Neutrino astronomy: a key-player for multi-messenger astronomy

Kyujin Kwak (UNIST)

Celebrating the 10th anniversary of GW detection

@Seoul National Univ.

August 28, 2025

Multi-Messenger Astronomy

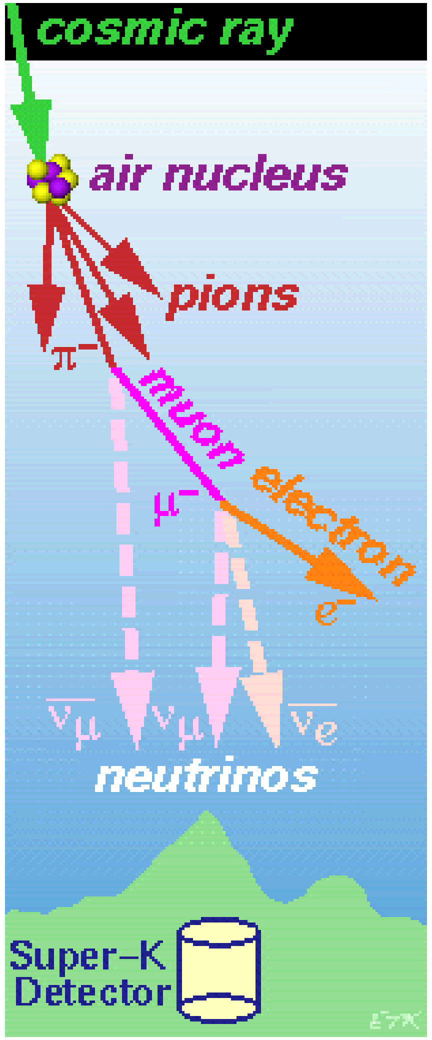
- Electromagnetic (EM) signal vs. Non-EM signal
- Multi-Messenger (MM)
  - EM (photons)
  - Gravitational wave (GW)
  - Neutrino
  - Cosmic-ray (nuclei)
- MMA has a long history even before the first detection of GW in 2015!

Neutrino Astronomy and Astrophysics

- Neutrino astronomy
  - Emerging as an important part of multi-messenger astronomy together with gravitational wave (GW)
  - Many neutrino detectors/observatories are operating, under construction, and planned: ICECUBE, KM3NET, DUNE, Hyper-Kamiokande, JUNO
  - (Tentative) Korean Neutrino Observatory (KNO) is being pursued
- Neutrino astrophysics is not new at all!
  - Various astrophysical sites and production mechanisms for neutrino emission have been studied for a long time
  - But predicting detectability on operating/planned detectors is NEW!!

Astrophysical Sites for Neutrino Emission I

- Cosmic-ray: high energy neutrinos (> GeV, typically > TeV or even PeV)
  - Anywhere high energy particles (protons) exist
  - Strong acceleration processes such as shock waves, magnetic fields, and jets are required -> correlation among high energy electromagnetic radiation like X-ray and gamma-ray, ultra-high cosmic-ray, and neutrino emission
  - Atmospheric neutrino: detected
  - Active galaxies (with active galactic nuclei: AGN/blazar): detected
  - Clusters of galaxies & nearby star-burst galaxies: predicted to have negligible detectability (recent work by Prof. Ryu and his students at UNST/CHEA)
  - Other sites?

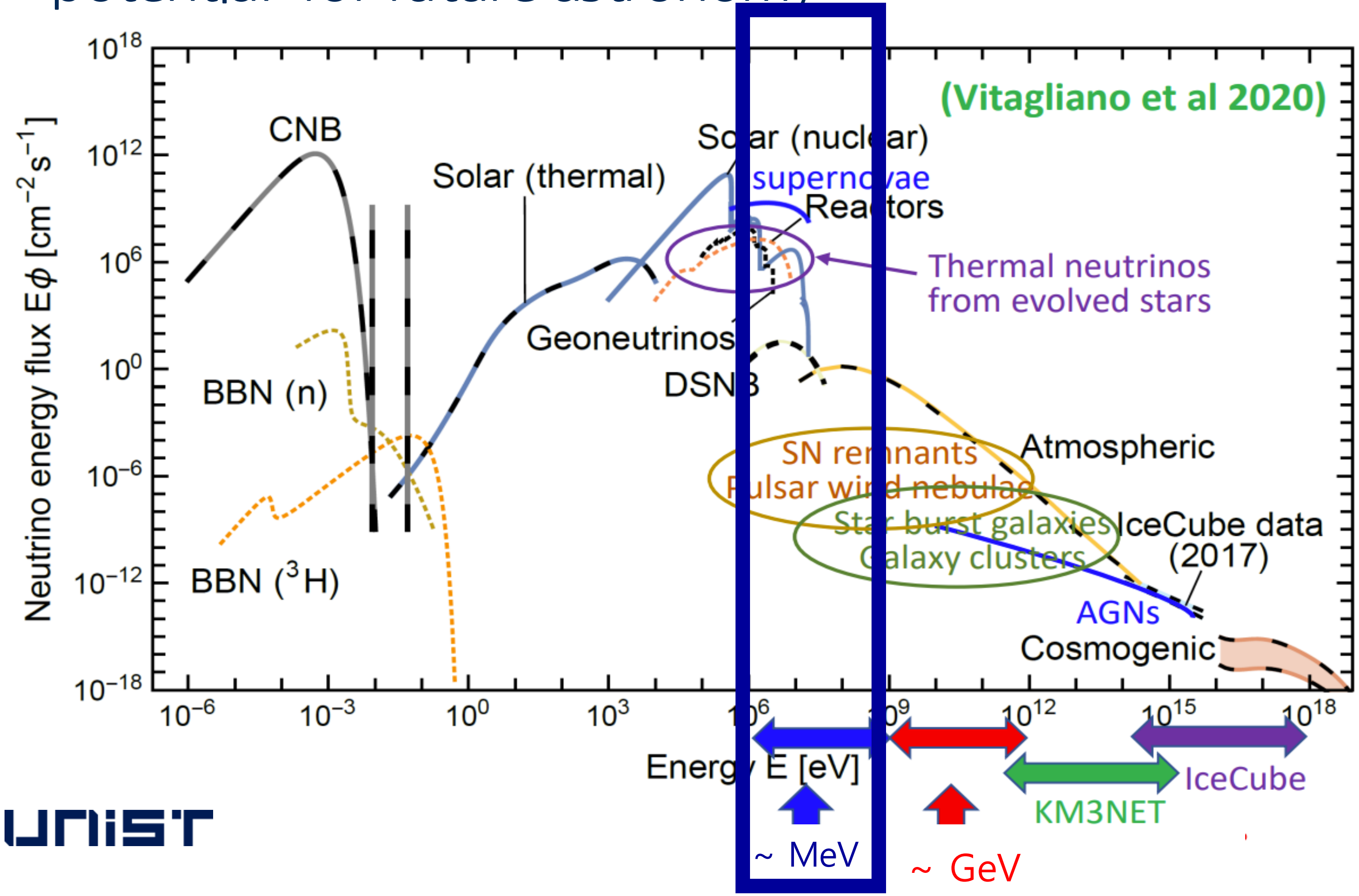


Astrophysical Sites for Neutrino Emission II

- Anywhere in the universe where weak interaction occurs!
- Nuclear reactions: low energy neutrinos (< GeV, typically a few tens of MeV)
  - Inside stars -> Solar neutrinos (detected)
  - Supernovae -> SN 1987A (detected)
  - Compact binary mergers (NS-NS or NS-BH): only GW detected -> many predictions (# of models >> # of observed events: very common in astronomy/astrophysics)
  - X-ray bursts: from rp-process. Did not get much attention thus/but worth investigating their potential contribution to detectability
  - Other sites? Carbon-burning massive stars (Red SuperGiants)

Cosmic Neutrinos

Neutrino astronomy, as a part of multi-messenger astronomy, has a great potential for future astronomy



UNIST

중성미자란? (中性微子, neutrino 뉴트리노)

별칭: 유령 입자 혹은 수수께끼 입자

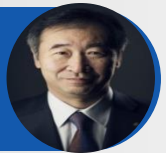
존재 예측: 1930년 볼프강 파울리 (1945년 노벨상 수상자)

최초 발견: 1956년 프레더릭 라이너스 (1995년 노벨상)

중성미자 “노벨상의 화수분”

1988년  리언 레더먼, 멜빈 슈워츠, 잭 스타인버거

2002년  고시바 마사토시, 레이먼드 데이비스 2세

2015년  가지타 다카아키, 아서 맥도널드

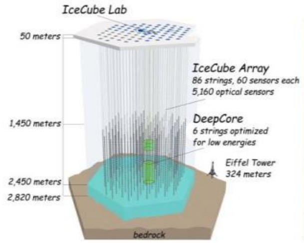
중성미자 “물리학” 과 “천문학”

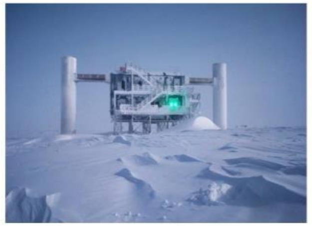
- ✓ 중성미자의 무게(질량)는 얼마일까?
- ✓ 중성미자의 종류는 몇 가지일까?
- ✓ 중성미자의 무게와 종류 사이에는 어떤 관계가 있을까?
- ✓ 중성미자의 반입자는 자기 자신일까?

