Multi-Messenger Astronomy
(다중신호 천문학)

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2025 수치상대론 및 중력파 여름학교
한국천문연구원
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Contents

- Multi-messenger astronomy (MMA) within my own perspective
- Neutrino astronomy in MMA
  - Solar neutrinos
  - Nearby massive evolved stars
  - Supernovae
  - (X-ray bursts)
  - (High energy neutrinos)
  - **Binary neutron stars in highly eccentric closed (elliptical) orbits**

Astronomy vs. Astrophysics

- Astronomy vs. Physics
- Observation vs. Theory
- Astrophysics as an interdisciplinary field of study like biophysics
- Nuclear astrophysics, astro-particle-physics, and more
- Astrochemistry, astrobiology, and beyond

Multi-Messenger Astronomy

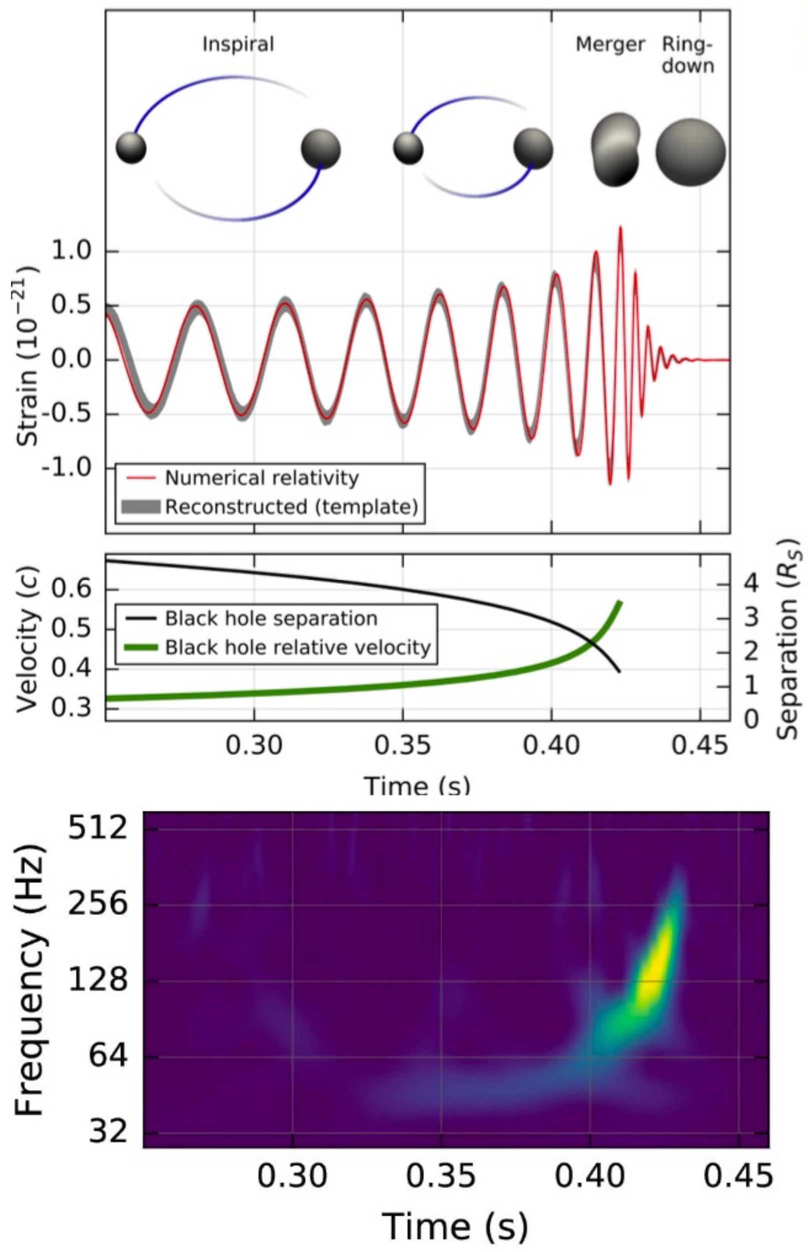
- Electromagnetic (EM) signal vs. Non-EM signal
- Multi-Messenger (MM)
  - EM (photons)
  - Gravitational wave (GW)
  - Neutrino
  - Cosmic-ray (protons and heavy nuclei)
- MMA has a long history even before the first detection of GW in 2015!

Multi-Wavelength Astronomy

- Observing (seeing) the same region of sky (target) with different telescopes (EM wave with different wavelength)
- The more, the better
- Makes the observer's life more difficult
- Sometimes opens an entirely new subject in astronomy
  - Gamma-ray burst (GRB)

A brief history of GRB

- First discovered serendipitously with gamma-ray in 1960s
- Confirmed as cosmological sources with optical detection which provided distance measurement (redshift) in 1990s
- Drove a multi-wavelength satellite mission “Swift” in 2004 which is equipped with X-ray, UV, and optical telescopes. Swift is still operating.
- Origin of GRB
  - Collapse of massive stars (collapsars)
  - Merging of binary neutron stars (related to GW sources)
    - https://en.wikipedia.org/wiki/History_of_gamma-ray_burst_research
    - https://en.wikipedia.org/wiki/Gamma-ray_burst



BINARY BLACK HOLE (BBH) MERGER

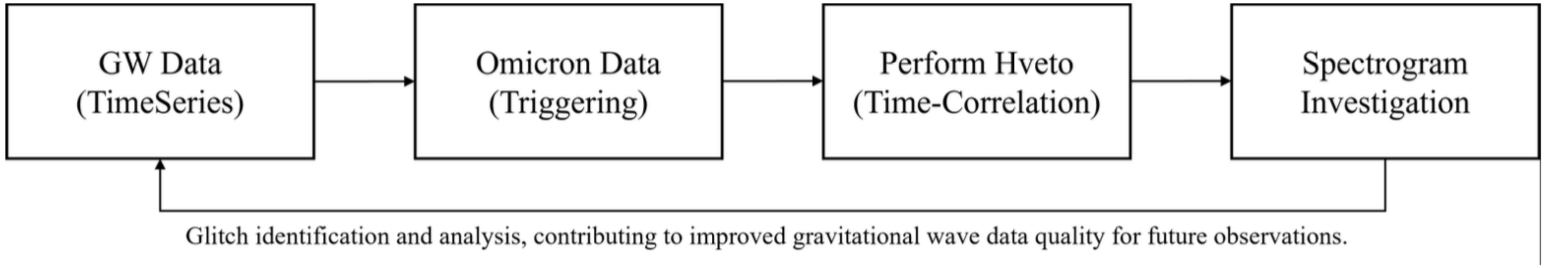
- The first case in which humans detected gravitational waves
- GW150914
  - First detected
  - 36 M_s + 29 M_s -> 62 M_s + GW (3M_s)
  - Relativity velocity increased from 0.3c to 0.6c
  - About 1.3 * 10^{10} ly
  - 0.2 sec
  - GW's spectrogram is called "chirp"

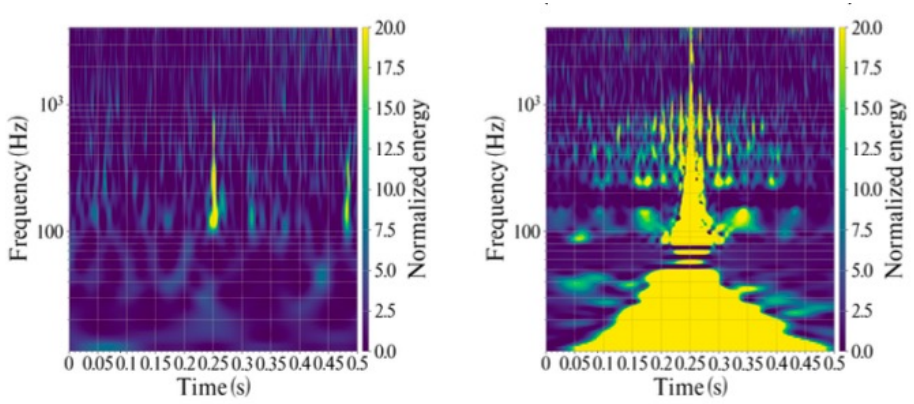
PTEP

Prog. Theor. Exp. Phys. **2015**, 00000 (32 pages)
DOI: 10.1093/ptep/0000000000

Identification of Noise-Associated Glitches in KAGRA O3GK with Hveto

T. Akutsu[1,2], M. Ando[3,4], M. Aoumi[5], A. Araya[6], Y. Aso[1,7], L. Baiotti[8], R. Bajpai[9], K. Cannon[4], A. H.-Y. Chen[10], D. Chen[11], H. Chen[12], A. Chiba[13], C. Chou[14], M. Eisenmann[1], K. Endo[13], T. Fujimori[15], S. Garg[4], D. Haba[16], S. Haino[17], R. Harada[4], H. Hayakawa[5], K. Hayama[18], S. Fujii[19], Y. Himemoto[20], N. Hirata[1], C. Hirose[21], H.-F. Hsieh[22], H.-Y. Hsieh[23], C. Hsiung[24], S.-H. Hsu[14], K. Ide[25], R. Iden[16], S. Ikeda[11], H. Imafuku[4], R. Ishikawa[25], Y. Itoh[15,26], M. Iwaya[19], H.-B. Jin[28,27], K. Jung[29], T. Kajita[30], I. Kaku[15], M. Kamiizumi[5], N. Kanda[26,15], H. Kato[13], T. Kato[19], R. Kawamoto[15], S. Kim[31], K. Kobayashi[19], K. Kohri[32,33], K. Kokeyama[34], K. Komori[4,3], A. K. H. Kong[22], T. Koyama[13], J. Kume[35,36,4], S. Kuroyanagi[37,38], S. Kuwahara[4], K. Kwak[29], S. Kwon[4], H. W. Lee[39], R. Lee[12], S. Lee[40], K. L. Li[41], L. C.-C. Lin[41], E. T. Lin[22], Y.-C. Lin[22], G. C. Liu[24],





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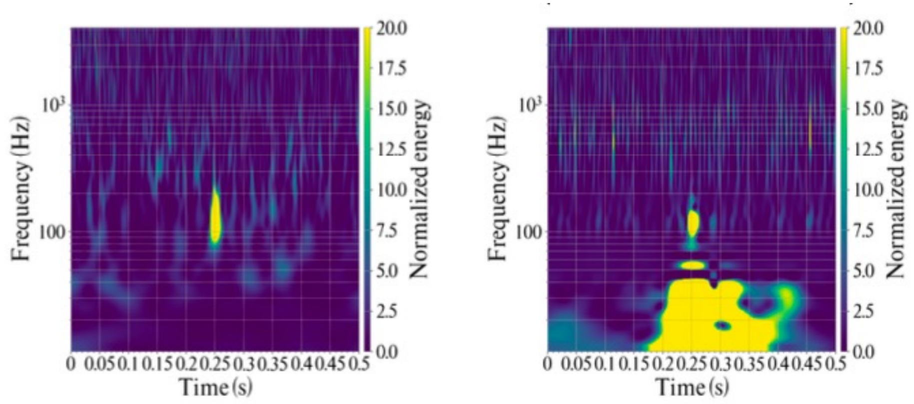

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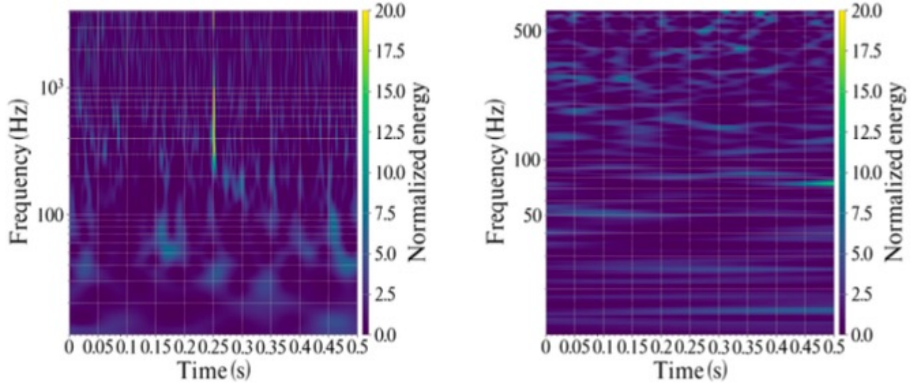
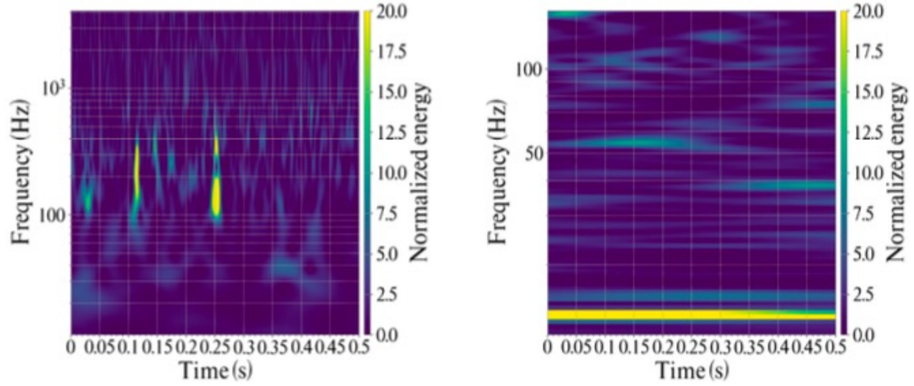


K1:PEM-MIC_SR_BOOTH_SR_Z_OUT_DQ

Apr 16, 2020 04:44:25 UTC (GPS: 1271047483)



K1:PEM-SEIS_IXV_GND_EW_IN1_DQ

Apr 07, 2020 20:45:57 UTC (GPS: 1270327575)

Draft version May 20, 2025
Typeset using LaTeX **twocolumn** style in AASTeX631

Analysis of LIGO gravitational wave data using AI*

Woojin Lee[1] and Kyujin Kwak[1]

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Submitted to The Astrophysical Journal

ABSTRACT

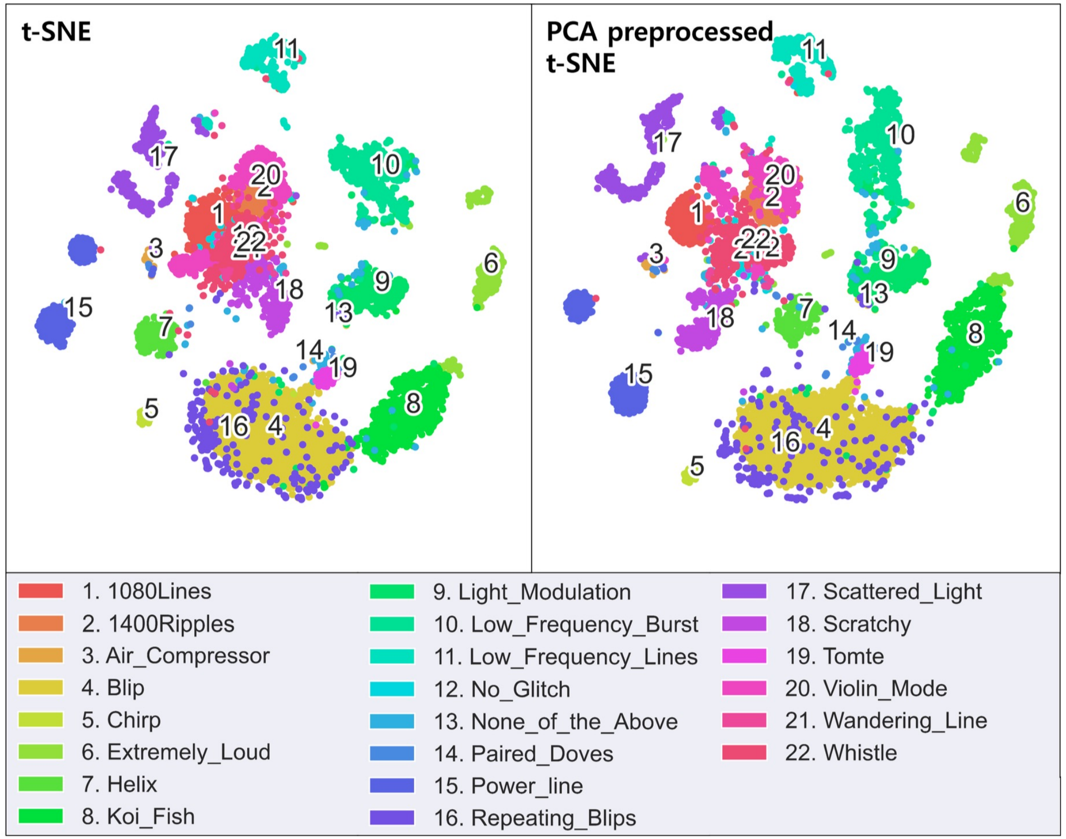
After the first detection of gravitational waves by LIGO in 2015, a substantial amount of data have been collected. While LIGO detects gravitational waves using laser interferometers, the system is affected by various types of noise, known as glitches. To analyze gravitational wave data and improve data characterization performance, these glitches need to be classified. For labeled datasets, supervised machine learning algorithms are typically used, whereas for unlabeled datasets, unsupervised machine learning algorithms such as t-SNE and UMAP are applied. Our study demonstrated that applying PCA pre-processing to t-SNE datasets improved classification performance.

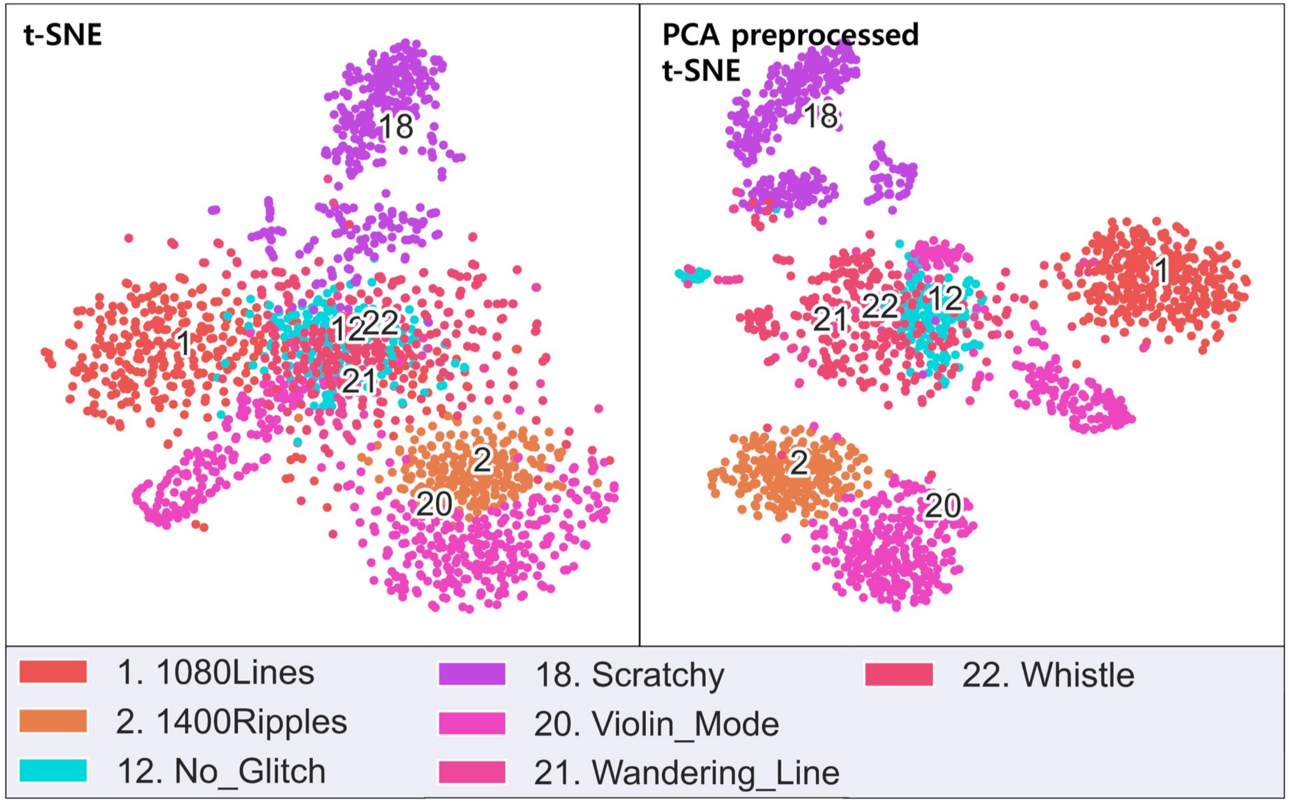
Keywords: Gravitational Wave (251) — Multi-messenger astronomy(1736) — Unsupervised machine learning(1868) — t-SNE(804)

1	***1080Lines*** (1312)
2	*1400Ripples* (928)
3	Air_Compressor (232)
4	**Blip** (7476)
5	**Chirp** (264)
6	**Extremely_Loud** (1816)
7	**Helix** (1116)
8	**Kor_Fish** (3320)
9	Light_Modulation (2292)
10	Low_Frequency_Burst (2628)
11	**Low_Frequency_Lines** (1812)
12	*No_Glitch* (724)
13	None_of_the_Above (352)
14	**Paired_Doves** (108)
15	**Power_line** (1812)
16	**Repeating_Blips** (1140)
17	Scattered_Light (1836)
18	***Scratchy*** (1416)
19	Tomte (464)
20	*Violin_Mode* (1888)
21	***Wandering_Line*** (176)
22	*Whistle* (1220)

Table 1. Names and number of data of each 22 types of glitch classes. Vertical and Horizontal 12 types of glitch classes are in bold, Center clustered glitch classes are in italic text.

