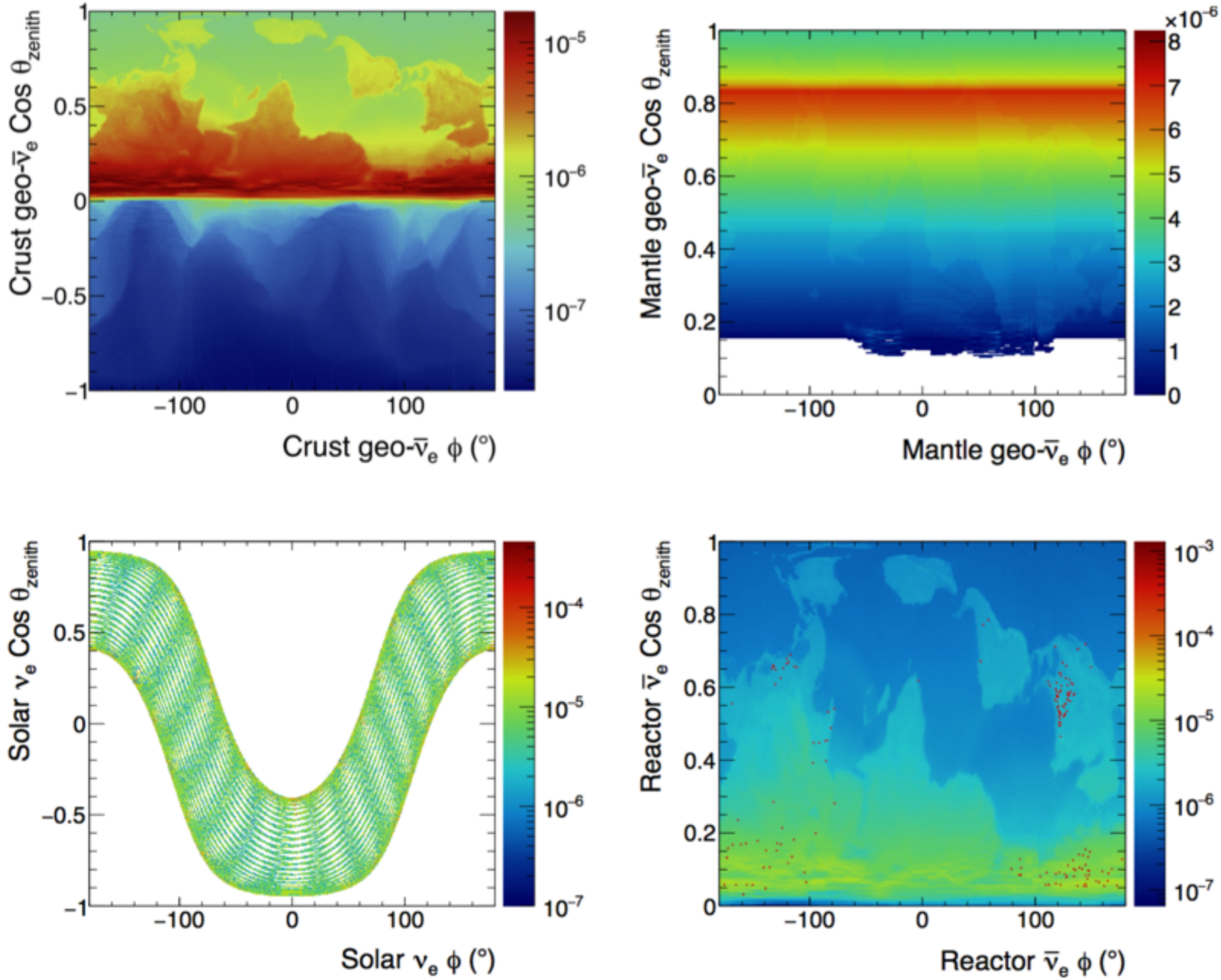
Reactor-ν model

- Reactor positions and intensities taken from Baldoncini et al. *Phys. Rev.* D91, 065002 (2015)
    - Total of 439 reactor cores
- Assume 6 νbar/fission and 205 MeV/fission
- $\pm$6% uncertainty:
    - power value reported by plant operators
    - oscillation parameters
    - conversion of reactor power to flux
    - seasonal changes in the reactor power output



$$N(E_{\overline{\nu}}) = \frac{6}{2.0523} e^{-(0.3125 E_{\overline{\nu}} + 0.25)^2}$$

