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MeV to GeV Neutrinos

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Outline

- *Introduction*
- *MeV neutrinos*
  1. *Solar neutrino oscillations*
  2. *Supernova neutrinos*
- *GeV neutrinos*
  1. *Atmospheric neutrino oscillations*
  2. *Search for neutrinos from dark matter annihilation*
- *MeV to GeV neutrino detectors in the CTA era*
- *Summary*

I will not discuss man-made neutrinos.
Apology: I should speak MeV to GeV neutrinos related to "multi-messenger astronomy". But I do not have much to say on this topic. Also, some data may not be most updated….

Introduction

Discovery of atmospheric neutrinos (1965)

Photo by H.Sbel

In 1965, atmospheric neutrinos were observed for the first time by detectors located very deep underground.

➔ In India
C.V. Achar et al., PL 18, 196 (1965)

🡐In South Africa
F. Reines et al., PRL 15, 429 (1965)

The South Africa experiment later observed a substantial deficit of atmospheric ν_μ flux, although the flux uncertainty was large.

M.F.Crouch et al., PRD 18 (1978) 2239

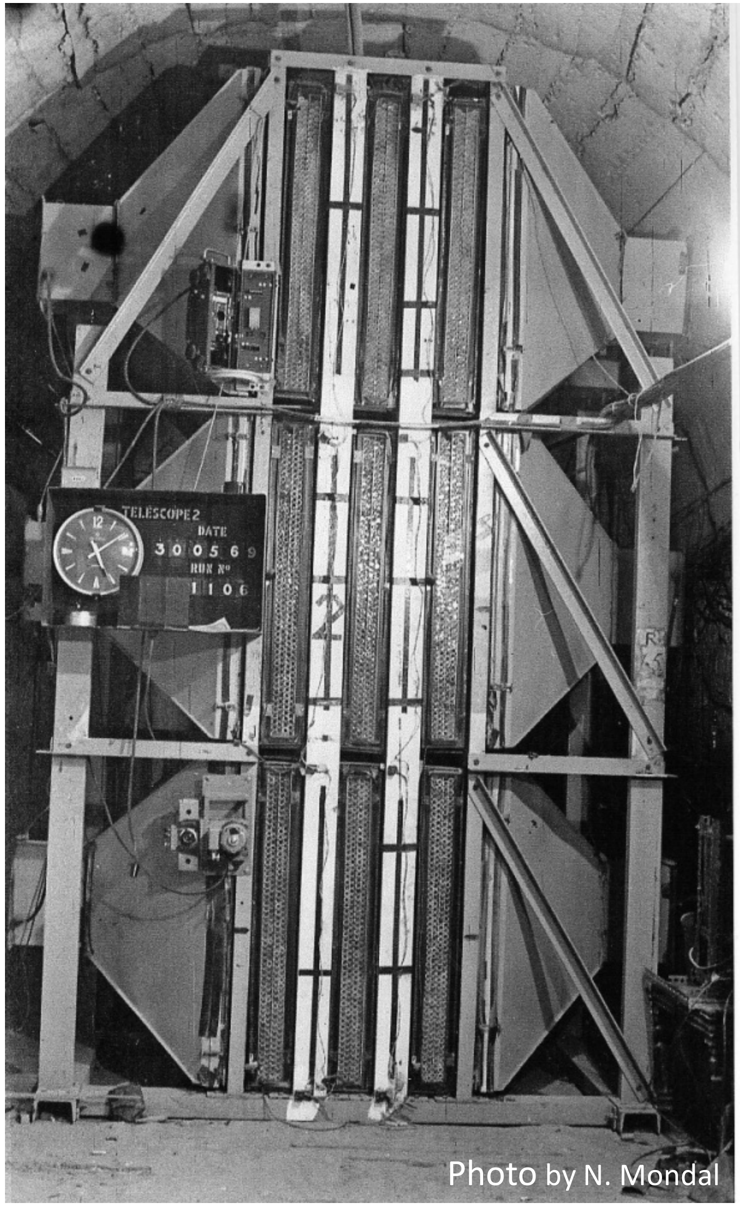


Photo by N. Mondal

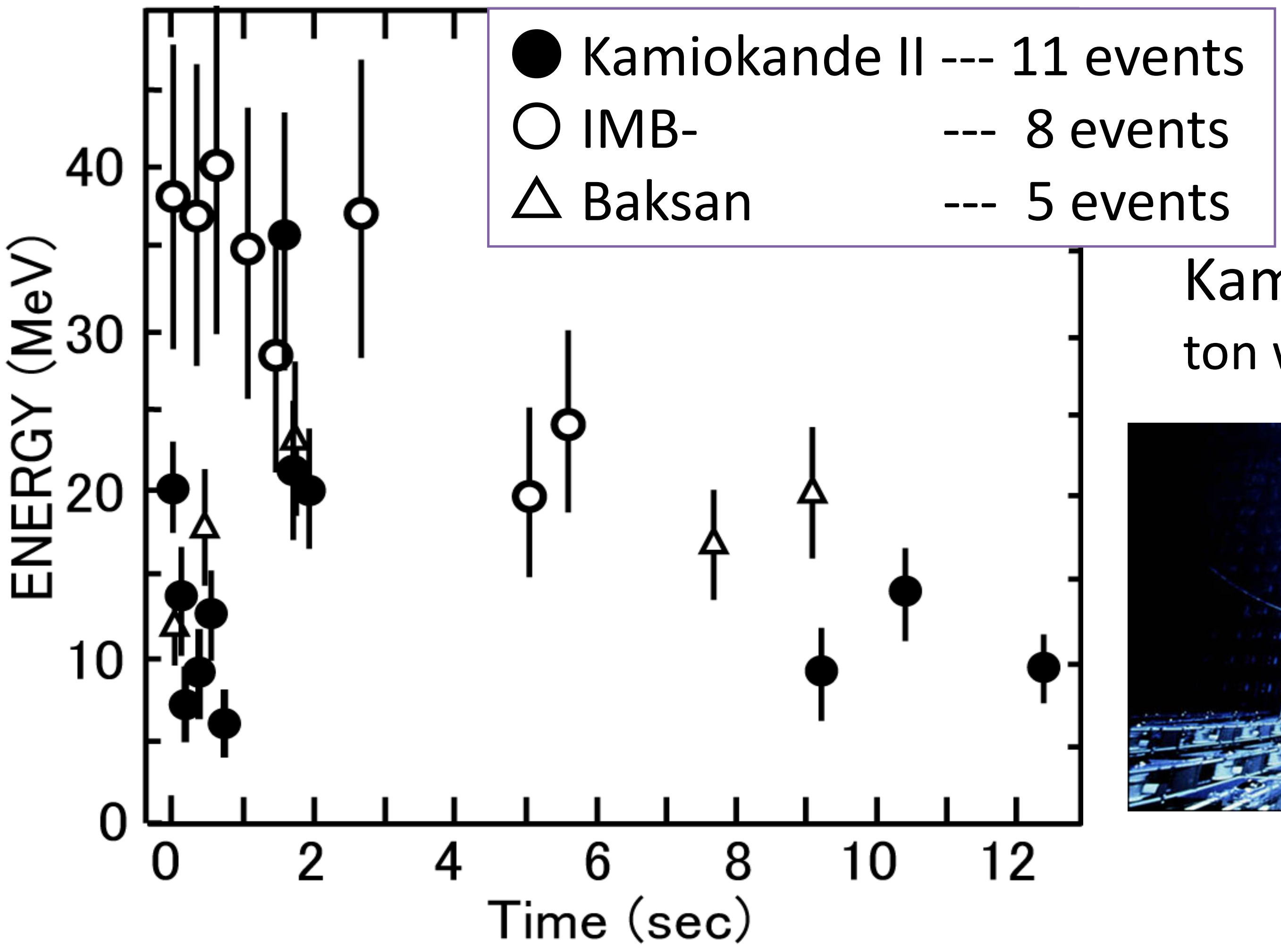
Solar neutrinos

600 ton
C_2Cl_4

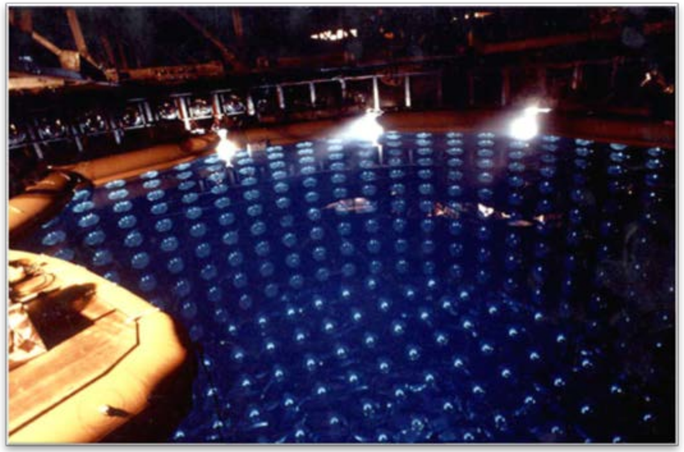
R. Davis Jr.

Pioneering Homestake solar neutrino experiment led by R. Davis began in the 1960's and observed solar neutrinos for the first time. The observed flux was about 1/3 of the prediction.

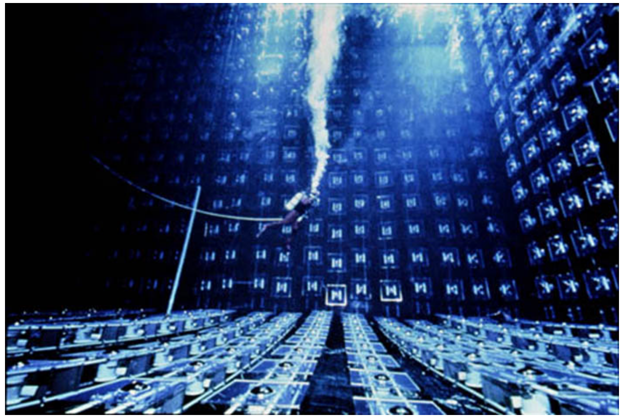
Detection of Supernova neutrinos



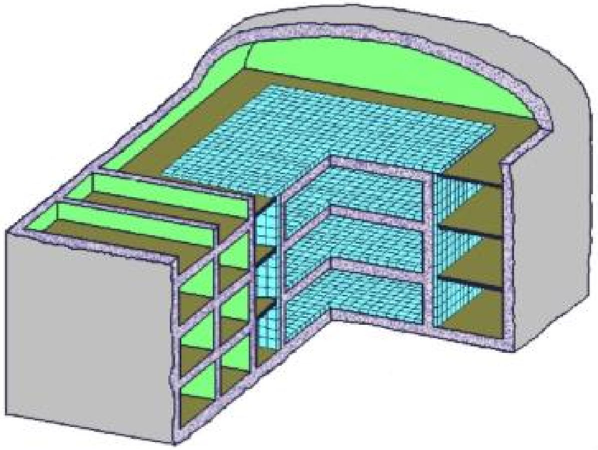
Kamiokande (3000 ton water Ch. detector)



IMB-3 (8000 ton water Ch detector)



Baksan (330 ton segmented Liq. scintillator detector)



→ Understood the basic mechanism of the supernova explosion!

Summary of Introduction

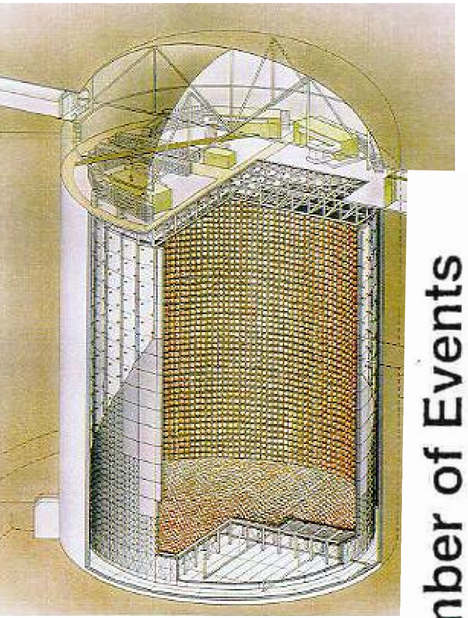
- ✓ About 40-50 years ago, it was already suspected that neutrinos might not behave as we expected.

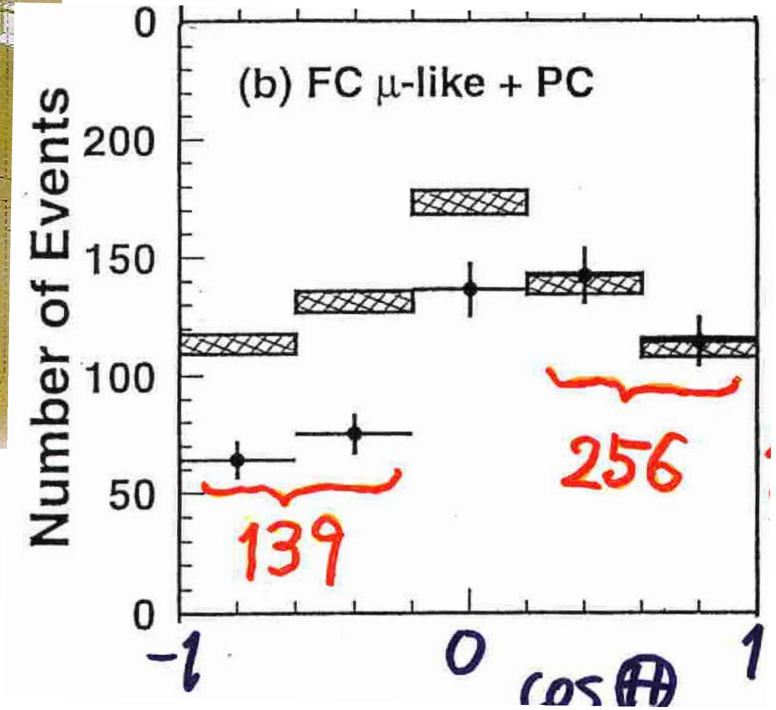
- ✓ About 30 years ago, it was proven that neutrinos are extremely useful for the understanding of some of the phenomena in astrophysics.

