Detection of supernovae, solar and geo-neutrinos -review-

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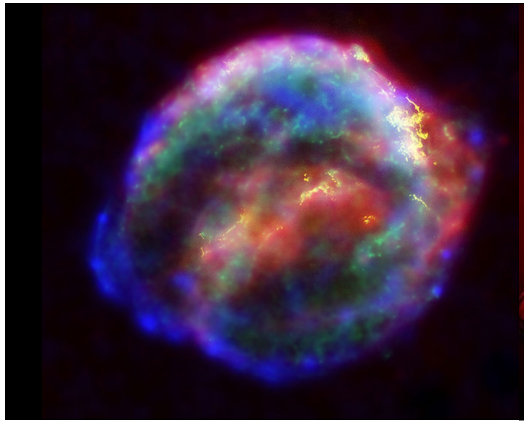
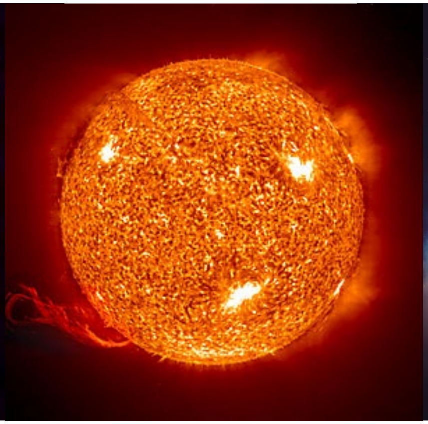
Vienna
Aug. 28, 2023

TAUP VIENNA 2023

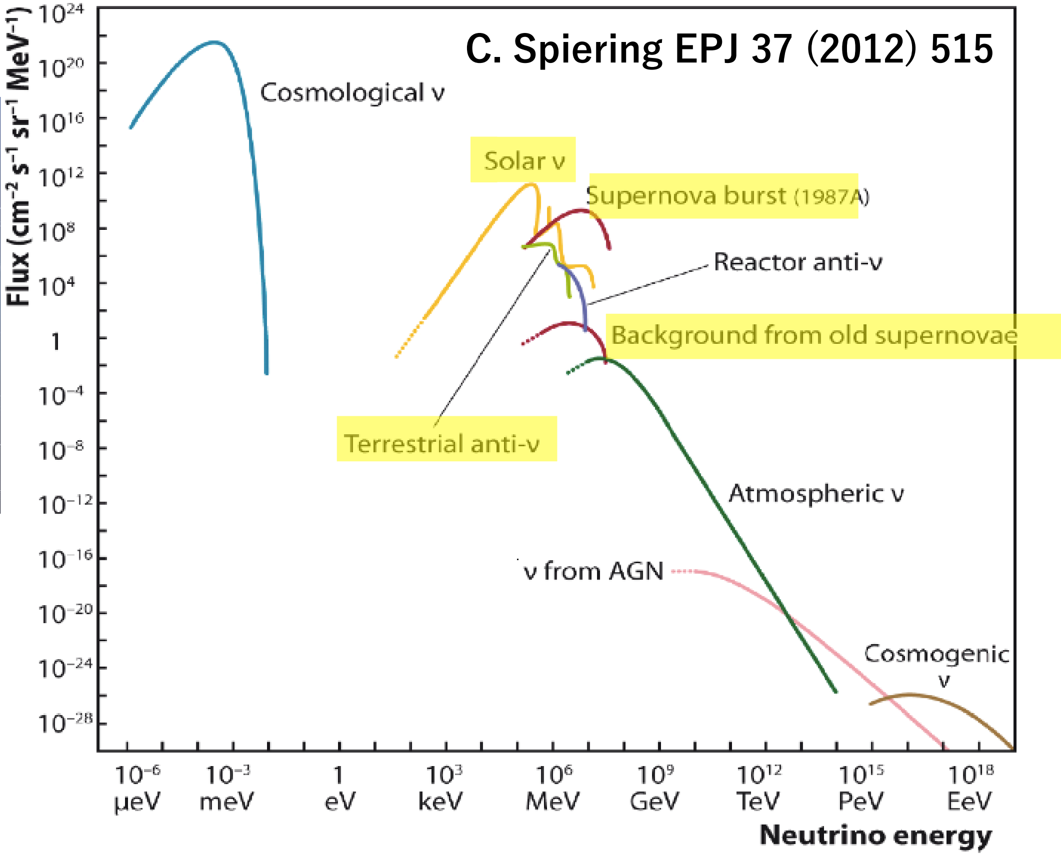
MeV neutrinos from SN/Sun/Earth

- **Key to understanding the origin of elements and the neutrino's role in the universe.**

star formation, element formation, emission, and accumulation
solar mechanism and dynamics, solar system formation,
earth formation, earth dynamics, … and neutrino oscillation


MeV neutrino fluxes



Contents
- **Detection technologies**
- **Physics motivations**
- **Results of recent experiments**
- **Future experiments**

Disclaimer and Acknowledgments

- It is impossible to review everything in 25 minutes.
  - I would focus on currently running experiments/projects.
  - Sorry if your projects are not highlighted.
- Thank you for sharing the talk information in advance.
  - I also apologize for not being able to include most of them.

Nanami Kawada (KamLAND)
Davide Basilico (Borexino)
Sandra Zavatarelli (Borexino)
Tanner Kaptanoglu (SNO+)
Mark Chen(LiquidO&SNO+)
Cong Guo(JUNO)
Cloé Girard-Carillo(LiquidO)

Clara Cuesta (DUNE)
Bob Svoboda(THEIA)
Lucas Machando(SK)
Shota Izumiyama(SK)
Masayuki Harada(SK)

Francesco Villante (SSM)
Pablo Martínez-Miravé (CPT Solar/reactor)
Pilar Iváñez Ballesteros (ν decay and DSNB)

Detectors in TAUP2023+

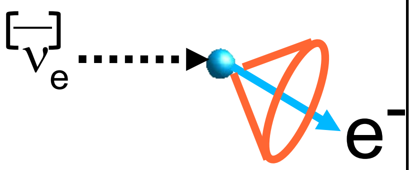
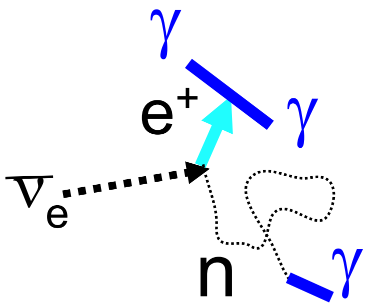
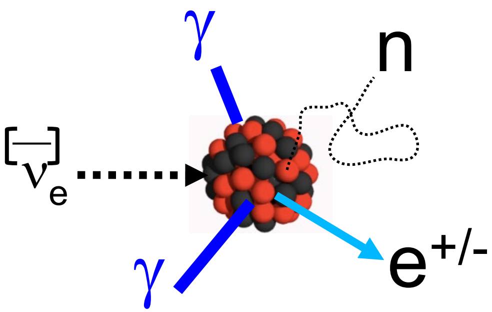
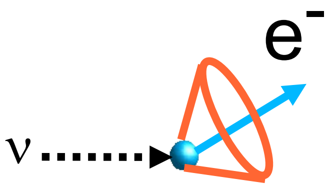
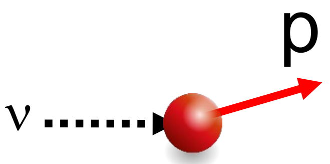
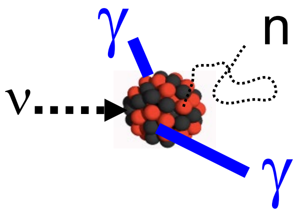
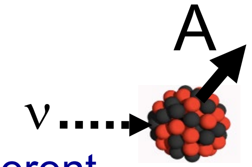
N.B. This is a partial list.

	Current	Soon	Future
Water	**Super-Kamiokande (SNO+) IceCube**	**KM3NET (ORCA,ARCA)**	**Hyper-Kamiolande**
Liquid scintillator	**KamLAND (Borexino) SNO+ NovA LVD**	**JUNO**	**THEIA Jinping**
Others	**HALO DM detectors(Xe,Ar)**	**DarkSide-20k**	**DUNE DARWIN/ XLZD**

- Water and LS are the two major target materials.
- Each detector has its own characteristics, and **complementary** cooperation will lead to a better understanding of SN, Solar, and Geo neutrinos.

The detection channel in MeV range

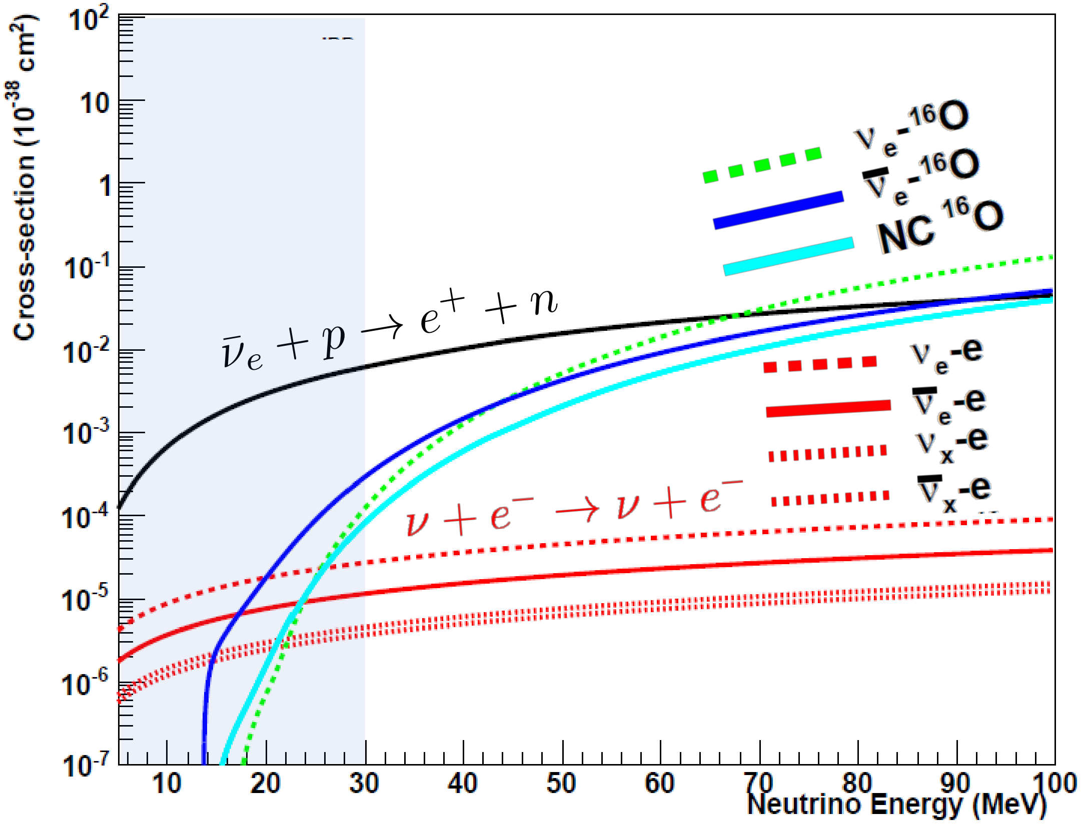
Kate Scholberg Neutrino2014

	Electrons	Protons	Nuclei
Charged current	Elastic scattering $\nu + e^- \rightarrow \nu + e^-$  	Inverse beta decay $\bar{\nu}_e + p \rightarrow e^+ + n$  	$\nu_e + (N, Z) \rightarrow e^- + (N-1, Z+1)$ $\bar{\nu}_e + (N, Z) \rightarrow e^+ + (N+1, Z-1)$  Various possible ejecta and deexcitation products
Neutral current	 Useful for pointing	Elastic scattering  very low energy recoils	$\nu + A \rightarrow \nu + A^*$  $\nu + A \rightarrow \nu + A$  Coherent elastic (CEνNS)

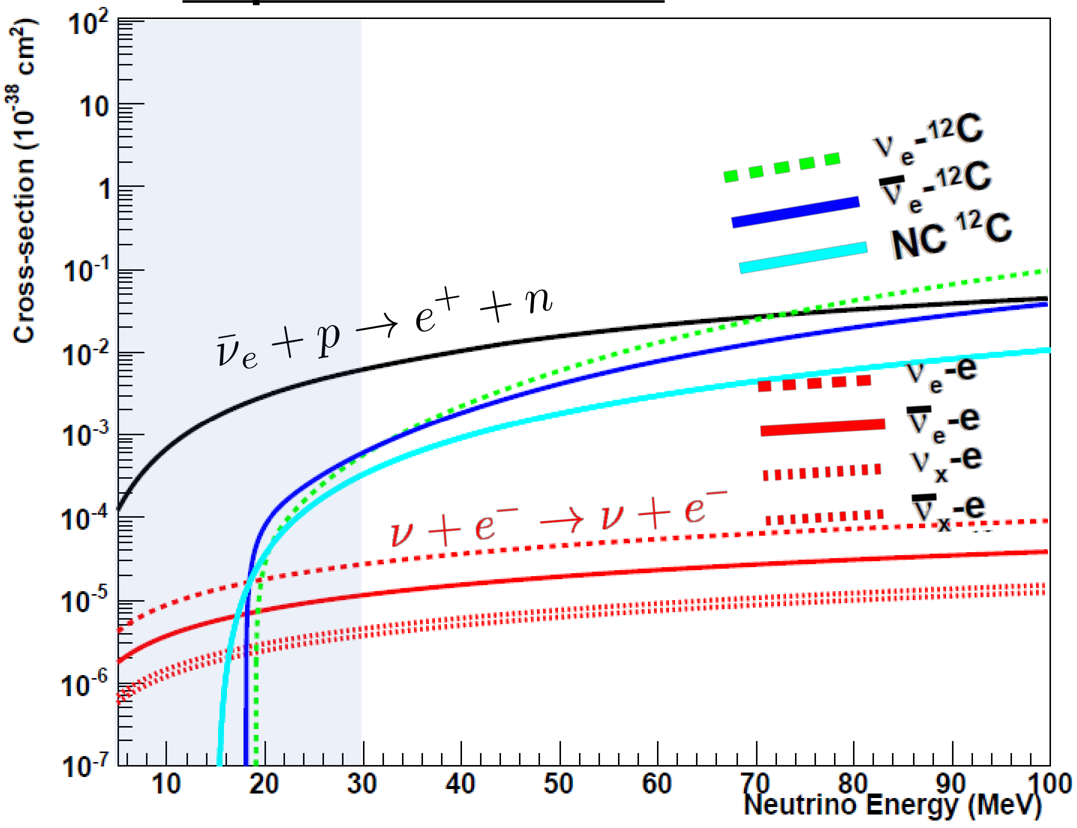
Relevant cross-sections (1)

SNOwGLoBES http://www.phy.duke.edu/~schol/snowglobes/

- **Water detectors**



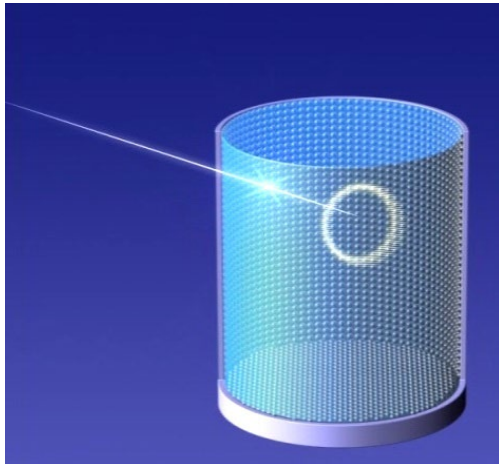
- **Liquid scintillators**



- IBD dominates in the target region
- IBD selection/rejection if the neutron is tagged.
  - Elastic scatterings are utilized for the directional information extraction

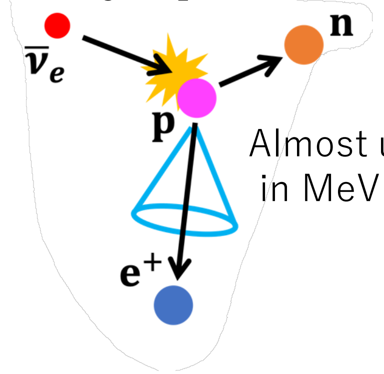
Water Cherenkov detector

- **Directionality of Cherenkov light**



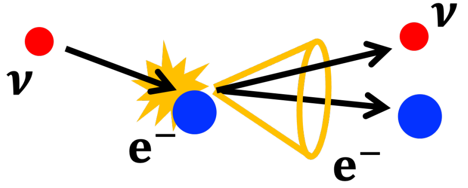
Inverse Beta Decay (IBD)

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



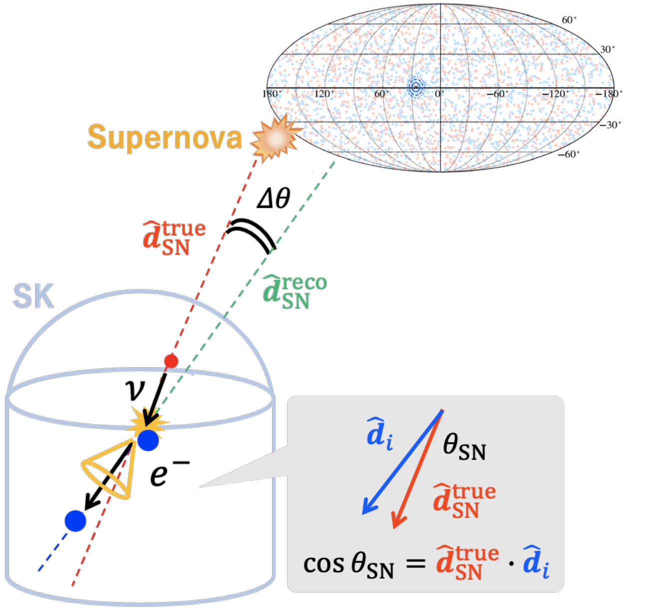
Elastic Scattering (ES)

$\nu + e^- \rightarrow \nu + e^-$



Forward scattering
→**direction info.**

ES Telescope!



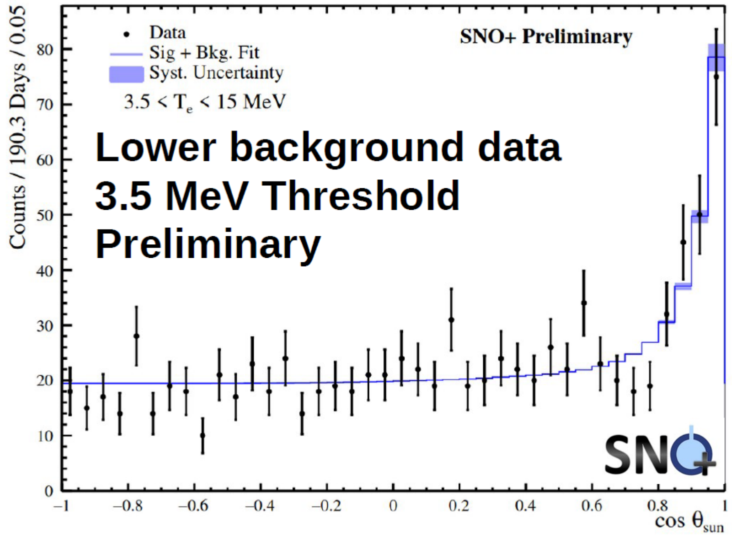
Aug 28 14:15 Shota Izumiyama

- **Low energy BG rejection by directional information**

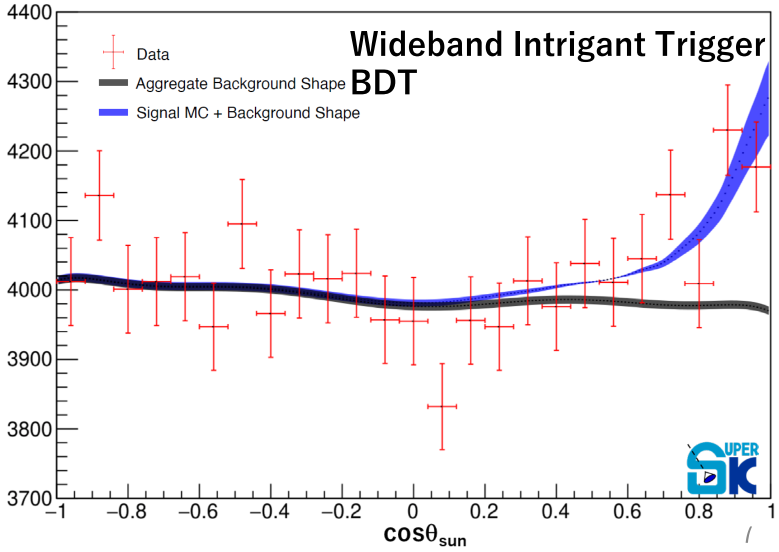
Solar angle distributions
$\cos\theta_{sun}$ →

^{8}B neutrino detection ~3MeV, where RI (Rn) BG dominates, is possible thanks to the directional sensitivity

SNO+ (water) 3.5~15MeV



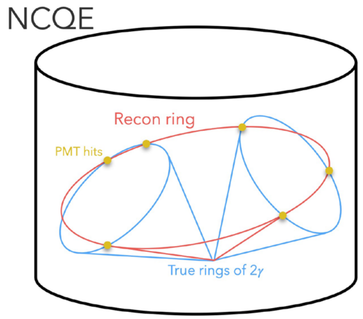
SK-IV(662davs) 2.5~3.5MeV

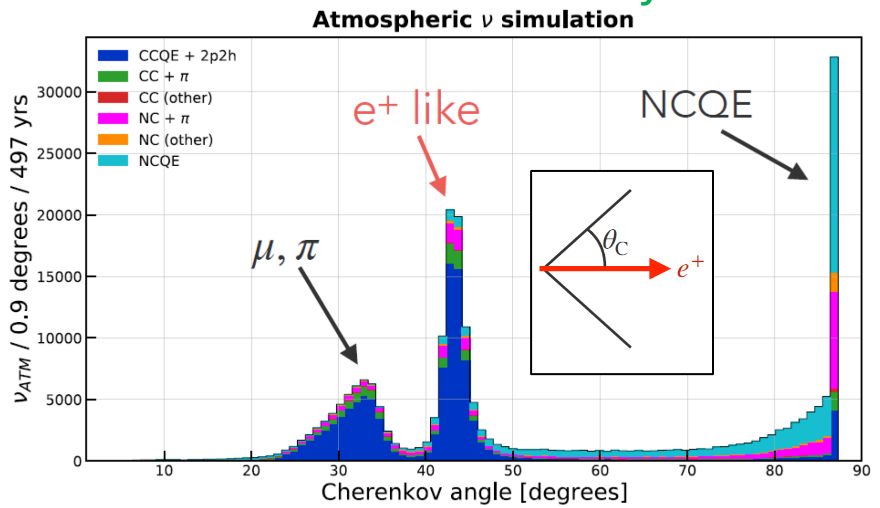


Aug 28 14:30
Seiya Sakai

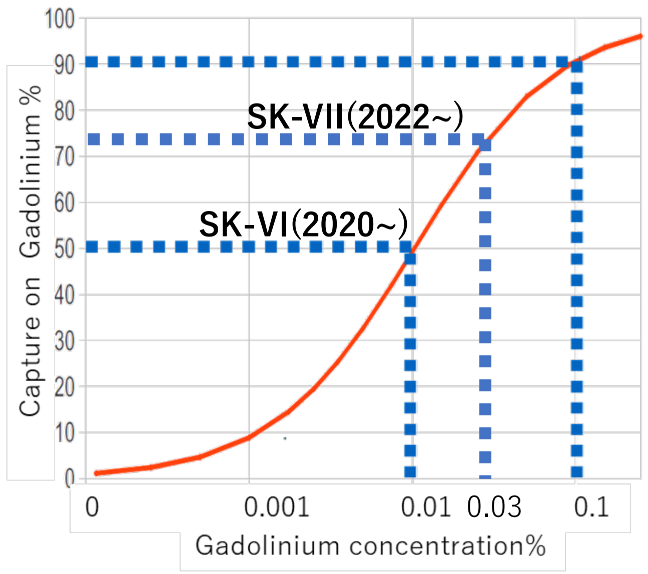
Water Cherenkov detector

- **Cherenkov angle for interaction identification**
  - 42° for signal
  - Multiple gamma events reconstruction →





- **Neutron tagging for interaction (especially IBD) identification**
  - By delayed coincidence with 2.2MeV gamma from p-capture (as LS)
  - **Gd-loading** significantly enhances its efficiency



