Core-collapse supernovae as probes of non-standard neutrino physics

Anna M. Suliga
N3AS-PFC Fellow

University of California, Berkeley
University of California, San Diego

Solving the Boltzmann Equation for Neutrino Transport in Relativistic Astrophysics
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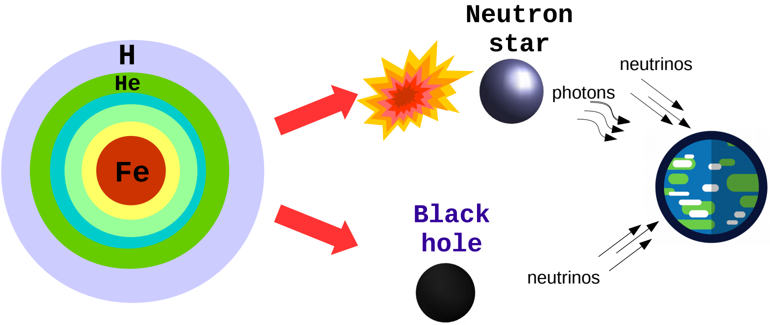
Network for Neutrinos, Nuclear Astrophysics, and Symmetries
PHYSICS FRONTIER CENTER

Why are neutrinos important for a core-collapse supernova?

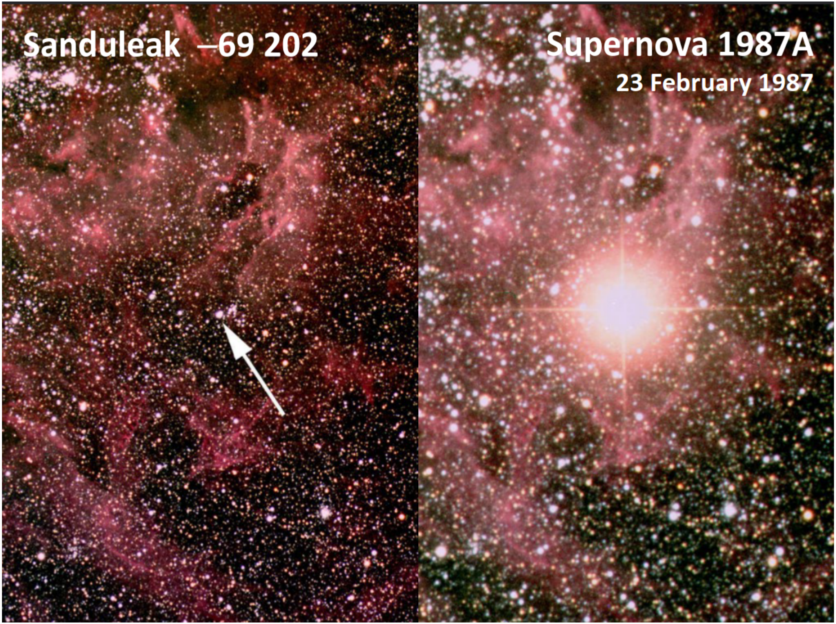
Neutrinos:

- $\sim 10^{58}$ 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 *

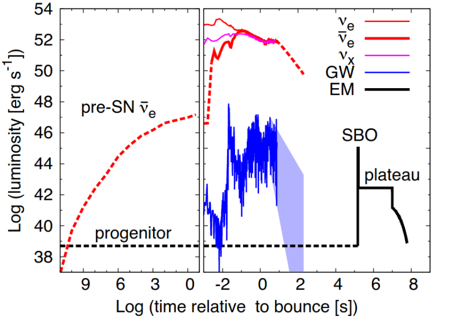


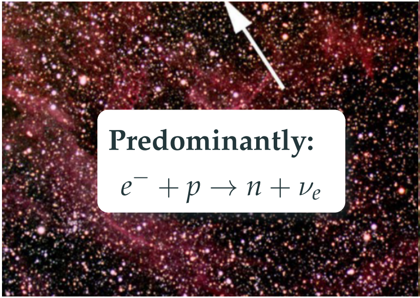
*fallback, tiny explosion

Observation of neutrinos from core-collapse supernova



Observation of neutrinos from core-collapse supernova

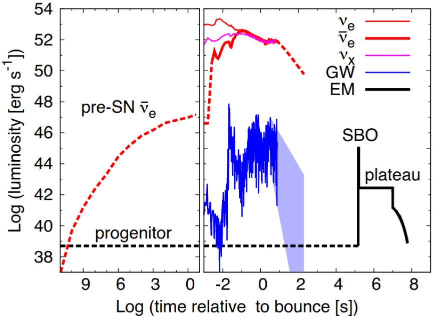


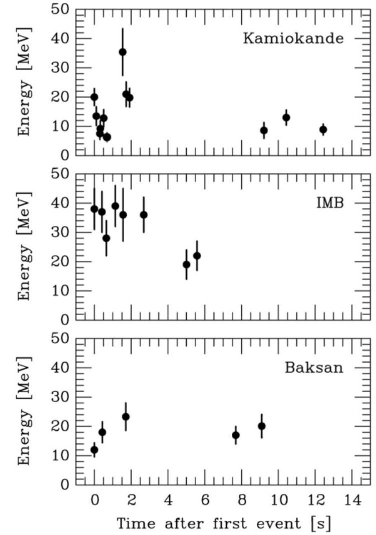


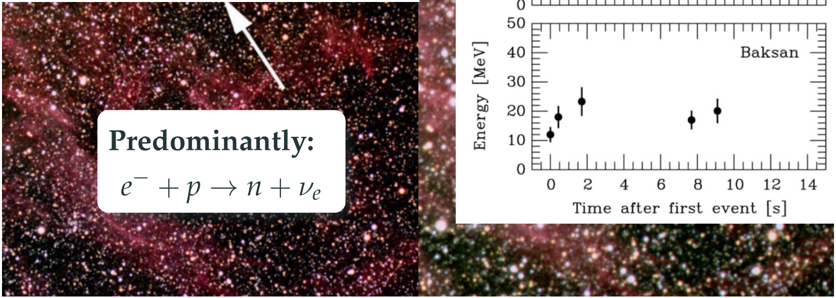
Predominantly:

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

Observation of neutrinos from core-collapse supernova







Predominantly:

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

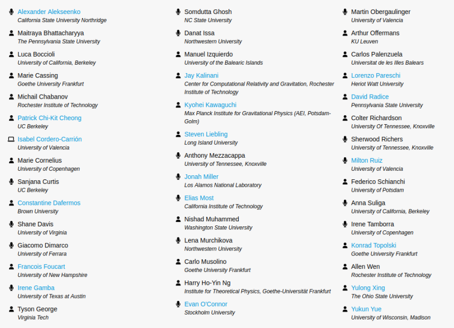
Why core-collapse supernovae are good physics probes?

Advantages

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

What can we learn with a variety of detectors?

