

# Astrophysical Neutrinos Uncover Neutrino Properties and Decode New Physics

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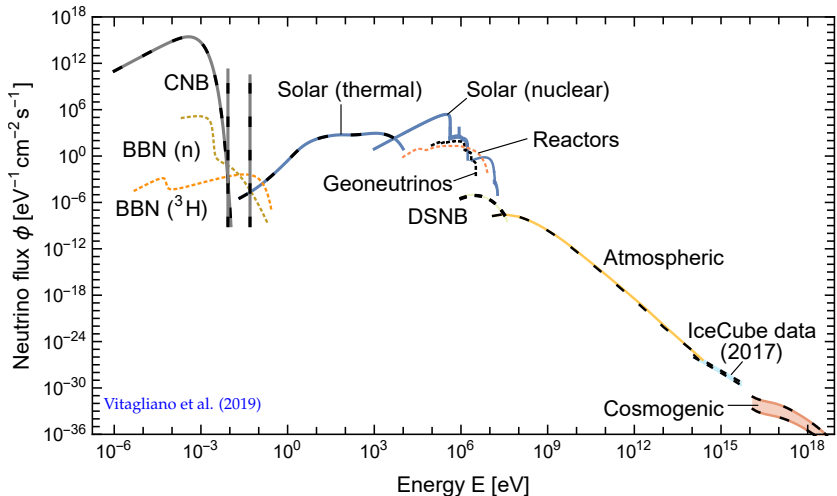
Fermilab, March 27, 2025



- Why is studying astrophysical neutrinos crucial?
- Core-collapse Supernovae as New Physics Probes
- Diffuse Supernova Neutrino Background
- Summary and Outlook

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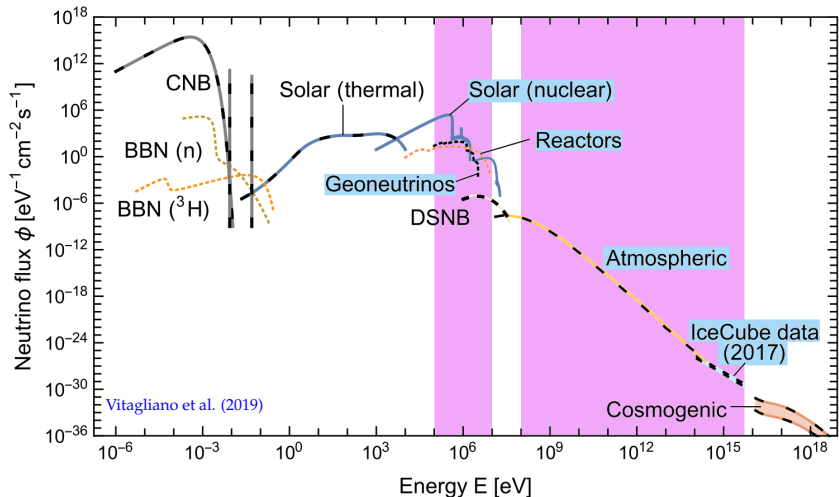
# Why is studying astrophysical neutrinos crucial?



Free neutrino sources spanning nearly 25 decades in energy



# Why is studying astrophysical neutrinos crucial?



**Significant progress, but still room for new discoveries**

## Established track record of neutrino discoveries: solar $\nu$



# Established track record of neutrino discoveries: solar $\nu$

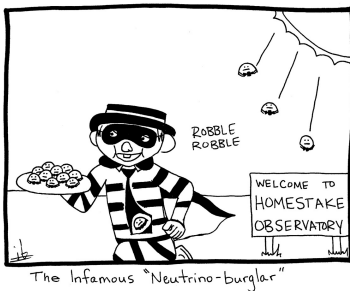


Homestake, USA

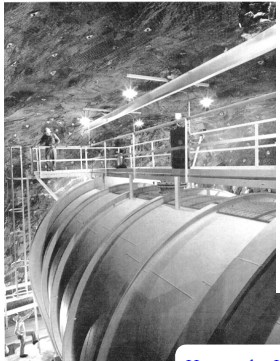
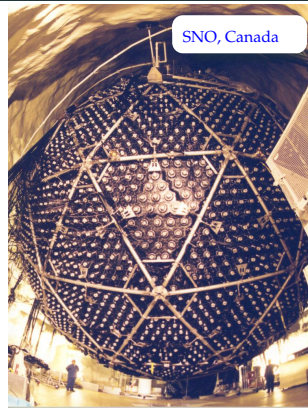
# Established track record of neutrino discoveries: solar $\nu$



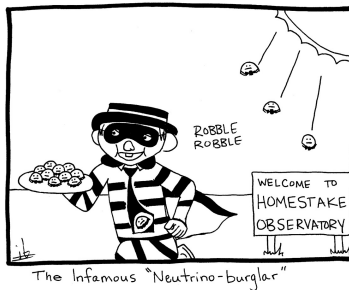
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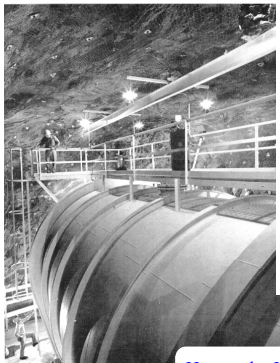
# Established track record of neutrino discoveries: solar $\nu$



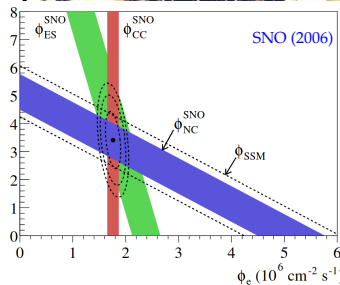
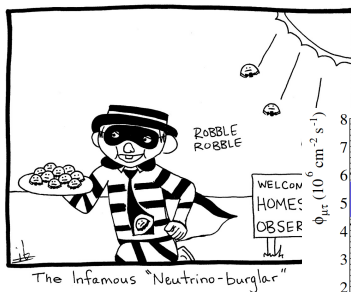
Homestake, USA



