Neutrino Self-Interaction and Core-Collapse Supernovae

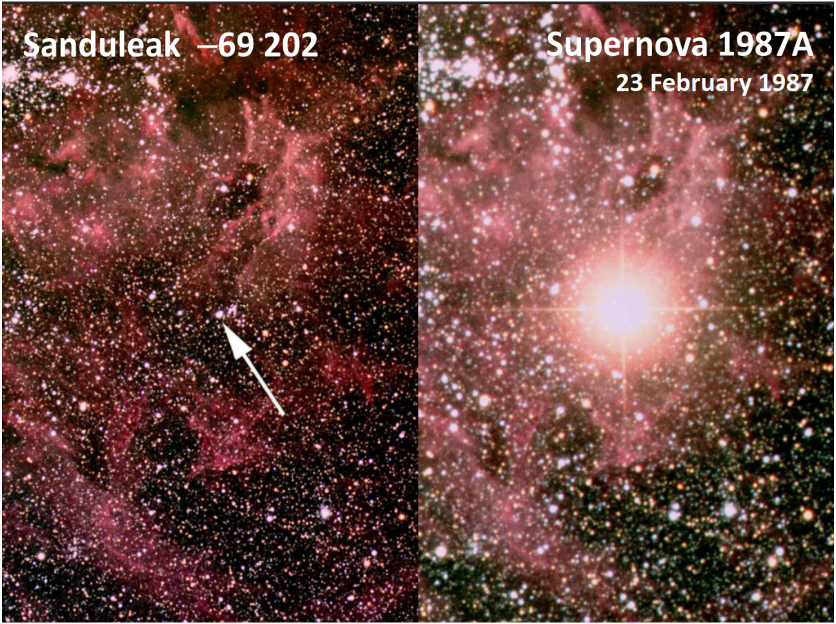
Anna M. Suliga

Neutrino Theory Network Fellow
New York University

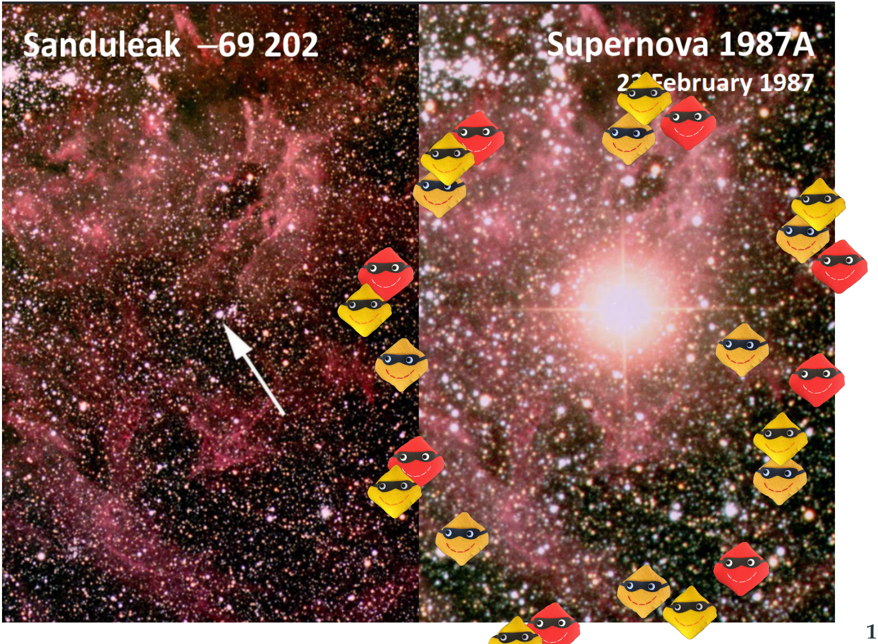
Neutrino Theory and Experiment Workshop, Colorado State University

May 29, 2025

Why is studying astrophysical neutrinos crucial?



Why is studying astrophysical neutrinos crucial?



Why is studying astrophysical neutrinos crucial?

Hubble (2017)

JWST (2023)

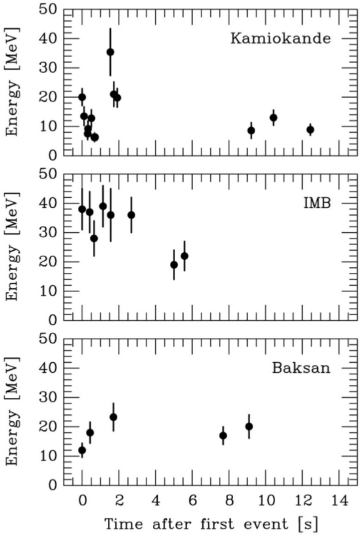
- Neutron star remnant

  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

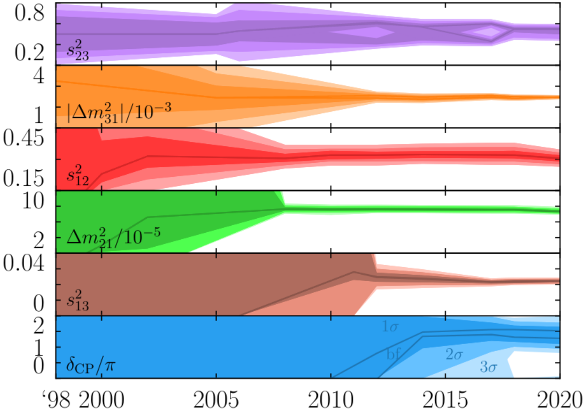
Towards Precise Neutrino Properties Measurements

We known now:

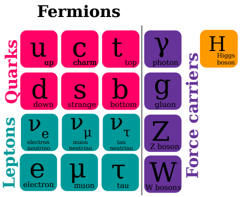
- large mixing angles
- non-zero masses

Remaining questions

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



Snowmass Neutrino Frontier Report (2022)



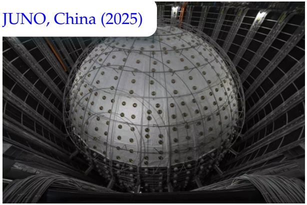
$$\begin{bmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{bmatrix} = U \begin{bmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{bmatrix}$$