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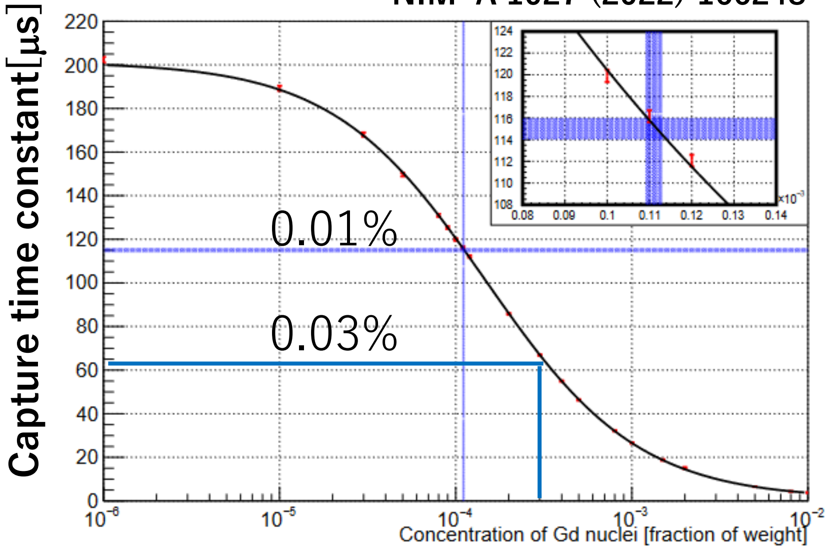
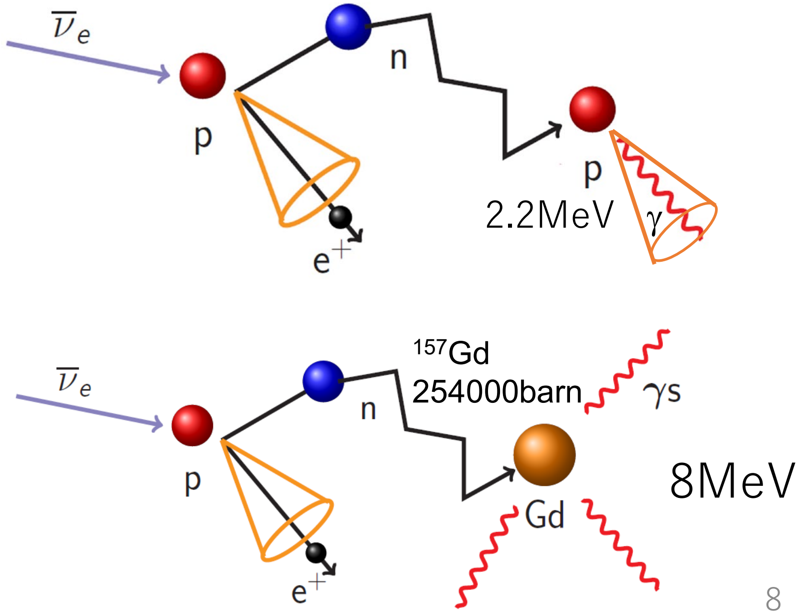
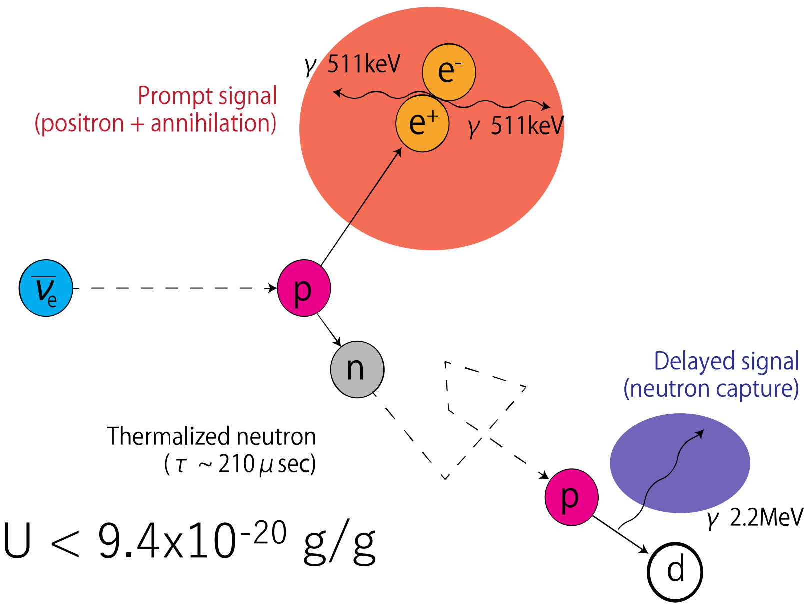




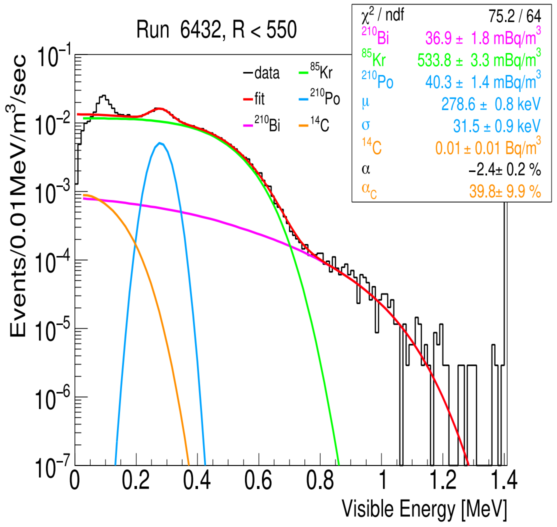
Liquid scintillator

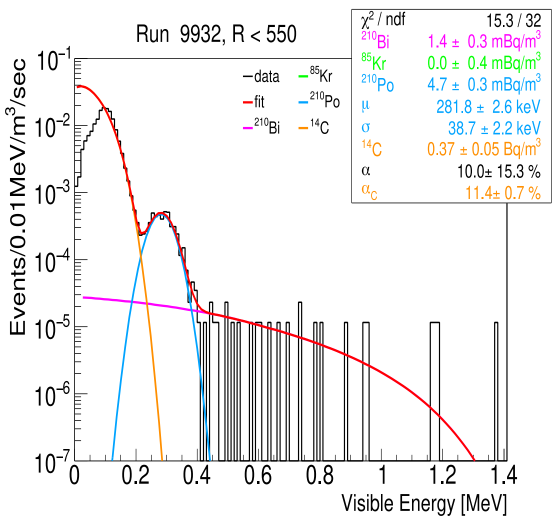
- **High light yields.**
    - **High delayed coincidence performance**
    - High energy resolution!
    - Low threshold （> 200keV,　water C > 3MeV)
- **Ultra-low BG by purification process**

Borexino (**0.3 kton** PC+PPO) achieved ^{232}Th < 5.7x10^{-19} g/g, ^{238}U < 9.4x10^{-20} g/g



KamLAND's ^{210}Pb reduction by distillation in 2007-2008 (**1kton** PC+Dodecane+PPO)





Figures from Nanami Kawada

JUNO's purification system (**20kton** LAB+PPO+bisMSB)

➢ *Four purification plants to achieve target radio-purity 10^{-17} g/g U/Th and 20 m attenuation length at 430 nm.*

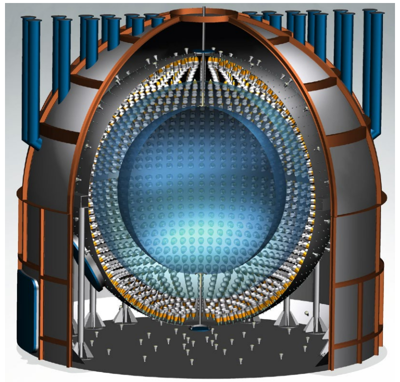
Aug 28 15:30 Guo Cong, Aug 28 17:45 Loic-René LABIT

Liquid scintillator

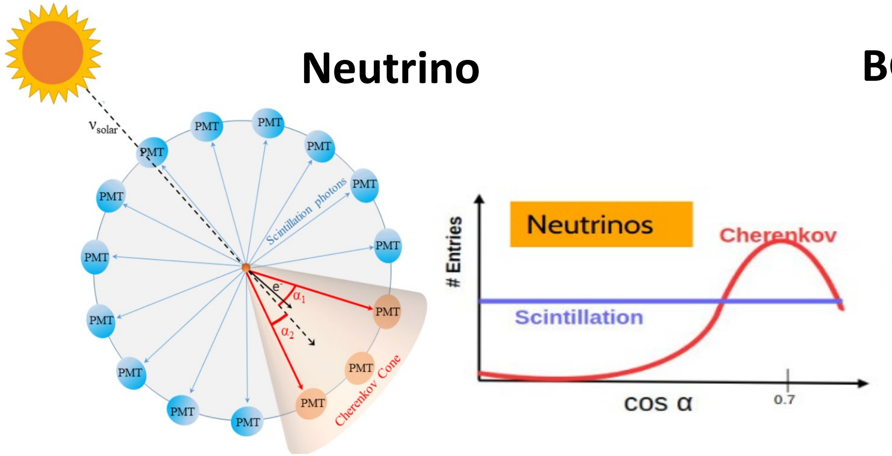
- Directional sensitivity via Cherenkov light (~o(1%) of the scintillation light)

BOREXINO exploited it to disentangle the neutrino and background events
→ Correlated and Integrated Directionality (**CID method**)

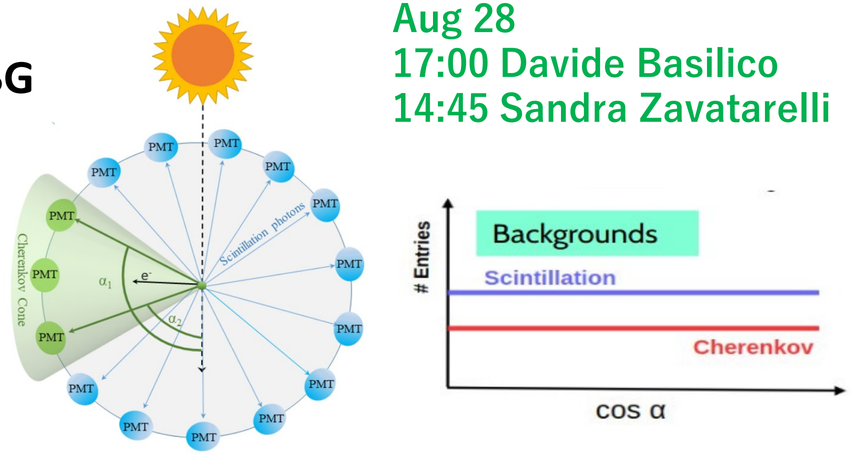
2007 - 2021: **280t LS**



Neutrino

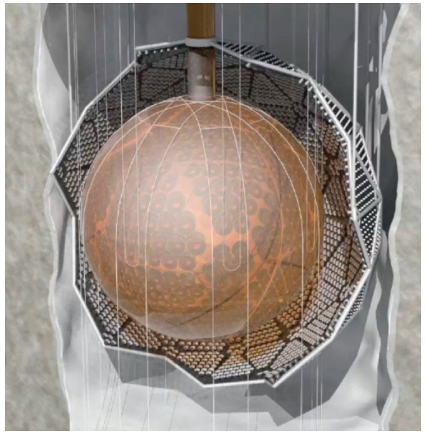


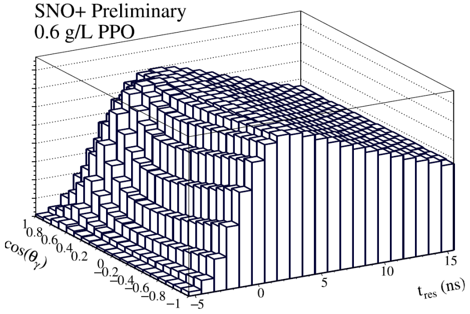
BG



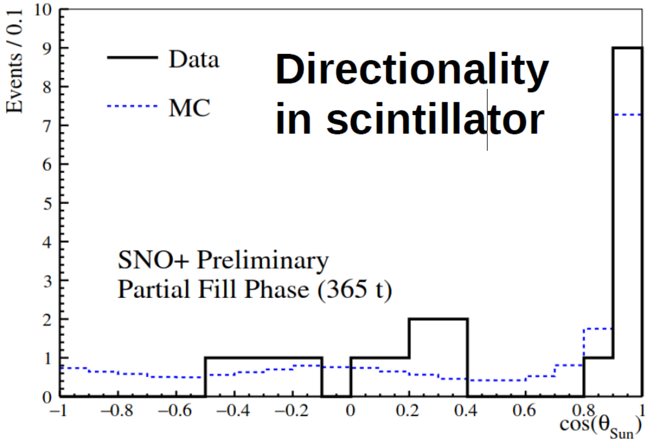
Aug 28
17:00 Davide Basilico
14:45 Sandra Zavatarelli

SNO+ 2D PDF in reconstructed time residuals and photon angle used to fit events direction.





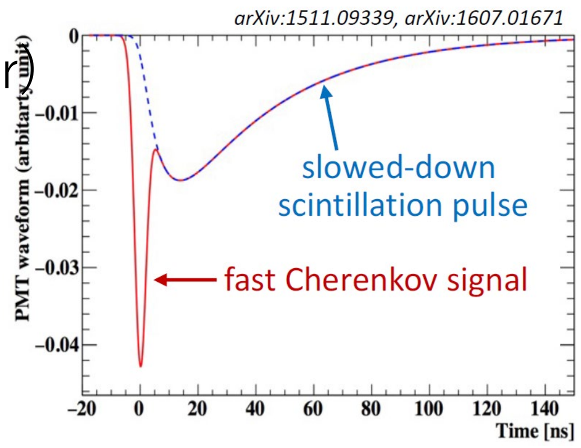
2017-2019 905 t of water
2022- **780 t of LS**

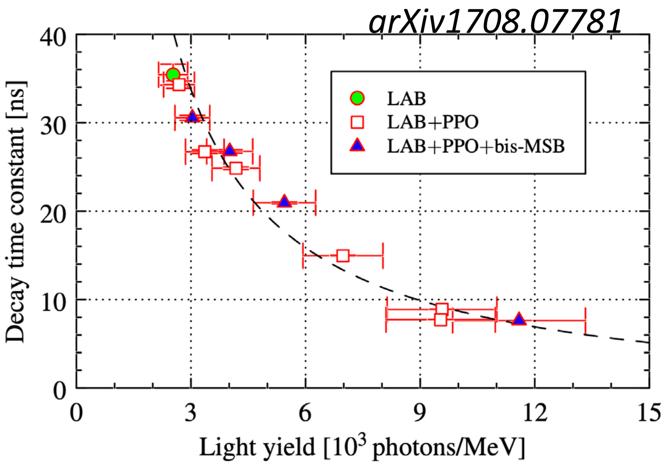


Tanner Kaptanoglu
Aug 31 15:15

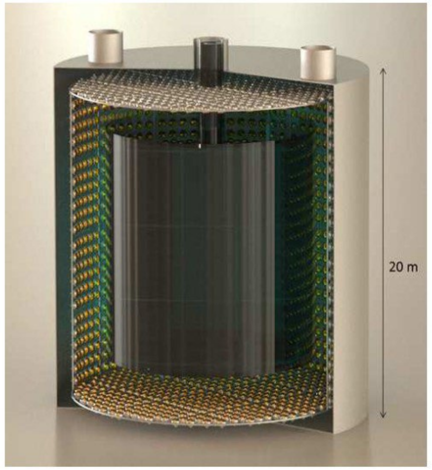
Liquid scintillator R&Ds for enhancing Cherenkov signal

- **Slow LS**: LAB(solvent)+0.1g/l PPO(fluor)
  - Slowed-down scintillation signal
  - Reduced scintillation LY
  - Higher transparency

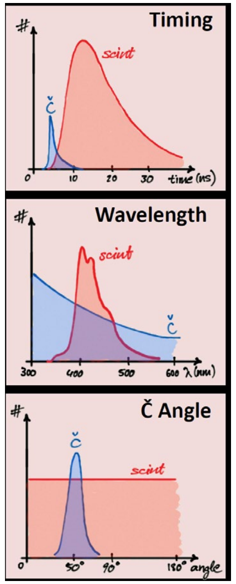


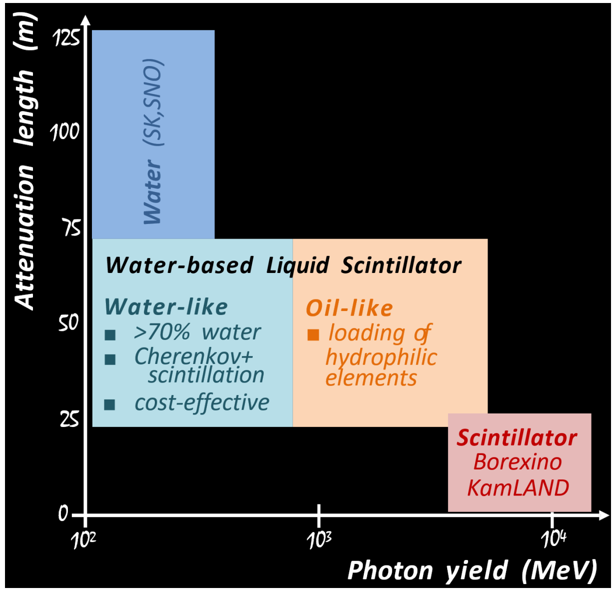


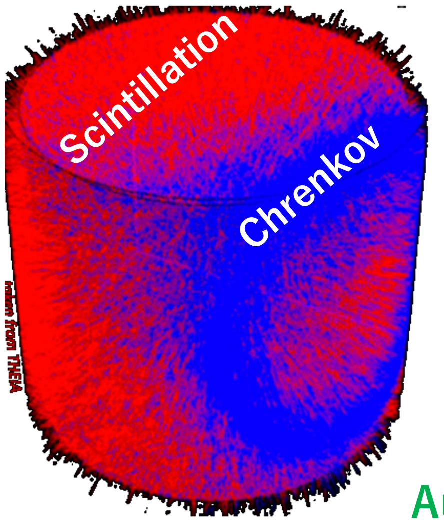
Jingping Neutrino experiment

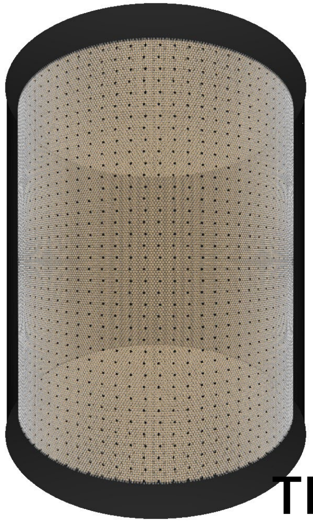


- **WbLS**: water + tenside + LAB + PPO
  - Lower organic fraction→higher transparency→ Cherenkov signal

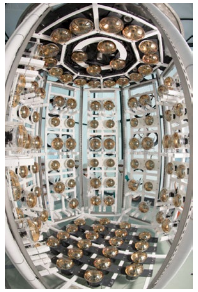








THEIA



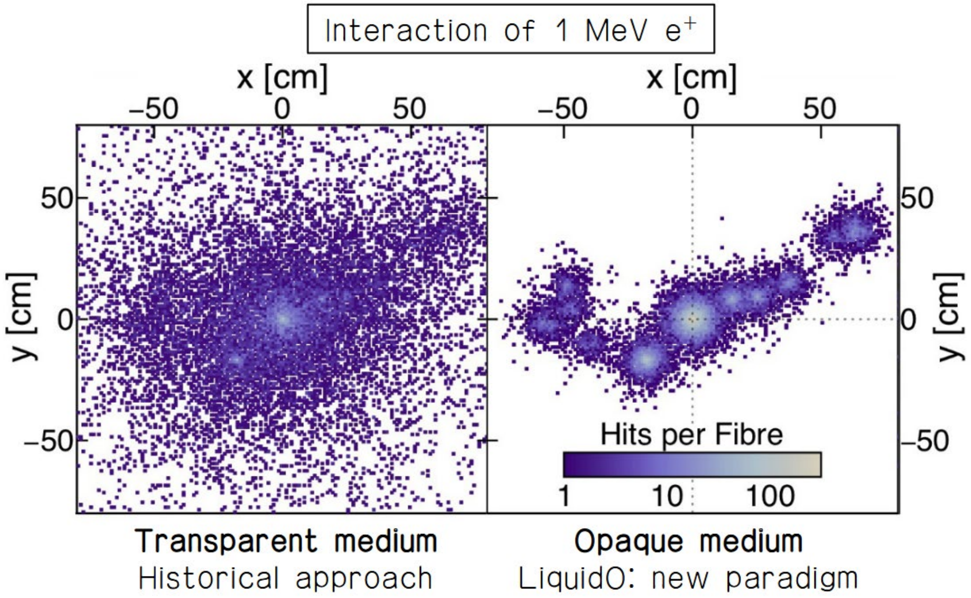
ANNIE

Aug 28 18:15 Bob Svoboda 15:45 Michael Wurm

Liquid scintillator R&Ds for higher vertex resolution

- **Opaque/low transparency scintillator**:
  - Confine light near its creation point to preserve the topological information of particle interactions
  - Collect light with a lattice of fibers

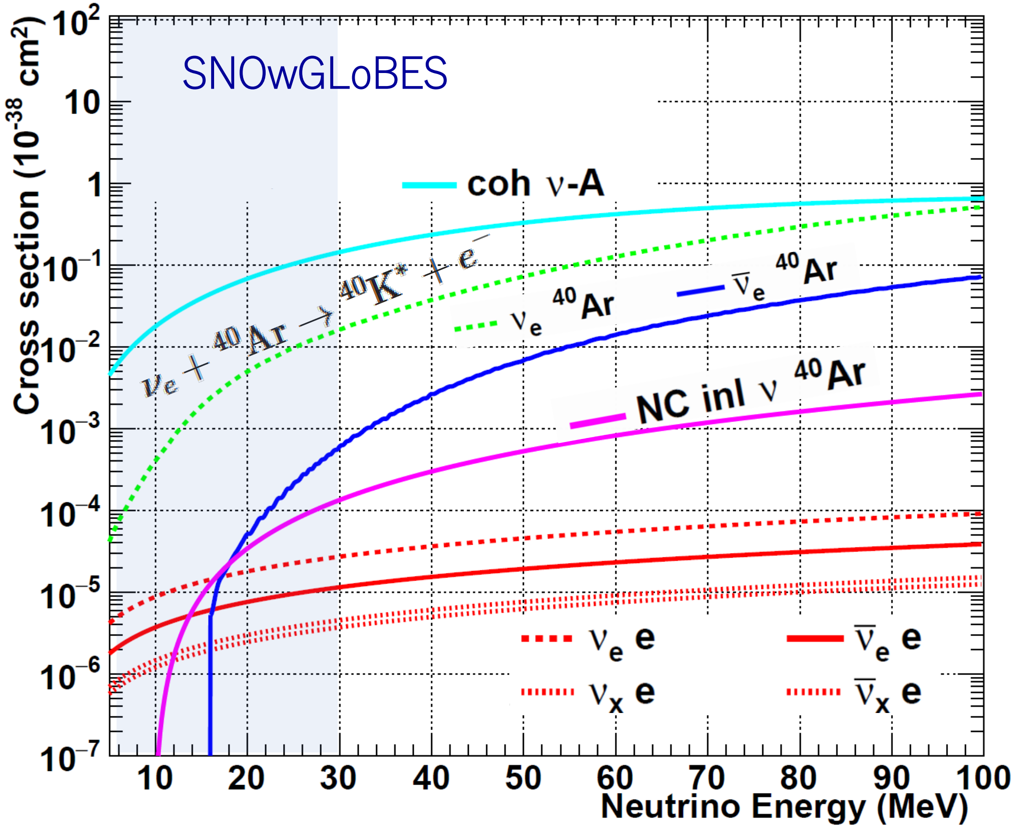
Aug 28 18:00
Cloé Girard-Carillo



Relevant cross-sections (2)

SNOwGLoBES http://www.phy.duke.edu/~schol/snowglobes/

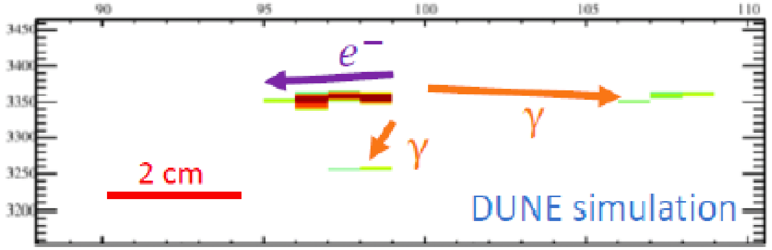
- **Liquid Ar detectors**



- **CEνNS** has the largest cross-section; however, its energy deposit is **in keV**
  → **Dark matter/0νββ detectors**
- **ν_e cc is the main channel**

