Tsung-Dao Lee Institute

22nd edition

PANIC Lisbon Portugal

Particles and Nuclei International Conference

Observational Multi-messenger Physics with Neutrinos and Beyond

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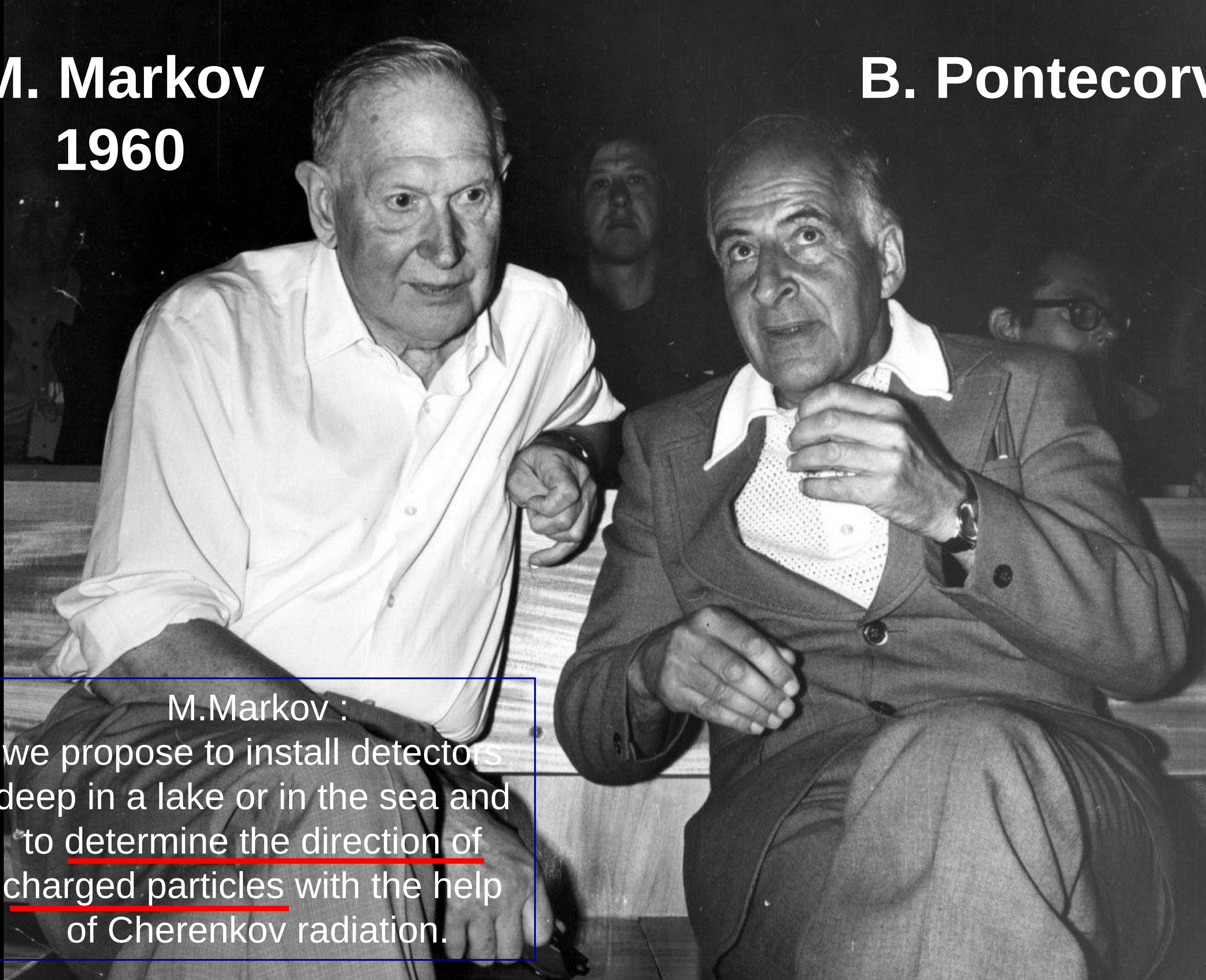
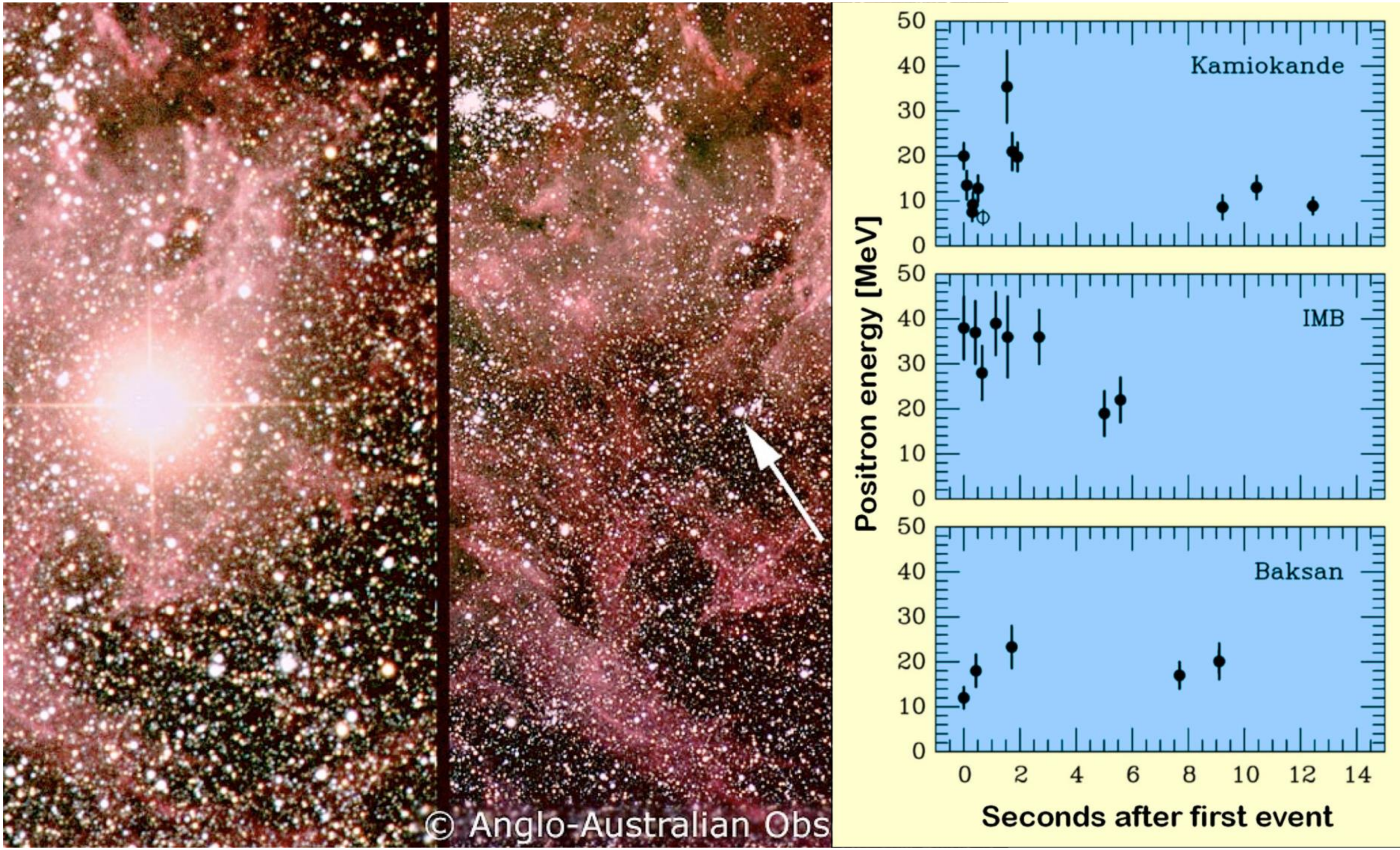
PANIC 2021 Conference

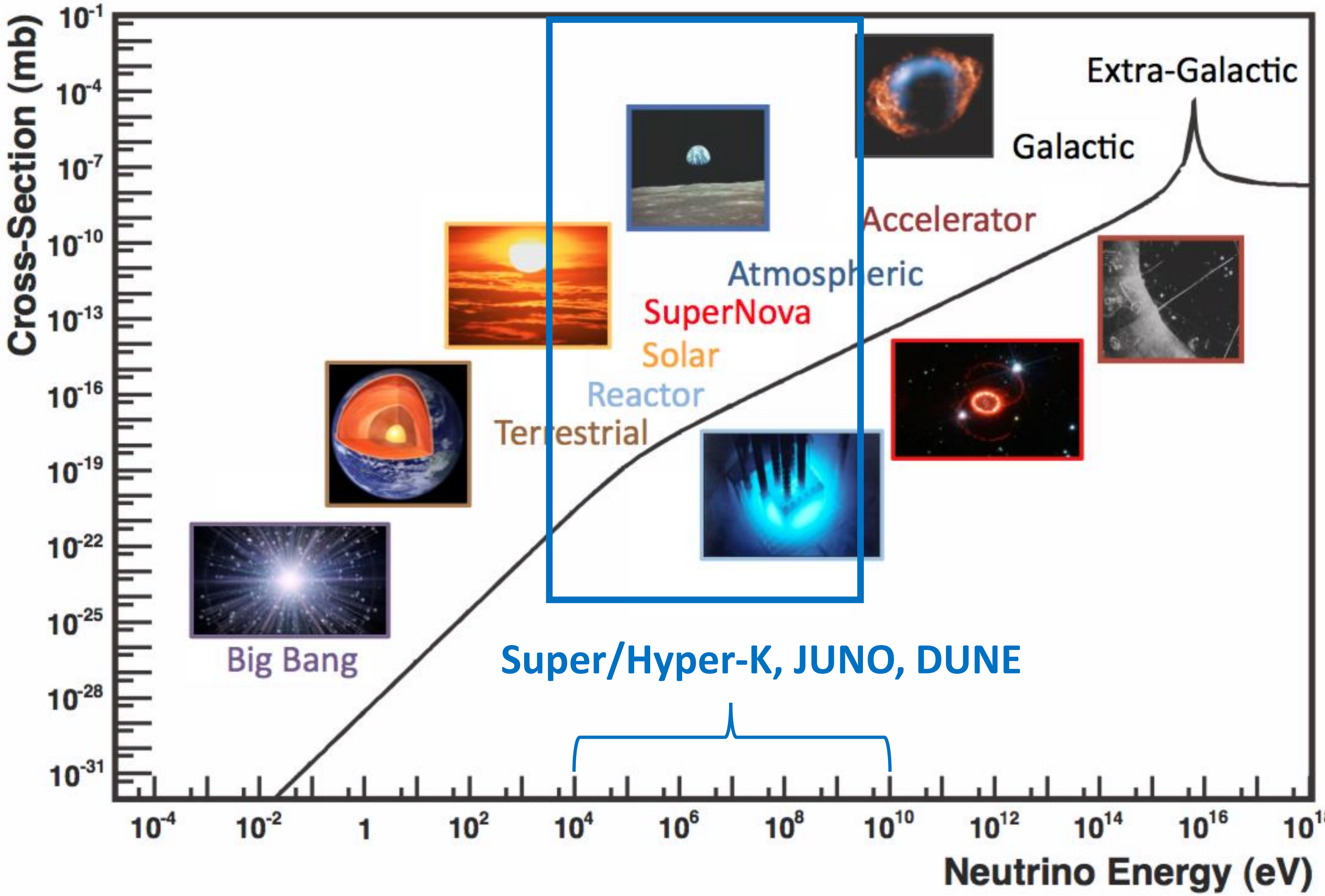
2021.09.05-10, Online


M. Markov
1960
B. Pontecorv
M.Markov :
we propose to install detectors deep in a lake or in the sea and to determine the direction of charged particles with the help of Cherenkov radiation.

Birth of neutrino astronomy: SN1987A



Cosmic Neutrinos



New Era of Multi-messenger Astronomy

The transient sky is very vibrant… potentially with low energy MeV neutrinos!

