Earth Tomography with Atmospheric Neutrino Absorption at TRIDENT

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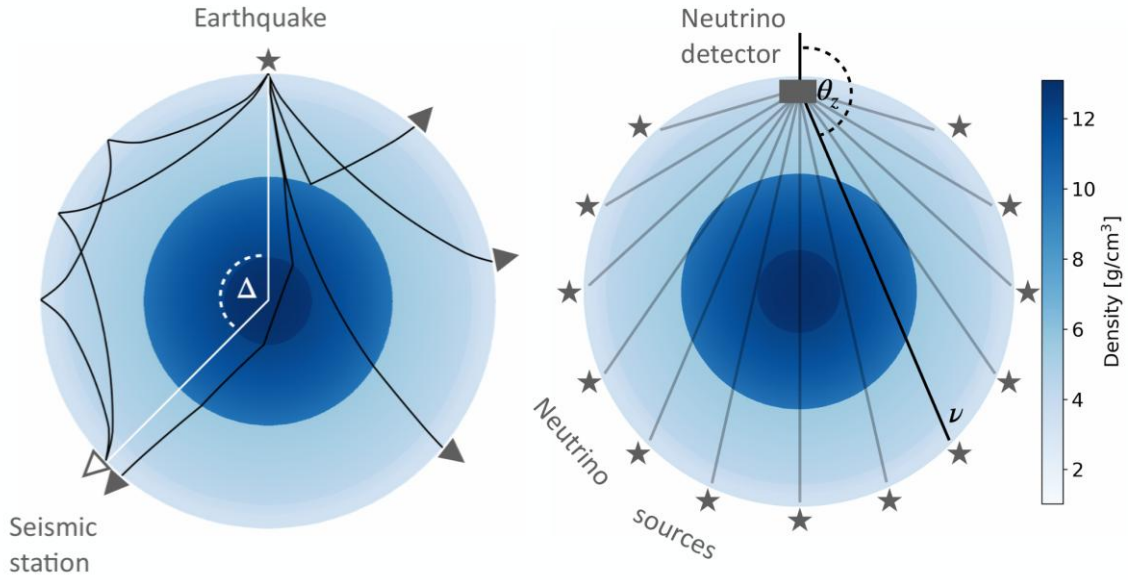
2026.11.17 @ Neutrino Geoscience 2026

Introduction: Earth tomography

Earth tomography: Using through-going neutrinos to probe the Earth’s interior

Why?

- Earth’s density matters
- The conventional method (seismology) will be affected by T, P, and composition.
- Neutrinos can directly tell us the density from the nuclei



seismic tomography neutrino tomography

Image Credit: Isabel Goos @ Neutrino Geoscience 2025

Introduction: Earth tomography

- Main idea: use up-going atmospheric neutrinos that traverse the Earth

- Two modes:

  1) Absorption tomography (TeV-PeV)

$$\Phi(E,\theta) = \Phi_0(E,\theta) \cdot \exp[-\sigma(E) \cdot N_A \cdot \int \rho(r)\, dl\,]$$

  2) Oscillation tomography (MeV-GeV)

$$n_e = \frac{N_A}{m_n}\,\rho\,\frac{Z}{A}$$

- Expected result: Map a 1D radial density profile:

$$\rho(r)$$

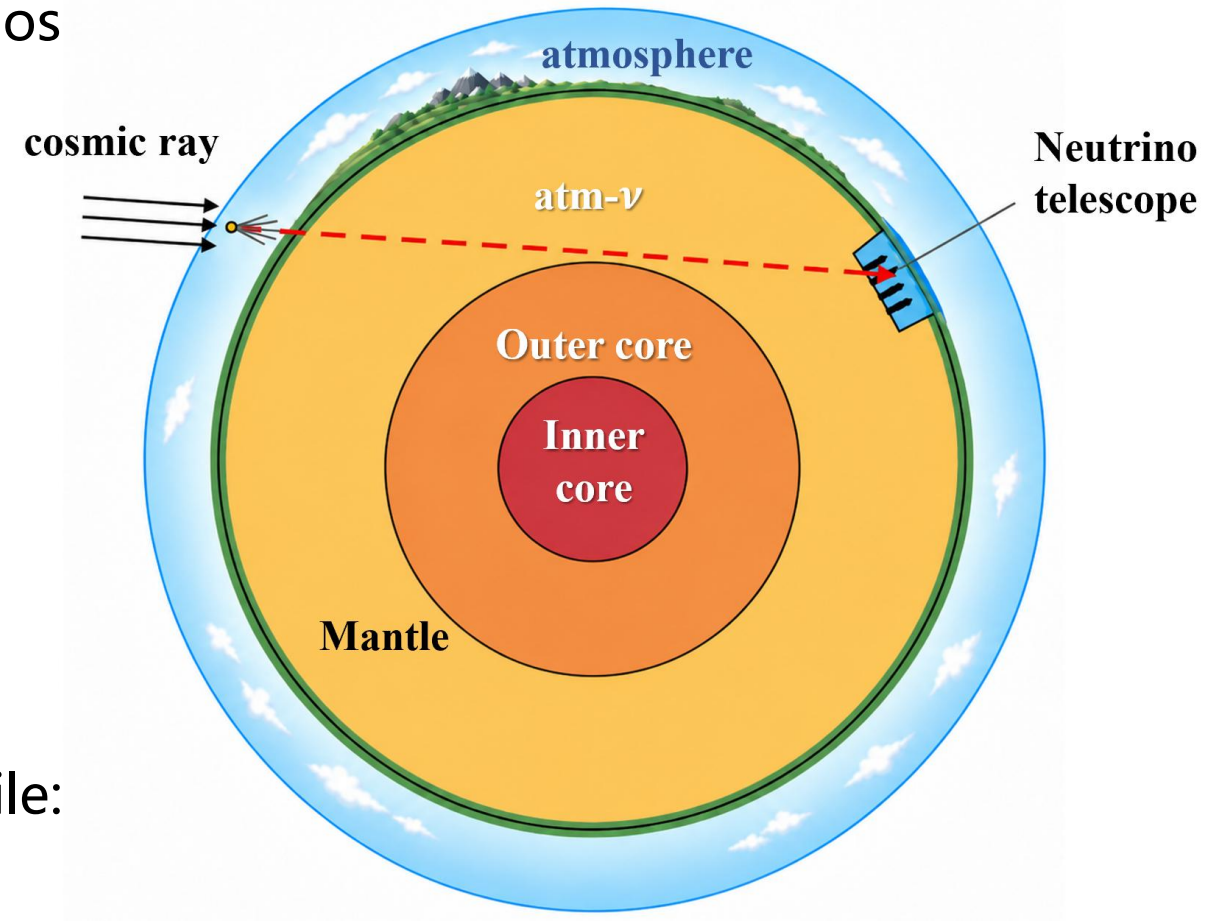
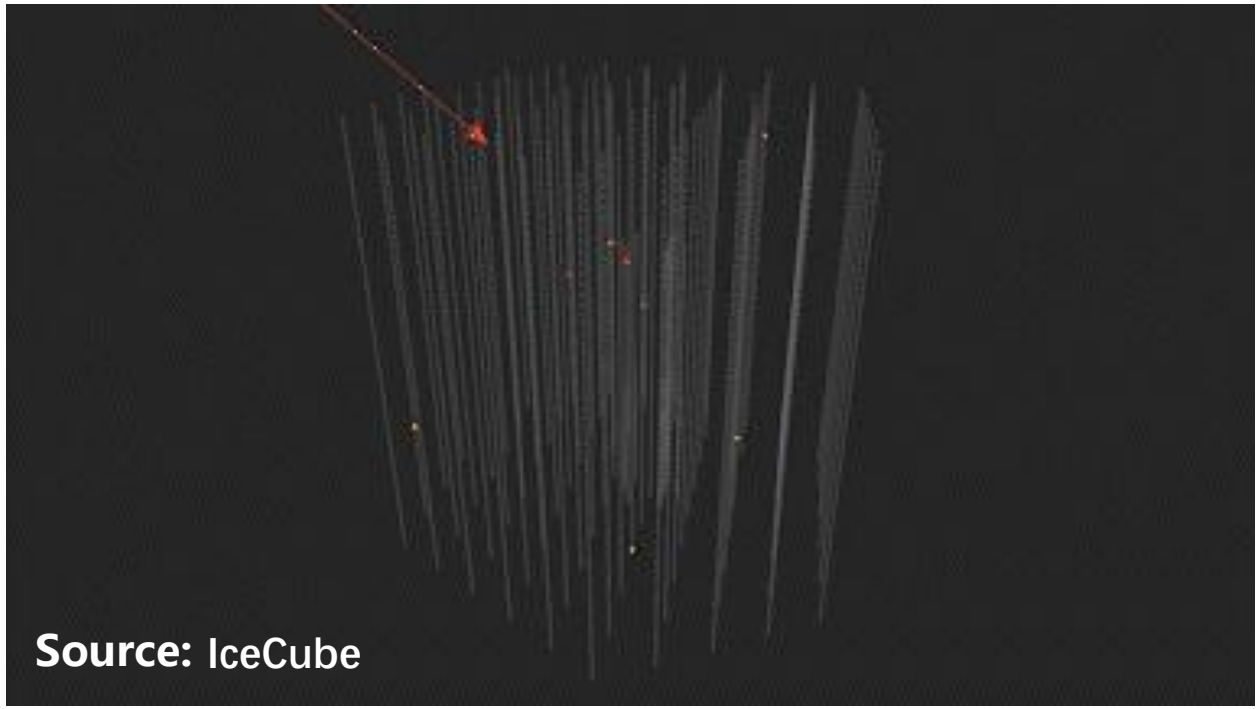
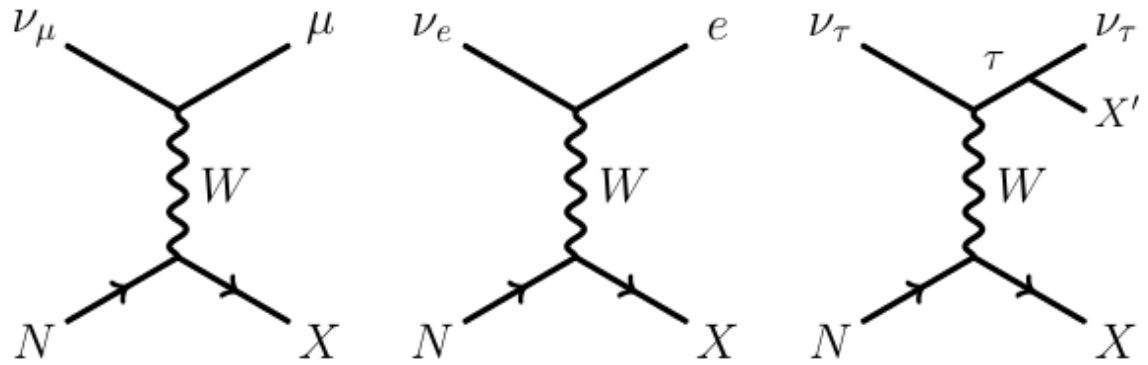
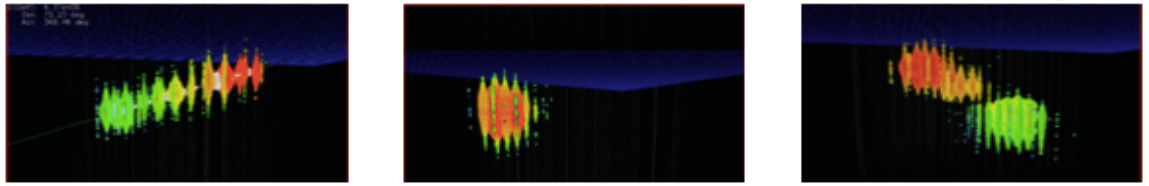