Applying Unsupervised Algorithm





- t-SNE (t-distributed stochastic neighbor embedding)
- PCA (Principal Component Analysis)

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!!

중성미자란? (中性微子, neutrino 뉴트리노)

별칭: 유령 입자 혹은 수수께끼 입자

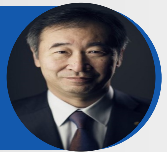
존재 예측: 1930년 볼프강 파울리 (1945년 노벨상 수상자)

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

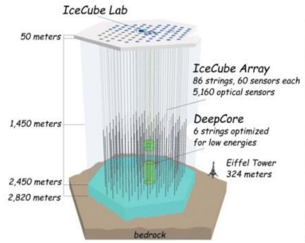
중성미자 "물리학"과 "천문학"

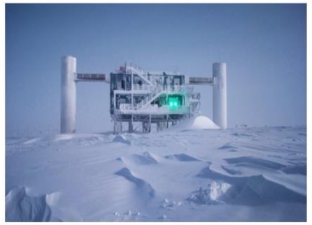
- ✓ 중성미자의 무게(질량)는 얼마일까?
- ✓ 중성미자의 종류는 몇 가지일까?
- ✓ 중성미자의 무게와 종류 사이에는 어떤 관계가 있을까?
- ✓ 중성미자의 반입자는 자기 자신일까?

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

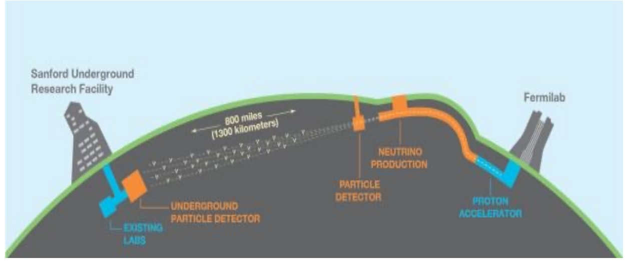
해외 중성미자 관측 시설

ICECUBE 남극 얼음 이용

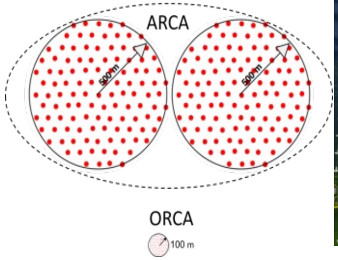


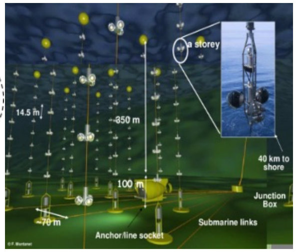


DUNE 지하액체아르곤탱크

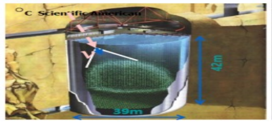


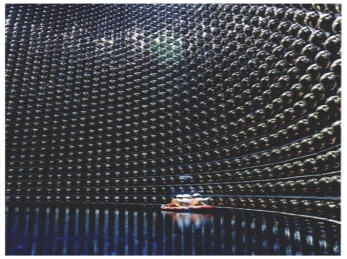
KM3NET 지중해 물이용





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 '수퍼 가미오칸데'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)

중력파 망원경

카그라 (2012년, 초기 건설비용 1500억원 규모)

도야마 대학교

관련 연구시설 및 박물관

도야마시

인구 약 40만

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

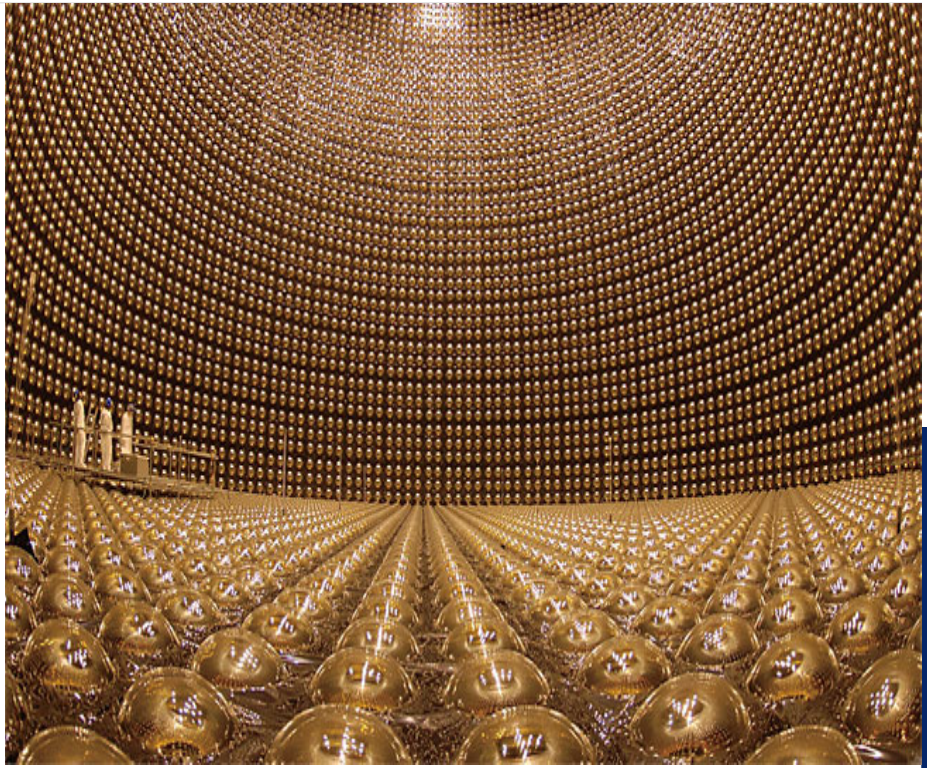
한국 중성미자 관측소 개요

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

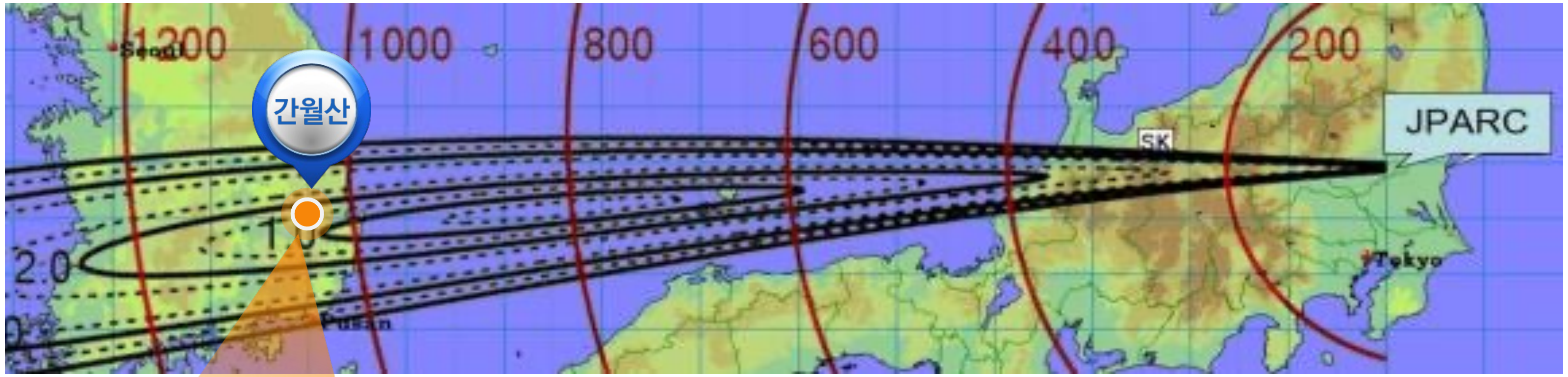


KNO 중성미자 검출기 내부 예상도

한국 중성미자 관측소 개요

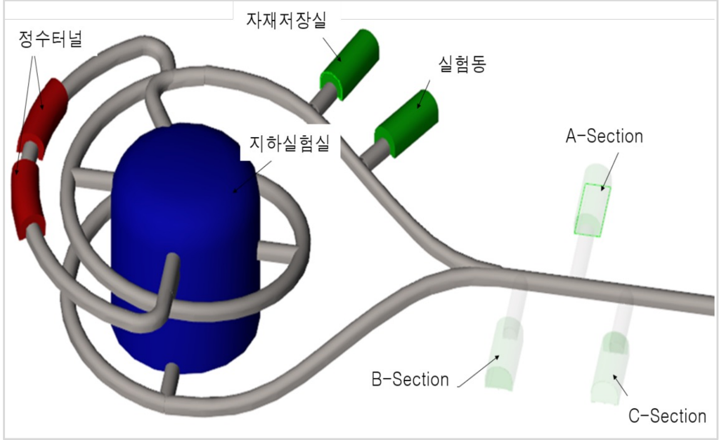
KNO 울산 입지 필요성

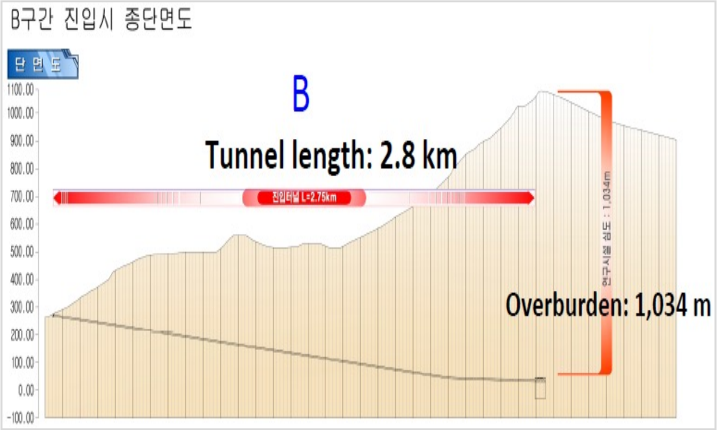
간월산



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

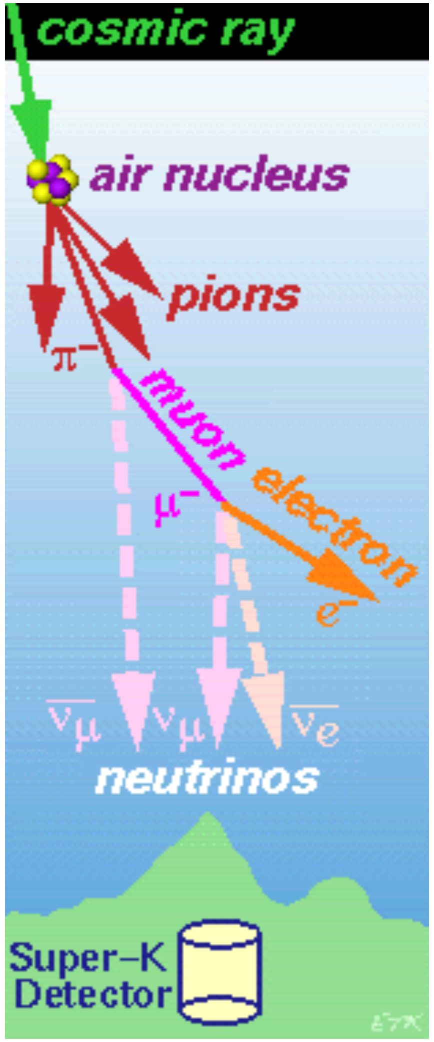
KNO 지하시설





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)

Solar Neutrino

Kyujin Kwak (UNIST)

International Forum on Korea Neutrino Observatory

December 21, 2023

Seoul National University

Contents

- Brief History of Solar Neutrino Detection
- Current Issues of Solar Neutrino
  - Solar Abundance (Metallicity) Problem
  - Detection of undetected solar neutrino (or Precise detection of solar neutrino)
- Solar Neutrino in the KNO Era
- Summary and Prospect

Reference

Annu. Rev. Nucl. Part. Sci. 2021. 71:491–528

Annual Review of Nuclear and Particle Science

The Future of Solar Neutrinos

Gabriel D. Orebi Gann,[1,2] Kai Zuber,[3] Daniel Bemmerer,[4] and Aldo Serenelli[5,6,7]

[1]Department of Physics, University of California, Berkeley, Berkeley, California 94720, USA; email: gabrielog@berkeley.edu

[2]Nuclear Science Division, Lawrence Berkeley National Laboratory, Berkeley, California 94549, USA

[3]Institute for Nuclear and Particle Physics, Technische Universität Dresden, 01069 Dresden, Germany

[4]Nuclear Physics Division, Helmholtz-Zentrum Dresden-Rossendorf, 01328 Dresden, Germany

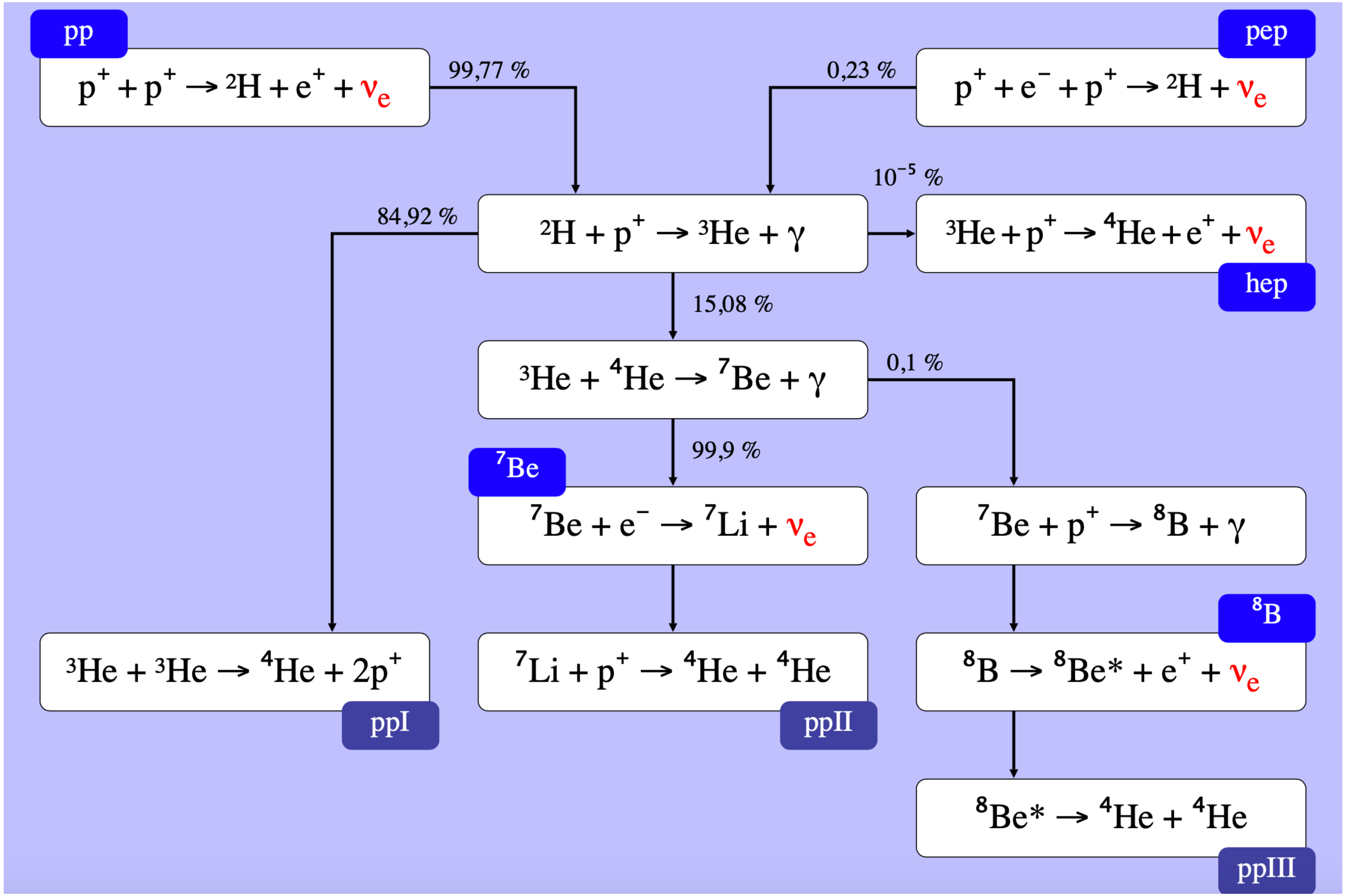
[5]Institute of Space Sciences (ICE-CSIC), 08193 Barcelona, Spain

[6]Institut d'Estudis Espacials de Catalunya (IEEC), 08034 Barcelona, Spain

[7]Max Planck Institute for Astronomy, 69117 Heidelberg, Germany

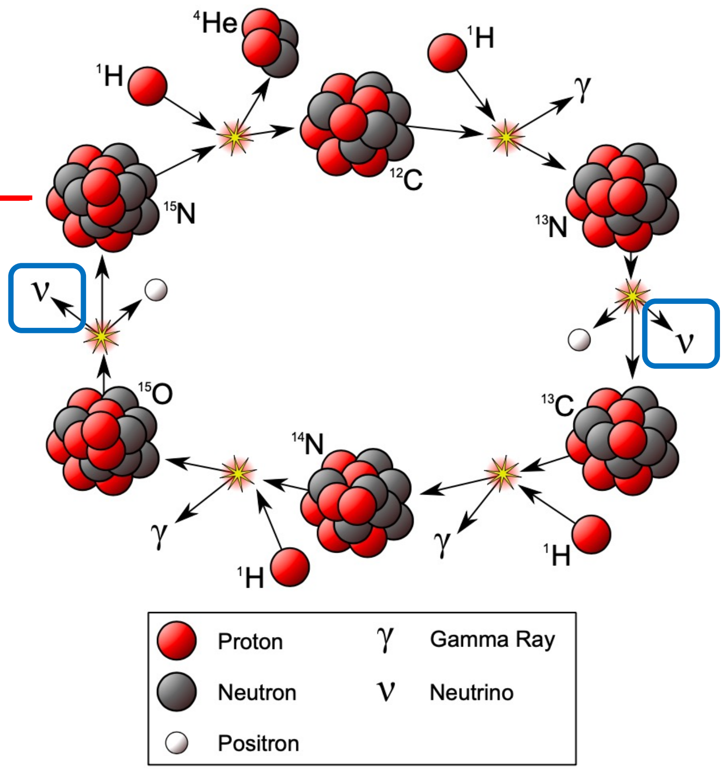
Contents

Proton-Proton (PP) Chain



CNO Cycle

CNO-I Cycle



CNO-II

$$^{15}_{7}N + ^{1}_{1}H \rightarrow ^{16}_{8}O + \gamma \quad + 12.13\ MeV$$

$$^{16}_{8}O + ^{1}_{1}H \rightarrow ^{17}_{9}F + \gamma \quad + 0.60\ MeV$$

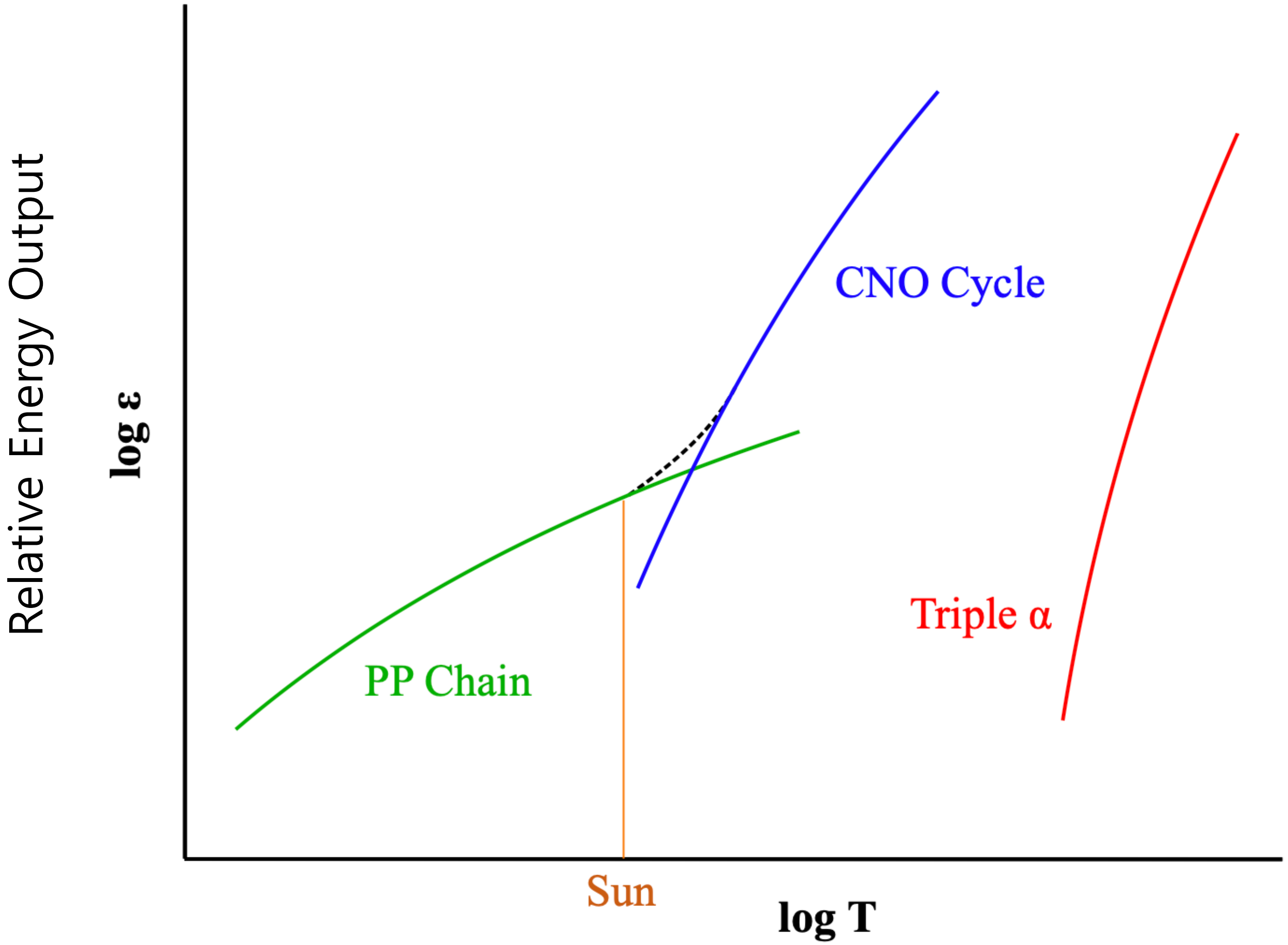
$$^{17}_{9}F \rightarrow ^{17}_{8}O + e^{+} + \nu_e + 2.76\ MeV$$ (half-life of 64.49 seconds)

