Astrophysical Neutrinos Uncover Neutrino Properties and Decode New Physics

Anna M. Suliga

Neutrino Theory Network Fellow
New York University

Triangle Nuclear Theory Colloquium
NCSU April 8, 2025

Overview

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

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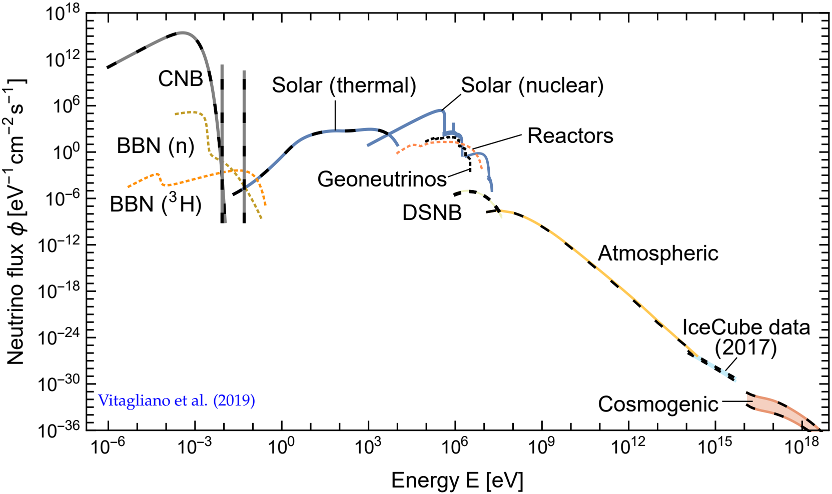
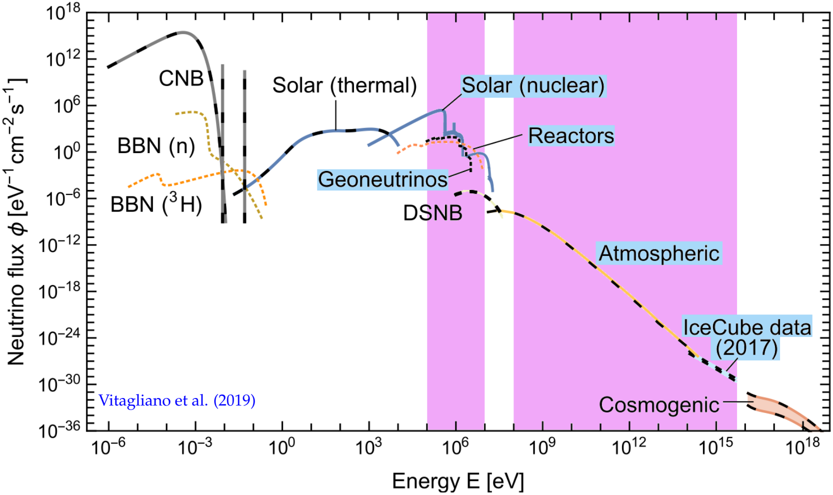
Why is studying astrophysical neutrinos crucial?



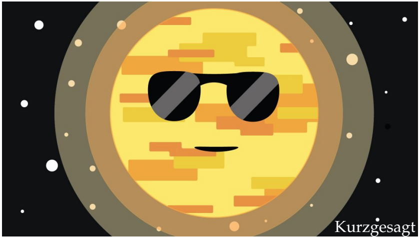
Free neutrino sources spanning nearly 25 decades in energy

Why is studying astrophysical neutrinos crucial?



Significant progress, but still room for new discoveries

Established track record of neutrino discoveries: solar ν



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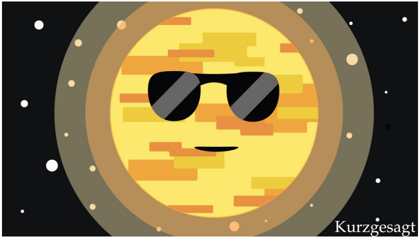

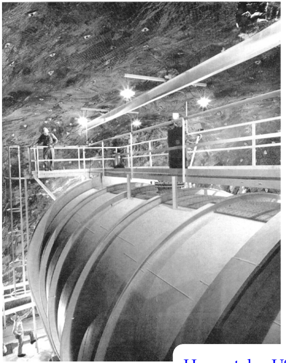

Homestake, USA

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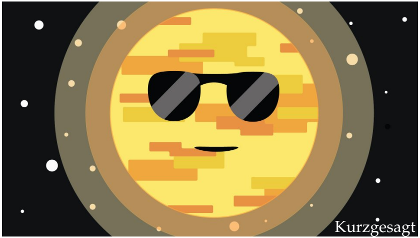
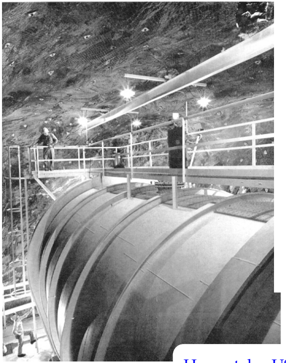
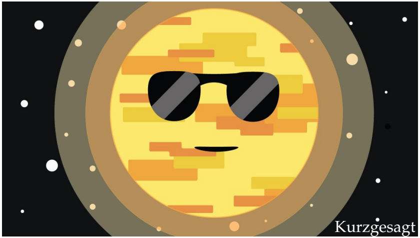




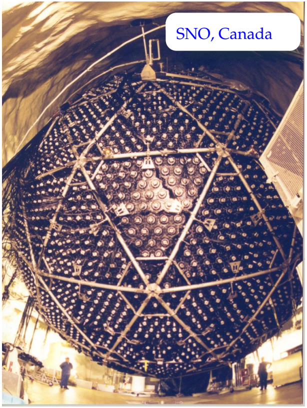
Homestake, USA

The Infamous "Neutrino-burglar"

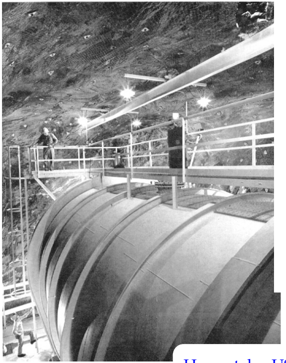
Established track record of neutrino discoveries: solar ν



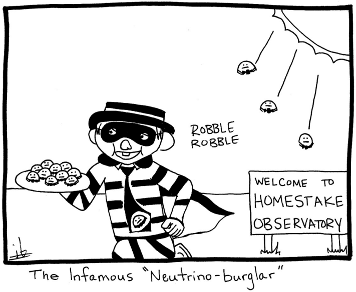
Kurzgesagt



SNO, Canada



Homestake, USA



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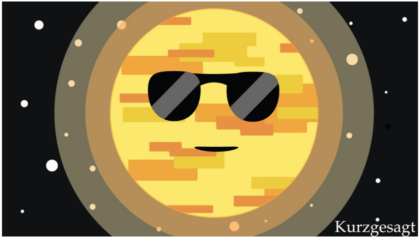
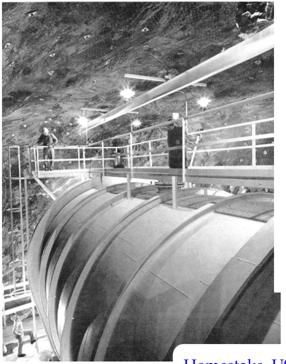
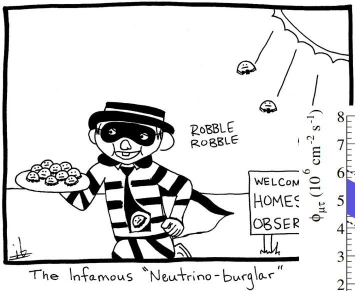
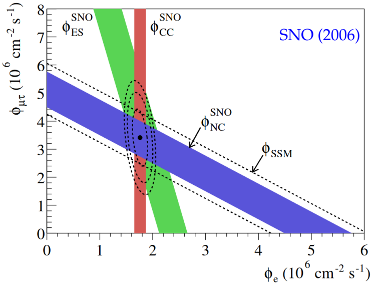
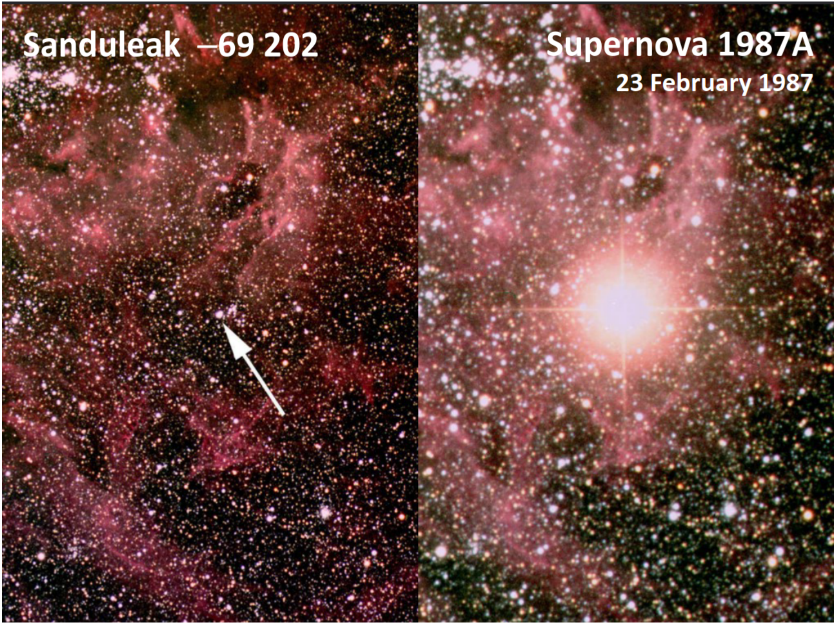









Sanduleak –69 202
Supernova 1987A
23 February 1987

Graduate StudentPostdoctoral FellowSummer SalaryTravel MoneyTe

NSF grant for the more asto projects

Faculty Early Career Development Program (CAREER)

Bridge grant

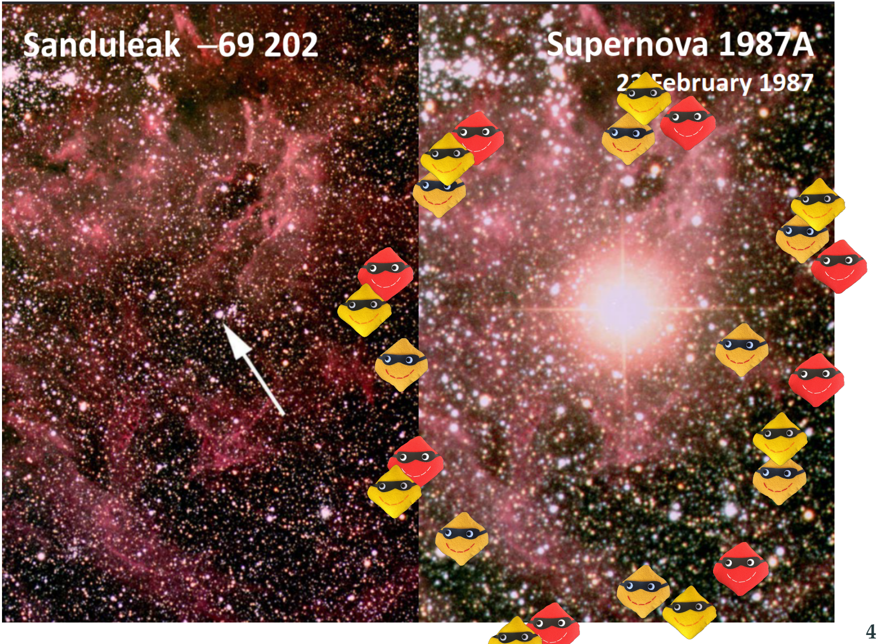
Joining on the existing proposal cycle

DOE grant for the more particle projects

- Early Career Research Program
- Bridge grant
- Joining on the existing proposal cycle

Potential Private Sources

- Heising-Simons Foundation. Does VT has any programs?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Hubble (2017)


JWST (2023)

- Neutron star remnant

  Fransson et al. (2024)

- Binary system

  Morris & Podsiadlowski (2007), (2009)

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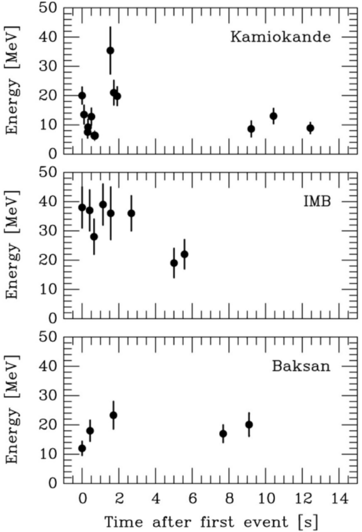

Courtesy of G. Raffelt

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

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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

