GOBIERNO DE ESPAÑA
MINISTERIO DE UNIVERSIDADES

MINISTERIO DE CIENCIA E INNOVACIÓN
Financiado por la Unión Europea NextGenerationEU
Plan de Recuperación, Transformación y Resiliencia
AGENCIA ESTATAL DE INVESTIGACIÓN

Low-Energy Physics with Hyper-K

Nataly Ospina

Universidad Autónoma de Madrid

Universidad Autónoma de Madrid
Departamento de Física Teórica

LOCAL WORKSHOP ON HYPER-K PHYSICS San Sebastián, June 14th, 2023

H2020-MSCA-RISE-2019—872549—SK2HK // AMD-872549-6

UAM Universidad Autónoma de Madrid

Low energy neutrinos

Low energy neutrinos are mainly produced in nuclear processes, such as the ones in the Sun or in the center of an exploding supernova.

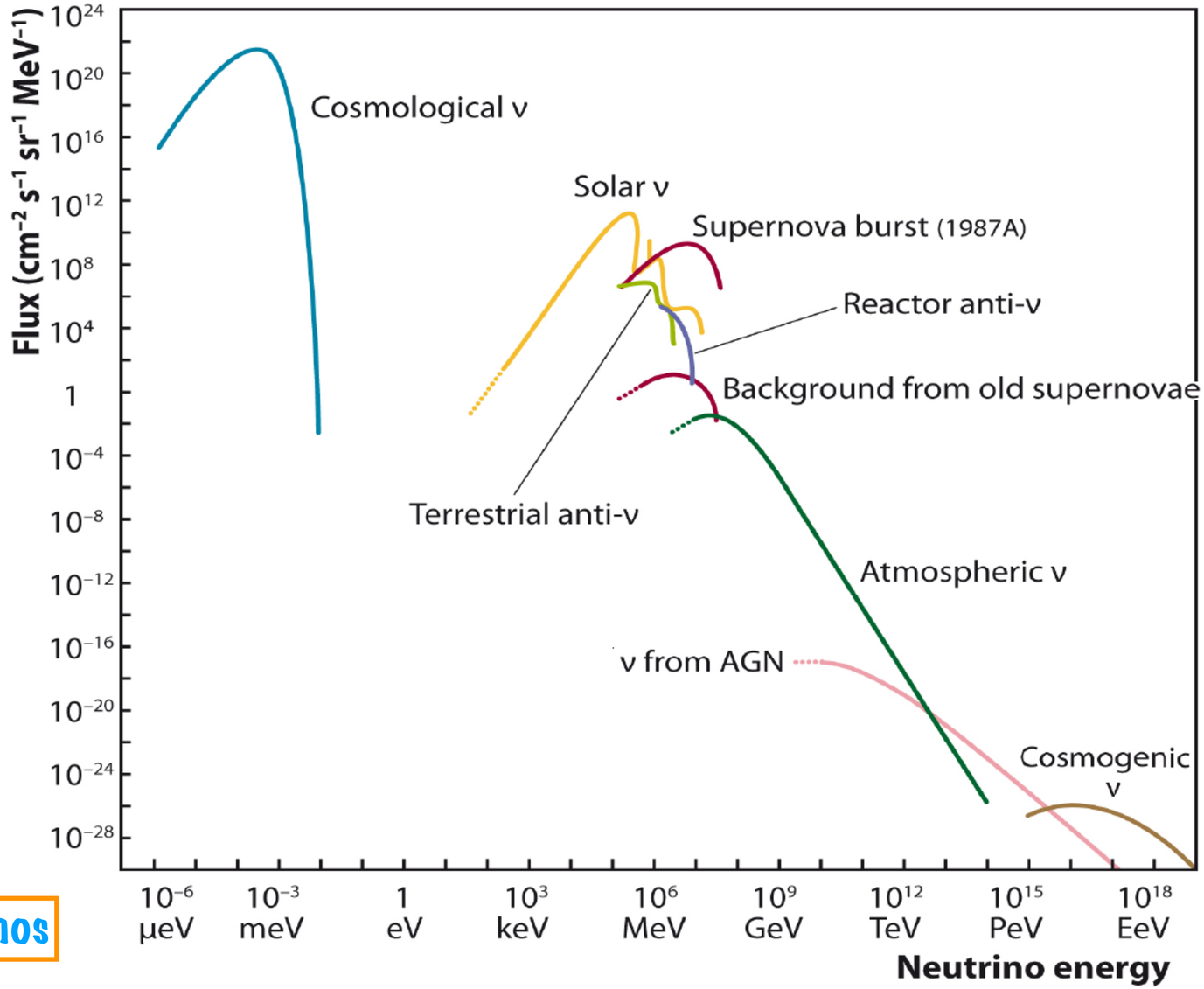
Energy range: 10th of MeV

High energy neutrinos are mainly produced in high energy particle collisions producing short lived mesons, decaying to neutrinos and other particles.

Energy range: 10th of GeV up to tenths of PeV

Very high energy neutrinos

C. Spiering, 2012



Low energy neutrinos

Low energy neutrinos are mainly produced in nuclear processes, such as the ones in the Sun or in the center of an exploding supernova.

