Probing self-interacting sterile neutrino dark matter with the diffuse supernova neutrino background

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July 5, 2024

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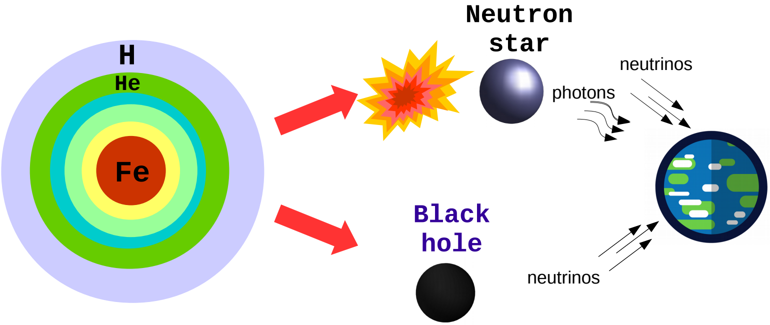
PHYSICS FRONTIER CENTER

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



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?

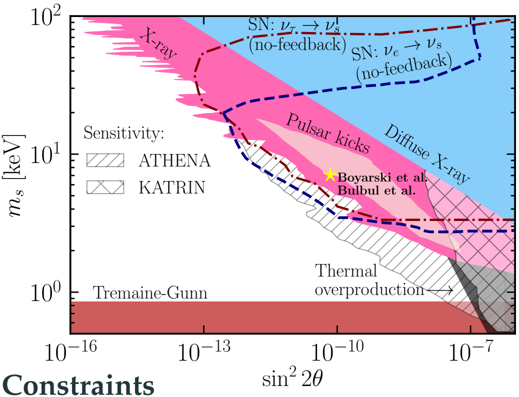
- explosion mechanism — Bethe & Wilson (1985), Fischer et al. (2011)...
- nucleosynthesis — Woosley et al. (1994), Surman & McLaughlin (2003)...
- compact object formation — Warren et al. (2019), Li, Beacom et al. (2020)...
- neutrino mixing — Balantekin & Fuller (2013), Tamborra & Shalgar (2020)...
- non-standard physics — McLaughlin et al. (1999), de Gouvêa et al. (2019) ...

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),

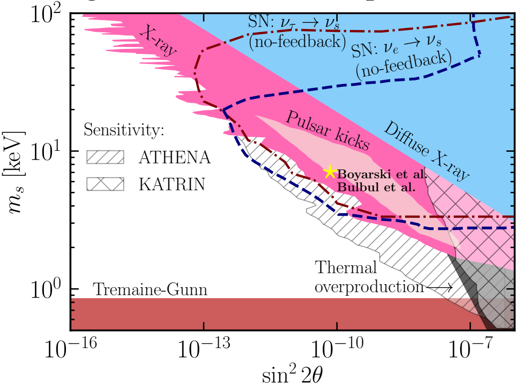
E. Bulbul et al. (2014)

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))

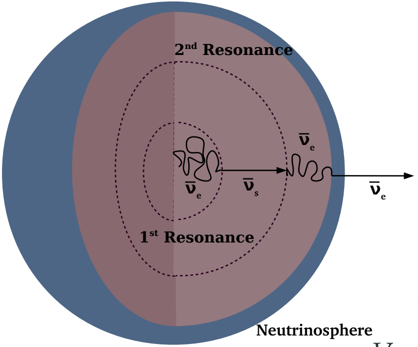
The role of sterile neutrinos in supernovae; previous studies

