

Crossroads of Particle Physics and Core-Collapse Supernovae

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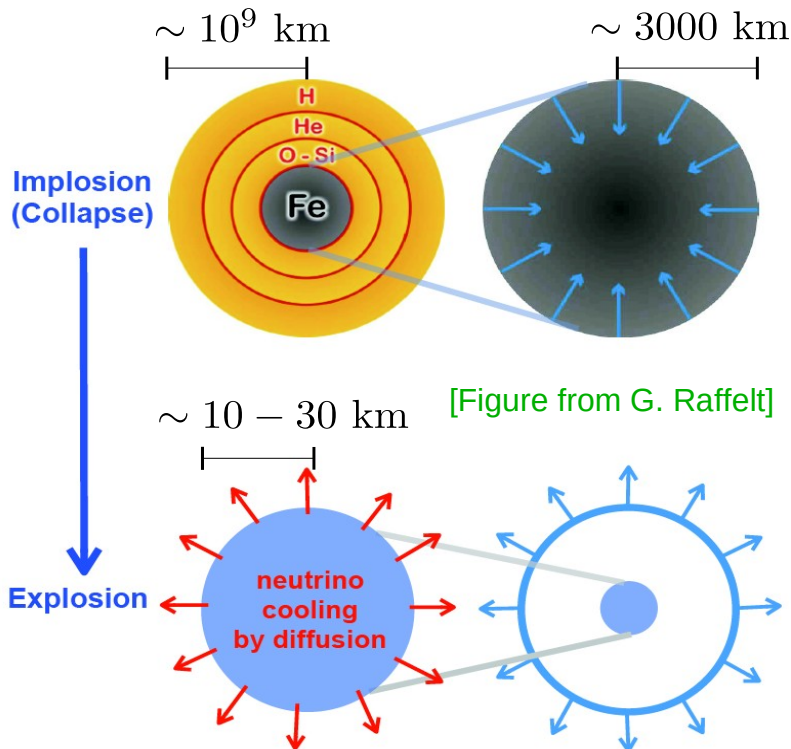


NSTC 國家科學及技術委員會
National Science and Technology Council



Core-collapse supernovae

- the death of massive stars $\gtrsim 8 M_{\odot}$
- important multimessenger source
 $(E_{\gamma} \sim 10^{49} \text{ erg}, E_{\text{expl}} \sim 10^{51} \text{ erg},$
 $E_{\nu} \sim 10^{53} \text{ erg}, E_{\text{GW}} \sim 10^{45-48} \text{ erg})$
- producing nature's elements after BBN



$E_{\text{grav}} \sim \frac{GM_{\text{PNS}}^2}{R_{\text{PNS}}} \sim 10^{53} \text{ erg}$, radiated predominantly by $\sim 10^{58}$ neutrinos in ~ 10 seconds

→ neutrinos dominate the dynamics and observables of a supernova

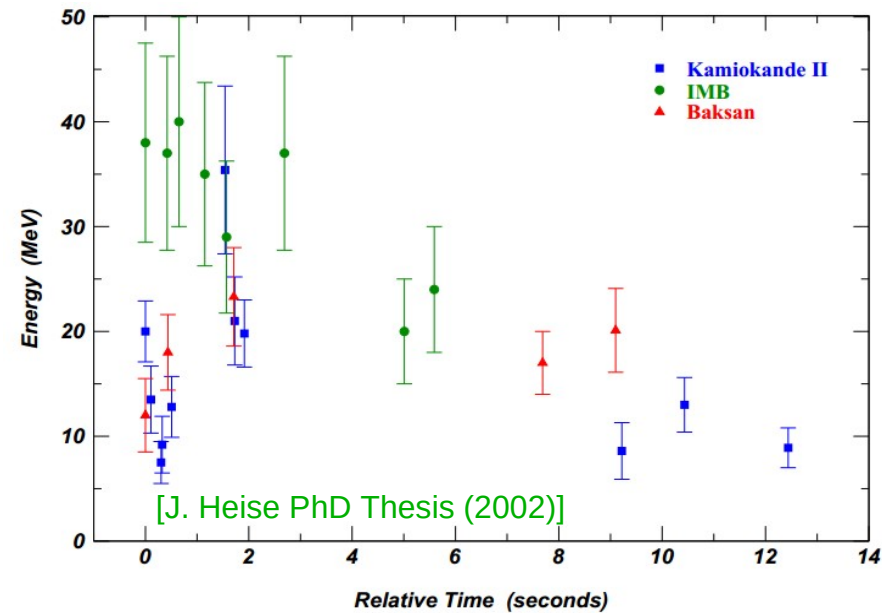
(see Takiwaki's talk)

Supernova neutrinos

~ 20 SN $\bar{\nu}_e$ detected from SN1987a
in ~ 10 seconds,

$$L_{\bar{\nu}_e} \sim 10^{52} \text{ erg}, \langle E_{\bar{\nu}_e} \rangle \sim 15 \text{ MeV}$$

- qualitatively confirms supernova theory
- offer leading constraints on non-standard ν interaction, light exotic particles (axions, sterile neutrinos,...), ν -DM interaction, ...etc



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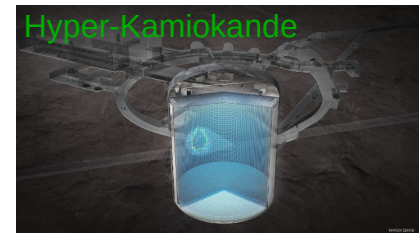
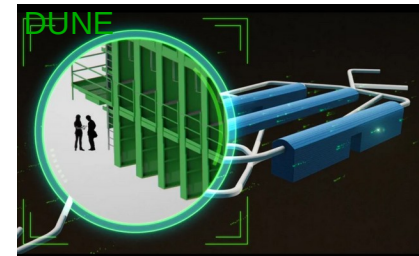
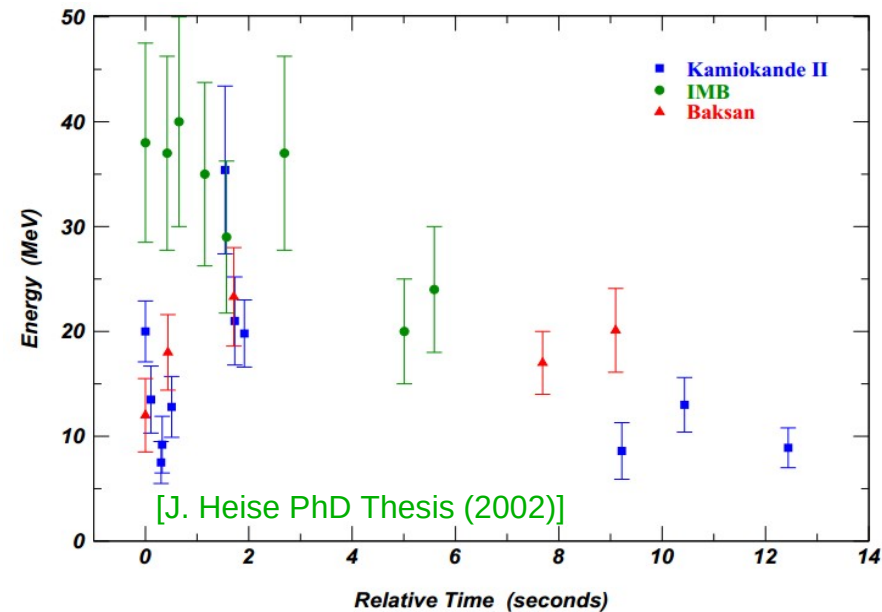
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When the next galactic supernova occurs (once-in-a-life-time!),
 $\mathcal{O}(10^5)$ events will probe or answer:

- explosion mechanism and interior properties of stellar progenitor
- properties of matter at nuclear densities
- neutrino mass, mass ordering, and interaction
- candidates beyond Standard Model (bSM)

→ requires robust theory modeling to achieve these goals



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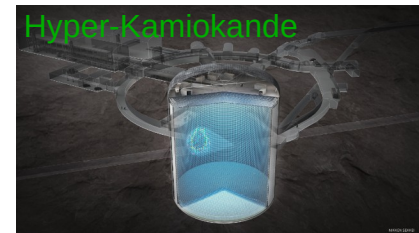
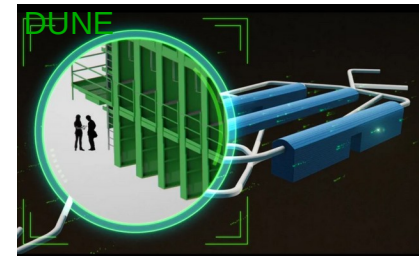
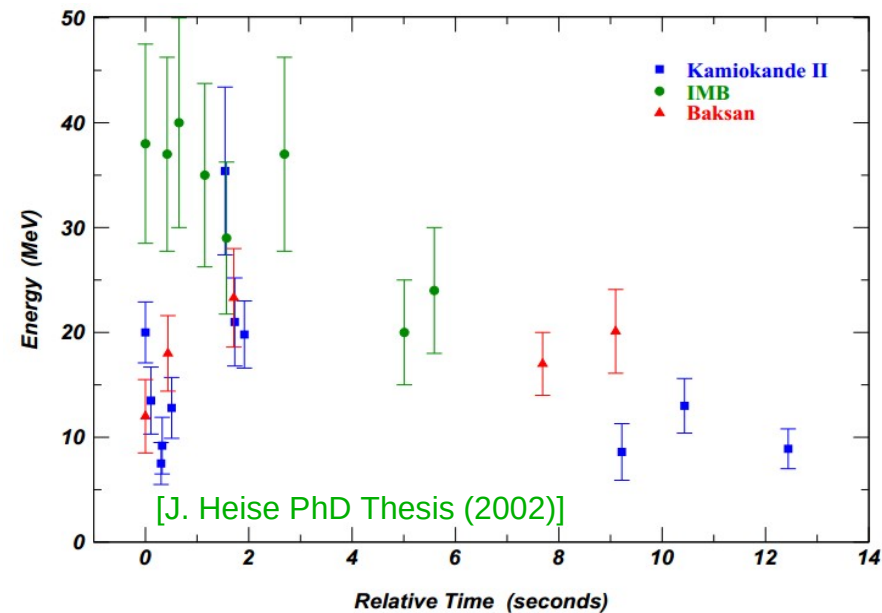
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(see Horiuchi's talk for DSNB)

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Core-collapse supernovae probing physics
beyond the Standard Model:

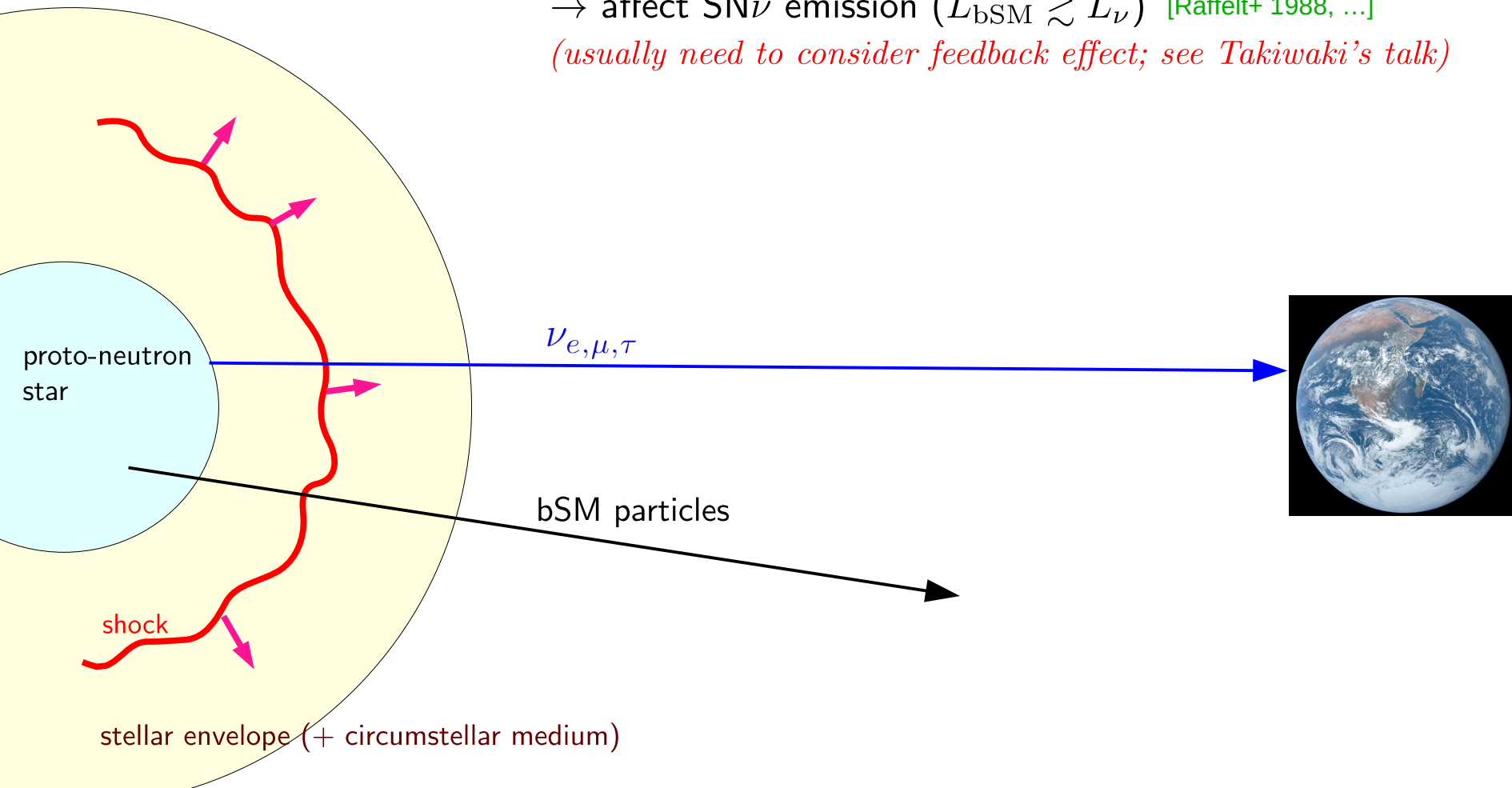
Exotic particle emission and their decay

Exotic particle emission from proto-neutron star

In proto-neutron star core: $T_c \sim 30$ MeV, $\rho_c \sim 5 \times 10^{14}$ g/cm³

→ produce beyond-Standard-Model (bSM) particles of mass $\lesssim \mathcal{O}(100)$ MeV

- (A) take away PNS thermal energy
→ affect SN ν emission ($L_{\text{bSM}} \gtrsim L_\nu$) [Raffelt+ 1988, ...]
(usually need to consider feedback effect; see Takiwaki's talk)