$$^{17}_{8}O + ^{1}_{1}H \rightarrow ^{14}_{7}N + ^{4}_{2}He \quad + 1.19\ MeV$$

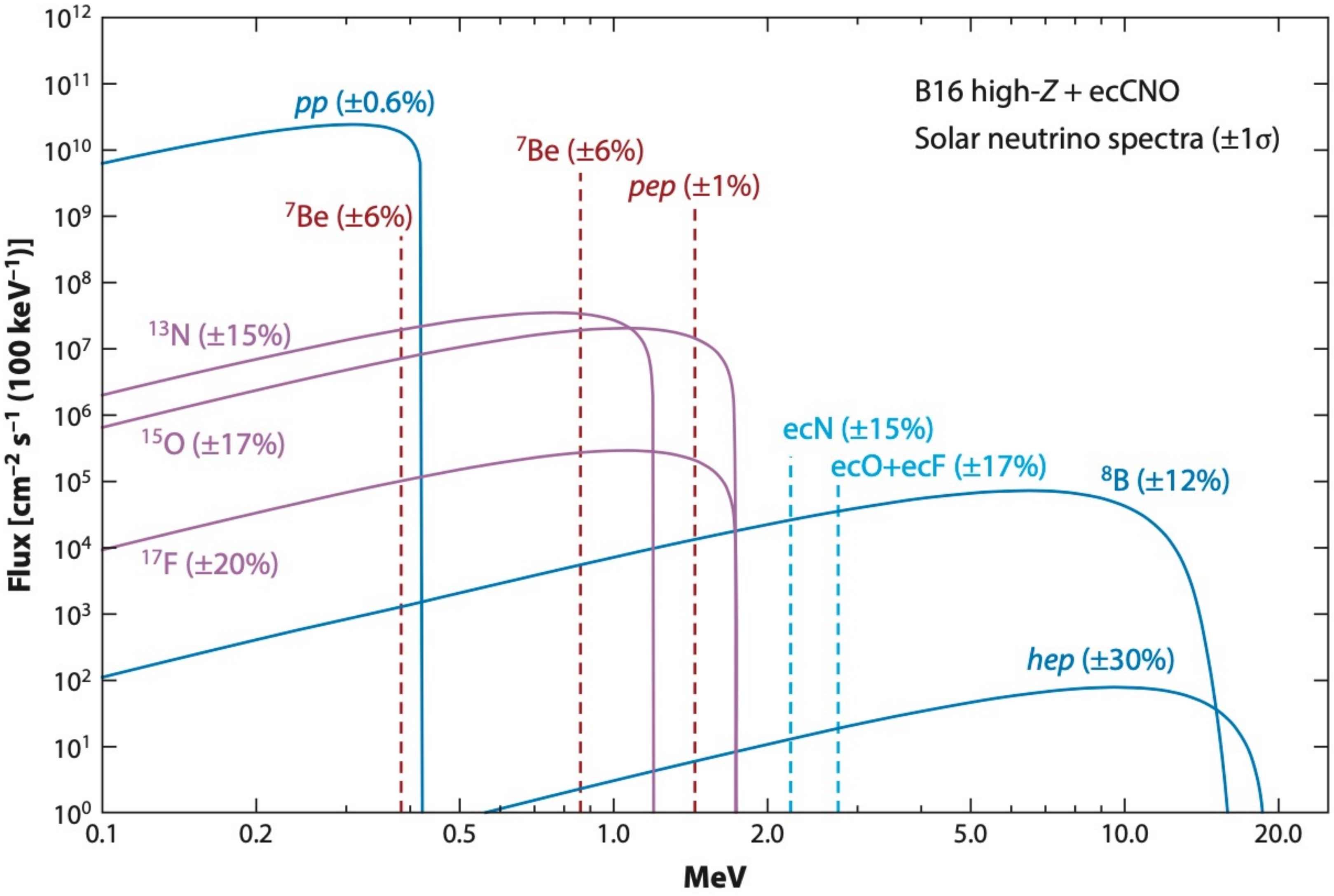
$$^{14}_{7}N + ^{1}_{1}H \rightarrow ^{15}_{8}O + \gamma \quad + 7.35\ MeV$$

$$^{15}_{8}O \rightarrow ^{15}_{7}N + e^{+} + \nu_e + 2.75\ MeV$$ (half-life of 122.24 seconds)

PP vs. CNO inside the Sun

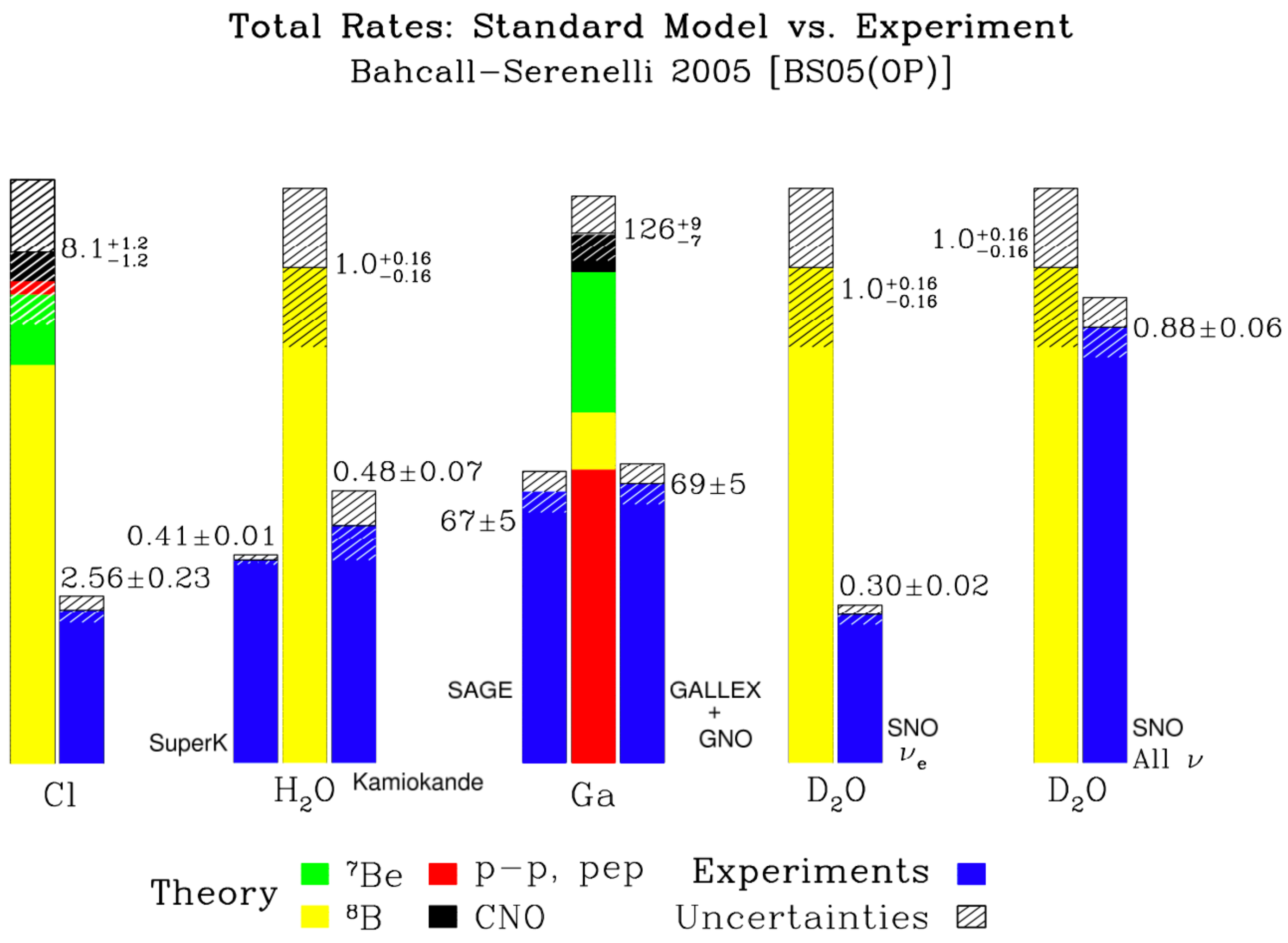


Solar Neutrino Flux in SSM



Solar Neutrino Problem

- Discrepancy between prediction from the standard solar model and experimental measurement for solar neutrinos
- Resolved by the neutrino oscillation, e.g., MSW effect
- Neutrino oscillation in a nutshell
  - Neutrino has mass.
  - Mass eigenstate is different from flavor (e.g., electron, muon, tau neutrinos observed) eigenstate.
  - Flavor eigenstate changes over time, i.e., oscillates because it is a combination of mass eigenstates.



Neutrino Experiments/Observatories

- Radiochemical: (ex) HOMESTAKE–CHLORINE: C_2Cl_4 (615 tons) a.k.a. dry-cleaning fluid
  - Count the number of transformed ^{37}Ar in $\nu_e + {}^{37}\mathrm{Cl} \longrightarrow {}^{37}\mathrm{Ar} + e^-$
  - Sensitive to electron neutrinos only
  - Reaction threshold: 814 keV
  - **SAGE:** reaction threshold of 233.2 keV in $\nu_e + {}^{71}\mathrm{Ga} \rightarrow {}^{71}\mathrm{Ge} + e^-$
- Cherenkov: (ex) Sudbury Neutrino Observatory (SNO): D_2O (heavy water)
  - Can detect all types of neutrinos with reaction threshold of 3.5 MeV

$$\nu_e + {}^2\mathrm{D} \rightarrow 2p + e^-$$
$$\nu_x + {}^2\mathrm{D} \rightarrow \nu_x + n + p$$
$$\nu_e + e^- \rightarrow \nu_e + e^-$$

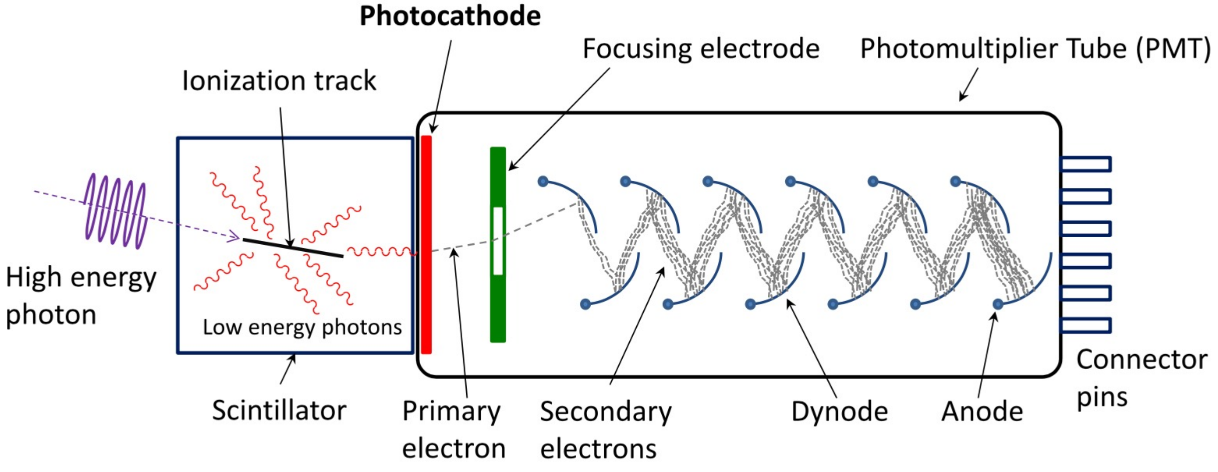
- Charged Current: electrons detected
- Neutral Current: neutrons captured, gamma-ray emitted, electrons accelerated and detected via Cherenkov radiation
- Electron Scattering: electrons detected via Cherenkov radiation

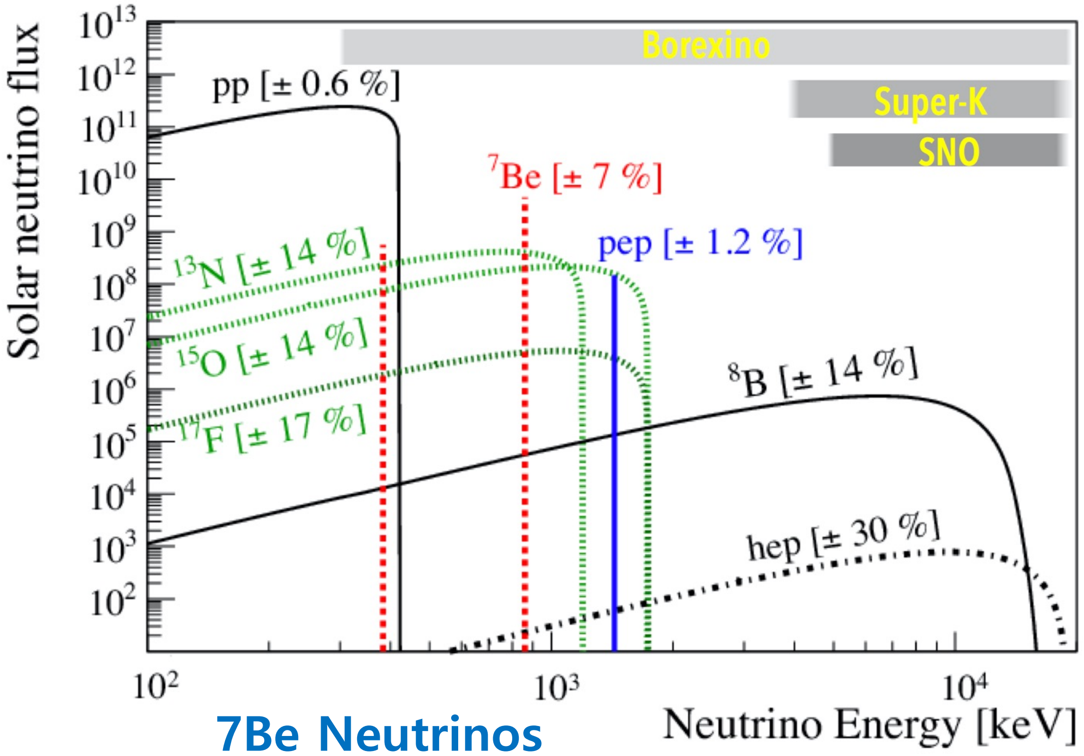
  - **Super-K:** larger volume of H_2O with reaction threshold of about 4 MeV

Neutrino Experiments/Observatories

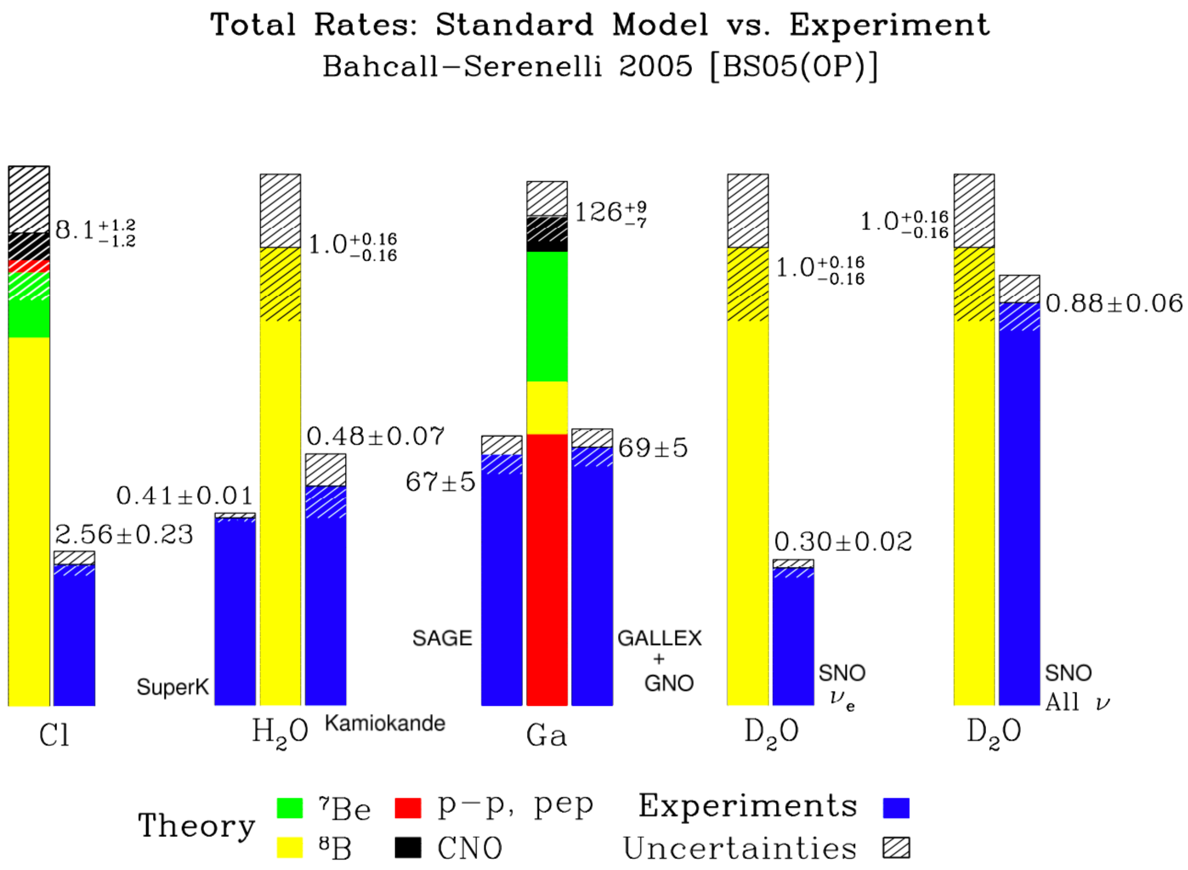
- Scintillation: (ex) Borexino, BOREX (BORon solar neutrino EXperiment)
  - Transparent (water-like) liquid as scintillators
  - Photons are produced via Cherenkov radiation in the elastic scattering of electron neutrinos
  - Reaction threshold: 250–665 keV. Optimal for ^{7}Be neutrinos
  - Originally designed with trimethyl borate (containing Boron) but replaced with PC (1,2,4-trimethylbenzene) + PPO (2,5-Diphenyloxazole)
  - **DUNE**: uses liquid argon for scintillating material
    - Gamma-ray from electron-positron annihilation in $\bar{\nu}_e + p \rightarrow e^+ + n$
- Wiki page for more information
  - https://en.wikipedia.org/wiki/List_of_neutrino_experiments#endnote_Sensitivity

