THEIA

An Advanced Scintillation Detector

Physics Potential and R&D Program

FROST-ii
Oct 22nd 2016

Gabriel D. Orebi Gann
UC Berkeley & LBNL

Transformational Opportunity

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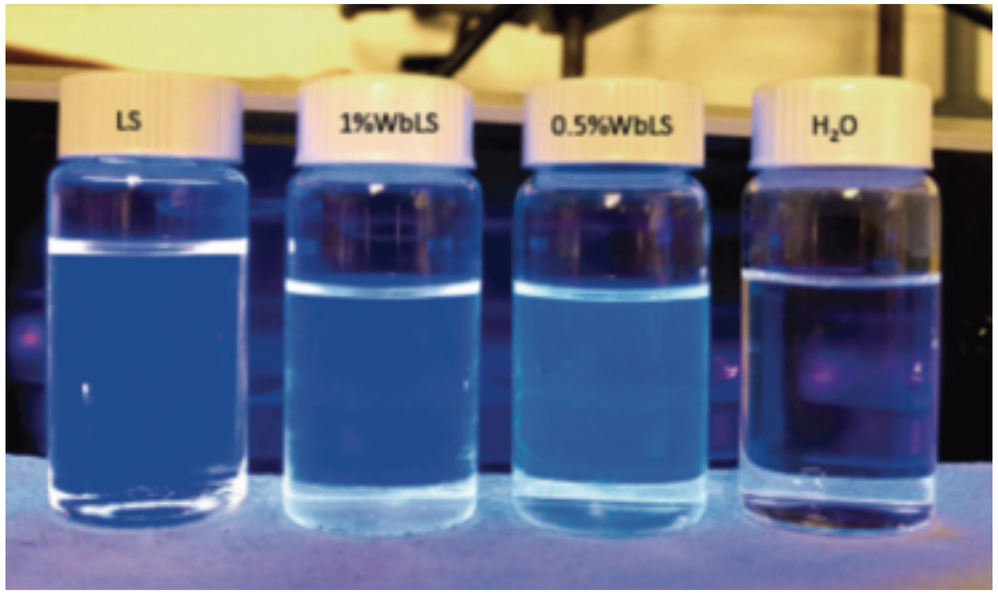

Development of new scintillators e.g. WbLS

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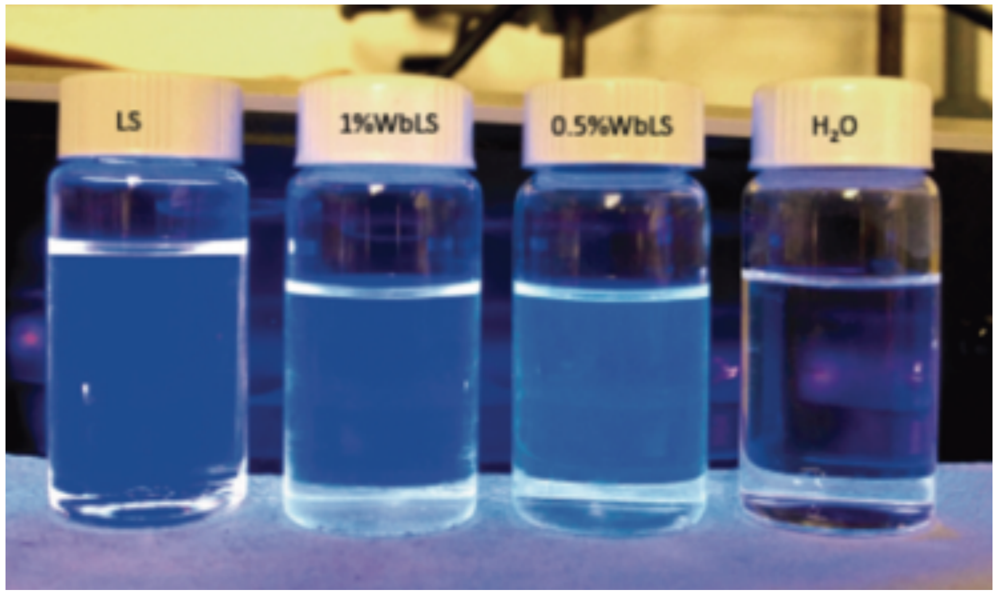

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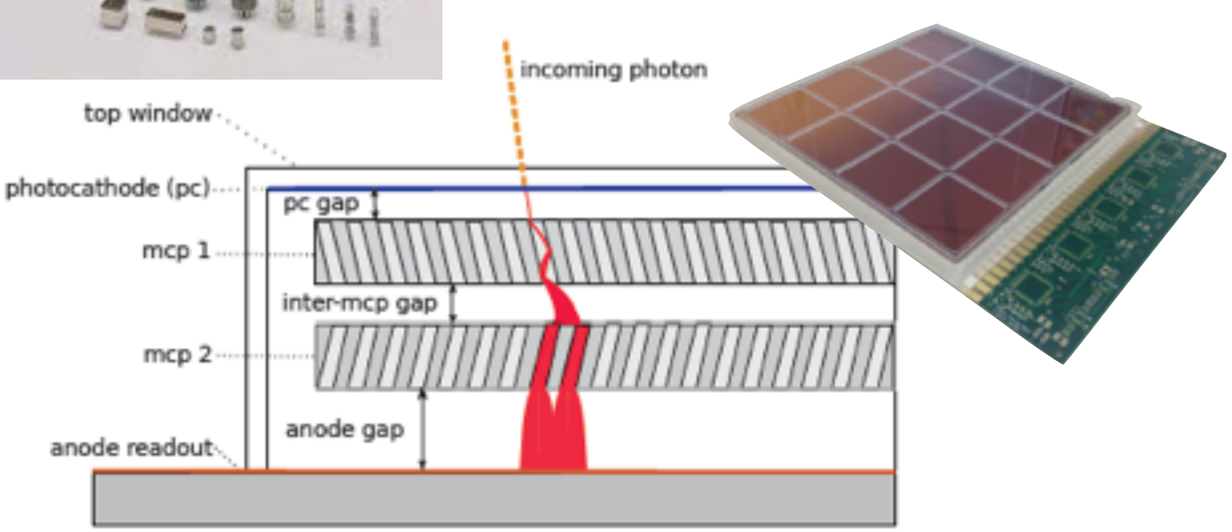
Fast, efficient photodetectors



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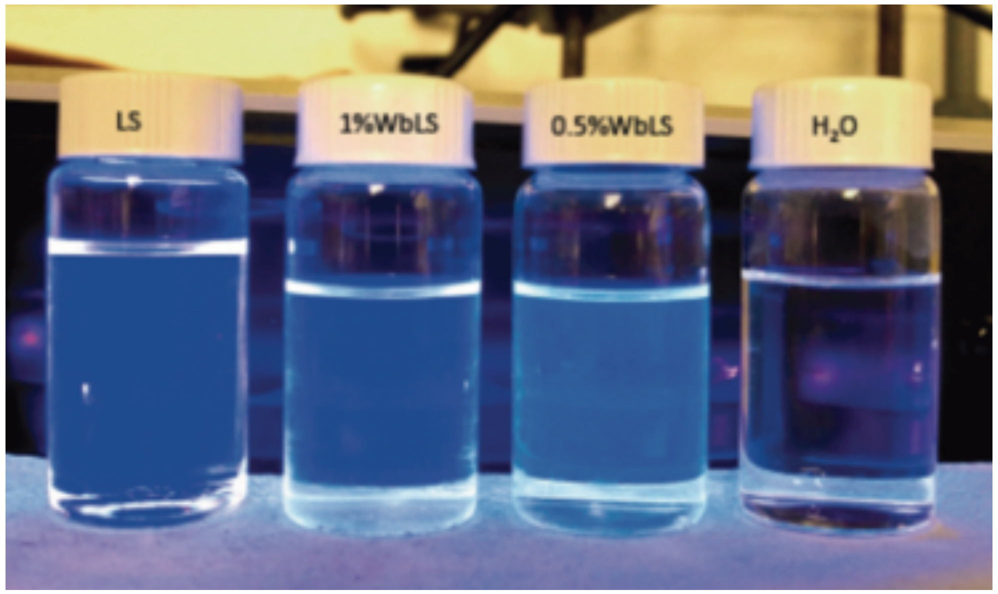

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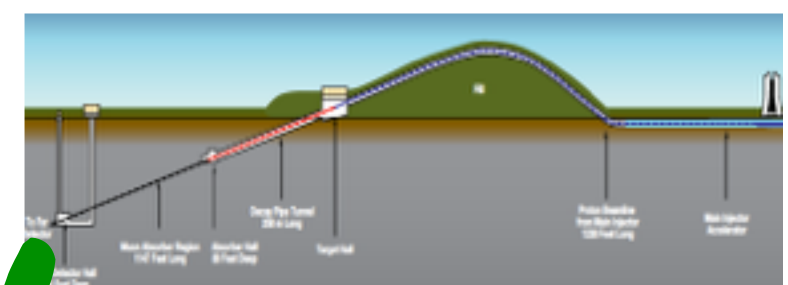
Fully-equipped, deep underground labs (+ beam)



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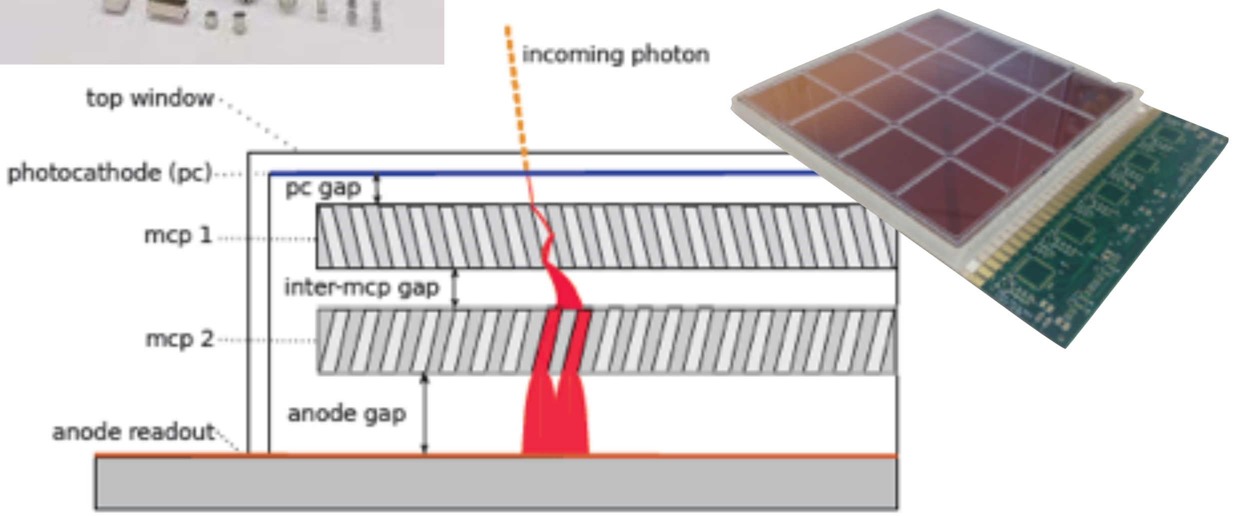

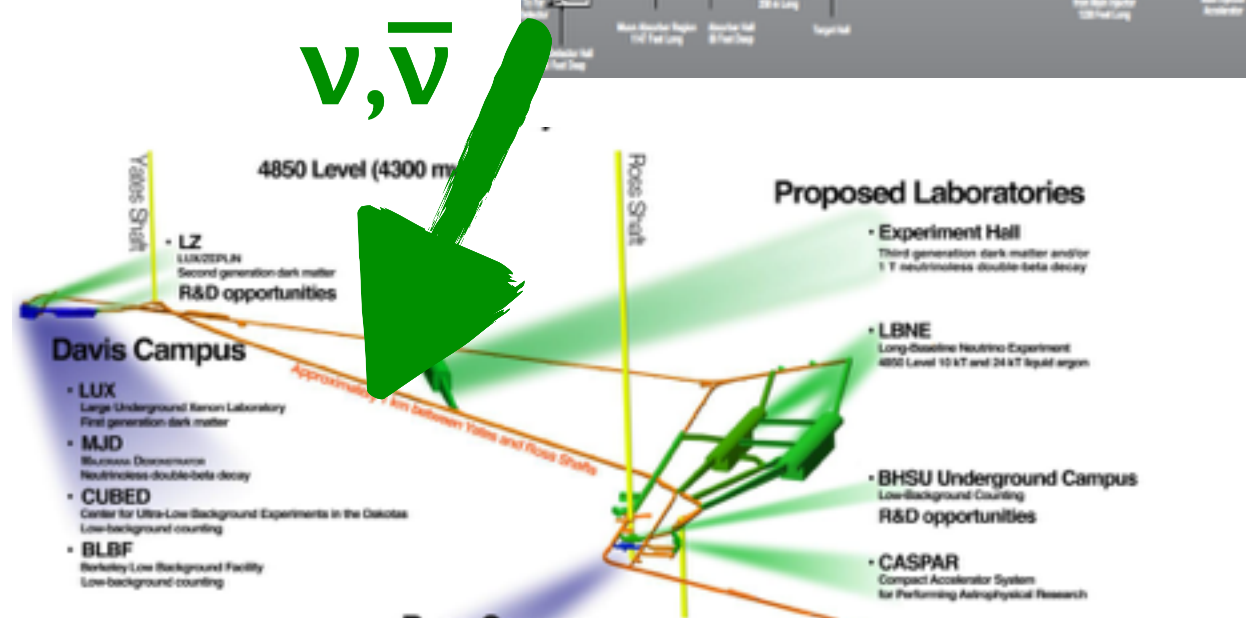

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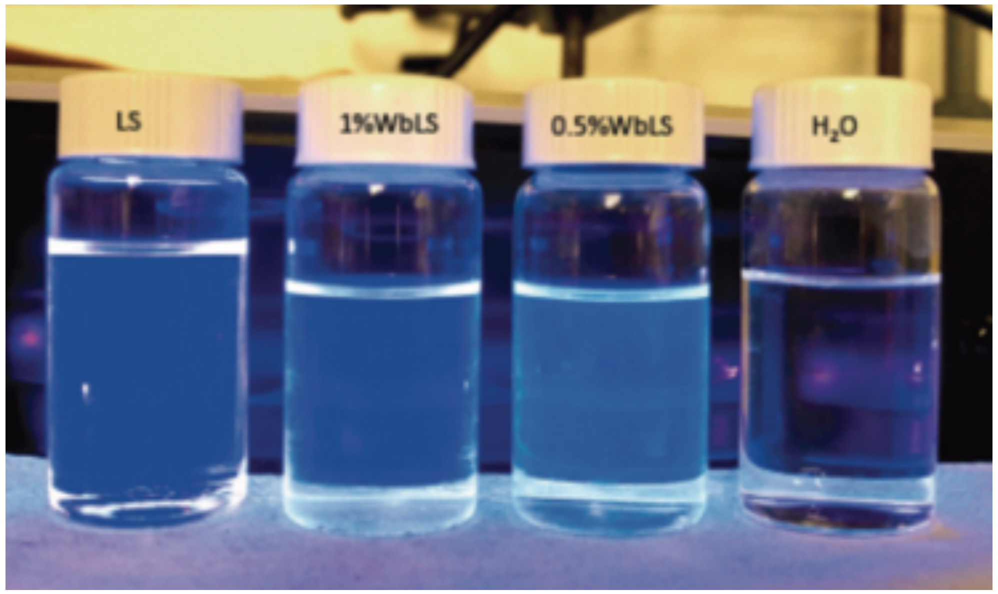

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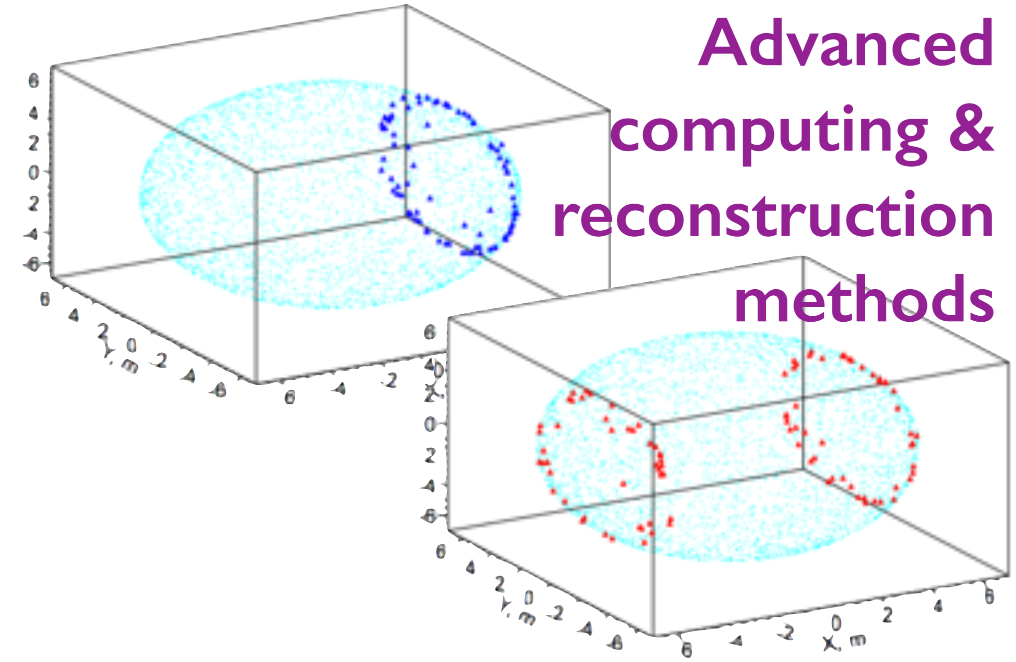

Advanced computing & reconstruction methods

A. Elagin et al., arXiv:1609.09865

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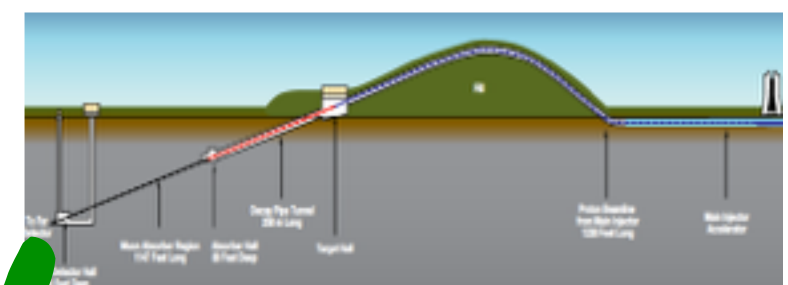

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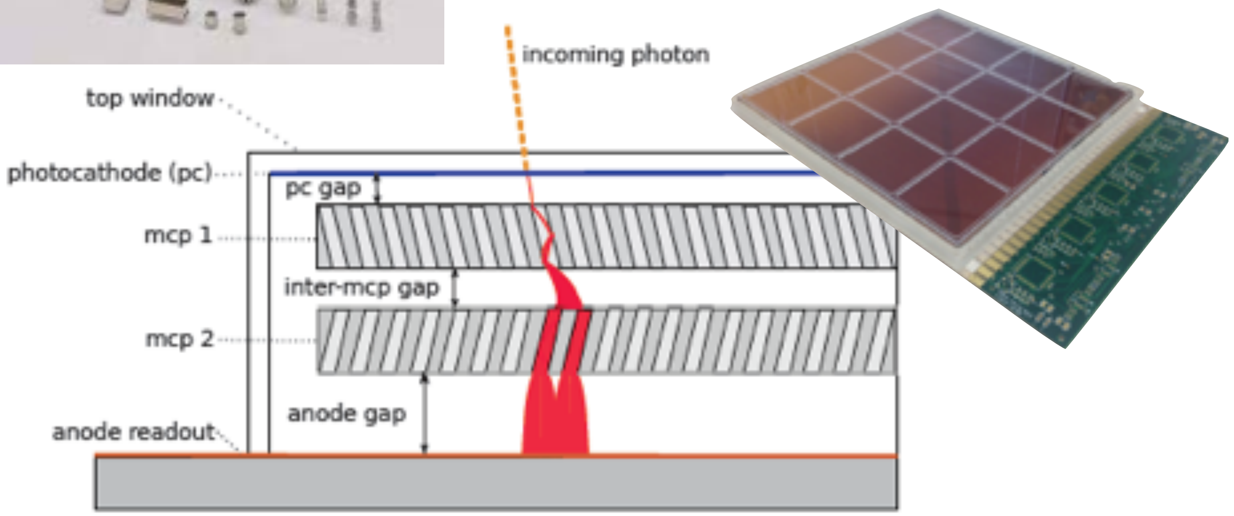

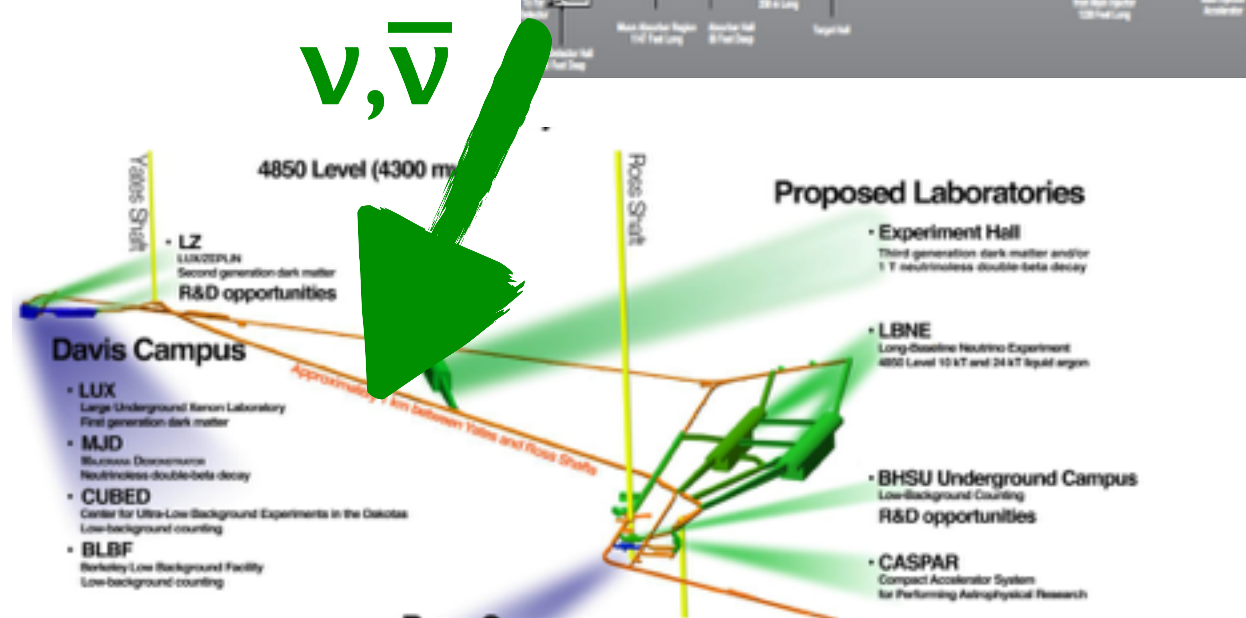

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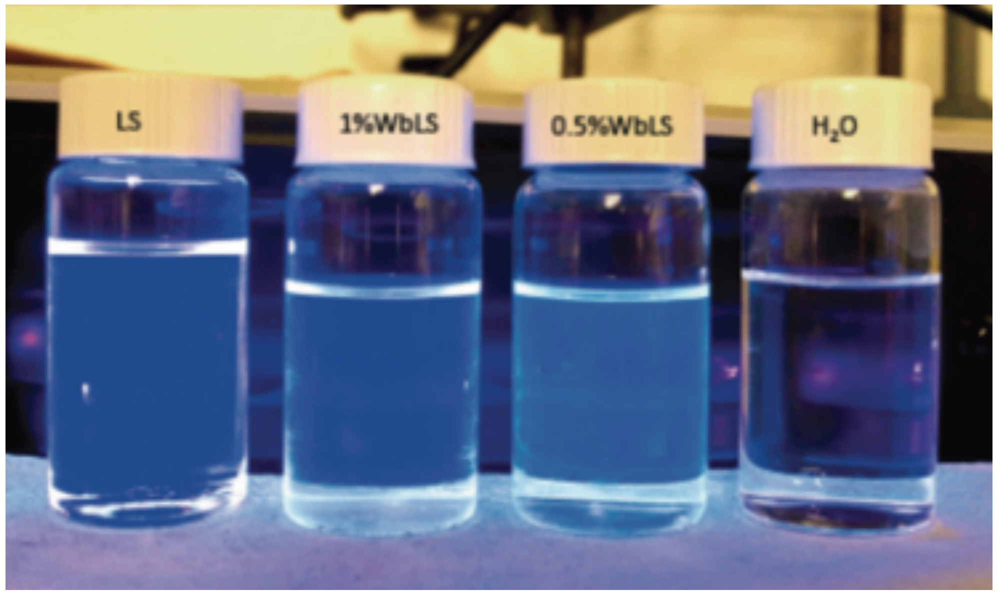
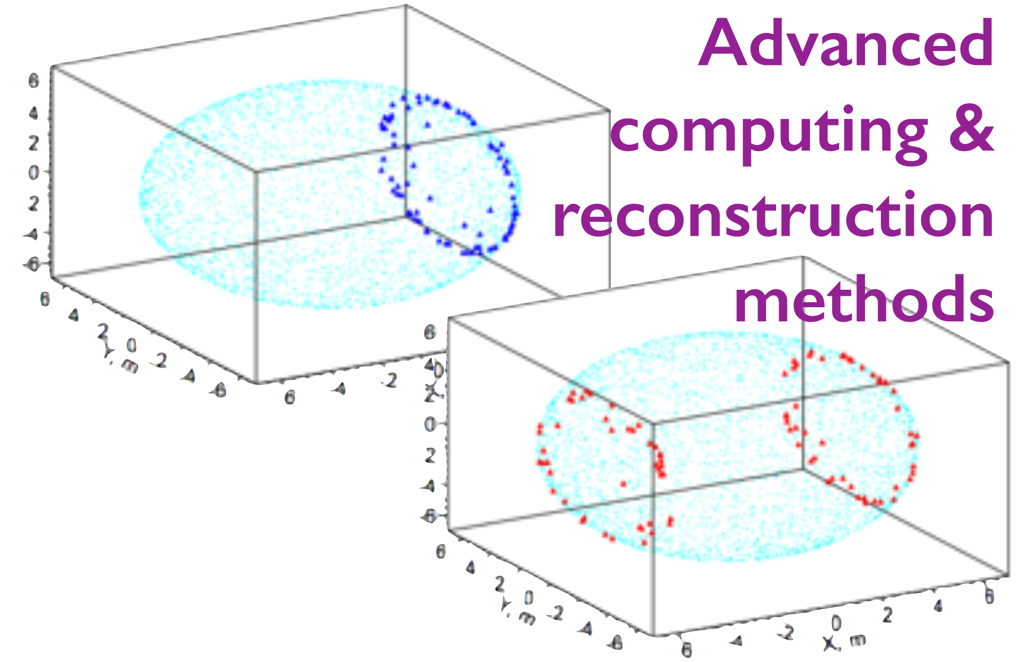


Development of new scintillators e.g. WbLS

New-generation of large-scale, low-threshold, directional detectors



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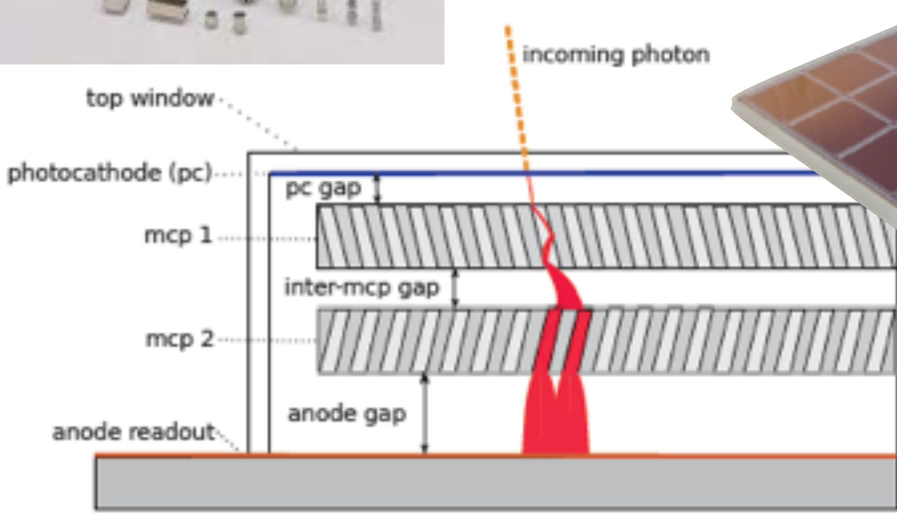

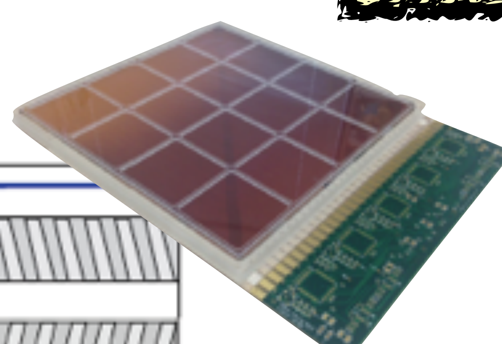

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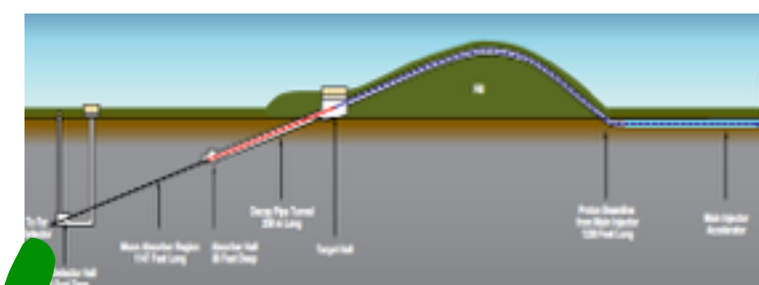

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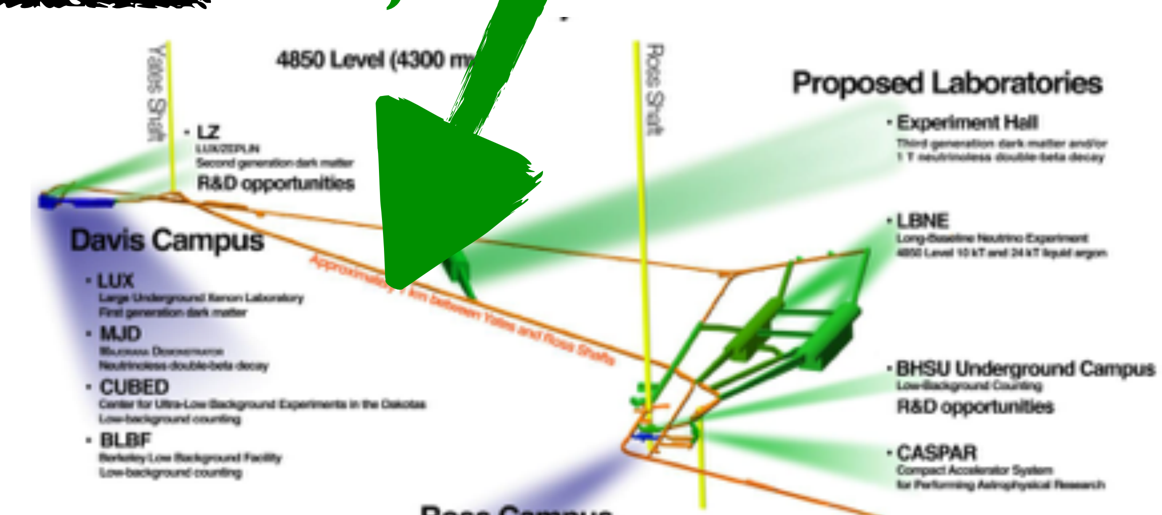


