Astrophysical neutrinos

An experimental overview

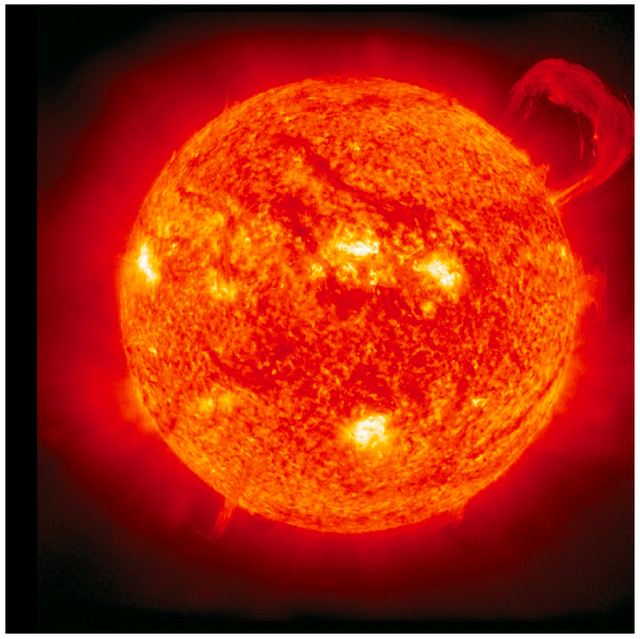
Gabriel D. Orebi Gann
UC Berkeley & LBNL
CosSURF conference
12th May, 2022

Overview

- Physics motivation
- Overview of experimental approaches
  - Water Cherenkov
  - Liquid scintillator
  - (See later talks for LAr, LXe)
- Prospects

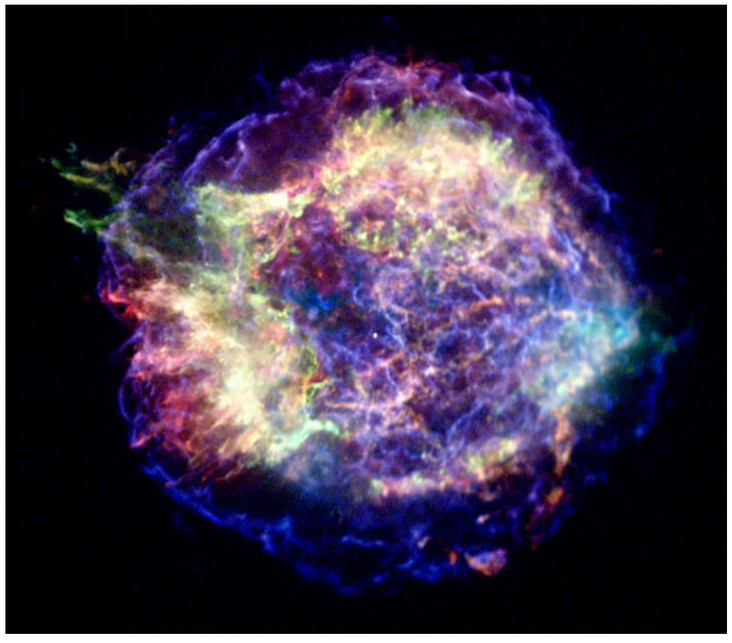
Physics motivation

See excellent talk by Michael Smy!



- Solar neutrinos
  - Probe interaction of ν with matter
  - Study stellar astrophysics e.g. metallicity, T
  - Search for new physics

- Supernova neutrinos
  - Understand explosion mechanism
  - Probe neutrino flavour physics
  - Early warning for astronomers



Why is it Hard?

Not to scale

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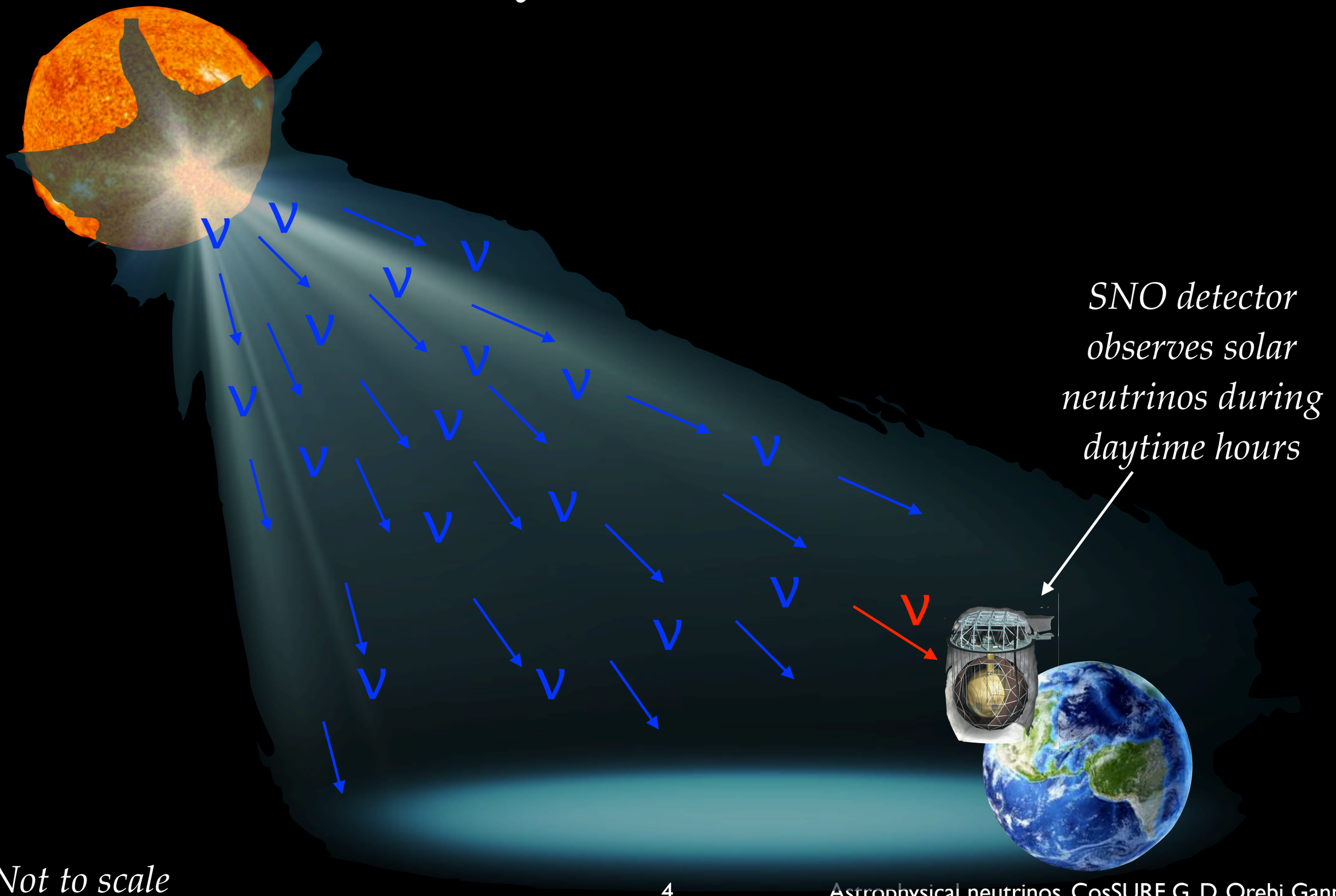

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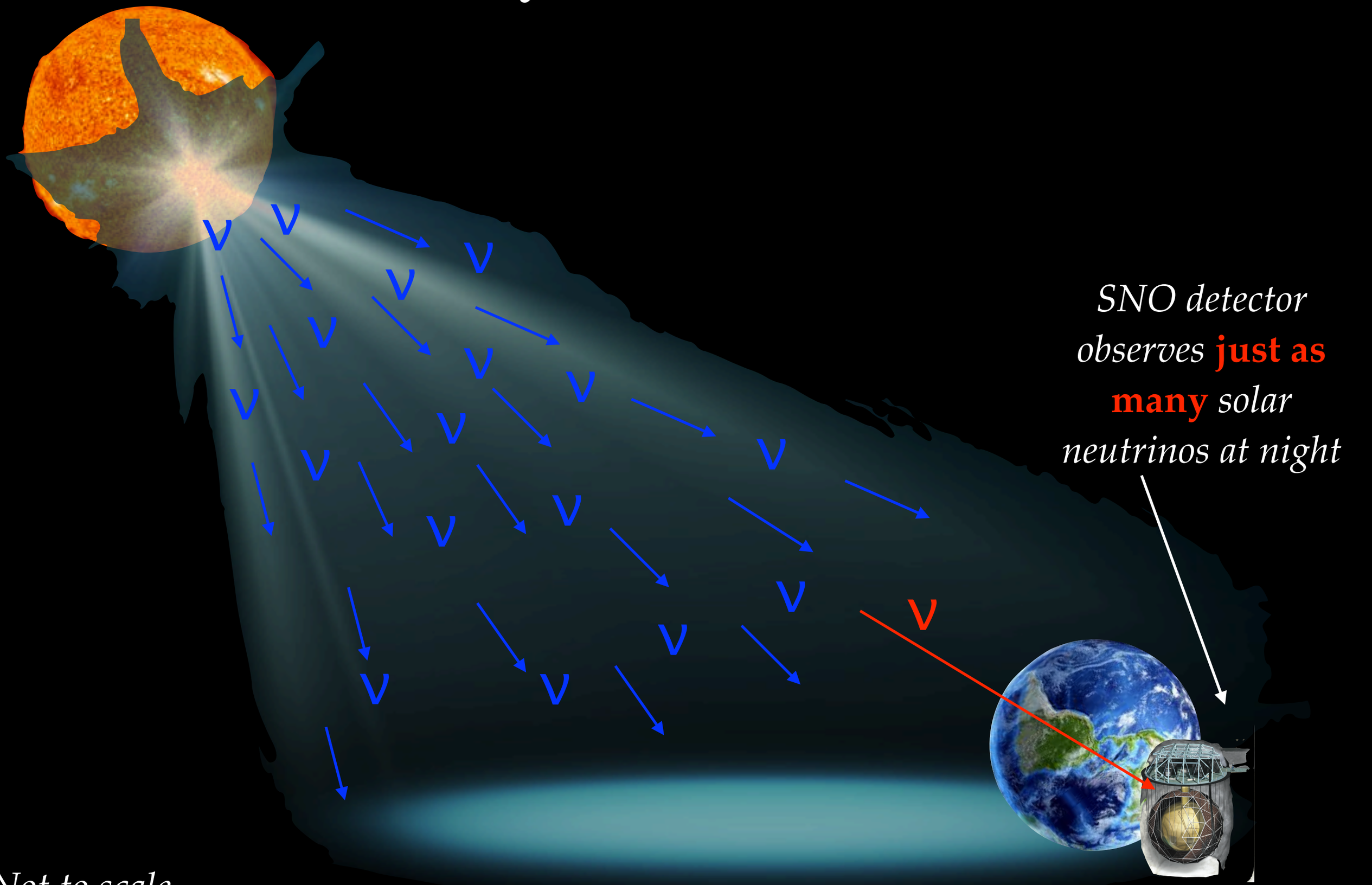
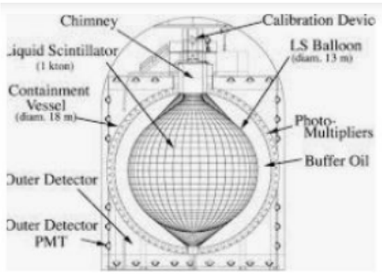
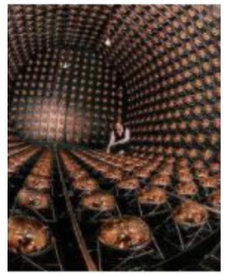
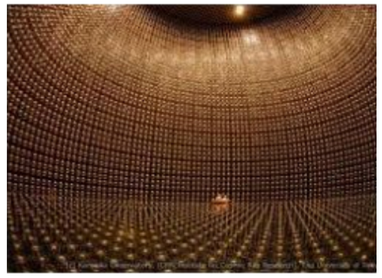
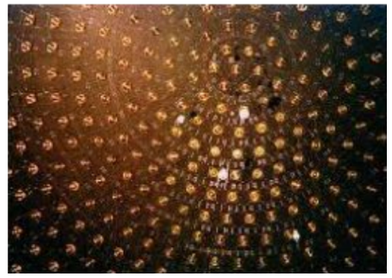


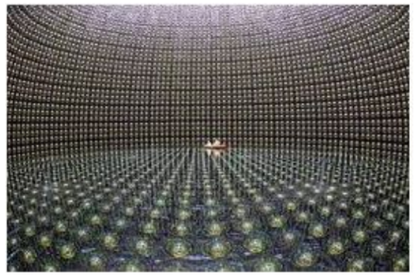
Experimental approaches

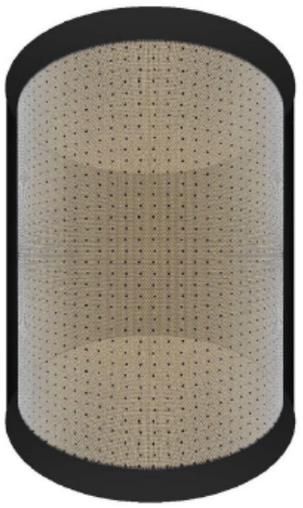




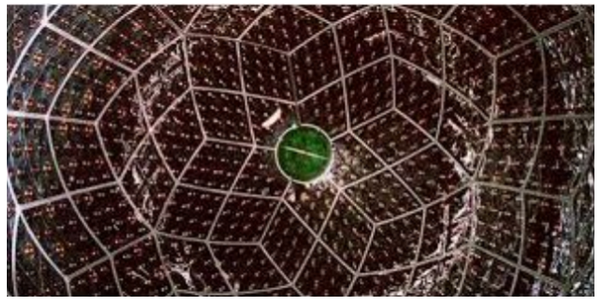


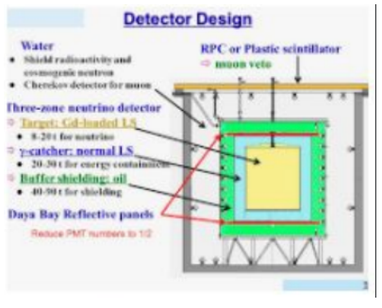


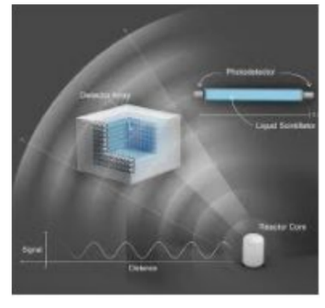




- Water Cherenkov detectors
- Liquid scintillator detectors
- "Hybrid" detection
- Noble liquid detectors — covered in later talks
- Solid state detectors — CEvNS with low threshold
- Prospects







Sudbury Neutrino Observatory

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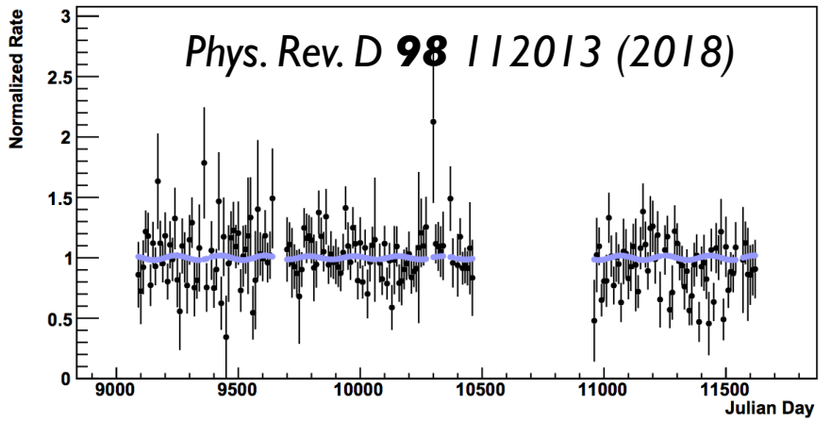
- Search for Lorentz violating effects (preferred direction)
- New / improved constraints on 38 / 16 model parameters



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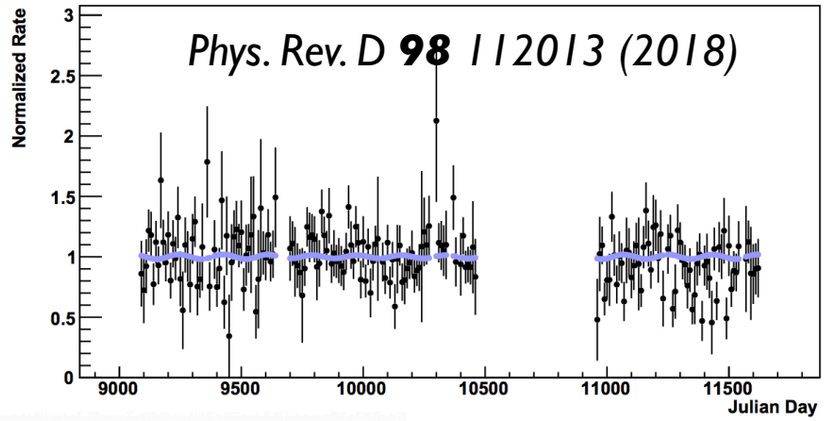
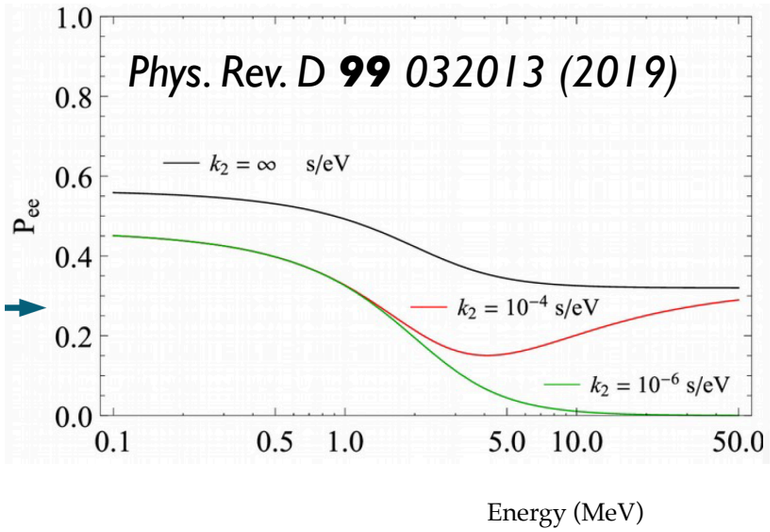


- Search for neutrino decay
- Energy-dependent disappearance
- New limit on lifetime
  k_2 (= τ_2/m_2) > 1.92 x 10-3 s/eV (90% CL)



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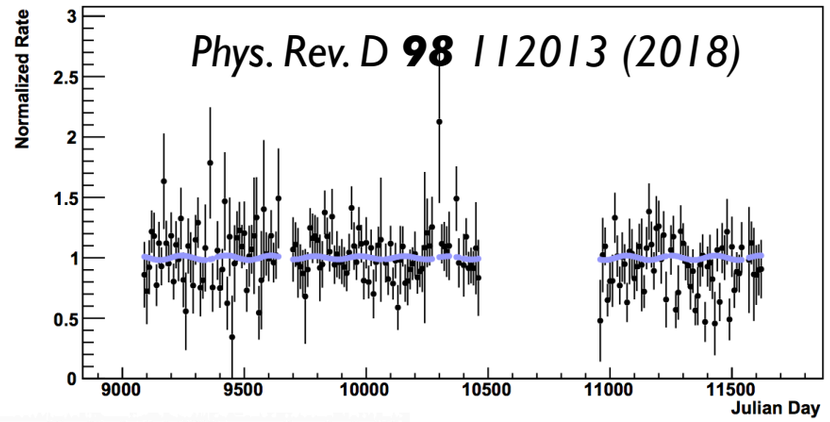

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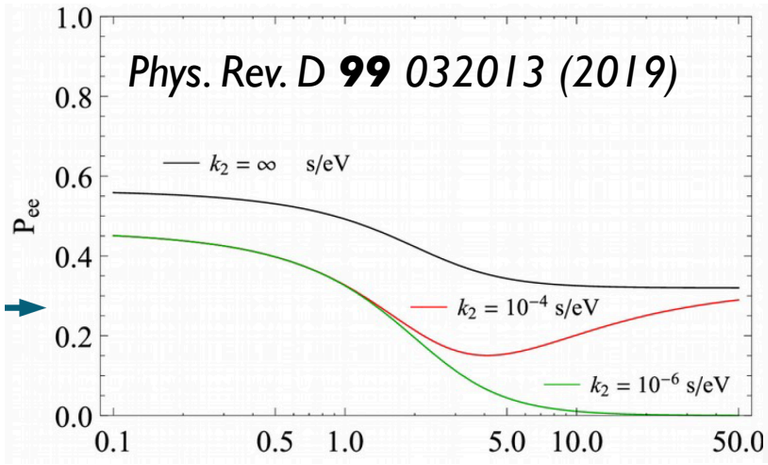


- Search for hep & DSNB neutrinos
- Final undetected solar ν flux
- Probe "glow" from past core-collapse SNe

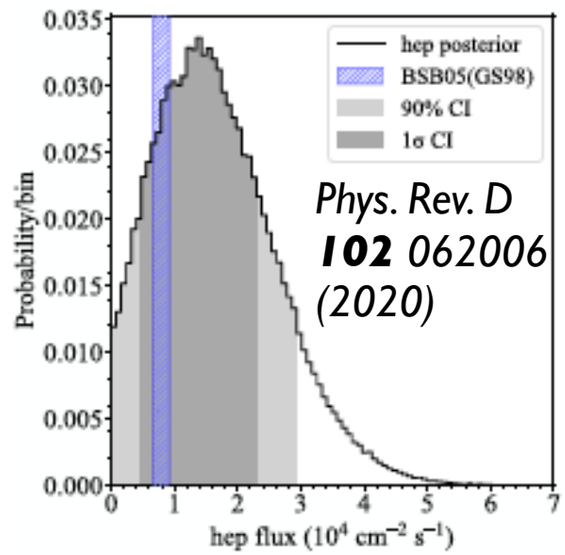
Bayesian one-sided 90% CI:

$\Phi_{DSNB}^{*} < 19$ cm^{-2} s^{-1} ($22.9 < E_\nu < 36.9$ MeV)

(*sensitivity ~ 30 cm^{-2} s^{-1})

Bayesian 90% CI:

$\Phi_{hep} < 30 \times 10^3$ cm^{-2} s^{-1}



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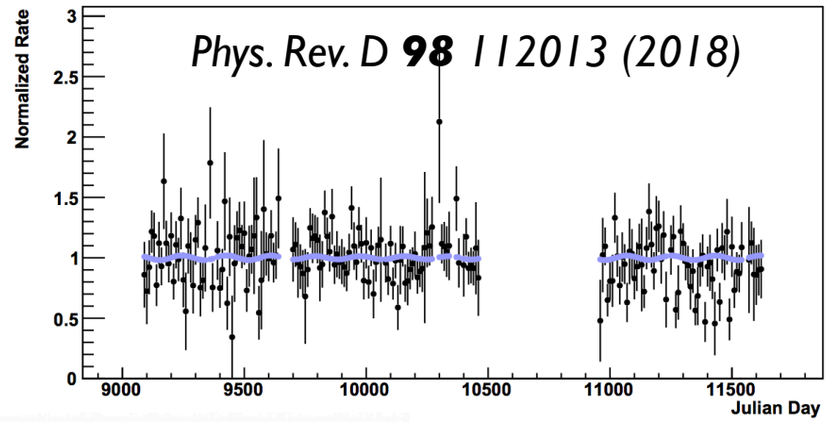

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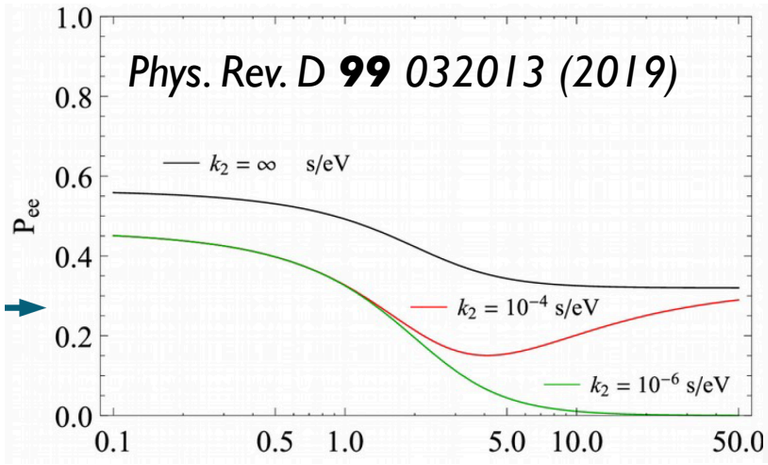

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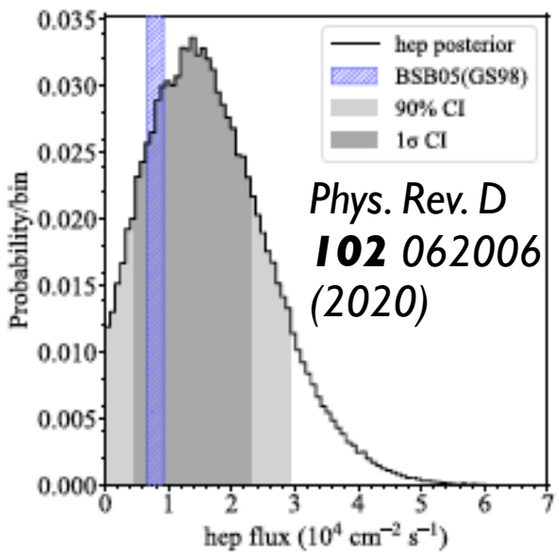
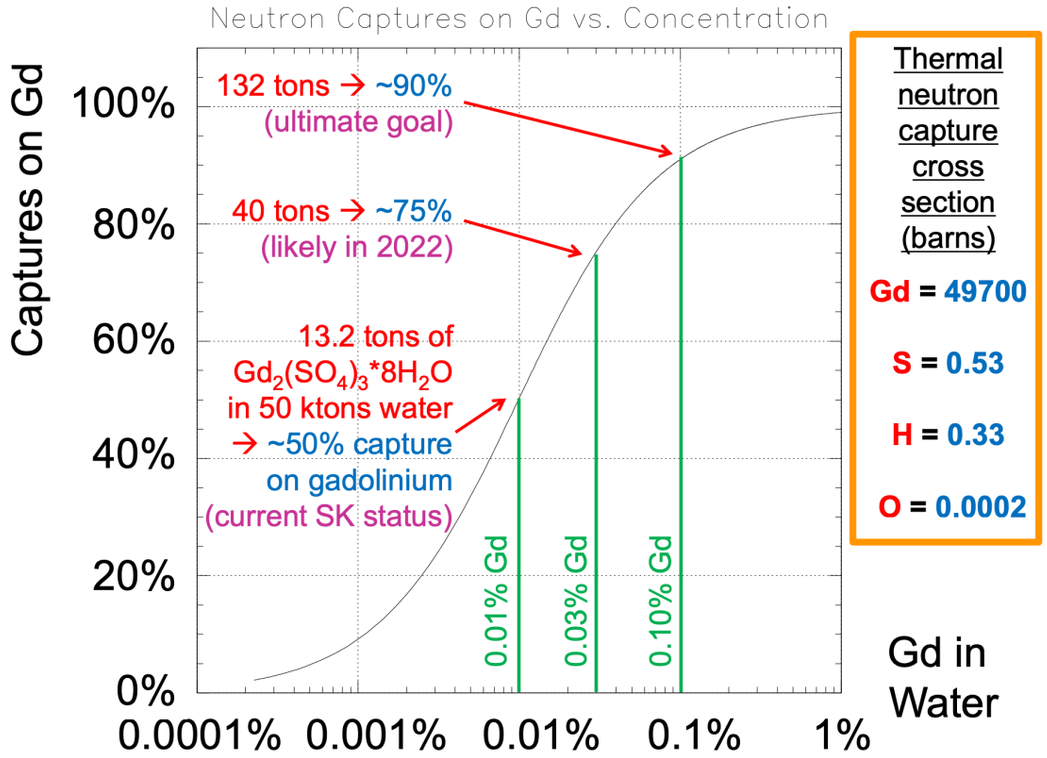


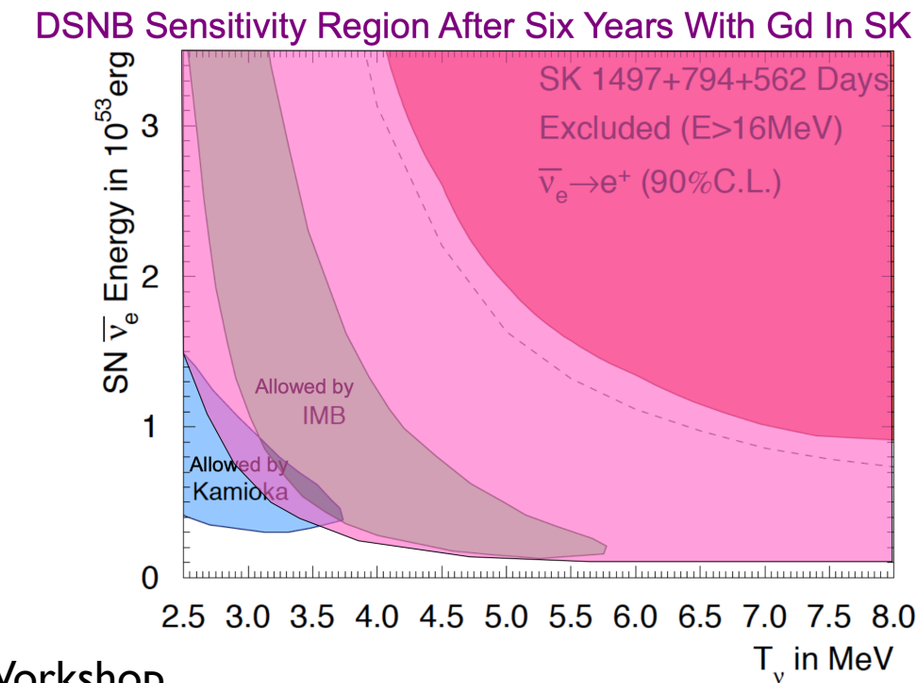
- Measurements of n production from μ and atm ν

Phys. Rev. D ***99*** *112007 (2019), Phys. Rev. D* ***100*** *112005 (2019)*

Super-Kamiokande (+Gd)

- Super-K is the first large detector ever to be filled with Gd-H2O (0.021% $Gd_2(SO_4)_3$ ~0.01% Gd)
- Enhance neutron capture efficiency, improve sensitivity to low-energy antineutrinos
- Transparency observed to be as good as H2O phase (!)
- Next phase (0.03%Gd) should allow the first detection of DSNB
- Ongoing measurements of low-energy solar neutrinos

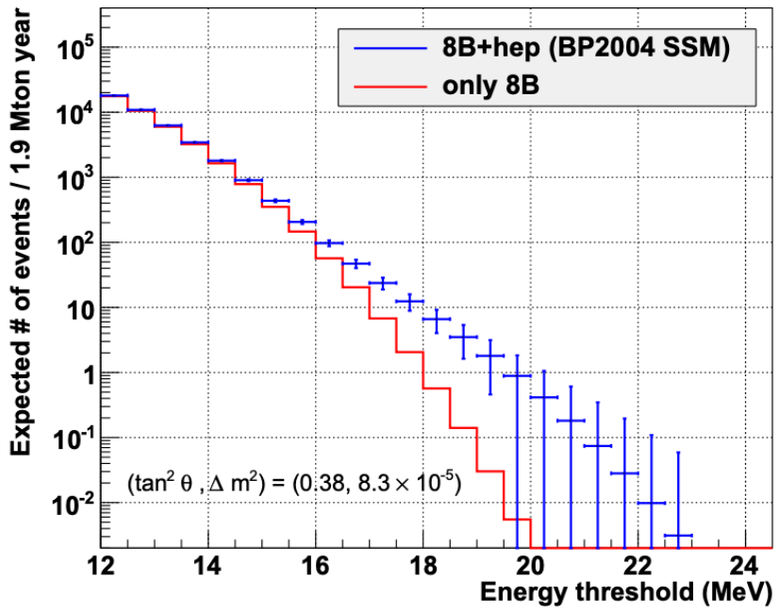




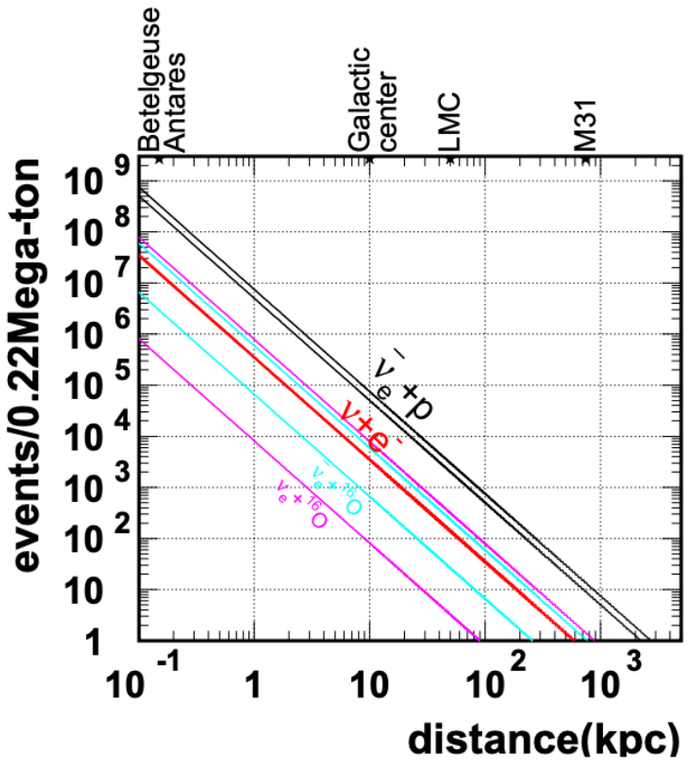
https://arxiv.org/pdf/2109.00360.pdf; M.Vagins Supernova and Early Universe Workshop

