

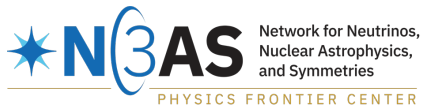
Distinctive nuclear signatures of low-energy atmospheric neutrinos

Anna M. Suliga

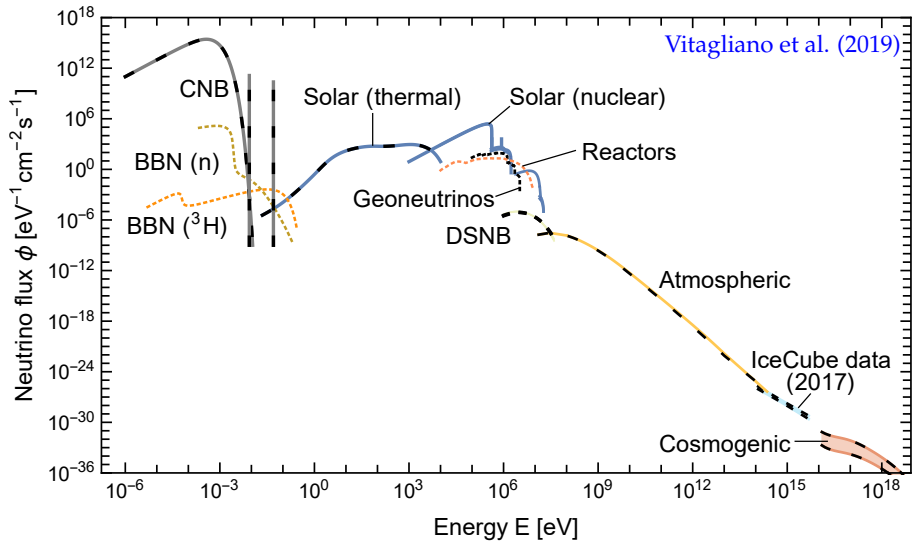
with J. F. Beacom, arXiv: 2306.11090

University of California, Berkeley
University of Wisconsin-Madison

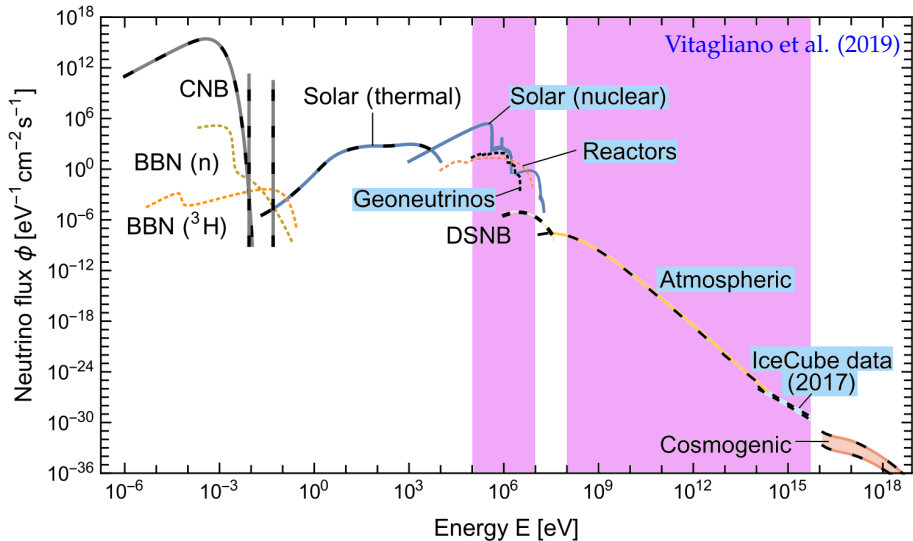
CETUP*
Lead, SD USA
July 10, 2023



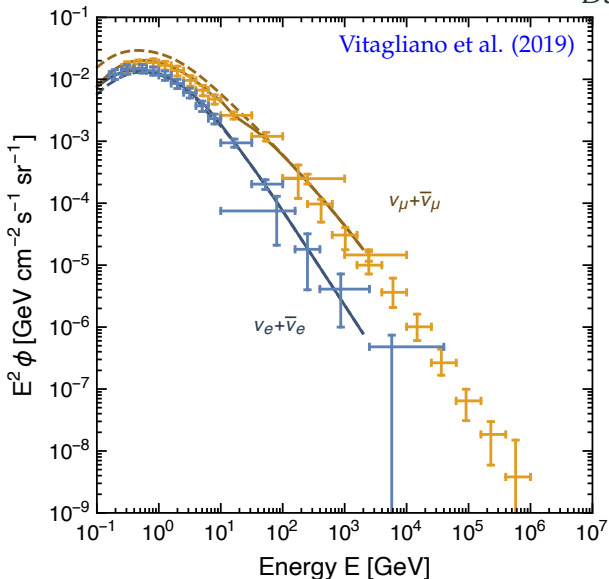
Grand Unified Neutrino Spectrum



Grand Unified Neutrino Spectrum - Detected Fluxes



Atmospheric neutrino measurements



Data points from:

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

**No measurements
below 100 MeV**

**Why it is important to measure
low-energy atmospheric neutrinos?**

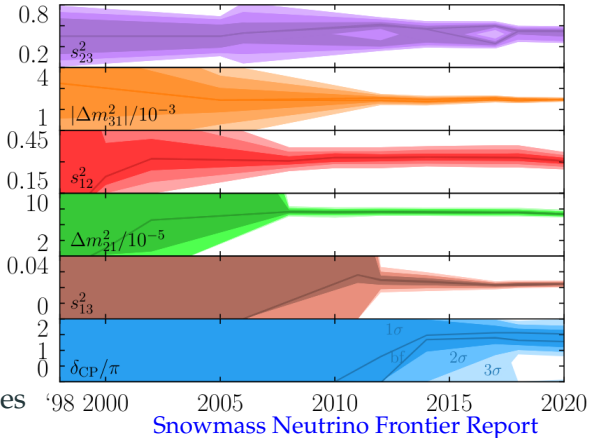
Towards precise neutrino mixing measurements

Past measurements

- large mixing angles
- non-zero masses

Remaining questions

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



How to achieve it? All hands on deck

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

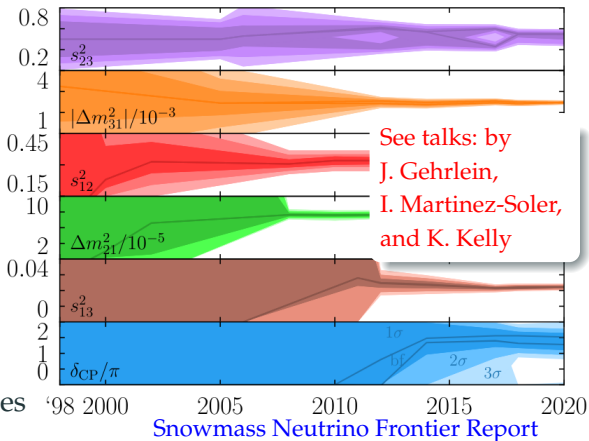
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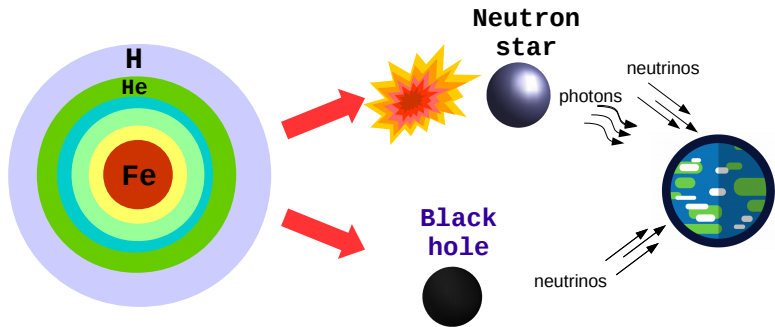
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Why are neutrinos important for a core-collapse supernova?