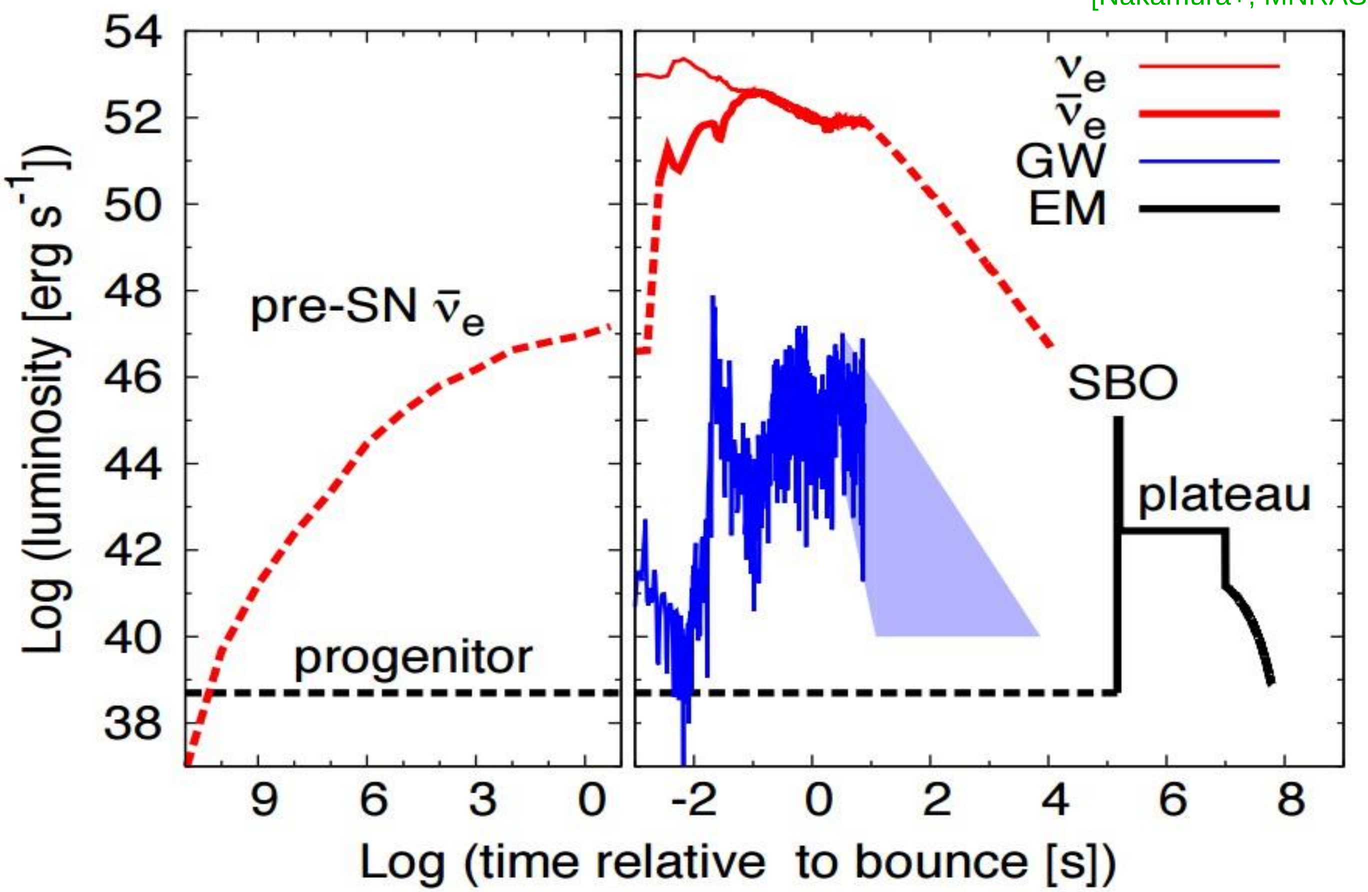
- **Supernovae**：
  - Pre-burst: **~ days**, <1kpc
  - Core collapse (Type II): **~ 10 s**, Galactic & vicinity
  - Type Ia: **~1s**, <1kpc
  - Neutrinos as diagnostics for explosion mechanism: quark-hadron phase transition, **~ms**
- The Sun
- Neutron star mergers
- Gamma ray bursts
- Fast radio bursts

Model-independent, self-adaptive, broadband monitoring is essential

Multi-messengers from Core-collapse SNe

energy release:
$E_\gamma \sim 10^{49}$ erg, $E_{GW} \sim 10^{46}$ erg, $E_{\rm kinetic} \sim 10^{51}$ erg, $E_\nu \sim 10^{53}$ erg.

[Nakamura+, MNRAS 461, 3 (2016)]

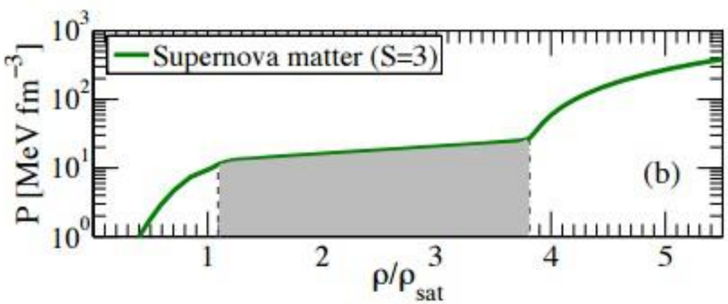


Courtesy slide:
M. R. Wu

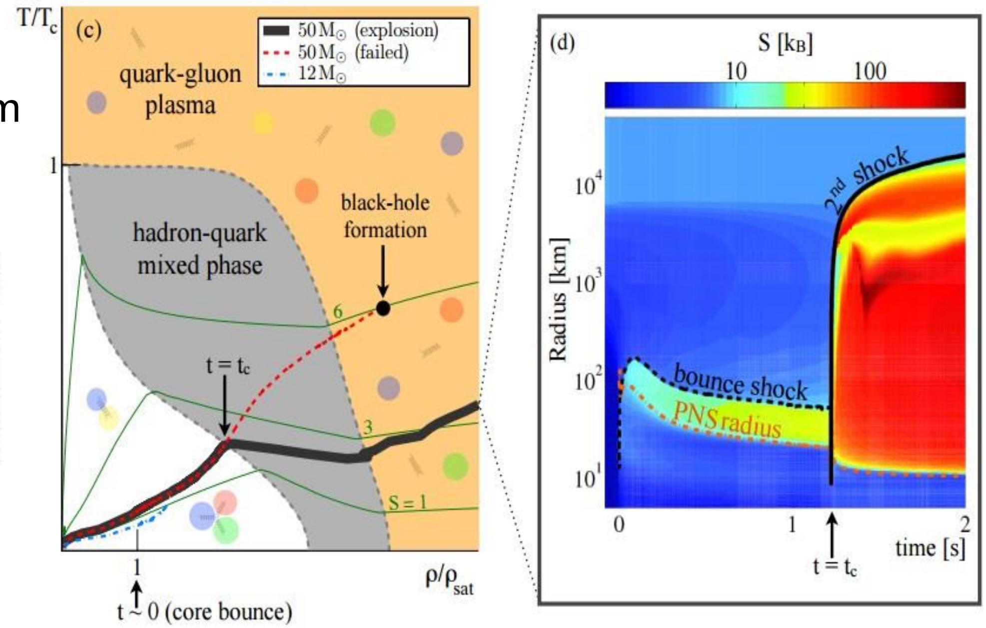
(c.f. $L_\odot \approx 4 \times 10^{33} \mathrm{erg\ s^{-1}}$)

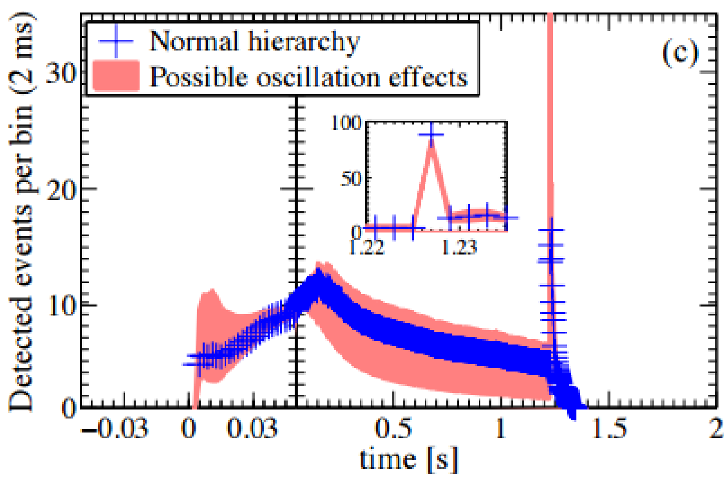
Neutrinos as Diagnostics for Explosion Mechanism

If an SN explosion is triggered by the first-order phase transition from hadronic matter to quark matter



[Fischer+ Nature Astronomy 2, 980 (2018)]



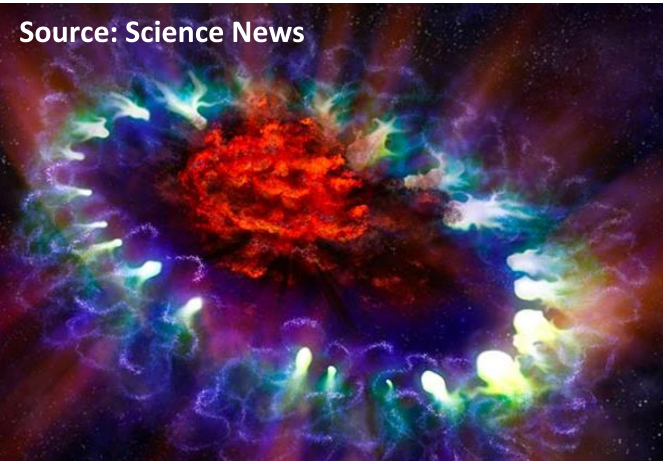


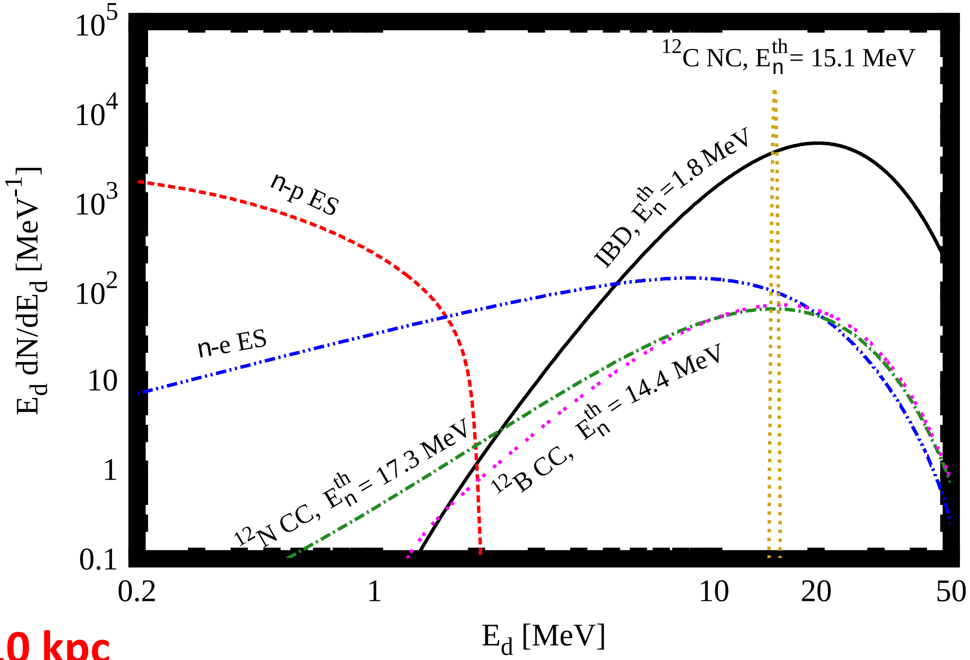
Phase transition

a millisecond neutrino burst!

Courtesy slide: M. R. Wu

Supernova Burst Neutrinos





Astrophysics

- Stellar evolution
- Explosion mechanism
- Production of heavy elements
- Multi-messenger alerts

Particle physics

- Bound on neutrino mass
- Neutrino mass ordering
- Collective neutrino oscillation
- BSM new physics

SNe @ 10 kpc

Channel	Type	Events for different $\langle E_\nu \rangle$ values		
		12 MeV	14 MeV	16 MeV
$\overline{\nu}_e + p \rightarrow e^+ + n$	CC	4.3×10^3	5.0×10^3	5.7×10^3
$\nu + p \rightarrow \nu + p$	NC	0.6×10^3	1.2×10^3	2.0×10^3
$\nu + e \rightarrow \nu + e$	ES	3.6×10^2	3.6×10^2	3.6×10^2
$\nu + {}^{12}C \rightarrow \nu + {}^{12}C^*$	NC	1.7×10^2	3.2×10^2	5.2×10^2
$\nu_e + {}^{12}C \rightarrow e^- + {}^{12}N$	CC	0.5×10^2	0.9×10^2	1.6×10^2
$\overline{\nu}_e + {}^{12}C \rightarrow e^+ + {}^{12}B$	CC	0.6×10^2	1.1×10^2	1.6×10^2

Neutrino Physics with JUNO, **JPG, 16**

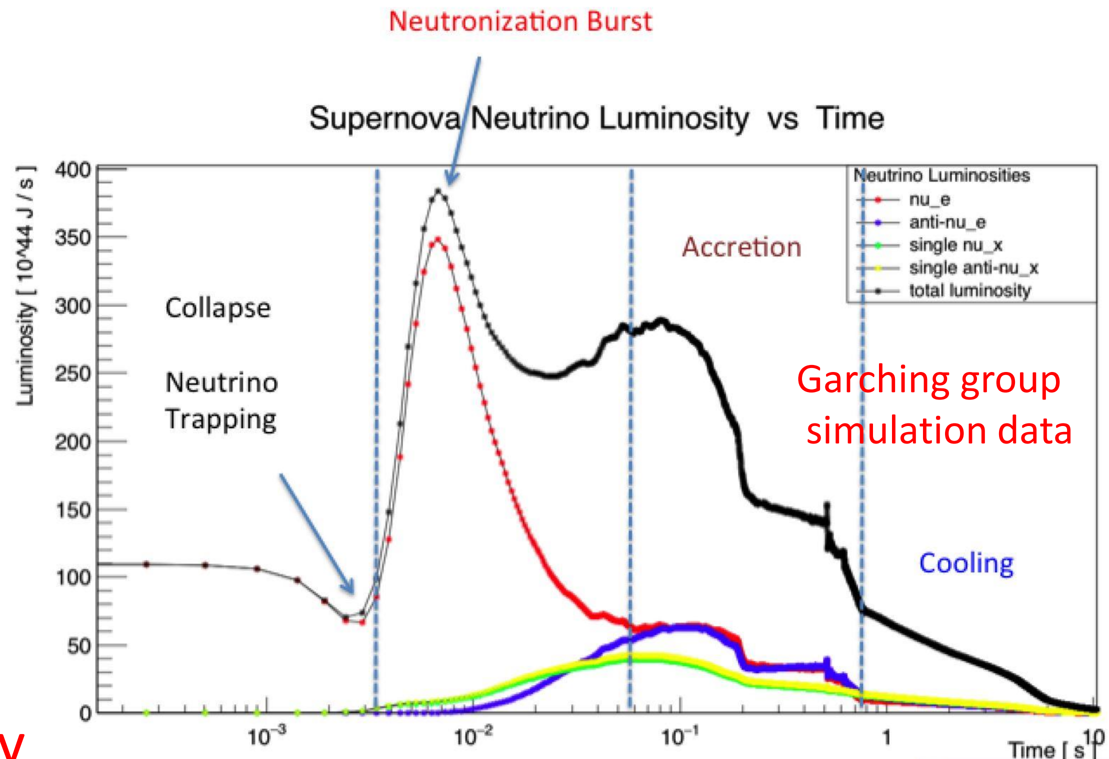
Supernova Burst Neutrinos

- Neutronization burst

ν_e only, not detectable via **IBD**

ν-p ES is ideal channel to observe it

Robust theory prediction:
Insensitive to progenitor mass, treatment of neutrino transport, and the nuclear equation of state (EOS)