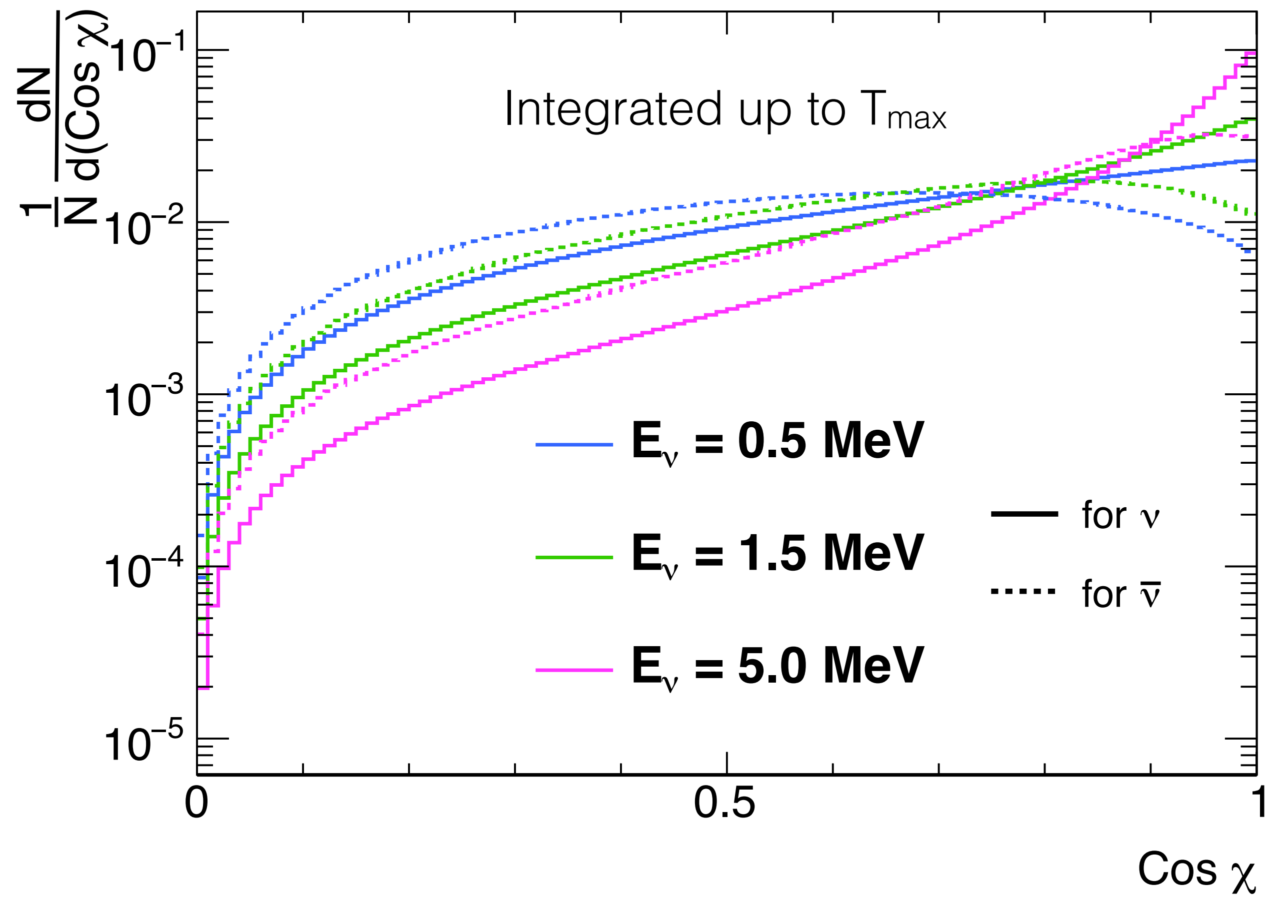
Incident angular distributions



Scattering kinematics and differential cross section

T = kinetic energy of outgoing e⁻

$$\cos\chi = \frac{E_\nu + m_e}{E_\nu}\left[\frac{T}{T+2m_e}\right]^{1/2}$$

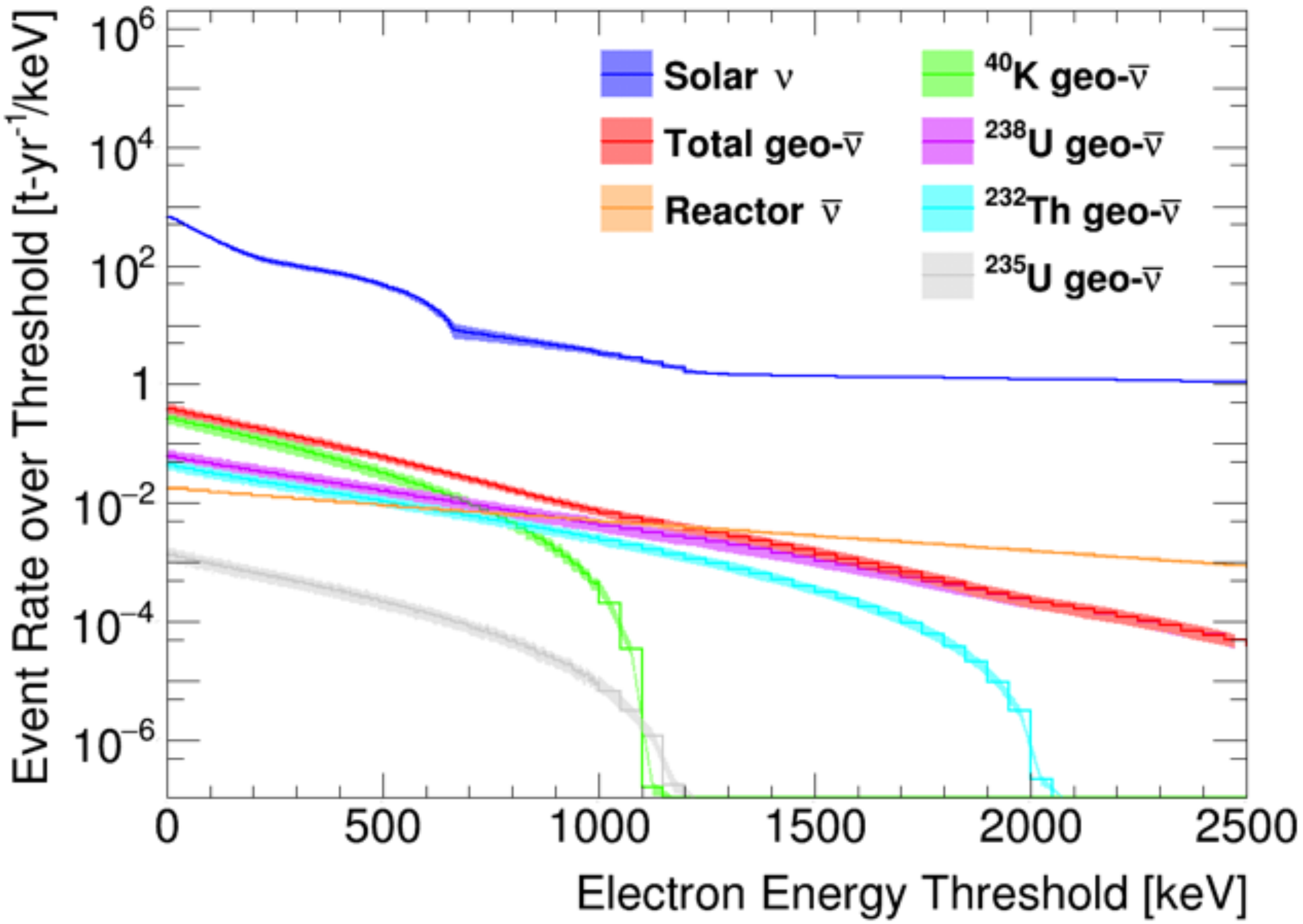


Assuming zero neutrino charge radius and magnetic moment, then:

$$\frac{d\sigma}{dT} = \frac{G_F^2 m_e}{2\pi}\left[(g_V+g_A)^2 + (g_V-g_A)^2\left(1-\frac{T}{E_\nu}\right)^2 + (g_A^2-g_V^2)\frac{m_e T}{E_\nu^2}\right]$$

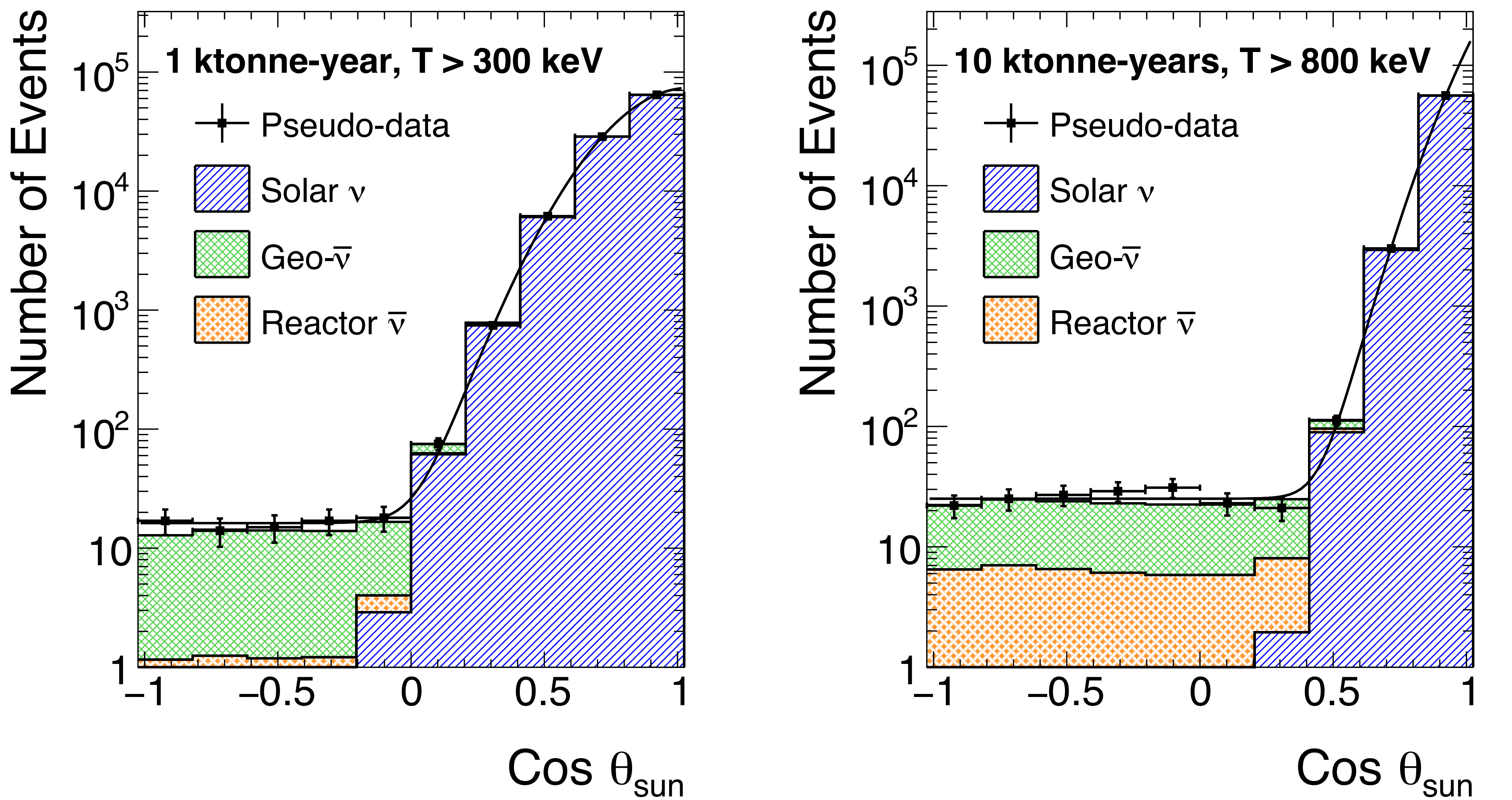
$$g_V = \begin{cases} 2\sin^2\theta_W + \frac{1}{2}, & \text{for } \nu_e \\ 2\sin^2\theta_W - \frac{1}{2}, & \text{for } \nu_\mu, \nu_\tau \end{cases} \qquad g_A = \begin{cases} +\frac{1}{2}, & \text{for } \nu_e \\ -\frac{1}{2}, & \text{for } \nu_\mu, \nu_\tau \end{cases}$$

Event rates (CF_4 target)



*Includes 55% survival probability after oscillation and subsequent ν_μ, ν_τ elastic scattering

θ_{sun}



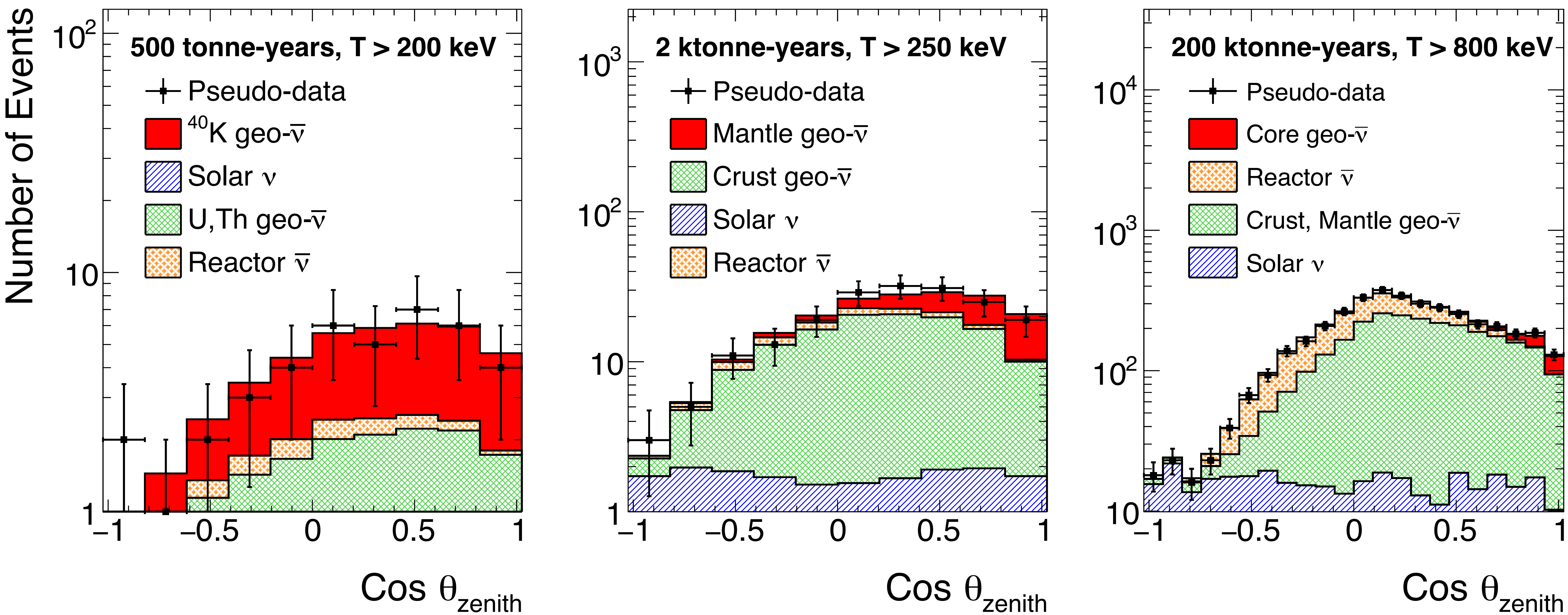
Pseudo-data includes smearing by MUNU angular and energy resolutions

$$f(\cos\theta) = A\frac{e^{\kappa\cos(\theta-\mu)}}{2\pi I_0(\kappa)} + C,$$

Sensitivity analysis

For a given exposure and geo-ν contribution, run 1000 pseudo-experiments and use PL statistic to determine exposure required to:

- set a 95% (90%) CL upper limit for 'background-only' pseudo-experiments
- exclude null hypothesis at 95% (90%) CL for 'signal+background' pseudo-experiments



Results	40K	Mantle (no radioactivity in core)	Core (10 p.p.b. U, Th)	Reactor monitoring
Energy threshold	200 keV	250 keV	800 keV	1.5 MeV
$\cos \theta_{sun}$	< -0.09	< 0.02	< 0.54	< 0.53
Solar-v flux uncertainty	+11.2, -5.3 %	+12.3, -5.8 %	+20.0, -11.5 %	+2.2, -1.4 %
Geo-v flux uncertainty	±18-20%	±11%	±5%	±18-20%
90% <UL> (tonne-yrs)	**73-87**	**435-560**	**47000-53000**	**111-200**
90% <CI> (tonne-yrs)	**89-106**	**1051-1557**	**134000-138000**	**98-301**
High-res	↓37-40%	↓32-34%	↓15-22%	↓4-5%

* ±5% systematic uncertainty applied to all pseudo-data

Reactor monitoring

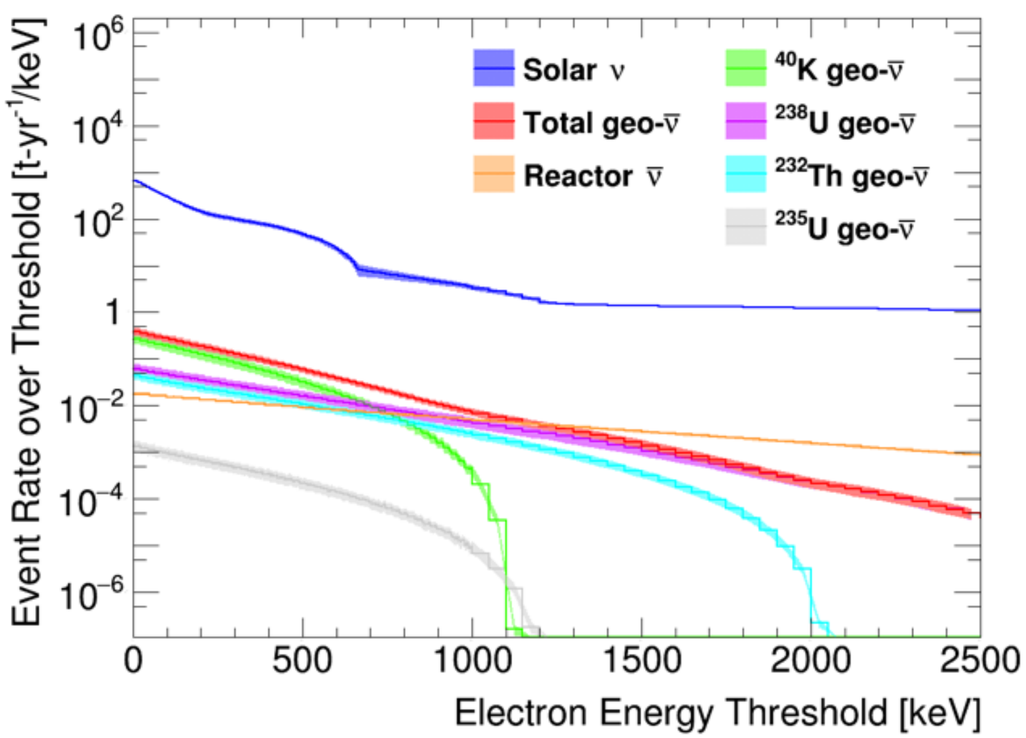
Goal #1: Detect a 50-MW reactor from a distance of 10 km

Goal #2: Detect monthly on/off cycling of the reactor

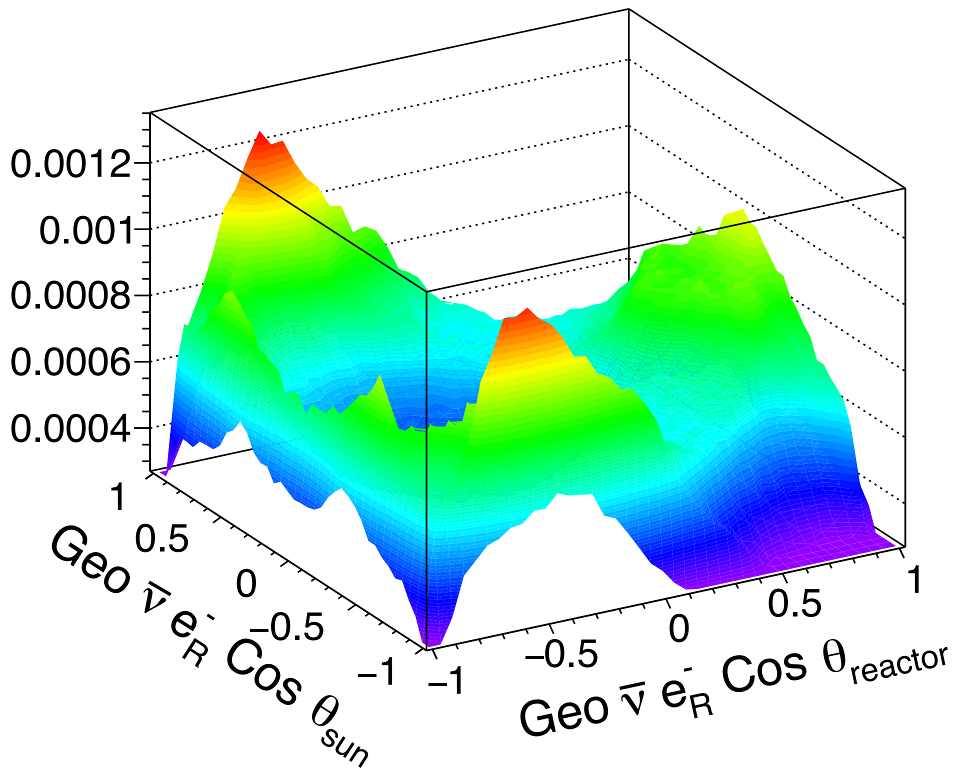
➔ Assume reactor is positioned 10 km <u>south</u> of each experimental site

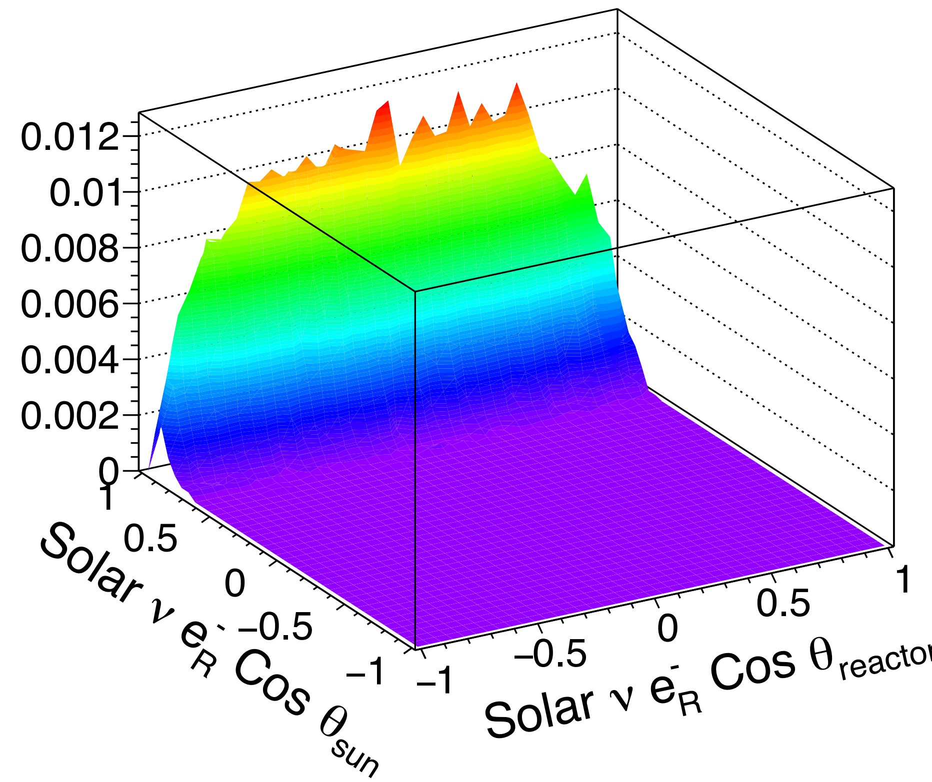
- Sensitivity will depend on position, power of neighboring reactors

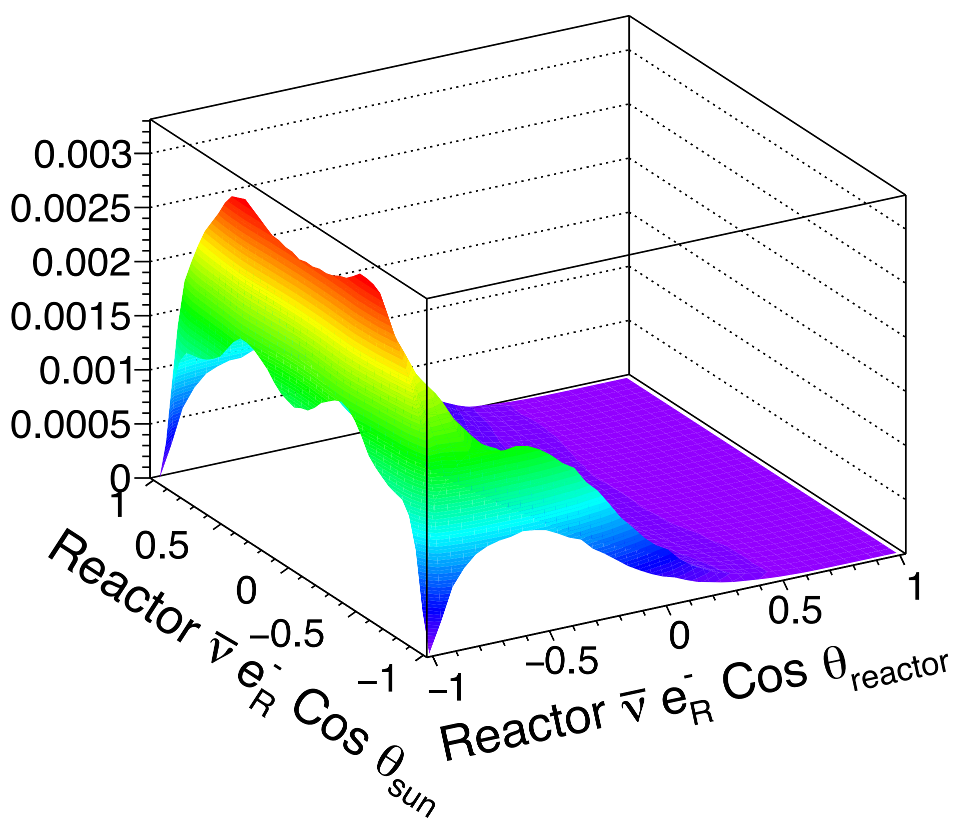
Use similar analysis, but with higher energy threshold (T > 1.5 MeV)