Summary of Introduction: (2) Discovery of neutrino oscillations

Atmospheric neutrinos

Super-K, PRL 81 (1998) 1562

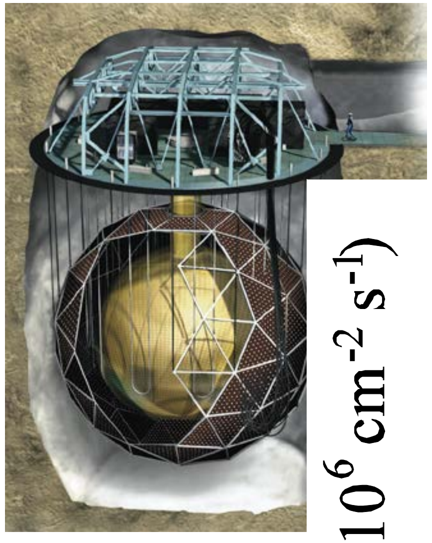


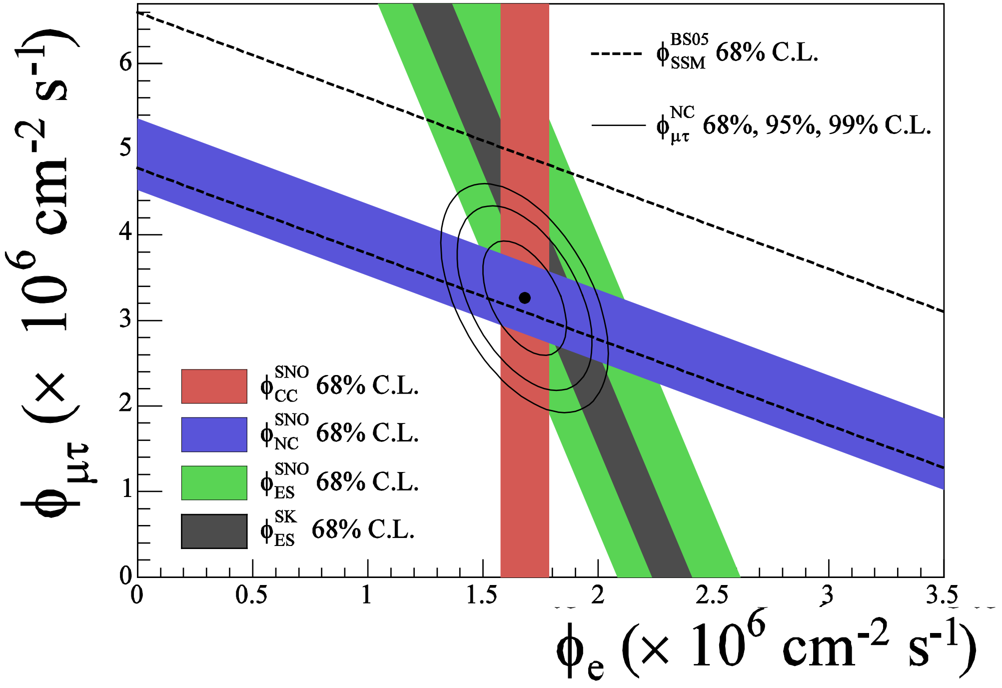


➔ Evidence for zenith-angle dependent ν_μ deficit ➔ Evidence for ν_μ oscillation

Solar neutrinos

SNO PRL 89 (2002) 011301
SNO PRC 72, 055502 (2005)



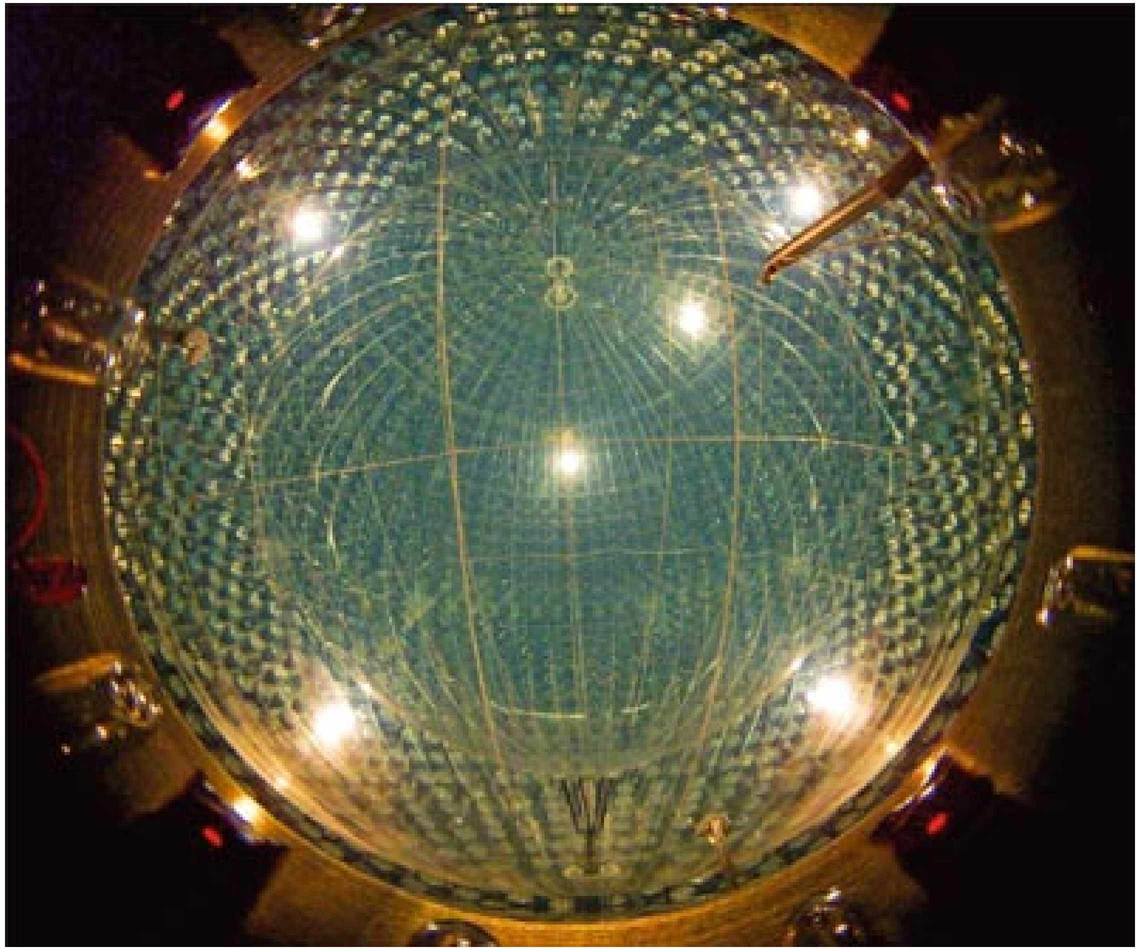


➔ Evidence for (ν_μ+ν_τ) flux ➔ Evidence for ν_e oscillation

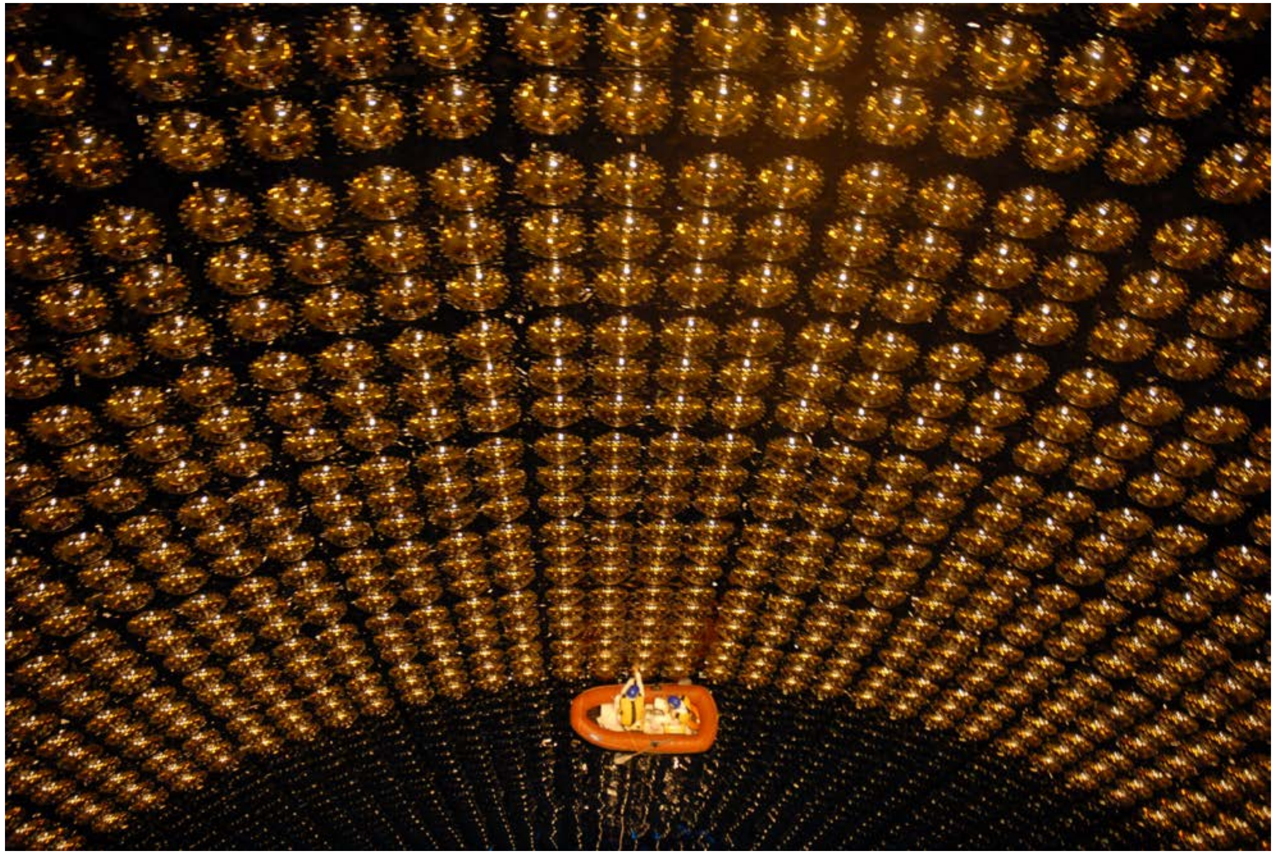
MeV neutrinos

1. Solar neutrino oscillations

Present solar neutrino experiments



Borexino
(300 ton liq. Sci. detector)

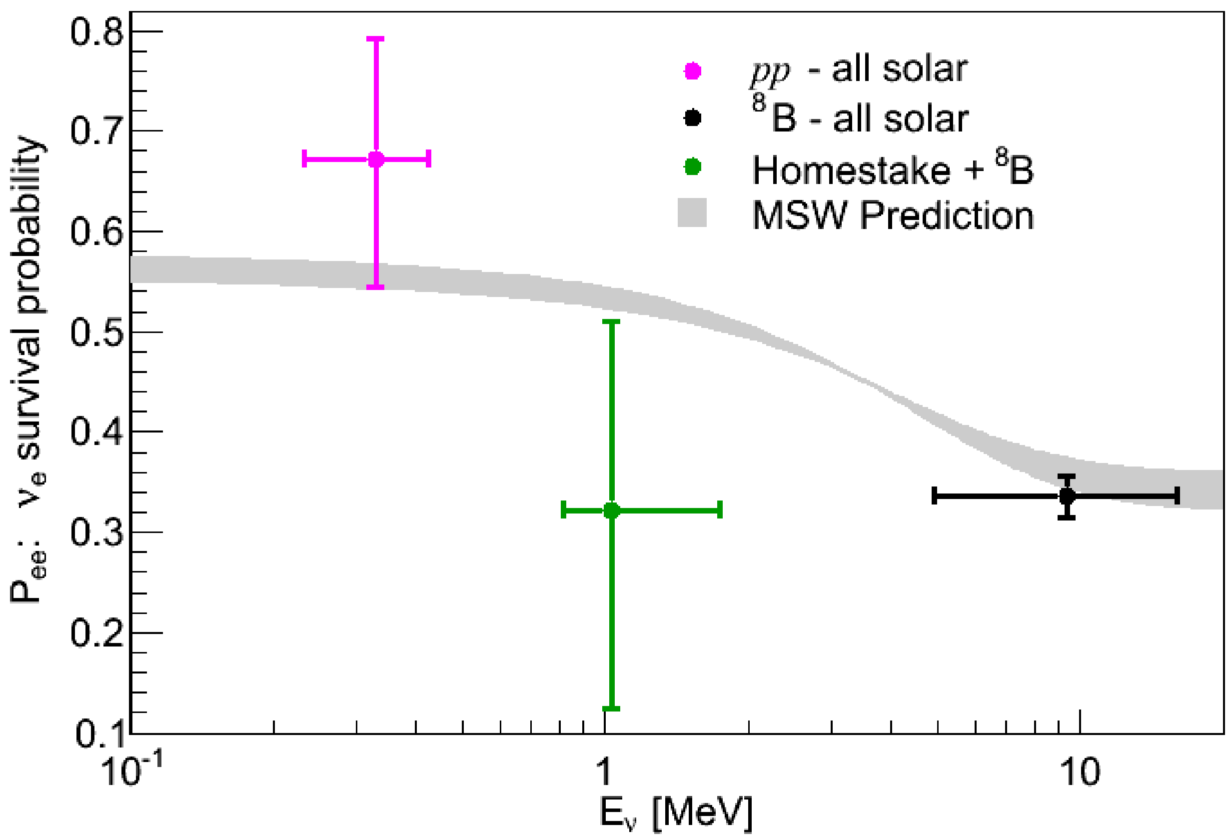


Super-Kamiokande
(22500 ton water detector)

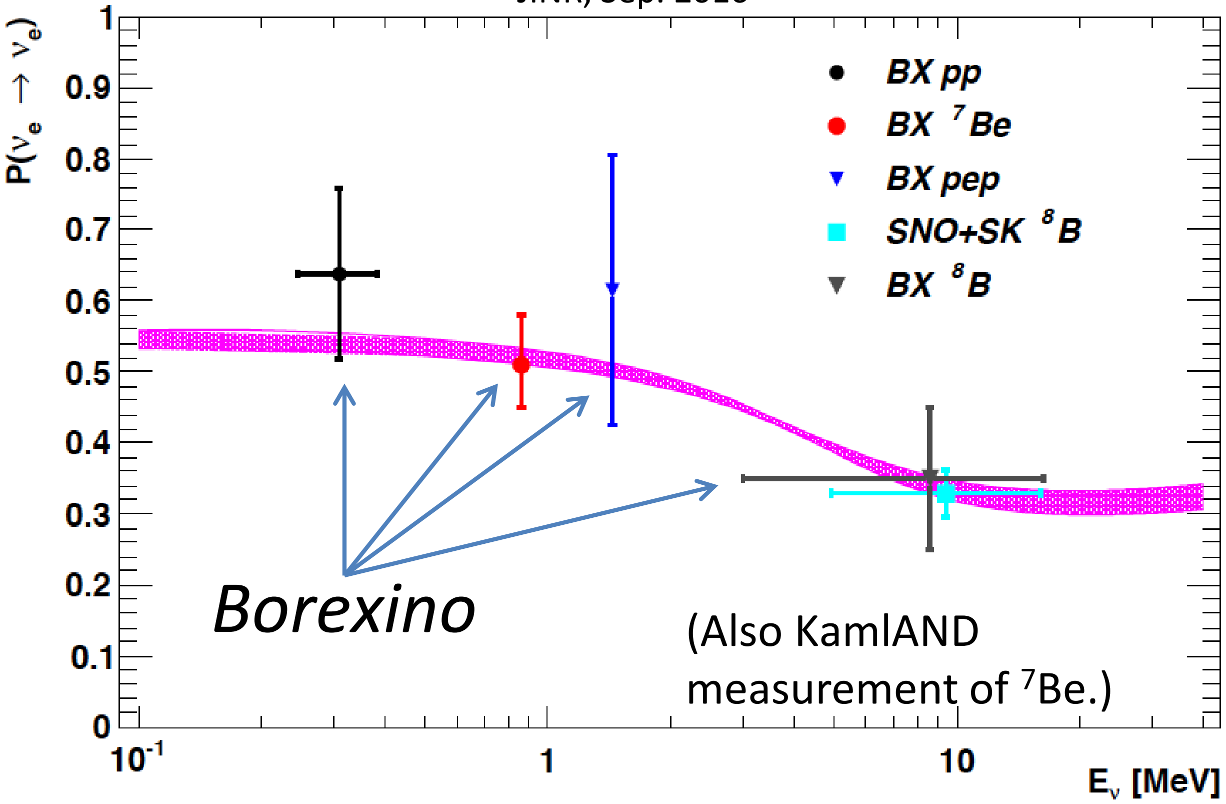
To what extent do we understand solar neutrino osci.

