Theia
and Report from LS Town Hall

- Theia Concept
- Technology and Physics Program
- Summary of the Liquid Scintillator Town Hall

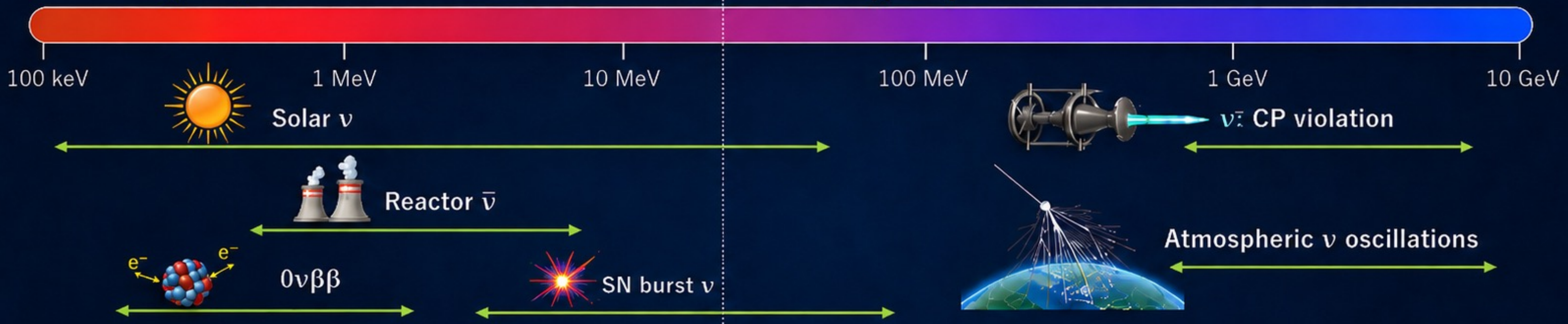
Josh Klein

Breadth and Detectors

Neutrino physics across 100 keV - 10 GeV

Typically scintillator

Typically Cherenkov



100 keV
1 MeV
10 MeV
100 MeV
1 GeV
10 GeV

Solar ν

Reactor $\bar{\nu}$

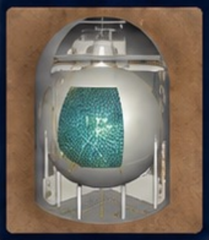
$0\nu\beta\beta$

SN burst ν

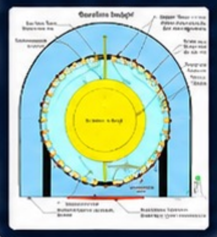
ν: CP violation

Atmospheric ν oscillations

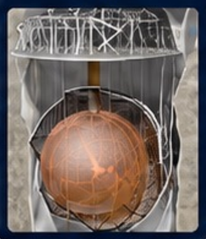
KamLAND



Borexino

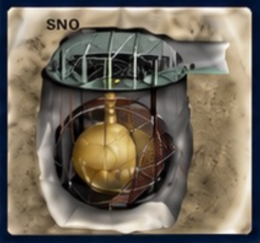


SNO+



JUNO

SNO



Super-K

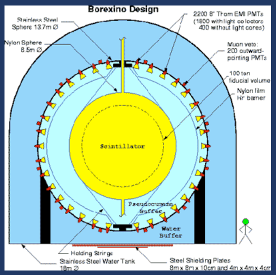
Requirements:

- Low radio backgrounds
- Excellent energy resolution
- Directional information
- Neutron tagging

Requirements:

- Excellent particle ID
- Directional information
- Very big detector
- (Neutron tagging)

Hybrid Detection



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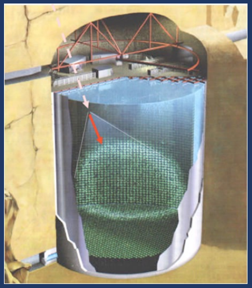

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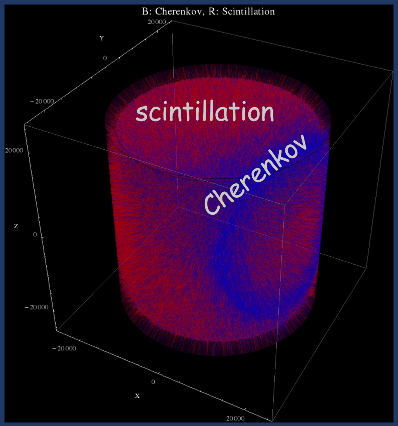
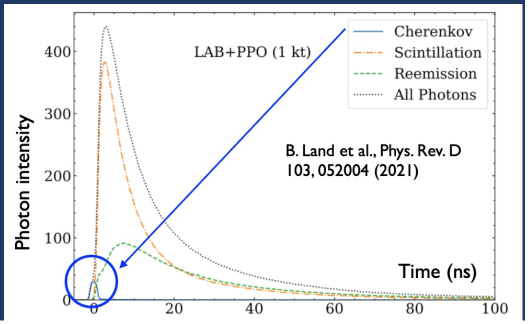


- Low-energy physics using scintons
- High-energy physics with chertons
- Exploit *both* to do otherwise very difficult physics

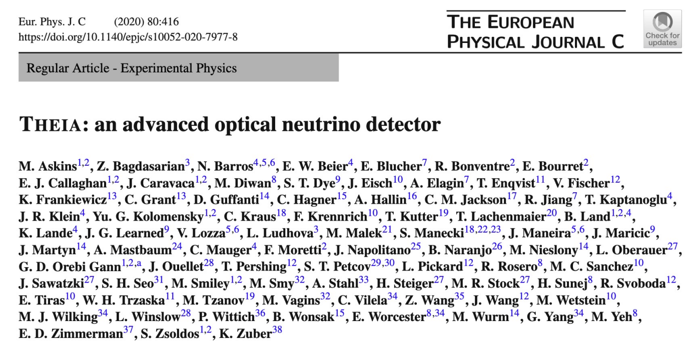
But:

- 100x more scintillation light in than Cherenkov light
- `Chertons’ are buried by `scintons’
- And need detector to be very big…



B. Land et al., Phys. Rev. D 103, 052004 (2021)

THEIA



Eur. Phys. J. C (2020) 80:416
https://doi.org/10.1140/epjc/s10052-020-7977-8

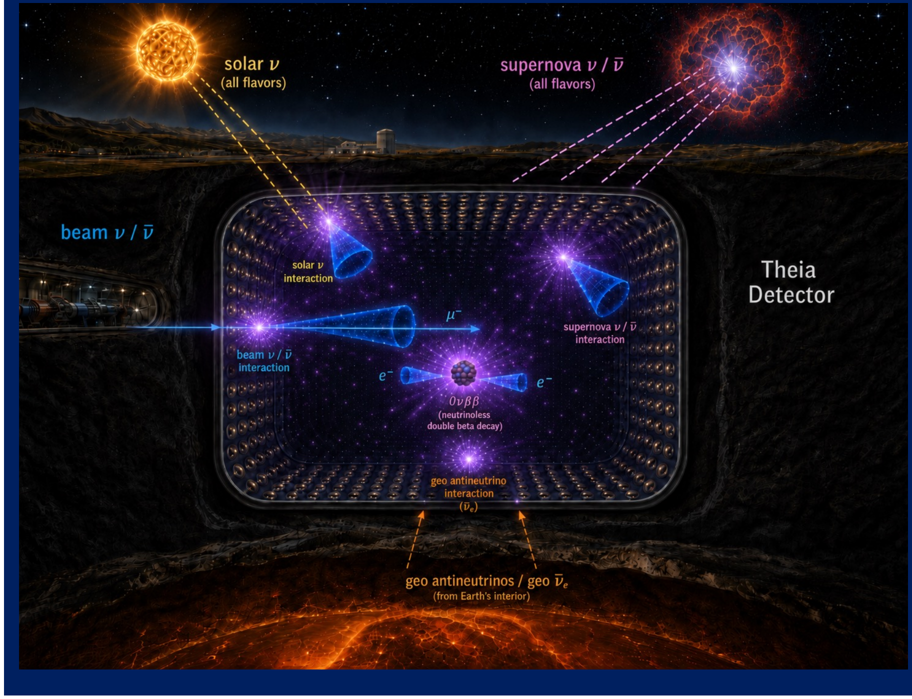
THE EUROPEAN PHYSICAL JOURNAL C

Regular Article - Experimental Physics

THEIA: an advanced optical neutrino detector

M. Askins[1,2], Z. Bagdasarian[3], N. Barros[4,5,6], E. W. Beier[4], E. Blucher[7], R. Bonventre[2], E. Bourret[2], E. J. Callaghan[1,2], J. Caravaca[1,2], M. Diwan[8], S. T. Dye[9], J. Eisch[10], A. Elagin[7], T. Enqvist[11], V. Fischer[12], K. Frankiewicz[13], C. Grant[13], D. Guffanti[14], C. Hagner[15], A. Hallin[16], C. M. Jackson[17], R. Jiang[7], T. Kaptanoglu[4], J. R. Klein[4], Yu. G. Kolomensky[1,2], C. Kraus[18], F. Krennrich[10], T. Kutter[19], T. Lachenmaier[20], B. Land[1,2,4], K. Lande[4], J. G. Learned[9], V. Lozza[5,6], L. Ludhova[3], M. Malek[21], S. Manecki[18,22,23], J. Maneira[5,6], J. Maricic[9], J. Martyn[14], A. Mastbaum[24], C. Mauger[4], F. Moretti[2], J. Napolitano[25], B. Naranjo[26], M. Nieslony[14], L. Oberauer[27], G. D. Orebi Gann[1,2,a], J. Ouellet[28], T. Pershing[12], S. T. Petcov[29,30], L. Pickard[12], R. Rosero[8], M. C. Sanchez[10], J. Sawatzki[27], S. H. Seo[31], M. Smiley[1,2], M. Smy[32], A. Stahl[33], H. Steiger[27], M. R. Stock[27], H. Sunej[8], R. Svoboda[12], E. Tiras[10], W. H. Trzaska[11], M. Tzanov[19], M. Vagins[32], C. Vilela[34], Z. Wang[35], J. Wang[12], M. Wetstein[10], M. J. Wilking[34], L. Winslow[28], P. Wittich[36], B. Wonsak[15], E. Worcester[8,34], M. Wurm[14], G. Yang[34], M. Yeh[8], E. D. Zimmerman[37], S. Zsoldos[1,2], K. Zuber[38]

See also:
“Advanced Scintillator Detector Concept,” arXiv 1409.5864



Physics Goals:

- $0\nu\beta\beta$ search to $m_{\beta\beta}<6$ meV
- Long-baseline oscillation physics (in LBNF beam)
- Solar CNO ν flux to < 10%
- Explore MSW Vac/matter transition region
- Diffuse SN burst ν 5σ discovery in 6 years
- SN burst νs out to LMC
- Invisible nucleon decay to > 10^{32} years

- Looking increasingly like mass ordering is not inverted
- Discovery of $0\nu\beta\beta$ still possible with next-gen expts
- Excluding Majorana hypothesis may be hard(er)
- Any experiment that pushes further on $m_{\beta\beta}$ will cost a lot
- Such an experiment needs a compelling broad program
- [Which should include signals, not just null results]

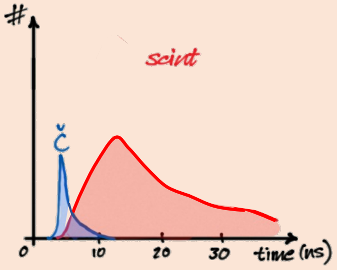
Hybrid Cherenkov/Scintillation Detectors

Many Ways of Doing This

Ratio

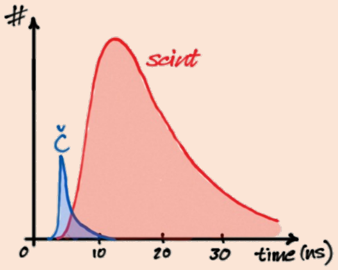
Add just a little scintillation

→ new materials/fluors



Timing

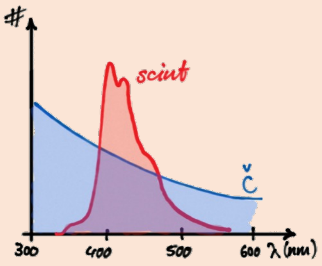
“instantaneous chertons” vs. delayed “scintons”
→ ns resolution or better



M. Wurm

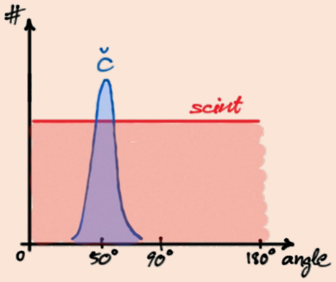
Spectrum

UV/blue scintillation vs. blue/green Cherenkov
→ wavelength-sensitivity



Angular distribution

increased PMT hit density under Cherenkov angle
→ sufficient granularity



Past ~10 years has seen rapid growth in exploring these approaches.

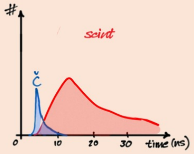
Adjust Cher/Scint Ratio

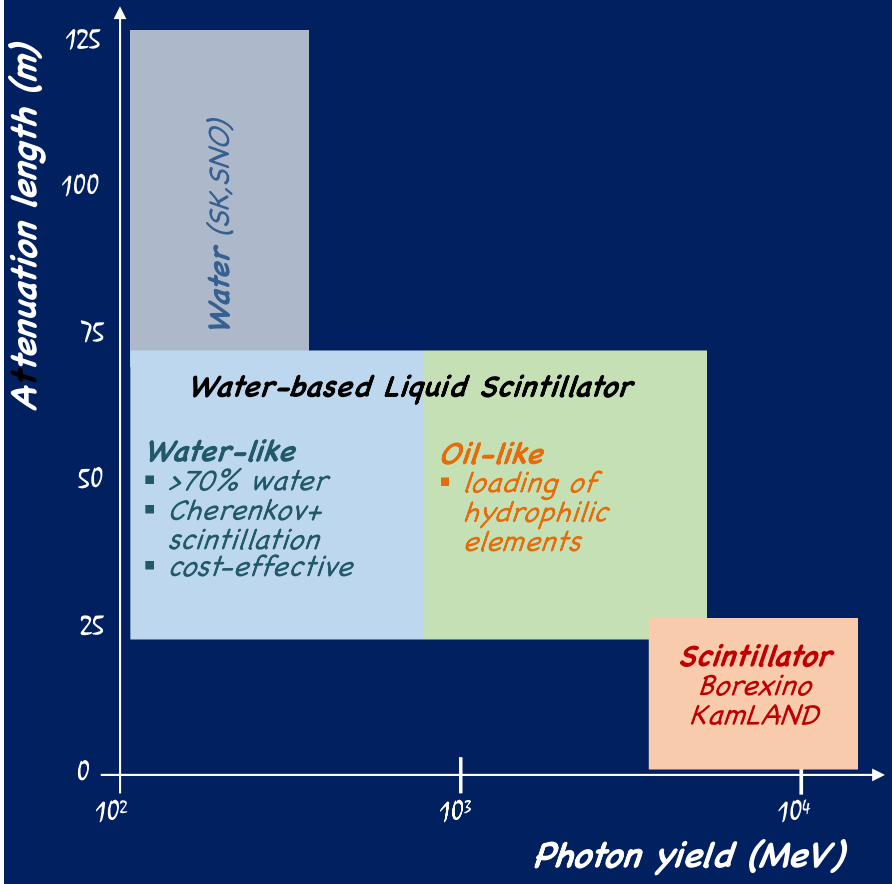
Water-based liquid scintillator (WbLS)

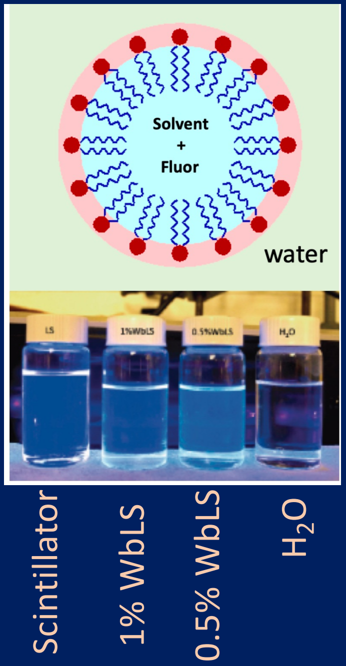
Ratio

Reduce number of scintons

→ new materials/fluors







Other possibilities:

- Low light-yield scintillator (SNO+ 0.6 g/l PPO, Jinping)
- Mineral oil (MiniBooNE)
- Oil+a little scintillator

