Supernova Neutrinos – within the Standard Model and beyond

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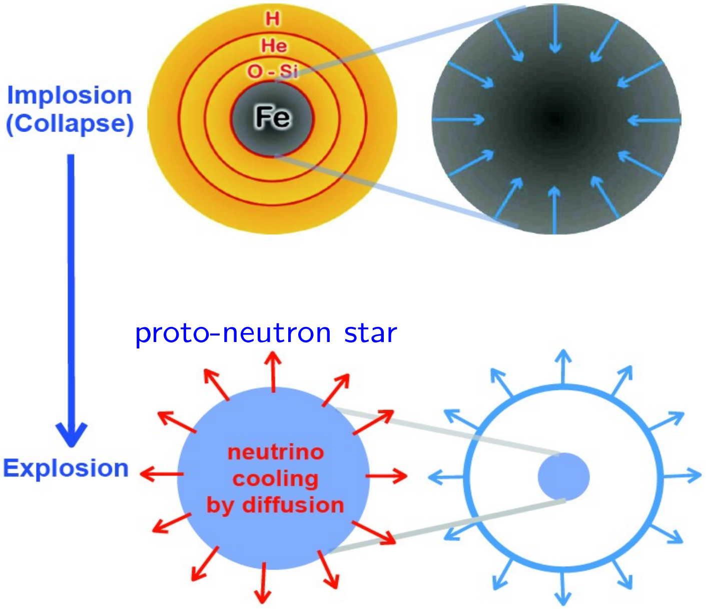
International Symposium on Neutrino Physics and Beyond (NPB 2024)
HKUST Jockey Club Institute for Advanced Study, Hong Kong, Feb 19-21, 2024

Core-collapse supernovae

(From AAO website)



progenitor star ($\gtrsim 8\ M_\odot$)

[Figure from G. Raffelt]

$$M_{\rm Fe,core} \approx 1.4 M_\odot$$
$$R_{\rm Fe,core} \approx 3000\ {\rm km}$$
$$\rho_c \approx 10^9\ {\rm g\ cm^{-3}}$$
$$T_c \approx 10^{10}\ {\rm K} \sim 1\ {\rm MeV}$$

proto-neutron star

$$M_{\rm PNS} \approx 1.4 M_\odot$$
$$R_{\rm PNS} \approx 15\text{–}50\ {\rm km}$$
$$\rho_c \approx 3 \times 10^{14}\ {\rm g\ cm^{-3}}$$
$$T_c \approx 30\ {\rm MeV}$$

$E_{\rm grav} \sim \frac{G M_{\rm PNS}^2}{R_{\rm PNS}} \sim 10^{53}$ erg, radiated mostly by $\sim 10^{58}$ ν's in $\sim$ 10 seconds

→ ~ 20 events from SN1987a at LMC

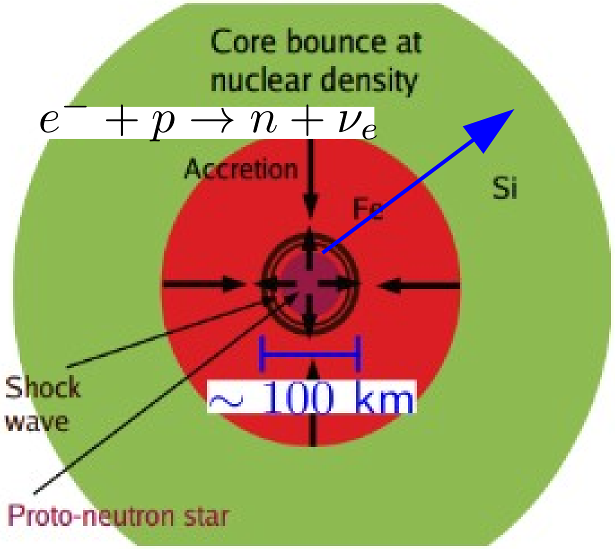
→ thousands of events in ALL FLAVORs expected from the next Galactic SN

General feature of supernova neutrino emission

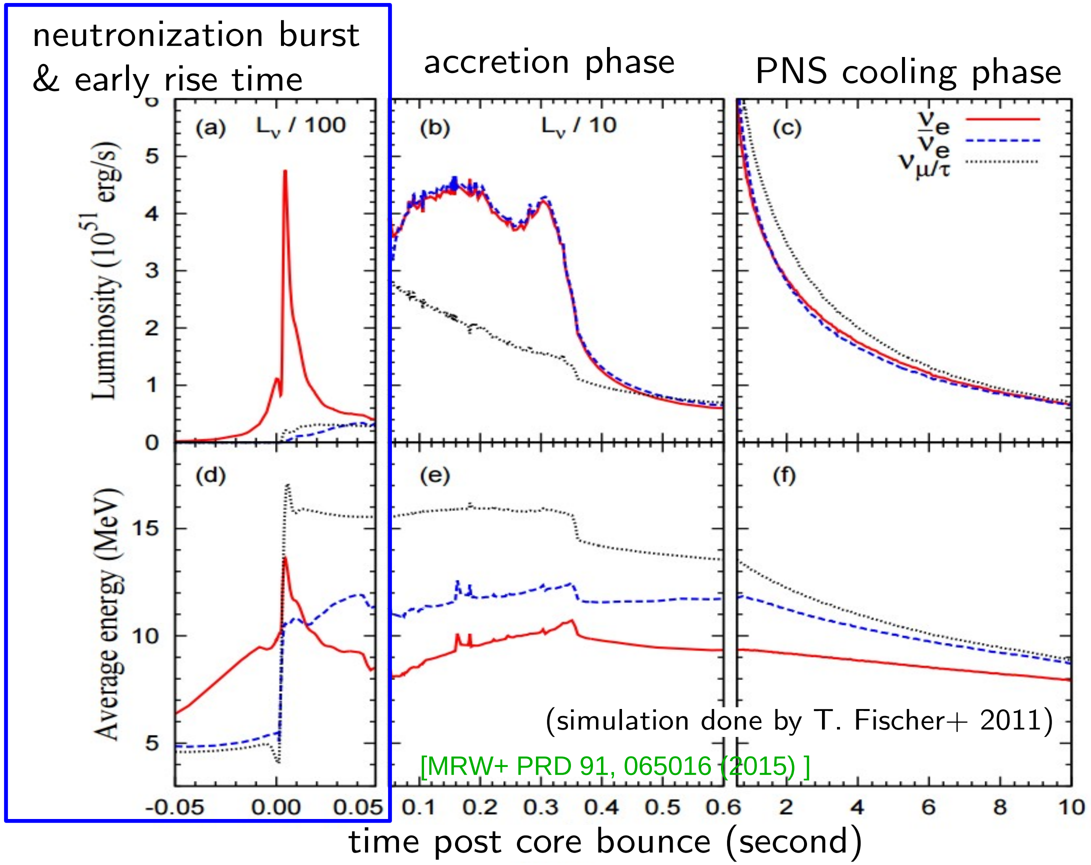
- neutronization burst: dominant ν_e emission for ~ 30 ms from shock-breakout off neutrinosphere; robust theory prediction

- accretion phase: powered by accreting material for $\mathcal{O}(100)$ ms; neutrinos play key role in reviving the shock

- cooling phase: $\mathcal{O}(10)$ s emission from PNS; ν-driven wind for nucleosynthesis



[Janka+, PTEP 01A309, 2012]



(simulation done by T. Fischer+ 2011)

[MRW+ PRD 91, 065016 (2015)]

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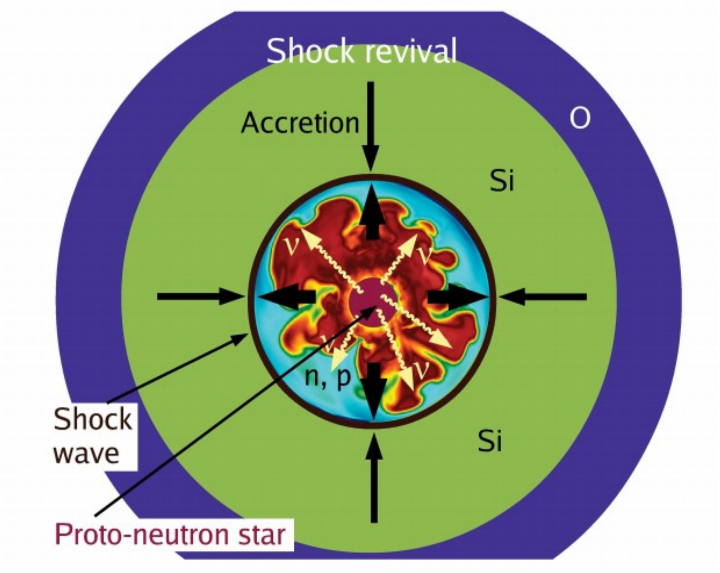