Borexino, PRL 101, 091302 (2008), PRD 82 (2010) 033006, PRL 108, 051302 (2012), Nature 512, 383 (2014), PRD 89, 112007 (2014), G. Bellini, JINR, Sep. 2016

Before Borexino

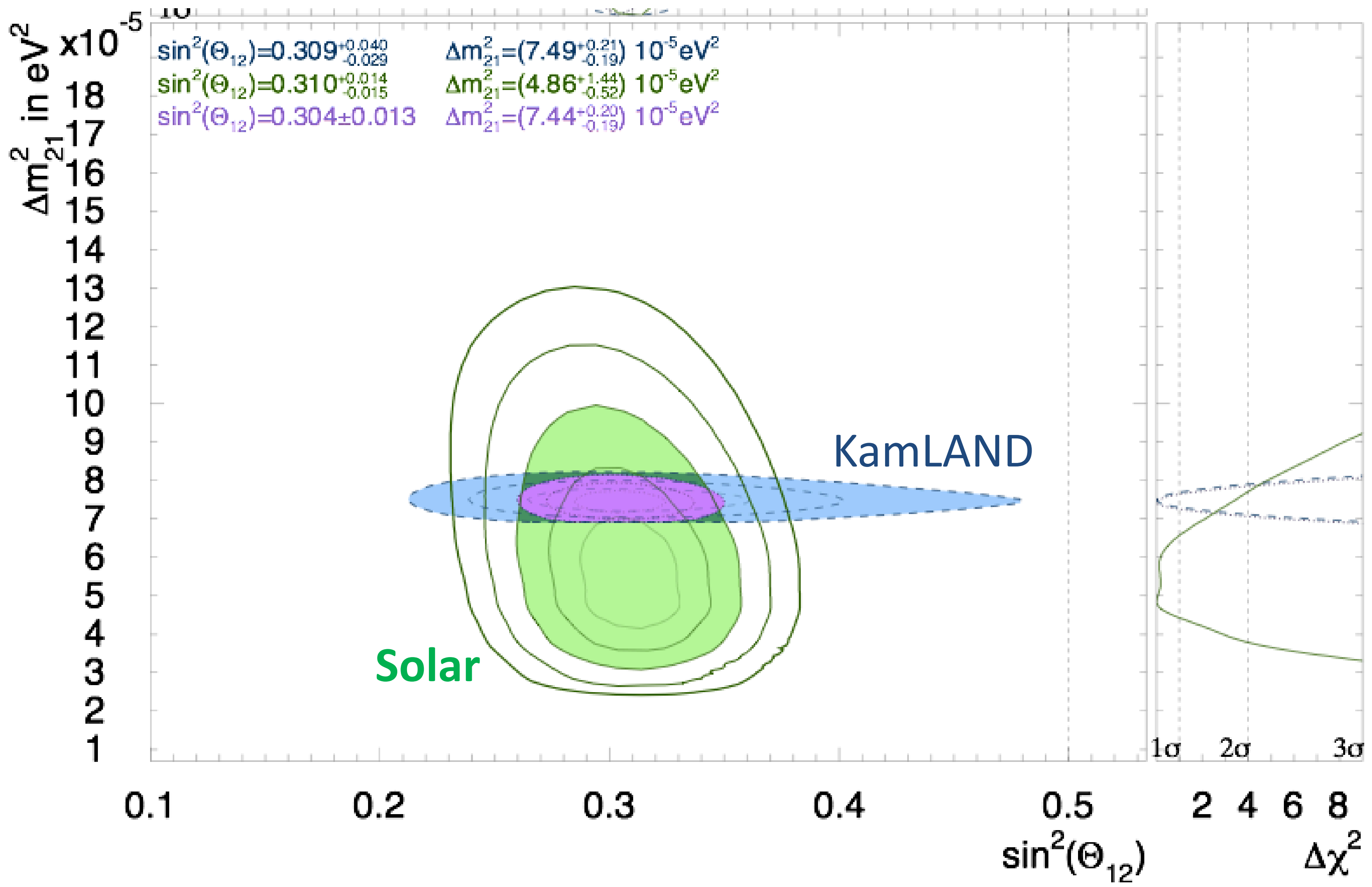


After Borexino



The data are consistent with the MSW prediction!

To what extent do we understand solar neutrino osci. (2)

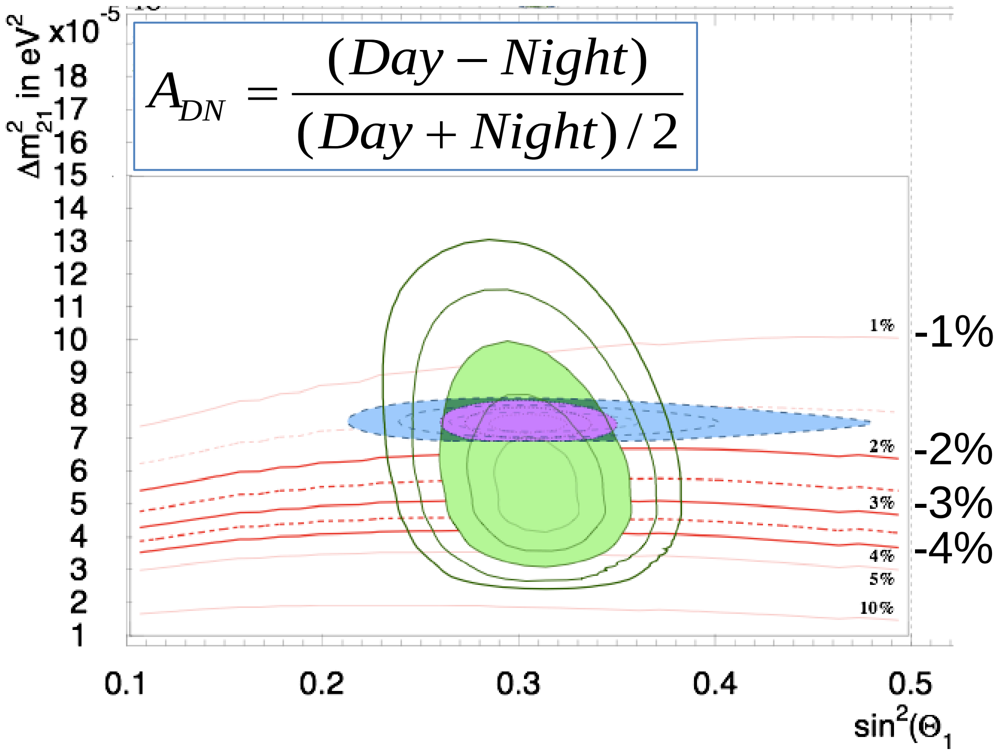


There is □ ^{2} ~(<) 4 tension in Δm_{12}^2 (solar neutrinos vs. KamLAND).

To what extent do we understand solar neutrino osci. (2)

Day-Night effect

Super-K, PRD94, 052010 (2016)



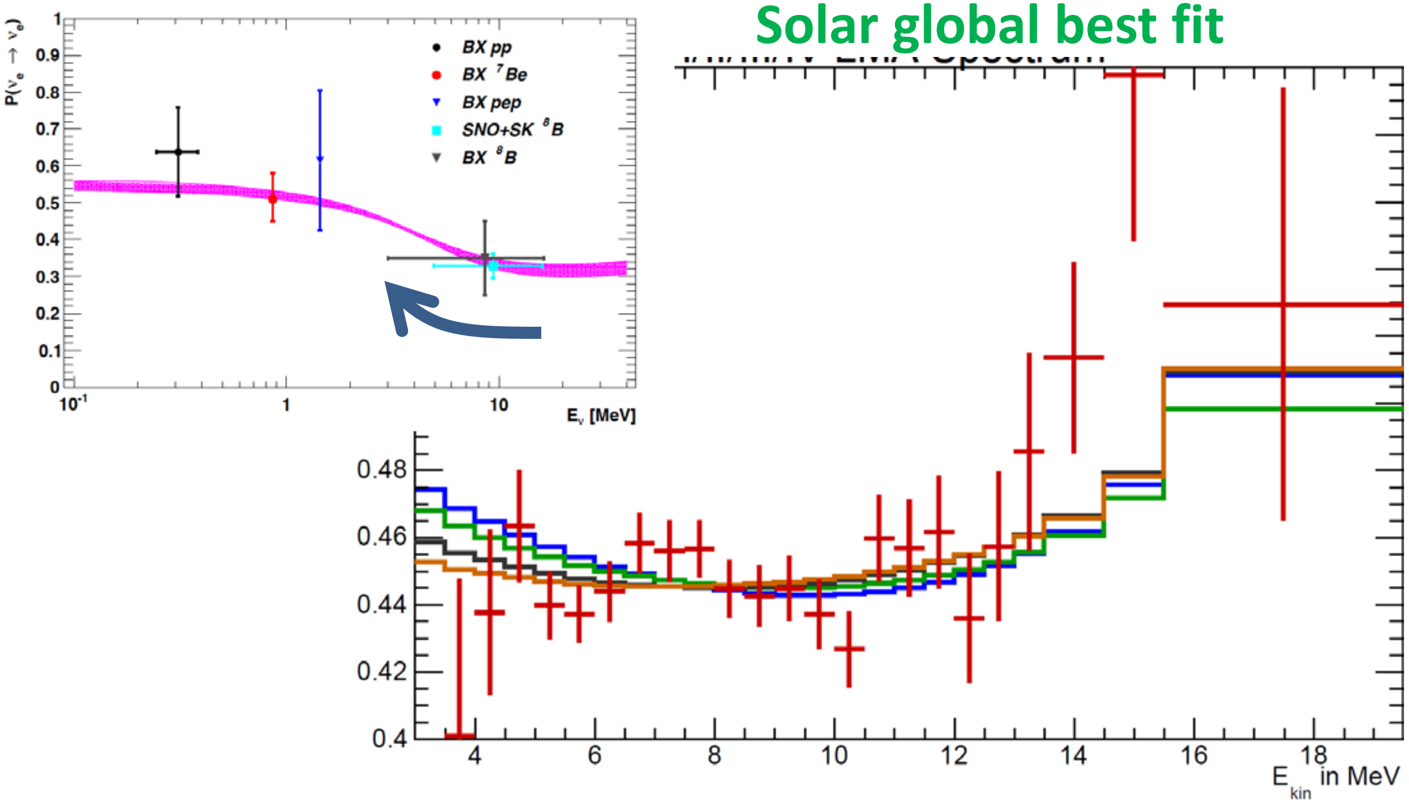
	A_{DN}^{fit} (%)
SK-I~IV, 4499 days	-3.3+/-1.0+/-0.5
Non-zero significance	2.9 σ

Spectrum upturn

(Super-K, June 2017)

Solar+KamLAND best fit

Solar global best fit



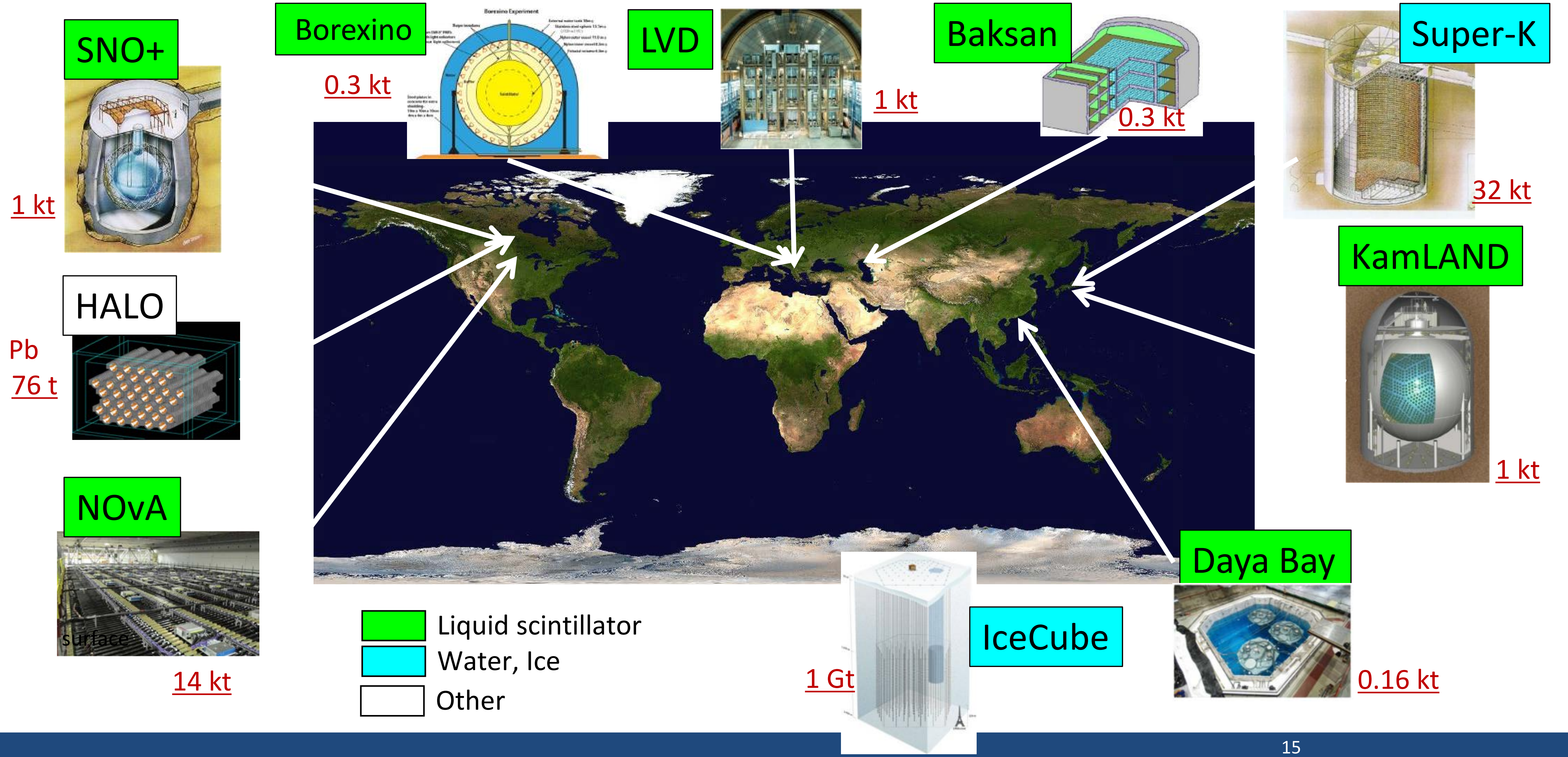
Solar best fit	**Consistent within ~1σ**
Solar+KamLAND best fit	Marginally within ~2σ

Interesting. But we need more data.