- 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

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

Collisions

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

$\nu_e - \nu_s$ mixing: multiple resonances

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

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

Sterile neutrino conversions in the stellar core

Collisional production

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

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

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

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

Collisional production

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

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

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

MSW production

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

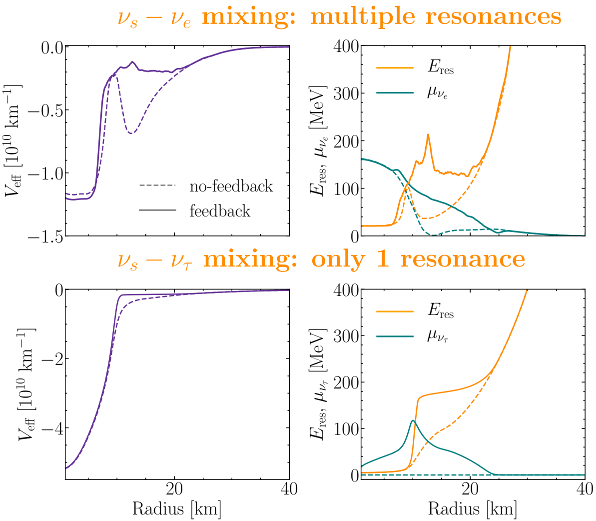
$$\Delta_{\text{res}} = \tan 2\theta \left|\frac{dV_{\text{eff}}/dr}{V_{\text{eff}}}\right|^{-1}$$

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

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**



1D SN model
Garching group archive

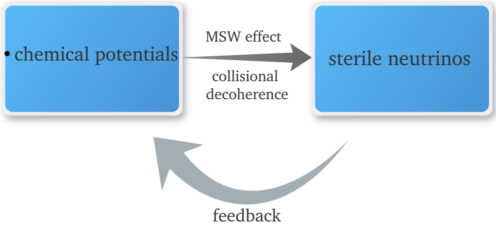
$$E_{\rm res} = \frac{\cos 2\theta \Delta m_s^2}{2V_{\rm eff}}$$

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

- **Negative $V_{\rm eff} \rightarrow$ 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;**

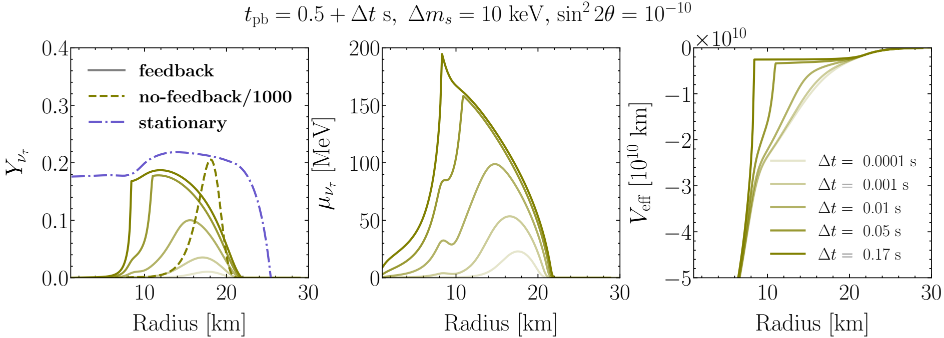
since they were **strongly coupled** to the rest of the particles in the medium, a **new equilibrium state forms.**

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

Active + sterile neutrinos

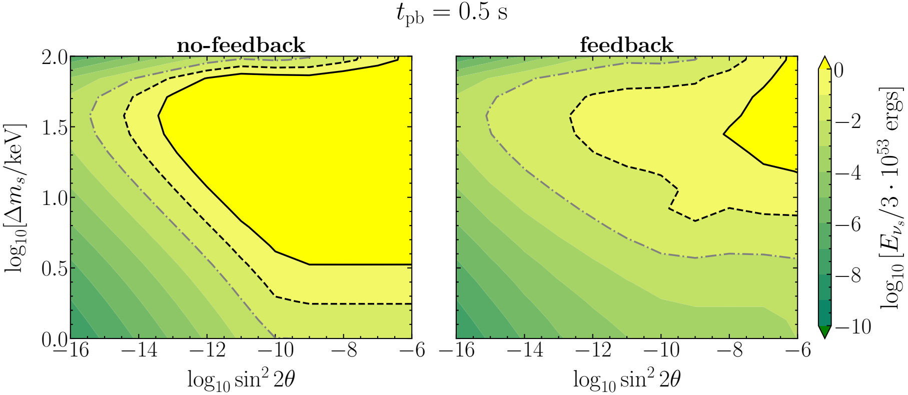
$$Y_{\nu_\tau}(r,t) = \frac{1}{n_b(r)} \int_0^t dt' \, \frac{d\left(P_{\nu_\tau \to \nu_s} n_{\nu_\tau}(r,t') - P_{\bar{\nu}_\tau \to \bar{\nu}_s} n_{\bar{\nu}_\tau}(r,t')\right)}{dt'}$$

