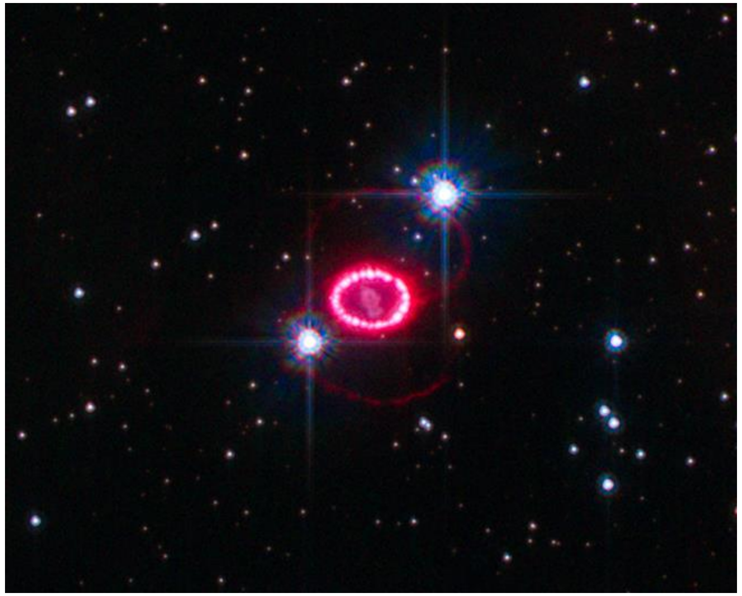
PROBING NEW PHYSICS WITH THE DIFFUSE SUPERNOVA NEUTRINO BACKGROUND

Clément Ehrhardt


[1]

[1] NASA, ESA, K. France (University of Colordo, Boulder), and P. Challis and R. Kirshner (Harvard-Smithsonian Center for Astrophysics)

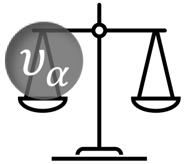
Quick reminder: neutrino physics

→ weakly interacting particle: $l_{matter} = \frac{10^9\text{km}}{E/\text{GeV}}$

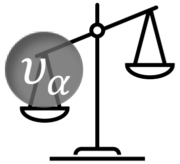
$\sim 10^4\text{km}$

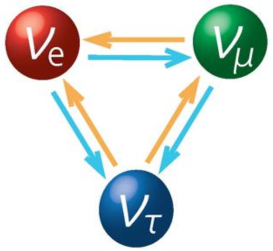
$\Rightarrow$ $E \sim 10^5\,\text{GeV}$

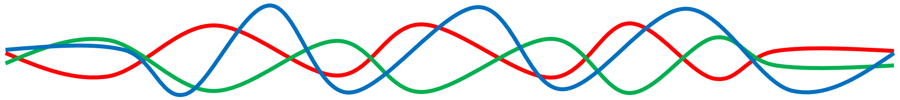
Standard Model | Experimentally

→ 

$\neq$





→ flavour fields ≠ mass fields  neutrino flavour oscillation

$$|\nu_\alpha\rangle = \sum_k U^*_{\alpha k}\,|\nu_k\rangle$$

└── PMNS matrix

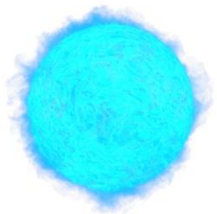
→ neutrino oscillation in **vacuum** + resonant flavour transition in **matter** (MSW effect)

└── Solar neutrino problem └── Atmospheric anomaly

→ unknown properties: mass, nature, oscillation parameters, …

C. Giunti and C.-W. Kim, Fundamentals of neutrino physics and astrophysics

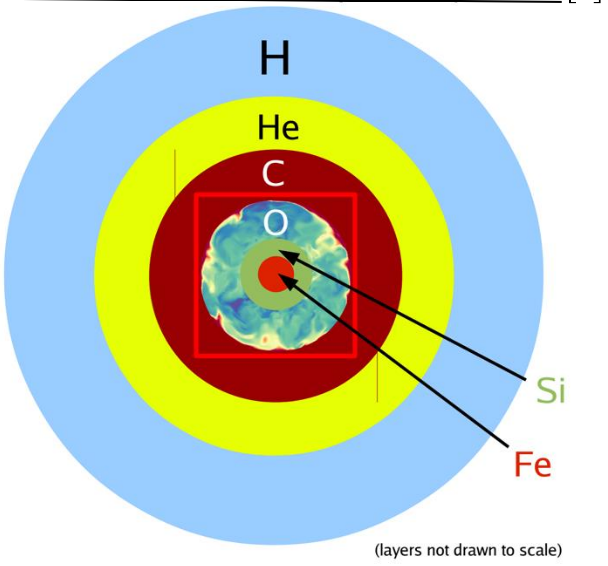
Supernova neutrino emission



Main sequence end

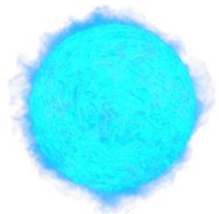
$\geq 8M_{\odot}$

Onion-shell structure of pre-collapse star [2]



[1] M.A. Acero et al JCAP10(2020)014
[2] Janka, HT. (2017). Neutrino-Driven Explosions
[3] Sumiyoshi and al. (2023). Equation of State in Neutron Stars and Supernovae.