- ✓ 우주에서 만들어진 중성미자를 지구에서 관측할 수 있을까?
- ✓ 관측하려면 어떤 장비가 필요할까?

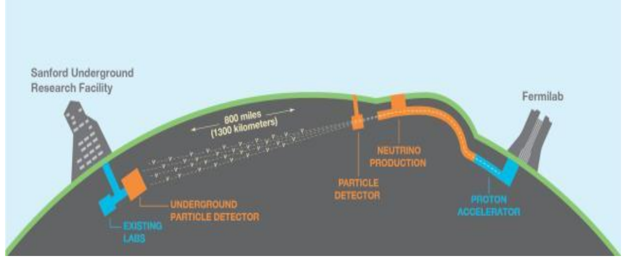
해외 중성미자 관측 시설

ICECUBE 남극 얼음 이용

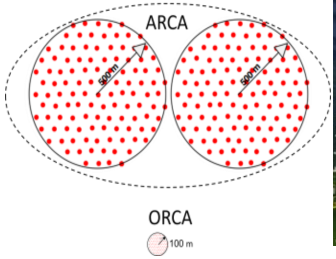


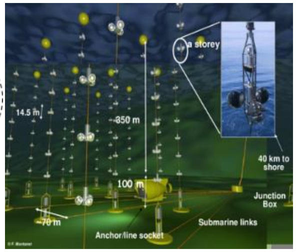


DUNE 지하 액체 아르곤 탱크

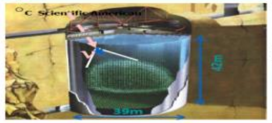


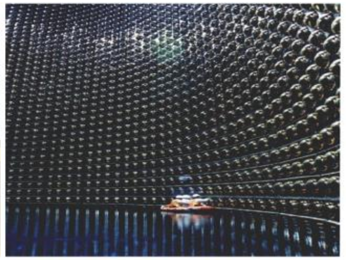
KM3NET 지중해 물이용





KAMIOKANDE 지하 물 탱크





중성미자 언론보도

사이언스 타임즈 2016년 7월 22일

노벨상의 화수분, 중성미자 연구

먼 훗날에는 중성미자 전자기파의 간섭 문제 등을 극복하고
우주개발 시대에도 적합한 새로운 통신수단으로 활용...

조선비즈 2017년 12월 9일

중성미자 연구의 성지, 일본 '수퍼가미오칸데' 를 가다

여기는 지하 1000m...
'우주의 유령'이 숨어 있다

"기초과학자들이 정보를 나누기 위해 웹을 발명한 것이 인터넷 시대를 낳은 것처럼 기초과학을 해야 미래 세대가 쓸 수 있는 아이디어가 나온다"고 말했다.

모두 1조원대 이상 거대 과학 장비

일본 카미오칸데 관측소

중성미자 망원경

카미오칸데 (1983년, 수백억원 규모)
수퍼 카미오칸데 (1995년, 천억원 규모)
하이퍼 카미오칸데 (2020년, 1조원 규모)

도야마 대학교

관련 연구시설 및 박물관

중력파 망원경

카그라 (2012년, 초기 건설비용 1500억원 규모)

도야마시
인구 약 40만

국제 회의 관광도시
일본 정부에 의해 환경 모델 도시에 선정
오른편 일본 중부 산악 국립공원으로 인해 해마다 많은 관광객이 방문

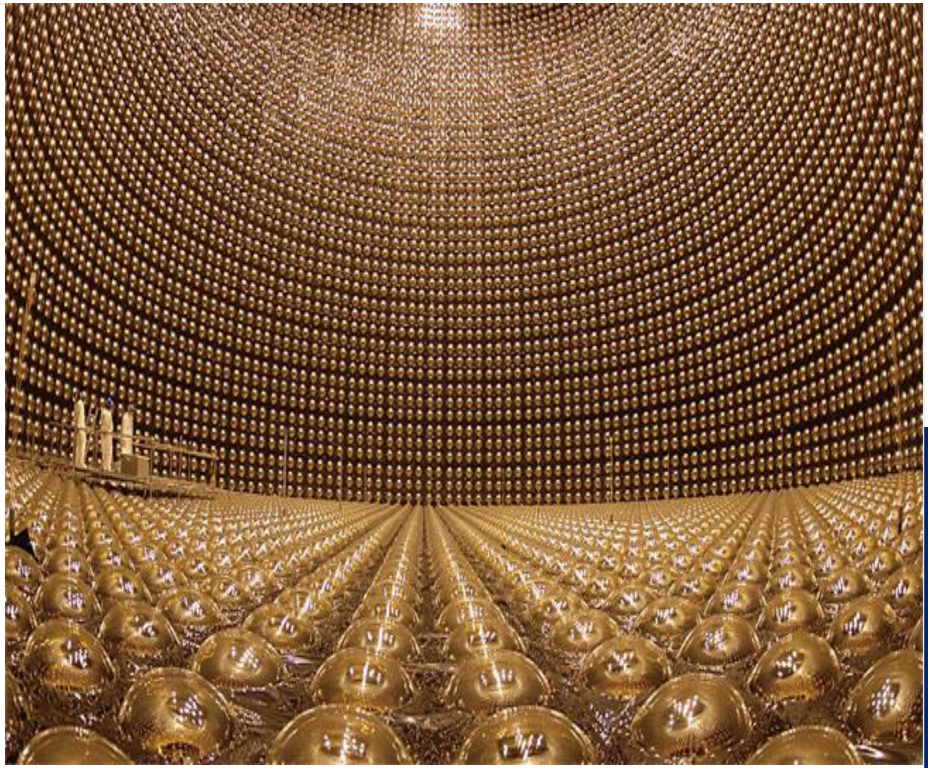
한국 중성미자 관측소 개요

연구목표

- ✓ 세계 최대 지하 중성미자 망원경을 설치해 입자물리학과 천체물리학 연구를 선도
- ✓ 이산화탄소 처리 시설 구축을 위한 지하 탐사와 지하 저장 연구 그리고 超深地 환경 방사능 측정
- ✓ 의료 및 생명과학 연구와 재료과학 연구

사업규모

- ✓ 약 3,000~5,000억원 규모(국비), 7년
- ✓ 약 25~50만톤 超純粹 물을 채운 물 탱크 + 광센서
- ✓ 광센서: 물 탱크를 지나는 중성미자가 방출하는 약한 빛을 측정 초고감도 광센서