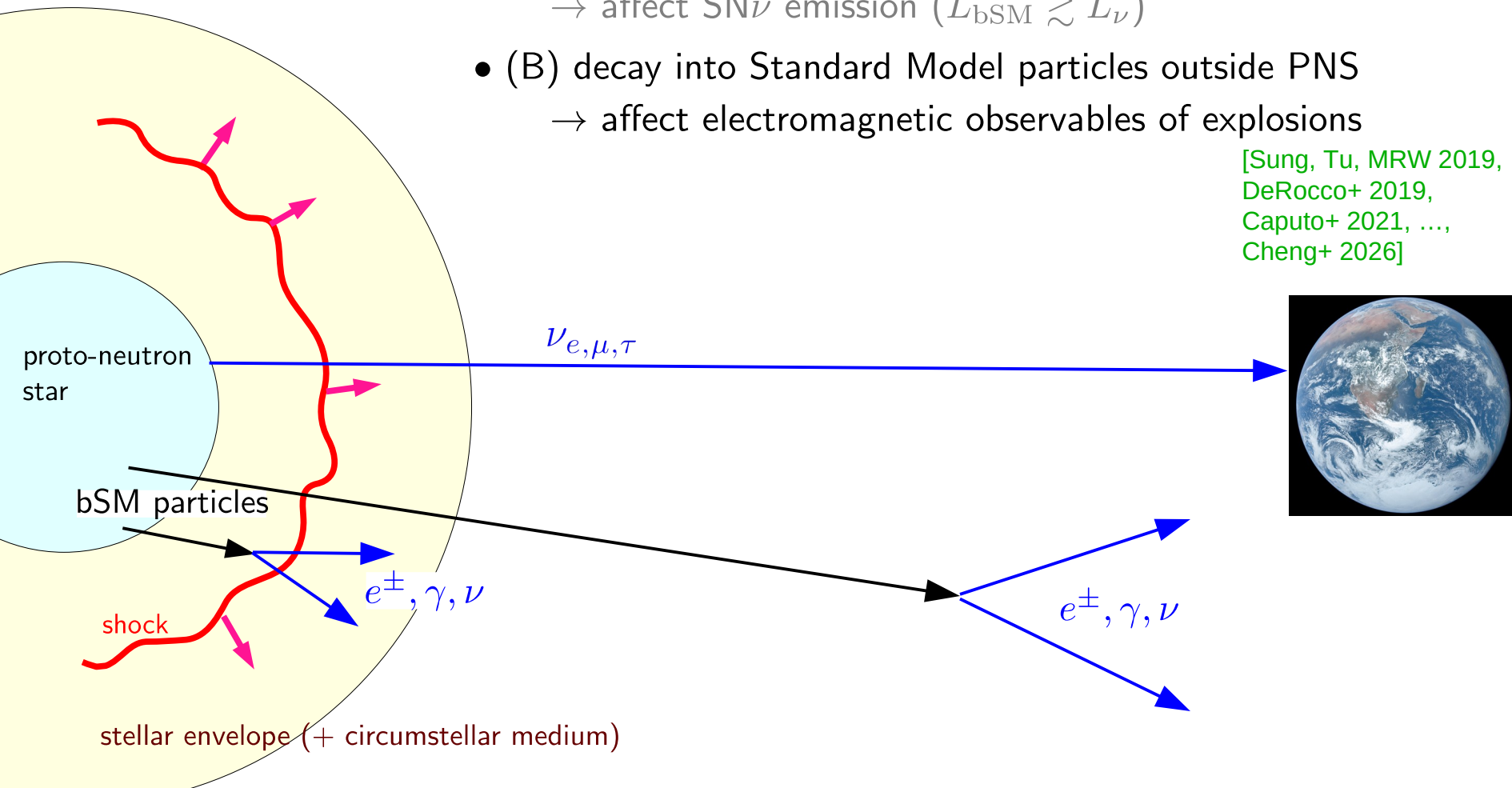
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→ affect electromagnetic observables of explosions

[Sung, Tu, MRW 2019,
DeRocco+ 2019,
Caputo+ 2021, ...,
Cheng+ 2026]



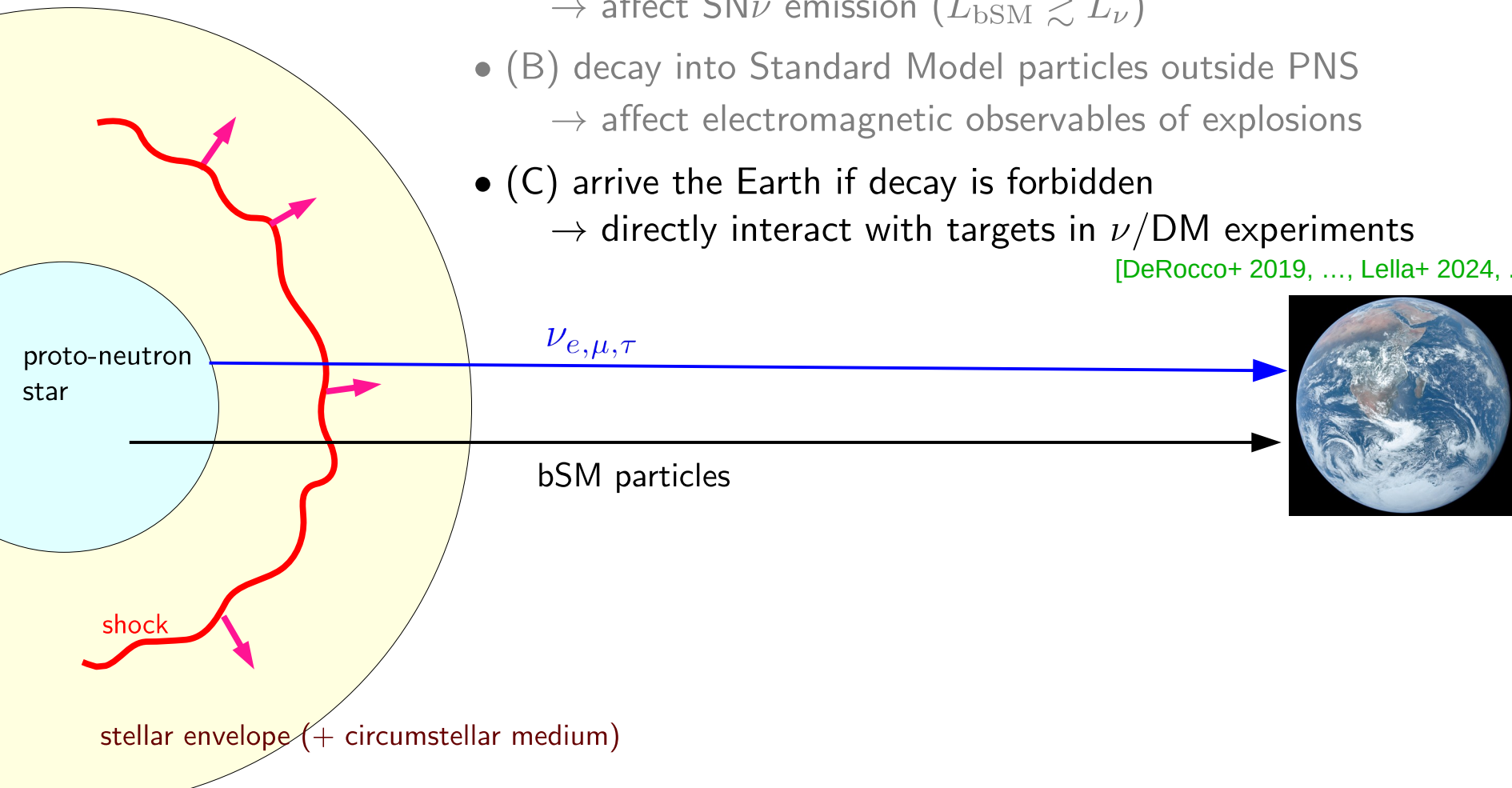
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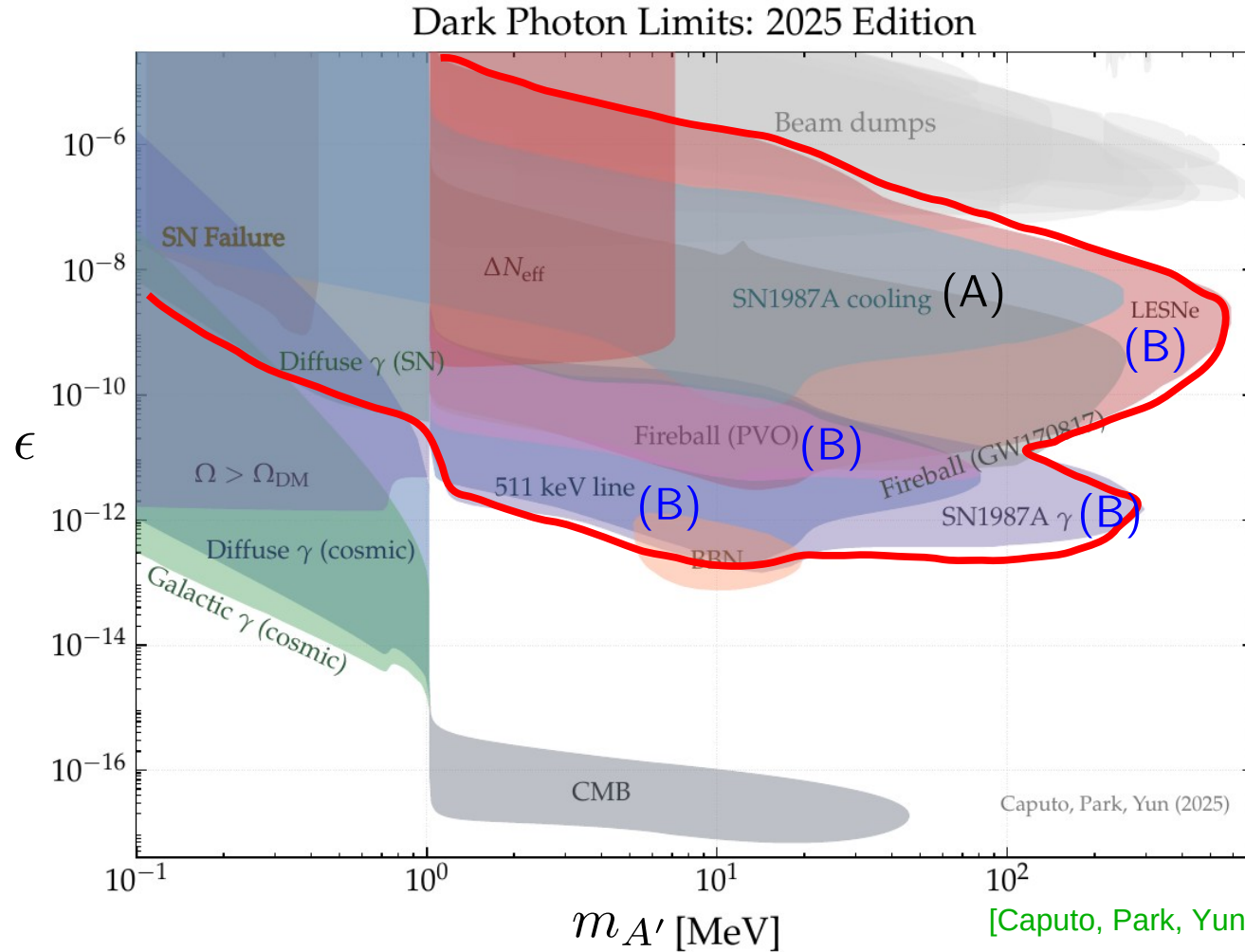
- (A) take away PNS thermal energy
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- (B) decay into Standard Model particles outside PNS
→ affect electromagnetic observables of explosions
- (C) arrive the Earth if decay is forbidden
→ directly interact with targets in ν /DM experiments

[DeRocco+ 2019, ..., Lella+ 2024, ...]



Taking dark photon (A' ; hypothetical $U(1)$ gauge boson that mixed with photon kinetically) as an example:

$$\mathcal{L} \supset -\frac{1}{4}F'_{\mu\nu}F'^{\mu\nu} - \frac{\epsilon}{2}F'_{\mu\nu}F^{\mu\nu} + \frac{1}{2}m_{A'}^2 A'_\mu A'^\mu$$

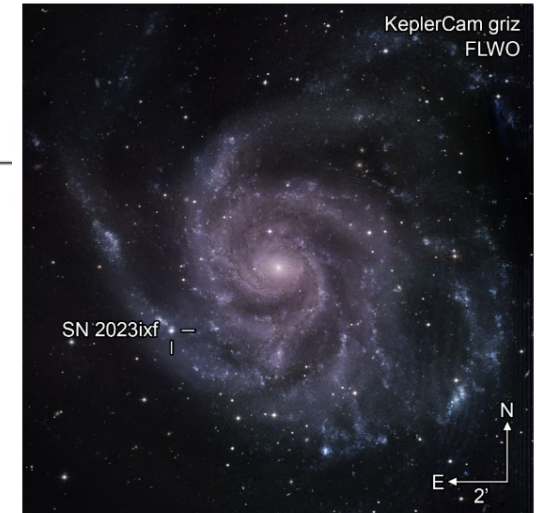
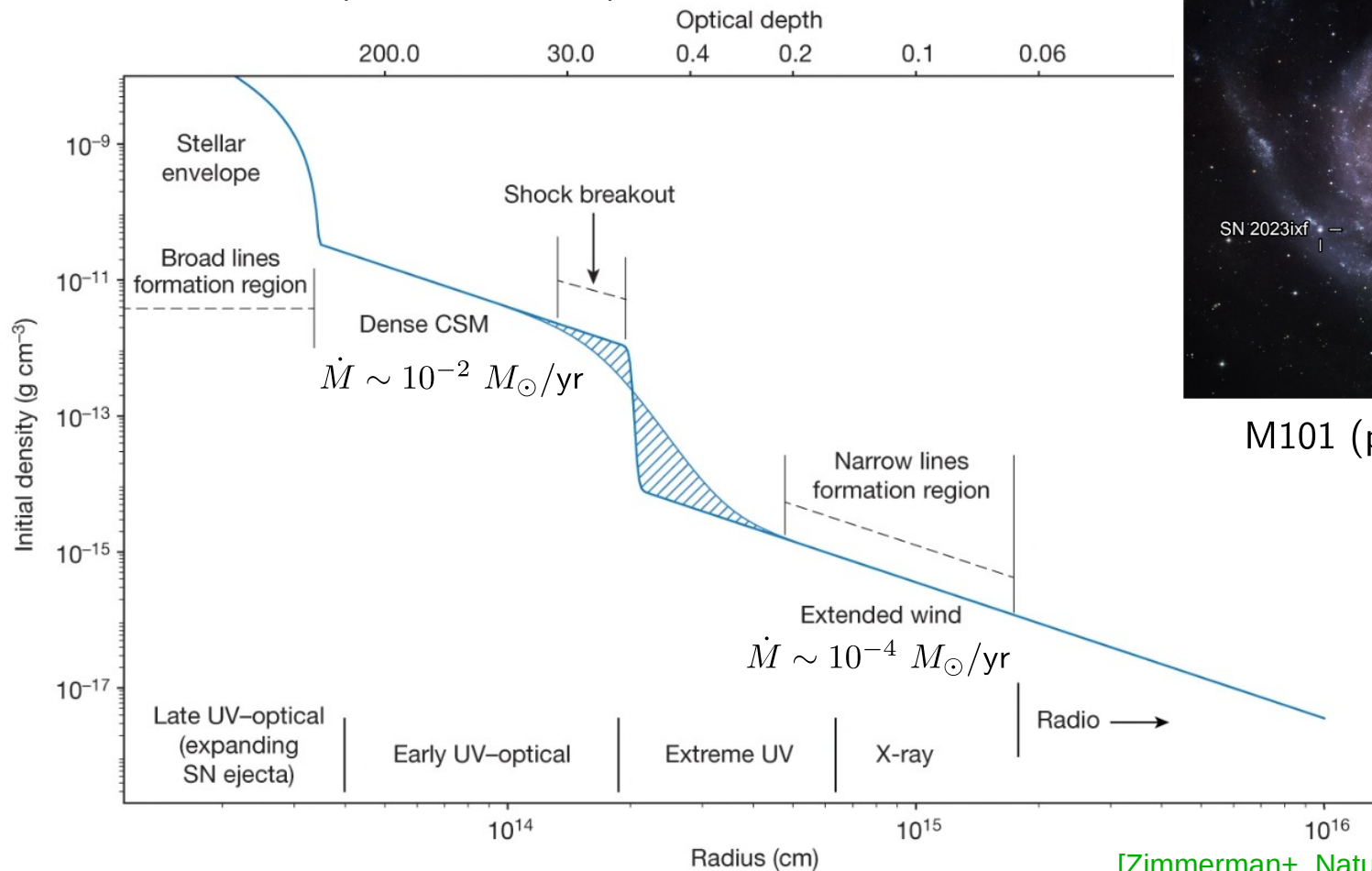


Supernovae are the leading “laboratories” for $1 \lesssim m_{A'} \lesssim \mathcal{O}(100)$ MeV

Supernovae with circumstellar medium (CSM) as new probes

Recent observations suggest $\gtrsim 30\%$ of SNe are surrounded by dense CSM

E.g., SN2023ixf (6.4 Mpc away)