- explosion mechanism
- nucleosynthesis
- compact object formation
- neutrino mixing
- non-standard physics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California State University Northridge
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The Pennsylvania State University
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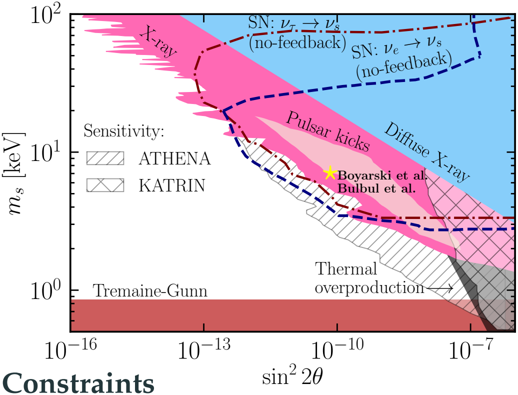
Konrad Topolski
Goethe University Frankfurt
Allen Wen
Rochester Institute of Technology
Yulong Xing
The Ohio State University
Yukun Yue
University of Wisconsin, Madison

Sterile neutrinos with keV masses in supernovae

In collaboration with I. Tamborra and M-R. Wu

JCAP 12 (2019) 019 and JCAP 08 (2020) 018

Sterile neutrino as dark matter candidate



Favorable regions

- Pulsar kicks

A. Kusenko, G. Segrè (1998),

G. Fuller, A. Kusenko, et al. (2003)

- 3.5 keV line

A. Boyarsky et al. (2014),

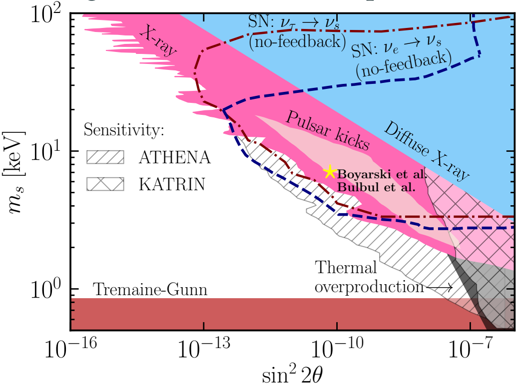
E. Bulbul et al. (2014)

Constraints

- Supernovae energy bounds (X. Shi & G.Sigl (1994)), ...
- DM overproduction (S. Dodelson, L. M. Widrow (1994), X. Shi, G. M. Fuller (1999))
- Radiative decay (NuSTAR, XMM, Chandra), K. C. Y. Ng et al. (2019), K. C. Y. Ng et al. (2015), S. Horiuchi et al. (2013)...
- Tremaine-Gunn bound (S. Tremaine, J.E. Gunn (1979))

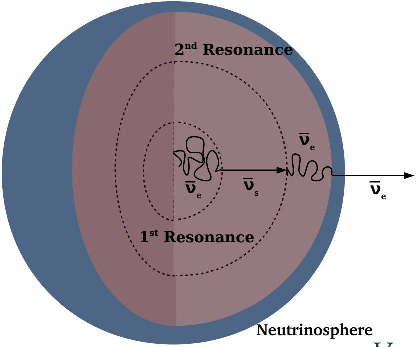
The role of sterile neutrinos in supernovae; previous studies

- Change of the electron or neutrino (ν_e, ν_μ, ν_τ) fractions
- Suppression/enhancement of the SN explosion
- Exclusion of a large fraction of the DM parameter space



Raffelt & Sigl (1992), Shi & Sigl (1994), Nunokawa et al. (1997), Hidaka & Fuller (2006), Hidaka & Fuller (2007), Raffelt & Zhou (2011), Warren et al. (2014), Argüelles et al. (2016), **Suliga**, Tamborra, Wu (2019, 2020), Syvolap et al. (2019), Ray, Qian (2023, 2024)

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

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

$\nu_e - \nu_s$ 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)...

Sterile neutrino conversions in the stellar core

Collisional production

$$\langle P_{\nu_{\rm active}\to\nu_s}(E)\rangle \approx \frac{1}{2}\frac{\sin^2 2\theta}{(\cos 2\theta - 2V_{\rm eff}E/m_s^2)^2 + \sin 2\theta^2 + D^2}$$

$$\Gamma_{\nu_{\rm active}}(E) \simeq n(r)\sigma(E,r)$$

$$D = \frac{E\Gamma_{\nu_{\rm active}}(E)}{m_s^2}$$

C. W. Kim et al. (1987), S. J. Parke (1987), S. P. Mikheev and A. Yu. Smirnov (2007)

Sterile neutrino conversions in the stellar core

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$$\Gamma_{\nu_{\rm active}}(E) \simeq n(r)\sigma(E,r)$$

$$D = \frac{E\Gamma_{\nu_{\rm active}}(E)}{m_s^2}$$

MSW production

$$P_{\nu_{\rm active}\to\nu_s}(E_{\rm res}) = 1 - \exp\left(-\frac{\pi^2}{2}\gamma\right), \gamma = \Delta_{\rm res}/l_{\rm osc}$$

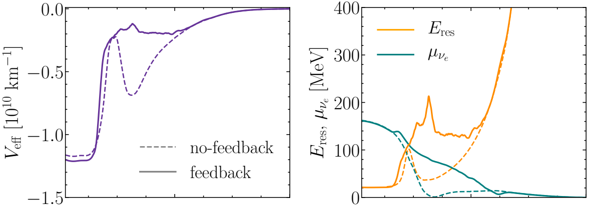
$$\Delta_{\rm res} = \tan 2\theta \left|\frac{dV_{\rm eff}/dr}{V_{\rm eff}}\right|^{-1}$$

$$l_{\rm osc}(E_{\rm res}) = (2\pi E_{\rm res})/(m_s^2 \sin 2\theta)$$

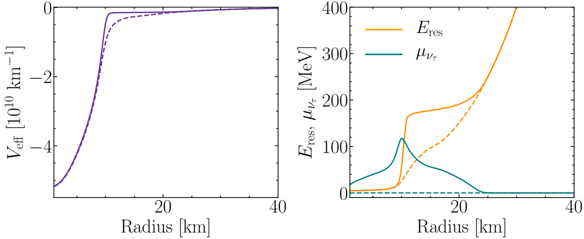
C. W. Kim et al. (1987), S. J. Parke (1987), S. P. Mikheev and A. Yu. Smirnov (2007)

Sterile neutrino conversions in the stellar core

$\nu_s - \nu_e$ mixing: multiple resonances



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



1D SN model
Garching group archive

$$E_{\rm res} = \frac{\cos 2\theta \Delta m_s^2}{2V_{\rm eff}}$$

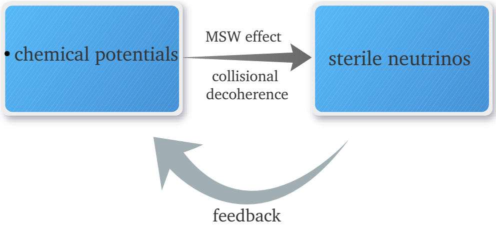
$m_s = 10$ keV,
$\sin^2 2\theta = 10^{-8}$

- **Negative $V_{\rm eff} \to$ MSW resonances only for antineutrinos.**
- **Growing chemical potential slows down $\bar{\nu}_s$ production.**