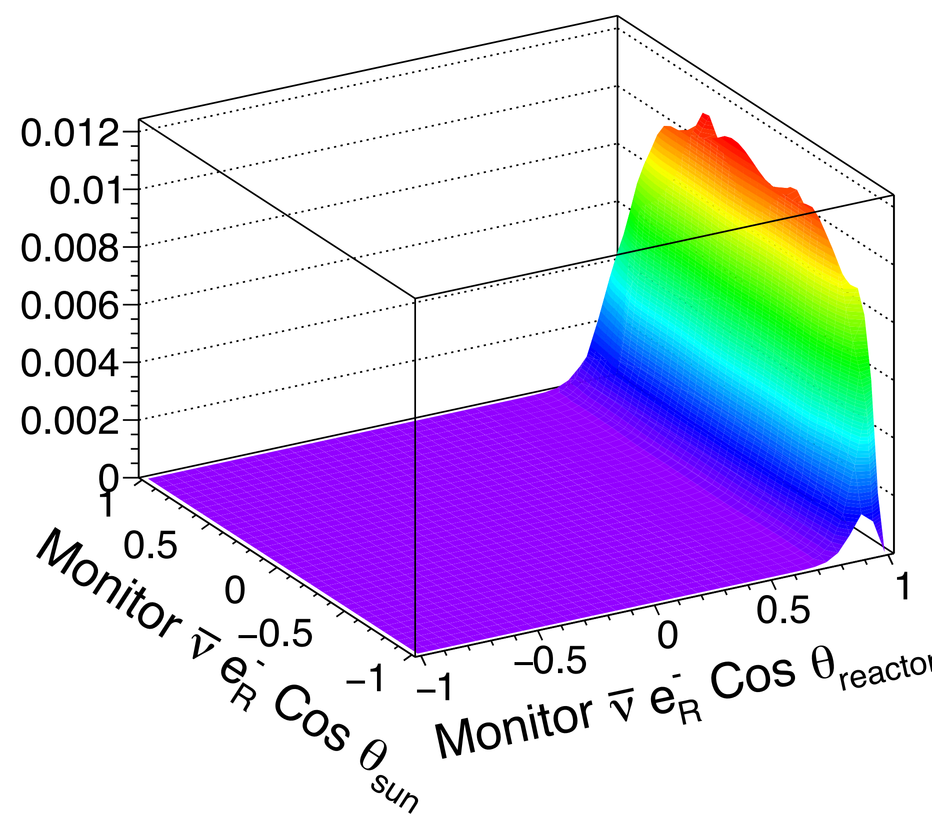


$\theta_{reactor}$ and θ_{sun}









Conclusions

- Direction-sensitive detectors with modest angular resolution are capable of measuring previously unresolved sources of radiogenic heating via ν-e^- elastic scattering
  - Exposures needed to access ^{40}K, mantle and core geo-ν's at 90% CL are 100 tonne-yrs, 1.5 ktonne-yrs and 135 ktonne-yrs
  - Up to 30-40% reduction in required exposure if angular resolution is improved by a factor of 2, relative to MUNU measurements
- Same detector is also capable of monitoring nearby nuclear reactors
  - Exposures as low as 1.3 ktonne-months can detect monthly on/off cycling of a 50-MW reactor at a distance of 10 km with 90% CL
  - Exact exposure depends on position and power of neighboring reactors

Stay tuned!

Viewing the Earth's hidden interior with direction-sensitive detectors

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(Dated: December 1, 2016)

The Earth radiates more than 10^{25} anti-neutrinos ($\overline{\nu}$) to space every second. This immense $\overline{\nu}$ luminosity is fueled predominantly by the β^- decays of radiogenic isotopes in the Earth's crust and mantle. The anti-neutrinos produced by these decays, called geo-neutrinos due to their geophysical origin, give us important clues about the composition of the Earth's interior and the size and sources of the Earth's radiogenic heat flow, both in the current epoch and throughout its evolution. In this paper, we discuss a novel way to directly measure various contributions to the Earth's $\overline{\nu}_e$ flux using $\overline{\nu}_\ell$-e^- elastic scattering and low-background, direction-sensitive tracking detectors. We calculate the exposures needed to make the first-ever direct measurements of geo-$\overline{\nu}_e$s from ^{40}K decays, the Earth's mantle, and the Earth's core. Together, these measurements offer a unique view into the Earth's hidden interior and could help unravel long-standing mysteries surrounding the origin, formation and thermal evolution of our planet, as well as the 'missing' source of heat for the geo-magnetic field, vital for protecting life on Earth from the Sun's radiation.

Backup slides

Event rates (CF_4 target)

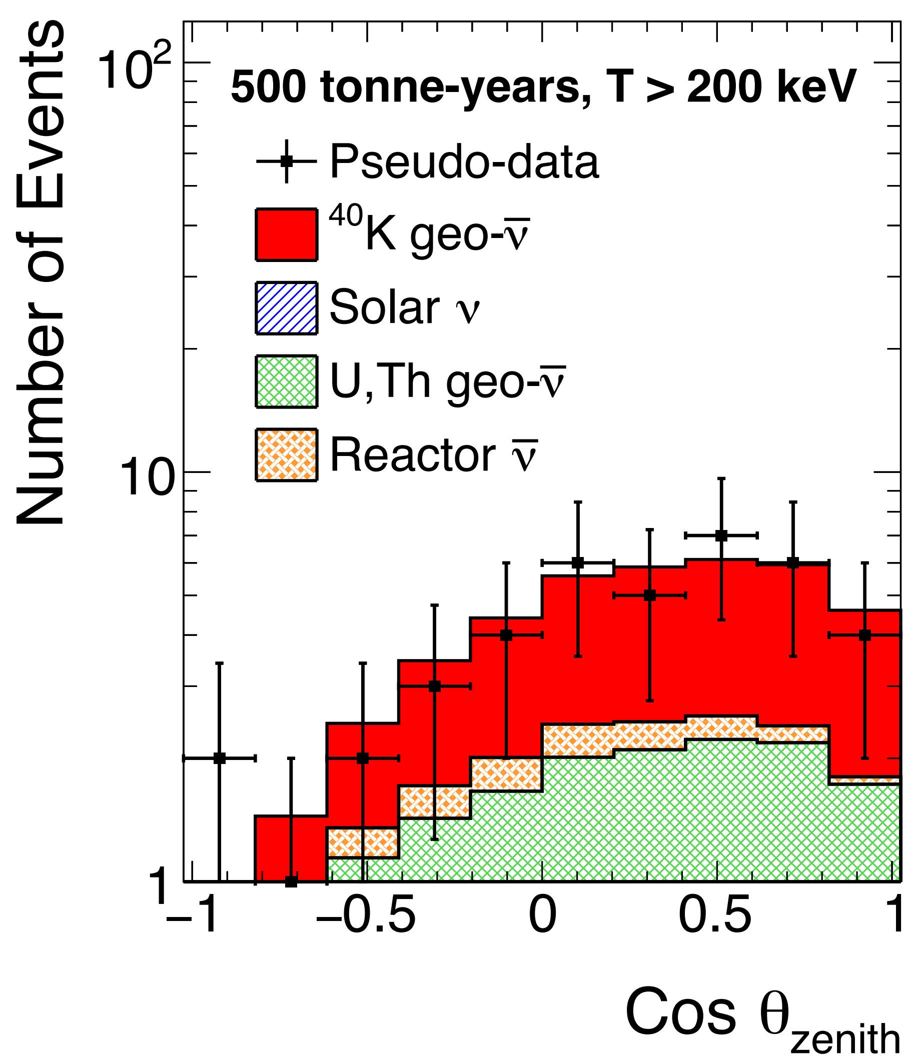
Source	Total	> 200 keV	> 250 keV	> 800 keV
pp	$433.97^{+2.69}_{-2.40}$	$16.09^{+0.10}_{-0.09}$	$0.50^{+0.00}_{-0.00}$	$0.00^{+0.00}_{-0.00}$
^{7}Be (1)	$156.78^{+7.84}_{-7.19}$	$105.88^{+5.29}_{-4.85}$	$93.59^{+4.68}_{-4.29}$	$0.00^{+0.00}_{-0.00}$
^{7}Be (2)	$3.57^{+0.18}_{-0.16}$	$0.43^{+0.02}_{-0.02}$	$0.00^{+0.00}_{-0.00}$	$0.00^{+0.00}_{-0.00}$
^{13}N	$13.88^{+23.88}_{-8.33}$	$8.47^{+14.57}_{-5.08}$	$7.30^{+12.56}_{-4.38}$	$0.24^{+0.41}_{-0.14}$
^{15}O	$5.64^{+5.64}_{-3.90}$	$4.16^{+4.16}_{-2.88}$	$3.79^{+3.79}_{-2.62}$	$0.95^{+0.95}_{-0.66}$
^{17}F	$0.23^{+3.36}_{-0.23}$	$0.17^{+2.48}_{-0.17}$	$0.16^{+2.29}_{-0.16}$	$0.04^{+0.56}_{-0.04}$
^{8}B	$1.80^{+0.05}_{-0.03}$	$1.75^{+0.04}_{-0.03}$	$1.73^{+0.04}_{-0.03}$	$1.58^{+0.04}_{-0.03}$
hep	$0.01^{+0.01}_{-0.00}$	$0.01^{+0.01}_{-0.00}$	$0.01^{+0.01}_{-0.00}$	$0.01^{+0.01}_{-0.00}$
pep	$9.39^{+0.08}_{-0.08}$	$7.73^{+0.07}_{-0.07}$	$7.33^{+0.07}_{-0.07}$	$3.09^{+0.03}_{-0.03}$
solar ν total	$625.28^{+26.12}_{-11.92}$	$144.70^{+16.24}_{-7.60}$	$114.40^{+14.12}_{-6.67}$	$5.90^{+1.18}_{-0.68}$

