Astrophysical Neutrinos Uncover Neutrino Properties and Decode New Physics

Anna M. Suliga

Neutrino Theory Network Fellow
New York University

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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

Overview

- **Why is studying astrophysical neutrinos crucial?**
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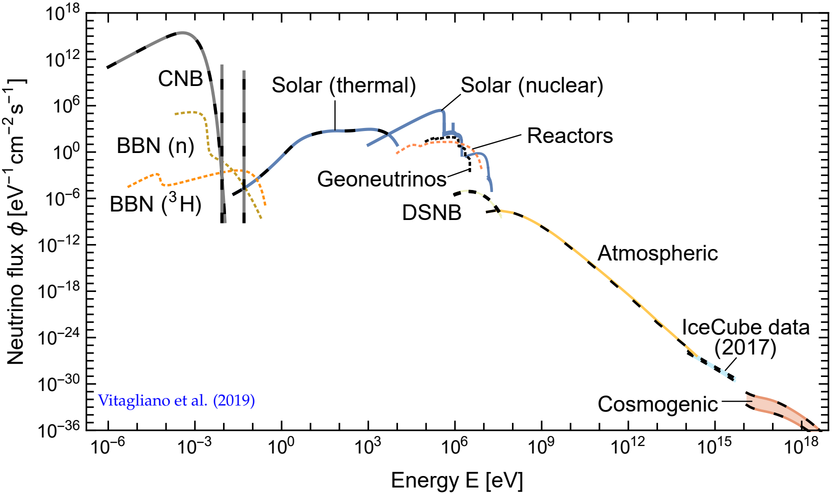
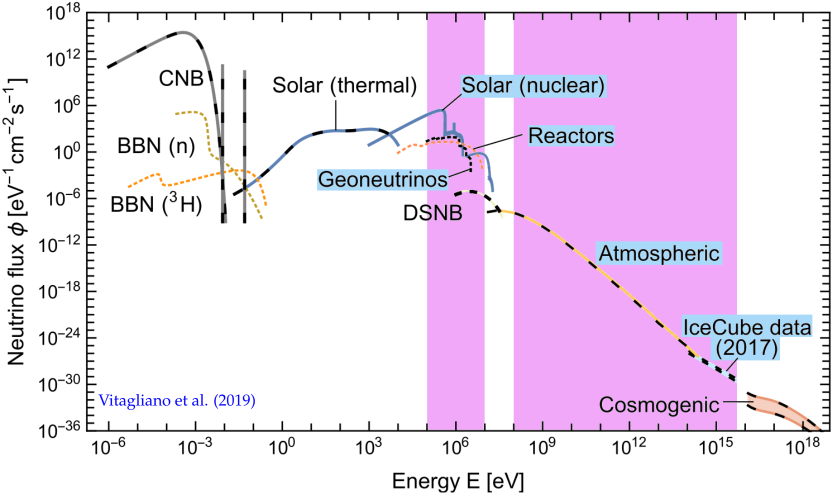
Why is studying astrophysical neutrinos crucial?



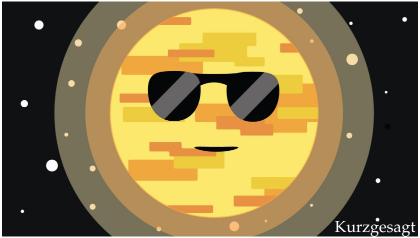
Free neutrino sources spanning nearly 25 decades in energy

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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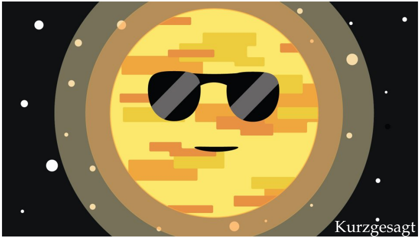
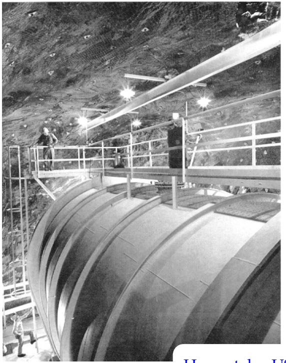
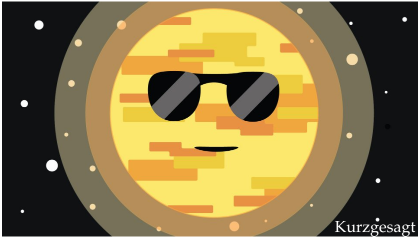


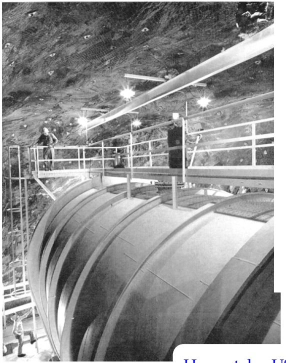


Homestake, USA

Established track record of neutrino discoveries: solar ν



Kurzgesagt



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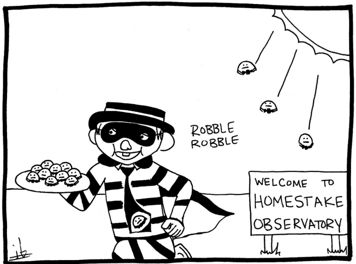
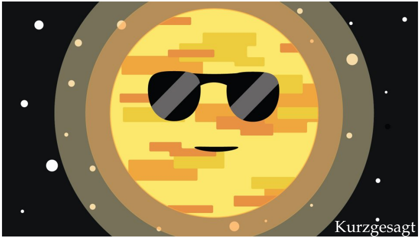
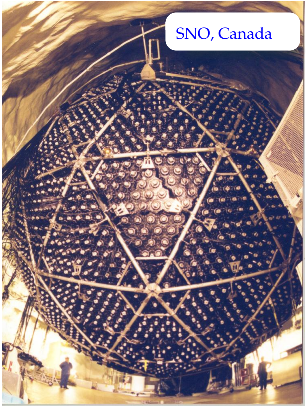
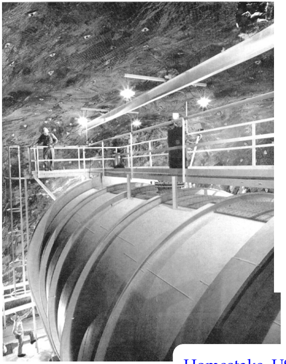


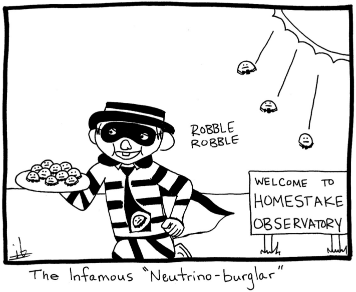
The Infamous "Neutrino-burglar"

Established track record of neutrino discoveries: solar ν









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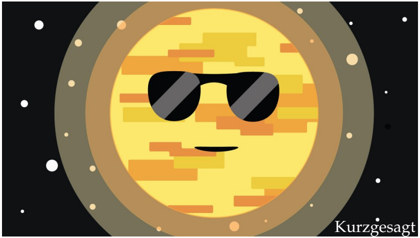