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

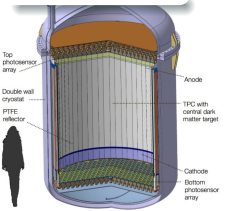
$$U = \begin{bmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{bmatrix} \begin{bmatrix} c_{13} & 0 & s_{13}e^{-i\delta_{CP}} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta_{CP}} & 0 & c_{13} \end{bmatrix} \begin{bmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

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

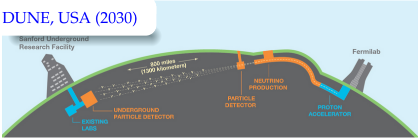
JUNO, China (2025)



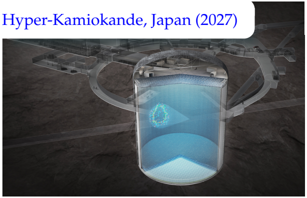
XLZD, DARWIN (20XX)



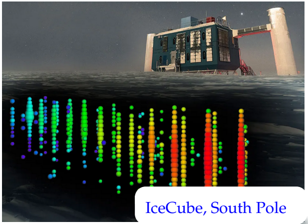
DUNE, USA (2030)



Hyper-Kamiokande, Japan (2027)



Rubin Observatory, Chile (2025)



IceCube, South Pole

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

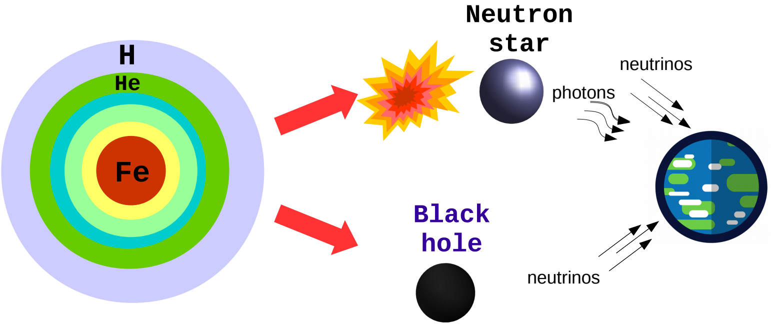
- Complementarity with:
  - reactor and accelerator searches
  - electromagnetic surveys
  - other astrophysical messengers

Neutrinos from Core-collapse Supernovae

Why are neutrinos important for a core-collapse supernova?

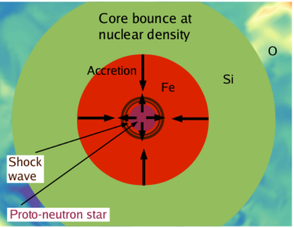
Neutrinos:

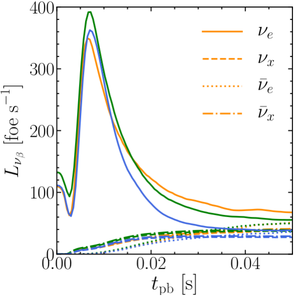
- $\sim 10^{58}$ of them emitted from a single core collapse
- only they can reveal the deep interior conditions
- only particles detectable from the collapse to a black hole



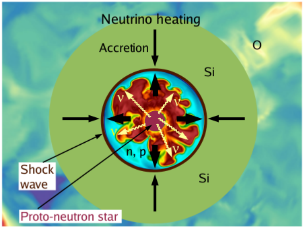
Different Phases of Supernova Explosion

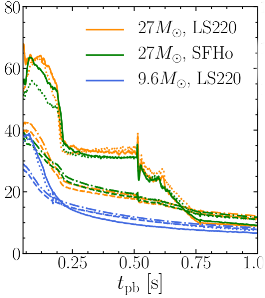
- Infall phase,
  ν_e burst ~ 40 ms



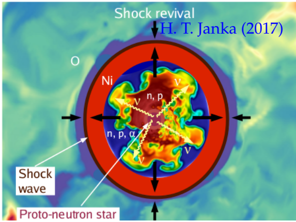


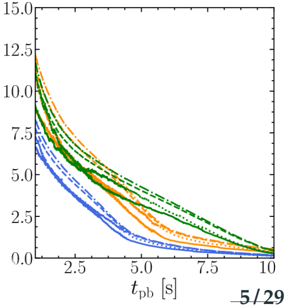
- Accretion phase,
  ~ 100 ms





- 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

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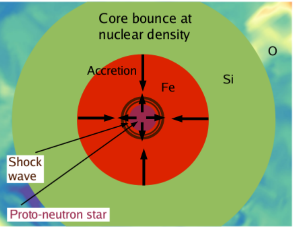
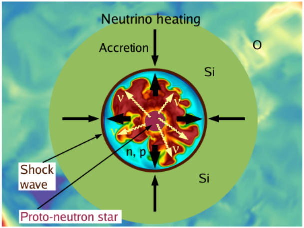
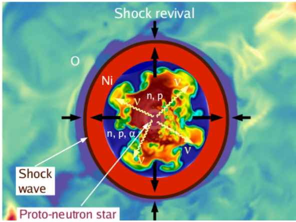


- Accretion phase, ~ 100 ms



- Cooling phase, ~ 10 s

H. T. Janka (2017)



New neutrino physics affects the core-collapse supernovae:

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

astrophysical feedback often ignored

How important is astrophysical feedback?

Do non-standard neutrino self-interactions help or inhibit supernova explosion?

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

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

PRL accepted

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), ...

