Supernova neutrinos: probing physics within and beyond the Standard Model

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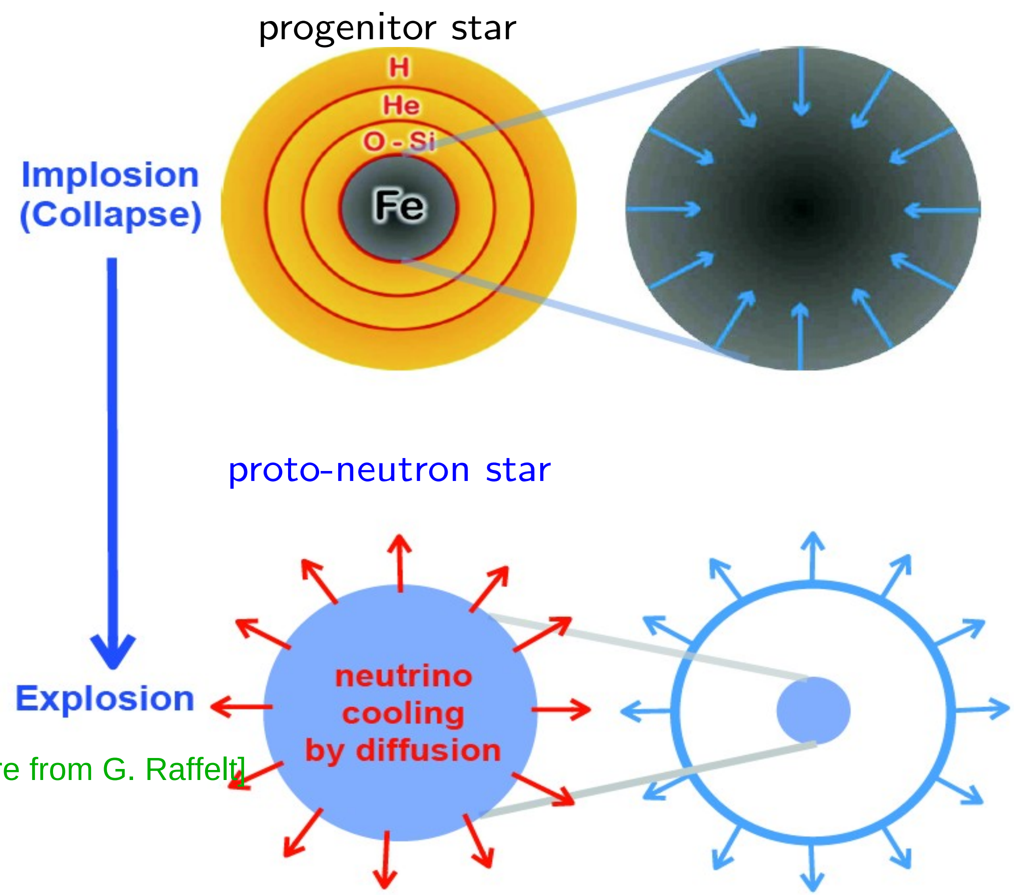
Core-collapse supernovae – turning implosion into explosion



[Figure from G. Raffelt]

$M_{\rm Fe,core} \approx 1.4 M_\odot$

$R_{\rm Fe,core} \approx 3000$ km

$\rho_c \approx 10^9$ g cm^{-3}

$T_c \approx 10^{10}$ K~ 1 MeV

$M_{\rm PNS} \approx 1.4 M_\odot$

$R_{\rm PNS} \approx 15$–50 km

$\rho_c \approx 3 \times 10^{14}$ g cm^{-3}

$T_c \approx 30$ 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 ~ 10 seconds

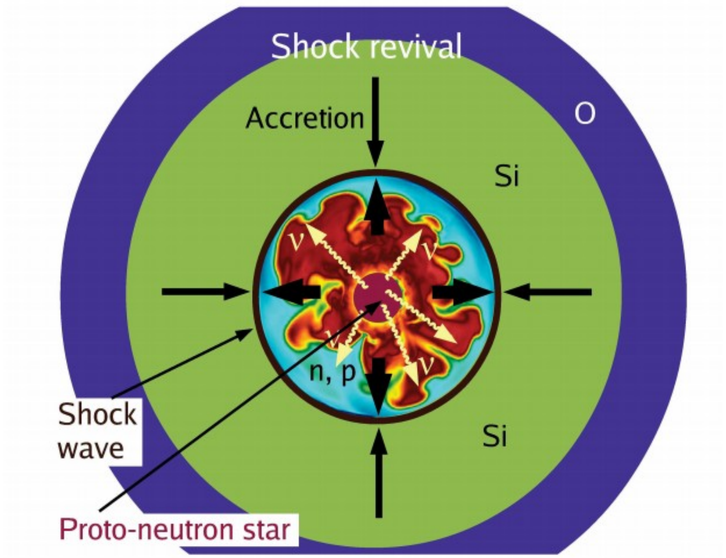
$\rightarrow \sim 20$ $\bar{\nu}_e$ events (inverse β decay) from SN1987a at LMC

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

Core-collapse supernovae

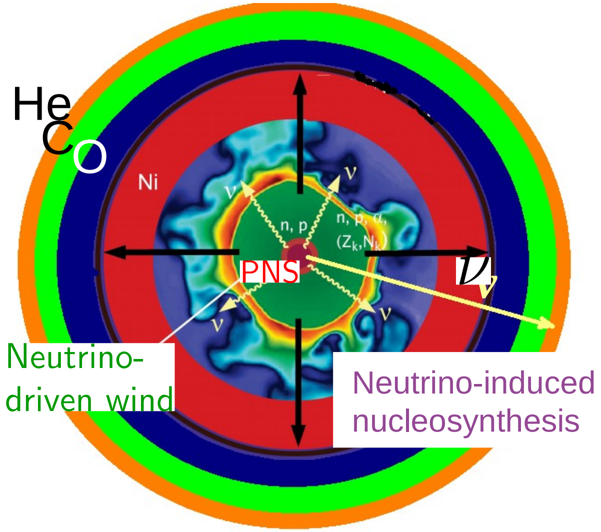
As these neutrinos dominate the energy budget released during the collapse, they play key roles in:

shock revival



[Janka+, PTEP 01A309, 2012]

Nucleosynthesis



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

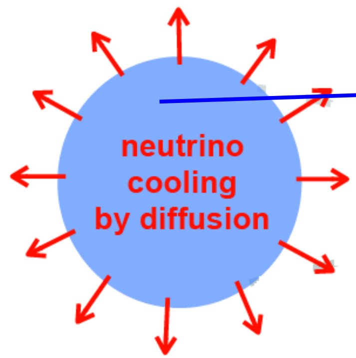
Detection of the next galactic SN's neutrinos would offer unprecedented opportunity to probe supernova interior, neutrino physics, and physics beyond the Standard Model