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

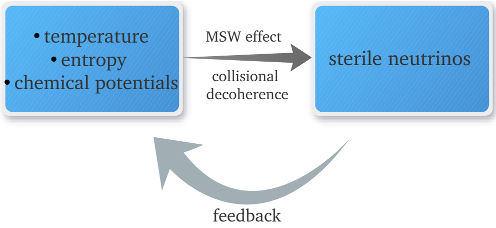
$$Y_p(r,t)+Y_n(r,t)=1\;,$$

Charge conservation

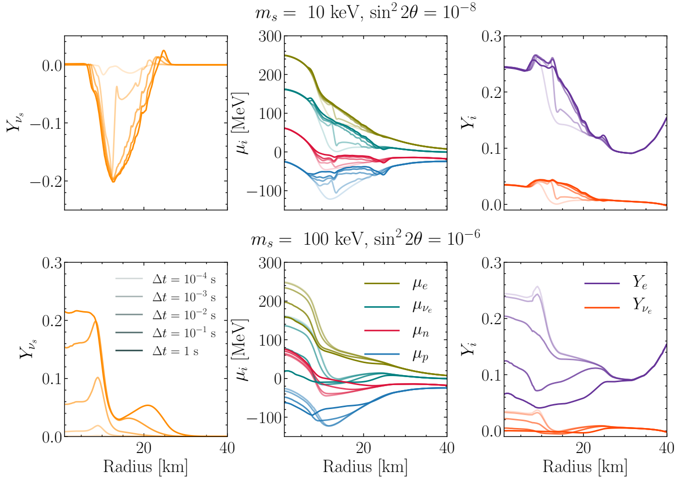
$$Y_p(r,t)=Y_e(r,t)\;,$$

Entropy change

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

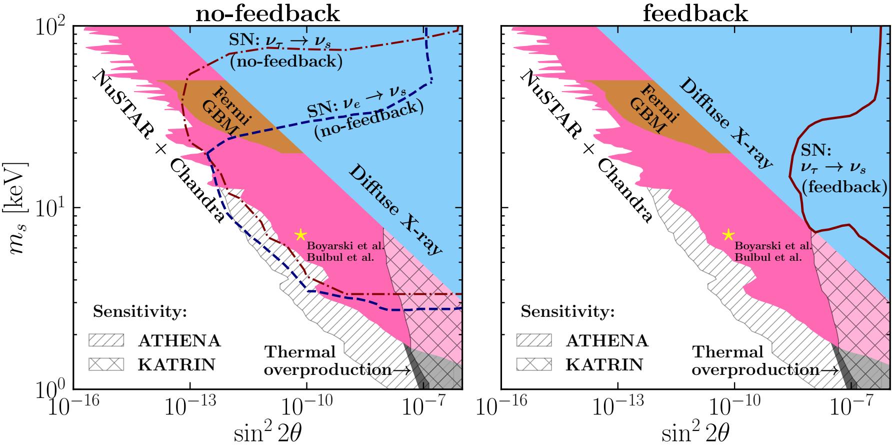


Radial evolution of the asymmetry



- 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



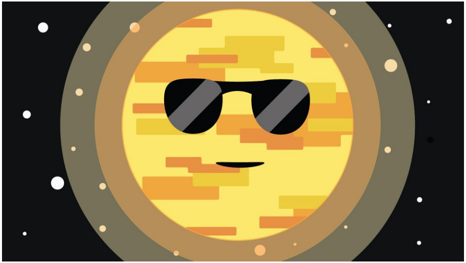
- **The inclusion of feedback greatly reduces the excluded region.**
- **CC-SNe cannot exclude any region of the DM parameter space.**

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?