per tonne-yr

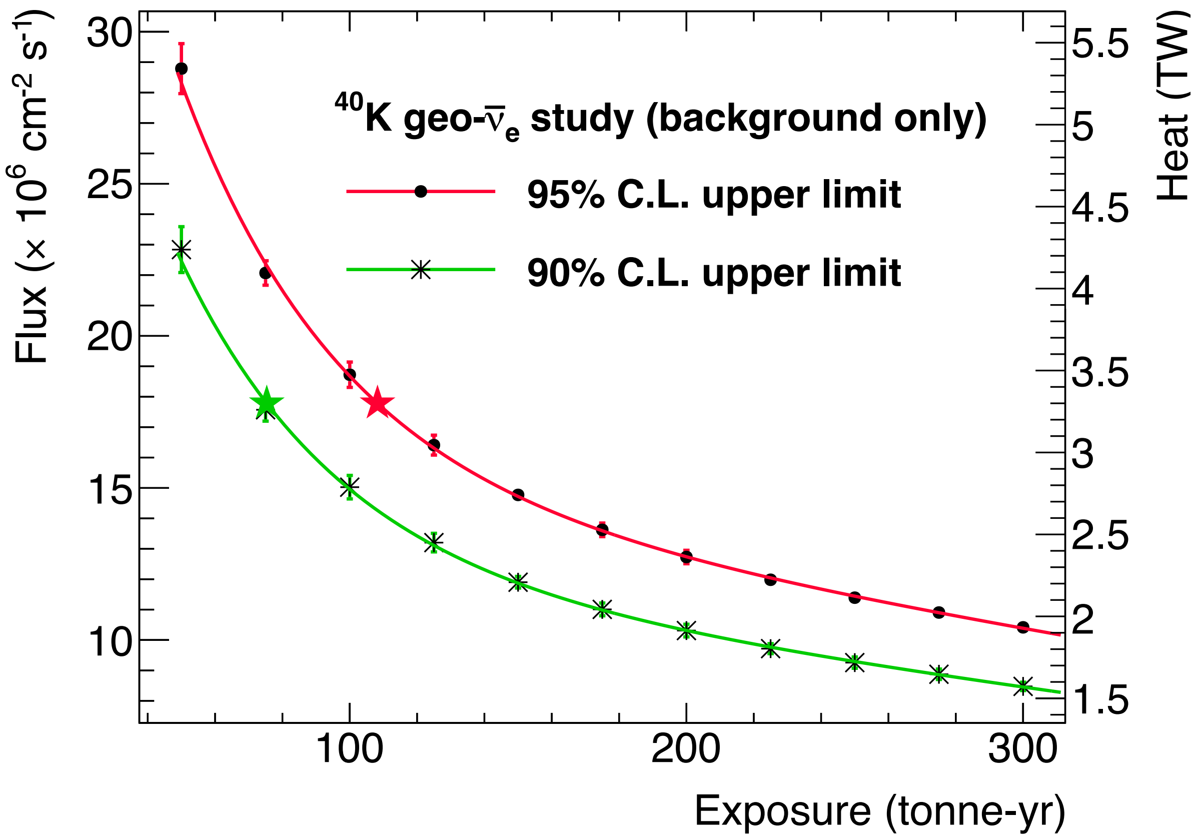
Source	Total	> 200 keV	> 250 keV	> 800 keV
^{238}U	61.26 ± 16.68	35.60 ± 9.69	31.73 ± 8.64	7.44 ± 2.02
^{235}U	1.36 ± 0.37	0.68 ± 0.19	0.59 ± 0.16	0.05 ± 0.01
^{232}Th	44.19 ± 9.17	24.18 ± 5.02	21.55 ± 4.47	4.65 ± 0.96
^{40}K	272.17 ± 69.90	126.66 ± 32.53	105.97 ± 27.21	4.69 ± 1.21
geo $\overline{\nu}$ total	378.98 ± 72.44	187.12 ± 34.31	159.83 ± 28.90	16.83 ± 2.55
reactor $\overline{\nu}$	17.69 ± 1.06	13.35 ± 0.80	12.50 ± 0.75	6.42 ± 0.38

per ktonne-yr

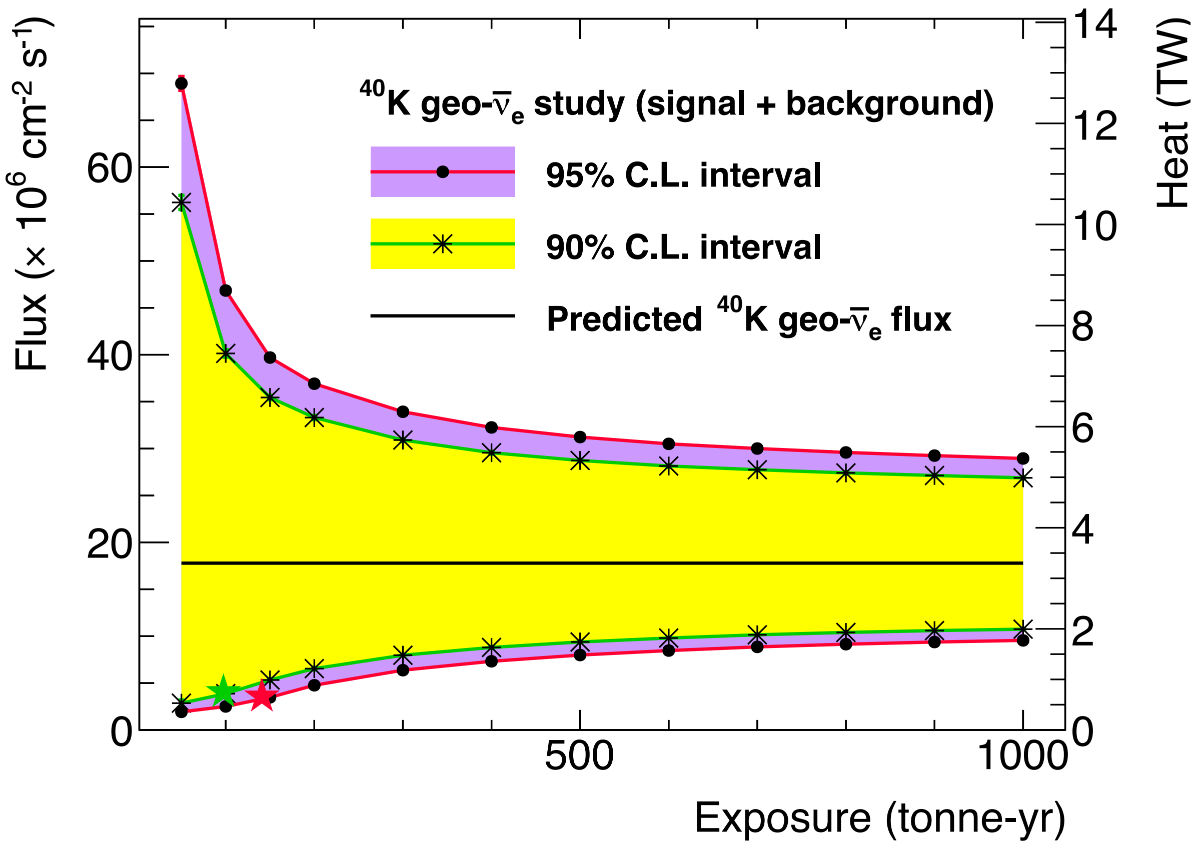
^{40}K



500 tonne-years, T > 200 keV
Pseudo-data
40K geo-ν̄
Solar ν
U,Th geo-ν̄
Reactor ν̄
Number of Events
Cos θzenith