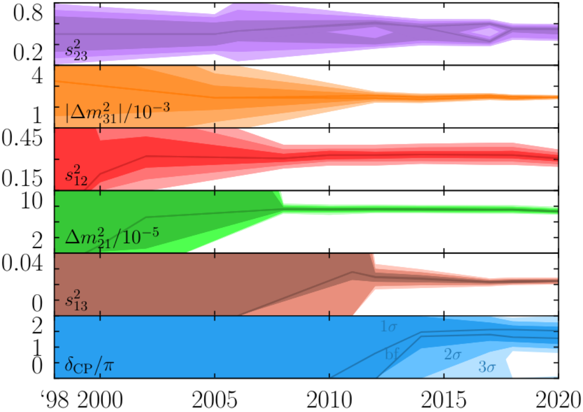
Towards Precise Neutrino Properties Measurements

We known now:

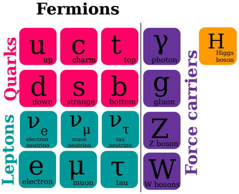
- large mixing angles
- non-zero masses

Remaining questions

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



Snowmass Neutrino Frontier Report (2022)



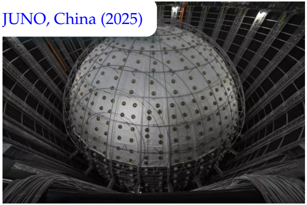
$$\begin{bmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{bmatrix} = U\begin{bmatrix}\nu_1\\ \nu_2\\ \nu_3\end{bmatrix}$$

beam, atmospheric — **beam, reactor** — **solar, reactor**

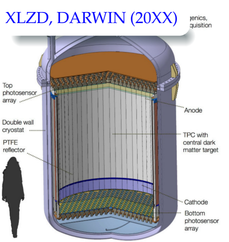
$$U = \begin{bmatrix}1 & 0 & 0\\ 0 & c_{23} & s_{23}\\ 0 & -s_{23} & c_{23}\end{bmatrix}\begin{bmatrix}c_{13} & 0 & s_{13}e^{-i\delta_{CP}}\\ 0 & 1 & 0\\ -s_{13}e^{i\delta_{CP}} & 0 & c_{13}\end{bmatrix}\begin{bmatrix}c_{12} & s_{12} & 0\\ -s_{12} & c_{12} & 0\\ 0 & 0 & 1\end{bmatrix}$$

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

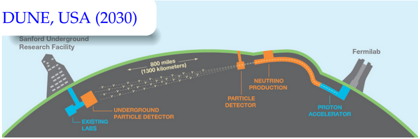
JUNO, China (2025)



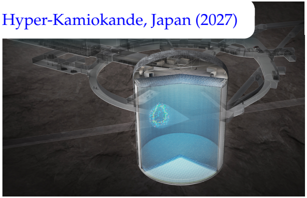
XLZD, DARWIN (20XX)



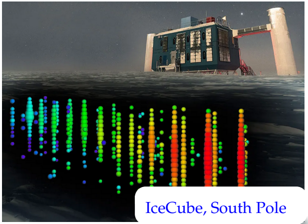
DUNE, USA (2030)



Hyper-Kamiokande, Japan (2027)



Rubin Observatory, Chile (2025)



IceCube, South Pole

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

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

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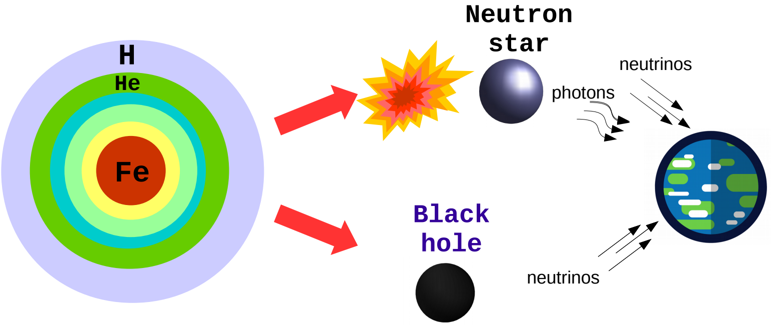
Neutrinos from Core-collapse Supernovae

Why are neutrinos important for a core-collapse supernova?

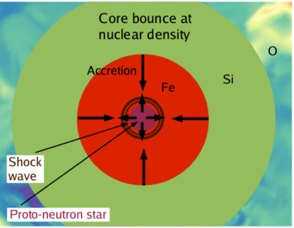
Neutrinos:

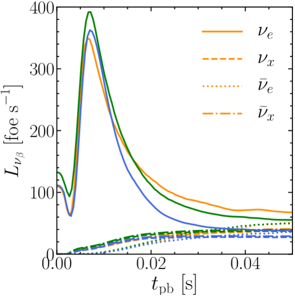
- $\sim 10^{58}$ of them emitted from a single core collapse
- only they can reveal the deep interior conditions
- only particles detectable from the collapse to a black hole



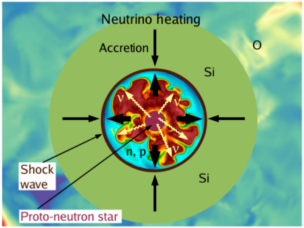
Different Phases of Supernova Explosion

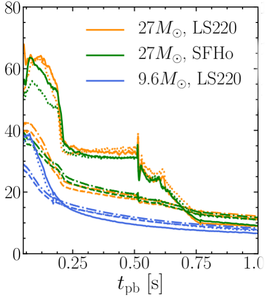
- Infall phase, ν_e burst ~ 40 ms



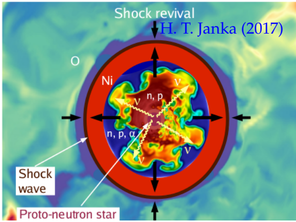


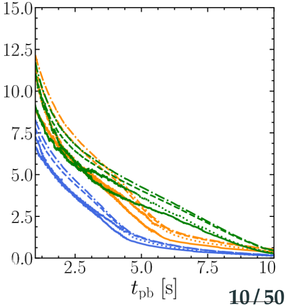
- Accretion phase, ~ 100 ms





- Cooling phase, ~ 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

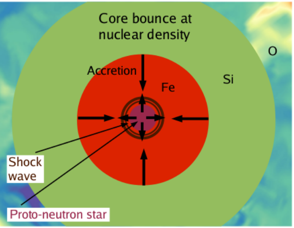
What can we learn with a variety of detectors?

- 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

Different Phases of Supernova Explosion

- Infall phase,
  ν_e burst ~ 40 ms



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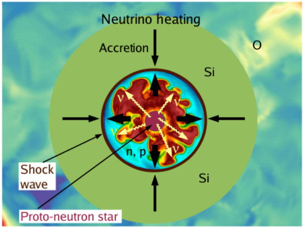
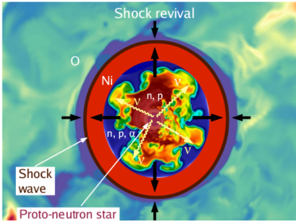


- Cooling phase,
  ~ 10 s

H. T. Janka (2017)



New neutrino physics affects the core-collapse supernovae:

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

astrophysical feedback often ignored

Which bounds remain unchanged with astrophysical feedback?

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.

Zofia Białynicka-Birula (1964)

Lepton number violating neutrino self-interactions

Motivation - to be taken with a grain of salt:

- lepton number conservation - accidental symetry
- potential cosmological hints

  Barenboim et al. (2019), Song, Gonzalez-Garcia, Salvado (2018), ..
- strong impact on core-collapse supernova

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

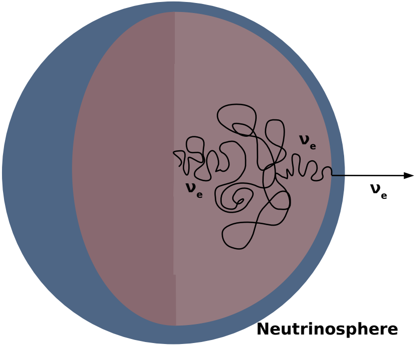
New Interaction Lagrangian

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

Probability of the New Interaction

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

Neutrino Trapping and $\beta-$equilibrium



Neutrino trapping

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

β-equilibrium

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

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

Implementation:

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

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

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

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

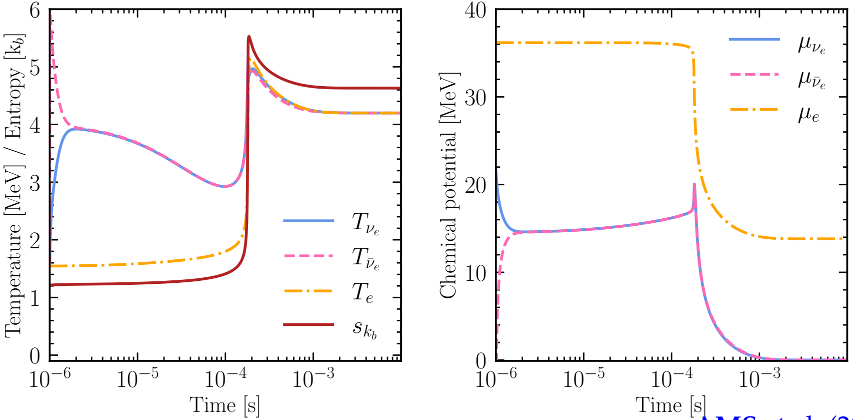
$$e^- + p \leftrightharpoons \nu_e + n$$

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

Temperature and chemical potential evolution for leptons

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

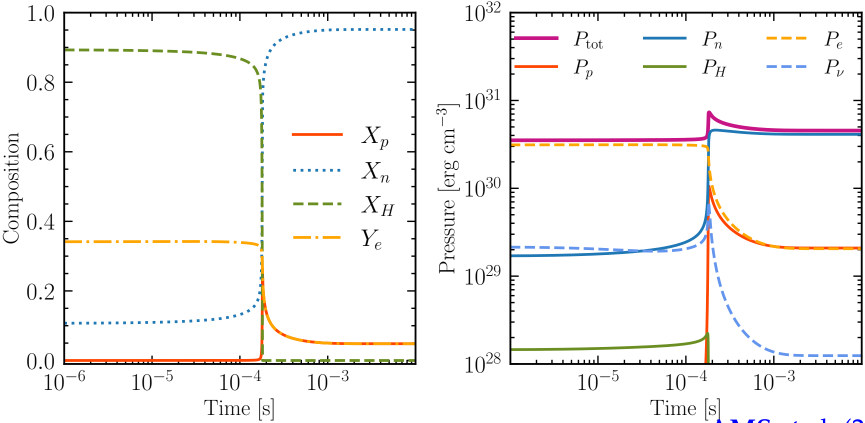
$$\frac{d\mu_i}{dt} = \left(\frac{\partial \rho_i}{\partial T_i} \frac{dn_i}{dt} - \frac{\partial n_i}{\partial T_i} \frac{d\rho_i}{dt} \right) \Big/ \left(\frac{\partial n_i}{\partial \mu_i} \frac{\partial \rho_i}{\partial T_i} - \frac{\partial n_i}{\partial T_i} \frac{\partial \rho_i}{\partial \mu_i}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



AMS et al. (2024)

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

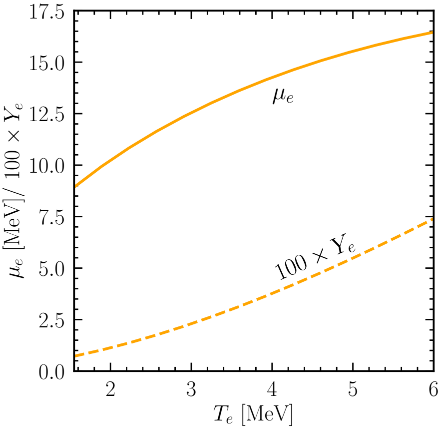
Composition and Pressure Support of the Core

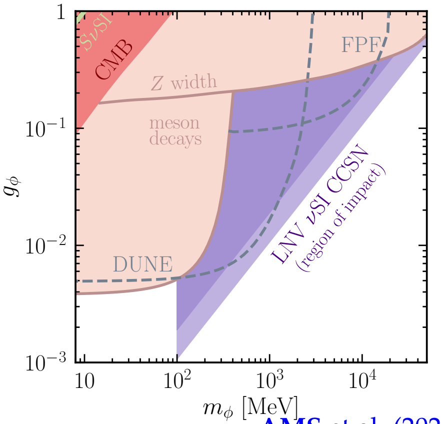


AMS et al. (2024)

- 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 β-equilibrium with LNV νSI

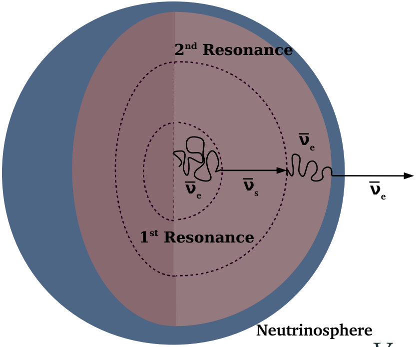




AMS et al. (2024)

- 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 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

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

Collisions

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

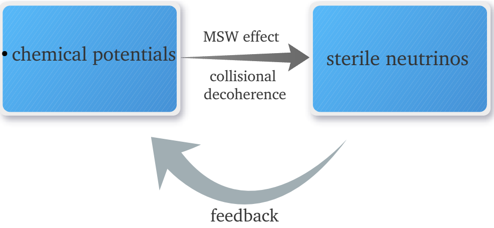
$\nu_e - \nu_s$ mixing: multiple resonances

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

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

The sterile-tau neutrino mixing: growth of the asymmetry

Only active neutrinos



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

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.**

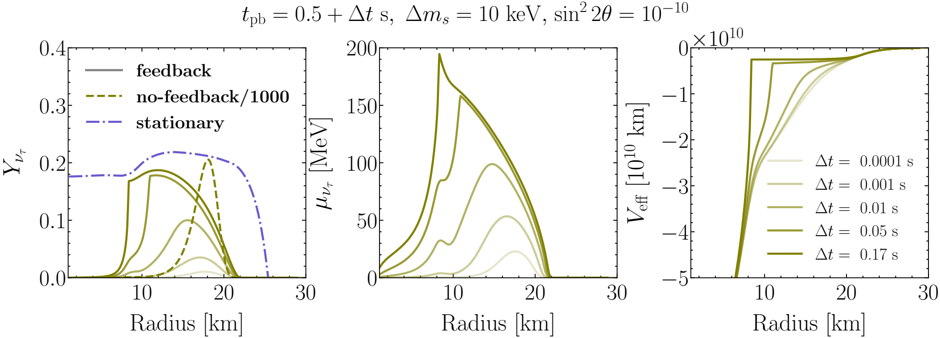
The change imposed on the SN medium is referred to as the **dynamical feedback.**

Active + sterile neutrinos

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

AMS et al. (2018)

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.