Target can be adjusted for different physics goals

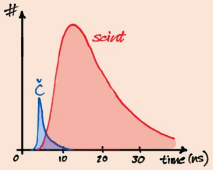
Timing

Improving photosensor timing has lots of benefits

Timing

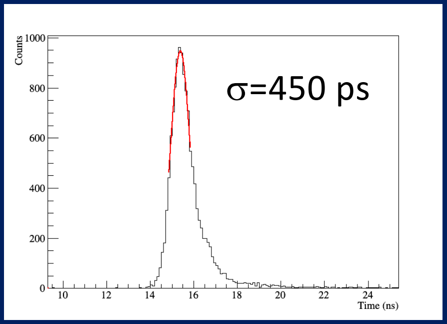
"instantaneous chertons" vs. delayed "scintons"

→ ns resolution or better



R14668 new **8"** PMT from Hamamatsu

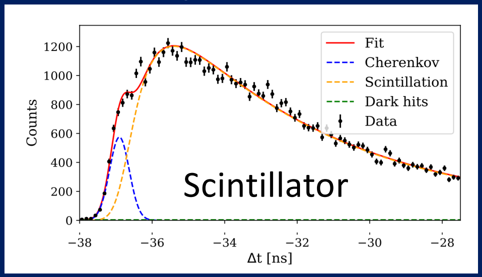
Quantum efficiency = 34%

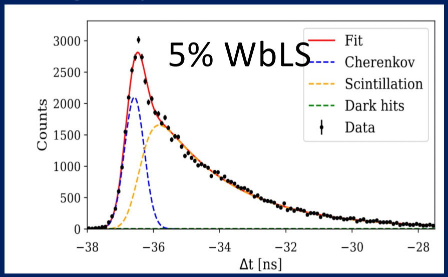


T. Kaptanoglu

But: small, not cheap

Can do separation even in full light-yield scintillator

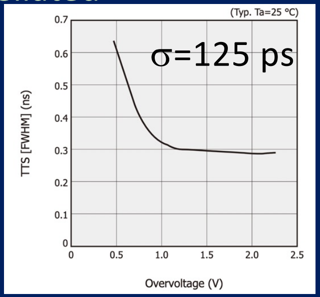




LBNL

Silicon photomultiplier arrays (6x6 mm)

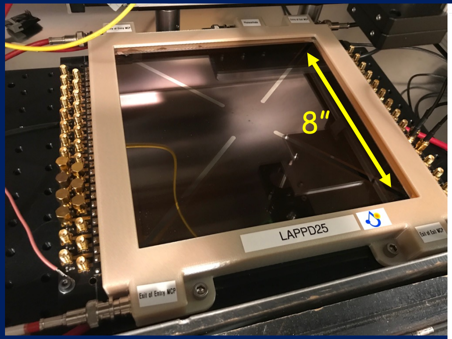
QE = 50%, highly pixellated

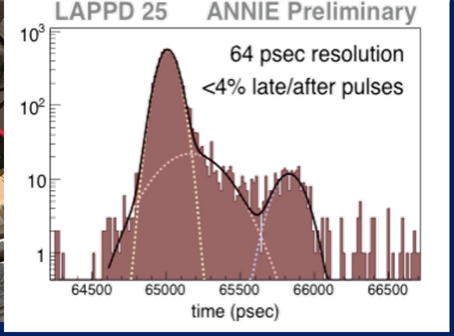


But: noisy, expensive

Large Area Picosecond Photodetector

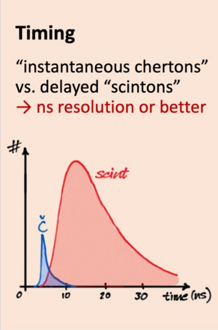
QE = 20%





But: VERY expensive

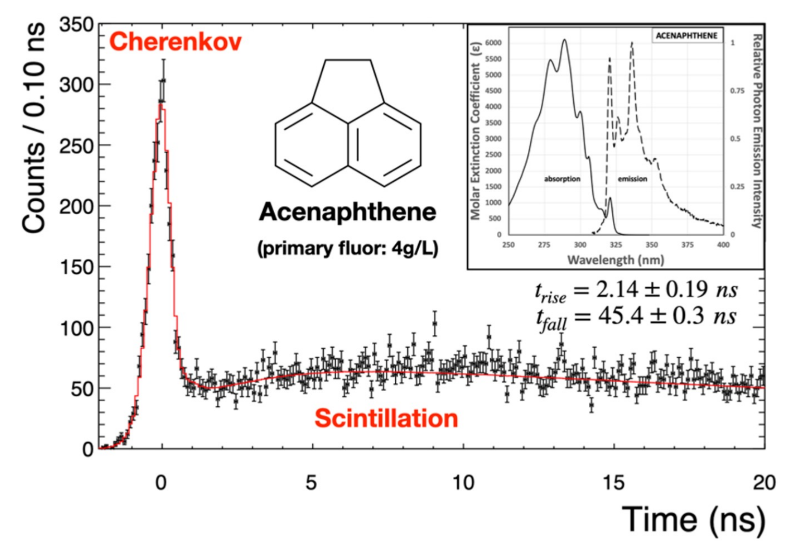
Timing


Timing

“instantaneous chertons” vs. delayed “scintons”

→ ns resolution or better

Slow(er) Scintillator

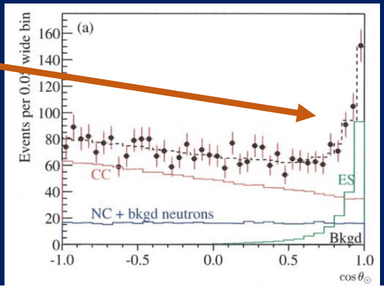


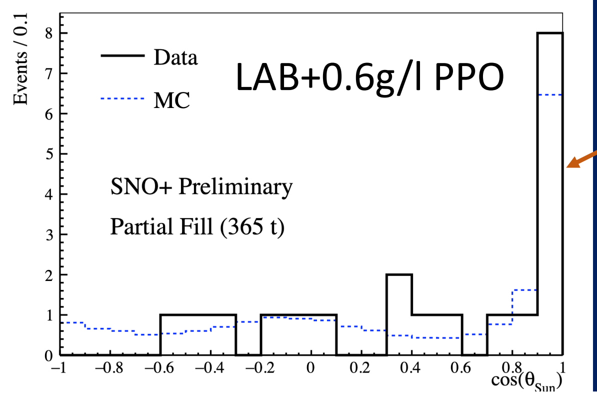
Biller, Leming, Paton, NIM A 972 (2020) 164106

But: position reconstruction degraded, “multisite” rejection affected

Can also slow down scintillator by using a small amount of fluor

SNO D_2O Cherenkov





Solar peak in scintillator event-by-event

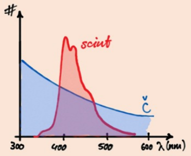
But: light yield reduced (poorer resolution)

Spectrum

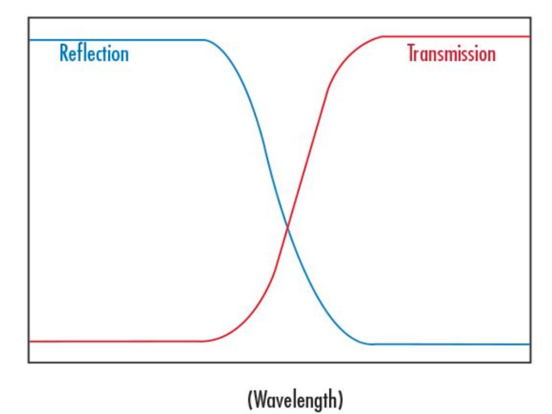
Spectral Photon **Sorting**

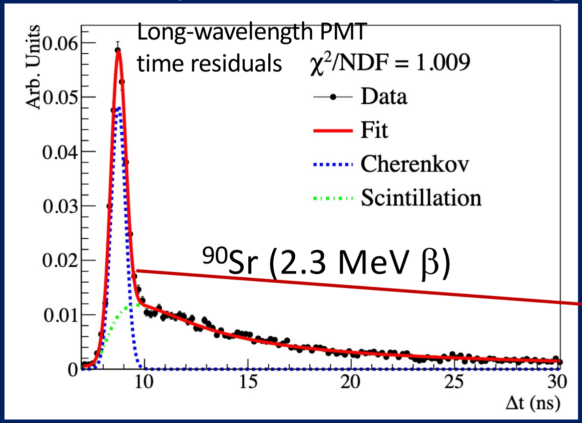
Spectrum

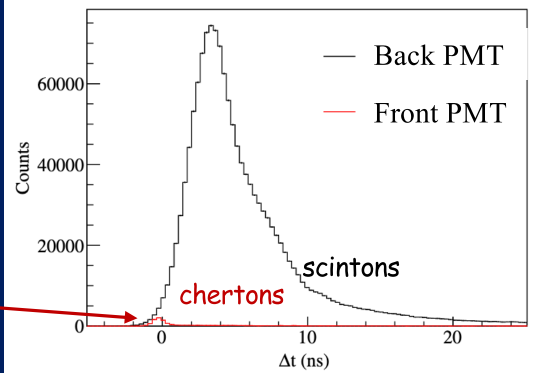
UV/blue scintillation vs.
blue/green Cherenkov
→ wavelength-sensitivity



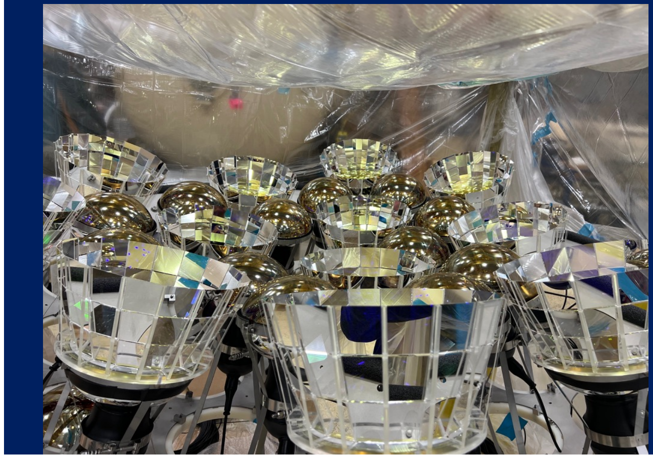
Dichroic mirrors reflect half spectrum and transmit other half

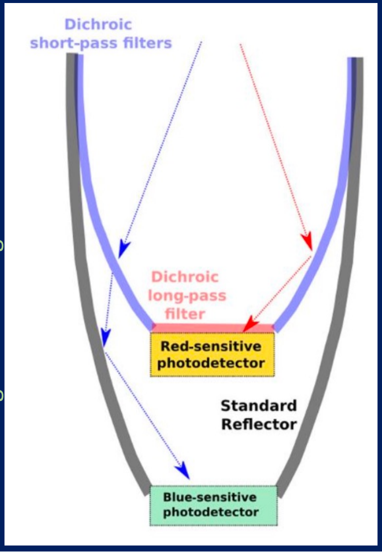






450 nm Eos (10“) dichroicons

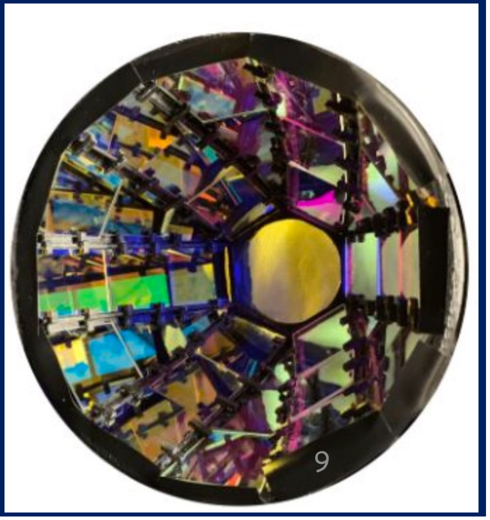




Human-generated image

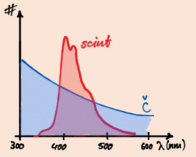
“Dichroicon”: Winston light concentrator using dichroic mirrors

500 nm 6” dichroicon



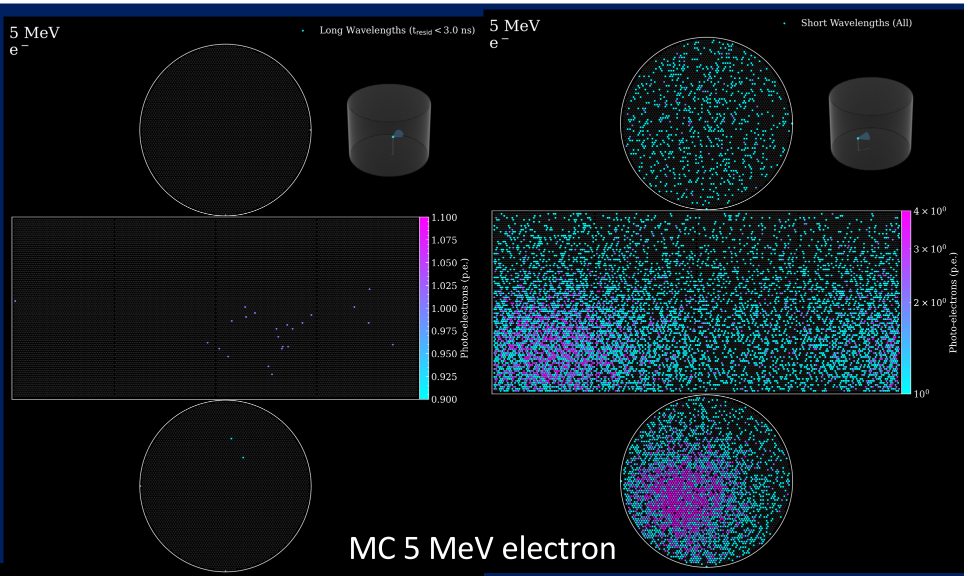
Spectrum

UV/blue scintillation vs.
blue/green Cherenkov
→ wavelength-sensitivity

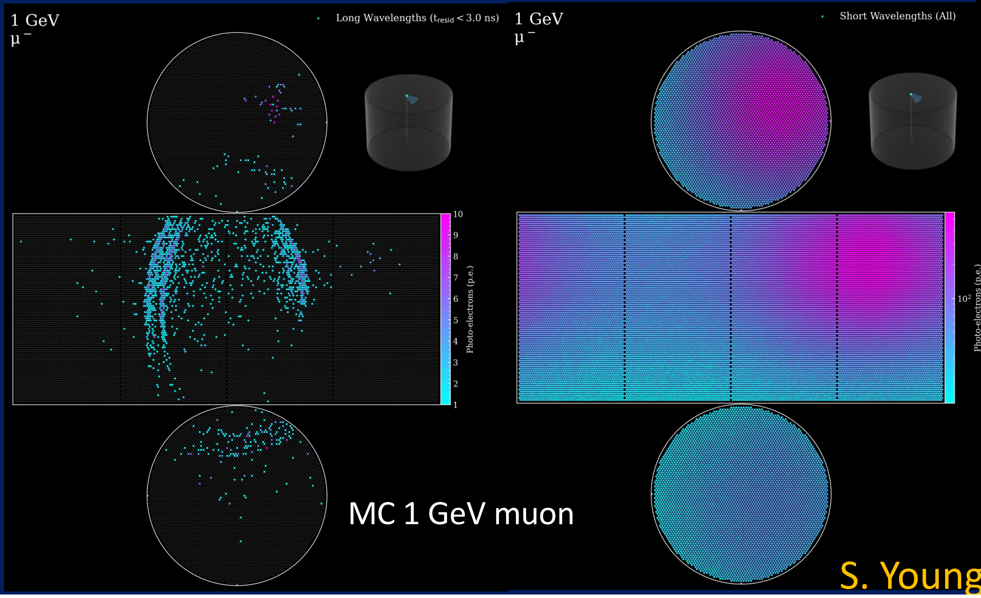


Spectrum

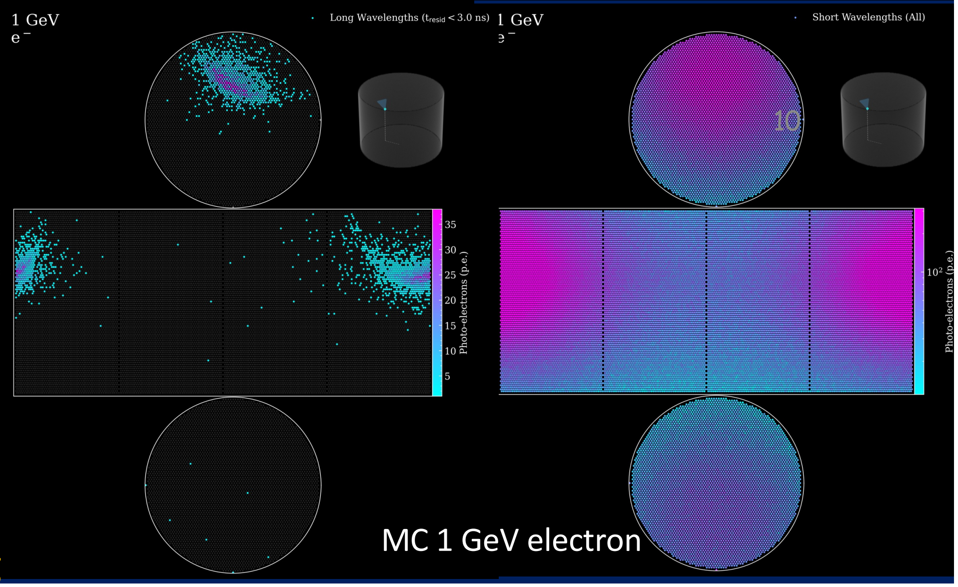
LAB-PPO+dichroicons
Two detectors-in-one