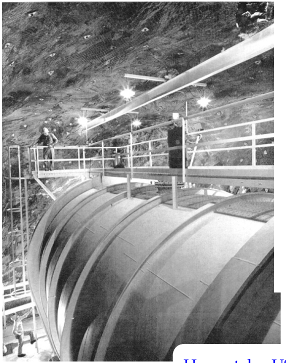

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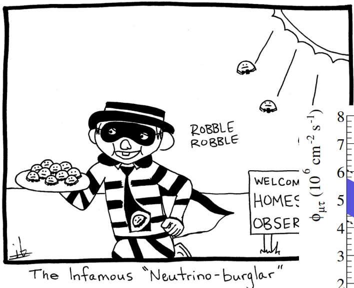
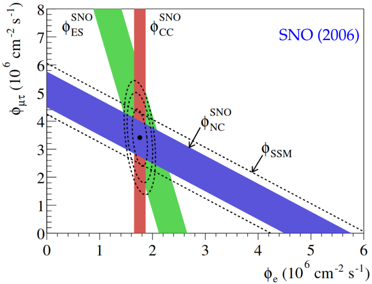
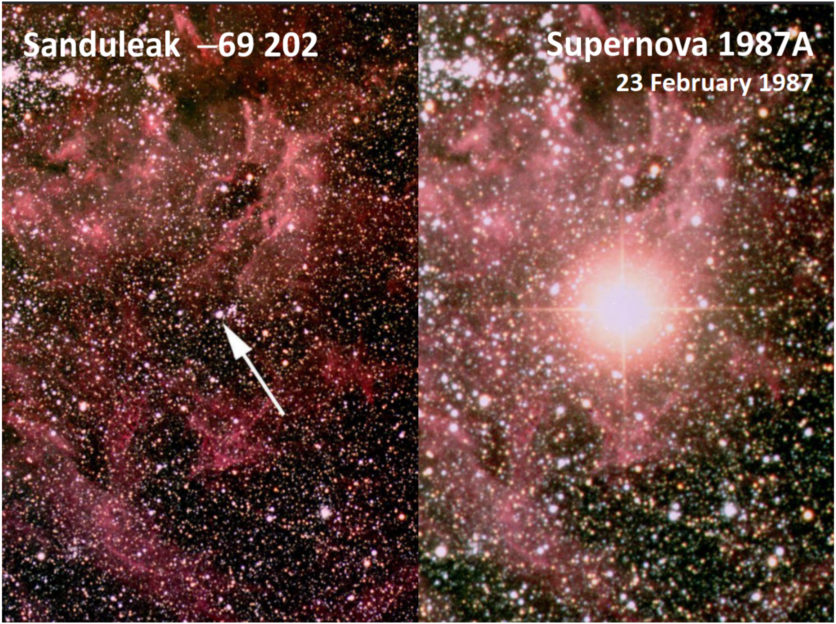
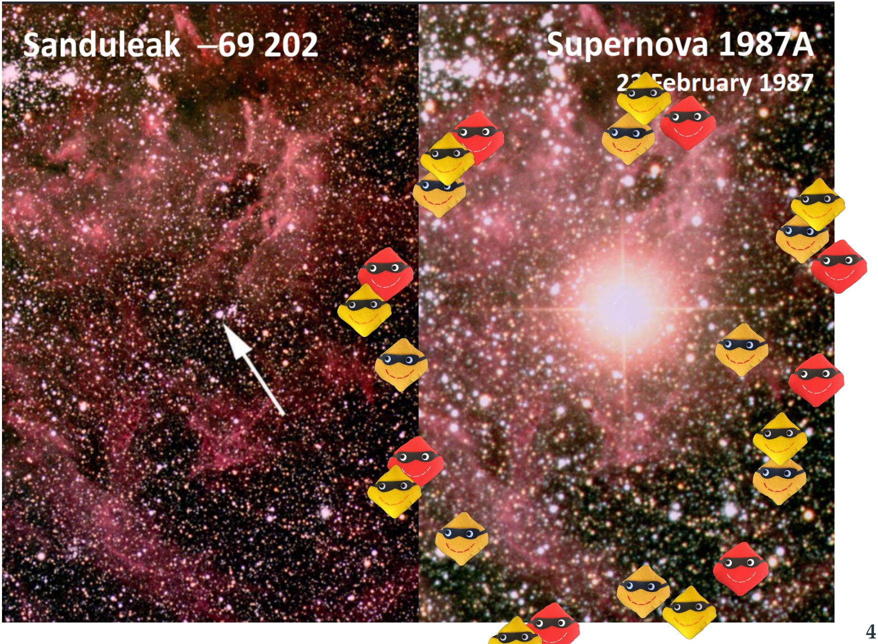




Established track record of neutrino discoveries: SN 1987A



Established track record of neutrino discoveries: SN 1987A



Established track record of neutrino discoveries: SN 1987A

Hubble (2017)

JWST (2023)

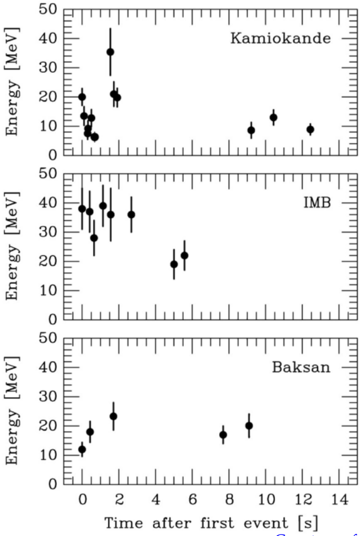
- Neutron star remnant

  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 ν 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

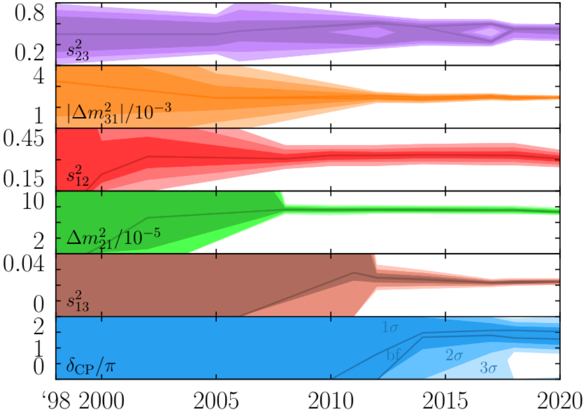
Towards Precise Neutrino Properties Measurements

We known now:

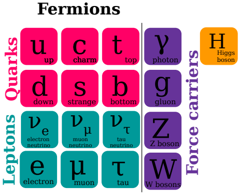
- large mixing angles
- non-zero masses

Remaining questions

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



Snowmass Neutrino Frontier Report (2022)

