

Neutrinos in astrophysical explosions

Meng-Ru Wu (Institute of Physics, Academia Sinica)

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Cosmology, IBS, Daejeon, Korea, June 12-16, 2023



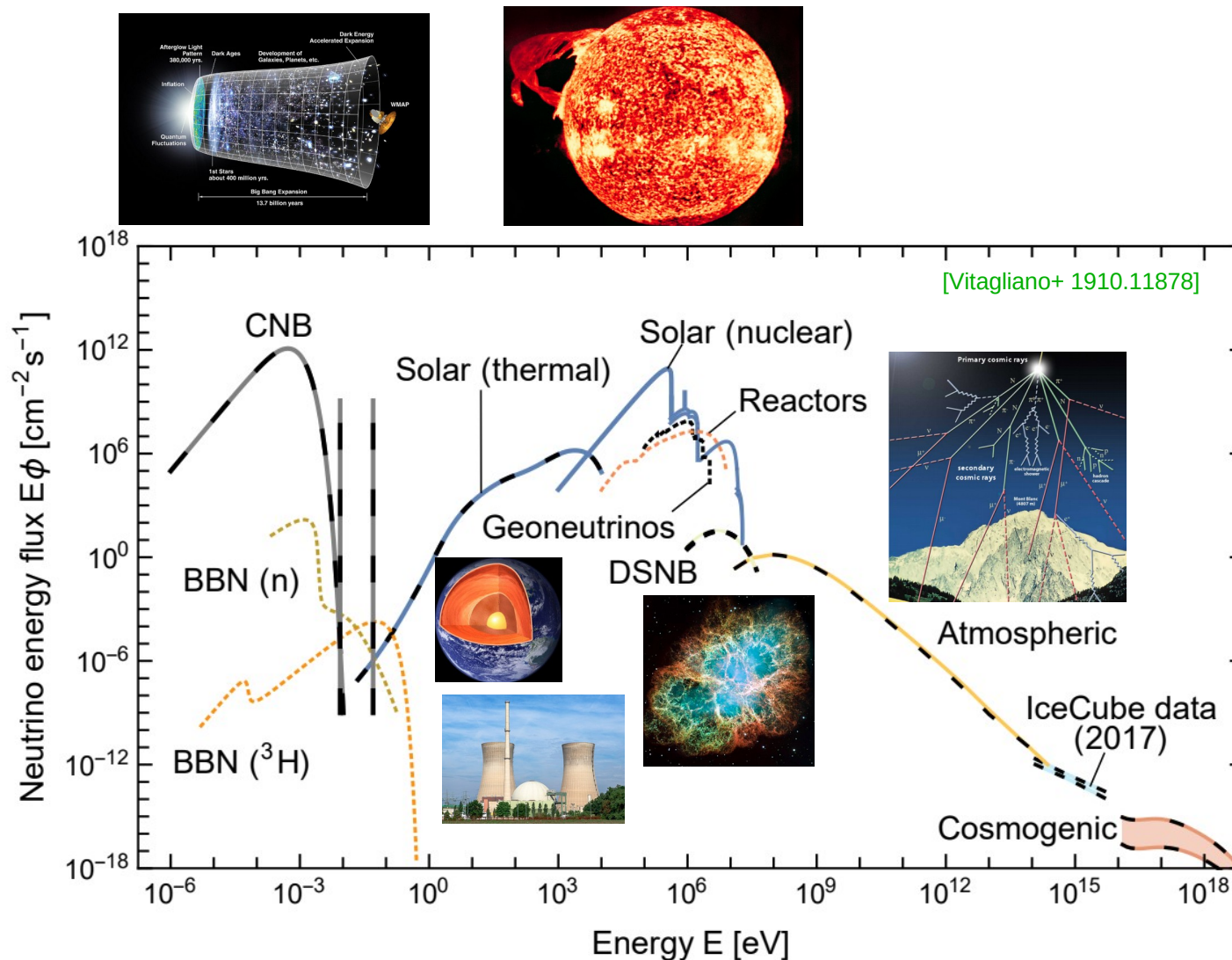
中央研究院物理研究所
INSTITUTE OF PHYSICS, ACADEMIA SINICA



NSTC 國家科學及技術委員會
National Science and Technology Council



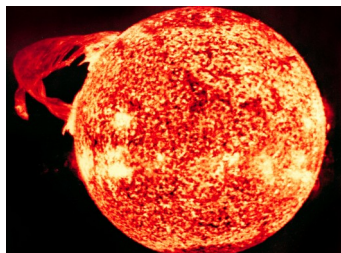
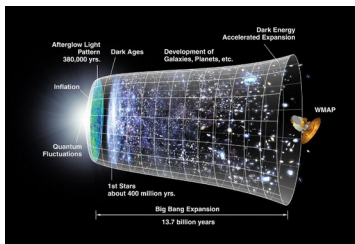
Neutrinos: key messengers for cosmology and astrophysics



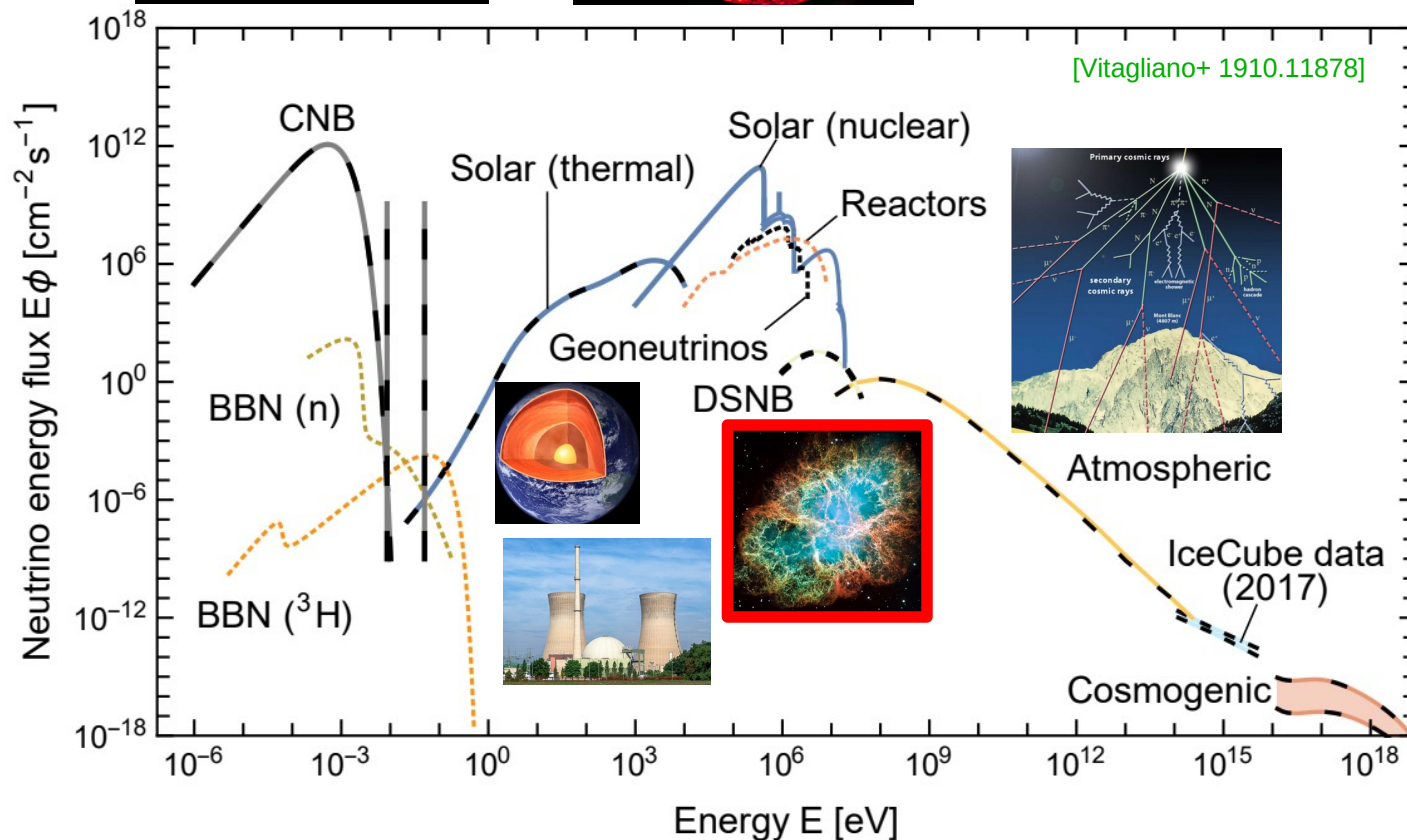
detection of these neutrinos offer tremendous insights to particle physics, astrophysics and cosmology

+...?

Neutrinos: key messengers for cosmology and astrophysics



Supernovae, collapsars,
neutron star mergers

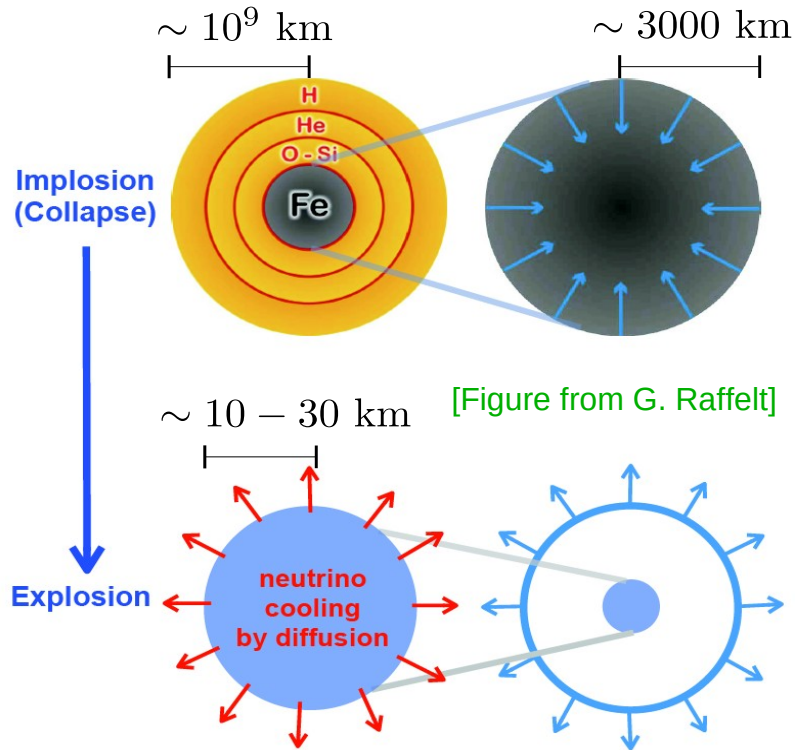


detection of these neutrinos offer tremendous insights to
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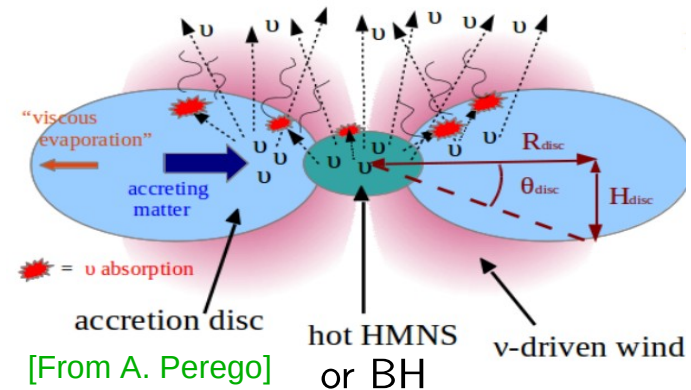
+...?

