Astrophysical Neutrinos Uncover Neutrino Properties and Decode New Physics

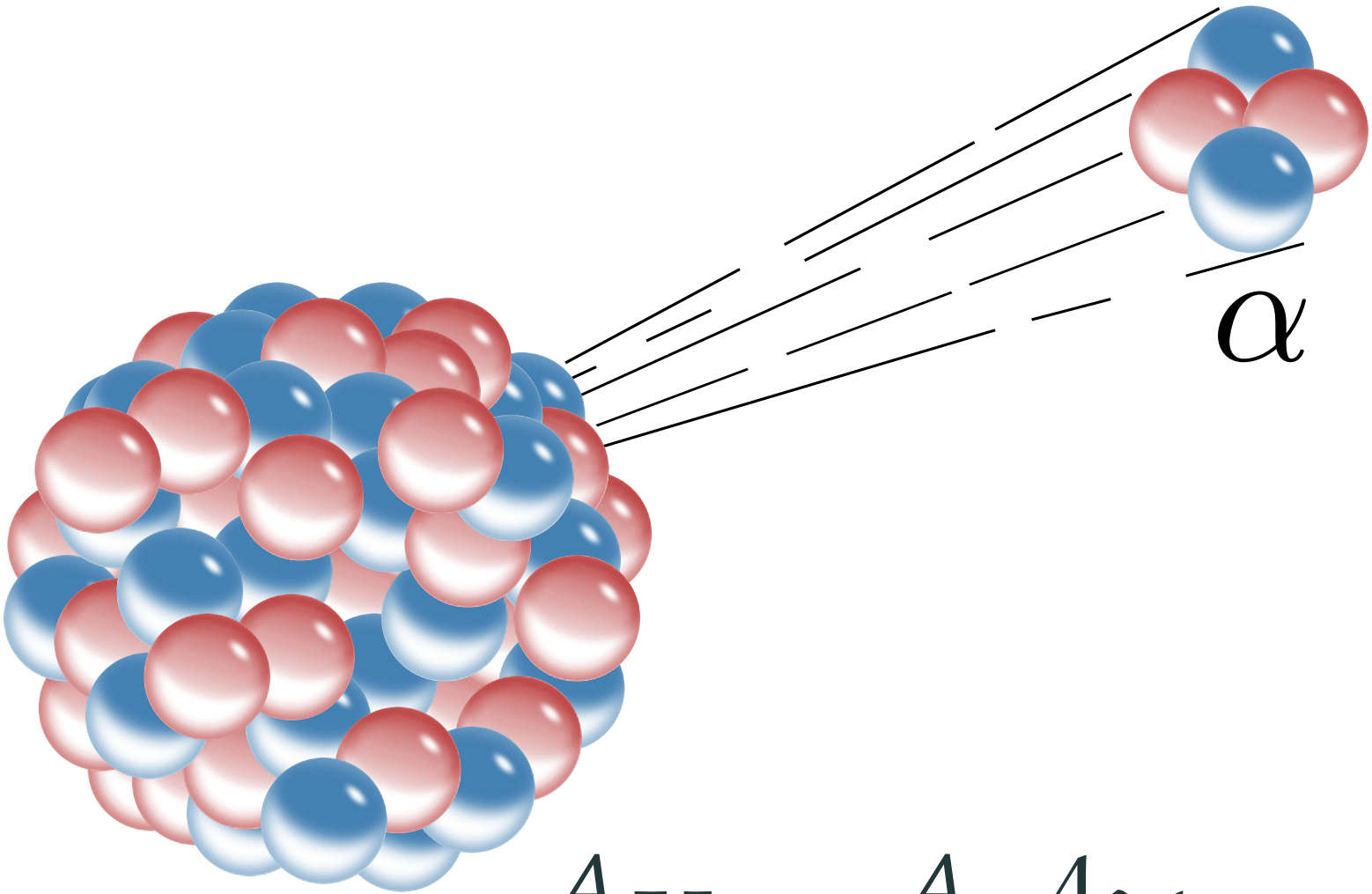
Anna M. Suliga

Neutrino Theory Network Fellow
New York University

Kent State University, April 9, 2026

Data interpretation 101 by W. Pauli

Alpha decay

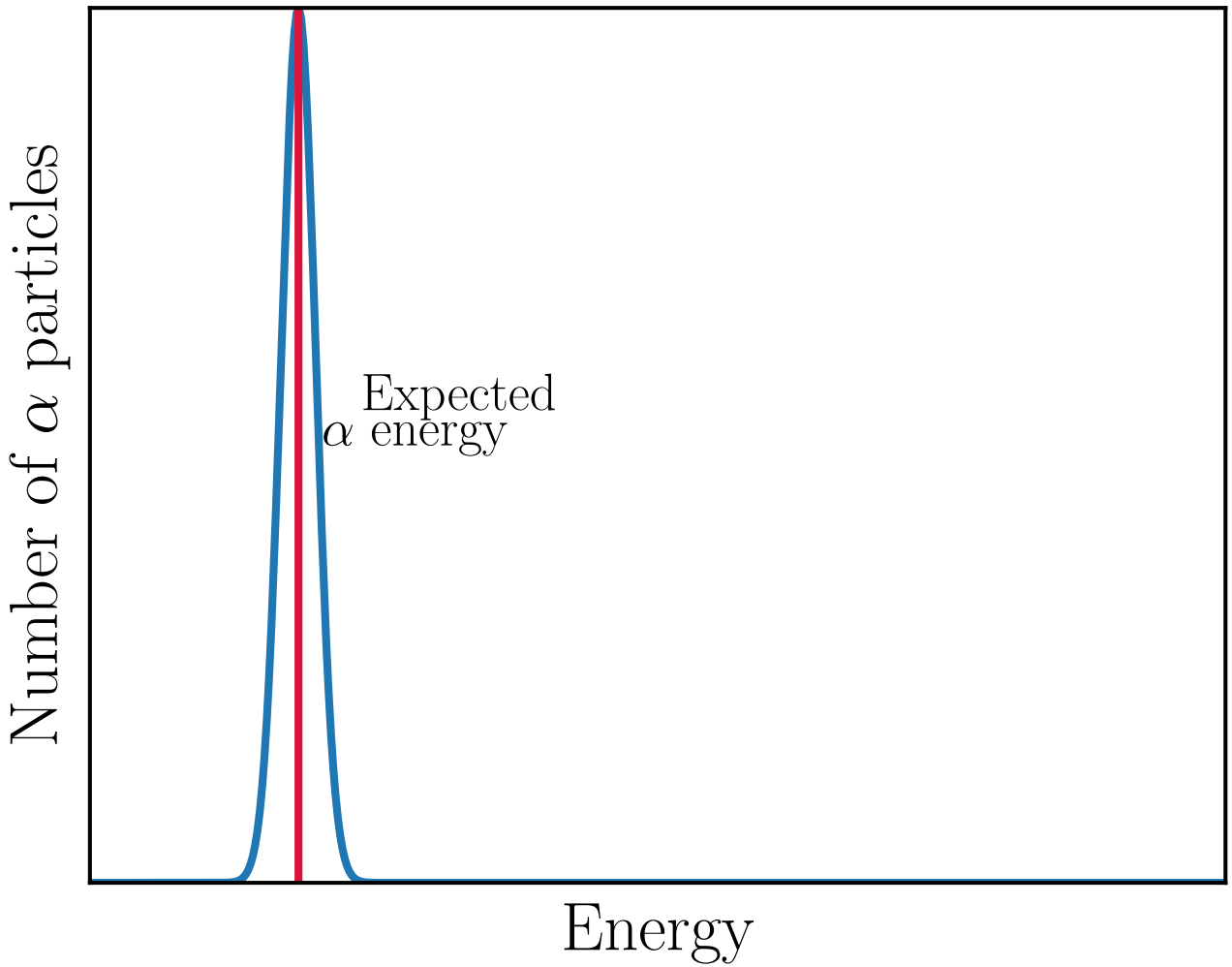


$$^{A}_{Z}X \rightarrow ^{A-4}_{Z-2}Y + \alpha$$

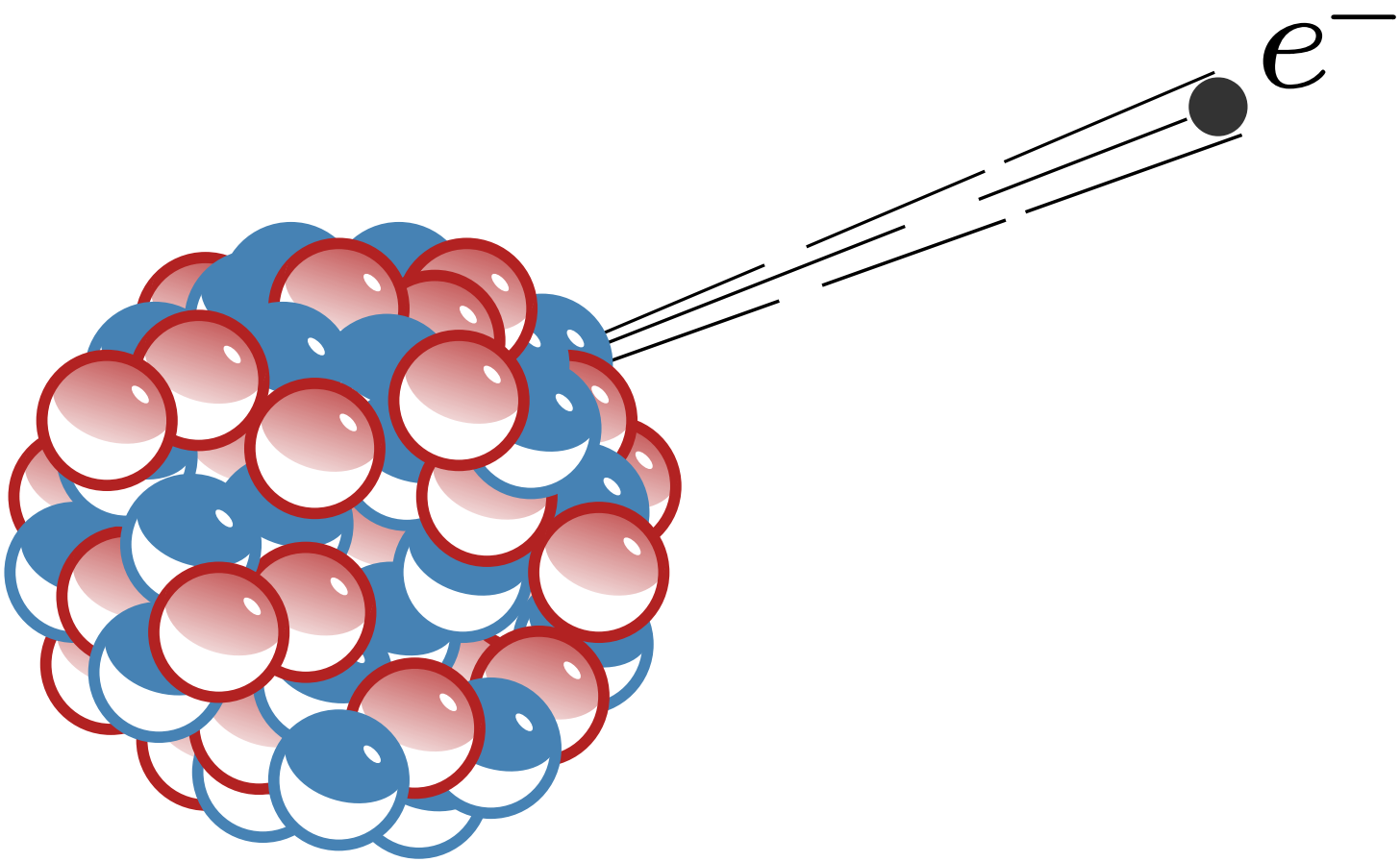
Wikipedia

Rutherford (1899), Gamow (1928)

Alpha decay - spectrum



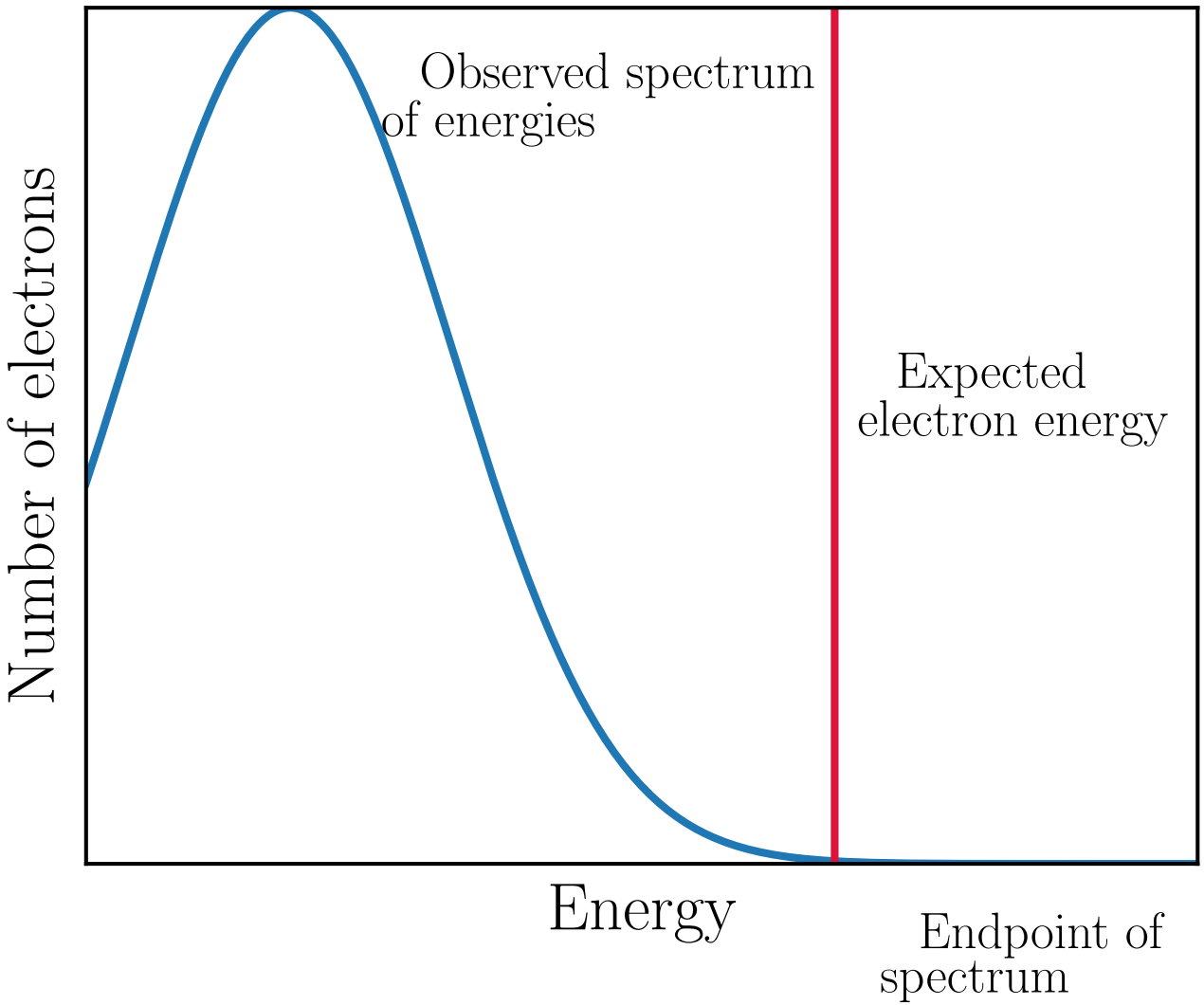
Beta decay



Wikipedia

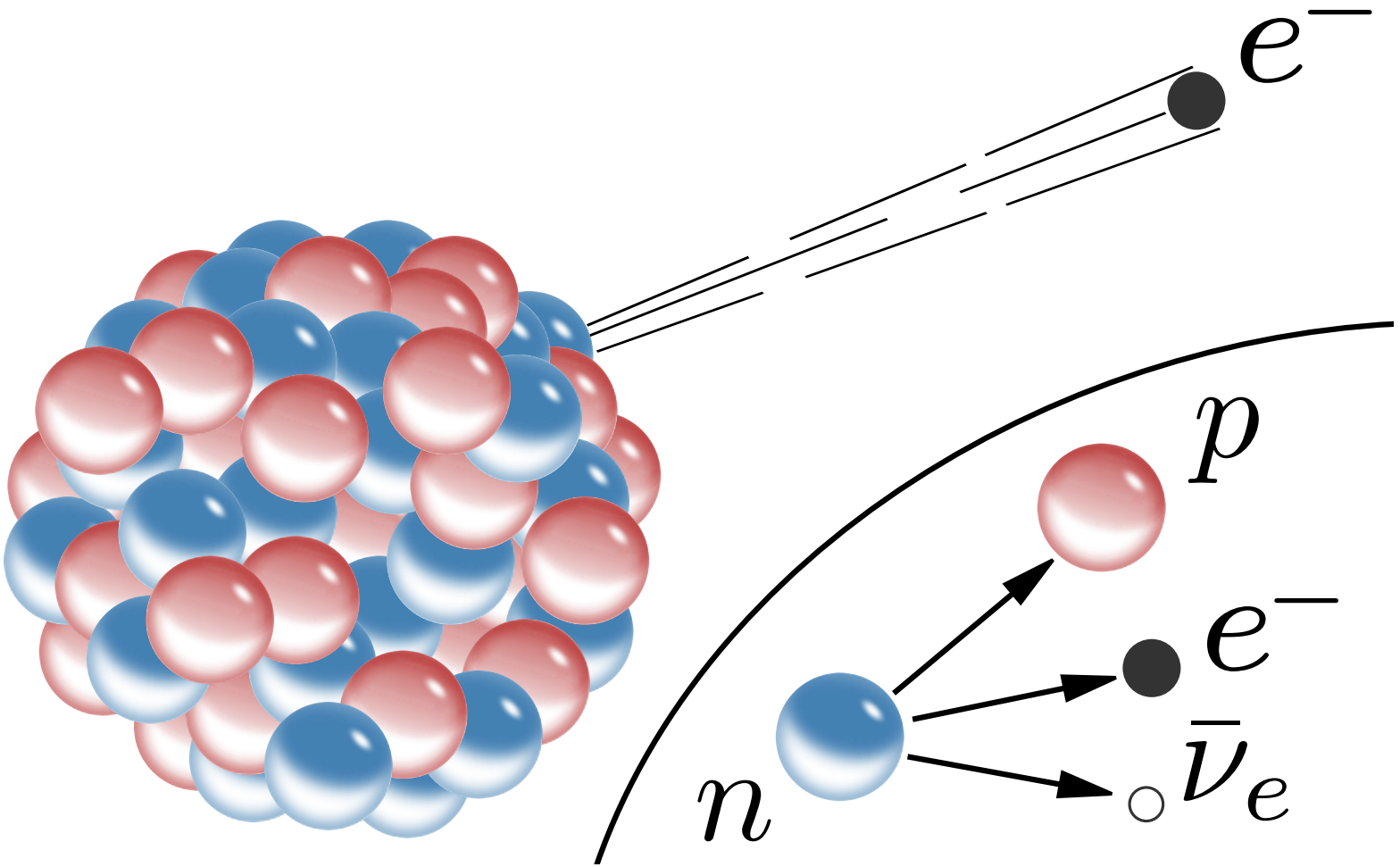
Rutherford (1899)

Beta decay - spectrum



Meitner, Ellis, Chadwick, Mott (1920-1927)

Beta decay - explanation of the spectrum



Pauli (1930),

Beta+ decay Joliot, Joliot-Curie (1934)

Wikipedia

How to detect a ghost?

Neutrino factories



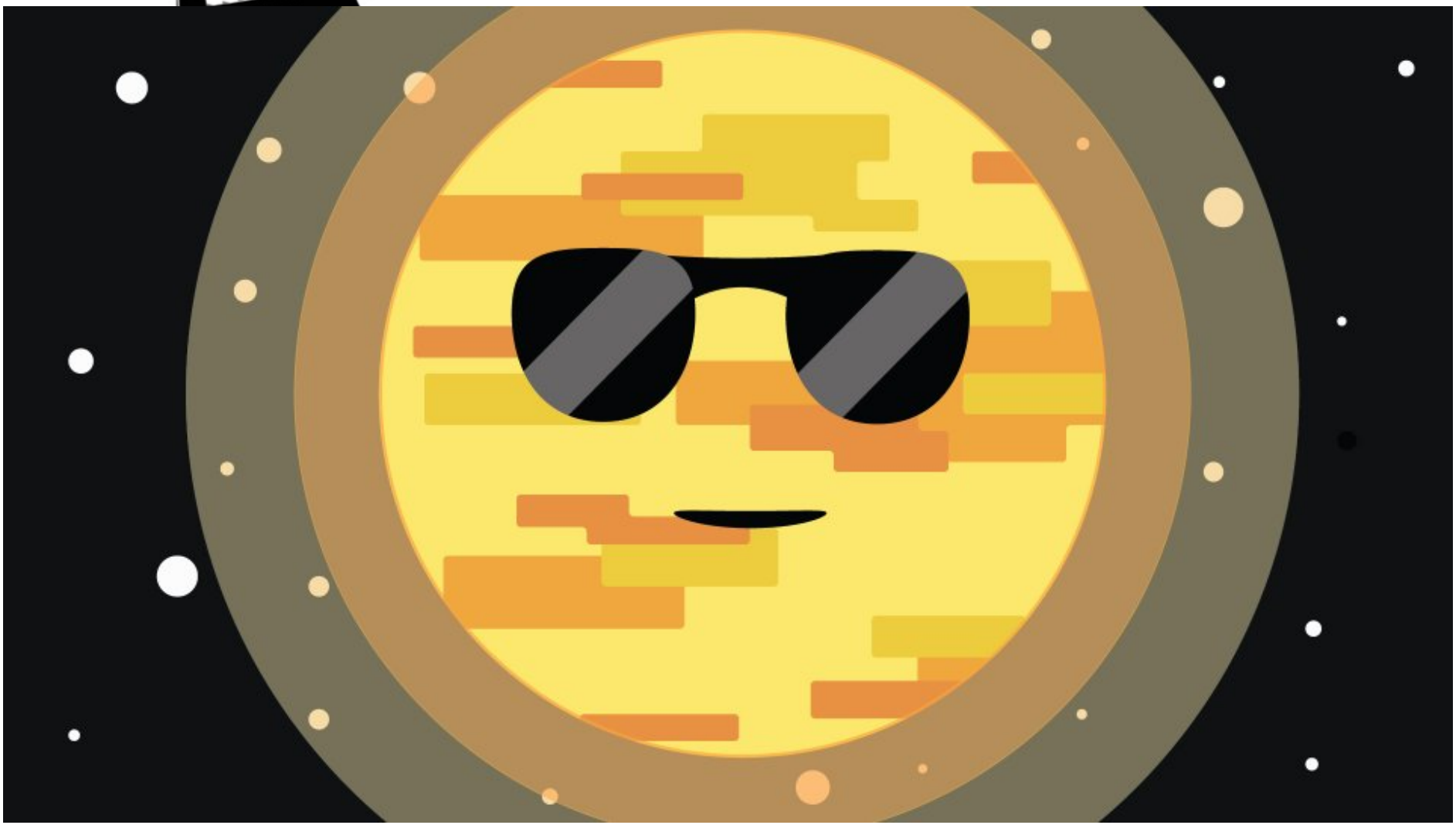
Kurzgesagt, Wikipedia

Neutrino factories



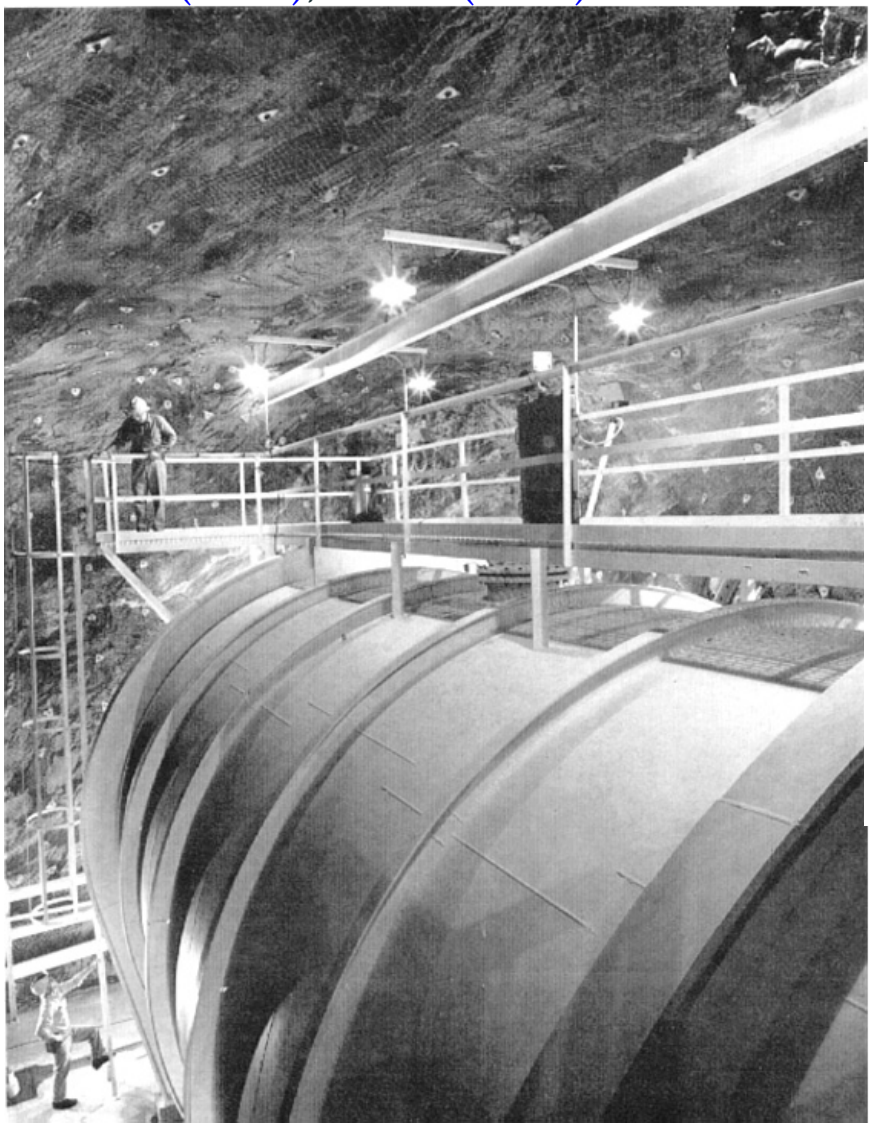


Neutrino factories



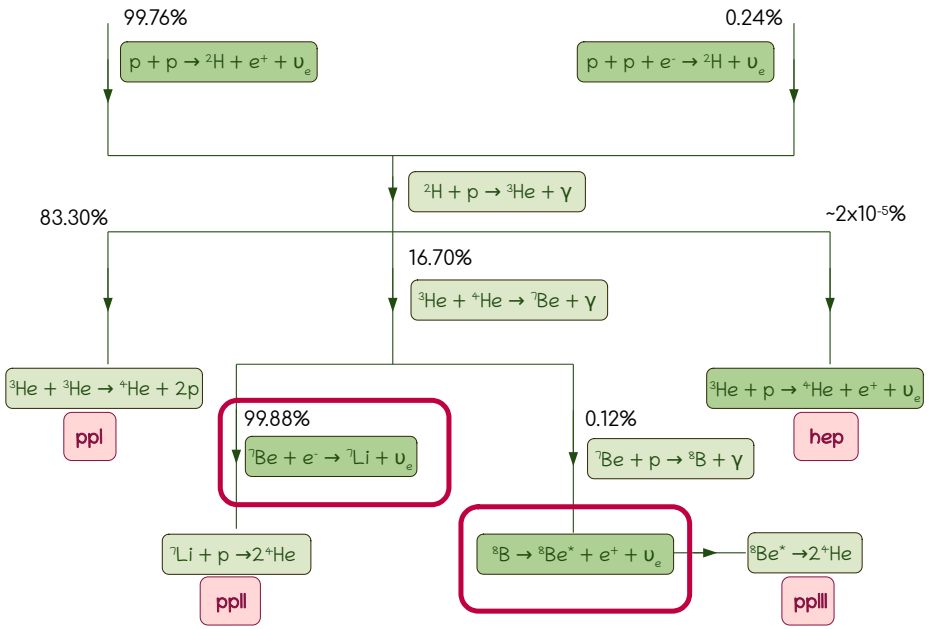
Homestake experiment - solar neutrino detector

Bahcall (1964), Davis(1964)

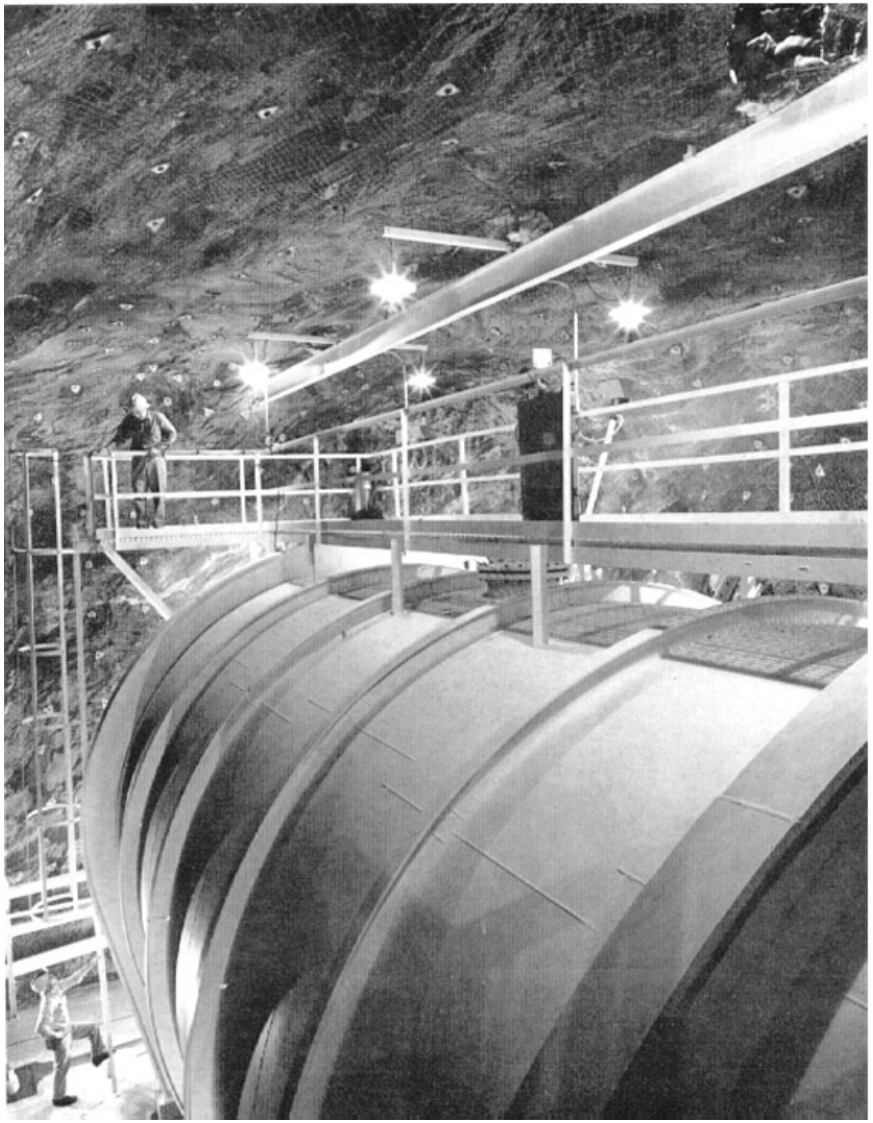


Fermilab picture archive

pp-chain



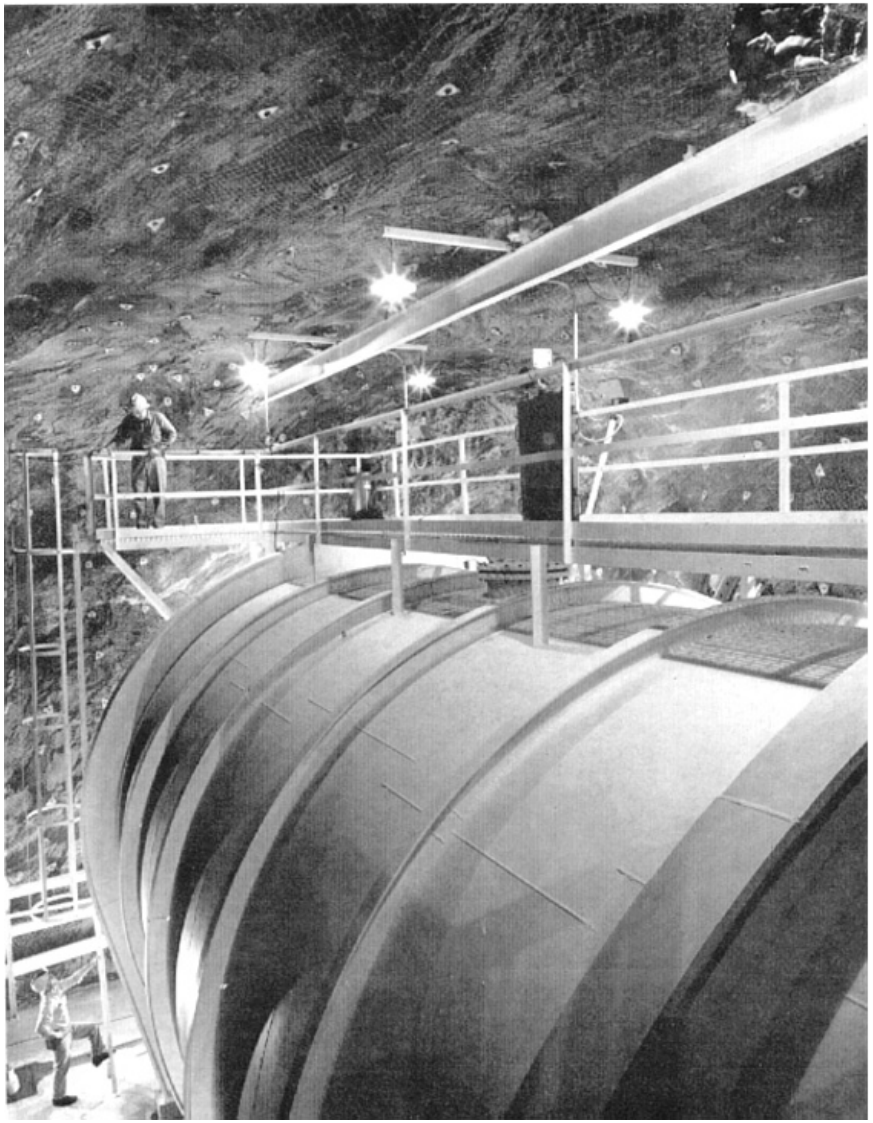
Homestake experiment - solar neutrino detector



Fermilab picture archive

1. BIG detector

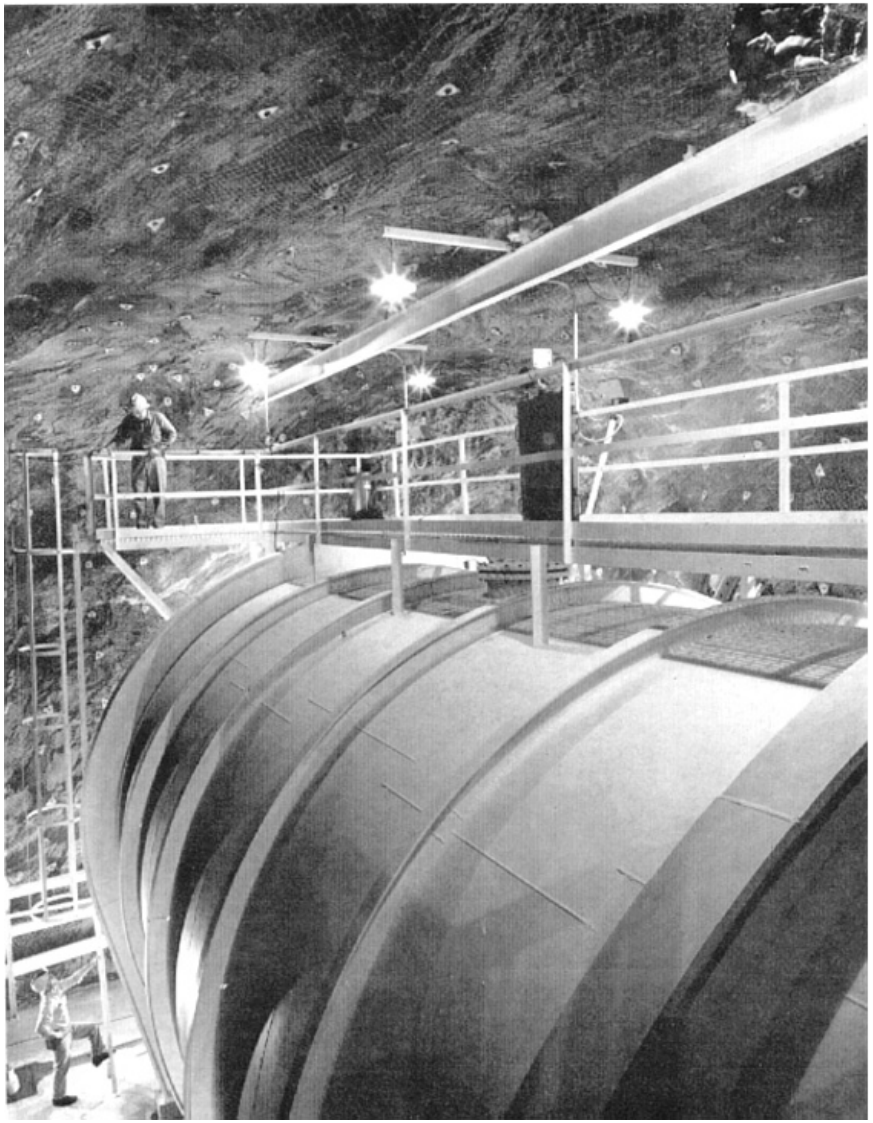
Homestake experiment - solar neutrino detector



Fermilab picture archive

1. BIG detector
2. isolate from other particles

Homestake experiment - solar neutrino detector



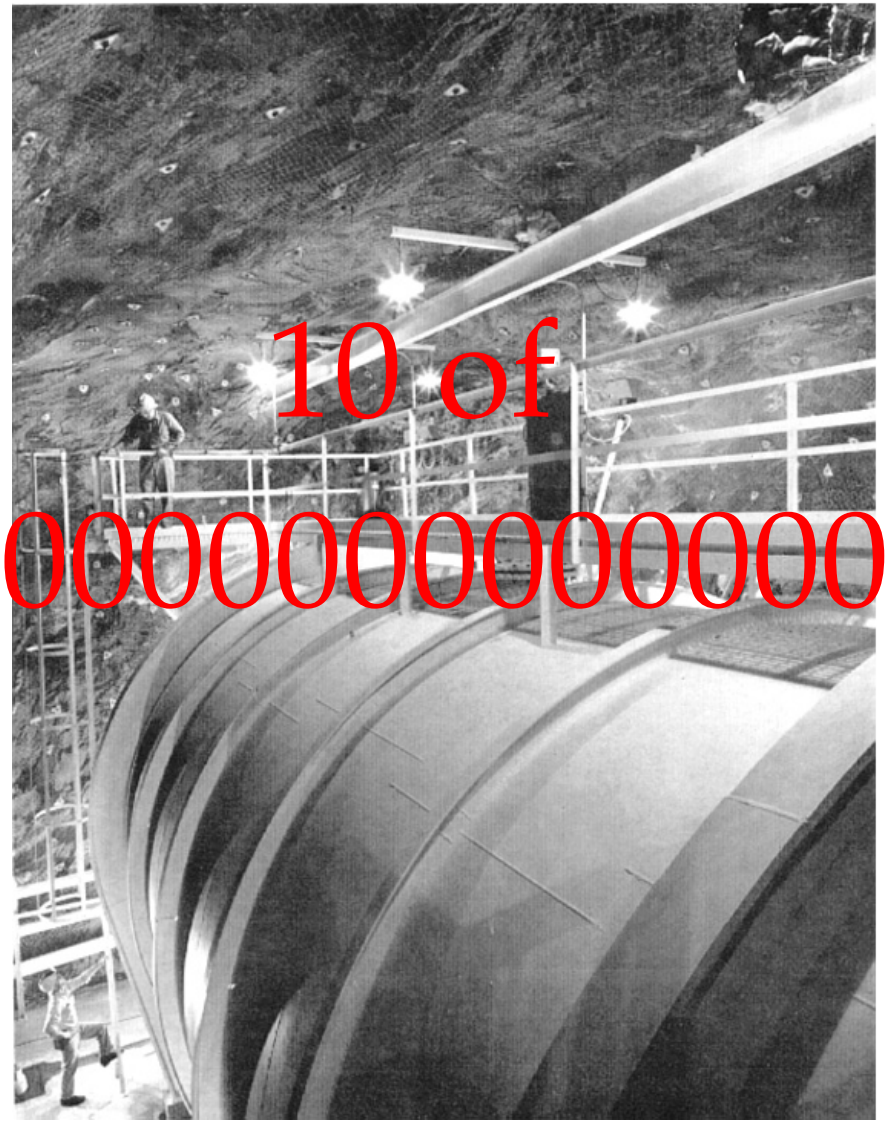
Fermilab picture archive

1. BIG detector
2. isolate from other particles

- 378,000 l of perchloroethylene (C_2Cl_4 "dry-cleaning fluid")
- 1.5 km underground

$$^{37}\mathrm{Cl} + \nu_e \rightarrow {}^{37}\mathrm{Ar} + e^-$$

Homestake experiment - solar neutrino detector



Fermilab picture archive

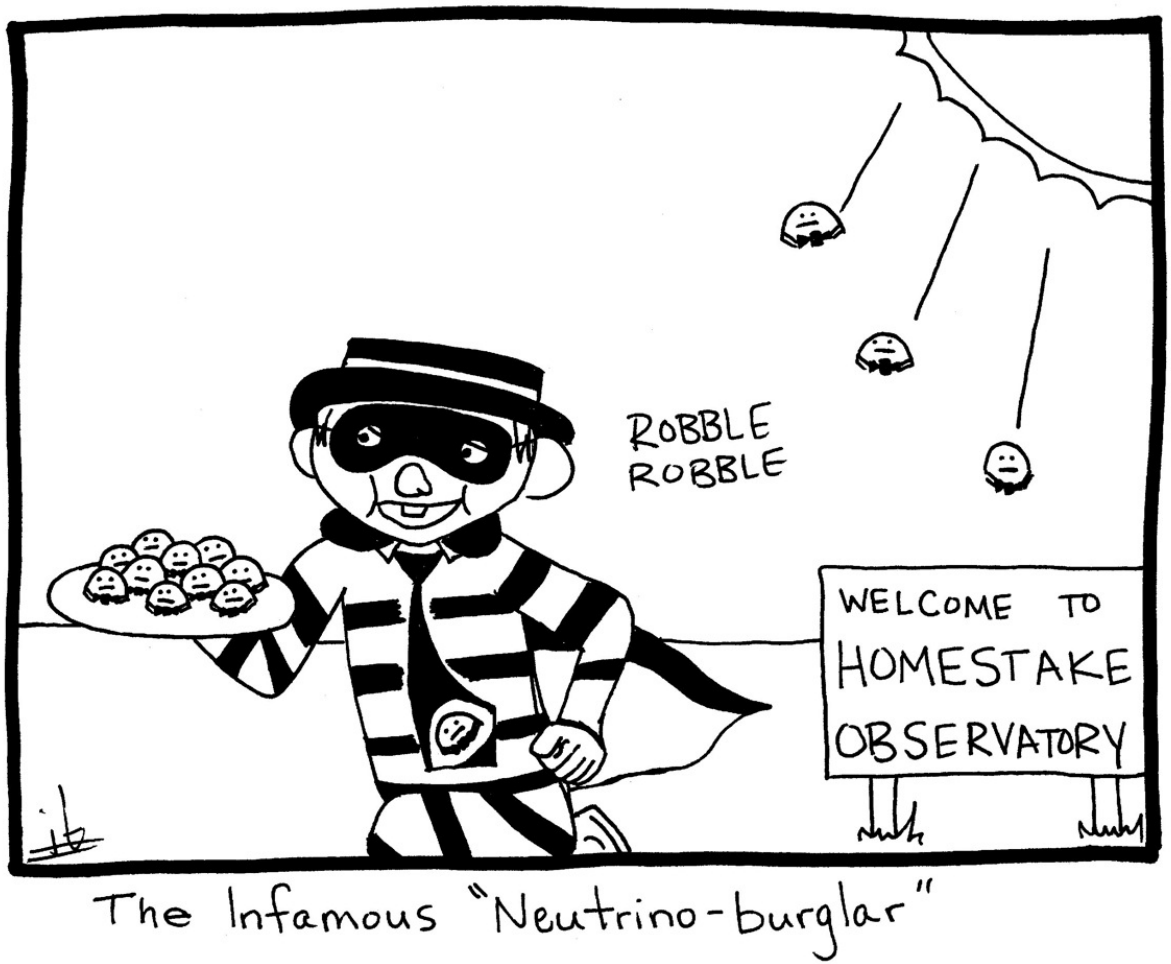
1. BIG detector
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Solar neutrino problem