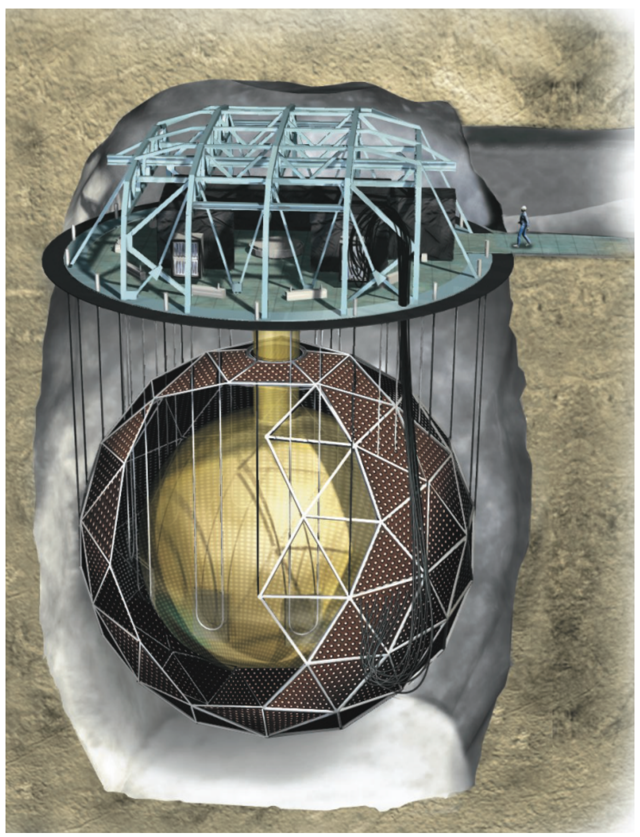
Bird's-Eye View

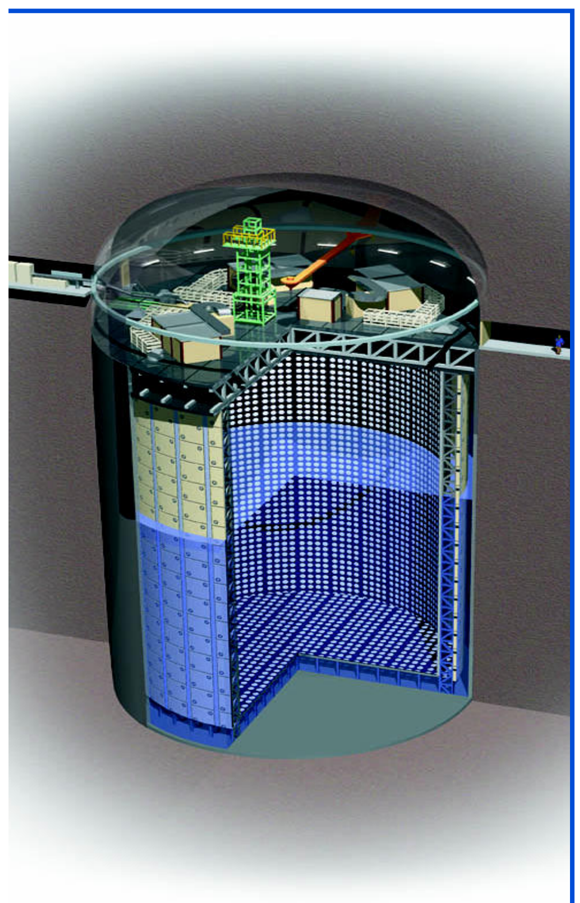
1. The Advanced Scintillation Detector Concept
2. Physics Program
    - Low-energy physics
    - Rare-event searches
    - Long-baseline physics
3. THEIA Development
    - R&D Program
    - Site selection
    - Path forwards

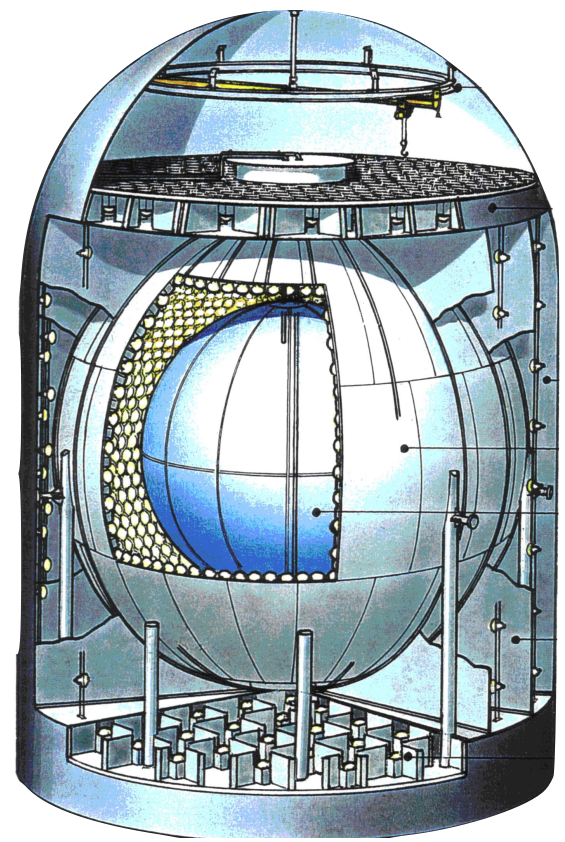
1. Advanced Scintillation Detector Concept

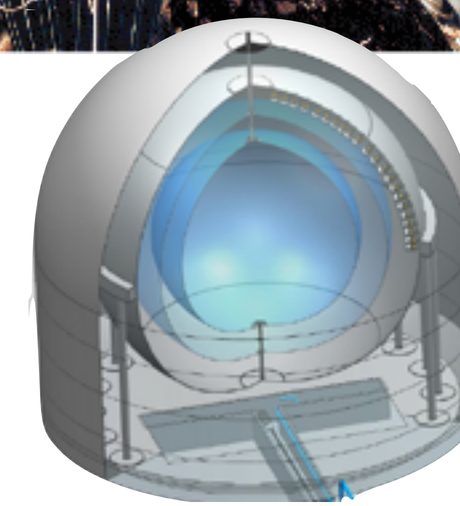
Advanced Scintillation Detector Concept (ASDC)

- **New technology with proven methodology**









House light-producing target inside large monolithic detector

Novel, breakthrough target medium

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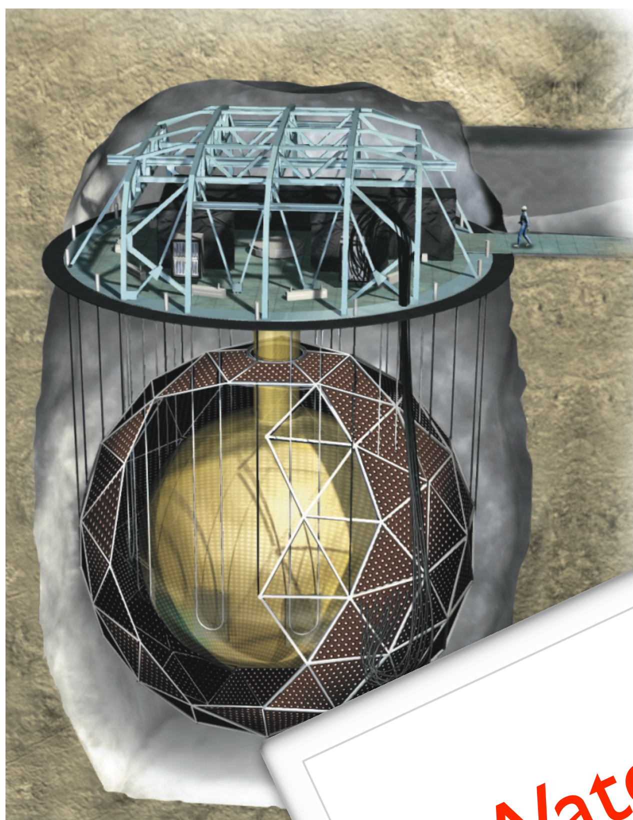

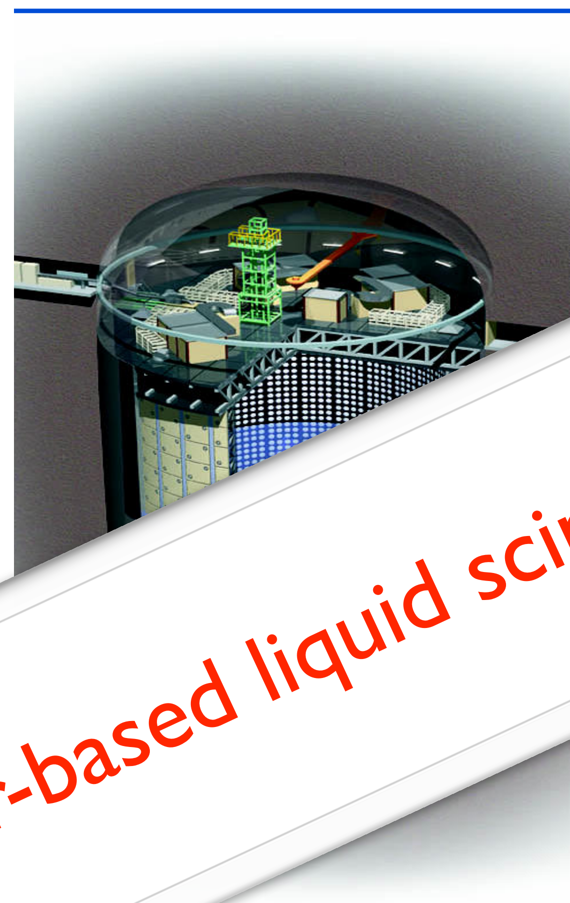

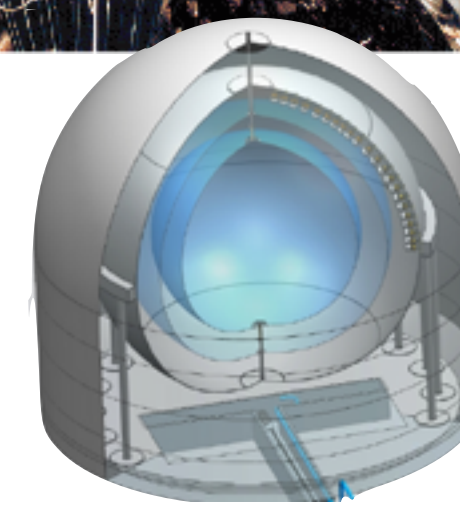

Water-based liquid scintillator — Minfang Yeh et al.

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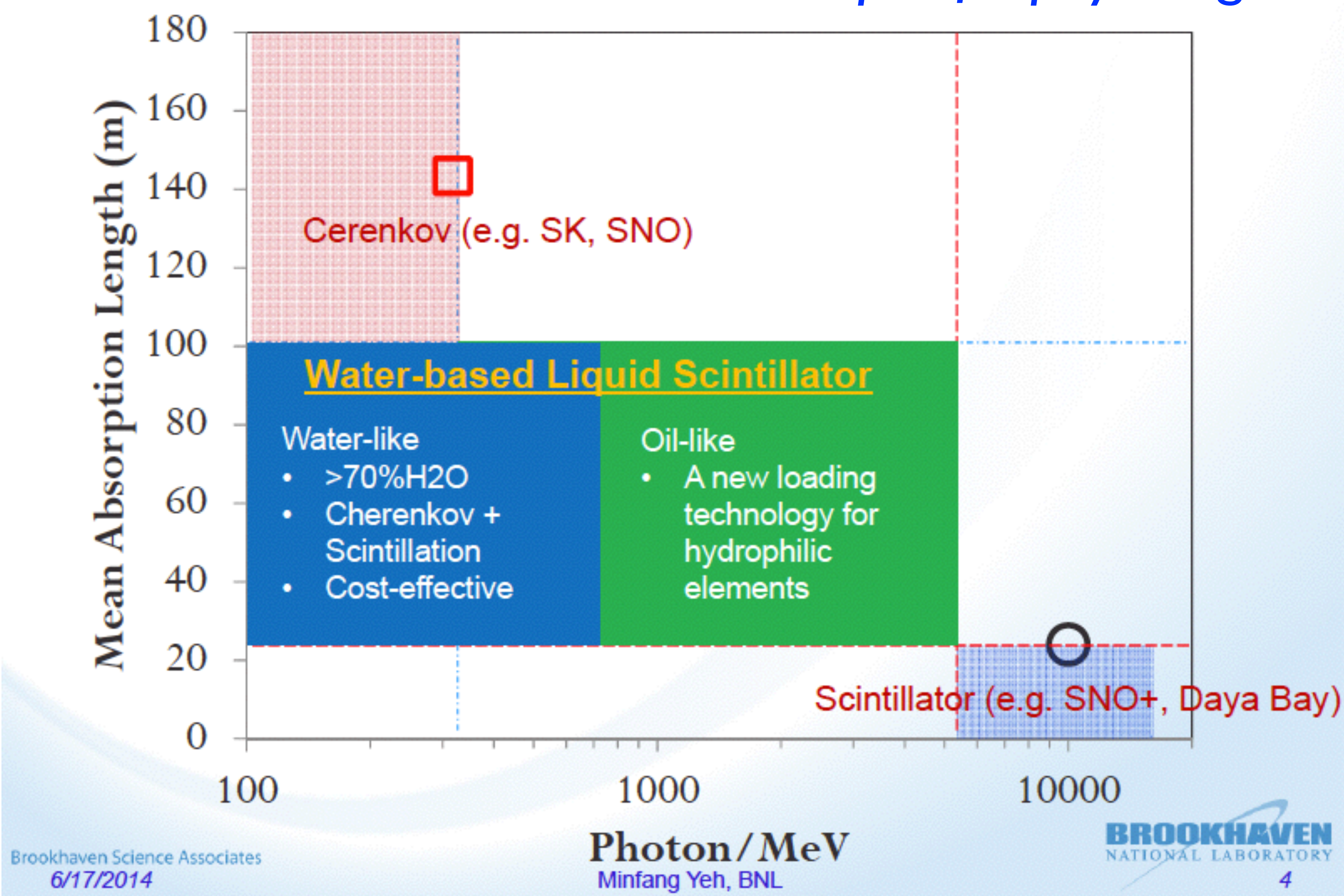
Powerful Target Medium

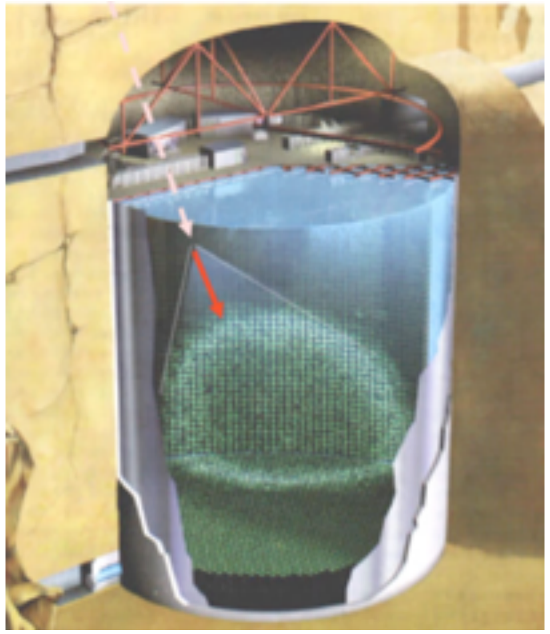
-- Tune to specific physics goals



The Precision of a Cherenkov Detector

- High transparency: good light collection
- Topological information
  - Particle identification (ring imaging)
  - Directionality
- Metal loading potential

Demonstrated at 1–50 kt-scale (SNO, SuperK)



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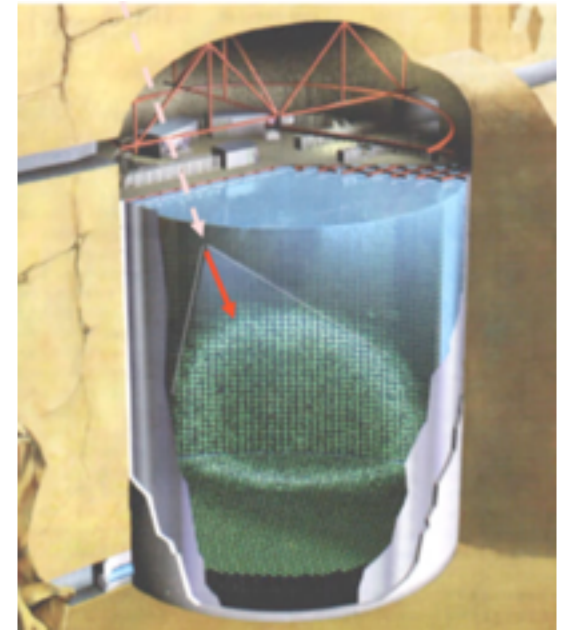

The Power of a Scintillator Detector

- High light yield
  - Low threshold, sub-Cherenkov-t/h detection
  - Good energy & vertex resolution
- “Fast” timing at low threshold: coincidence tag
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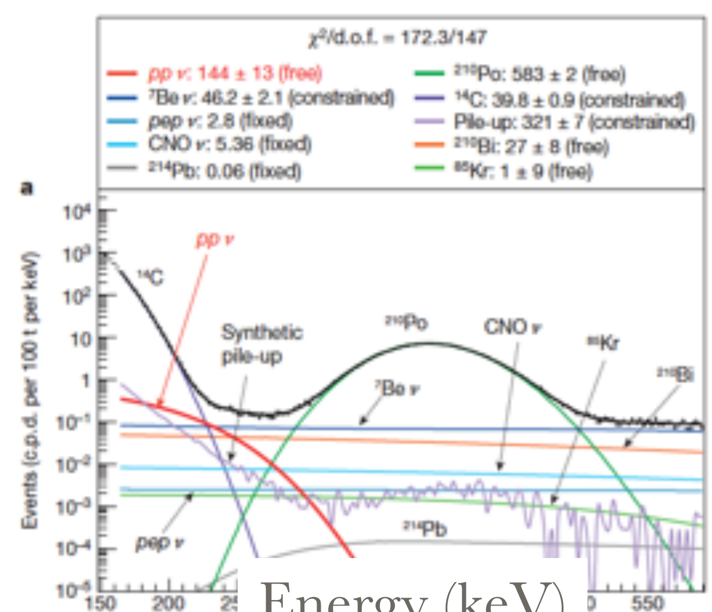
- Can be made ultra clean

Demonstrated at kt-scale (KL, Borexino)

Borexino Nature article



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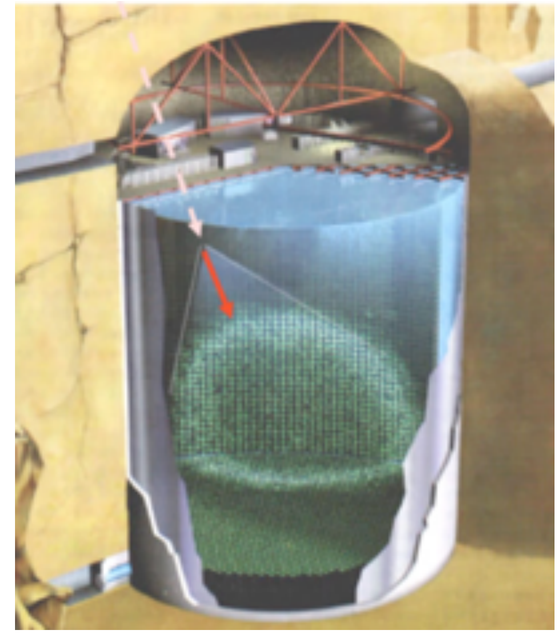

Cher / scint ratio provides additional handle on particle ID

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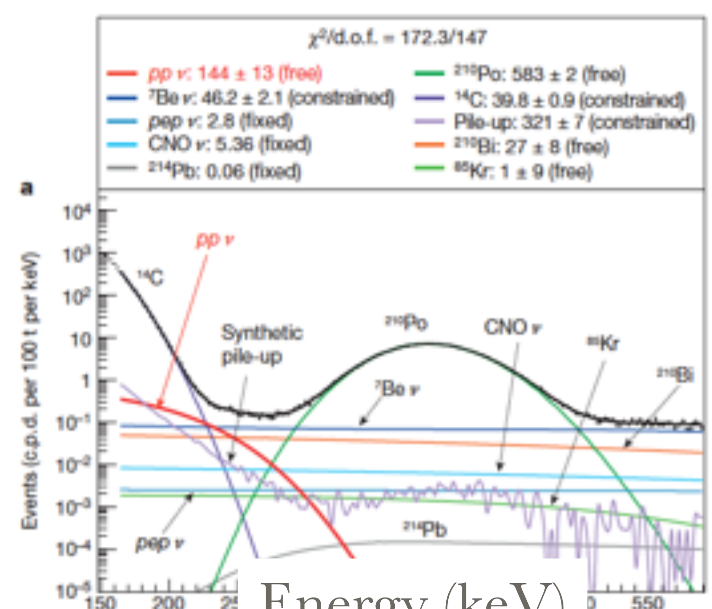
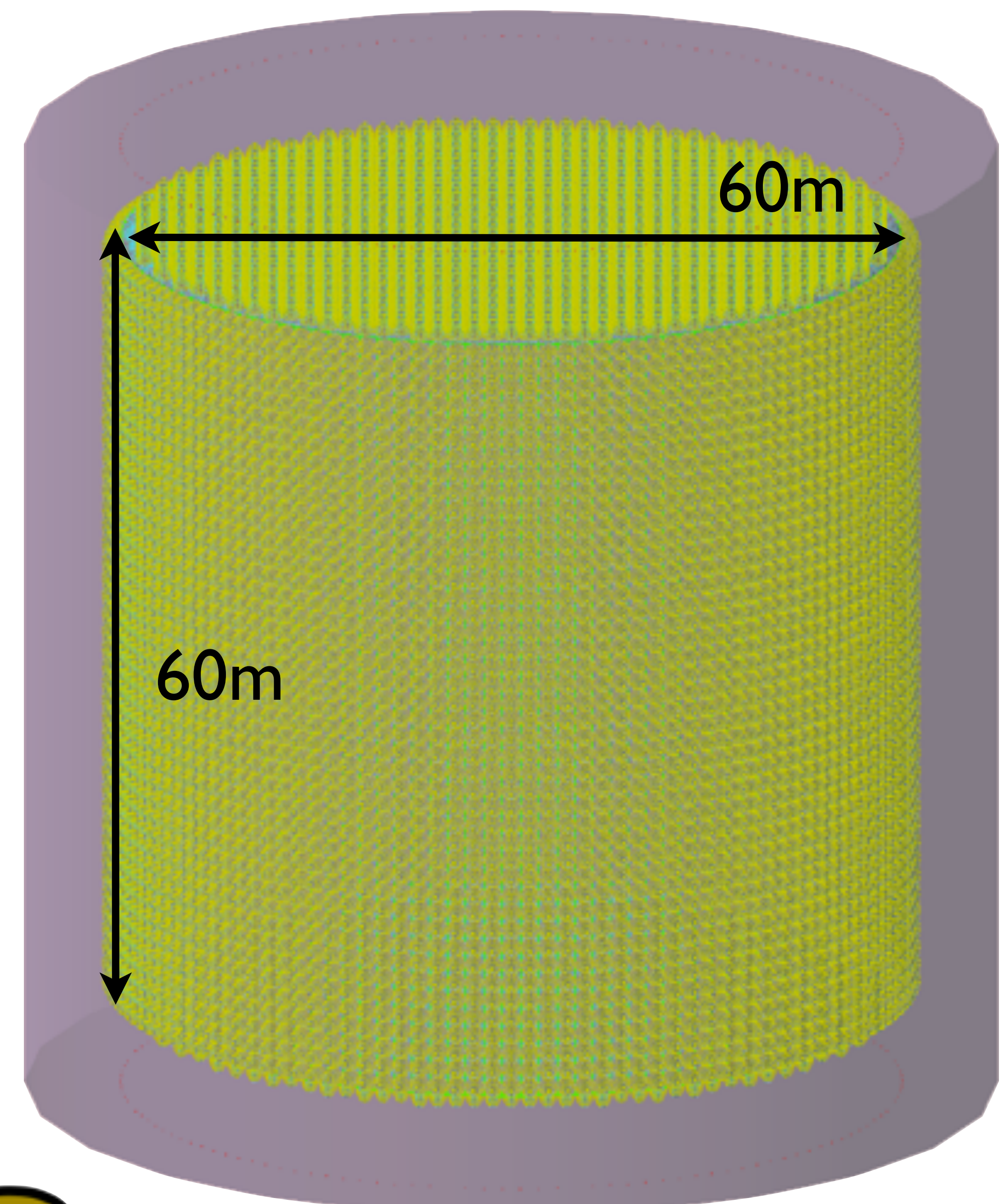


THEIA:
A realisation of the Advanced Scintillation Detector Concept (ASDC)

- Large-scale detector (50-100 kton)
- WbLS target
- Fast, high-efficiency photon detection with high coverage
- Deep u/ground (Pyhäsalmi, Homestake)
- Isotope loading (Gd, Te, Li...)
- *Flexible*! Target, loading, configuration

➡ **Broad physics program!**



Concept paper - arXiv:1409.5864

Detector image product of RAT-PAC

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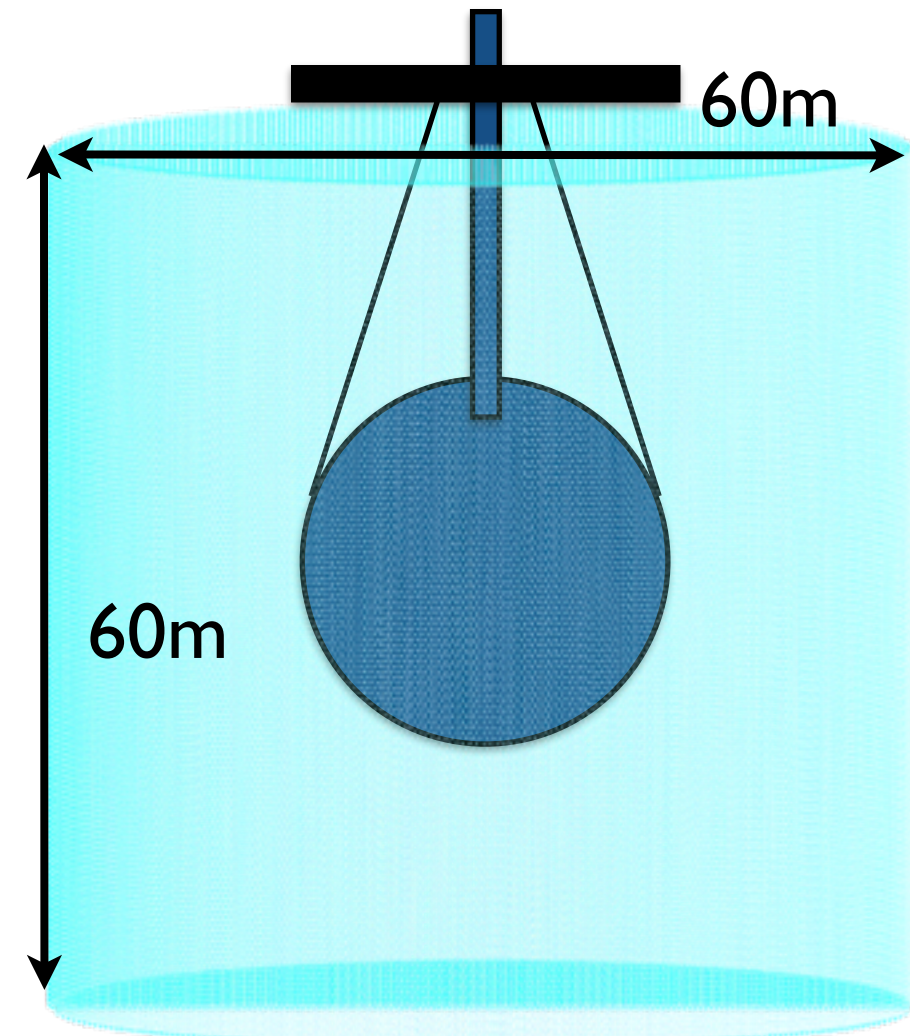

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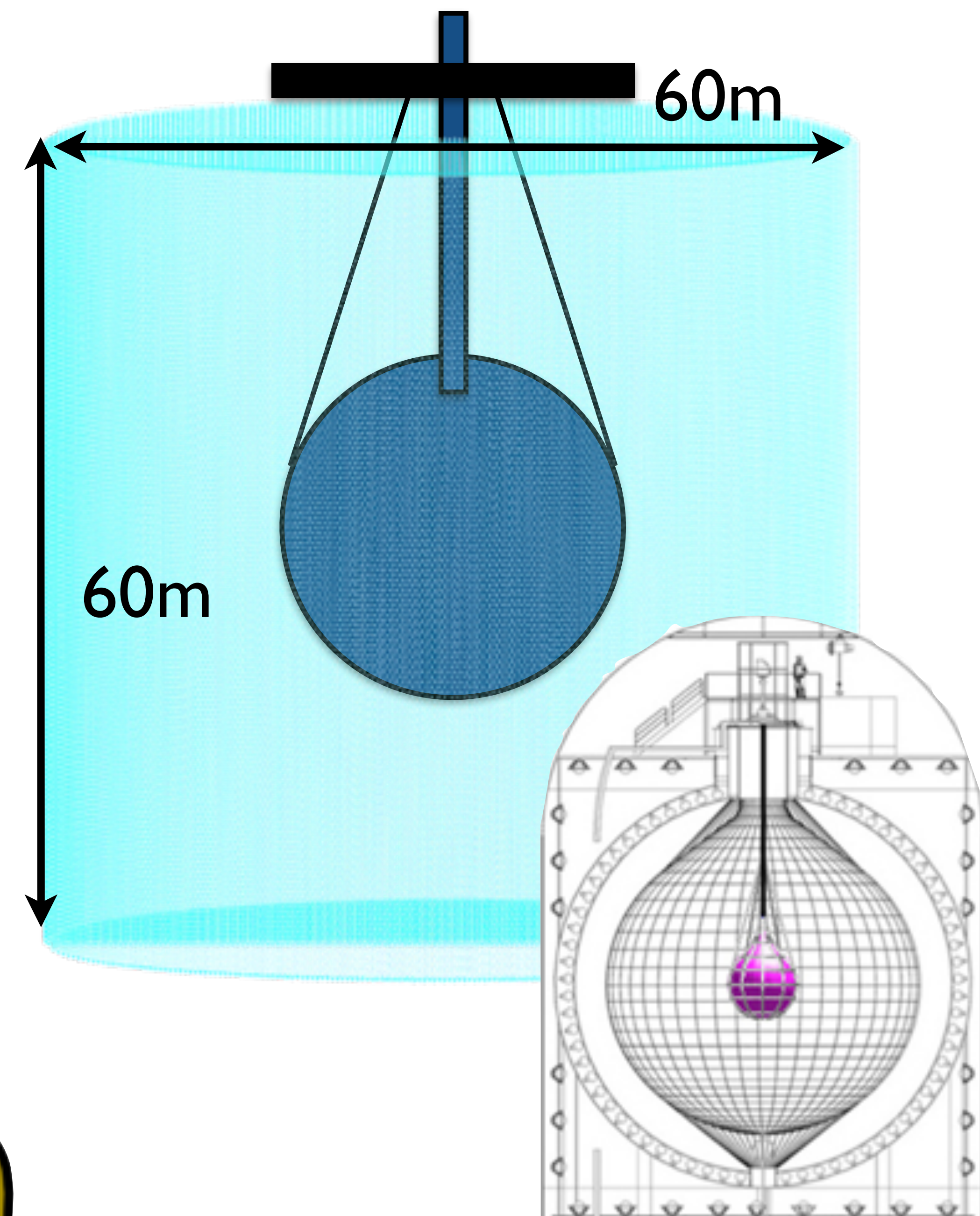

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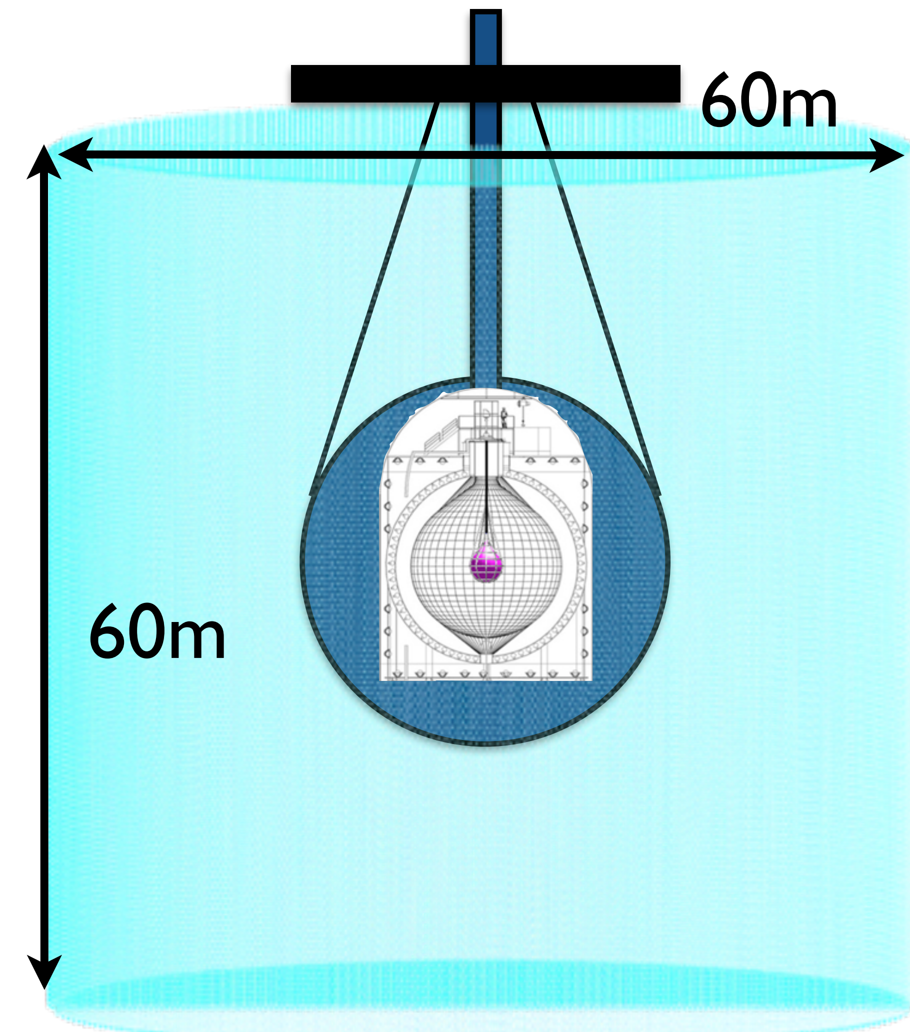