Hyper-Kamiokande

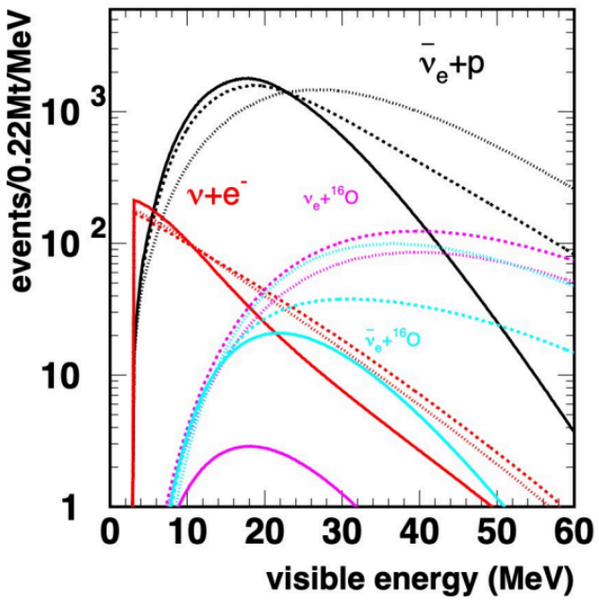
- >200 kton, 40% coverage
- 4 (8)σ sensitivity to day/night effect in 10 years for values currently predicted by reactor (solar) experiments
- 8B spectrum, hep neutrino observation
- Supernova sensitivity primarily via electron antineutrino detection (IBD)
- Highly complementary to DUNE
- Sensitive to time profile, energy spectrum —> supernova physics and particle physics



Solid, dashed, and dotted curves correspond to no oscillation, N.H., and I.H., respectively

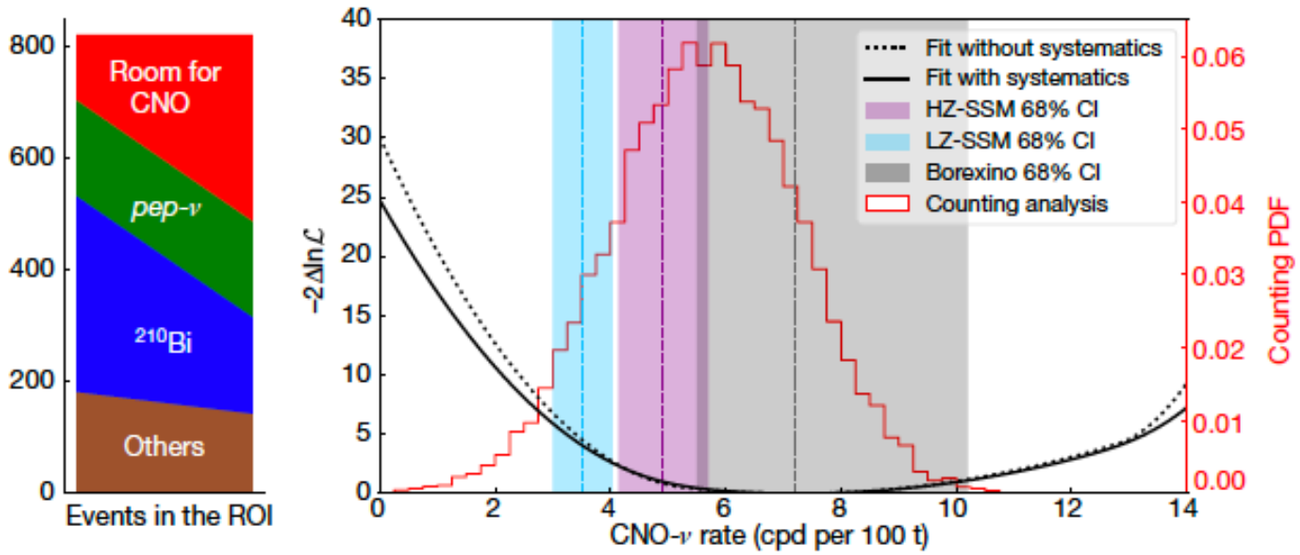


HyperK:



https://arxiv.org/abs/1805.04163

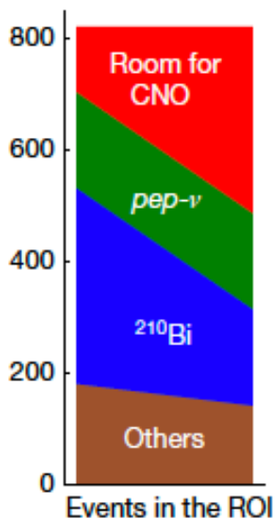
Borexino

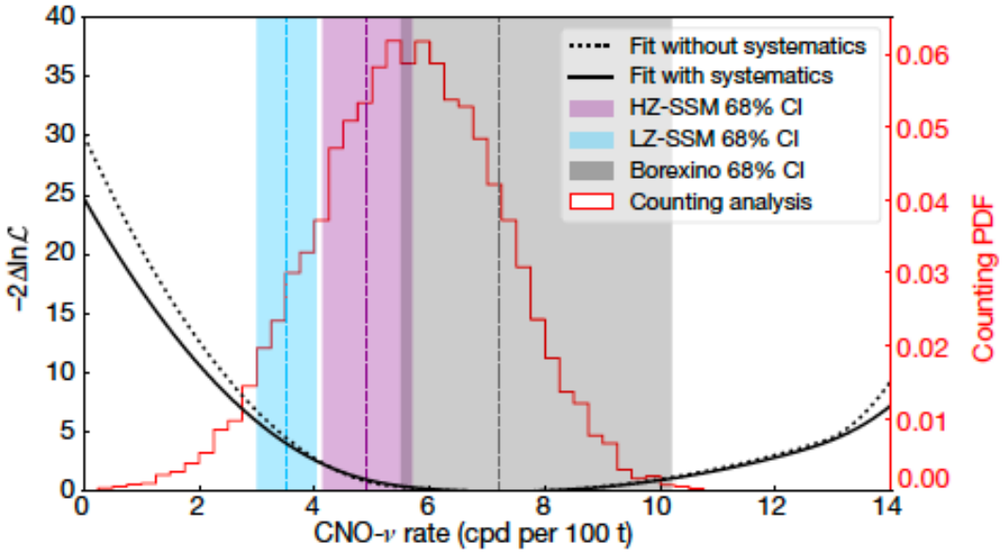


Nature volume 587, pages 577–582 (2020), Phys.Rev.Lett. 128 (2022) 9, 091803, Phys.Rev.D 105 (2022) 5, 052002

Borexino

- First measurement of CNO ν flux!
  - Counting analysis and spectral fit
  - Astonishingly low levels of bkg
  - ^{232}Th and ^{238}U ~ 10^{-19}g/g
  - ^{210}Bi events ≤11.5 ± 1.3 cpd/100t
  - CNO rate of 7.2 $^{+3}_{-1.7}$ cpd/100t





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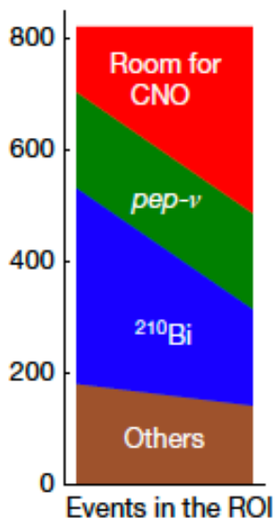
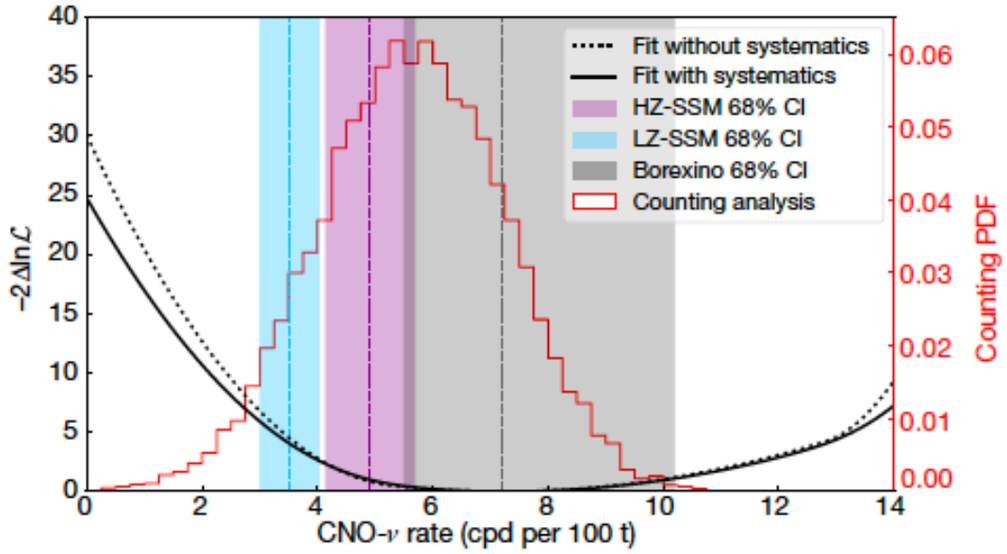
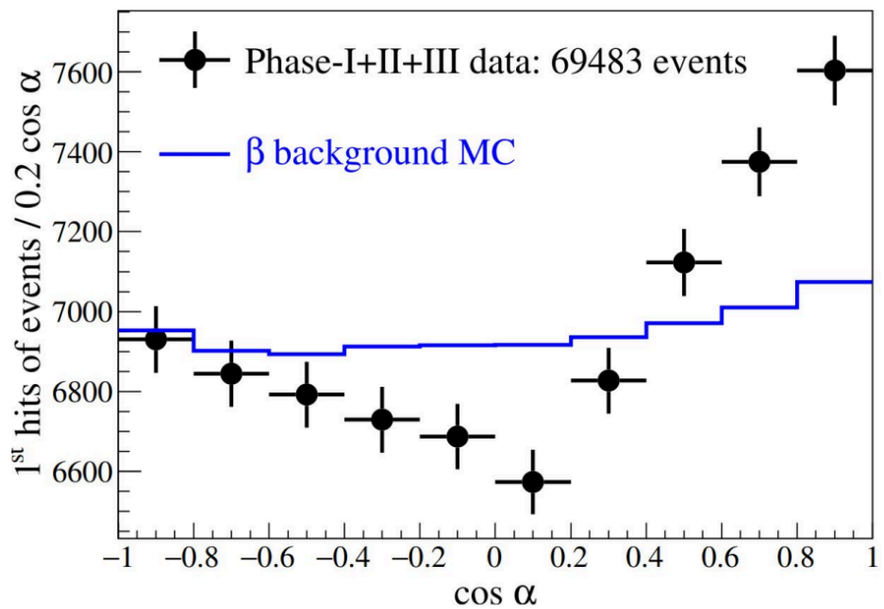




- Integrated directionality :
  - consider earliest photons in the event
  - take angle between early photons and solar direction
- Measurement of primarily 7Be ν demonstrates sub-MeV directionality, statistically across the data set



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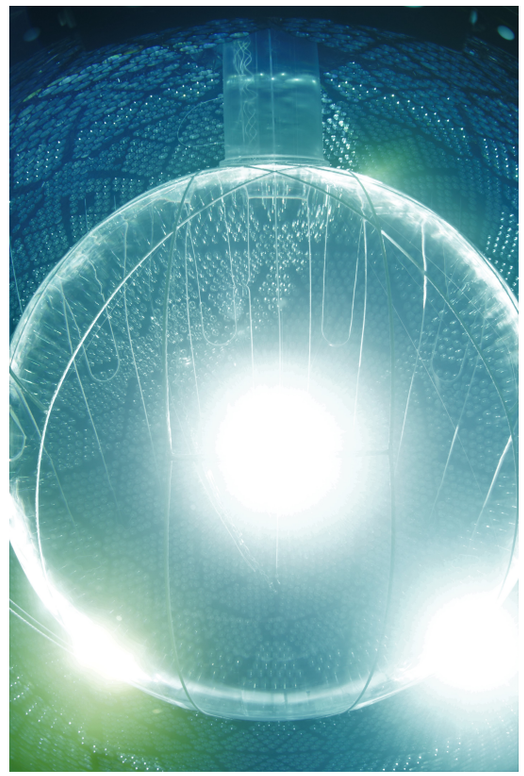
SNO+

See T. Kroupova talk in next session

- LS fill complete, end of March, 2021 (780kg LAB+PPO); PPO top-up complete
- Largest, deepest operating LS detector
- NLDBD target backgrounds achieved!
- Broad ongoing physics program
  - n-p capture in H2O Phys. Rev. C 102 014002 (2020)
  - 8B solar ν flux Phys. Rev. D **99** 012012 (2019)
  - Invisible modes of nucleon decay Phys. Rev. D **99** 032008 (2019)



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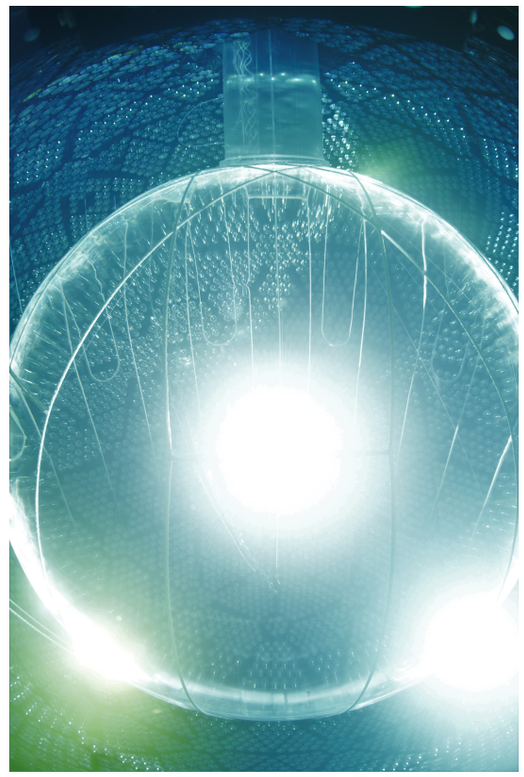
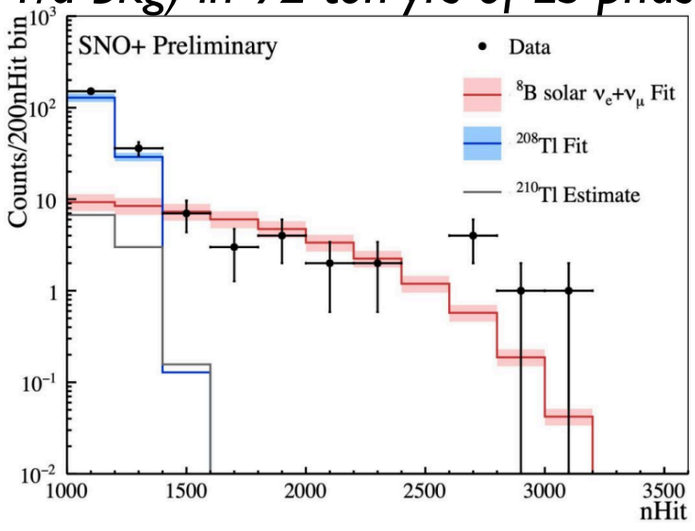


8B flux measurement (L fit for sig, r/a bkg) in 92 ton-yrs of LS phase



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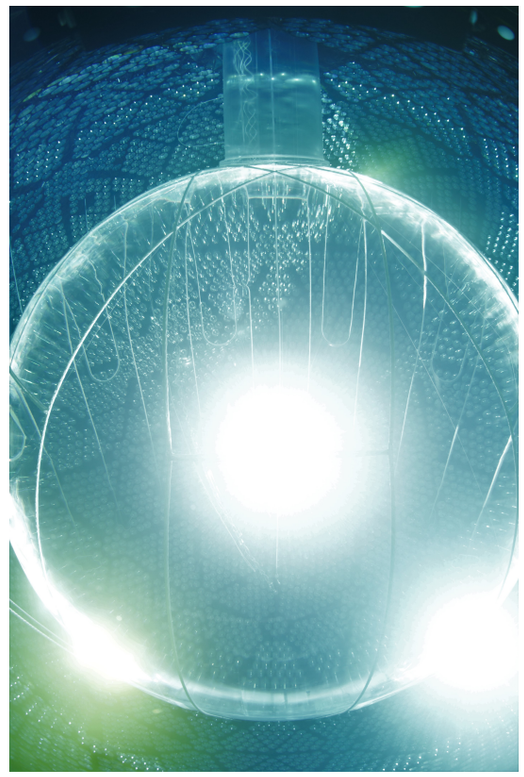

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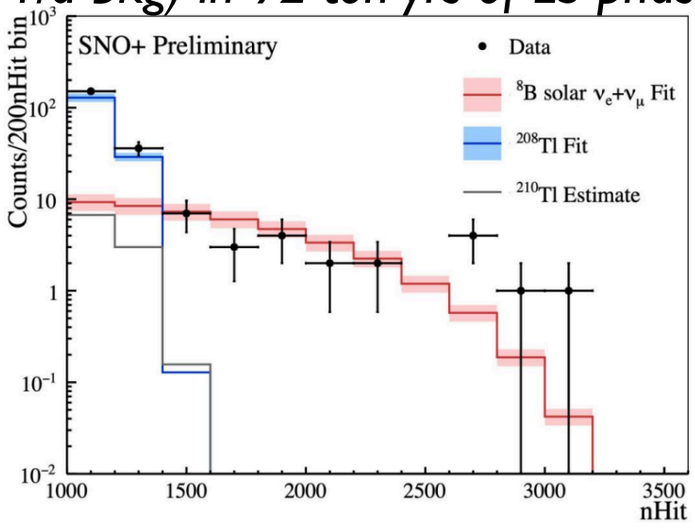
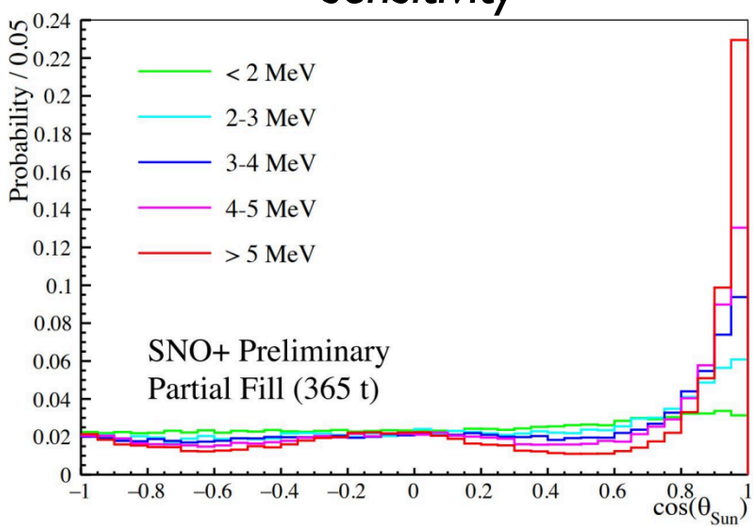


MC for event-by-event directional sensitivity



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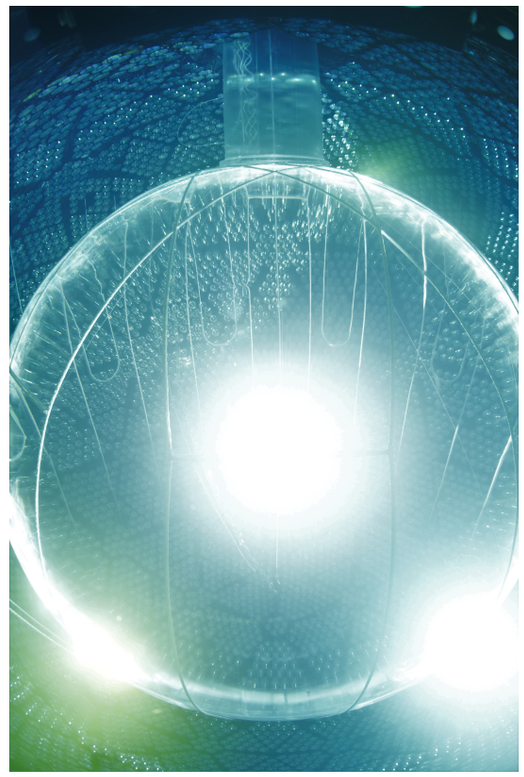

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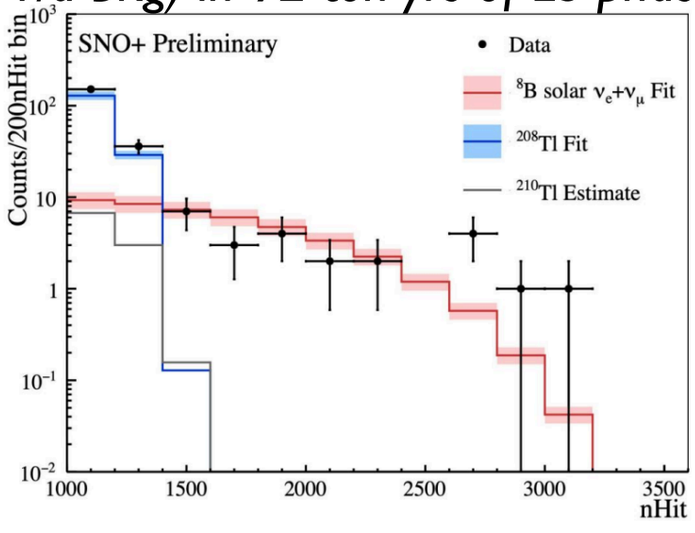

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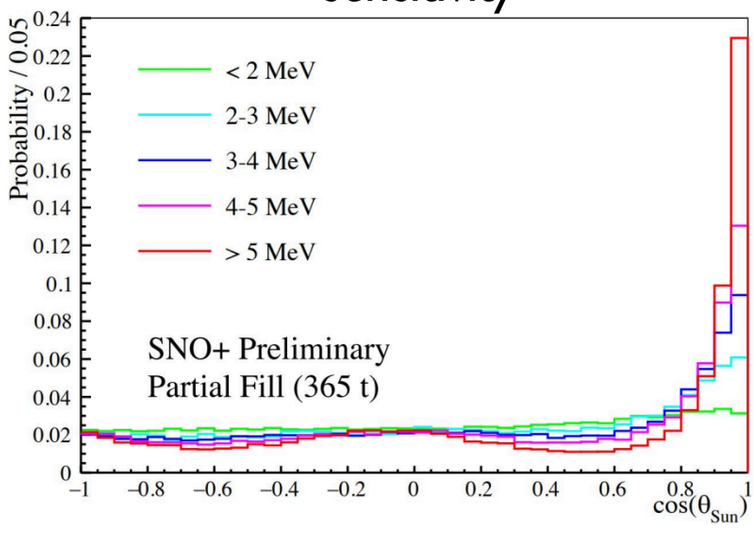
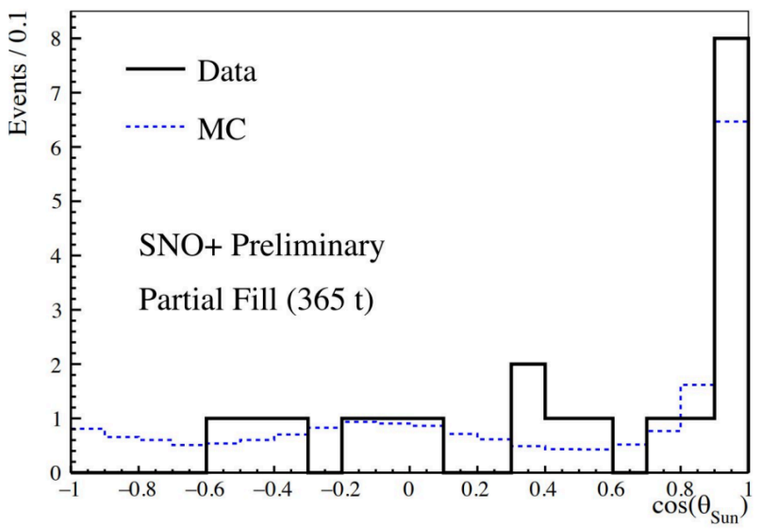
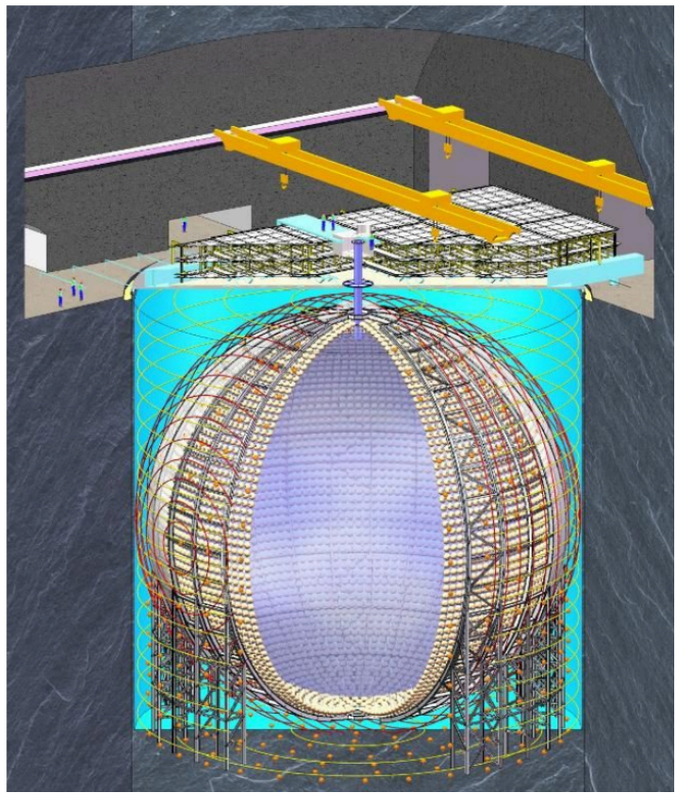


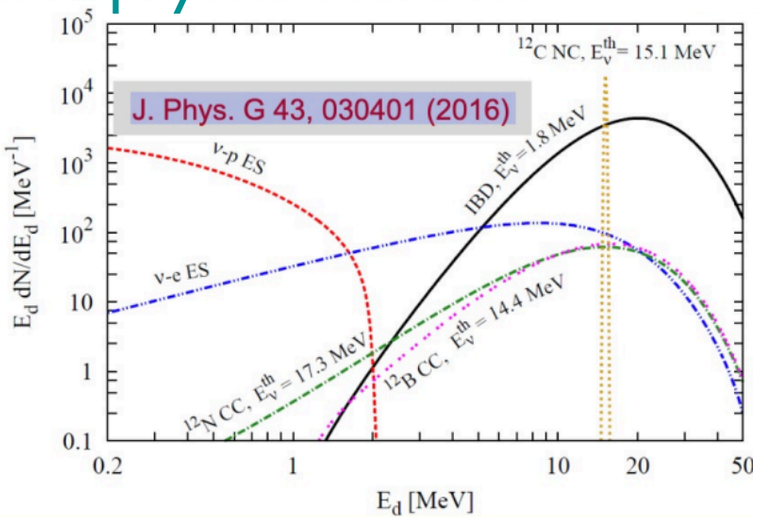
Measurement of directionality for 8B neutrinos >~ 5MeV

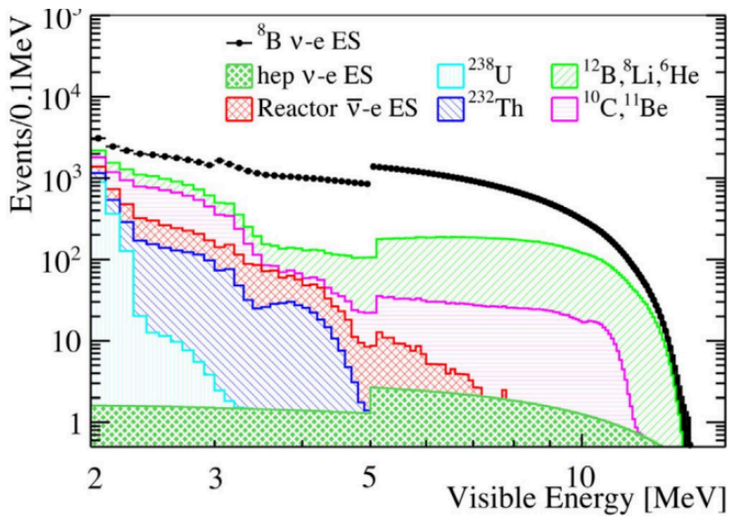


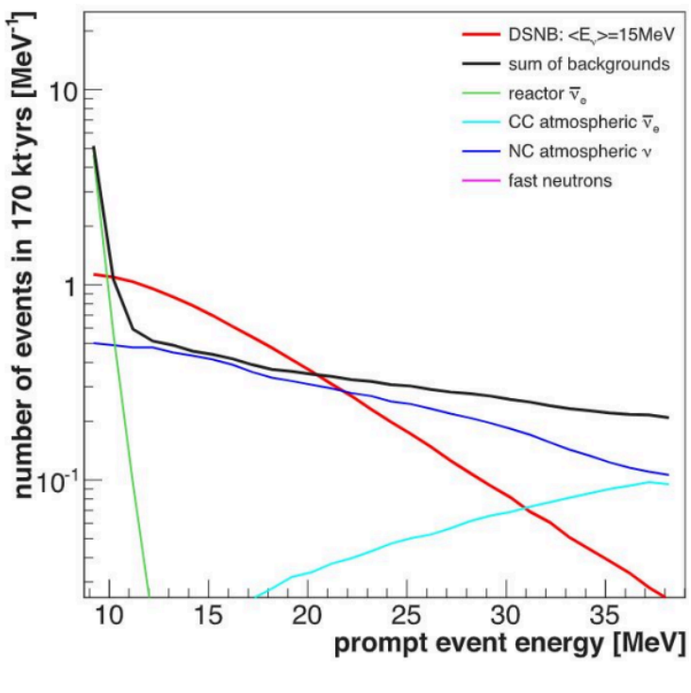
JUNO

- 20 kton, 3% / MeV resolution
- 0.7 km overburden (Guangdong, China)
- Due to complete construction this year
- Will be the largest LS to-date, with world-leading sensitivity to several oscillation parameters and physics searches
- 3σ for DSNB in 10 years
- Supernova sensitivity via IBD
- 2-MeV t/h:
  sensitivity to probe transition region via low-energy ^{8}B ν
- 2-3σ sensitivity to day/night
- Precision measurement of ΔM^2_{21}









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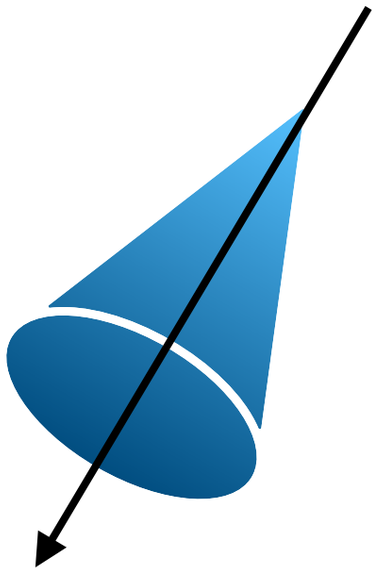
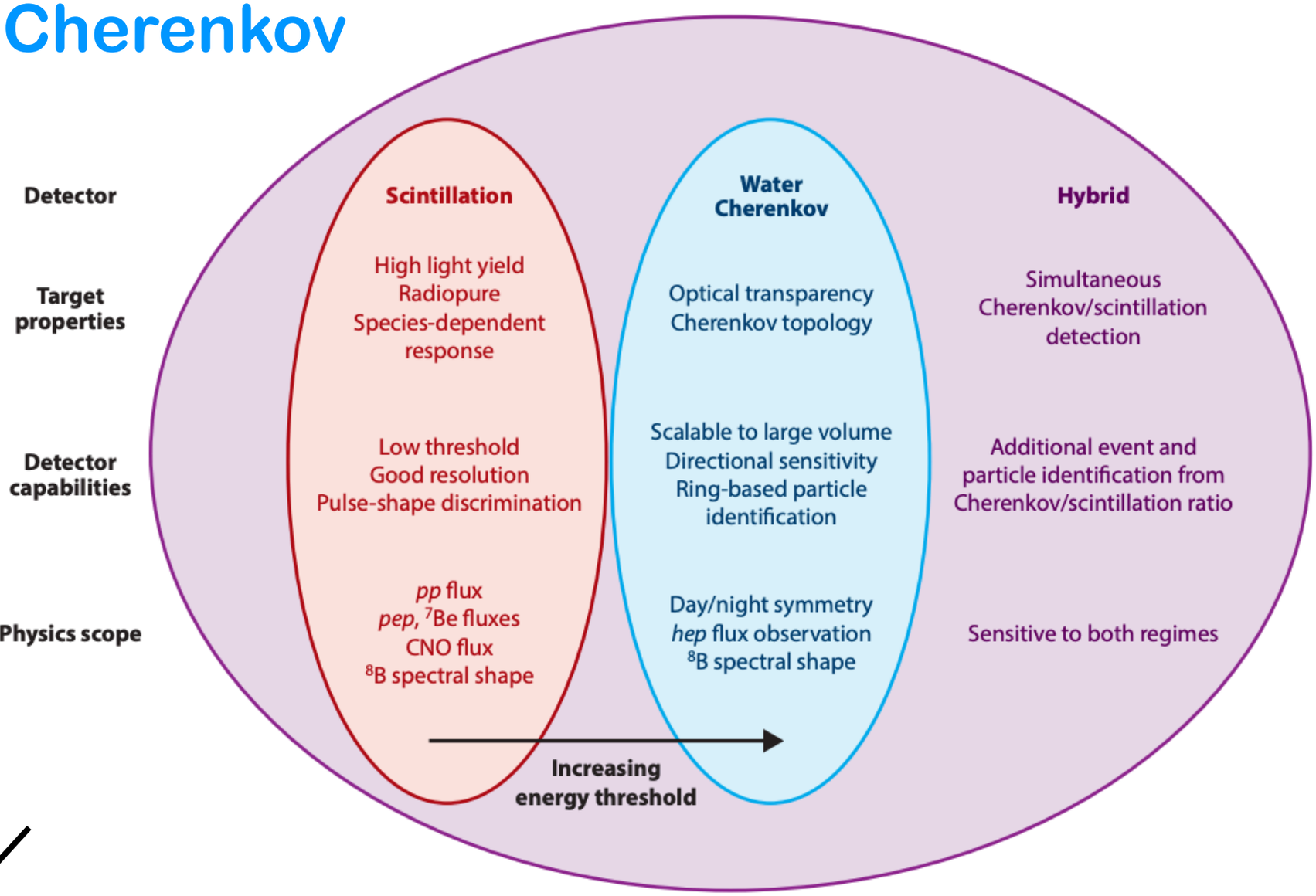
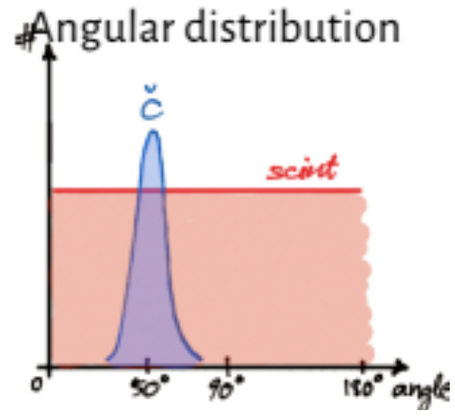
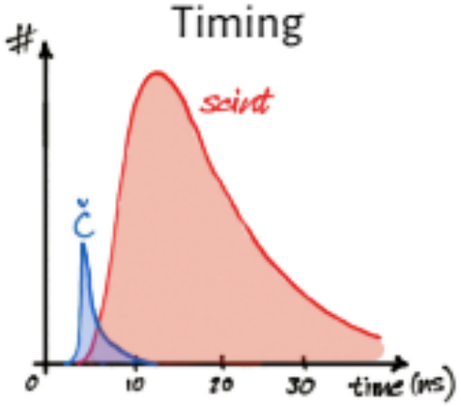
Hybrid Detectors