Image Credit: ChatGPT

Neutrino Telescope "Events"







Track
~ 0.1°

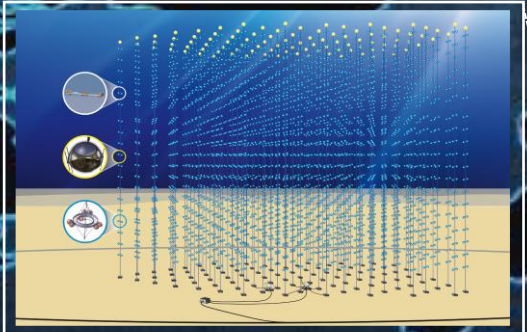
Cascade
~ 2°

Double Cascade

υ_μ υ_e υ_τ

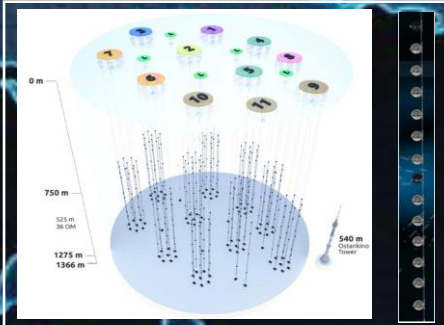
- **Neutrinos interact with ice/seawater nuclei, producing relativisitic secondary particles which emit Chenrenkov light**

Next-gen Neutrino Telescopes under Planning



KM3NeT (Mediterranean Sea)

Medium: Deep-sea water
Depth: ~ 3.5 km (ARCA)
Volume: ~ 1 km^3
Number of strings : ~230

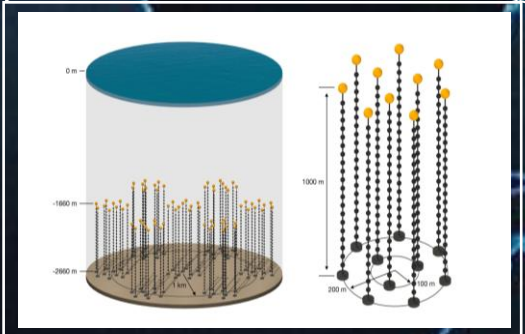


Baikal-GVD (Lake Baikal)

Medium: Deep-lake water
Depth: ~ 1.4 km
Volume: ~ 1 km^3
Number of strings : ~140

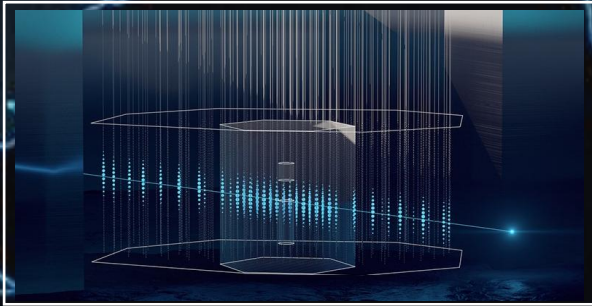
(also **HUNT**)

(also **NEON**)



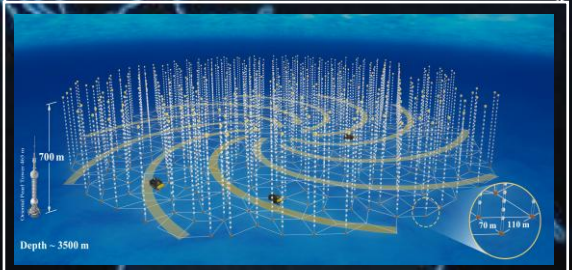
P-ONE (East Pacific Ocean)

Medium: Deep-sea water
Depth: ~ 2.6 km
Volume: ~ 1 km^3
Number of strings: ~70



IceCube Gen-2 (South Pole)

Medium: Glacial ice
Depth: ~ 2.5 km
Volume: ~ 8 km^3
Number of strings : ~210

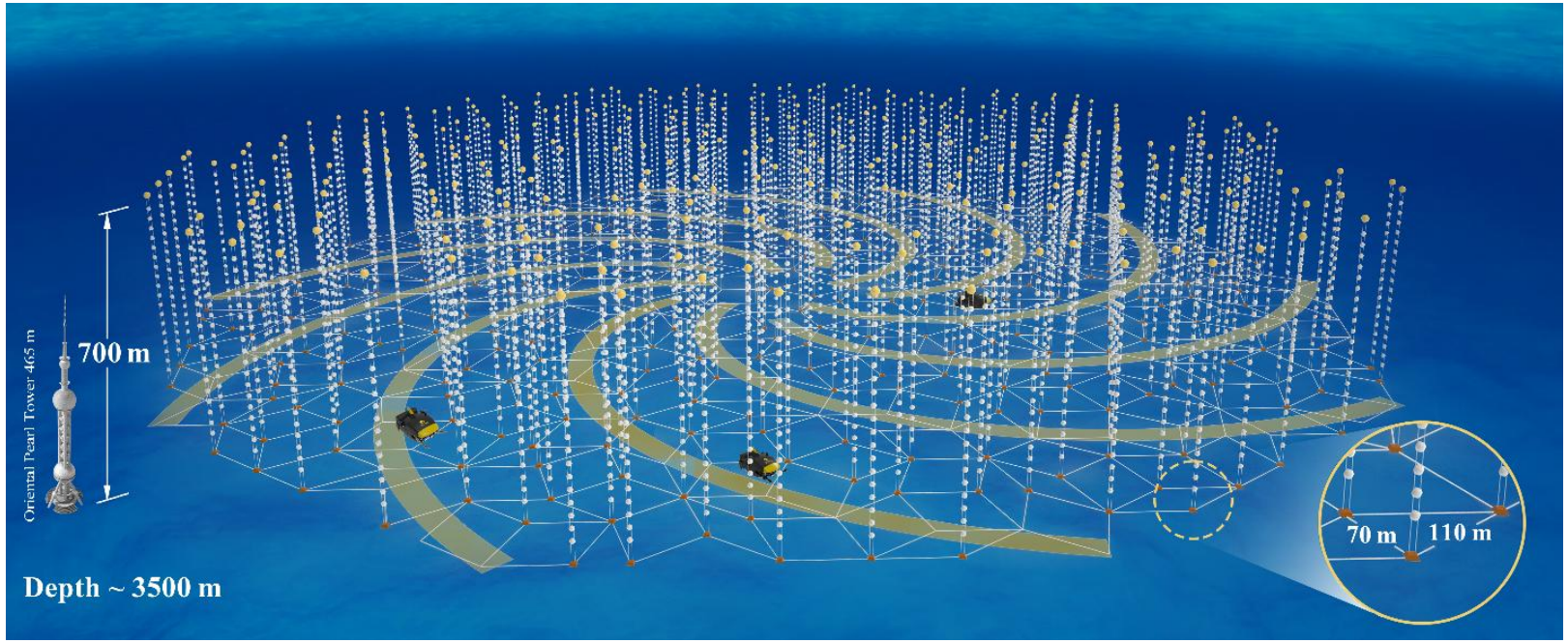


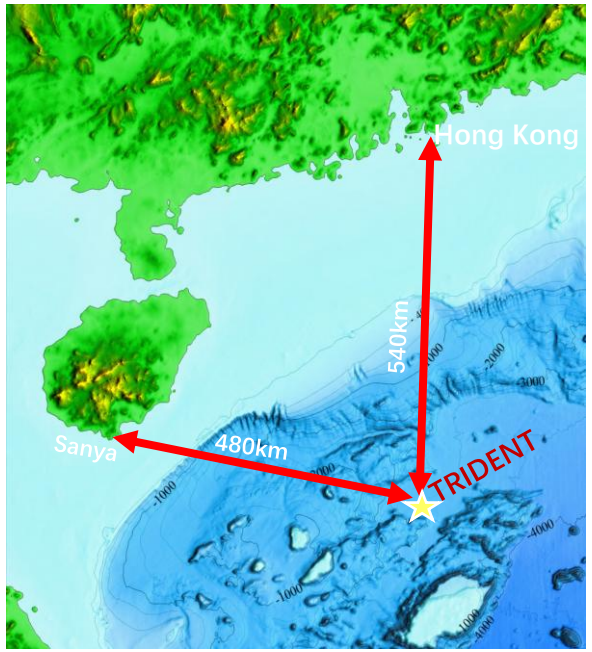
TRIDENT (South China Sea)

