Neutrino geoscience and reactor monitoring with direction-sensitive detectors

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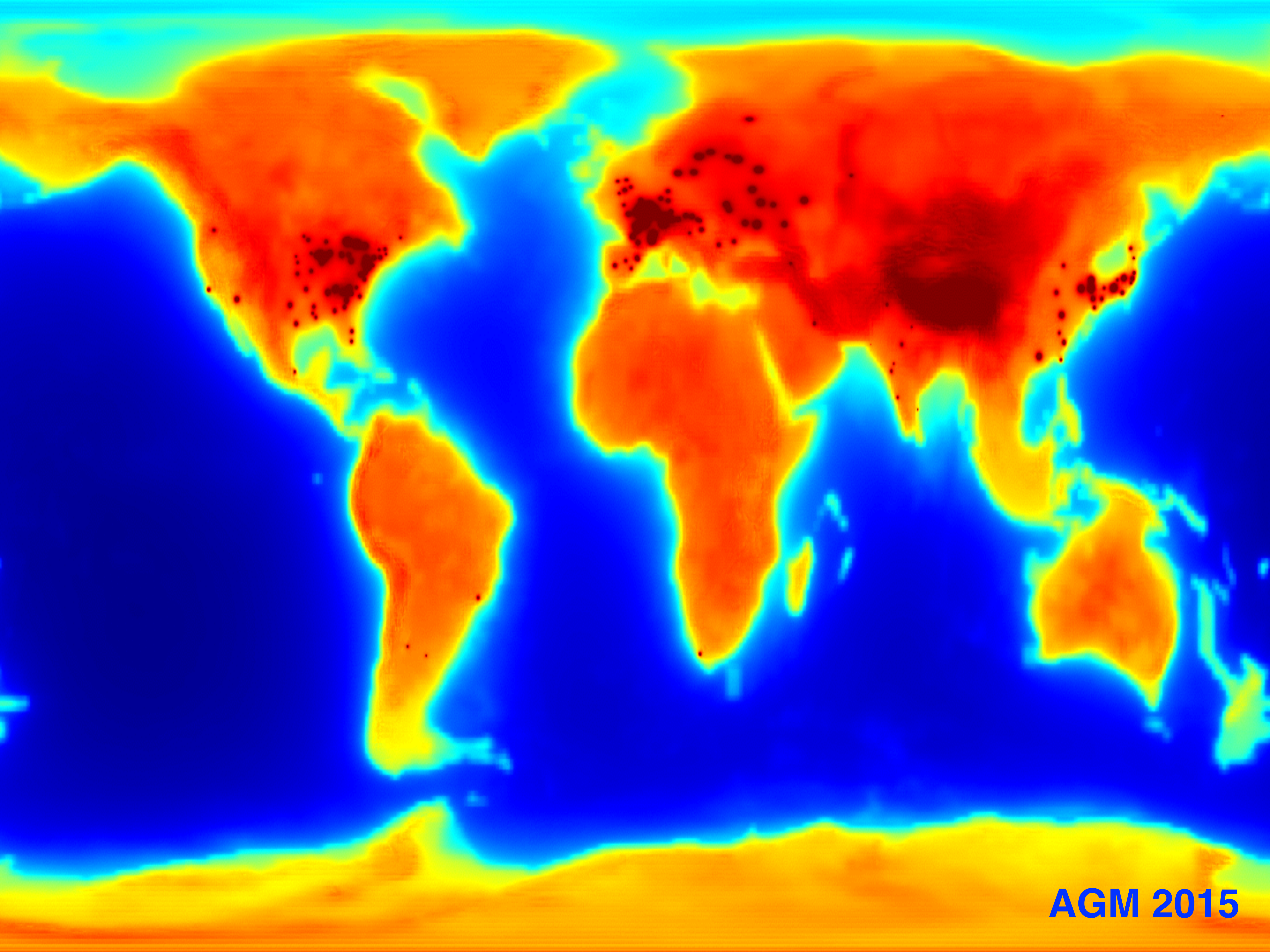
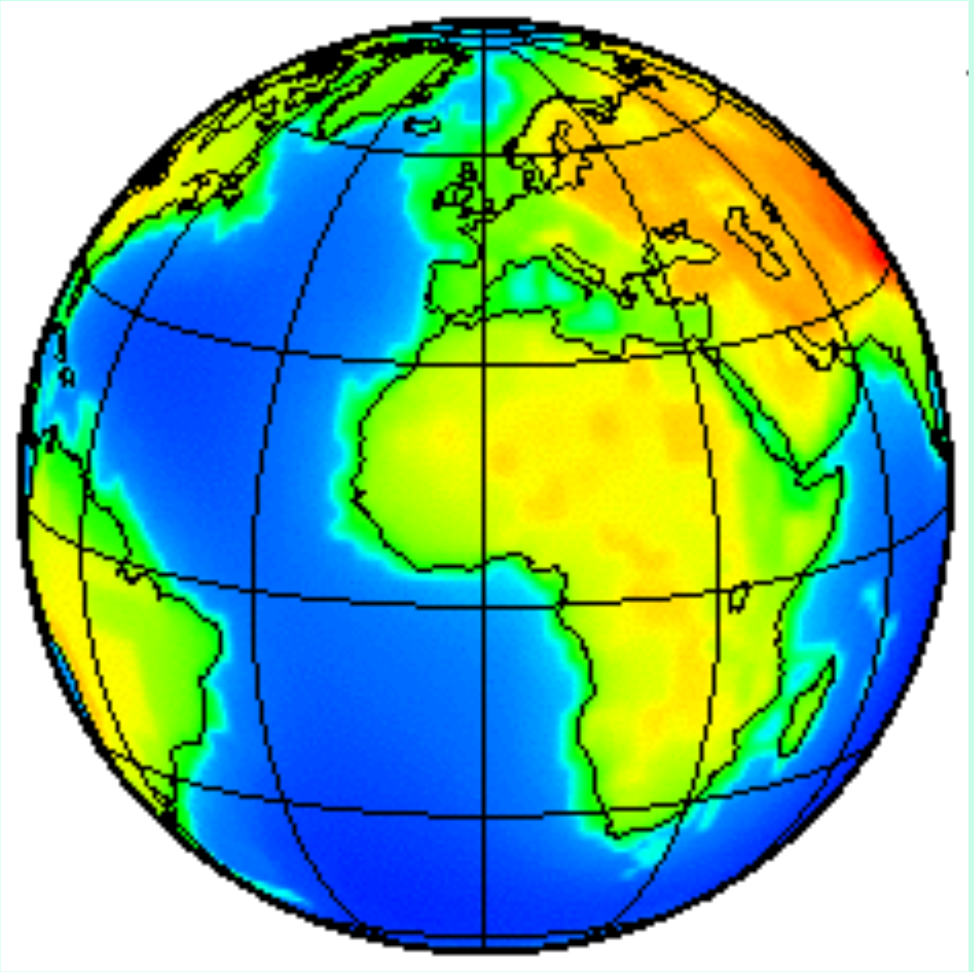
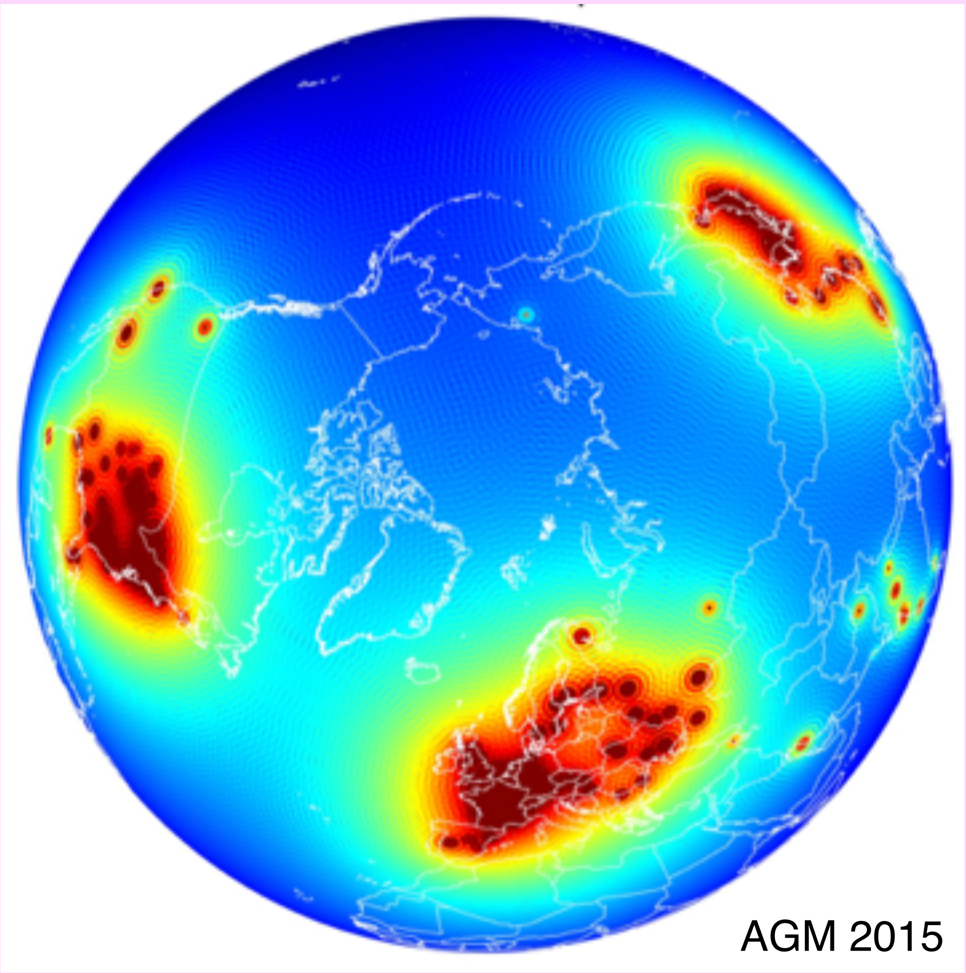

AGM 2015

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}

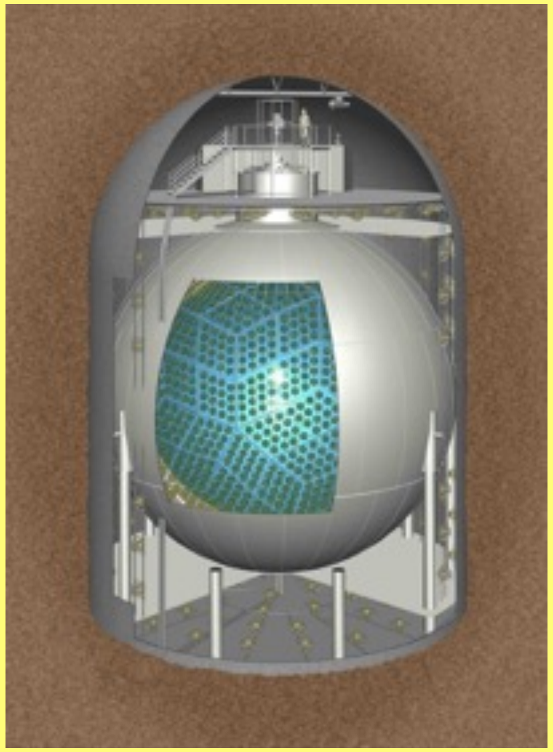
Geo-ν's give us clues about:

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

Geo-ν measurements

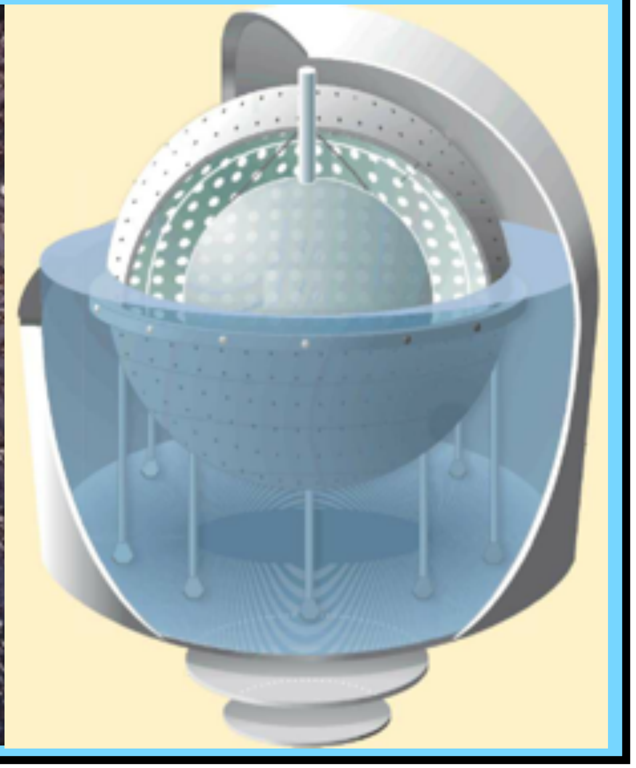
KamLAND, Kamioka, Japan

- 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)
- $<P_{ee}> = 0.551 \pm 0.015$
- $\Phi(U+Th) = 3.9^{+0.7}_{-0.6} \times 10^6$ /cm²/s
- 164^{+28}_{-25} 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 188 ^{238}U, ^{232}Th geo-ν events ...

✘ but no ^{40}K geo-ν events

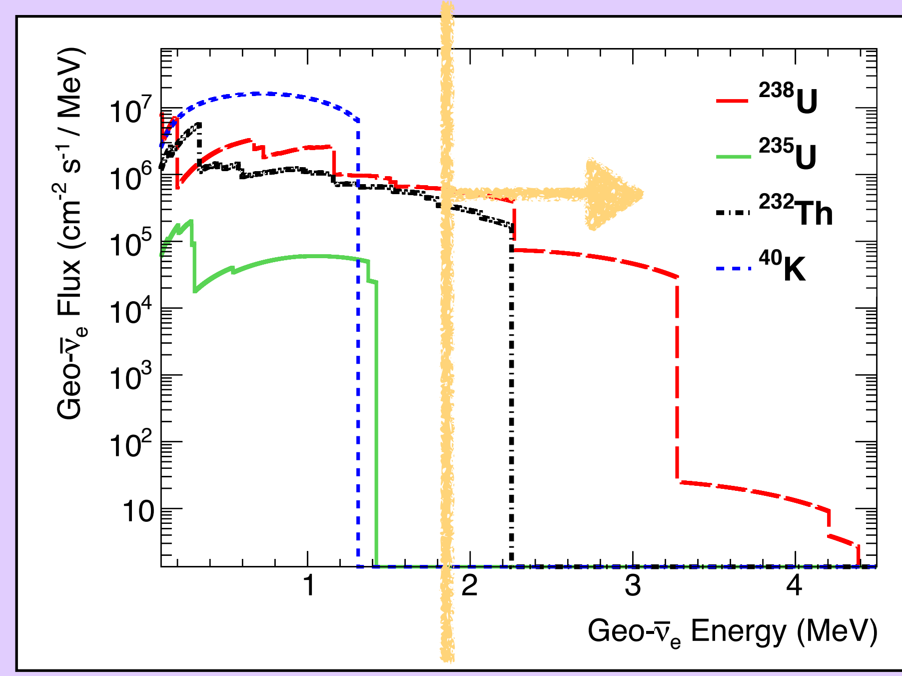
✔ Rate and energy measured ...

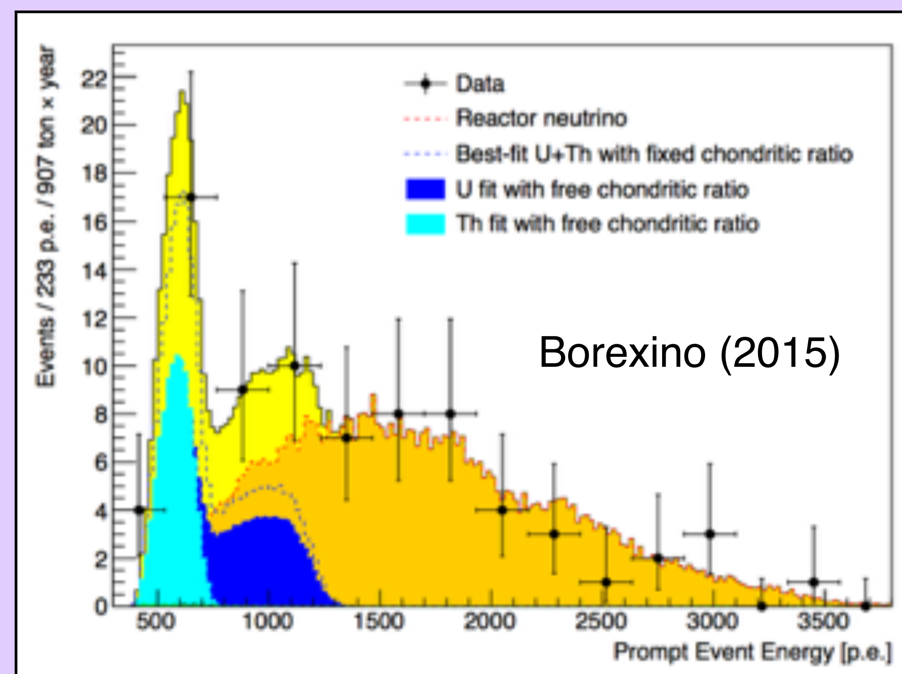
✘ but not direction

✔ Measured signals are consistent ...