scintillation



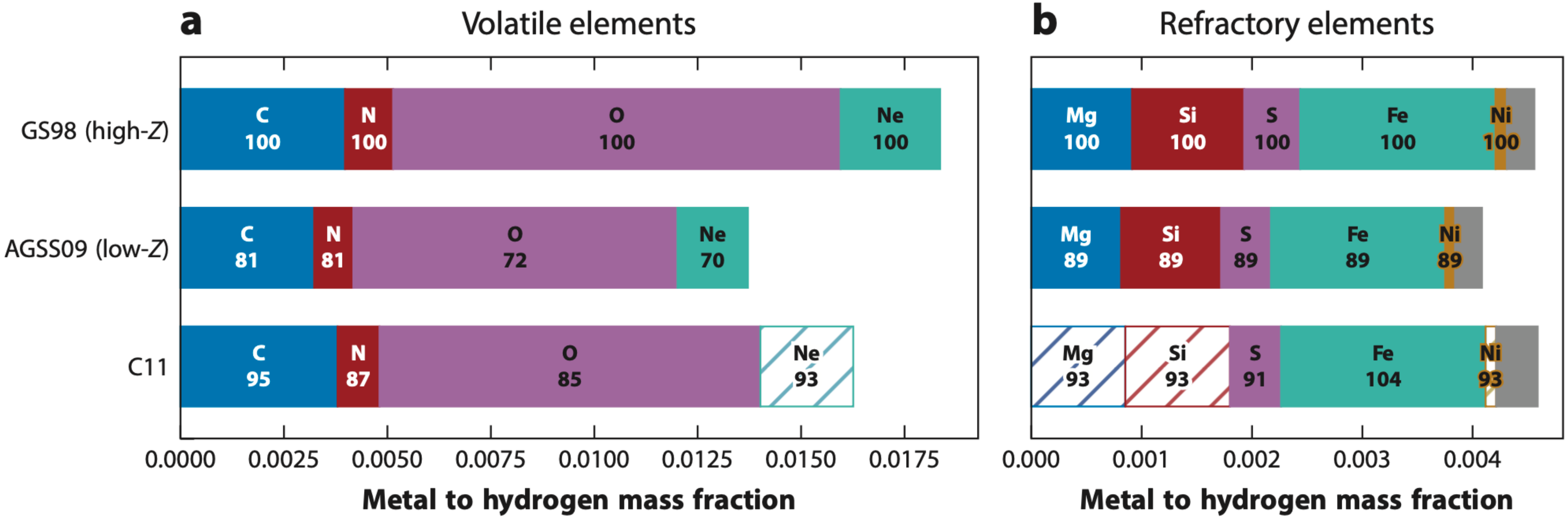


7Be Neutrinos



Solar Abundance Problem I

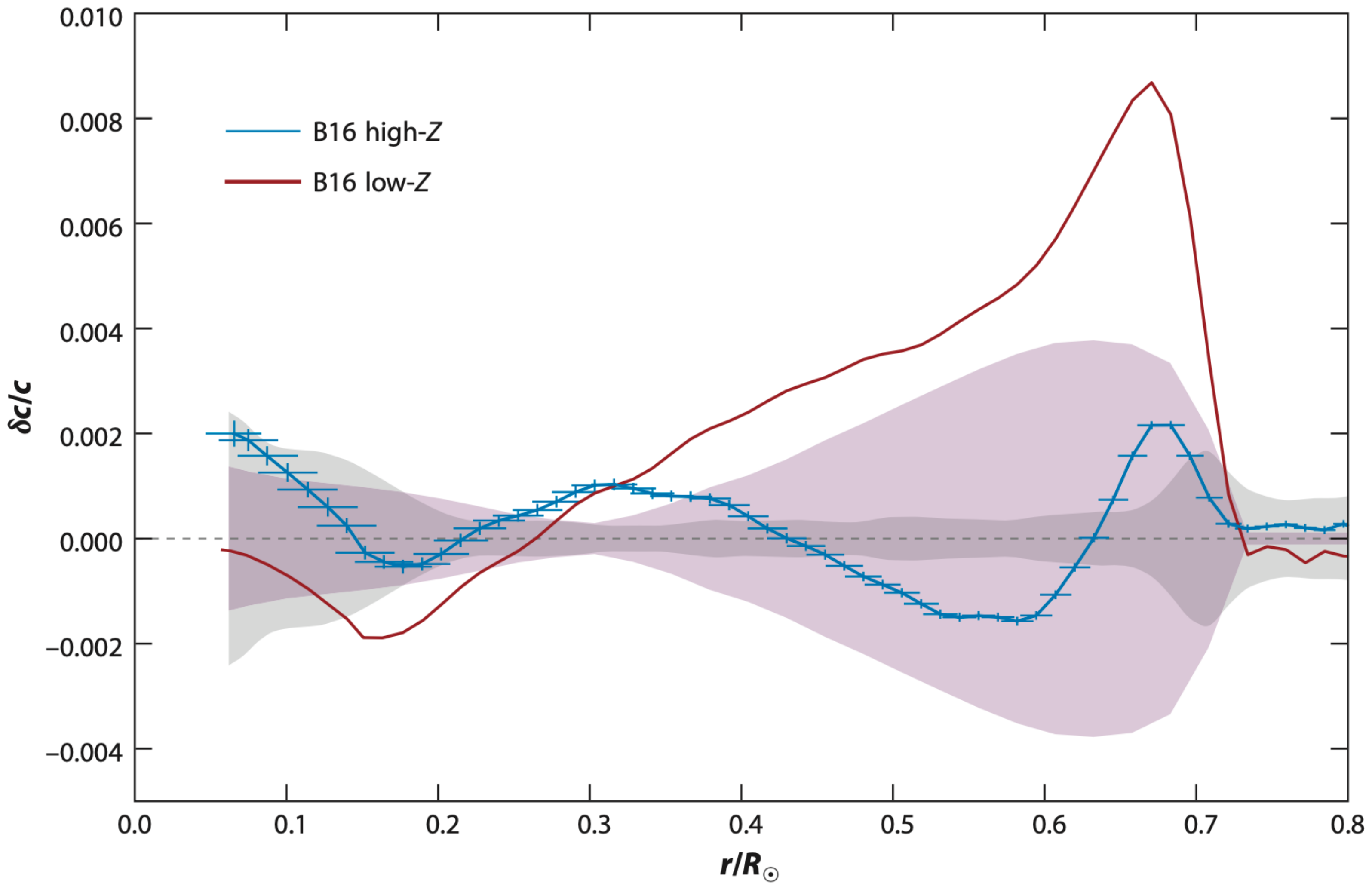
- Solar abundance (or solar mixture)
  - The chemical composition of the solar photosphere measured spectroscopically
  - Old High-Z (GS98) vs. New Low-Z (AGSS09)



Solar Abundance Problem II

- Solar Models
  - Seismic models: stellar structure -> helioseismic data (sound speed inside the sun) -> variation of the surface brightness
  - Standard Solar Models (SSMs): same as the stellar evolution models
- Solar Abundance Problem
  - "Conflict between state-of-the-art spectroscopic methods and solar structure models; arises because of a 30–40% reduction of the inferred C, N, O, and Ne abundances from novel spectroscopic analysis methods"

Solar Abundance Problem III



Fractional sound speed difference in the (Sun − model)/model for standard solar models based on high-Z and low-Z solar abundance mixtures. Error bars denote uncertainties due to measurement uncertainties in the solar acoustic oscillation frequencies (vertical direction) and size of kernels in the inversion (horizontal direction). Shaded areas represent model (light purple) and inversion technique (gray) 1σ errors.

Solar Neutrino as a Solution to Solar Abundance Problem (?)

Table 1 Solar neutrino fluxes

Flux	Solar (global)		SSM-B16		Uncertainties		
	No LC	LC	High-Z	Low-Z	Nuclear	Environmental	CNO
$\Phi(pp)$ (10^{10} cm^{-2} s^{-1})	6.21 ± 0.50	$5.971^{+0.037}_{-0.033}$	5.98 (0.6%)	6.03 (0.5%)	0.4%	0.4%	0.1%
$\Phi(pep)$ (10^{8} cm^{-2} s^{-1})	1.51 ± 0.12	1.448 ± 0.013	1.44 (1%)	1.46 (1%)	0.6%	0.8%	0.3%
$\Phi(hep)$ (10^{3} cm^{-2} s^{-1})	19^{+12}_{-9}	19^{+12}_{-9}	7.98 (30%)	8.25 (30%)	30%	1.3%	0.4%
$\Phi(^{7}\mathrm{Be})$ (10^{9} cm^{-2} s^{-1})	4.85 ± 0.19	$4.80^{+0.24}_{-0.22}$	4.93 (6%)	4.50 (6%)	5.0%	4.1%	0.8%
$\Phi(^{8}\mathrm{B})$ (10^{6} cm^{-2} s^{-1})	$5.16^{+0.13}_{-0.09}$	$5.16^{+0.13}_{-0.09}$	5.46 (12%)	4.50 (12%)	7.6%	9.2%	1.9%
$\Phi(^{13}\mathrm{N})$ (10^{8} cm^{-2} s^{-1})	$\leq$13.7	$\leq$13.7	2.78 (15%)	2.04 (14%)	6.2%	6.9%	12%
$\Phi(^{15}\mathrm{O})$ (10^{8} cm^{-2} s^{-1})	$\leq$2.8	$\leq$2.8	2.05 (17%)	1.44 (16%)	8.7%	8.4%	12%
$\Phi(^{17}\mathrm{F})$ (10^{6} cm^{-2} s^{-1})	$\leq$85	$\leq$85	5.29 (20%)	3.26 (18%)	9.3%	9.0%	16%
$\chi 2$			6.0	7.0			

The Solar columns show experimental results with and without the inclusion of the LC. The SSM-B16 columns show results and uncertainties based on GS98 and AGSS09 solar mixtures. The Uncertainties columns show the contributions to model uncertainties from different types of sources. Solar data from Bergström et al. (150). SSM fluxes and uncertainties from Vinyoles et al. (4). Abbreviations: LC, luminosity constraint; SSM, standard solar model.

Solar Neutrino Fluxes

- Concept of Luminosity Constraint (LC)

$$\frac{L_{\rm nuc}}{(1\,{\rm AU})^2} = \sum_{i=1,8} \alpha_i \Phi(X_i),$$

$$L_{\rm nuc} = 1.04^{+0.07}_{-0.08}\, L_\odot.$$

$\Rightarrow$

$$L_{\rm nuc} = 0.991^{+0.005}_{-0.005} + 0.009^{+0.004}_{-0.005}\, L_\odot,$$

Solar Neutrino in the KNO Era

Collaboration and Competition with Hyper-Kamiokande

Hyper-Kamiokande

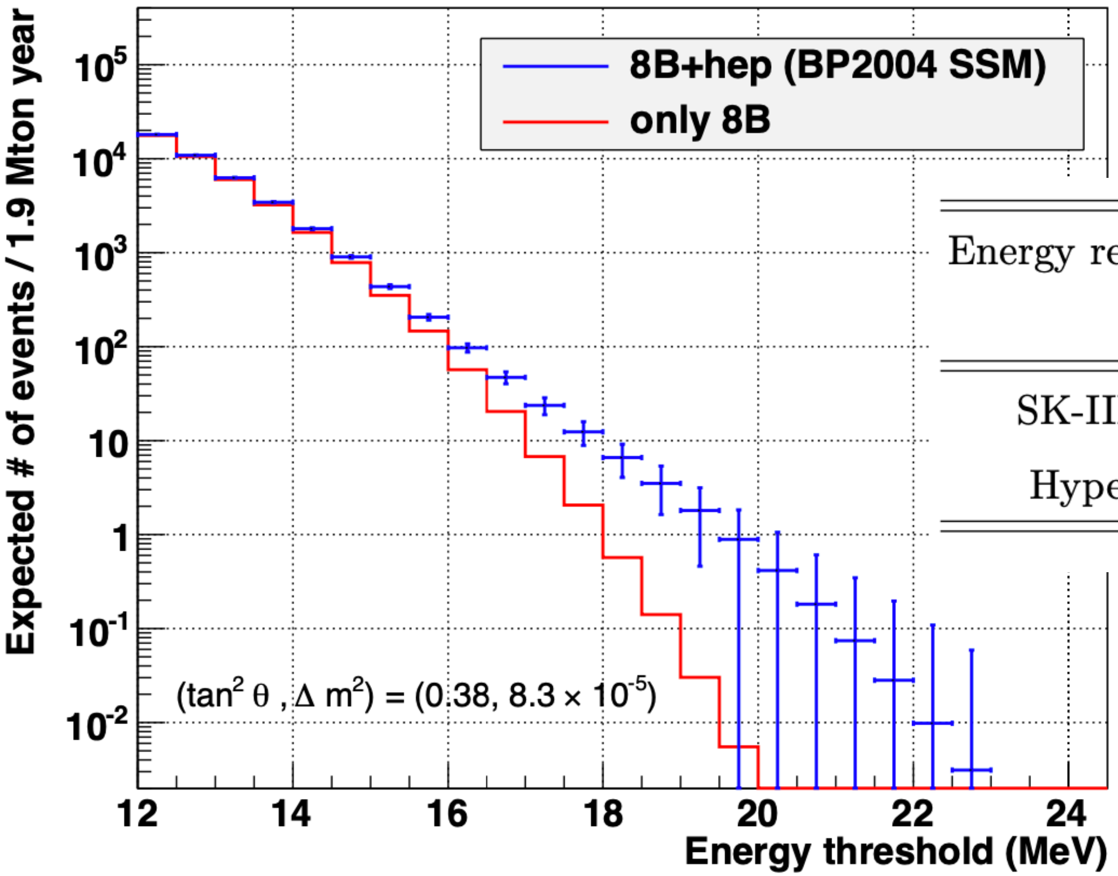
Design Report
(Dated: May 9, 2018)

arXiv:1805.04163v1 [physics.ins-det] 9 May 2018

III Physics Potential 204

Measuring HEP Neutrino

"The separation between 8B and hep solar neutrinos highly depends on the energy resolution of the detector."



Energy resolution	Energy range [MeV]	^{8}B [/1.9 Mton/year]	hep [/1.9 Mton/year]	hep / ^{8}B
SK-III/IV	19.5–25.0	0.77	3.03	3.9
Hyper-K	18.0–25.0	0.56	6.04	10.6

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

Summary and Prospect

- Precision measurement of solar neutrino will provide an answer to the solar abundance problem.
- KNO will collaborate and compete with Hyper-Kamiokande (HK) for the solar neutrino science and may be able to perform better for the precision measurements due to its larger volution although it is later than HK.
- A small hybrid detector, which can be constructed with a small additional cost of the entire KNO project, will contribute to the solar neutrino science as a prototype of next generation low-energy neutrino telescopes.

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CrossMark

Neutrinos from Carbon-burning Red Supergiants and Their Detectability

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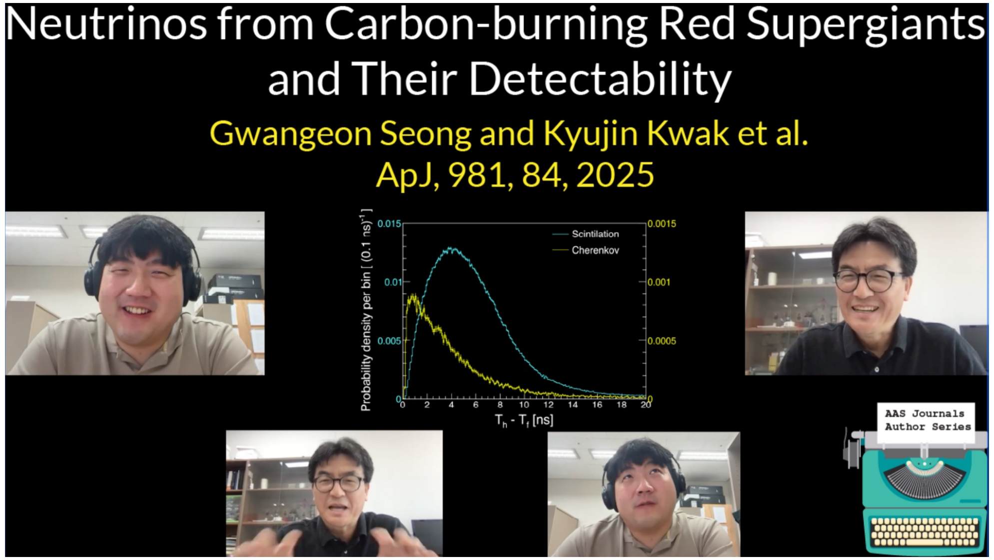
Abstract

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.

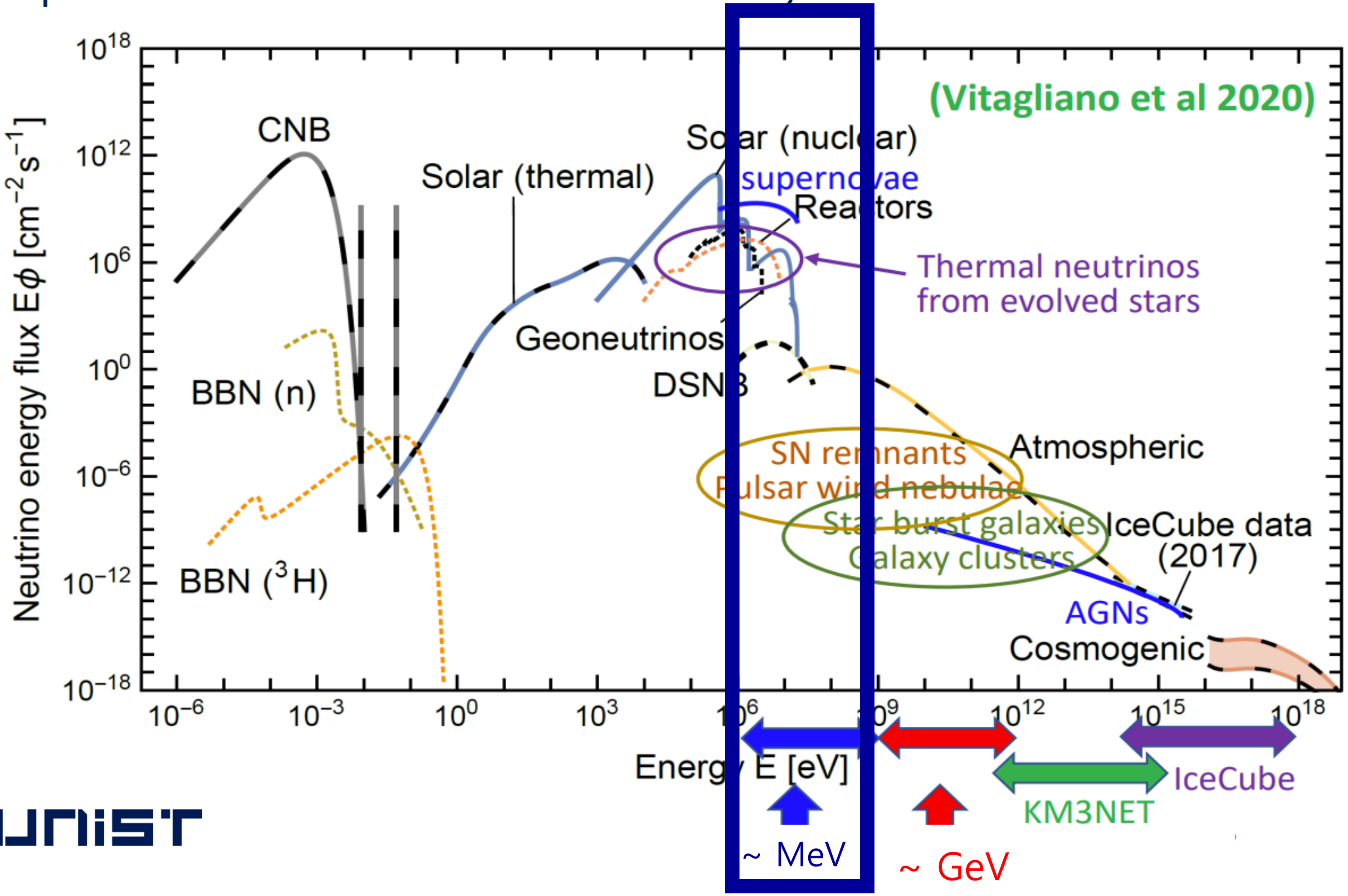
Unified Astronomy Thesaurus concepts: Carbon burning (195); Neutrino astronomy (1100); Neutrino telescopes (1105); Stellar evolution (1599)



- https://youtu.be/G7y8OsUdhHM

Motivation

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



Neutrinos interact **weakly** with baryonic matters

Cross sections of neutrinos with baryonic matter

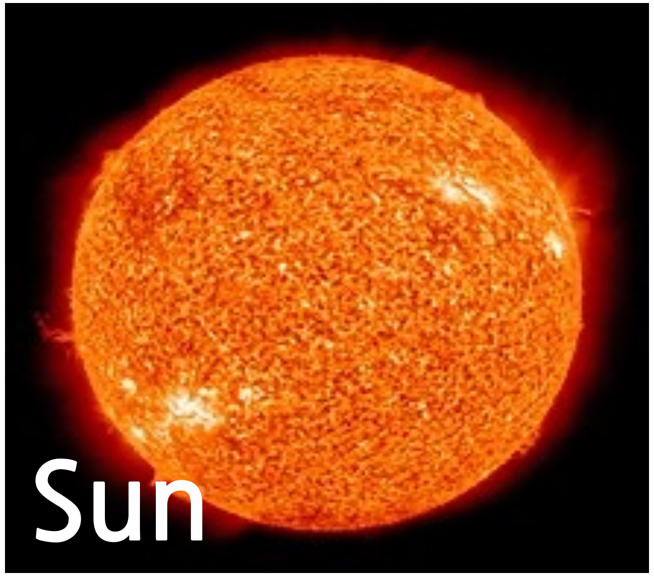
$$\simeq 10^{-44}\ \mathrm{cm}^2$$

Cross sections of Photons with baryonic matter

$$\simeq 10^{-24}\ \mathrm{cm}^2$$

MeV Neutrino sources

Motivation



Alias	SIMBAD ID	Distance [pc]	T_{eff} [K]	Luminosity [$L_\odot$]	Mass [$M_\odot$]
Betelgeuse	alf Ori	168^{+27}_{-15}	3600 ± 200	126000^{+83000}_{-50000}	16.5~19
Antares	alf Sco	170	3660 ± 200	98000^{+40000}_{-29000}	11~14.3
5 Lacertae	5 Lac	505.05	3660 ± 200	17473 ± 3344	5.11 ± 0.18
119 Tauri	119 Tau	550	3820 ± 135	66000^{+21000}_{-20000}	$14.37^{+2.00}_{-2.77}$
NO Aurigae	NO Aur	600	3700	67000	-
V424 Lacertae	V424 Lac	623	3790 ± 110.5	11176.69	-
KQ Puppis	KQ Pup	659	3660 ± 170	59,800	13~20
MZ Puppis	MZ Pup	703	3745 ± 170	19586.643	-
μ Cephei	mu Cep	940^{+140}_{-40}	3551 ± 136	$269000^{+111,000}_{-40,000}$	15~20
V419 Cephei	V419 Cep	941	3660 ± 170	17693.234	-

Table 1. Red Supergiant Catalog in 1kpc

Motivation

From what other sources can MeV neutrinos be detected? → Red supergiant?

