Neutrinos in astrophysical explosions

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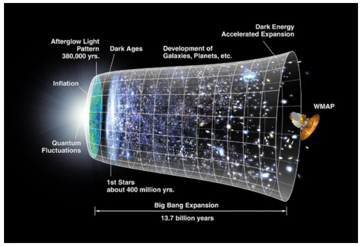
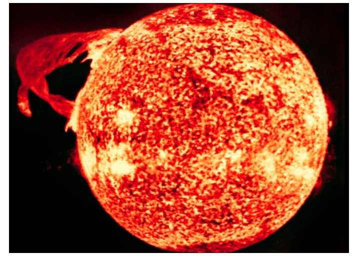
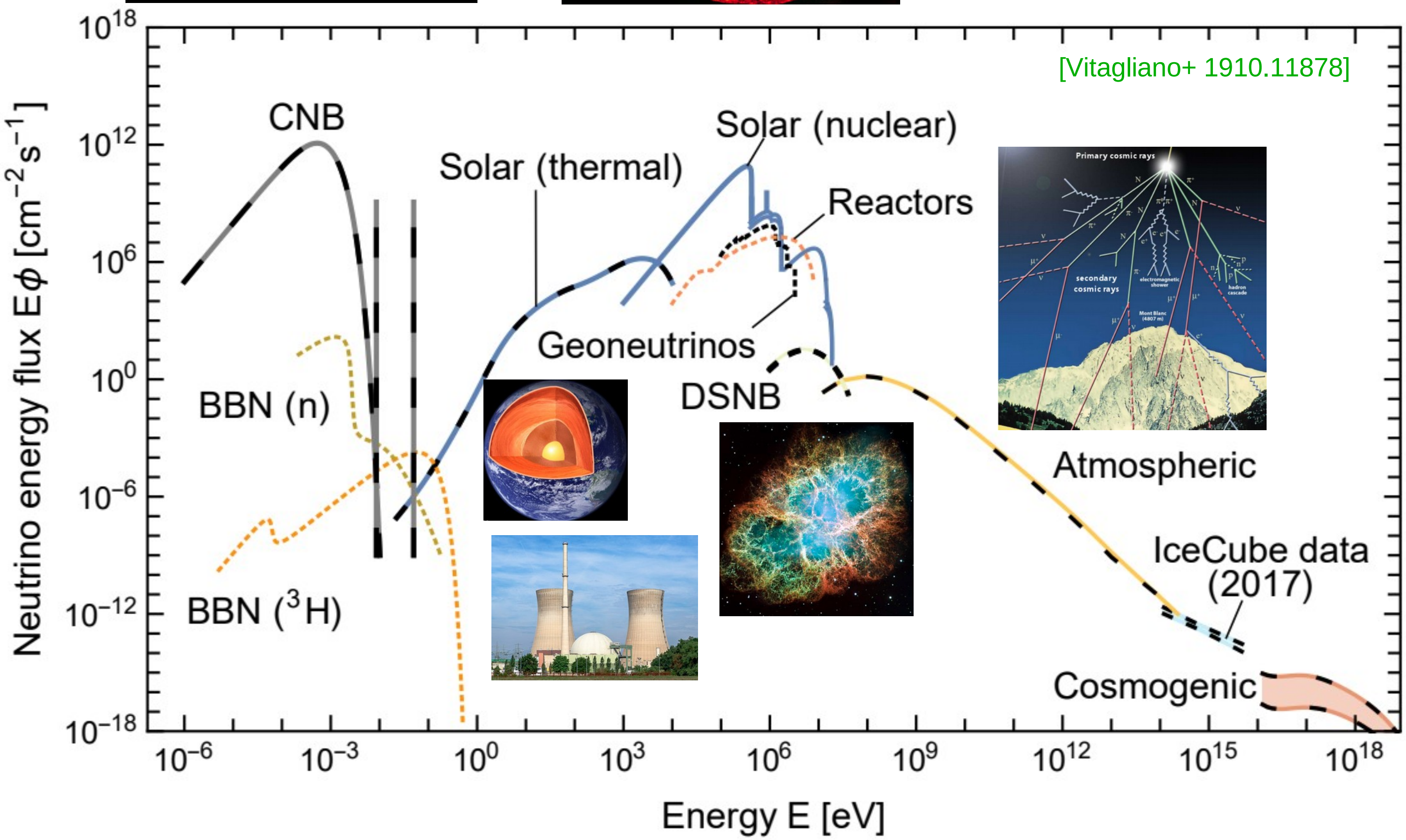
Neutrinos: key messengers for cosmology and astrophysics



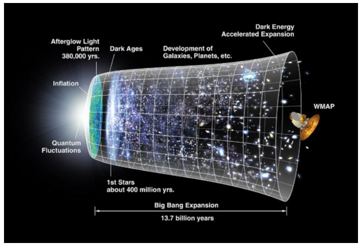


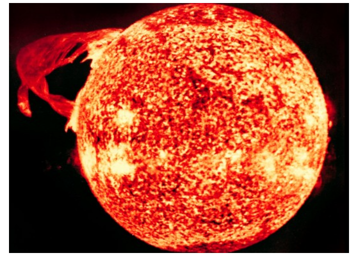


+...?

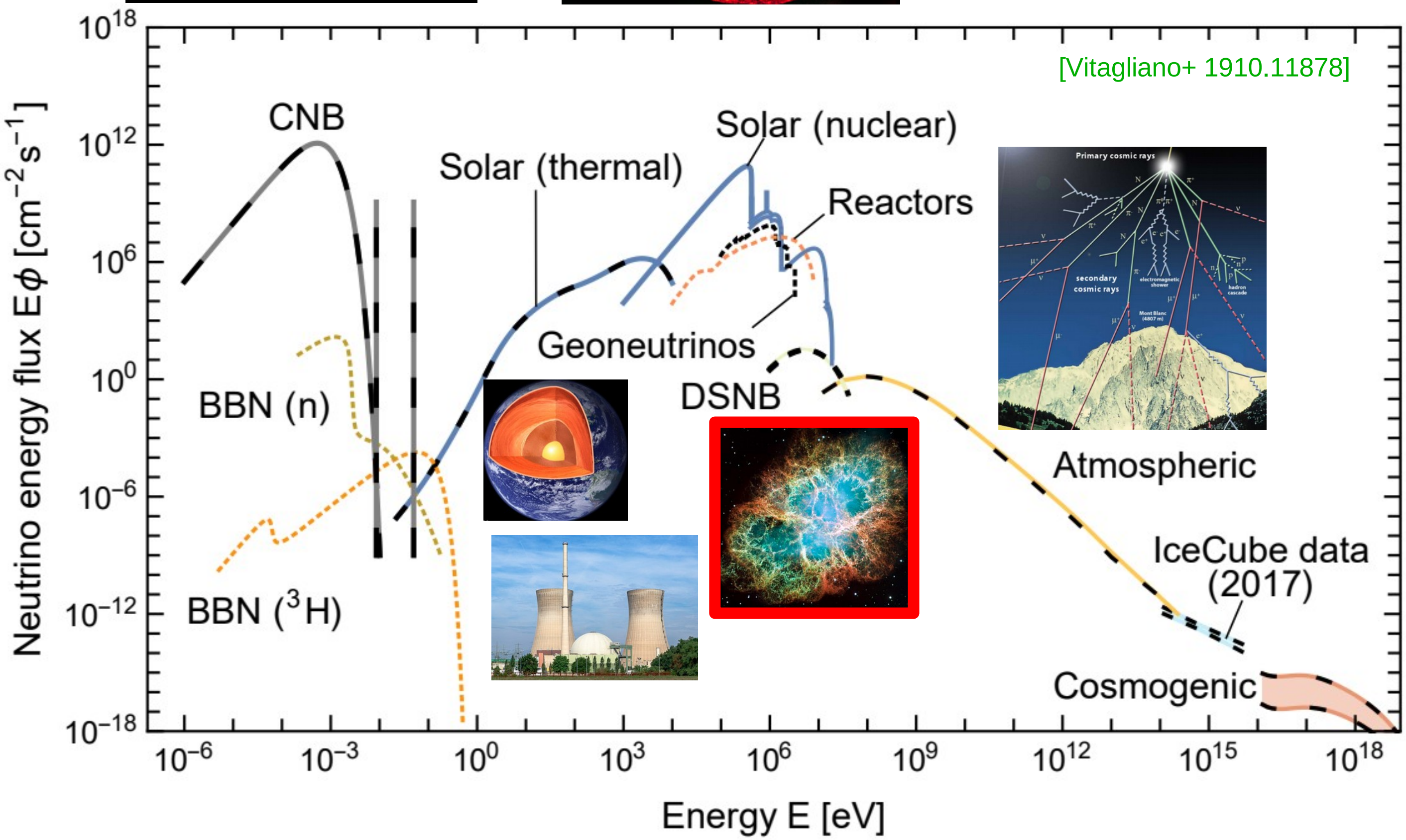
detection of these neutrinos offer tremendous insights to particle physics, astrophysics and cosmology

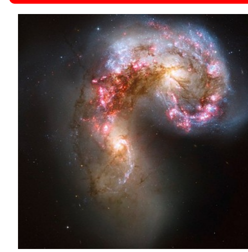
Neutrinos: key messengers for cosmology and astrophysics





