Probing physics beyond the Standard Model with supernovae

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

The 3rd New Physics Opportunities at Neutrino Facilities Workshops:
Astrophysical Neutrinos, SLAC, USA, July 11-13, 2023

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

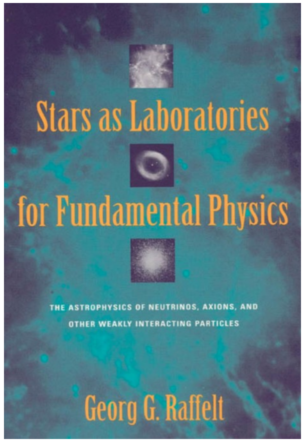
NSTC 國家科學及技術委員會
National Science and Technology Council

NCTS

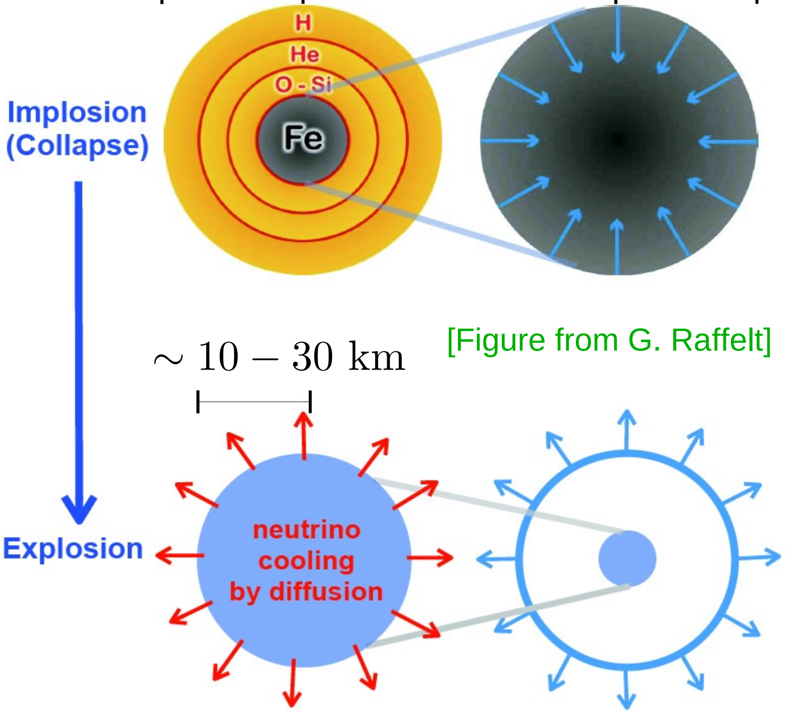
Core-collapse supernovae

- the death of massive stars $\gtrsim 8\ M_\odot$
- luminosity $\simeq 10^9 L_\odot$ for $\sim \mathcal{O}(100)$ days
  $(E_\gamma \sim 10^{49}$ erg)
- explosion energy $\sim 10^{51}$ erg $\equiv 1$ B(ethe)
- strong MeV neutrino emission $\sim 10^{53}$ erg within ~ 10 s ($\sim 10^{58}$ neutrinos)

The high density ($\rho_c \gtrsim 10^{14}$g cm^{-3}) and temperature $T_c \gtrsim 30$ MeV of the proto-neutron stars make them interesting astrophysical "laboratory" complementary to terrestrial experiments



SN1987a (From AAO website)



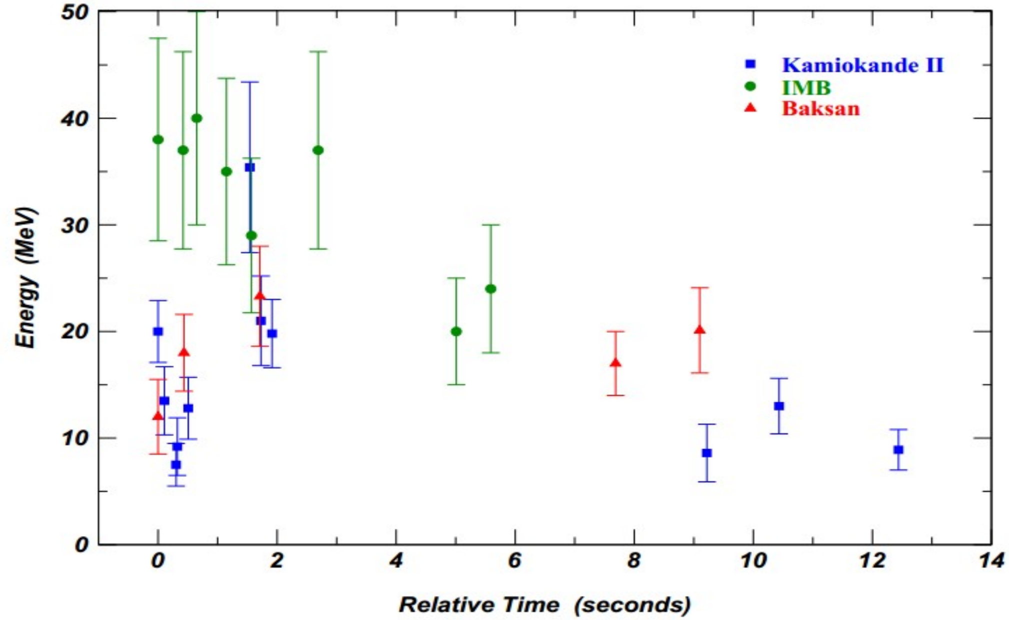
[Figure from G. Raffelt]

SN neutrinos

Detected $\sim 20\ \bar{\nu}_e$ in ~ 10 s from SN1987a

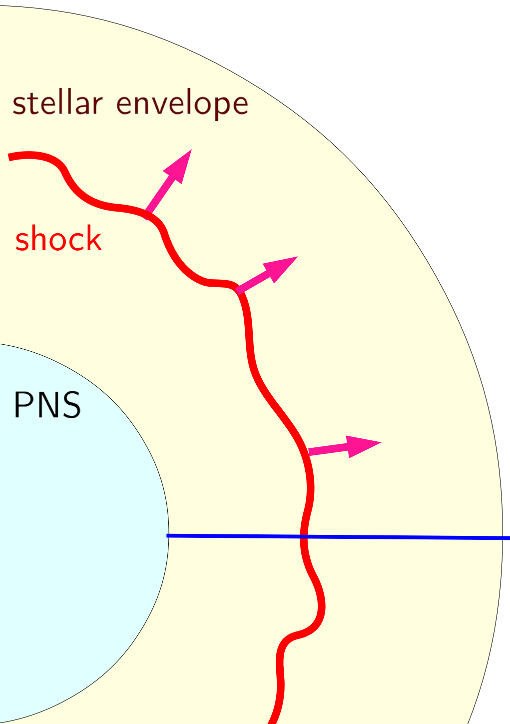
broadly consistent with SN theory, although "tensions" are claimed recently
[e.g., Olson & Qian 2021, 2022, Li+ 2023]