Neutrinos:

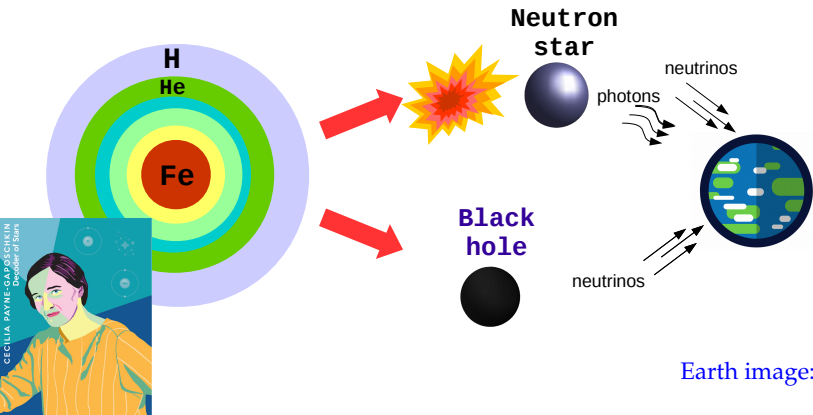
- $\sim 10^{58}$ of them emitted from a single core collapse
- only they (+ GW) can reveal the deep interior conditions
- only they (+ GW) are emitted from the collapse to a black hole



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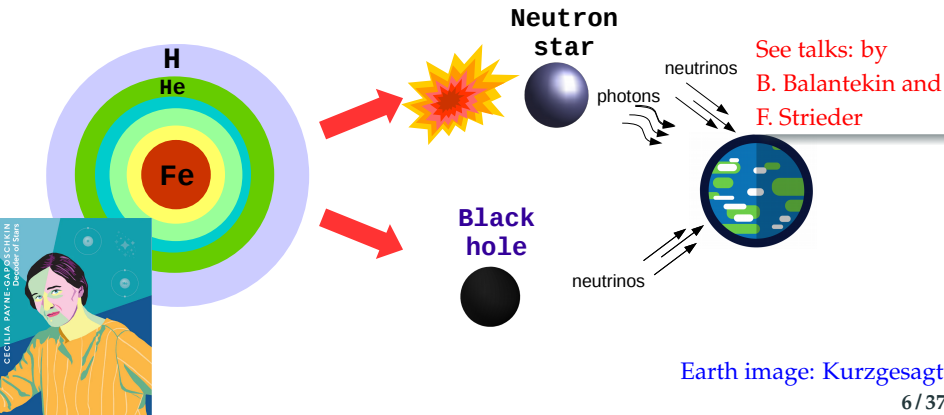
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Why core-collapse supernovae are good physics probes?

Advantages

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

What can we learn with a variety of detectors?

- explosion mechanism [Bethe & Wilson \(1985\)](#), [Fischer et al. \(2011\)](#)...
- 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 \(2013\)](#), [Tamborra & Shalgar \(2020\)](#)...
- non-standard physics [McLaughlin et al. \(1999\)](#), [de Gouvêa et al. \(2019\)](#) ...

Why focus only on a single rare event?

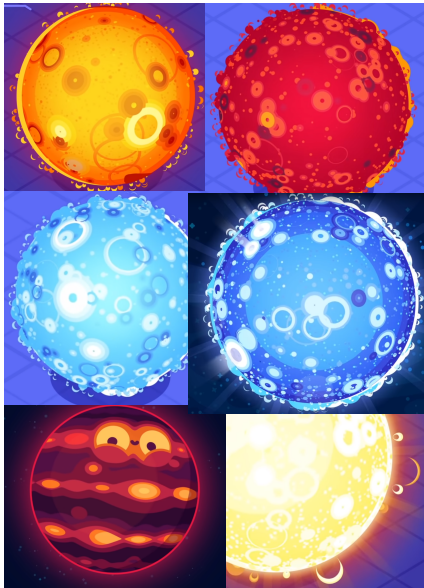


Single galactic SN event

- rare event
- precise information about one star

Multiple SN events (larger distances)

- accumulation of events
- will detect in coming years



Diffuse supernova neutrino background

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

cosmological supernovae rate (orange arrow pointing to $R_{\text{SN}}(z, M)$)

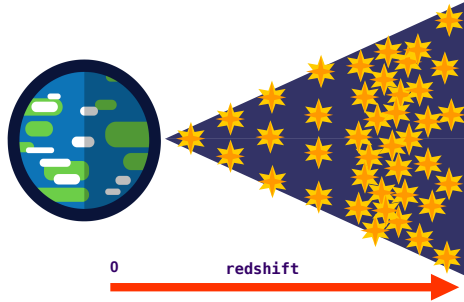
fraction of black-hole-forming progenitors (light blue arrow pointing to $f_{\text{BH-SN}}$)

fraction of neutron-star-forming progenitors (red arrow pointing to $f_{\text{CC-SN}}$)

neutrino flux from a single star (purple arrow pointing to $F_{\nu\beta, \text{CC-SN}}(E', M)$ and $F_{\nu\beta, \text{BH-SN}}(E', M)$)

The DSNB is sensitive to:

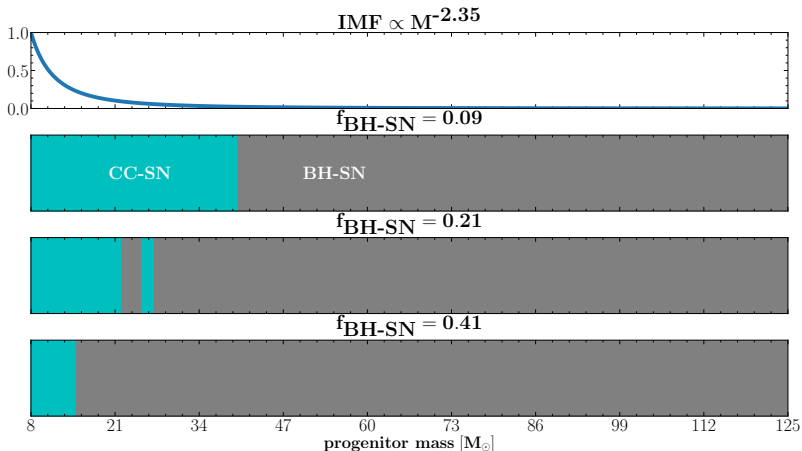
- $R_{\text{SN}}, f_{\text{BH-SN}}$
- neutrino flavor evolution
- equation of state
- mass accretion rate in BH-SN
- non-standard physics



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), ...