The sterile-tau neutrino mixing: growth of the asymmetry

Only active neutrinos

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



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

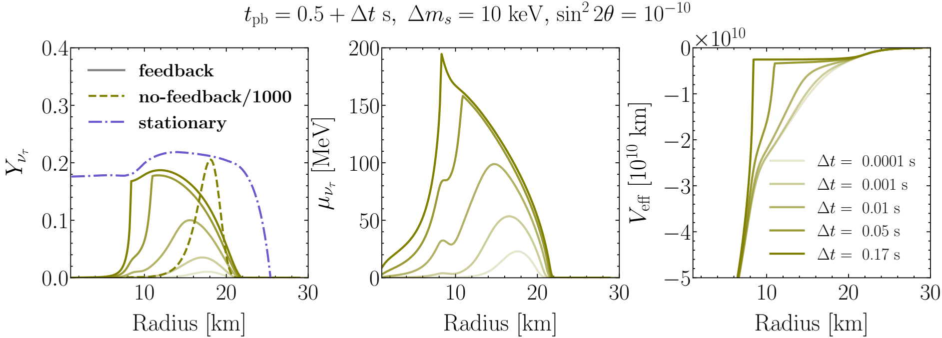
since they were **strongly coupled** to the rest of the particles in the medium, a **new equilibrium state forms.**

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

Active + sterile neutrinos

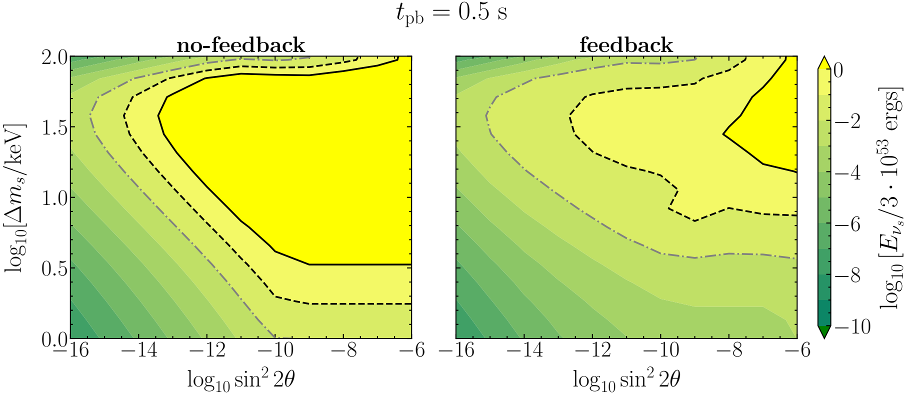
$$Y_{\nu_\tau}(r,t) = \frac{1}{n_b(r)} \int_0^t dt' \, \frac{d\left(P_{\nu_\tau \to \nu_s} n_{\nu_\tau}(r,t') - P_{\bar{\nu}_\tau \to \bar{\nu}_s} n_{\bar{\nu}_\tau}(r,t')\right)}{dt'}$$

Radial evolution of the asymmetry w and w/o feedback



- Feedback inhibits Y_{ν_τ} from unphysical growth.
- The ν_τ chemical potential grows significantly.

Supernova bounds on the mixing parameters



- The inclusion of feedback greatly reduces the excluded region.
- Large region of the parameter space still compatible with SNe

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

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

Baryon number conservation

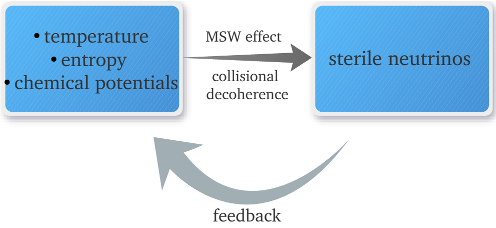
$$Y_p(r,t) + Y_n(r,t) = 1 \, ,$$

Charge conservation

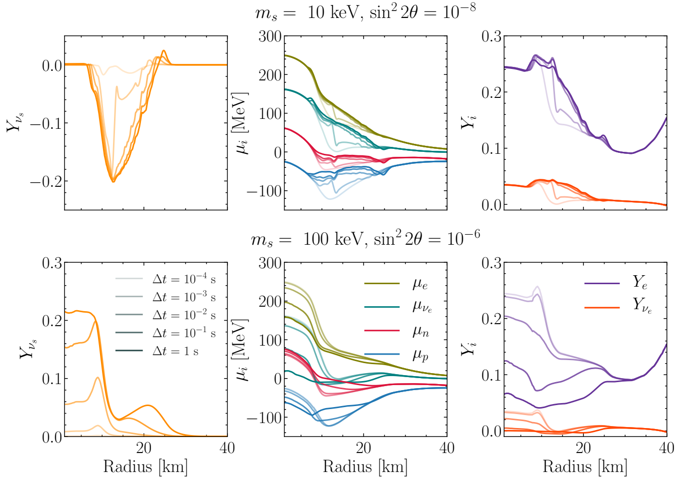
$$Y_p(r,t) = Y_e(r,t) \, ,$$

Entropy change

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

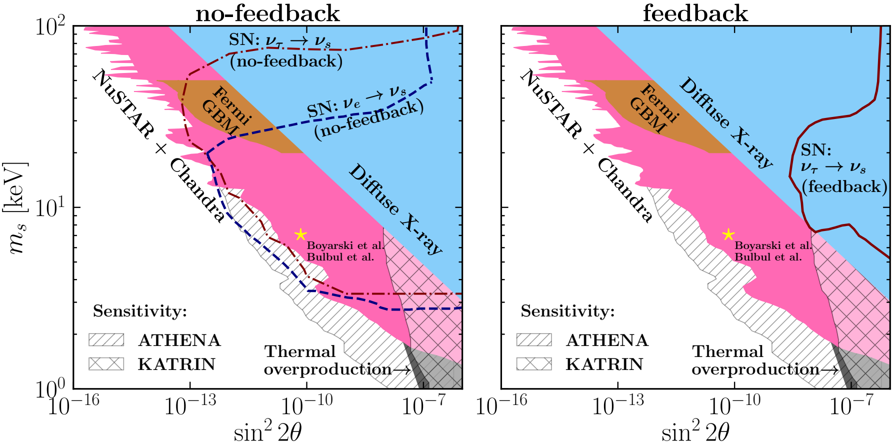


Radial evolution of the asymmetry



- Sterile neutrinos modify Y_e, Y_{ν_e}, Y_p and Y_n.
- Feedback on the physical quantities depends greatly on the m_s.

