Liquid Scintillation Counter
@Yemilab

Sunny Seo
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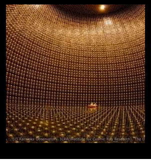
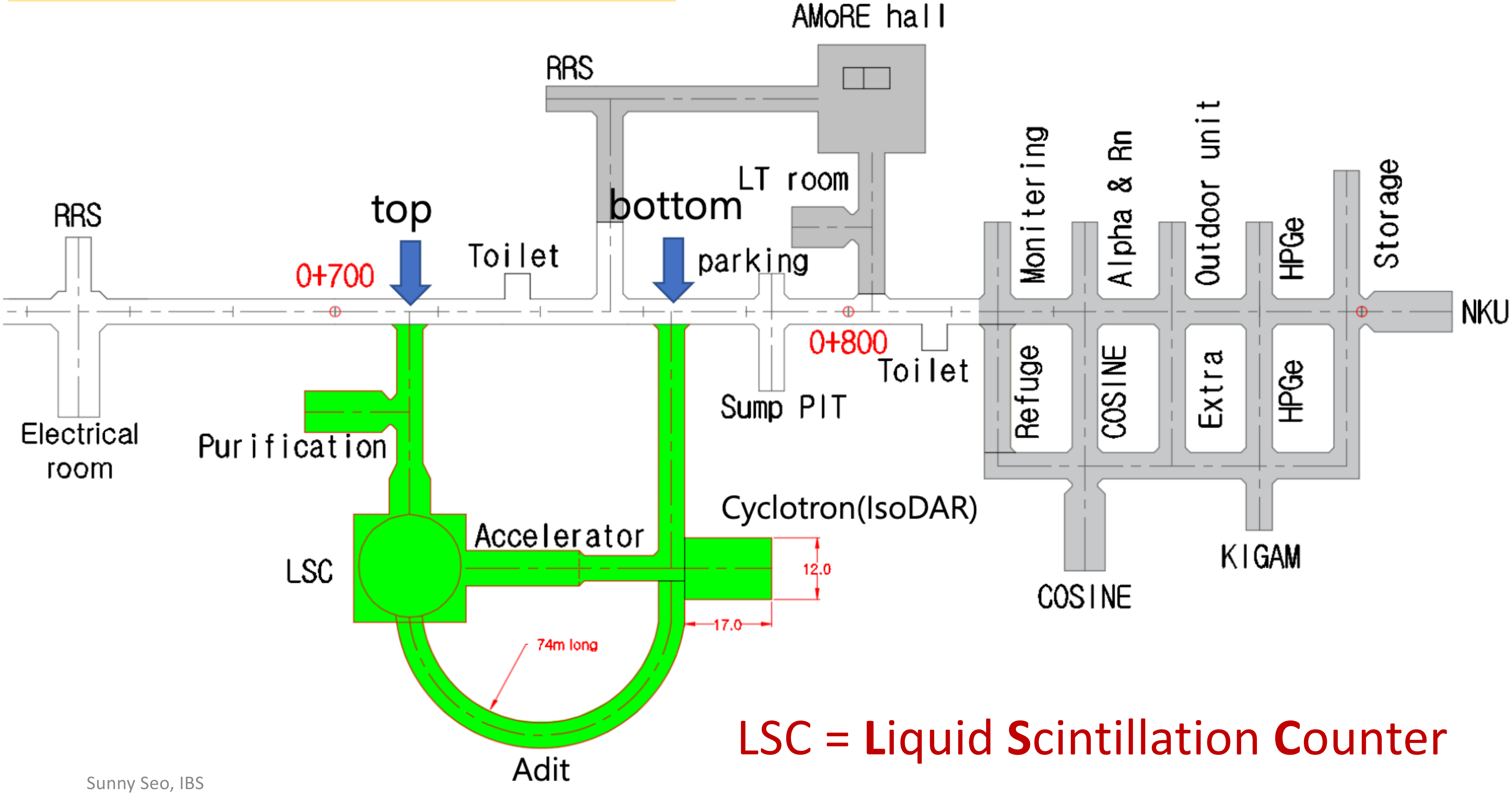
KPS DPF Meeting 2022, Korea
SKKU-Seoul Campus



2022.12.16

❖ Yemilab Layout (Top view)



LSC = **L**iquid **S**cintillation **C**ounter

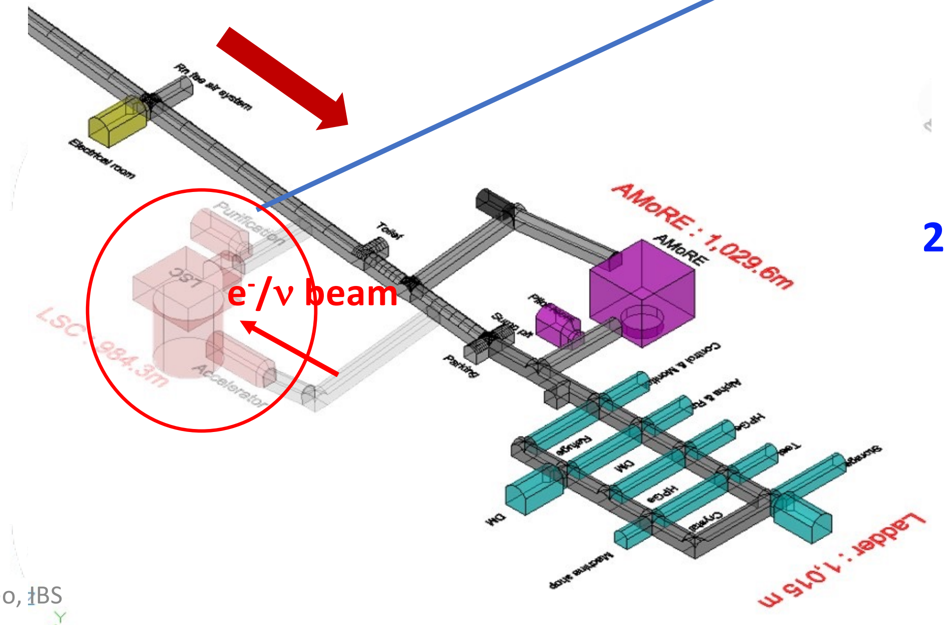
Sunny Seo, IBS

LSC @Yemilab

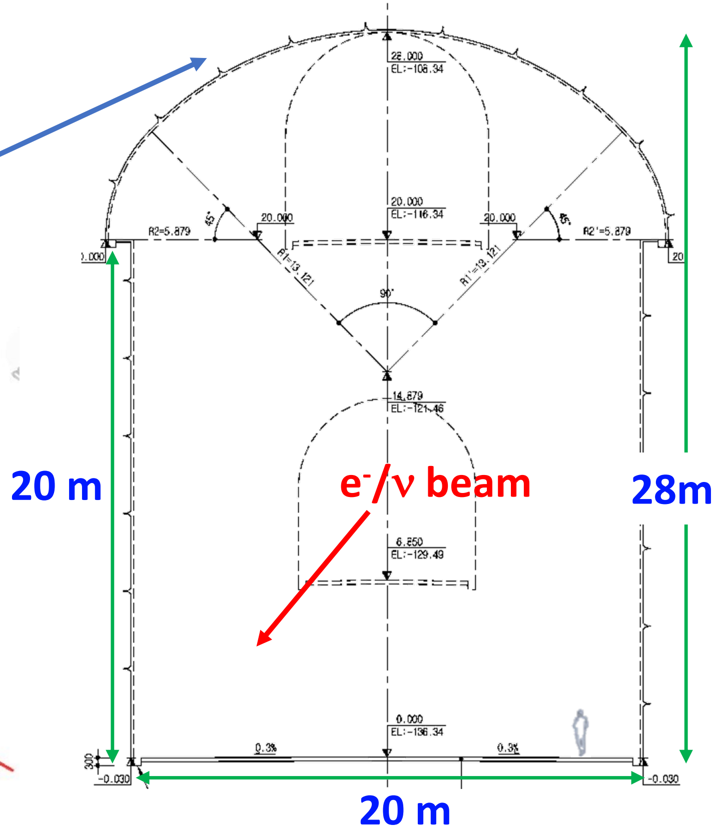
LSC = Liquid Scintillation Counter

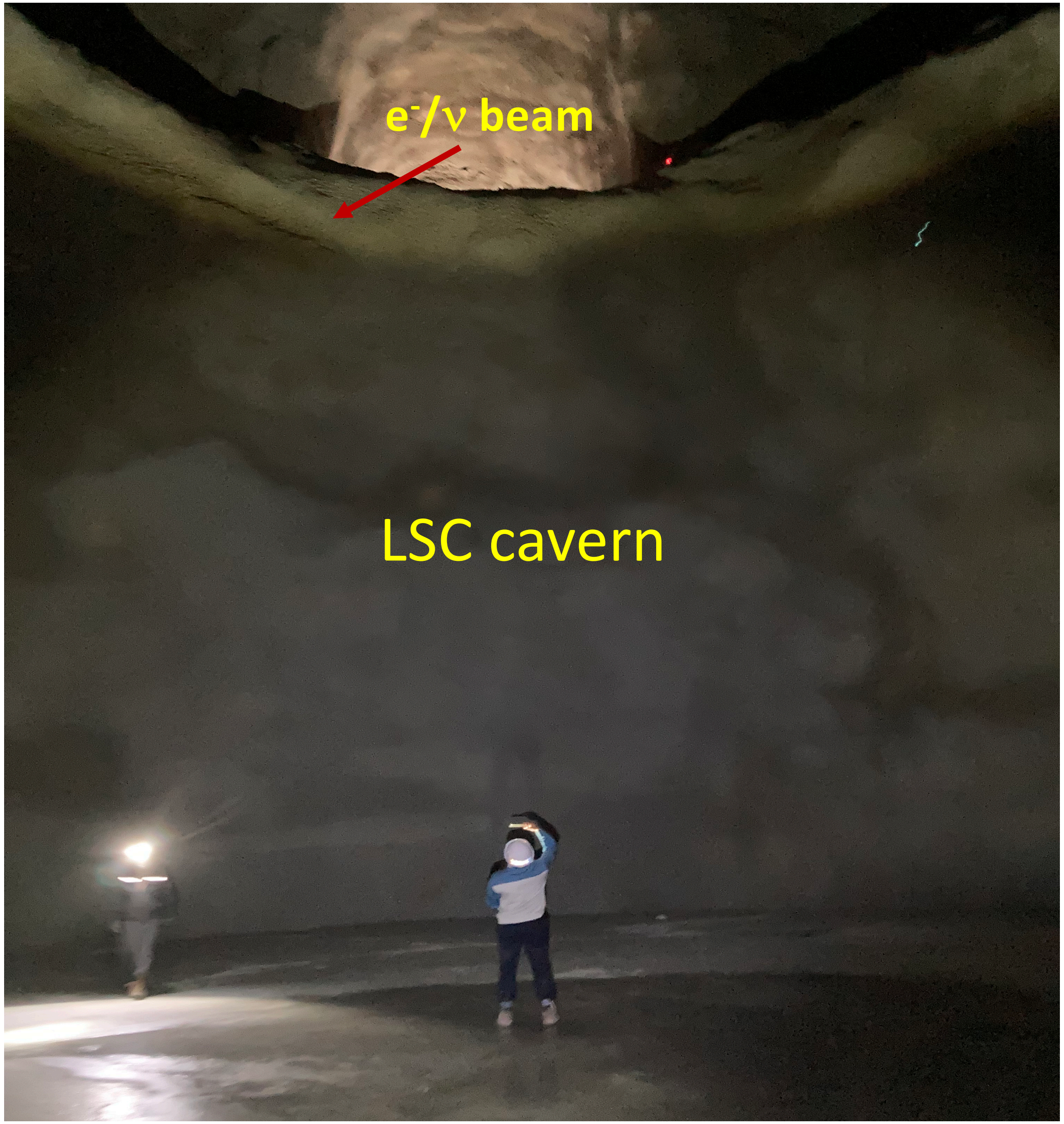
LSC Pit: 20 m (D) x 20 m (H)