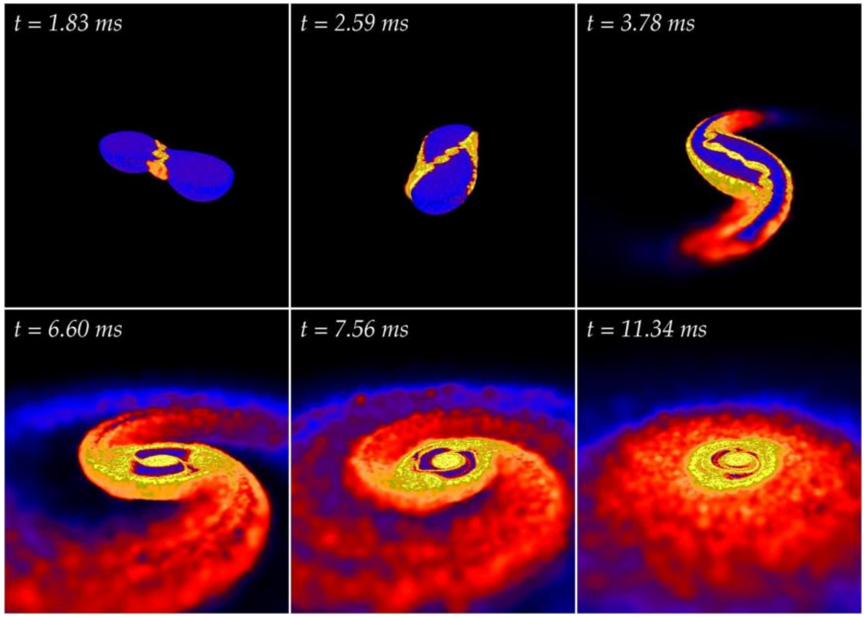


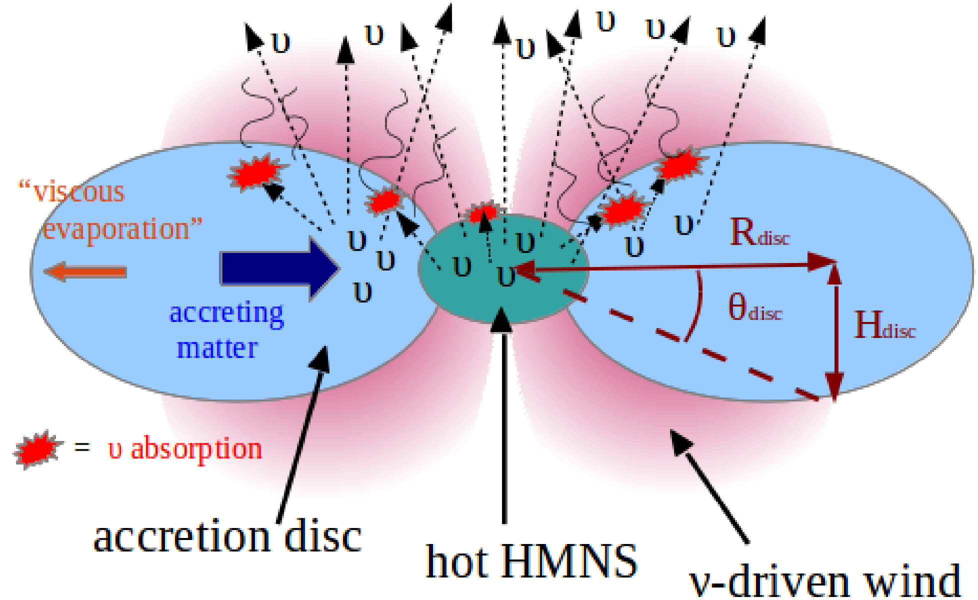
- Neutrino Mass Hierarchy

ν_e survival probability is very sensitive to mass hierarchy:
NH : $P_{ee} \approx 0.02$; IH : $P_{ee} \approx 0.3$

Need the **neutral current ν-p ES** to measure **the total neutrino flux**
SN trigger on **ν-p ES events** can be ~ **50 ms faster** than on **IBD** events

Neutron Star Merger Neutrinos





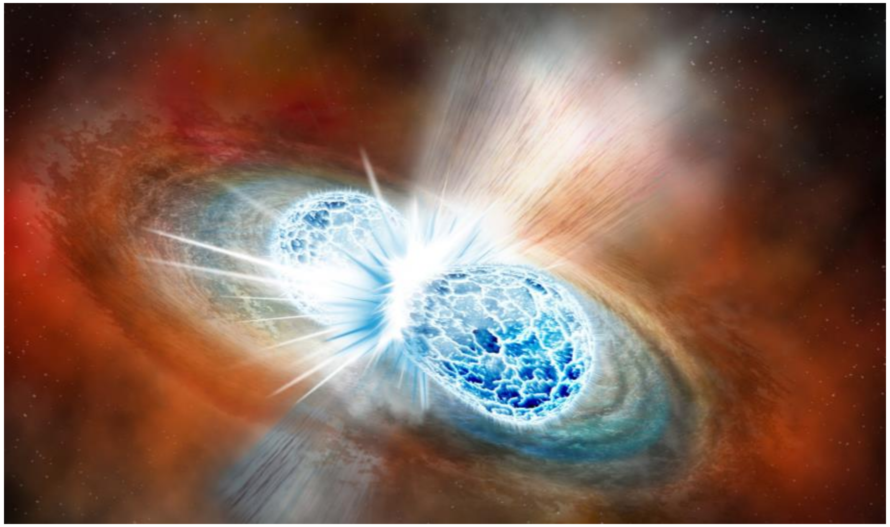
Source: Daniel Price (U/Exeter) and Stephan Rosswog (Int. U/Bremen)

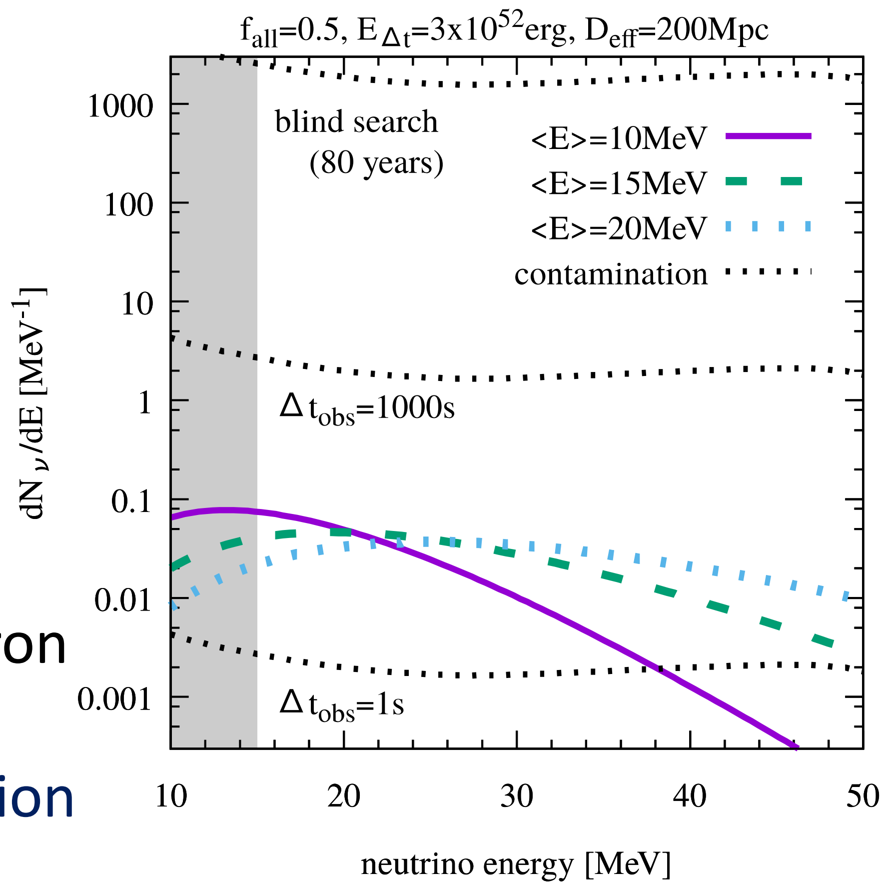
HMNS: Hyper Massive Neutron Star

Source: A. Perego et al., MNRAS 443 (2014)

- Thermal neutrinos peak at tens of ms after the coalescence of the two neutron stars
- Multi-messenger observation (especially with GW) is essential!

Neutron Star Merger Neutrinos





- Little is known about the thermal neutrino spectra from binary neutron star mergers
- Rate of mergers is low (~ 1 per million year in the Galaxy)
- GW170817 ~ 40 Mpc away, no neutrinos detected – neutrinos were beamed and missed Earth?

arXiv:1710.05922

Multi-Messenger Trigger System of JUNO

Model-independent

& Self-adaptive

Monitoring

of the

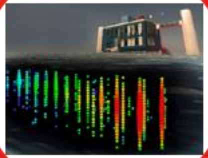
Neutrino Sky

MM Trigger

as a powerful

Transient Machine

Alert
Optical telescopes



Communicate
Neutrino observatories

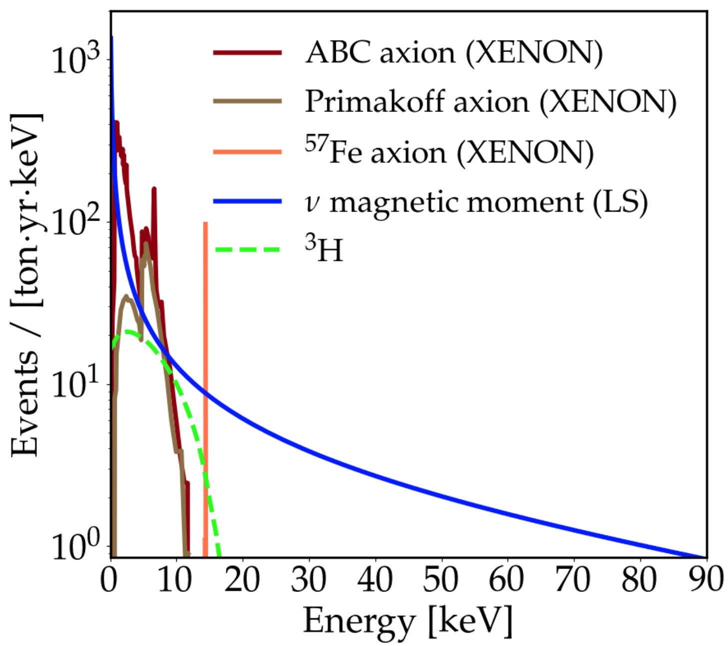
Alert
Gamma/x-ray telescopes

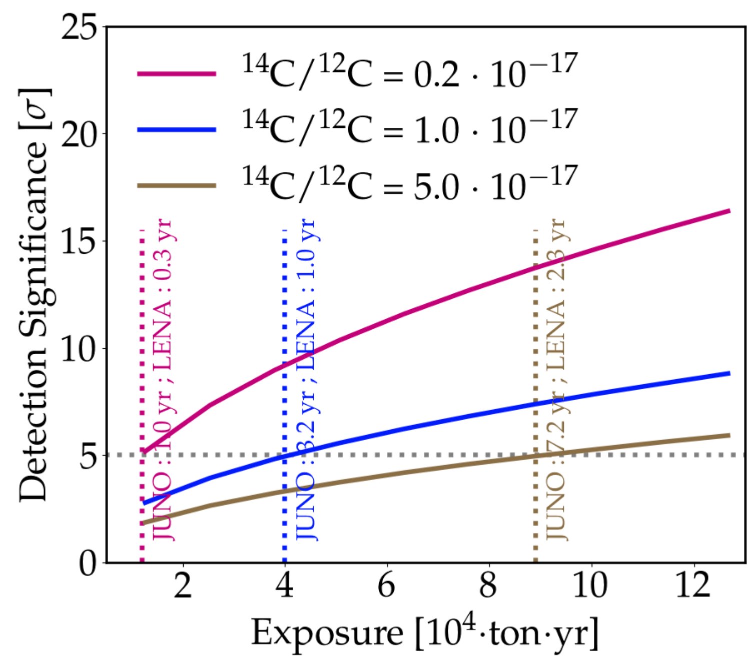
Receive GW alerts & do trigger-less readout
LIGO/VIRGO, KAGRA, LISA, Tianqin, Taiji

Multi-Messenger & Low-threshold Physics

- **Two major trigger systems in JUNO**: Global trigger (threshold ~ 200 keV); Multi-messenger trigger (threshold ~ 20 keV)
- **Low threshold physics potential:** Significantly improve physics potential in this unprecedentedly low-threshold territory, e.g. low energy solar neutrinos
- XENON1T reported a low energy event excess at 1-7 keV, could be compatible with a most probable enhanced neutrino magnetic moment $\mu_\nu = 2.1 \times 10^{-11}\ \mu_B$