AMS et al. (2018)

The sterile-electron neutrino mixing: dynamical feedback

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

β equilibrium

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

Lepton number conservation

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

Baryon number conservation

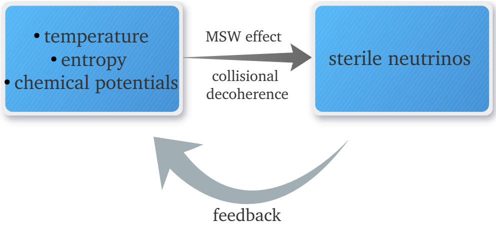
$$Y_p(r,t) + Y_n(r,t) = 1\ ,$$

Charge conservation

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

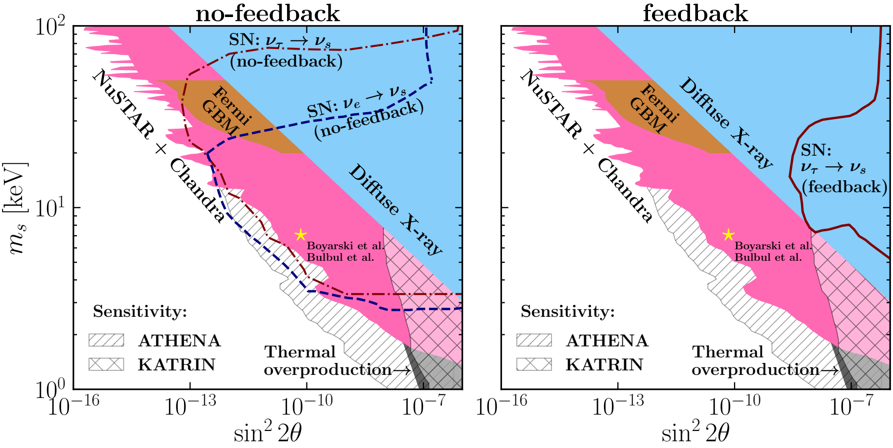
Entropy change

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



AMS et al. (2019)

Supernova bounds on the mixing parameters

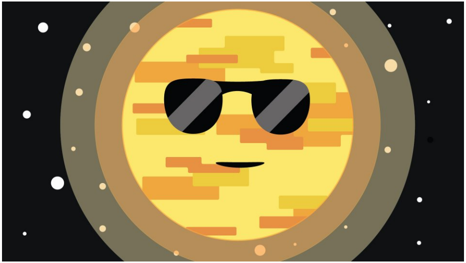


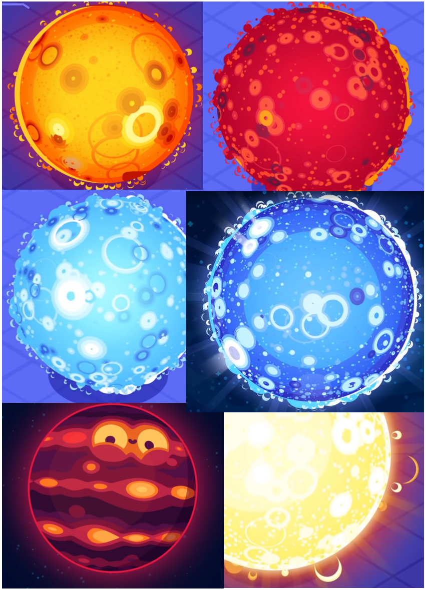
AMS et al. (2018), (2019)

- 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**
- Low-energy Atmospheric Neutrinos
- Summary and Outlook

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

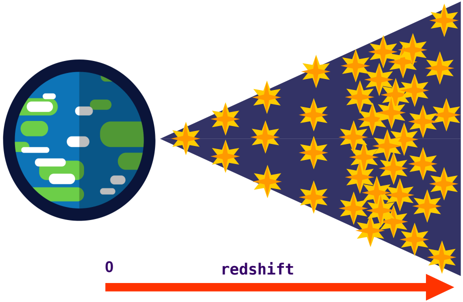
$$\Phi_{\nu_\beta}(E) = \frac{c}{H_0}\int dM \int dz \frac{R_{\rm SN}(z,M)}{\sqrt{\Omega_M(1+z)^3+\Omega_\Lambda}}\left[f_{\rm CC-SN}F_{\nu_\beta,{\rm CC-SN}}(E',M)+f_{\rm BH-SN}F_{\nu_\beta,{\rm BH-SN}}(E',M)\right]$$

fraction of neutron-star-forming progenitors

neutrino flux from a single star

The DSNB is sensitive to:

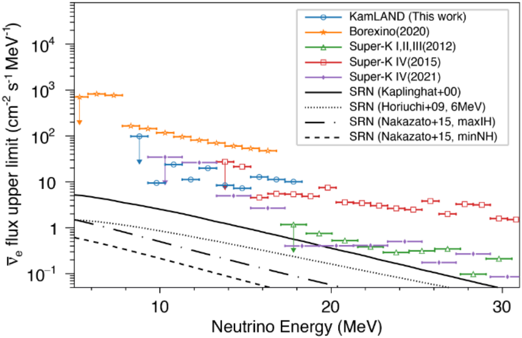
- $R_{\rm SN}, f_{\rm BH-SN}$
- neutrino flavor evolution
- equation of state
- mass accretion rate in BH-SN
- non-standard physics



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)

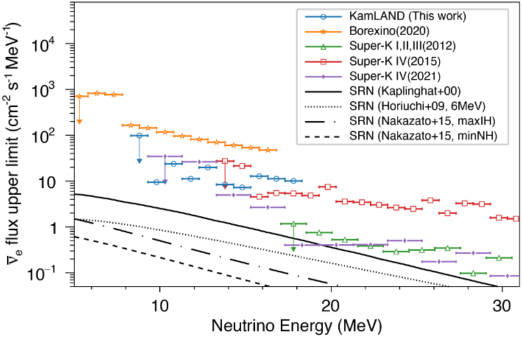


DSNB limits:

- $\bar{\nu}_e \approx 2.7\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}$ 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 $E_\nu \in [22.9, 36.9\ \mathrm{MeV}]$ SNO collab. (2020)
  possibly detectable by DUNE Møller, **AMS**, et al. (2018), Zhu et al. (2019)
- $\nu_x \approx 750\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}$ for $E_\nu > 19.3$ MeV Lunardini, Peres (2008)

Diffuse supernova neutrino background: current limits

SK collab. (2021)



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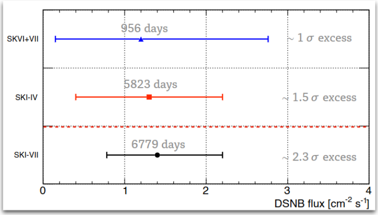
  possibly detectable by DUNE Møller, **AMS**, et al. (2018), Zhu et al. (2019)
- $\nu_x \lesssim 100\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}$ for $E_\nu > 19.3$ MeV **AMS**, Beacom, Tamborra (2021)

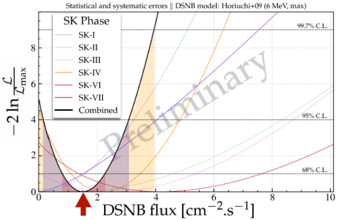
Tension from zero assumption

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_ν > 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_ν > 17.3 MeV

➡ **exhibit ~2.3 σ excess!!**

17

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)

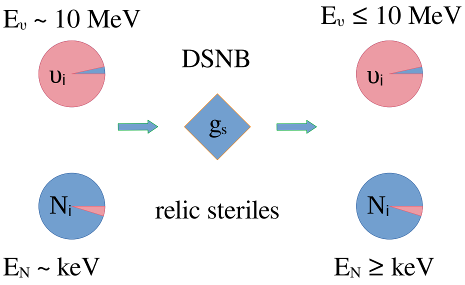
  Sanduleak and Betelgeuse in binary systems? Morris & Podsiadlowski (2007), (2009), Goldberg et al (2024), MacLeod et al (2024)

Non exhaustive list of references

How to probe new physics with these uncertainties?

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 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

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

Modified DSNB flux

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

Probability of interaction

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

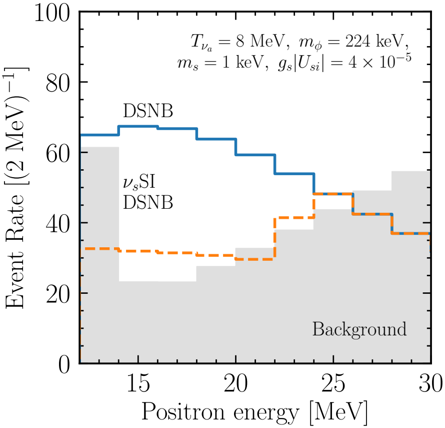
$$\tau_i(E_\nu, z) \simeq \tau_R \Theta(z - z_R) = \frac{\Gamma_R(z_R)}{(1+z_R)H(z_R)} \Theta(z - z_R)$$

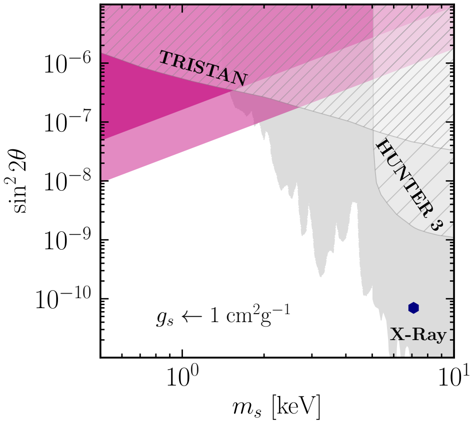
where $z_R = E_R/E_\nu - 1$,
interaction rate $\Gamma_R(z_R) \simeq |U_{si}|^2 n_{\nu_s}(z_R) \sigma_R$,
and sterile neutrino number density $n_{\nu_s}(z_R) = n_{\nu_s}(1+z_R)^3$

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)

Secret neutrino interactions: DSNB

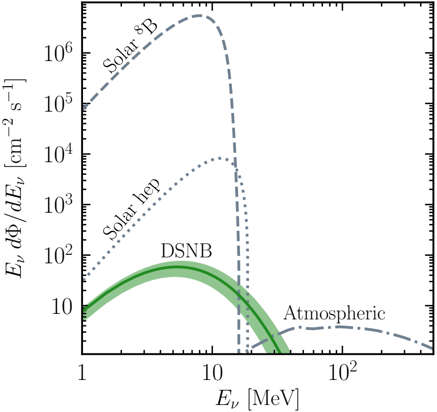
Balantekin, Fuller, Ray, **AMS** (2023)





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

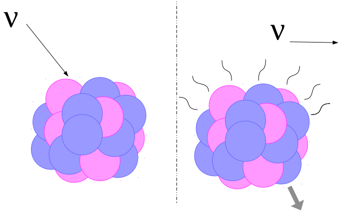
Can we detect the x-flavor DSNB? Maybe



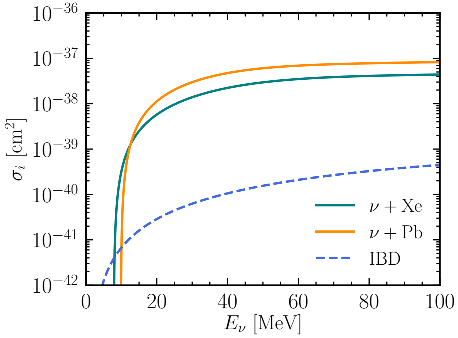
DSNB modeling:
Møller, **AMS**, et al. (2018)