Medium: Deep-sea water
Depth: ~ 3.5 km
Volume: ~ 10 km^3
Number of strings : ~1000

Slide edited from
W. Tian @ ICRC2025

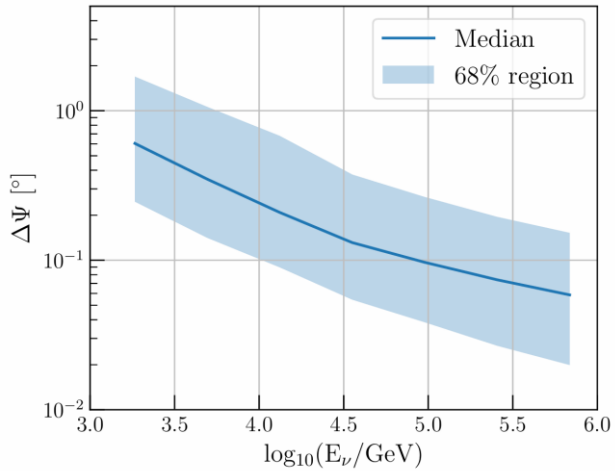
TRIDENT (TRopIcal DEep-sea Neutrino Telescope)





Ye Z.P et al.. Nat Astro 7, 1497 – 1505 (2023).

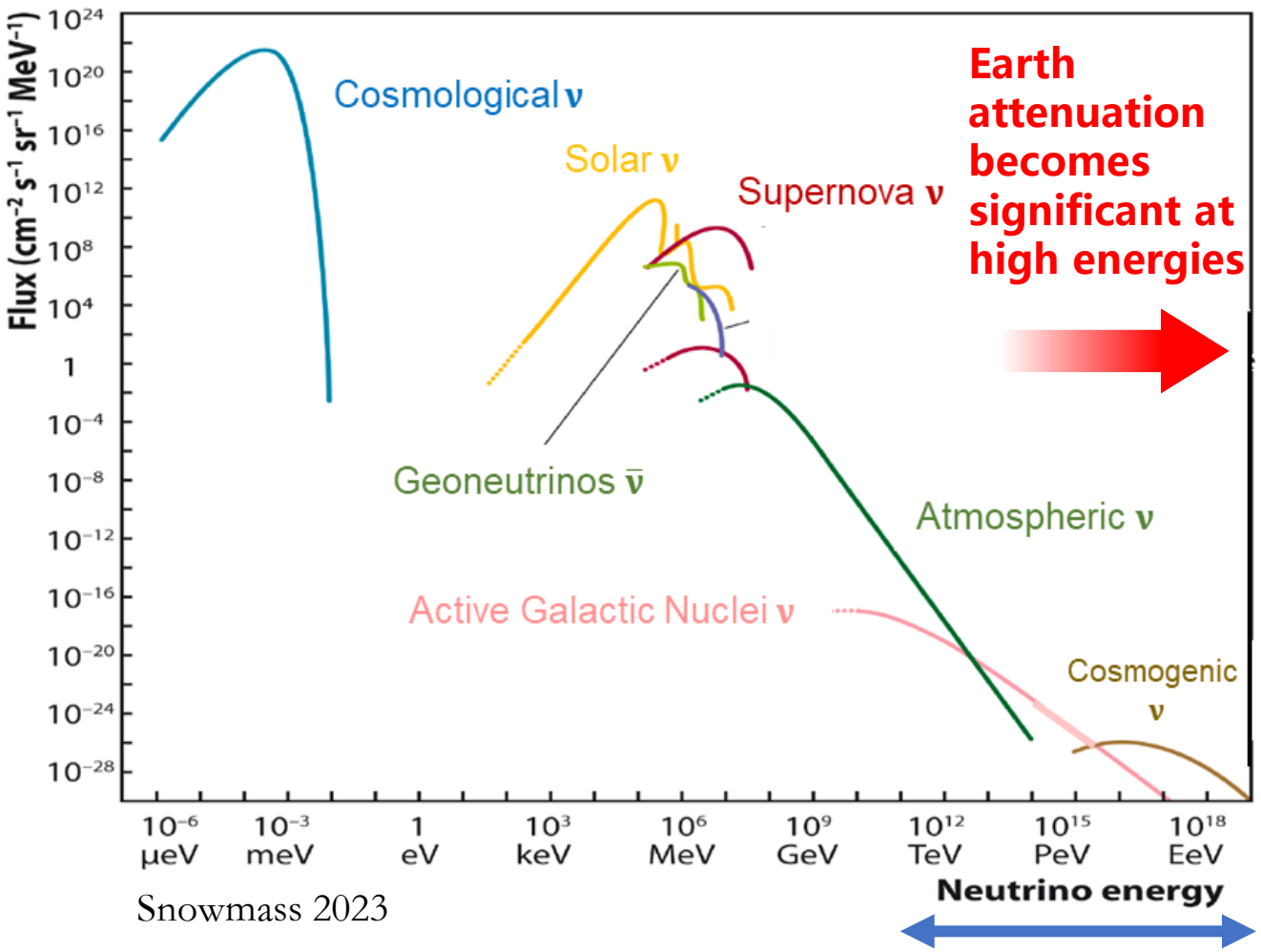
- Including ~1000 strings with 20 hDOMs (hybrid digital optical modules) per string
- Size: ~10 km³
- Broad neutrino sensitivity from sub-TeV to EeV



Very good angular resolution

I. Morton-Blake et al.. Phys. Rev. D 113, 043030 (2026)

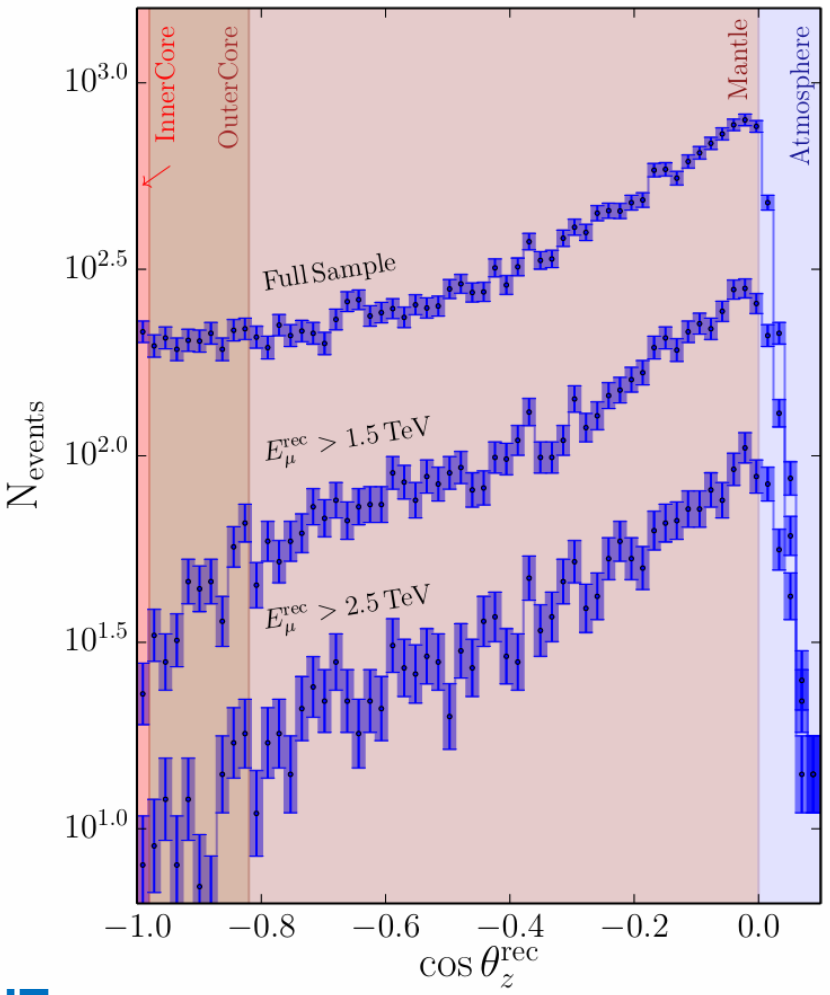
Earth's attenuation



Snowmass 2023

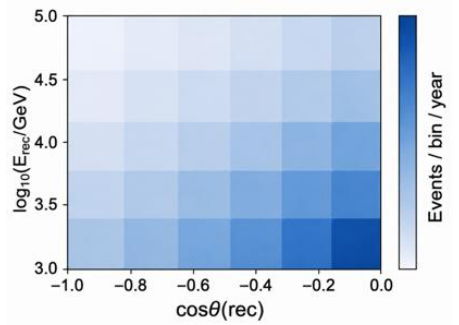
Sensitive region of TRIDENT

IceCube 1yr events



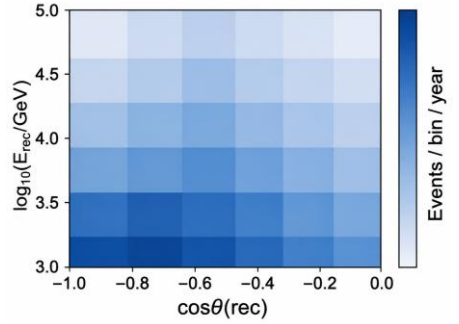
Donini, A. Nature Phys **15**, 37 – 40 (2019).