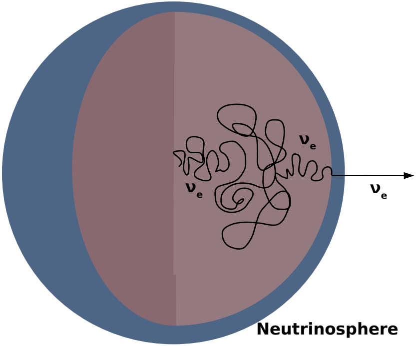
New Interaction Lagrangian

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

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



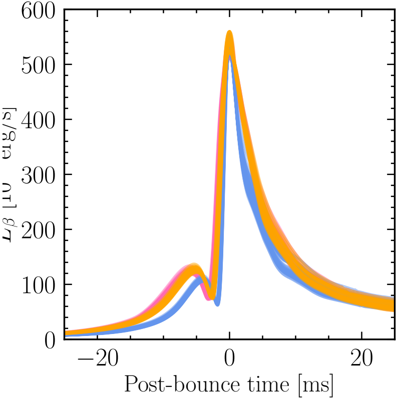
Neutrino trapping

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

β-equilibrium

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

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



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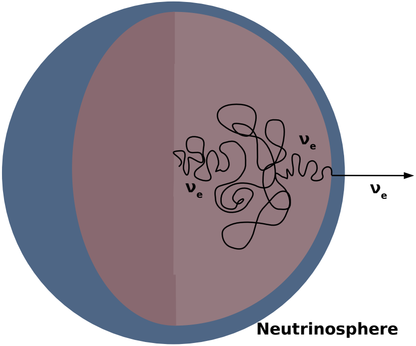

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$$A(N,Z)+\nu \rightarrow A(N,Z)+\nu$$

β-equilibrium

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

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LNV νSI Implementation:

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

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

LNV νSI in supernovae illustrated by cats

Without LNV νSI

Pics credit: Tony Zhouw who's courageously cat sitting Aurora and Beetle

LNV νSI in supernovae illustrated by cats

With LNV νSI

Pics credit: Tony Zhouw who's courageously cat sitting Aurora and Beetle

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

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

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

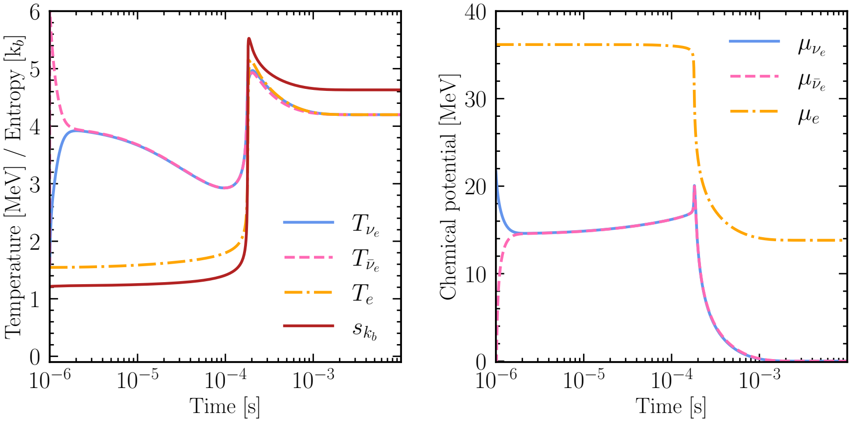
$$\frac{dY_e}{dt} = R_{\nu_e} - R_{\bar{\nu}_e} - R_{e^-} + R_{e^+} \ ,$$

Temperature and chemical potential evolution for leptons

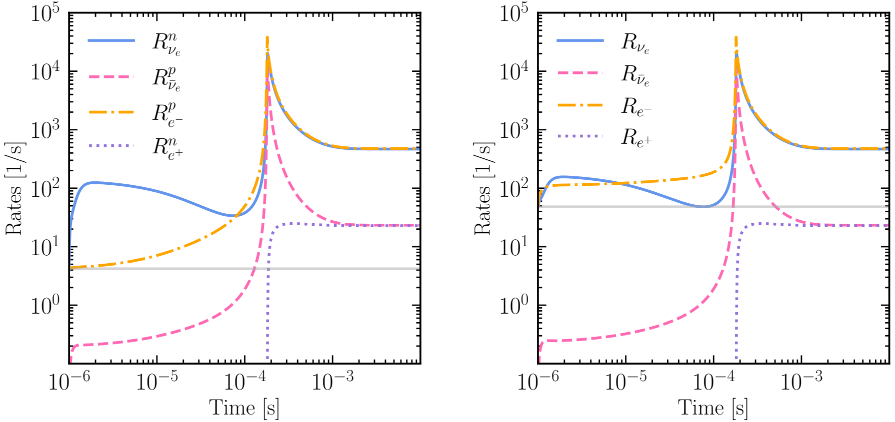
$$\frac{dT_i}{dt} = \left(\frac{\partial \rho_i}{\partial \mu_i} \frac{dn_i}{dt} - \frac{\partial n_i}{\partial \mu_i} \frac{d\rho_i}{dt} \right) \Big/ \left(\frac{\partial n_i}{\partial T_i} \frac{\partial \rho_i}{\partial \mu_i} - \frac{\partial n_i}{\partial \mu_i} \frac{\partial \rho_i}{\partial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

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

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



- 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

Fast LNV νSI - Approximate Evolution

LNV νSI timescale much faster than weak timescale $\rightarrow$ a single ν species evolution

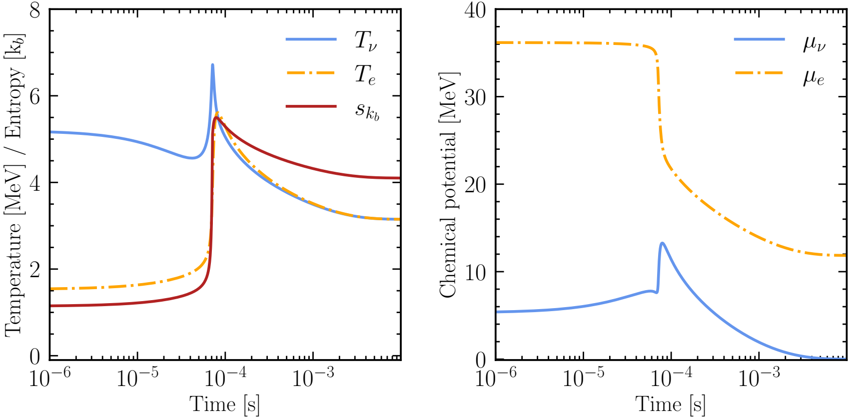
$$\sum_\alpha \left(\frac{dn_{\nu_\alpha}}{dt} + \frac{dn_{\bar{\nu}_\alpha}}{dt} \right) = \frac{\delta n_\nu}{\delta t}$$
$$\sum_\alpha \left(\frac{d\rho_{\nu_\alpha}}{dt} + \frac{d\rho_{\bar{\nu}_\alpha}}{dt} \right) = \frac{\delta \rho_\nu}{\delta t}$$