Z. Ye, F. Zhang, **DLX** and J. Liu, arX:2103.11771

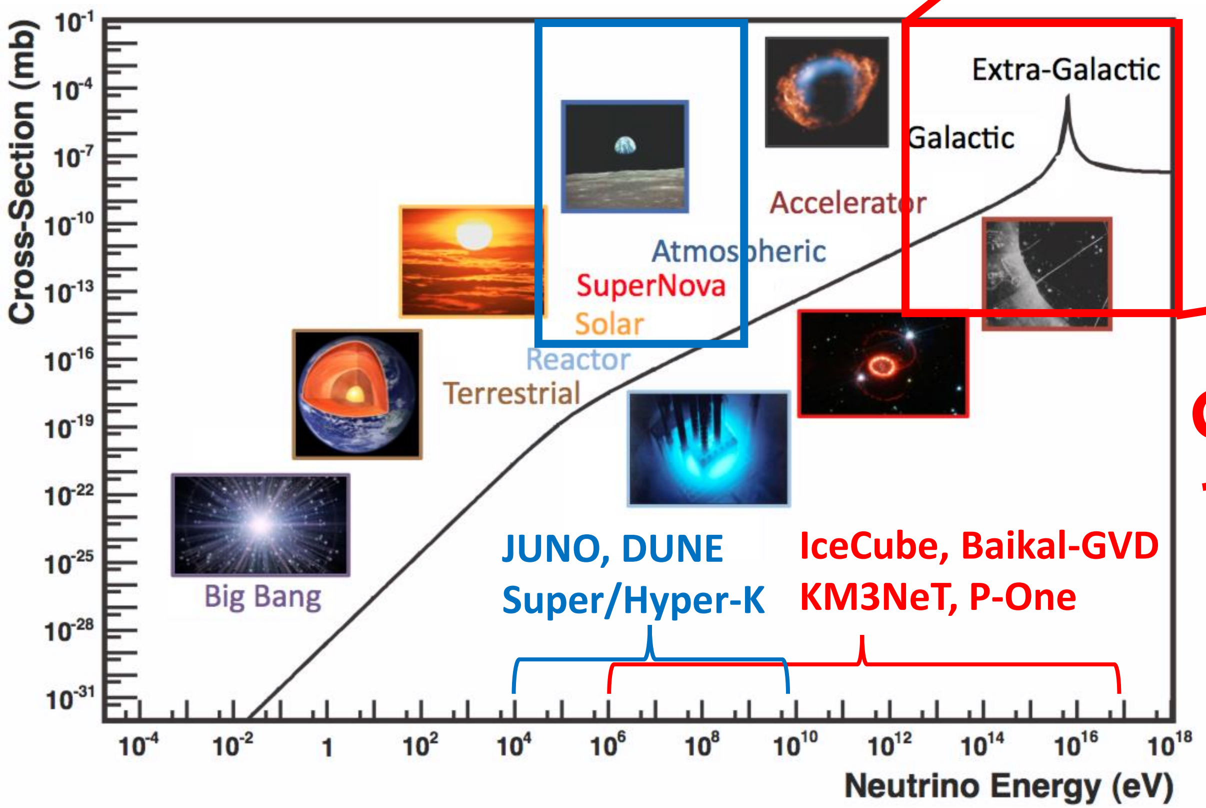


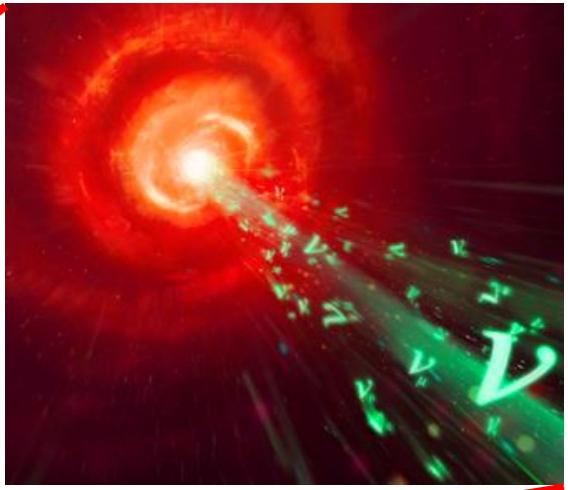


Cosmic Neutrinos

Oldest question in astronomy:

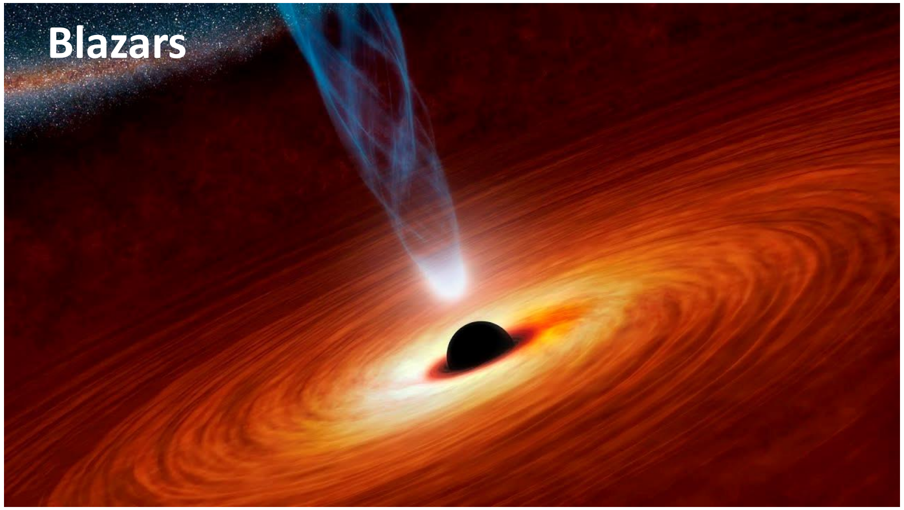
Origin of cosmic rays?

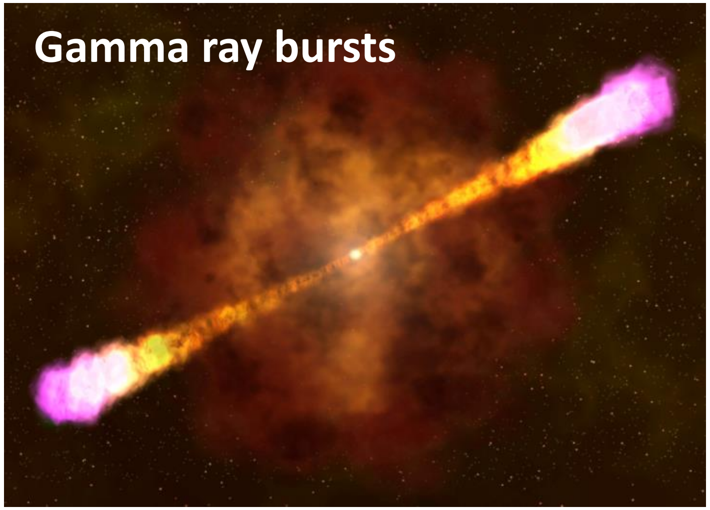


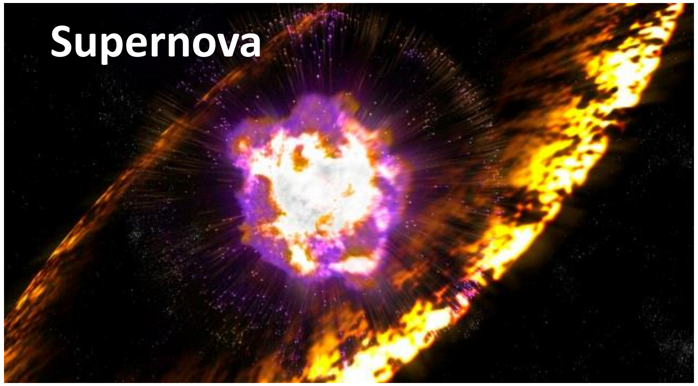


Connected with the ultra-high-energy cosmic rays (UHECR)!

Potential Cosmic Neutrino Sources



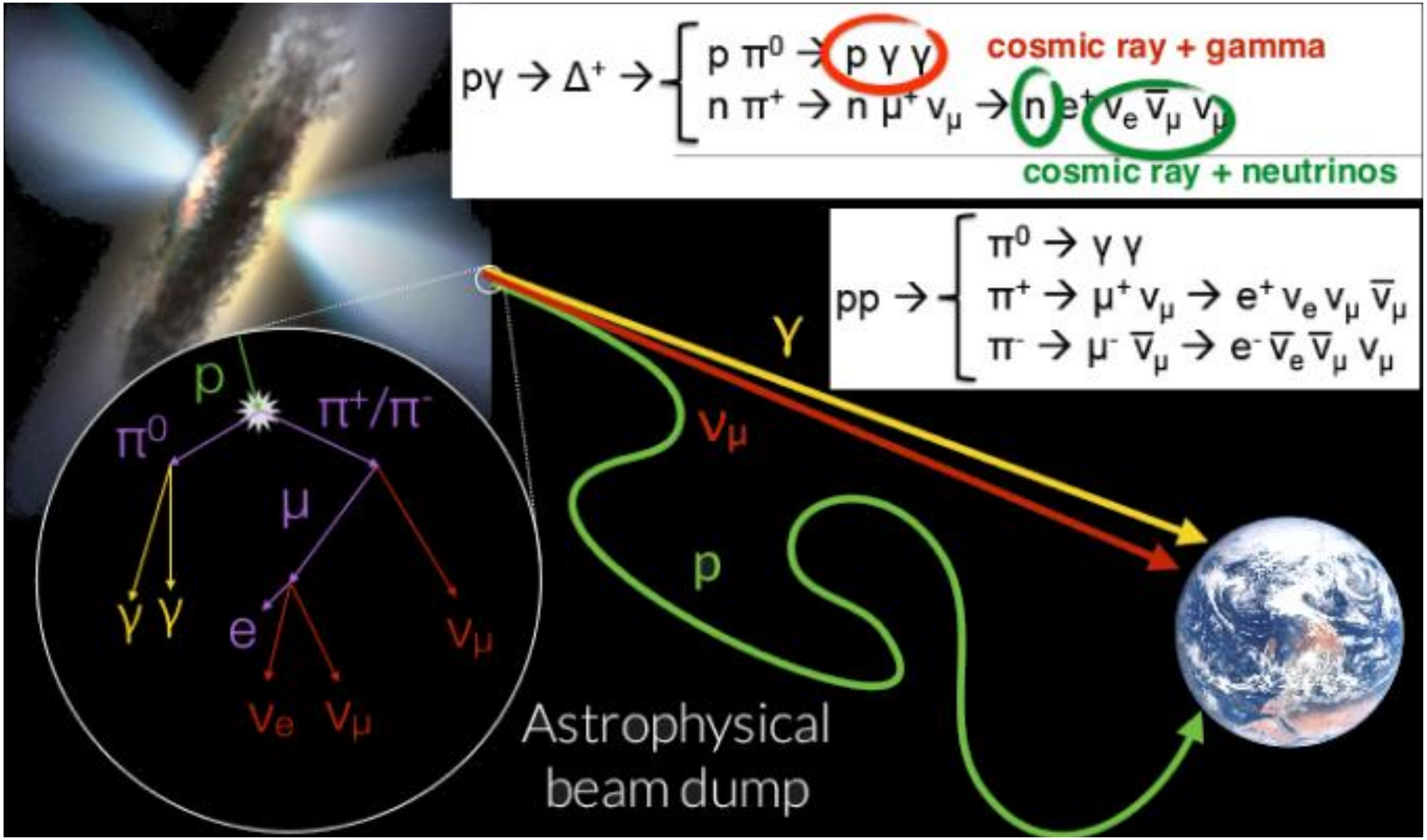




Astrophysical Beam Dump

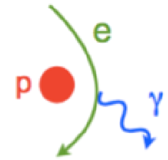
Hadronic processes:

Direct correlation between gamma and neutrinos!

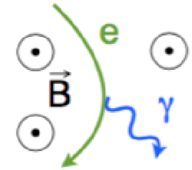


Hadronic vs Leptonic Processes

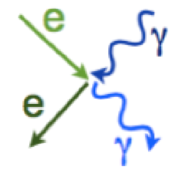
Leptonic processes:
no neutrino production



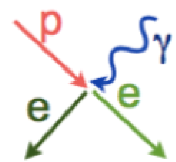
Bremsstrahlung



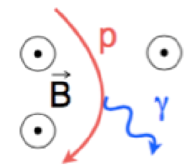
Synchrotron



Inverse Compton

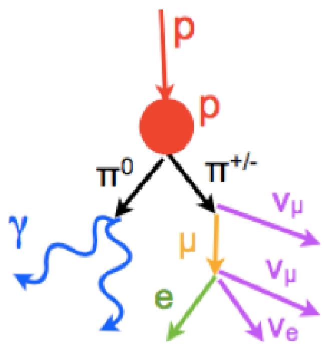


Pair production



p - Synchrotron

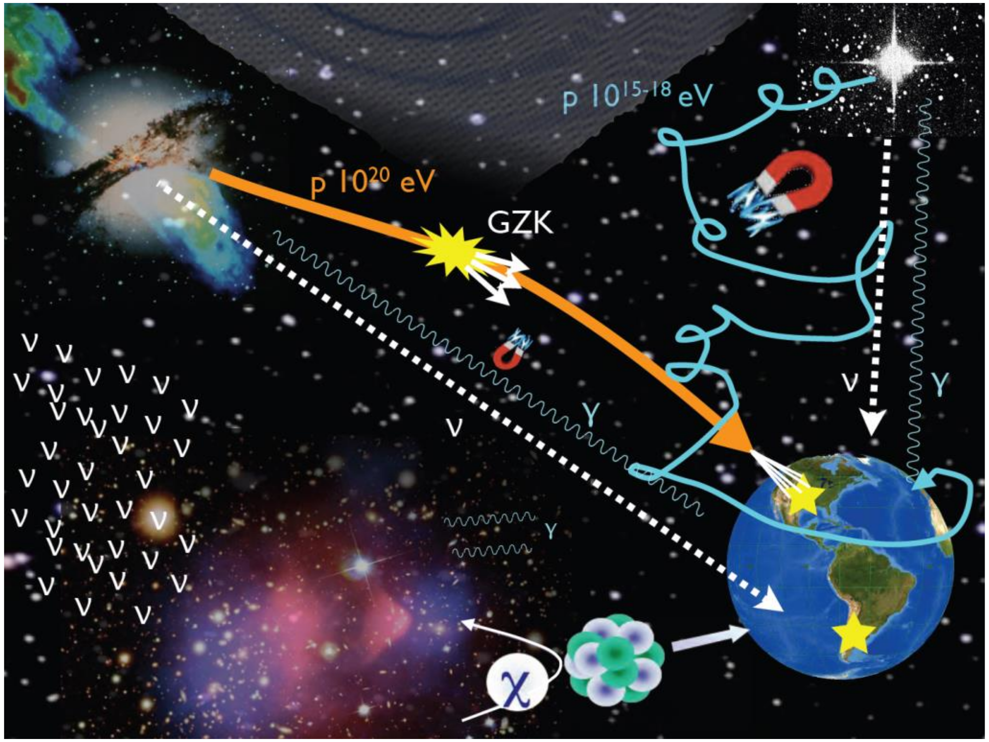
Hadronic processes:
neutrino production



Neutrinos are a diagnostic for hadronic interactions

Detecting high-energy neutrinos from astrophysical sources would be the "smoking gun" evidence for UHECR origin