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3 MeV β, 5% WbLS, 50kt, 90%

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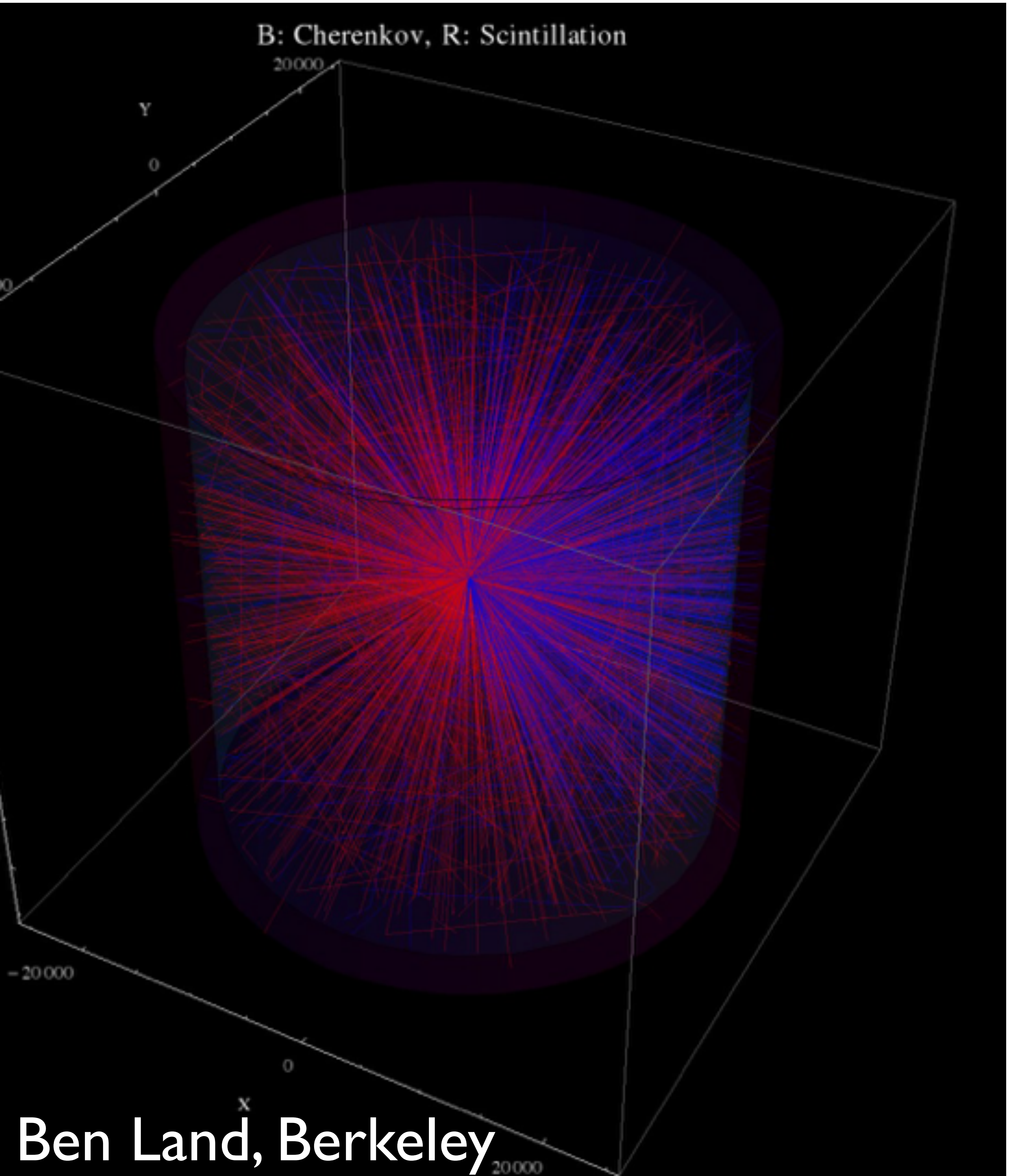

Ben Land, Berkeley

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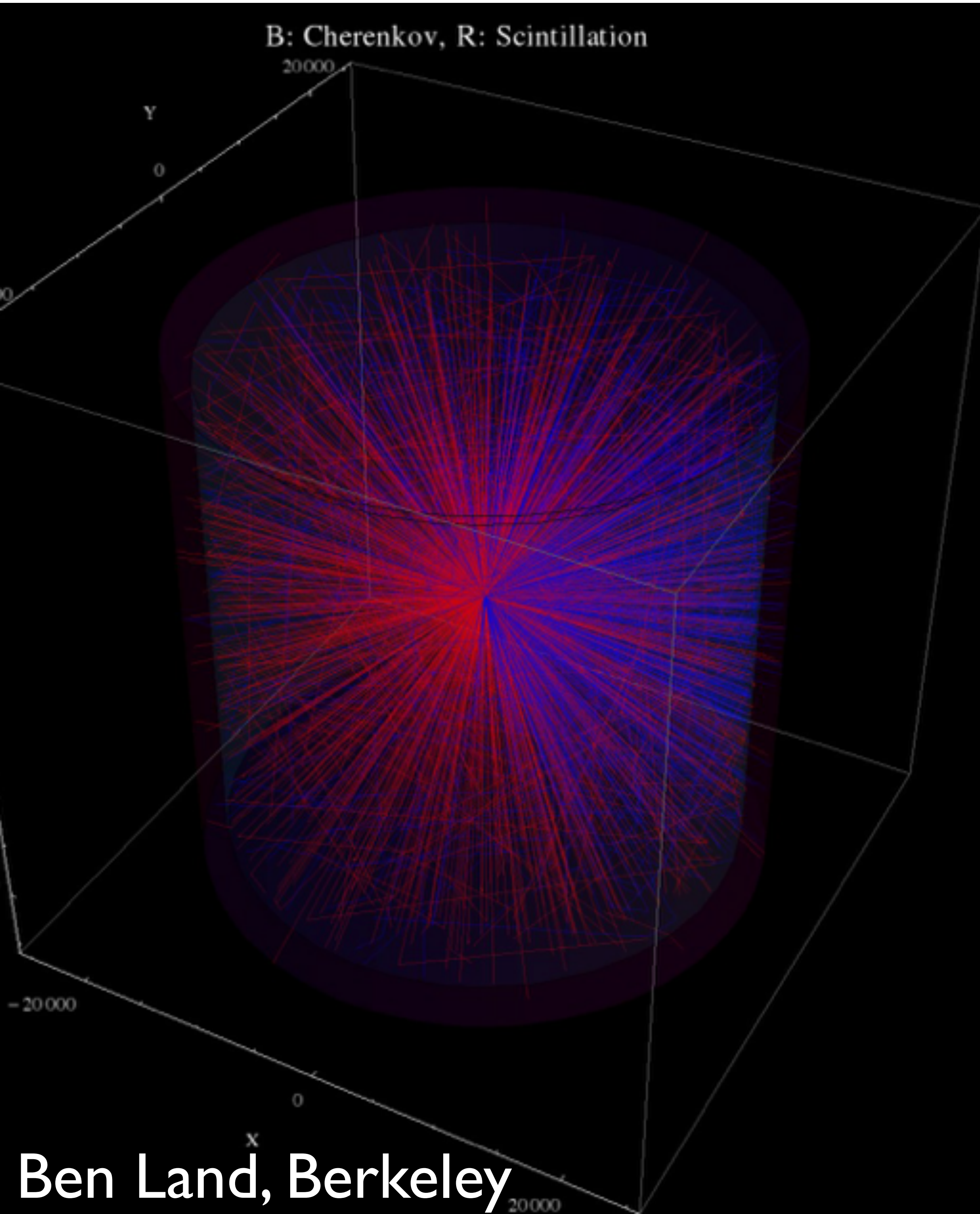

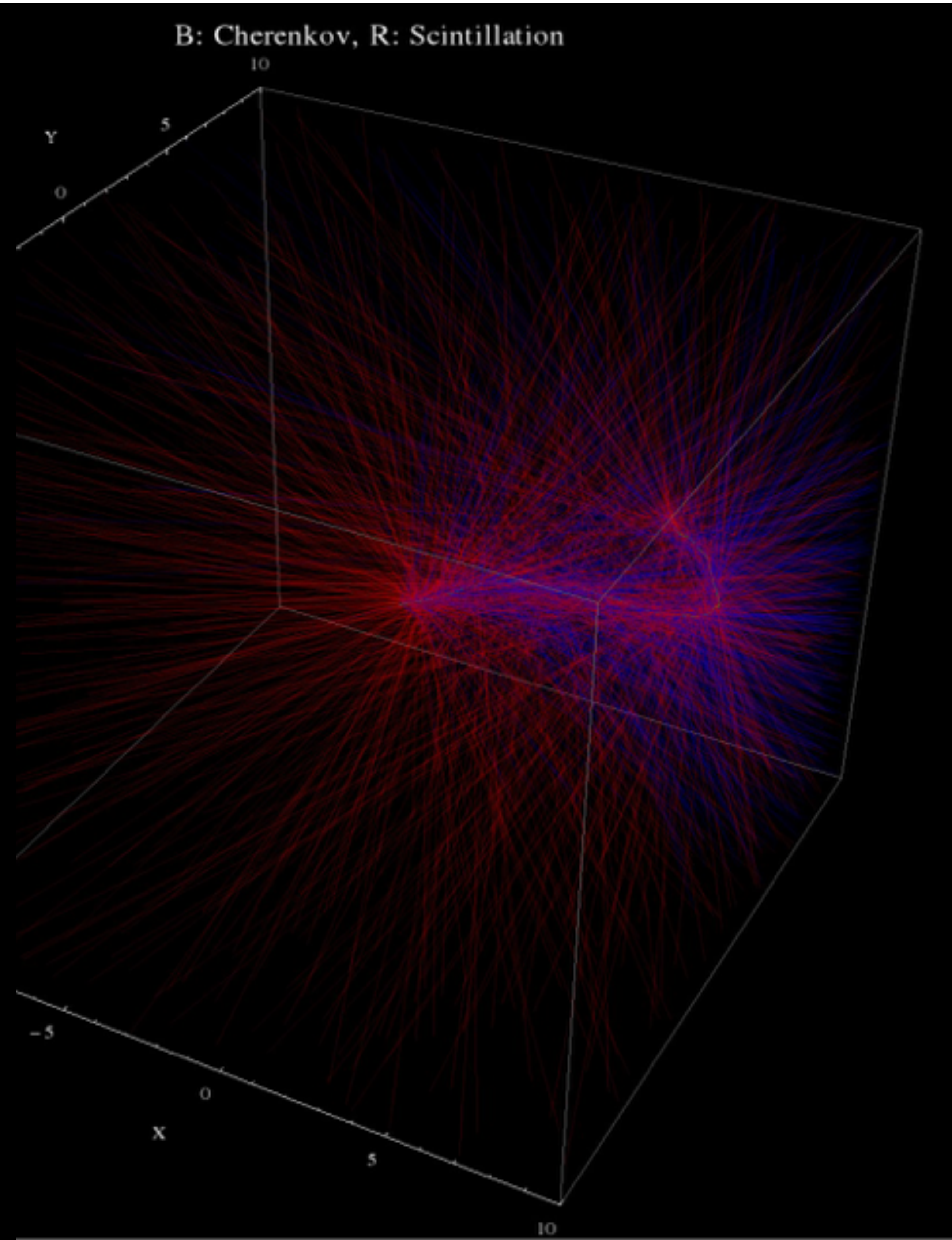

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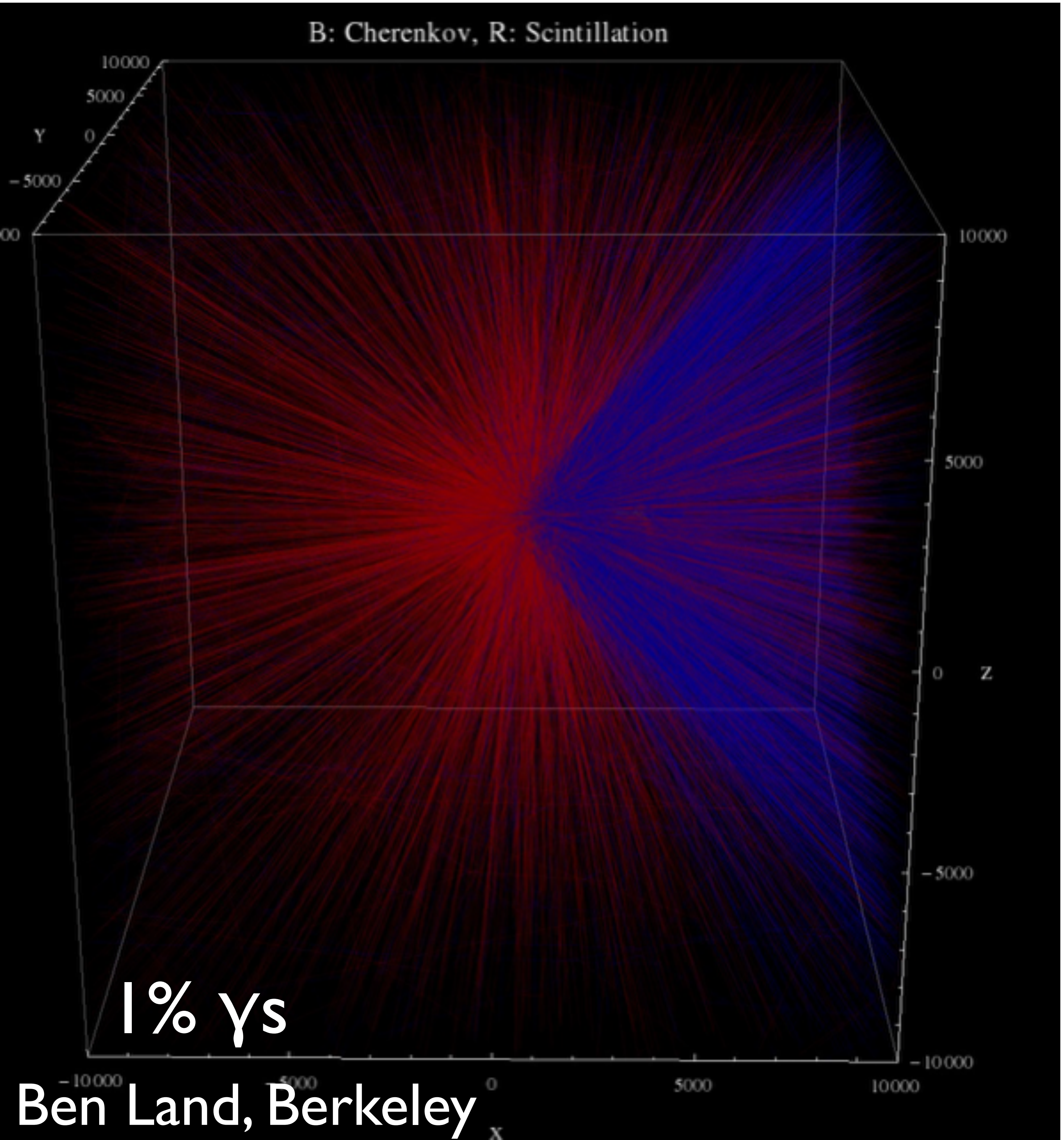

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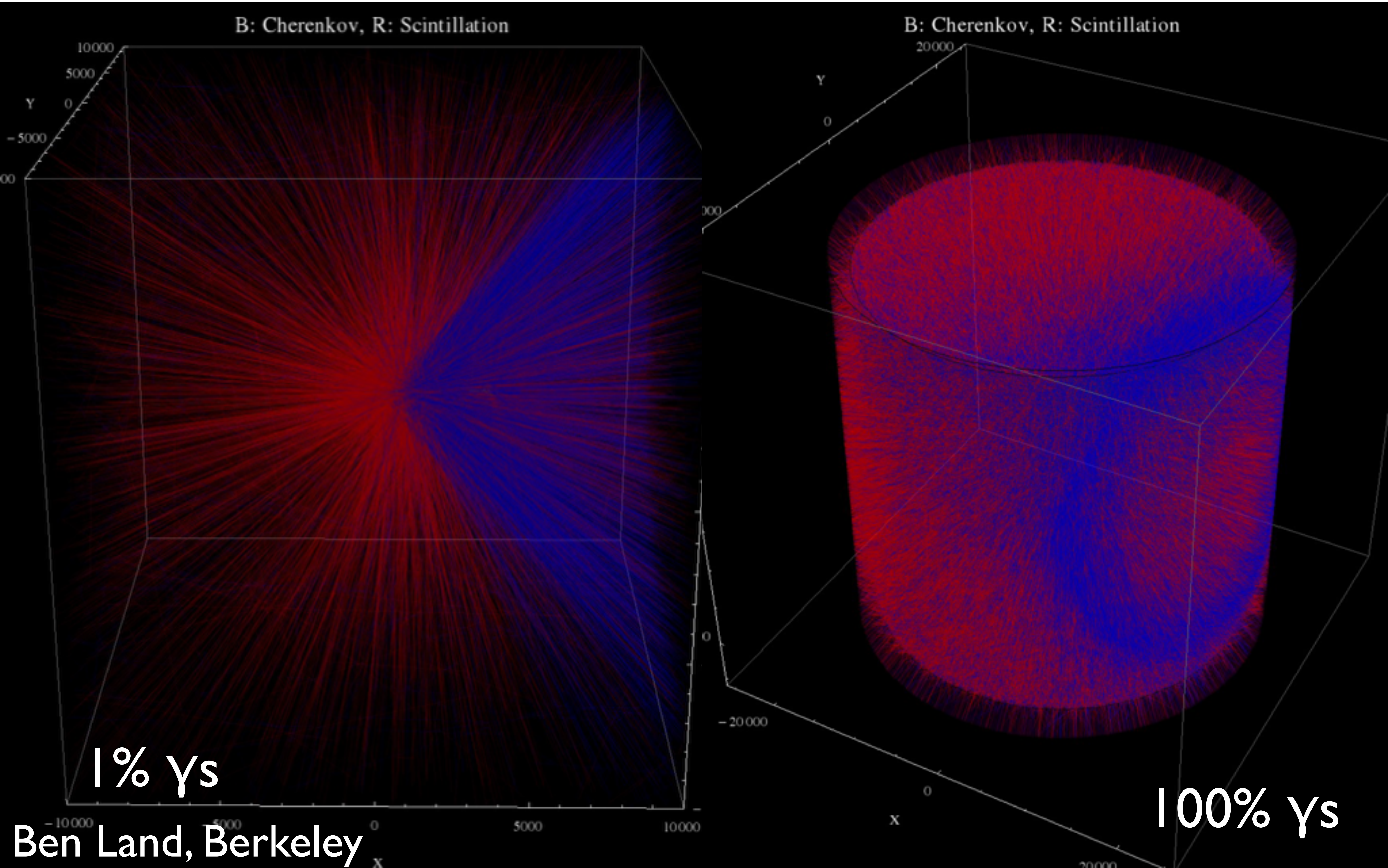
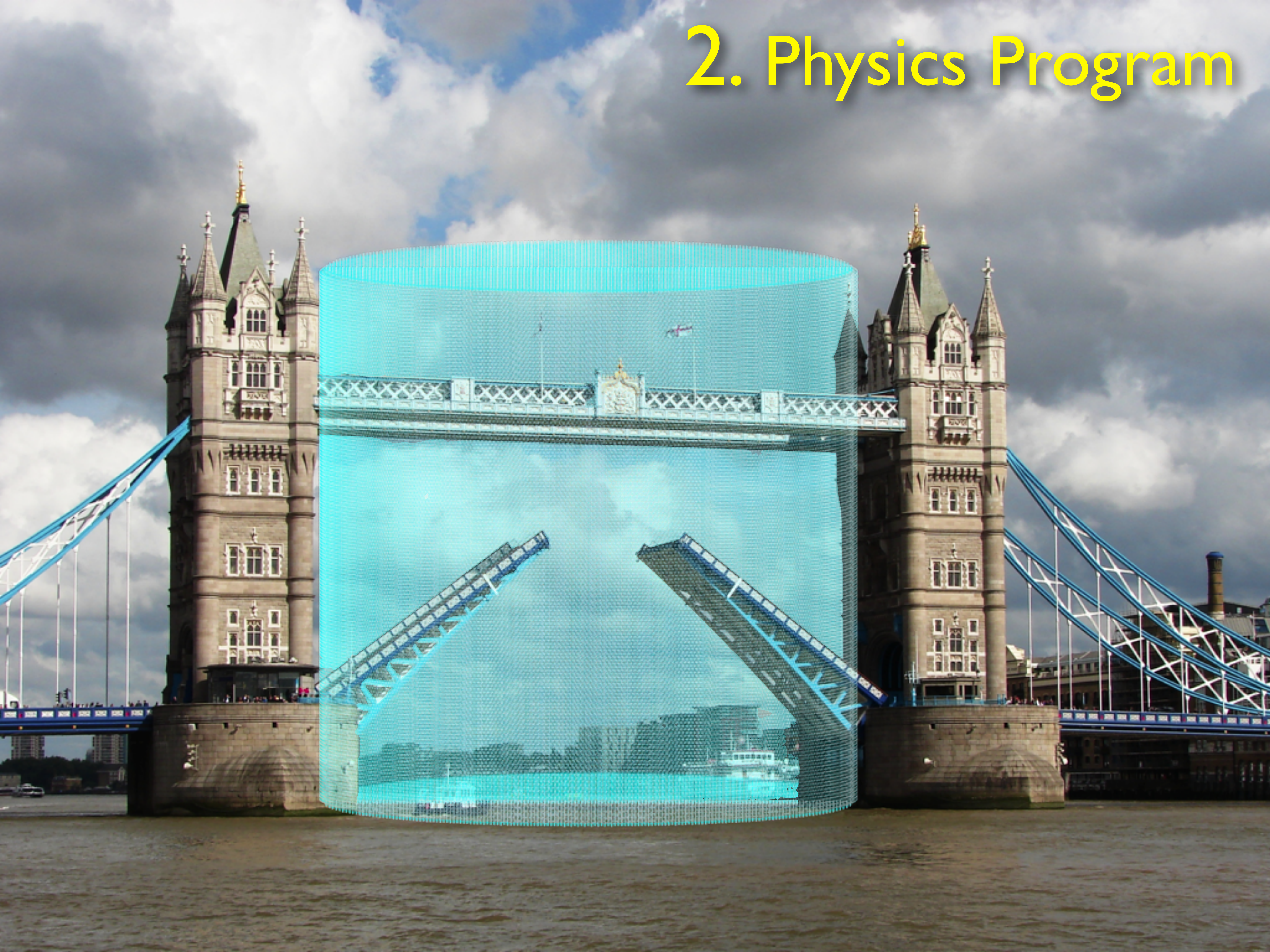


2. Physics Program



Physics Program

1. Neutrinoless double beta decay
2. Solar neutrinos (solar metallicity, luminosity)
3. Geo-neutrinos
4. Supernova burst neutrinos & DSNB
5. Source-based sterile searches
6. Nucleon decay
7. Long-baseline physics (mass hierarchy, CP violation)

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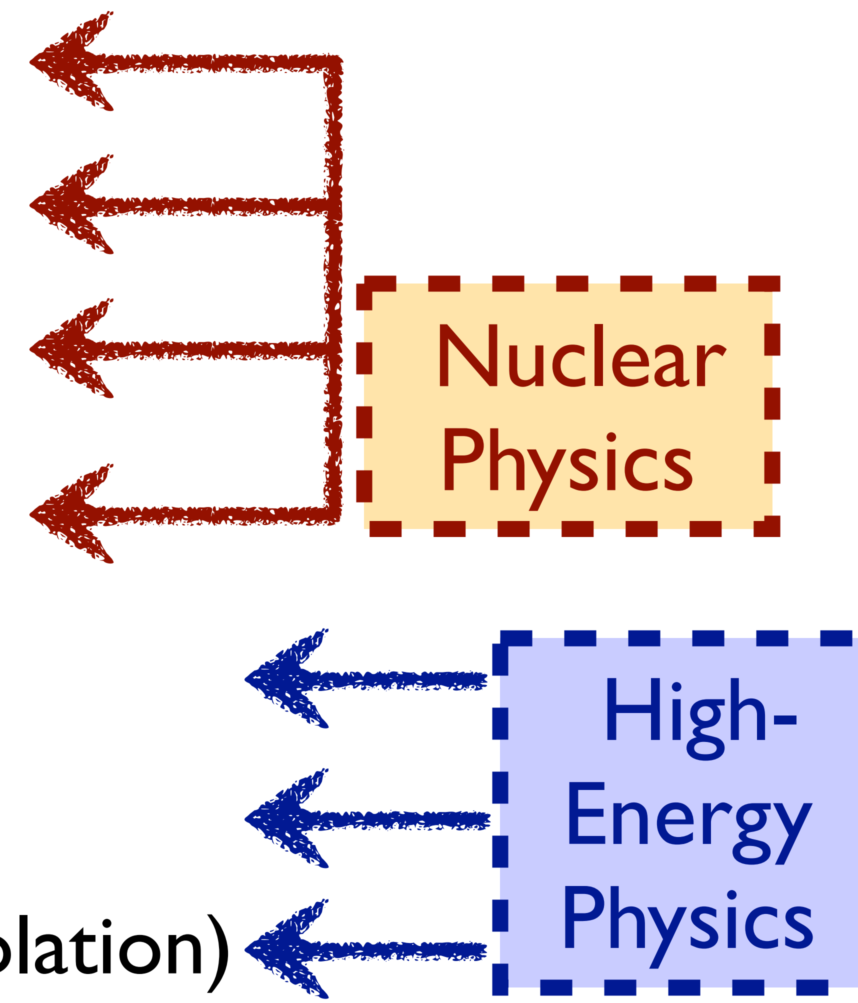

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Physics over 5 orders of magnitude

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Nuclear Physics (items 1–4)

High-Energy Physics (items 5–7)

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Nuclear Physics

High-Energy Physics

Remarkably, the same detector could show that neutrinos and antineutrinos are the same, *and* that "neutrinos" and "antineutrinos" oscillate differently

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Leptogenesis

Low-Energy Program

Low threshold

Directionality

Isotope loading

Neutron tag

Cher/scint ratio

Low-Energy Program

Neutrinoless Double Beta Decay

Reject (dominant!) ^{8}B background

^{130}Te or ^{136}Xe

Low threshold

Directionality

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Low-Energy Program

Neutrinoless Double Beta Decay

Reject (dominant!) ^{8}B background

^{130}Te or ^{136}Xe

Low threshold

Directionality

Isotope loading

CNO and
pep sensitivity

Signal /
background
separation

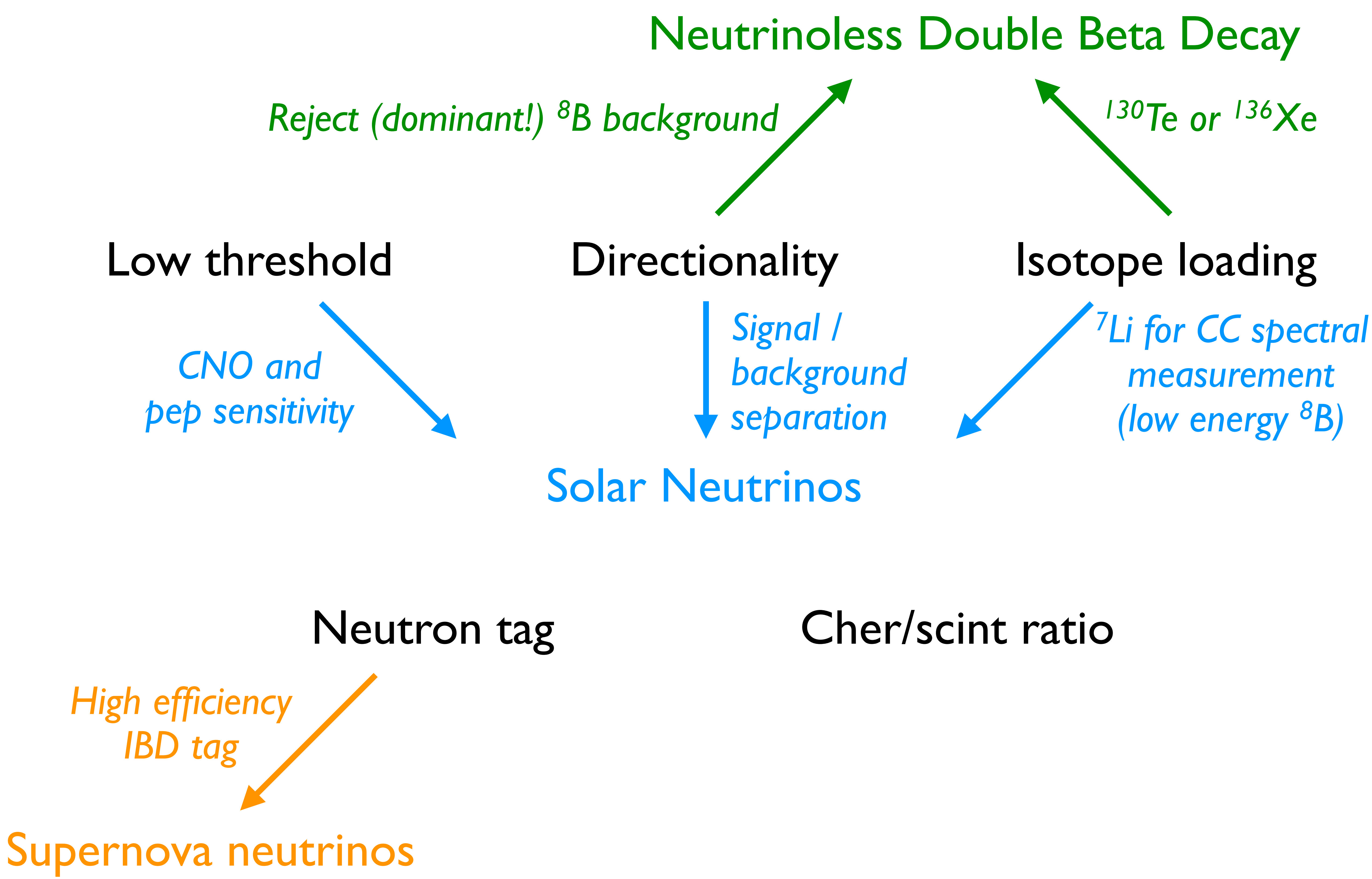
^{7}Li for CC spectral
measurement
(low energy ^{8}B)

Solar Neutrinos

Neutron tag

Cher/scint ratio

Low-Energy Program



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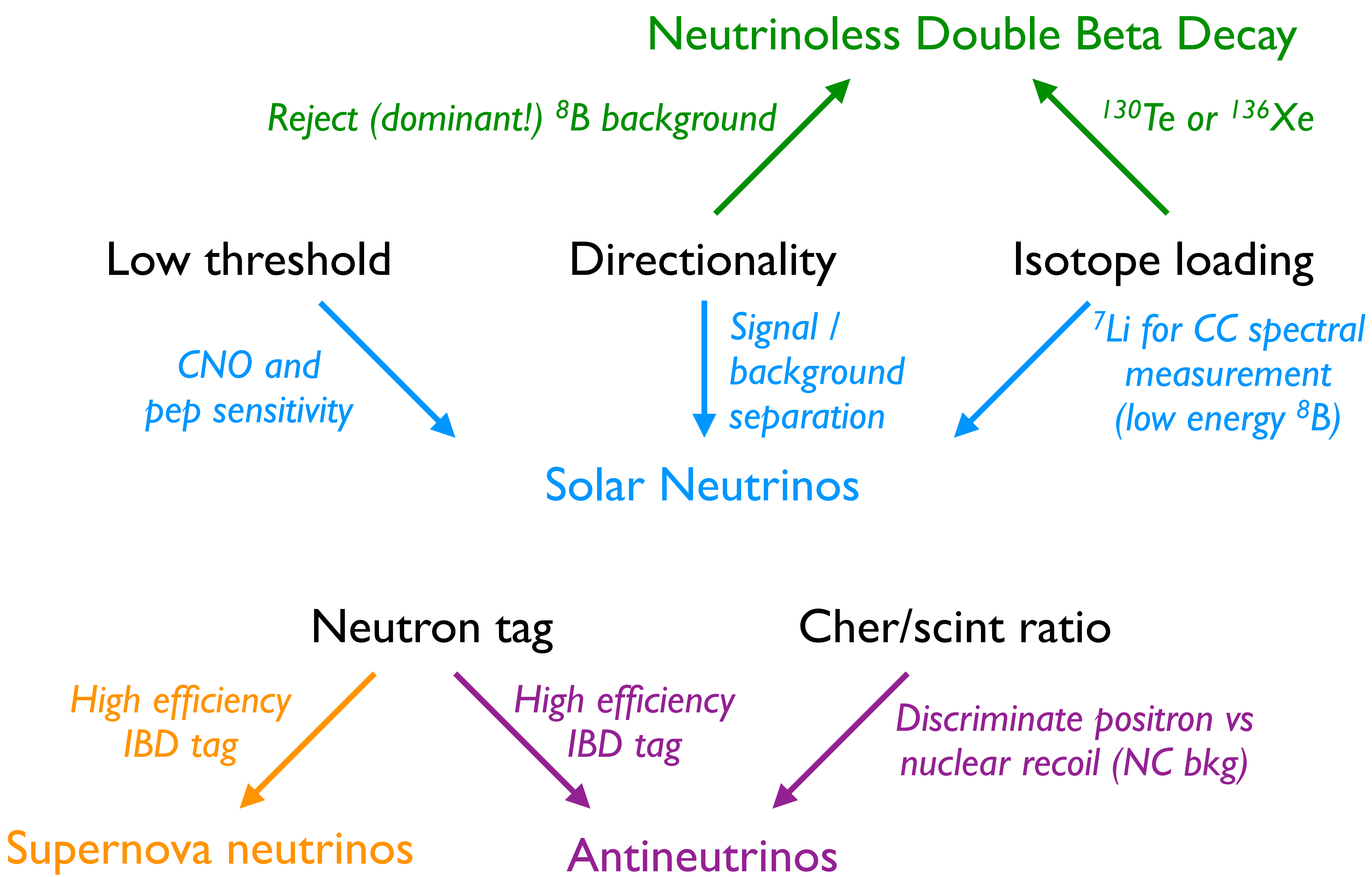