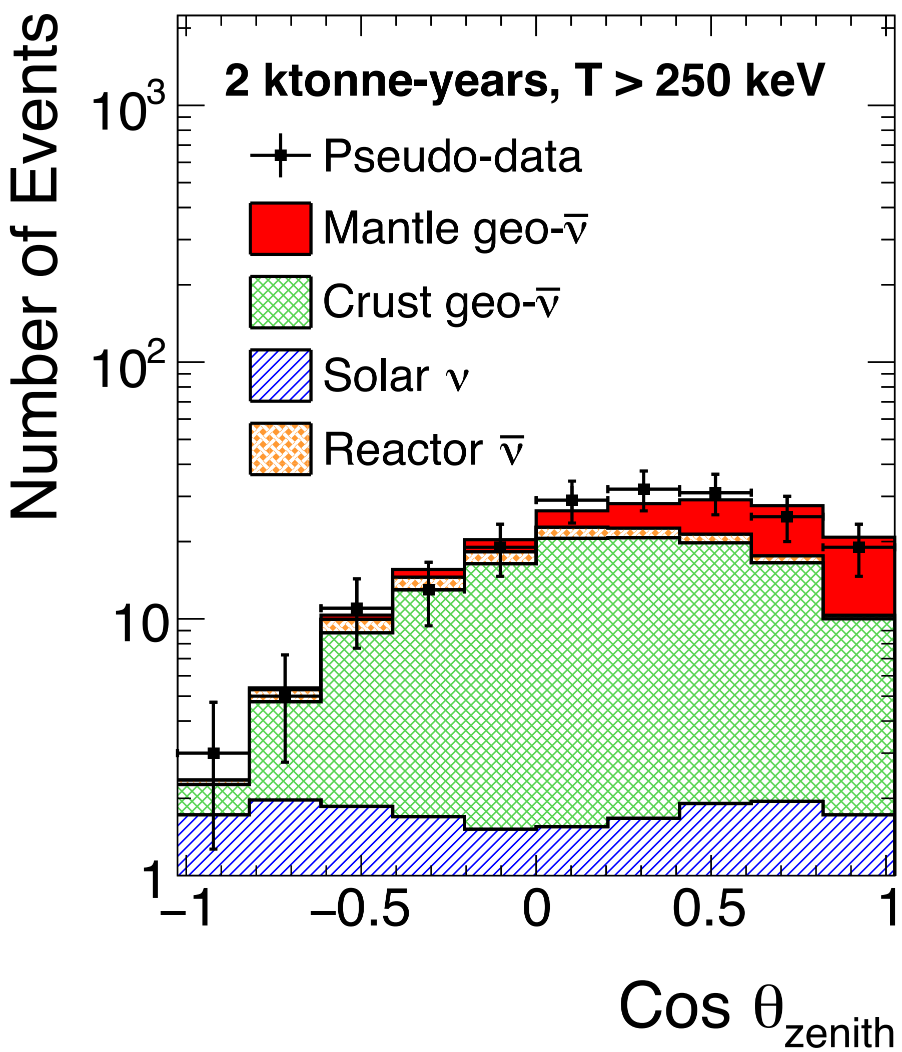


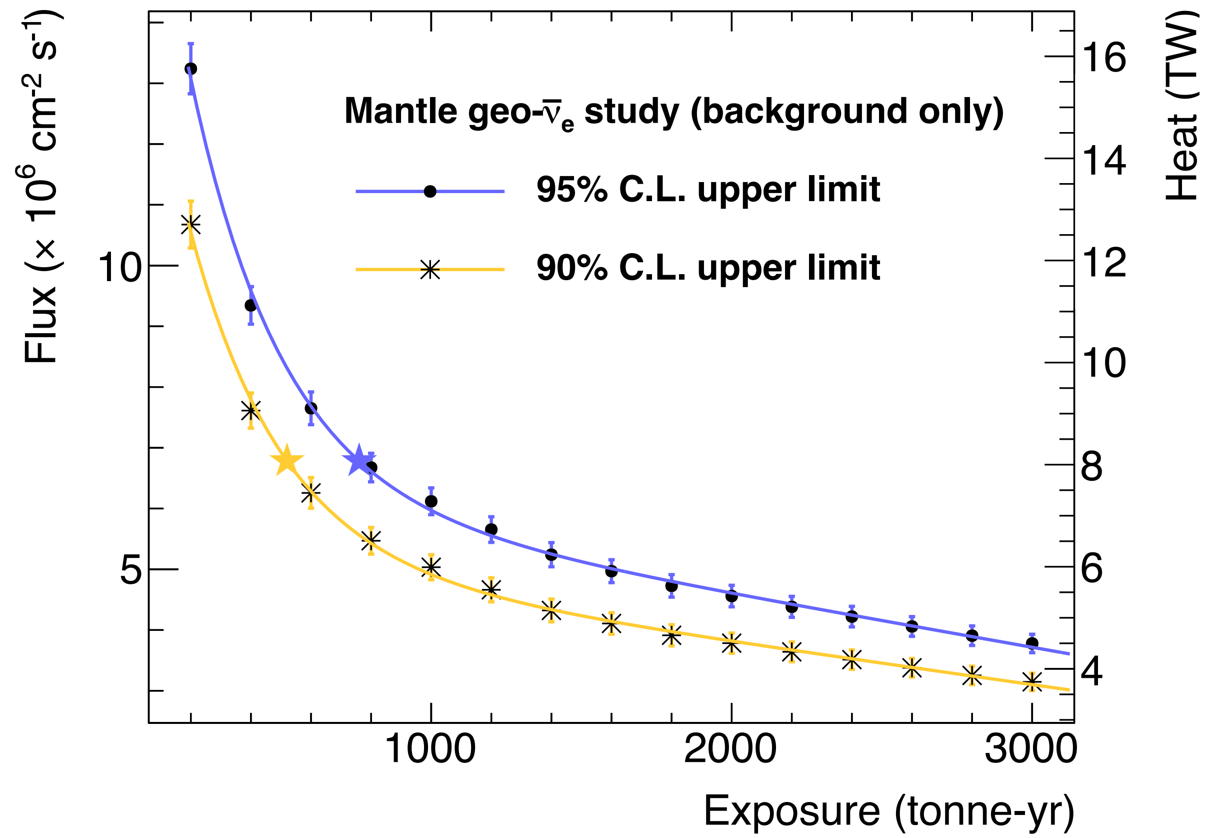
40K geo-ν̄e study (background only)
95% C.L. upper limit
90% C.L. upper limit
Flux (× 10^6 cm^-2 s^-1)
Heat (TW)
Exposure (tonne-yr)

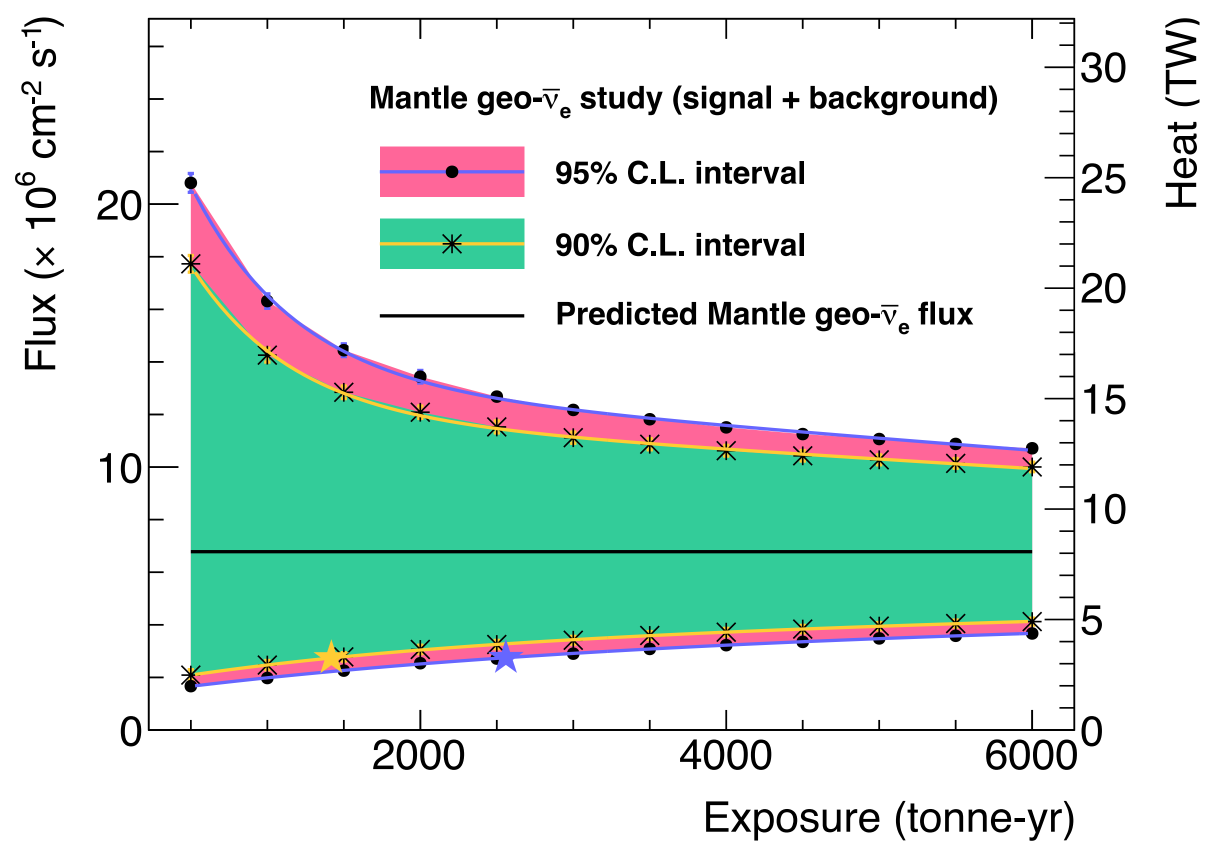


40K geo-ν̄e study (signal + background)
95% C.L. interval
90% C.L. interval
Predicted 40K geo-ν̄e flux
Flux (× 10^6 cm^-2 s^-1)
Heat (TW)
Exposure (tonne-yr)