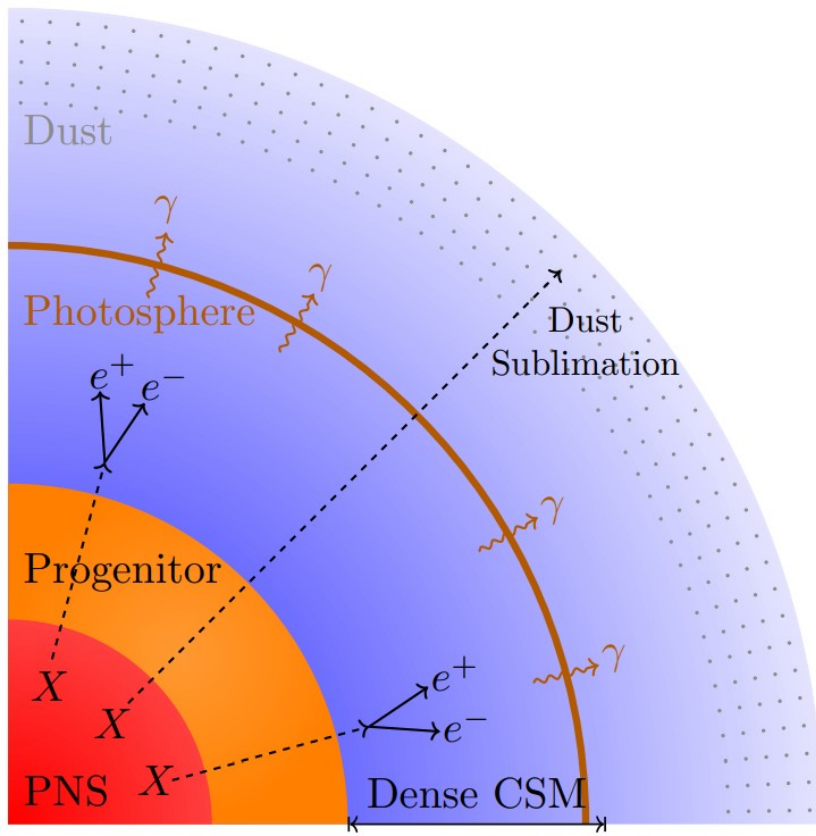


M101 (pinwheel galaxy)

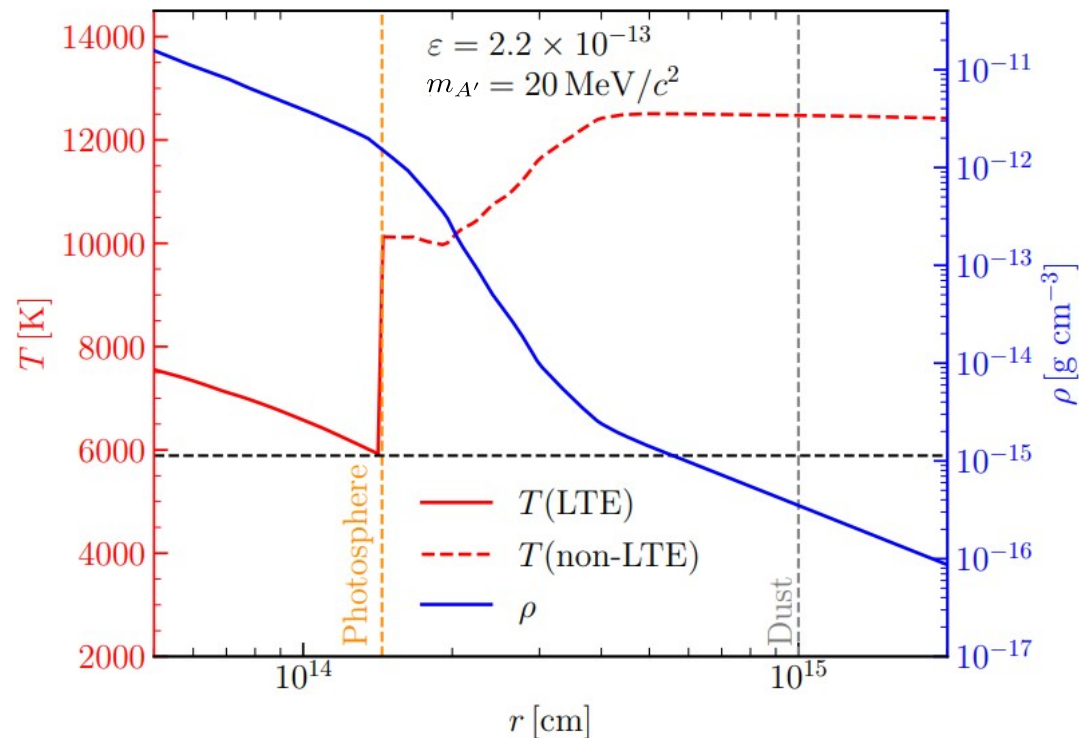
[Zimmerman+, Nature '24 (2310.10727)]

Supernovae with circumstellar medium (CSM) as new probes

bSM particles' visible decay products ($e^\pm$) in dense CSM lose energy efficiently:



[Cheng, Kong, Lin, MRW, Yun, PRL '26 (2603.09615)]



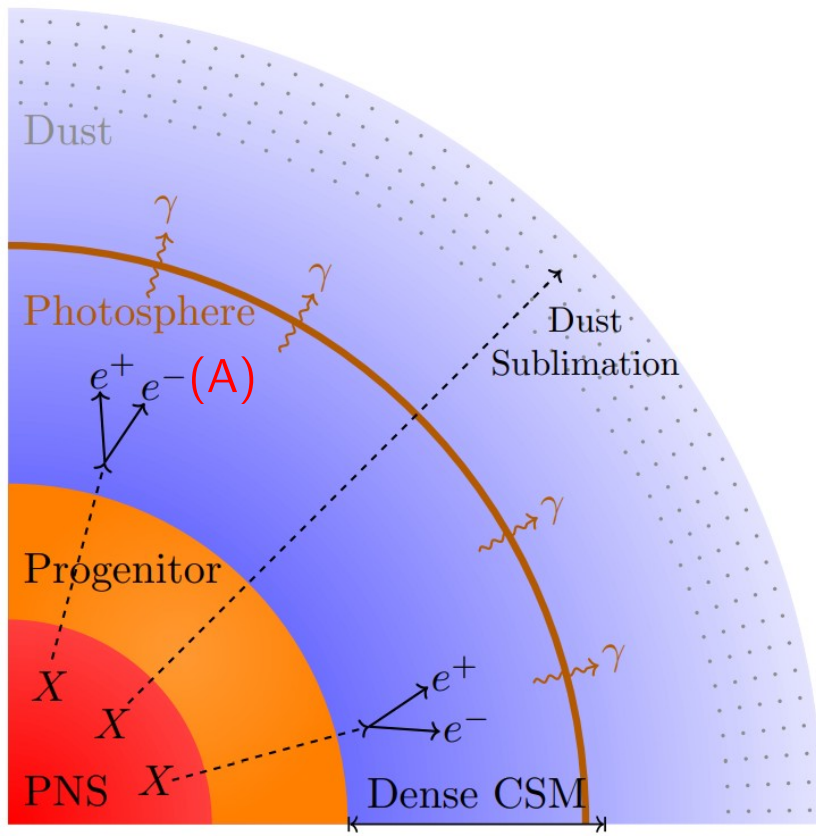
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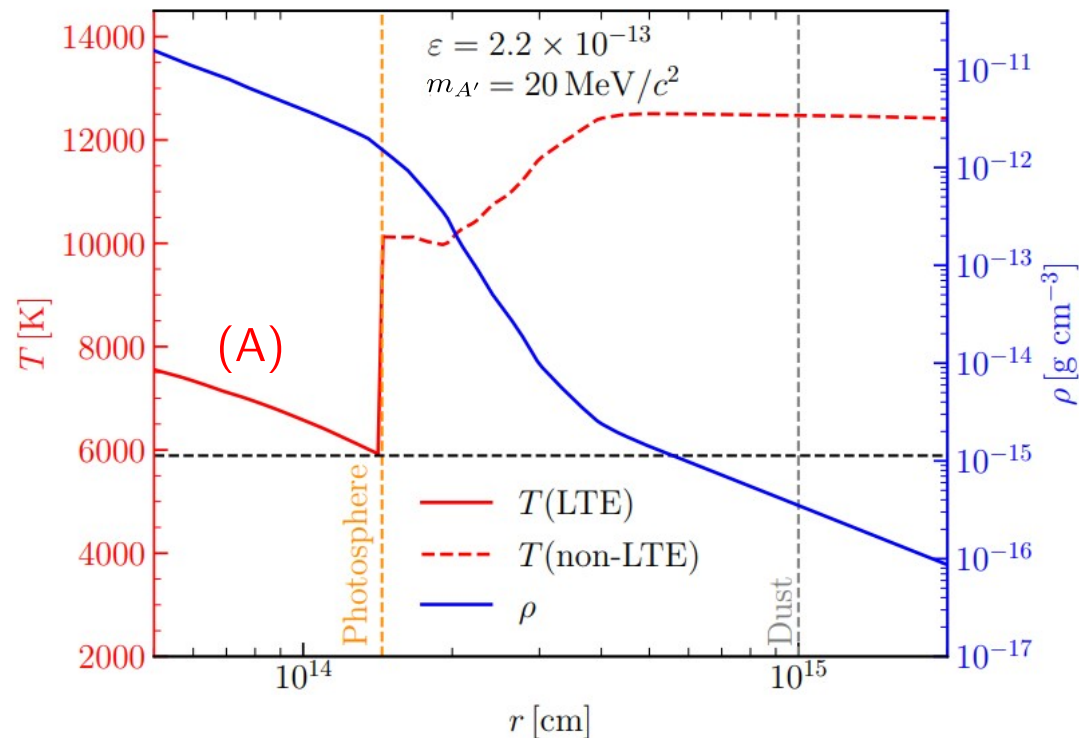
(A) heat up dense CSM

→ new photosphere with $T_{\text{ph}} \simeq 6000$ K at $r \sim 1.4 \times 10^{14}$ cm

→ enhanced luminosity $\gtrsim 10^{40}$ erg/s prior to shock break-out



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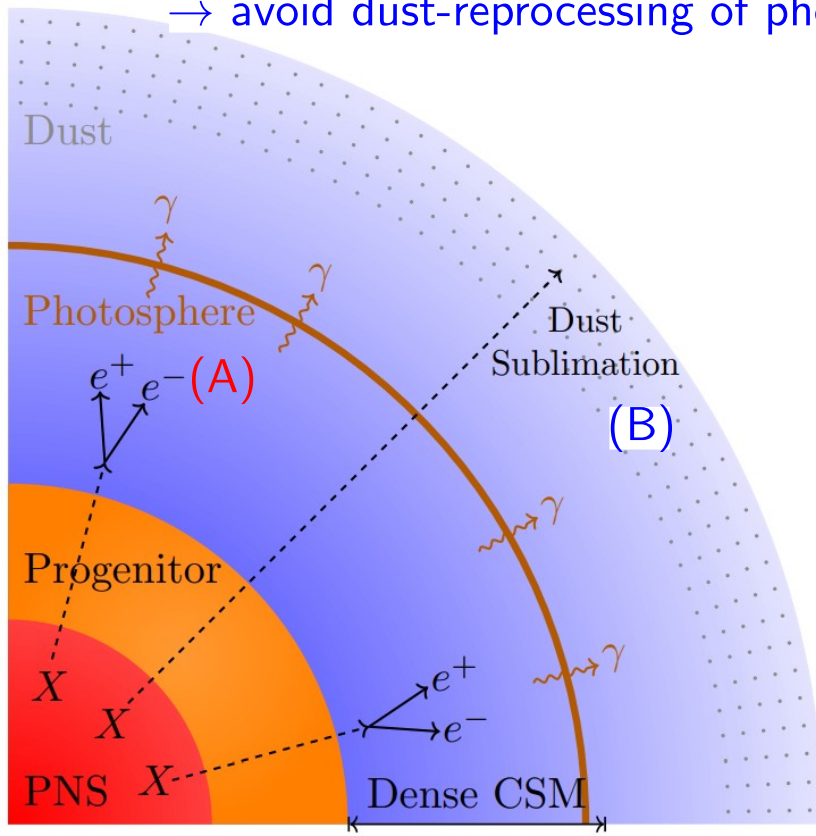
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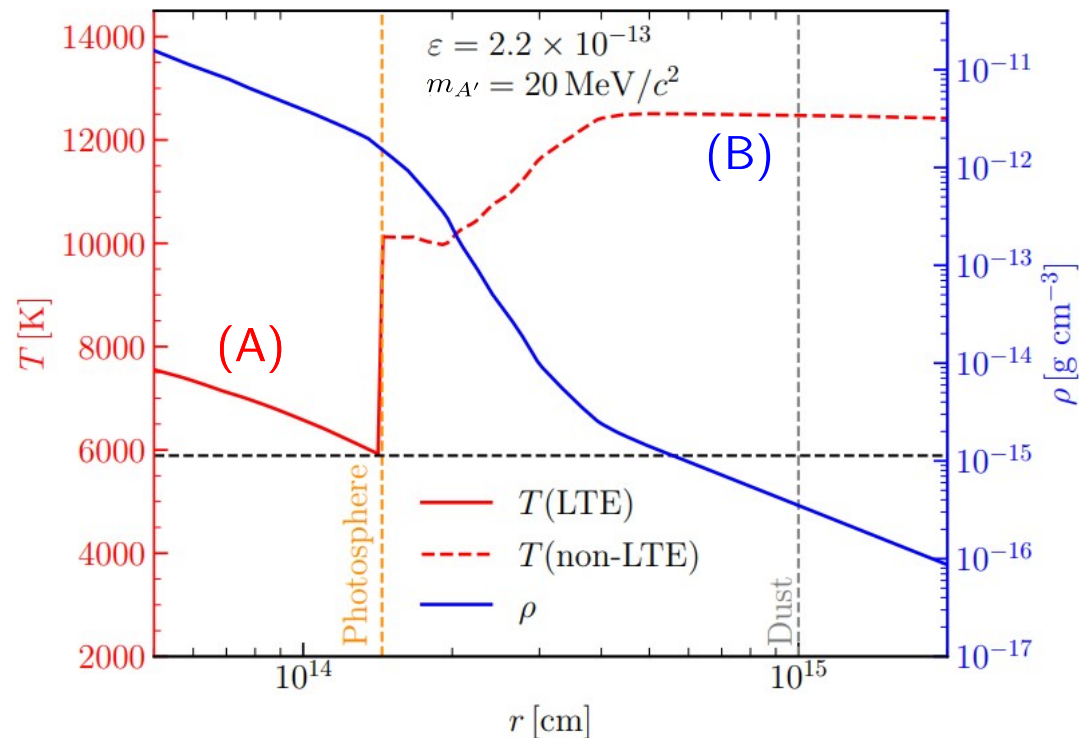
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(B) destroy CSM dust at $r \sim 10^{15}$ cm