Supernova neutrino emission



$\geq 8M_\odot$

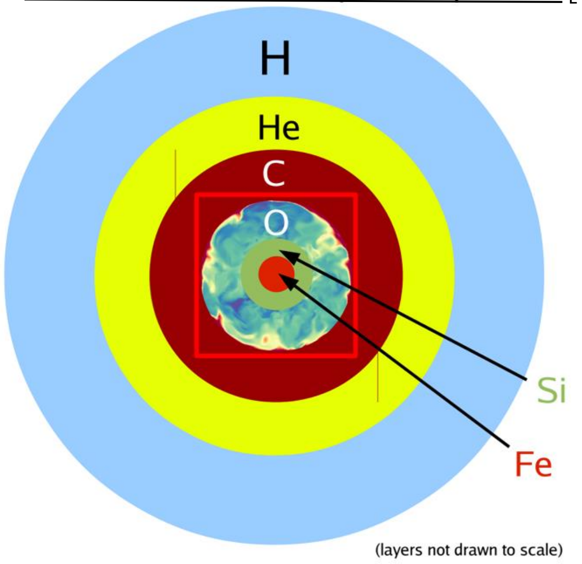
Main sequence end →

Gravitational core-collapse supernovae

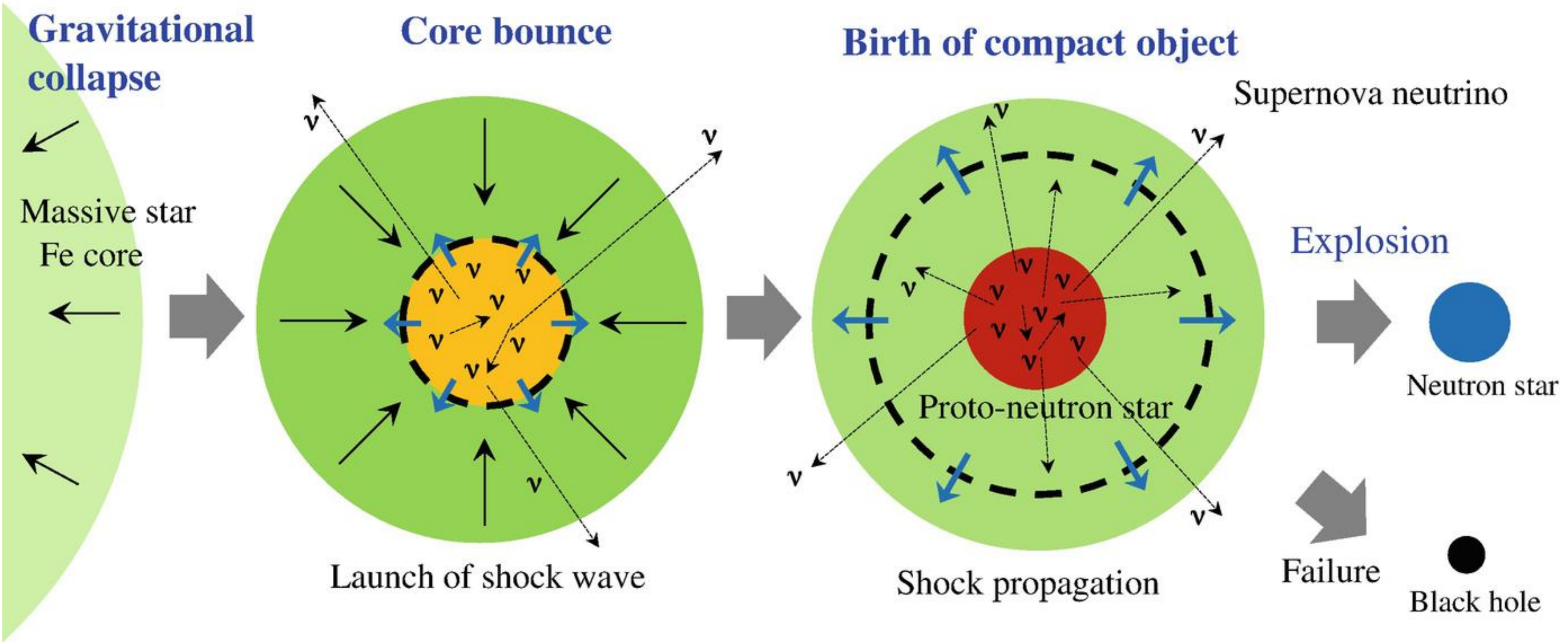
Black hole

Neutron star

Onion-shell structure of pre-collapse star [2]



Gravitational core-collapse mechanism [3]



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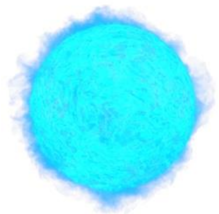
Supernova neutrino emission



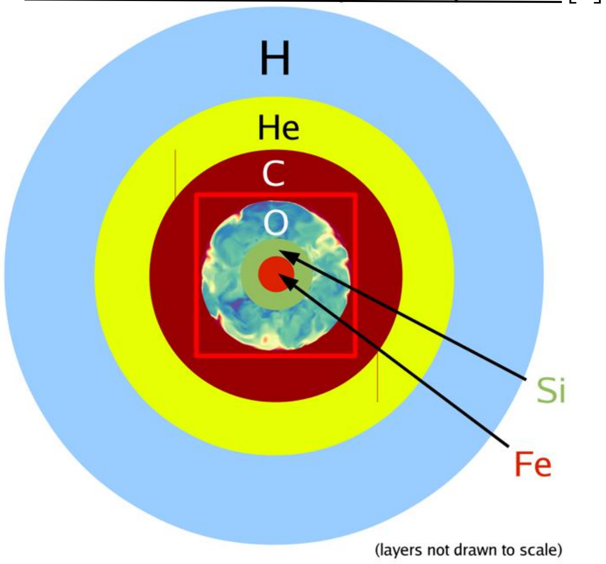
$\geq 8M_\odot$

Main sequence end → Gravitational core-collapse supernovae → emission → $\sim 10^{58}$ neutrinos

Gravitational core-collapse supernovae → Black hole / Neutron star

$\sim 10^{58}$ neutrinos →
- 99% of the energy [1]
- Emitted in 10s
- $E_\nu \sim$ tens of MeV

