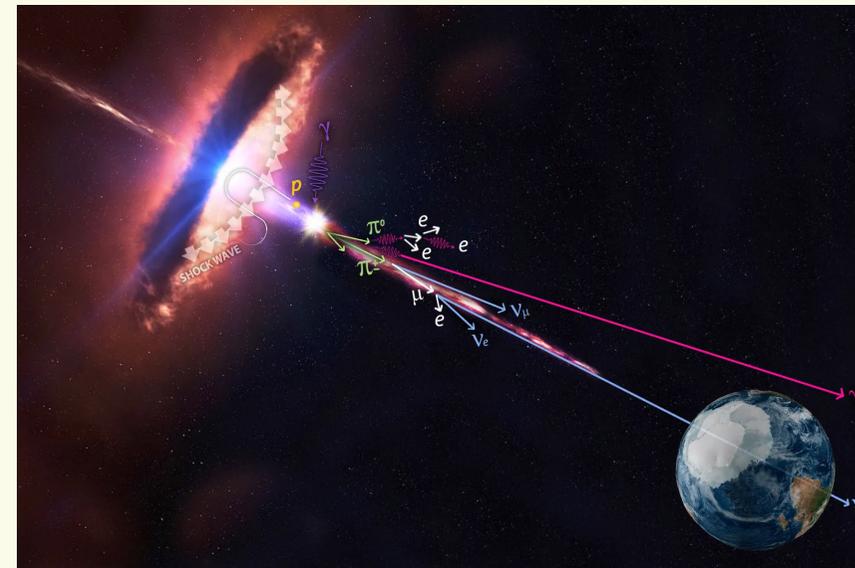


# Neutrinos

as a multi-messenger astrophysical signal  
- from keV to ZeV -



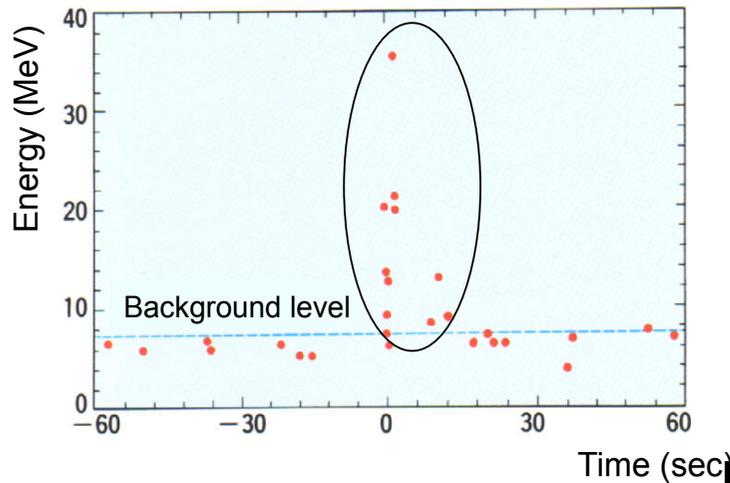
**Yusuke Koshio**  
Okayama University



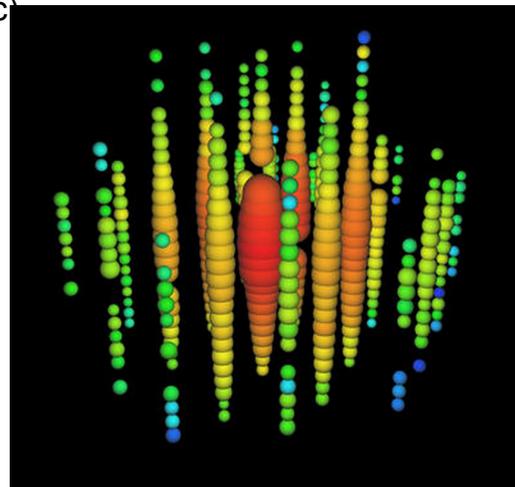
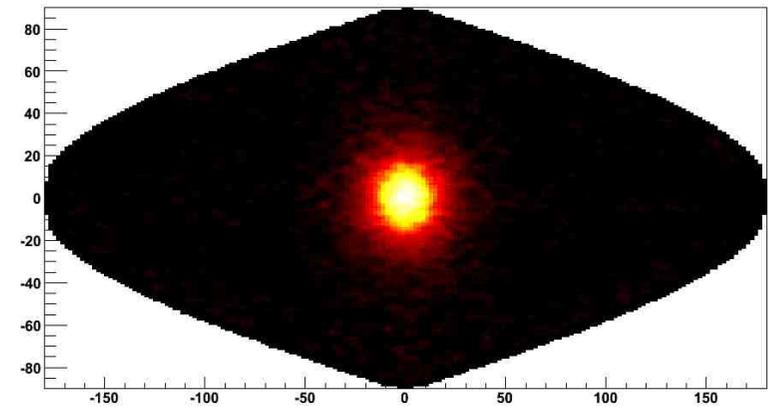
II Synergies at new frontiers  
25-26 March, 2024  
Kashiwa, Chiba, Japan

# Astrophysical neutrinos observed so far

## Supernova (1987A)



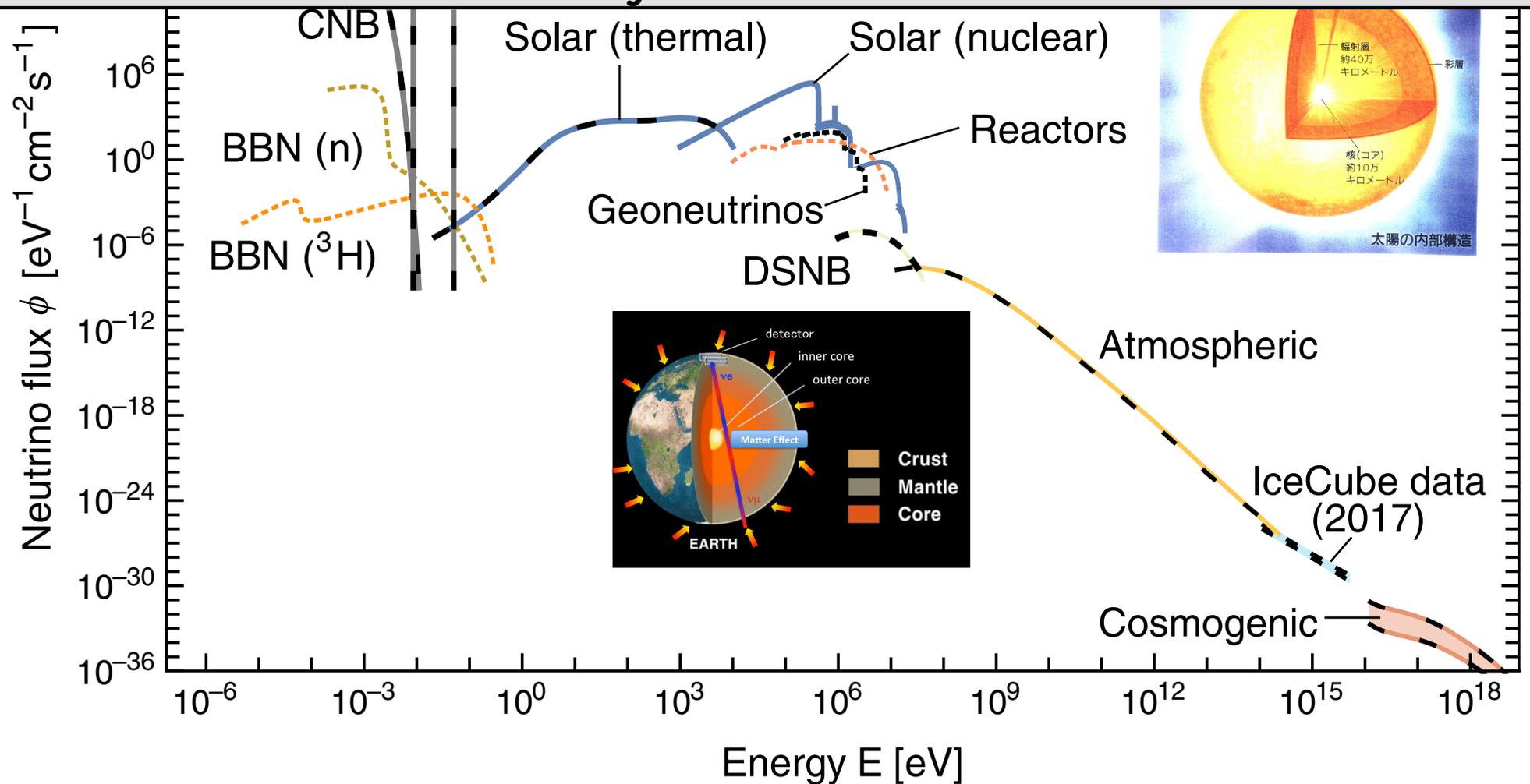
## Solar neutrino



## High-energy astrophysical neutrino

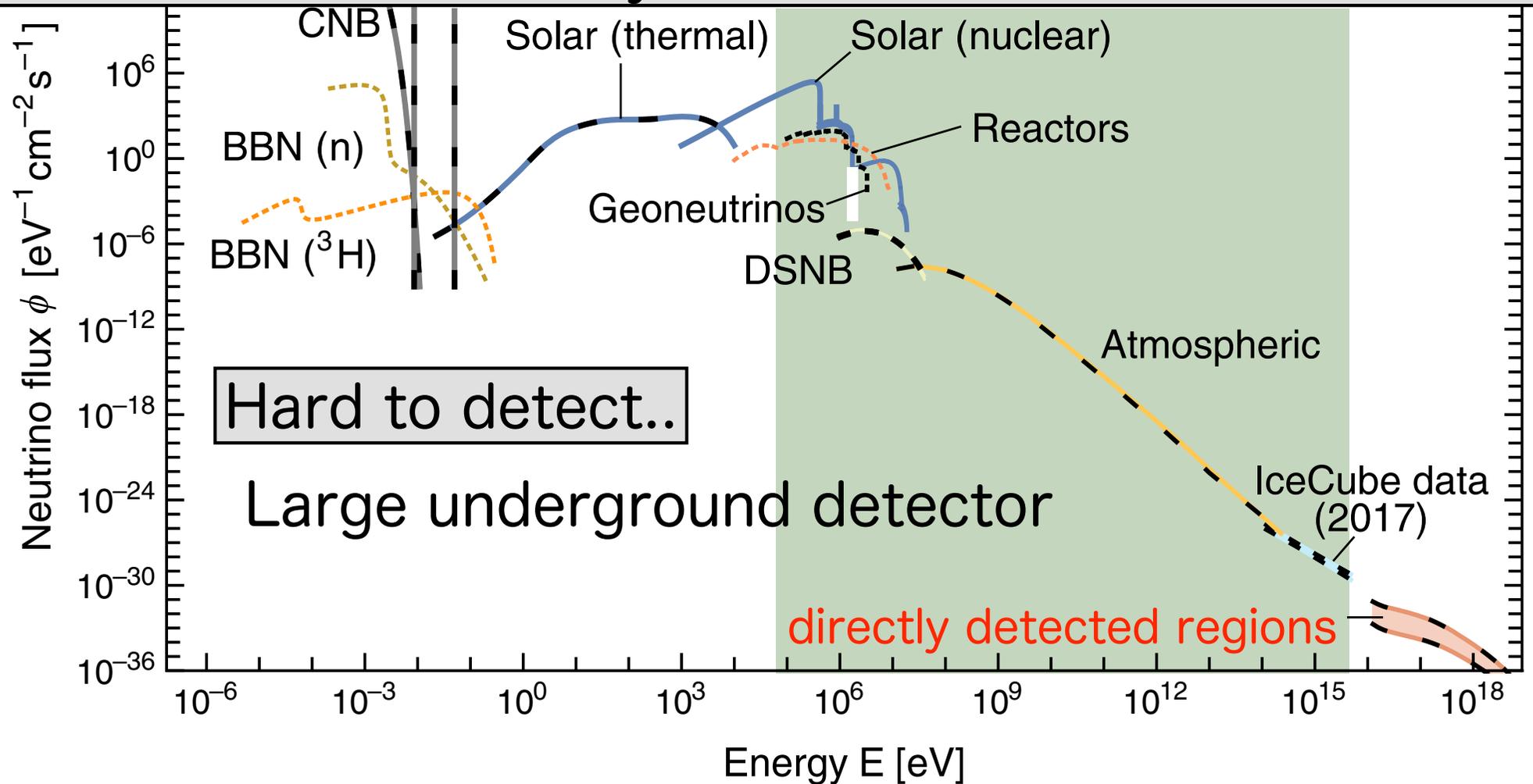
# Neutrino sources

Direct messages from deep inside astronomical objects  
undisturbed by matters and EM fields