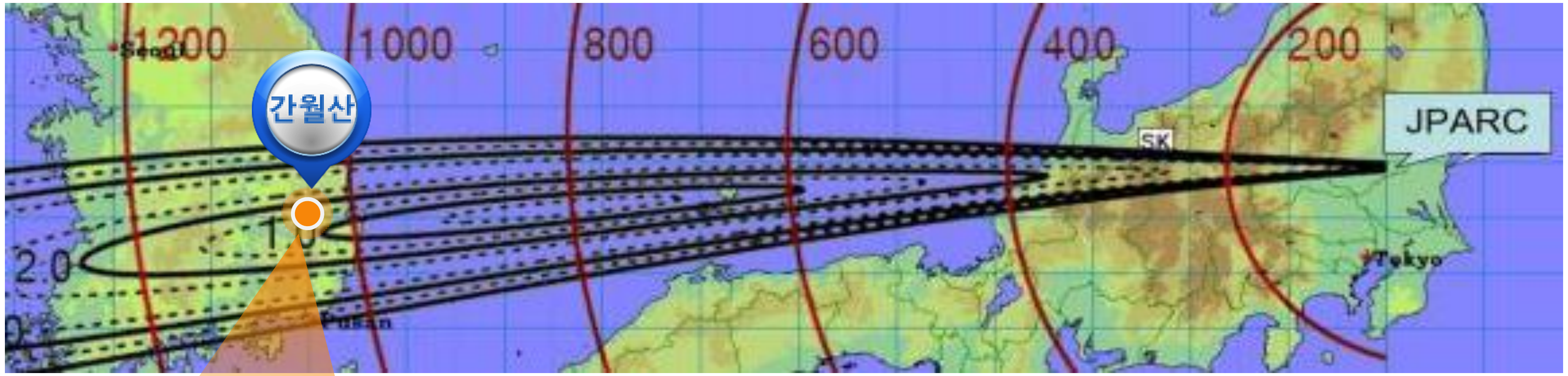


KNO 중성미자 검출기 내부 예상도

한국 중성미자 관측소 개요

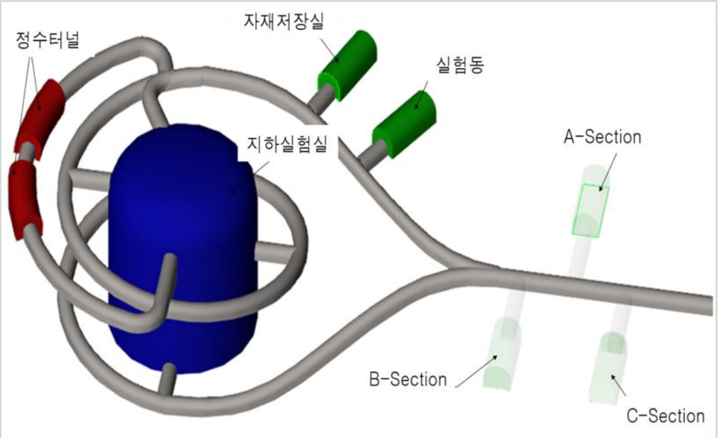
KNO 울산 입지 필요성

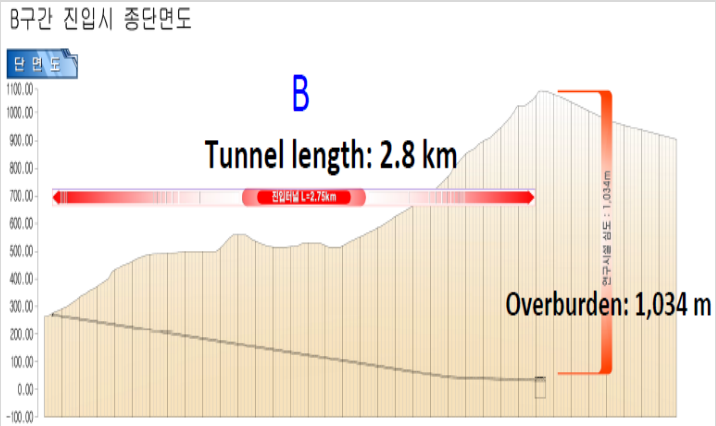
간월산



- ✓ 연구시설 후보지 (연구동, 견학시설, 연구자 숙소)
- ✓ 터널진입로 (지질 조사 후 결정)
- ✓ 최소 지하 1,000미터 깊이의 터널

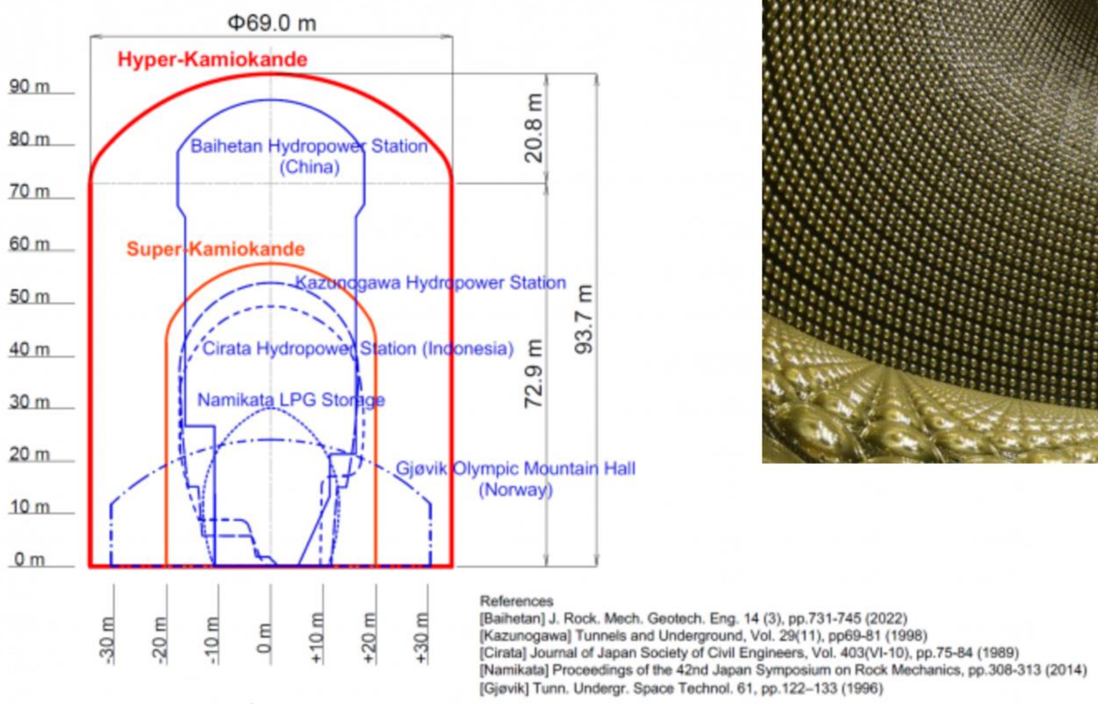
KNO 지하시설

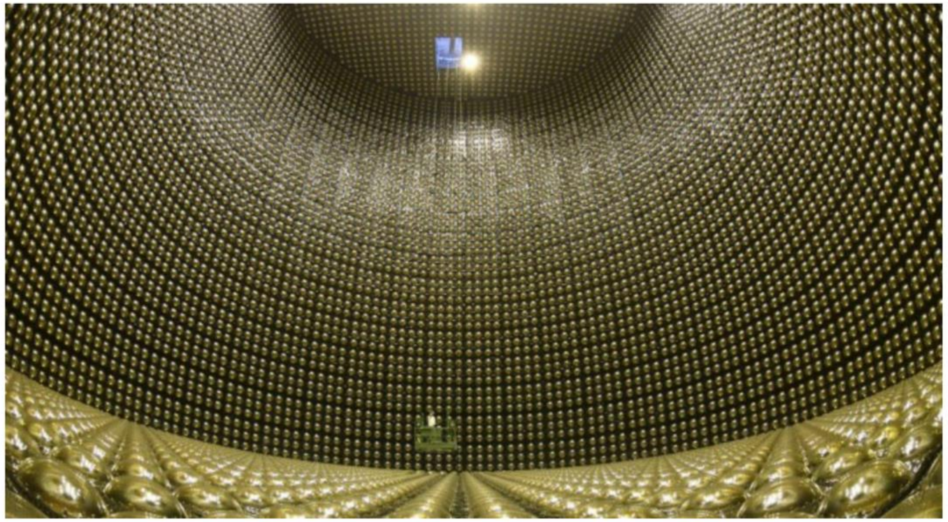




높이 93.7m 인류 최대 지하공동 굴착…日 중성미자 검출기 들어선다

2025.08.05 15:07





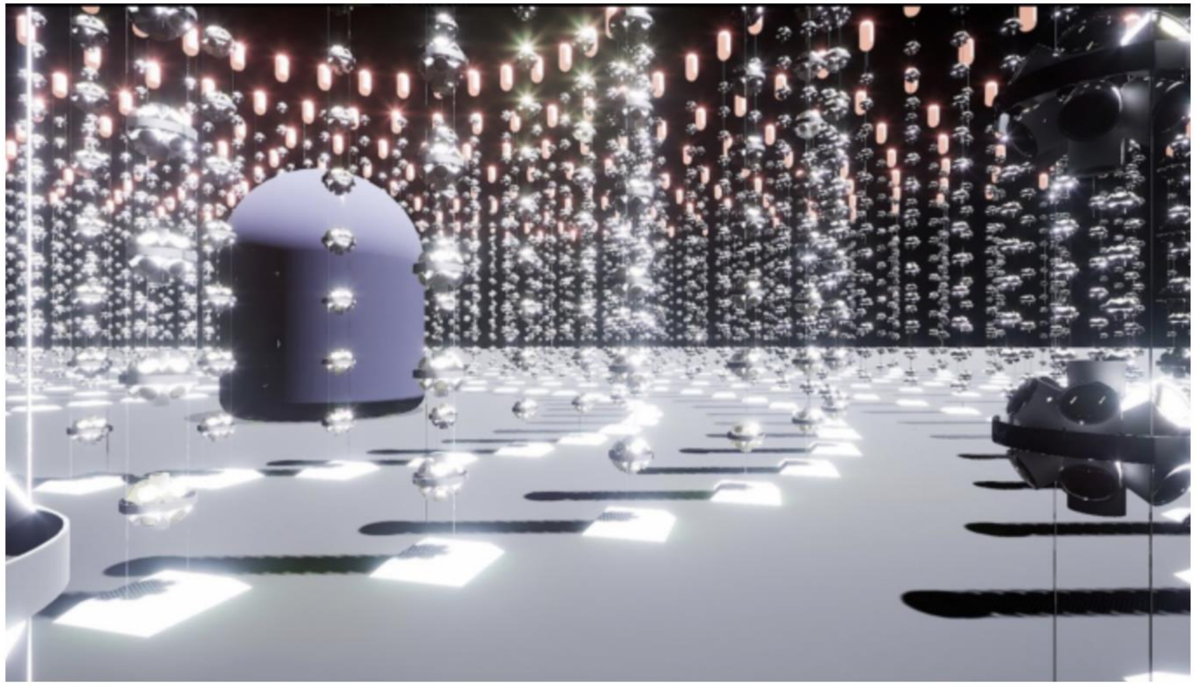
전세계에서 굴착된 주요 대형 지하공동의 단면 크기를 비교한 그림. The University of Tokyo 제공