Supernovae, collapsars, neutron star mergers



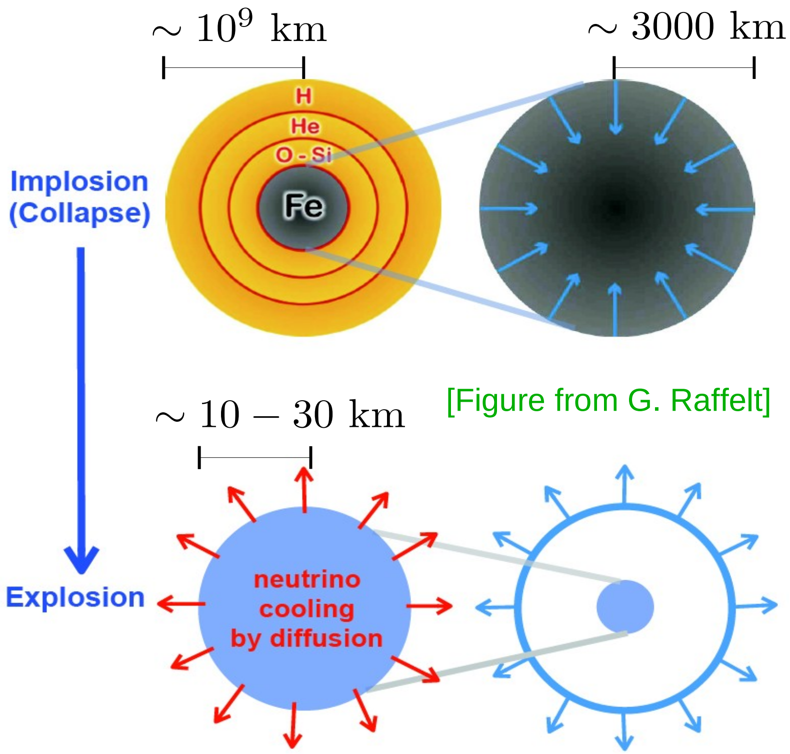


detection of these neutrinos offer tremendous insights to particle physics, astrophysics and cosmology

$+ \ldots ?$

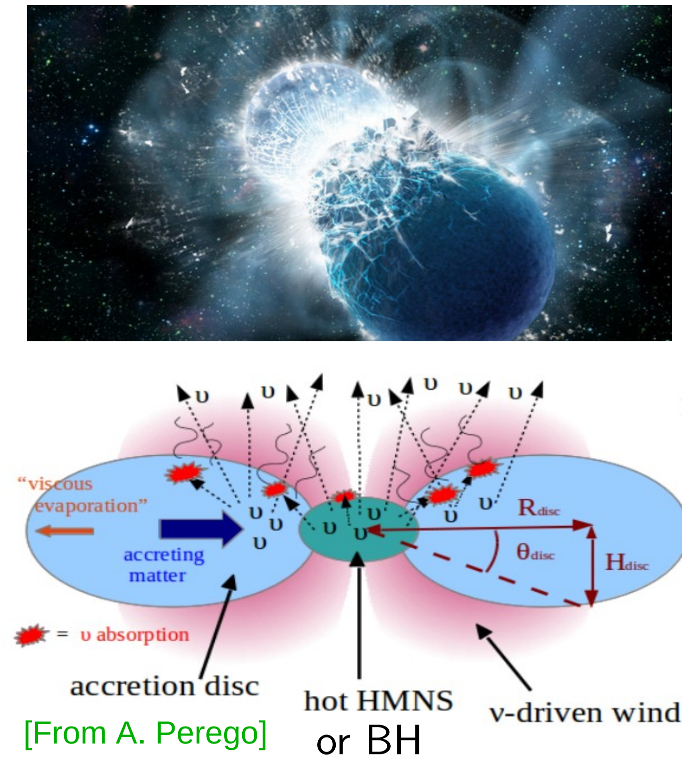
Neutrinos from SNe and from mergers

Core-collapse supernovae



[Figure from G. Raffelt]

Neutron star mergers



[From A. Perego]

inspiral → explosion

gravitational energy → thermal energy → neutrinos!

$L_\nu \sim 10^{51-53}$ erg/s, $N_\nu \sim 10^{56-58}$ of $\mathcal{O}(10)$ MeV emitted in $\sim \mathcal{O}(1-10)$ s

Key questions that we try to answer (2020-2023)

- How do "collective" neutrino flavor oscillations happen in supernovae and in mergers? What are their potential impact? How to include them in astrophysical simulations?

- What are the missing ingredients that can be potentially important in modeling the r-process sites and the related observables?

- What are the imprints of various possible New Physics candidates on astrophysical observables?

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  George+ PRD 102 (2020) 103015; MRW+ PRD 104 (2021) 103003; Just+ PRD 105 (2022) 083024; Richers+ PRD 106 (2022) 043011; George+ CPC 283 (2023) 108588; Xiong+ PRD 107 (2023) 083016; Xiong+ 2212.03750; Xiong+ 2303.05906; Xiong+ 2307.11129

- What are the missing ingredients that can be potentially important in modeling the r-process sites and the related observables?

  Fischer+ ApJ 894 (2020) 9; Banerjee+ ApJL 902 (2020) L34; Banerjee+ MNRAS 512 (2022) 4948; MRW+ AAPPS Bull. 32 (2022) 19; Guo+ PRD 108 (2023) L021303; An+ 2306.07659

- What are the imprints of various possible New Physics candidates on astrophysical observables?

  Guo+ JCAP 10 (2020) 049; Suliga+ JCAP 08 (2020) 018; Tang+ JCAP 10 (2020) 038; Guo+ PRD 102 (2020) 103004; Sung+ PRD 103 (2021) 103005; Sigurdarson+ PRD 106 (2022) 123030; Bauswein+ PRD 107 (2023) 083002; Lin+ PRL 130 (2023) 111002; Lin+ 2007.03552;

Key questions that we try to answer (2020-2023)

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Yi-Siou Wu (NTU/ASIoP)
Zewei Xiong (GSI)
Masamichi Zaizen (Waseda)

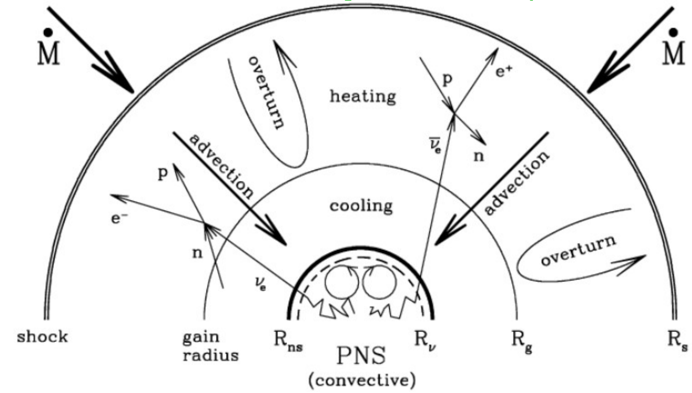
Collective neutrino oscillations in supernovae and in merger remnants

Modeling SNe and mergers with neutrinos

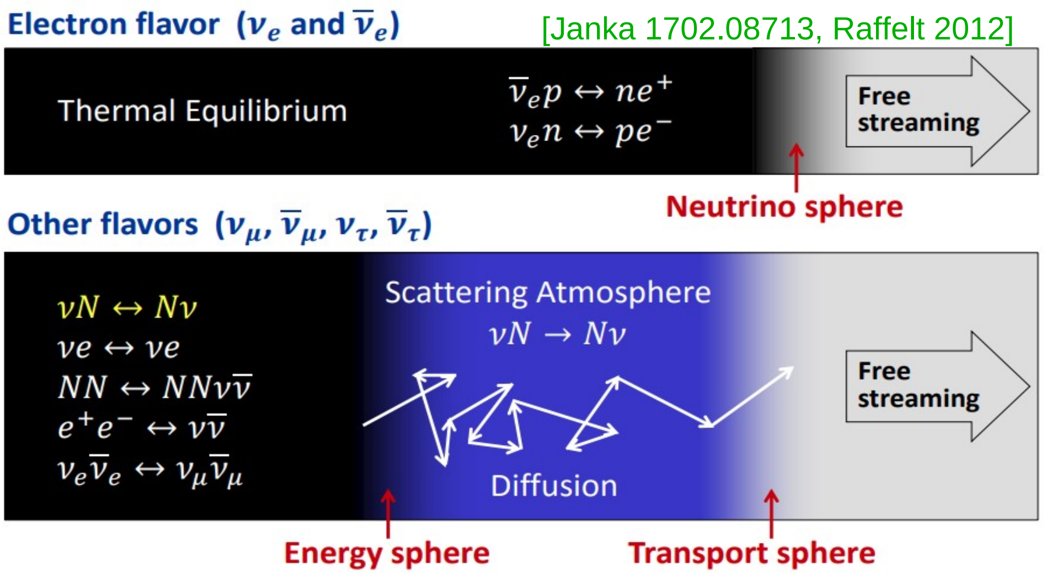
State-of-the-art general relativistic (magneto-) hydrodynamic simulations of supernovae and neutron star mergers include approximate treatment of classical Boltzmann transport of neutrinos

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

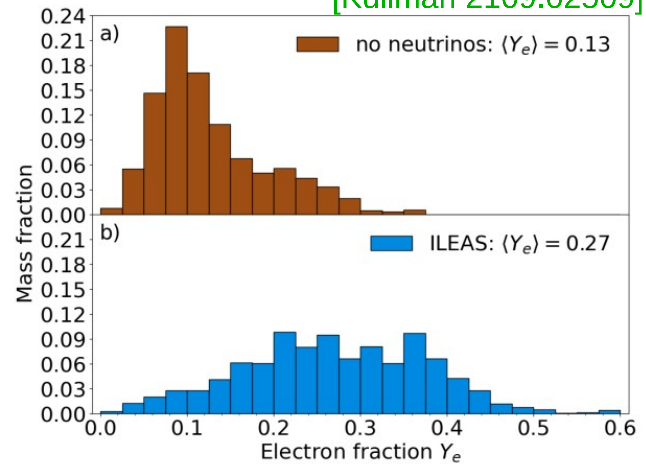
[Janka astro-ph/0008432]



[Janka 1702.08713, Raffelt 2012]



[Kullman 2109.02509]



Accurate neutrino transport holds the key to model the evolution of these systems and predict reliable observables

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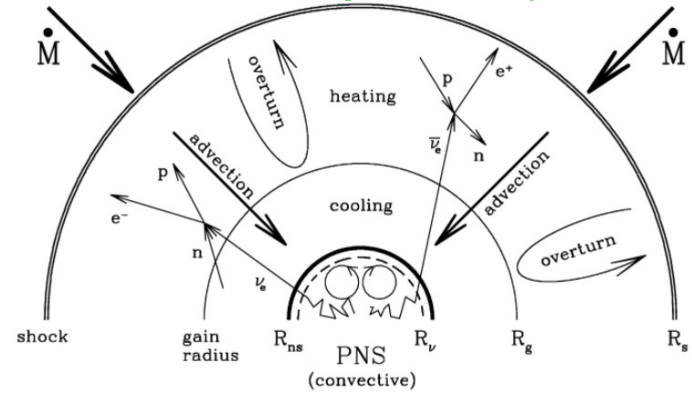