Neutrinos from SNe and from mergers

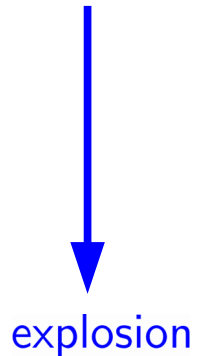
Core-collapse supernovae



Neutron star mergers



inspiral



explosion

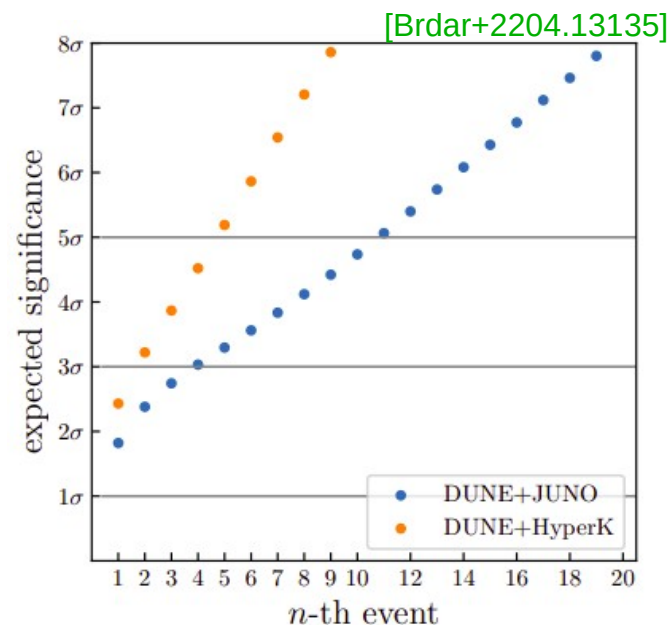
gravitational energy $\rightarrow$ thermal energy $\rightarrow$ neutrinos!

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

CCSNe (and BNSMs) 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,...]



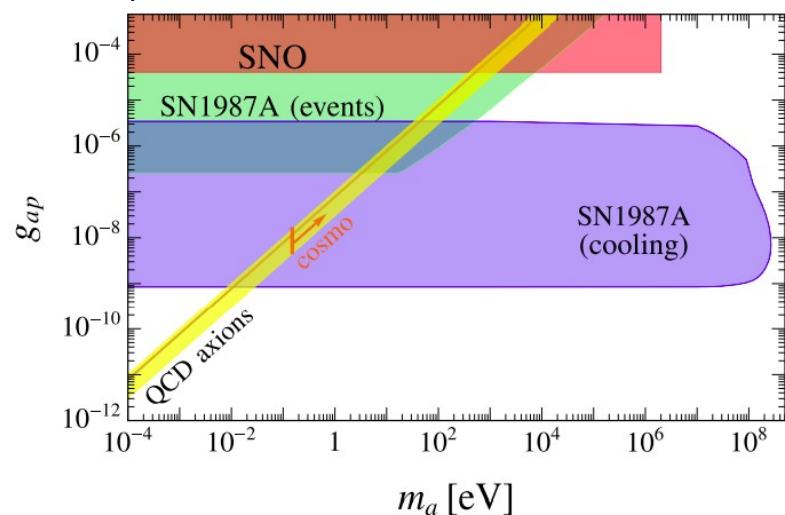
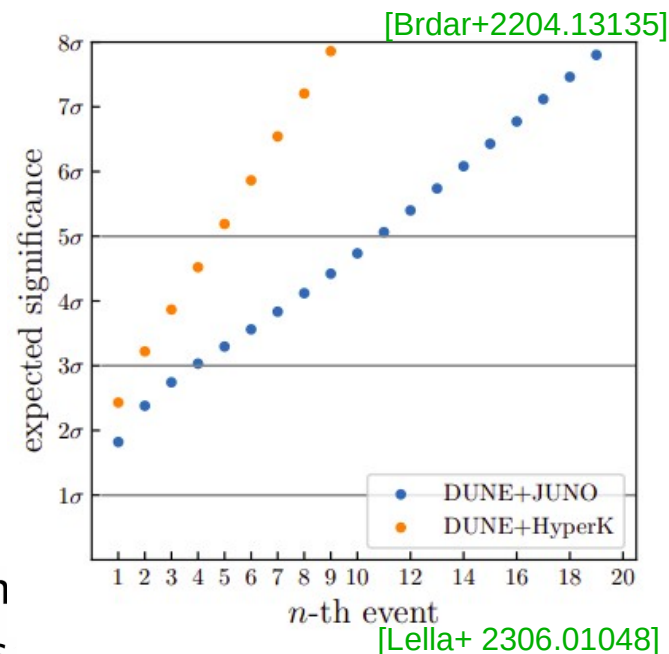
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- **bSM physics:** emission of light bSM particles from SN core/merger remnants, eV-MeV sterile neutrinos, non-Standard neutrino interactions, neutrino-DM interaction,...

[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, Darne+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, Pillumbi+ 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...]



Full understanding of neutrino emissions + treatment of feedback are needed

see also Horiuchi's talk

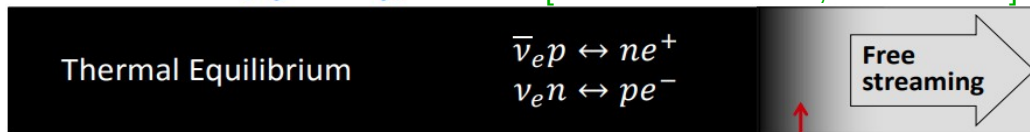
Modeling SNe and mergers with neutrinos

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

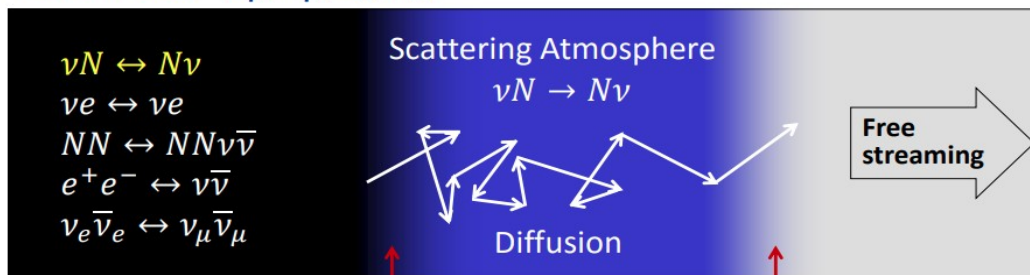
$$(\partial_t + \mathbf{v} \cdot \partial_{\mathbf{x}} + \mathbf{F} \cdot \partial_{\mathbf{p}}) f_{\nu_\alpha}(\mathbf{x}, \mathbf{p}, t) = \mathcal{C}$$

Electron flavor (ν_e and $\bar{\nu}_e$)

[Janka 1702.08713, Raffelt 2012]

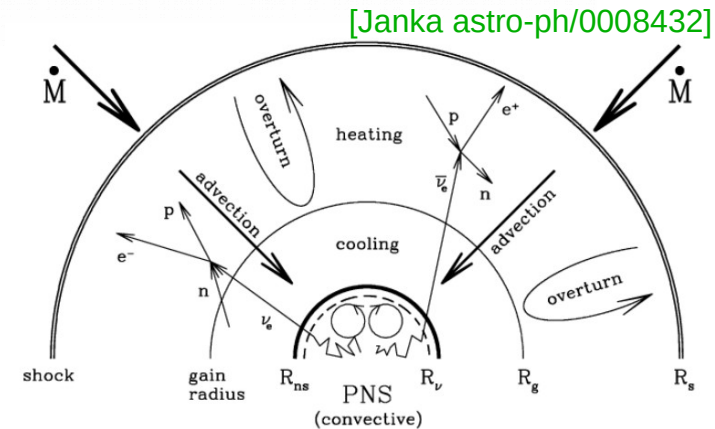


Other flavors ($\nu_\mu, \bar{\nu}_\mu, \nu_\tau, \bar{\nu}_\tau$)

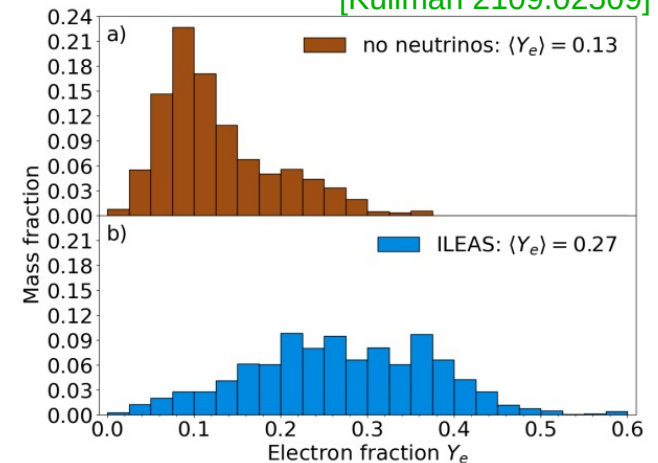


Energy sphere

Transport sphere



[Kullman 2109.02509]



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

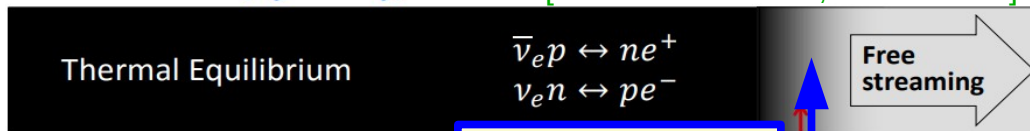
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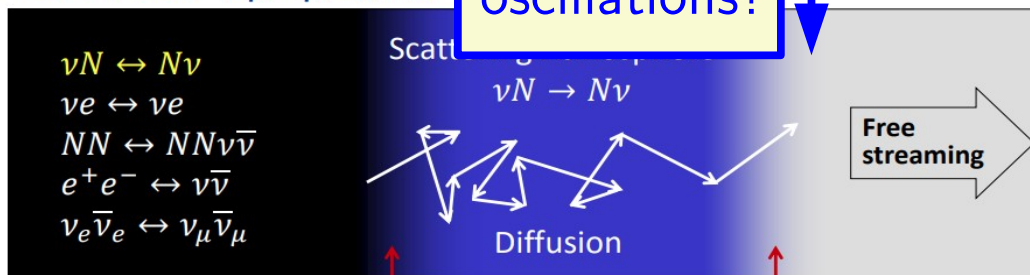
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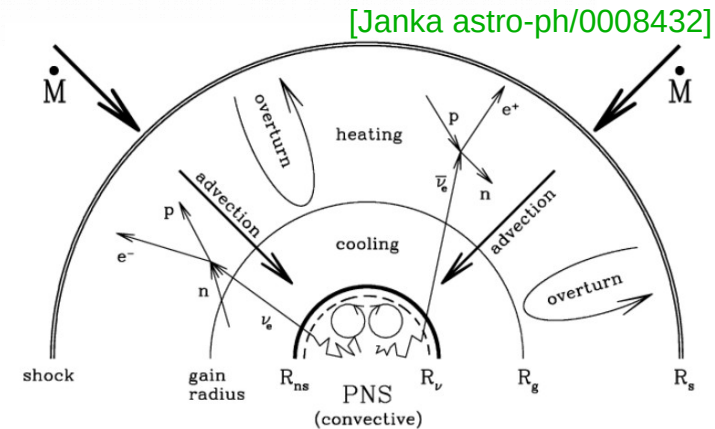