Onion-shell structure of pre-collapse star [2]



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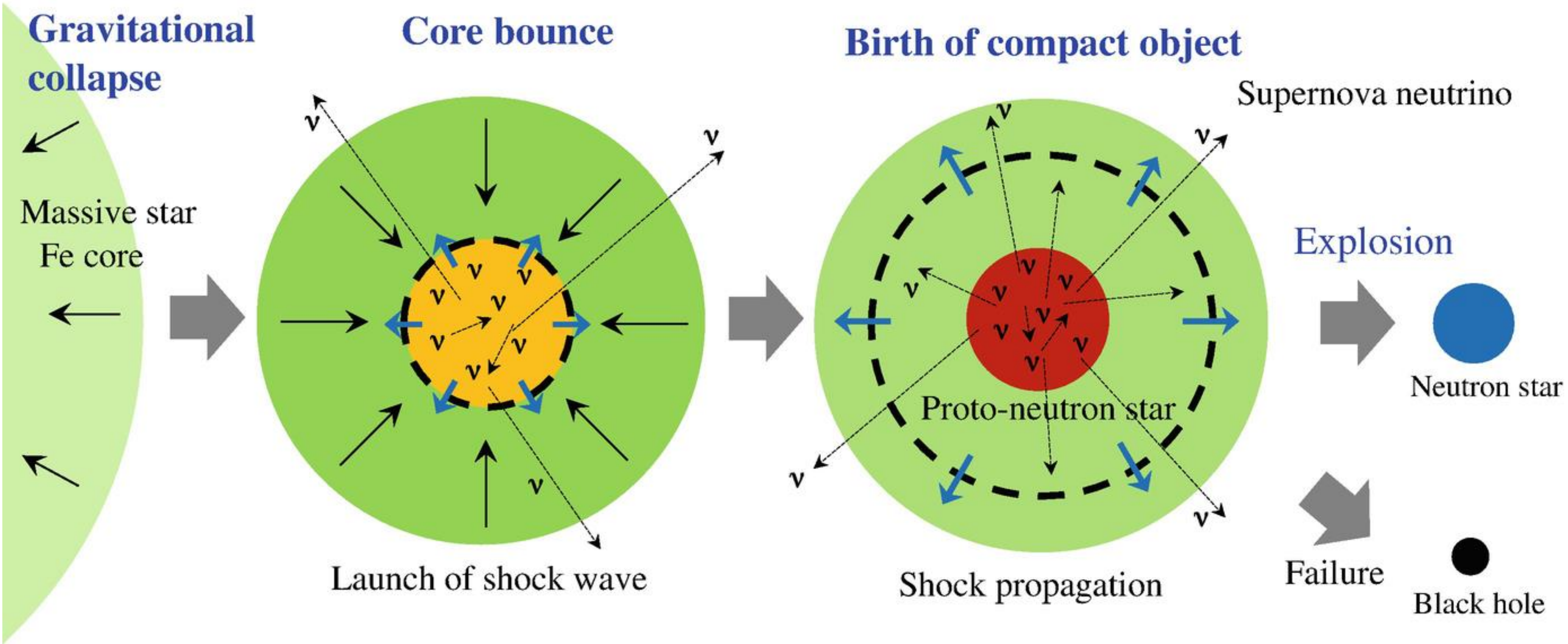

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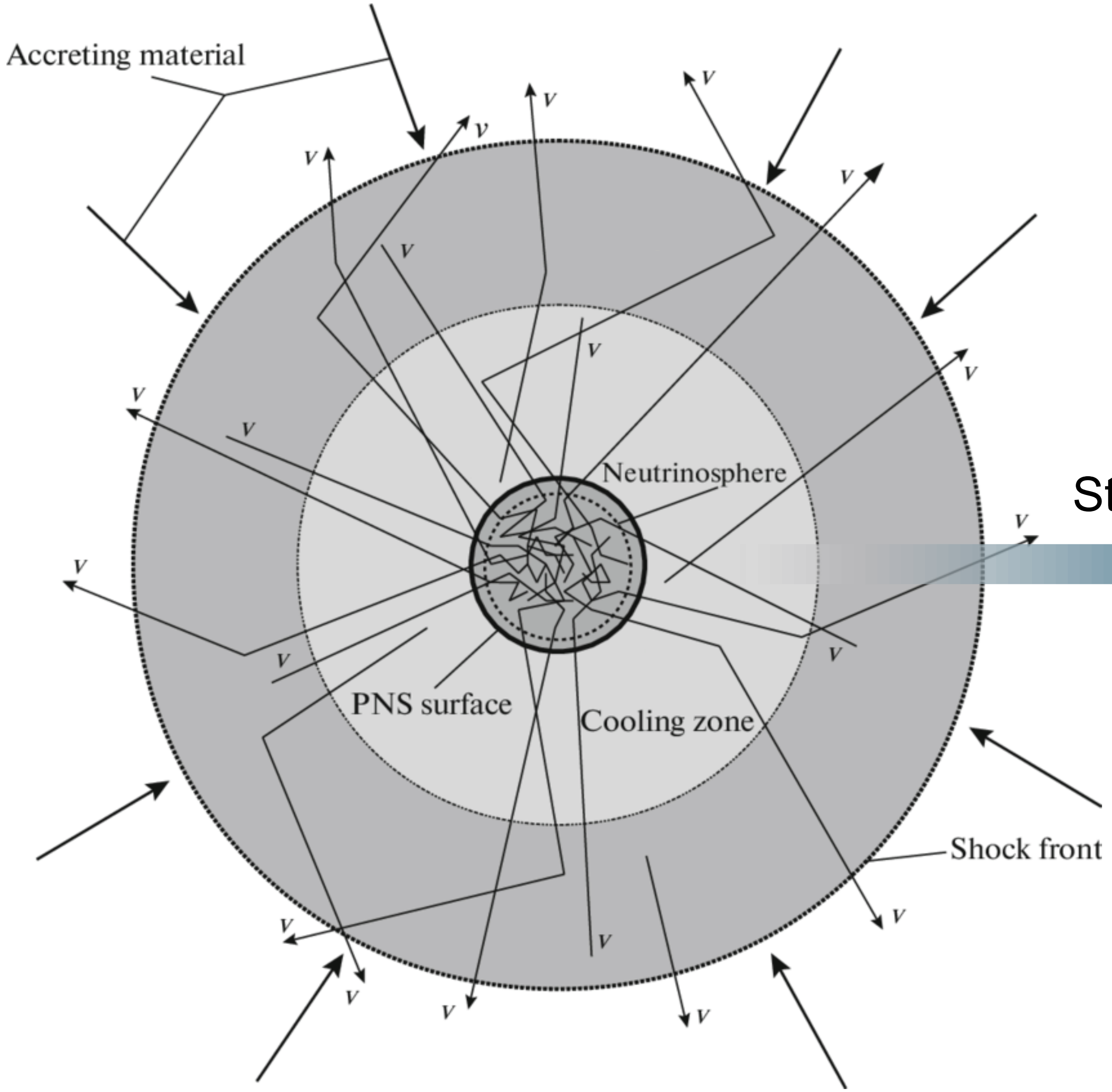
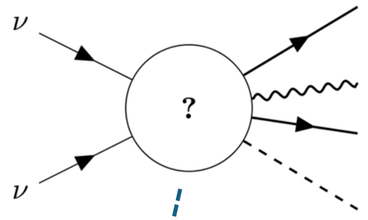
Non-standard effect