Methods

Φ_0 → Earth → Φ → 

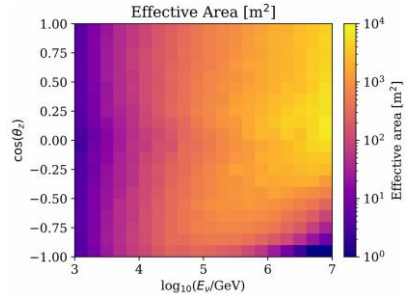
N^{data}

Daemonflux[1]

Φ_0' → Assumed density profile → Φ' → ×A_{eff} [3] → 

$N^{expected}$

Propagate by **nuSQuIDS**[2]



$$\ln \mathcal{L}(\boldsymbol{\rho}, \boldsymbol{\eta}) = \sum_{i \in bins} \left(N_i^{data} \ln N_i^{expected}(\boldsymbol{\rho}, \boldsymbol{\eta}) - N_i^{expected}(\boldsymbol{\rho}, \boldsymbol{\eta}) \right) - \sum_j \frac{\left(\eta_j - \eta_j^0\right)^2}{2\sigma_j^2}$$

[1] Juan Pablo Yañez, Anatoli Fedynitch. Phys. Rev. D 107, 123037, 2023
[2] Carlos A. Argüelles, et al.. Comput. Phys. Commun. 277, 108346, 2022.
[3] Z. P. Ye et al., Nat. Astron. 7, 1497 – 1505, 2023.

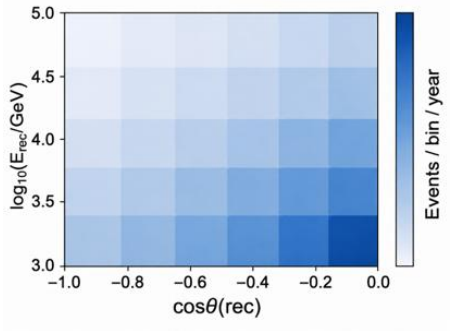
Methods

PREM
(Preliminary Reference Earth Model)



Φ

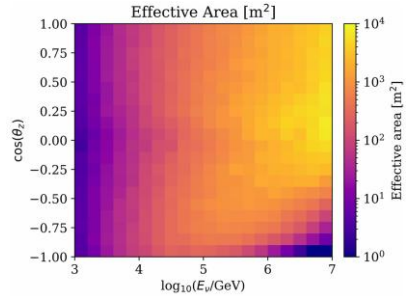
$\times A_{\mathrm{eff}}$ [3]



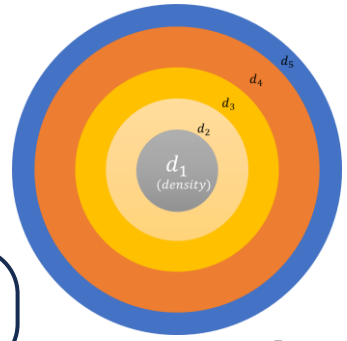
N^{asimov}

Daemonflux[1]

Φ_0'



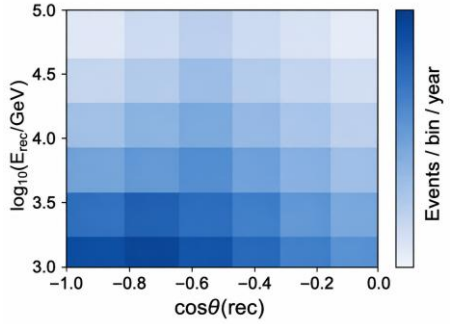
Propagate by **nuSQuIDS**[2]



Assumed density profile

Φ'

$\times A_{\mathrm{eff}}$ [3]

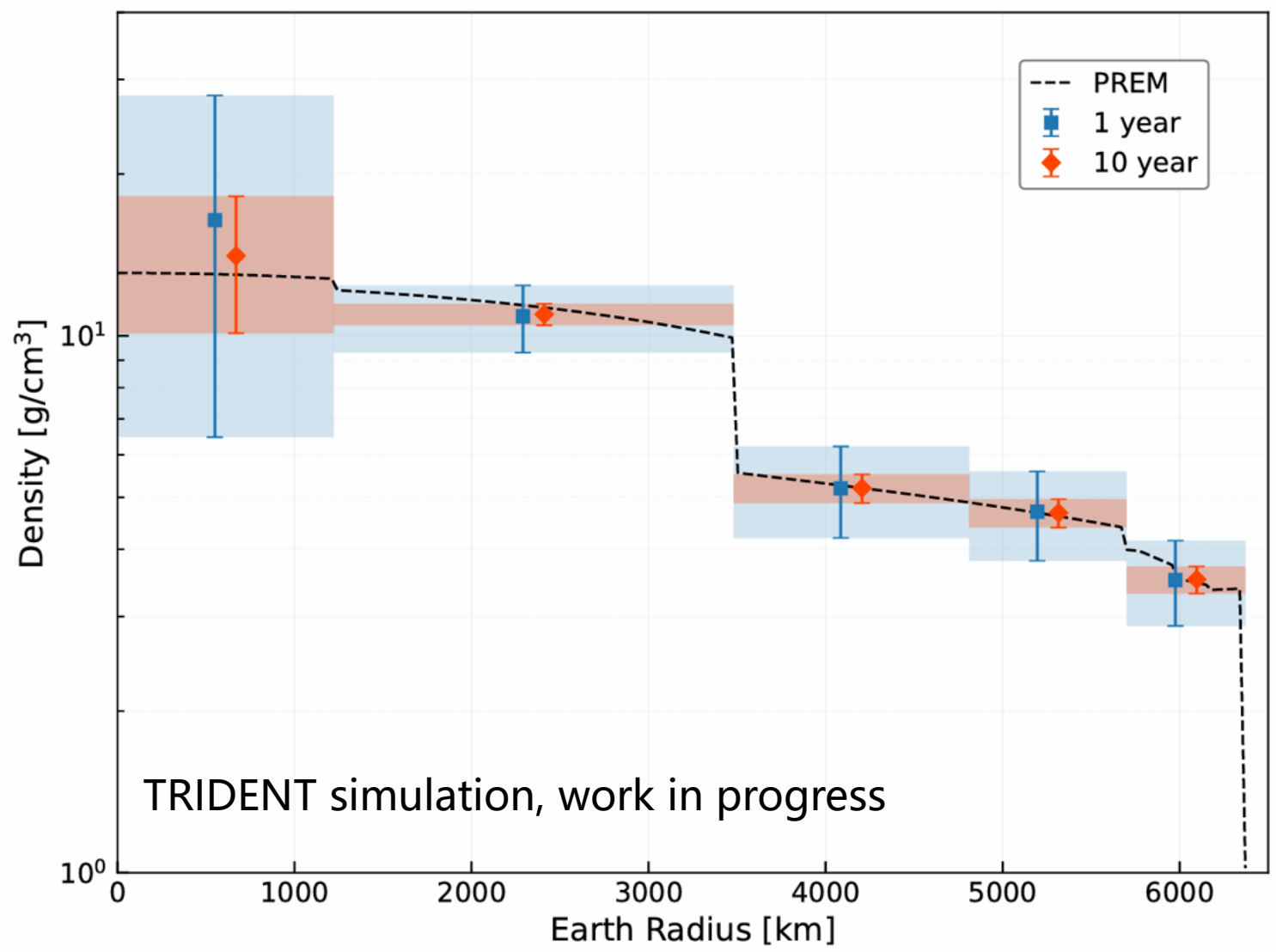


$N^{expected}$

$$\ln \mathcal{L}(\boldsymbol{\rho}, \boldsymbol{\eta}) = \sum_{i \in bins} \left(N_i^{asimov} \ln N_i^{expected}(\boldsymbol{\rho}, \boldsymbol{\eta}) - N_i^{expected}(\boldsymbol{\rho}, \boldsymbol{\eta}) \right) - \sum_j \frac{\left(\eta_j - \eta_j^0\right)^2}{2\sigma_j^2}$$

[1] Juan Pablo Yañez, Anatoli Fedynitch. Phys. Rev. D 107, 123037, 2023
[2] Carlos A. Argüelles, et al.. Comput. Phys. Commun. 277, 108346, 2022.
[3] Z. P. Ye et al., Nat. Astron. 7, 1497 − 1505, 2023.