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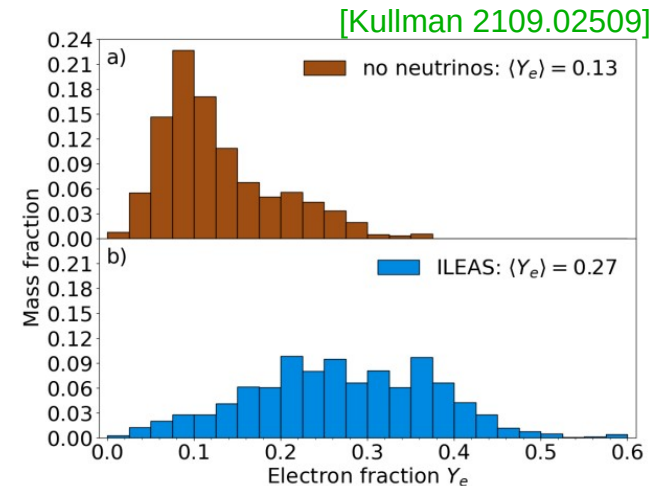


Energy sphere

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[Janka astro-ph/0008432]

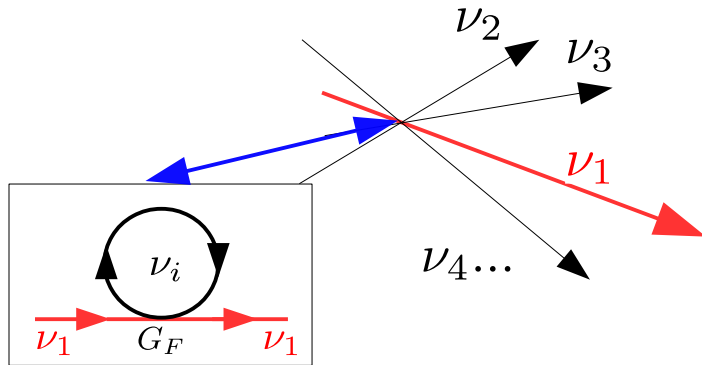


[Kullman 2109.02509]

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

→ quantum kinetic equation (extended Boltzmann equation):

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

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

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

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

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

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

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

→ strong coupling in flavor space leading to collective modes!

Separation of two regimes?

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

flavor oscillations

Earlier studies on collective oscillation found that it only starts to develop at $\mathcal{O}(10^2 \text{ km})$, due to decoherence effect, with

$$\omega_{\text{col}} \sim (\omega_{\text{vac}} \mu)^{1/2} \sim \mathcal{O}(1) \text{ km}^{-1} \quad (\text{slow mode})$$

[Duan+, Raffelt+, Mirizzi+, ... many others]

→ no impact on supernova dynamics, but can affect nucleosynthesis and neutrino signals

dominated
by collisions

ν -sphere ($r \sim 10 - 50 \text{ km}$)

Fast neutrino oscillations

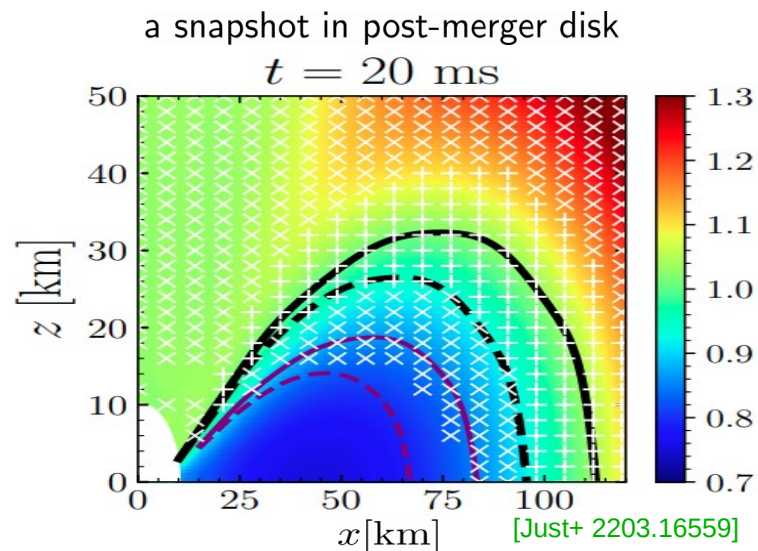
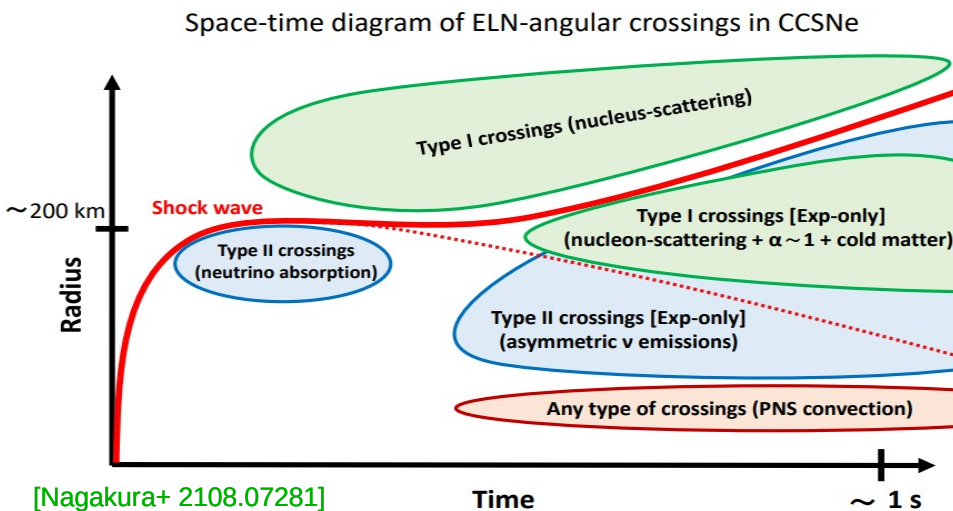
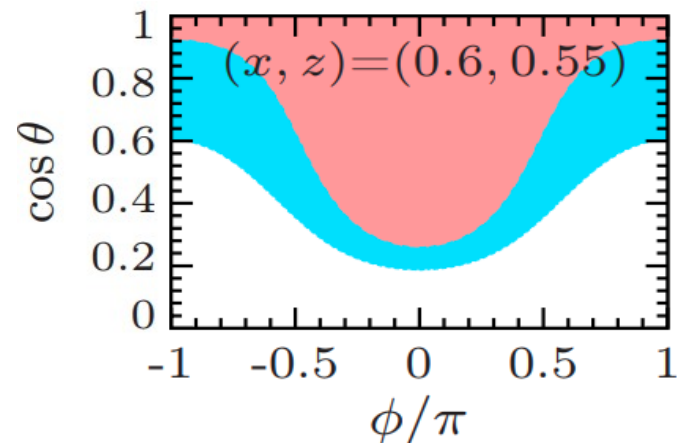
Recent studies revealed that a novel kind of “fast collective oscillation mode” at regions when there “ $e - \mu$ crossing” exists in neutrino angular distribution

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

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

Further investigations found that fast oscillations should occur in SNe and in mergers

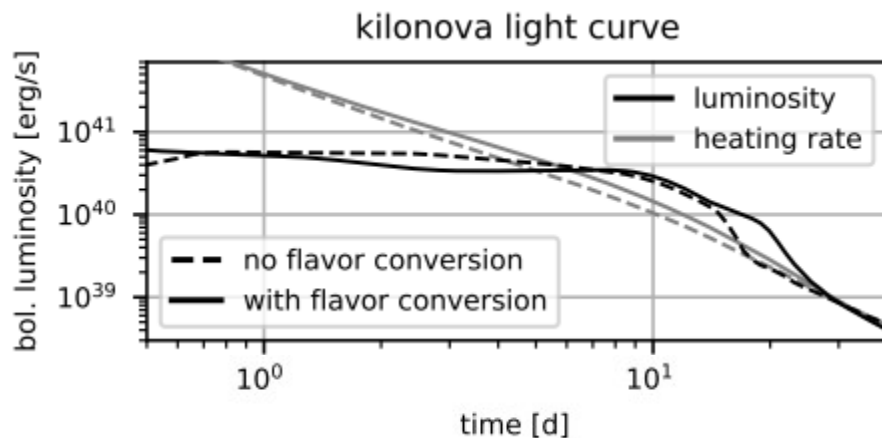
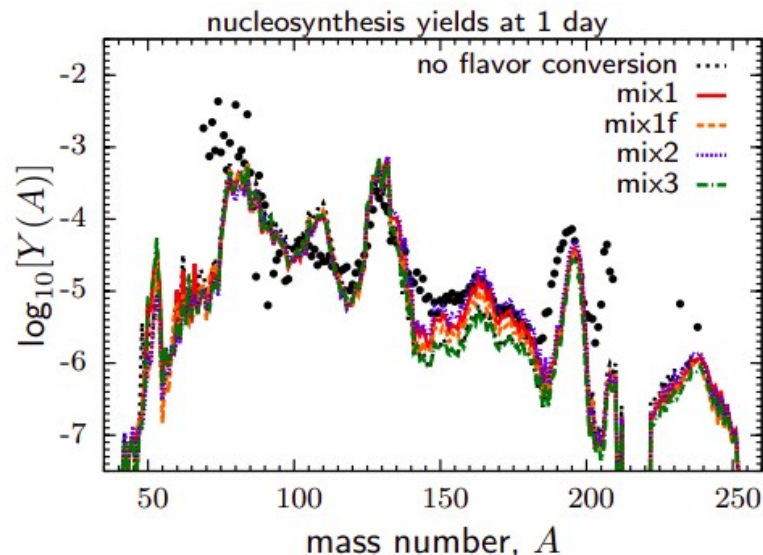
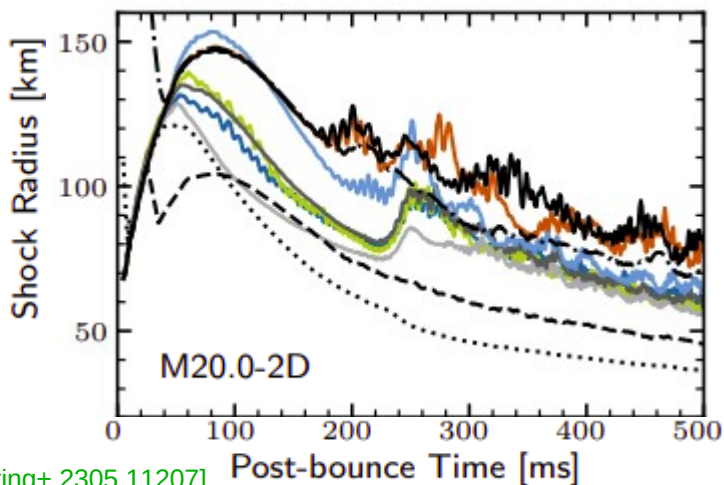
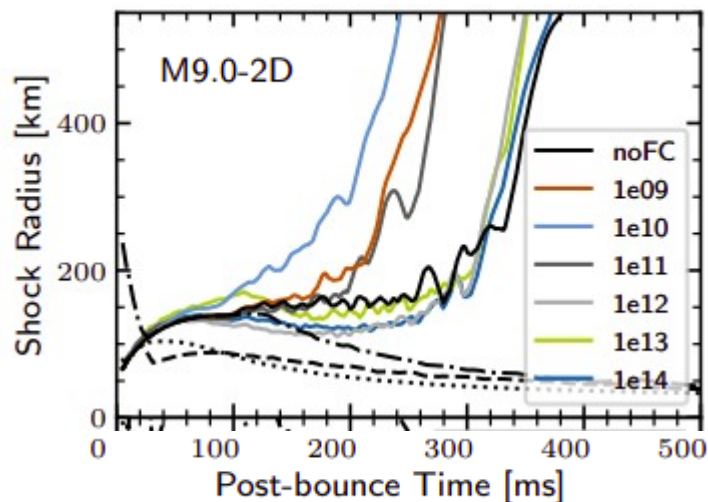
$$G(\theta, \phi) \propto \int dE_\nu E_\nu^2 (f_{\nu_e} - f_{\nu_\mu} - f_{\bar{\nu}_e} + f_{\bar{\nu}_\mu})$$