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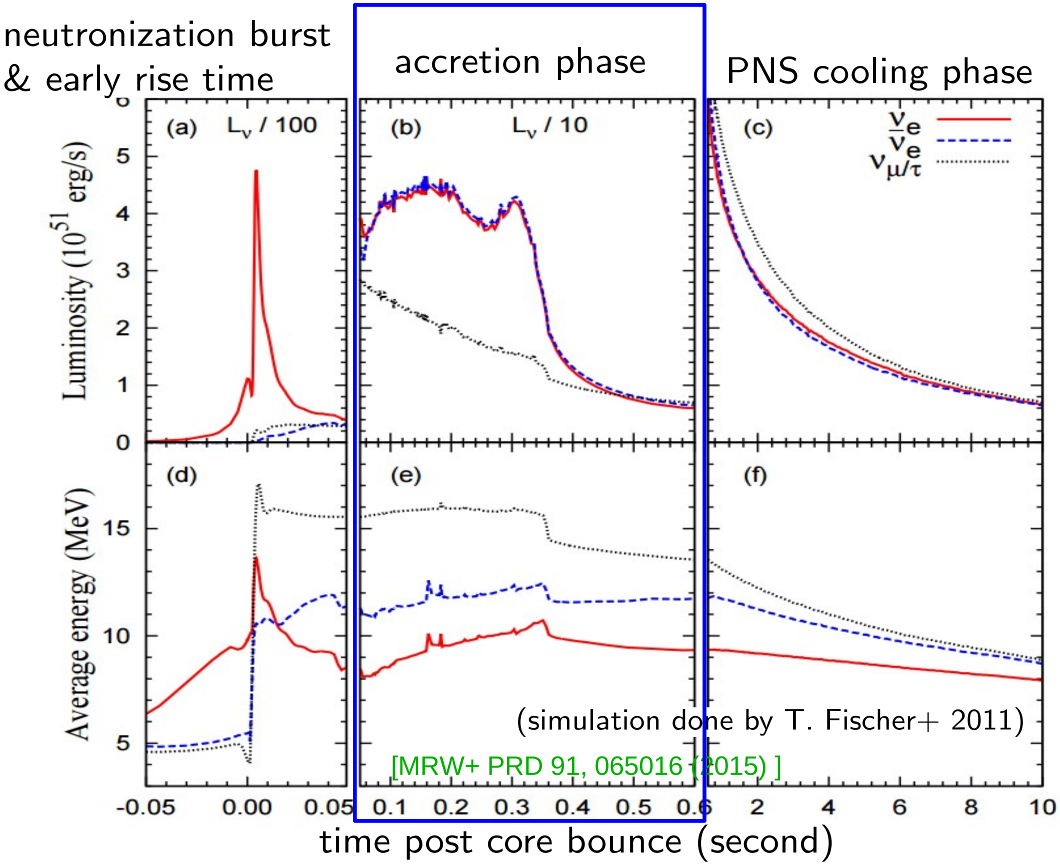

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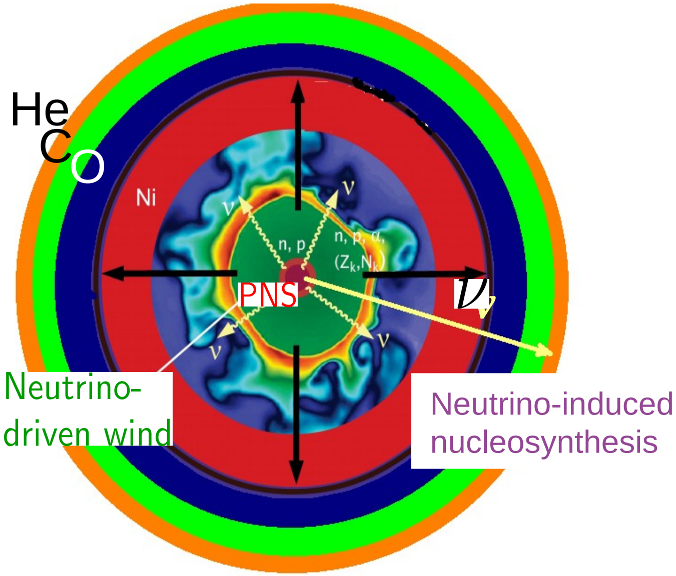
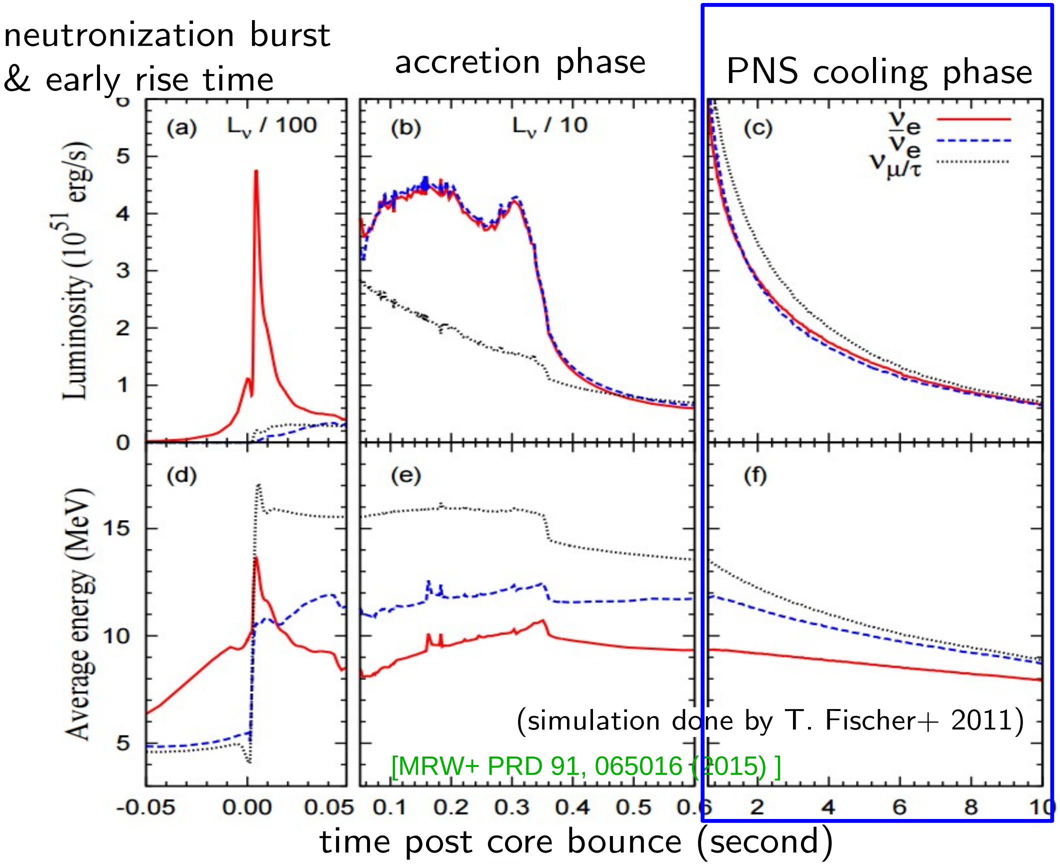


[Modified from Janka+, PTEP 01A309, 2012]



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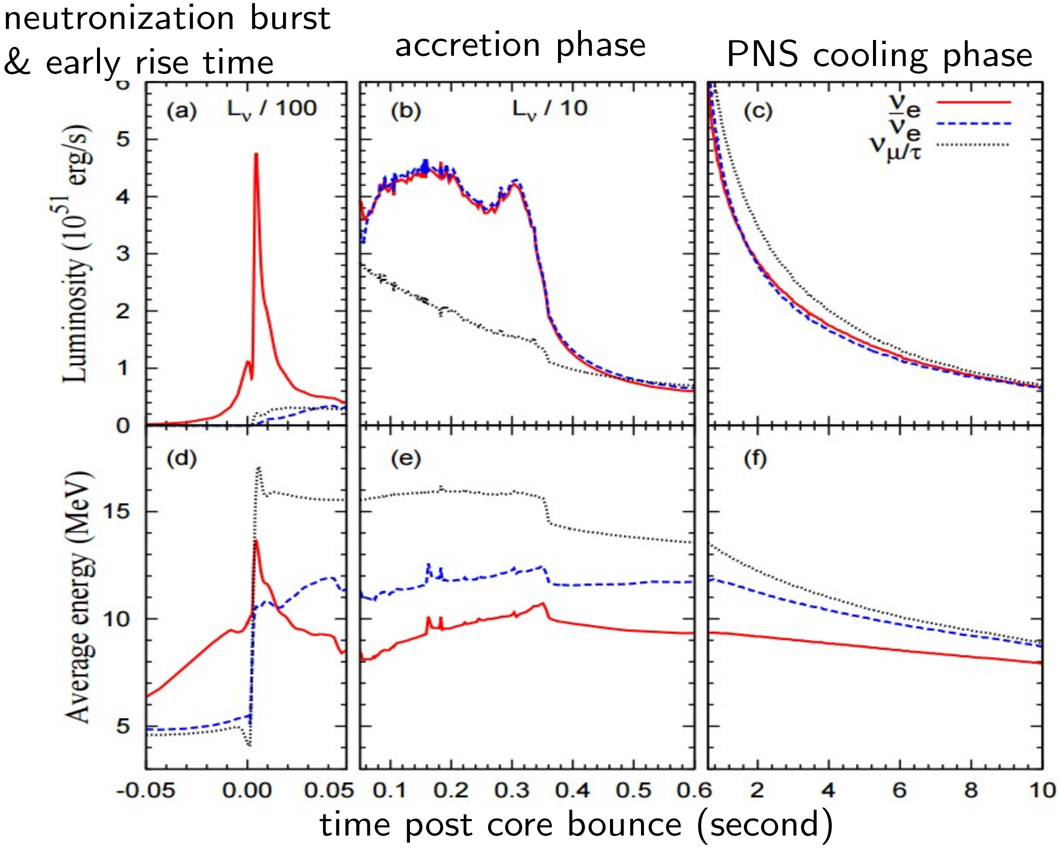


- What have we learned / what will we learn from the detection of SNν?
- How well do we understand SNν and their role in SN explosions?

What have we learned / what will we learn from the detection of SNν?