Phys.Rev.Lett.110 : 062502 (2013);
SNO+ white paper (in progress);
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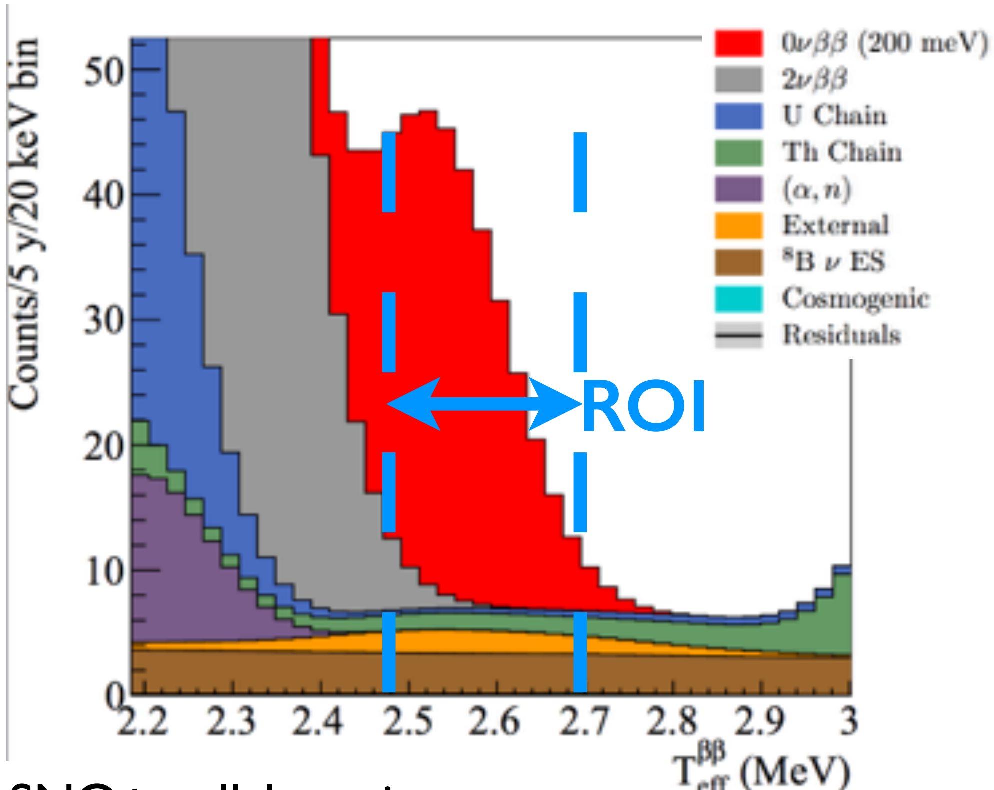
NLDBD

Builds on critical developments by KLZ & SNO+ collaborations

Projected spectrum in SNO+: 5 years, 0.5% ^{nat}Te



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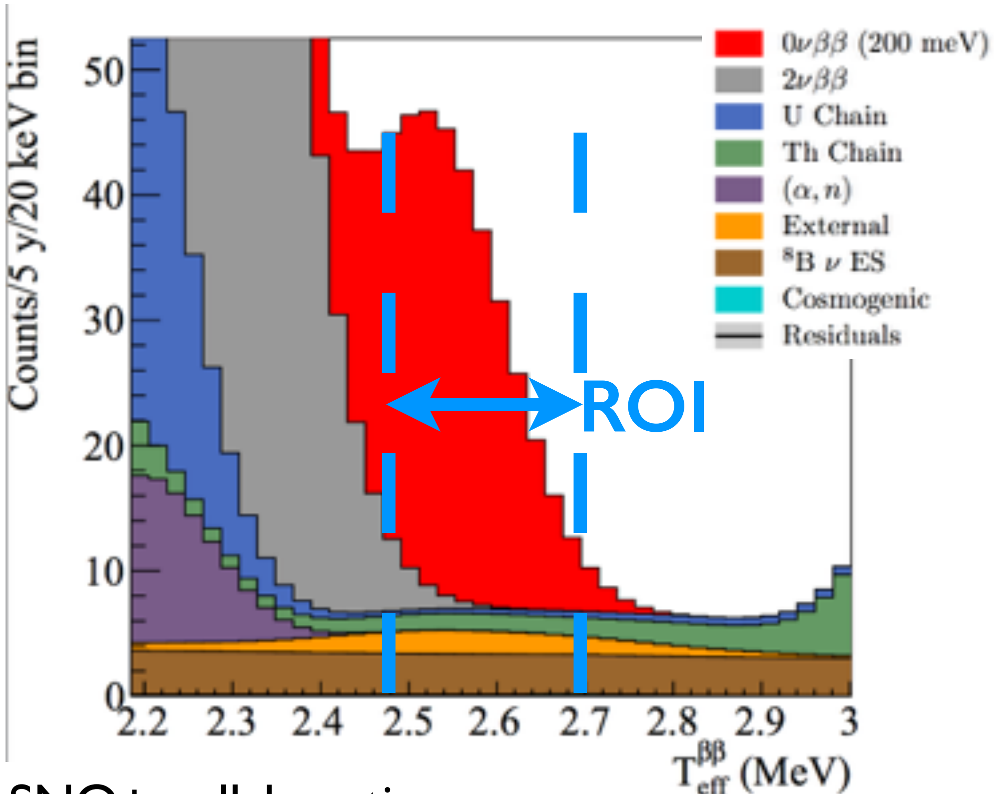

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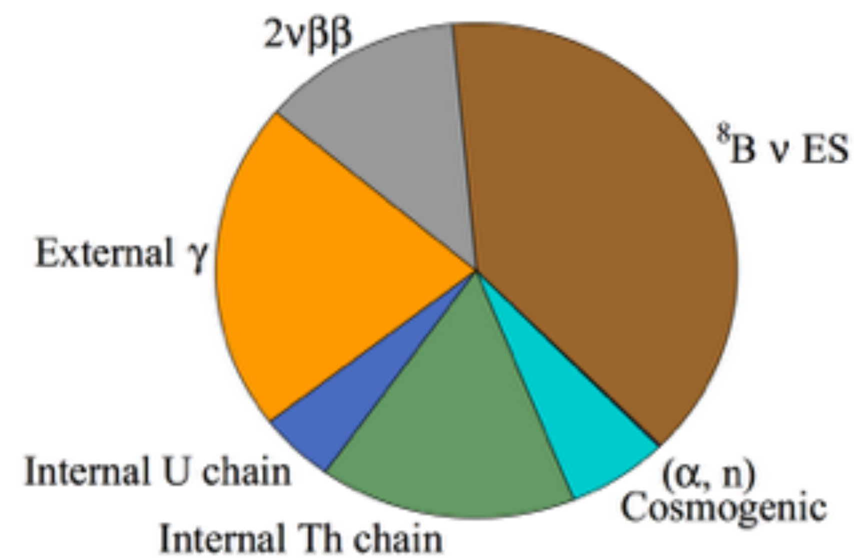
Asymmetric ROI
(-0.5 - 1.5 σ):
Background dominated by ^{8}B solar neutrinos!



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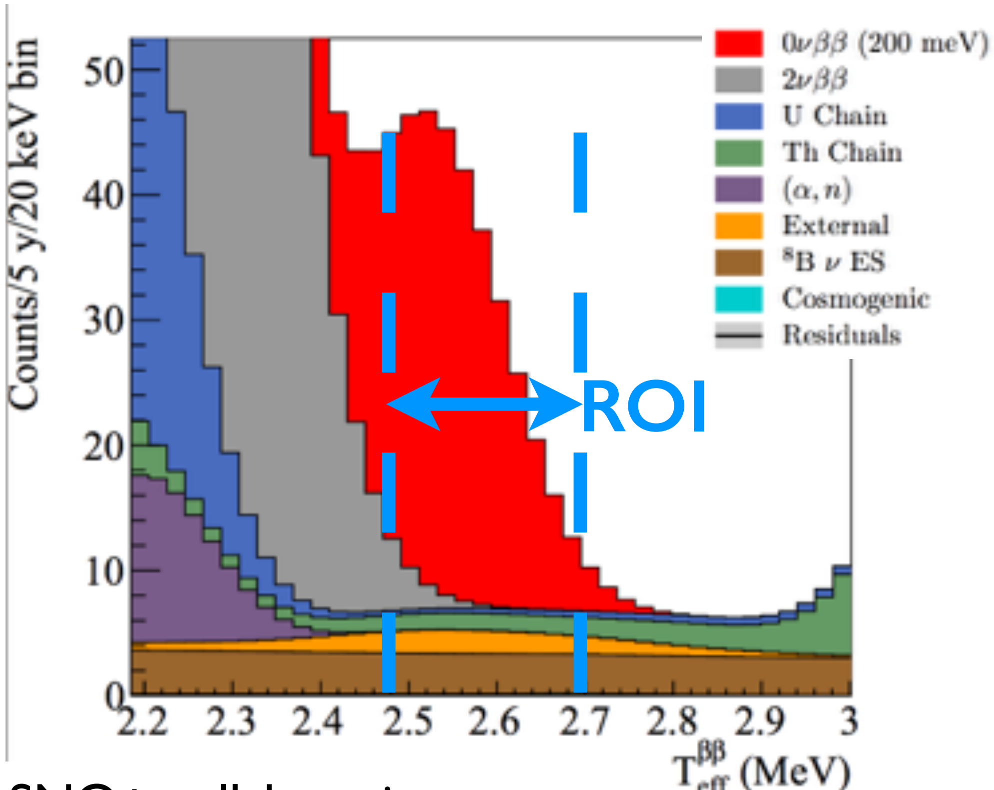

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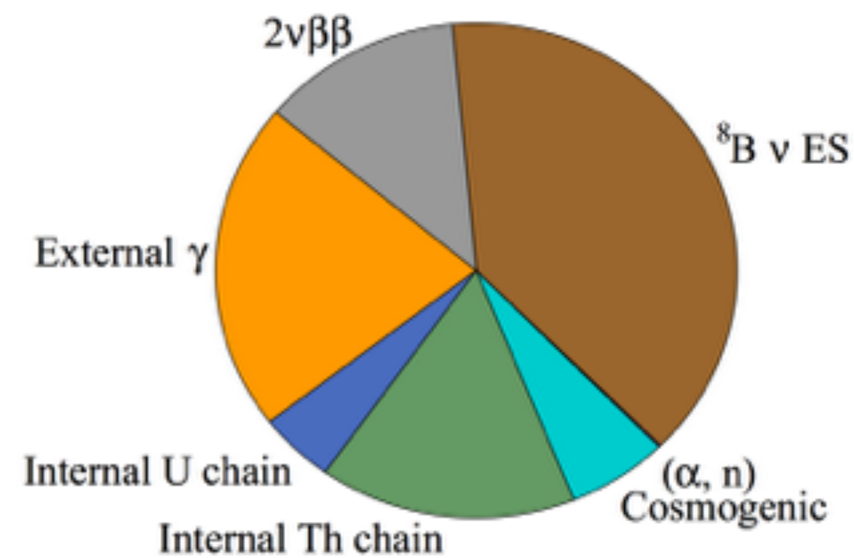

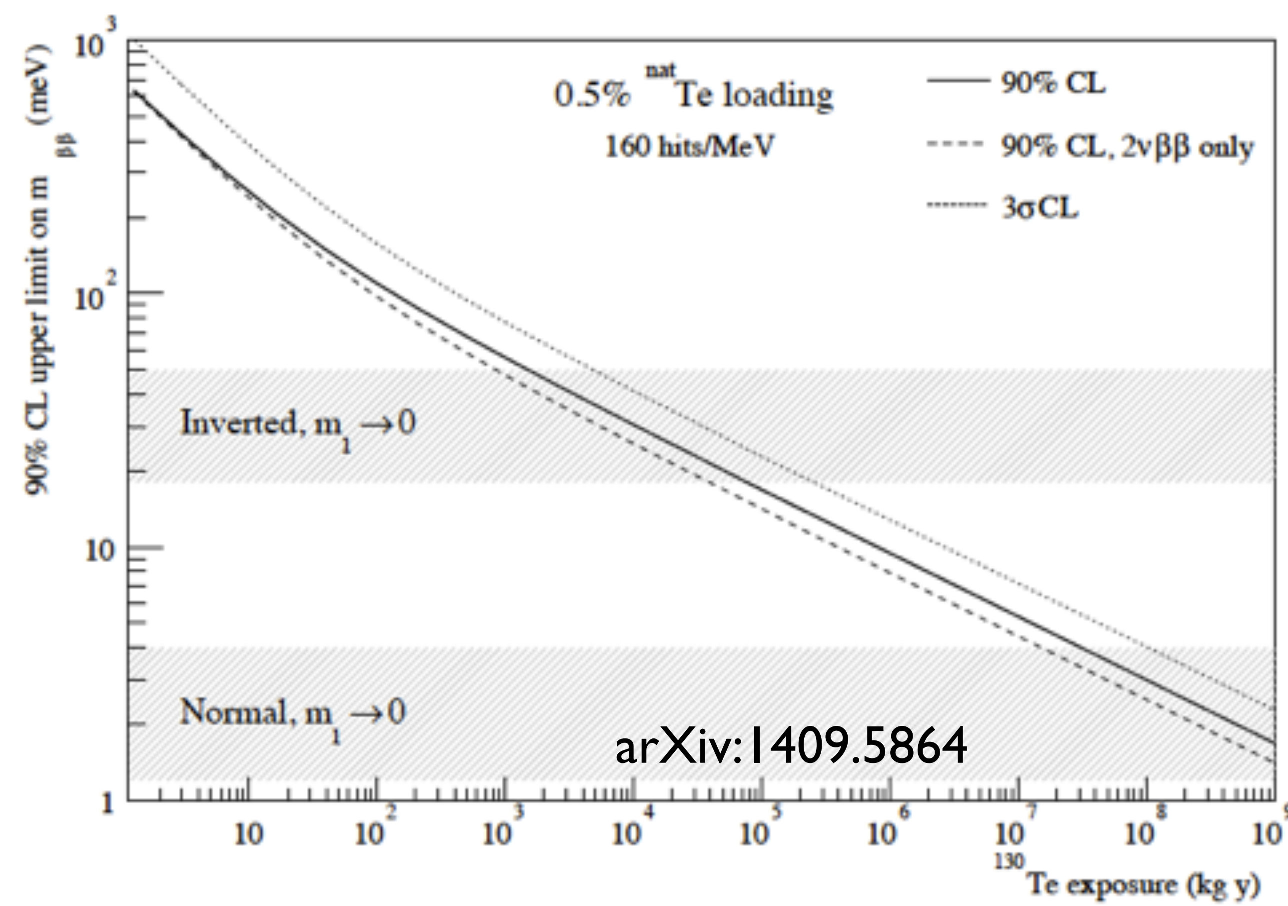

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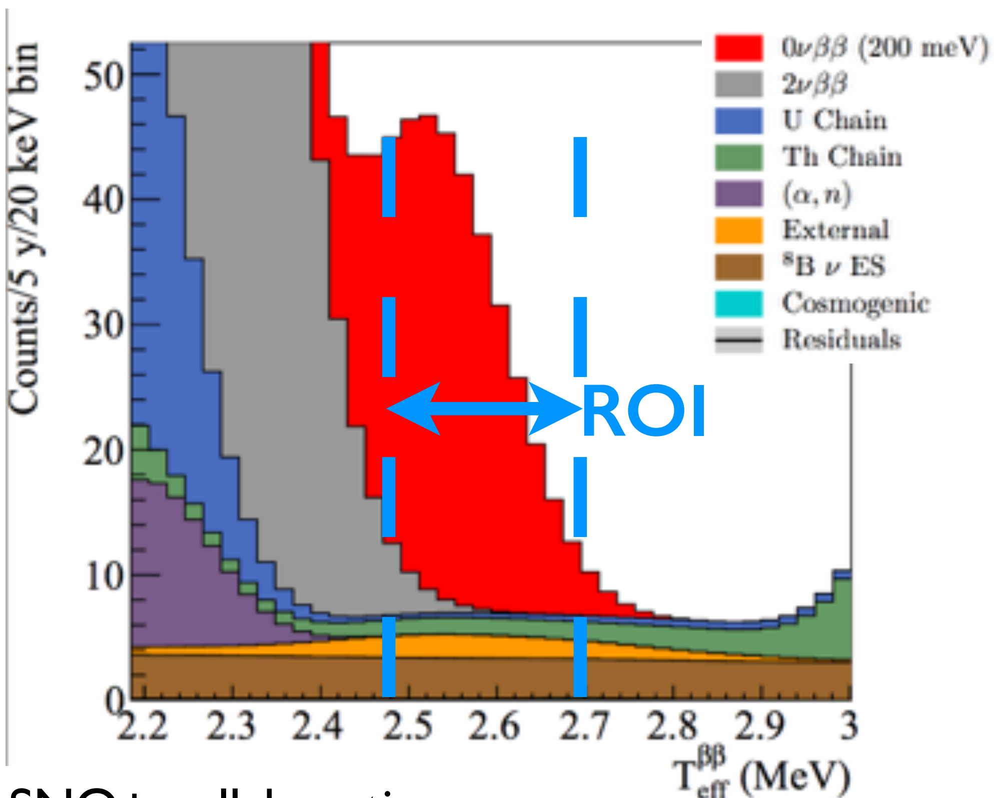
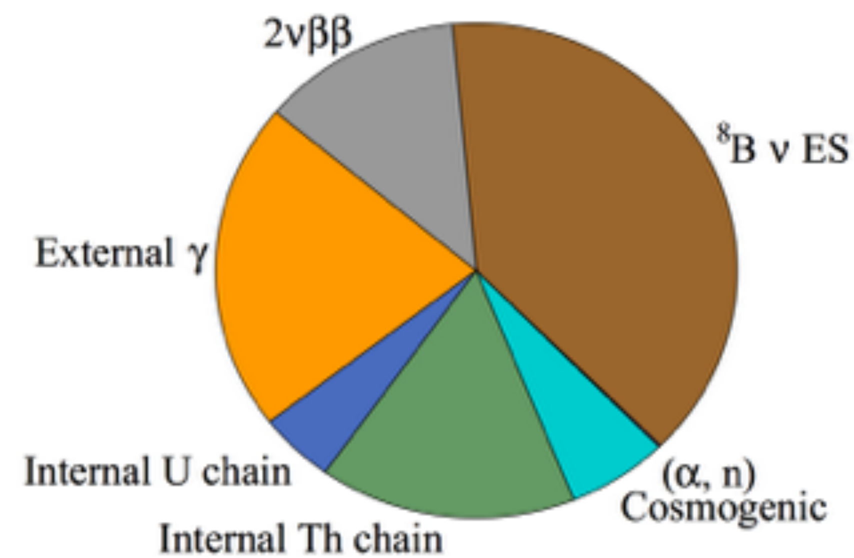
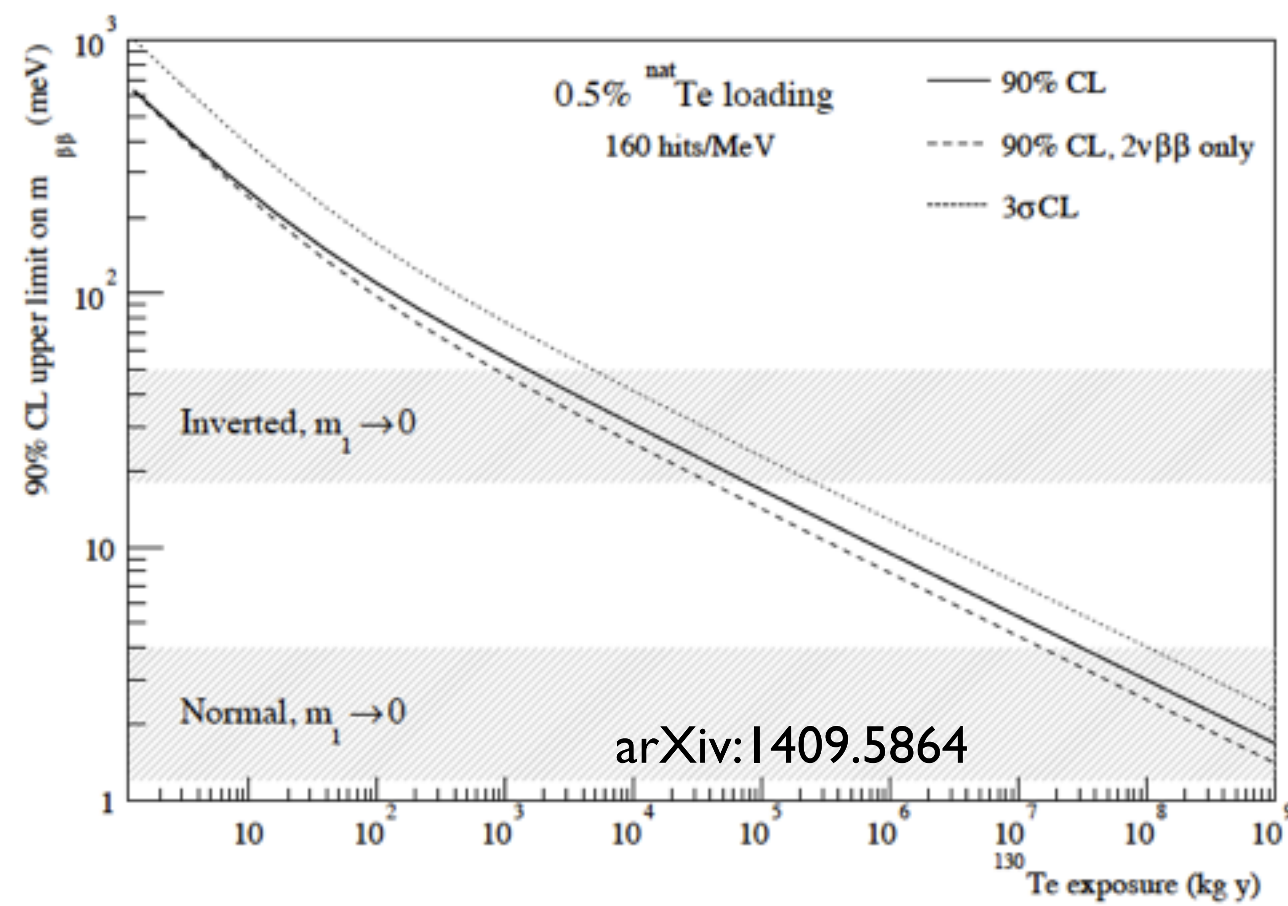


SNO+ collaboration

Asymmetric ROI
(-0.5 - 1.5 σ):
Background dominated by ^8B solar neutrinos!



50kt detector
50% reduction of ^8B
Particle ID / coincidence tags for int r/a
R_{fit} > 5.5m from PMTs (30kt fid)



Phys.Rev.Lett.110 : 062502 (2013);
SNO+ white paper (in progress);
Phys. Rev. D 87 no. 7 : 071301 (2013)

NLDBD

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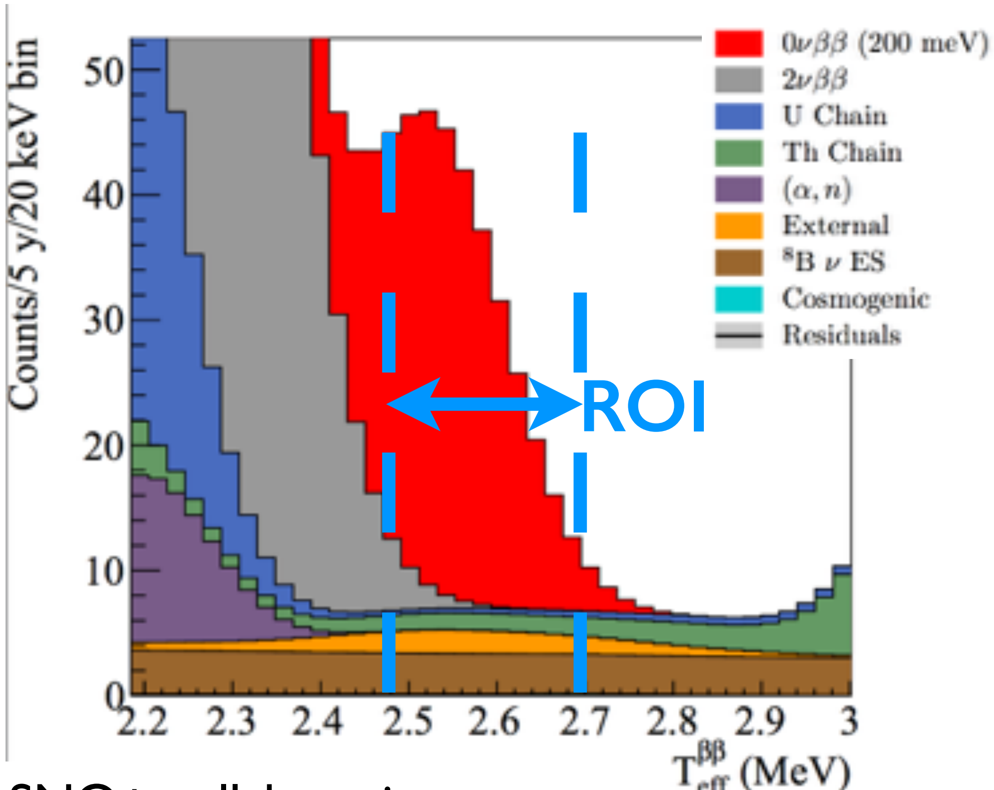

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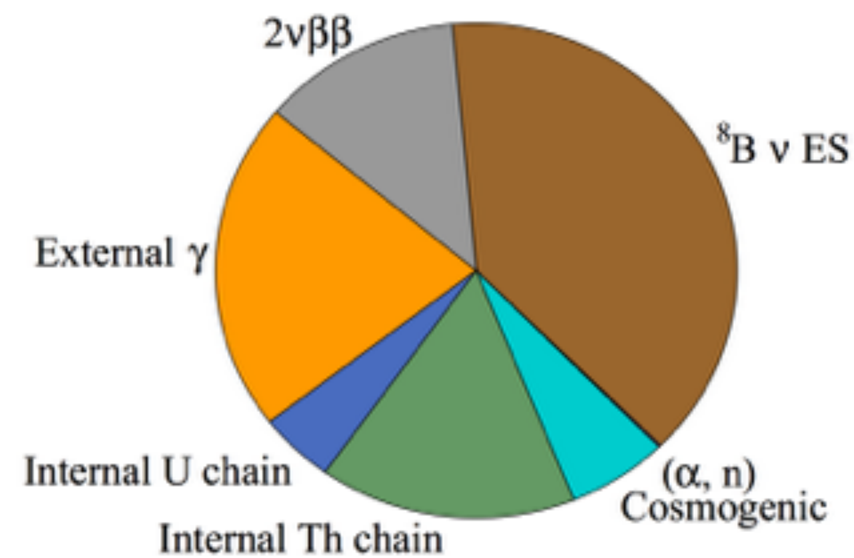

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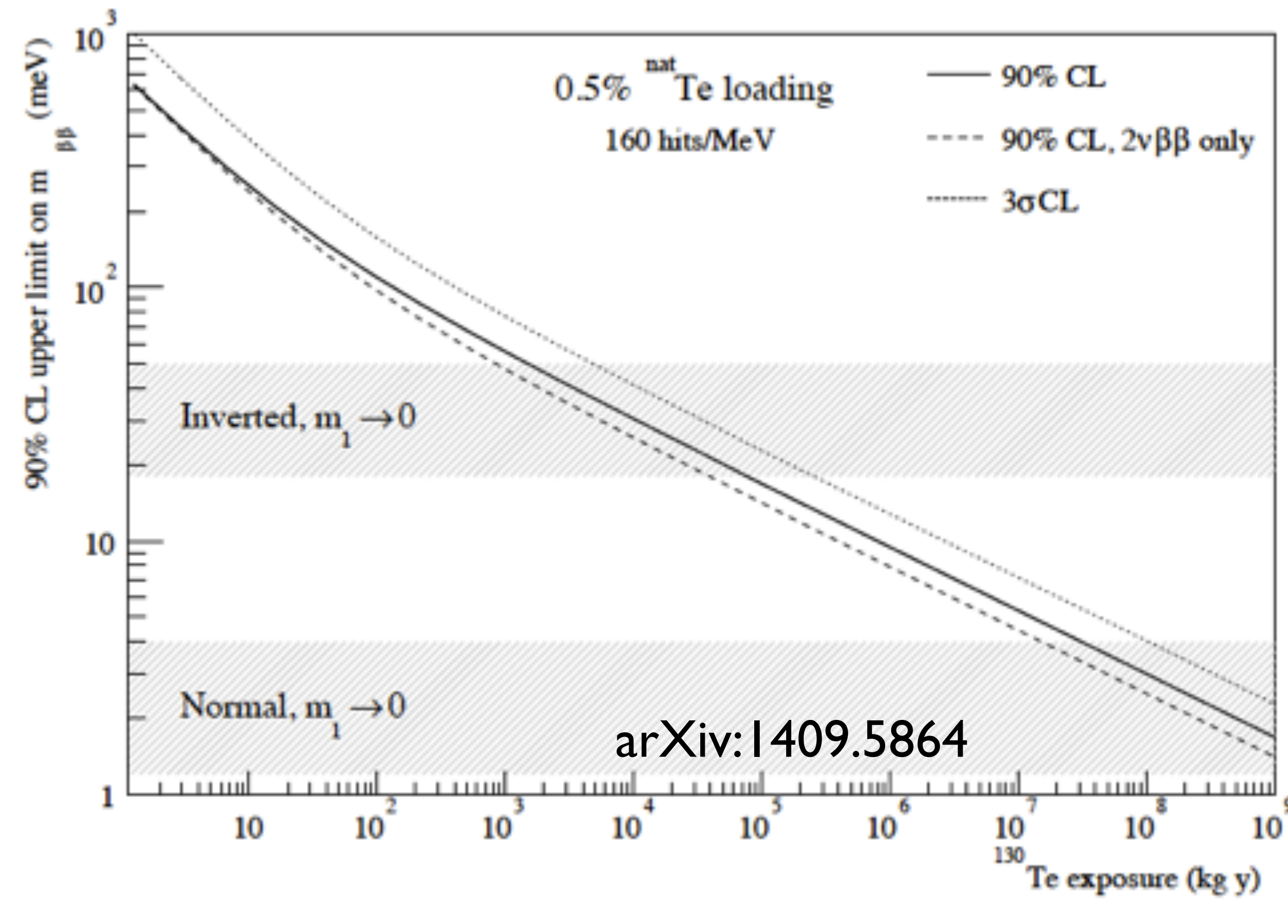
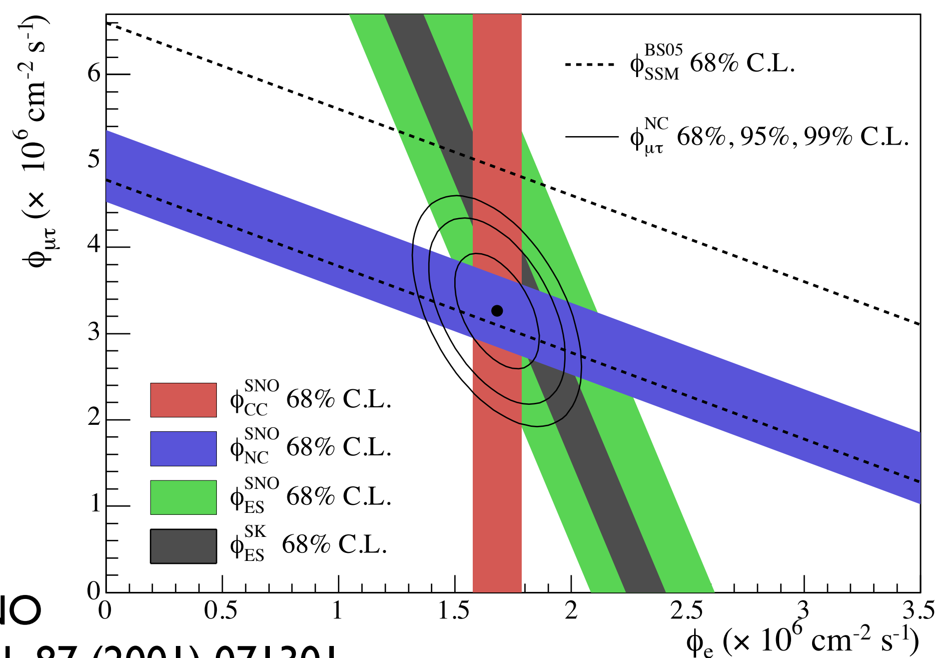
$m_{\beta\beta}$=6.7 meV (1% Te),
5.5 meV (2% ^{enr}Xe)
90% CL in 5 yrs