✘ but large uncertainties (±18-26%)

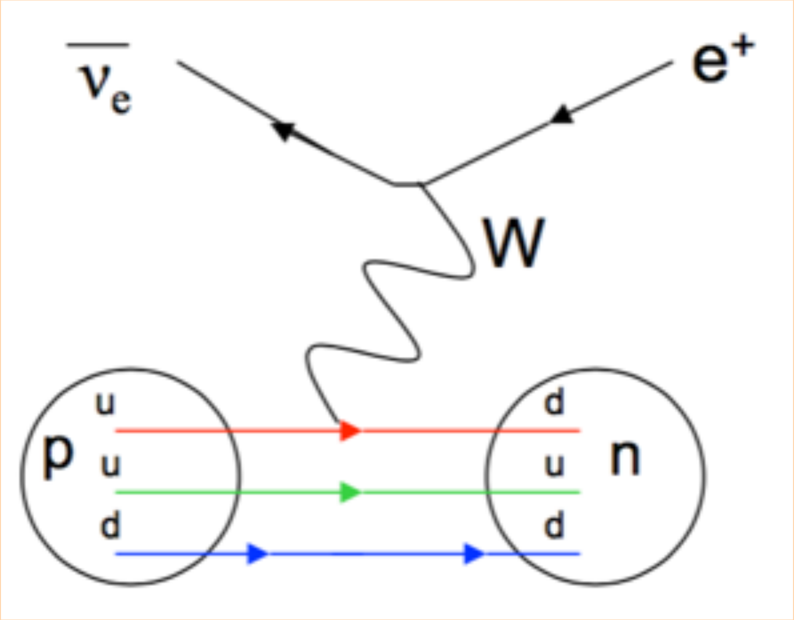
➜ Model-dependent assumptions required for interpreting results





Inverse beta decay

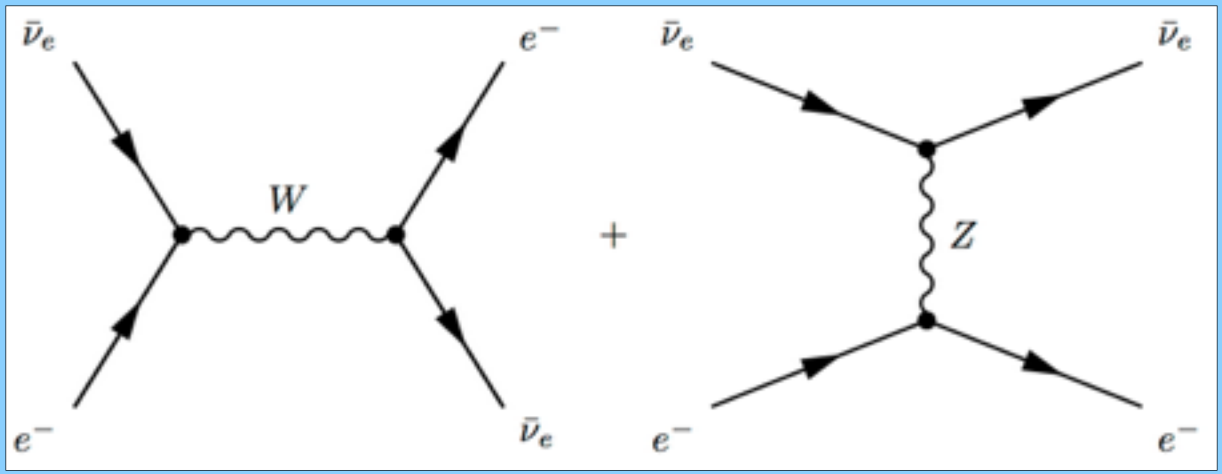
$$\overline{\nu}_e + p^+ \rightarrow e^+ + n$$



- 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

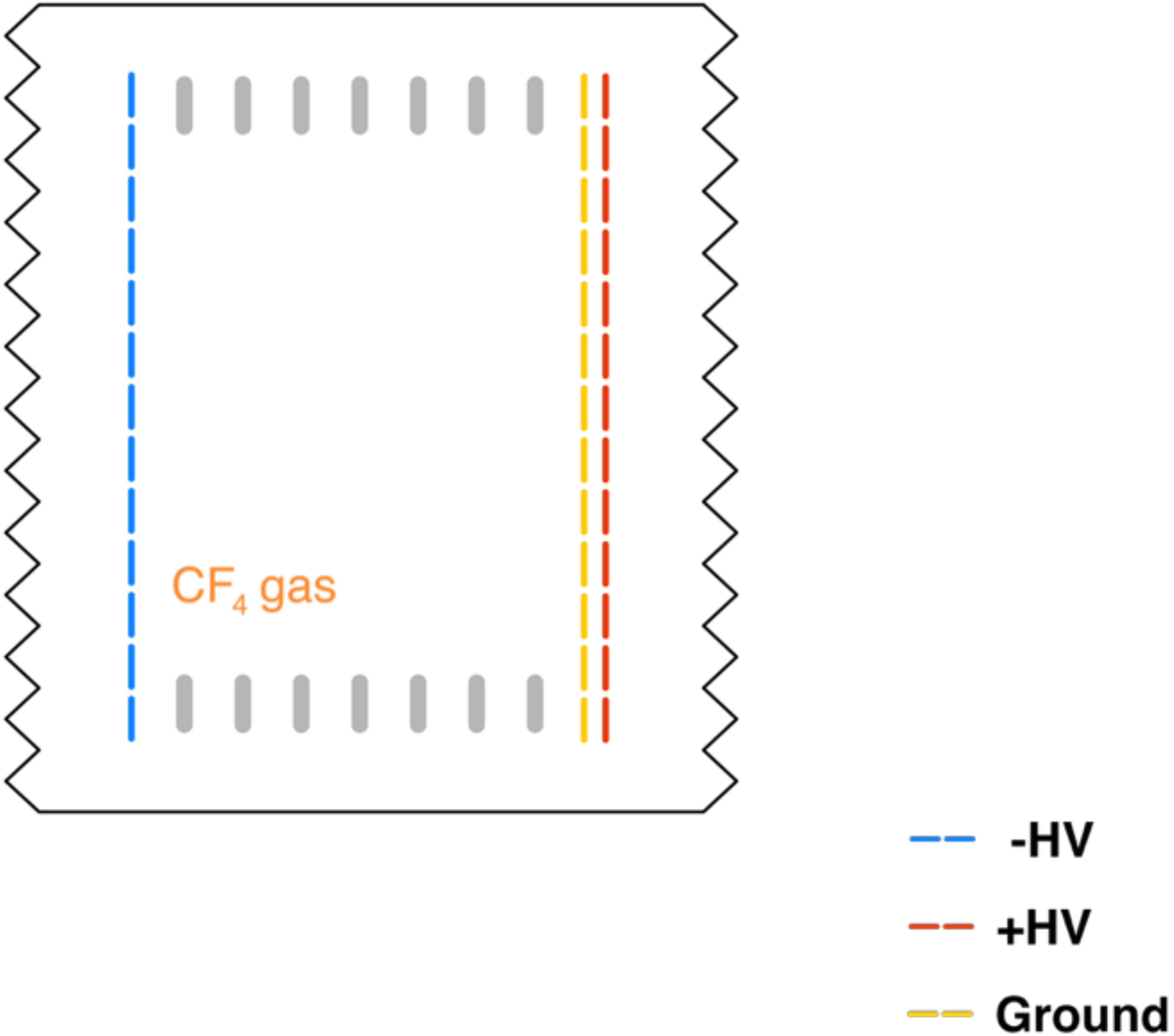
Elastic scattering

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

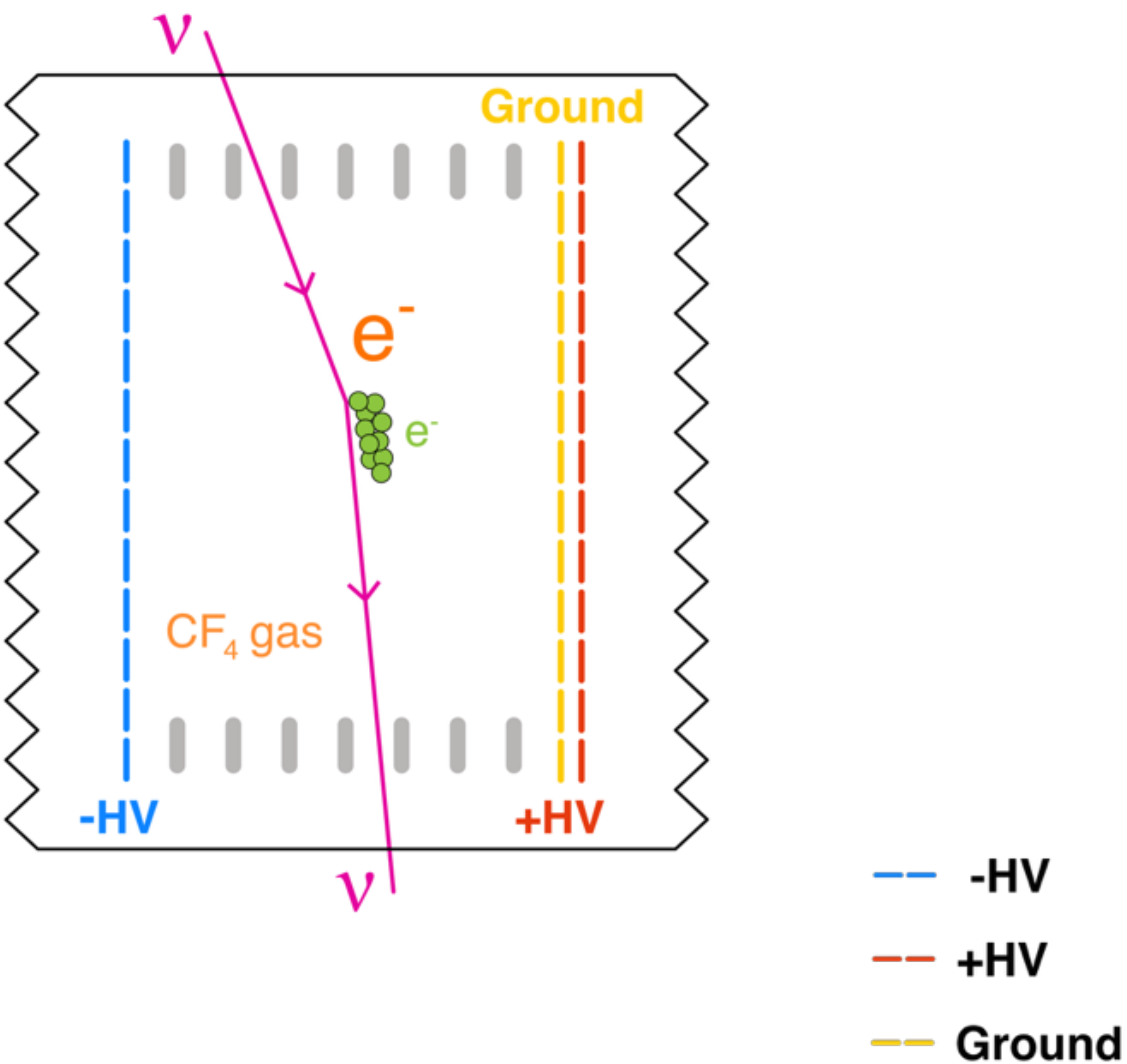


- Electron target, no energy threshold
- $\sigma(E_\nu) \approx 4.0\text{x}10^{-45} (E_\nu) \text{ cm}^2$
- Direction of outgoing e^- closely correlated to direction of incoming ν