Fast neutrino oscillations

Exploratory works found that this effect may affect the dynamics and nucleosynthesis in these systems [MRW+, George+, Xiong+, Li+, Abbar+, Fernandez+, Nakagura+, Ehrling+,...]

on SN explosion



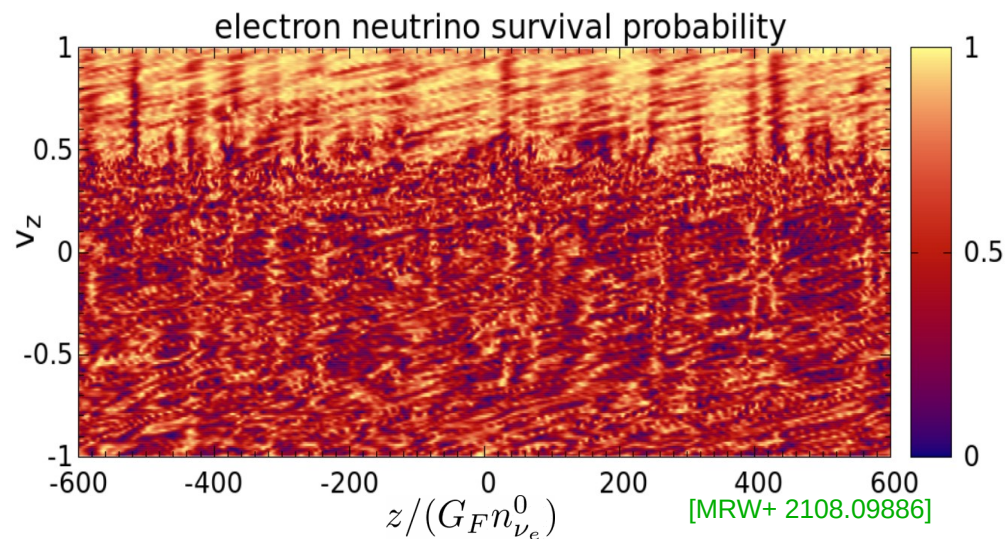
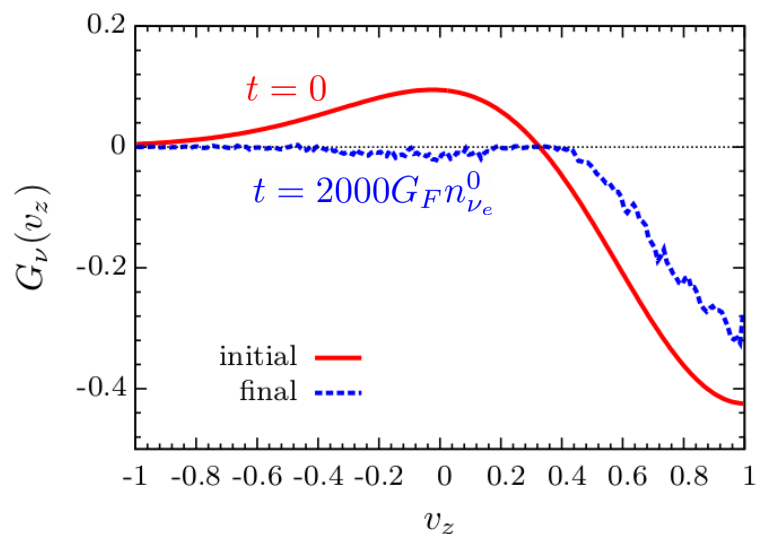
Simulation of fast neutrino oscillations

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

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

→ fast oscillations tend to erase the $e - \mu$ crossing

[Bhattacharyya+, Richers+, MRW+]



→ analytical prescription or machine-learning based methods are proposed or under investigation

[Bhattacharyya+2020, 2022, Zaizen 2022, Xiong+ (in preparation)]

→ could allow more consistent inclusion of fast conversions in simulations

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

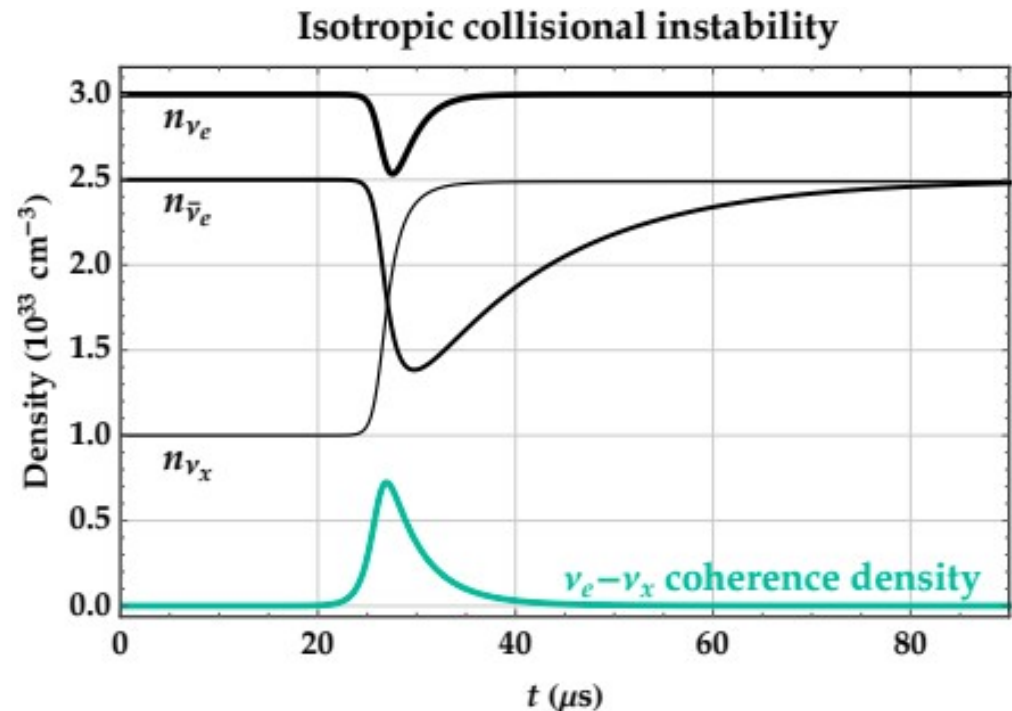
$$(\partial_t + \mathbf{v} \cdot \partial_{\mathbf{x}} + \mathbf{F} \cdot \partial_{\mathbf{p}})\varrho(\mathbf{x}, \mathbf{p}, t) = -i[H_{\text{vac}} + H_{\text{m}} + H_{\nu\nu}, \varrho(\mathbf{x}, \mathbf{p}, t)] + \mathcal{C}(\varrho)$$