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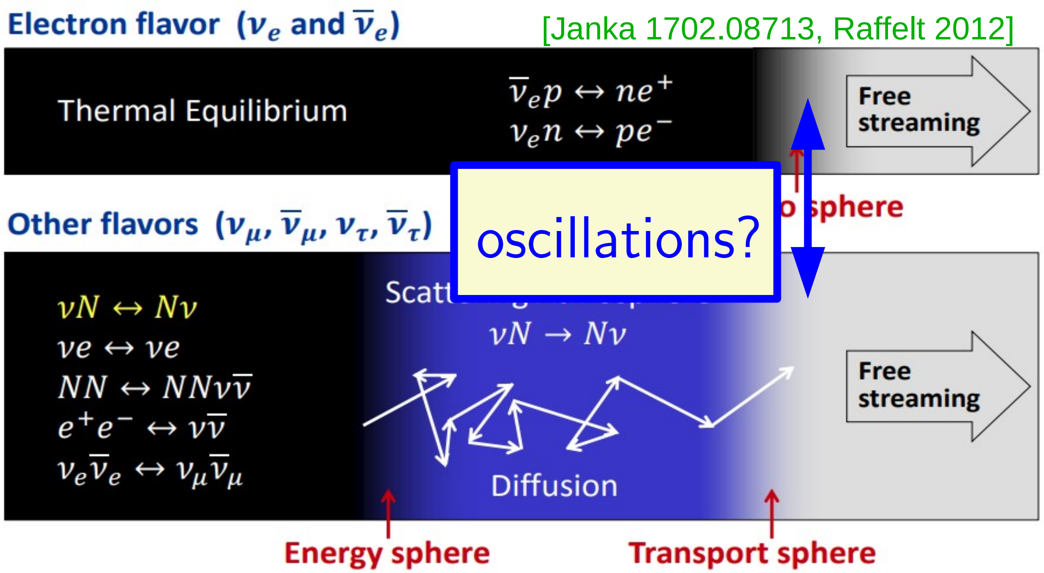

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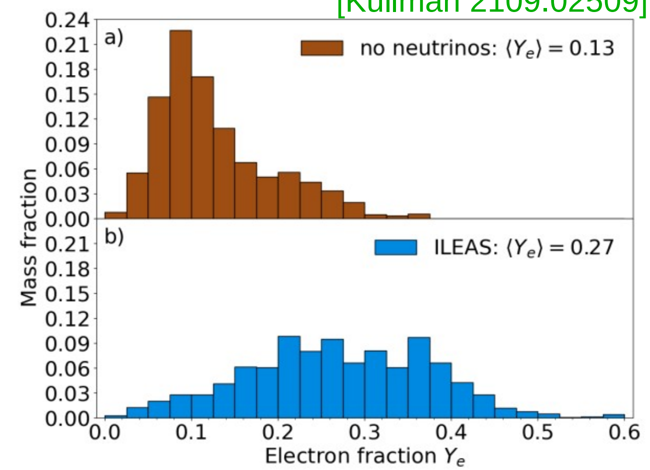
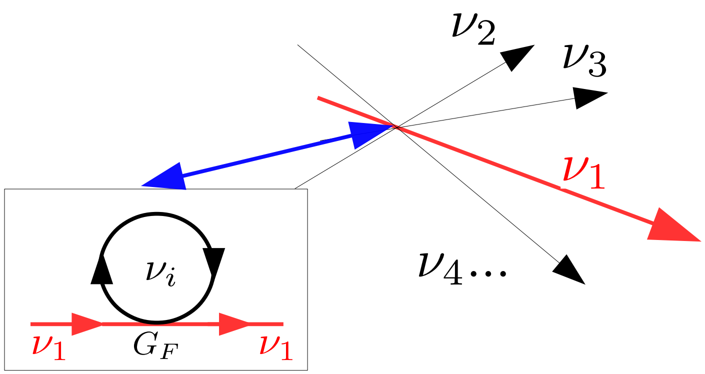


Accurate neutrino transport holds the key to model the evolution of these systems and predict reliable observables

Collective neutrino oscillations



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

In a neutrino-dense environment, the flavor evolution of ν with different momenta are coupled through the forward scattering contribution of ν-ν interaction

$\rightarrow$ quantum kinetic equation (extended Boltzmann equation):

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

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

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

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

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

flavor density matrix of the neutrino ensemble

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

$$\omega_{\rm vac} \sim \frac{\delta m^2_{13}}{2E_\nu} \sim 0.6\ {\rm km}^{-1}$$

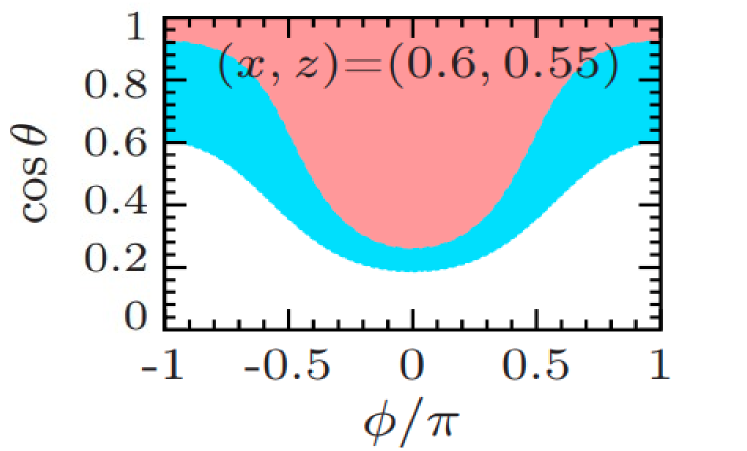
- for $n_\nu \sim 10^{33}$ cm^{-3}:

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

$\rightarrow$ strong coupling in flavor space leading to collective modes!

Fast neutrino oscillations

$$G(\theta, \phi) \propto \int dE_\nu E_\nu^2 (f_{\nu_e} - f_{\nu_\mu} - f_{\bar{\nu}_e} + f_{\bar{\nu}_\mu})$$



Recent studies revealed that a novel kind of "fast collective oscillation mode" at regions when there "$e-\mu$ crossing" exists in neutrino angular distribution

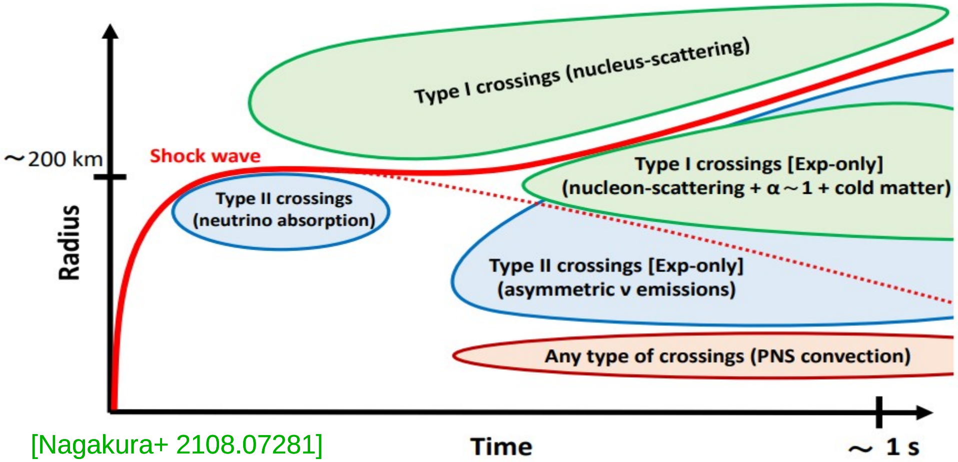
[Sawyer+, Izaguirre+, Dasgupta+,...many others]

$$\rightarrow \omega_{\rm col} \sim \mu \sim \mathcal{O}(1){\rm cm}^{-1}$$

Exploratory investigations found that fast oscillations should occur in SNe and in mergers and may significantly affect their dynamics and nucleosynthesis

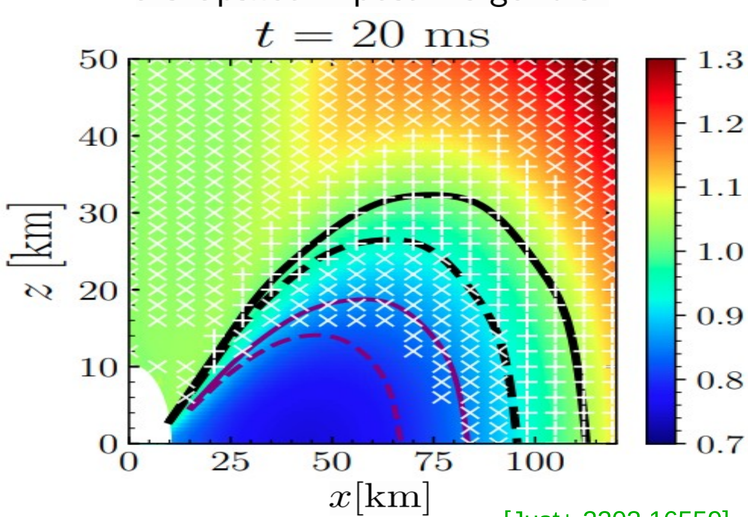
[MRW+, George+, Xiong+, Li+, Abbar+, Fernandez+, Nakagura+, Ehring+,...]

Space-time diagram of ELN-angular crossings in CCSNe



[Nagakura+ 2108.07281]

a snapshot in post-merger disk



[Just+ 2203.16559]

What are the oscillation outcome? How to include them in SN simulations?