→ avoid dust-reprocessing of photospheric emission



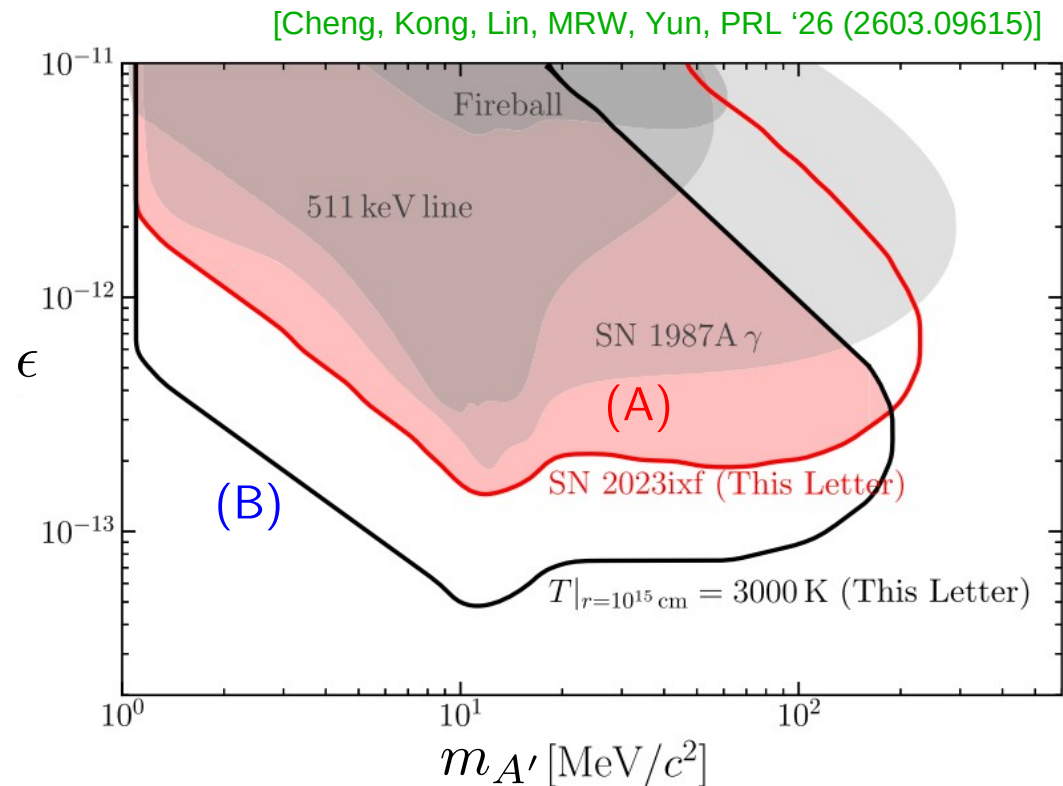
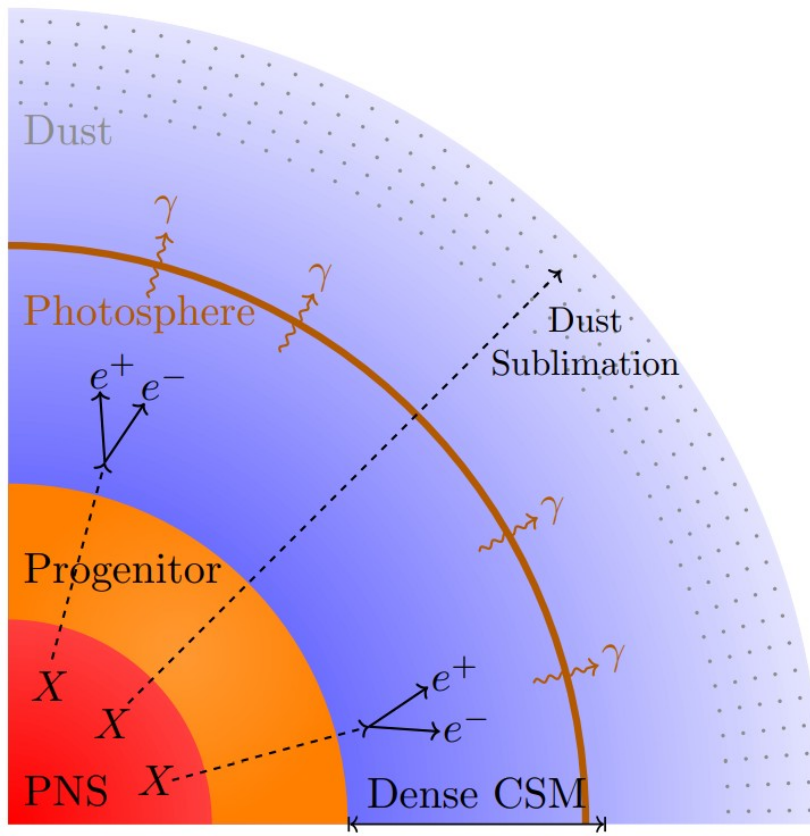
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bSM particles' visible decay products ($e^\pm$) in dense CSM lose energy efficiently:

(A) + (B) + observation upper limits: further extend SN bound on dark photon to lower ϵ

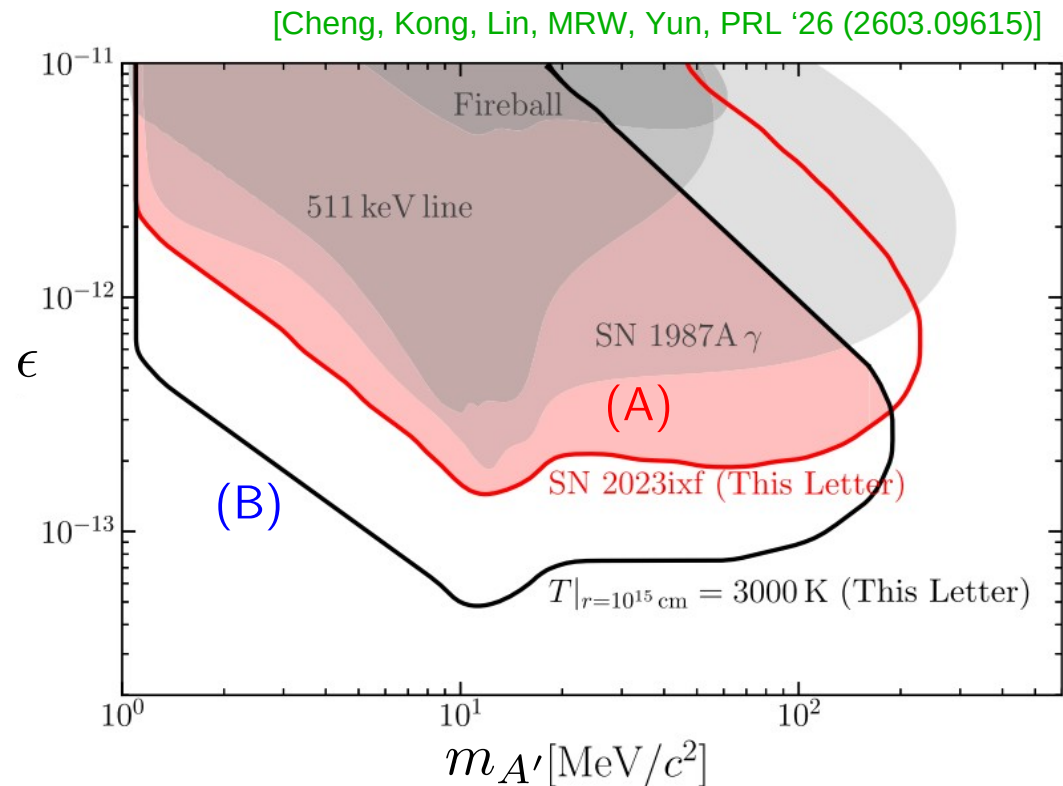
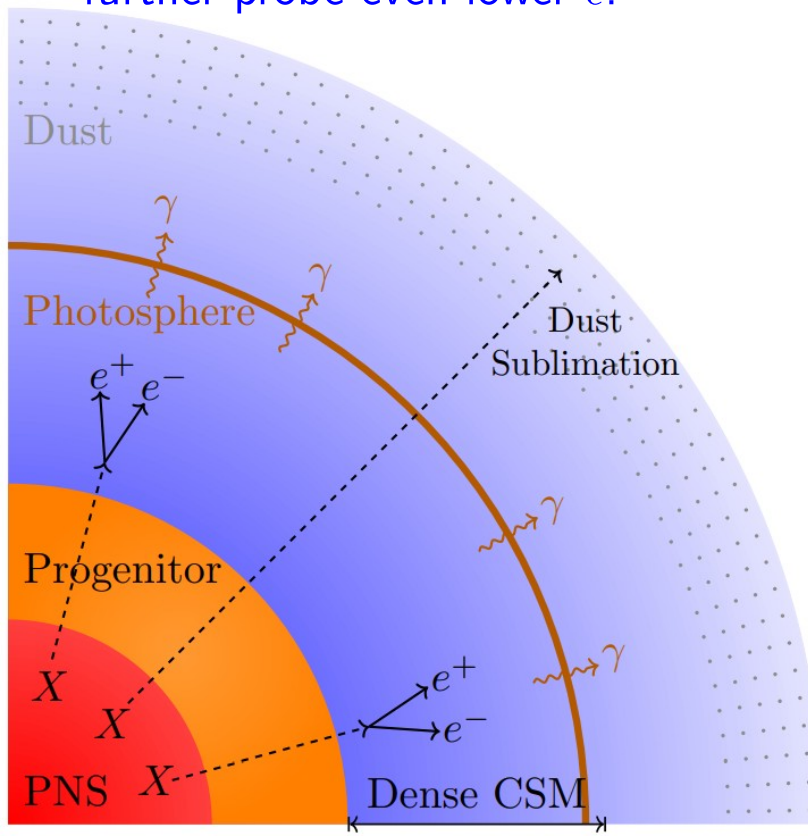


Supernovae with circumstellar medium (CSM) as new probes

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When next galactic SN goes off, dust sublimation that leads to rapid infrared to optical transition of progenitor emission prior to the shock break-out signature can further probe even lower ϵ !



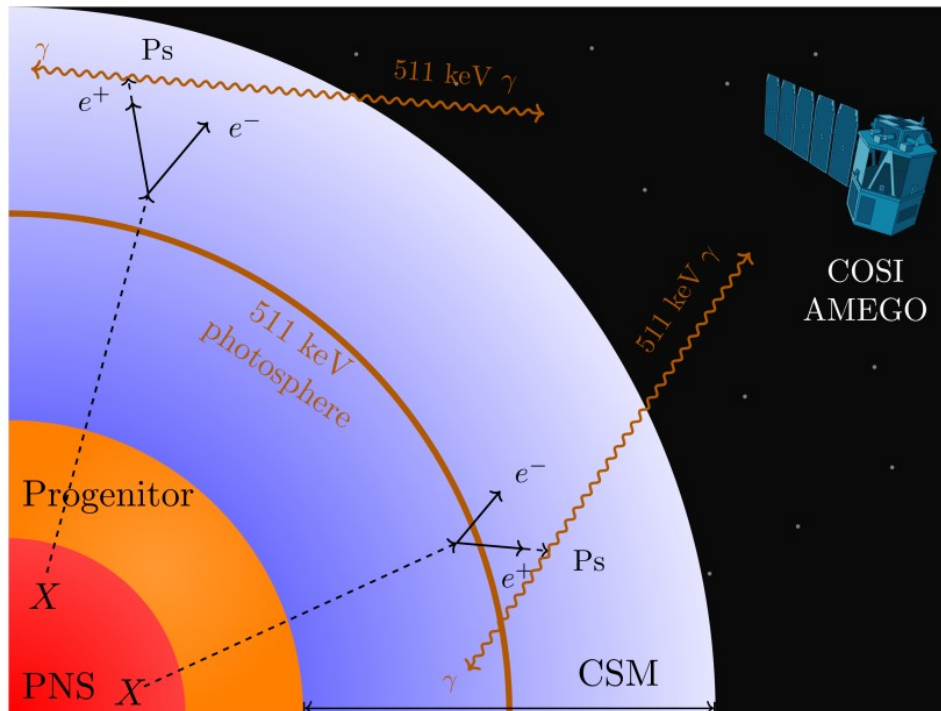
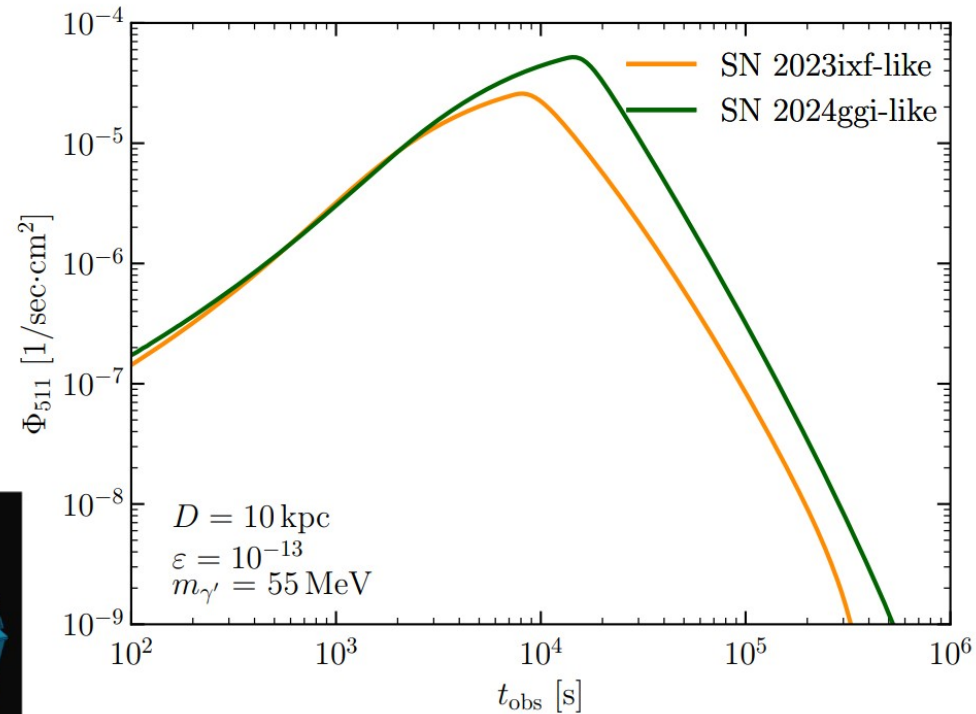
Supernovae with circumstellar medium (CSM) as new probes

[Cheng, Kong, Lin, MRW, Yun, 2609.18247]

Beyond heating, the stopped e^+ annihilate with electrons, producing 511 keV lines