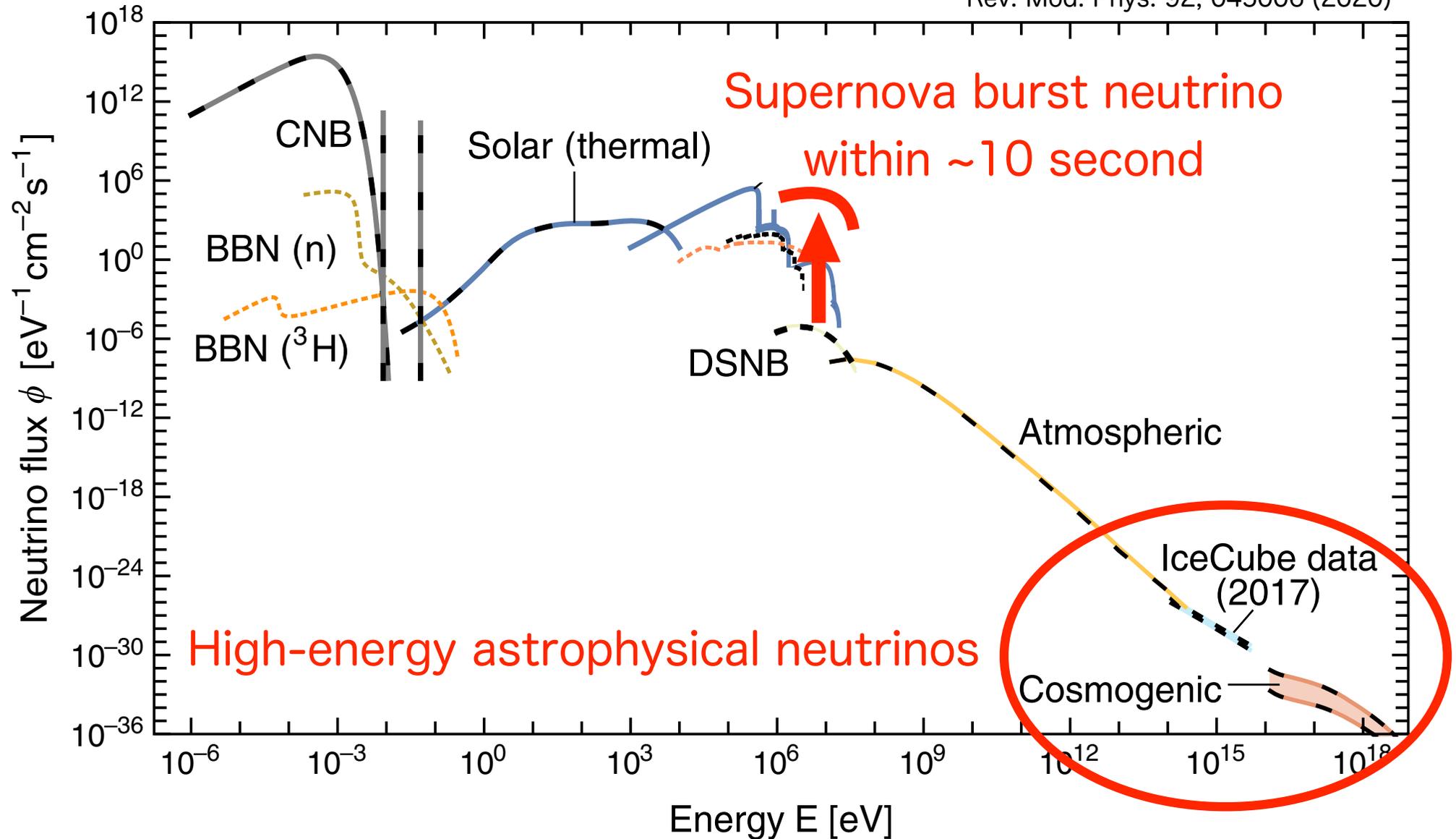
# Neutrino detection

Direct messages from deep inside astronomical objects  
undisturbed by matters and EM fields



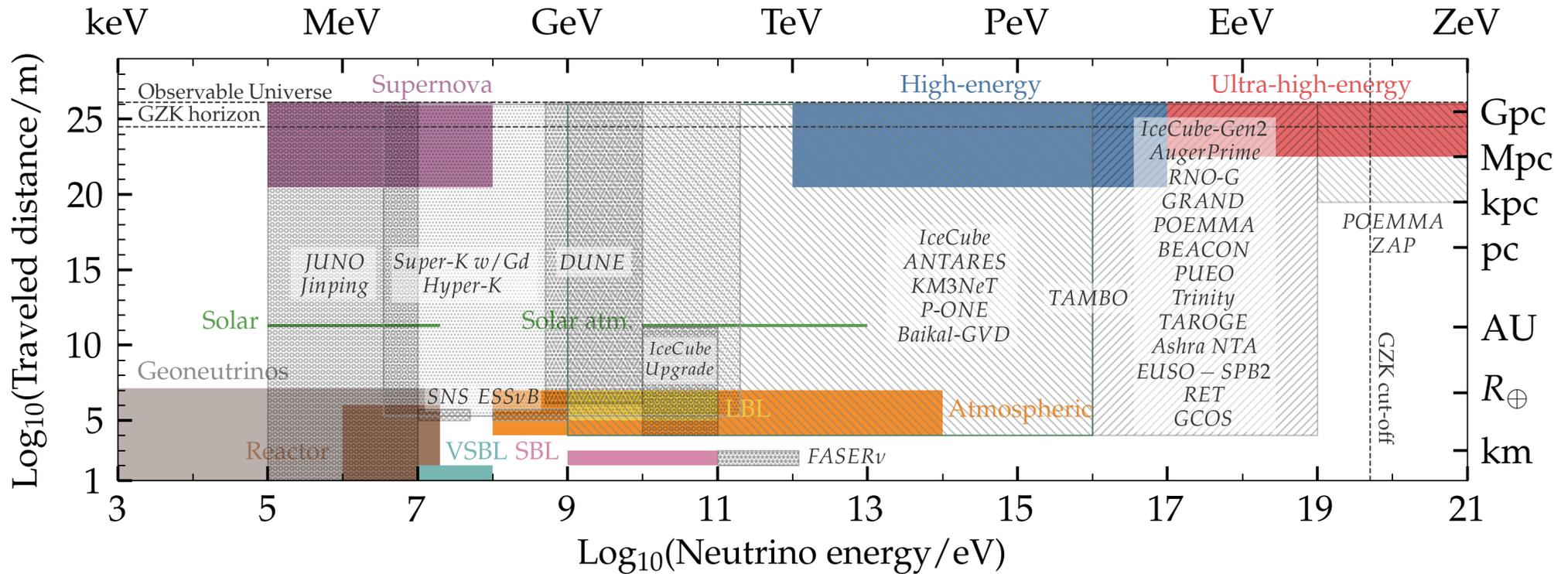
# Multi-messenger targets

Rev. Mod. Phys. 92, 045006 (2020)



# Various detectors with wide energy range

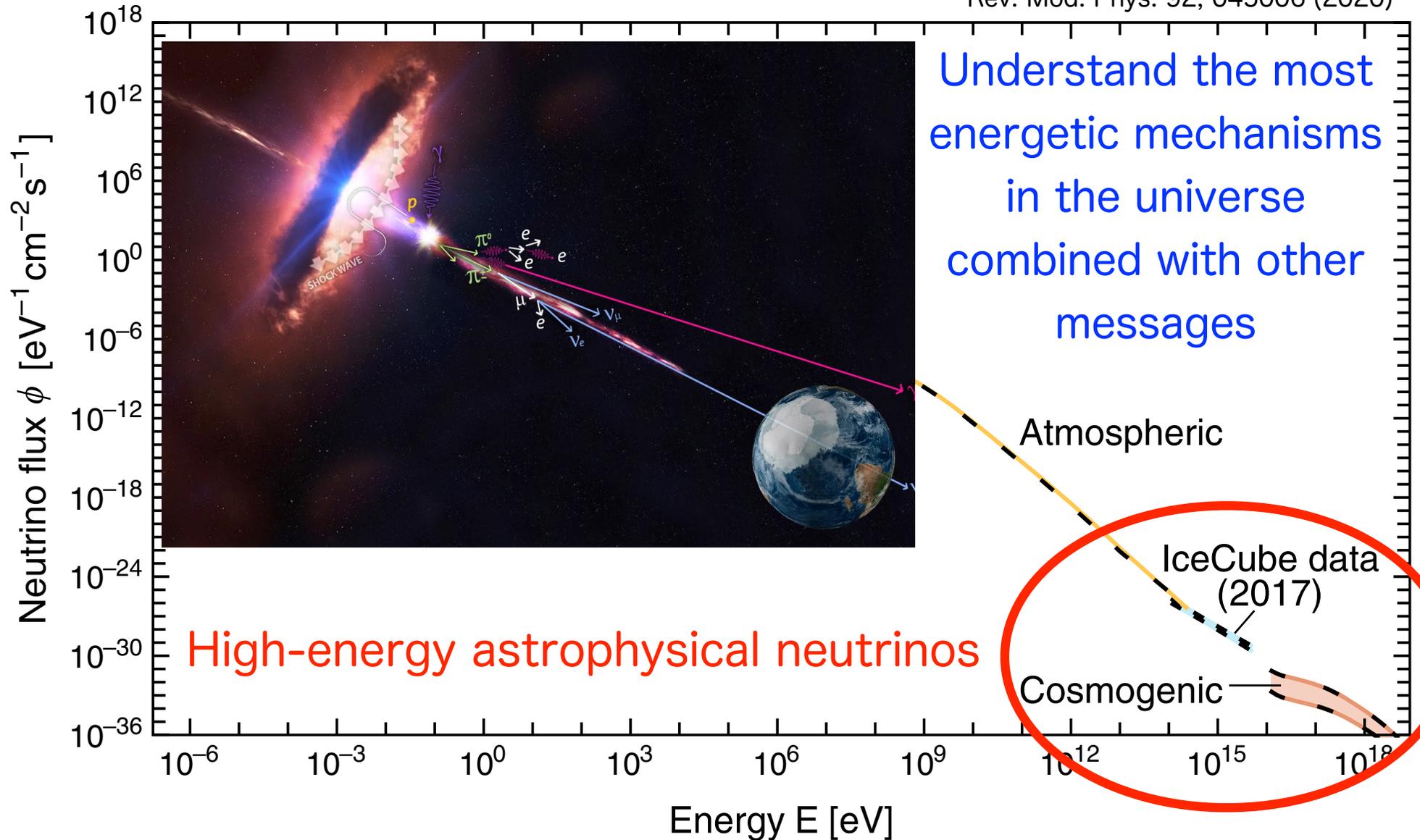
arXiv 2203.08096



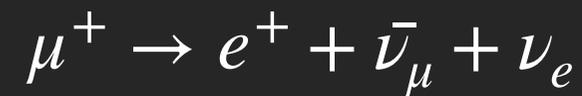
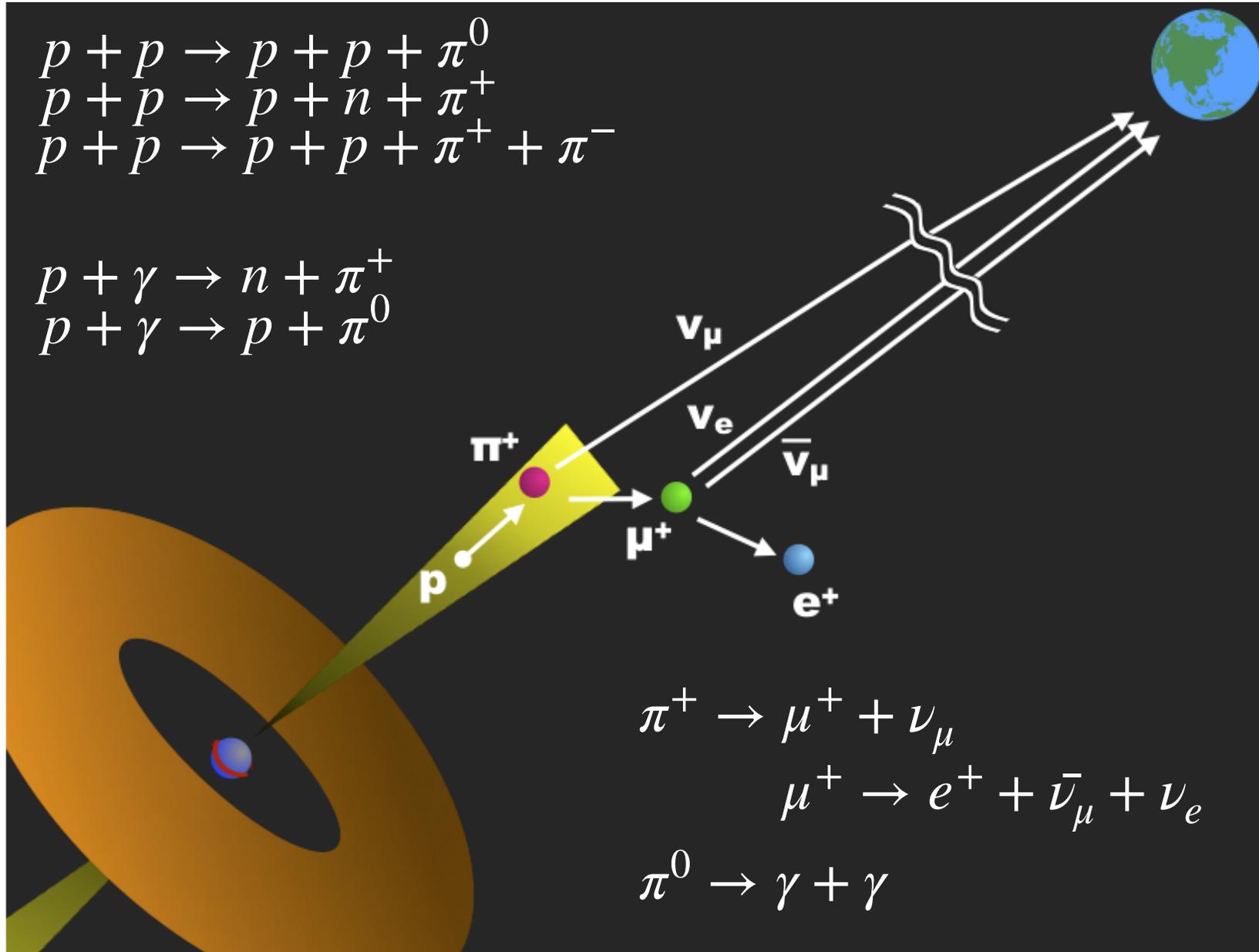
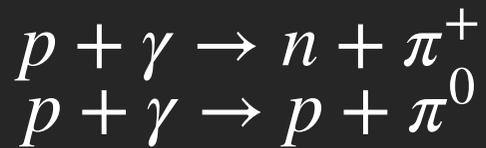
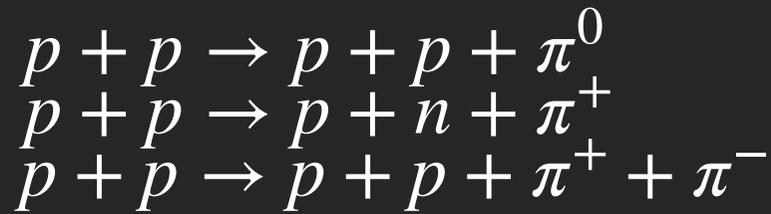
# High-energy astrophysical neutrinos