Astrophysical uncertainties

The fraction of black-hole-forming progenitors

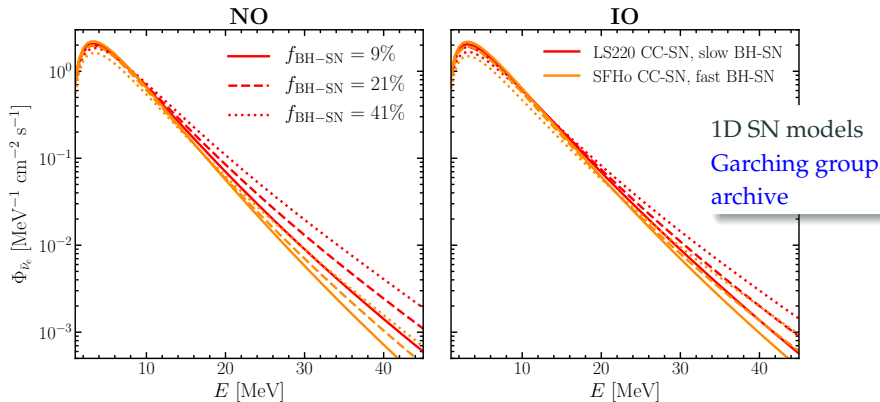


Fraction of black-hole-forming progenitors influences the highly energetic part of the DSNB, above ~ 15 MeV.

C. Lunardini (2009)

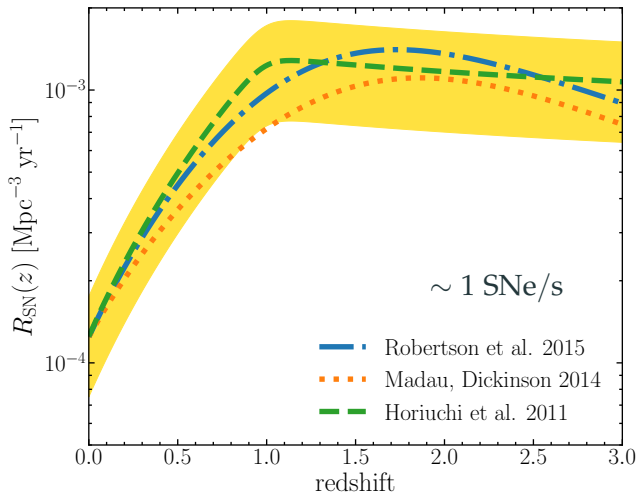
Ertl et al. 2015, Sukhbold et al. 2015, Adams et al. 2016, Heger et al. 2001, Kochanek et al. 2001, Basinger et al. 2020, ...

The fraction of black-hole-forming progenitors



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

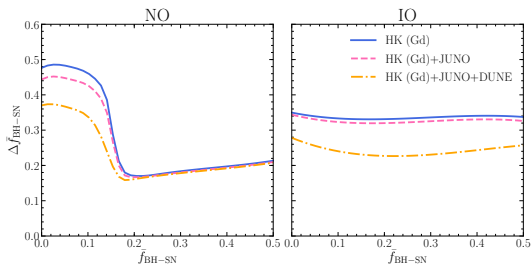
Cosmological supernovae rate



The supernovae rate influences the normalization of the DSNB.

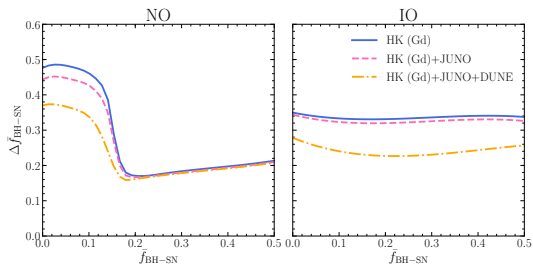
Ando, Sato (2004), Beacom (2010), Horiuchi et al. (2011), Møller, AMS, Tamborra, Denton (2018), Nakazato et al. (2018), ...

Expected 1σ uncertainty: fraction of BH forming progenitors



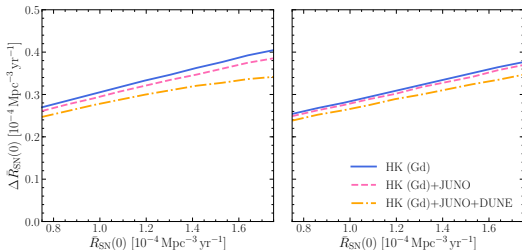
- The high uncertainty comes from $f_{\text{BH-SN}}$ -mass accretion rate degeneracy
- DUNE is sensitive to neutrinos \rightarrow helps to reduce the uncertainty

Expected 1σ uncertainty: local supernova rate

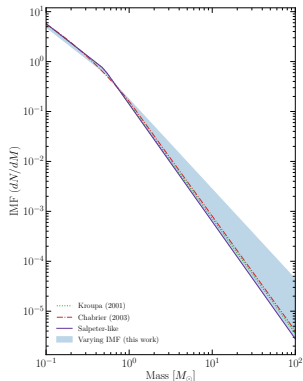


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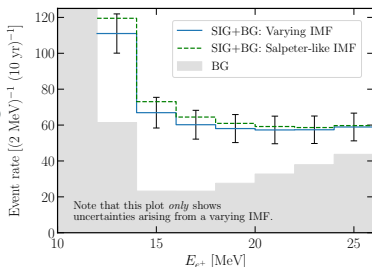
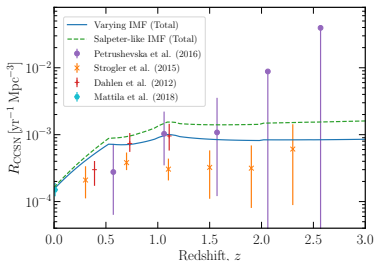
- Relative error of 20%-33% independent of the mass ordering.



Varying Initial Mass Function



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



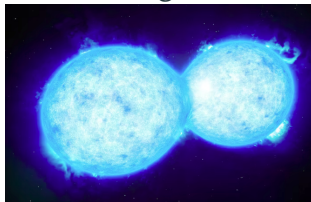
Binary interactions

Majority of massive stars have stellar companions
and experience binary interactions [Sana et al. 2012](#), [Zapartas et al. 2020](#)

Mass transfer



Mergers



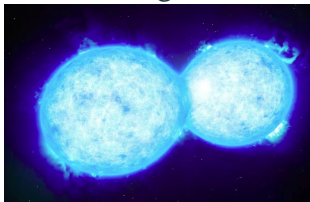
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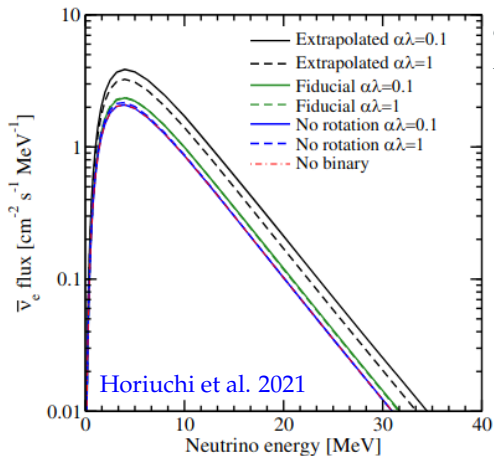


Effects on the stellar population [Horiuchi et al. 2021](#)