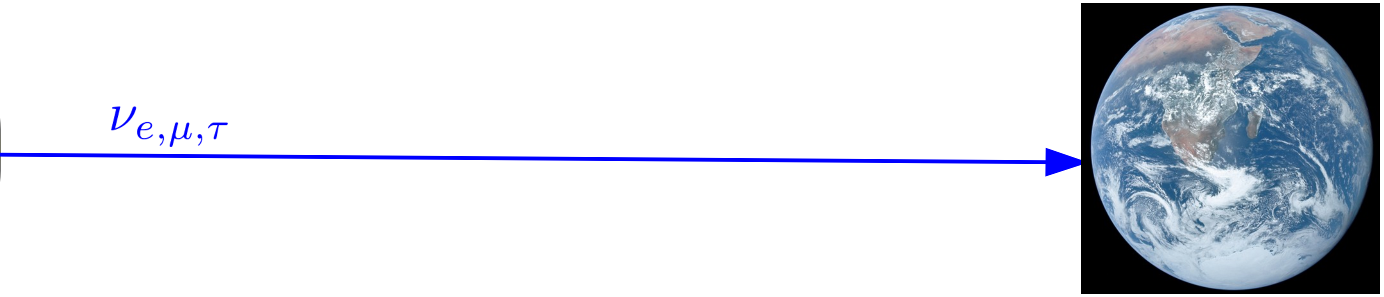
[J. Heise PhD Thesis (2002)]



will see $\mathcal{O}(10^4 - 10^5)$ events from the next galactic SN!

implication for bSM physics?

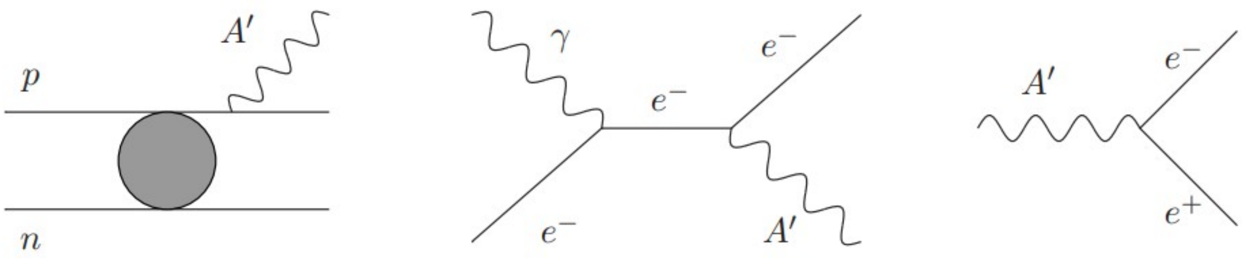




Production of bSM particles in SNe

- collisional production (dark photons, axions, light dark fermions, sterile ν,...)

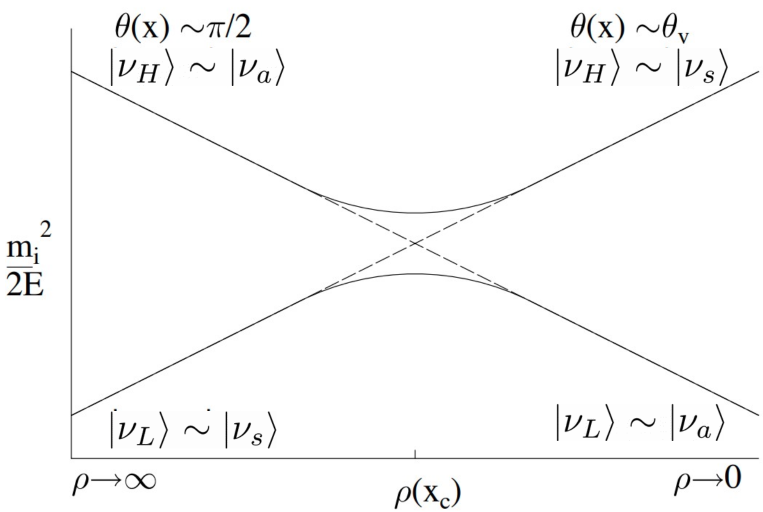
$$\mathcal{L} \supset -\frac{1}{4}F'_{\mu\nu}F'^{\mu\nu} - \frac{\epsilon}{2}F'_{\mu\nu}F^{\mu\nu} + \frac{1}{2}m^2_{A'}A'_{\mu}A'^{\mu}$$



$+ \ldots$

[Adapted from J. Chang]

- resonant conversion (eV – keV sterile neutrinos):



[Adapted from Haxton]

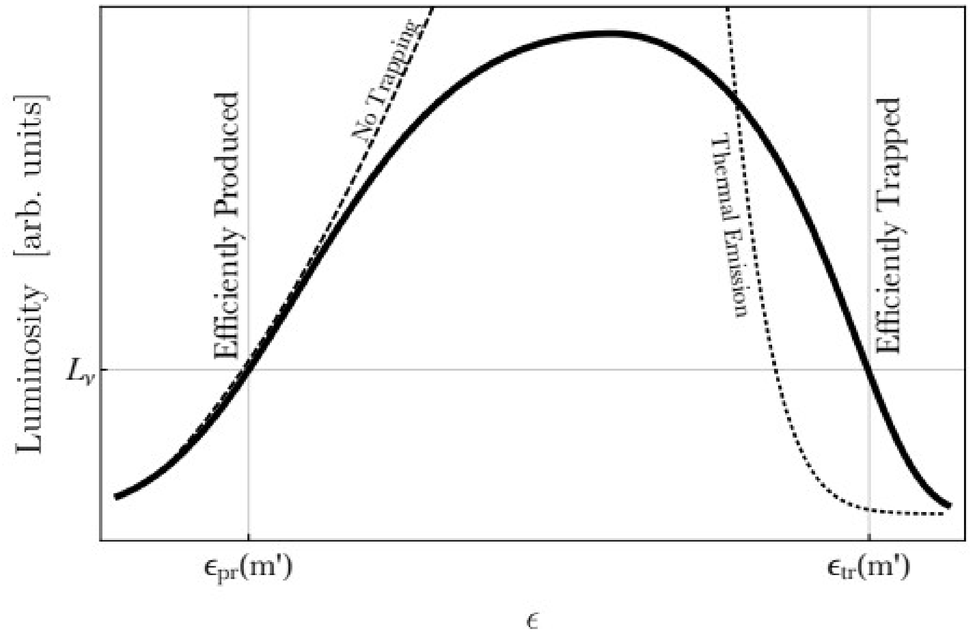
bSM v.s. SN: (i) excessive cooling

[Chang+ 1611.03864]