**LSC Hall construction:
June 2021 – Feb. 2022**



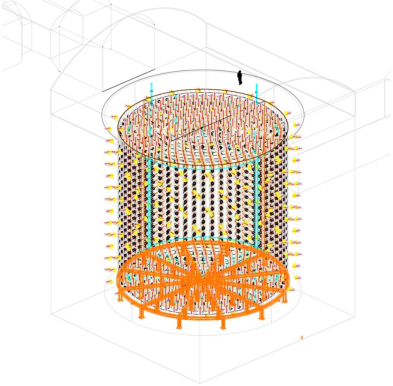
LSC Hall

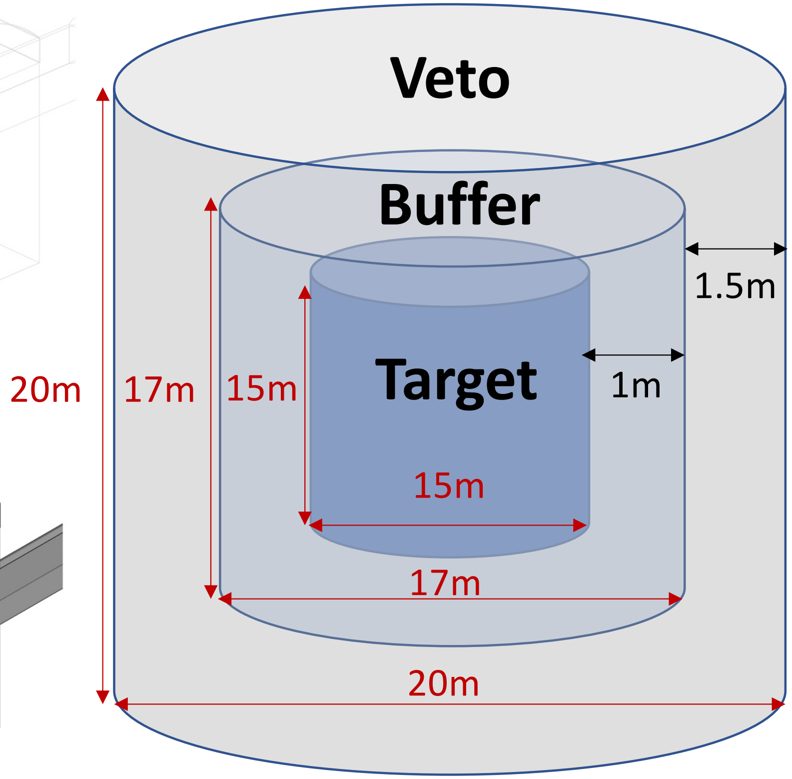



e^-/ν beam
LSC cavern

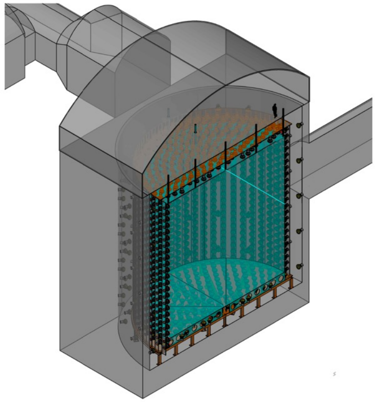

LSC cavern
Oct. 5, 2022
e^-/ν beam

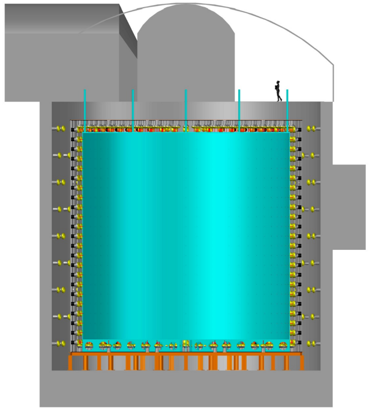
Candidate Detector Design





Target: **2.26 kton LS**
Buffer: 1.14 kton mineral oil
Veto: 2.41 kton water





1200(1800,2400) x 20 inch PMTs = 20% (30, 40)% coverage

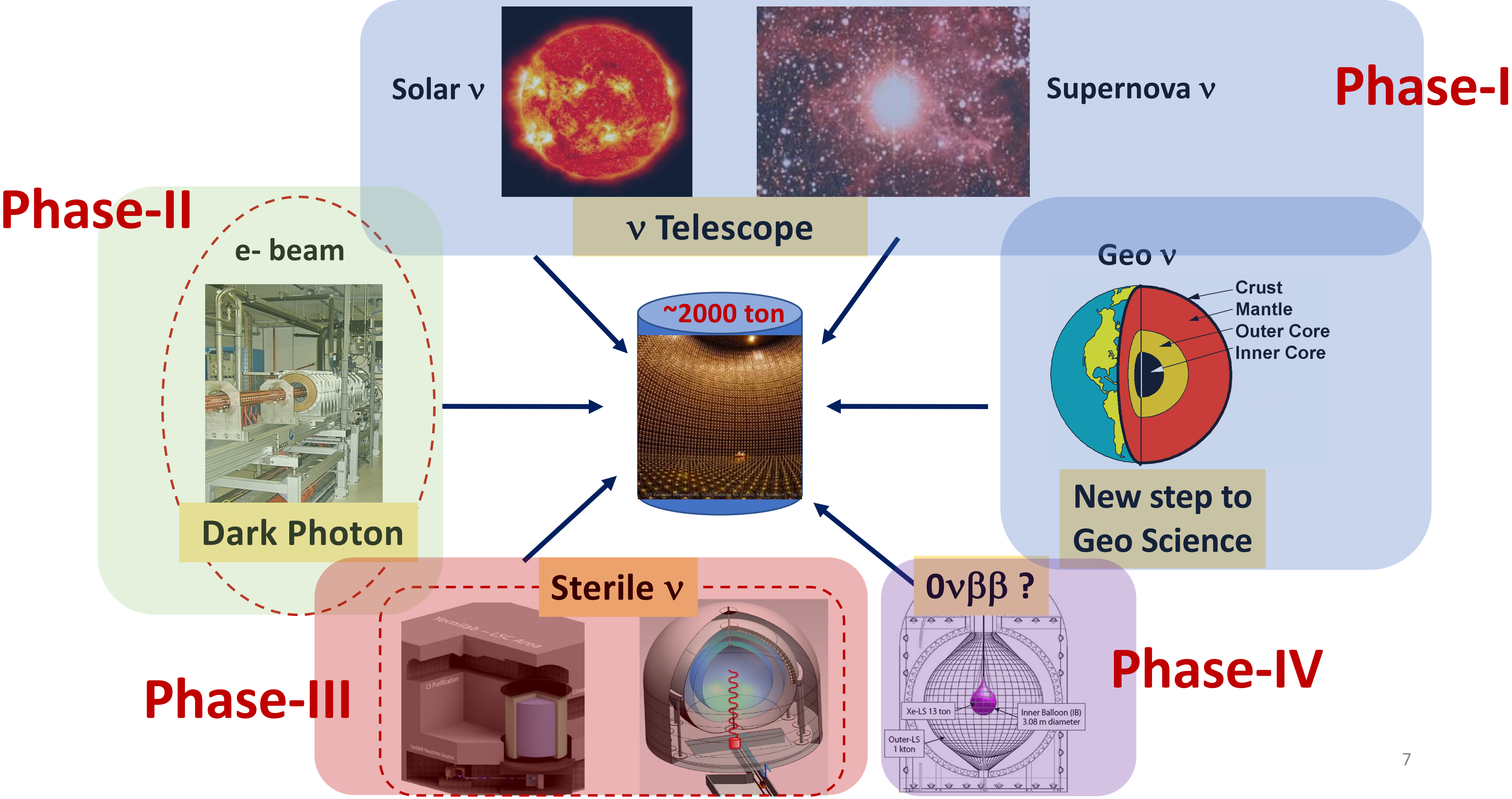
Why LS Detector?

❑ Light yield of LS is high.

→Good energy resolution, low threshold of energy
→Good for physics at O(1~10 MeV)

- ✓ Discovery of neutrino in 1956 was done using LS detector by **Reines and Cowan**'s team.
- ✓ θ_{13} in PMNS matrix was discovered using LS detectors in 2012 by **Daya Bay** & **RENO**.
- ✓ Many sterile neutrino search experiments using reactors use LS detector (**NEOS**, **PROSPECT, STEREO** etc).
- ✓ **Borexino** solar ν experiment used LS detector.
- ✓ **JUNO** is a LS detector to determine ν mass ordering.

Broad Physics Program



Phase-I

Solar ν

Supernova ν

ν Telescope

Geo ν

New step to Geo Science

~2000 ton

Phase-II

e- beam

Dark Photon

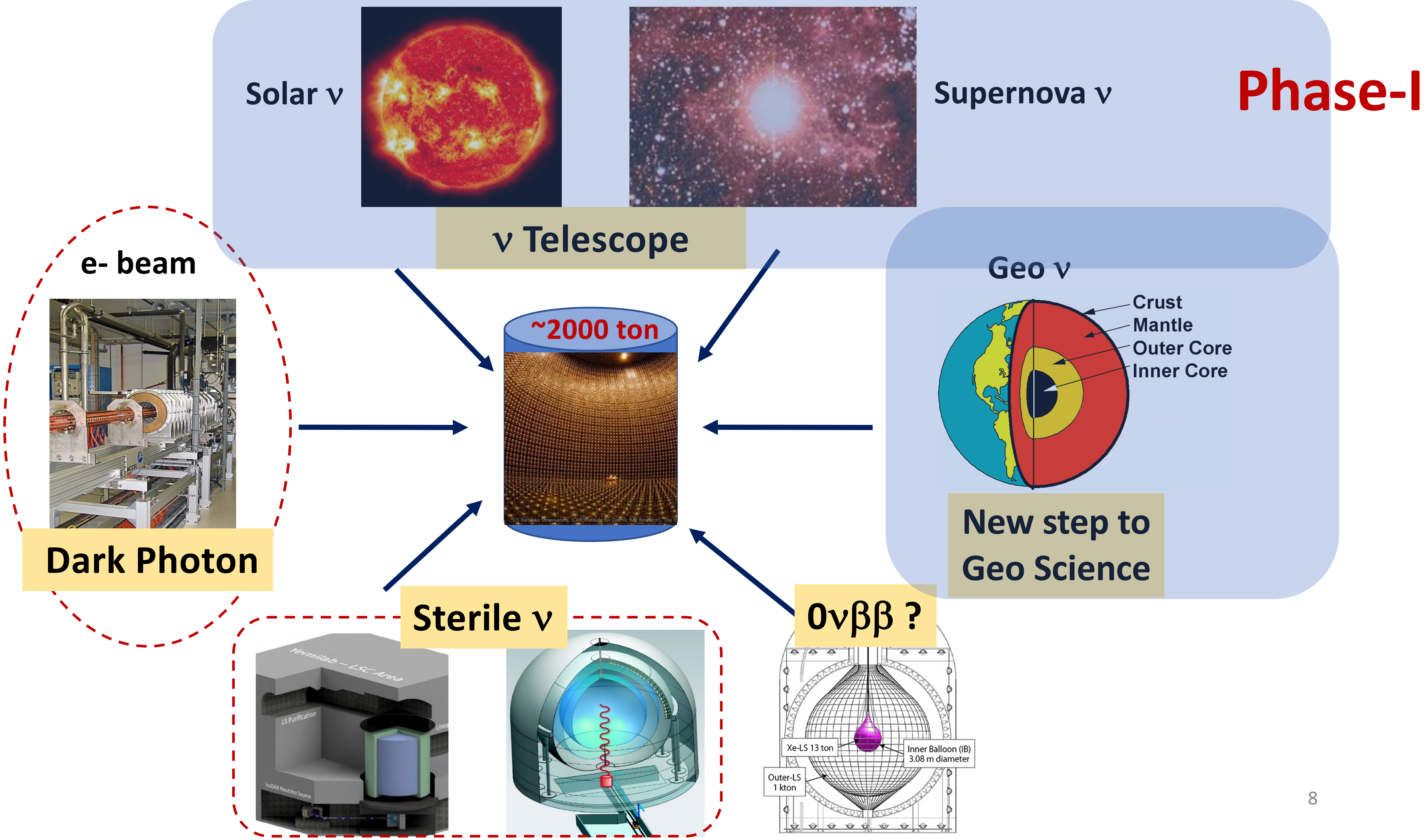
Phase-III

Sterile ν

Phase-IV

0νββ ?

Broad Physics Program



Phase-I

Solar ν

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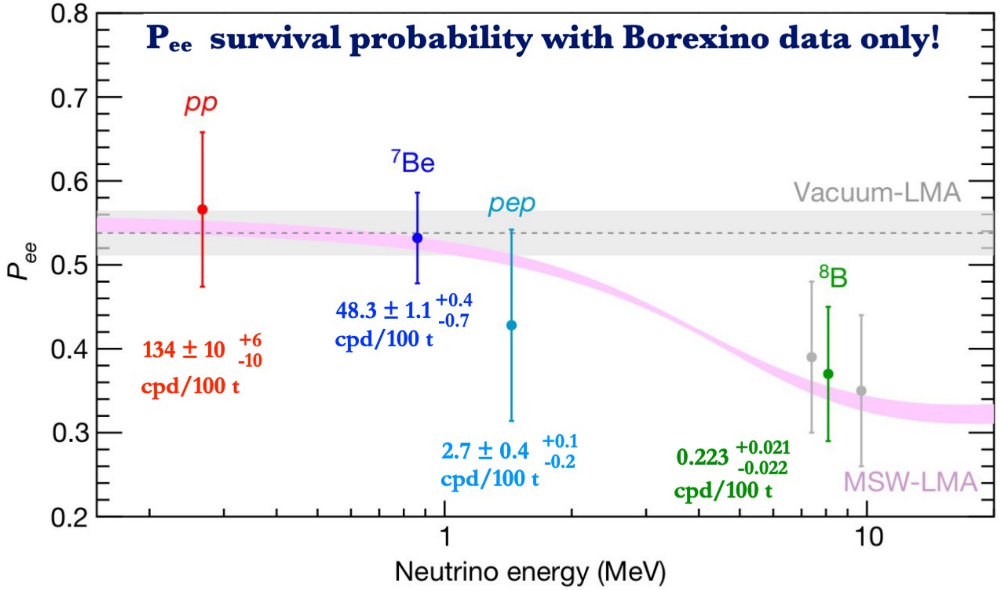
0νββ ?

❖ Borexino Solar Neutrino Measurements

Source	Count Rate [cpd/100t/d]	Comments on detection	First detection in BX
^{7}Be	~ 48	Clear signature on the shoulder	2007
^{8}B	< 1	Small, but high energy, low background	2010
pep	~ 3	Weak signature on top of ^{11}C	2012
pp	~ 140	Low energy, partially covered by ^{14}C	2014
CNO	~ 5	Small signal, migrating background (see talk)	2020
hep	Not measurable today	Signal too low, mostly covered by ^{8}B	never



Comprehensive chain:
Nature 562 (2018) 7728, 505.
Phys. Rev. D (2019)

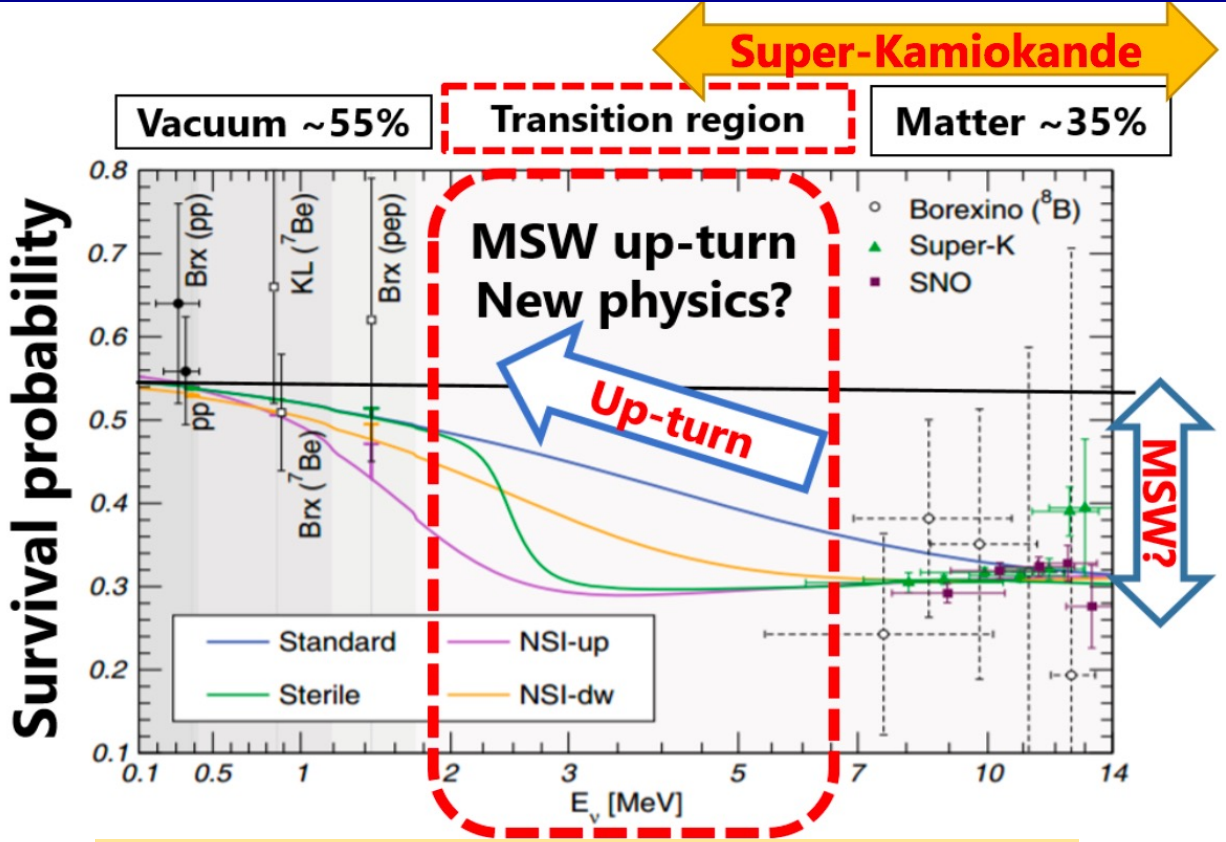
pp:
Nature 512 (2014) 7515, 383.

^{7}Be:
Phys. Lett. B658 (2008) 101
PRL 107 (2011) 141302

pep:
PRL 108 (2012) 051302

^{8}B:
Phys. Rev. D82 (2010) 033006

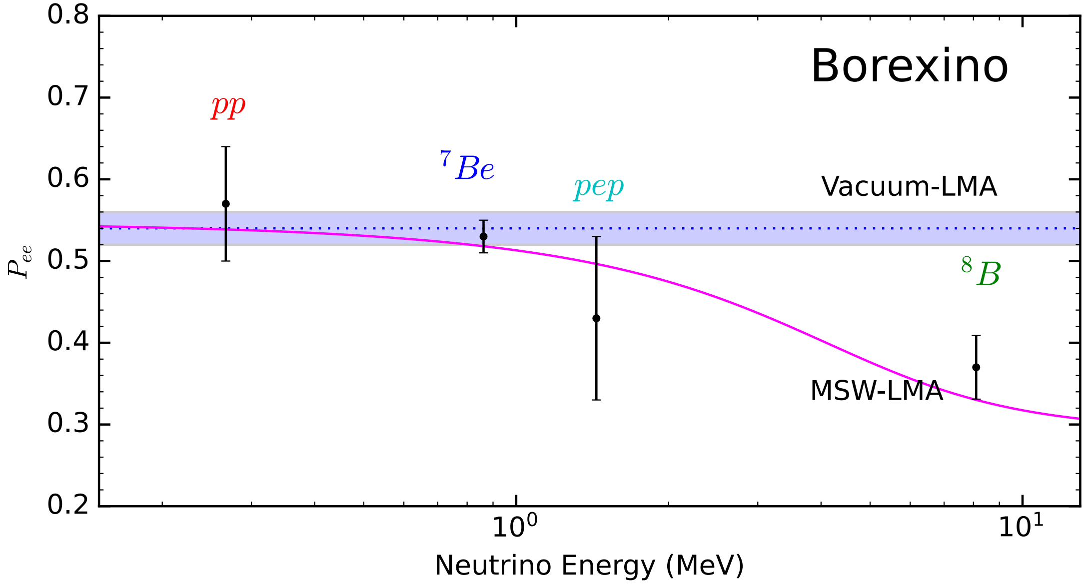
New Physics with Solar Neutrinos ?