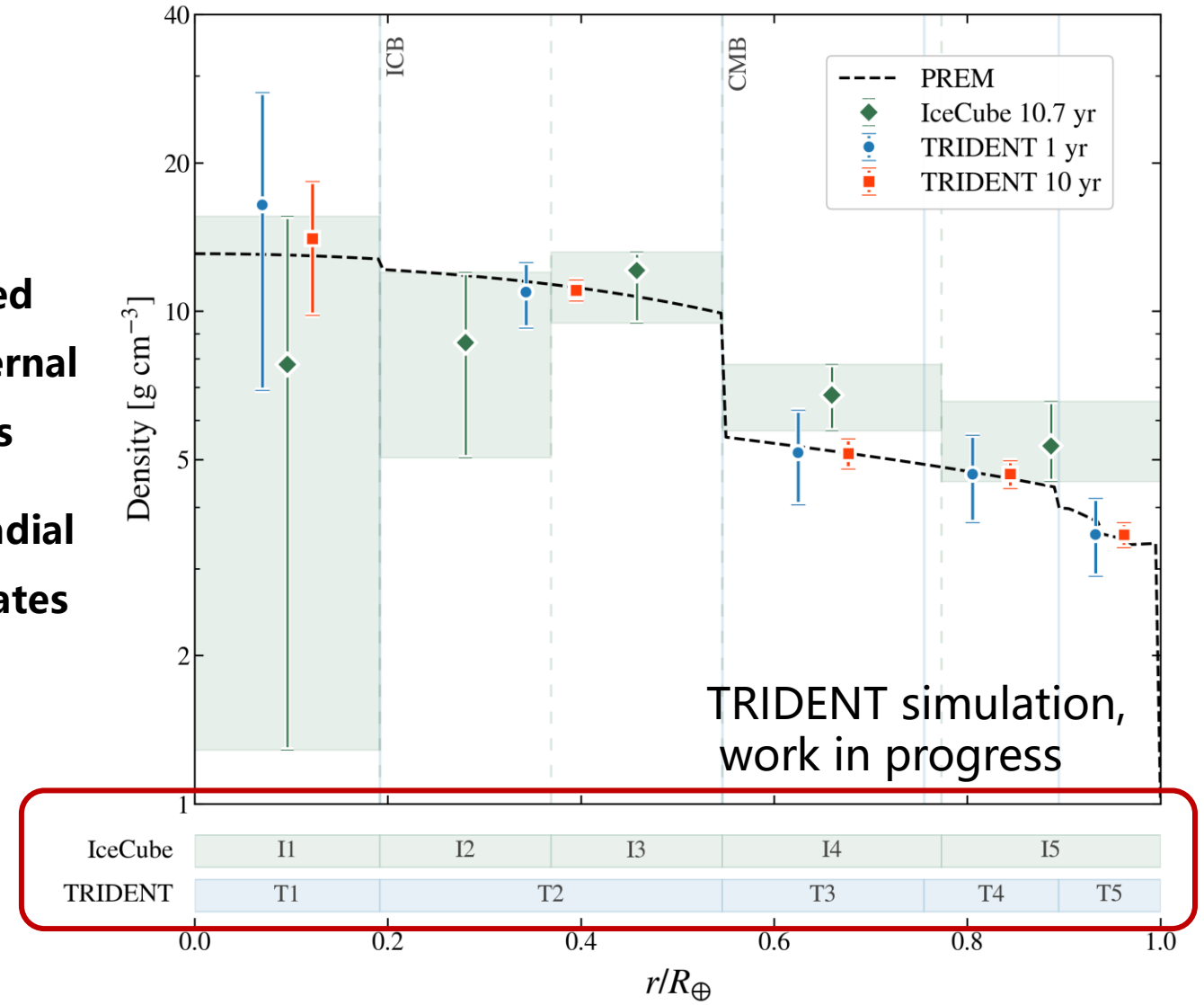
Sensitivity



- **With enough statistics TRIDENT expects to reconstruct a multi-layer Earth density profile.**
- **Most Earth layers can be well constrained, while the innermost region remains the most challenging.**

Comparison with Previous Studies

- **Outer core: limited sensitivity to internal density variations**
- **Mantle: higher radial sensitivity motivates finer subdivision**



- **Improved precision in several radial regions**
- **Inner-core sensitivity remains limited in both studies**

[1] IceCube Coll. arXiv:2607.02644

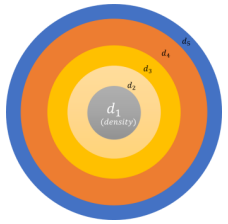
To Higher Accuracy: different models

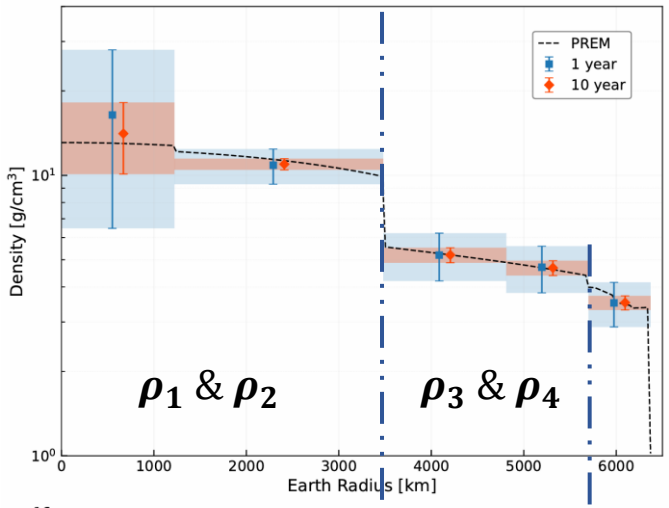
Constant Density

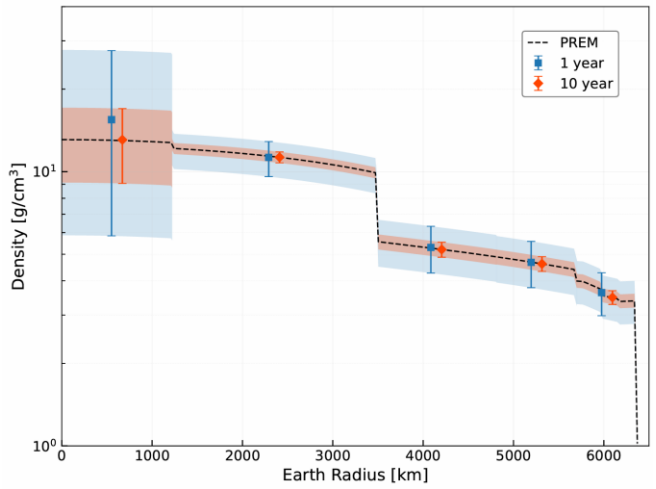
PREM-like

For 1yr exposure

5 layers

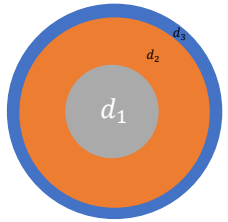


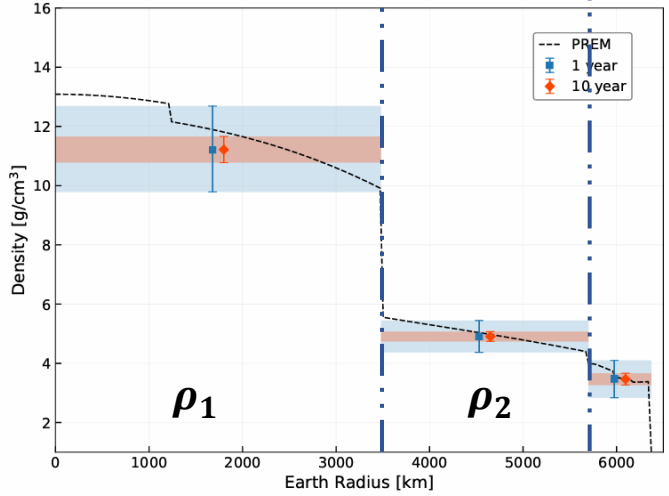


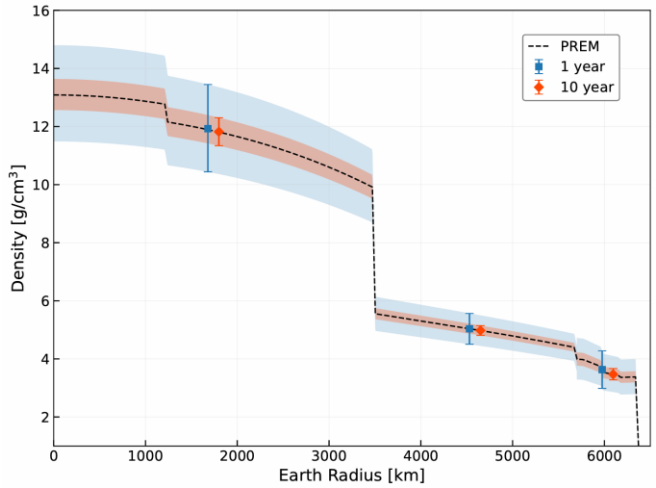


	Constant ρ		PREM-like	
Layer	$\rho[g/cm^3]$	Unc. [%]	$\rho[g/cm^3]$	Unc. [%]
ρ_1	$16.42^{+11.60}_{-9.95}$	65.6	$15.32^{+12.04}_{-9.55}$	70.5
ρ_2	$10.87^{+1.54}_{-1.57}$	14.3	$10.78^{+1.53}_{-1.61}$	14.6
ρ_3	$5.20^{+1.02}_{-1.00}$	19.4	$5.25^{+1.02}_{-1.01}$	19.4
ρ_4	$4.70^{+0.89}_{-0.89}$	18.9	$4.61^{+0.89}_{-0.89}$	19.2
ρ_5	$3.51^{+0.64}_{-0.63}$	18.1	$3.55^{+0.63}_{-0.63}$	17.8