Energy range: 10th of MeV

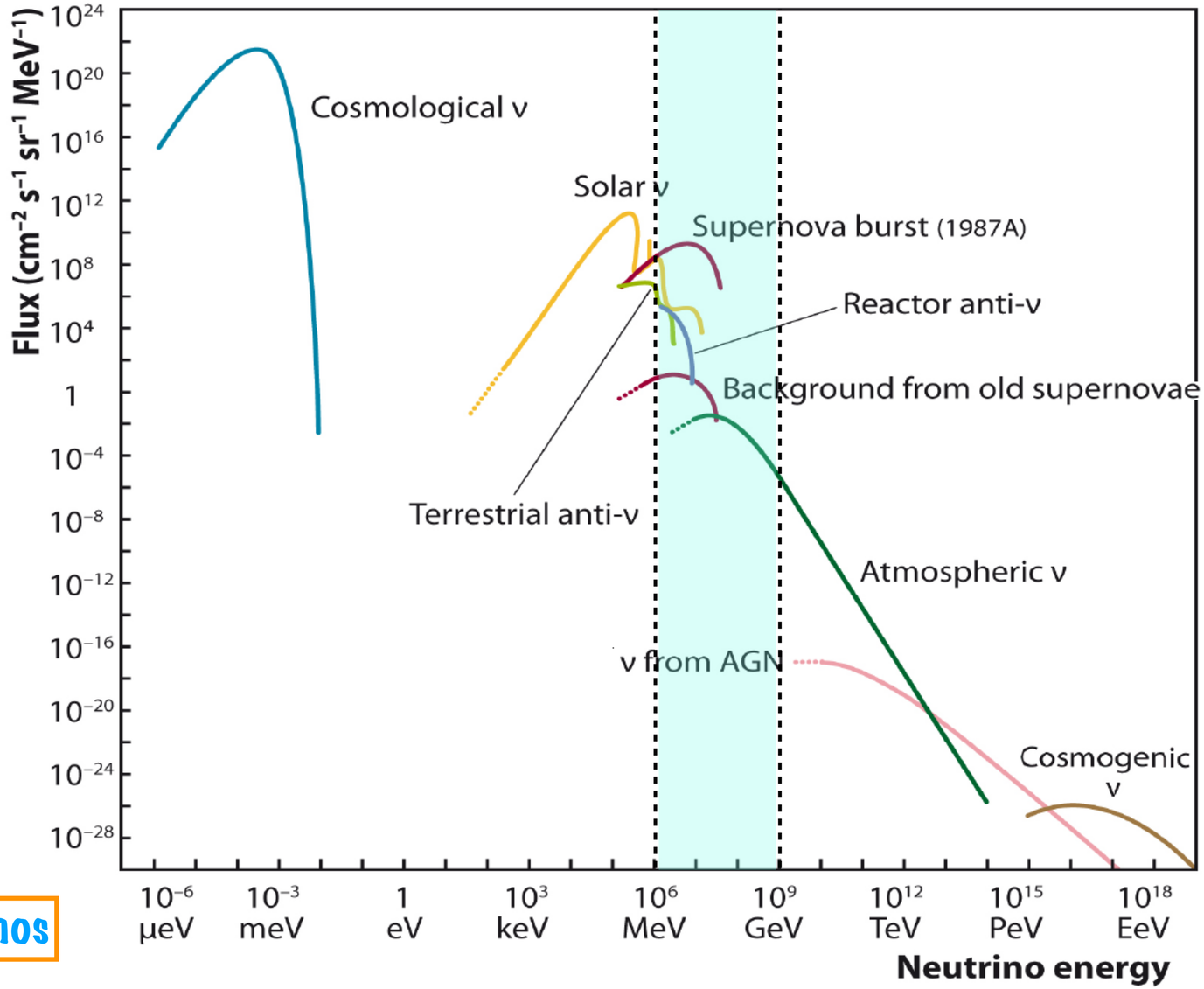
High energy neutrinos are p roduced in high energy partic ducing short lived mes neutrinos and other particles.

Pilar Casado's talk

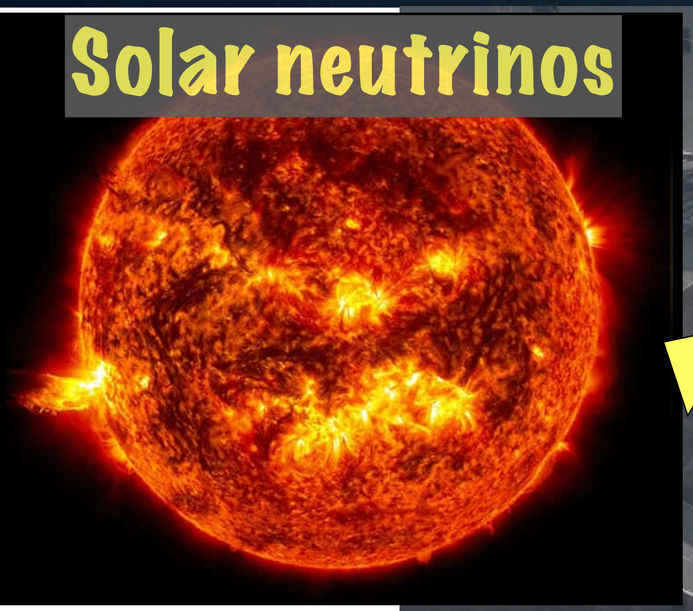
Energy range: 10th of GeV up to tenths of PeV