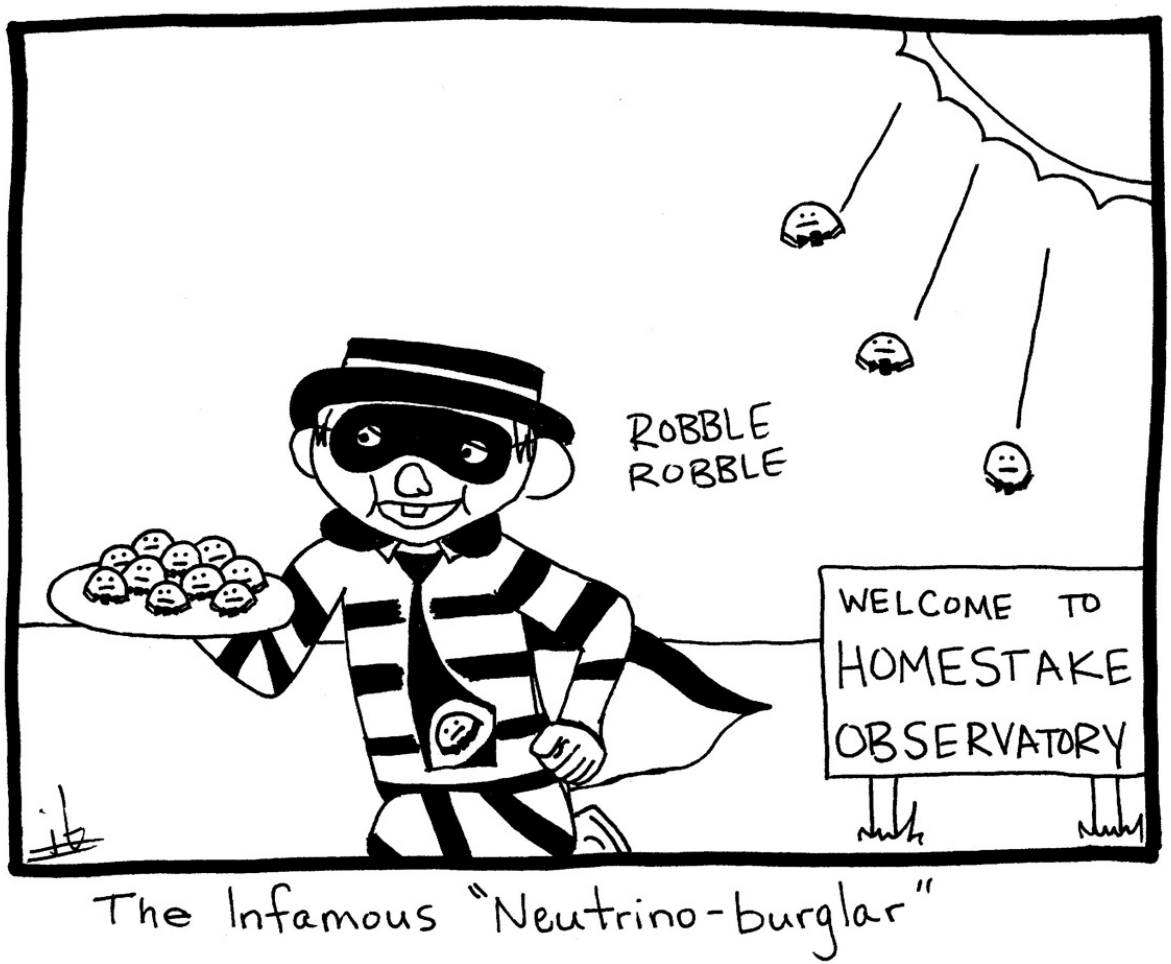
The number of detected neutrinos $\sim$ 3x smaller than expected



Comic

Solar neutrino problem

The number of detected neutrinos $\sim$ 3x smaller than expected



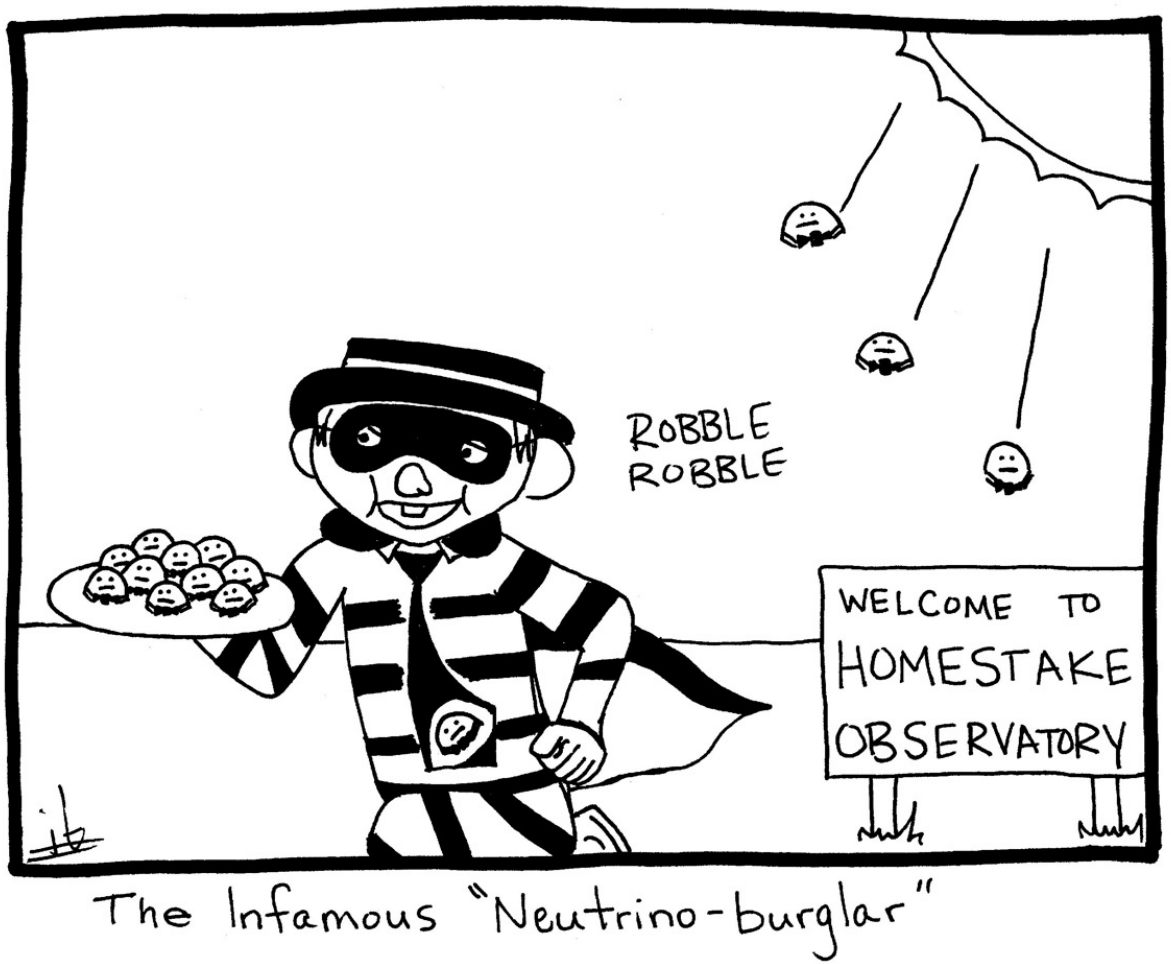
Plausible Solutions:

- Incorrect calculation
- Faulty detector
- New Physics

Comic

Solar neutrino problem

The number of detected neutrinos $\sim$ 3x smaller than expected



The Infamous "Neutrino-burglar"

Plausible Solutions:

- Incorrect calculation
- Faulty detector
- New Physics

Comic

Neutrino properties

Neutrino flavors



Neutrino flavors



Neutrino flavors



Neutrino flavors









Neutrino flavors











The Particle Zoo

Neutrino flavors





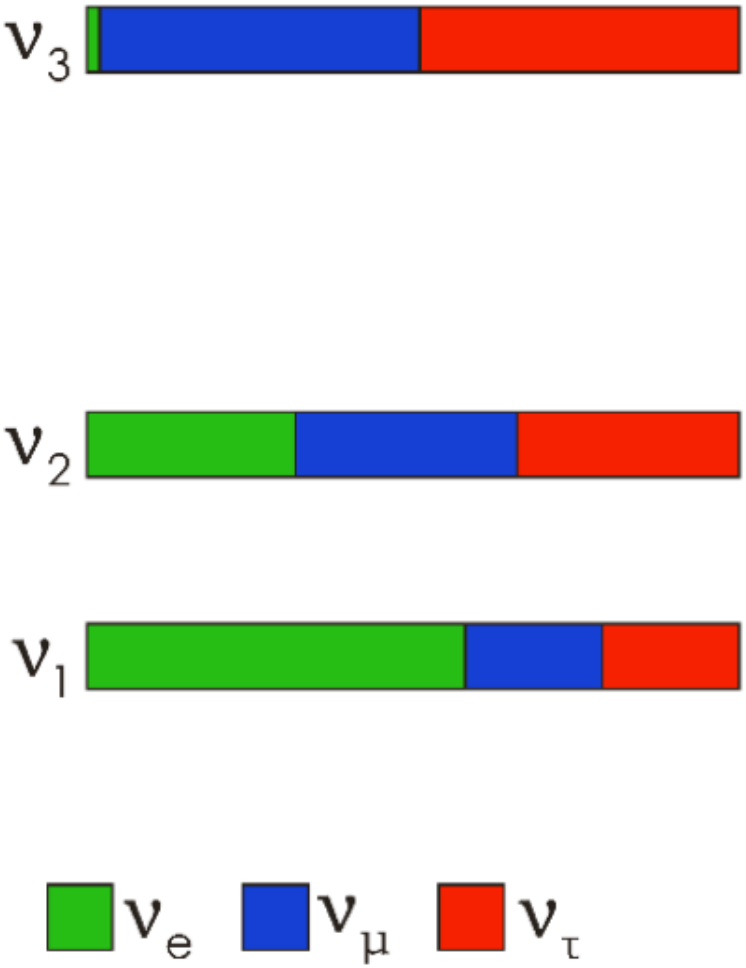








Neutrino mass and flavor states

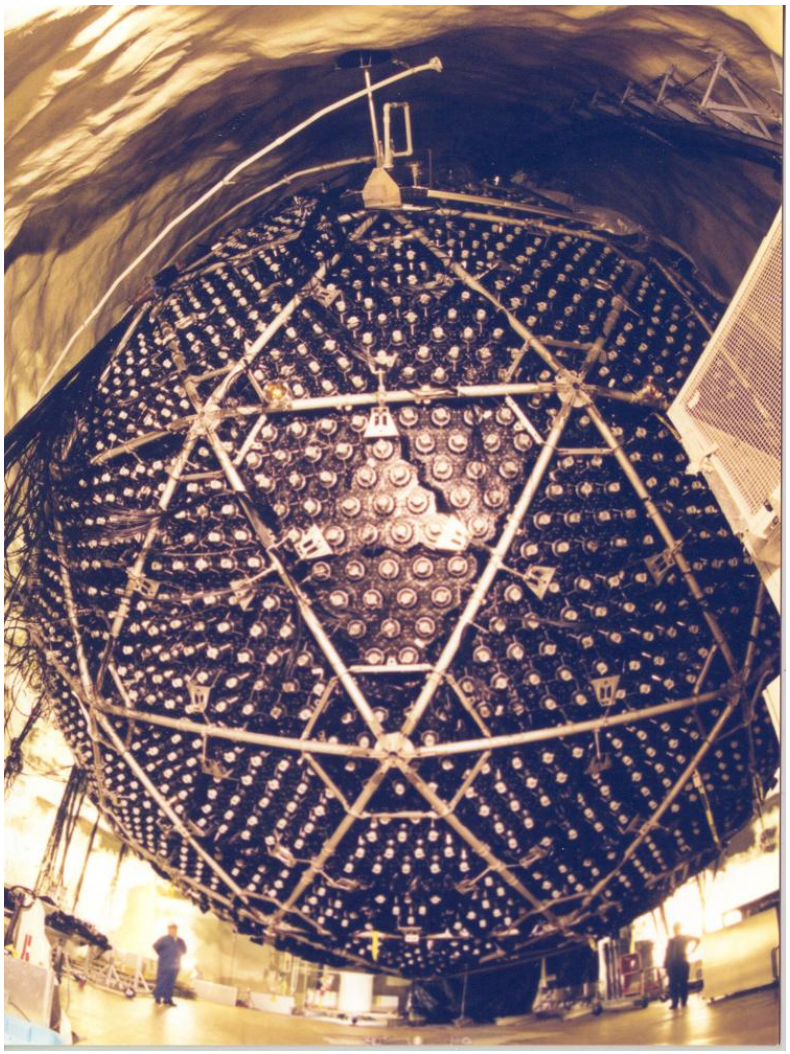


mass states $\neq$ flavor states



All-neutrino-flavor sensitive detector

Sudbury Neutrino Observatory (SNO)



- 2.1 km underground
- filled with 1000 tonnes of heavy water
- sensitive to all neutrino flavors

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

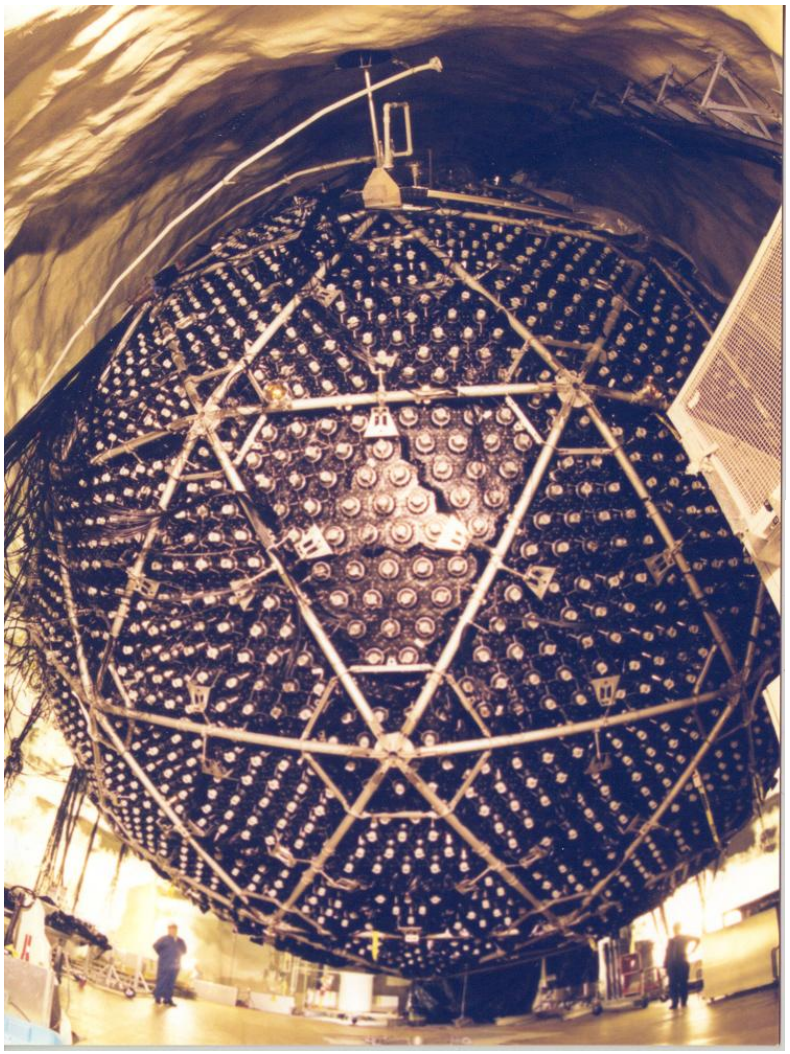
$$\nu_x + \mathrm{D} \rightarrow \mathrm{p} + \mathrm{n} + \nu_x$$

$$\nu_x + e^- \rightarrow \nu_x + e^-$$

SNO

All-neutrino-flavor sensitive detector

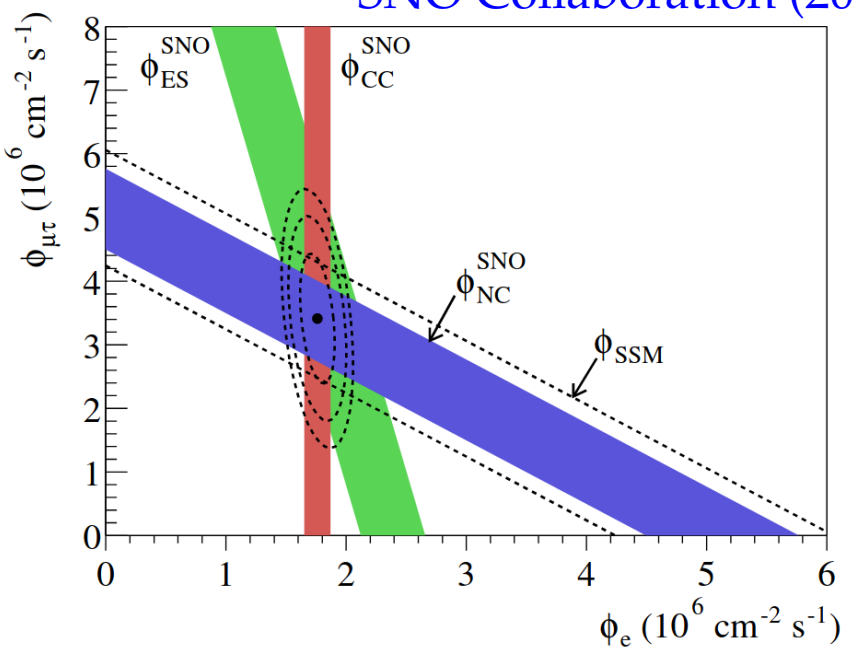
Sudbury Neutrino Observatory (SNO)



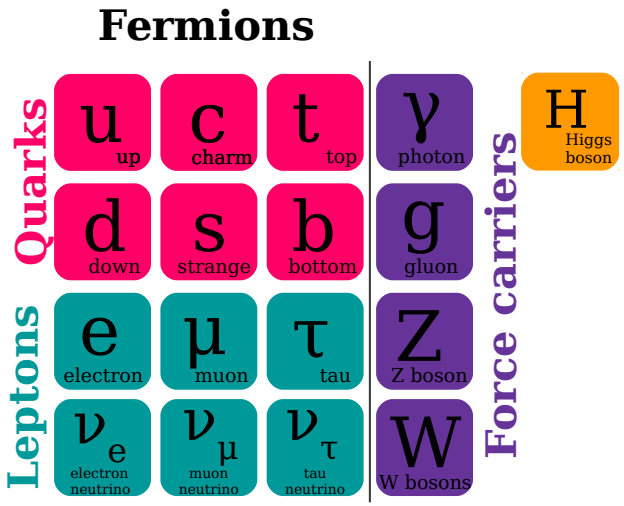
SNO

- 2.1 km underground
- filled with 1000 tonnes of heavy water
- sensitive to all neutrino flavors

SNO Collaboration (2002)



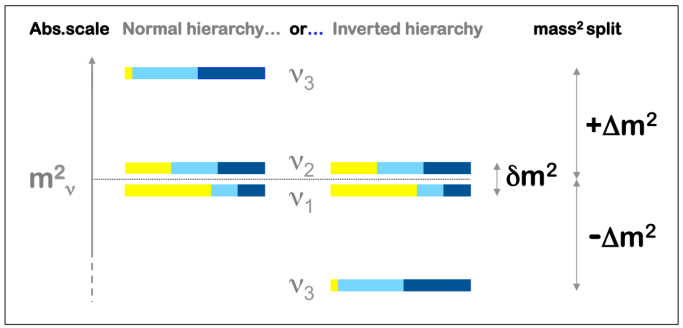
Neutrino flavor and mass states



flavor basis mass basis

$$\begin{bmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{bmatrix} = U \begin{bmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{bmatrix}$$

e μ τ E. Lisi



beam, atmospheric | beam, reactor | solar, reactor

$$U = \begin{bmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{bmatrix} \begin{bmatrix} c_{13} & 0 & s_{13}e^{-i\delta_{CP}} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta_{CP}} & 0 & c_{13} \end{bmatrix} \begin{bmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

is ν_s (ν_4) missing?



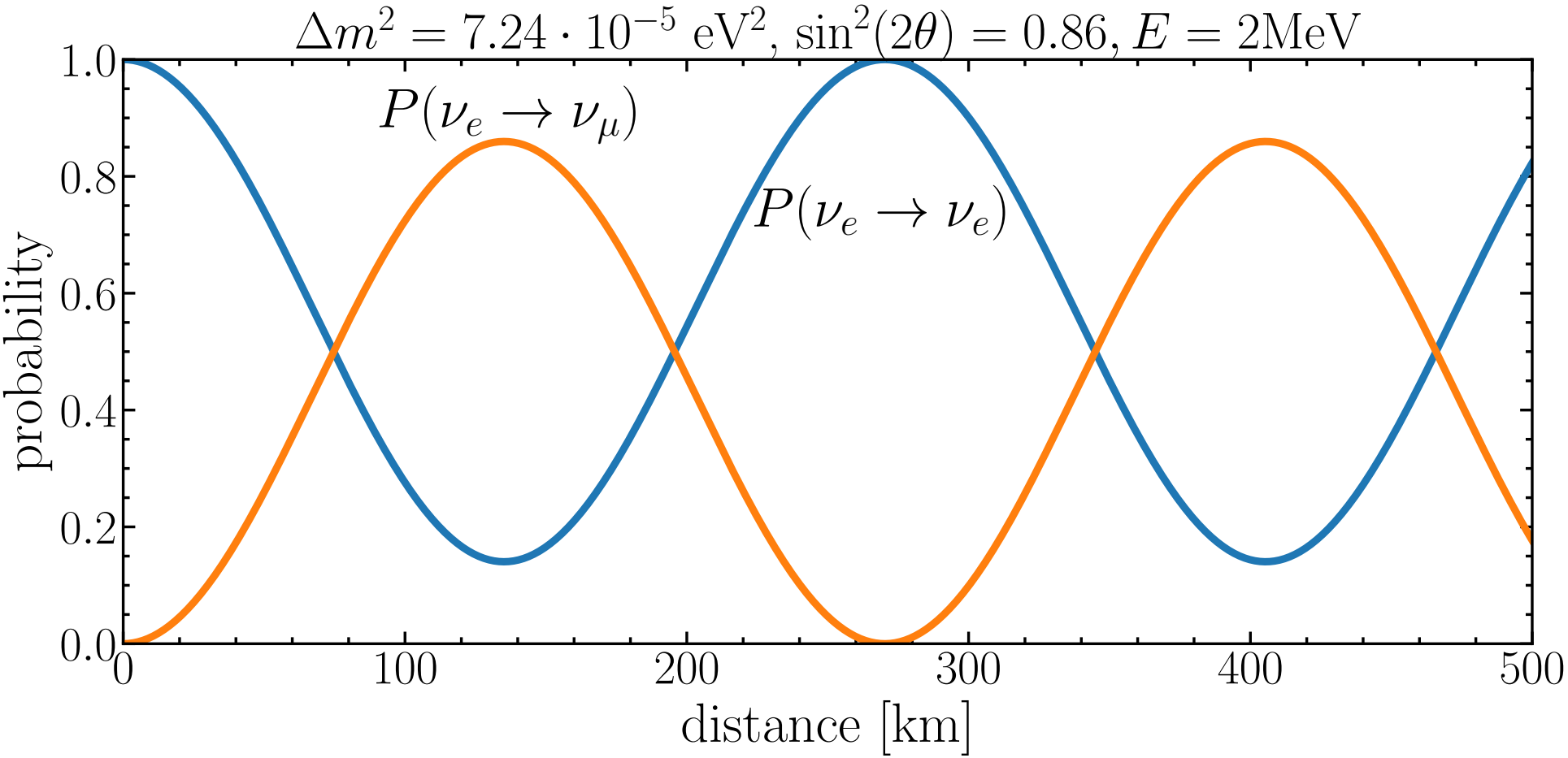
Pontecorvo (1957), Maki, Nakagawa, Sakata (1962)

Neutrino oscillations in vacuum

$$P_{\nu_e \to \nu_e} = 1 - \sin^2 2\theta \sin^2 \frac{\Delta m^2 L}{4E}$$

2ν mixing = easy dependence on

- mixing angle
- mass squared difference



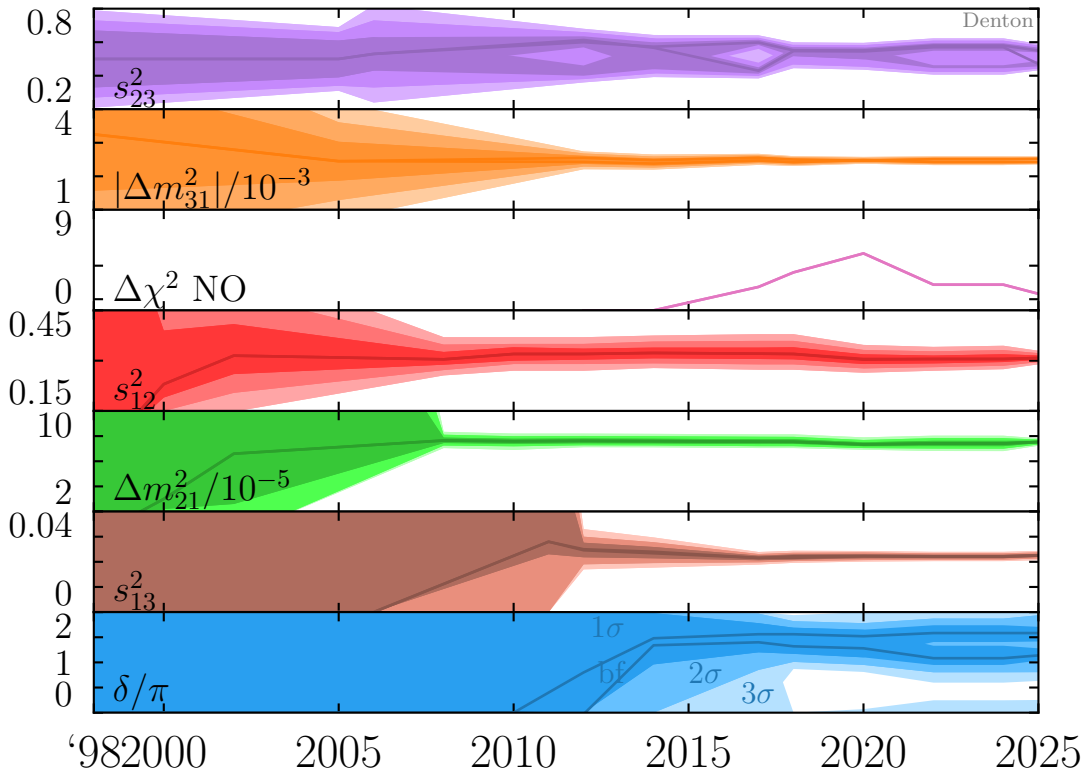
Towards precise neutrino properties measurements

Past measurements

- large mixing angles
- non-zero masses

Remaining questions

- Majorana vs Dirac
- absolute masses
- degree of CP violation
- some low-energy ν fluxes

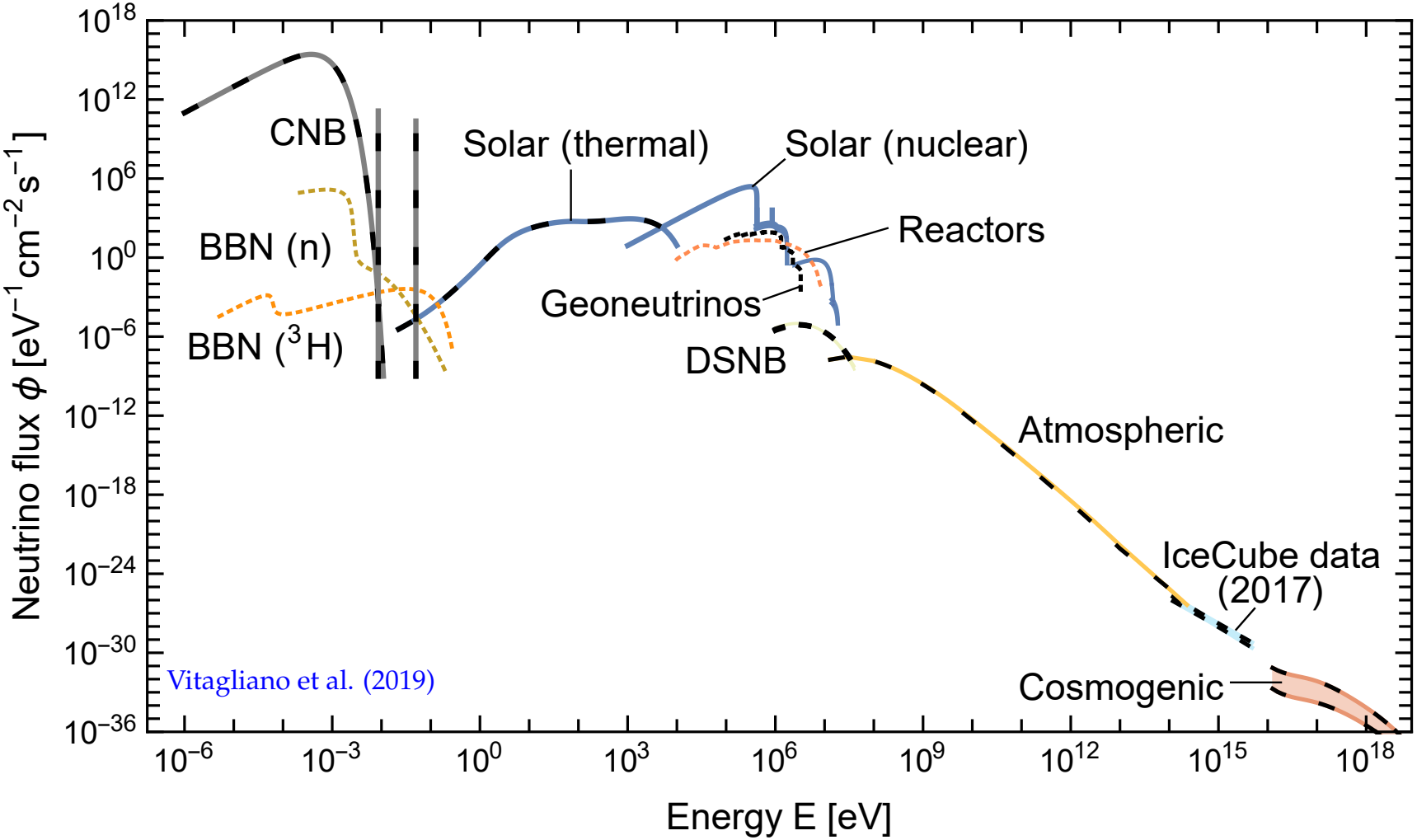


P. Denton (2025)

How to achieve it? All hands on deck

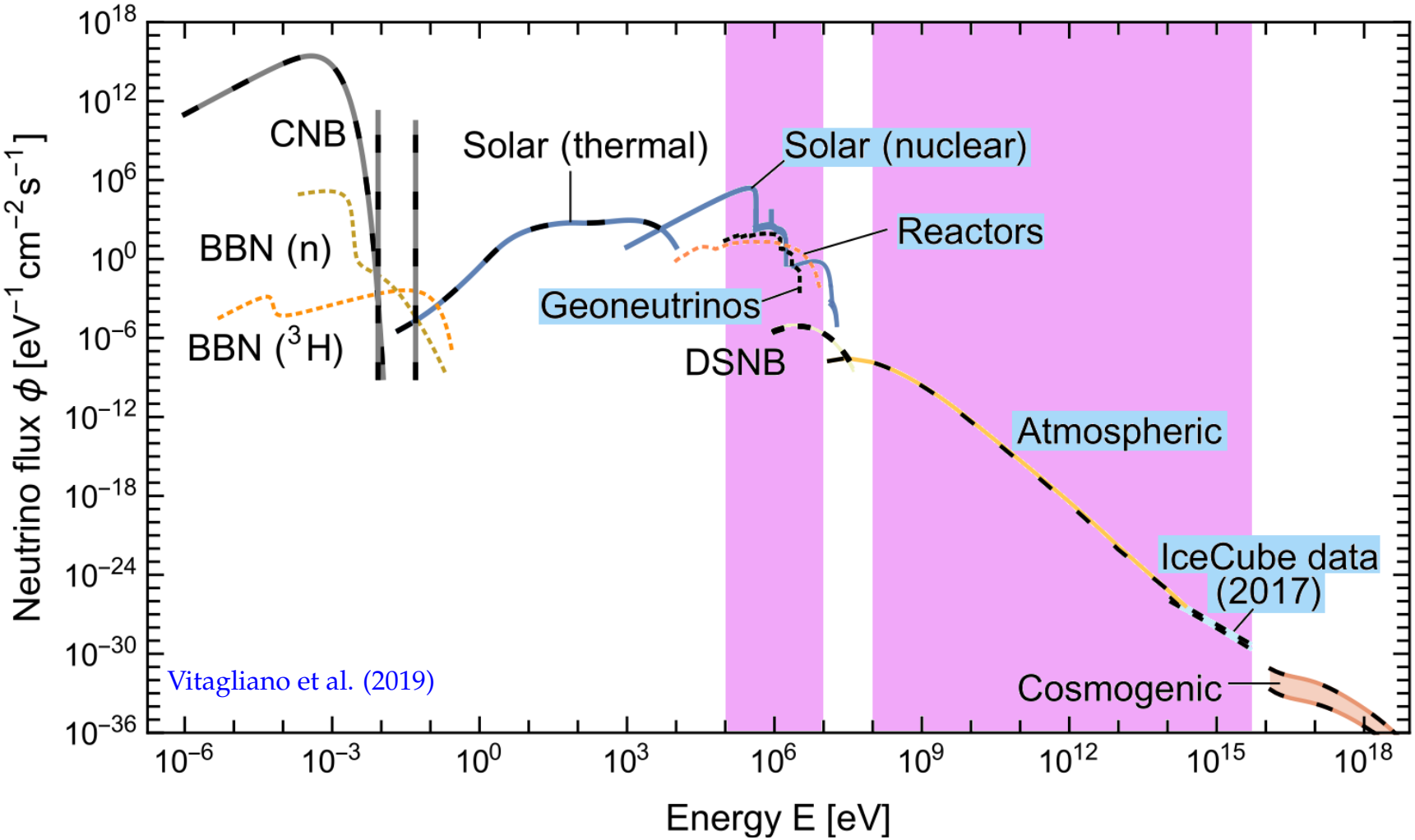
- Many new experiments comimg online soon, DUNE, JUNO, HK, SBND, DARWIN-LZ...
- variety of approaches $\rightarrow$ superb sensitivity

Why is studying astrophysical neutrinos crucial?



Free neutrino sources spanning nearly 25 decades in energy

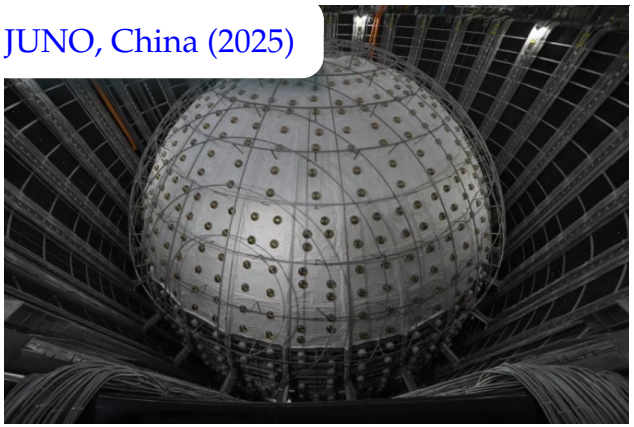
Established track record of neutrino discoveries



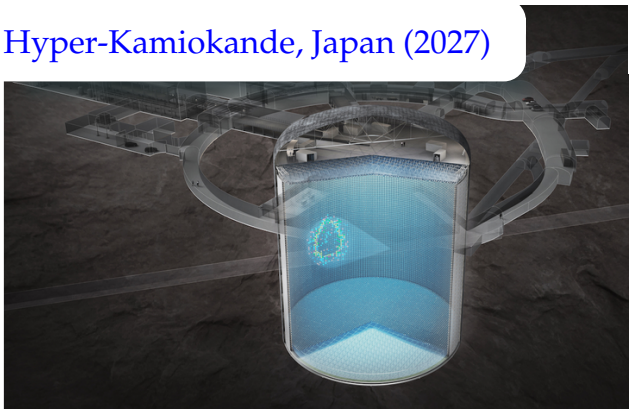
Significant progress, but still room for new discoveries

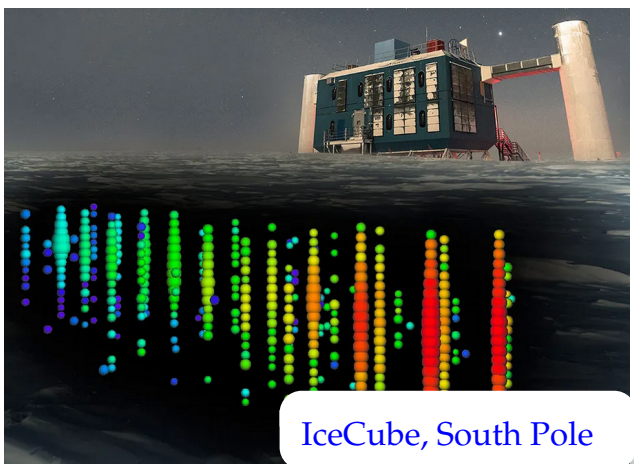
How to achieve full picture of neutrinos? All hands on deck!