For a condition that satisfies

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

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

→ can lead to excessive production of heavy-lepton flavor neutrinos

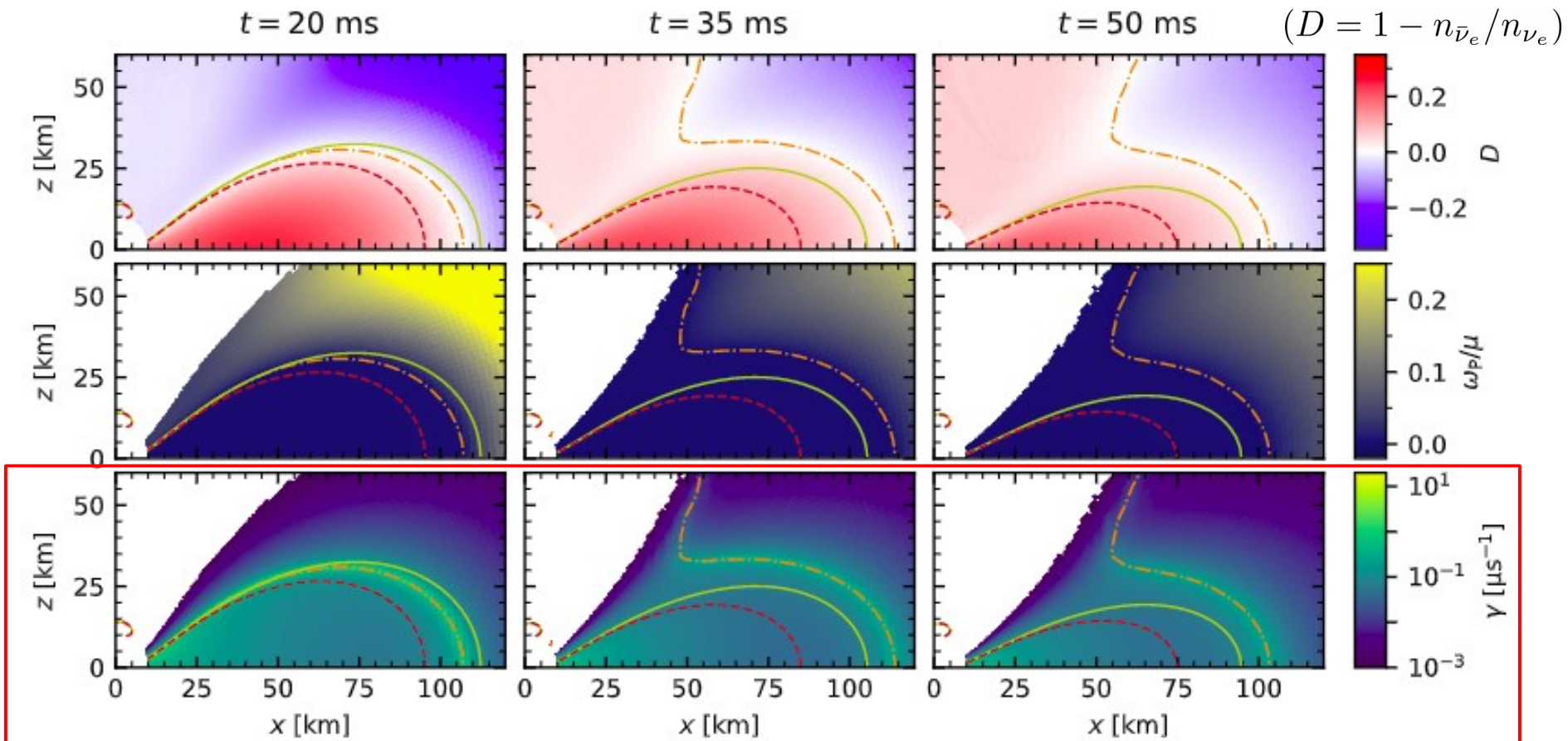


[Johns, 2104.11369]

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

Collision-induced instabilities in BH disks

In the BH-disk remnants from neutron star mergers, collision-induced flavor instabilities can be present universally inside the remnant disk



[Xiong, Johns, MRW, Duan, 2212.03750]

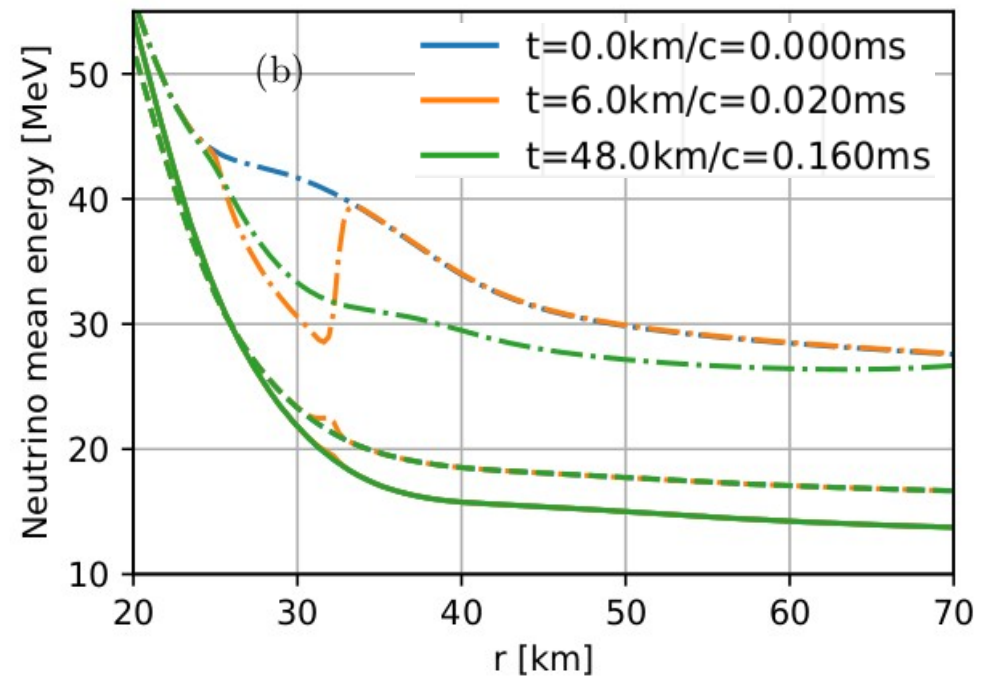
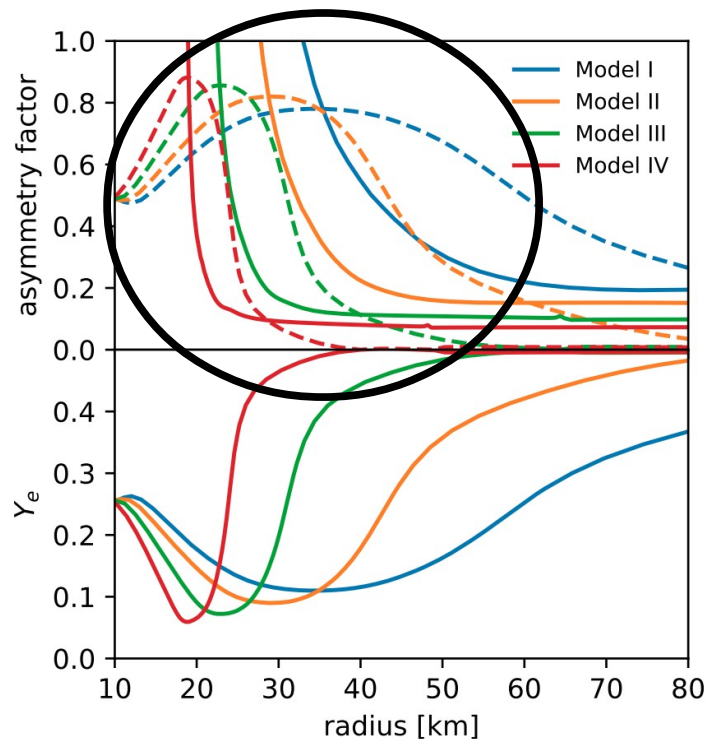
peaks at where $n_{\nu_e} \simeq n_{\bar{\nu}_e}$

Global simulations of collision-induced oscillations in SNe

[Z. Xiong, MRW+ 2210.08254]

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

- generically exist around the ν -sphere
- affects the emission properties of μ and τ neutrinos



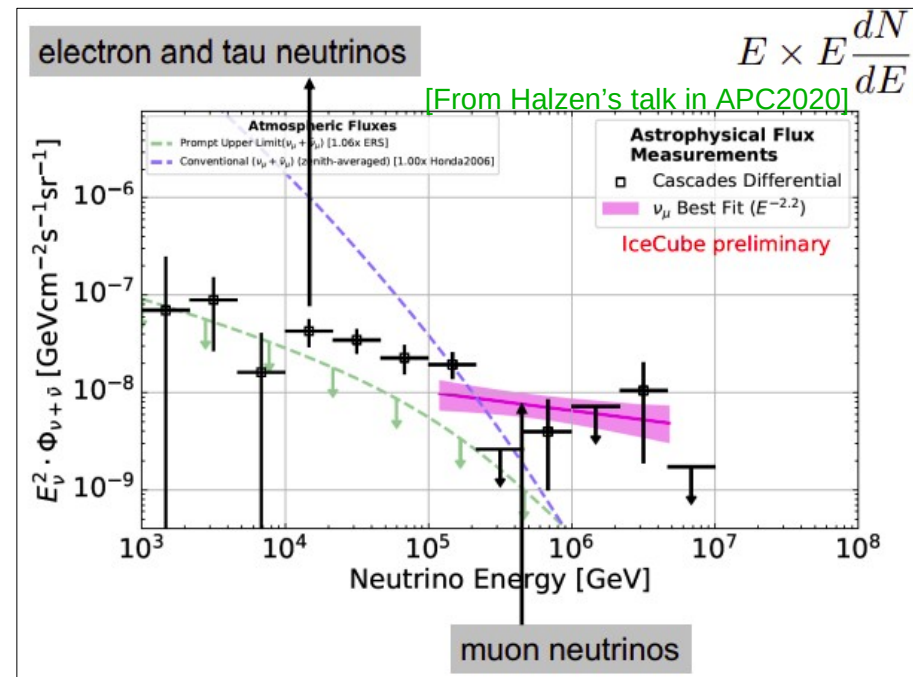
→ most likely need to solve the full QKE in SN simulations

High-energy neutrinos

see Ishihara's talk

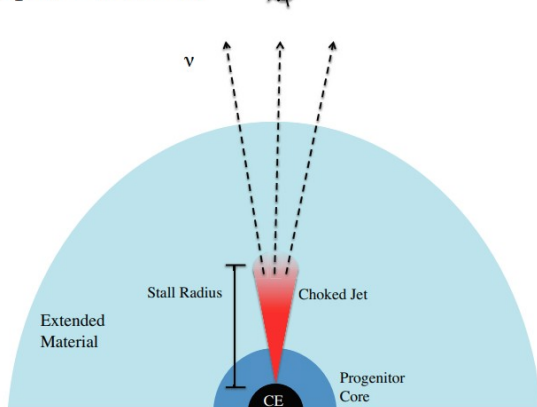
IceCube has detected extragalactic HE neutrinos above ~ 10 TeV

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

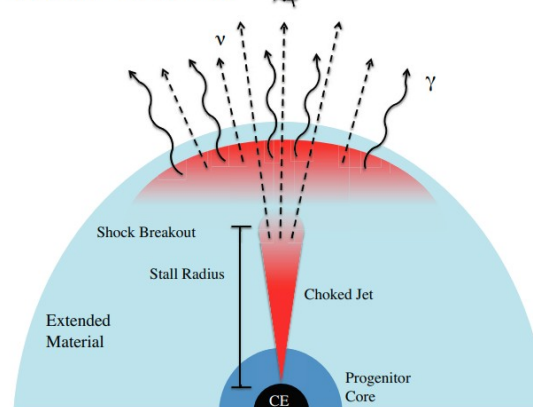


Very tight constraints on bright GRBs as sources, but LLGRBs or choked ones remain possible [Meszaros+, Razzaque+, Ando+, Horiuchi+, Hummer+, Murase+, Frajia+, Tamborra+, Senno+, Carpio+,...]