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

Maybe: Coherent elastic neutrino-nucleus scatterings (CEνNS)



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



Cross section

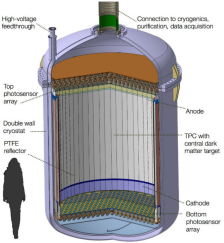
$$\frac{d\sigma_{\rm SM}}{dE_r} = \frac{G_F^2 m_T}{4\pi} Q_w^2 \left(1 - \frac{m_T E_r}{2E_\nu^2}\right) F^2(Q), \;\; Q_w = \left[N - Z(1 - 4\sin^2\theta_W)\right]$$

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

Cross section:
Theory: Freedman (1974),
Measured: COHERENT (2017)

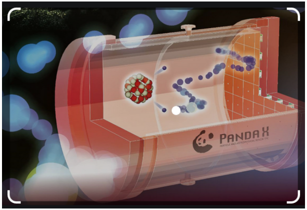
Current and future CEνNS detectors

XENONnT, DARWIN



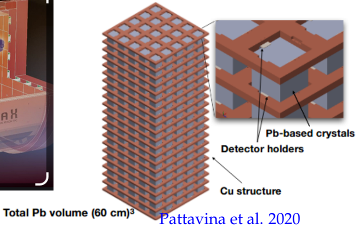
Aalbers al. 2016

PandaX-4T, PandaX-xT



Menget al. 2021

RES-NOVA



Pattavina et al. 2020

fiducial volumes: few - hundreds ton

target materials: Xe, Pb

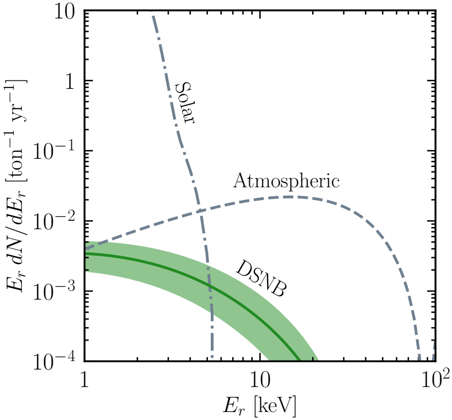
thresholds: $\mathcal{O}(1)$ keV

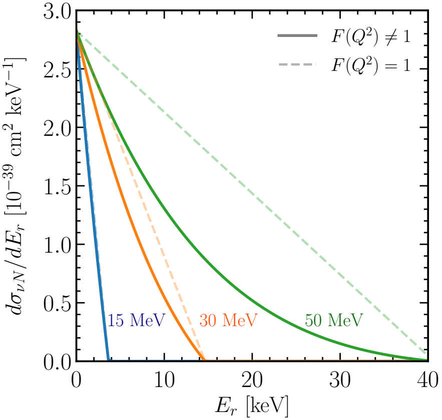
efficiency: $\sim$ 80-100%

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

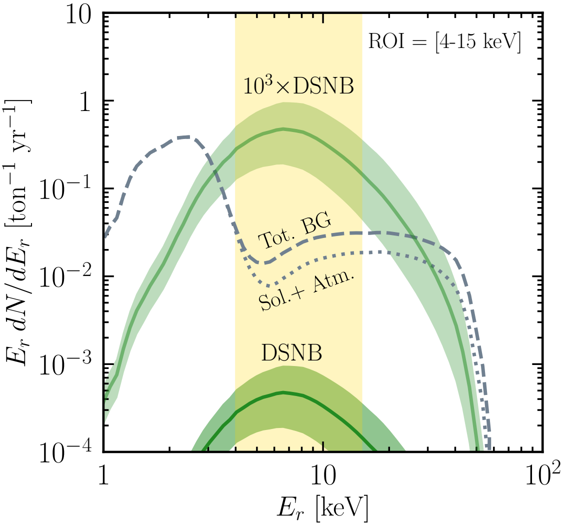




- The potential energy window displayed by the bare fluxes disapears
- Reason: Low energy recolis are most probable for all neutrino energies
- Detection of the x-flavor DSNB seems out of reach, BUT...

AMS, Beacom, Tamborra (2022)

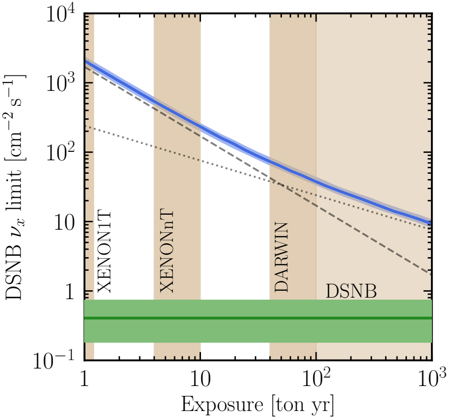
Can we improve the limits on the x-flavor DSNB? Yes

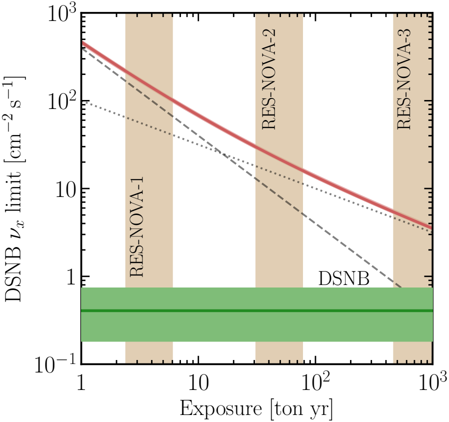


- Potential for an imporevement by $\gtrsim 1-2$ orders of magnitude

AMS, Beacom, Tamborra (2022)

Sensitivity bounds on the normalization of the x-flavor DSNB

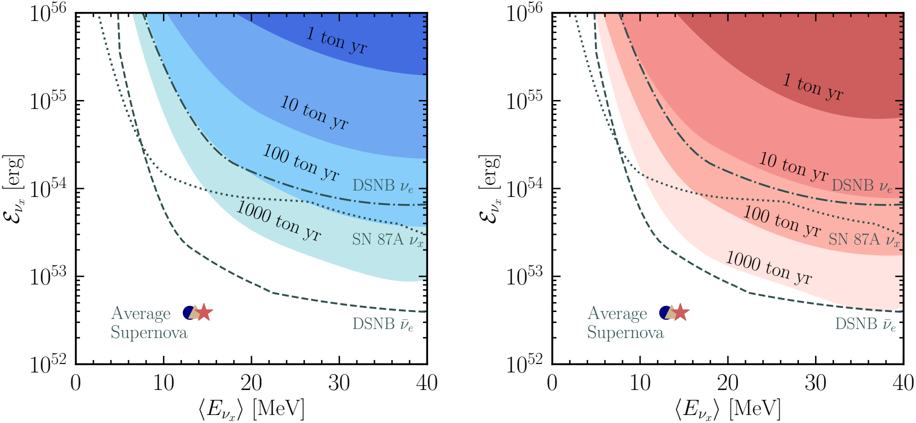




- XENON1T, PandaX-4T: limits comparable to the SK ν_x DSNB limit
- Constant energy window: limits can improve $\mathcal{O}(10\%)$ for wider windows at small exposures and narrower windows at large exposures

AMS, Beacom, Tamborra (2022)

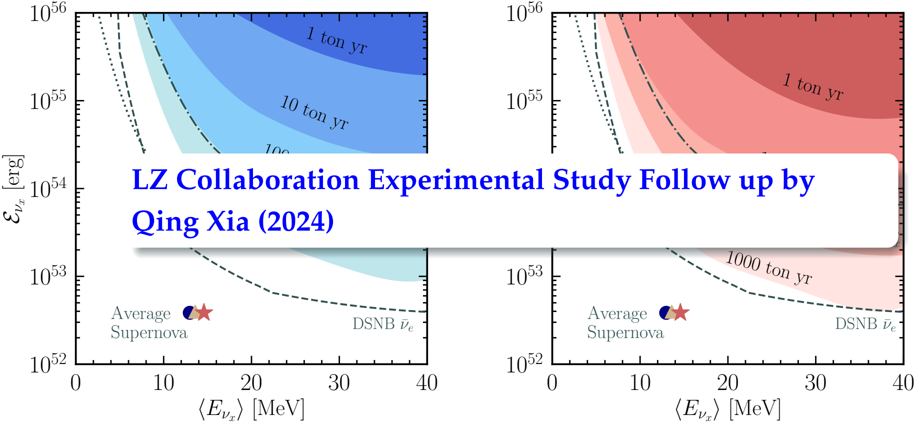
Sensitivity bounds on the x-flavor DSNB



- 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

AMS, Beacom, Tamborra (2022)

Sensitivity bounds on the x-flavor DSNB



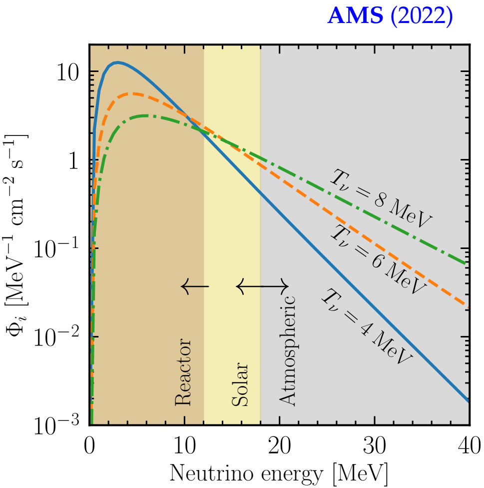
LZ Collaboration Experimental Study Follow up by Qing Xia (2024)

- 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

AMS, Beacom, Tamborra (2022)

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

Diffuse Supernova Neutrino Background (DSNB)



- DSNB $\rightarrow$ isotropic and stationary guaranteed neutrino flux

  Guseinov (1967), Totani et al. (2009), Ando, Sato (2004), Lunardini (2009), Beacom (2010),..

- mitigating uncertainties in the atmospheric neutrinos helps the discovery limits

Better Knowledge of Atmospheric Neutrinos $\rightarrow$ Helps Direct Dark Matter Detection

Low-energy Atmospheric Neutrino Flux

Primary production channels

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

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

Non-oscillated flavor ratio

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

Sources of uncertainty

solar wind modulations

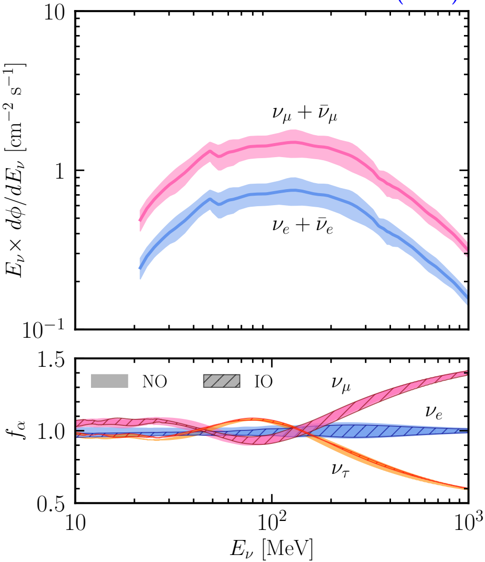
Earth's geomagnetic field

Oscillated flavor ratio

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

Past measurements: energies > 100 MeV

AMS & Beacom (2023)



Neutrino flux: Zhuang (2021)

Mixing: NuCraft

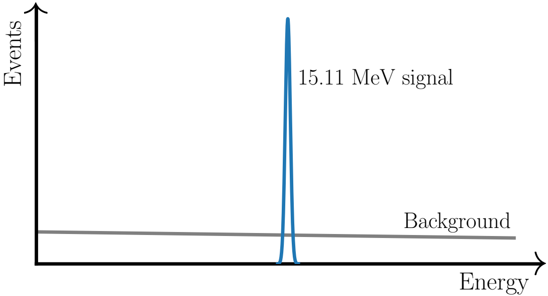
Distinctive nuclear channels in JUNO

AMS & Beacom (2023)

Neutral current channels

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

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



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

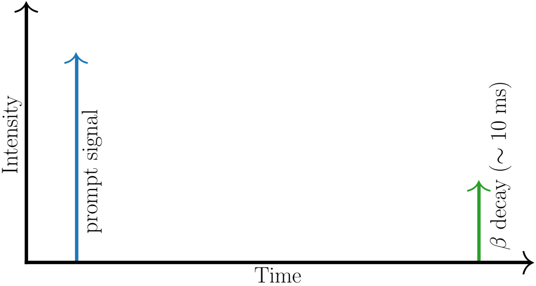
Distinctive nuclear channels in JUNO

AMS & Beacom (2023)