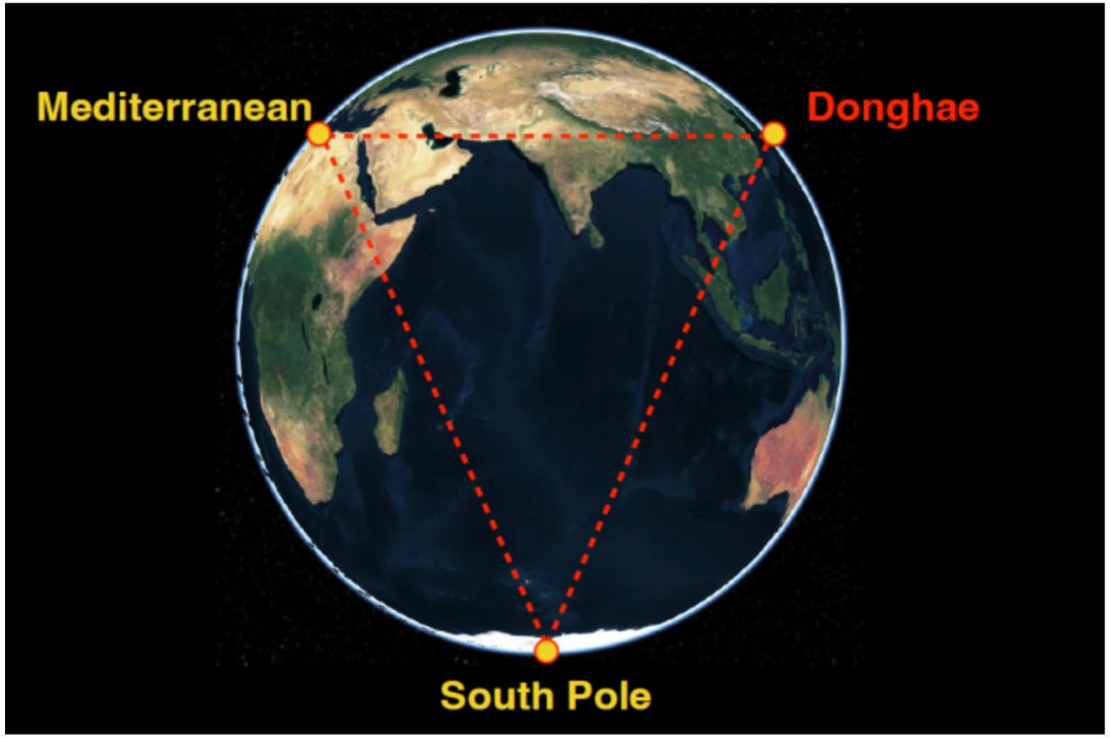
한국 연구자들도 하이퍼카미오칸데 프로젝트에 참여한다. 현재 유종희 서울대 물리천문학부 교수팀을 주축으로 전남대, 동신대, 광주과학기술원(GIST), 경북대, 성균관대, 울산과학기술원(UNIST) 등 7개 기관이 구축 과정에 참여하고 있다.

동아사이언스

"동해 심해에서 중성미자 검출하자…韓, 입자물리학 선도 기회"

2025.05.12 07:00





The Astrophysical Journal, 981:84 (9pp), 2025 March 1
https://doi.org/10.3847/1538-4357/adb41f

CrossMark

Neutrinos from Carbon-burning Red Supergiants and Their Detectability

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[2] Korea Astronomy and Space Science Institute, Daejeon 34055, Republic of Korea
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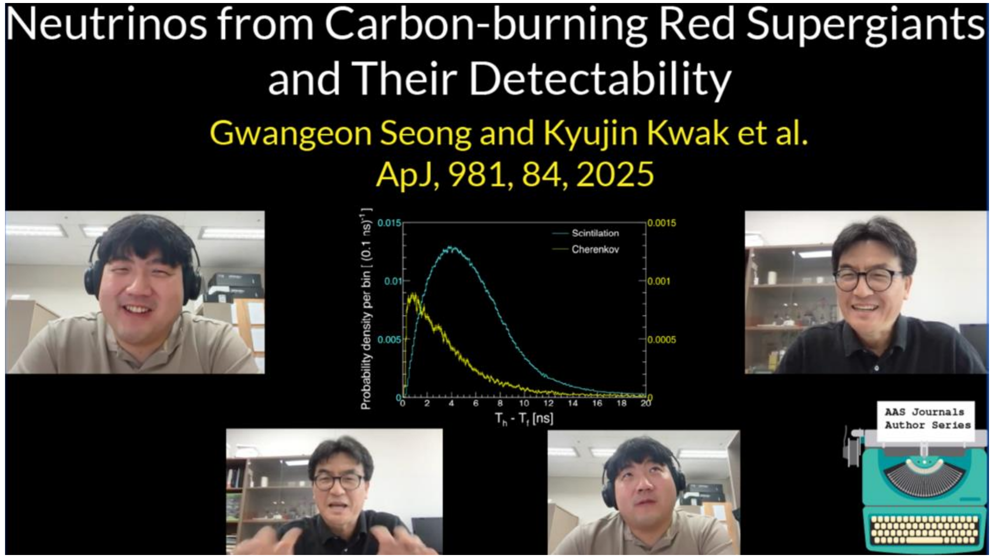
Abstract

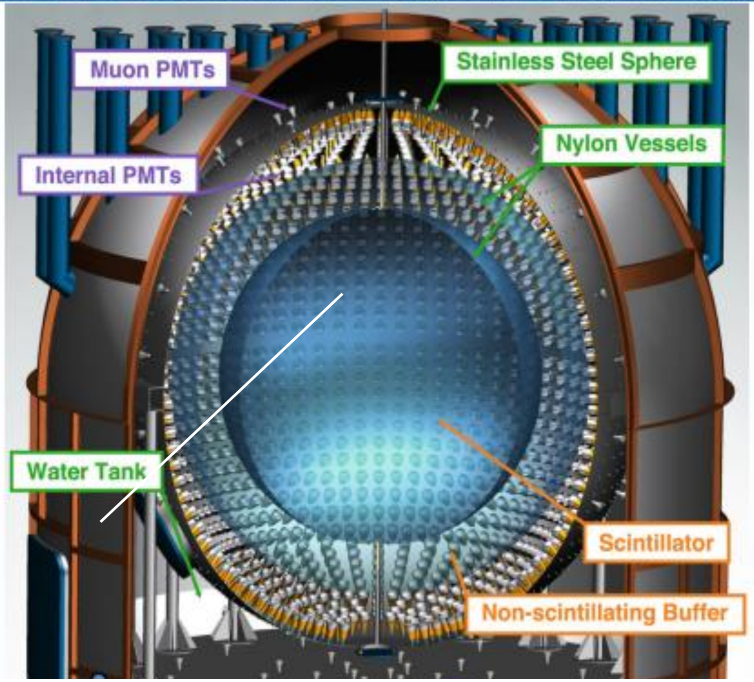
Stars emit megaelectronvolt neutrinos during their evolution via nuclear syntheses and thermal processes, and detecting them could provide insights into stellar structure beyond what is accessible through electromagnetic wave observations. So far, megaelectronvolt neutrinos have been observed from the Sun and SN 1987A. It has been suggested that pre-supernova stars in the oxygen- and silicon-burning stages would emit enough megaelectronvolt neutrinos to be detectable on Earth, provided they are in the local Universe. In this study, we investigate the prospect of detecting neutrinos from red supergiants (RSGs) in the carbon-burning phase. In our Galaxy, around a thousand RSGs have been cataloged, and several are expected to be in the carbon-burning phase. We first calculate the luminosity and energy spectrum of the neutrinos emitted during the post-main-sequence evolution of massive stars. For a nearby carbon-burning RSG located $\sim$200 pc away, we estimate the neutrino flux reaching Earth to be as large as $\sim 10^5\ \mathrm{cm^{-2}\ s^{-1}}$, with a spectrum peaking at $\sim$0.6 MeV. We then assess the feasibility of detecting these neutrinos in underground facilities, particularly in hybrid detectors equipped with a water-based liquid scintillator and ultrafast photodetectors. In detectors with a volume comparable to Super-Kamiokande, for the above flux, we anticipate up to $\sim$50 neutrino events per year with directional information. Although this is a fair number, the number of events from radioactive backgrounds would be much larger. Our results indicate that studying neutrinos from carbon-burning RSGs and predicting supernovae well in advance before their explosion would be challenging with currently available detector technologies.