Probing bSM physics with SN neutrinos

Supernova as laboratory – bSM physics

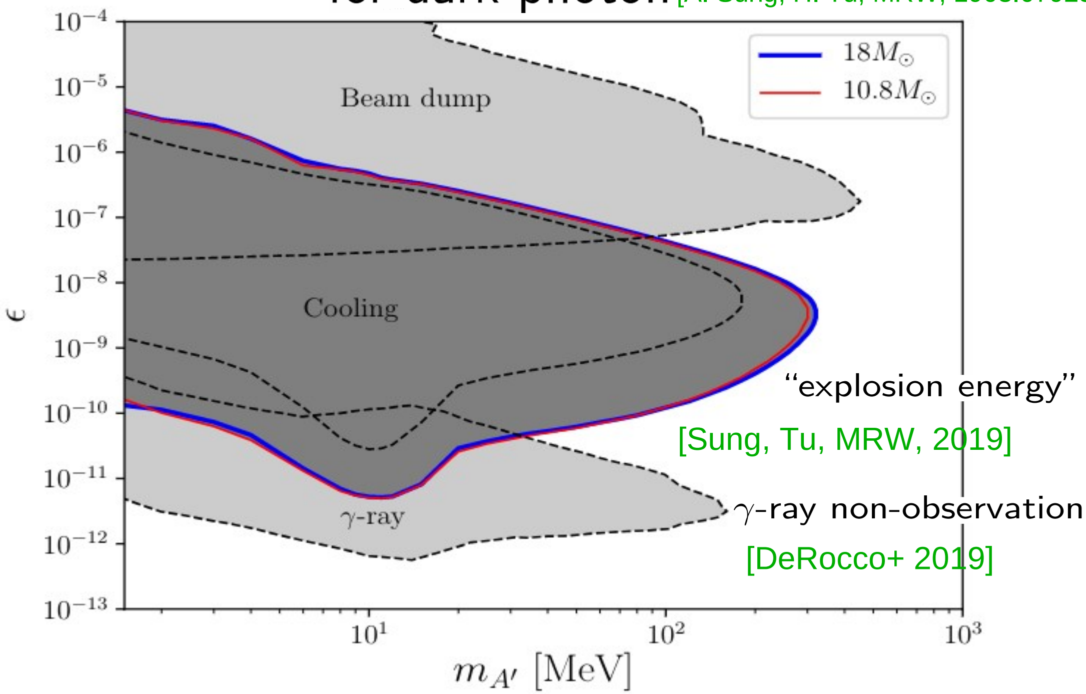
Many ways to utilize supernova to probe physics beyond the Standard Model:

- Emission of bSM particle from SN core
  - cooling bound
  - explosion energy
  - γ-rays, neutrinos



weakly-interacting bSM particles?

for dark photon [A. Sung, H. Tu, MRW, 1903.07923]



[see also:
Raffelt+1988, Turner+1988, Janka+9507023, Fischer+1605.08780, Bar+1907.05020, Lucente+2008.04918, Fischer+2108.13726, Mori+2112.03613, Lucente+2203.15812, Ferreira+ 2205.07896... for axions; Dent+1201.2683, Rrapaj+1511.09136, Hardy+1611.05852, Chang+1803.00993, DeRocco+1901.08596, Sung+1903.07923, DeRocco+1905.09284, Dev+2005.00490, Darme+2012.07894, Sung+2102.04601, Balaji+2205.01669, ... for dark photons (sector); Raffelt+1102.5124, Arguelles+1605.00654, Suliga+1908.11382, Syvolap+1909.06320, Suliga+2004.11389, ... for keV sterile neutrinos; Rembiasz+1806.03300, Mastrototaro+ 1910.10249, ... for MeV sterile neutrinos, ...]

(see also Balaji's talk yesterday)

Supernova as laboratory – bSM physics

Many ways to utilize supernova to probe physics beyond the Standard Model:

- Emission of bSM particle from SN core
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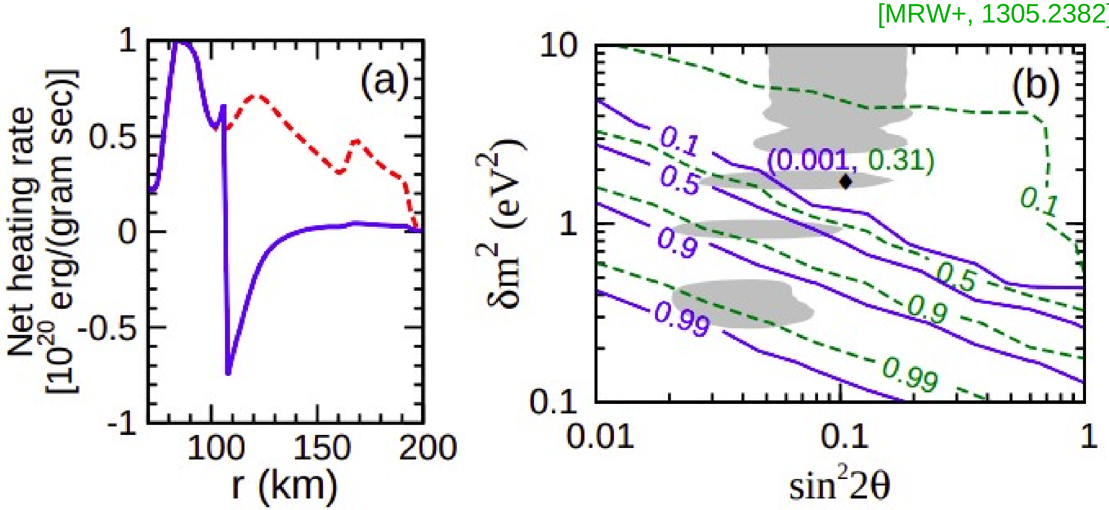
  - γ-rays, neutrinos
- light ($\sim$ eV) sterile neutrinos
  - failure of explosion mechanism
  - reduced SNν events

[MRW+, 1305.2382]



[see also: Esmaili+ 2014, Franarin+ 2017, Tang+2020 on neutrino signals and Tamborra+ 2011, Pllumbi+ 2014, Xiong+ 2019, Ko+2019 for other impacts]

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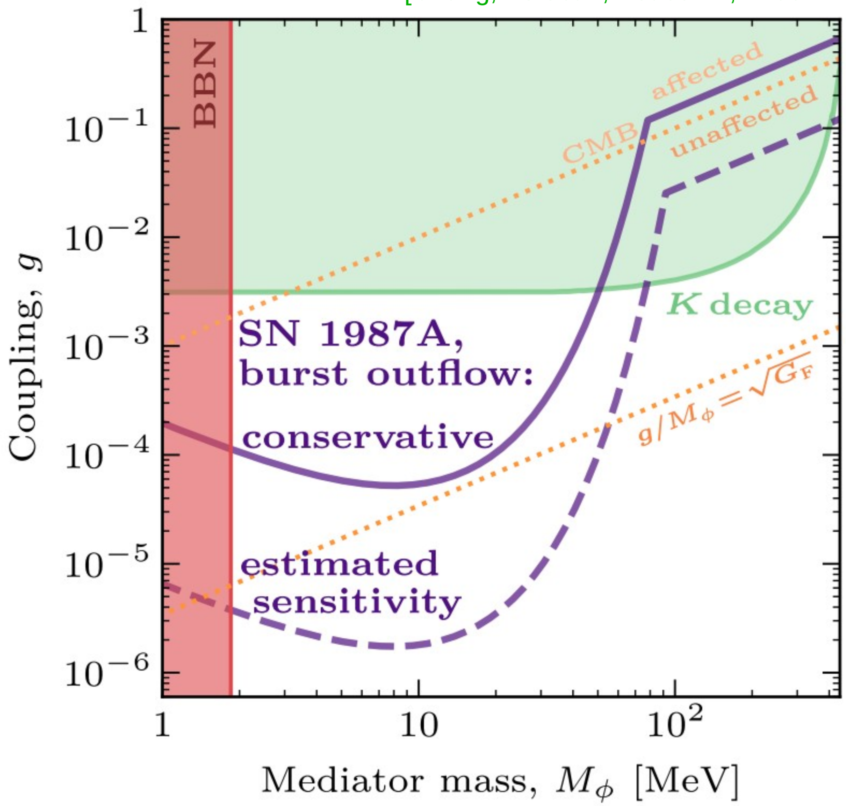
- non-Standard neutrino interaction
  - neutrino flavor conversion
  - SNν duration and energy
  - SNν interaction with relic ν

[Chang, Esteban, Beacom+, 2206.12426]



[see also: 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...]