Solar Neutrinos

Successful history for both Cherenkov and scintillation detection



SNO
PRL 87 (2001) 071301,
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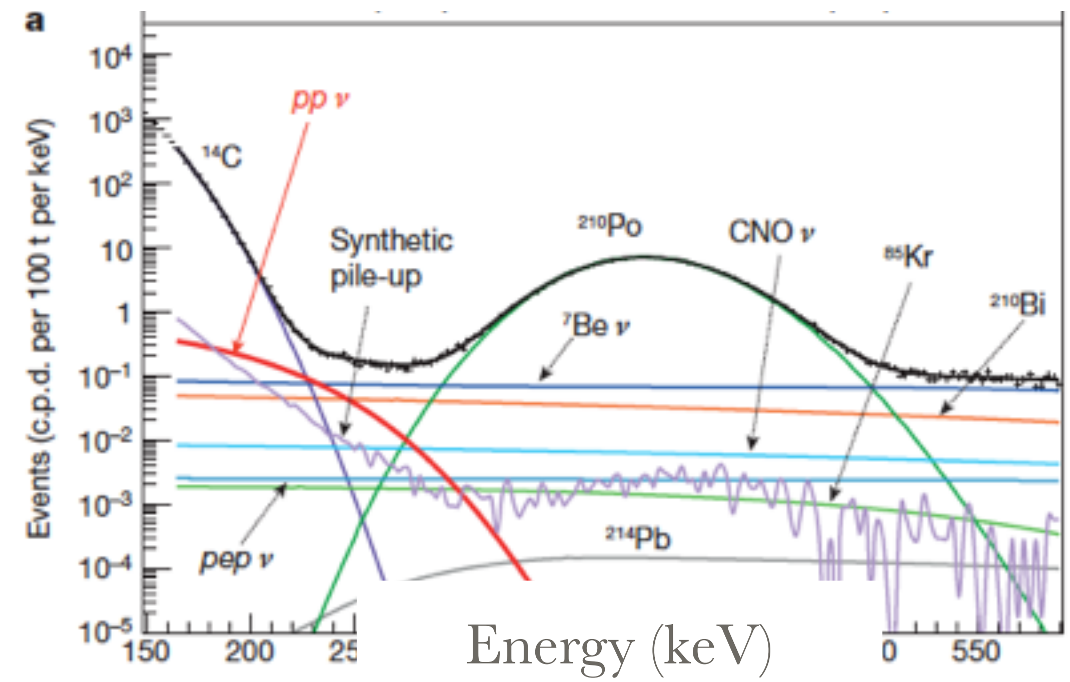

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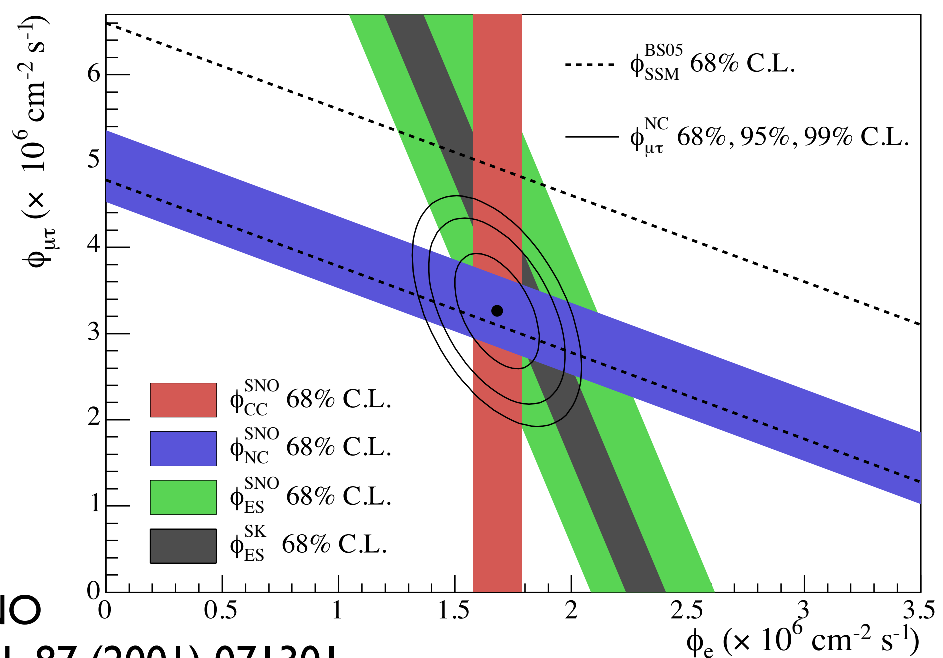

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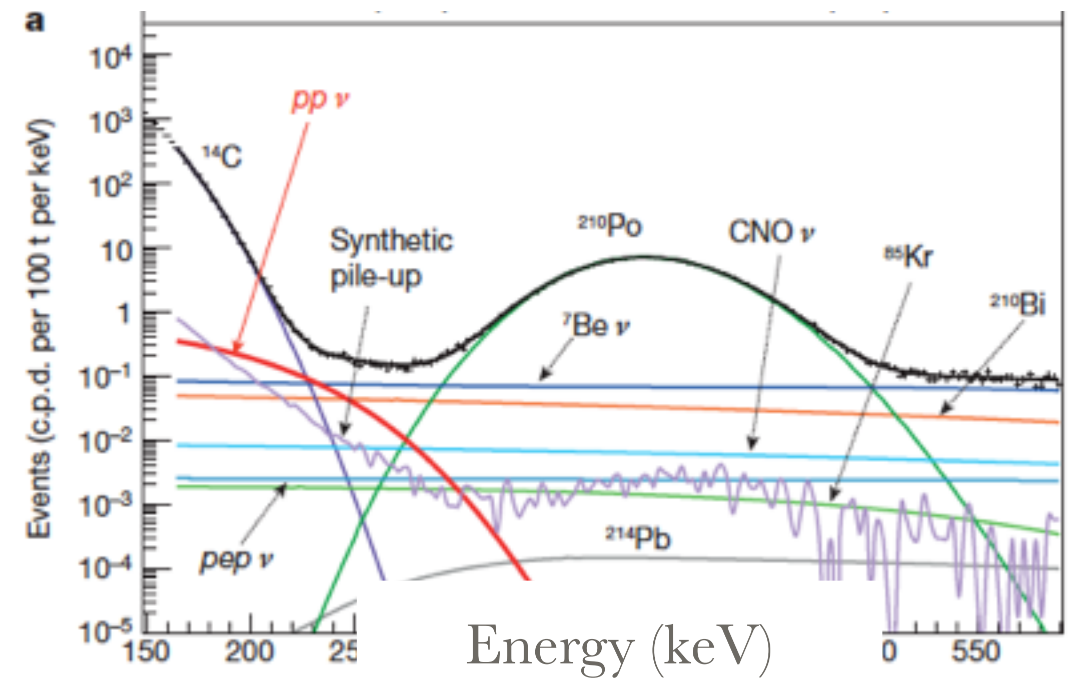

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Exciting questions still to address

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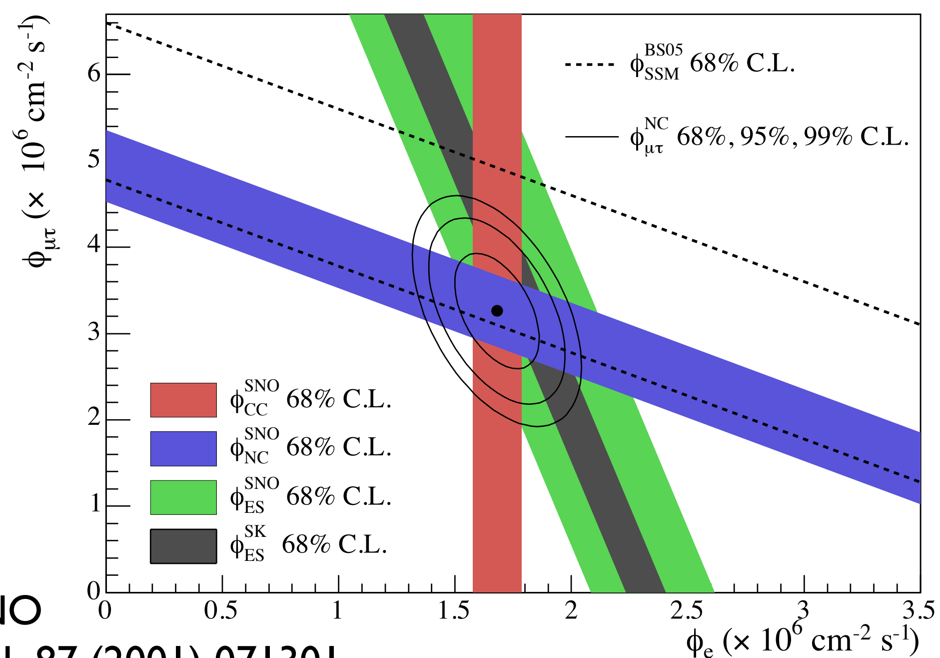

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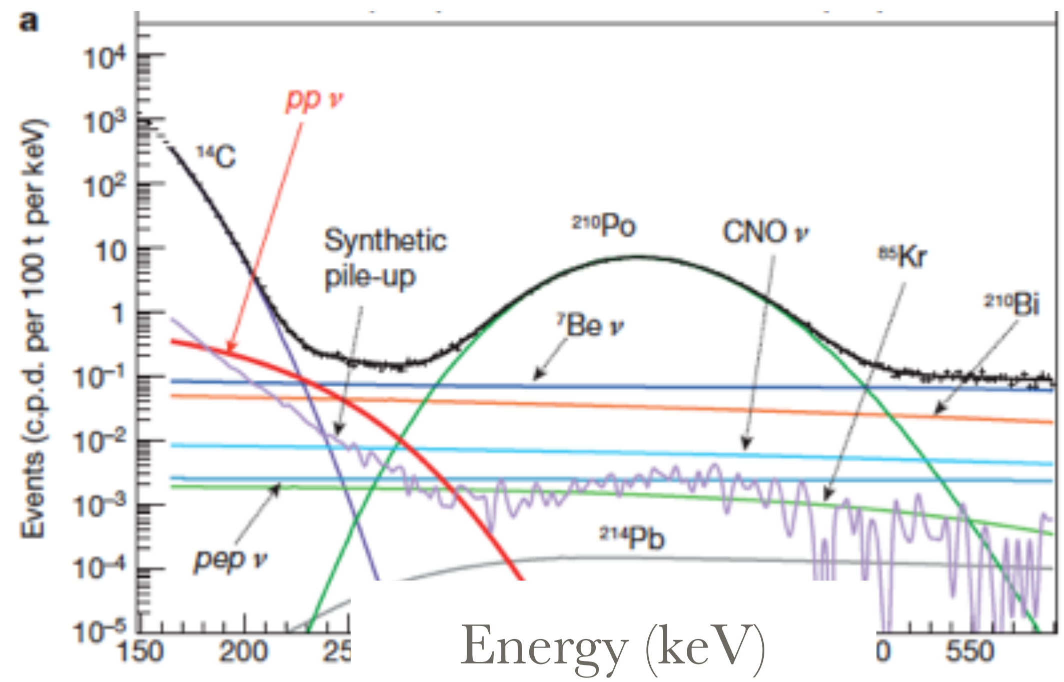

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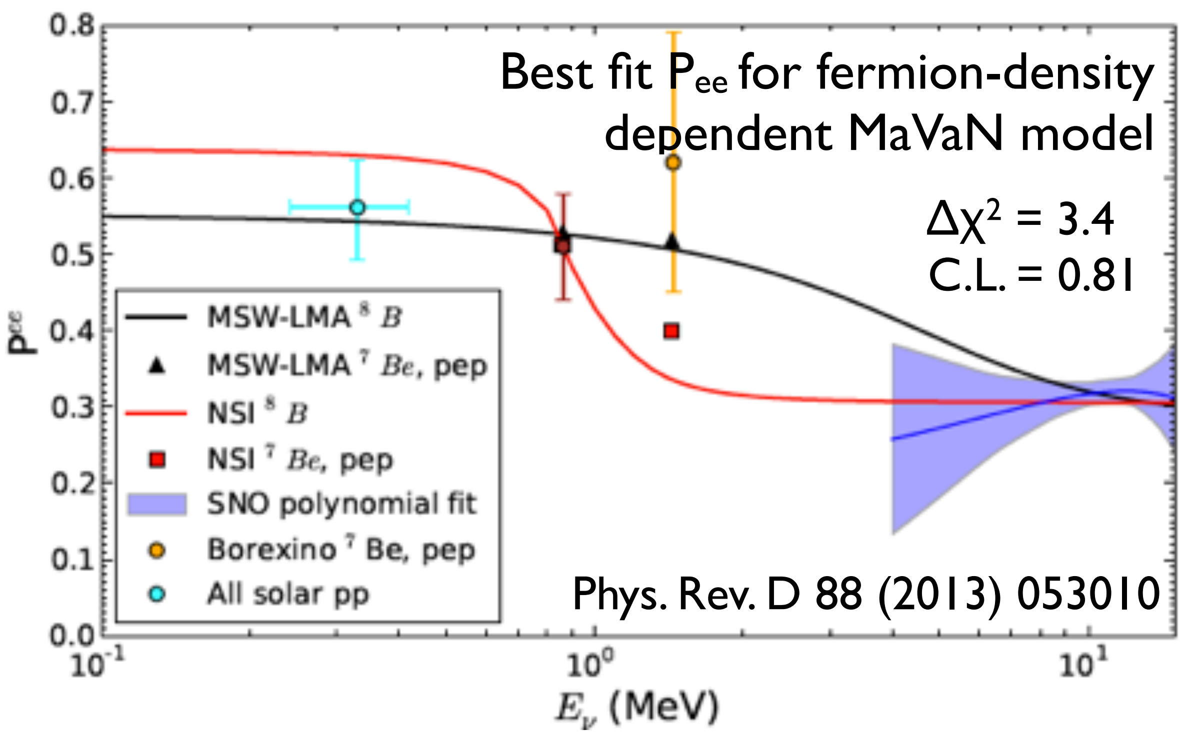
Probe MSW transition



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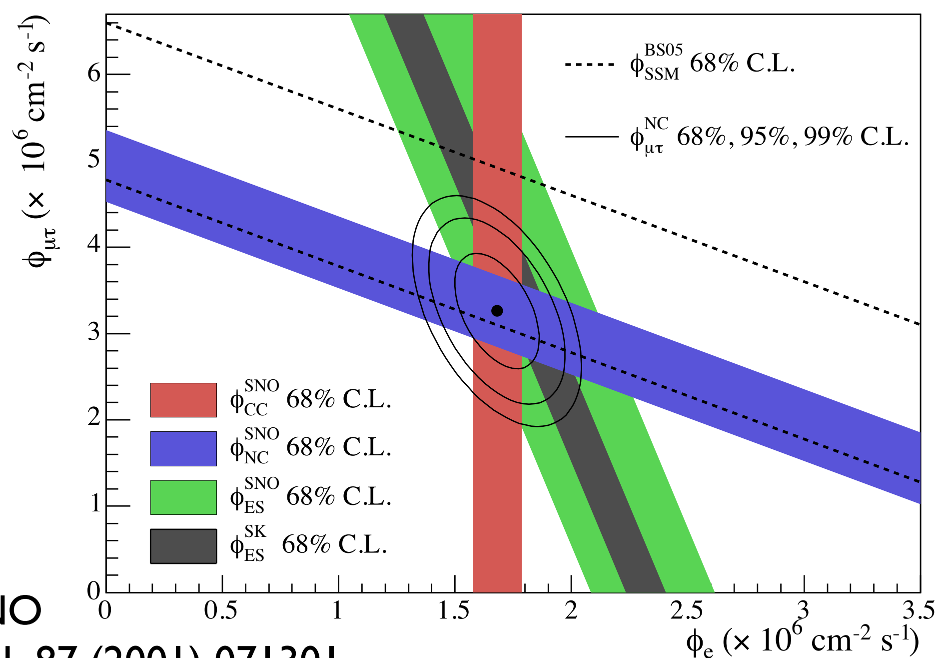

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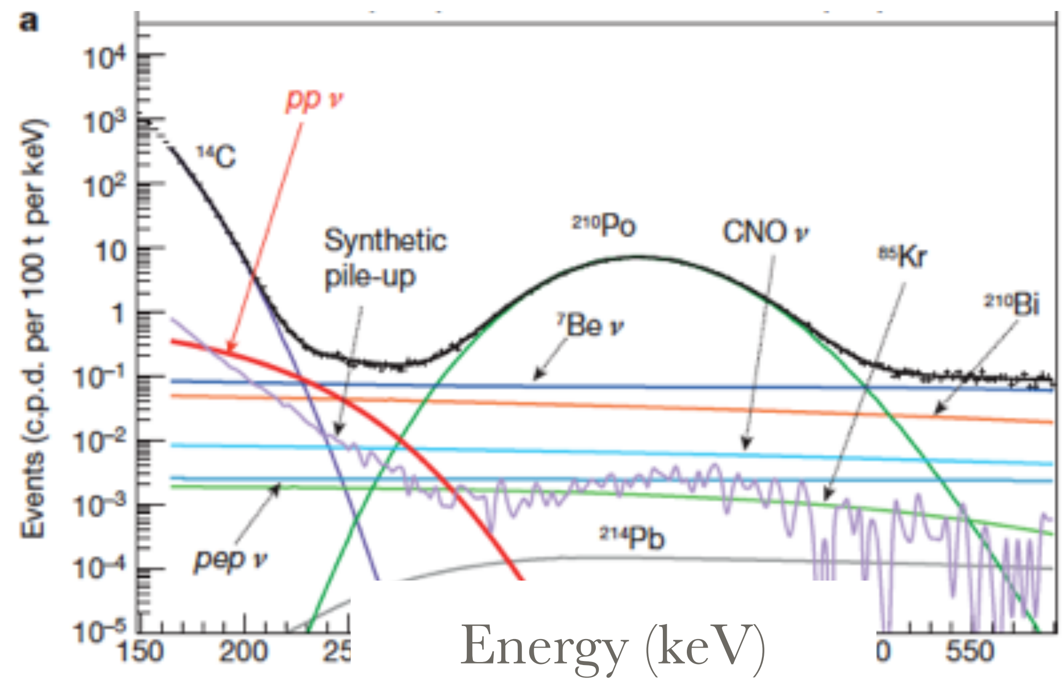

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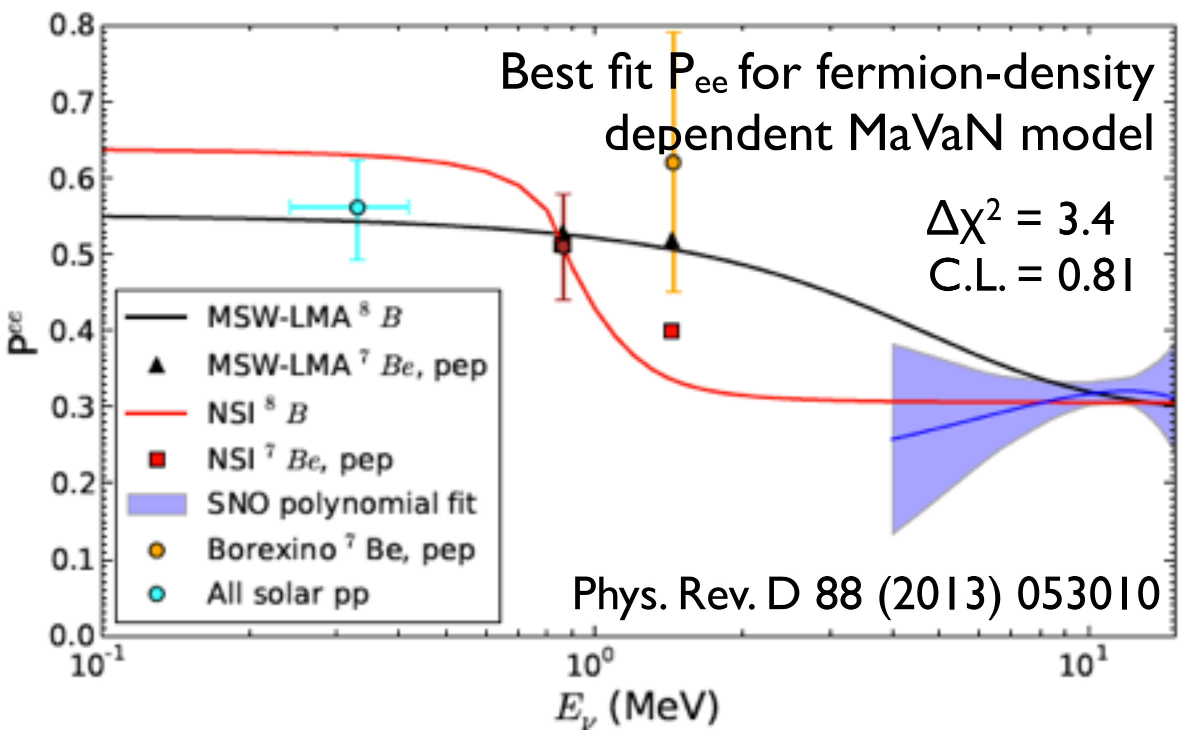
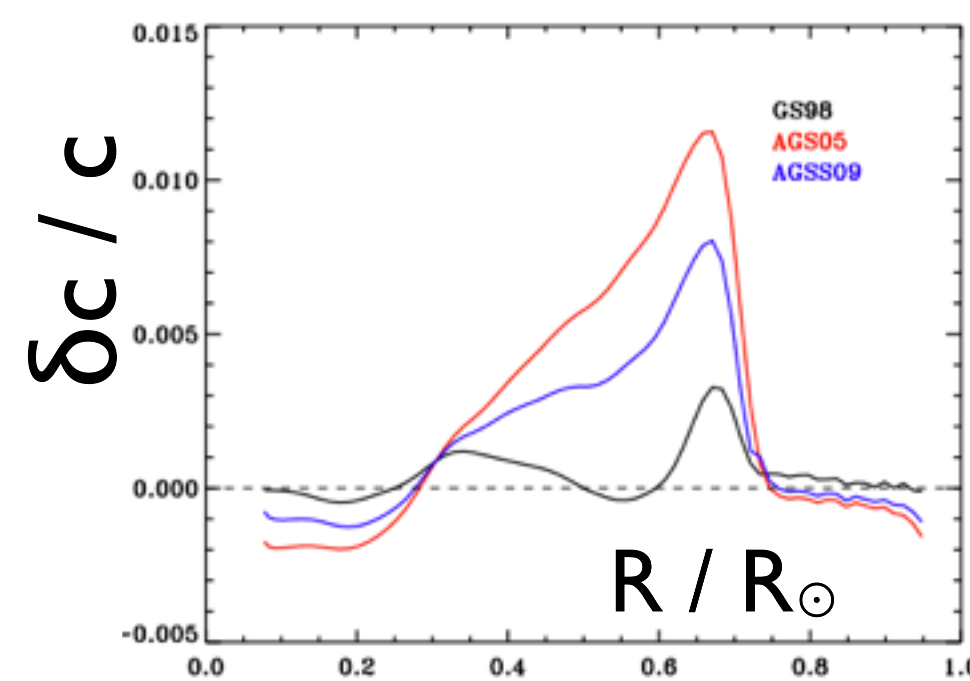


Phys. Rev. D 88 (2013) 053010

Resolve solar metalicity



THEIA Spectral Sensitivity

"Salty water Cherenkov detectors" W.C. Haxton PRL 76 (1996) 10

arXiv:1409.5864

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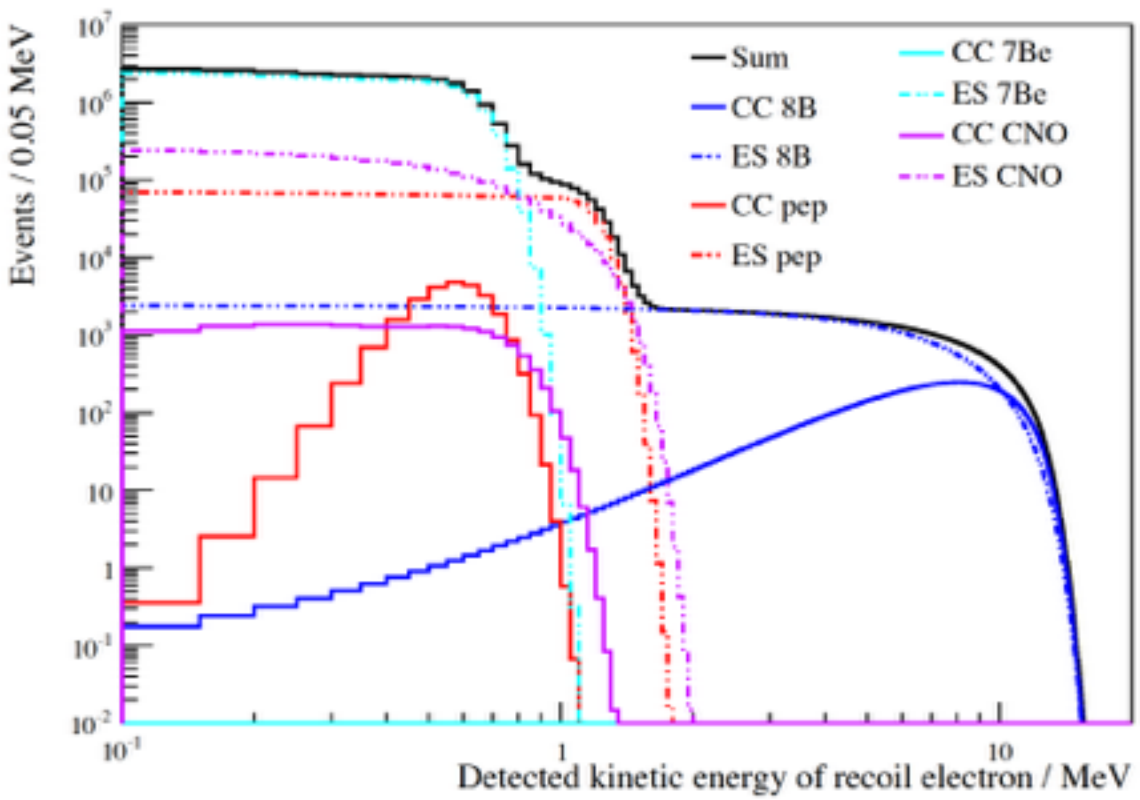

30kt fiducial
1% ^{7}Li by mass
Conservative
100 pe/MeV

Similar to LENA — Astropart. Phys. 35 (2011) 685-732
+ directionality from Cherenkov

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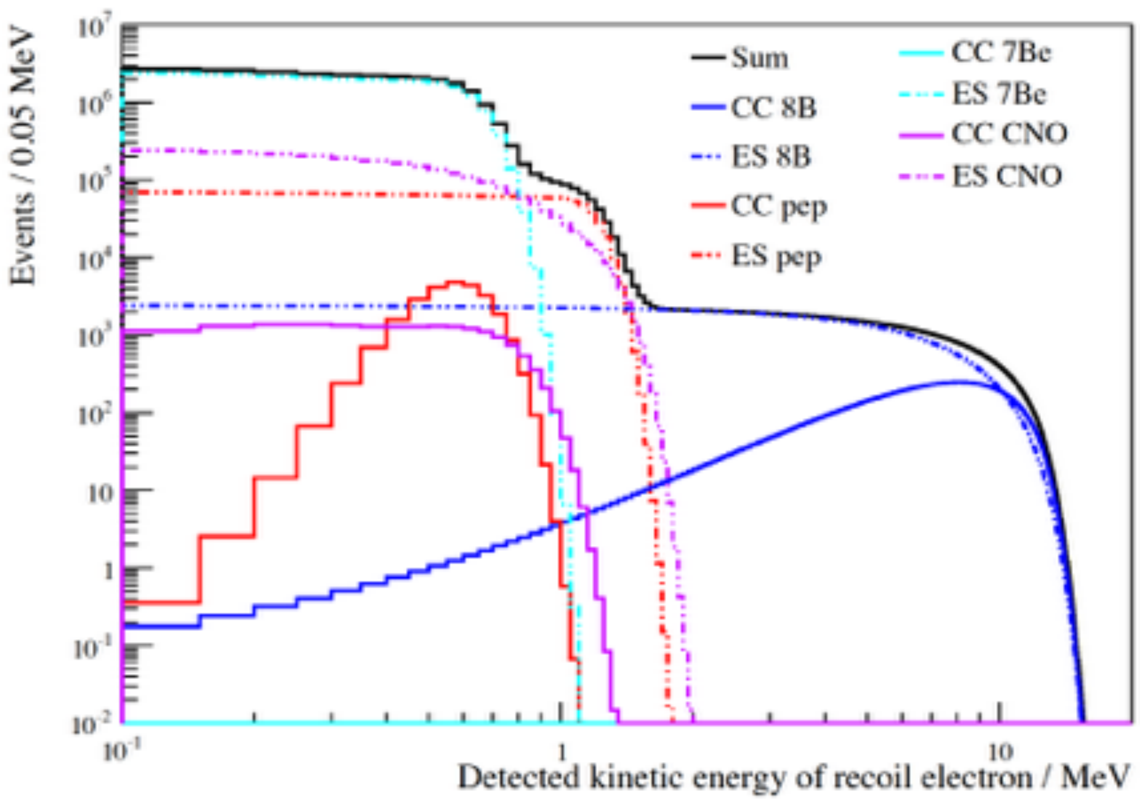