Neutrino and Multi-messenger Astronomy



http://web.physik.rwth-aachen.de/~wiebusch/Research.html

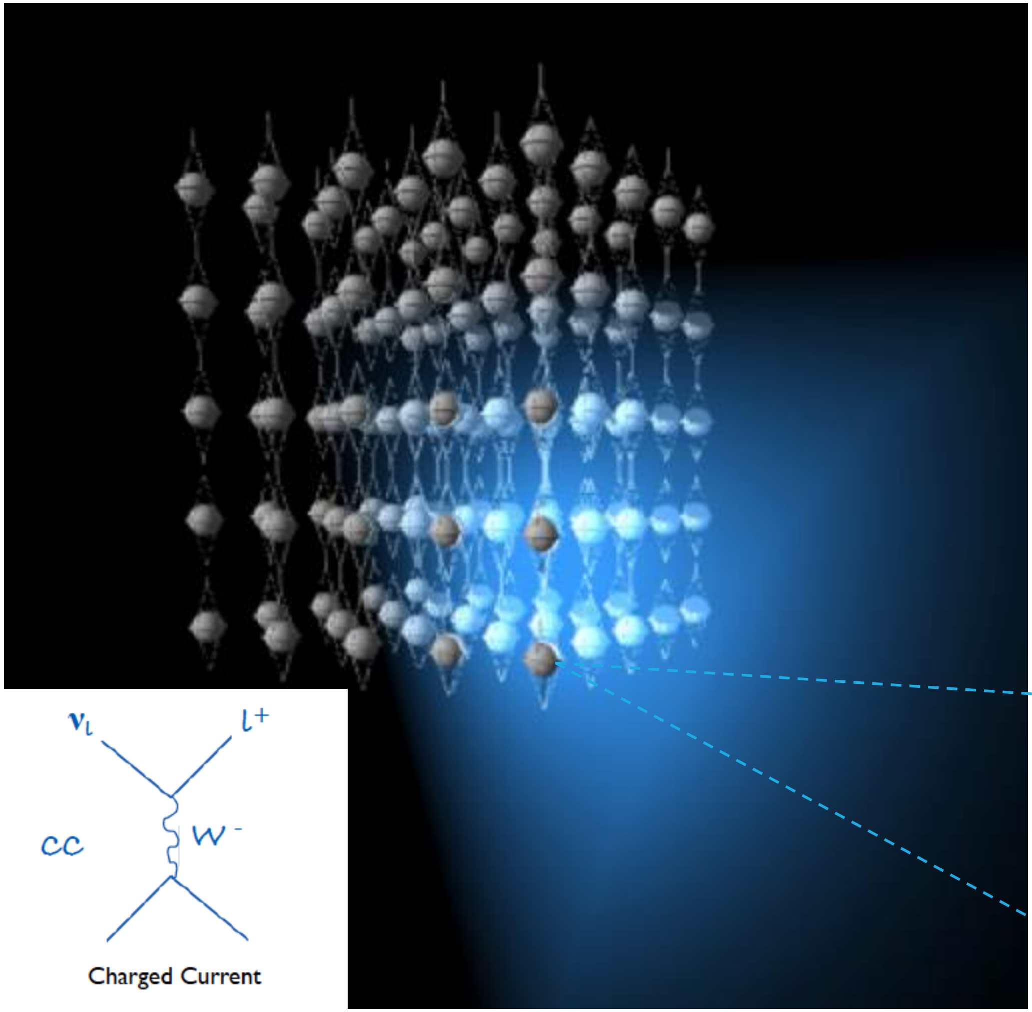
Cosmic Rays:
- Abundant
- Origin unknown
- Charged, trajectory deflected
- Absorbed by CMB at highest energies → GZK horizon

Gamma Rays:
- Interact with CMB
- Absorbed by infrared background → observational horizon

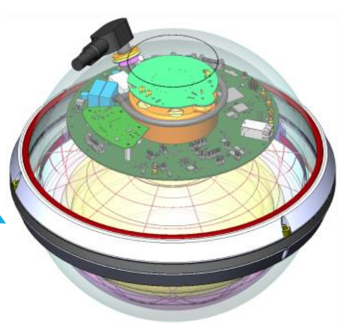
Gravitational waves:
- Highly penetrating
- No observational horizon

Neutrinos:
- Weakly interact
- Point back to sources → unique messenger to trace the high energy Universe!

Detection Principle – Cherenkov Radiation



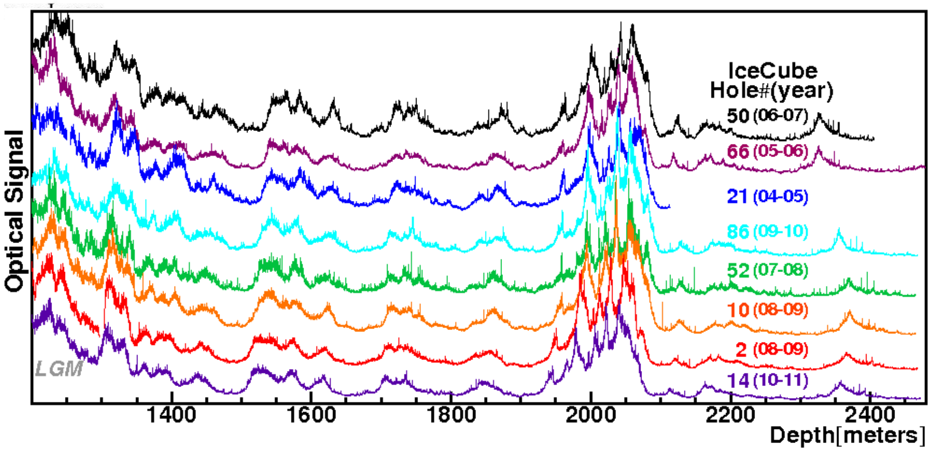
- Neutrinos cannot be detected directly
- Detecting light from neutrino interactions with the ice nuclei (Deep Inelastic Scattering)
- Sensitive to single photon



Interaction Media

Glacial ice

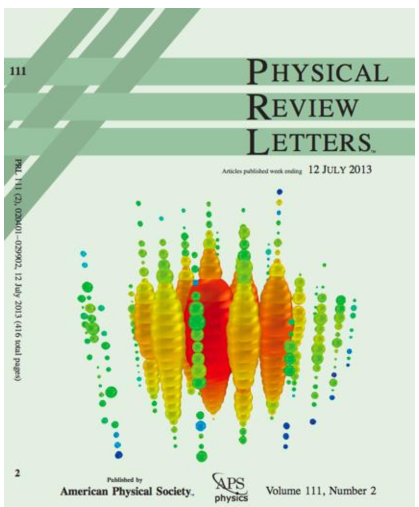
Most transparent medium on Earth!
Scattering length: ~**25**m
Absorption length: >**100**m

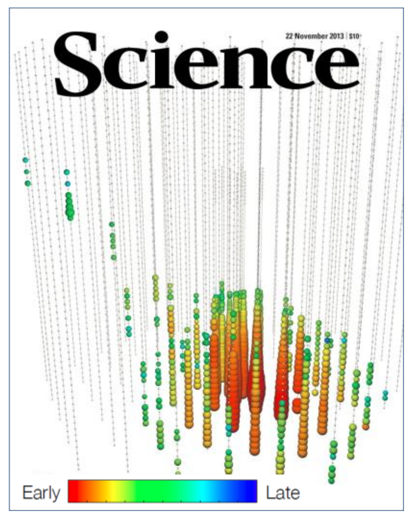


Lake/sea water

Current Status of Nu Astronomy

- In 2013, IceCube discovered a diffuse extraterrestrial neutrino flux – **the true breakthrough of the field !**
- In 2017, IceCube observed the first evidence of a a high energy neutrino source TXS0506+056