3 layers



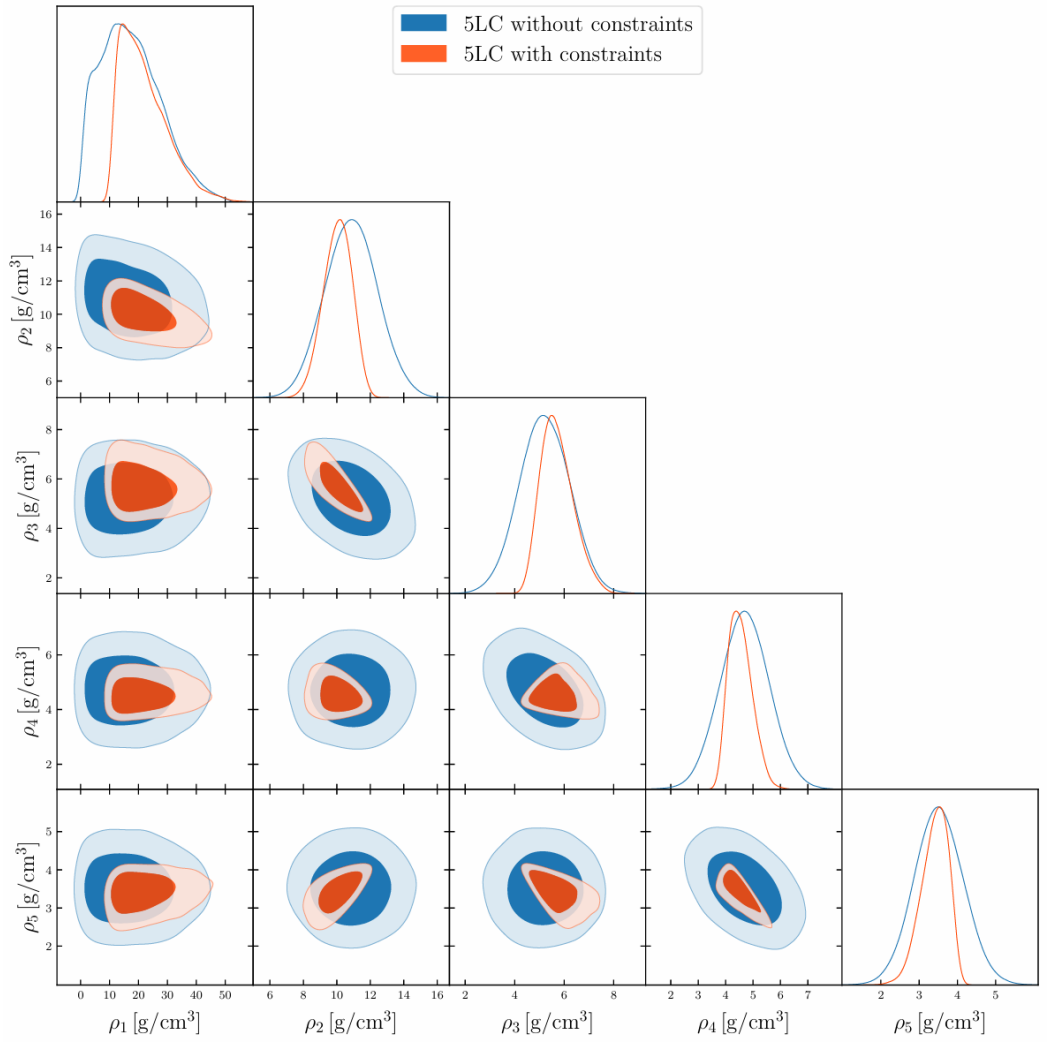




	Constant ρ		PREM-like	
Layer	$\rho[g/cm^3]$	Unc. [%]	$\rho[g/cm^3]$	Unc. [%]
ρ_1	$11.21^{+1.48}_{-1.42}$	**12.9**	$11.01^{+1.40}_{-1.37}$	12.6
ρ_2	$4.91^{+0.54}_{-0.54}$	11.0	$4.91^{+0.52}_{-0.52}$	10.5
ρ_3	$3.47^{+0.62}_{-0.64}$	18.1	$3.55^{+0.63}_{-0.63}$	17.8

3-layer seems to be better

To Higher Accuracy: applying constraints



Constrains:

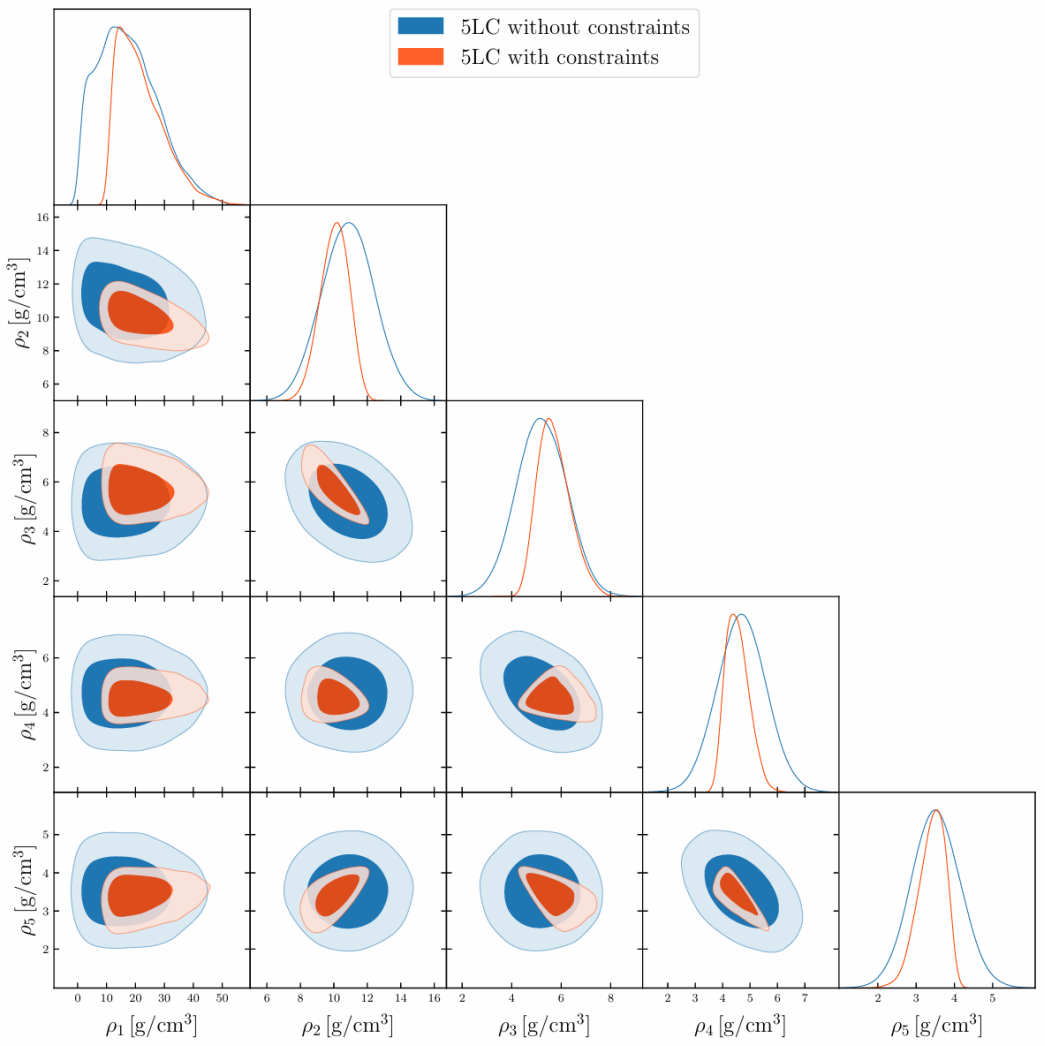
- $M_\oplus$, the total mass of the Earth
- $I_\oplus$, the moment of inertia of the Earth
- Earth hydrostatic equilibrium (EHE)[1], $\rho_{\text{inner}} > \rho_{outer}$

For 1yr exposure

	Without constraints		With constraints	
Layer	$\rho[g/cm^3]$	Unc. [%]	$\rho[g/cm^3]$	Unc. [%]
ρ_1	$16.42^{+11.60}_{-9.95}$	65.6	$20.33^{+9.88}_{-6.61}$	**40.6**
ρ_2	$10.87^{+1.54}_{-1.57}$	14.3	$10.08^{+0.83}_{-0.91}$	**8.6**
ρ_3	$5.20^{+1.02}_{-1.00}$	19.4	$5.64^{+0.74}_{-0.59}$	**11.8**
ρ_4	$4.70^{+0.89}_{-0.89}$	18.9	$4.50^{+0.48}_{-0.40}$	**9.7**
ρ_5	$3.51^{+0.64}_{-0.63}$	18.1	$3.44^{+0.33}_{-0.40}$	**10.6**