→ peaks at 10^4 s,
line flux $\gtrsim \mathcal{O}(10^{-5}) \text{ cm}^{-2} \text{ s}^{-1}$

for a galactic SN at 10 kpc

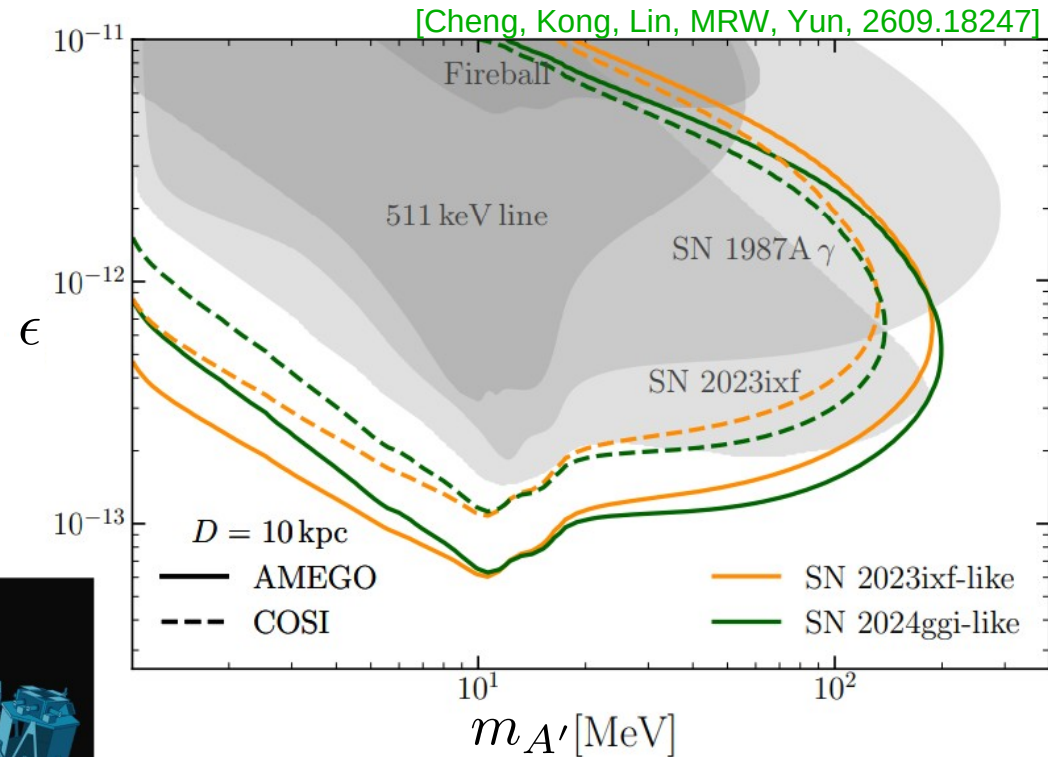
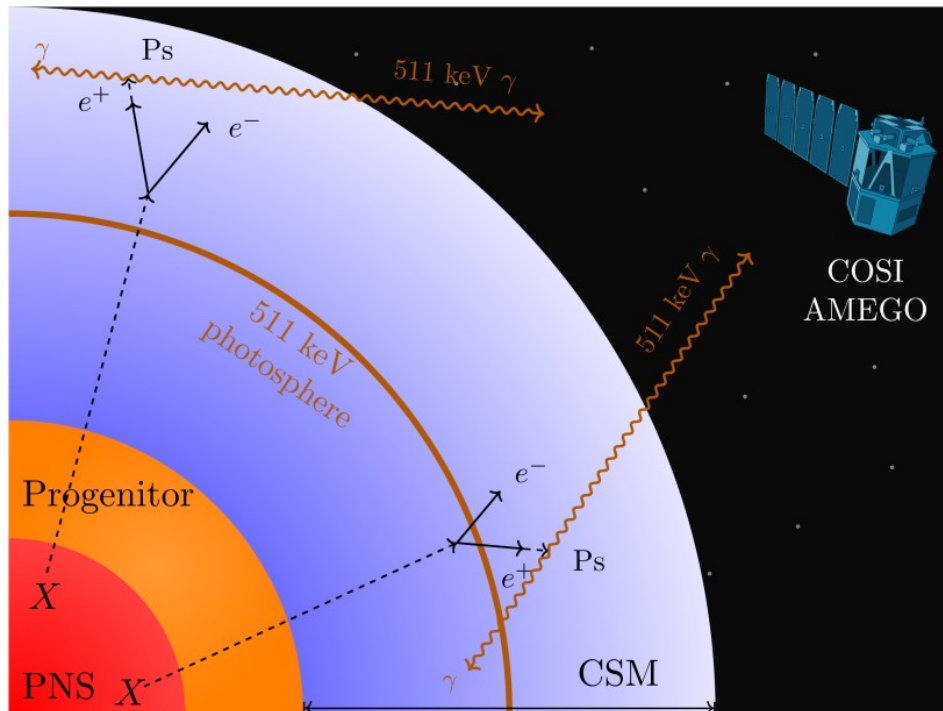


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probe the same parameter space
together with dust-sublimation
feature with the next galactic SN

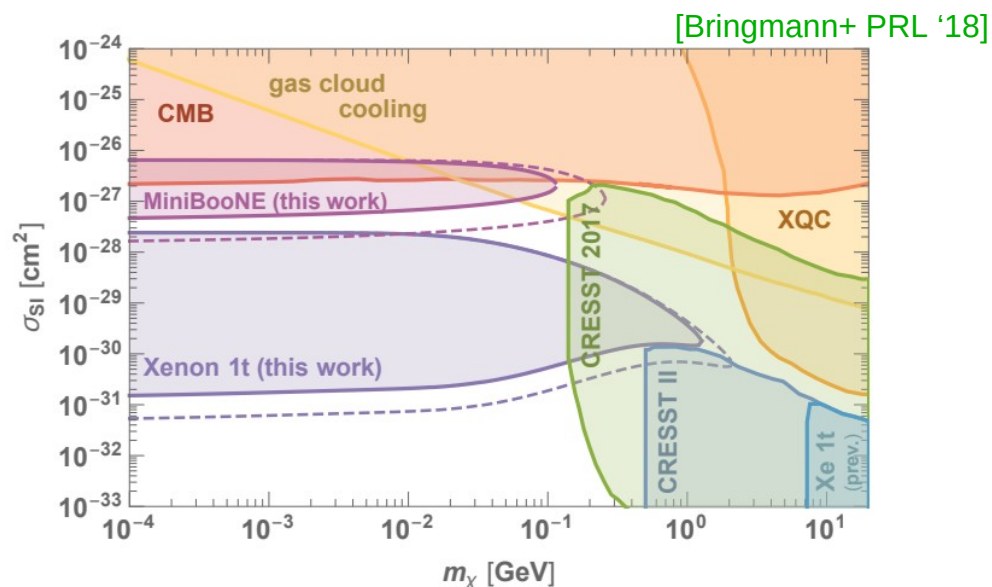
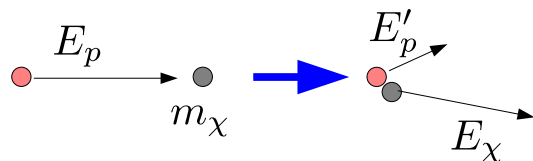
Core-collapse supernovae probing physics
beyond the Standard Model:

Neutrino – dark matter interaction

Dark matter searches – boosted component?

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

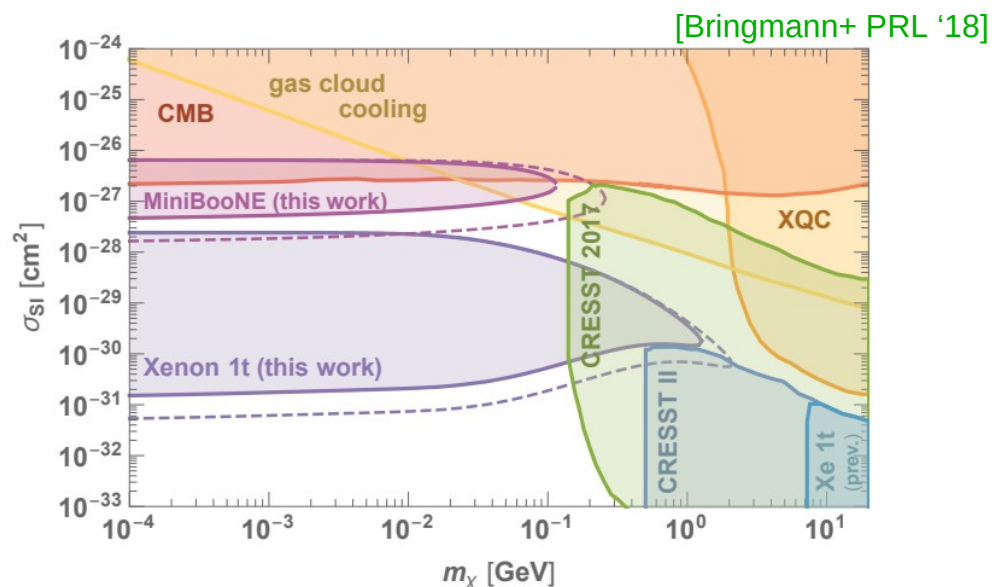
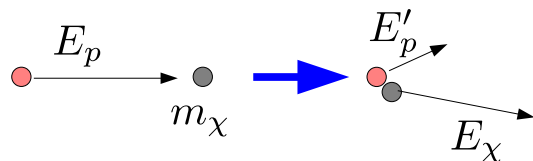
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[Zhang+, Jho+, Das+, Ghosh+, Lin+,...]

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

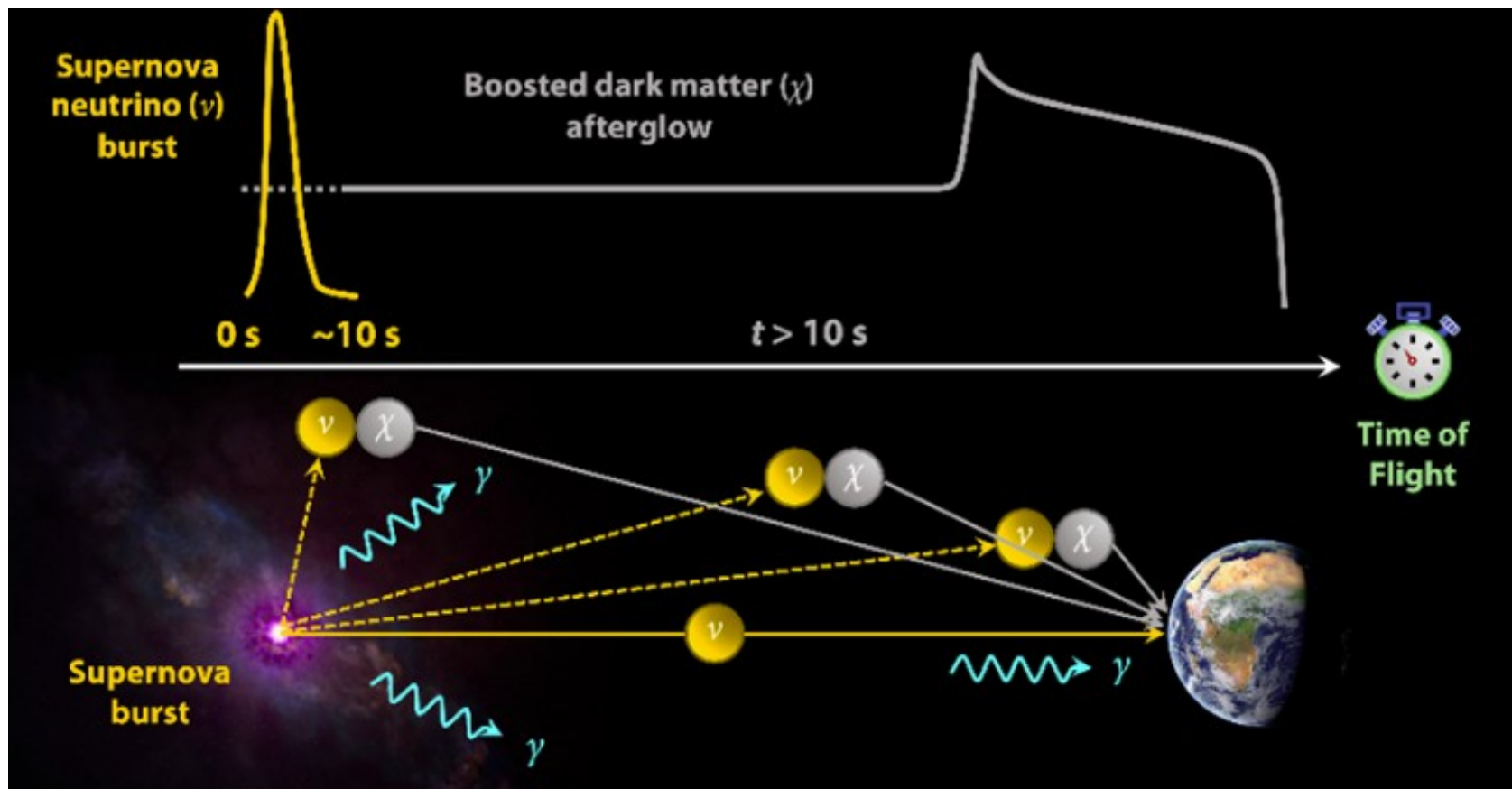
Light dark matter boosted by supernova neutrinos

For light DM ($m_\chi \sim 10$ keV), if it obtains an energy of ~ 10 MeV (kicked by $\text{SN}\nu$)

→ 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 $\text{SN}\nu$ → **afterglow events**

($t = 0$ is calibrated by $\text{SN}\nu$)

[Lin, Wu, MRW, Wong, PRL '23 (2206.06864)]



Light dark matter boosted by supernova neutrinos

[Lin, Wu, MRW, Wong, PRL '23 (2206.06864)]

Two major features:

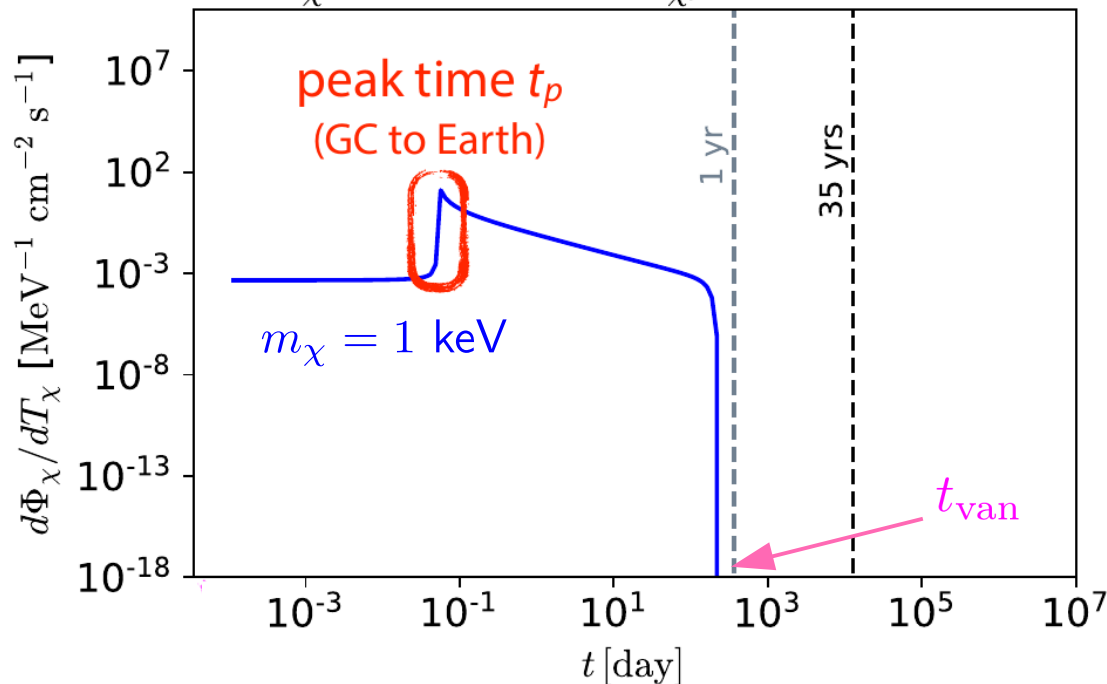
- sharp rise at $t_p = \frac{R_s}{v_\chi} - t_\nu$
 $\approx \frac{m_\chi^2}{2T_\chi^2} \frac{R_s}{c}$

→ arrival time of BDM
from SN location to Earth

- cut-off at $t_{\text{van}} \approx \frac{m_\chi}{4T_\chi} \frac{R_s}{c}$
 → longest arrival time
for BDM

for a SN exploded in the MW center

$$T_\chi = 10 \text{ MeV and } \sigma_{\chi\nu} = 10^{-35} \text{ cm}^2$$



(see Lin+, PRD '23 (2307.03522) for
SN location or model dependency)