Supernova bounds on the mixing parameters



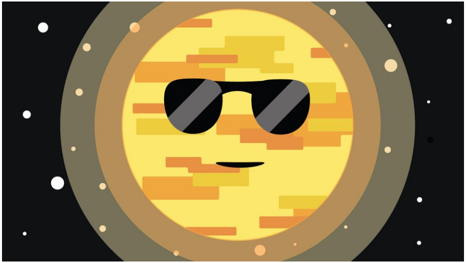
- **The inclusion of feedback greatly reduces the excluded region.**
- **CC-SNe cannot exclude any region of the DM parameter space.**

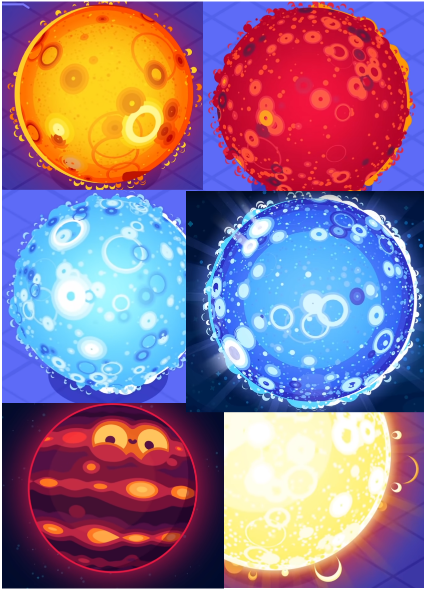
Probing self-interacting sterile neutrino dark matter with the DSNB

In collaboration with B. Balantekin, G. Fuller, and A. Ray

Phys.Rev.D in 108 (2023) 12, 123011

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

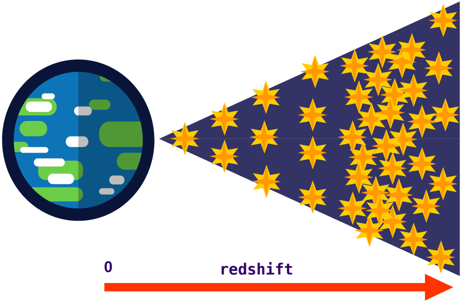
$$\Phi_{\nu_\beta}(E) = \frac{c}{H_0}\int dM \int dz \frac{R_{\rm SN}(z,M)}{\sqrt{\Omega_M(1+z)^3+\Omega_\Lambda}}\left[f_{\rm CC-SN}F_{\nu_\beta,{\rm CC-SN}}(E',M) + f_{\rm BH-SN}F_{\nu_\beta,{\rm BH-SN}}(E',M)\right]$$

fraction of neutron-star-forming progenitors

neutrino flux from a single star

The DSNB is sensitive to:

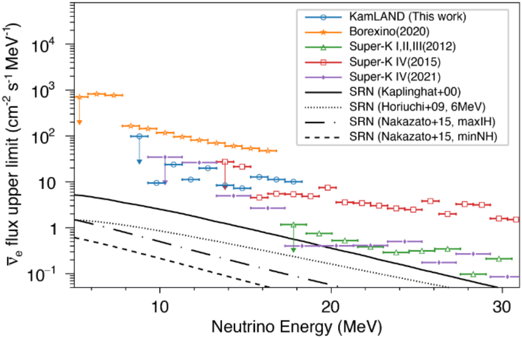
- $R_{\rm SN}, f_{\rm BH-SN}$
- neutrino flavor evolution
- equation of state
- mass accretion rate in BH-SN
- non-standard physics



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:

- $\bar{\nu}_e \approx 2.7\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}$ 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)

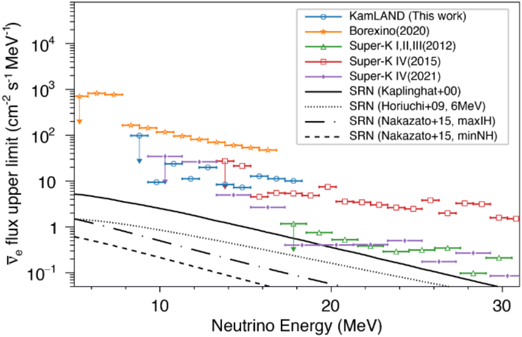
- $\nu_e \approx 19\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}$ for $E_\nu \epsilon\ [22.9, 36.9\ \mathrm{MeV}]$ SNO collab. (2020)

  possibly detectable by DUNE Møller, **AMS**, Tamborra, Denton (2018), Zhu et al. (2019)

- $\nu_x \approx 750\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}$ for $E_\nu > 19.3$ MeV Lunardini, Pestes (2008)

Diffuse supernova neutrino background: current limits

SK collab. (2021)



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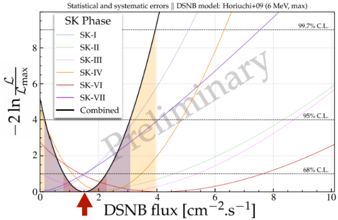
  possibly detectable by DUNE Møller, **AMS**, Tamborra, Denton (2018), Zhu et al. (2019)
- $\nu_x \lesssim 100\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}$ for $E_\nu > 19.3$ MeV **AMS**, Beacom, Tamborra (2021)

Tension from zero assumption

Spectral-fitting analysis

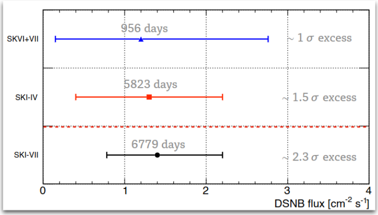
Spectrum fitting analysis to extract significance

- Total 6779 days of SK (5823 d pure-water and 956 d Gd-water) combined
- Analysis threshold: $E_\nu > 17.3$ MeV
- Suppress uncertainty of background prediction by fitting both N_n=1, $N_n \neq 1$



Best fit: 1.4

(Rogly, poster 79)



Highlight:

- Sensitivity of SK-Gd ~1000 days exposure is already comparable level it with ~6000 days of pure-water SK
- Best fit of whole SK observation is **$1.4^{+0.8}_{-0.6}$ cm^{-2} s^{-1}** for $E_\nu > 17.3$ MeV

➡ **exhibit ~2.3 σ excess!!**

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Slide credit: Masayuki Harada talk at Neutrino 2024

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)

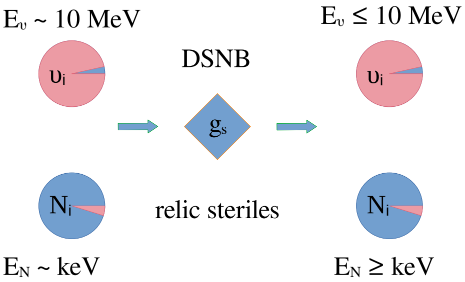
- Fraction of Black-Hole-Forming Progenitors

  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



Resonant interaction for sterile neutrinos

$$\mathcal{L}^{\phi} = g_s \phi \nu_s \nu_s$$

$$\sigma(E_\nu) = \frac{g_s^4}{4\pi} \frac{s}{(s - m_\phi^2)^2 + m_\phi^4 \Gamma_\phi^2} \approx \frac{\pi g_s^2}{m_\phi^2} E_\nu \delta(E_R - E_\nu), \text{ where } E_R = m_\phi^2 / 2m_s$$

- sterile component in the DSNB ν_i interacts with the mostly sterile relic background of N_i

bigger parameter space for keV serile neutrino dark matter with self-interactions:
Maria D. Astros and S. Vogl (2023), T. Bringmann et al. (2022)

Modeling secret neutrino interactions in DSNB

Modified DSNB flux

$$\phi_\alpha(E_\nu) \simeq \sum_{i=1}^{3} |U_{\alpha i}|^2 \int_0^{z_{\max}} dz\, \frac{P_i(E_\nu, z)}{H(z)} \times\ R_{\rm SN}(z)\, F^i_{\rm SN}\,(E_\nu(1+z))$$