[1] Kevin J. Kelly, et al.. JHEP05(2022)187

To Higher Accuracy: applying constraints



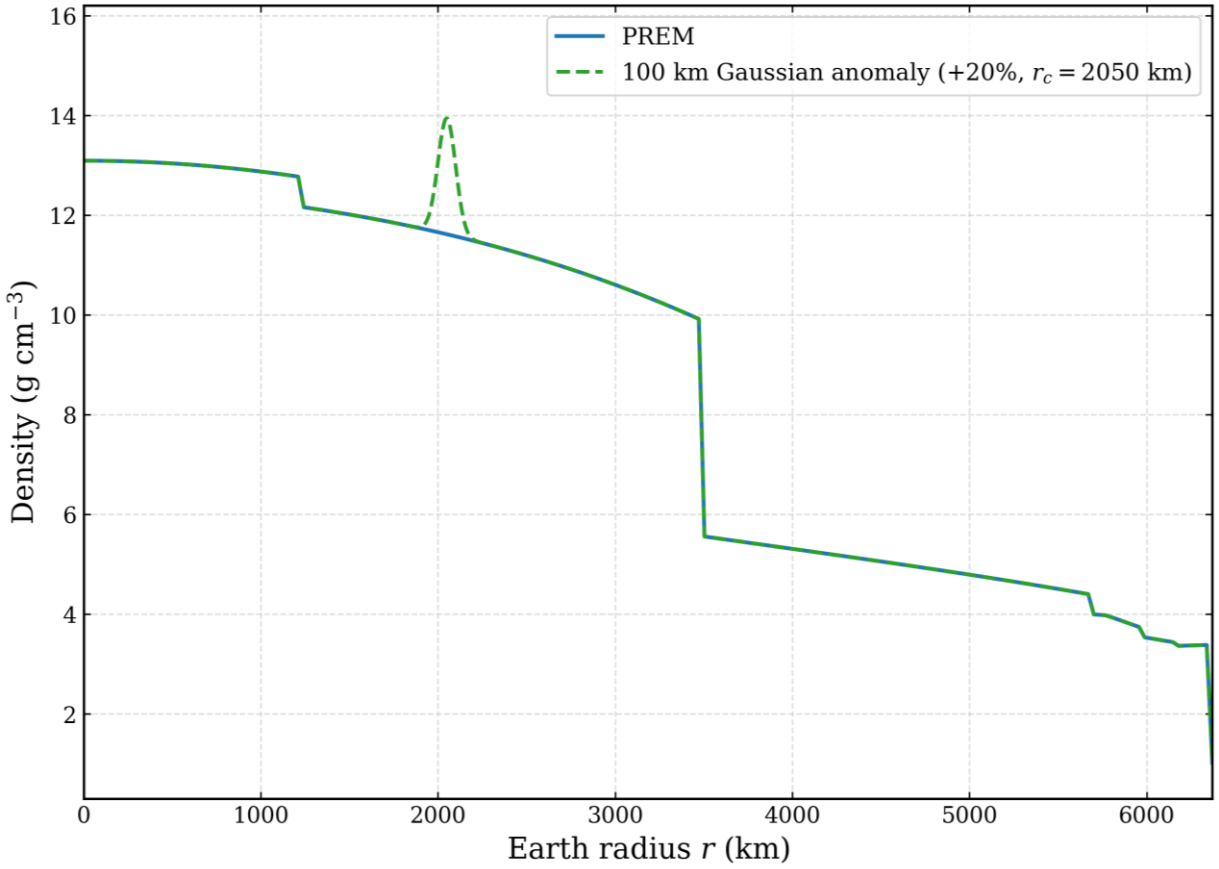
1yr exposure with constraints

	Constant ρ		PREM-like	
Layer	$\rho[g/cm^3]$	Unc. [%]	$\rho[g/cm^3]$	Unc. [%]
ρ_1	$20.33^{+9.88}_{-6.61}$	40.6	$19.56^{+9.32}_{-6.20}$	**39.7**
ρ_2	$10.08^{+0.83}_{-0.91}$	8.6	$10.00^{+0.79}_{-0.87}$	**8.3**
ρ_3	$5.64^{+0.74}_{-0.59}$	11.8	$5.63^{+0.75}_{-0.60}$	12.0
ρ_4	$4.50^{+0.48}_{-0.40}$	9.7	$4.47^{+0.44}_{-0.37}$	**9.1**
ρ_5	$3.44^{+0.33}_{-0.40}$	10.6	$3.56^{+0.30}_{-0.39}$	**9.6**

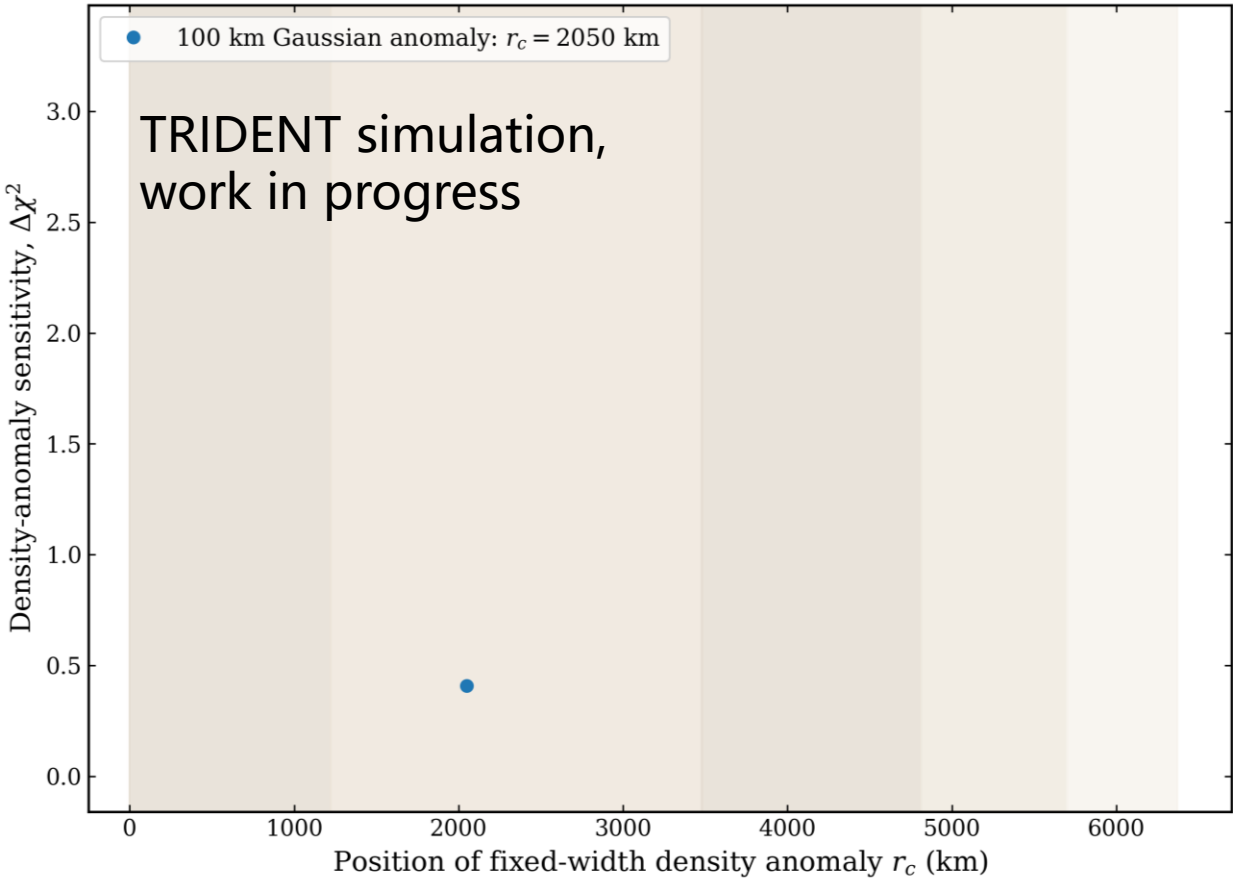
	Constant ρ		PREM-like	
Layer	$\rho[g/cm^3]$	Unc. [%]	$\rho[g/cm^3]$	Unc. [%]
ρ_1	$11.32^{+0.63}_{-0.71}$	6.0	$10.95^{+0.60}_{-0.67}$	**5.8**
ρ_2	$4.91^{+0.46}_{-0.41}$	8.8	$4.91^{+0.42}_{-0.38}$	**8.1**
ρ_3	$3.36^{+0.43}_{-0.48}$	13.4	$3.55^{+0.39}_{-0.44}$	**11.6**

Sensitivity to Density Anomalies

What if the Earth contains a localized density anomaly?