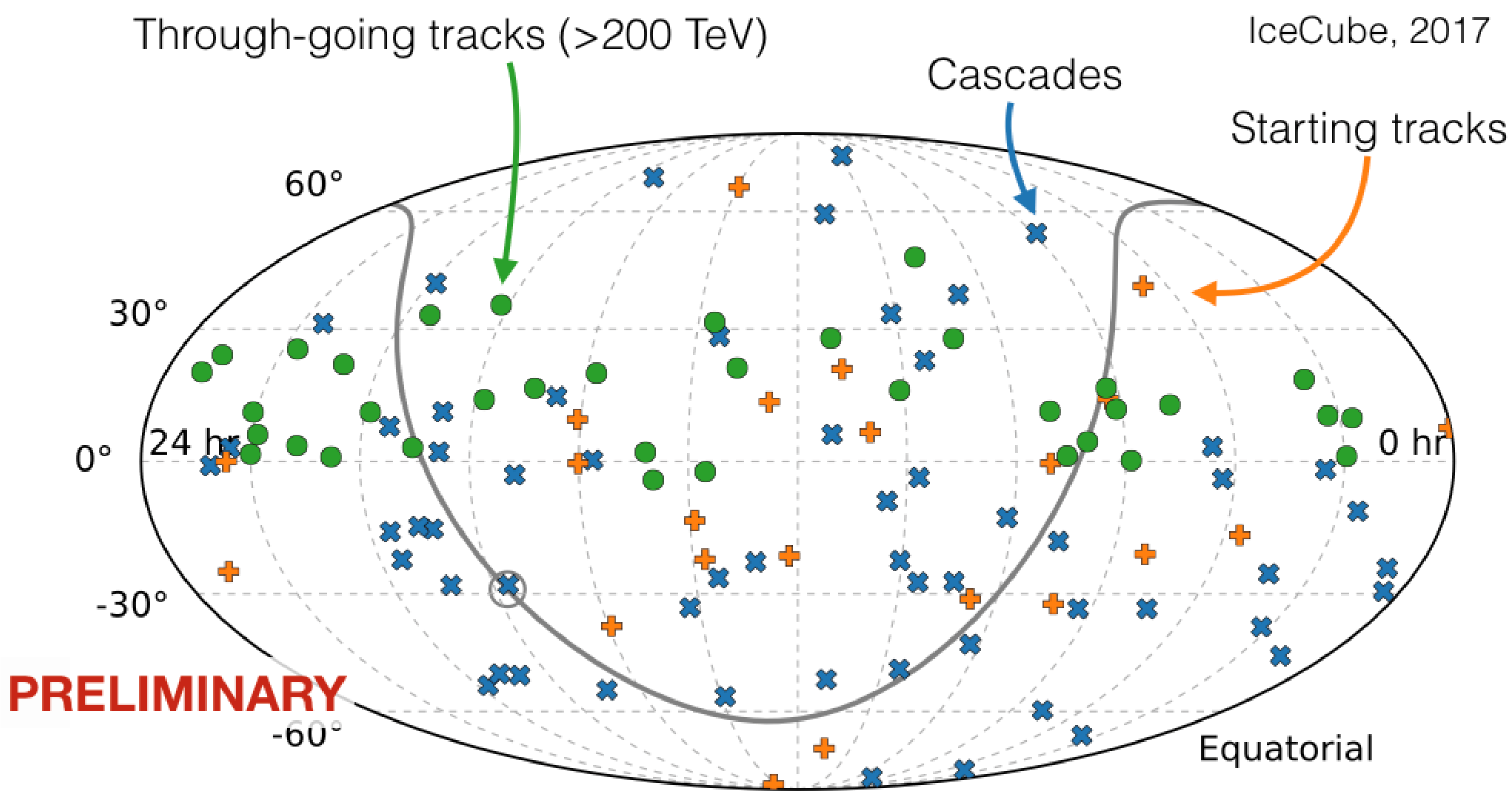


Origin of most IceCube neutrinos remains elusive

No definitive tau neutrinos have been identified

Current Status of Nu Astronomy

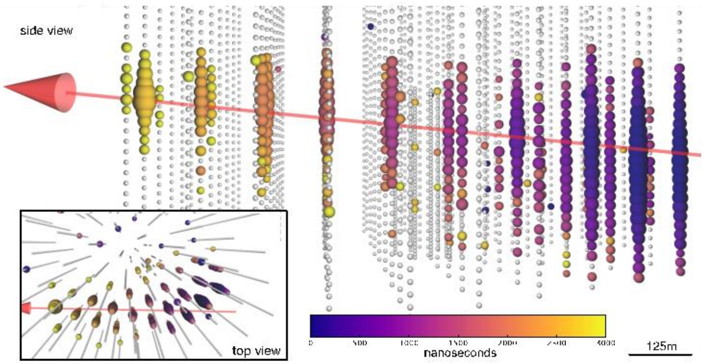
IceCube neutrino sky map



Slide courtesy: M. Kowalski, TeVPA2017

First Source Candidate

1. IC170922 (290 TeV) + Multi-messenger: chance probability: **3σ**



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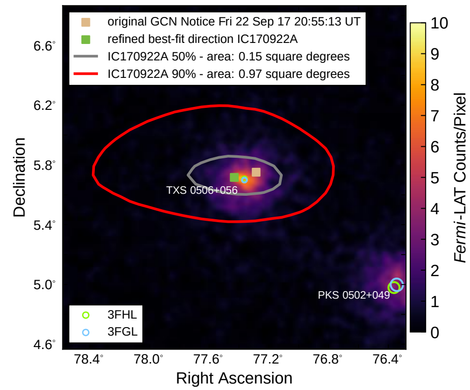
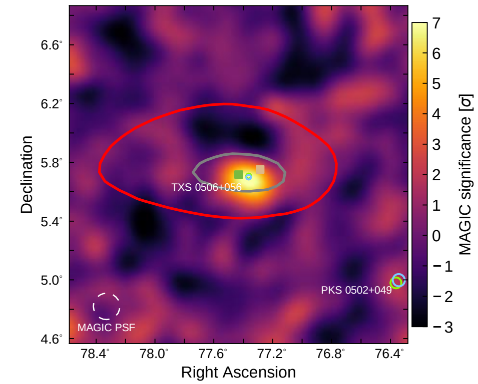
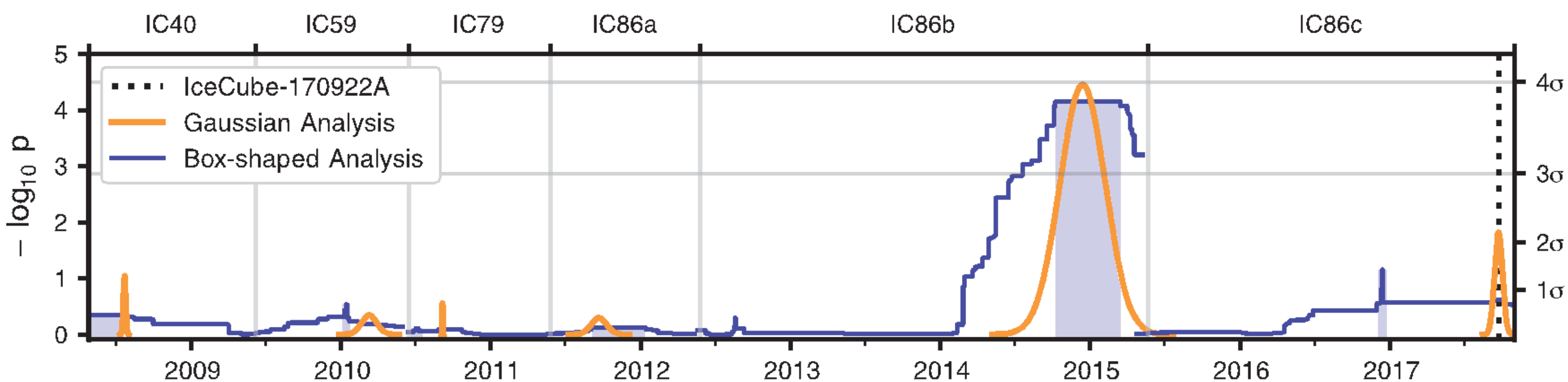




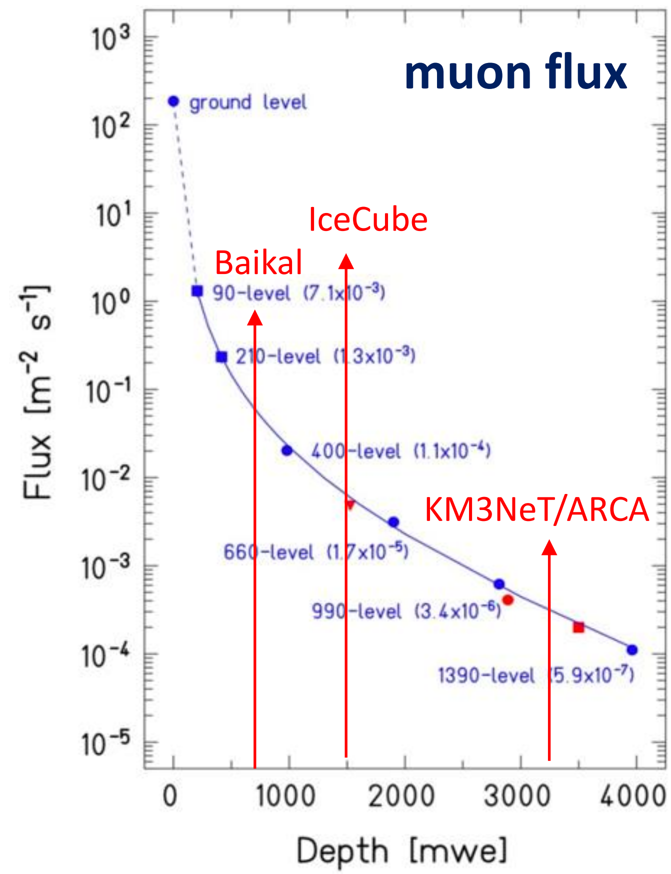
2. Neutrino emission in archival data: 19 (6 exp. bg) events ; **3.5σ**



Science 361, eaat1378 (2018); **Science** 361, eaat2890 (2018)

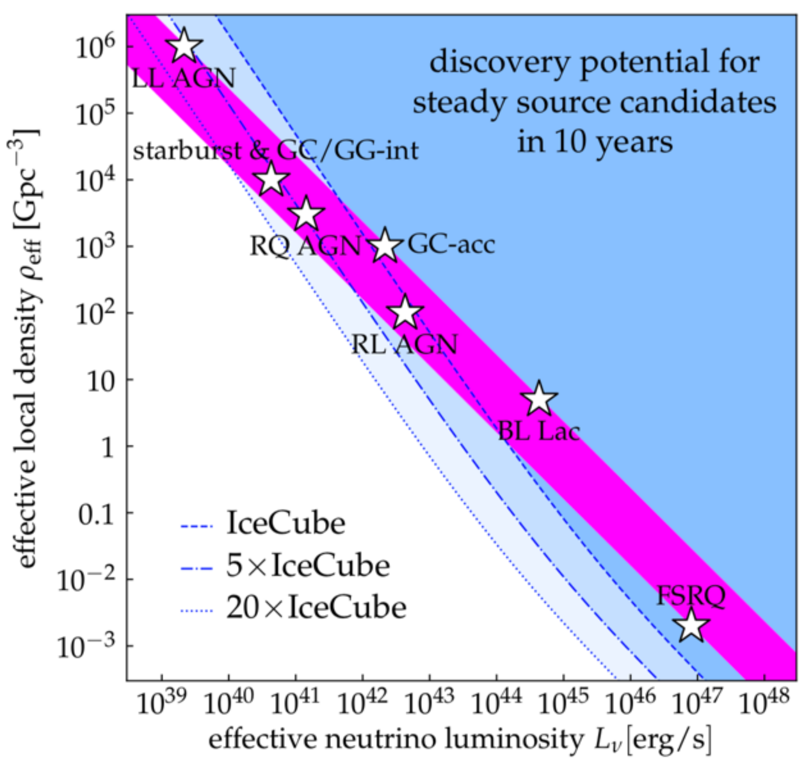
Optimizing Next-Gen Nu Telescopes?

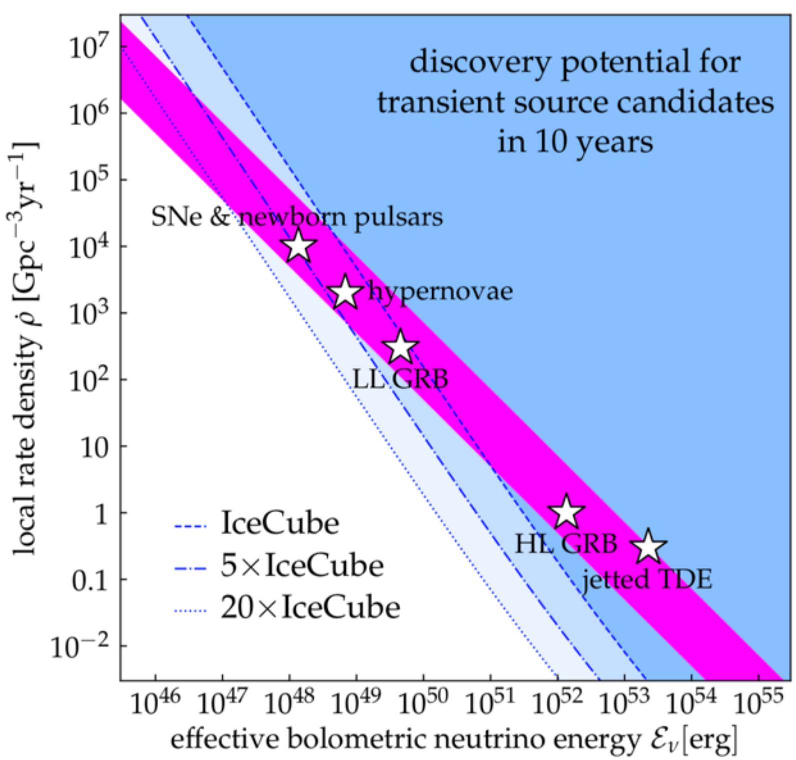
- **Angular resolution**
  - Limited by medium optical properties for high-E neutrino events
- **All flavor neutrino discrimination efficiency, especially tau neutrinos：**
  - Long duration waveform readout (double pulse method)
  - Geometry layout optimization… limited by spacing
- **Geographic sites：**
  - Most sensitive to the Galactic Center?
  - Duty cycles
- **Construction cost：**
  - Open water vs Antarctic glacial ice drilling
  - Deep ocean engineering vs lake operation



Resolving More Astro Nu Sources?

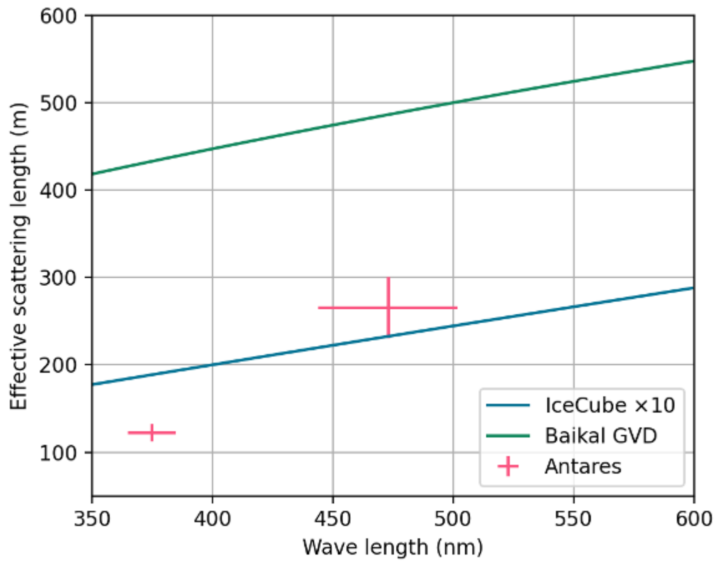
US Astro2020 Decadal Survey: 1903.04334

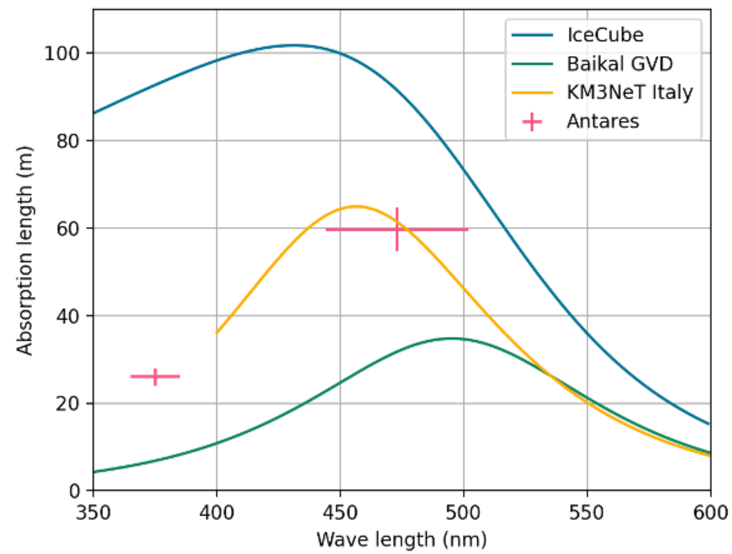




It requires better than 0.1° pointing to resolve the most pessimistic source scenarios… K. Fang et al. JCAP 12, 017 (2016)