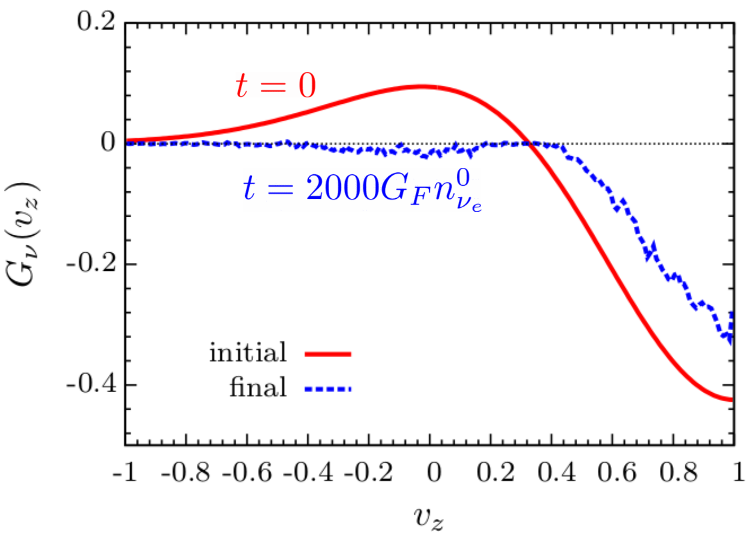
(code available at https://github.com/cosenu/cosenu)

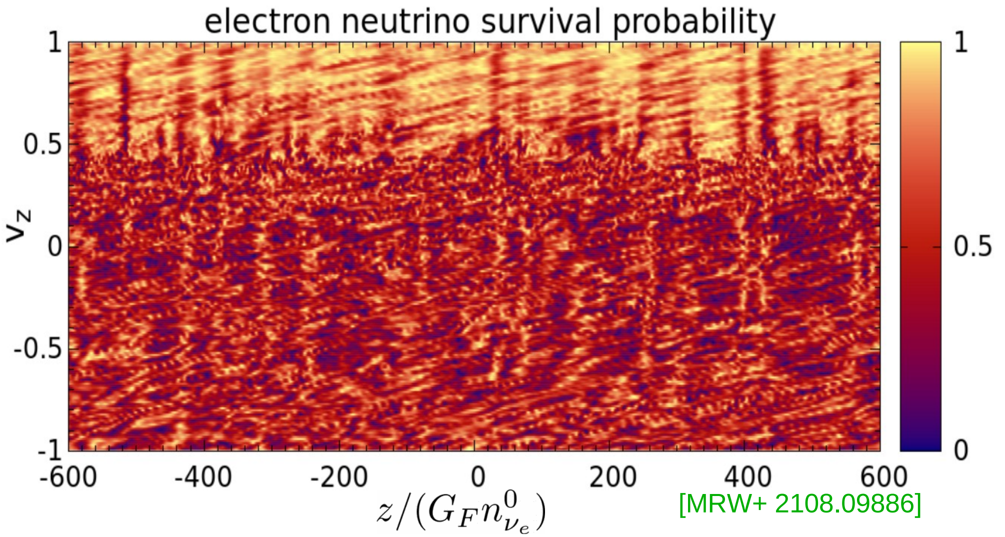
Local-box simulation of fast neutrino oscillations

Several groups started to develop multidimensional simulation code to compute the outcome of fast oscillations in a small and perodic box, mimicking a tiny volume inside SNe or mergers

[See Richers+ 2205.06282 for detailed comparison of simulation results]

$\rightarrow$ fast oscillations tend to erase the $e-\mu$ crossing [Bhattacharyya+, Richers+, MRW+]





[MRW+ 2108.09886]

$\rightarrow$ analytical prescription or machine-learning based methods are proposed or under investigation [Bhattacharyya+2020, 2022, Zaizen 2022, Xiong+2023]

$\rightarrow$ could allow more consistent inclusion of fast conversions in simulations

three flavors? bounday conditions?

Collision-induced collective oscillations

L. Johns (2021) discovered that another kind of collective oscillation mode can be triggered when one considers both collision term and the forward-scattering term

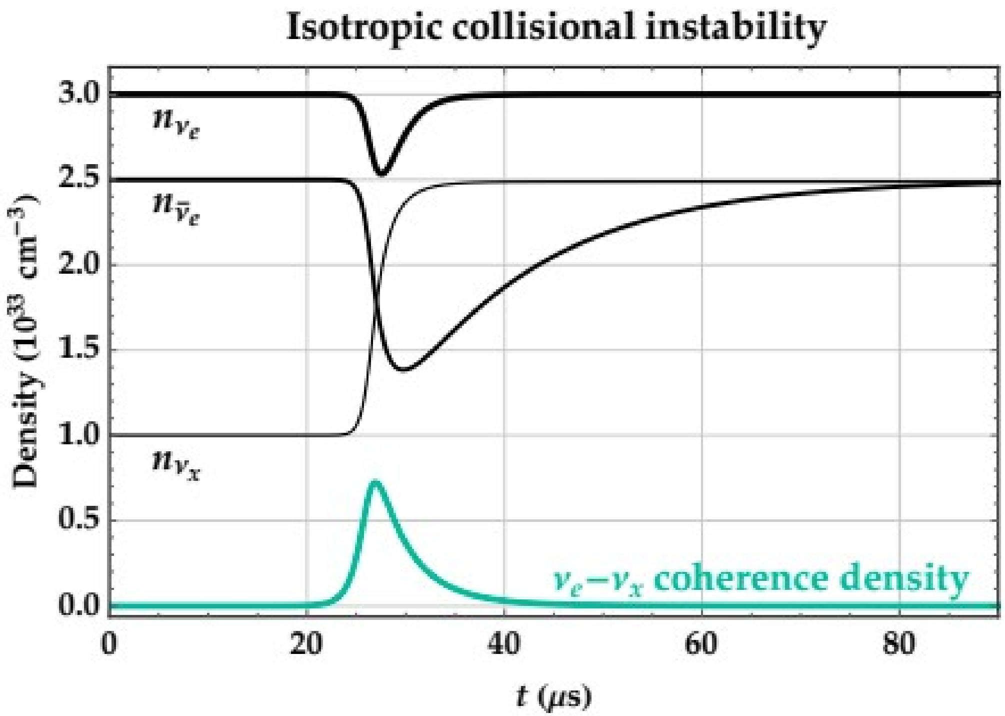
$$(\partial_t + \mathbf{v}\cdot\partial_{\mathbf{x}} + \mathbf{F}\cdot\partial_{\mathbf{p}})\varrho(\mathbf{x},\mathbf{p},t) = -i[H_{\rm vac} + H_{\rm m} + H_{\nu\nu}, \varrho(\mathbf{x},\mathbf{p},t)] + \mathcal{C}(\varrho)$$

For a condition that satisfies

$$\frac{\bar{\Gamma}}{\Gamma} \lesssim \frac{n_{\bar{\nu}_e} - n_{\bar{\nu}_x}}{n_{\nu_e} - n_{\nu_x}} \lesssim \frac{\Gamma}{\bar{\Gamma}}$$

$\rightarrow \omega_{\rm col} \sim \Gamma$ (collision rates) $\sim \mathcal{O}(1)$ km^{-1}

$\rightarrow$ can lead to excessive production of heavy-lepton flavor neutrinos



[Johns, 2104.11369]

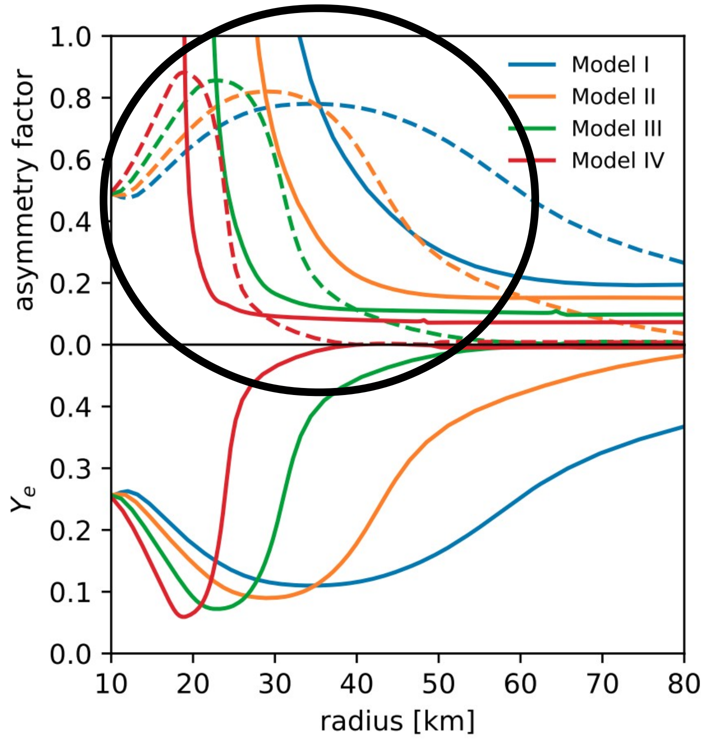
[see also Johns+2022, Xiong+2022, 2023, Liu+2023]

(Also exists everywhere in BH–disk after merger; see Xiong+ 2212.03750)

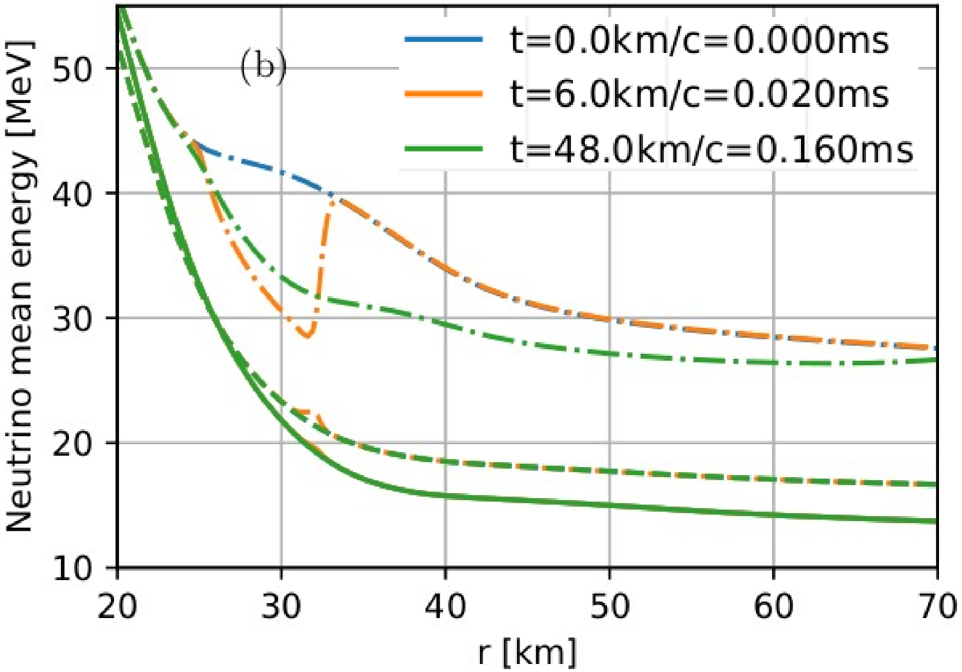
Global simulations of collision-induced oscillations in SNe