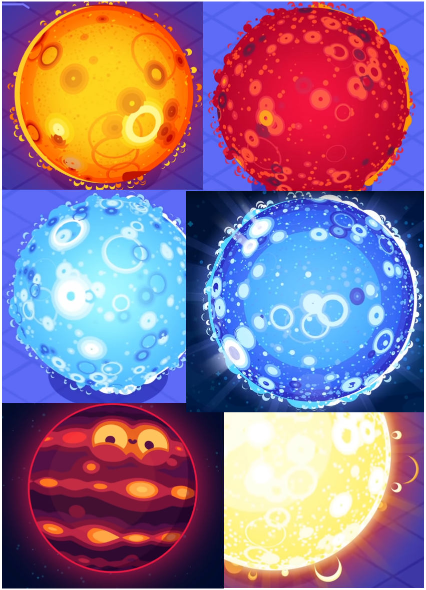


Single galactic SN event

- 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

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

cosmological supernovae rate

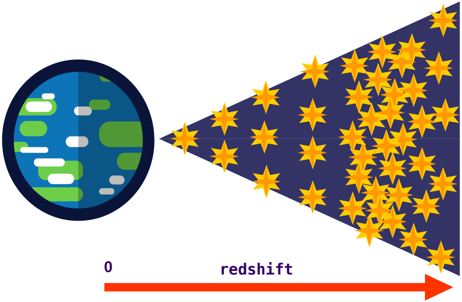
fraction of black-hole-forming progenitors

fraction of neutron-star-forming progenitors

neutrino flux from a single star

The DSNB is sensitive to:

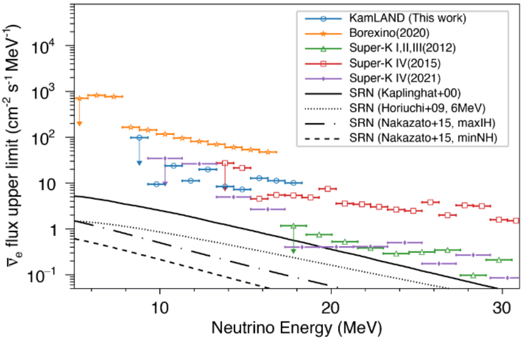
- $R_{\rm SN}, f_{\rm BH-SN}$
- neutrino flavor evolution
- equation of state
- mass accretion rate in BH-SN
- non-standard physics



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

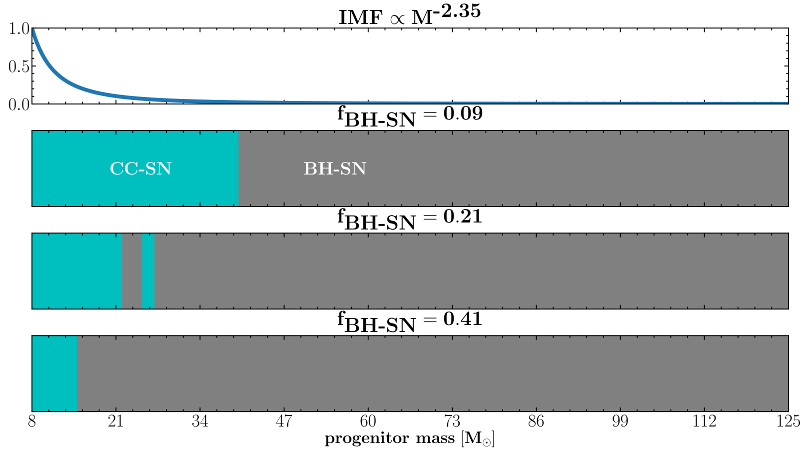
SK collab. (2021)



DSNB limits:

- $\bar{\nu}_e \approx 3\ \text{cm}^{-2}\ \text{s}^{-1}$ 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)
- $\nu_e \approx 19\ \text{cm}^{-2}\ \text{s}^{-1}$ 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)

The fraction of black-hole-forming progenitors

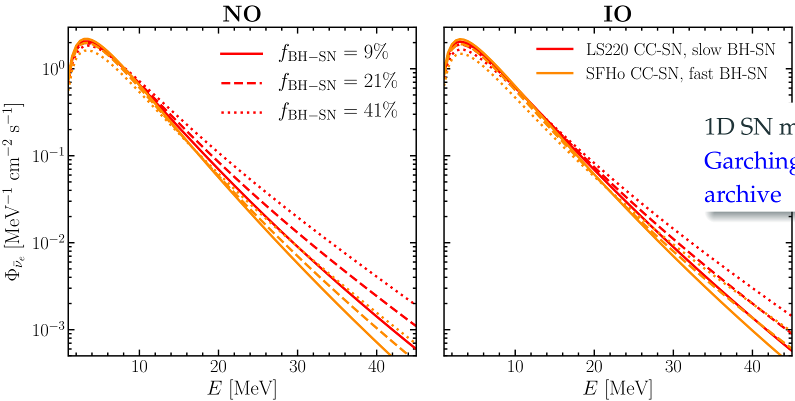


Fraction of black-hole-forming progenitors influences the highly energetic part of the DSNB, above ~ 15 MeV.