Neutrinosphere = virtual surface at which neutrinos start free-streaming

Standard effect : MSW

Non-standard effect



…

Shock wave

$\nu\nu$ self-interaction

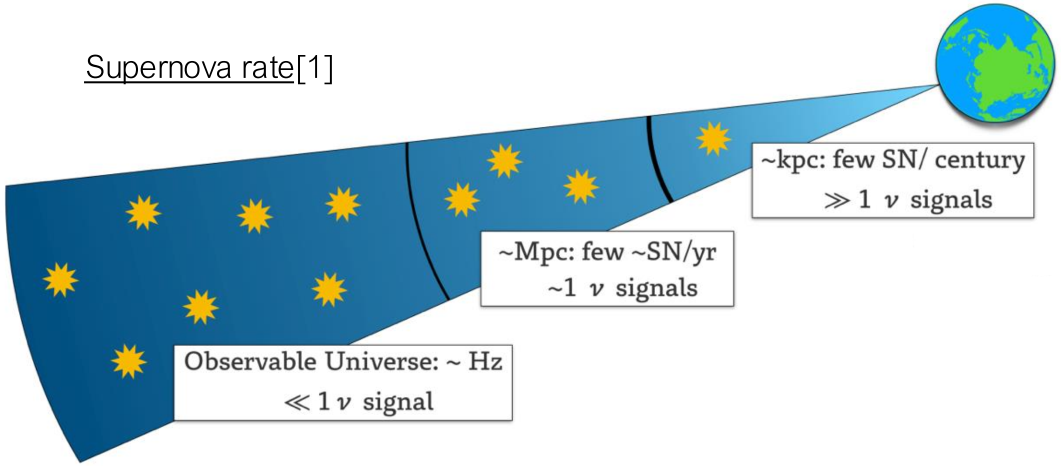
Two-body non radiative decay

[1] Krivosheyev & Bisnovatyi-Kogan (2018). Monte Carlo Simulations of Radiative and Neutrino Transport under Astrophysical Conditions.

Diffuse supernova neutrino background

→ Nearby supernovae are rare, the last one with 24 detected events was SN 1987A

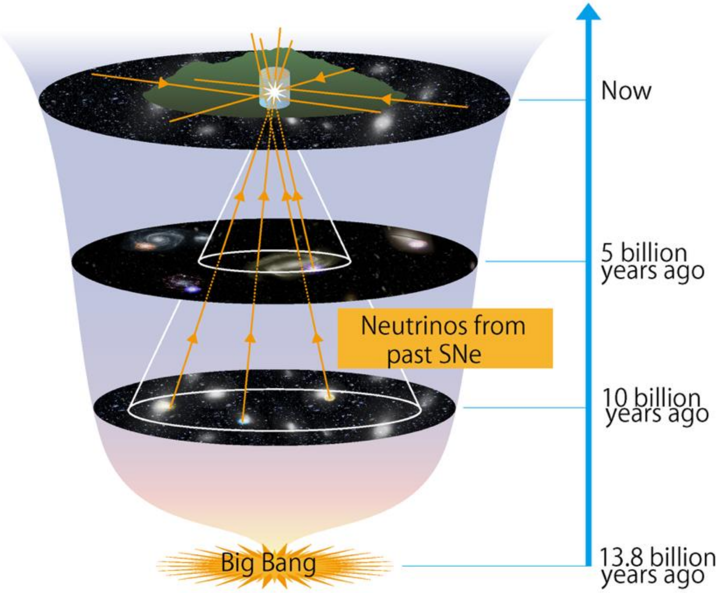
Supernova rate[1]



→ Diffuse supernova neutrino background (DSNB) = sum of all neutrinos emission from past supernovae

- Isotropic
- Time-independent
- In the MeV range
- **The DSNB is always present!**

DSNB[2]



[1] Masayuki Harada ICRR, University of Tokyo, NEUTRINO 2024
[2] 2020 Kamioka Observatory, ICRR (Institute for Cosmic Ray Research), The University of Tokyo