# Why high energy neutrinos?

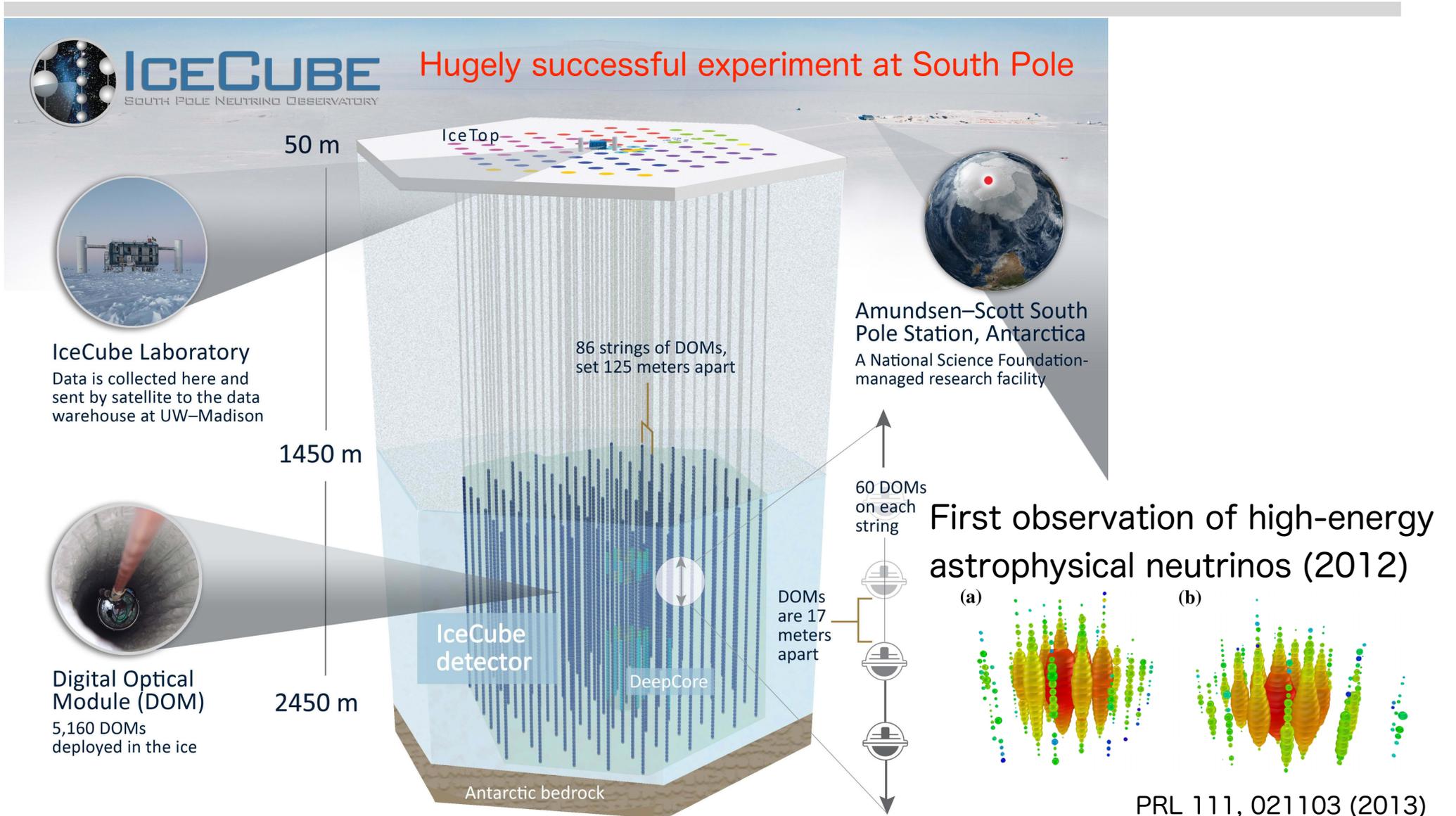
Rev. Mod. Phys. 92, 045006 (2020)



# Neutrino generation



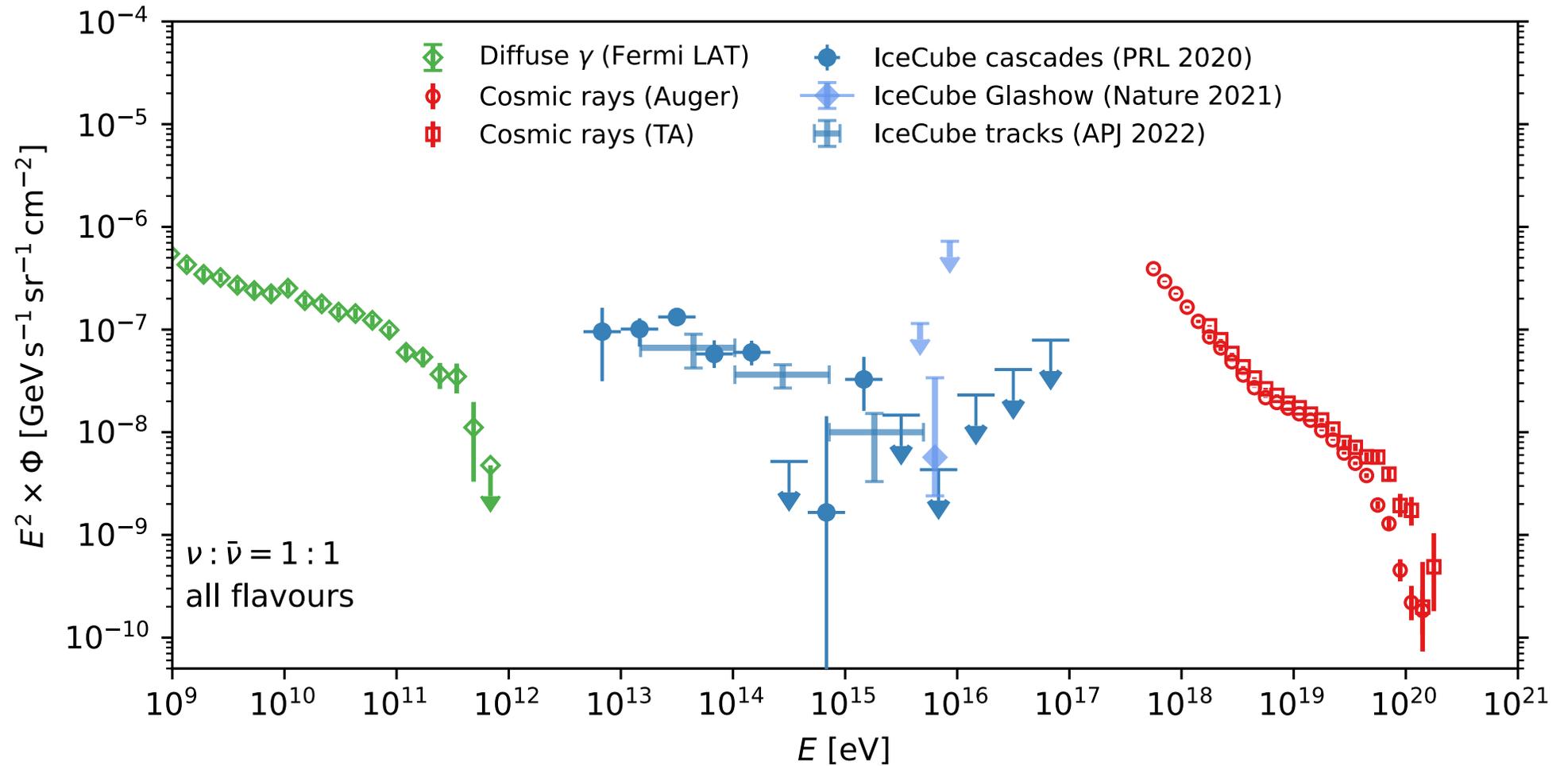
# IceCube



<https://icecube.wisc.edu/science/icecube/>

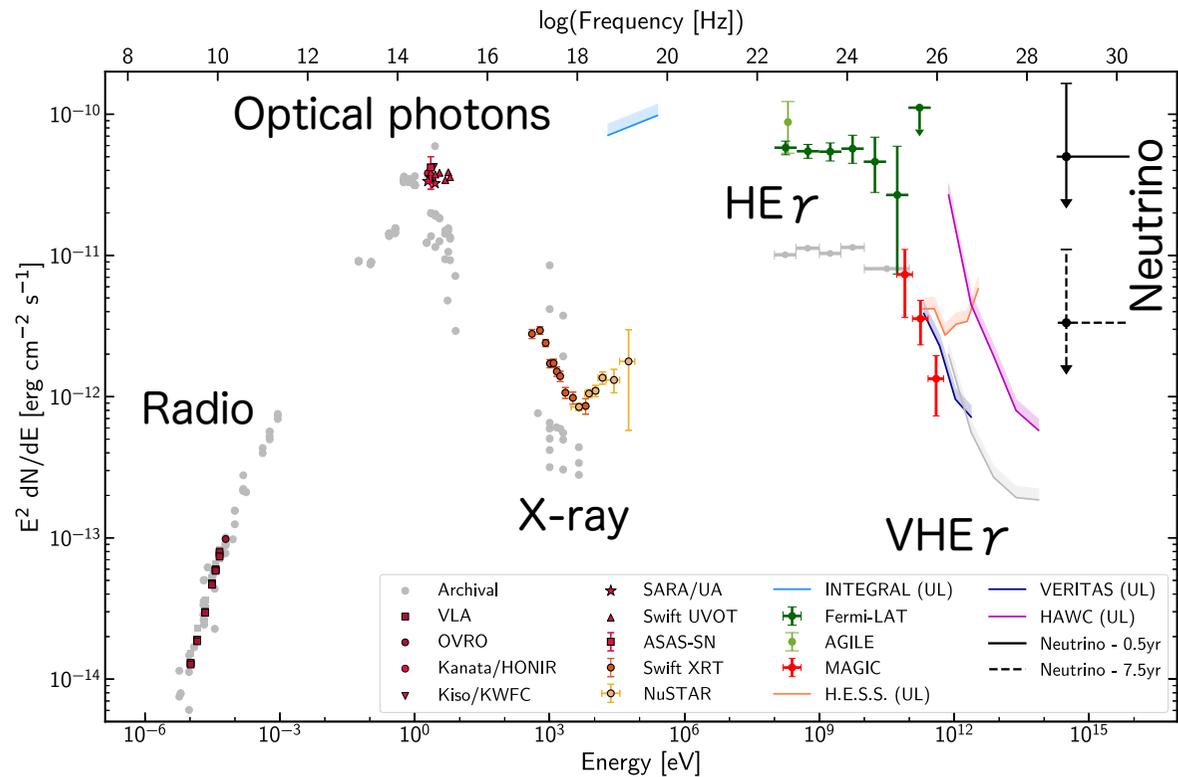
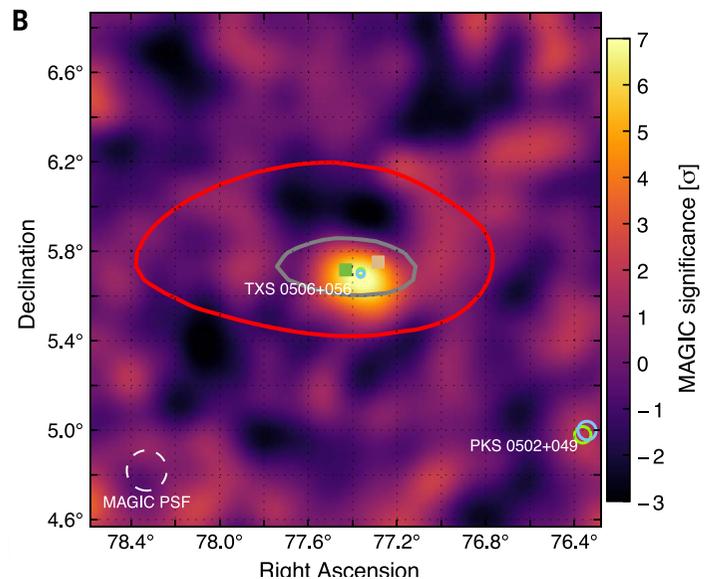
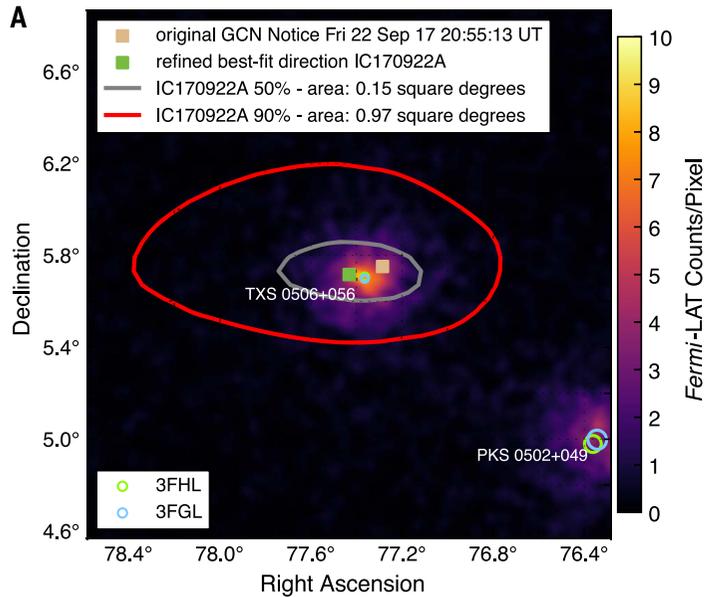
# Cosmic background radiations