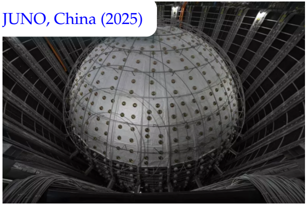


beam, atmospheric | **beam, reactor** | **solar, reactor**

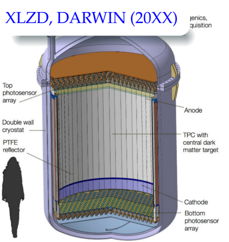
$$\begin{bmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{bmatrix} = U \begin{bmatrix}\nu_1\\ \nu_2\\ \nu_3\end{bmatrix} \qquad U = \begin{bmatrix}1&0&0\\0&c_{23}&s_{23}\\0&-s_{23}&c_{23}\end{bmatrix}\begin{bmatrix}c_{13}&0&s_{13}e^{-i\delta_{CP}}\\0&1&0\\-s_{13}e^{i\delta_{CP}}&0&c_{13}\end{bmatrix}\begin{bmatrix}c_{12}&s_{12}&0\\-s_{12}&c_{12}&0\\0&0&1\end{bmatrix}$$

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

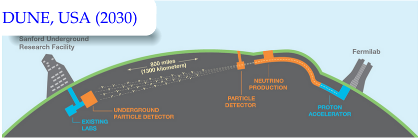
JUNO, China (2025)



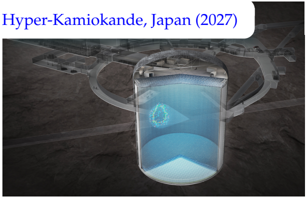
XLZD, DARWIN (20XX)



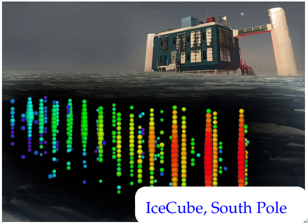
DUNE, USA (2030)



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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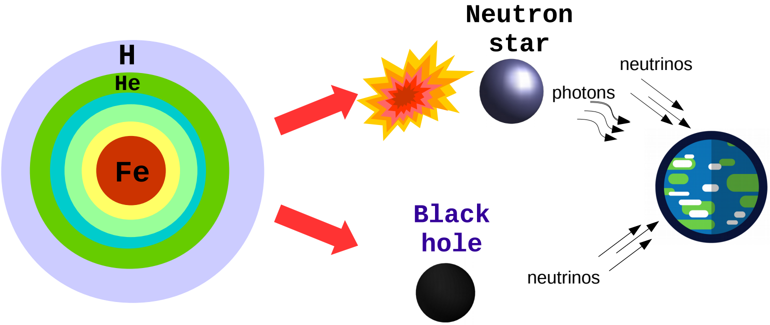
Neutrinos from Core-collapse Supernovae

Why are neutrinos important for a core-collapse supernova?

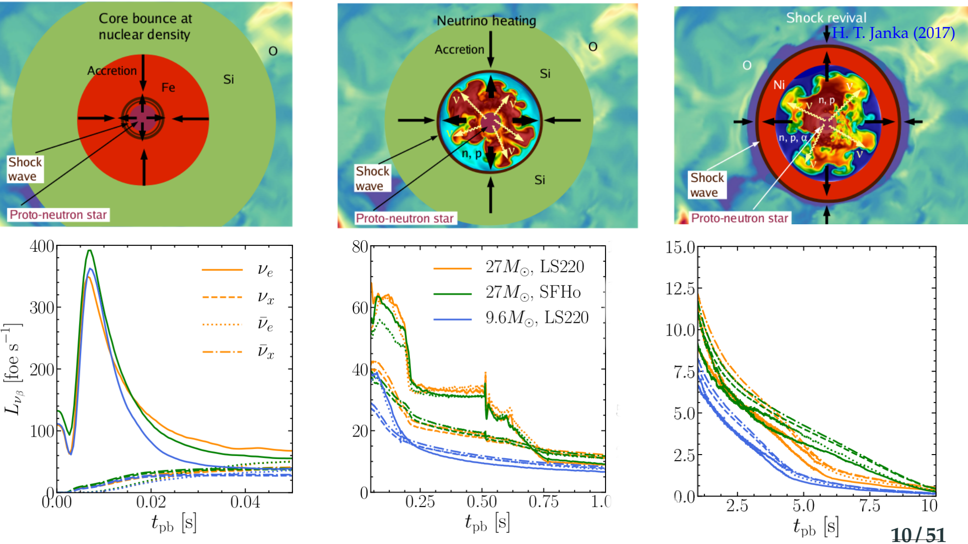
Neutrinos:

- $\sim 10^{58}$ 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 $\sim$ 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?

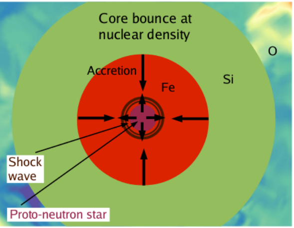
- explosion mechanism — Bethe & Wilson (1985), Fischer et al. (2011)...
- nucleosynthesis — Woosley et al. (1994), Surman & McLaughlin (2003)...
- compact object formation — Warren et al. (2019), Li, Beacom et al. (2020)...
- neutrino mixing — Balantekin & Fuller (2013), Tamborra & Shalgar (2020)...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

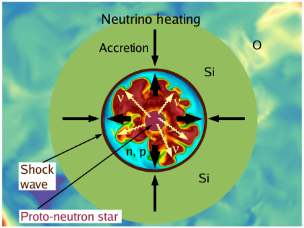
Neutrinos from Supernovae as Probes of New Physics

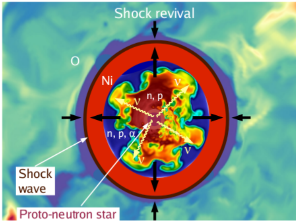
Different Phases of Supernova Explosion

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

LNV neutrino self-interactions in supernova explosion?

In collaboration with G. Fuller, L. Graf, P. Cheong,

J. Froustey, S. Shalgar, K. Kherer, O. Scholer

2410.01080, PRL under rewiev

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), ...