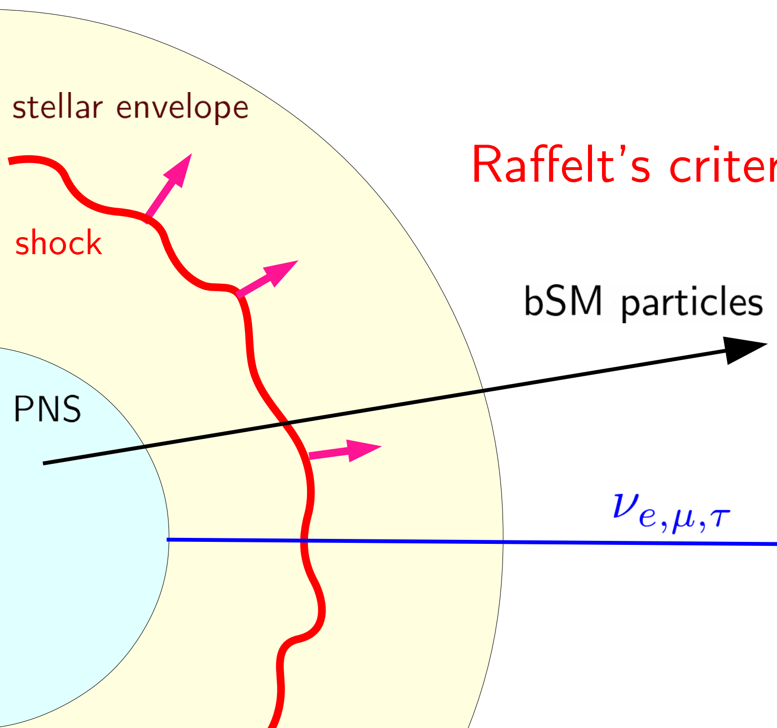
light ($\lesssim 100$ MeV) bSM particle that couple to $n, p, e^{\pm}, \mu^{\pm}, \gamma$ may be produced in PNS and escape

$\rightarrow$ reduce available thermal energy carried by SNν

$\rightarrow$ shorten SNν emission duration



Raffelt's criteria: $L_{\text{new particle}} < L_\nu \sim 3 \times 10^{52}$ erg/s



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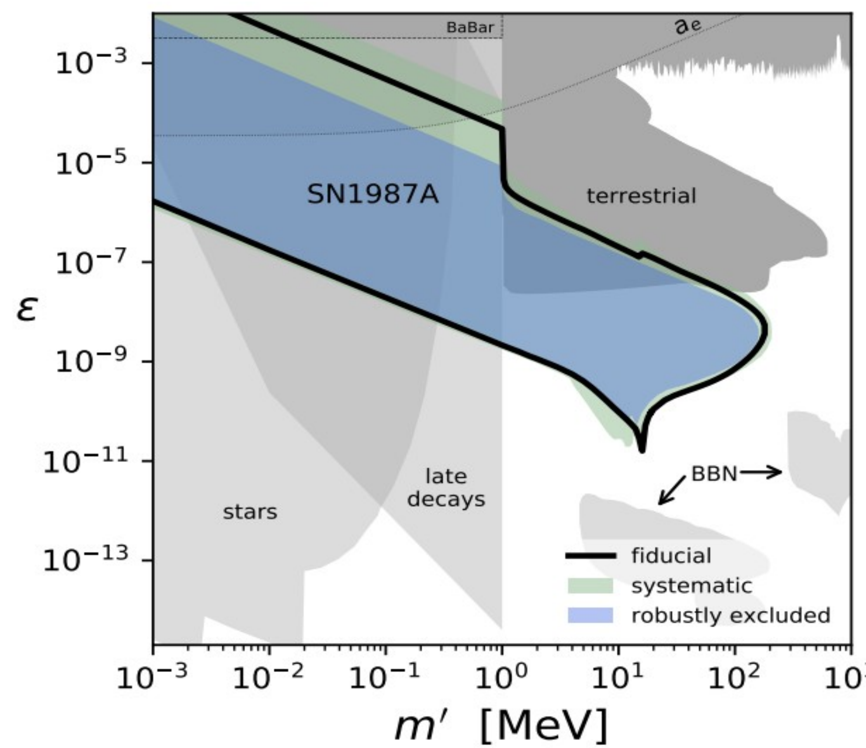

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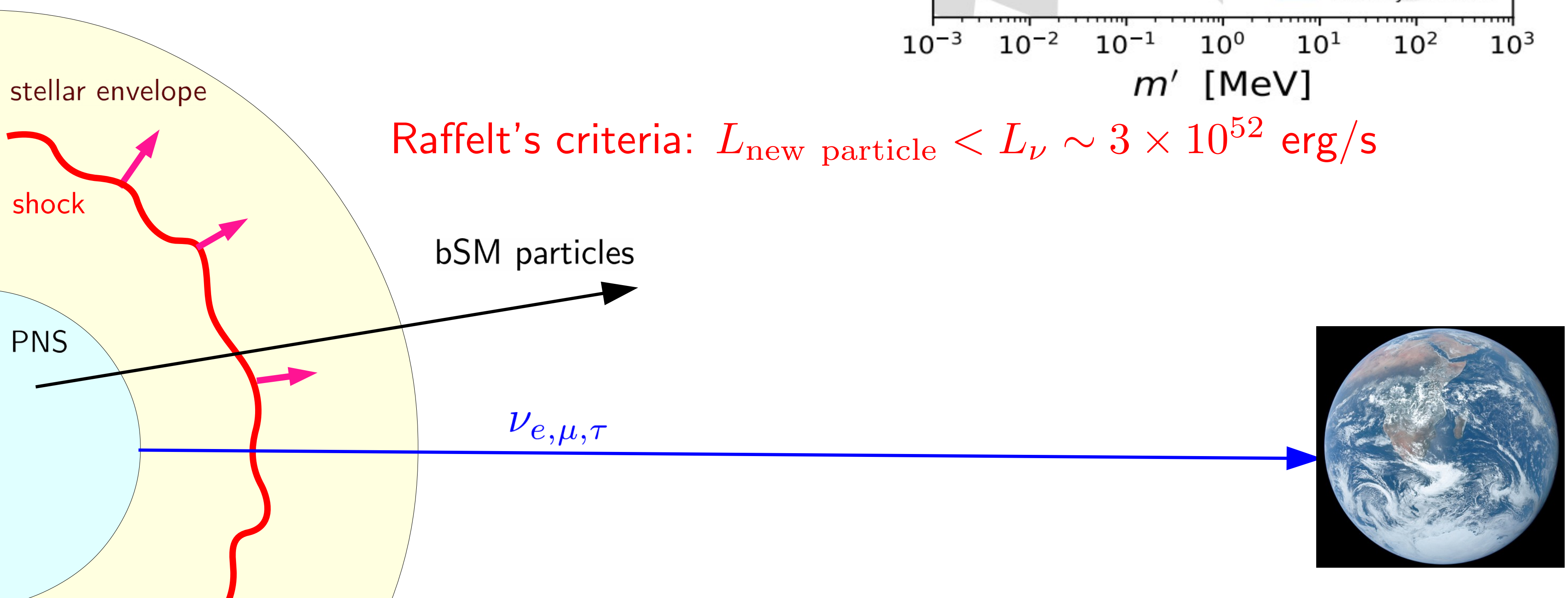

bSM v.s. SN: (i) excessive cooling

• This is the most widely studied scenario that was applied to a wide class of bSM particles, including axions, dark mediators, keV sterile neutrinos, ... etc.