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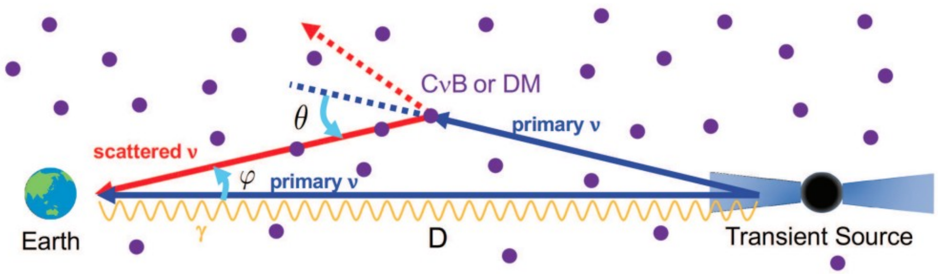
- neutrino interaction with dark matter
  - neutrino echo (deflection)
  - upscattered light dark matter

[Murase & Shoemaker 1903.08607]



[see also: Das+2021, Carpio+2022, Lin+2022, Carenza+2022...]

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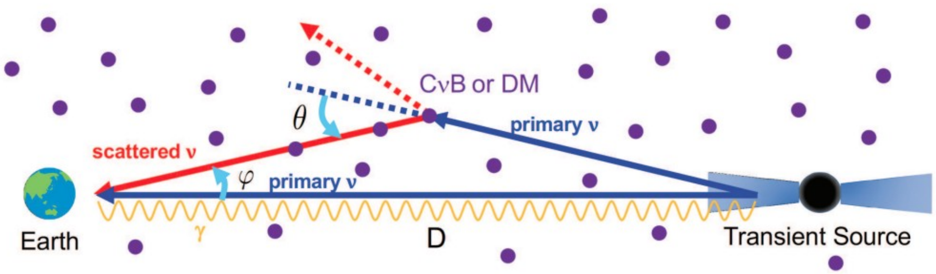


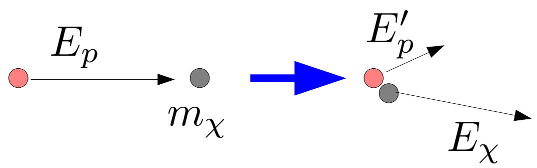
[see also: Das+2021, Carpio+2022, Lin+2022, Carenza+2022...]

[Yen-Hsun Lin, Wen-Hua Wu, MRW, Henry T.-K. Wong, 2206.06864]

Light dark matter boosted by supernova neutrinos?

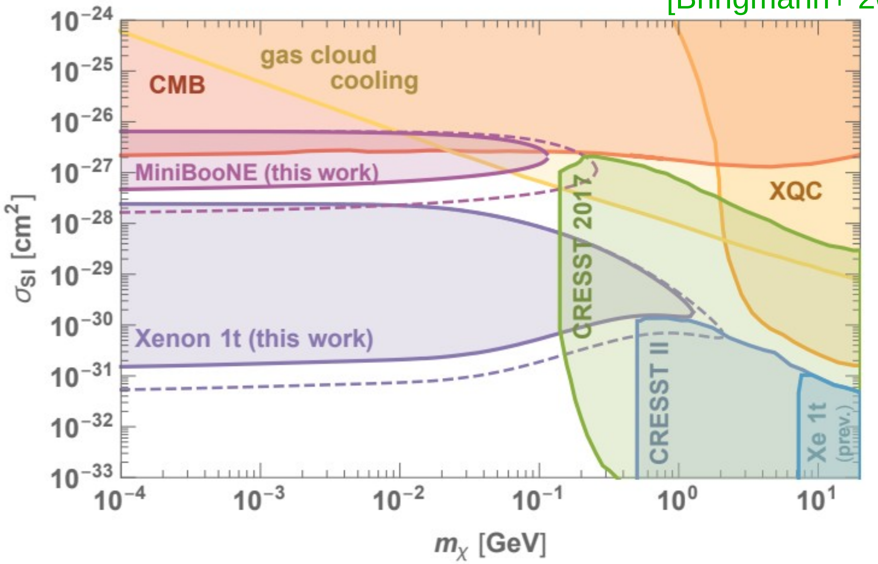
[Bringmann+ 2018, Ema+ 2018, Cappiello+ 2019,...]

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 ($\sigma_{\chi e}$)



(see Zhou's talk tomorrow)

[Bringmann+ 2018]



What if DM interacts with neutrinos? Can supernova neutrinos lead to any interesting new constraints?

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 $\times [d/(8 \text{ kpc})][m_\chi/(10 \text{ keV})^2][E_\chi/(10 \text{ MeV})^{-2}]$
after the arrival of SNν

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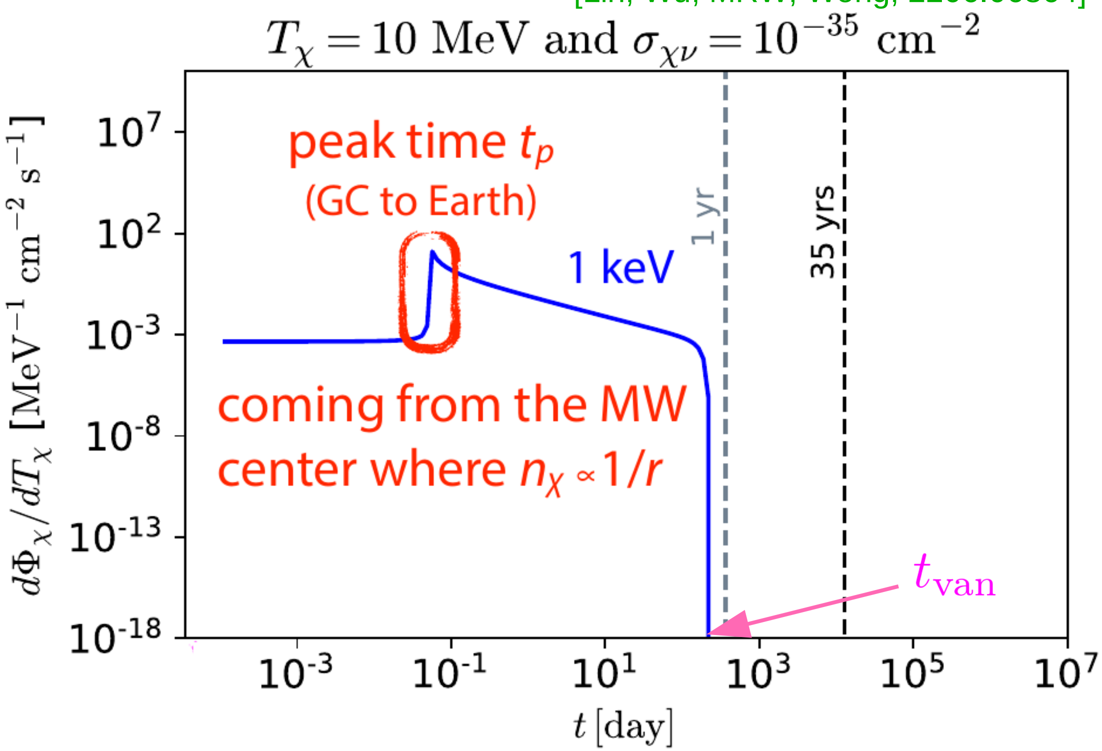
- time-dependent feature *independent* of $\sigma_{\chi\nu}$

