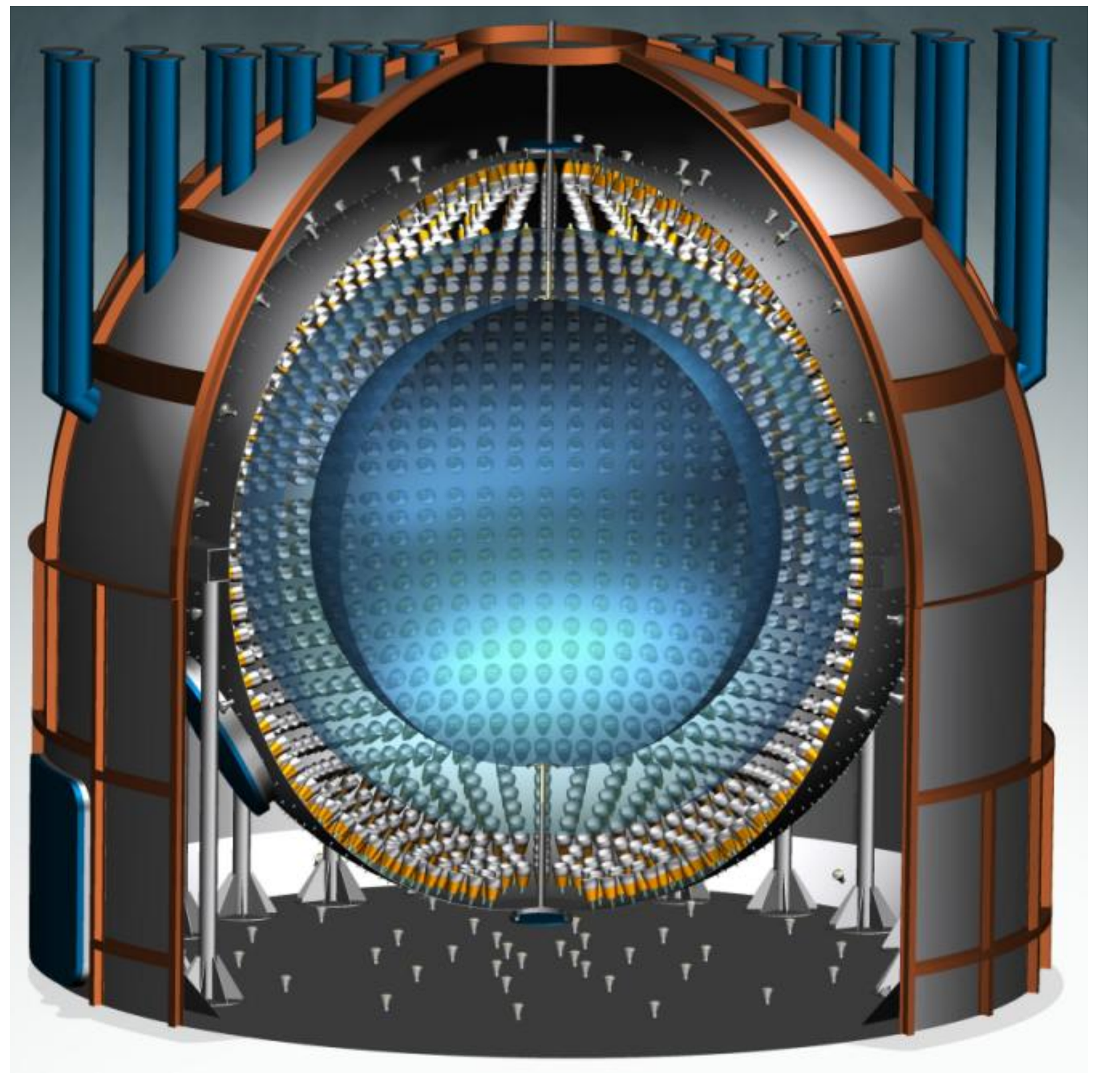
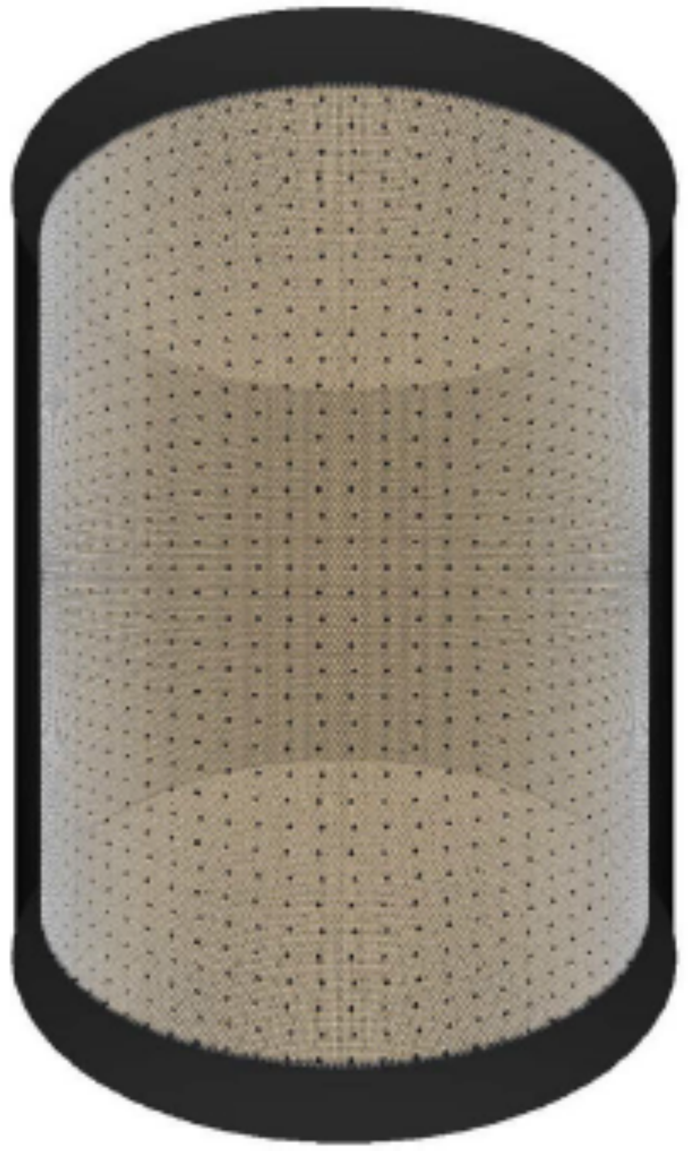
Studying the Earth with neutrinos: Borexino and Theia





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[1]University of California, Berkeley,

[2]Lawrence Berkeley National Laboratory

University of Tokyo joint seminar by ILANCE, IPMU and ICRR

August 31st 2022

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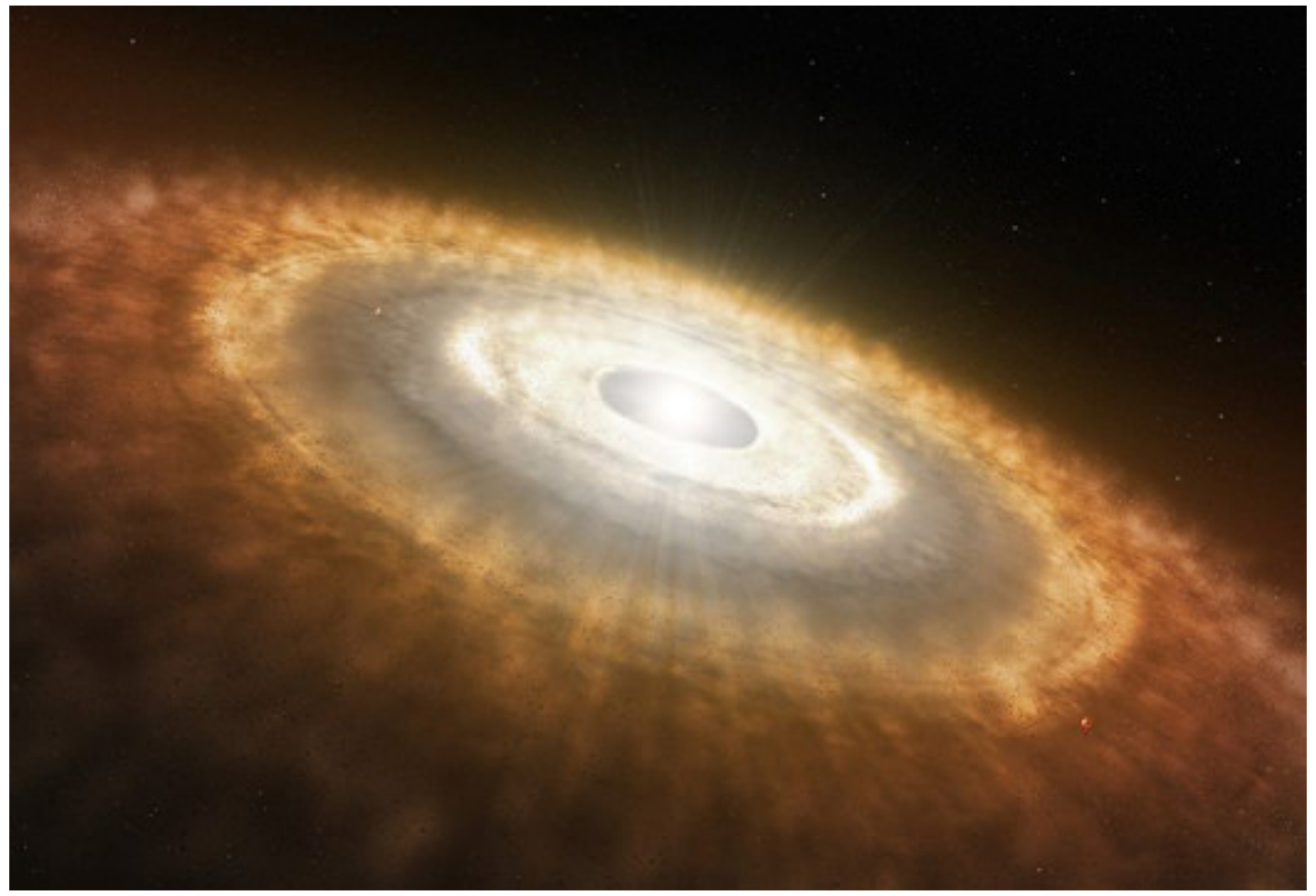
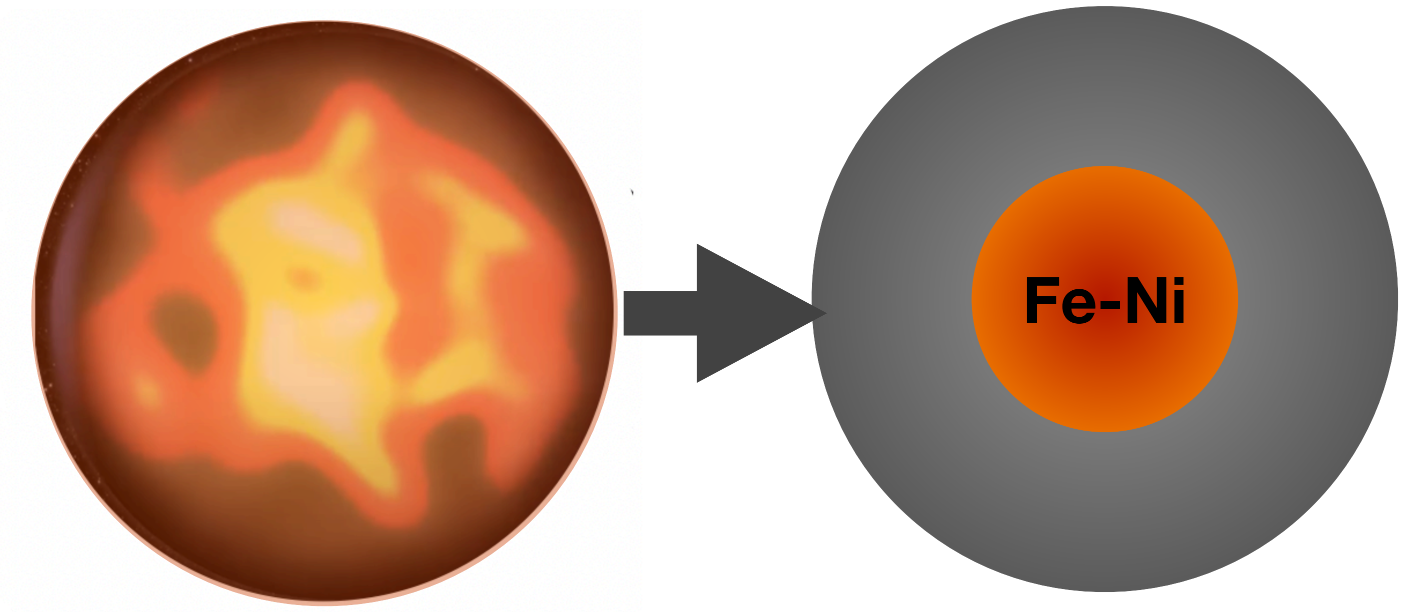
Earth Formation



Credit:ESO/L. Calçada

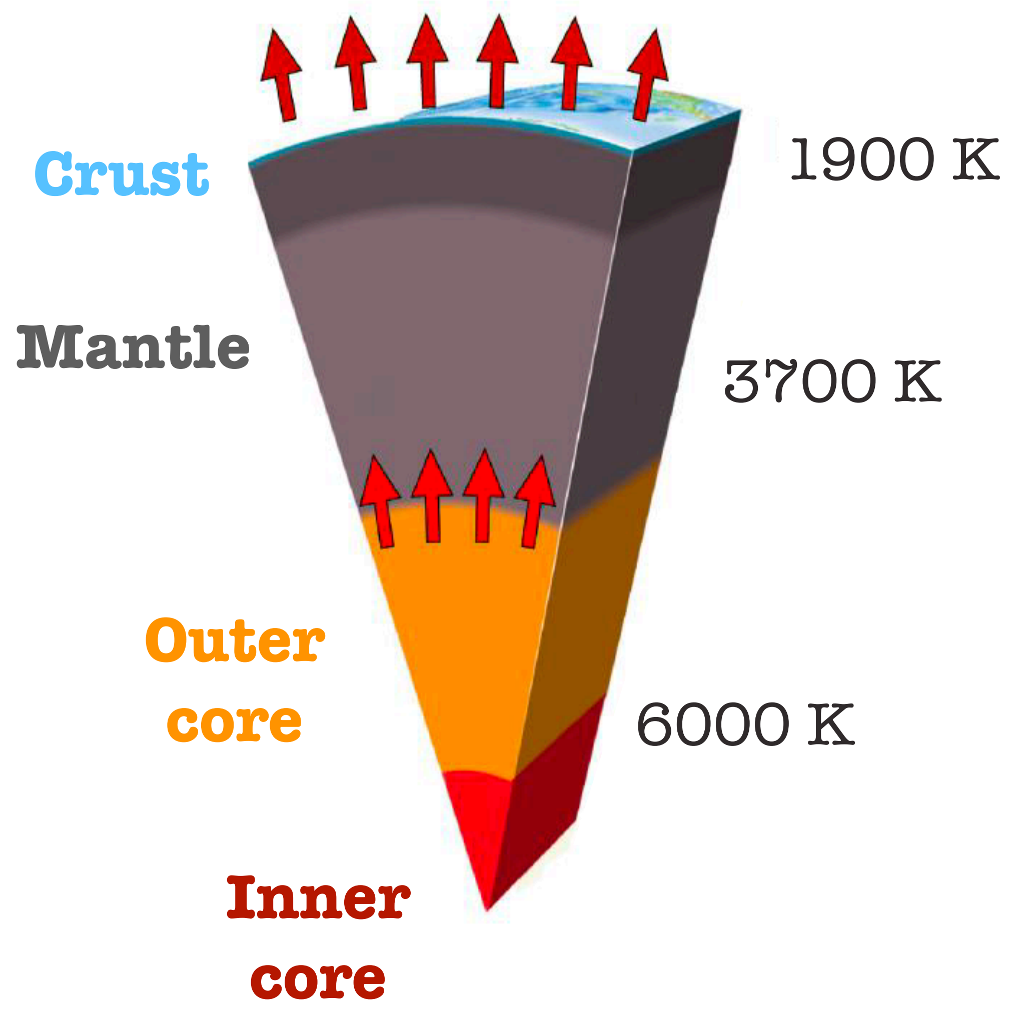
4.54 billion years ago



Primitive Silicate Mantle

- Accretion from solar nebula, a deep terrestrial magma ocean
- Siderophile elements (affinity to iron) 32.3% of Earth's mass segregate to the core
- Lithophile (affinity to silicates) elements in the primitive silicate mantle (aka Bulk Silicate Earth)
- U and Th heavy but prefer to bind with silicates

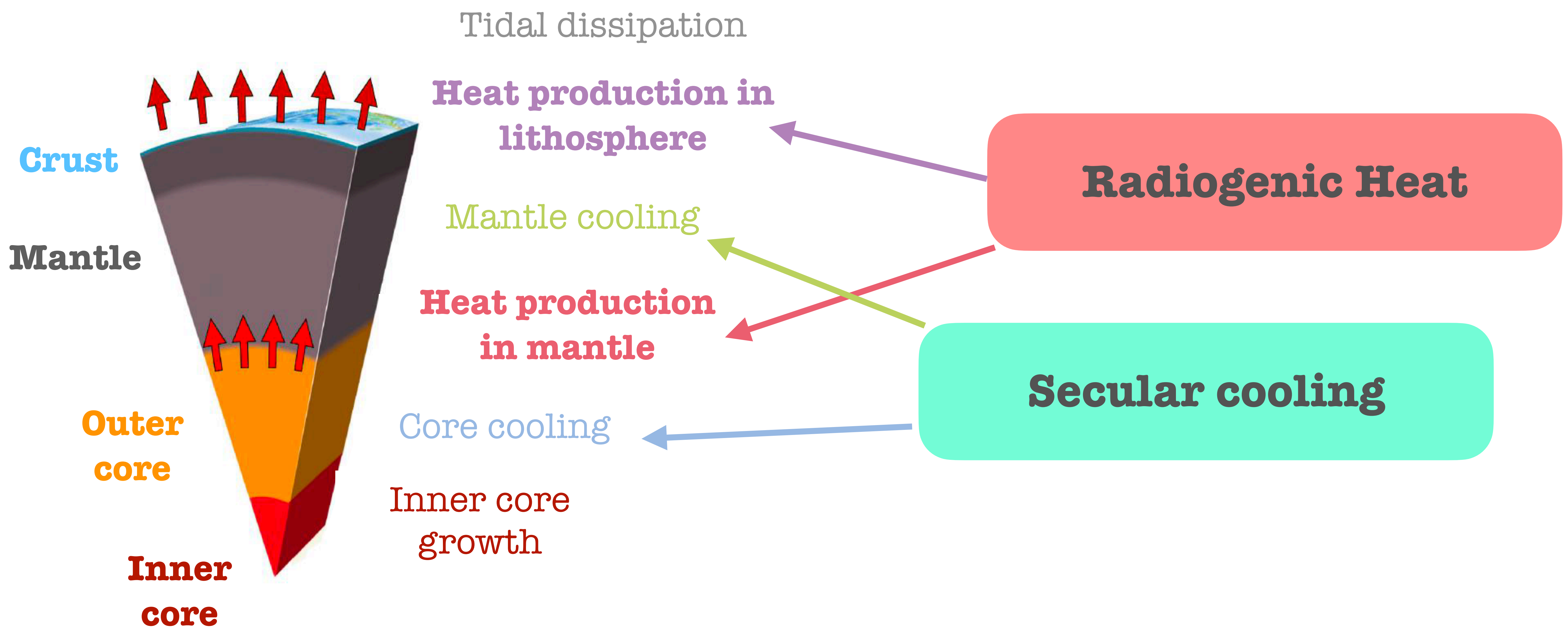
Earth’s Heat Budget



Earth's Heat Budget

Integrated surface heat flux:

$$H_{tot} = (47 \pm 2)\ \mathrm{TW}$$



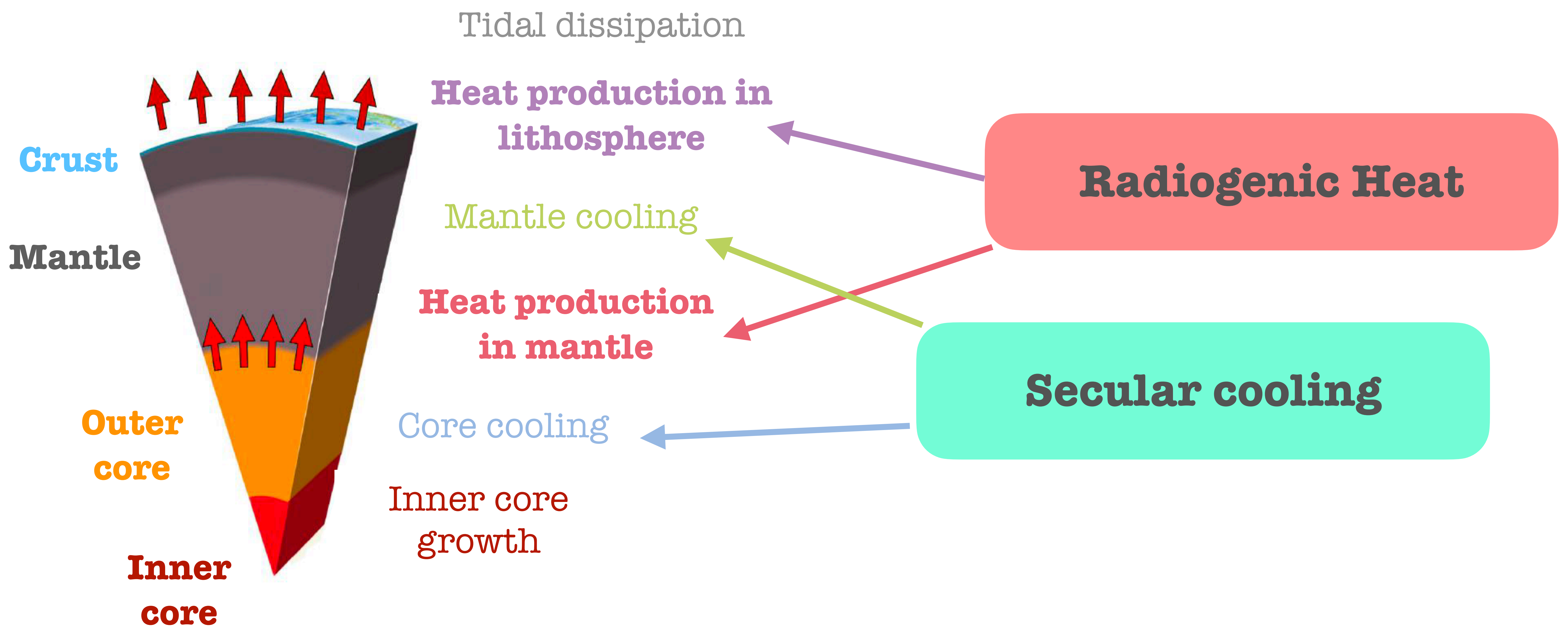
Earth's Heat Budget

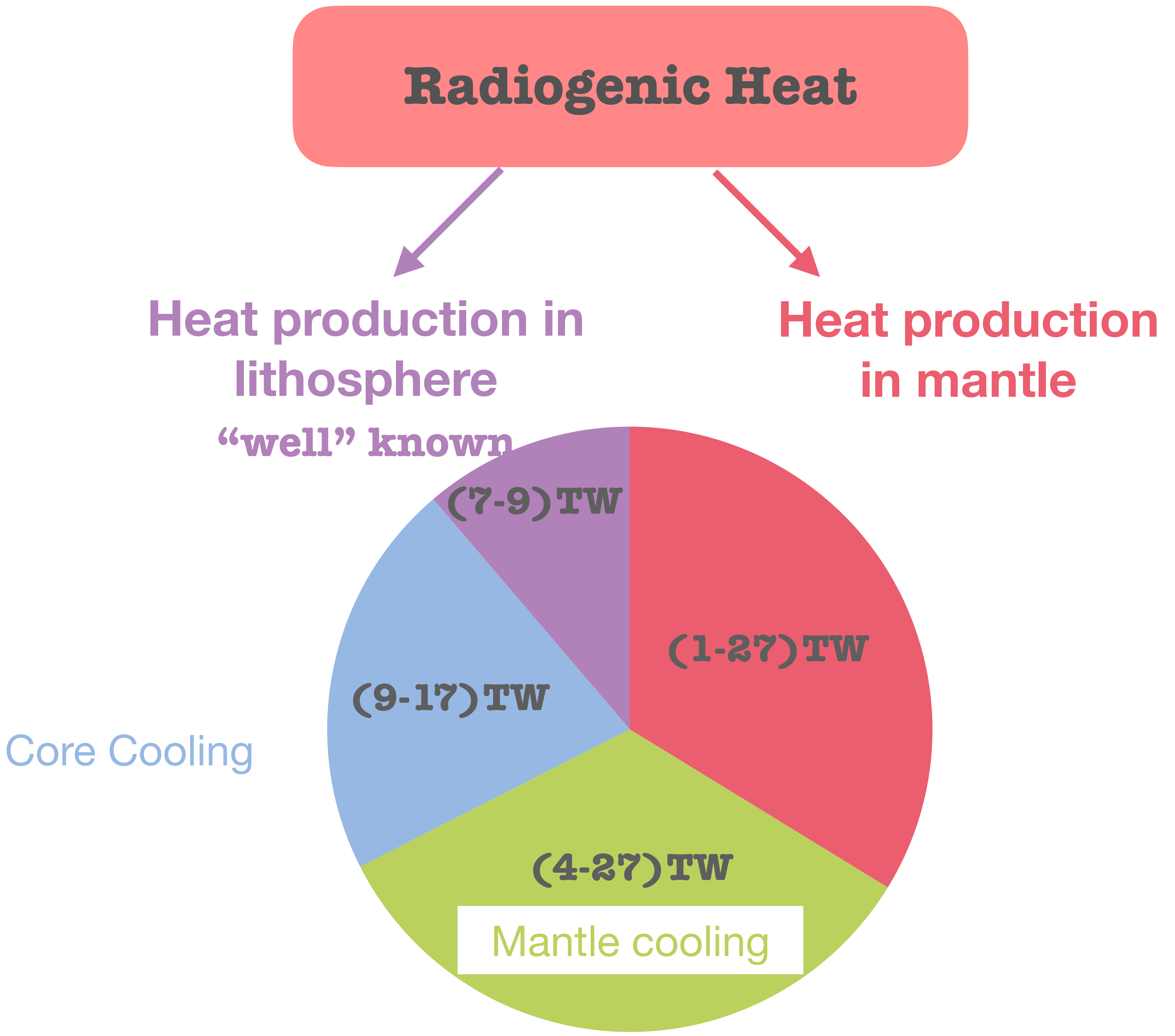
Integrated surface heat flux:

$$H_{tot} = (47 \pm 2)\ \mathrm{TW}$$

Predictions by different models:

Radiogenic heat = 10 – 35 TW





Bulk Silicate Earth

- Original composition of primitive mantle derived from the composition of the chondritic meteorites, with some corrections for the observed abundances in the Earth
- Identify the distribution of heat producing elements in the Earth
- Predict Radiogenic heat

Different BSE Models:

Cosmochemical	Geochemical	Geodynamical	Fully radiogenic
(11 ± 2) TW	(20 ± 4) TW	(33 ± 3) TW	(47 ± 2) TW

Predicted Radiogenic Heat

Various inputs: composition of the chondritic meteorites, correlations with the composition of the solar photosphere, composition of rock samples from upper mantle and crust, energy needed to run mantle convection…

Abundances of U/Th/K (and thus also radiogenic heat) in BSE = Lithosphere + MANTLE