Charged current channels: $\nu_\mathbf{e}$

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

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



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

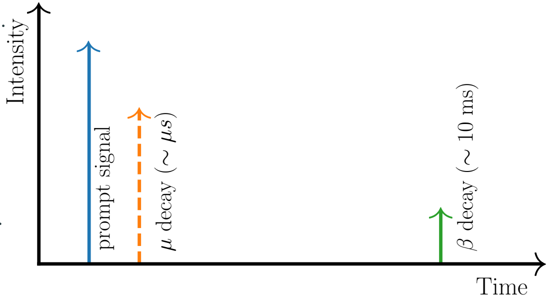
Distinctive nuclear channels in JUNO

AMS & Beacom (2023)

Charged current channels: ν_μ

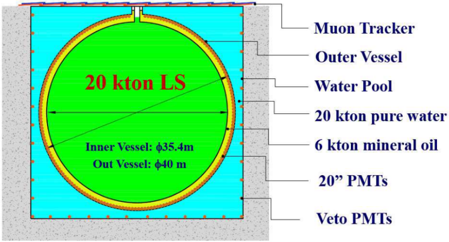
$$\nu_\mu + {}^{12}\text{C} \to \mu^- + {}^{12}\text{N}_{\text{g.s.}}$$
$$^{12}\text{N}_{\text{g.s.}} \to {}^{12}\text{C} + e^+ + \nu_e$$
$$\mu^- \to e^- + \bar{\nu}_e + \nu_\mu,$$

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



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

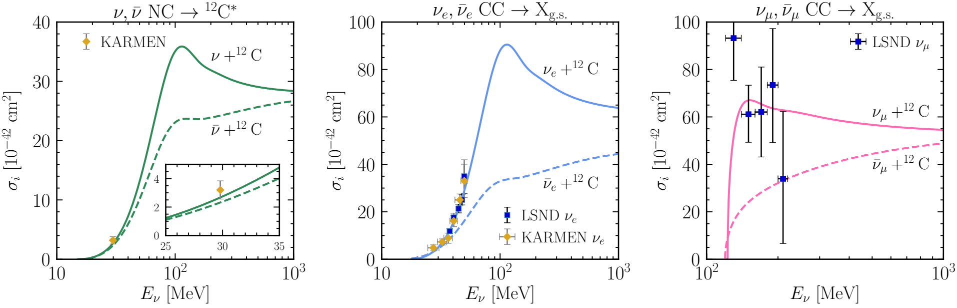
The Jiangmen Underground Neutrino Observatory (JUNO)



- large-scale carbon-based liquid scintilator detector
- soon operational ($\sim$ 2025)
- excellent energy resolution $\lesssim 3\%$
- excellent spatial resolution $\lesssim 10$ cm
- low backgrounds in the considerd channels

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

Cross section: elementary particle treatment (EPT)



AMS & Beacom (2023)

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

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

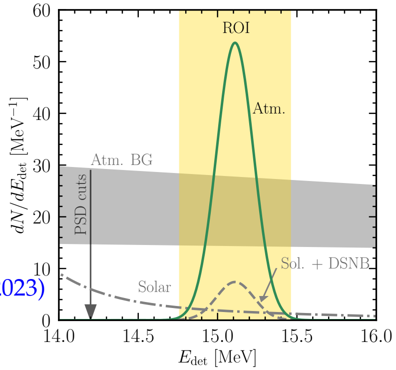
Atmospheric neutrino detection in JUNO

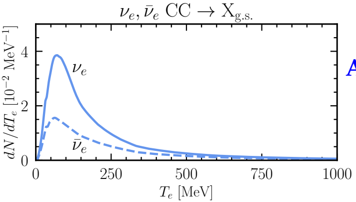
NC channel detection: single events

Irreducible BG: solar and DSNB ν

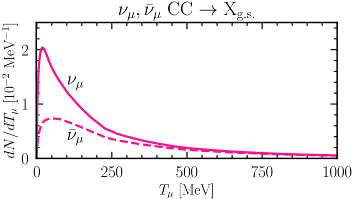
Reducible BG: atm. ν - p scattering

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





AMS & Beacom (2023)



CC channel detection: coincidence events

Irreducible BG: accidental coincidences

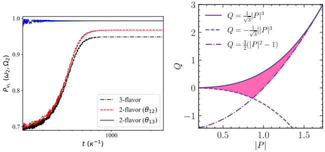
Rate per 85 kton yr: $\sim$0.0004

essentially background free channels

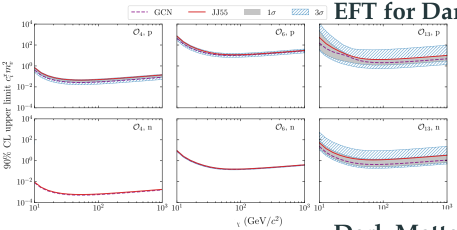
- Why is studying astrophysical neutrinos crucial?
- Core-collapse Supernovae as New Physics Probes
- Diffuse Supernova Neutrino Background
- Low-energy Atmospheric Neutrinos
- **Summary and Outlook**

Some More of My Favorite Astroparticle Topics

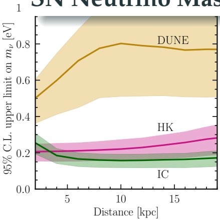
Entanglement and Many-body Neutrino Interactions



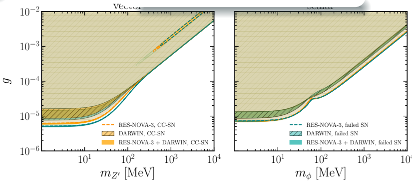
EFT for Dark Matter



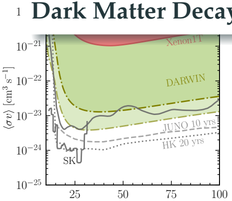
SN Neutrino Mass



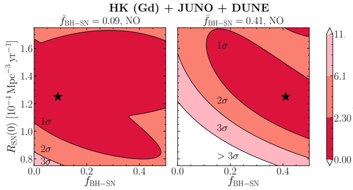
Astro Neutrinos NSI



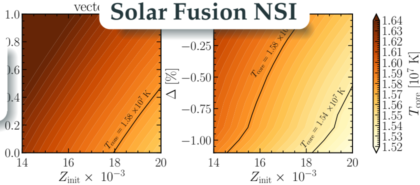
Dark Matter Decay



DSNB measures astro parameters



Solar Fusion NSI



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

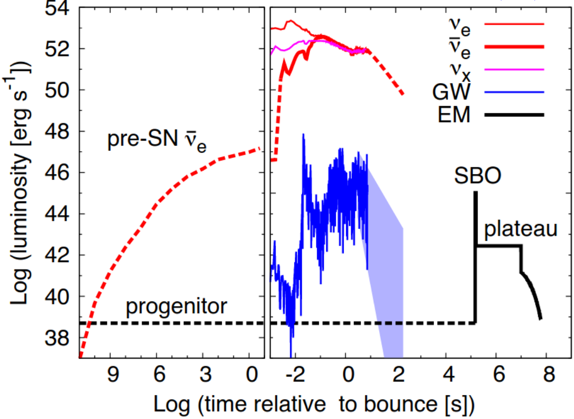
Exciting times ahead

Thank you for the attention!

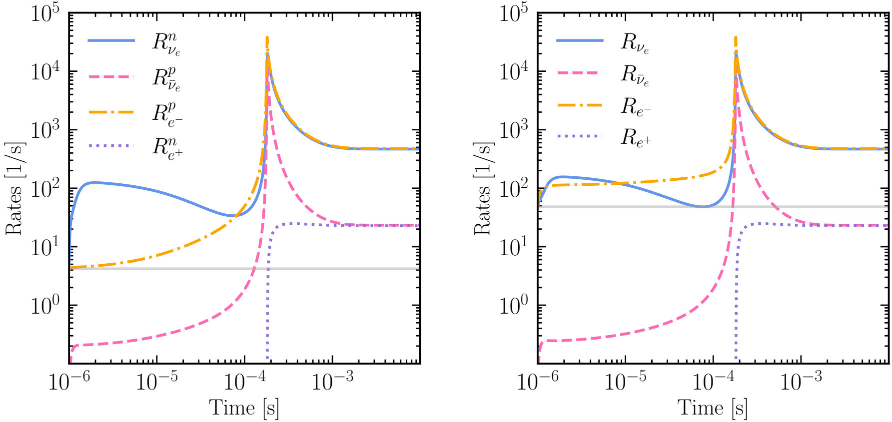
Backup

Core-Collapse Supernova Light Curve

Nakamura et al. (2016)

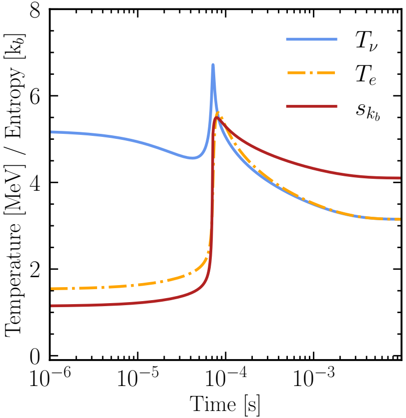


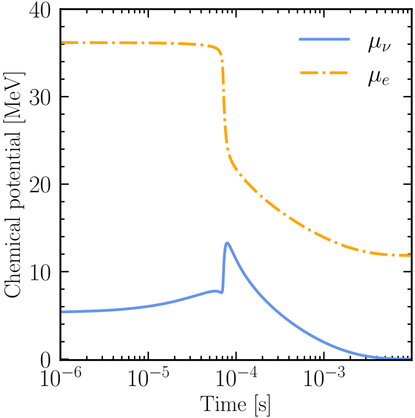
Weak reaction rates



- initial increase in $\nu_e + n$, $\nu_e + A$ and $e^- + A$
- enhanced ν_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

Partial Derivatives for the Fermi-Dirac distributions

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

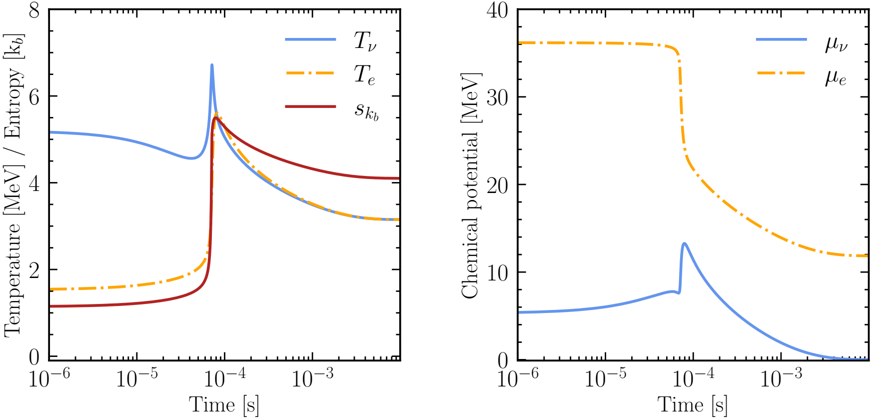
$$\frac{\partial n}{\partial T} = \frac{g}{2\pi^2} \int_m^\infty dE\, E \sqrt{E^2 - m^2}\, \frac{(E-\mu)}{4T^2} \cosh^{-2}\left(\frac{E-\mu}{2T}\right) , \tag{2a}$$

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

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

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

All flavors LNV νSI



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)

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

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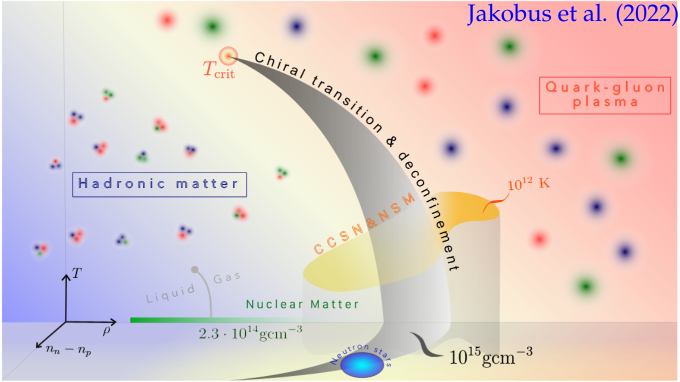
Exotic Supernovae as Probes of Neutrino Physics

QCD phase diagram

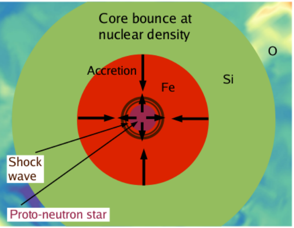


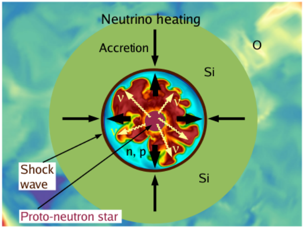
- Does the protocompact star contain non-leptonic degrees of freedom other than neutrons and protons?
- How to identify the presence of quark matter in astrophysical objects?