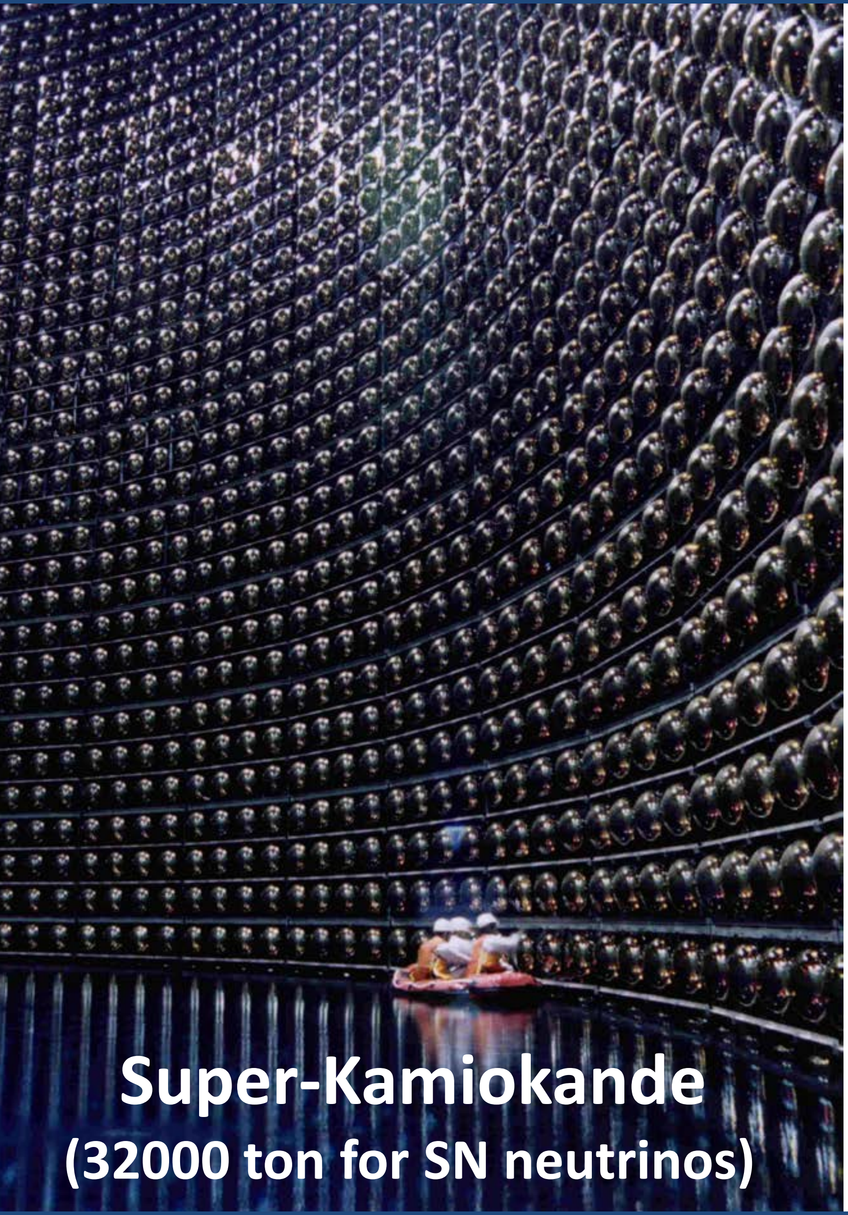
MeV neutrinos

2. Supernova neutrinos

Potential supernova detectors in the world now



Some features to be observed with the present detectors (1)

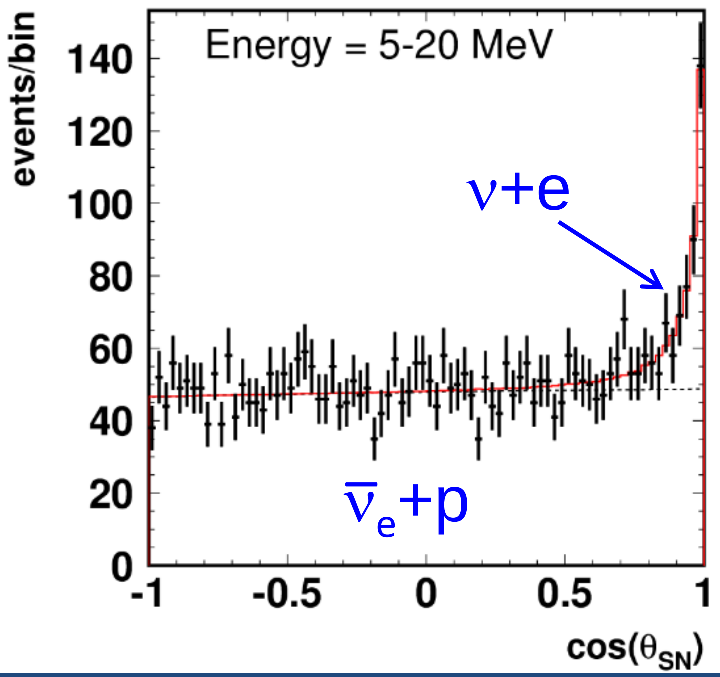


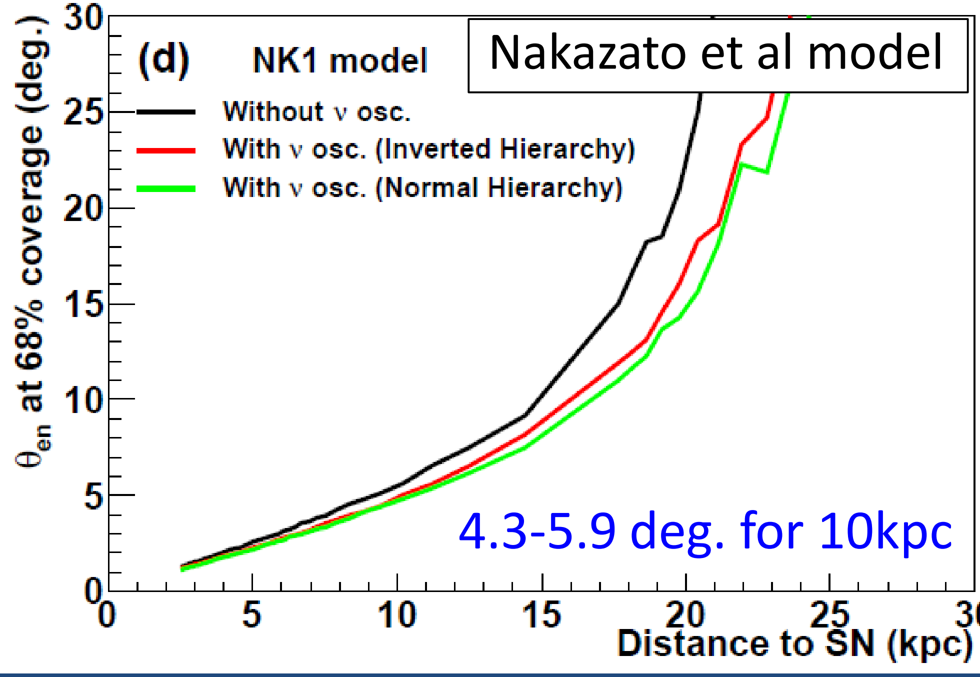
Supernova at 10 kpc

T.Totani et al., ApJ.496,216(1998)
K.Nakazato, ApJ.Suppl. 205 (2013) 2

(4.5MeV(kin) threshold. No oscillation case.)

	Totani et al.	Nakazato et al.
$\bar{\nu}_e p \rightarrow e^+ n$	7300	3100
$\nu + e^- \rightarrow \nu + e^-$	320	170
^{16}O CC	110	57

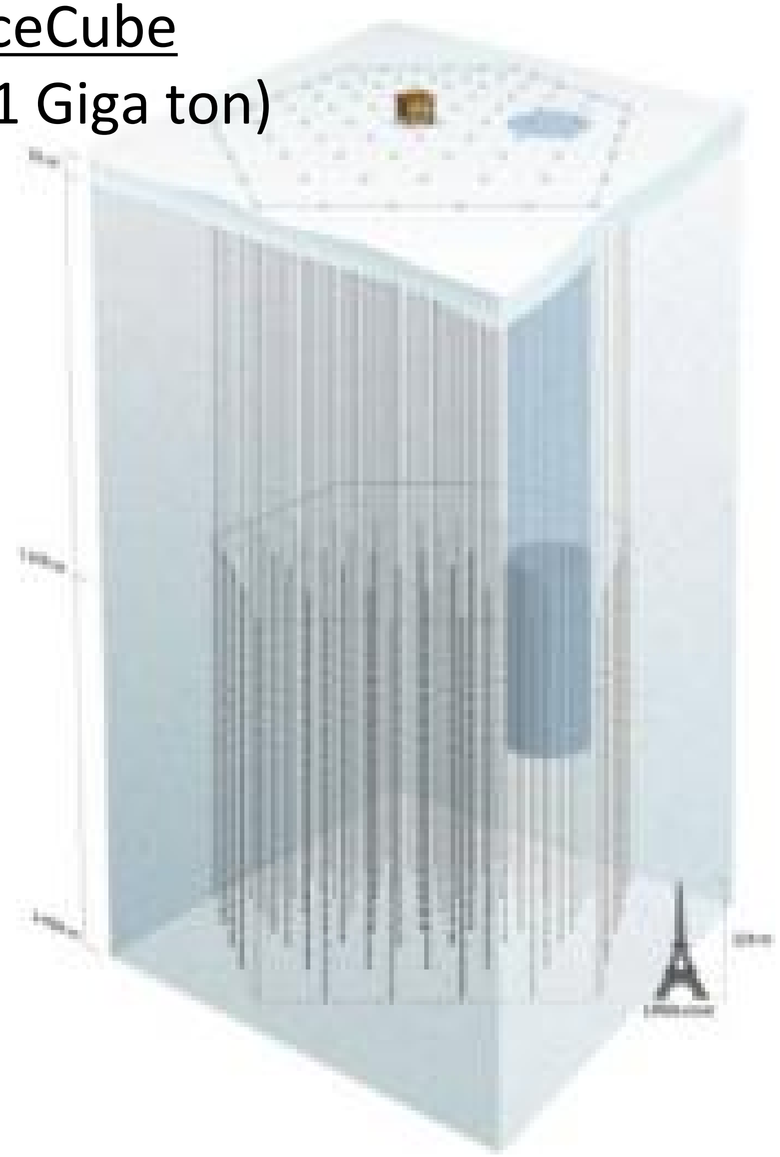




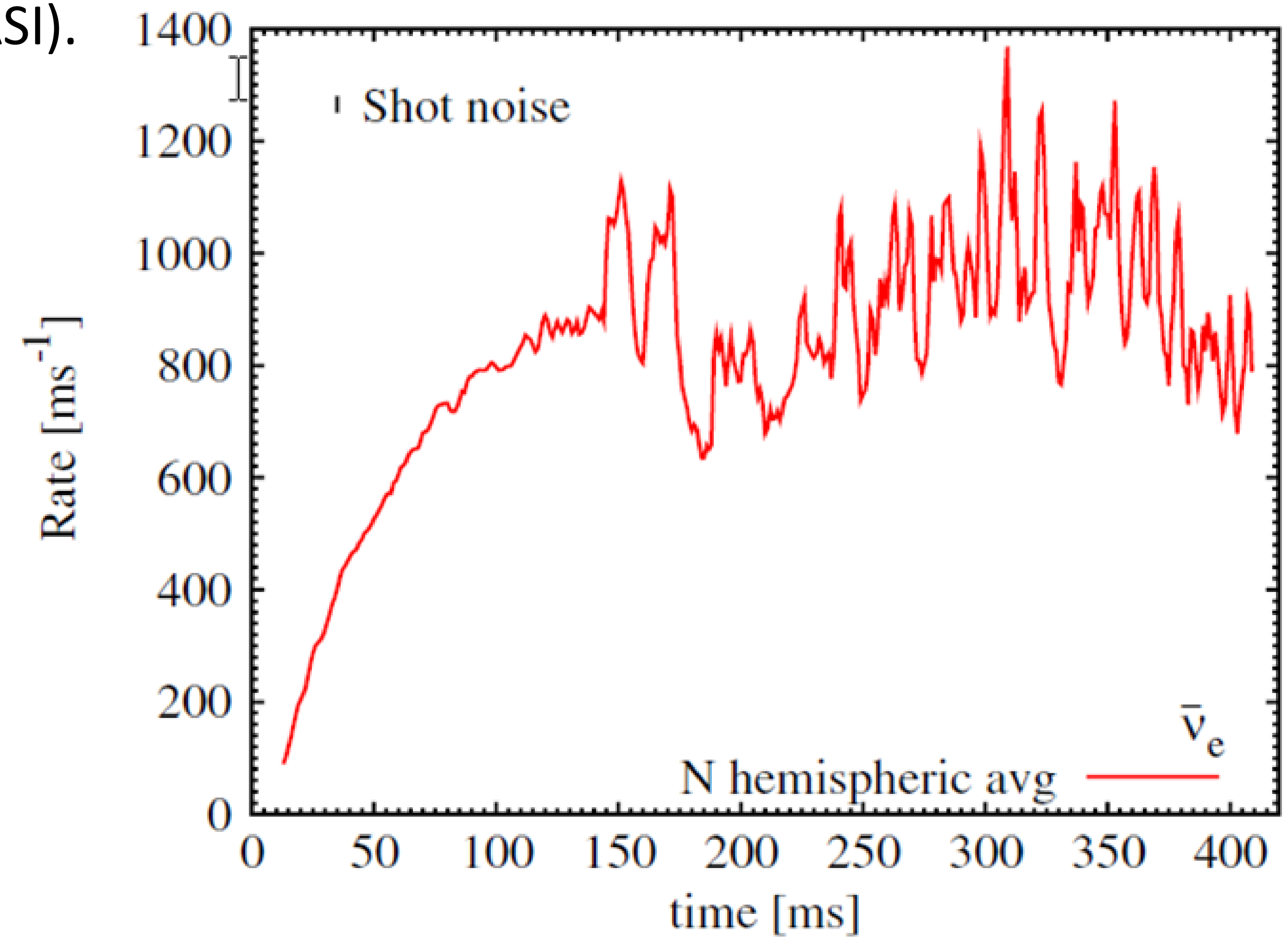
Some features to be observed with the present detectors (2)

T.Lund et al., Phys. Rev. D82, 063007(2010).

<u>IceCube</u>
(1 Giga ton)



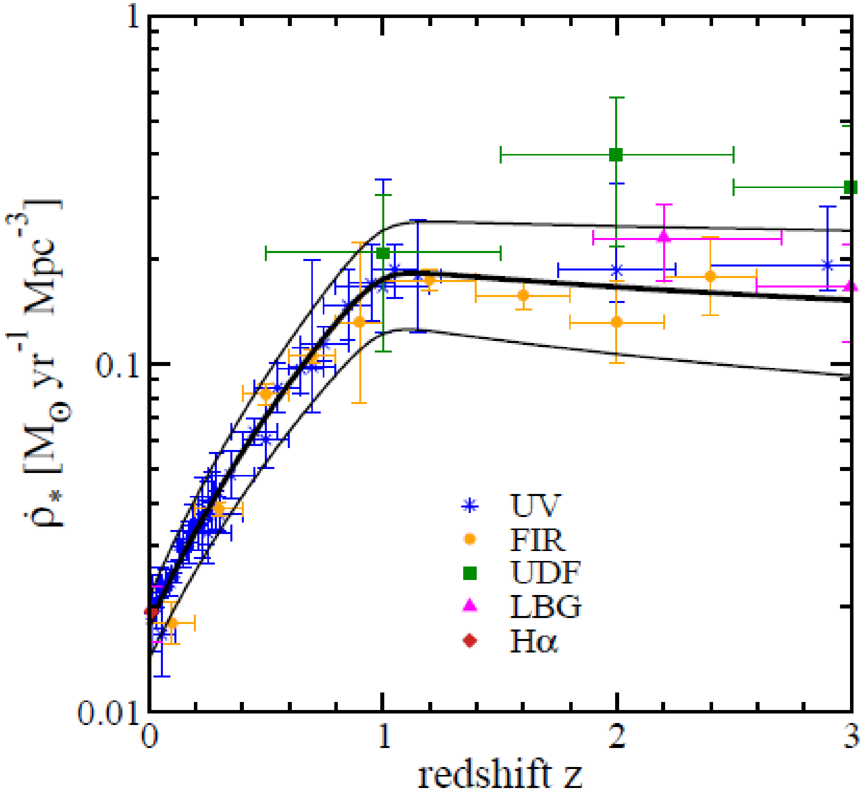
Signal variation by Standing Accretion Shock Instability (SASI).