# Established track record of neutrino discoveries: solar $\nu$



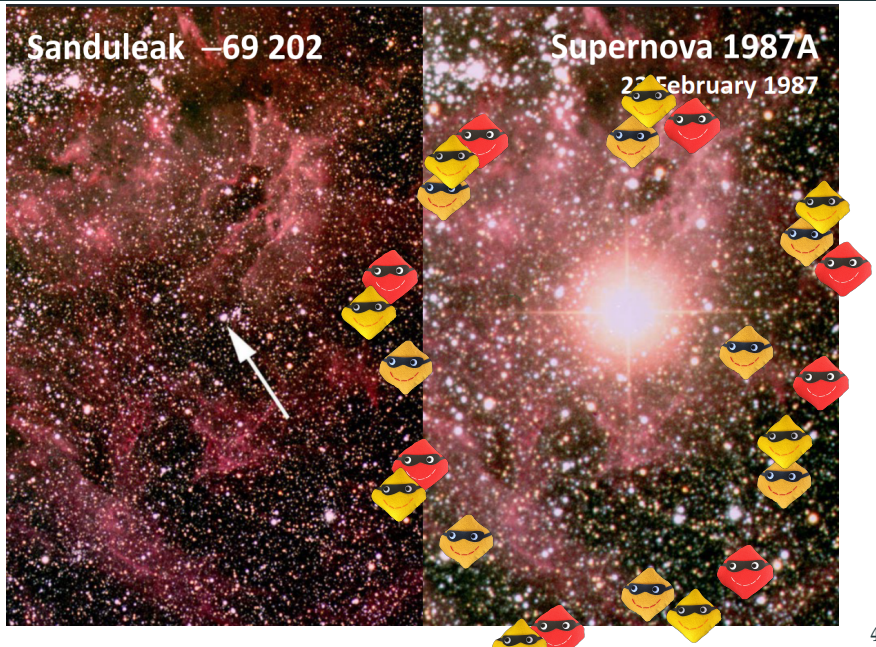
Homestake, USA



## 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)

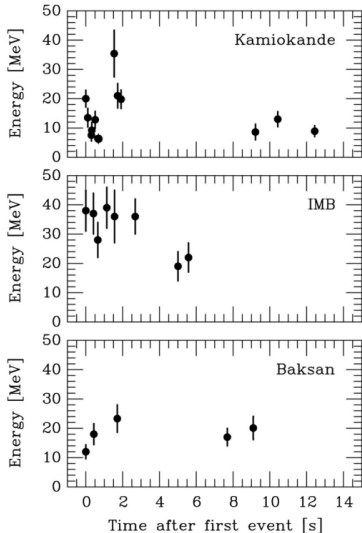
- Neutron star remnant

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  $\nu$  mass

# Why is studying astrophysical neutrinos crucial?

## Benefits to the field of neutrino physics

- free sources spanning nearly 25 decades in energy
- established track record of neutrino discoveries
- test of physics in conditions not accessible on Earth
- complements terrestrial neutrino experimental efforts

## Benefits to the field of multimessenger astrophysics

- unveils physics of the sources
- experimentally and observationally timely

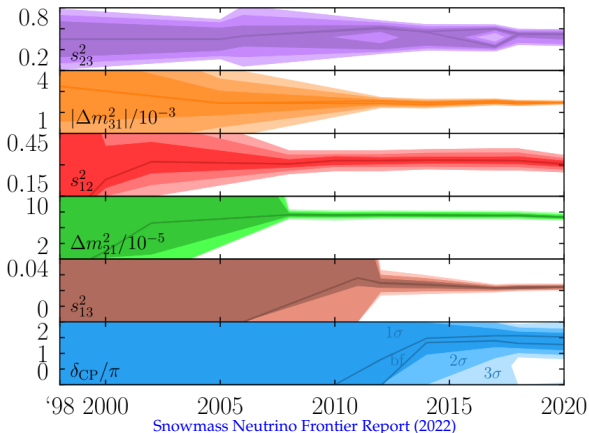
# Towards Precise Neutrino Properties Measurements

## We know now:

- large mixing angles
- non-zero masses

## Remaining questions

- Majorana vs Dirac
- absolute masses
- degree of CP violation



## Fermions

|         |        |                                     |                                 |                                |              |                  |
|---------|--------|-------------------------------------|---------------------------------|--------------------------------|--------------|------------------|
| Leptons | Quarks | u<br>up                             | c<br>charm                      | t<br>top                       | γ<br>photon  | H<br>Higgs boson |
|         |        | d<br>down                           | s<br>strange                    | b<br>bottom                    | g<br>gluon   |                  |
|         |        | ν <sub>e</sub><br>electron neutrino | ν <sub>μ</sub><br>muon neutrino | ν <sub>τ</sub><br>tau neutrino | Z<br>Z boson |                  |
|         |        | e<br>electron                       | μ<br>muon                       | τ<br>tau                       | W<br>W boson |                  |

Force carriers

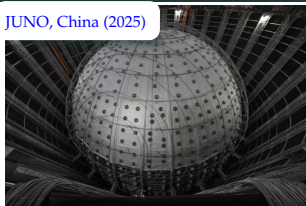
$$\begin{bmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{bmatrix} = U \begin{bmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{bmatrix}$$

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

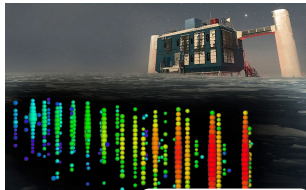
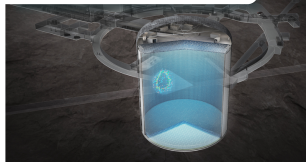
beam, atmospheric      beam, reactor      solar, reactor

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

JUNO, China (2025)

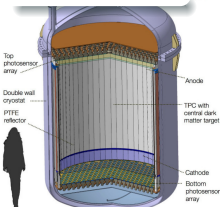


Hyper-Kamiokande, Japan (2027)



IceCube, South Pole

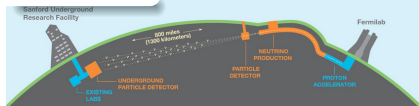
XLZD, DARWIN (20XX)



Rubin Observatory, Chile (2025)



DUNE, USA (2030)



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

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

- Why is studying astrophysical neutrinos crucial?
- **Core-collapse Supernovae as New Physics Probes**
- Diffuse Supernova Neutrino Background
- Summary and Outlook

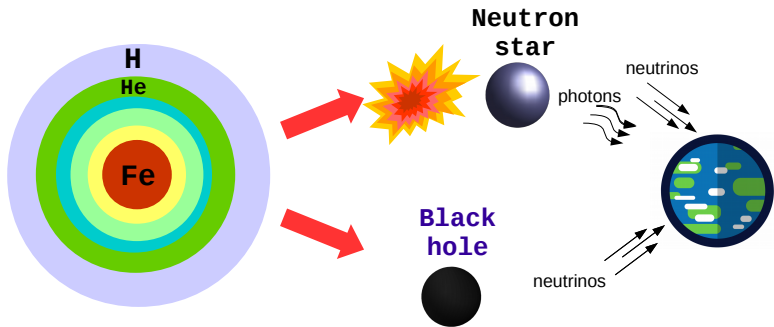
# Neutrinos from Core-collapse Supernovae

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# Why are neutrinos important for a core-collapse supernova?