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



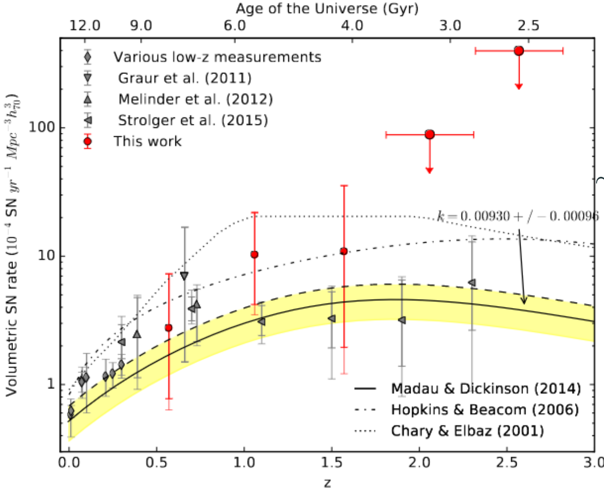
1D SN models
Garching group archive

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

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

Cosmological supernovae rate

Petrushevska et al (2016)



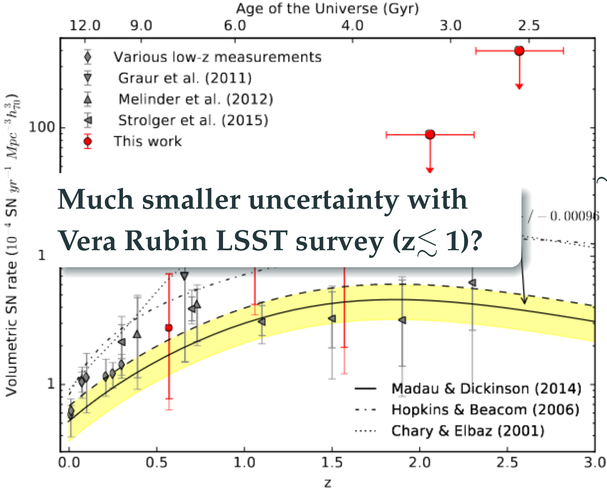
$\sim$ 1 SNe/s

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)



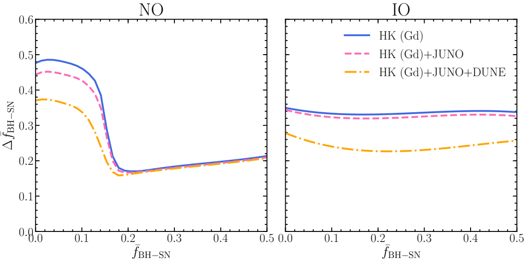
Much smaller uncertainty with Vera Rubin LSST survey (z$\lesssim$ 1)?

~ 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), ...

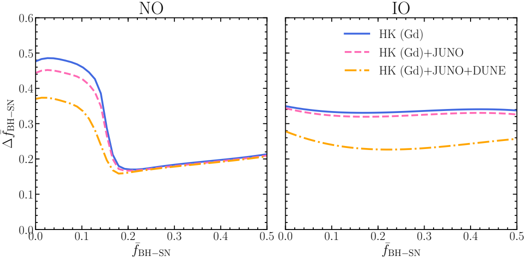
Expected 1σ uncertainty: fraction of BH forming progenitors



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

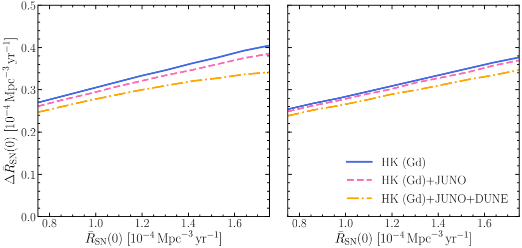
Møller, **AMS**, Tamborra, Denton (2018)