Exploring the history of Supernova explosion

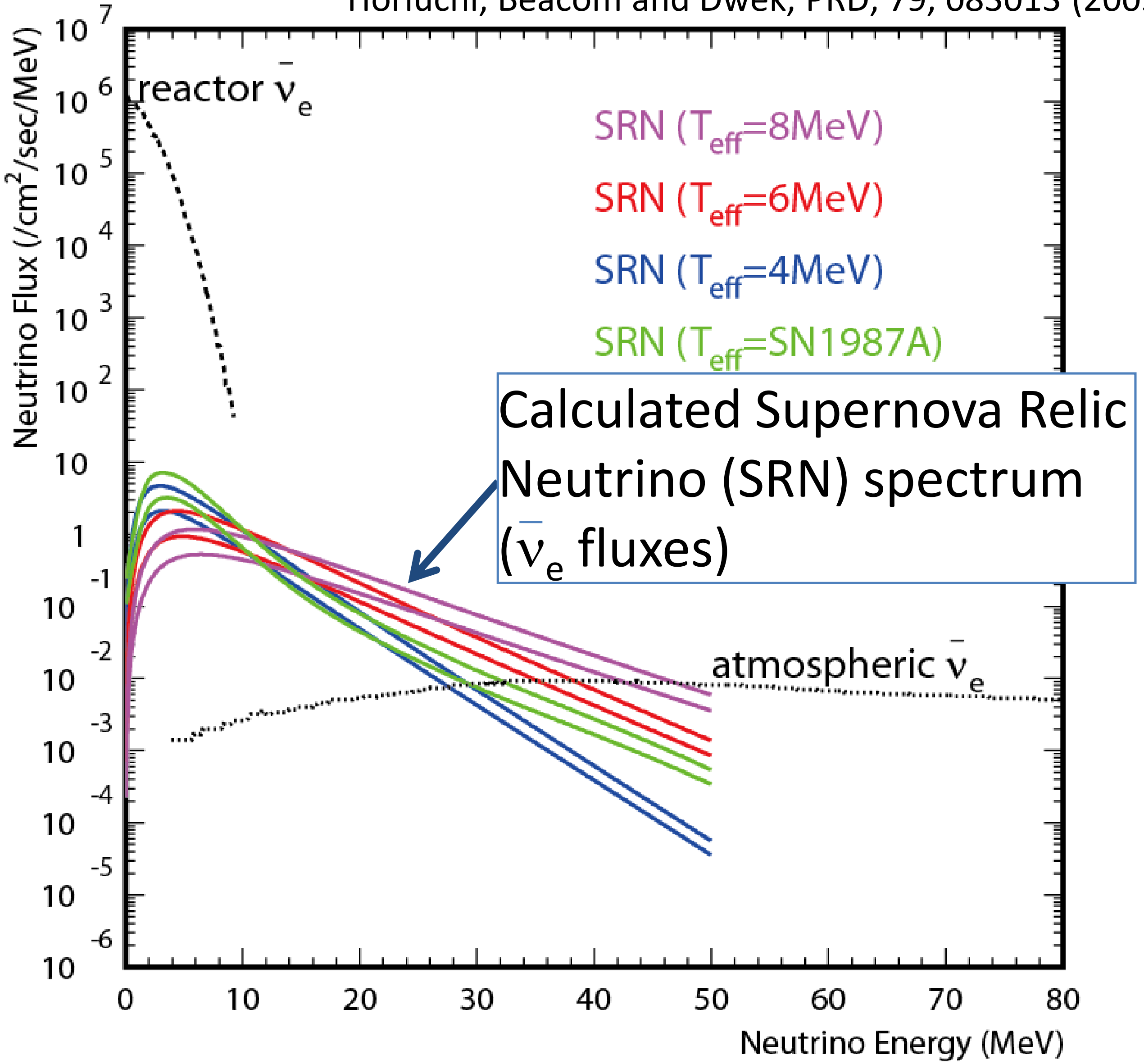
Horiuchi, Beacom and Dwek, PRD, 79, 083013 (2009)

Star Formation Rate

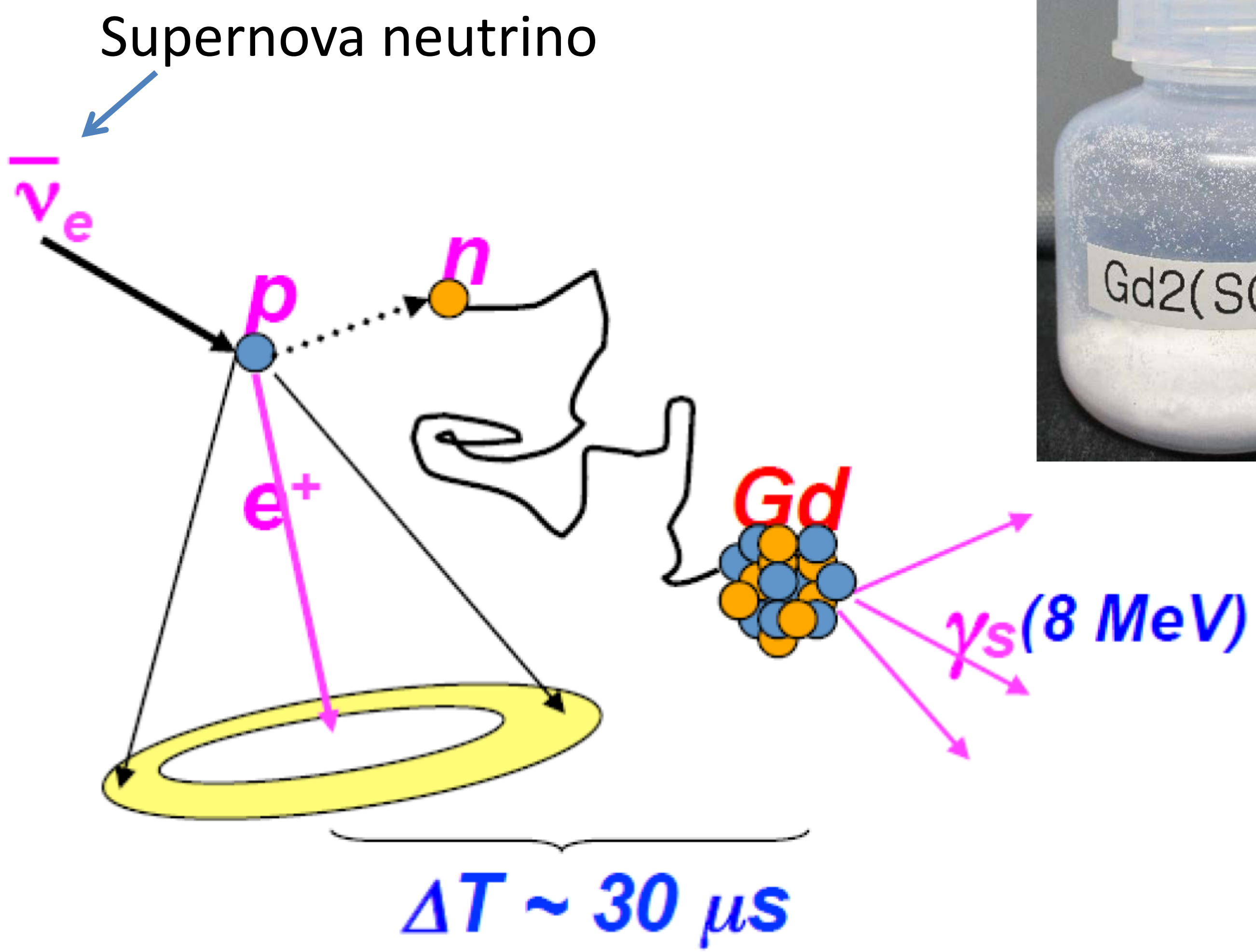


+ Initial Mass Function

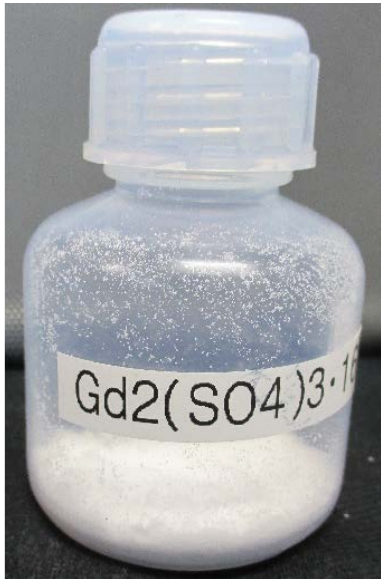
+ Neutrino spectrum



Toward the detection of relic Supernova neutrinos in Super-K



J. Beacom and M. Vagins PRL93,171101 (2004)



Super-K is going to put Gd into the 50,000 ton water. The coincidence of the prompt e^+ and the delayed γ (by neutron capture) reduces the non-Supernova neutrino background substantially.

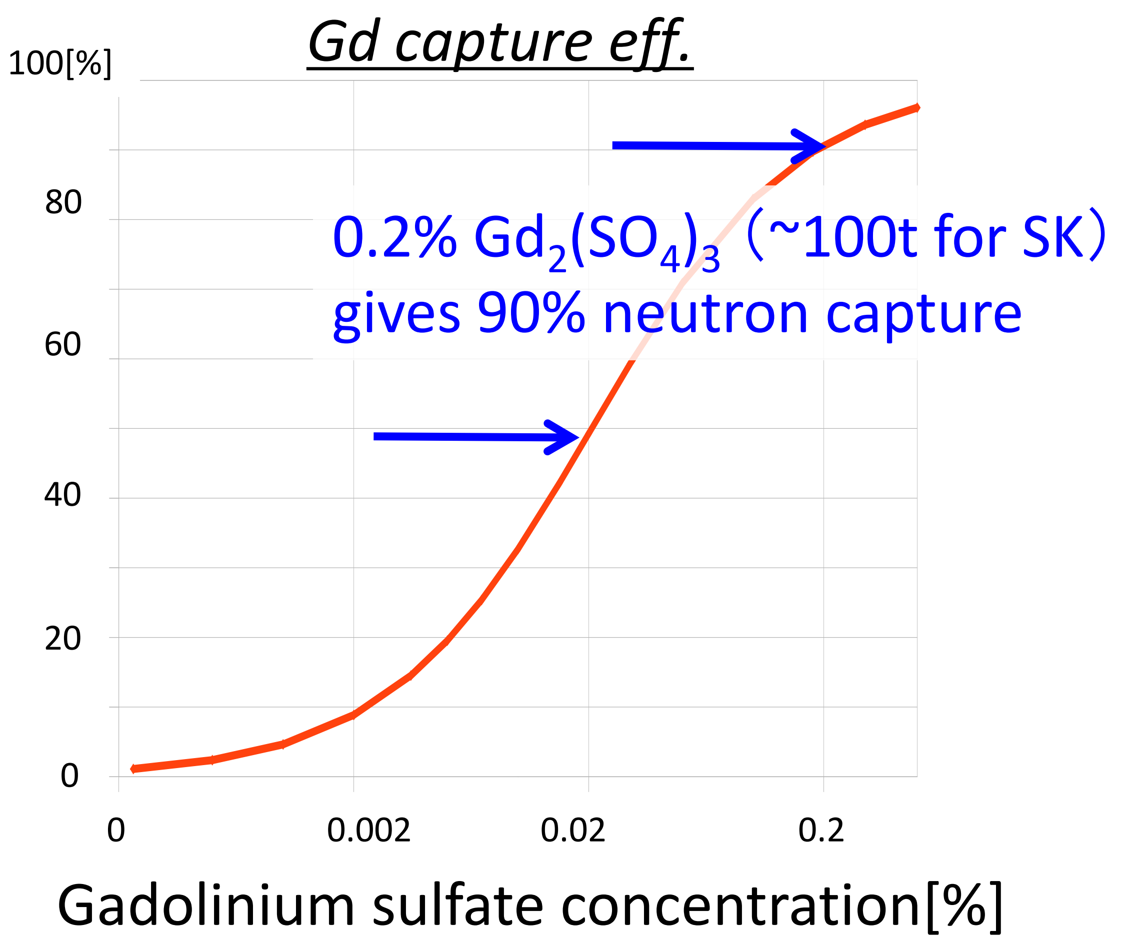
There is a challenge in the water purification system. Old system simply removed any impurities in the water. The new water purification system has to remove all the impurities except for Gd and SO_4.

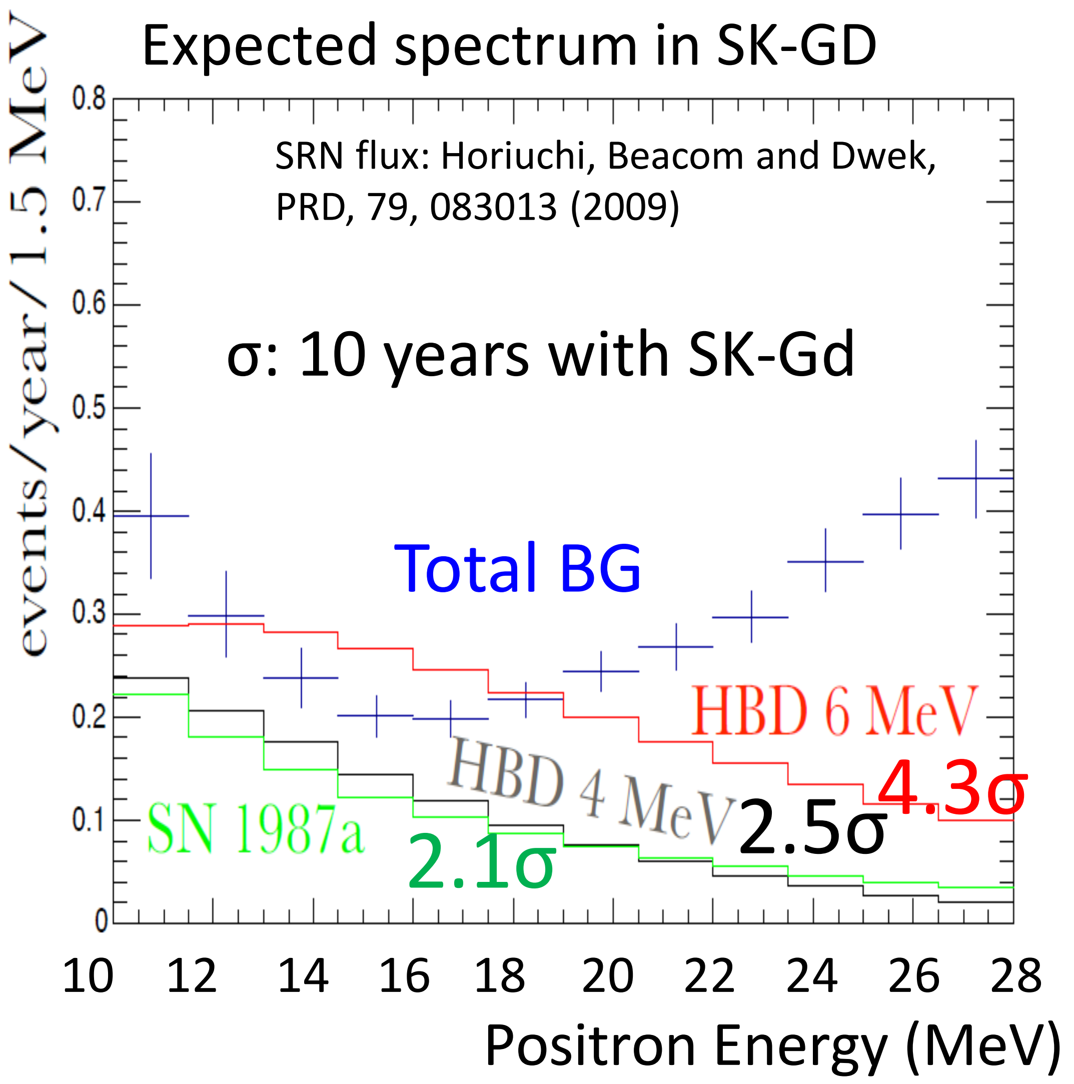
Detecting Supernova relic SN neutrinos

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

$n + Gd \rightarrow Gd + \gamma$'s (total E of γ's ~8MeV)