• Raffelt's criterion was formulated in fact based on simulations – valid for bSM particles that are created simply by collisional processes

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Caveats exist for:

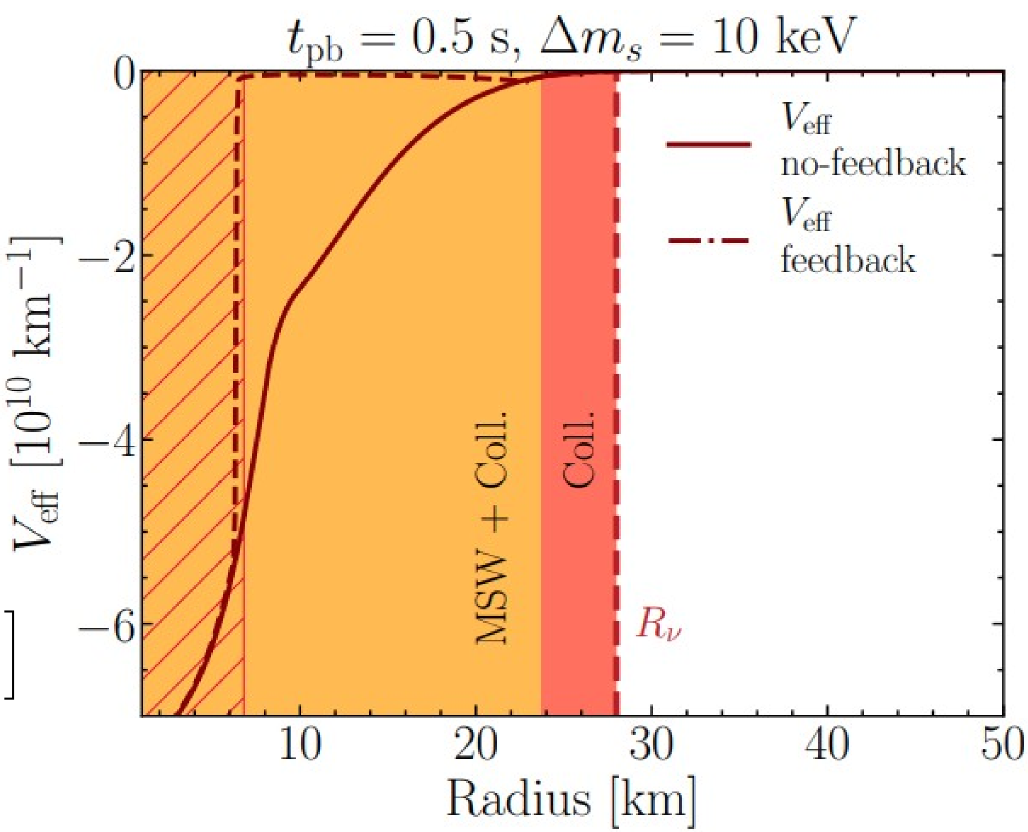
a. keV sterile neutrinos whose production depends on the adiabaticity of $V_{\rm eff}$

$$\frac{\delta m^2}{2E_\nu}\cos\theta_{\rm v} = V_{\rm eff}$$

for ν_τ–ν_s mixing

$$V_{\rm eff} = \pm\sqrt{2}G_F n_b\left[-\frac{(1-Y_e)}{2} + Y_{\nu_e} + Y_{\nu_\mu} + 2Y_{\nu_\tau}\right]$$

→ feedback effect is important!



[Suliga, Tamborra, MRW, 1908.11382]

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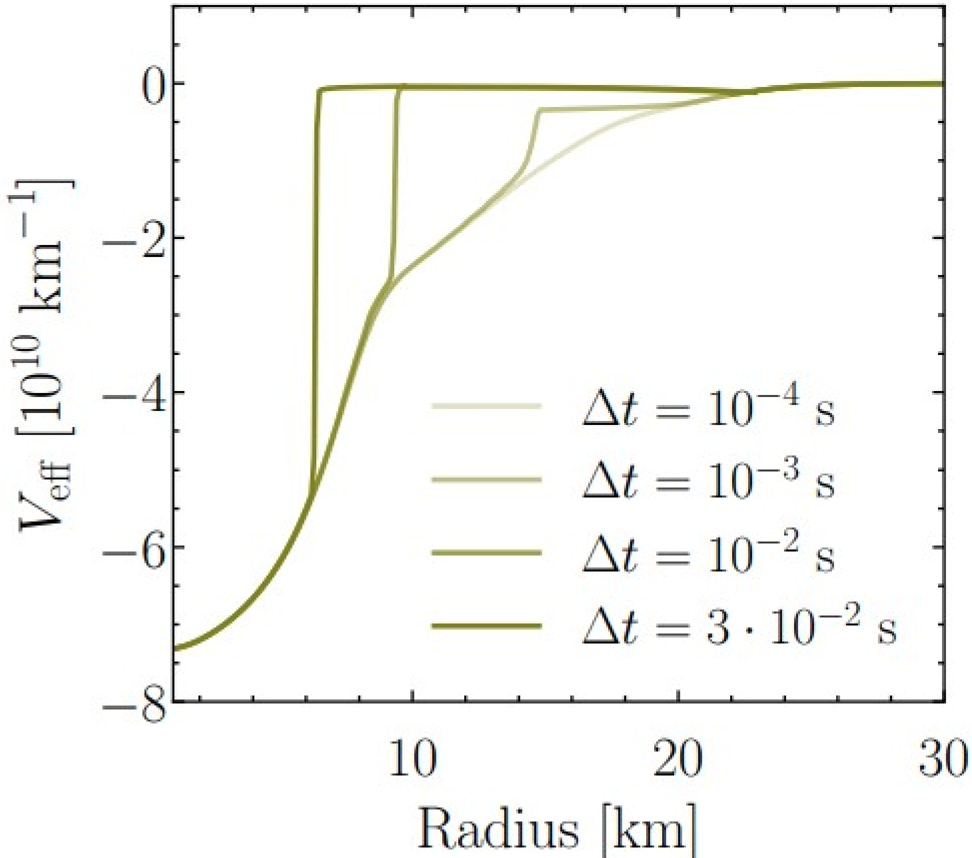