DSNB formula

Cosmological model (ΛCDM)

$$\left|\frac{dz}{dt_c}\right| = H_0(1+z)\sqrt{\Omega_\Lambda + (1+z)^3\Omega_m}$$

Core-collapse supernova rate

$$R_{\rm SN}(z,M) = \dot{\rho}_*(z)\frac{\phi(M)dM}{\int_{0.1M_\odot}^{100M_\odot} M\phi(M)dM}$$

COSMOLOGY

ASTROPHYSICS

$$\frac{d\phi_{\nu_\alpha}}{dE_\nu} = c\int\int dM\,dz\,(1+z)\left|\frac{dt_c}{dz}\right| R_{\rm SN}(z,M)\,\phi_{\nu_\alpha}(E_\nu(1+z),M)$$

ASTROPHYSICS +
PARTICLE PHYSICS

Neutrino flux for a given supernova

$$\frac{L_\nu^i}{\langle E_\nu^i\rangle}\phi_\nu^i(E_\nu)$$ + matter effects

DSNB detection

→ Contains information about cosmology, astrophysics and particle physics

$$\frac{d\phi_{\nu_\alpha}}{dE_\nu} = c \int \int dM\, dz\, (1+z) \left| \frac{dt_c}{dz} \right| R_{\rm SN}(z, M)\, \phi_{\nu_\alpha}(E_\nu(1+z), M)$$

DSNB detection

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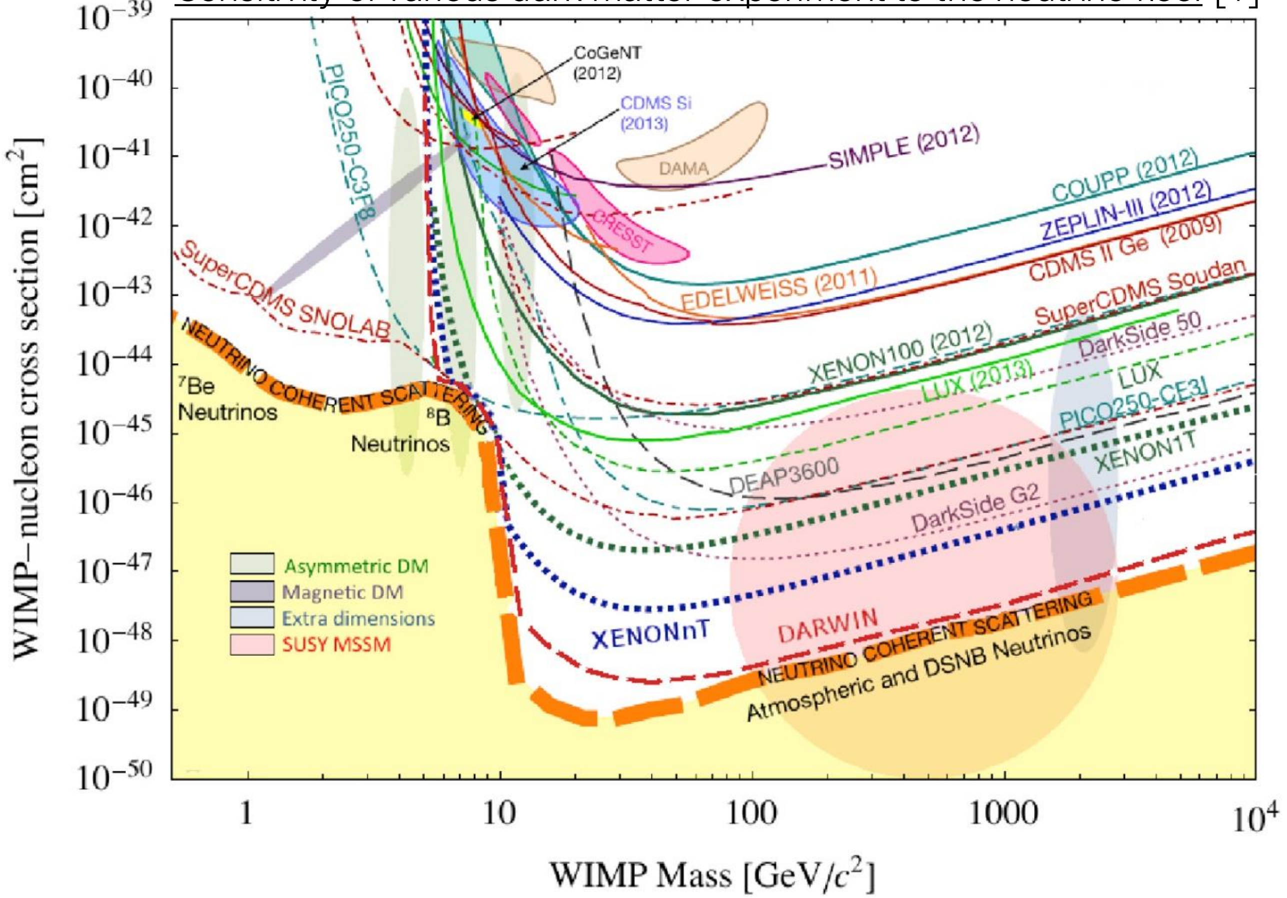
→ Background noise for dark matter experiments:

Sensitivity of various dark matter experiment to the neutrino floor [1]



[1] Snowmass CF1 Summary: WIMP Dark Matter Direct Detection (2013)