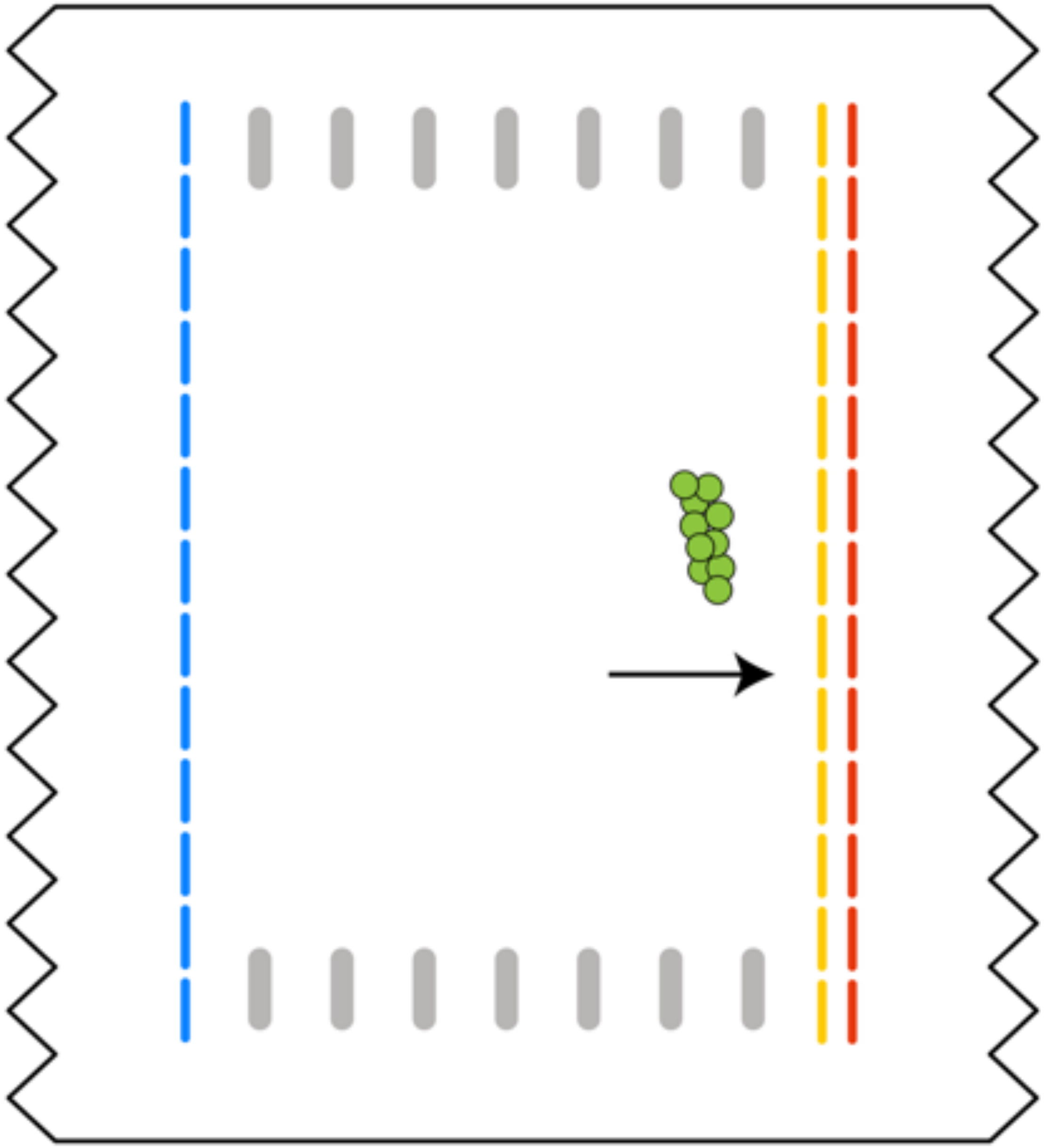
e⁻ recoils in gas TPCs

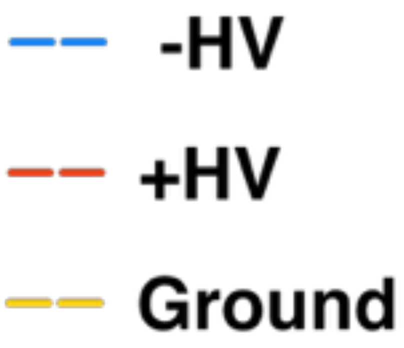


e^- recoils in gas TPCs

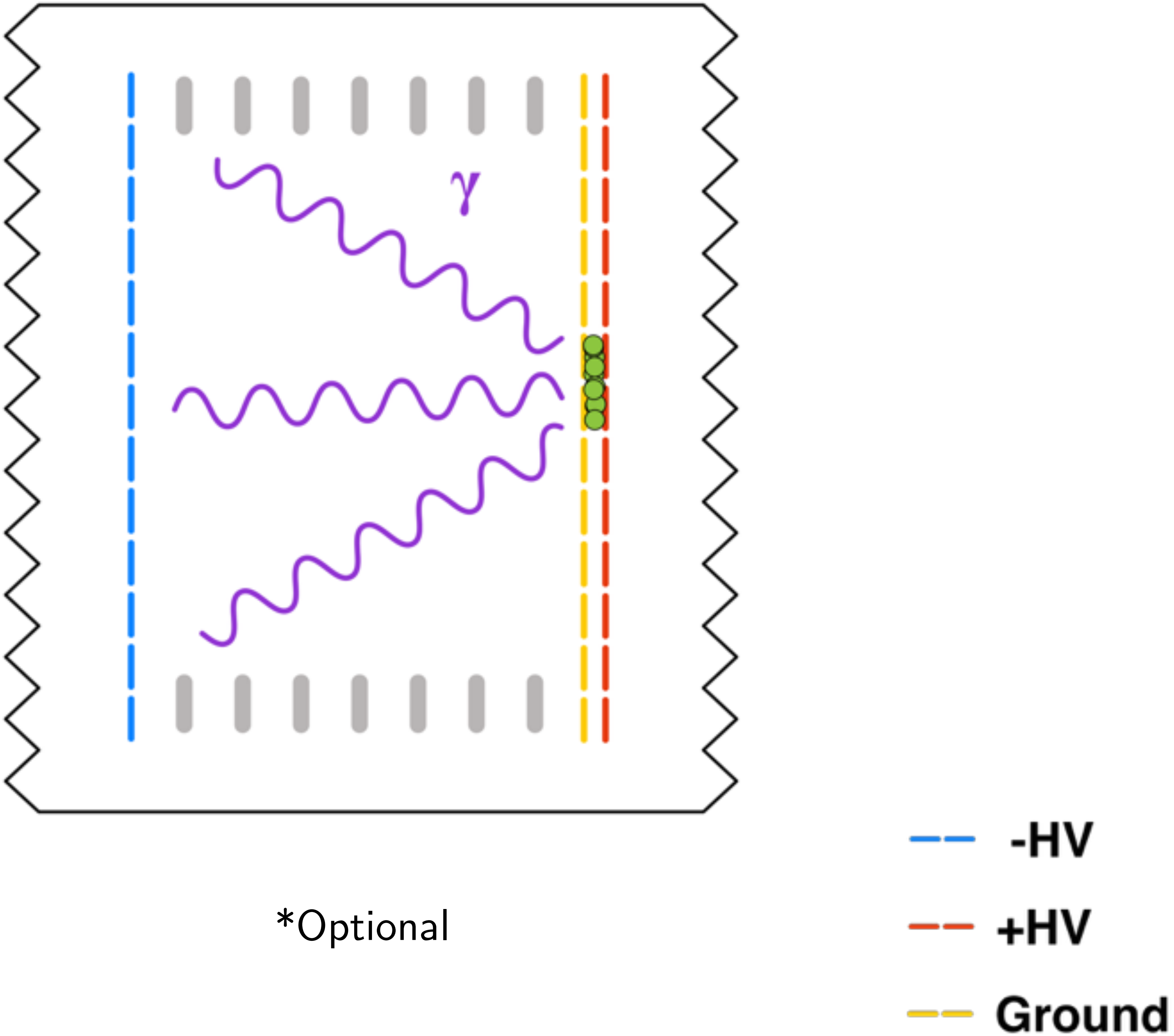


e⁻ recoils in gas TPCs





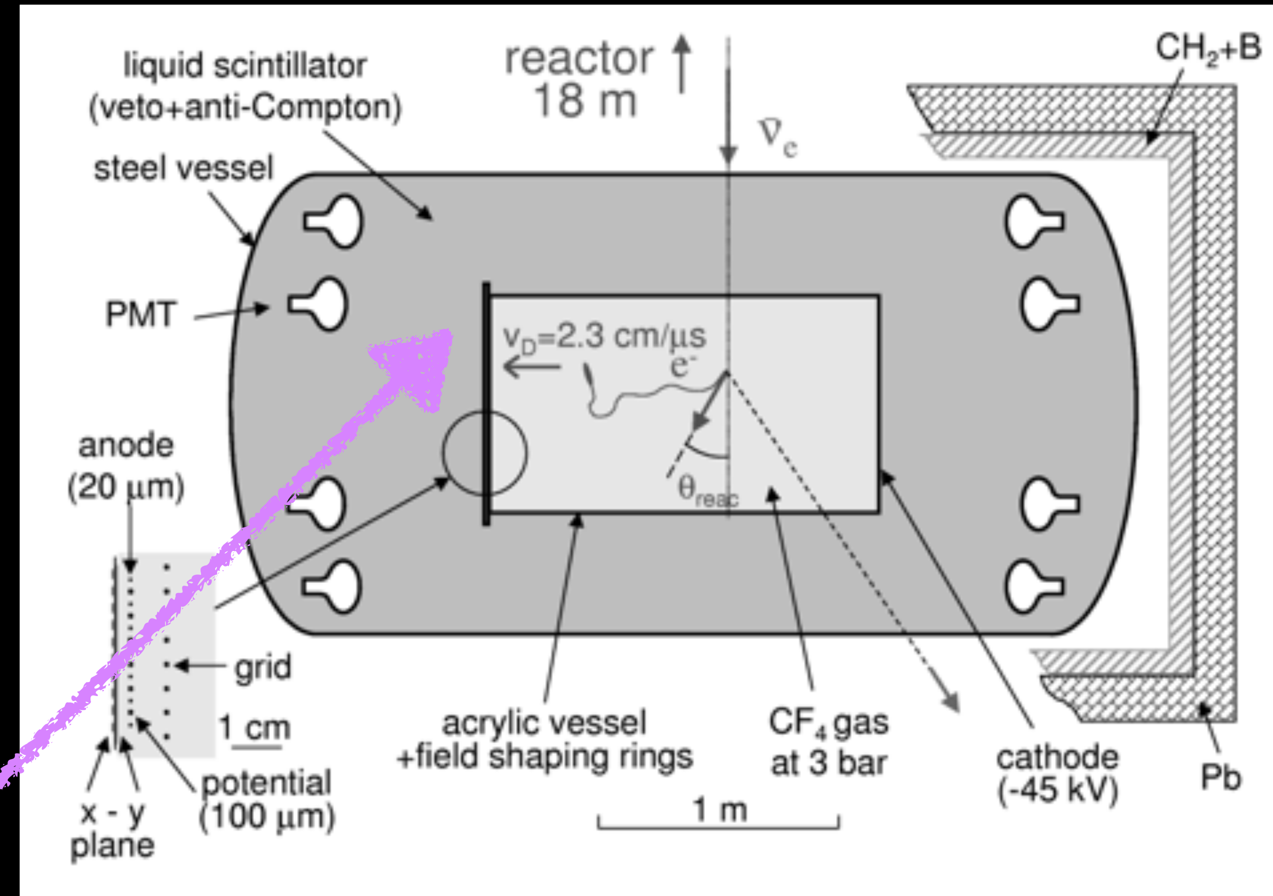
e⁻ recoils in gas TPCs

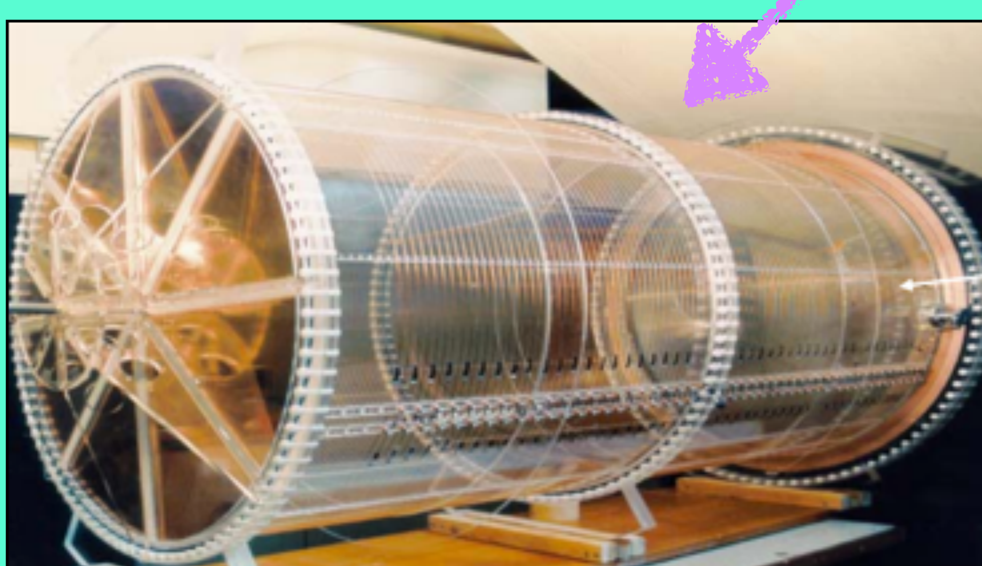


*Optional

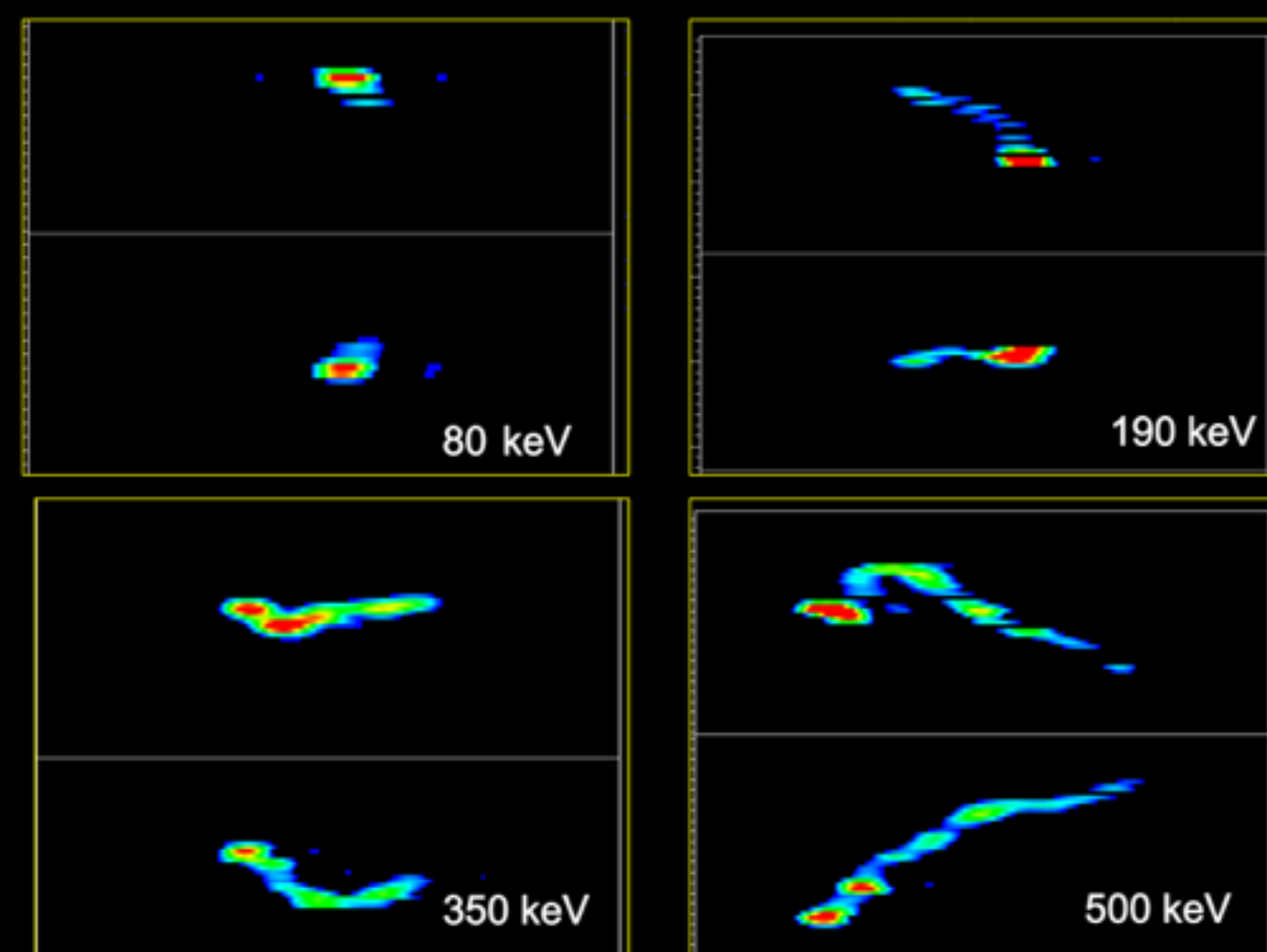
e^- recoils in MUNU

- 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*

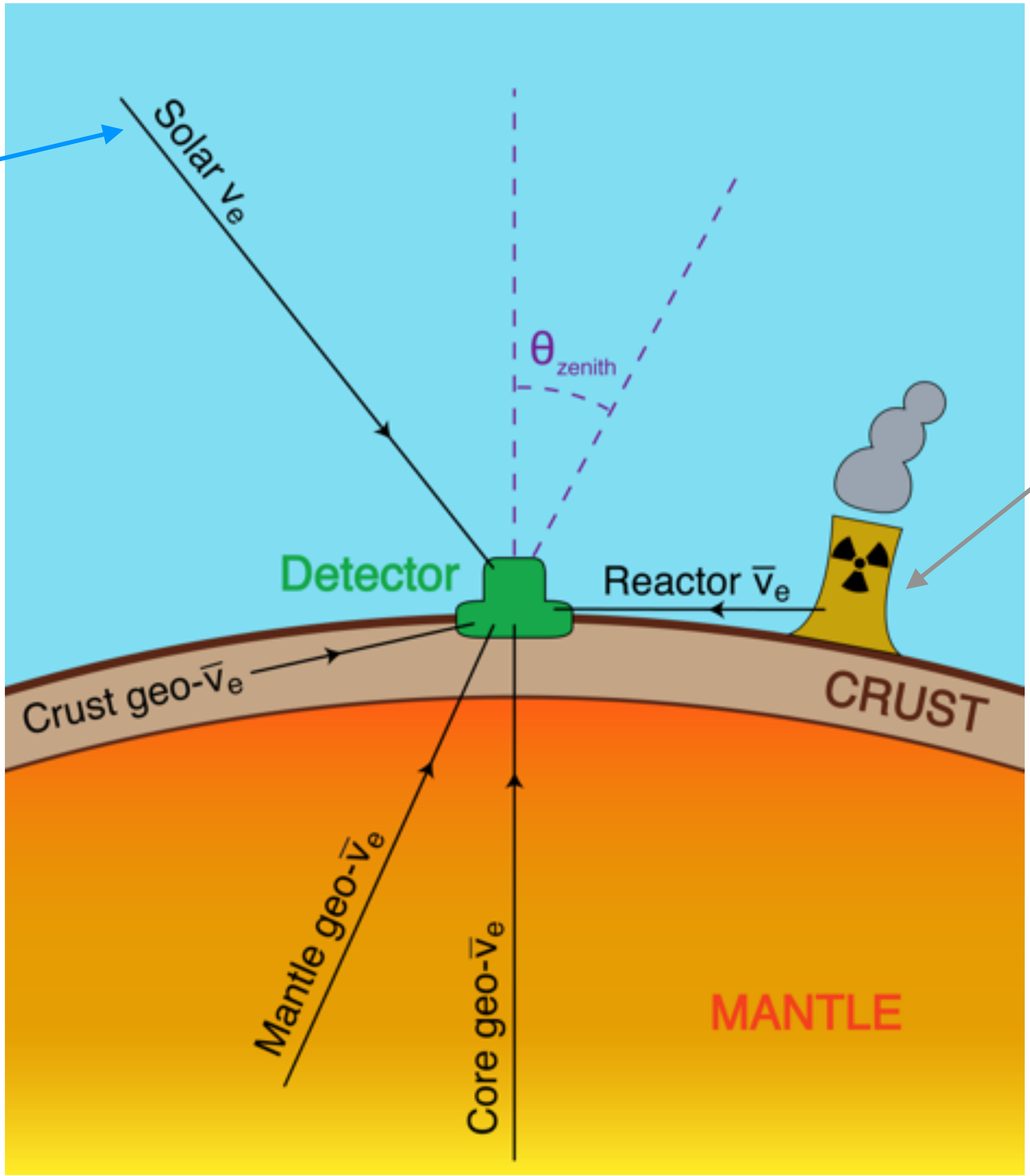
Neutrino flux model

Normalization from Bergstrom et al. *JHEP* **03**, 132 (2016)

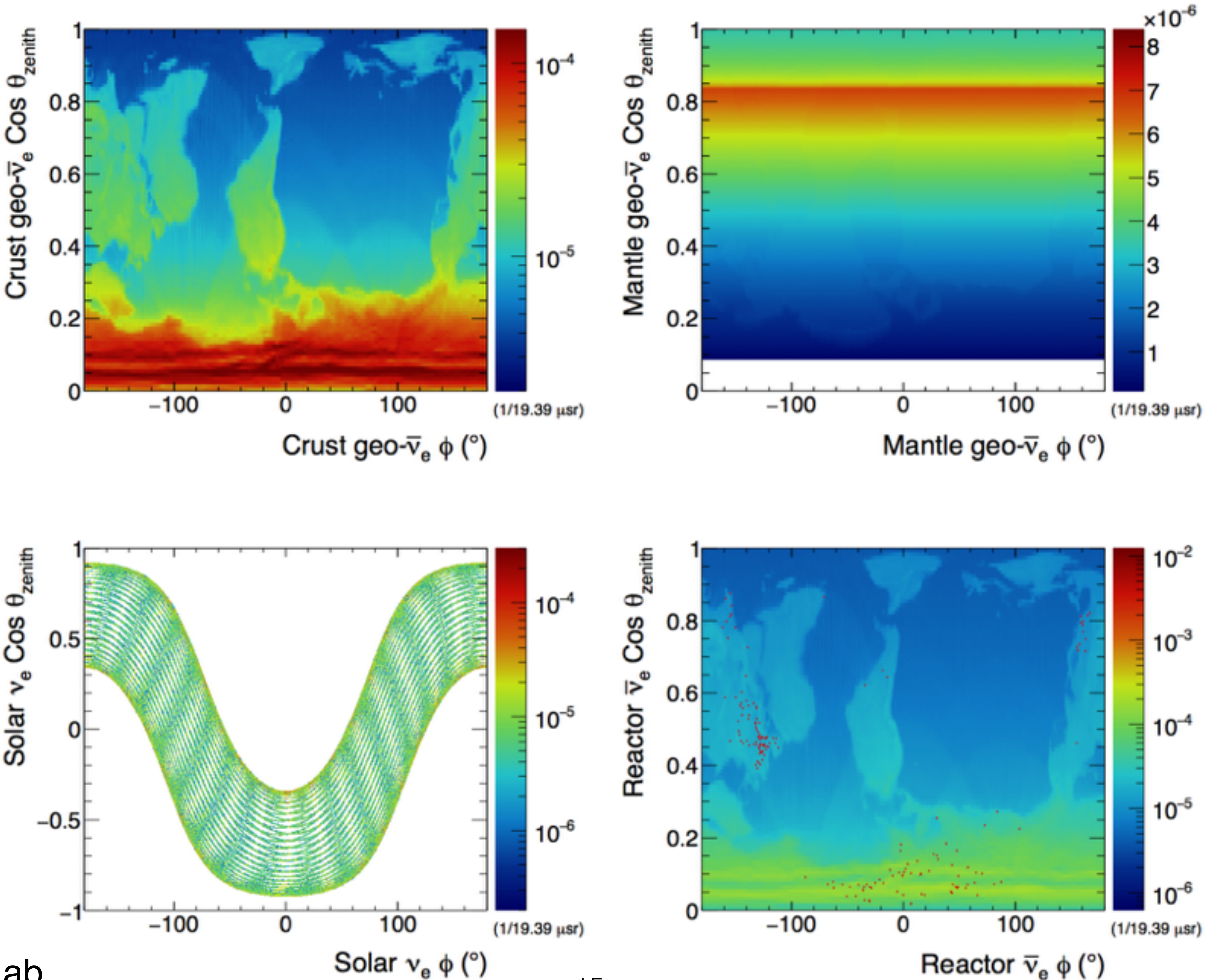
Positions and 2014 average powers from PRIS

Physical structure from seismology (CRUST 1.0)

Homogenous spherical shell (PREM)



Incident angular distributions

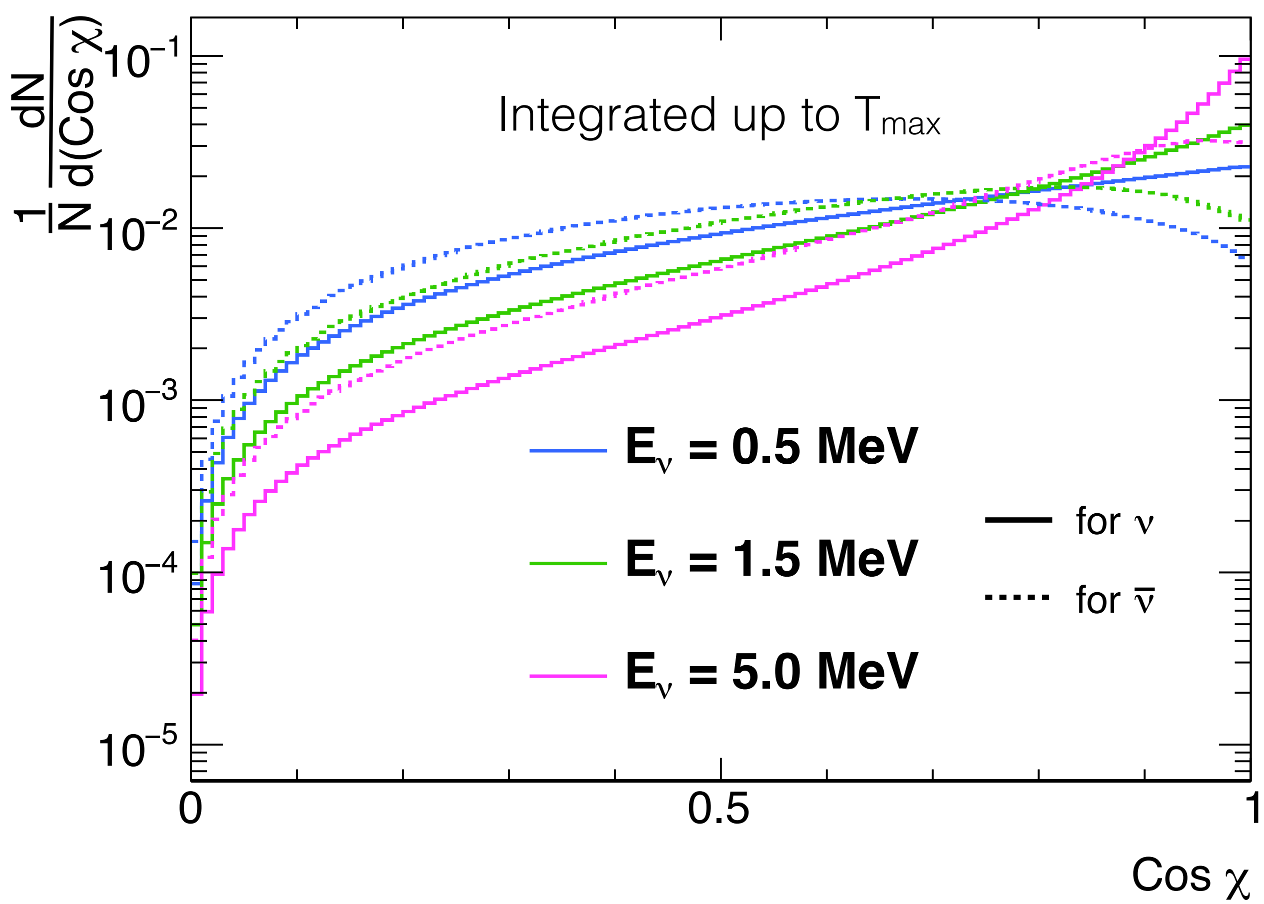


*at SNOLab

Scattering kinematics and differential cross section

T = kinetic energy of outgoing e⁻

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

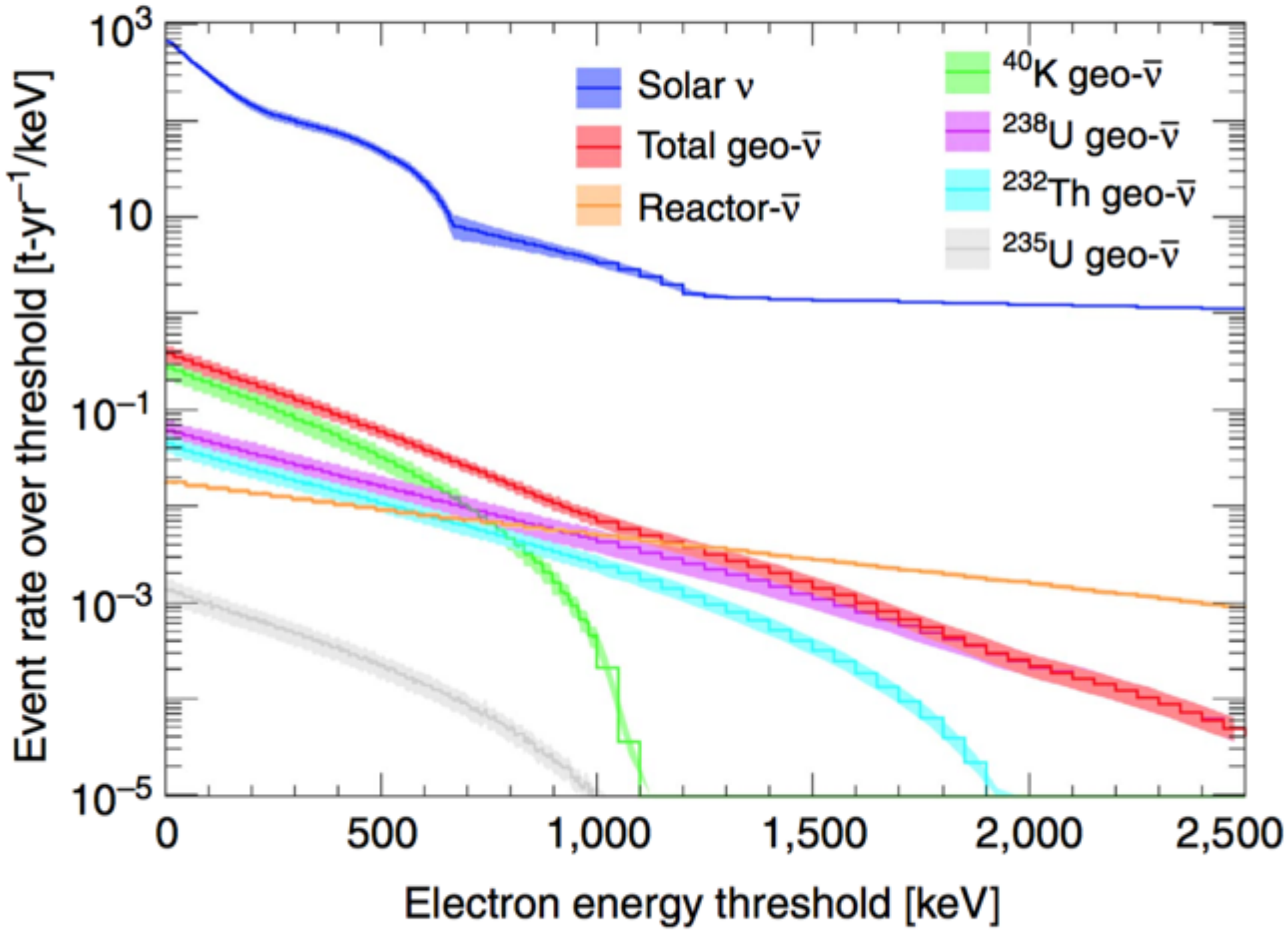


Assuming zero neutrino charge radius and magnetic moment, then:

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

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

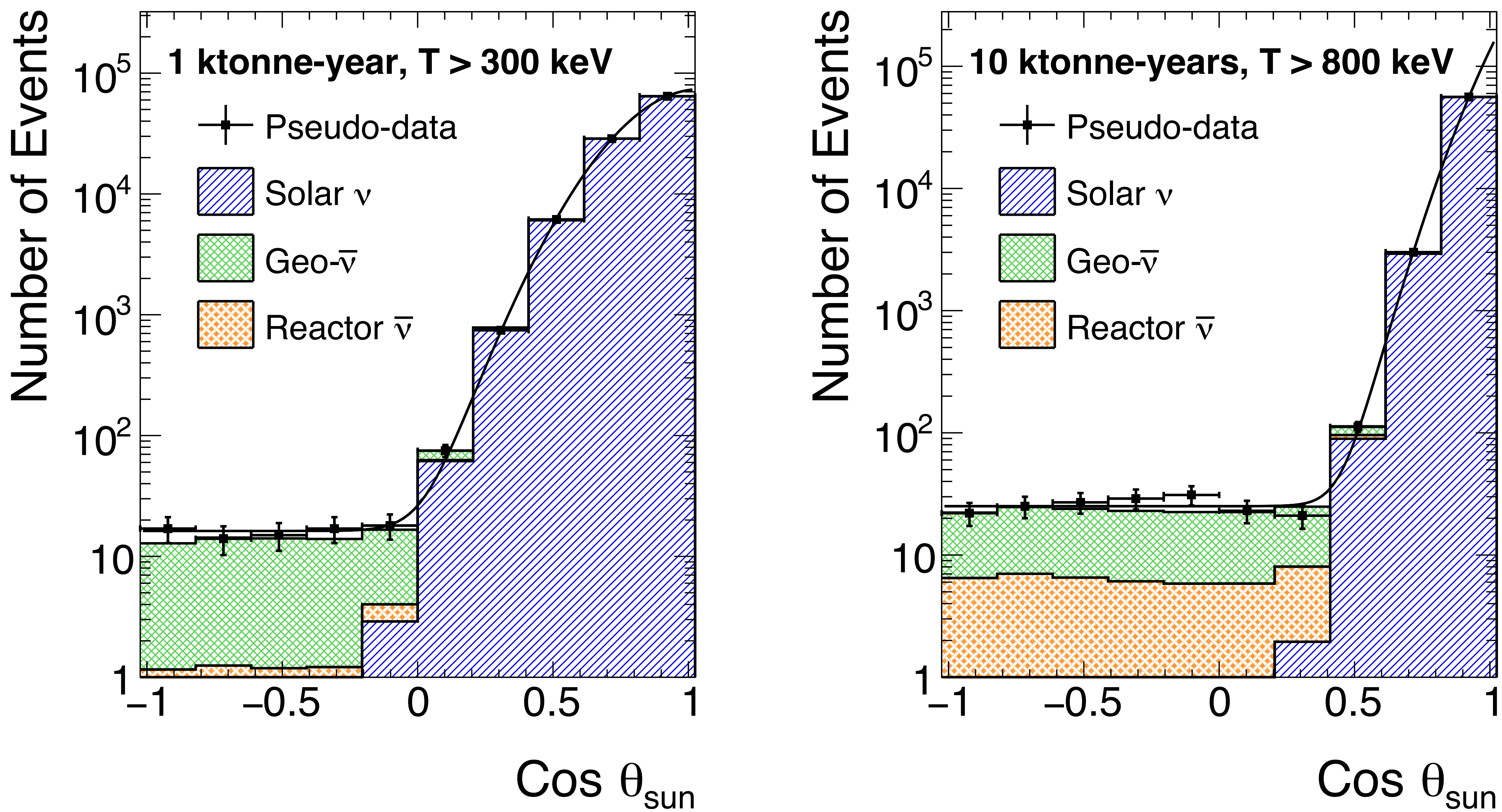
Event rates (CF_4 target)



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

*at Gran Sasso

Cut on solar angle separation (θ_{sun})



Pseudo-data includes smearing by MUNU angular and energy resolutions

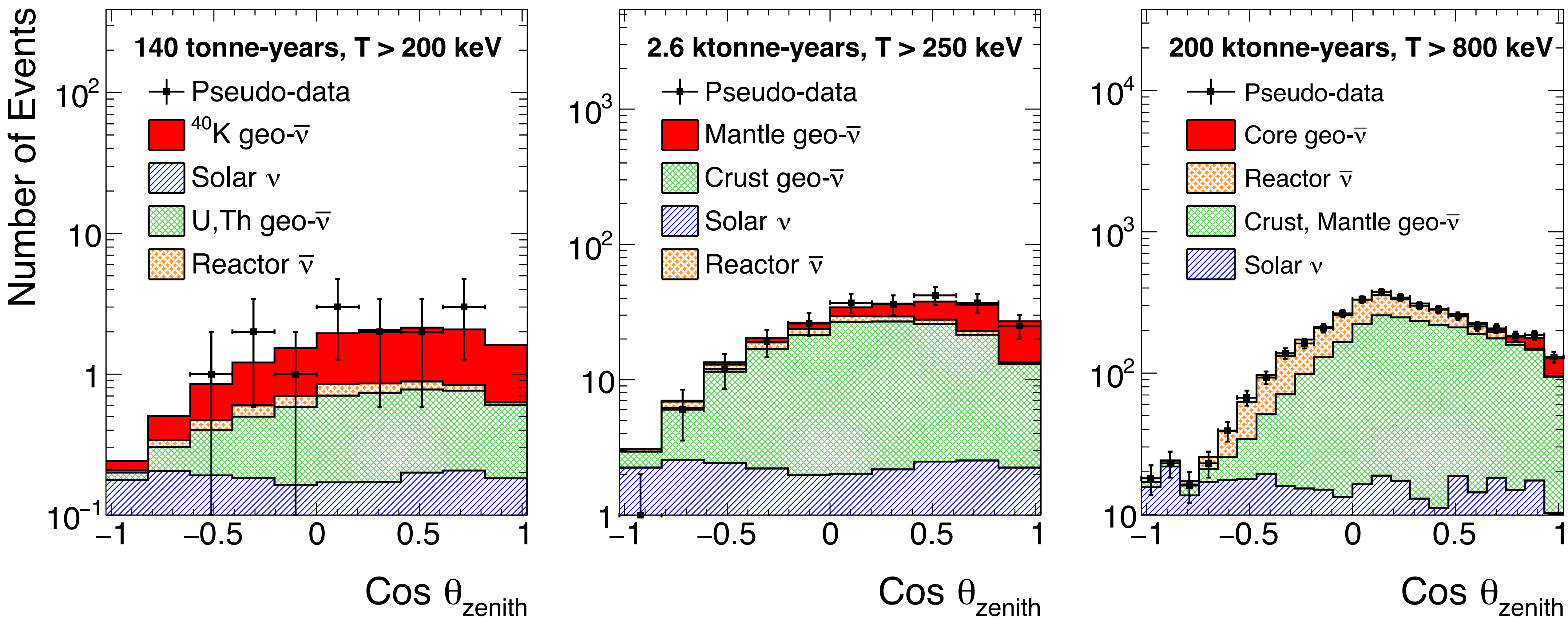
$$f(\cos\theta) = A\frac{e^{\kappa\cos(\theta-\mu)}}{2\pi I_0(\kappa)} + C,$$

*at Gran Sasso

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

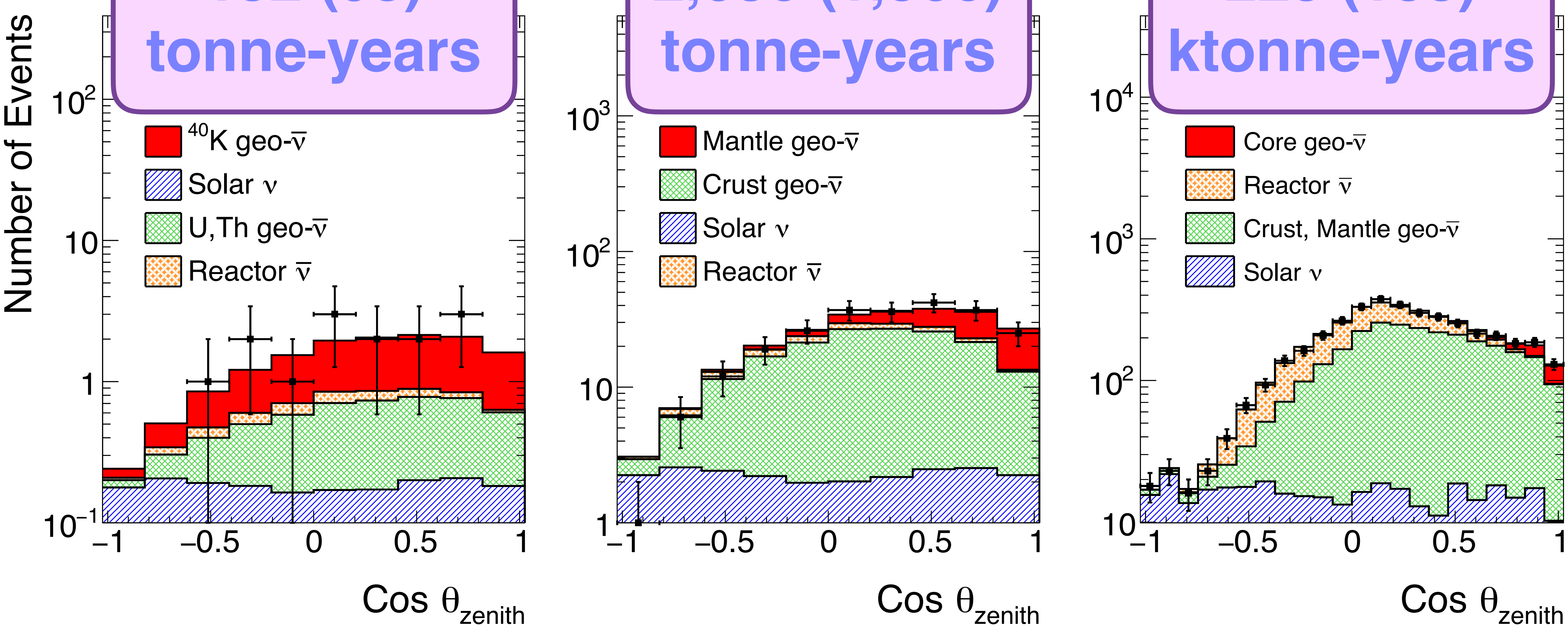


*at Gran Sasso

Results (SNOLab)

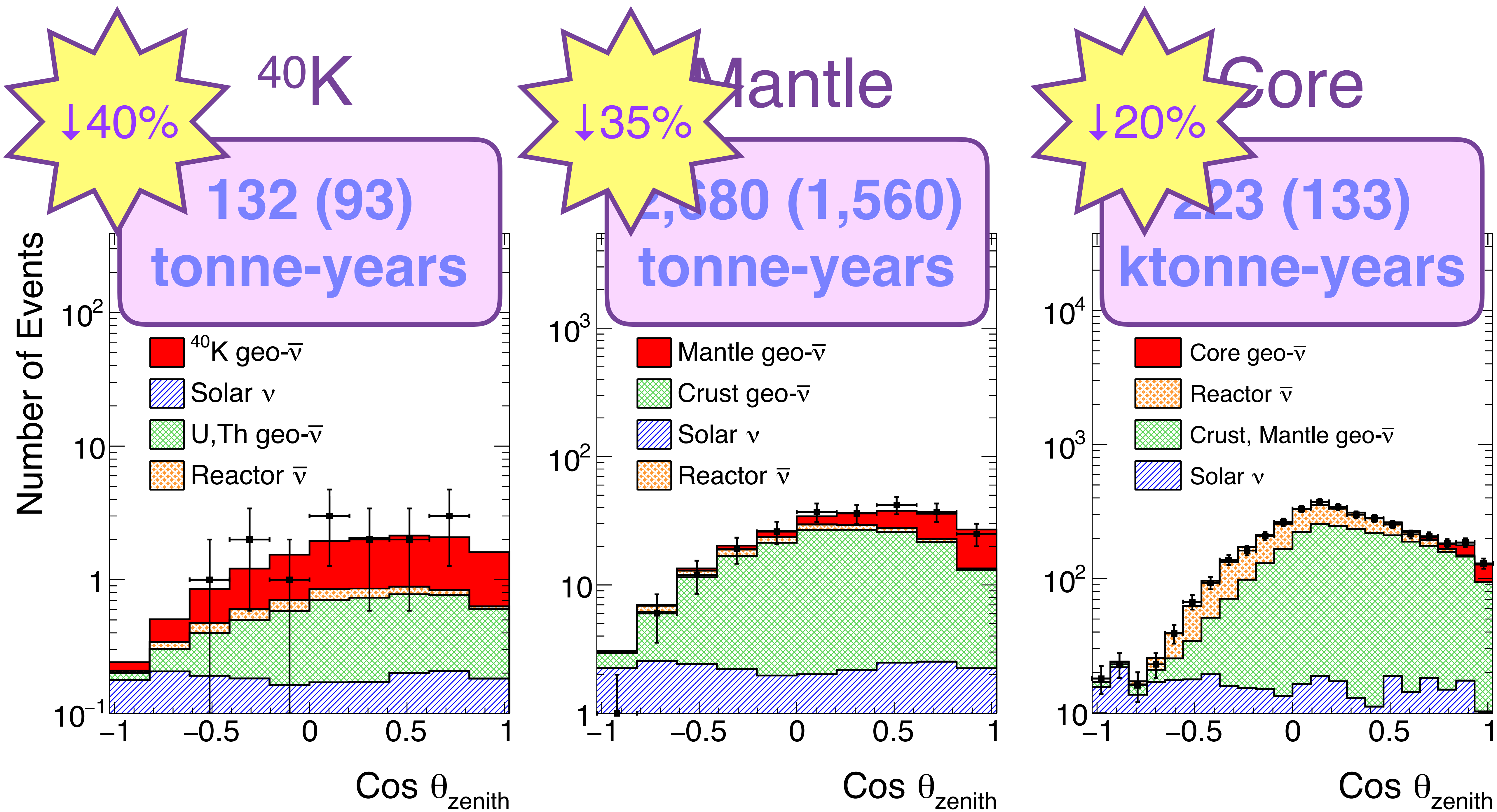
Exposures required to exclude null hypothesis at 95% (90%) CL for 95% (90%) of pseudo-experiments:

^{40}K	Mantle	Core
132 (93) tonne-years	**2,680 (1,560) tonne-years**	**223 (133) ktonne-years**



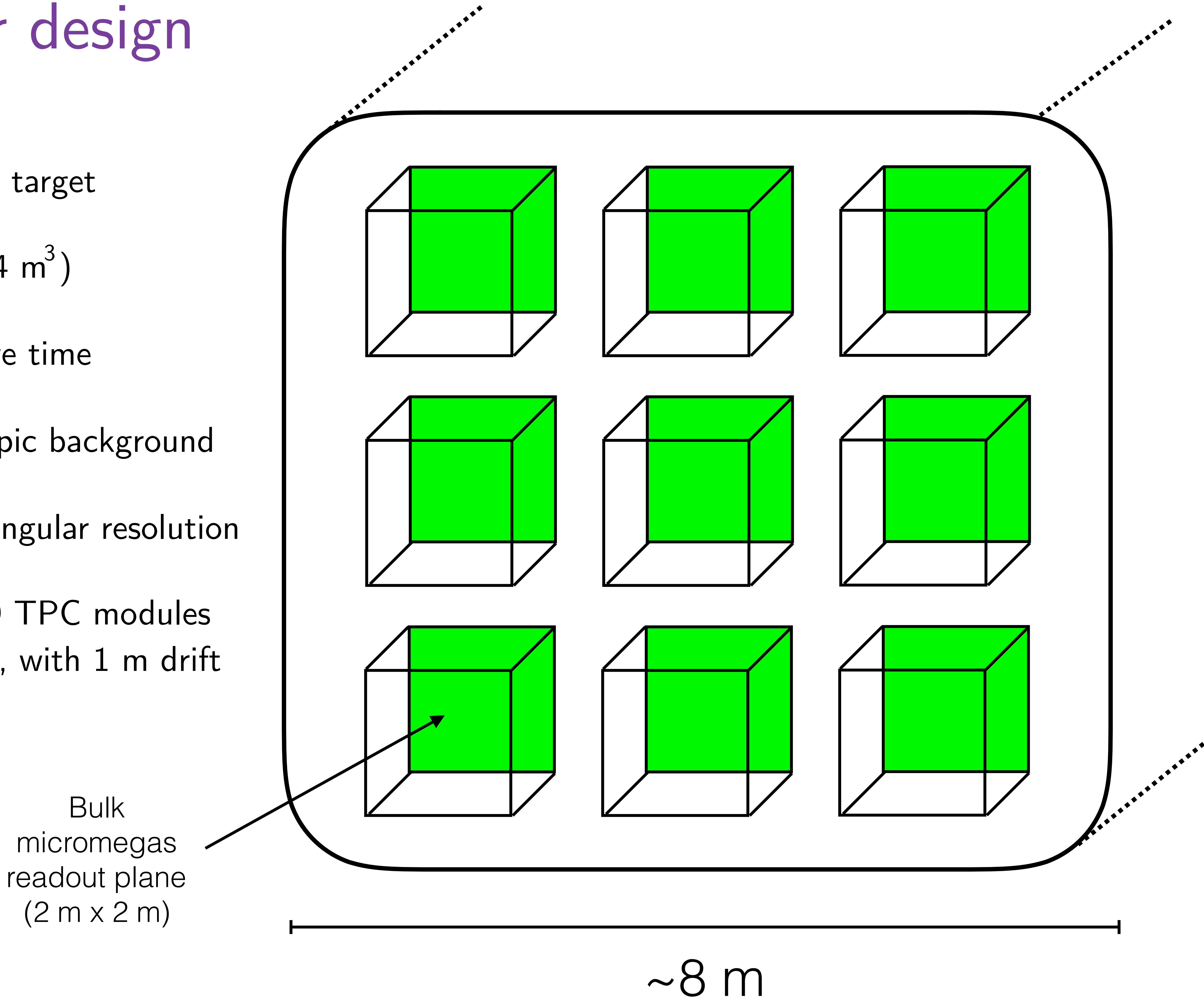
Improve angular resolution by factor of 2...