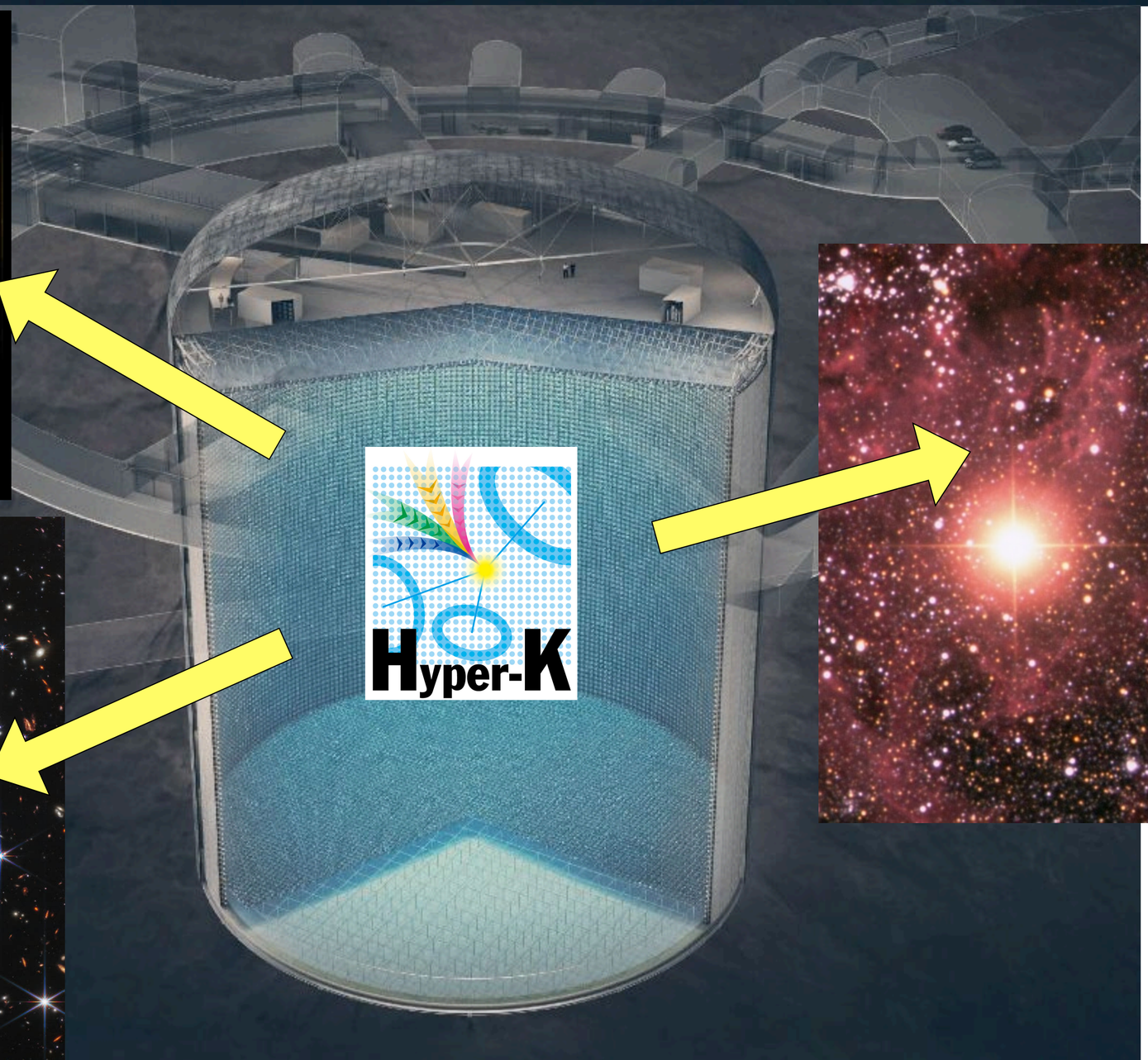
Very high energy neutrinos

C. Spiering, 2012



Low energy neutrino sources

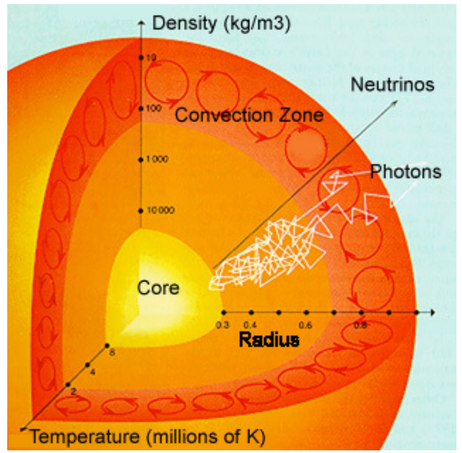




Solar neutrinos

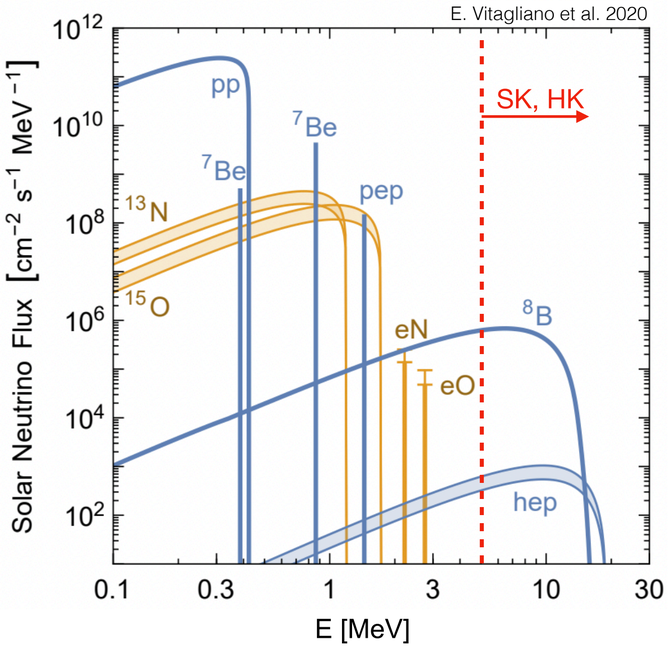
- Solar neutrinos are originated from nuclear reactions in the Sun.

Energy range solar neutrinos: 3.5 MeV - 15 MeV



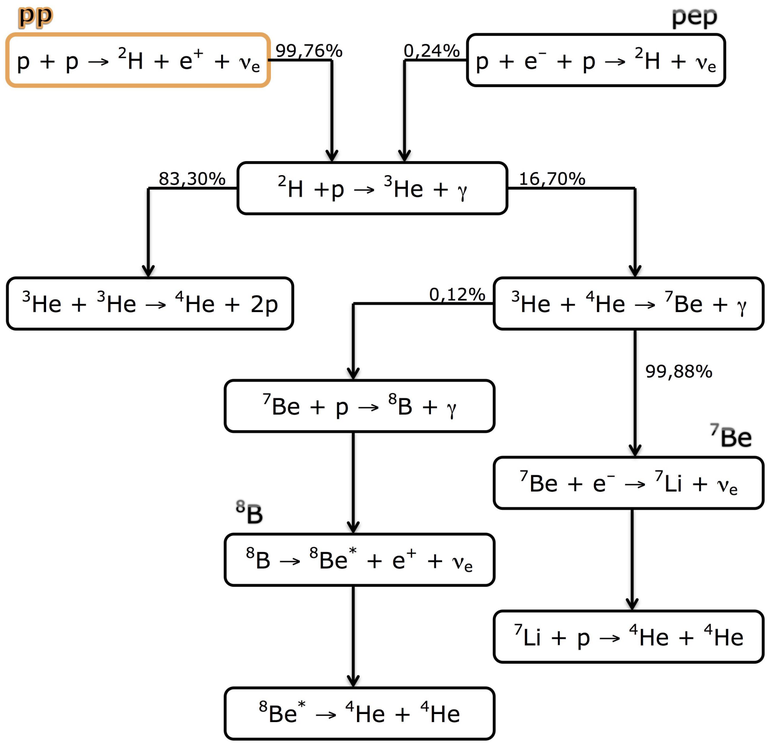
SSM

E. Vitagliano et al. 2020

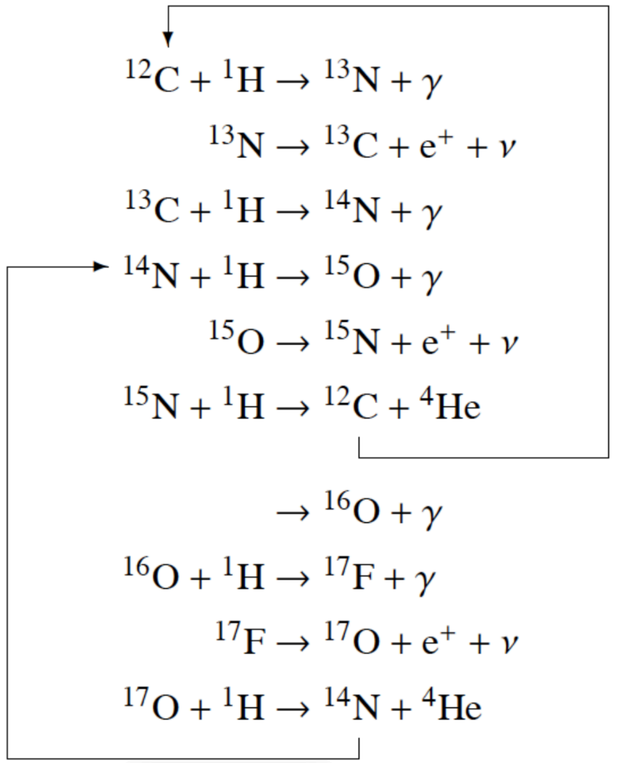


✺ The Sun emits **2.3%** of its nuclear energy production in the form of **MeV** range electron neutrinos.

pp-chain > 99%



CNO cycle < 1%

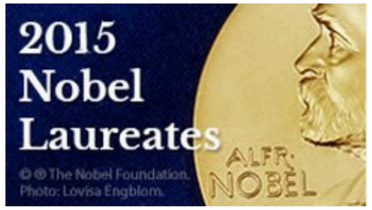


Solar neutrinos

- The measurement of solar neutrinos include several important topics.