## Neutrinos:

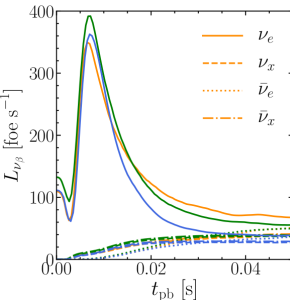
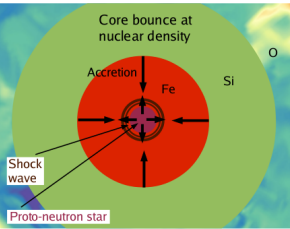
- $\sim 10^{58}$  of them emitted from a single core collapse
- only they can reveal the deep interior conditions
- only particles detectable from the collapse to a black hole



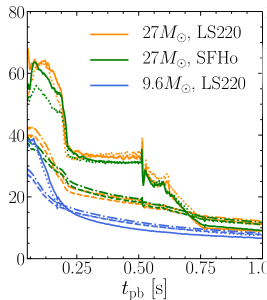
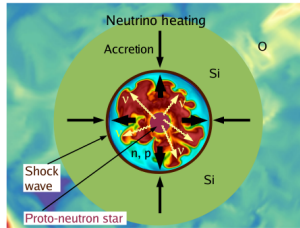


# Different Phases of Supernova Explosion

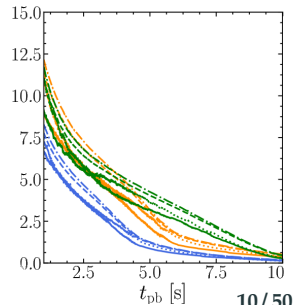
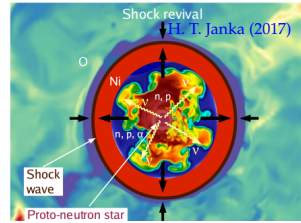
- Infall phase,  
 $\nu_e$  burst  $\sim 40$  ms



- Accretion phase,  
 $\sim 100$  ms



- Cooling phase,  
 $\sim 10$  s



# Why core-collapse supernovae are good physics probes?

## Advantages

- extreme physical conditions not accessible on Earth
- within the reach of existing and upcoming detectors

## What can we learn with a variety of detectors?

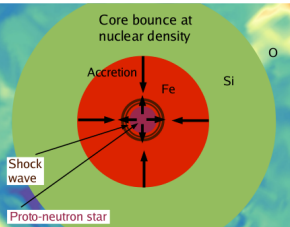
- explosion mechanism Bethe & Wilson (1985),  
Fischer et al. (2011)...
- nucleosynthesis Woosley et al. (1994),  
Surman & McLaughlin (2003)...
- compact object formation Warren et al. (2019),  
Li, Beacom et al. (2020)...
- neutrino mixing Balantekin & Fuller (2013),  
Tamborra & Shalgar (2020)...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

# Neutrinos from Supernovae as Probes of New Physics

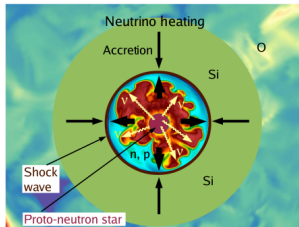
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# Different Phases of Supernova Explosion

- Infall phase,  
 $\nu_e$  burst  $\sim 40$  ms

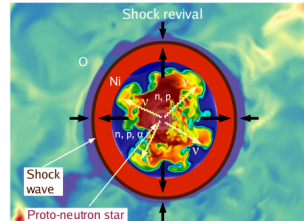


- Accretion phase,  
 $\sim 100$  ms



- Cooling phase,  
 $\sim 10$  s

H. T. Janka (2017)



## New neutrino physics affects the core-collapse supernovae:

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

**astrophysical feedback often ignored**

**Which bounds remain unchanged  
with astrophysical feedback?**

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# Do Neutrinos Have Self-Interactions?

IL NUOVO CIMENTO

VOL. XXXIII, N. 5

1° 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.

# Lepton number violating neutrino self-interactions

**Motivation** - to be taken with a grain of salt:

- lepton number conservation - accidental symmetry
- 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), ...

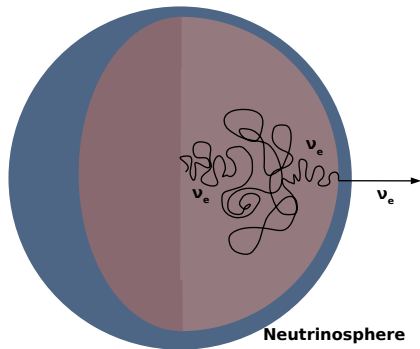
## New Interaction Lagrangian

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

## Probability of the New Interaction

$$\sigma_{\nu\text{SI}} \approx \frac{G_{\nu\text{SI}}^2}{8\pi} E_\nu^1 E_\nu^2 (1 - \cos \theta)$$

# Neutrino Trapping and $\beta$ -equilibrium



## Neutrino trapping

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

## $\beta$ -equilibrium

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

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

## Implementation:

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

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

$$\nu_e \rightleftharpoons \nu_e, \bar{\nu}_e, \nu_x, \bar{\nu}_x,$$

$$\nu_e \rightleftharpoons \nu_e, \bar{\nu}_e$$

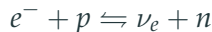


# Static, Homogenous and Isotropic Boltzmann Equation

## Boltzmann Equation

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

## Electron fraction evolution - weak rates



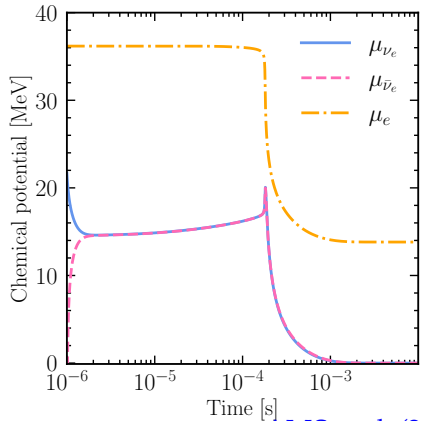
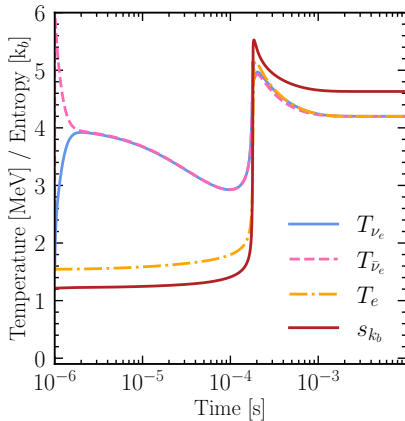
$$\frac{dY_e}{dt} = R_{\nu_e} - R_{\bar{\nu}_e} - R_{e^-} + R_{e^+} , \quad e^+ + n \rightleftharpoons \bar{\nu}_e + p$$

## Temperature and chemical potential evolution for leptons

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

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

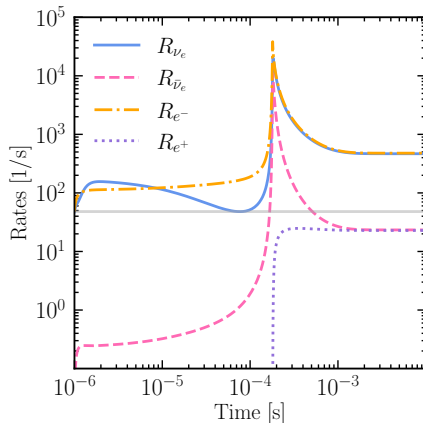
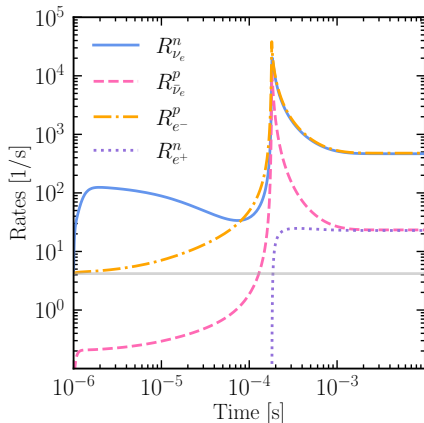
# Evolution of Thermodynamical Quantities