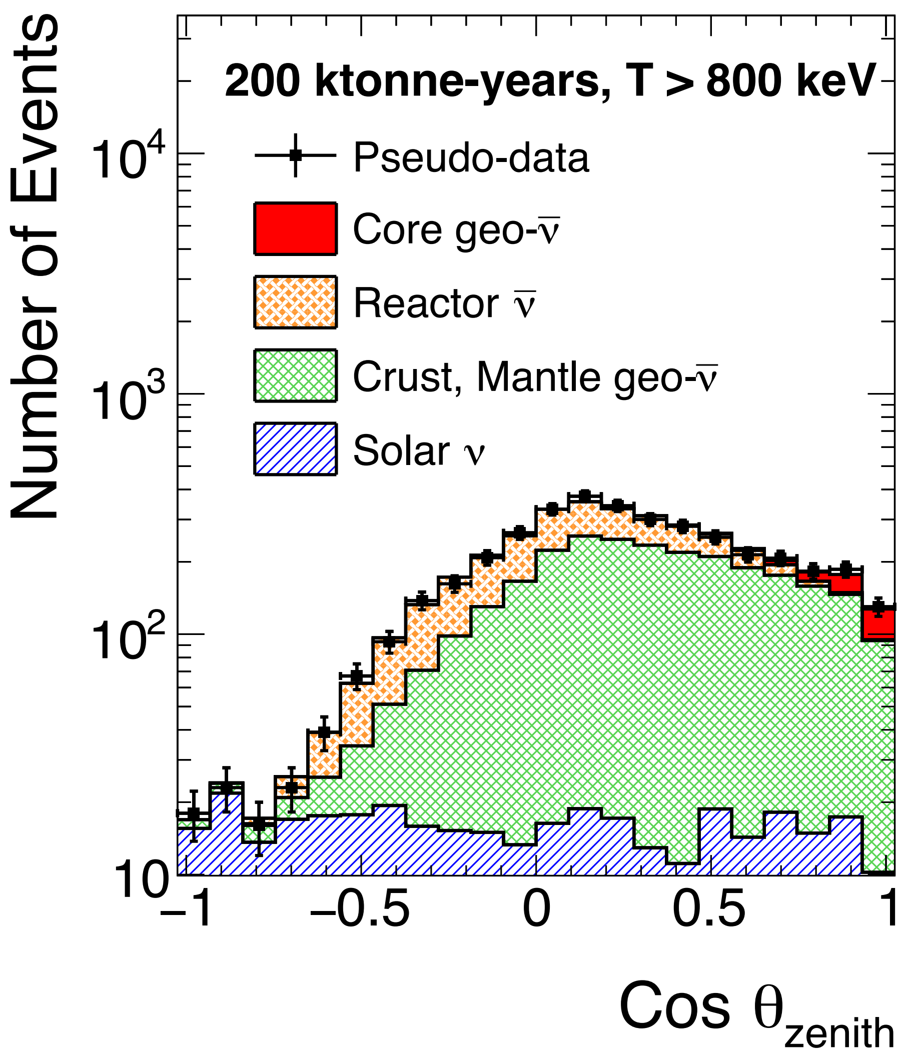
Mantle (no core radioactivity)

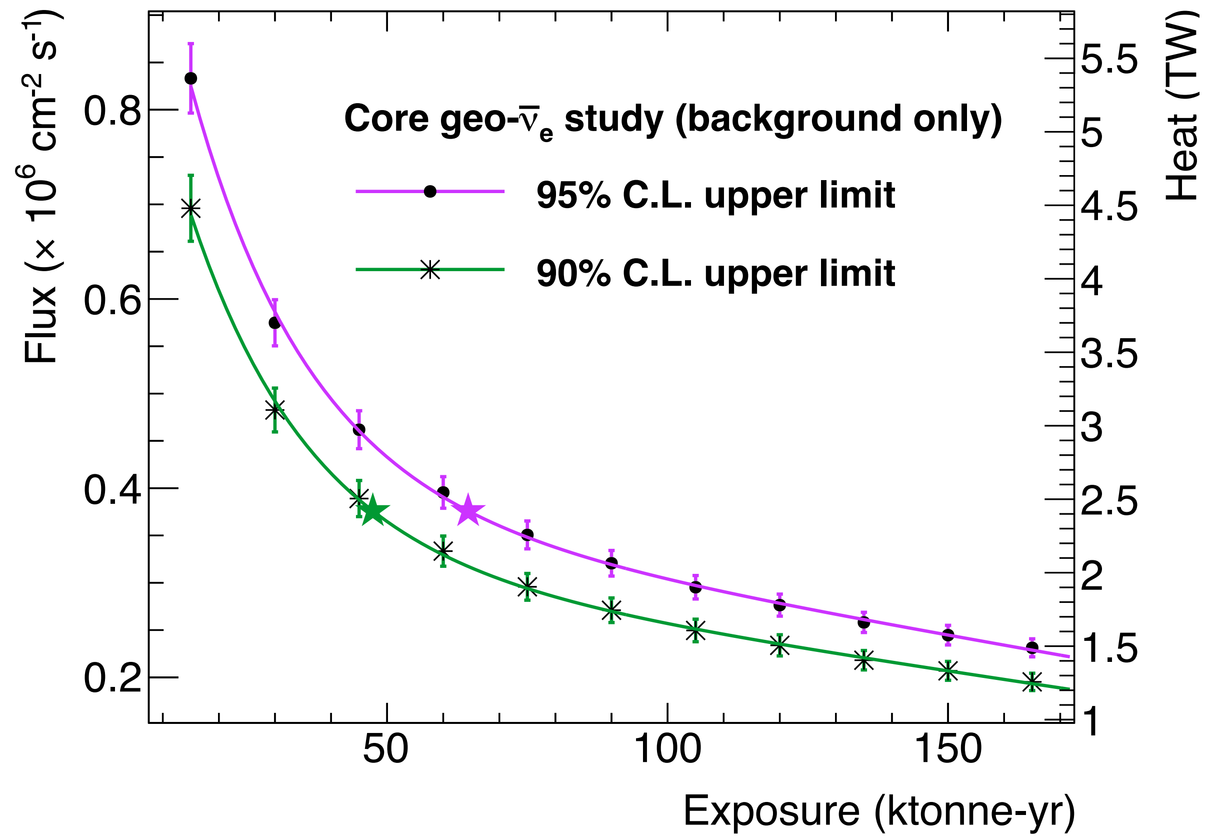


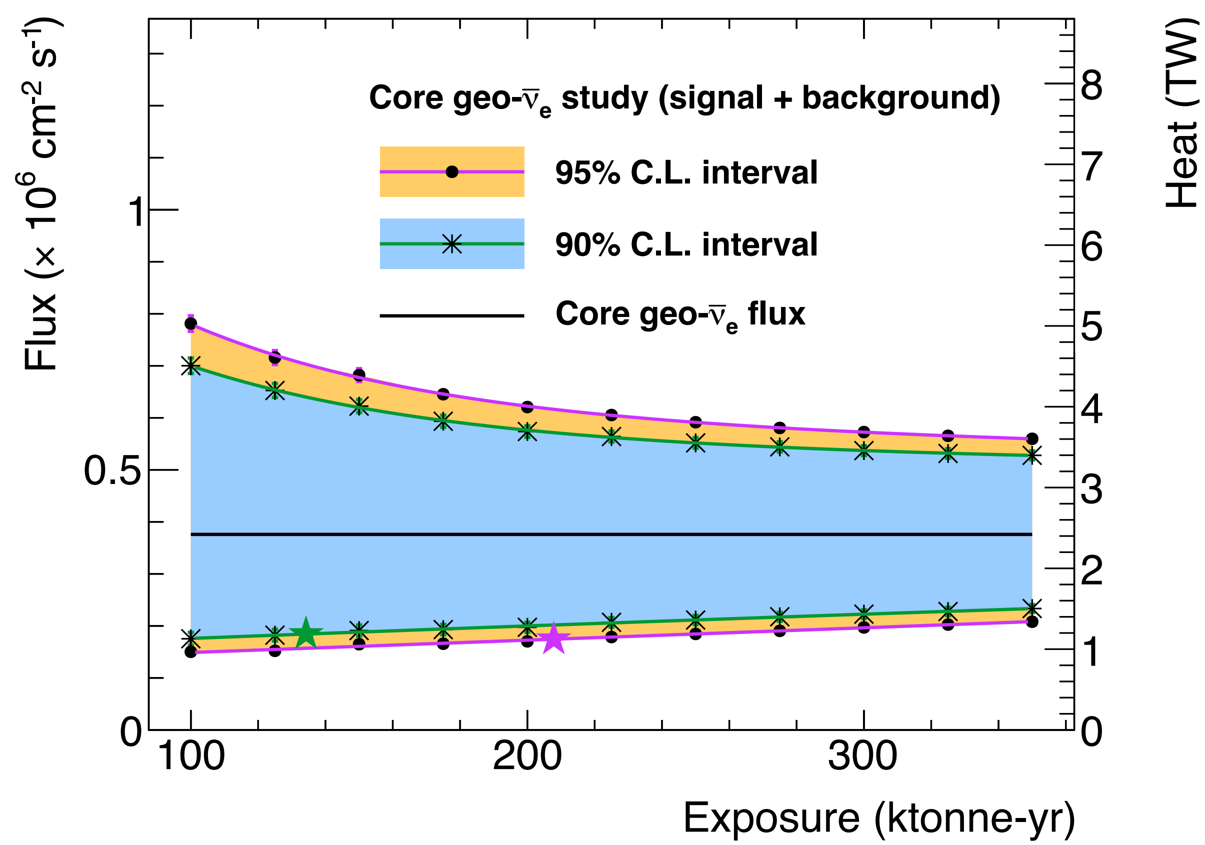




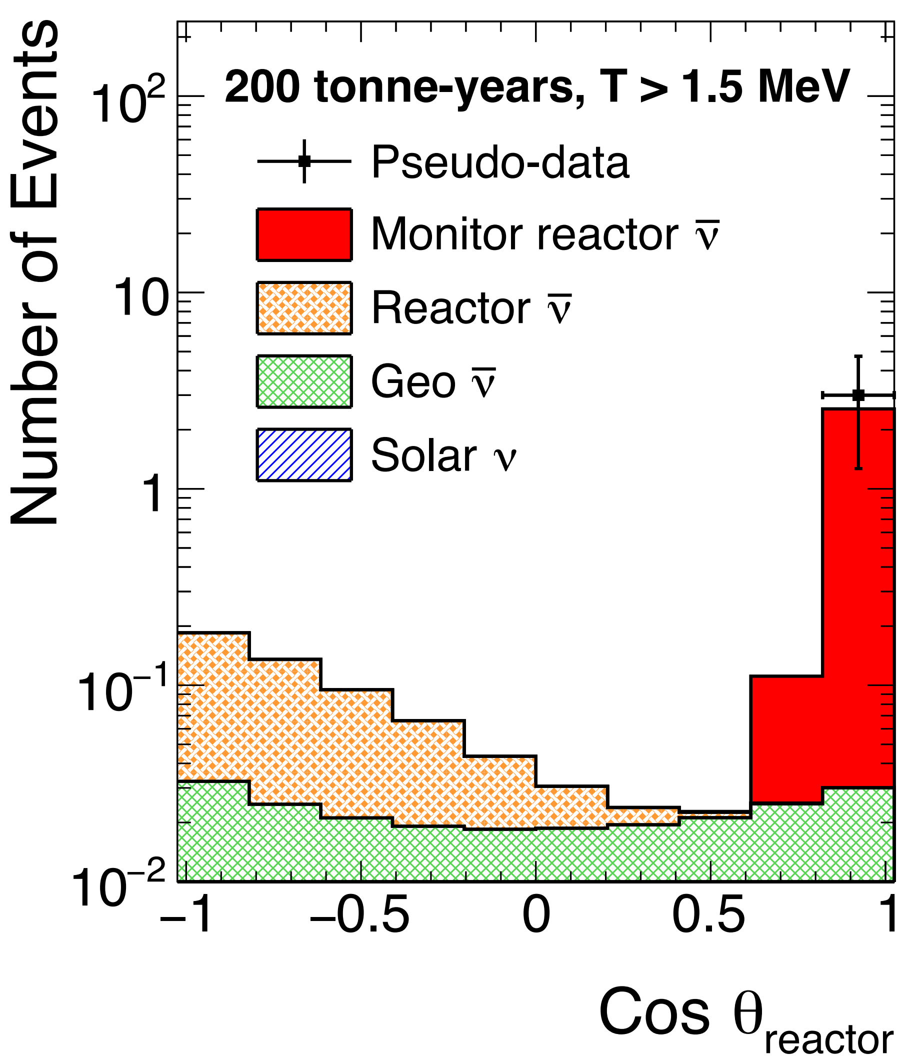
Core (10 p.p.b. U,Th)