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)

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

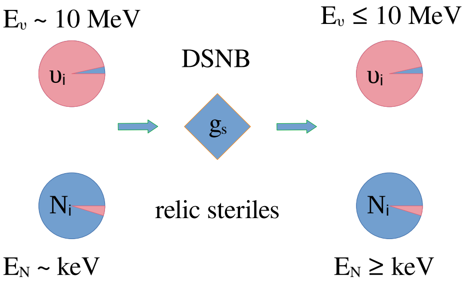
  Lunardini (2009), Lien et al. (2010), Keehn & Lunardini (2012), Priya & Lunardini (2017), Møller, **AMS**, Tamborra, Denton (2018), Horiuchi et al. (2018), Kresse et al. (2018), ...

- Binary Interactions

  Horiuchi, Kinugawa, Takiwaki, Takahashi (2021)

Non exhaustive list of references

KeV-mass sterile neutrino self-interactions



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

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

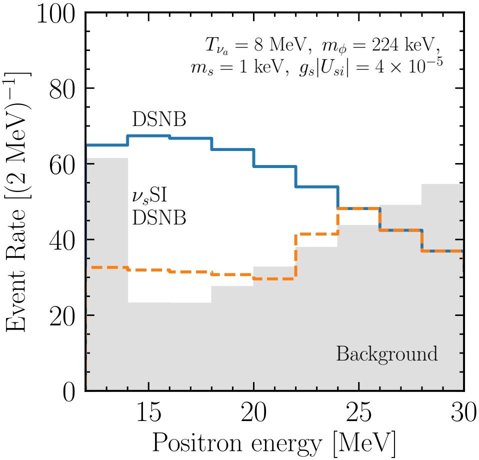
Probability of interaction

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

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

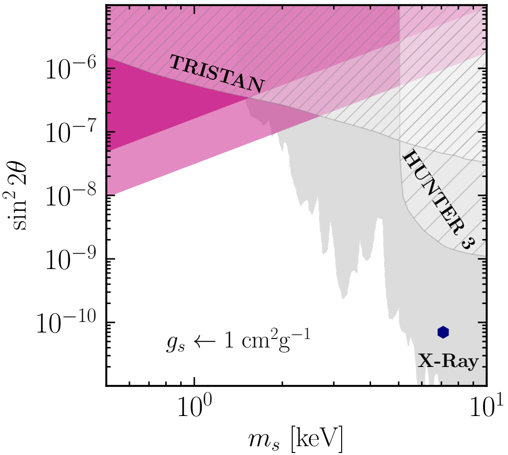
where $z_R = E_R/E_\nu - 1$,
interaction rate $\Gamma_R(z_R) \simeq |U_{si}|^2 n_{\nu_s}(z_R)\sigma_R$,
and sterile neutrino number density $n_{\nu_s}(z_R) = n_{\nu_s}(1+z_R)^3$

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)



- **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**

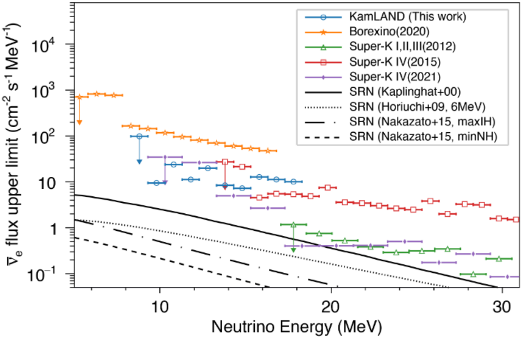
Towards probing the DSNB in all flavors

In collaboration with J. Beacom, and I. Tamborra

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

Diffuse supernova neutrino background: current limits

SK collab. (2021)