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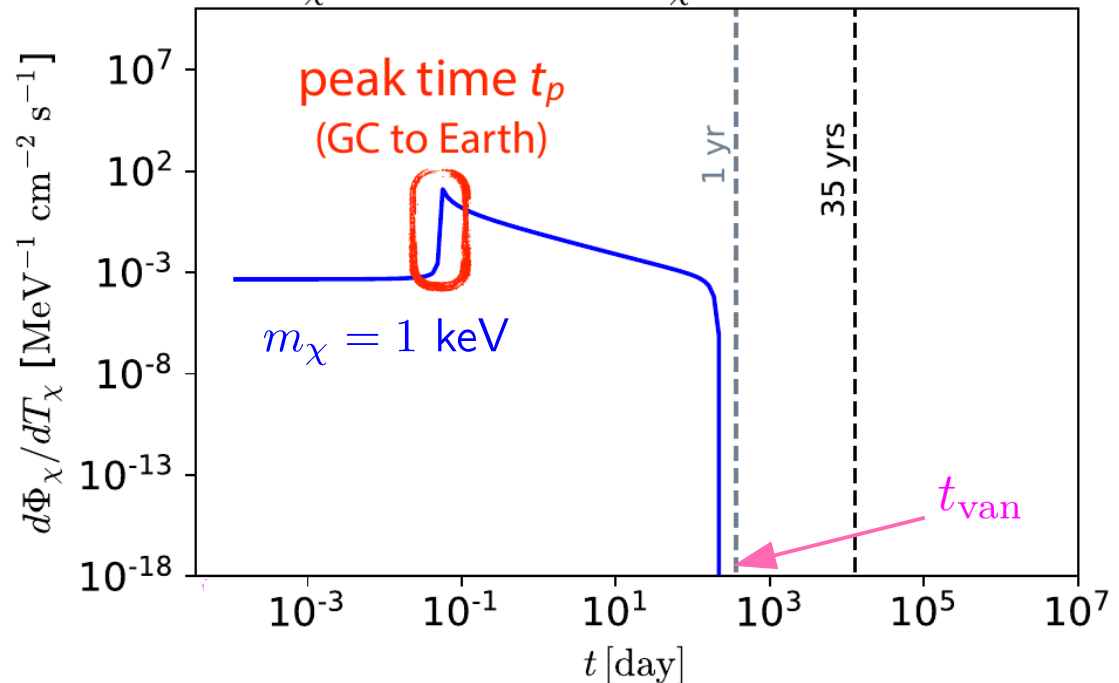
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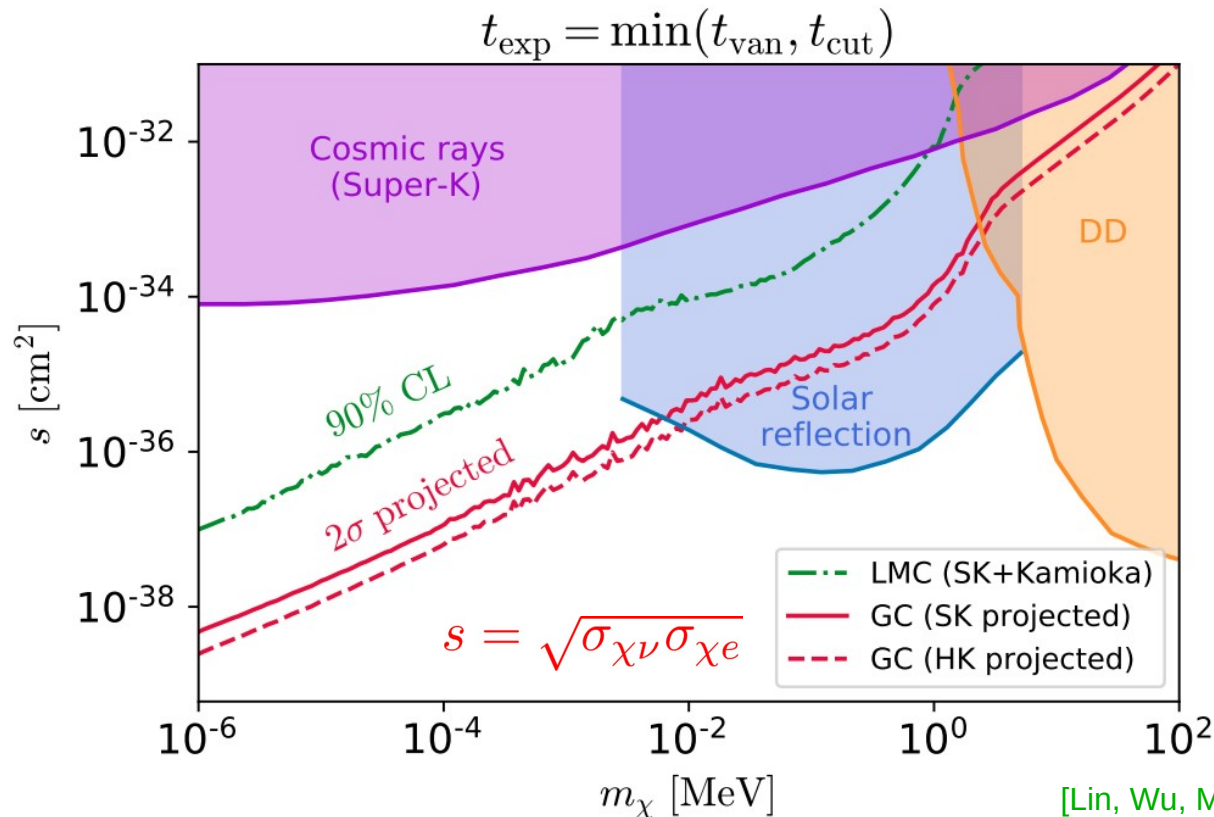


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→ with also non-zero χ - e interaction, it allows neutrino or DM experiments to measure m_χ if these time-dependent features are detected, or place constraint on $\sigma_{\chi\nu}\sigma_{\chi e}$ with nearby SN explosions (e.g., SN1987a)

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



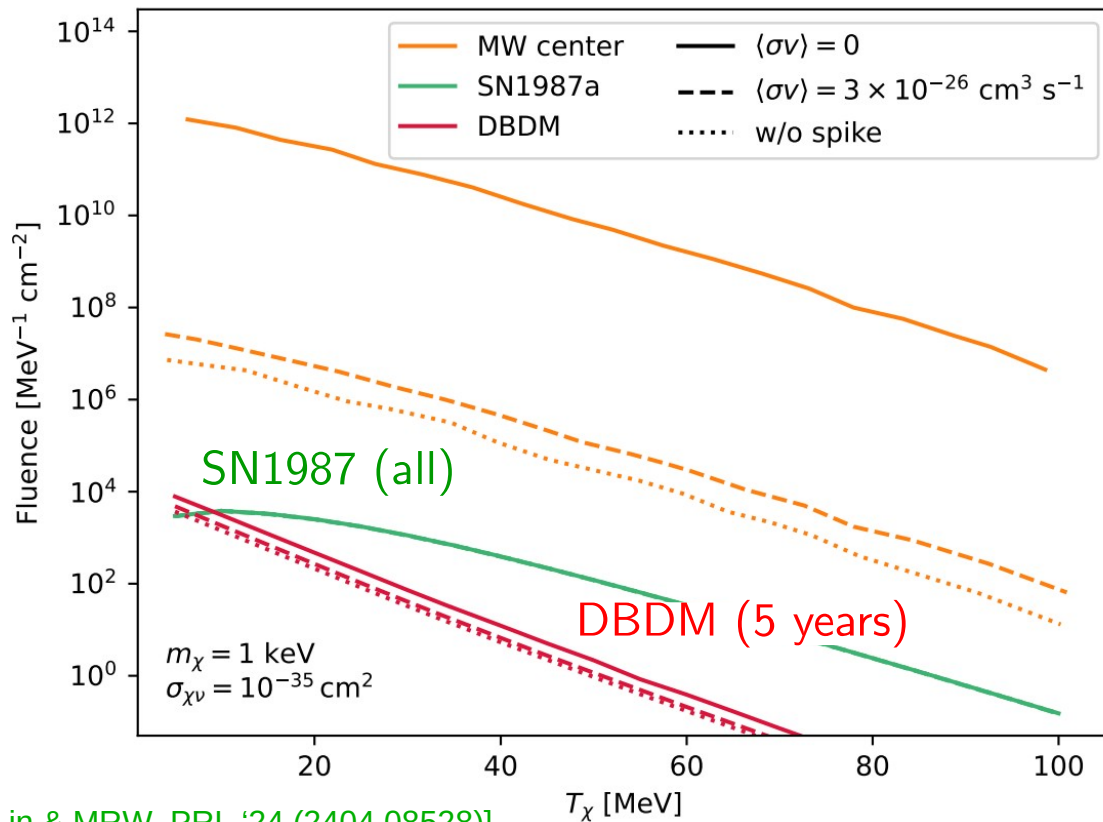
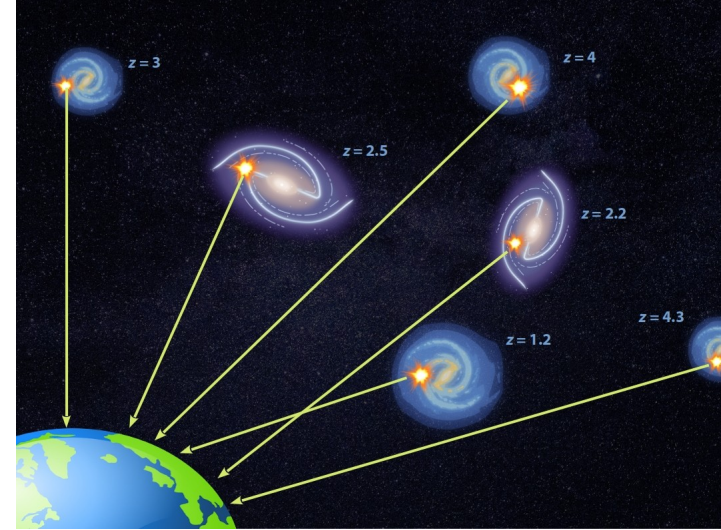
[Lin, Wu, MRW, Wong, PRL '23 (2206.06864)]

**provide complementary constraint to models that couple the dark sector to SM leptons [Lin+, PRD '23 (2307.03522)]

Diffuse component of $\text{SN}\nu$ boosted DM

Beyond single SN, one can also consider $\text{SN}\nu$ boosted DM from all galaxies at different redshifts that arrive at Earth (similar to DSNB!)

→ a persistent diffuse boosted DM flux (DBDM)

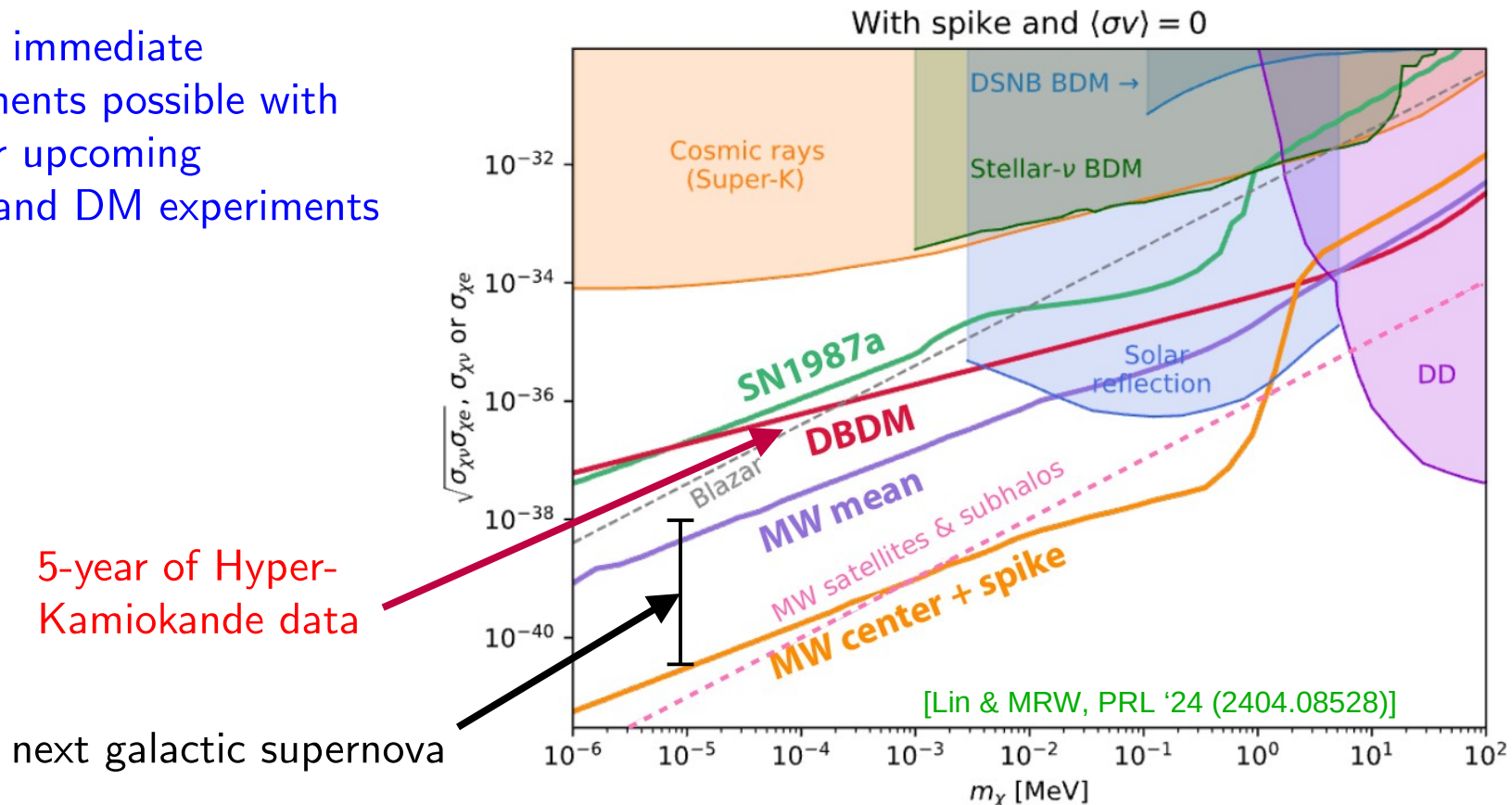
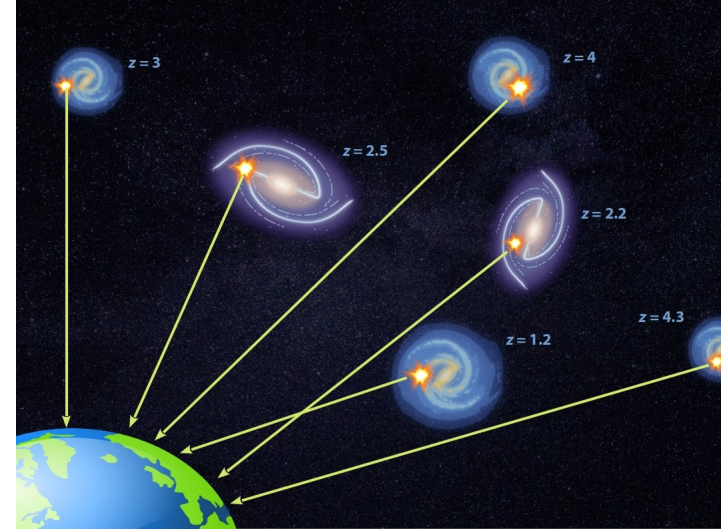


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→ makes immediate measurements possible with current or upcoming neutrino and DM experiments