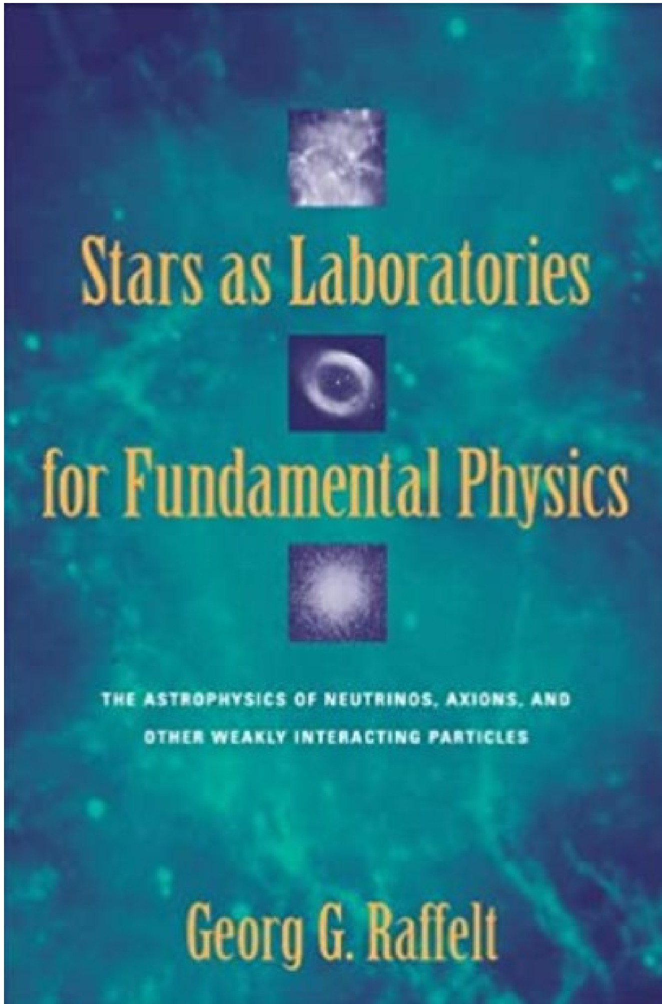
Supernovae as particle/nuclear physics laboratories

- SM physics: neutrino mass & ordering, strange quark contribution to proton's spin, explosion mechanism, nuclear equation of state, quark-hadron phase transition, ...

[Kachelriess+2004, Serpico+2012, MRW+2014, Vale+2015, Scholberg+2012, Jia+2017, Lai+2020, Brdar+2022,Takiwiki+2013, Mueller+2014, Tamborra+2014, Brueen+2014, Kuroda+2017, Takiwiki+2017, Seadrow+2018, Walk+2018, 2019, Lin+2019, Nakazato+2008, Sagert+2008, Dasgupta+2009, Nishimura+2011, Fischer+2020, Zha+2020, 2021, Fischer+2021, Kuroda+2021, Lin+2022, Jakobus+2022, Roberts+2011, Horowitz+2016, Rosso+2017, Roggero+2017, Nakazato+2017, Rosso+2018, Suwa+2019, Nakazato+2020, Li+2020,...]

- bSM physics: emission of light bSM particles from SN core/merger remnants, eV-MeV sterile neutrinos, non-Standard neutrino interactions, neutrino–DM interaction,...

[Raffelt+1988, Turner+1988, Janka+1995, Fischer+2016, Bar+2019, Lucente+2020, Fischer+2021, Mori+2021, Lucente+2022, Ferreira+ 2022, Dent+2012, Rrapaj+2015, Hardy+2016, Chang+2018, DeRocco+2019, Sung+2019, Dev+2020, Darme+2020, Sung+2021, Balaji+2022, Raffelt+2011, Arguelles+2016, Suliga+2019, 2020, Syvolap+2019, Rembiasz+2018, Mastrototaro+ 2019, Esmaili+ 2014, Franarin+ 2017, Tang+2020, MRW+2013, Tamborra+ 2011, Pllumbi+ 2014, Xiong+ 2019, Ko+2019, Kolb+1982, Fuller+1988, Choi+1988, Grifols+1988, Berezhiani+1989, Blennow+2008, Stapleford+2016, Das+2017, Yang+2018, Dighe+2018, Shalgar+2021, Das+2022, Abbar+2022, Murase+2019, Das+2021, Carpio+2022, Lin+2022, Carenza+2022, 2023, Lella+ 2023, Diamond+2021, 2023, Bhupal Dev+2023, Caputo+ 2021-2023...]


Stars as Laboratories for Fundamental Physics

THE ASTROPHYSICS OF NEUTRINOS, AXIONS, AND OTHER WEAKLY INTERACTING PARTICLES

Georg G. Raffelt

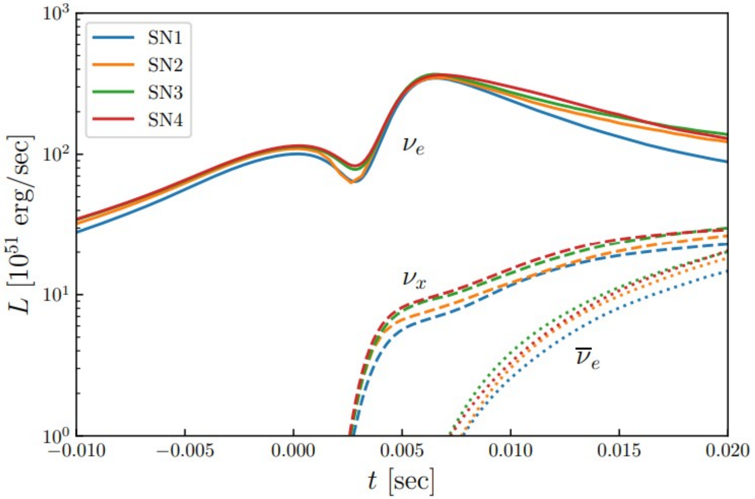
Mass ordering and absolute mass

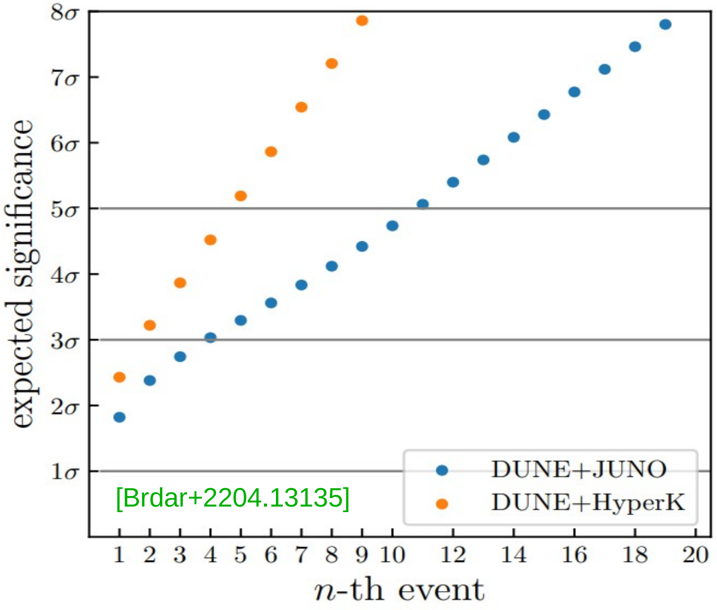
(see also Kachelriess+04, Serpico+12, MRW+14, Vale+15, Scholberg+17, Jia+17, Lai+20,...)

NO: $\nu_e^{\text{final,MSW}} \approx \nu_x^{\text{initial}}$

IO: $\nu_e^{\text{final,MSW}} \approx 0.3\nu_e^{\text{initial}} + 0.7\nu_x^{\text{initial}}$

The distinct hierarchy in luminosity of different flavors during the neutronization burst allows independent determination of mass ordering





[Brdar+2204.13135]