Unified Astronomy Thesaurus concepts: Carbon burning (195); Neutrino astronomy (1100); Neutrino telescopes (1105); Stellar evolution (1599)

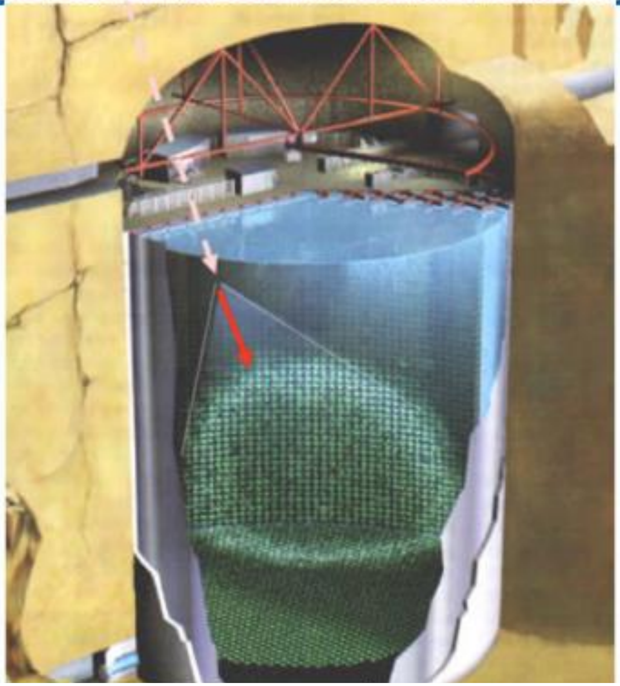


- https://youtu.be/G7y8OsUdhHM

Neutrino Detectors for ~ MeV neutrinos



Borexino



Super Kamiokande

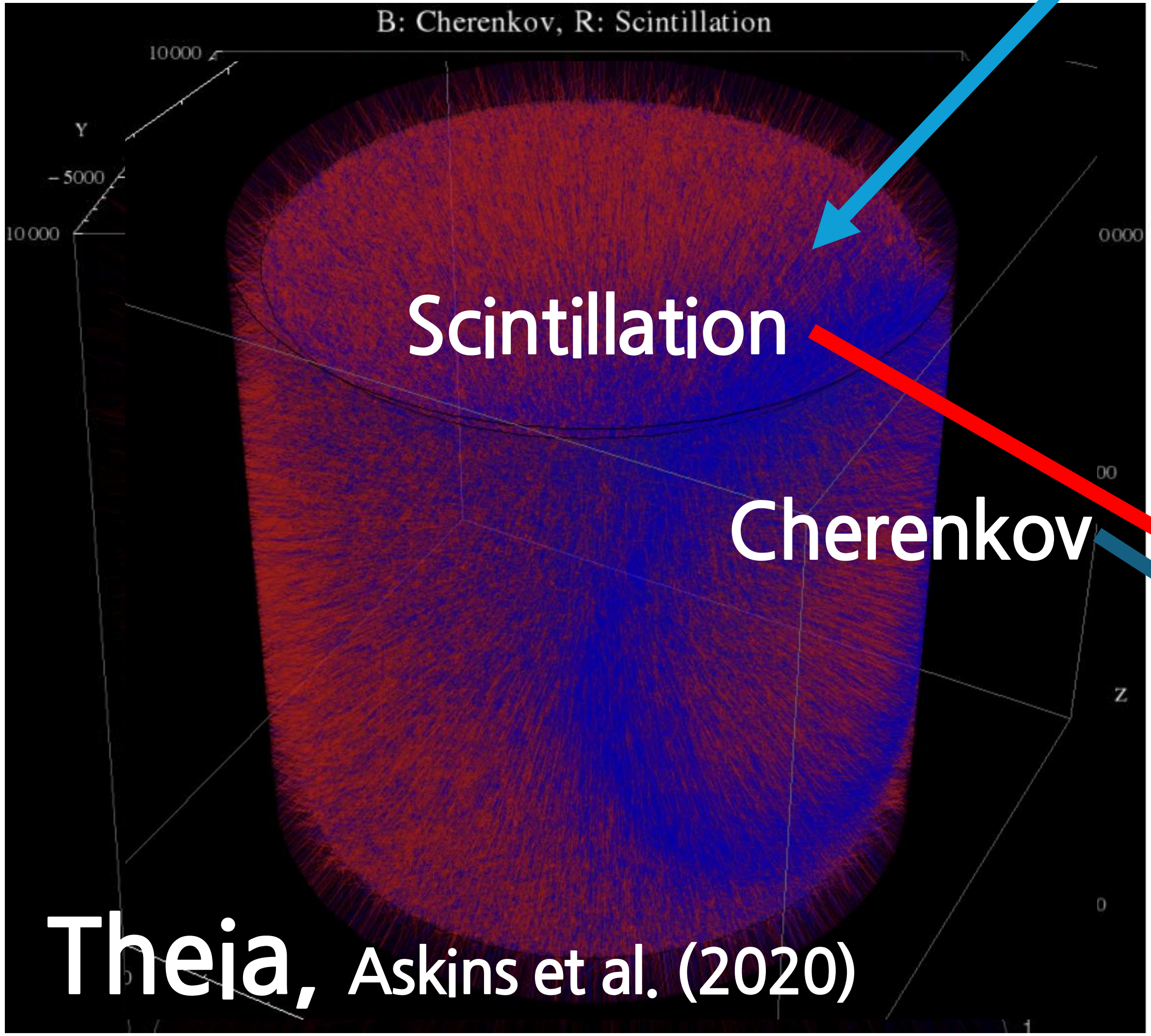
Liquid scintillator

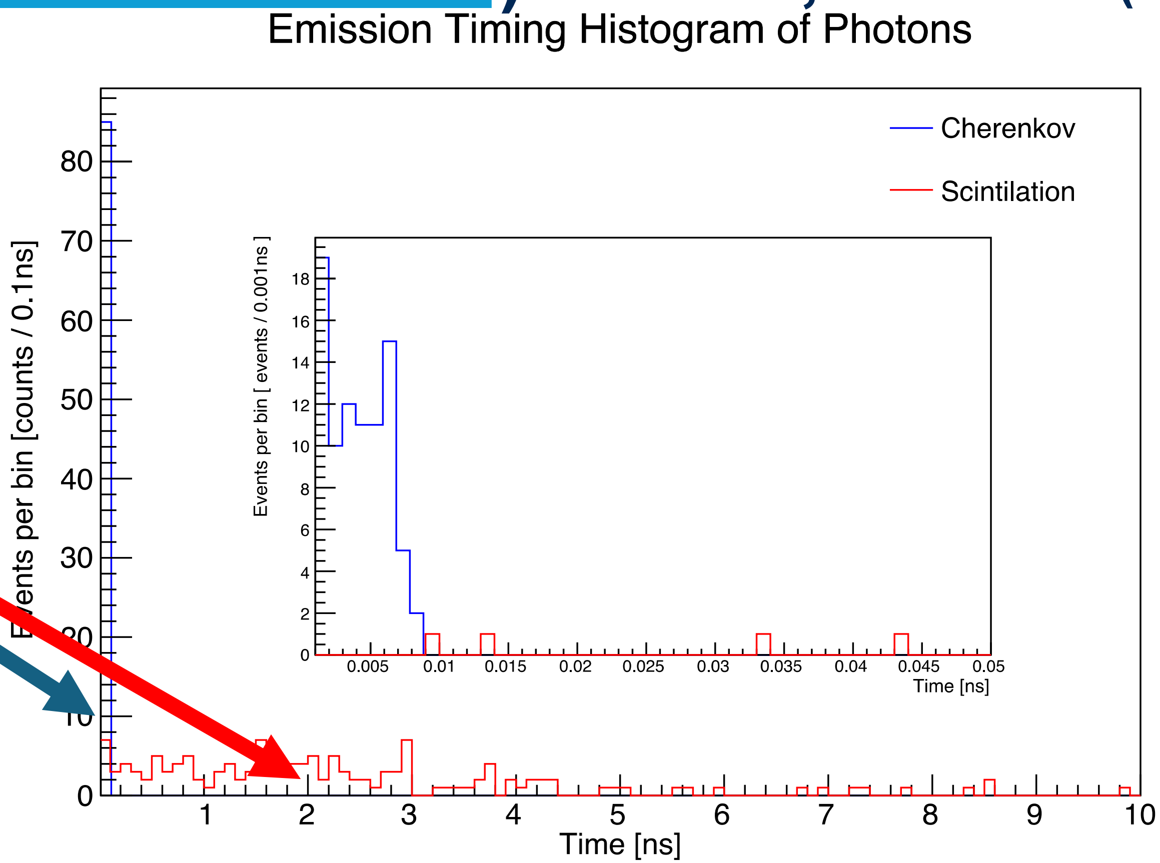
High Energy Resolution/ NO Source Direction

Cherenkov detector

Source Direction / Energy Range 3.5MeV~

Hybrid detector (Water based liquid scintillator) – Theia, Askin et al. (2020)