sum over charged-current weak interactions

$$\frac{dT_\nu}{dt} = \frac{\frac{\partial \rho_\nu}{\partial \mu_\nu}\frac{\delta n_\nu}{\delta t} - \frac{\partial n_\nu}{\partial \mu_\nu}\frac{\delta \rho_\nu}{\delta t}}{2N_F\left(\frac{\partial n_\nu}{\partial T_\nu}\frac{\partial \rho_\nu}{\partial \mu_\nu} - \frac{\partial n_\nu}{\partial \mu_\nu}\frac{\partial \rho_\nu}{\partial T_\nu}\right)}$$

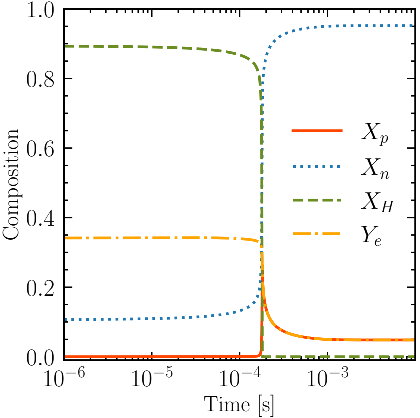
$$\frac{d\mu_\nu}{dt} = \frac{\frac{\partial \rho_\nu}{\partial T_\nu}\frac{\delta n_\nu}{\delta t} - \frac{\partial n_\nu}{\partial T_\nu}\frac{\delta \rho_\nu}{\delta t}}{2N_F\left(\frac{\partial n_\nu}{\partial \mu_\nu}\frac{\partial \rho_\nu}{\partial T_\nu} - \frac{\partial n_\nu}{\partial T_\nu}\frac{\partial \rho_\nu}{\partial \mu_\nu}\right)}$$

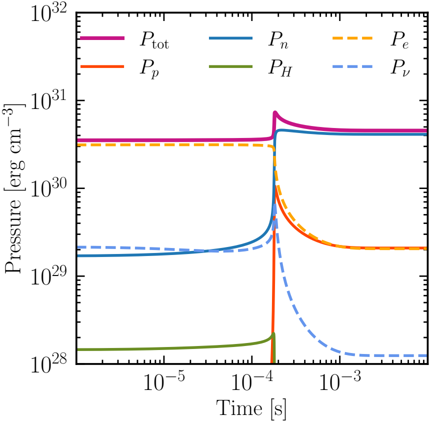
Evolution of Thermodynamical Quantities



- the same qualitative results for all six flavor equilibration

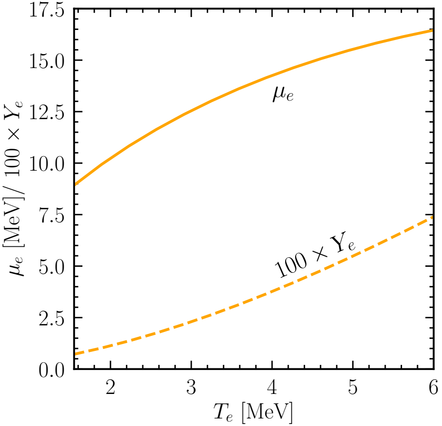
Composition and Pressure Support of the Core

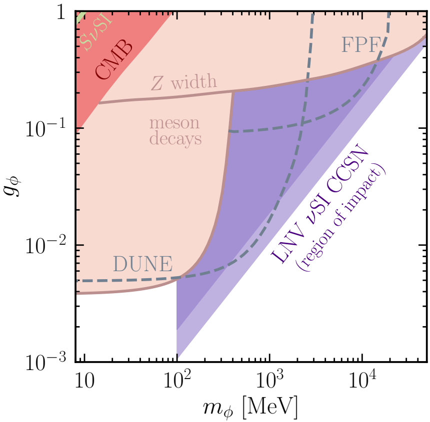




- s_{k_b} - entropy generation shifts composition towards no heavy nuclei
  $X_H \propto s_{k_\mathrm{B}}^{1-\langle A \rangle} n_p^Z n_n^N \exp(E_b/T_e)$
- enhanced deleptonization changes the pressure support of the core

New β-equilibrium with LNV νSI

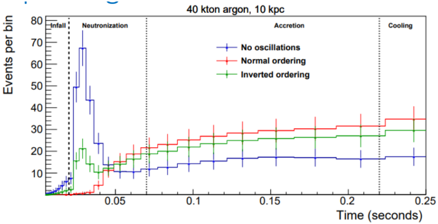




- regardless of the final T_e the new equilibrium has a very low Y_e
  $\mu_e = \delta m_{np} - T_e \ln\left(\frac{Y_e}{1-Y_e}\right)$, with $Y_e = \frac{1}{\pi^2 \rho}\int_0^\infty dp_e\, p_e^2\, f_e(E_e, T_e, \mu_e)$
- complementarity with future accelerator-based experiments

Why focus only on a single rare event?

Images: Kurzgesagt



D. Pershey slides

Single galactic SN event

- rare event
- precise infromation about one star

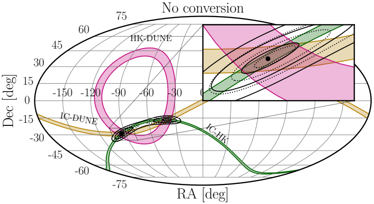
Ready for rare supernovae too?