Geoneutrinos’ role in understanding Earth

Abundance of Radioactive Elements

Radiogenic Heat (Main Goal)

$$^{238}U \rightarrow {}^{206}Pb + 8\,\alpha + 6\,e^- + 6\,\boxed{\bar{\nu}} + \;51.7\;MeV$$

$$^{235}U \rightarrow {}^{207}Pb + 7\,\alpha + 4\,e^- + 4\,\boxed{\bar{\nu}} + \;46.4\;MeV$$

$$^{232}Th \rightarrow {}^{208}Pb + 6\,\alpha + 4\,e^- + 4\,\boxed{\bar{\nu}} + \;42.7\;MeV$$

$$^{40}K \rightarrow {}^{40}Ca \;+\; e^- + \boxed{\bar{\nu}} + \;1.31\;MeV$$

$$^{40}K + e^- \rightarrow {}^{40}Ar \;+\; \boxed{\nu} + \;1.505\;MeV$$

Distribution of Radioactive Elements

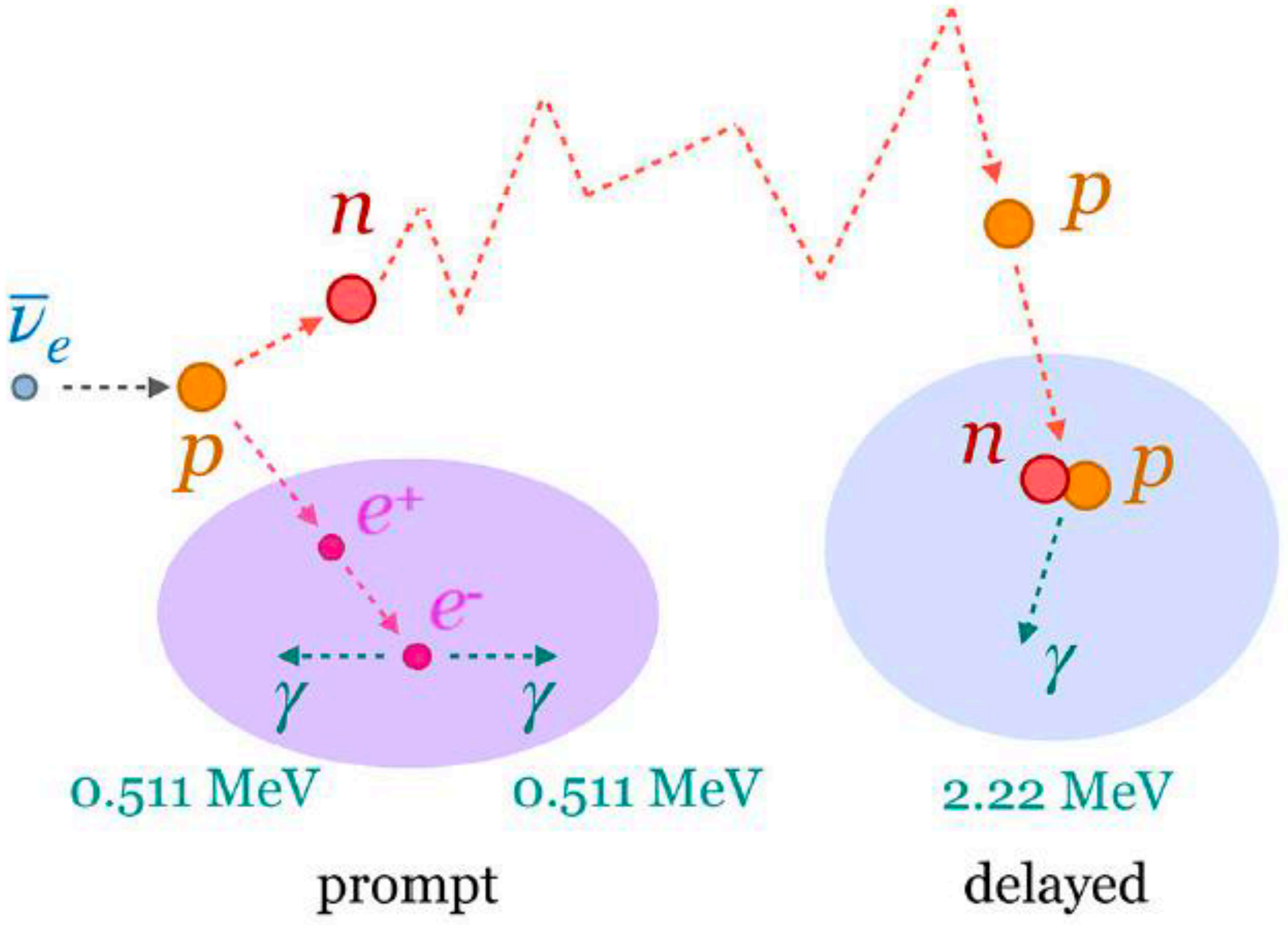
(Models)

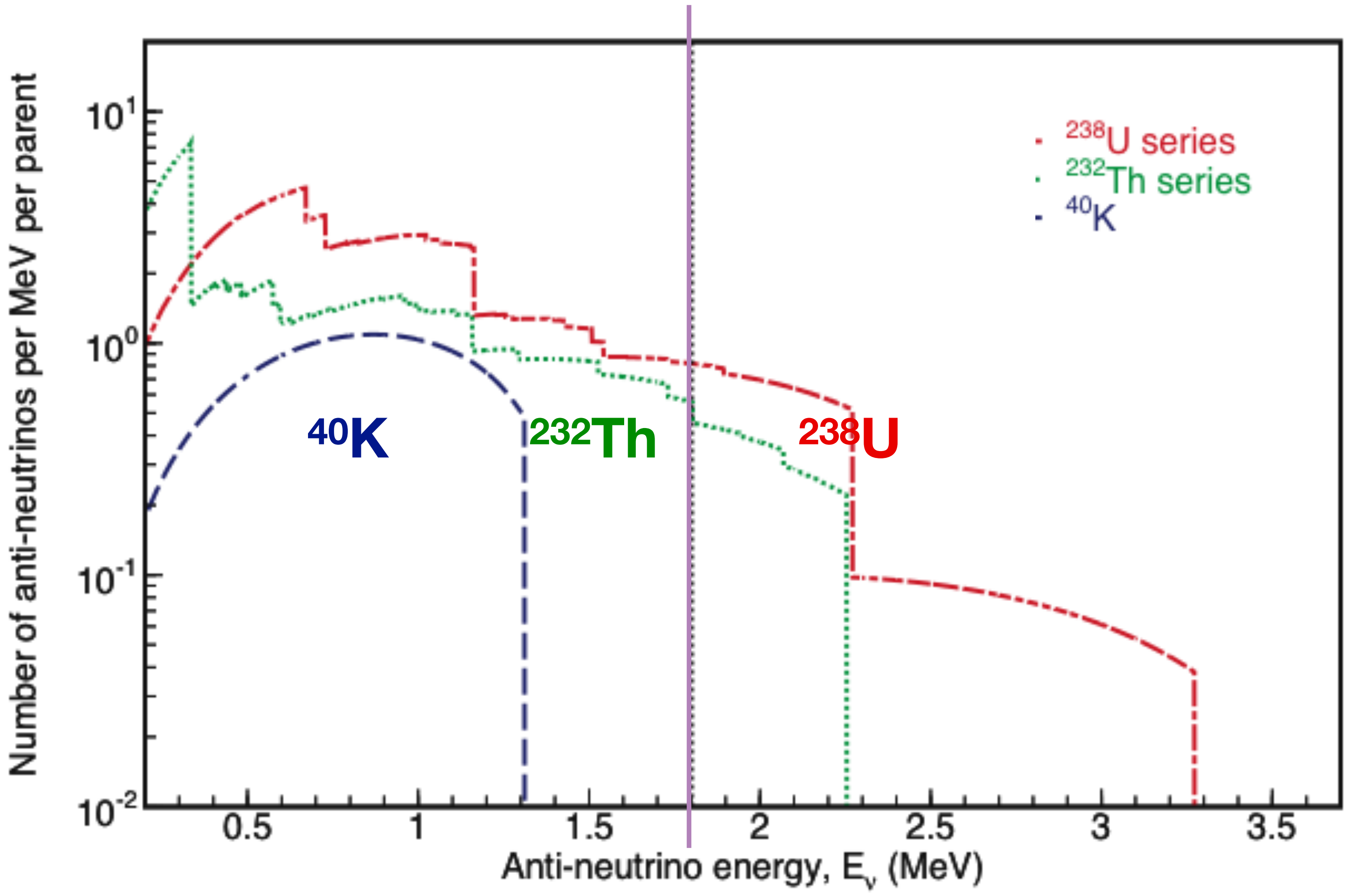
Geoneutrino Flux

Expected geoneutrino flux ~10^6 cm^{-2} s^{-1}

- **Geoneutrinos -** direct probe of the deep Earth. Released heat and geoneutrino flux in a well fixed ratio
- Contribution of the **radiogenic heat** flux to the total Earth’s surface flux: margin test and input to many geophysical and geochemical models of the Earth
- **U/Th bulk ratio:** tests and discrimination among geological models, Earth composition models, study of the mantle homogeneity or stratification, insights to the Earth’s formation, testing additional sources of heat

Antineutrino detection





Inverse beta decay (IBD) unique signature

(Historically the first detection of neutrinos)

Cross section (~ 10^{-42} cm^2)

IBD threshold = $m_n + m_e - m_p$ =1.8 MeV

$E_{vis} = E_\nu$ - 1.8 MeV + 2 * 0.511 MeV

Prompt positron annihilaiton + delayed neutron capture

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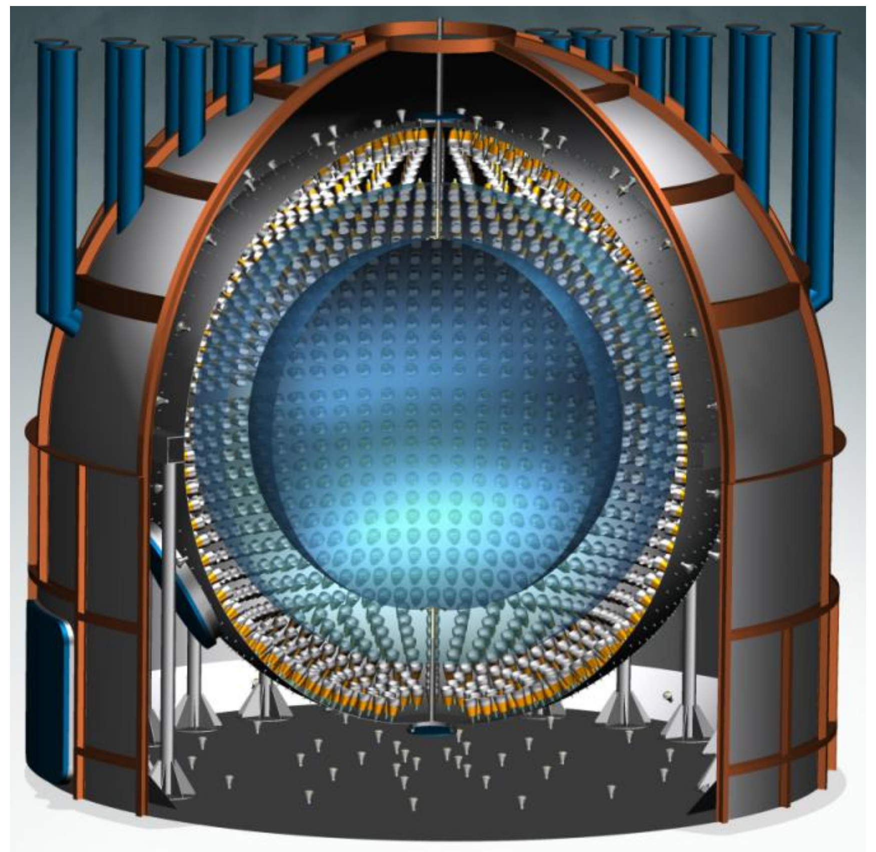
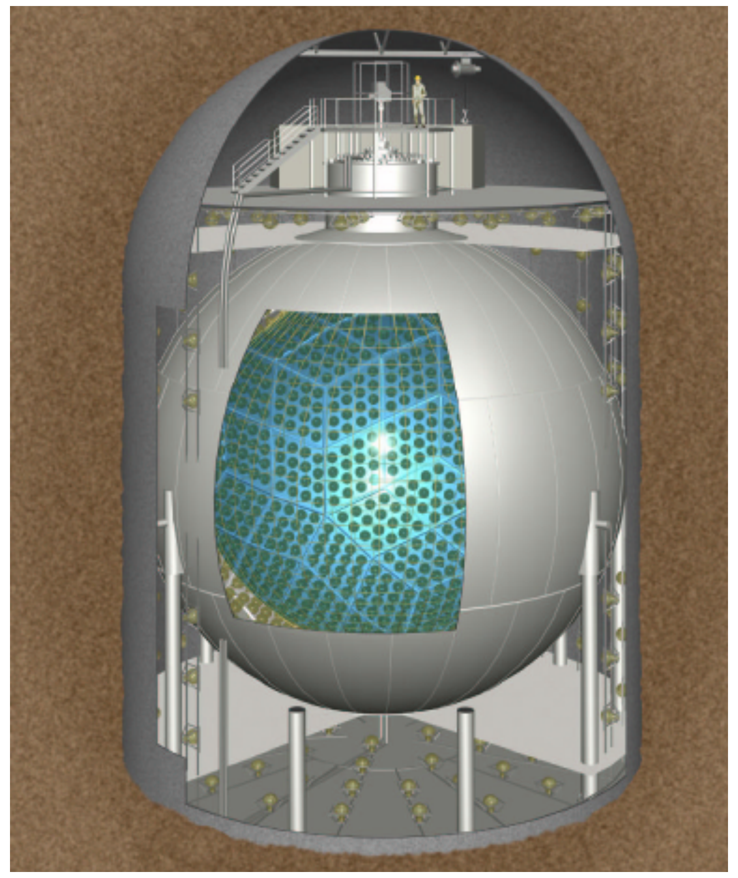
Current State of Affairs

- Currently there are only two measurements in the world: KamLAND(Japan) Borexino (Italy)
- High statistics geoneutrinos studies at a different location -> better understanding of mantle signal. Future experiments: JUNO, SNO+, Theia, Jinping, Ocean Bottom Detector

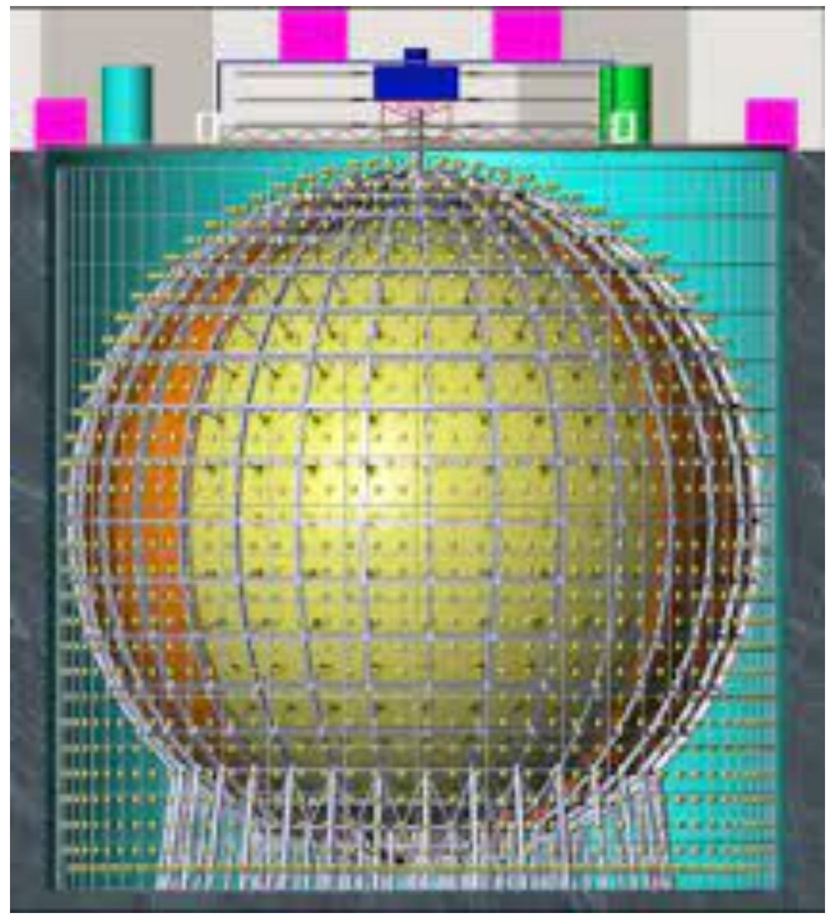
Borexino



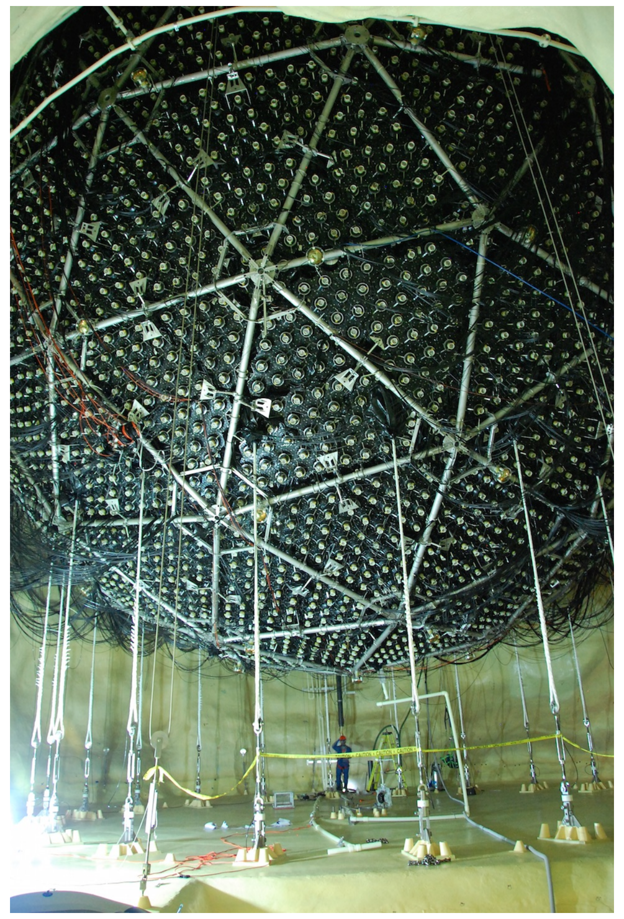
KamLAND



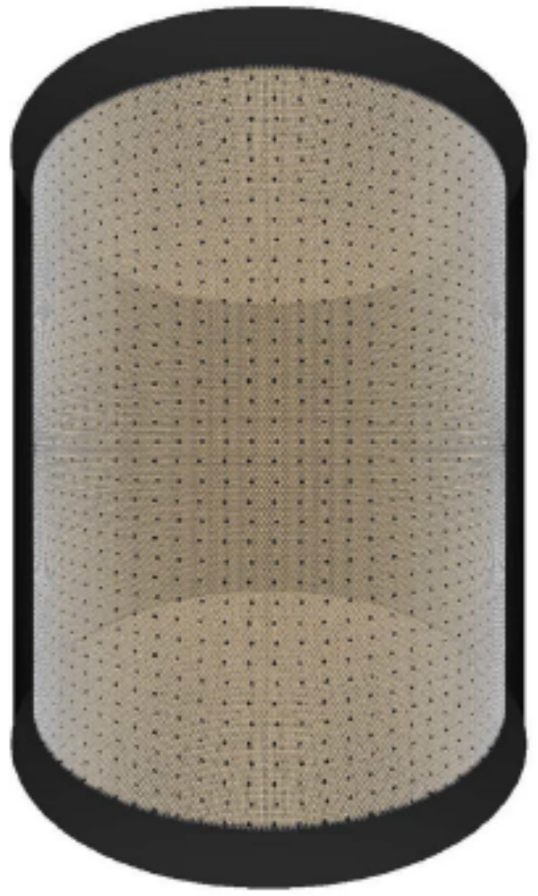
JUNO



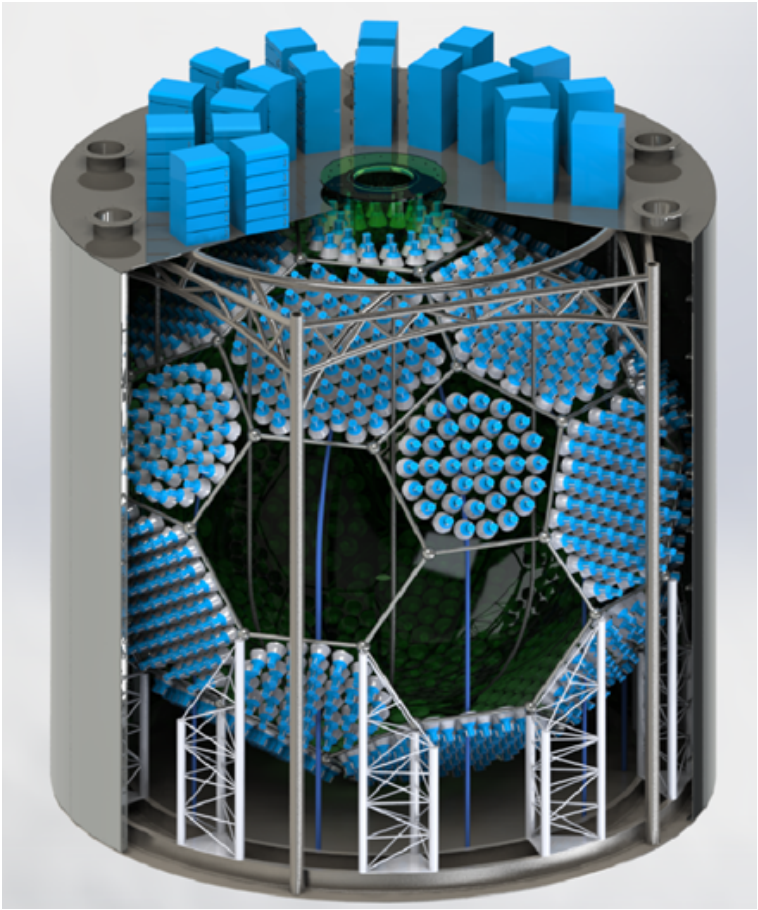
SNO+



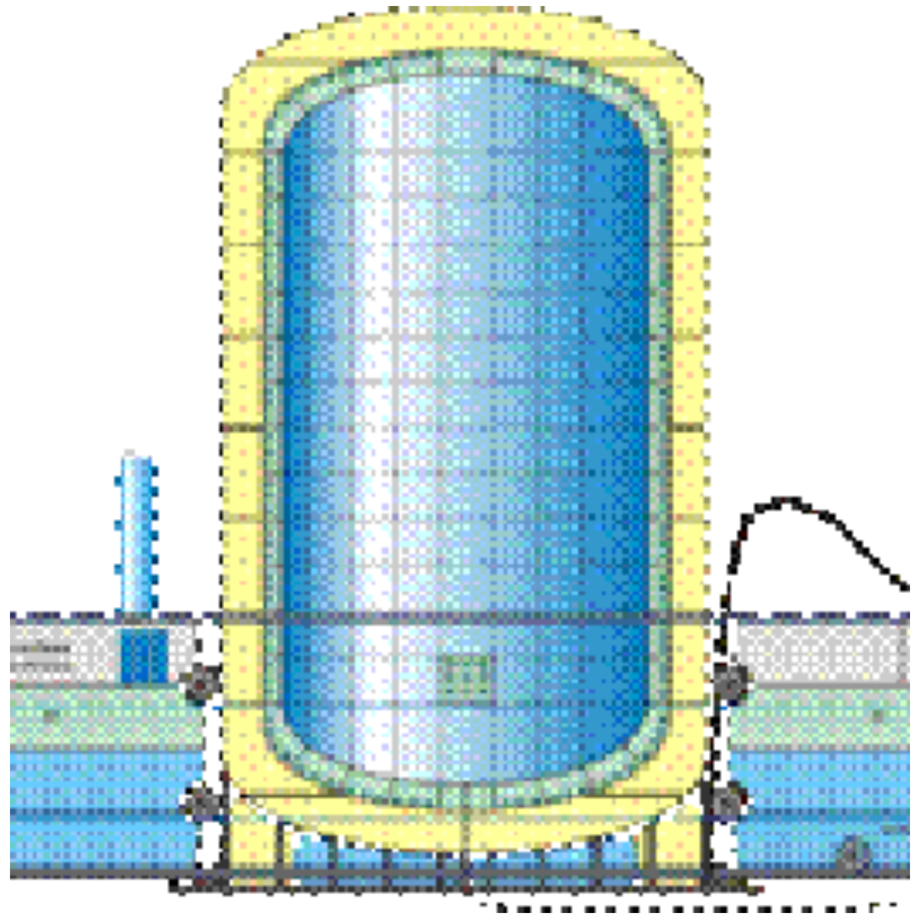
Theia



Jinping



OBD



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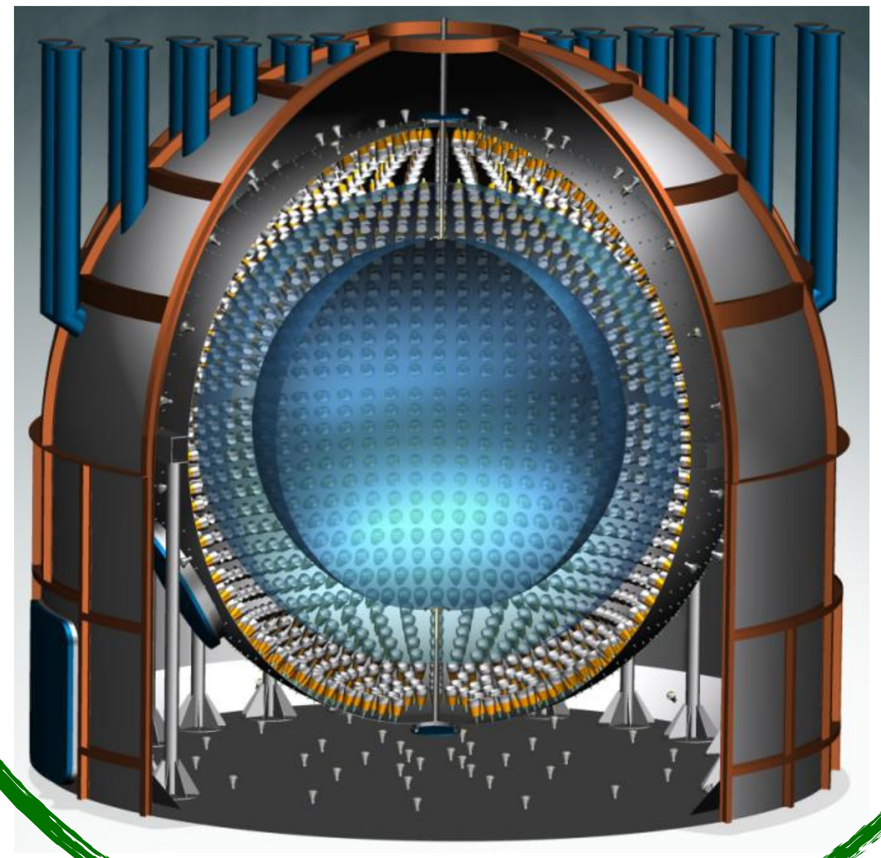
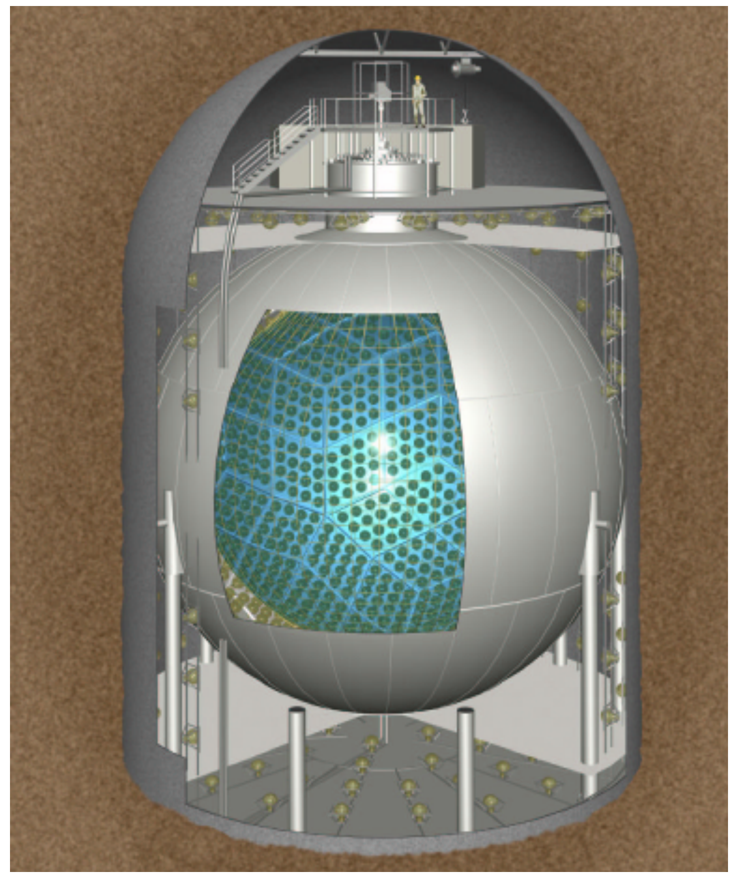
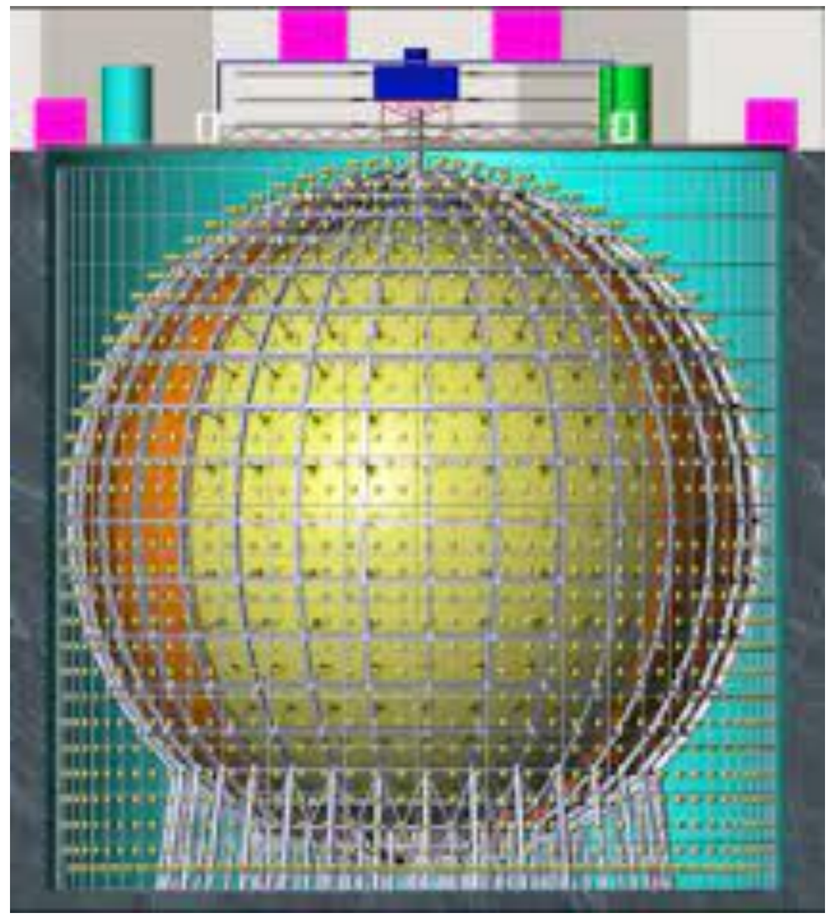