JUNO, China (2025)



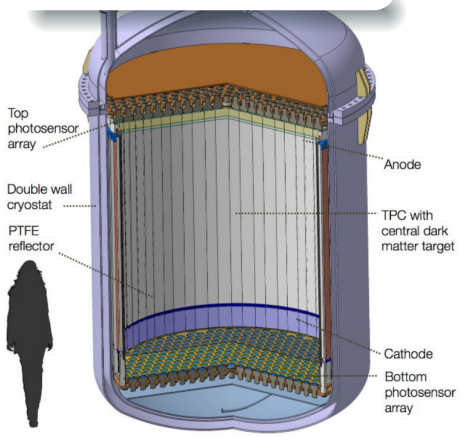
Hyper-Kamiokande, Japan (2027)





IceCube, South Pole

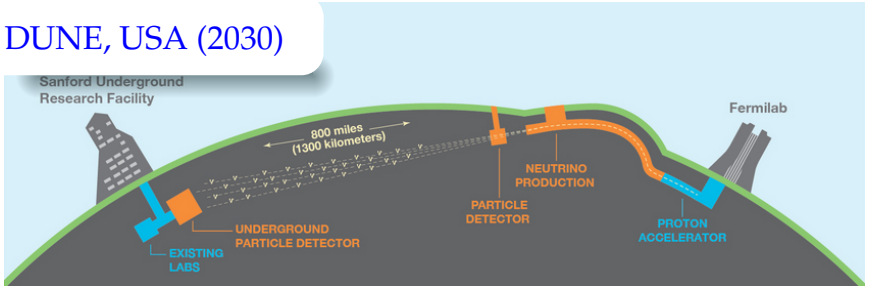
XLZD, DARWIN (20XX)



Rubin Observatory, Chile (2025)



DUNE, USA (2030)

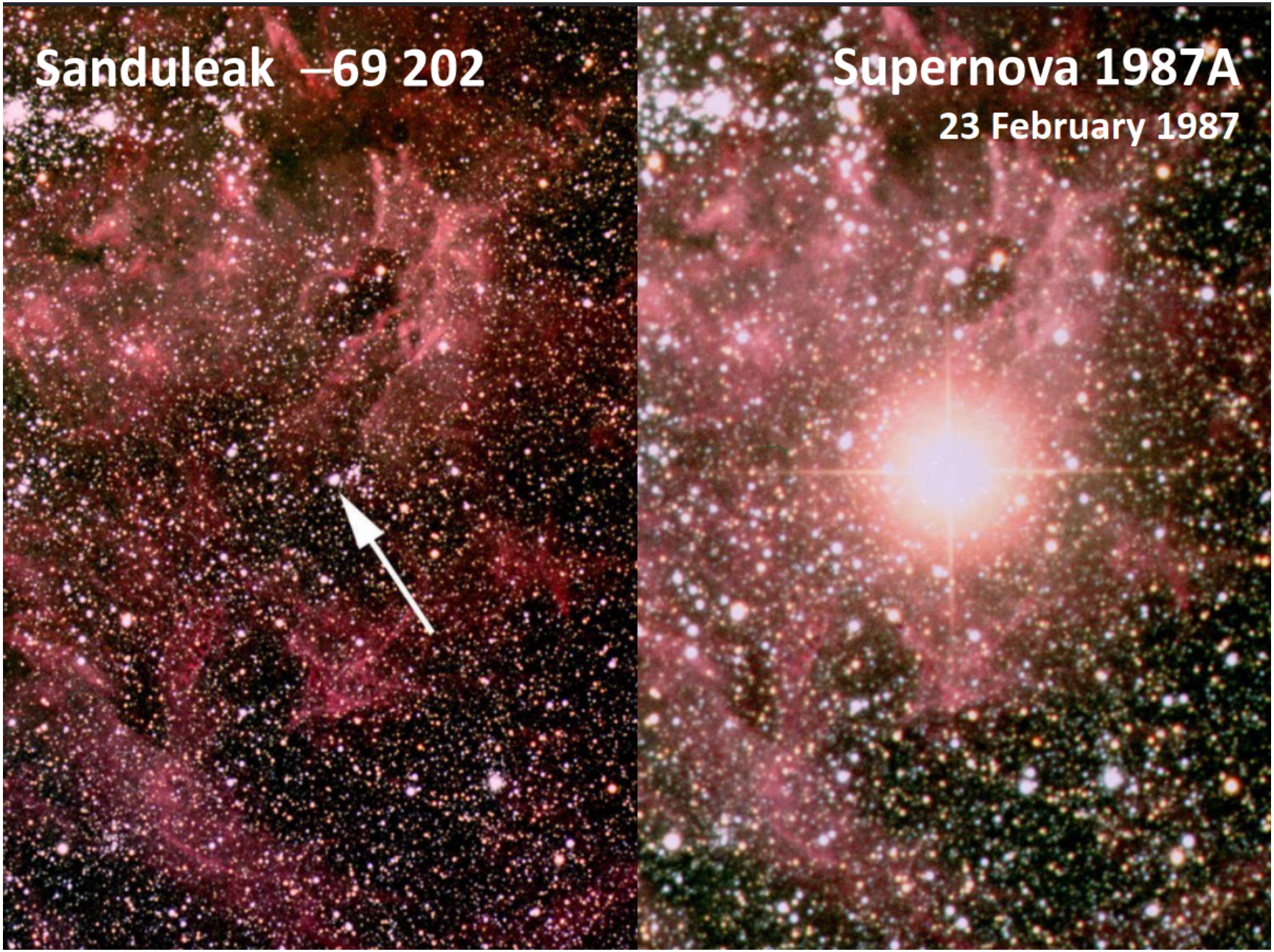


- Many new experiments comimg online soon
- variety of approaches → superb sensitivity

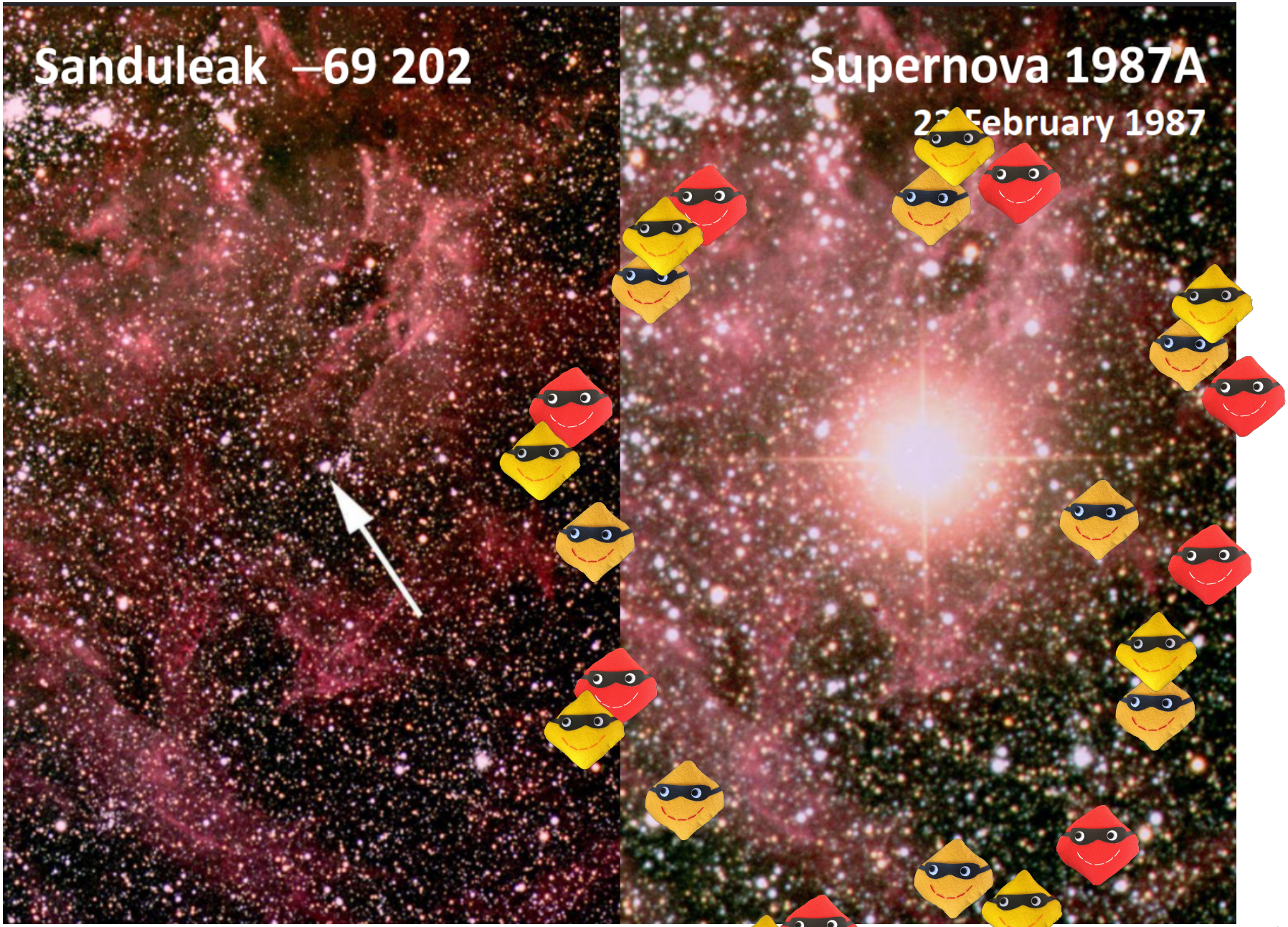
- Complementarity with:
  - reactor and accelerator searches
  - electromagnetic surveys
  - other astrophysical messengers

Core-collapse supernovae and neutrinos

Established track record of neutrino discoveries: SN 1987A



Established track record of neutrino discoveries: SN 1987A



Established track record of neutrino discoveries: SN 1987A



Hubble (2017)



JWST (2023)

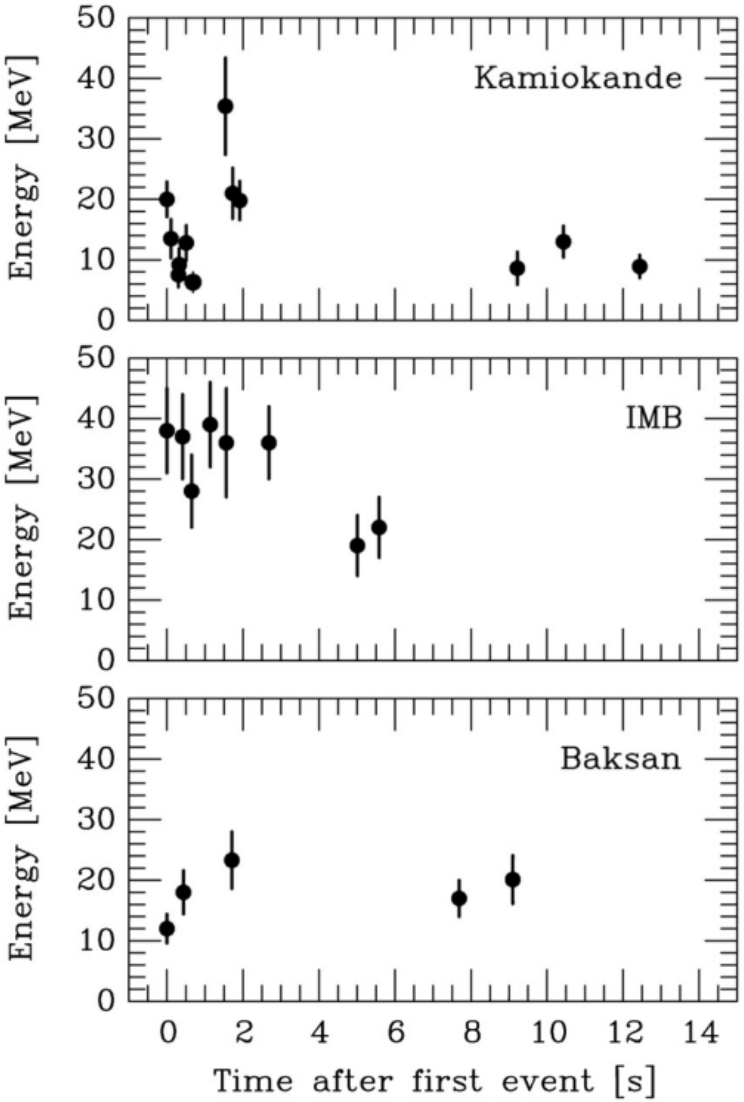
- Neutron star remnant

  Fransson et al. (2024)

- Binary system

  Morris & Podsiadlowski (2007), (2009)

Established track record of neutrino discoveries: SN 1987A



Courtesy of G. Raffelt

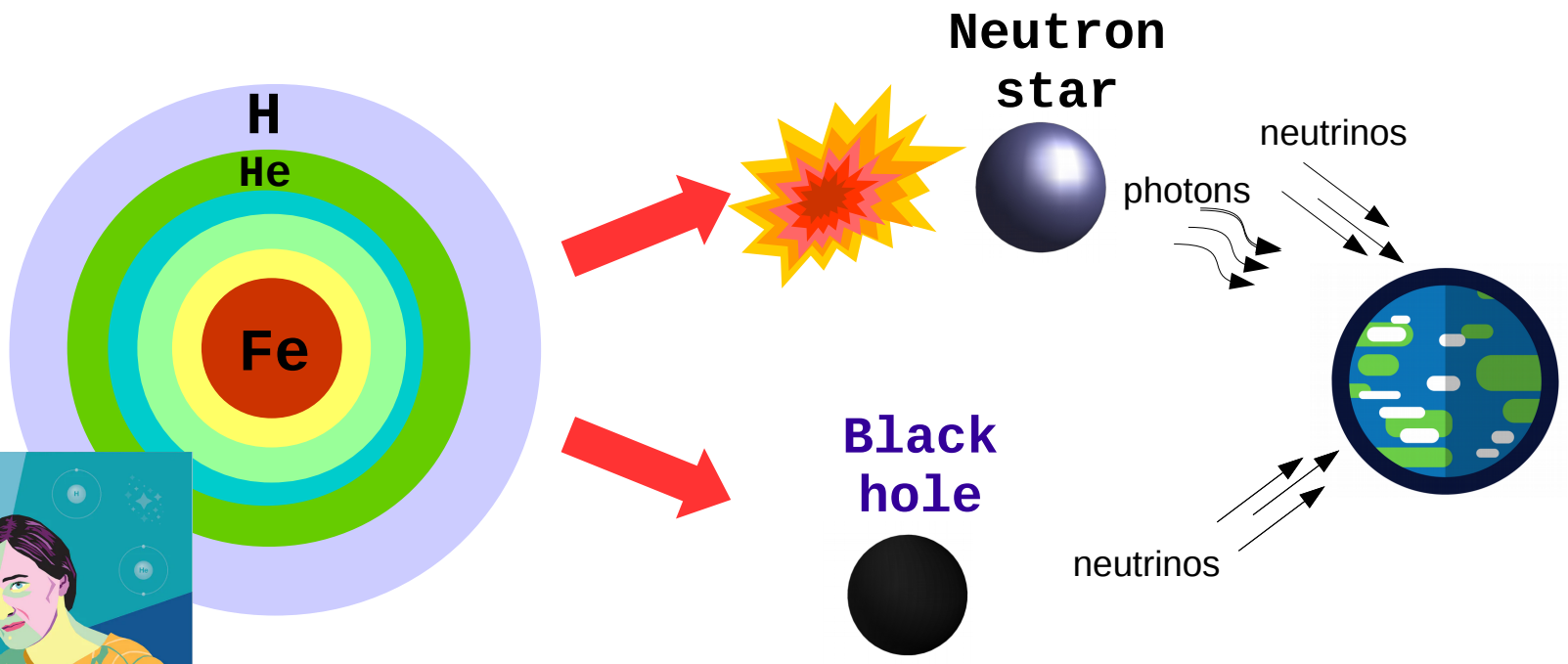


- Neutrino detection from SN 1987A:
  - confirmed the core-collapse scenario
  - 99% of the energy emitted in neutrinos
  - best limit at the time on the ν mass

Why are neutrinos important for a core-collapse supernova?

Neutrinos:

- $\sim 10^{58}$ of them emitted from a single core collapse
- only they can reveal the deep interior conditions
- only they are emitted from the collapse to a black hole





Earth image: Kurzgesagt

What can we learn with a variety of detectors?

Advantages

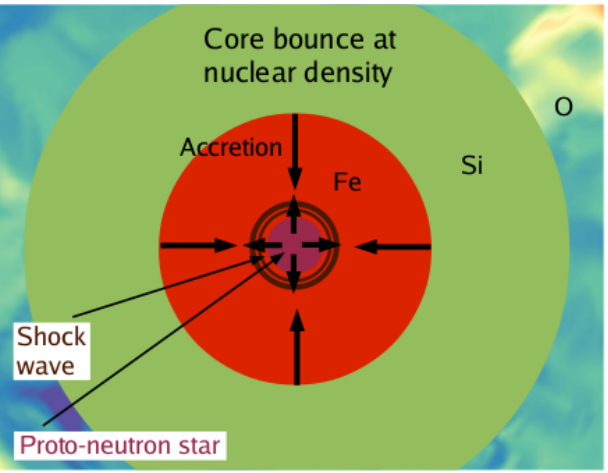
- extreme physical conditions not accessible on Earth: very high densities, long baselines etc.
- within our reach to detect (SK, JUNO, XENON, PandaX...)

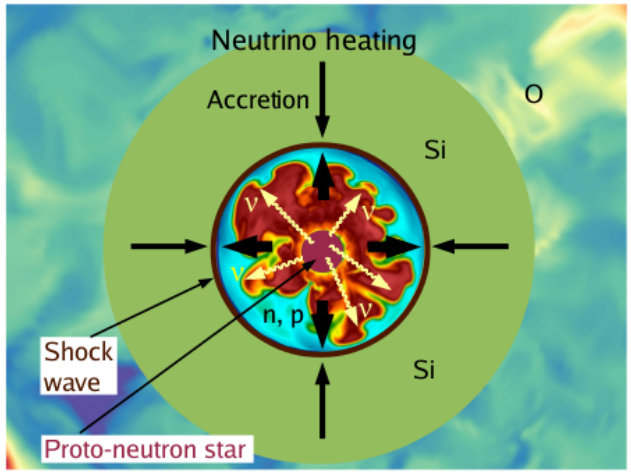
Why such an exciting problem? Synergy between many fields

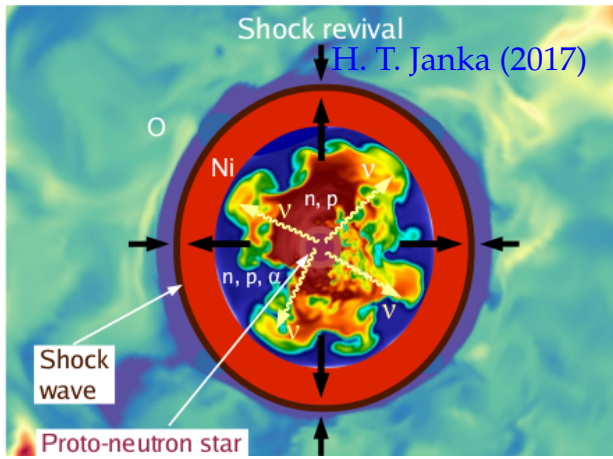
- explosion mechanism — Bethe & Wilson (1985), **AMS** et al. (2022)...
- yields of heavy elements — Woosley et al. (1994), Surman & McLaughlin (2003)...
- compact object formation — Warren et al. (2019), Li, Beacom et al. (2020)...
- neutrino flavor evolution — Balantekin & Fuller (2013), Siwach, **AMS**, Balantekin (2022)...
- non-standard physics — **AMS** et al. (2020), **AMS**, Tamborra (2020) ...

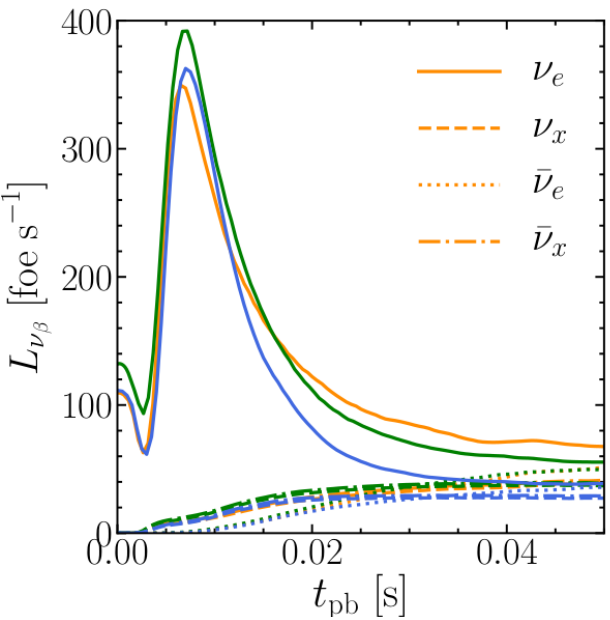
Different phases of supernova explosion

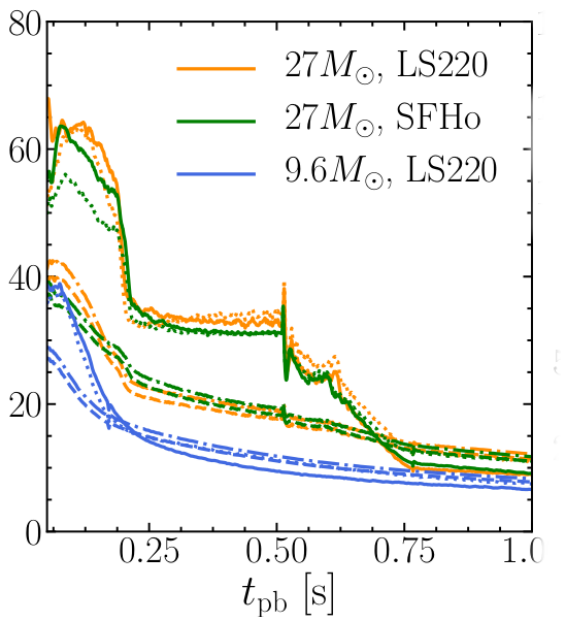
- Infall phase,
  ν_e burst $\sim$ 40 ms
- Accretion phase,
  $\sim$ 100 ms
- Cooling phase,
  $\sim$ 10 s

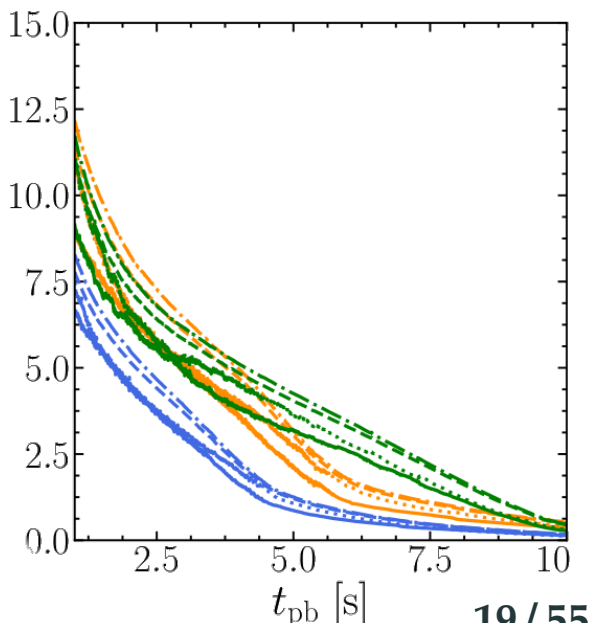












Neutrinos from Supernovae as Probes of New Physics

How new physics affects core-collapse supernovae?

How past works were setting limits on new physics?

- change diffusion time $\rightarrow$ possible change in the star's fate
- changed diffusion time $\rightarrow$ shorter neutrino signal
- new cooling channel $\rightarrow$ affects explosion probability

Astrophysical feedback often ignored!

My personal motivation:
During my PhD I showed that supernova bounds on sterile neutrinos are relaxed by several orders of magnitude once astrophysical feedback is included in calculations
AMS, Tamborra, Wu (2019) and (2020)

How astrophysical feedback affects the bounds on new physics?

LNV neutrino self-interactions in supernova explosion?

In collaboration with P. Cheong, G. Fuller, J. Froustey,

L. Graf, K. Kherer, S. Shalgar, O. Scholer

PRL 134 (2025) 24, 24

Do neutrinos have self-interactions?

IL NUOVO CIMENTO Vol. XXXIII, N. 5 1º Settembre 1964

Do Neutrinos Interact between Themselves?

Z. Bialynicka-Birula

Institute of Physics, Polish Academy of Sciences - Warsaw

(ricevuto il 26 Giugno 1964)



1. – Introduction.

The neutrino is the only elementary particle, which, according to our present knowledge, does not take part in other than weak and gravitational interactions. Its role in nature is not yet fully understood and its interaction properties are only partially known.

The purpose of this note is to answer the following question: Do the present experimental data allow for the existence of interactions between neutrinos much stronger than their weak interactions? The answer to this question is positive. It turns out that such interactions even if they were 10^6 times stronger than weak interactions could not be detected with the present experimental accuracy.

Zofia Białynicka-Birula (1964)

Lepton number violating neutrino self-interactions

Motivation - to be taken with a grain of salt:

- lepton number conservation - accidental symetry
- potential cosmological hints

  Barenboim et al. (2019), Song, Gonzalez-Garcia, Salvado (2018), ..

- strong impact on core-collapse supernova

  Kolb et al. (1982), Fuller et al. (1988), Farzan et al. (2018), **AMS**, Tamborra (2020), ...

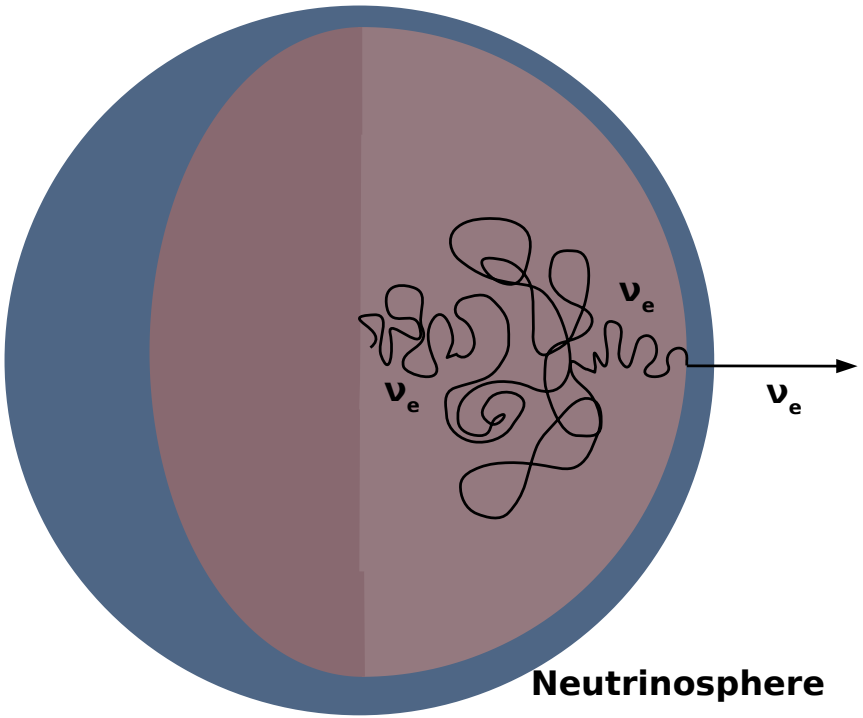
New Interaction Lagrangian

$$\mathcal{L}^{\phi} = g_{\phi,\alpha\beta}\,\phi\,\overline{\nu_{L,\alpha}}\,\nu^{c}_{L,\beta}$$

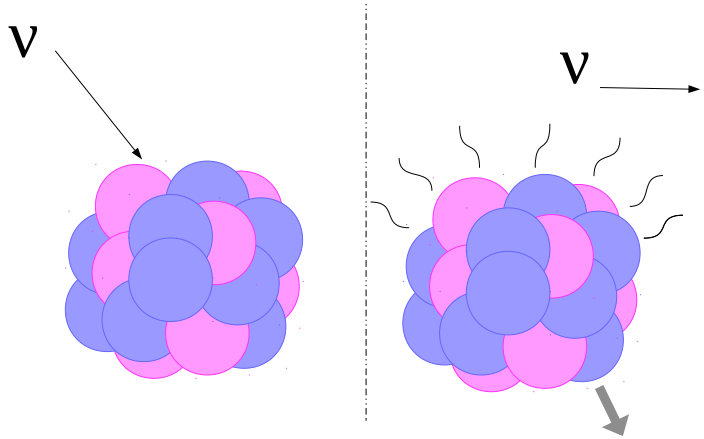
Probability of the New Interaction

$$\sigma_{\nu\mathrm{SI}} \approx \frac{G^2_{\nu\mathrm{SI}}}{8\pi} E^1_\nu E^2_\nu (1-\cos\theta)$$

Neutrino trapping and $\beta-$equilibrium



Neutrino trapping by "sevens"



$$\nu + A(Z,N) \rightarrow \nu + A(Z,N)$$

β-equilibrium

$$e^- + p \rightleftharpoons \nu_e + n$$

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

Implementation:

Thermalize the population of ν and $\bar{\nu}$ once $\rho \sim 10^{11} - 10^{12}$g cm^{-3}

$\nu_e \rightleftharpoons \nu_e, \bar{\nu}_e, \nu_\mu, \bar{\nu}_\mu, \nu_\tau, \bar{\nu}_\tau,$ $\nu_e \rightleftharpoons \nu_e, \bar{\nu}_e, \nu_x, \bar{\nu}_x,$ $\nu_e \rightleftharpoons \nu_e, \bar{\nu}_e$

LNV νSI in supernovae illustrated by cats

Without LNV νSI



Pics credit: Tony Zhou who was courageously cat sitting Aurora and Beetle

LNV νSI in supernovae illustrated by cats

With LNV νSI



Pics credit: Tony Zhou who was courageously cat sitting Aurora and Beetle

Static, Homogenous and Isotropic Boltzmann Equation

Boltzmann Equation

$$\frac{df_\nu}{dt} = (1 - f_\nu) j_\nu - f_\nu \chi_\nu \ ,$$

Electron fraction evolution - weak rates

$$\frac{dY_e}{dt} = R_{\nu_e} - R_{\bar{\nu}_e} - R_{e^-} + R_{e^+} \ ,$$

$$e^- + p \leftrightharpoons \nu_e + n$$

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

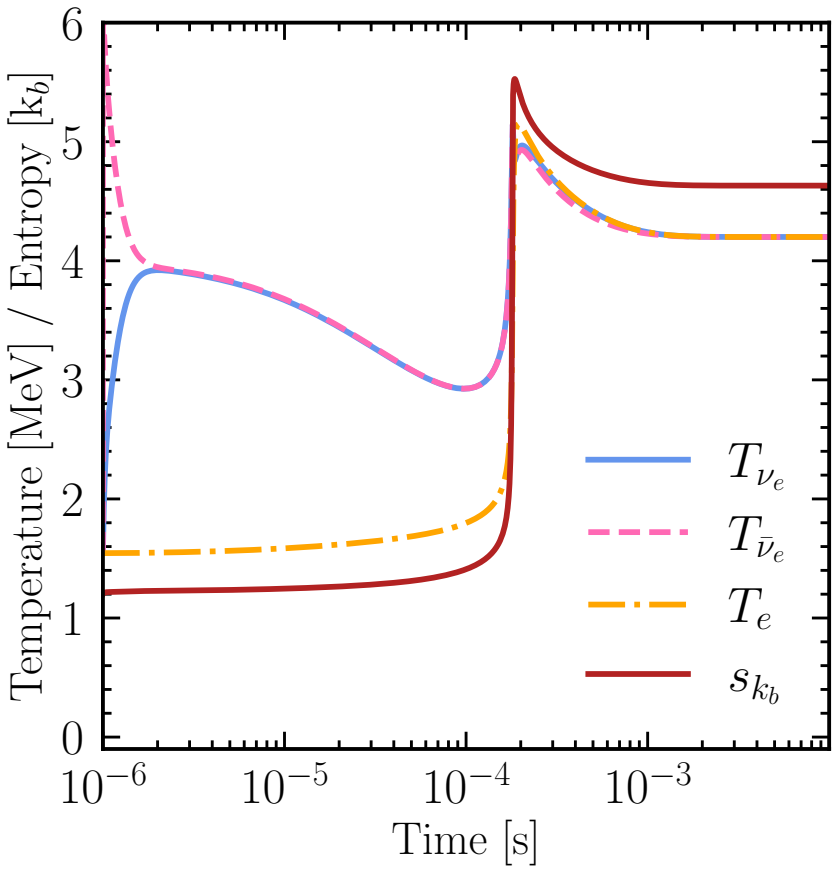
Temperature and chemical potential evolution for leptons

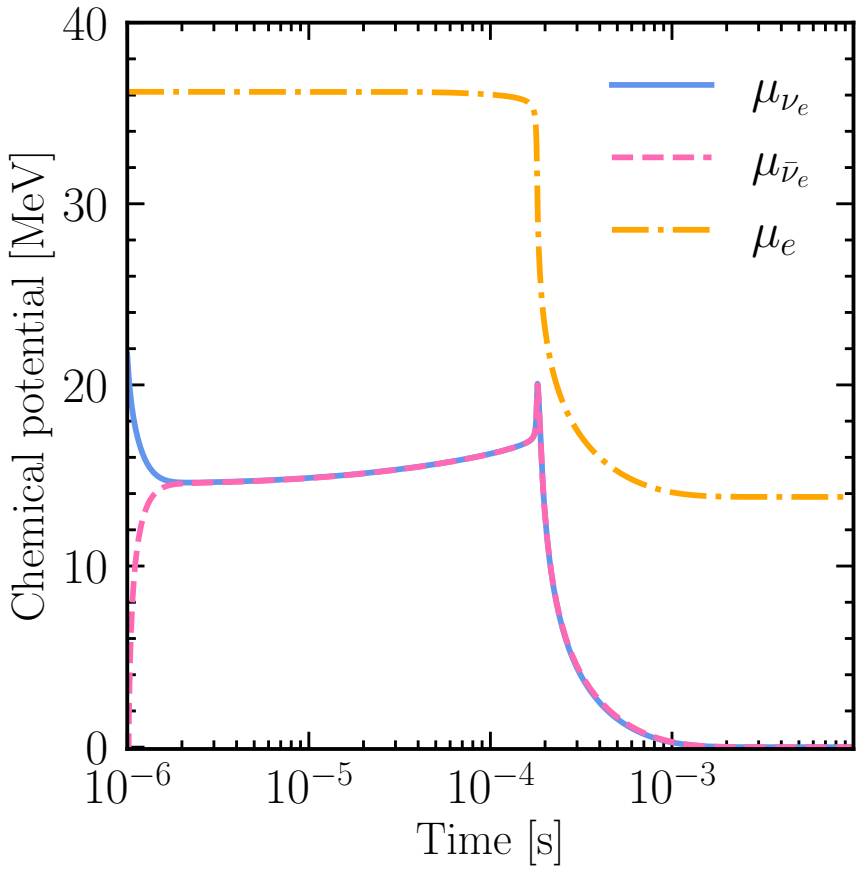
$$\frac{dT_i}{dt} = \left(\frac{\partial \rho_i}{\partial \mu_i} \frac{dn_i}{dt} - \frac{\partial n_i}{\partial \mu_i} \frac{d\rho_i}{dt} \right) \Big/ \left(\frac{\partial n_i}{\partial T_i} \frac{\partial \rho_i}{\partial \mu_i} - \frac{\partial n_i}{\partial \mu_i} \frac{\partial \rho_i}{\partial T_i} \right) \ ,$$

$$\frac{d\mu_i}{dt} = \left(\frac{\partial \rho_i}{\partial T_i} \frac{dn_i}{dt} - \frac{\partial n_i}{\partial T_i} \frac{d\rho_i}{dt} \right) \Big/ \left(\frac{\partial n_i}{\partial \mu_i} \frac{\partial \rho_i}{\partial T_i} - \frac{\partial n_i}{\partial T_i} \frac{\partial \rho_i}{\partial \mu_i} \right) \ .$$

+**BBAL** (1979) EOS

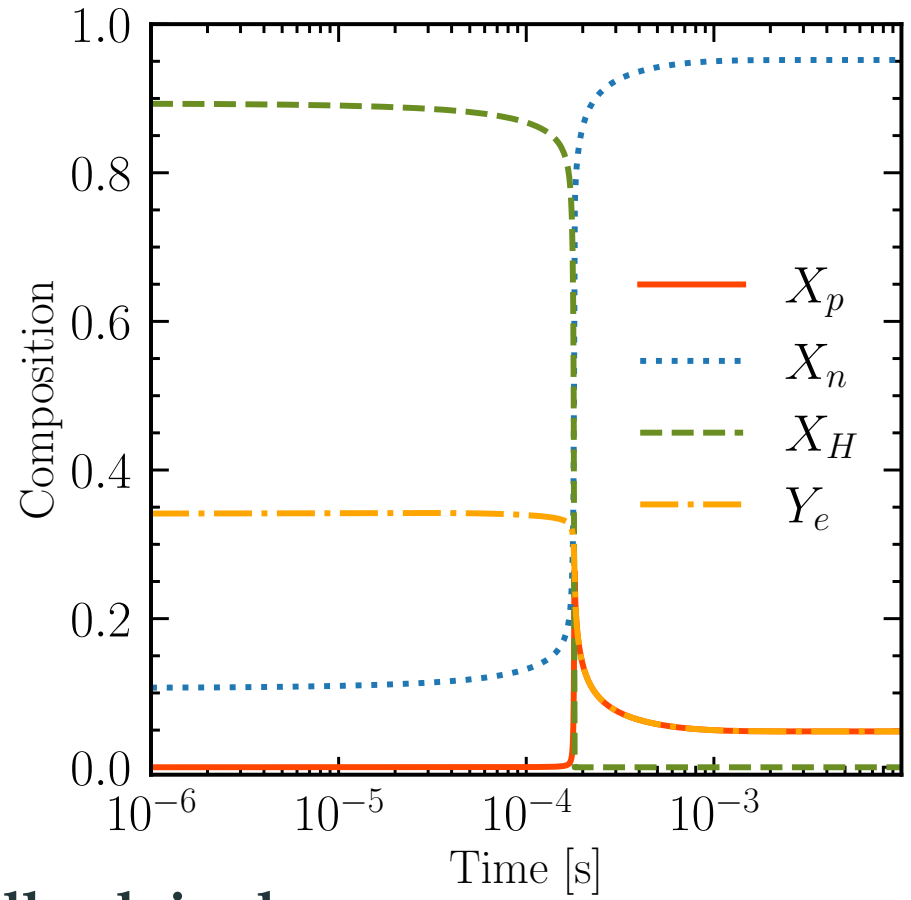
Evolution of Thermodynamical Quantities





- new interactions quickly equilbrate ν_e and $\bar{\nu}_e$ seas
- enhanced ν_e and e^- captures heat up the matter
- similar results for all flavors equilibration

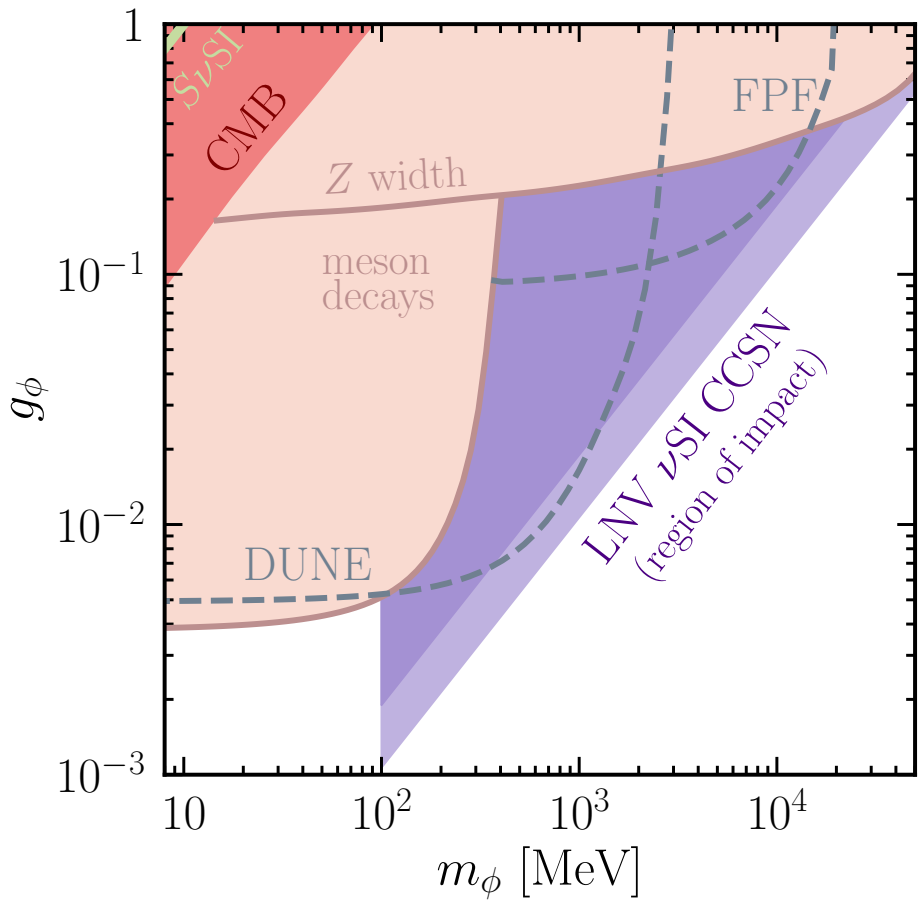
Composition and pressure support of the core



Astrophysical feedback is clear:

- entropy generation shifts composition towards no heavy nuclei
- enhanced deleptonization changes the pressure support of the core

Sensitivity limits on LNV νSI



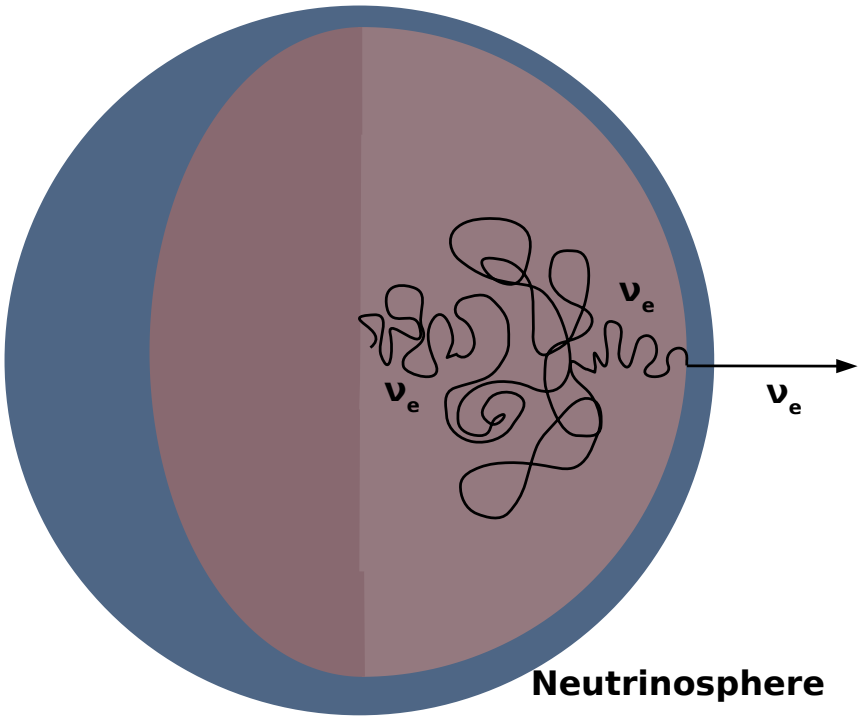
- impossible to see in SN 1987A neutrino signal
- complementarity with future accelerator-based experiments
- multi-flavor neutrino burst? 1st order phase transition 2510.23713?

Can we detect non-standard neutrino-quark interactions in supernova neutrino signal?