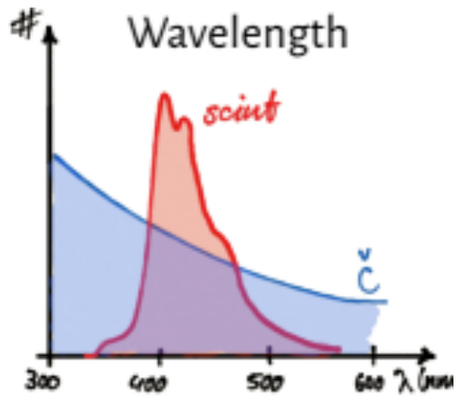
Cherenkov

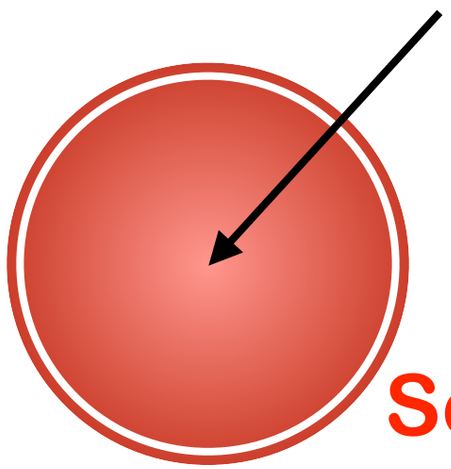








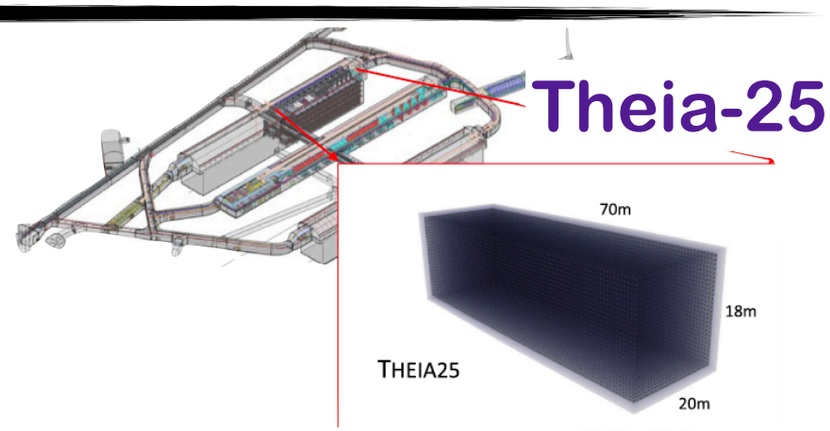




Scintillation

See L. Pickard talk in Module of opportunity session (Weds pm) for details of active ongoing international R&D program

THEIA



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Eur. Phys. J. C 80, 416 (2020);
Eur. Phys. J. C (2018) 78: 435;
Phys. Rev. D 103, 052004 (2021)

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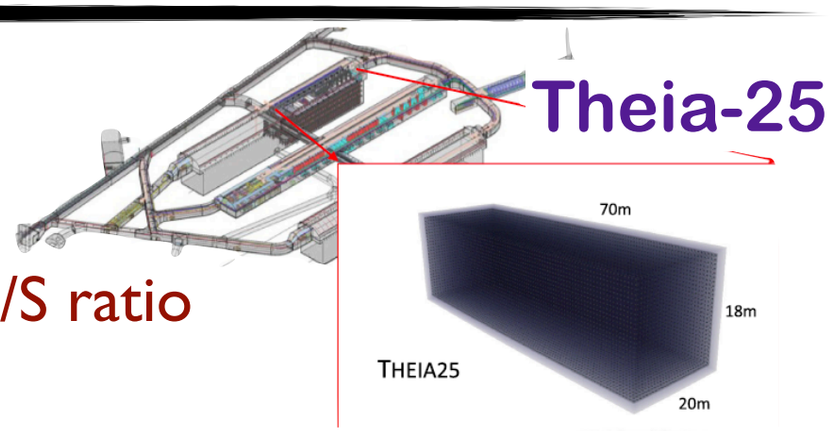

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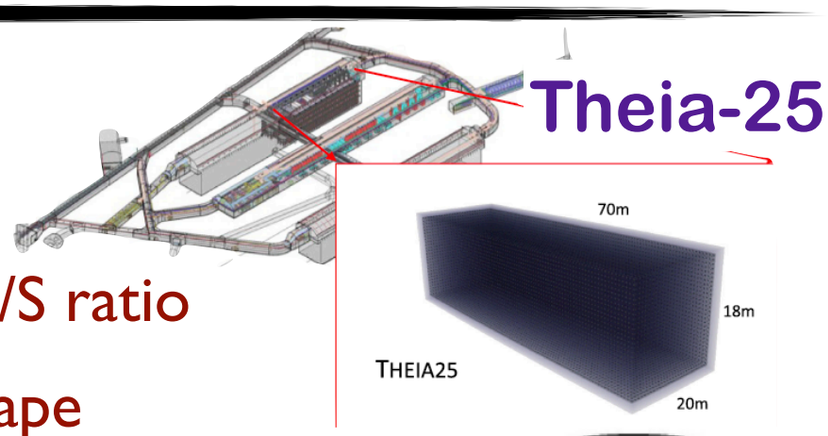

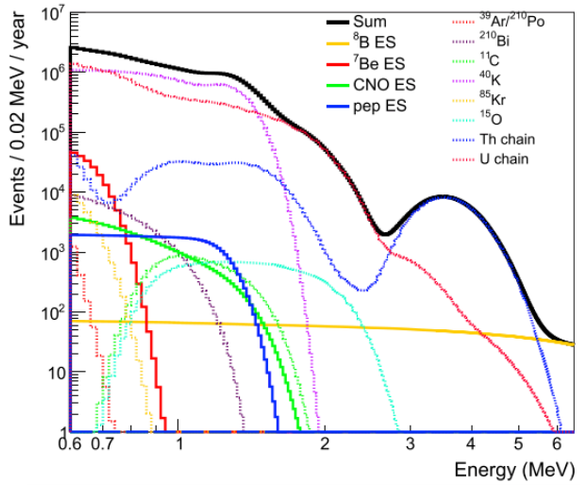

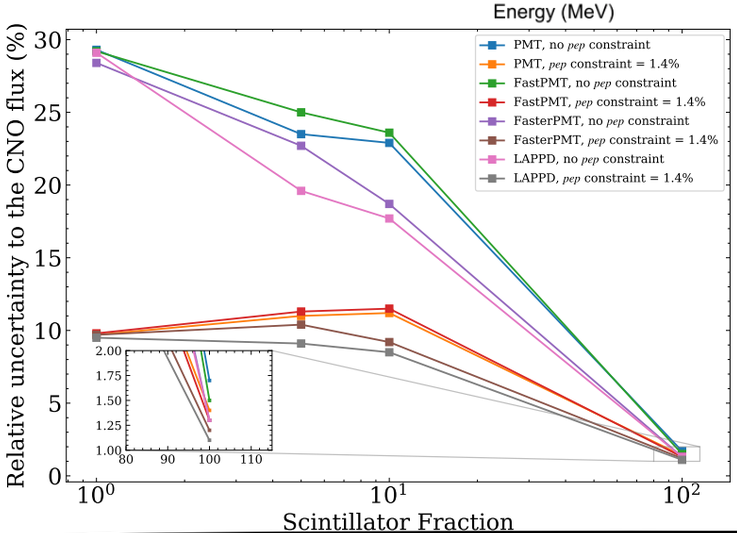

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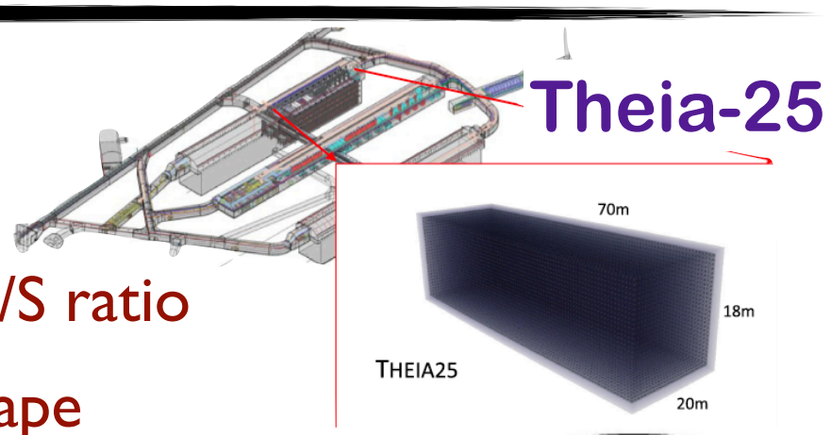

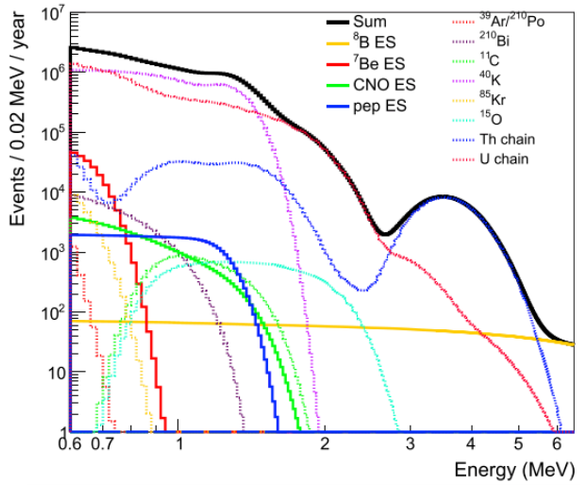

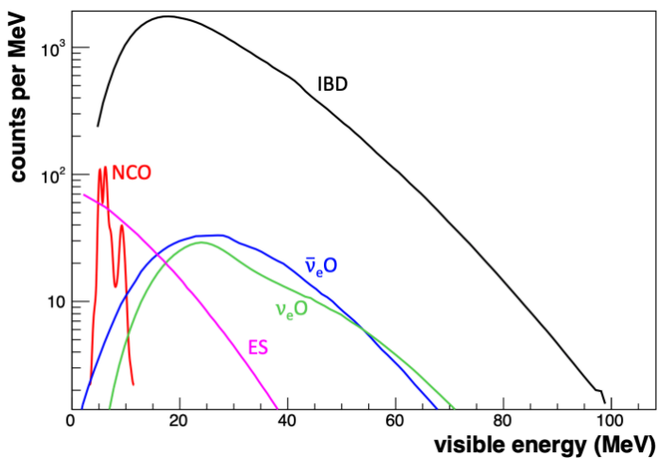

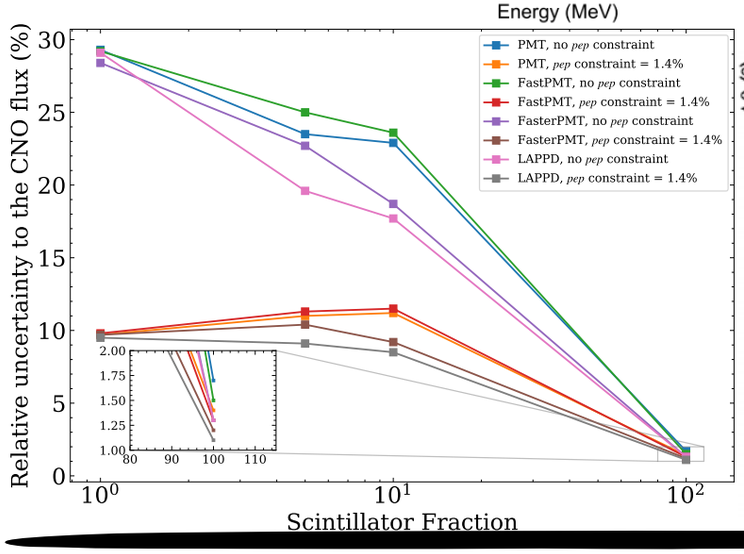

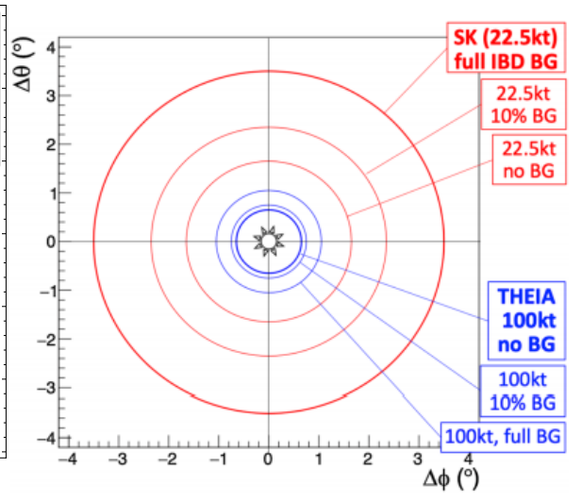

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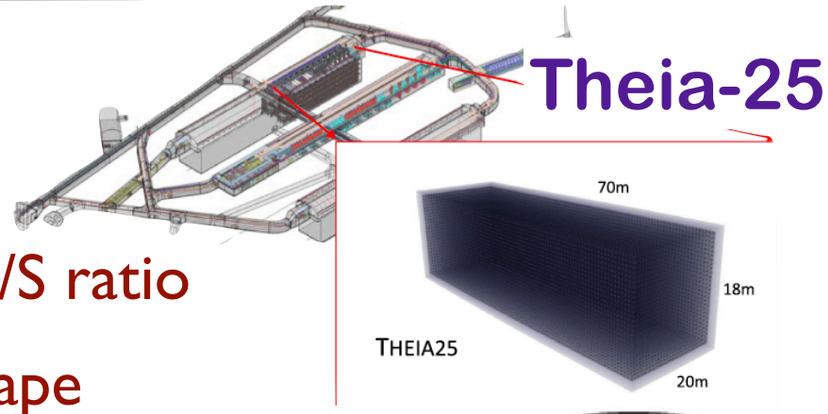

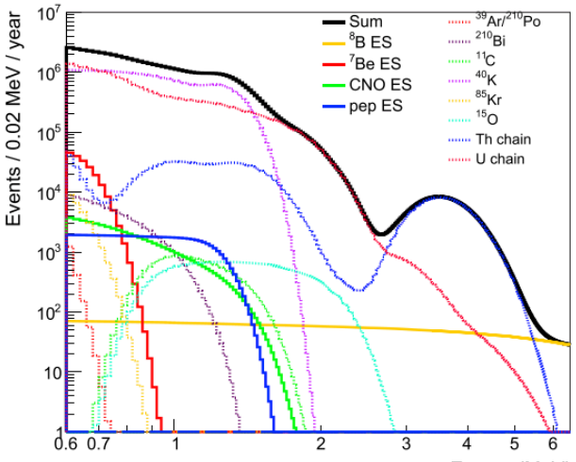

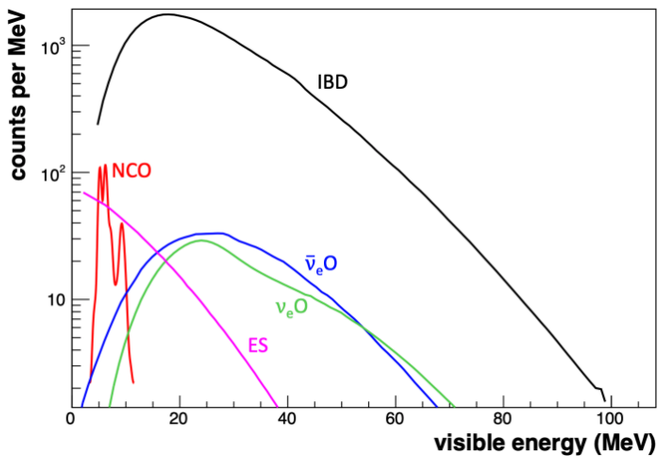

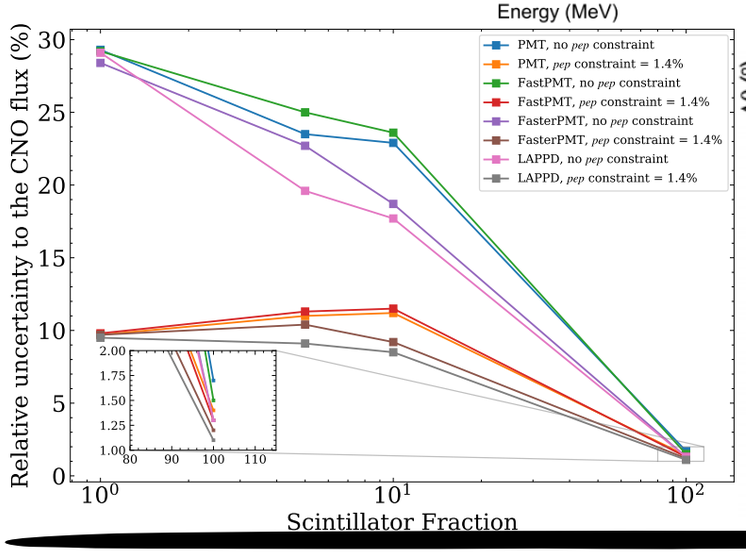

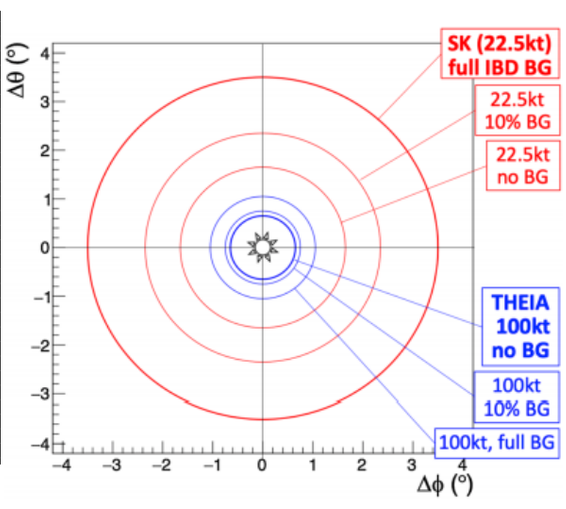

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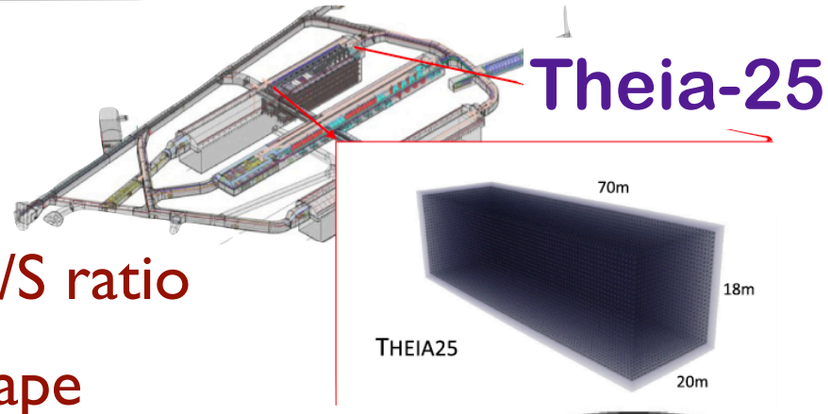
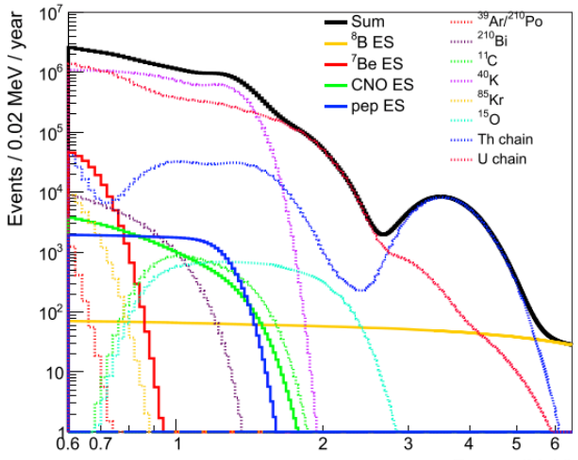
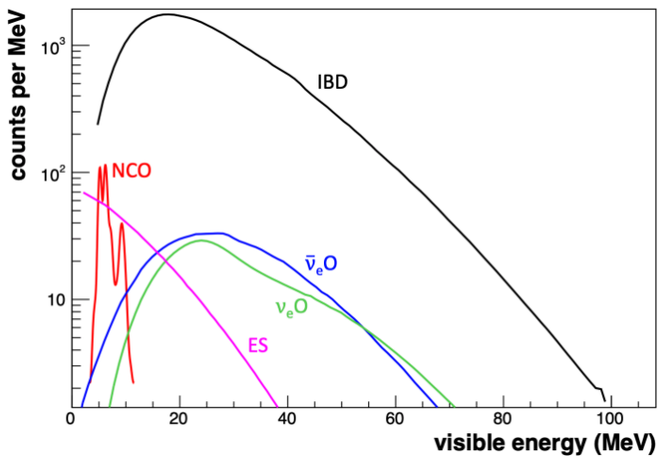
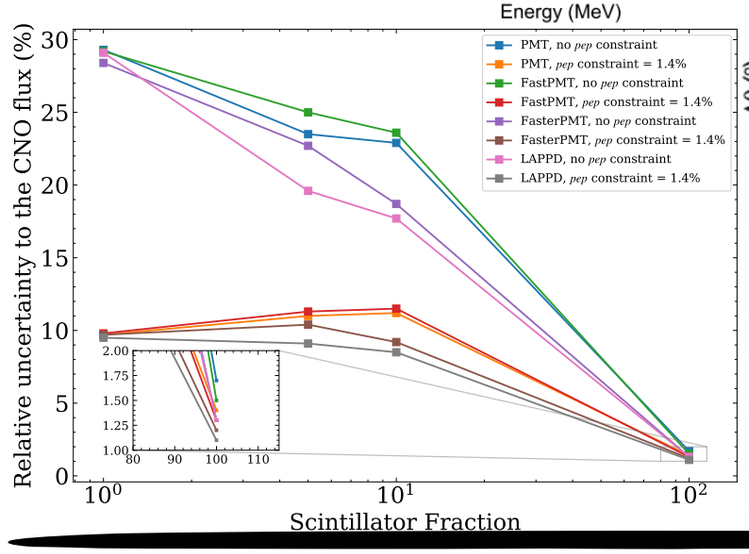
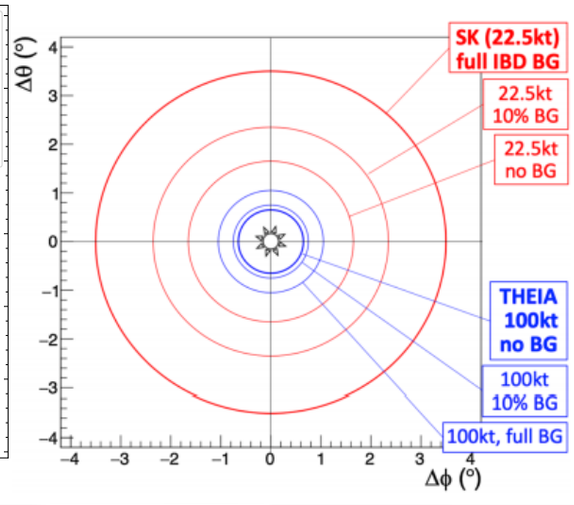


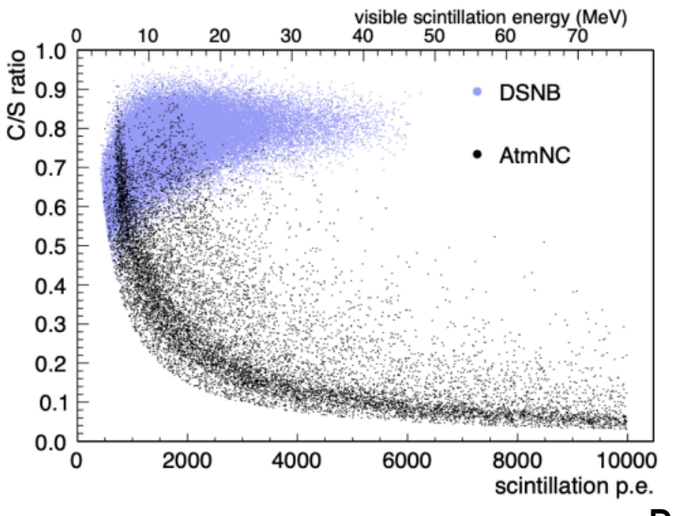




- Complementary to, and could act as trigger for DUNE S/N
- 5σ DSNB discovery in 6 (1) yrs for Theia-25 (100)







See L. Pickard talk in Module of opportunity session (Weds pm) for details of physics program

Eur. Phys. J. C 80, 416 (2020);
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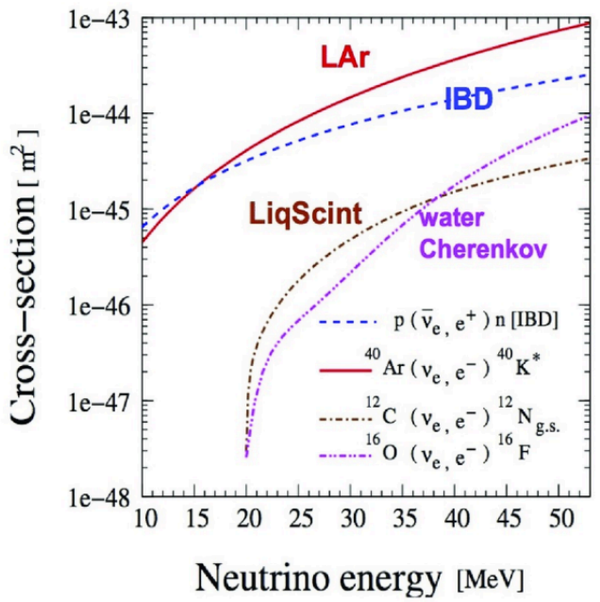
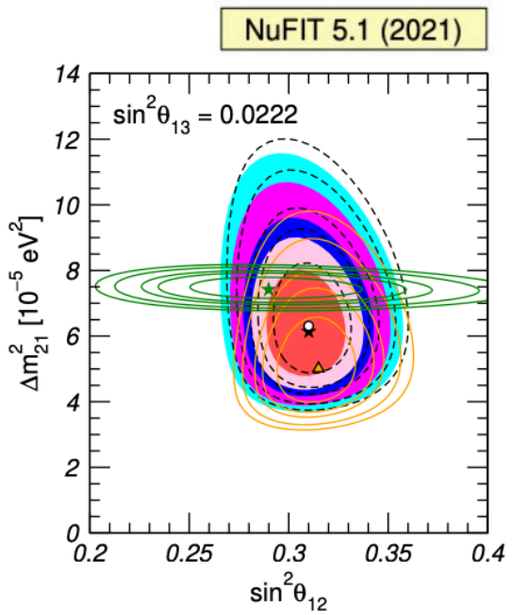
Other experimental approaches

- Jinping: 2.4-km rock overburden, proposed few-kton hybrid detector with excellent solar and SN sensitivity
- Possible few-kton LS detector in YemiLab, Korea
- LiquidO: ultra-short scattering length scintillator detector read out with fibres, offers topological information for event ID (e-/e+/γ)
- Solid-state detectors: potential CEνNS+ES signal for low-energy neutrino detection e.g. *pp*
- DUNE (LAr detection) : see Daniel Pershey talk, + Nicola McConkey, Eric Church (MoD session, weds pm)
- Noble liquid detectors: see Matthew Szydagis talk

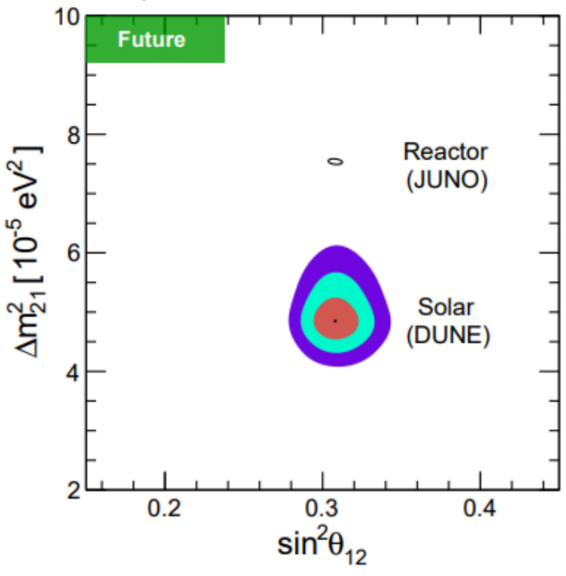
Prospects

- Leverage multi-purpose experiments
- Complementarity between experiments will be critical
- Precision measurement of CNO is within the reach of next-gen detectors





Capozzi et al., PRL **123** 131803



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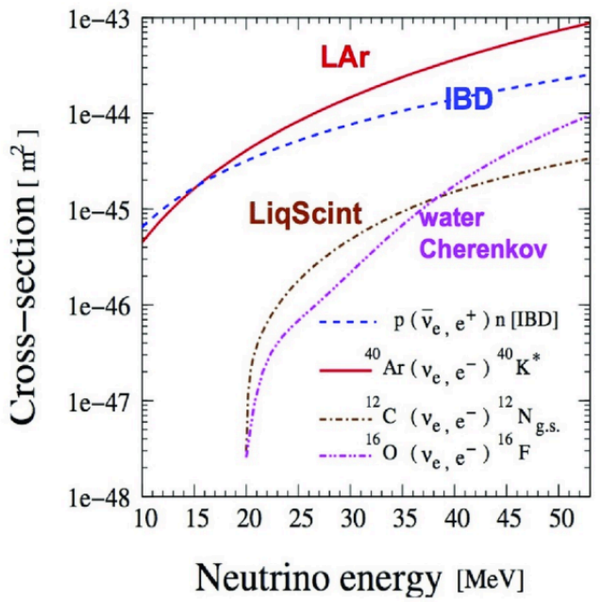

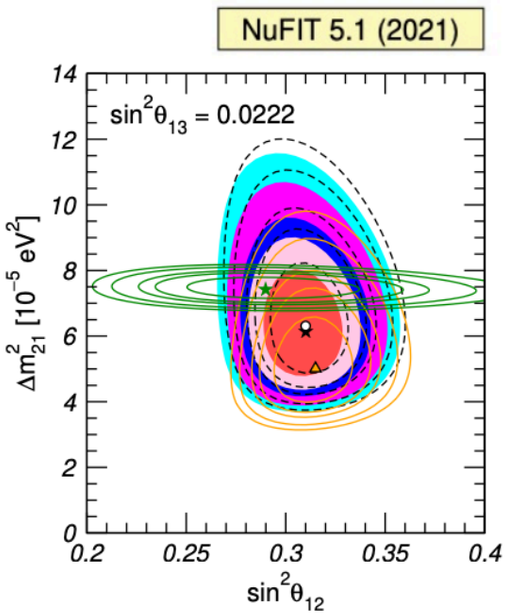

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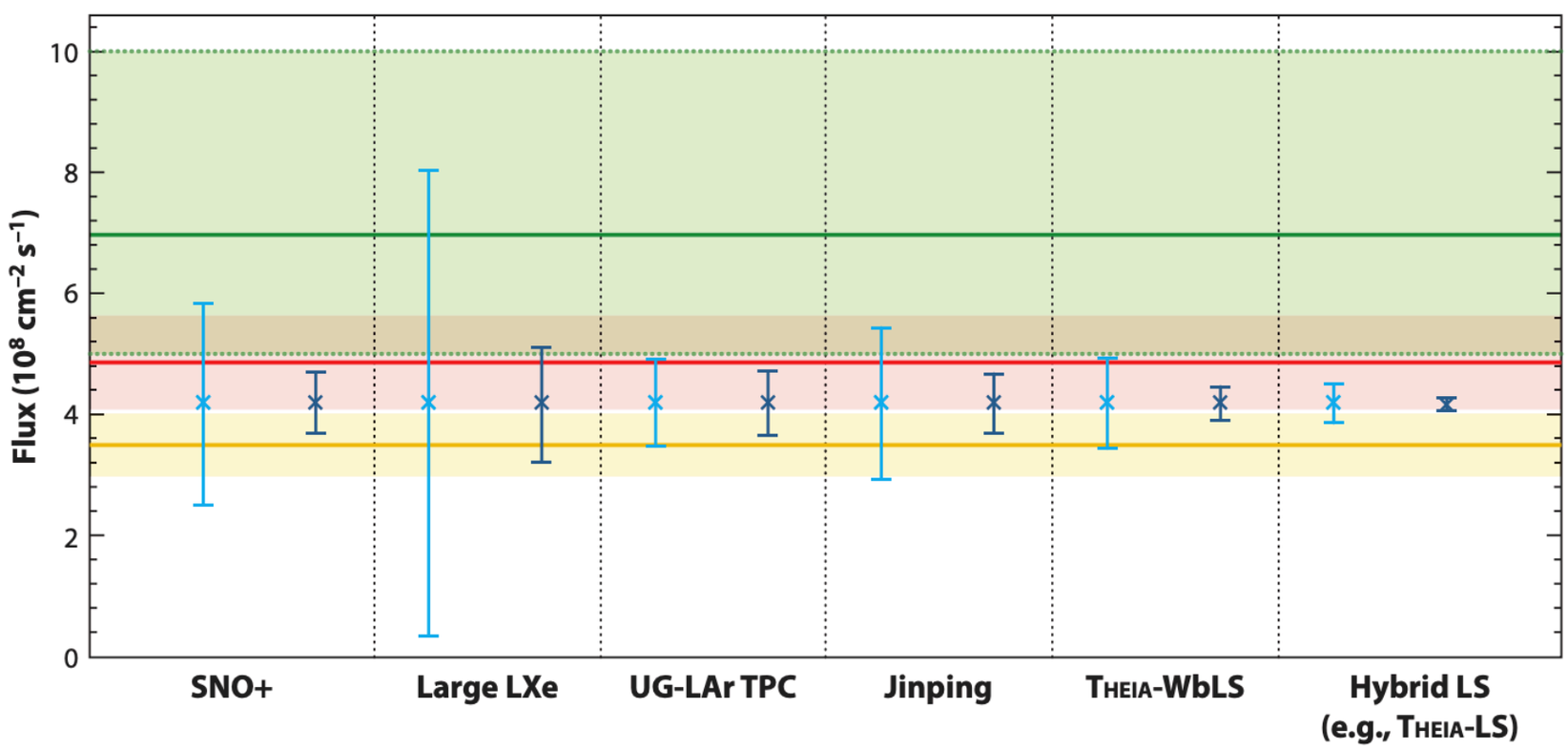
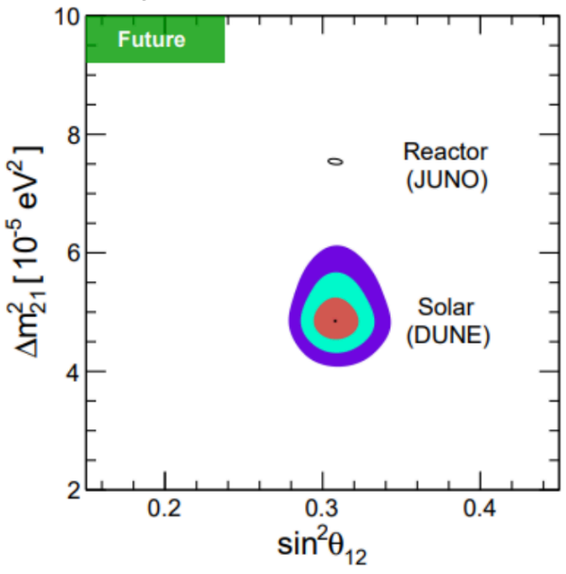




https://www.annualreviews.org/doi/pdf/10.1146/annurev-nucl-011921-061243

Summary

- Astrophysical neutrinos offer us insights into nature, and into the unique behaviour of these mysterious particles
- The future program will leverage large multi-purpose detectors
- We all benefit from the complementarity between different approaches
- A future, robust program in astrophysical neutrino detection will be a broad program, bringing together expertise from different technologies and different energy regimes