LArTPC

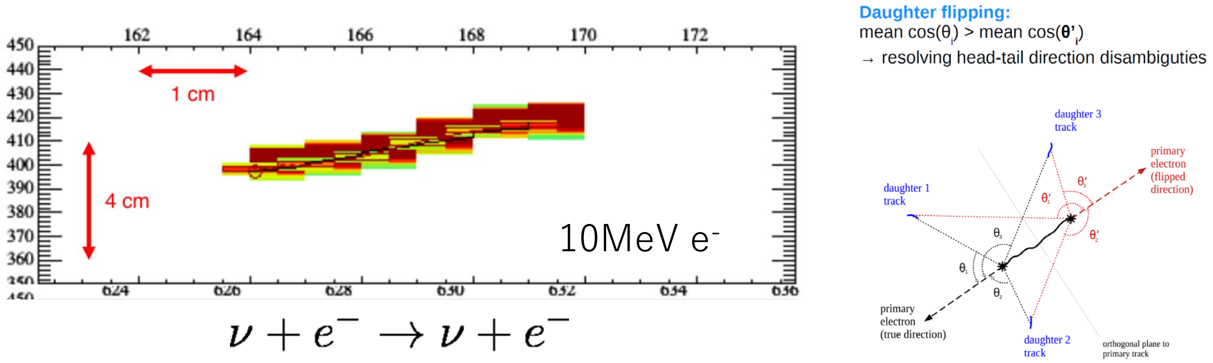
- The signal leaves an e$^-$ track + γ cascade + scintillation light



$$\nu_e + {}^{40}Ar \rightarrow e^- + {}^{40}K^*$$

Aug 31 15:00 Clara Cuesta

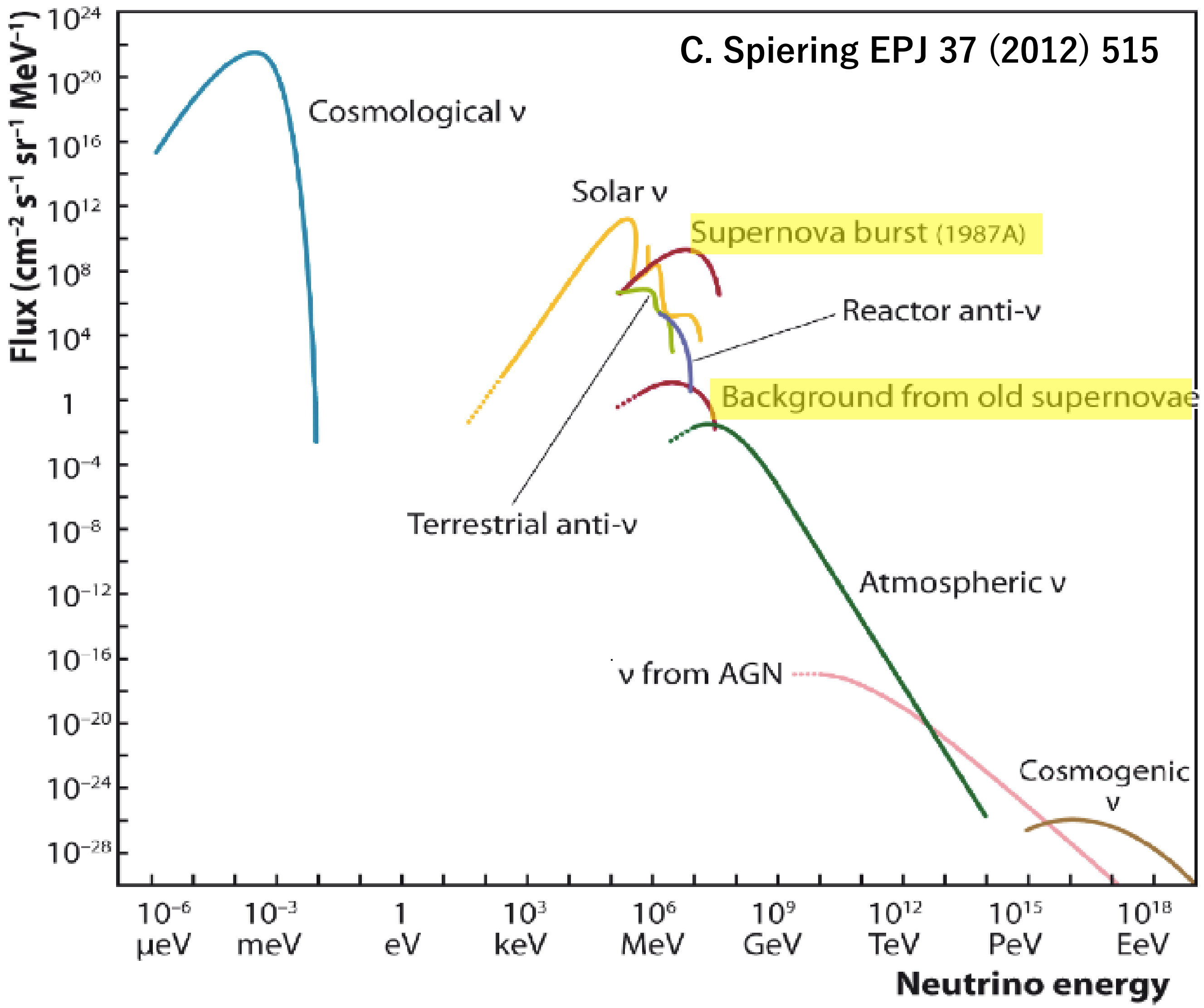
- Directional sensitivity
  - ν_eCC: (Fermi and Gamov-Teller transitions) →flat cosine distribution
  - **ES selection** is indispensable as other detectors
  - Reconstruction of the scattered electron's head-tail information is the key



$$\nu + e^- \rightarrow \nu + e^-$$

Janina Hakenmüller SN ORNL workshop Mar. 2023

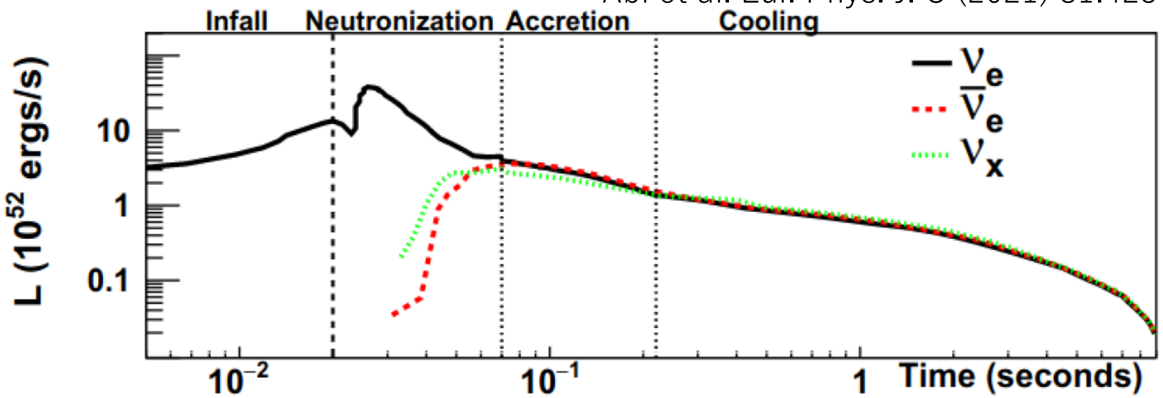
Supernova neutrino



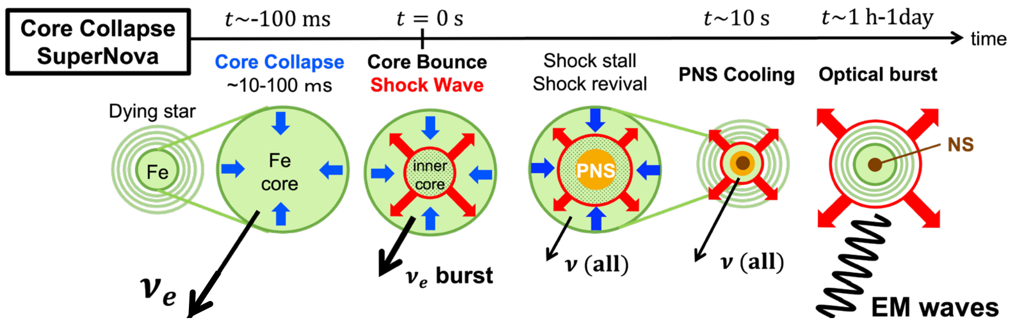
Core-collapse supernova (>8$M_\odot$)

- The basic mechanism of core-collapse supernovae explosions (CCNS) was established by detecting 24 neutrinos from 1987A. Neutrinos play a key role in the explosion.

Abi et al. Eur. Phys. J. C (2021) 81:423



Luminosity vs. time



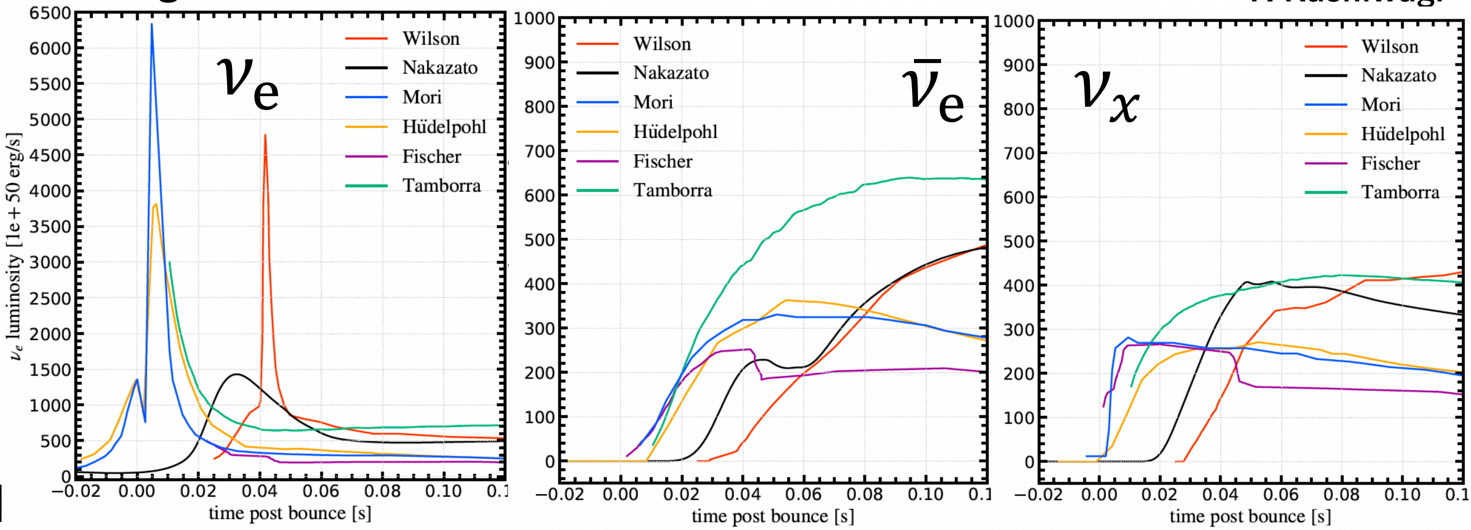
However, details are largely unknown

- Shock revival mechanism, equation of state, PNS formation
- Convection, SASI, …
- Fail, BH formation,…
- Many unknowns, models, and predictions

Ex) Wilson, Nakazato, Mori, Hüdelpohl, Fischer, Tamborra

Light curves ~0.1 sec

Y. Kashiwagi

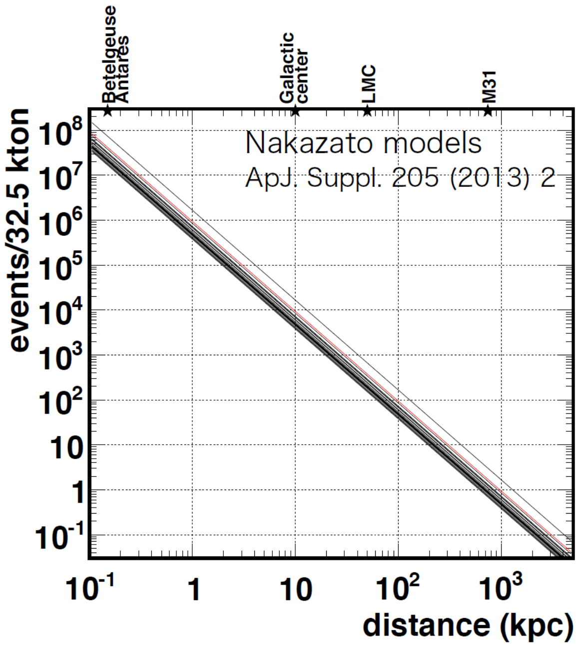


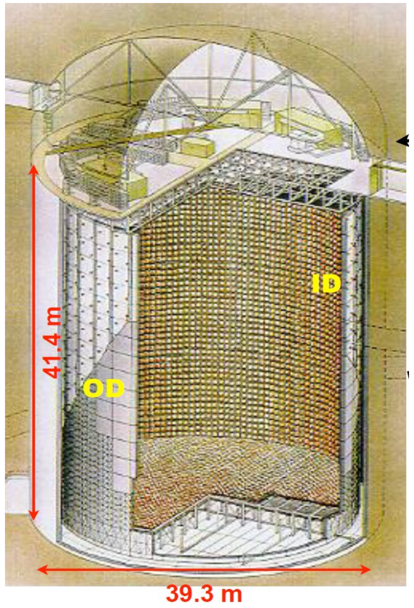
- We must prepare for the next nearby SN
- Explore the time, energy, and flavor structure to get at the details of the explosion mechanism

The expected statistics

- **The larger detectors cover SMC**

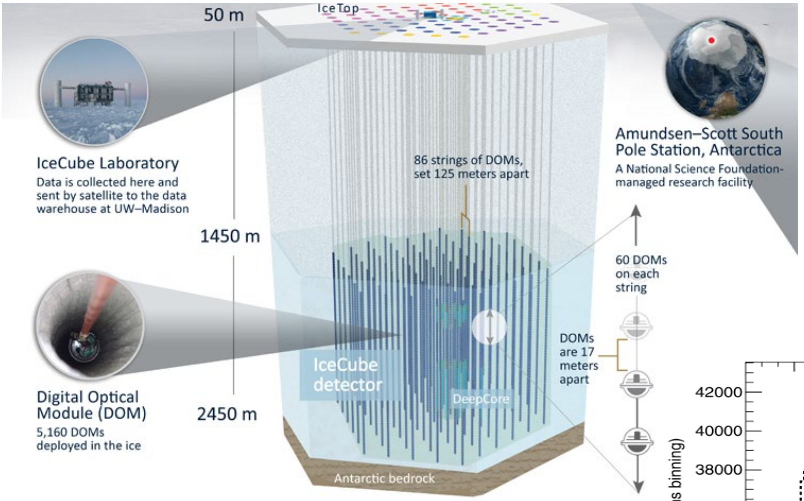
32.5 kton water





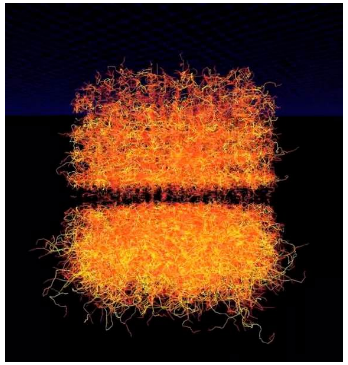
	Nakazato (SN)	Nakazato (BH)
Betelgeuse (150pc)	16.7~37.7 M	73.8 M
at 10kpc (Galactic center)	3.76~8.49 k	16.6 k
LMC (50kpc)	150~340	664

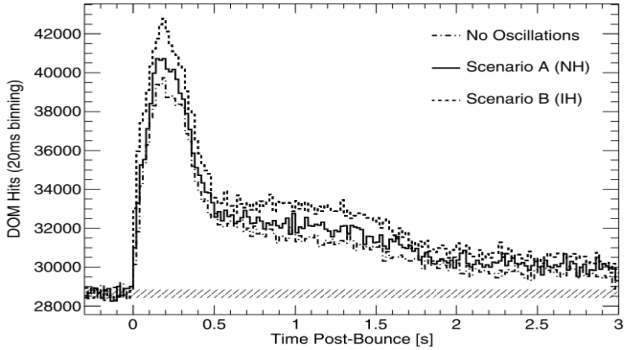
Giga-ton ice



SN MeV events

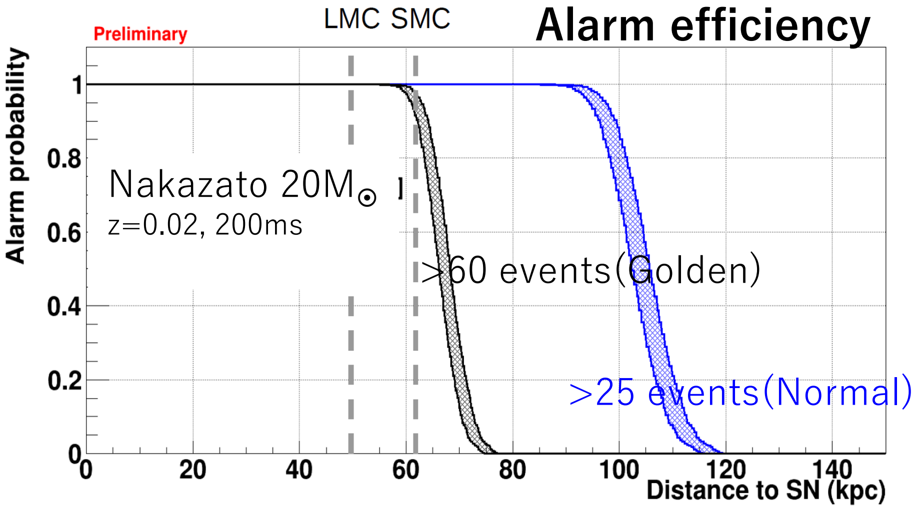
Benedikt Riedel



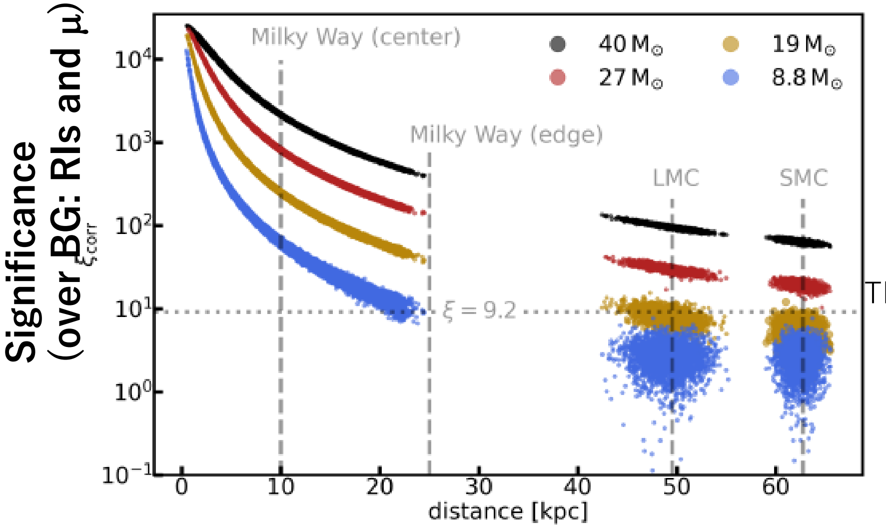


By increase of PMT single rates, time structure is obtained.

Alarm efficiency

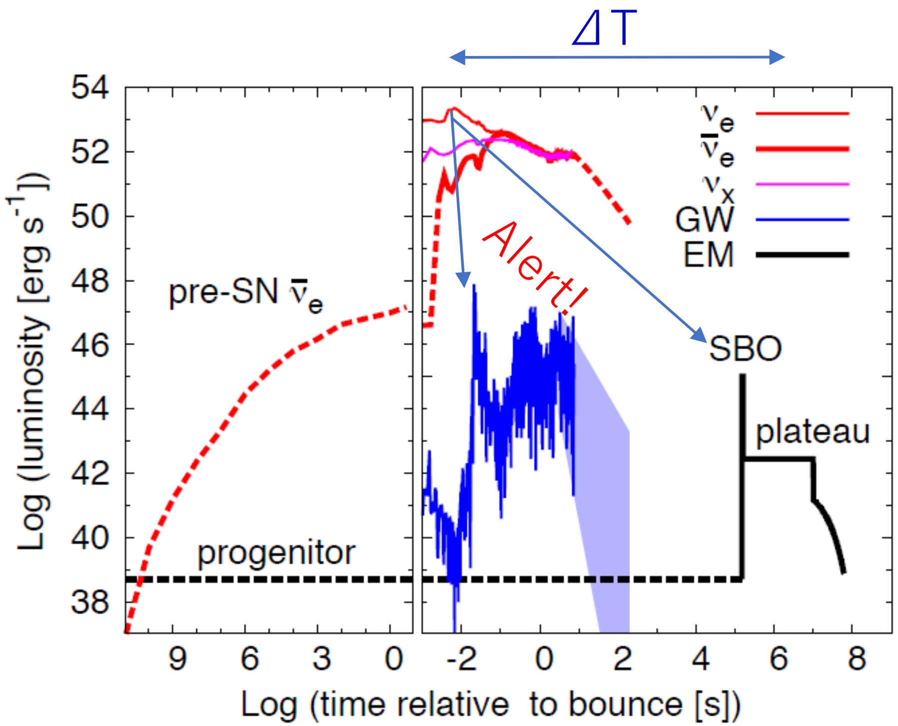


arXiv:2308.0117

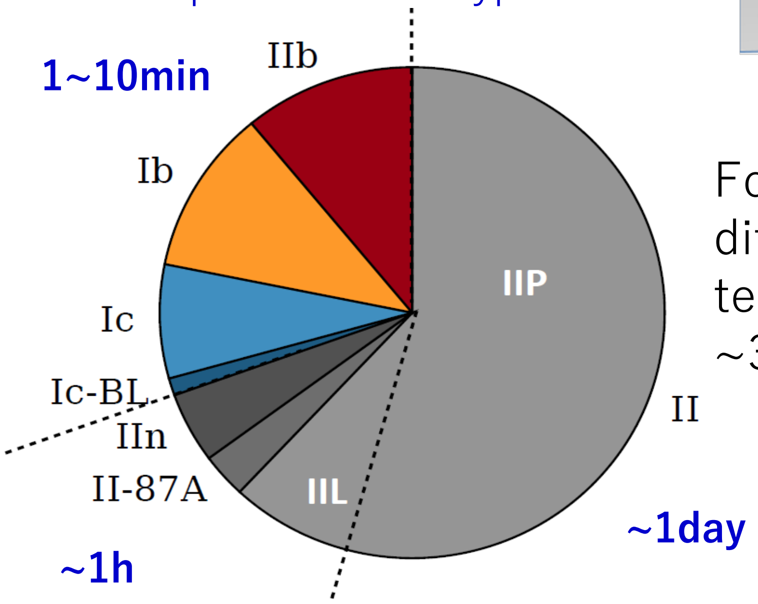


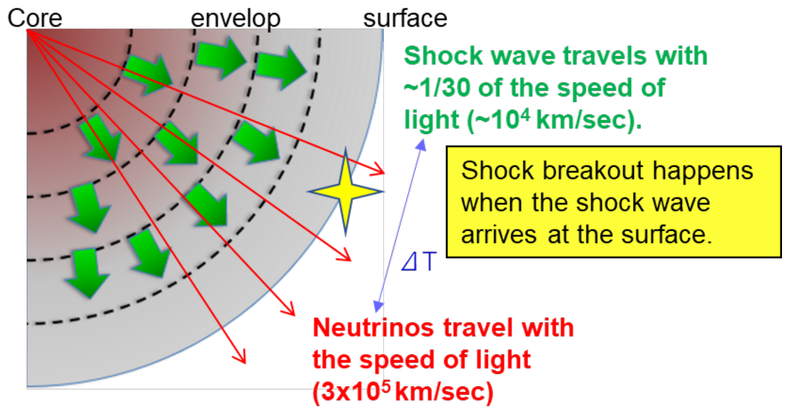
For multi-messenger astronomy

The vital role for neutrino detectors →**Neutrino burst alarm**



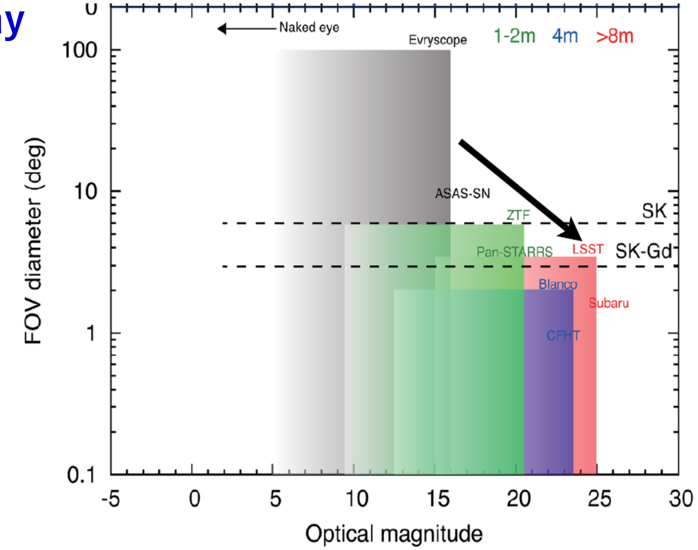
⊿T depends on the type of SN



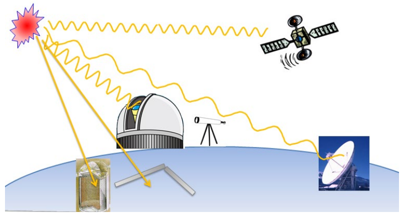


For ~70% of SNe, the time difference is several hours to tens of hours. For the remaining ~30%, that is several minutes.