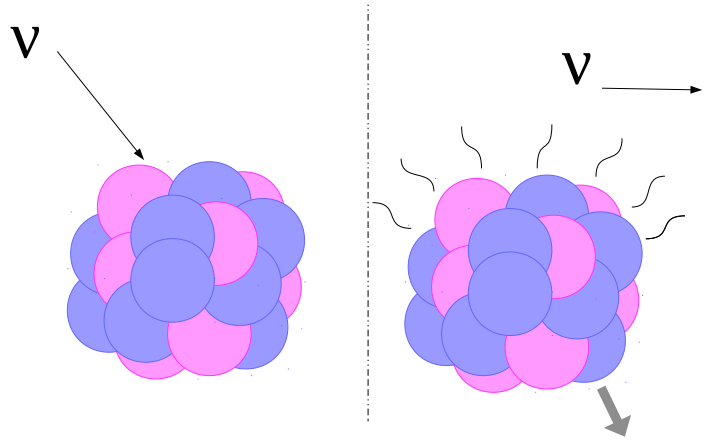
In collaboration with A. Beatty and V. Takhistov

arXiv: 2509.07856

Neutrino trapping



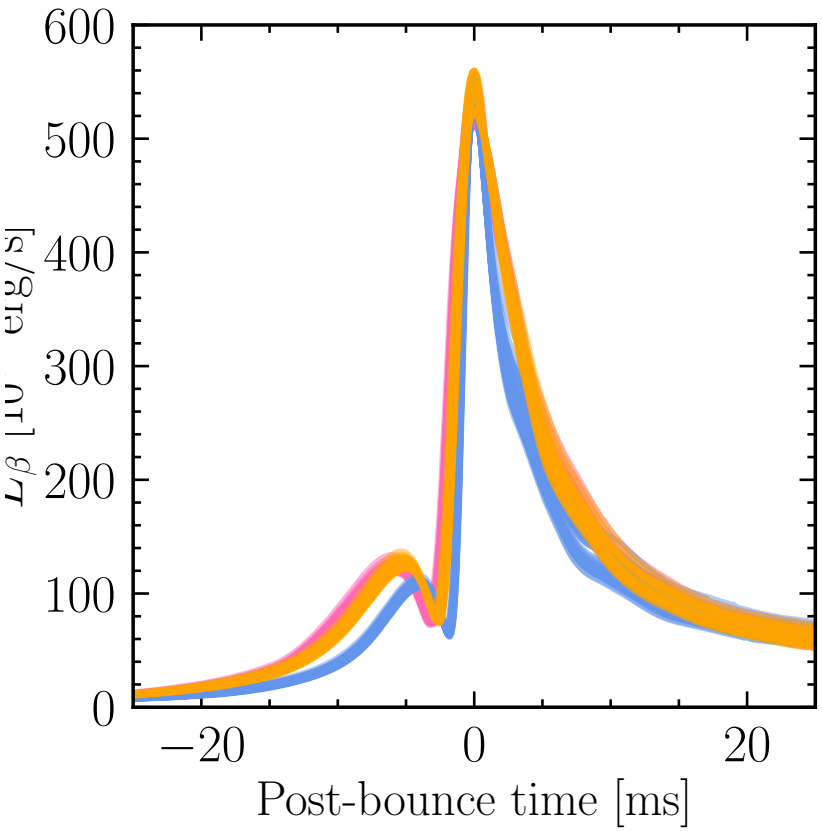
Neutrino trapping by "sevens"



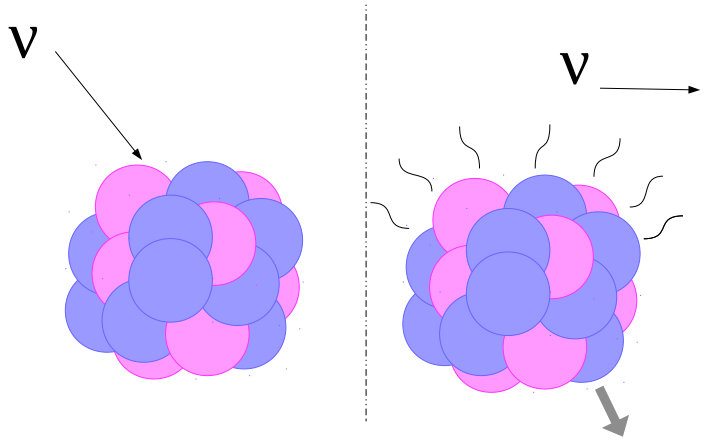
$$\nu + A(Z,N) \rightarrow \nu + A(Z,N)$$

Coherent Elastic Neutrino-Nucleus Scattering (CEvNS)

Neutrino trapping



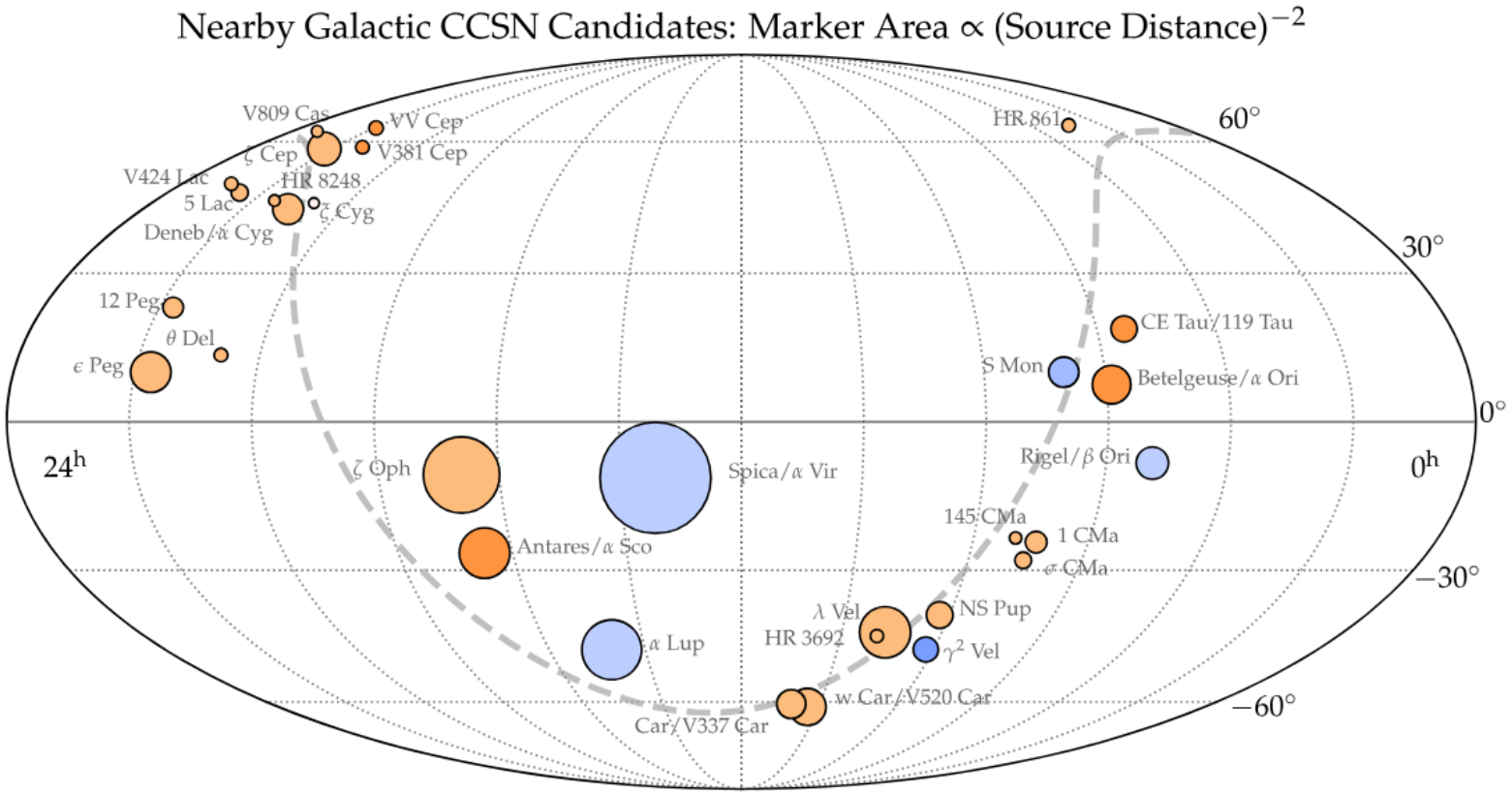
Neutrino trapping by "sevens"



$$\nu + A(Z,N) \rightarrow \nu + A(Z,N)$$

Coherent Elastic Neutrino-Nucleus Scattering (CEvNS)

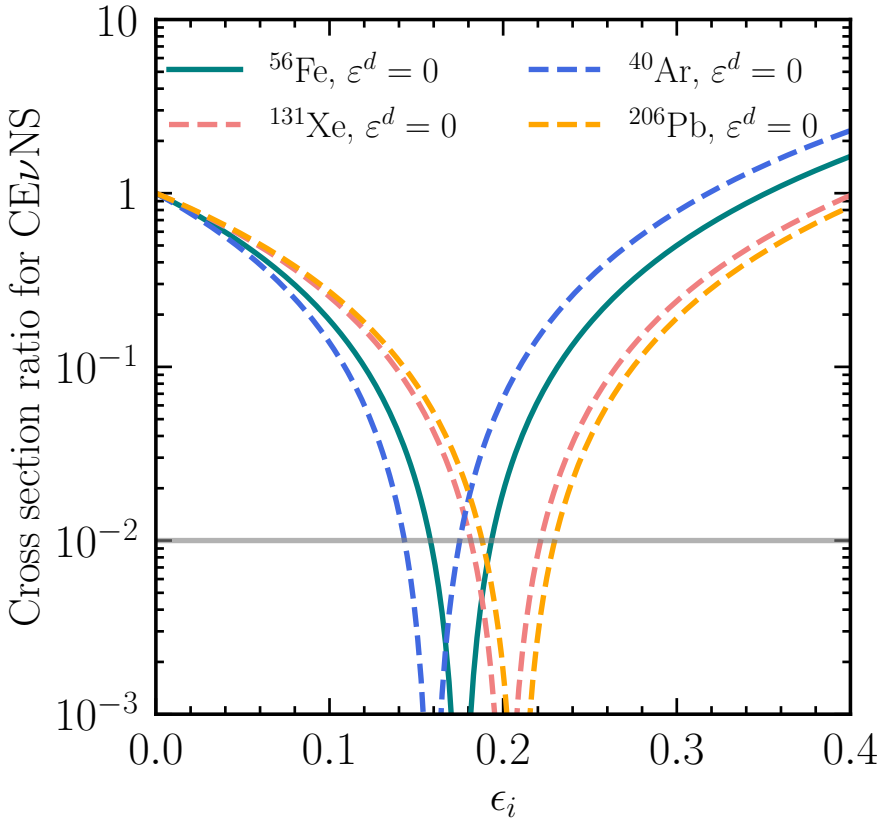
Supernova-ready supergiant stars within ∼1 kpc of Earth

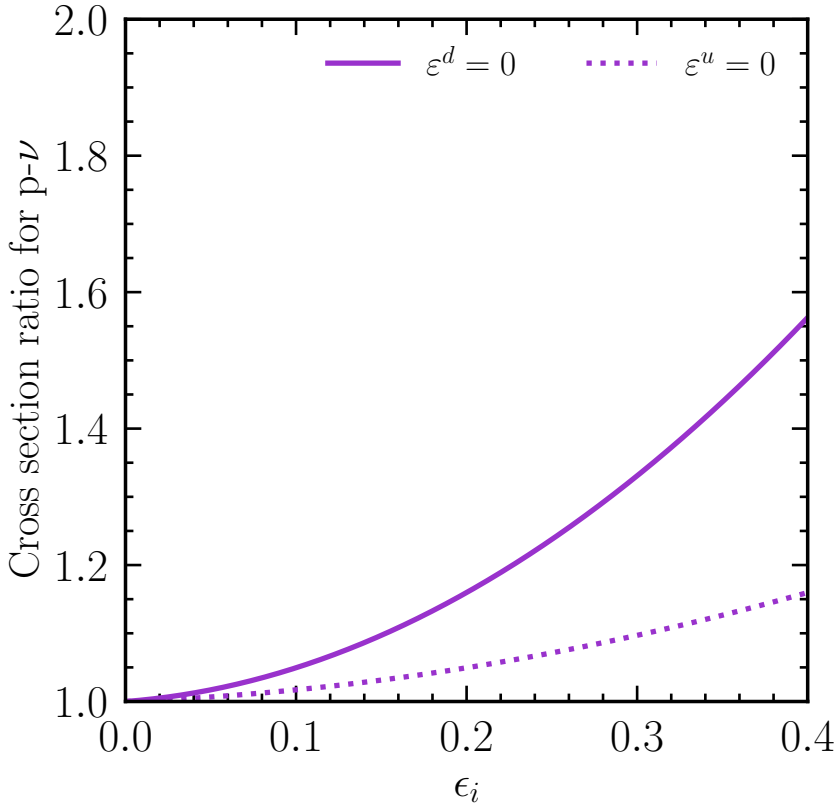


- ∼40 supernova-ready stars within 1 kpc
- best-known Betelgeuse at ∼ 0.2 kpc

SNEWS 2.0 (2021)

Non-standard neutrino-quark interactions





New Interaction Lagrangian

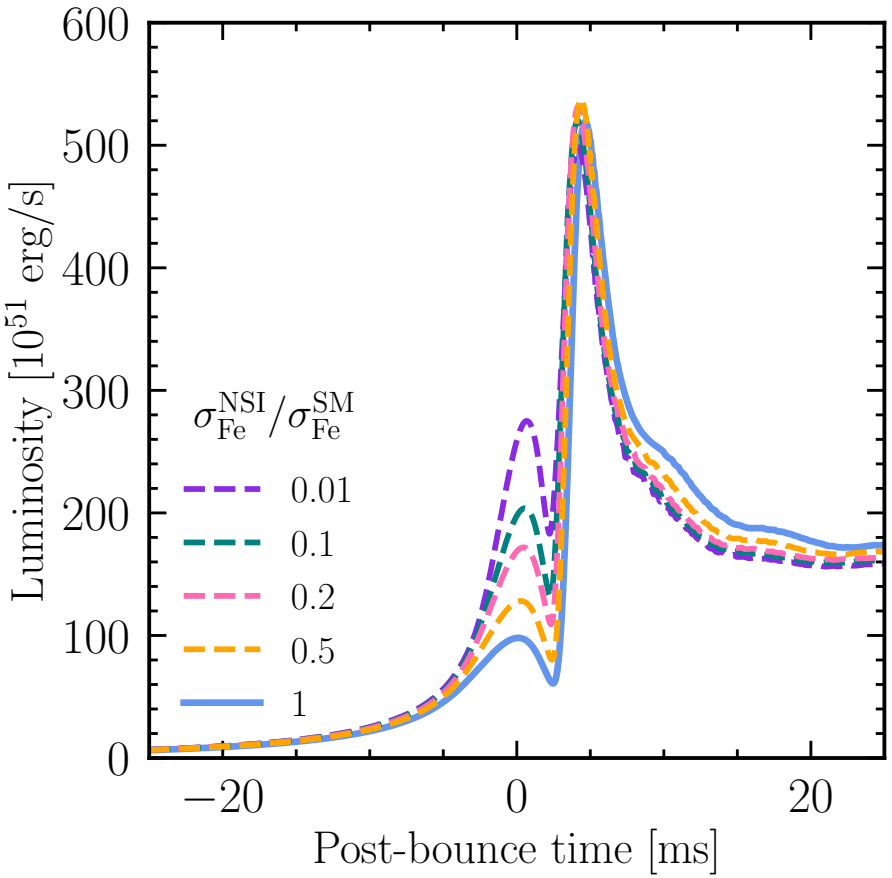
$$\mathcal{L}_{\text{NSI}} = -2\sqrt{2}G_F\varepsilon^{fV}_{\alpha\alpha}(\overline{\nu}_{\alpha L}\gamma^\rho\nu_{\alpha L})(\overline{f}\gamma_\rho f)$$

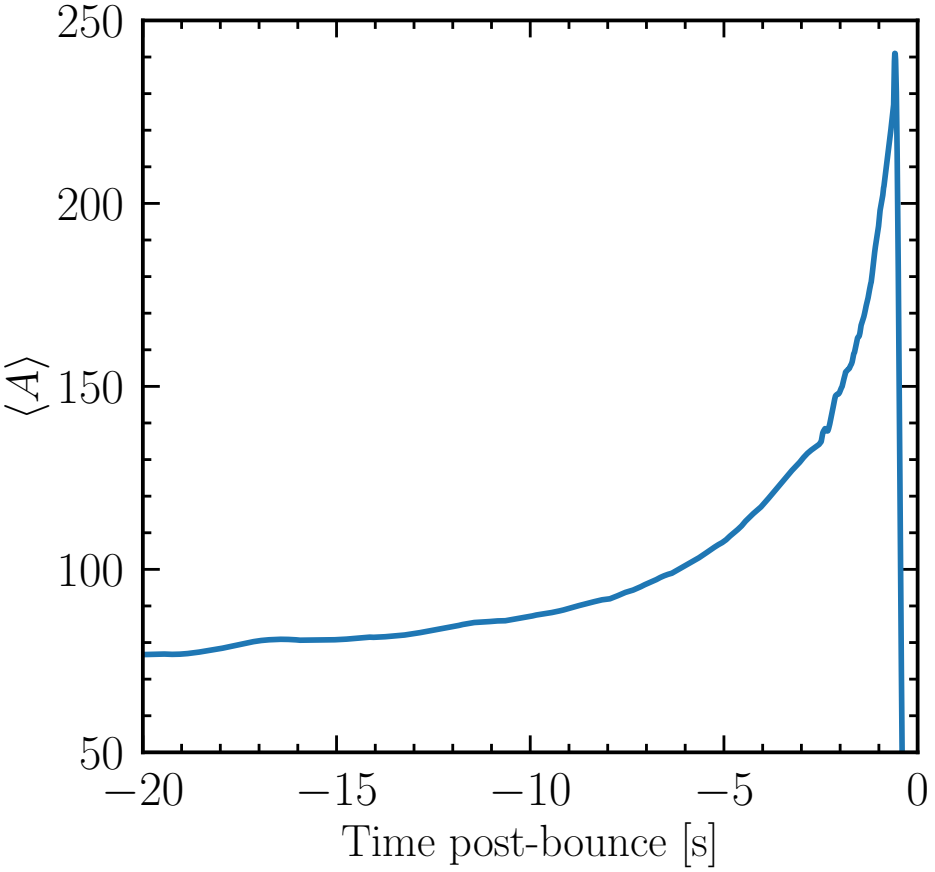
$$\varepsilon^{u(d)} = \varepsilon^{u(d)V}_{ee} = \varepsilon^{u(d)V}_{\mu\mu} = \varepsilon^{u(d)V}_{\tau\tau}$$

- Extreme changes for CEνNS
- Moderate changes for ν-p

D. Z. Freedman (1973), L. Wolfenstein (1977), B. Dev et al. (2016), Huang et al. (2021)

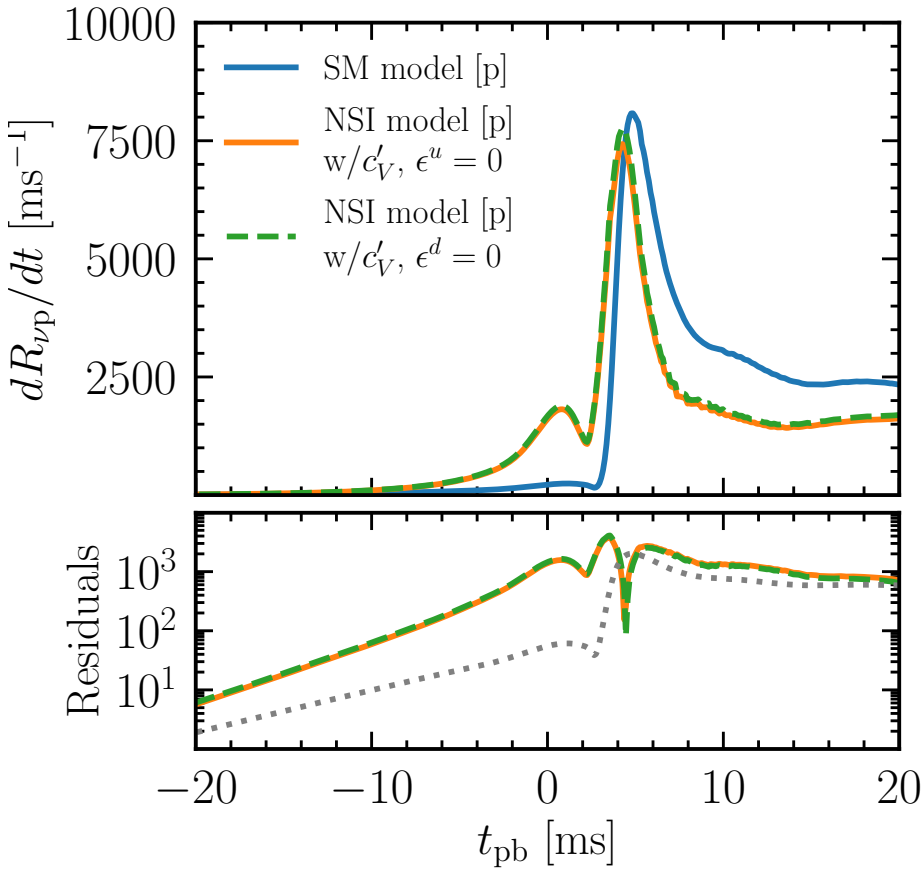
Changes in the neutrino signal: GR1D simulations

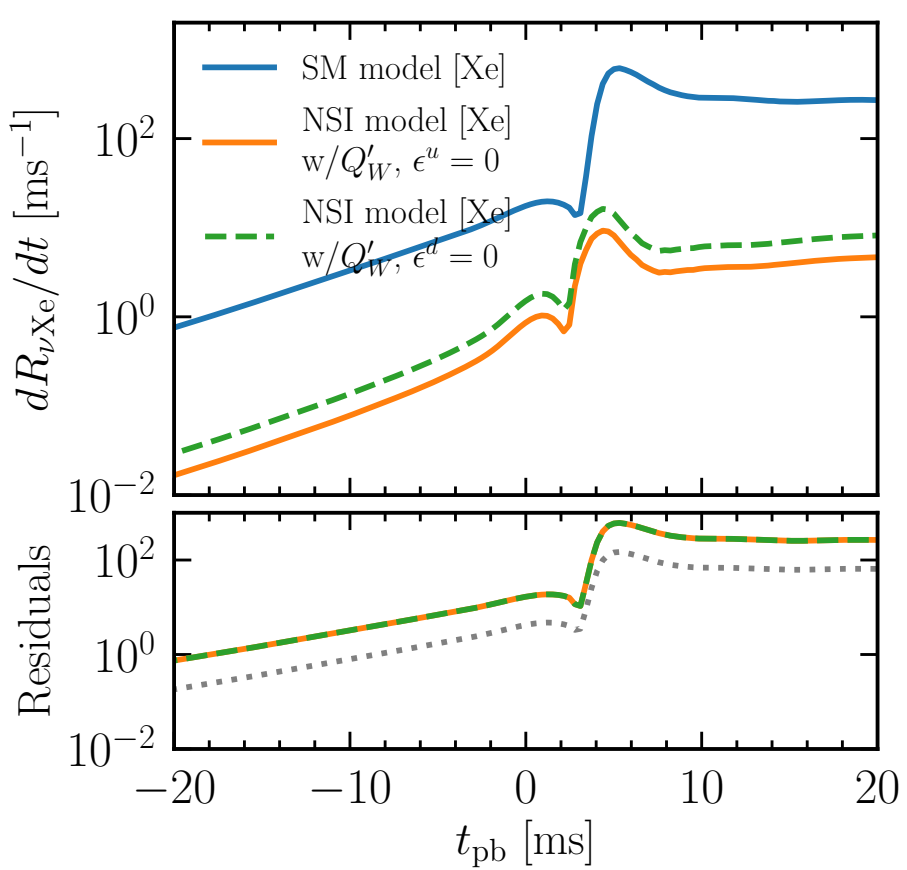




- Significant change in the luminosity pre-bounce
- Pre-bounce - heavy nuclei in the core
- Post-bounce - nucleons in the core

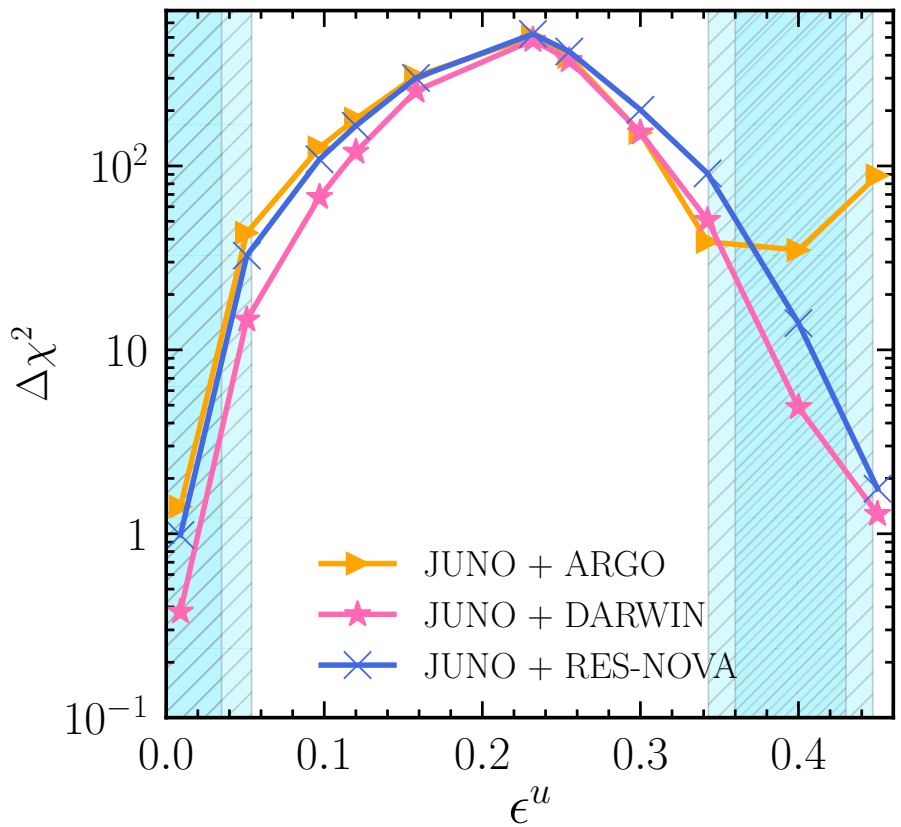
Rates in JUNO and DM detectors for the Betelgeuse





- JUNO - rate changed for the infall signal
- DARWIN - rate changed always
- approximately opposite effects

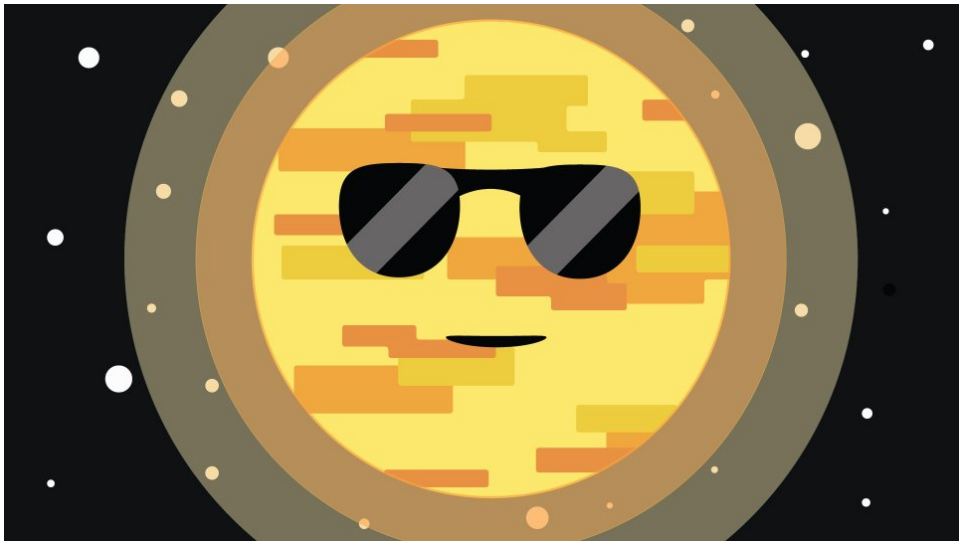
Statistical analysis and sensitivity limits to NSI



- opposite responses of the detectors - robust against astro uncertainty
- sensitivity limits at the level of terrestrial limits

Diffuse supernova neutrino background

Why focus only on a single rare event?

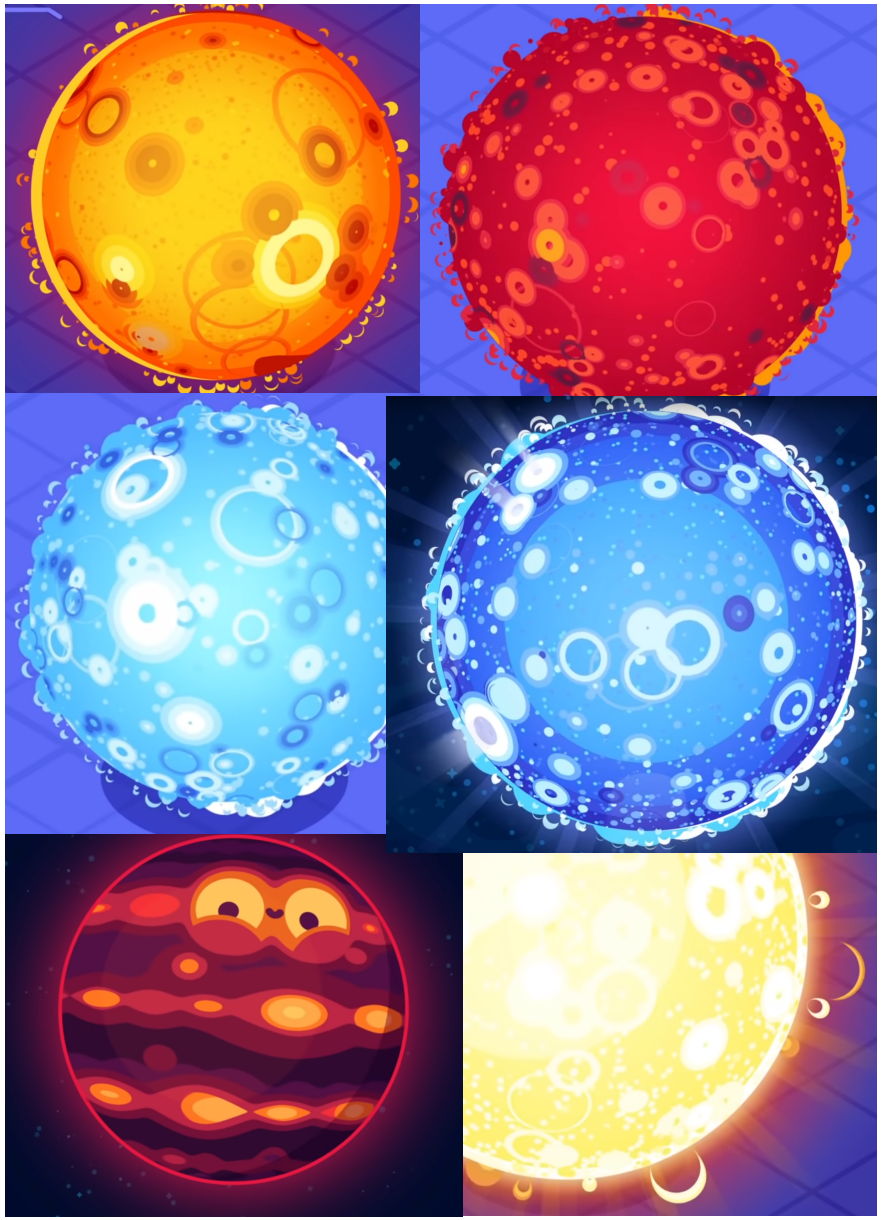


Single galactic SN event

- rare event
- precise infromation about one star

Multiple SN events (larger distances)

- accumulation of events
- will detect in coming years



Images: Kurzgesagt

Diffuse supernova neutrino background

cosmological supernovae rate

fraction of black-hole-forming progenitors

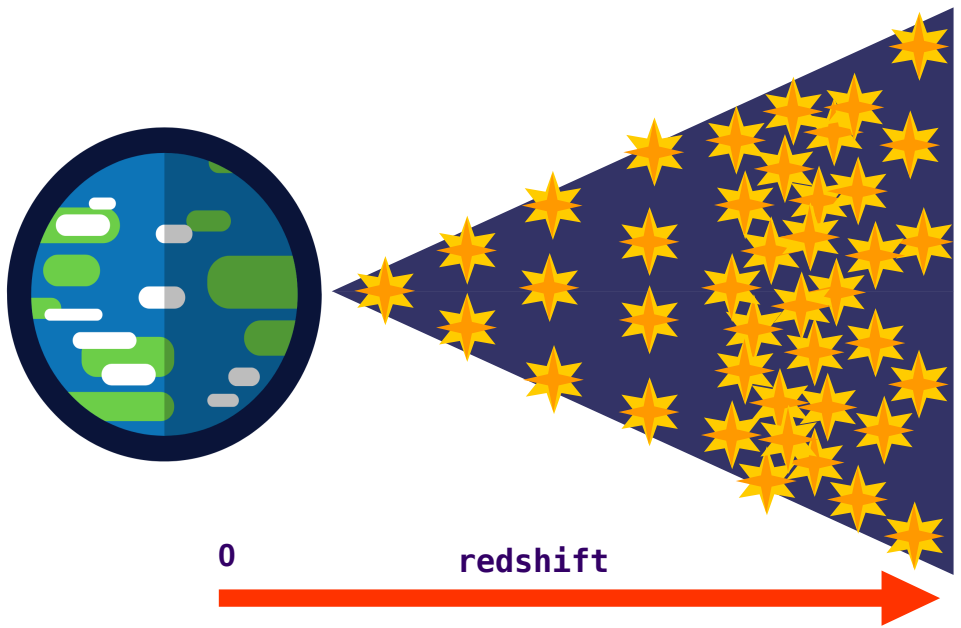
$$\Phi_{\nu_\beta}(E) = \frac{c}{H_0}\int dM \int dz \frac{R_{\rm SN}(z,M)}{\sqrt{\Omega_M(1+z)^3+\Omega_\Lambda}} \left[f_{\rm CC-SN}F_{\nu_\beta,\rm CC-SN}(E',M) + f_{\rm BH-SN}F_{\nu_\beta,\rm BH-SN}(E',M)\right]$$

fraction of neutron-star-forming progenitors

neutrino flux from a single star

The DSNB is sensitive to:

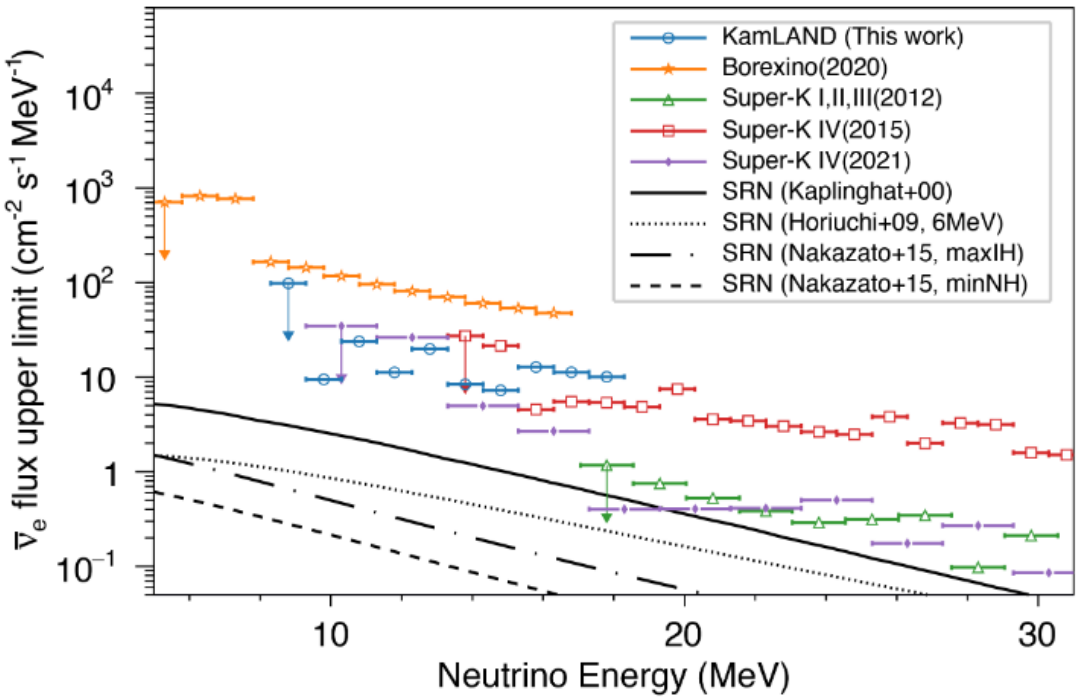
- $R_{\rm SN}, f_{\rm BH-SN}$
- neutrino flavor evolution
- equation of state
- mass accretion rate in BH-SN
- non-standard physics



Guseinov (1967), Totani et al. (2009), Ando, Sato (2004), Lunardini (2009), Beacom (2010),..
Recent reviews: Kresse et al. (2020), **AMS** (2022), Ando et al. (2023), ...

Diffuse supernova neutrino background: current limits

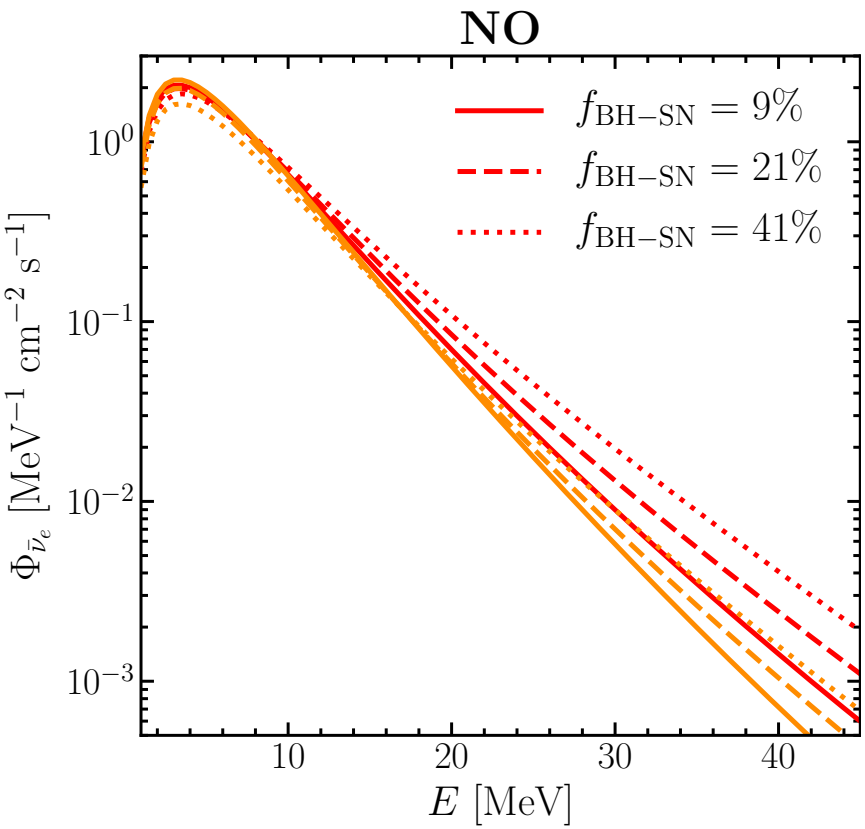
SK collab. (2021)



DSNB limits:

- $\bar{\nu}_e \approx 3\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}$ for $E_\nu > 17.3$ MeV SK collab. (2021), SK collab. (2023)
  soon detected by SK (Gd) Beacom, Vagins (2004) and JUNO JUNO collab. (2021)
- $\nu_e \approx 19\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}$ for $E_\nu\ \epsilon\ [22.9, 36.9\ \mathrm{MeV}]$ SNO collab. (2020)
  possibly detectable by DUNE Møller, **AMS**, Tamborra, Denton (2018), Zhu et al. (2019)

The fraction of black-hole-forming progenitors



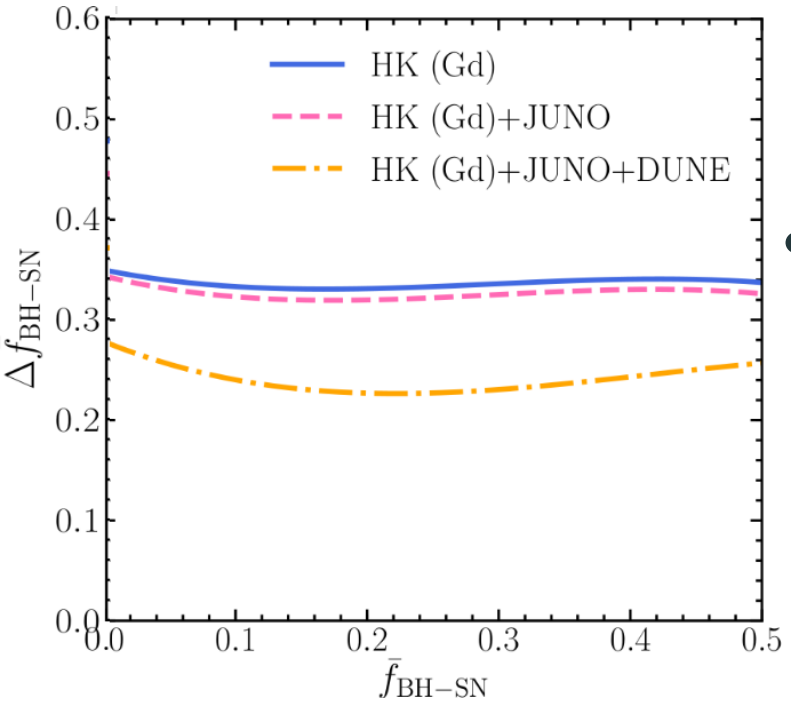
1D SN models
Garching group archive

Fraction of black-hole-forming progenitors influences the highly energetic part of the DSNB, above ~ 15 MeV.

C. Lunardini (2009)

Keehn, Lunardini (2010), Lunardini, Tamborra (2012), Priya, Lunardini (2017), Møller, **AMS** et al. (2018), Nakazato et al. (2018) Kresse et al. (2020), ...

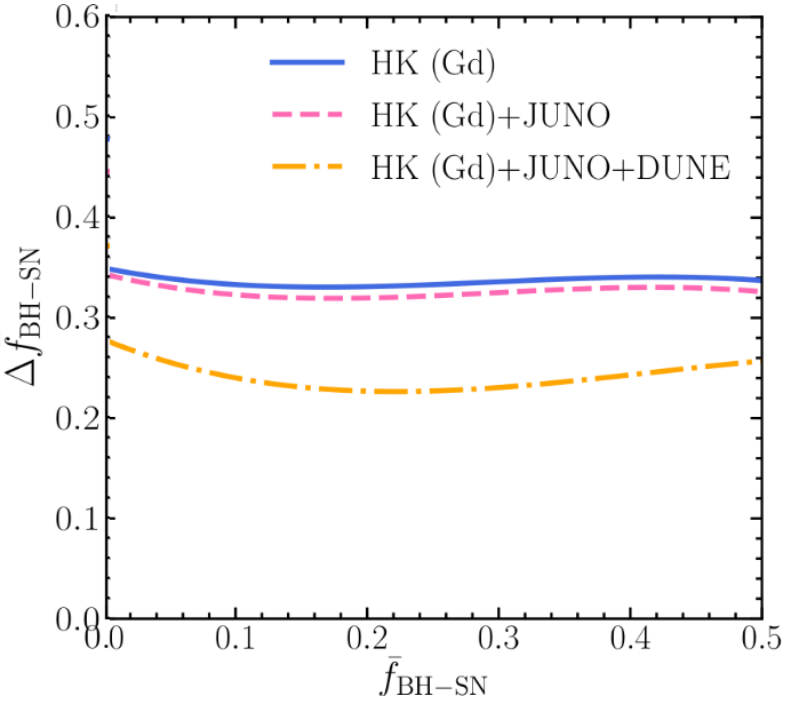
Expected 1σ uncertainty: fraction of BH forming progenitors



- DUNE is sensitive to neutrinos $\rightarrow$ helps to reduce the uncertainty

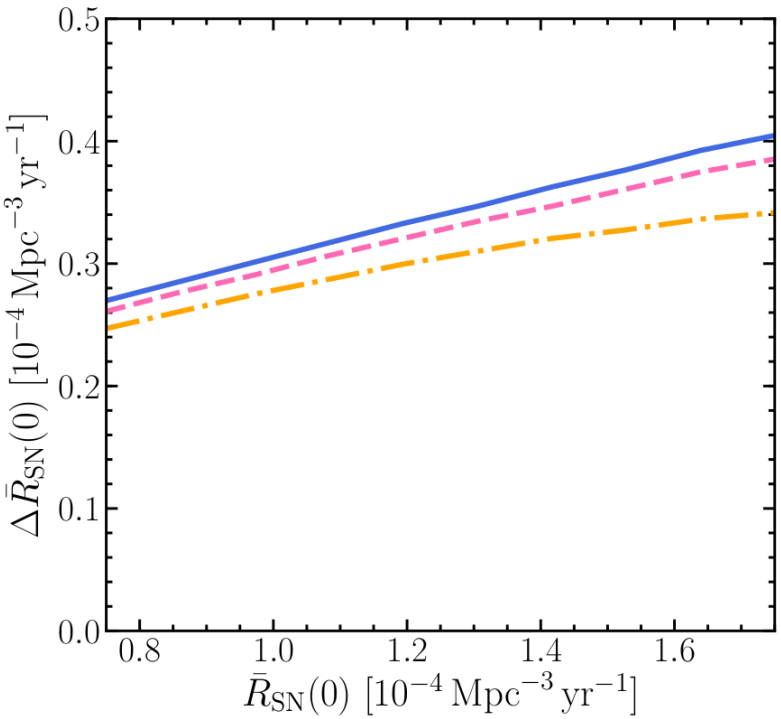
Møller, **AMS**, Tamborra, Denton (2018)

Expected 1σ uncertainty: local supernova rate



- DUNE is sensitive to neutrinos $\rightarrow$ helps to reduce the uncertainty

- Relative error of 20%-33% comparable to current electromagnetic limits



Møller, **AMS**, Tamborra, Denton (2018)

Astrophysical uncertainties affecting the DSNB

- Neutrino Flux from an "Average Supernova"

  Lunardini (2009), Lunardini & Tamborra (2012), Horiuchi et al. (2018), Kresse et al. (2018), ...