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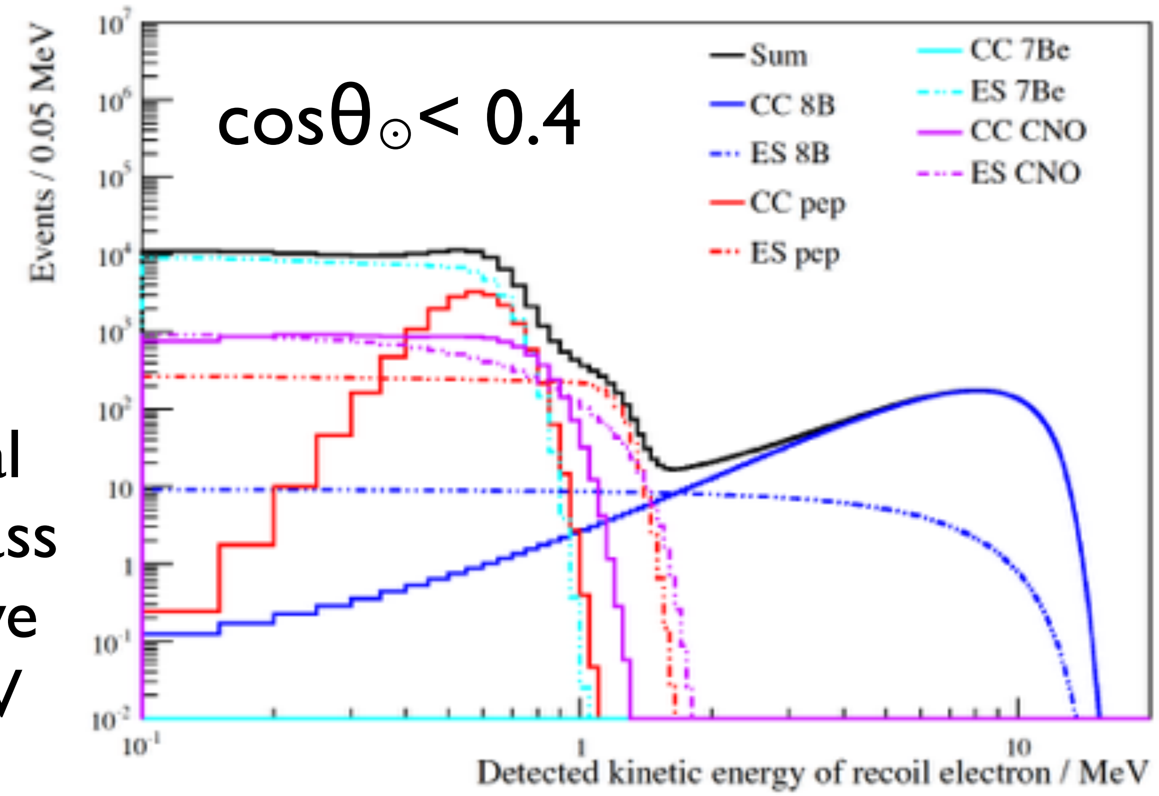
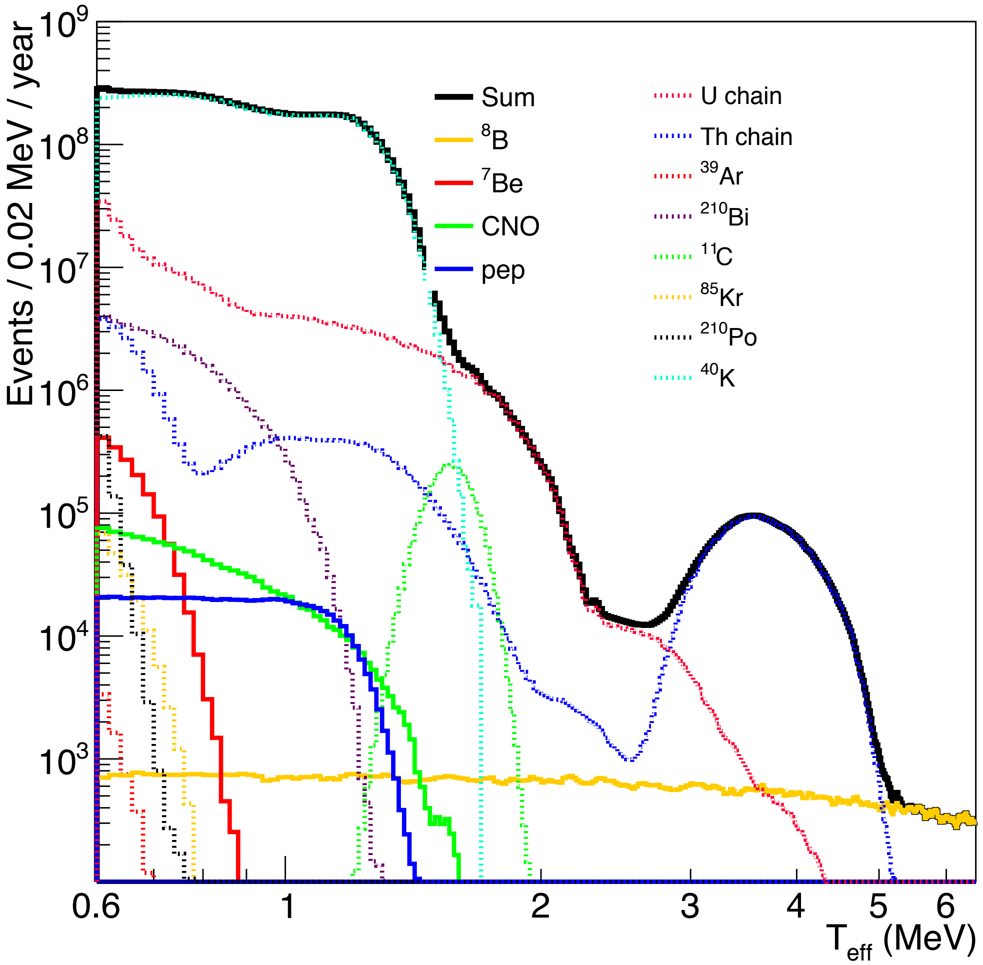


Enabled by use of WbLS (^{7}Li, CC)

arXiv:1409.5864

R. Bonventre, Berkeley

THEIA Flux Sensitivity



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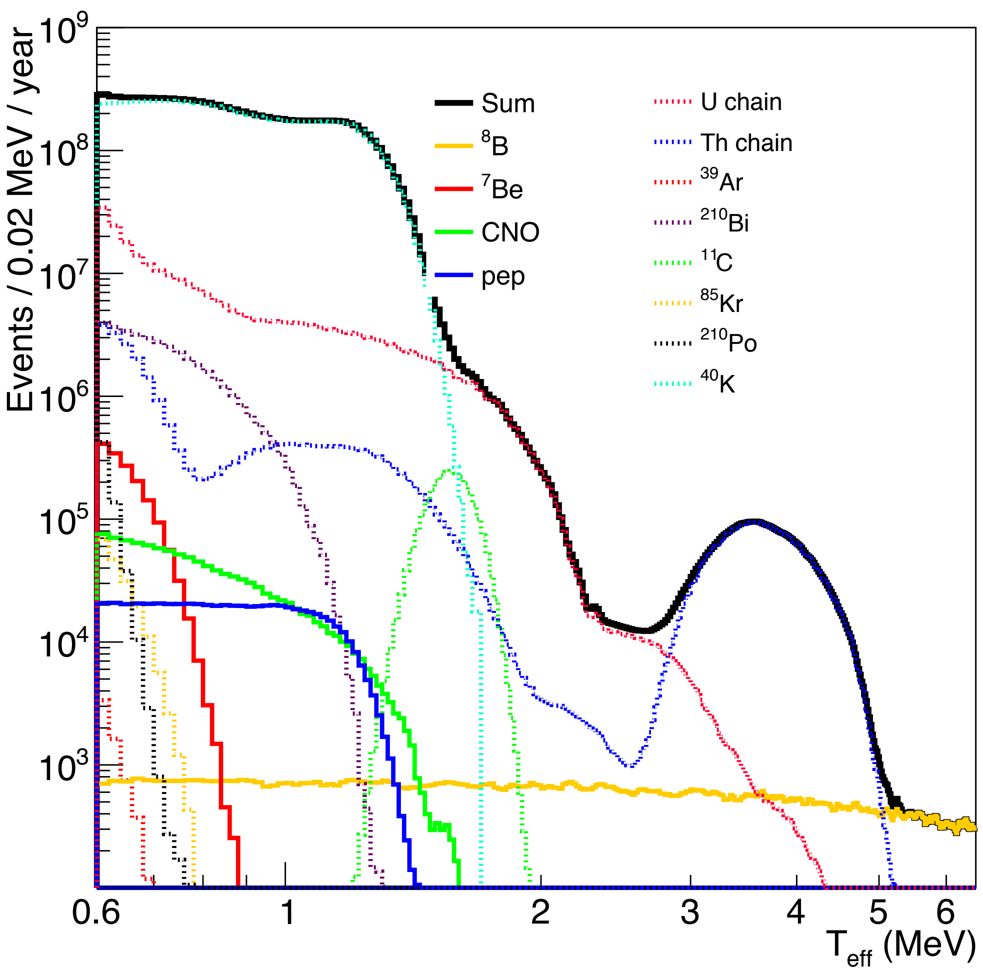

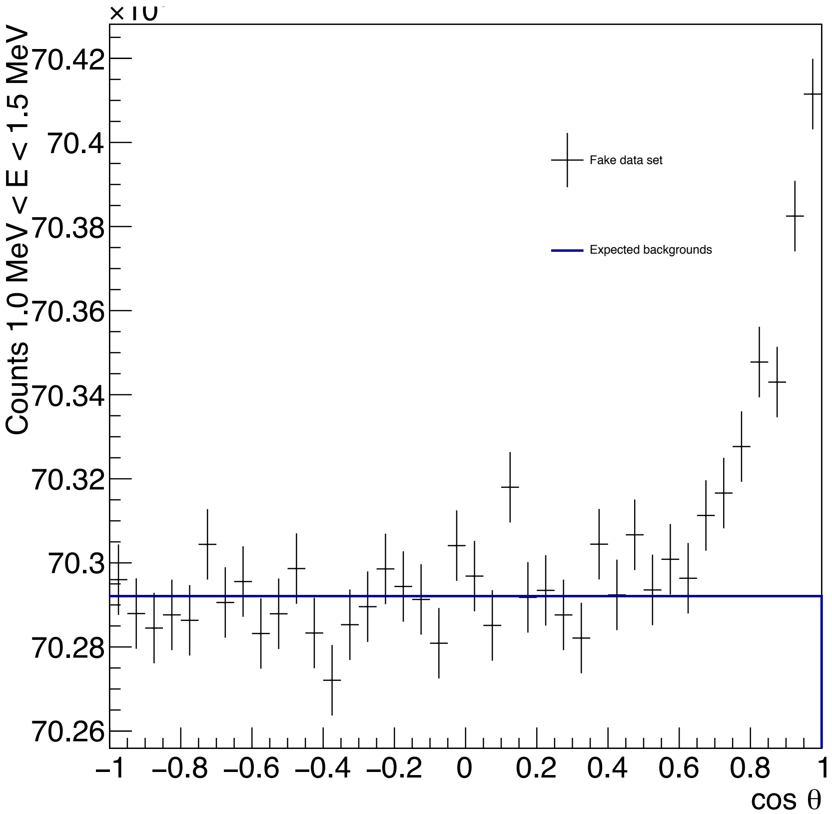

5% WbLS

25^0 ang res

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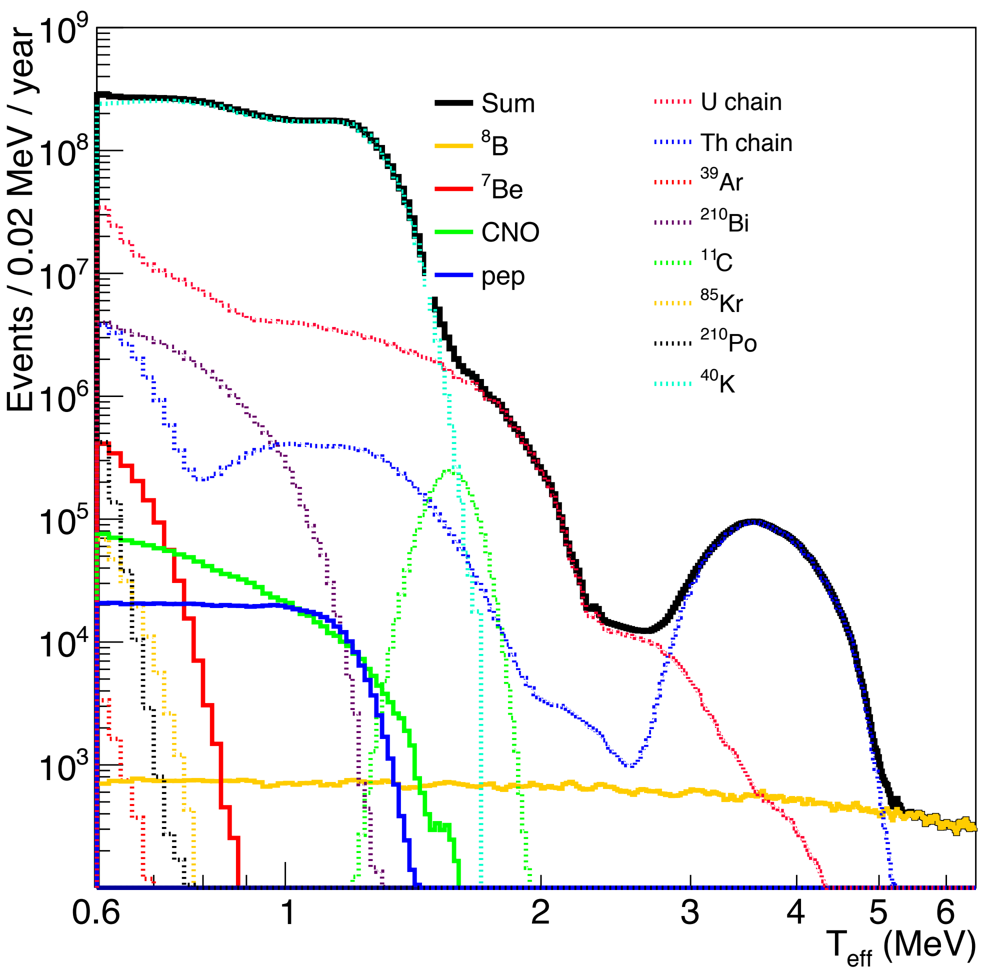
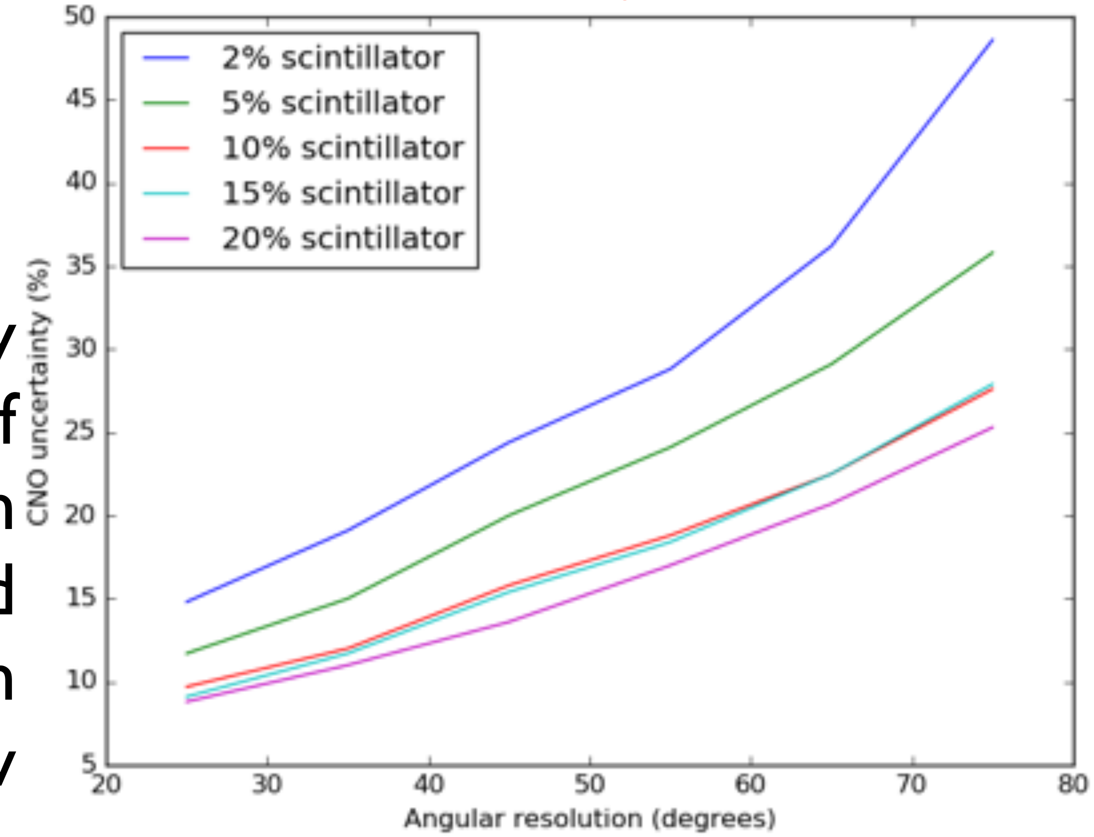
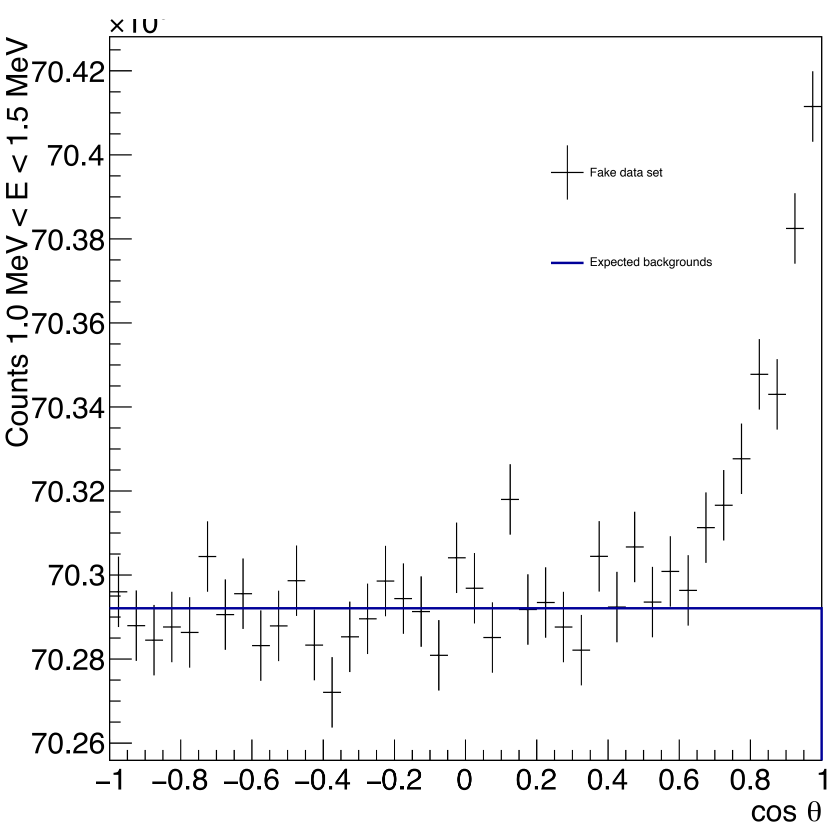


CNO sensitivity as a function of LS fraction and angular resn

40K at SNO lv





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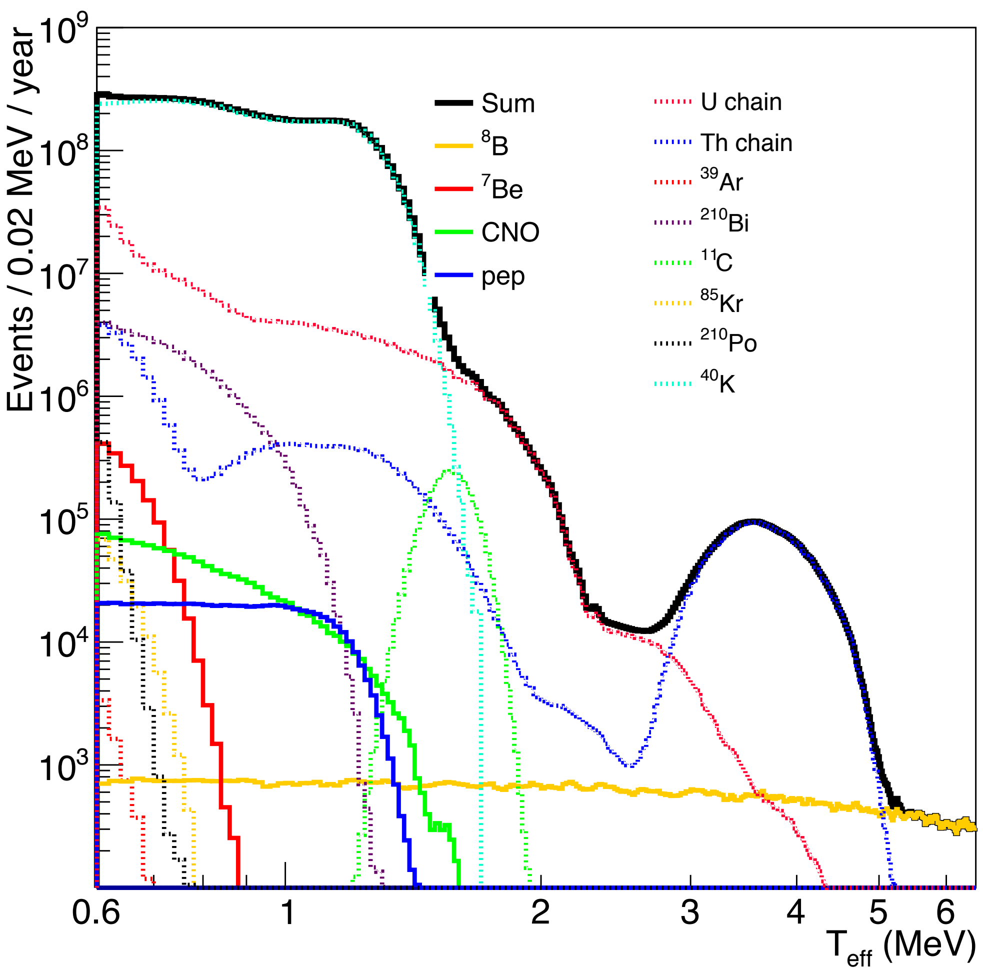

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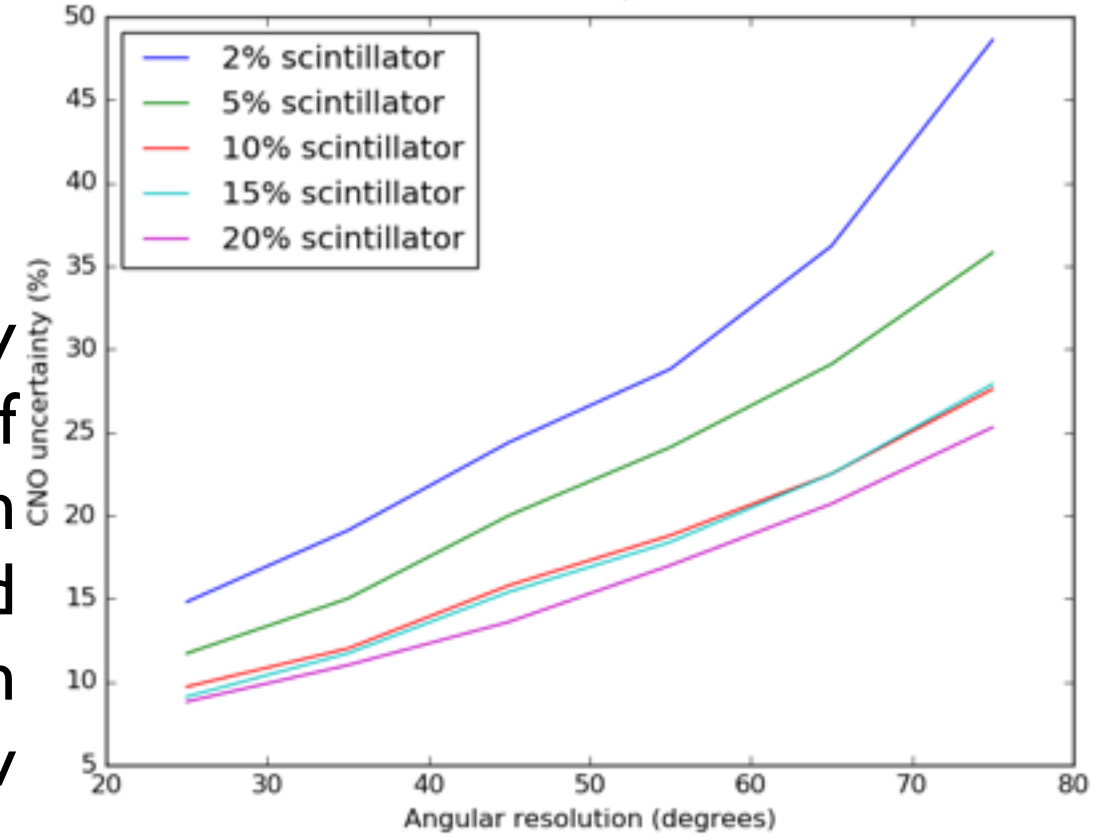

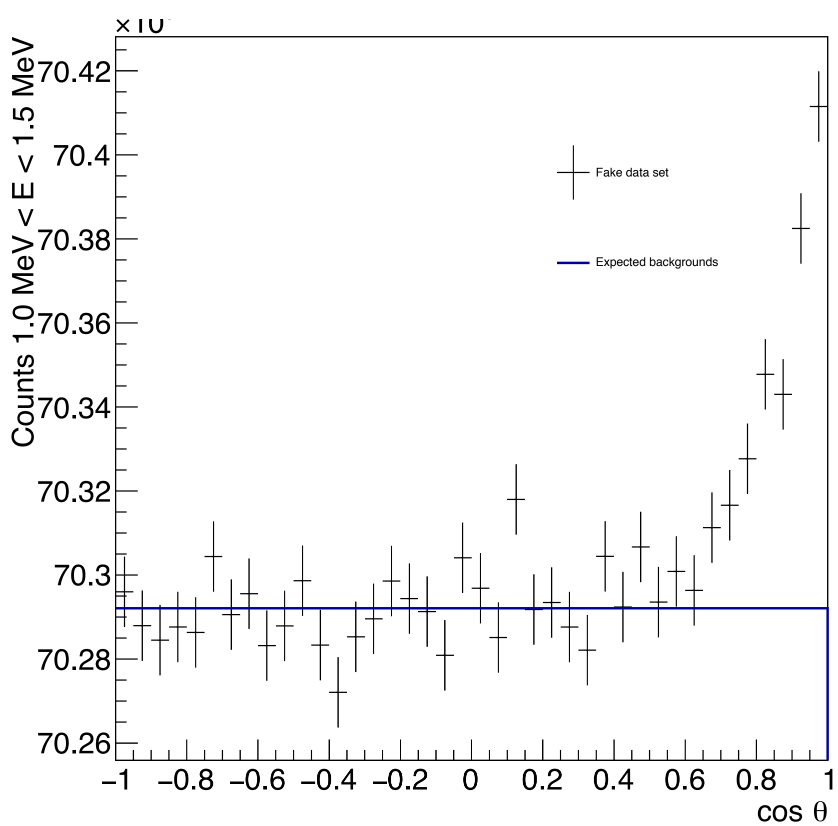

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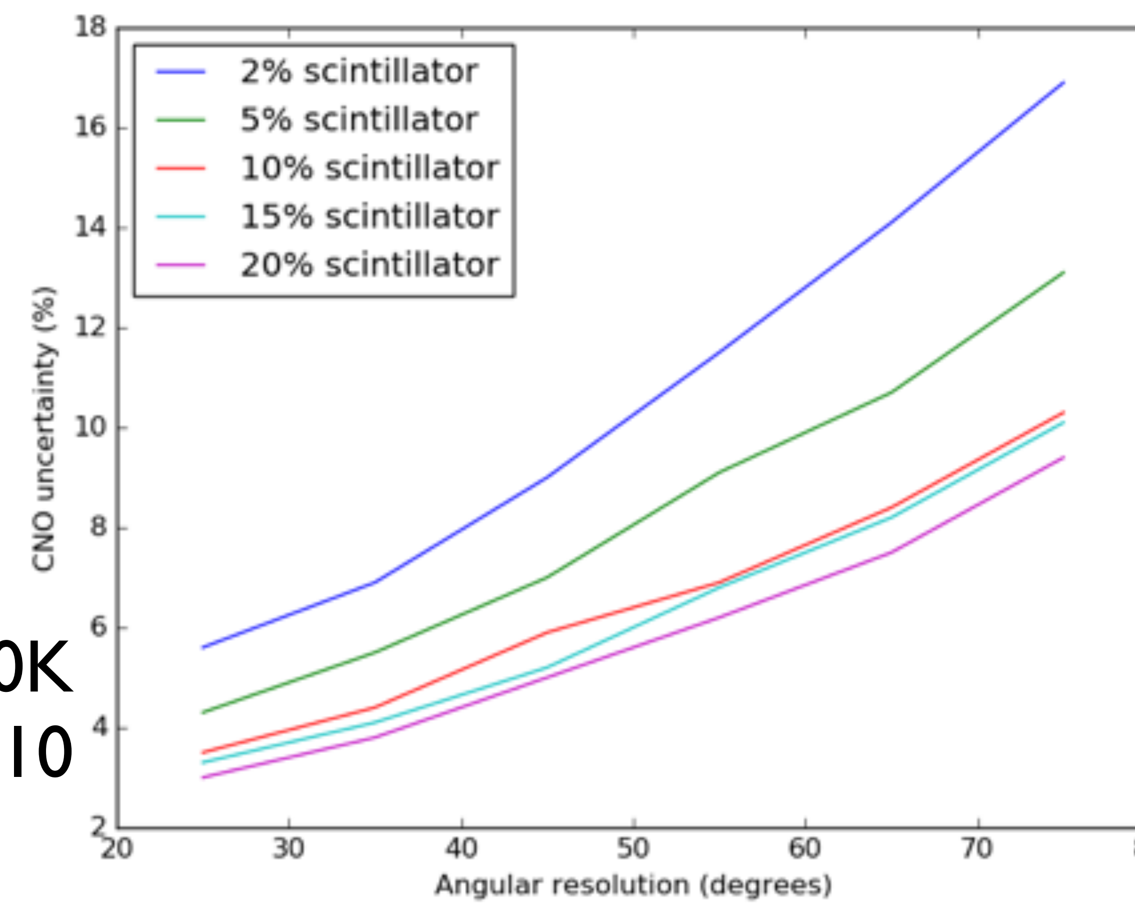
Reduce 40K by x10



See geoneutrino talk, Steve Dye

Antineutrino Detection

- Detect via IBD
- High light yield allows enhanced n tag : 2.2 MeV γ from ^{1}H
  - Suppress single-event background that limits water Cherenkov
- Higher detection efficiency than Gd-H_2O due to high scint. yield
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- Current total geo-ν exposure: < 10kt-yr (KL + Borexino)
  - **THEIA**: large statistics in a complementary geographical location

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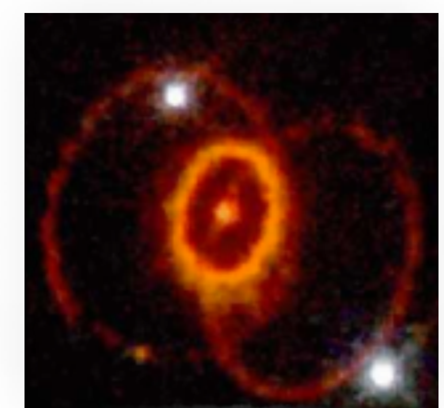
DSNB



- Enhanced n tag
- Reduced NC background
- Most sensitive search to-date
- Plus NaCl for ν signal

See supernova talk, Zhe Wang

Supernova

Neutrinos

See supernova talk, Zhe Wang

Supernova Burst in THEIA

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- ID CC & monoE γ from NC ⇒ sensitive to burst T & subsequent ν mixing

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- Bkg reduction for ES, doubling pointing accuracy
- ID CC & monoE γ from NC ⇒ sensitive to burst T & subsequent ν mixing

Early warning (PR value)

High-Energy Program

Big, Deep, Clean

Neutron tag

Sub-Cher t/h detection

Ring imaging (high E)