☑ Information of the current status of the solar center.
☑ Study:
  - Mechanism of the energy generation in the Sun.
  - Properties of neutrinos.

Why to study Solar neutrino?



Takaaki Kajita (SK)

Art McDonald (SNO)

☆ Discover neutrino oscillations ⇨ evidence of mass!

Solution to the solar missing neutrino problem:

📌 The detected electron neutrino flow was inexplicable too much low.

Roughly two-thirds of electron neutrino ν_e change their flavor as they traveled, arriving as μ or τ neutrinos.

Solar neutrinos with Hyper-K

- Solar neutrino with $E_\nu > 4.5$ **MeV**, corresponding to the reaction of the ^{8}B neutrinos
- **130 events/day**, $E_{e,kin} > 4.5$ MeV through neutrino-electron elastic scattering.
- The energy, direction and time of the original neutrinos can be measured through the reconstruction of the recoil electron.

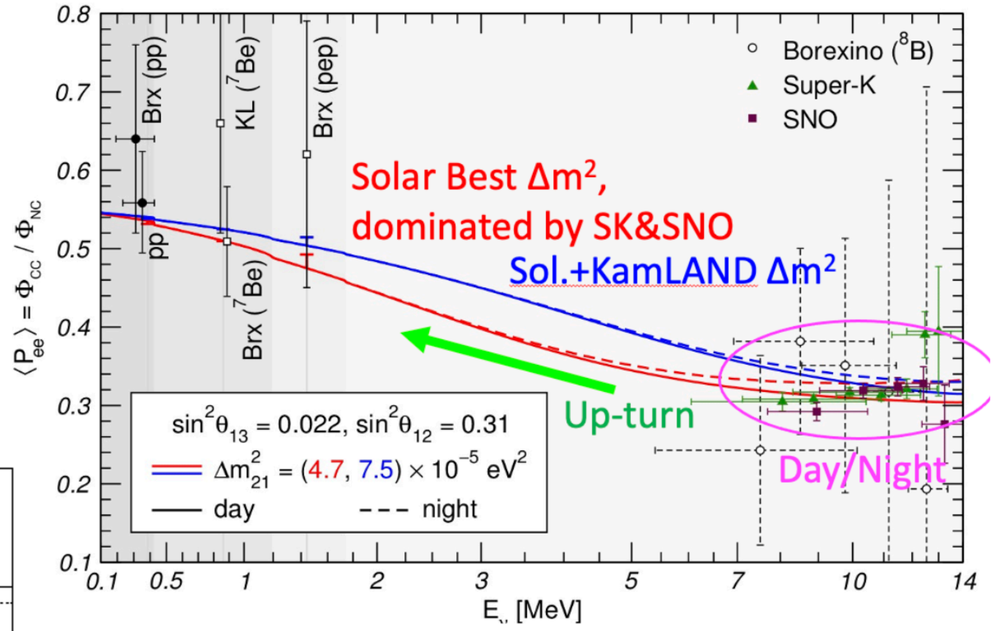
Particle physics:

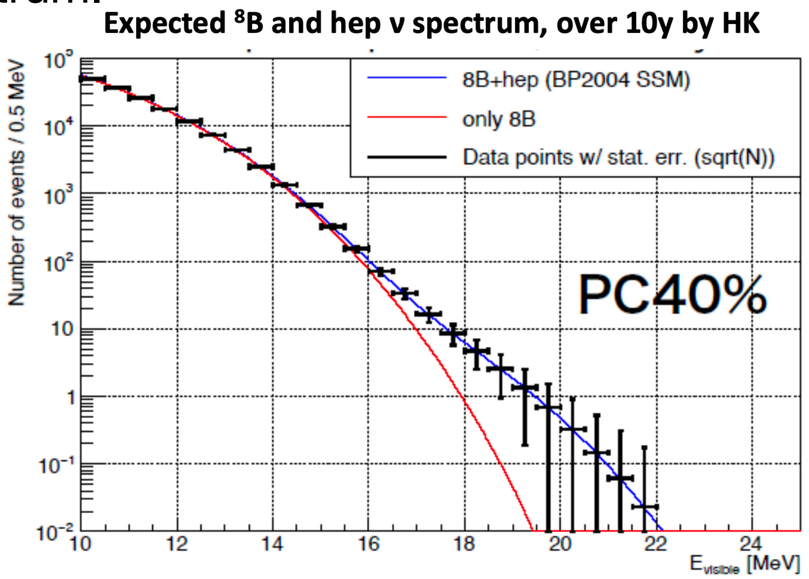
- Precision measurement, Δm^2_{21}
- Day/Night asymmetry of solar ν flux caused by terrestrial matter effect (indicated by SK).
- The «upturn» of the Solar ν spectrum.

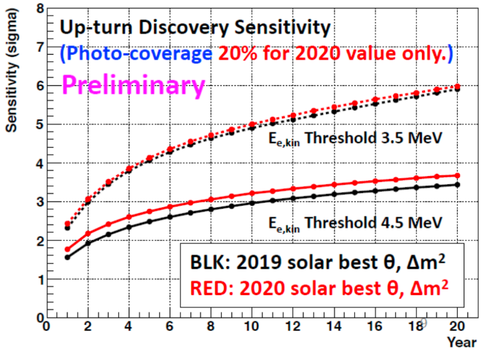
Astrophysics:

- Variation of solar ν flux.
- Discovery of hep neutrino.