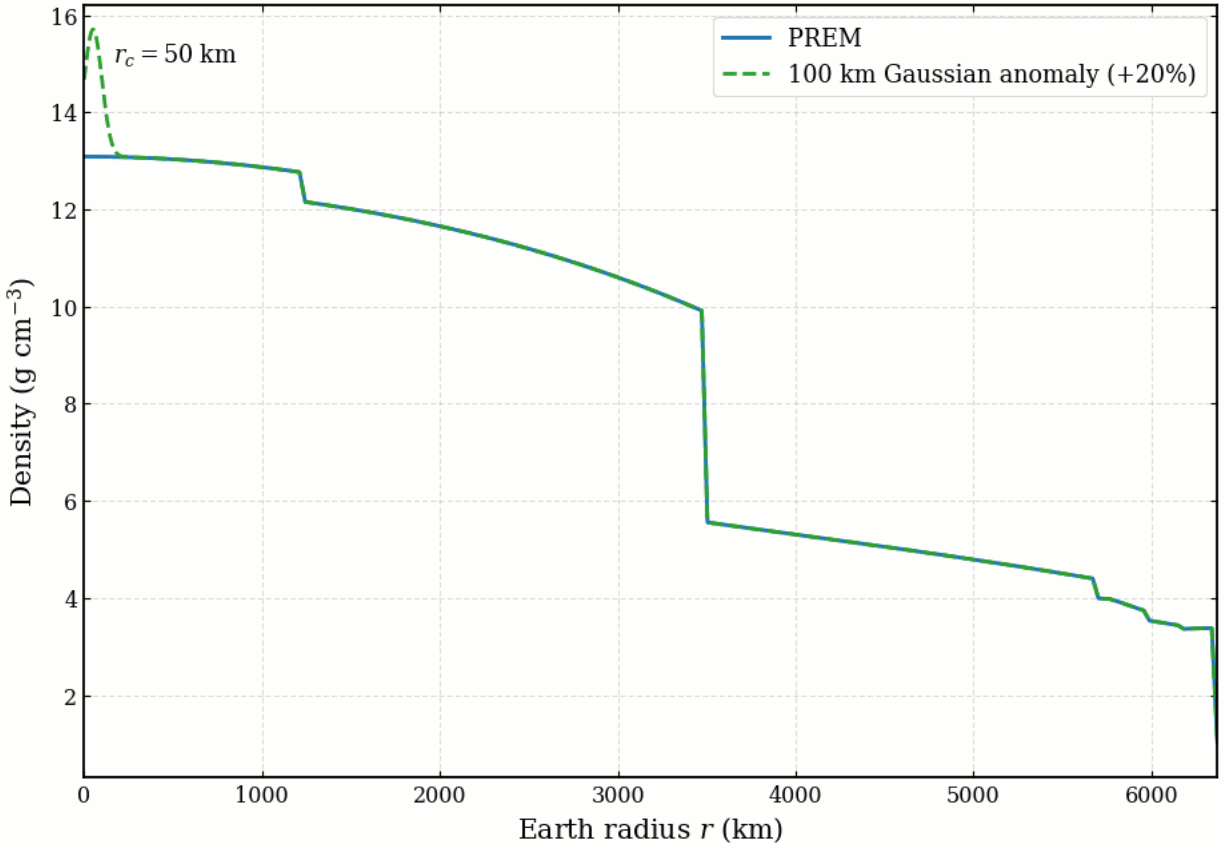


Sensitivity for TRIDENT-10y to localized density anomalies

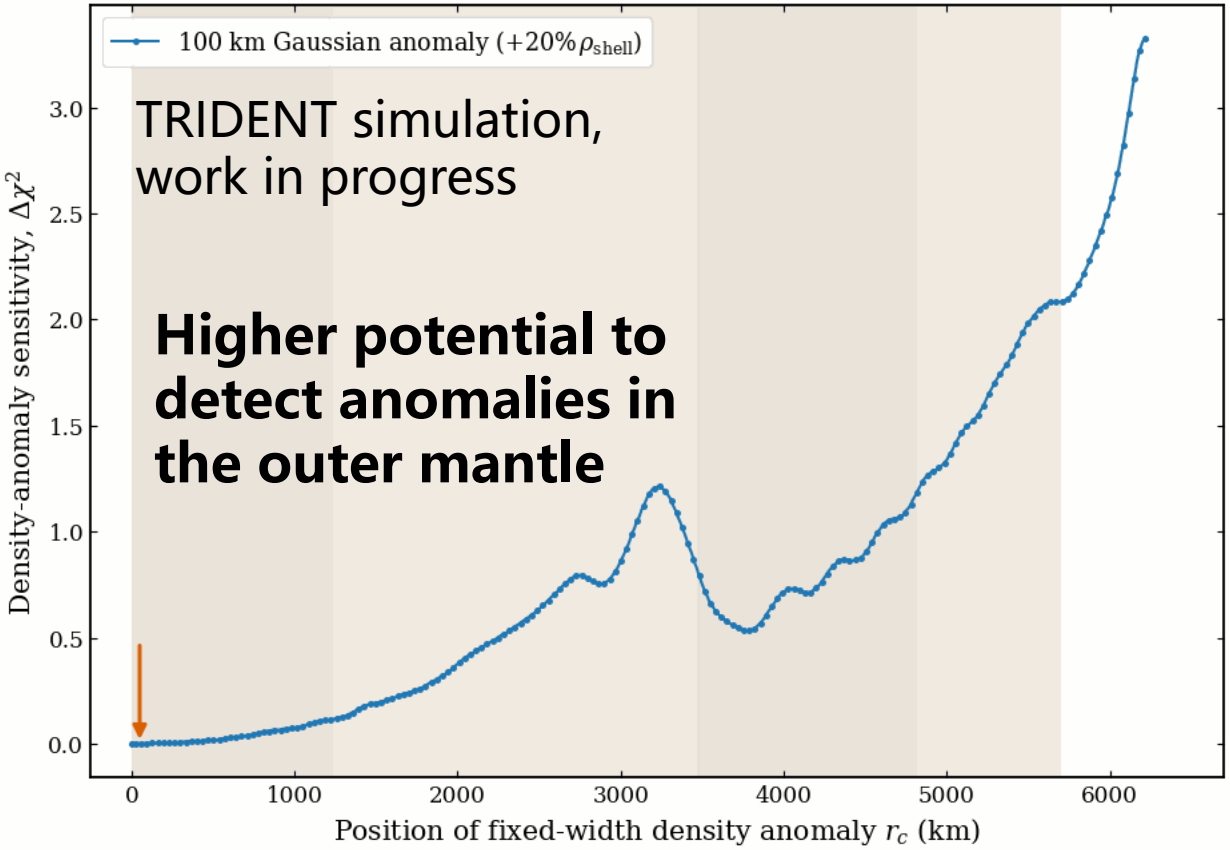


Sensitivity to Density Anomalies

What if the Earth contains a localized density anomaly?



Sensitivity for TRIDENT-10y to localized density anomalies



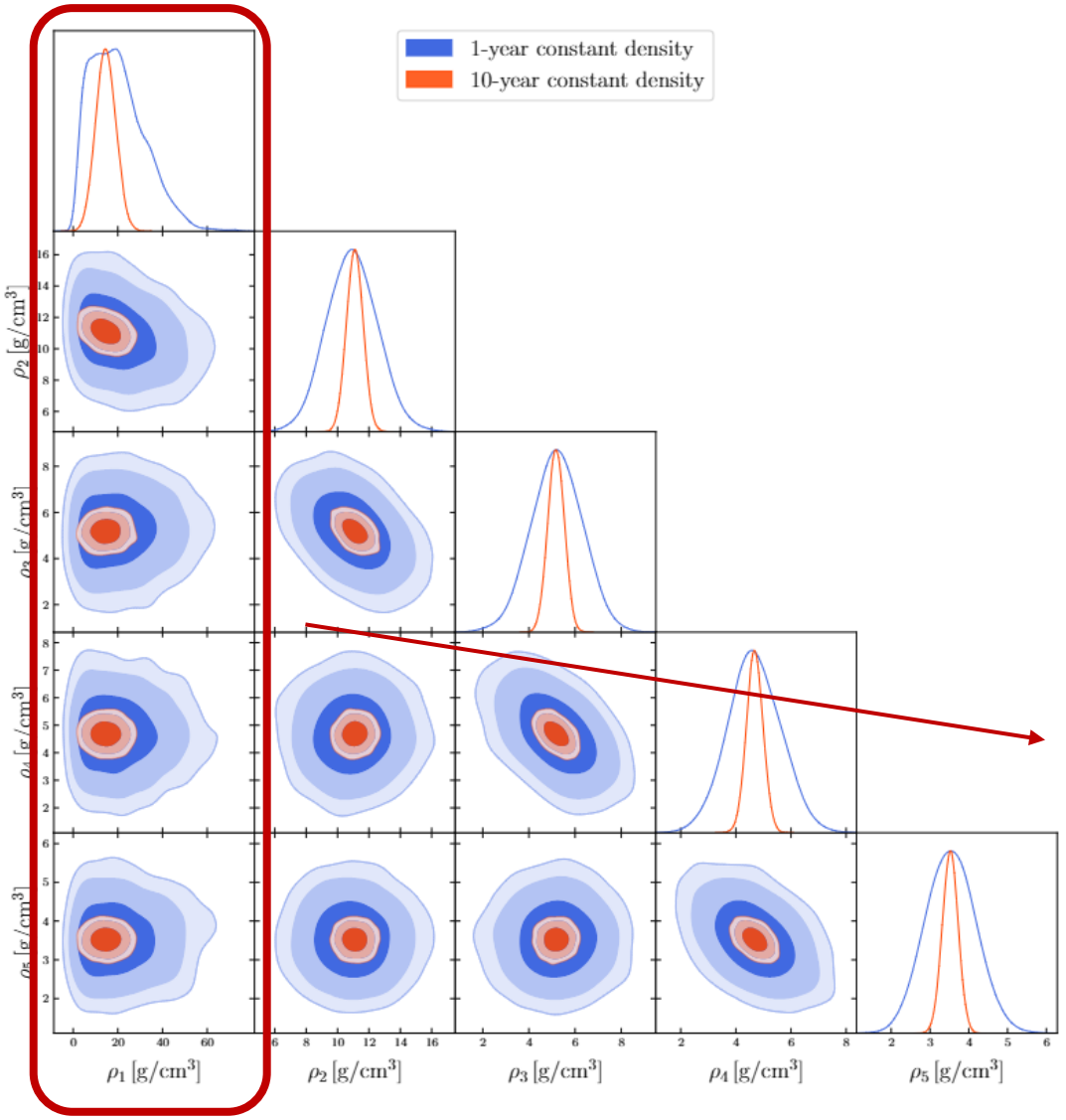
Summary

- Neutrinos give a directly probes of Earth matter density profiles.
- A few constrains can provide a better resolution of the reconstruction .
- We are relatively more sensitive to density variations in the Earth's outer layers, but less so in the inner core.


TRIDENT
海 | 铃 | 计 | 划
Thank you!

Backup

Results from Multinest



- Posterior distributions of the five constant-density layers for 1-year and 10-year exposures.
- Diagonal panels show **marginalized 1D posteriors**; off-diagonal panels show correlations between layer densities.
- The 10-year exposure significantly narrows the allowed parameter space, especially for the outer layers.
- The innermost density remains the least constrained, while clear inter-layer correlations persist.
- **The innermost density is biased high due to the asymmetric prior range**: the large uncertainty extends toward low densities but is truncated at the physical boundary $\rho > 0$