MC 5 MeV electron



MC 1 GeV muon



MC 1 GeV electron

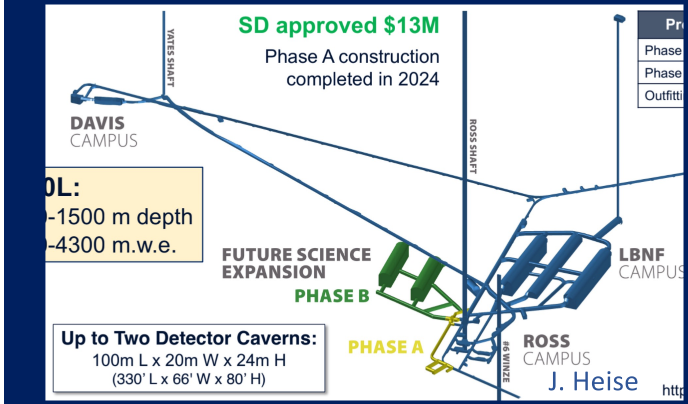
S. Young

Reference Design and Site

Requirements:

- Scintillation yield good enough for low E program (> 1200 pe/MeV)
- Cherenkov reconstruction good enough for high E program (~Hyper-K)
- Large enough for 0νββ, SN burst, and long-baseline physics sensitivity
- Deep enough that cosmic spallation rate has negligible impact on CNO and 0νββ
- Fits into possible spaces

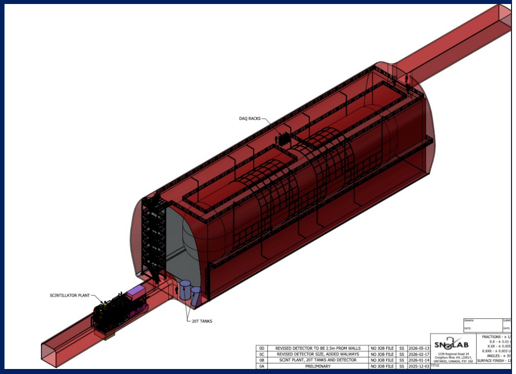
SURF



Fully exploit huge international investment in LBNF Beam+ broad low E program

Existing FD4 cavern or new space

SNOLAB



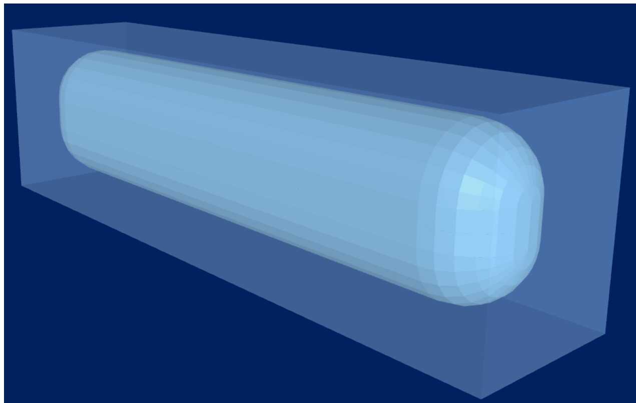
Great depth+cleanliness to optimize low E program

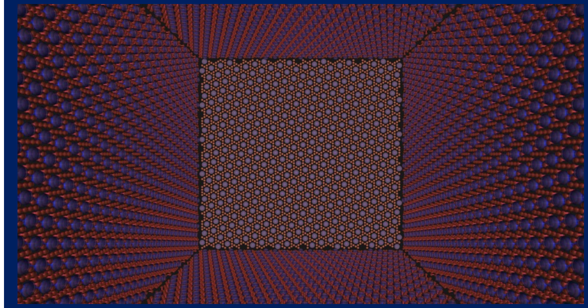
Requires new space

`Gateway 0' granted by SNOLAB

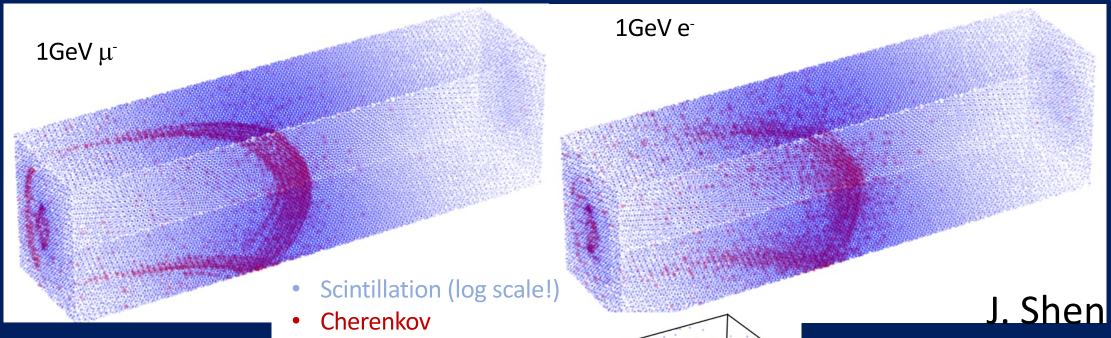
Reference Design and Site

- "Shoebox" shape to fit in SURF or SNOLAB
- 25 kilotonnes total size (to fit in SURF FD4)
- Inner vessel to hold scintillator for low E program
- Water/WbLS in rest of volume
- 60% coverage 20" + 8" PMTs (HQE)

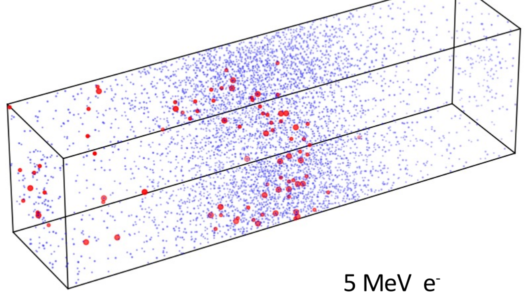


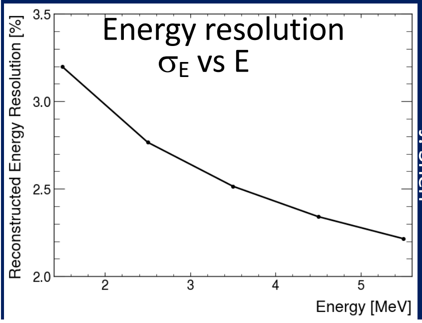


RAT-PAC2 complete optical+PMT model
Full reconstruction tools

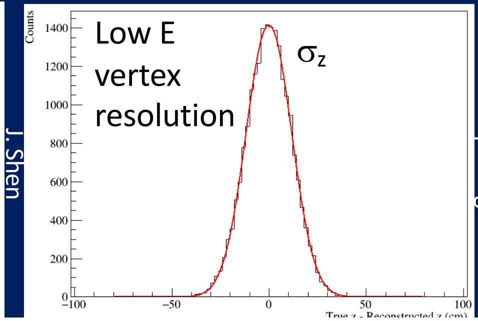


J. Shen





J. Shen



T. Kaptanoglu

Alternate Options:

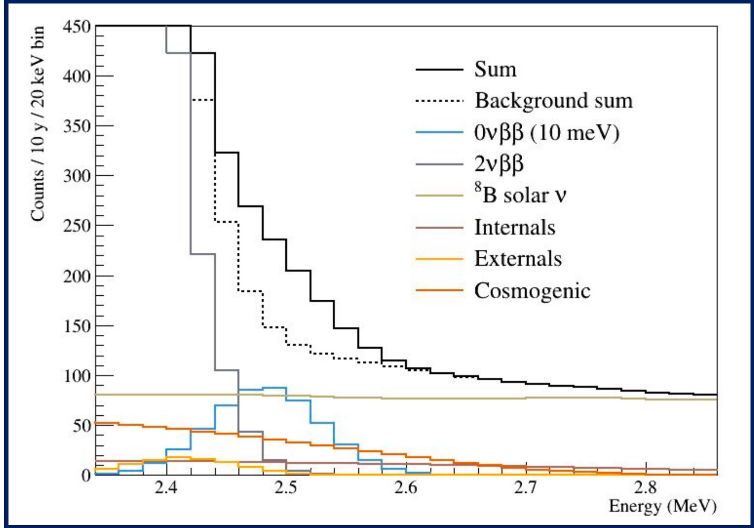
- Dichroicons
- LAPPDs (some)
- Fast/Slow scintillator

See talk by G.D. Orebi Gann

Physics Program

$0\nu\beta\beta$

Use Te for high natural abundance (34%)
440 tonnes of *natural* Te in 8.8 ktonne of scintillator (5% by mass)
=150 tonnes of ^{130}Te (affordable scaling to > 100 t)

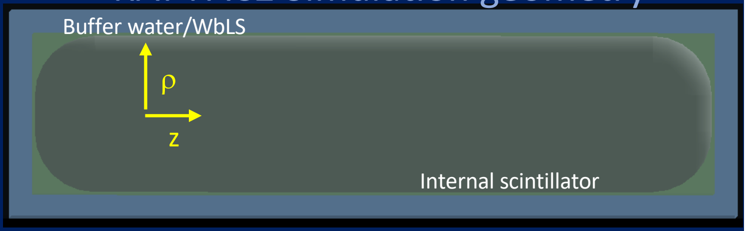


- May be able to reduce ^{8}B with directionality
- May cut some ^{130}I with (very) delayed coincidence tag

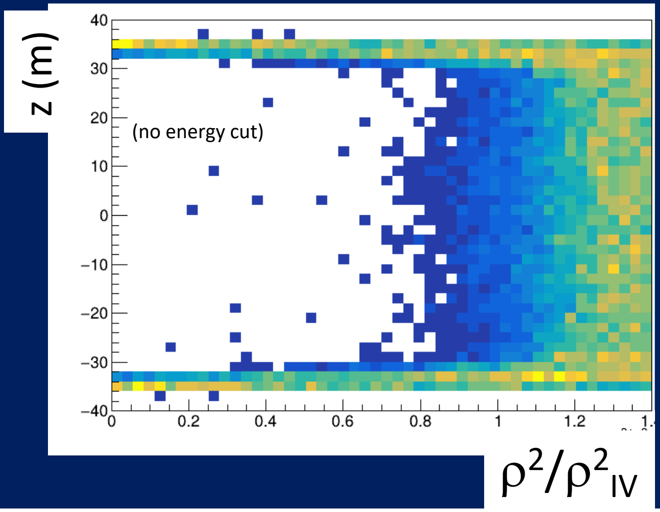
Theia White Paper:
$m_{\beta\beta} < 6$ meV

End-to-end analysis with full simulation and reconstruction now ongoing to push improvements

RAT-PAC2 Simulation geometry



External γ reconstruction



Physics Program

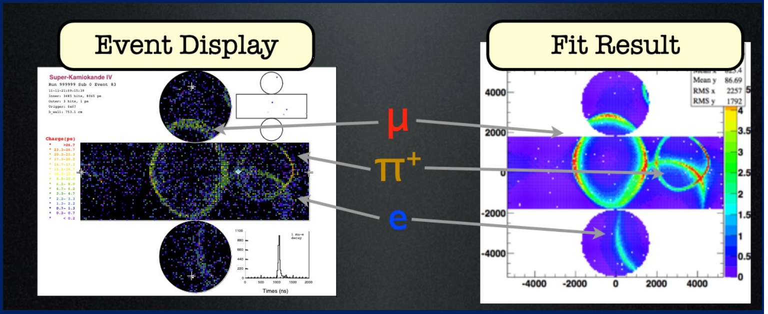
Long Baseline

M. Wilking

- LBNF beam is major international investment
- Theia adds O,H, and C targets (can compare against HK)
- And neutron energy and tagging
- Work to date ignores information from scintillation light

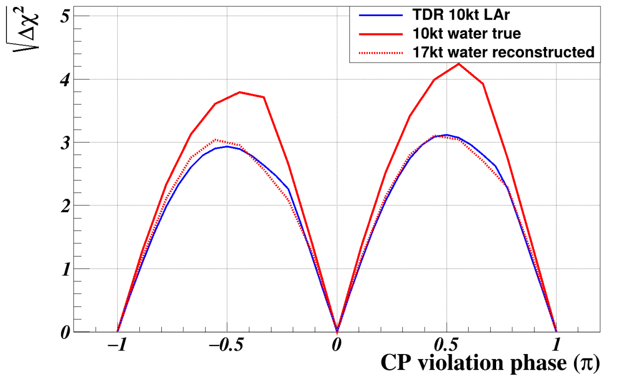
(0νββ+LBL oscillations combines HEP+NP= HENP)

FitQUN reconstruction

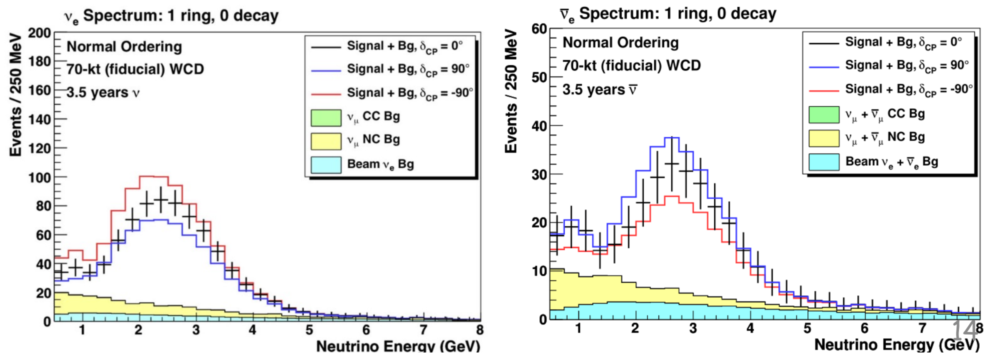


RAT-PAC2 model being developed with check against HK geometry

End-to-end analysis with systematics same as DUNE



- Similar sensitivity to CP δ as 1 DUNE module
- Very different target and detector systematics
- DUNE Phase II “alternate” technology



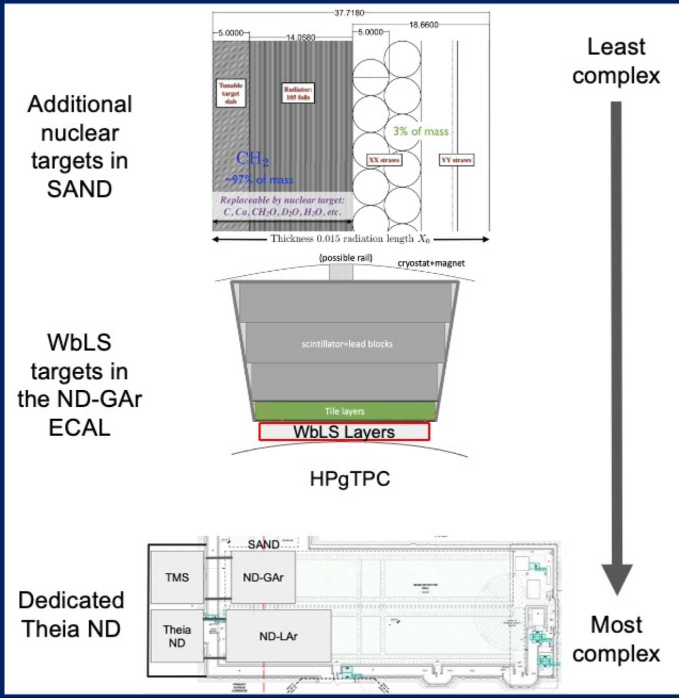
To get same systematic precision as DUNE, need Near Detector changes

Physics Program
Long Baseline

M. Wilking

Near Detector Options

- Will depend on projection of uncertainties at time of Theia deployment
- (And cost)
- Existing on-axis detector has C and H, could add O
- Space inside Phase II GAr-TPC ECAL
- Or totally new dedicated (movable) detector