arXiv 2203.08096



# First signal from transient source

## ICECUBE-170922A vs $\gamma$ -ray Blazar TXS0506+056

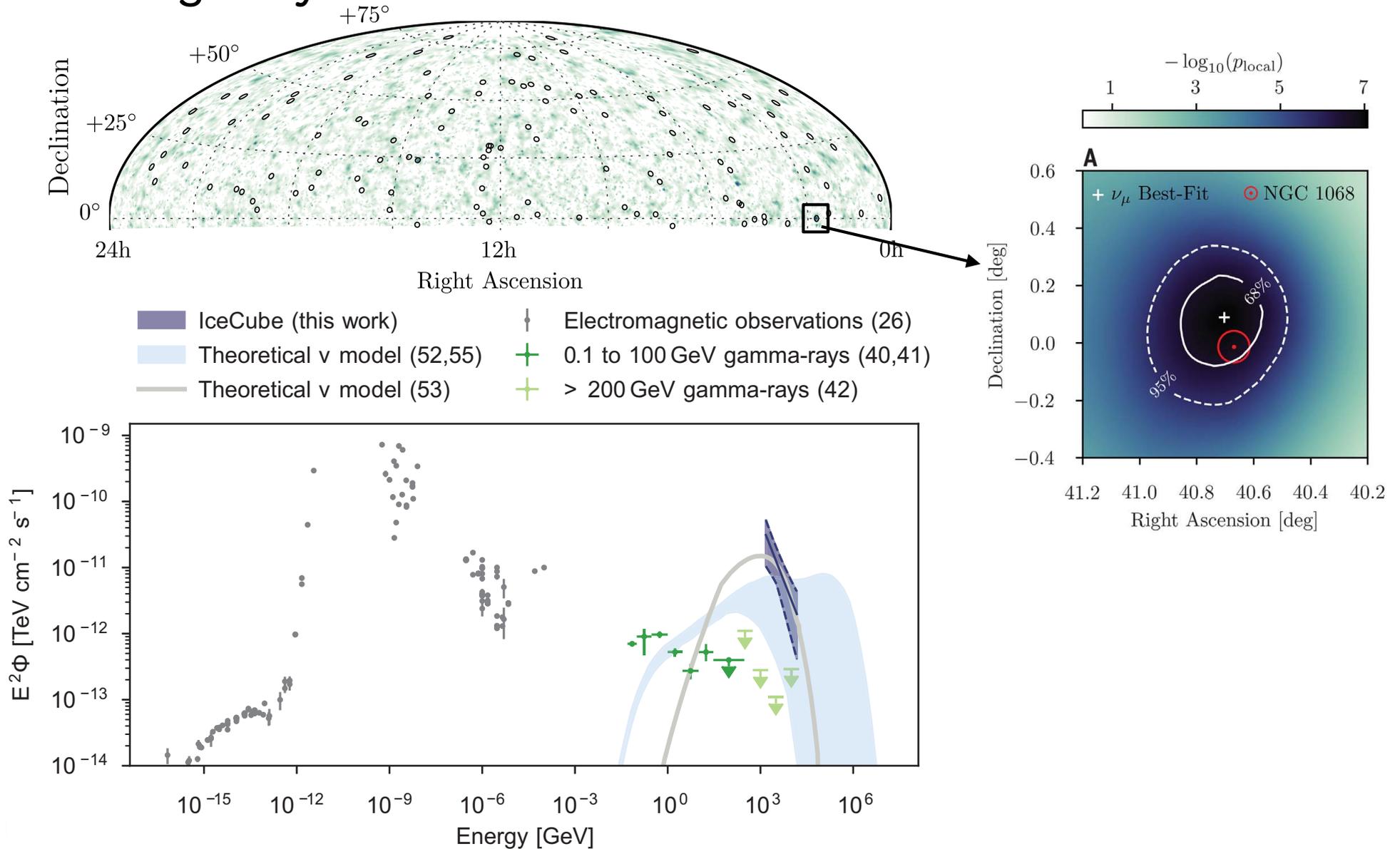


Science 361, 1378 (2018)

# First signal from steady source

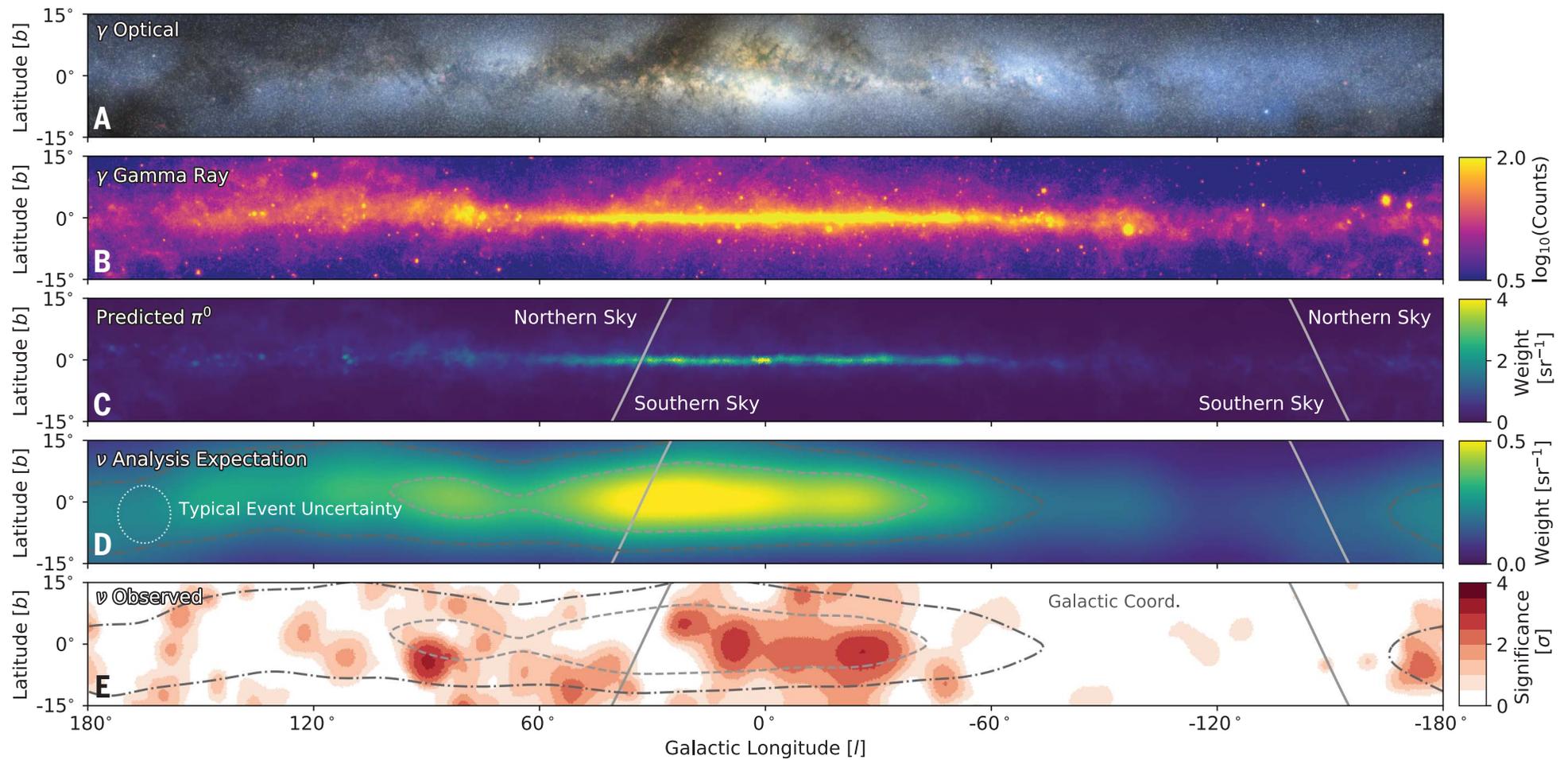
Active galaxy NGC 1068

Science 378, 538 (2022)