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

(knowing $t_{\rm van}$ is useful in reducing the exposure time)

[Lin, Wu, MRW, Wong, 2206.06864]



for a SN exploded in the MW center

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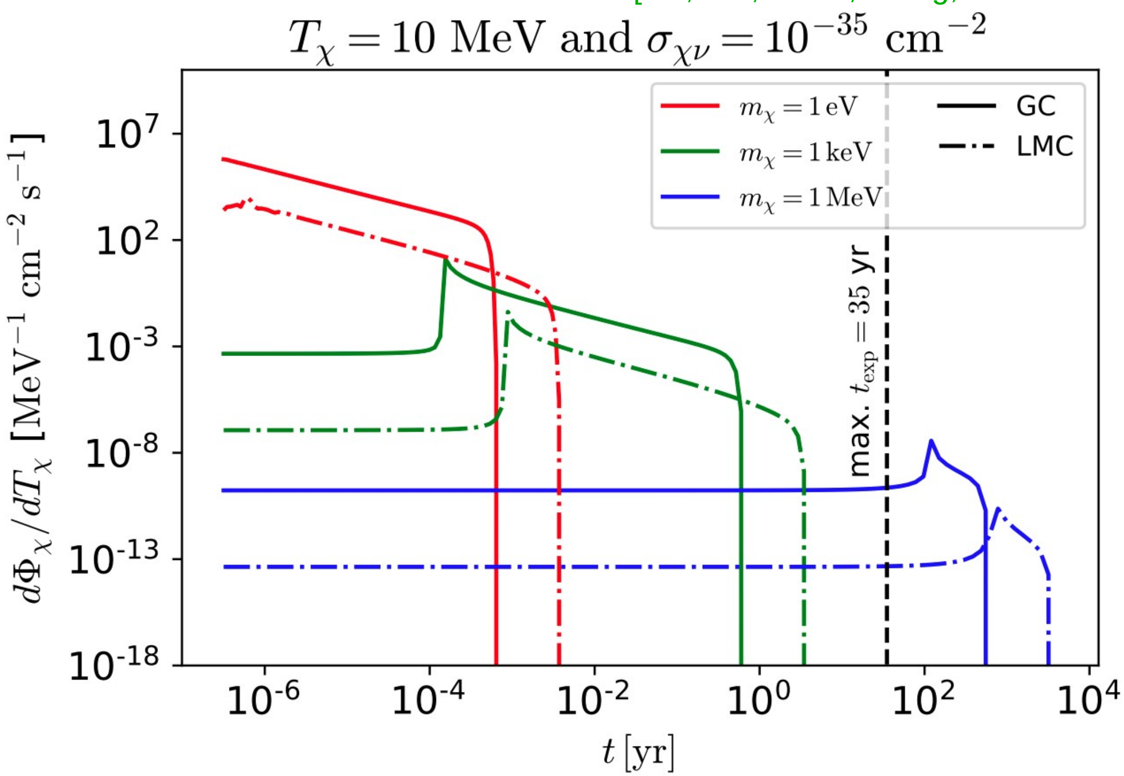

GC: a SN exploded in the MW center

LMC: a SN exploded in the LMC center

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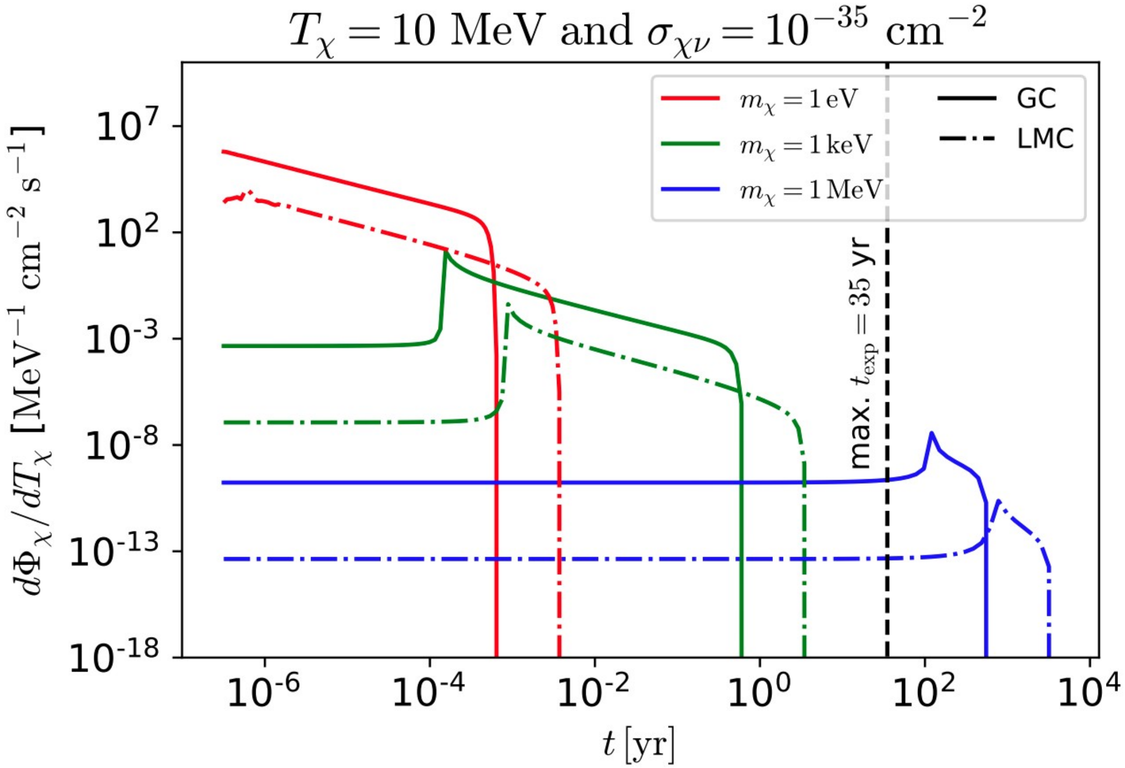
- time-dependent feature *independent* of $\sigma_{\chi\nu}$

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

  (knowing t_{van} is useful in reducing the exposure time)

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

[Lin, Wu, MRW, Wong, 2206.06864]