Maltoni & Smirnov 2016



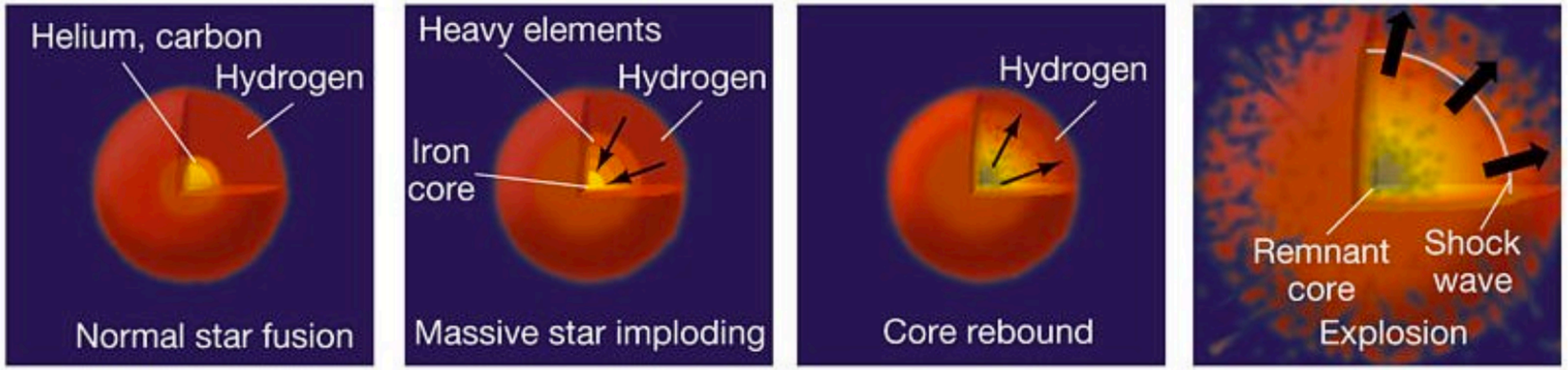




Supernova neutrinos

CCSNe

$M_\star > 8.0\ M_\odot$

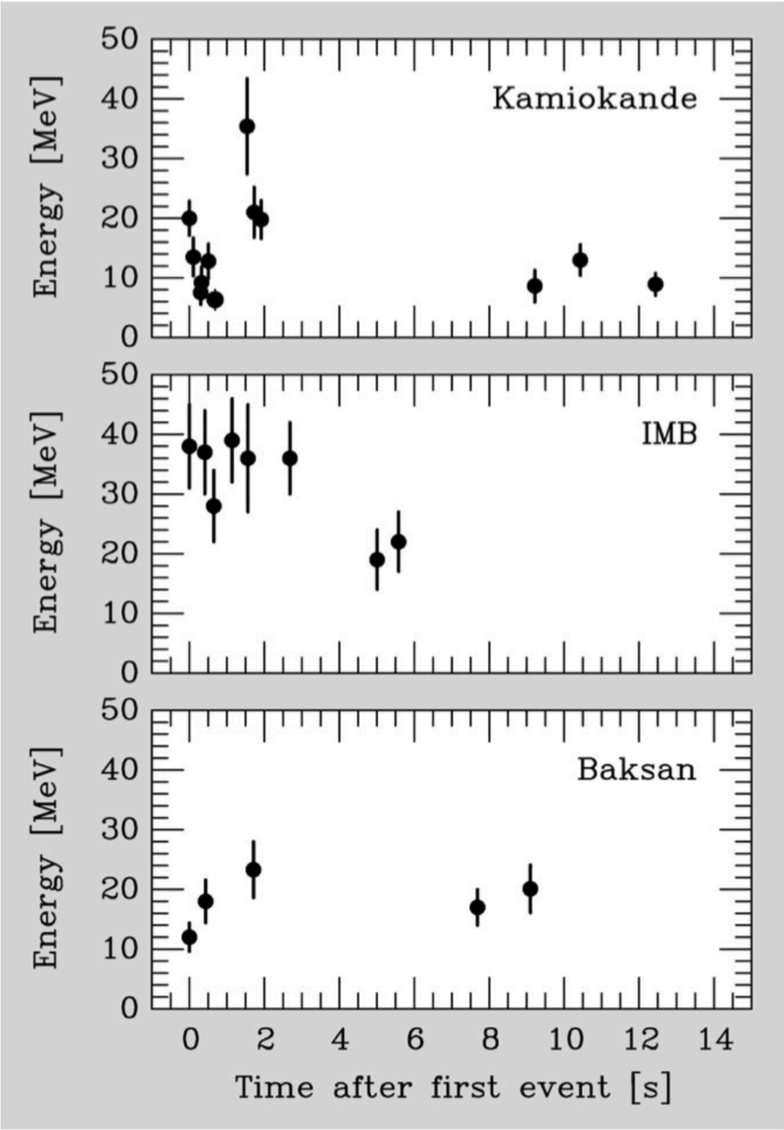


❋ Energy released by a CCSNe: ~3×10^{53} erg

99% of energy carried out by all 3 species of neutrinos and antineutrinos

☑ Information about the explosion mechanisms in the core of the collapsing star

Supernova neutrinos



SN1987A at 50 kpc : first detection of supernova burst neutrino

✦ Progenitor star properties:

– 18 $M_{\odot}$

– 51.4 kpc distance (LMC)

✦ 25 supernova neutrinos detected in three neutrino telescopes:

– **12 at Kamiokande.**

– 8 at Irvine-Michigan-Brookhaven (IMB).

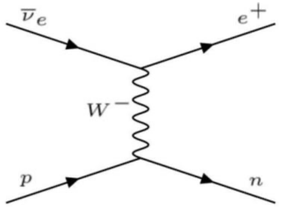
– 5 at the Baksan Observatory.

Confirmed that neutrinos bring most of the burst energy only in 10 sec

Supernova neutrino interactions in Hyper-K

✦ Dominant interaction is IBD

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



~90% of the expected interactions

✦ Sub-dominant interaction: elastic scattering

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

~5% of the expected interactions

Preserves direction information:

—> Directional resolution of 1° @ 10 kpc

MM observations

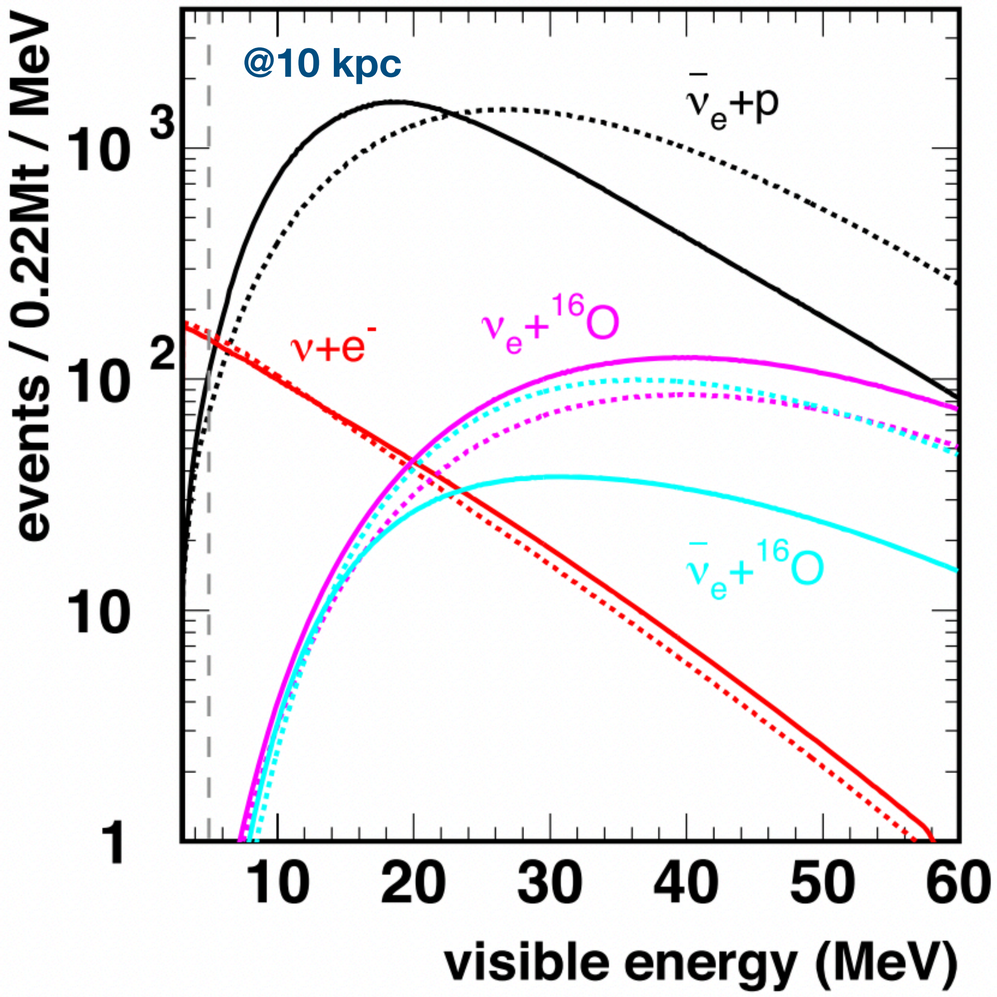
✦ Other modes: highly model dependent, due to threshold effects

