Low-energy neutrino physics at Theia

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Seattle Snowmass Summer Meeting 2022
July 24th 2022

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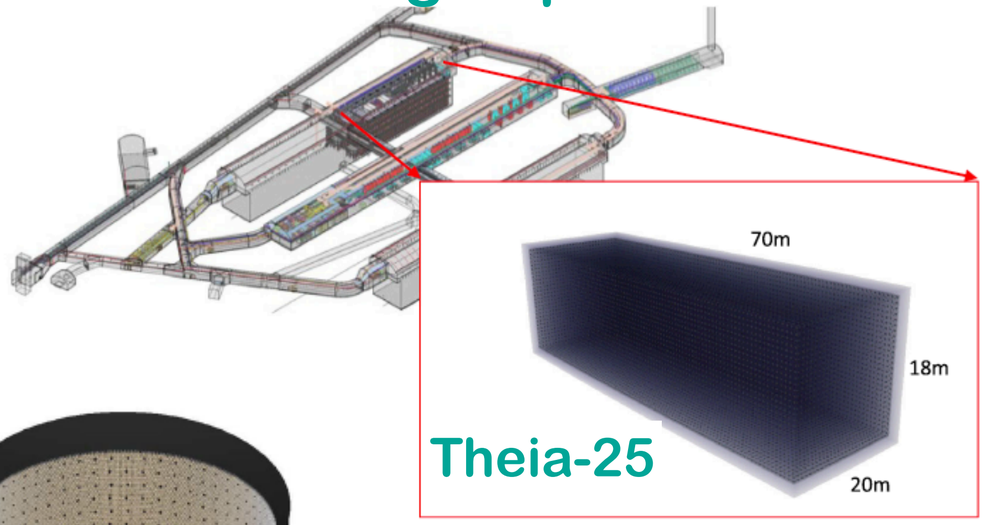
Theia: advanced optical multipurpose neutrino detector

Cutting edge developments in the target material and photodetection

Design options



Large scale, multipurpose detector

- Baseline: 25ktonne (17kt FV)
- Ideal: 100 ktonne (70kt FV)

Broad physics program: Studying neutrino fundamental properties and astrophysical objects

THEIA: An advanced optical neutrino detector Eur. Phys. J. C 80, 416

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

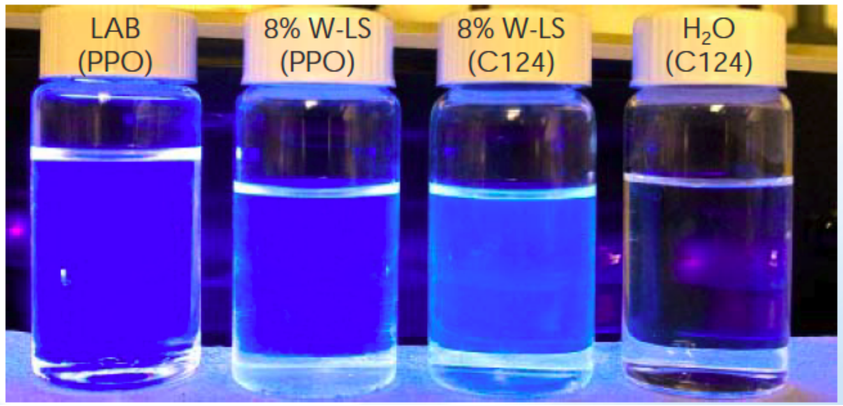
🚫 No access to physics below the Cherenkov threshold

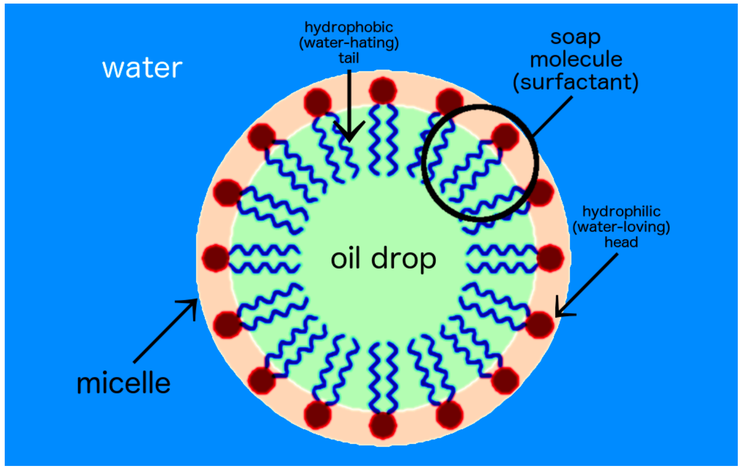
🚫 Low light yield

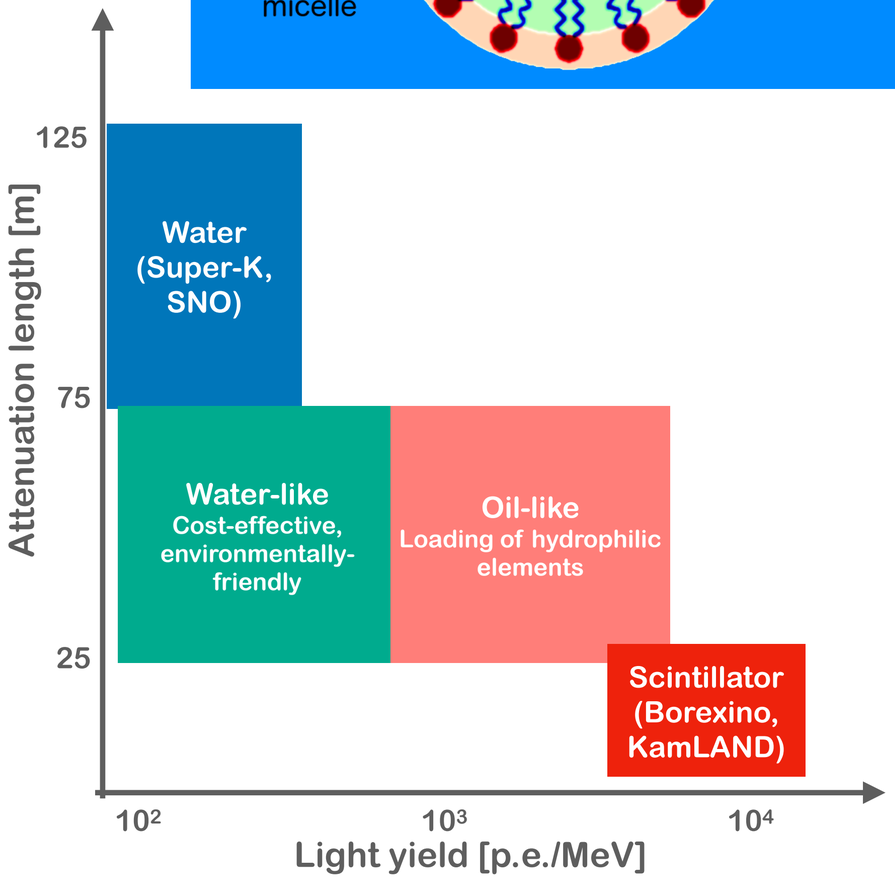
Water-based Liquid Scintillation (WbLS) Detectors: Get best of two worlds