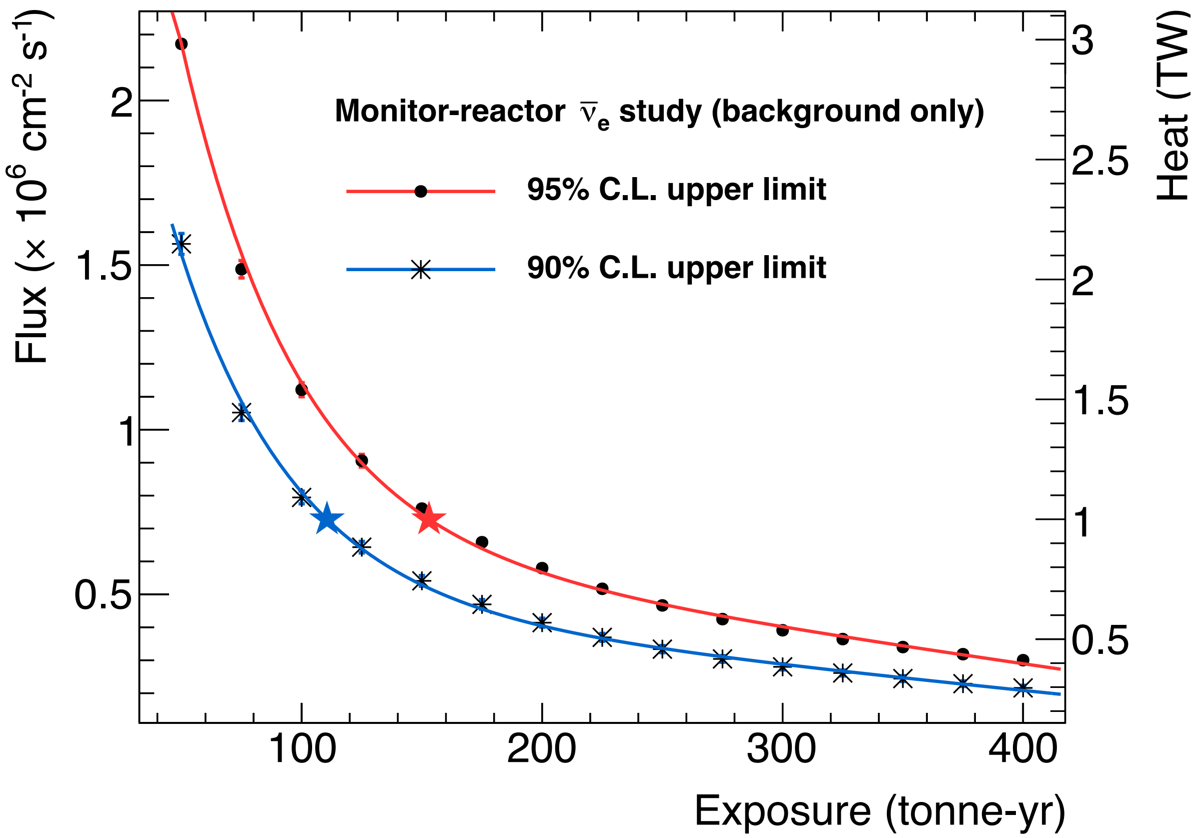


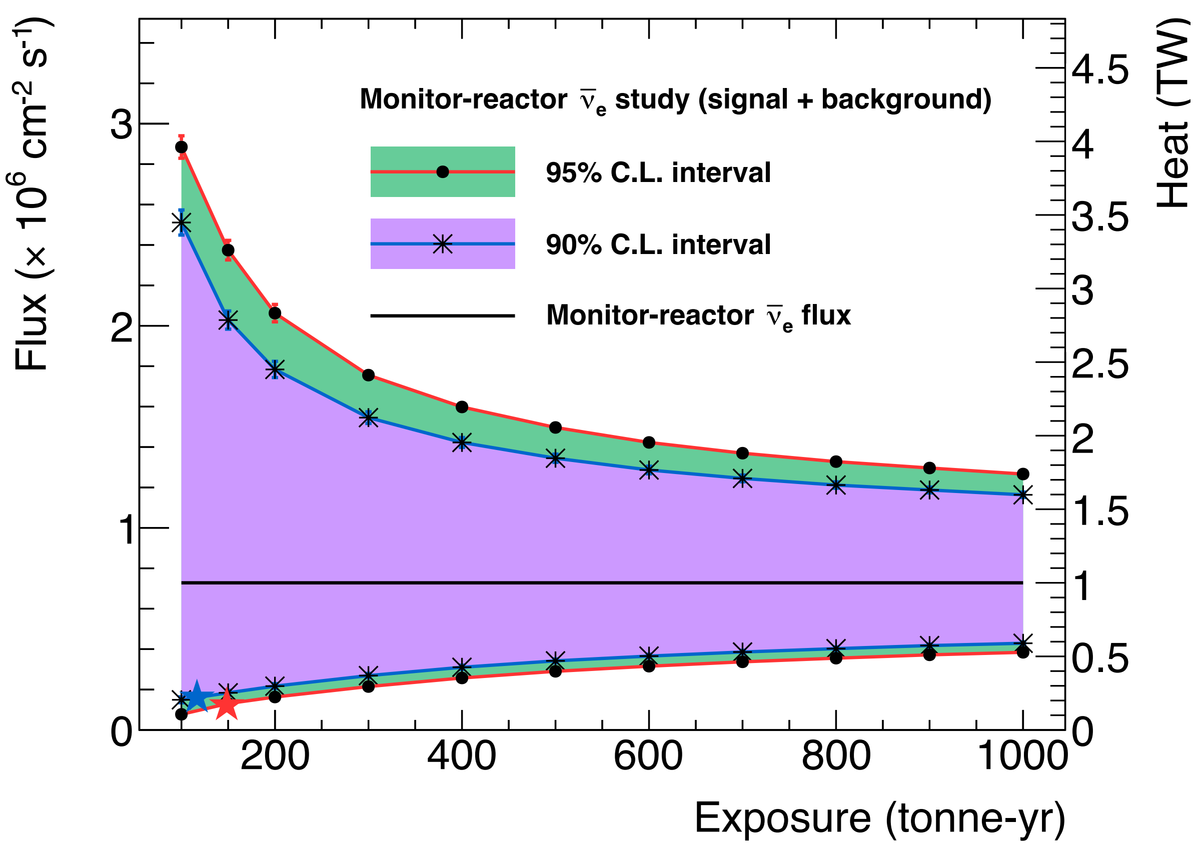




Reactor monitoring







Results: 95% (90%) CL

Φ	Site (*configuration*)	Case (i) background only (tonne-yr)	Case (ii) signal + background (tonne-yr)	Case (ii) signal + background ($10^6\,cm^{-2}\,s^{-1}$)
^{40}K	Kamioka	123.0 (86.5)	156.5 (106.0)	2.86 (3.30)
	LNGS	108.2 (75.4)	140.8 (97.4)	3.58 (4.05)
	LNGS (*high res.*)	70.0 (47.5)	82.0 (58.5)	3.27 (3.88)
	LNGS (*no syst.*)	105.7 (74.1)	132.6 (94.1)	3.70 (4.13)
	SNOLab	105.7 (73.4)	132.7 (89.8)	3.69 (4.08)
Mantle (no radioactivity in core)	Kamioka	630 (435)	1978 (1051)	2.58 (2.52)
	LNGS	760 (520)	2559 (1419)	2.75 (2.74)
	LNGS (*high res.*)	521 (354)	1632 (933)	2.72 (2.69)
	LNGS (*no syst.*)	705 (488)	1850 (1050)	2.50 (2.51)
	SNOLab	818 (560)	2675 (1557)	2.81 (2.84)
Core	Kamioka	72855 (53013)	216634 (137531)	0.177 (0.186)
	LNGS	64443 (47444)	207852 (134233)	0.174 (0.184)
	LNGS (*high res.*)	54128 (40245)	168930 (104542)	0.174 (0.182)
	LNGS (*no syst.*)	61974 (46210)	192290 (125890)	0.180 (0.188)
	SNOLab	64241 (46823)	236398 (136847)	0.172 (0.175)

Reactor monitoring results: 95% (90%) CL

	Case (i)	Case (ii)	
Site (*configuration*)	background only	signal + background	
	(tonne-yr)	(tonne-yr)	(10^6 cm^{-2} s^{-1})
Kamioka	152.5 (110.5)	126.9 (98.1)	0.102 (0.146)
LNGS	153.0 (110.5)	148.5 (111.9)	0.126 (0.154)
LNGS (*high res.*)	146.2 (105.8)	133.5 (105.9)	0.124 (0.151)
LNGS (*no syst.*)	152.6 (110.4)	148.5 (111.9)	0.126 (0.156)
SNOLab	285.7 (199.1)	422.0 (300.8)	0.181 (0.206)