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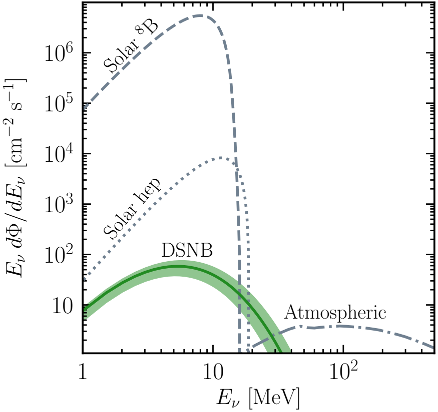
  possibly detectable by DUNE Møller, **AMS**, Tamborra, Denton (2018), Zhu et al. (2019)

Can we detect the *x*-flavor DSNB? Maybe

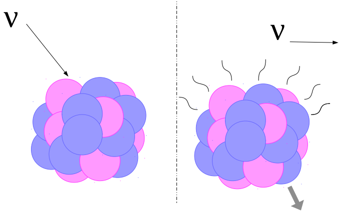


DSNB modeling:
Møller, **AMS**, Tamborra, Denton (2018)

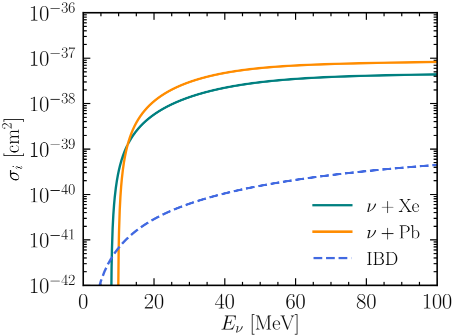
- Favor-blind channel: potential detection window $\sim 18 - 30$ MeV
- Current limit: $\nu_x \approx 750$ cm^{-2} s^{-1} for $E_\nu > 19.3$ MeV Lunardini, Peres (2008)

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

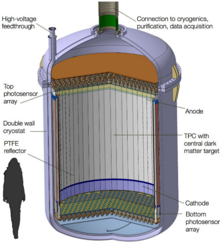
$$\frac{d\sigma_{\rm SM}}{dE_r} = \frac{G_F^2 m_T}{4\pi} Q_w^2 \left(1 - \frac{m_T E_r}{2E_\nu^2}\right) F^2(Q), \;\; Q_w = \left[N - Z(1 - 4\sin^2\theta_W)\right]$$

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

Freedman (1974), Strigari (2009)