Least complex

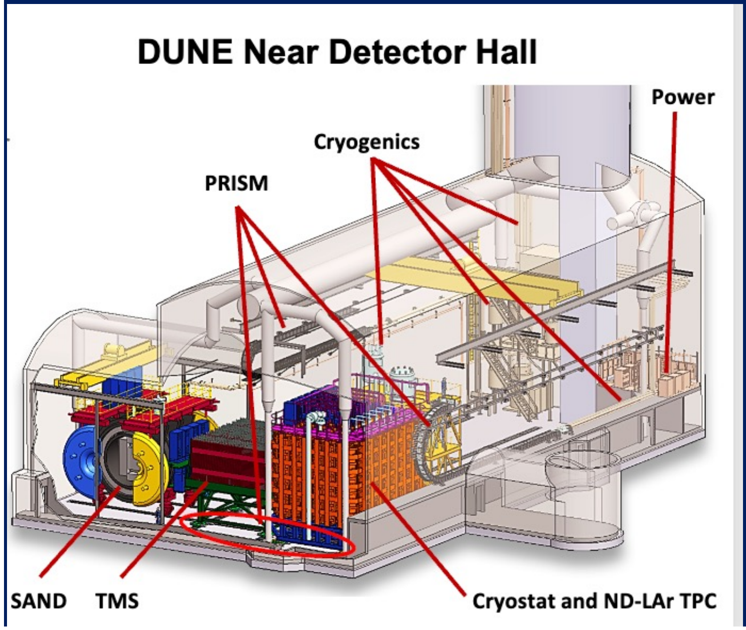
Additional nuclear targets in SAND

WbLS targets in the ND-GAr ECAL

Dedicated Theia ND

Most complex

M. Wilking



DUNE Near Detector Hall

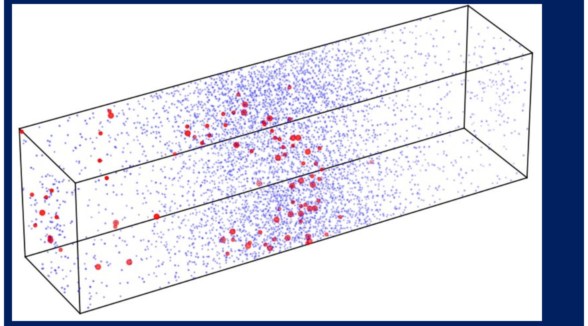
Dedicated detector options:

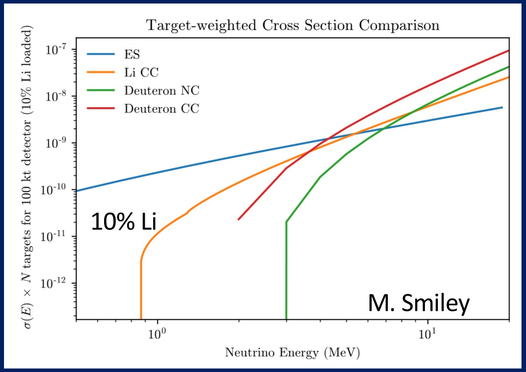
- LiquidO
- Re-use NOvA ND
- Eos/ANNIE like

Physics Program

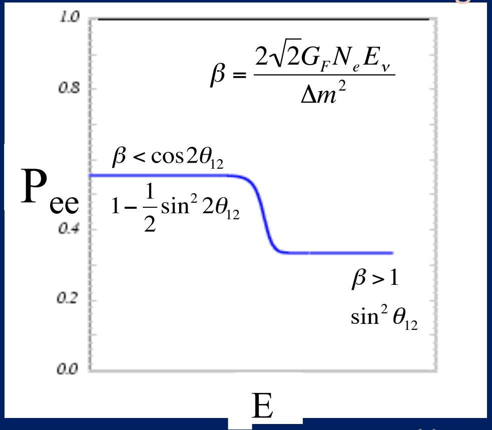
Solar Neutrinos

- Directionality improves signal/background separation for CNO ES reaction
- Alternate `loading' is ^{7}Li for narrow CC response for MSW transition

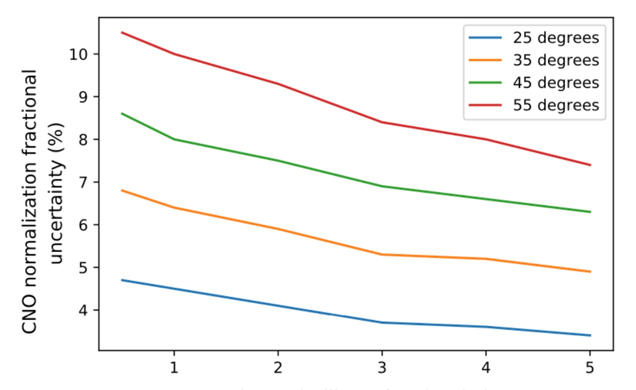




What about MSW transition region?



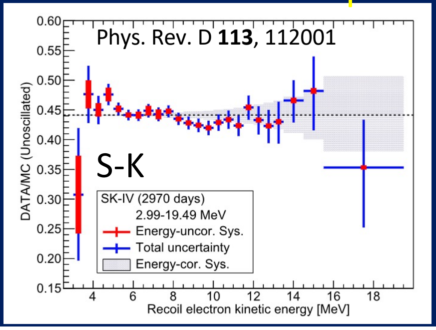
CNO uncertainty for different angular resolutions



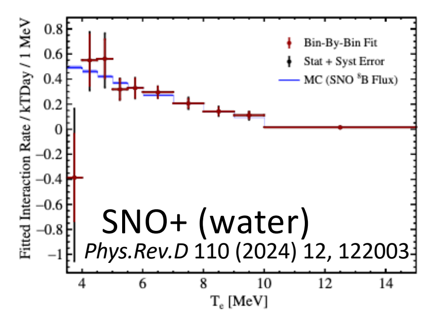
Bonventre and Orebi Gann, Eur.Phys.J.C 78 (2018) 6, 435

Final BOREXINO uncertainties:
+20%
-13%

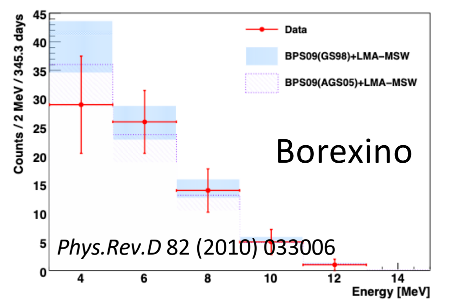
Low E ^{8}B spectral data



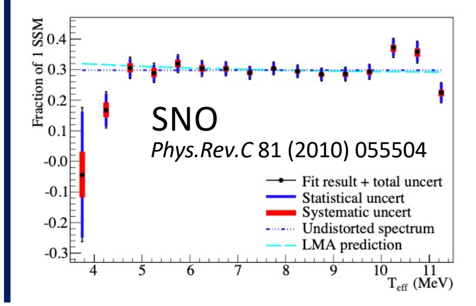
Phys. Rev. D **113**, 112001



Phys.Rev.D 110 (2024) 12, 122003



Phys.Rev.D 82 (2010) 033006

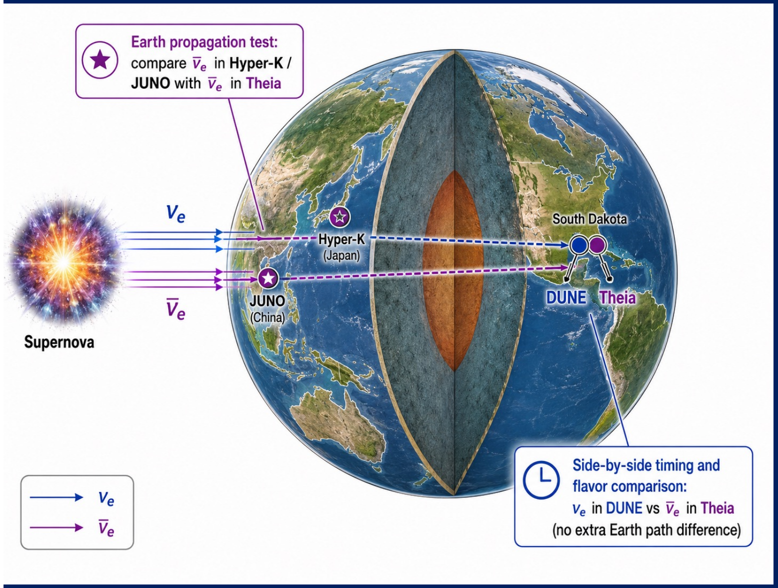


Phys.Rev.C 81 (2010) 055504

Physics Program

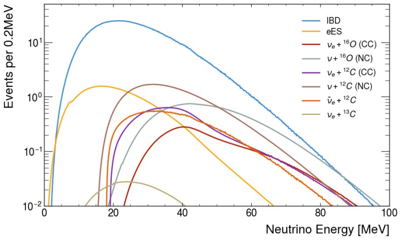
Supernova Burst Neutrinos

Literally complementary…



Long Asia/North America ν baseline

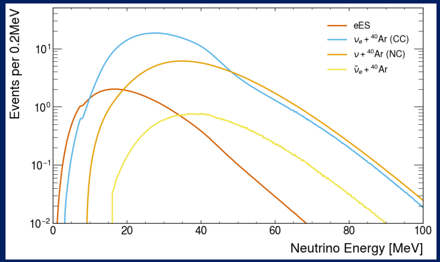
- Direction via timing
- Comparison of ν_e and $\overline{\nu}_e$ propagation through galactic potential
- Relative ν_e and $\overline{\nu}_e$ arrival times with no direction confusion



Theia (LAB+water/WbLS)

Reaction (10 kpc)	Channel	Inner 9 kt LAB	Outer 10 kt H_2O/WbLS	Total
(IBD)	$\bar{\nu}_e + p \to e^+ + n$	1,670	1,980	3,650
(ES)	$\nu + e^- \to \nu + e^-$	75	96	171
(νp)	$\nu + p \to \nu + p$	4,951	–	4,951
(ν_eC)	$\nu_e + {}^{12}C \to {}^{12}N + e^-$	31	–	31
($\bar{\nu}_e$C)	$\bar{\nu}_e + {}^{12}C \to {}^{12}B + e^+$	81	–	81
(NCC)	$\nu + {}^{12}C \to {}^{12}C^* + \nu + \gamma$	505	–	505
(ν_eC)	$\nu_e + {}^{12}C \to {}^{11}C + e^- + p$	1.8	–	1.8
($\bar{\nu}_e$C)	$\bar{\nu}_e + {}^{12}C \to {}^{11}B + e^+ + n$	1.8	–	1.8
(NCC)	$\nu + {}^{12}C \to {}^{11}B + \nu + p$	18	–	18
(NCC)	$\nu + {}^{12}C \to {}^{11}C + \nu + n$	5.8	–	5.8
(ν_eO)	${}^{16}O(\nu_e, e^-){}^{16}F$	–	34	34
($\bar{\nu}_e$O)	${}^{16}O(\bar{\nu}_e, e^+){}^{16}N$	–	44	44
(NCO)	${}^{16}O(\nu, \nu'){}^{16}O^*$	–	110	110

Neutron tag of IBDs allows precise pointing via ES—no CC/ES confusion (expect about 2-3°)



DUNE (30 kt LAr)

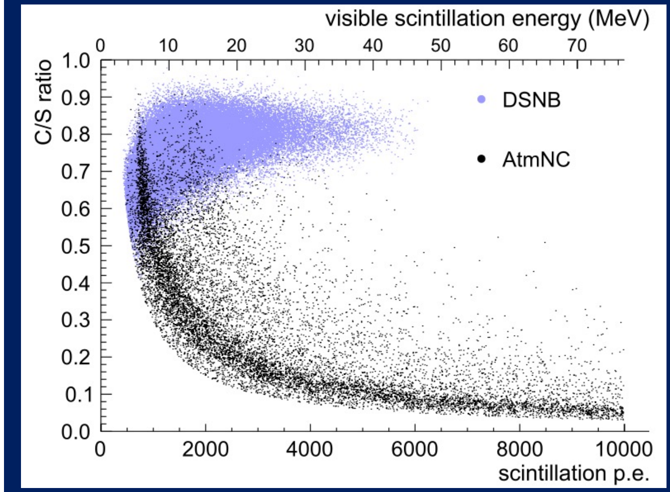
(10 kpc)	Channel	Expected event count
	$\nu_e + {}^{40}Ar \to e^- + {}^{40}K^*$	**2475.0**
	$\nu + e^- \to \nu + e^-$ (all flavors)	**244.4**
	$\nu_e + e^- \to \nu_e + e^-$	116.6
	$\bar{\nu}_e + e^- \to \bar{\nu}_e + e^-$	50.5
	$\nu_{\mu,\tau} + e^- \to \nu_{\mu,\tau} + e^-$	41.4
	$\bar{\nu}_{\mu,\tau} + e^- \to \bar{\nu}_{\mu,\tau} + e^-$	35.9
	Total	**2719.4**

1 Theia module at SURF has ~same total statistics as 3 DUNE modules---cross-triggering possible , same timing system

Physics Program

Other Physics

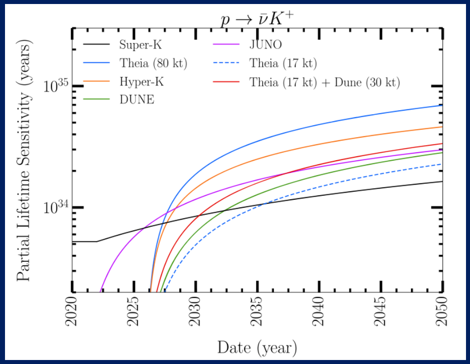
- Diffuse supernova background neutrino

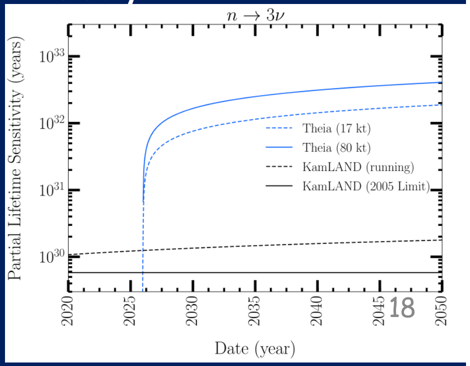


Sawatzki, Wurm, and Kresse, PHYS. REV. D 103, (2021)

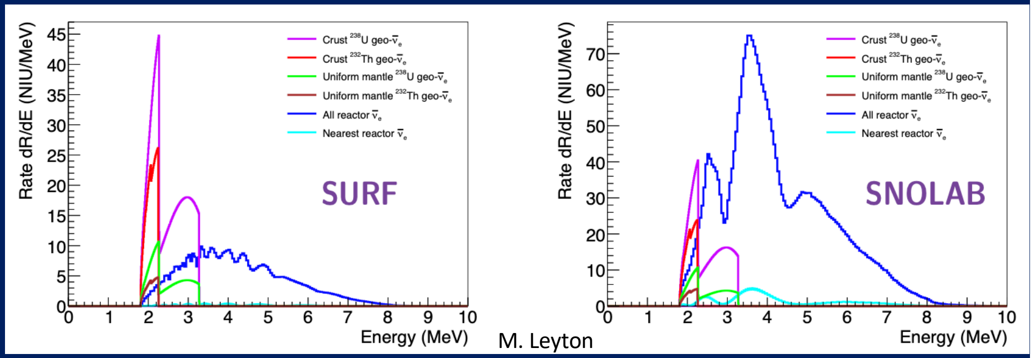
Detection exploits cherton/scinton ratio—atmospheric backgrounds can be removed

- Nucleon Decay





- Geo/Reactor Anti-nu



M. Leyton

SURF has ”cleaner” geo-ν while SNOLAB has high-order reactor minima and maxima to explore

Liquid Scintillator Town Hall

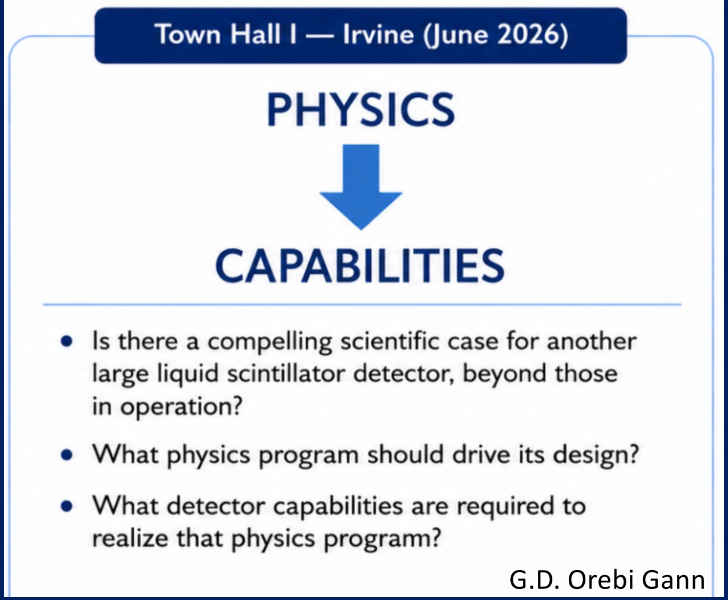

PHYSICS OPPORTUNITIES OF LARGE LIQUID SCINTILLATOR DETECTORS

TOWN HALL

UCI Department of Physics & Astronomy

Opportunity for community to step back and examine the very broad physics enabled by a future detector and requirements to achieve it, with input from experts from the field.