We recently solve the neutrino flavor evolution equation with collision terms over spherically symmetric background obtained by 1D SN simulations where the fast instability is absent

$\rightarrow$ exist around the ν-sphere and can affect the emission of μ and τ neutrinos



[Z. Xiong, MRW+ 2210.08254]



If verified to be important $\rightarrow$ need to solve the full QKE in SN simulations

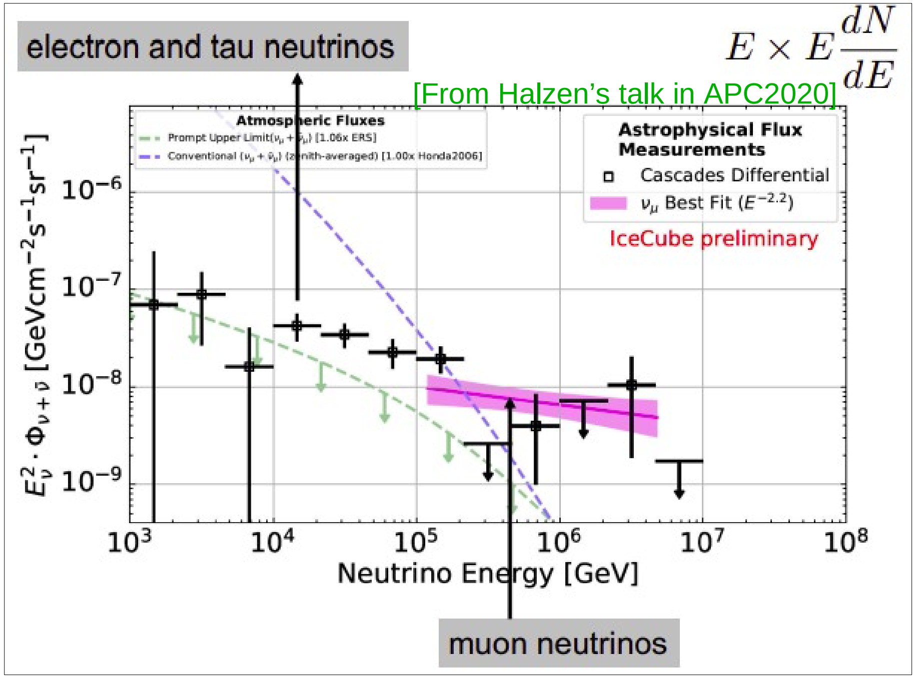
Any interplay with fast oscillations?

Neutrinos from r-process and their imprints on potential observables

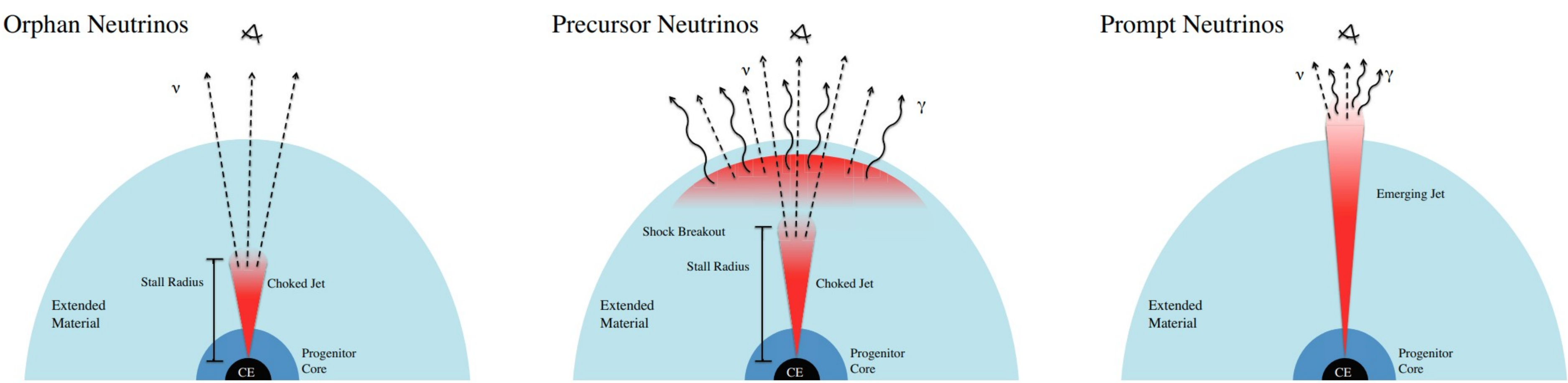
High-energy neutrinos

IceCube has detected extragalactic HE neutrinos above ~ 10 TeV

Some of the events can be associated with blazars, AGNs, or TDEs(?), but the astrophysical origin for the majority remains uncertain



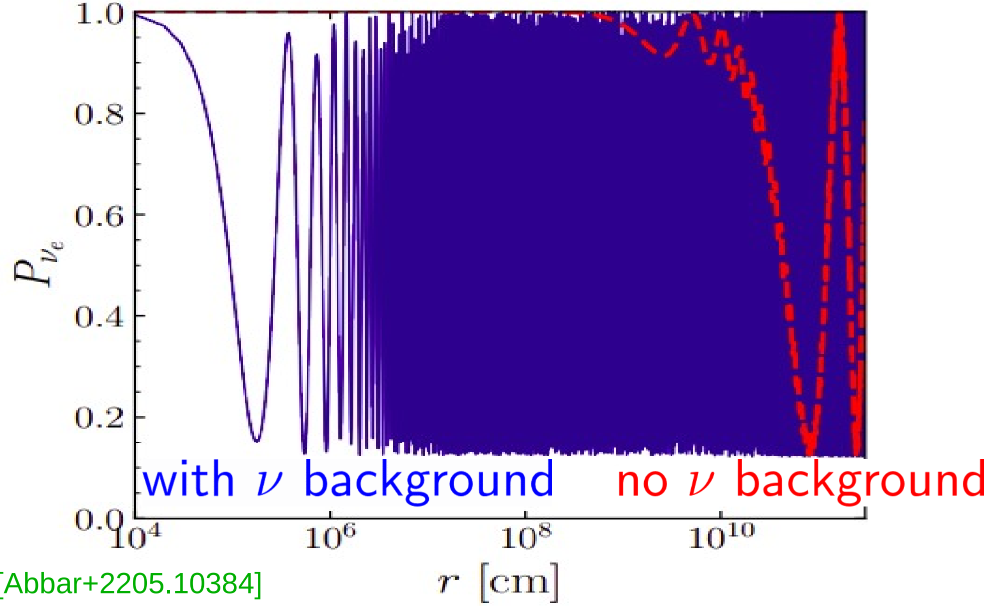
Very tight constraints on bright GRBs as sources, but LLGRBs or chocked ones remain possible [Meszaros+, Razzaque+, Ando+, Horiuchi+, Hummer+, Murase+, Frajia+, Tamborra+, Senno+, Carpio+,...]



[Senno, Murase, Meszaros, 1512.08513]

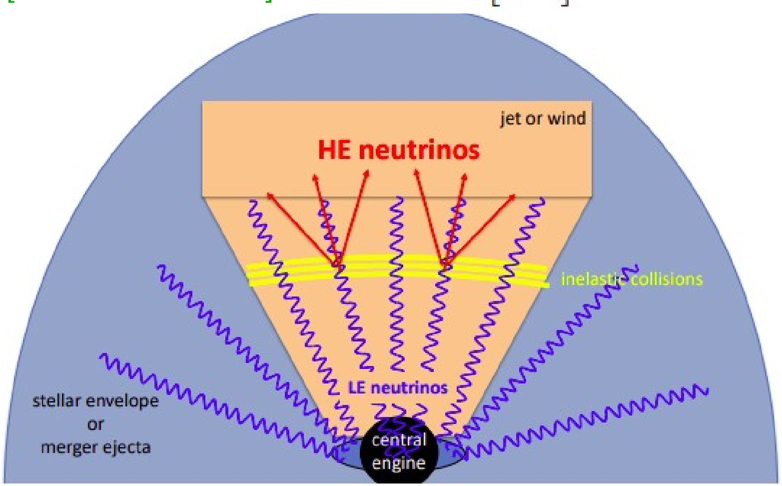
Neutrino-neutrino interactions?