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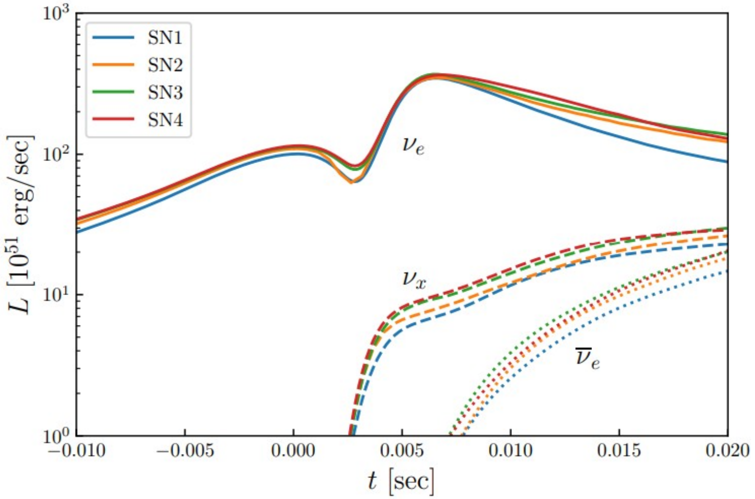
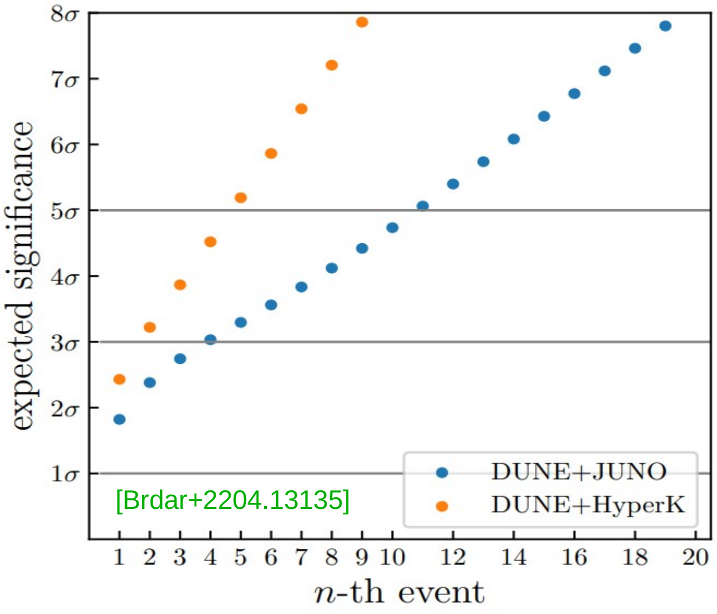
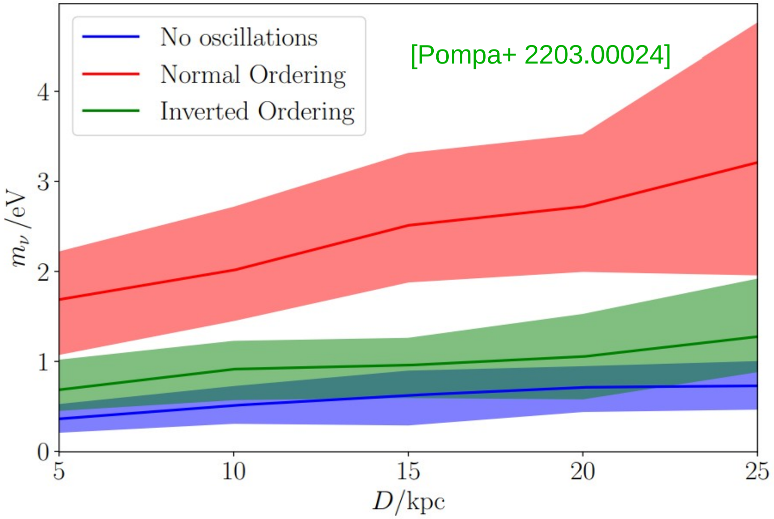




[Brdar+2204.13135]

The temporal information of SNν events also allows to probe the absolute ν mass down to $m_\nu \lesssim \mathcal{O}$(eV)

(see also Loredo+01, Nardi+04, Pagliaroli+10, Lu+15, Hansen+19, Pitik+22, ...)



[Pompa+ 2203.00024]

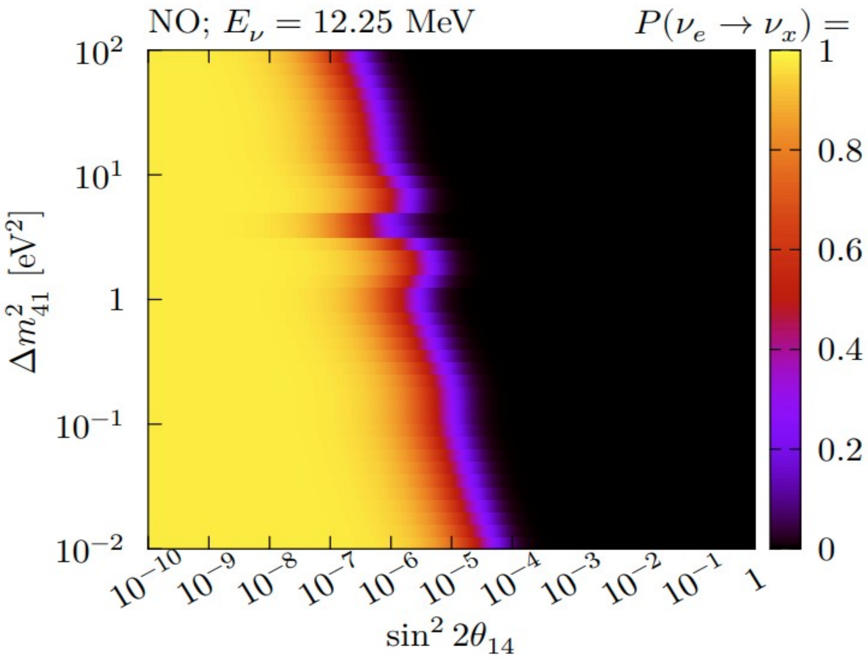
Light ($\sim$ eV) sterile neutrinos?

If light ($\sim$ eV) sterile ν exists and mixes with electron-flavor neutrinos, ν_e and $\bar{\nu}_e$ will be converted to ν_s and $\bar{\nu}_e$ after leaving the supernova core

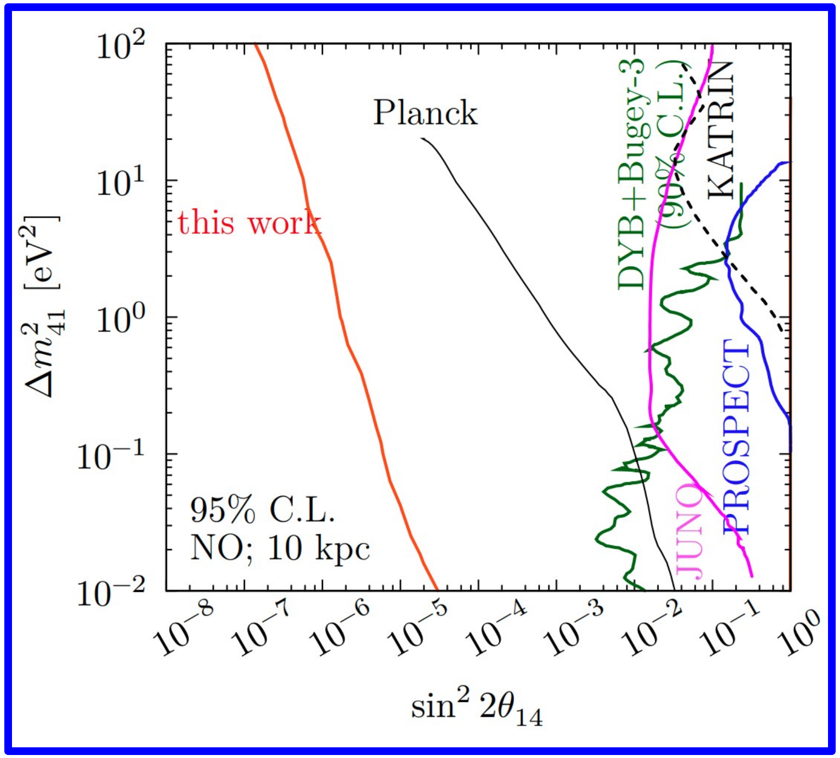
Event number at first ~ 10 ms

ν_e; @10 kpc (NO)	DUNE ArCC	Hyper K eES	JUNO eES	JUNO pES
3-ν mixing	12.8	36.5	2.2	9.1
$\sin^2 2\theta_{14} = 10^{-3}$, $\Delta m^2_{41} = 1$ eV^2	10.3	11.3	0.7	3.3

(for IO, both CC and eES are important)



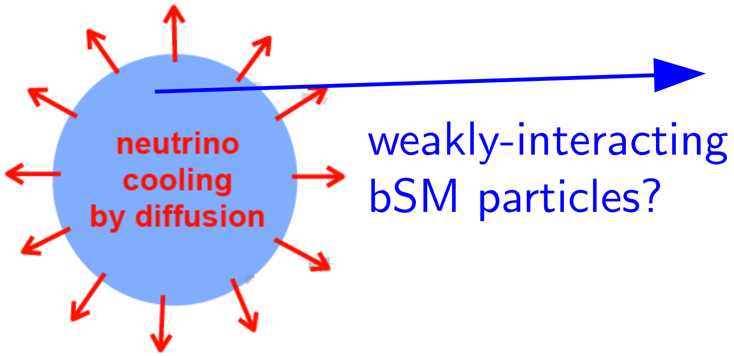
[Tang, Wang, MRW, 2005.09168]



Other bSM physics

PNS cooling bound:

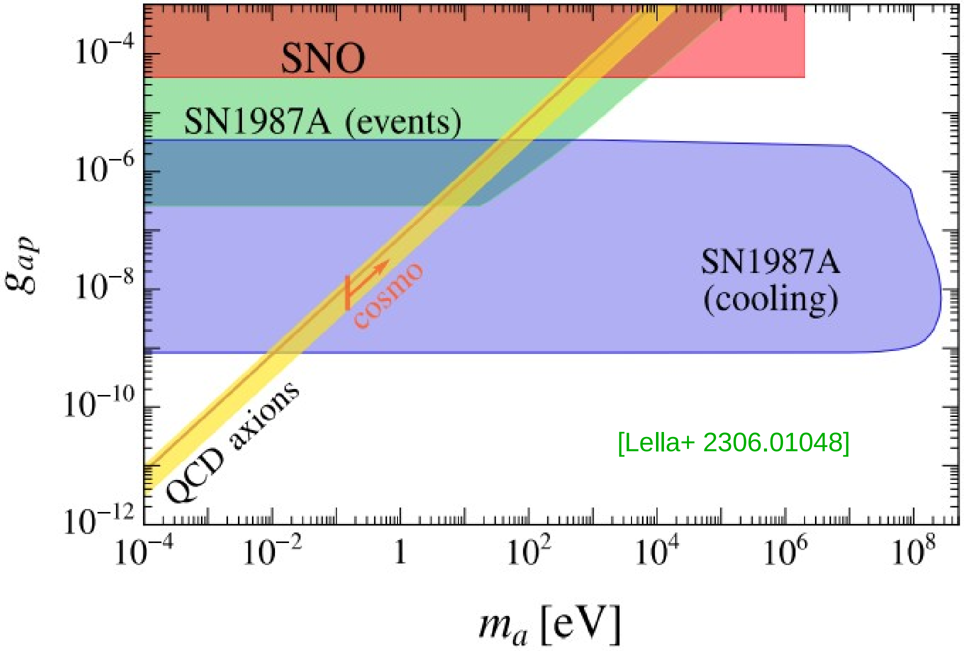
$L_{\text{exotic}} < L_\nu \sim 3 \times 10^{52}$ erg/s



neutrino cooling by diffusion

weakly-interacting bSM particles?