Probability of interaction

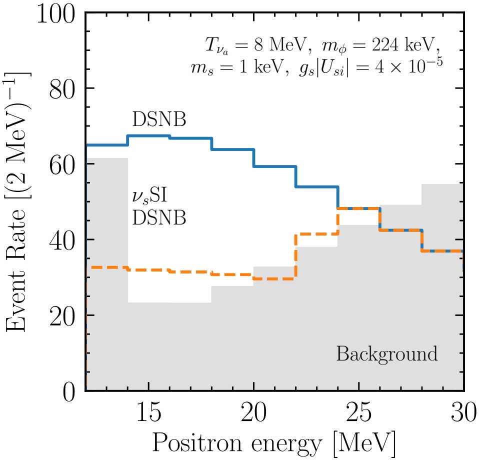
$$P_i(E_\nu, z) = e^{-\tau_i(E_\nu, z)}$$

$$\tau_i(E_\nu, z) \simeq \tau_R \Theta(z - z_R) = \frac{\Gamma_R(z_R)}{(1+z_R)H(z_R)}\Theta(z - z_R)$$

where $z_R = E_R/E_\nu - 1$,
interaction rate $\Gamma_R(z_R) \simeq |U_{si}|^2 n_{\nu_s}(z_R)\sigma_R$,
and sterile neutrino number density $n_{\nu_s}(z_R) = n_{\nu_s}(1+z_R)^3$

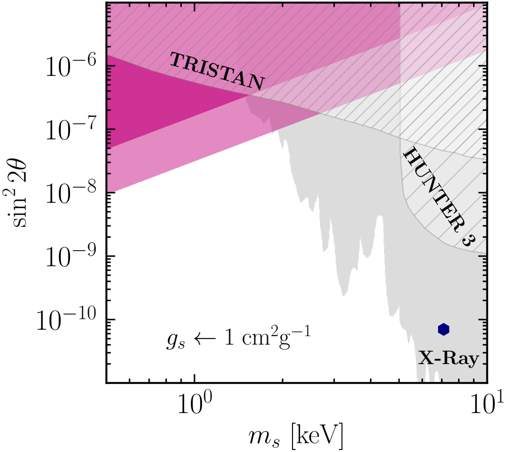
smilar studies for active neutrino self-interactions and eV-mass sterile neutrinos:
Goldberg et al. (2005), Baker et al. (2007), Farzan, Palomares-Ruiz (2014), Reno et al. (2018), Creque-Sarbinowski et al. (2021)

Secret neutrino interactions: DSNB



- **Sterile neutrino self-interactions may result in features in DSNB**

Sensitivity limits



- **Overalap with the TRISTAN experiment paramater space**
- **Reduction of the astrophysical uncertainties helps but not by a lot**

Conclusions

Core-collapse supernovae

- can serve as powerful testing grounds in constraining standard and 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 probe potential new physics scenarios

Exciting times ahead

Thank you for the attention!

Backup

Partial Derivatives for the Fermi-Dirac distributions

The partial derivatives for the Fermi-Dirac distributions are given by EscuderoAbenza (2020)

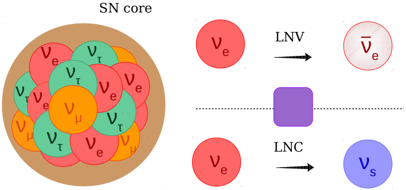
$$\frac{\partial n}{\partial T} = \frac{g}{2\pi^2} \int_m^\infty dE\, E\sqrt{E^2 - m^2}\, \frac{(E-\mu)}{4T^2} \cosh^{-2}\left(\frac{E-\mu}{2T}\right), \quad (1a)$$

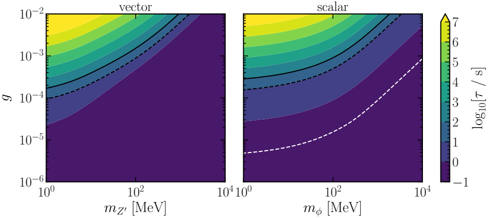
$$\frac{\partial \rho}{\partial T} = \frac{g}{2\pi^2} \int_m^\infty dE\, E^2\sqrt{E^2 - m^2}\, \frac{(E-\mu)}{4T^2} \cosh^{-2}\left(\frac{E-\mu}{2T}\right), \quad (1b)$$

$$\frac{\partial n}{\partial \mu} = \frac{g}{2\pi^2} \int_m^\infty dE\, E\sqrt{E^2 - m^2} \left[2T\cosh\left(\frac{E-\mu}{T}\right) + 2T\right]^{-1}, \quad (1c)$$

$$\frac{\partial \rho}{\partial \mu} = \frac{g}{2\pi^2} \int_m^\infty dE\, E^2\sqrt{E^2 - m^2} \left[2T\cosh\left(\frac{E-\mu}{T}\right) + 2T\right]^{-1} \quad (1d)$$

Non-standard coherent scattering in the supernova core

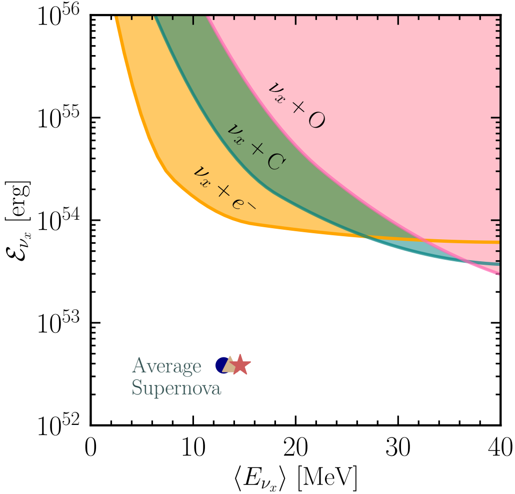




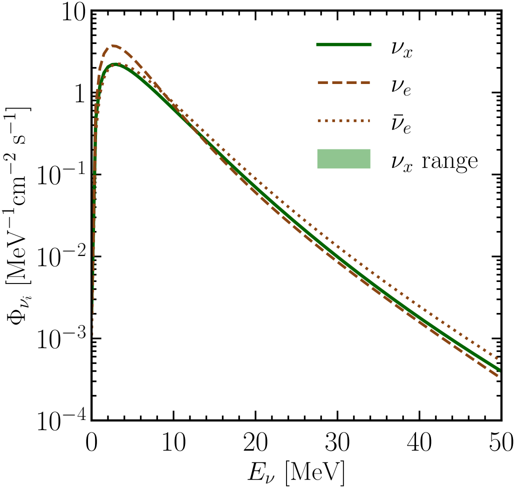
- prolonged diffusion time → possible change in the star's fate
- prolonged diffusion time → changed duration of the neutrino signal
- LNC scalar mediator → new cooling channel due to ν_R

Kolb & Turner (1987), Fuller et al. (1988) Farzan et al.(2018), Heurtier & Zhang (2016), Shalgar et al. (2019), AMS & Tamborra (2020), Reddy & Zhou(2021)