AMS et al. (2024)

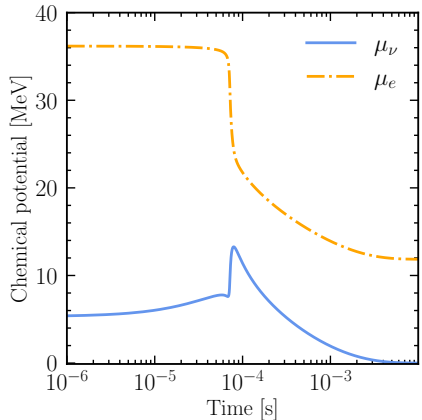
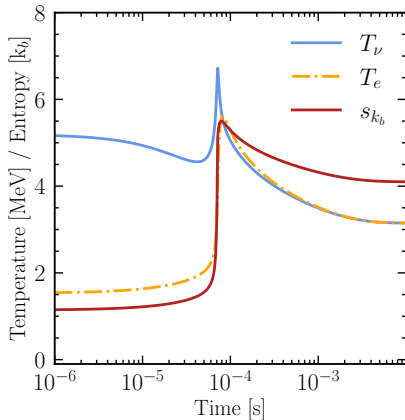
- new interactions quickly equilibrate  $\nu_e$  and  $\bar{\nu}_e$  seas
- enhanced  $\nu_e$  and  $e^-$  captures heat up the matter
- similar results for all flavors equilibration

# Weak reaction rates



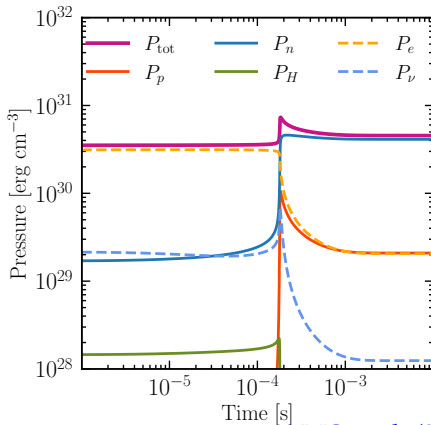
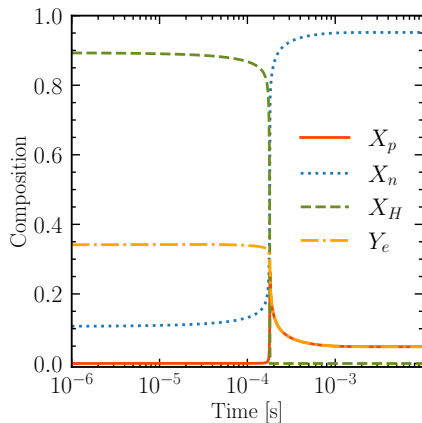
- initial increase in  $\nu_e + n$ ,  $\nu_e + A$  and  $e^- + A$
- enhanced  $\nu_e$  and  $e^-$  captures heat up the matter
- similar results for all flavors equilibration

# Evolution of Thermodynamical Quantities



- the same qualitative results for all six flavor equilibration

# Composition and Pressure Support of the Core

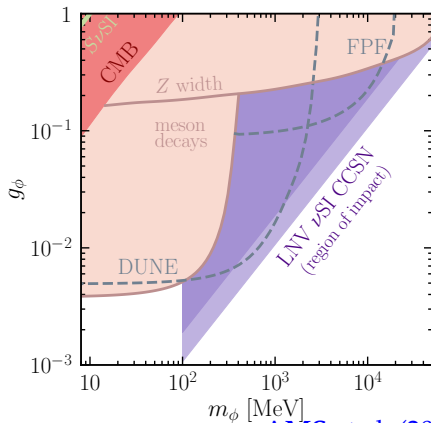
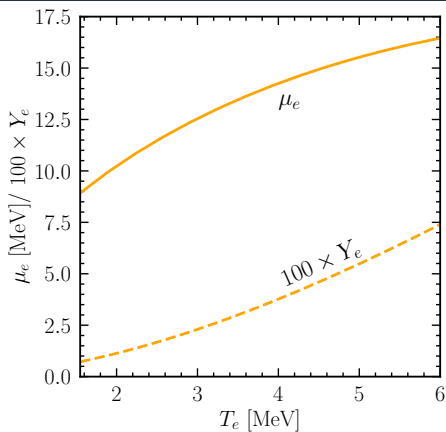


AMS et al. (2024)

- $s_{k_b}$  - entropy generation shifts composition towards no heavy nuclei  

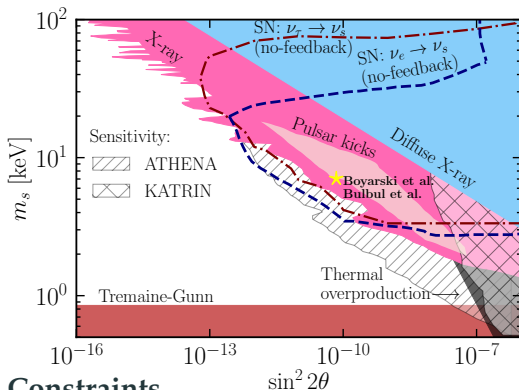
$$X_H \propto s_{k_b}^{1-\langle A \rangle} n_p^Z n_n^N \exp(E_b/T_e)$$
- enhanced deleptonization changes the pressure support of the core

# New $\beta$ -equilibrium with LNV $\nu$ SI



- regardless of the final  $T_e$  the new equilibrium has a very low  $Y_e$   
 $\mu_e = \delta m_{np} - T_e \ln \left( \frac{Y_e}{1-Y_e} \right)$ , with  $Y_e = \frac{1}{\pi^2 \rho} \int_0^\infty dp_e p_e^2 f_e(E_e, T_e, \mu_e)$
- complementarity with future accelerator-based experiments

# Sterile neutrino as dark matter candidate



## Constraints

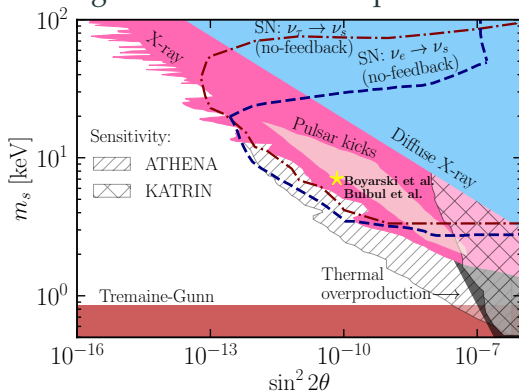
- Supernovae energy bounds (X. Shi & G. Sigl (1994)), ...
- DM overproduction (S. Dodelson, L. M. Widrow (1994), X. Shi, G. M. Fuller (1999))
- Radiative decay (NuSTAR, XMM, Chandra), K. C. Y. Ng et al. (2019), K. C. Y. Ng et al. (2015), S. Horiuchi et al. (2013)...
- Tremaine-Gunn bound (S. Tremaine,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