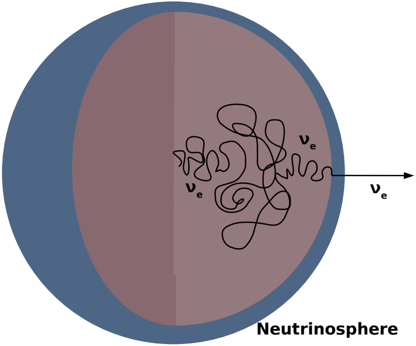
New Interaction Lagrangian

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

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

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

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 $\rho \sim 10^{11} - 10^{12}\mathrm{g\ cm}^{-3}$

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

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

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

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

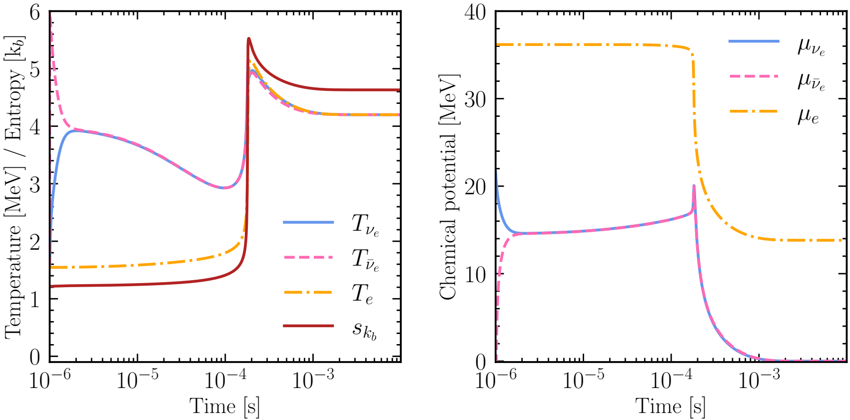
$$\frac{dY_e}{dt} = R_{\nu_e} - R_{\bar{\nu}_e} - R_{e^-} + R_{e^+} \; ,$$

Temperature and chemical potential evolution for leptons

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

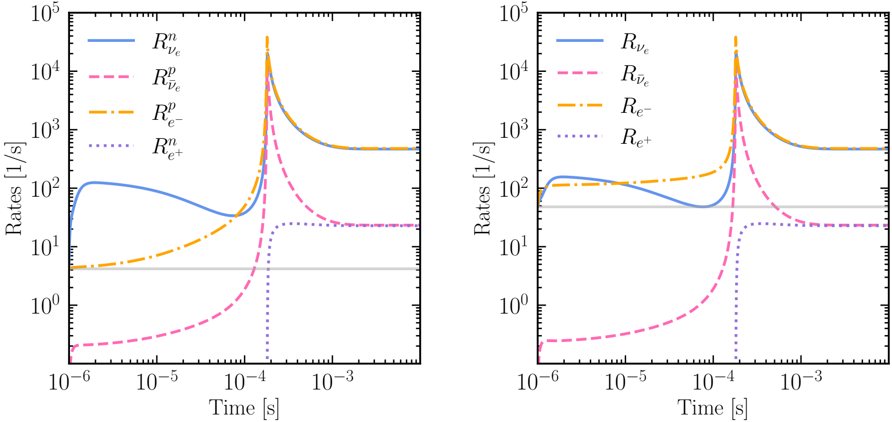
$$\frac{d\mu_i}{dt} = \left(\frac{\partial \rho_i}{\partial T_i} \frac{dn_i}{dt} - \frac{\partial n_i}{\partial T_i} \frac{d\rho_i}{dt} \right) \Big/ \left(\frac{\partial n_i}{\partial \mu_i} \frac{\partial \rho_i}{\partial T_i} - \frac{\partial n_i}{\partial T_i} \frac{\partial \rho_i}{\partial \mu_i}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

Evolution of Thermodynamical Quantities



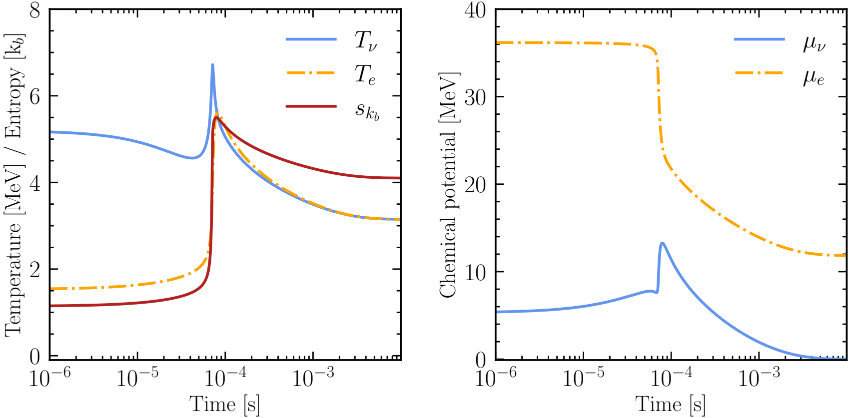
- new interactions quickly equilbrate ν_e and $\bar{\nu}_e$ seas
- enhanced ν_e and e^- captures heat up the matter
- similar results for all flavors equilibration

Weak reaction rates



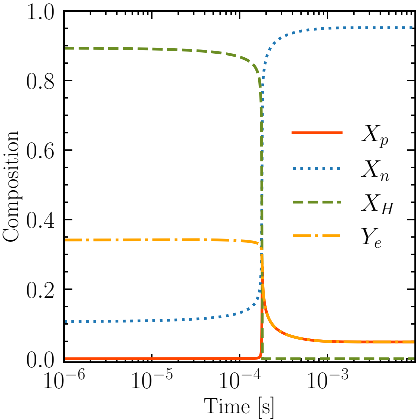
- initial increase in $\nu_e + n$, $\nu_e + A$ and $e^- + A$
- enhanced ν_e and e^- captures heat up the matter
- similar results for all flavors equilibration

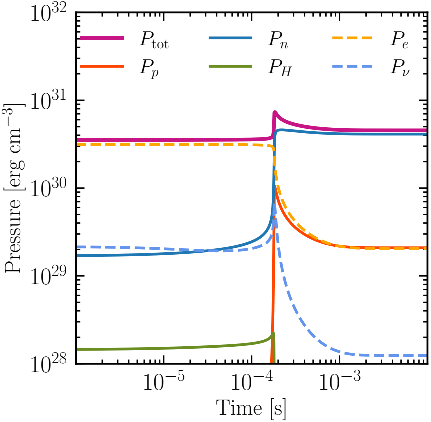
Evolution of Thermodynamical Quantities



- the same qualitative results for all six flavor equilibration

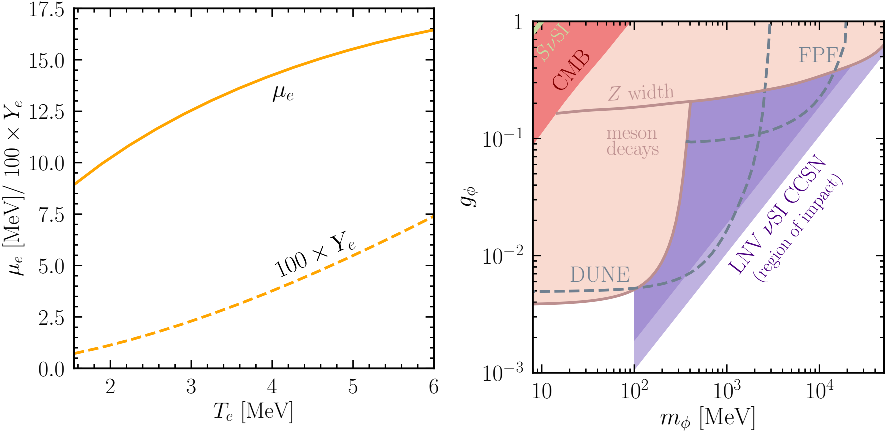
Composition and Pressure Support of the Core