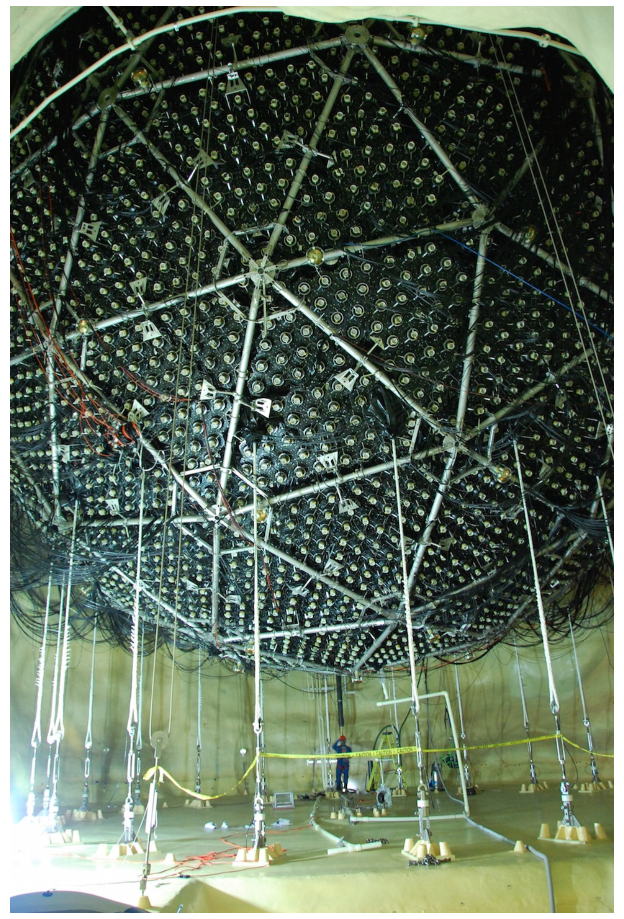
Borexino



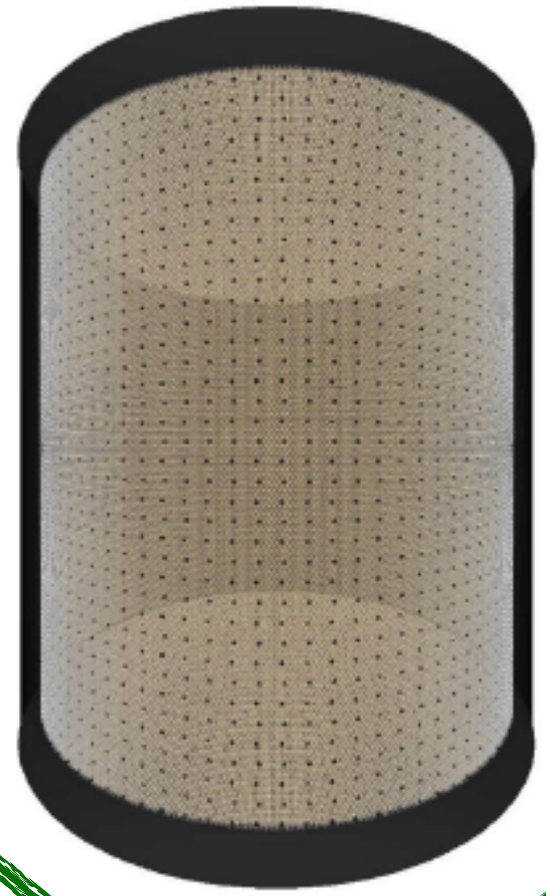
KamLAND



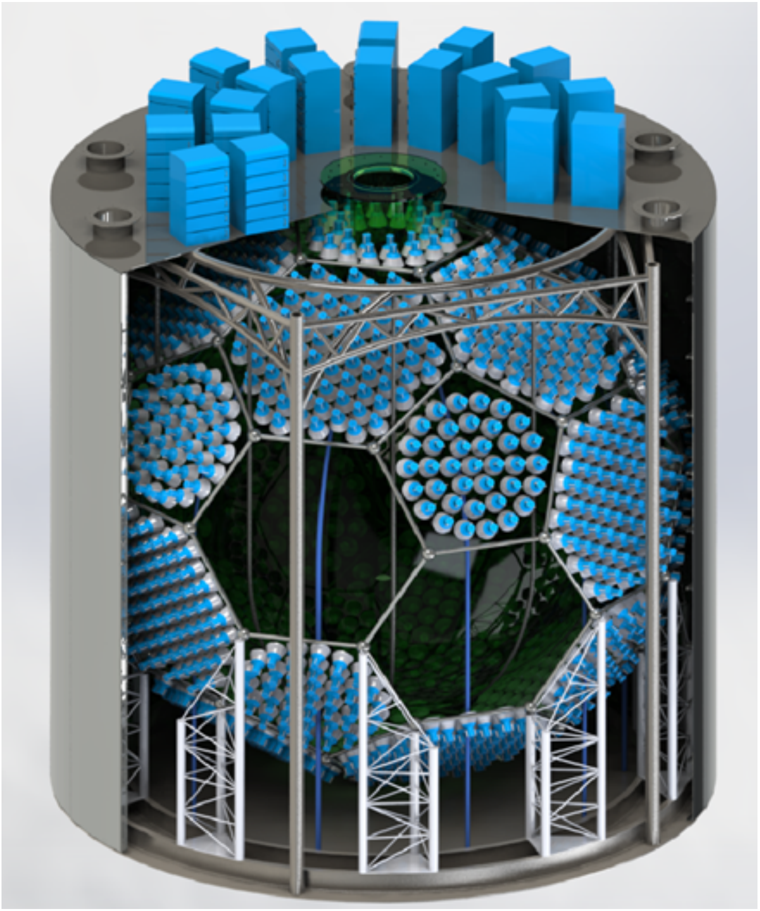
JUNO



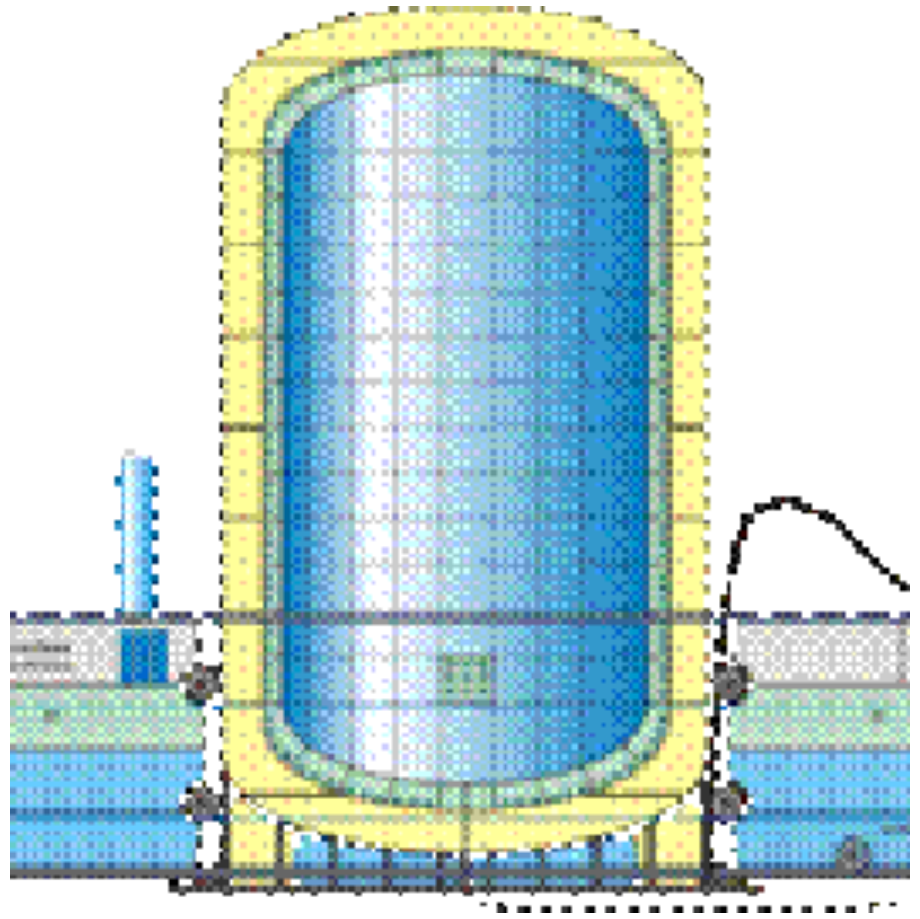
SNO+



Theia



Jinping



OBD

Borexino at Laboratori Nazionali del Gran Sasso (LNGS)

CV

Data taking: May 2007 - October 2021

Location: Gran Sasso National Laboratories, Hall C

Qualifications:

Unprecedented scintillator radiopurity

Low-energy threshold

High light yield

Good energy and position resolution

Interests/Activities:

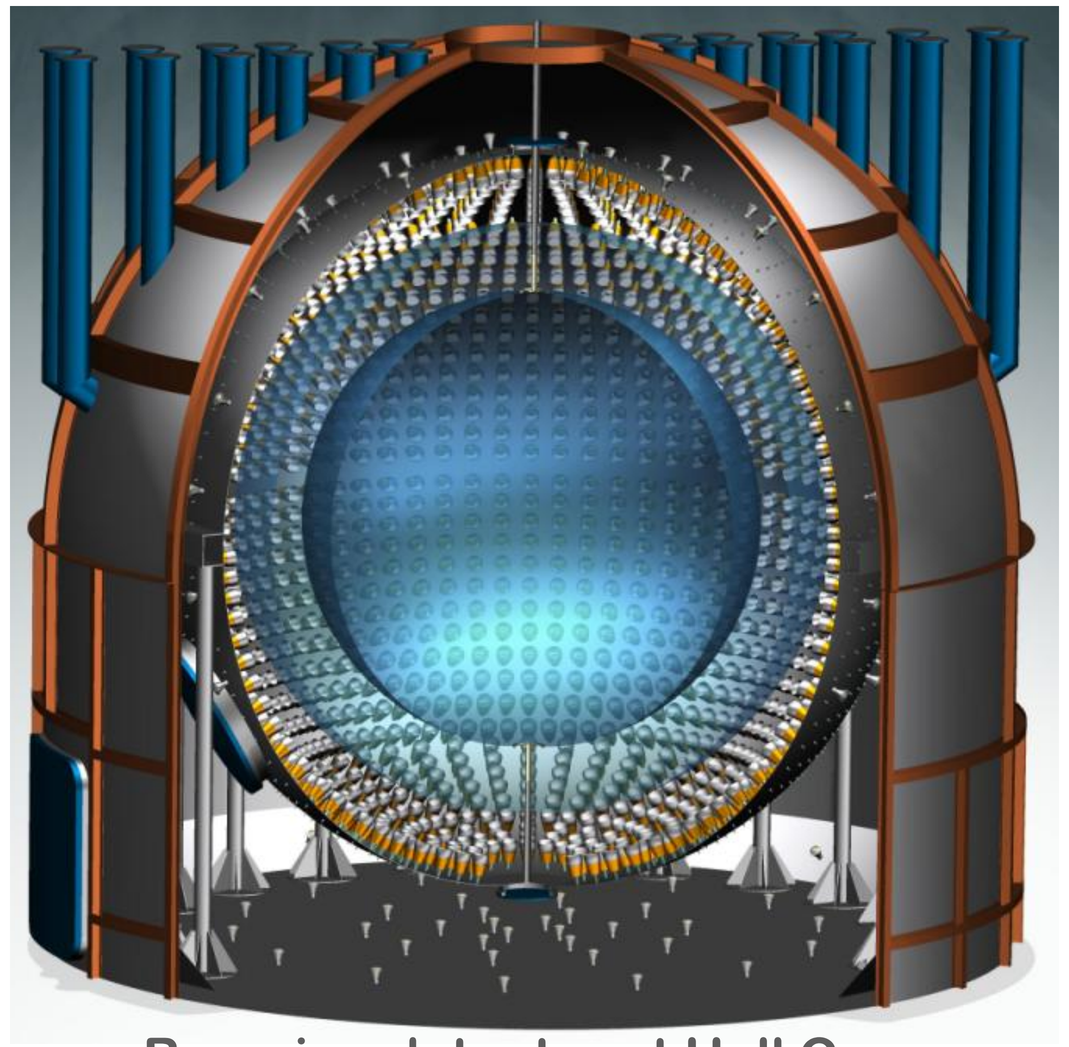
Solar neutrinos

Geoneutrinos

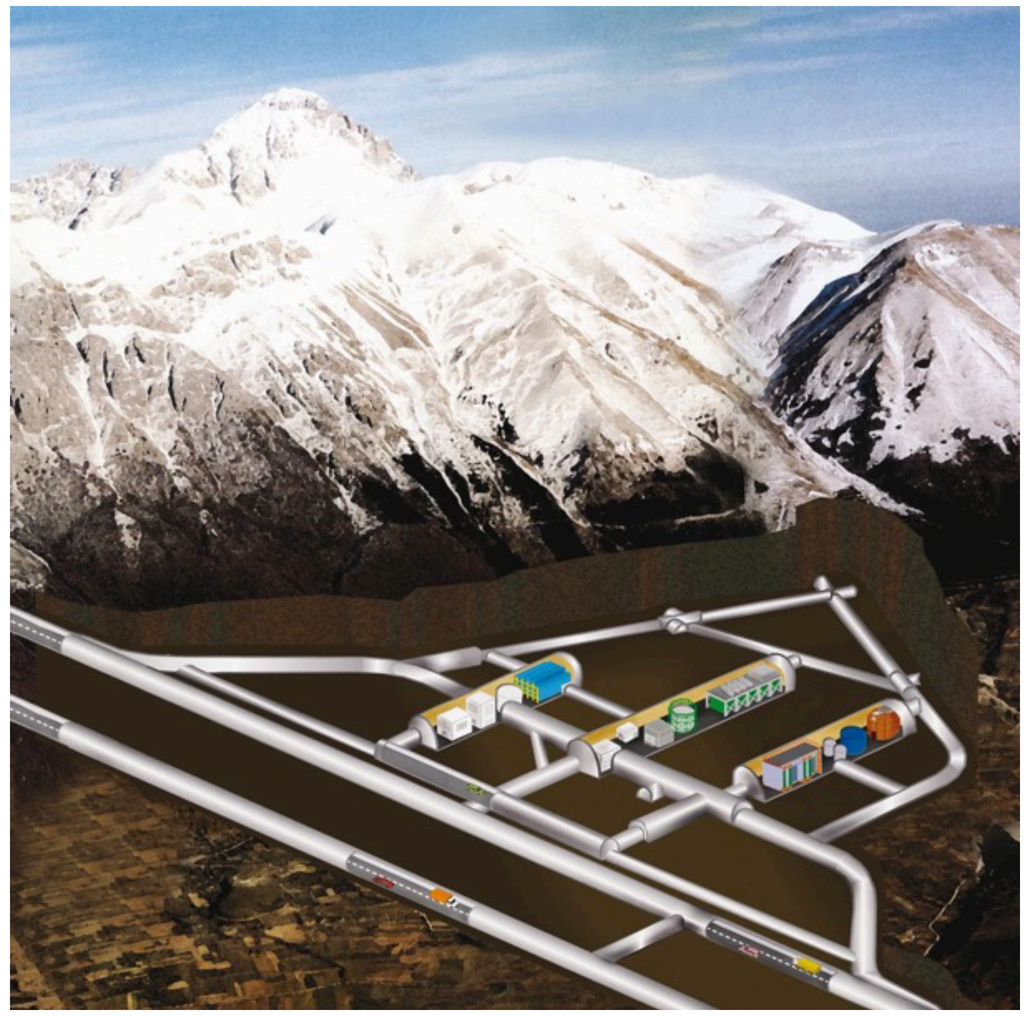
Physics beyond the Standard Model

Detection channels: elastic scattering (ES), inverse beta decay (IBD)

Weakness: Limited directionality, “small” (~300t)



Borexino detector at Hall C.
Credit: Borexino Collaboration



Laboratori Nazionali del Gran Sasso Credit: LNGS

With my students at LNGS. Credit: Zara Bagdasarian

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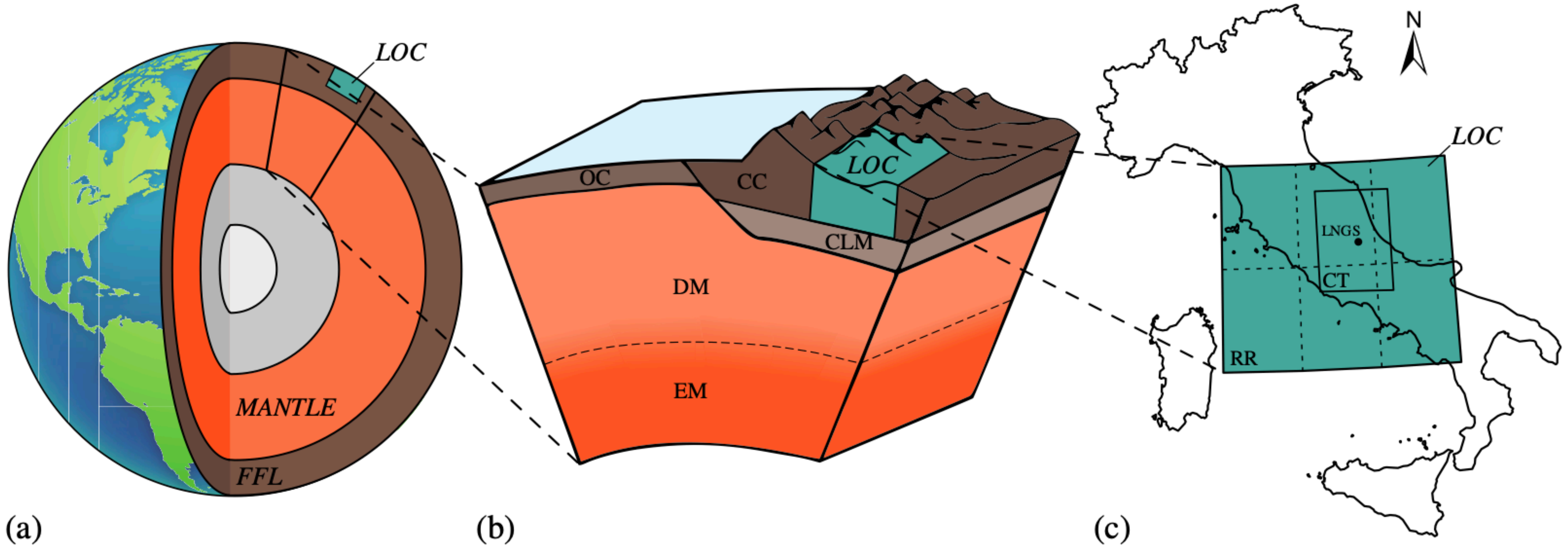
Expected Geoneutrino signal at LNGS

Local and global geological information:



	S (U +Th) [NIU]	H (U+Th+K) [TW]
Local Crust (~500 km around LNGS)	9.2 ± 1.2	-
Bulk Lithosphere	$25.9^{+4.9}_{-4.1}$	$8.1^{+1.9}_{-1.4}$
Mantle = Bulk Silicate Earth model - lithosphere	2.5 - 19.6	3.2 - 25.4
Total	28.5 - 45.5	11.3 - 33.5

1 NIU corresponds to 1 antineutrino event detected via IBD over 1 year by a detector with 100% detection efficiency containing 10^{32} free target protons (roughly corresponds to 1 kton of LS).

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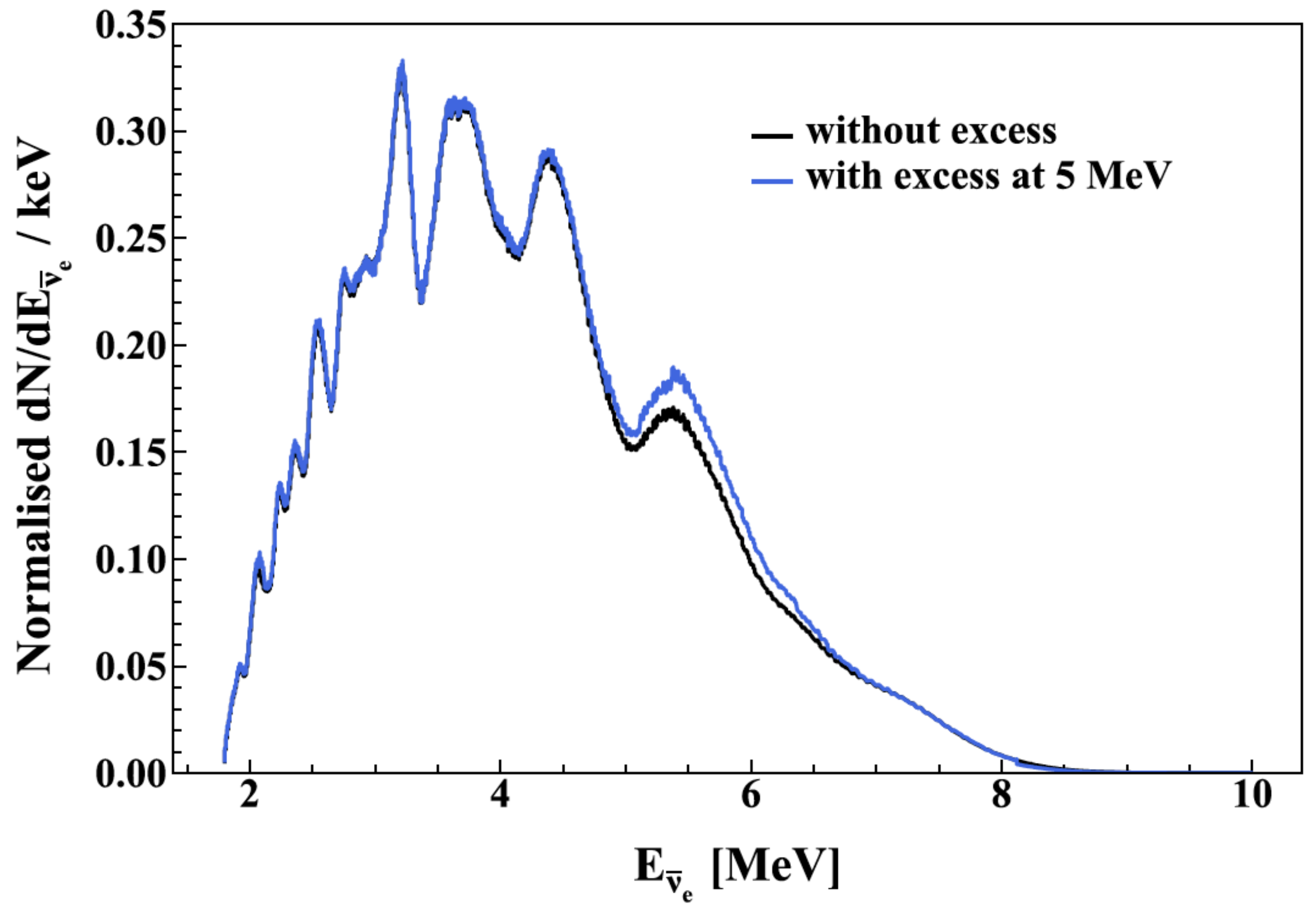
Antineutrino backgrounds