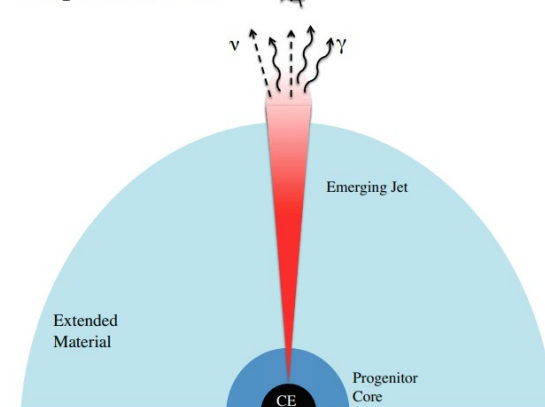
Orphan Neutrinos



Precursor Neutrinos

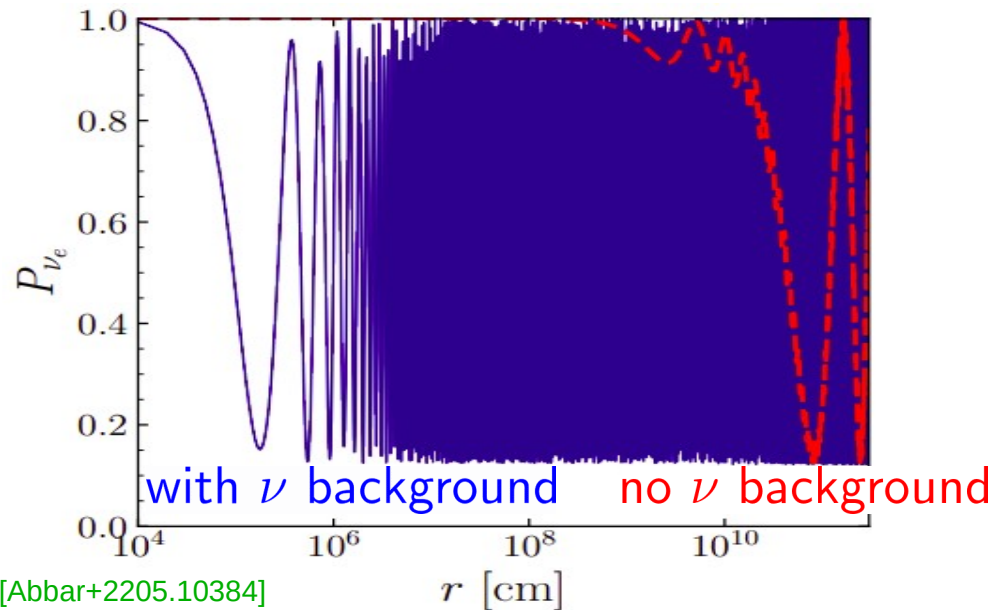


Prompt Neutrinos



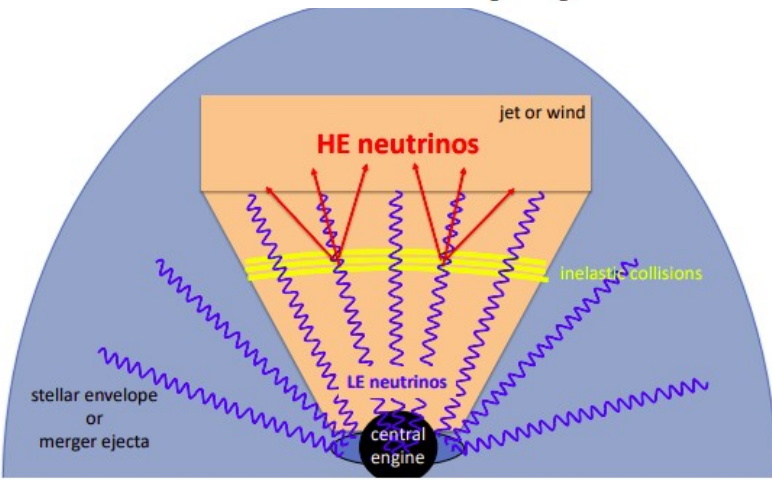
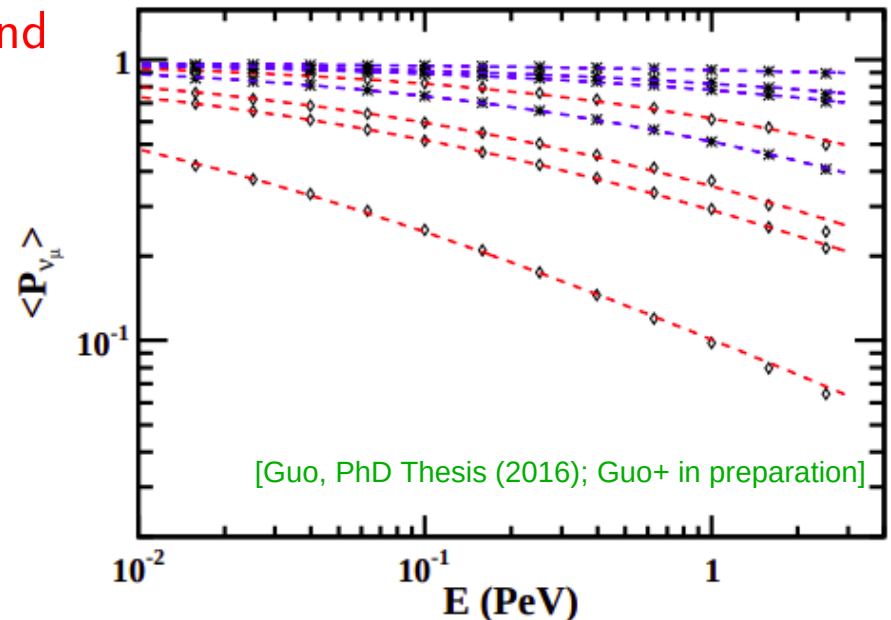
Neutrino-neutrino interactions?

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



may affect flavor evolution
and/or survival of HE neutrinos

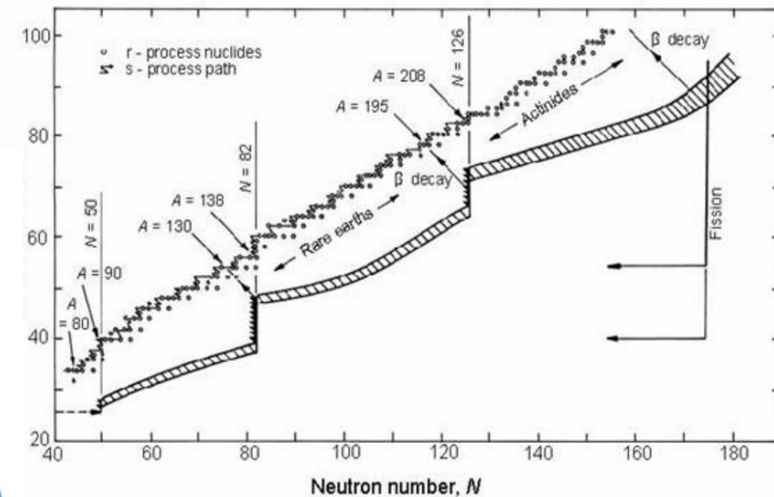
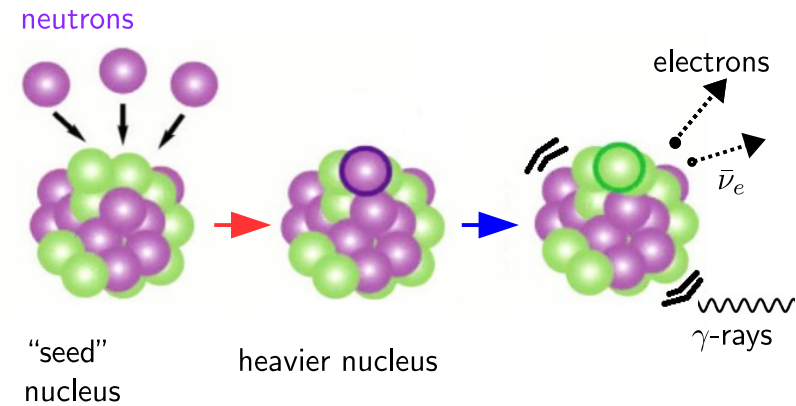
different internal shock radii



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

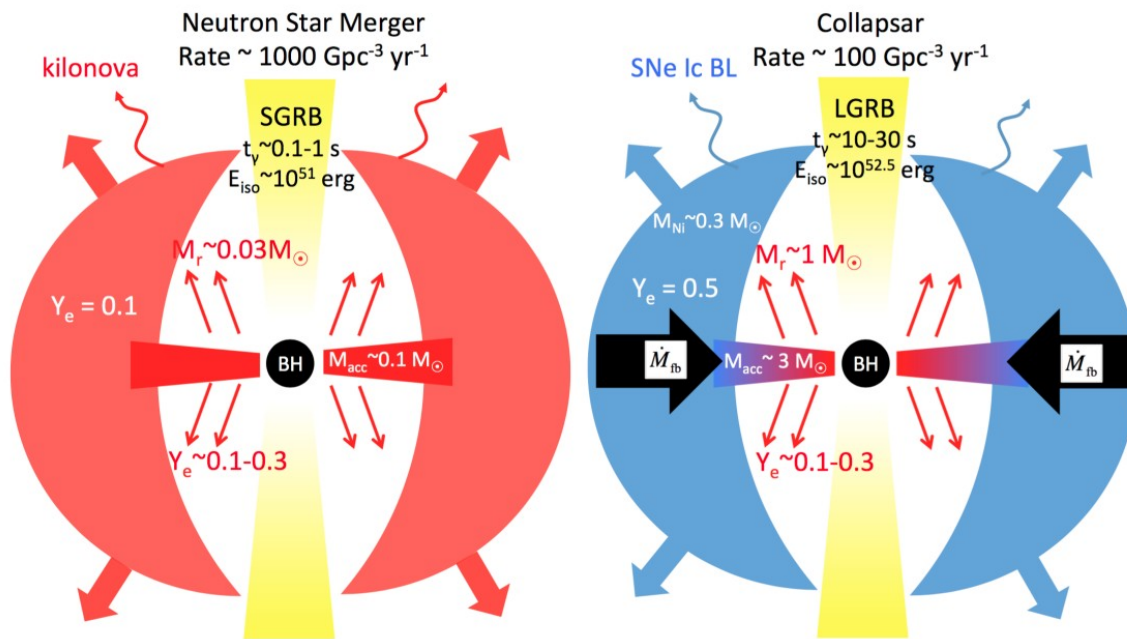
The r -process may occur in collapsar outflows and produces neutron-rich unstable nuclei that β decay

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



its viability is still under-debate

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



[Siegel, Barnes, Metzger, 1810.00098]