Organized by Gabriel Orebi Gann, Bob Svoboda

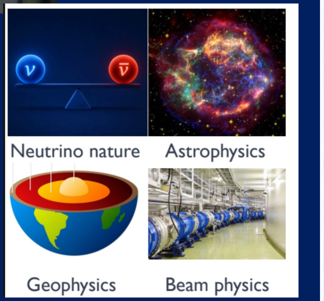

Town Hall I — Irvine (June 2026)

PHYSICS

CAPABILITIES

- Is there a compelling scientific case for another large liquid scintillator detector, beyond those in operation?
- What physics program should drive its design?
- What detector capabilities are required to realize that physics program?

G.D. Orebi Gann



~100 in-person participants

- Experimentalists representing at least 10 different detectors
- Many theorists: nuclear, particle, astroparticle
- 50/50 senior/junior mix

Follow-up from technology-focused workshop in 2025

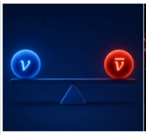

Workshop on Hybrid Cherenkov/Scintillation Detection Technologies

June 3–5, 2025

David Rittenhouse Laboratories, Room A4 , University of Pennsylvania, Philadelphia

Liquid Scintillator Town Hall

Physics Landscape and Program



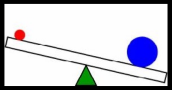
Neutrino nature

Astrophysics

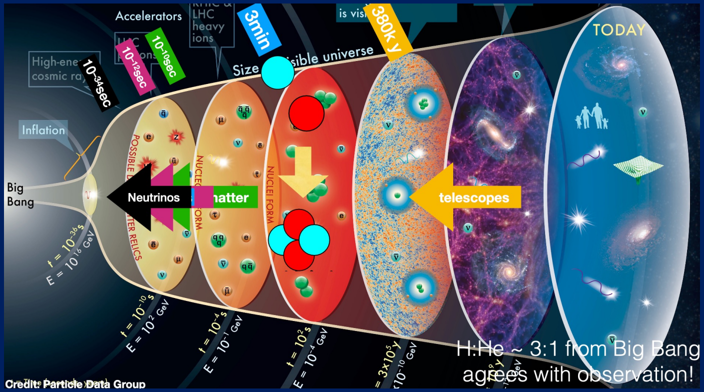
H. Muryama:

Yo! Neutrino mass points toward 10^{14} GeV physics! What's wrong wit' you??

$$\begin{pmatrix} \nu_L & \nu_R \end{pmatrix} \begin{pmatrix} & m_D \\ m_D & M \end{pmatrix} \begin{pmatrix} \nu_L \\ \nu_R \end{pmatrix} \qquad m_\nu = \frac{m_D^2}{M} \ll m_D$$



To obtain $m_3 \sim (\Delta m^2_{atm})^{1/2}$, $m_D \sim m_t$, $M_3 \sim 10^{14}$GeV (GUT?)

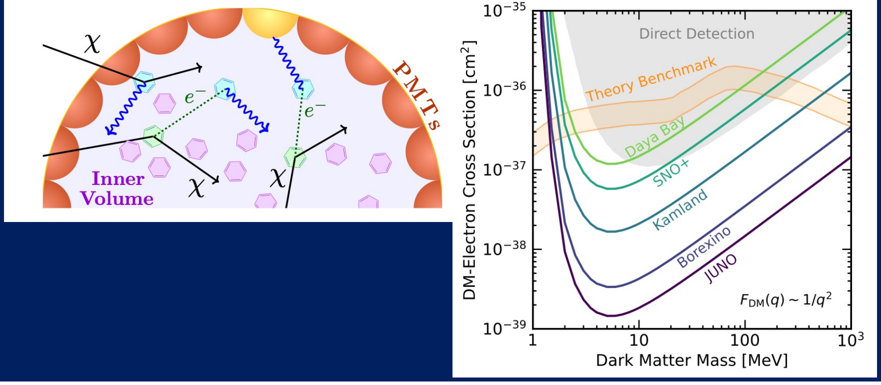


H:He ~ 3:1 from Big Bang agrees with observation!

Breadth of liquid scintillator techniques keeps growing

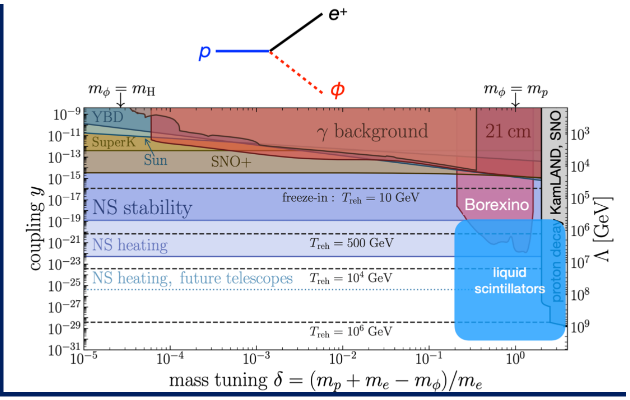
Sub-GeV Dark Matter Detection with Dark Rates in Liquid Scintillators

Lillian Santos-Olmsted,[1, 2, *] Rebecca K. Leane,[1, 2, †] Carlos Blanco,[3, 4, 5, ‡] and John F. Beacom[6, 7, 8, §]



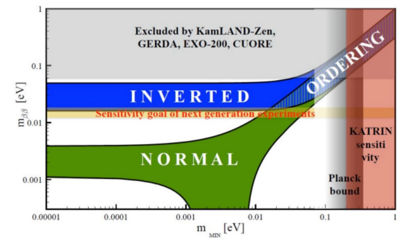
Minimal Proton-Mass Dark Matter

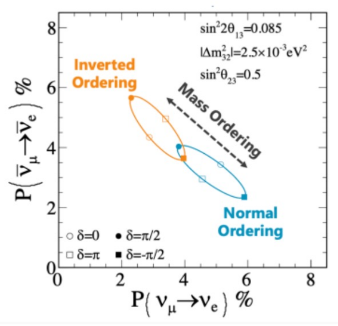
Majed Khalaf,[1] Eric Kuflik,[1] Alessandro Lenoci,[1] Hitoshi Murayama,[2, 3, 4] and Edoardo Vitagliano[5, 6]



Liquid Scintillator Town Hall

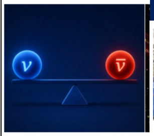
Physics Landscape and Program





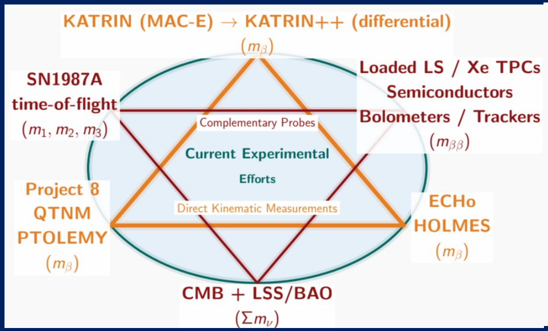
K. Heeger:

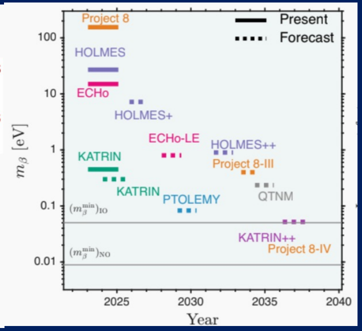
CP, MO, and Majorana nature are the biggest questions in neutrino physics---Hybrid/LS techniques can measure all three



Neutrino nature

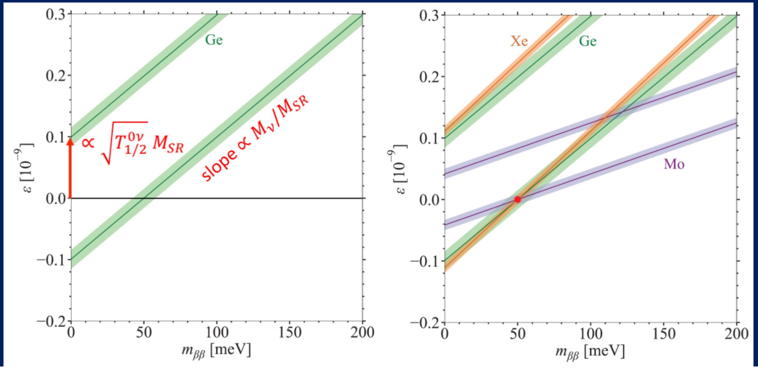
Beam physics





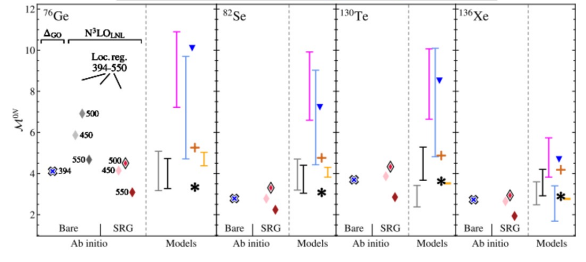
T. Lasserre:

Direct mass measurements, cosmology, and $0\nu\beta\beta$ experiments approaching m_ν in complementary ways



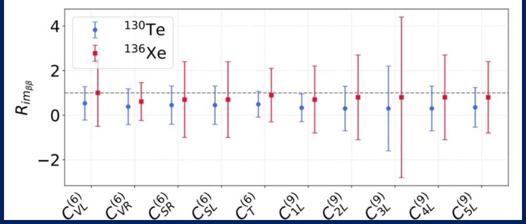
“Master formula”

$$\frac{d\Gamma}{dy\, d\cos\theta} = g_A^4\Big\{ g_{01}\left(|\mathcal{A}_\nu|^2 + |\mathcal{A}_R|^2\right) - 2(g_{01}-g_{04})\mathrm{Re}\mathcal{A}_\nu^*\mathcal{A}_R + 4g_{02}\,|\mathcal{A}_E|^2 + 2g_{04}\left[|\mathcal{A}_{m_e}|^2 + \mathrm{Re}\left(\mathcal{A}_{m_e}^*(\mathcal{A}_\nu+\mathcal{A}_R)\right)\right] - 2g_{03}\,\mathrm{Re}\left((\mathcal{A}_\nu+\mathcal{A}_R)\mathcal{A}_E^* + 2\mathcal{A}_{m_e}\mathcal{A}_E^*\right) + g_{09}\,|\mathcal{A}_M|^2 + g_{06}\,\mathrm{Re}\left((\mathcal{A}_\nu-\mathcal{A}_R)\mathcal{A}_M^*\right)\Big\},$$



E. Mereghetti:

Progress is increasing in very difficult work to understand nuclear complexity in $0\nu\beta\beta$

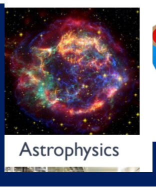


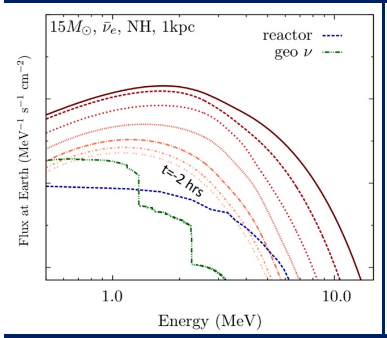
J. Detwiler:

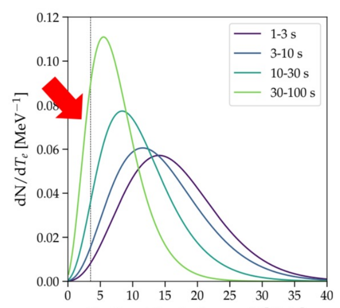
Precision era+multiple isotopes may help determine mechanism. Is kinematic (E,θ) approach possible with Cherenkov light?

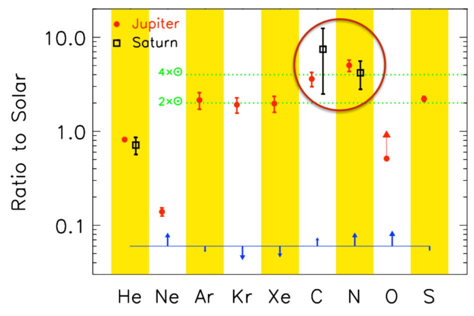
Liquid Scintillator Town Hall

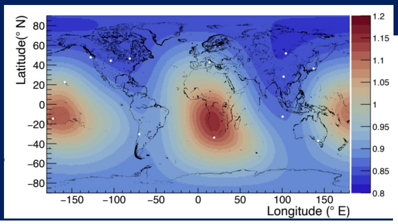
Physics Landscape and Program

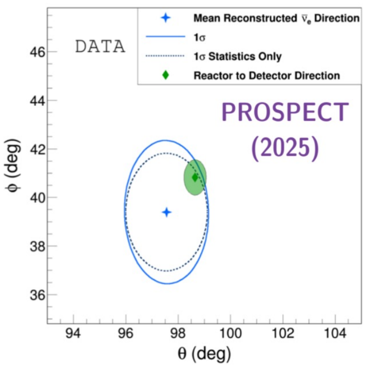


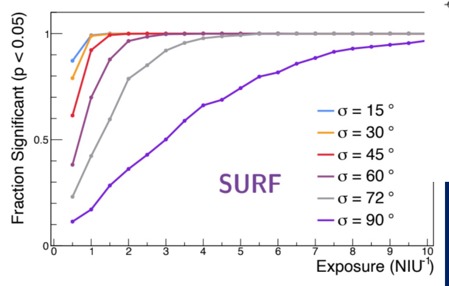




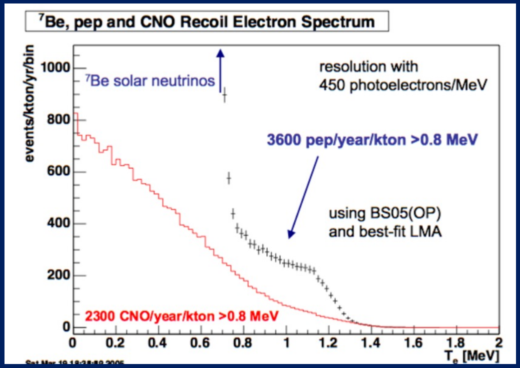




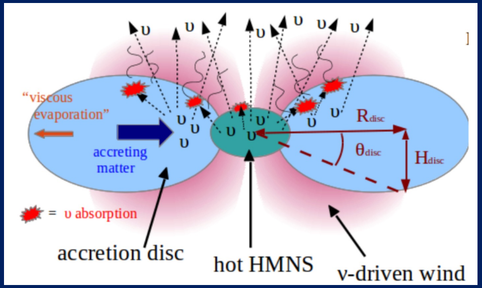




C. Lunardini:
Hybrid/LS approaches particularly critical for pre-SNB and SNB cooling phase, when neutrino energies are very low, for DSNB and mergers because of big IBD cross section



M. Leyton, M. Dornfest:
New approaches to geo-ν direction with IBDs may allow reconstruction of non-uniformity of Earth’s mantle

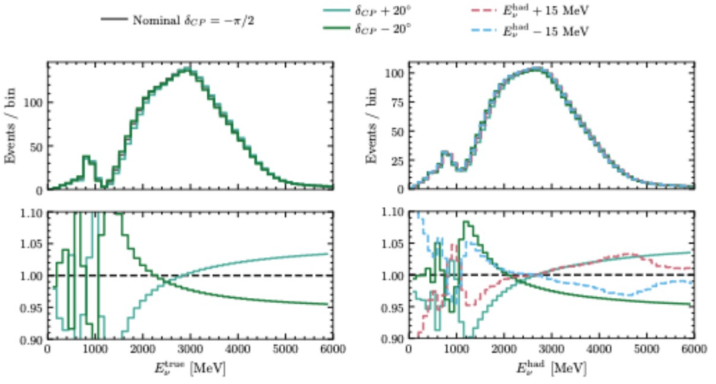


W. Haxton:
Solar neutrinos are great opportunity for neutrino astronomy! *pp* neutrino flux known to great precision; CNO neutrinos may explain solar system formation. Solar ν physics deserves to be more than “parasitic” science in future detectors.