## 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)
- Lyman- $\alpha$  forest  
Villasenor et al. (2022)

# The role of sterile neutrinos in supernovae; previous studies

- Change of the electron or neutrino ( $\nu_e, \nu_\mu, \nu_\tau$ ) fractions
- Suppression/enhancement of the SN explosion
- Exclusion of a large fraction of the DM parameter space

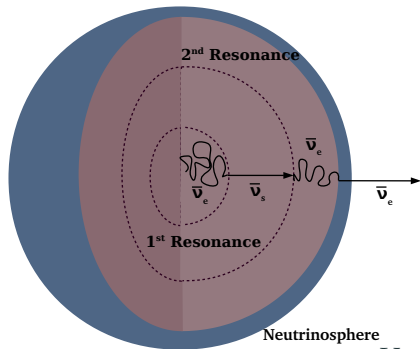


Raffelt & Sigl (1992), Shi & Sigl (1994), Nunokawa et al. (1997), Hidaka & Fuller (2006), Hidaka & Fuller (2007), Raffelt & Zhou (2011), Warren et al. (2014), Argüelles et al. (2016), **AMS et al. (2019, 2020)**, Syvolap et al. (2019), Ray & Qian (2023, 2024)



# Sterile neutrino conversions in the stellar core

1D SN model  
Garching group  
archive



MSW

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

$\nu_\tau - \nu_s$  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

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

$\nu_e - \nu_s$  mixing: multiple resonances

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

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

# Sterile neutrino conversions in the stellar core

## Collisional production

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

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

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

# Sterile neutrino conversions in the stellar core

## Collisional production

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

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

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

## MSW production

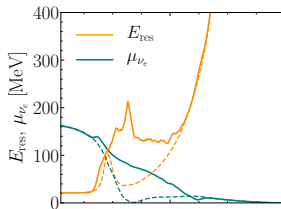
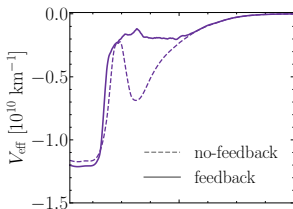
$$P_{\nu_{\text{active}} \rightarrow \nu_s}(E_{\text{res}}) = 1 - \exp\left(-\frac{\pi^2}{2}\gamma\right), \gamma = \Delta_{\text{res}}/l_{\text{osc}}$$

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

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

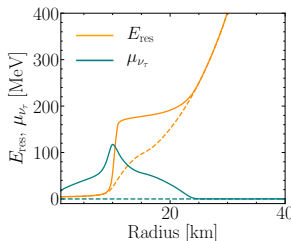
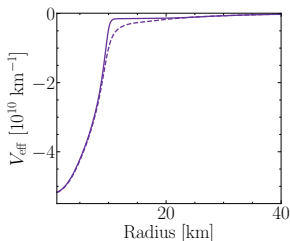
# Sterile neutrino conversions in the stellar core

$\nu_s - \nu_e$  mixing: multiple resonances



1D SN model  
Garching group  
archive

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



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

$$m_s = 10 \text{ keV},$$

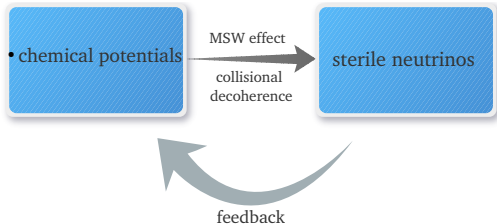
$$\sin^2 2\theta = 10^{-8}$$

- Negative  $V_{\text{eff}} \rightarrow$  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

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



## Active + **sterile** neutrinos

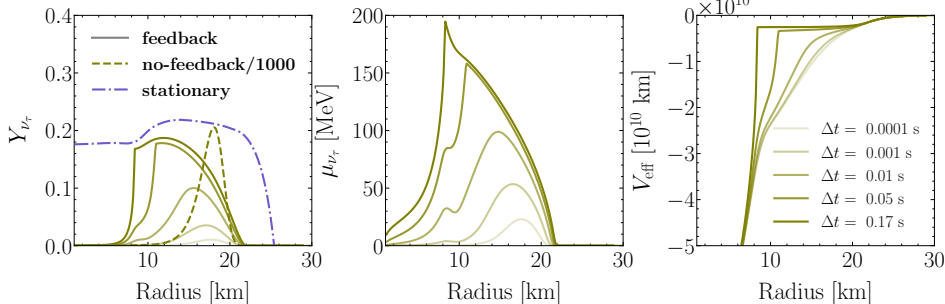
The active neutrinos after being **converted to sterile ones** effectively disappear; since they were **strongly coupled** to the rest of the particles in the medium, a **new equilibrium state forms**.

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

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

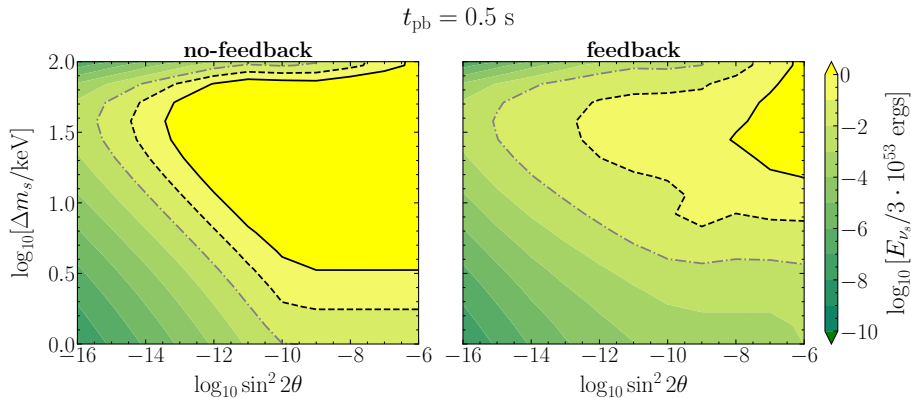
# Radial evolution of the asymmetry w and w/o feedback

$$t_{\text{pb}} = 0.5 + \Delta t \text{ s}, \Delta m_s = 10 \text{ keV}, \sin^2 2\theta = 10^{-10}$$



- Feedback inhibits  $Y_{\nu_\tau}$  from unphysical growth.
- The  $\nu_\tau$  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