Cher/scint ratio

High-Energy Program

Sterile Neutrinos

Deployed source

Big, Deep, Clean

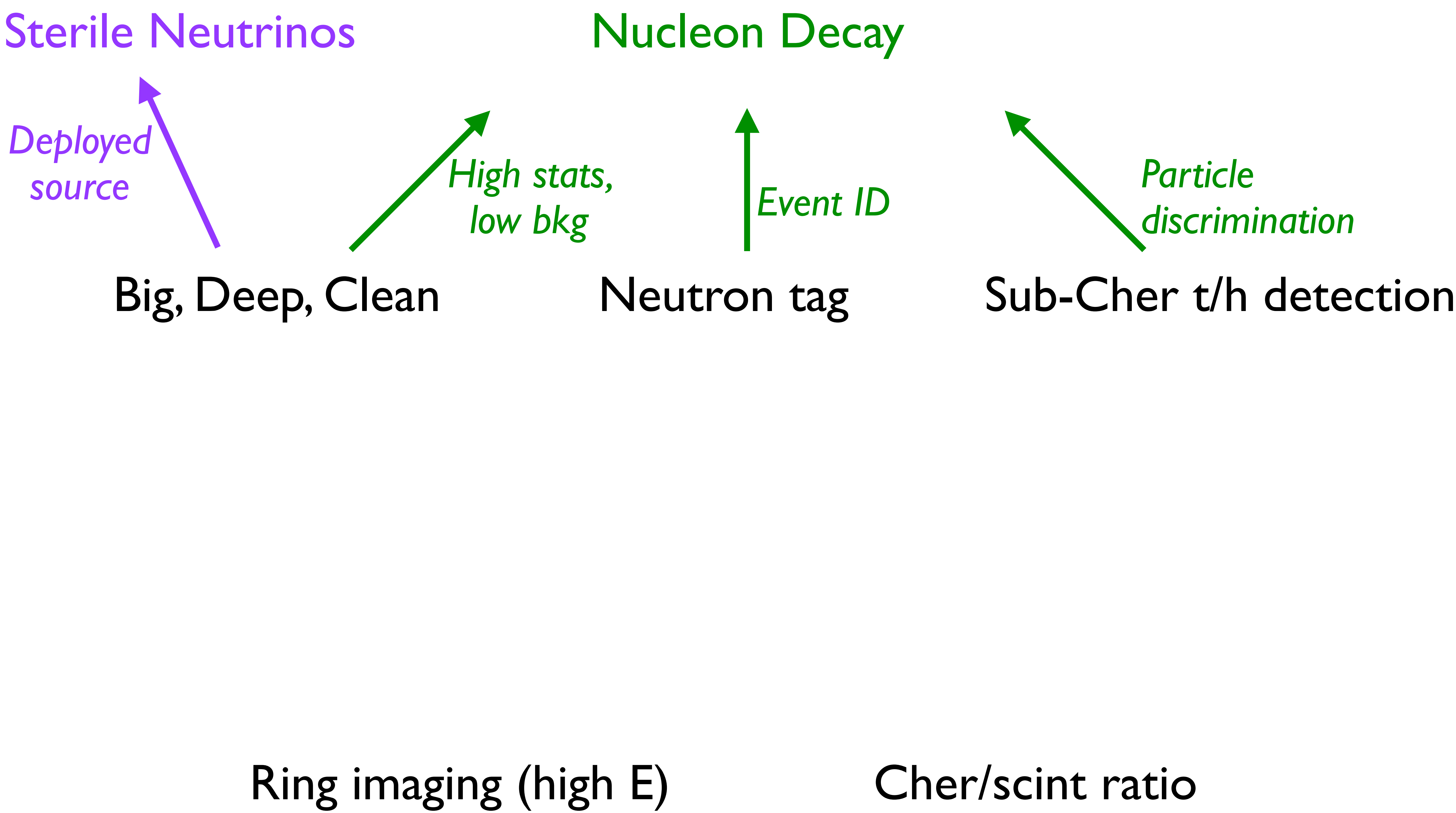
Neutron tag

Sub-Cher t/h detection

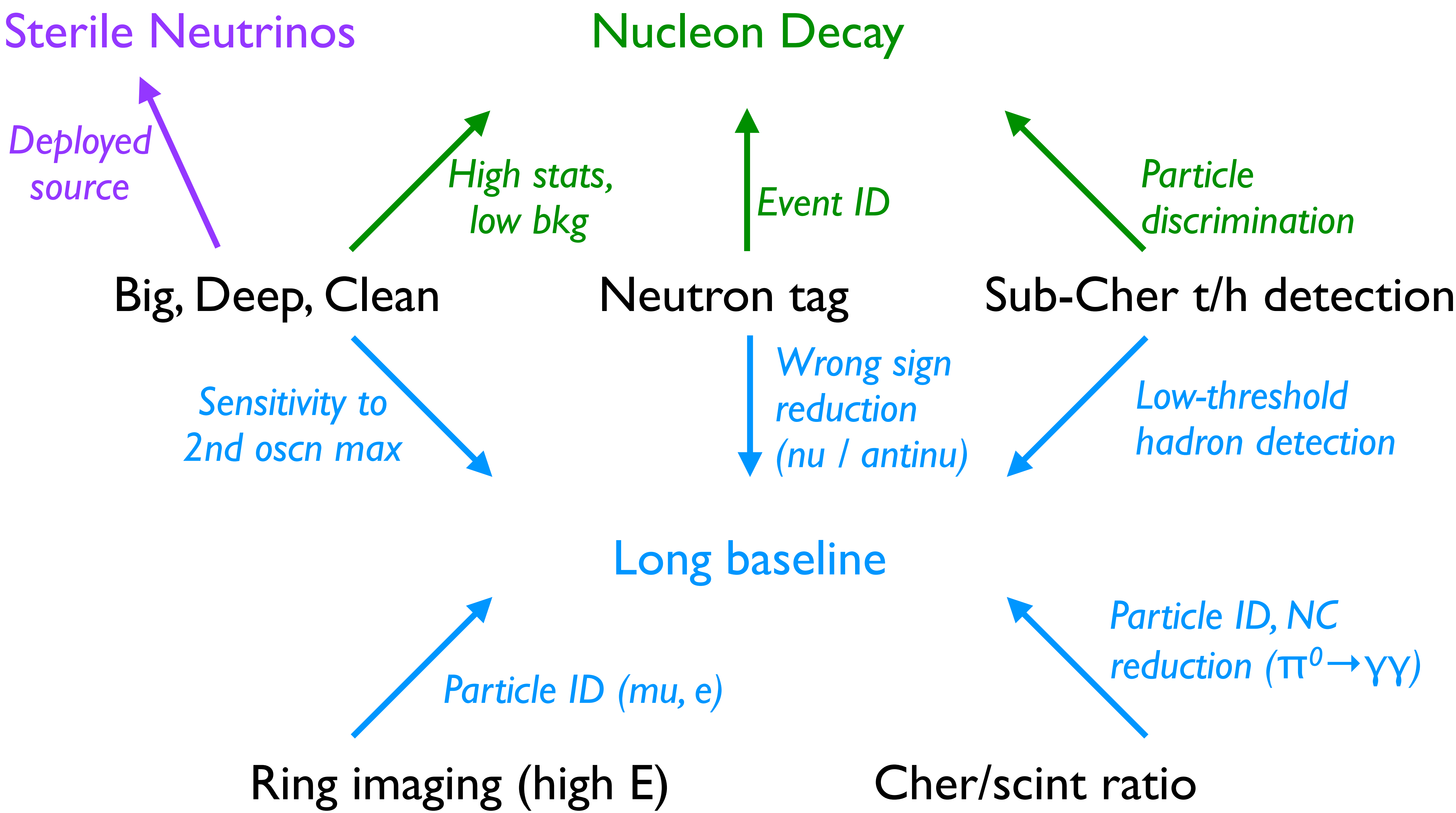
Ring imaging (high E)

Cher/scint ratio

High-Energy Program



High-Energy Program

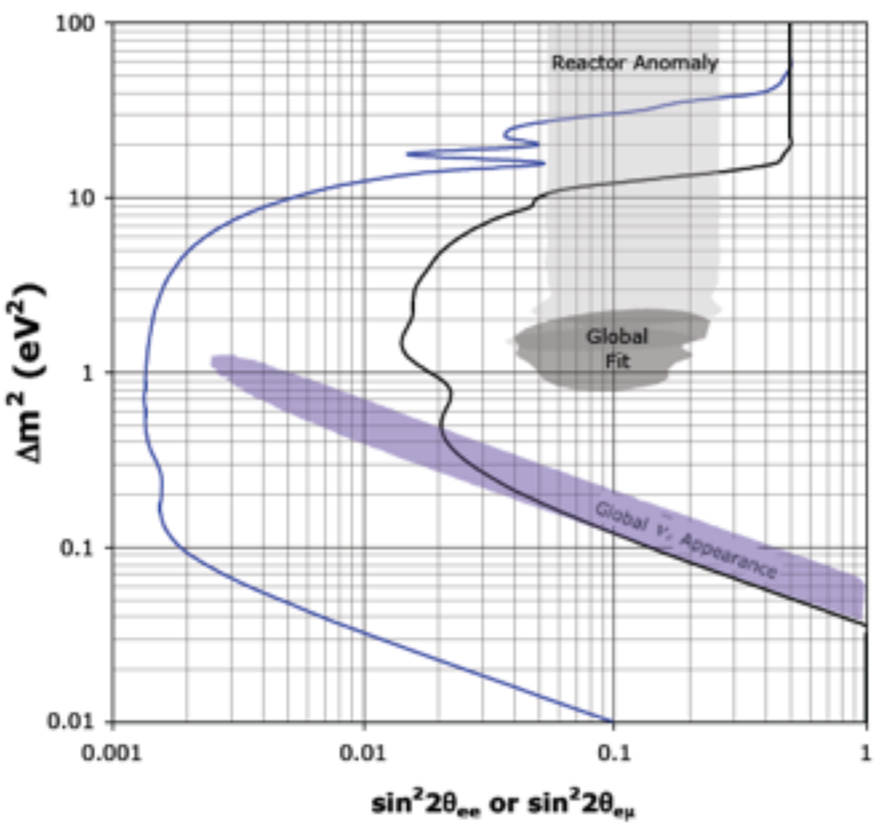


Sterile Neutrinos

Figs from arXiv:1409.5864

Sterile Neutrinos

- Deploy ^{8}Li decay-at-rest (IsoDAR)
  - 13MeV endpoint (above r/a)
  - Required detector response:
    15% (E) & 50cm (R)
  - 5 yrs, 1kt (black) / 20kT fid. (blue)



- Heavy-water based LS: 2n tag
  (reduce bkg in IBD searches)

Figs from arXiv:1409.5864

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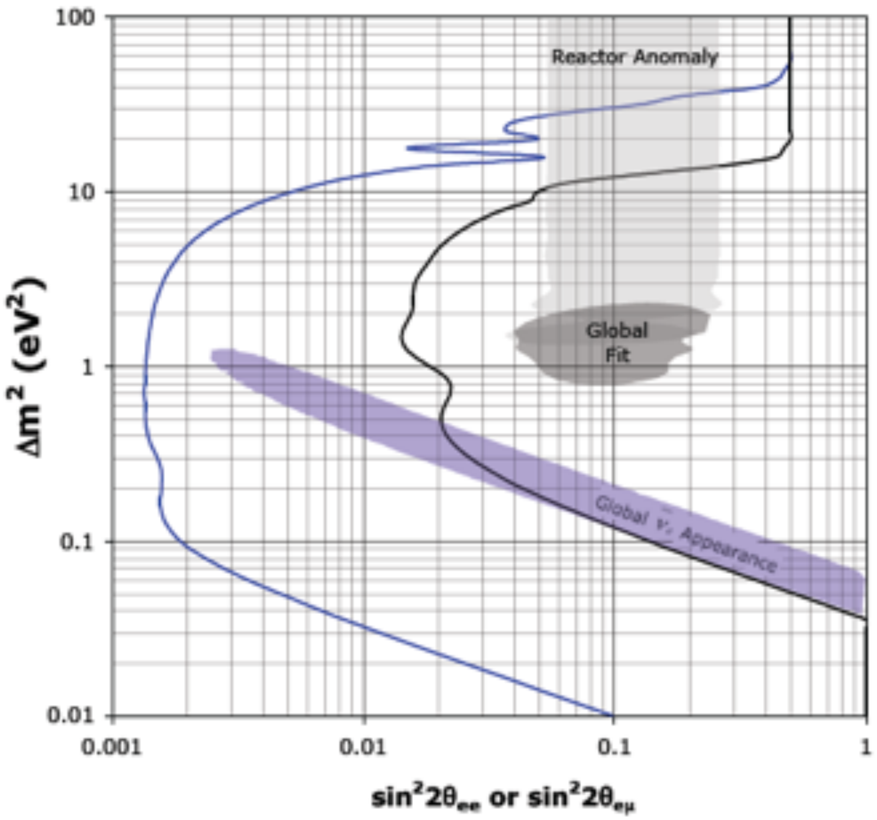

- Heavy-water based LS: 2n tag (reduce bkg in IBD searches)

Nucleon Decay

- Large, deep, very clean
- Enhanced n tag
- Sub-Cherenkov threshold detection
- Sensitive to several modes

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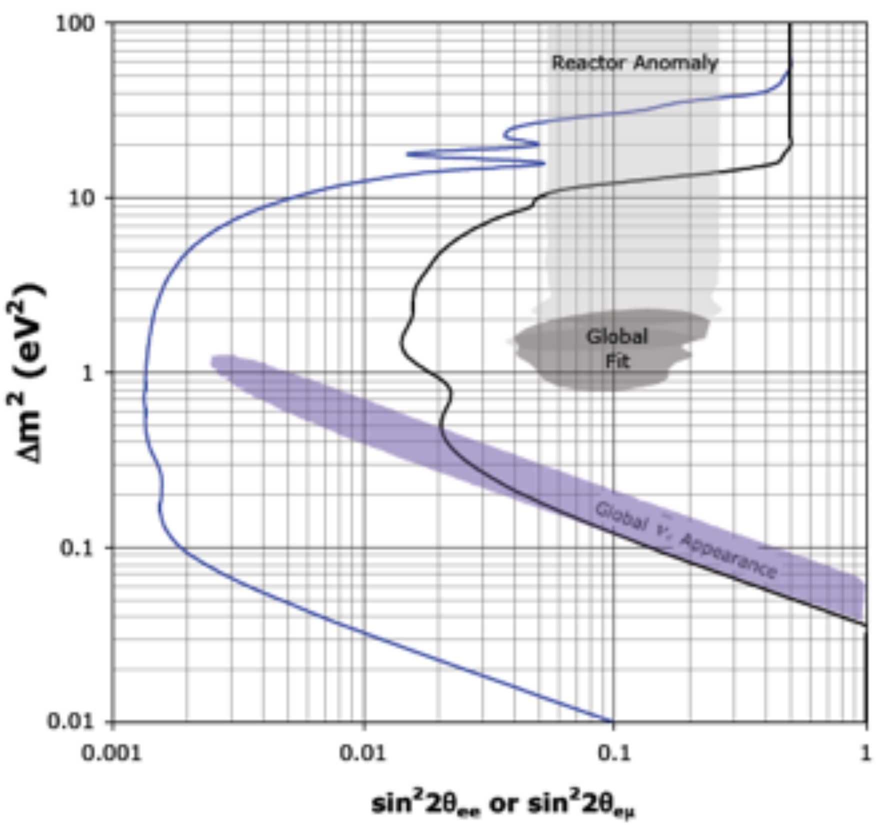

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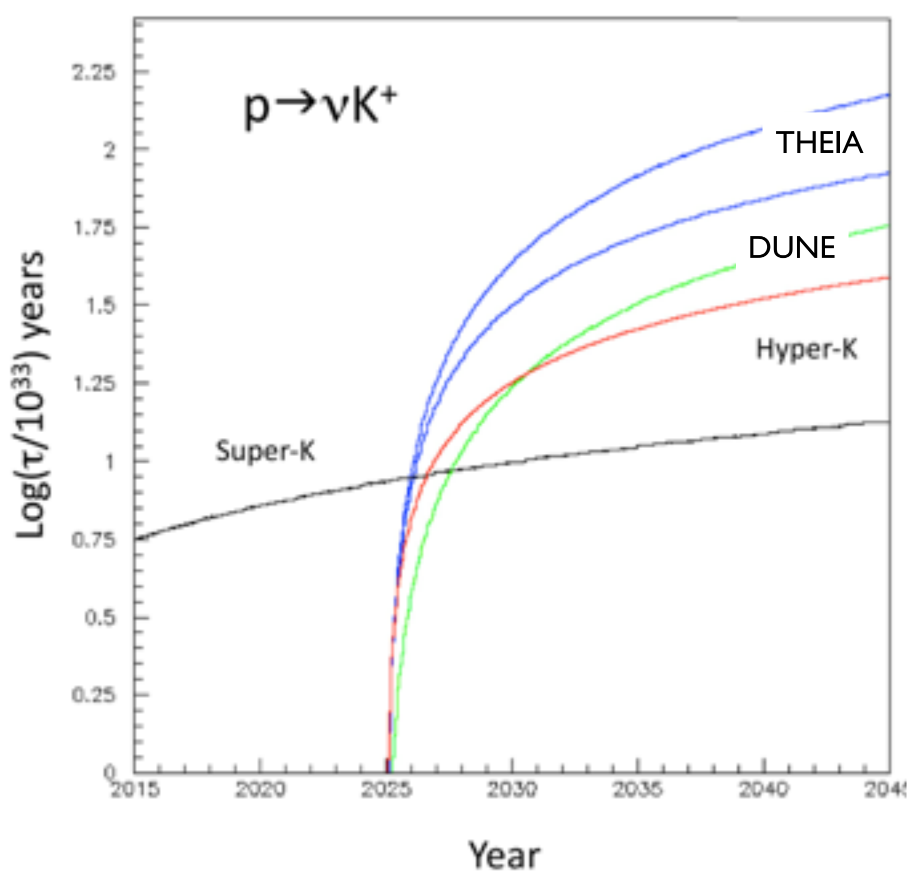


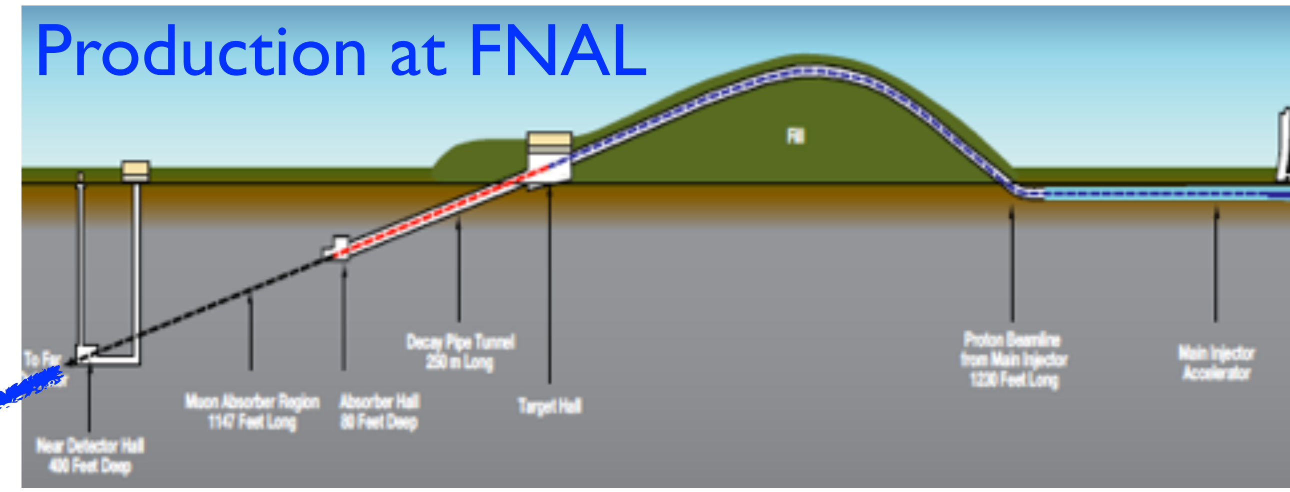
Sub-Chr t/h detection
⇒ Directly visible K^+

Figs from arXiv:1409.5864

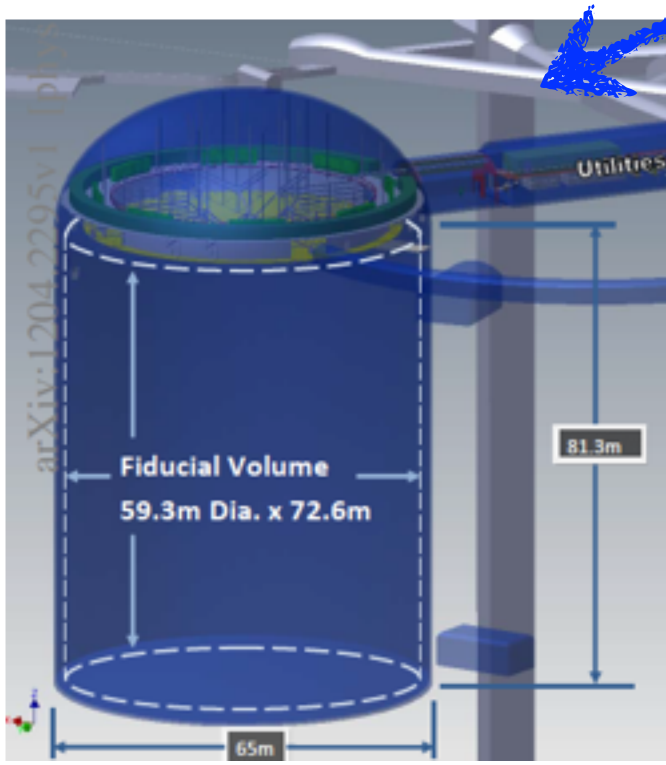
See long baseline talk, Mike Wilking

Long Baseline Program

- Large-scale detector at Homestake, in the LBNF beam
- Complementary program to LArTPC (DUNE)
- Build on WCD studies (arXiv:1204.2295)



1300km



Images from arXiv:1204.2295

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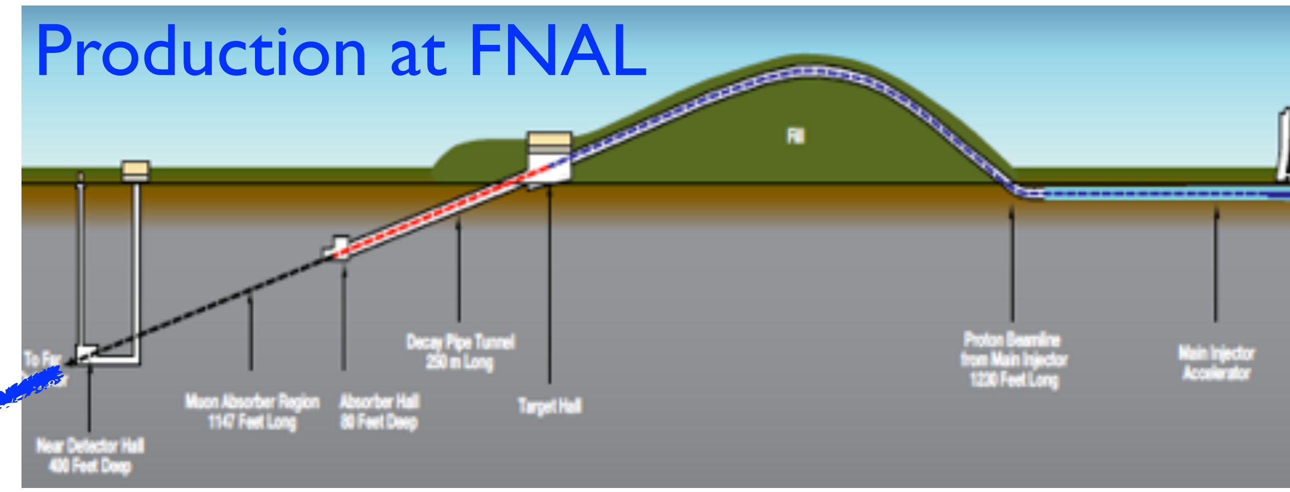

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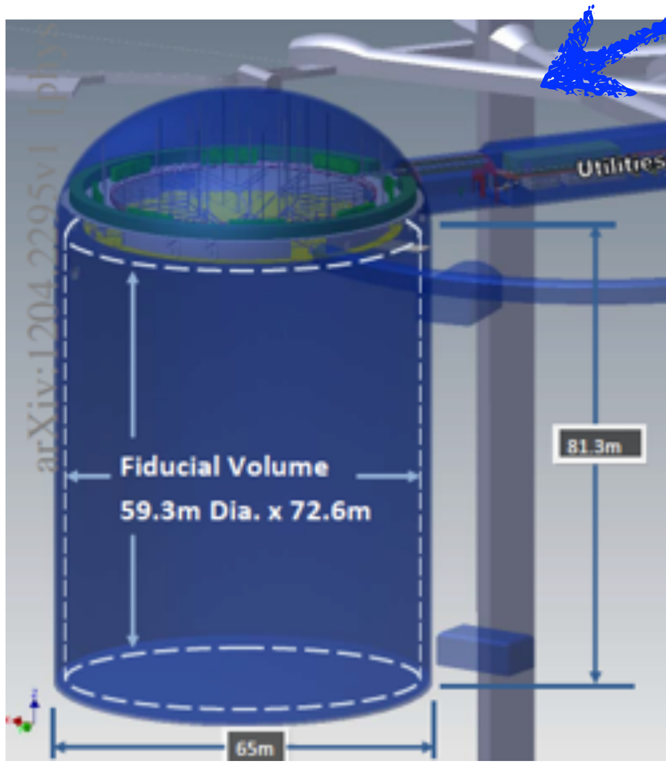
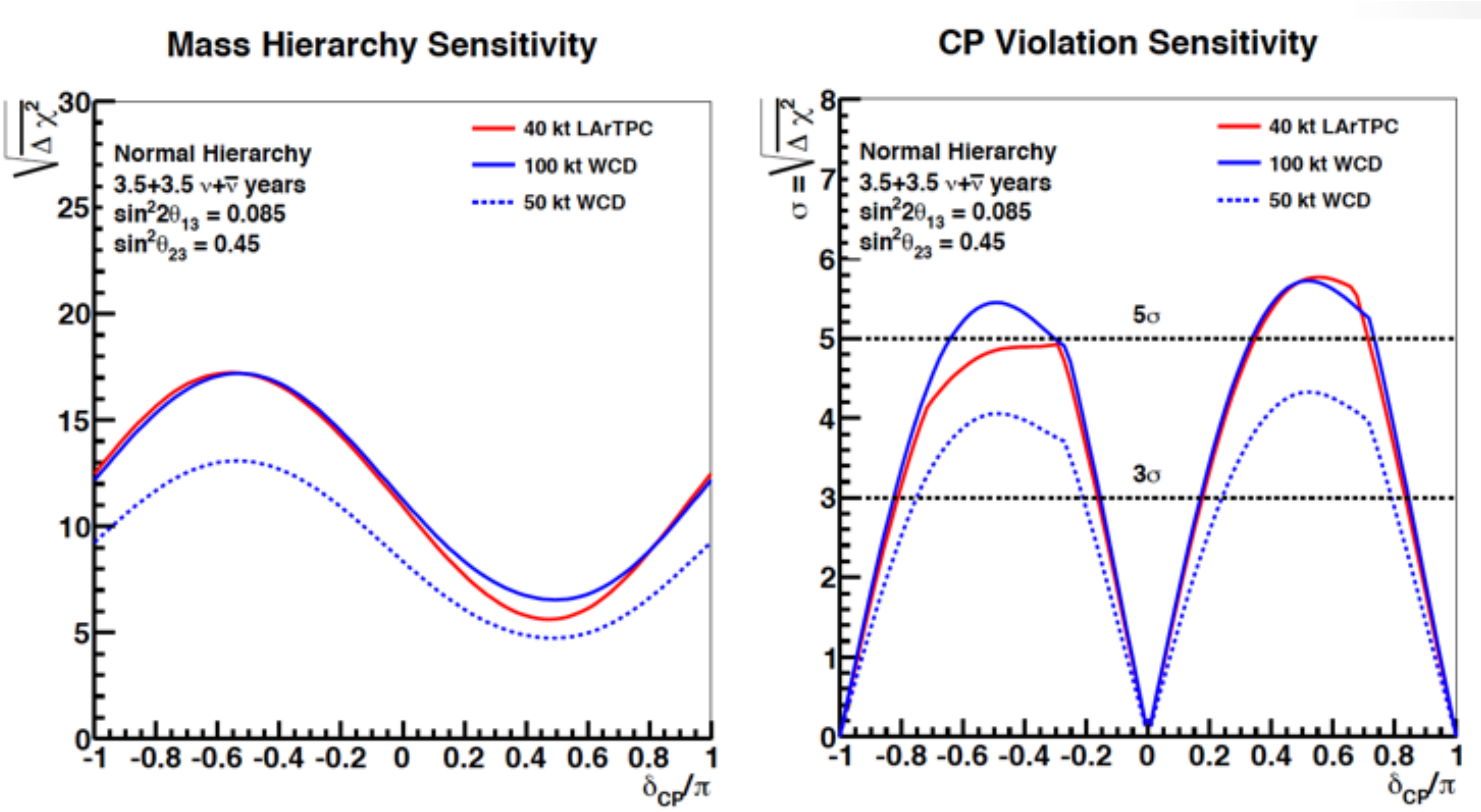


- Ring-imaging of a water Cherenkov detector
- Particle ID from Cher/scint separation
- n and low-E hadron detection (low threshold)
  - reduce wrong-sign component (nu vs anti-nu)
  - reduce NC background by detecting $\pi^0 \to \gamma\gamma$
- Large size → sensitivity to 2nd oscn max

Images from arXiv:1204.2295

See long baseline talk, Mike Wilking

Long-baseline Sensitivity



Synergy with LAr TPC

Independent systematics

High-energy events

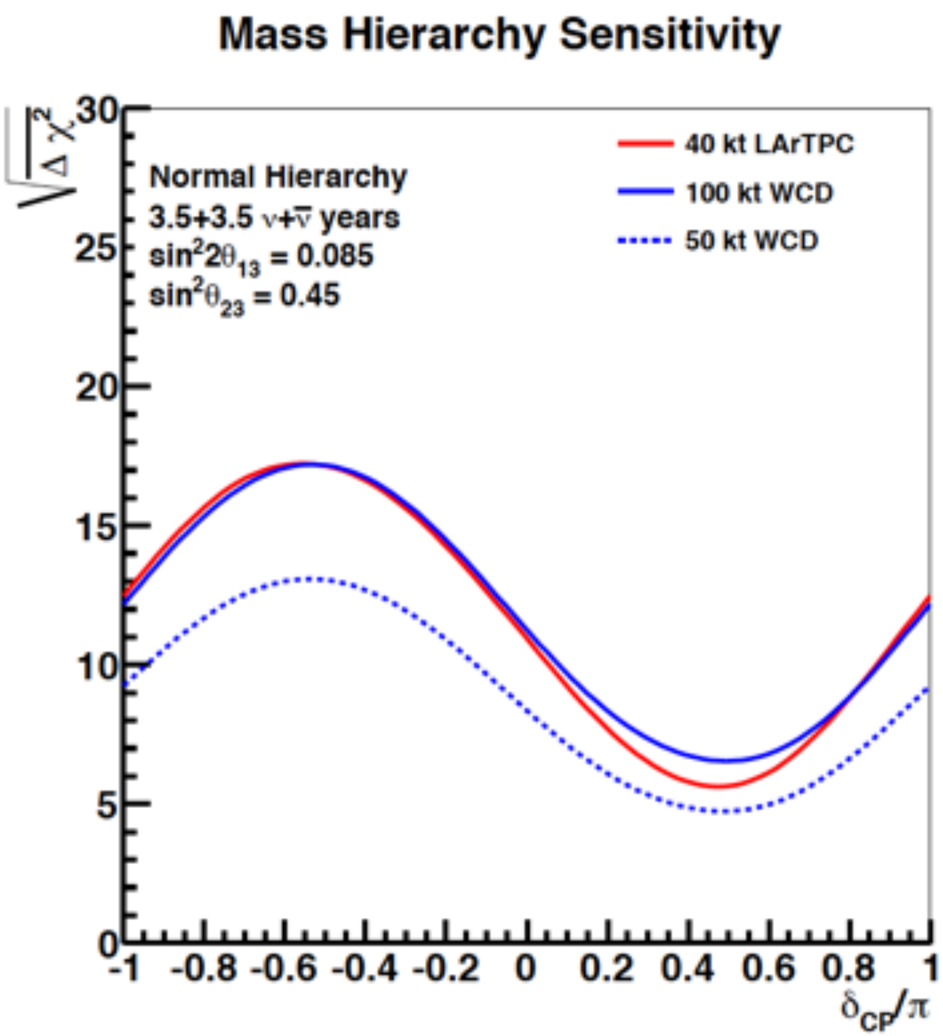
~300 kt-MW-yr exposure (40kt LAr)

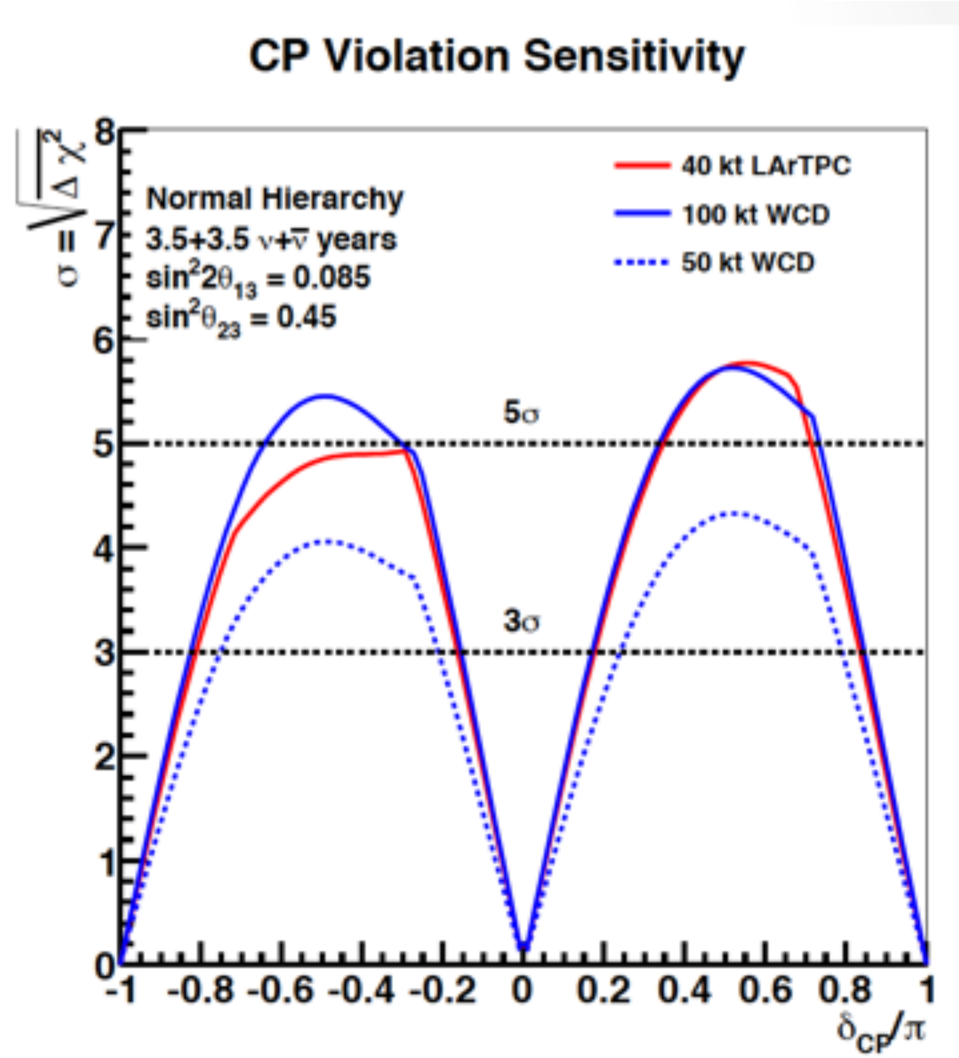
Performance competitive with 40kt LAr TPC !!