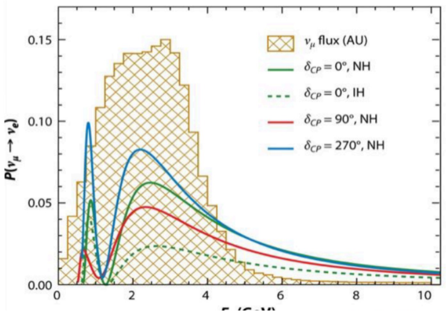
Liquid Scintillator Town Hall

Detector Requirements

To add value to DUNE/HK LBL program



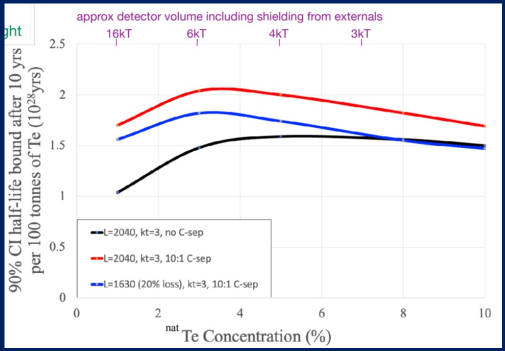
- > 1 DUNE module size for meaningful statistics
- Energy scale precision to ~0.5% for oscillation precision
- Cherenkov light for particle ID (e/μ, high multiplicities)
- Neutron tagging for missing energy recon
- Neutron KE to control model uncertainties
- Precision near detector with relevant targets
- Second oscillation max possible---bigger CP asymmetry

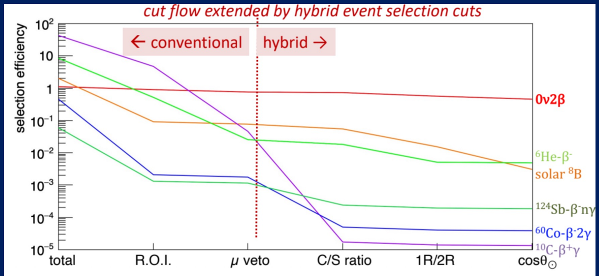


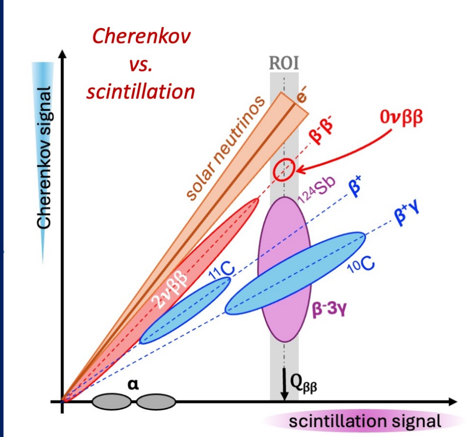
L. Munteanu, A. Sousa

To go below 6 meV on $0\nu\beta\beta$

- Isotope with low 2ν/0ν rate (Xe, Te)
- ”Loaded” light yield better than 1200 pe/MeV
- Endpoint resolution 1-2%
- >100 t of ^{nat}Te or 50 t ^{nat}Xe (5 t ^{enr}Xe)
- Either Xe or faster Te loading technique than SNO+
- Cherenkov+scint light for ^{8}B rejection at >90%





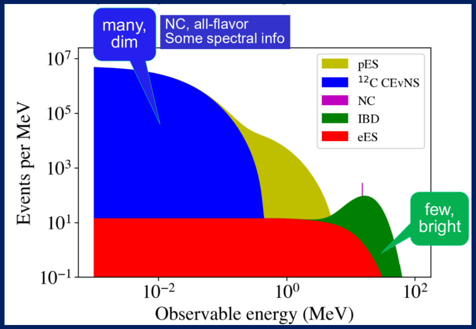


S. Biller, M. Wurm,
V. Palusova, L. Lebanowski

Liquid Scintillator Town Hall

Detector Requirements

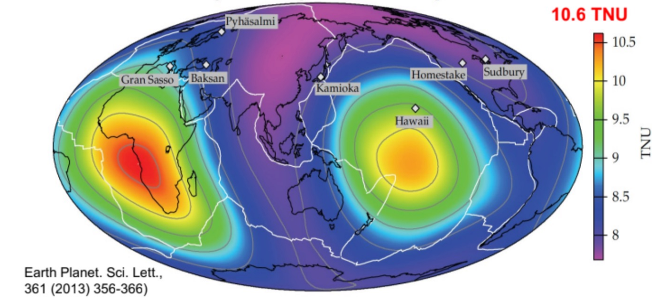
To leverage new sensitivities to SNB



- $E_{threshold}$ low enough to see NC ν+p (and obviously IBD)
- Or maybe even ν+^{12}C “glow”
- Directionality via fast timing, Cherenkov, or oscillations
- Measurements of relevant cross sections

K. Scholberg

To use geo-νs for Earth science

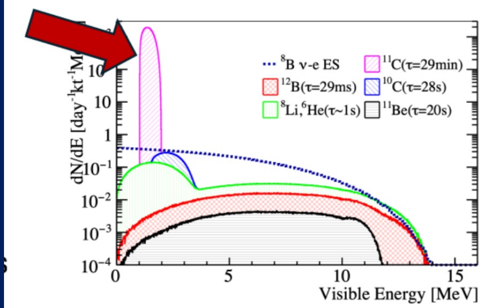


Earth Planet. Sci. Lett., 361 (2013) 356-366)

- Large size to see (tiny) mantle signal
- Low reactor backgrounds
- Deep enough to reduce cosmogenics
- Low α backgrounds (α,n), (α,p)
- Directionality would be very nice…

L. Ludhova, M. Leyton

To measure CNO and ^{8}B MSW rise

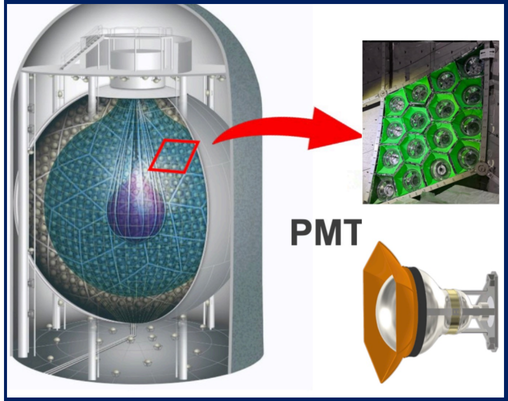


- Big enough for significant statistics, even at low end of ^{8}B
- Deep enough to avoid significant ^{11}C
- Neutron tagging to avoid other cosmogenics
- Radioactive background levels like Borexino for low threshold
- Directionality to avoid remaining backgrounds

O. Nairat

Liquid Scintillator Town Hall

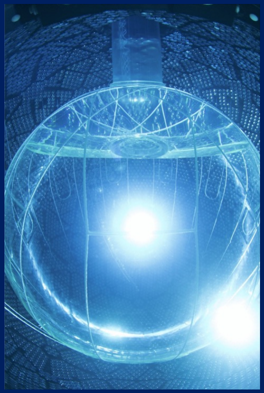
Lessons Learned



KamLAND-Zen

- Improve energy resolution
  - Better PMTs
- Improve cosmogenic tagging
  - New electronics
- Improve energy uncertainty
  - Better calibrations
- Improve background tagging
  - Scintillating balloon

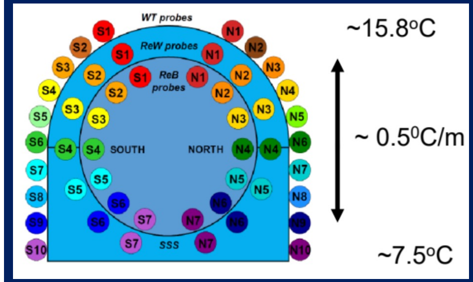
S. Axani



SNO+

- "Phasing" is good!
  - Broad physics program
- Depth is great
  - Few in situ cosmogenics
- Underground isotope purification
  - Cooldown of intrinsic cosmogenics
- Multi-pe sensitivity would be helpful
  - Analog processing?

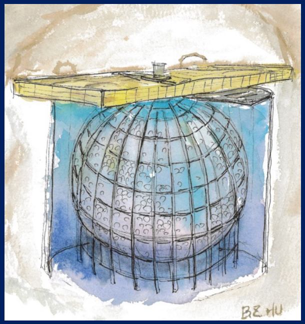
JRK



Borexino

- Unparalleled cleanliness
- Extreme care in construction
- Temperature tracking to tag backgrounds
- New techniques for removal of cosmogenics

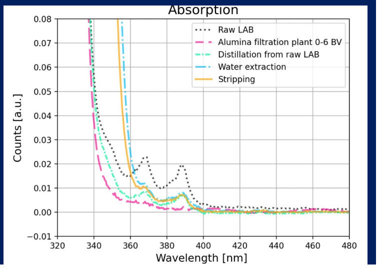
G. Ranucci



JUNO

- Exceptional light yield! (1700 pe/MeV)
- Incredible size (34 m diameter)
- Remarkable timeline
- Purification very successful especially for large detector!
- Working toward Te loading

L. Wen



Liquid Scintillator Town Hall

Discussion and Debate

What ultimately limits next-generation $0\nu\beta\beta$ experiments?

Optimizing detector design for a broad physics program

- Sole-purpose $0\nu\beta\beta$ vs. multipurpose?
  - For multipurpose experiment, $0\nu\beta\beta$ program is `flagship’
  - Debate: would nothing but a null $0\nu\beta\beta$ result justify cost?
  - Broad program provides `signal’ that motivates people and is exciting in its own right
  - Phasing program (water->scintillator->isotope) provides breadth
- What is argument for pushing $0\nu\beta\beta$ if MO is not inverted?
  - Quasi-degenerate, non-standard mechanisms
  - Discovery is possible (likely?); exclusion is hard
  - Broad program more critical
- How do we push limits on size, cleanliness, and light yield?
- Any new detector must clear the bar set by JUNO
  - Size, light yield, and performance are remarkable
  - Deeper detector would have broader capabilities
- We should consider breadth beyond neutrino physics

Summary and Next Steps

- Future large hybrid detector like Theia offers broad program of compelling physics
- While pushing the boundaries of $0\nu\beta\beta$ mass limits well below inverted ordering
- Detector needs to:
  - Be big (DUNE module size or larger) for long-baseline physics
  - Be deep (SURF or SNOLAB) and as clean as Borexino for $0\nu\beta\beta$ and solar ν
  - Allow `phasing’ to do multiple physics programs with various targets
  - Have narrow energy resolution to do $0\nu\beta\beta$
  - Be able to observe and discriminate Cherenkov light for LBL and solar ν rejection/physics
- Next--

Town Hall II — Mainz (October 2026)

CAPABILITIES

TECHNOLOGY

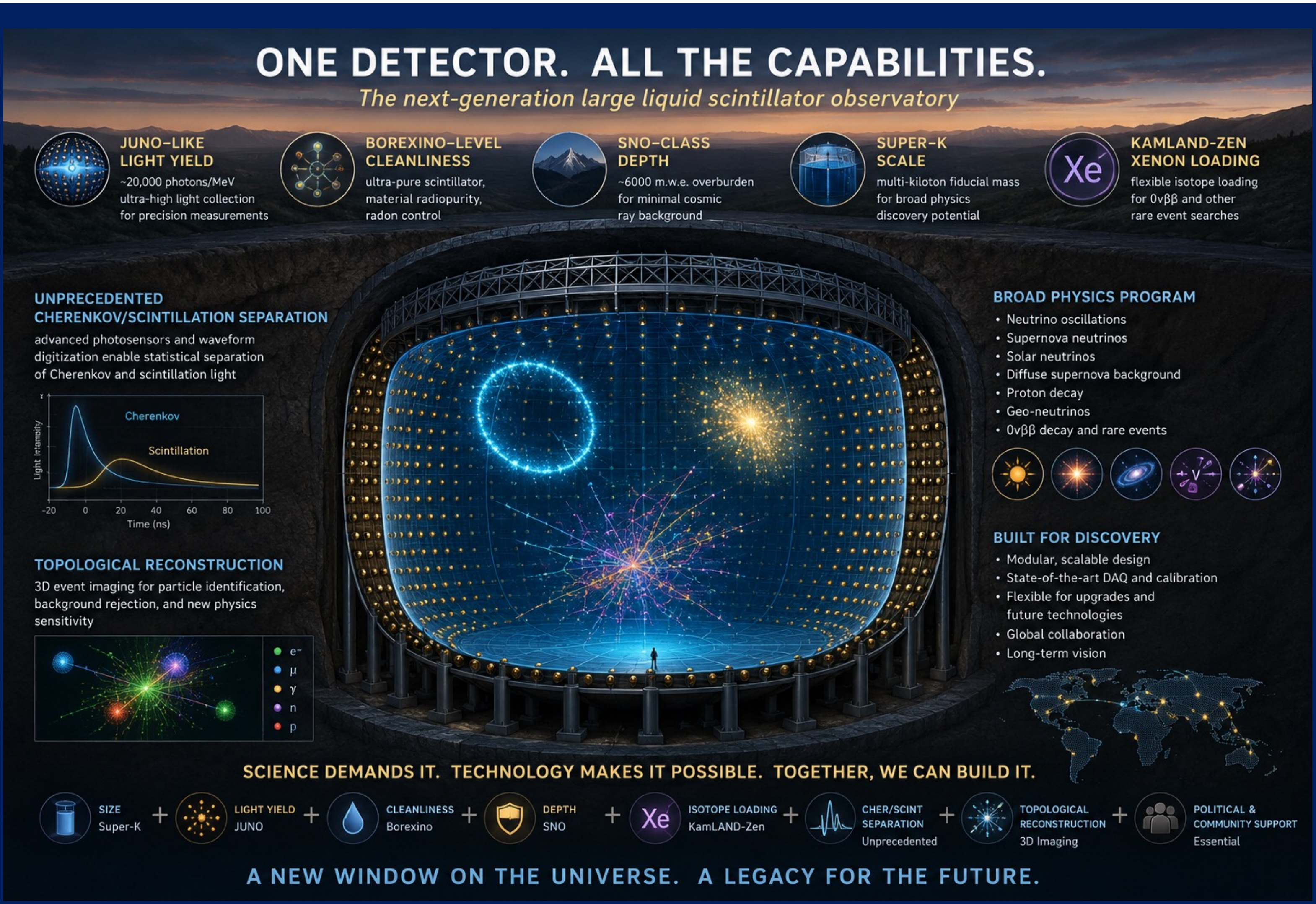
- What technologies can achieve those capabilities?

Hosted by

Alfons Weber and Michi Wurm

Oct 13-15 2026

Everyone welcome!



ONE DETECTOR. ALL THE CAPABILITIES.

The next-generation large liquid scintillator observatory

JUNO-LIKE LIGHT YIELD
~20,000 photons/MeV
ultra-high light collection
for precision measurements

BOREXINO-LEVEL CLEANLINESS
ultra-pure scintillator,
material radiopurity,
radon control

SNO-CLASS DEPTH
~6000 m.w.e. overburden
for minimal cosmic
ray background

SUPER-K SCALE
multi-kiloton fiducial mass
for broad physics
discovery potential

KAMLAND-ZEN XENON LOADING
flexible isotope loading
for 0νββ and other
rare event searches

UNPRECEDENTED CHERENKOV/SCINTILLATION SEPARATION

advanced photosensors and waveform digitization enable statistical separation of Cherenkov and scintillation light

TOPOLOGICAL RECONSTRUCTION

3D event imaging for particle identification, background rejection, and new physics sensitivity

BROAD PHYSICS PROGRAM

- Neutrino oscillations
- Supernova neutrinos
- Solar neutrinos
- Diffuse supernova background
- Proton decay
- Geo-neutrinos
- 0νββ decay and rare events

BUILT FOR DISCOVERY

- Modular, scalable design
- State-of-the-art DAQ and calibration
- Flexible for upgrades and future technologies
- Global collaboration
- Long-term vision

SCIENCE DEMANDS IT. TECHNOLOGY MAKES IT POSSIBLE. TOGETHER, WE CAN BUILD IT.

SIZE Super-K + LIGHT YIELD JUNO + CLEANLINESS Borexino + DEPTH SNO + ISOTOPE LOADING KamLAND-Zen + CHER/SCINT SEPARATION Unprecedented + TOPOLOGICAL RECONSTRUCTION 3D Imaging + POLITICAL & COMMUNITY SUPPORT Essential

A NEW WINDOW ON THE UNIVERSE. A LEGACY FOR THE FUTURE.