Back up

Table 2 Detector assumptions regarding potential future measurements of the CNO neutrino flux

Experiment	Scenario 1	Scenario 2
SNO+ (252)	5 years' exposure 1.4% *pep* constraint Current background levels	×10 reduction of ^{238}U and ^{232}Th ×1,000 reduction of ^{210}Bi
Large LXe (285)	200-tonne-year exposure 10^2 reduction of $2\nu\beta\beta$ 1% knowledge of backgrounds	2,000-tonne-year exposure 10^3 reduction of $2\nu\beta\beta$ Perfect knowledge of backgrounds
UG-LAr TPC (288)	400-tonne-year exposure 6,000 PEs per MeV, 0.6-MeV threshold Underground argon (negligible impact from ^{42}Ar, or pileup with ^{39}Ar) ^{222}Rn at 200 μBq per 100 t	^{222}Rn at 10 μBq per 100 t
Jinping (260)	1,500 days' exposure 1 kt fiducial 500 PEs per MeV	4 kt fiducial 1,000 PEs per MeV
THEIA-WbLS (202)	5 years' exposure 12.5 kt fiducial 55° angular resolution	60 kt fiducial 45° angular resolution
Hybrid LS (e.g., THEIA-LS) (262)	5 years' exposure 500 t fiducial Nanosecond-scale PMT TTS or 1.4% constraint on *pep*	25 kt fiducial 1.6 ns or better TTS No constraint on *pep*

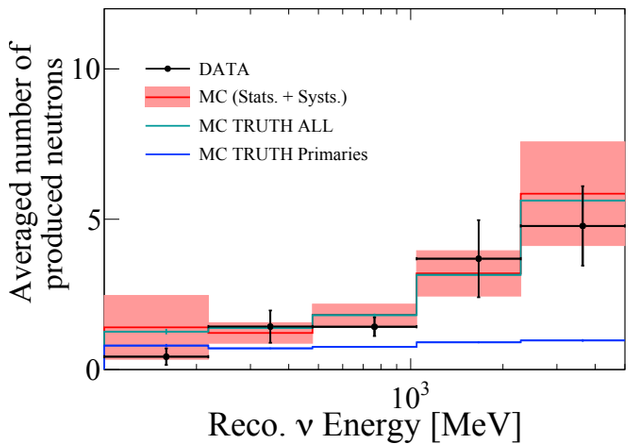
Neutron production

Atmospheric neutrino-induced

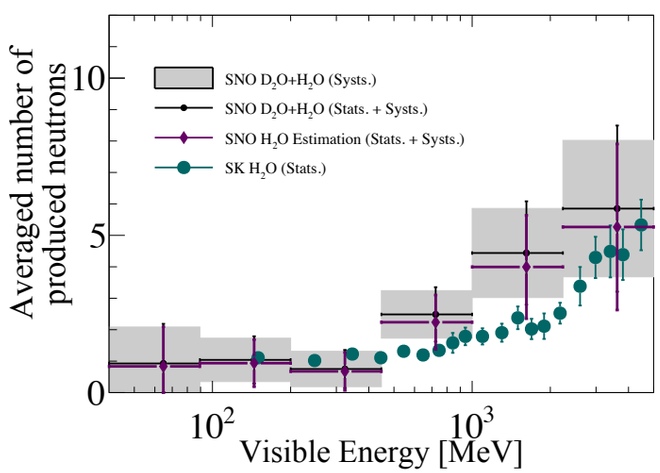
Measure multiplicity as a function of energy & interaction channel

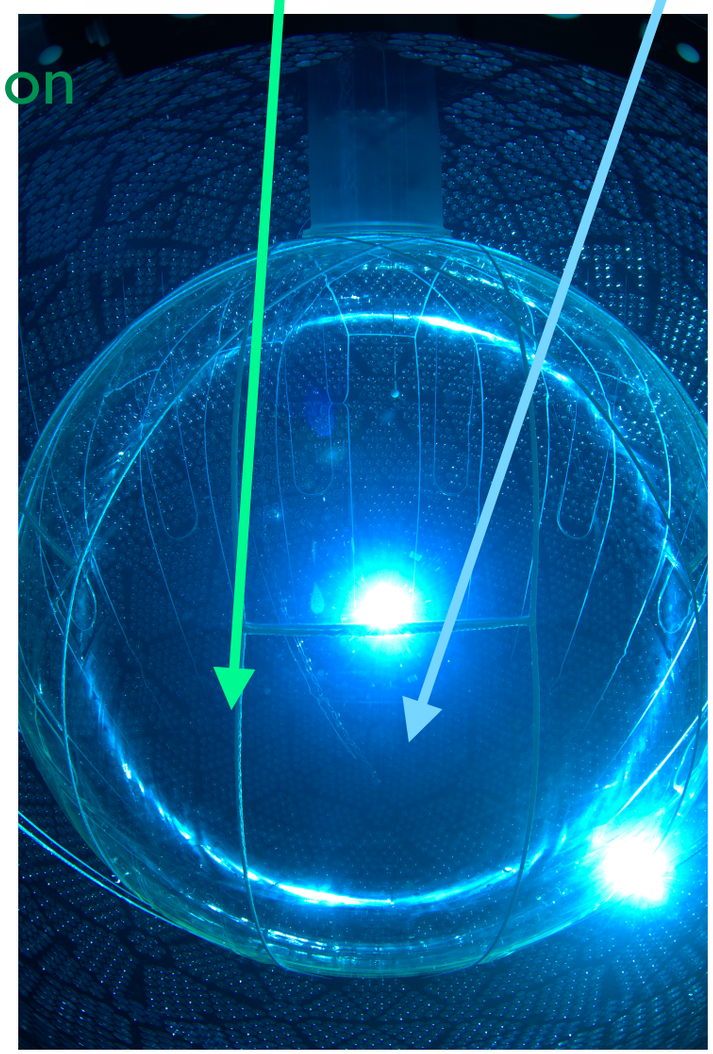
Probe of GeV-scale physics

ν- vs anti-ν neutron production



Phys. Rev. D ***99*** *112007 (2019)*





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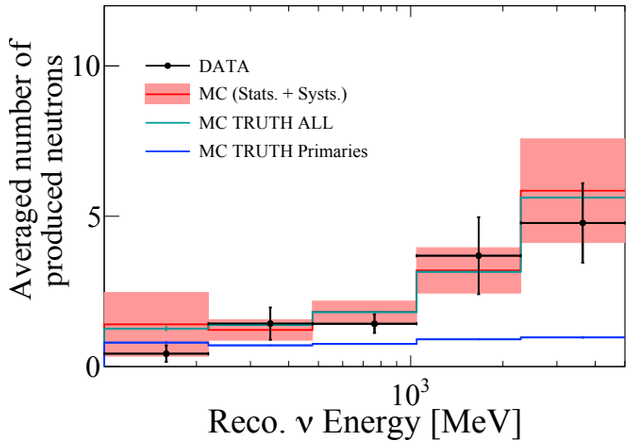

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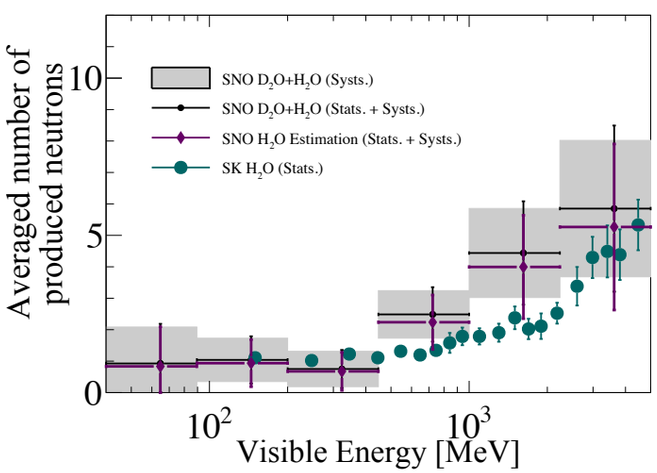
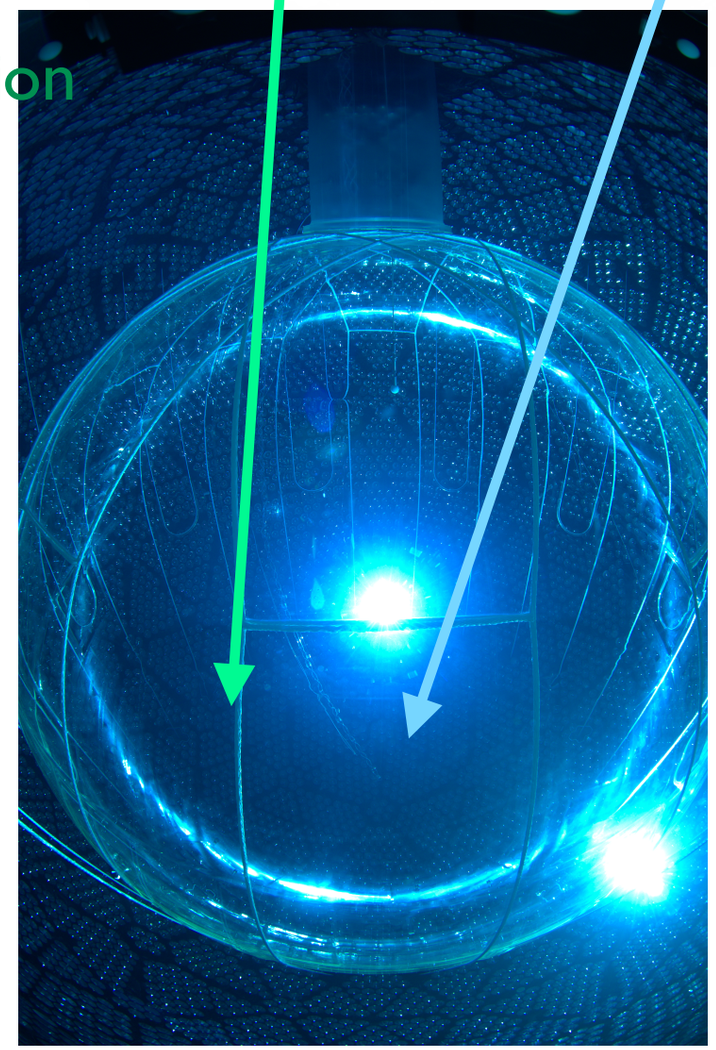
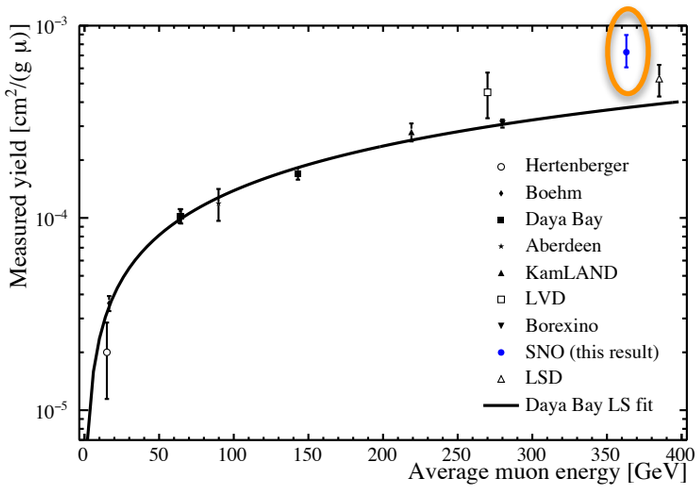




High-energy muons penetrate deep underground (3/hr @ SNO)

Spallation products: excited nuclei & neutrons

Phys. Rev. D ***100*** *112005 (2019)*



Hep and DSNB

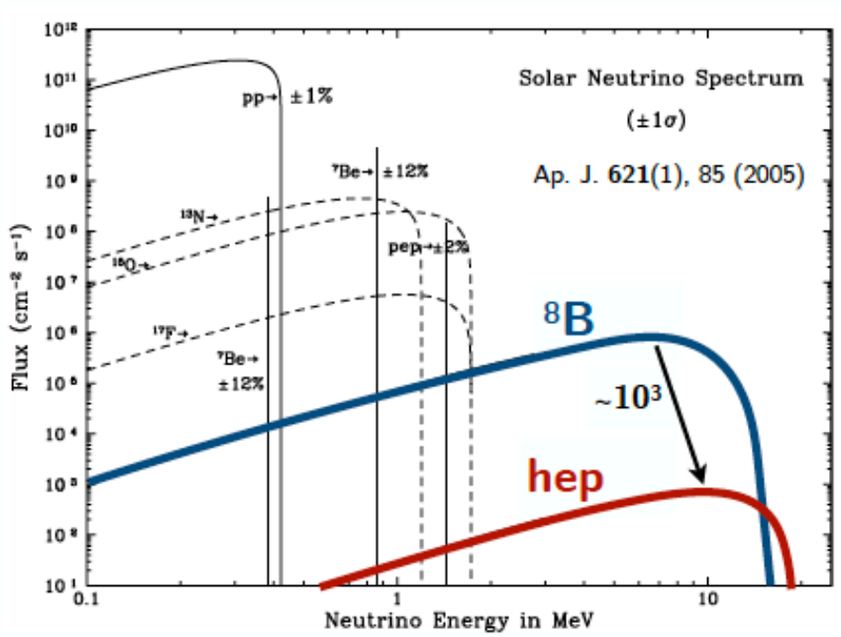
PRD **102**, 062006 (2020)

Hep & DSNB Neutrinos

A Search with the Full SNO Dataset

hep Solar Neutrinos

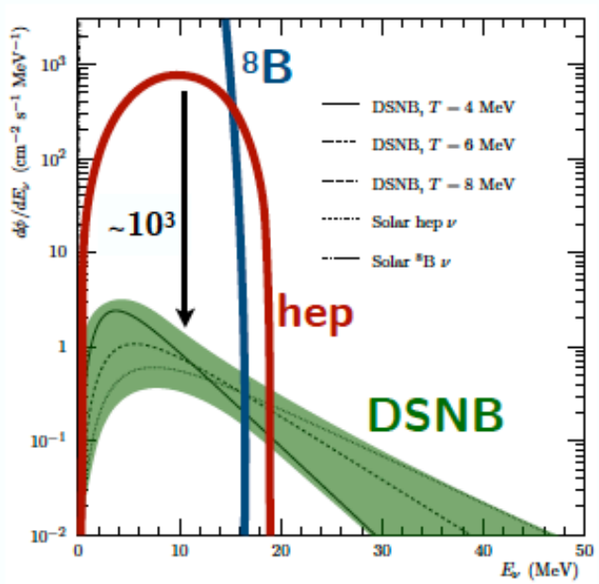
- ^{3}He+p fusion: ^{3}He(p,e$^+\nu_e$)^{4}He
- Highest-energy solar neutrino flux
- The last unobserved in the *pp* chain
- Sensitivity through SNO's ν_e–d CC
- Complete the *pp* picture, test SSM, extends 2006 SNO Phase I analysis[1]



[1]Astrophys. J. **653**, 1545 (2006)

Diffuse Supernova Neutrino Background

- Diffuse glow of past core-collapse SNe
- Redshifted spectrum with a tail beyond the 18 MeV *hep* endpoint
- SNO sensitive to DSNB ν_e via CC
- Information on average SNe neutrino luminosity and temperature



Model: Beacom & Strigari, Annu. Rev. Nucl. Part. Sci **60**, 439 (2010).

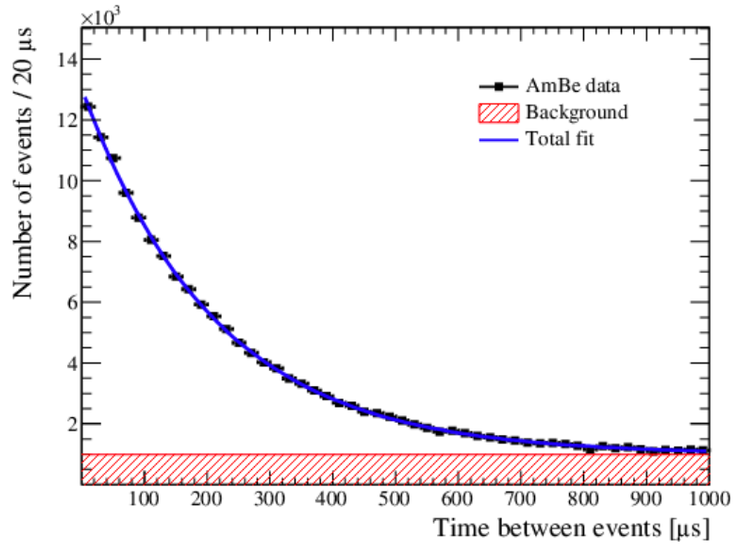
SNO+ physics results

- Measurement of n-p capture in water

  ~50% efficiency for 2.2-MeV γ from n capture

  n capture τ = 202.35 +0.87/-0.76 μs

Phys. Rev. C ***102*** *014002 (2020)*



SNO+ physics results

- Measurement of n-p capture in water

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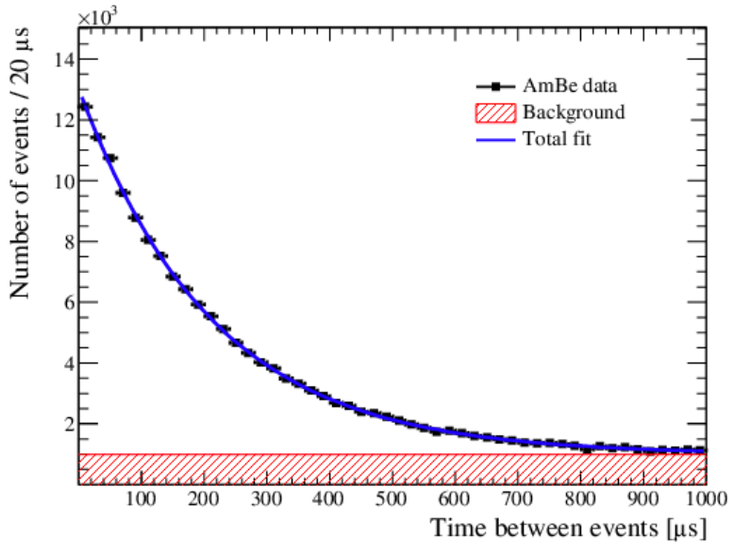
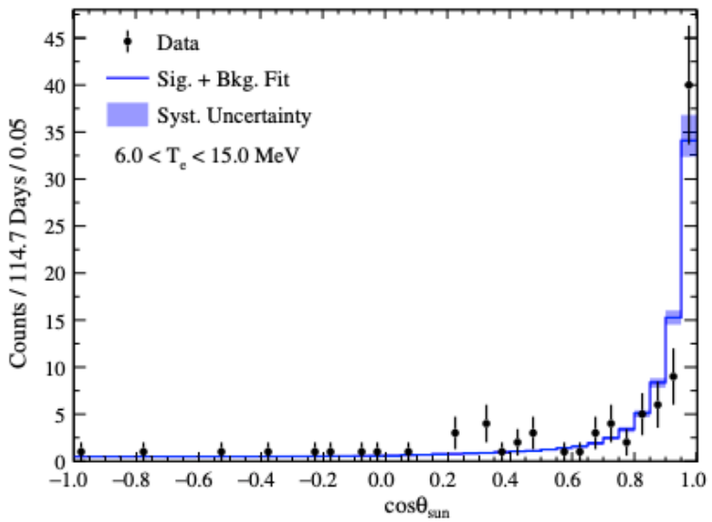
  *Phys. Rev. C **102** 014002 (2020)*





- Measurement of 8B solar ν flux with very low backgrounds: 0.25 +0.09/-0.07 ev/kt-day

$$\Phi_{^8\mathrm{B}} = 5.95^{+0.75}_{-0.71}(\mathrm{stat})^{+0.28}_{-0.30}(\mathrm{syst}) \times 10^6\ \mathrm{cm}^{-2}\,\mathrm{s}^{-1}$$

*Phys. Rev. D **99** 012012 (2019)*

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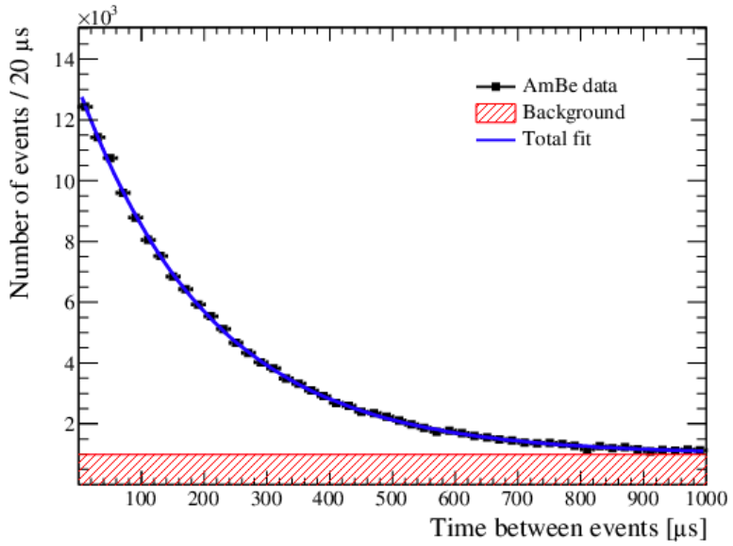

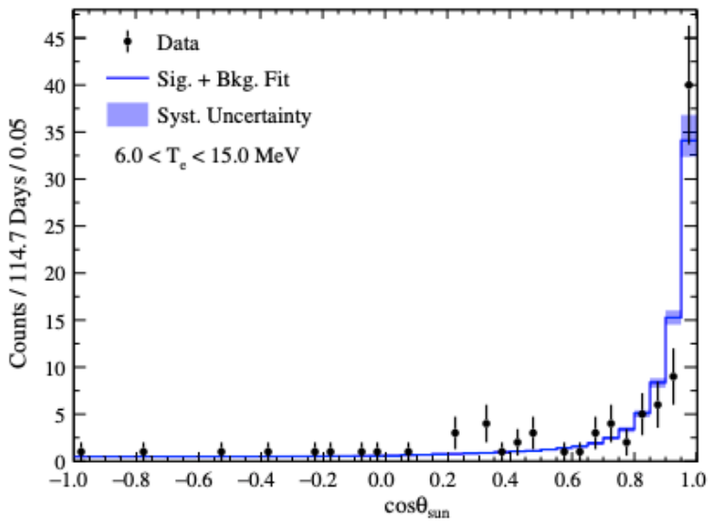

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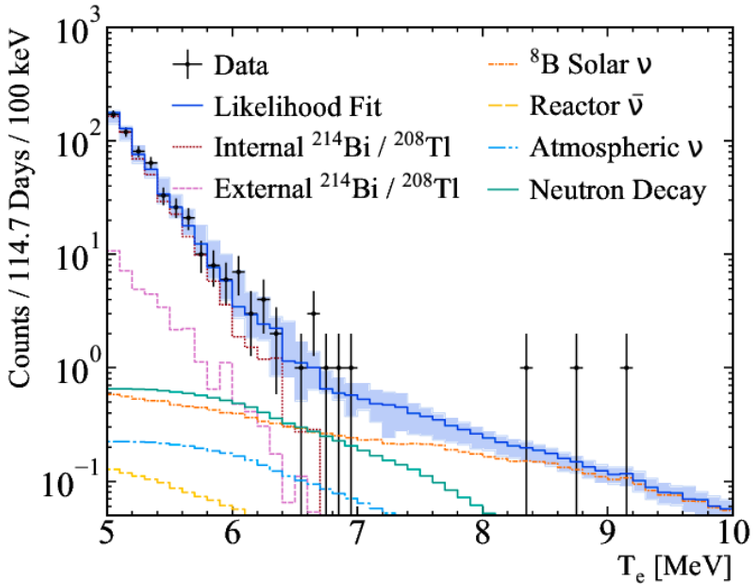
*Phys. Rev. D **99** 012012 (2019)*

- Search for invisible modes of nucleon decay via observable de-excitation γs

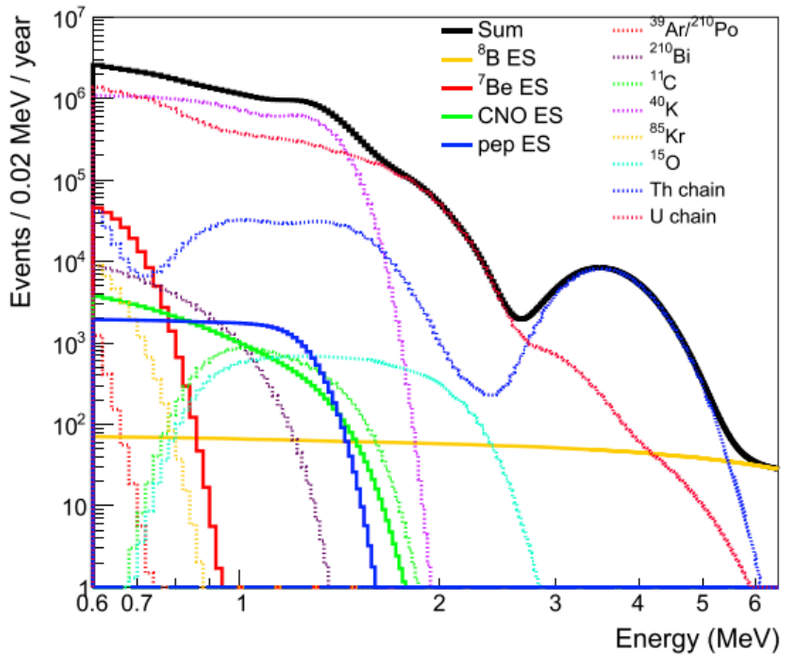
  Box & spectral analysis

*Phys. Rev. D **99** 032008 (2019)*

Mode	SNO+ Limits (years)	Current Limits
n	2.49×10^{29}	5.8×10^{29} [KamLAND]
p	3.56×10^{29}	2.1×10^{29} [SNO]
pp	4.68×10^{28}	5.0×10^{25} [Borexino]
pn	2.57×10^{28}	2.1×10^{25} [Tretyak et. al.]
nn	1.25×10^{28}	1.4×10^{30} [KamLAND]



Solar Neutrinos with Theia



- Dominant background to CNO ν measurement: ^{210}Bi
- Theia offers unique low-threshold, directional detection

Eur. Phys. J. C 80, 416 (2020); Eur. Phys. J. C (2018) 78: 435

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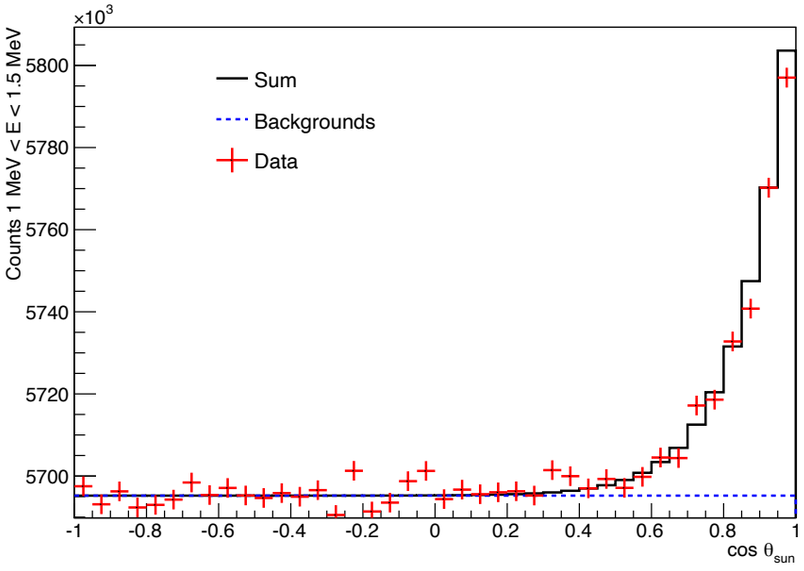

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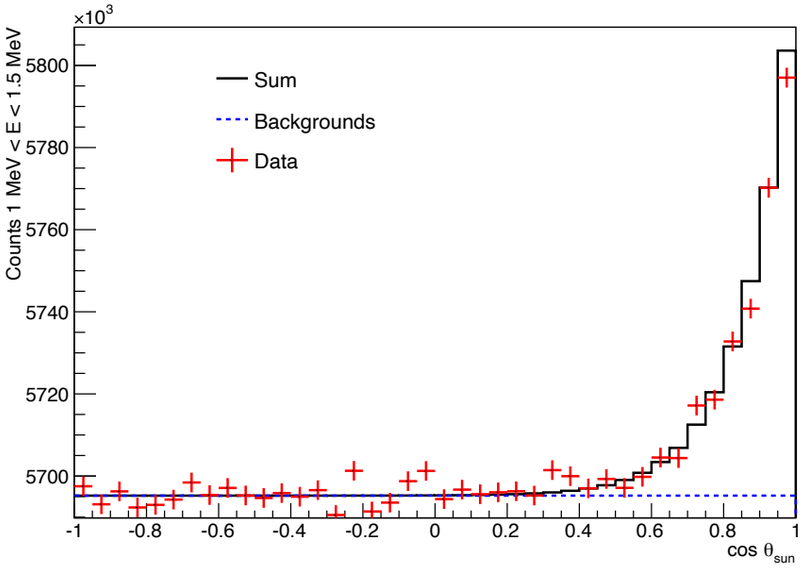
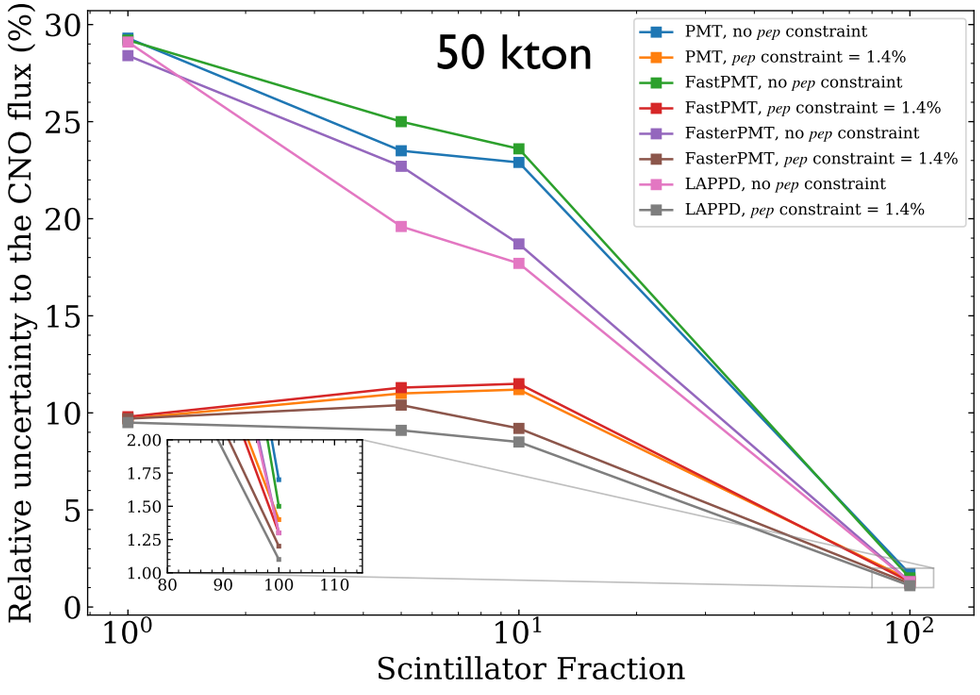