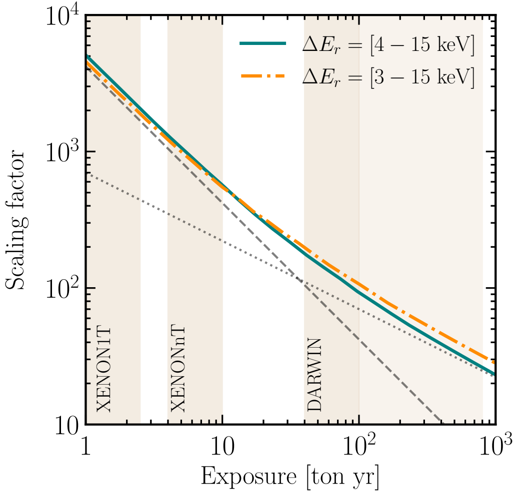
Limits from the SN 1987A



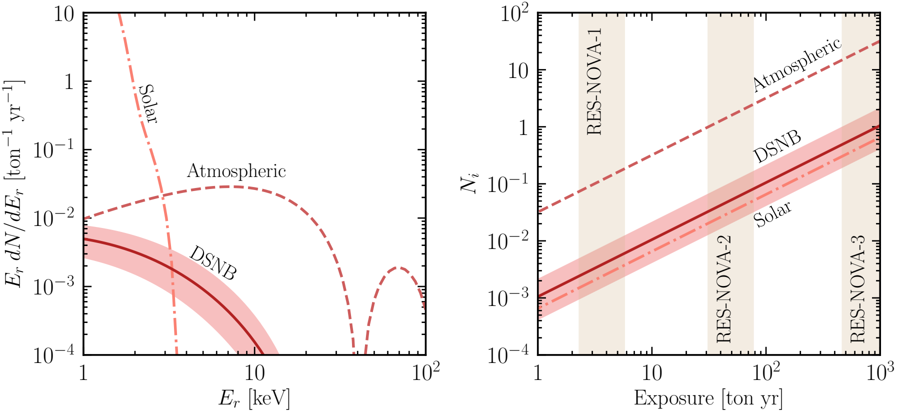
DSNB variability



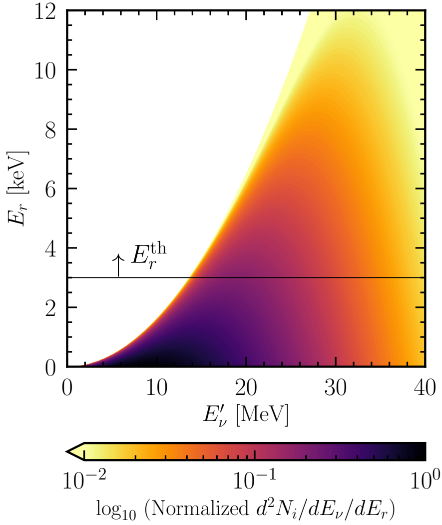
Sensitivity of the limits to a detection window



Event rate: lead detector

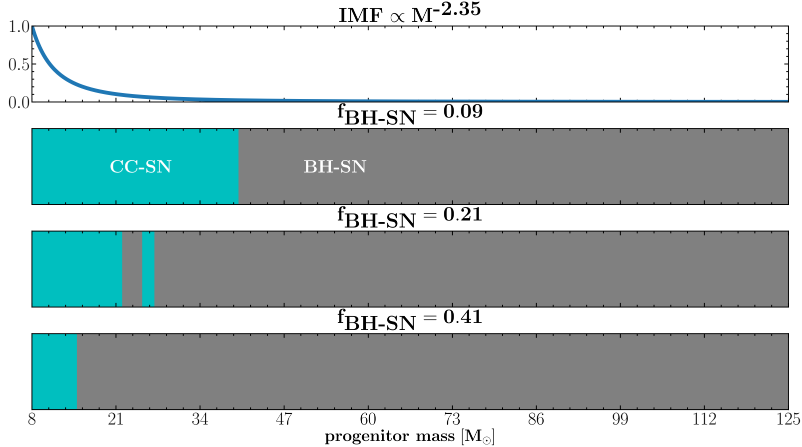


Which part of the spectrum are CEνNS detectors sensitive to?



Astrophysical uncertainties

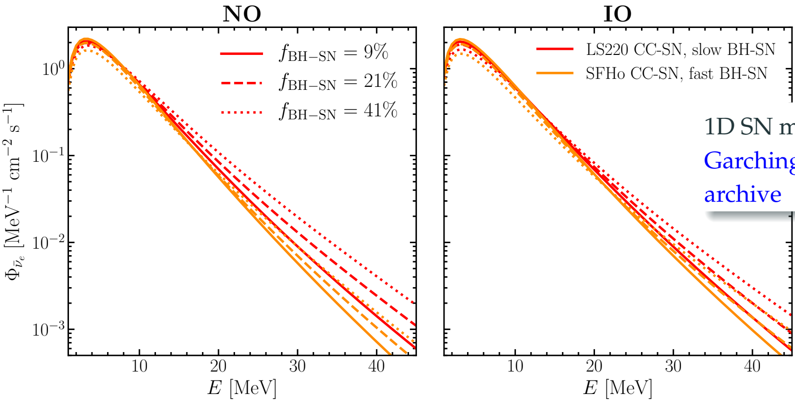
The fraction of black-hole-forming progenitors



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

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

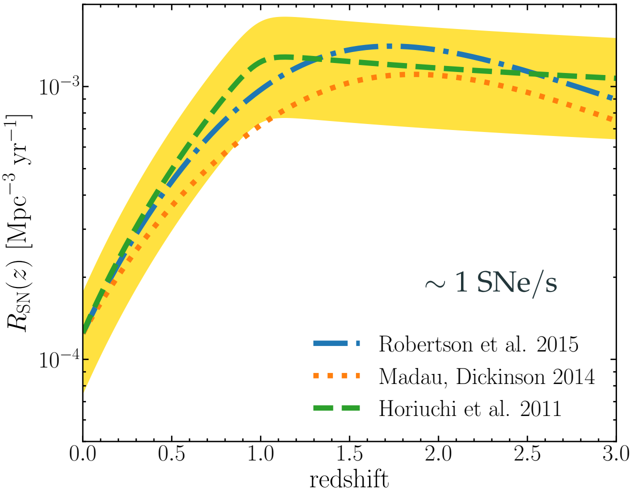


1D SN models
Garching group archive

Fraction of black-hole-forming progenitors influences the highly energetic part of the DSNB, above ~ 15 MeV. Lunardini (2009)

Lunardini (2009), Keehn, Lunardini (2010), Lunardini, Tamborra (2012), Priya, Lunardini (2017), Møller, AMS, Tamborra, Denton (2018), Nakazato et al. (2018) Kresse et al. (2020), ...

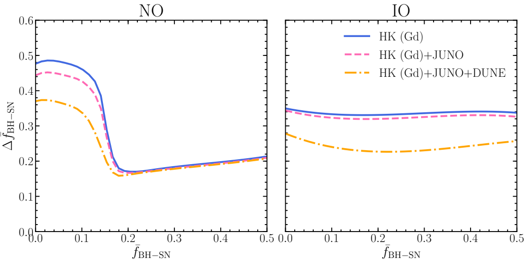
Cosmological supernovae rate



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), ...