(M. Ikeda, neutrino 2018)





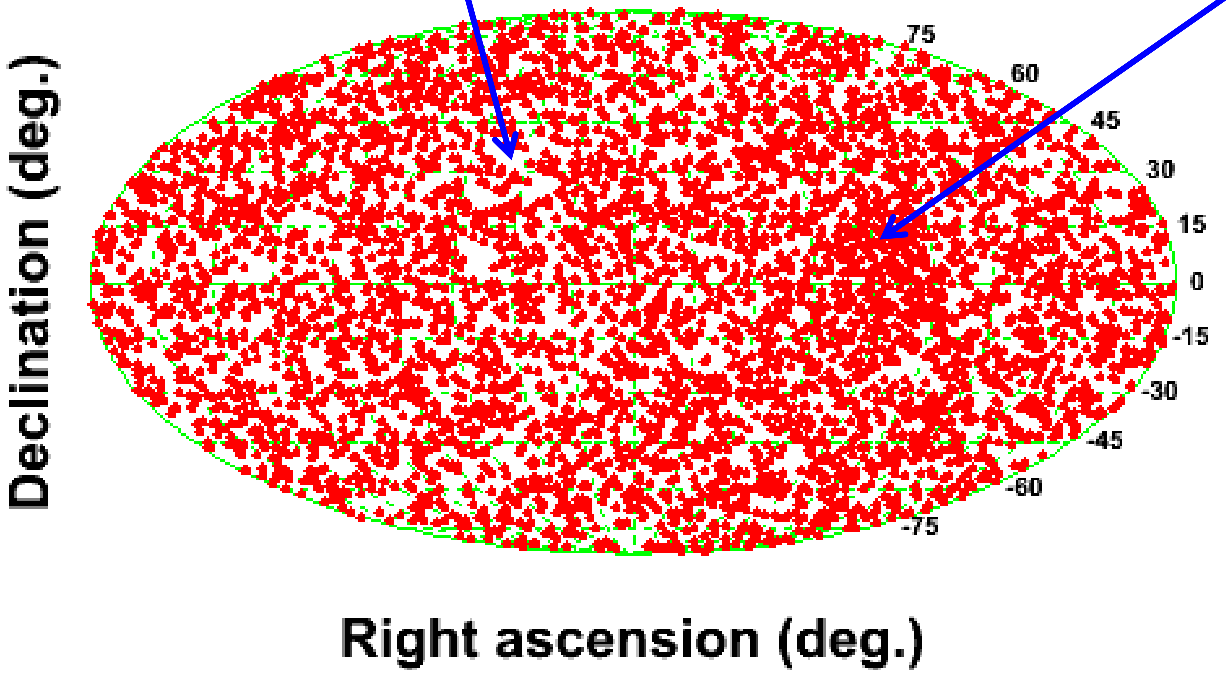
Detecting Supernova neutrino burst with SK-Gd

M. Nakahata (2018)

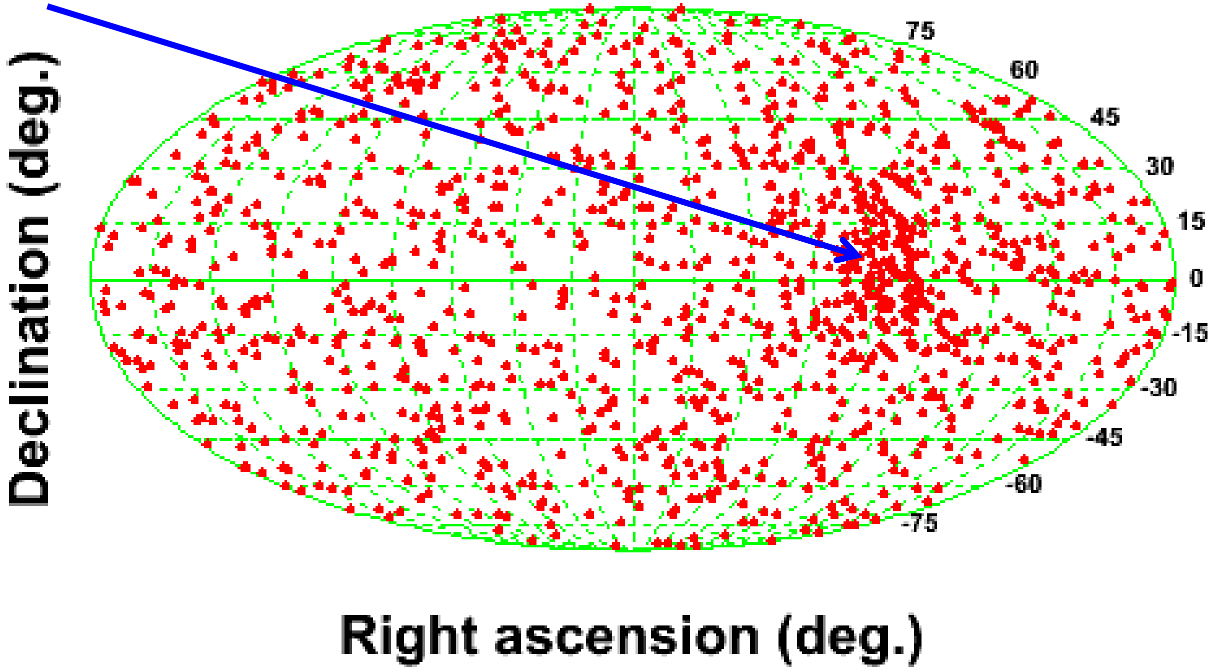
No identification of $\bar{\nu}_e$ (pure water)

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

$\nu + e \rightarrow \nu + e$



Identification of $\bar{\nu}_e$ with 80% efficiency (SK-Gd)

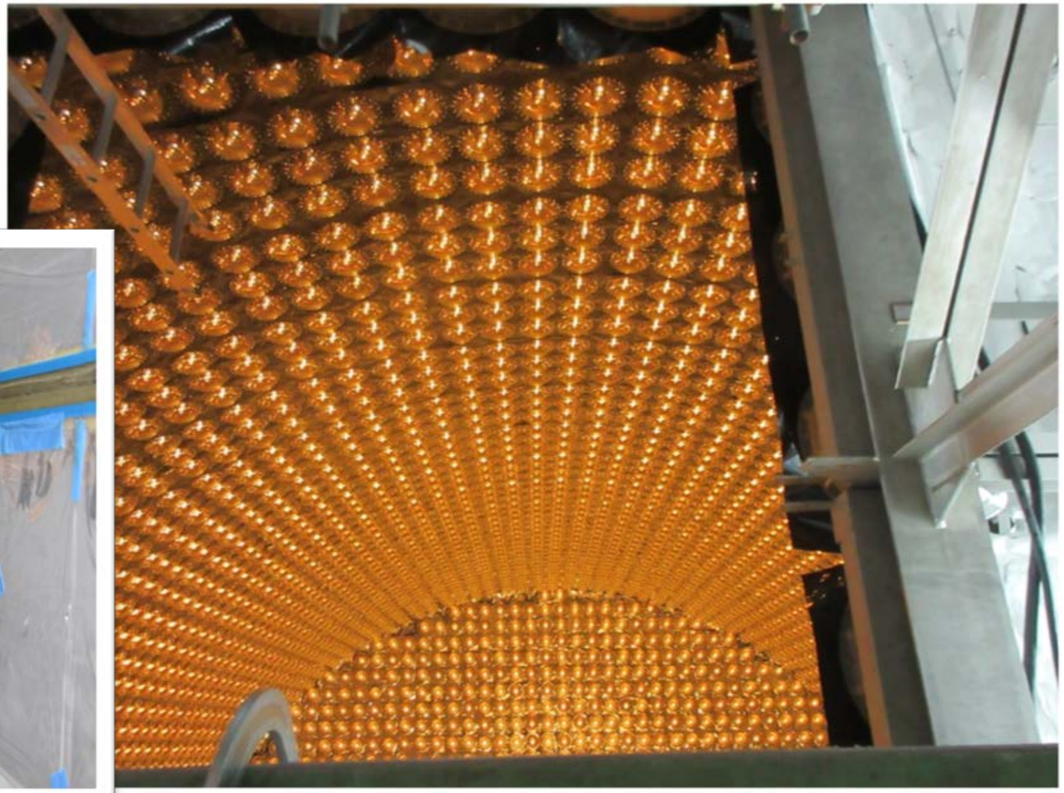


→ The accuracy of the Supernova direction will be improved from 4.3 – 5.9 degrees (pure water) to 3.3 – 4.1 degrees (SK-Gd) for a SN at 10 kpc.

Status and plans

Water system to treat Gd loaded water (2017)

July 2018



End of Aug., 2018

Super-K resumed the data taking in Jan. 2019. No detectable water leak!
Probably, Super-K-Gd with $Gd_2(SO_4)_3$ (0.02%) will begin in late 2019 (or early 2020).
Super-K-Gd with $Gd_2(SO_4)_3$ (0.2%) will begin in 202X.

GeV neutrinos

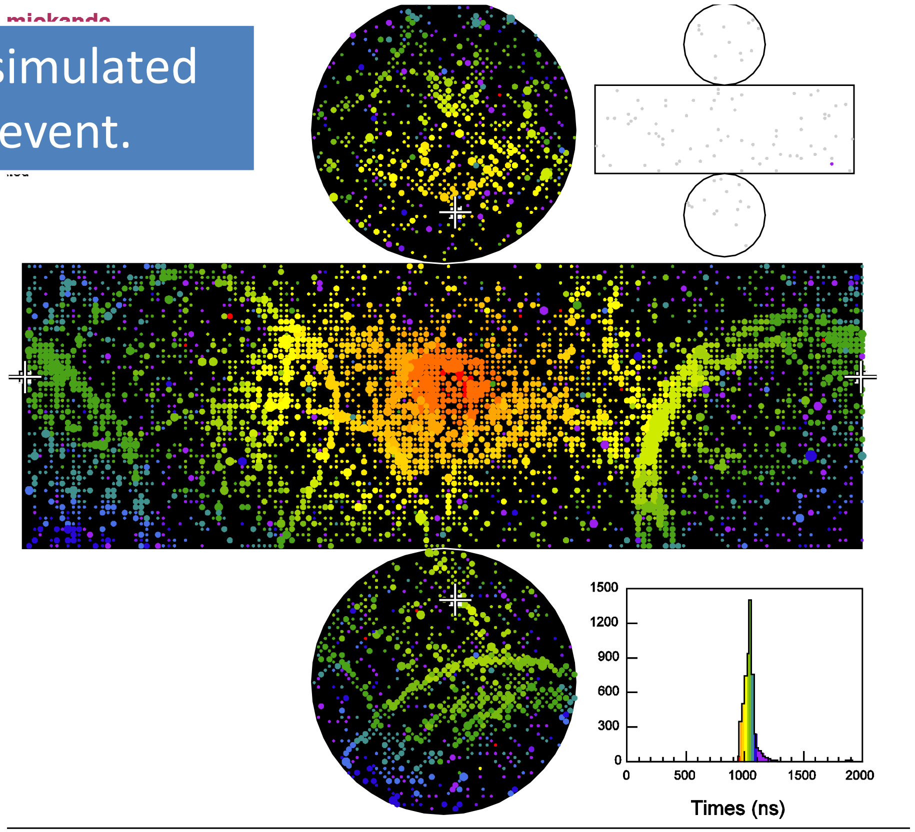
1. Atmospheric neutrino oscillations

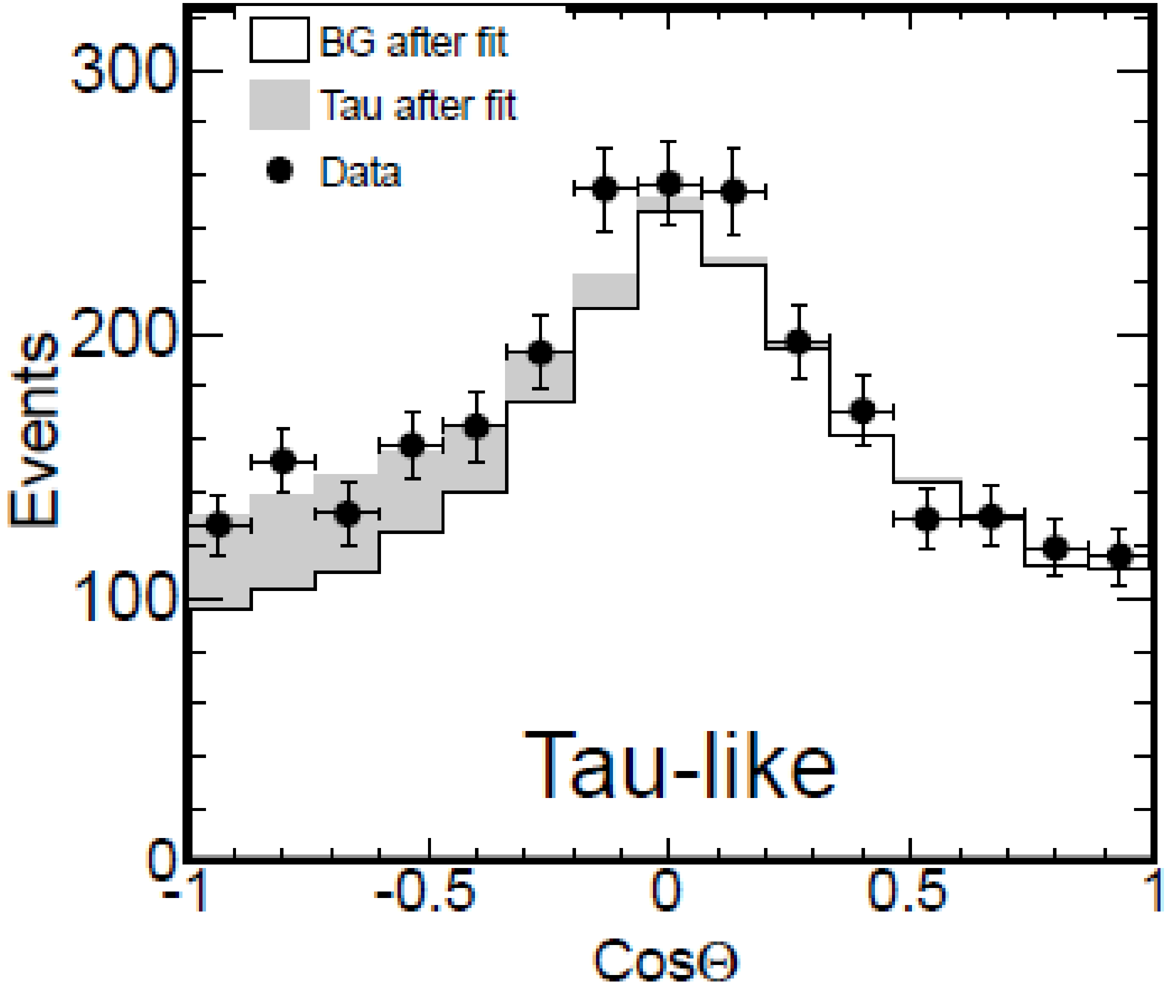
Detecting tau neutrinos

If the oscillations are between ν_μ and ν_τ, one should be able to observe ν_τ's.