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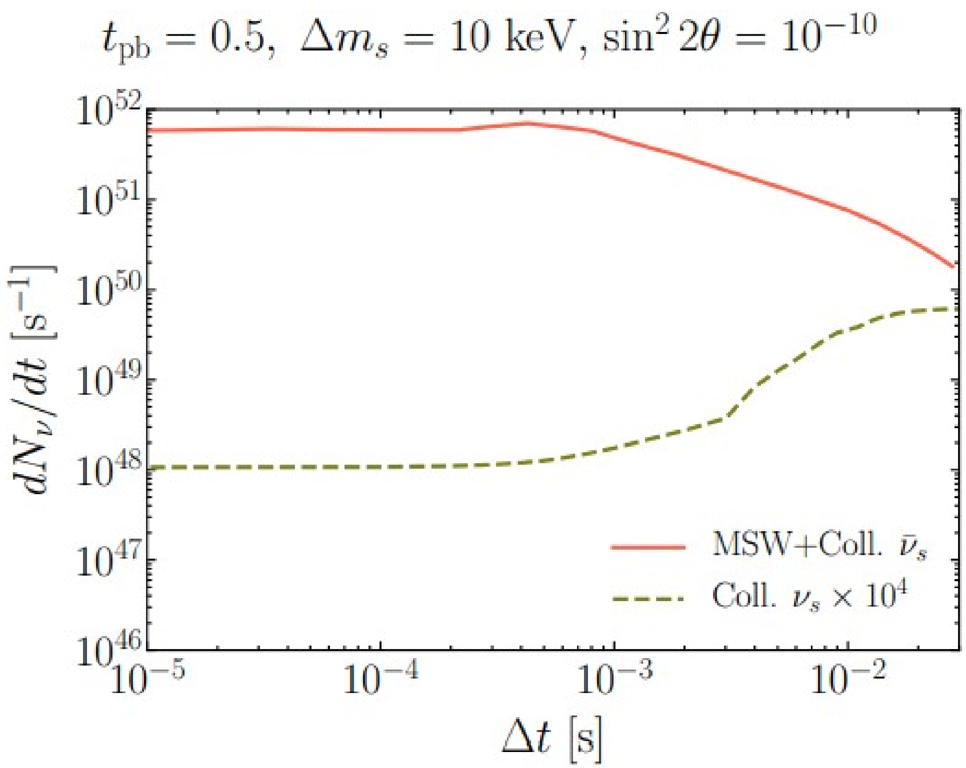

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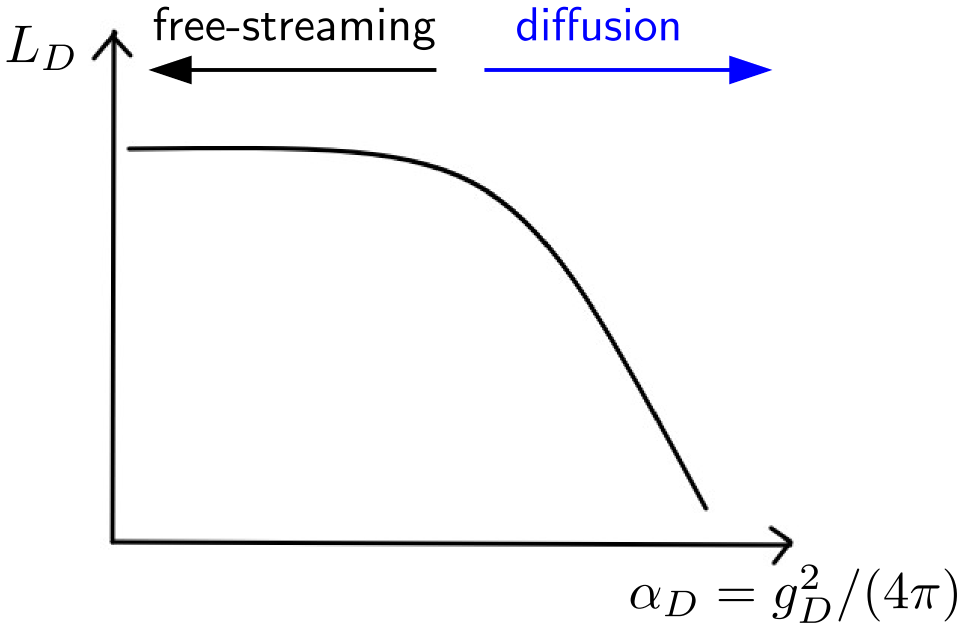
Caveats exist for:

b. self-interacting light dark sector

coupling among dark sector particles can be strong, which may lead to "self-trapping"

$$\mathcal{L} \supset -\frac{1}{4} F'_{\mu\nu} F'^{\mu\nu} - \frac{\epsilon}{2} F'_{\mu\nu} F^{\mu\nu} + \frac{1}{2} m_{A'}^2 A'_\mu A'^\mu + \bar{\chi} \left(i\gamma^\mu \partial_\mu - m_\chi \right) \chi + g_D \bar{\chi} \gamma^\mu A'_\mu \chi$$

dark photon + dark fermion



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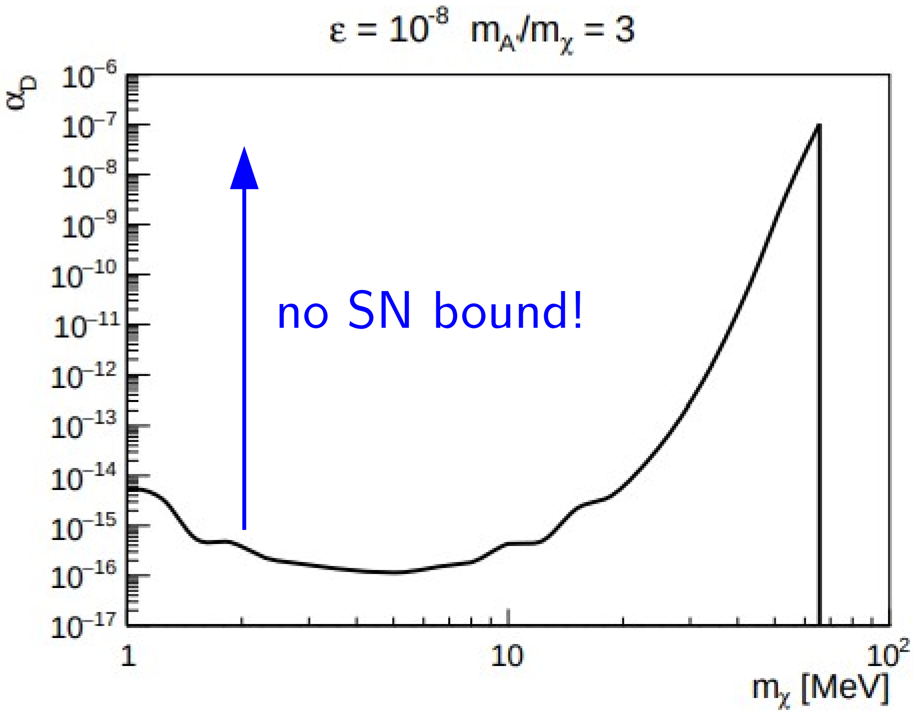

[Sung, Guo, MRW, 2102.04601]