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

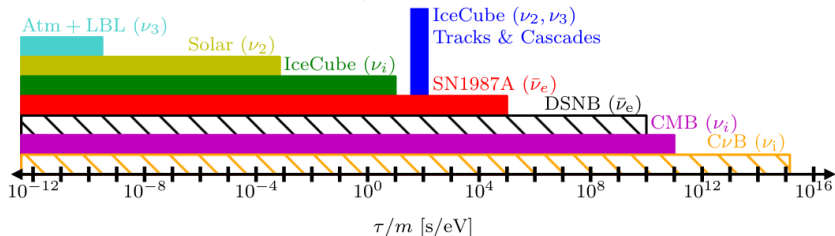
BSM scenarios affecting DSNB

Neutrino decay

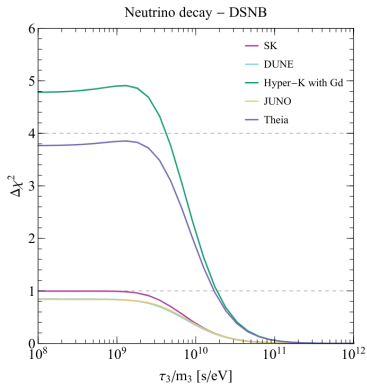
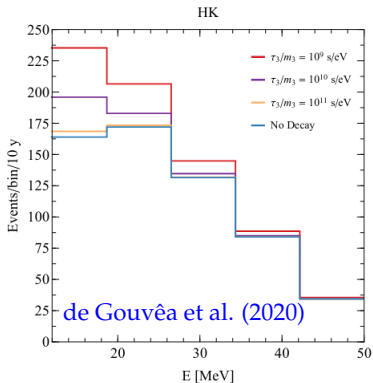
Active neutrinos are massive and masses are not identical

- SM decays are loop suppressed
- lifetimes \gg age of the Universe

If neutrinos have BSM interactions they can decay faster



Neutrino decay: impact on DSNB

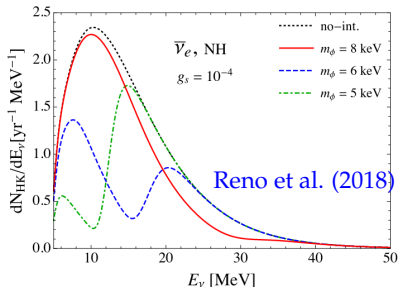
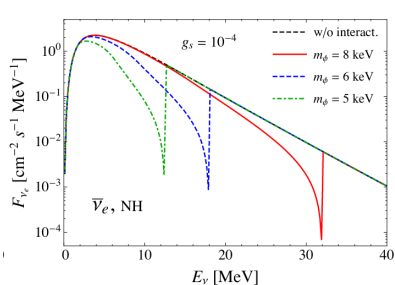


Exact detector features depend on

- Mass ordering
- Dirac vs Majorana nature
- details of the BSM model

Ando et al. 2003, Fogli et al. 2004, de Gouvêa et al. 2020, Tabrizi & Horiuchi (2020), Ivanov-Ballesteros & Volpe (2023),...

Secret neutrino interactions: impact on DSNB

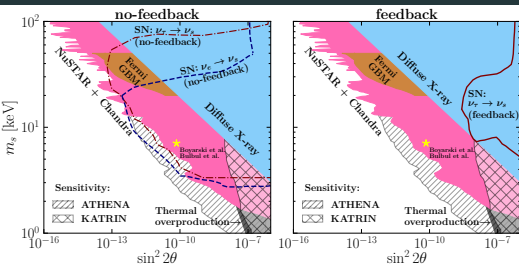


DSNB interactions with

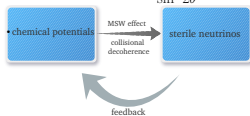
- cosmic relic neutrinos
Goldberg et al. (2005), Baker et al. (2007), Reno et al. (2018)
- dark matter Farzan, Palomares-Ruiz (2014)

result in spectral features in DSNB

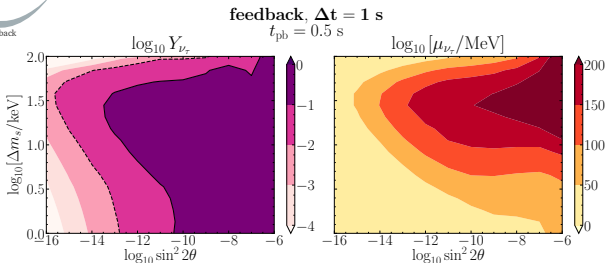
KeV sterile neutrinos



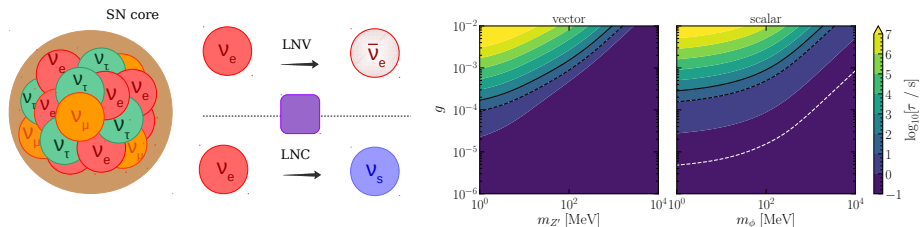
- The inclusion of feedback: reduction of the excluded region
- CC-SNe cannot exclude any region the DM parameter space



- The inclusion of feedback: growth of asymmetries
- Neutrino spectrum affected

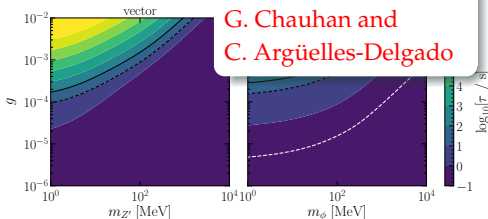
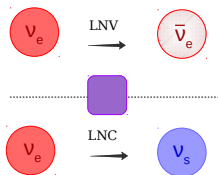
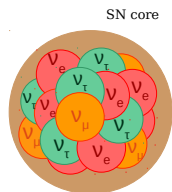


Non-standard coherent scattering in the supernova core



- prolonged diffusion time \rightarrow possible change in the star's fate
- prolonged diffusion time \rightarrow changed duration of the neutrino signal
- LNC scalar mediator \rightarrow new cooling channel due to ν_R

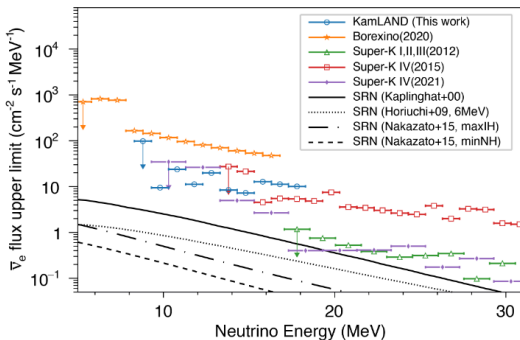
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Diffuse supernova neutrino background: current limits