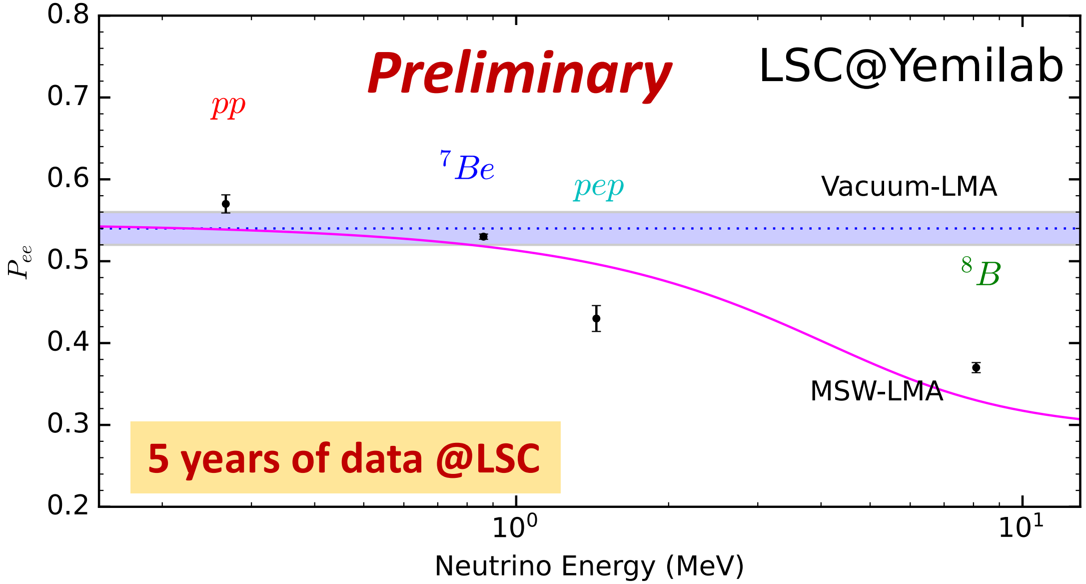


❑ Reduction of error bars by LSC detector
→ sensitive to new physics search

This is possible by making LSC "Bigger & Better" than Borexino detector

Solar Neutrinos





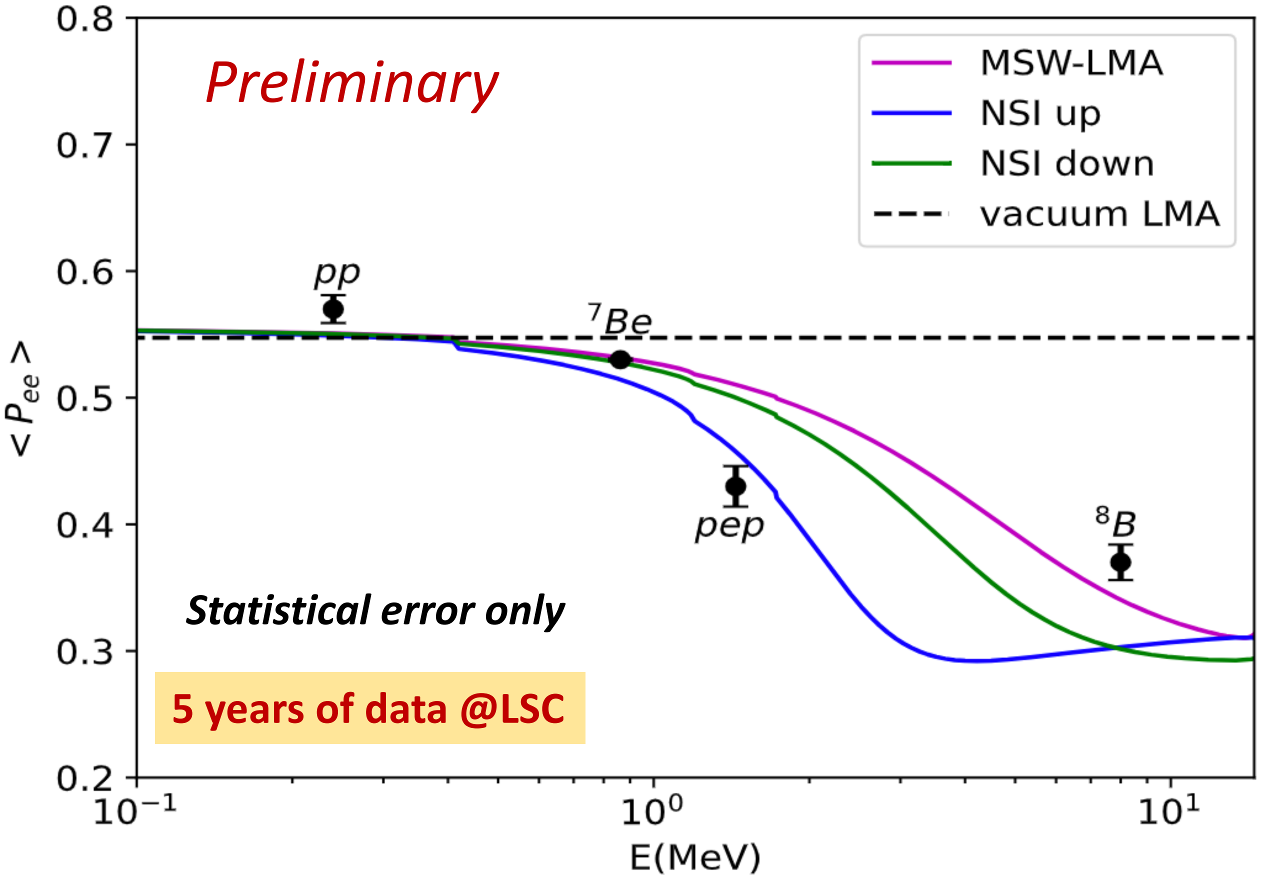
5 years of data @LSC

→ Shows Statistical Error Only.

Huge Reduction
of
Statistical Error!

Searching for BSM
would be possible!

If systematic uncertainties
are well in control.



Borexino-measured values are used with LSC statistical error.

Solar Metallicity (Z)

The mass abundance of **metals**
(all elements heavier than He)

Year	1998	2009	2011	2021	2022
Model	GS98	AGS09met	Caffau11	AGG21	MB22
Z/X	0.023	0.018	0.0209	0.0187	0.0225
	HZ	LZ	LZ	LZ	HZ

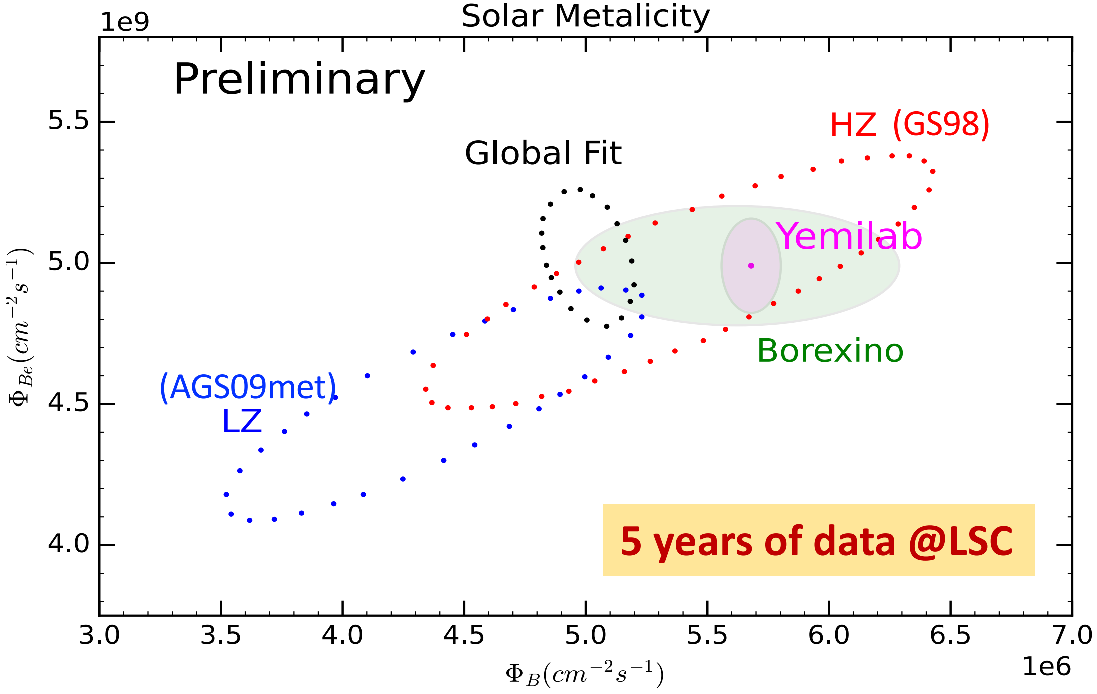
FLUX	Dependence on T	SSM-/HZ [1]	SSM-/LZ[2]	DIFF. (HZ-LZ)/HZ
pp (10^{10} cm^{-2} s^{-1})	$T^{-0.9}$	5.98(1±0.006)	6.03(1±0.005)	-0.8%
pep (10^{8} cm^{-2} s^{-1})	$T^{-1.4}$	1.44(1±0.01)	1.46(1±0.009)	-1.4%
^{7}Be (10^{9} cm^{-2} s^{-1})	T^{11}	4.94(1±0.06)	4.50(1±0.06)	8.9%
^{8}B (10^{6} cm^{-2} s^{-1})	T^{24}	5.46(1±0.12)	4.50(1±0.12)	17.6%
^{13}N (10^{8} cm^{-2} s^{-1})	T^{18}	2.78(1±0.15)	2.04(1±0.14)	26.6%
^{15}O (10^{8} cm^{-2} s^{-1})	T^{20}	2.05(1±0.17)	1.44(1±0.16)	29.7%

pp chain

CNO cycle

> "Even a very small fraction of metals is sufficient to alter the behavior of a star completely."

- Impact the fate of a start:
  size, temperature, brightness, lifespan, etc.
- Solar metalicity becomes a standard for other stars' metalicity.

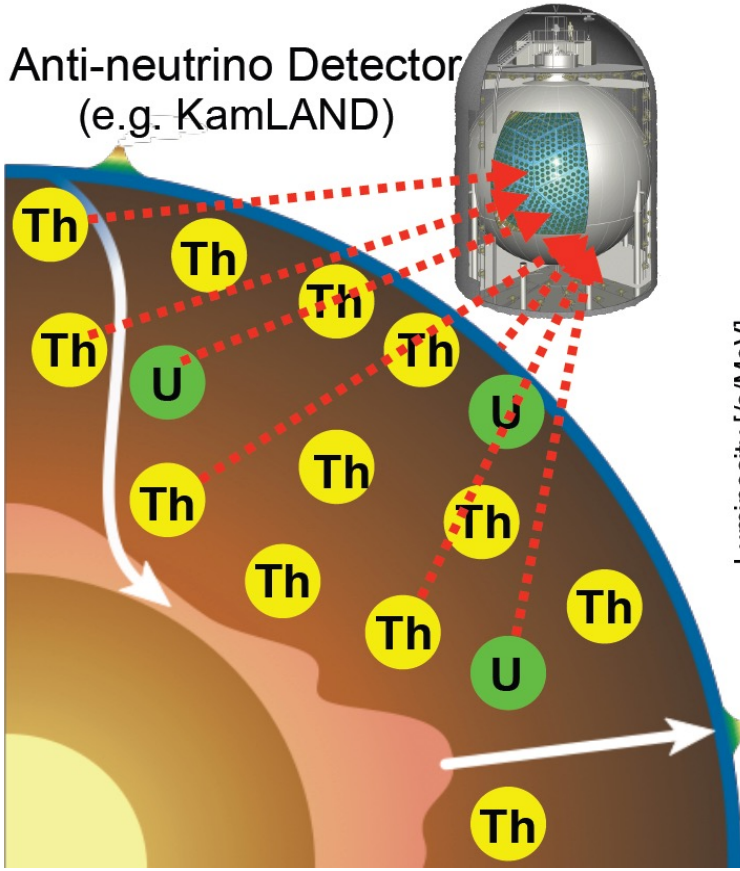


Geo Neutrinos

Electron-antineutrinos from natural radioactive decays

Watanabe
2021

$\bar{\nu}_e \;\; 4.1 \times 10^6/\mathrm{cm}^2/\mathrm{sec}$



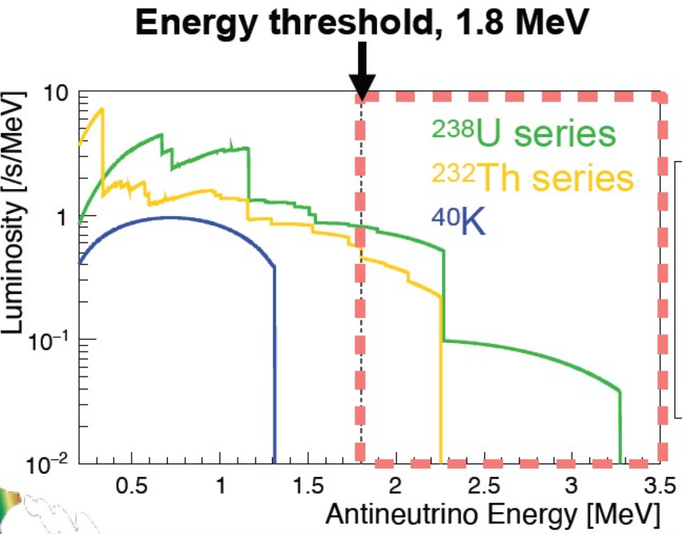
β-decay

geo-neutrinos

$$^{238}\mathrm{U} \rightarrow {}^{206}\mathrm{Pb} + 8\alpha + 6\mathrm{e}^- + 6\bar{\nu}_\mathrm{e} + 51.7\,\mathrm{MeV}$$

$$^{232}\mathrm{Th} \rightarrow {}^{208}\mathrm{Pb} + 6\alpha + 4\mathrm{e}^- + 4\bar{\nu}_\mathrm{e} + 42.7\,\mathrm{MeV}$$

$$^{40}\mathrm{K} \rightarrow {}^{40}\mathrm{Ca} + \mathrm{e}^- + \bar{\nu}_\mathrm{e} + 1.311\,\mathrm{MeV}\,(89.28\%)$$



inverse β-decay

$$\bar{\nu}_e + p \rightarrow e^+ + n$$

- *Only geo-neutrinos from U and Th are detectable right now
- *^{40}K geo-neutrino detection needs another technology.

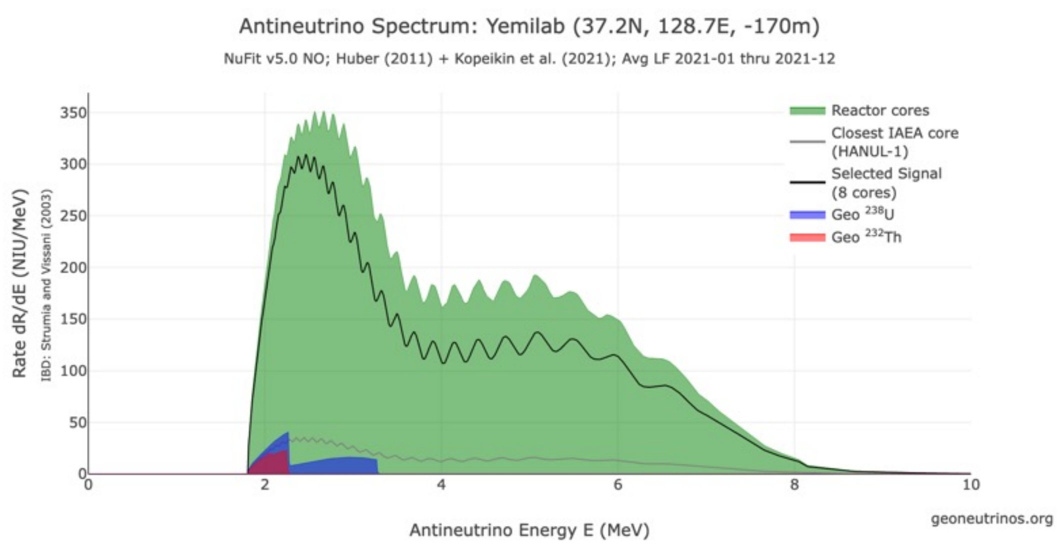
Number of geo $\bar{\nu}_e \propto$ amount of U Th, **radiogenic heat**

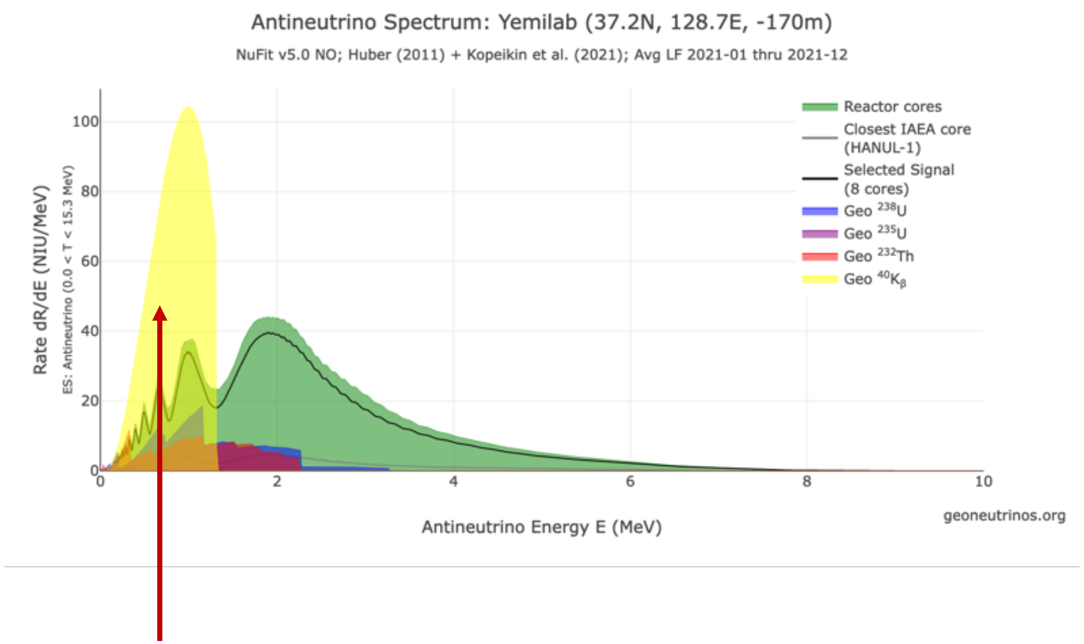
Geo & Reactor ν Estimations at LSC

IBD channel

Preliminary

eES channel



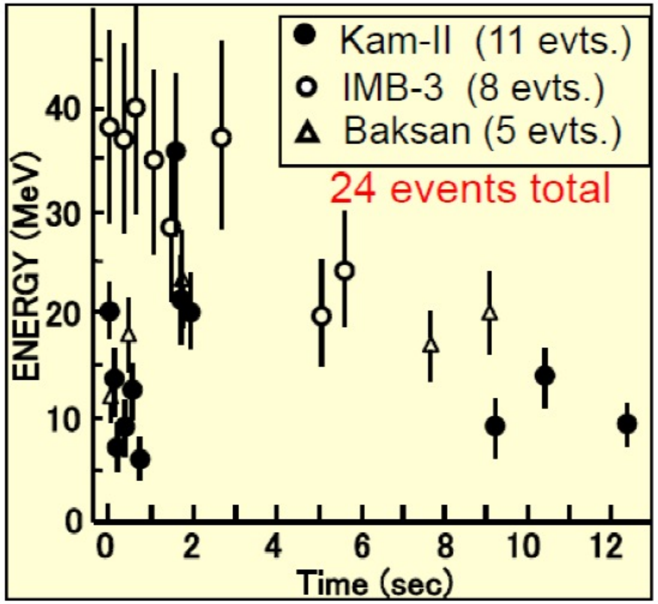


Geo-neutrinos: 60.6 ± 13.6 IBD/year
Reactor-neutrinos: 460 ~ 1500 IBD/year

Geo-neutrinos are enhanced in this channel.