e.g. $\nu_e + {}^{16}O \rightarrow e + {}^{16}F$ (E_{thresh} = 15 MeV)

~5% of the expected interactions

Sensitive probe of the high-energy tail of the supernova neutrino flux

K. Abe et al 2021 ApJ 916 15



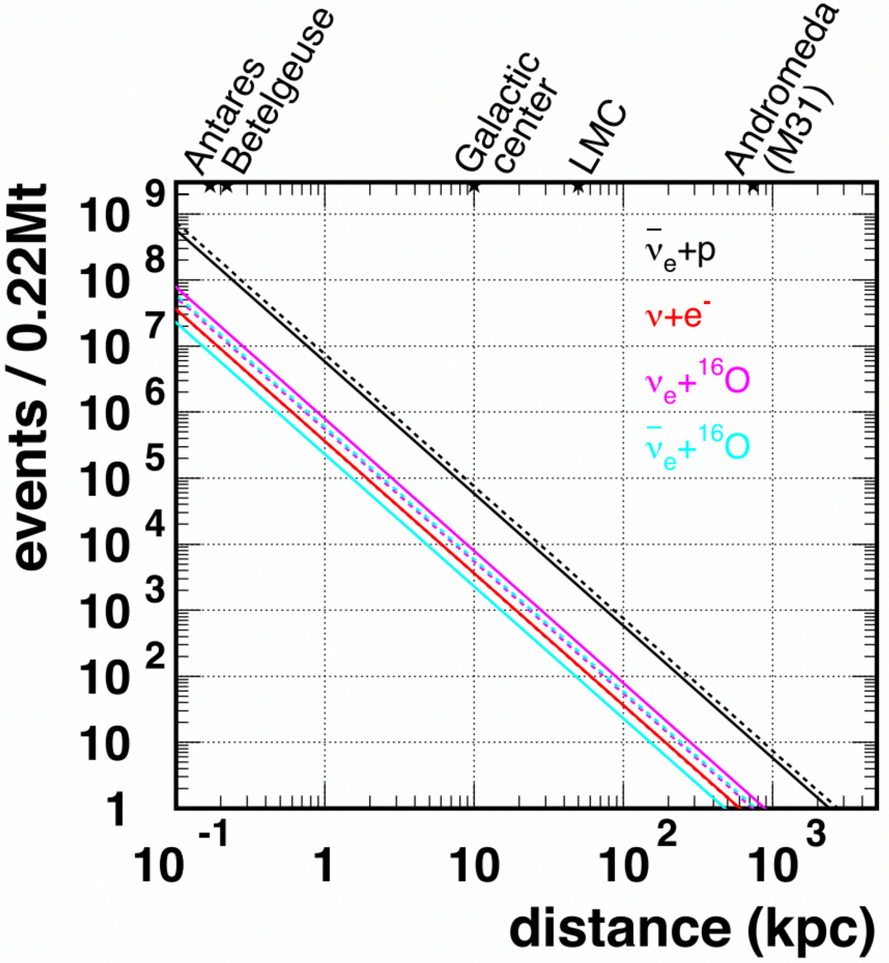
Supernova neutrinos in Hyper-K

K. Abe et al 2021 ApJ 916 15

- In case of Galactic supernova at a distance of **10 kpc**, Hyper-K is expected to observe **54 000 to 90 000 events** in a burst with a duration of a few tens of seconds.

The large volume also gives Hyper-K an unprecedented ability to detect neutrinos from supernovae beyond the Milky Way:

- For a supernova in the Large Magellanic Cloud at **50 kpc**, it would still detect about **3000 events**,
- For a supernova in the Andromeda galaxy (M31) at **780 kpc** distance, ~10 events are expected.



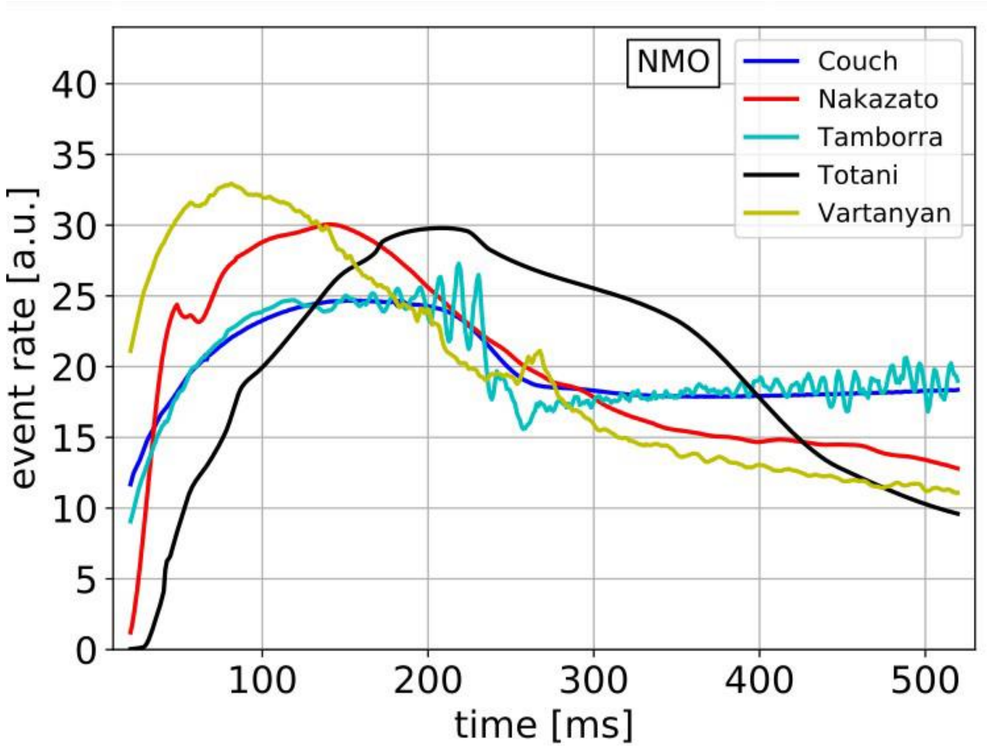
Supernova neutrinos in Hyper-K

✳ Hyper-K will be able to distinguish between different explosion mechanism models.