- Cosmological Supernovae Rate

  Beacom (2010), Horiuchi et al. (2011), Ando et al. (2023), ...

- Initial Mass Function

  Ziegler, Edwards, **AMS**, Tamborra, Horiuchi, Ando, Freese (2022)

- Fraction of Black-Hole-Forming Progenitors

  Lunardini (2009), Lien et al. (2010), Keehn & Lunardini (2012), Priya & Lunardini (2017),

  Møller, **AMS**, Tamborra, Denton (2018), Horiuchi et al. (2018), Kresse et al. (2018), ...

- Binary Interactions

  Horiuchi, Kinugawa, Takiwaki, Takahashi (2021)

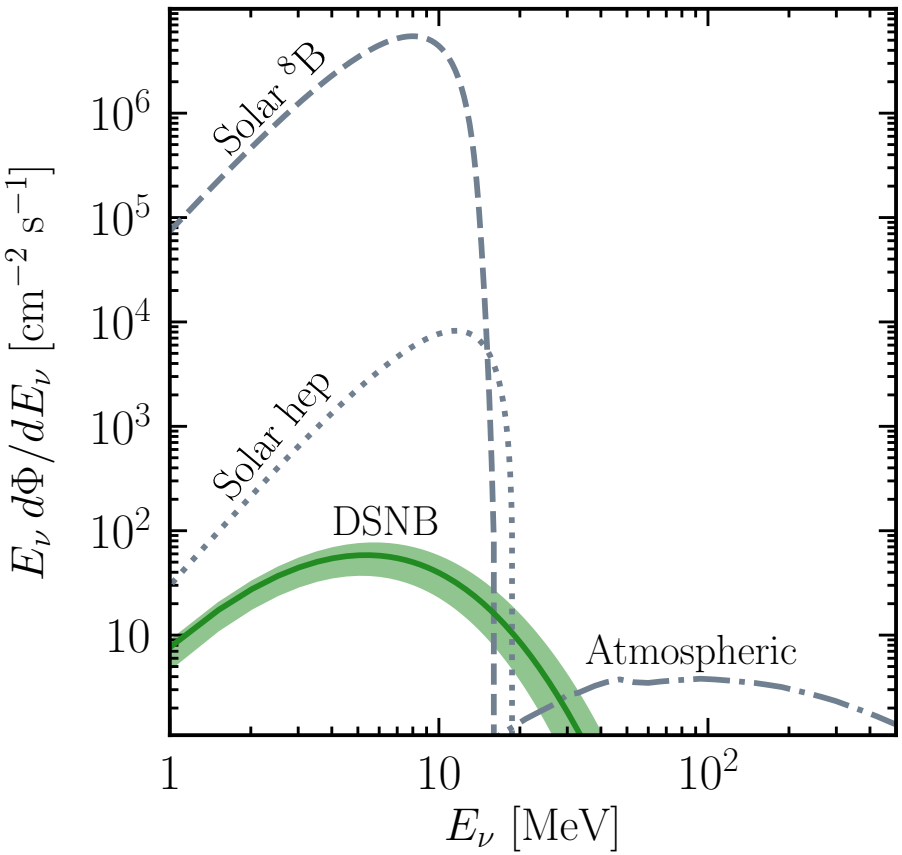
Non exhaustive list of references

Towards probing the DSNB in all flavors

In collaboration with J. Beacom, and I. Tamborra

Phys.Rev.D 105 (2022) 4, 043008

Can we detect the x-flavor DSNB? Maybe

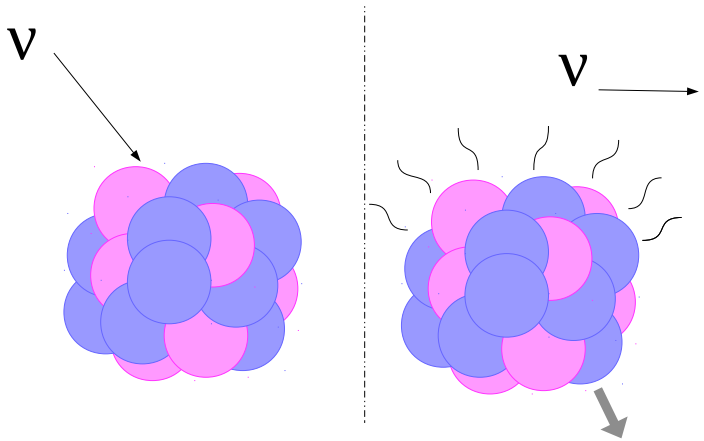


DSNB modeling:
Møller, **AMS**, Tamborra, Denton (2018)

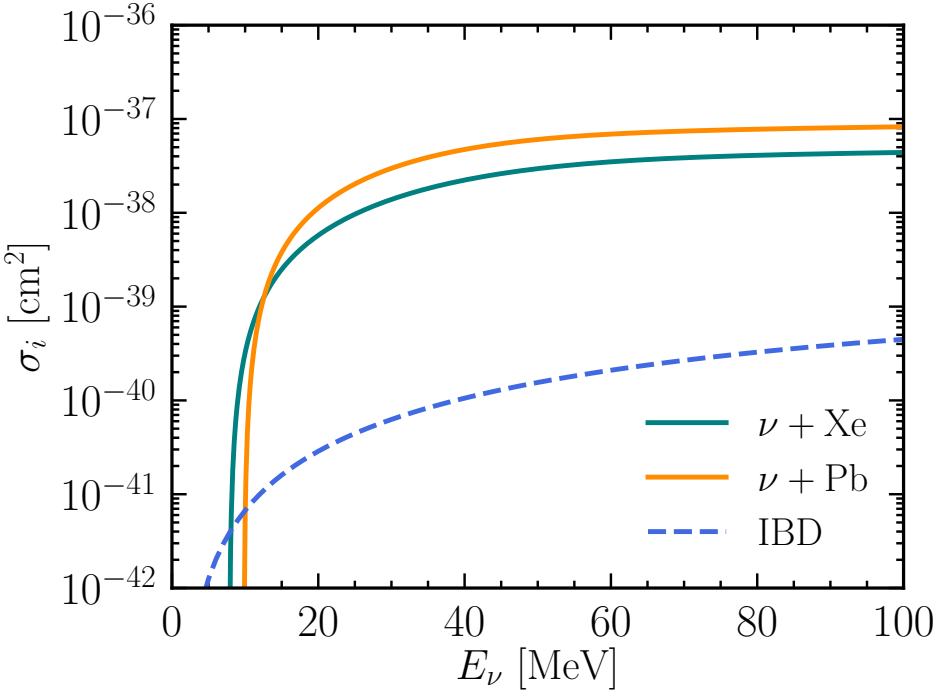
- Favor-blind channel: potential detection window $\sim 18 - 30$ MeV
- Current limit: $\nu_x \approx 750\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}$ for $E_\nu > 19.3$ MeV Lunardini, Peres (2008)

Vitagliano et al. (2019), Honda et al. (2011), Newstead et al. (2020)

Maybe: Coherent elastic neutrino-nucleus scatterings (CEνNS)



$$\nu + T(A,Z) \to \nu + T(A,Z)$$



Cross section

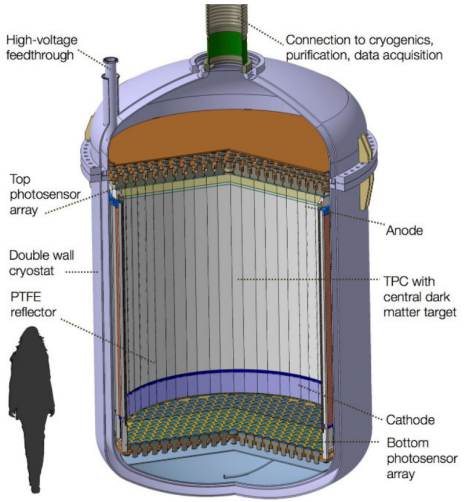
$$\frac{d\sigma_{\rm SM}}{dE_r} = \frac{G_F^2 m_T}{4\pi} Q_w^2 \left(1 - \frac{m_T E_r}{2E_\nu^2}\right) F^2(Q), \;\; Q_w = \left[N - Z(1 - 4\sin^2\theta_W)\right]$$

- coherently enhanced by the square of the neutron number
- flavor insensitive
- coherent up to ~ 50 MeV

Freedman (1974)

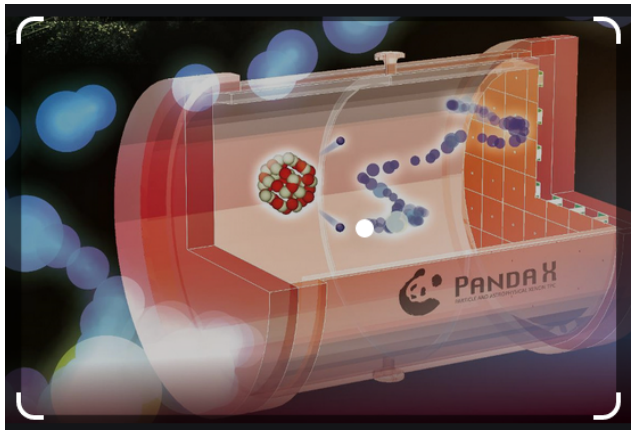
Current and future CEνNS detectors

XENONnT, DARWIN



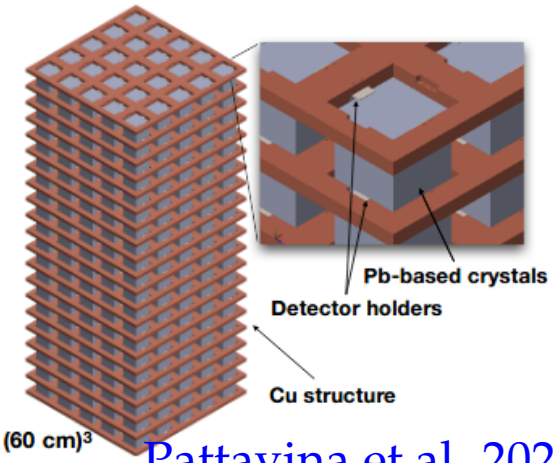
Aalbers al. 2016

PandaX-4T, PandaX-xT



Menget al. 2021

RES-NOVA



Pattavina et al. 2020

fiducial volumes: few - hundreds ton

target materials: Xe, Pb

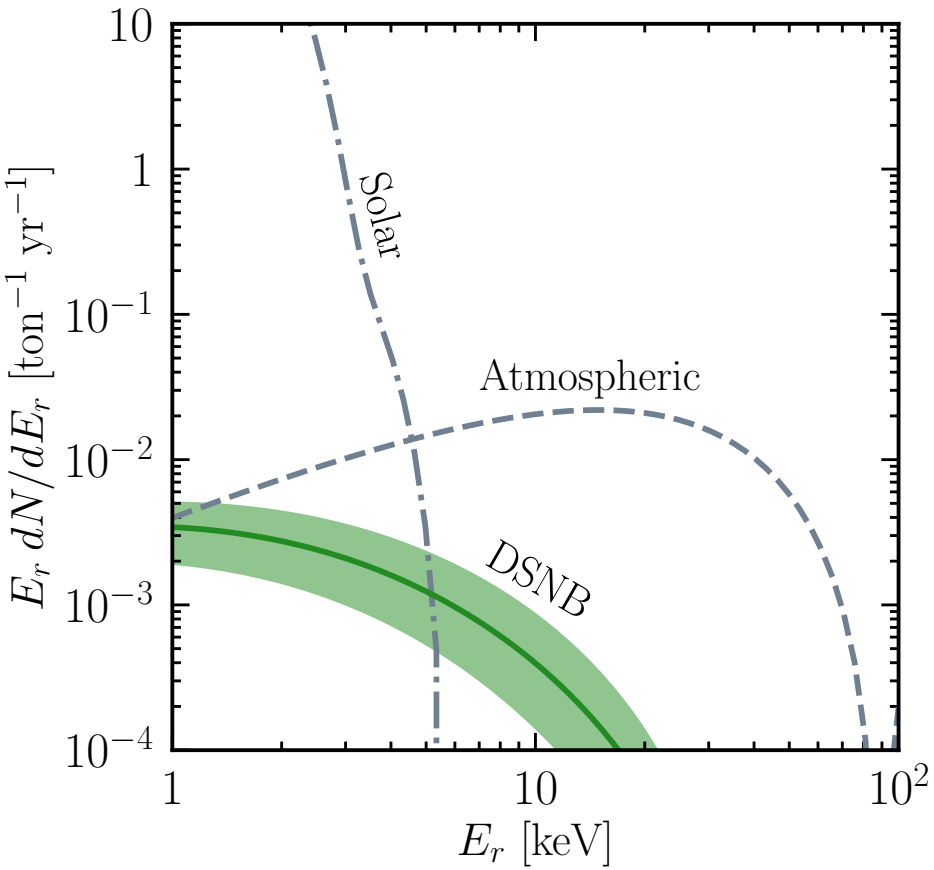
thresholds: $\mathcal{O}(1)$ keV

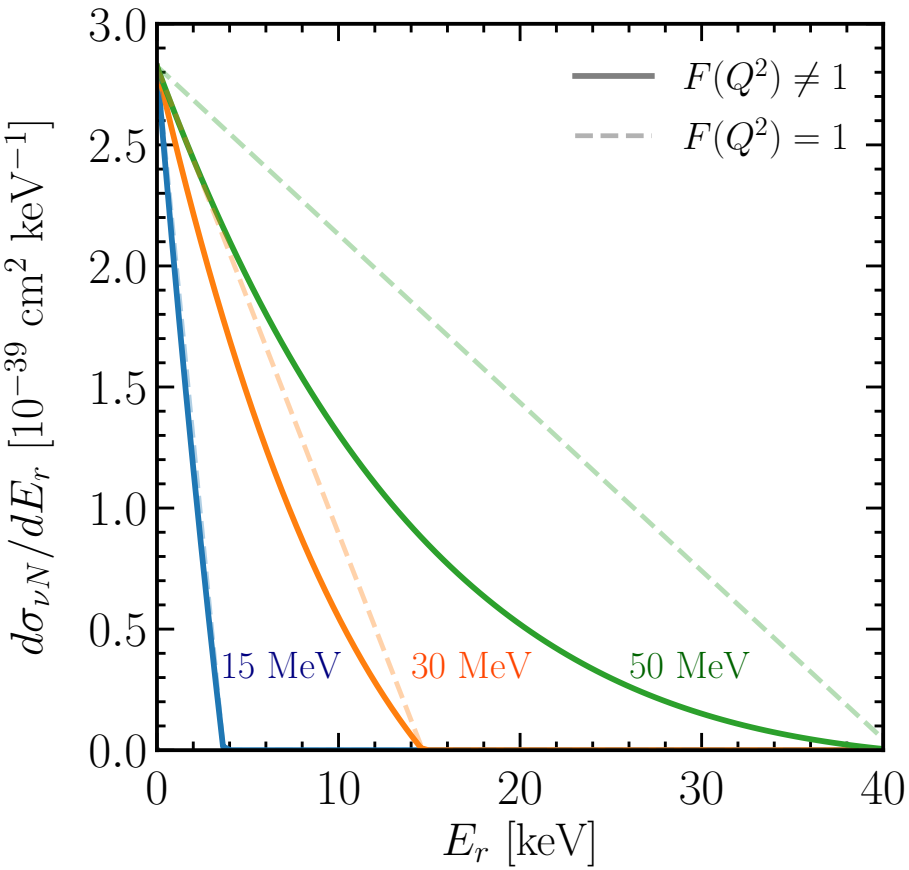
efficiency: $\sim$ 80-100%

Scattering rate

$$\frac{dR_{\nu N}}{dE_r dt} = N_T\, \epsilon(E_r) \int dE_\nu\, \frac{d\sigma_{\nu N}}{dE_r}\, \psi(E_\nu, t)\, \Theta(E_r^{\max} - E_r), \quad E_r^{\max} = \frac{2E_\nu^2}{m_T + 2E_\nu}$$

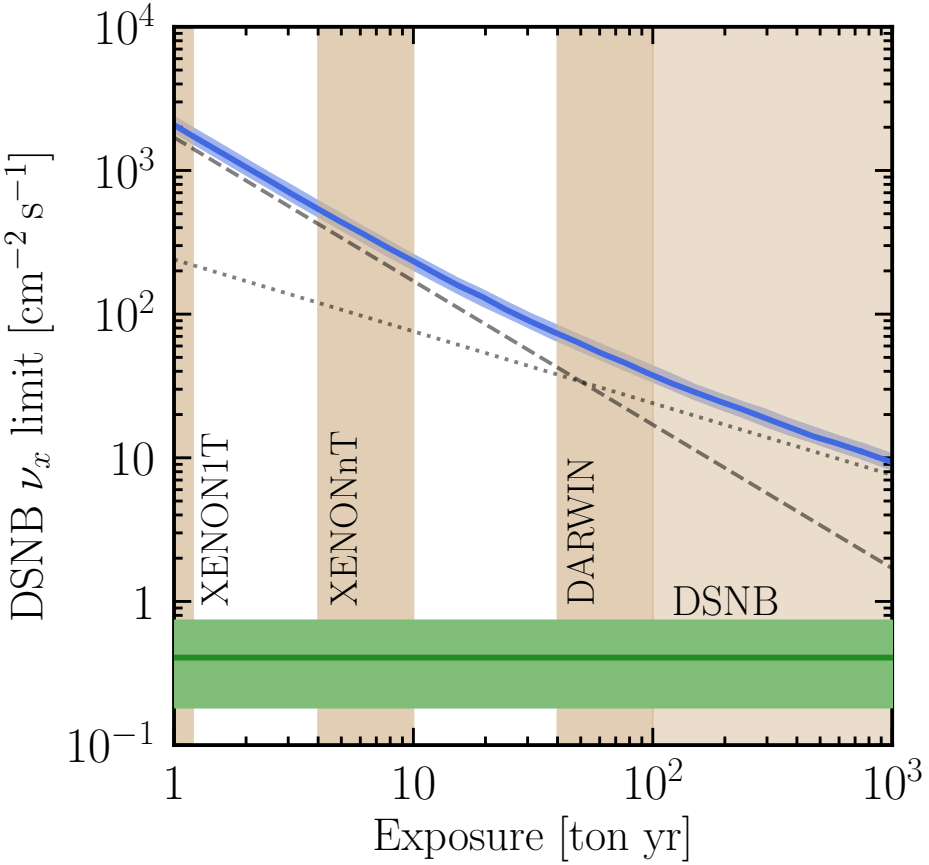
Event rate in the xenon-based detector





- The potential energy window displayed by the bare fluxes disapears
- Reason: Low energy recolis are most probable for all neutrino energies
- Detection of the x-flavor DSNB seems out of reach, BUT...

Can we improve the limits on the x-flavor DSNB? Yes



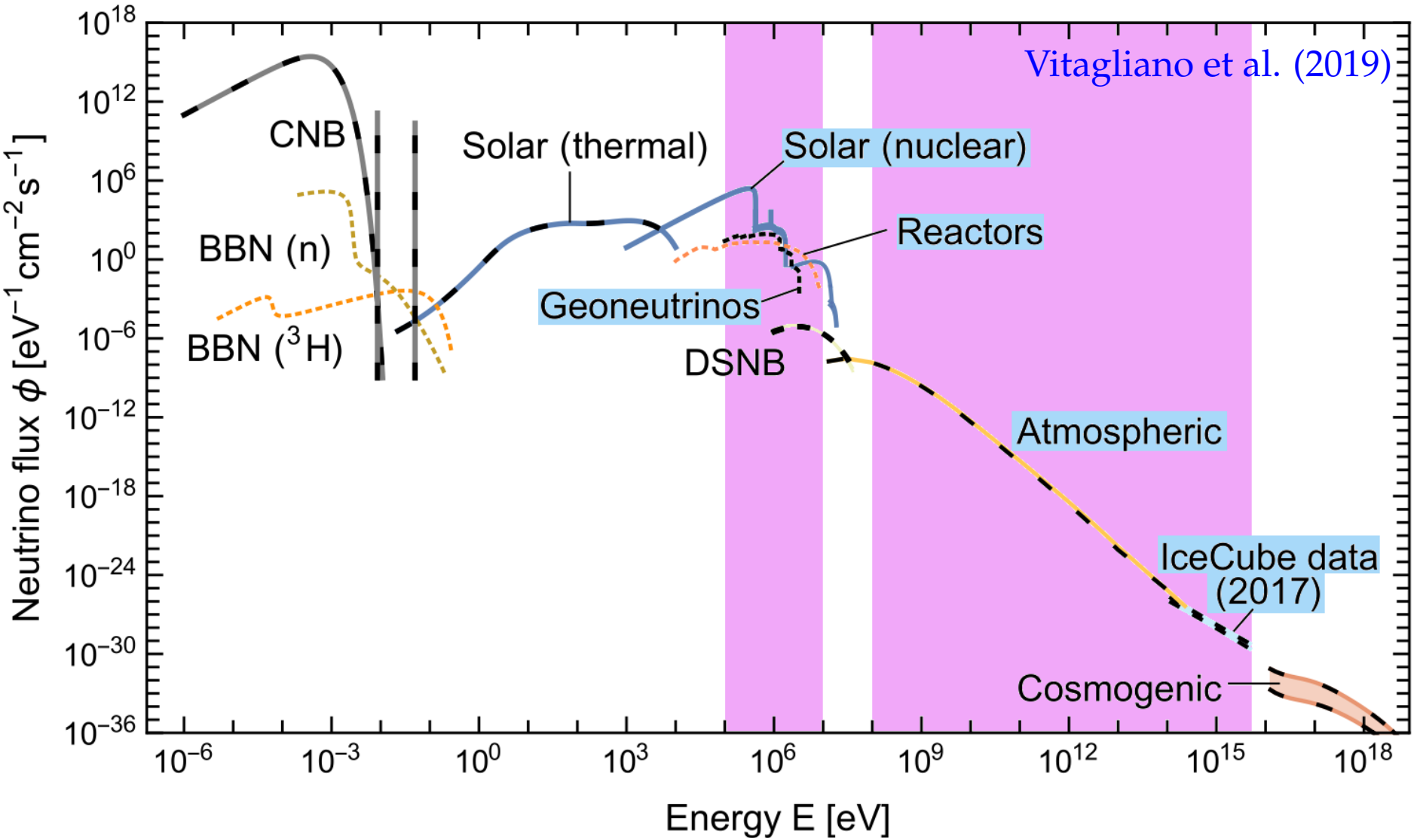
- XENON1T, PandaX-4T: limits comparable to the SK ν_x DSNB limit
- Constant energy window: limits can improve $\mathcal{O}(10\%)$ for wider windows at small exposures and narrower windows at large exposures

Distinctive nuclear signatures of low-energy atmospheric neutrinos

In collaboration with J. Beacom

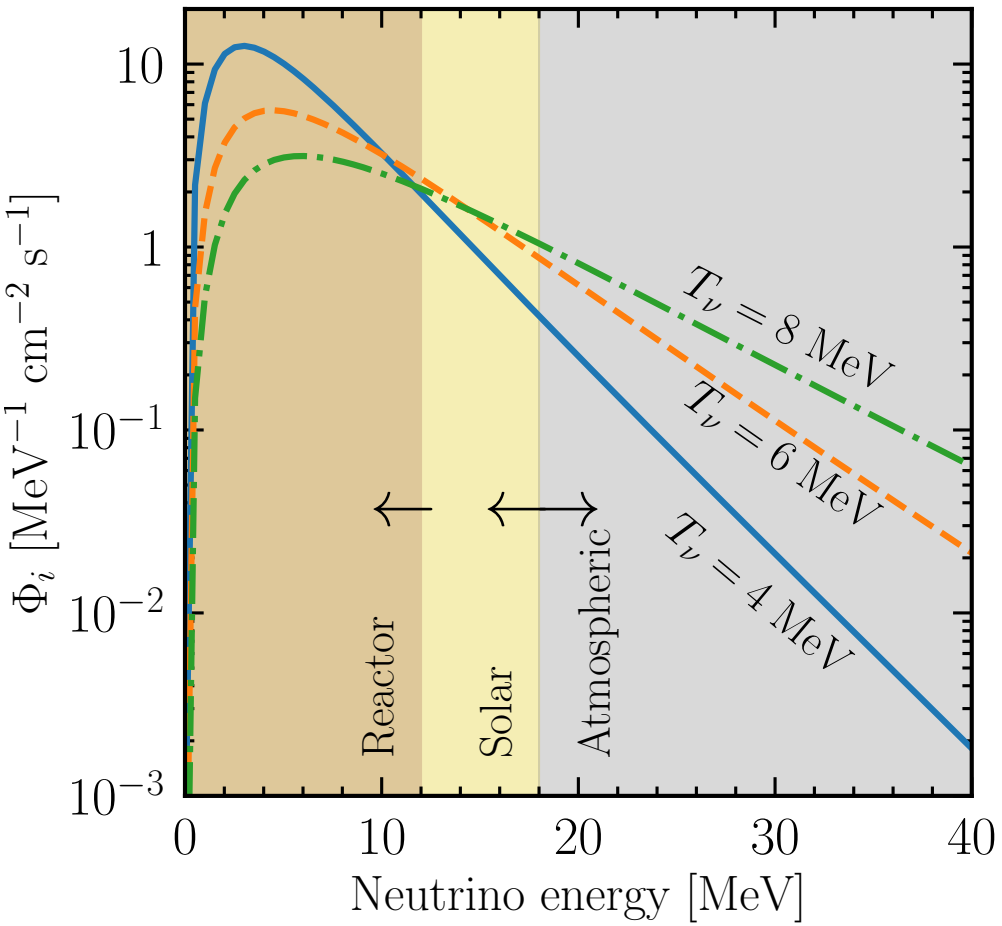
Phys.Rev.D 108 (2023) 4, 043035

Grand Unified Neutrino Spectrum - Detected Fluxes



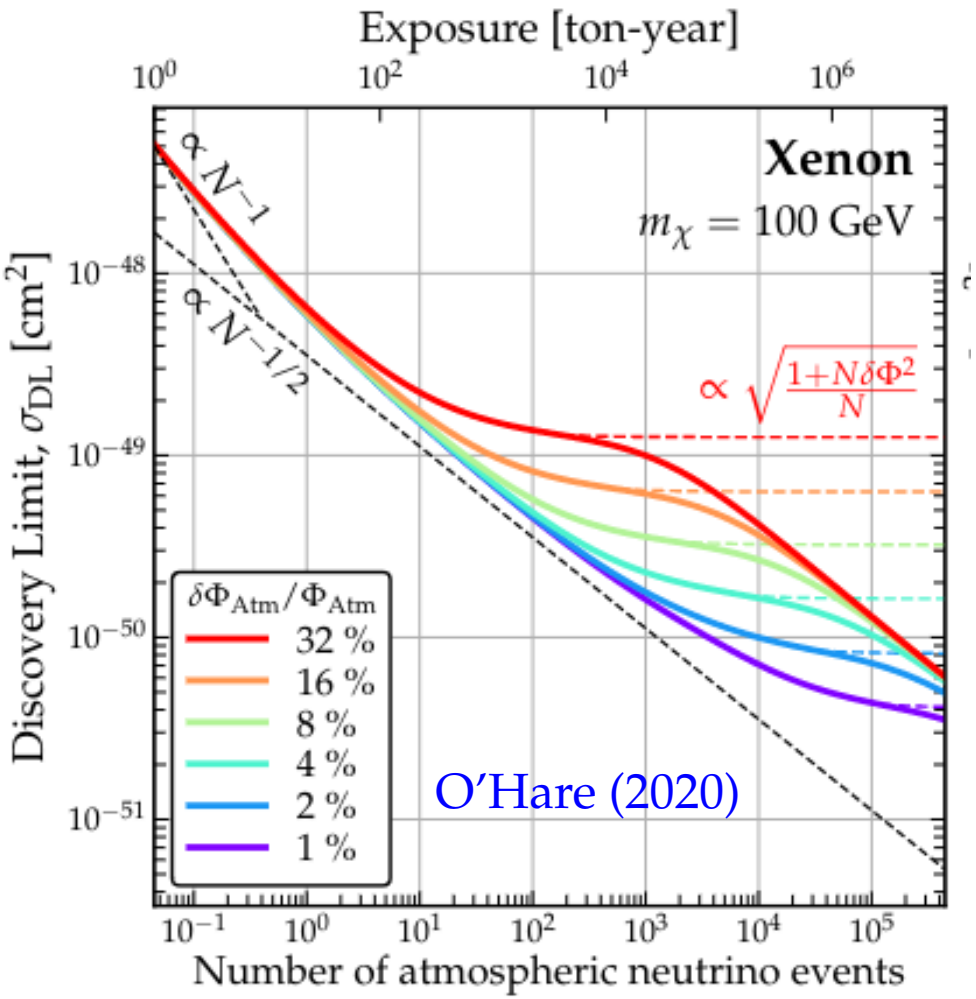
Diffuse Supernova Neutrino Background (DSNB)

AMS (2022)



- DSNB →
  isotropic and stationary guaranteed neutrino flux
  Guseinov (1967), Totani et al. (2009), Ando, Sato (2004), Lunardini (2009), Beacom (2010),..
- mitigating uncertainties in the atmopsheric neutrinos helps the discovery limits

Direct Dark Matter Detection Experiments - Neutrino Fog



- neutrino floor/fog $\rightarrow$ barrier for dark matter direct detection experiments Vergados & Ejiri (2008), Strigari (2009), Baudis et al. (2013), ...
- mitigating uncertainties in the atmopsheric neutrinos helps the discovery limits

Low-energy Atmospheric Neutrino Flux

Primary production channels

$\pi^+ \to \mu^+ + \nu_\mu;\ \mu^+ \to e^+ + \bar{\nu}_\mu + \nu_e$

$\pi^- \to \mu^- + \bar{\nu}_\mu;\ \mu^- \to e^- + \nu_\mu + \bar{\nu}_e$

Non-oscillated flavor ratio

$\nu_e : \nu_\mu : \nu_\tau = 1 : 2 : 0$

Sources of uncertainty

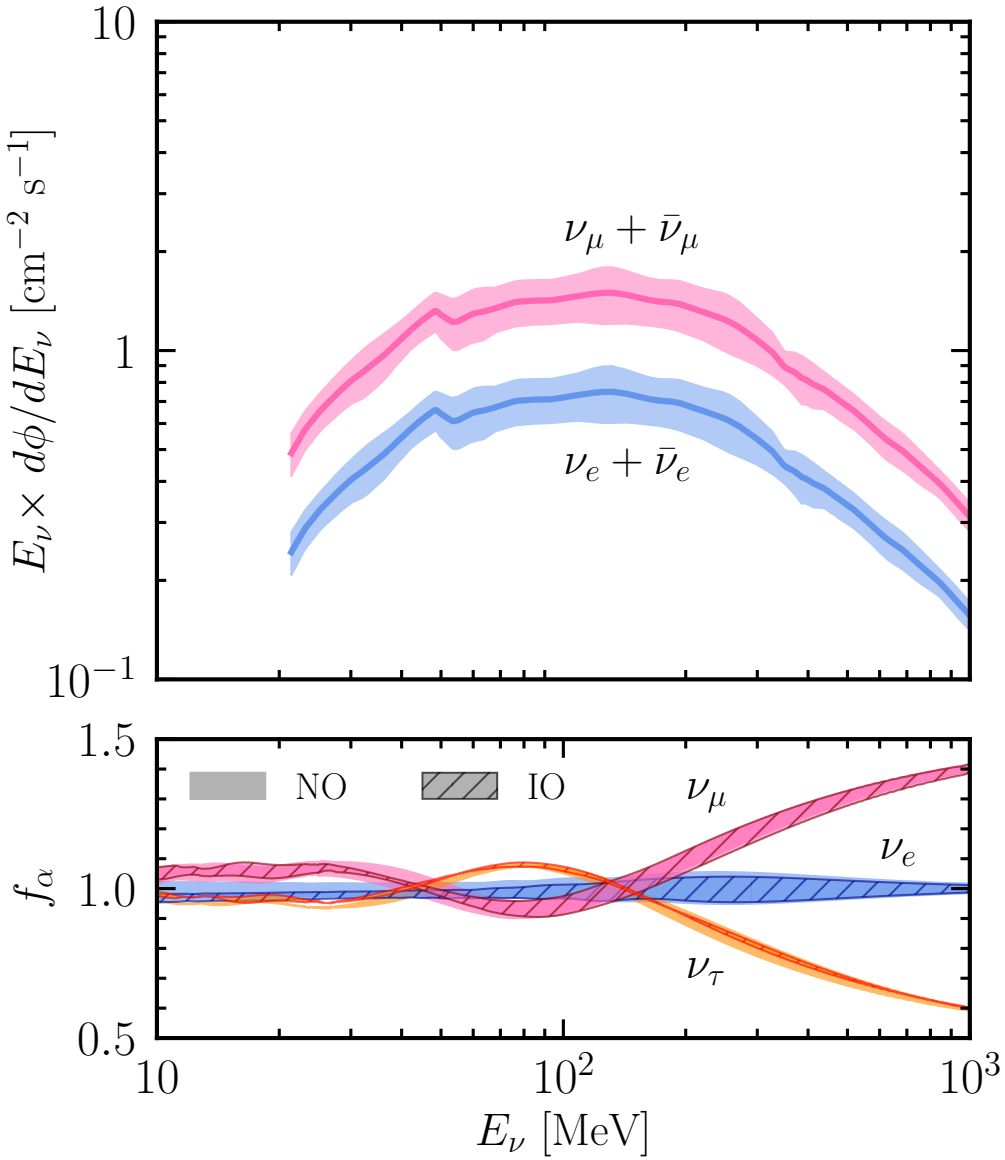
solar wind modulations

Earth's geomagnetic field

Oscillated flavor ratio

$\nu_e : \nu_\mu : \nu_\tau \approx 1 : 1 : 1$

Past measurements: energies $>$ 100 MeV



Neutrino flux: Zhuang (2021)

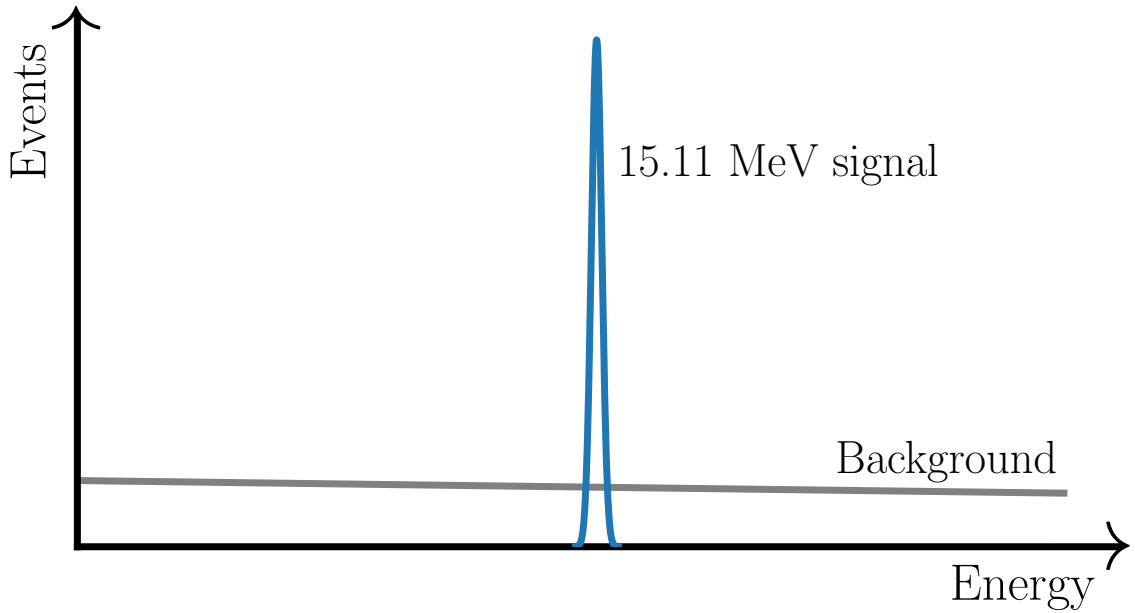
Mixing: NuCraft

Distinctive nuclear channels

Neutral current channels

$$\nu + {}^{12}\mathrm{C} \to \nu + {}^{12}\mathrm{C}^*$$
$${}^{12}\mathrm{C}^* \to {}^{12}\mathrm{C} + \gamma,$$

$$\bar{\nu} + {}^{12}\mathrm{C} \to \bar{\nu} + {}^{12}\mathrm{C}^*$$
$${}^{12}\mathrm{C}^* \to {}^{12}\mathrm{C} + \gamma,$$



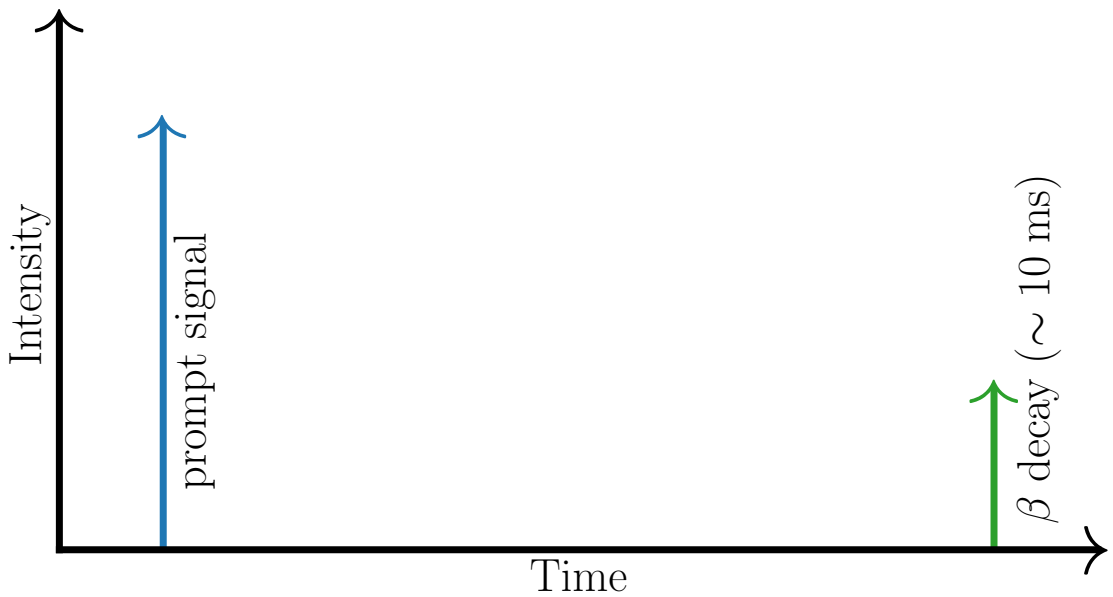
- instantaneous decay of ${}^{12}\mathrm{C}^*$
- emission of a monoenergetic γ

Distinctive nuclear channels

Charged current channels: ν_e

$$\nu_e + {}^{12}\mathrm{C} \to e^- + {}^{12}\mathrm{N}_{\mathrm{g.s.}}$$
$${}^{12}\mathrm{N}_{\mathrm{g.s.}} \to {}^{12}\mathrm{C} + e^+ + \nu_e,$$

$$\bar{\nu}_e + {}^{12}\mathrm{C} \to e^+ + {}^{12}\mathrm{B}_{\mathrm{g.s.}}$$
$${}^{12}\mathrm{B}_{\mathrm{g.s.}} \to {}^{12}\mathrm{C} + e^- + \bar{\nu}_e.$$



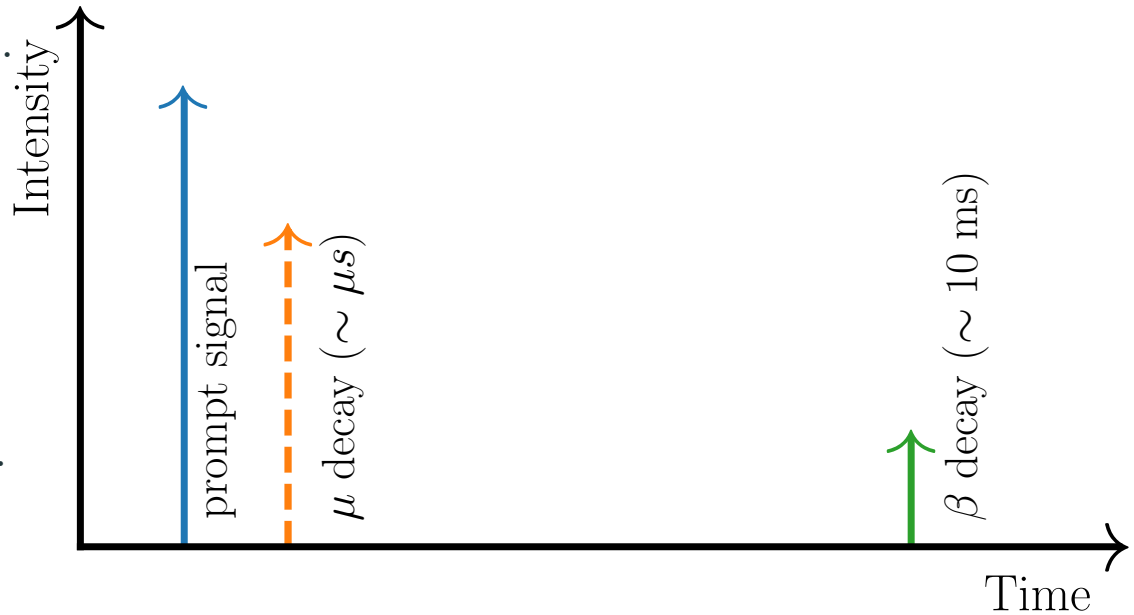
- coincidence detection of e^+ and e^-
- difference in ${}^{12}\mathrm{B}_{\mathrm{g.s.}}$ and ${}^{12}\mathrm{N}_{\mathrm{g.s.}}$ lifetimes $\to \nu_e$ vs. $\bar{\nu}_e$ distinction