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)

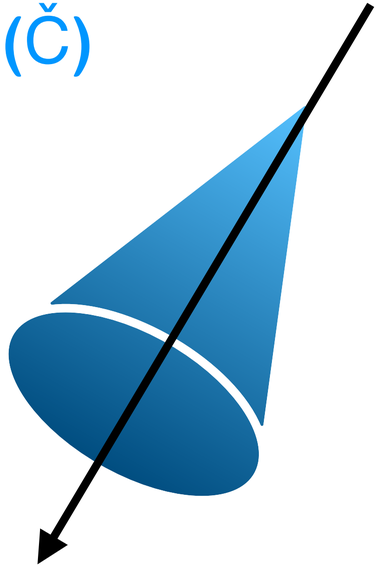




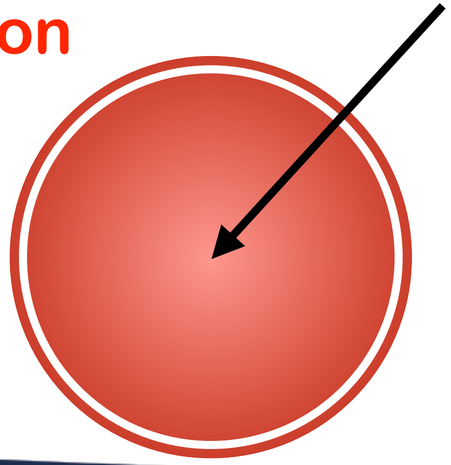


Cherenkov/scintillation photons separation

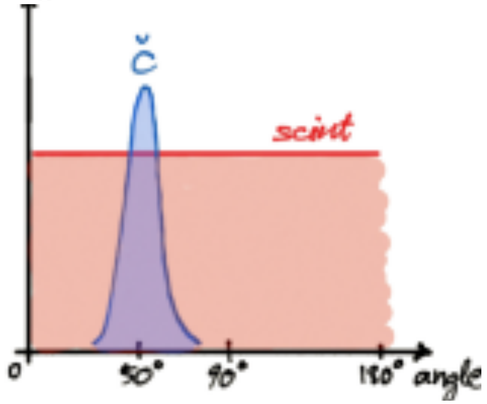
Cherenkov (Č)



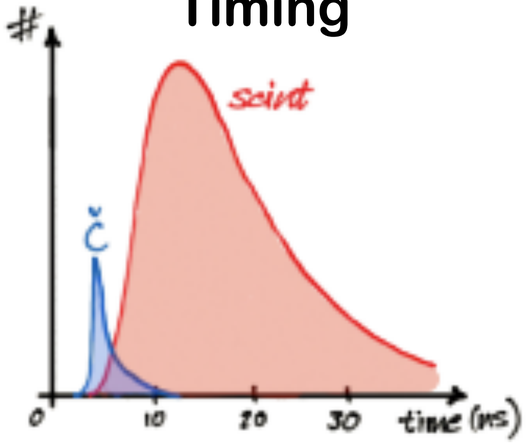
Scintillation



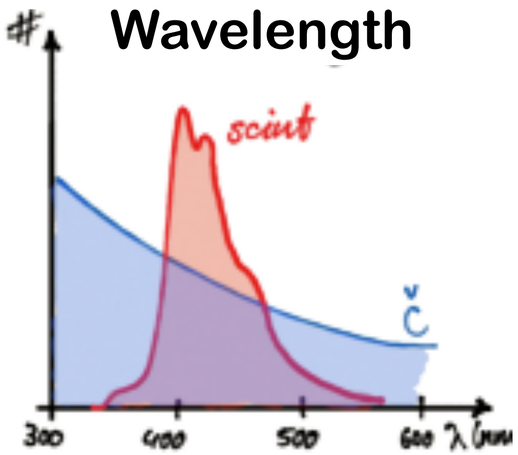
Angular distribution



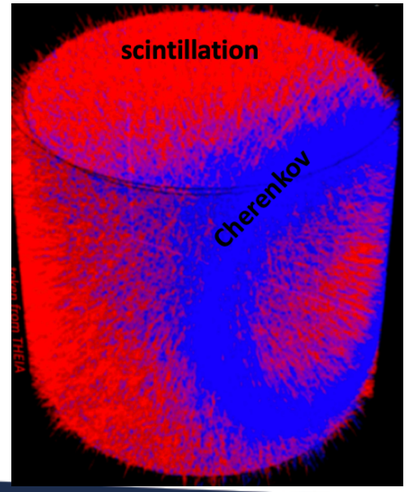
Timing



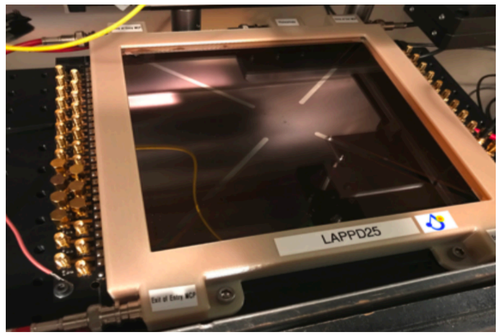
Wavelength



Angular resolution

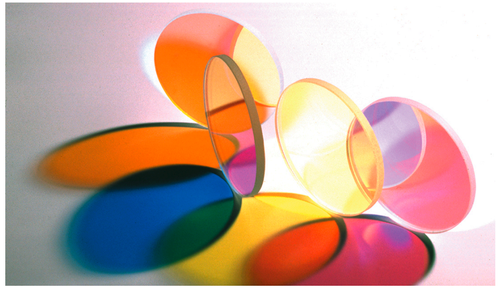


Large area picosecond photodetectors LAPPDs (~70 ps TTS) or other fast photodetectors