Focusing on the first 500 ms of the neutrino burst, corresponding to the accretion phase, and using a newly developed, high-precision supernova event generator to simulate Hyper-K's response to five different supernova models.

K. Abe et al 2021 ApJ 916 15

Model	Mass		events at 10 kpc*	N=100	N=300
Totani arXiv:astro-ph/9710203	20 $M_\odot$	1D	19716	140 kpc	81 kpc
Nakazato arXiv:1210.6841	20 $M_\odot$	1D	17978	134 kpc	77 kpc
Couch arXiv:1902.01340	20 $M_\odot$	1D	27539	166 kpc	96 kpc
Vartanyan similar to arXiv:1804.00689	9 $M_\odot$	2D	10372	102 kpc	59 kpc
Tamborra arXiv:1406.0006	27 $M_\odot$	3D	25021	158 kpc	91 kpc



Supernova Relic Neutrino (or DSNB)

★ **Neutrino flux** from all past **Core Collapse SNe (CCSNe)**.

★ DSNB is composed of neutrinos of all flavors whose energies have been redshifted when propagating to Earth.

★ Spectrum contains unique information: Detection and characterization would allow for the study of aggregate properties of **core-collapse supernovae**, while probing the **history of the Universe** and **neutrino properties**.

DSNB flux:

$$\frac{d\Phi(E_\nu)}{dE_\nu} = c\int_0^\infty \frac{dz}{H_0\sqrt{\Omega_m(1+z)^3+\Omega_\Lambda}} \times \left[R_{CCSN(z)}\int_0^{Z_{max}} \Psi_{ZF}(z,Z)\left\{\int_{M_{min}}^{M_{max}} \Psi_{IMF(M)}\frac{dN(M,Z,E'_\nu)}{dE'_\nu}dM\right\}dZ\right]$$