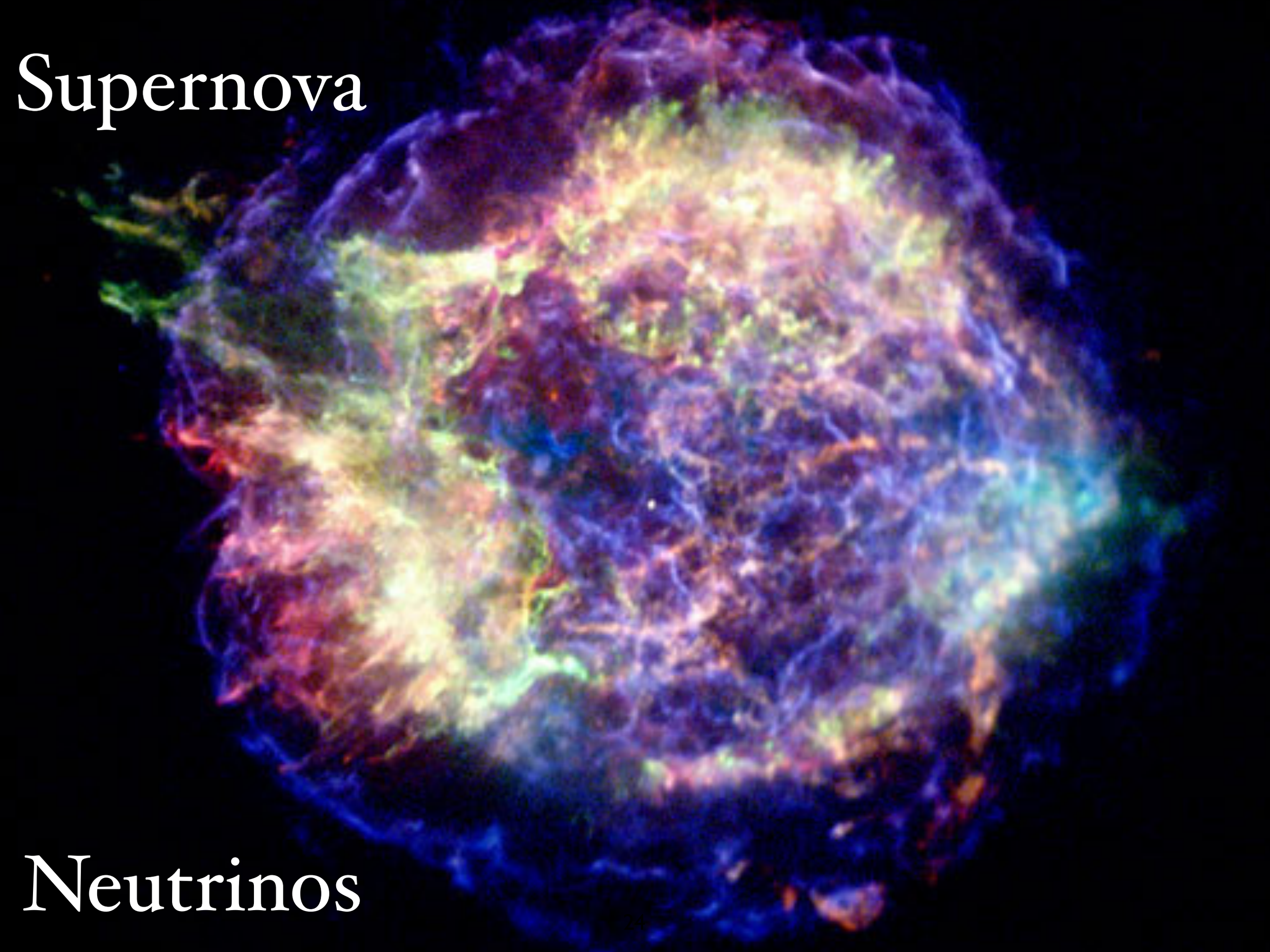


Sensitivity based on MC study of detector response, including full vertex and direction reconstruction

Phys. Rev. D 103, 052004 (2021)

Eur. Phys. J. C 80, 416 (2020); Eur. Phys. J. C (2018) 78: 435

Supernova



Neutrinos

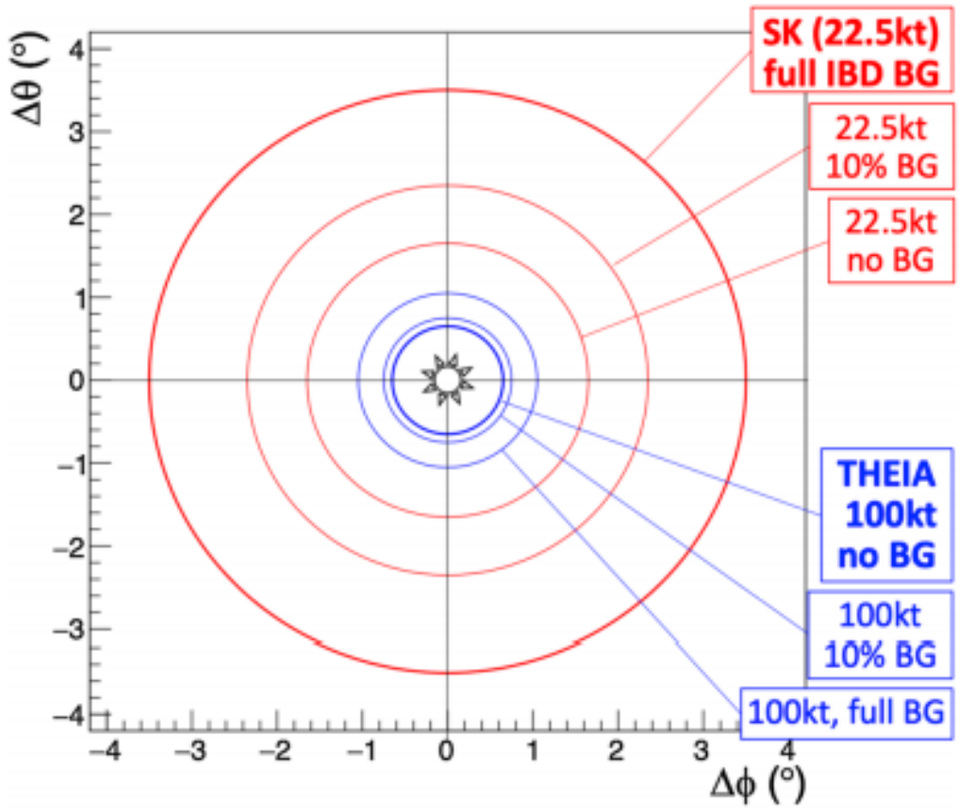
Supernova Detection

- ~90% events are IBD

  Highly complementary to ν_e LAr signal
- ES ⇒ pointing accuracy < 1°
- CC & monoE γ from NC ⇒ burst T & subsequent mixing
- Flavour-resolved neutrino spectra
- High-stats, low-threshold signal with good resolution
- Pre-supernova neutrino sensitivity

Event rate in 100-kt WbLS, SN at 10 kpc

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

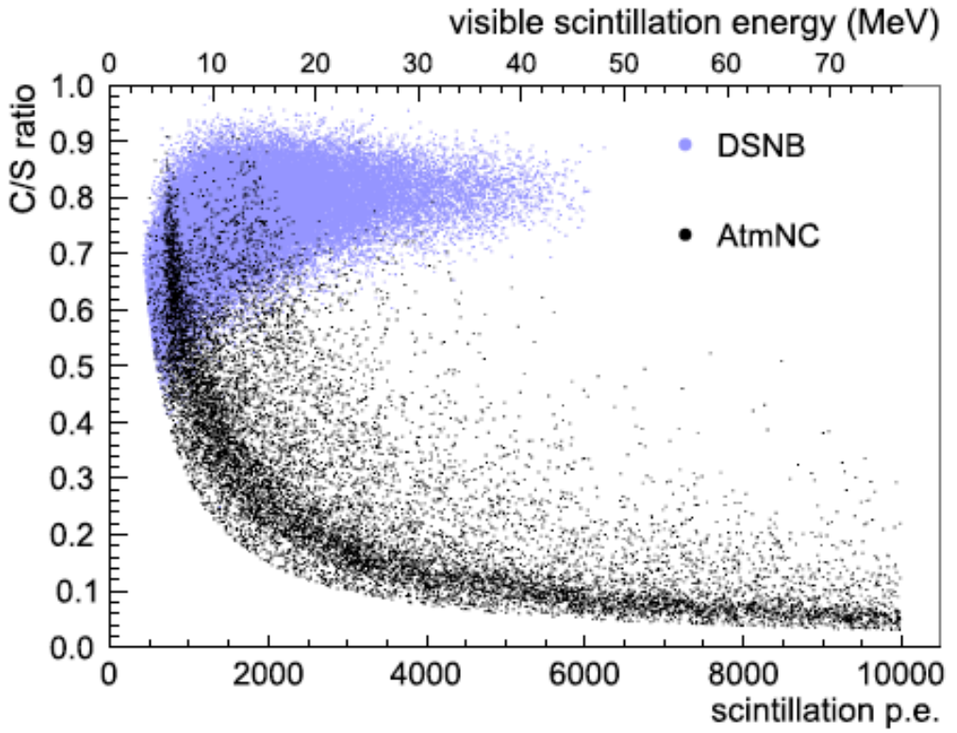


Eur. Phys. J. C 80, 416 (2020)

Anti-ν Detection

DSNB

- Diffuse ν "glow" from past core-collapse supernovae
- Cherenkov/scintillation ratio gives a powerful handle to discriminate atmospheric NC background
- 5σ in 125 kton-yrs
- Astrophysics of SNe



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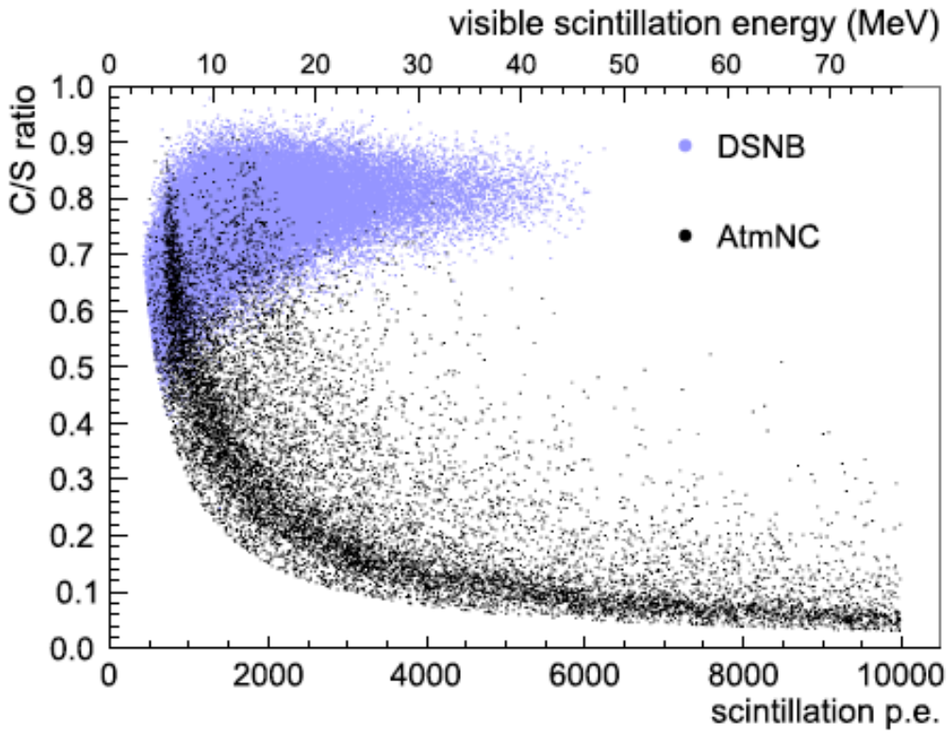
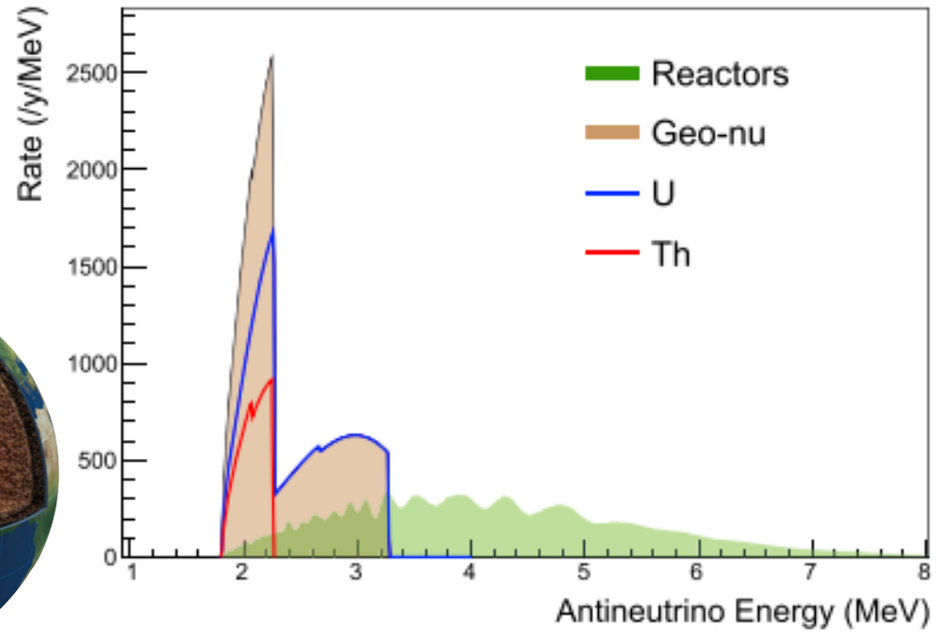


Geo- and reactor

- Current geo-ν exposure < 10kt-yr (KL + Borexino)
- **THEIA**: large statistics in a complementary geographical location: 26.5 ev/kt-yr
- Could offer first evidence for surface variation
- ~ 20 reactor ev/kt-yr
  Demonstrate techniques for remote reactor monitoring
  Range & direction at > 1000-km standoff

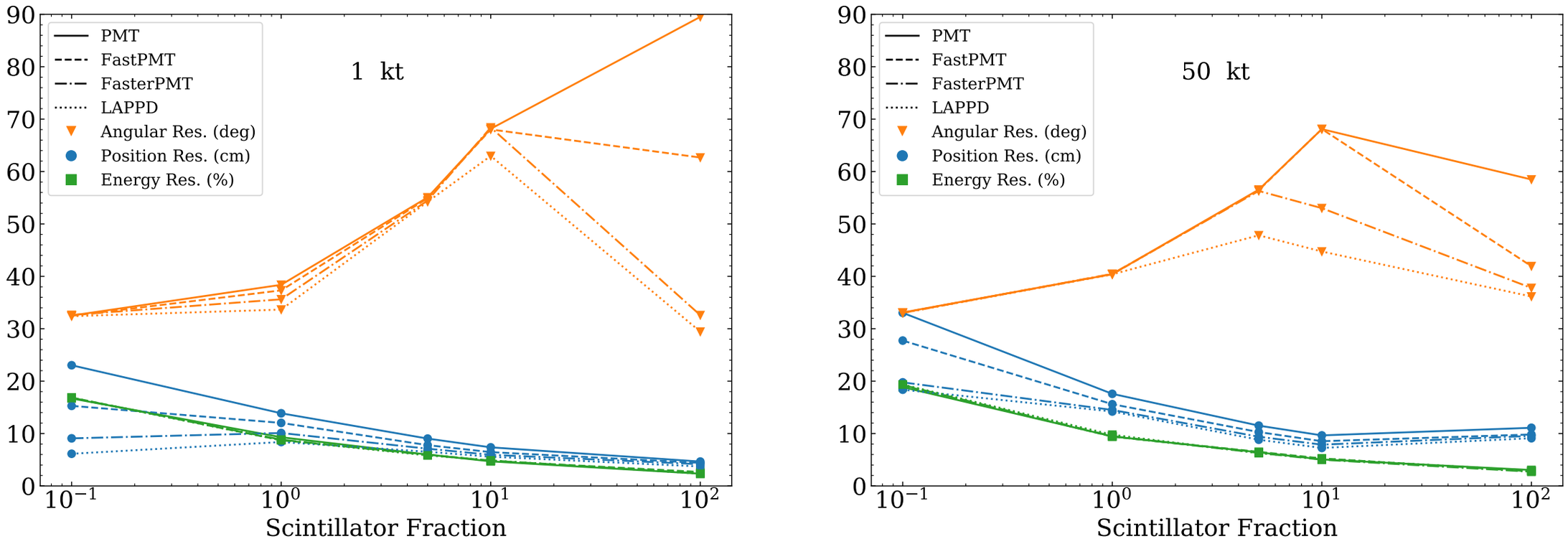


Low-energy detector response

A number of metrics are considered for detector performance:

1. Energy resolution — *Reduce flux uncertainty, increase background rejection*
2. Vertex resolution — *Reduce flux uncertainty, increase background rejection*
3. Angular resolution — *Elastic scattering event ID, physics scope*
4. Cherenkov (C) / scintillation (S) separation — *Particle & event ID*

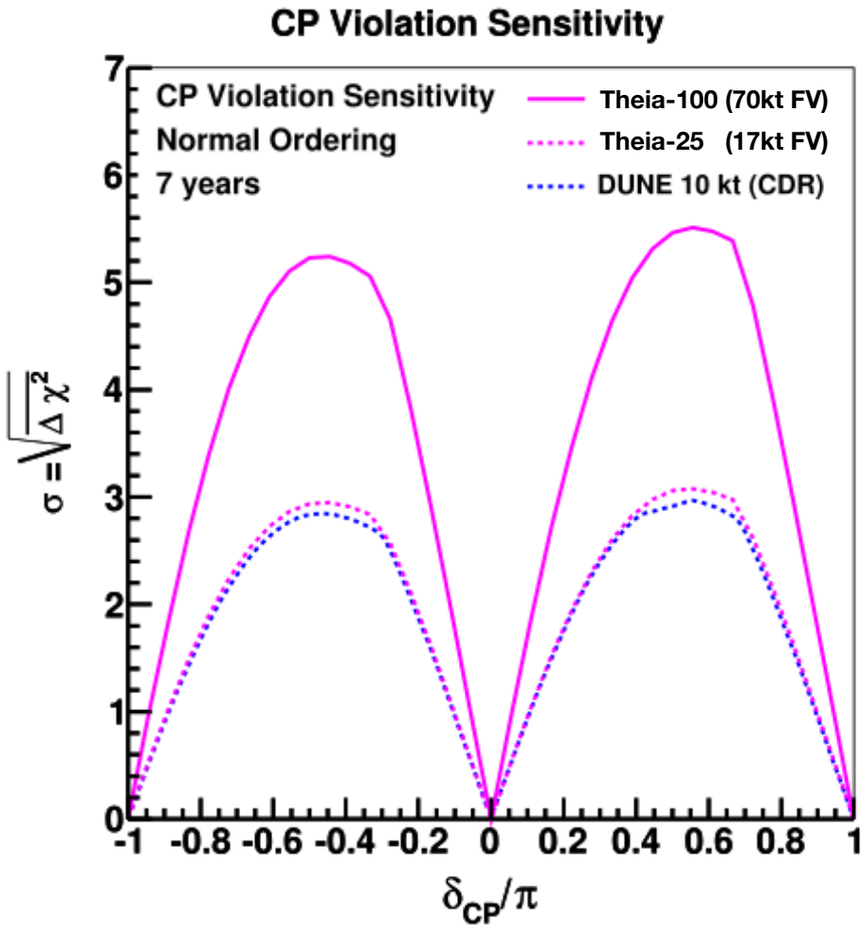
These tools can be used to define "desired" properties for WbLS

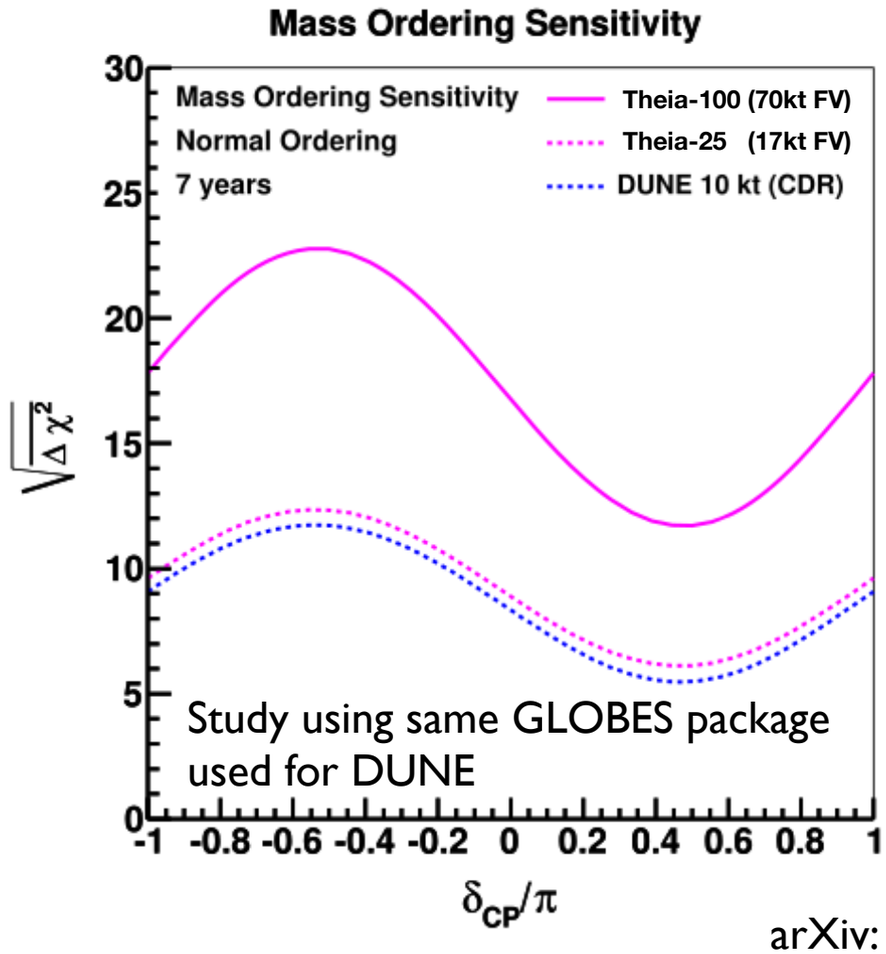


Impact of target properties and photon detector response on detector performance for (left) 1-kton and (right) 50-kton detectors

Phys. Rev. D ***103*** *052004 (2021)*

Long-Baseline Sensitivity





Synergy with LAr TPC

Independent systematics

High-energy events

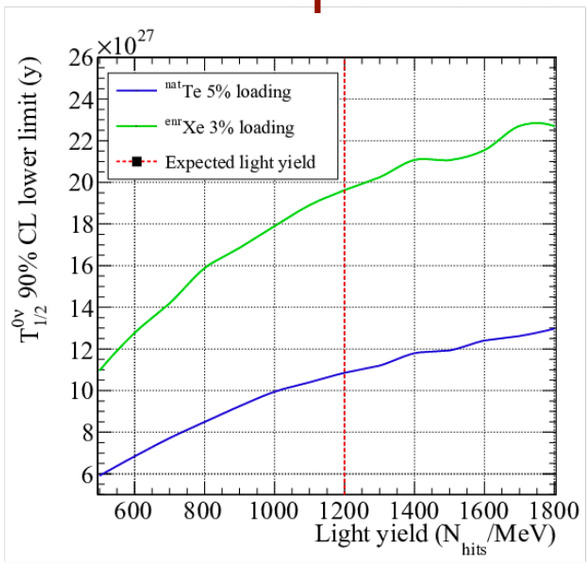
arXiv: 1606.09550

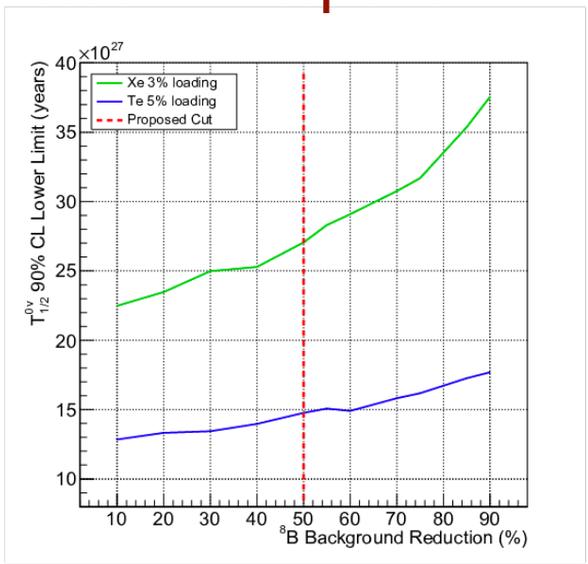
Performance of small (25kt) Theia module competitive with 10kt LAr TPC

Eur. Phys. J. C 80, 416 (2020)

NLDBD with Theia

Dependence on detector response





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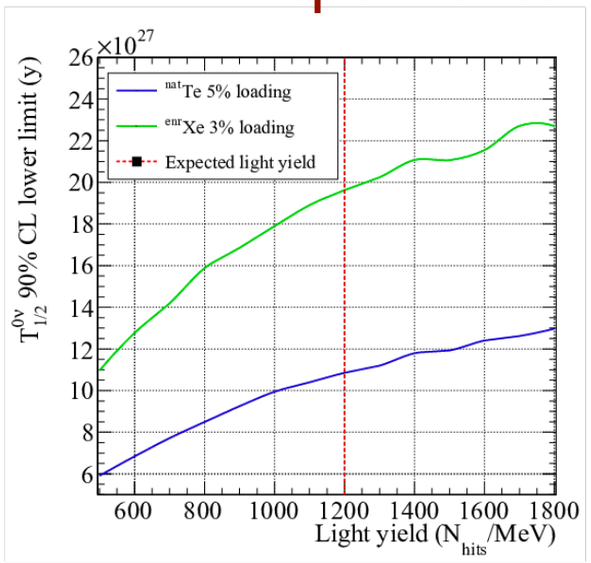

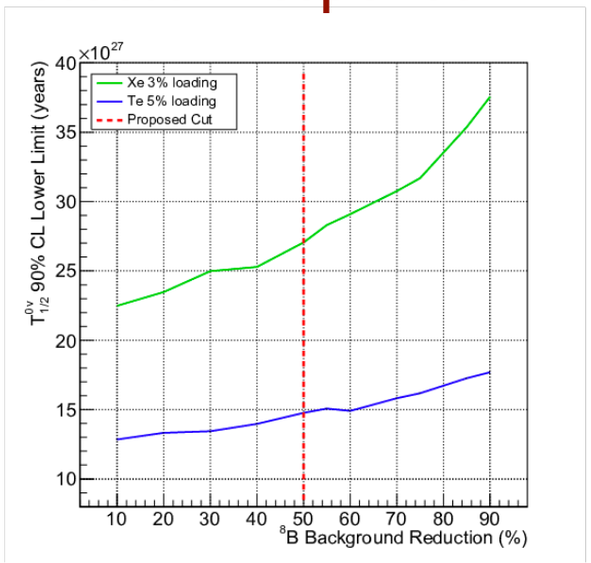

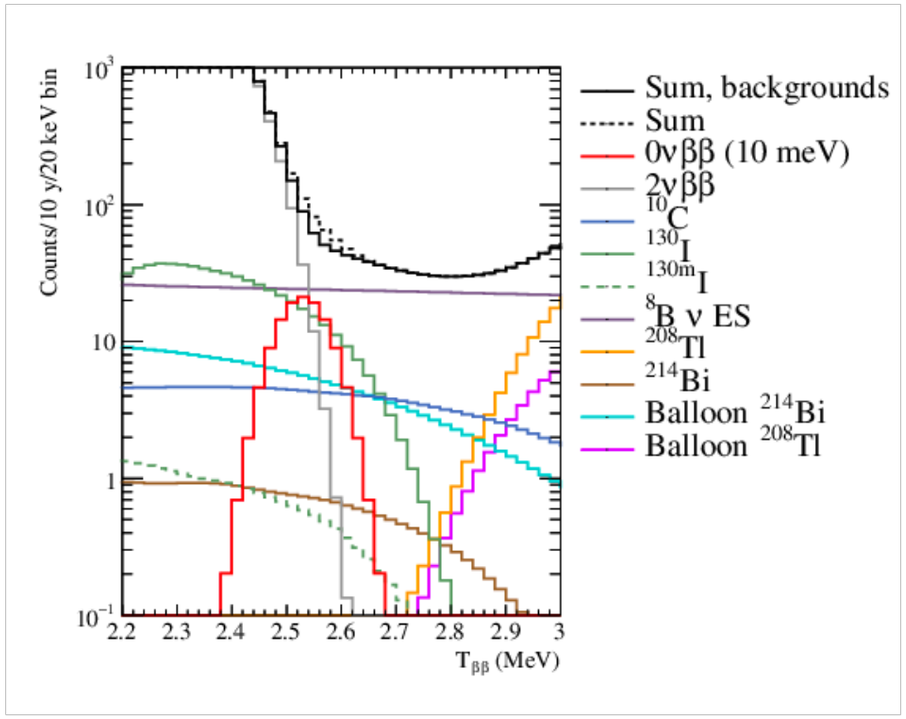

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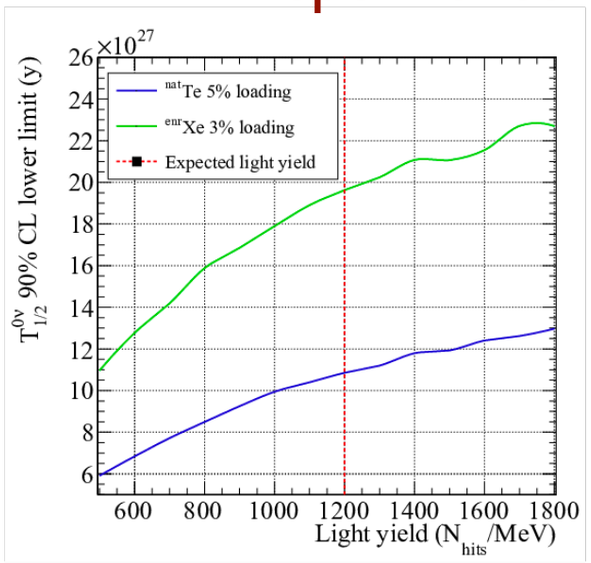

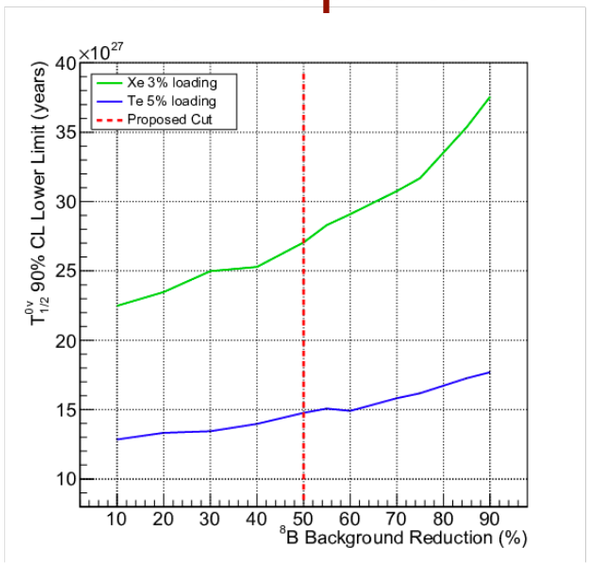

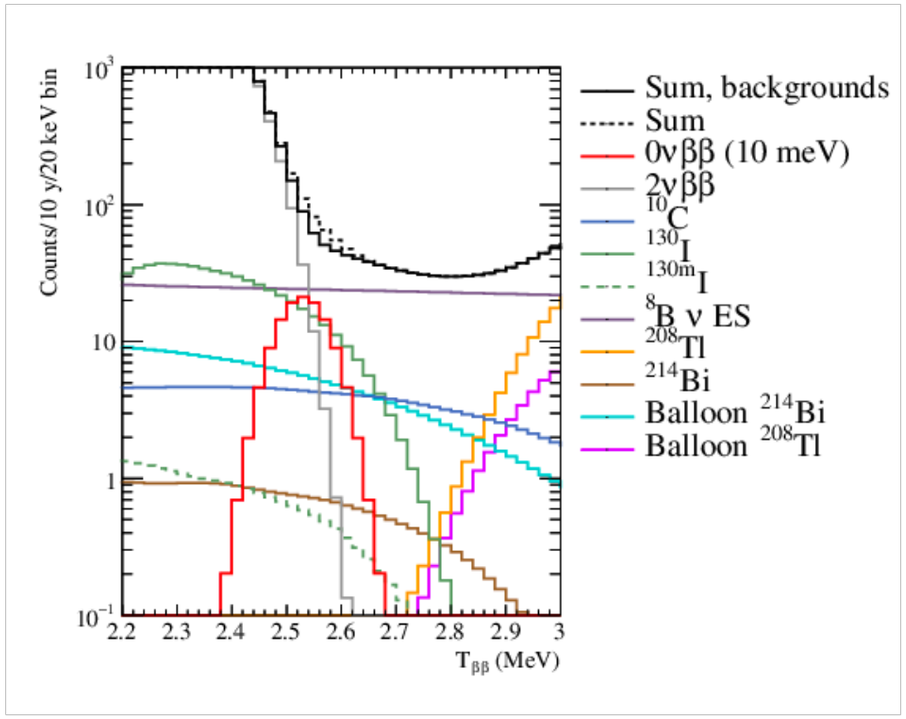

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90% CL for Te (Xe)

$m_{\beta\beta} < 6.3\ (5.6)$ meV

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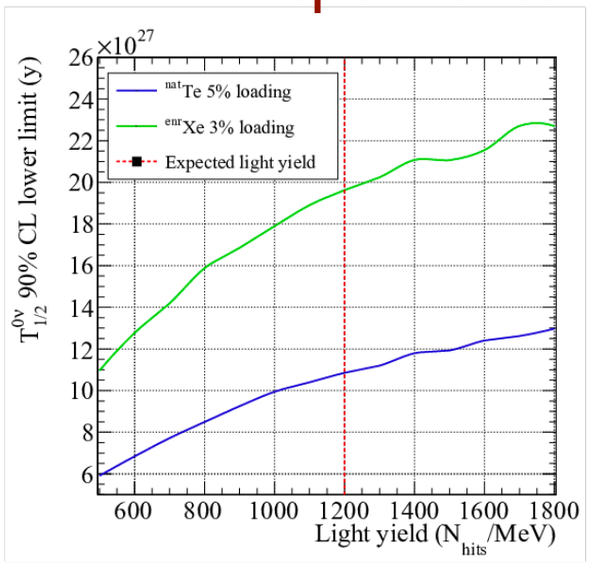