Detection MeV neutrinos: Only Sun, and SN1987A

How can MeV neutrinos be detected?

Number of targets (Detector size)

Event rate $= f \times N \times \sigma(E) \times \phi(E)$

Trigger rate

Cross-section

Neutrino flux + energy

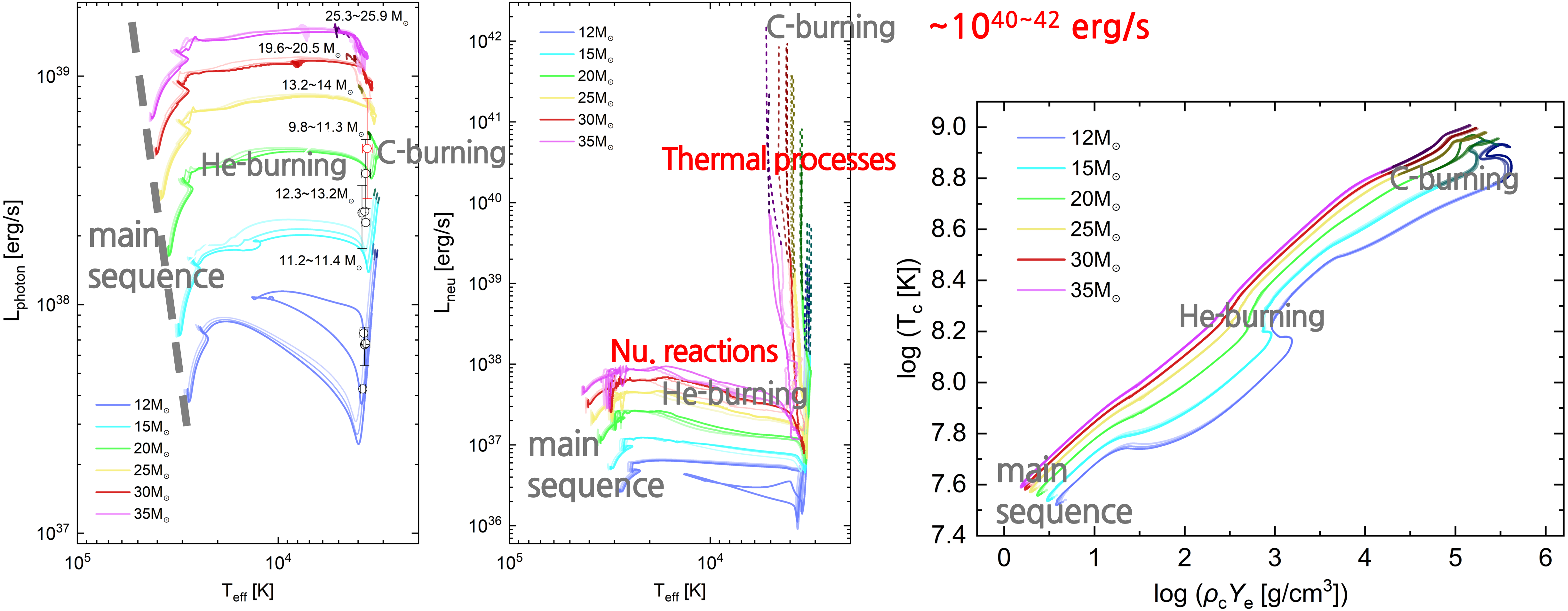
→ 2) Detector simulation

→ 1) Stellar evolution + Neu. spectrum

Single star models

Cf) Sun : $L_{\nu,\odot} = 0.02398 \cdot L_{\gamma,\odot}$ ~10^{31}erg/s

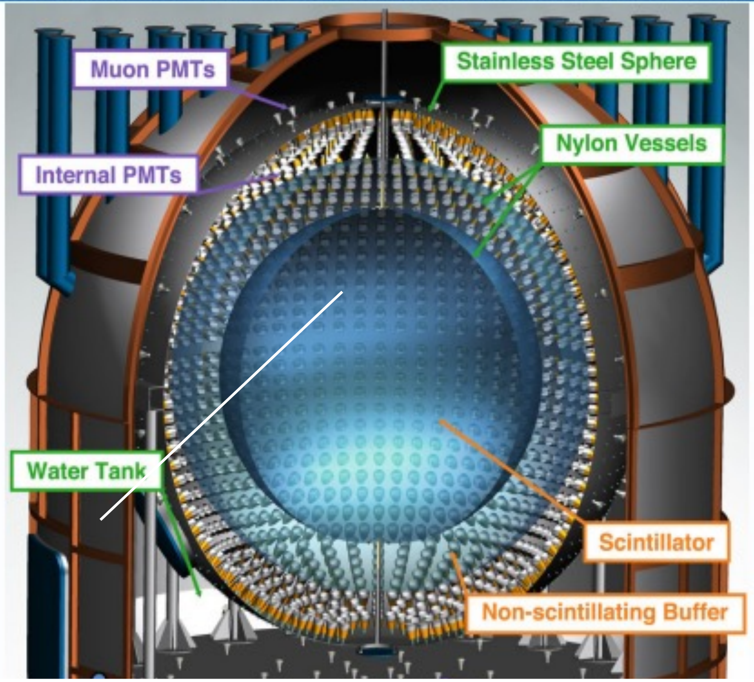
~$10^{40\sim42}$ erg/s



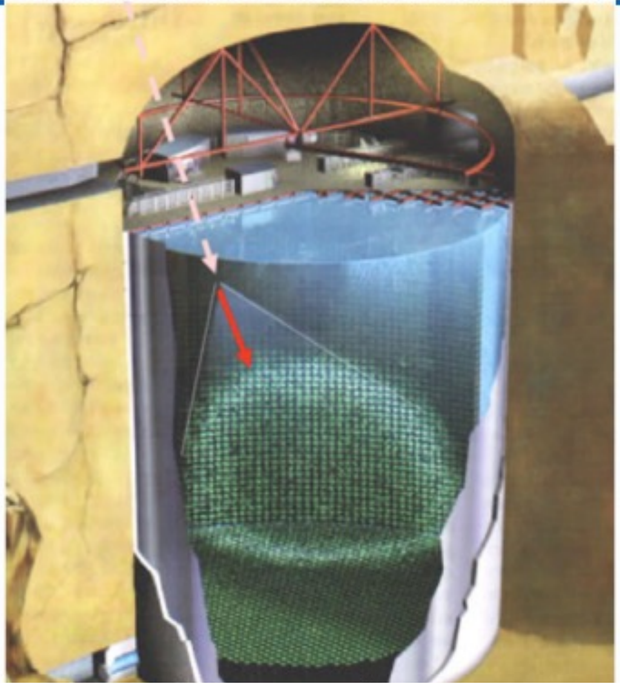
Performed by MESA(Modules for Experiments in Stellar Astrophysics)

Z = 0.01, 0.015, and 0.02

Neutrino Detectors for ~ MeV neutrinos



Borexino



Super Kamiokande

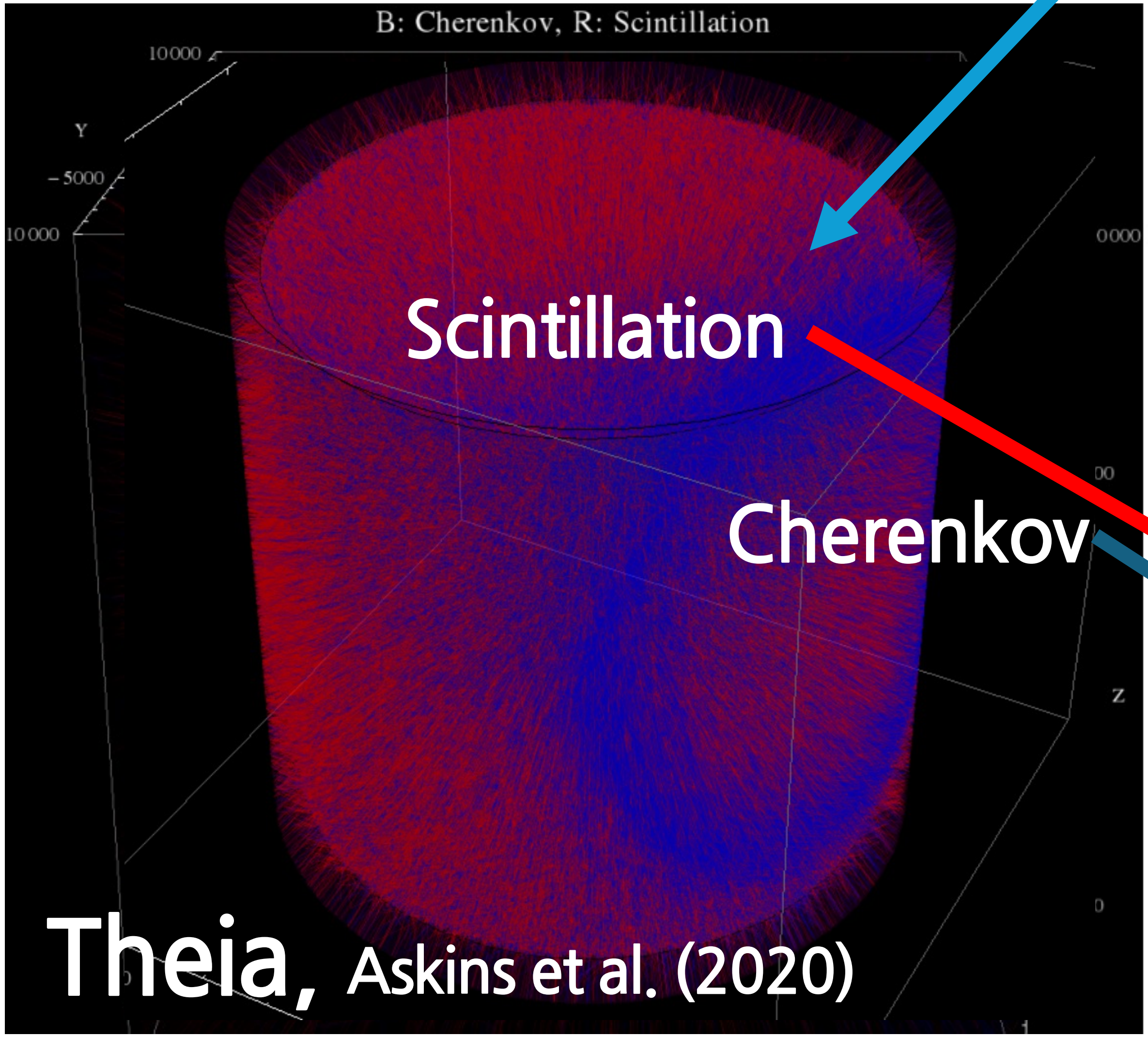
Liquid scintillator

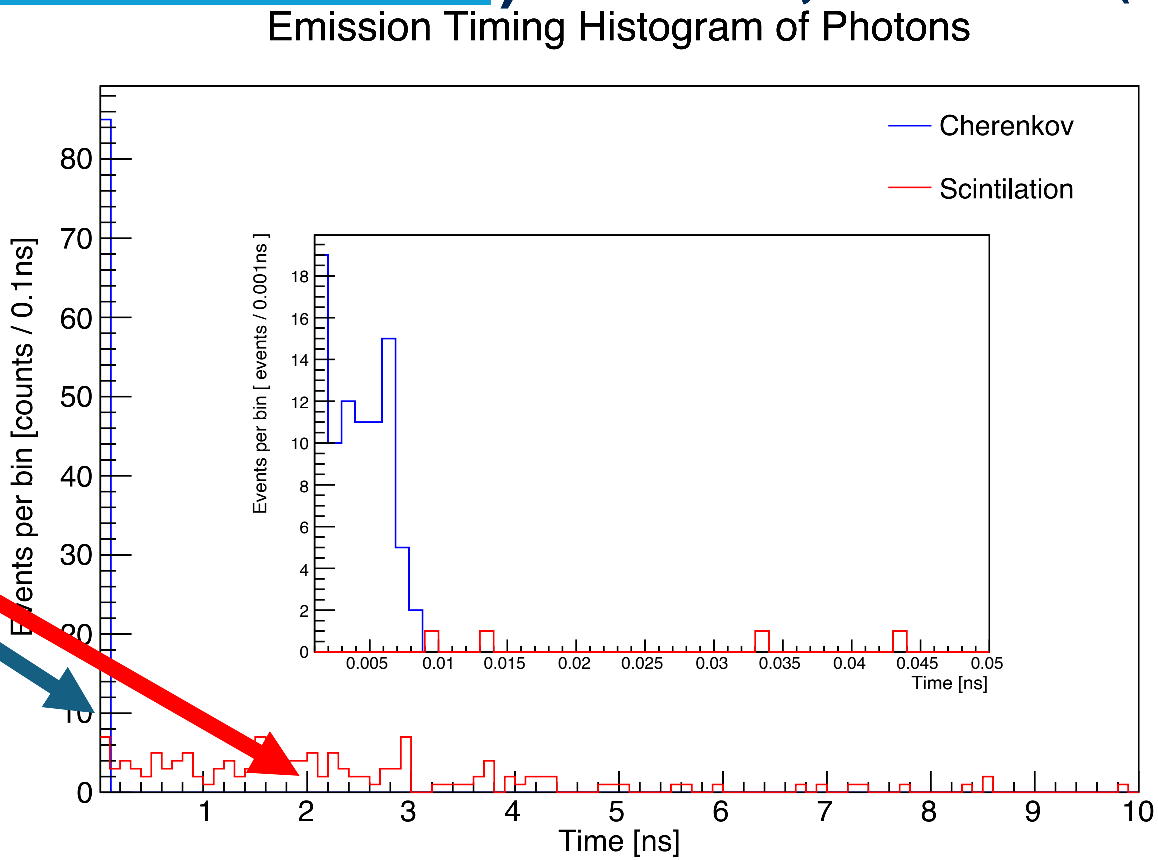
High Energy Resolution/ NO Source Direction

Cherenkov detector

Source Direction / Energy Range 3.5MeV~

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



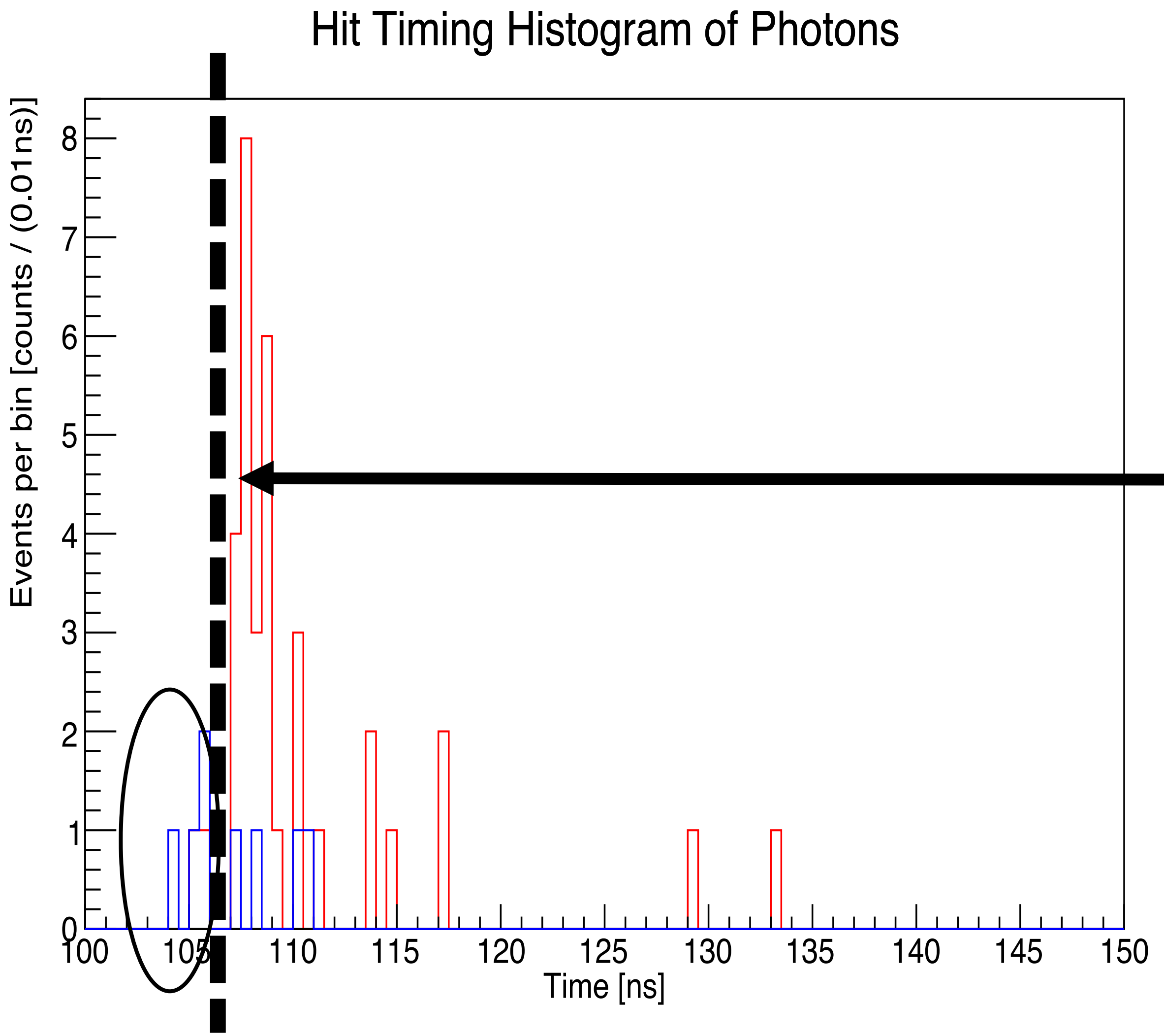


PMT → LAPPD

(Large Area Picosecond Photo-Detectors)