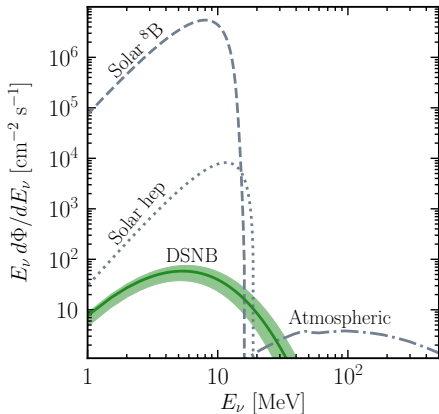
SK collab. (2021)



DSNB limits:

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

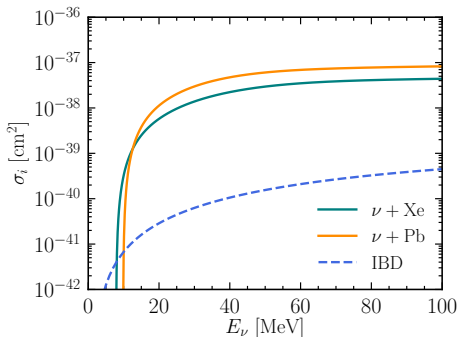
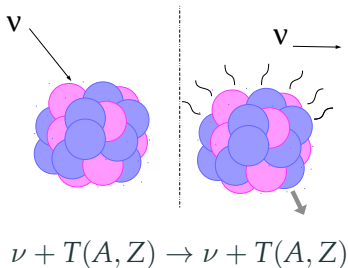
Can we detect the x -flavor DSNB? Maybe



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

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

Maybe: Coherent elastic neutrino-nucleus scatterings (CE ν NS)



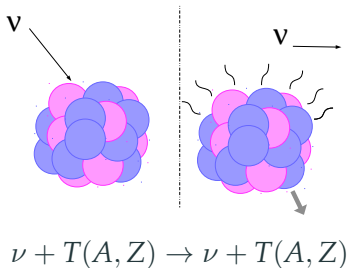
Cross section

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

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

Freedman (1974),
Strigari (2009)

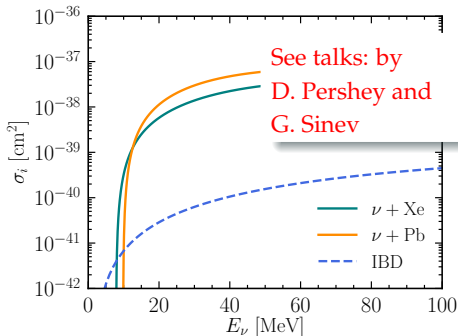
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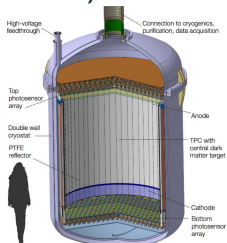
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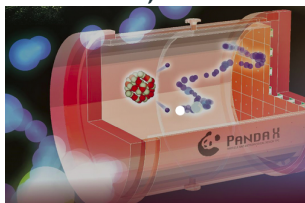
Current and future CE ν NS detectors

XENONnT, DARWIN



Aalbers et al. 2016

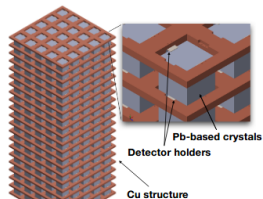
PandaX-4T, PandaX-xT



Menget et al. 2021

Total Pb volume (60 cm)³

RES-NOVA



Pattavina et al. 2020

fiducial volumes: few - hundreds ton

target materials: Xe, Pb

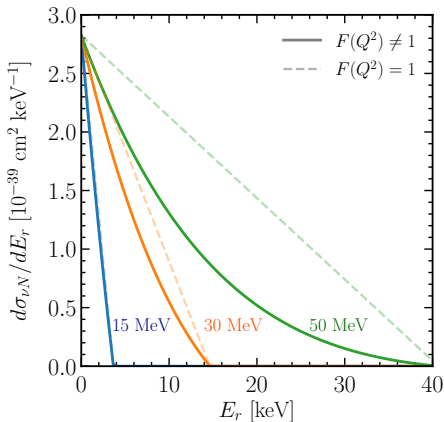
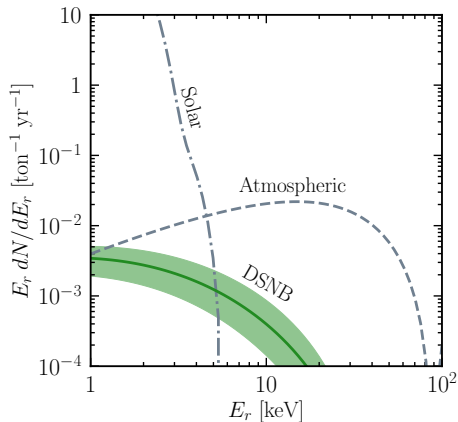
thresholds: $\mathcal{O}(1)$ keV

efficiency: ~ 80 - 100%

Scattering rate

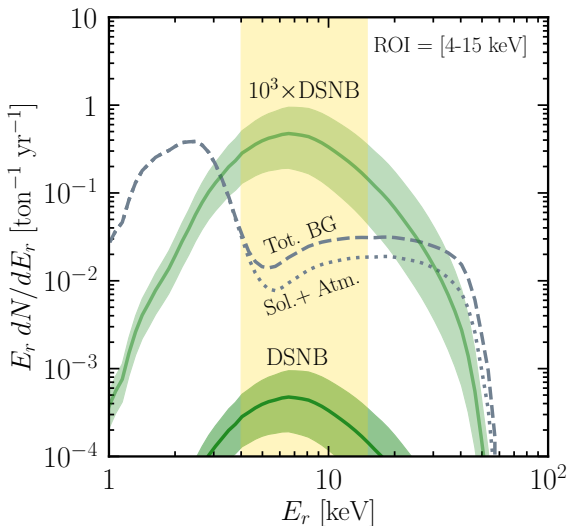
$$\frac{dR_{\nu N}}{dE_r dt} = N_T \epsilon(E_r) \int dE_\nu \frac{d\sigma_{\nu N}}{dE_r} \psi(E_\nu, t) \Theta(E_r^{\max} - E_r), \quad E_r^{\max} = \frac{2E_\nu^2}{m_T + 2E_\nu}$$

Event rate in the xenon-based detector



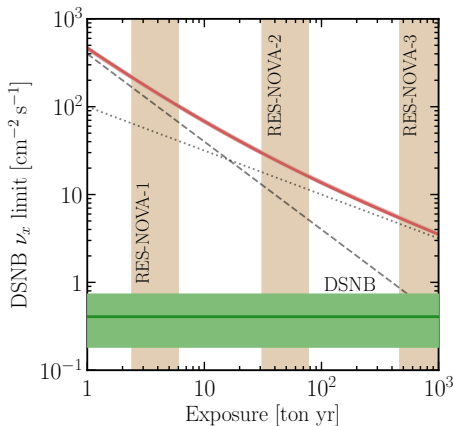
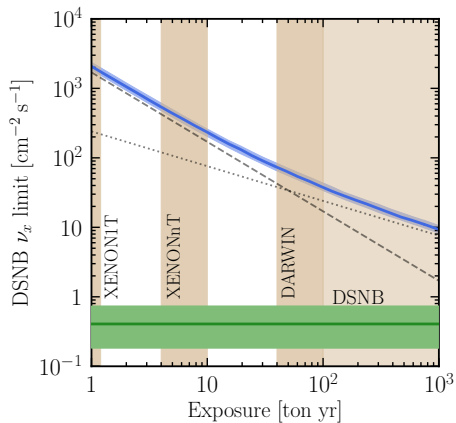
- The potential energy window displayed by the bare fluxes disappears
- Reason: Low energy recoils are most probable for all neutrino energies
- Detection of the x -flavor DSNB seems out of reach, BUT...