★ MAIN EVENT ★

SIZE	SUPER-K SCALE	✓
LIGHT YIELD	JUNO LEVEL	✓
CLEANLINESS	BOREXINO LEVEL	✓
DEPTH	SNO DEPTH (~6000 m.w.e.)	✓
ISOTOPE LOADING	KAMLAND-ZEN (Xe)	✓
CHER/SCINT SEPARATION	UNPRECEDENTED	✓
TOPOLOGICAL RECONSTRUCTION	3D TOPO IMAGING	✓
POLITICAL SUPPORT	MAXIMUM	✓

G.D. Orebi Gann

Backups

Breadth and Detectors

100 keV--10 Gev

Typically scintillator

Typically Cherenkov

Solar νs

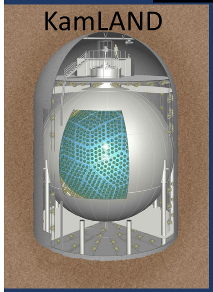
CP Violation

Reactor $\bar{\nu}$

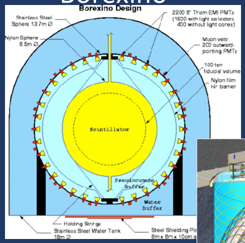
Atmospheric ν oscillations

SN burst νs

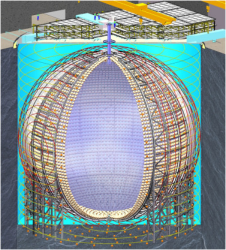
$0\nu\beta\beta$

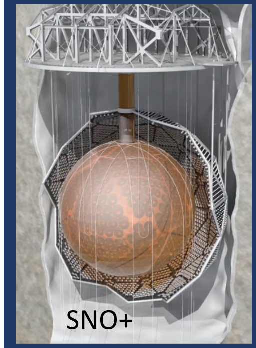

KamLAND

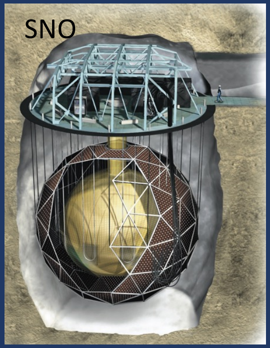
Borexino



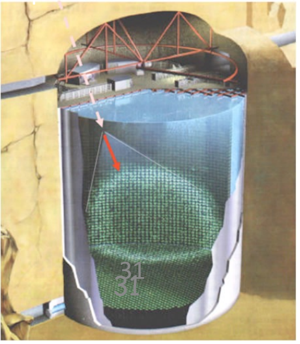
JUNO




SNO+


SNO

Super-Kamiokande



Requirements:

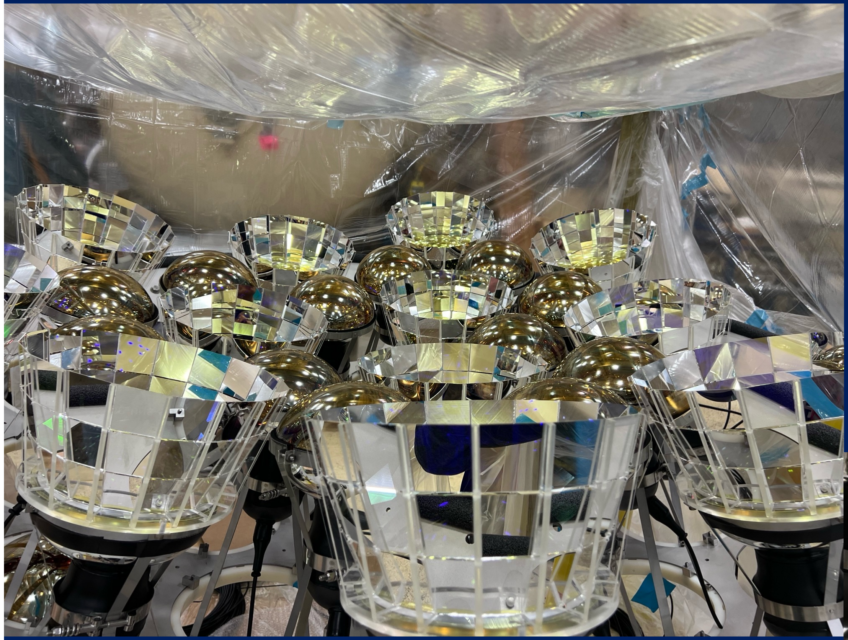
- Low radio backgrounds
- Excellent energy resolution
- Directional information
- Neutron tags

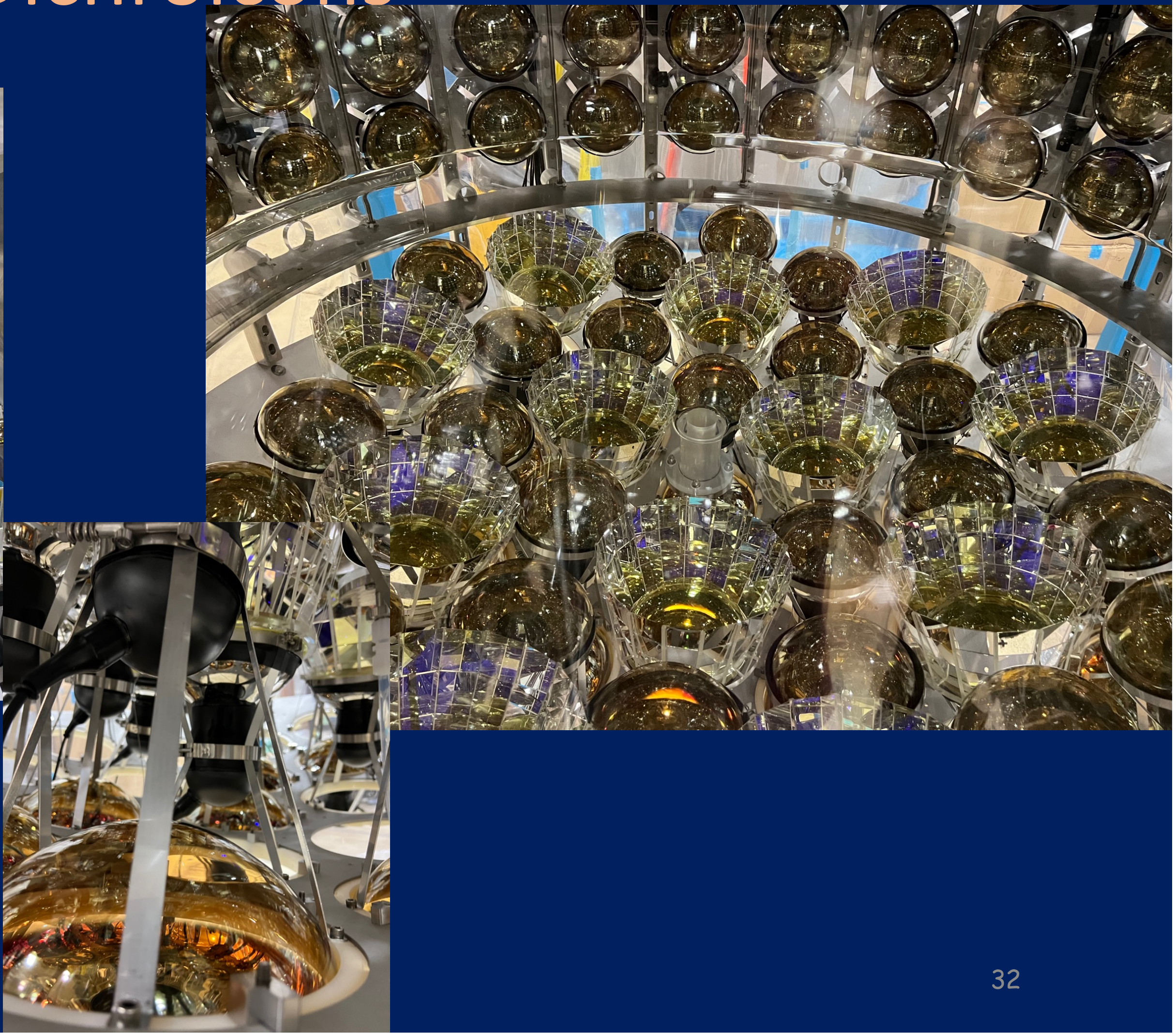
Requirements:

- Excellent particle ID
- Directional information
- Very big detector
- (Neutron tags)

Dichroicons

Eos at LBNL





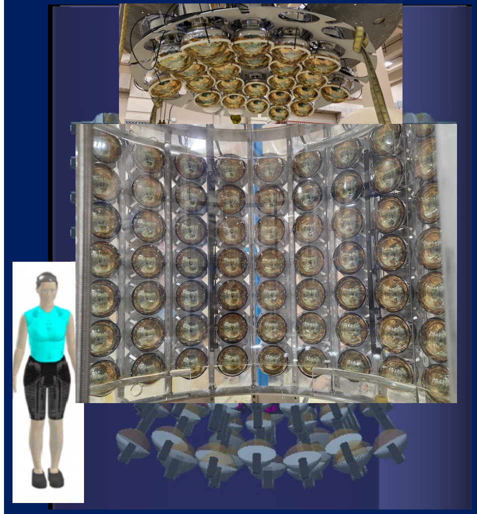
Theia

Timeline

Now: Demonstrators being built and operated:

Eos

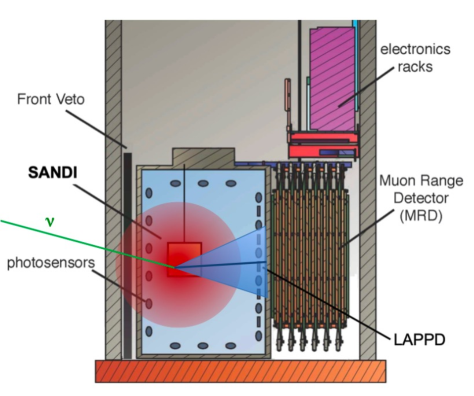
5 tonnes WbLS
240 fast PMTs
12 dichroicons



Goal: low-energy cher/scint response

ANNIE

26 t H2O + 1 t of WbLS
60 PMTs
5 LAPPDs

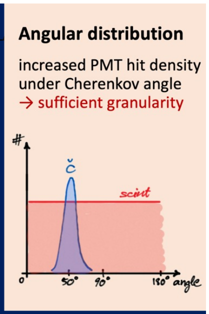


Goal: high-energy cher/scint response, Fast timing

BNL 30t

30 t of WbLS
20 PMT

Goal: WbLS stability


Angular distribution

increased PMT hit density under Cherenkov angle

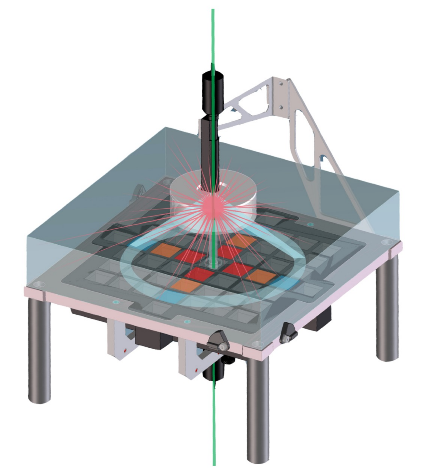
→ sufficient granularity

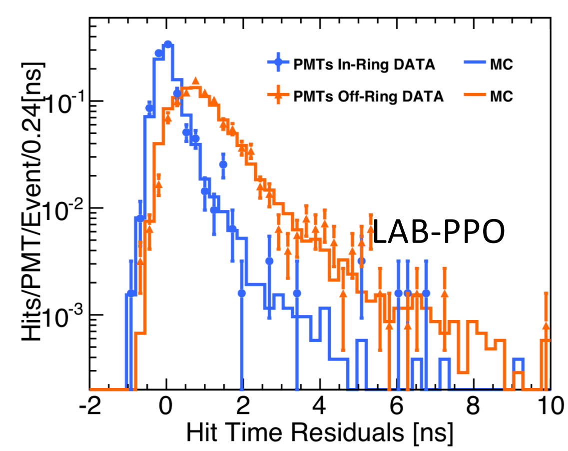
Angular Distribution

Basically an analysis approach---

Time profile of photons in Cherenkov ring is separated from scintillation light

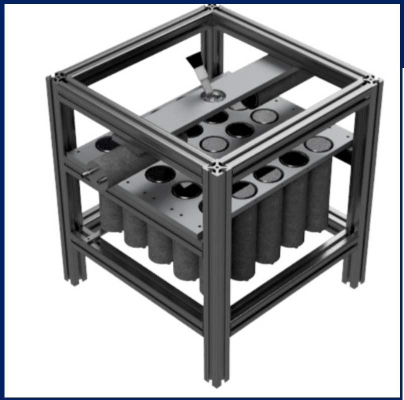
CHESS at LBNL Measurements



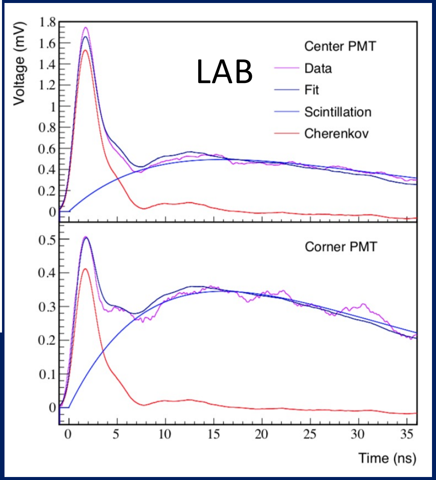


Caravaca et al, EPJC (2017) 77:811

"FlatDOT" (MIT/UNC)



Gruszko et al, JINST 14 (2019) 02, P02005



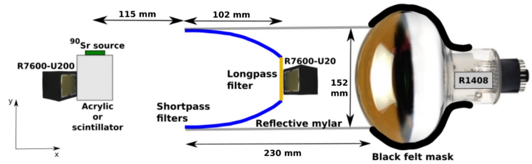
Upsides:

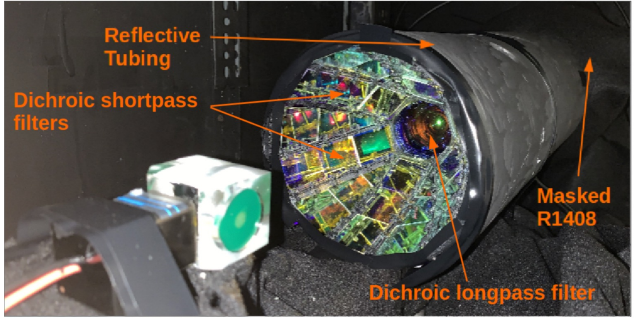
- Easy to do
- Can be used in any configuration

Downsides:

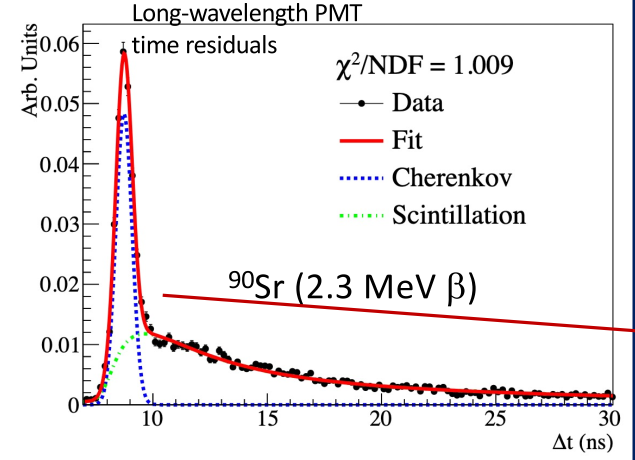
- Separation is not good enough by itself
- Need high pixelization to see ring well

Spectrum

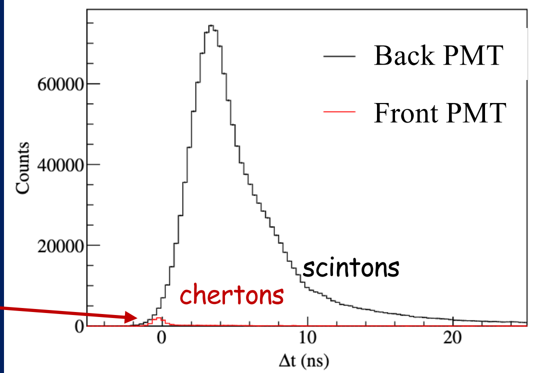


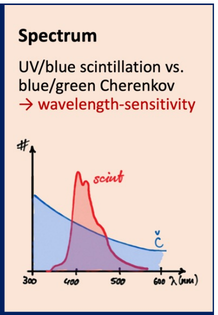


Phys. Rev. D 101, 072002



^{90}Sr (2.3 MeV β)