Distinctive nuclear channels

Charged current channels: ν_μ

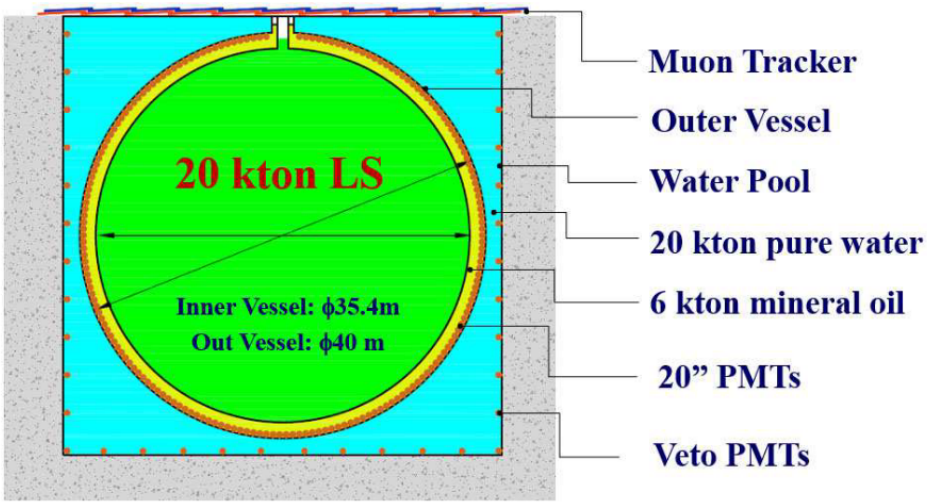
$$\nu_\mu + {}^{12}\mathrm{C} \to \mu^- + {}^{12}\mathrm{N}_{\mathrm{g.s.}}$$
$${}^{12}\mathrm{N}_{\mathrm{g.s.}} \to {}^{12}\mathrm{C} + e^+ + \nu_e$$
$$\mu^- \to e^- + \bar{\nu}_e + \nu_\mu,$$

$$\bar{\nu}_\mu + {}^{12}\mathrm{C} \to \mu^+ + {}^{12}\mathrm{B}_{\mathrm{g.s.}}$$
$${}^{12}\mathrm{B}_{\mathrm{g.s.}} \to {}^{12}\mathrm{C} + e^- + \bar{\nu}_e$$
$$\mu^+ \to e^+ + \nu_e + \bar{\nu}_\mu.$$



- coincidence detection of μ, its decay e and β-decay e
- difference in ${}^{12}\mathrm{B}_{\mathrm{g.s.}}$ and ${}^{12}\mathrm{N}_{\mathrm{g.s.}}$ lifetimes $\to \nu_\mu$ vs. $\bar{\nu}_\mu$ distinction
- triple vs. double coincidence detection $\to \nu_e$ vs. ν_μ distinction

The Jiangmen Underground Neutrino Observatory (JUNO)



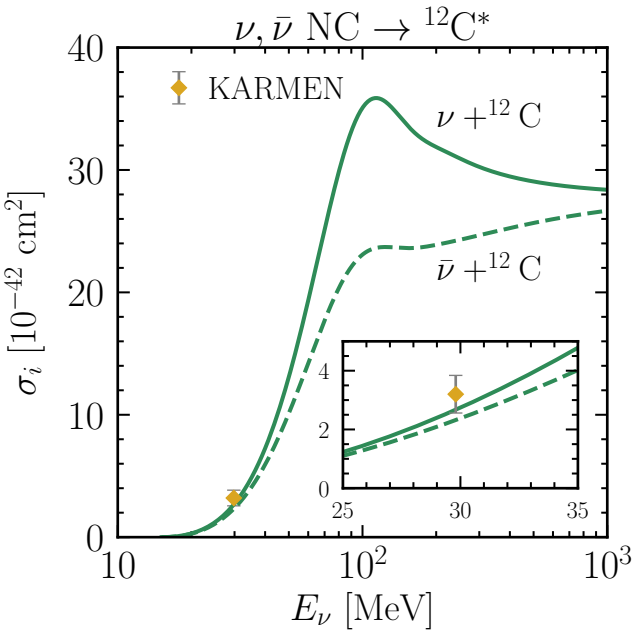


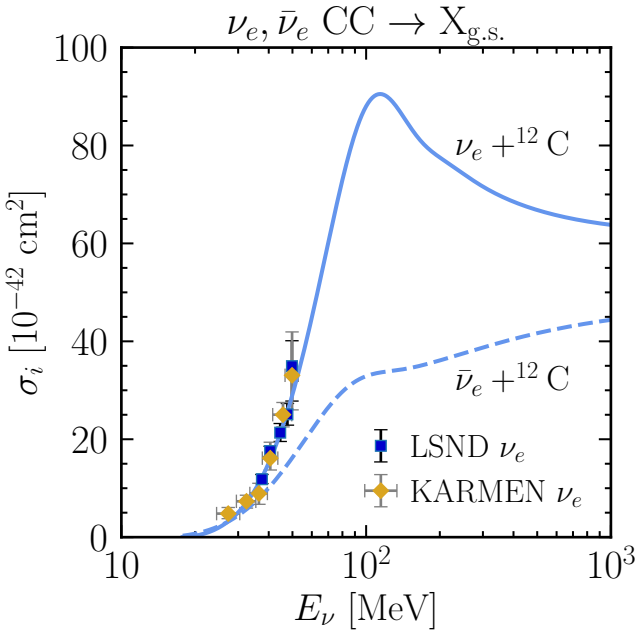
- large-scale carbon-based liquid scintilator detector
- already operational since 2025
- excelent energy resolution $\lesssim 3\%$
- excelent spatial resolution $\lesssim 10$ cm
- low backgrounds in the considerd channels

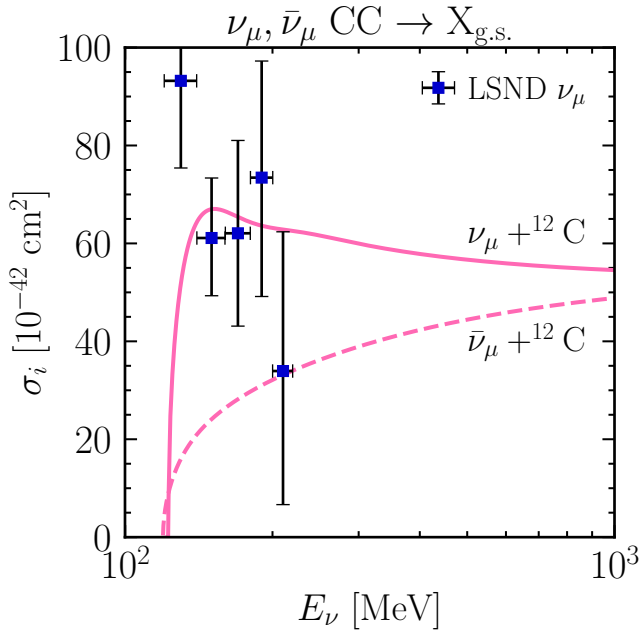
JUNO inclusive studies:
Cheng et al. (2020),
Cheng et al. (2020),
JUNO Collaboration (2022)

JUNO collabortation (2015), Sitsi (2022)

Cross section: elementary particle treatment (EPT)







- superallowed transitions from 0^+ to 1^+ states in A=12 triad
- the exclusive ν - ^{12}C cross sections measured only at low energies
- experimental data agrees well with the EPT treatment
- 5-40% difference with respect to, e.g., RPA calculations

Fukugita et al. (1988), Pourkaviani & Mintz (1990), Kubodera & Nozawa (1993), Engel et al. (1996), Kolbe (1996), Samana et al. (2010)

Atmospheric neutrino detection in JUNO

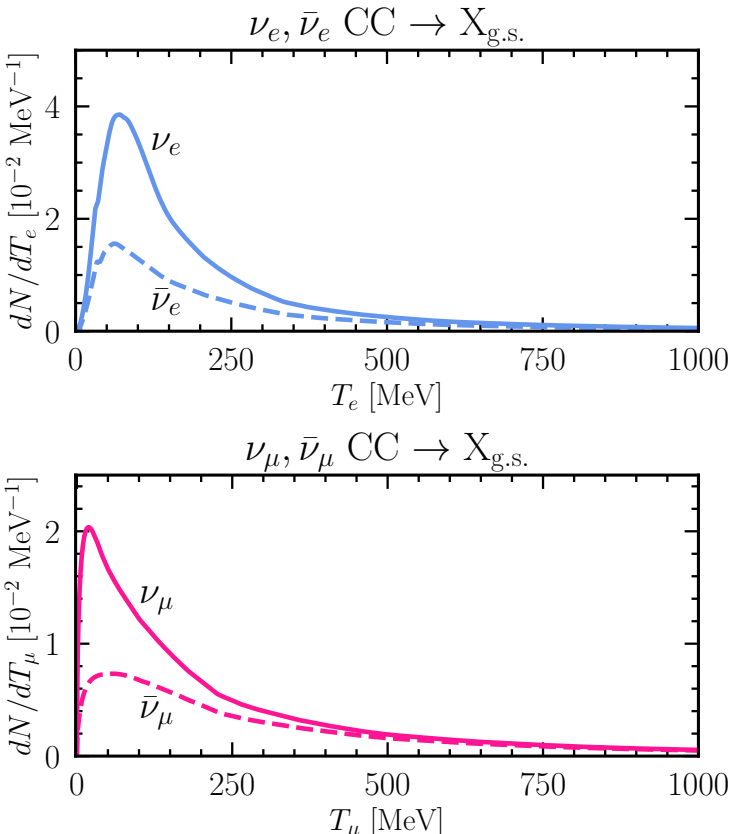
NC channel detection: single events

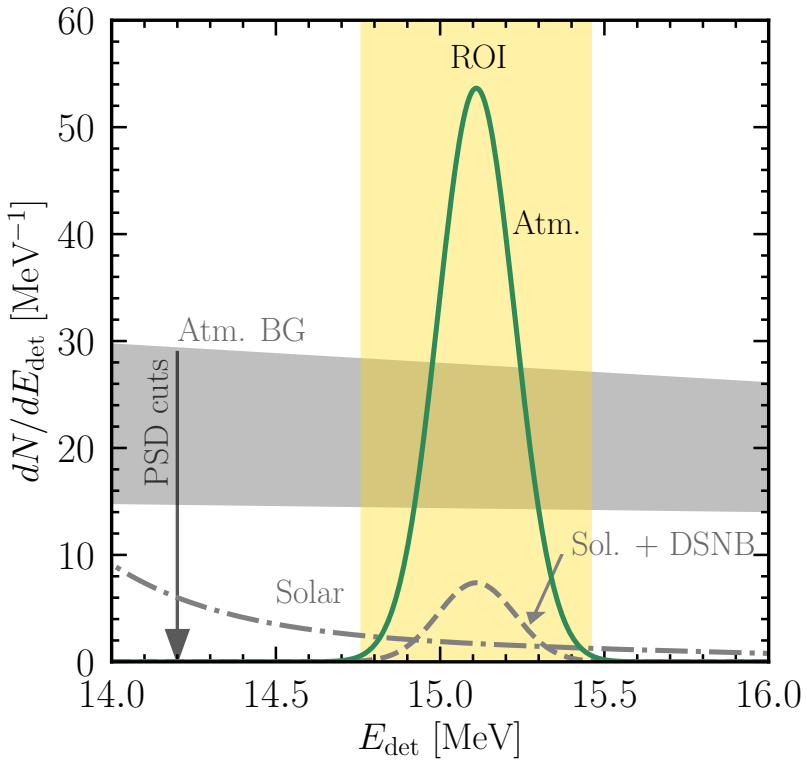
Irreducible BG: solar and DSNB ν

Reducible BG: atm. ν - p scattering

85 kton yr exposure → 25(40)%

uncertainty of the atmospheric ν rate





CC channel detection: coincidence events

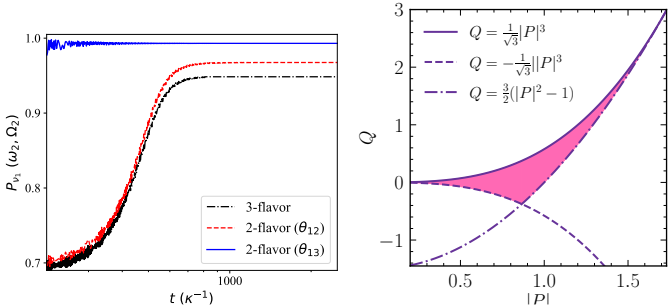
Irrediciuble BG: accidental coincidences

Rate per 85 kton yr: ∼0.0004

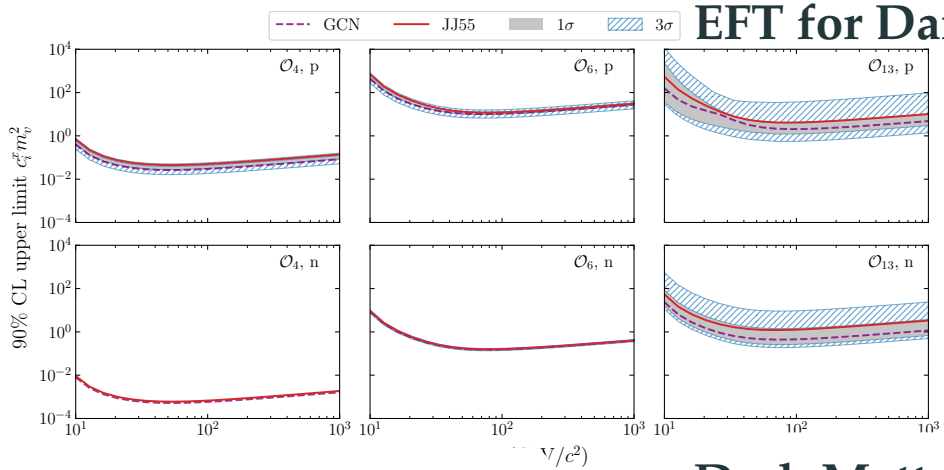
essentially background free channels

Some More of My Favorite Astroparticle Topics

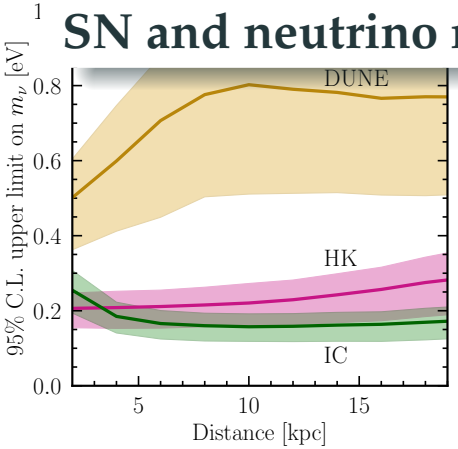
Entanglement and Many-body Neutrino Interactions



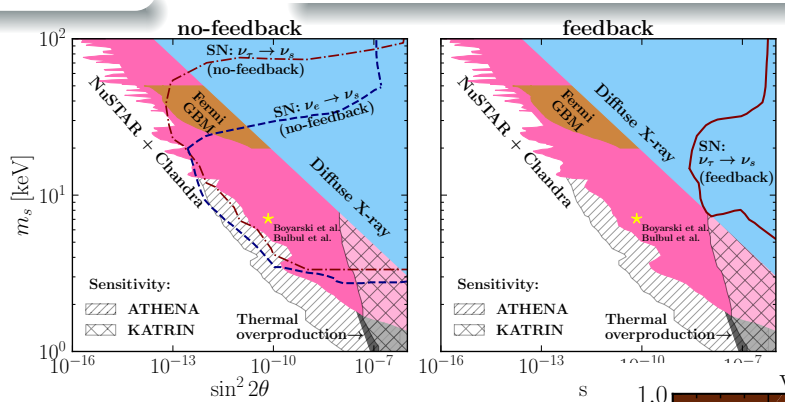
EFT for Dark Matter



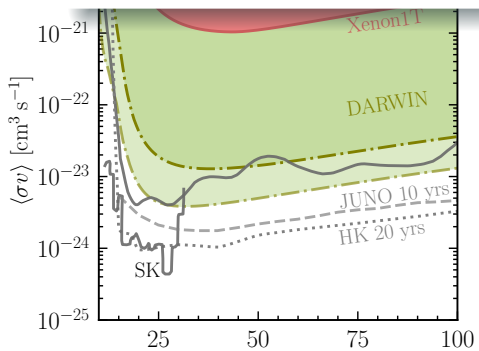
QCD phase transition in SN and neutrino mass



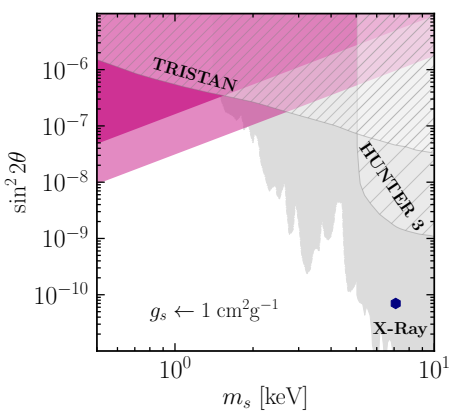
Sterile neutrinos in SN



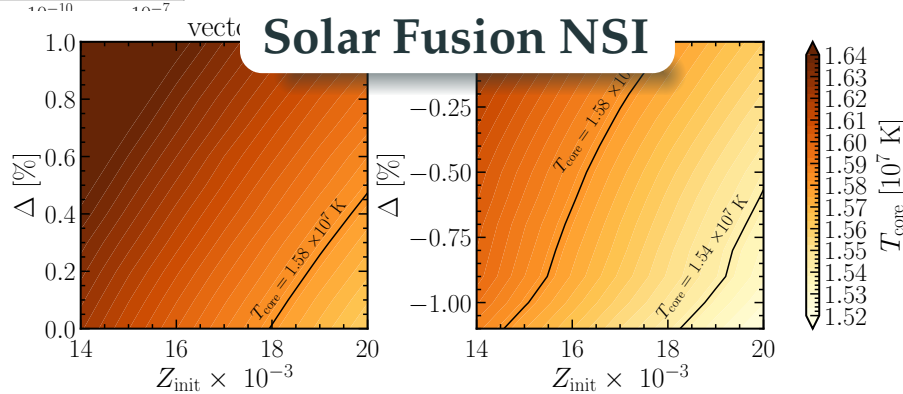
Dark Matter Decay



Sterile neutrino hints in DSNB



Solar Fusion NSI



Conclusions

Astrophysical sources of MeV neutrinos

- can serve as powerful testing grounds in constraining new physics
- reliable limits, only when the sources are accurately modeled

Detection of astrophysical neutrino fluxes

- brings us closer to fully understanding the physics inside the sources
- help us to rule out potential new physics scenarios

Exciting times ahead, a truly high statistic era of neutrino physics!

Thank you for the attention!

Backup Slides

Why studying astrophysical neutrinos is crucial?

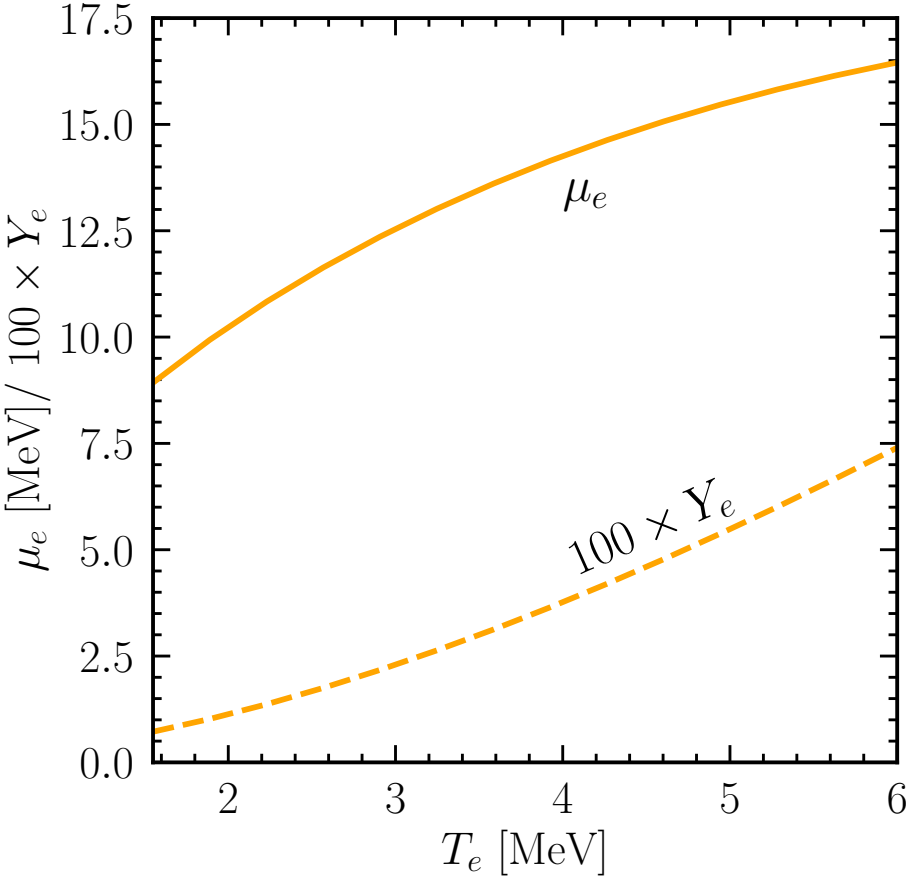
Benefits to the field of neutrino physics

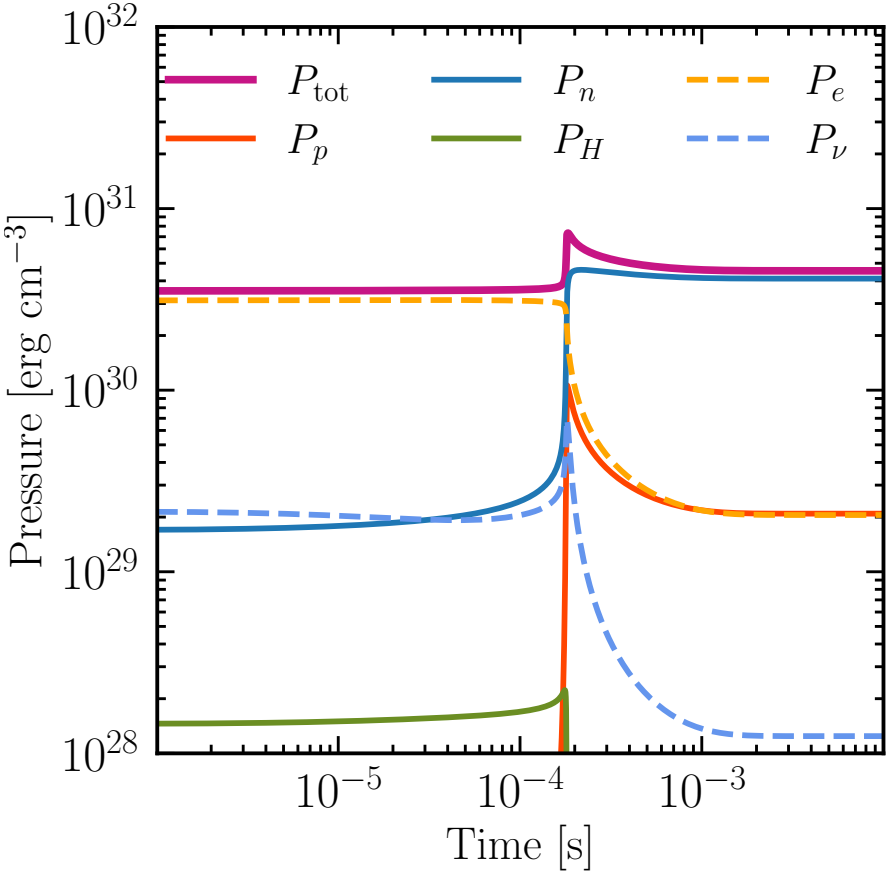
- free sources spanning over 20 decades in energy
- test of physics in the conditons not acessible on Earth
- established track record of neutrino discoveries
- complements terrestrial neutrino experminetal efforts

Benefits to the field of multimessenger astrophysics

- unveils physics of the sources
- experminetally and observationally timely

LNV νSI


17.5
15.0
12.5
10.0
7.5
5.0
2.5
0.0
2
3
4
5
6
μ_e [MeV]/ 100 × Y_e
T_e [MeV]
μ_e
100 × Y_e


10^{32}
10^{31}
10^{30}
10^{29}
10^{28}
10^{-5}
10^{-4}
10^{-3}
Pressure [erg cm^{-3}]
Time [s]
$P_{\rm tot}$
P_p
P_n
P_H
P_e
P_ν

Fast LNV νSI - Approximate Evolution

LNV νSI timescale much faster than weak timescale $\rightarrow$ a single ν species evolution

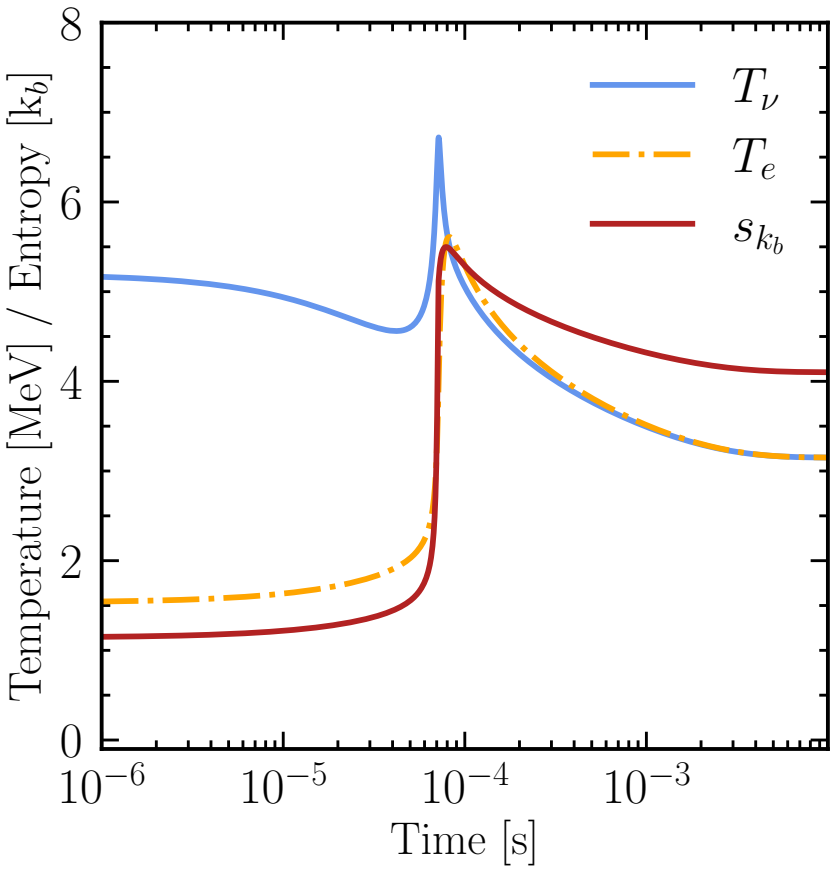
$$\sum_\alpha \left(\frac{dn_{\nu_\alpha}}{dt} + \frac{dn_{\bar{\nu}_\alpha}}{dt} \right) = \frac{\delta n_\nu}{\delta t}$$
$$\sum_\alpha \left(\frac{d\rho_{\nu_\alpha}}{dt} + \frac{d\rho_{\bar{\nu}_\alpha}}{dt} \right) = \frac{\delta \rho_\nu}{\delta t}$$

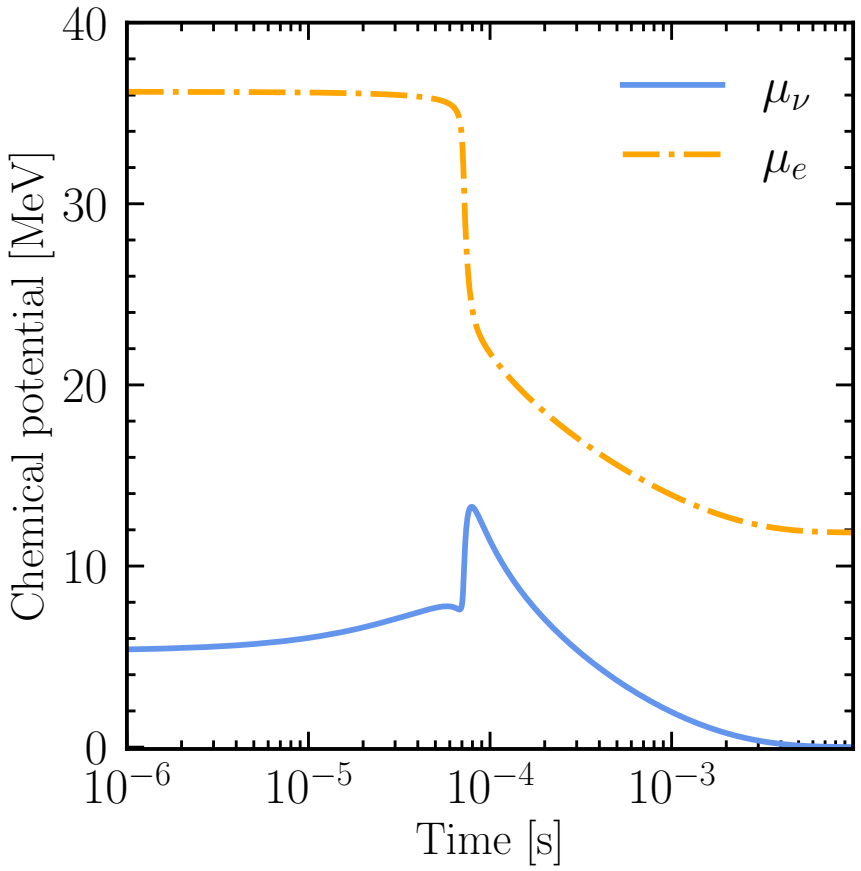
sum over charged-current weak interactions

$$\frac{dT_\nu}{dt} = \frac{\frac{\partial \rho_\nu}{\partial \mu_\nu}\frac{\delta n_\nu}{\delta t} - \frac{\partial n_\nu}{\partial \mu_\nu}\frac{\delta \rho_\nu}{\delta t}}{2N_F\left(\frac{\partial n_\nu}{\partial T_\nu}\frac{\partial \rho_\nu}{\partial \mu_\nu} - \frac{\partial n_\nu}{\partial \mu_\nu}\frac{\partial \rho_\nu}{\partial T_\nu}\right)}$$

$$\frac{d\mu_\nu}{dt} = \frac{\frac{\partial \rho_\nu}{\partial T_\nu}\frac{\delta n_\nu}{\delta t} - \frac{\partial n_\nu}{\partial T_\nu}\frac{\delta \rho_\nu}{\delta t}}{2N_F\left(\frac{\partial n_\nu}{\partial \mu_\nu}\frac{\partial \rho_\nu}{\partial T_\nu} - \frac{\partial n_\nu}{\partial T_\nu}\frac{\partial \rho_\nu}{\partial \mu_\nu}\right)}$$

All flavors LNV νSI





- new interactions quickly equilbrates all 6 neutrino seas
- temperature and entropy increase

Non-standard neutrino-quark interactions

New Interaction Lagrangian

$$\mathcal{L}_{\mathrm{NSI}} = -2\sqrt{2}G_F\varepsilon^{fV}_{\alpha\alpha}(\overline{\nu}_{\alpha L}\gamma^{\rho}\nu_{\alpha L})(\overline{f}\gamma_{\rho}f)$$

$$\varepsilon^{u(d)} = \varepsilon^{u(d)V}_{ee} = \varepsilon^{u(d)V}_{\mu\mu} = \varepsilon^{u(d)V}_{\tau\tau}$$

New Cross Sections

1. Coherent Elastic Neutrino-Nucleus Scattering

$$\frac{d\sigma_{\nu X}}{dE_r} \approx \frac{G_{\mathrm{F}}^2 m_X}{4\pi} Q_W^2 \left(1 - \frac{m_X E_r}{2E_\nu^2}\right) F^2(Q), \qquad Q_W = [N - Z(1 - 4\sin^2(\theta_W)]$$

with NSI $Q_W \to Q'_W = Q_W + Q_W^{\mathrm{NSI}}$

$$Q_W^{\mathrm{NSI}} = -2[Z(2\varepsilon^u + \varepsilon^d) + N(\varepsilon^u + 2\varepsilon^d)]$$

2. Elastic Neutrino-Proton Scattering

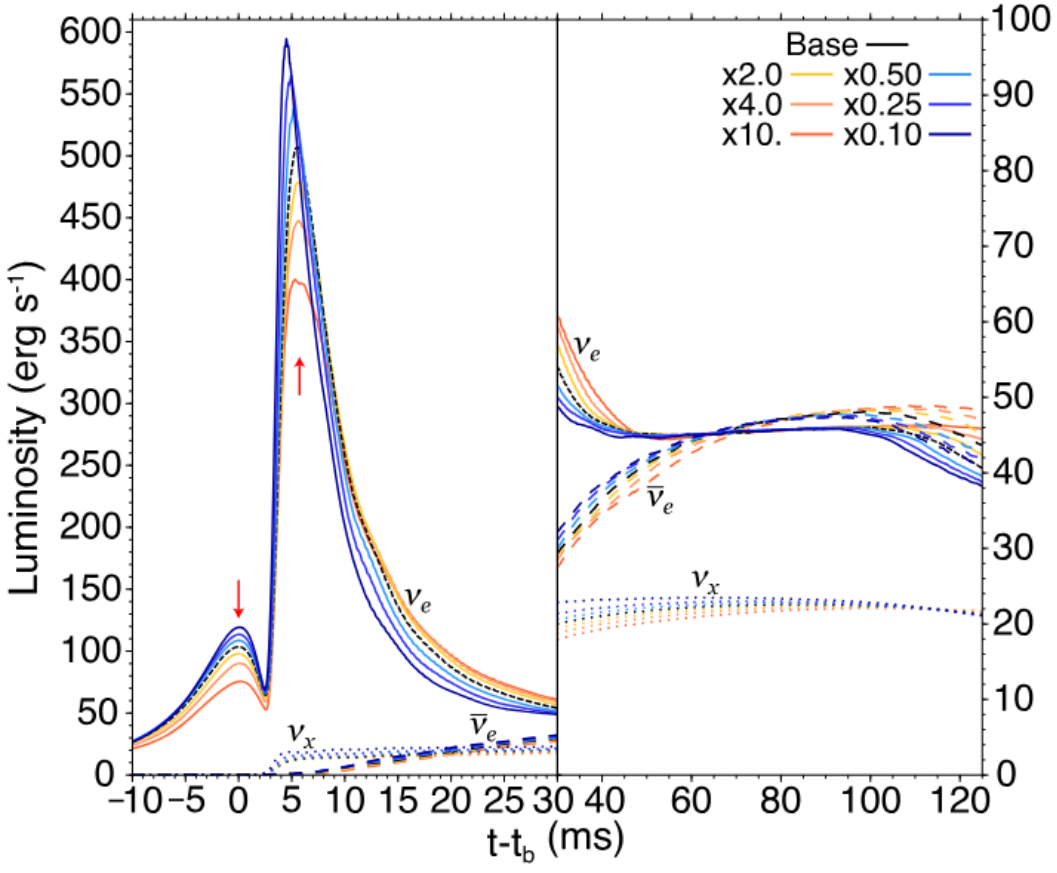
$$\frac{d\sigma_{\nu \mathrm{p}}}{dE_{\mathrm{p}}} \simeq \frac{G_{\mathrm{F}}^2 m_{\mathrm{p}}^2}{2\pi E_\nu^2}\left(BE_\nu^2 + C(E_\nu - E_{\mathrm{p}})^2 + Dm_{\mathrm{p}}E_{\mathrm{p}}\right)$$

$$B = (c_V + c_A)^2, C = (c_V - c_A)^2, D = (c_V^2 + c_A^2)$$

with NSI $c_V \to c'_V = c_V + \varepsilon^p$

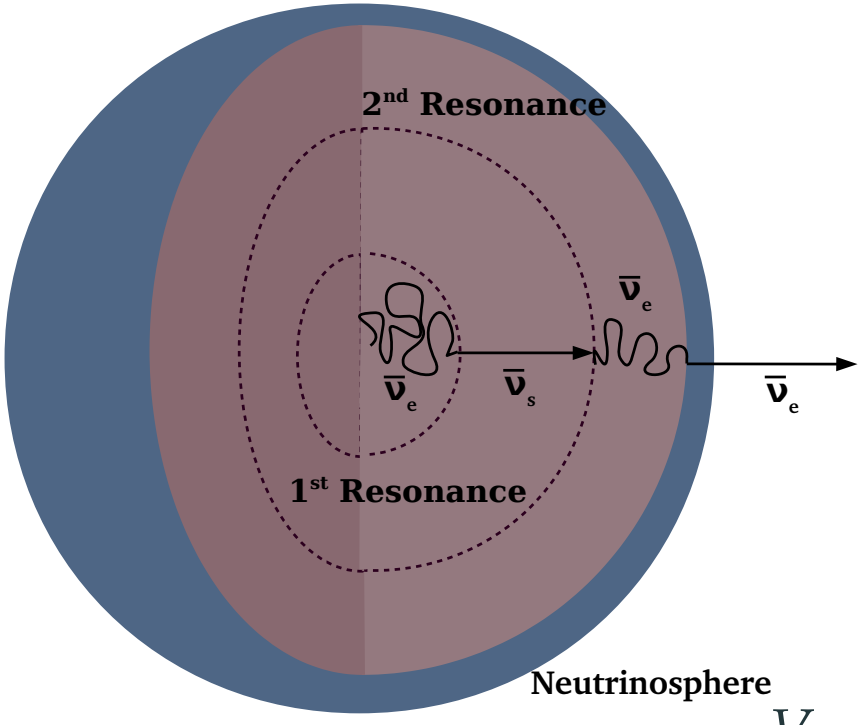
D. Z. Freedman (1973), L. Wolfenstein (1977), B. Dev et al. (2016), Huang et al. (2021)

Standard Model Electron Capture Uncertainty Effects



Sullivan et al. (2016)

Sterile neutrino conversions in the stellar core



1D SN model
Garching group archive

$$Y_i = \frac{n_i - n_{\bar{i}}}{n_B}$$

MSW

$\nu_\tau - \nu_s$ mixing: only 1 resonance

$$V_{\text{eff}} = \sqrt{2} G_F n_B \left[\frac{1}{2} Y_e + Y_{\nu_e} + Y_{\nu_\mu} + 2 Y_{\nu_\tau} - \frac{1}{2} \right]$$

Collisions

$$\Gamma_{\nu_s} = \frac{1}{4} \sin^2 2\tilde{\theta}\, \Gamma_{\nu_{\text{active}}}$$

$\nu_e - \nu_s$ mixing: multiple resonances

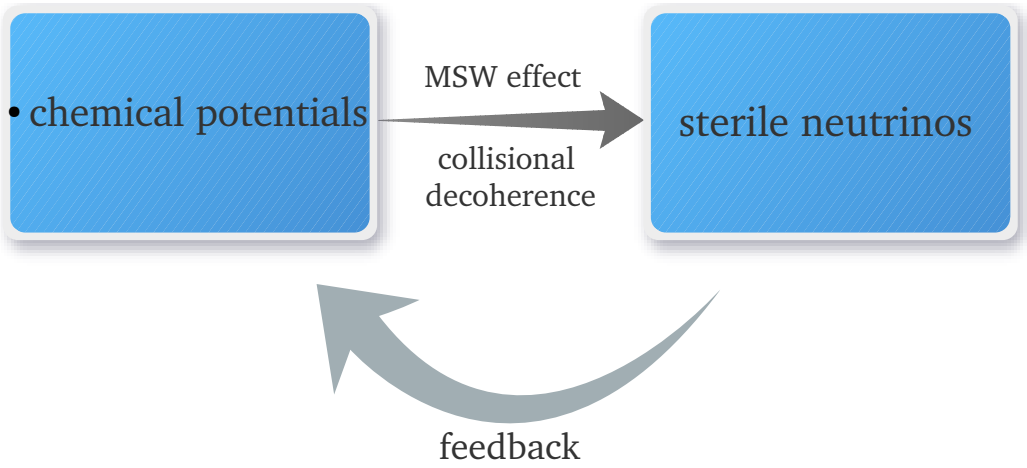
$$V_{\text{eff}} = \sqrt{2} G_F n_B \left[\frac{3}{2} Y_e + 2 Y_{\nu_e} + Y_{\nu_\mu} + Y_{\nu_\tau} - \frac{1}{2} \right]$$

L. Stodolsky (1987), H. Nunokawa et al. (1997), K. Abazajian et al. (2001)...

The sterile-tau neutrino mixing: growth of the asymmetry

Only active neutrinos

$$\Upsilon_{\nu_\tau}(r,t) \equiv 0$$



Active + sterile neutrinos

The active neutrinos after being **converted to sterile ones effectively disappear;**

since they were **strongly coupled** to the rest of the particles in the medium, a **new equilibrium state forms.**

The change imposed on the SN medium is referred to as the **dynamical feedback.**

$$\Upsilon_{\nu_\tau}(r,t) = \frac{1}{n_b(r)} \int_0^t dt' \, \frac{d\left(P_{\nu_\tau \to \nu_s} n_{\nu_\tau}(r,t') - P_{\bar{\nu}_\tau \to \bar{\nu}_s} n_{\bar{\nu}_\tau}(r,t')\right)}{dt'}$$

AMS et al. (2018)

The sterile-electron neutrino mixing: dynamical feedback

$$e^+ + p \leftrightarrow \nu_e + n \quad \text{and} \quad e^- + n \leftrightarrow \bar{\nu}_e + p \, .$$

β equilibrium

$$\mu_e(r,t) + \mu_p(r,t) + m_p = \mu_{\nu_e}(r,t) + \mu_n(r,t) + m_n \, ,$$

Lepton number conservation

$$\Upsilon_e(r,t) + \Upsilon_{\nu_e}(r,t) + \Upsilon_{\nu_s}(r,t) = \text{const.} \, ,$$

Baryon number conservation

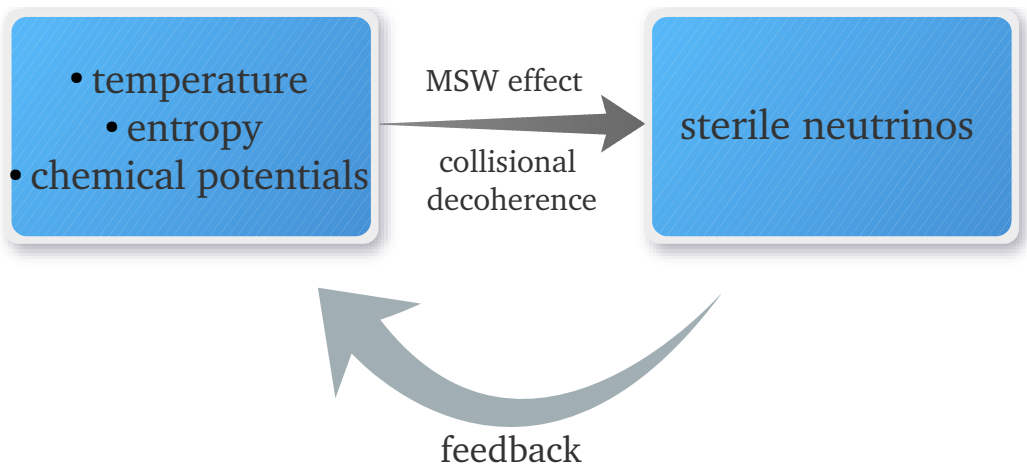
$$\Upsilon_p(r,t) + \Upsilon_n(r,t) = 1 \, ,$$