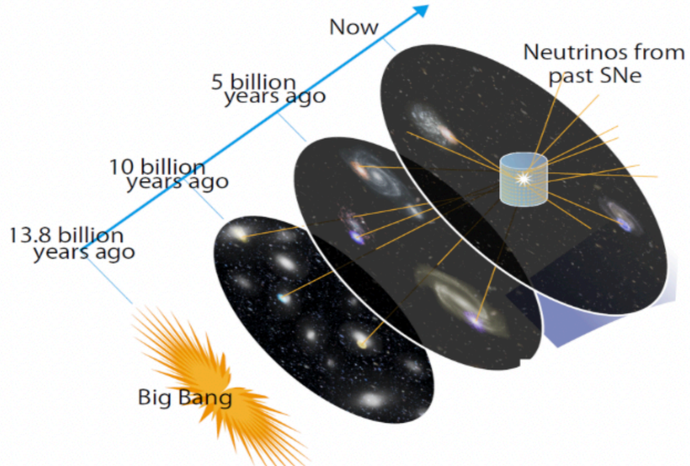
cosmological parameters

neutrino number spectrum for CCSNe

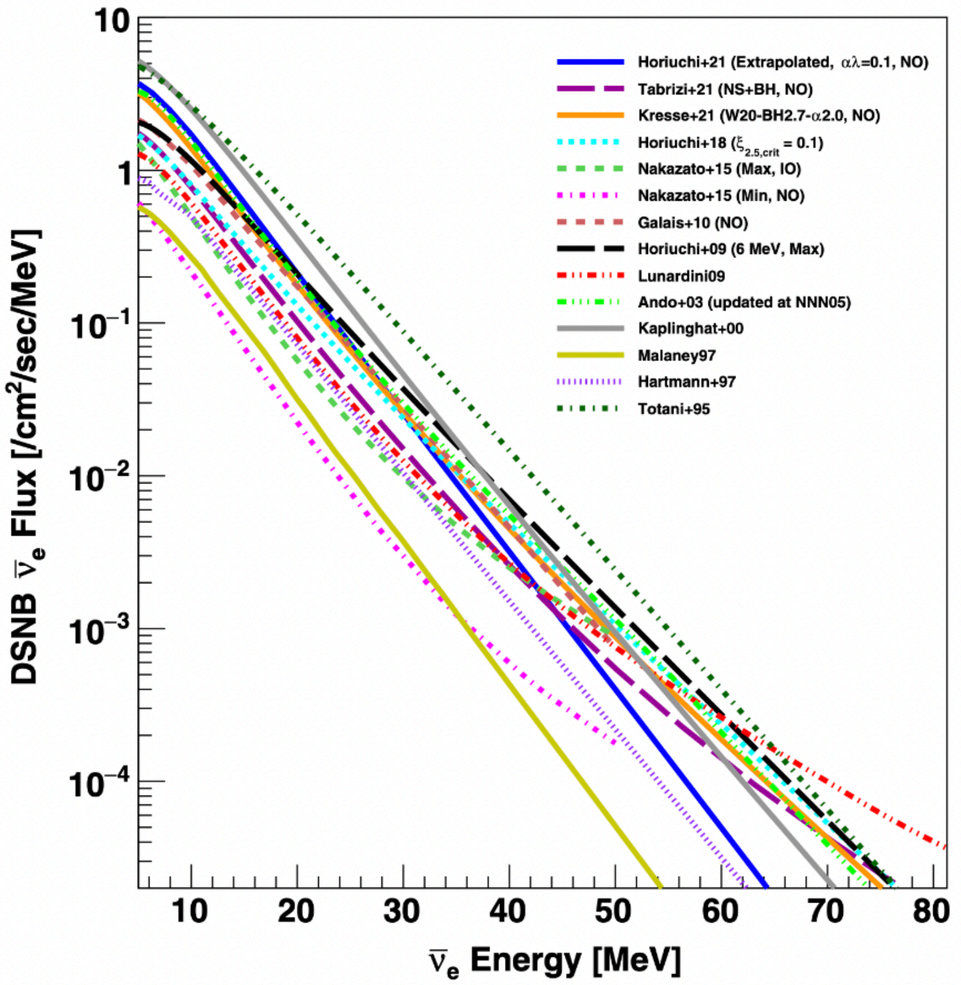
CCSNe rate

metallicity distribution of progenitors

initial mass function of progenitors



DSNB Flux predictions

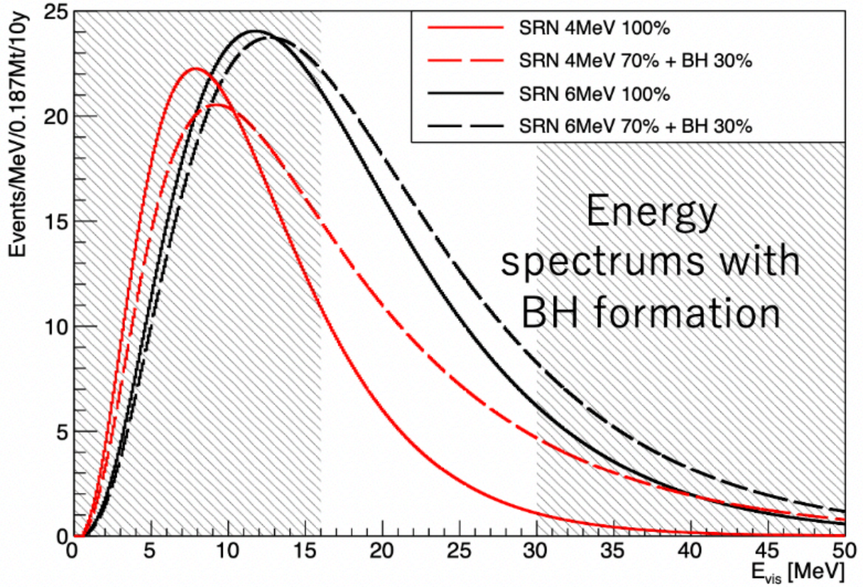


★ **No evidence for the DSNB signal has been confirmed.**

→ upper limits set by various underground experiments:
SK holds the current best limits for the DSNB flux.

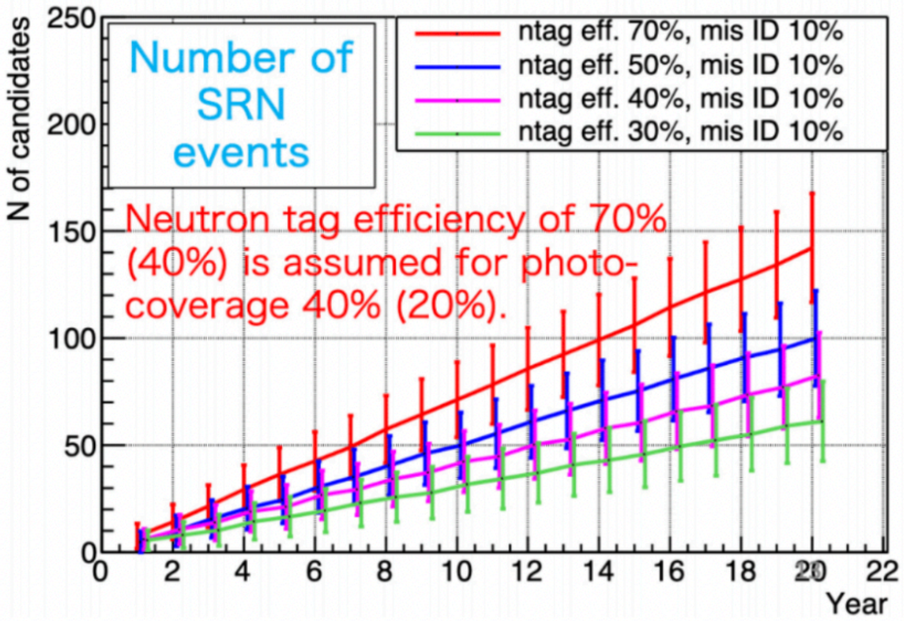
Supernova Relic Neutrino

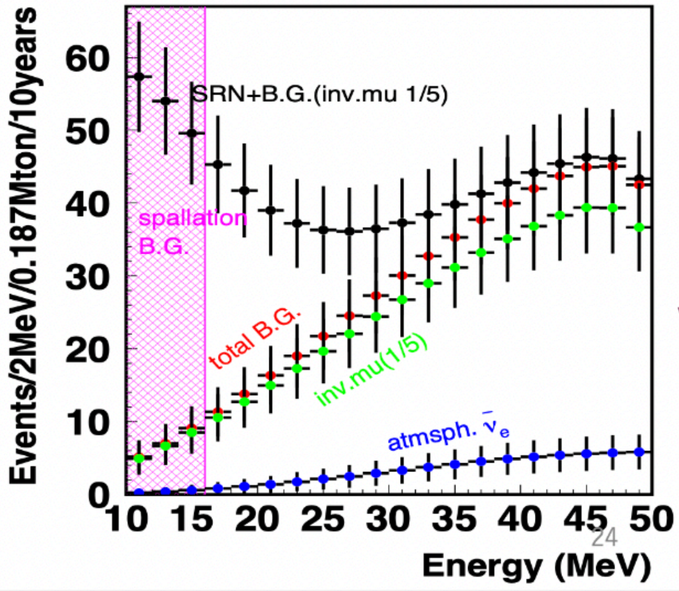
- The number of detected **SRN** events is predicted for various neutron-tagging configurations.
- Expected SRN events in E=16-30 MeV are **~70±17 events** observed by HK in **10y**.
- This corresponds to **4σ sensitivity.**
- We will go beyond the discovery and aim to measurement of SRN.



SRN signal expectations

More details:
- **ApJ, 916, 1, 15 (2021)**
- **arxiv: 1805.04163**





SRN expected spectrum with neutron tagging

Summary

Solar neutrino measurement is one of the features of Hyper-K.

Several precise measurements of solar neutrinos would be possible with Hyper-K and its high statistics:

- Solar neutrino oscillations
- The search for physics beyond the standard model
- The first measurement of hep process neutrino
- The seasonal variation measure of the ^8B neutrino flux.

Unique high statistics information for SN burst and SRN:

For a galactic supernova at a fiducial distance of 10 kpc, Hyper-K will detect 10^5 neutrinos within about 10 s:

- Time variations can be revealed
- Information on properties of the progenitor (like its rotation) or on details of the supernova explosion mechanism.

✤ Newly-developed, high-precision supernova event generator to simulate Hyper-Kamiokande's response to five different supernova models.

✤ Hyper-K will be able to distinguish between these models with high accuracy for a supernova at a distance of up to 100 kpc.

Summary

✤ Hyper-Kamiokande will provide the largest sample of SN neutrino events, including elastic scatter events with direction of the supernova and enable the astronomical community to engage in multi-messenger discoveries.

✤ Better understand the core-collapse in SN, the explosion mechanism, the proto-neutron star formation…

✤ SN alert with directional information could be followed up on multi-messenger analyses, combining observations with gravitational wave, gamma-ray, X-ray emissions.

✤ Pre-Supernova alarm could be developed → early warnings for Supernova detection!