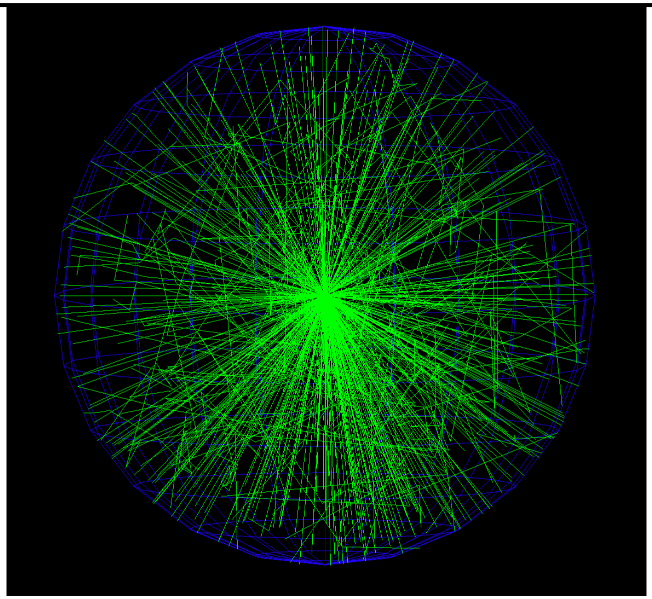
→ Time resolution ~ 100ps

Detector simulations (NuWro + Geant4)

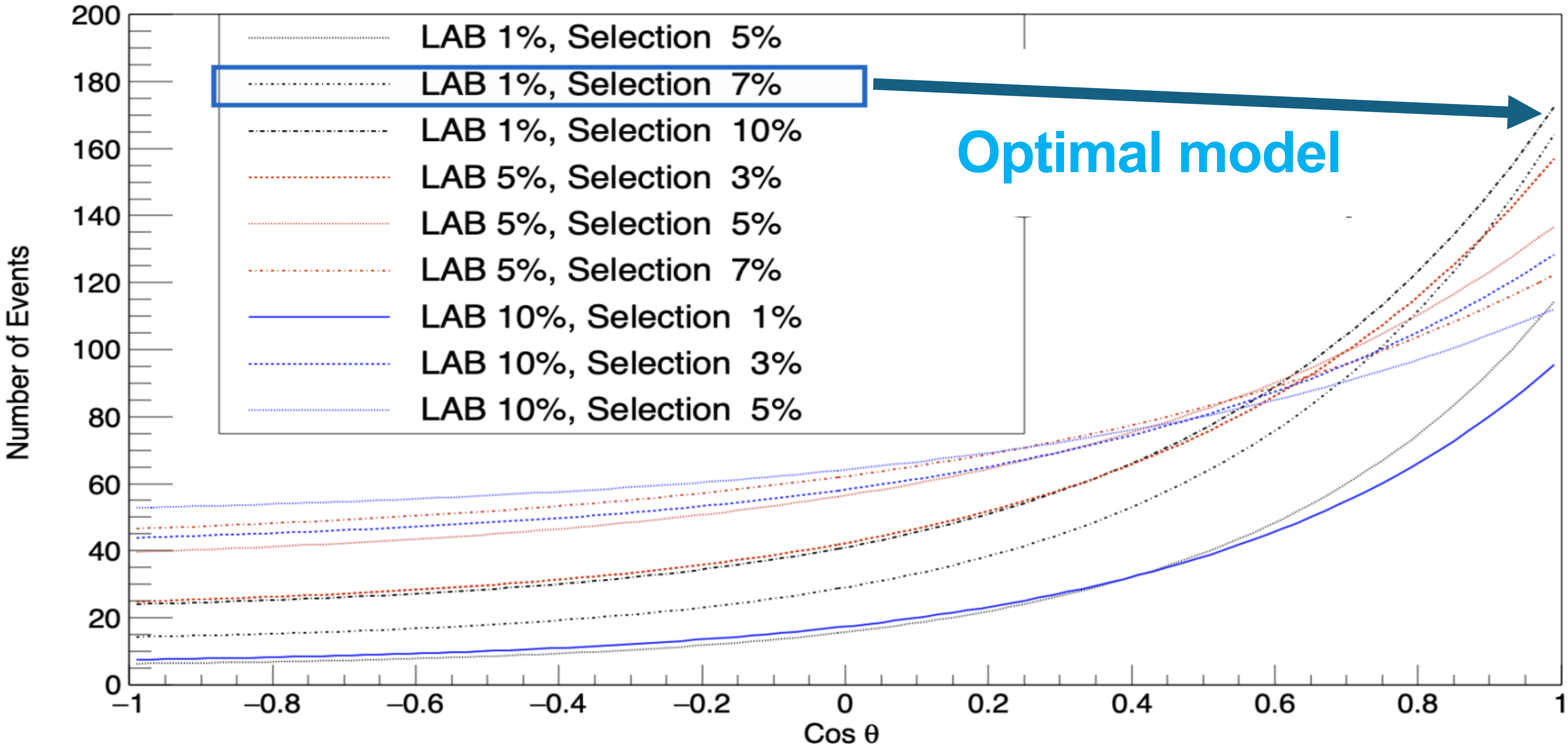


- 50kT $(r = 23\ [m])$, Sphere
- 100% LAPPD coverage

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

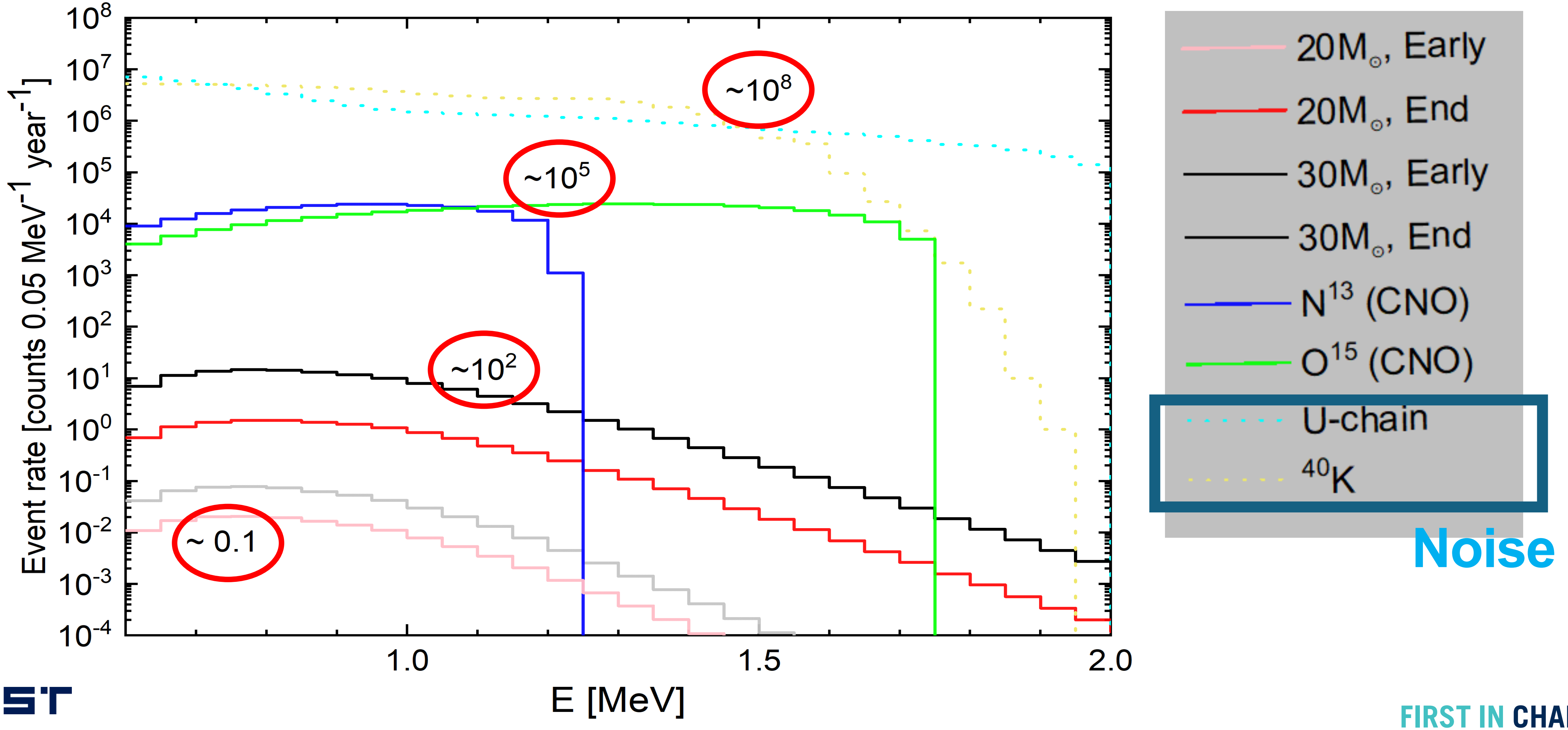


Detector performance



RSG's neutrinos (C-burn) with HD

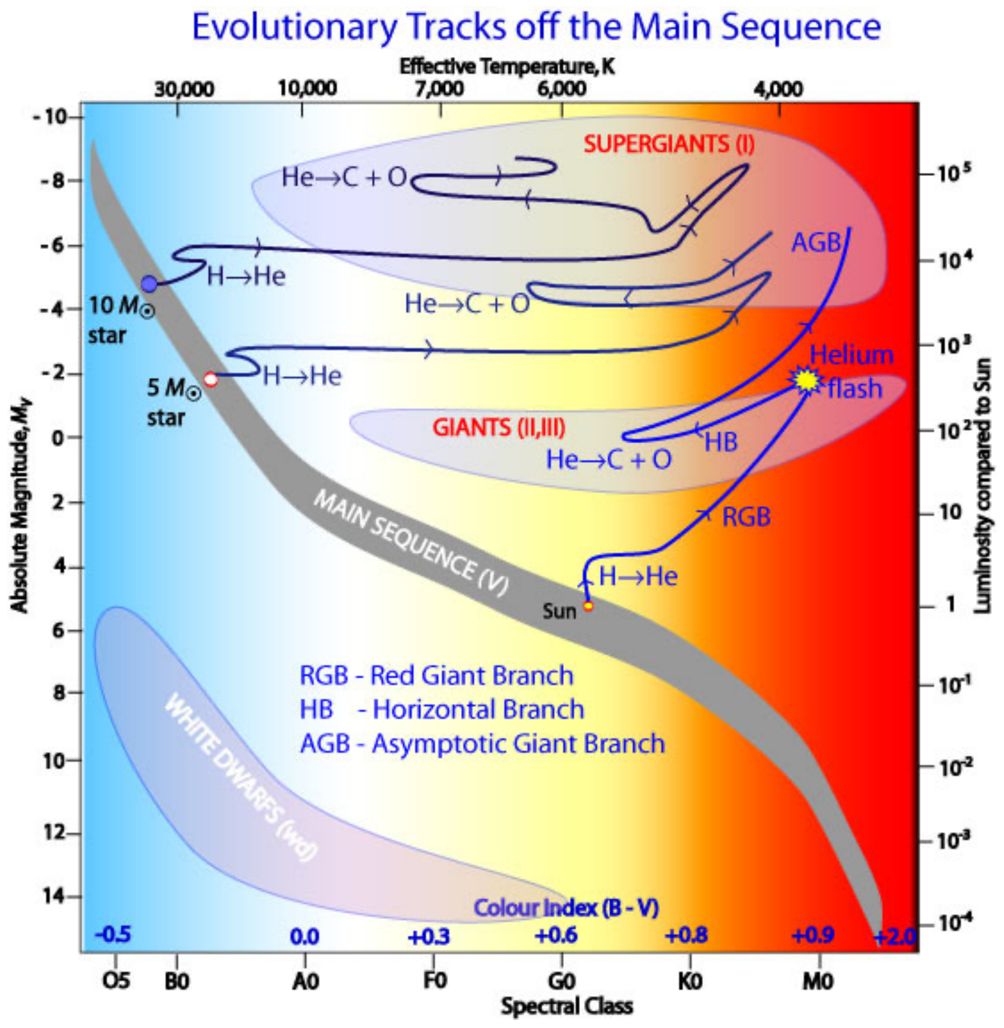
RSG at 200 pc



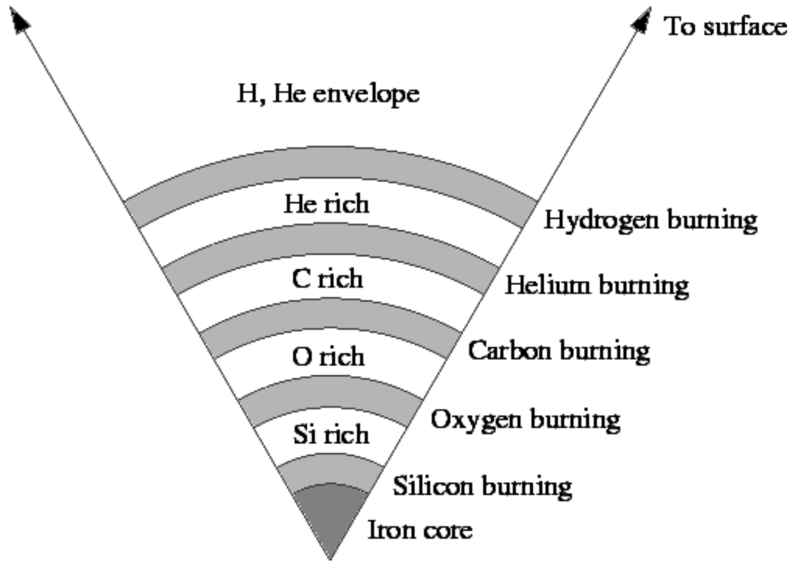
Outline

- Introduction to supernova simulations and neutrino emission at each stage
  - Stellar evolution
  - Collapse and bounce
  - Post-bounce and shock revival due to neutrino interaction
- Neutrinos from relic supernovae
- Gamma-ray bursts (GRBs)/active galactic nuclei (AGN) and neutrino emission from them

Single Star Evolution



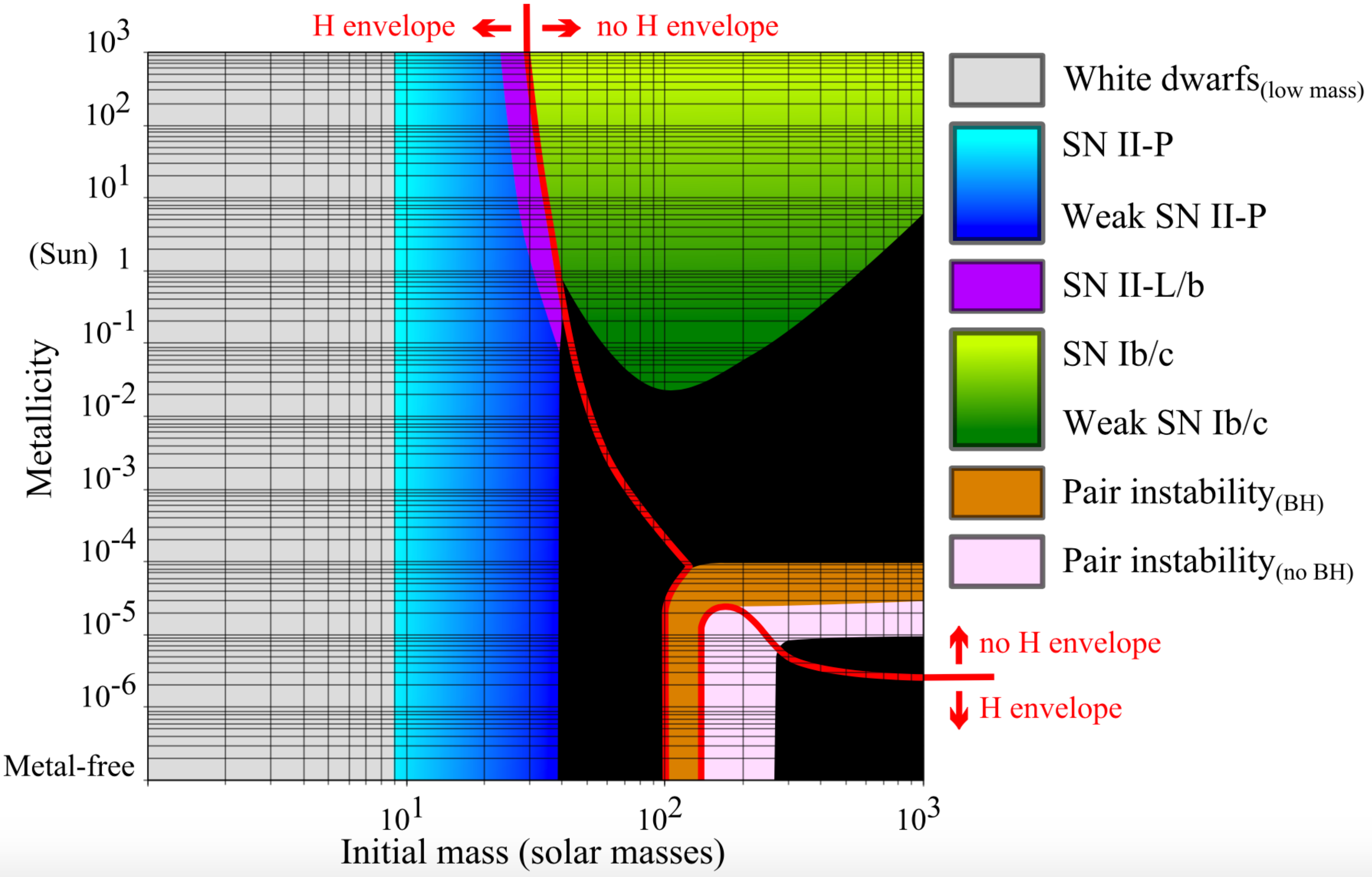
www.atnf.csiro.au



Pre-supernova at the end of the massive star evolution

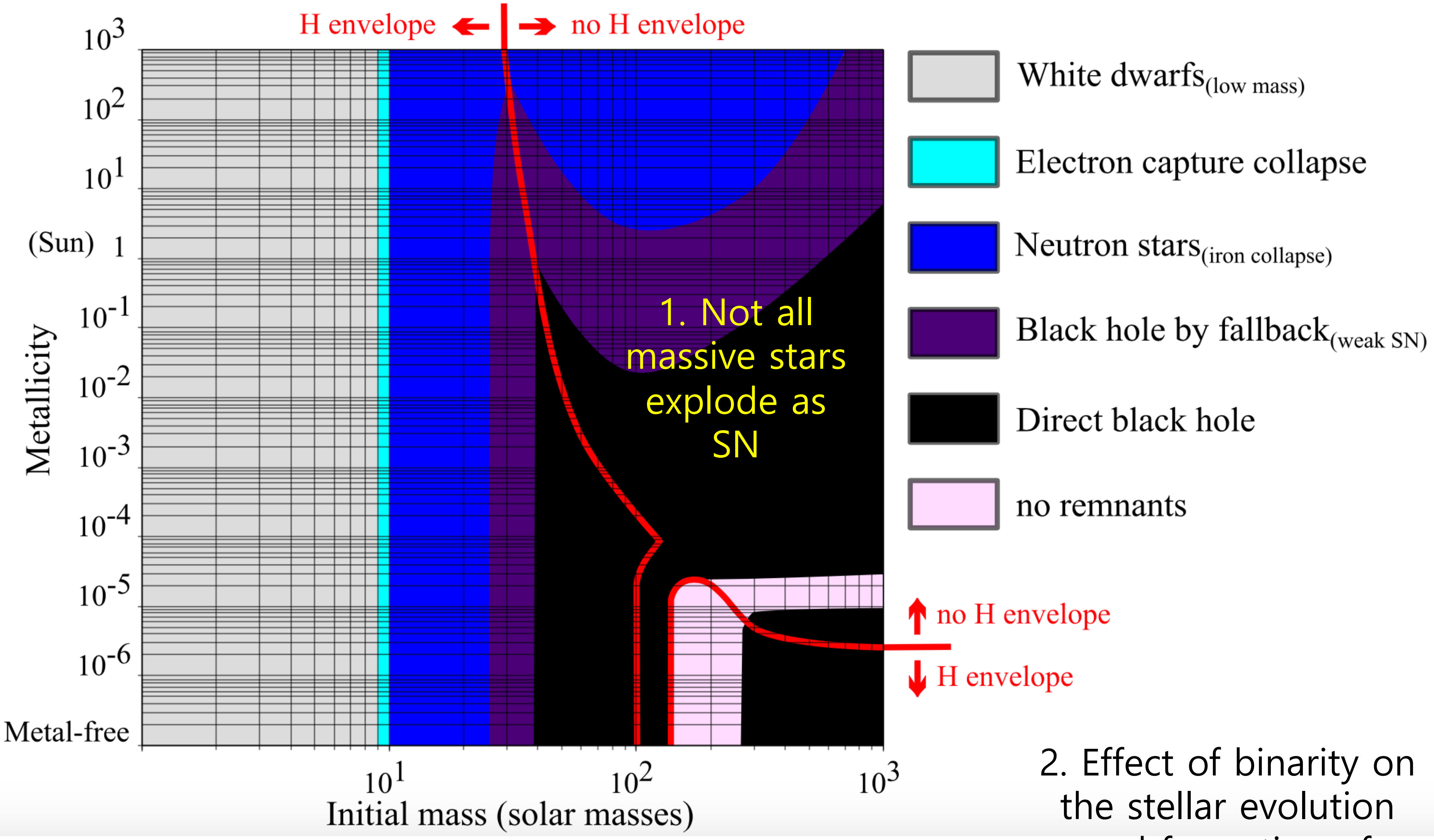
http://burro.astr.cwru.edu

Supernovae / mass-metallicity



From Wiki (Heger + 2005, ApJ)