All figs from E. Worcester

Study by E.T. Worcester using same GLOBES package used for ELBNF

Long-baseline Sensitivity





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Performance competitive with 40kt LAr TPC !!

MH sensitivity for 50kt WbLS alone > 5σ

All figs from E.Worcester

Study by E.T.Worcester using same GLOBES package used for ELBNF

Physics Requirements

	Size (kt)	Loading	Resolution (light yield * coverage)	Direction / rings	Cleanliness	Depth	Bag
NLDBD	10	*Te, Nd…*					
Solar	10	*Li*					
Geo	100	*Gd*					
DSNB	50	*Gd*					
Supernova	50	*Gd*					
Nucleon decay	100						
Sterile	10						
Long baseline	50						

Critical Important Nice to have / not important

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Critical

See next talk / discussion, Ed Blucher

o have / not important

C. Theia Development

R&D Program - i

- WbLS cocktail development
  - LS fraction
  - Fluor choice & fraction
  - Isotope loading
- WbLS deployment questions
  - Nanofiltration
  - Purification
  - Recirculation
  - Background levels
  - Materials compatibility
- WbLS cocktail properties
  - Light yield
  - Attenuation
  - Absorption
  - Scattering
  - Quenching
  - Emission spectrum
  - WbLS timing
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R&D Program - ii

- Photon sensor development
  - Large-area PMTs
  - High efficiency (QE)
  - Ultra-fast detectors
  - Hybrid scheme
  - Characterization

- THEIA physics program
  - Monte Carlo model
  - Detector design
  - Reconstruction techniques
  - Particle ID
  - Background rejection
  - Physics sensitivity studies

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  Talks by Elagin, Qian

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    Talks by Learned, Lorenz

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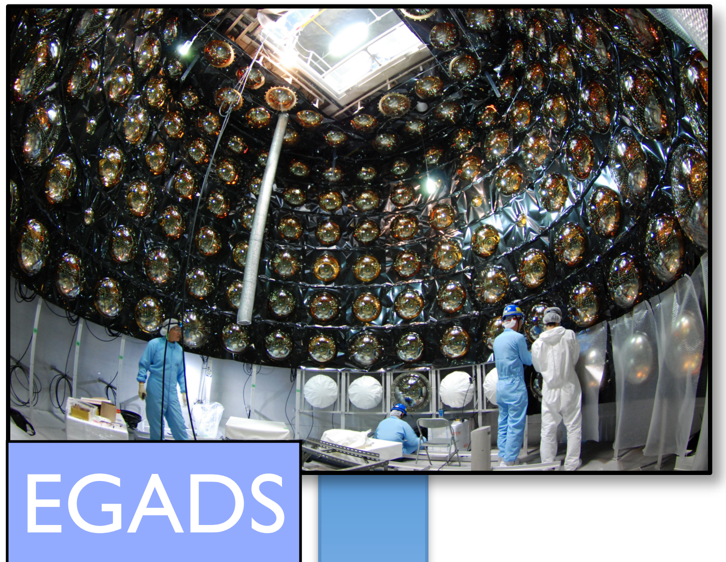
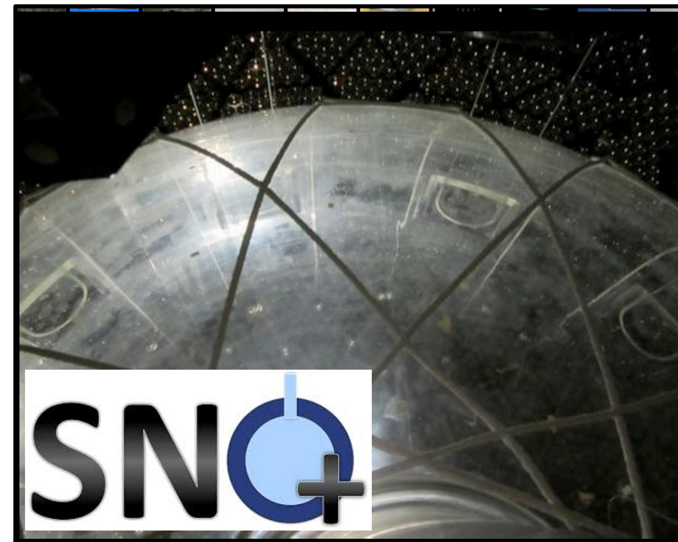
Plus afternoon discussion (Sunday)

Community Interest

Site	Scale	Target	Measurements	Timescale
UChicago	bench top	H2O	fast photodetectors	Exists
CHIPS	10 kton		electronics, readout, mechanical infrastructure	2019
EGADS	200 ton	H2O+Gd	isotope loading, fast photodetectors	Exists
ANNIE	30 ton			Exists
WATCHMAN	1 kton			2020
NuDot	1 ton	LS	directionality	2017
Penn	30 L	(Wb)LS	light yield, timing, loading	Exists
SNO+	780 ton			2017
CHESS (LBNL)	bench top	WbLS	signal separation, tracking, reconstruction / light yield, loading, attenuation	Exists
BNL	1 ton			Filling





Gd loading and purification

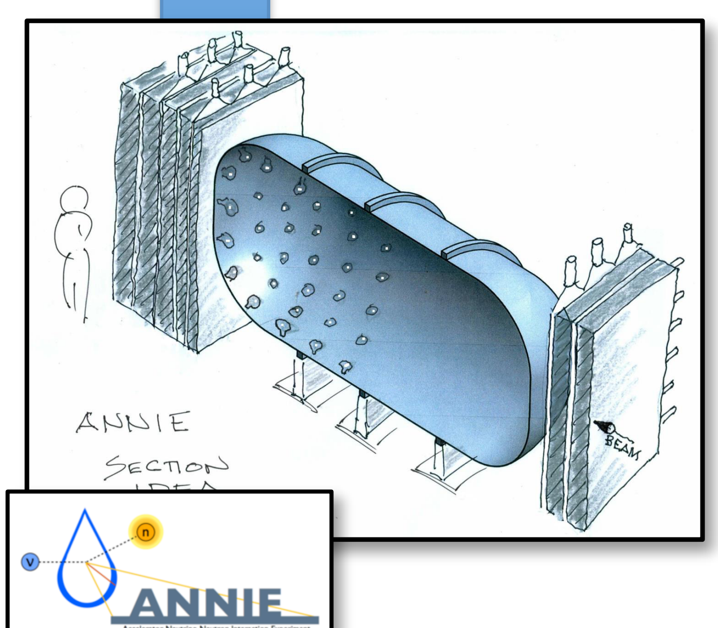
Water-based liquid scintillator

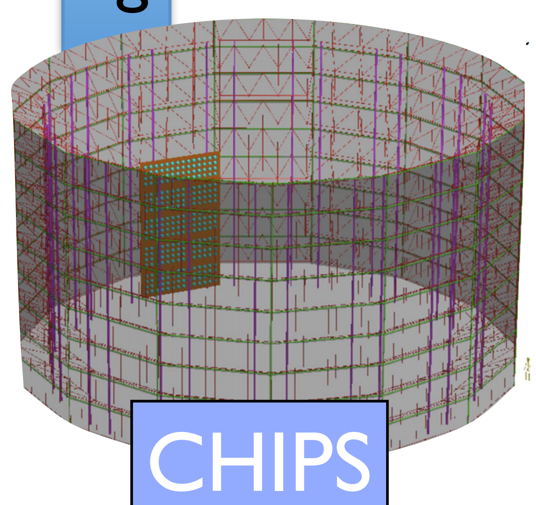
Te loading

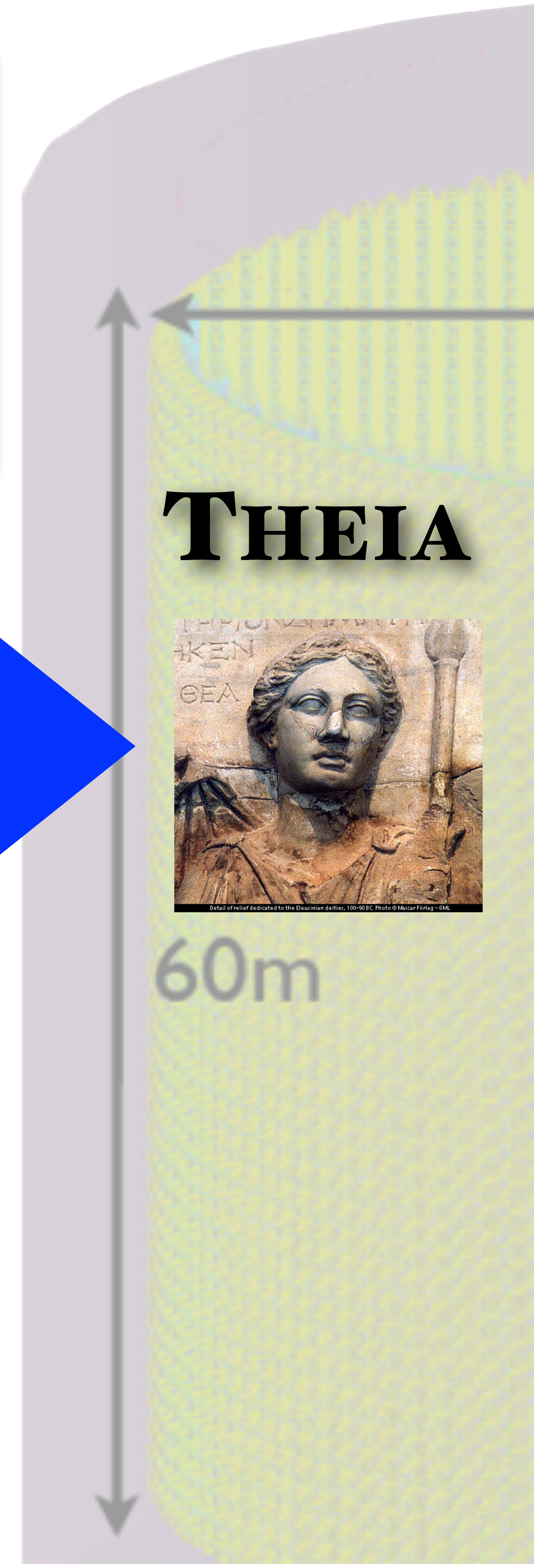
Neutron yield, LAPPD deployment

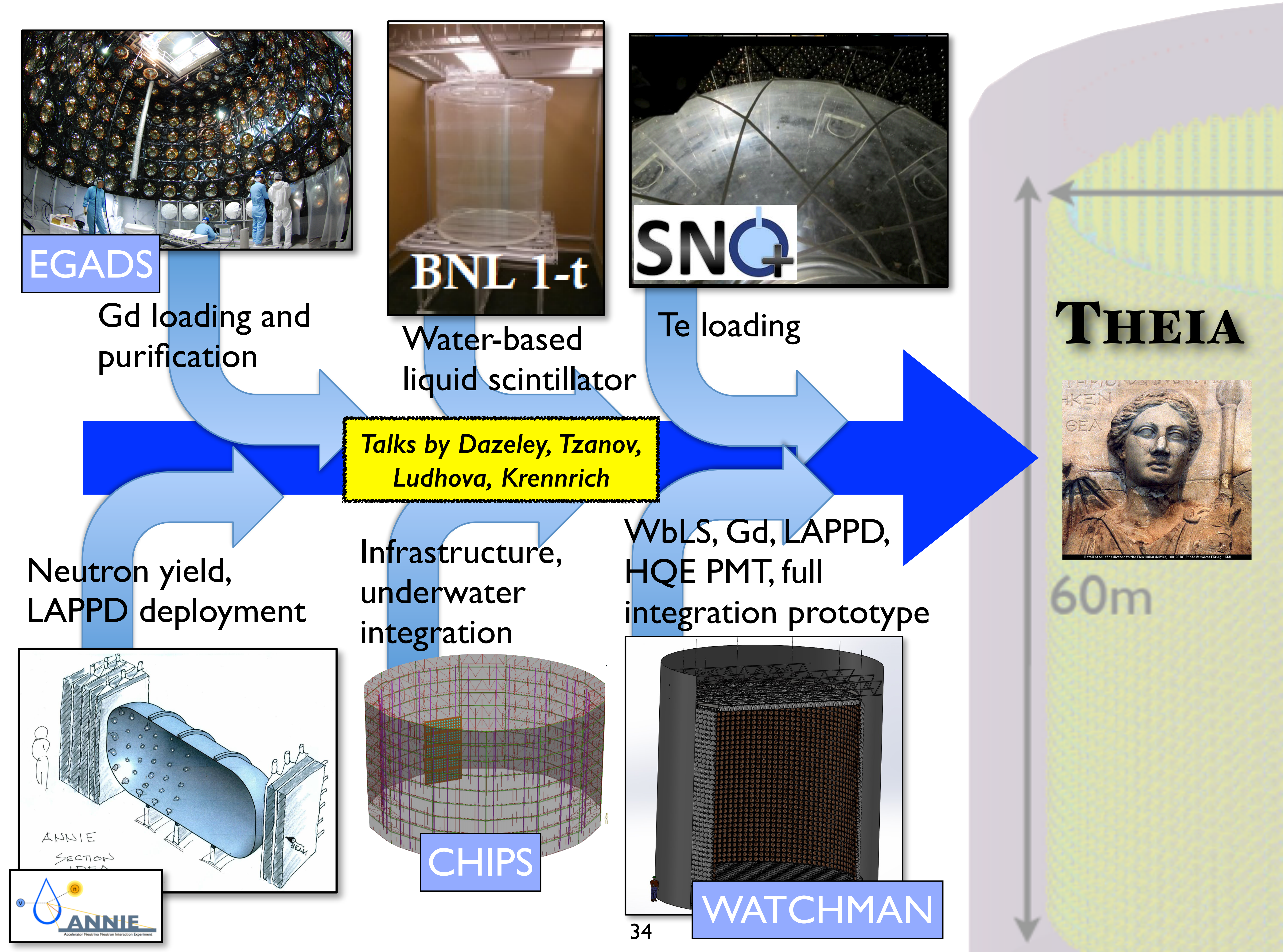
Infrastructure, underwater integration

WbLS, Gd, LAPPD, HQE PMT, full integration prototype








EGADS
Gd loading and purification
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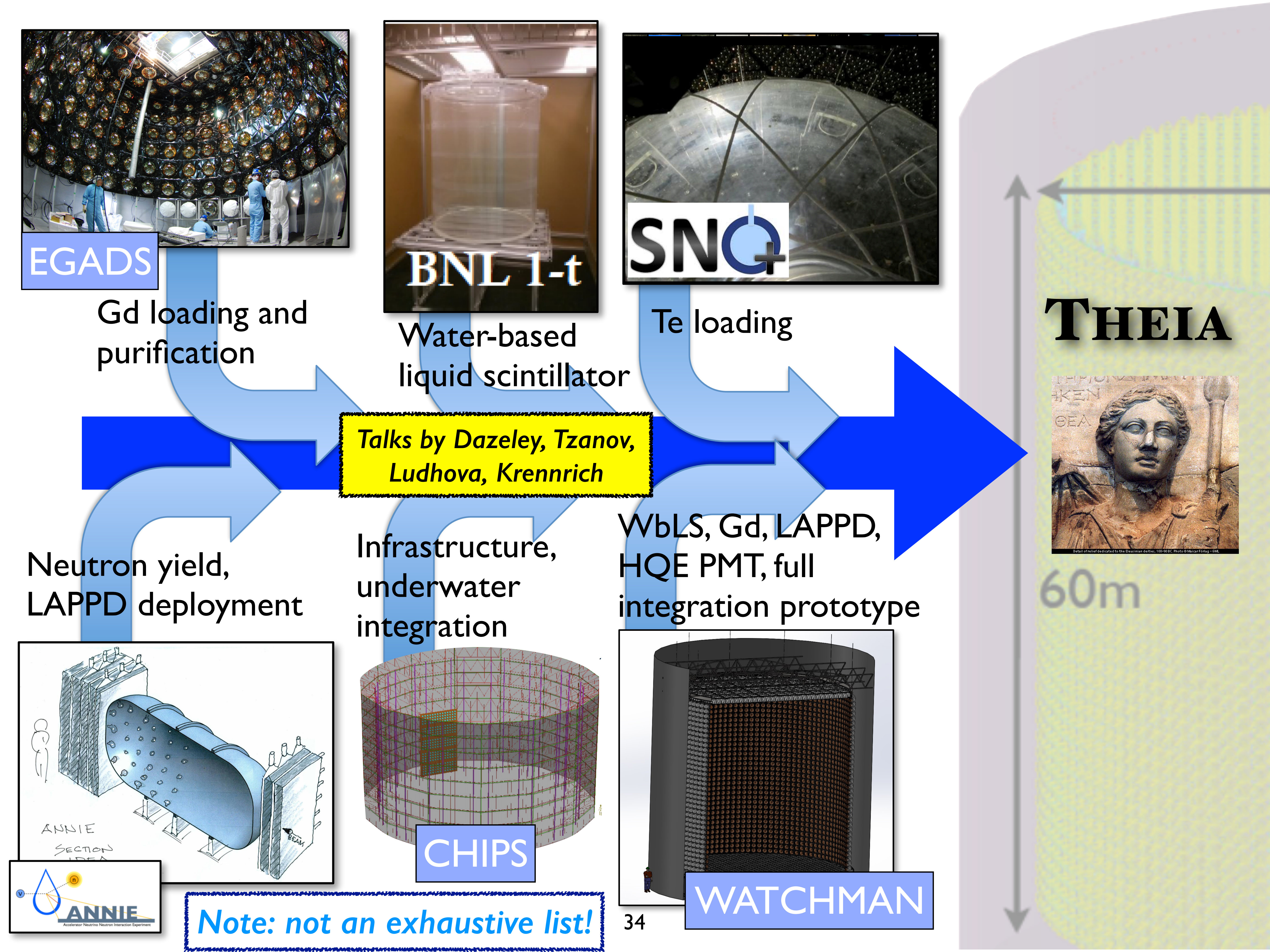
Te loading
THEIA
60m
Talks by Dazeley, Tzanov, Ludhova, Krennrich
Neutron yield, LAPPD deployment
ANNIE
Infrastructure, underwater integration
CHIPS
WbLS, Gd, LAPPD, HQE PMT, full integration prototype
WATCHMAN



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ANNIE
CHIPS
WATCHMAN
Note: not an exhaustive list!
34

Site Selection

- Factors to consider —
  - Depth — *potential for low energy program*
  - Beam — *potential for long-baseline program*
  - Current status
  - Cost

- Potential sites
  - SURF
  - Pyhäsalmi
  - Korea
  - Other?

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  - Other?

Plus discussion to follow

THEIA To Date

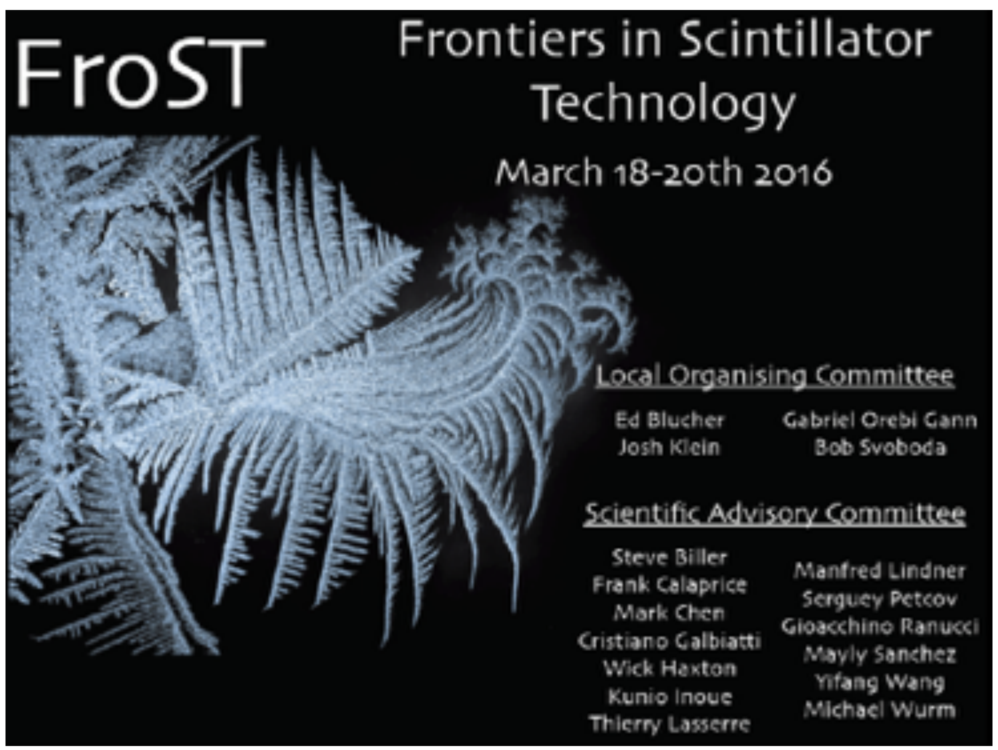
THEIA "Interest Group" formed with concept paper:

Advanced Scintillator Detector Concept (ASDC):
A Concept Paper on the Physics Potential of Water-Based Liquid Scintillator

arXiv:1409.5864

J. R. Alonso,[1] N. Barros,[2] M. Bergevin,[3] A. Bernstein,[4] L. Bignell,[5] E. Blucher,[6] F. Calaprice,[7] J. M. Conrad,[1] F. B. Descamps,[8] M. V. Diwan,[5] D. A. Dwyer,[8] S. T. Dye,[9] A. Elagin,[6] P. Feng,[10] C. Grant,[3] S. Grullon,[2] S. Hans,[5] D. E. Jaffe,[5] S. H. Kettell,[5] J. R. Klein,[2] K. Lande,[2] J. G. Learned,[11] K. B. Luk,[8,12] J. Maricic,[11] P. Marleau,[10] A. Mastbaum,[2] W. F. McDonough,[13] L. Oberauer,[14] G. D. Orebi Gann*,[8,12,†] R. Rosero,[5] S. D. Rountree,[15] M. C. Sanchez,[16] M. H. Shaevitz,[17] T. M. Shokair,[18] M. B. Smy,[19] A. Stahl,[20] M. Strait,[6] R. Svoboda,[3] N. Tolich,[21] M. R. Vagins,[19] K. A. van Bibber,[18] B. Viren,[5] R. B. Vogelaar,[15] M. J. Wetstein,[6] L. Winslow,[1] B. Wonsak,[22] E. T. Worcester,[5] M. Wurm,[23] M. Yeh,[5] and C. Zhang[5]

50 authors, 23 institutions, lots of experience: Borexino, DUNE, KamLAND, SNO, Double CHOOZ, SNO+, Daya Bay, LENA, KamLAND-Zen, MiniBOONE, Super-Kamiokande, WATCHMAN, ANNIE, T2K....



First US meeting at LBNL (May '14)

International workshop at FNAL (Mar '16)

Technical Workshop, Mainz (Oct '16)

JOHANNES GUTENBERG UNIVERSITÄT MAINZ

Cluster of Excellence PRISMA Precision Physics, Fundamental Interactions and Structure of Matter

FroST - Topical Workshop for THEIA

THEIA Interest Group

New participation welcome
contact G. D. Orebi Gann, B. Svoboda, E. Blucher, J. R. Klein, M. Wurm, L. Oberauer

Brookhaven National Laboratory
Brunel University
University of California, Berkeley
University of California, Davis
University of California, Irvine
University of Chicago
Columbia University
University of Hawaii at Manoa
University of Hamburg
Hawaii Pacific University
Iowa State University
Johannes Gutenberg-University Mainz
Lawrence Berkeley National Laboratory
Lawrence Livermore National Laboratory
Los Alamos National Laboratory
University of Maryland
MIT
University of Pennsylvania
Princeton University
RWTH Aachen University
Sandia National Laboratories
TUM, Physik-Department
Virginia Polytechnic Inst. & State University
University of Washington



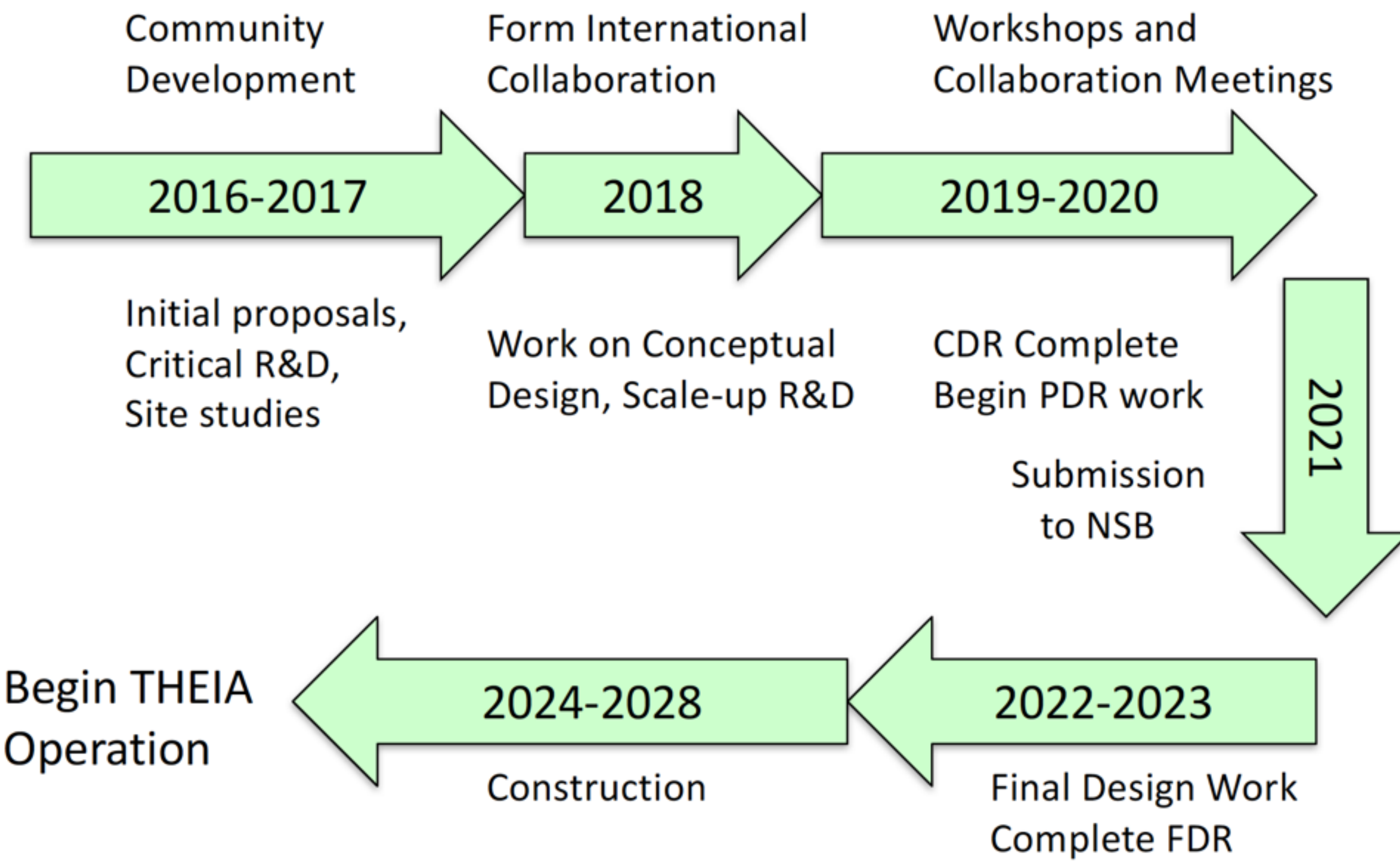
Concept paper - arXiv:1409.5864

Theia Moving Forwards

The plan for Monday

- Coordinated R&D program
- Coordinated physics studies (working groups)
- Develop white paper
- Coordinated R&D proposals —> develop full (preliminary) CDR
- Discuss international organization (form a collaboration?)

THEIA Notional Technically Limited Timeline



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- Powerful instrument of discovery
- **Let's make it happen!**

Back up

R&D Highlights

- WbLS cocktail development [BNL]
- Nanofiltration [Davis]
- Materials compatibility [Davis, BNL]
- WbLS timing [Chicago, Penn, Berkeley]
- Cherenkov/scintillation separation [Berkeley]
- Monte Carlo, physics reach [Penn, Berkeley, Davis, MIT]
- Reconstruction techniques [Chicago, Hawaii, MIT]
- Photon sensor development [ANL, Chicago, Hamamatsu, Penn]
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- Hybrid photosensor scheme [Aachen]
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Talk by G. D. Orebi Gann

Talks by Learned, Lorenz

Caveat: to best of speaker's (limited) knowledge

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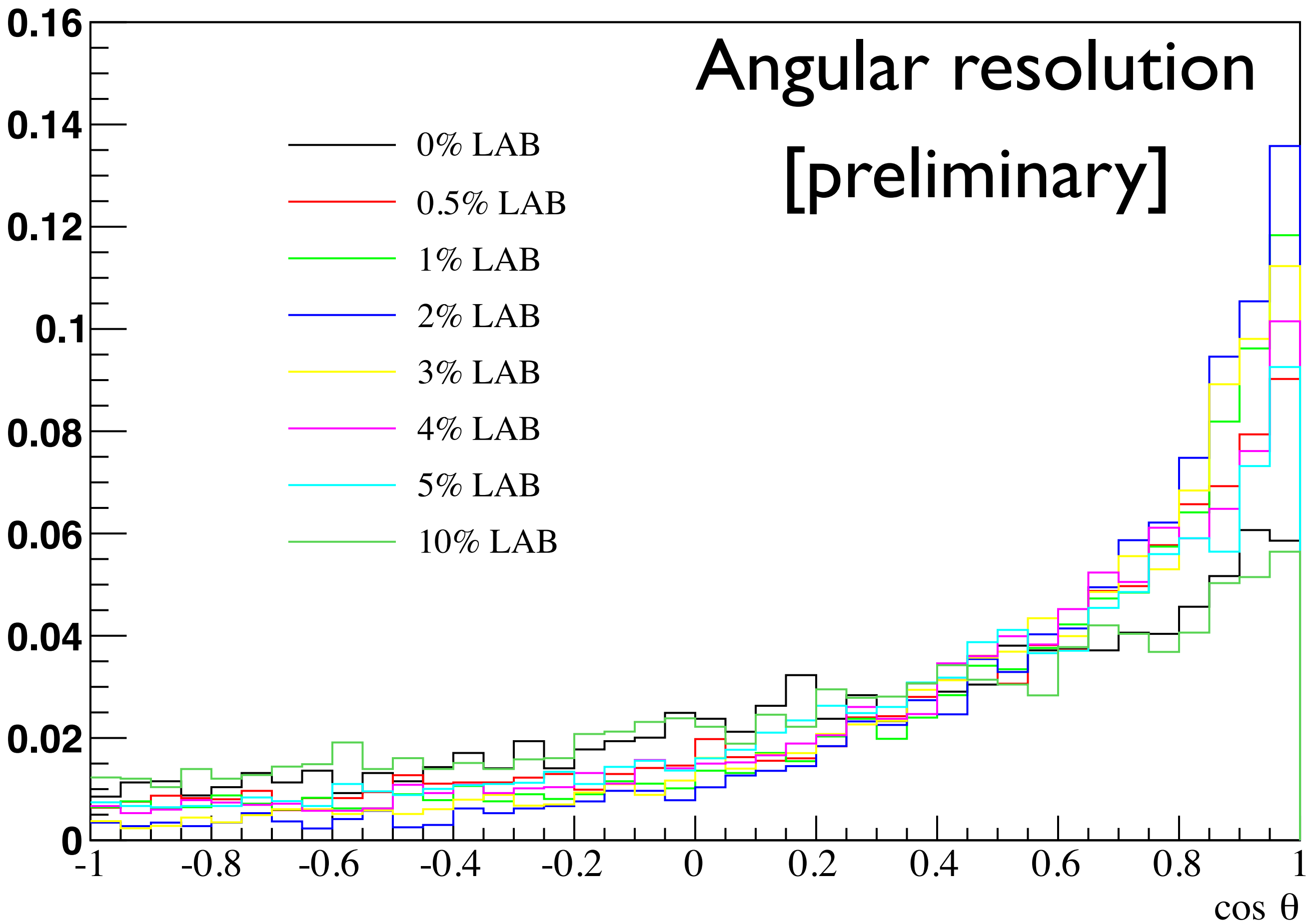
Talk by Bob Svoboda

Talk by G. D. Orebi Gann

Talks by Learned, Lorenz

Solar sensitivity [LBNL]

50 kton detector
50% fiducial (neglect externals)
90% coverage
5 years data
SNO+-level backgrounds in LAB
SNO-level backgrounds in water
SNO+-level background rejection



CNO flux sensitivity as a function of WbLS cocktail

[preliminary]