Interaction Media Comparison





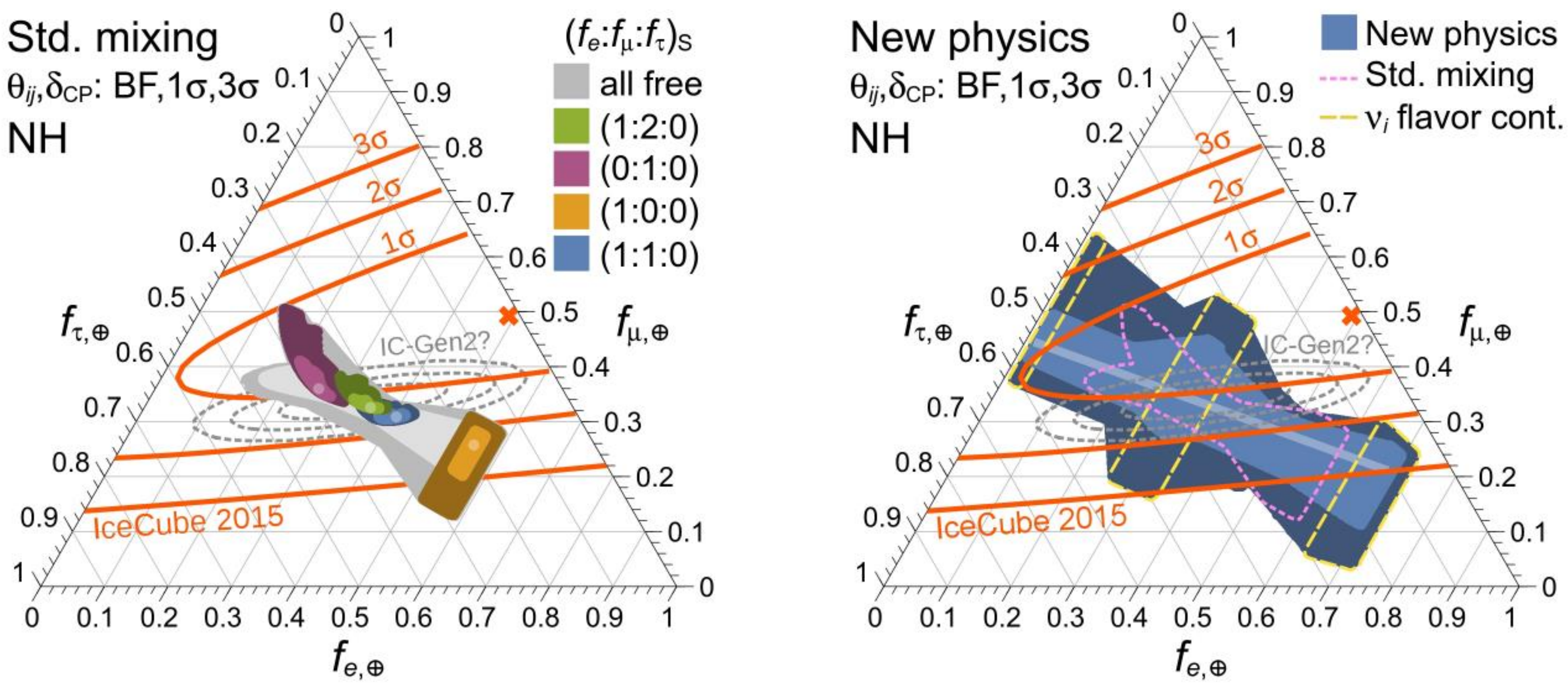
Angular Errors

	Track	Cascade
KM3NeT	$\sim 0.1°$	$\sim 1°$
IceCube	$\gtrsim 1°$	$> 10°$

South Pole: IceCube Collaboration, J. Geophys. Res. 111, D13203, 2006
KM3Net Italy: NEMO Collaboration, Astropart. Phys., 27, 1—9, 2007
Antares: Antares Collaboration, Astropart. Phys., 23, 131—155, 2005
Lake Baikal: A. Avrorin et.al., Nucl. Instrum. Meth. A, 693, 186—194, 2012

Neutrino Oscillation over Astro Baselines

Observable / probe: astrophysical neutrino **flavor ratio**



M. Bustamante, J. Beacom and W. Winter, Phys. Rev. Lett. 115, 161302 (2015)

Significantly boosting tau neutrino identification efficiency is the key !

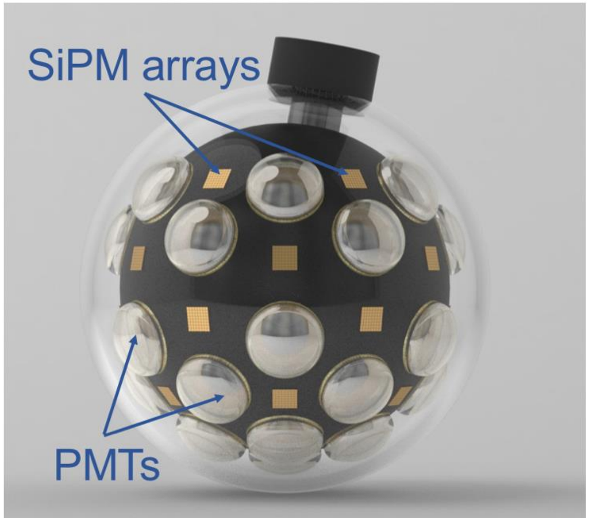
Improving Angular Resolution?

hDOM

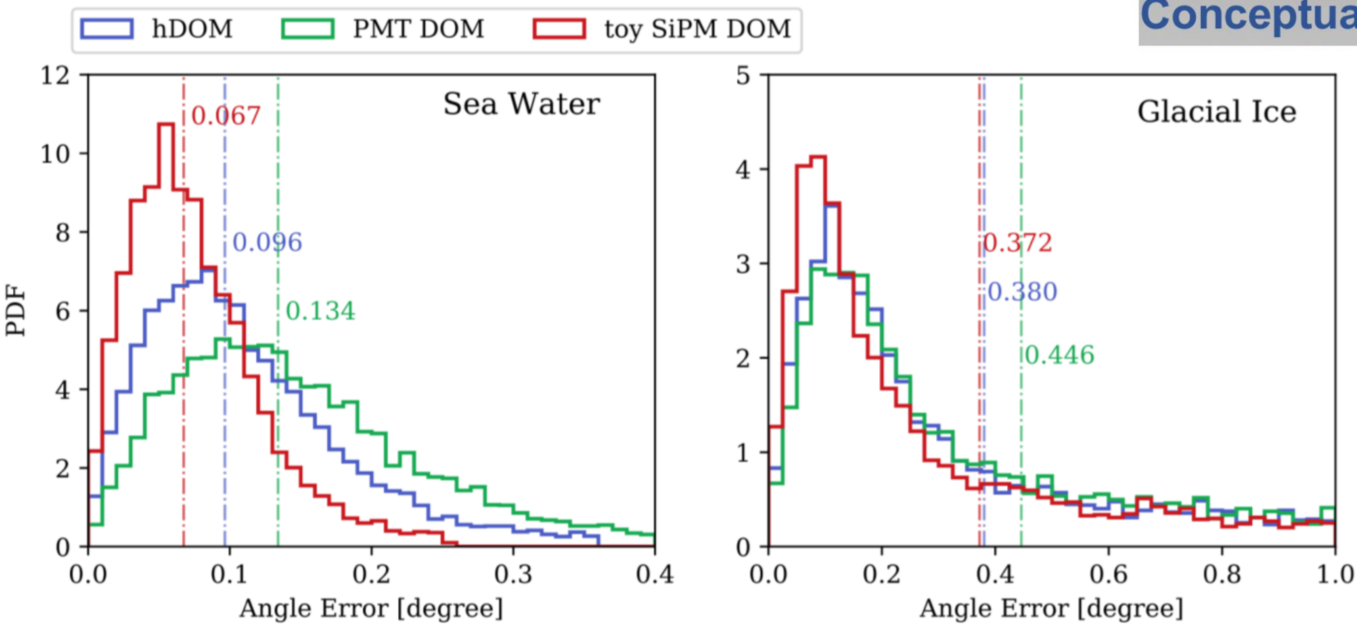
*PMT + SiPM **hybrid Digital Optical Module***

hDOM vs KM3NeT **mDOM:**

- ~100% improvement in pointing with SiPM-only
- ~40% improvement in pointing with hDOM
- hDOM in ice do not benefit as much as in water



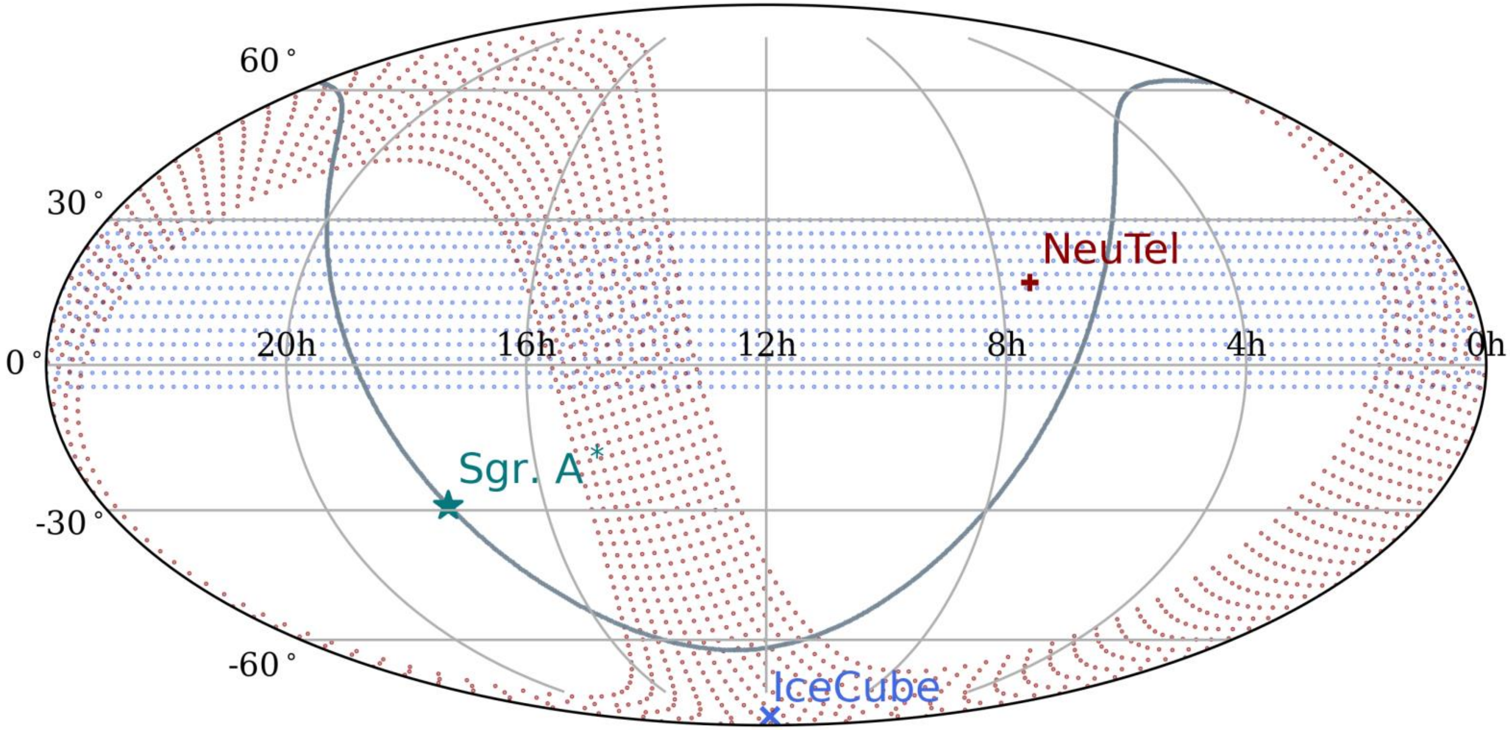
Conceptual Design of hDOM



F. Hu, Z. Li and **DLX**
PoS(ICRC2021)1043

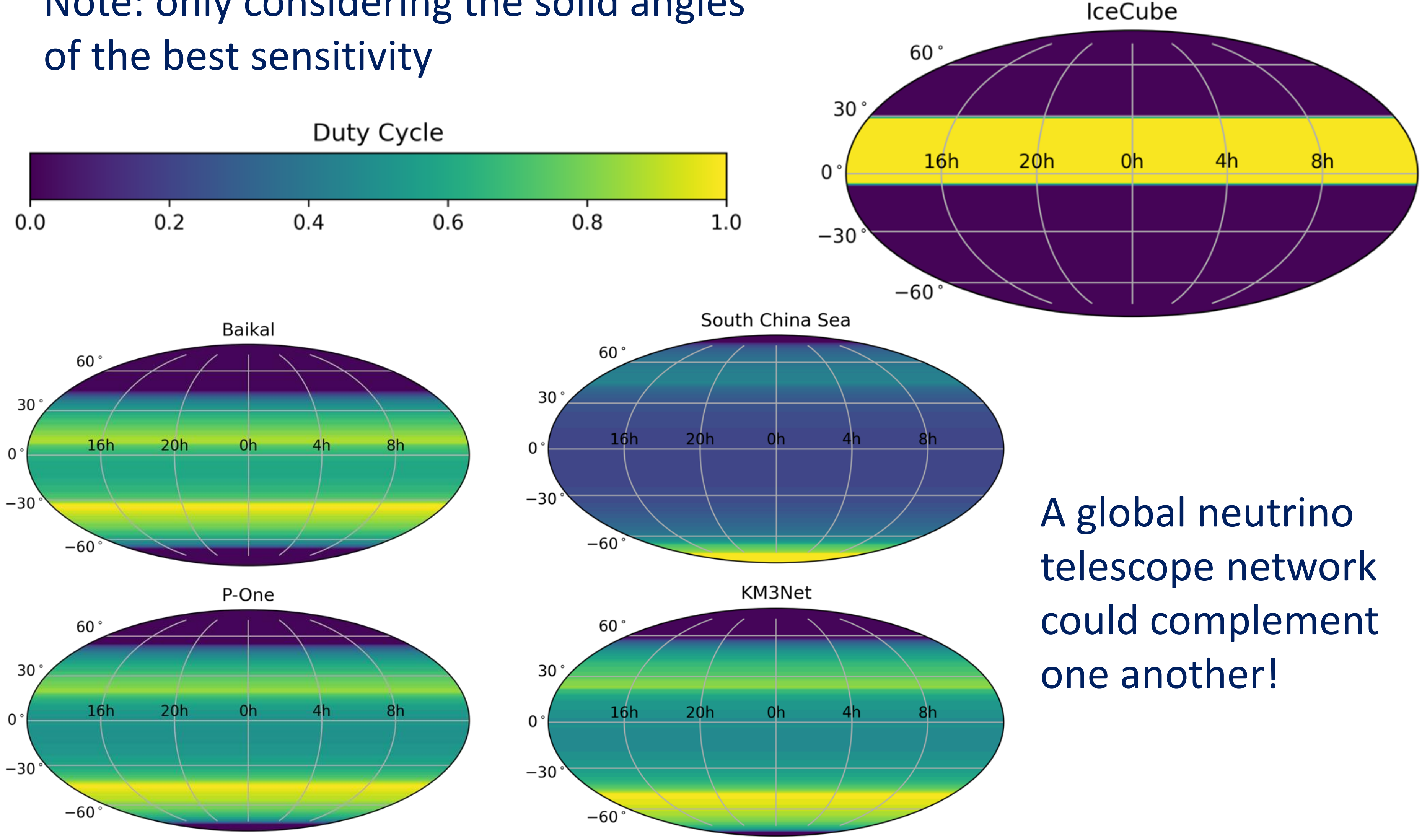
Geographic sites?