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



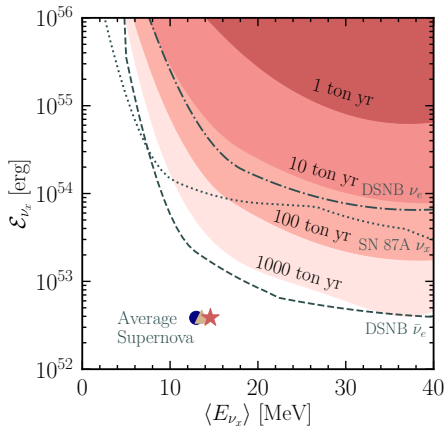
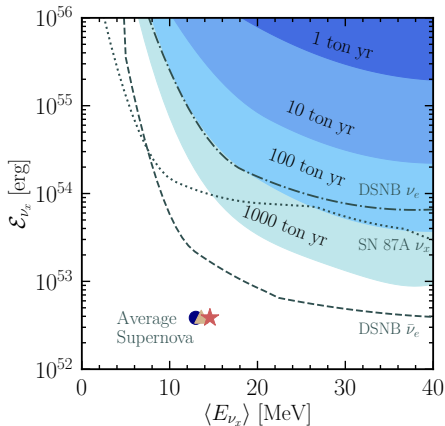
- Potential for an improvement by $\gtrsim 1 - 2$ orders of magnitude

Sensitivity bounds on the normalization of the x-flavor DSNB



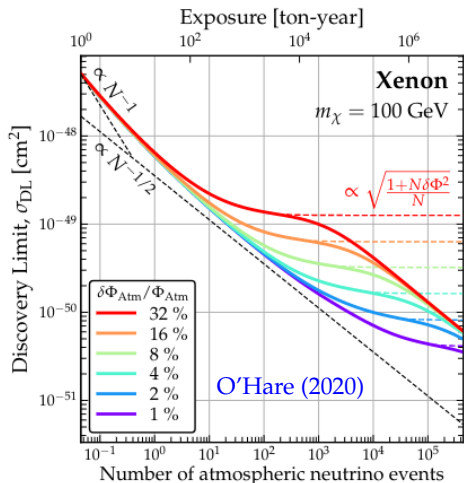
- XENON1T, PandaX-4T: limits comparable to the SK ν_x DSNB limit
- Constant energy window: limits can improve $\mathcal{O}(10\%)$ for wider windows at small exposures and narrower windows at large exposures

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

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 atmospheric neutrinos helps the discovery limits



Low-energy Atmospheric Neutrino Flux

Primary production channels

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

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

Non-oscilated flavor ratio

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

Sources of uncertainty

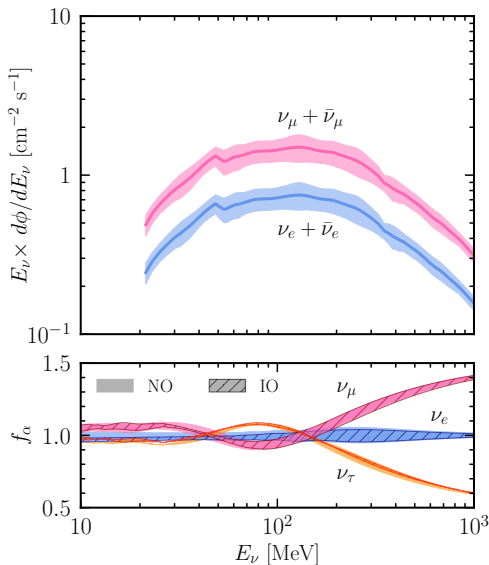
solar wind modulations

Earth's geomagnetic field

Oscilated flavor ratio

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

Past measurements: energies > 100 MeV

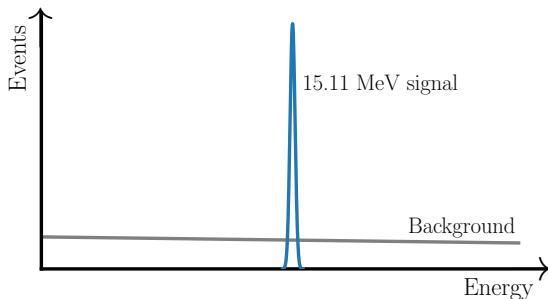


Neutrino flux: Zhuang (2021)

Mixing: NuCraft

Distinctive nuclear channels

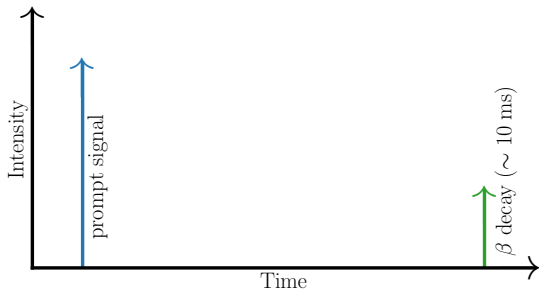
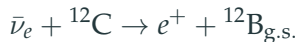
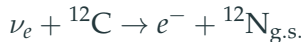
Neutral current channels



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

Distinctive nuclear channels

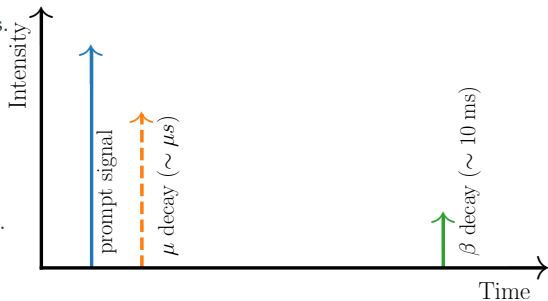
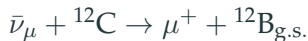
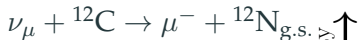
Charged current channels: ν_e



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

Distinctive nuclear channels

Charged current channels: ν_e

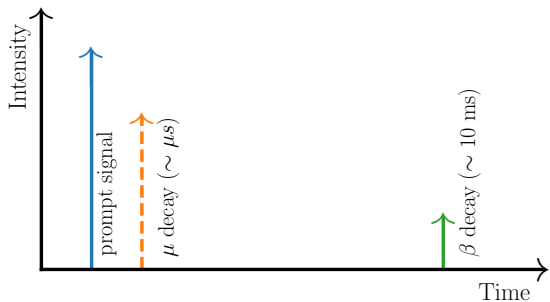
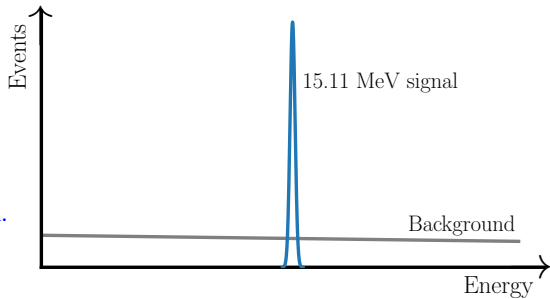