B.W.Adams et al. NIM A Volume 795, 1 (2015)

- Dichroic filters
- Red-sensitive PMTs
- Filtering



T. Kaptanoglu et al.
Phys. Rev. D 101, 072002 (2020)

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See Tanner Kaptanoglu's Talk for more info

Theia: multipurpose neutrino detector

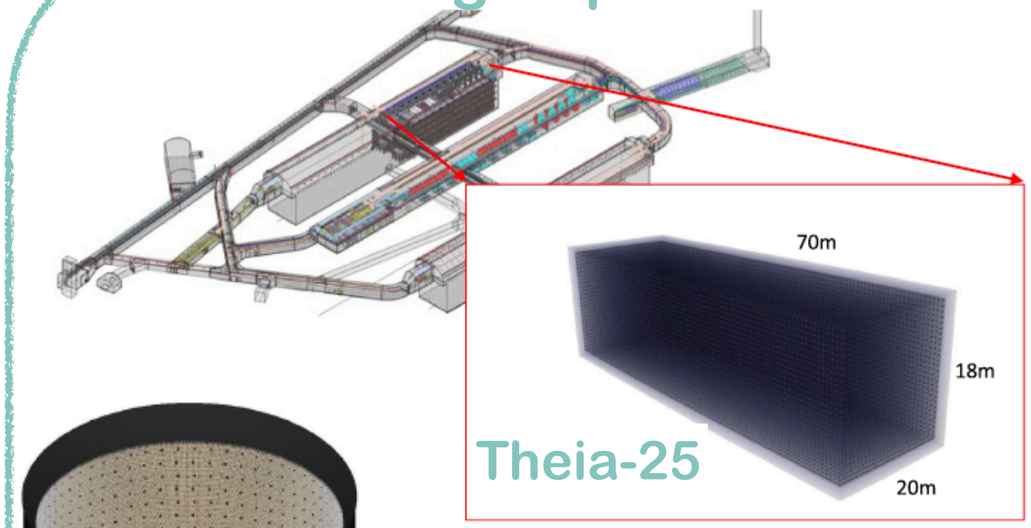
solar neutrinos (CNO, ^{8}B)

geoneutrinos

diffuse supernova neutrinos (DSNB)

supernova burst neutrinos

Design options



Large scale, multipurpose detector

- Baseline: 25ktonne (17kt FV)
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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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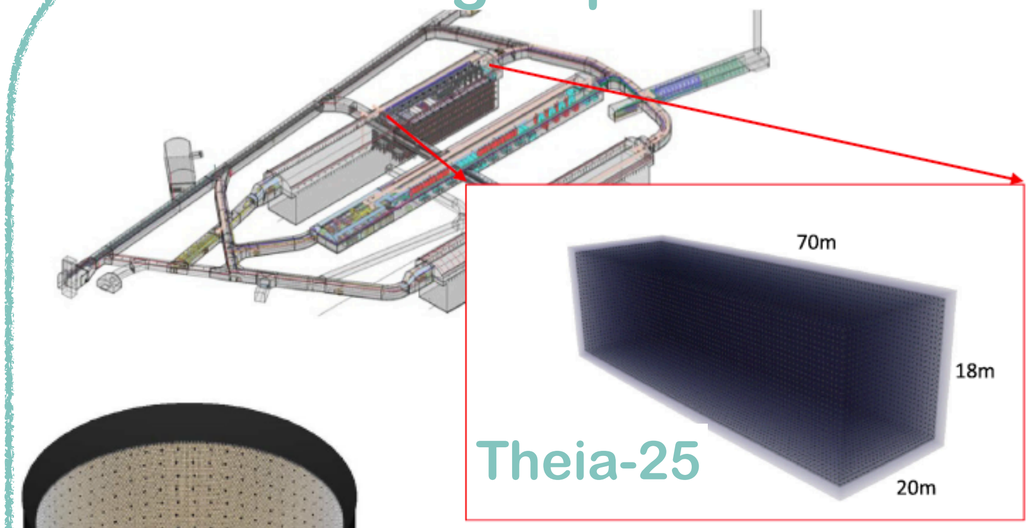

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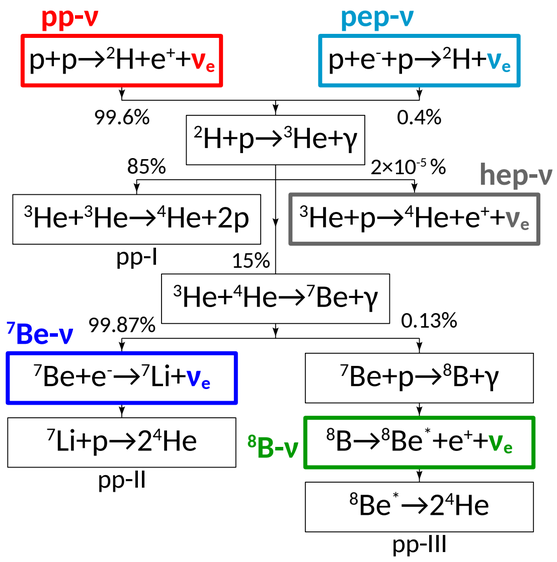
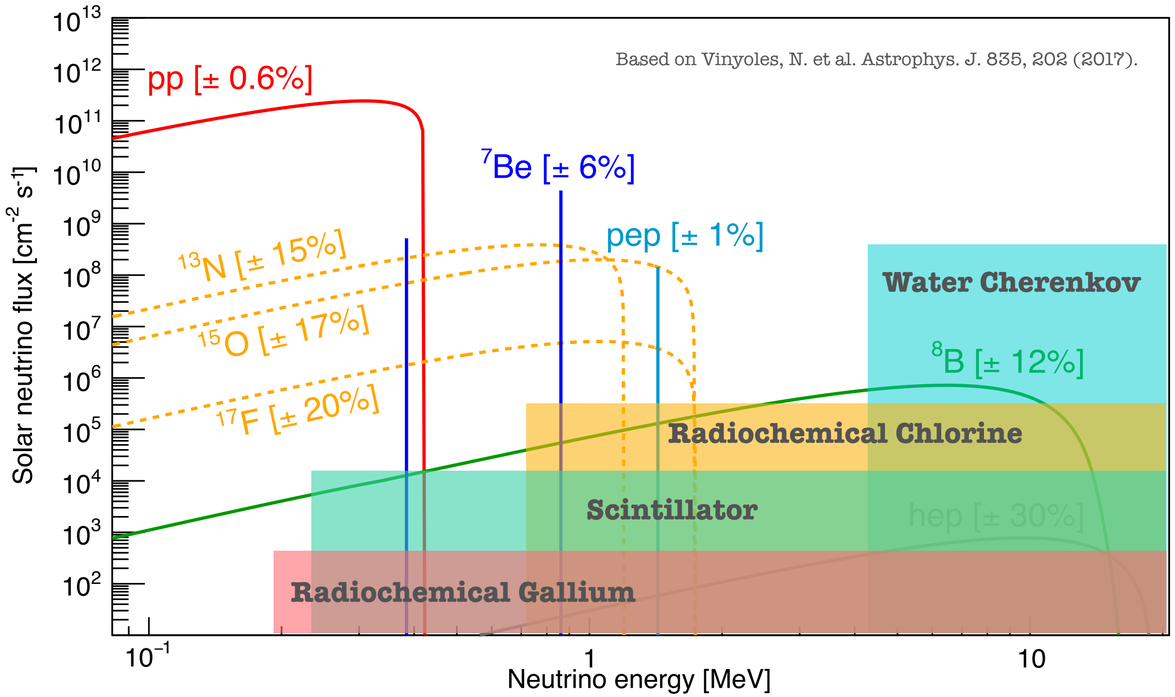
Solar neutrinos