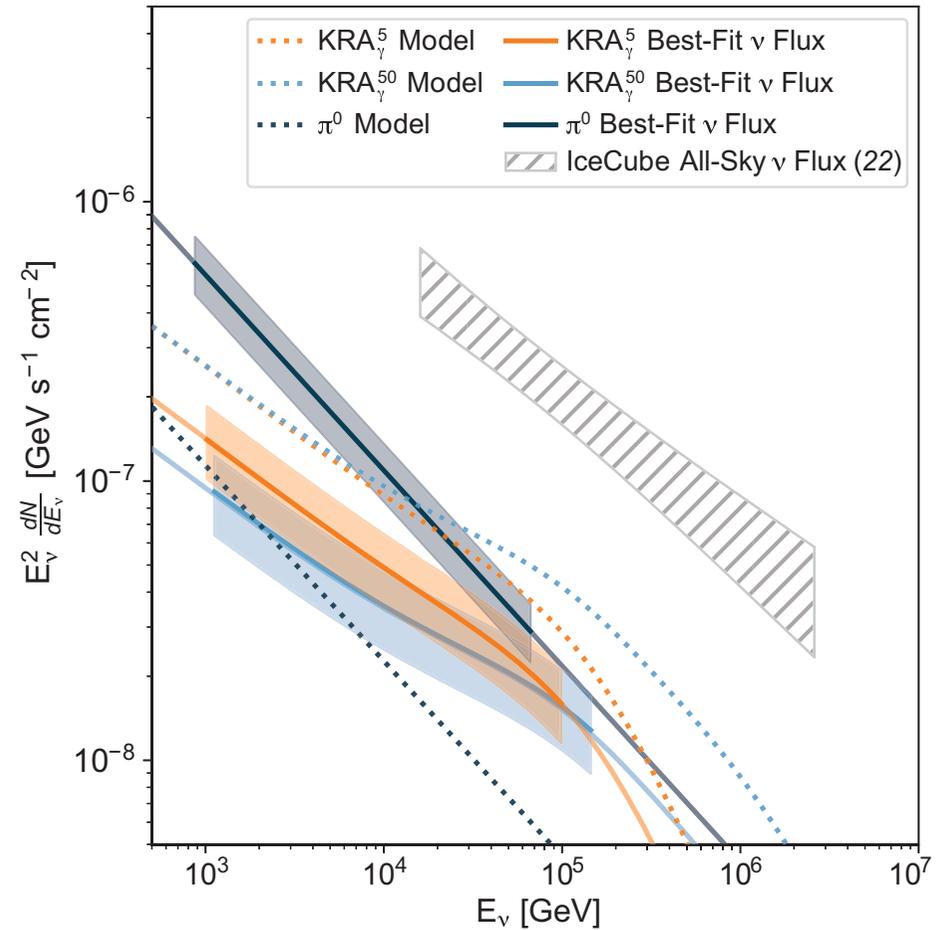
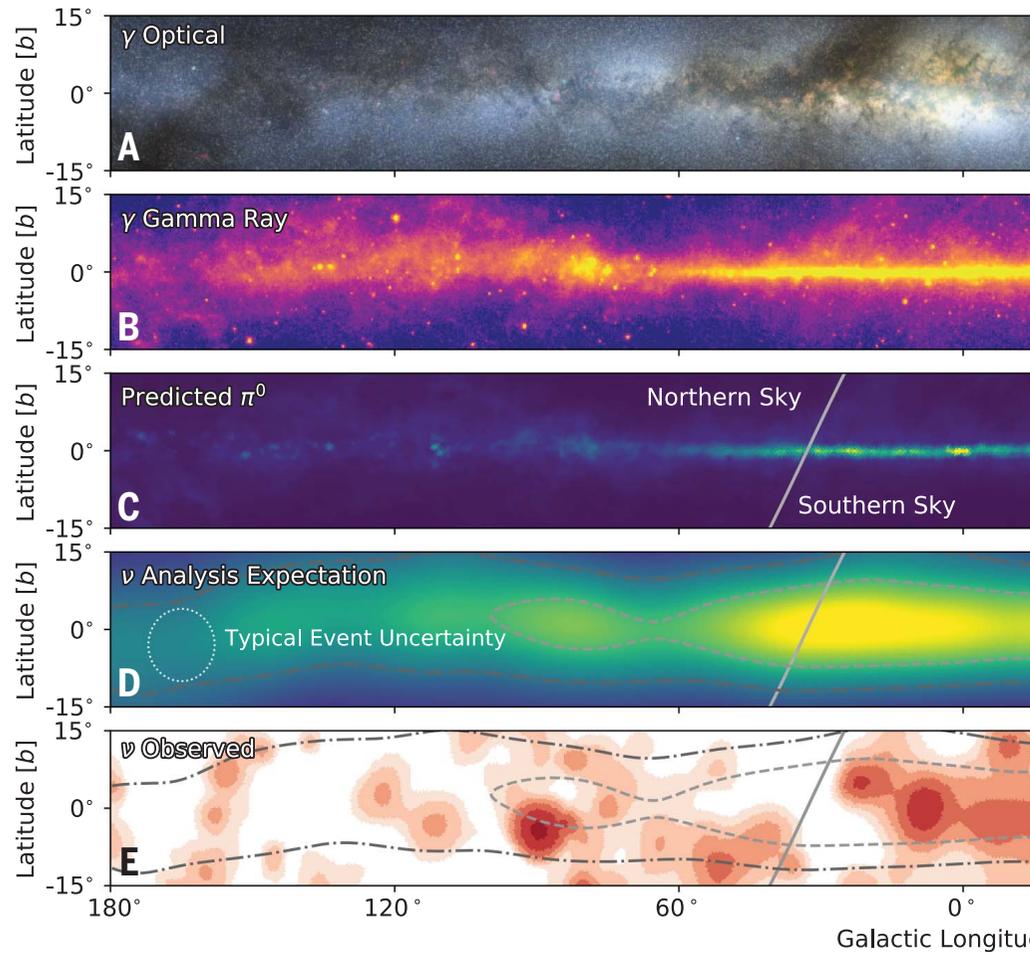
# From the galactic plane

Science 380, 1338 (2023)



# From the galactic plane

Science 380, 1338 (2023)



# Future neutrino telescope

P-ONE

KM3NeT

GVD

E. Resconi

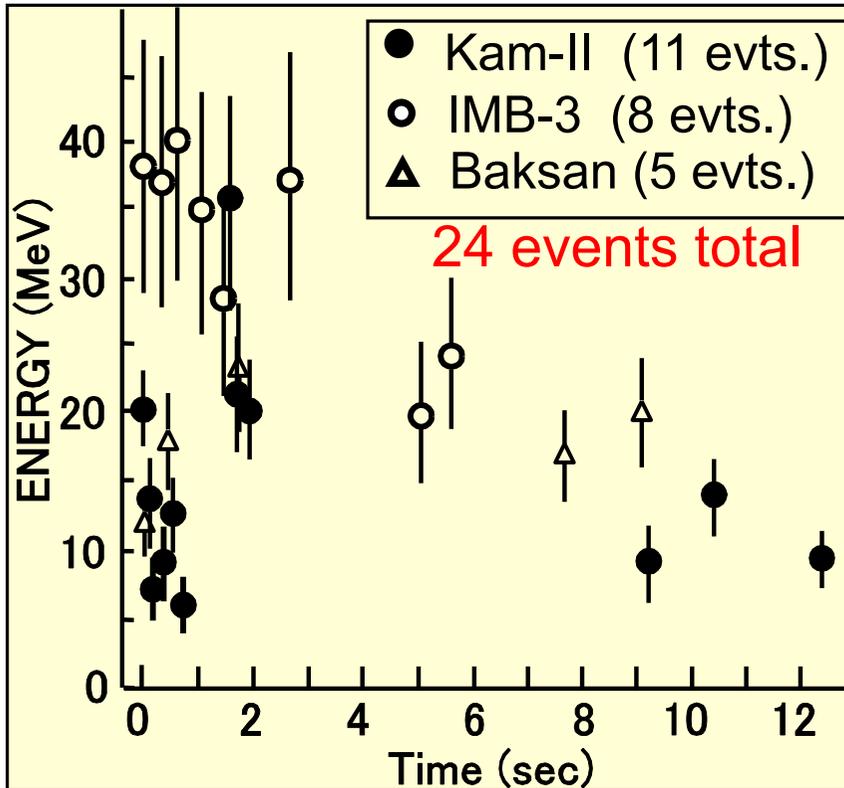
IceCube  
Gen2

@SouthPole

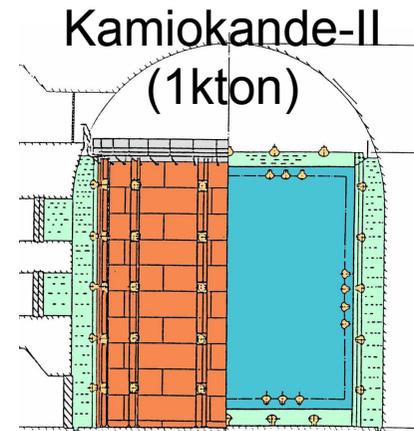
More and more neutrino signals!

# Supernova neutrinos

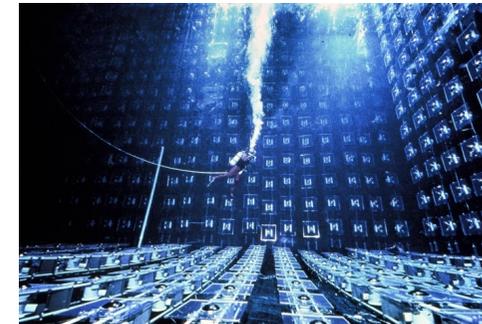
# SN1987A



## Water Cherenkov

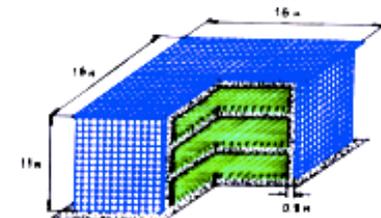


## IMB-3 (8kton)



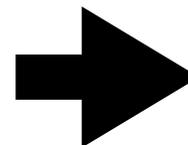
## Liquid Scintillator

Baksan



**Optical** (Feb. 24 1:30~4:30 (UTC))

First observation in Feb. 23-24  
by optical telescope in Chile

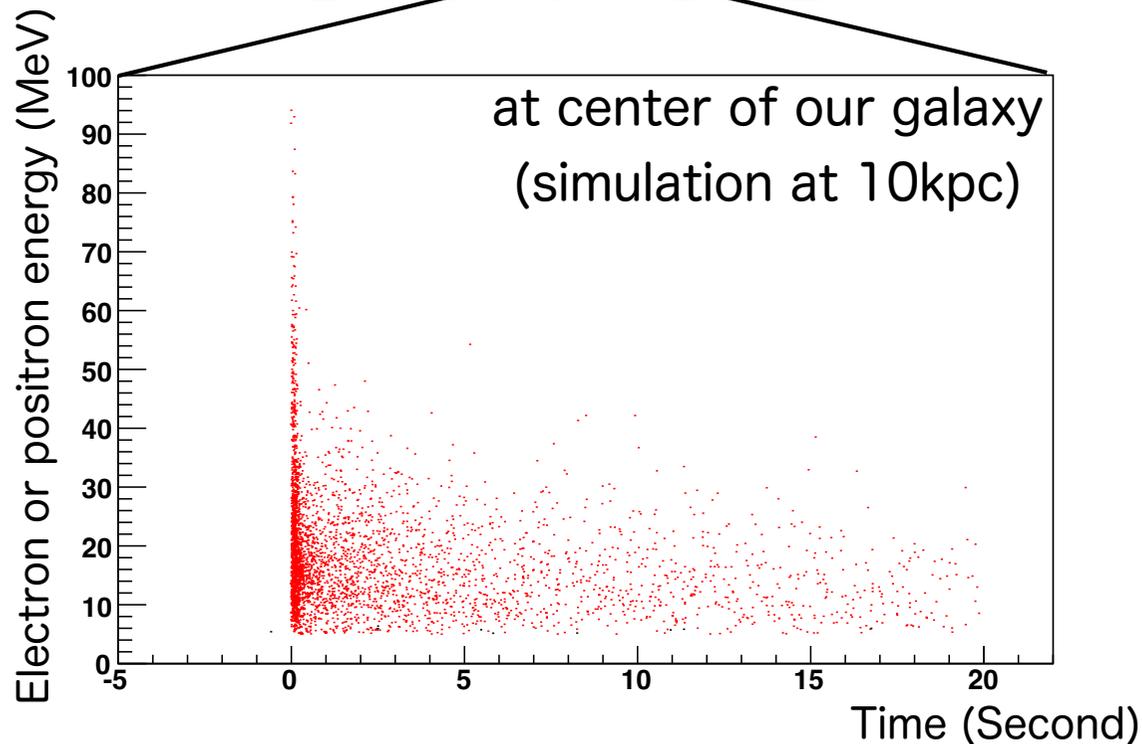
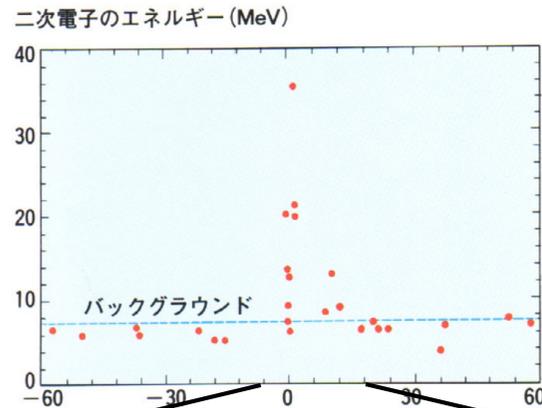


**Neutrino** (Feb. 23 7:35 (UTC))

Published paper by Kamiokande  
on March. 7

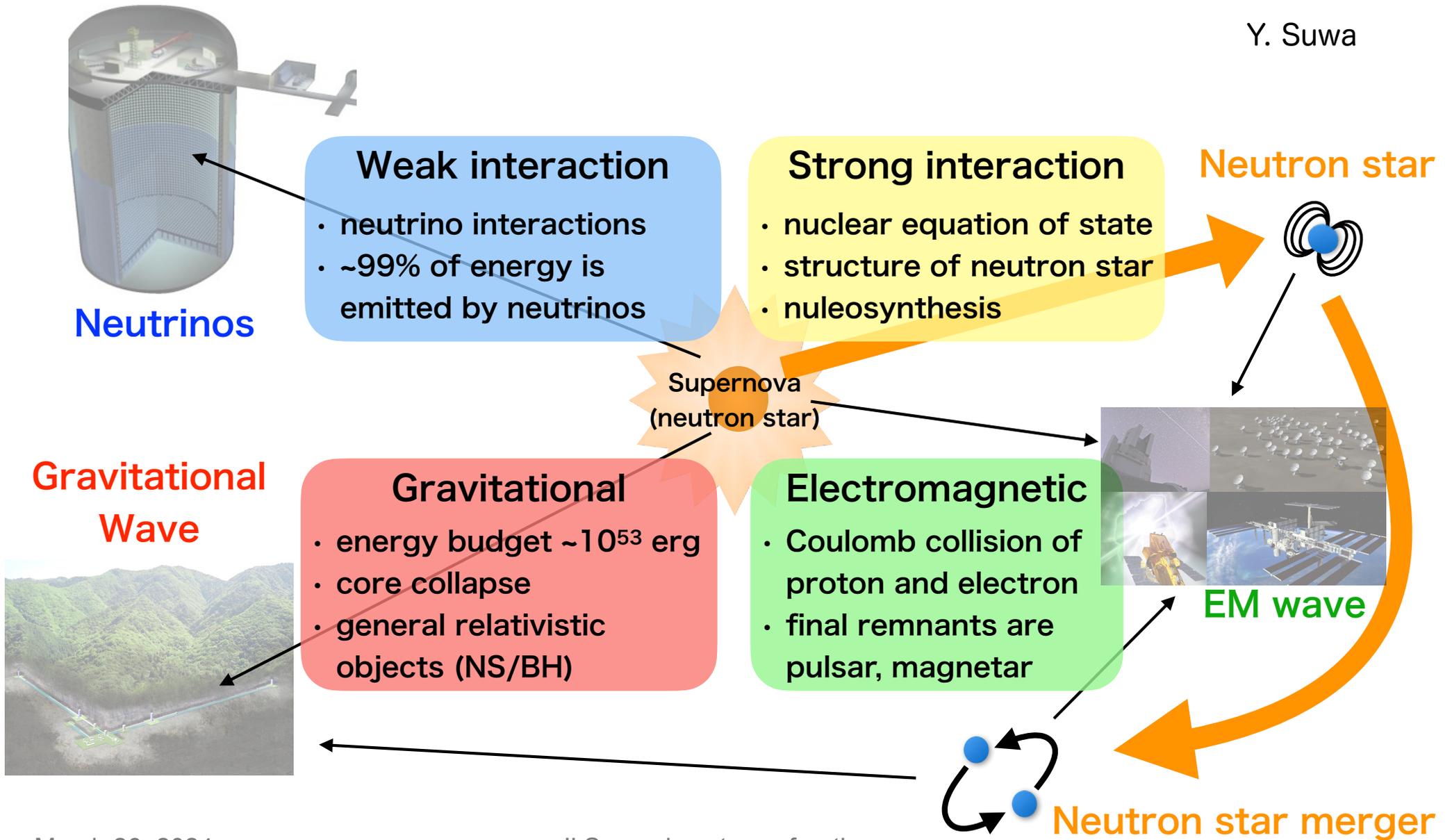
# If a nearby supernova happens now...