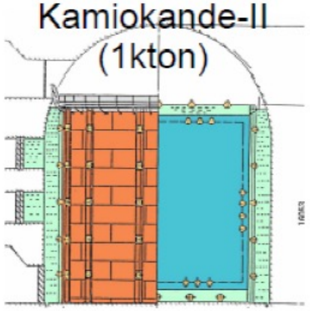
SN 1987A @Large Magellanic Cloud

7:35 (UT), Feb. 23, 1987, at 50kpc

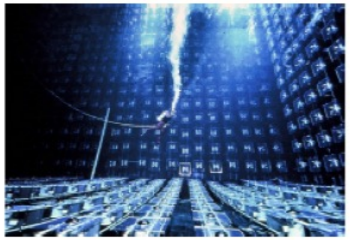


Water Cherenkov

Kamiokande-II
(1kton)

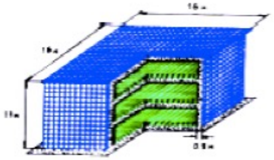


IMB-3 (8kton)



Liquid Scintillator

Baksan



First observation of SN neutrinos → Nobel prize 2002

(Koshiba & Kamiokande)

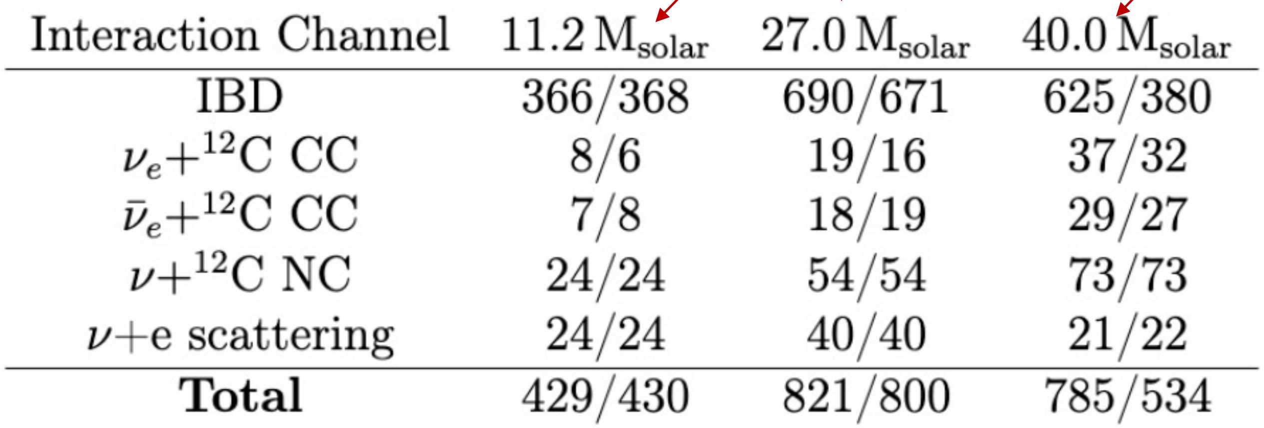
We need more precise measurement w/ more statistics.

Supernova Burst ν Estimations @ 10 kpc

Preliminary

Forming
Netron star

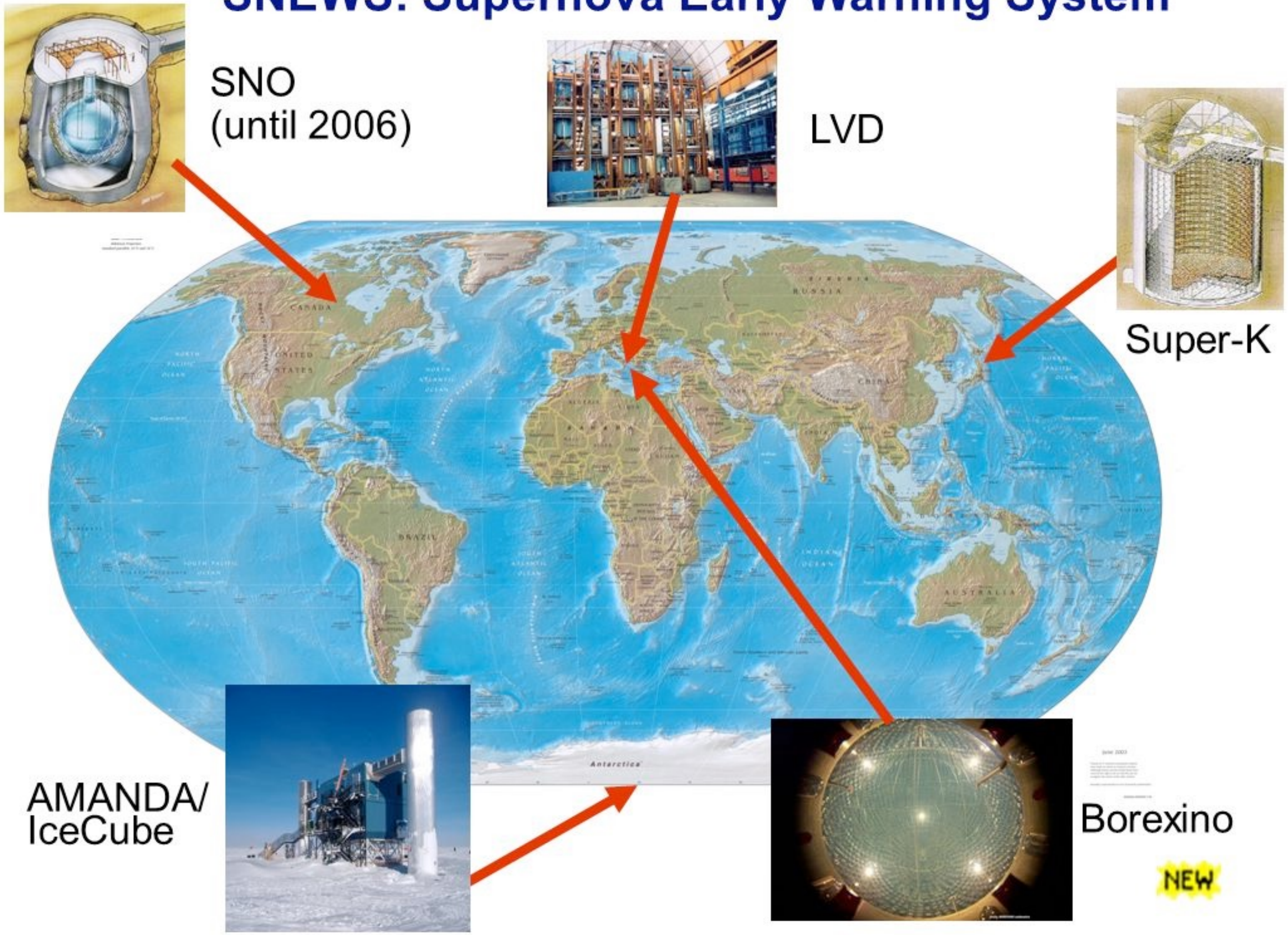
Forming
Blackhole



Interaction Channel	11.2 M_{solar}	27.0 M_{solar}	40.0 M_{solar}
IBD	366/368	690/671	625/380
ν_e+^{12}C CC	8/6	19/16	37/32
$\bar{\nu}_e$+^{12}C CC	7/8	18/19	29/27
ν+^{12}C NC	24/24	54/54	73/73
ν+e scattering	24/24	40/40	21/22
Total	429/430	821/800	785/534

- LSC is expected to observe 430~820 ν events from SN burst at 10 kpc.

SNEWS: Supernova Early Warning System



SNO
(until 2006)

LVD

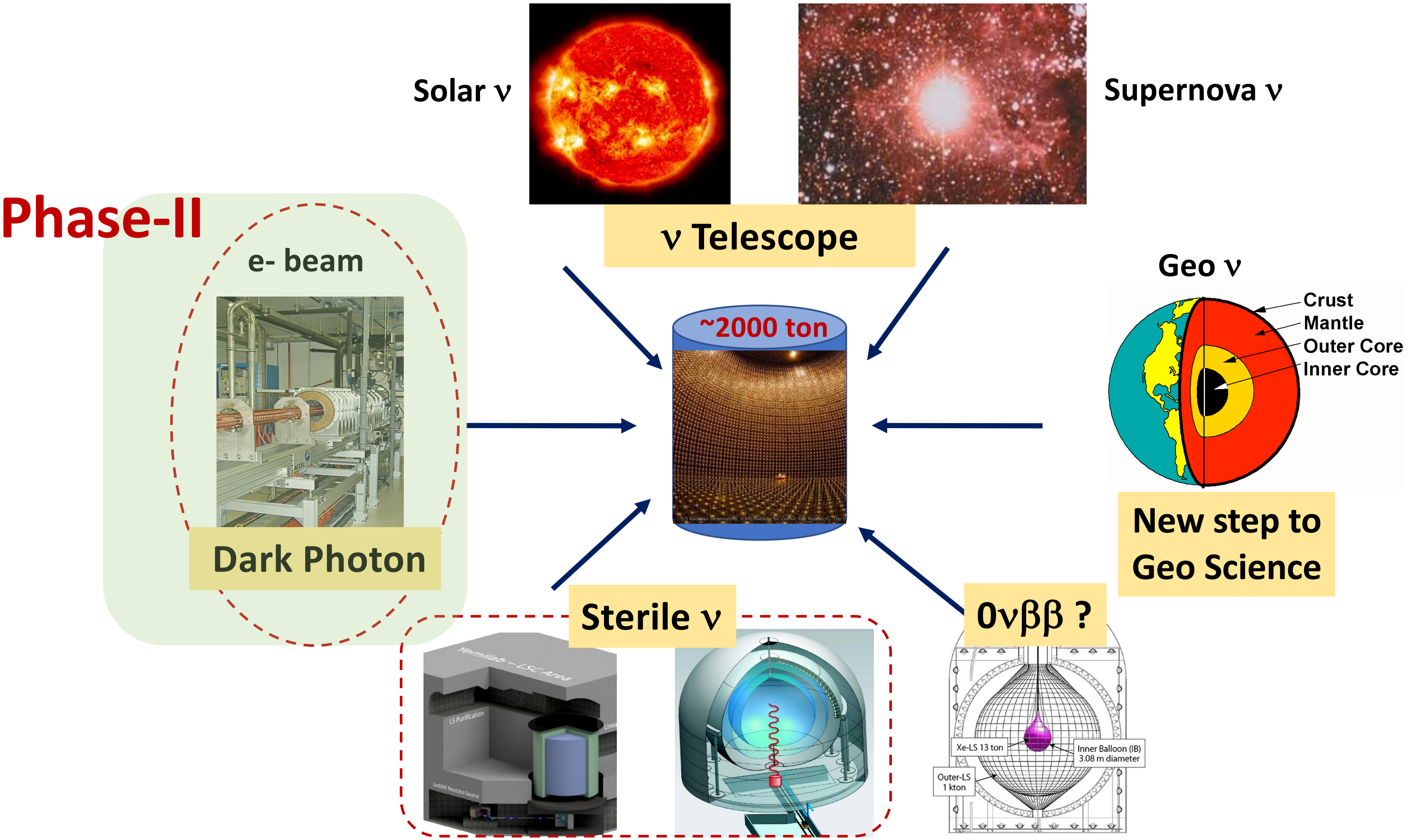
Super-K

AMANDA/
IceCube

Borexino

NEW

Broad Physics Program



Solar ν

Supernova ν

ν Telescope

Phase-II

e- beam

Dark Photon

~2000 ton

Geo ν

New step to Geo Science

Sterile ν

0νββ ?

Dark Photon (DP) *ϕ, γ', A'*

❖ DP is the simpleset and most popular hypothetical particle in a dark sector.

- DP can mediate interaction w/ dark matter.
- DP itself can be a candidate of dark matter.
- DP can be searched via vector portal.

$$\boxed{\mathcal{L} \supset -\frac{1}{4}F'_{\mu\nu}F'^{\mu\nu} + \frac{\epsilon}{2}F'_{\mu\nu}F^{\mu\nu} + \frac{m_\phi^2}{2}A'_\mu A'^\mu}$$

DP field strength tensor

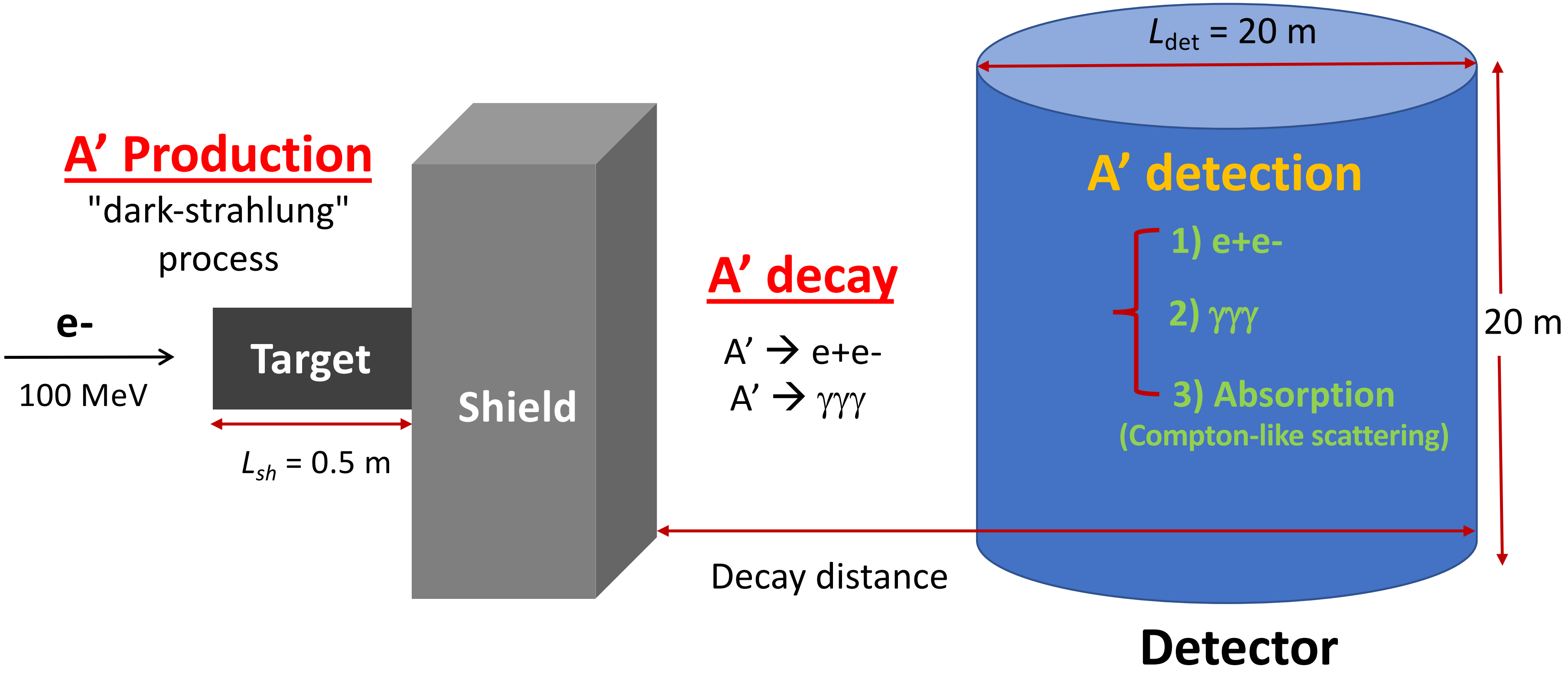
$U(1)_D$ gauge field

ε: "kinetic mixing" parameter

Dark Photon Search Scheme w/ LSC

- **Currently, no DP search experiments at underground.**

Izaguirre, Krnjaic, Pospelov, PRD 92, 095014 (2015)