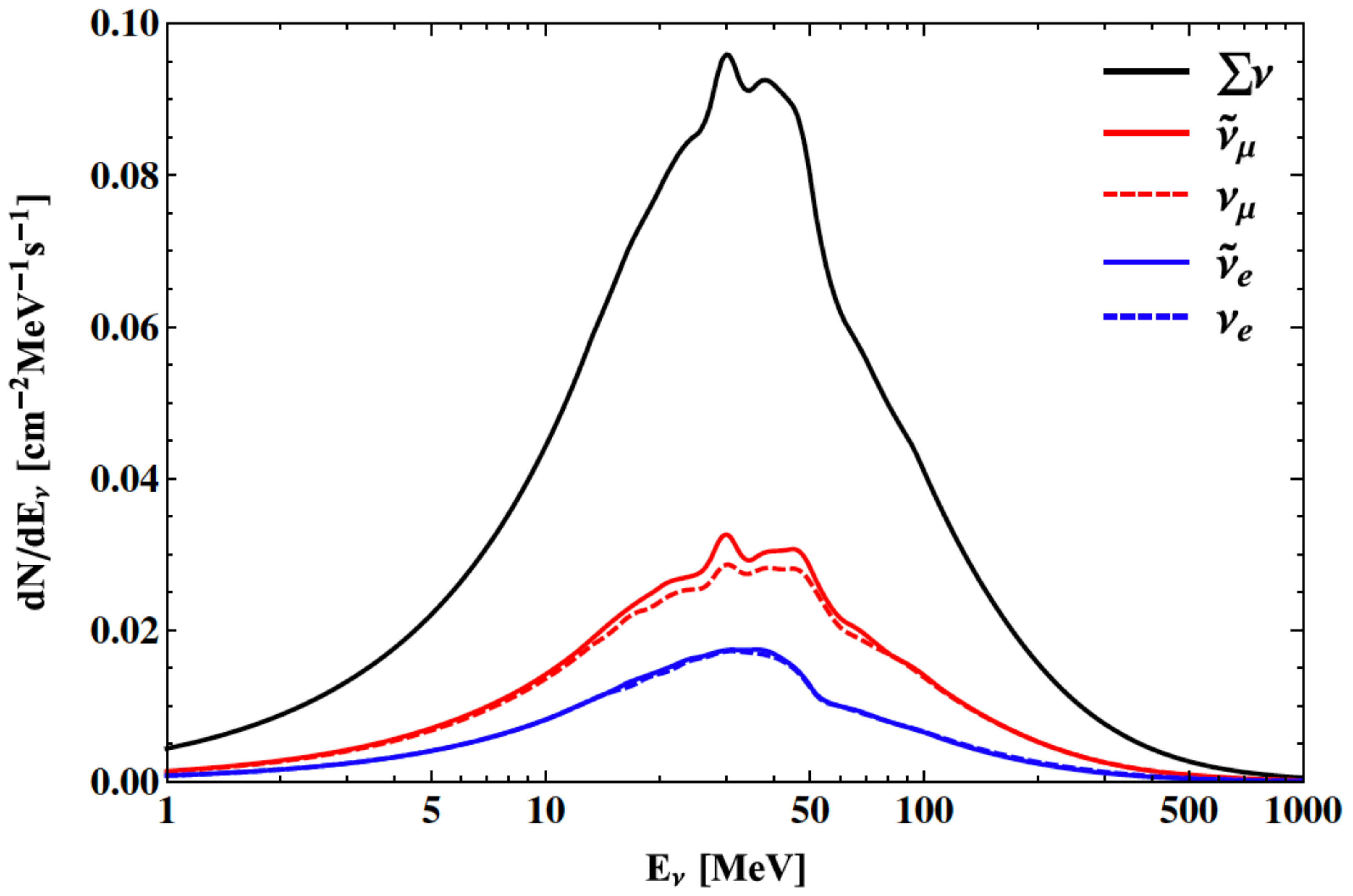
Reactor antineutrinos:

For all ~440 world reactors (1.2 TW total power)
- large distance to LNGS (no reactors in Italy)
- With and without 5 MeV excess



Atmospheric:

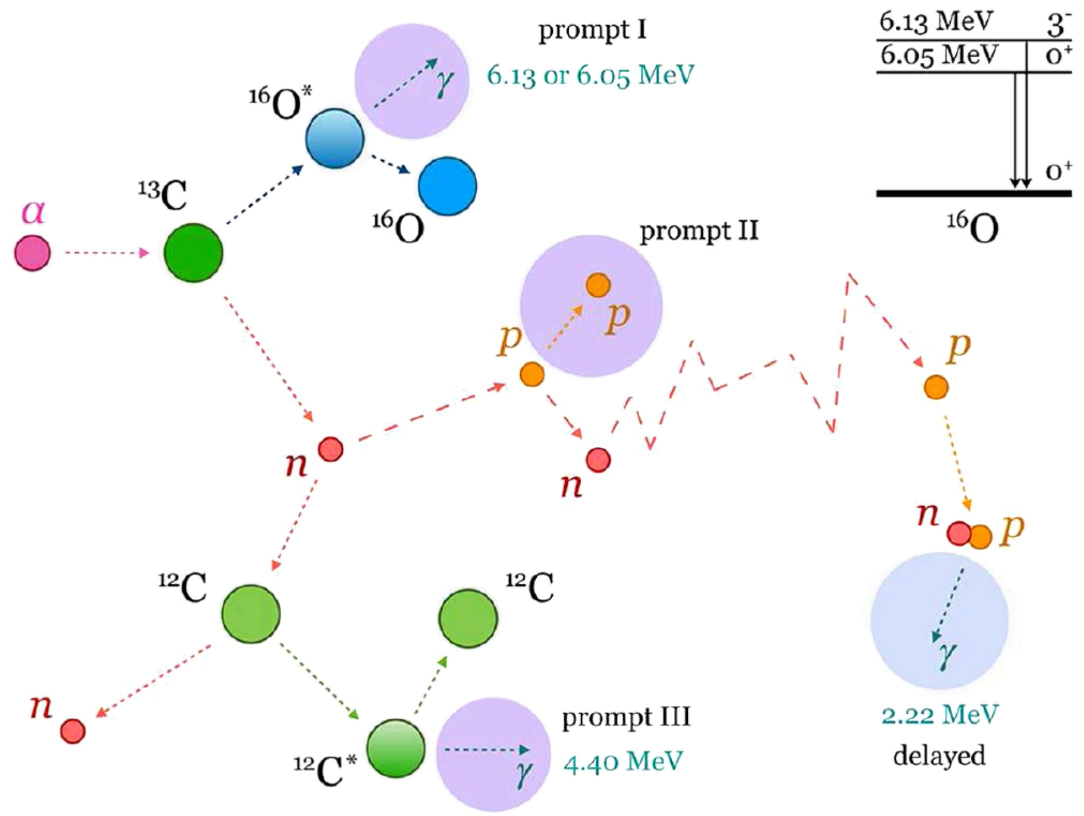
Estimated 50% uncertainty on the prediction
- Indications of overestimation
- Included in the systematic error
- Atmospheric neutrino fluxes
from HKKM2014 (>100 MeV) and FLUKA (<100 MeV)
- Matter effects included



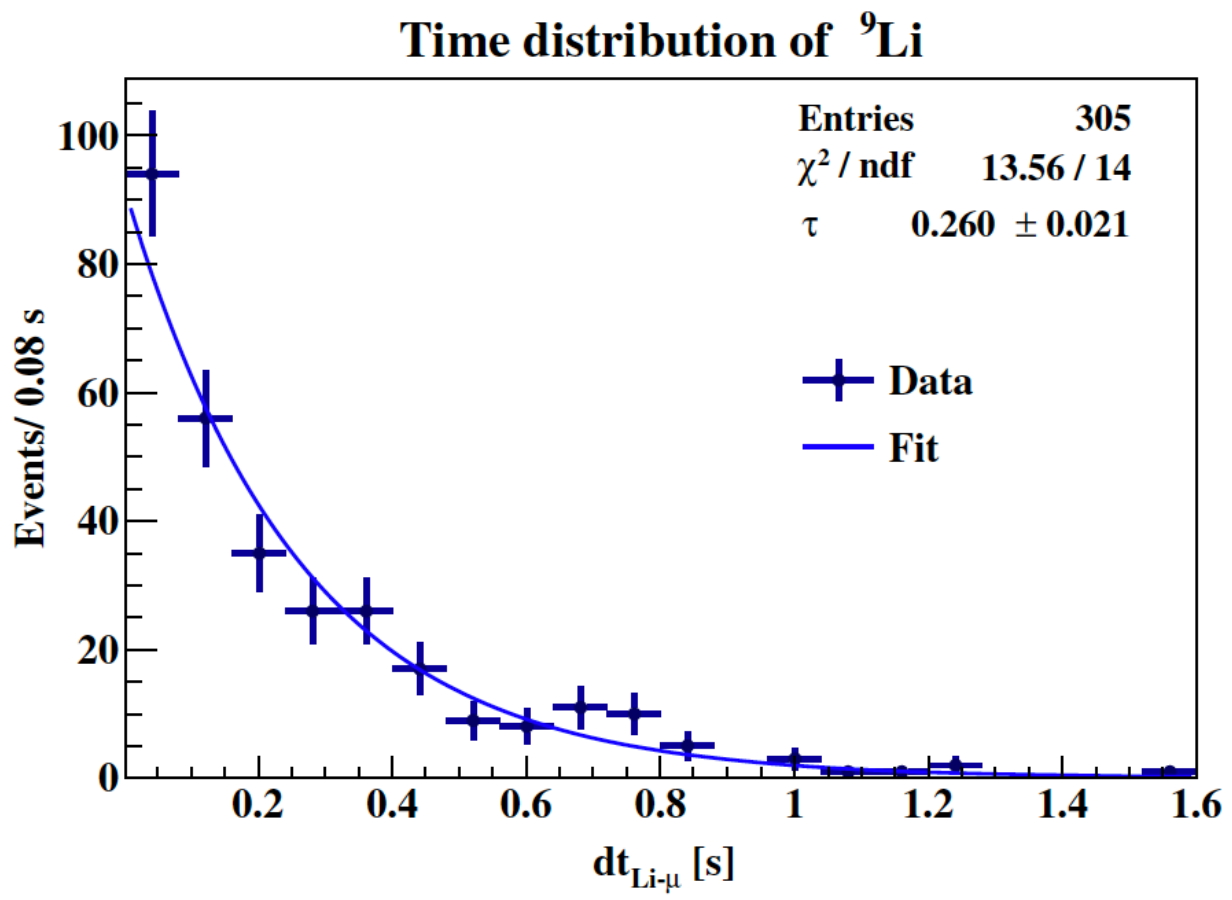
Non-Antineutrino backgrounds

Background Type	Events
^{9}Li background	3.6 ± 1.0
Untagged Muons	0.023 ± 0.007
Fast n's (μ in WT)	<0.013
Fast n's (μ in rock)	<1.43
Accidental coincidences	3.846 ± 0.017
(α, n) in scintillator	0.81 ± 0.13
(α, n) in buffer	<2.6
(γ, n)	<0.34
Fission in PMTs	<0.057
^{214}Bi-^{214}Po	0.003 ± 0.0010
Total	8.28 ± 1.01

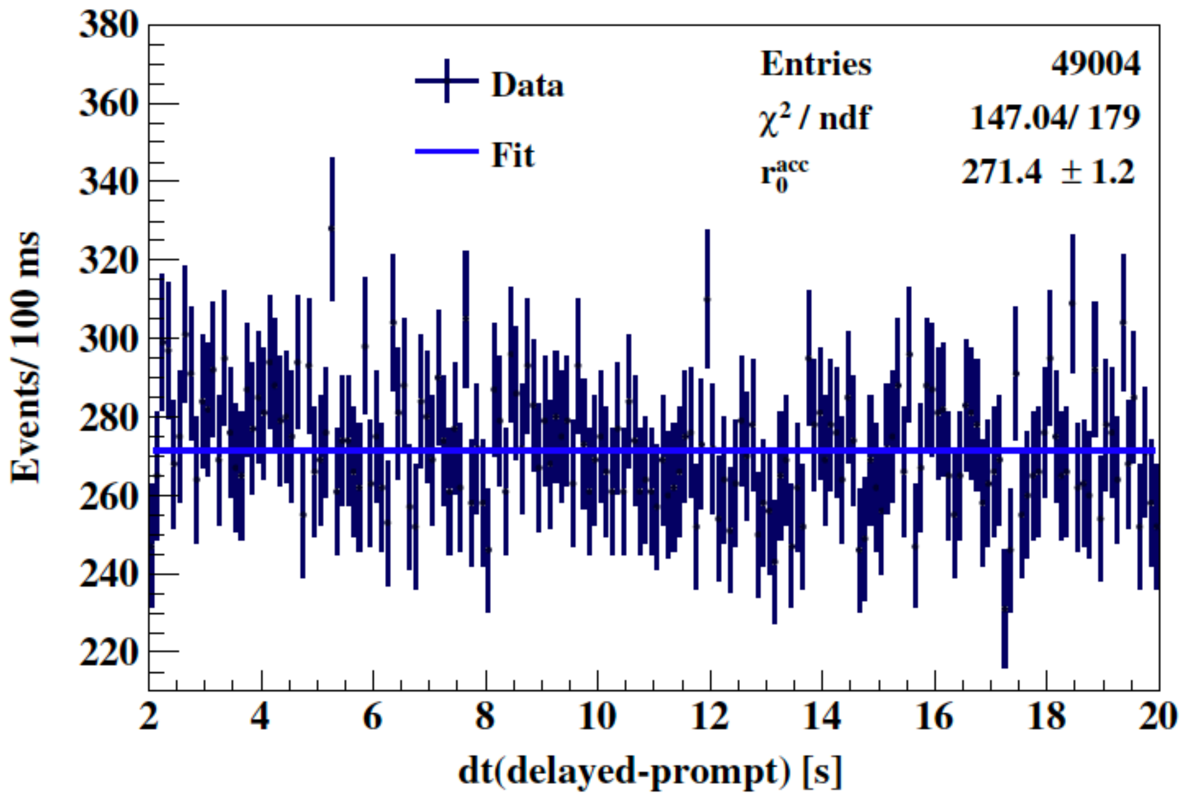
(α,n) in scintillator

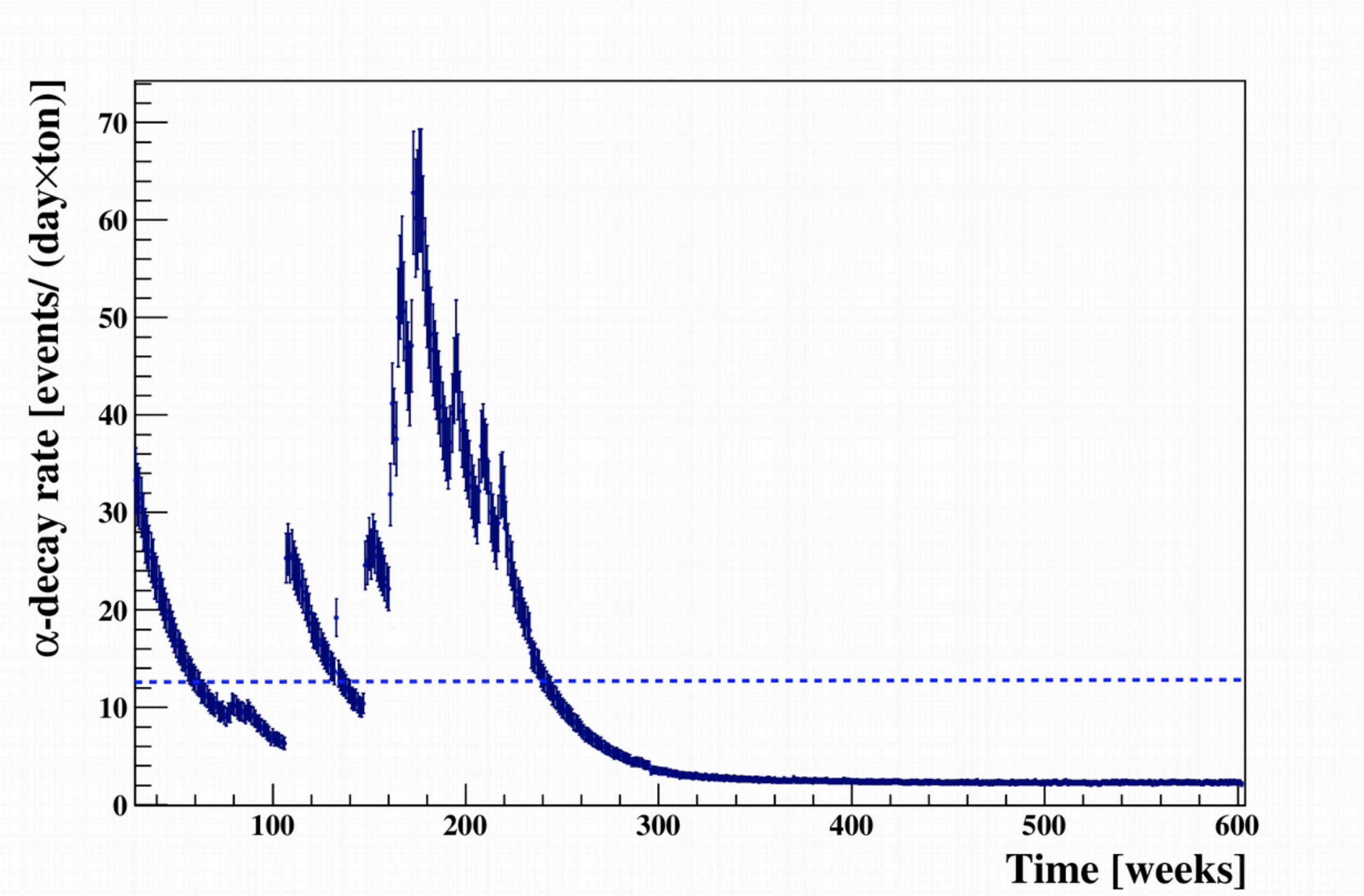


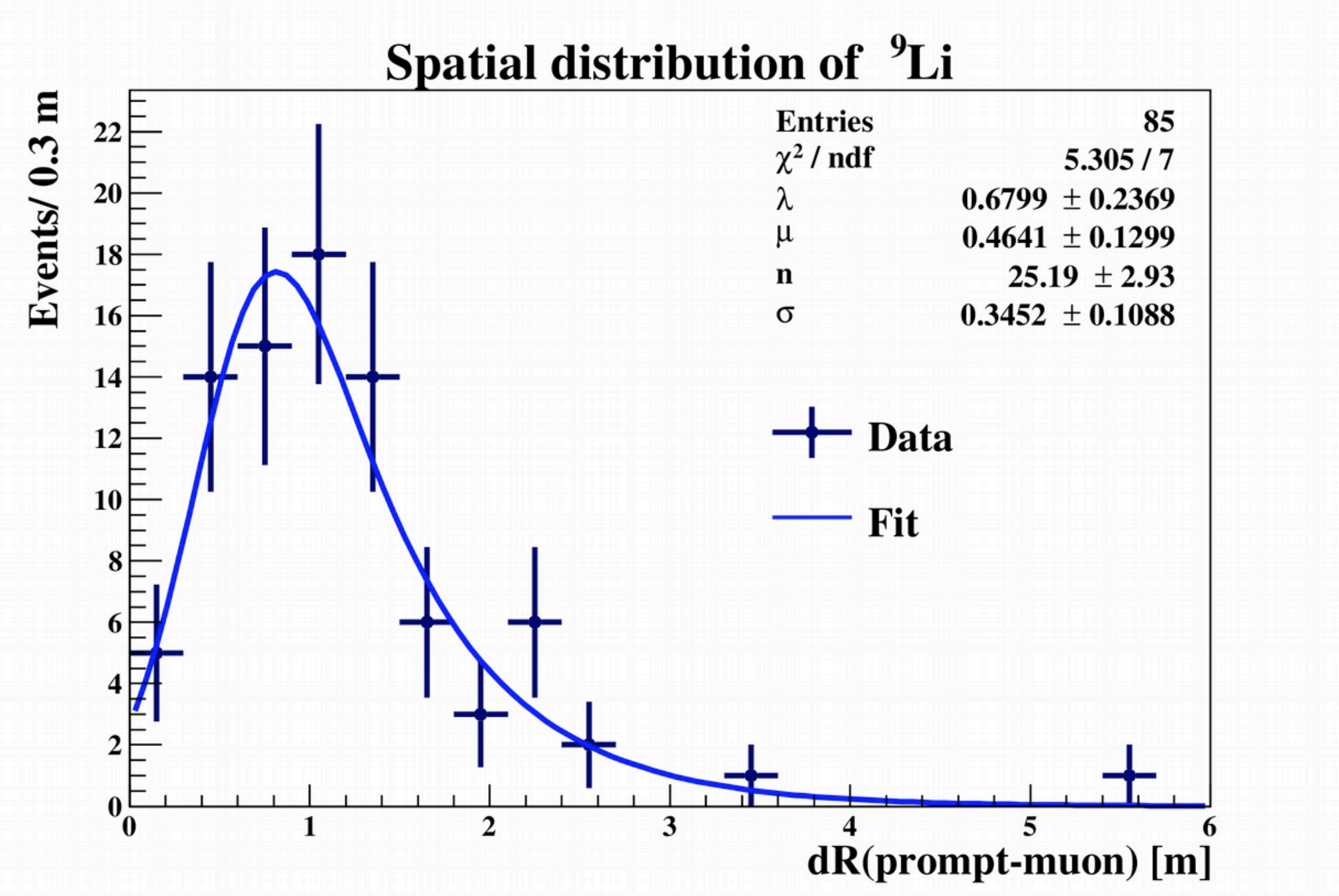
^{9}Li cosmogenic background



Accidental coincidences







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Optimized selection cuts

Charge of prompt

Charge of Q_p > 408 pe

- Prompt spectrum starts at 1 MeV
- Assuming 5% energy resolution @ 1 MeV prompt

Charge of delayed

Charge of Q_d: 700 - 3000 pe

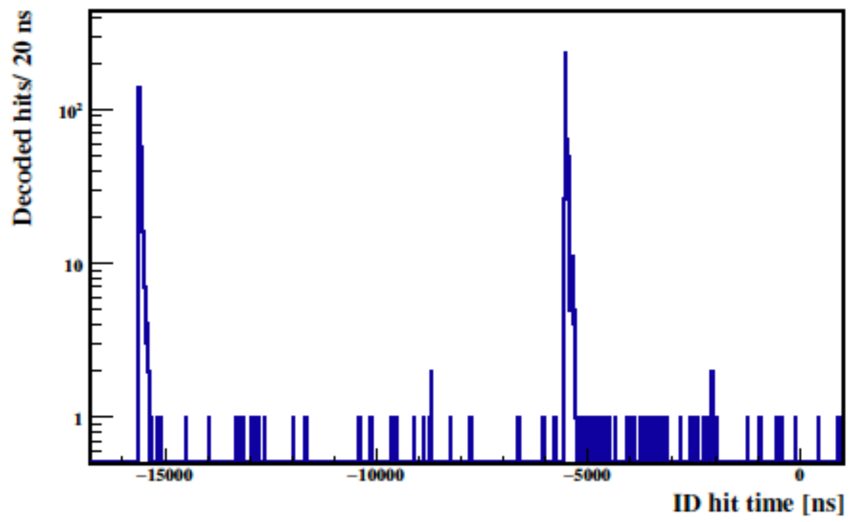
- Neutron captures on proton (2.2 MeV) and in about 1% of cases on ^{12}C (4.95 MeV)
- Radon correlated $^{214}Po(\alpha + \gamma)$ decays from ^{214}Po and ^{214}Bi fast coincidences

Time correlation

dt = (2.5-12.5) μs + (20-1280) μs

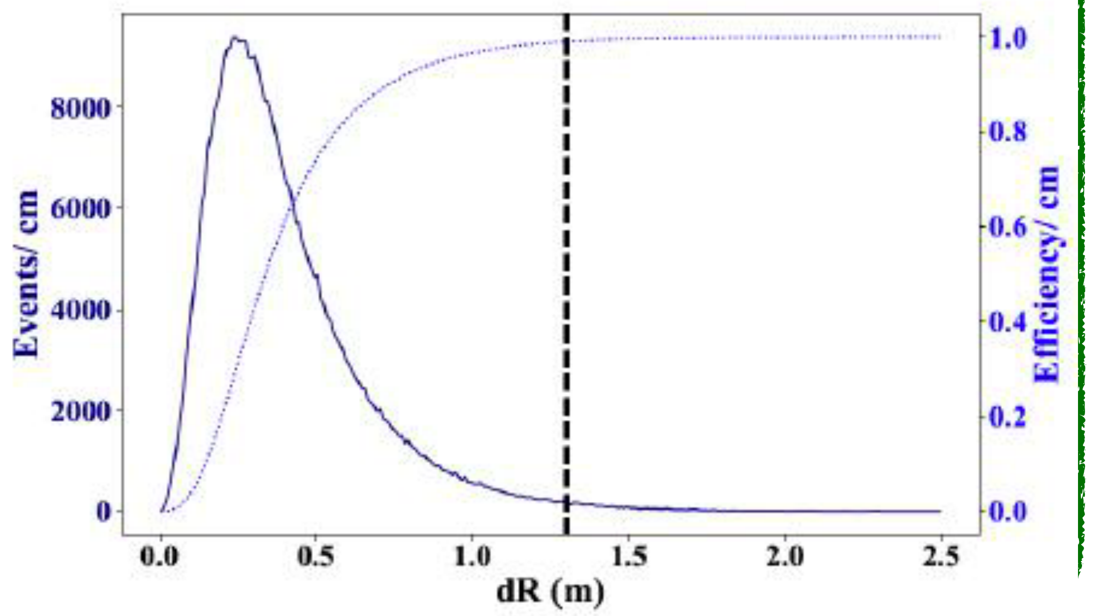
2 cluster event in 16 μs DAQ gate

5 *neutron capture τ = 254.5 ± 1.8 μs



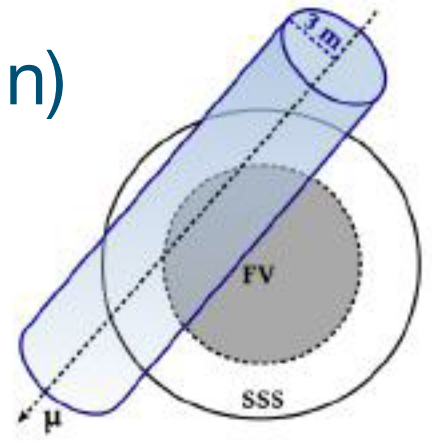
Space correlation

dR < 1.3 m,
(from a dedicated sensitivity study)



Muon veto

2s || 1.6 s : $^{9}Li(\beta + n)$
2 ms: neutrons

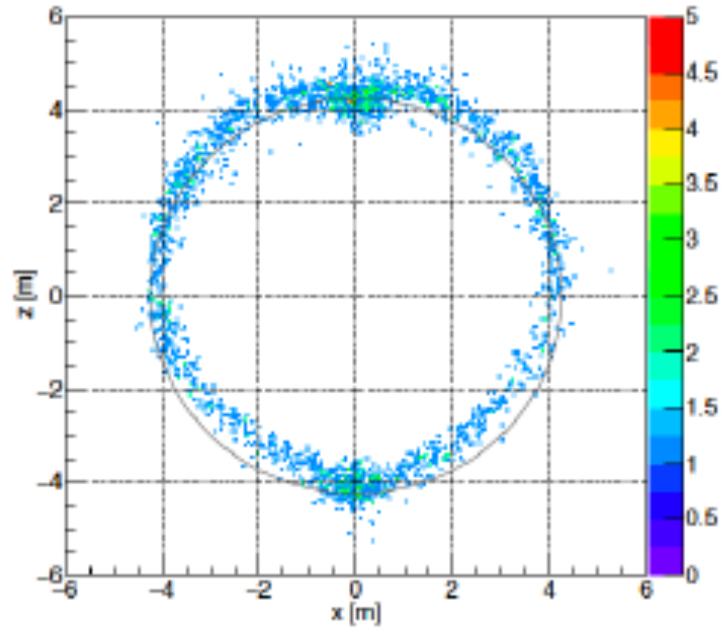


- Several veto categories:
  - Whole detector
  - Cylinder

Only 2.2% exposure loss (previously 11%)

Dynamic FV

Fiducial Volume (FV)
Prompt >10 cm from inner vessel (IV)