pp chain reaction (~99%)

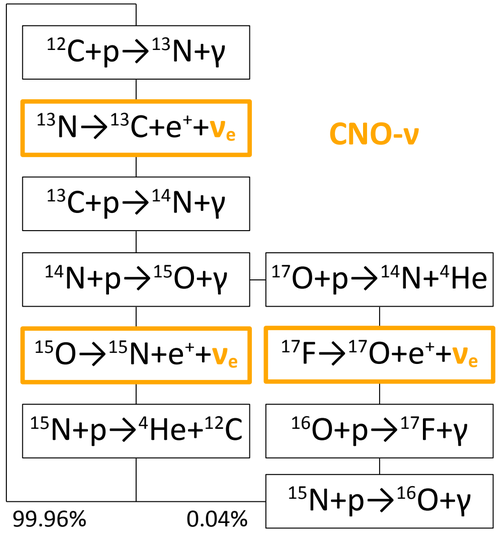


$$4p \rightarrow {}^4\mathrm{He} + 2e^+ + 2\nu_e$$

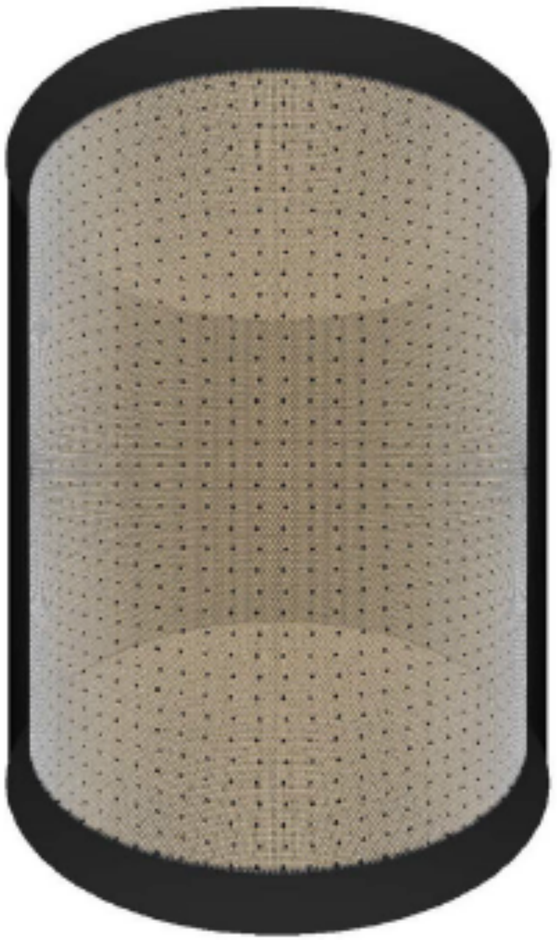
Released energy ~26 MeV



CNO cycle (< 1%)



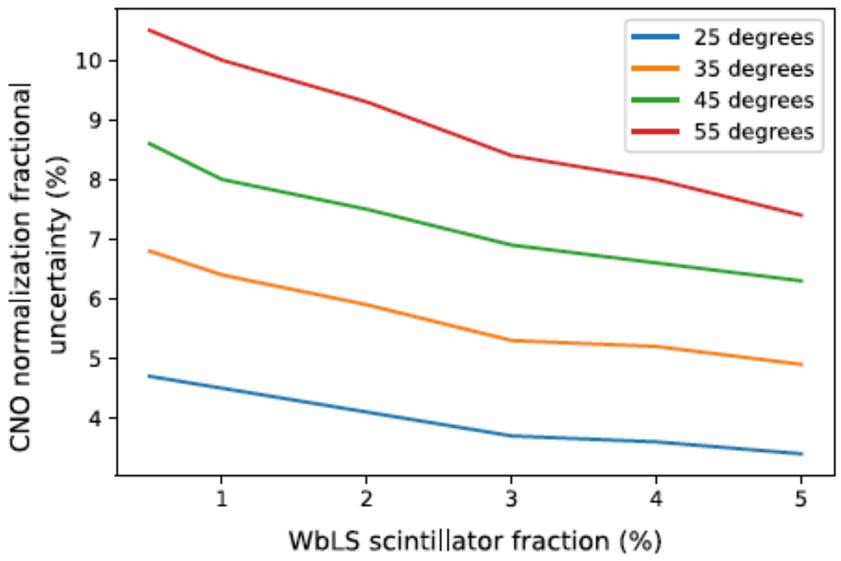
Theia: Solar neutrinos



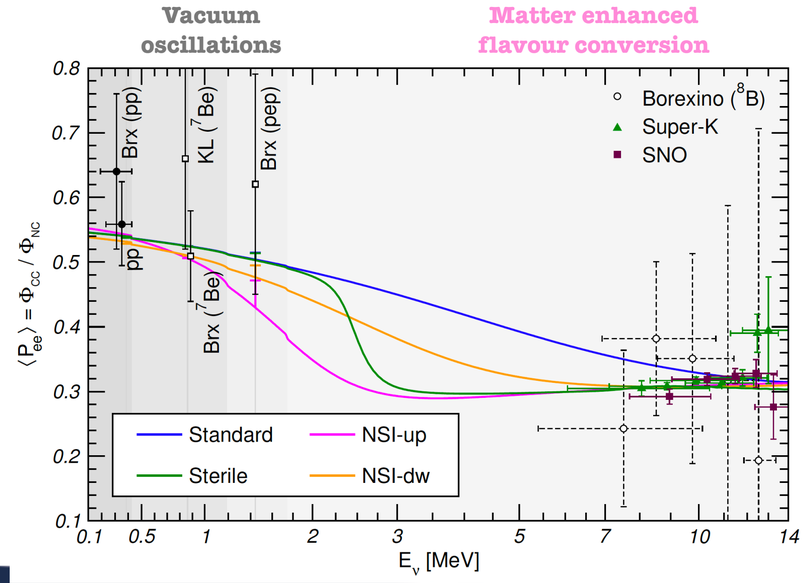
Theia can significantly contribute to solar neutrinos studies:

- CNO neutrinos (directionality based background rejection, solar metallicity puzzle)

- ^{8}B solar neutrinos high-statistics, low-threshold -> new physics in the MSW-vacuum transition region



M. Askins, Z.Bagdasarian et al Eur. Phys. J. C 80, 416



M. Maltoni, A. Smirnov Eur. Phys. J. A 52, 87 (2016)

Theia: multipurpose neutrino detector

solar neutrinos (CNO, ^{8}B)

geoneutrinos

diffuse supernova neutrinos (DSNB)

supernova burst neutrinos

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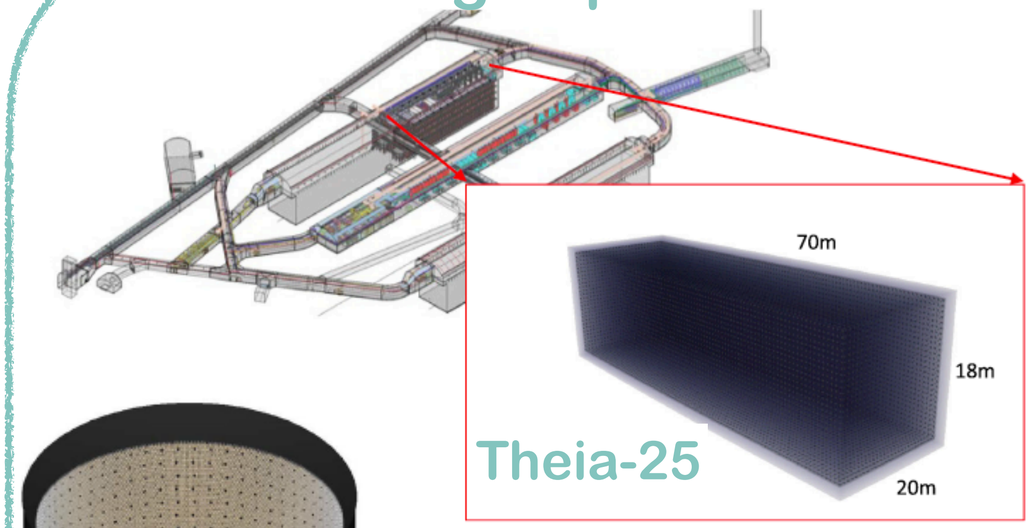

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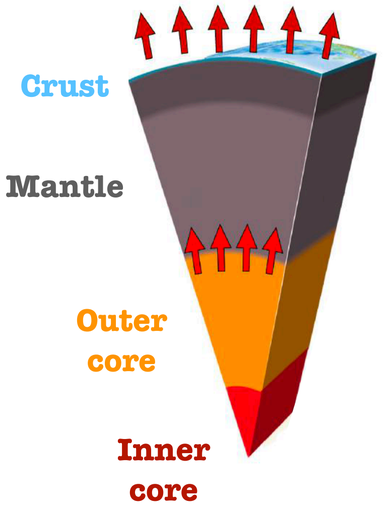
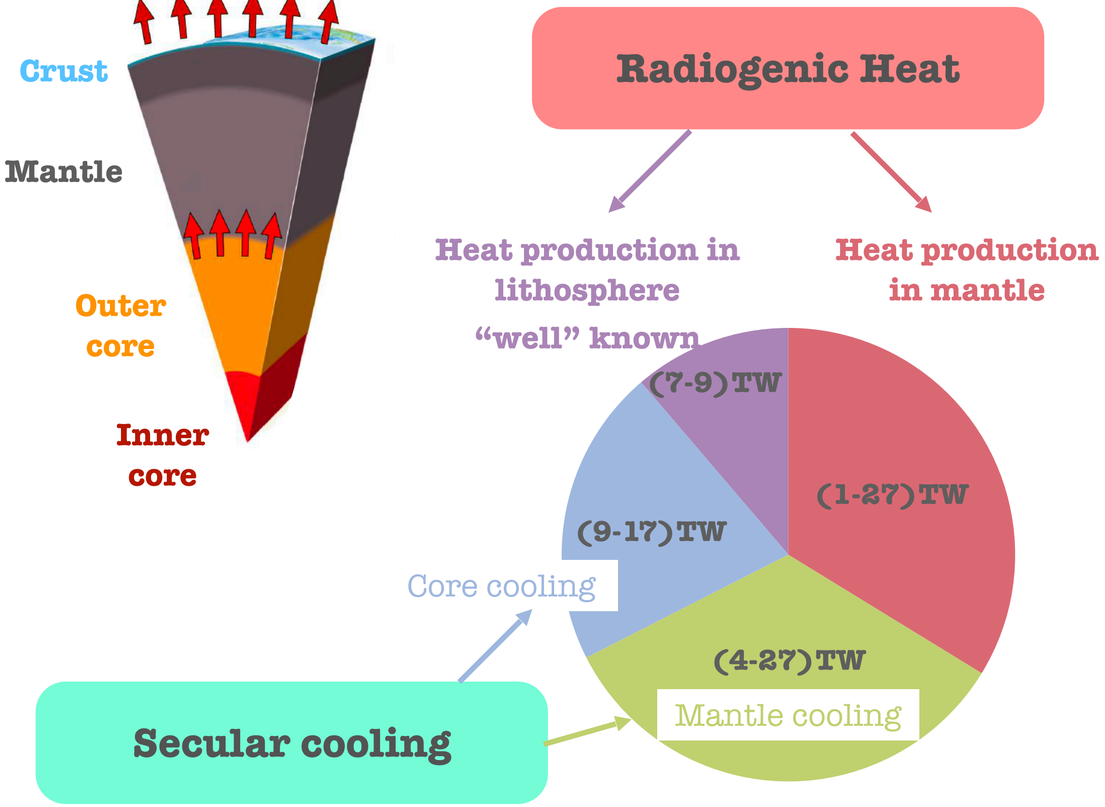
Geoneutrinos