Expected # of Dark Photons

- ☐ **Production: “dark-strahlung”**
- ☐ **Detection : *A’ → e+e- or 3γ, or A’ absorption***

DP production x-section

$$N_\phi \approx \frac{N_e X}{M} \int_{E_{\min}}^{E_0} dE \int_{x_{\min}}^{x_{\max}}$$

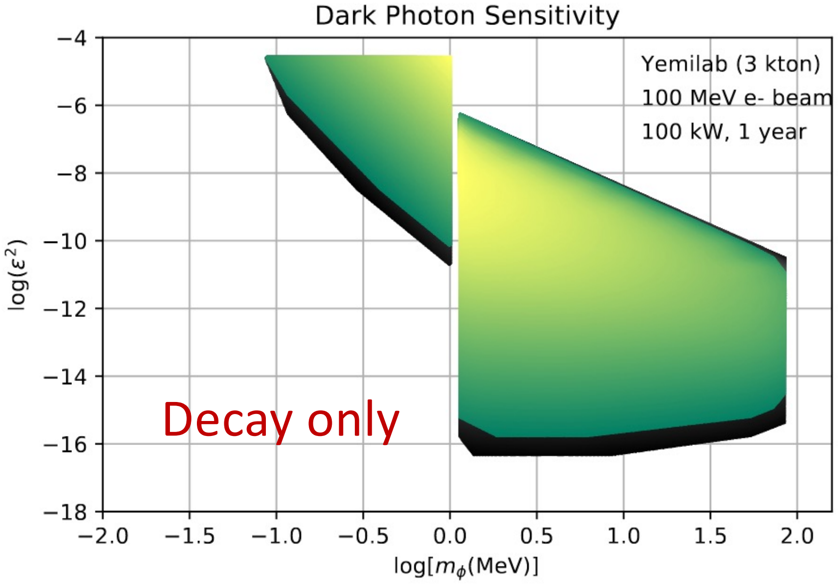
$$\times dx \int_0^T dt I_e(E_0, E, t) \frac{d\sigma}{dx} e^{-L_{\mathrm{sh}}\left(\frac{1}{l_\phi}+\frac{1}{\lambda}\right)} \underbrace{\left(1 - e^{-L_{\mathrm{dec}}/l_\phi}\right)}_{\text{only decay signal}}$$

Liu & Miller: PRD 96, 016004 (2017)

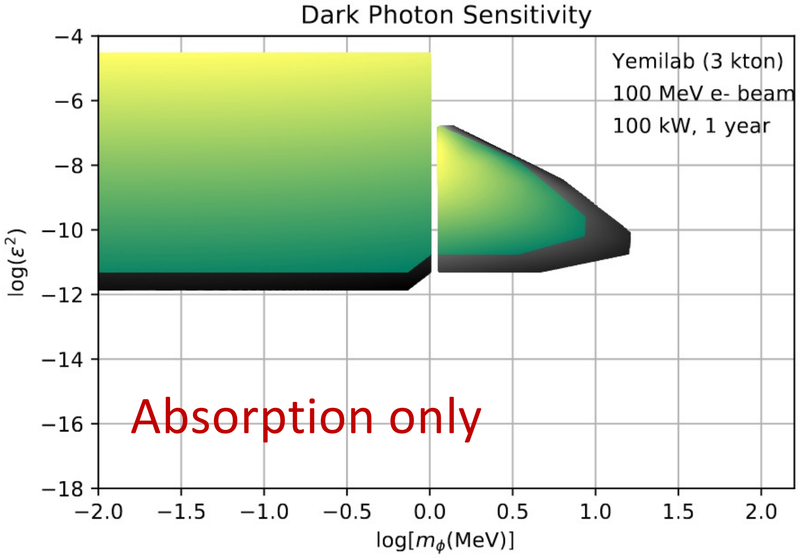
We should add an additional term of DP absorption signal to decay signal.

$$\underbrace{\boxed{x[1 - \exp(- L_{dec}/l_\phi - L_{det}/\lambda_{det})]}}_{\text{decay or absorption signal}}$$

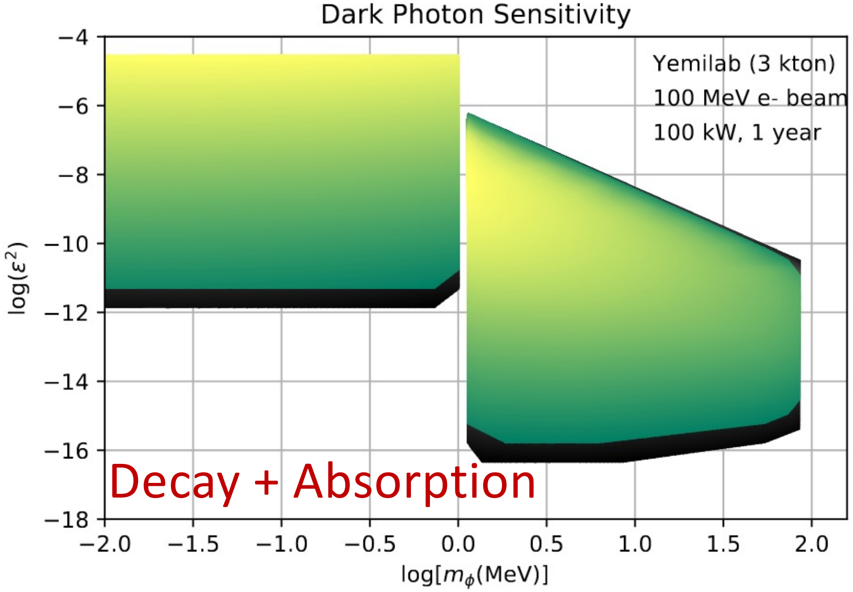
where,
L_{det}: detector length
λ_{det}: DP abs. length in detector



Decay only



Absorption only



Decay + Absorption

Rough Background Estimation

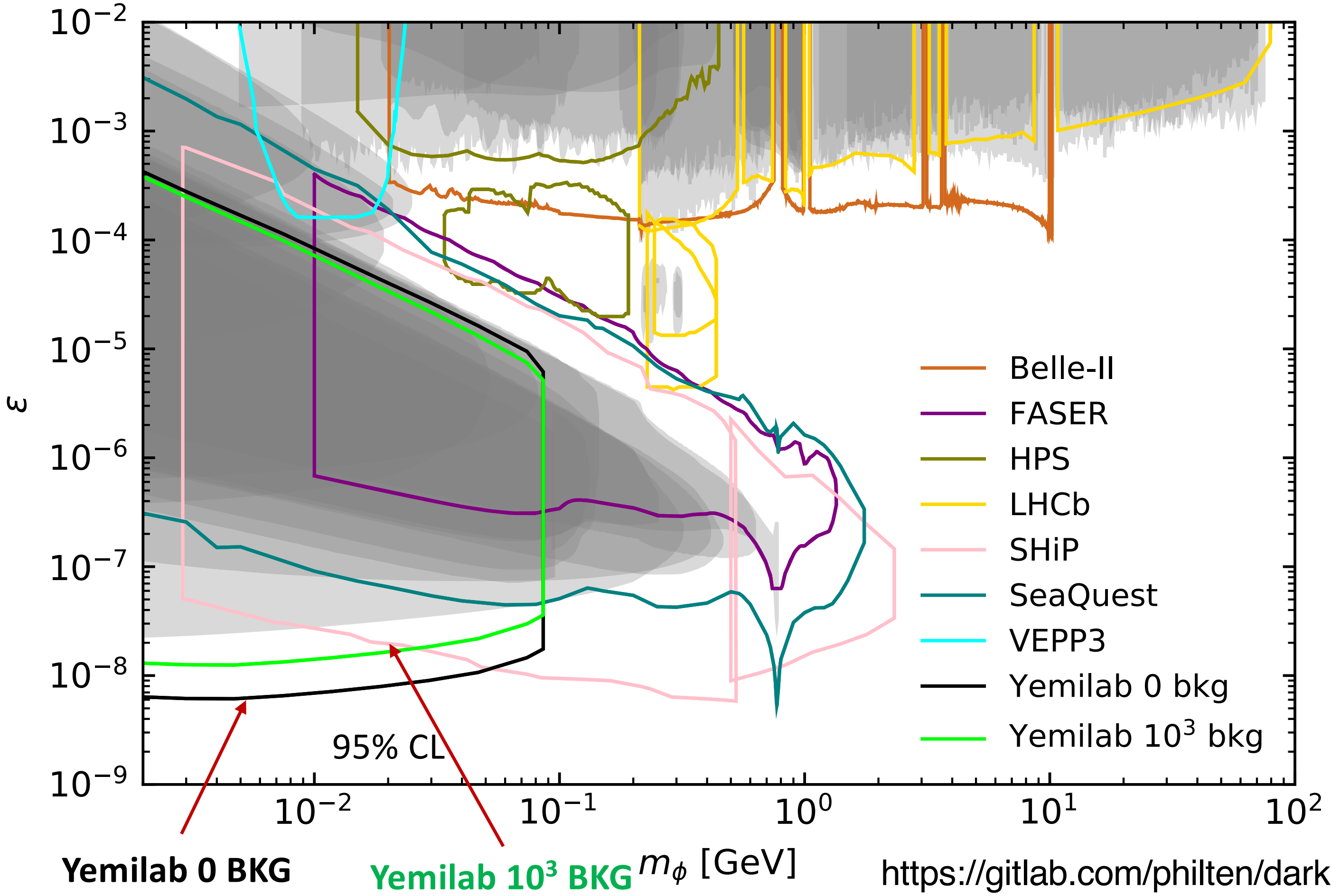
Signal = Beam (ON – OFF) data ~ 0 events

→ # of background events in beam OFF data can affect our sensitivity

Background types	**#. BKG events (/year/1 kton fiducial vol.)**	**Comments**
Solar ν (^{8}B), residual, external BKG	935	Estimated from Borexino arXiv:1709.00756
Atmospheric ν	67	Estimated from Borexino *J.Phys.Conf.Ser.* 675 (2016) 1, 012014
Neutrons from beam	0	Block w/ rocks (few meters) & 5 MeV cut
ν from beam	0	negligible
Total	1002	

Current Limits & Future Projections

S.H. Seo & Y.D. Kim
JHEP04(2021)135



Yemilab 0 BKG

Yemilab 10^3 BKG

https://gitlab.com/philten/darkcast

Best “direct” DP search sensitivity in $M_\phi < 30$ MeV (10^3 BKG)

$\gamma \rightarrow$ A’ Oscillations ($m_\phi < 1$ MeV)

- γ—> A’ oscillation @ target (**T**ungsten)

$$P(\gamma \to A') = \epsilon^2 \times \frac{{m_\phi}^4}{(\Delta m^2)^2 + E_\gamma^2 \Gamma^2},$$

1812.02719
1804.10777
1501.07292

- A’—> γ oscillation @ detector (**W**ater)

$$P(A' \to \gamma) = \epsilon^2 \times \frac{{m_\phi}^4}{(\Delta m^2)^2 + E_\gamma^2 \Gamma^2} \times \Gamma L,$$

where $\Delta m^2 = \sqrt{(m_\phi^2 - m_\gamma^2)^2 + 2\epsilon^2 m_\phi^2 (m_\phi^2 + m_\gamma^2)} \approx |m_\phi^2 - m_\gamma^2|, \; m_\gamma = \sqrt{4\pi\alpha n_e / m_e}$

$$\boxed{P(\gamma \leftrightarrow A') = \epsilon^4 \times \frac{m_\phi^8}{\left((m_\phi^2 - m_\gamma^{\mathrm{T}\,2})^2 + E_\gamma^2 \Gamma_{\mathrm{T}}^2\right) \times \left((m_\phi^2 - m_\gamma^{\mathrm{W}\,2})^2 + E_\gamma^2 \Gamma_{\mathrm{W}}^2\right)} \times \Gamma_{\mathrm{W}} L,}$$

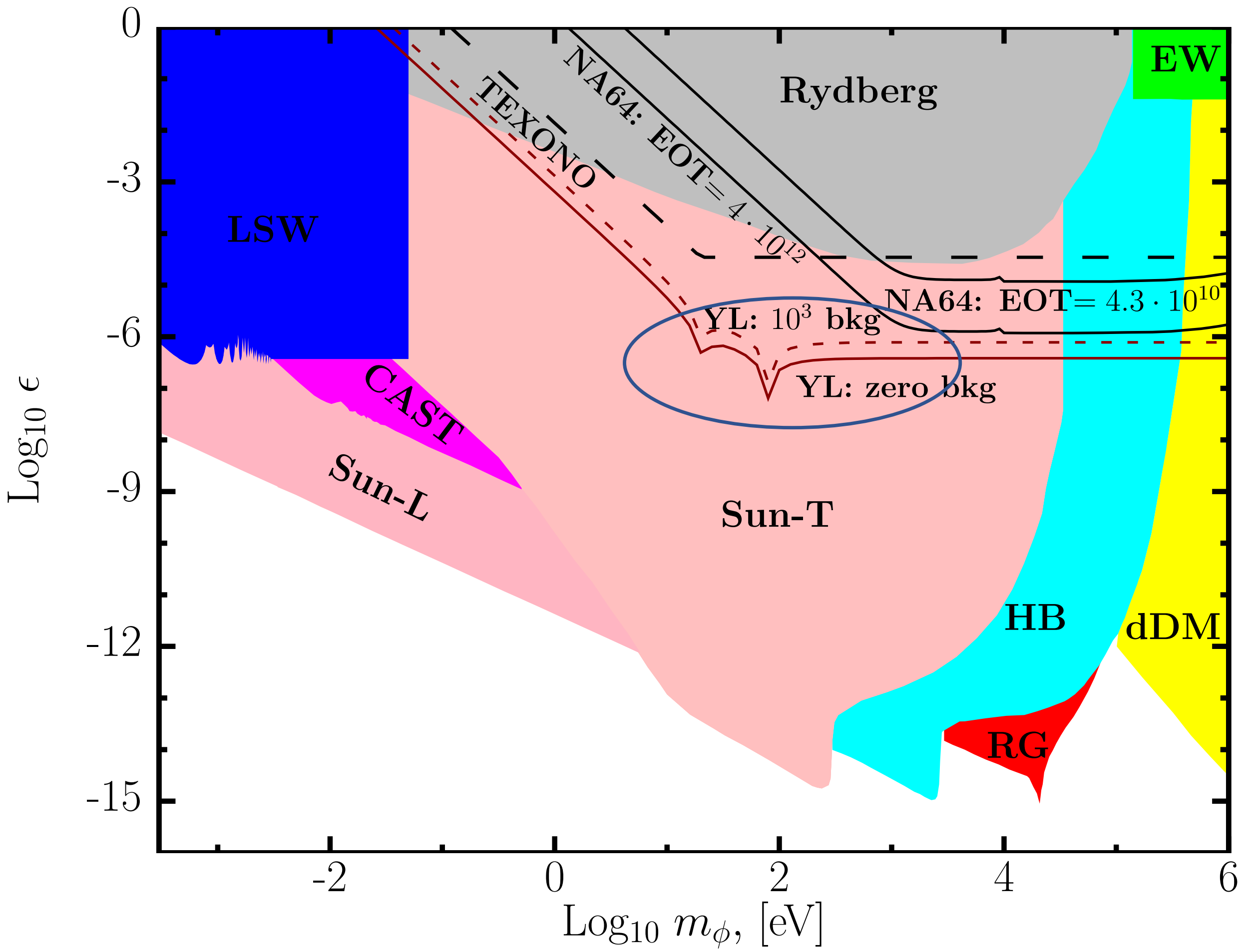
$$\boxed{N_\phi^{\mathrm{osc}} \approx N_{\mathrm{e}} \times \int_{E_\gamma^{\mathrm{min}}}^{E_\gamma^{\mathrm{max}}} dE_\gamma P(\gamma \leftrightarrow A') \int_0^T dt \left(I_\gamma^{(1)}(t, E_\gamma) + I_\gamma^{(2)}(t, E_\gamma) \right)}$$

Photon flux per electron

Tsai & Whitis, Phys.Rev. 149 (1966) 1248-1257

γ → A' Oscillation Sensitivity

S.H. Seo & Y.D. Kim
JHEP04(2021)135

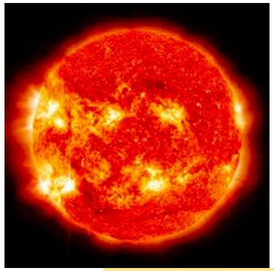


$m_{\phi} < 1$ MeV

Best "direct" DP search sensitivity at sub-MeV region

Broad Physics Program

Solar ν

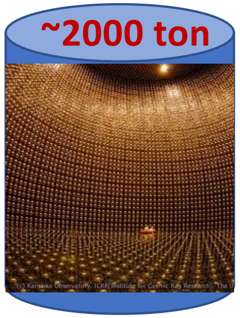


Supernova ν

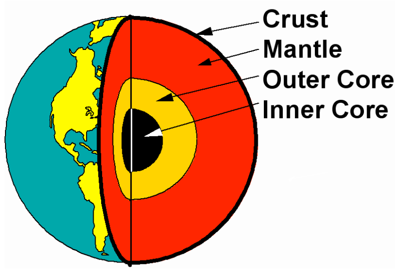
ν Telescope

e- beam

Dark Photon


~2000 ton

Geo ν

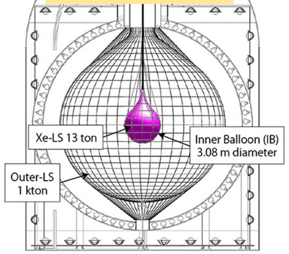


New step to Geo Science

Sterile ν

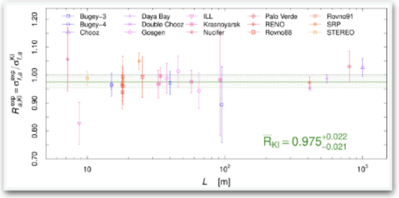
Phase-III

0νββ ?