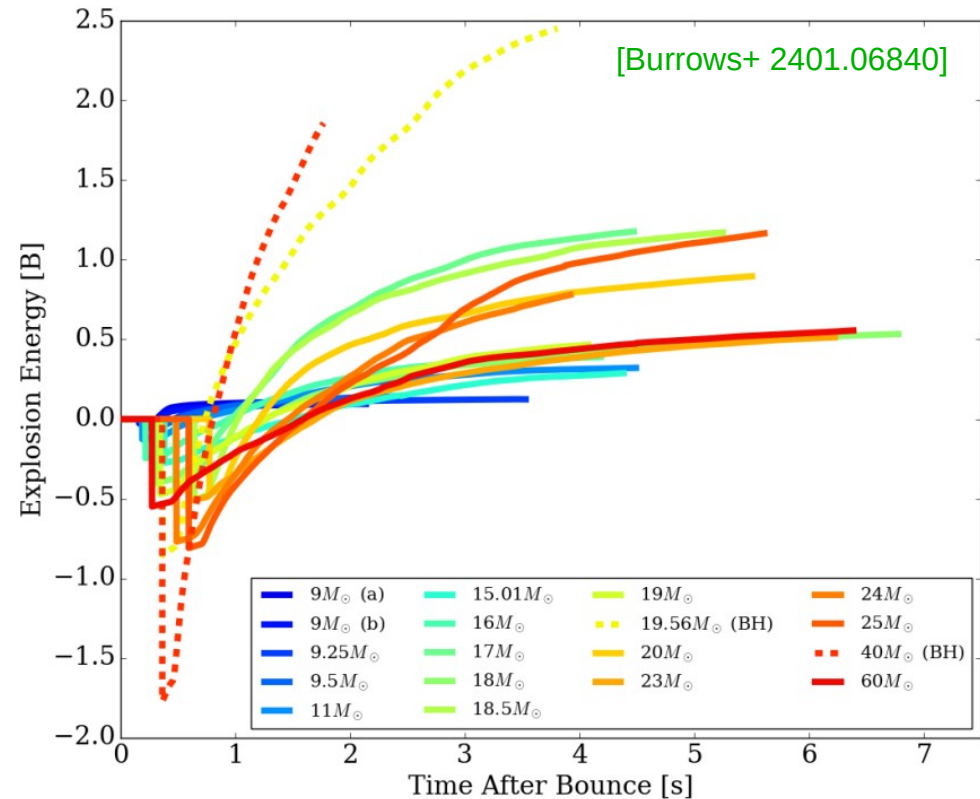
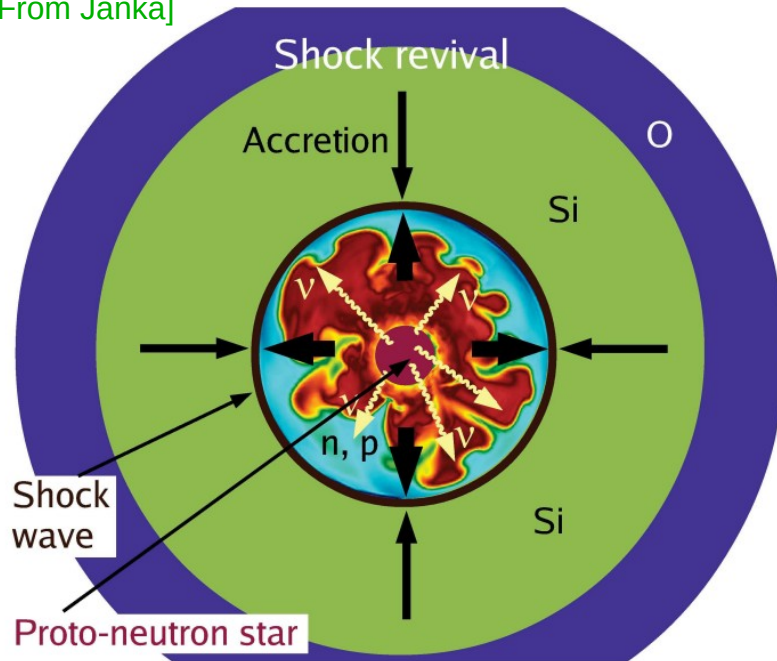


Collective Neutrino flavor oscillations in supernovae

Neutrino and supernova explosion mechanism

Simulating core-collapse supernovae is a daunting task – involving all four fundamental forces, fluid dynamics, and **non-equilibrium neutrino radiation transport**

[From Janka]



Neutrino energy deposition by $\nu_e + n \rightarrow p + e^-$ and $\bar{\nu}_e + p \rightarrow n + e^+$ holds the key to turn implosion to explosion

During the accretion phase, $\langle E_{\nu_\mu, \nu_\tau} \rangle > \langle E_{\nu_e, \bar{\nu}_e} \rangle \rightarrow$ **neutrino flavor oscillations?**

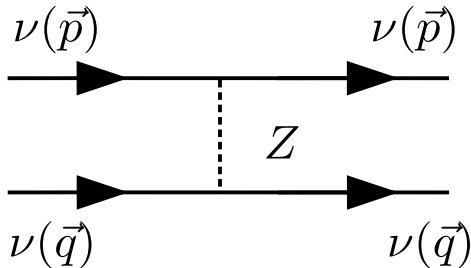
how? when? where? and impact?

Collective neutrino flavor oscillations

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

It requires solving **neutrino quantum kinetic transport equation (ν QKE)**:

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



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

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

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

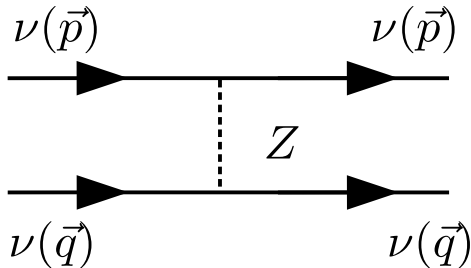
[Fuller+1987, Pantaleone 1992, Sigl & Raffelt 1992]

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

When $G_F n_\nu \gg \frac{\delta m_{ji}^2}{2E_\nu}$ in supernova interior

→ flavor evolution of neutrinos with different momenta **strongly coupled in a non-linear way**

→ **collective oscillations**

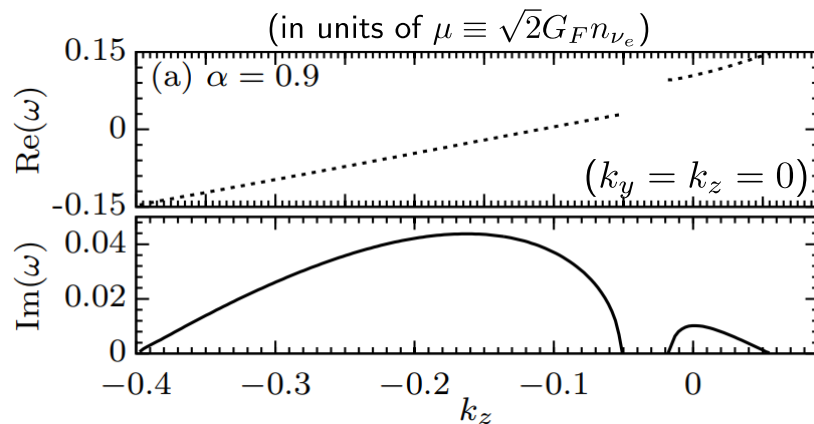
[recent reviews: Volpe 2301.11814, Johns, Richers, MRW 2503.05959, Fiorillo 2609.19256]

Collective neutrino flavor oscillations

[see reviews: Johns, Richers, MRW 2503.05959 and Fiorillo 2609.19256 for references]

Q1: Do collective flavor oscillations lead to large $\rho_{e\mu}$ and $\rho_{e\tau}$?

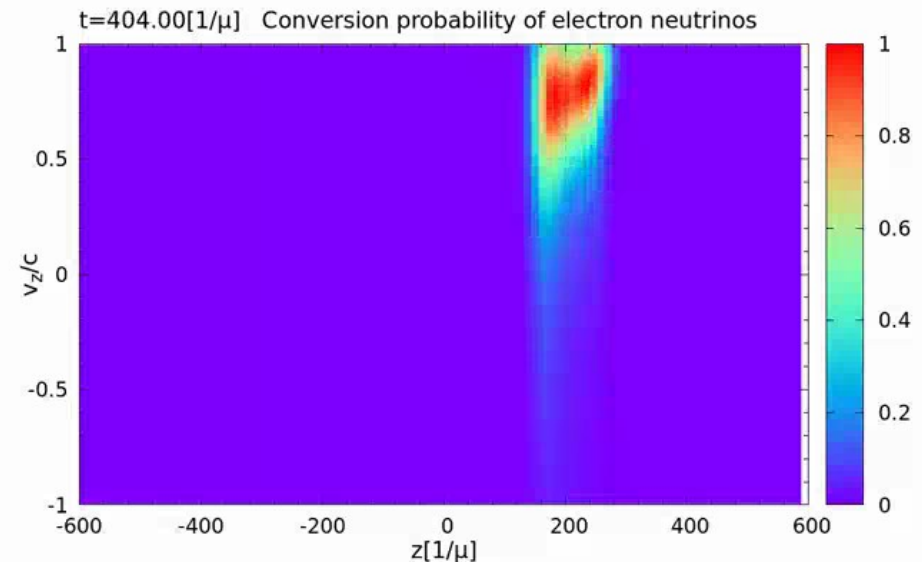
→ Yes, various “collective flavor instabilities” (fast, slow, or collisional) results in “flavor waves” whose amplitudes grow exponentially



dispersion relation solution of fast

flavor wave: $\varrho_{e\mu} \propto e^{-i(\omega t - k_z z)}$

[MRW, George, Lin, Xiong, PRD '21 (2108.09886)]



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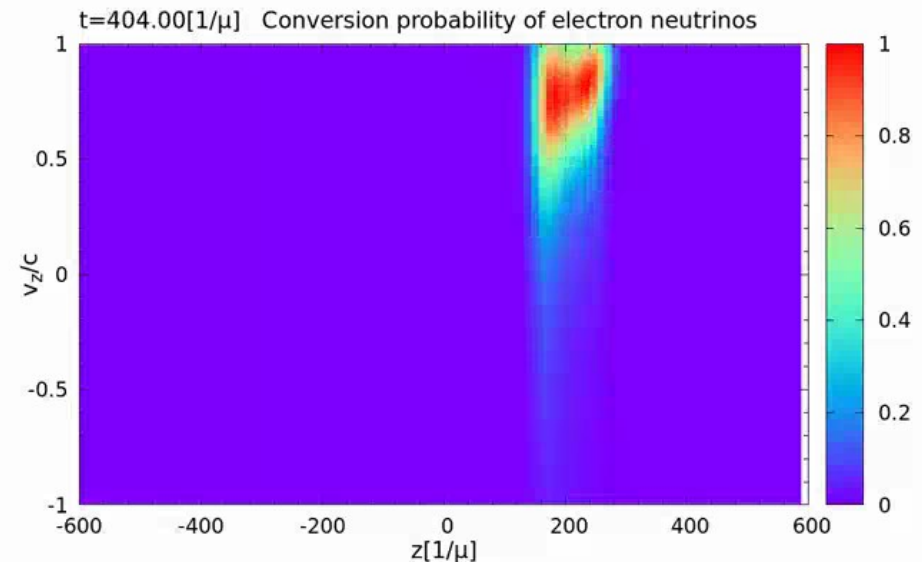
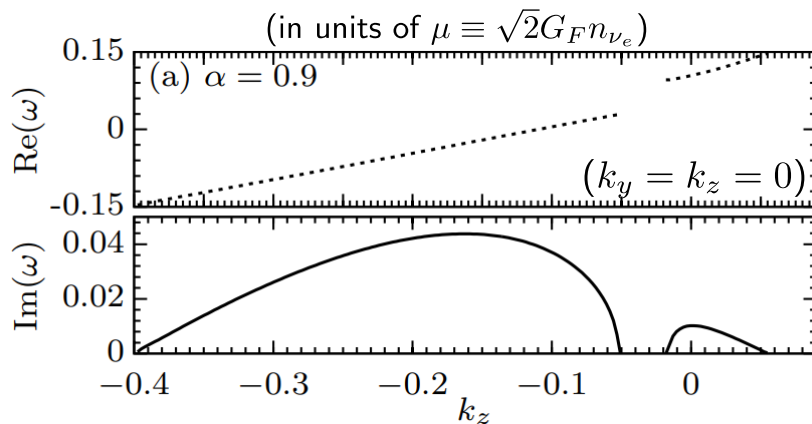
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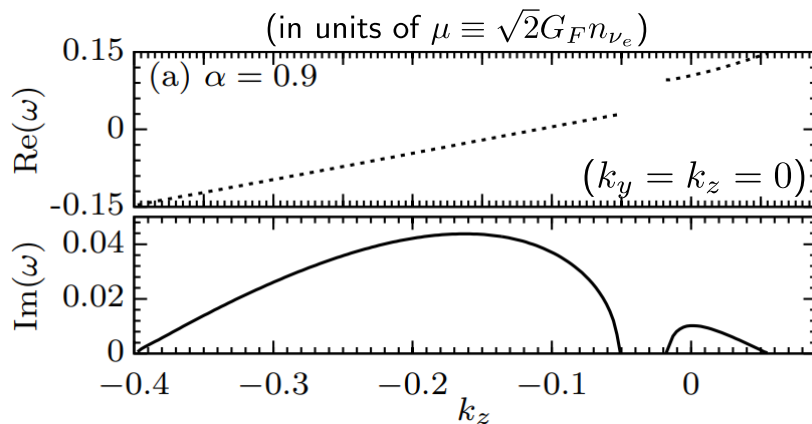
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Q3: Characteristic growth rate of wave amplitudes?

→ depending on the instability type, can range from $\mathcal{O}(1)$ ns to $\mathcal{O}(1)$ ms

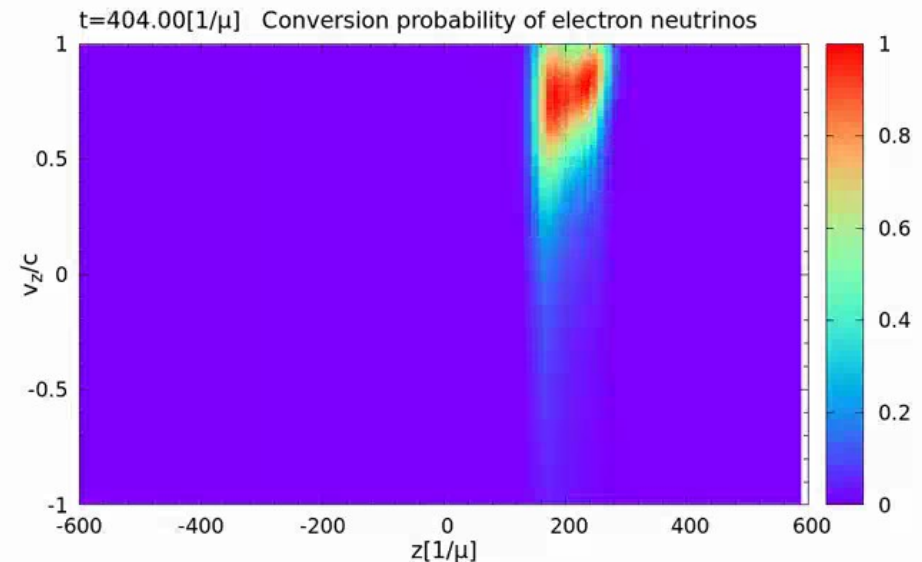
→ need sub-grid models to include them in SN simulations!