Charge conservation

$$\Upsilon_p(r,t) = \Upsilon_e(r,t) \, ,$$

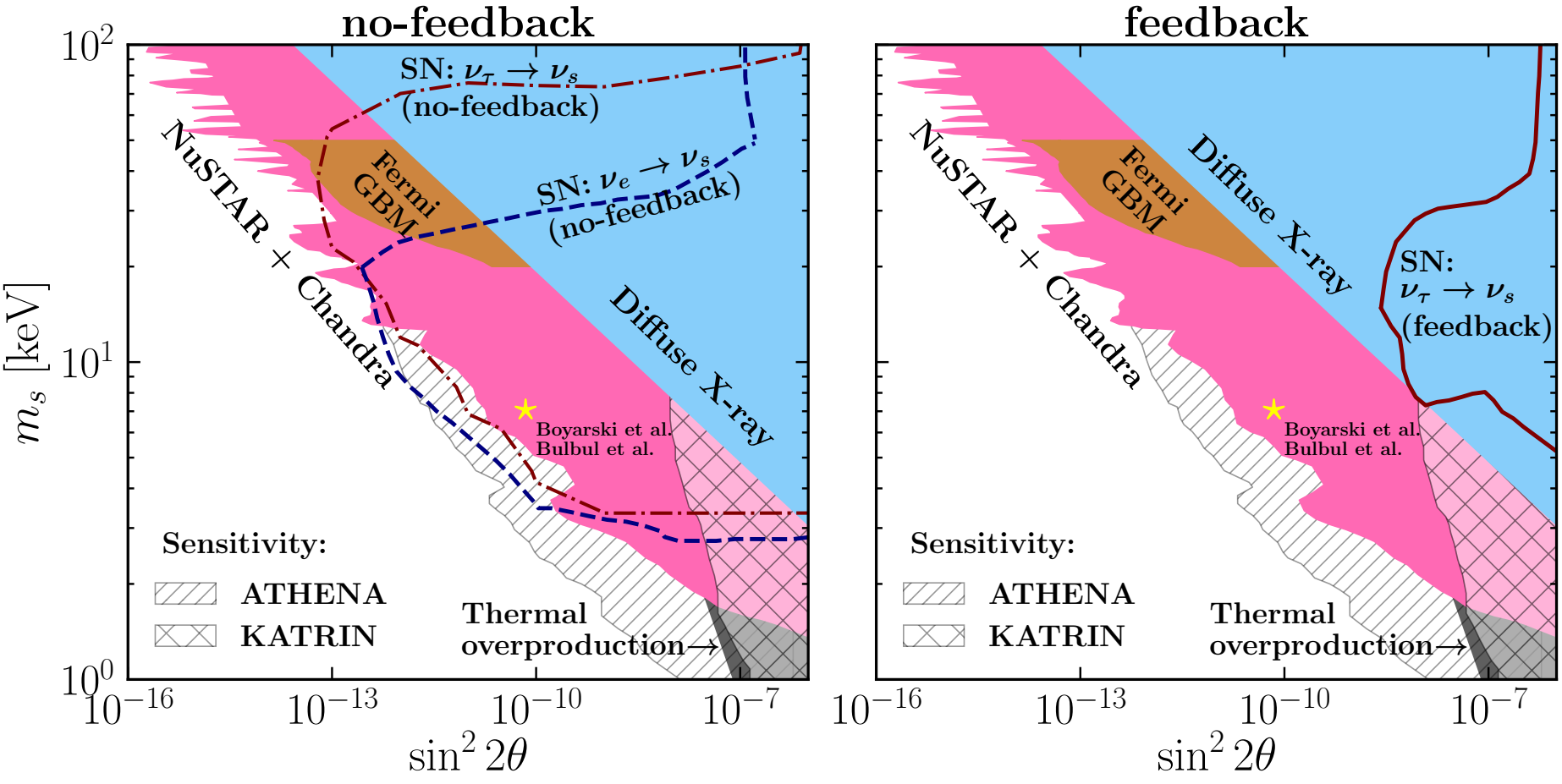
Entropy change

$$dS = \frac{dQ}{T} + \frac{P}{T} dV - \sum_i \frac{\mu_i}{T} d\Upsilon_i \, .$$



AMS et al. (2020)

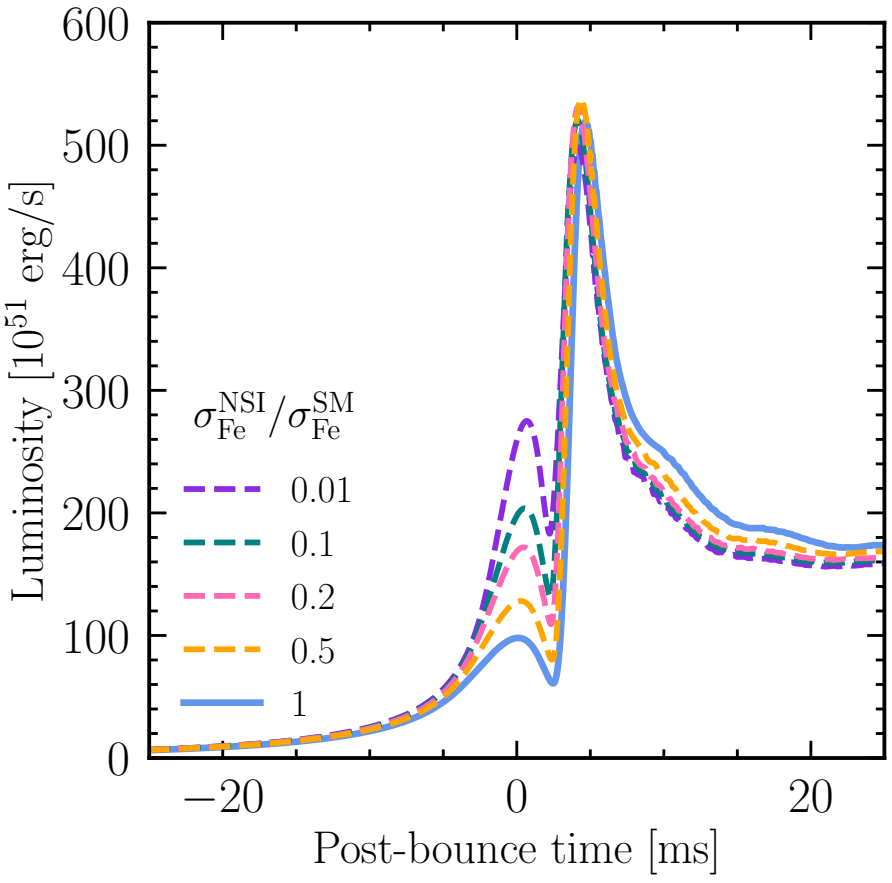
Supernova bounds on the mixing parameters

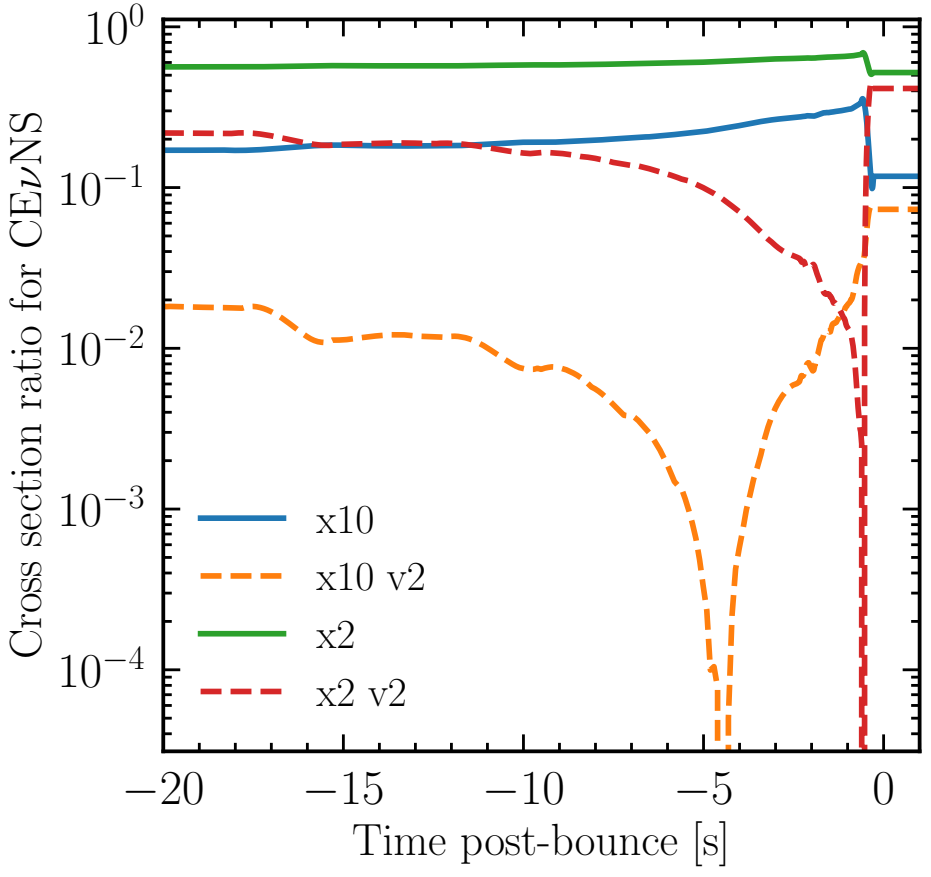


AMS et al. (2020), (2019)

- The inclusion of feedback greatly reduces the excluded region.
- CC-SNe cannot exclude any region of the DM parameter space.

Changes in the neutrino signal: GR1D simulations

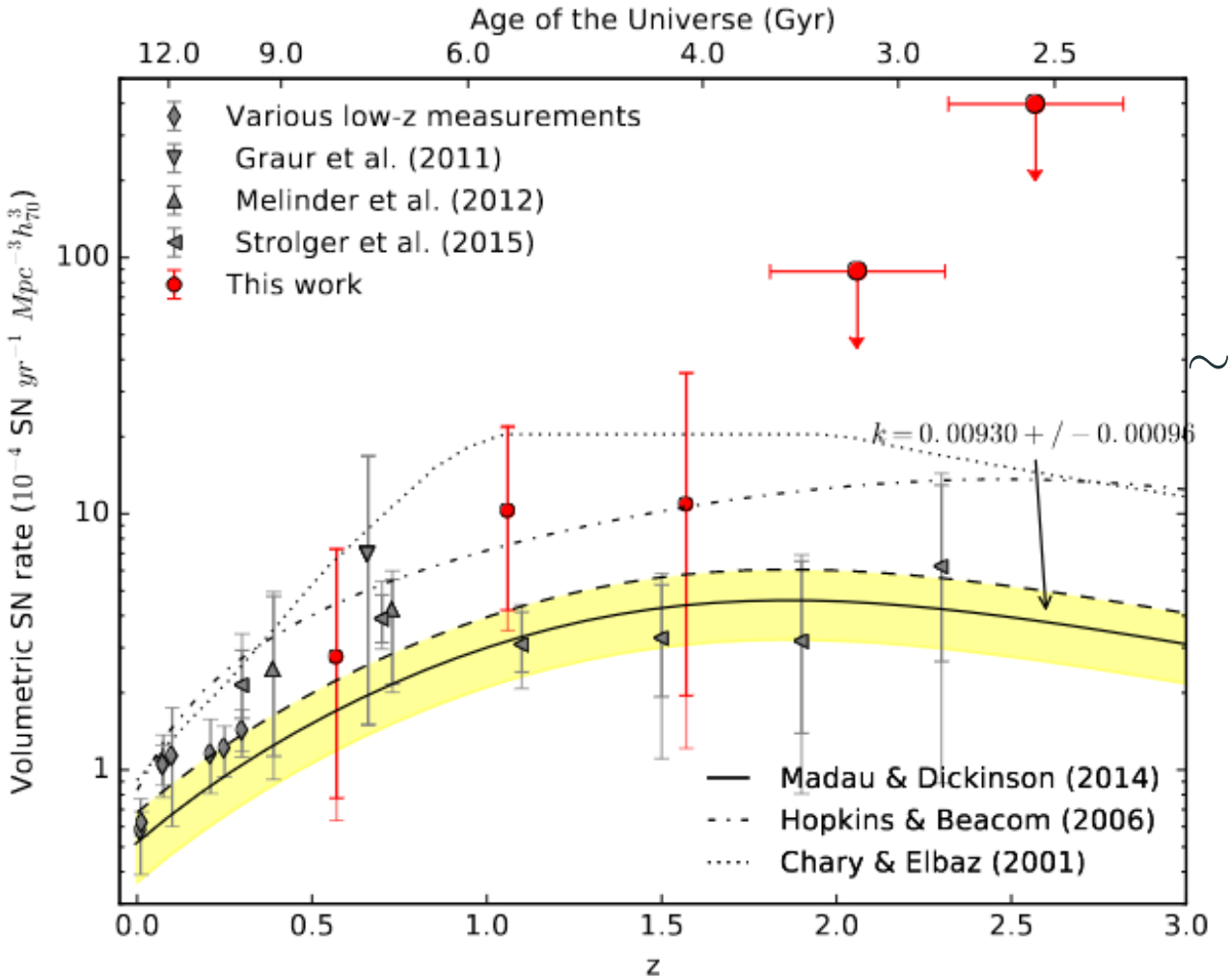




- Significant change in the luminosity pre-bounce
- Pre-bounce - heavy nuclei in the core
- Post-bounce - nucleons in the core

Cosmological supernovae rate

Petrushevska et al (2016)



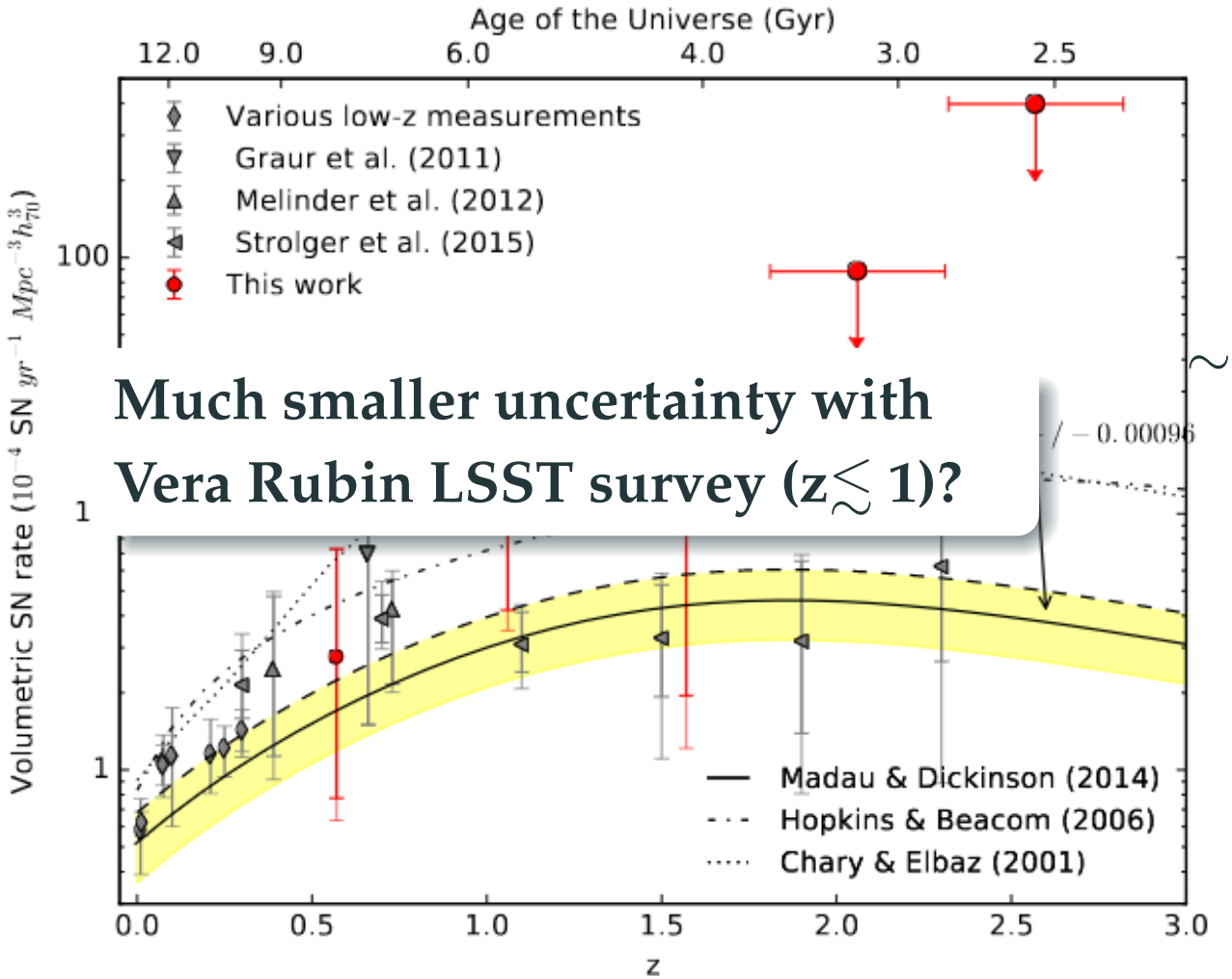
$\sim$ 1 SNe/s

The supernovae rate influences the normalization of the DSNB.

Ando, Sato (2004), Beacom (2010), Horiuchi et al. (2011), Møller, **AMS**, Tamborra, Denton (2018), Nakazato et al. (2018), ...

Cosmological supernovae rate

Petrushevska et al (2016)



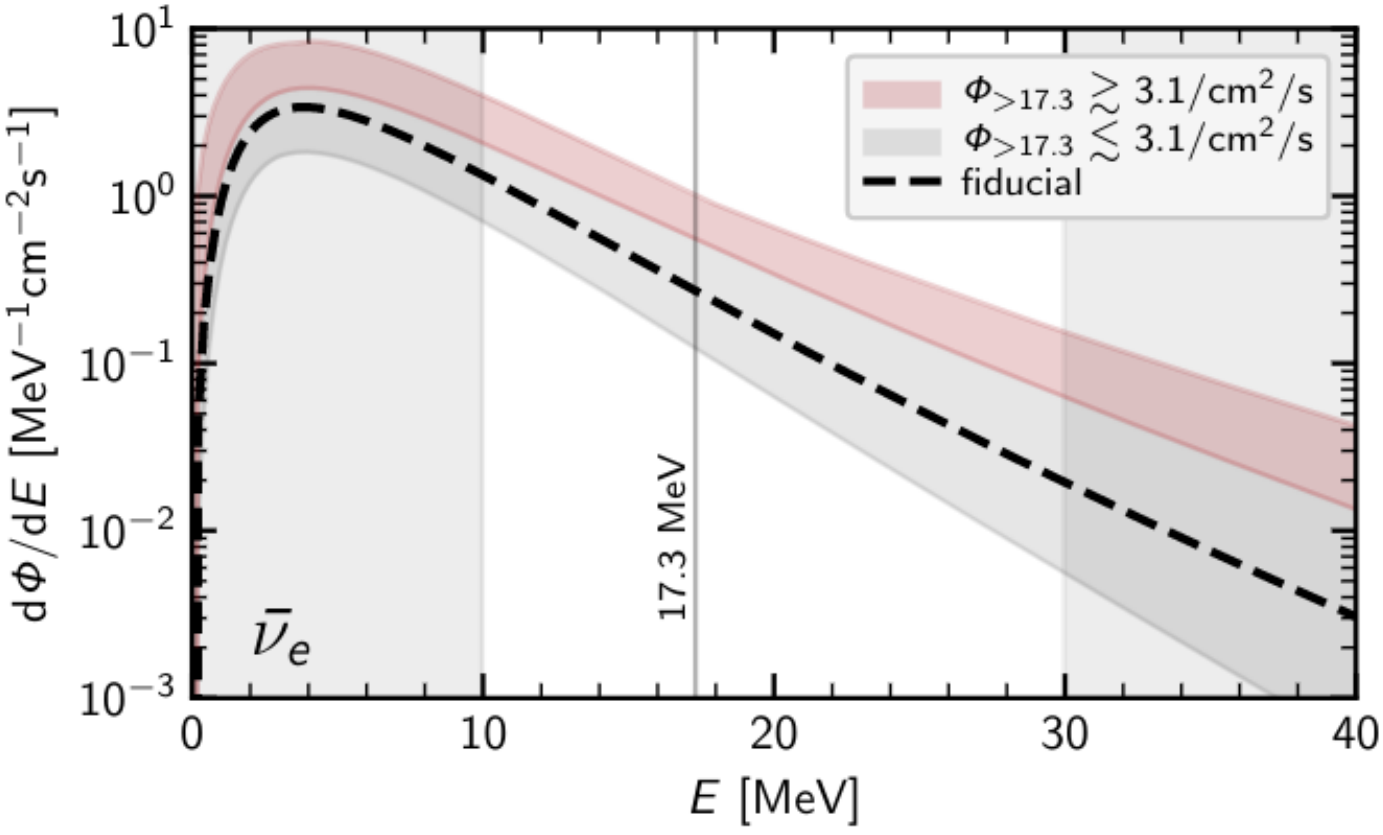
~ 1 SNe/s

The supernovae rate influences the normalization of the DSNB.

Ando, Sato (2004), Beacom (2010), Horiuchi et al. (2011), Møller, **AMS**, Tamborra, Denton (2018), Nakazato et al. (2018), ...

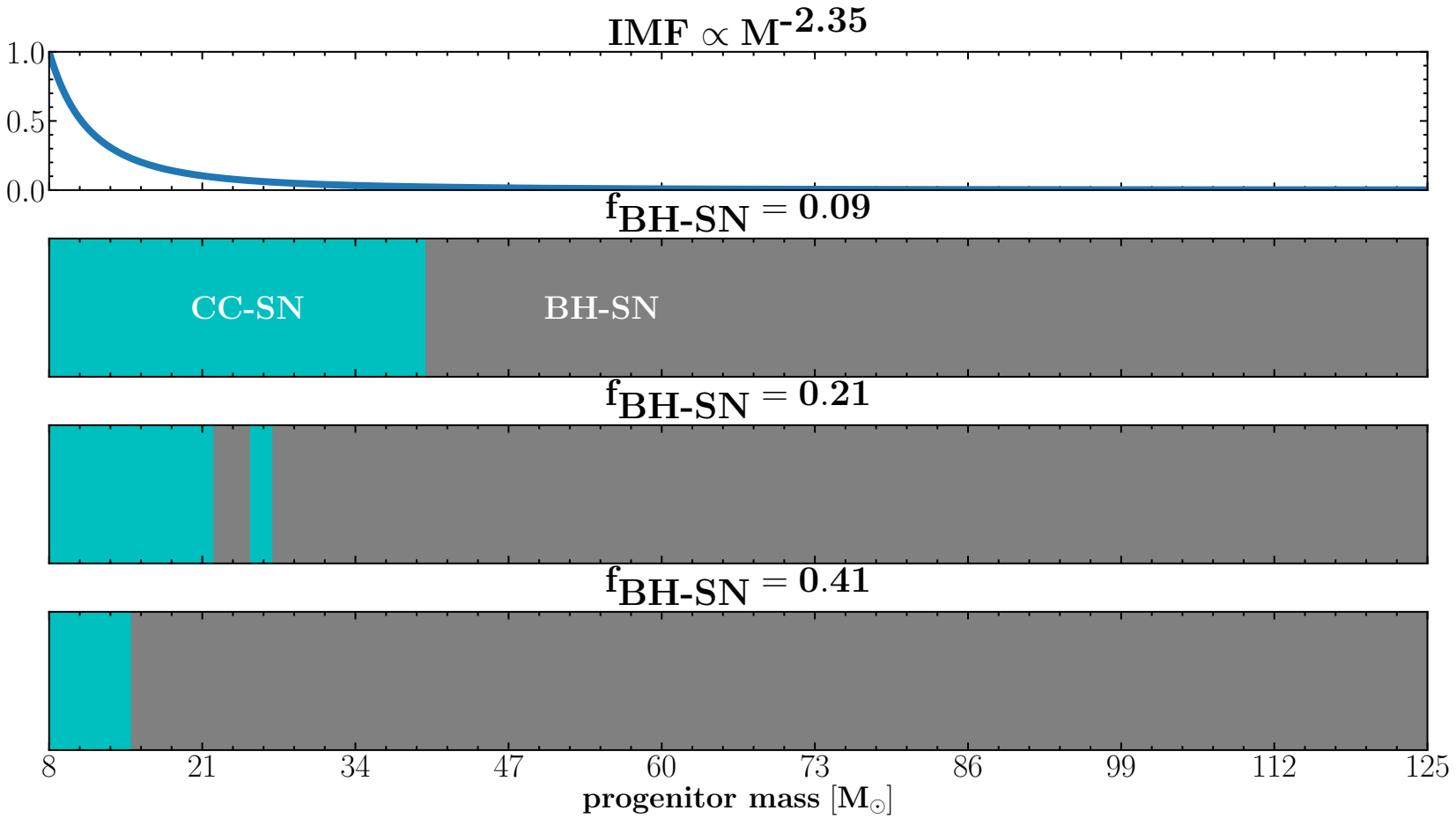
Astrophysical uncertainties affecting the DSNB

Kresse et al. (2020)



- models with the extreme combinations of parameters are disfavoured
  - large emission from black-hole-forming collapses and their fraction

The fraction of black-hole-forming progenitors

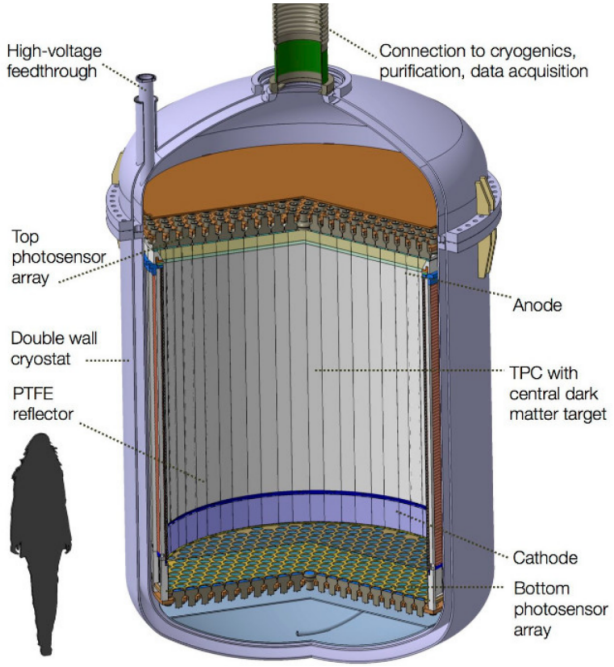


Fraction of black-hole-forming progenitors influences the highly energetic part of the DSNB, above $\sim$ 15 MeV.

Ertl et al. 2015, Sukhbold et al.2015, Adams et al. 2016, Heger et al. 2001, Kochanek et al. 2001, Basinger et al. 2020, ...

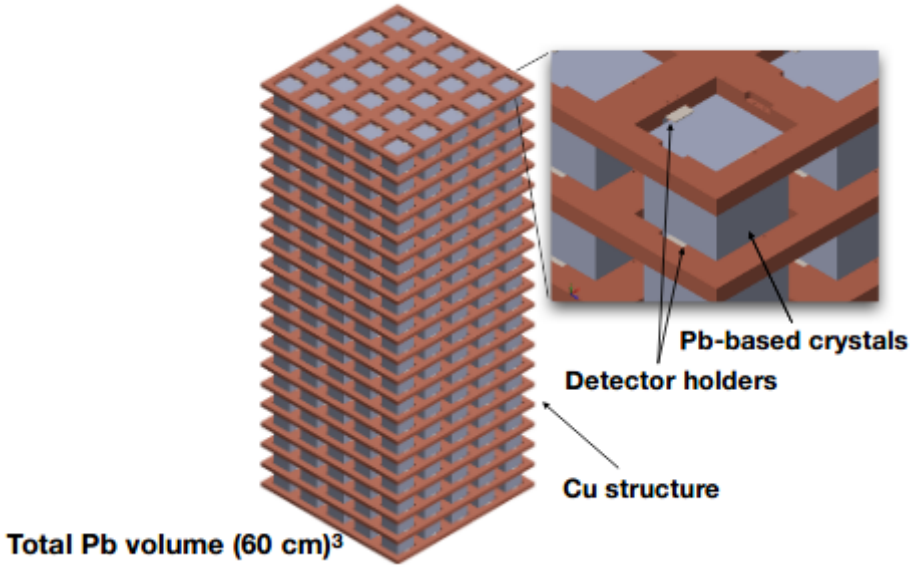
Current and future CEνNS detectors

DARWIN (arXiv: 1606.07001)



fiducial volume: 40 ton
target material: Xe
threshold: 1 keV
efficiency: XENON1T - 100%

RES-NOVA (arXiv: 2004.06936)

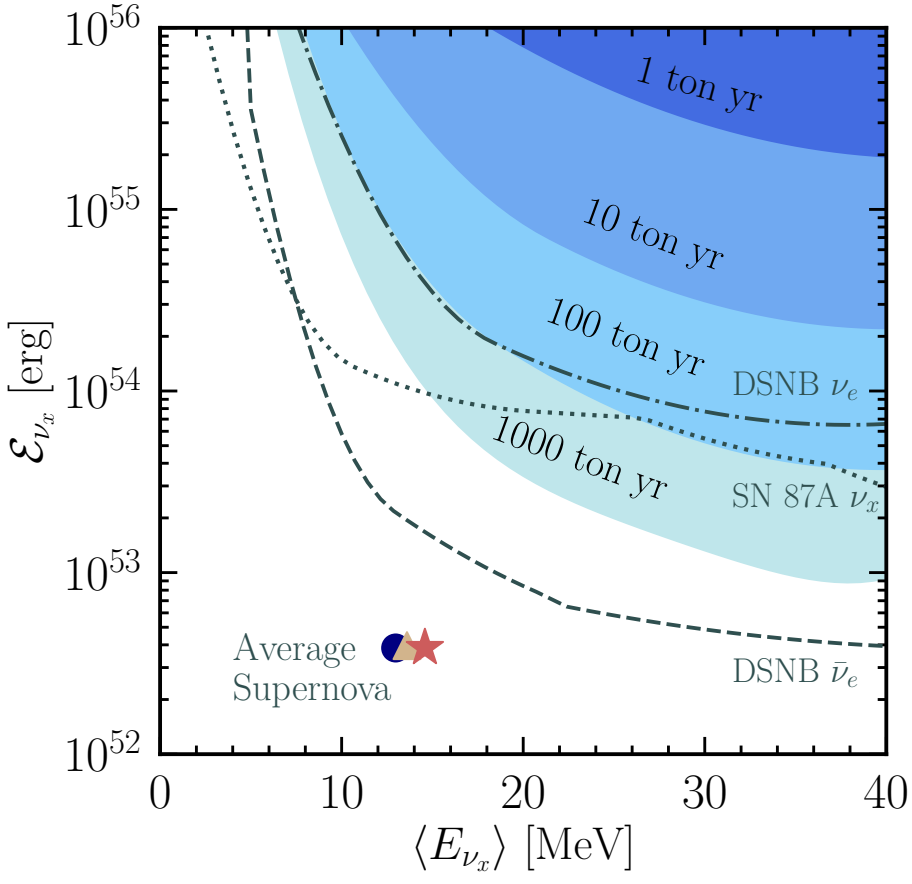


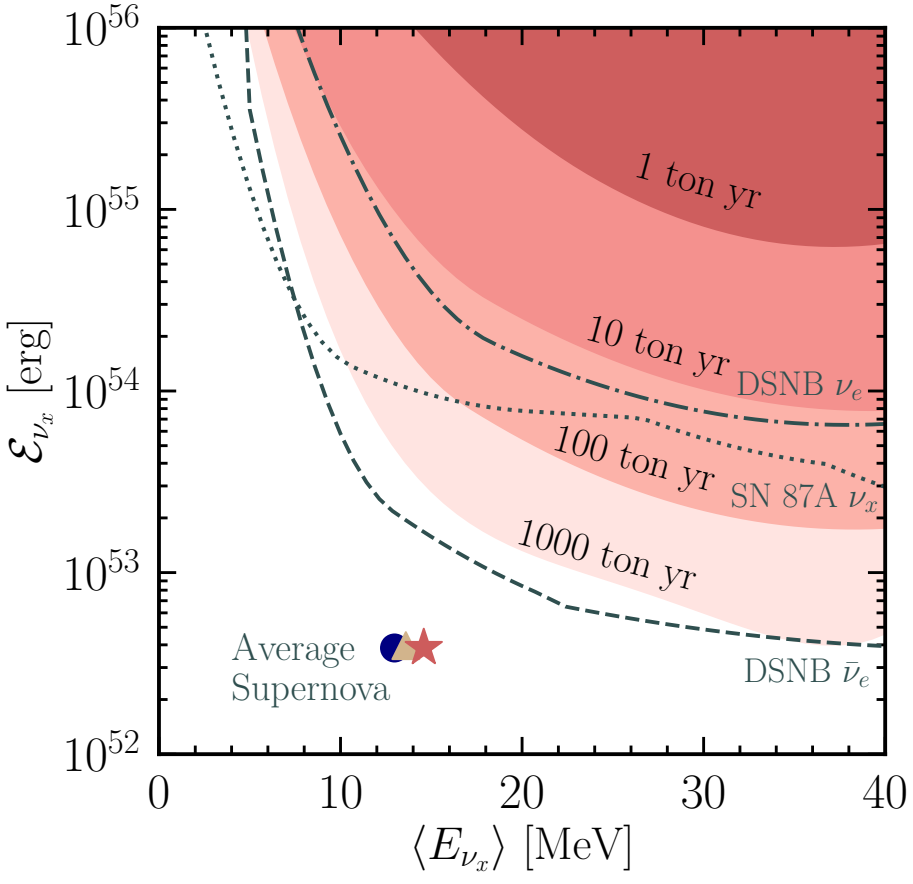
fiducial volume: 2.4 - 456 ton
target material: Pb
threshold: 1 keV
efficiency: 100%

Scattering rate

$$\frac{dR_{\nu N}}{dE_r dt} = N_T\,\epsilon(E_r)\int dE_\nu\,\frac{d\sigma_{\nu N}}{dE_r}\,\psi(E_\nu,t)\,\Theta(E_r^{\max}-E_r),\quad E_r^{\max}=\frac{2E_\nu^2}{m_T+2E_\nu}$$

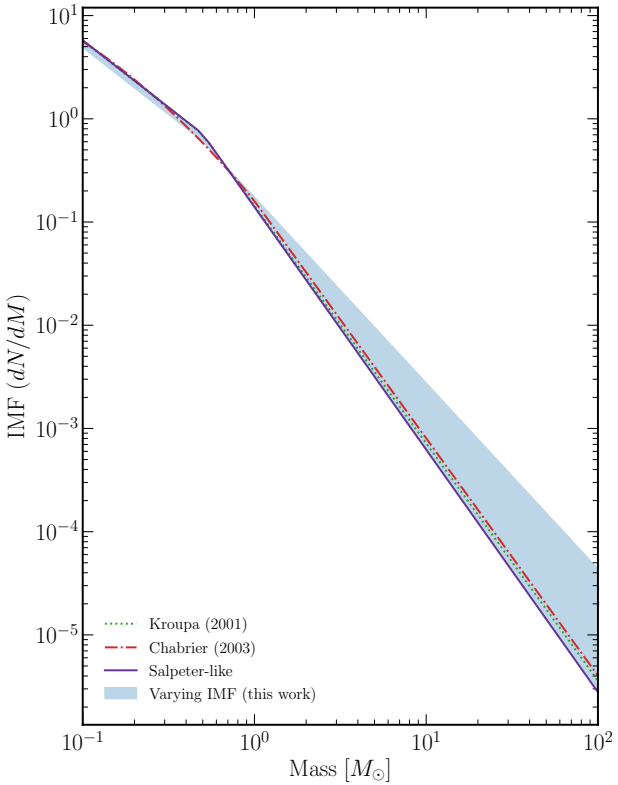
Sensitivity bounds on the x-flavor DSNB

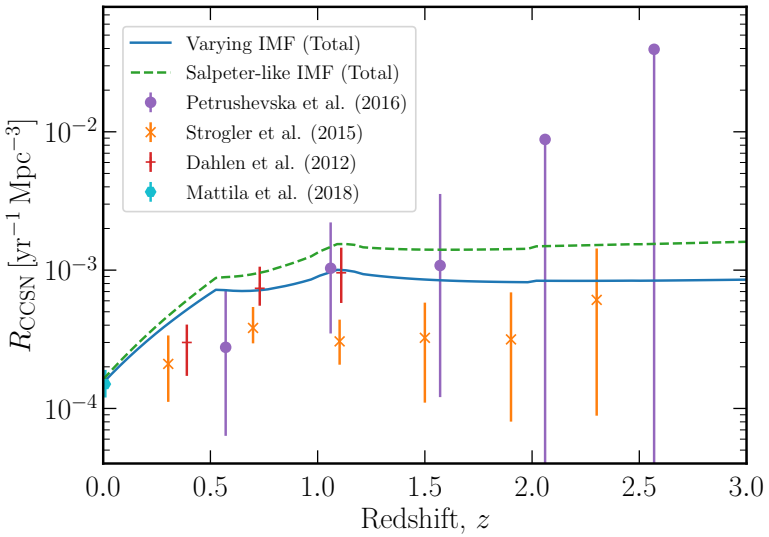


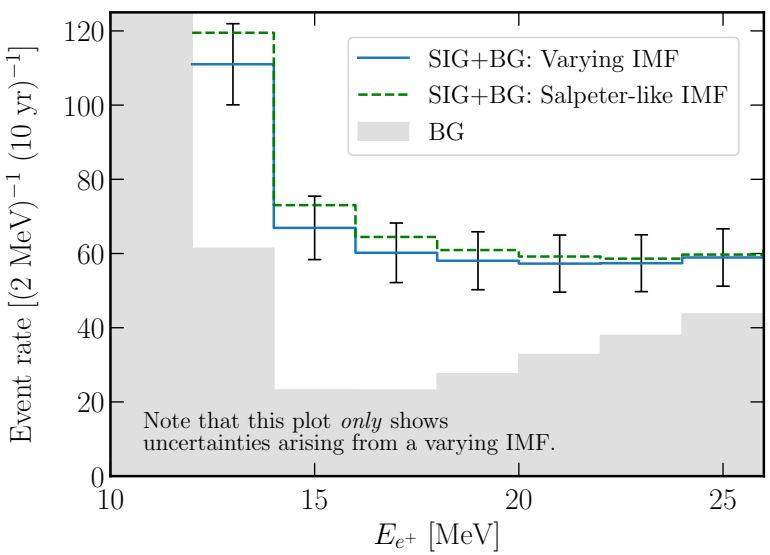


- Simple DSNB: all supernovae emit the same Fermi-Dirac ν_x spectrum
- Potential handle on the normalization and mean energy of the SN ν_x
- 1000 ton yr: limits comparable with current SK limit on $\bar{\nu}_e$ DSNB

Varying Initial Mass Function







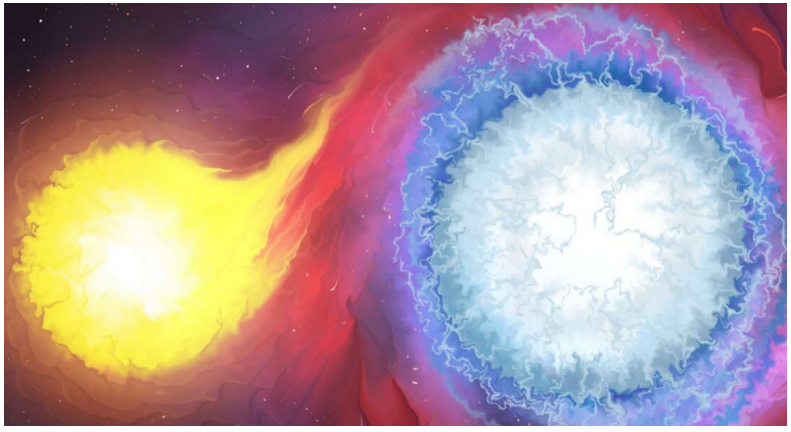
- larger fraction of stars may evolve to black holes at high redshift
- changed rate of the core-collapse supernovae

Ziegler, Edwards, **AMS**, Tamborra, Horiuchi, Ando, Freese (2022)

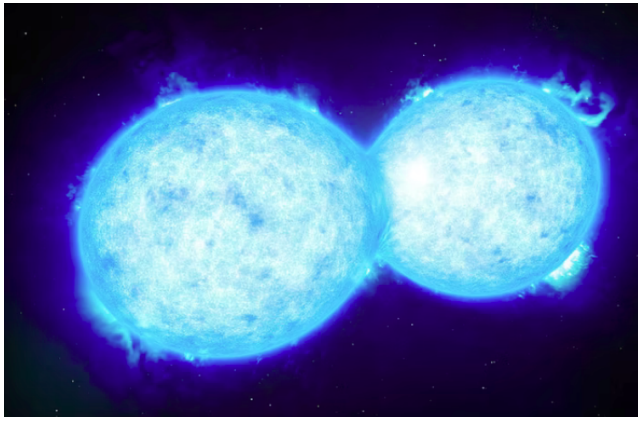
Binary interactions

Majority of massive stars have stellar companions and experience binary interactions Sana et al. 2012, Zapartas et al. 2020