Exposures required to exclude null hypothesis at 95% (90%) CL for 95% (90%) of pseudo-experiments:



Detector design

- 6-tonne Xe target
- 10 bar (104 m^3)
- 10 years live time
- 20% isotropic background
- Improved angular resolution
- 3 rows of 9 TPC modules ($4\ m^3$ each, with 1 m drift length)

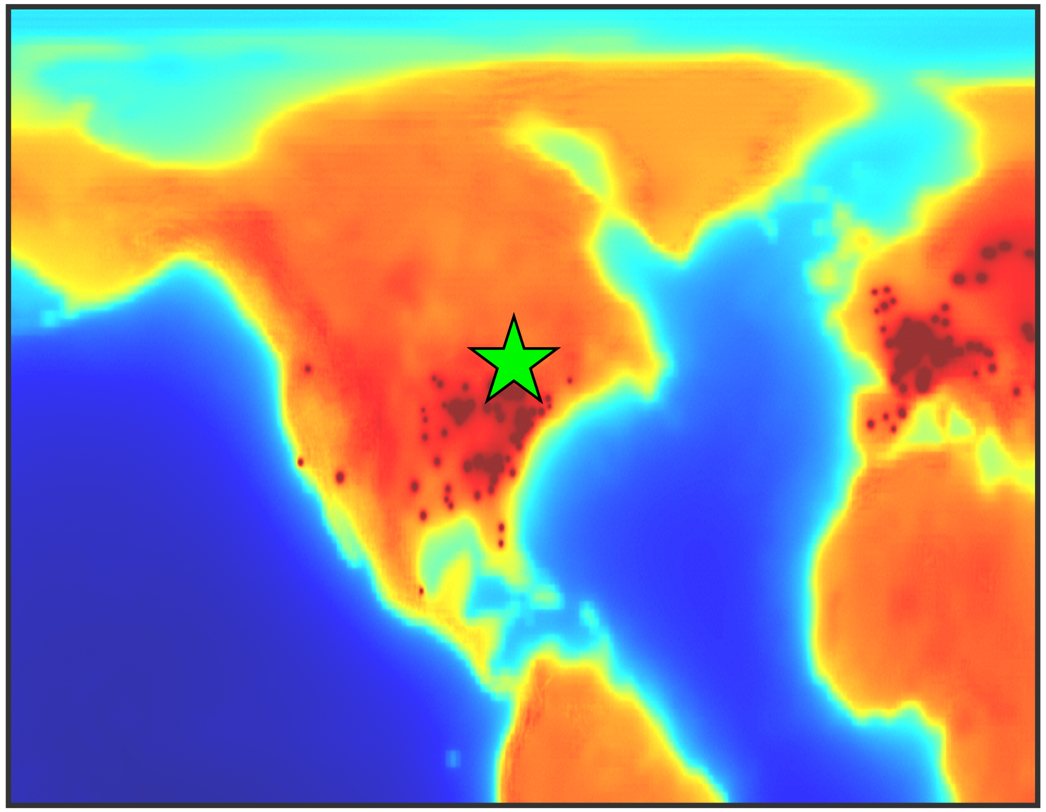


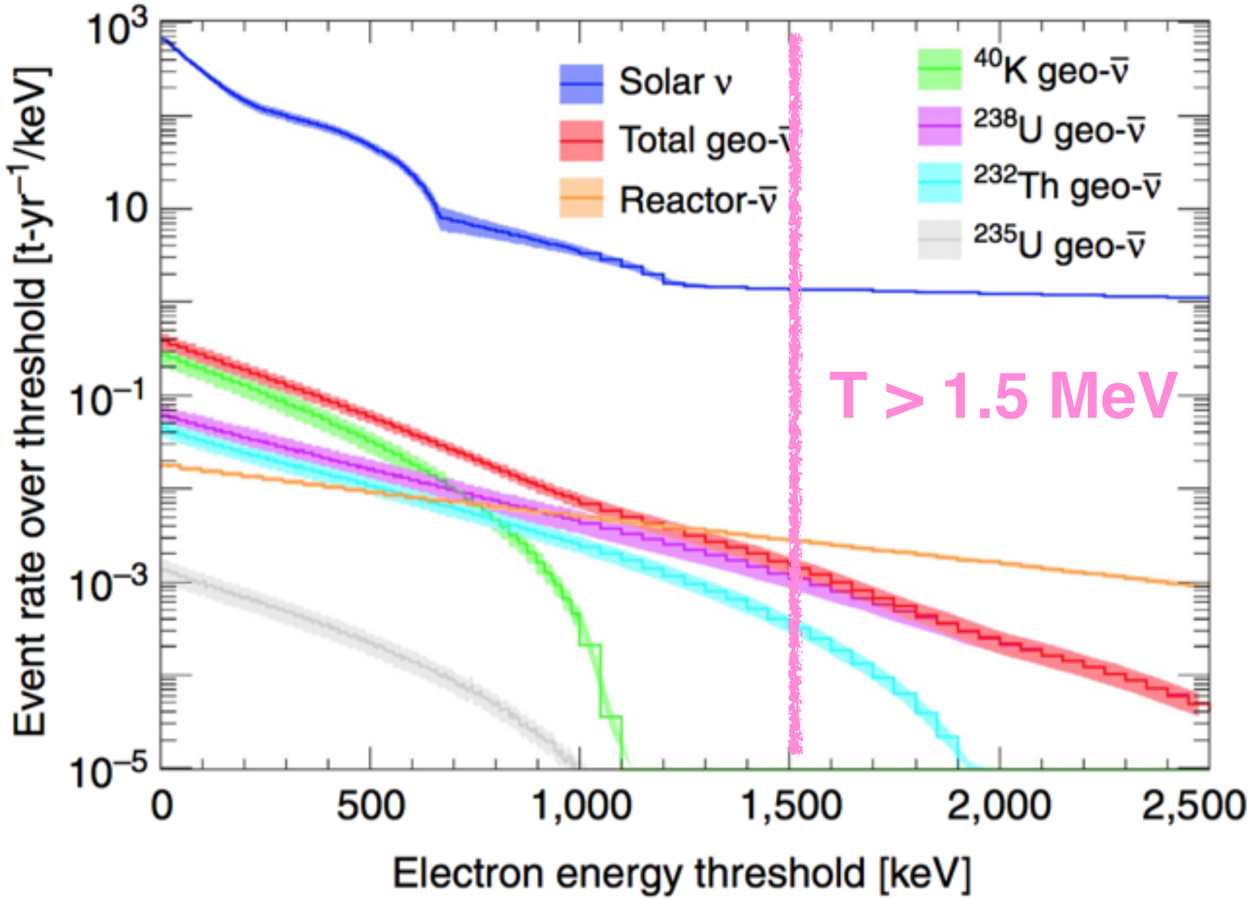
Reactor monitoring demonstration

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

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

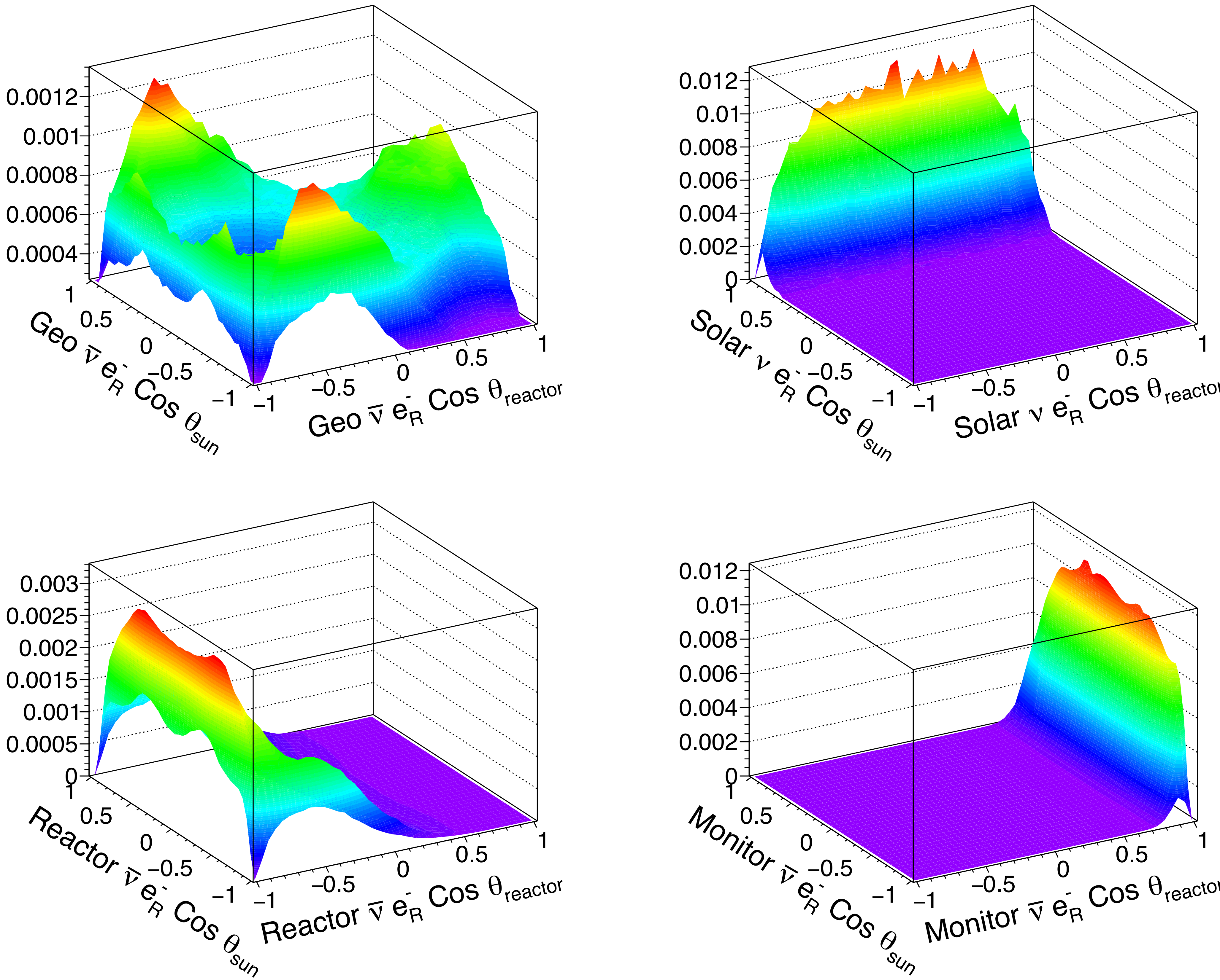
➔ Assume 50-MW reactor 10 km away from SNOLab





$\theta_{reactor}$ and θ_{sun}

T > 1.5 MeV

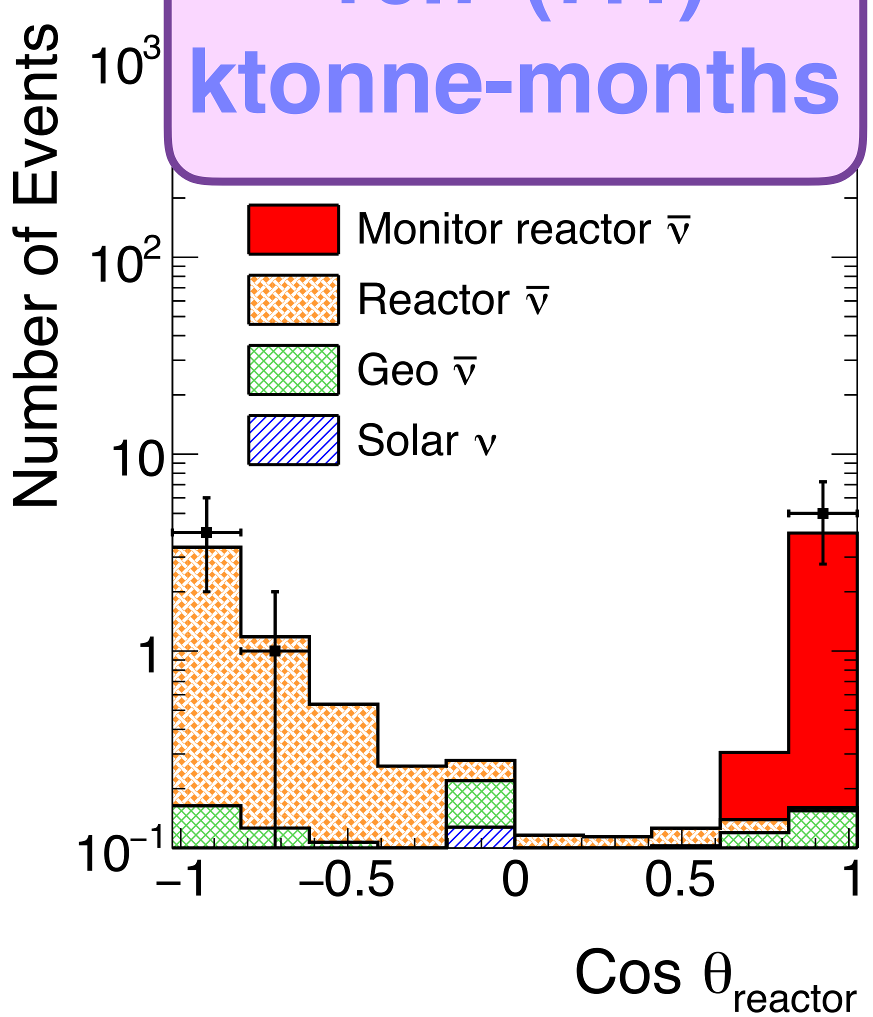


Results (SNOLab)

Exposures required to detect reactor on/off in 1 month at 95% (90%) CL depend on position of signal reactor:

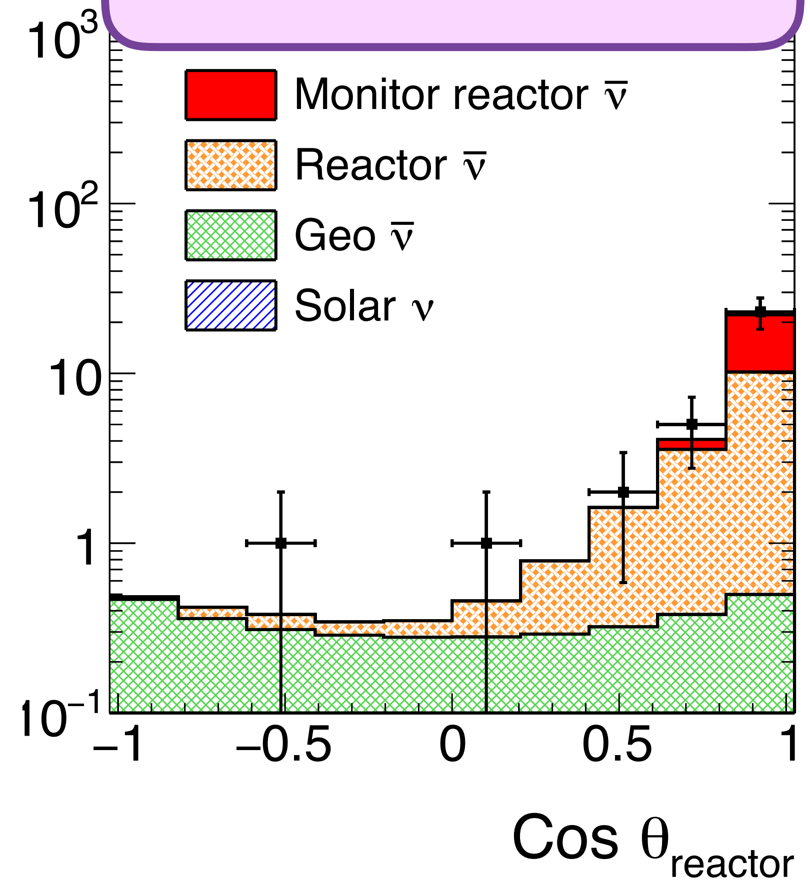
ON (North)

10.7 (7.1) ktonne-months



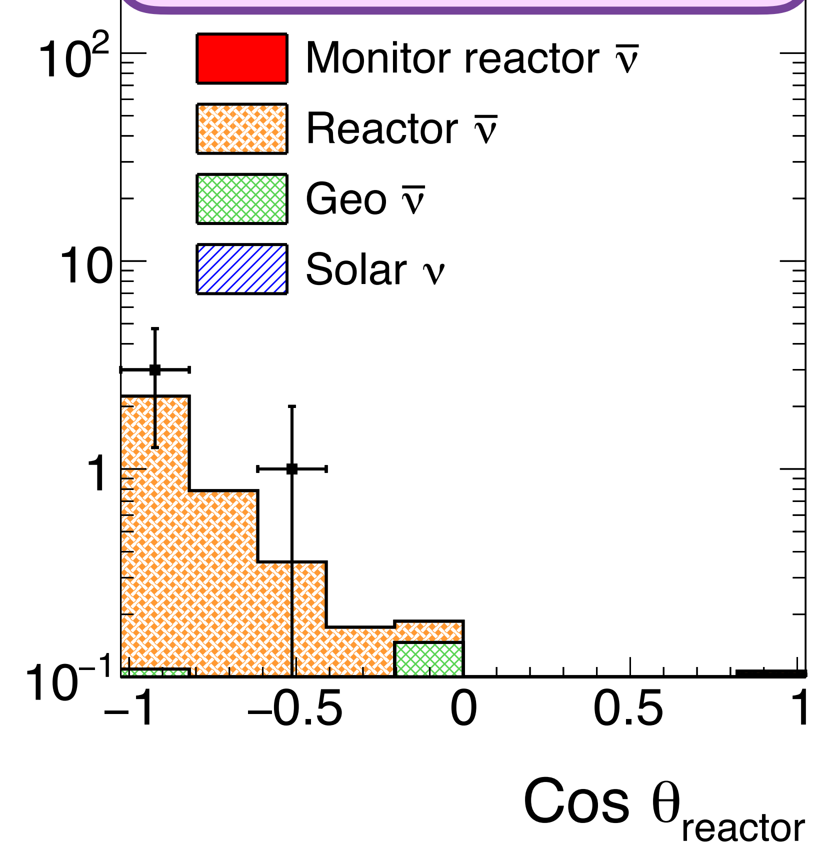
ON (South)

32.7 (19.8) ktonne-months



OFF (North)

5.8 (4.1) ktonne-months



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 with a detector at SNOLab are 90 tonne-yrs, 1.6 ktonne-yrs and 130 ktonne-yrs
  - Up to 30-40% reduction in required exposure if angular resolution is improved by a factor of 2, relative to MUNU measurements
  - For more details, see https://www.nature.com/articles/ncomms15989
- Direction-sensitive detectors are also capable of monitoring nearby nuclear reactors
  - Required exposure is dependent on location of signal reactor relative to background reactors
  - 7-20 ktonne detector at SNOLab can detect monthly on/off cycling of a 50-MW reactor at a distance of 10 km with 90% CL

Thank you!