- coincidence detection of μ , its decay e and β -decay e
- difference in ${}^{12}\text{B}_{\text{g.s.}}$ and ${}^{12}\text{N}_{\text{g.s.}}$ lifetimes $\rightarrow \nu_\mu$ vs. $\bar{\nu}_\mu$ distinction
- triple vs. double coincidence detection $\rightarrow \nu_e$ vs. ν_μ distinction

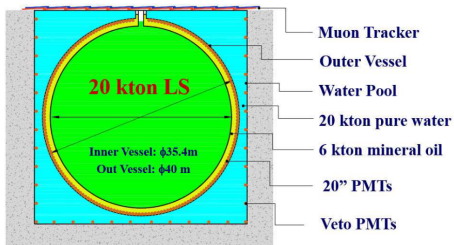
Distinctive nuclear channels

Also suggested for supernova neutrino detection

Fukugita et al. (1988), Cadonati et al. (2000), Laha et al. (2014), Lu et al. (2016)



The Jiangmen Underground Neutrino Observatory (JUNO)

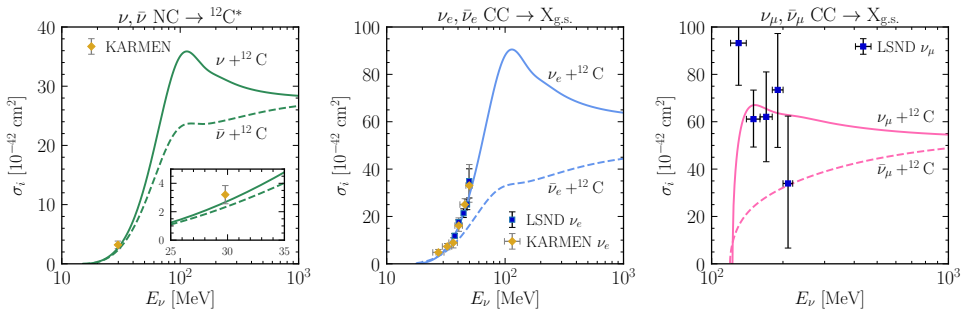


- large-scale carbon-based liquid scintillator detector
- soon operational (~ 2024)
- excellent energy resolution $\lesssim 3\%$
- excellent spatial resolution $\lesssim 10\text{ cm}$
- low backgrounds in the considered channels

JUNO inclusive studies:
[Cheng et al. \(2020\)](#),
[Cheng et al. \(2020\)](#),
[JUNO Collaboration \(2022\)](#)

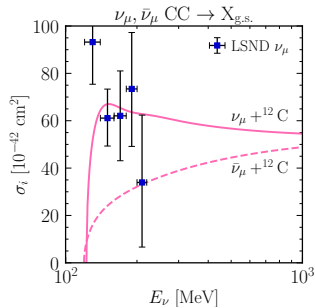
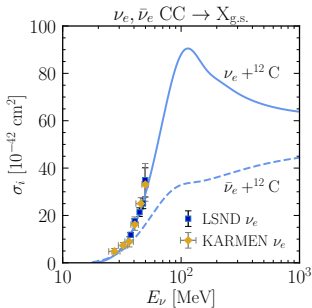
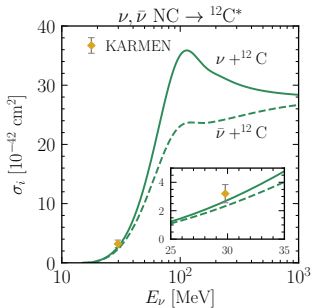
[JUNO collaboration \(2015\)](#), [Sitsi \(2022\)](#)

Cross section: elementary particle treatment (EPT)



- superallowed transitions from 0^+ to 1^+ states in $A=12$ triad
- the exclusive $\nu - ^{12}\text{C}$ 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

Cross section: elementary particle treatment (EPT)



See talks: by
J. Reichenbacher

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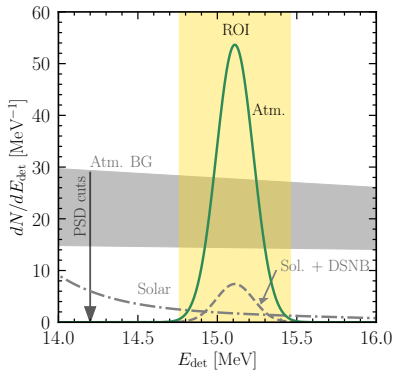
Atmospheric neutrino detection in JUNO

NC channel detection: single events

Irreducible BG: solar and DSNB ν

Reducible BG: atm. ν - p scattering

**85 kton yr exposure \rightarrow 25(40)%
uncertainty of the atmospheric ν rate**

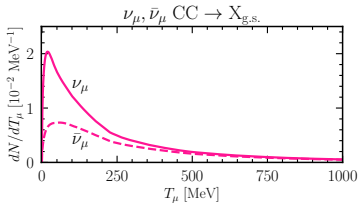
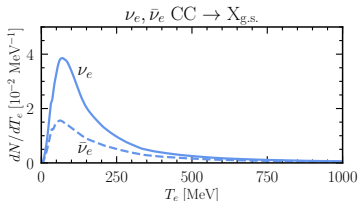


CC channel detection: coincidence events

Irreducible BG: accidental coincidences

Rate per 85 kton yr: ~ 0.0004

essentially background free channels

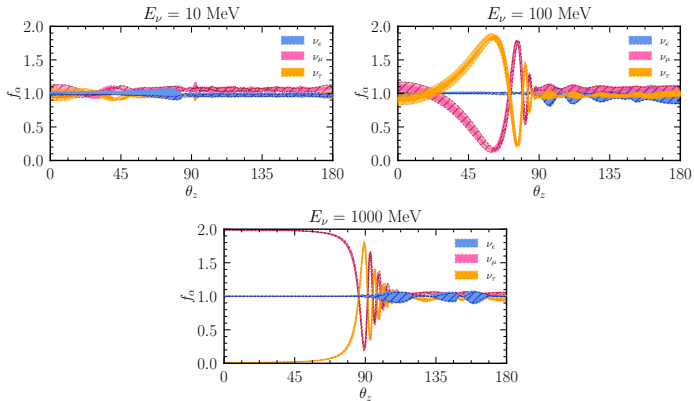


Conclusions

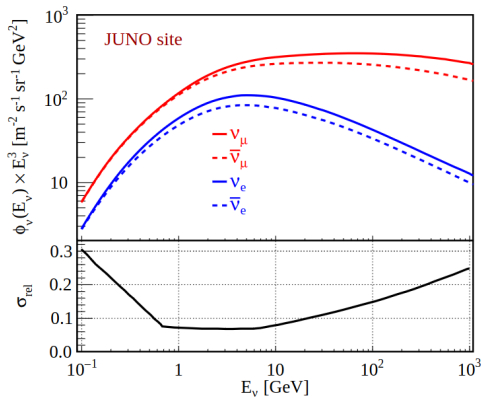
- high statistic era of neutrino physics → exploring all the available channels
- potentially first measurement of the sub-100 MeV atmospheric neutrino flux
- potentially first measurement of the exclusive ^{12}C cross sections for $\bar{\nu}$
- helps high-precision measurements of the mixing parameters and neutrino fluxes
- exclusive nuclear channels → clean observables
- similar channels exist for C and different nuclei?
- helps DSNB and WIMP studies

Thank you for the attention!