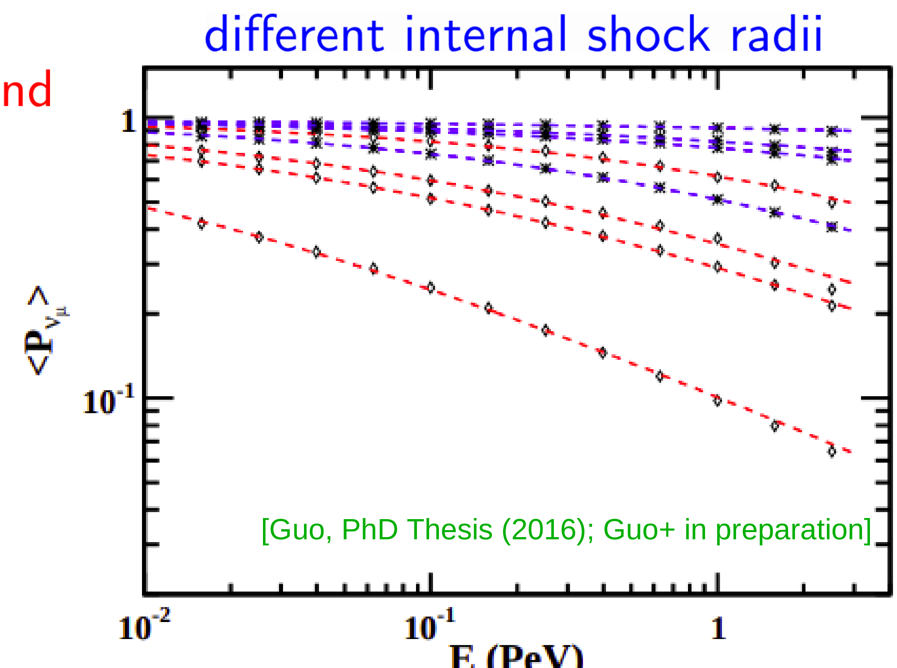
For jets associated with stellar sources, lots of low-energy neutrinos from the central engines, e.g., BH-accretion disks in collapsars or in BNSMs



[Abbar+2205.10384]

may affect flavor evolution and/or survival of HE neutrinos



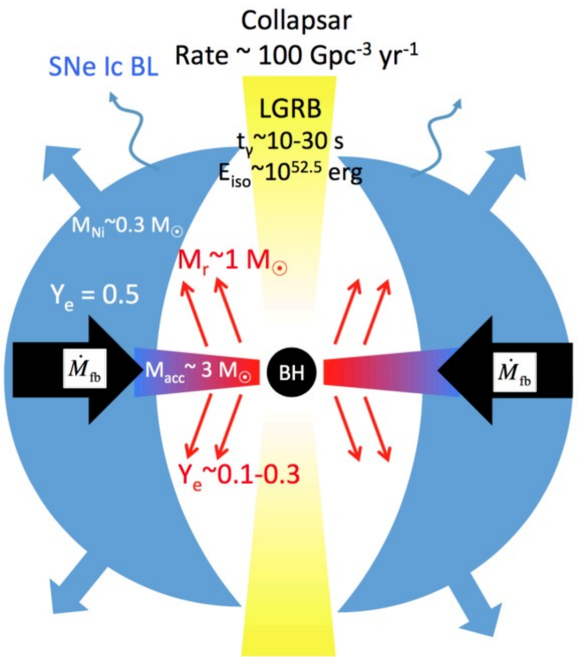


[Guo, PhD Thesis (2016); Guo+ in preparation]

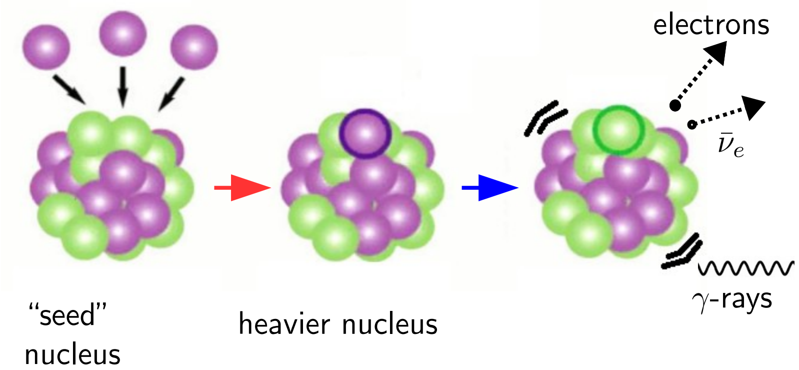
r-process $\bar{\nu}_e$ in collapsars?

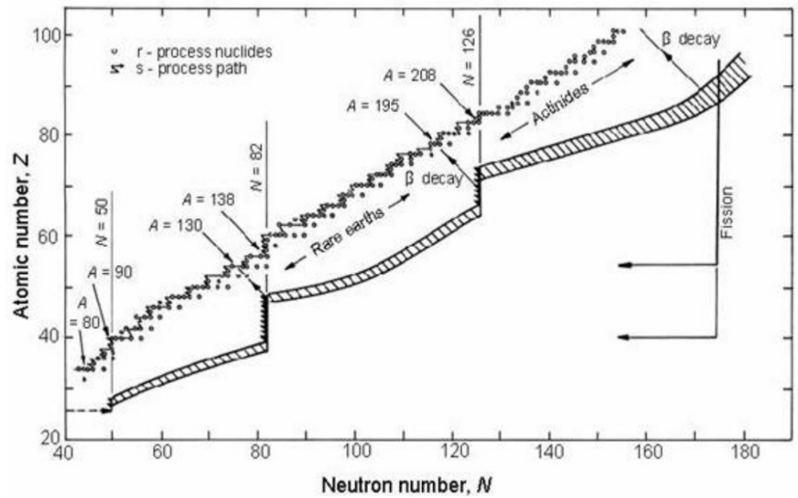
The r-process may occur in collapsar outflows and produces neutron-rich unstable nuclei that β decay

$\rightarrow$ produce $\sim 10^{56}$ $\bar{\nu}_e$ of $E_L \sim 5 - 10$ MeV for ~ 1 $M_\odot$ material



[Siegel, Barnes, Metzger, 1810.00098]





its viability is still under-debate

[Miller+, Just+, Fujibayashi+, Zenati+, Macias+, Bartos+, Brauer+, Lee+,...]

Annhilation of low- and high-energy neutrinos

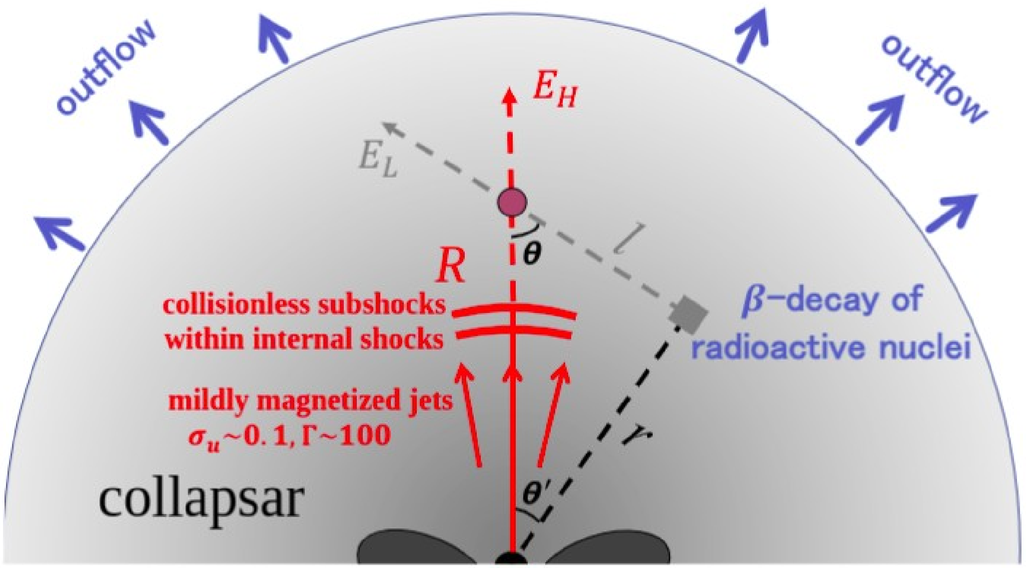
These r-process decay neutrinos can oscillate to different flavors and annhiliate with high-energy neutrinos of $E_H \sim 100 - 1000$ TeV via Z-resonance

At $R \sim 10^{10}$ cm, $n_{\bar{\nu},\mathrm{LE}} \sim 10^{23}\ \mathrm{cm}^{-3} \left(\frac{\dot{M}}{0.02 M_\odot/\mathrm{s}}\right)\left(\frac{0.05c}{v_{\mathrm{ej}}}\right)\left(\frac{10^{10}\ \mathrm{cm}}{R}\right)^2$

With $\sigma_{\mathrm{res}} \sim 10^{-31}$ cm^2

$\rightarrow \sigma_{\mathrm{res}} n_{\bar{\nu},\mathrm{LE}} R \gg \mathcal{O}(1)$

efficient annhiliation

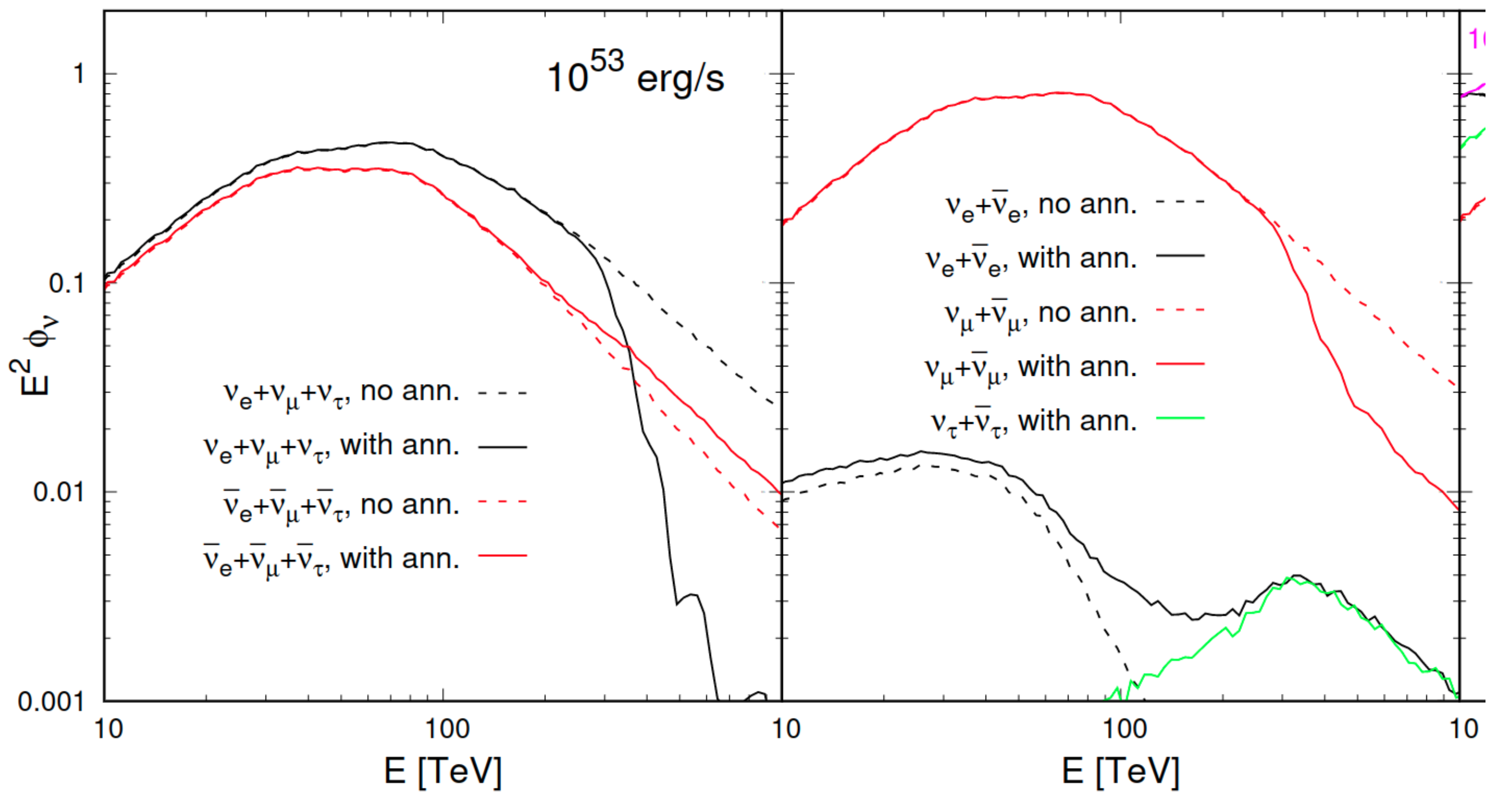


[G. Guo, Y.-Q. Qian, MRW, 2212.08266]