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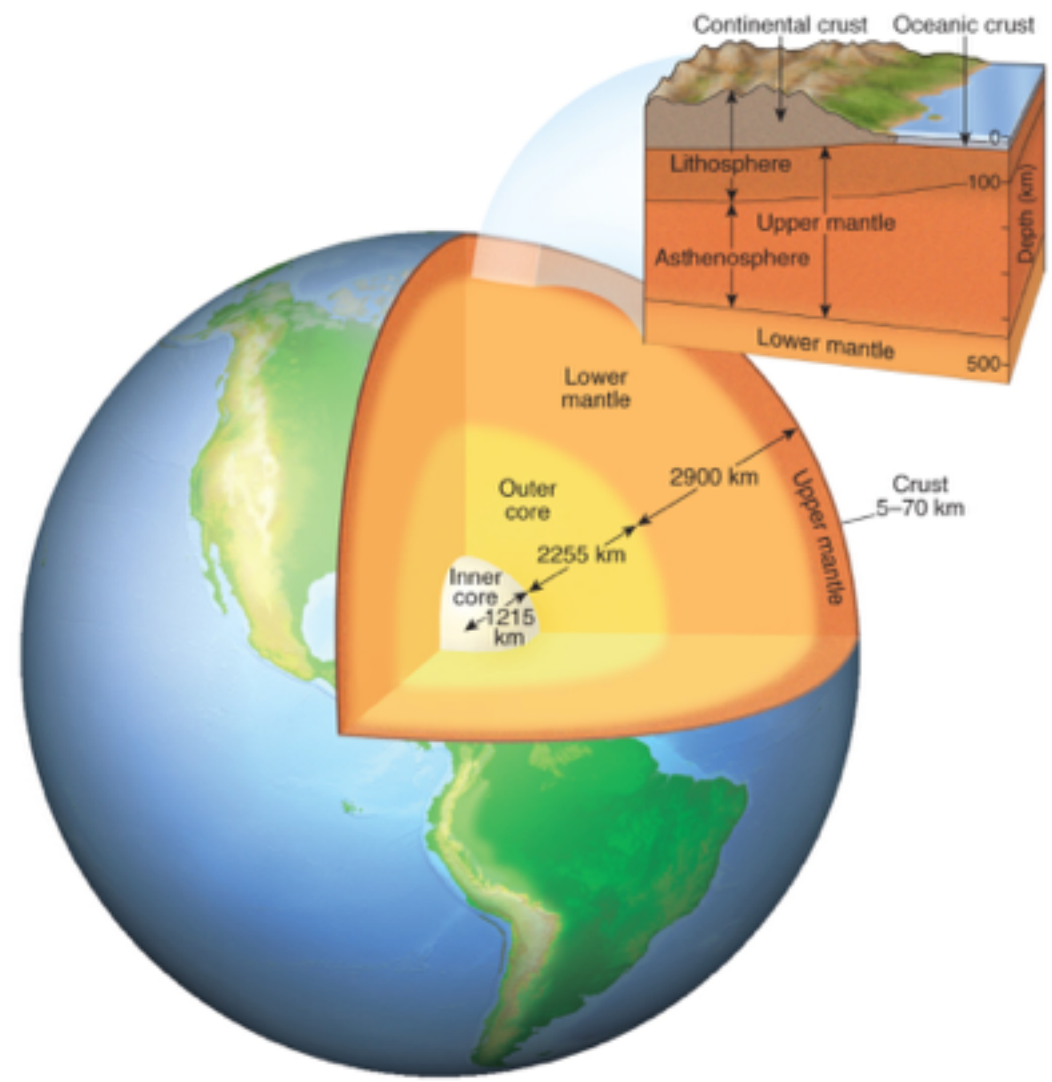
Backup slides

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

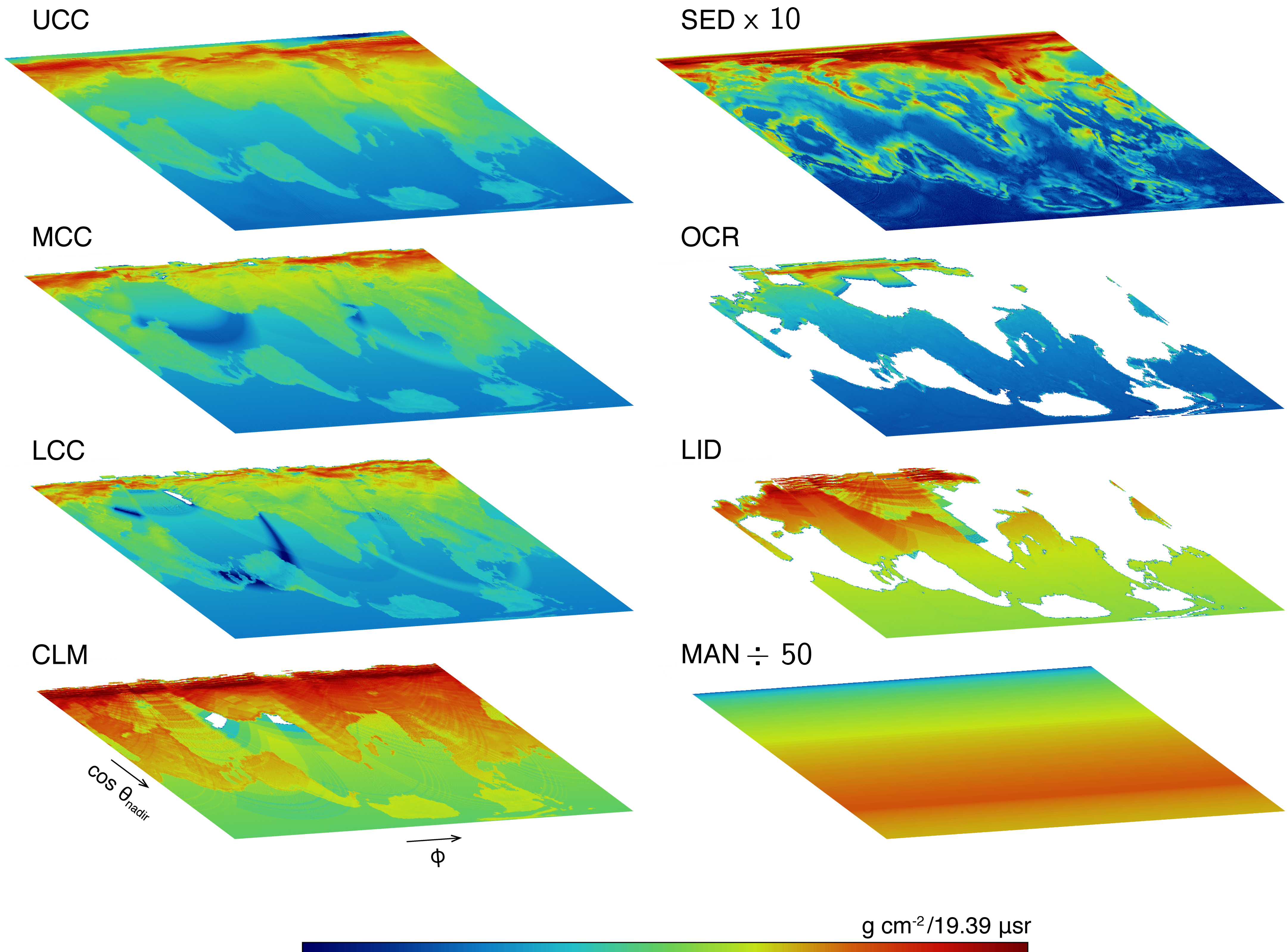


- Mantle modeled as homogeneous spherical shell (with and without radioactivity in core)

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

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

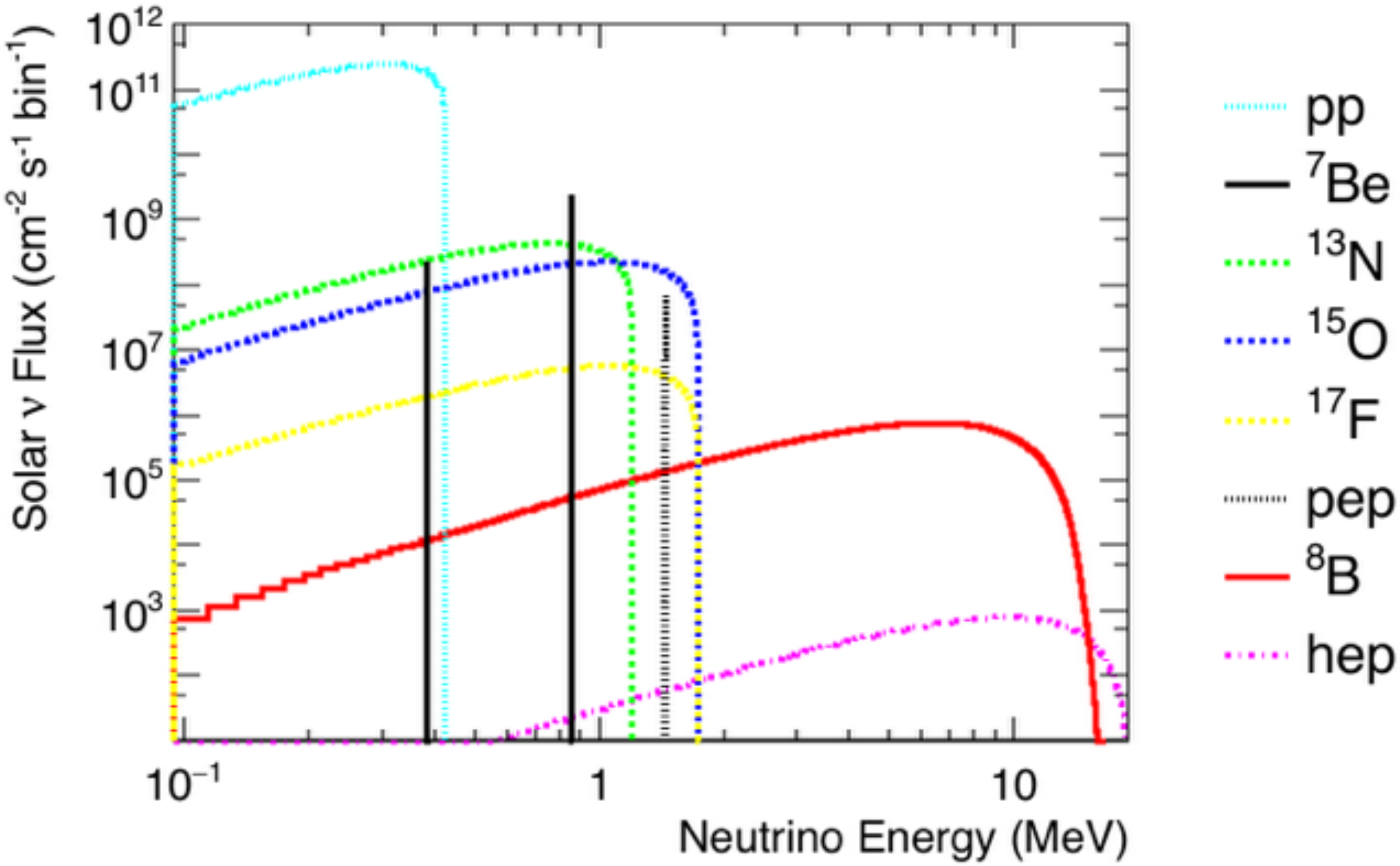
Geophysical response



*at Gran Sasso

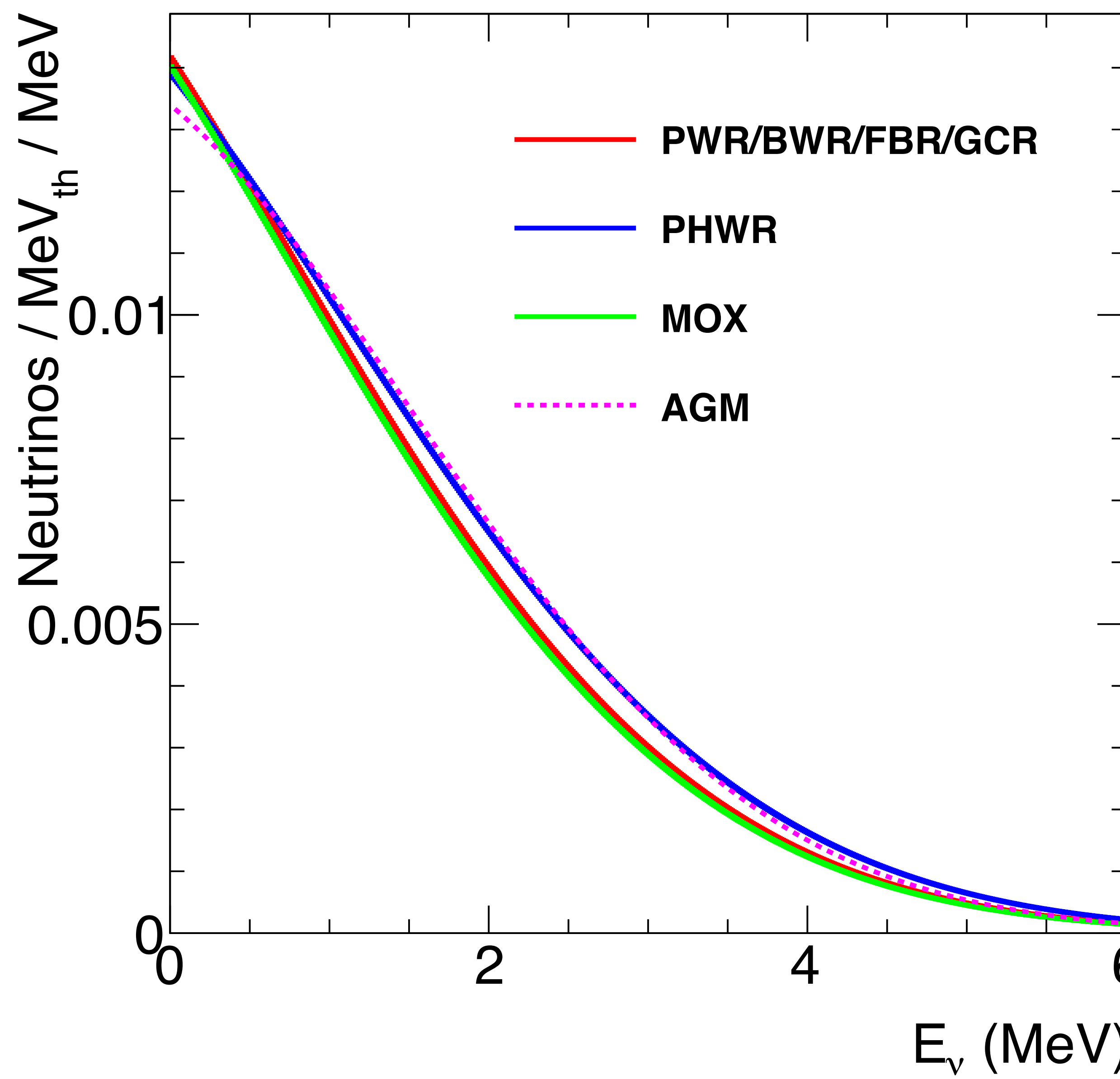
Solar-ν model

- 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 2014 average powers taken from Power Reactor Information System (PRIS)
- Neutrino spectra:
  - ~6 νbar and 205 MeV per fission
  - Geo-ν analysis uses AGM spectrum (conservative)
  - Reactor monitoring analysis uses more precise isotope spectra —>
- ±6% uncertainty:
  - power value reported by plant operators
  - oscillation parameters
  - seasonal changes in the reactor power output



Fission/power fractions from Baldoncini et al. *Phys. Rev.* D91, 065002 (2015).

Event rates (CF_4 target)

per tonne-yr

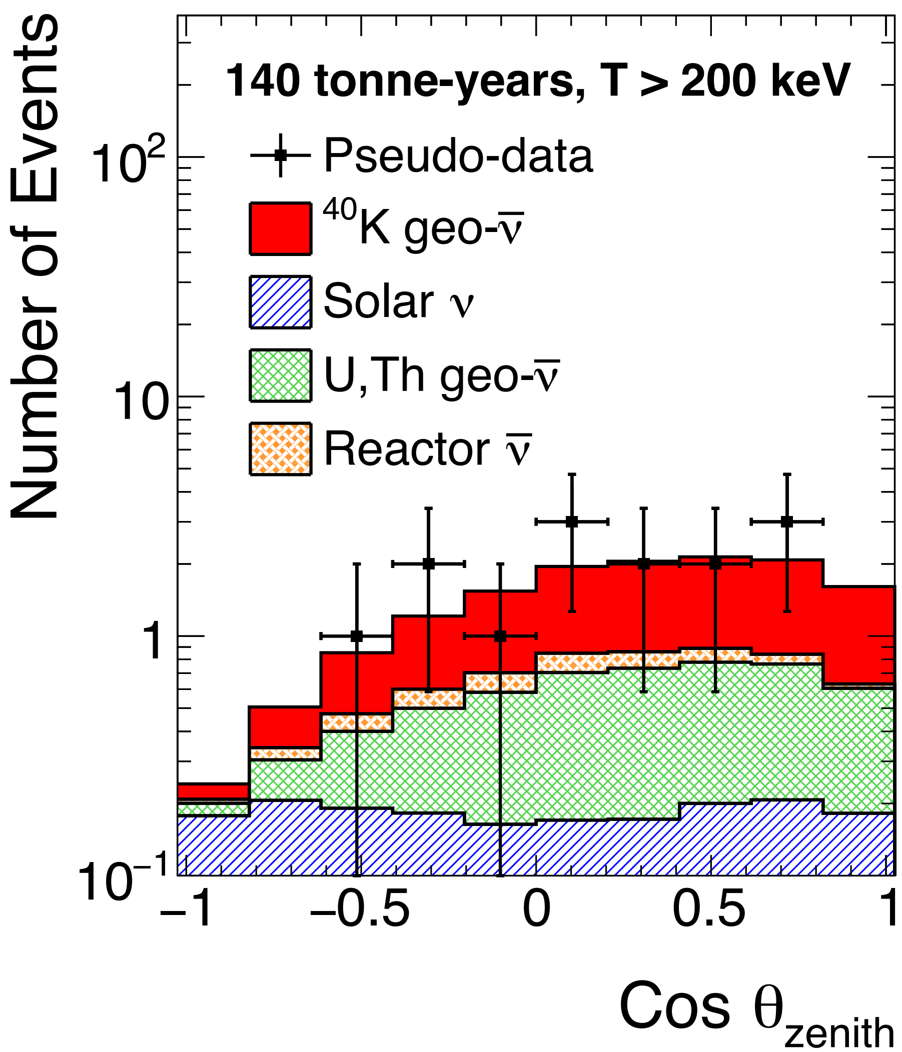
Source	Total	> 200 keV	> 250 keV	> 800 keV
pp	$433.97^{+2.69}_{-2.40}$	$16.09^{+0.10}_{-0.09}$	$0.50^{+0.00}_{-0.00}$	$0.00^{+0.00}_{-0.00}$
^{7}Be (1)	$156.78^{+7.84}_{-7.19}$	$105.88^{+5.29}_{-4.85}$	$93.59^{+4.68}_{-4.29}$	$0.00^{+0.00}_{-0.00}$
^{7}Be (2)	$3.57^{+0.18}_{-0.16}$	$0.43^{+0.02}_{-0.02}$	$0.00^{+0.00}_{-0.00}$	$0.00^{+0.00}_{-0.00}$
^{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_ℓ total	$625.28^{+26.12}_{-11.92}$	$144.70^{+16.24}_{-7.60}$	$114.40^{+14.12}_{-6.67}$	$5.90^{+1.18}_{-0.68}$