- s_{k_b} - entropy generation shifts composition towards no heavy nuclei $X_H \propto s_{k_\mathrm{B}}^{1-\langle A \rangle} n_p^Z n_n^N \exp(E_b/T_e)$
- enhanced deleptonization changes the pressure support of the core

New β-equilibrium with LNV νSI



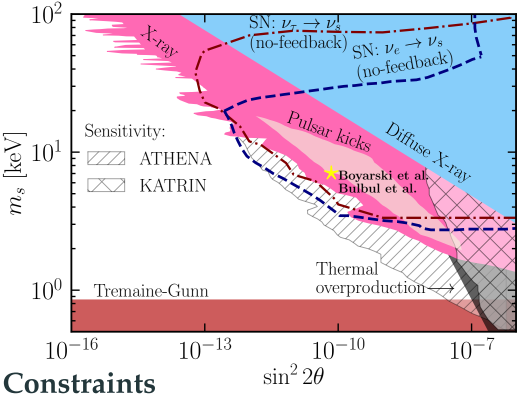
- regardless of the final T_e the new equilibrium has a very low Y_e
  $\mu_e = \delta m_{np} - T_e \ln\left(\frac{Y_e}{1-Y_e}\right)$, with $Y_e = \frac{1}{\pi^2 \rho}\int_0^\infty dp_e\, p_e^2\, f_e(E_e, T_e, \mu_e)$
- complementarity with future accelerator-based experiments

Sterile neutrinos with keV masses in supernovae

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

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

Sterile neutrino as dark matter candidate



Favorable regions

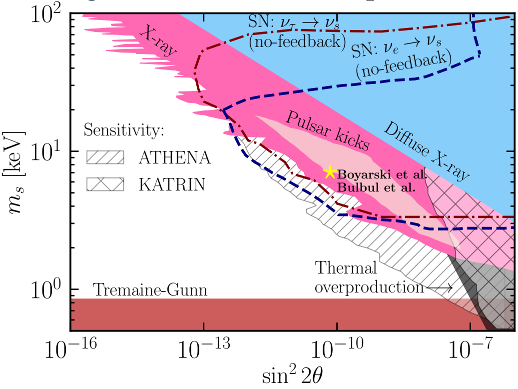
- Pulsar kicks
  A. Kusenko, G. Segrè (1998), G. Fuller, A. Kusenko, et al. (2003)
- 3.5 keV line
  A. Boyarsky et al. (2014), E. Bulbul et al. (2014)
- Lyman-α forest
  Villasenor et al. (2022)

Constraints

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

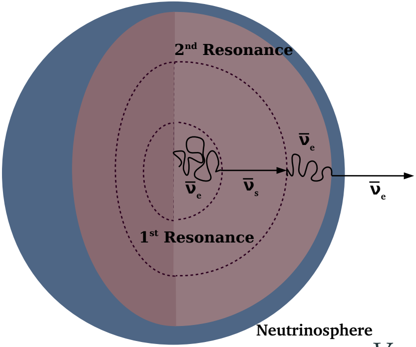
The role of sterile neutrinos in supernovae; previous studies

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



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

Sterile neutrino conversions in the stellar core



1D SN model
Garching group archive

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

MSW

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

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

Collisions

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

$\nu_e - \nu_s$ mixing: multiple resonances

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

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

Sterile neutrino conversions in the stellar core

Collisional production

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

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

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

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

Sterile neutrino conversions in the stellar core

Collisional production

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

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

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

MSW production

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

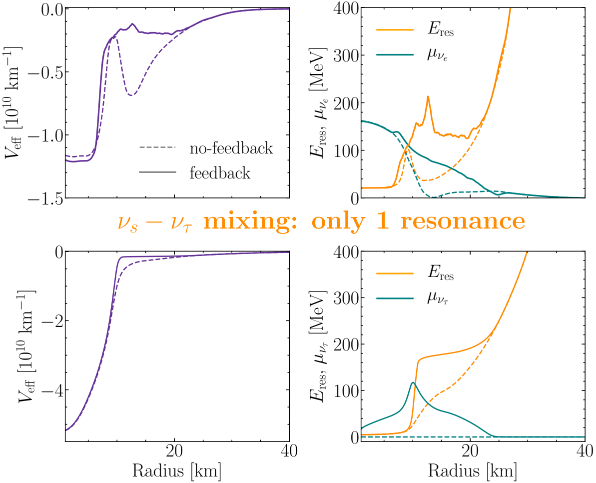
$$\Delta_{\rm res} = \tan 2\theta \left|\frac{dV_{\rm eff}/dr}{V_{\rm eff}}\right|^{-1}$$

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

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

Sterile neutrino conversions in the stellar core

$\nu_s - \nu_e$ **mixing: multiple resonances**



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

1D SN model
Garching group archive

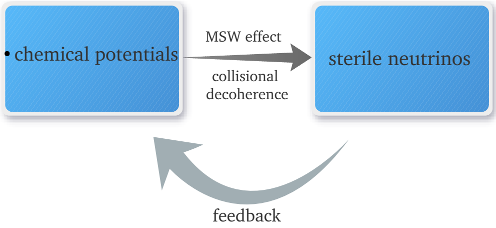
$$E_{\rm res} = \frac{\cos 2\theta \Delta m_s^2}{2V_{\rm eff}}$$

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

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

The sterile-tau neutrino mixing: growth of the asymmetry

Only active neutrinos



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

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

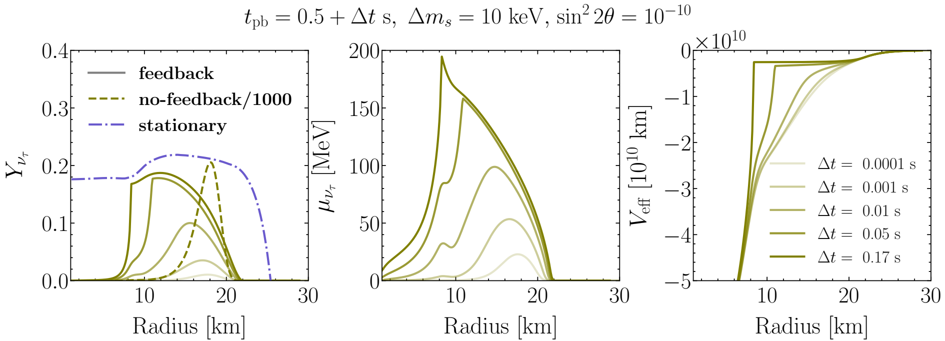
since they were **strongly coupled** to the rest of the particles in the medium,
a **new equilibrium state forms.**