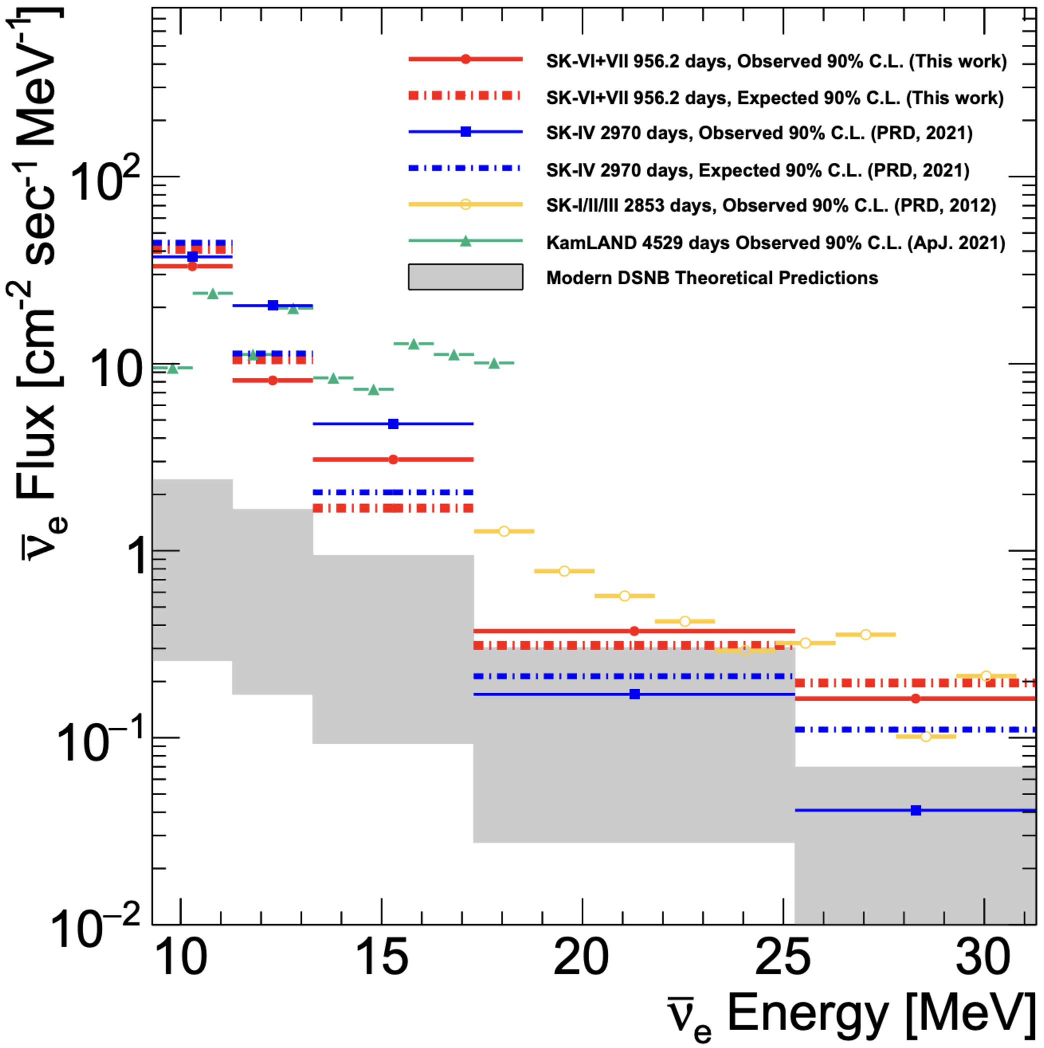
DSNB detection

→ Contains information about cosmology, astrophysics and particle physics

→ Background noise for dark matter experiments

→ Excess 2.3σ[1] in the concerned energy range

With SK-Gd for a ~ 1000 days:



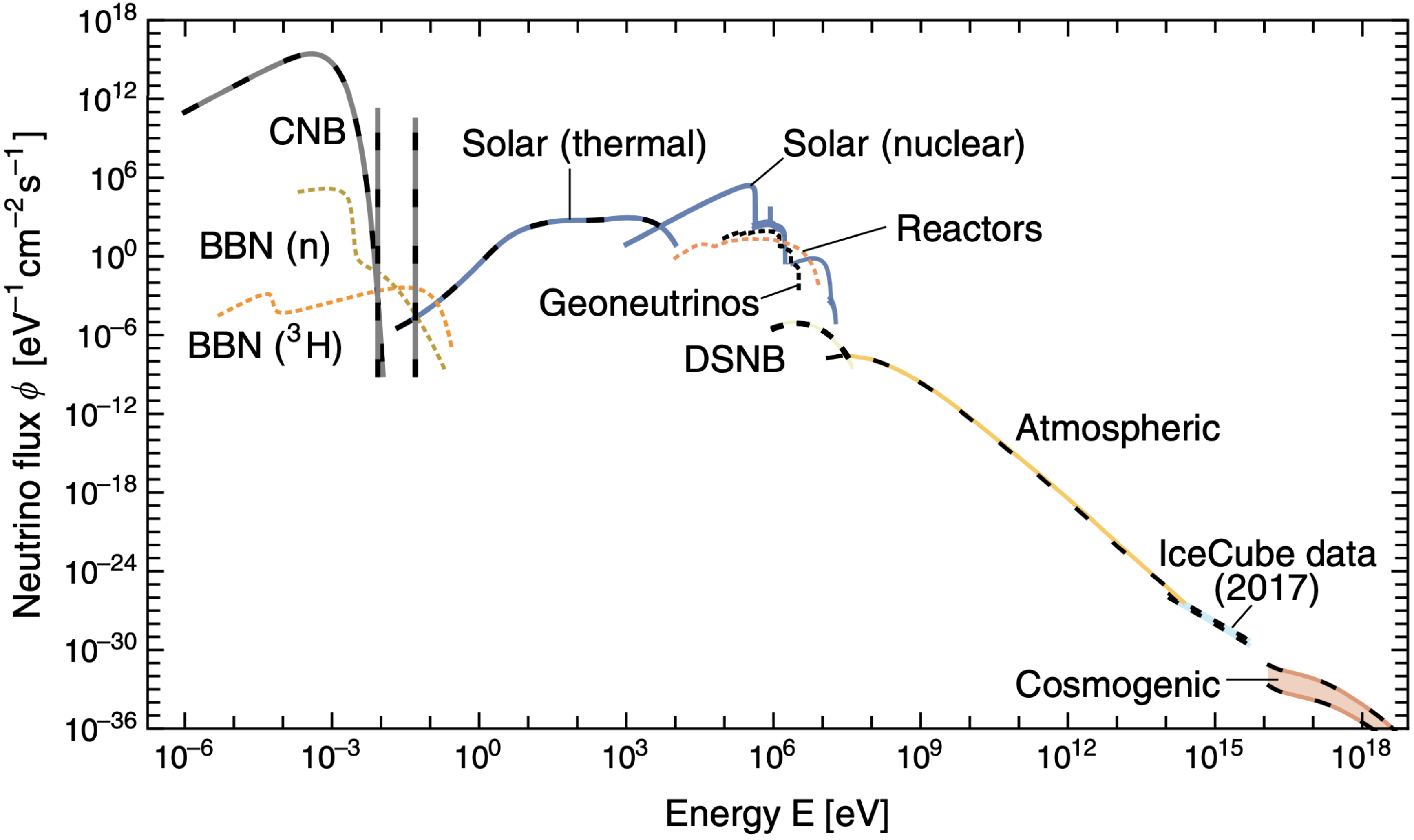
Abe and al. (2025). Search for Diffuse Supernova Neutrino Background with 956.2 days of Super-Kamiokande Gadolinium Dataset