dispersion relation solution of fast

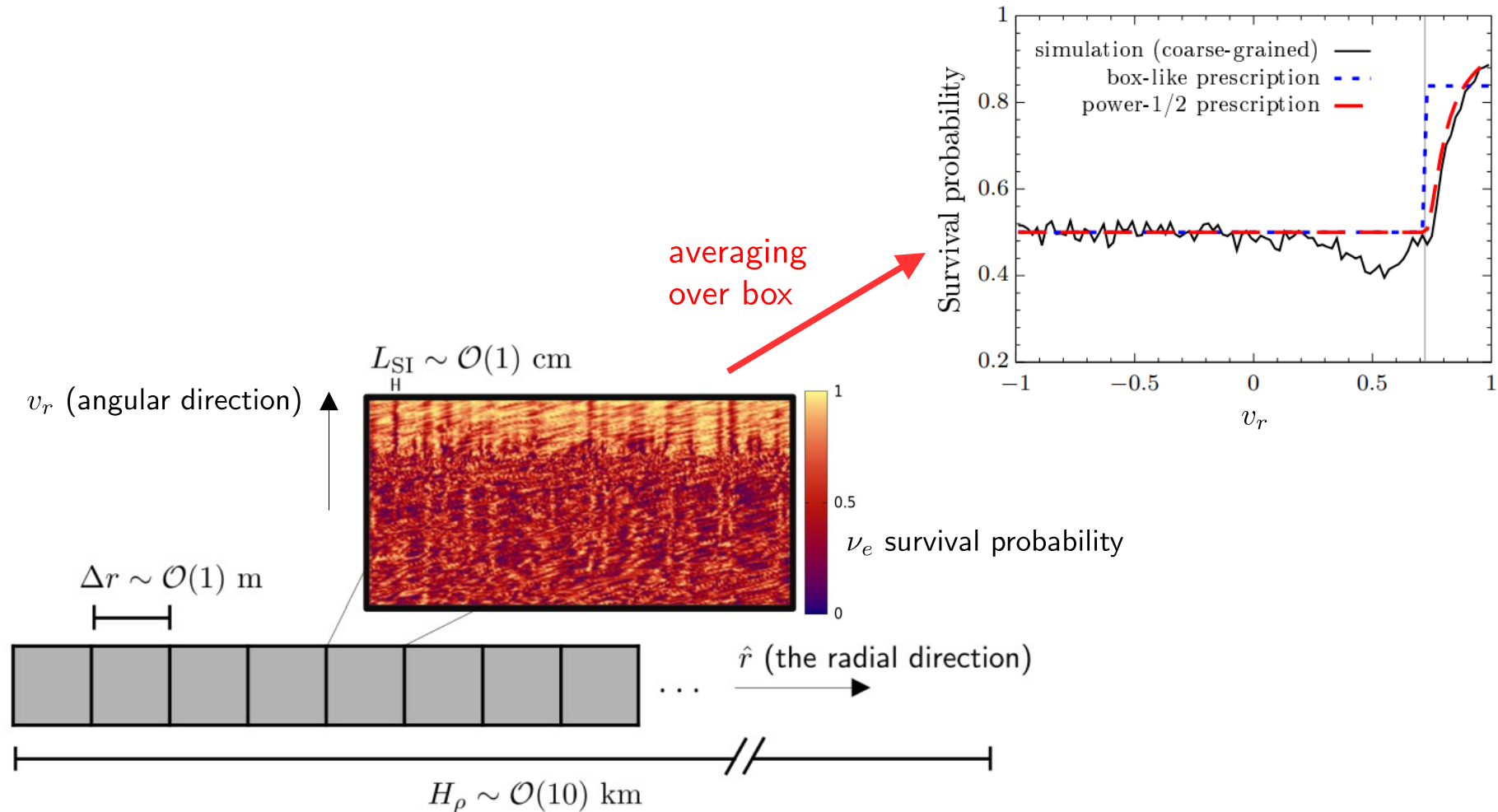
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Subgrid models and potential impact

So far the only “validated” subgrid models are for collective oscillations purely driven by **fast flavor instabilities**, based on the assumption of **relaxation toward locally coarse-grained equilibration** [Nagakura+ 2024, Xiong+ 2025]



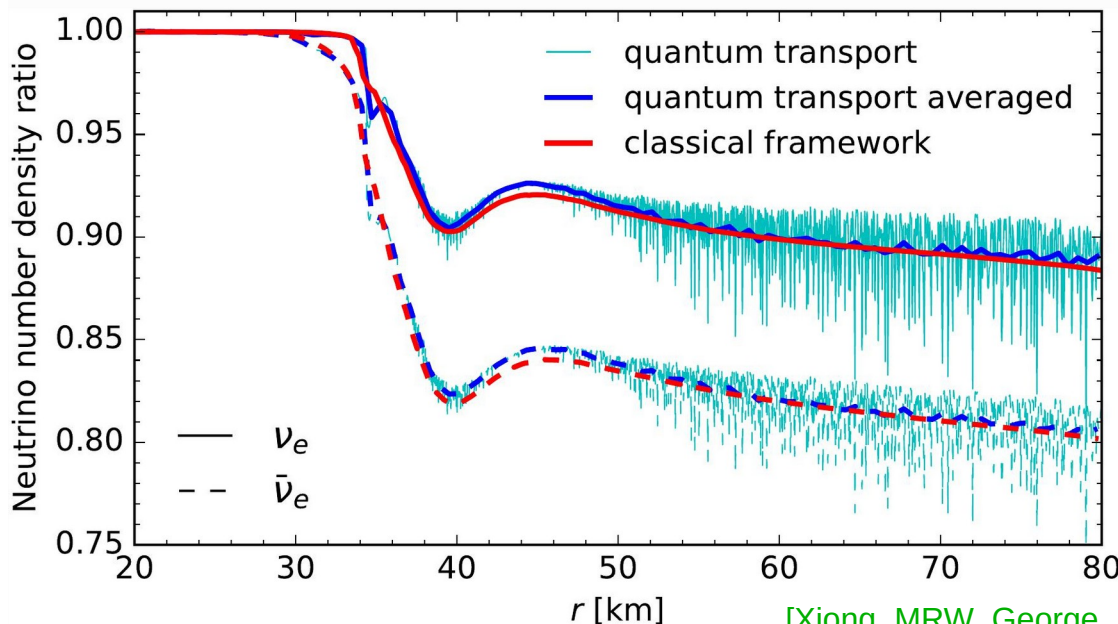
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E.g., sub-grid model “effective classical ν transport”:

→ running classical neutrino transport and simply redistribute ν number densities of different flavors at every spatial grid where the fast flavor instability condition is satisfied [Xiong+ 2025, Xiong & MRW 2026]

global ν QKE v.s. effective classical transport



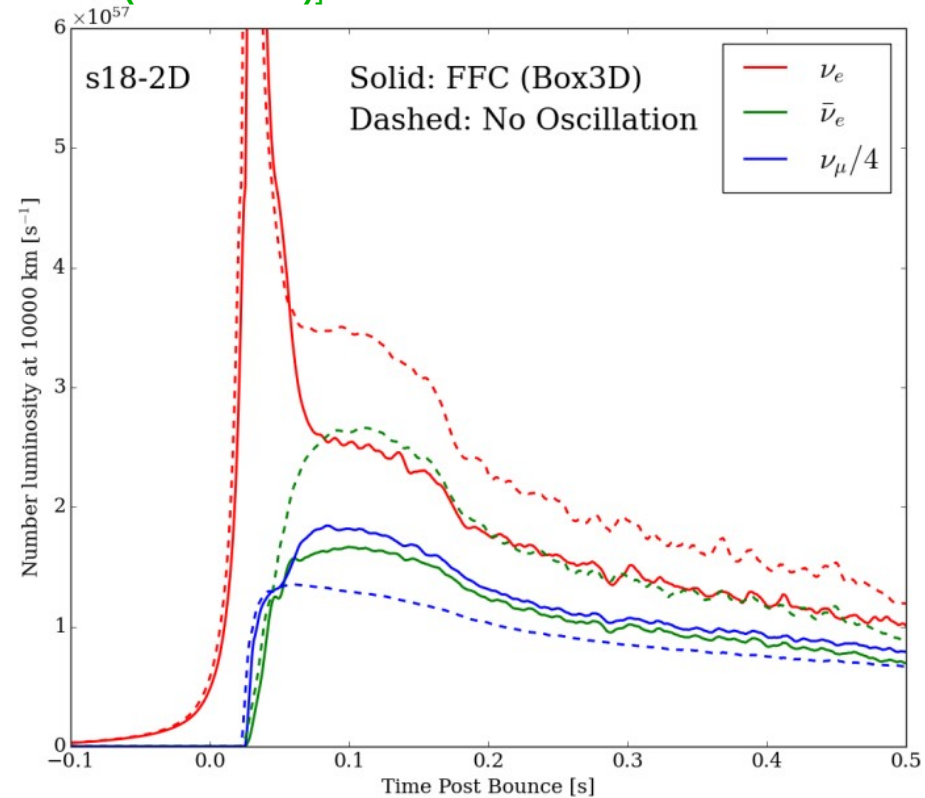
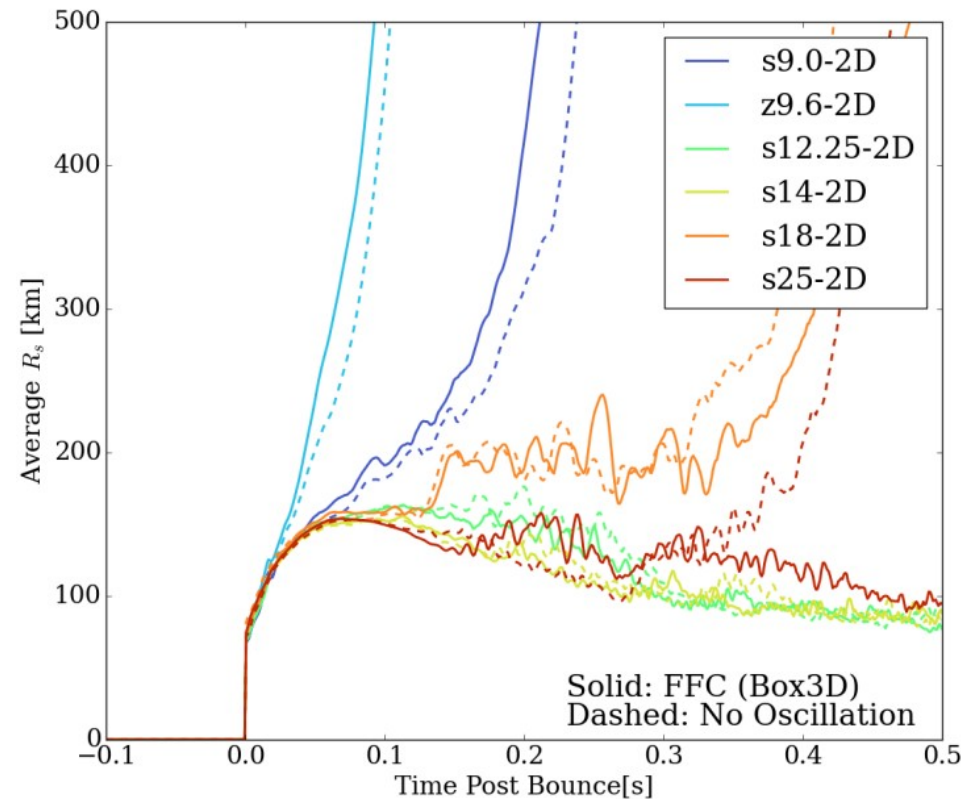
$$(\partial_t + \mathbf{v} \cdot \partial_{\mathbf{x}} + \mathbf{F} \cdot \partial_{\mathbf{p}}) \varrho(\mathbf{x}, \mathbf{p}, t) = -i[H_{\text{vac}} + H_{\text{m}} + H_{\nu\nu}, \varrho(\mathbf{x}, \mathbf{p}, t)] + \mathcal{C}(\varrho)$$

$$(\partial_t + \mathbf{v} \cdot \partial_{\mathbf{x}} + \mathbf{F} \cdot \partial_{\mathbf{p}}) \varrho(\mathbf{x}, \mathbf{p}, t) = \mathcal{C}(\varrho) + \text{redistribution formula}$$

Subgrid models and potential impact

Implementation of simple sub-grid models for **fast flavor oscillations** in hydrodynamic SN simulations found impact on supernova dynamics and neutrino signals

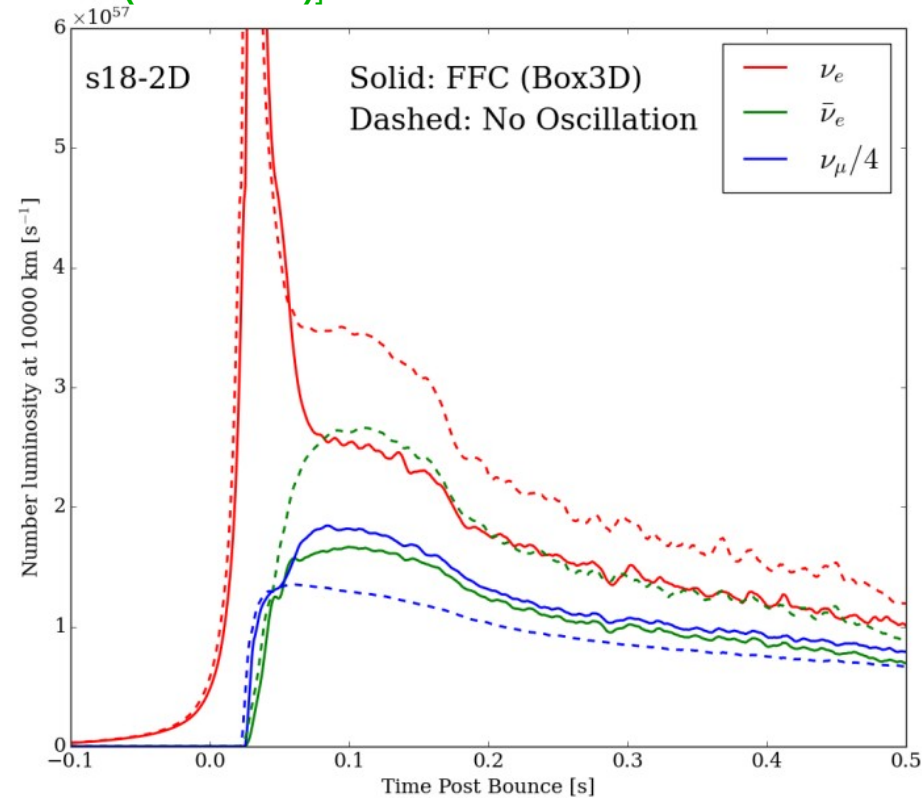
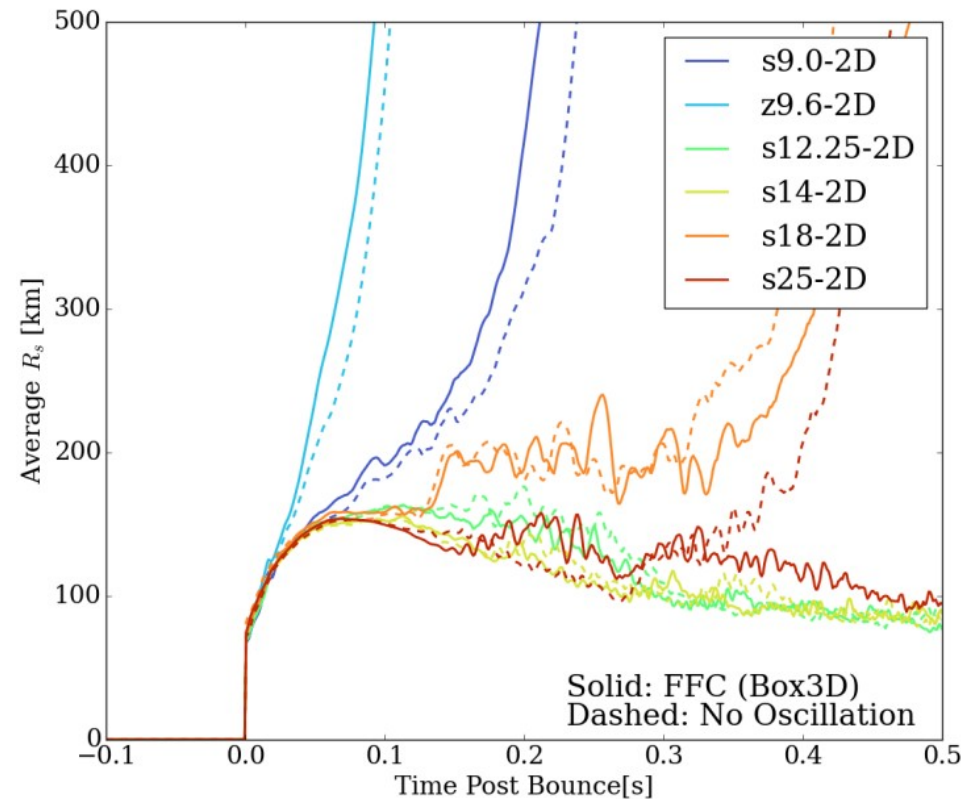
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More efforts are needed to fully incorporate flavor oscillation physics in supernova models

Summary

- Core-collapse supernovae provide a rich array of means to study beyond-Standard-Model physics that involve a sub-GeV sector.
- We recently propose new probes utilizing exotic particle decays in supernovae with circumstellar materials: pre-supernova photospheric emission and 511 keV line.
- If supernova neutrinos upscatters light dark matter, it results in a correlated, time-dependent afterglow signal encoding unknown dark matter mass, as well as a stationary diffuse component.
- It is crucial not only to understand the non-linear flavor oscillations of neutrinos in the supernova core, but also to include them in supernova simulations with sub-grid models – a long way to go but necessary for the next galactic supernova.

Summary