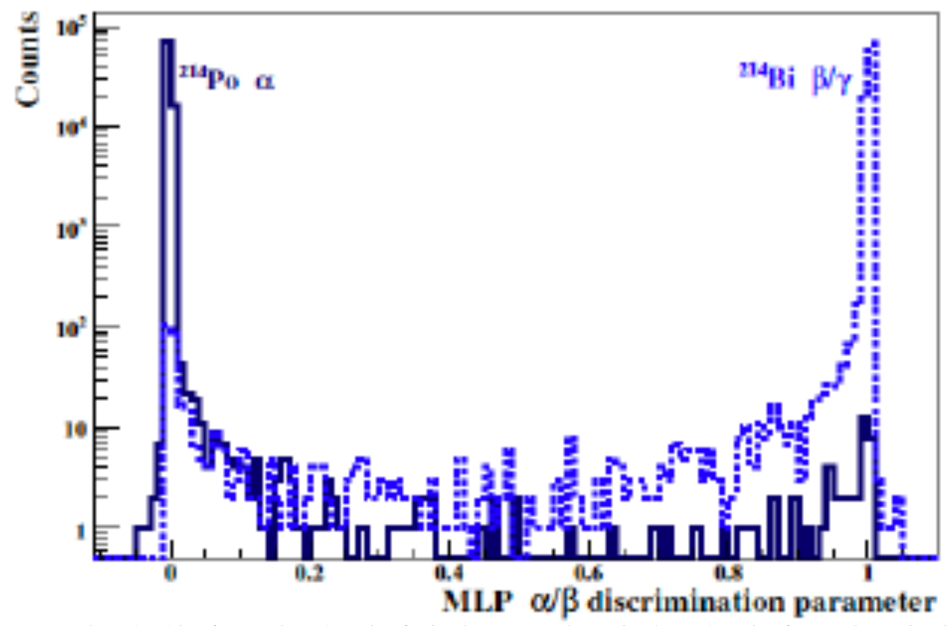
Multiplicity

No >400 pe event ±2 ms around promt/ delayed

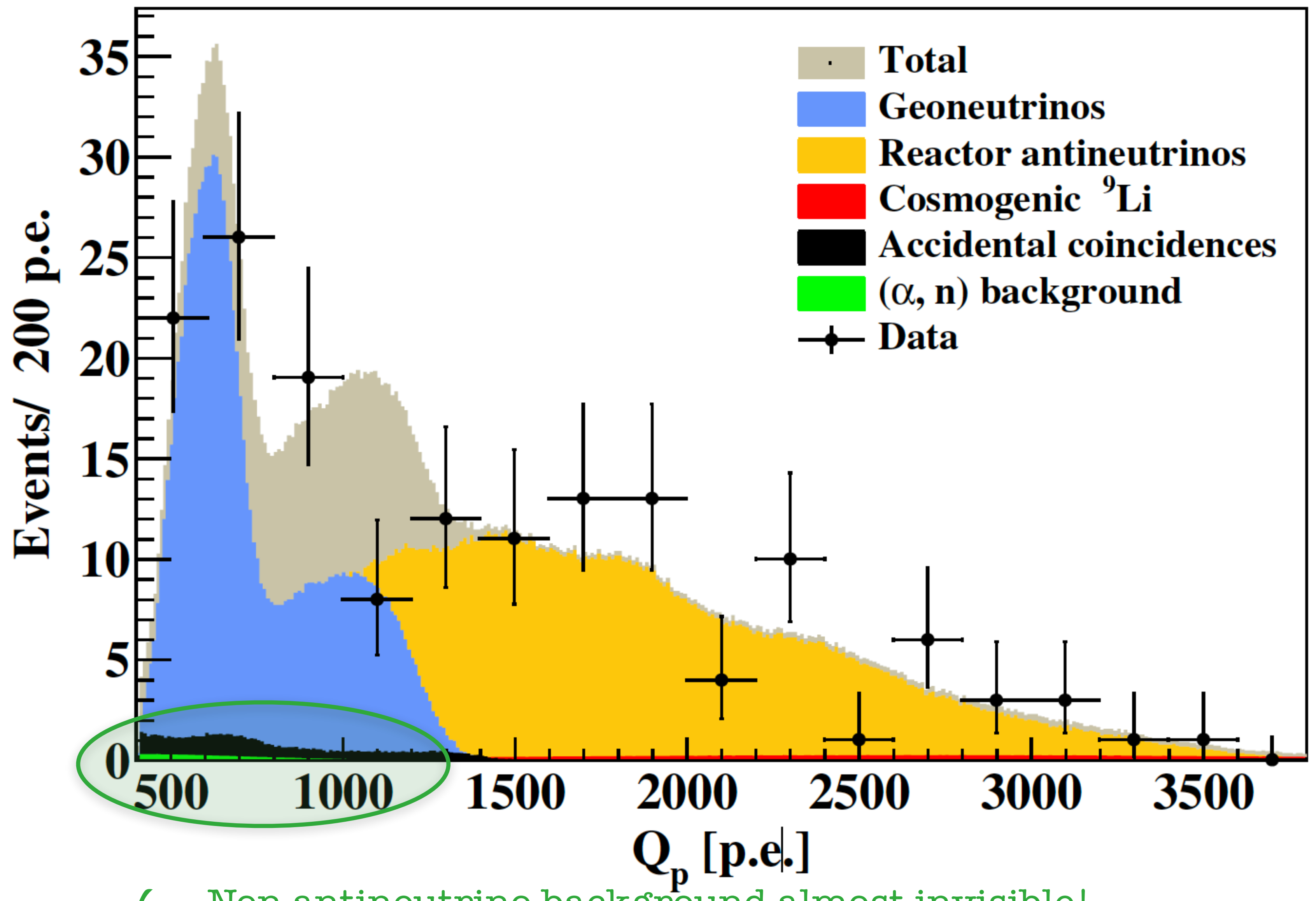
- Suppressing undetected cosmogenic background, mostly multiple neutrons
- Negligible exposure loss

alpha/beta discrimination

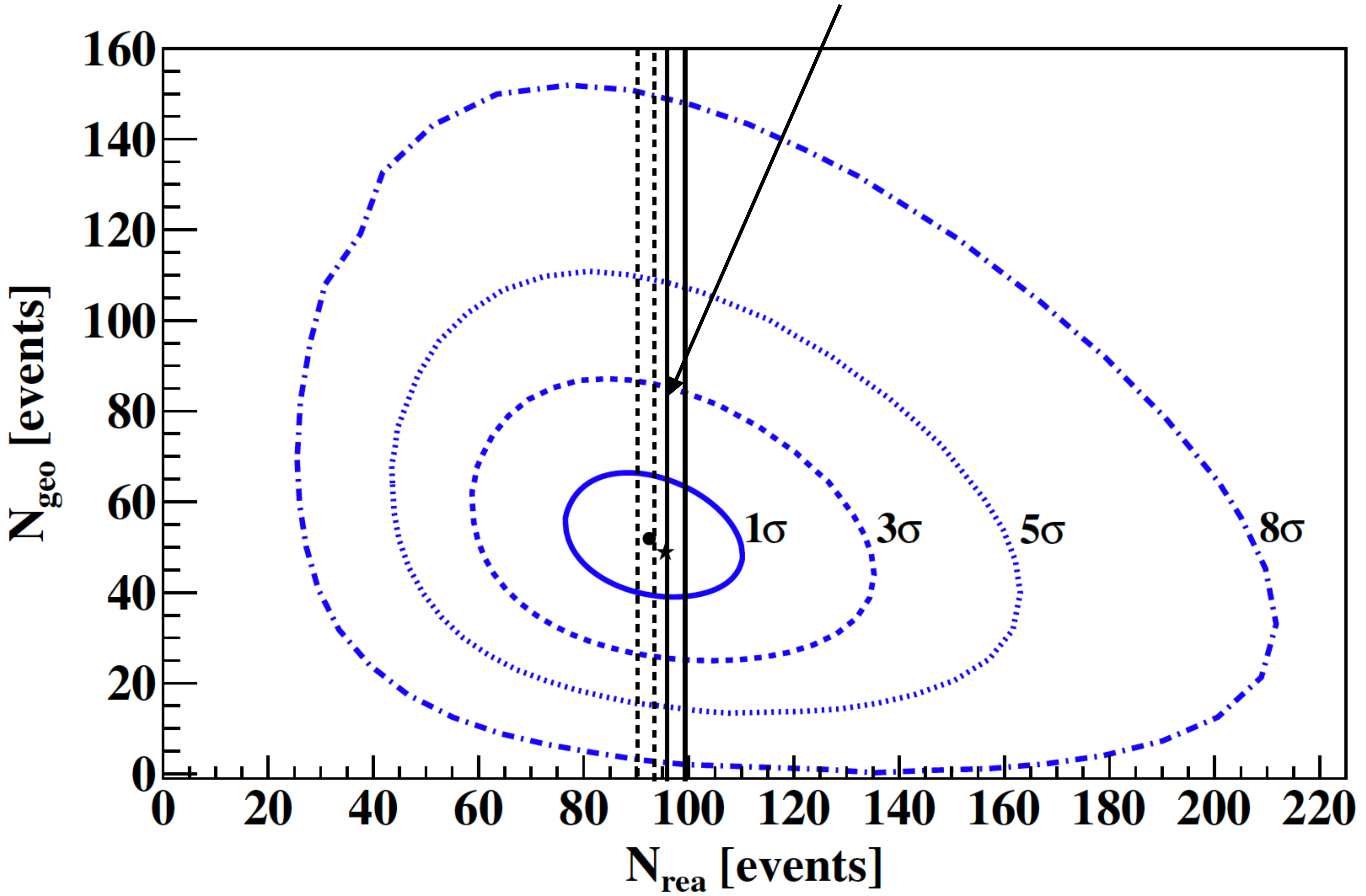
- Radon correlated $^{214}Po(\alpha+\gamma)$
- MLP_d > 0.8 to select betas



Spectral fit: Measured geoneutrinos at LNGS



✓ Non antineutrino background almost invisible!



- Unbinned likelihood fit of charge spectrum of 154 prompt events
- S(Th)/S(U) = 2.7 (corresponds to chondritic Th/U mass ratio of 3.9)
- Reactor signal unconstrained: result compatible with expectations
- ^{9}Li, accidentals, and (α, n) backgrounds constrained according to expectations
- Systematics include atmospheric neutrinos, shape of reactor spectrum, detection efficiency, vessel shape, and position reconstruction

Geoneutrinos: 52.6 $^{+9.4}_{-8.6}$(stat) $^{+2.7}_{-2.1}$(sys) events $^{+18.3\%}_{-17.2\%}$(tot)

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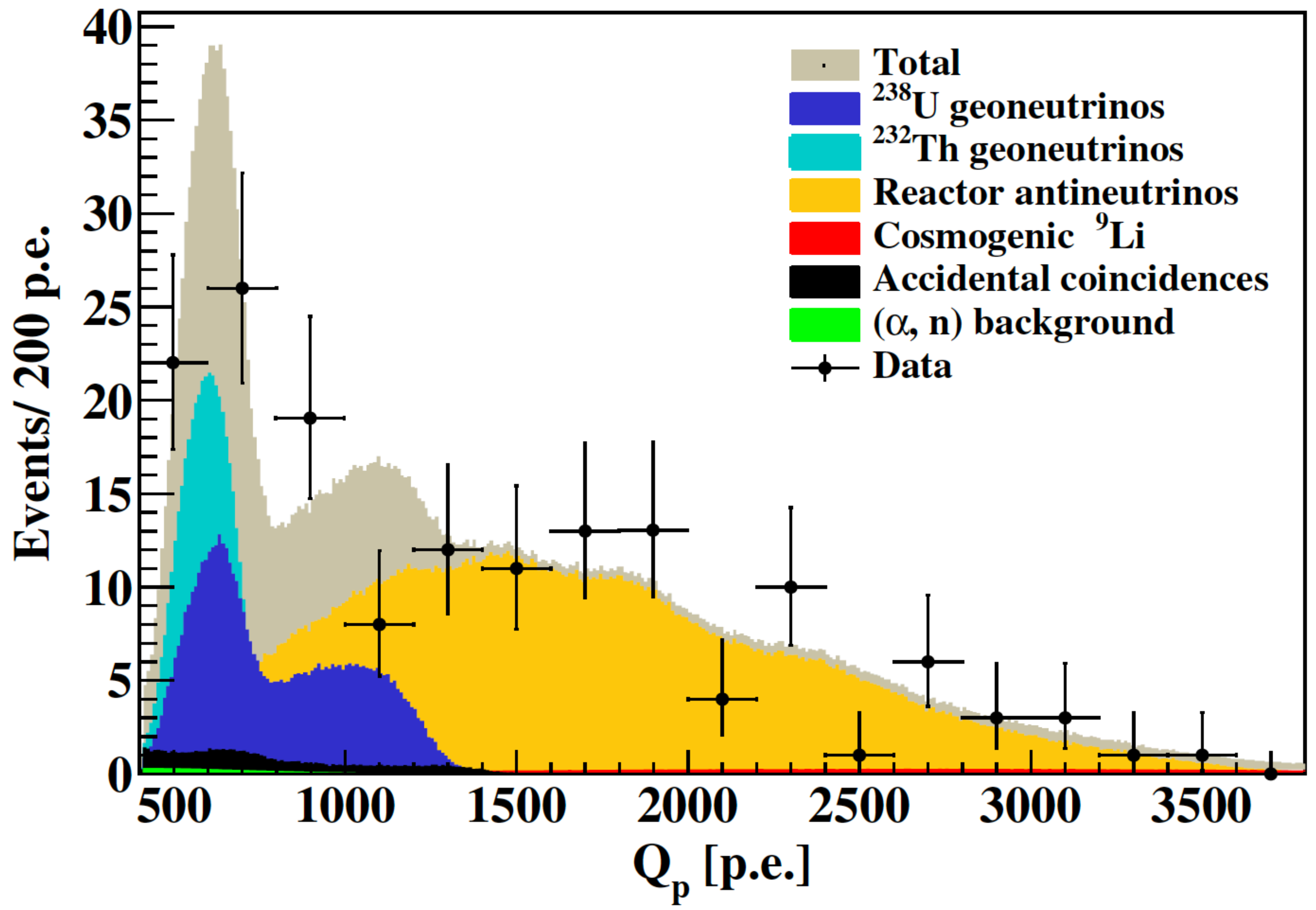
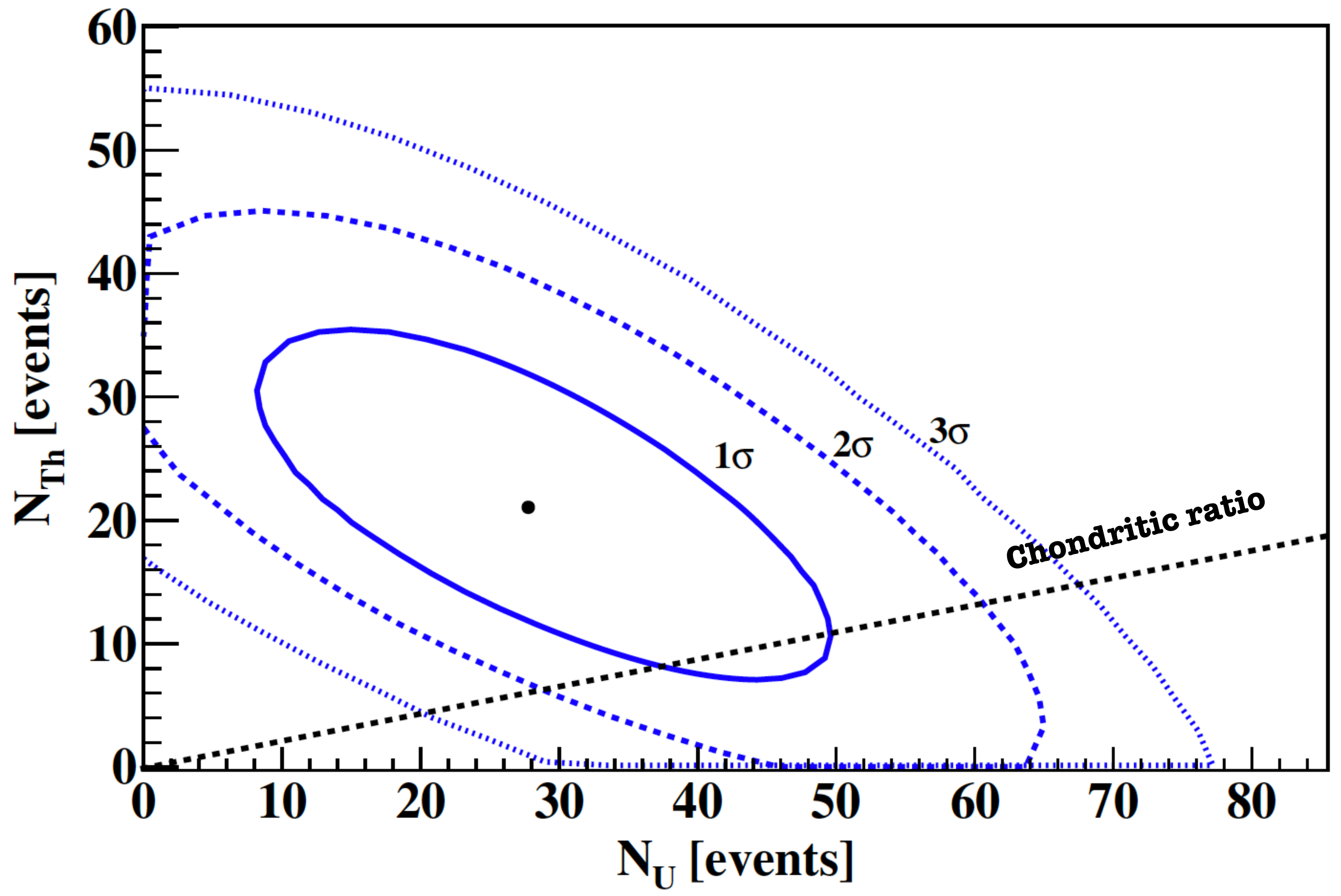
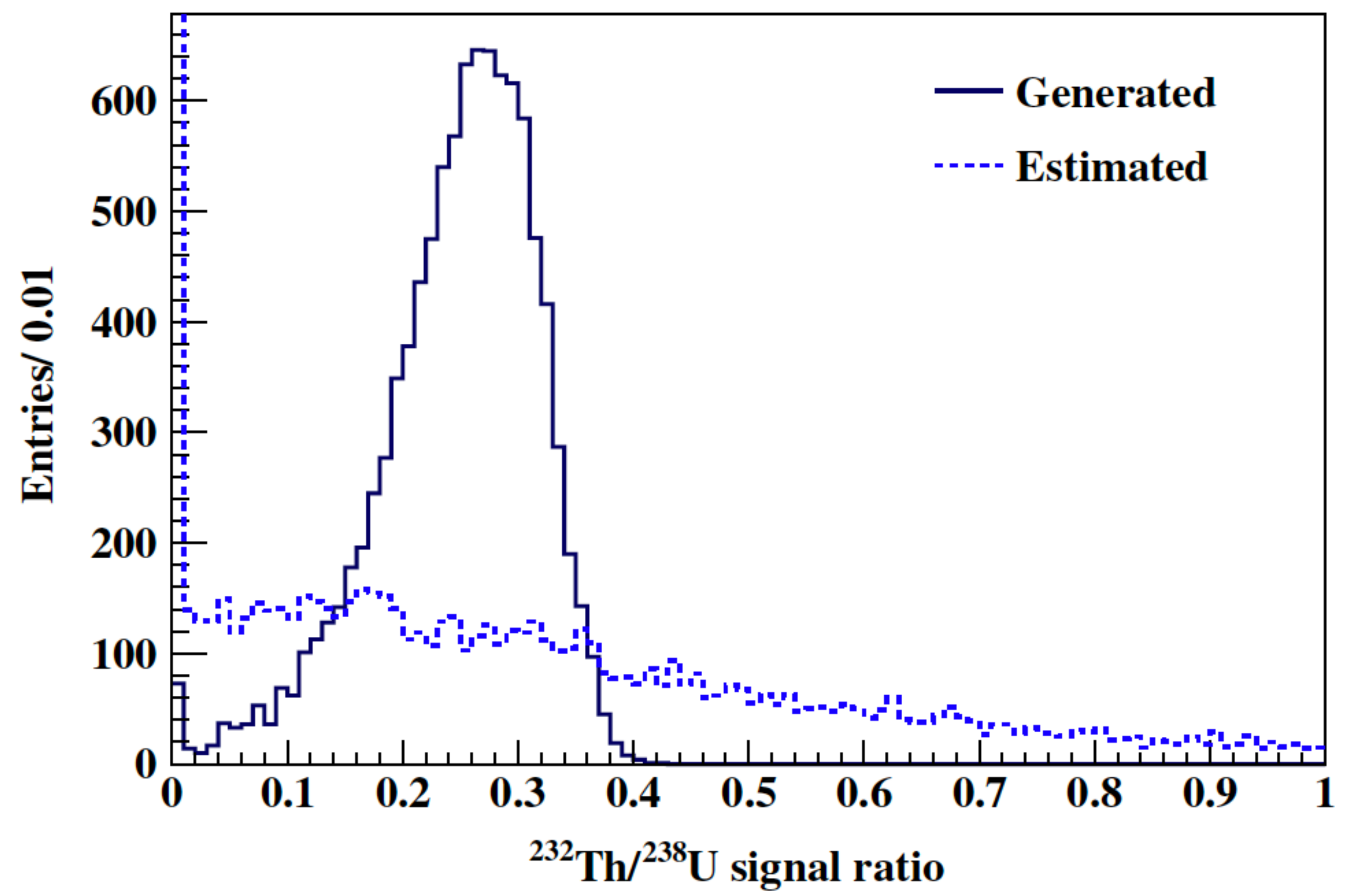
Spectral fit with U and Th free







Geoneutrinos: 50.4 $^{+46.8\%}_{-44.05\%}$(tot) events

- In agreement with the fit with Th/U fixed
- Larger error
- No sensitivity to measure Th/U ratio

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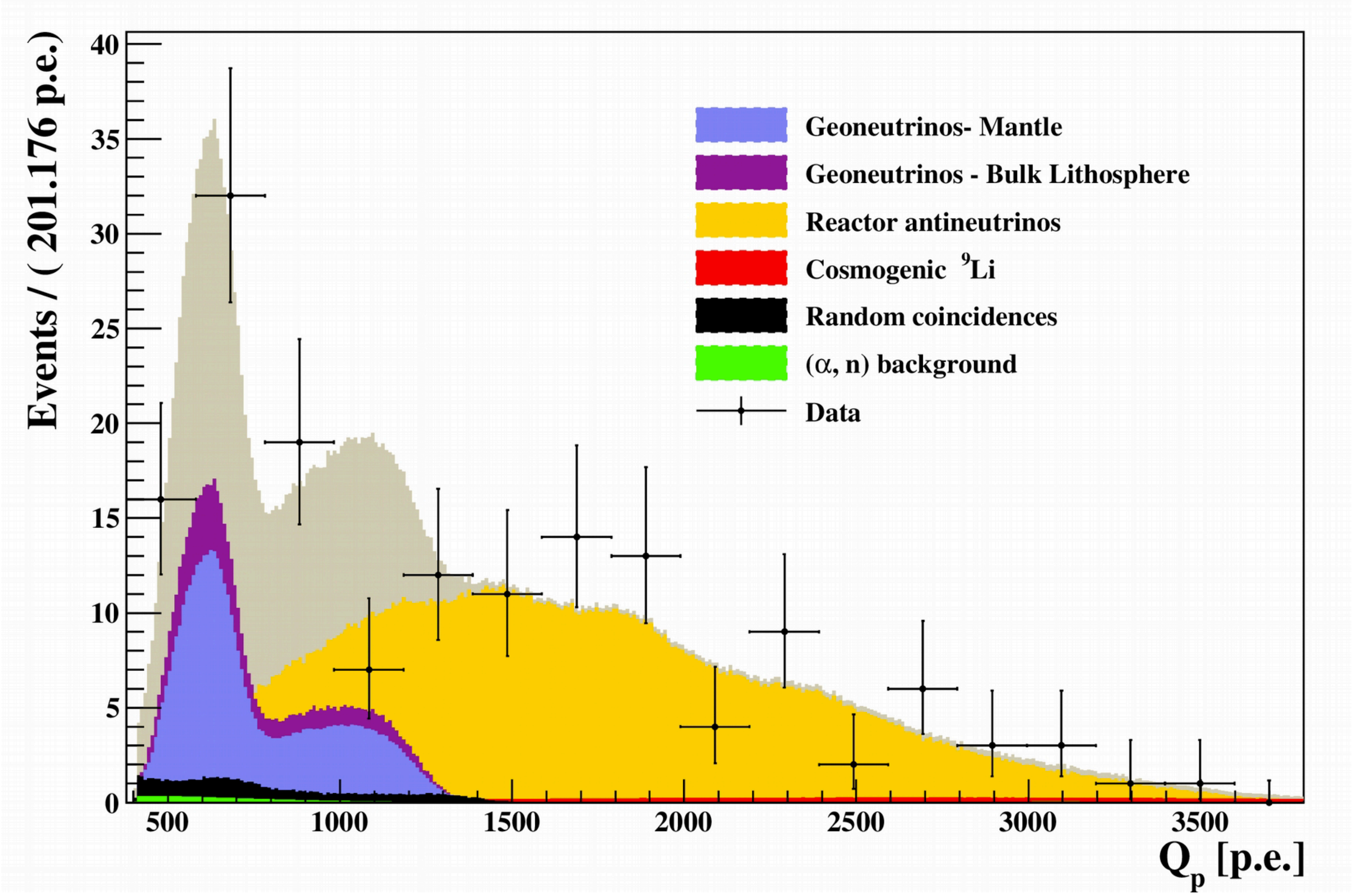
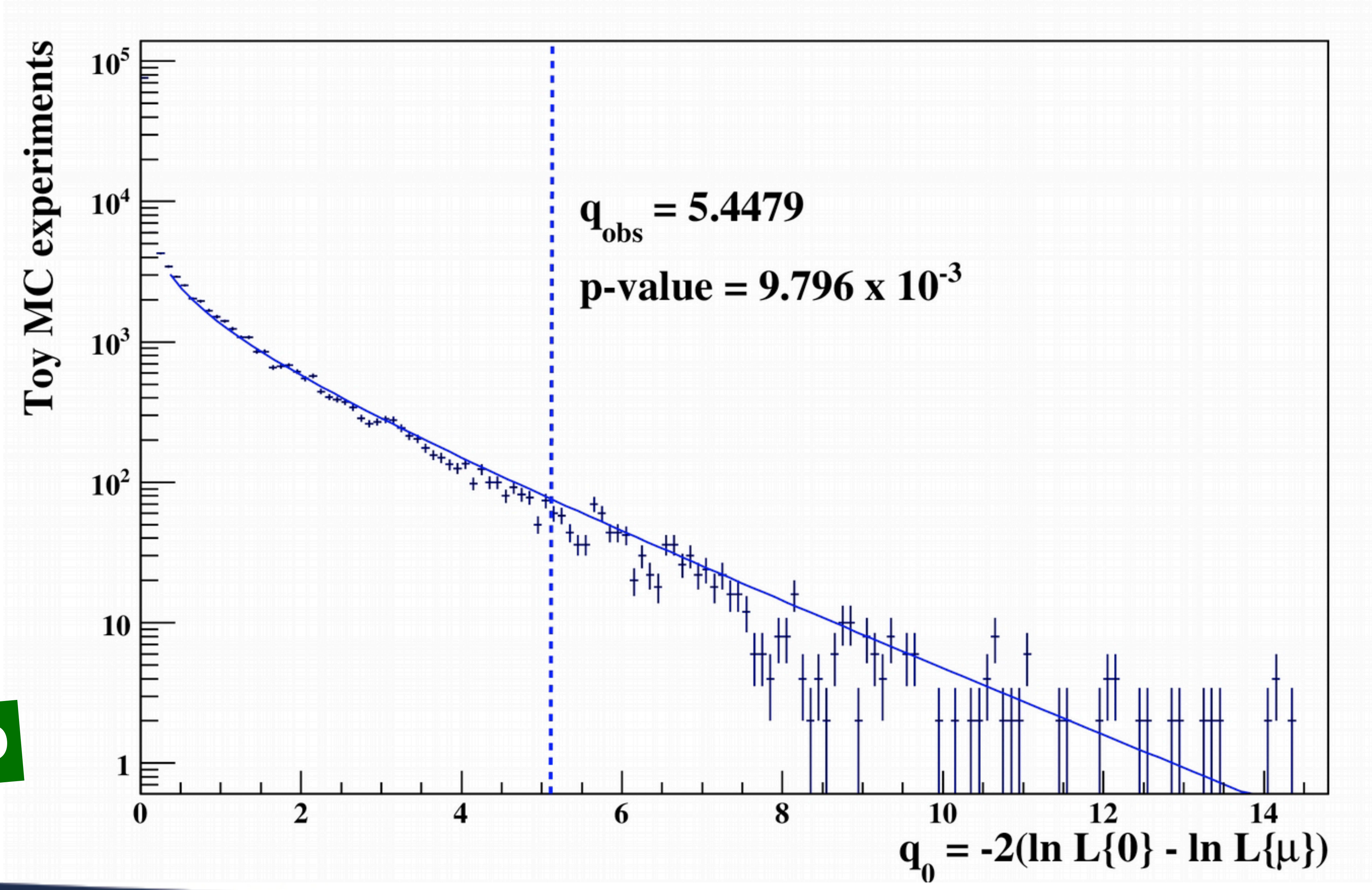
First no-mantle signal exclusion with 99% C.L.