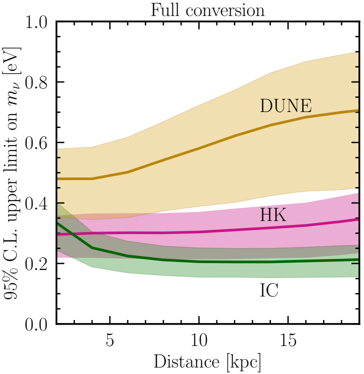
Why focus only on a single rare event?

Images: Kurzgesagt

Single galactic SN event

- rare event
- precise infromation about one star





Pitik, Heimsoth, **AMS**, Balantekin (2022)

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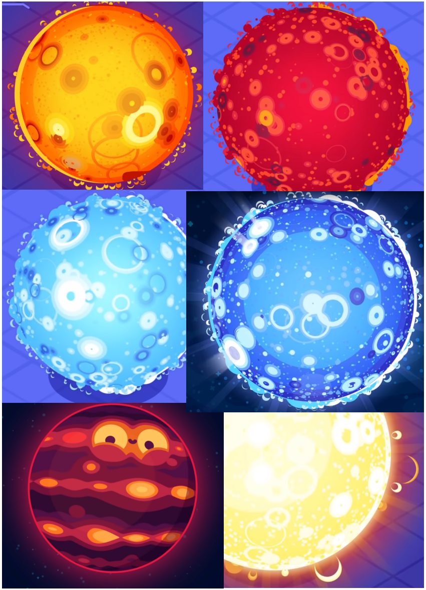


Single galactic SN event

- rare event
- precise infromation about one star

Multiple SN events (larger distances)

- accumulation of events
- will detect in coming years

Diffuse supernova neutrino background

cosmological supernovae rate

fraction of black-hole-forming progenitors

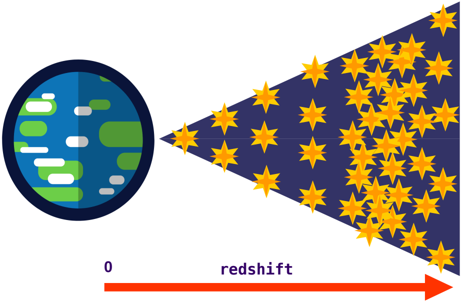
$$\Phi_{\nu_\beta}(E) = \frac{c}{H_0}\int dM \int dz \frac{R_{\mathrm{SN}}(z,M)}{\sqrt{\Omega_M(1+z)^3+\Omega_\Lambda}} \left[f_{\mathrm{CC-SN}} F_{\nu_\beta,\mathrm{CC-SN}}(E',M) + f_{\mathrm{BH-SN}} F_{\nu_\beta,\mathrm{BH-SN}}(E',M)\right]$$

fraction of neutron-star-forming progenitors

neutrino flux from a single star

The DSNB is sensitive to:

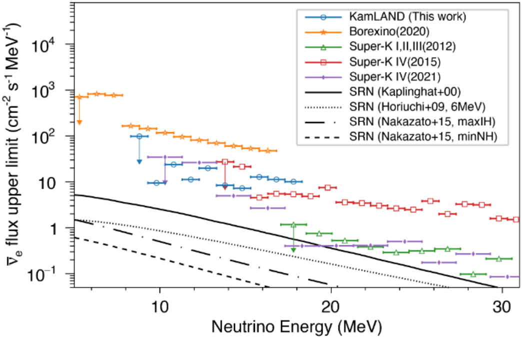
- $R_{\mathrm{SN}}, f_{\mathrm{BH-SN}}$
- neutrino flavor evolution
- equation of state
- mass accretion rate in BH-SN
- non-standard physics



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)

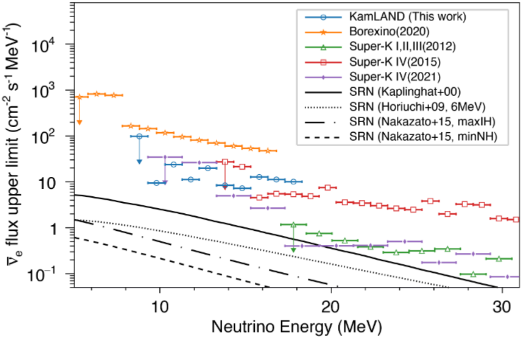


DSNB limits:

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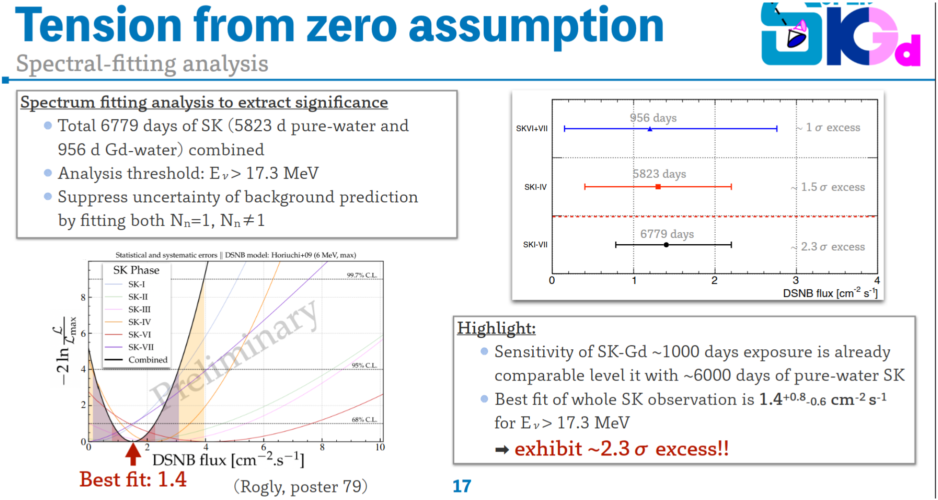
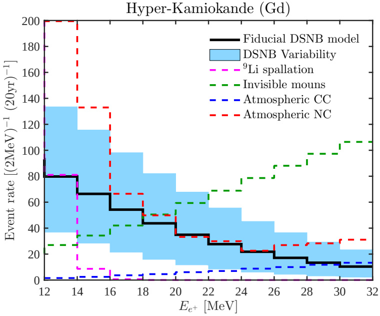
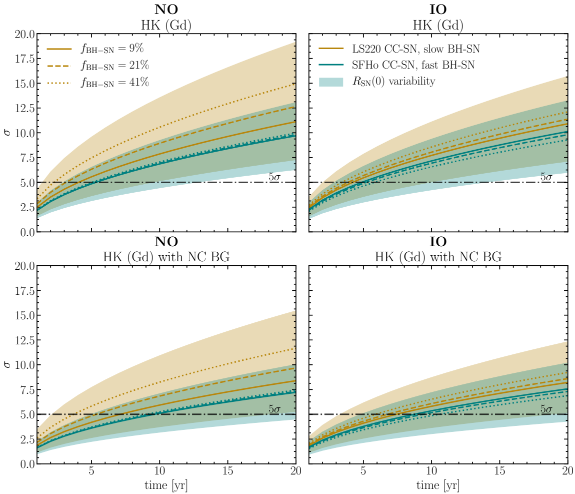
  possibly detectable by DUNE Møller, **AMS**, et al. (2018), Zhu et al. (2019)
- $\nu_x \lesssim 100\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}$ for $E_\nu > 19.3$ MeV **AMS**, Beacom, Tamborra (2021)