11 events in  
KAMIOKANDE  
for SN1987A



# Supernova as 'Multi-physics' object

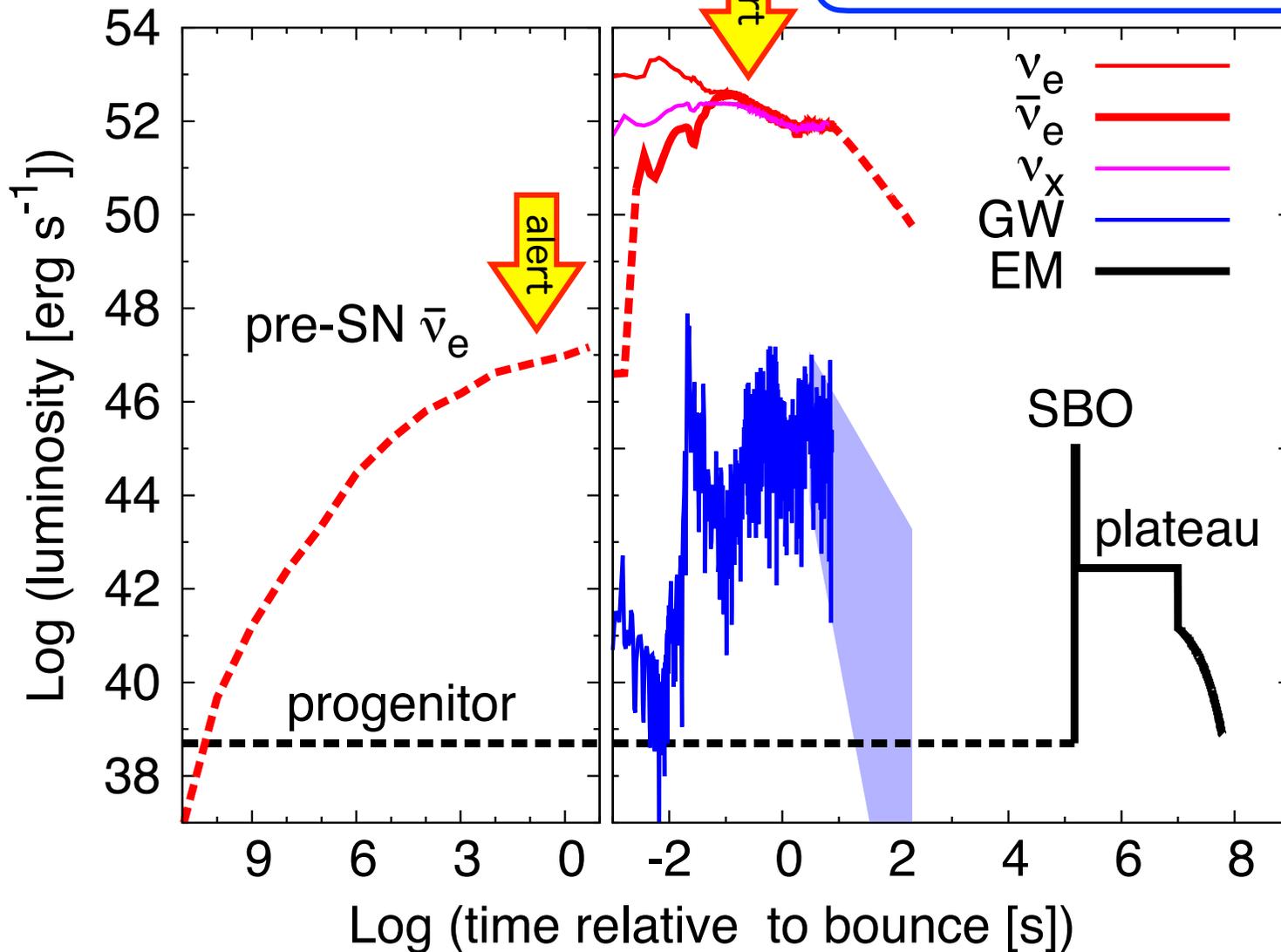
Y. Suwa



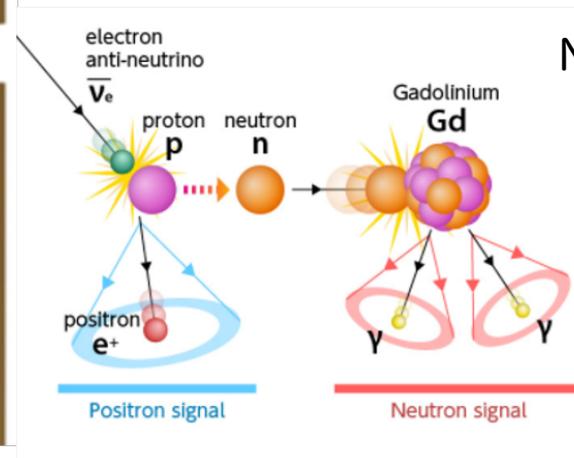
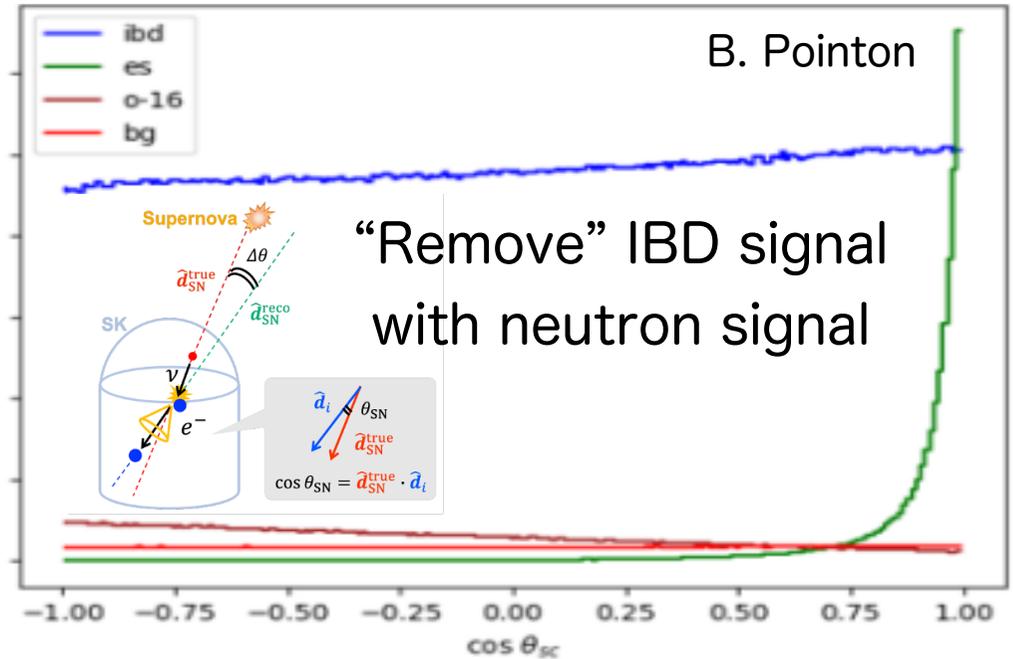
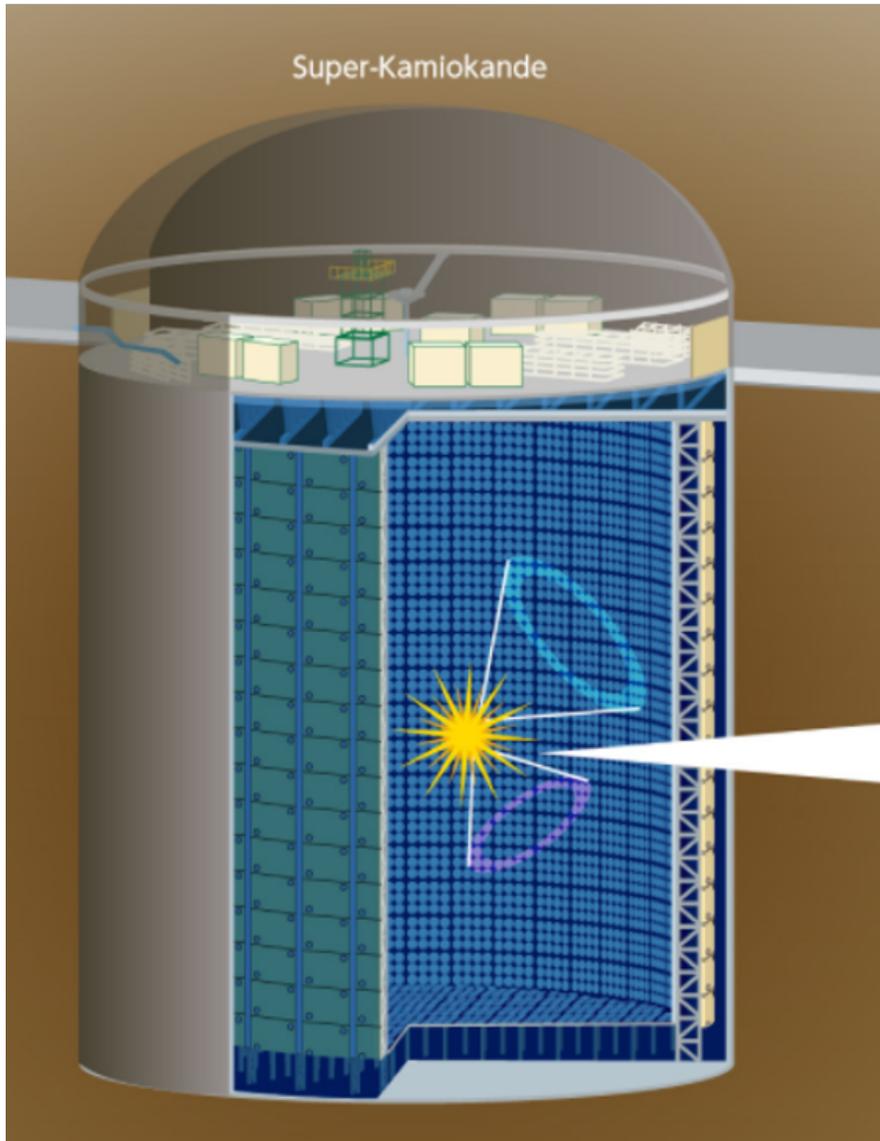
# Multi-messenger emission

K.Nakamura et. al. MNRAS 461, 3296 (2016)