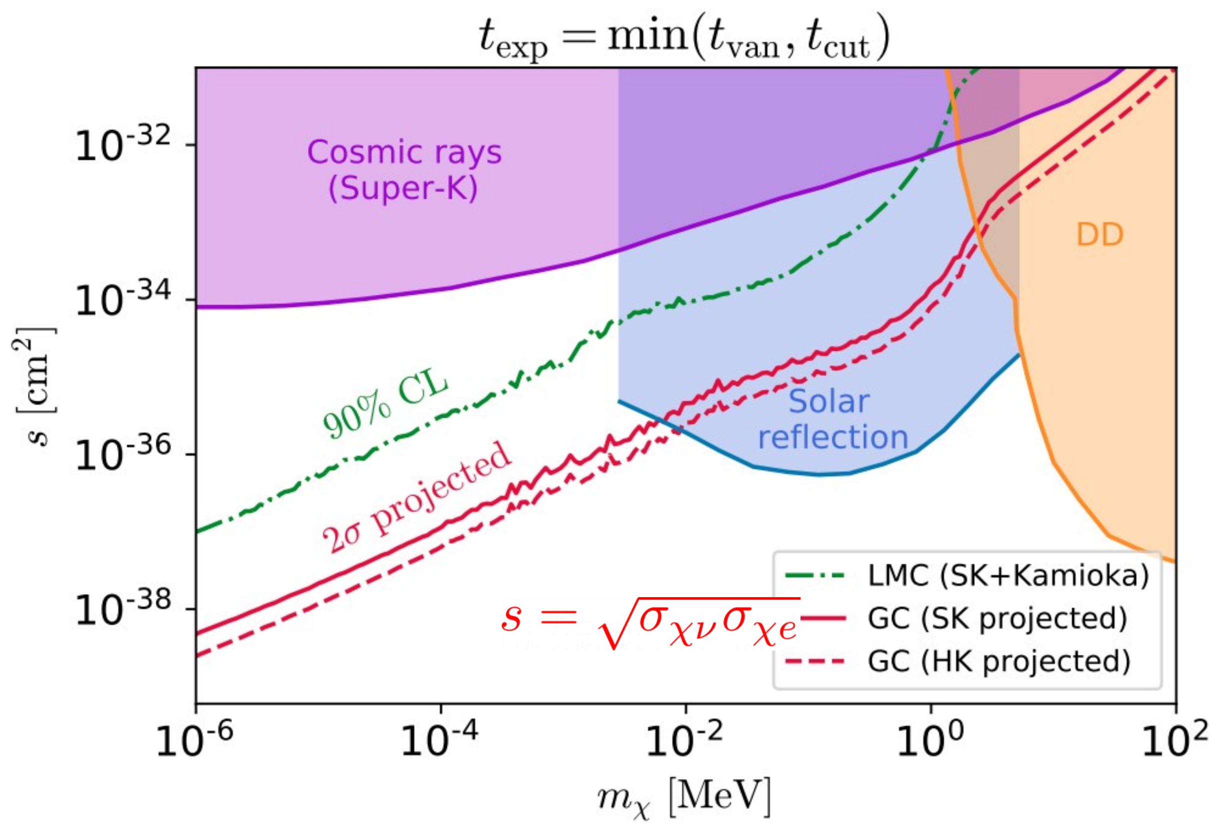


GC: a SN exploded in the MW center

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,...)

Probing Standard Model physics with SN neutrinos

Supernova as laboratory – physics within SM

Similar to bSM cases, lots of works were proposed to use SN neutrinos to probe physics within the Standard Model:

- neutronization burst:
  - neutrino mass ordering [Kachelriess+2004, Serpico+2012, MRW+2014, Vale+2015, Scholberg+2017,Jia+2017, Lai+2020, Brdar+2022]
  - strange quark contribution to proton's spin [Chauhan+2022]

- accretion phase:
  - explosion mechanism (SASI? phase-transition? thermonuclear?) [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,...]

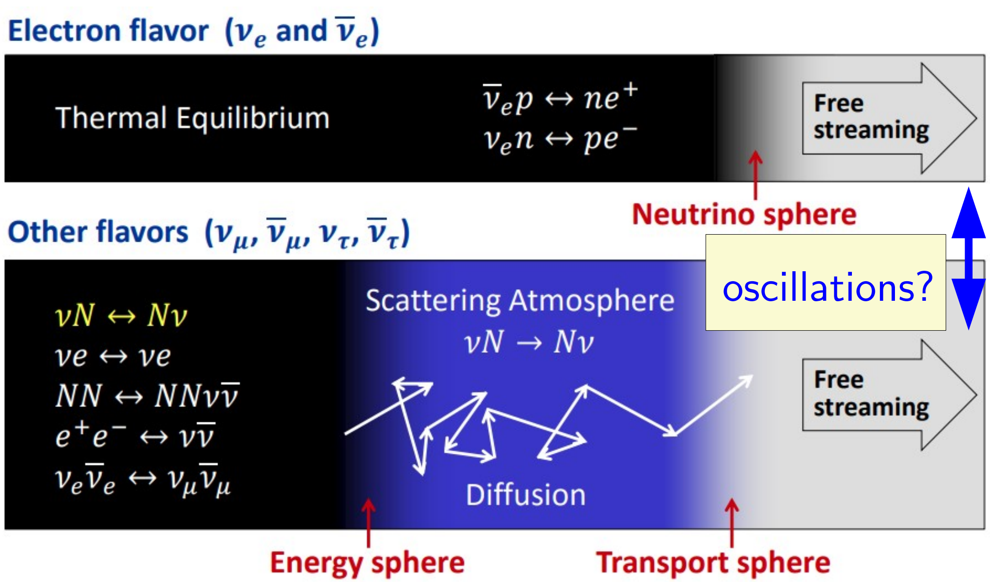
- cooling phase:
  - nuclear property or progenitor [see also: Roberts+2011, Horowitz+2016, Rosso+2017, Roggero+2017, Nakazato+2017, Rosso+2018, Suwa+2019, Nakazato+2020, Li+2020, ...]

However, probing physics within SM requires high precision. Some of those can sensitively depend on uncertain factors in modeling SNν emission

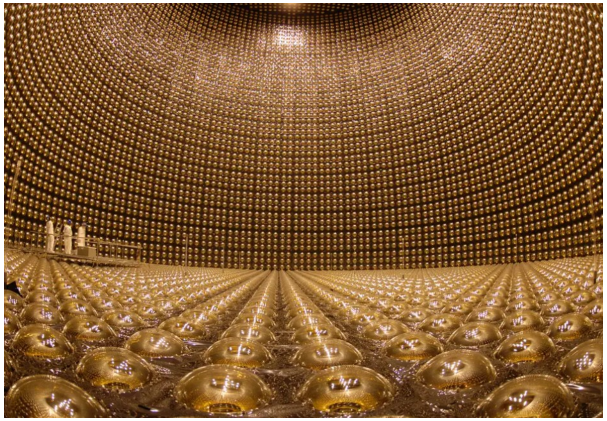
Fore-front (neutrino-related) theory issues in supernovae

• neutrino nuclear matter interaction: uncertainty can be large (a factor of a few) at high densities; impacts the neutrino luminosities at level of $\sim$ tens percents; affects shock revival dynamics and nucleosynthesis [Burrows+, Fischer+, Guo+, Horowitz+, Lin+, Martinez-Pinedo+, Oertel+ Reddy+, Roberts+, Schwenk+,...]

• neutrino flavor oscillations: new and exciting effects every few years, but no consistent and trustable global impact yet;
[Abbar+, Balantekin+, Capozzi+, Cervia+, Chakraborty+, Dasgupta+, Duan+, Fuller+, Friedland+, Johns+, Kato+, Kajino+, Kneller+, Martin+, Manibrata+, Mclaughlin+, Mirizzi+, Morigana+, Nagakura+, Raffelt+, Richers+, Rogerro+, Rrapaj+, Sawyer+, Shalgar+, Tamborra+, Volpe+, MRW+, Xiong+, Yamada+...]