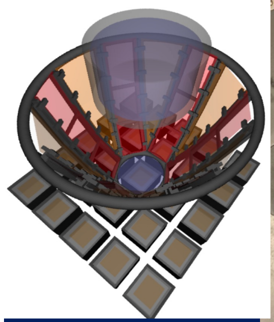


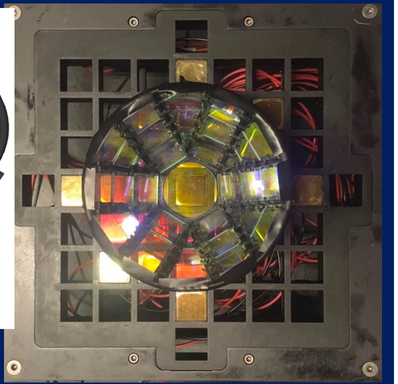

Spectrum

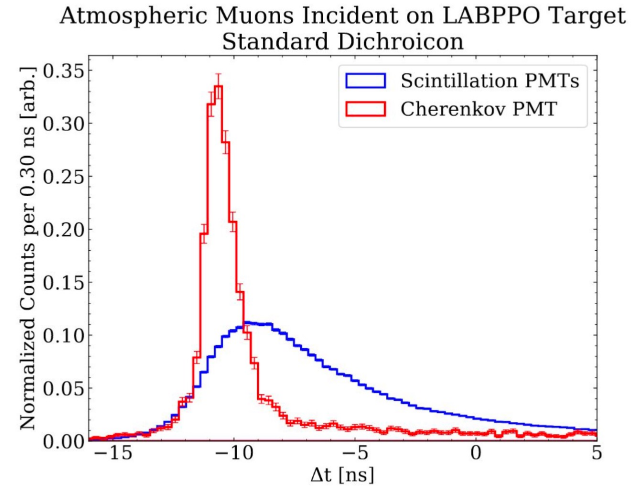
UV/blue scintillation vs. blue/green Cherenkov

→ wavelength-sensitivity

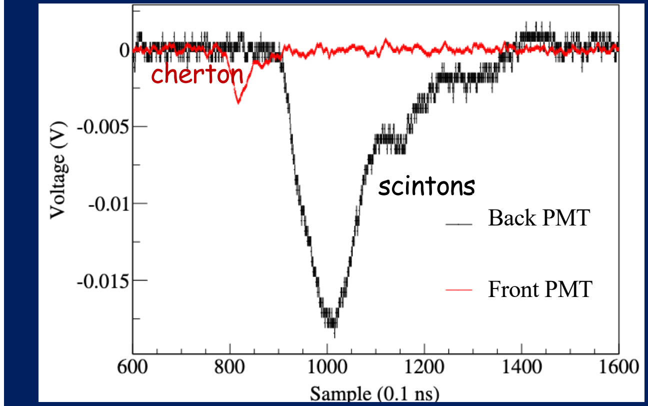
Dichroicon at CHESS



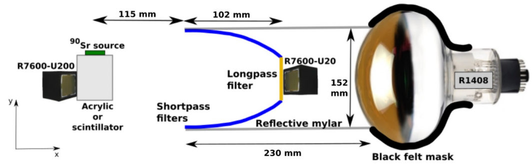


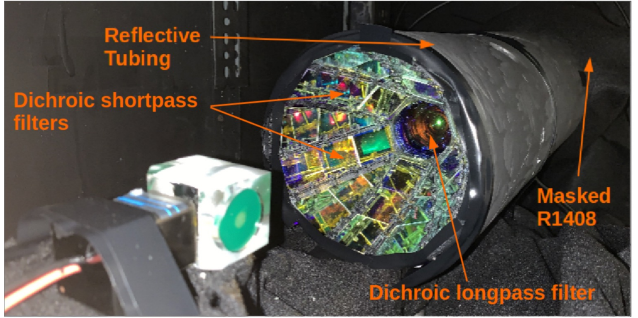


Cherton-scinton coincidence

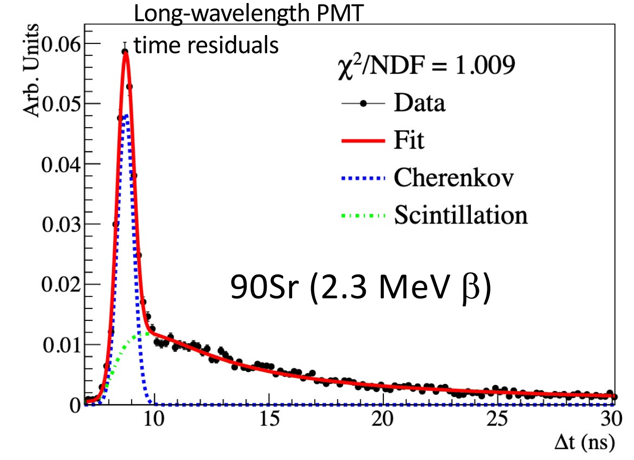


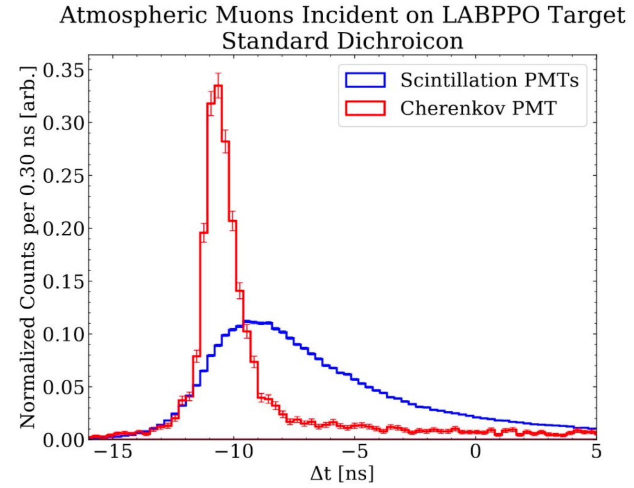
Spectrum



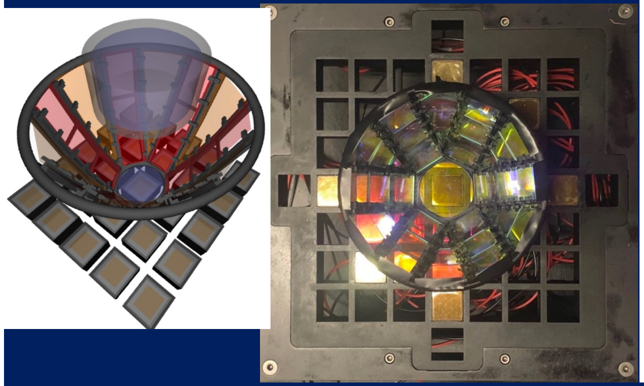


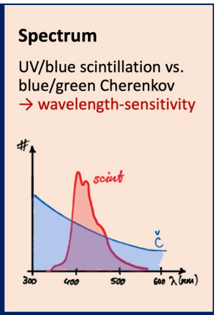
Phys. Rev. D 101, 072002





Dichroicon at CHESS

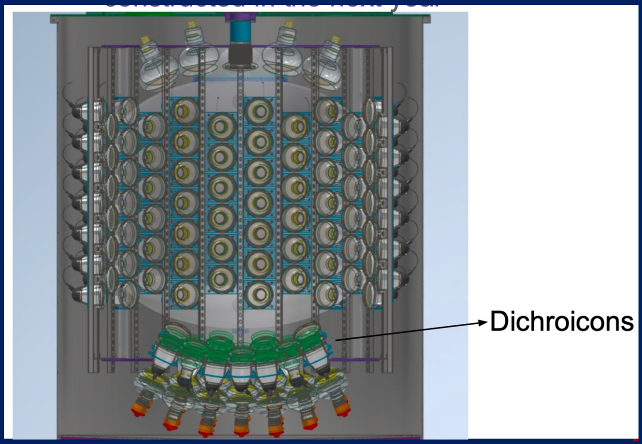




Spectrum

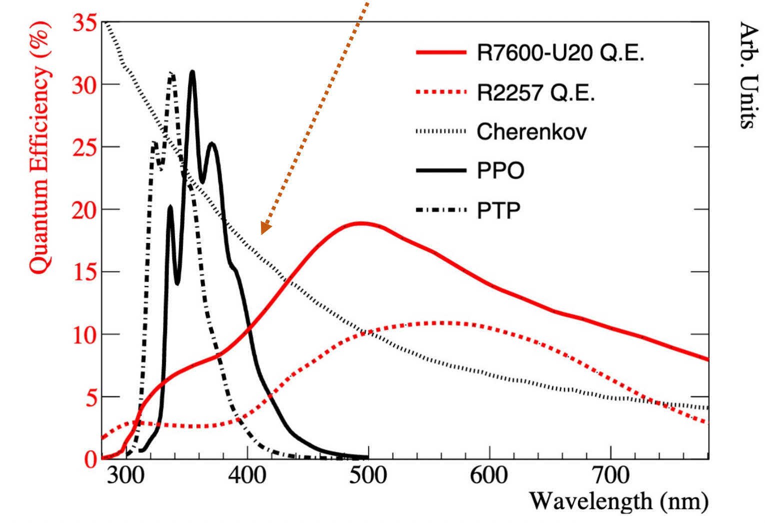
UV/blue scintillation vs. blue/green Cherenkov
→ wavelength-sensitivity

Eos demonstrator (~5 t) at LBNL will have several of these

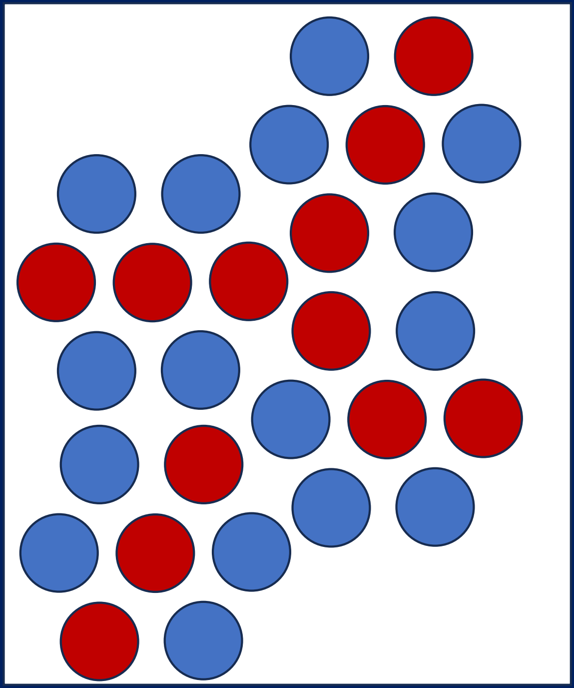


Spectrum

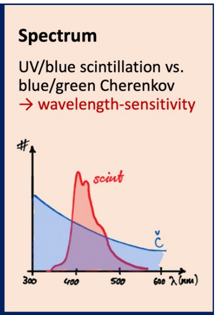
$N^{\gamma}_{cer} \sim 1/\lambda^2$



Spectral differences allow separation---could use filters or red-sensitive PMTs:



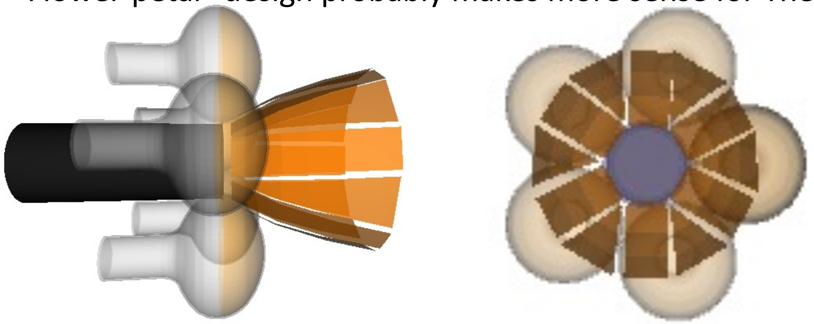
But now we have lost a lot of our scintillation photons---can we instead ***sort*** the photons so they go to the right sensors…?



Spectrum

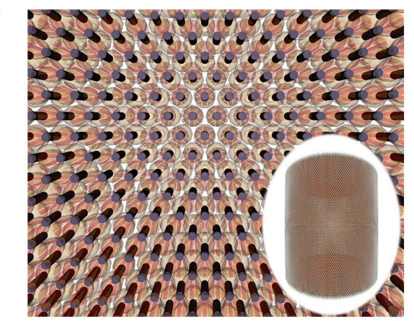
UV/blue scintillation vs.
blue/green Cherenkov
→ wavelength-sensitivity

“Flower-petal” design probably makes more sense for Theia



Spectrum

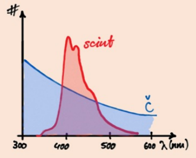
MC simulation model

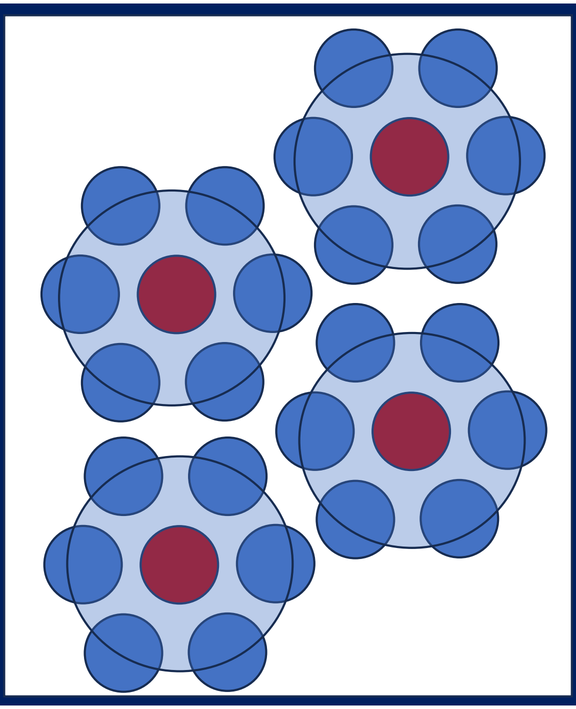


Spectrum

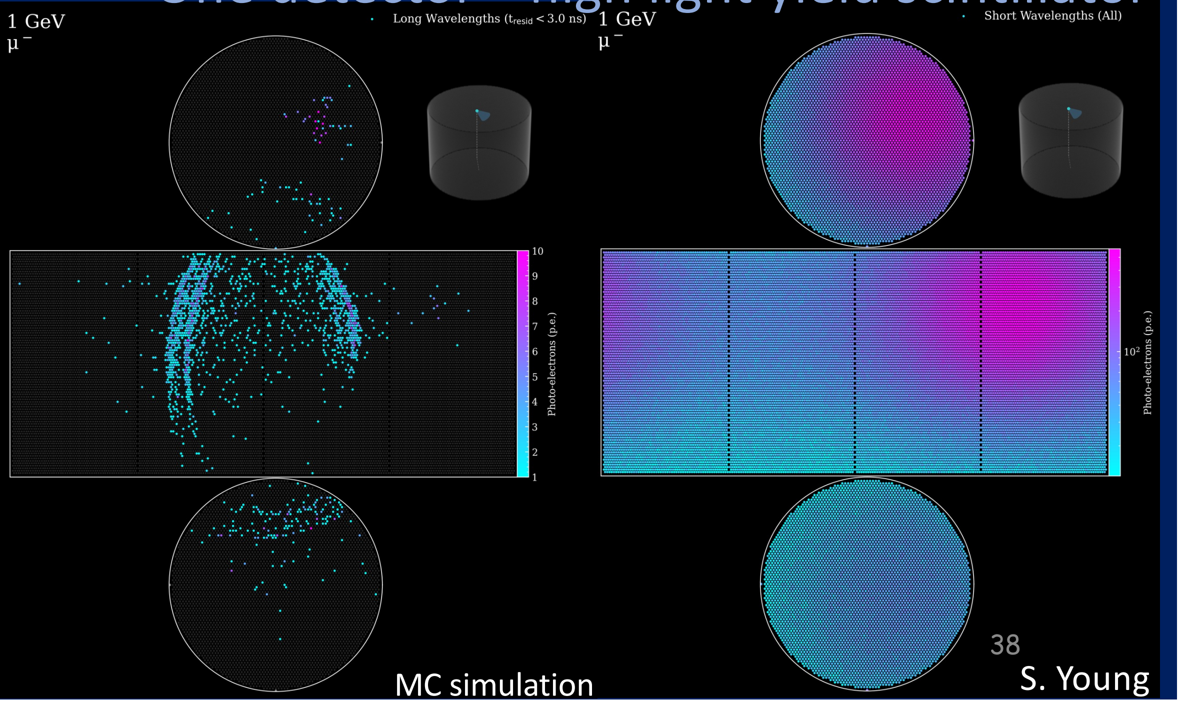
UV/blue scintillation vs. blue/green Cherenkov

→ wavelength-sensitivity





One detector---high light yield scintillator



MC simulation

S. Young