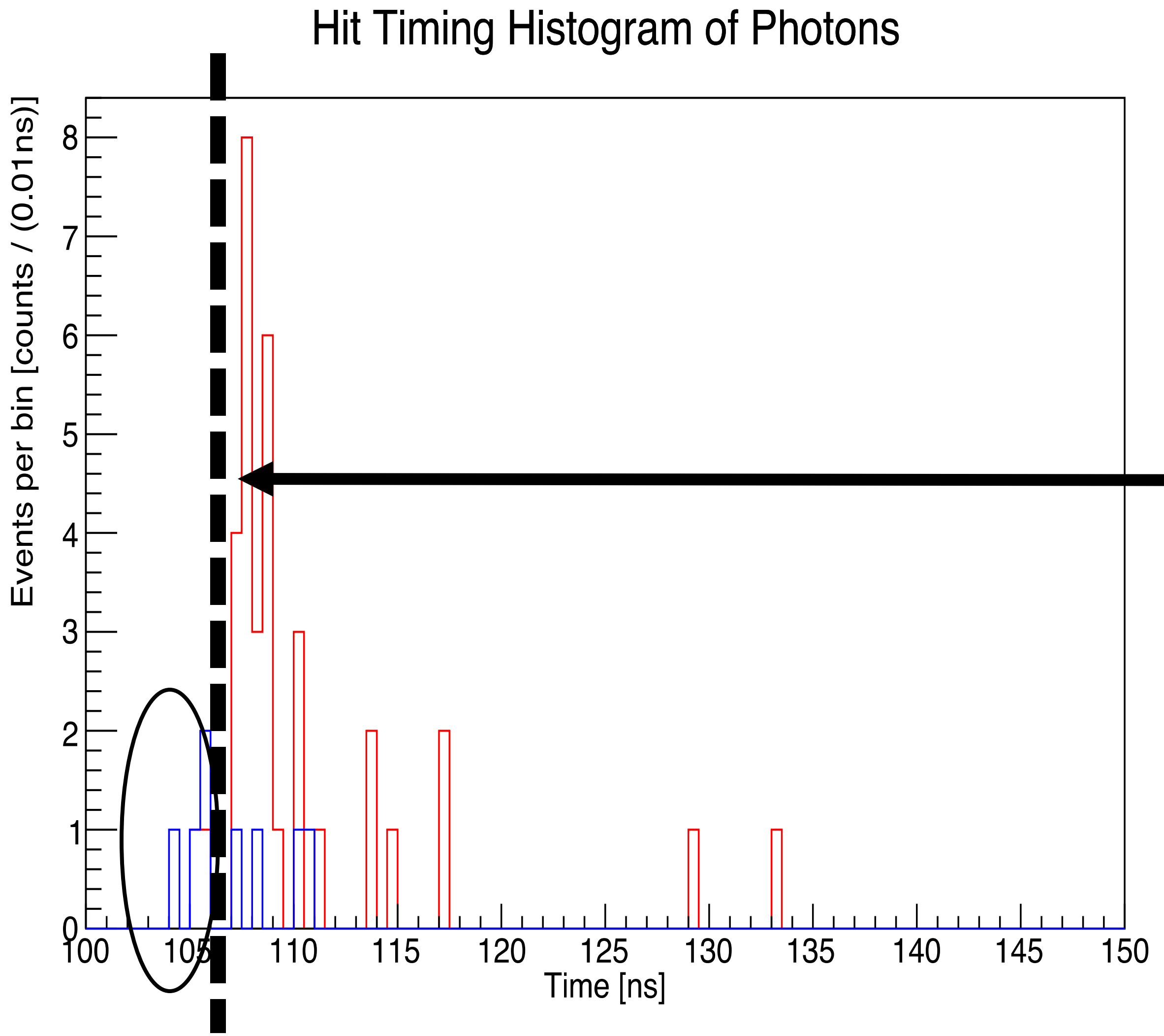


PMT → LAPPD

(Large Area Picosecond Photo-Detectors)

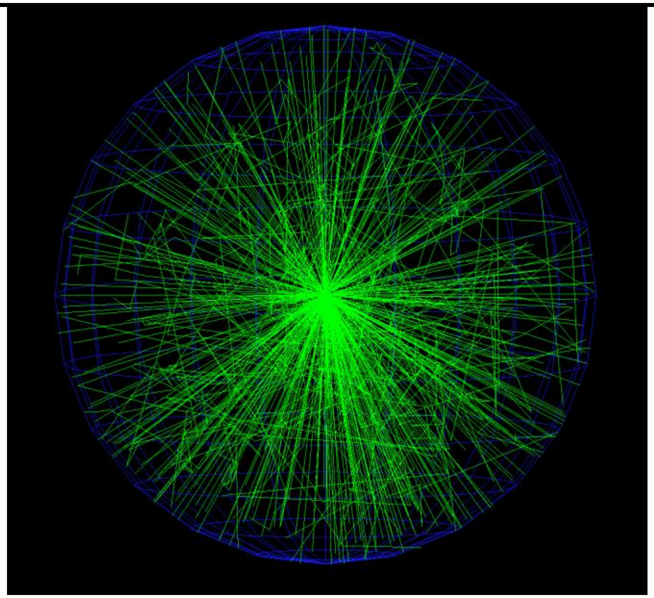
→ Time resolution ~ 100ps

Detector simulations (NuWro + Geant4)