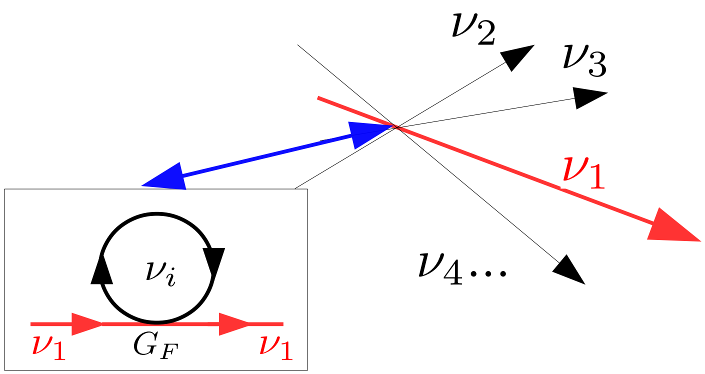


[Janka 1702.08713, Raffelt 2012]



[from Super-K]

Collective neutrino oscillations



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

flavor evolution for ν with different momenta are coupled through the forward scattering contribution of ν-ν interaction

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

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

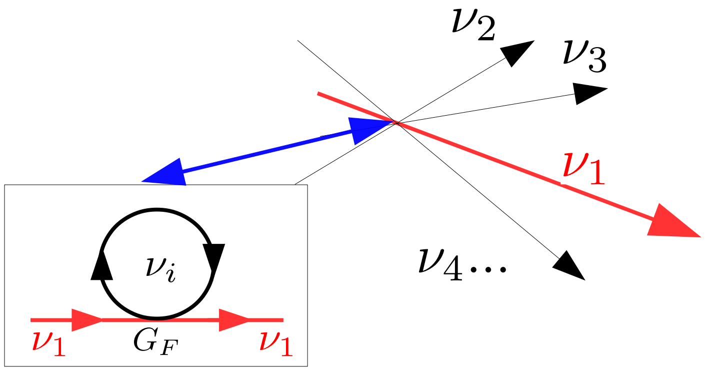
$$H_{\rm MSW}(\mathbf{x},t) = \sqrt{2}G_F n_e \times {\rm diag}(1,0,0)$$

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

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

flavor density matrix of the neutrino ensemble

Collective neutrino oscillations



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

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flavor density matrix of the neutrino ensemble

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

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

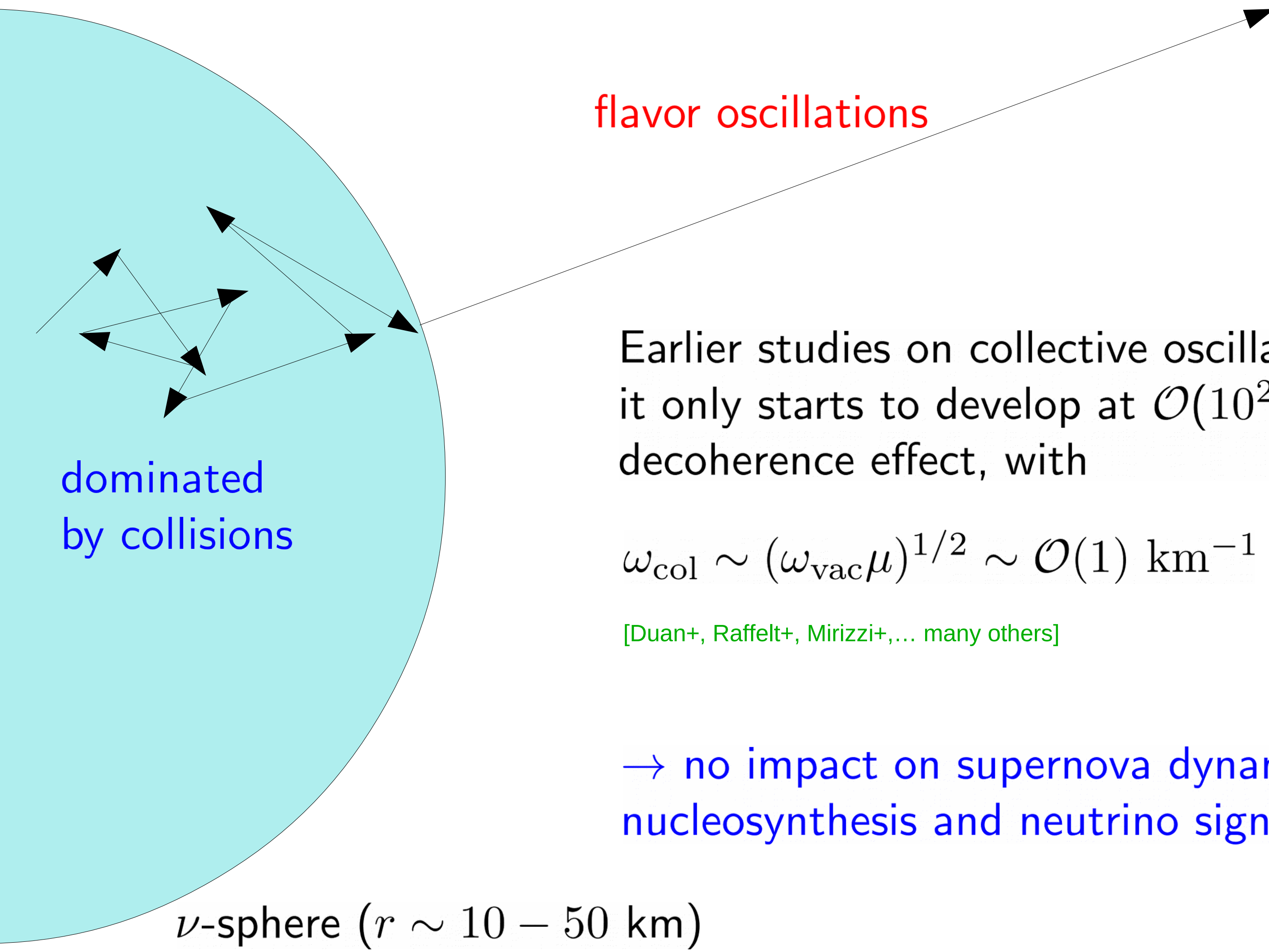
- for $n_\nu \sim 10^{33}$ cm^{-1}:

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

→ strong coupling in flavor space leading to collective modes!

Separation of two regimes?

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



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

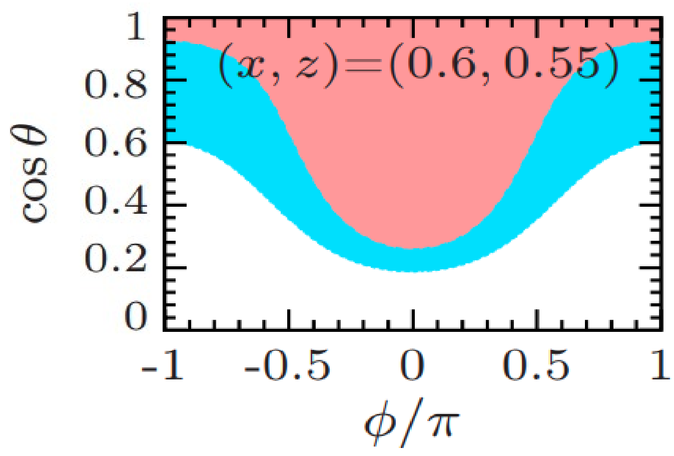
$$\omega_{\text{col}} \sim (\omega_{\text{vac}}\mu)^{1/2} \sim \mathcal{O}(1)\ \text{km}^{-1} \qquad \text{(slow mode)}$$

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

$\rightarrow$ no impact on supernova dynamics, but can affect nucleosynthesis and neutrino signals