For axion-like particles



[Lella+ 2306.01048]

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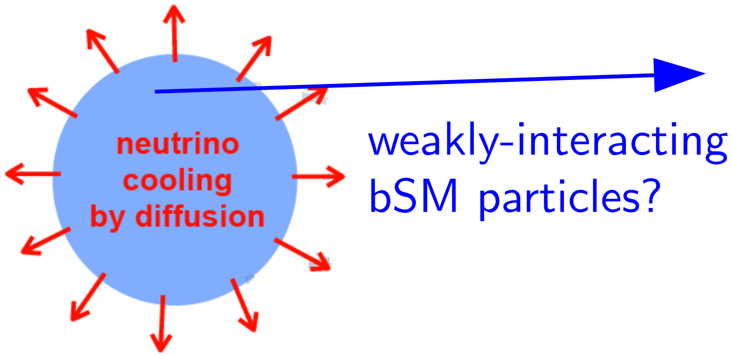

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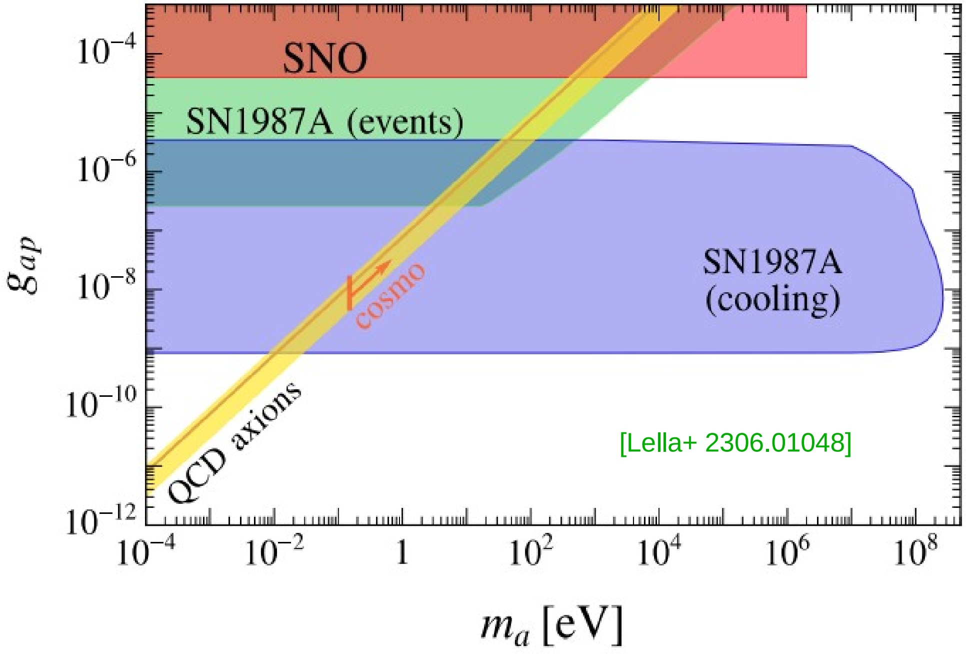
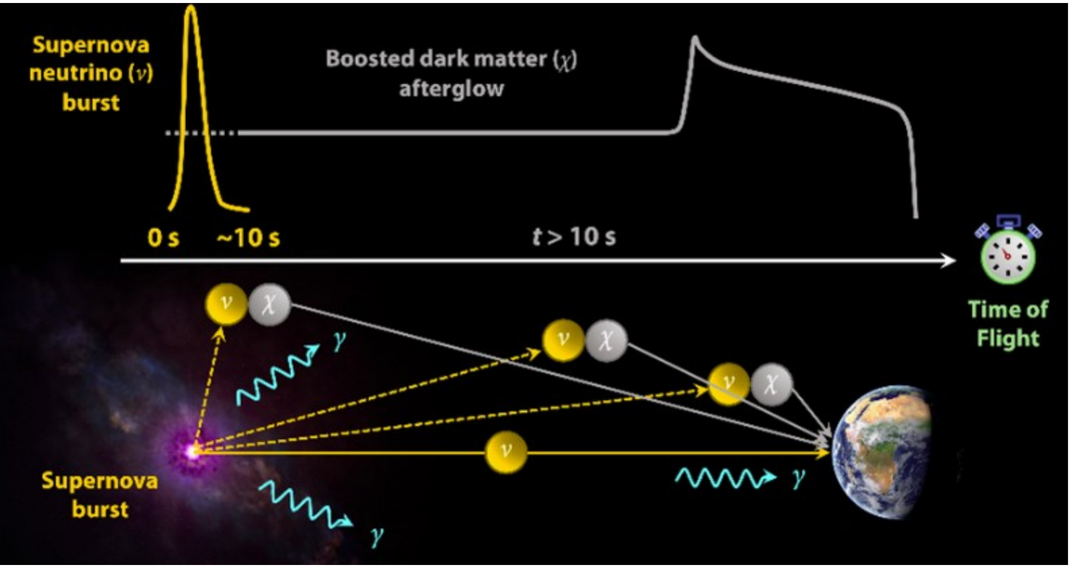
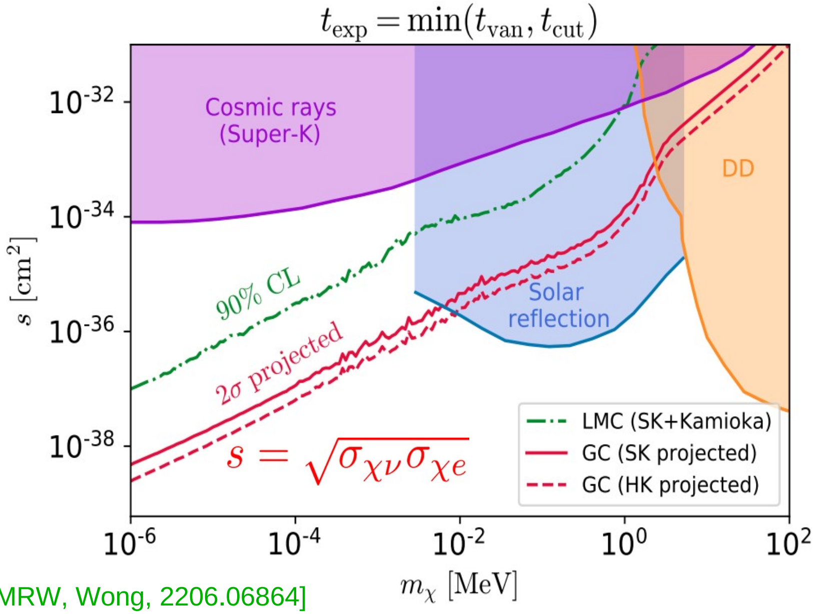


[Lella+ 2306.01048]

neutrino – dark matter interaction?





[Lin, Wu, MRW, Wong, 2206.06864]

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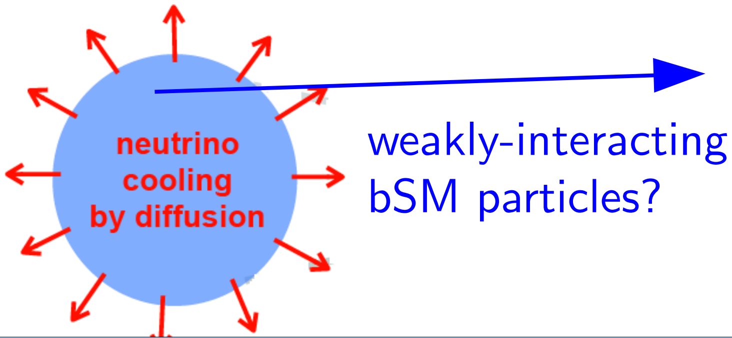