Neutrino → Others



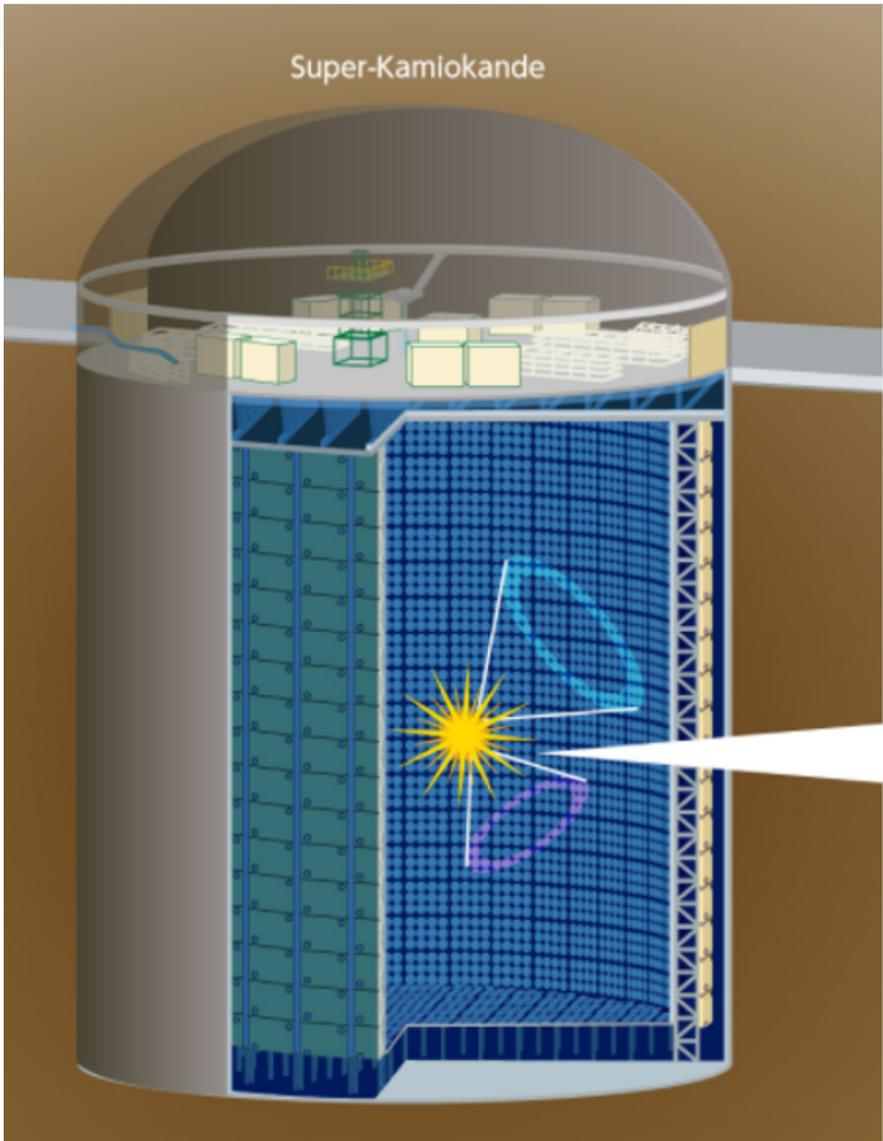
# Super-Kamiokande with Gd



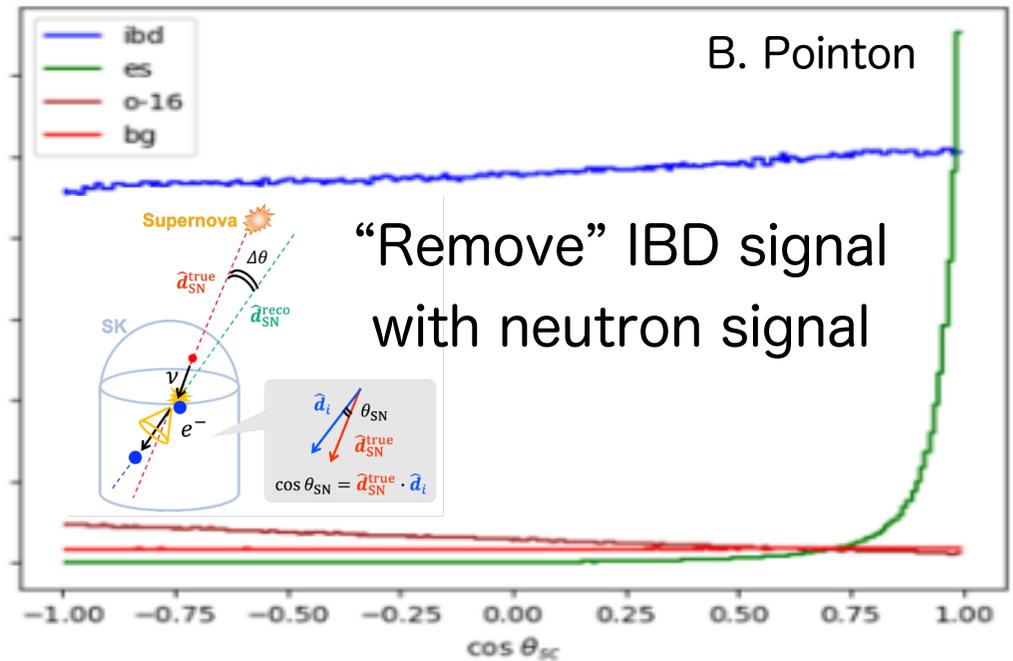
NIM A 1027, 166248 (2022)  
arXiv 2403.07796

J.Beacom and M.Vagins PRL 93, 171101 (2004)

# Super-Kamiokande with Gd

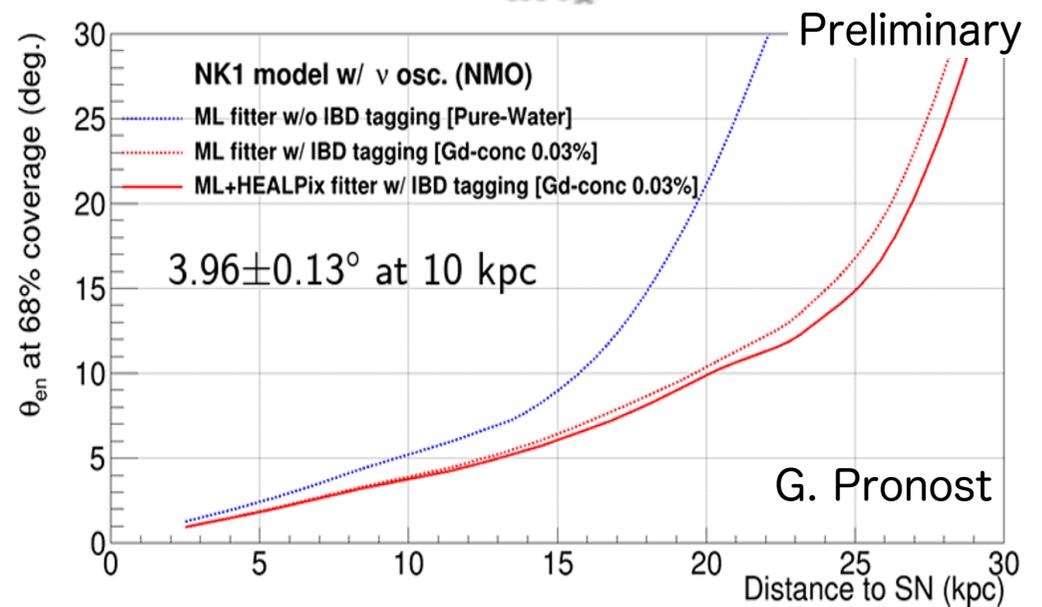


J.Beacom and M.Vagins PRL 93, 171101 (2004)



B. Pointon

“Remove” IBD signal  
with neutron signal



Preliminary

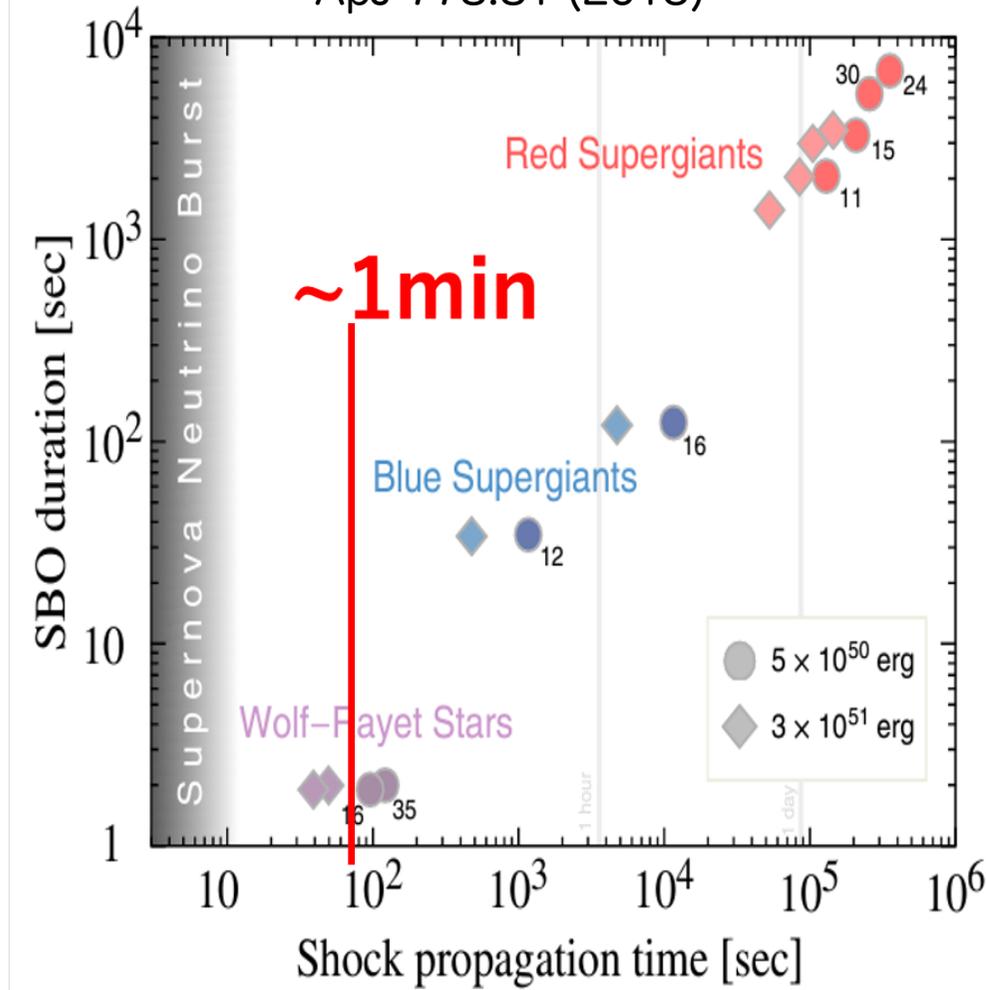
- NK1 model w/  $\nu$  osc. (NMO)
- ML fitter w/o IBD tagging [Pure-Water]
- ML fitter w/ IBD tagging [Gd-conc 0.03%]
- ML+HEALPix fitter w/ IBD tagging [Gd-conc 0.03%]

$3.96 \pm 0.13^\circ$  at 10 kpc

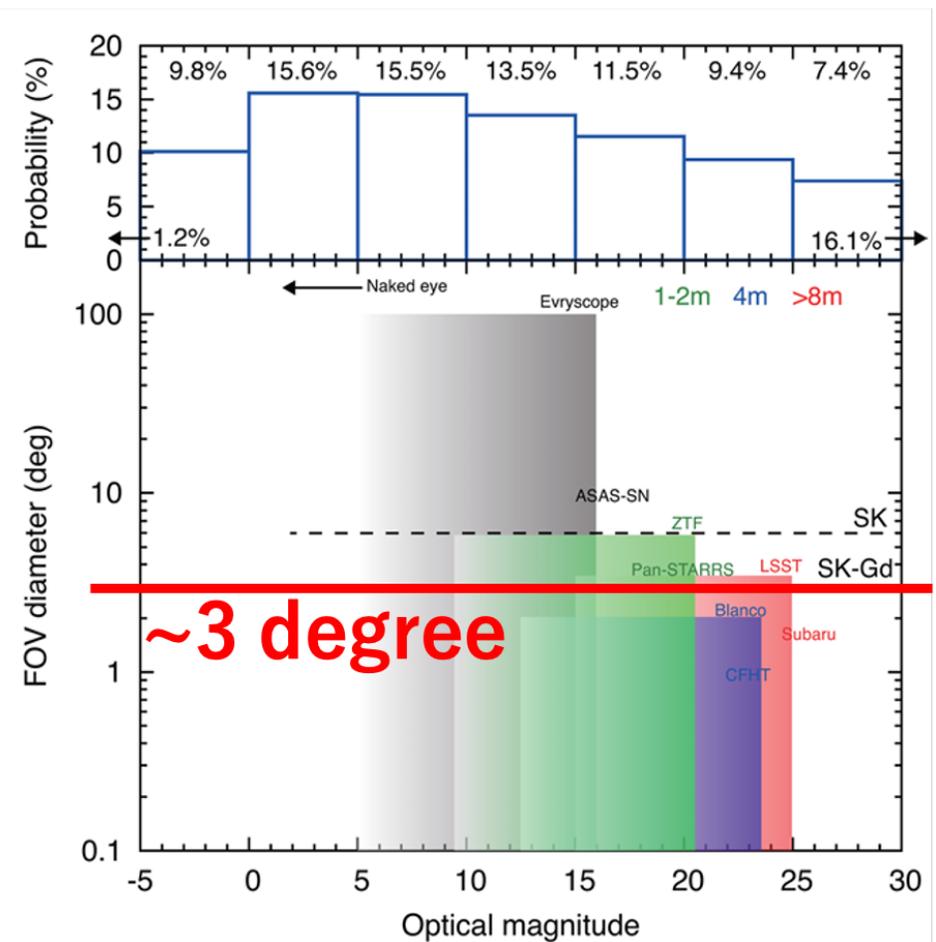
G. Pronost

# Target of the early alert

M.Kistler, W.Haxton, H.Yuksel,  
ApJ 778:81 (2013)