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

## $\beta$ 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

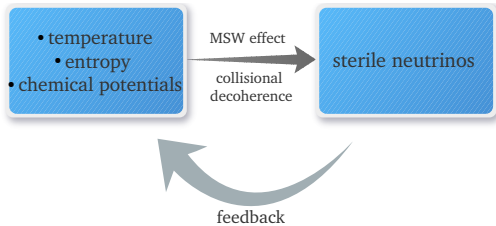
$$Y_p(r, t) + Y_n(r, t) = 1 ,$$

## Charge conservation

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

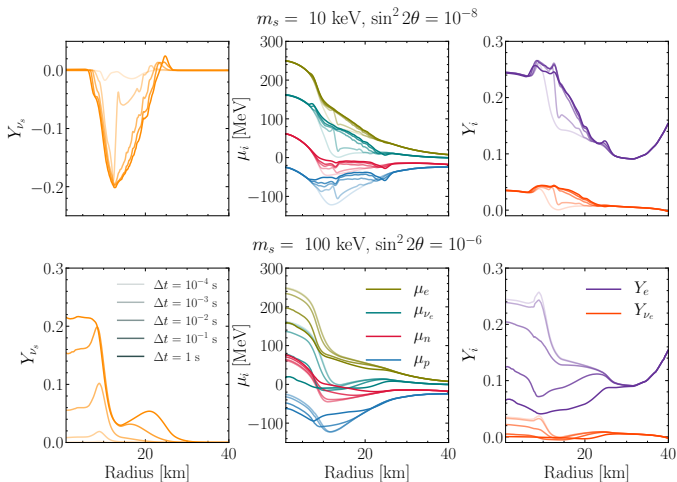
## Entropy change

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



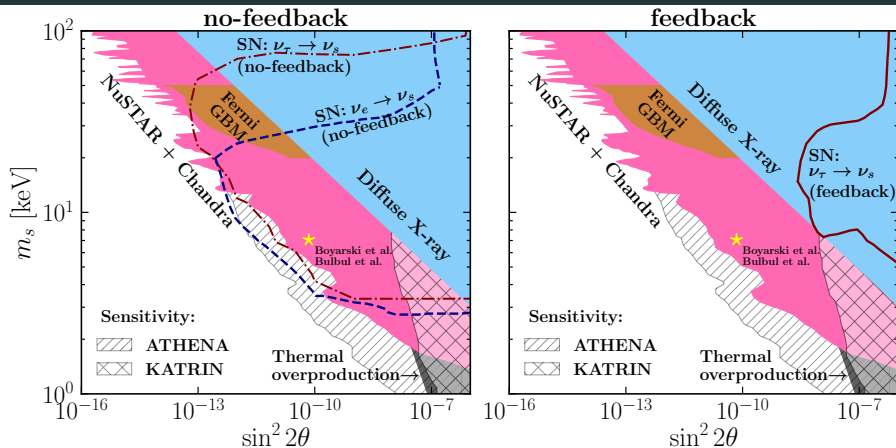


# Radial evolution of the asymmetry



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

# Supernova bounds on the mixing parameters

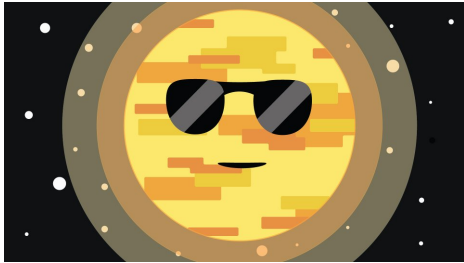


AMS et al. (2018), (2019)

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

- Why is studying astrophysical neutrinos crucial?
- Core-collapse Supernovae as New Physics Probes
- **Diffuse Supernova Neutrino Background**
- Summary and Outlook

# Why focus only on a single rare event?

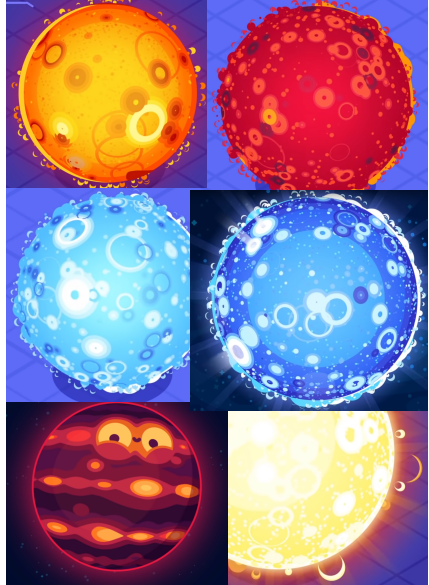


## Single galactic SN event

- rare event
- precise information about one star

## Multiple SN events (larger distances)

- accumulation of events
- will detect in coming years



# Diffuse supernova neutrino background

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

**cosmological supernovae rate** (points to  $R_{\text{SN}}(z, M)$ )

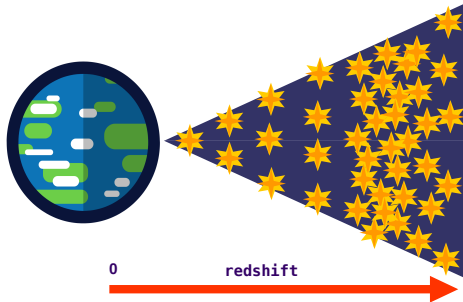
**fraction of black-hole-forming progenitors** (points to  $f_{\text{BH-SN}}$ )

**fraction of neutron-star-forming progenitors** (points to  $f_{\text{CC-SN}}$ )

**neutrino flux from a single star** (points to  $F_{\nu_\beta, \text{CC-SN}}(E', M)$  and  $F_{\nu_\beta, \text{BH-SN}}(E', M)$ )

The DSNB is sensitive to:

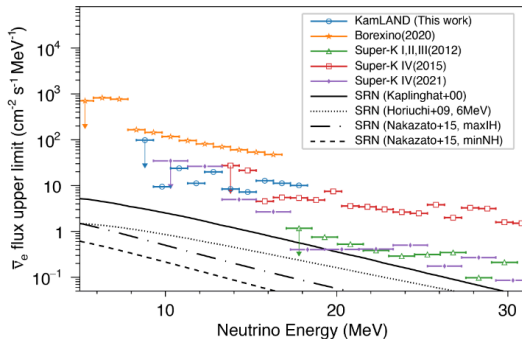
- $R_{\text{SN}}, f_{\text{BH-SN}}$
- neutrino flavor evolution
- equation of state
- mass accretion rate in BH-SN
- non-standard physics



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), ...

# Diffuse supernova neutrino background: current limits

SK collab. (2021)

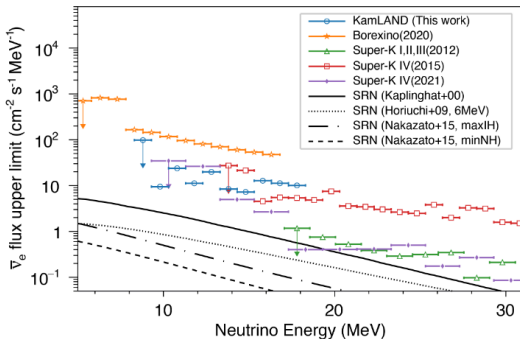


## DSNB limits:

- $\bar{\nu}_e \approx 2.7 \text{ cm}^{-2} \text{ s}^{-1}$  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, et al. (2018), Zhu et al. (2019)
- $\nu_x \approx 750 \text{ cm}^{-2} \text{ s}^{-1}$  for  $E_\nu > 19.3 \text{ MeV}$  Lunardini, Peres (2008)

# Diffuse supernova neutrino background: current limits

SK collab. (2021)



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

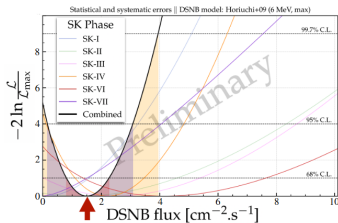
# Tension from zero assumption

## Spectral-fitting analysis



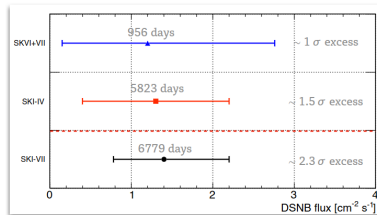
### Spectrum fitting analysis to extract significance

- 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  $1.4^{+0.8}_{-0.6} \text{ cm}^{-2} \text{ s}^{-1}$  for  $E_\nu > 17.3$  MeV
- exhibit ~2.3  $\sigma$  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), Horiuchi et al. (2018), Kresse et al. (2018), ...