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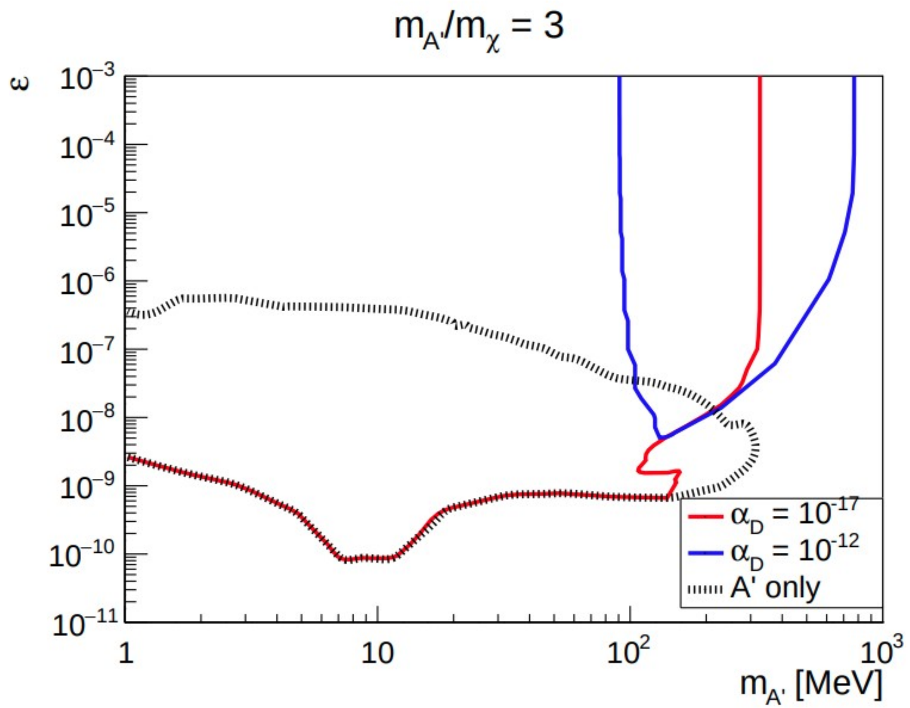


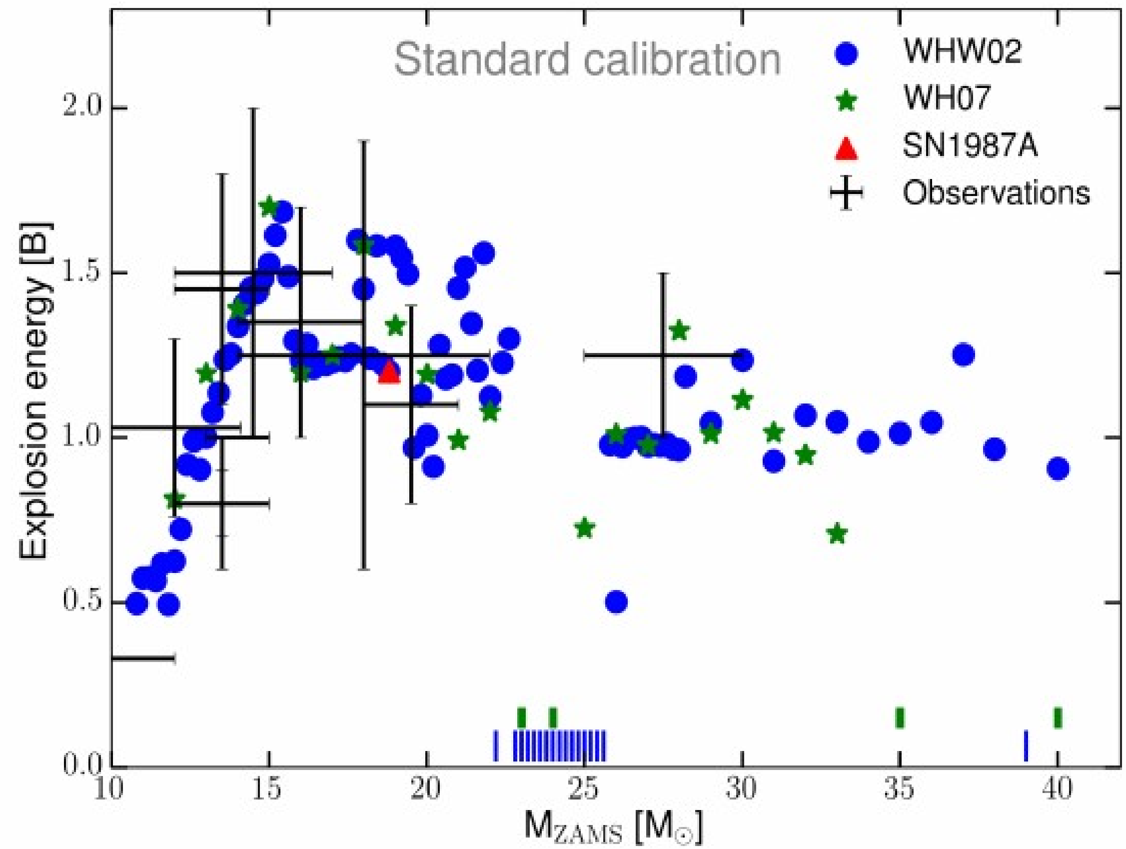
[Sung, Guo, MRW, 2102.04601]