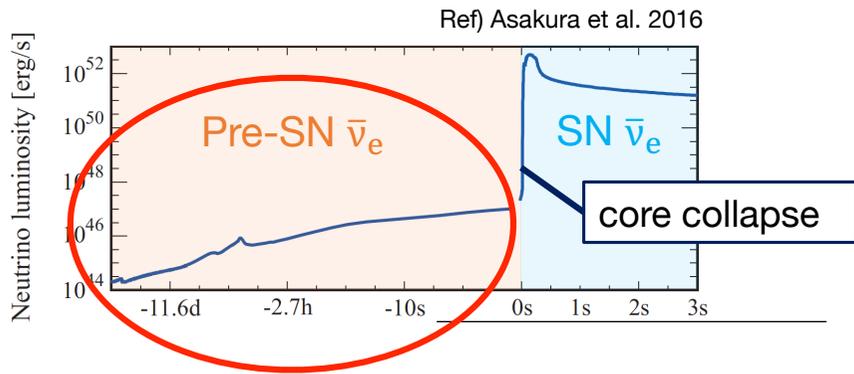
K.Nakamura et. al. MNRAS 461, 3296 (2016)



Other topics -> Lluís's presentation

# pre-SN neutrinos

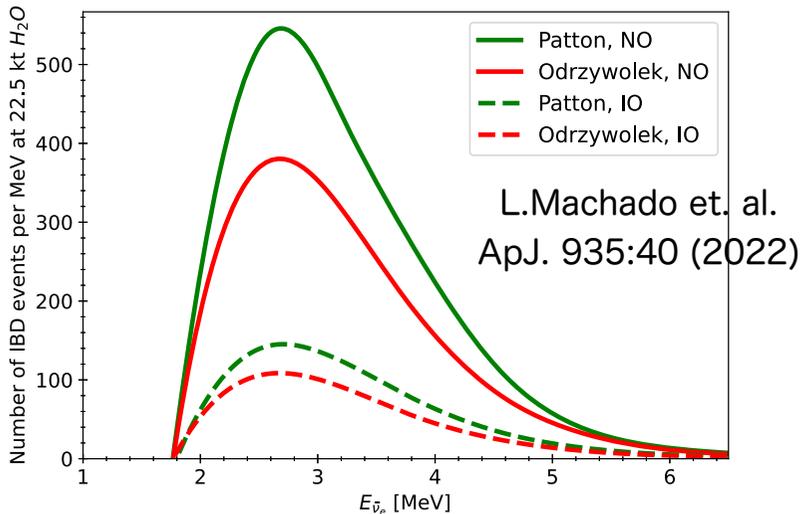
## Si-burning phase



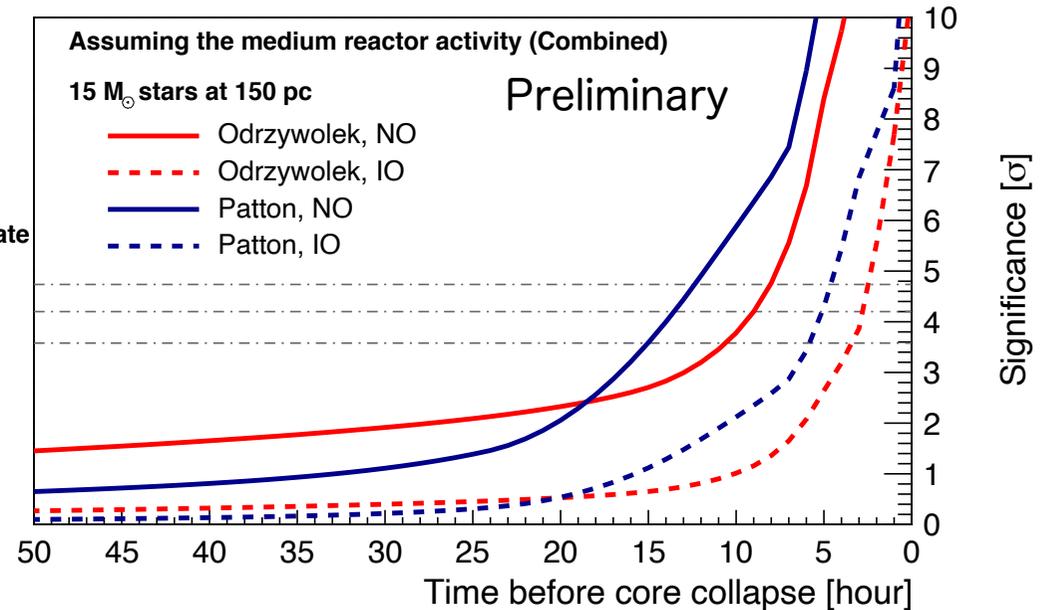
Online combined alert between SK and KamLAND is running

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

Expected energy distribution  
Betelgeuse-like (15Msun, 150pc)



False Alarm Rate  
1 / century  
10 / century  
100 / century



Alert will be issued at the latest  
2.6 hours before core collapse  
of the Betelgeuse-like SN

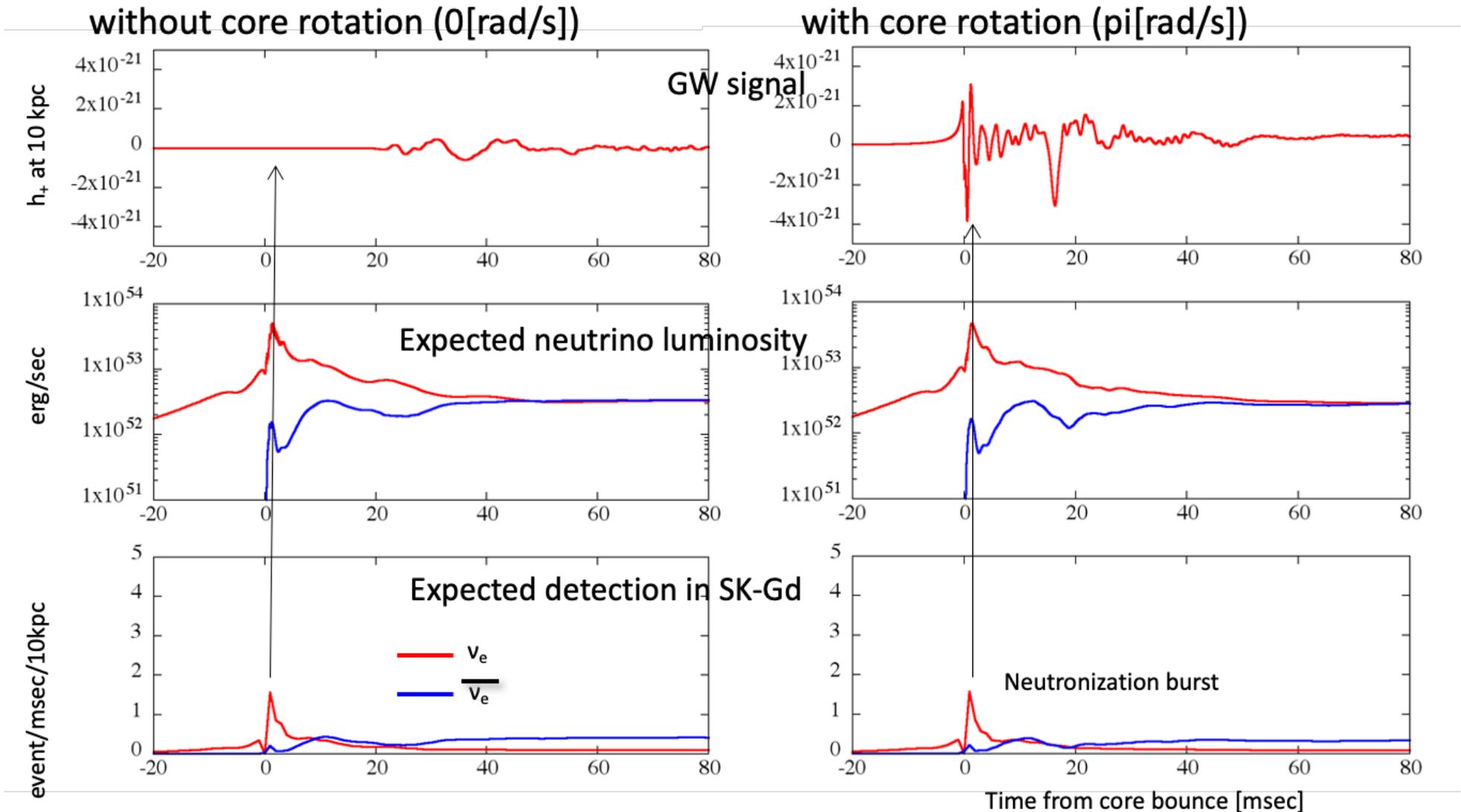
# SNEWS



Combining signals from the detectors around the world  
for a high-confidence prompt alert (~a few seconds)

# GW coincidence

ApJ 811, 86 (2015)

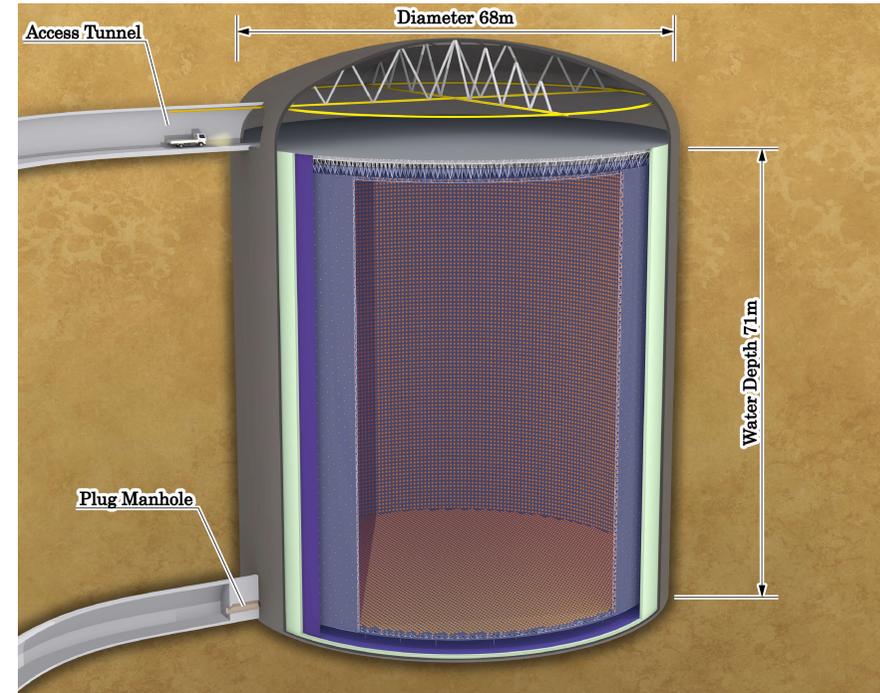


# Future neutrino detectors

JUNO

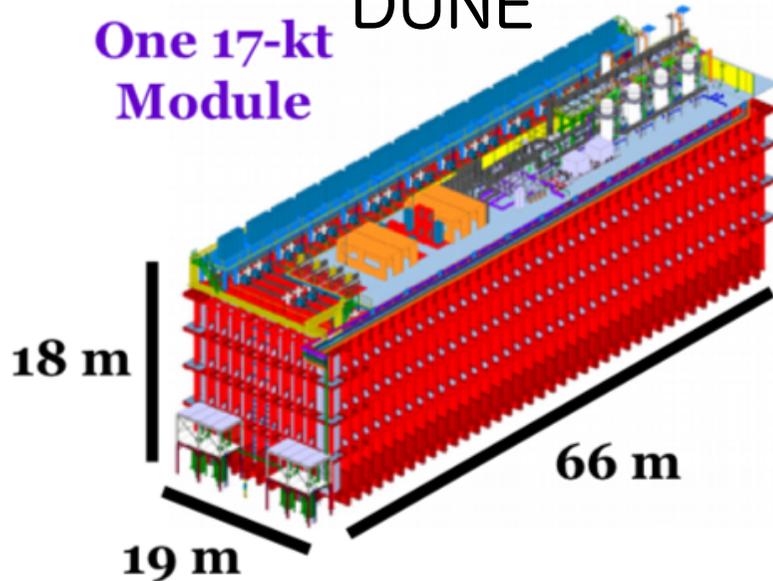


Hyper-Kamiokande



DUNE

One 17-kt  
Module



One supernova  
nearby galaxy!

# Summary

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- Neutrino is the important role of multi-messenger astronomy.
- High-energy astrophysical neutrinos are key for understanding the energetic mechanisms in the universe. IceCube is successful to detect several signals, and provided the important information.
- Several neutrino detectors are waiting the next supernova nearby galaxy. Once it happens, the core-collapse mechanism will be well understood.