A Nu Telescope Near the Equator?



Duty cycles

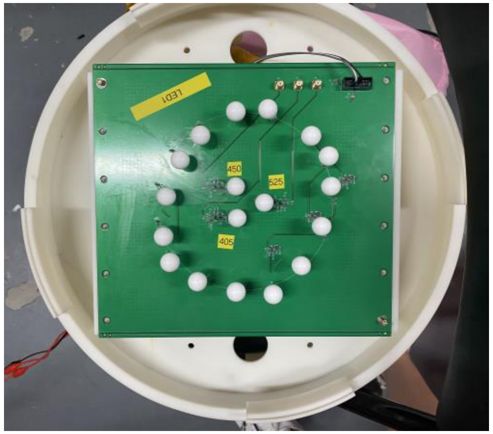
Note: only considering the solid angles of the best sensitivity

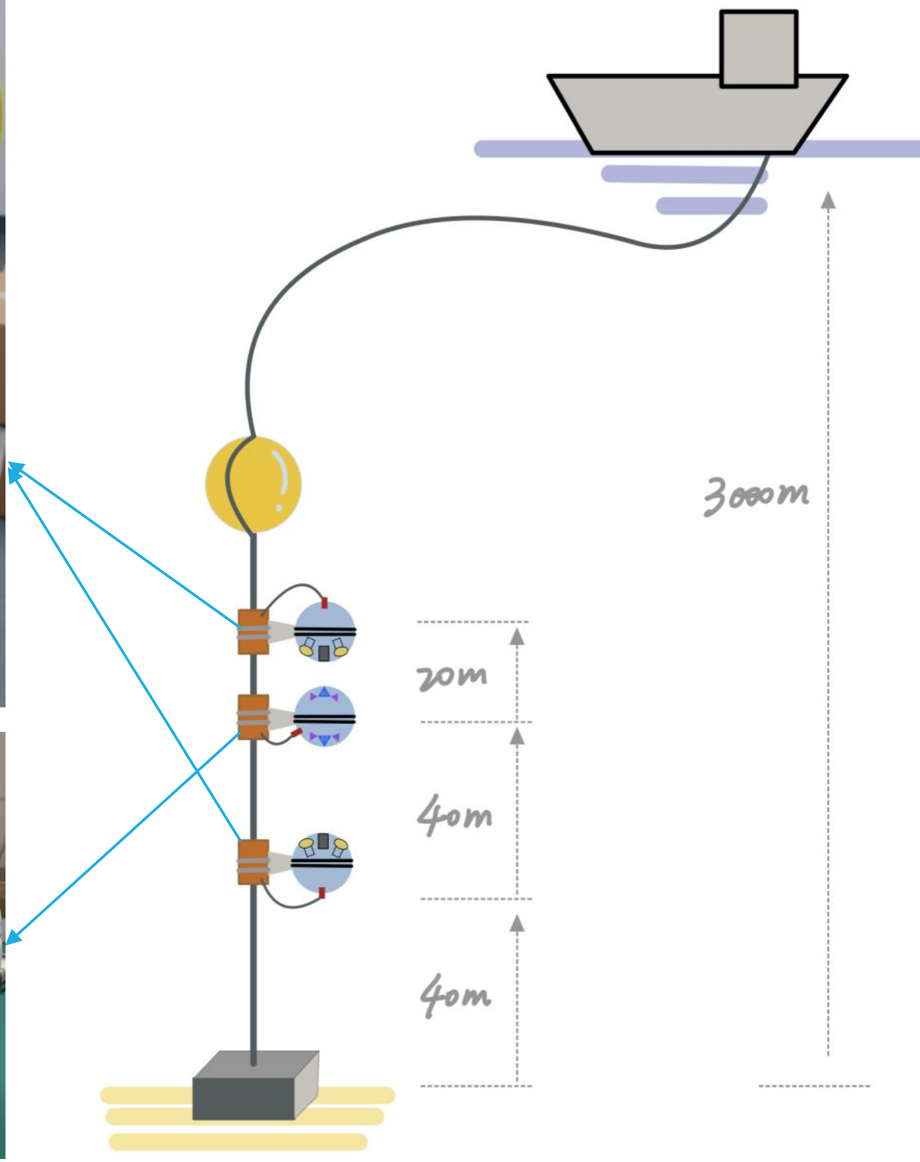


A global neutrino telescope network could complement one another!

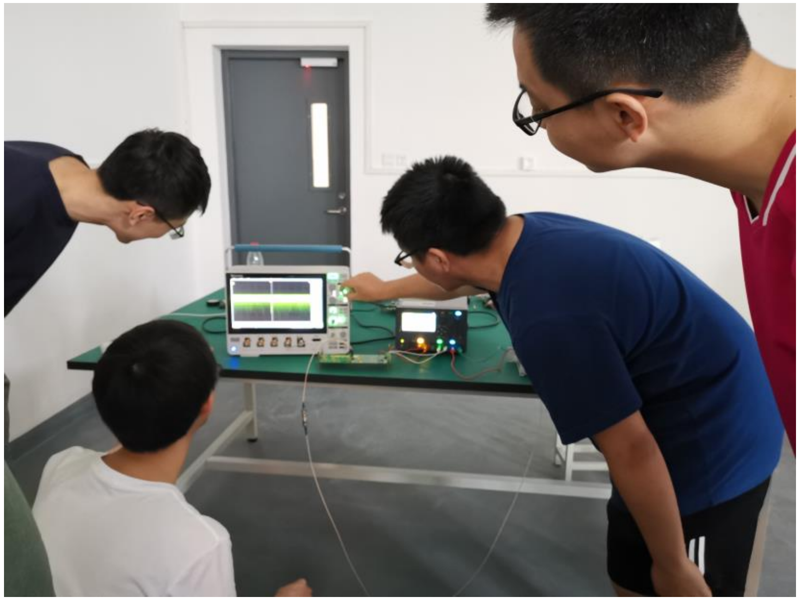

Where I am now! ☺

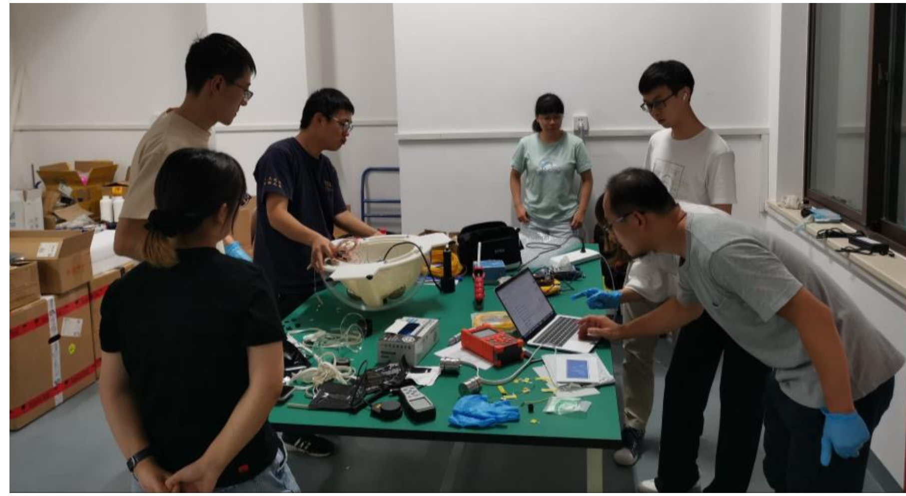
NeuTel Site Exploration in South China Sea

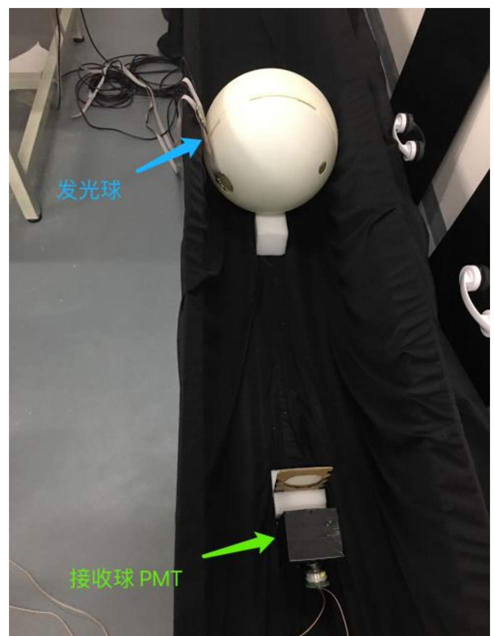




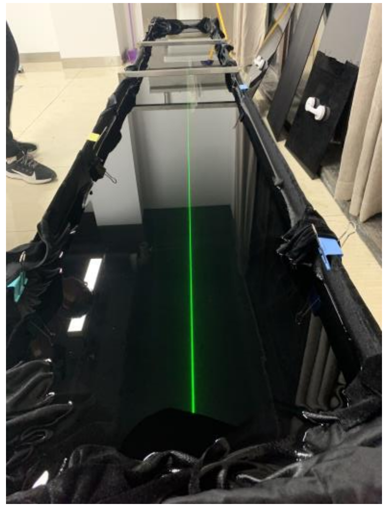
Testing & Calibrating the PMT System

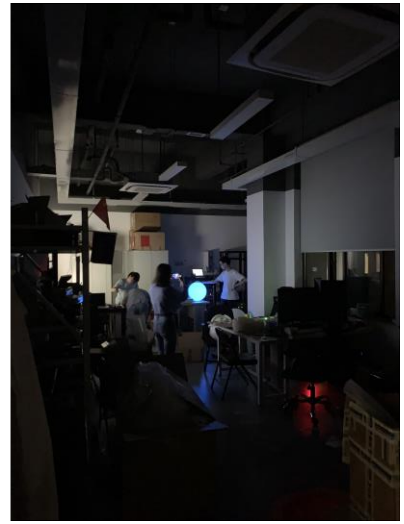


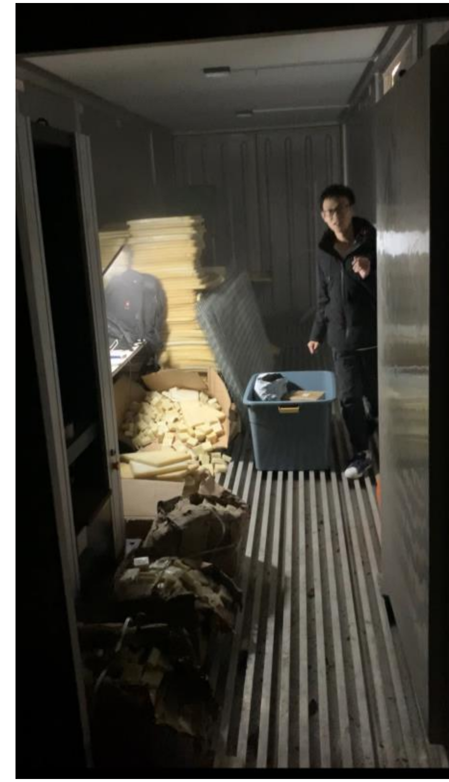




Testing & Calibrating the CCD System







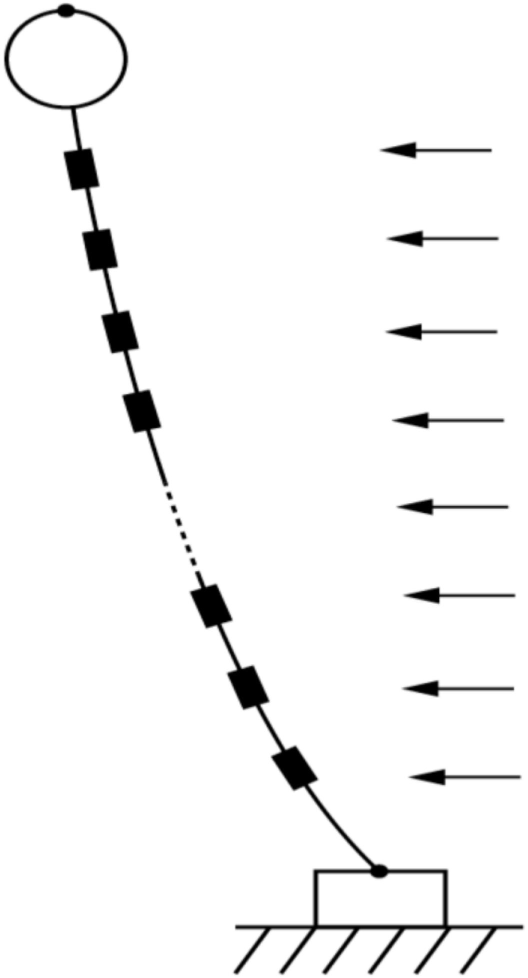
Pressure Test for Glass Vessels


Ready for pressure test


Pressure test for 8 hours at 38 MPa

Deployment System

Candidate Site Four-season Monitoring



Stay tuned!

Summary

- The serendipitous detection of SN1987A started a new field of neutrino astronomy
- IceCube's discovery of high-energy cosmic neutrinos has marked the new era of nu astronomy
- Neutrino and multi-messenger astronomy is still in its infancy
- The upcoming JUNO, Hyper-K and DUNE will play important roles in detecting the next Galactic supernova
- The campaign to hunt for more cosmic neutrino sources via both multi-messengers and better designed next-gen neutrino telescopes is ON…