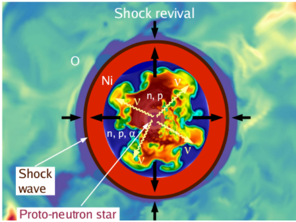
Different phases of core-collapse supernova explosion

- Infall phase,
  ν_e burst ~ 40 ms
- Accretion phase,
  ~ 100 ms
- Cooling phase,
  ~ 10 s

H. T. Janka (2017)







What drives the supernova supernova explosions?

- neutrino heating Colgate & White (1966), Bethe & Wilson (1985)
- magneto-rotational mechanism LeBlanc and Wilson (1970), Takiwaki et al. (2009)
- particles beyond the Standard Model Fuller et al. (2008), **AMS** et al. (2020) ...
- phase transition to quark matter Sagert et al. (2008)...

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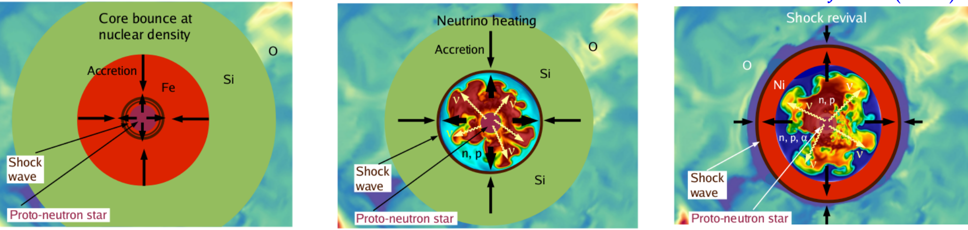

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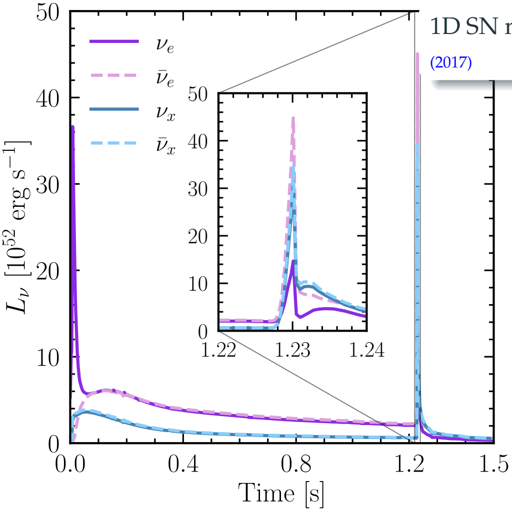
- **phase transition to quark matter** Sagert et al. (2008)..

Neutrino Emission Properties from the QHPT CCSN

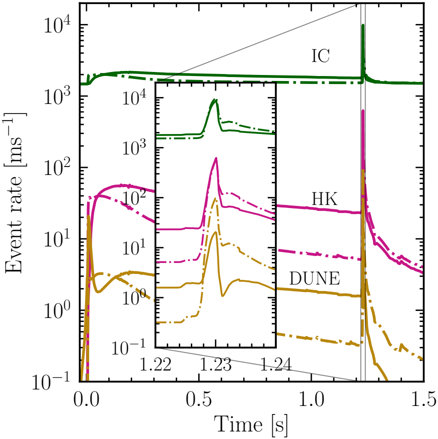


1D SN model Fischer, Bastian, Wu et al. (2017)

- second sharp neutrino burts dominated by $\bar{\nu}_e$
- non-exploding models can explode

Pitik, Heimsoth, **AMS**, Balantekin (2023)

Neutrino Event Rates



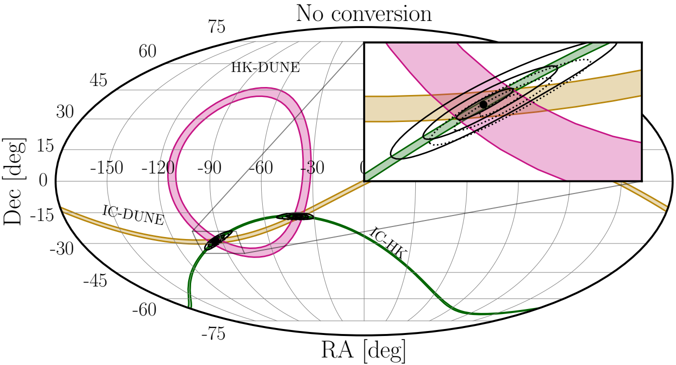
Impact of neutrino conversions

- Event rate in the antineutrino detectors comparable for both conversion scenarios
- Event rate in the neutrino detector larger for the full conversion case

$$R(t) = N_t \int_{E_\nu^{\min}}^{\infty} dE_\nu \int_{E_{\rm th}}^{E_{\max}} dE \; \varepsilon\sigma_i(E, E_\nu) \; F_{\nu_\beta}(E_\nu, t)$$

Pitik, Heimsoth, **AMS**, Balantekin (2023)

Determination of the Supernova Localization



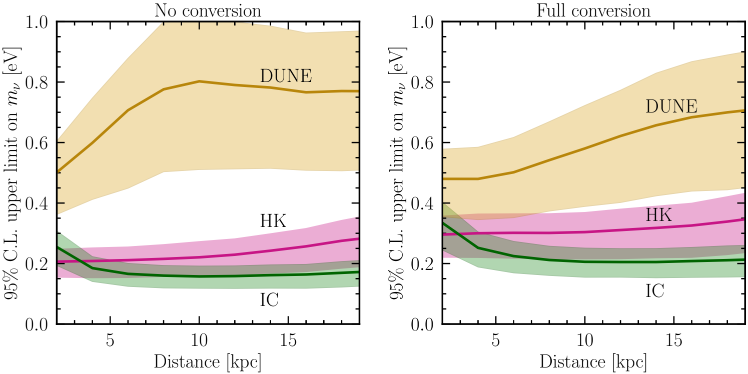
Pitik, Heimsoth, **AMS**, Balantekin (2023)

- improvement by 4.5-10 times compared to neutronization burst
- comparable results for black hole forming supernovae
- not far off from elastic scattering on electrons

Sensitivity to the Absolute Neutrino Mass

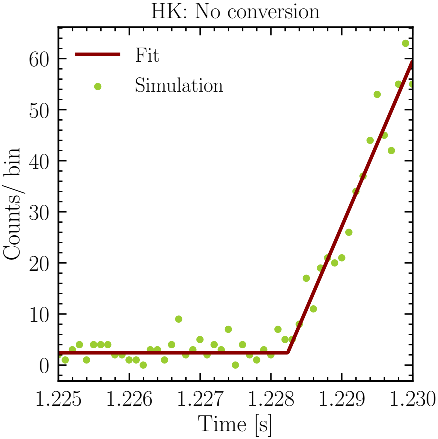
$$\Delta t \approx 5.15 \left(\frac{D}{10\ \text{kpc}}\right) \left(\frac{m_\nu}{1\ \text{eV}}\right)^2 \left(\frac{10\ \text{MeV}}{E_\nu}\right)^2\ \text{ms}$$

Pitik, Heimsoth, **AMS**, Balantekin (2023)



- up to $\sim$ 10x improvement compared to neutronization burst
- more stringent limits than from the laboratory experiments (0.4 eV)

Timing the Neutrino Signal



Detectors	No conversion	Full conversion
	B_{ij} [ms]	
IC-HK	-0.32 ± 0.10	-0.32 ± 0.10
IC-DUNE	-0.11 ± 0.48	-0.27 ± 0.20
HK-DUNE	0.22 ± 0.50	0.05 ± 0.22
	$\delta(\theta_{ij})$ (min, max) [deg]	
IC-HK	$(0.30, 5.00)$	$(0.29, 4.90)$
IC-DUNE	$(1.00, 10.67)$	$(0.41, 6.90)$
HK-DUNE	$(2.27, 12.85)$	$(1.00, 8.54)$
	95% C.L. upper limit on m_ν [eV]	
IC	$0.16^{+0.03}_{-0.04}$	$0.21^{+0.05}_{-0.05}$
HK	$0.22^{+0.05}_{-0.06}$	$0.30^{+0.07}_{-0.09}$
DUNE	$0.80^{+0.21}_{-0.29}$	$0.58^{+0.14}_{-0.19}$

$$\Delta t_{ij}^{\text{true}} = \frac{(\mathbf{r}_i - \mathbf{r}_j) \cdot \mathbf{n}}{c} = \frac{\mathrm{D}_{ij} \cos\theta}{c}$$

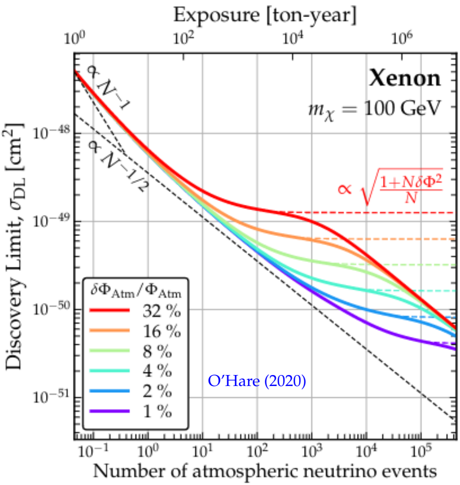
$$R_{\text{exp}} = \begin{cases} R_*, & \text{if } t < t_0 \\ R_* + a(t - t_0), & \text{otherwise} \end{cases},$$

$$\Delta t_{ij}^{\text{measured}} = \Delta t_{ij}^{\text{true}} + B_{ij}$$

Pitik, Heimsoth, **AMS**, Balantekin (2023)

Fit: Halzen and Raffelt (2009)

Direct Dark Matter Detection Experiments - Neutrino Fog

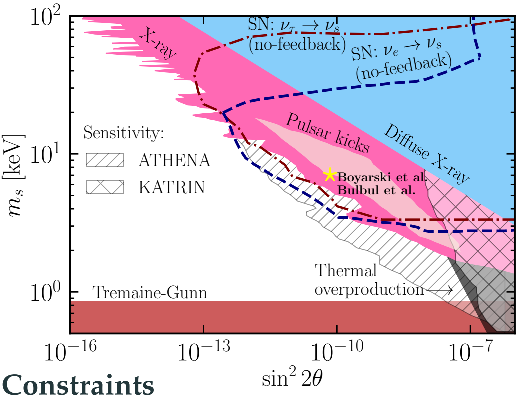


- neutrino floor/fog $\rightarrow$ barrier for dark matter direct detection experiments

  Vergados & Ejiri (2008), Strigari (2009), Baudis et al. (2013), ...

- mitigating uncertainties in the atmospheric neutrinos helps the discovery limits

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))

Sterile neutrino conversions in the stellar core

Collisional production

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

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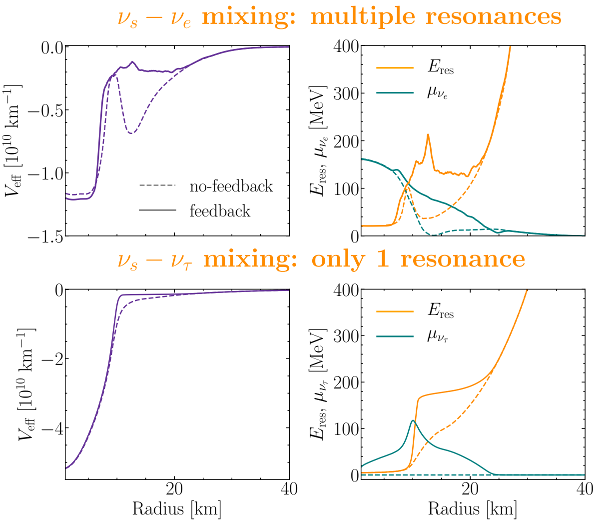


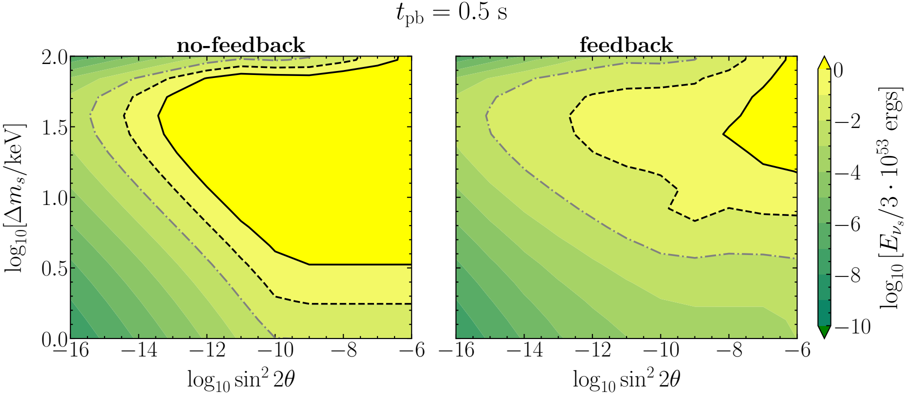
1D SN model
Garching group archive

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

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

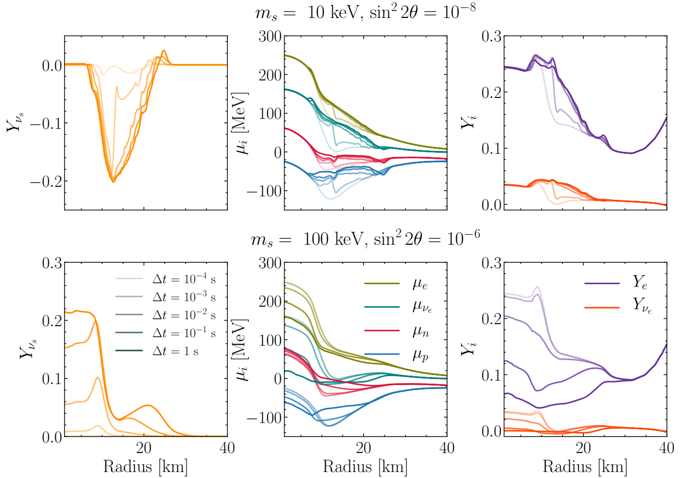
- **Negative $V_{\rm eff} \rightarrow$ MSW resonances only for antineutrinos.**
- **Growing chemical potential slows down $\bar{\nu}_s$ production.**