Effect of neutrino pair annhiliation

$L_{\rm iso} = 10^{53}$erg, $\Gamma_r = 2\Gamma_s \sim 450$, $\epsilon_{B,u} = B_u^2/(8\pi\rho_u c^2) = 0.05$, $R \sim \times 10^{10}$cm:

[G. Guo, Y.-Q. Qian, MRW, 2212.08266]

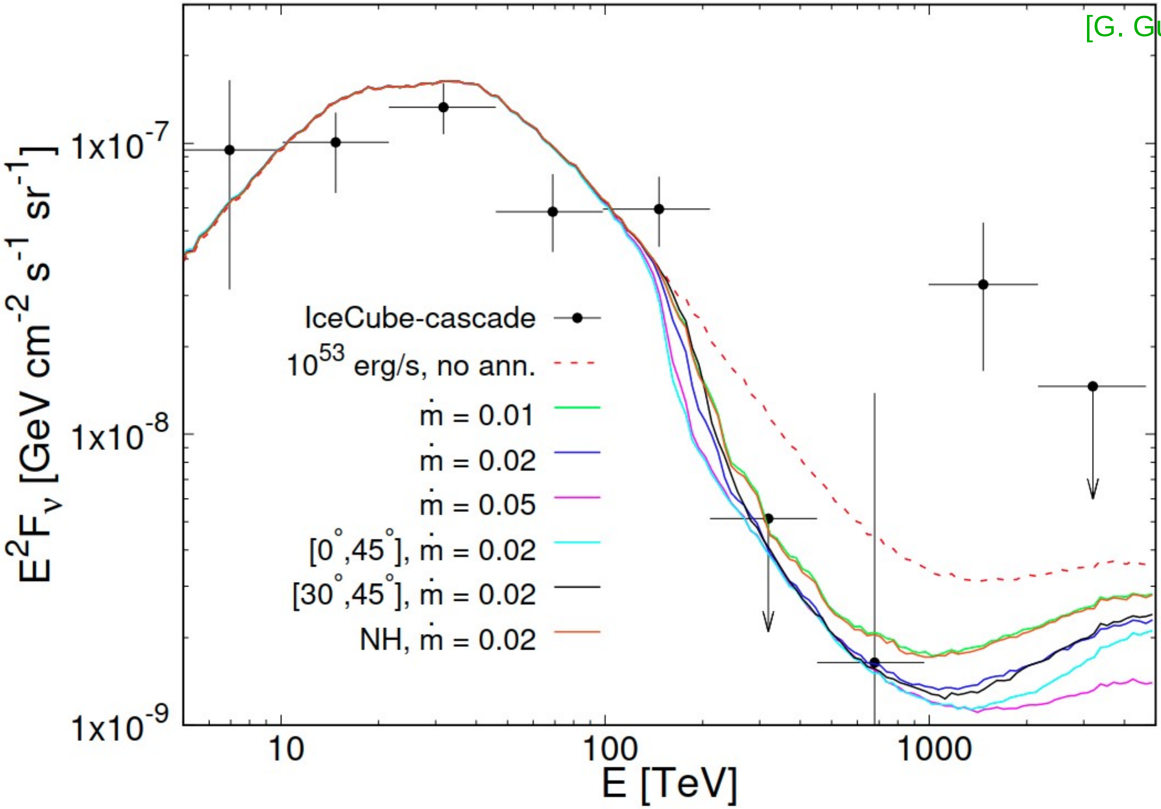


- μ flavor neutrinos dominate due to efficient cooling of $\mu^\pm$
- strong cutoff of ν above ~ 300 TeV due to efficient annhilation
- similar results hold for different values of $L_{\rm iso}$ and $\epsilon_{B,u}$

Diffuse flux v.s. IceCube detection

Assuming that such sources are ~ 10 times more frequent than the bright GRB, the resulting diffuse flux may be compatible to what detected at IceCube

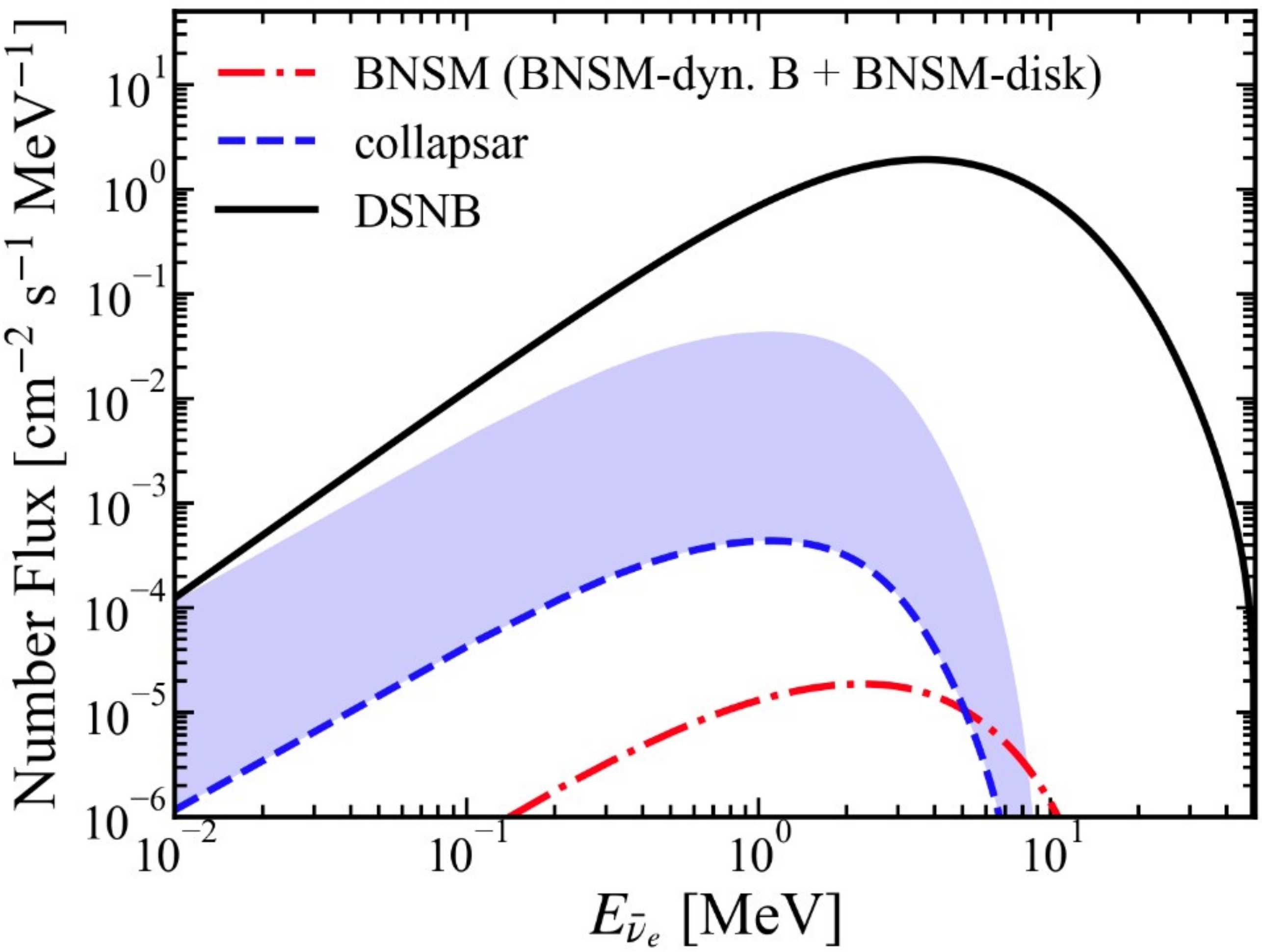
[G. Guo, Y.-Q. Qian, MRW, 2212.08266]



May be further tested with imporved statistics on diffuse flux, precise flavor measurements, or from nearby (~ 100 Mpc) point-source event

Diffuse r-process neutrino background (DrNB)?

[An, MRW+, 2206.07659]



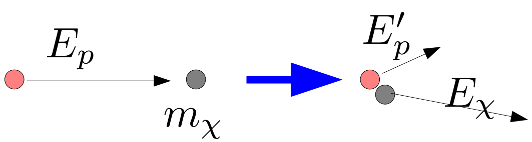
Won't be significant background for DSNB at relevant energy of $\sim \mathcal{O}(10)$ MeV, but may (at best) become comparable at sub-MeV

Light dark matter boosted by supernova neutrinos?