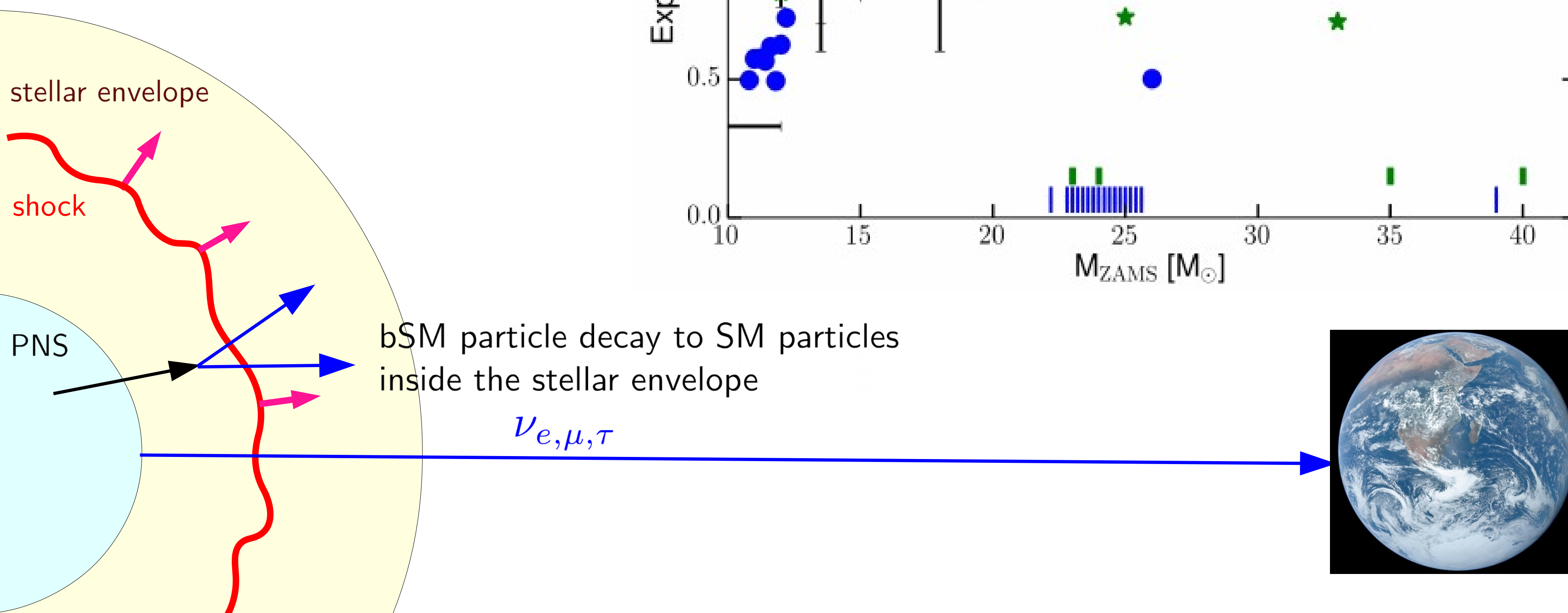
if bSM particles can decay to or be converted back to SM particle...

bSM v.s. SN: (ii) explosion energy bound

[Ebinger+, 1804.03182]

$$E_{\rm expl} \sim \text{K.E. of ejecta}$$
$$\sim \frac{1}{2} M_{\rm ej} v_{\rm ej}^2$$
$$\sim 10^{51}\ \text{erg} \equiv 1\ \text{B(ethe)}$$





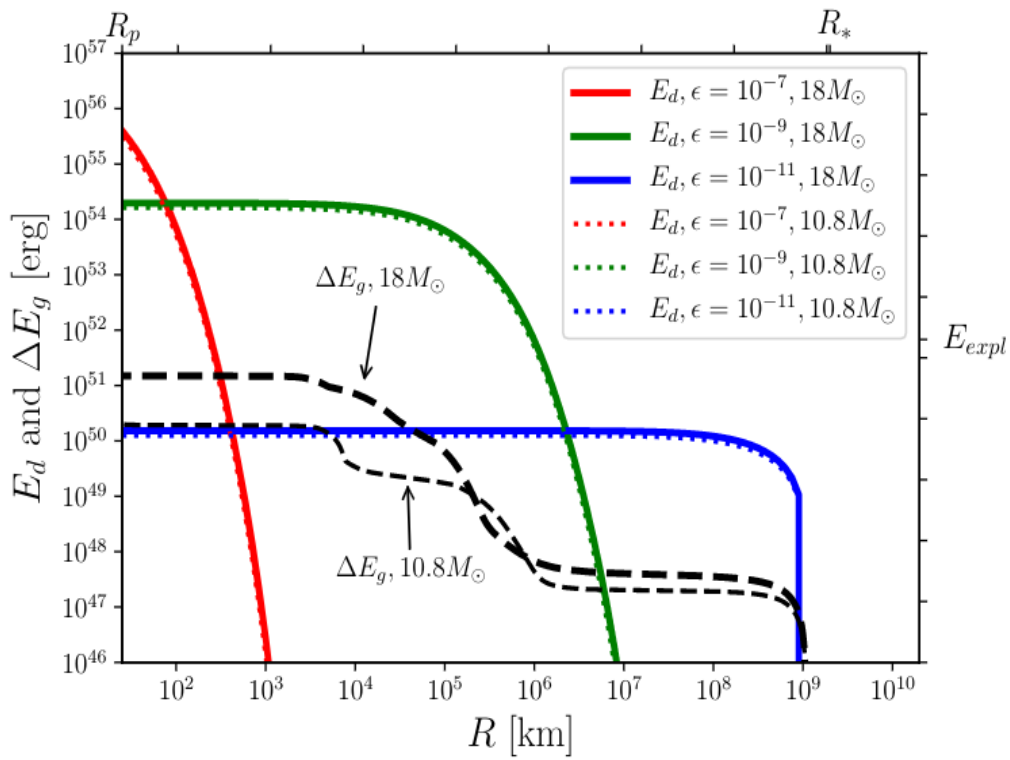
bSM v.s. SN: (ii) explosion energy bound

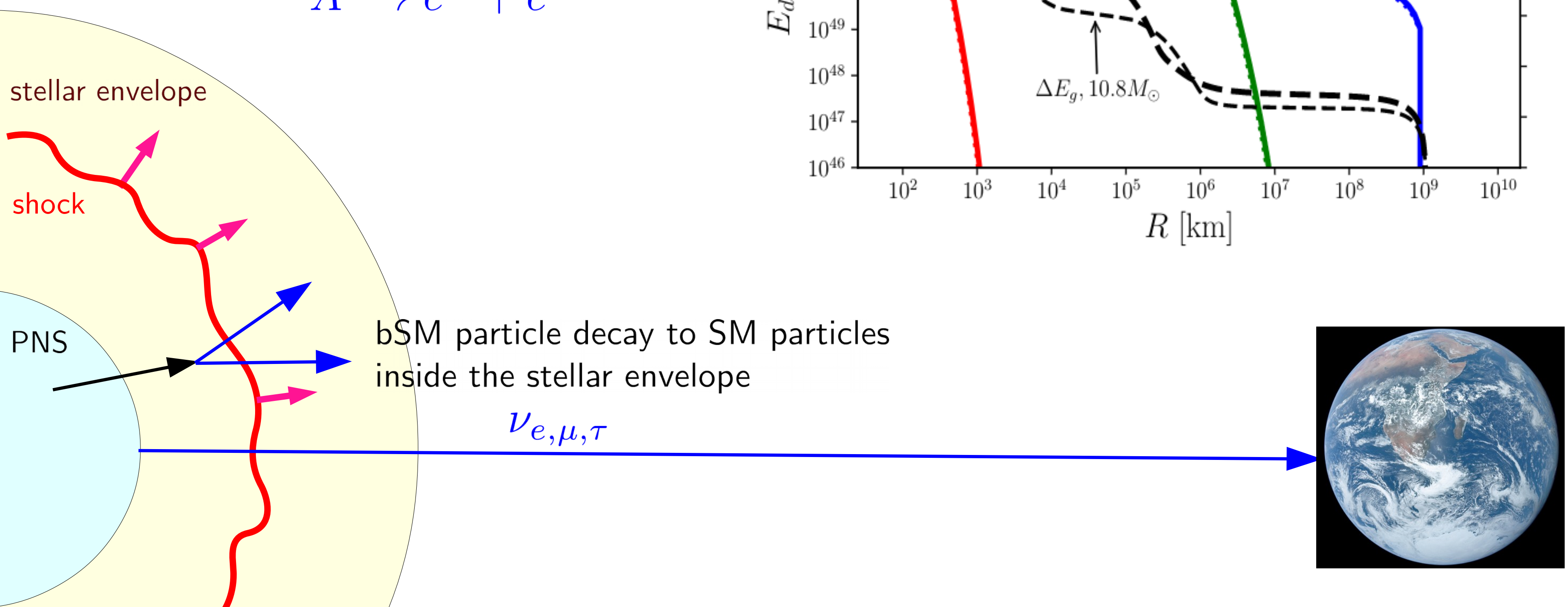
For bSM particles that can escape PNS but decay to SN particles, they should NOT deposit too much energy into ejecta or envelope

for dark photon

$A' \to e^+ + e^-$

[A. Sung, H. Tu, MRW, 1903.07923]