Fast neutrino oscillations

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

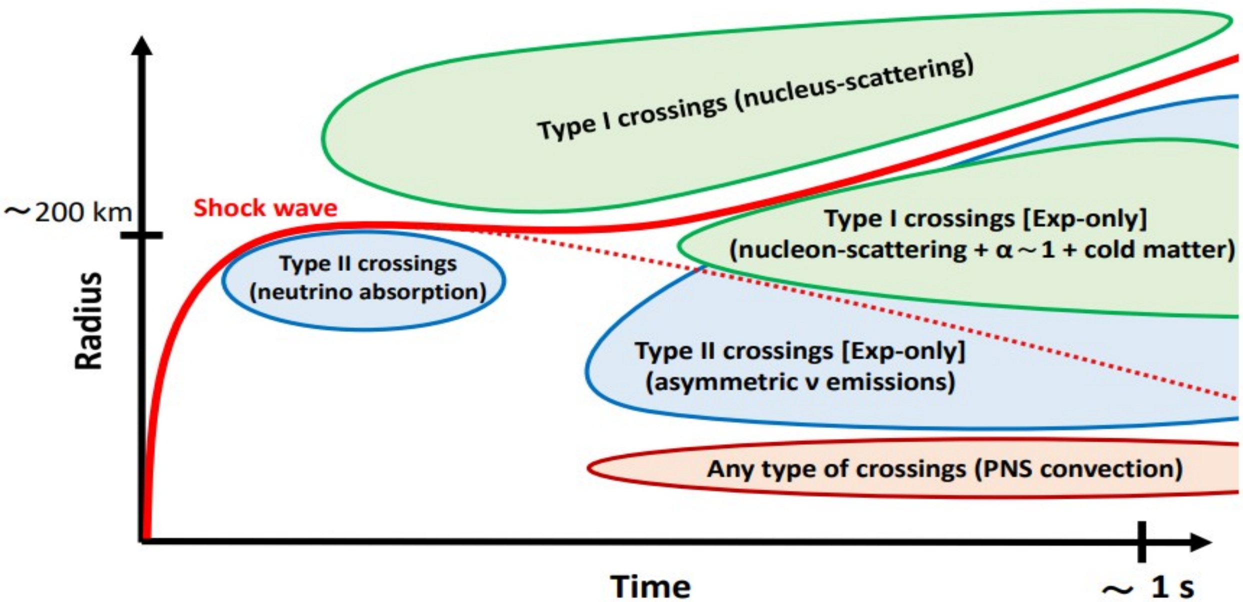


Recent studies revealed that a novel kind of "fast collective mode" can happen when there exist a "crossing" in the $e-\mu$ neutrino angular distribution

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

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

Space-time diagram of ELN-angular crossings in CCSNe



can exist in different regions and epochs of SN evolution, even inside the ν-sphere

$\to$ need to include this effect in SN simulations!

[Nagakura+ 2108.07281]

[See also Morigana+ 1909.13131, Nagakura+ 1910.04288, Johns+ 1910.05682, Delfan Azari+ 1910.06176, Glas+ 1912.00274, Abbar+ 2003.00969, Capozzi+ 2005.14204, Abbar+ 2012.06594, Capozzi+ 2012.08525, Johns+ 2104.04106, Nagakura+ 2106.02650, Harada+ 2110.08291,...]

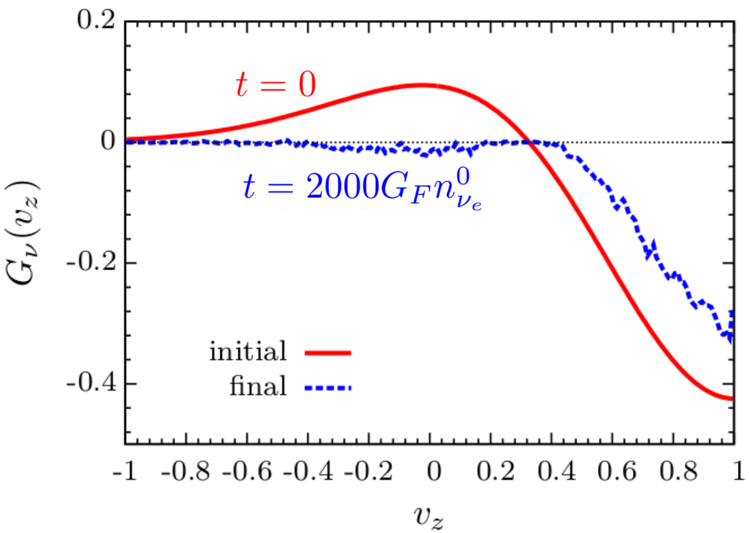
(code available at https://github.com/cosenu/cosenu)

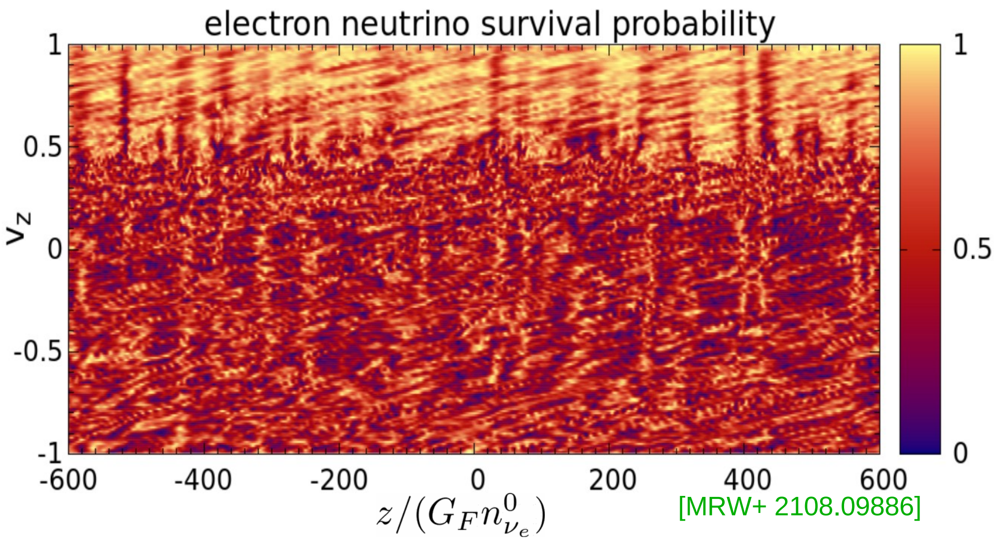
Fast neutrino oscillations

Several groups started to develop multidimensional simulation code to compute the outcome of fast oscillations in a perodic box

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

→ fast oscillations that tend to erase the ELN crossing [Bhattacharyya+, Richers+, MRW+]





[MRW+ 2108.09886]

These local simulations motivate the formulations of analytical approximation of final state of neutrino distribution, which may allow SN modelers to include this effect in their simulations [Bhattacharyya+2020, 2022, Zaizen 2022]

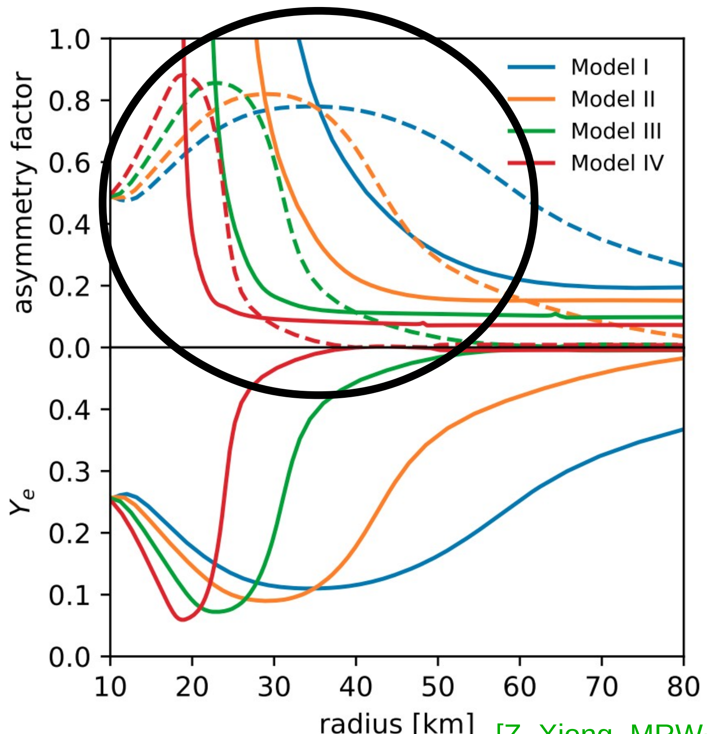
Even more...collision-induced collective oscillation mode