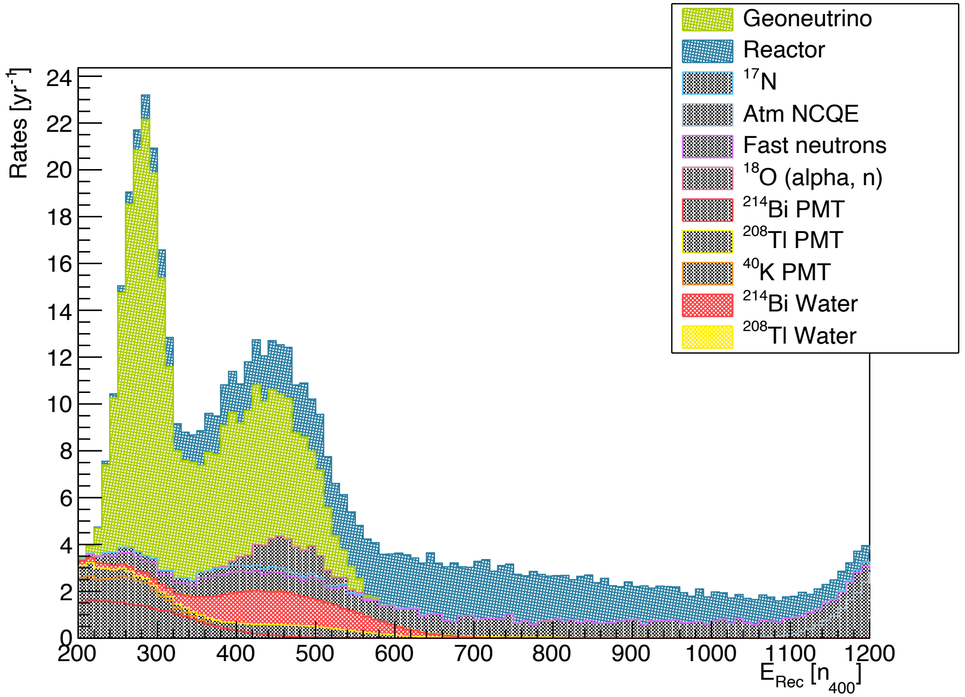
$$^{238}U \rightarrow ^{206}Pb + 8\,\alpha + 6\,e^- + 6\,\bar{\nu} + 51.7\ MeV$$
$$^{232}Th \rightarrow ^{208}Pb + 6\,\alpha + 4\,e^- + 6\,\bar{\nu} + 42.8\ MeV$$
$$^{40}K \rightarrow ^{40}Ca + e^- + \bar{\nu} + 1.32\ MeV$$



Predictions by different models:
Radiogenic heat = 10 – 35 TW

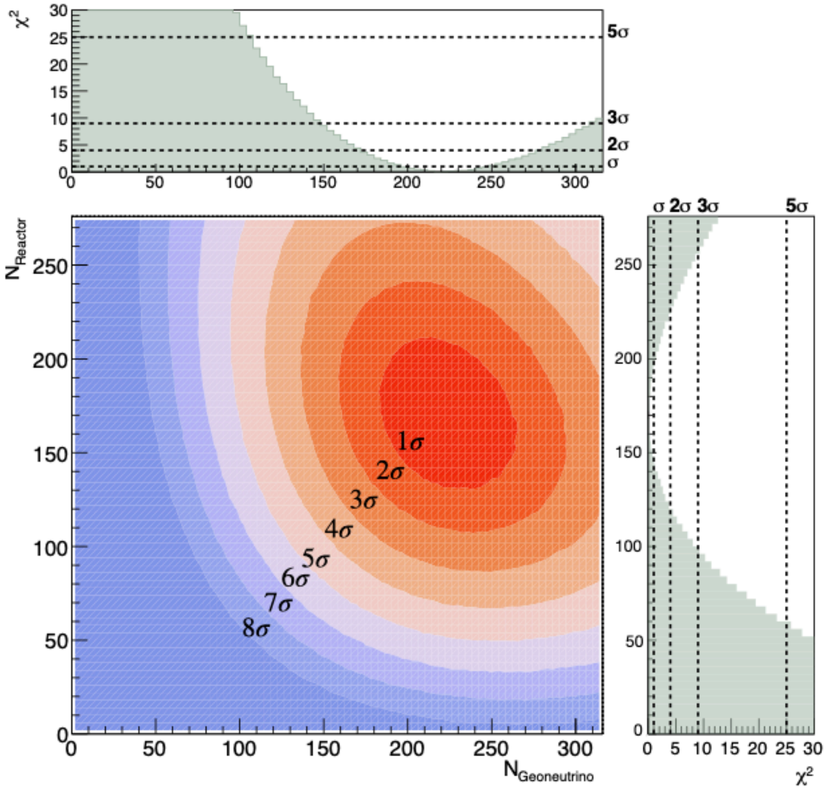


- Currently only two measurements: Borexino (Italy), KamLAND (Japan)