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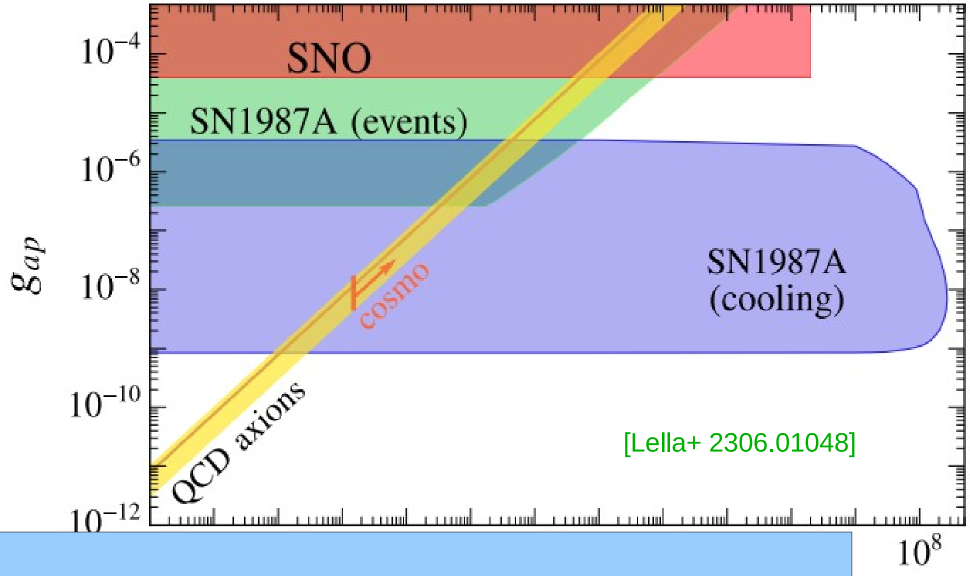
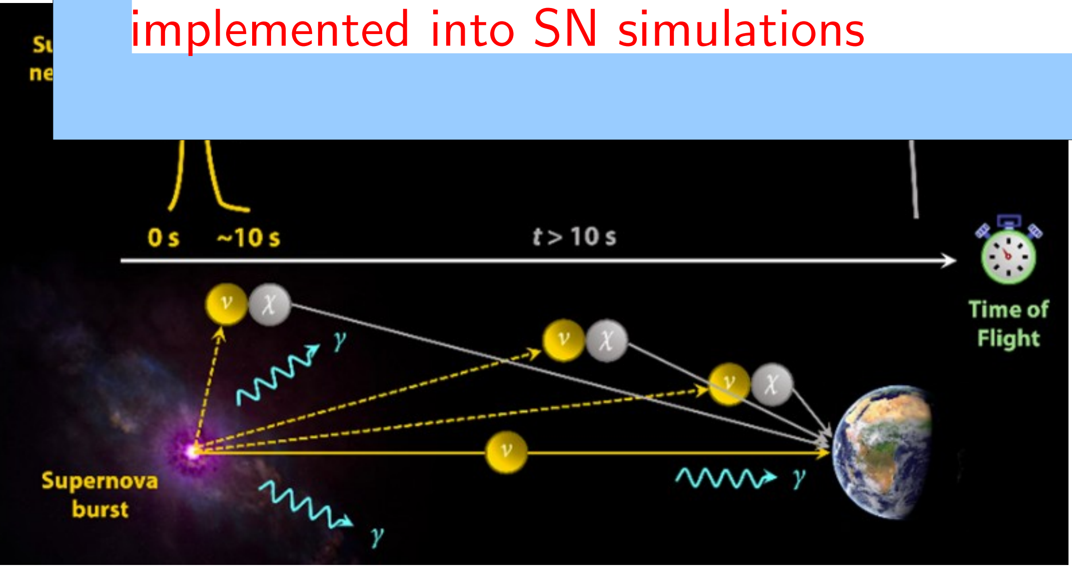
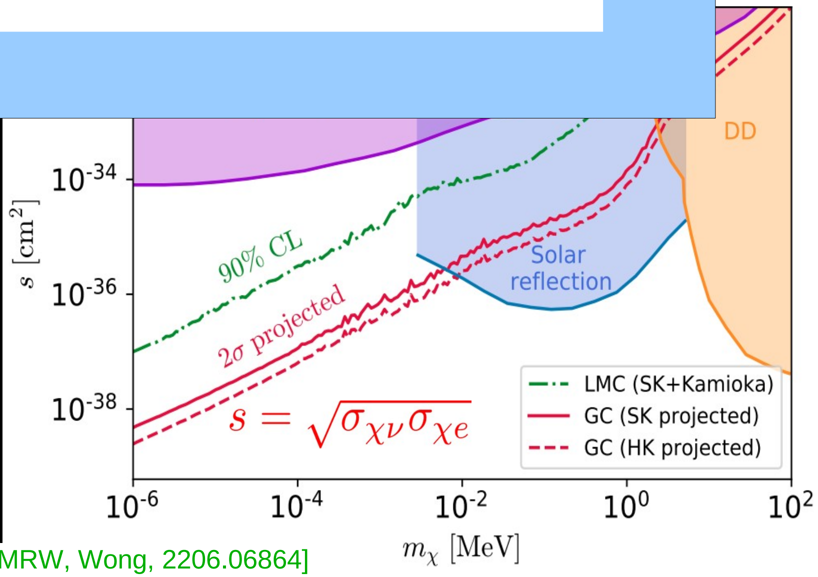


[Lella+ 2306.01048]

Better / more robust bounds may be obtained with detailed statistics from the next galactic SN, provided that these exotic physics can be implemented into SN simulations





[Lin, Wu, MRW, Wong, 2206.06864]

How well do we understand SNν and their role in SN explosions?

SN explosion and ν transport

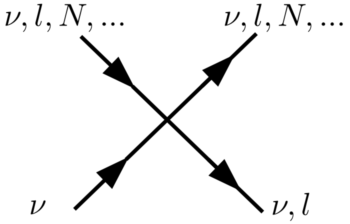
In SN explosions: $E_\nu \sim E_{\mathrm{G,NS}} \sim 10^{53}$ erg $\gg E_{\mathrm{expl}} \sim 10^{51}$ erg

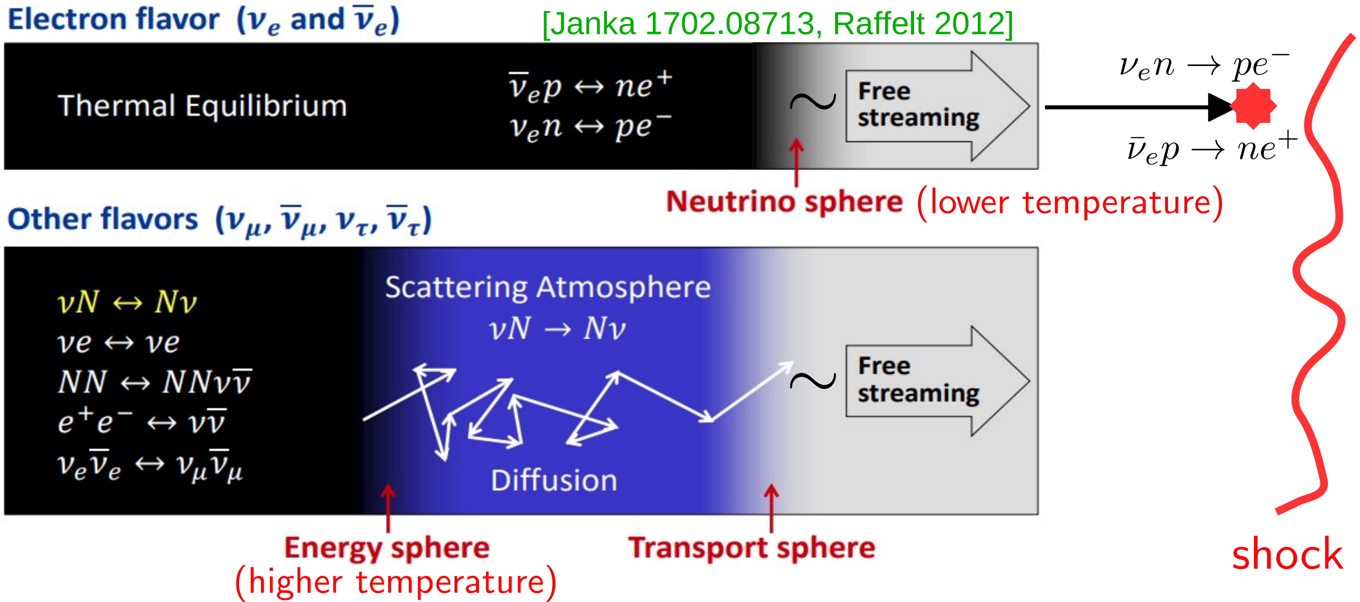
→ a few percent of neutrino energy deposition is enough to deliver the explosion

→ needs to model the neutrino transport accurately

State-of-the-art general relativistic (magneto-) hydrodynamic simulations of supernovae include approximate treatment of classical Boltzmann transport of neutrinos

$$(\partial_t + \mathbf{v}\cdot\partial_{\mathbf{x}} + \mathbf{F}\cdot\partial_{\mathbf{p}})f_{\nu_\alpha}(\mathbf{x},\mathbf{p},t) = \mathcal{C}$$




[Janka 1702.08713, Raffelt 2012]