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

Active + sterile neutrinos

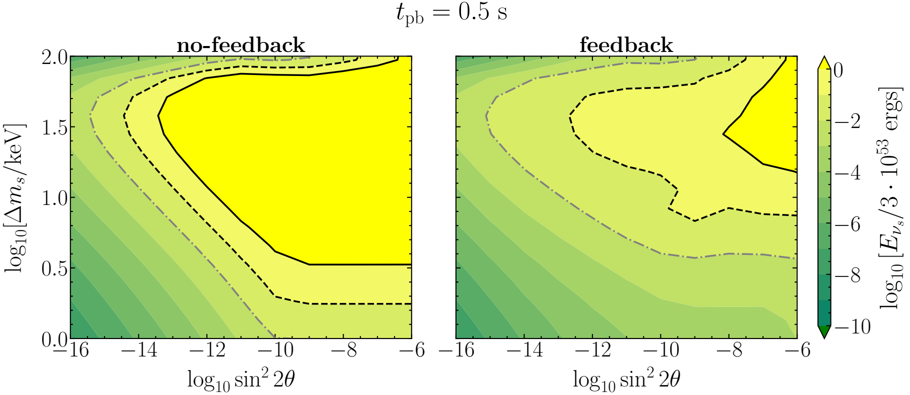
$$Y_{\nu_\tau}(r,t) = \frac{1}{n_b(r)} \int_0^t dt' \, \frac{d\left(P_{\nu_\tau \to \nu_s} n_{\nu_\tau}(r,t') - P_{\bar{\nu}_\tau \to \bar{\nu}_s} n_{\bar{\nu}_\tau}(r,t')\right)}{dt'}$$

Radial evolution of the asymmetry w and w/o feedback



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

Supernova bounds on the mixing parameters



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

The sterile-electron neutrino mixing: dynamical feedback

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

β equilibrium

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

Lepton number conservation

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

Baryon number conservation

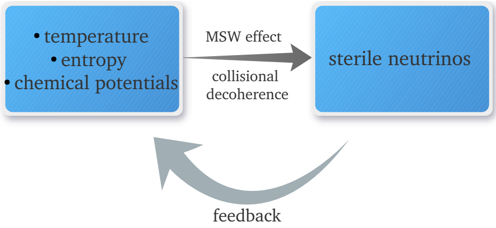
$$Y_p(r,t) + Y_n(r,t) = 1\ ,$$

Charge conservation

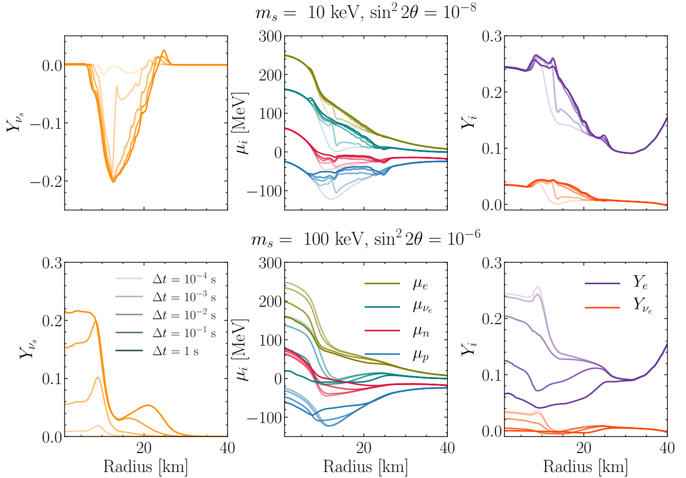
$$Y_p(r,t) = Y_e(r,t)\ ,$$

Entropy change

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

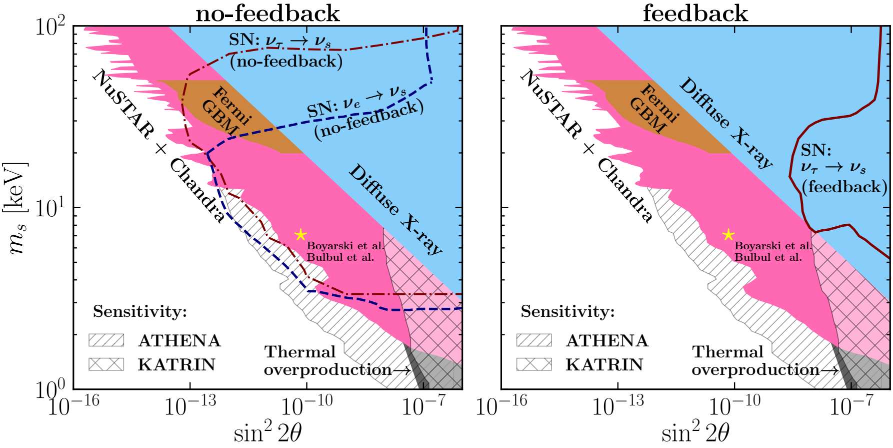


Radial evolution of the asymmetry



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

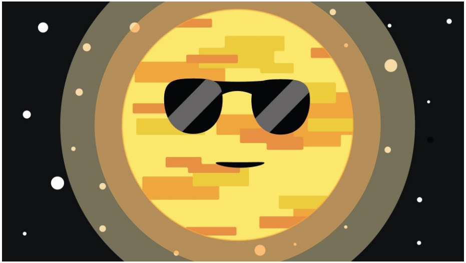
Supernova bounds on the mixing parameters



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

- 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?

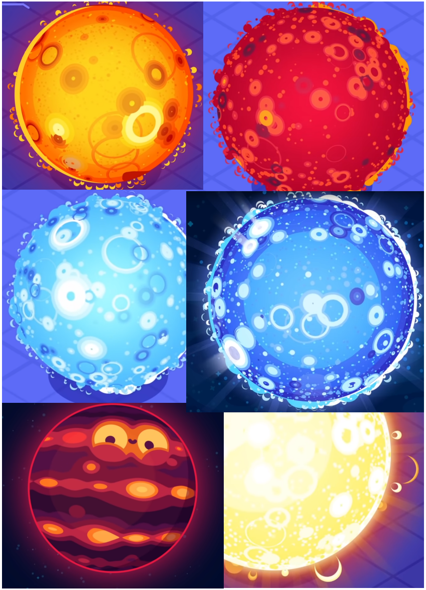


Single galactic SN event

- 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

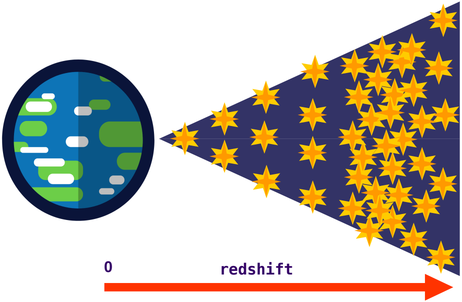
$$\Phi_{\nu_\beta}(E) = \frac{c}{H_0}\int dM \int dz \frac{R_{\rm SN}(z,M)}{\sqrt{\Omega_M(1+z)^3+\Omega_\Lambda}}\left[f_{\rm CC-SN}F_{\nu_\beta,\rm CC-SN}(E',M) + f_{\rm BH-SN}F_{\nu_\beta,\rm BH-SN}(E',M)\right]$$

fraction of neutron-star-forming progenitors

neutrino flux from a single star

The DSNB is sensitive to:

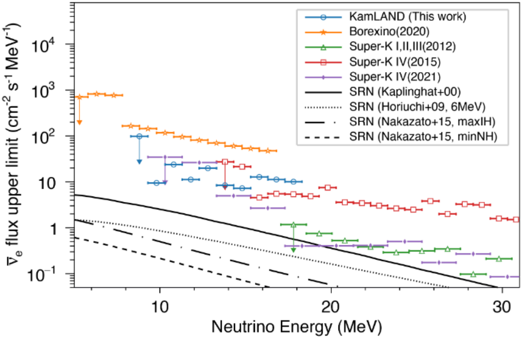
- $R_{\rm SN}, f_{\rm BH-SN}$
- neutrino flavor evolution
- equation of state
- mass accretion rate in BH-SN
- non-standard physics



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)

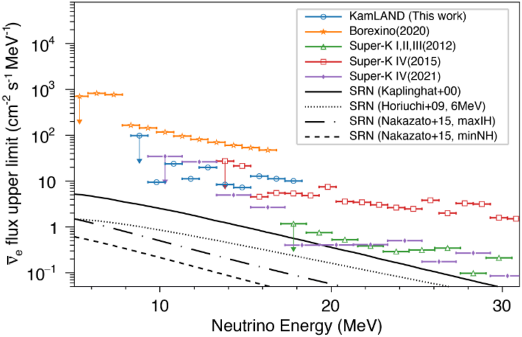


DSNB limits:

- $\bar{\nu}_e \approx 2.7\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}$ 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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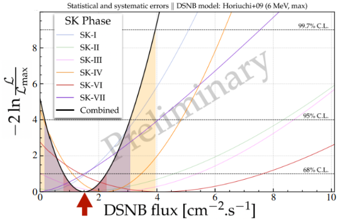
  possibly detectable by DUNE Møller, **AMS**, et al. (2018), Zhu et al. (2019)
- $\nu_x \lesssim 100\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}$ for $E_\nu > 19.3$ MeV **AMS**, Beacom, Tamborra (2021)

Tension from zero assumption

Spectral-fitting analysis

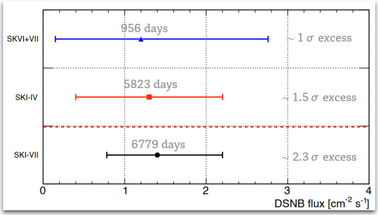
Spectrum fitting analysis to extract significance

- Total 6779 days of SK (5823 d pure-water and 956 d Gd-water) combined
- Analysis threshold: $E_\nu > 17.3$ 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 $\mathbf{1.4^{+0.8}_{-0.6}}$ $\mathbf{cm^{-2}\,s^{-1}}$ for $E_\nu > 17.3$ 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

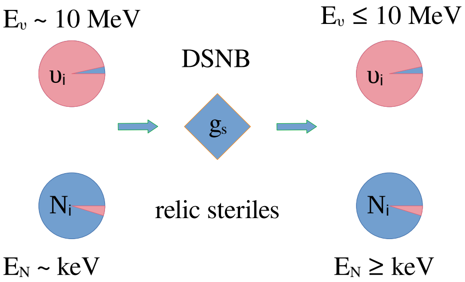
How to probe new physics with these uncertainties?

Probing self-interacting sterile neutrino dark matter with the DSNB

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

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

Do KeV-mass Sterile Neutrinos Have Self-Interactions?



Resonant interaction for sterile neutrinos
$$\mathcal{L}^{\phi} = g_s \phi \nu_s \nu_s$$

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

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

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

Modeling secret neutrino interactions in DSNB

Modified DSNB flux

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

Probability of interaction

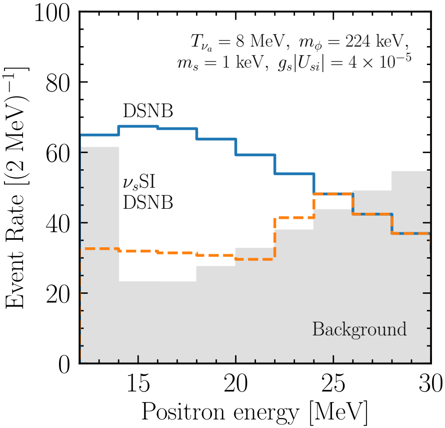
$$P_i(E_\nu, z) = e^{-\tau_i(E_\nu, z)}$$

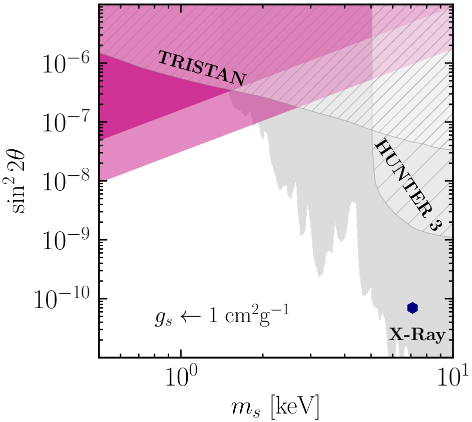
$$\tau_i(E_\nu, z) \simeq \tau_R \Theta(z - z_R) = \frac{\Gamma_R(z_R)}{(1+z_R)H(z_R)} \Theta(z - z_R)$$

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

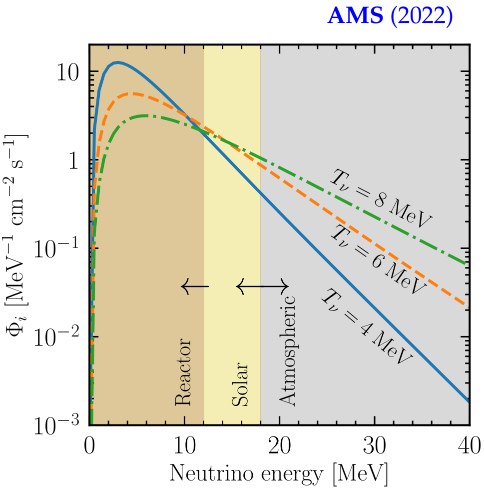




- Sterile neutrino self-interactions may result in features in DSNB
- Overalap with the TRISTAN experiment paramater space
- Reduction of the astrophysical uncertainties helps but not by a lot

- 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)

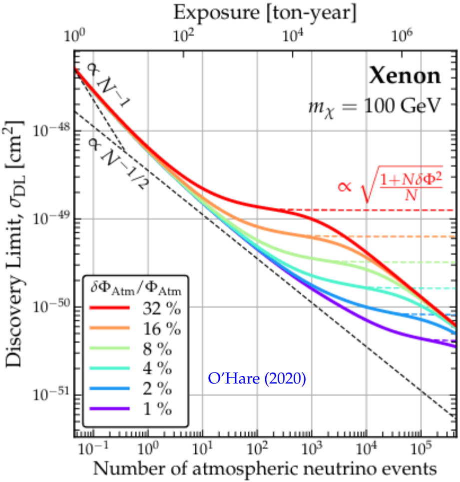


- DSNB $\rightarrow$
  isotropic and stationary guaranteed neutrino flux

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

- mitigating uncertainties in the atmospheric neutrinos helps the discovery limits