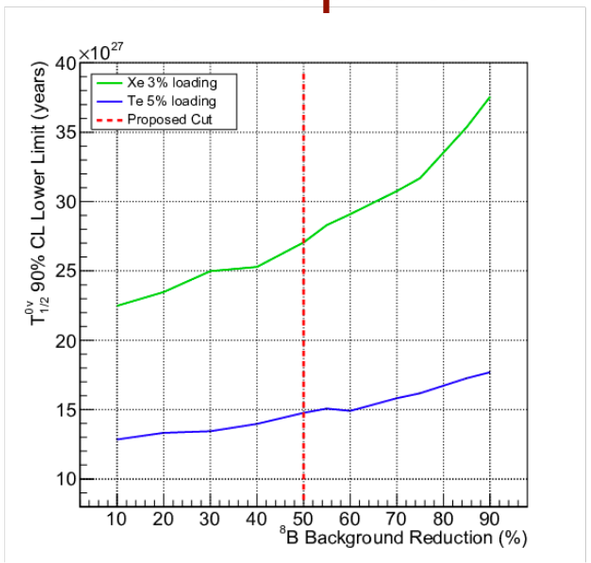

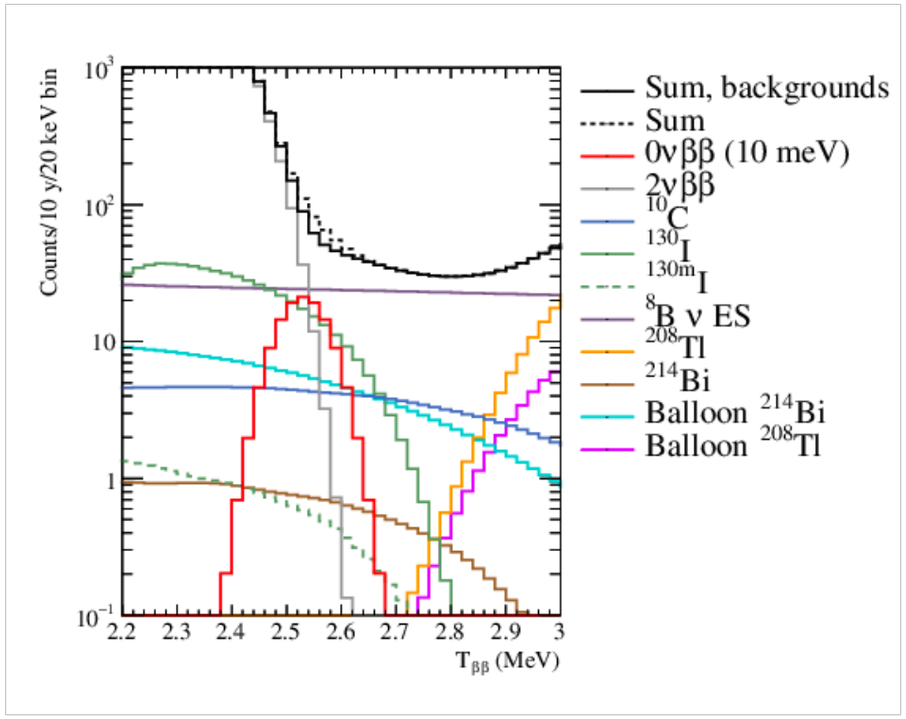

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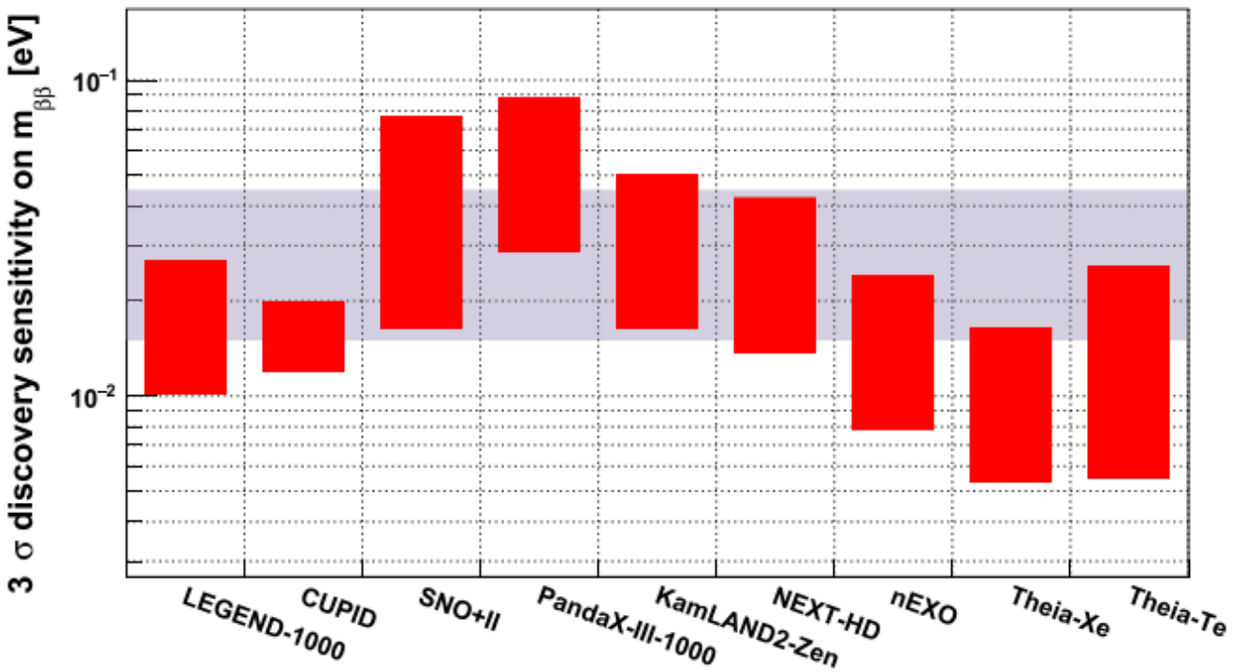


CHESS:
CHErenkov-Scintillation Separation

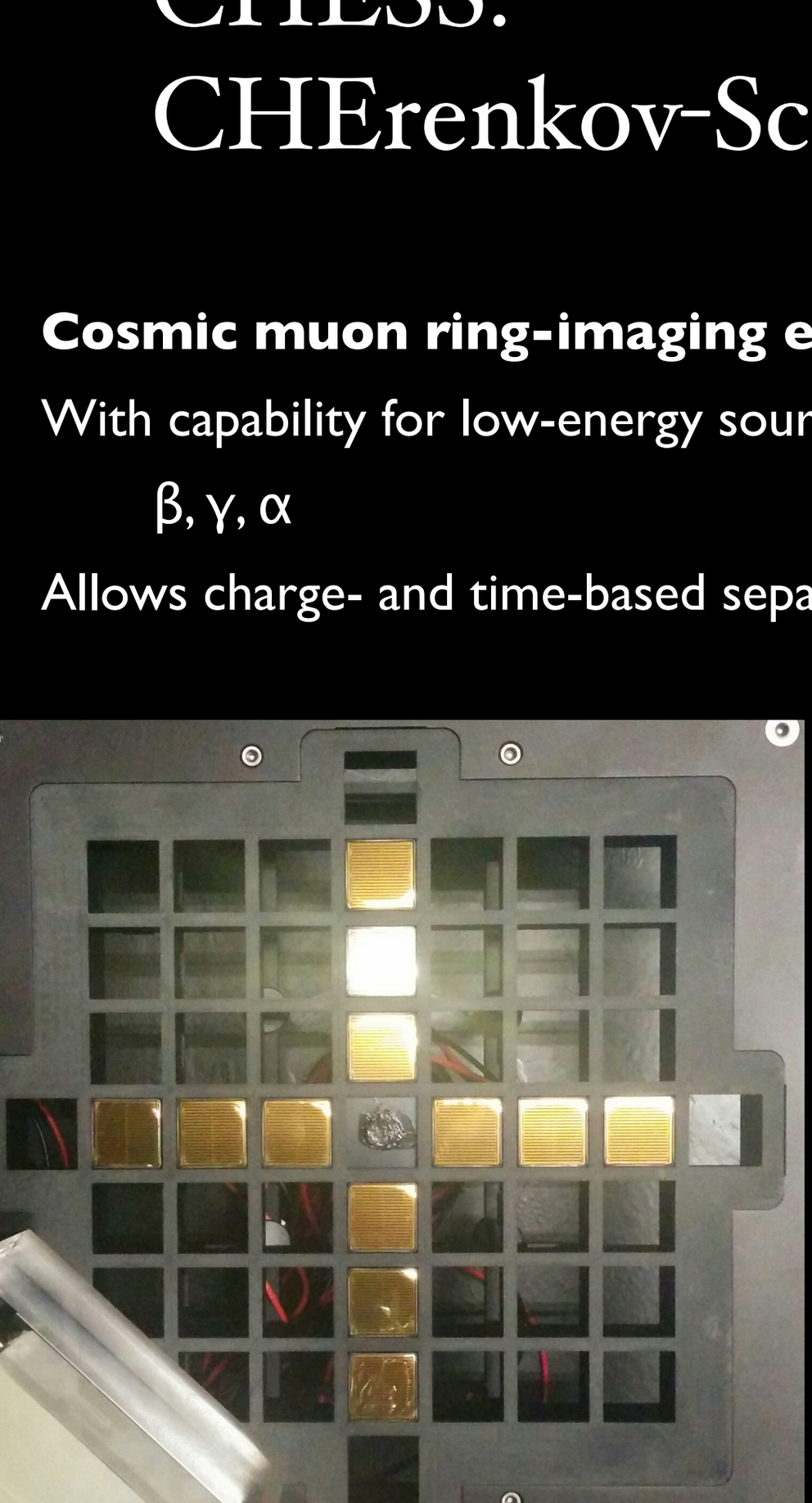
PRC 95 055801 (2017)

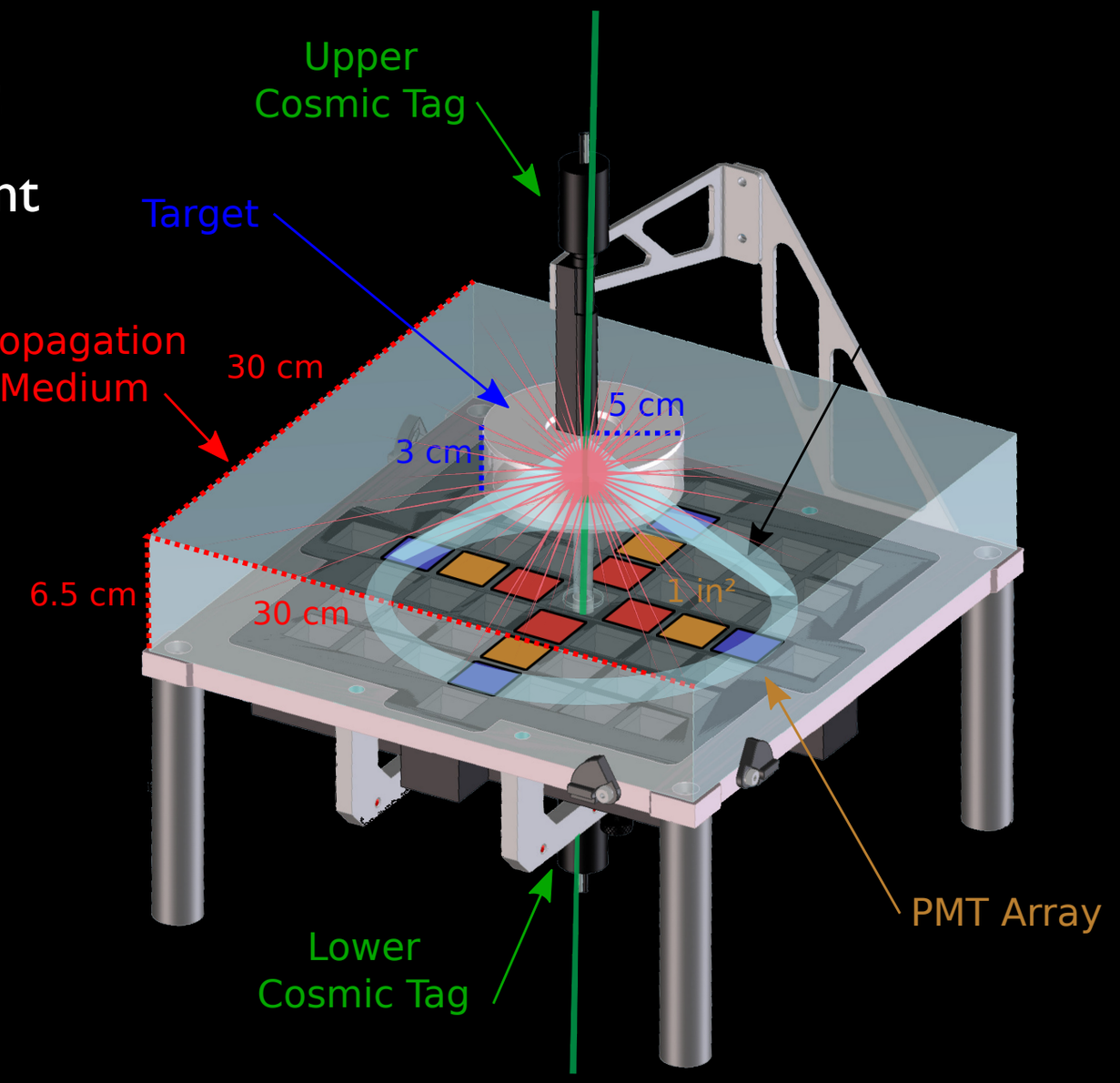
Cosmic muon ring-imaging experiment

With capability for low-energy source deployment

β, γ, α

Allows charge- and time-based separation





12 1-inch H11934 PMTs (300ps FWHM, 42% QE)
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675 samples (135ns window)
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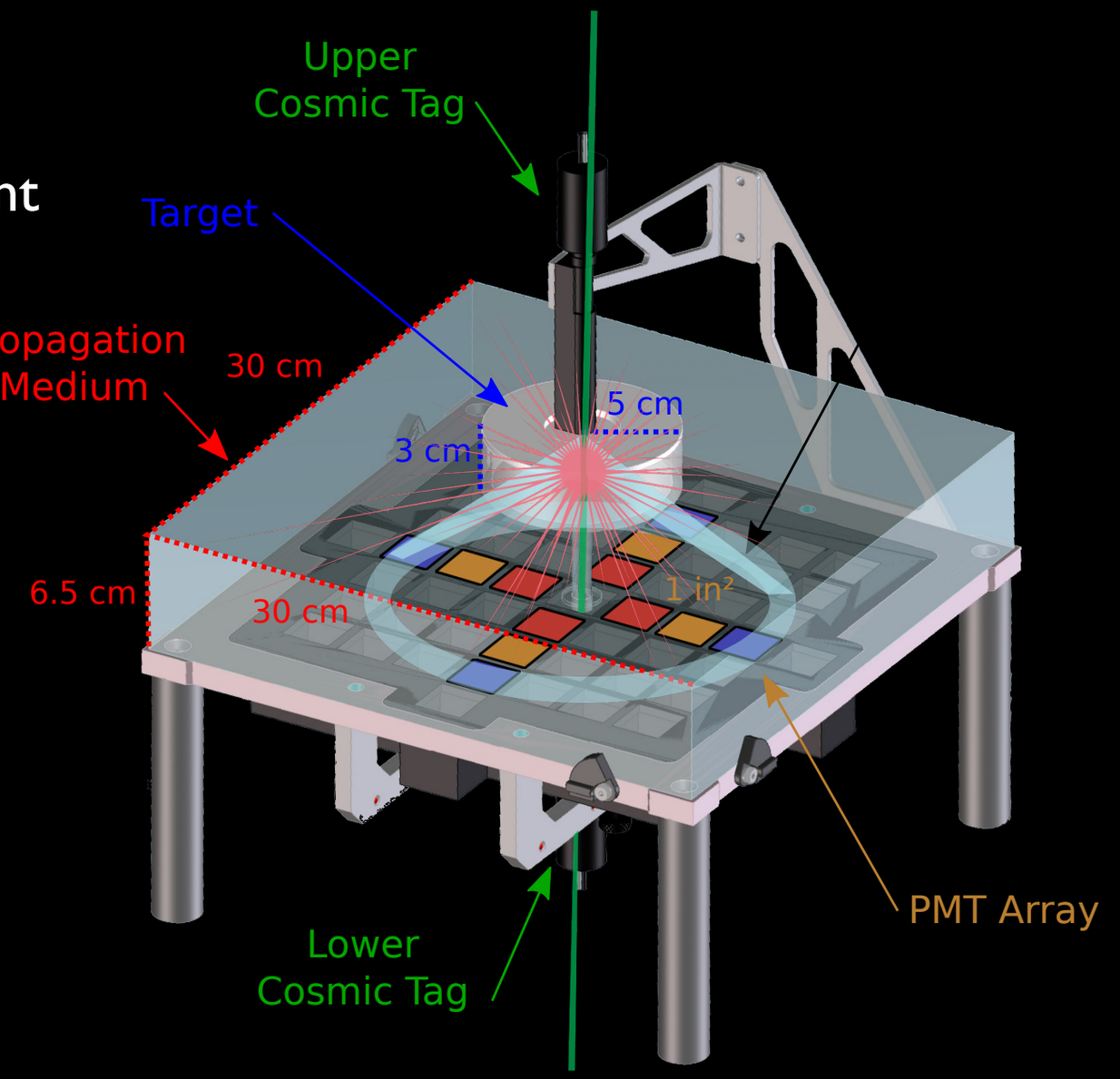

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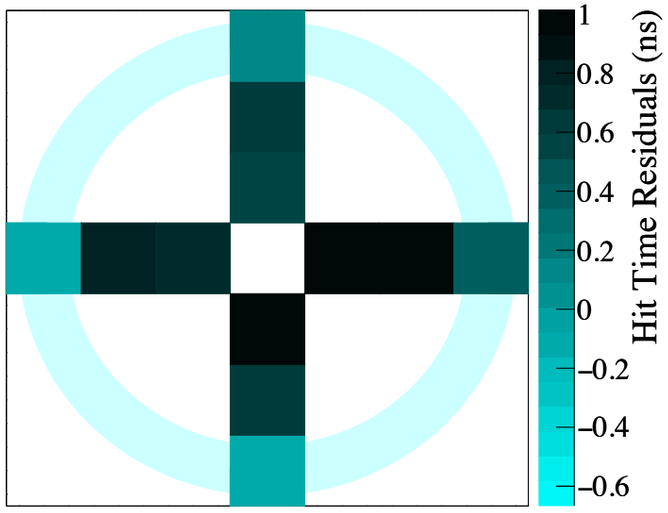
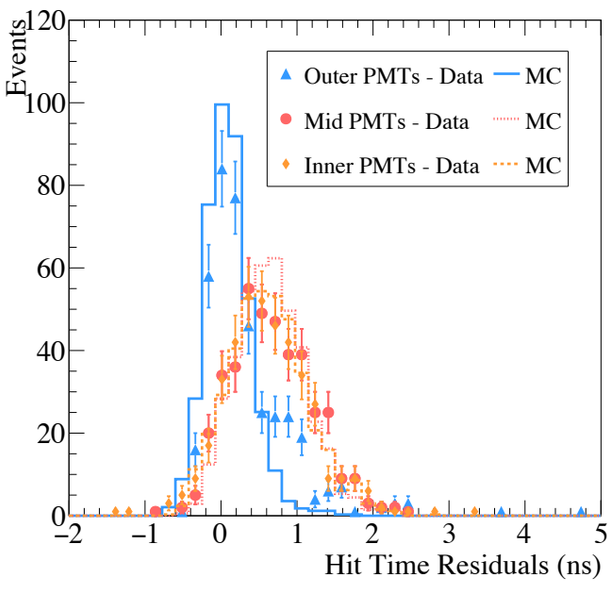
CHESS Results

Ring imaging and Cher/scint separation in high light yield scintillator

Eur. Phys. J. C (2017) 77: 811



Typical ring candidate event



Rise time = 0.75 ± 0.25 ns

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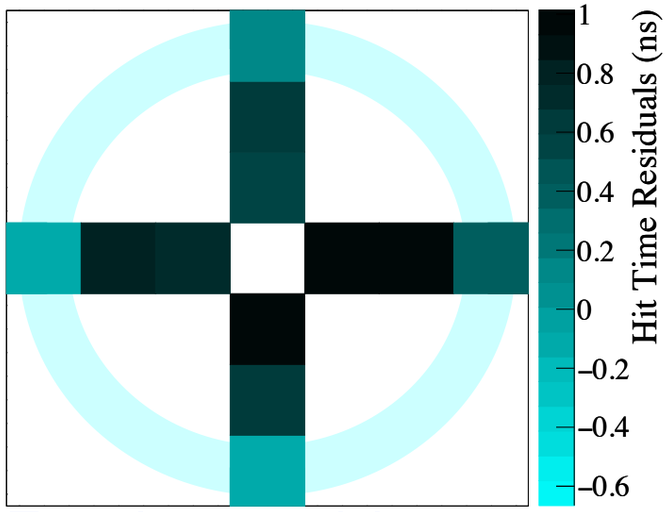

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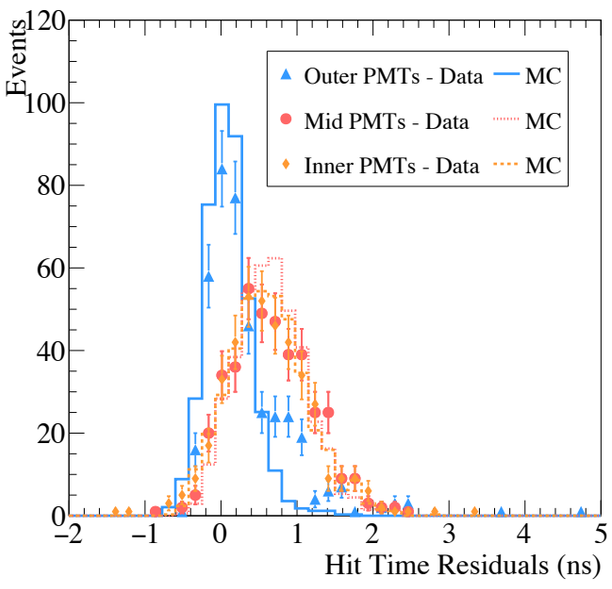

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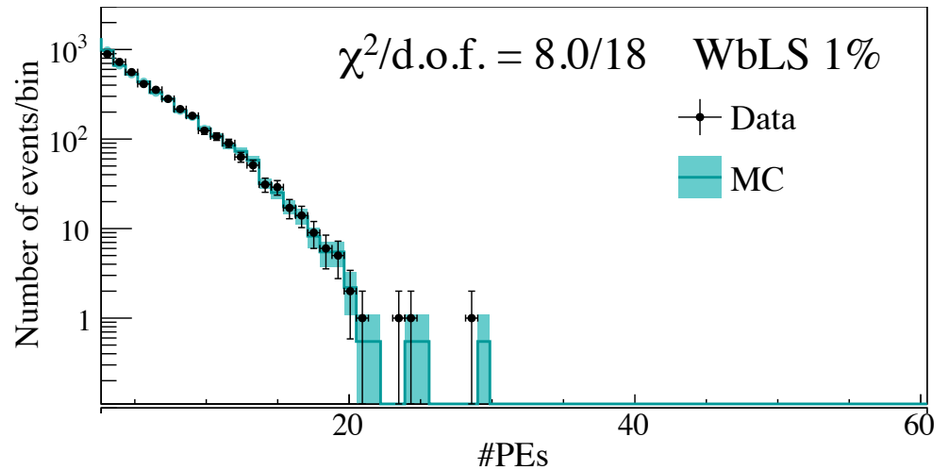
Microphysical measurement of WbLS properties

Eur. Phys. Jour. C 80 867 (2020)



Light yield	[photons/MeV]
1% WbLS	234 ± 30
5% WbLS	770 ± 72
10% WbLS	1357 ± 125

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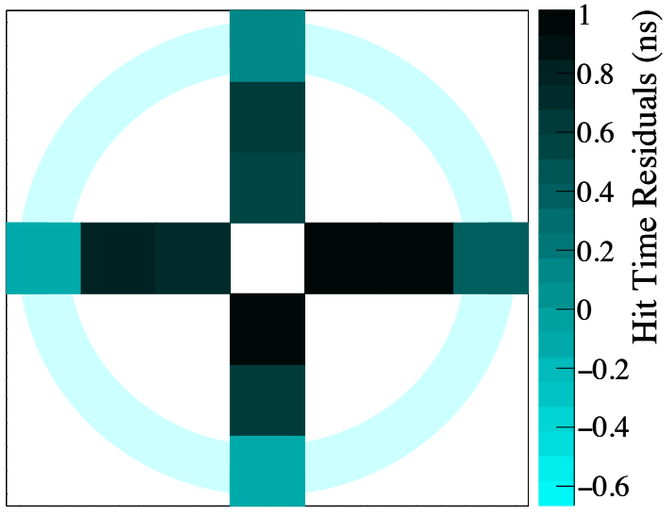
Eur. Phys. J. C (2017) 77: 811



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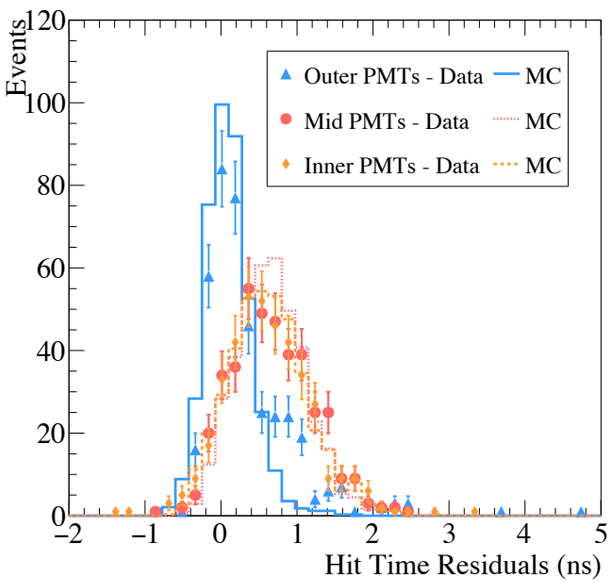

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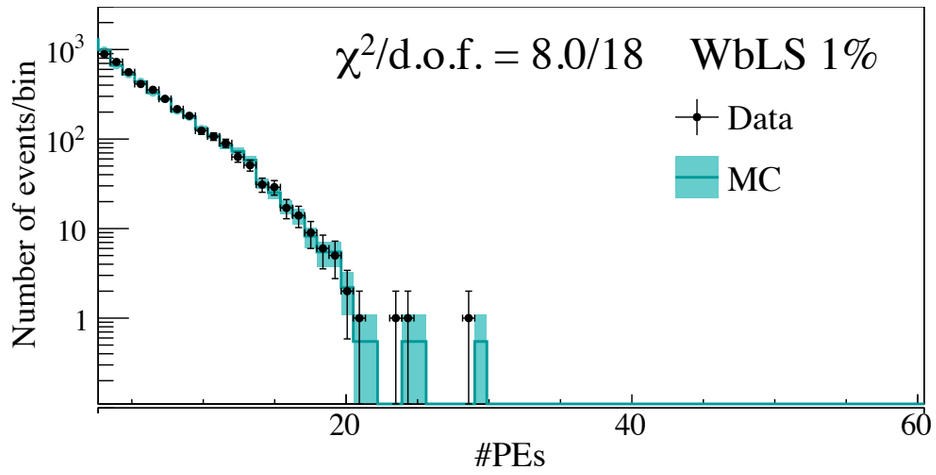

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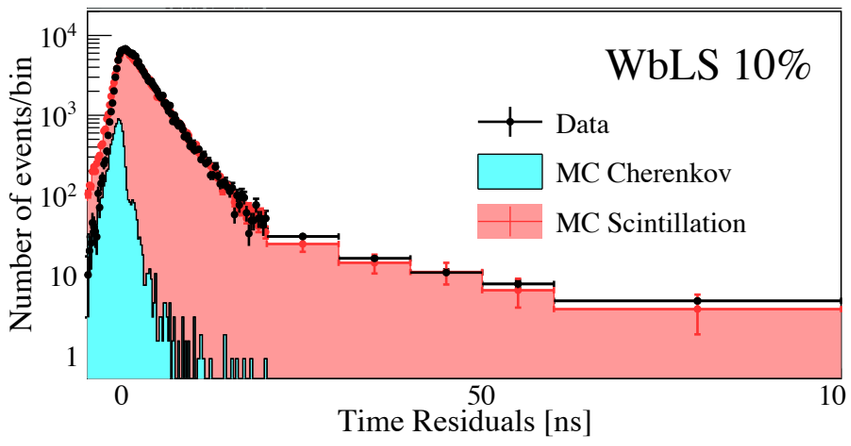
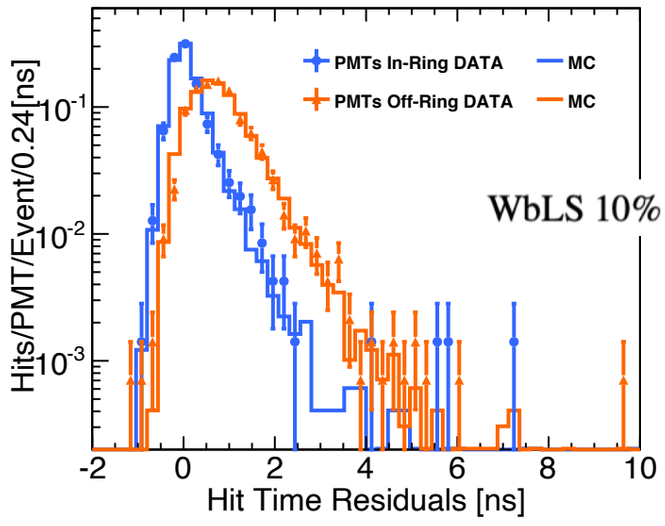
Time profile fit to hit-time residuals





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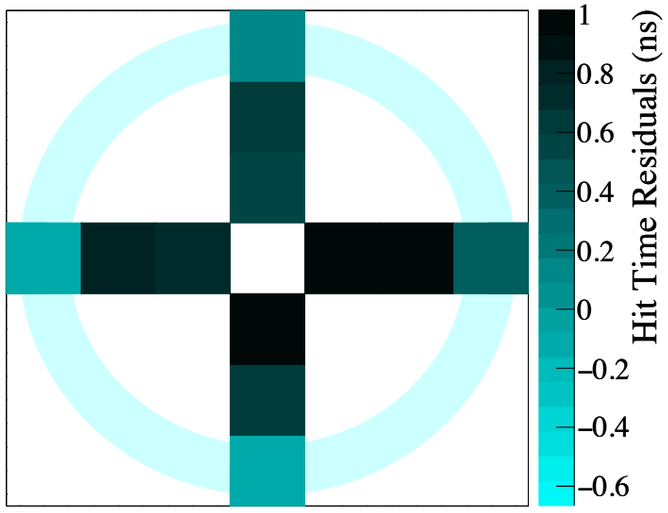
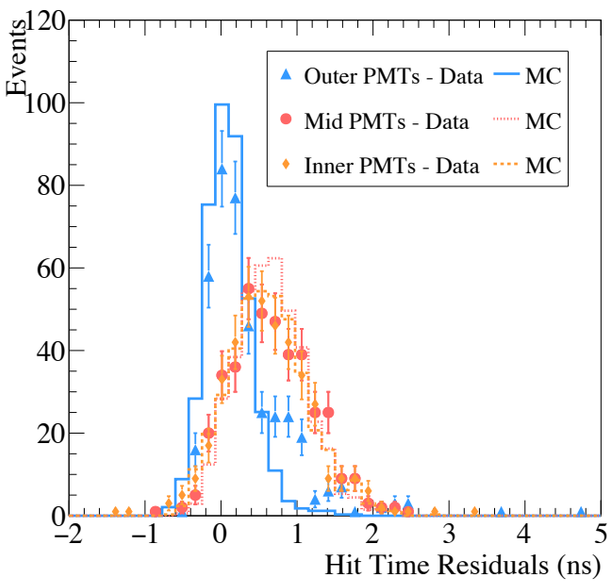


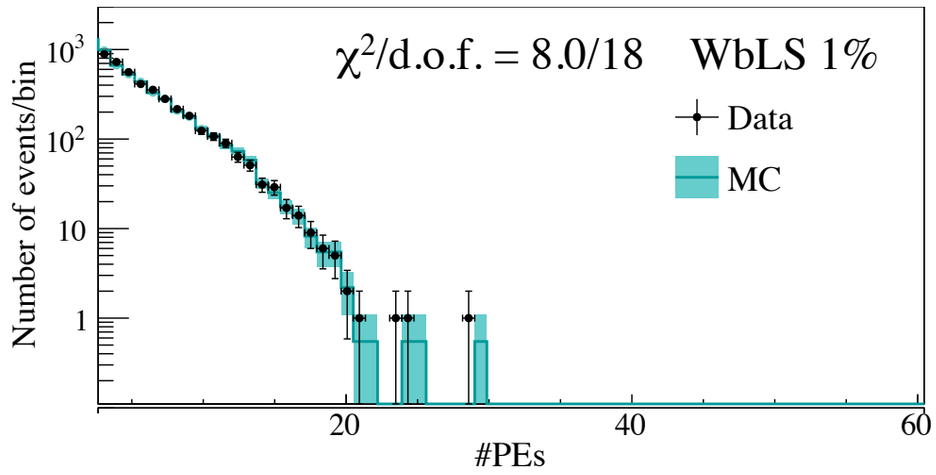
Typical ring candidate event



Rise time = 0.75 ± 0.25 ns

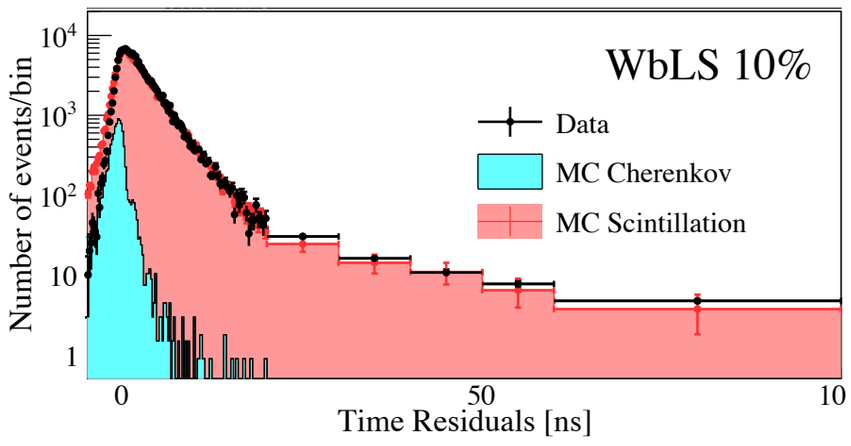
Microphysical measurement of WbLS properties

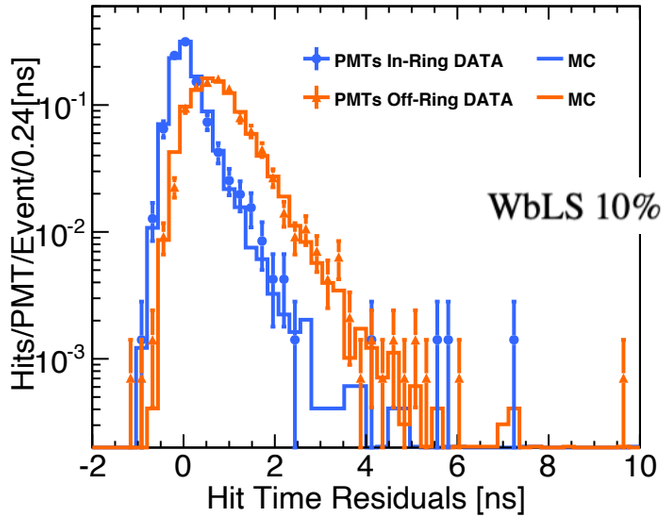
Eur. Phys. Jour. C 80 867 (2020)



Light yield	[photons/MeV]
1% WbLS	234 ± 30
5% WbLS	770 ± 72
10% WbLS	1357 ± 125

Time profile fit to hit-time residuals





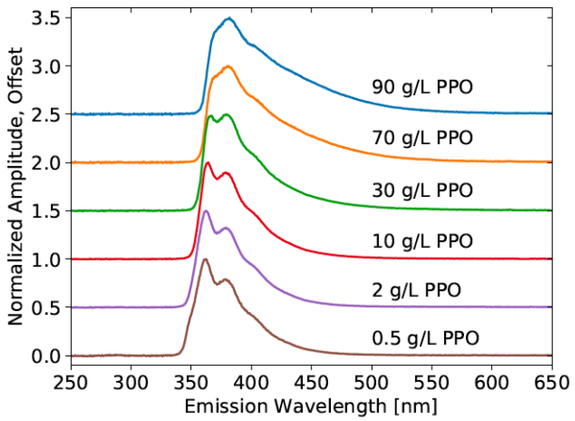
More light than "naive" expectation based on %LS scaling.