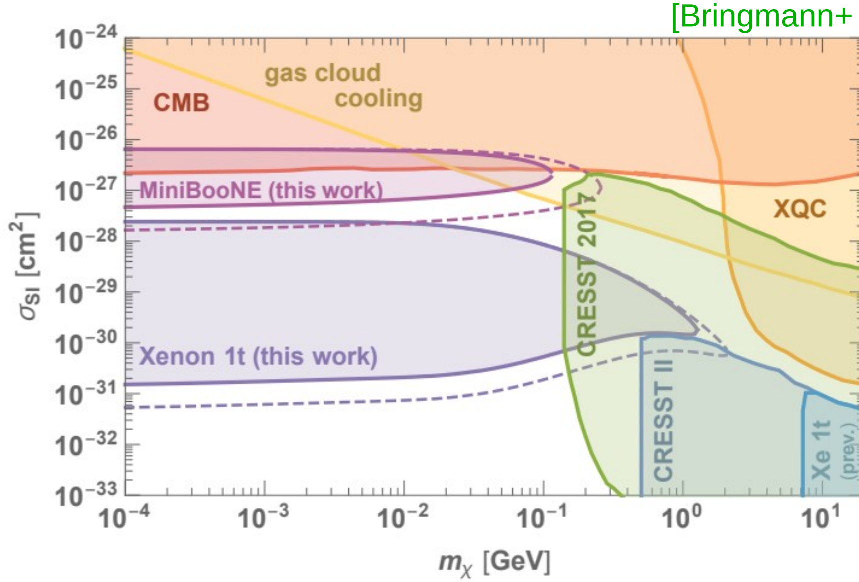
Neutrino-DM interactions?

[Bringmann+ 2018, Ema+ 2018, Cappiello+ 2019,...]

It's realized in recent years that light (sub-GeV) DM particles can be "boosted" by energetic cosmic rays, which can probe the dark matter – nucleon interaction cross section ($\sigma_{\chi N}$) or that of dark matter – electron interaction ($\sigma_{\chi e}$)



[Bringmann+ 2018]



The same idea was applied to cosmic neutrinos, including those from the Sun, Stars, Blazar, AGN, and DSNB, ...

[Zhang+2020, Jho+2021, Das+2021, Ghosh+2021, Cline+2022, 2023, Ferrer+2022,...]

How about individual supernova? e.g., SN1987a?

Light dark matter boosted by supernova neutrinos

For light DM ($m_\chi \sim 10$ keV), if it obtains an energy of ~ 10 MeV (kicked by SNν)

$\rightarrow$ arrives the Earth ~ 10 days $\times [d/(8\ \mathrm{kpc})][m_\chi/(10\ \mathrm{keV})^2][E_\chi/(10\ \mathrm{MeV})^{-2}]$ after the arrival of SNν

($t = 0$ is calibrated by SNν)

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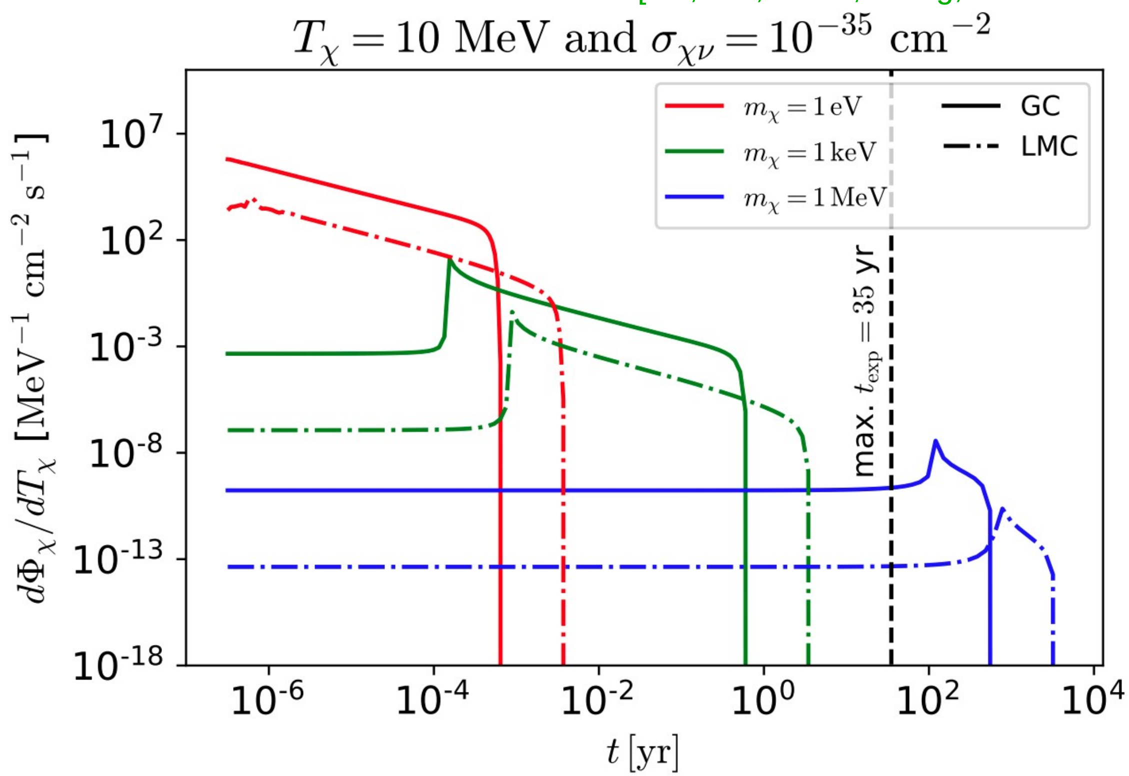
[Lin, Wu, MRW, Wong, 2206.06864]



- time-dependent feature *independent* of $\sigma_{\chi\nu}$

  t_p and $t_{\rm van}$ determined by the distance and m_χ

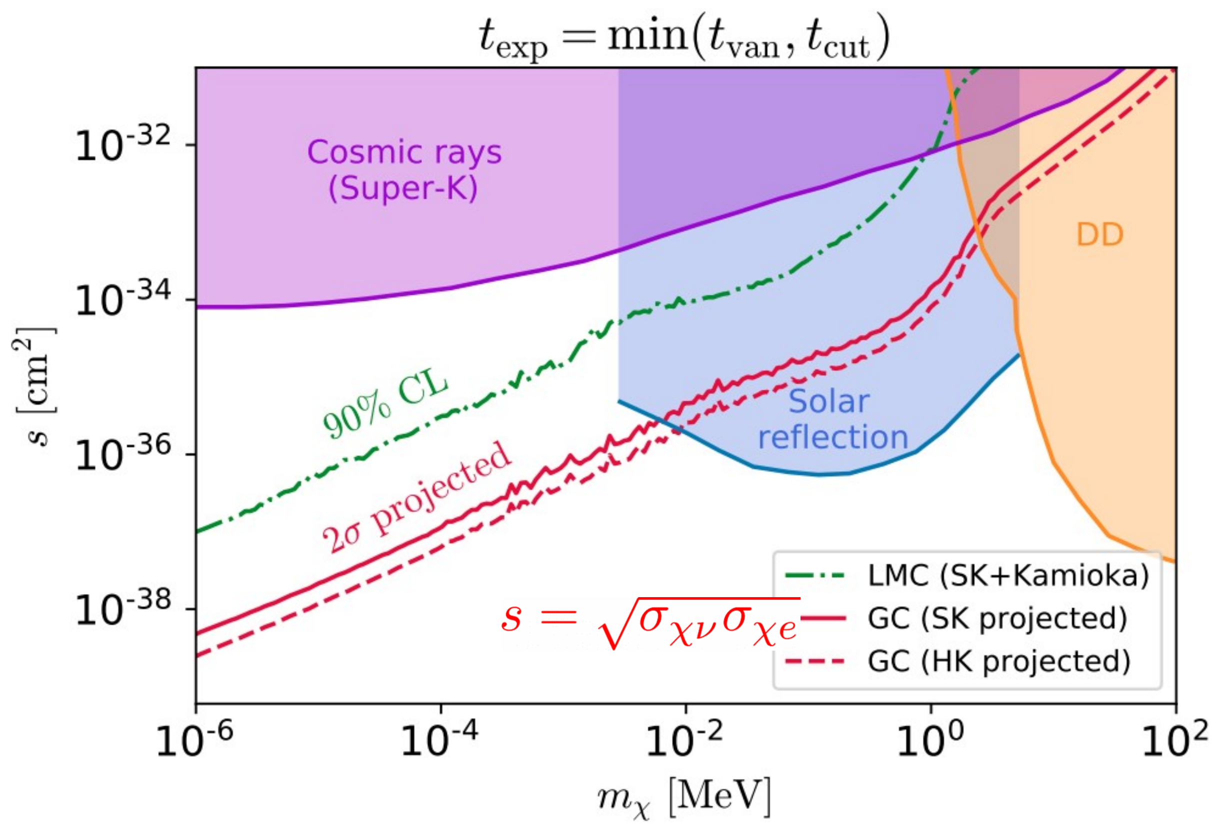
- constraint exists with SN1987a if $\chi - e$ interaction also exists!

GC: a SN exploded in the MW center

LMC: a SN exploded in the LMC center

SNν boosted DM events and constraints

Consider total event and background counts within an exposure time $t_{\rm exp}$ =min($t_{\rm van}$, 35 years) with Kamiokande from 1987-1996 and Super-Kamiokande from 1996 on



($s = \sigma_{\chi e}$ for shaded region from other considerations)

[Lin, Wu, MRW, Wong, 2206.06864]

$\rightarrow$ can provide complementary constraint to models where $\sigma_{\chi\nu} \lesssim 10^{-6}\sigma_{\chi e}$

(can be further improved with detailed analysis, e.g., direction, energy bins,...)

(generalization to arbitrary SN location and $U(1)_{L_\mu - L_\tau}$ model in Lin+, 2307.03522)

Summary

• Neutrinos can be produced copiously in astrophysical explosions and play important roles in their evolution. Detection of these neutrinos can offer unique probes for astrophysics and particle physics

• Neutrino flavor oscillations can happen collectively very deep in supernova interior or neutron star merger remnants. The outcome remains unclear but steady progress are being made. Multi-dimensional simulations of neutrino quantum kinetic equation are carried out and offer insights

• The interaction of low-energy neutrinos with the high-energy neutrinos from the same source can have interesting impact on HE neutrino spectrum. E.g., The antineutrinos produced by r-process nuclei in collapsars leave unique annhiliation signatures

• Supernova neutrinos can also upscatter light dark matter, and can provide competing bounds on neutrino-DM interaction. If detected, the temporal profile can offer important diagnostics for DM mass