K. Nakamura MNRAS, 461, 3296 (2016)



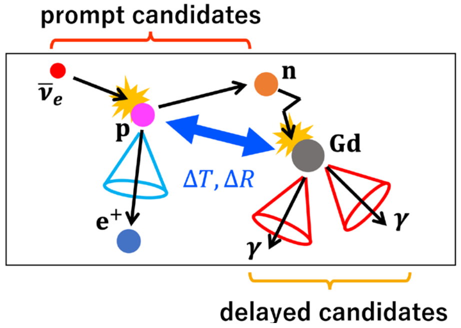
- **Neutrino burst alarm <~1 min. with the DIRECTION INFORMATION <~3^o must help the pointing of EM telescopes**



For multi-messenger astronomy

- **Neutrino burst alarm with direction information**

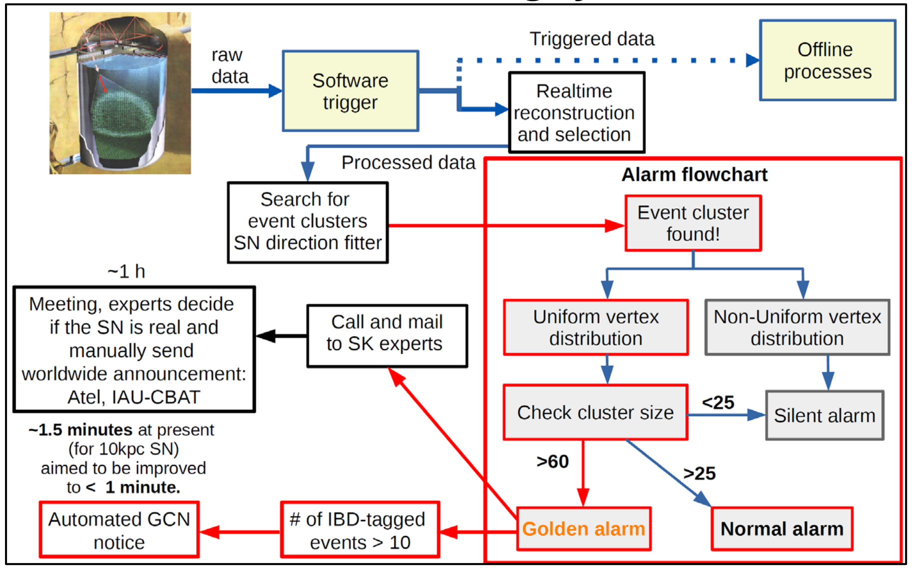
0.03% Gd makes IBD tagging efficient in SN monitoring
Speed-oriented real-time simple IBD tagging algorithm

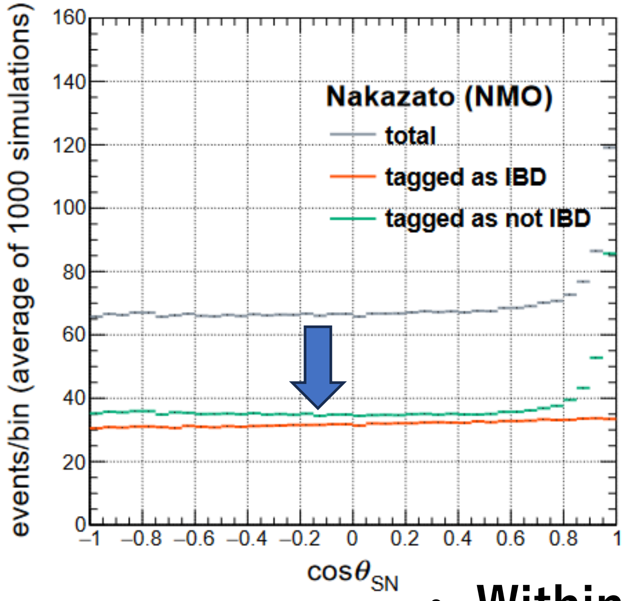


① Selection of prompt candidates ≧7MeV
② Selection of delayed candidates
③ Neutron tagging pair of events with

$$\Delta T < 500\ \mu s\ \&\ \Delta R < 300\ \text{cm}$$

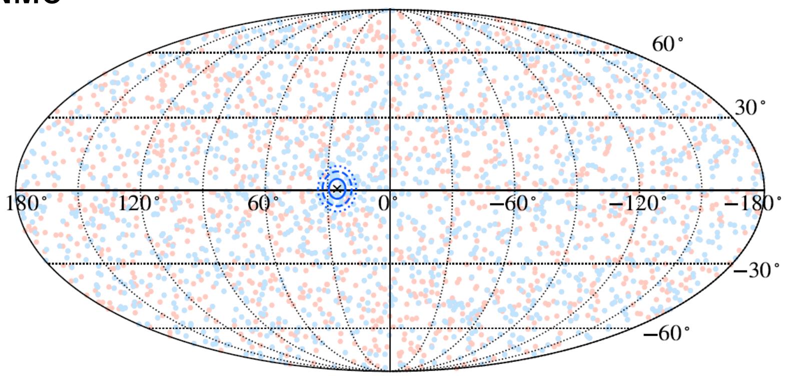
The automated monitoring system in SK-Gd



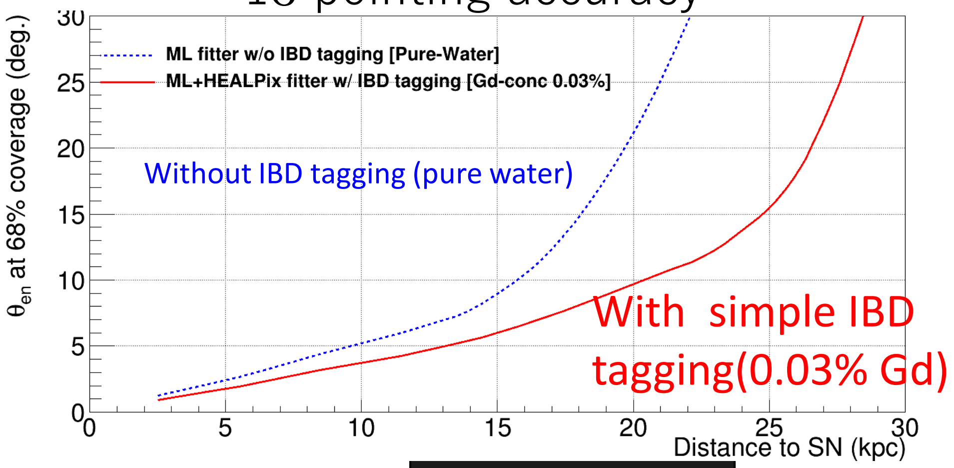


10kpc
Nakazato 20M$_\odot$
z=0.02, 200ms
NMO

3.96±0.13°
(68%CL)@10kpC



1σ pointing accuracy



- **Within 1.5min, SK_SN notice will be sent through GCN Notice**

General Coordinates Network
GCN Circulars are now part of the new GCN!

For multi-messenger astronomy

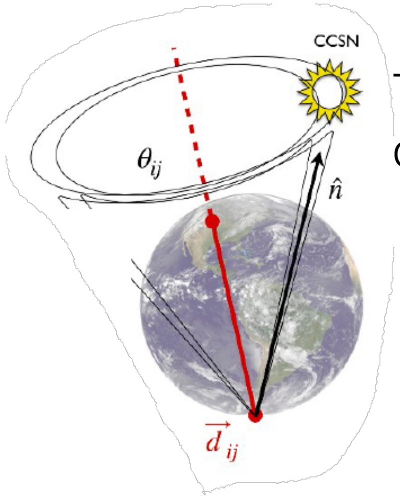
- **Future neutrino burst alarm with direction information**

Triangulation

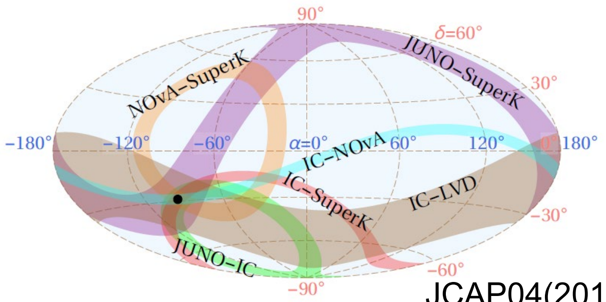
ex) SNEWS 1.0→2.0

SNEWS SUPERNOVA EARLY WARNING SYSTEM

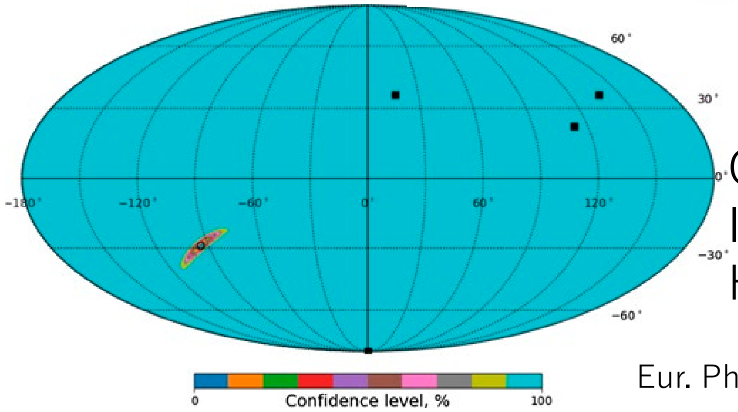
New J. Phys. 23 031201



The time delay between the signal at different detectors define a sky region



JCAP04(2018)025



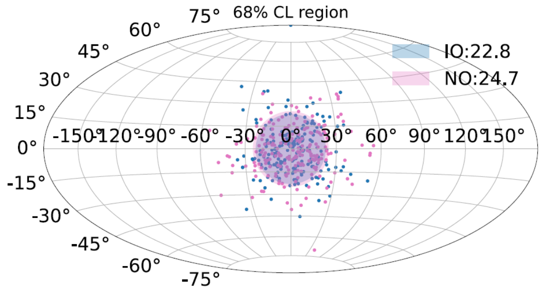
Combination of IceCube, KM3NeT/ARCA, Hyper-Kamiokande and JUNO

Eur. Phys. J. C (2020) 80:856

JUNO

The direction between the IBD prompt p and delayed n capture reconstructed vertexes in 20kton LS give the SN direction

12° (68%CL)@10kpC

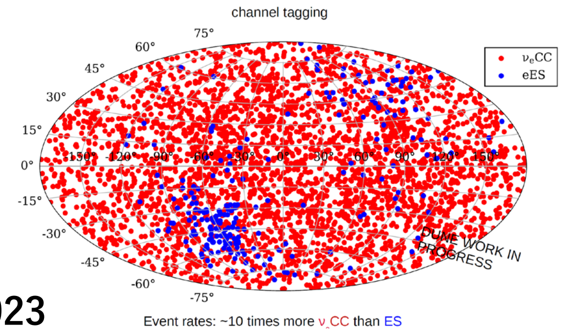


Marta Colomer Molla @ICRC2023

DUNE

CC/ES channel separation is the key.

5° (68%CL)@10kpC



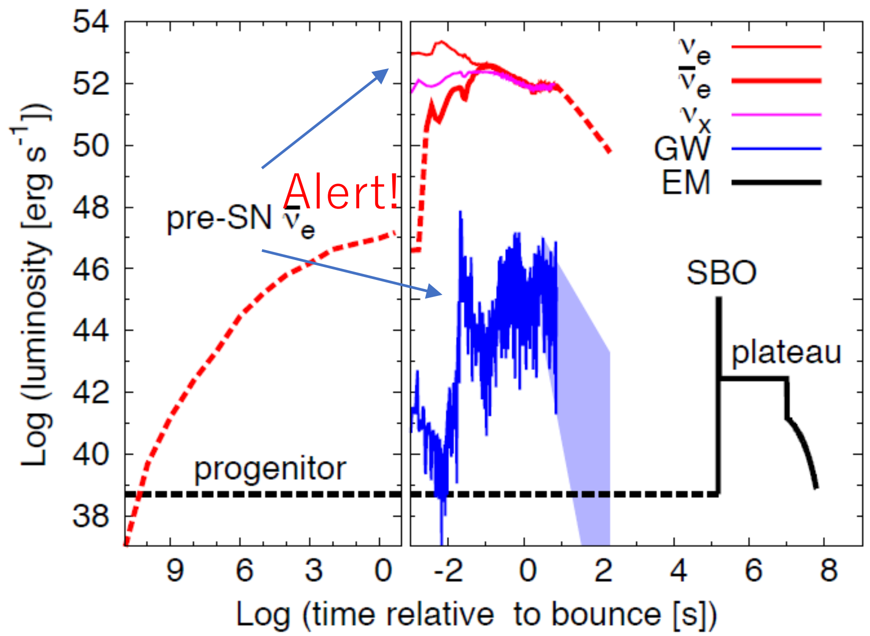
Janina Hakenmüller @SN ORNL workshop Mar. 2023

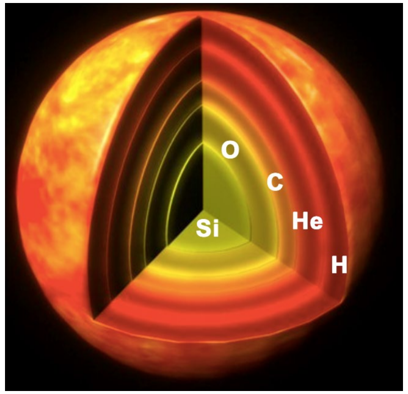
LAr volume	40kt	10kt (one module)
Perfect disambiguation	3.7 deg	7.4 deg
4% ν_eCC as eES	5.0 deg	10.6 deg

(68% confidence level)

GKVM model, 10kpc distance

Pre-SN alarm for nearby SNe





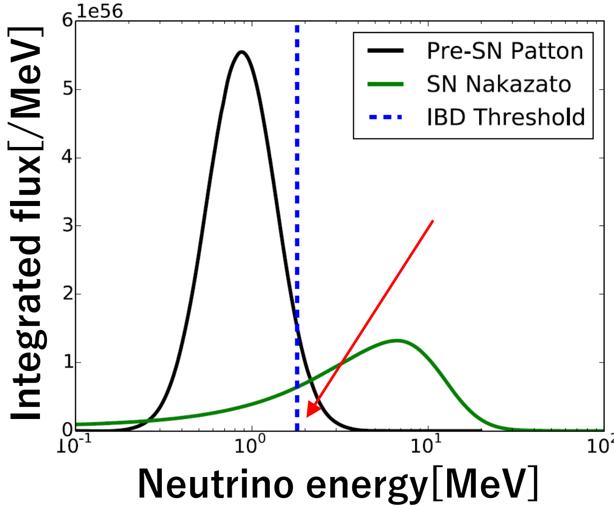
Burning Stage	Duration	Average **ν** energy
C	300 years	0.71 MeV
Ne	140 days	0.99 MeV
O	180 days	1.13 MeV
Si	**2 days**	**1.85 MeV**

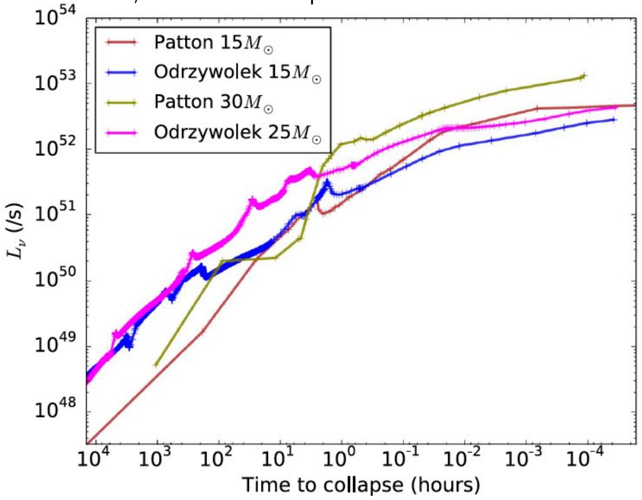
Duration of burning stages and the fraction and average energy of electron neutrinos emitted by **pair-annihilation** for a 20 M⊙ star (**Astropart.Phys. 21 (2004) 303-313**)

- and many Models・・・

Odrzywolek, et al 2010 Acta Phys. Pol. B 41, 1611
Patton, et al 2017 ApJ 851 6

ApJ 885:133, 2019



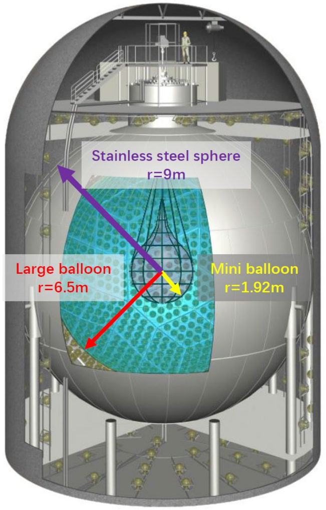


- Low-BG low-threshold required
  - Liquid scintillators/ Gd-Water Cherenkov
- IBD is the main channel
  - The energy threshold for IBD is 1.8 MeV
  - Large volume is needed.

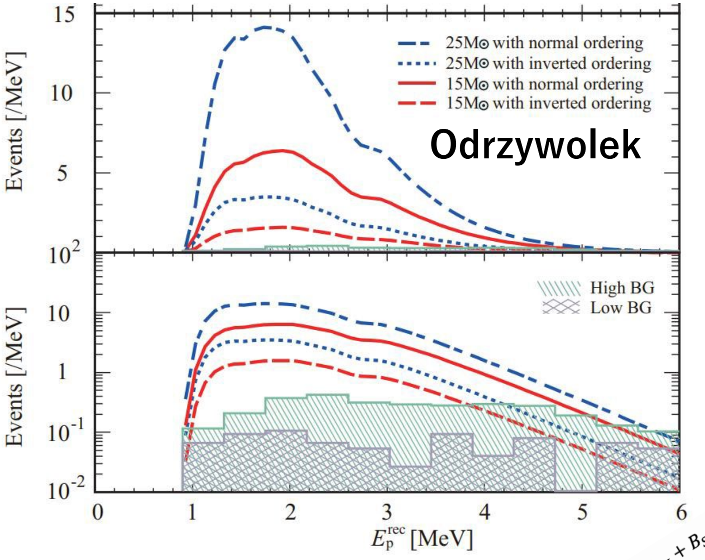
Pre-SN alarm

Aug 31st 14:30
Lucas Nascimento Machado

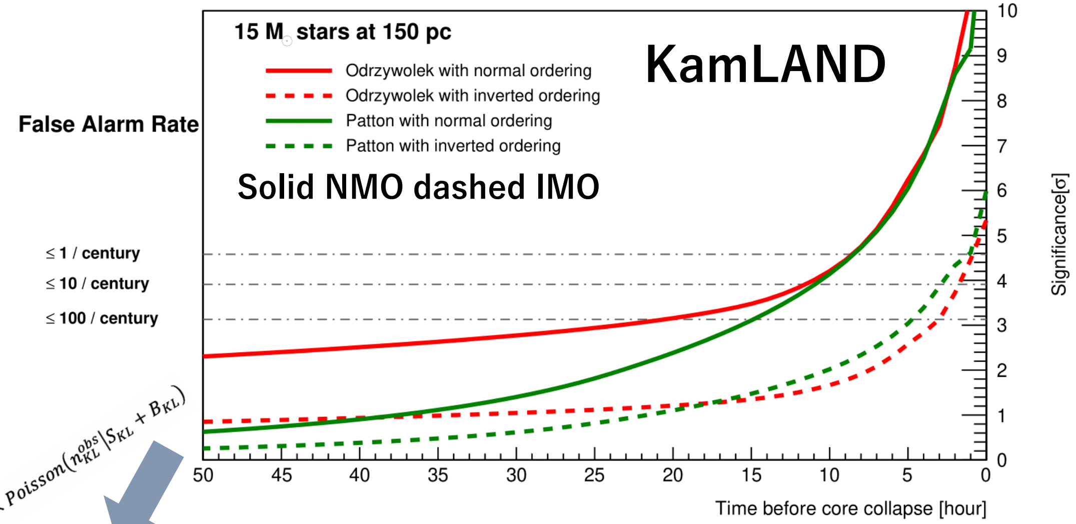
ApJ Journal, 818:91 (8pp), 2016



1kt LS



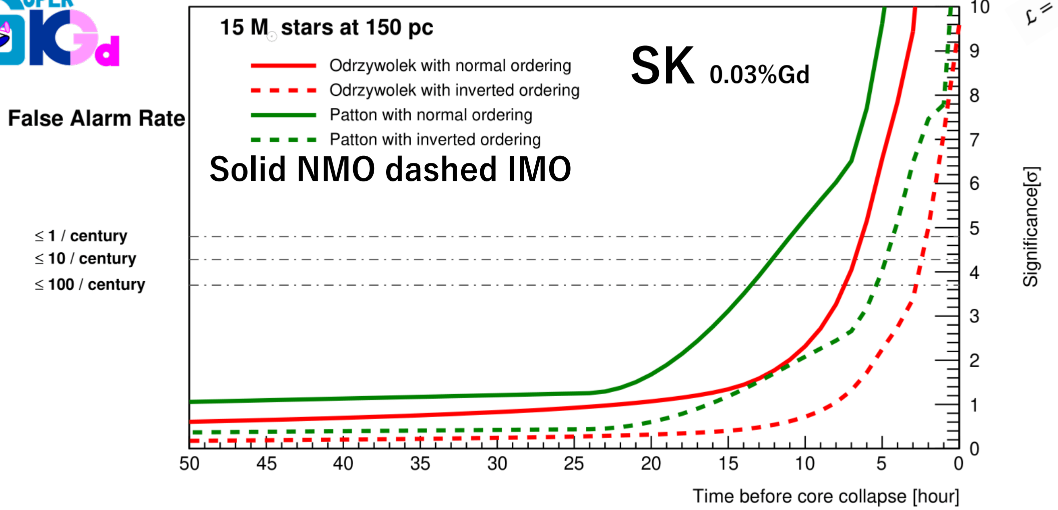
The significance of detection based on the number of accumulated events for Betelgeuse

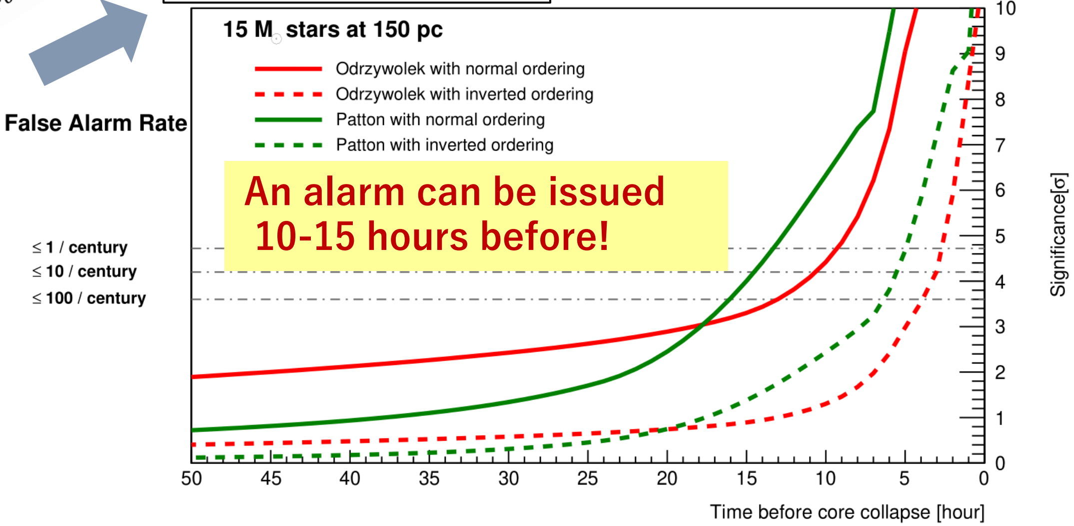


$$\mathcal{L} = Poisson(n_{SK}^{obs}|S_{SK}+B_{SK}) \times Poisson(n_{KL}^{obs}|S_{KL}+B_{KL})$$

SK+KamLAND

https://www.lowbg.org/presnalarm/





An alarm can be issued 10-15 hours before!

A combined alarm with SK and KL has been available since May 2022 (MoUed)

GCN circular is also available

SNO+ should have a similar, and JUNO should have better sensitivity

Diffuse Supernova Neutrino Background

Supernova Relic Neutrino

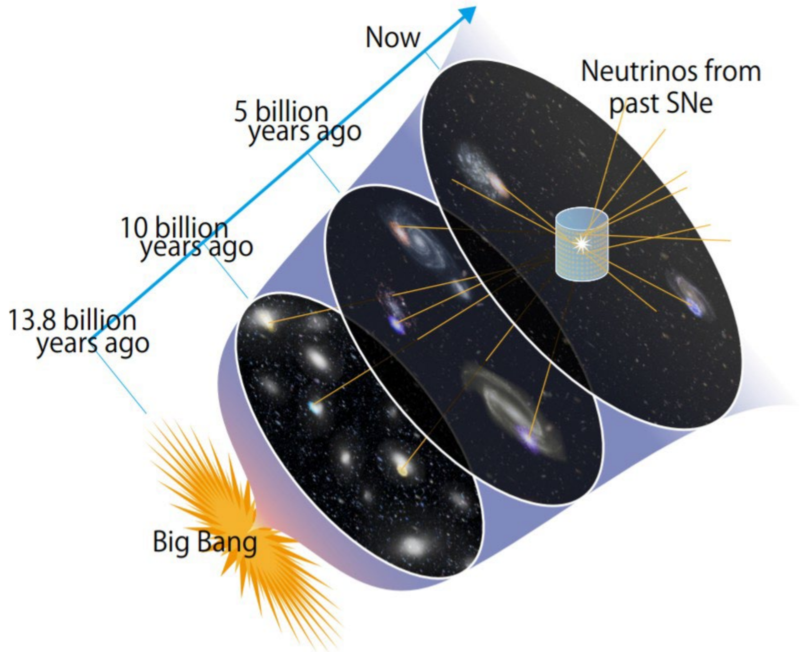
Neutrinos emitted in past supernova explosions and stored in the current universe → **promising extra-galactic ν**

- In the entire universe, several supernova explosions occur every second.
- There must have been O(10^{18}) explosions in the history of the universe.