ν_e and $\bar{\nu}_e$ dominate the energy deposition to the shock

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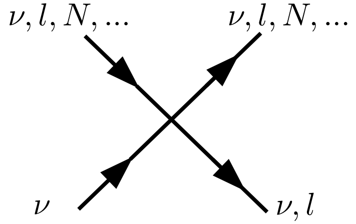
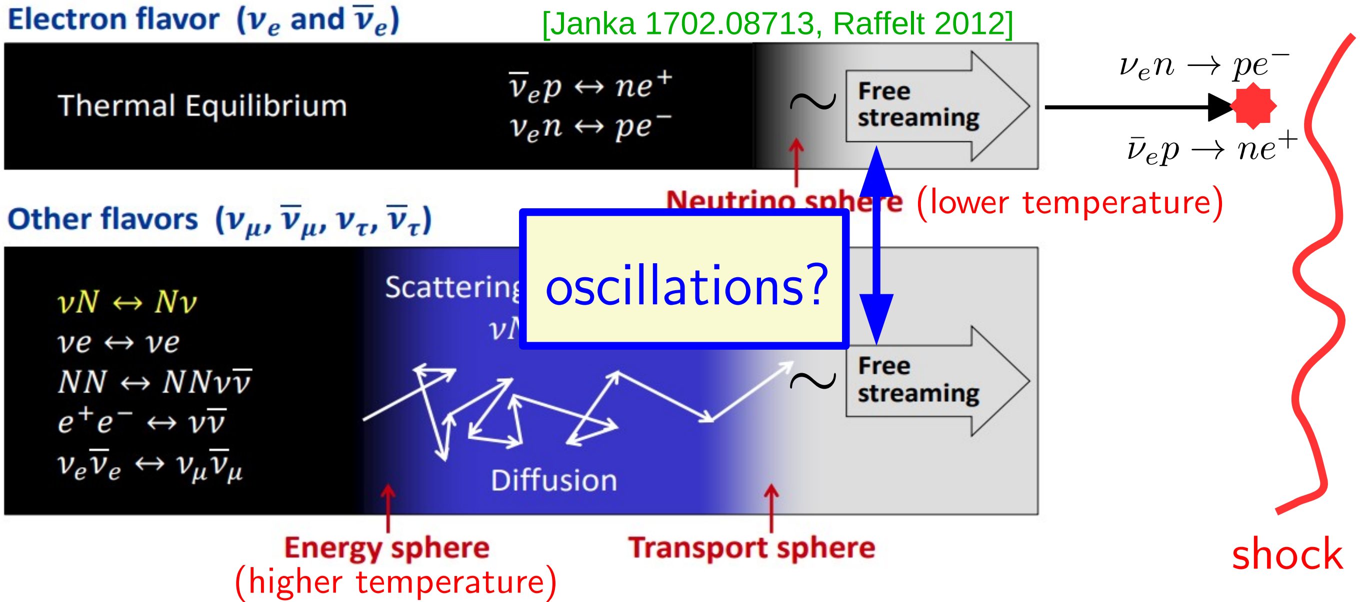
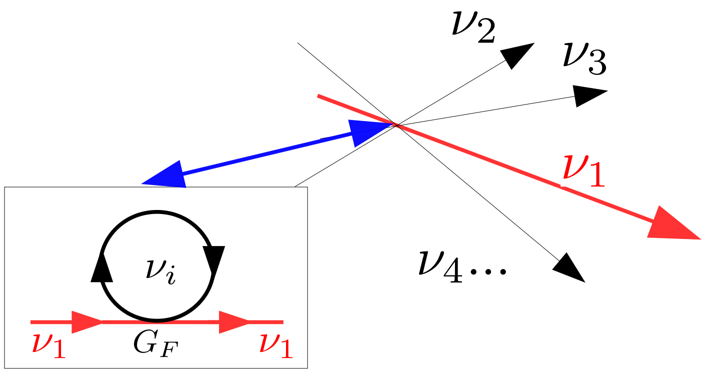




ν_e and $\bar{\nu}_e$ dominate the energy deposition to the shock

Collective neutrino oscillations

[Fuller+ 1987, Pantaleone 1992, Sigl & Raffelt, 1992]



The forward scattering of ν-ν interaction couples the flavor evolution of ν with different momenta and introduce a new time scale $\mu \sim \sqrt{2} G_F n_\nu$

→ quantum kinetic equation (extended Boltzmann equation):

$$\boxed{(\partial_t + \mathbf{v} \cdot \partial_{\mathbf{x}} + \mathbf{F} \cdot \partial_{\mathbf{p}}) \varrho(\mathbf{x}, \mathbf{p}, t) = -i[H_{\text{vac}} + H_{\text{m}} + H_{\nu\nu}, \varrho(\mathbf{x}, \mathbf{p}, t)] + \mathcal{C}(\varrho)}$$

$$H_{\text{vac}}(p) = U M^2 U^\dagger / (2|\mathbf{p}|),$$

$$H_{\text{MSW}}(\mathbf{x}, t) = \sqrt{2} G_F n_e \times \text{diag}(1, 0, 0)$$

$$H_{\nu\nu}(\mathbf{x}, \mathbf{p}, t) = \frac{\sqrt{2} G_F}{(2\pi)^3} \int d^3 q (1 - \hat{\mathbf{p}} \cdot \hat{\mathbf{q}}) [\varrho - \bar{\varrho}^*]$$

$$\varrho(t, \mathbf{x}, \mathbf{p}) = \begin{bmatrix} f_{\nu_e} & \varrho_{e\mu} & \varrho_{e\tau} \\ \varrho_{e\mu}^* & f_{\nu_\mu} & \varrho_{\mu\tau} \\ \varrho_{e\tau}^* & \varrho_{\mu\tau}^* & f_{\nu_\tau} \end{bmatrix}$$

flavor density matrix of the neutrino ensemble

- for $E_\nu \sim 10$ MeV:

$$\omega_{\text{vac}} \sim \frac{\delta m_{13}^2}{2E_\nu} \sim 0.6 \text{ km}^{-1}$$

- for $n_\nu \sim 10^{33}$ cm^{-3}:

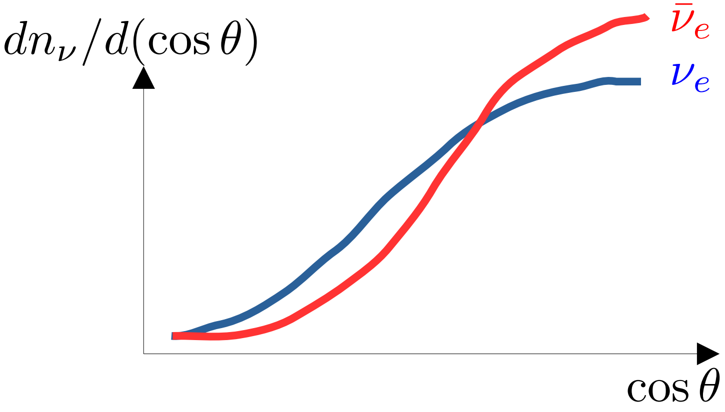
$$\mu \sim \sqrt{2} G_F n_\nu \sim 6 \times 10^5 \text{ km}^{-1}$$

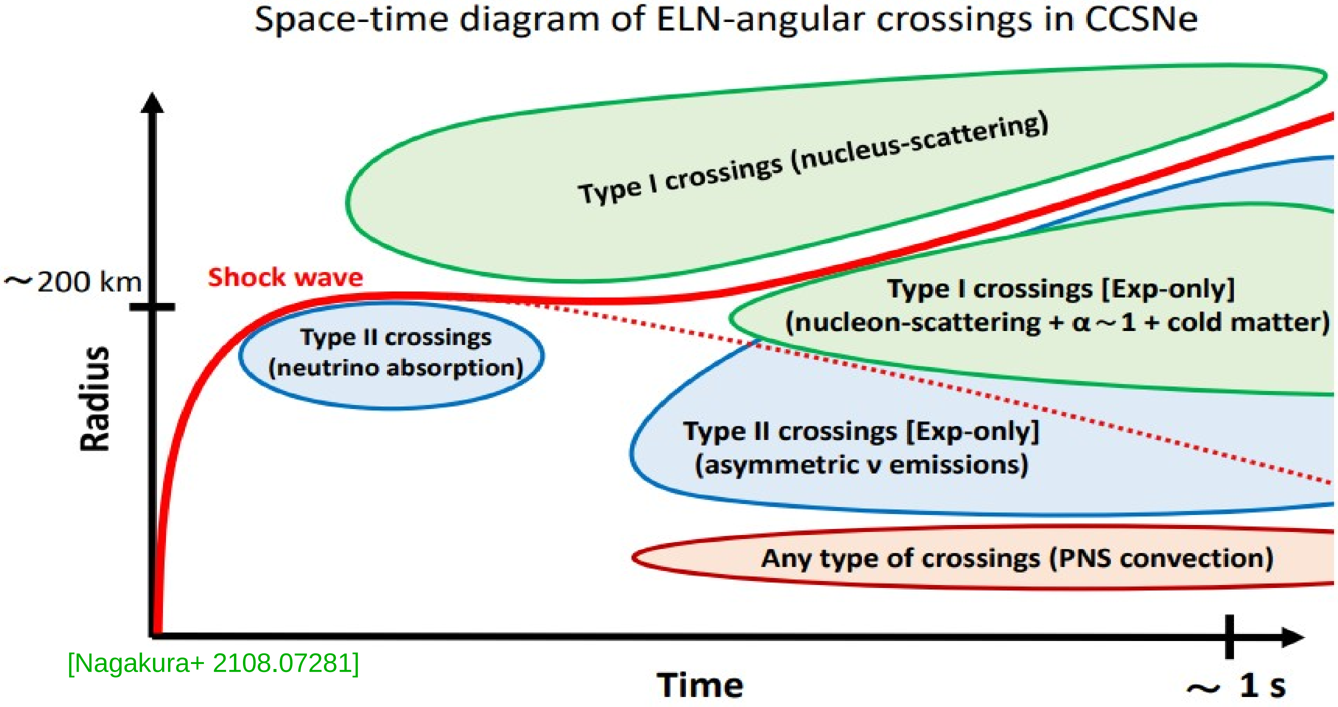
→ strong coupling in flavor space leading to collective oscillations with "fast" frequency ($\omega_{\text{col}} \sim \mu \sim \mathcal{O}(1)$cm^{-1})

Fast flavor conversions (FFC)

Fast flavor conversions can be very effective at regions where the "$e-\mu$ lepton number crossing" exists in neutrino angular distribution

[Sawyer+, Izaguirre+, Dasgupta+,...many others]





[Nagakura+ 2108.07281]