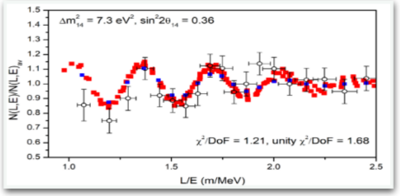
Short-Baseline Anomalies: Current Status

J. Kopp
@Nu2022



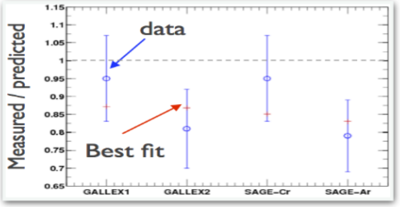
reactor flux anomaly
resolved with new input data
to flux calculation

✓



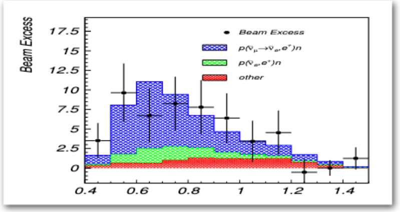
reactor spectra
is there really an anomaly?

?



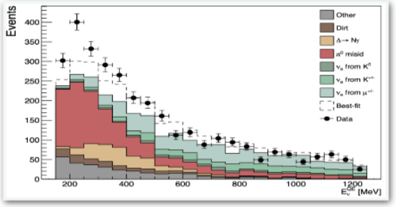
gallium anomaly
unresolved, recently reinforced

?



LSND
unresolved

?



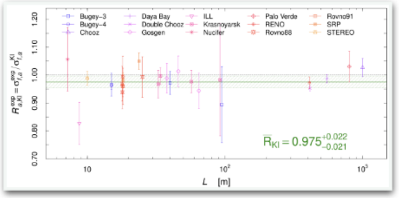
MiniBooNE
unresolved

?

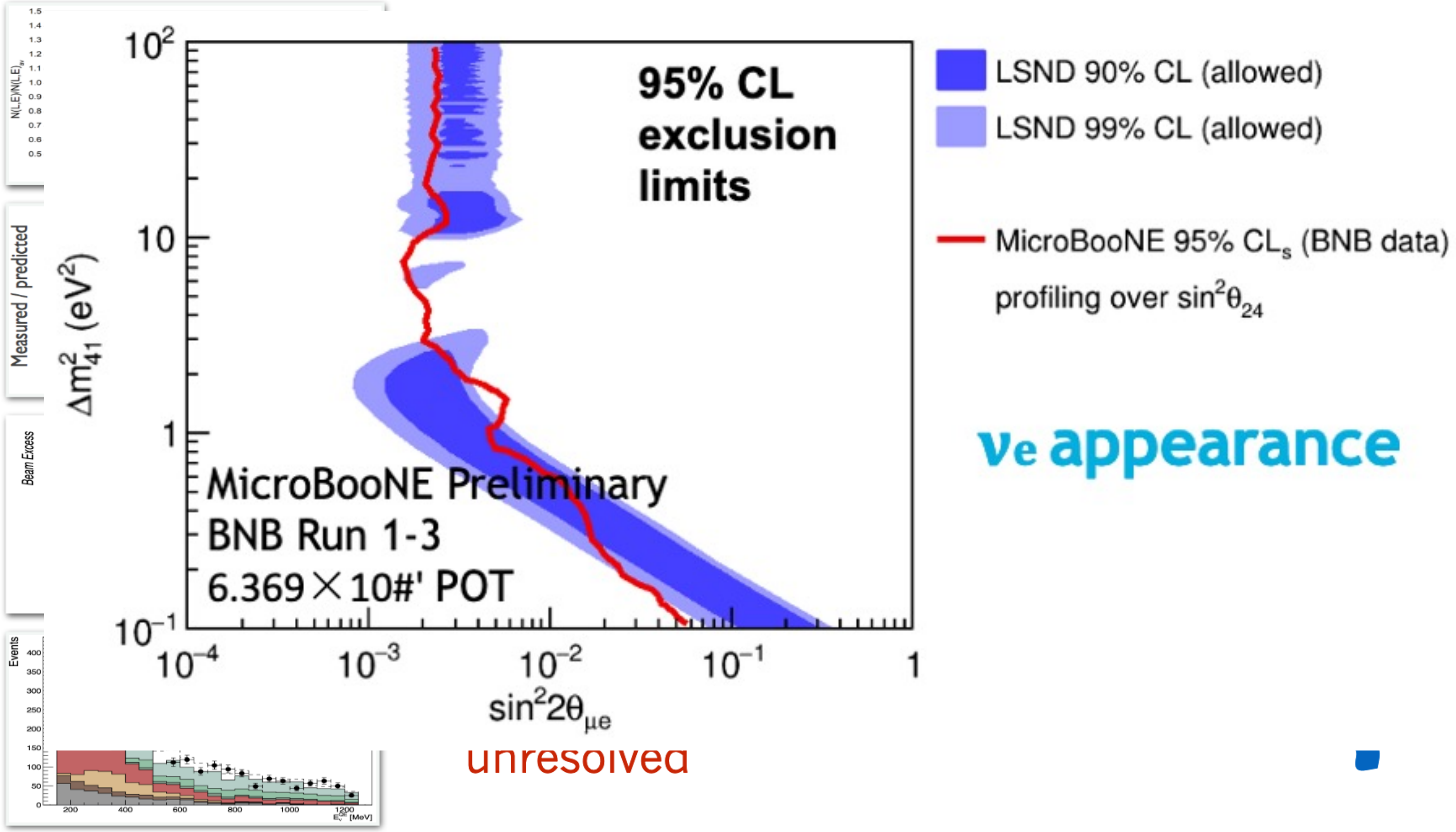
Still
unresolved

Short-Baseline Anomalies: Current Status

J. Kopp
@Nu2022



reactor flux anomaly
resolved with new input data
to flux calculation



ν_e appearance

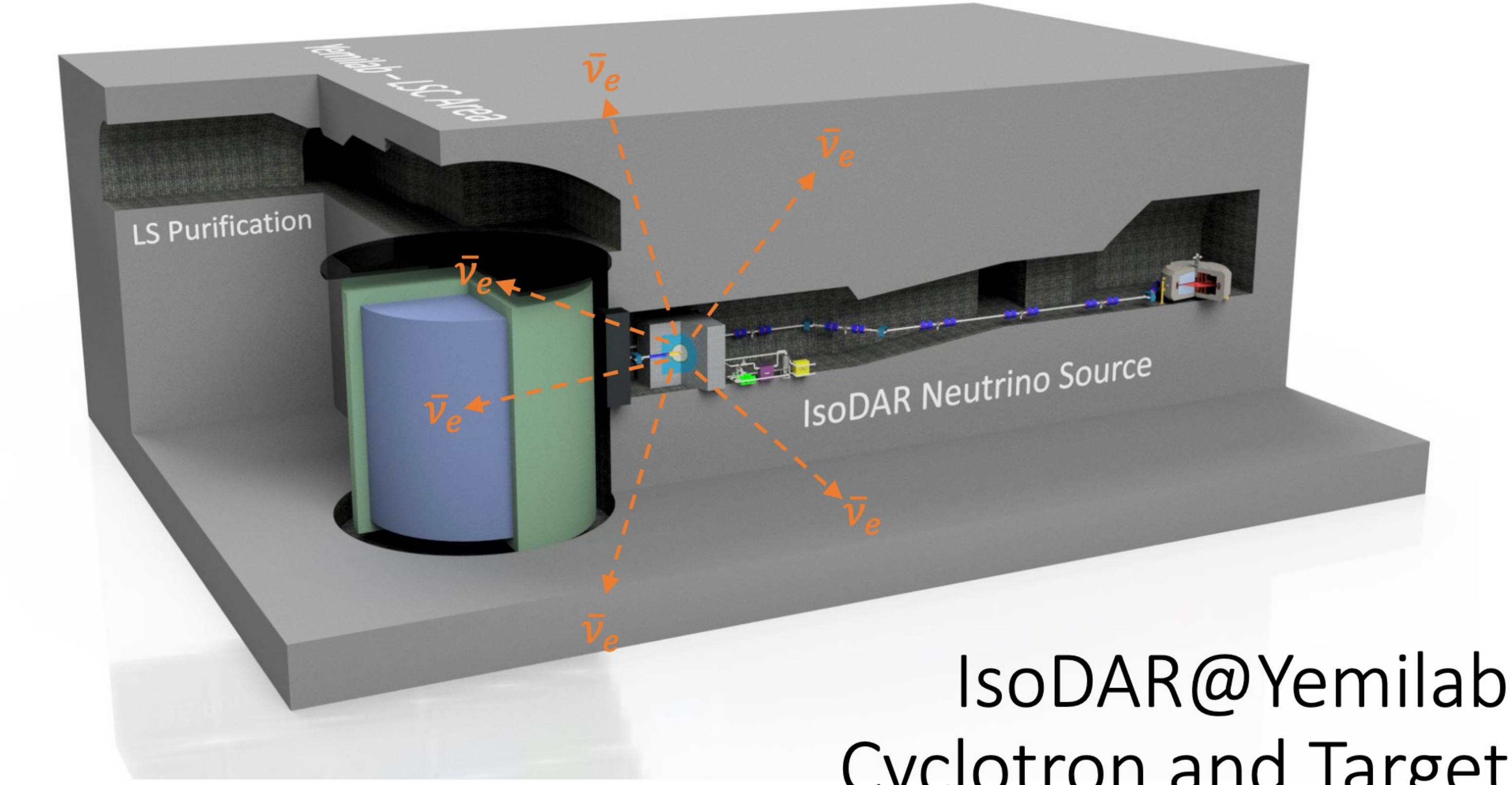
unresolved

Still unresolved

[1] Sterile neutrino search with IsoDAR @Yemilab

Isotope **D**ecay **A**t **R**est

→ This method has never been tried!

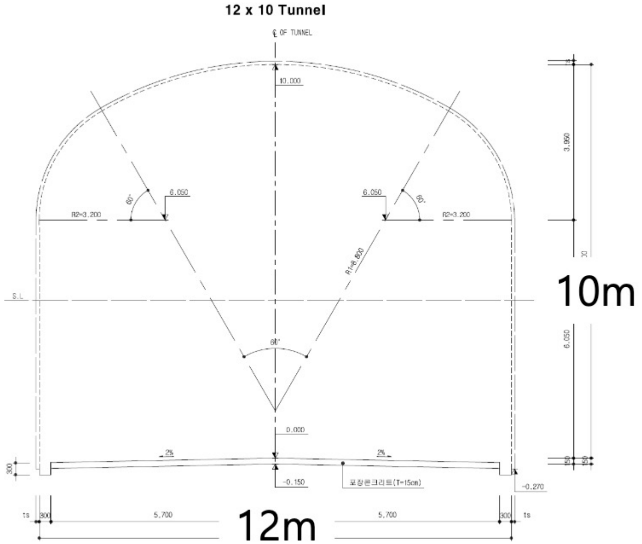


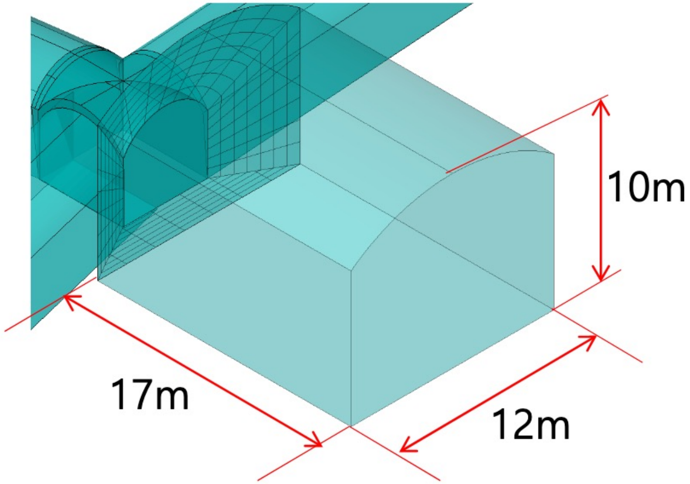
IsoDAR@Yemilab
Cyclotron and Target

Publications:

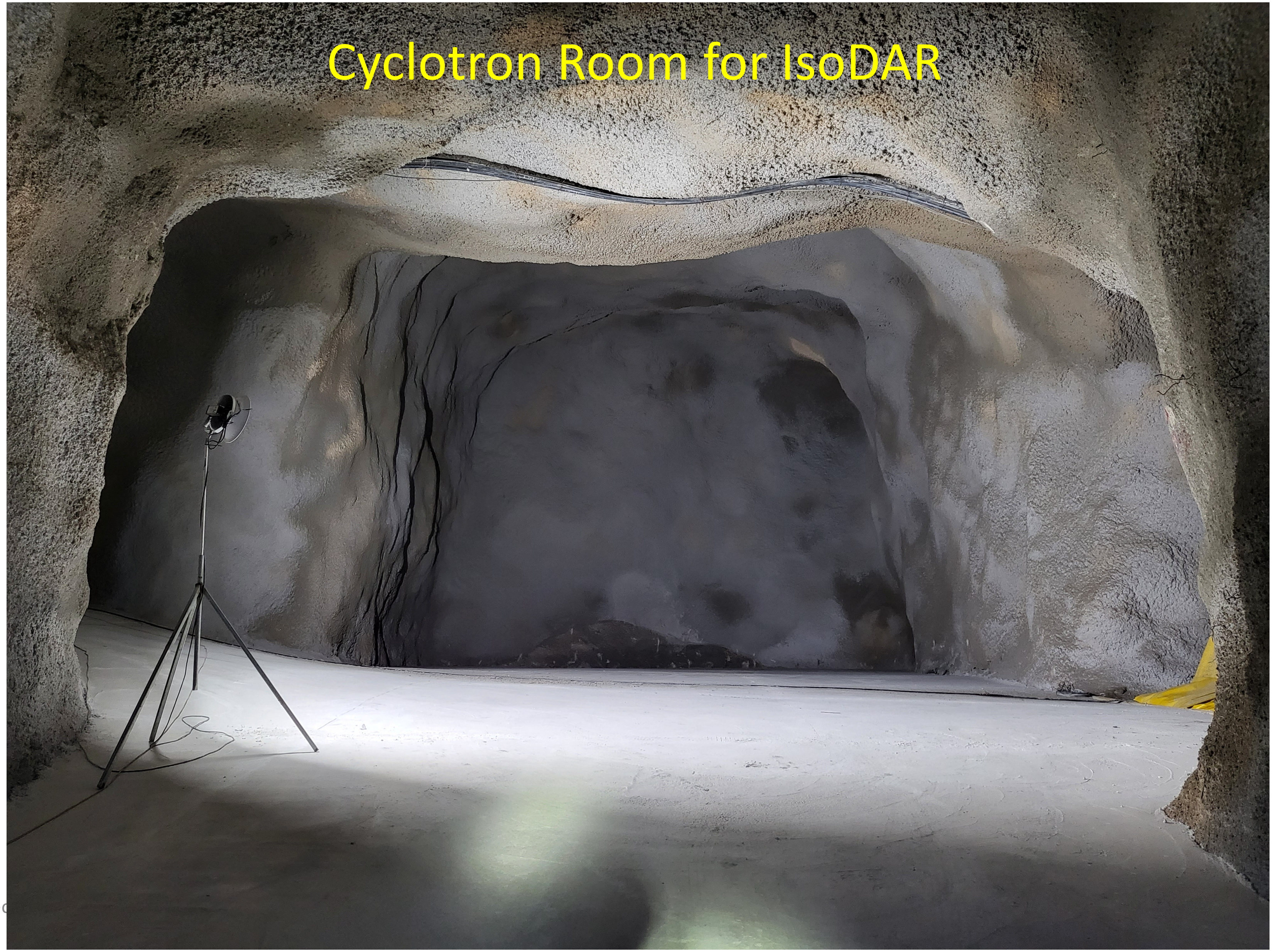
* arXiv:2111.09480
(**PRD**.105.052009)
* arXiv:2201.10040
(submitted to **JINST**)
* arXiv:2110.10635