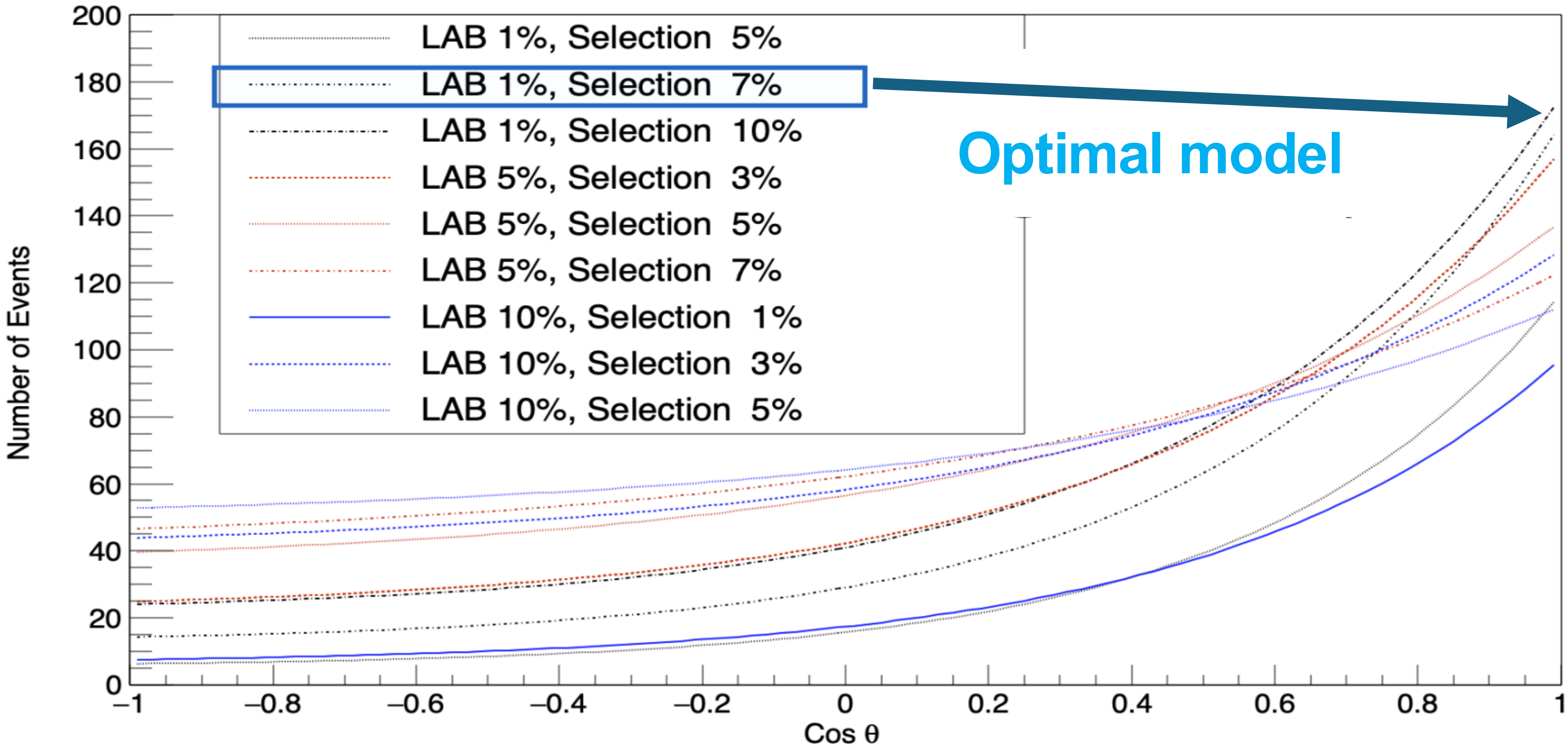


- 50kT $(r = 23\ [m])$, Sphere
- 100% LAPPD coverage

1. Water + LAB (Liquid Argon Benzene)
   1 - 10%
2. Selection-cut 1 - 10%, 7%

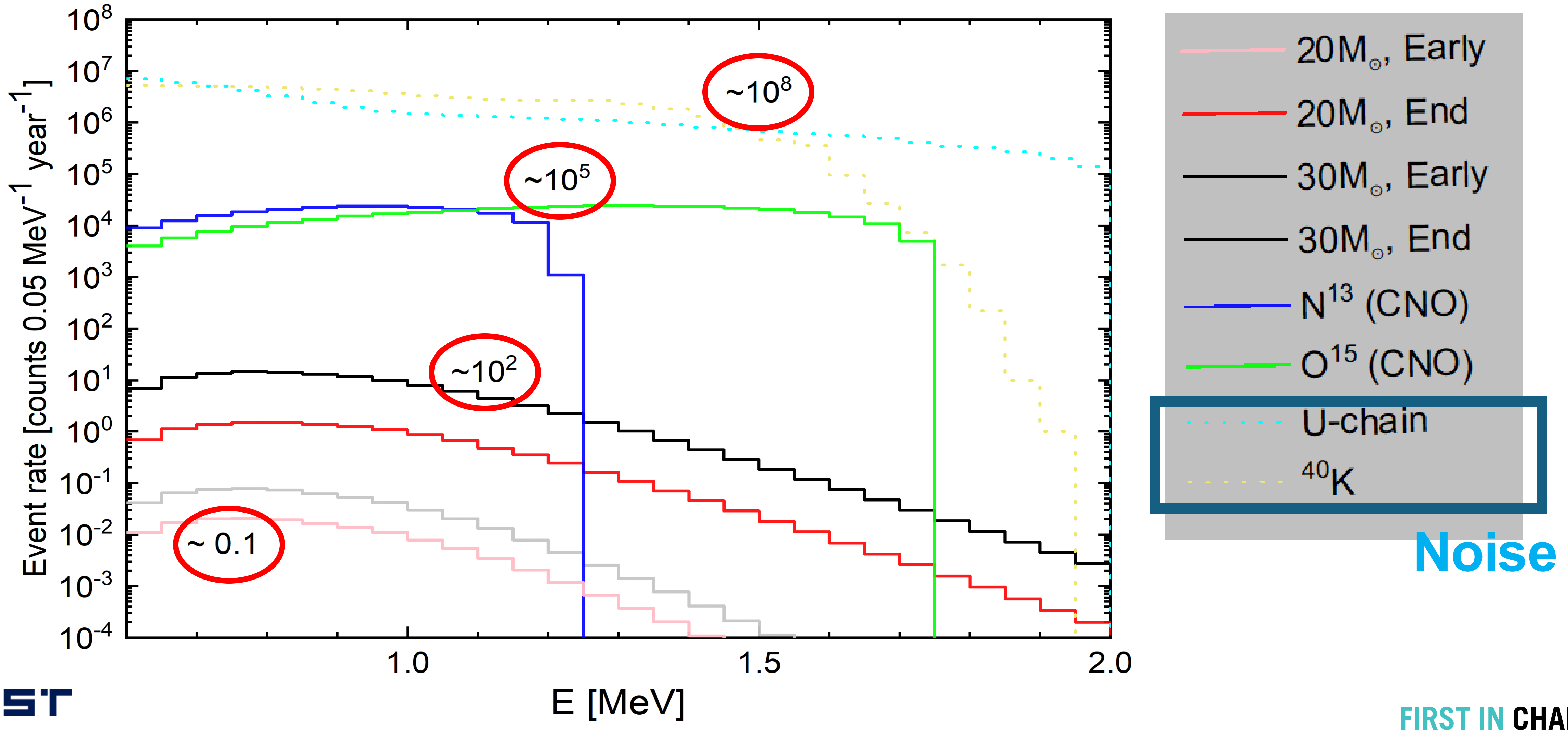


Detector performance



RSG's neutrinos (C-burn) with HD

RSG at 200 pc



Measuring CNO Neutrinos

- With KNO (Underground Water Cherenkov Detector) (?)
- Pro: Can confirm that it is "really" solar neutrino by constraining its incoming direction
- Con: Have to lower the current energy threshold and to beat the large noises of radioactive isotopes
- Suggestion: Hybrid detector
  - Can lower the energy threshold
  - Large CNO neutrino fluxes may beat the noises -> Need to estimate the size of the hybrid detector

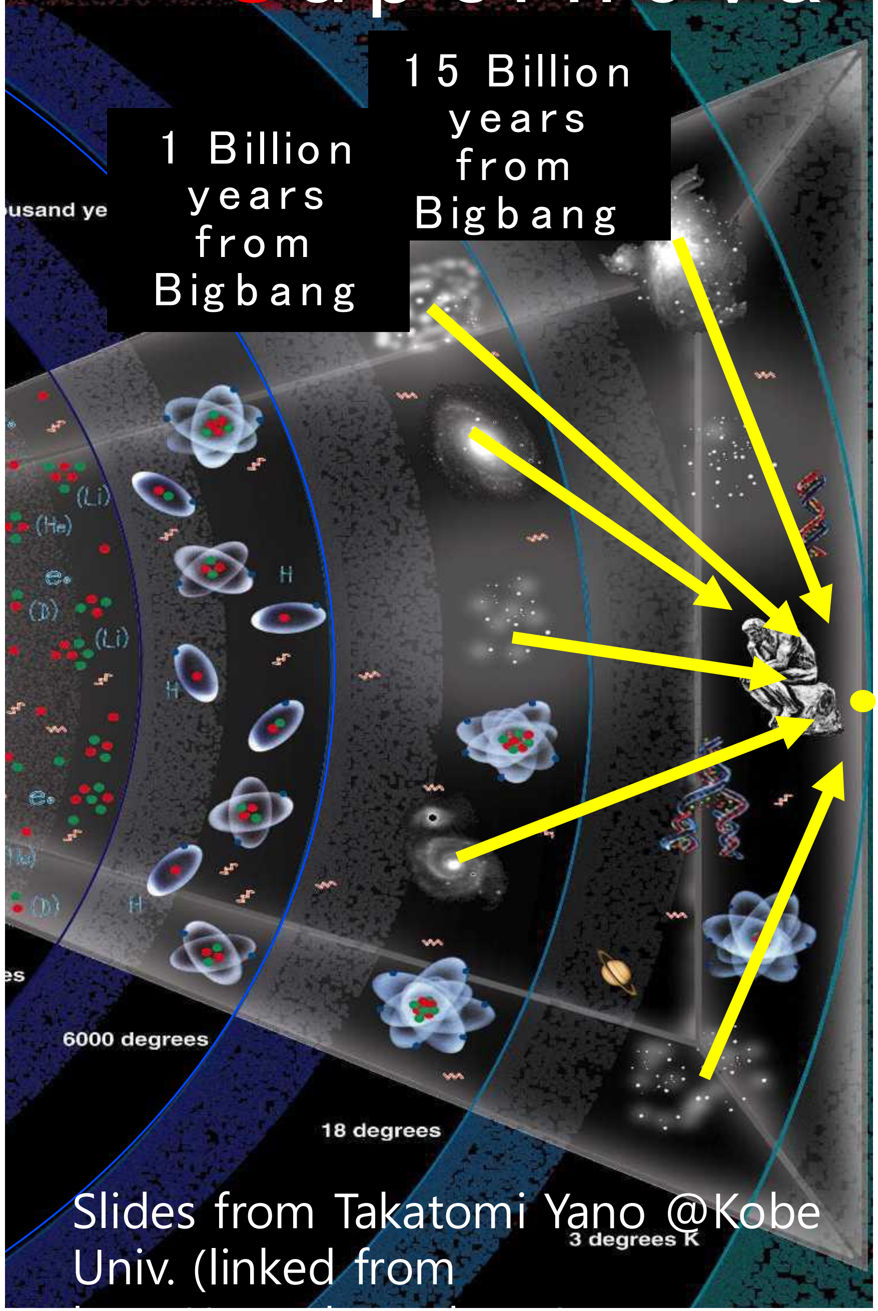
A New Suggestion for KNO

- Build a small hybrid detector next to KNO
  - Detecting all of 8B, HEP, CNO (and other solar neutrinos) simultaneously
  - A prototype detector for next generation neutrino telescopes that can detect low-energy (sub-MeV) astrophysical sources
  - The construction cost is a small fraction of the primary KNO detector

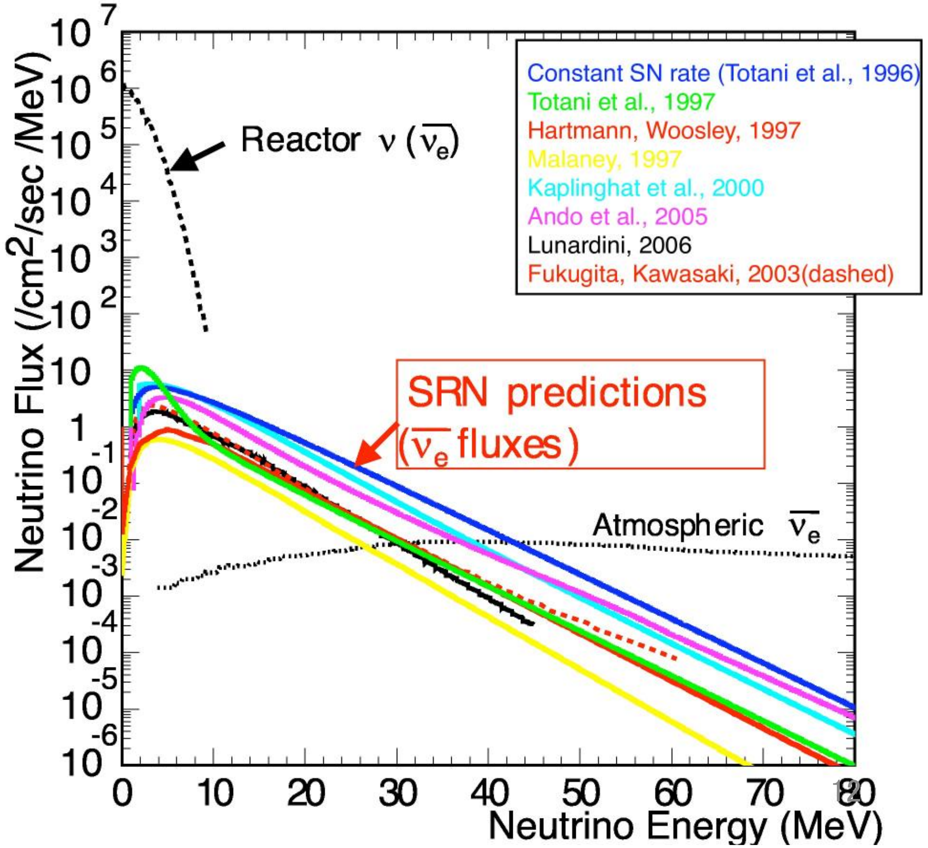
Challenges in (Low-Energy) Neutrino Astronomy in comparison with GW astronomy