Supernova bounds on the mixing parameters



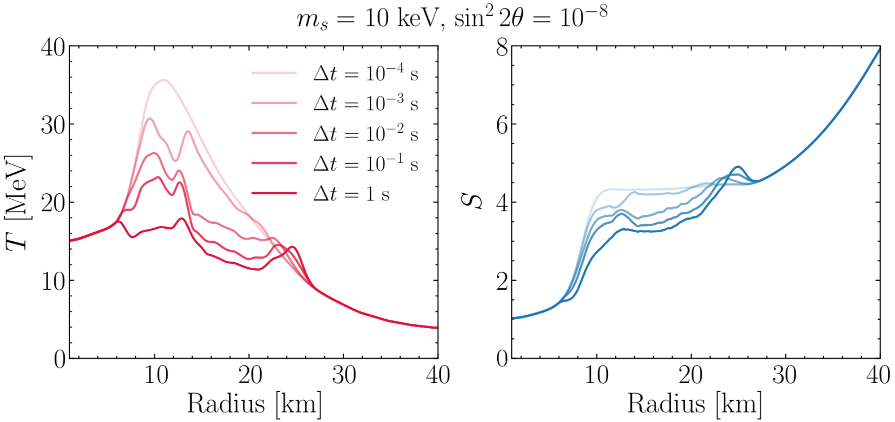
- The inclusion of feedback greatly reduces the excluded region.
- Large region of the parameter space still compatible with SNe

Radial evolution of the asymmetry



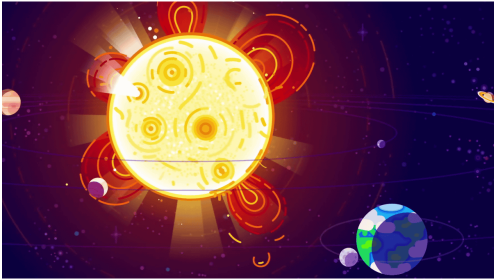
- Sterile neutrinos modify $Y_e,\ Y_{\nu_e},\ Y_p$ and Y_n.
- Feedback on the physical quantities depends greatly on the m_s.

Radial evolution of temperature and entropy per baryon



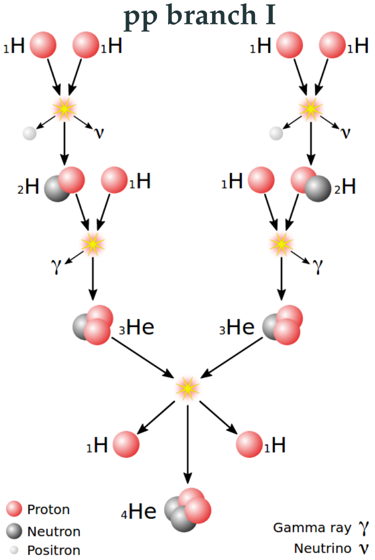
- The $\nu_s - \nu_e$ mixing induces large variations on
  - the entropy per baryon,
  - the supernova medium temperature.

Why our sun is an interesting place to look at?



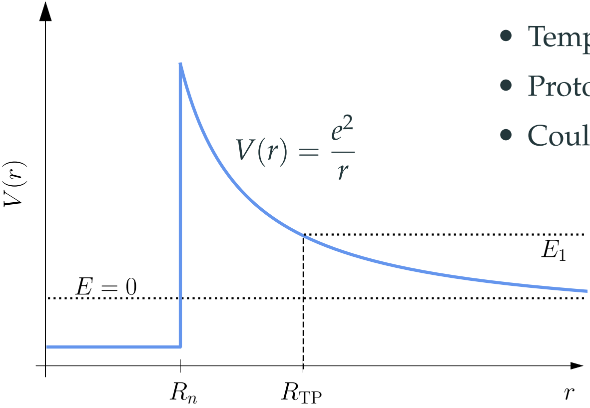
The Sun

- Closest star
- Well studied and well measured
- Better measurements will come
- *pp*-chain - primary channel (99.7%)



Pictures: Kurzgesagt, Wikipedia

Quantum tunneling through Coulomb barrier



- Temperature $\approx 1.56 \times 10^7$ K
- Proton energy $E \approx 10$ keV
- Coulomb barrier $E_c \approx 1$ MeV

Coulomb barrier penetration factor

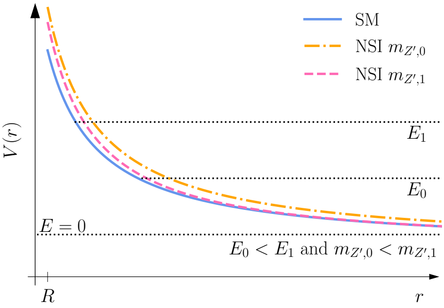
$$P_{0,\mathrm{SM}} \approx \frac{E_c}{E} \exp\left[-\frac{2\pi e^2}{\hbar v}\right] \approx \frac{E_c}{E} \exp\left[-\frac{b}{\sqrt{E}}\right] = \frac{E_c}{E} \exp\left[-W_{0,\mathrm{SM}}\right]$$

Gamow (1928), Condon & Gurney (1929), Clayton (1968)

Non-standard mediators coupling to protons

vector boson (Z') **scalar (ϕ)**

$$\mathcal{L}^{Z'} = g Z'_\mu \bar{\mathrm{p}} \gamma^\mu \mathrm{p} \qquad \mathcal{L}^{\phi} = g \phi \bar{\mathrm{p}} \mathrm{p}$$



Interaction potential

$$V(r) = \frac{e^2}{r} \pm \frac{g^2}{r} \exp\left[-m_{\{Z',\phi\}} r\right]$$

Coulomb barrier penetration factor

$$P_{0,\mathrm{SM}} \approx \frac{E_c}{E} \exp\left[-\frac{2\pi e^2}{\hbar v}\right] \approx \frac{E_c}{E} \exp\left[-W_{0,\mathrm{SM}}\right]$$

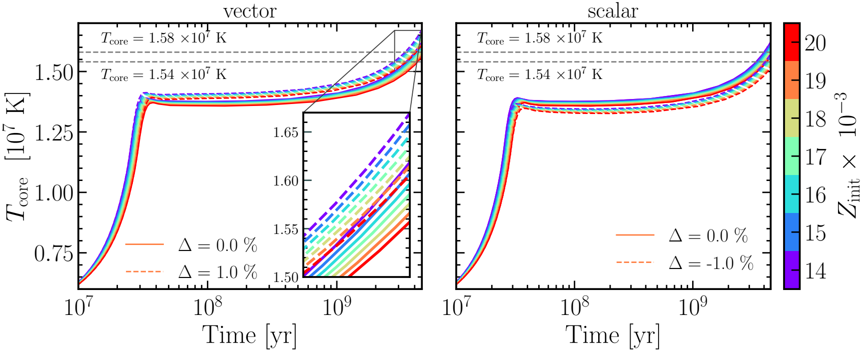
$$\Delta \approx \frac{\left| W_{0,\mathrm{NSI}}^{\frac{2}{3}} - W_{0,\mathrm{SM}}^{\frac{2}{3}} \right|}{W_{0,\mathrm{SM}}^{\frac{2}{3}}}$$

pp interaction rate

$$\Gamma_{pp} \propto \exp\left(-3.381(1 \pm \Delta) \left(\frac{T}{10^9\ \mathrm{K}}\right)^{\frac{1}{3}}\right)$$

D. D. Clayton (1968)

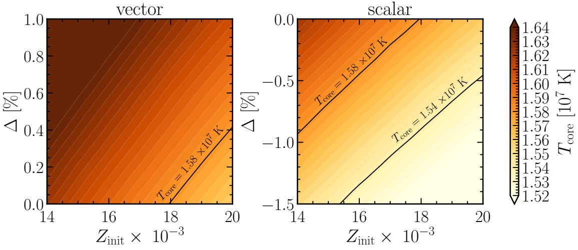
Temporal evolution of the solar core's temperature



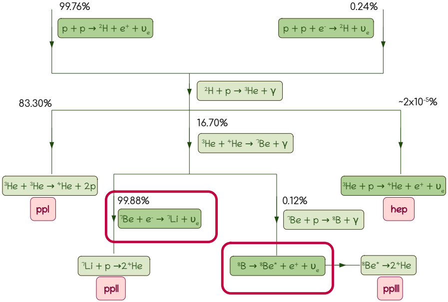
- Modules for Experiments in Stellar Astrophysics *MESA*
- The evolution has been followed until the current solar age
- Changes in the barrier and metallicity due to NSI affect the outcome

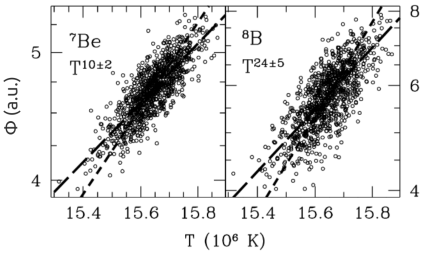
Changes in the solar parameters

Sun's core temperature



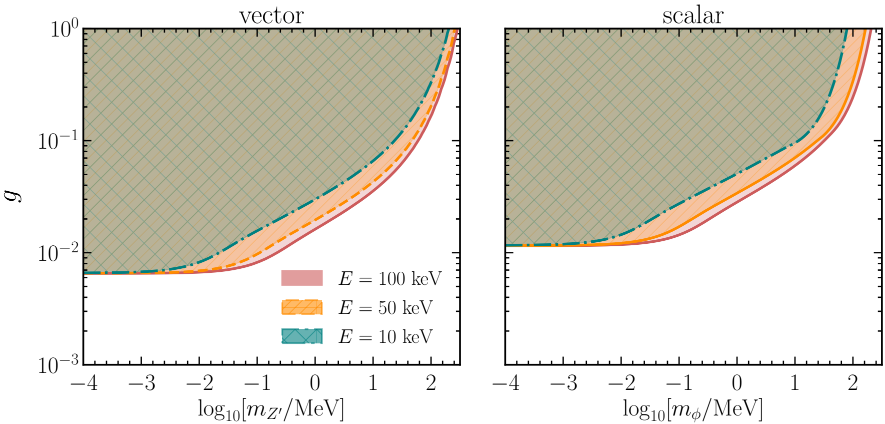
- vector boson mediator
  temperature increase
- scalar mediator
  temperature decrease





J. N. Bahcall, A. Ulmer (1996)

Sensitivity bounds on the non-standard mediators



- low mediator mass $\rightarrow$ limits are insensitive to the mediator mass
- higher proton energies $\rightarrow$ the excluded region grows
- conservative bounds $\rightarrow$ there is room for improvement

Astrophysical neutrino fluxes

Supernova neutrinos

• large flux for Galactic SN

• transient event

Solar neutrinos

$^8\mathrm{B} \to {}^8\mathrm{Be}^* + e^+ + \nu_e$

$^3\mathrm{He} + p \to {}^4\mathrm{He} + e^+ + \nu_e$

• neutrino energies up to $\sim$15 MeV

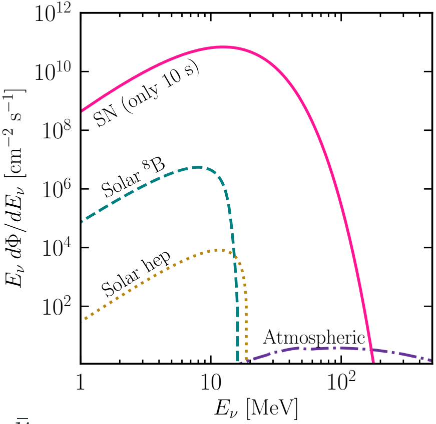
Atmospheric neutrinos

$\pi^+ \to \mu^+ + \nu_\mu$ and $\pi^- \to \mu^- + \bar{\nu}_\mu$

$\mu^+ \to e^+ + \bar{\nu}_\mu + \nu_e$ and $\mu^- \to e^- + \nu_\mu + \bar{\nu}_e$