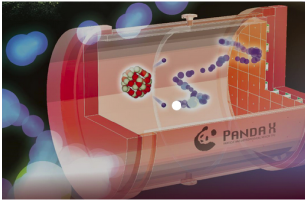
Current and future CEνNS detectors

XENONnT, DARWIN



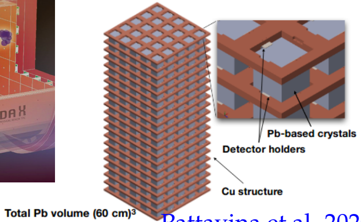
Aalbers al. 2016

PandaX-4T, PandaX-xT



Menget al. 2021

RES-NOVA



Pattavina et al. 2020

fiducial volumes: few - hundreds ton

target materials: Xe, Pb

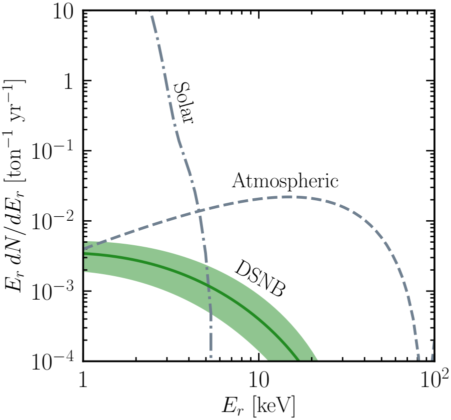
thresholds: $\mathcal{O}(1)$ keV

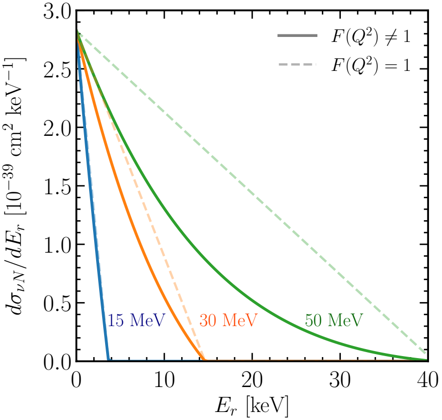
efficiency: $\sim$ 80-100%

Scattering rate

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

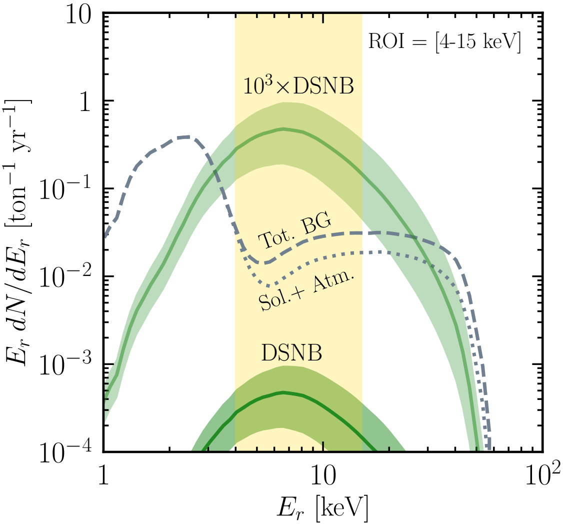
Event rate in the xenon-based detector





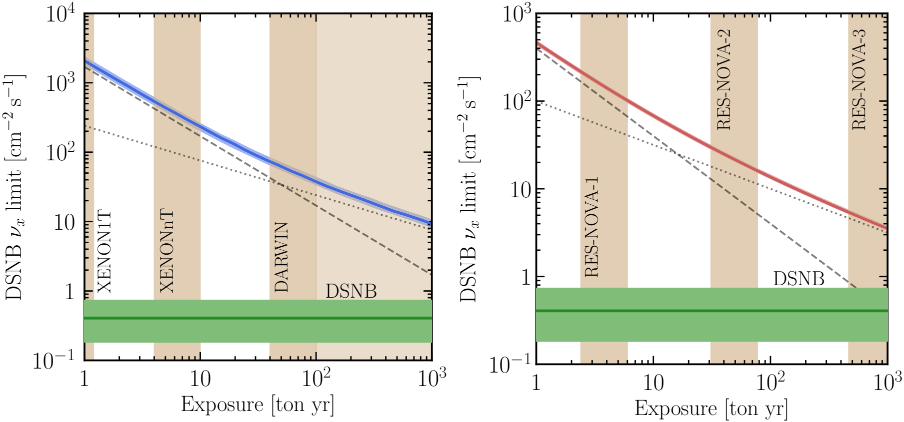
- The potential energy window displayed by the bare fluxes disapears
- Reason: Low energy recolis are most probable for all neutrino energies
- Detection of the x-flavor DSNB seems out of reach, BUT...

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



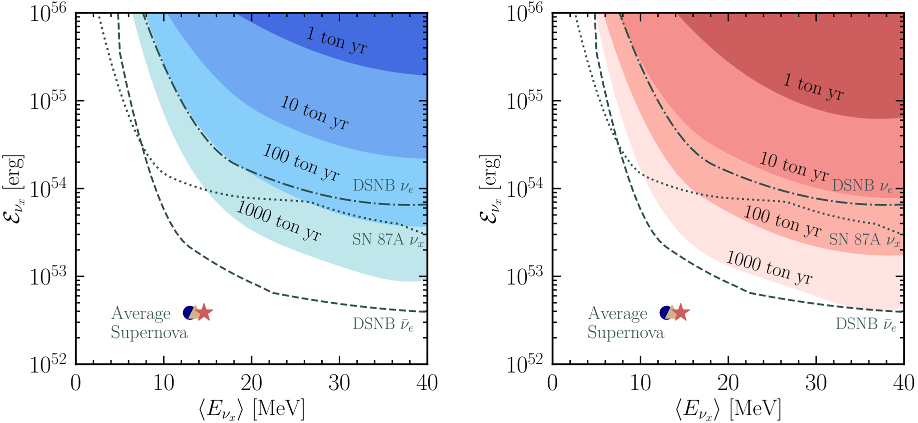
- Potential for an imporevement by $\gtrsim 1-2$ orders of magnitude

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

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!