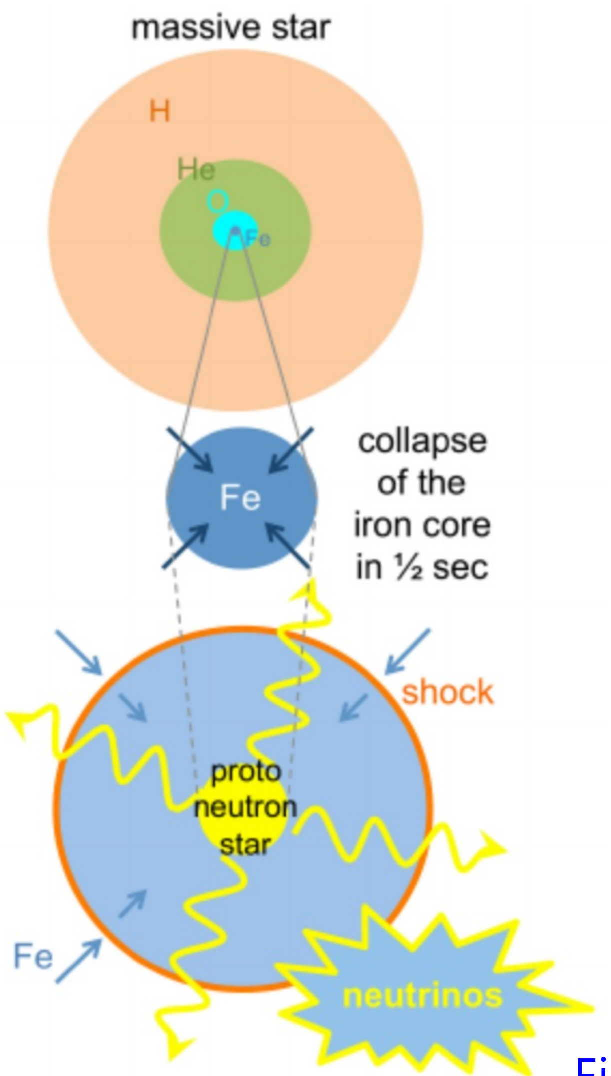
Remnants of massive single stars



From Wiki (Heger + 2005, ApJ)

2. Effect of binarity on the stellar evolution and formation of NS/BH is actively investigated.

On the Way to Explosion

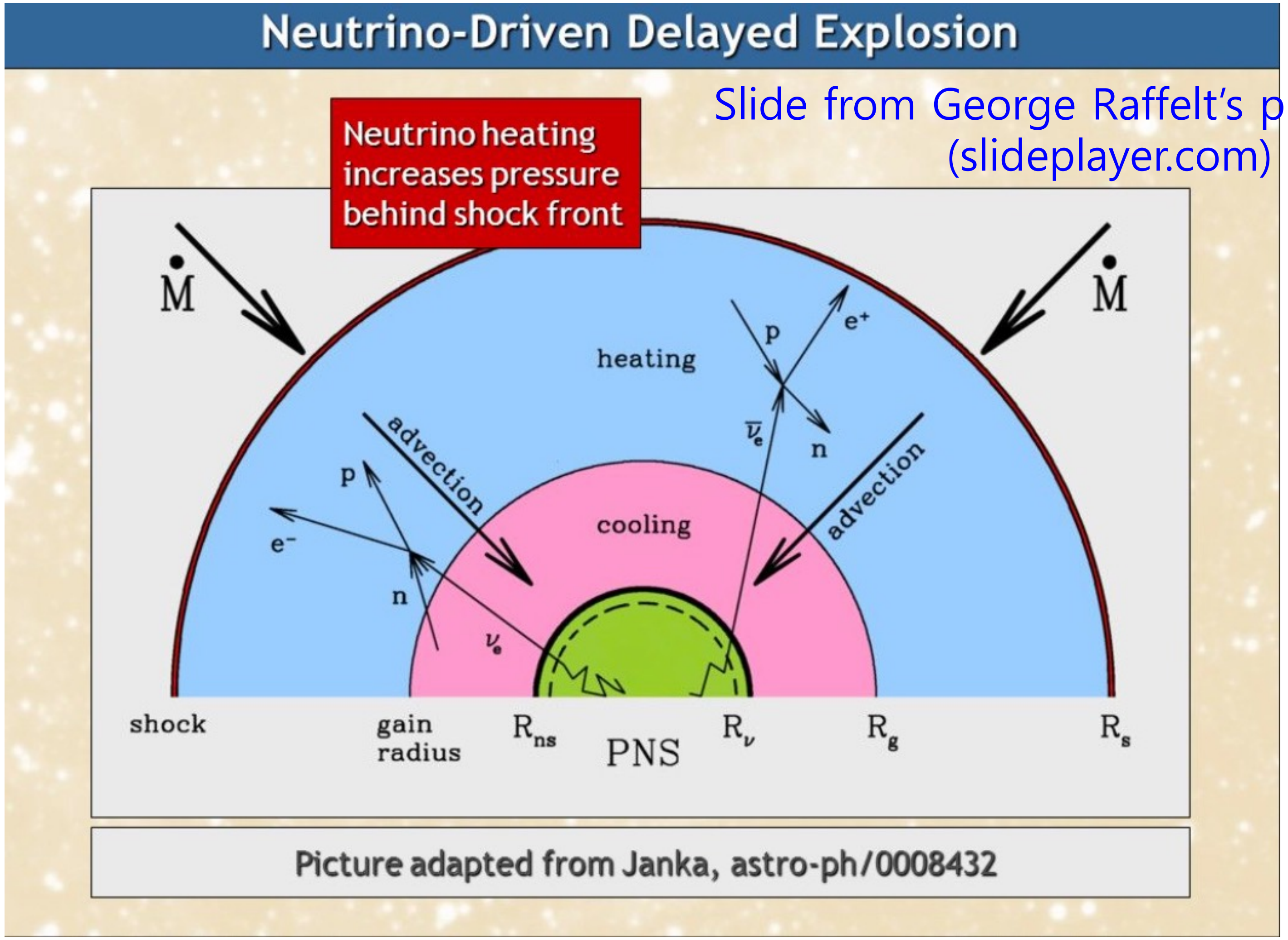


- ✓ Inner core (about 0.5 $M_\odot$) contracts homologously.
- ✓ Size of inner core weakly depends on the pre-SN structure.
- ✓ Outer core falls supersonically.
- ✓ Central region exceeds nuclear saturation density, which leads to bounce depending on equation of state. Alternatively, it collapses into a black hole.
- ✓ Bouncing results in shock wave that forms near the edge of inner core.

(From Introduction of Pejcha & Thomson 2015. See the references therein.)

Figure from www.researchgate.net.

Slide from George Raffelt’s presentation (slideplayer.com)



✓ Shock wave is stalled by losing energy to dissociate iron and standing accretion shock forms through the balance between neutrino emission from proto-neutron star (PNS) and infalling matter from outer core.

(From Introduction of Pejcha & Thomson 2015. See the references therein.)

From the stalled shock to an explosion ???

- Classical delayed neutrino-driven mechanism :

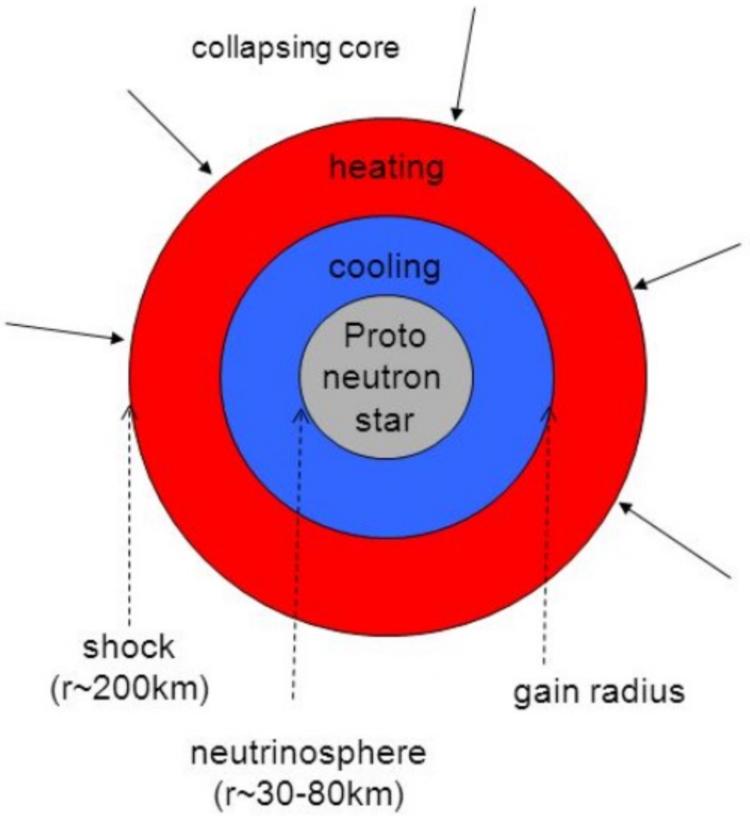
  Neutrino heating below the shock drives the explosion

- Many physical ingredients :
  - Nuclear physics
  - Neutrino transport
  - General relativity
  - Multi-Dimensional hydrodynamics
  - Magnetic field

  -->Extremely challenging numerical task !

- No explosion in the most sophisticated 1D simulations… (Liebendorfer *et al* 2001)

Asymmetries are essential for the explosion mechanism !!



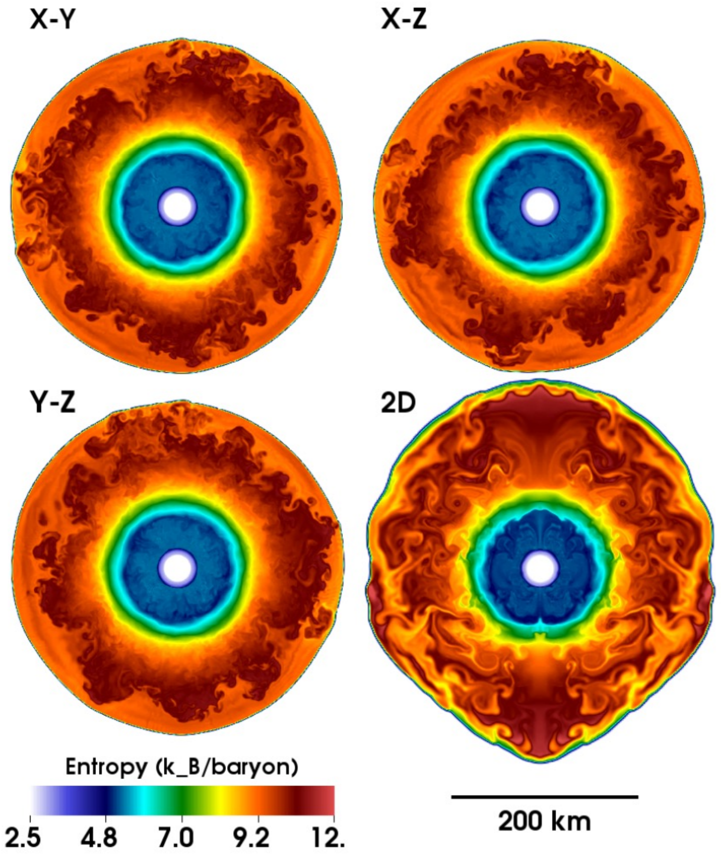
From http://slideplayer.com/slide/6963513/

$\boldsymbol{\nu}$-Related Issues in Supernova Simulations

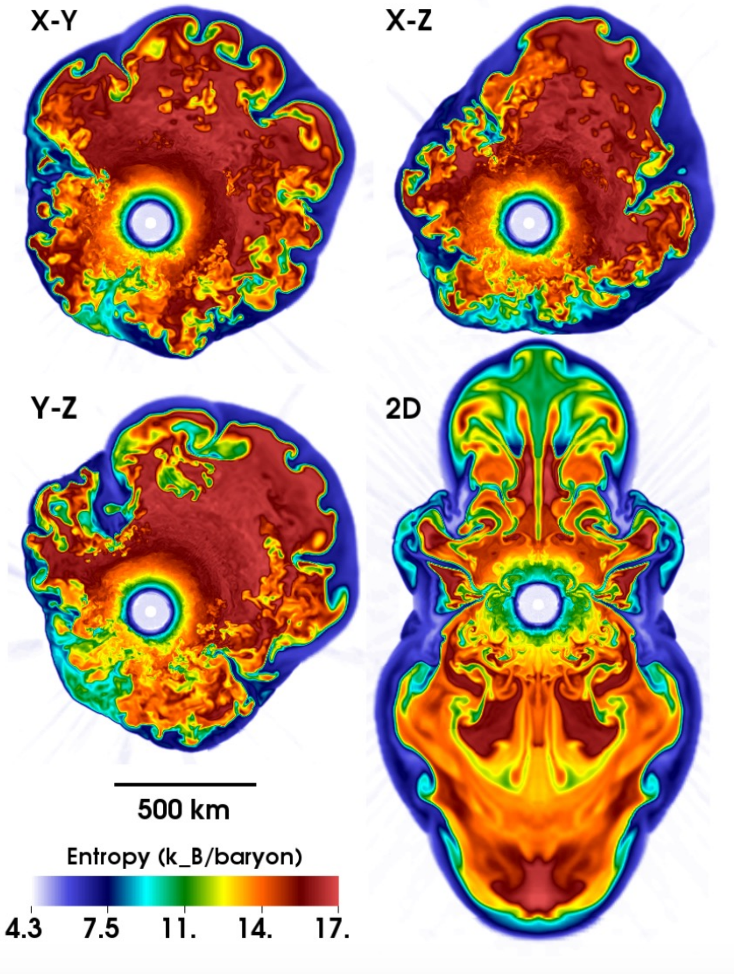
- Uncertain physics
  - Neutrino self-interactions including oscillation at high luminosity
  - Equation of state for dense (nuclear/quark) matter that affects the emissivity and opacity of neutrino transport
- Technical (numerical) challenges
  - Proper implementation of general relativity
  - 3D simulations with neutrino radiative transfer
  - Other effects (e.g., magnetic field)

Standing Accretion Shock Instability (SASI)

Neutrino Luminosity = 1.7 x 10^{52} ergs/s



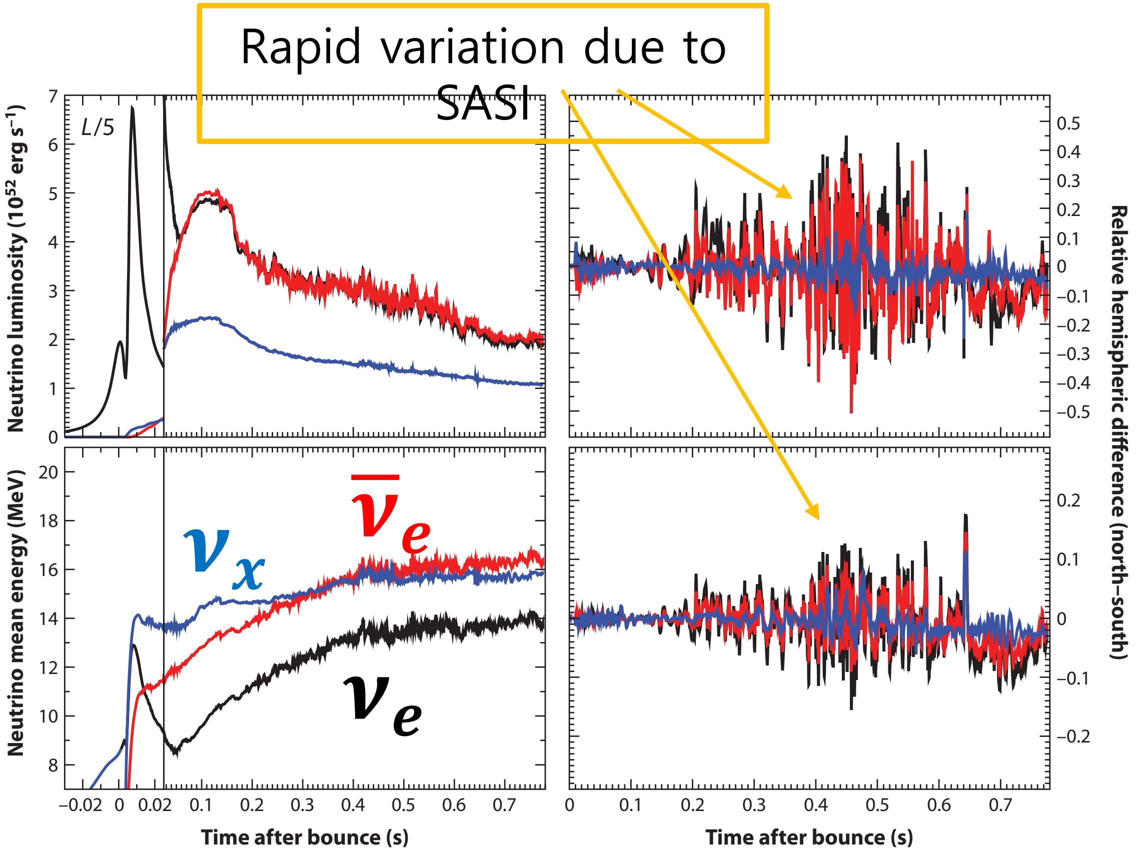
t=100 ms post-bounce

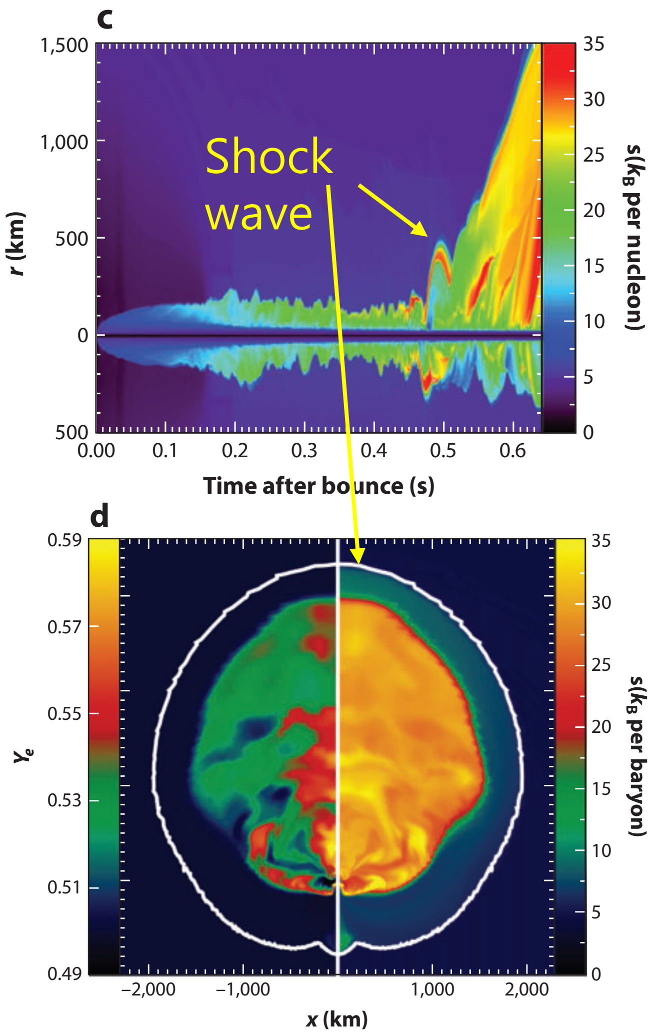


time of explosion, t=388 ms (2D), t=821 ms (3D)