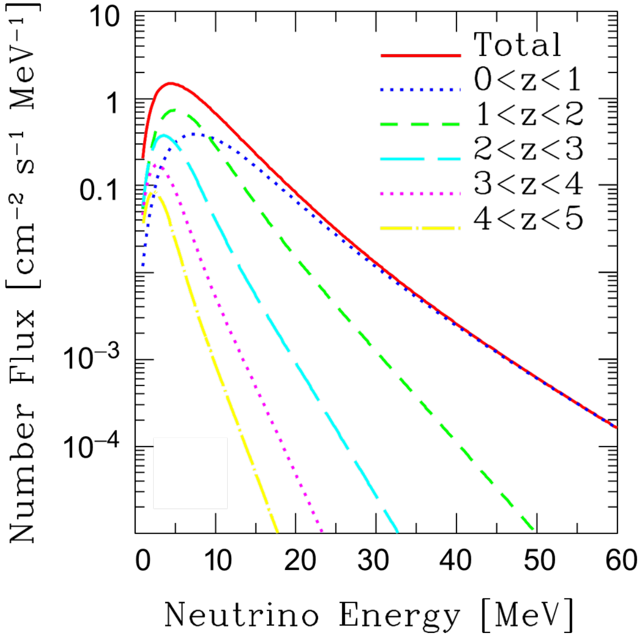
$$\frac{dF_\nu}{dE_\nu} = c\int_0^{z_{\max}} R_{\rm SN}(z)\frac{dN_\nu(E'_\nu)}{dE'_\nu}(1+z)\frac{dt}{dz}dz$$

SN rate at z — **(averaged) SN spectrum**

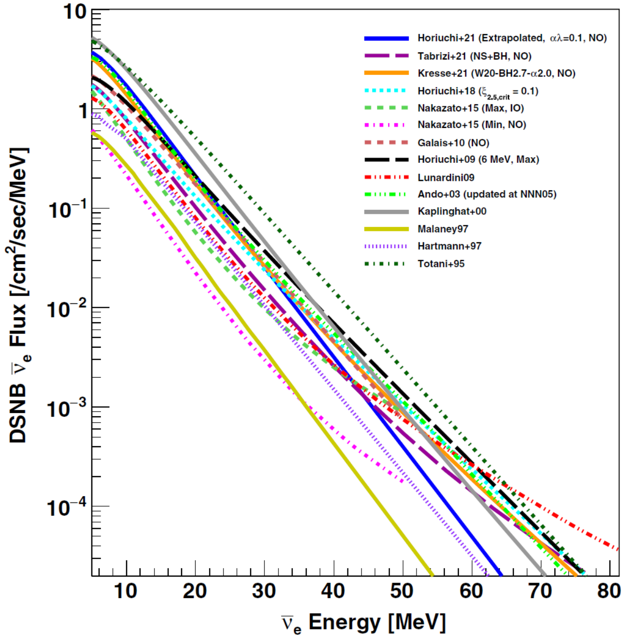
Access to
- ✓ **History of Star Formation**
- ✓ **BH formation**
- ✓ **Mechanism of the supernova explosion**



S. Ando 2004 *ApJ* 607 20



PRD 104, 122002 (2021)



Many models

+ ν MO or/and exotic process (ex ν-decay) affects!

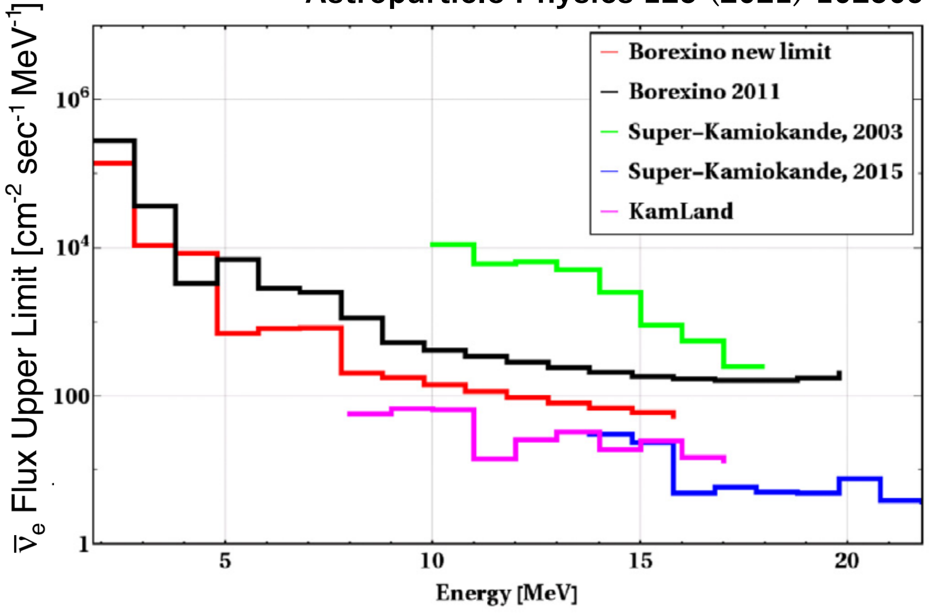
Aug 31 14:45 Pilar Iváñez-Ballesteros

DSNB search results

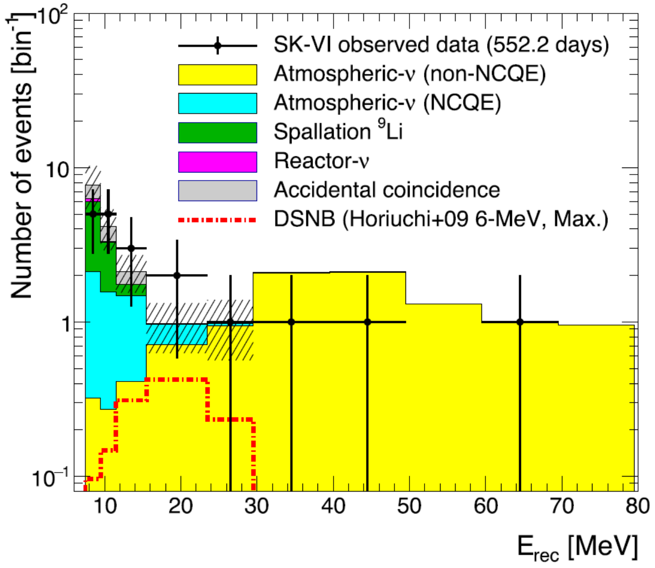
Aug 31st 14:30
Masayuki Harada

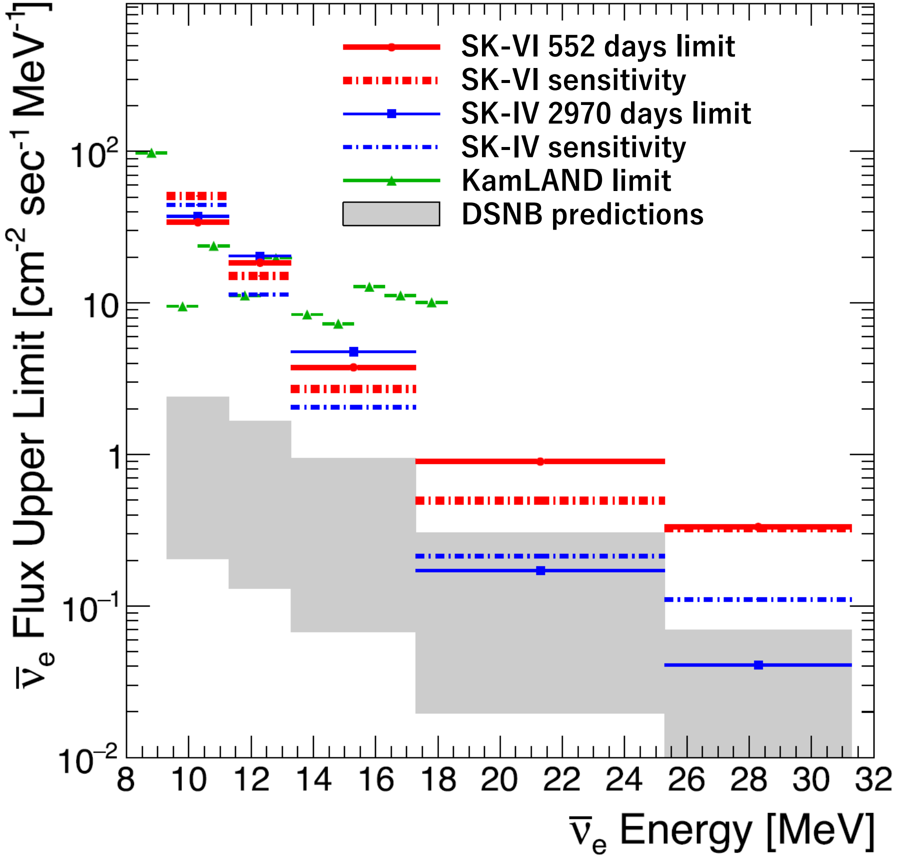
- **The 1st SK-Gd 0.01% (SK-VI) results with 552 days**

Astroparticle Physics 125 (2021) 102509



ApJ Lett., 951:L27, 2023





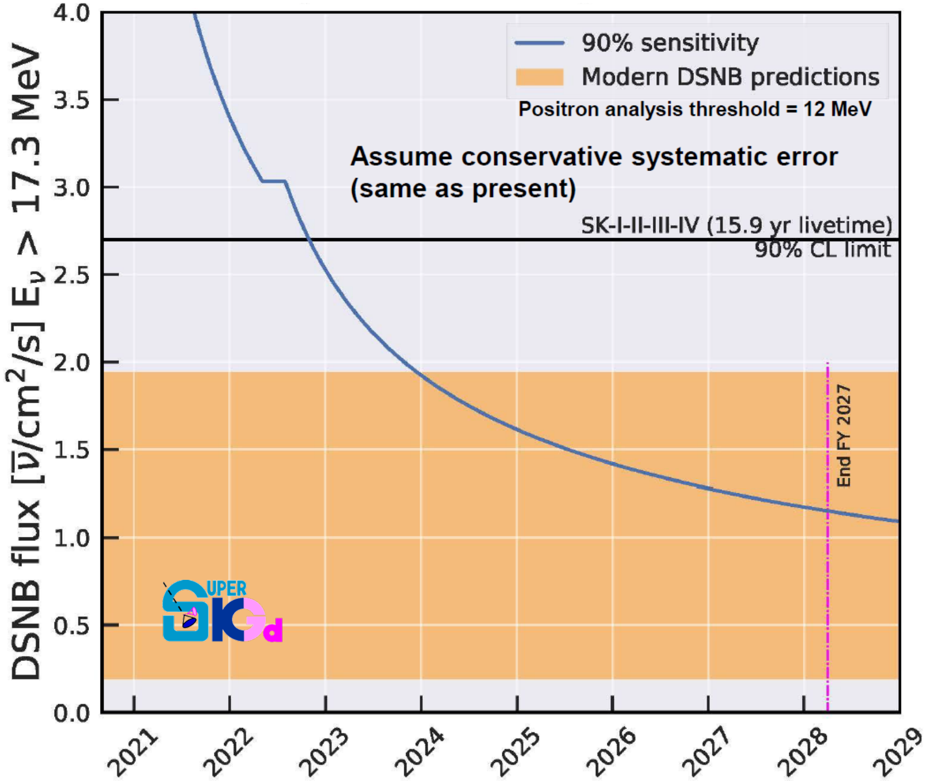
The best limits are given by

<7MeV	**Borexino**
7~13MeV	**KamLAND**
>13MeV	**SK**

- 1.5 years of data with 0.01% SK-Gd is comparable to 10 years of pure-water SK data thanks to the improvement of neutron detection efficiency.
  → Promising 0.03% SK-Gd (SK-VII)'s DSNB search!

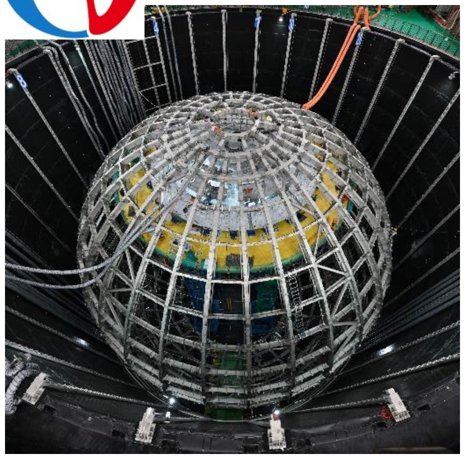
Future DSNB search

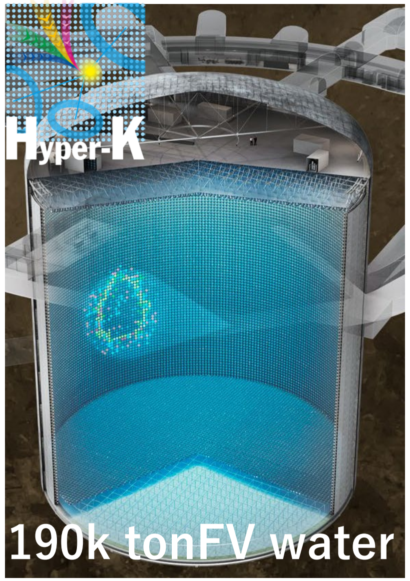
SK-Gd sensitivity



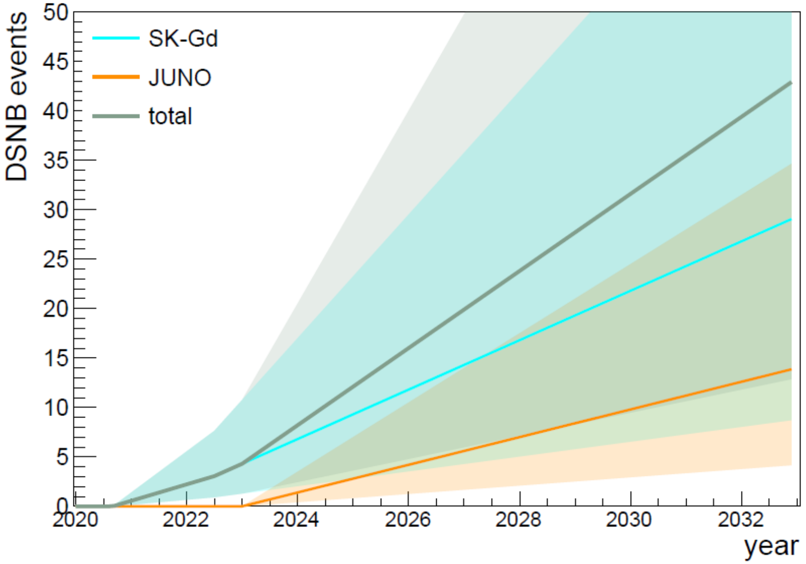
Assume the atmospheric NC background is the same as SK-IV (super conservative)

17k tonFV LS

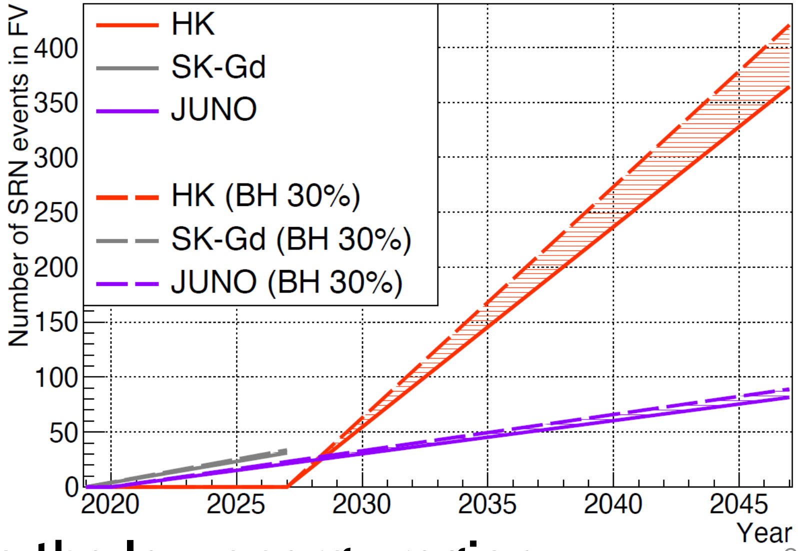




Universe 2022, 8, 181

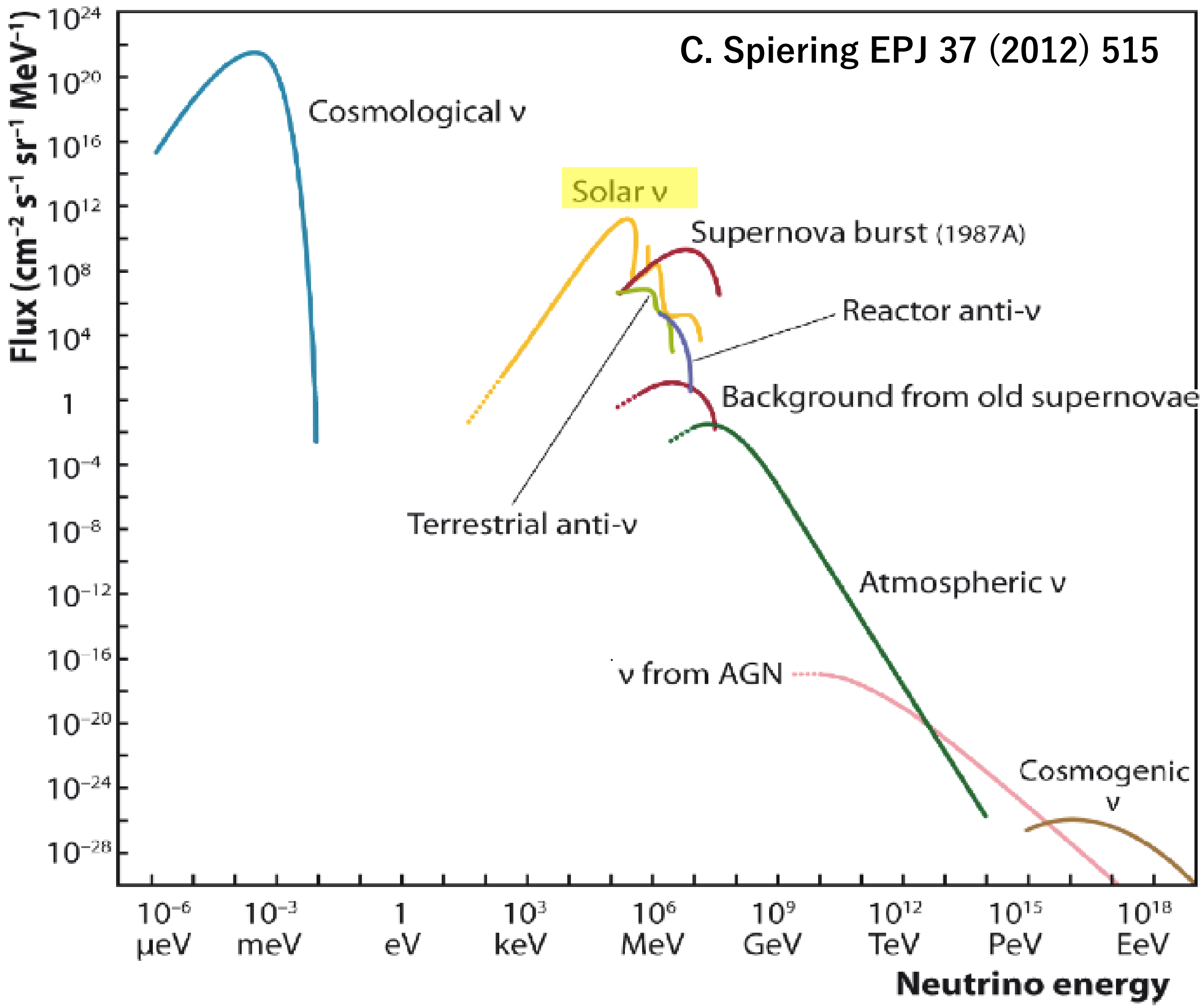


arXiv:1611.06118



KamLAND and SNO+ will also explore the low energy region

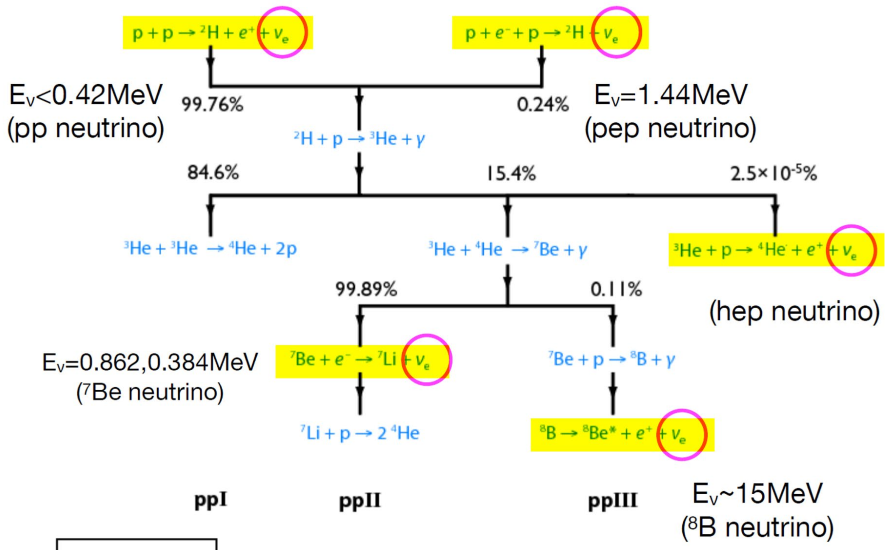
Solar neutrino

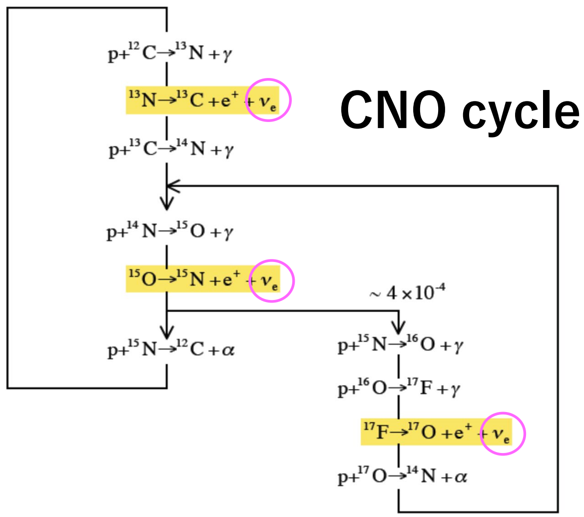


$1M_\odot$ Star case: Solar Neutrinos

- **Standard Solar Model**

pp-chain (~99%)

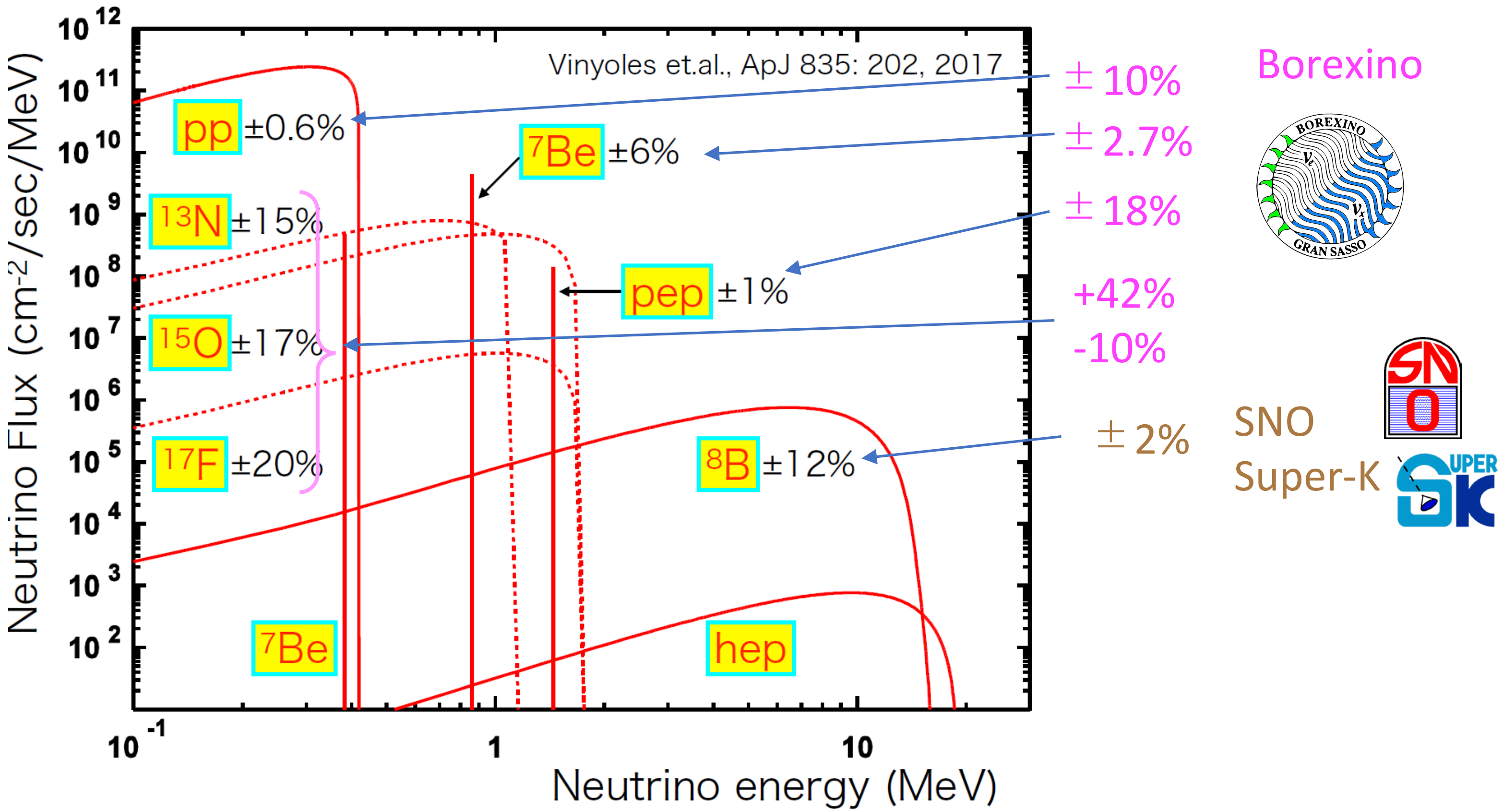




CNO cycle (~1%)

Energy spectra w/ SSM uncertainties

Measured flux errors



⁷Be and ⁸B are measured more precisely than SSM!