Super-K,arXiv:1711.09436

A simulated ν_τ event.





It is not possible for Super-K to identify ν_τ events by an event by event bases. ➔ Statistical analysis knowing that ν_τ's are upward-going only.

τ-appearance at 4.6σ (consistent with OPERA and IceCube)

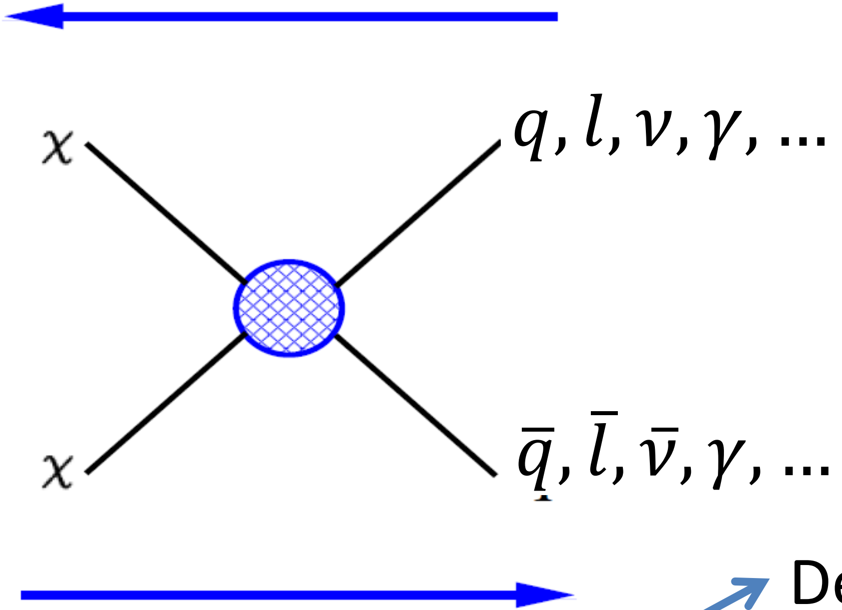
GeV neutrinos

2. Search for neutrinos from dark matter annihilation

Dark matter searches

Accelerator exp.
(LHC, …)

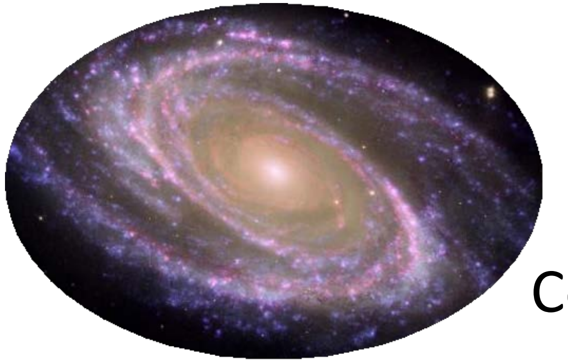
Direct detection exp.



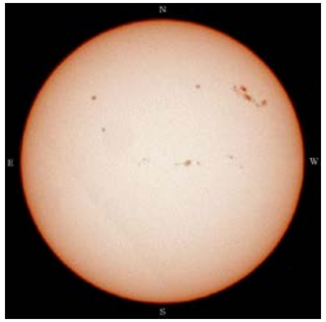
Indirect detection

Detection of;
- ✓ Anti-protons
- ✓ Positrons
- ✓ Gamma rays
- ✓ Neutrinos

Where are we searching?



Center of our galaxy



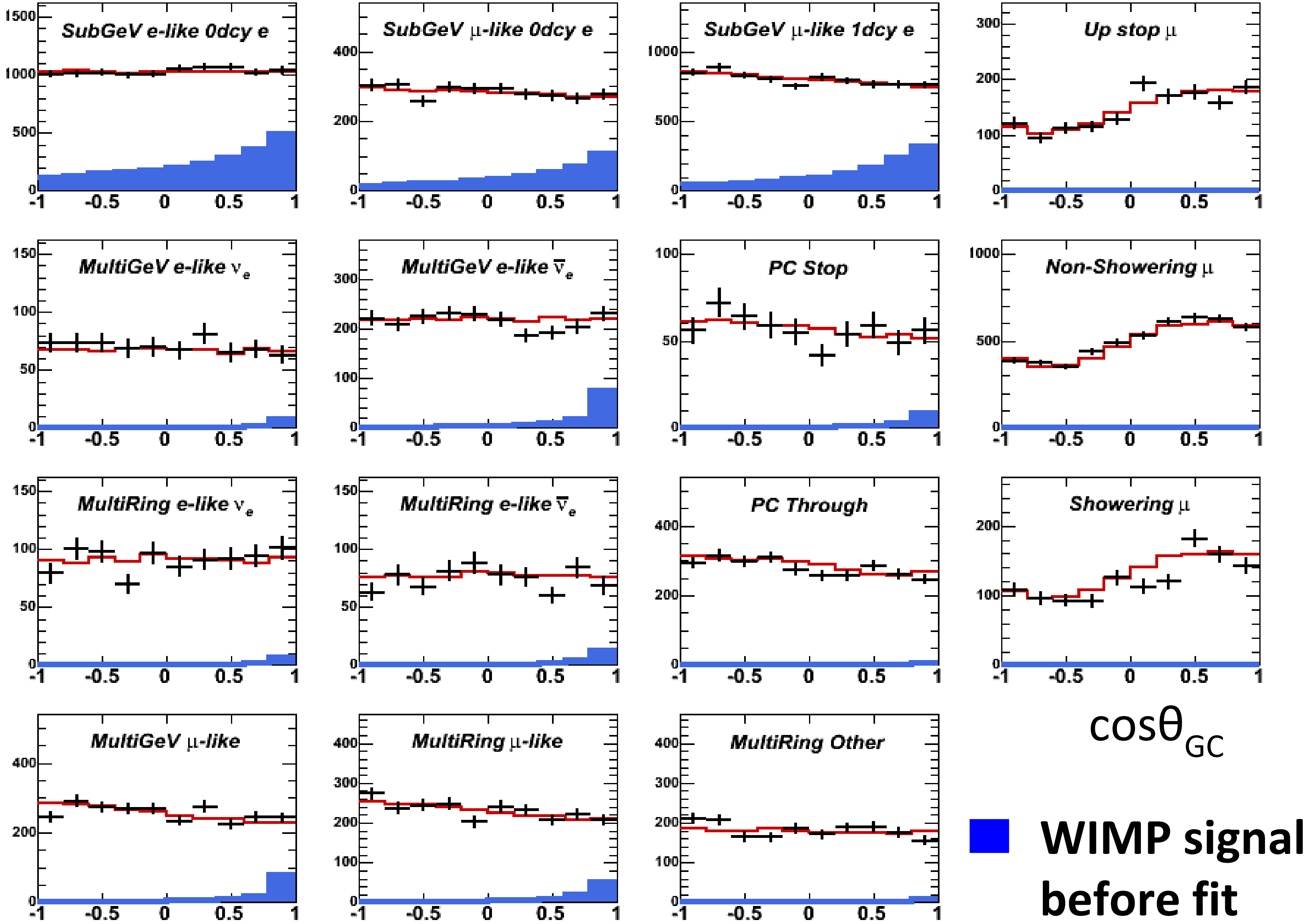
The Sun

The Earth
(skipped)

How the signals look like?

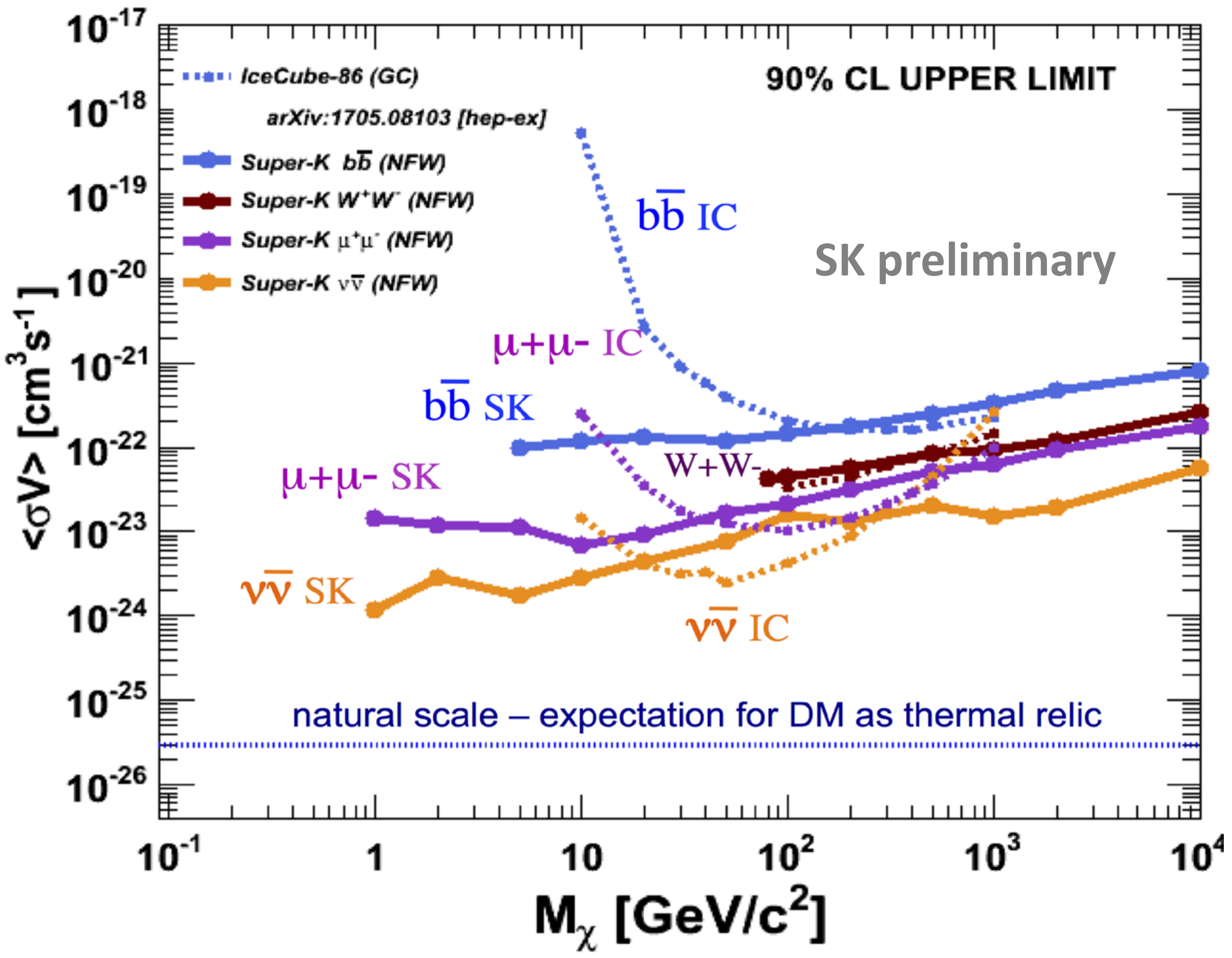
K. Frankiewicz (Super-K), WIN 2017, June 2017

Example:
WIMP signal search from Galactic center
(5 GeV WIMPs , bb ann. Channel)



Search for neutrinos from the center of the galaxy

K. Frankiewicz (Super-K), WIN 2017, June 2017

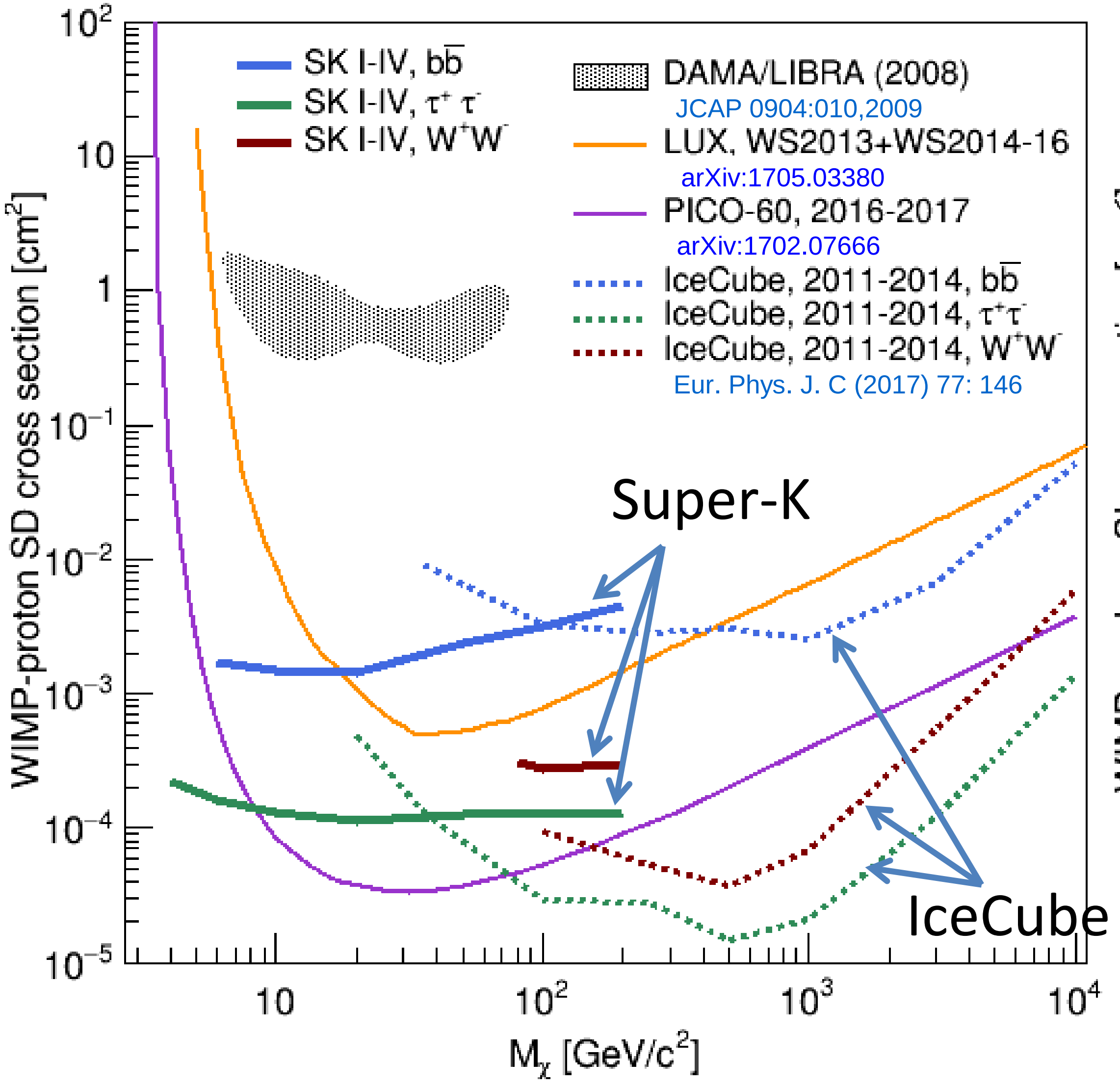


- ✓ Super-K and IceCube give most strigent limit.
- ✓ Still at least a factor of 30 improvement needed to reach the canonical annihilation cross section of ~3×10^{-26} cm^{-2}.