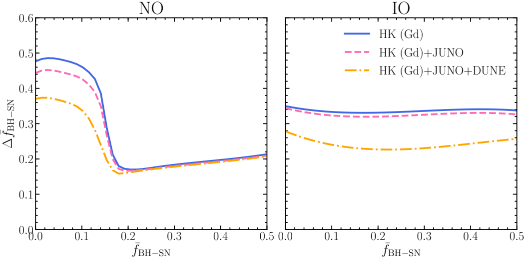
Expected 1σ uncertainty: fraction of BH forming progenitors



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

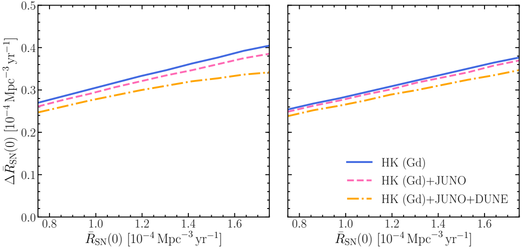
Møller, AMS, Tamborra, Denton (2018)

Expected 1σ uncertainty: local supernova rate



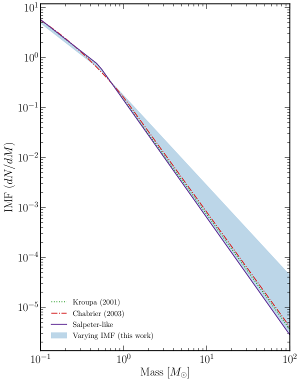
- The high uncertainty comes from $f_{\mathrm{BH-SN}}$–mass accretion rate degeneracy
- DUNE is sensitive to neutrinos $\rightarrow$ helps to reduce the uncertainty

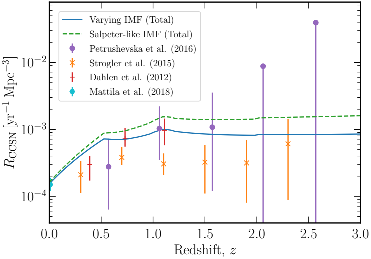
- Relative error of 20%-33% independent of the mass ordering.

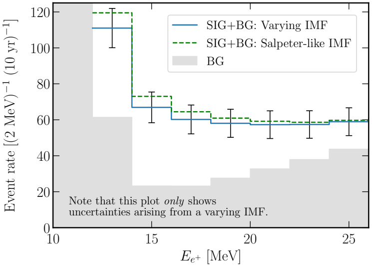


Møller, AMS, Tamborra, Denton (2018)

Varying Initial Mass Function







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

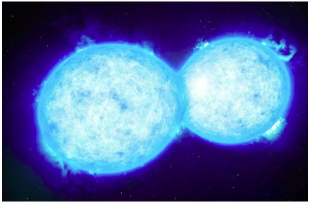
Ziegler, Edwards, AMS, Tamborra, Horiuchi, Ando, Freese (2022)

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

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Mass transfer

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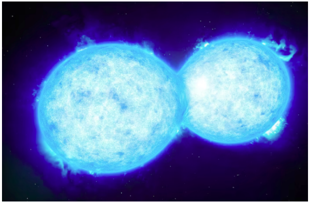
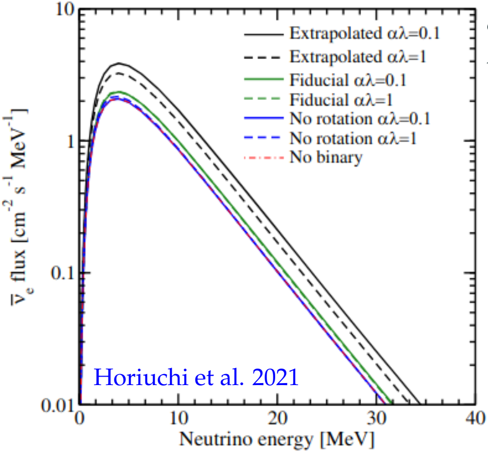


Effects on the stellar population Horiuchi et al. 2021

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

Images: iflscience, Wiki

Binary interactions: impact on DSNB

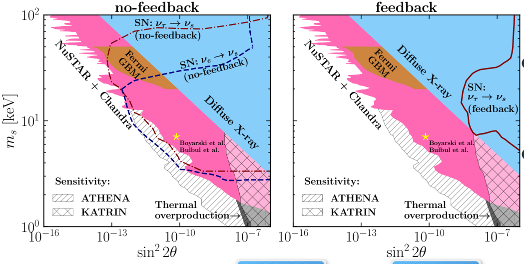


$\alpha\lambda$ - measure how hard it is to unbind the envelope

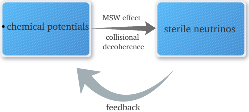
- enhancement $\leqslant$ 75% compared to estimate w/o binary considerations
- core mass increases due to rotational effects
- more studies needed

BSM impacting neutrinos inside CCSN

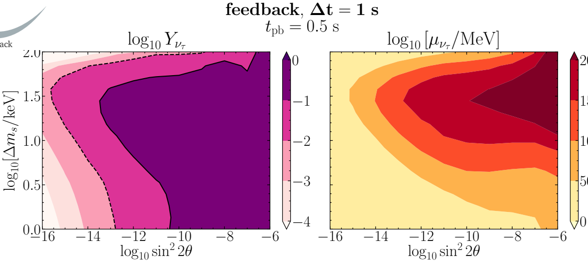
KeV sterile neutrinos



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

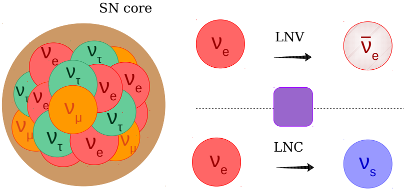


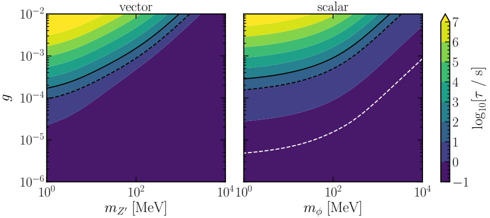
- The inclusion of feedback: growth of asymmetries
- Neutrino spectrum affected



Raffelt & Sigl (1992), Shi & Sigl (1994), Nunokawa et al. (1997), Abazajian et al. (2001), Hidaka & Fuller (2006), Hidaka & Fuller (2007), Raffelt & Zhou (2011), Warren et al. (2014), Argüelles et al. (2016), AMS et al. (2019, 2020), Syvolap et al. (2019), Ray & Qian (2023)

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

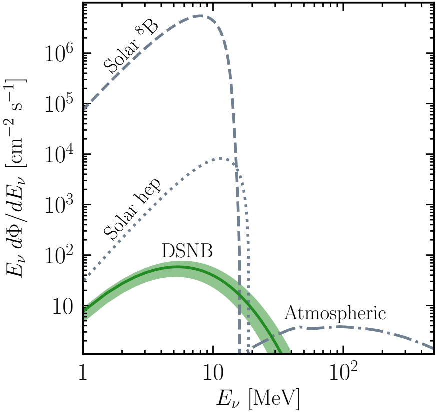
Kolb & Turner (1987), Fuller et al. (1988) Farzan et al.(2018), Heurtier & Zhang (2016), Shalgar et al. (2019), AMS & Tamborra (2020), Reddy & Zhou(2021)

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

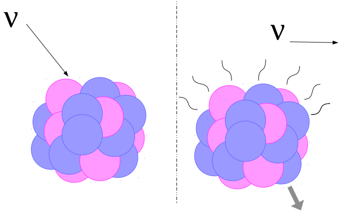


DSNB modeling:
Møller, AMS, Tamborra, Denton (2018)