→ Importance of the solar neutrino measurement

→Latest SSM with latest helioseismic and solar neutrino data: Francesco L. Villante Aug 31,4:30 PM

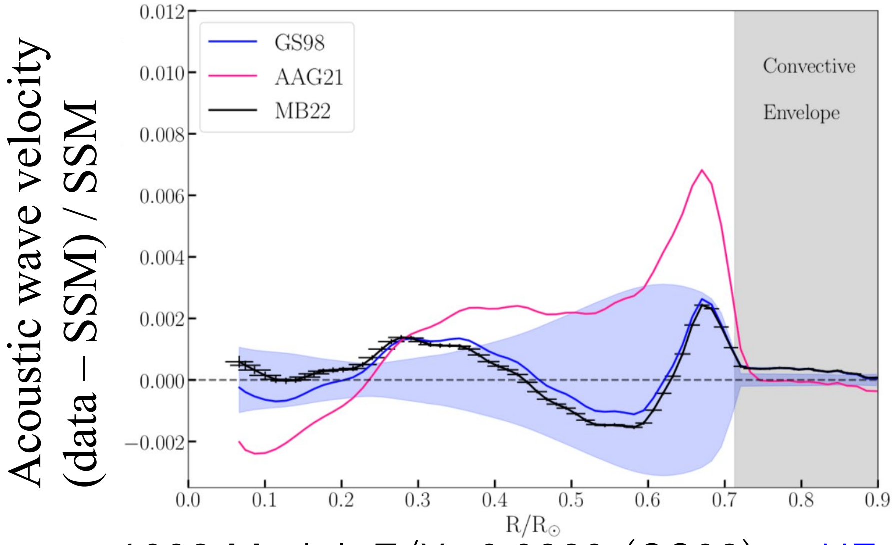
Metallicity problem and SSM

- **Metallicity = Z/X**
  - Heavy element (>Li) abundance
  - X: H, Y: He, Z: (Z≥3)
  - **High-Z or Low-Z?**

Helio-seismic results@2022

Z/X=0.2485 ± 0.0035 → HZ ?

Magg et al., 2022



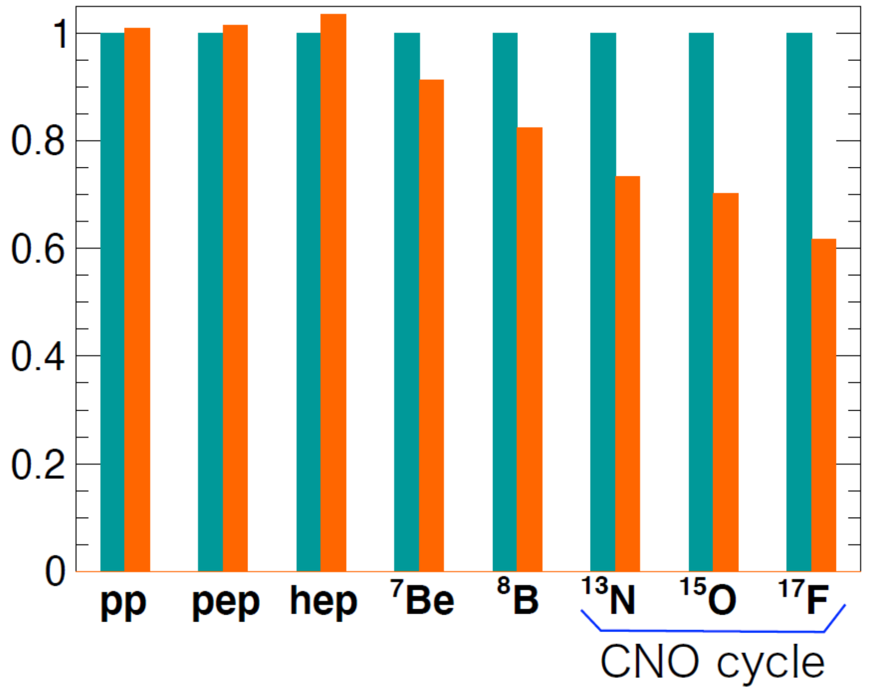
1998 Model Z/X=0.0229 (GS98) HZ
2009 Model Z/X=0.0178 (AGSS09) LZ
2021 Model Z/X=0.0187 (AGG21) LZ
2022 Model Z/X=0.0225 (MB22) HZ

Neutrino flux

Metallicity influences the solar neutrino fluxes:

- Indirectly for all neutrinos:
  opacity →temperature →cross sections → flux
- Directly for the CNO neutrinos:
  C, N, O content in the core of the Sun

Ratio of LZ to HZ (=1)
in each solar neutrino flux



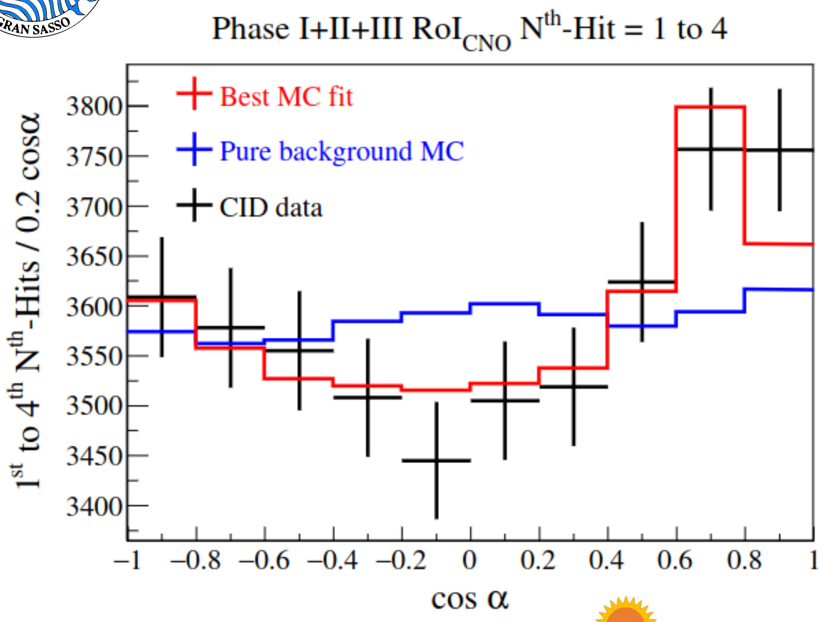
CNO flux measurement is the key to determine HZ or LZ

CNO flux status

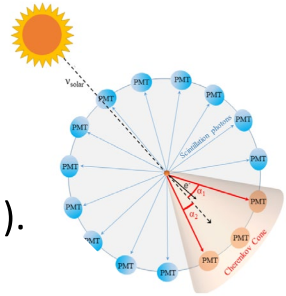
The complete Borexino dataset (2009-2021):

Aug 28th 17:00
Davide Basilico
arXiv:2307.14636

Borexino CID analysis



Inclusion of systematics
Subtraction of pep and ^{8}B without assumptions on the background (in particular 210Bi).

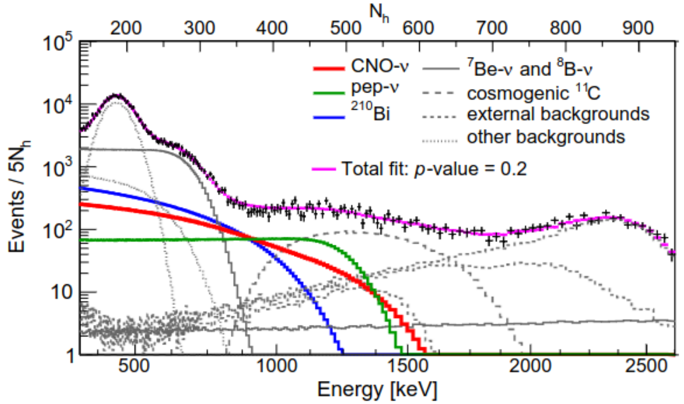


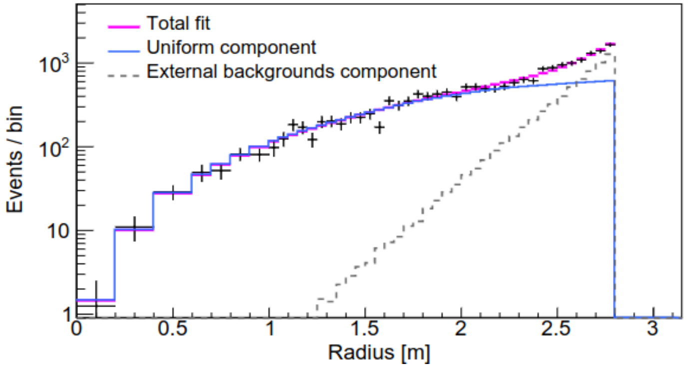
- no-CNO hypothesis, with *pep* constraint only, rejected at 5.3σ level

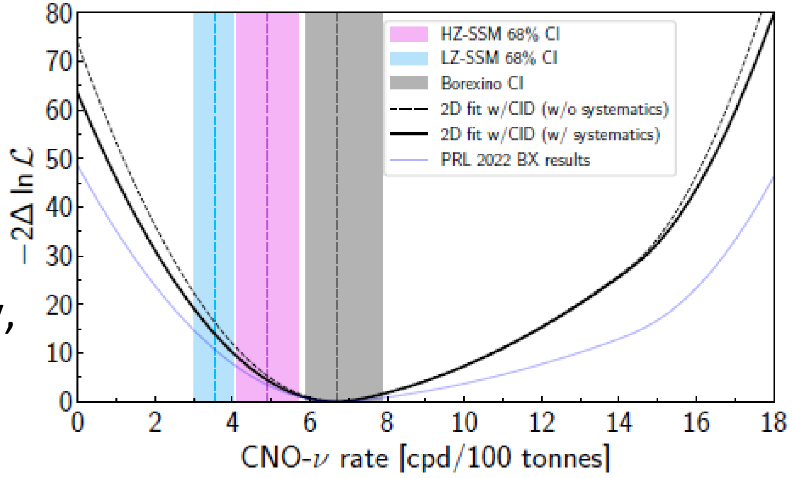
Borexino Final CNO results

$$\mathcal{L}_{MV+CID} = \mathcal{L}_{MV} \cdot \mathcal{L}_{pep} \cdot \mathcal{L}_{^{210}Bi} \cdot \mathcal{L}_{CID}^{P-I} \cdot \mathcal{L}_{CID}^{P-II+III}$$

energy+radial fit | *pep* neutrino constraint | 210Bi rate constraint | CID analysis



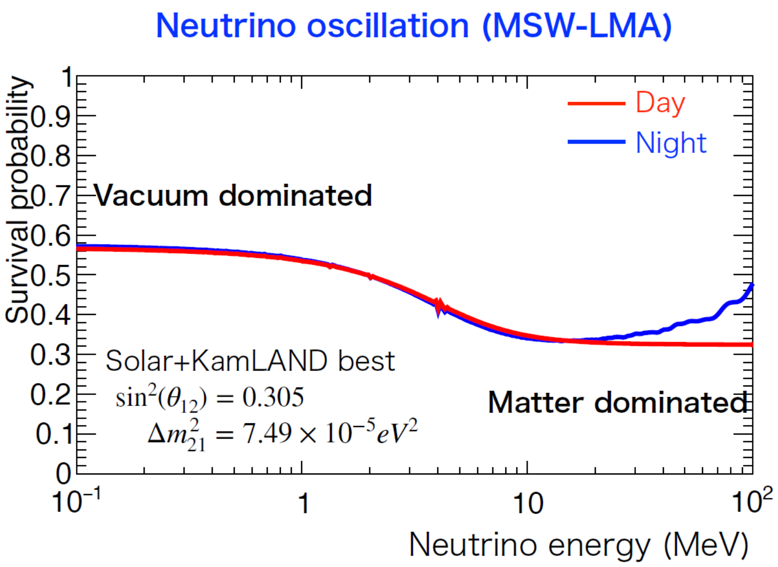


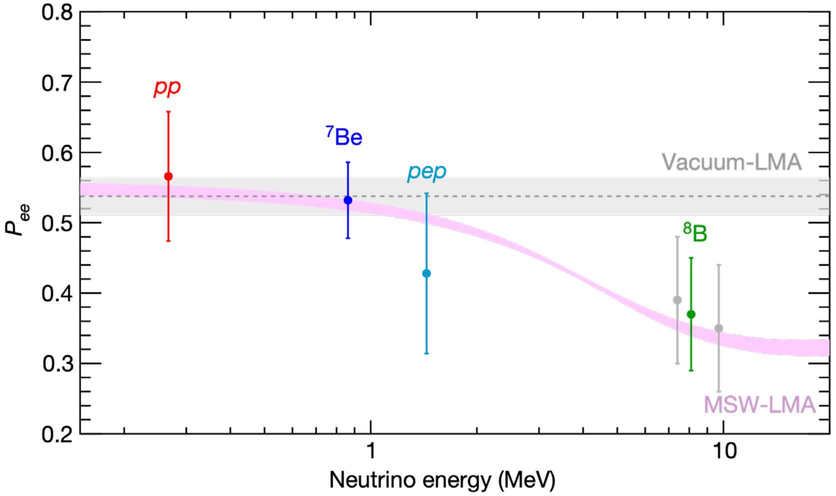


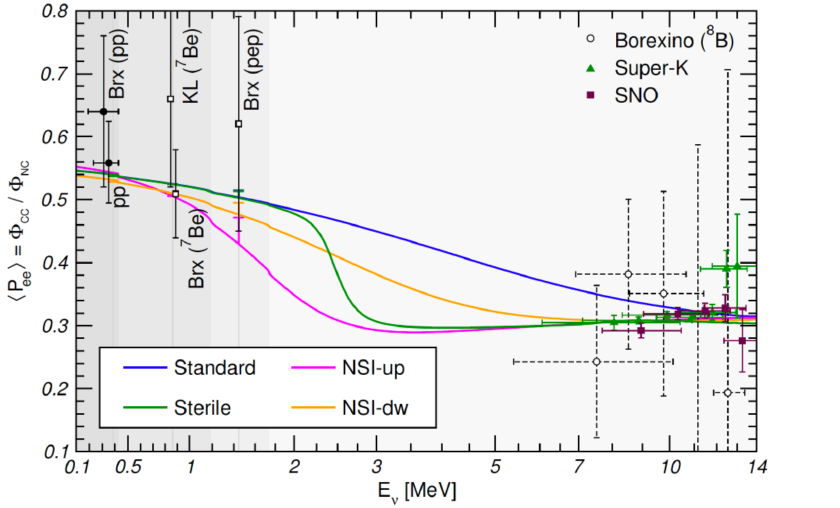
- Significance against no CNO hypothesis about 8σ
- $\Phi CNO = 6.7^{+1.2}_{-0.8} \times 10^{8}\ cm^{-2}s^{-1}$,
- Results in agreement with High Metallicity scenario (Low Metallicity scenario disfavoured at 3.1σ significance)

Neutrino Oscillation

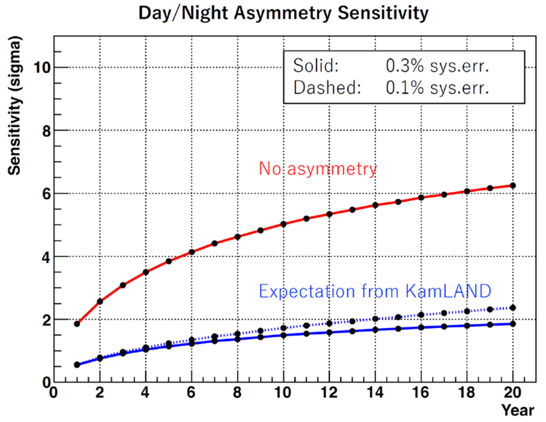
- The standard model: MSW-LMA
  - The survival probability as a function of energy







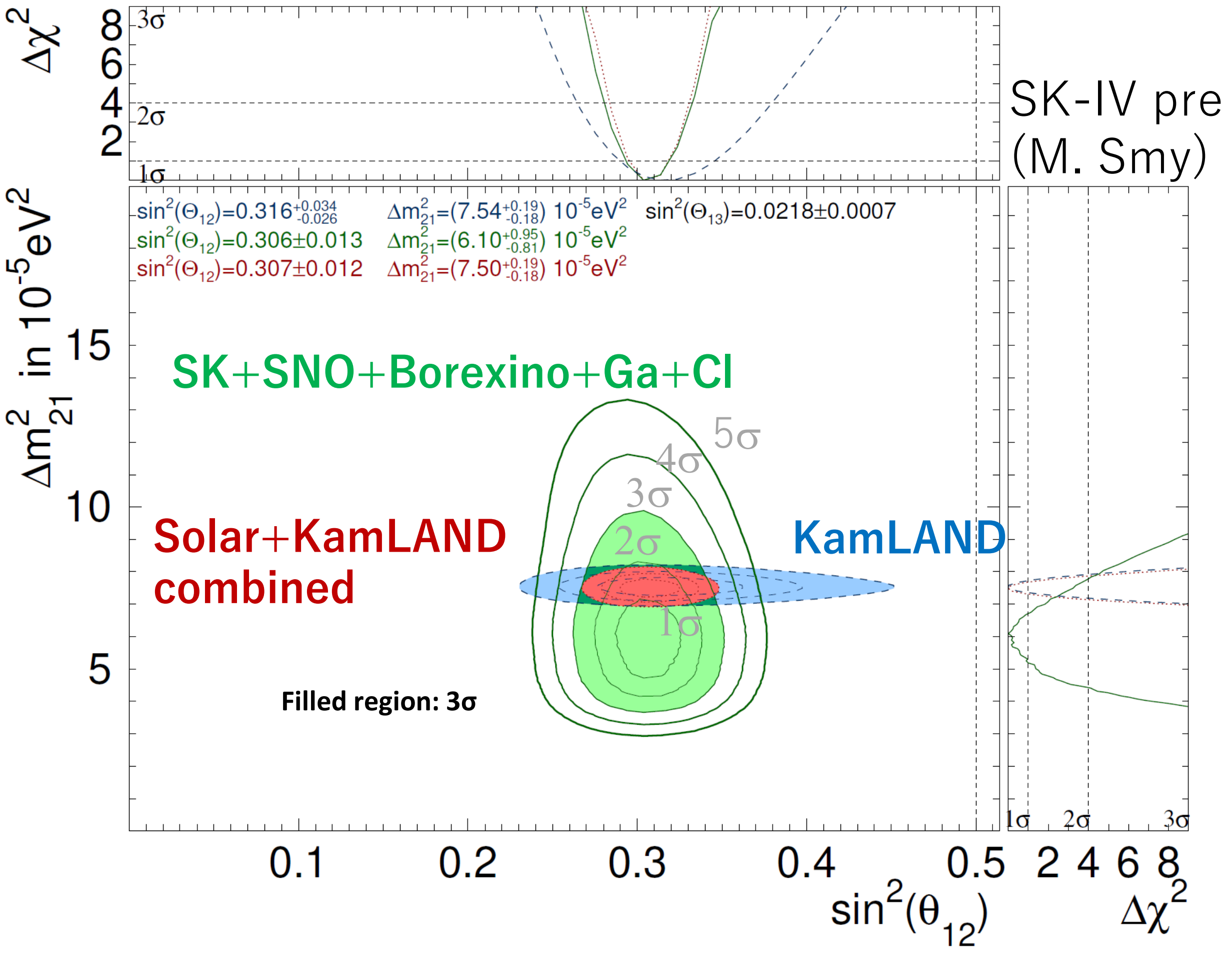
- **Borexino data by itself consistent with the expectation from MSW-LMA**
- **Loweinrg ^{8}B detection threshold (SK, SNO+) will test the transition from matter-dominated to vacuum-dominated regions if NSI exits.**
- **Day/Night flux asymmetry will test the earth matter effect (HK)**



Global oscillation parameters, incl. Borexino

With reactor θ_{13} constraint

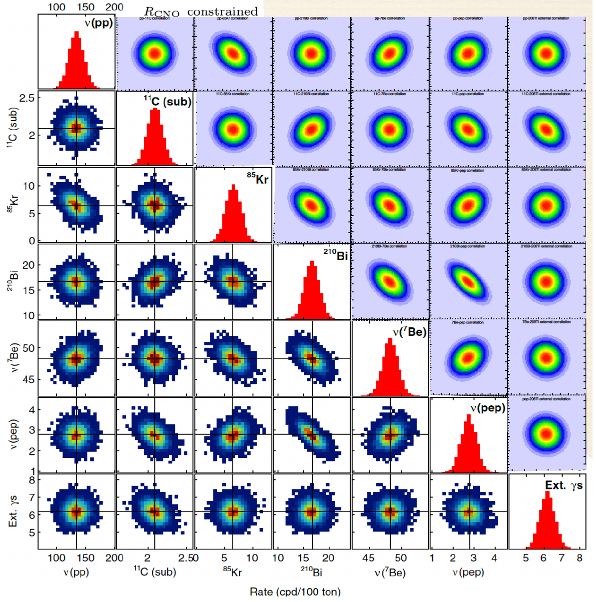
PRD 100, 082004
CNO: Nature 587, 577



SK-IV preliminary
(M. Smy)

Assumed correlation matrix
Generalized Gaussian

published by Borexino



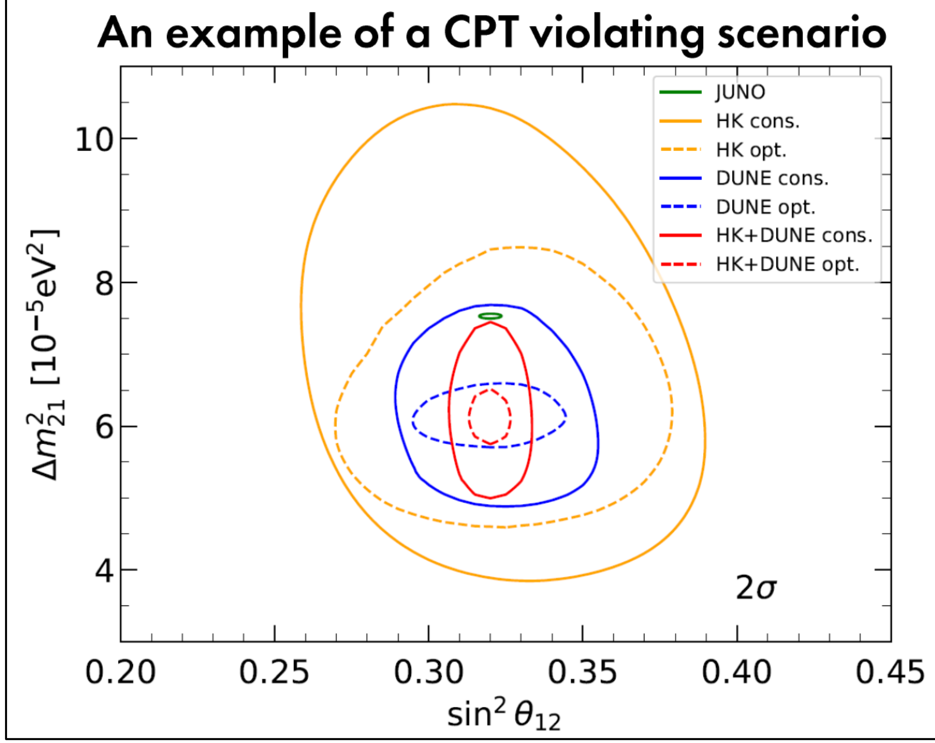
~1.5σ tension
between solar neutrinos and KamLAND antineutrinos

Future prospect

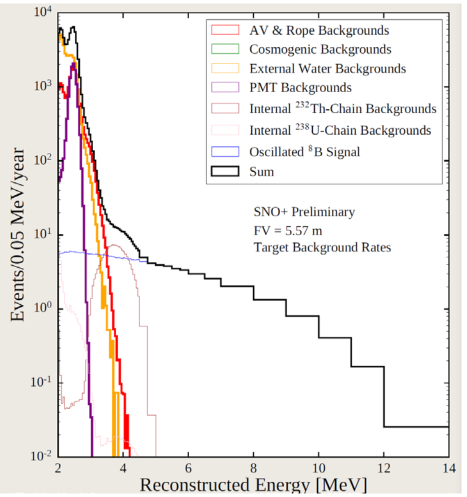
Morgan Askins
New Physics Opportunities 2023

CPT Theorem ensures that particles and antiparticles have the same mass and, if unstable, the same lifetime. Then, CPT violation could manifest as different oscillation parameters for neutrinos and antineutrinos.