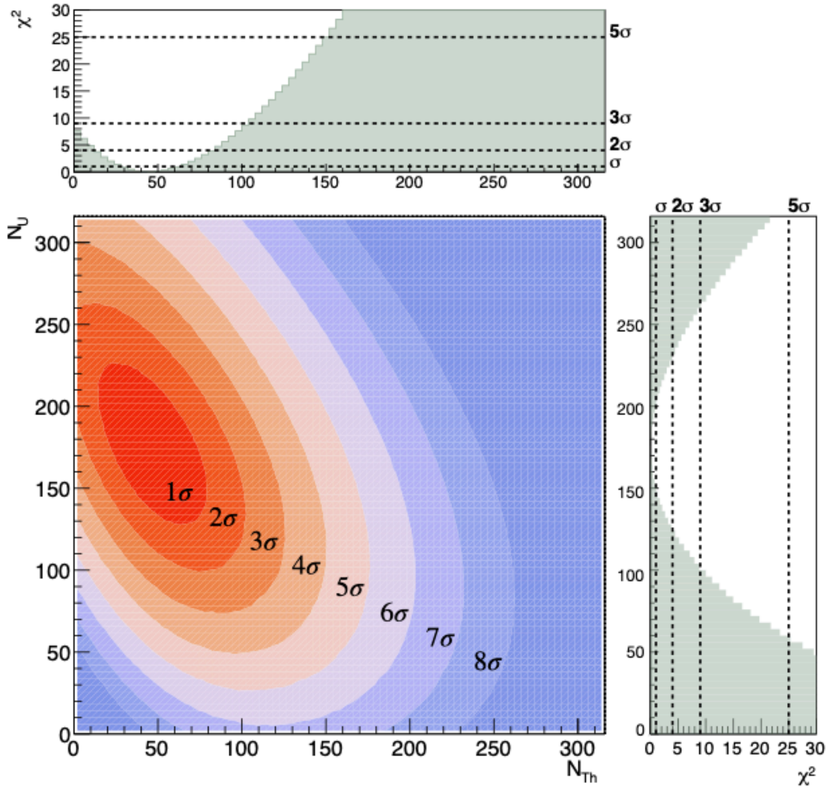


Theia: Geoneutrinos

Geo vs Reactor



U vs Th



- Likelihood fit extracting geoneutrinos rate with 8.6% precision and reactor neutrons with 6.7% precision in just one year
- Extracting U and Th individual rates, and measuring Th/U ratio with 56%-15% precision
- First high statistics measurement in a new geographical location useful to extract mantle contribution

S.Zsoldos, Z. Bagdasarian et al Antineutrino sensitivity at THEIA
https://doi.org/10.48550/arXiv.2204.12278

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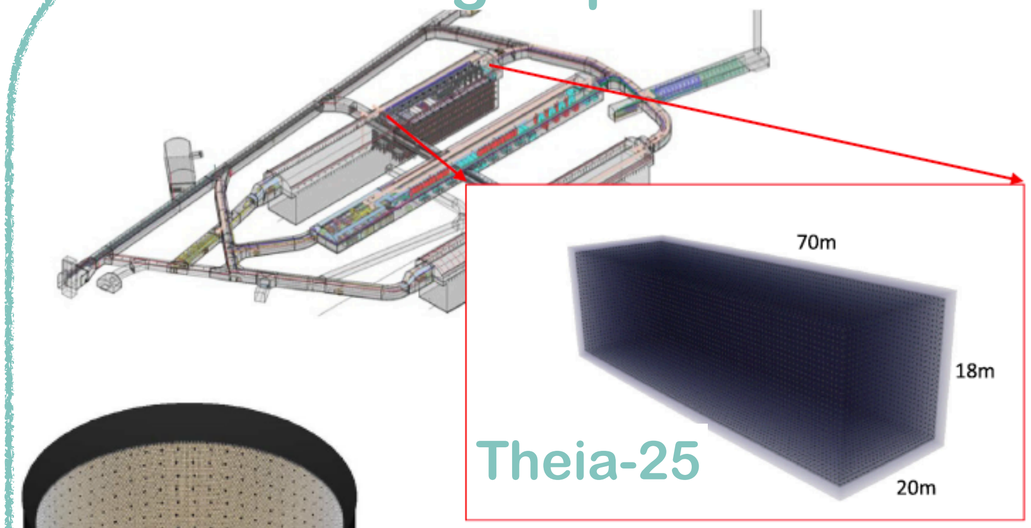

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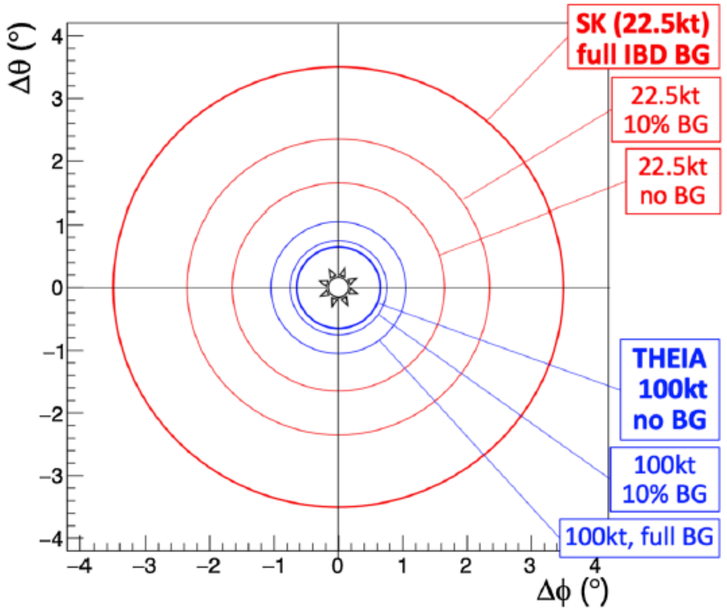
Theia: supernova burst neutrinos

- **dynamics of the core collapse** (neutronization, reheating, proto-neutron star cooling)
- **the properties of the neutrinos themselves** (mass hierarchy, absolute mass scale, collective oscillations)

Only one observed: SN1987A

- Flavor-resolved neutrino spectra
- low energy threshold/good energy resolutions
- Supernova pointing
- Separate ES from IBD events for directionality.



Expected event rates in 100kt 10% WbLS for SN at 10kpc:

Reaction		*Rate*
(IBD)	$\bar{\nu}_e + p \rightarrow n + e^+$	19,800
(ES)	$\nu + e \rightarrow e + \nu$	960
(ν_eO)	$^{16}O(\nu_e, e^-)^{16}F$	340
($\bar{\nu}_e$O)	$^{16}O(\bar{\nu}_e, e^+)^{16}N$	440
(NCO)	$^{16}O(\nu, \nu)^{16}O^*$	1100

- **At LBNF:** the combination of WbLS (THEIA) and liquid argon (DUNE) detectors at the same site -> high-statistics co-detection of neutrinos and antineutrinos.
- Complementarity to JUNO and Hyper-K: opposite side of the Earth -> Earth matter effects
- Pre-supernova neutrinos