Annihilation of low- and high-energy neutrinos

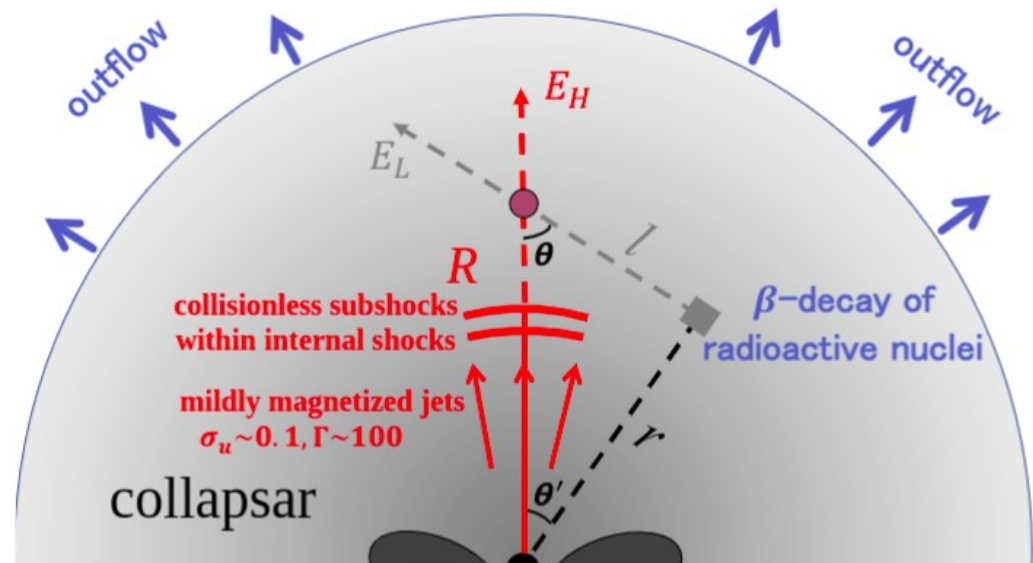
These r -process decay neutrinos can oscillate to different flavors and annihilate with high-energy neutrinos of $E_H \sim 100 - 1000$ TeV via Z-resonance

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

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

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

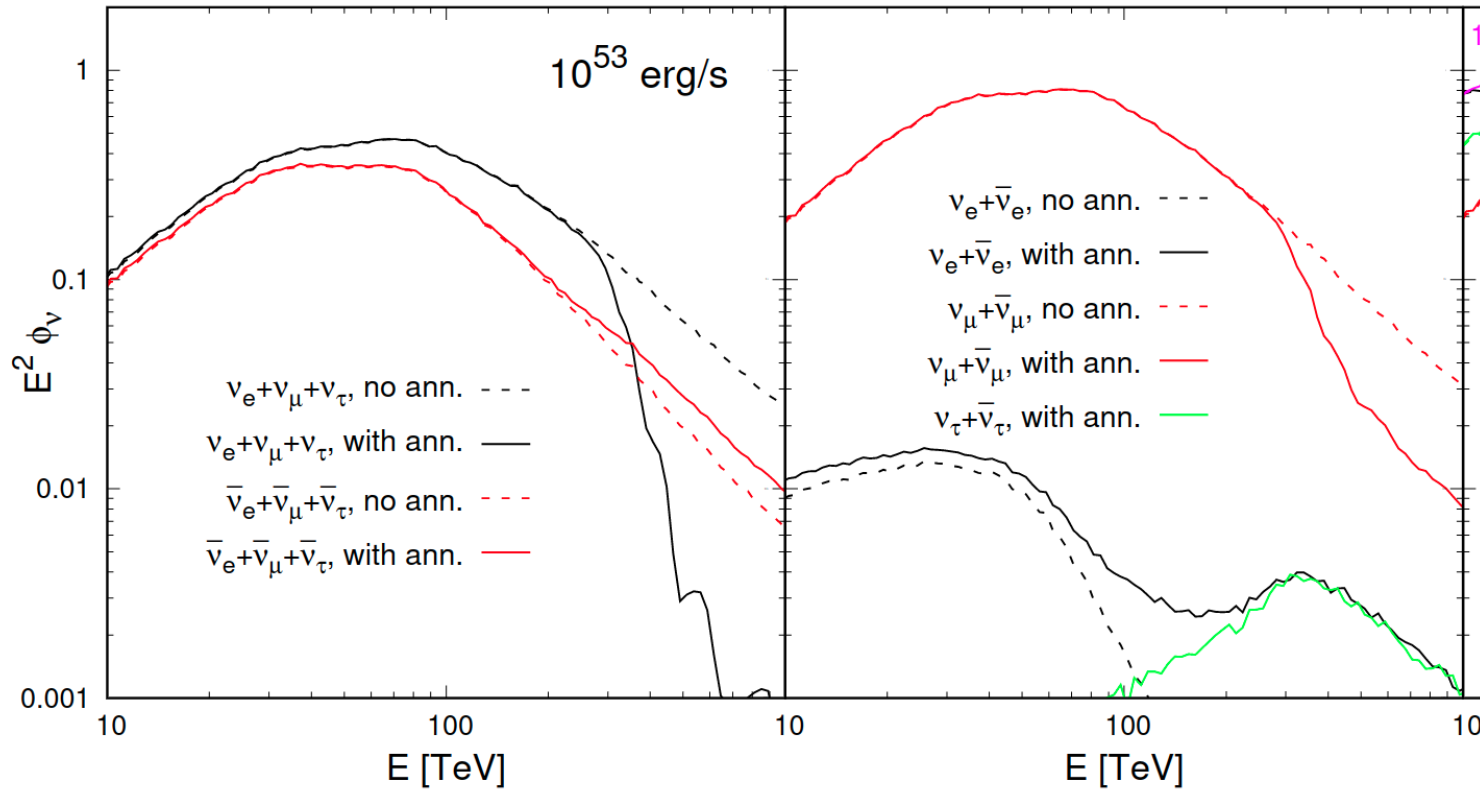
efficient annihilation



Effect of neutrino pair annihilation

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

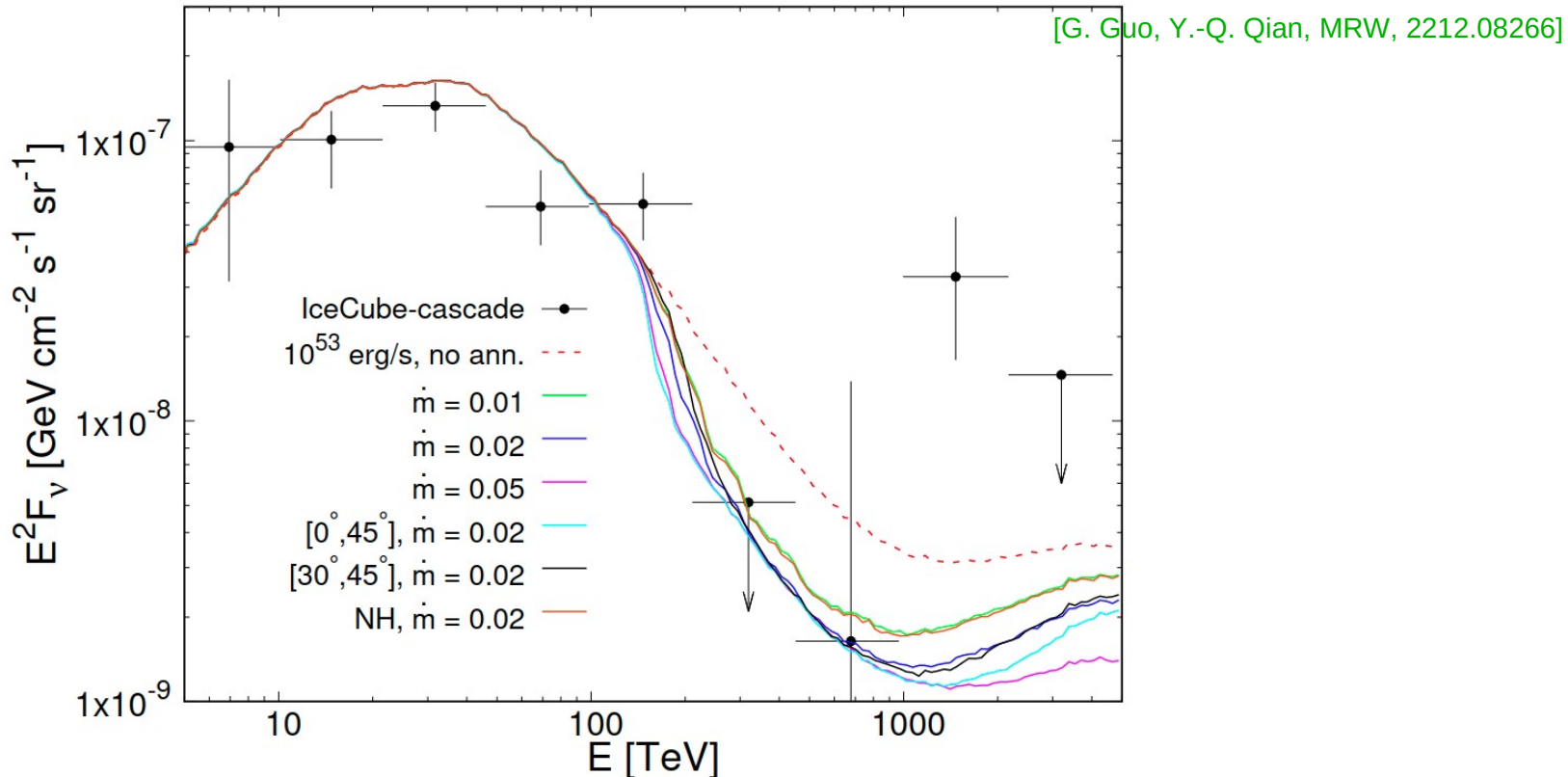
[G. Guo, Y.-Q. Qian, MRW, 2212.08266]