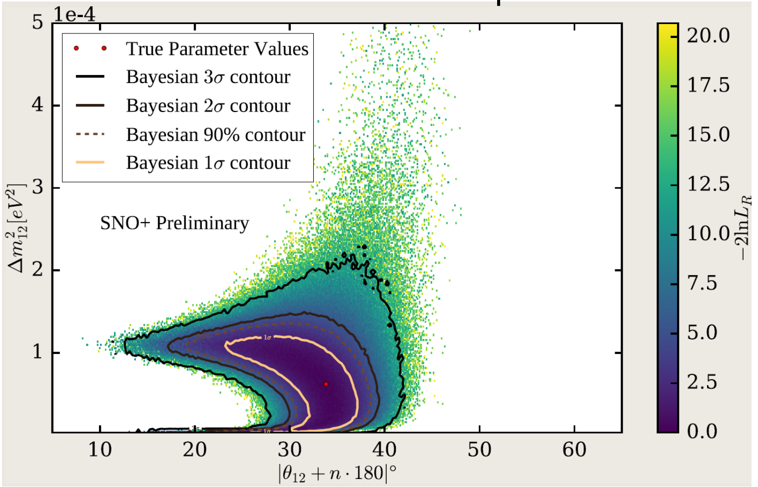
Aug 28th 17:15
Pablo Martinez-Mirave



JUNO, Hyper-Kamiokande and DUNE (and a combined analysis of both) will improve existing limits significantly or provide evidence of CPT violation in the neutrino sector.

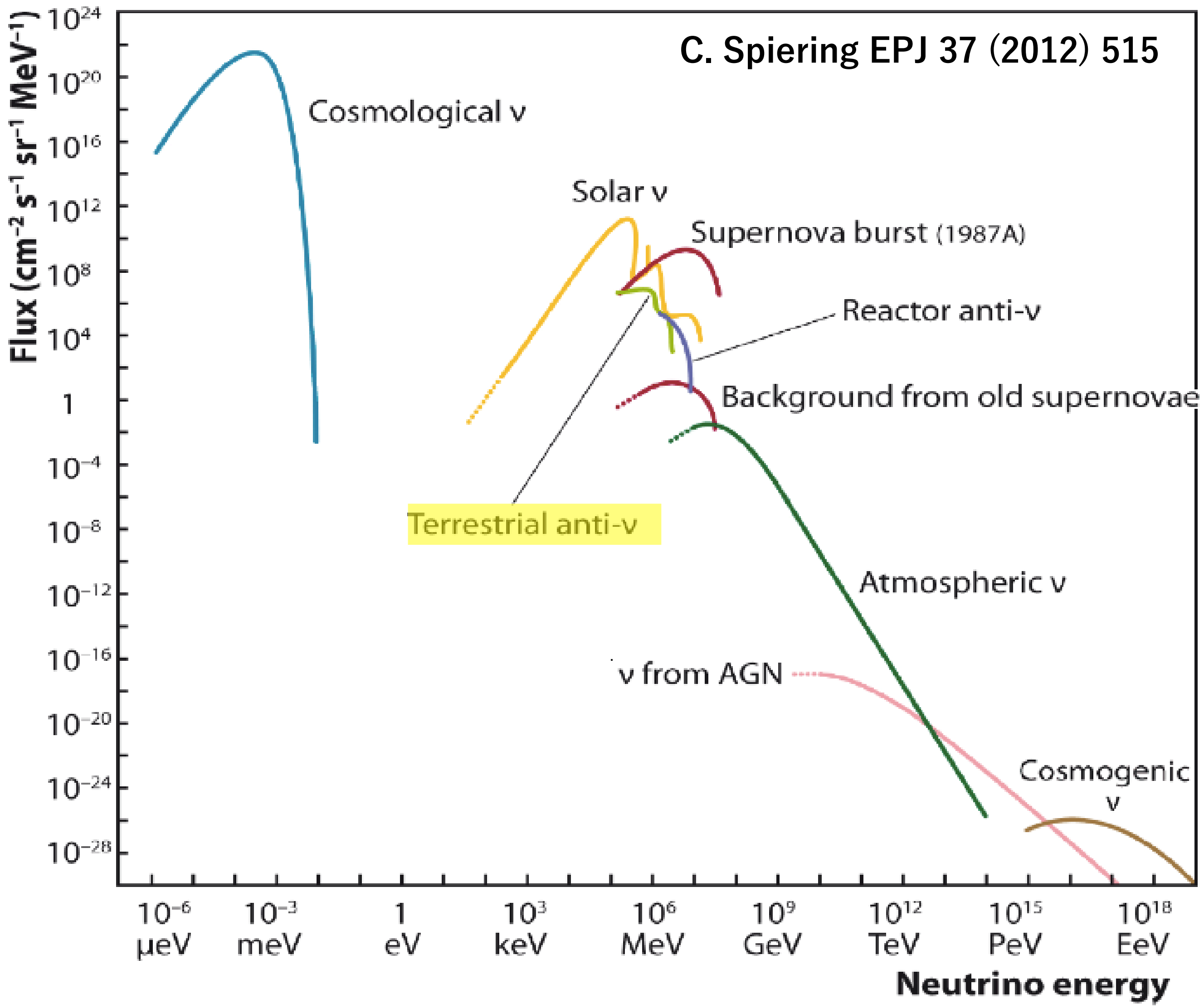


^{8}B expectation

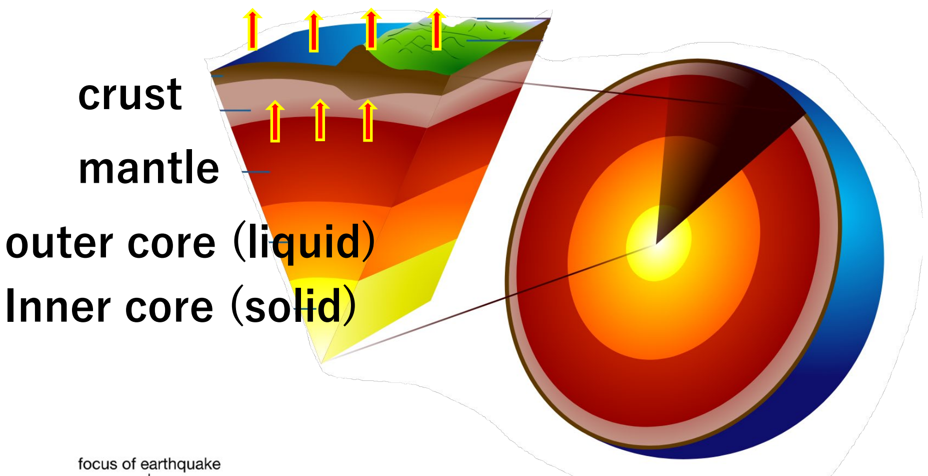


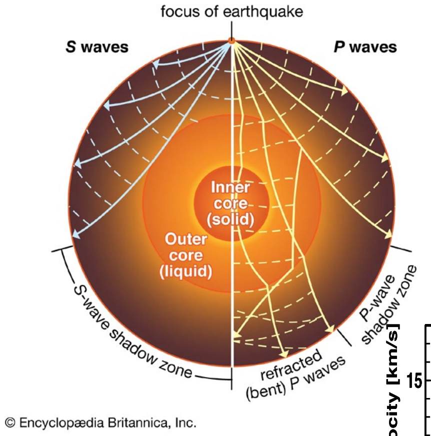
Aug. 28 16:30 DUNE/SoLAr
Saba Parsa

Geo neutrino

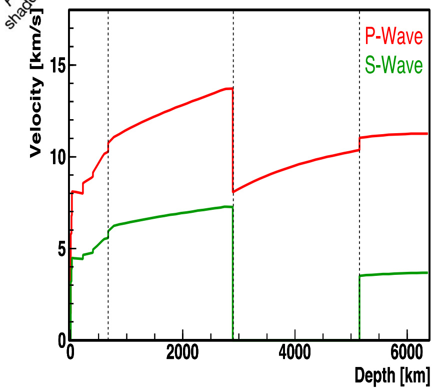


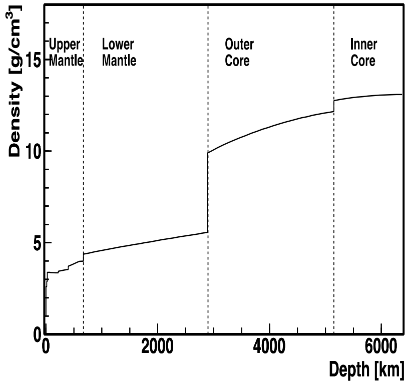
Inner structure of Earth and the heat source





Seismology provides density and viscosity profiles of deep earth multi-layer of core-mantle–crust but no compositional information





Open questions 1:

- What is in the mantle?
- Which type of meteorites formed the Earth?
- How many layers are in the mantle?

Geo/Cosmo-chemistry and Geo-thermology
give the average composition of mantle+crust.

Bulk-Silicate Earth (BSE) models [Sramek et al., 2013]

High-Q model

Based on balancing mantle viscosity and heat dissipation, predicting a relatively large amount of radiogenic heat for single-layer mantle convection.

Middle-Q model

Based on CI carbonaceous chondrites and mantle samples, predicting multi-layer mantle convection.

Low-Q model

Based on enstatite chondrites (~solar surface compositions), predicting multi-layer mantle convection.

Inner structure of Earth and the heat source

Open questions 2:

- What is the heat source of the earth?
- Primordial heat+radiogenic heat, which is dominant?
- How much fuel/source is remaining?

Bore-hole heat measurement and estimation
Total surface heat flux:
47±1 TW [Davies and Davies(2010)]
46±3 TW [Jaupart et al.(2007)]

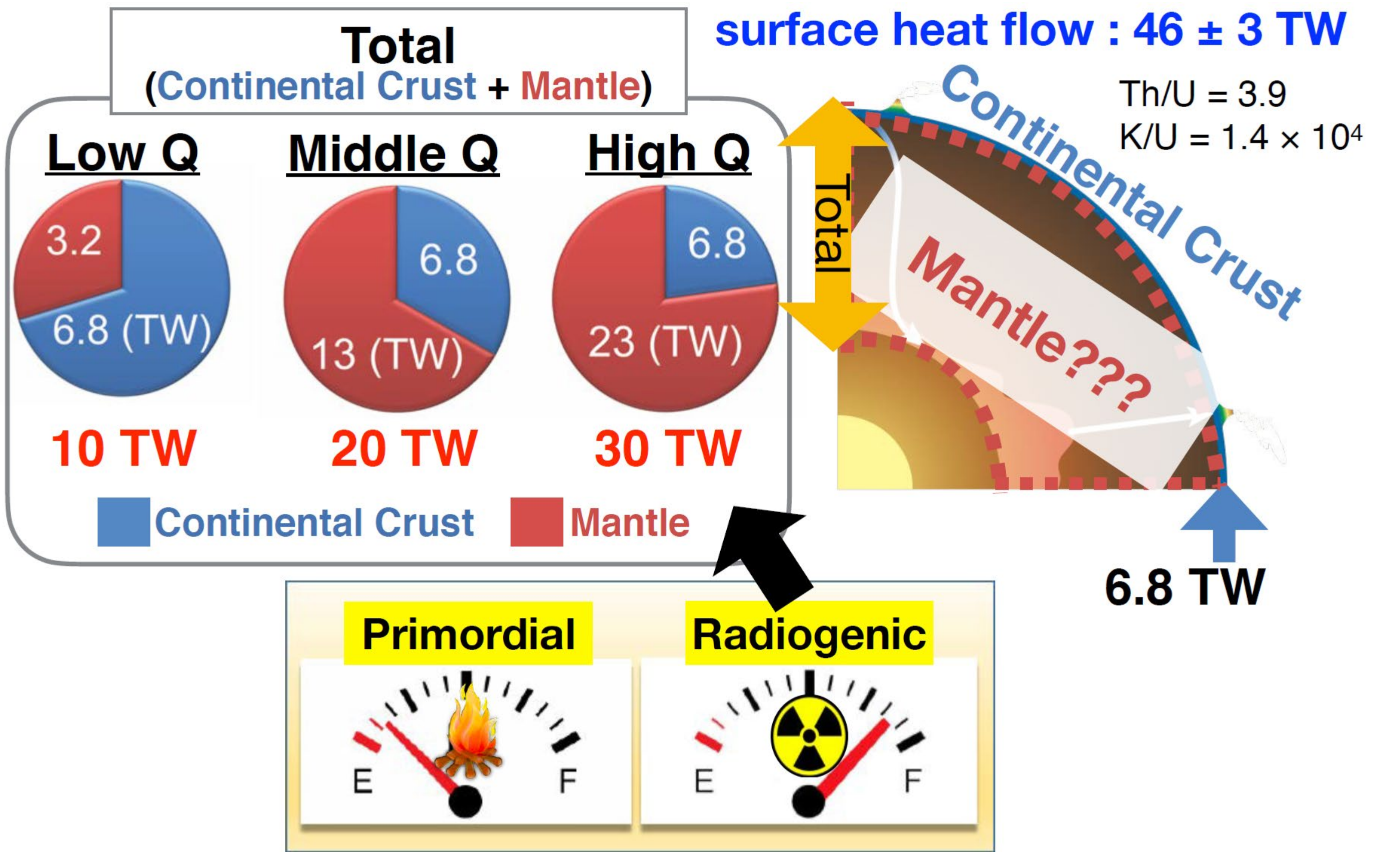
Radiogenic heat prediction:

High-Q model (>25 TW)
U : 35±4 ppb, Th : 140±14 ppb

Middle-Q model (17-22 TW)
U : 20±4 ppb, Th : 80±13 ppb

Low-Q model (10-15 TW)
U : 12±2 ppb, Th : 43±4 ppb

H. Watanabe
Geoneutrino workshop @Hawaii 2023

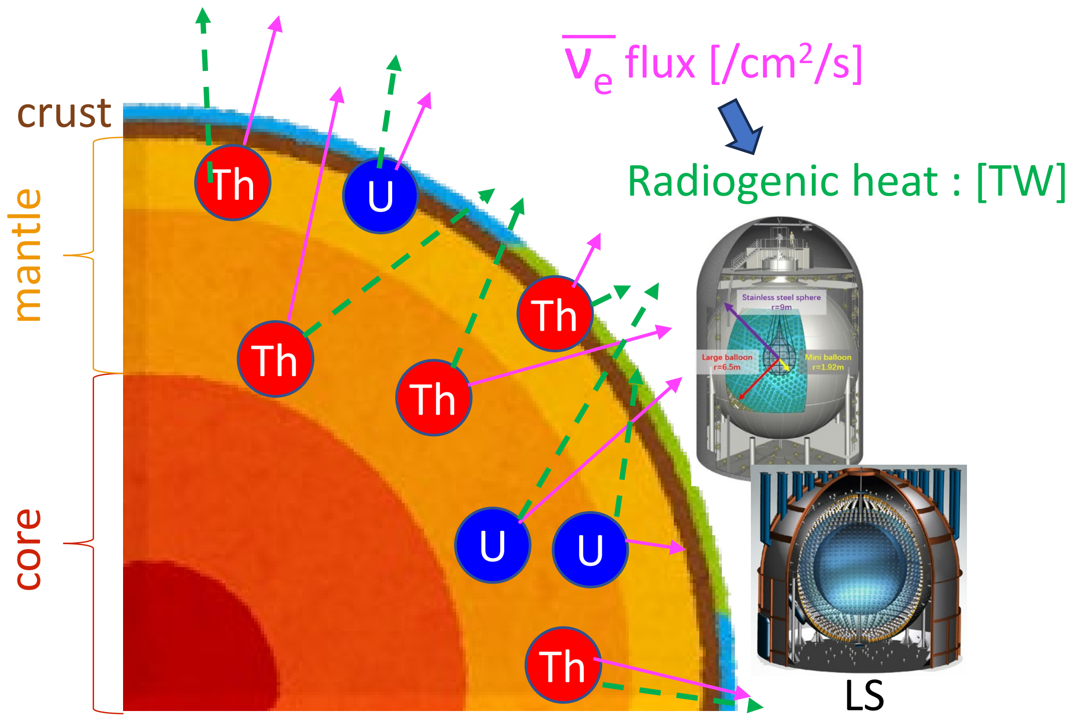


Geo-neutrinos are key to determining the BSE model and the earth's heat source!

Geo neutrino

Figures from Nanami Kawada

Electron-antineutrinos from natural radioactive decays



Emission of $\overline{\nu}_e$ from U, Th and K.

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

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

$$^{40}\mathrm{K} \rightarrow \, ^{40}\mathrm{Ca} + e^- + \overline{\nu}_e + 1.311\ \mathrm{MeV}$$

Geoneutrino total flux measurement

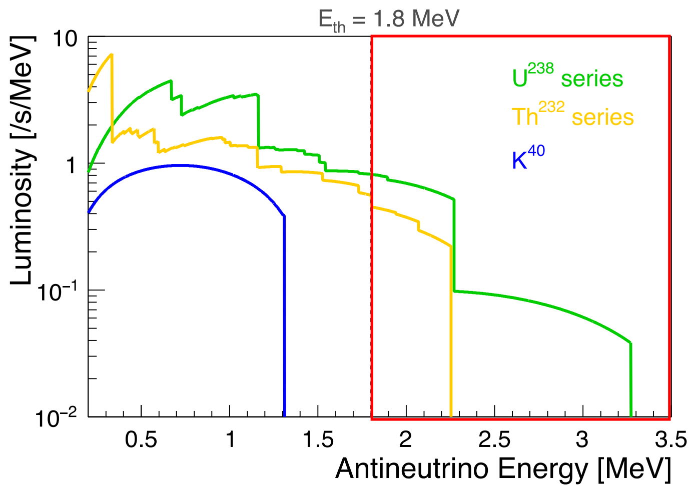
$\overline{\nu}_e$ flux $\propto$ U, Th $\propto$ **Radiogenic heat**

→Test of Earth's heat budget

Geoneutrino spectrum measurement

U and Th have different $\overline{\nu}_e$ energy.

→Test of Earth's chemical composition



IBD threshold 1.8MeV

Only geo-neutrinos from U and Th are detectable by LS

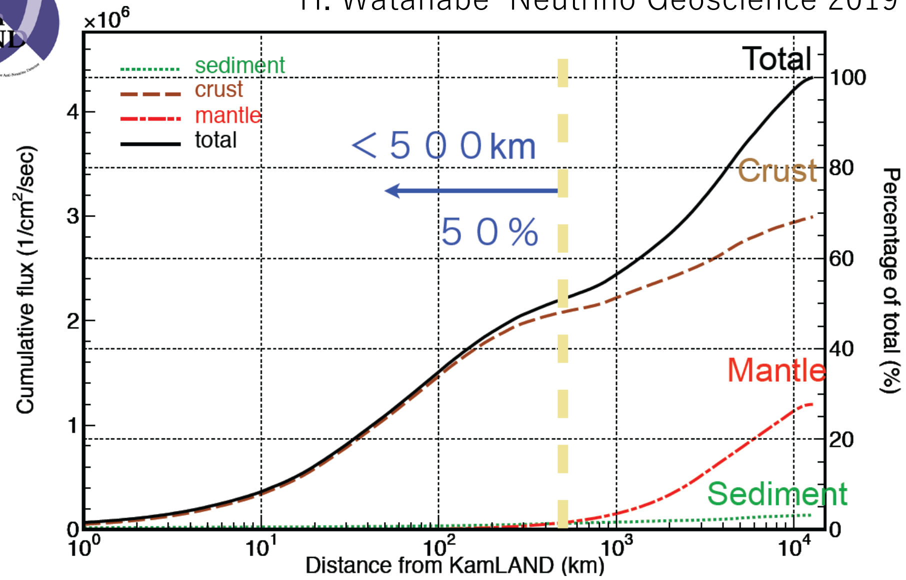
^{40}K geo-neutrino detection needs another technology

Aug 28 15:15
Mark Chen

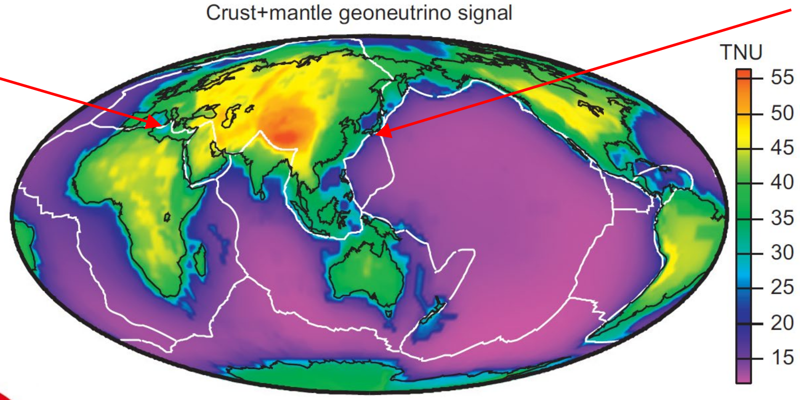
Necessity of global measurements

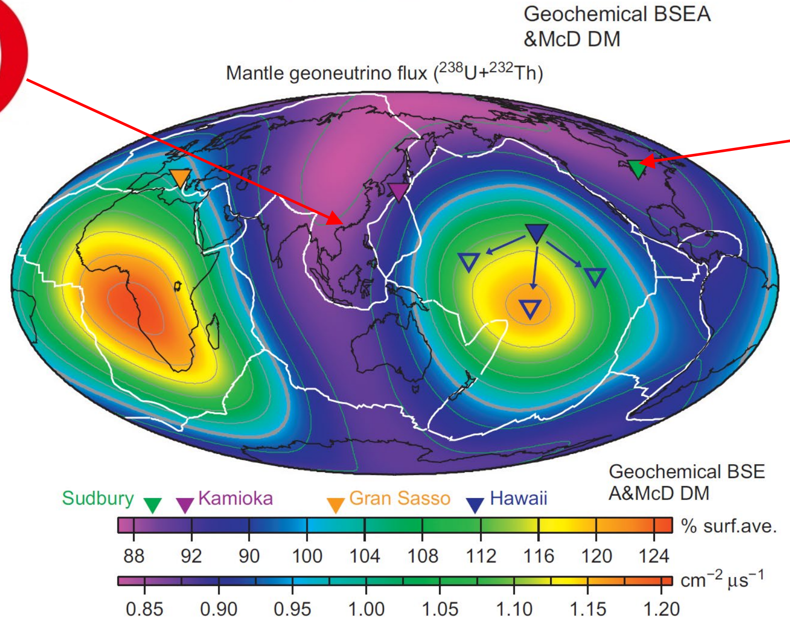
O. Sramek et al., Earth and Planetary Science Letters 361 (2013) 356

- Local contribution is large
  - 50%: distance < 500km
  - 25%: distance < 50km
  - 1~2%: from Kamioka mine



- Fluxes not homogeneous over the earth



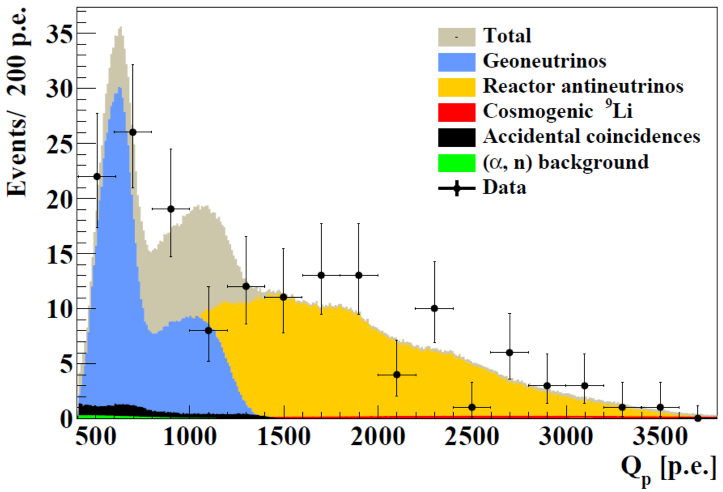


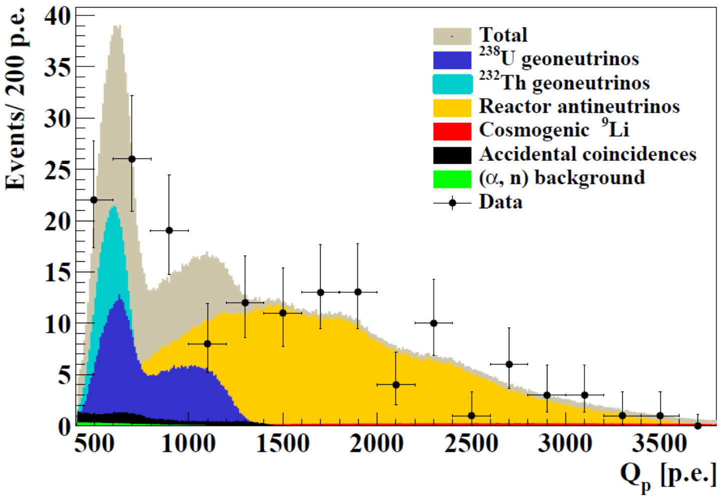
To separate crust ν and mantle ν precisely,
Needs for multi-site measurements