[1] Masayuki Harada ICRR, University of Tokyo, NEUTRINO 2024

Thank you for your attention!

Backup : neutrinos spectrum

Grand unified neutrino spectrum



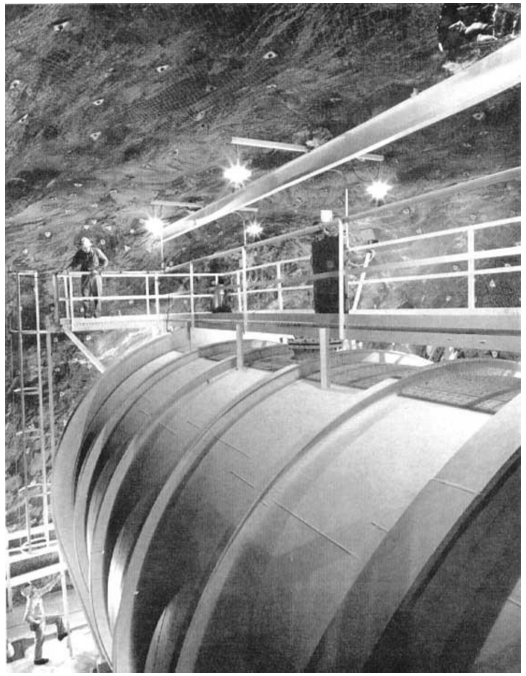
Vitagliano and al. (2020). Grand unified neutrino spectrum at Earth: Sources and spectral components

Backup : neutrino investigation

Solar neutrino problem

→ First solar neutrinos detected in 1968 by the Homestake experiment

→ Problem : only one-third of the predicted solar neutrino flux was actually reaching the Earth



Atmospheric anomaly

→ IMB experiment sensitive to the atmospheric neutrinos from the interaction of cosmic rays with the atmosphere

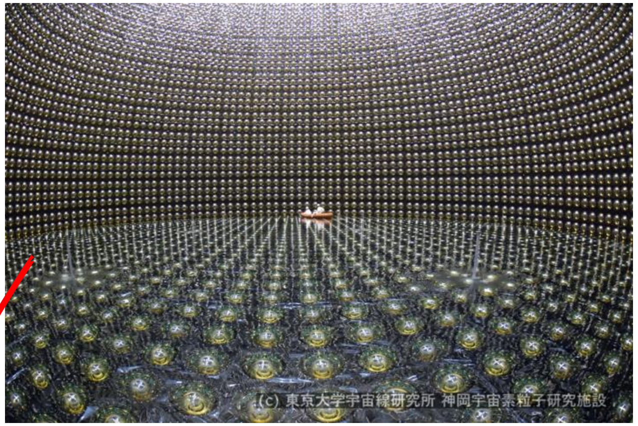
→ Problem : measured reduced ratio υ_μ/υ_e

⇒ Solution : MSW effect from Wolfenstein (1978) and Mikheev and Smirnov (1986)

└── Validated experimentally by SK (1998), SNO (2001) and KamLand (2003)

Backup : SK and HK

Expérience Super-Kamiokande [1]



Running from 2020

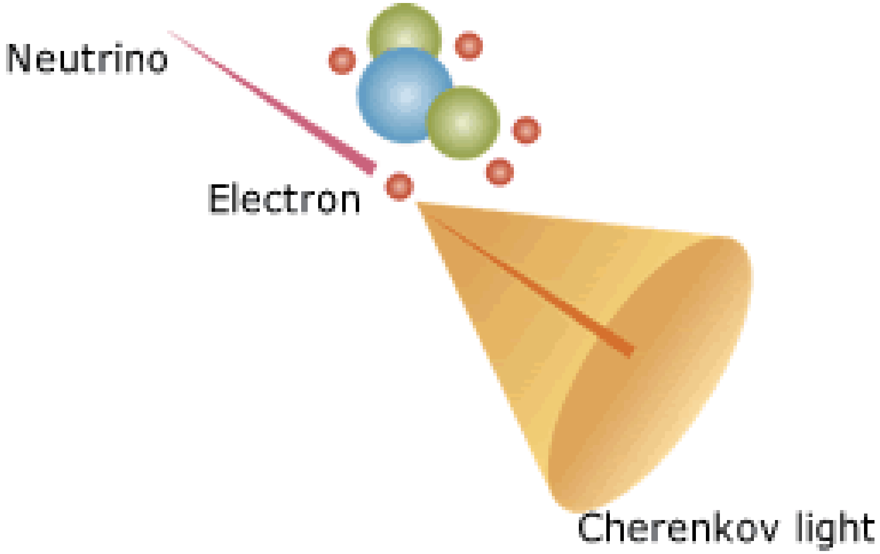
x8.3

Expérience Hyper-Kamiokande [2]