- Fit performed with signal from lithosphere constrained to (28.8 ± 5,6) events with S(Th)/S(U) = 0.29
- Mantle PDF constructed with S(Th)/S(U) = 0.26, maintaining the global Th/U ratio as in CI chondrites
- Sensitivity study using log-likelihood ratio method: null hypothesis rejected with 99.0% C.L.



Mantle: 23.7 $^{+10.7}_{-10.1}$ (tot) events

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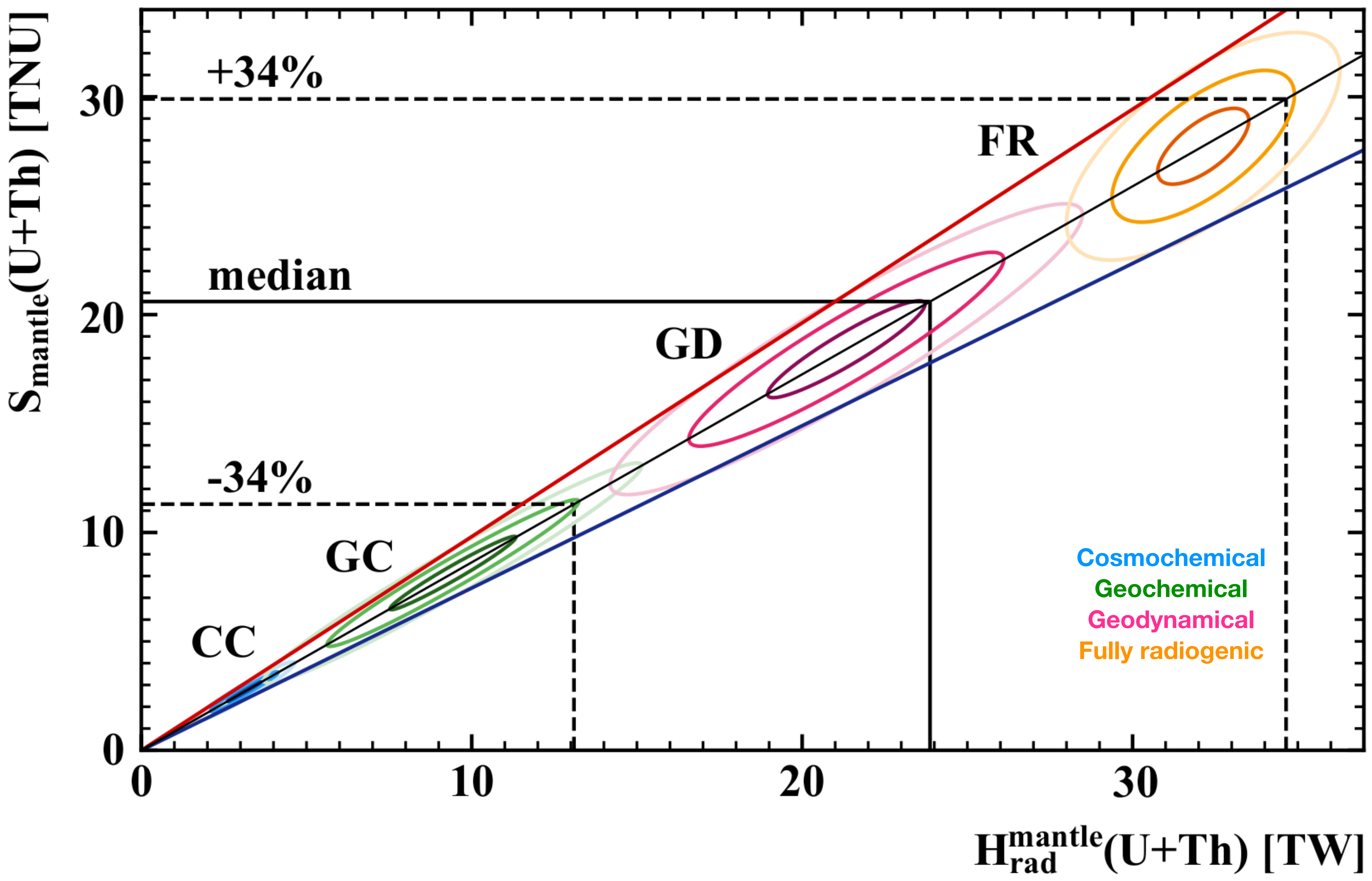
Radiogenic heat



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Mantle radiogenic heat from U + Th:
$24.6^{+11.1}_{-10.4}$ TW

- Compatible with predictions
- Least (2.4σ) compatible with the CosmoChemical model (CC) predicting lowest U+Th mantle abundances

Earth radiogenic heat from U+Th+K:
$38.2^{+13.6}_{-12.7}$ TW

- Assuming 18% ^{40}K mantle contribution
- Lithospheric radiogenic heat U+Th+K:$8.1^{+1.9}_{-1.4}$ TW

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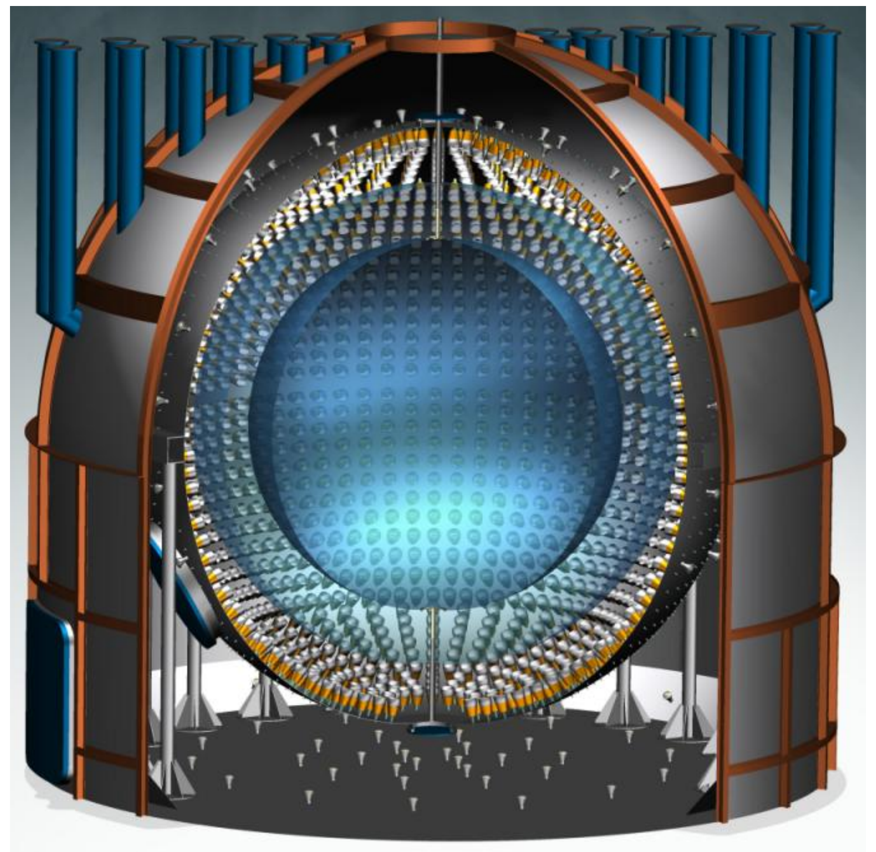
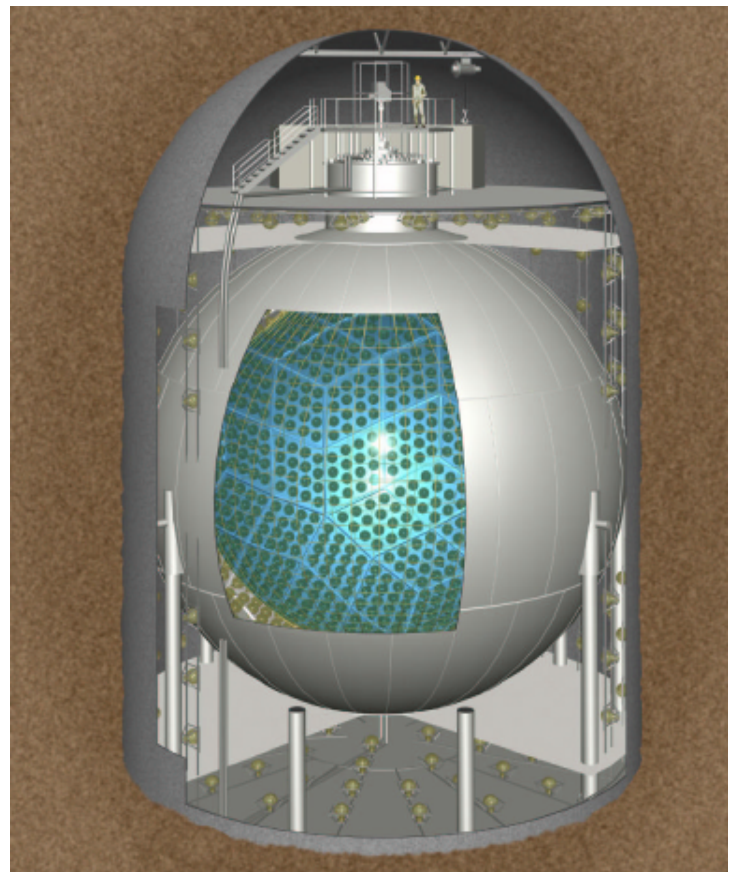
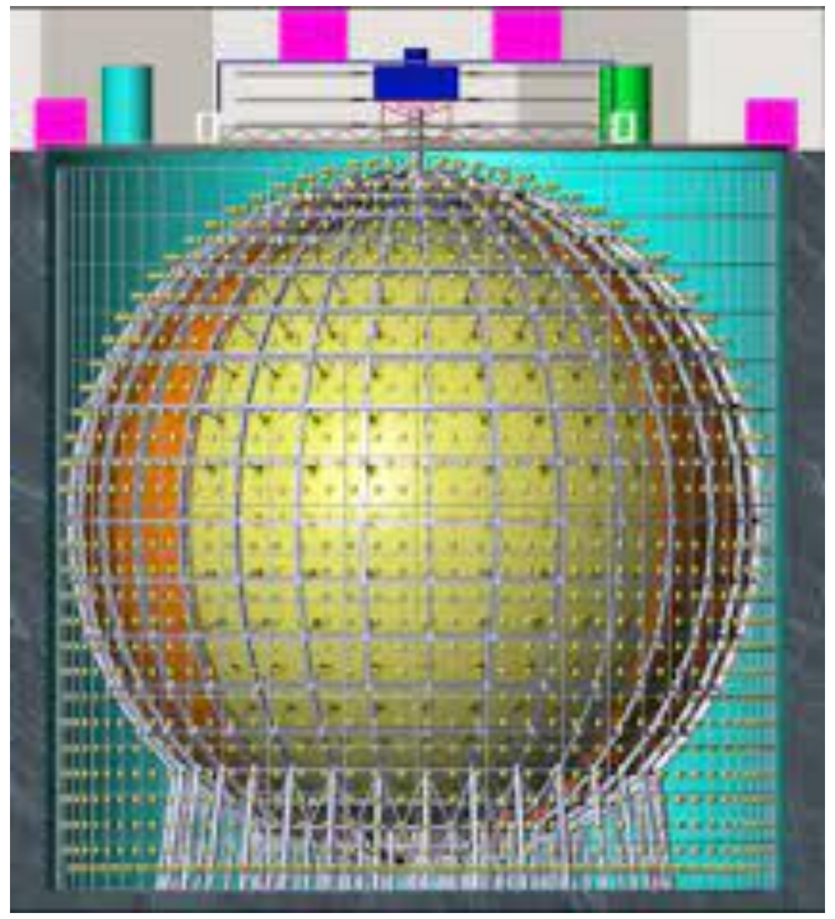


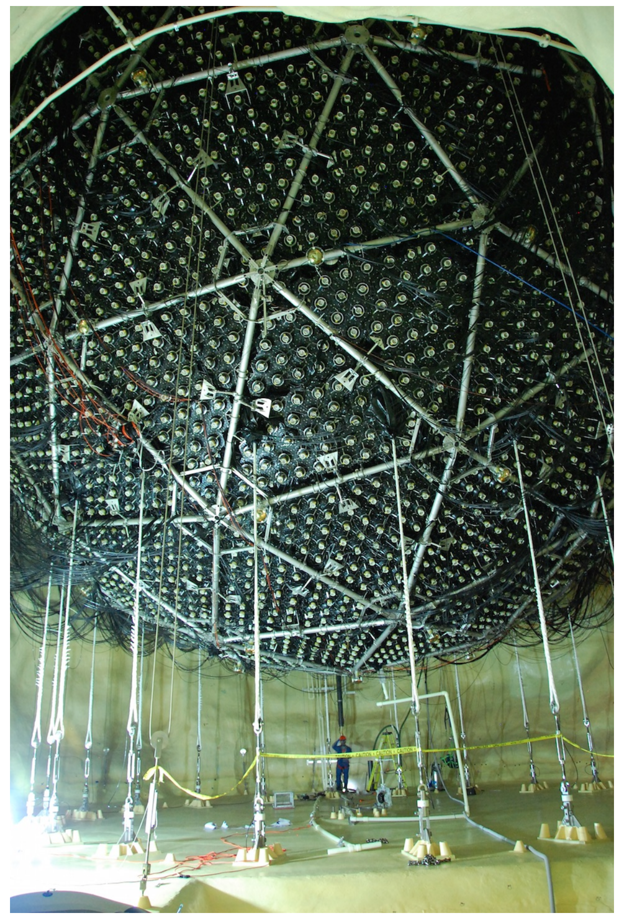
KamLAND



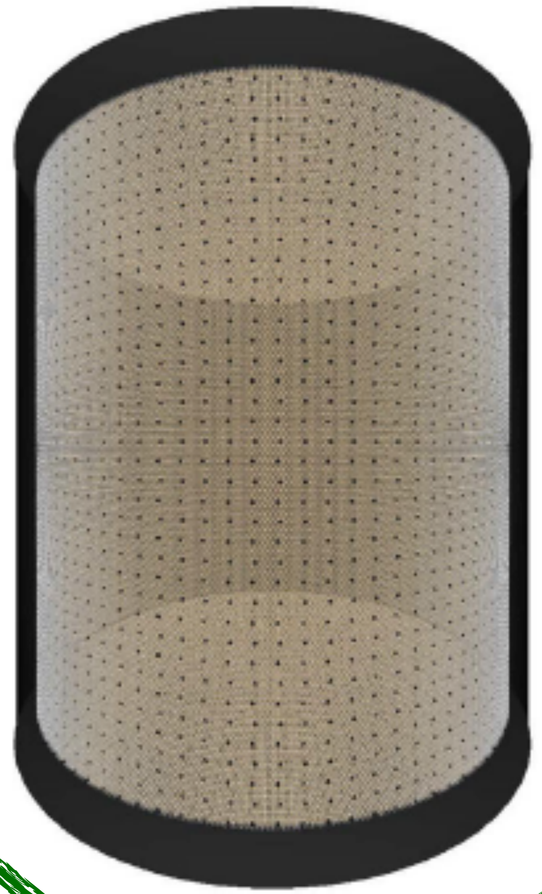
JUNO



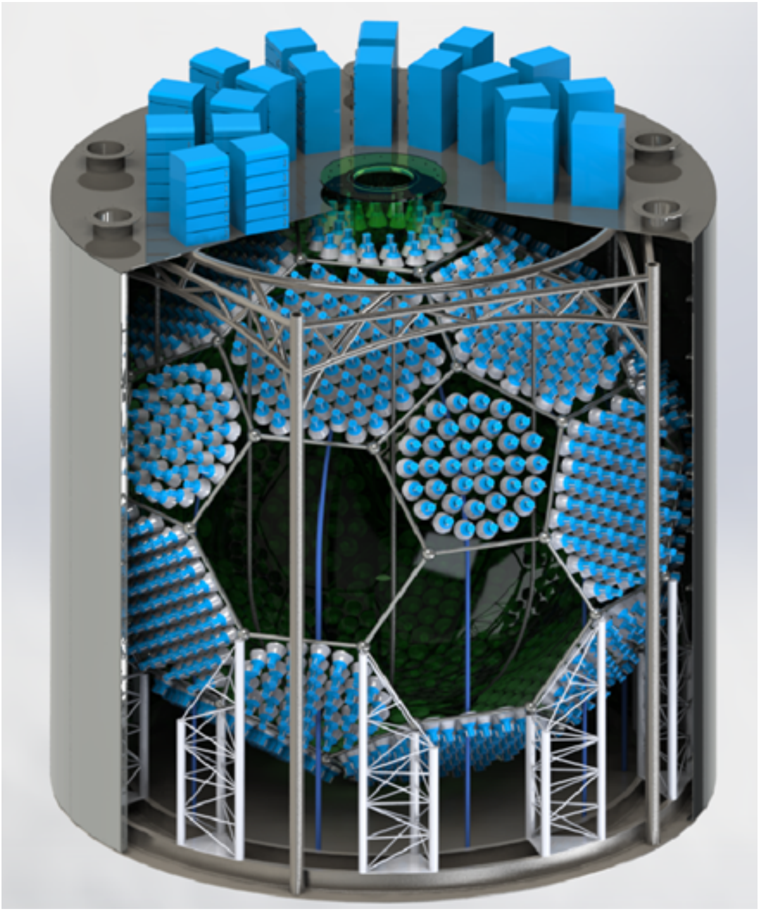
SNO+



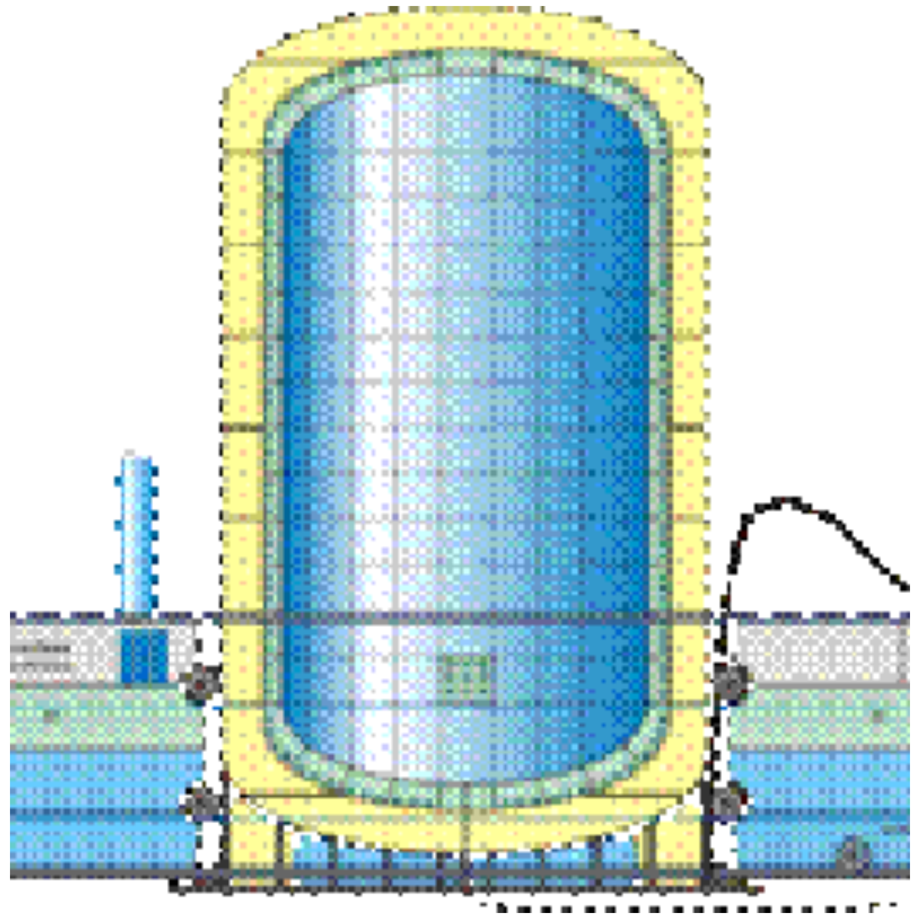
Theia



Jinping



OBD



How to broaden the current physics reach

Scintillation Detectors:
- ✅ High light yield
- ✅ Low energy threshold
- ✅ Good energy and position resolutions
- 🚫 Limited in size by absorption and cost
- 🚫 Limited directionality

Cherenkov Detectors:
- ✅ Directional information
- ✅ Can be very large (low absorption)
- ✅ Particle ID at high energies
- 🚫 No access to physics below the Cherenkov threshold
- 🚫 Low light yield

Water-based Liquid Scintillation (WbLS) Detectors: Get best of two worlds

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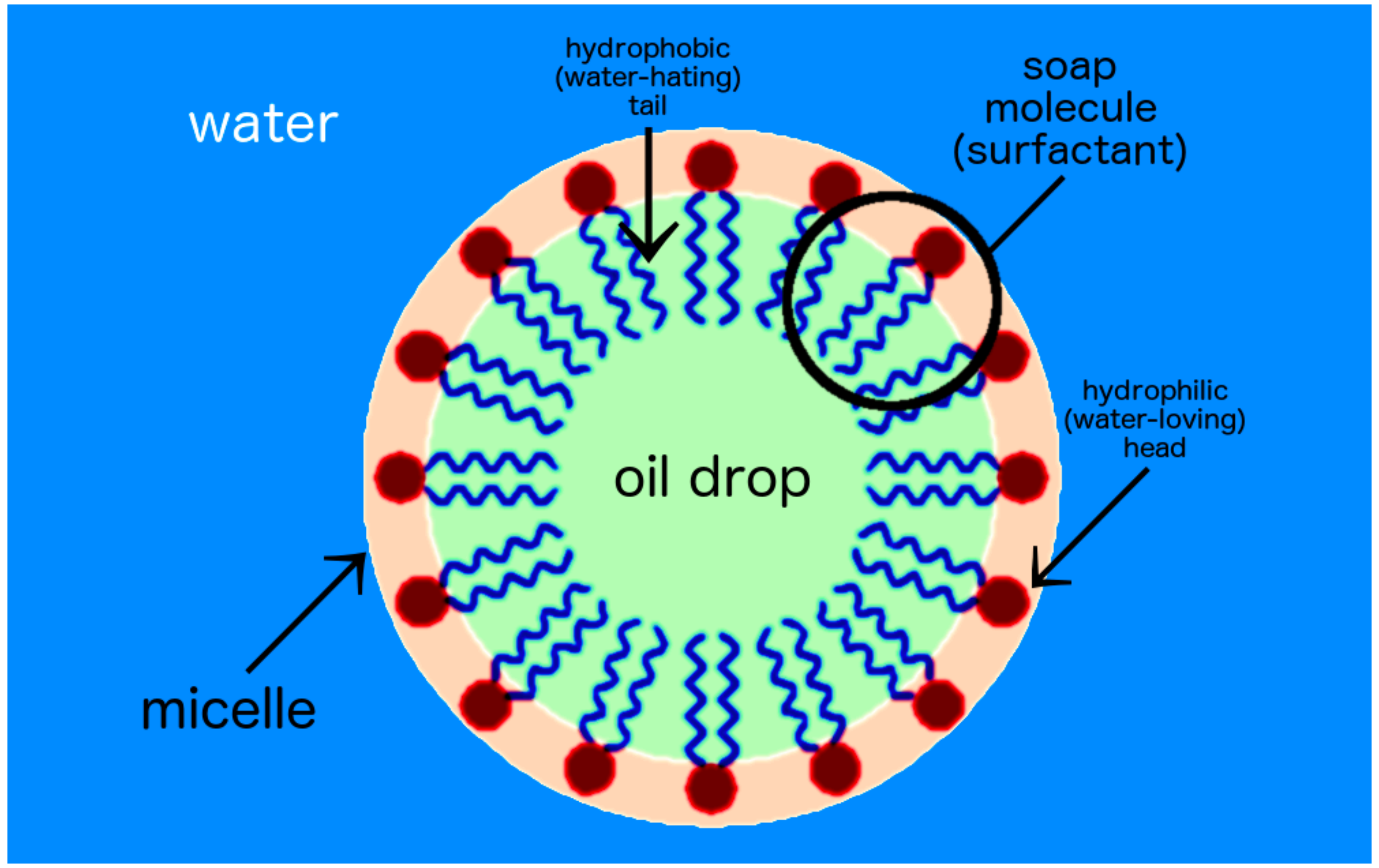
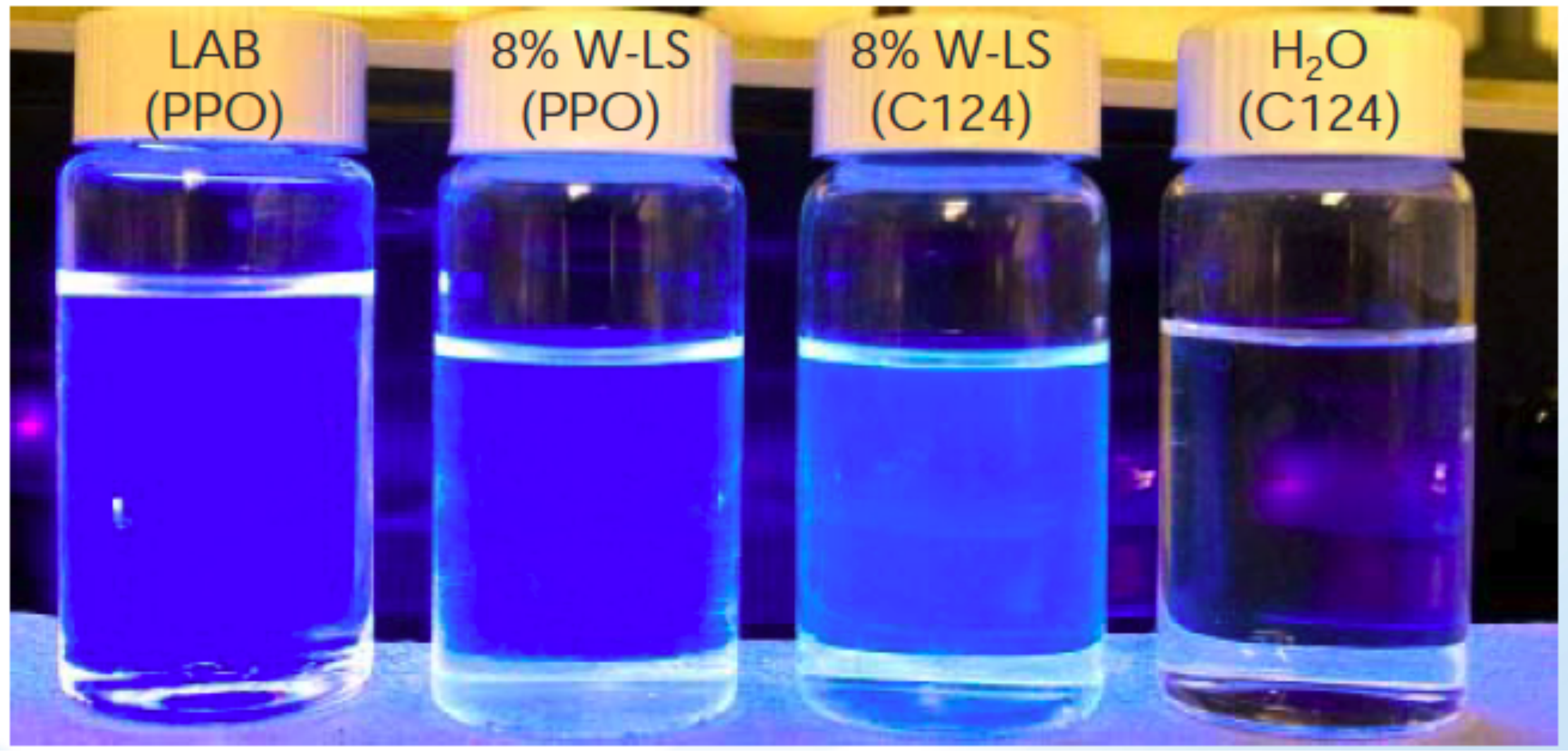
Water-based Liquid Scintillator - Basics