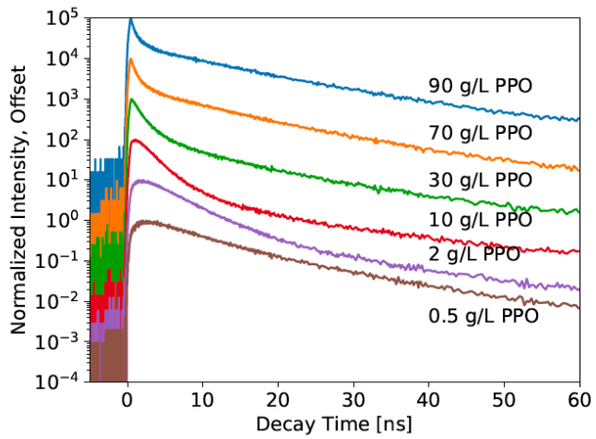
Substantially faster than pure LS (~2.5ns compared to 5ns).

WbLS properties

Collaborative with Bourret et al. (LBNL)

X-ray excitation measurement of emission spectra and time profile explains observed WbLS properties





Materials Advances 2020, 1, 71-76
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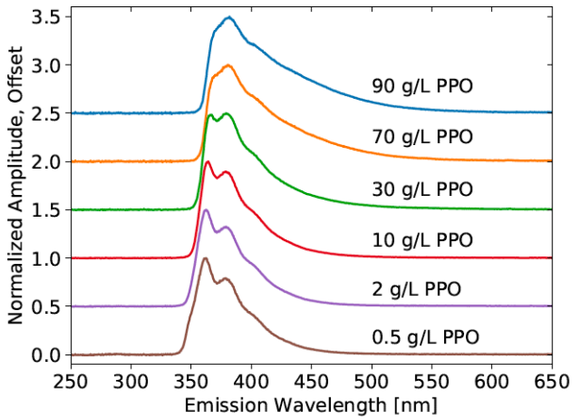

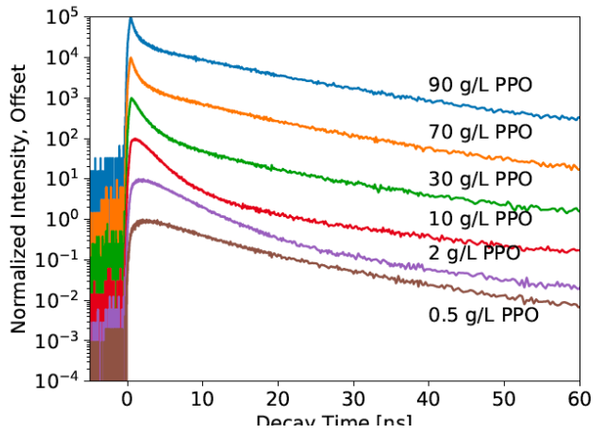

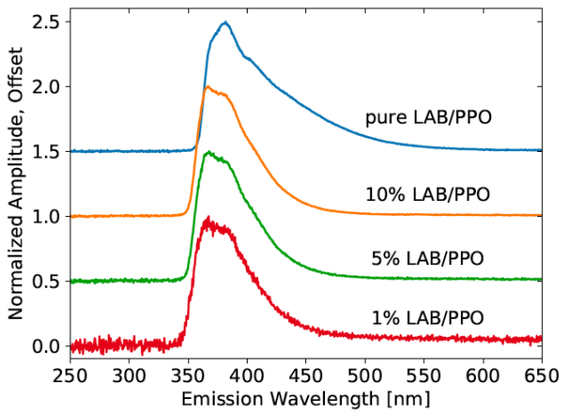

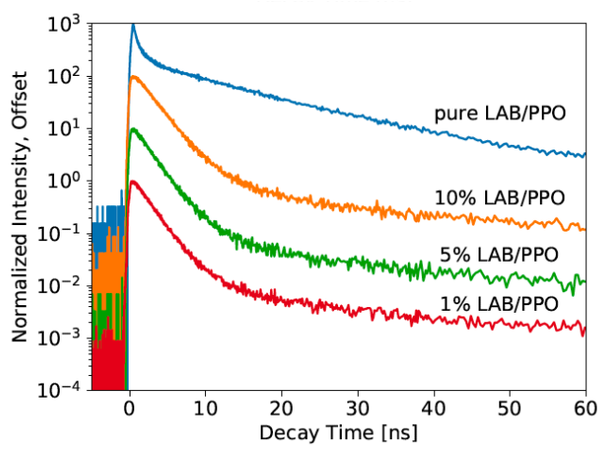

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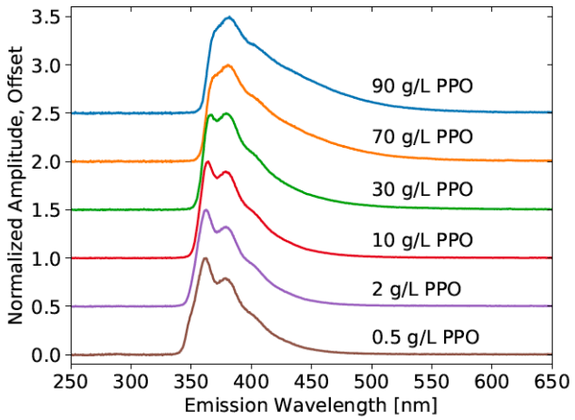

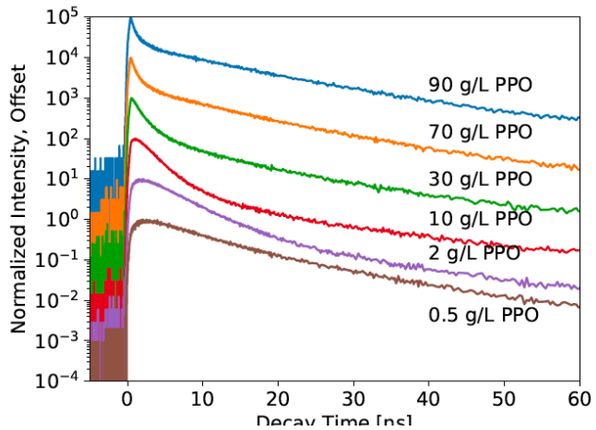

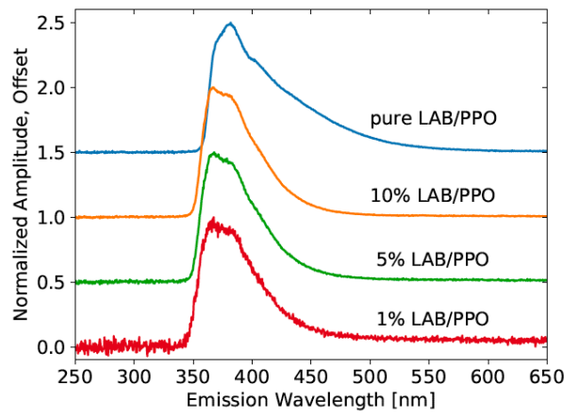

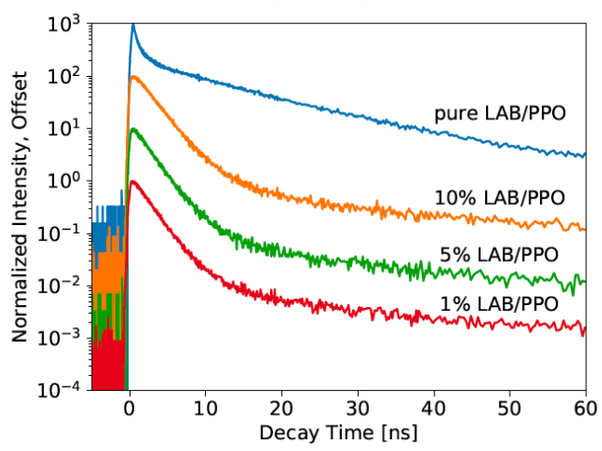

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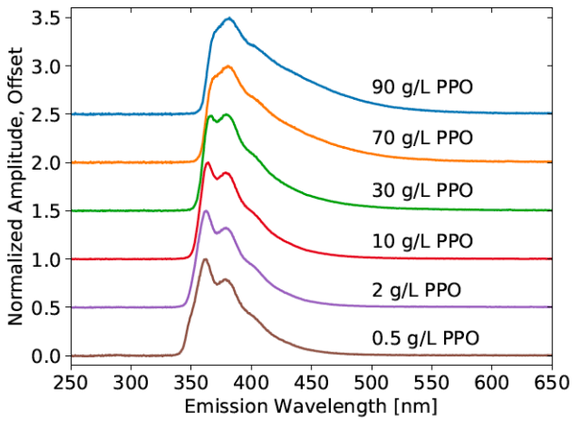

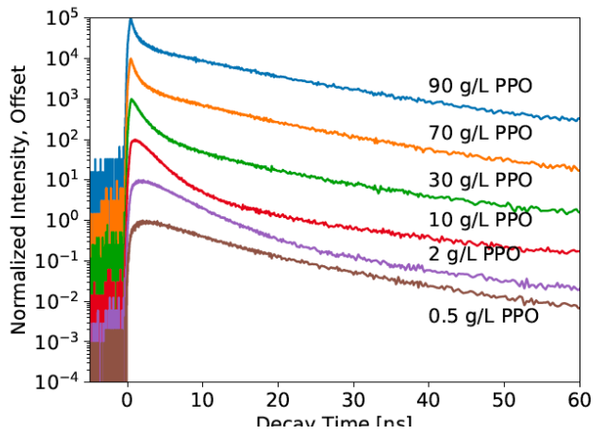

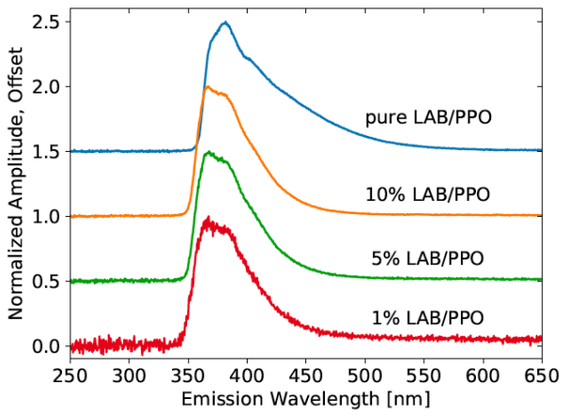

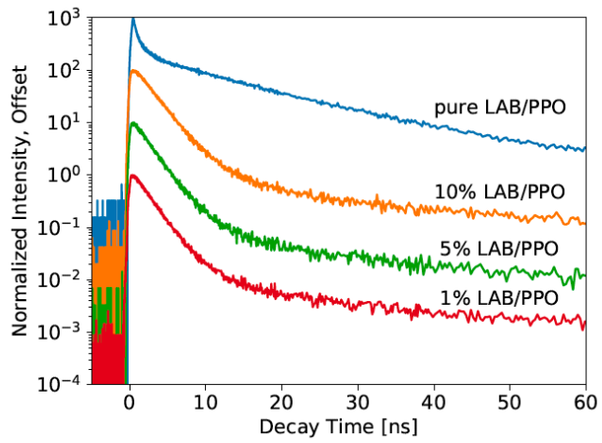

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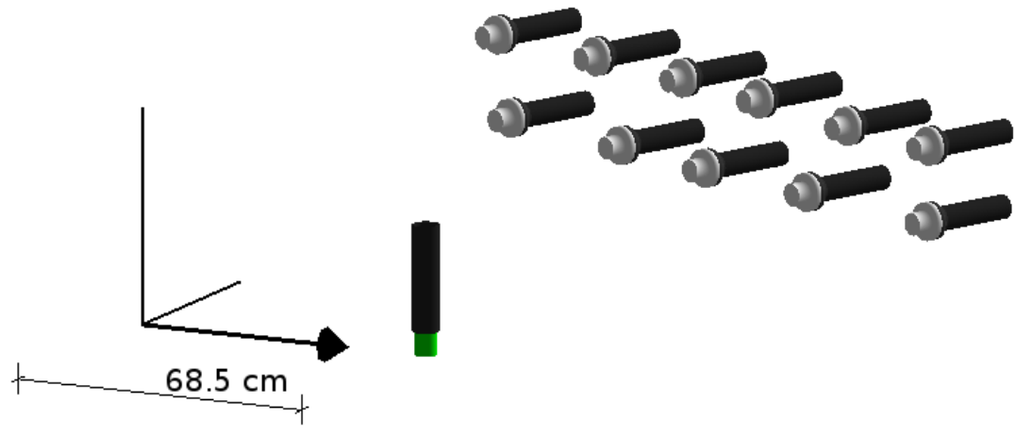
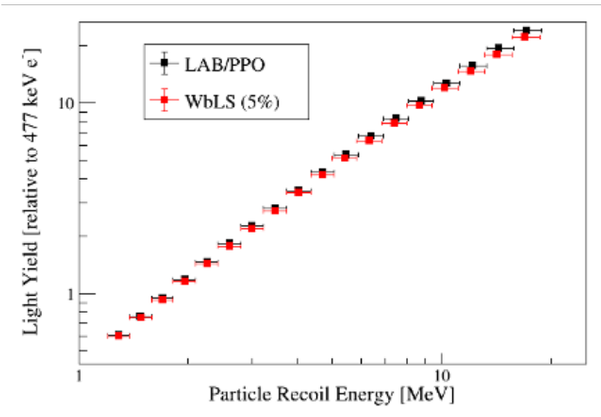
Collaborative with Goldblum et al. (LBNL) and Wurm, Steiger, Oberauer (Mainz/Munich)

Ongoing proton quenching measurements at 88" cyclotron (LBNL) and beam line in Padua



Measure proton recoil light yield relative to Compton edge, calibrated using γ sources. Relevant for understanding fast neutron background to IBD events and νe-p scattering for SN detection



LAPPD @ CHESS

Building on substantial work by U. Chicago, Iowa, LAPPD team, ANNIE collaboration & others

- High-precision fast-timing (~70 ps) photon detectors
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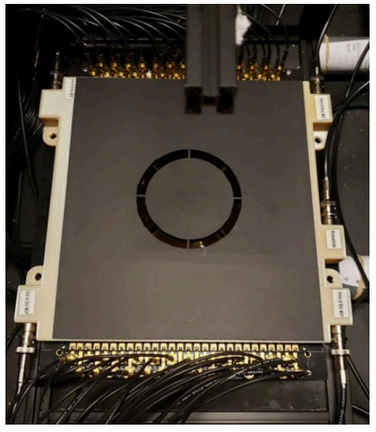

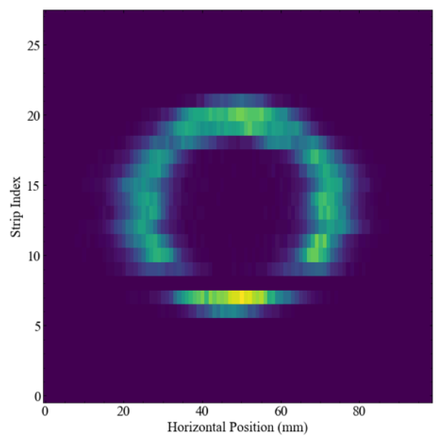

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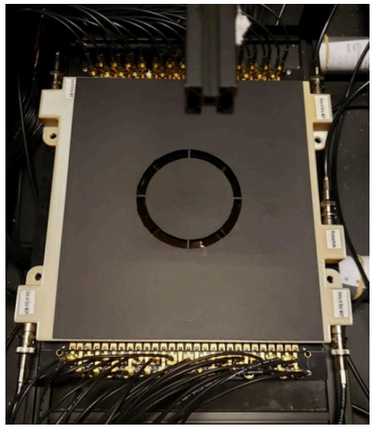

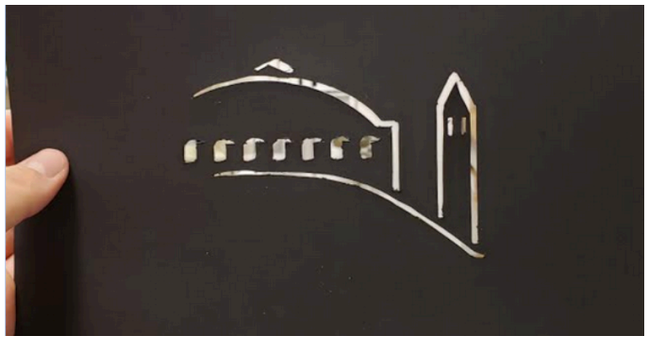

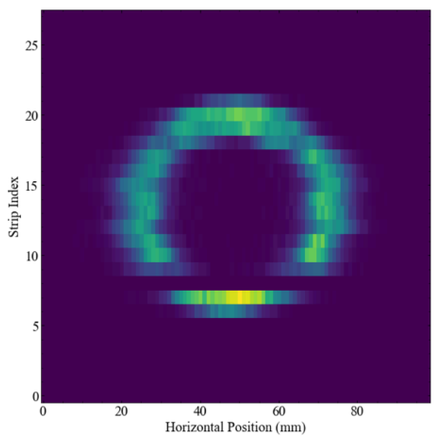

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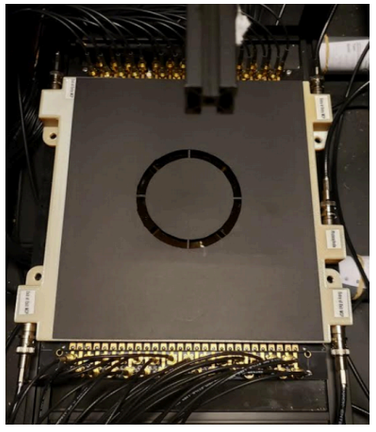

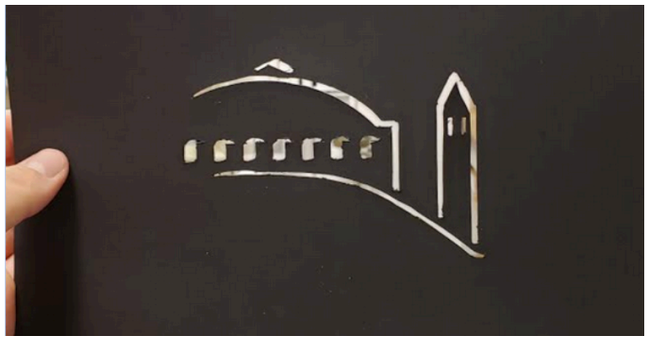

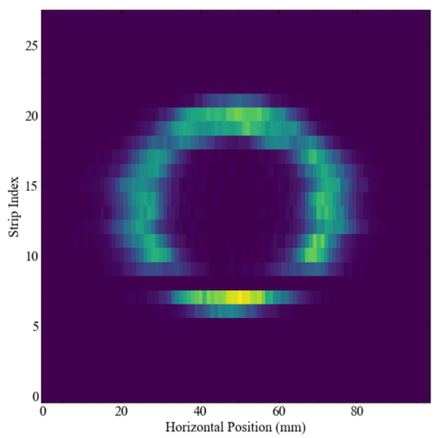

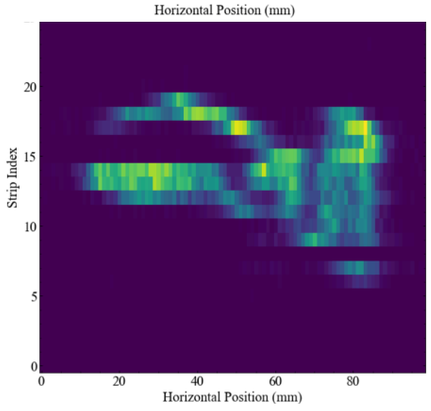

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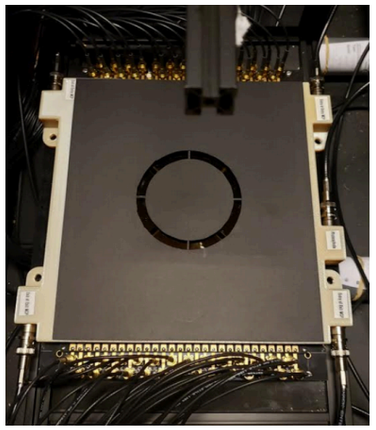
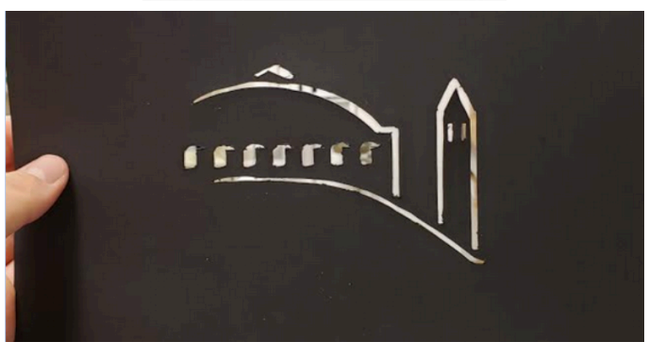
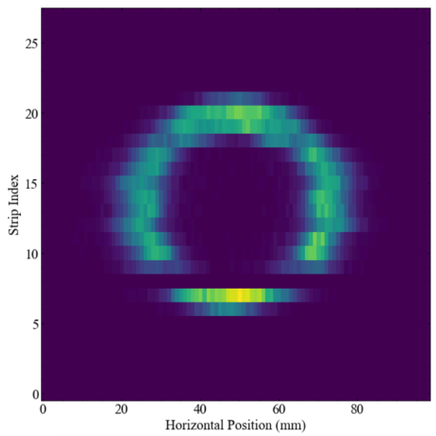
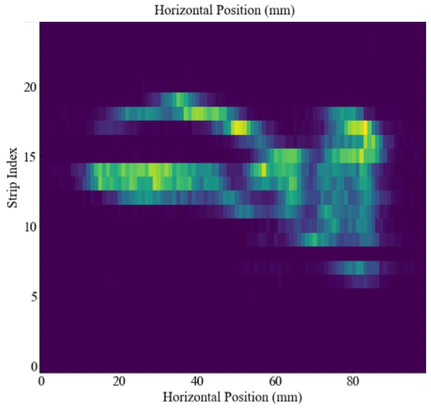
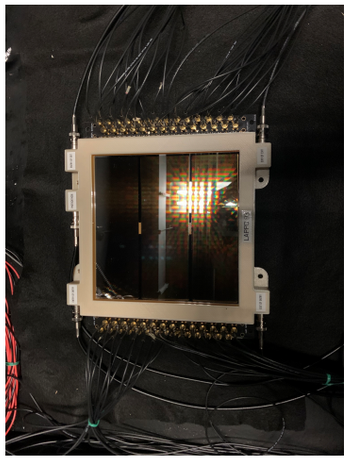








- New tile [#93] purchased via MTV consortium
  - 70 ps TTS, 34% QE, improved uniformity, excellent gain
- Physics deployment at CHESS ongoing



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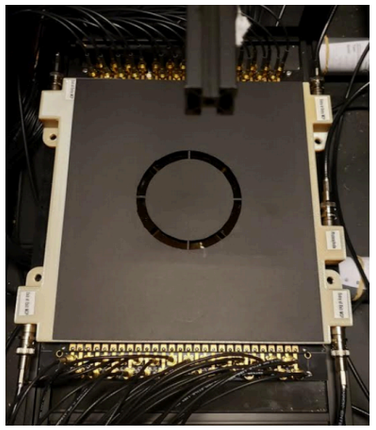

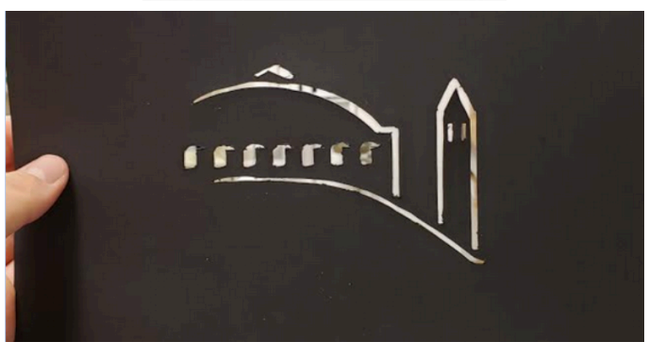

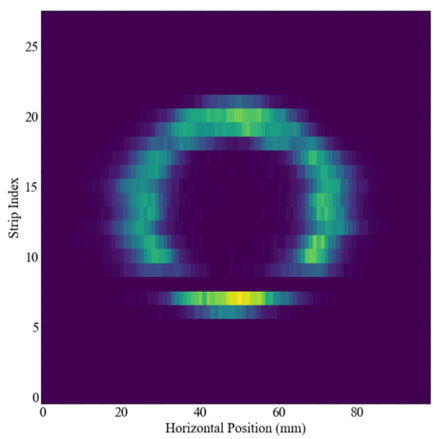

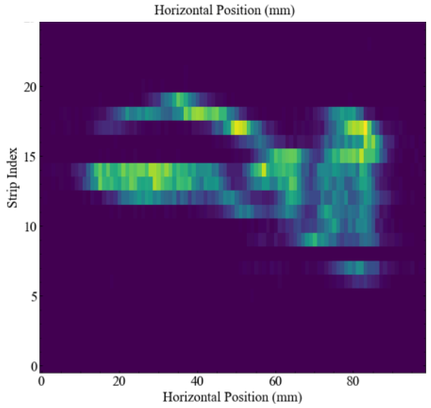

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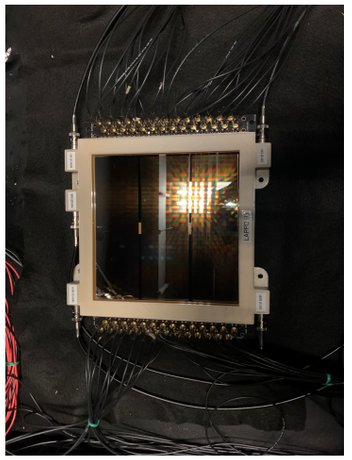
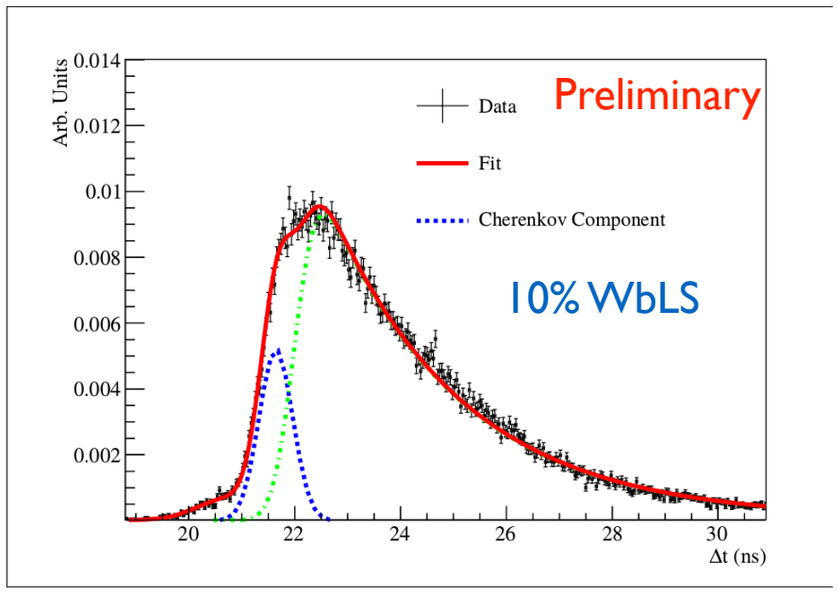
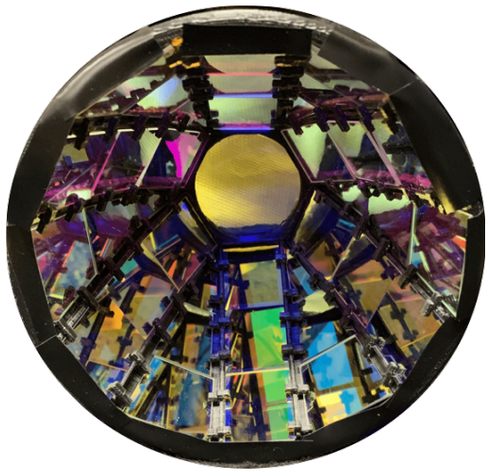




Chromatic quantum sensing



Collaborative effort with J. R. Klein (U. Penn)

Dichroicons sort incident photons by wavelength
Achieves spectral separation of Cherenkov and scintillation.
A dichroicon will be deployed at CHESS to quantify performance.