- GW astronomy
  - Gravity or general relativity
  - High efficiency in energy conversion (simple)
  - Cosmological observation is possible
- Neutrino Astronomy
  - Baryonic process
  - Low efficiency in energy conversion (complicated)
  - Only local observation is possible

Supernova Relic Neutrino



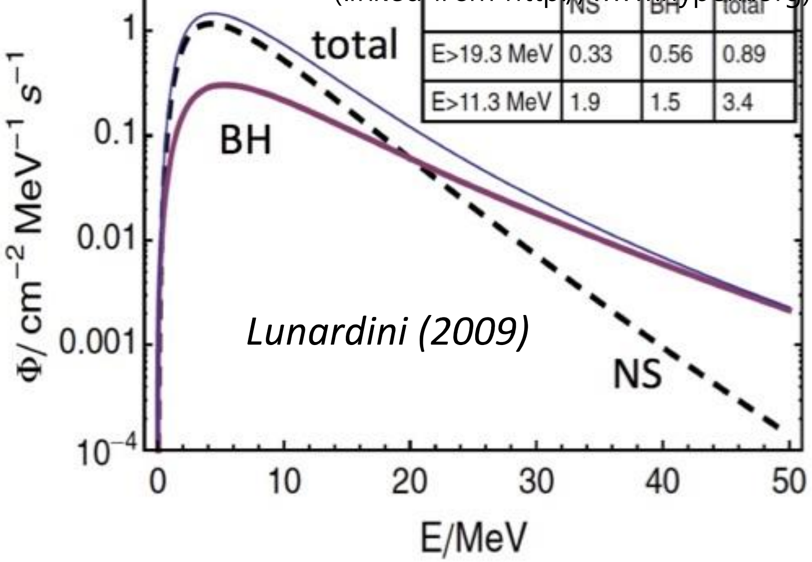
- Supernova Relic Neutrino (SRN) is diffued neutrinos coming from all past supernovae.
- Not discovered but promising source of extra-galactic neutrino.



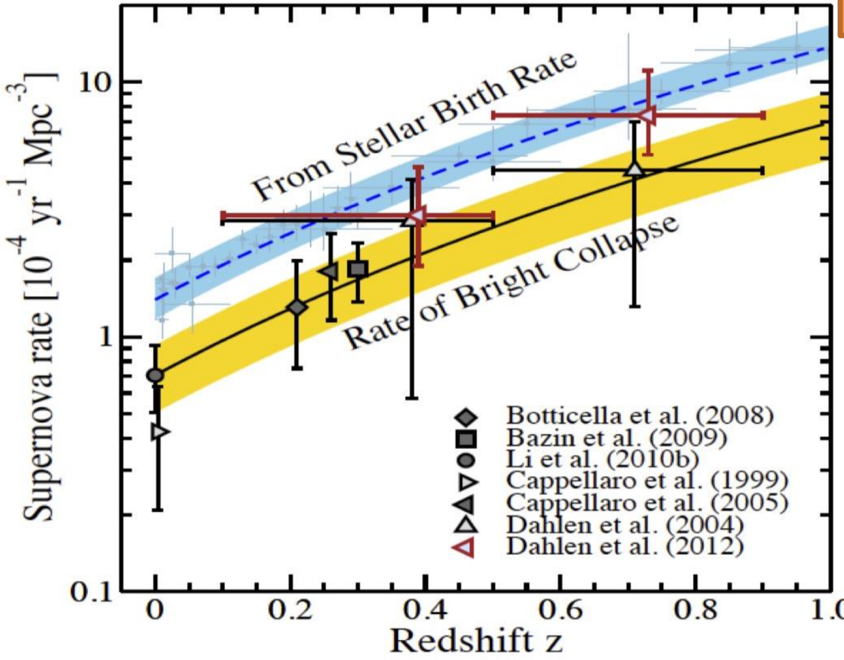
Physics of SRN

Slides from Takatomi Yano @Kobe Univ.
(linked from http://www.hyperk.org)

- Star formation rate
- Energy spectrum of supernova burst neutrinos
- Extraordinary SN (black hole, neutron star formation, dim supernova)



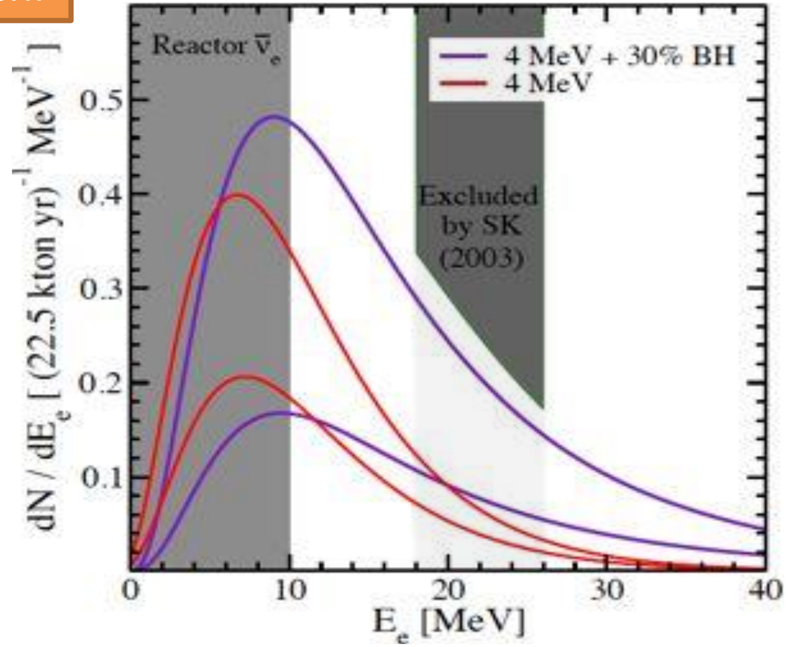
Stellar birth rate(=collapse rate)
and Bright collapse rate



Horiuchi et.al (2011) with data from Dahlen et.al (2012)

Horiuchi

Event spectra with uncertainties



Adopted from Horiuchi et al. (2009)

Deformed Neutron Star at Close Encounter in a Compact Binary

Energy Budget

- Gravitational self-energy
  - Ellipsoid
  - $U = -\frac{3}{10} GM^2 \int_0^\infty \frac{dx}{\sqrt{(A^2+x)(B^2+x)(C^2+x)}}$
  - Volume = $\frac{4\pi}{3} ABC$
  - Sphere: A=B=C=R then $U = -\frac{3}{5}\frac{GM^2}{R}$
- Energy difference due to deformation
  - A=B>C or A=B<C, but maintaining the same volume and uniform density, i.e., the same mass
  - A fraction of $\frac{GM^2}{R} \sim 10^{53}$ ergs depending on the degree of deformation

Conversion Efficiency

- Need to convert gravitational energy to neutrino emission
- May require numerical simulations which show how the gravitational energy available during deformation is converted to neutrino emission
- Neutrino emissivity is determined by conversion efficiency and energy budget
- Detectability at terrestrial detectors such as SK, HK, and KNO also depends on the energy spectra of emitted neutrinos
- So, there are MANY "ifs" at this moment

Neutrino Emission/Production Process

- Weak interaction during particle or nuclear interaction
  - URCA process: electron capture onto proton + neutron. beta decay
    - Core Collapse Supernovae
  - Nuclei-involved URCA process
    - In the crust of a neutron star
    - X-ray bursts
    - Deformed neutron star (?)

Detectability: Observable Scenario

- Close encounter of compact objects in highly eccentric orbits is possible at densely populated star clusters like globular clusters and/or at the Galactic bulge
- Direction toward a specific globular cluster (GC) and the Galactic bulge is well constrained
- Neutrino emission would be periodic
- SK accumulates the past 30-year data
- Fourier analysis of SK data toward a specific GC could detect the signal

Thank You!!