- Water-based Liquid Scintillator (WbLS) is a mixture of pure water and oil-based liquid scintillator
- WbLS is made using a surfactant (soap-like) such as PRS* (hydrophilic head and hydrophobic tail) to hold the scintillator molecules in water in a "micelle" structure
- Combines the advantages of water (transparency, low cost) and liquid scintillator (high light yield)
- Emission of prompt Cherenkov light and delayed scintillation light
- Low cost and environmentally-friendlier than pure LS





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Theia: multipurpose neutrino detector

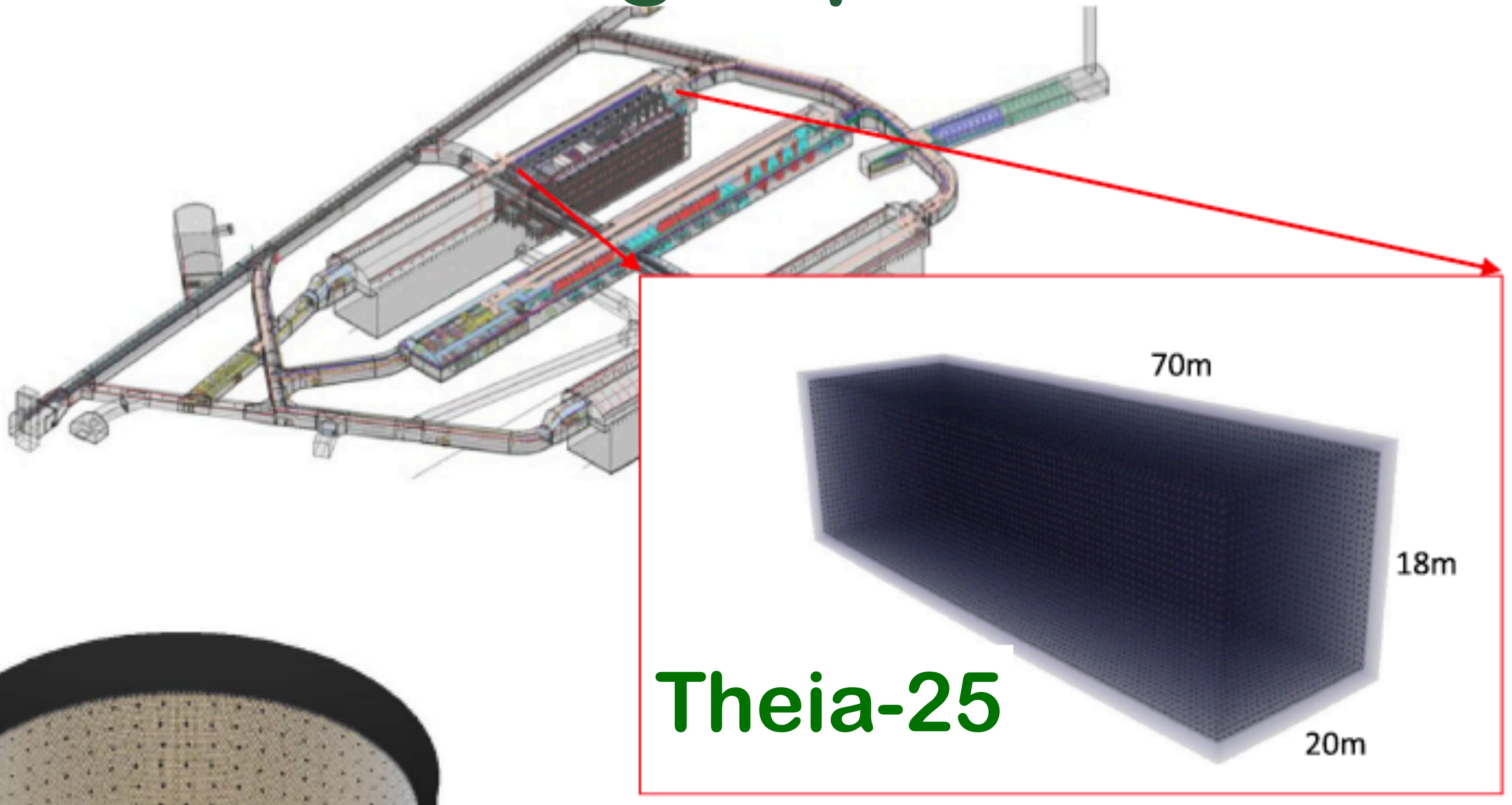
solar neutrinos (CNO, ^{8}B)

diffuse supernova neutrinos (DSNB)

supernova burst neutrinos

geoneutrinos

Design options



Large scale, multipurpose detector
- Baseline: 25ktonne (17kt FV)
- Ideal: 100 ktonne (70kt FV)

Scintillator fraction tunable depending on the physics goal ->staged approach

neutrino mass ordering

neutrino CP-violating phase δ

neutrinoless double beta decay

nucleon decay

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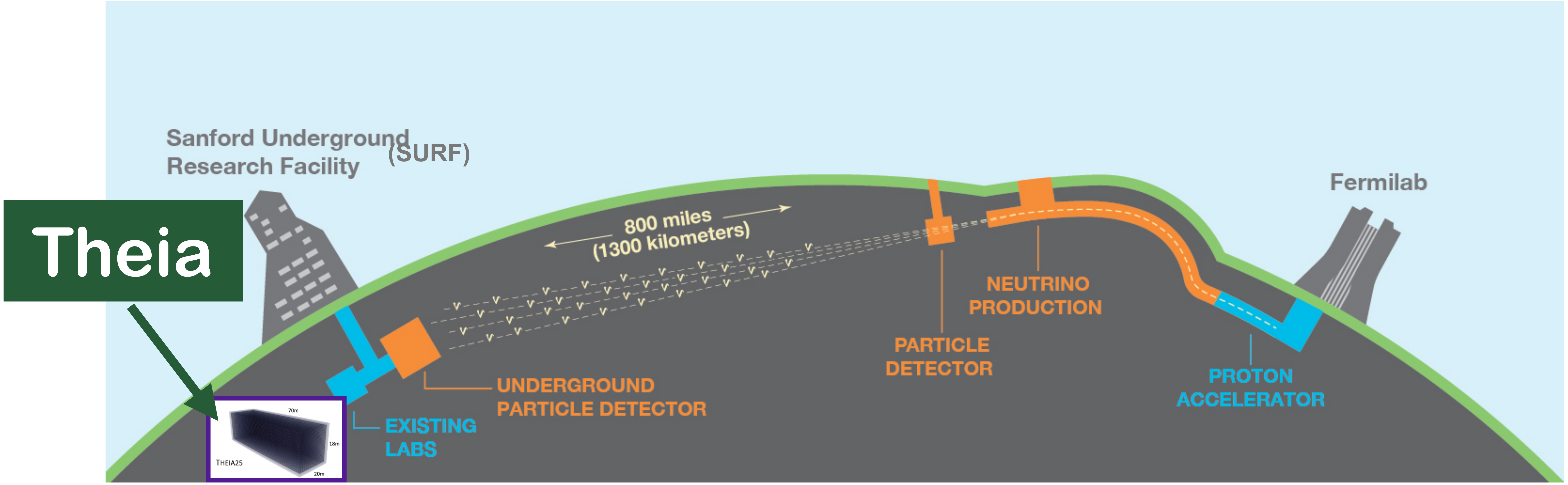
Theia-25 possible design, considered for this study



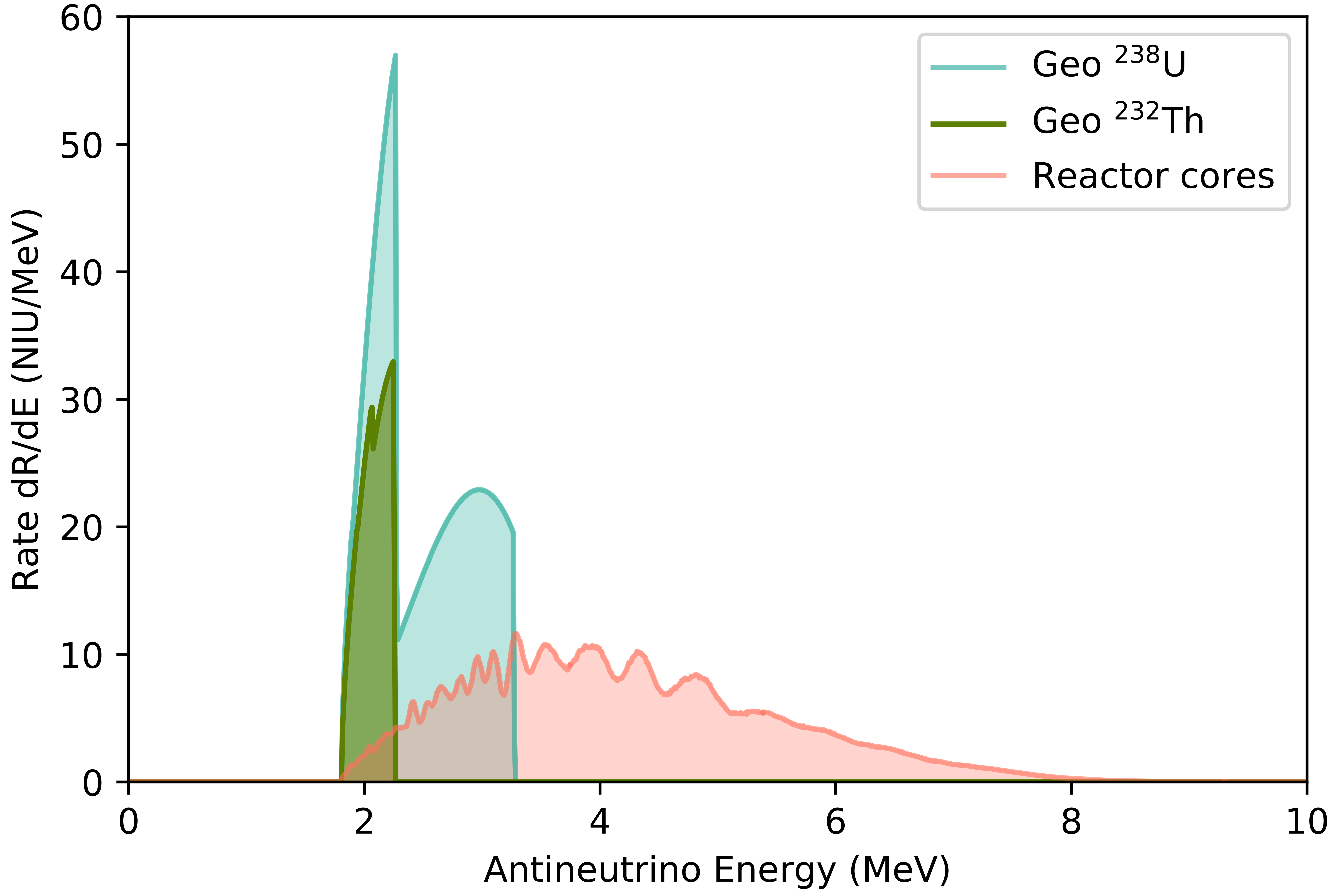
Can be placed at fourth DUNE cavern (Depth: 4300 m.w.e.)

Located at **Sanford Underground Research facility (SURF)**

Volume: 17ktonne

Target material: water-based liquid scintillator (500 photons/MeV)

Input Antineutrino Signal



Geoneutrinos: crust and mantle

	S(U) [NIU]	S(Th) [NIU]
Crust	28.6	8.5
Mantle	7.3	2.0
Total	35.8	10.5

Nuclear Reactors: 29.4 ± 0.8 NIU

~700-1000 km baseline

- Closest ones:
  Monticello (790 km)
  Cooper (802 km)

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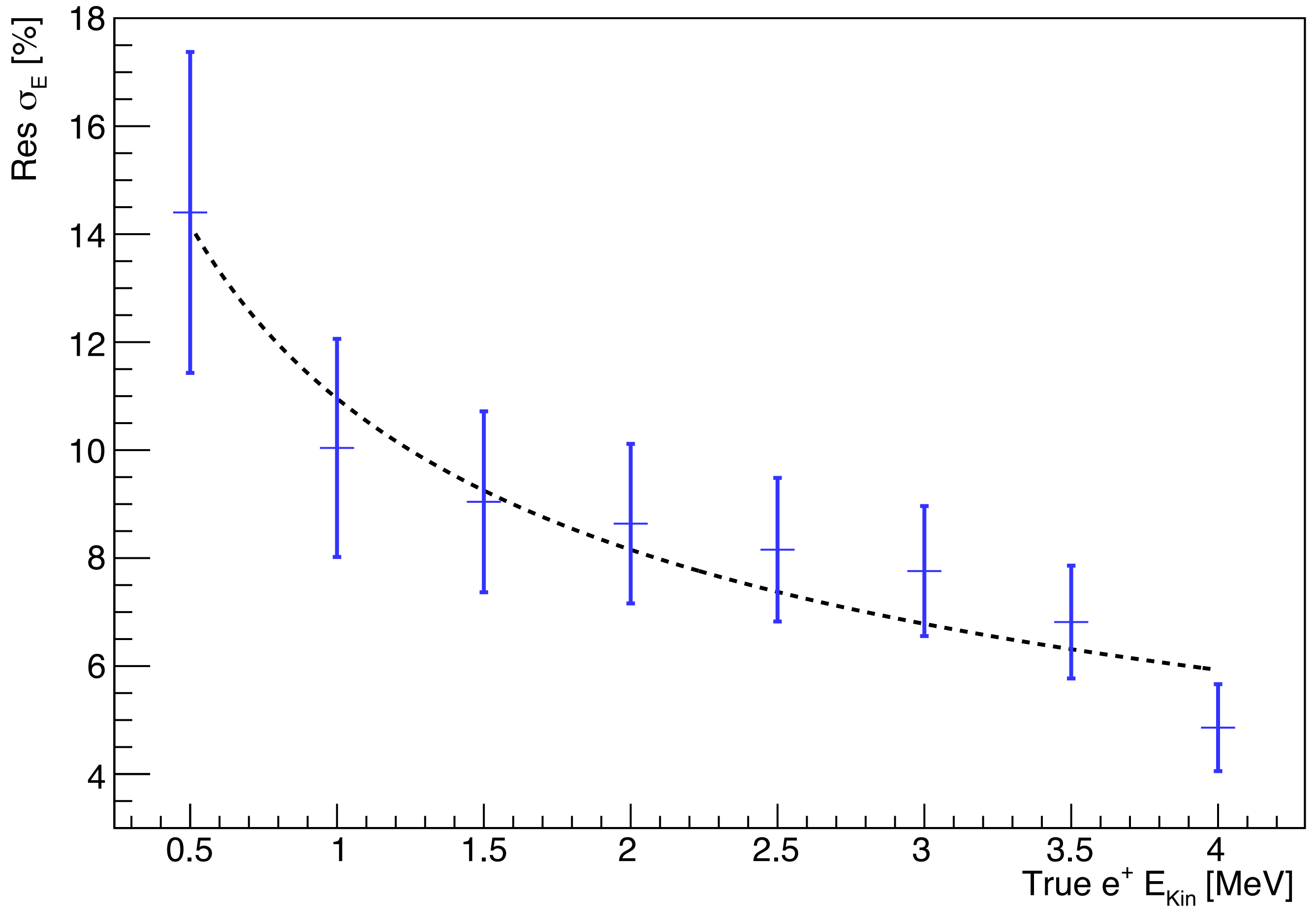
Monte Carlo simulations and Event reconstruction

Configuration:

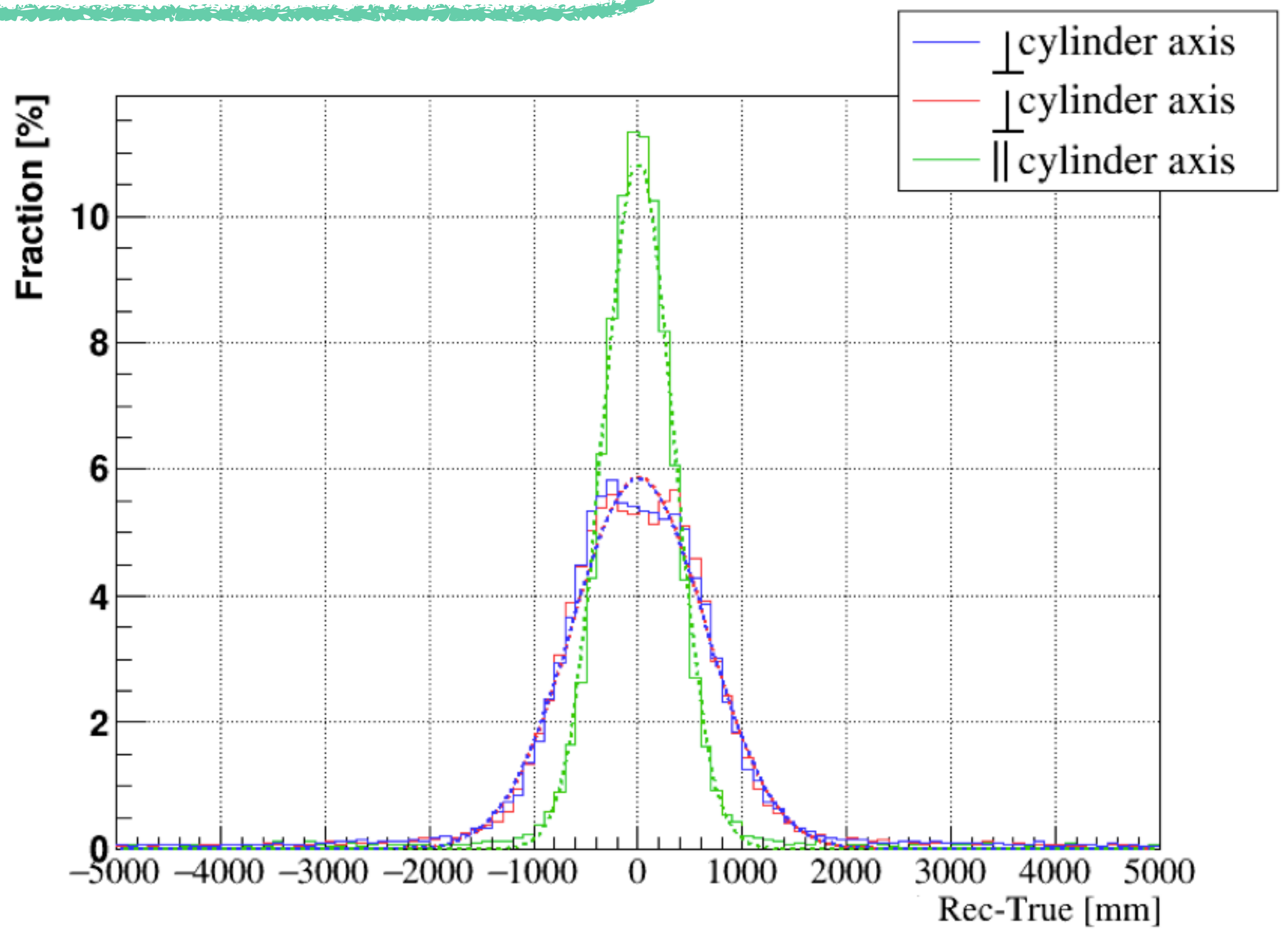
- Geometry: cylinder 70m x 18m ⌀
- Target: Wbls (3% LS, 97% Water)
- 90% photo coverage with 10” PMTs

Considered Signals and Backgrounds:

- Geo and reactor neutrinos
- Cosmogenic, fast neutrons, (α,n)
- Accidental coincidences



Positrons generated throughout the whole detector volume between 0.5 MeV to 4 MeV



Positron position reconstruction for geoneutrinos generated throughout the whole detector

Event Reconstruction:

- Energy resolution (3%WbLS) $\sim 12\,\%/\sqrt{E}$
- Vertex reconstruction:
  - Geoneutrinos:
    (58.0 ± 0.3) cm ⊥ cylinder axis
    (32.8 ± 0.2) cm ∥ cylinder axis
  - Reactor:
    (34.3 ± 0.2) cm ⊥ cylinder axis
    (26.6 ± 0.1) cm ∥ cylinder axis

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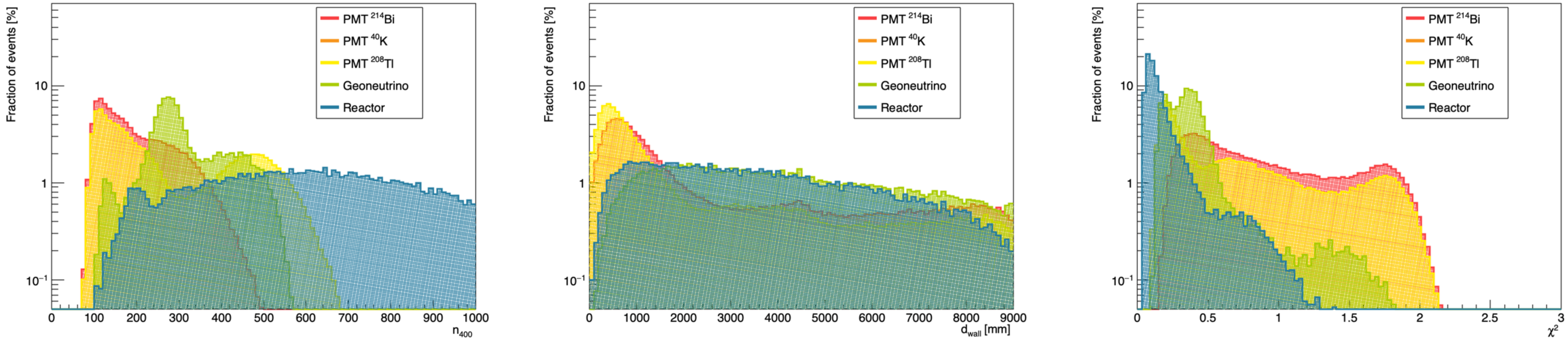
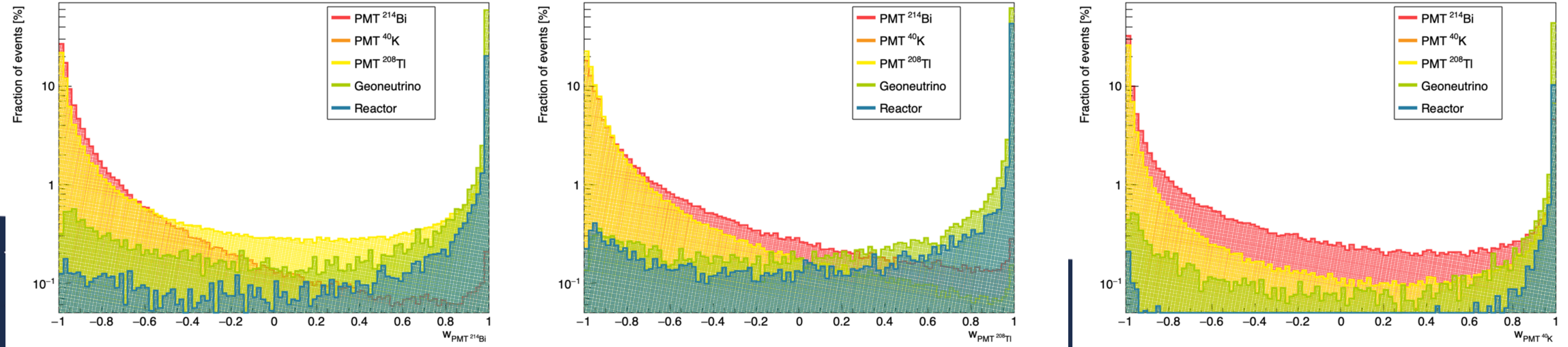
Boosted Decision Tree and Merged dataset

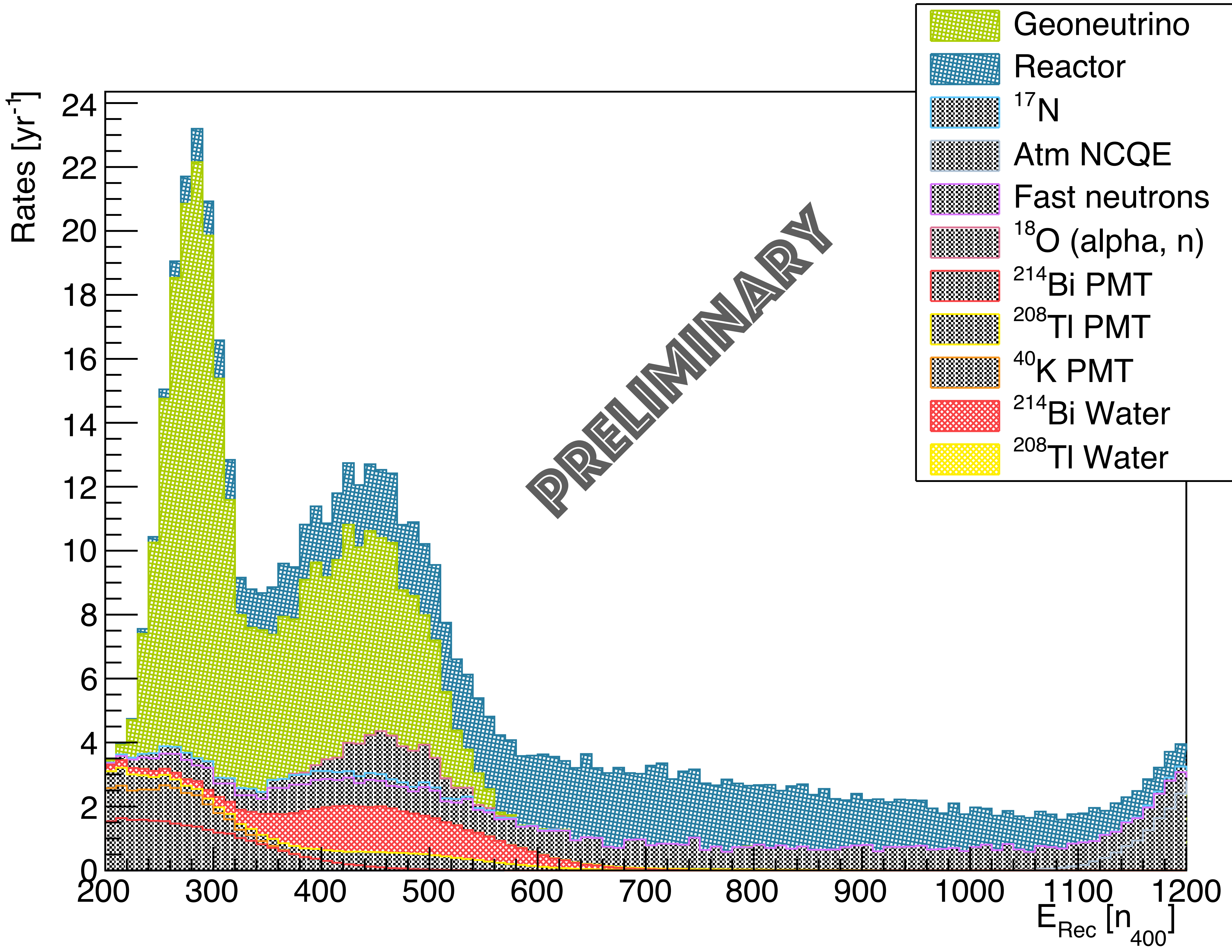
The variables for training BDT: n400 (energy estimator), dwall (min distance to the wall), chi2 of the vertex reconstruction:



The output of BDT training: the weight for each background hypothesis



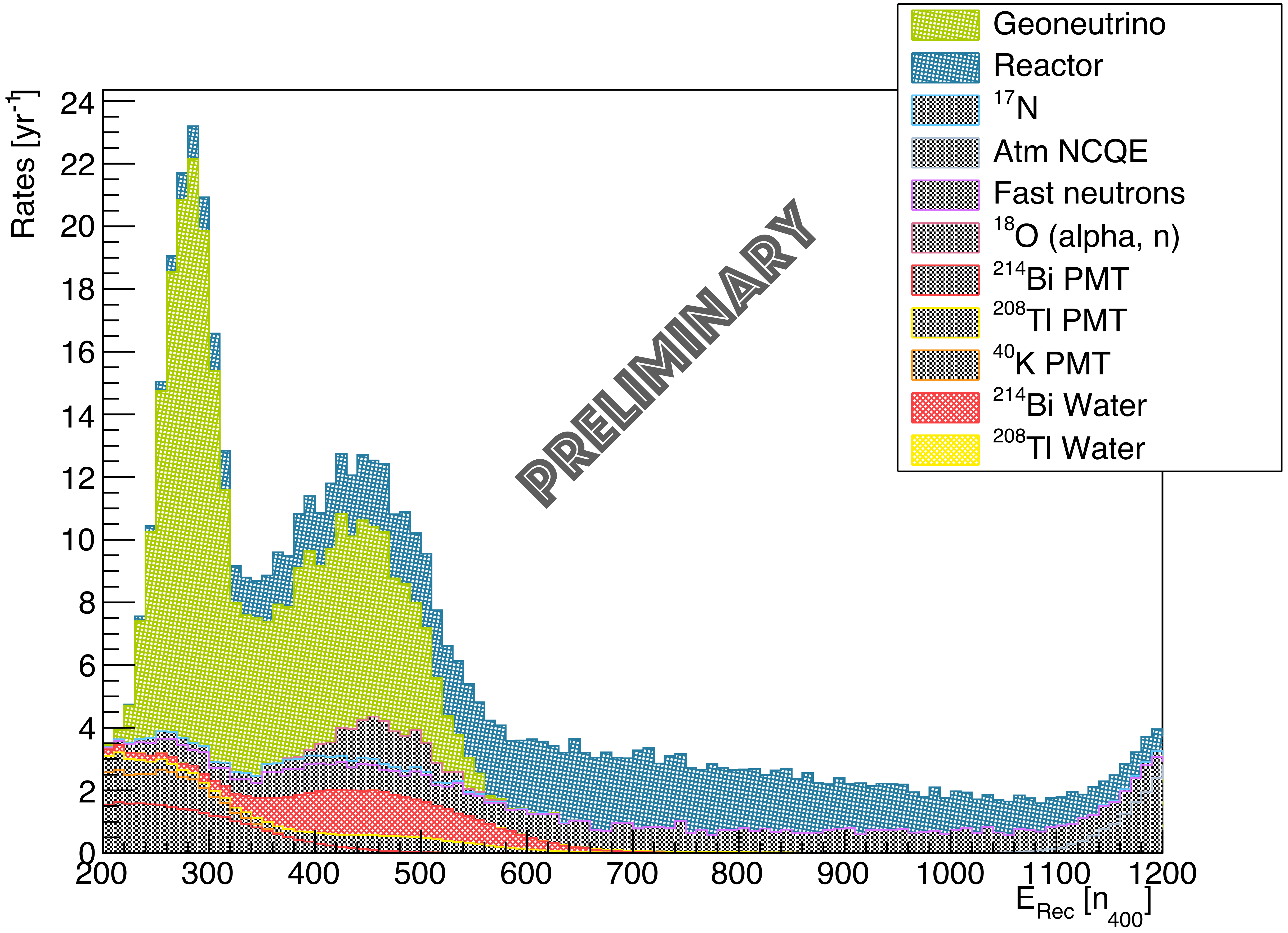
Signals and backgrounds in merged dataset



Stacked PDFs of all the signals and backgrounds

	Post-BDT singles rate [Hz]	Pair cand. post-merging [evts/yr]	Pair cand. in ROI [evts/yr]
PMT ^{214}Bi	4.24	6.80×10^4	24.0
PMT ^{208}Tl	3.10	4.68×10^4	13.6
PMT ^{40}K	1.47	2.41×10^4	11.6
Water ^{214}Bi	8.18×10^{-1}	1.21×10^4	32.9
Water ^{208}Tl	1.59×10^{-2}	0.21×10^4	0.78
Cosmic ^{17}N	5.78×10^{-6}	182	7.10
Atm. NCQE	1.13×10^{-6}	35.6	10.7
Cosmic n	4.48×10^{-4}	1411	69.6
PMTs(α, n)	1.51×10^{-4}	786	0.35
^{18}O(α, n)	4.58×10^{-7}	14.5	12.8
Reactor	7.61×10^{-6}	240	166
Geoneutrinos	9.36×10^{-6}	295	221

Box analysis



Stacked PDFs of all the signals and backgrounds

- Optimizing the selection cuts to maximize $\dfrac{S}{\sqrt{S+B}}$:
  - Energy ranges (**E_prompt, E_delayed**)
  - Position (definition of fiducial volume (FV) in and $\boldsymbol{\rho}$)
  - Time and space correlation (**dt, dR**)
- In one year (excluding systematics):

Geo: $\dfrac{S}{\sqrt{S+B}} = 11.2$ Reactor: $\dfrac{S}{\sqrt{S+B}} = 7.0$

Geo + Reactor: $\dfrac{S}{\sqrt{S+B}} = 15.0$

Used to define ROI for the fit (see next slide)

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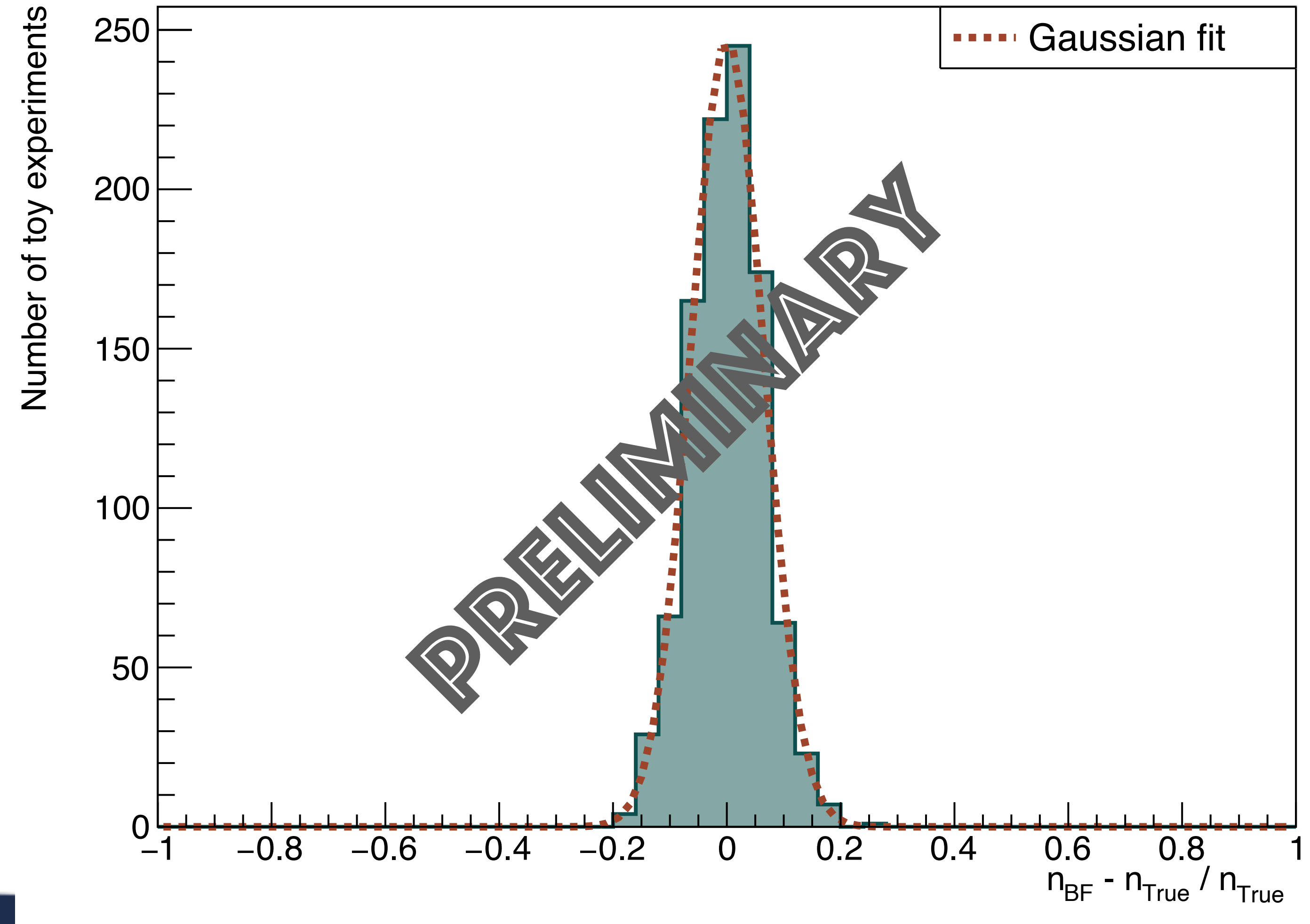
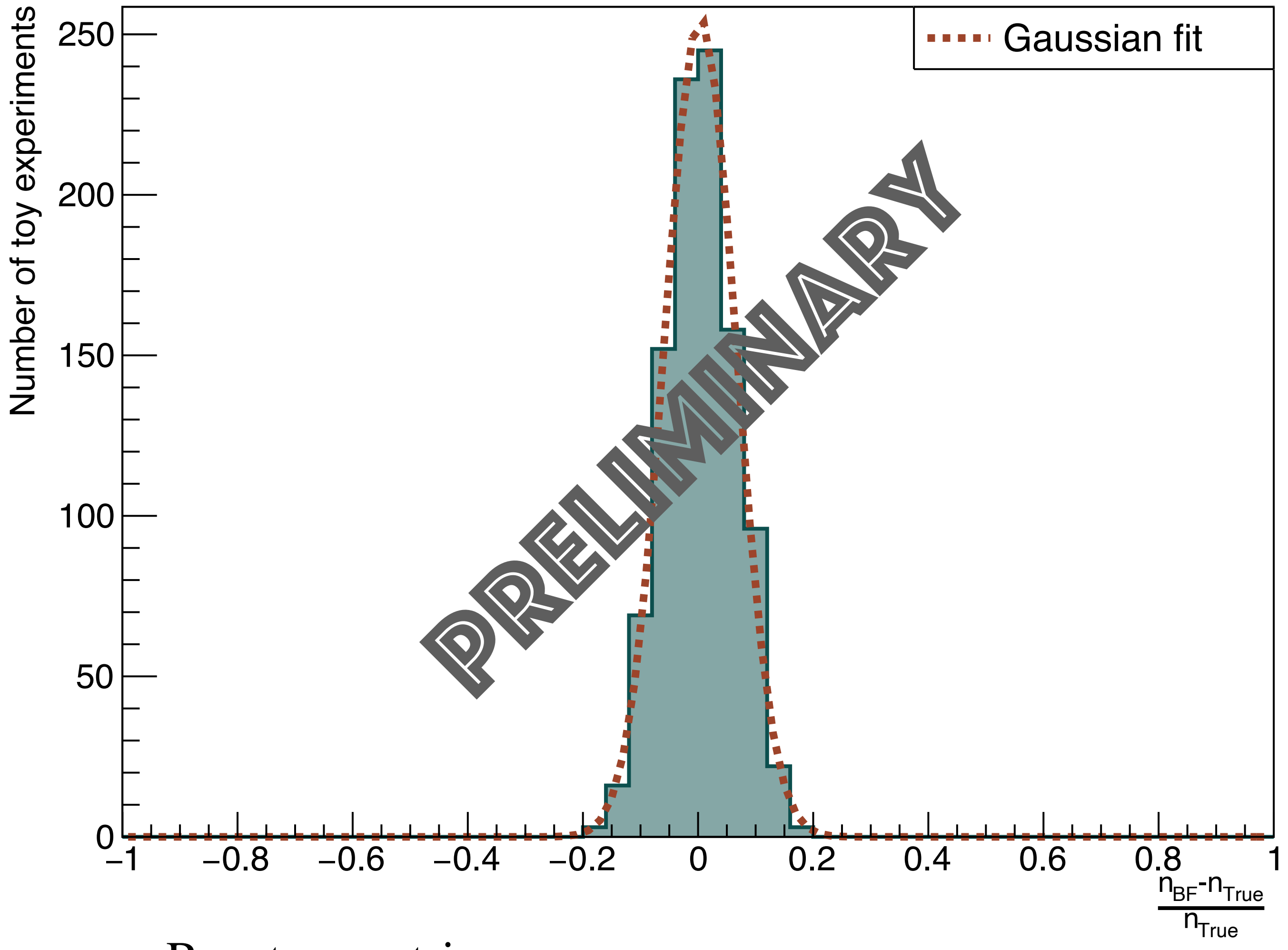
Likelihood fit results - Geo vs Reactors

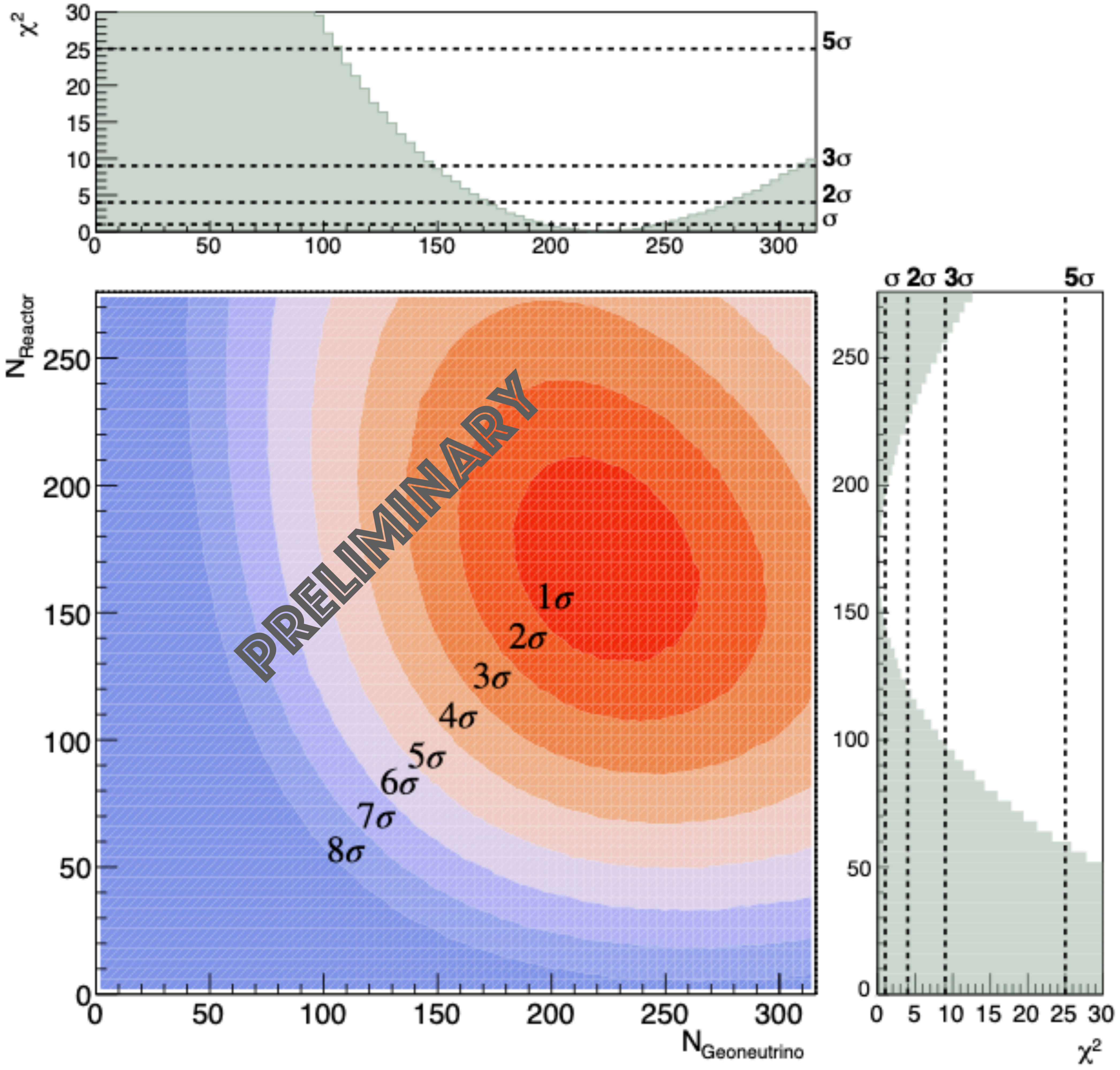
- Sampling PDFs to create 1000 one-year toy experiments
- Likelihood fit of Ngeo vs Nreactor, marginalizing other backgrounds: $N_{geo} = 218^{+28}_{-20}, N_{rea} = 170^{+24}_{-20}$
- Extracting precision of fit value vs input:
    - Geoneutrinos: 6.7%
    - Reactor: 8.6 %



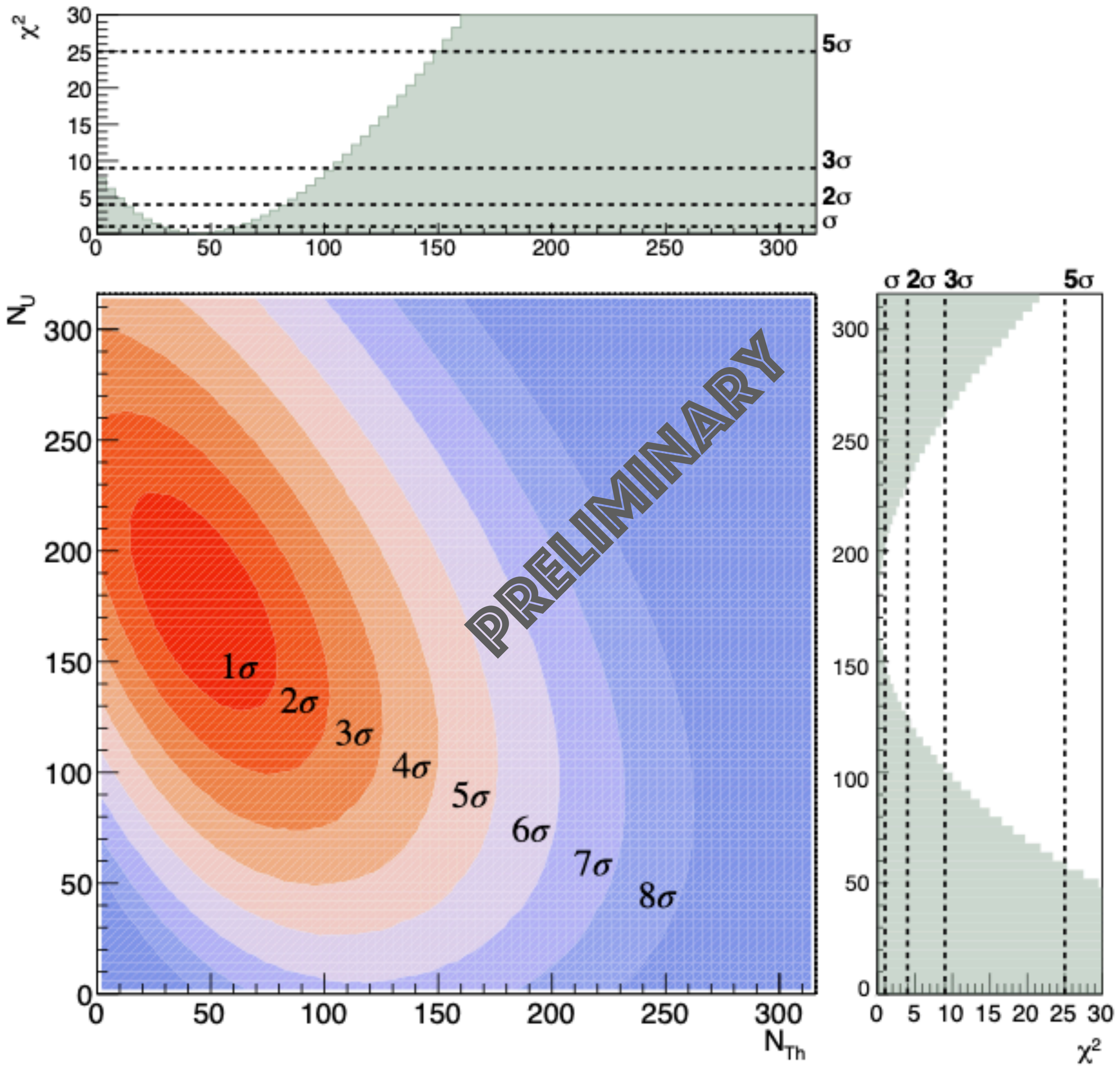
Geoneutrinos



Reactor neutrinos



Likelihood fit results - Geo U vs Th



- Sampling PDFs to create 1000 toy experiments
- Likelihood fit of N_U vs N_{Th} , marginalizing other backgrounds, including reactor neutrinos

$$N_U = 180^{+26}_{-22}, N_{Th} = 39^{+18}_{-15}$$

- Extracting $N_{Th}/N_U = 0.22 \pm 0.13$, corresponding to Th/U $= 4.3 \pm 2.6$ (60% rel error) (with input of 4.22)

Relative uncertainty reduced to 15% in ten years

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Summary of expected measurements in one year

	Geo fixed U/Th ratio		Free U/Th ratio	
	N(Geo) [events]	N(rea) [events]	N(U) [events]	N(Th) [events]
Best Fit	218	170	180	39
+1 sigma	28	24	26	18
-1 sigma	20	20	22	15

→

	Geo fixed U/Th ratio	Free U/Th ratio	
	S(Geo) [NIU]	S(U) [NIU]	S(Th) [NIU]
Best Fit	45.9	35.48	10.63
+1 sigma	5.9	5.1	4.9
-1 sigma	4.2	4.3	4.1

Input:	35.8	10.5

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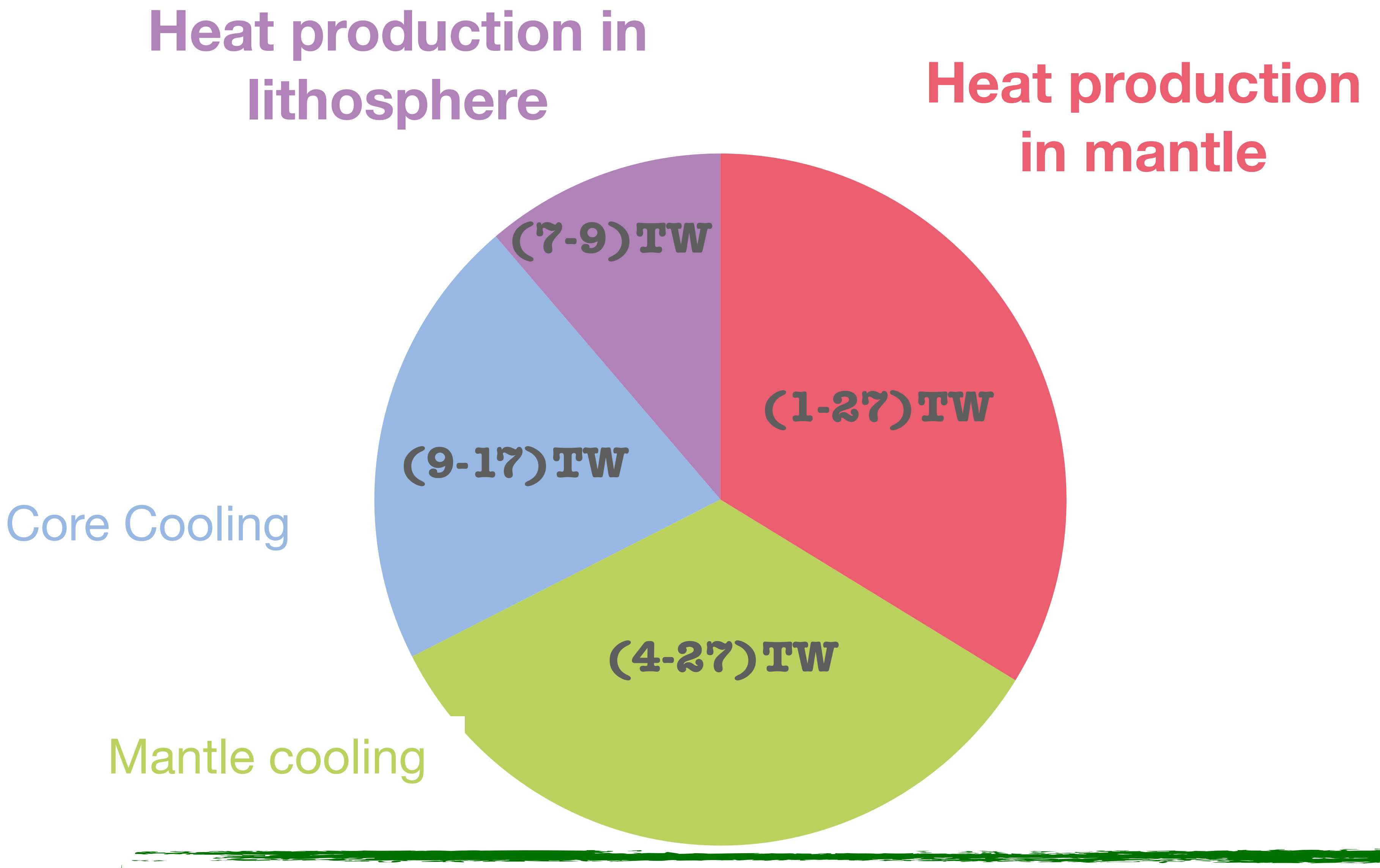
The extraction of mantle signal

$$S_{mantle} = S_{total} - S_{crust}$$



$$\boldsymbol{\sigma}^2{}_{mantle} = \boldsymbol{\sigma}^2{}_{total} + \boldsymbol{\sigma}^2{}_{crust}$$

$$\boldsymbol{\sigma}^2{}_{total} = \begin{pmatrix} \sigma_{Th}^2 & \rho\sigma_{Th}\sigma_U \\ \rho\sigma_{Th}\sigma_U & \sigma_U^2 \end{pmatrix} \qquad \boldsymbol{\sigma}^2{}_{crust} = \begin{pmatrix} {\sigma_{Th}^c}^2 & \rho^c\sigma_{Th}^c\sigma_U^c \\ \rho^c\sigma_{Th}^c\sigma_U^c & {\sigma_U^c}^2 \end{pmatrix}$$

-0.75

[0,1]

$$\boxed{S_{mantle} = 9.0 \pm [4.2, 4.5]\ \text{NIU}}$$

for crust flux uncertainties: 8.3% Th, and 7.0% for U and $\rho^c \in [0,1]$

$$H_{rad} = 10.7 \pm [5.0, 5.3]\ \text{NIU}$$

Conclusions

- Borexino: New geoneutrino measurement almost twice as many as published by the collaboration in 2015, due to updated statistics and improved analysis.

- Borexino: Null-hypothesis of mantle signal rejected at 99% C.L. using “well-known” lithosphere contribution.

- Borexino: Signal in agreement with geological predictions, with a preference for models predicting high U and Th abundances

- Theia: Likelihood fit extracting geoneutrinos rate with 8.6% precision and reactor neutrons with 6.7% precision in just one year

- Theia: Extracting U and Th individual rates, and measuring Th/U ratio with 56%-15% precision

- Theia: First high statistics measurement in a new geographical location useful to extract mantle contribution

QUESTIONS ARE WELCOME

now

or later

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