Slide credit: Masayuki Harada talk at Neutrino 2024

HK DSNB detection perspectives

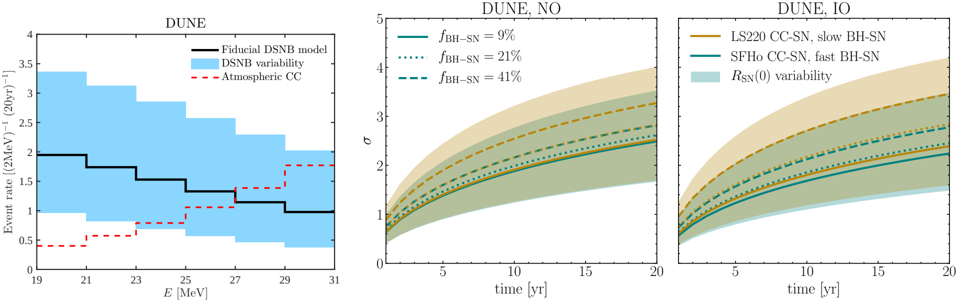




- fiducial volume: 374 kton
- efficiency: 67%

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

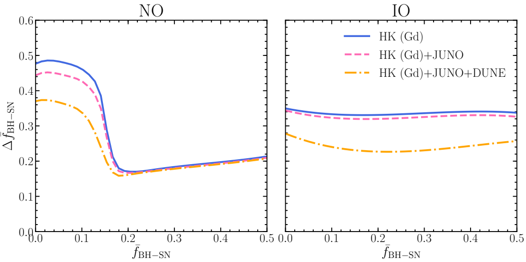
DUNE DSNB detection perspectives



- fiducial volume: 40 kton
- efficiency: 86%

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

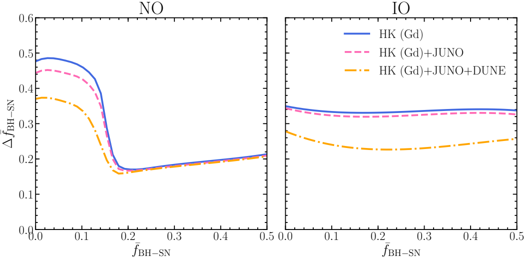
Expected 1σ uncertainty: fraction of BH forming progenitors



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

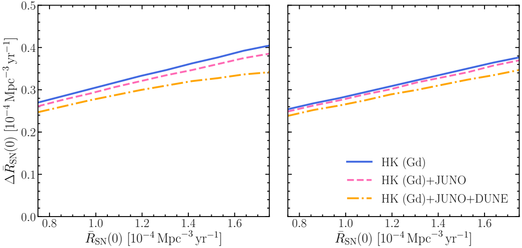
Møller, **AMS**, Tamborra, Denton (2018)

Expected 1σ uncertainty: local supernova rate



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

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



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

Astrophysical uncertainties affecting the DSNB

- Neutrino Flux from an "Average Supernova"

  Lunardini (2009), 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)

- Low-Energy Atmopsheric Neutrinos

  Detection of sub-100 MeV in JUNO **AMS** & Beacom (2023)

Non exhaustive list of references

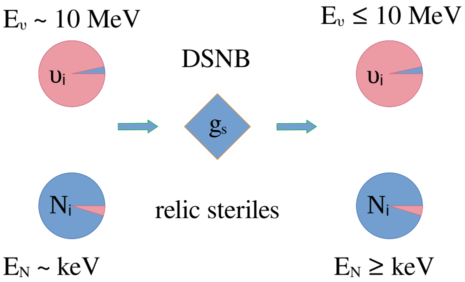
How to probe new physics with these uncertainties?

Probing self-interacting sterile neutrino dark matter with the DSNB

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

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

Do KeV-mass Sterile Neutrinos Have Self-Interactions?