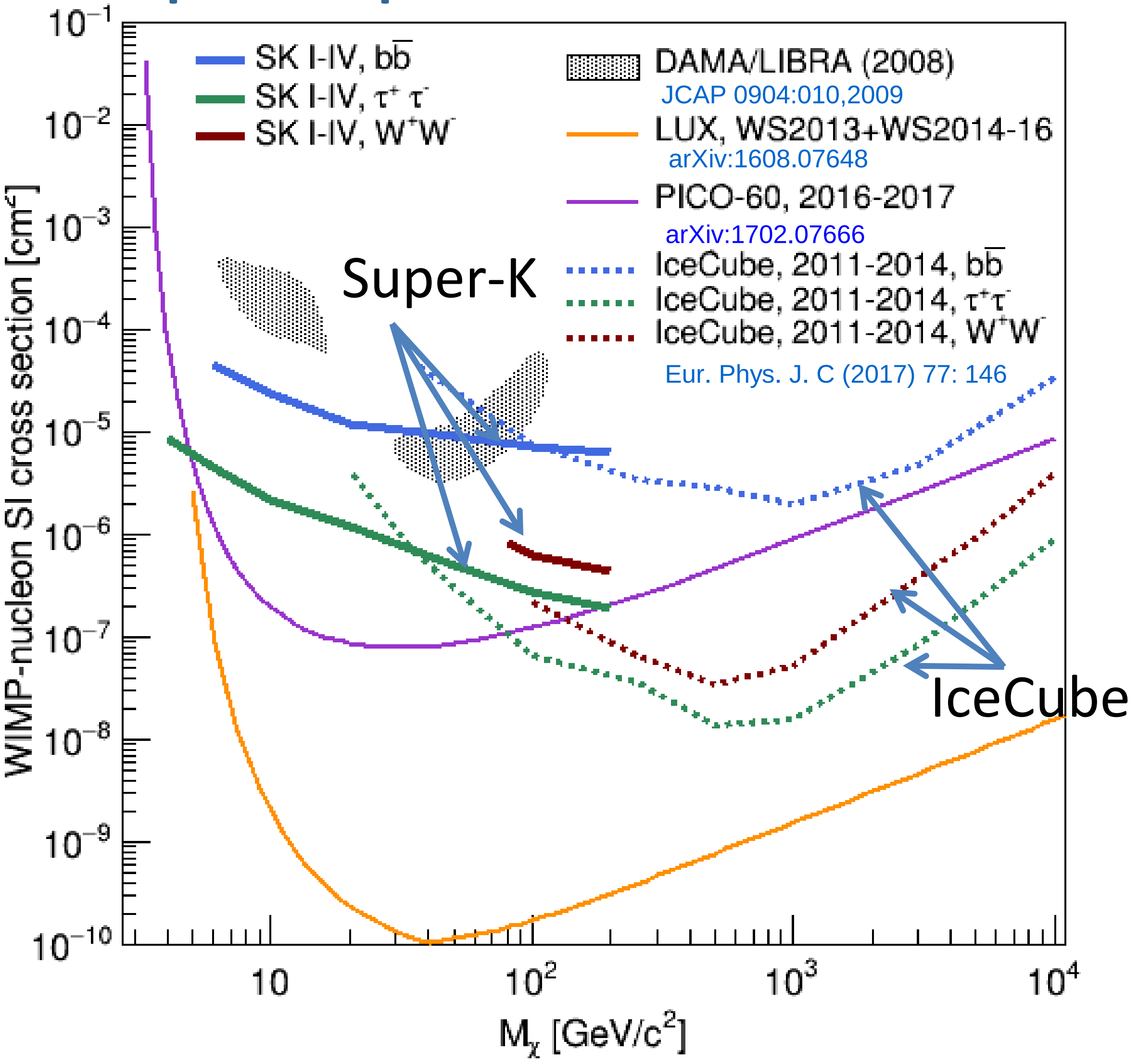
Search for neutrinos from the Sun

K. Frankiewicz (Super-K), WIN 2017, June 2017

Spin-dependent interactions

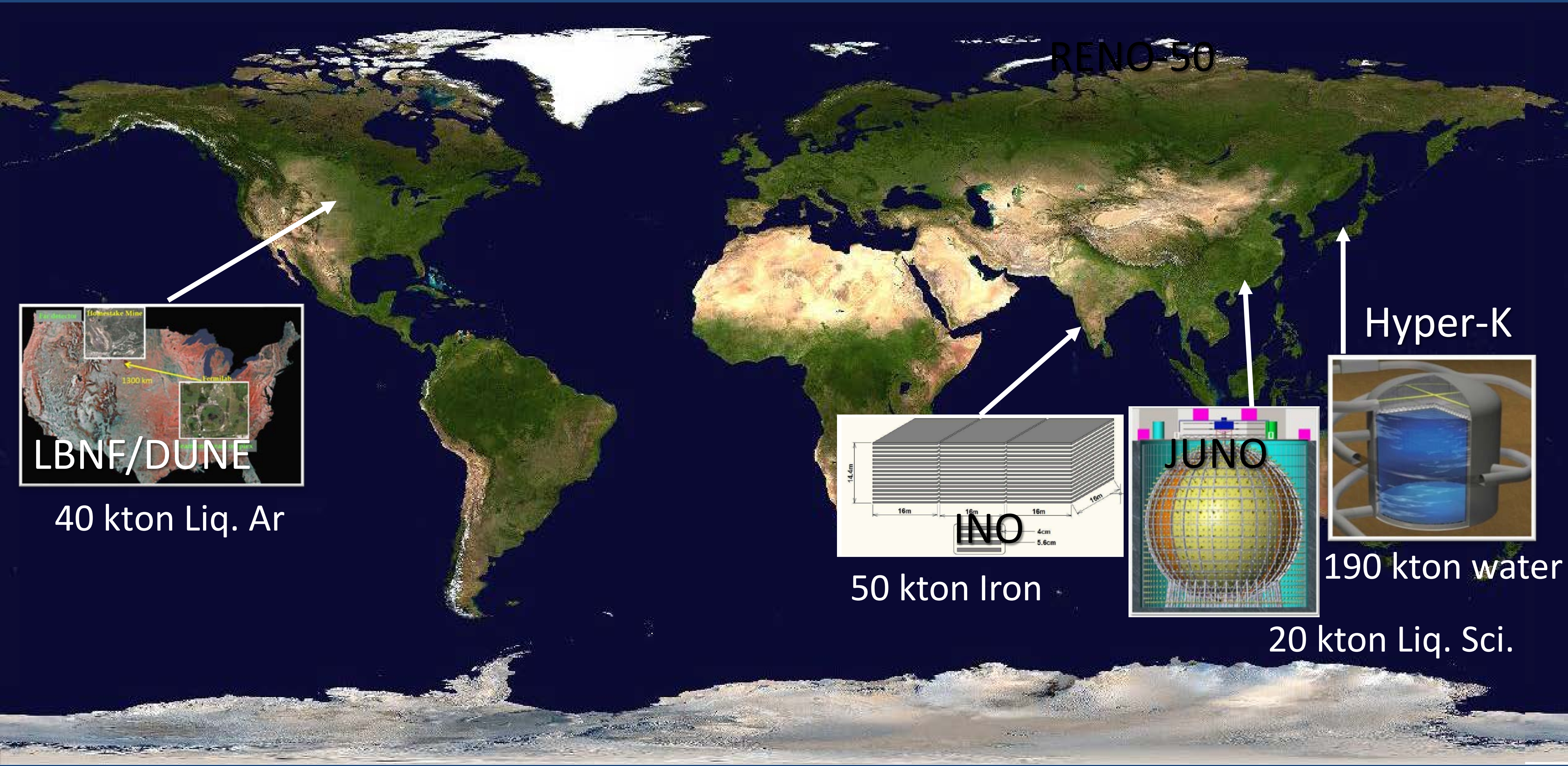


Spin-independent interactions

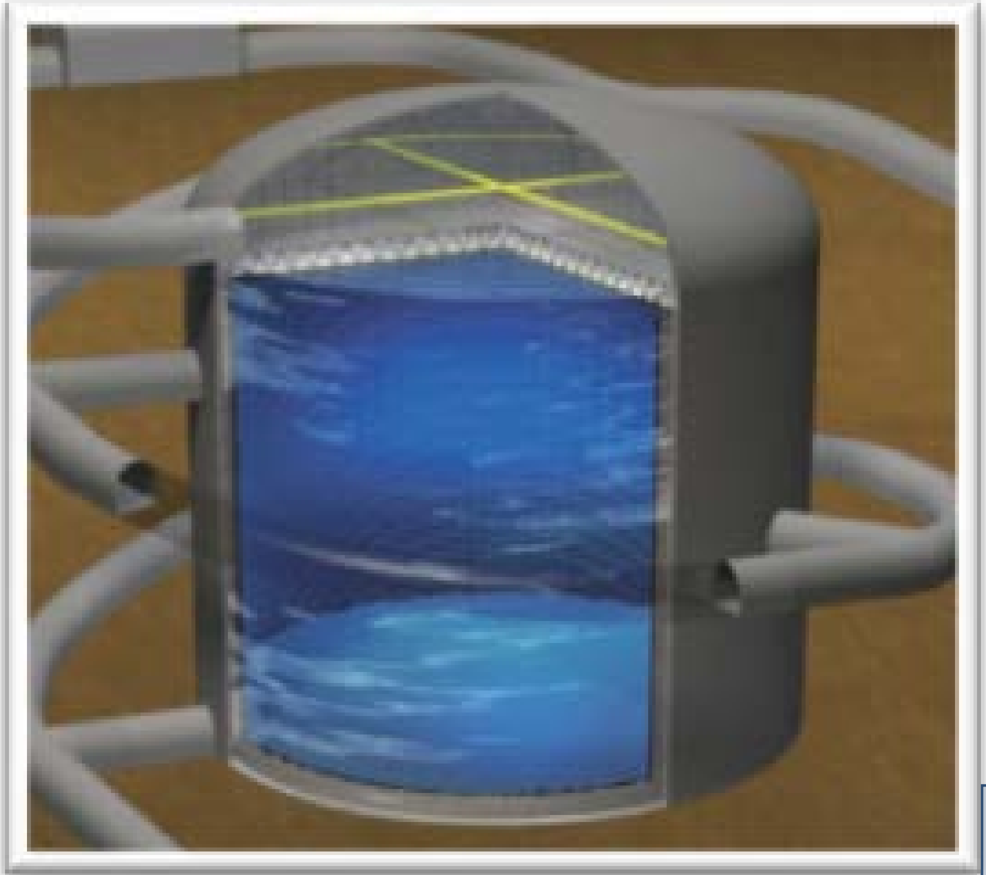


MeV to GeV neutrino detectors in the CTA era

Future MeV to GeV neutrino experiments



Hyper-K



- ◆Φ 74 meters and H 60 meters.
- ◆The total and fiducial volumes are 0.26 and 0.19 M tons, respectively.

Hyper-K detector will be used to study:

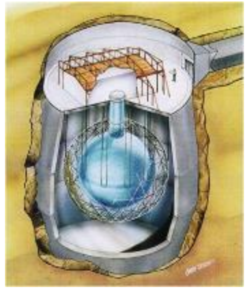
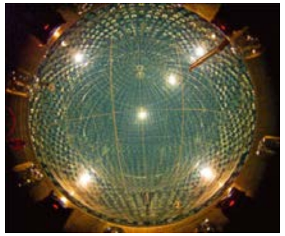
- ✓ Neutrino oscillations (CP violation) with J-PARC neutrino beam(1.3MW beam),
- ✓ atmospheric neutrino oscillations,
- ✓ solar neutrino oscillations
- ✓ Proton decays
- ✓ Supernova neutrino burst
- ✓ Past supernova neutrinos
- ✓ WIMP search
- ✓ ….

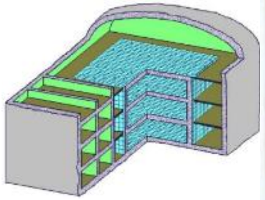
HK proto-collaboration (~300 people from 17 countries)

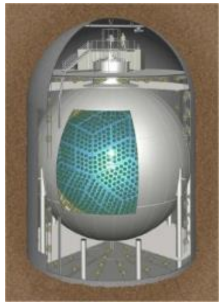
Plan: Construction from 2020, and operation from ~2027.

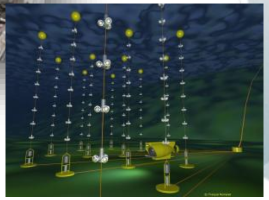
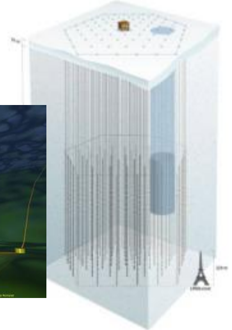
Summary

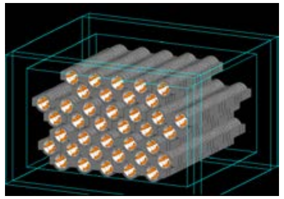
- MeV to GeV neutrinos have been contributing a lot on the discovery and studies of neutrino oscillations.
- We hope that MeV to GeV neutrinos will contribute to the multi-messenger astronomy and the studies of high-energy Universe.







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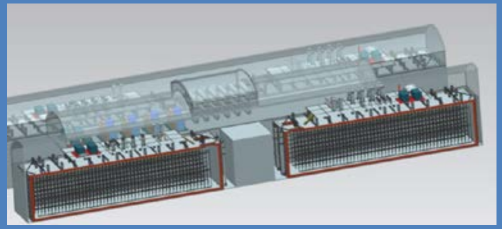
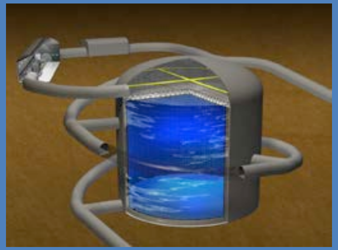
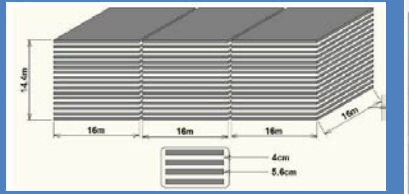
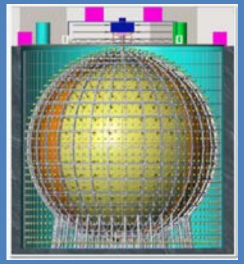

Future …

…