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

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

needs asymmetric $\bar{\nu}_e$ and ν_e collision rates

$$\mathcal{R} \equiv \frac{n_{\bar{\nu}_e} - n_{\bar{\nu}_x}}{n_{\nu_e} - n_{\nu_x}} \gtrsim \frac{\bar{\Gamma}}{\Gamma} \equiv \mathcal{R}_{\rm crit}$$



[Z. Xiong, MRW+ 2210.08254]

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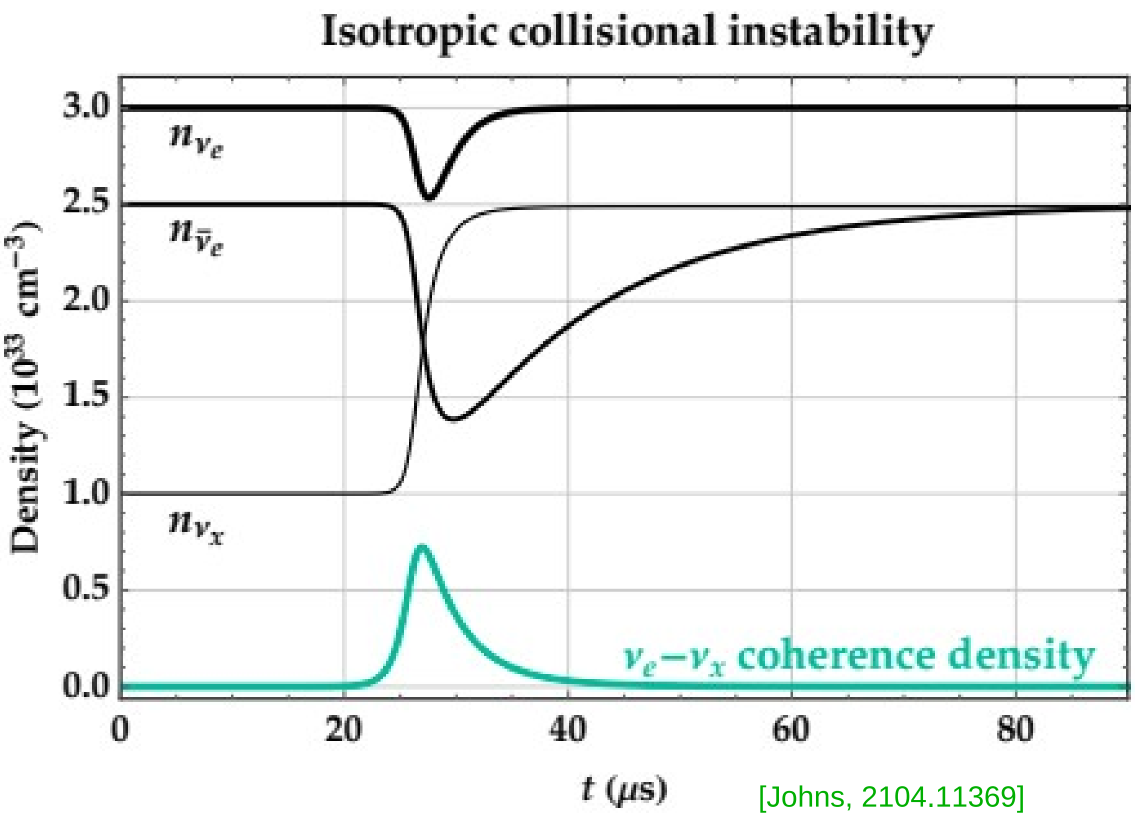
$\rightarrow$ can lead to large production of heavy-lepton flavor neutrinos



[Johns, 2104.11369]

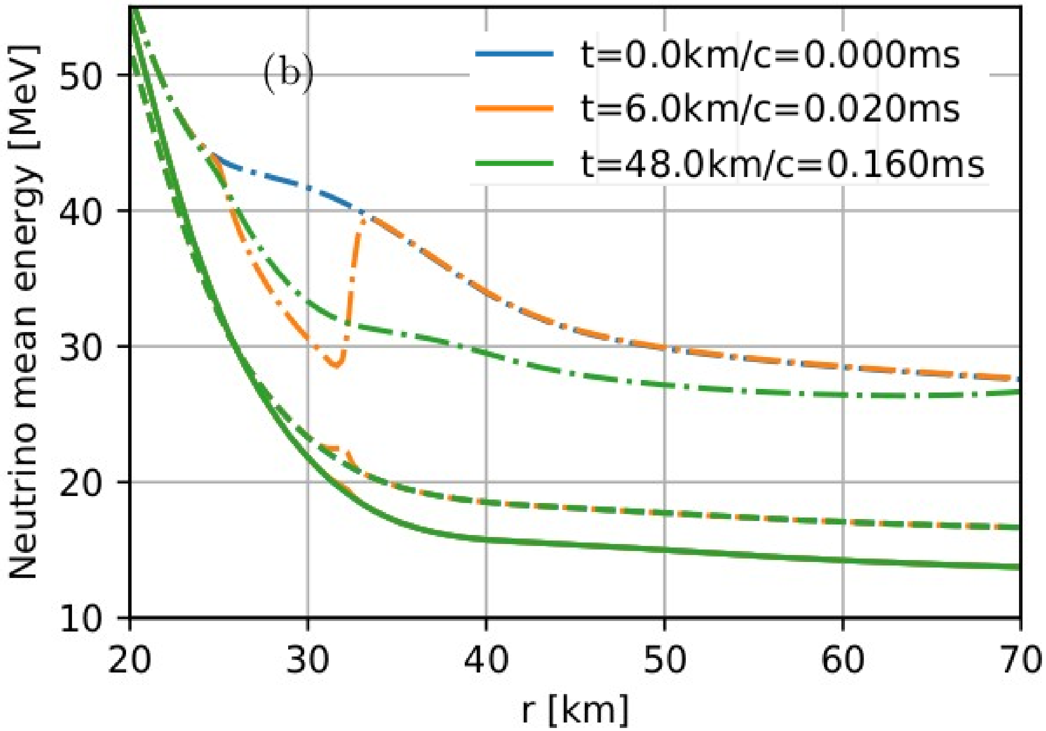
Global simulations of collision-induced oscillations

We recently solve the neutrino flavor evolution equation with collision terms over spherically symmetric background obtained by 1D SN simulation, where the fast modes are absent

[Z. Xiong, MRW+ 2210.08254]

– collisional instability exists generically around the neutrino sphere

– affects the local properties of neutrinos



$\rightarrow$ definitely needs to be implemented in SN simulations together with fast oscillations

Summary

- Core-collapse supernova is a rich laboratory for exploring physics within and beyond the Standard Model

- For light dark matter that interacts with the lepton sector of the Standard Model, they may be upscattered by supernova neutrinos. Competitive constraints on their cross sections are derived with SN1987a and projected for the next Galactic event.

- Collective neutrino flavor oscillations holds the key to understand the nature of supernova explosions and is perhaps the biggest uncertainty. New types of flavor conversion mechanisms (fast- and collisional-) were found in recent years. Active numerical and analytical studies are on-going to provide answers.