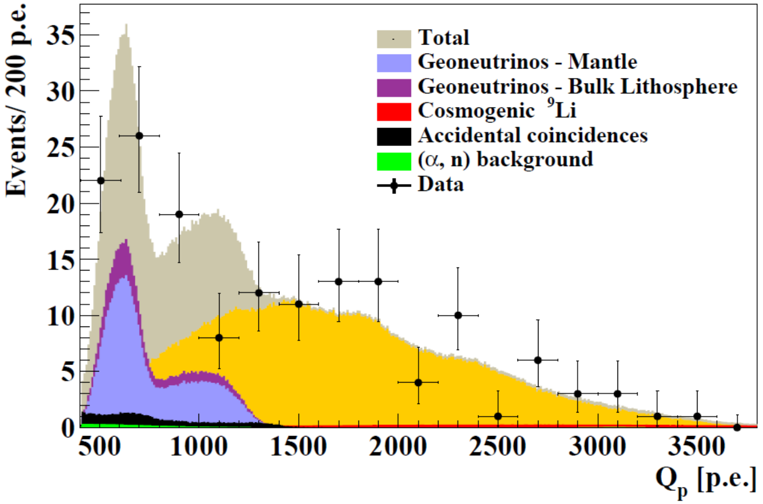
Borexino

PRD 101,012009 (2020)

Result of 3262.74 days Dec. 2007~ Apr.2019







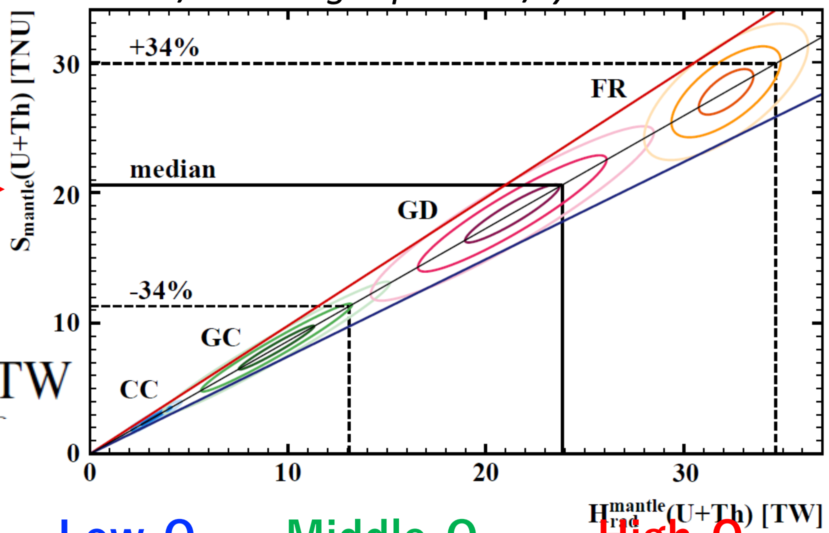
1 TNU= 1 event /10^{32} target protons/ year

mantle

$21.2^{+9.7}_{-9.0}$

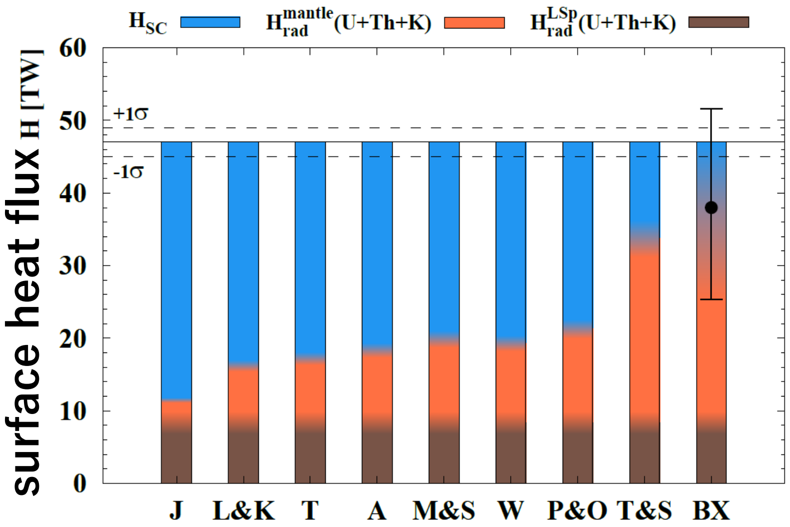
TNU

$24.6^{+11.1}_{-10.4}$ TW



Low-Q Middle-Q High-Q

1,2,3σ contour for each model



Low-Q Middle-Q High-Q

Primordial

Radiogenic

Surface heat flux

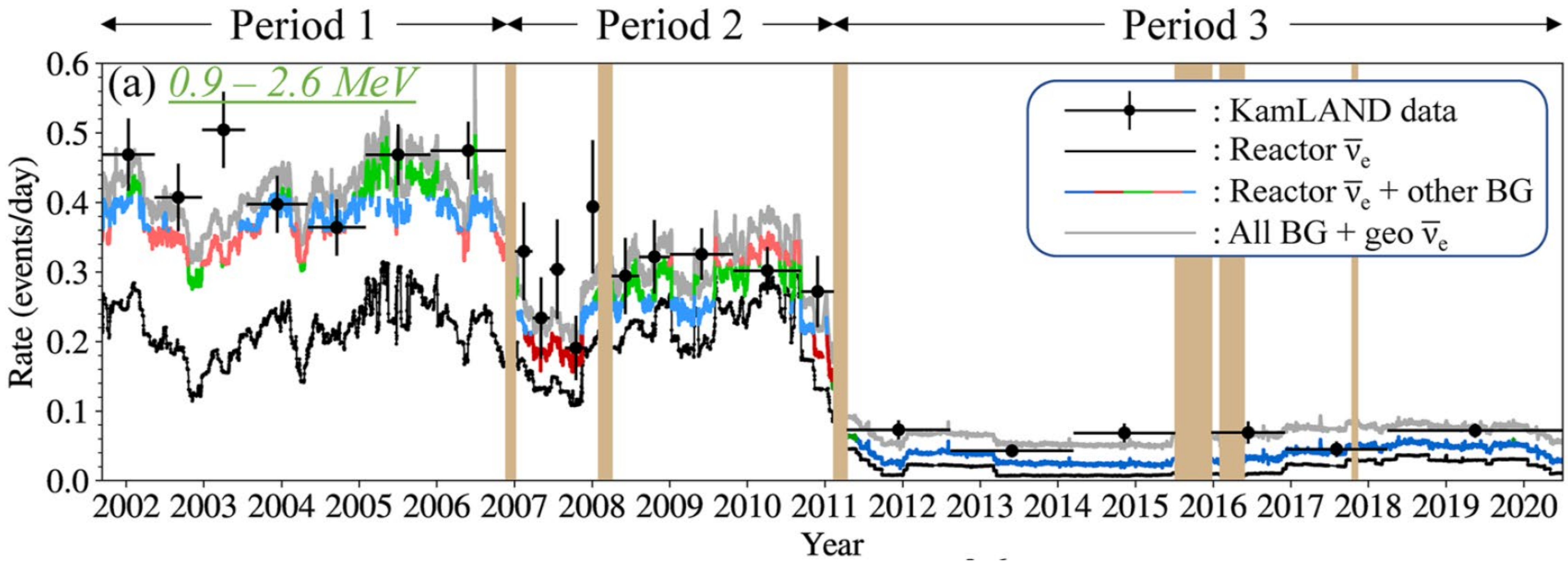
$38.2^{+13.6}_{-12.7}$ TW

2.4σ tension
with Low-Q model

KamLAND Geophysical Research Letters, 49, e2022GL099566

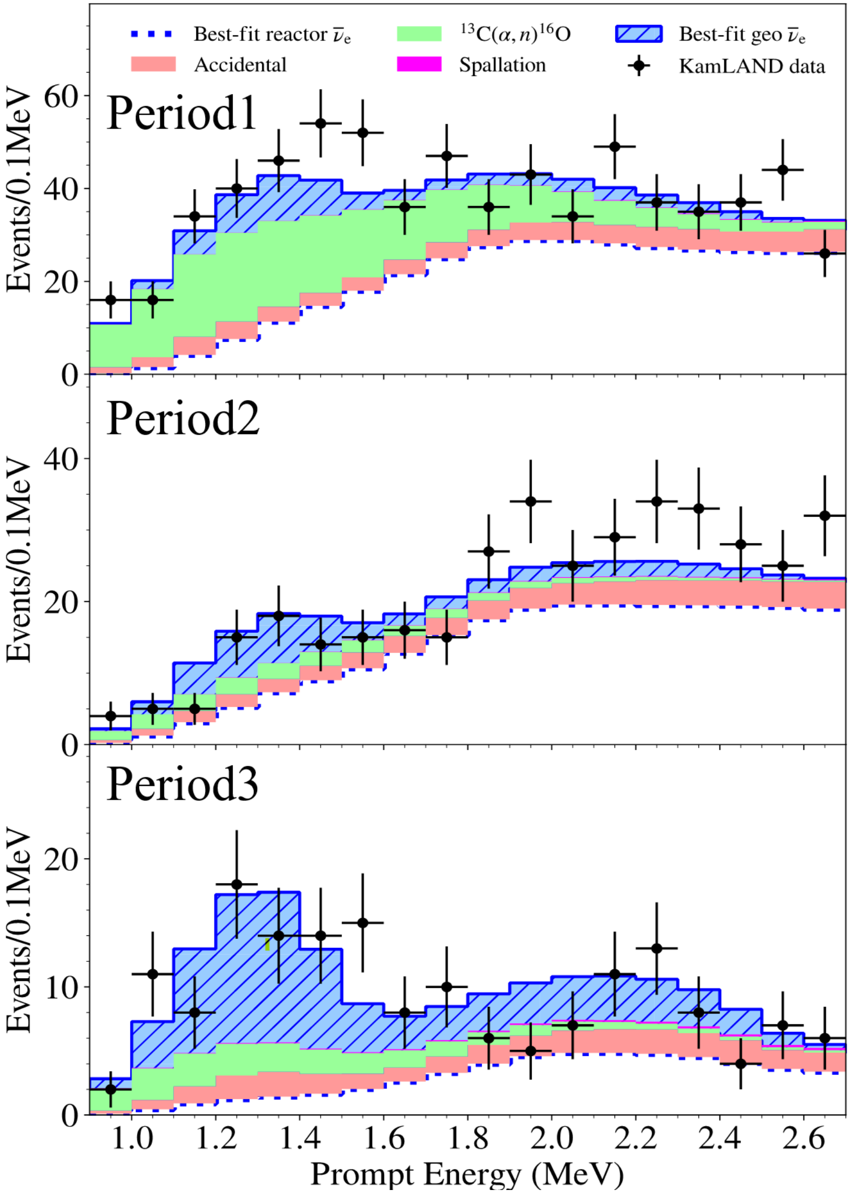
Aug 28th 15:00
Nanami Kawada

Result of 18 years 2002-2020, including Japanese reactor off period after 2011

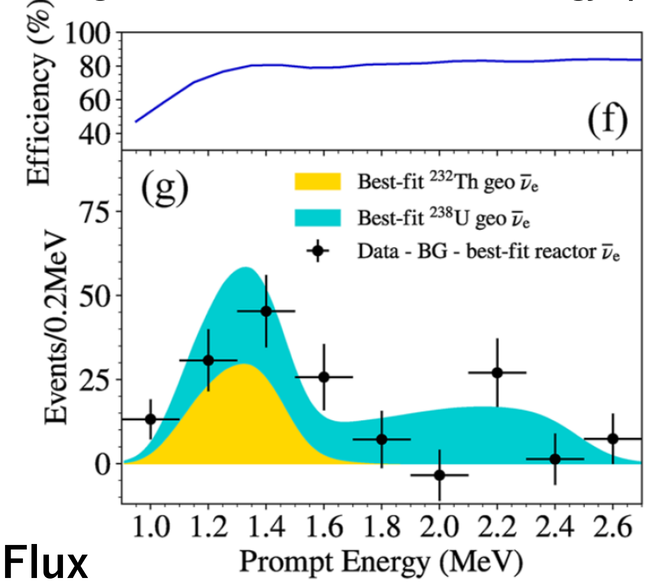


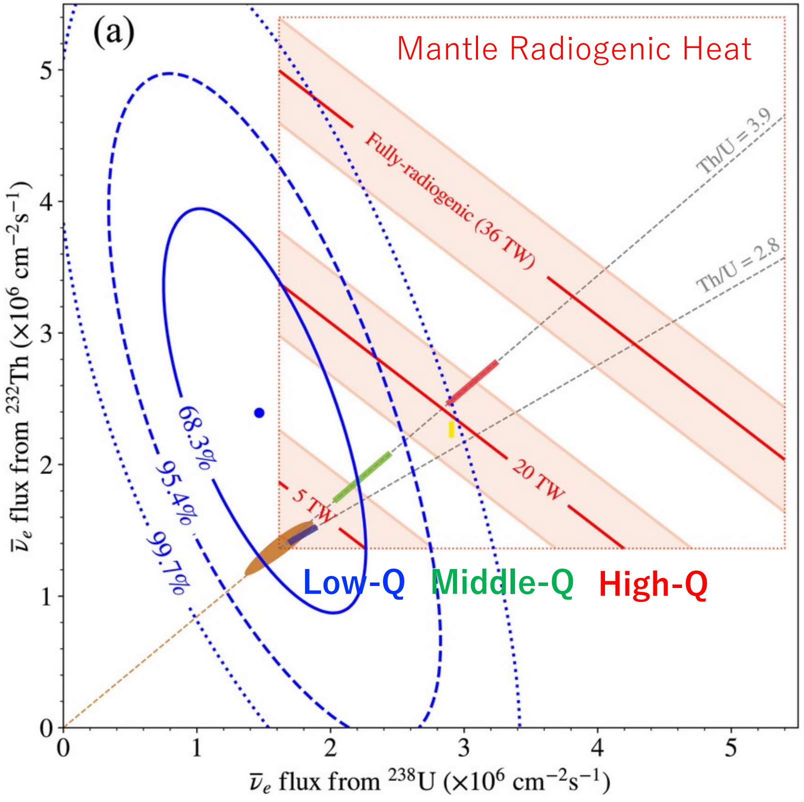
KamLAND

Aug 28th 15:00 Nanami Kawada



The background-subtracted observed energy spectrum





Flux

	$N_{U/Th}$ [event]	flux [$\times10^5$ cm^{-2}s^{-1}]	[TNU]	0-signal rejection
U	$116.6^{+41.0}_{-38.5}$	$14.7^{+5.2}_{-4.8}$	$19.1^{+6.7}_{-6.3}$	3.343σ
Th	$57.5^{+24.5}_{-24.1}$	$23.9^{+10.2}_{-10.0}$	$9.7^{+4.1}_{-4.1}$	2.386σ
U + Th	$173.7^{+29.2}_{-27.7}$	$32.1^{+5.8}_{-5.3}$	$28.6^{+5.1}_{-4.8}$	8.3σ

Radiogenic heat

$$Q^{\mathrm{U}} = 3.3^{+3.2}_{-0.8}\ \mathrm{TW}$$

$$Q^{\mathrm{Th}} = 12.1^{+8.3}_{-8.6}\ \mathrm{TW}$$

$$Q^{\mathrm{U}} + Q^{\mathrm{Th}} = 15.4^{+8.3}_{-7.9}\ \mathrm{TW}$$

Including heat estimate from crust, ^{238}U : 3.4 TW, ^{232}Th : 3.6 TW

Consistent with Low-Q and Middle-Q models, whereas the High-Q model is disfavored at 99.76%(>3σ) confidence level with assuming the homogeneous mantle composition, implying multi-layer mantle convection.

H. Watanabe
Geoneutrino workshop @Hawaii 2023

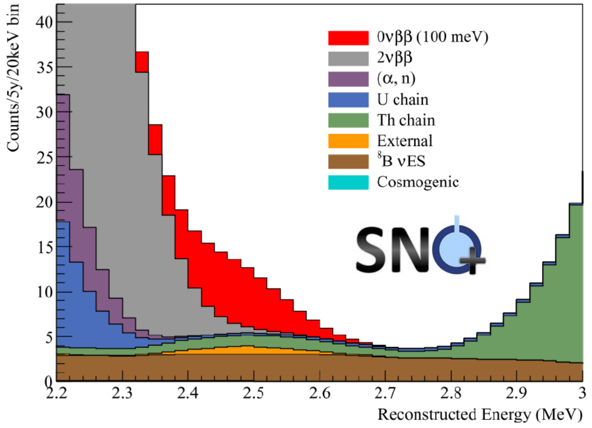
Future Geo-neutrino

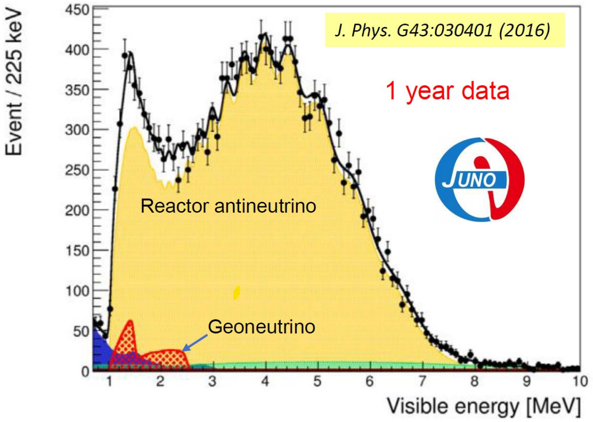
Observation = **Crust** + **Mantle**

(y = x + b)

1 TNU= 1 event /10^{32} target protons(1ktonLS)/year

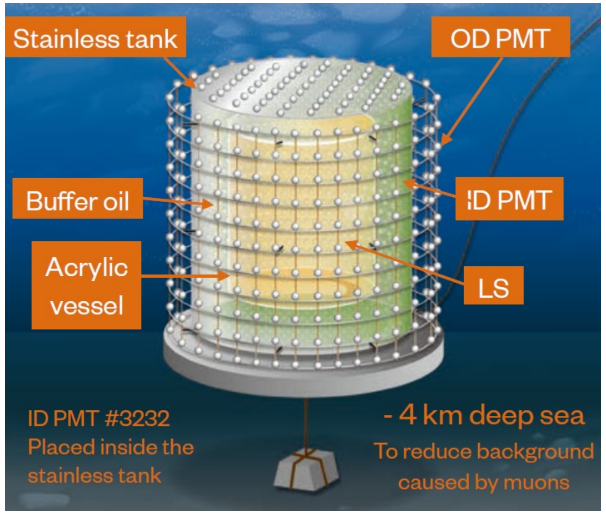
Needs for multi-site measurements

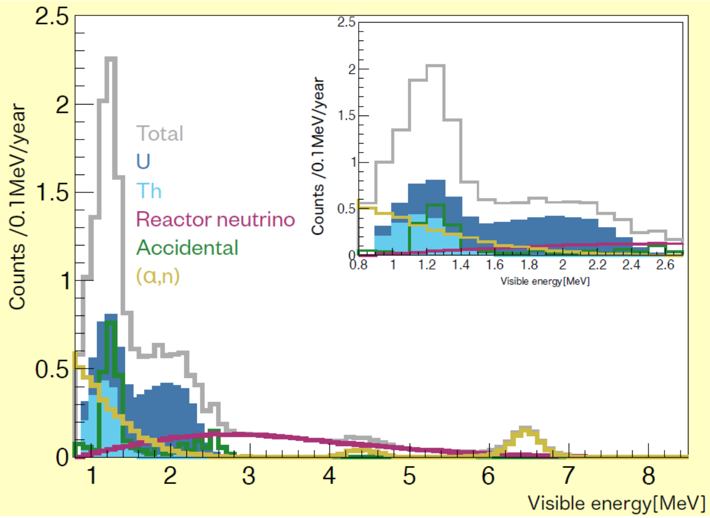


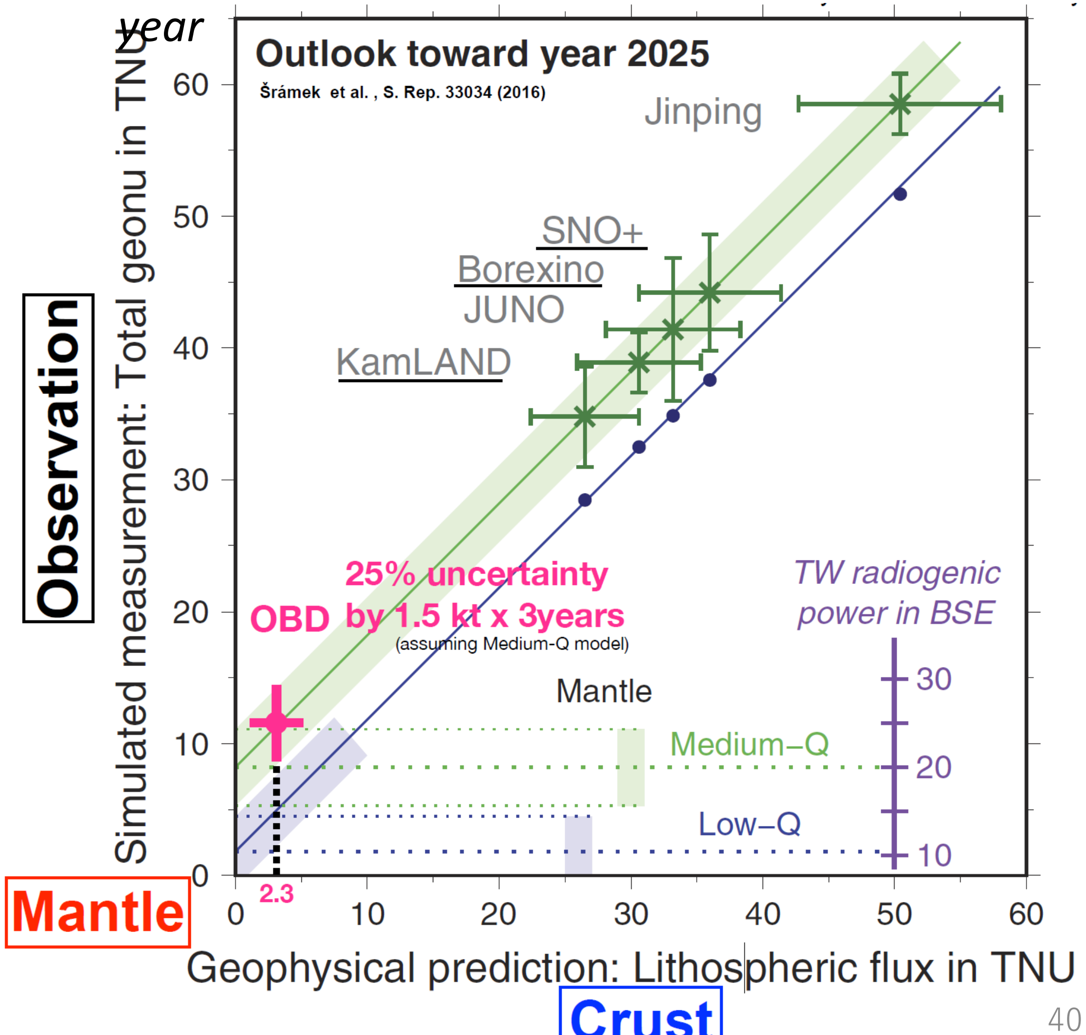


To measure mantle contribution directly

OBD: 1.5kton Ocean Bottom Detector







Summary

- Probing neutrinos in the MeV region is the key to understanding elements, stars, and the universe.
- Supernova-neutrino
  - Burst detection for SN mechanism
  - Alarms for Multi-messenger astronomy
  - DSNB search for the history of the universe
- Solar-neutrino
  - SSM and Metallicity
  - Neutrino Oscillation
  - New Physics
- Geo-neutrino
  - Mantle structure
  - Heat source of the earth
  - U/Th composition

N.B. This is a partial list.

	Current	Soon	Future
Water	Super-Kamiokande (SNO+) IceCube	KM3NET (ORCA,ARCA)	Hyper-Kamiolande
Liquid scintillator	KamLAND (Borexino) SNO+ NovA LVD	JUNO	THEIA Jinping
Others	HALO DM detectors(Xe,Ar)	DarkSide-20k	DUNE DARWIN/ XLZD

Thank you!