• the highest neutrino energies among the considered sources

• small normalization



fluxes: E. Vitagliano et al. (2019), M. Honda et al. (2011), J. L. Newstead et al. (2020)

Non-standard coherent neutrino-nucleus scatterings

$g = \sqrt{|g_{q,i} g_{\nu,i}|}, \ g_{q,i} g_{\nu,i} > 0$

new vector mediator

Z'

new scalar mediator

ϕ

Lagrangian terms

$$\mathcal{L}^{Z'} = g_{\nu,Z'} Z'_\mu \bar{\nu}_L \gamma^\mu \nu_L + Z'_\mu \bar{q} \gamma^\mu g_{q,Z'} q$$

$$\mathcal{L}^{\phi}_{\mathrm{LNC}} = g_{\nu,\phi} \phi \bar{\nu}_R \nu_L + \phi \bar{q} g_{q,\phi} q$$

$$\mathcal{L}^{\phi}_{\mathrm{LNV}} = g_{\nu,\phi} \phi \bar{\nu}^c_L \nu_L + \phi \bar{q} g_{q,\phi} q$$

D. G. Cerdeno et al. (2016), Y. Farzan et al.(2018), D. Aristizabal Sierra et al. (2019)

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Cross sections

$$\frac{d\sigma_{\nu N}}{dE_r} = \frac{G_F^2 m_T}{\pi} |\xi|^2 \left(1 - \frac{m_T E_r}{2E_\nu^2}\right) F^2(Q)$$

$$\xi = -\frac{Q_w}{2} + \frac{g_{\nu,Z'} Q'_w}{\sqrt{2} G_F (2 m_T E_r + m_{Z'}^2)}$$

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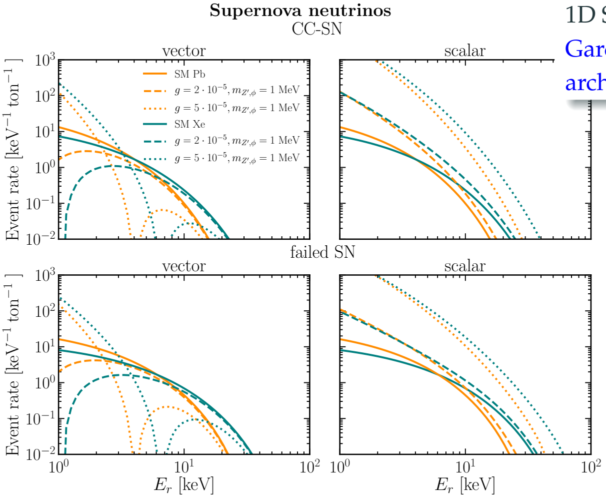
$$\frac{d\sigma_{\nu N}}{dE_r} = \frac{d\sigma_{\rm SM}}{dE_r} + \frac{d\sigma_\phi}{dE_r}$$

$$\frac{d\sigma_\phi}{dE_r} = \frac{(g_{\nu,\phi} g_{q,\phi} Q_s)^2}{2\pi (2 E_r m_T + m_\phi^2)^2} \ \frac{m_T^2 E_r}{2E_\nu^2}\ F^2(Q)$$

D. G. Cerdeno et al. (2016), Y. Farzan et al.(2018), D. Aristizabal Sierra et al. (2019)

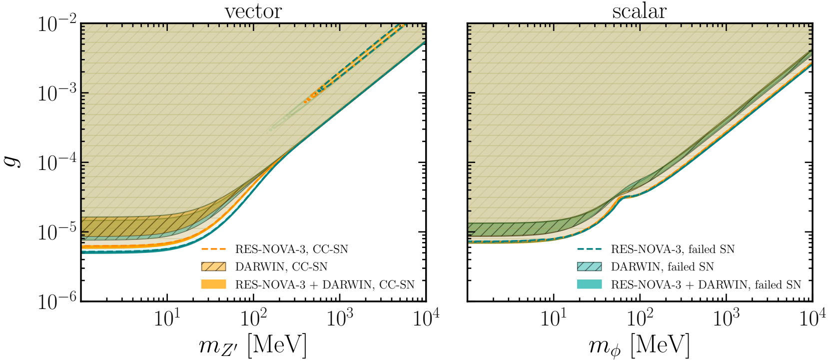
Event rates for supernova neutrinos



1D SN models
Garching group archive

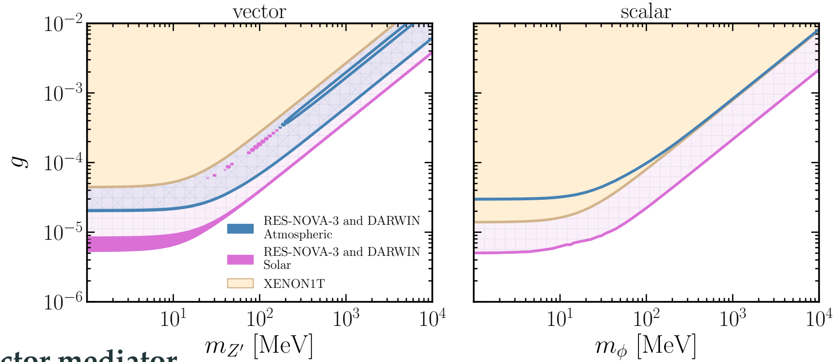
- Failed SN: hotter neutrino spectrum → longer recoil spectrum
- Heavier target: higher number of events but shorter recoil spectrum

Sensitivity bounds: supernova neutrinos



- failed SN: higher number of events → better constraints
- RES-NOVA-3 drives the limits due to higher volume
- vector mediator small unconstrained region due to the interference term
- limits on the vector mediator better for low mediator masses

Sensitivity bounds: solar and atmospheric neutrinos



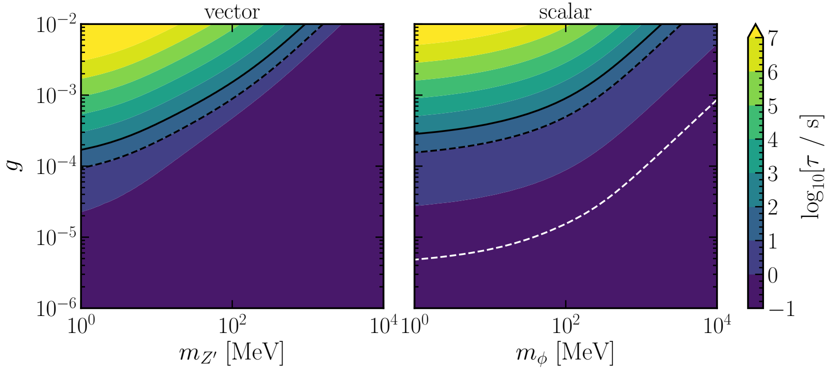
Vector mediator

- Solar neutrinos: bounds driven by Xe based detector
- Atmospheric neutrinos: bounds driven by Pb detector

Scalar mediator

- Bounds driven by Pb detector

Non-standard coherent scattering in the supernova core



- mean-free path

$$\lambda_{\nu_\beta} = \sum_{\text{CC,NC}} \frac{\int dE_{\nu_\beta} f(E_{\nu_\beta}) E_{\nu_\beta}^2}{n_t \int dE_{\nu_\beta} f(E_{\nu_\beta}) E_{\nu_\beta}^2 \sigma_i(E_{\nu_\beta})}$$

- diffusion time

$$\tau_{\nu_\beta} = \int_{R_1}^{R_2} dr \frac{r}{\lambda_{\nu_\beta}(r)}$$

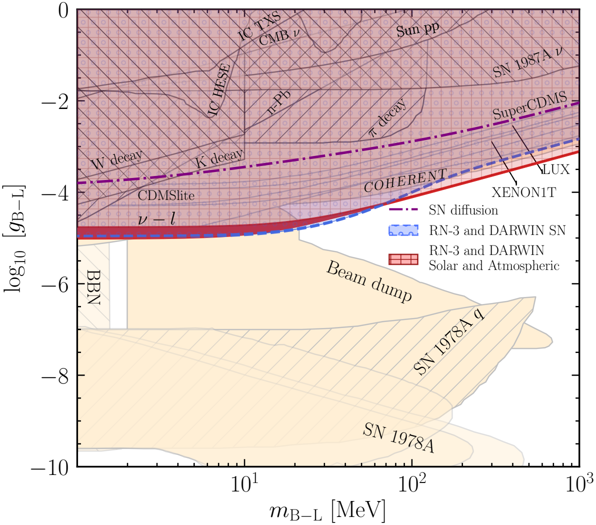
- number of scatters

$$N = \int_0^{R_2} \frac{2r}{\lambda(r)^2}\, dr$$

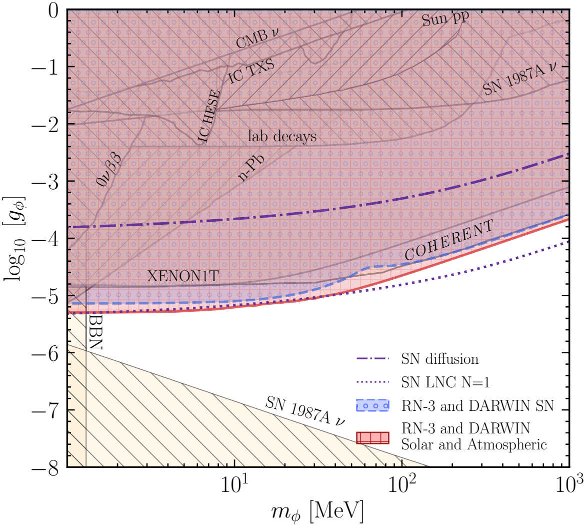
$R_1 = 10$ km

$R_2 = 40$ km

Comparison of limits from specific new physics models

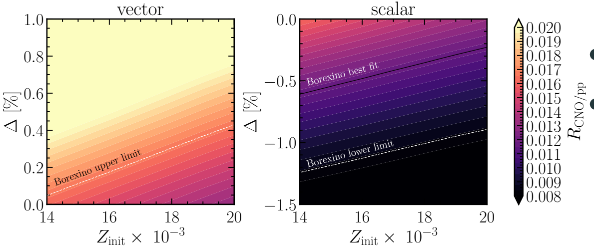


Comparison of limits from specific new physics models



Changes in the solar parameters

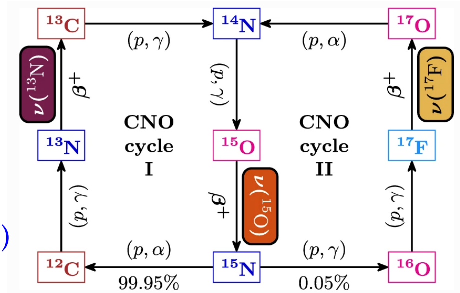
CNO to *pp* ratio, $R_{CNO/pp}$



- $R_{CNO/pp}$ – the same trends
- degeneracy between initial metallicity and NSI

CNO cycle

- sub-percent contribiution to the solar energy generation
- neutrinos recently observed by the Borexino collaboration (2020)



Sensitivity of the results

Bottelnecks:

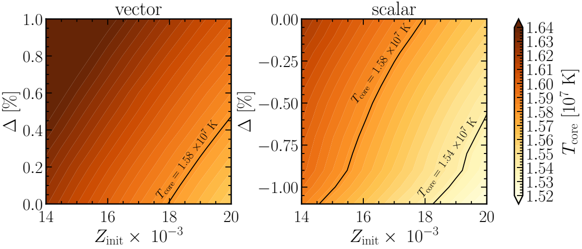
- pp-chain: $\mathrm{p} + \mathrm{p} \rightarrow \mathrm{D} + \nu_e + e^+$
  easy to calculate, not measured
- CNO cycle: $\mathrm{p} + {}^{14}\mathrm{N} \rightarrow {}^{15}\mathrm{O} + \gamma$
  not calculated exactly yet, possible to measure

Question marks in the extrapolated cross section

- measurements at higher energies than in the solar interior
- extrapolation procedures
- plagued by high uncertainty $\mathcal{O}(10)\%$

Changes in the solar parameters

Sun's core temperature



- vector boson mediator
  temperature increase
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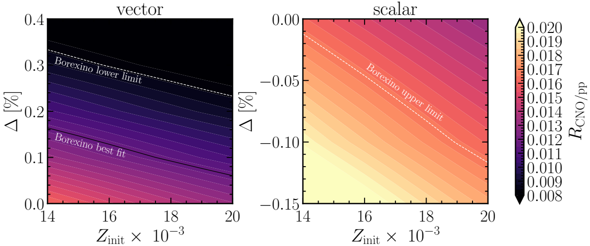
  temperature decrease

CNO to *pp* ratio, $\mathrm{R_{CNO/pp}}$

- $\mathrm{R_{CNO/pp}}$ – flipped trends
- more robust changes in CNO bottelneck reaction



Limits from SN1987A on ν_x