Direct Dark Matter Detection Experiments - Neutrino Fog



- neutrino floor/fog → 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

Measuring low-energy atmospheric neutrinos

In collaboration with J. F. Beacom

Phys.Rev.D 108 (2023) 4, 043035

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

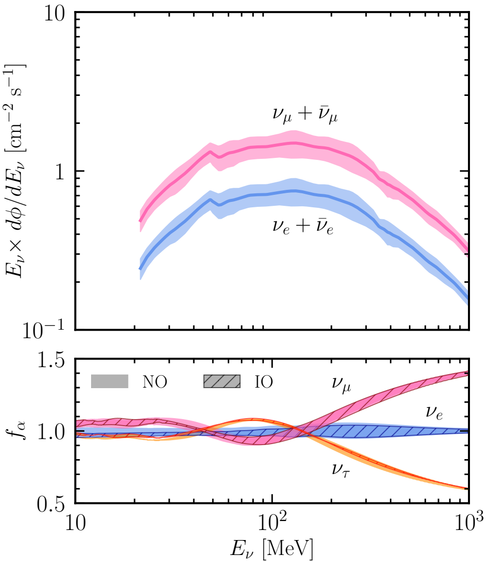
solar wind modulations

Earth's geomagnetic field

Oscillated flavor ratio

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

Past measurements: energies > 100 MeV



Neutrino flux: Zhuang (2021)

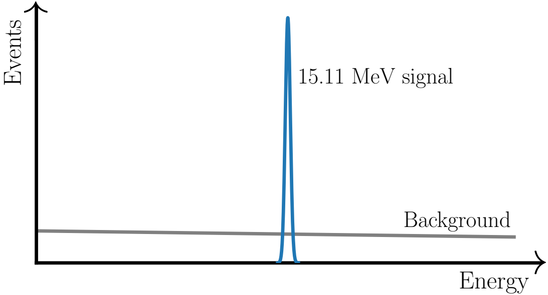
Mixing: NuCraft

Distinctive nuclear channels in JUNO

Neutral current channels

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

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



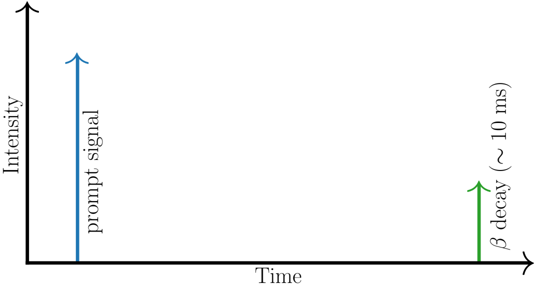
- instantaneous decay of ${}^{12}\mathrm{C}^*$
- emission of a monoenergetic γ

Distinctive nuclear channels in JUNO

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

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

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



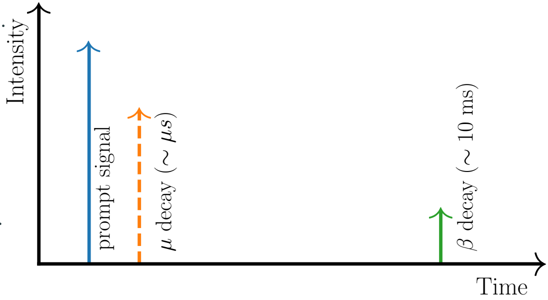
- coincidence detection of e^+ and e^-
- difference in $^{12}\mathrm{B}_{\mathrm{g.s.}}$ and $^{12}\mathrm{N}_{\mathrm{g.s.}}$ lifetimes $\to$ ν_e vs. $\bar{\nu}_e$ distinction

Distinctive nuclear channels in JUNO

Charged current channels: ν_μ

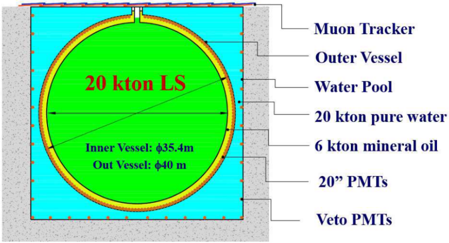
$$\nu_\mu + {}^{12}\mathrm{C} \to \mu^- + {}^{12}\mathrm{N}_{\mathrm{g.s.}}$$
$${}^{12}\mathrm{N}_{\mathrm{g.s.}} \to {}^{12}\mathrm{C} + e^+ + \nu_e$$
$$\mu^- \to e^- + \bar{\nu}_e + \nu_\mu,$$

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



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

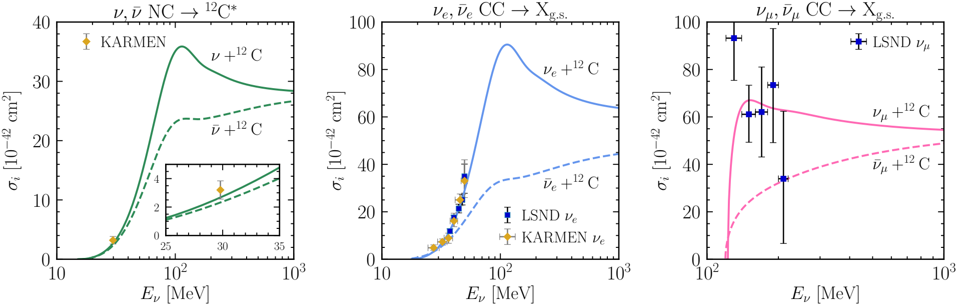
The Jiangmen Underground Neutrino Observatory (JUNO)



- 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)



- 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)

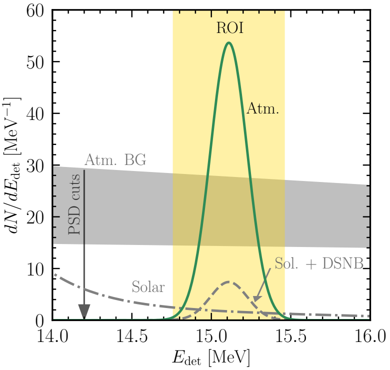
Atmospheric neutrino detection in JUNO

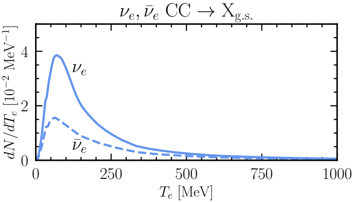
NC channel detection: single events

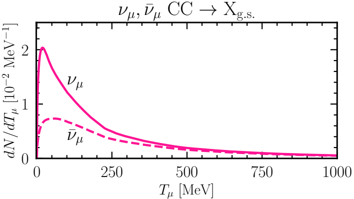
Irreducible BG: solar and DSNB ν

Reducible BG: atm. ν - p scattering

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







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**

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!