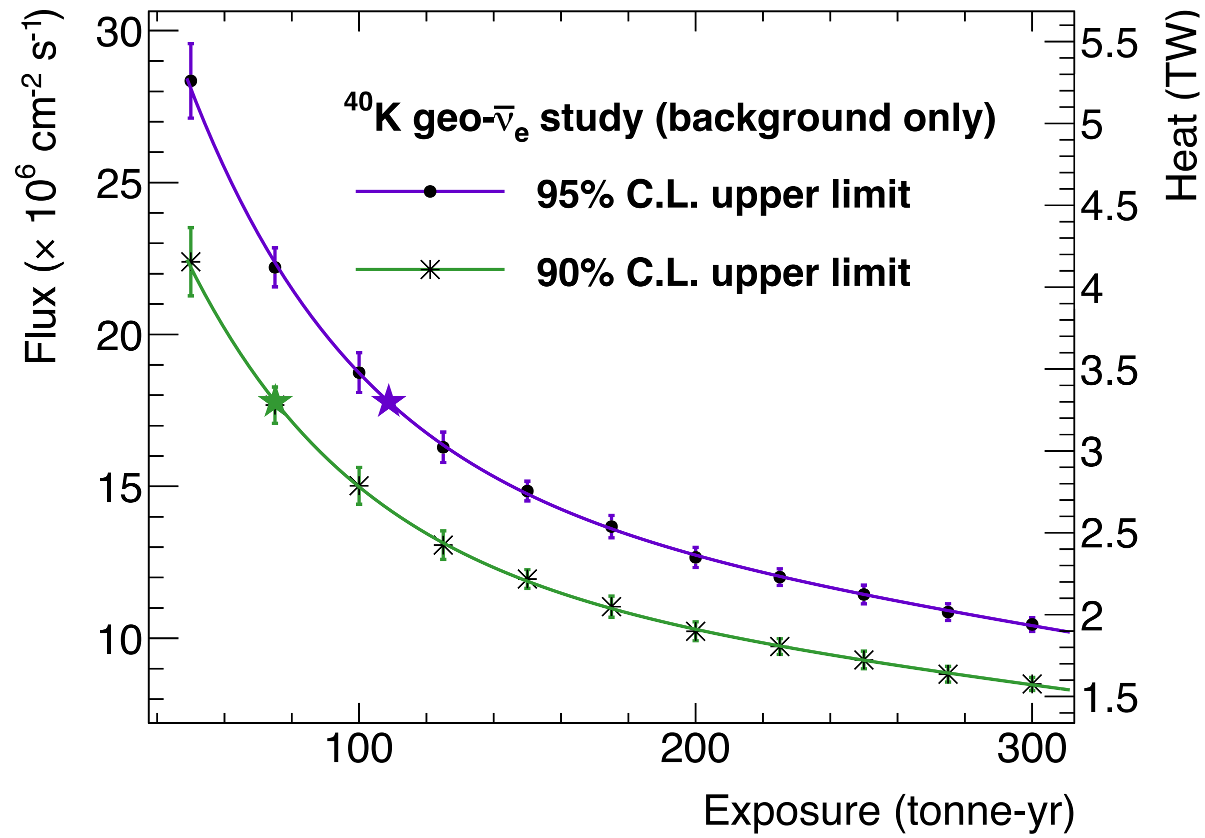
per ktonne-yr

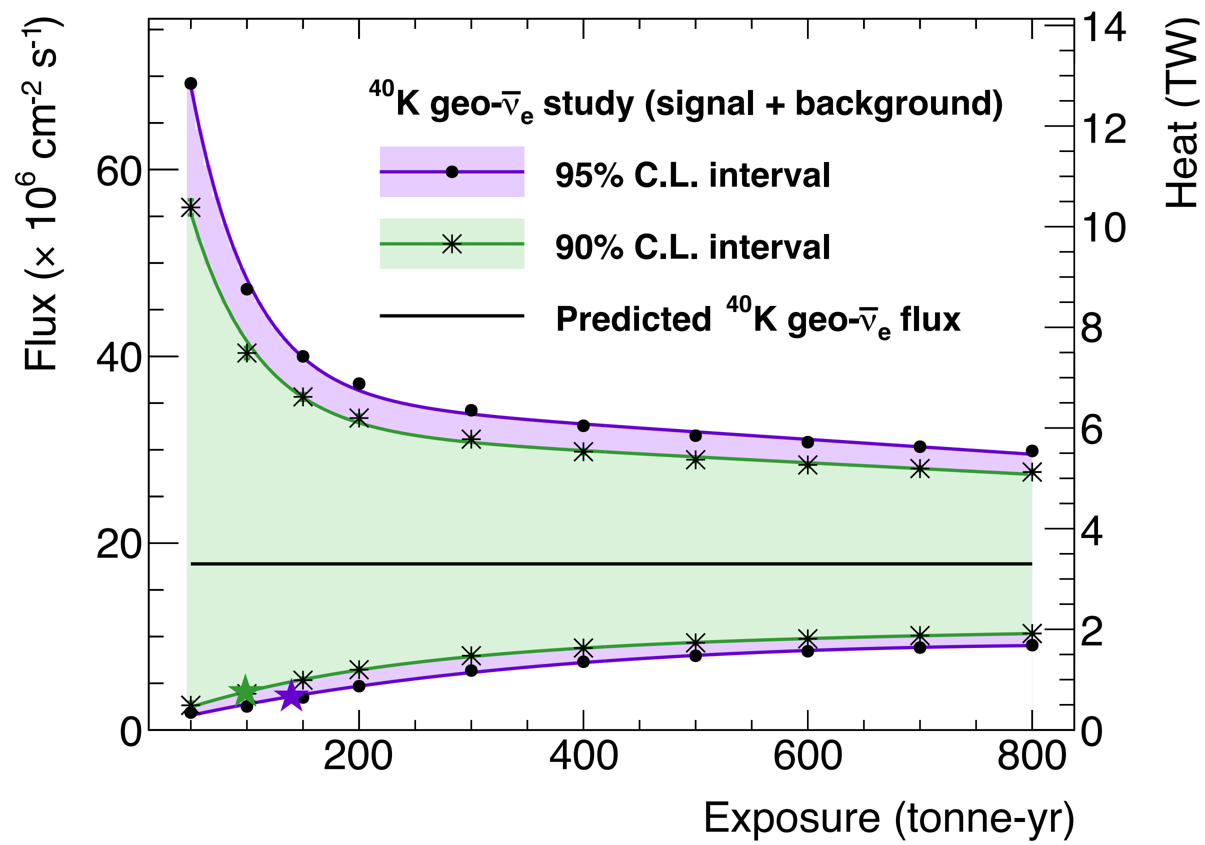
Source	Total	> 200 keV	> 250 keV	> 800 keV
^{238}U	61.26 ± 16.68	35.60 ± 9.69	31.73 ± 8.64	7.44 ± 2.02
^{235}U	1.36 ± 0.37	0.68 ± 0.19	0.59 ± 0.16	0.05 ± 0.01
^{232}Th	44.19 ± 9.17	24.18 ± 5.02	21.55 ± 4.47	4.65 ± 0.96
^{40}K	272.17 ± 69.90	126.66 ± 32.53	105.97 ± 27.21	4.69 ± 1.21
geo-$\bar{\nu}_\ell$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

*at Gran Sasso

^{40}K

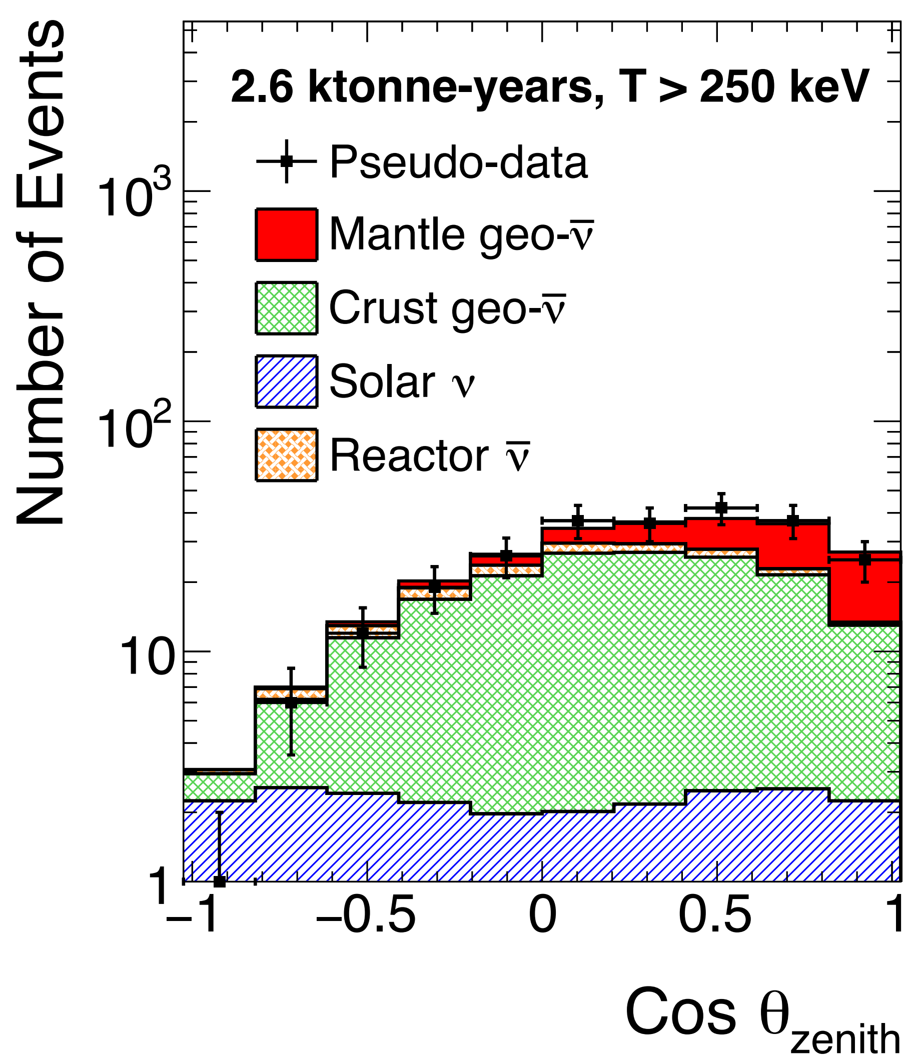


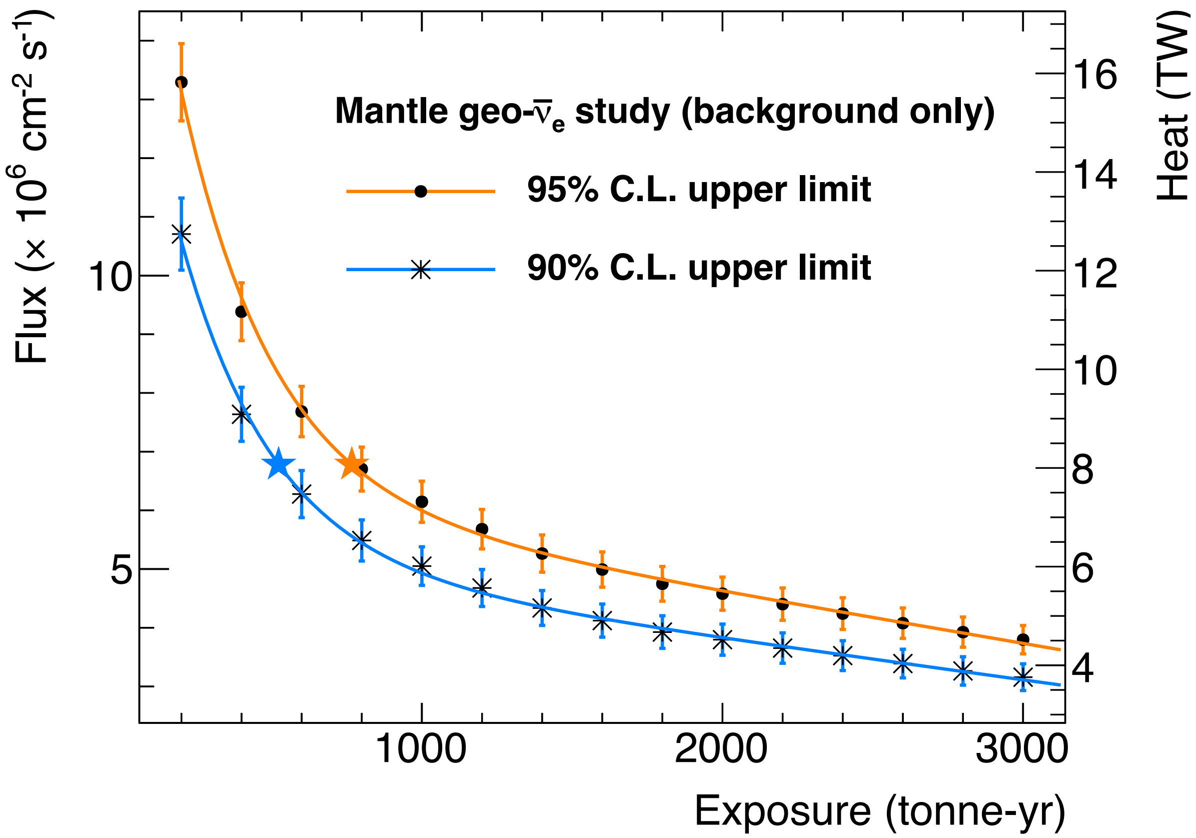


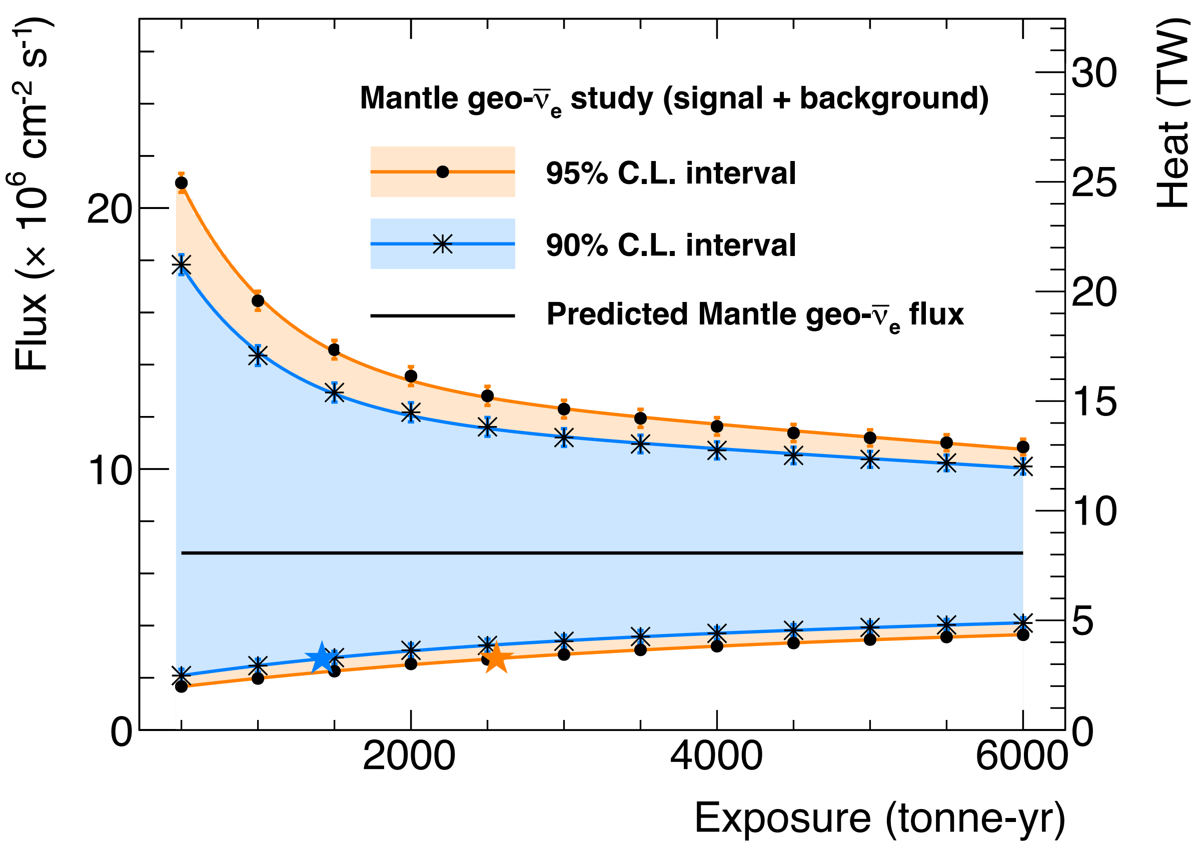


*at Gran Sasso

Mantle (no core radioactivity)