- Cosmological Supernovae Rate

Beacom (2010), Horiuchi et al. (2011), Ando et al. (2023), Ekanger et al. (2024)...

- 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)

Sanduleak and Betelgeuse in binary systems? Morris & Podsiadlowski (2007), (2009), Goldberg et al (2024), MacLeod et al (2024)

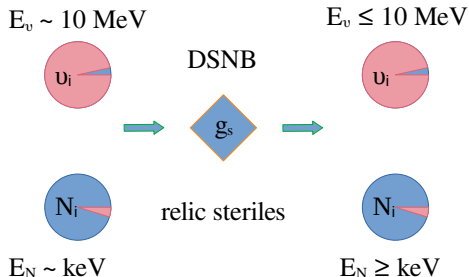
**Non exhaustive list of references**

**How to probe new physics with  
these uncertainties?**

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# Do KeV-mass Sterile Neutrinos Have Self-Interactions?

Balantekin, Fuller, Ray, **AMS** (2023)



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  $\nu_i$  interacts with the mostly sterile relic background of  $N_i$

bigger parameter space for keV sterile neutrino dark matter with self-interactions:

Maria D. Astros and S. Vogl (2023), T. Bringmann et al. (2022)

# Modeling secret neutrino interactions in DSNB

Balantekin, Fuller, Ray, **AMS** (2023)

## Modified DSNB flux

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

## 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  $\Gamma_R(z_R) \simeq |U_{si}|^2 n_{\nu_s}(z_R) \sigma_R$ ,

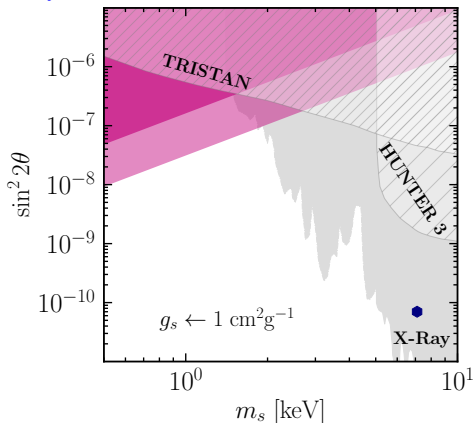
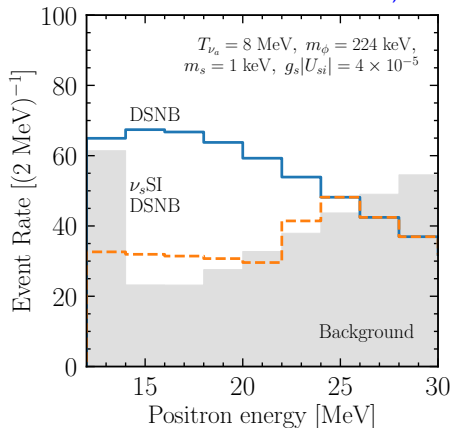
and sterile neutrino number density  $n_{\nu_s}(z_R) = n_{\nu_s}(1 + z_R)^3$

similar 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) **40 / 50**

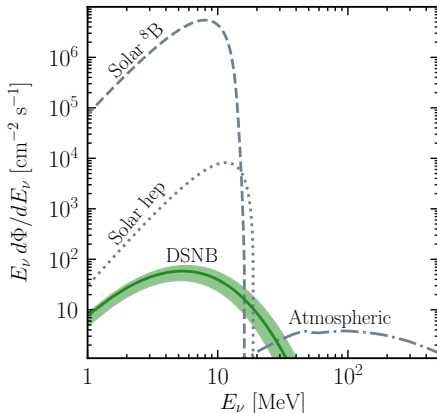
# Secret neutrino interactions: DSNB

Balantekin, Fuller, Ray, AMS (2023)



- Sterile neutrino self-interactions may result in features in DSNB
- Overlap with the TRISTAN experiment parameter space
- Reduction of the astrophysical uncertainties helps but not by a lot

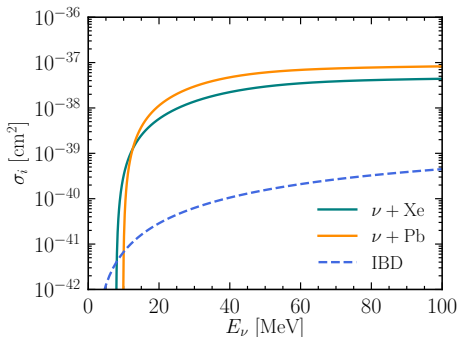
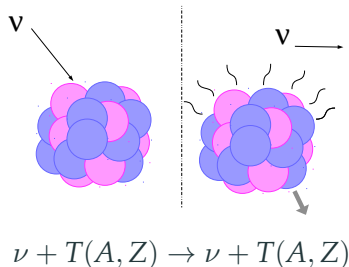
# Can we detect the $x$ -flavor DSNB? Maybe



DSNB modeling:  
Møller, AMS, et al.  
(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 $\nu$ 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  $\sim 50$  MeV

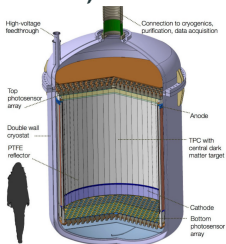
Cross section:

Theory: [Freedman \(1974\)](#),

Measured: [COHERENT \(2017\)](#)

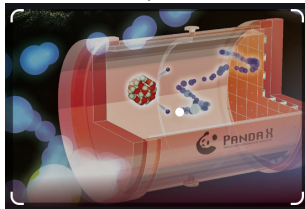
# Current and future CE $\nu$ NS detectors