Start in 2028

detection

Inverse Beta Decay (IBD)



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

[1] Masayuki Harada ICRR, University of Tokyo, NEUTRINO 2024
[2] Kamioka Observatory, ICRR, The Univ. of Tokyo

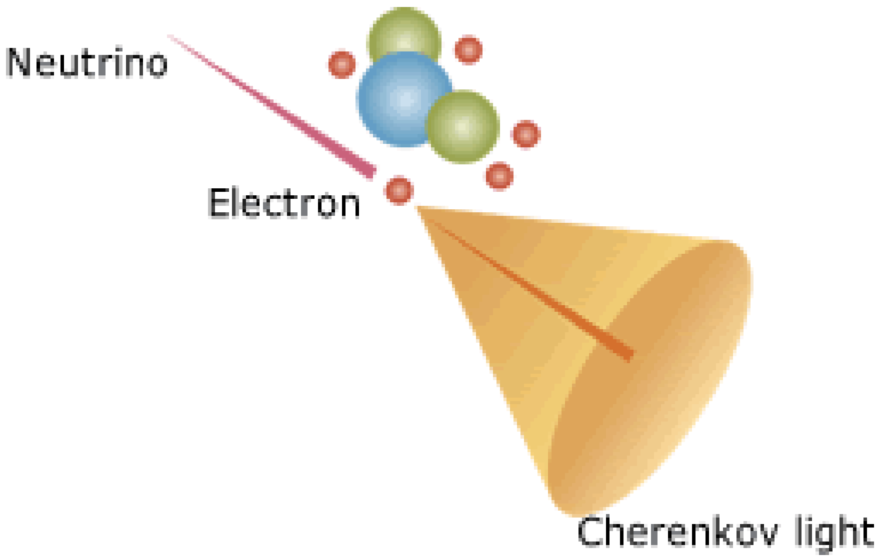
Backup : JUNO

Expérience JUNO [1]

Start in 2026

detection

Inverse Beta Decay (IBD)

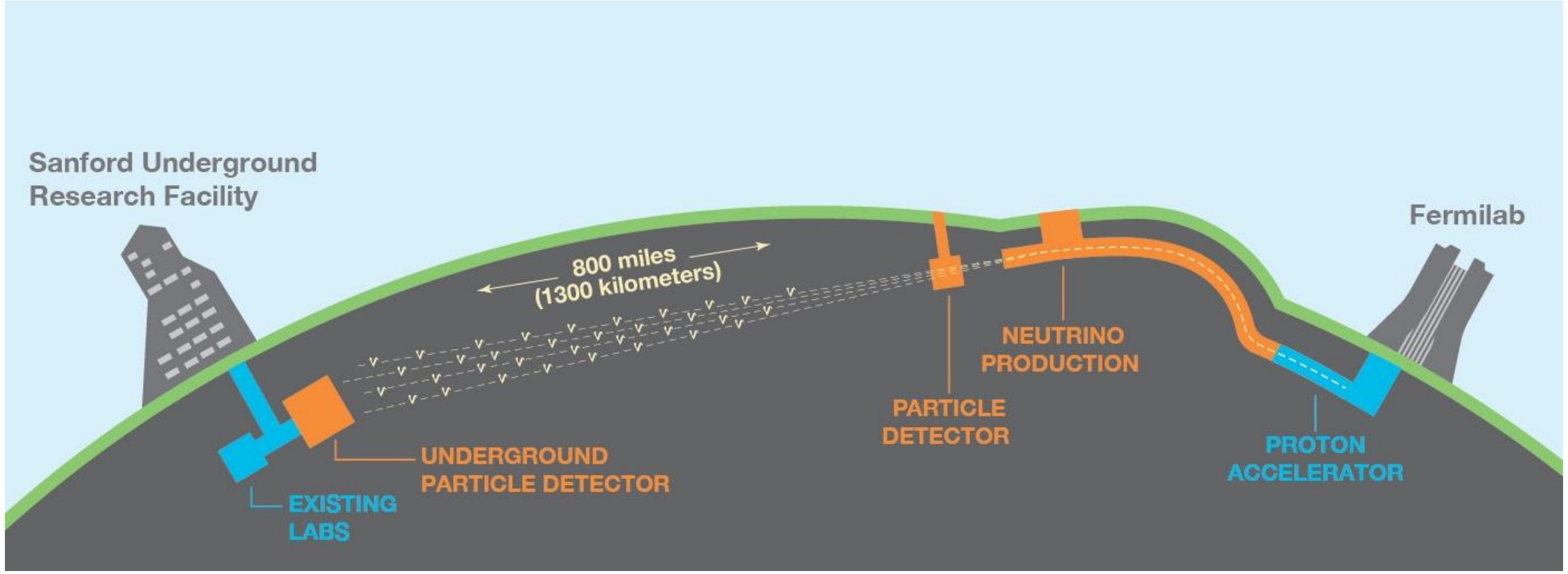


$$\bar{\nu}_e + p \rightarrow n + e^+$$

[1] JUNO collaboration

Backup : DUNE

Expérience DUNE [1]



Start 2029-2033

detection

charged-current neutrino-argon $\nu_e + {}^{40}\mathrm{Ar} \rightarrow e^- + {}^{40}\mathrm{K}^*$

[1] Deep Underground Neutrino Experiment, Fermilab