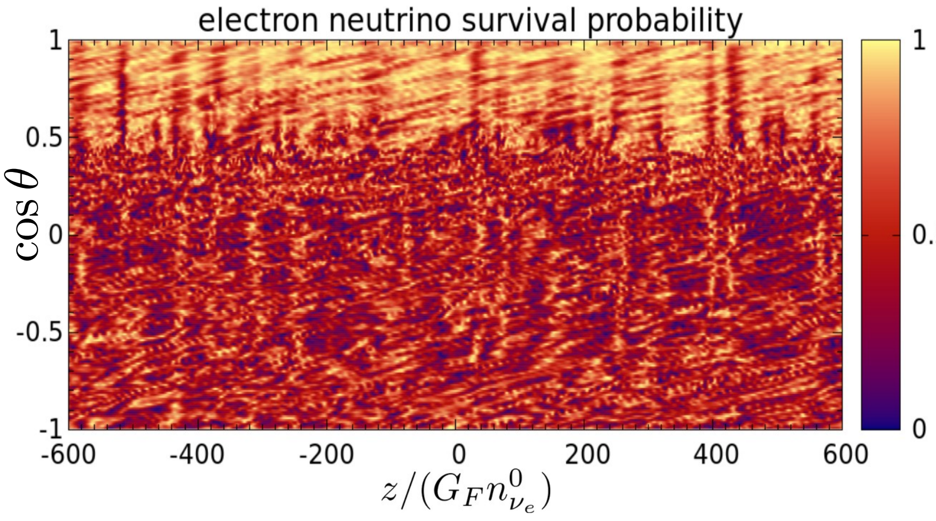
→ generally exist in regions below the shock, not only affect ν signals, but also the shock revival, i.e., the SN dynamics [see e.g., Ehring+ 2305.11207]

Fast flavor conversions (FFC)

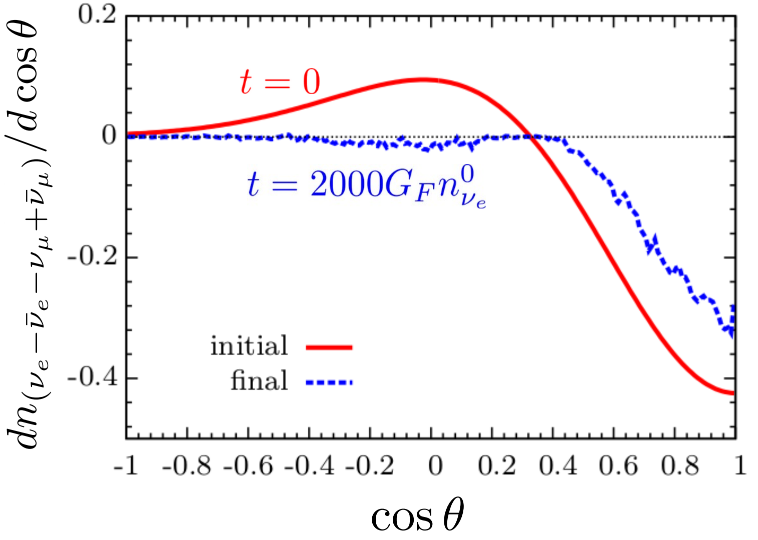
Several groups started to develop multidimensional simulation code to compute the outcome of FFC in a small and perodic box, mimicking a tiny volume inside supernovae [Bhattacharyya+, Richers+, MRW+, Martin+; see Richers+ 2205.06282 for detailed comparison of simulation results]

→ FFC will erase the $e-\mu$ lepton number angular crossing, i.e., lead to flavor equipartition in certain angular range

[MRW+ 2108.09886]



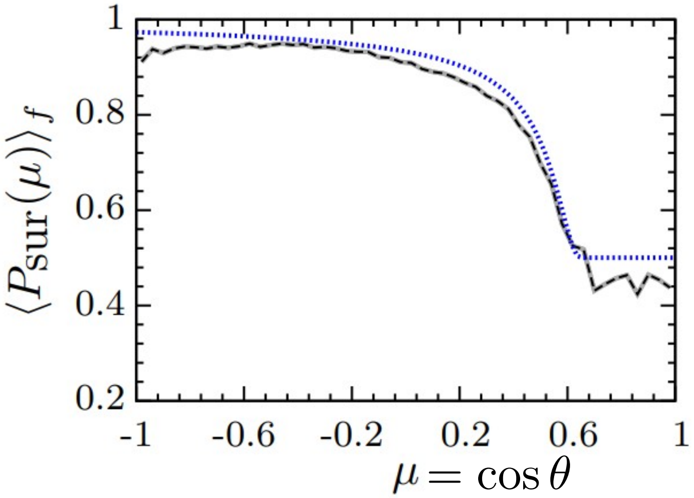
→ averaging over space



Toward including FFC in SN simulation

The simulation results can be well approximated by anayltical formulae, provided that the initial angular distributions are known (error $\lesssim 3\%$)

[Xiong+2307.11129]



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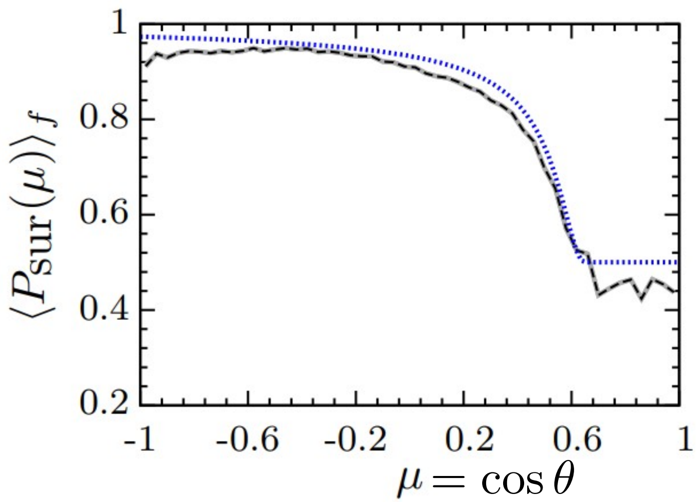
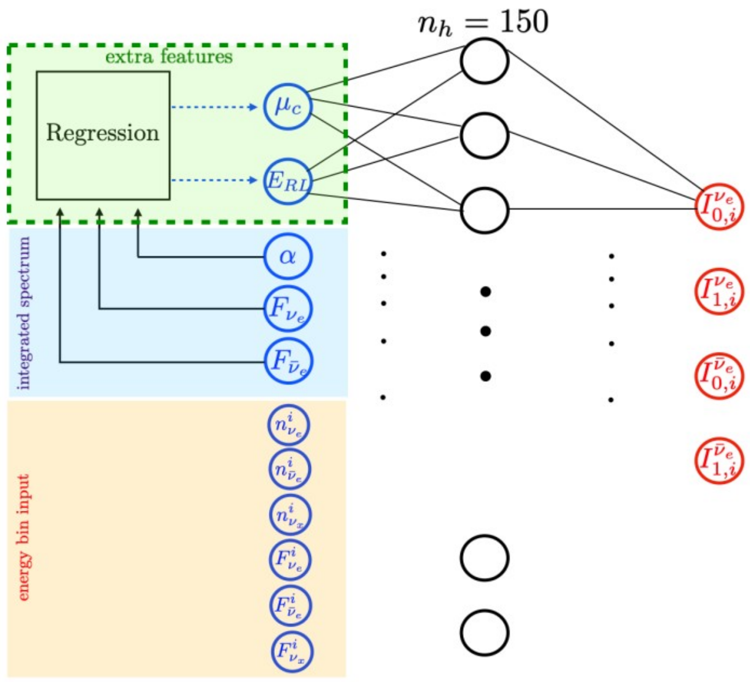
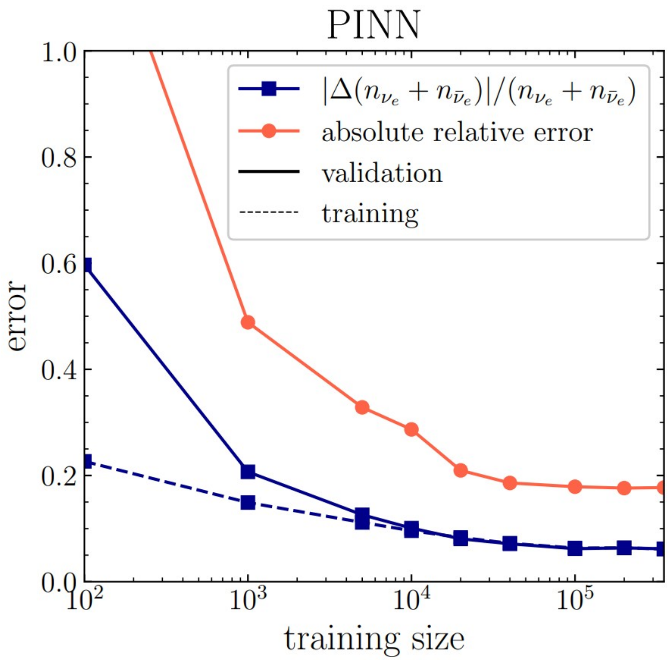


These serve as the fundamental inputs to construct physics-informed neural network to predict the ν angular moments post FFC, given the input moments





[Abbar+2311.15656, 2401.17424]

offer hopes to implement FFC in SN simulations

Summary

• The detection of neutrinos from the next galactic SN can provide independet probes to a wide array of fundamental physics properties, including (but not limited to) neutrino mass ordering, absolute mass, sterile neutrinos, ALPs, neutrino-DM interaction, etc.

• Significant progresses have been made rapidly in recent years to understand the daunting issue of collective neutrino flavor oscillations in SNe. In particular, practical inclusion of the fast flavor conversions in SN simulations may become feasible in the near future.