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

Diffuse flux v.s. IceCube detection

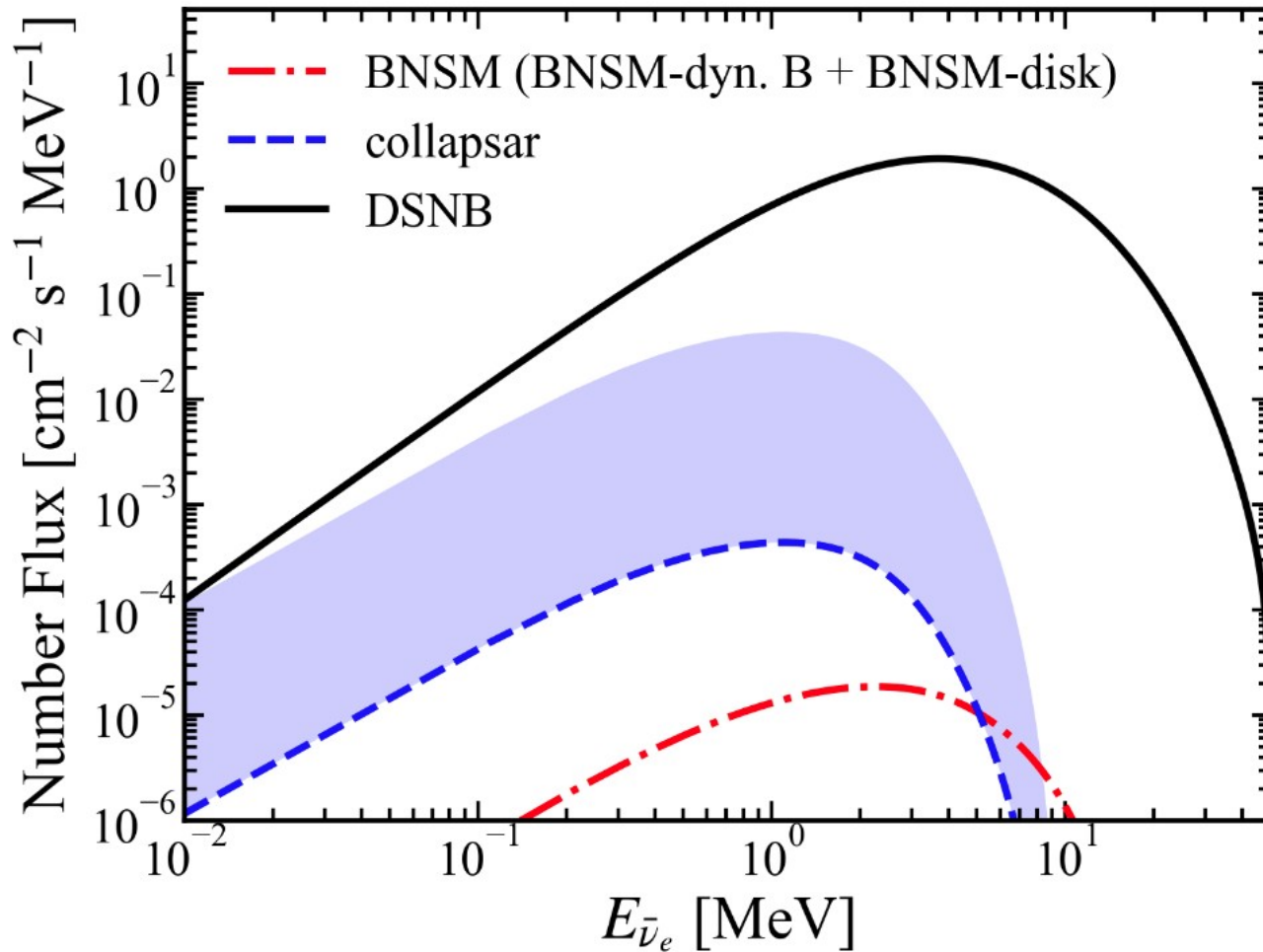
Assuming that such sources are ~ 10 times more frequent than the bright GRB, the resulting diffuse flux may be compatible to what detected at IceCube



May be further tested with improved statistics on diffuse flux, precise flavor measurements, or from nearby point-source events

Diffuse r -process neutrino background (Dr NB)?

[An, MRW+, 2206.07659]



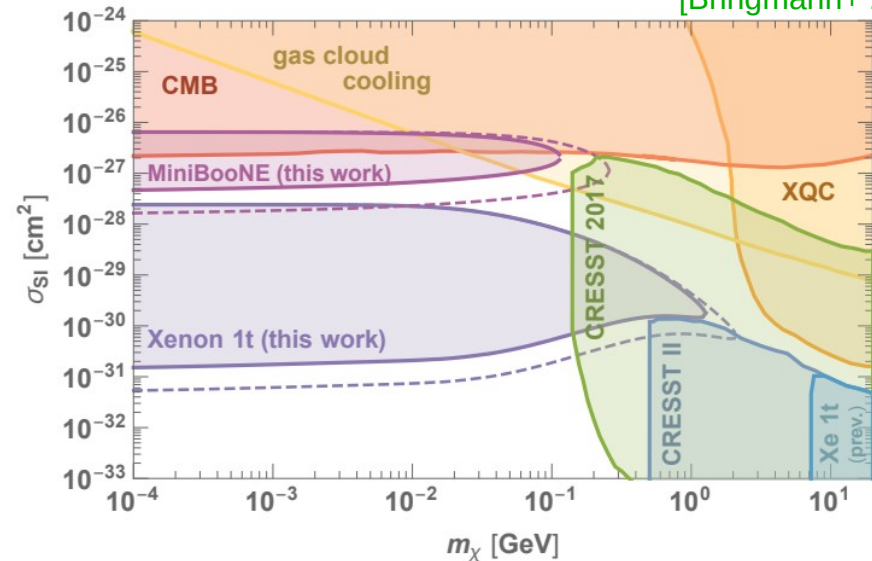
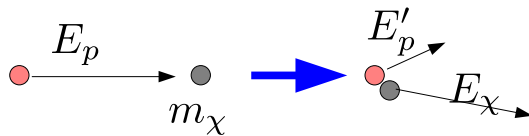
Won't be significant background for DSNB at relevant energy of $\sim \mathcal{O}(10)$ MeV, but may (at best) become comparable at sub-MeV

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,...]

*see talks from Jho, Herrera, Kang;
also cosmological bound from Akita*

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 $\text{SN}\nu$)

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

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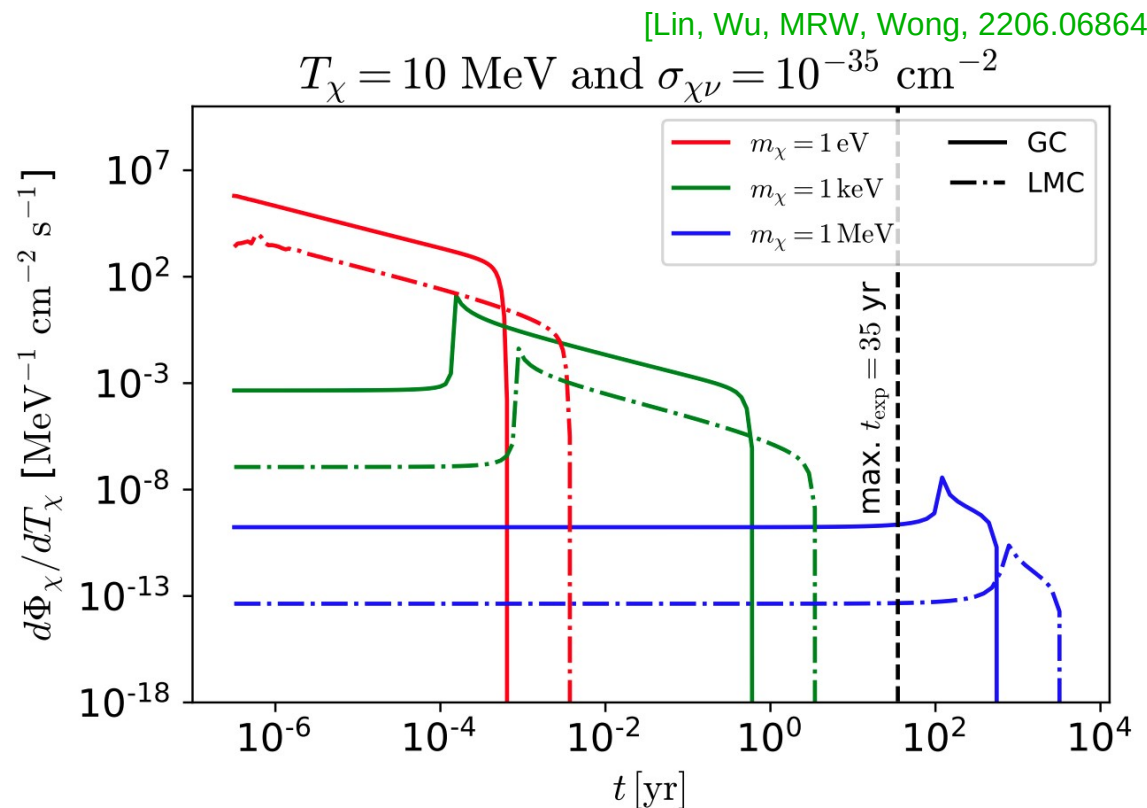
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- time-dependent feature
independent of $\sigma_{\chi\nu}$

t_p and t_{van} determined
by the distance and m_χ

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

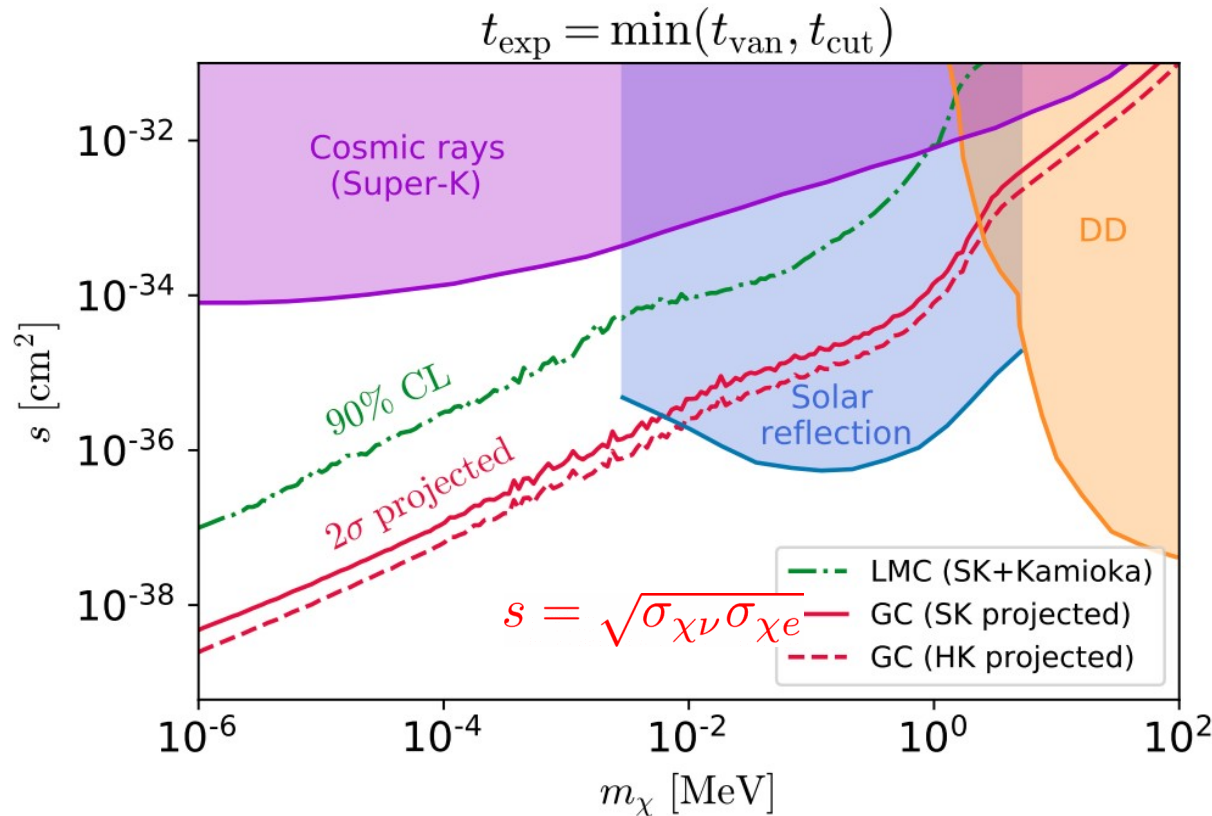


GC: a SN exploded in the MW center

LMC: a SN exploded in the LMC center

SN ν boosted DM events and constraints

Consider total event and background counts within an exposure time $t_{\text{exp}} = \min(t_{\text{van}}, 35 \text{ years})$ 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]

→ 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,...)

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 annihilation 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