## XENONnT, DARWIN



Aalbers et al. 2016

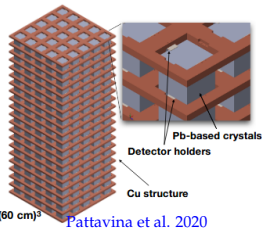
## PandaX-4T, PandaX-xT



Menget et al. 2021

Total Pb volume (60 cm)<sup>3</sup>

## RES-NOVA



Pattavina et al. 2020

**fiducial volumes:** few - hundreds ton

**target materials:** Xe, Pb

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

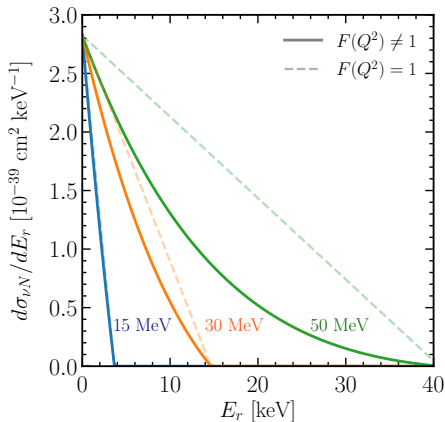
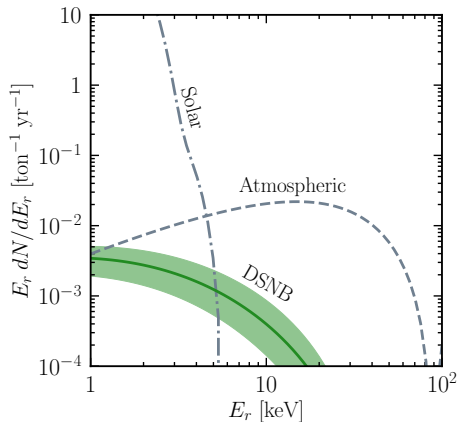
**efficiency:**  $\sim 80$ -100%

### Scattering rate

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

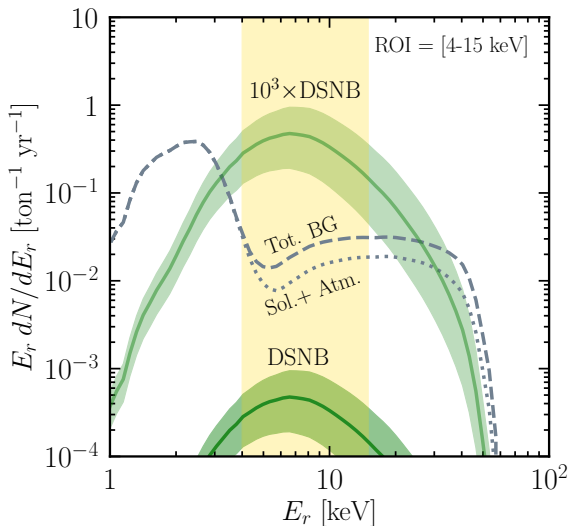


# Event rate in the xenon-based detector



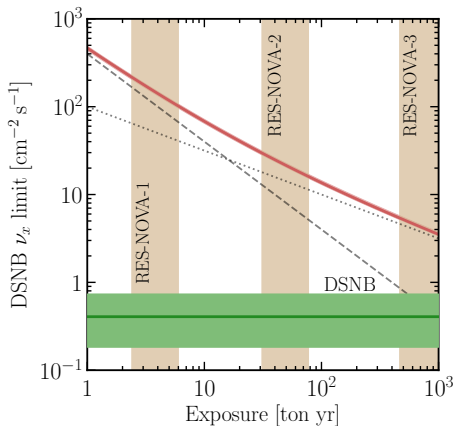
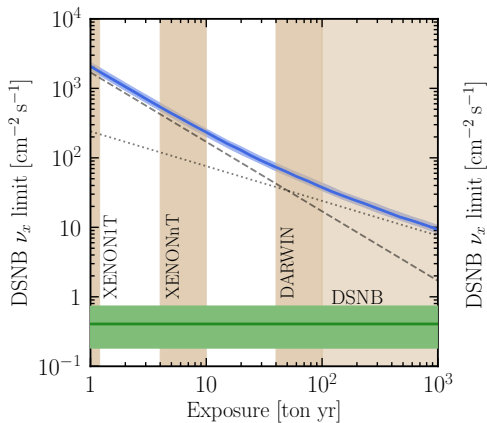
- The potential energy window displayed by the bare fluxes disappears
- Reason: Low energy recoils are most probable for all neutrino energies
- Detection of the  $x$ -flavor DSNB seems out of reach, BUT...

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



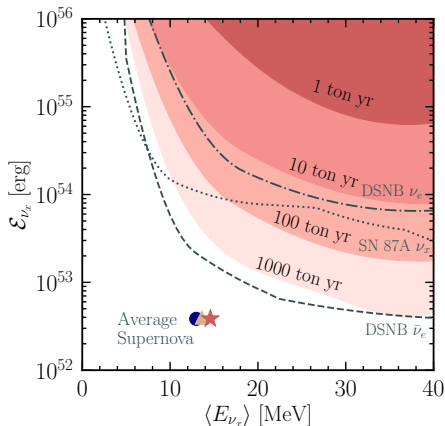
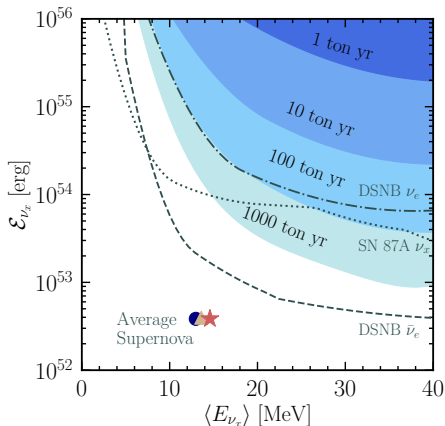
- Potential for an improvement by  $\gtrsim 1 - 2$  orders of magnitude

# Sensitivity bounds on the normalization of the x-flavor DSNB



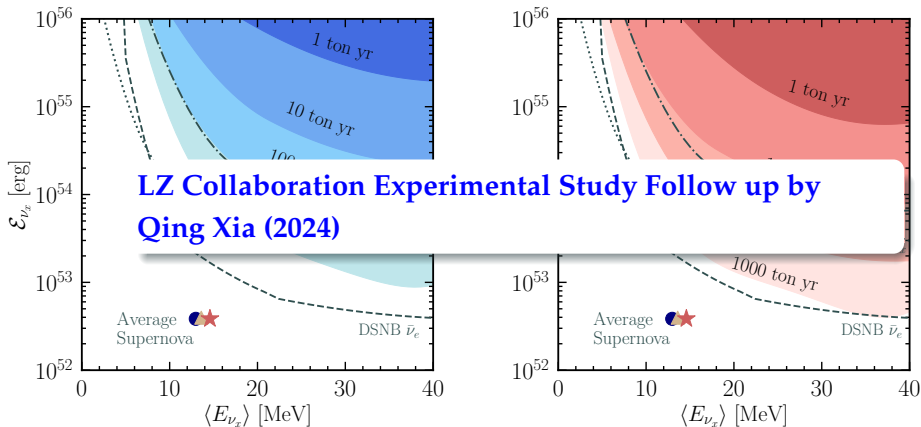
- XENON1T, PandaX-4T: limits comparable to the SK  $\nu_x$  DSNB limit
- Constant energy window: limits can improve  $\mathcal{O}(10\%)$  for wider windows at small exposures and narrower windows at large exposures

# Sensitivity bounds on the x-flavor DSNB



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

# Sensitivity bounds on the x-flavor DSNB



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- Why is studying astrophysical neutrinos crucial?
- Core-collapse Supernovae as New Physics Probes
- Diffuse Supernova Neutrino Background
- Low-energy Atmospheric Neutrinos
- **Summary and Outlook**

# 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!**