Resonant interaction for sterile neutrinos

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

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

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

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

Modeling secret neutrino interactions in DSNB

Modified DSNB flux

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

Probability of interaction

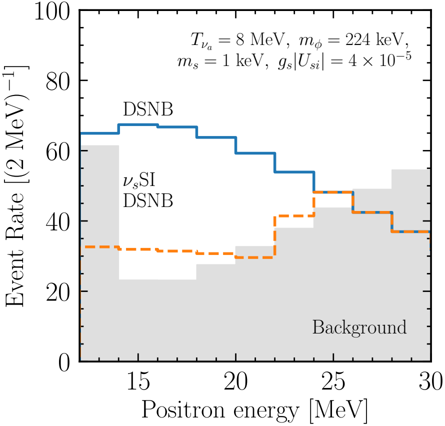
$$P_i(E_\nu, z) = e^{-\tau_i(E_\nu, z)}$$

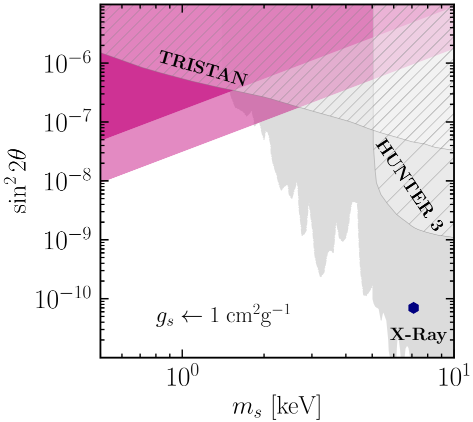
$$\tau_i(E_\nu, z) \simeq \tau_R \Theta(z - z_R) = \frac{\Gamma_R(z_R)}{(1+z_R)H(z_R)}\Theta(z - z_R)$$

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 (DUNE?)
- Reduction of the astrophysical uncertainties helps but not by a lot

Conclusions

Core-collapse supernovae

- serve as 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

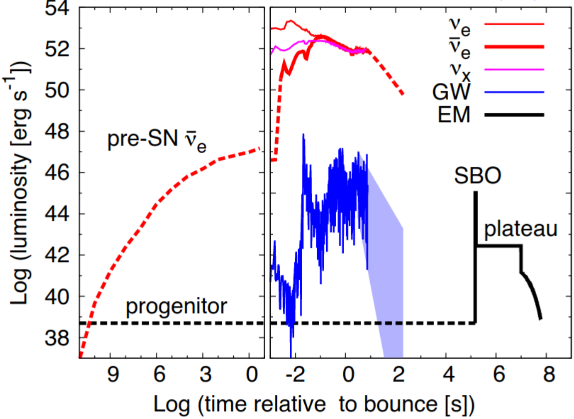
Exciting times ahead!

Thank you for the attention!

Backup

Core-Collapse Supernova Light Curve

Nakamura et al. (2016)



Partial Derivatives for the Fermi-Dirac distributions

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

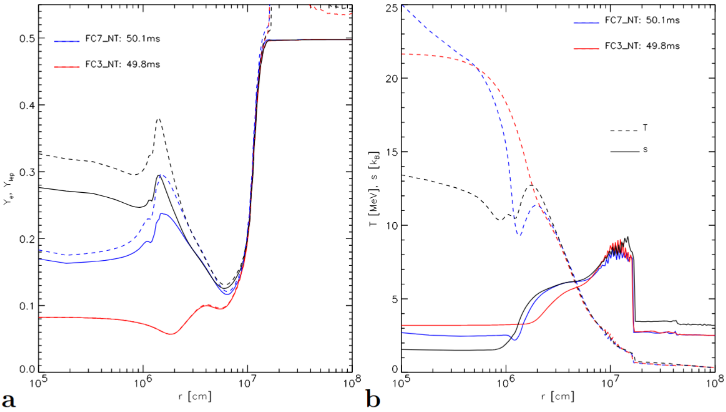
$$\frac{\partial n}{\partial T} = \frac{g}{2\pi^2} \int_m^\infty dE\, E \sqrt{E^2 - m^2}\, \frac{(E-\mu)}{4T^2} \cosh^{-2}\left(\frac{E-\mu}{2T}\right) , \tag{1a}$$

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

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

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

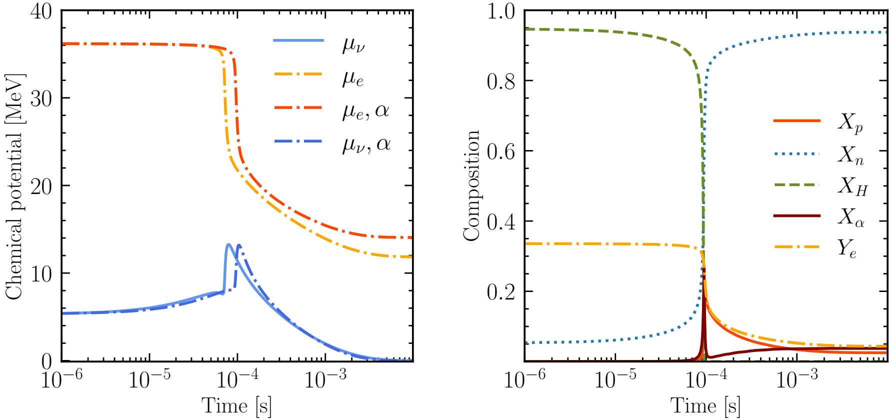
Proxy "Internal Deleptonization"



$$\nu_e + N \leftrightarrow \bar{\nu}_e + N$$

M. Rampp et al. (2002)

LS 220 Equation of State: impact of α particles



Combined likelihood analyses

Significance test

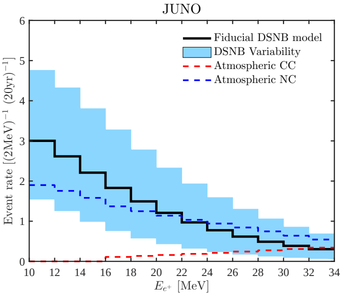
$$\chi^2 = \min_{A} \left(\sum_{j} \chi^2_{A,j} + \chi^2_{\mathrm{HK}} + \chi^2_{\mathrm{JUNO}} + \chi^2_{\mathrm{DUNE}}\right)$$

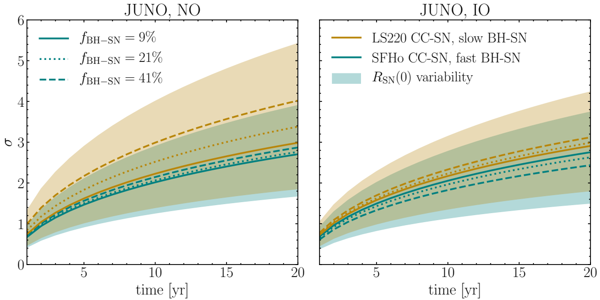
The set of parameters to be marginalized over:

- $f_{\mathrm{BH-SN}}$, $\Delta_{f_{\mathrm{BH-SN}}} = 0.2$
- $R_{\mathrm{SN}}(0)$, $\Delta_{R_{\mathrm{SN}}(0)} = 0.25 \times 10^{-4}\ \mathrm{Mpc}^{-3}\ \mathrm{yr}^{-1}$
- background normalization uncertainty, $\Delta_{\mathrm{BG}} = 20\%$
- liquid argon cross section uncertainty, $\Delta\sigma_{\mathrm{LAr}} = 15\%$
- mass accretion rate - equation of state uncertainty

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

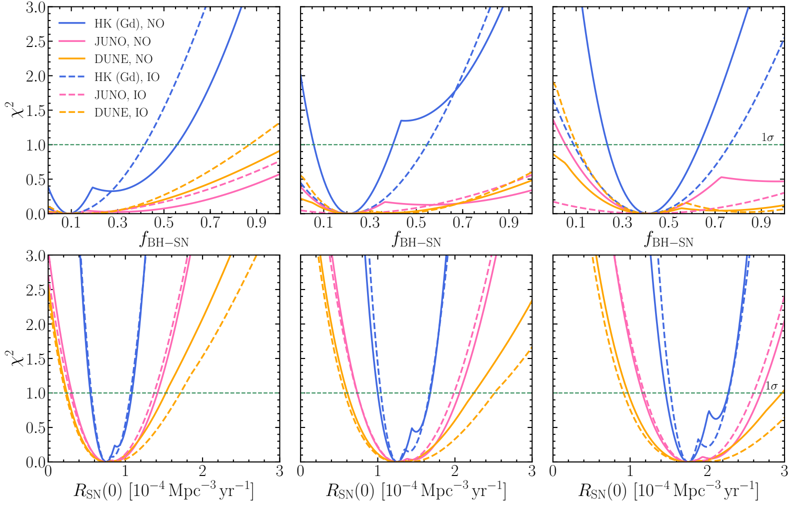
JUNO DSNB detection perspectives





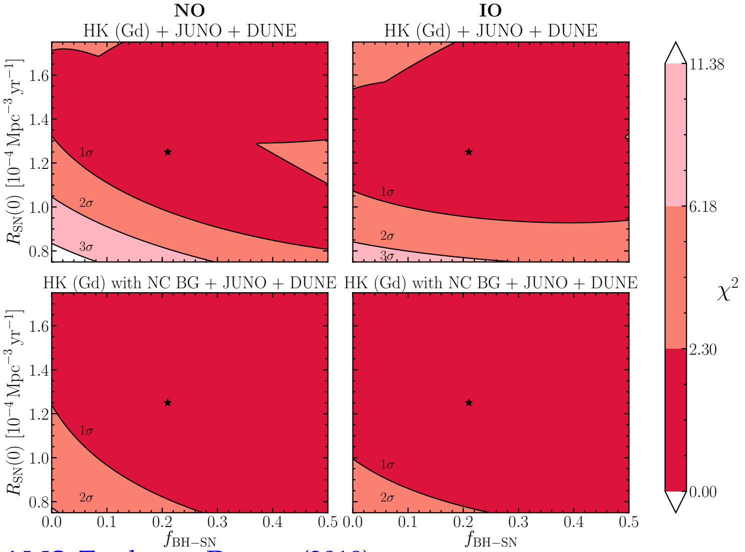
Moller, **AMS**, Tamborra, Denton (2018)

Expected 1D χ^2 as a function of $f_{\mathrm{BH-SN}}$ and $R_{\mathrm{SN}}(0)$



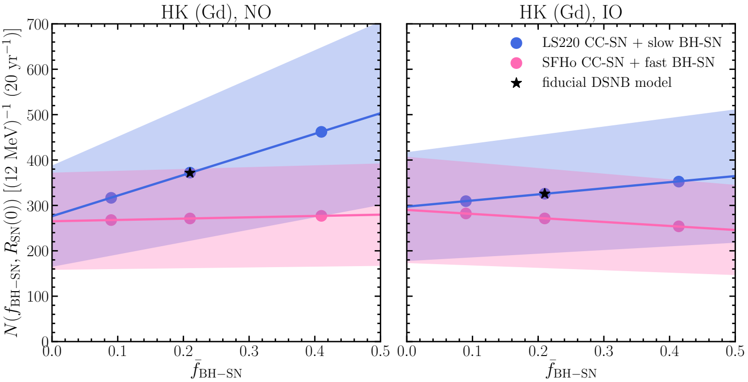
Moller, **AMS**, Tamborra, Denton (2018)

χ^2 for the fraction of BH forming progenitors - local supernova rate plane



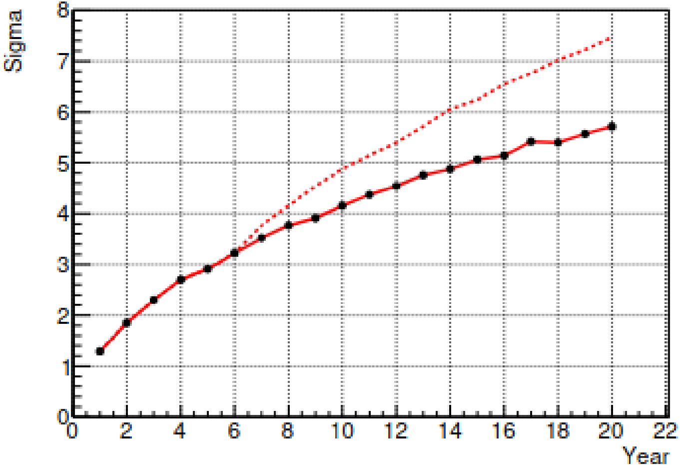
Moller, **AMS**, Tamborra, Denton (2018)

Number of events in HK (Gd) energy window



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

HK detection perspectives HK report



HK design report (2018)