Mass transfer



Mergers

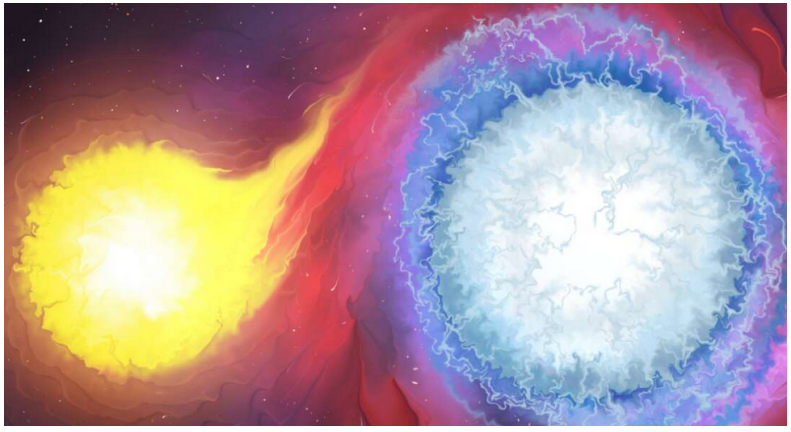


Images: iflscience, Wiki

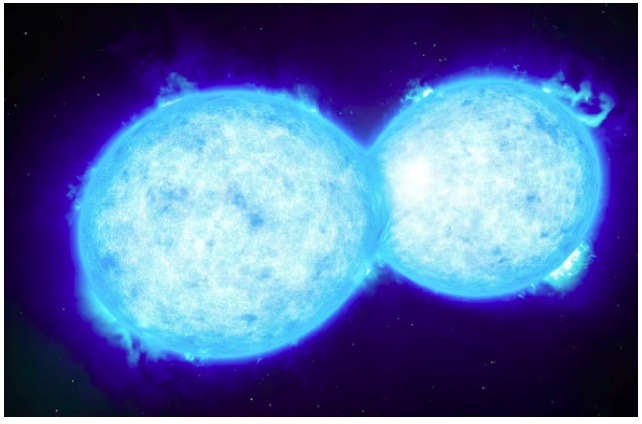
Binary interactions

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Mass transfer



Mergers

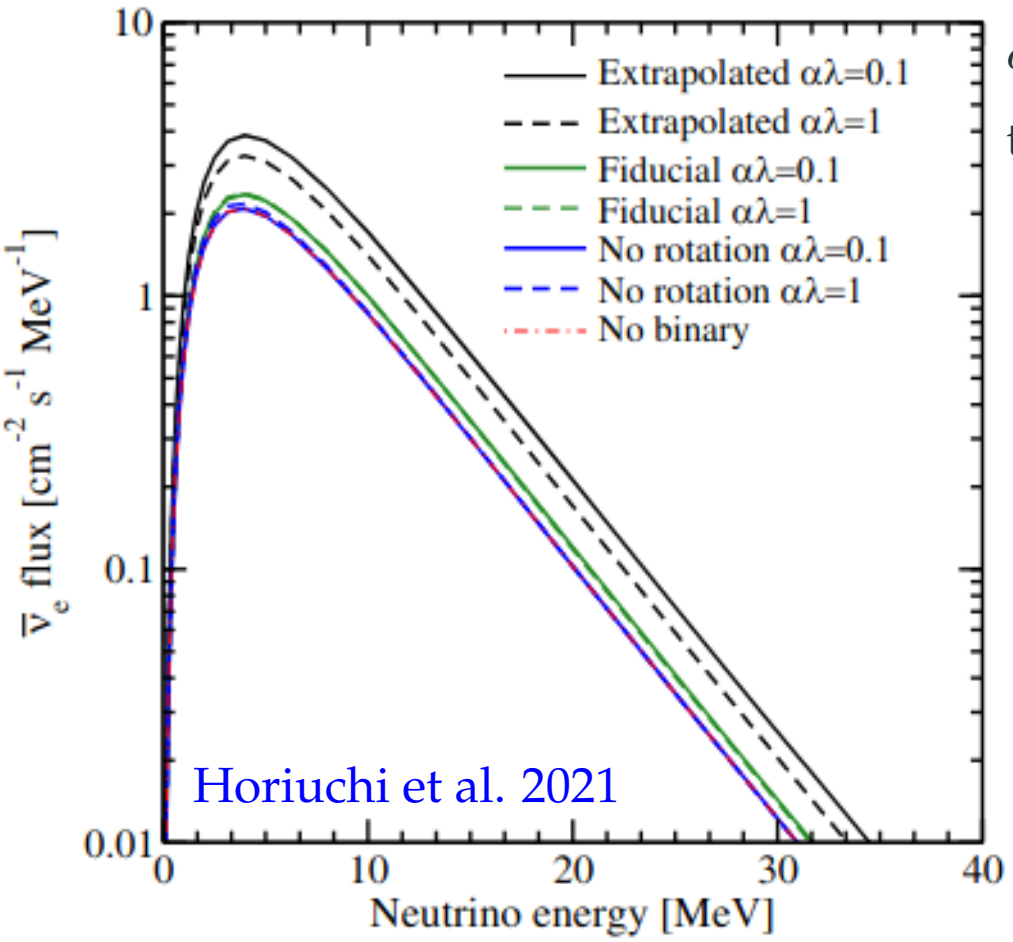


Effects on the stellar population Horiuchi et al. 2021

- change in mass due to mass transfer
- reduced progenitor counts
- increased progenitor counts

Images: iflscience, Wiki

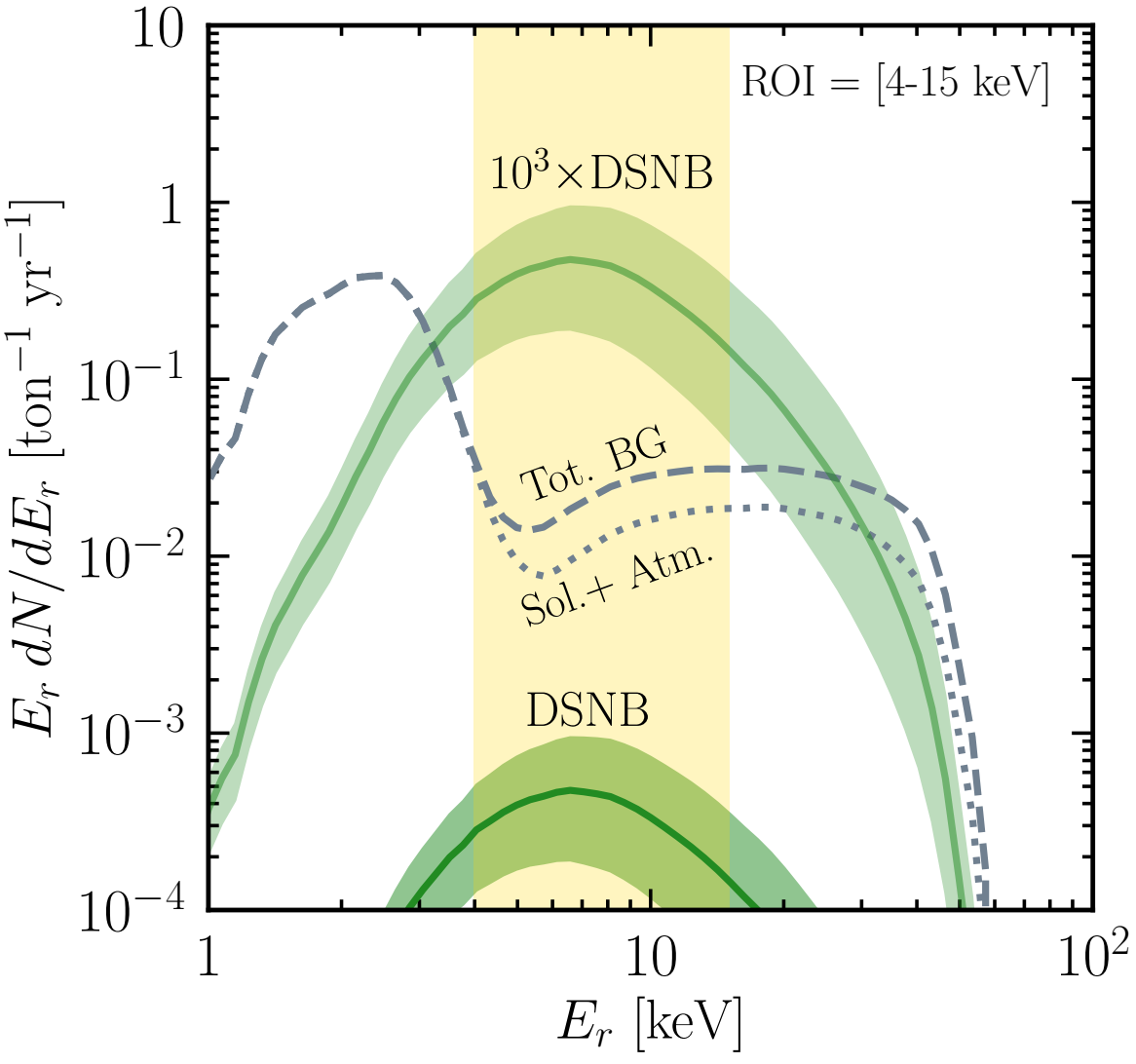
Binary interactions: impact on DSNB



$\alpha\lambda$ - measure how hard it is to unbind the envelope

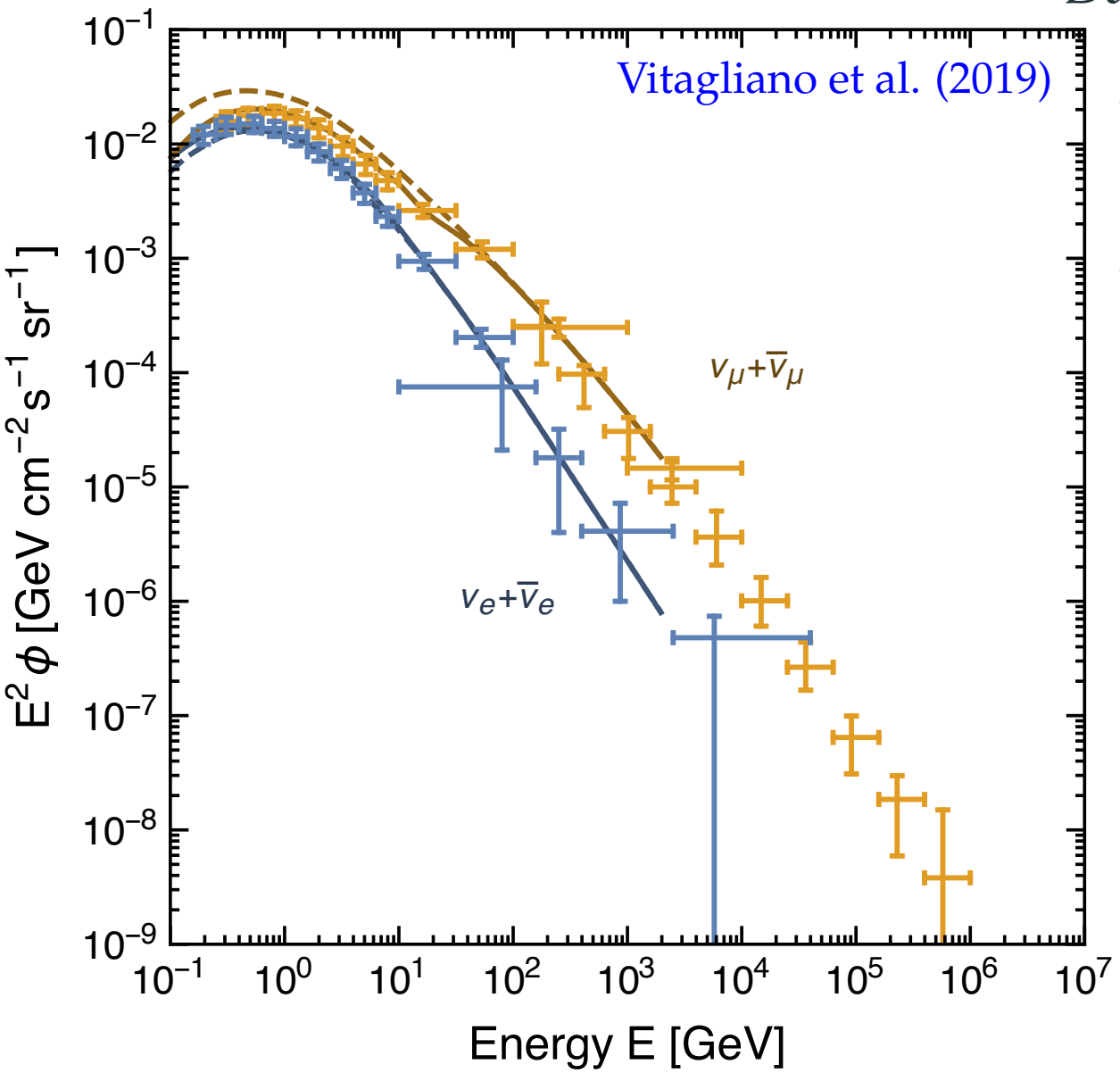
- enhancement $\leqslant 75\%$ compared to estimate w/o binary considerations
- core mass increases due to rotational effects
- more studies needed

Can we improve the limits on the x-flavor DSNB? Yes



- Potential for an imporevement by $\gtrsim 1-2$ orders of magnitude

Atmospheric neutrino measurements

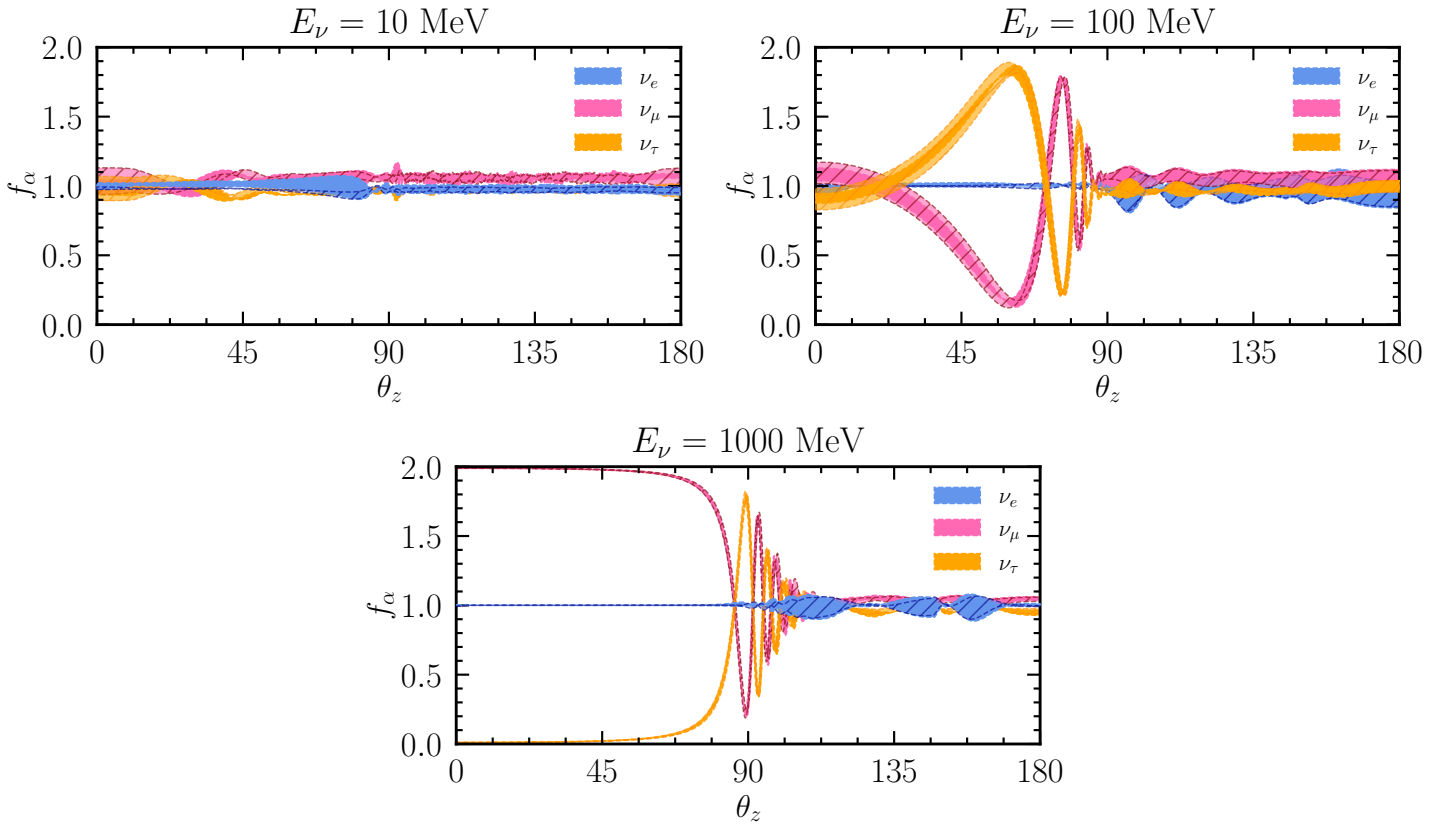


Data points from:

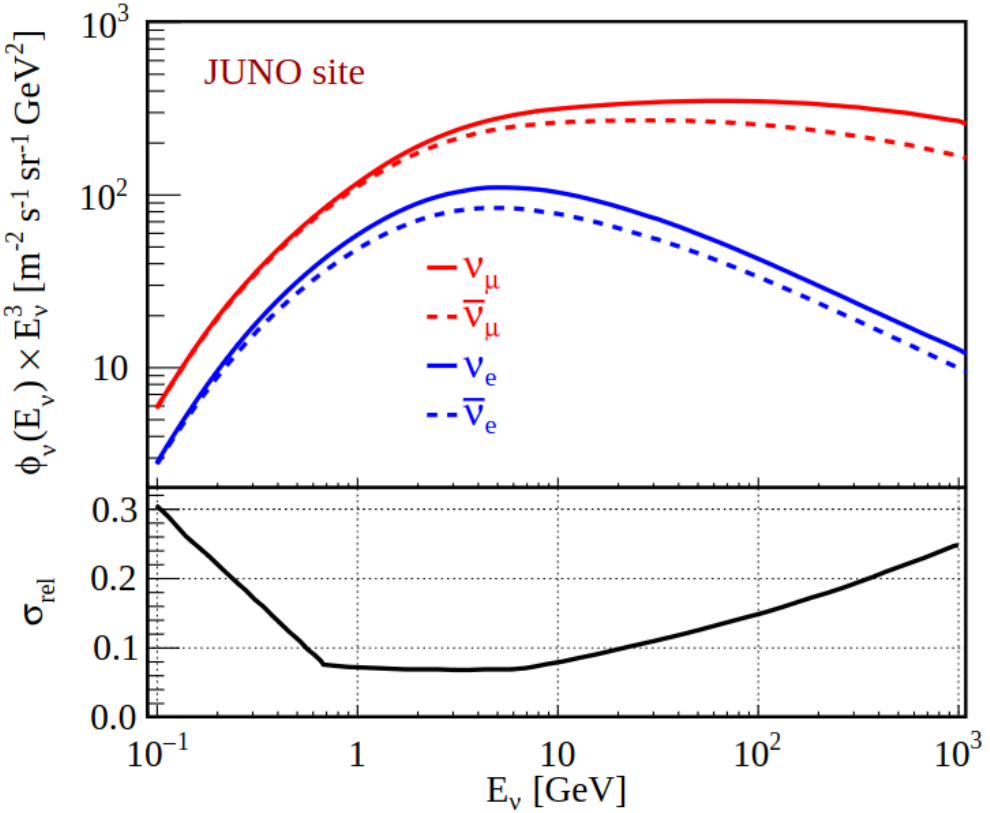
- Super-Kamiokande (SK)
  SK Collaboration (2015)
- Ice-Cube (IC)
  IC Collaboration (2015)

No measurements below 100 MeV

Atmospheric neutrino oscillations



Relative uncertainty of atmospheric neutrinos



Cheng et al. (2022)

EPT cross sections

$$\sigma(E_\nu) = \frac{3G_F^2}{2\pi} F_A^2 (E'_\nu)^2 I \,, \quad \sigma(E_\nu) = \frac{3G_F^2}{\pi} \cos\theta_C^2 F_A^2 E_e p_e I \mathcal{F}^{\pm}(Z, E_e) \,, \tag{2}$$

$$I = \frac{1}{2} \int_{-1}^{1} dz f(\mathbf{q}^2) \left(A + B + C\right) \,, \tag{3}$$

$$f(\mathbf{q}^2) = \left(\frac{F_A(q)}{F_A}\right)^2 = \left(1 - \frac{1-\rho}{6(b|\mathbf{q}|)^2}\right)^2 \exp\left(-\frac{(b|\mathbf{q}|)^2}{2}\right) \,, \tag{4}$$

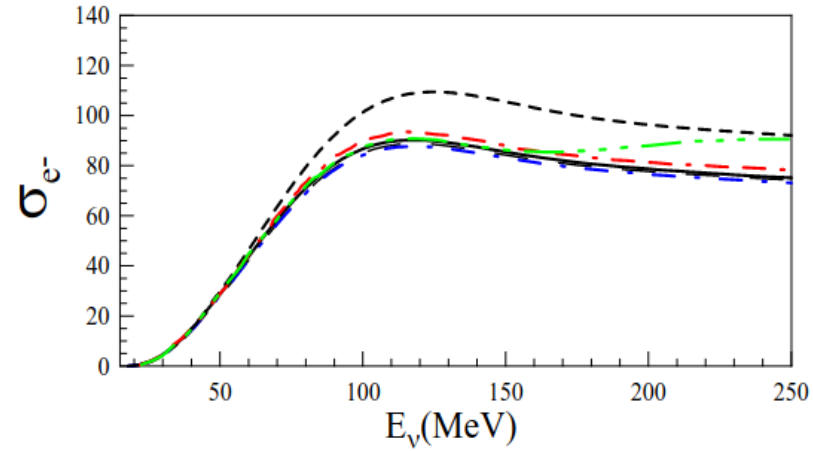
$$A = 1 - \frac{z}{3} \pm \frac{4}{3}(E_\nu + E'_\nu)(1 - 2\sin^2\theta_W)(1-z)\,\frac{F_M}{F_A} \,, \tag{5}$$

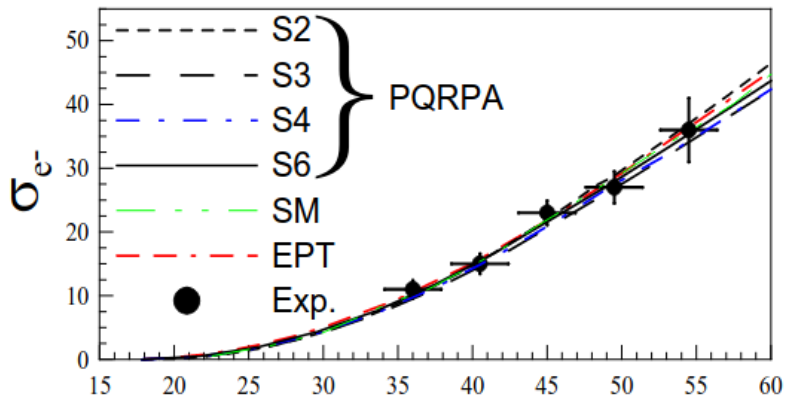
$$B = \frac{2}{3}\left(E'_\nu E_\nu (1-z^2) + (1-z)\mathbf{q}^2\right)(1 - 2\sin^2\theta_W)^2 \left(\frac{F_M}{F_A}\right)^2 \,, \tag{6}$$

$$C = -\frac{2}{3}\Delta M (1+z)\frac{F_T}{F_A} + \frac{1}{3}(1+z)\mathbf{q}^2 \left(\frac{F_M}{F_A}\right)^2 \,. \tag{7}$$

Fukugita et al. (1988)

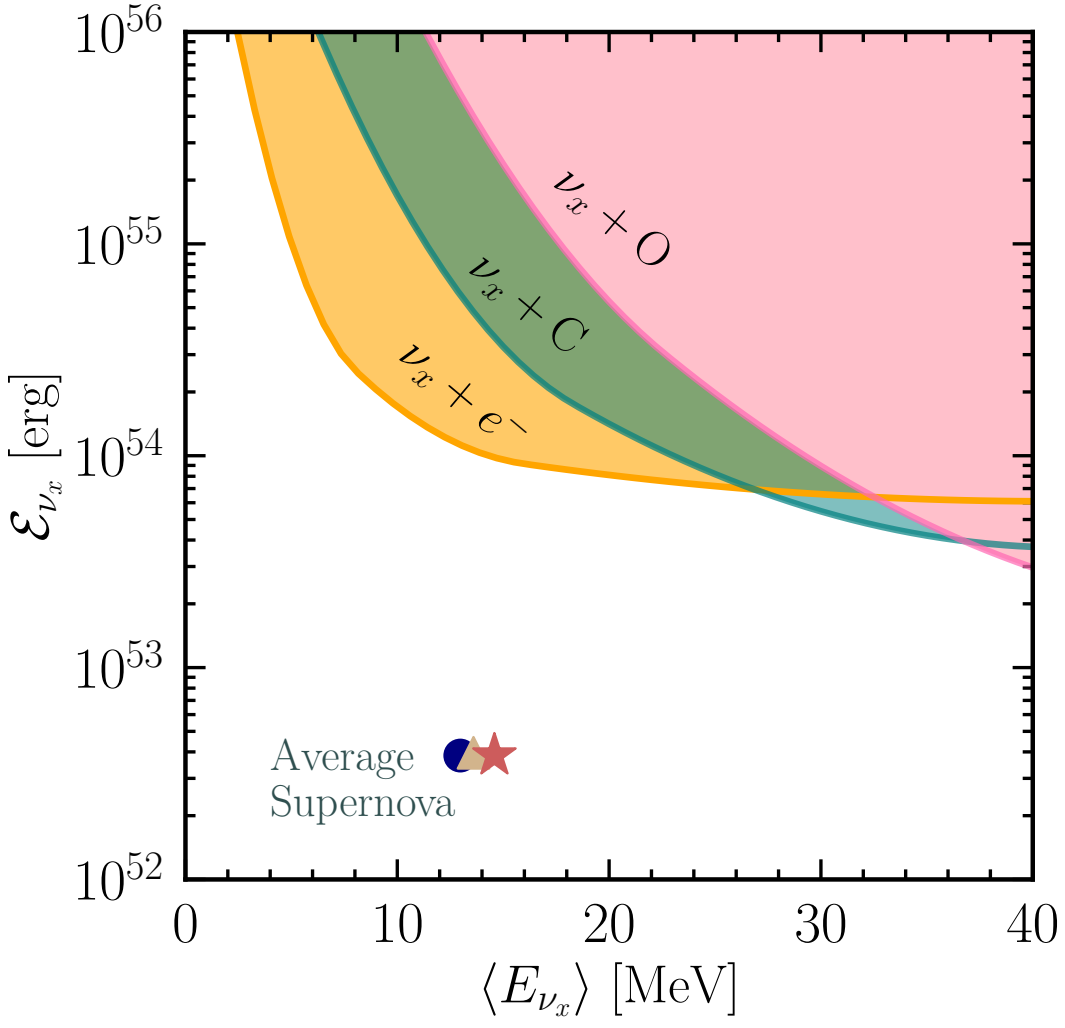
CQRPA cross sections



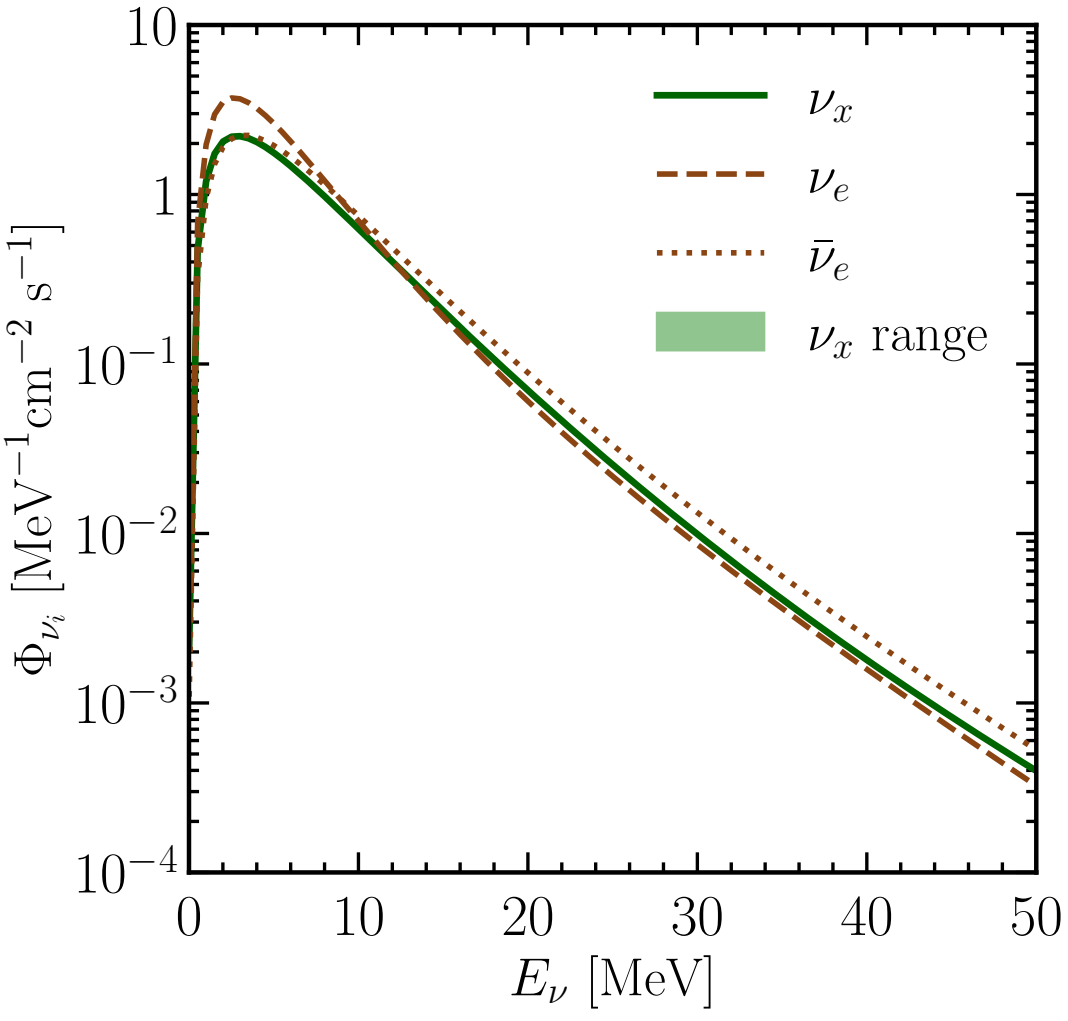


Samana et al. (2010)

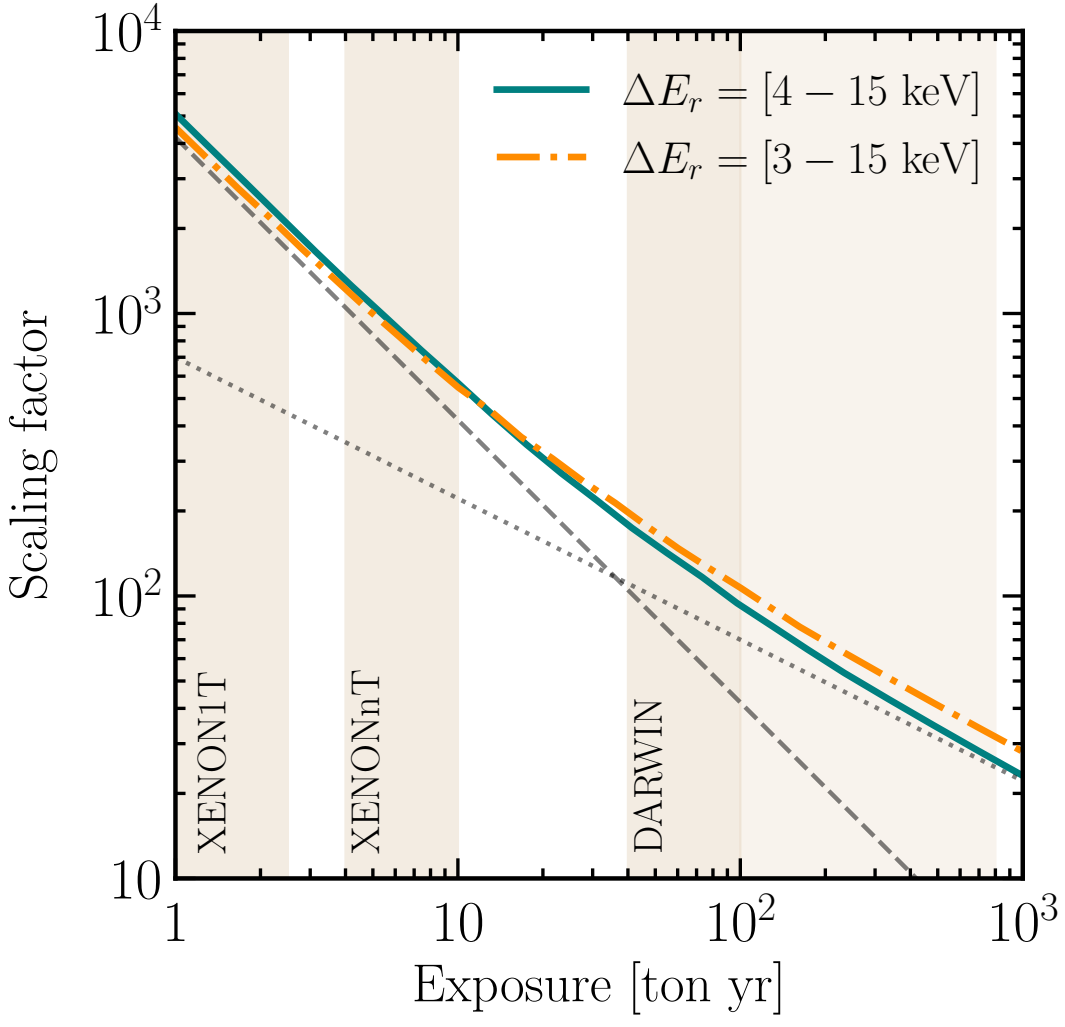
Limits from the SN 1987A



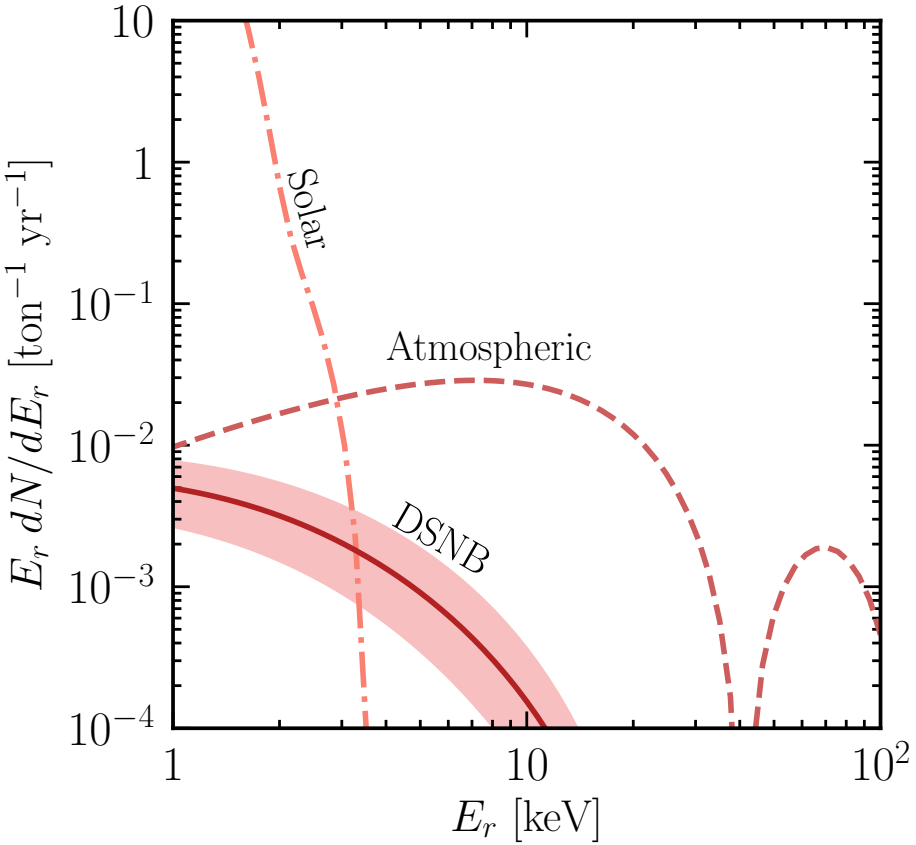
DSNB variability

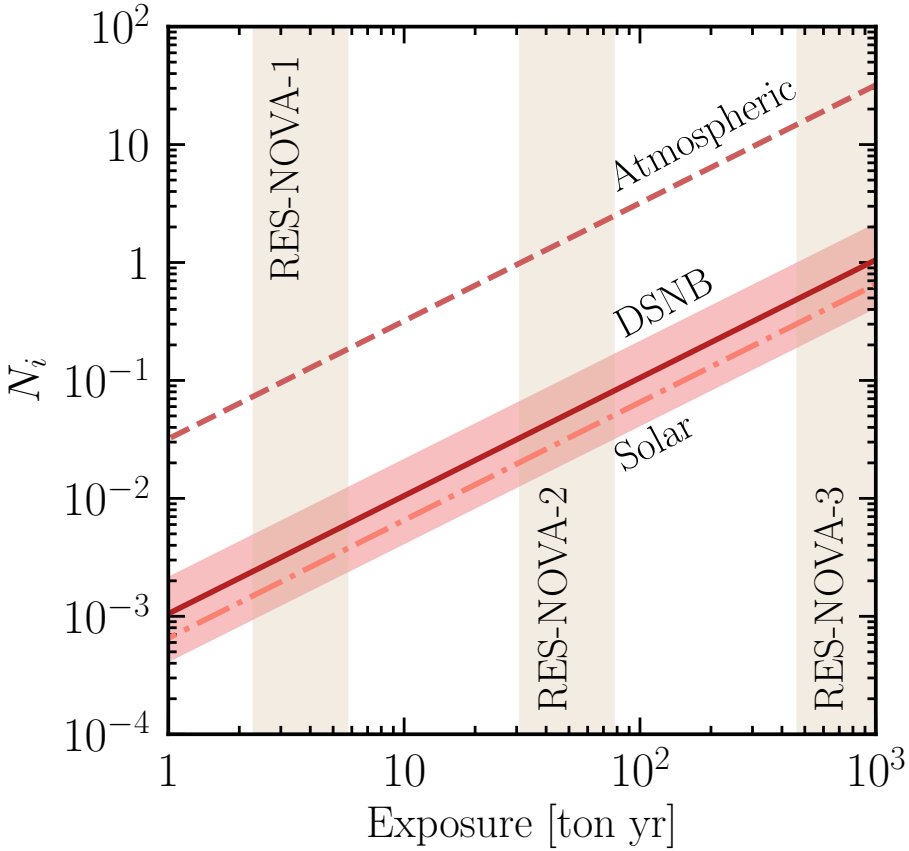


Sensitivity of the limits to a detection window

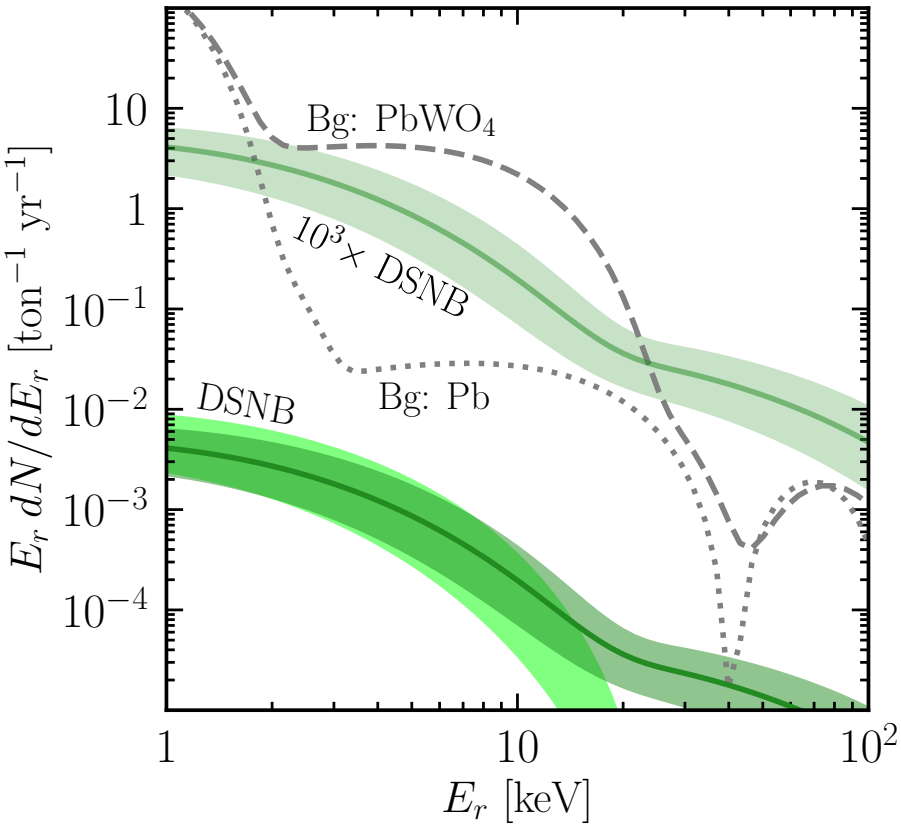


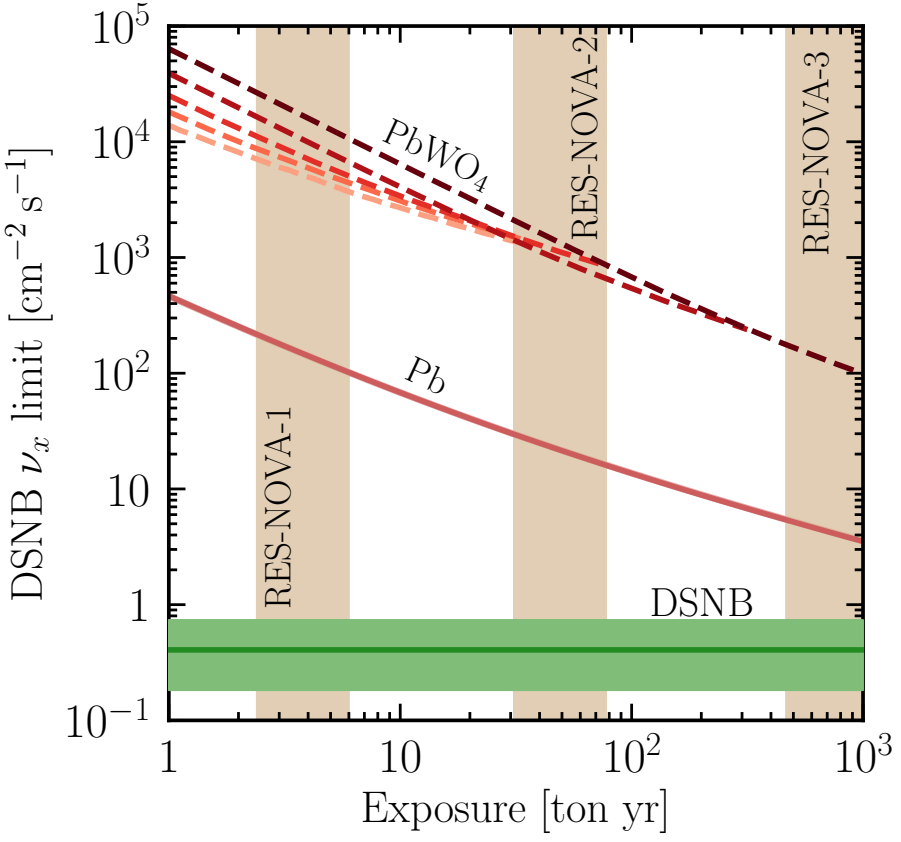
Event rate: lead detector





Event rate: lead crystals detector





Which part of the spectrum are CEνNS detectors sensitive to?