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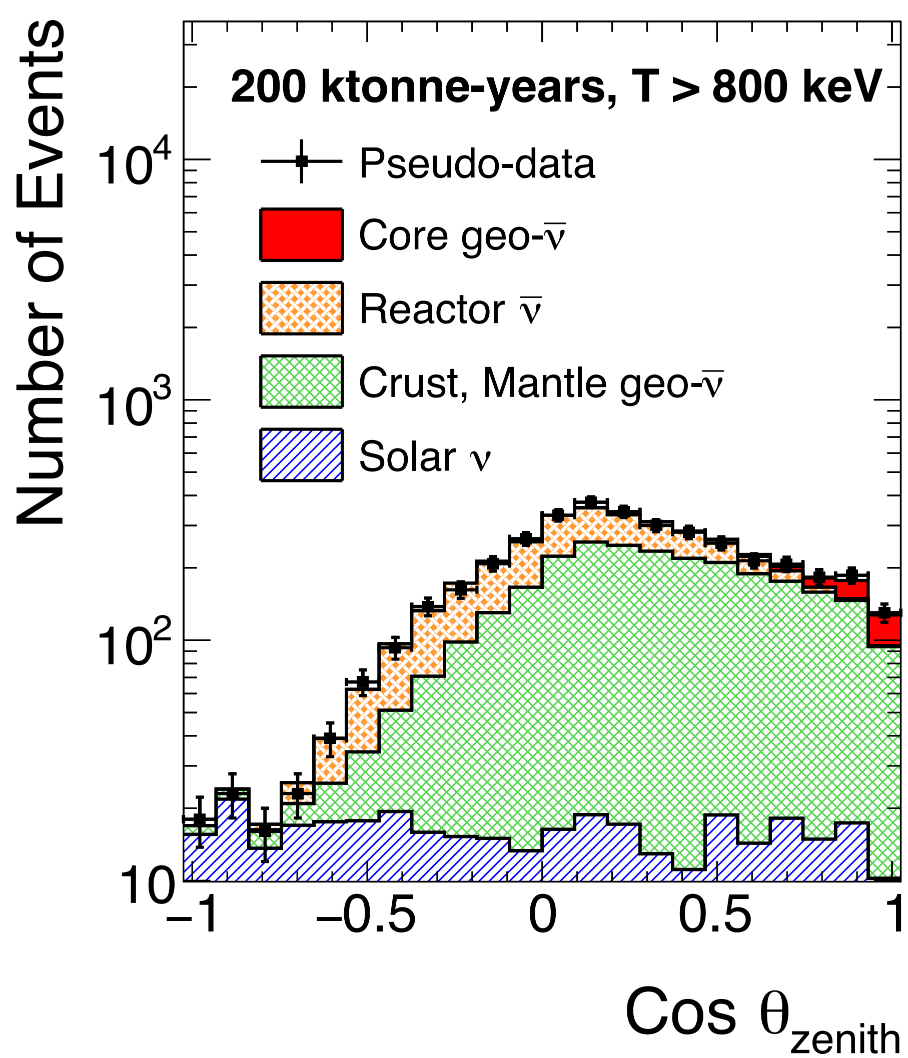
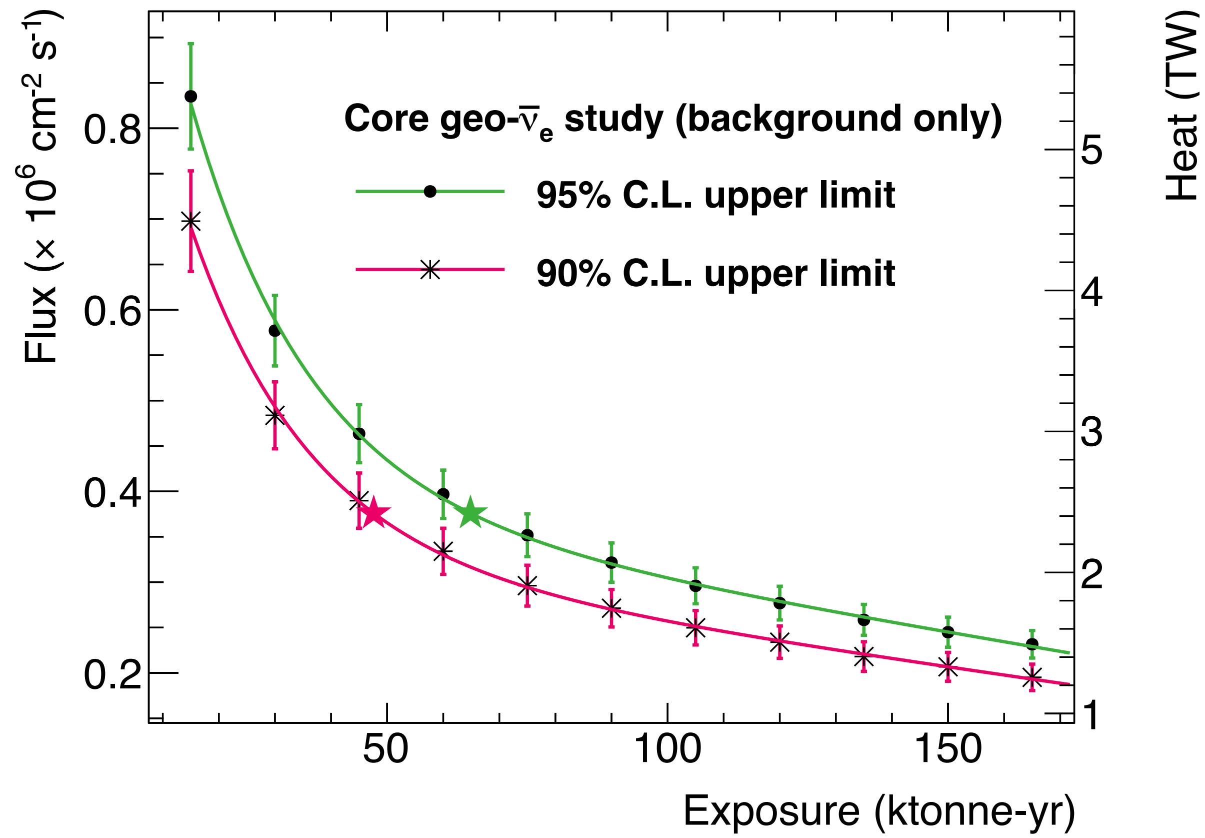
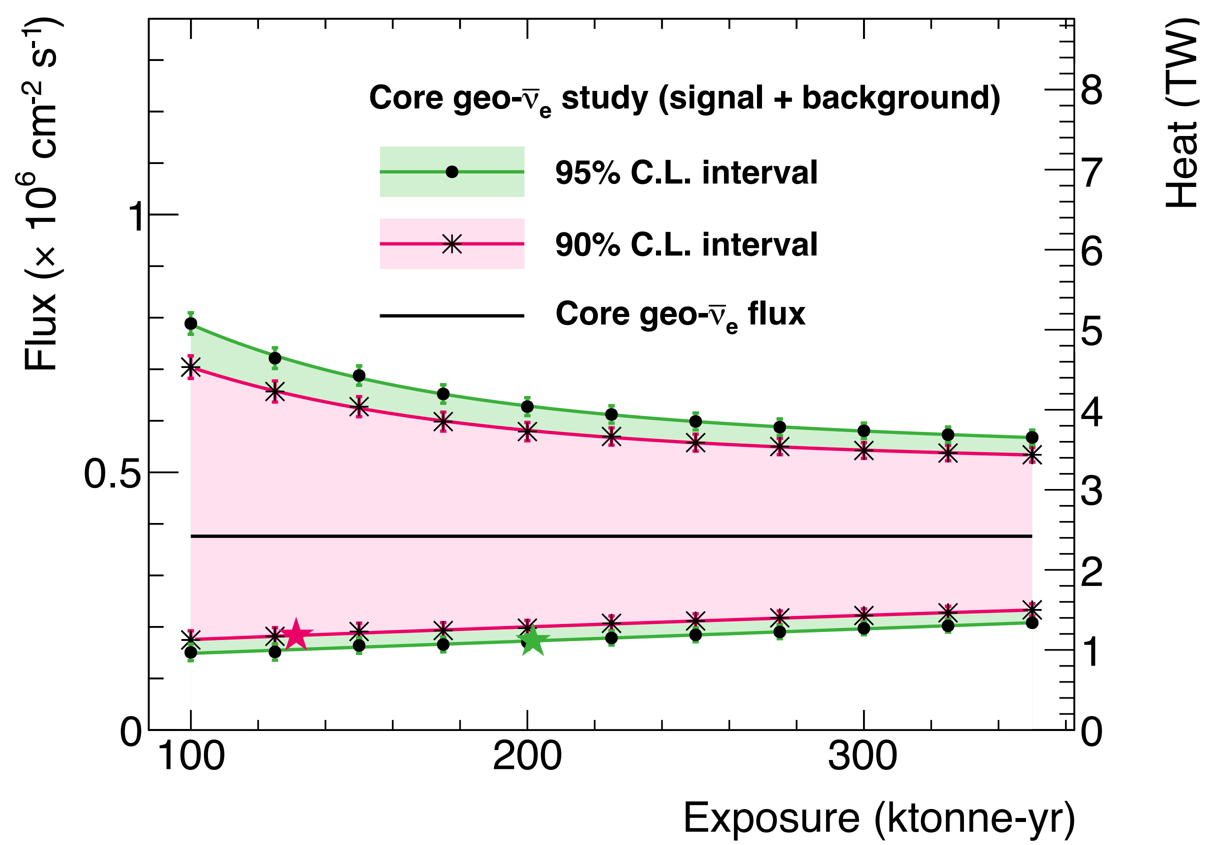
Core (10 p.p.b. U,Th)

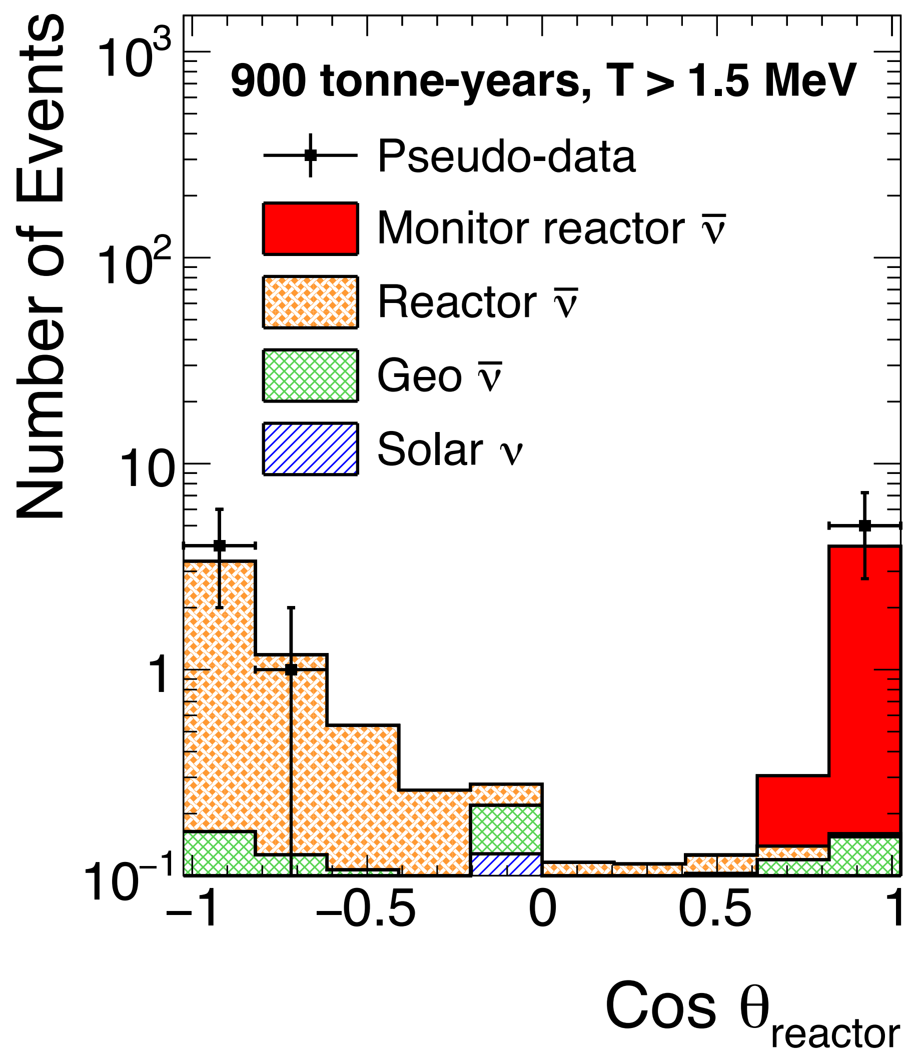


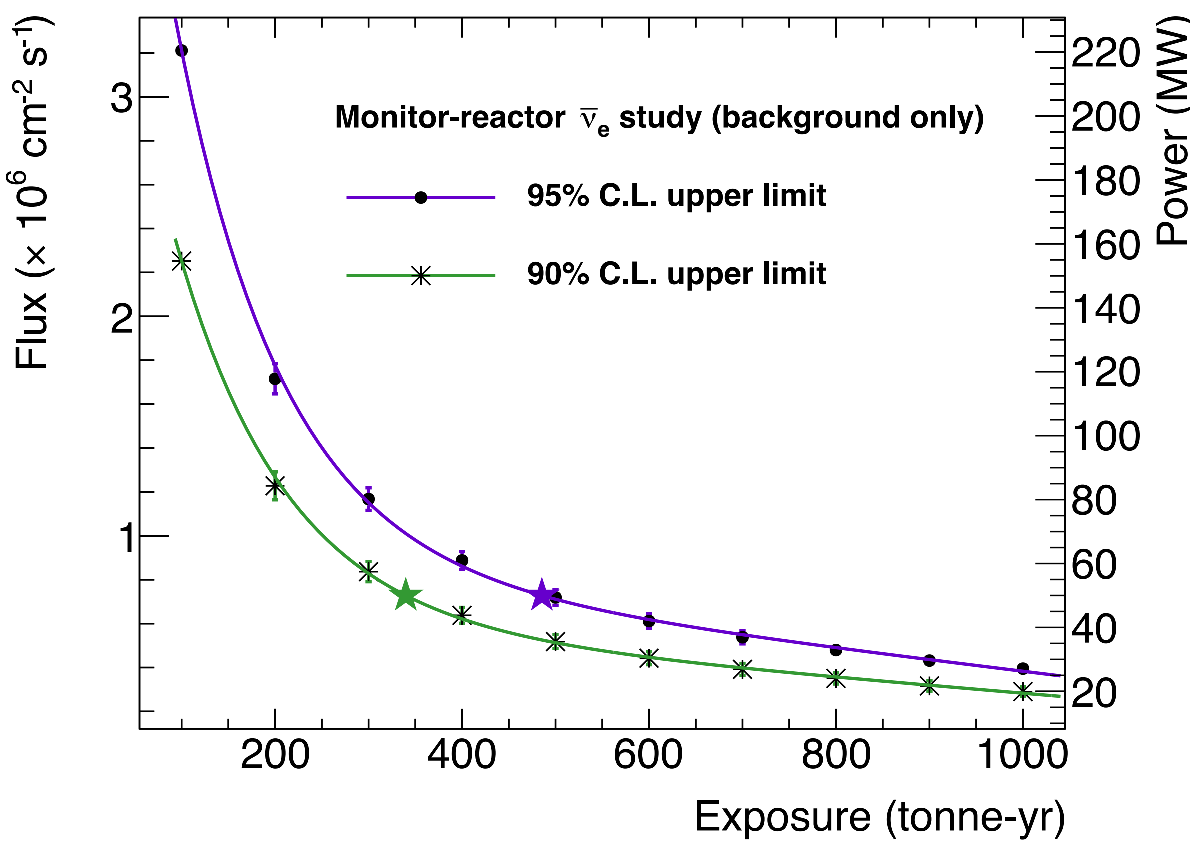


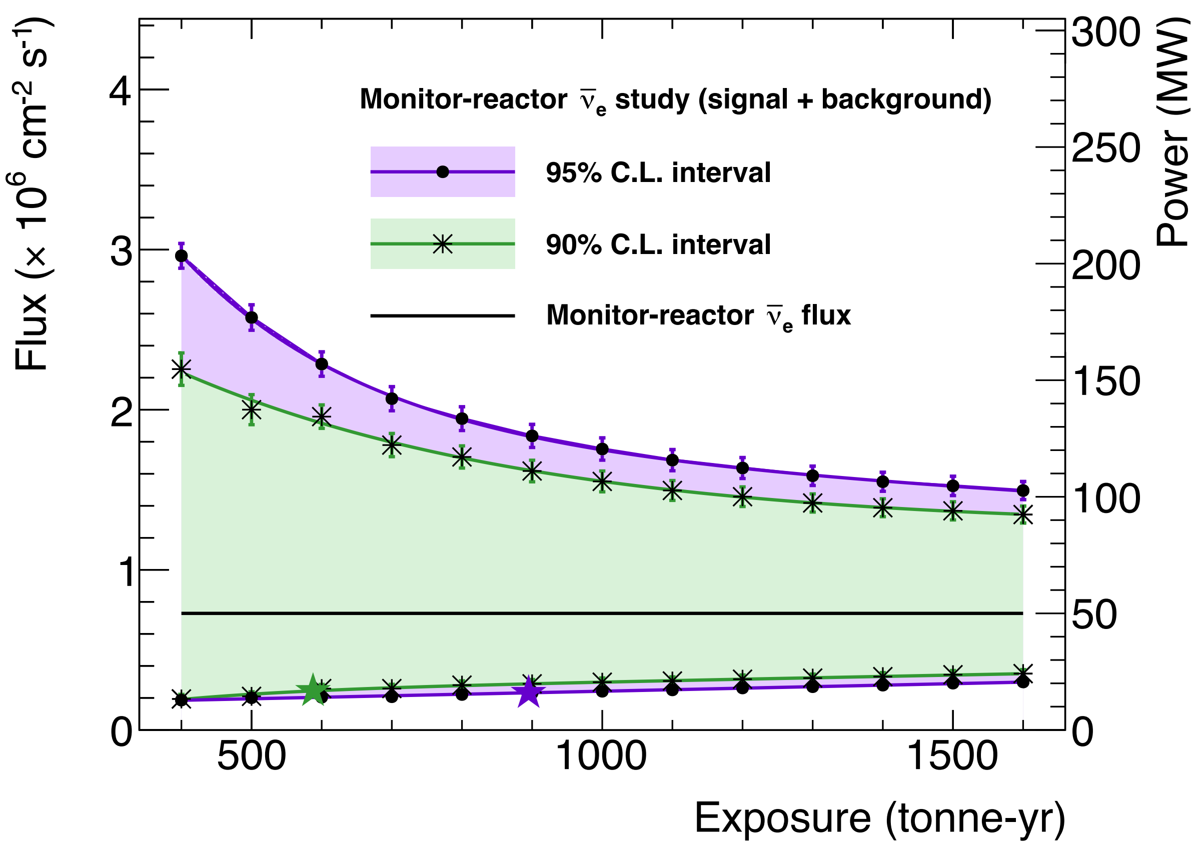


*at Gran Sasso

Reactor monitoring







*at SNOLab

Table 2 | Mean geo-neutrino flux sensitivity at three underground sites.

Φ	Site (configuration)	Case (i) Background only (tonne-year)	Case (ii) Signal + background (tonne-year)	Case (ii) Signal + background ($10^6\ cm^{-2} s^{-1}$)
^{40}K	Kamioka	122 (85)	157 (107)	2.84 (3.28)
	Kamioka (2010)	200 (130)	279 (190)	3.31 (3.67)
	Gran Sasso	109 (75)	140 (99)	3.51 (4.01)
	Gran Sasso (high res.)	70 (48)	85 (58)	3.38 (3.88)
	Gran Sasso (no syst.)	106 (74)	132 (94)	3.63 (4.07)
	Gran Sasso (w/bkgnd)	125 (86)	161 (113)	3.51 (4.12)
	SNOLab	105 (72)	132 (93)	3.62 (4.18)
Mantle (no radioactivity in core)	Kamioka	635 (437)	1,980 (1,050)	2.57 (2.51)
	Kamioka (2010)	829 (567)	2,630 (1,490)	2.79 (2.80)
	Gran Sasso	767 (523)	2,560 (1,420)	2.74 (2.73)
	Gran Sasso (high res.)	525 (356)	1,630 (933)	2.71 (2.68)
	Gran Sasso (no syst.)	705 (488)	1,850 (1,050)	2.50 (2.51)
	Gran Sasso (w/bkgnd)	915 (608)	3,010 (1,680)	2.76 (2.77)
	SNOLab	826 (564)	2,680 (1,560)	2.79 (2.83)
Core (10 p.p.b. U, Th in core)	Kamioka	73,600 (53,300)	215,000 (136,000)	0.176 (0.185)
	Kamioka (2010)	87,300 (59,000)	343,000 (200,000)	0.170 (0.176)
	Gran Sasso	64,900 (47,600)	202,000 (131,000)	0.173 (0.183)
	Gran Sasso (high res.)	54,400 (40,300)	165,000 (102,000)	0.172 (0.180)
	Gran Sasso (no syst.)	62,000 (46,200)	192,000 (126,000)	0.180 (0.188)
	SNOLab	64,000 (46,600)	223,000 (131,000)	0.171 (0.175)

Mean sensitivity to the geo-neutrino flux (Φ) from potassium (^{40}K) decays, the mantle, and the core, calculated at Kamioka (Japan), Gran Sasso (Italy) and SNOLab (Canada), assuming a CF_4 target and angular resolution given by equation (1). Case (i): exposure needed to achieve a mean 95% (90%) confidence level upper limit equal to the predicted flux, for background-only pseudo-experiments. Case (ii): exposure and mean lower limit at which 95% (90%) of signal + background pseudo-experiments have a non-zero 95% (90%) confidence level lower limit. An electron energy threshold of 200 keV (^{40}K), 250 keV (mantle) or 800 keV (core) has been applied. Systematic uncertainties for each study are discussed in the main text. Four variations of the baseline configuration are also presented here: (2010) uses reactor positions and powers from 2010, rather than 2014; (high res.) denotes improved angular resolution, equal to half that given by equation (1); (no syst.) denotes no systematic uncertainties; and (w/bkgnd) denotes inclusion of isotropic backgrounds, normalized to 20% ± 2% (62% ± 6%) of the ^{40}K (mantle) geo-neutrino signal.