❖ Cyclotron Room



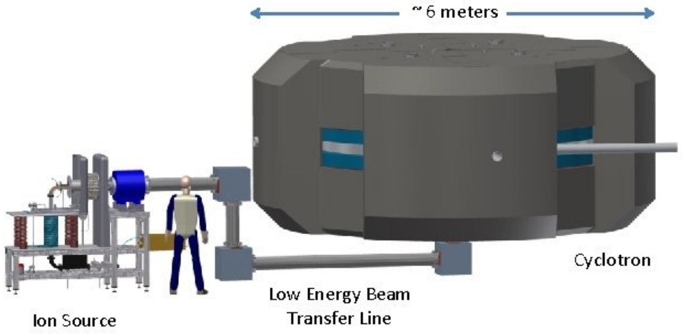


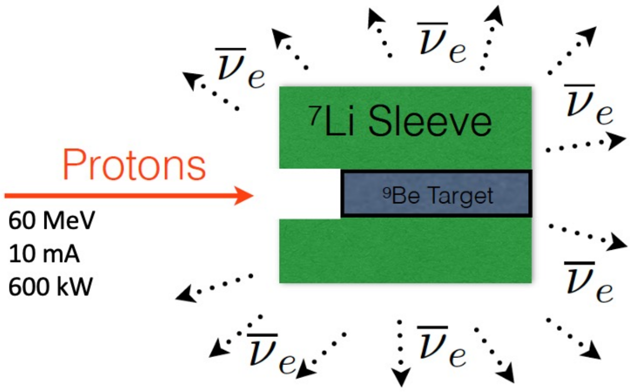
Cyclotron Room for IsoDAR

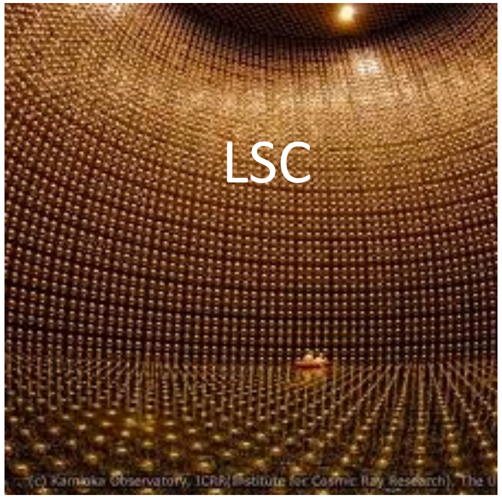


❑ Sterile ν search w/ IsoDAR@Yemilab

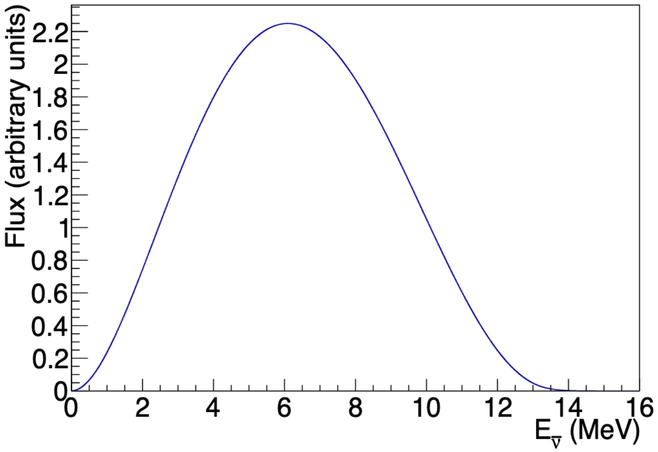
The IsoDAR Cyclotron and Ion Source

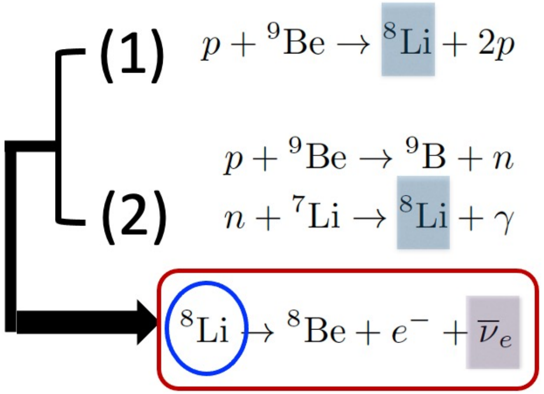






IsoDAR $\overline{\nu}$ spectrum





(1) $p + {}^9\mathrm{Be} \rightarrow {}^8\mathrm{Li} + 2p$

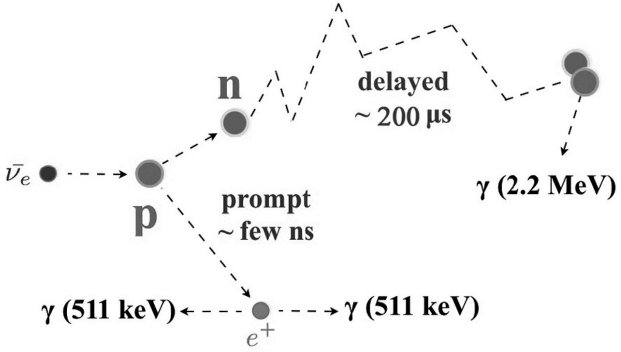
(2) $p + {}^9\mathrm{Be} \rightarrow {}^9\mathrm{B} + n$

$n + {}^7\mathrm{Li} \rightarrow {}^8\mathrm{Li} + \gamma$

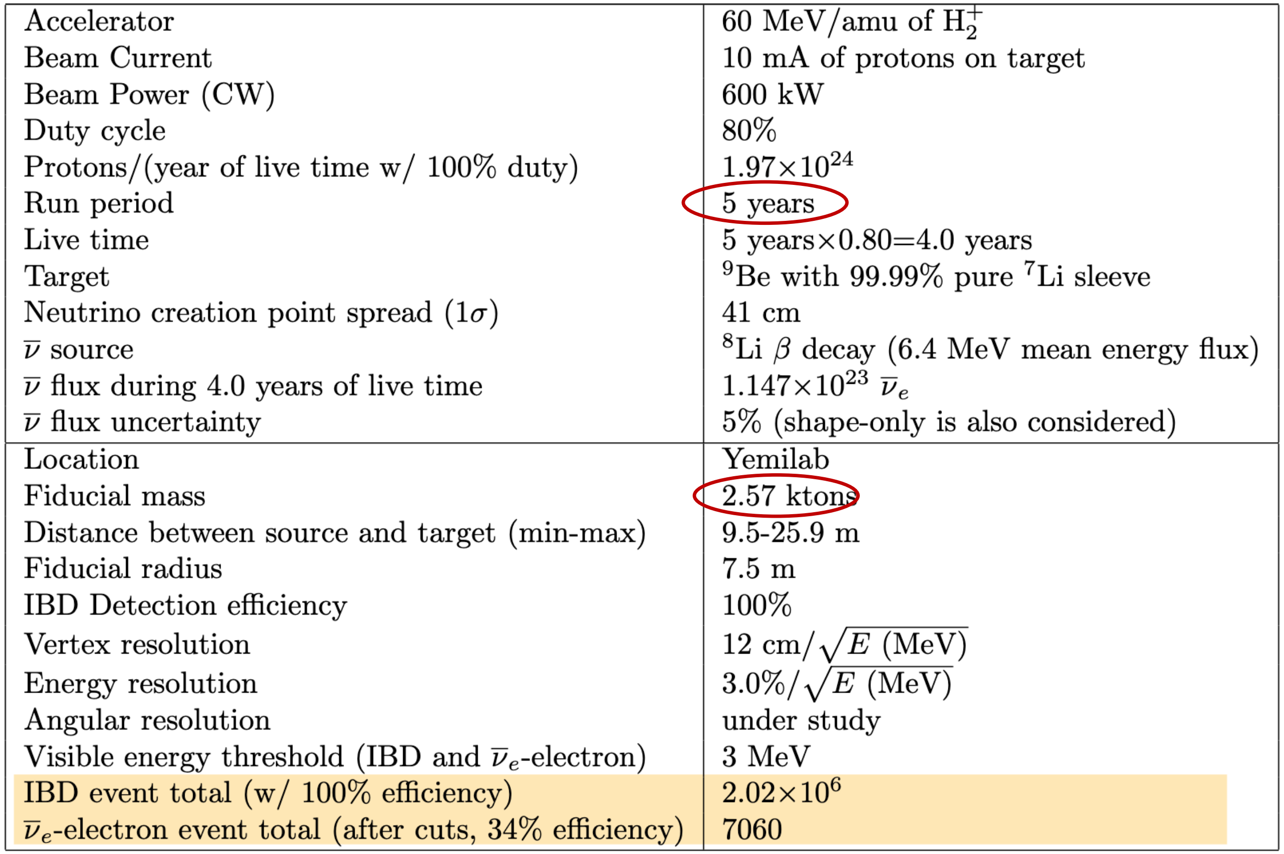
$${}^8\mathrm{Li} \rightarrow {}^8\mathrm{Be} + e^- + \overline{\nu}_e$$

IBD interaction

$$p^+ + \overline{\nu}_e \rightarrow e^+ + n^0$$



IsoDAR@Yemilab Performance



Accelerator	60 MeV/amu of H_2^+
Beam Current	10 mA of protons on target
Beam Power (CW)	600 kW
Duty cycle	80%
Protons/(year of live time w/ 100% duty)	1.97×10^{24}
Run period	5 years
Live time	5 years×0.80=4.0 years
Target	^{9}Be with 99.99% pure ^{7}Li sleeve
Neutrino creation point spread (1σ)	41 cm
$\overline{\nu}$ source	^{8}Li β decay (6.4 MeV mean energy flux)
$\overline{\nu}$ flux during 4.0 years of live time	1.147×10^{23} $\overline{\nu}_e$
$\overline{\nu}$ flux uncertainty	5% (shape-only is also considered)
Location	Yemilab
Fiducial mass	2.57 ktons
Distance between source and target (min-max)	9.5-25.9 m
Fiducial radius	7.5 m
IBD Detection efficiency	100%
Vertex resolution	$12\ \text{cm}/\sqrt{E\ (\text{MeV})}$
Energy resolution	$3.0\%/\sqrt{E\ (\text{MeV})}$
Angular resolution	under study
Visible energy threshold (IBD and $\overline{\nu}_e$-electron)	3 MeV
IBD event total (w/ 100% efficiency)	2.02×10^6
$\overline{\nu}_e$-electron event total (after cuts, 34% efficiency)	7060

2 M IBD events/5 yrs
~7000 ES events/5yrs

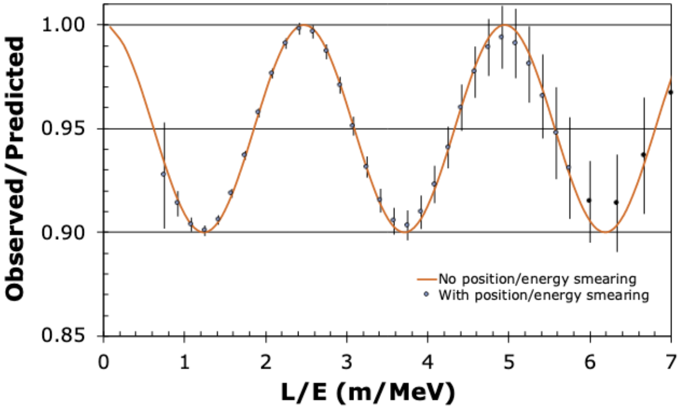
"Detector at Yemilab" assumptions are basically consistent with "KamLAND—897 tons, but bigger (and with the *possibility* of directional reconstruction)"

Sterile ν Search w/ IsoDAR@Yemilab

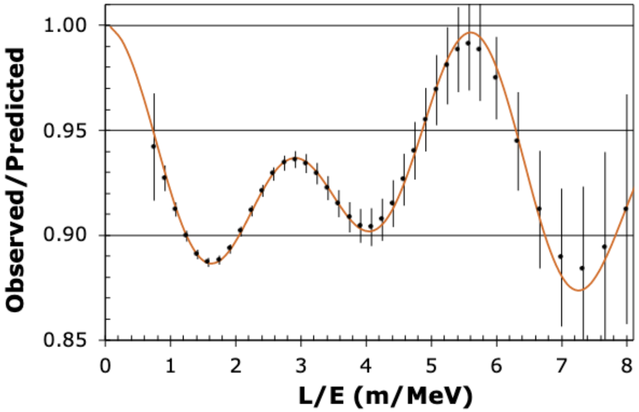
Possible Models & Signatures

arXiv:2111.09480
PRD 105 (2022) 5, 052009

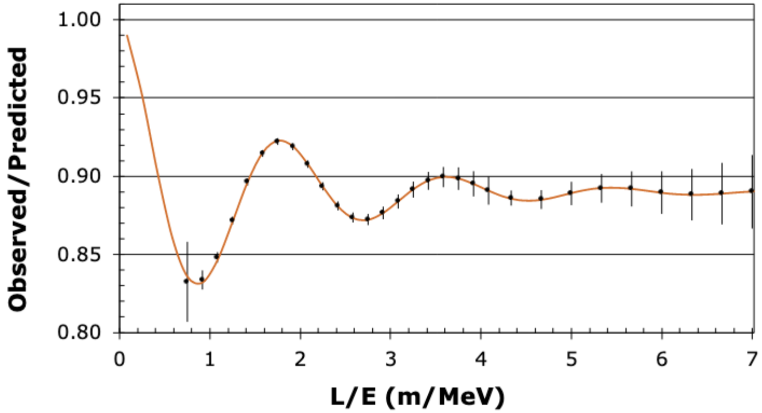
(3+1) ν


IsoDAR@ Yemilab: $\Delta m^2 = 1$ eV^2 and $\sin^2 2\theta = 0.1$

(3+2) ν


IsoDAR@Yemilab: (3+2) Model with Kopp/Maltoni/Schwetz Parameters

(3+1) ν + ν_s decay


IsoDAR@Yemilab: (3+1) plus Decay Model
$\Delta m^2 = 1.35$ eV^2, $\sin^2 2\theta = 0.214$ and $\tau = 4.5$ eV^{-1}

→ IsoDAR@Yemilab can well distinguish different new physics models.

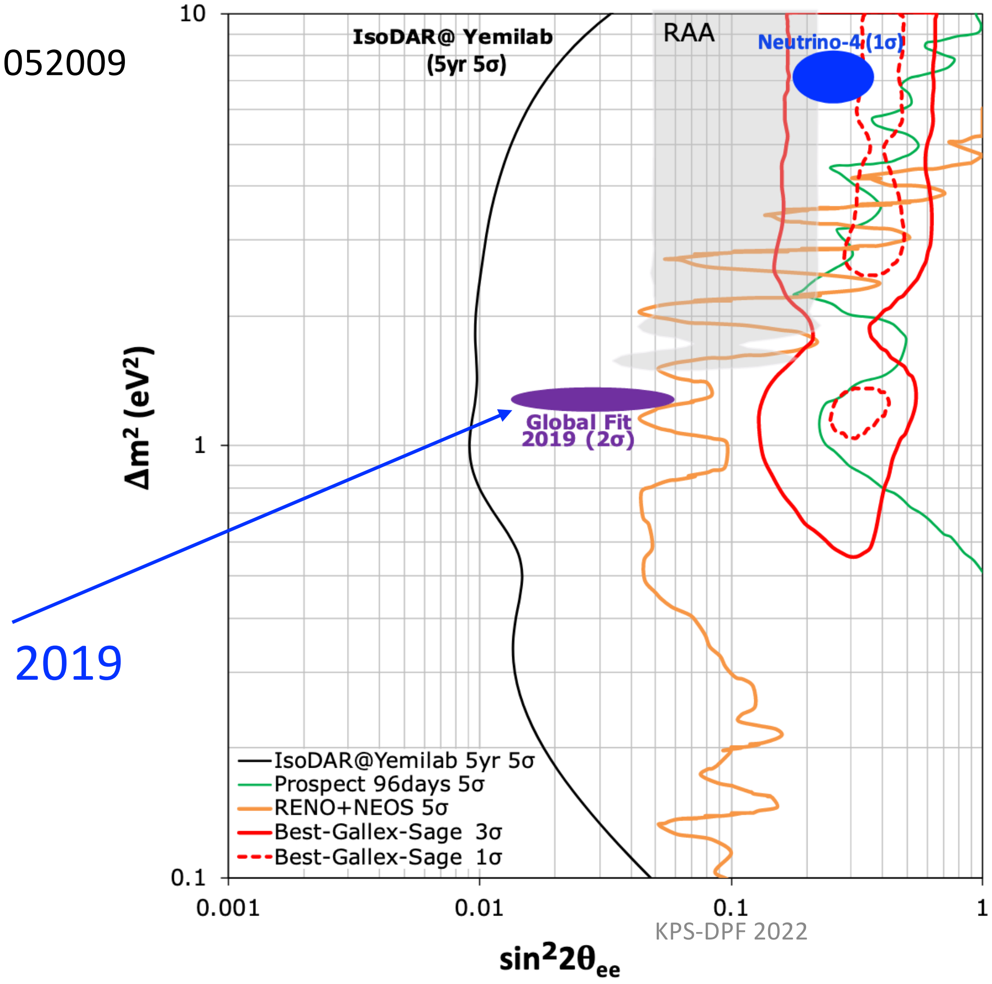
- The (3+1)+decay model significantly reduces the tension between appearance and disappearance experiments, improving the global-data goodness-of-fit.