Atmospheric neutrino oscillations



Relative uncertainty of atmospheric neutrinos



Cheng et al. (2022)

EPT cross sections

$$\sigma(E_\nu) = \frac{3G_F^2}{2\pi} F_A^2 (E'_\nu)^2 I, \quad \sigma(E_\nu) = \frac{3G_F^2}{\pi} \cos^2 \theta_C^2 F_A^2 E_e p_e I \mathcal{F}^\pm(Z, E_e), \quad (1)$$

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

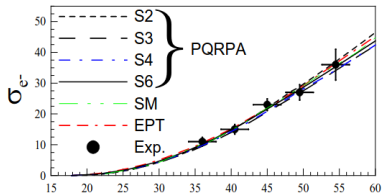
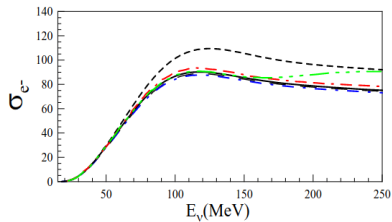
$$f(\mathbf{q}^2) = \left(\frac{F_A(q)}{F_A} \right)^2 = \left(1 - \frac{1 - \rho}{6(b|\mathbf{q}|)^2} \right)^2 \exp\left(-\frac{(b|\mathbf{q}|)^2}{2} \right), \quad (3)$$

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

$$B = \frac{2}{3} (E'_\nu E_\nu (1 - z^2) + (1 - z) \mathbf{q}^2) (1 - 2 \sin^2 \theta_W)^2 \left(\frac{F_M}{F_A} \right)^2, \quad (5)$$

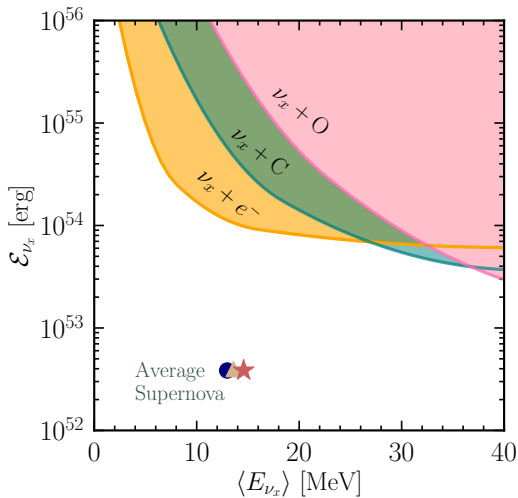
$$C = -\frac{2}{3} \Delta M (1 + z) \frac{F_T}{F_A} + \frac{1}{3} (1 + z) \mathbf{q}^2 \left(\frac{F_M}{F_A} \right)^2. \quad (6)$$

CQRPA cross sections

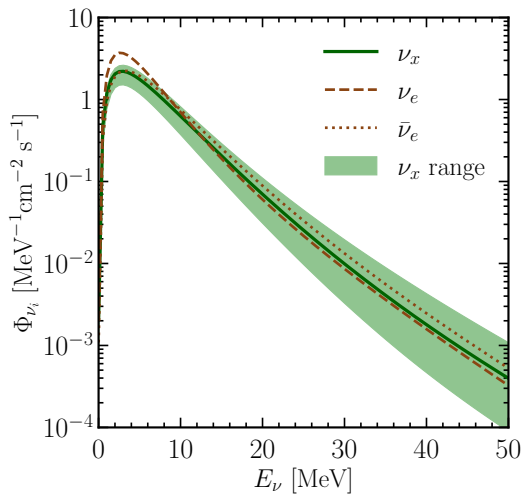


Samana et al. (2010)

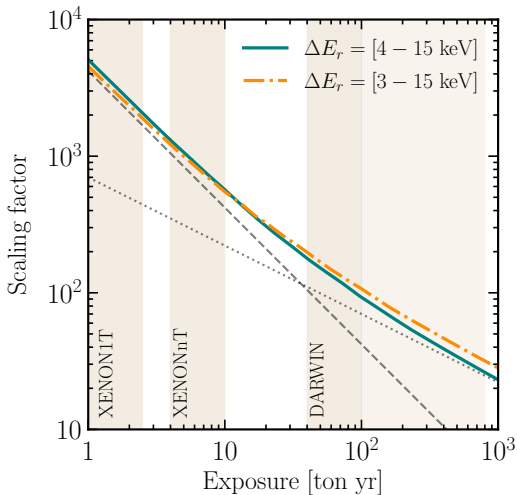
Limits from the SN 1987A



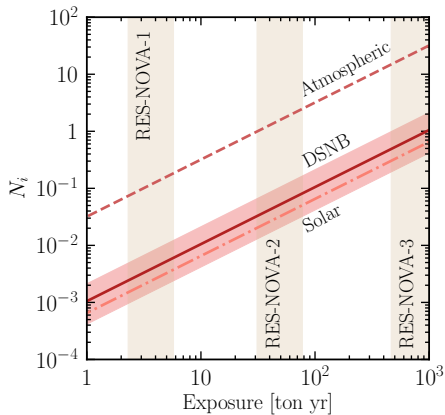
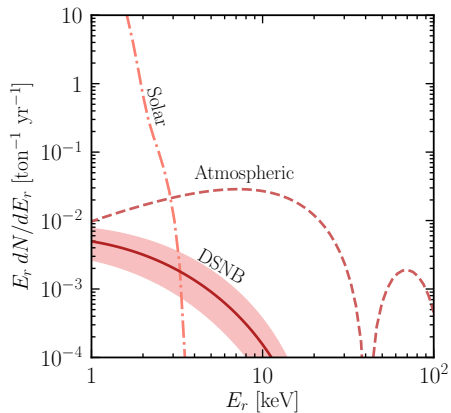
DSNB variability



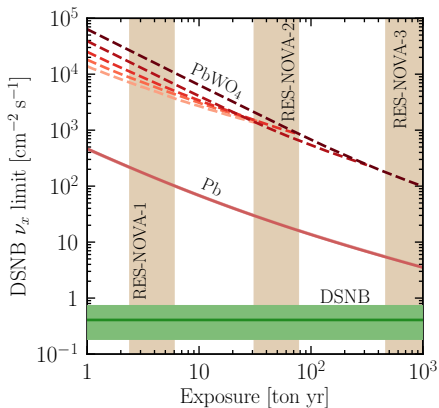
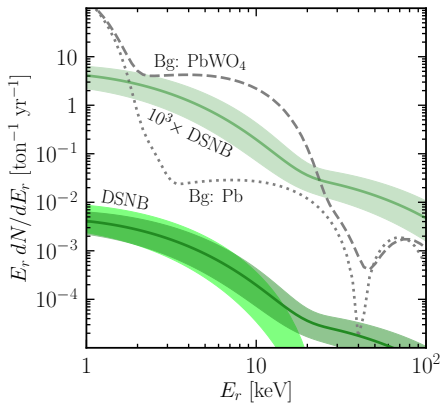
Sensitivity of the limits to a detection window



Event rate: lead detector



Event rate: lead crystals detector



Which part of the spectrum are CE ν NS detectors sensitive to?