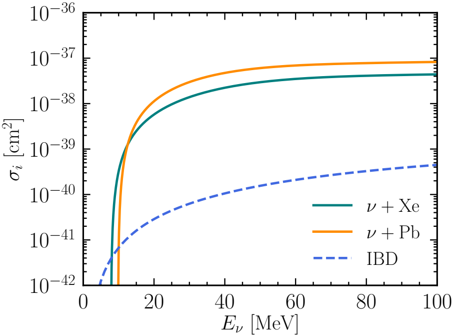
- Favor-blind channel: potential detection window $\sim 18 - 30$ MeV
- Current limit: $\nu_x \approx 750$ cm^{-2} s^{-1} for $E_\nu > 19.3$ MeV Lunardini, Peres (2008)

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

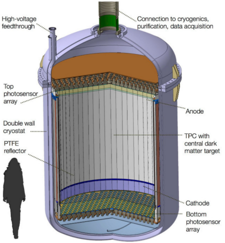
$$\frac{d\sigma_{\rm SM}}{dE_r} = \frac{G_F^2 m_T}{4\pi} Q_w^2 \left(1 - \frac{m_T E_r}{2E_\nu^2}\right) F^2(Q), \;\; Q_w = \left[N - Z(1 - 4\sin^2\theta_W)\right]$$

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

Freedman (1974)

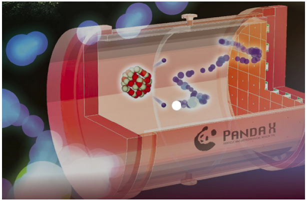
Current and future CEνNS detectors

XENONnT, DARWIN



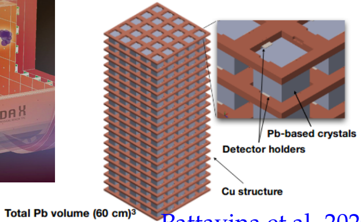
Aalbers al. 2016

PandaX-4T, PandaX-xT



Menget al. 2021

RES-NOVA



Pattavina et al. 2020

fiducial volumes: few - hundreds ton

target materials: Xe, Pb

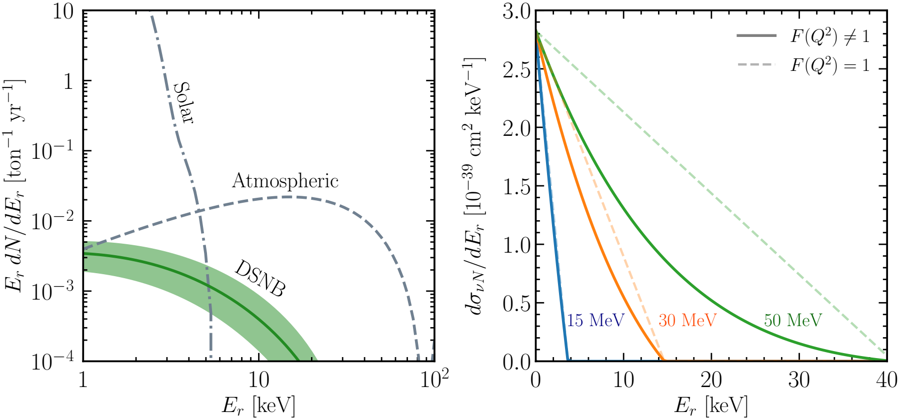
thresholds: $\mathcal{O}(1)$ keV

efficiency: $\sim$ 80-100%

Scattering rate

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

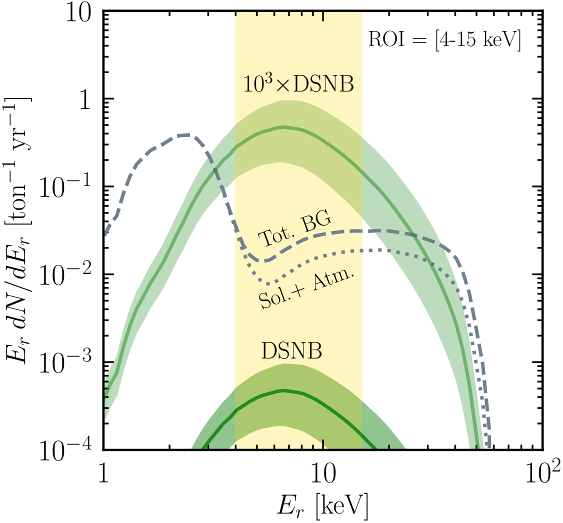
Event rate in the xenon-based detector



- 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?

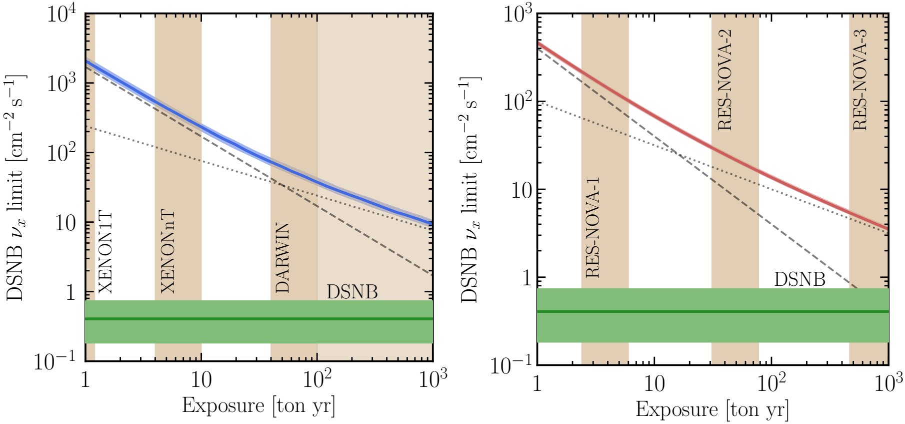
YES: Scaled event rate in the xenon-based detector



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

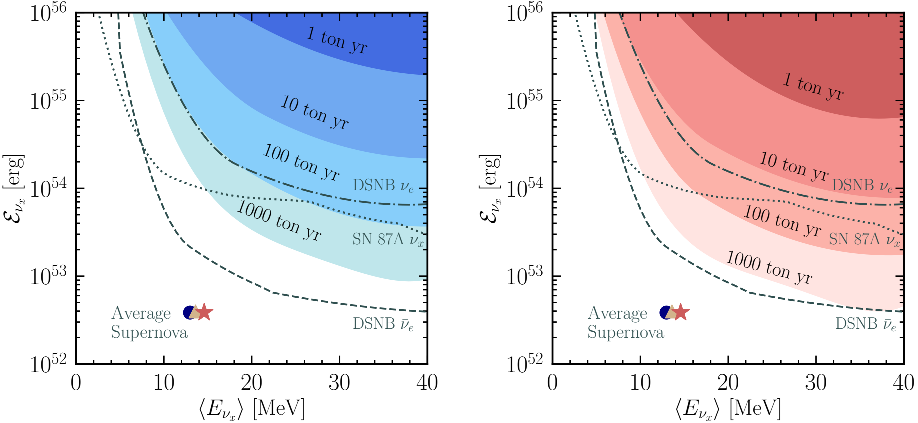
Sensitivity bounds on the x-flavor DSNB

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