Couch ApJ 2013

Neutrinos Predicted from SN Simulations



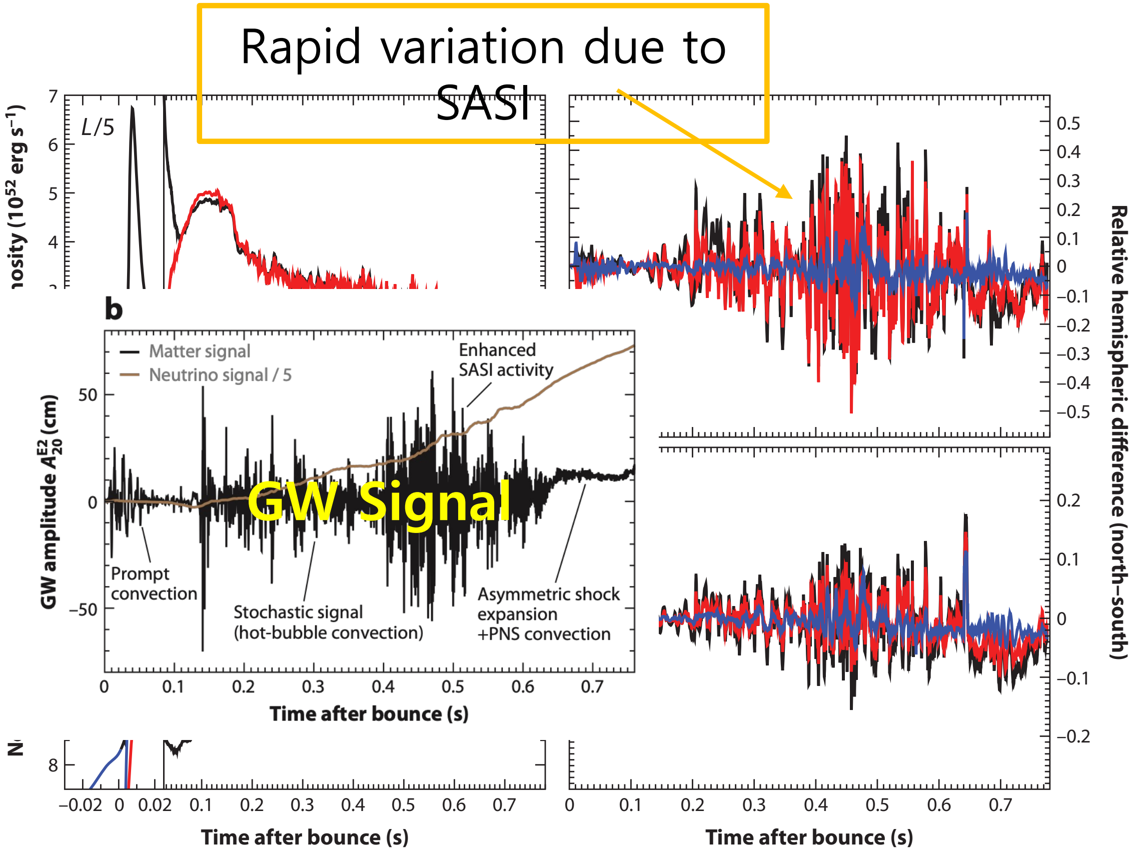


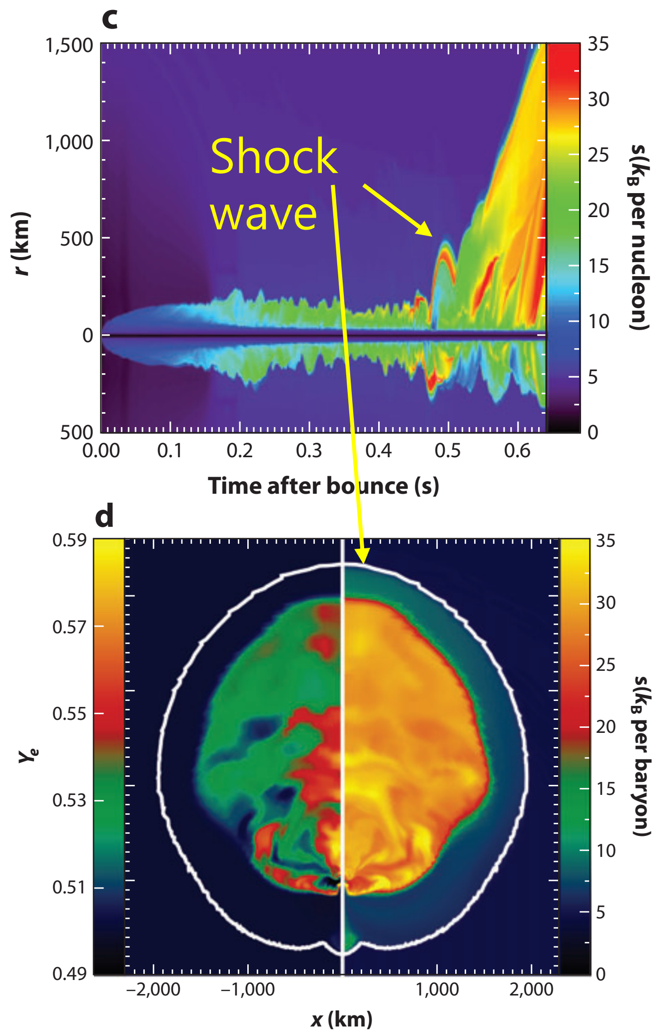
t=775 ms after bounce

- ✓ 2D GR simulations from a progenitor of 15 Msun and solar metallicity
- ✓ Neutrinos are emitted from proto-neutron star (PNS)

Janka 2010 ARNPS

Neutrinos Predicted from SN Simulations



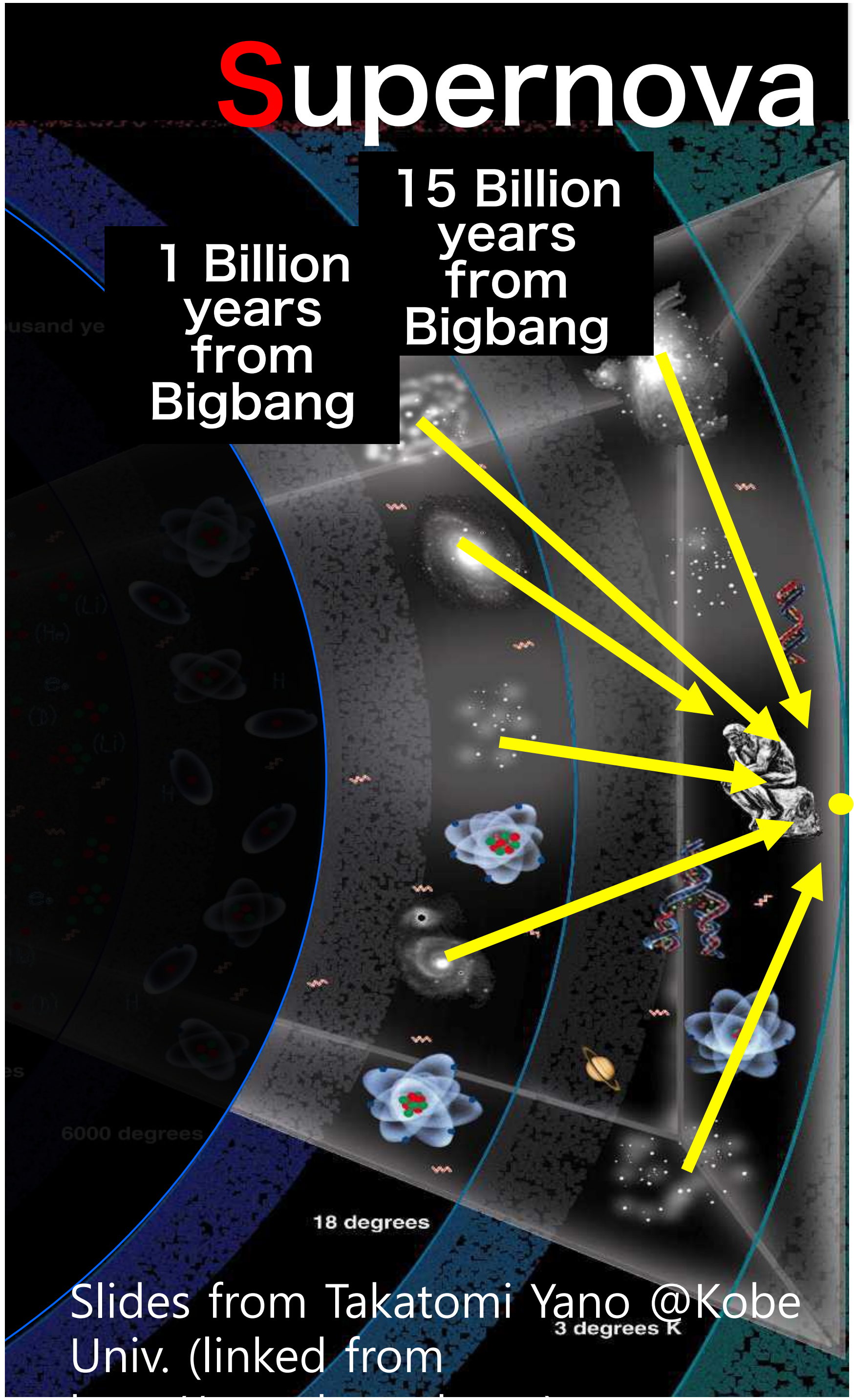


- ✓ 2D GR simulations from a progenitor of 15 Msun and solar metallicity
- ✓ Neutrinos are emitted from proto-neutron star (PNS)

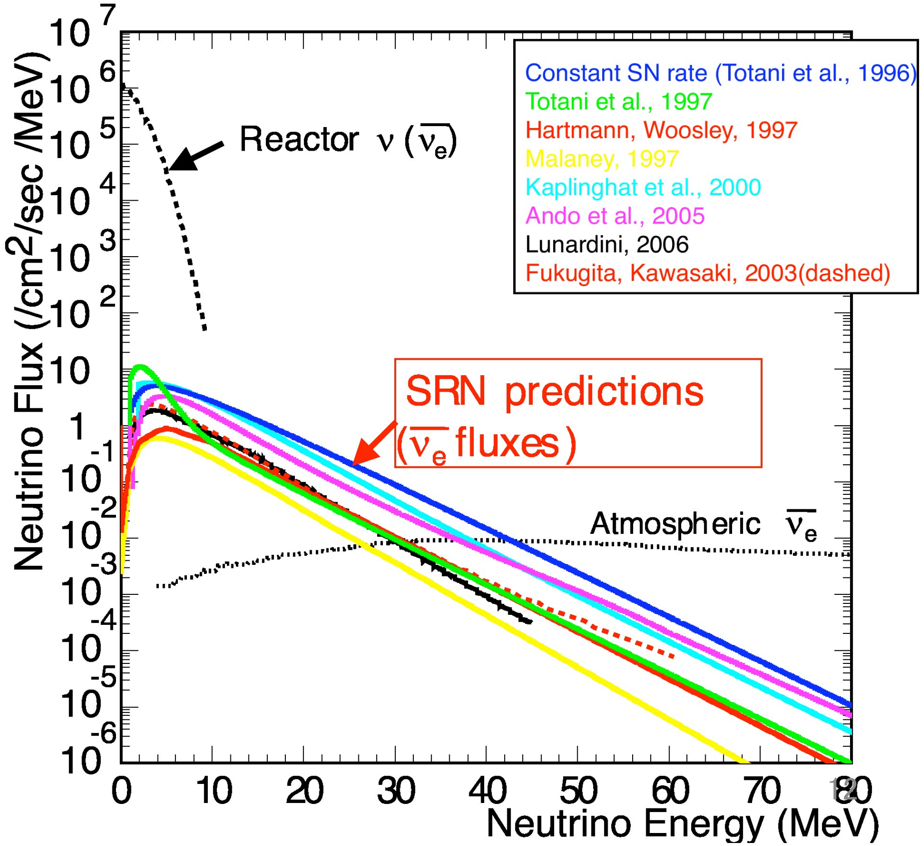
Janka 2010 ARNPS

t=775 ms after bounce

Supernova Relic Neutrino



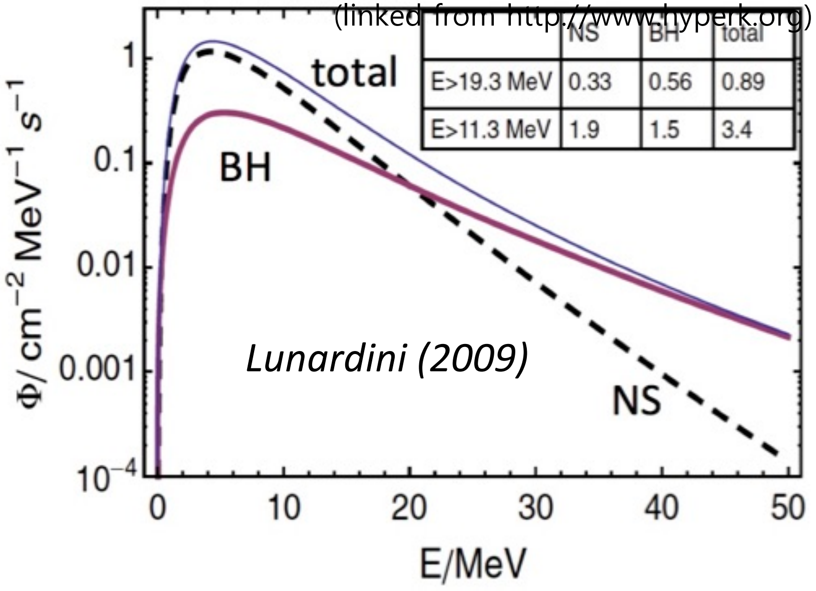
- **Supernova Relic Neutrino (SRN)** is diffused neutrinos coming from all past supernovae.
- Not discovered but **promising** source of extra-galactic neutrino.



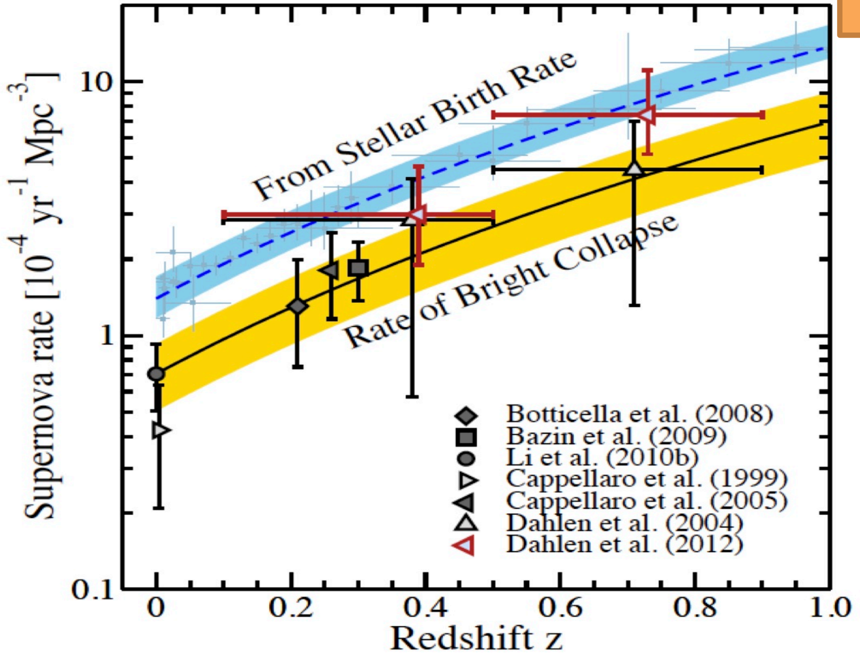
Physics of SRN

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)



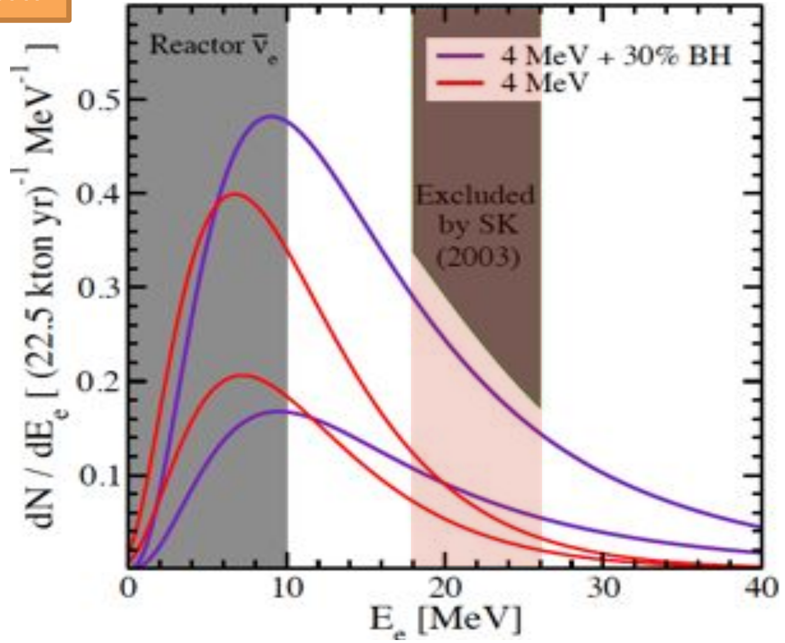
Stellar birth rate(=collapse rate) and Bright collapse rate



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

Horiuchi

Event spectra with uncertainties

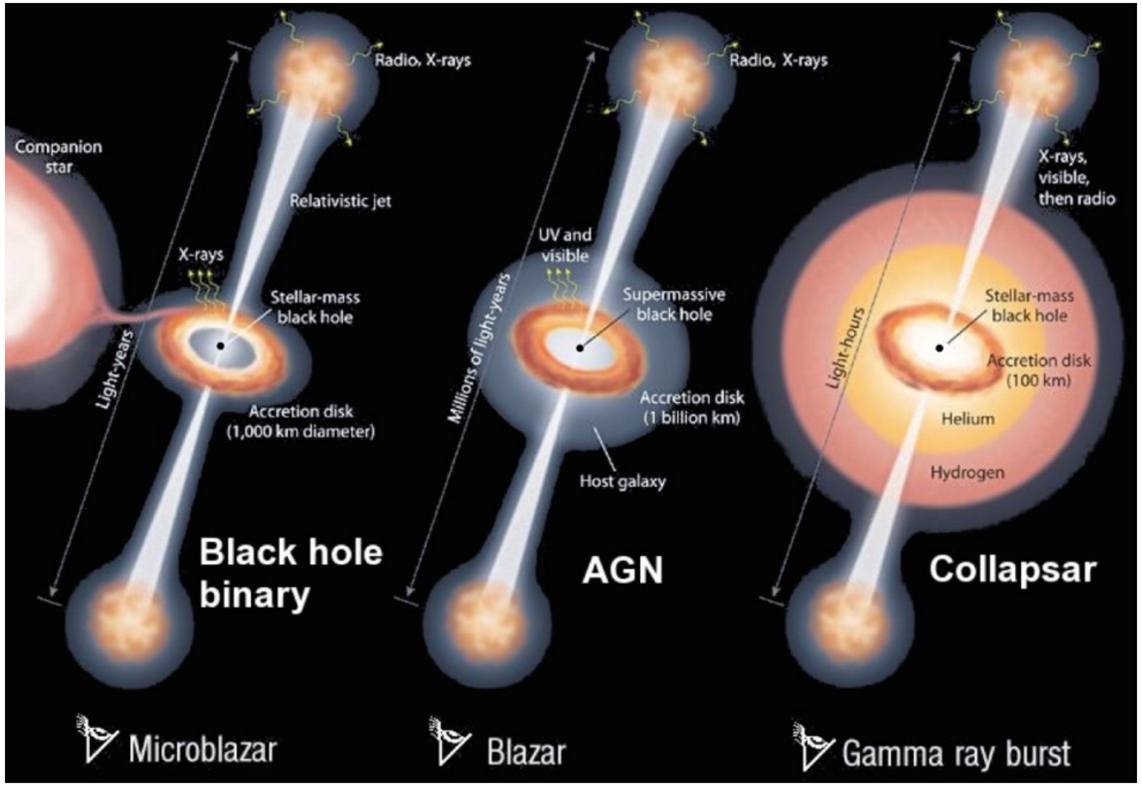


Adopted from Horiuchi et al. (2009)

Neutrinos from GRBs/AGNs

- Neutrino and ultra high energy cosmic ray emission from Jet in GRB and AGN via the following process

$$p + \gamma \rightarrow \Delta^{+} \rightarrow \pi^{+} + n \rightarrow e^{+} + \nu_e + \bar{\nu}_\mu + \nu_\mu + n.$$



https://rodrigonemmen.com

Summary

- KNT/KNO has great potentials for astronomy research because many celestial objects emit neutrinos which can be detected by KNT/KNO.
- New measurements will be able to constrain the models that predict astronomical neutrinos.
- As always in physics (and astronomy), unexpected discoveries are expected.

Astrophysical Neutrino Sources: Compact Binaries in Highly Eccentric Orbits

Kyujin Kwak
UNIST

CHEA Workshop @Sono Belle Cheonan

December 2, 2022

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

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

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Ringdown Gravitational Waves from Close Scattering of Two Black Holes

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We have numerically investigated close scattering processes of two black holes (BHs). Our careful analysis shows for the first time a nonmerging ringdown gravitational wave induced by dynamical tidal deformations of individual BHs during their close encounter. The ringdown wave frequencies turn out to agree well with the quasinormal ones of a single BH in perturbation theory, despite its distinctive physical context from the merging case. Our study shows a new type of gravitational waveform and opens up a new exploration of strong gravitational interactions using BH encounters.

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Thank You!!