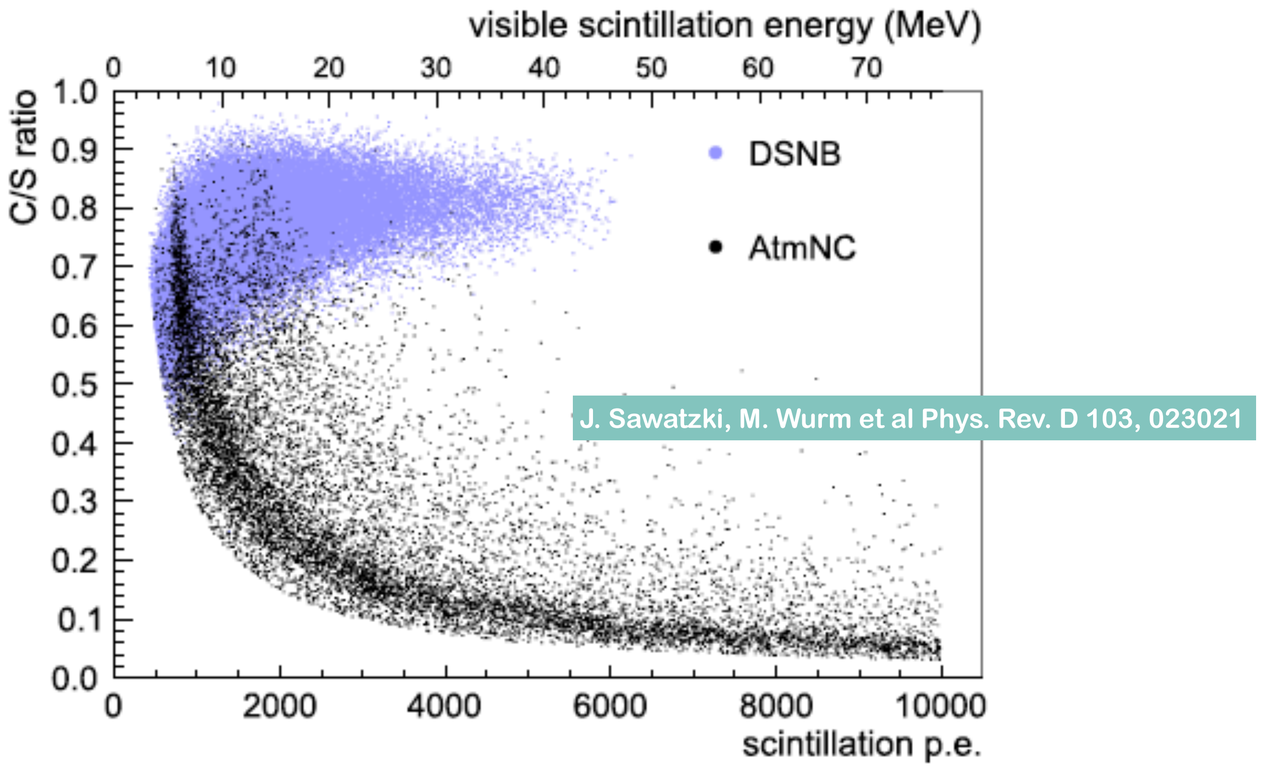
M. Askins, Z.Bagdasarian et al Eur. Phys. J. C 80, 41

Theia: Diffuse supernova neutrino background (DSNB)

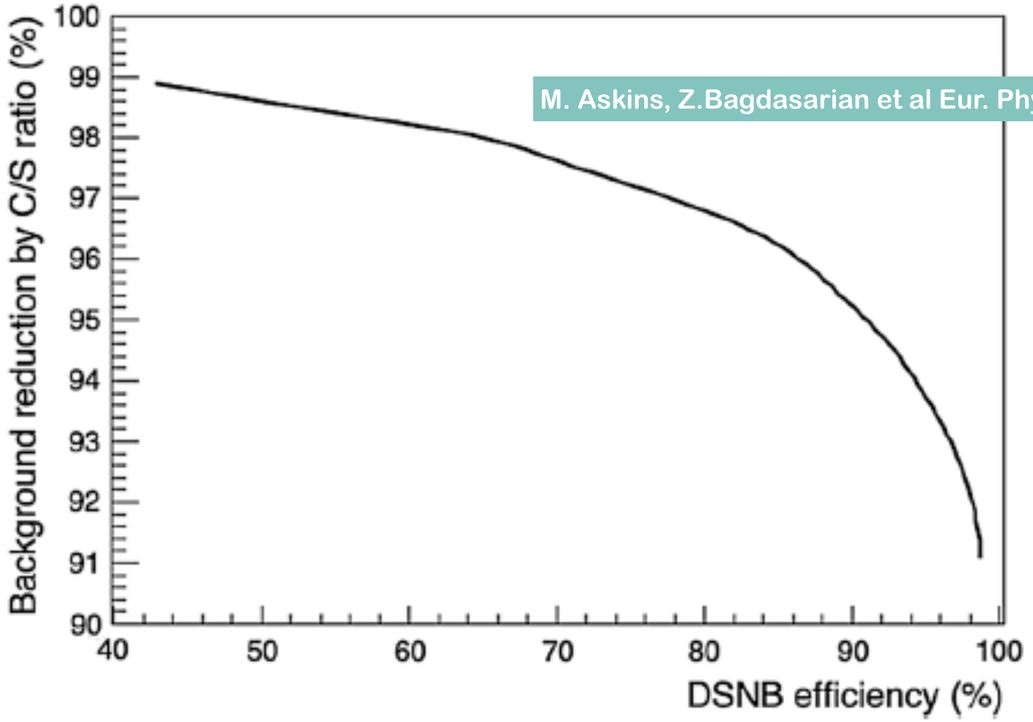
Diffuse, isotropic flux of ν from all SN explosions in the Universe.

Not yet experimentally observed

- **Cherenkov/Scintillation (C/S) ratio** gives a powerful handle to discriminate atmospheric neutral current background signals;
- substantial increase in event statistics when added to Super-K and JUNO;
- 5σ discovery (125 kton-year): ~8 years (Theia-25) or ~2 years (Theia-100)



J. Sawatzki, M. Wurm et al Phys. Rev. D 103, 023021



M. Askins, Z.Bagdasarian et al Eur. Phys. J. C 80, 416

Conclusions

- Broad low energy program to complement the high-energy program (see next talk by Leon)
- Directionality in solar neutrino analysis
- Likelihood fit extracting geoneutrinos rate with 8.6% precision and reactor neutrons with 6.7% precision in just one year. Extracting U and Th individual rates, and measuring Th/U ratio with 56%-15% precision
- High-statistics and reach physics potential for supernova burst neutrinos
- High-statisctics diffuse supernova neutrino background (currently not observed)

THEIA Collaboration

Canada
Alberta
Laurentian
Queens
SNOLAB
Toronto

China
Tsinghua

Finland
Jyvaskyla

Germany
Aachen
Dresden
Hamburg
Jülich
Mainz
TU Munich
Tübingen

Italy
SISSA/INFN

Korea
CUP

Portugal
LIP
Lisbon

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