T. Kaptanoglu, Nucl. Instrum. Meth. A889 (2018) 69-77
T. Kaptanoglu, M. Luo, J. Klein, JINST 14 no. 05 T05001 (2019)

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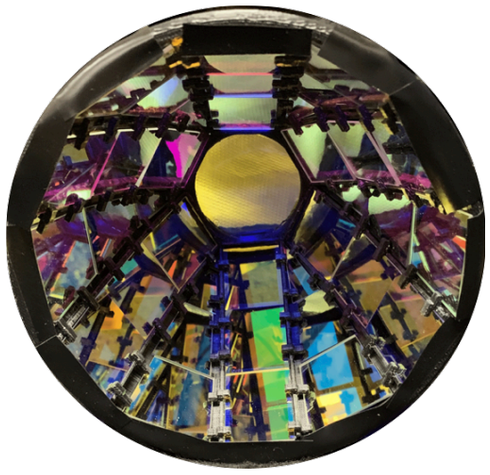

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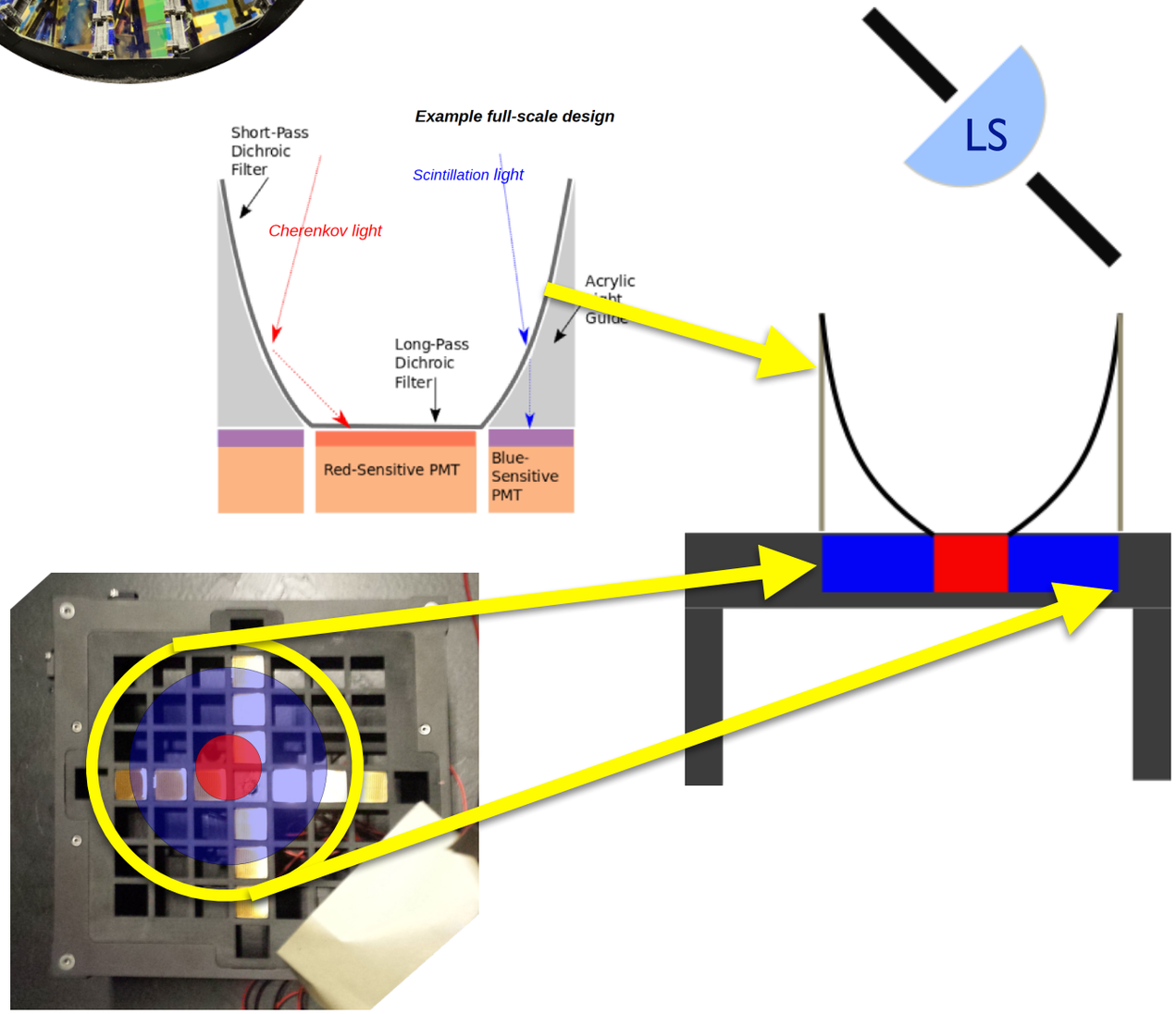

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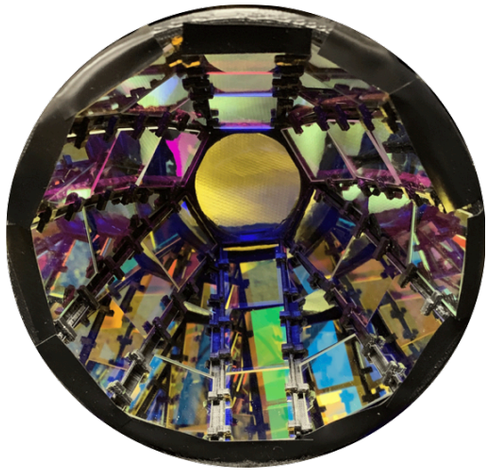

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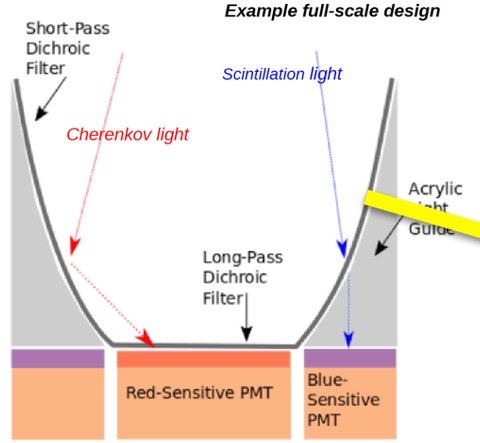
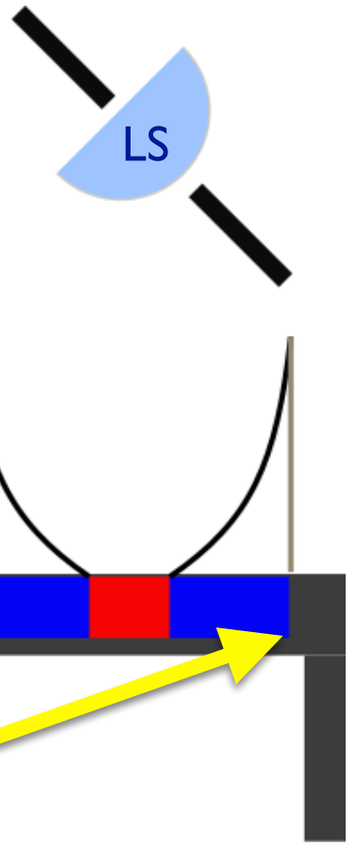
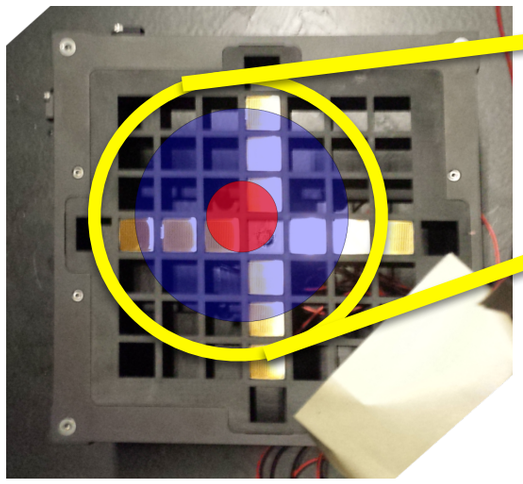
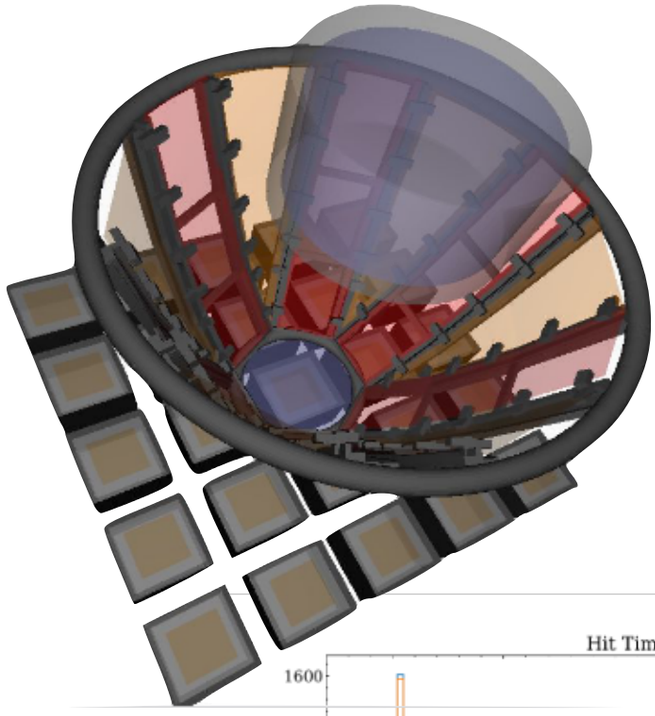


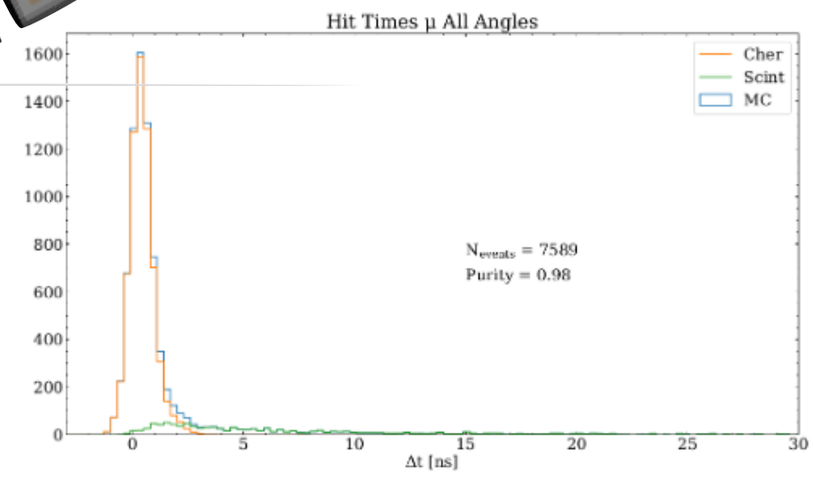
Example full-scale design

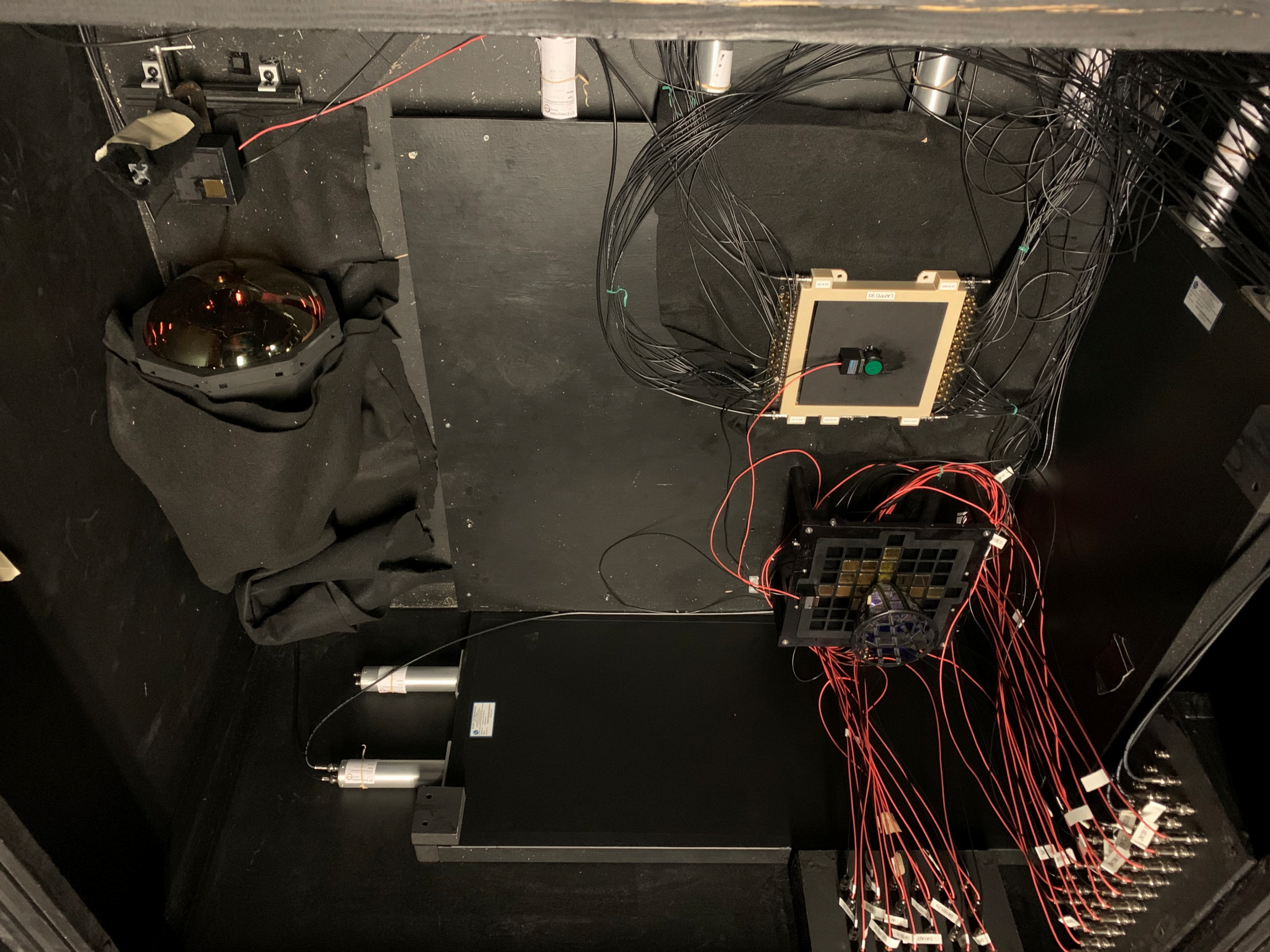






98% Cherenkov
"purity" predicted





Signal Separation in Theia

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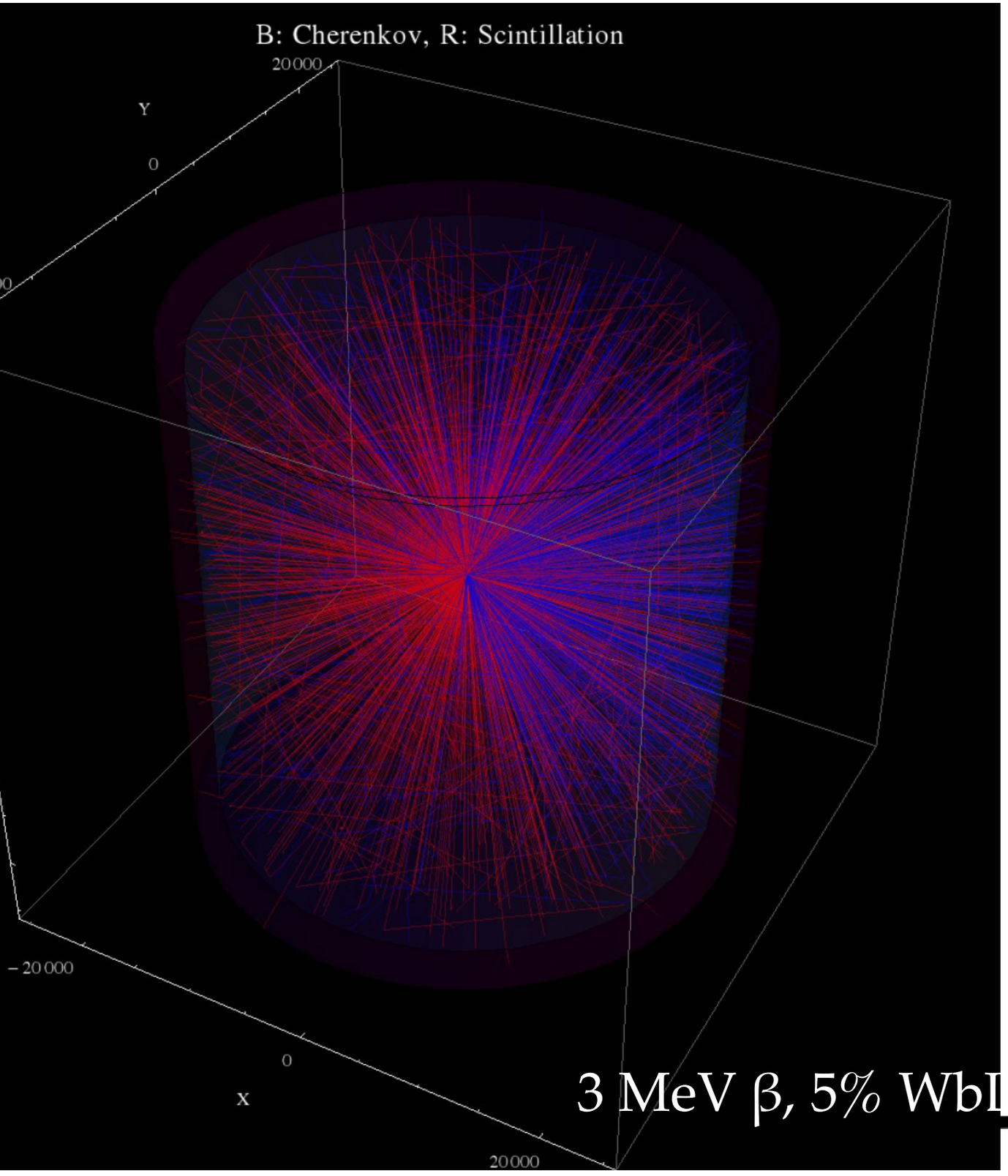
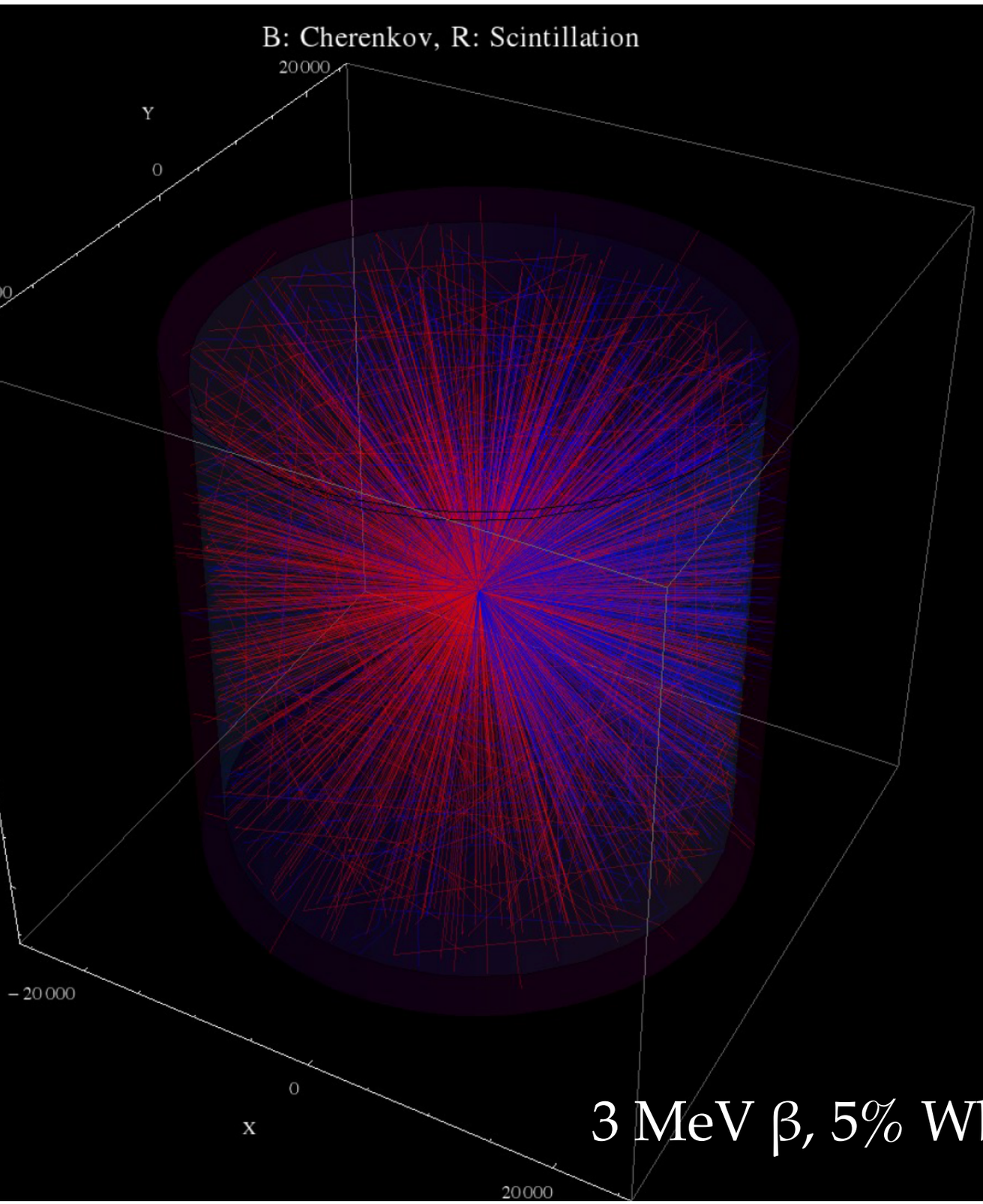
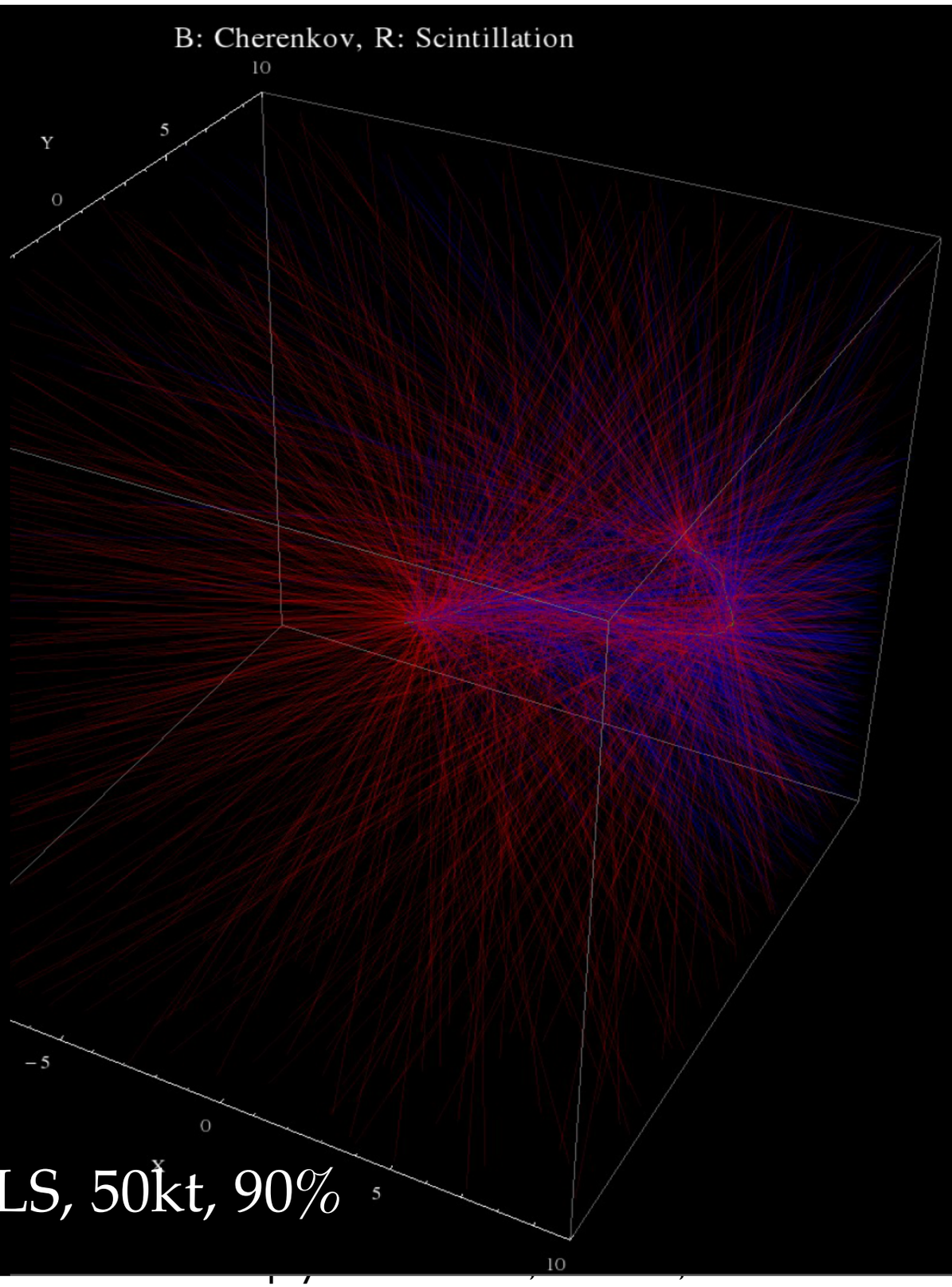


3 MeV β, 5% WbI

Signal Separation in Theia

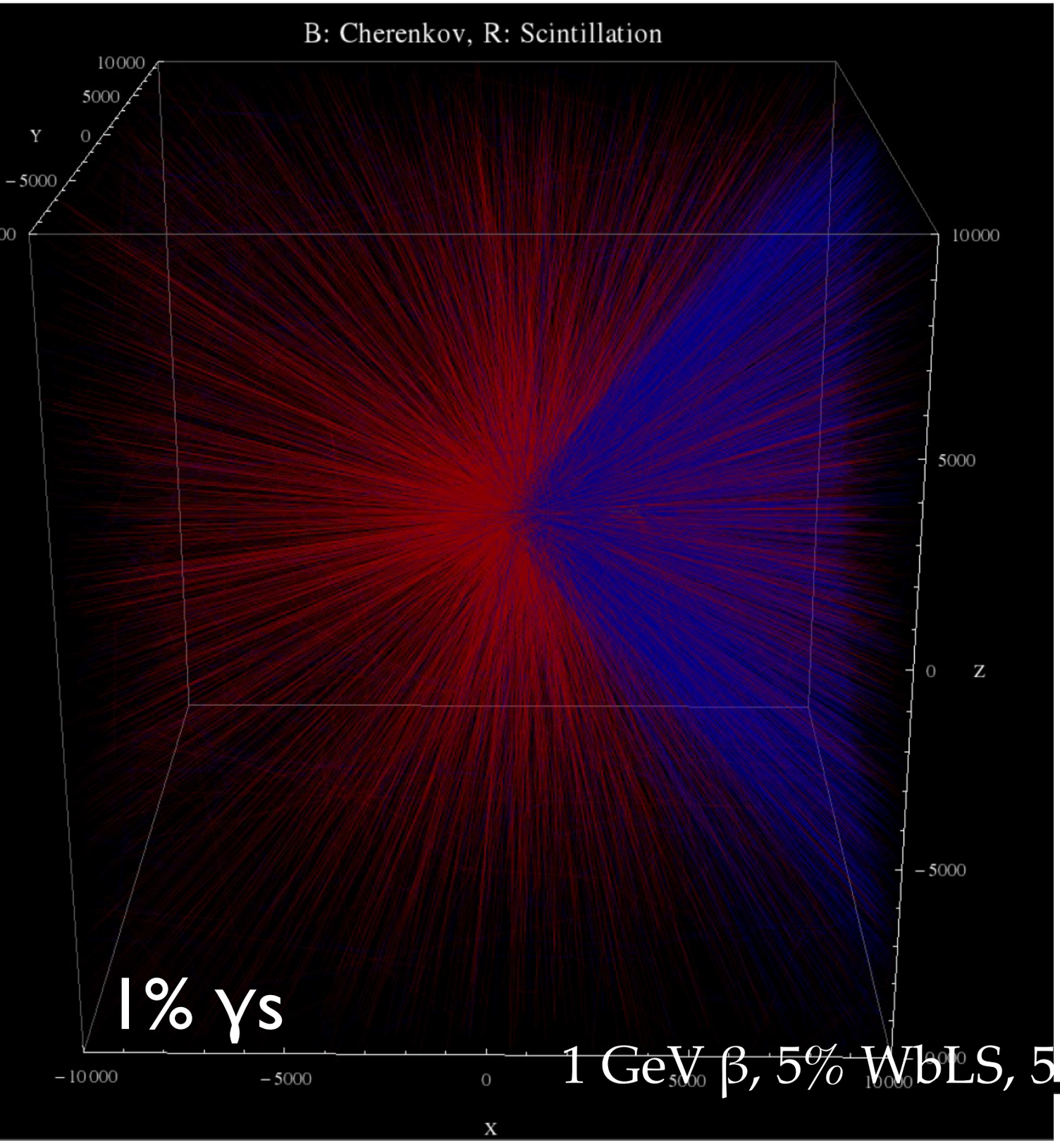




3 MeV β, 5% WbLS, 50kt, 90%

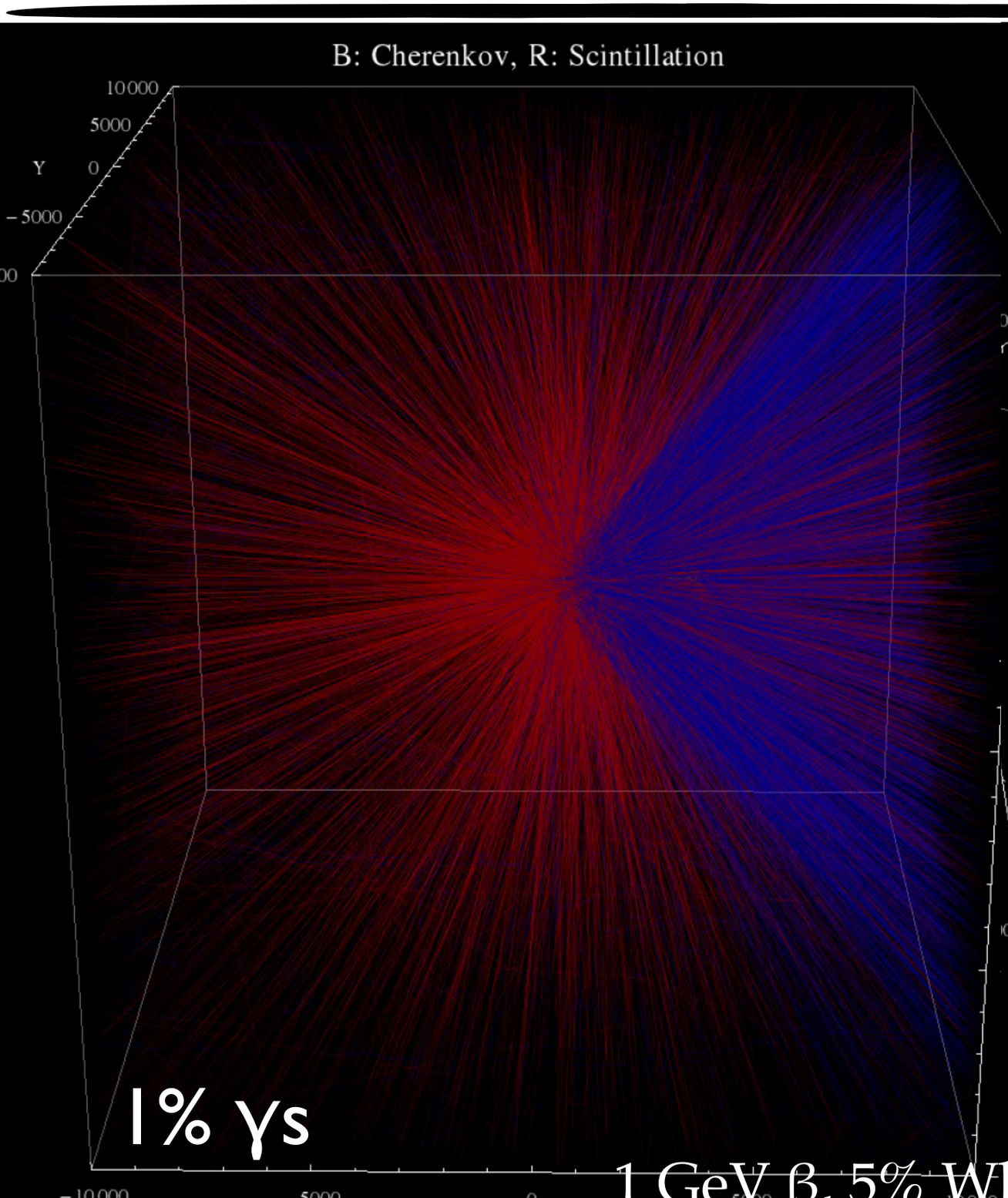
Ring Imaging

Ring Imaging

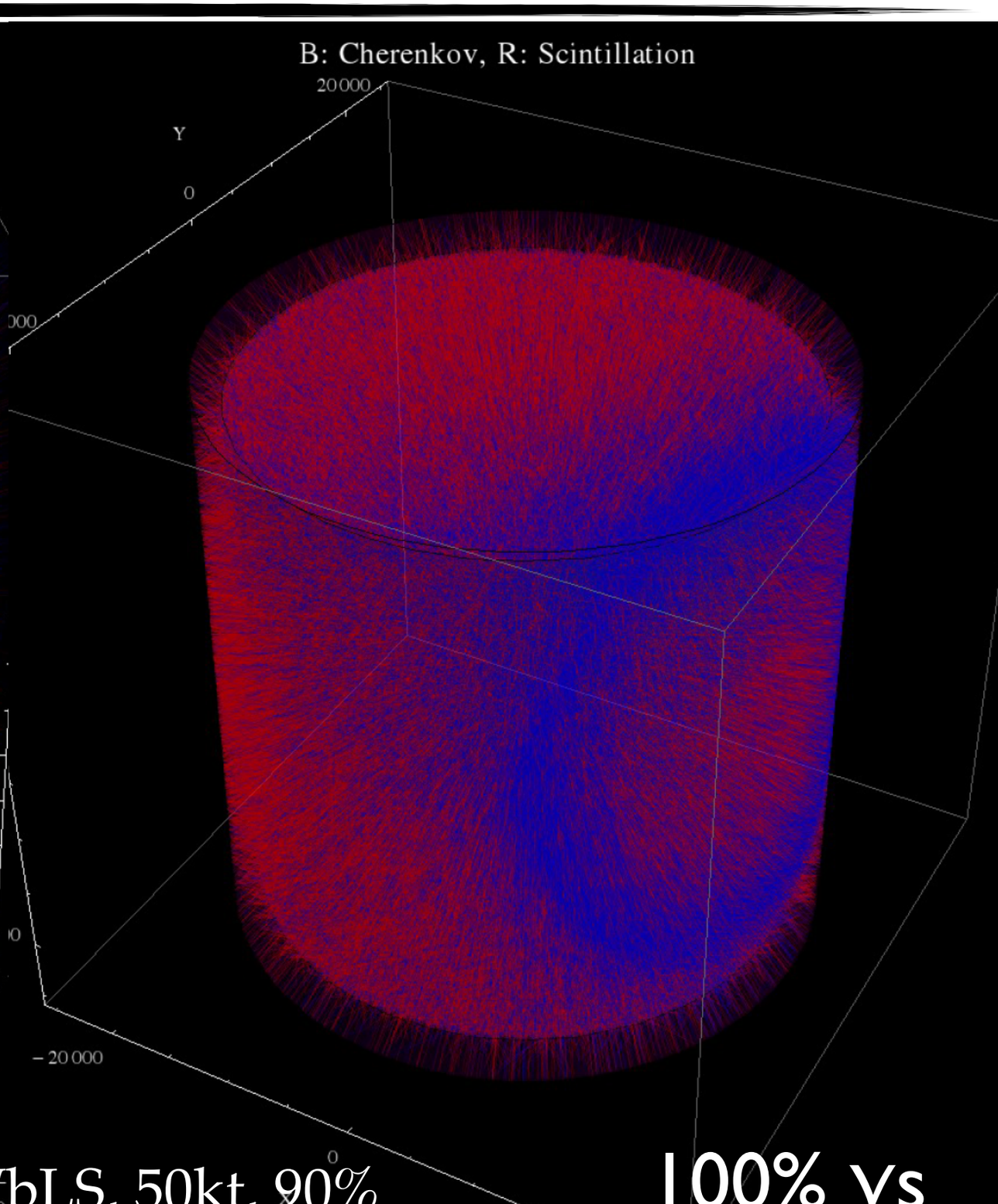


1 GeV β, 5% WbLS, 5

Ring Imaging



1% γs



100% γs

1 GeV β, 5% WbLS, 50kt, 90%

Eos: hybrid detector prototype

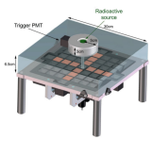
Data-driven demonstration

- ✓ *Demonstrate Cher+scint reconstruction*
- ✓ *Demonstrate Cher+scint particle ID*
- ✓ Enable broad, world-leading physics + nonpro program

Demonstration of next-generation detector capabilities

Develop **R&D infrastructure** — testbed for future programs

CHESS
200mL
LBNL LDRD
(FY13-14)



First demonstration of Cherenkov light detection from high yield liquid scintillators

Critical few-ton scale demonstration of detector performance capabilities

Importance for programs in NNSA + ONP, OHEP, & international partners

ANNIE: high-energy ν, neutrons

EOS: low-energy β,γ,α, event reconstruction and PID

Eos (Dawn)

Funded by NNSA,
DNN R&D
FY22-24

Let There be Light