1910.13456

Sterile neutrino search Sensitivity

IsoDAR @Yemilab $P(\overline{\nu}_e \rightarrow \overline{\nu}_e)$

arXiv:2111.09480
PRD 105 (2022) 5, 052009



Global Fit 2019

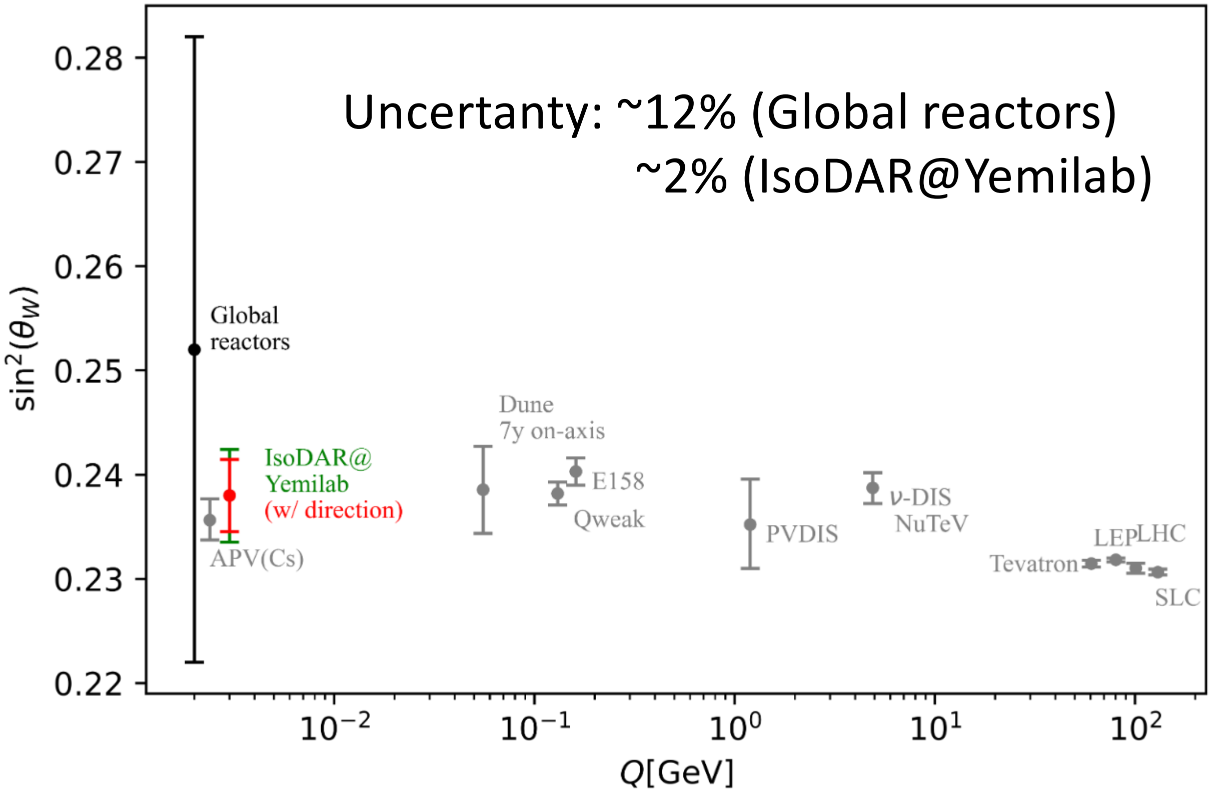
- World-leading result
- Definite conclusion on (3+1) ν or not

<u>Advantage</u>:
Unlike reactor/accelerator ν, IsoDAR has very well defined ν flux and shape.

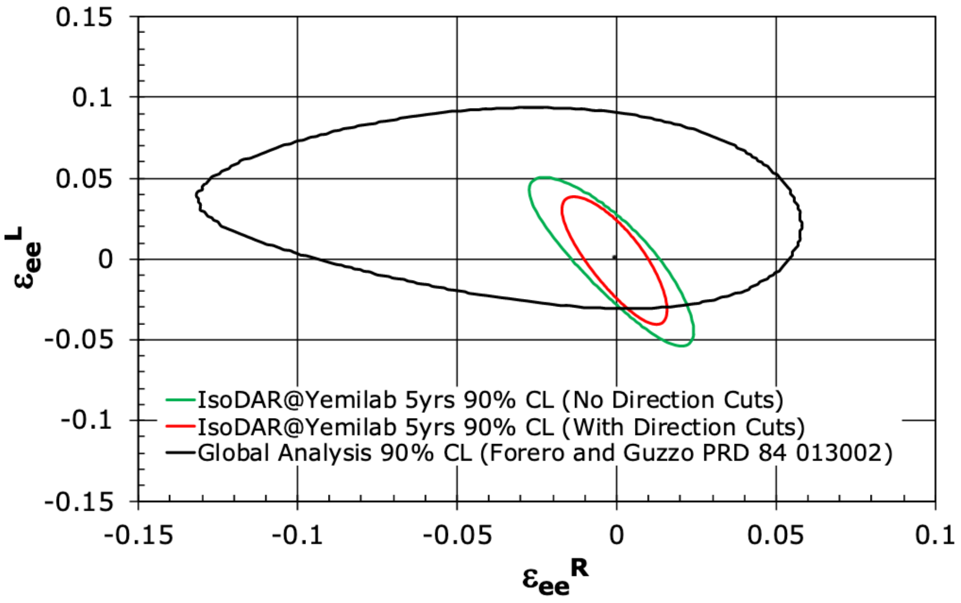
IsoDAR@Yemilab Elastic Scattering Events

arXiv:2111.09480
PRD 105 (2022) 5, 052009

Weak mixing angle θ_W measurement assuming standard ν interaction


Uncertanty: ~12% (Global reactors)
~2% (IsoDAR@Yemilab)

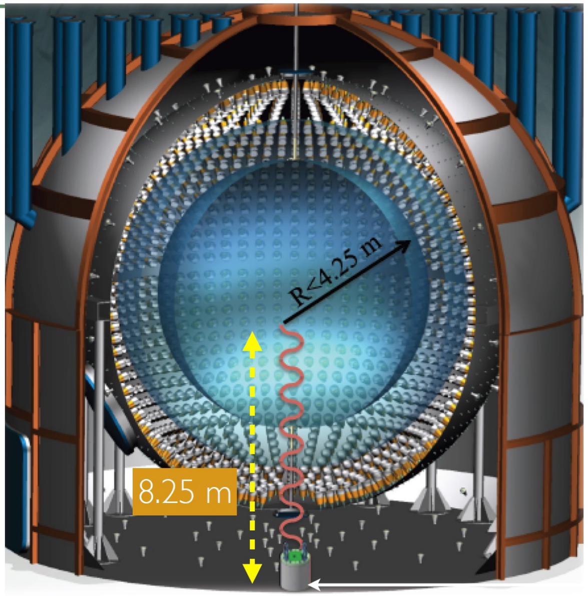
NSI



[2] Sterile ν search w/ radioactive sources

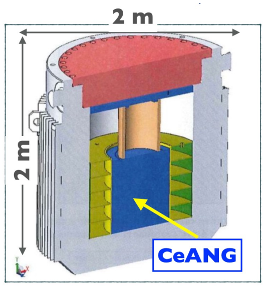
$P(\nu_e \rightarrow \nu_e)$

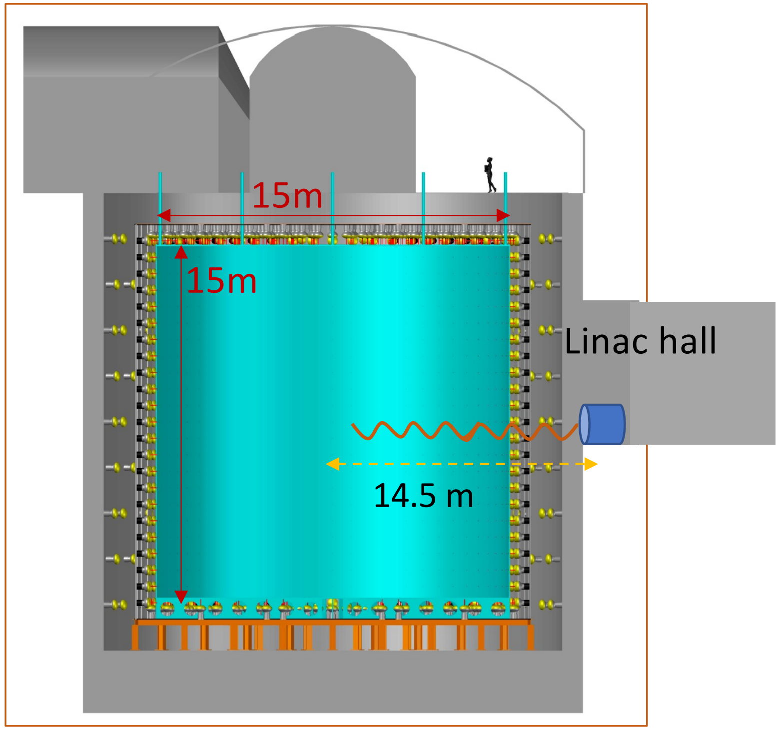
The Borexino detector and SOX



Useful data: distance range 4 - 12.25 m
(Yemilab will be better)

Source
inside shield





Distance range: 7 – 22 m

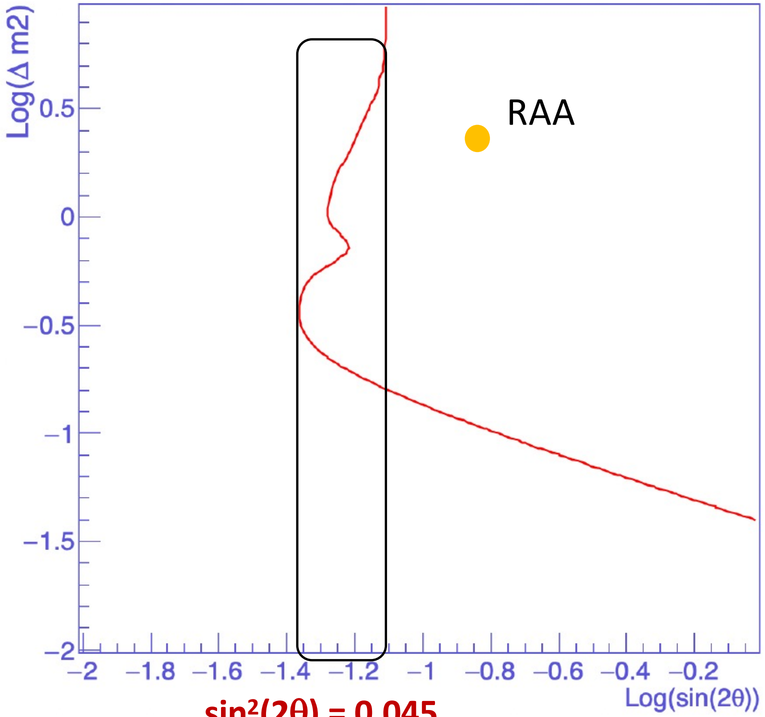
LSC @Yemilab

[2] Sterile ν Search Sensitivity w/ Radio-Source

Radio-active source

$P(\nu_e \rightarrow \nu_e)$

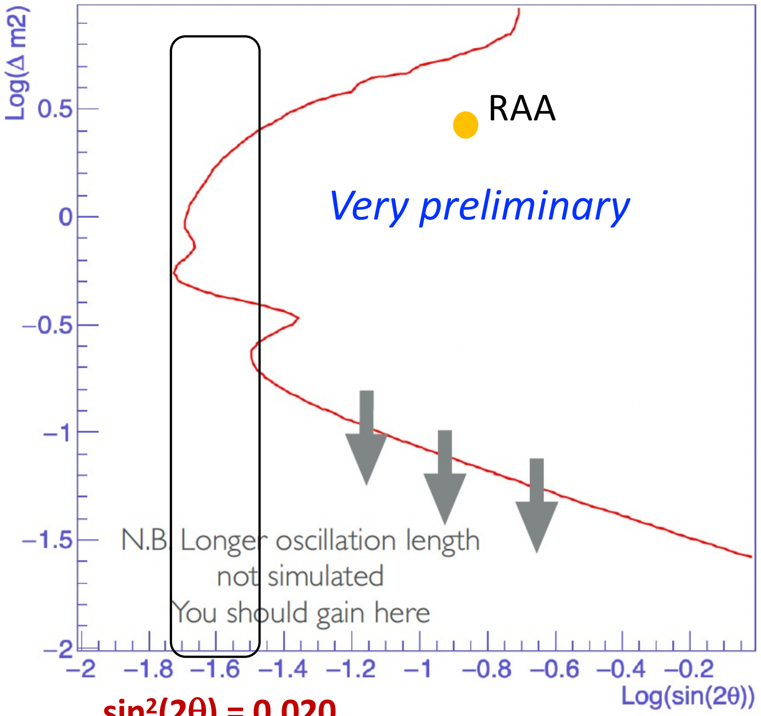
SOX original



$\sin^2(2\theta) = 0.045$

Ce-144 100 kCi

Yemilab



Very preliminary

N.B. Longer oscillation length
not simulated
You should gain here

$\sin^2(2\theta) = 0.020$

Ce-144 100 kCi

M. Pallavicini
Seminar @CUP-IBS

❑ **White Paper** on the large neutrino LS detector is currently being prepared.

Current Authors

- **LS purification**: JayBenziger (Princeton), Mingang Yeh (BNL)

- **IsoDAR**: Jose Alonso (MIT), Janet Conrad (MIT), Mike Shaevitz (Columbia), Joshua Spitz (Michigan), Daniel Winklehner (MIT)

- **Sterile nu** search w/ radioactive sources: Marco Pallavicini (Genoa U.)

- **$0\nu\beta\beta$**: Yeongduk Kim (IBS)

- **Solar ν**: Sunny Seo (IBS)

- **Supernova ν**: Jost Migenda (King's college, London)

- **SN Relic ν**: Michael Wurm (Mainz U.)

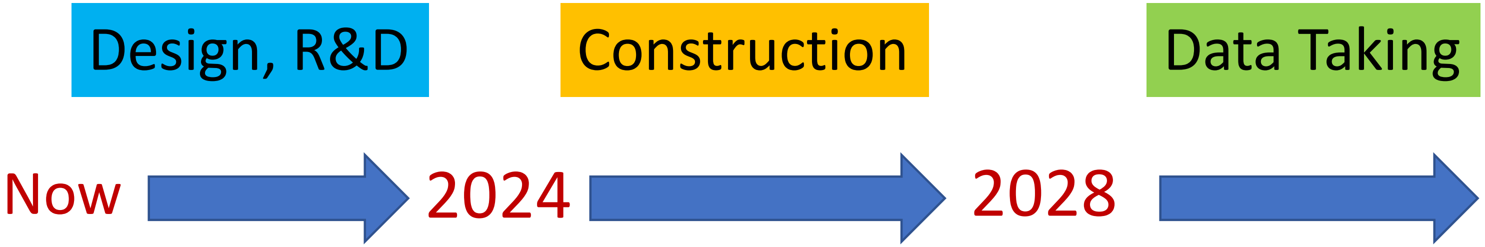
- **Geo ν**: Steve Dye (Hawaii U.)

- **New physics searches**: Doojin Kim (Texas A&M), Jongchul Park (CNU)

- **Introduction, Site, Detector**: Sunny Seo (IBS)

Rough Timeline

LSC @Yemilab



Design, R&D

Construction

Data Taking

Now → 2024 → 2028 →

We need funding for the LSC detector.

The construction depedns on when we get the funding.

Summary & Conclusion

☐ In new Yemilab, a **cavern** for ν detector (~2.3 kton LS target) is ready.

→ multi-purpose detector: **Solar/G**eo/SN ν, **dark photon, sterile** ν, etc.

☐ Best solar ν flux measurements in the world.

☐ 1 year operation of 100 MeV-100 kW e^- beam ($2\text{x}10^{23}$ EOT):
best "direct" dark photon search sensitivity
in O(1 eV) < M_ϕ < 30 MeV (assuming 10^3 bkg events/year)

☐ IsoDAR@Yemilab: best sensitivity for sterile ν search
in $P(\nu_e \rightarrow \bar{\nu}_e)$ channel. Can test different new physics models.

☐ To do: white paper publication, R&D, expand collaborators

You are very welcome to join LSC, just let me know!