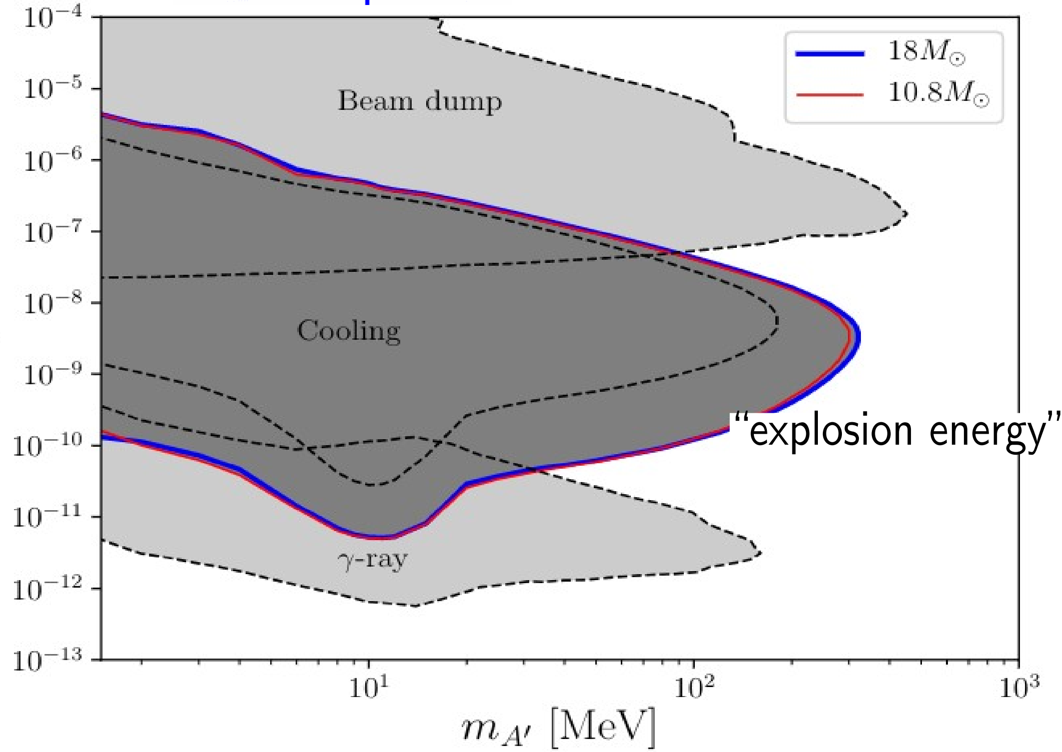
bSM v.s. SN: (ii) explosion energy bound

For bSM particles that can escape PNS but decay to SN particles, they should NOT deposit too much energy into ejecta or envelope

[See also Caputo+ 2201.09890, which applies to extreme case of low-energy SNe (0.1B) for axion]

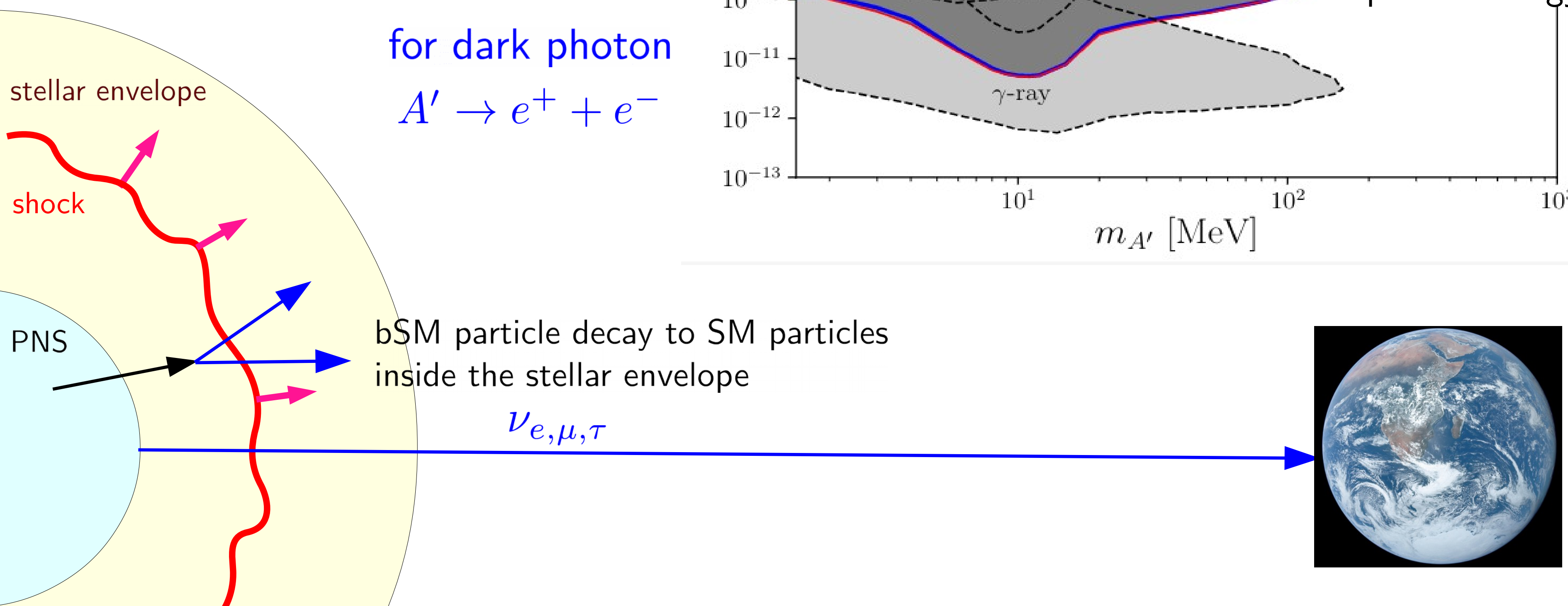
for dark photon

[A. Sung, H. Tu, MRW, 1903.07923]



for dark photon

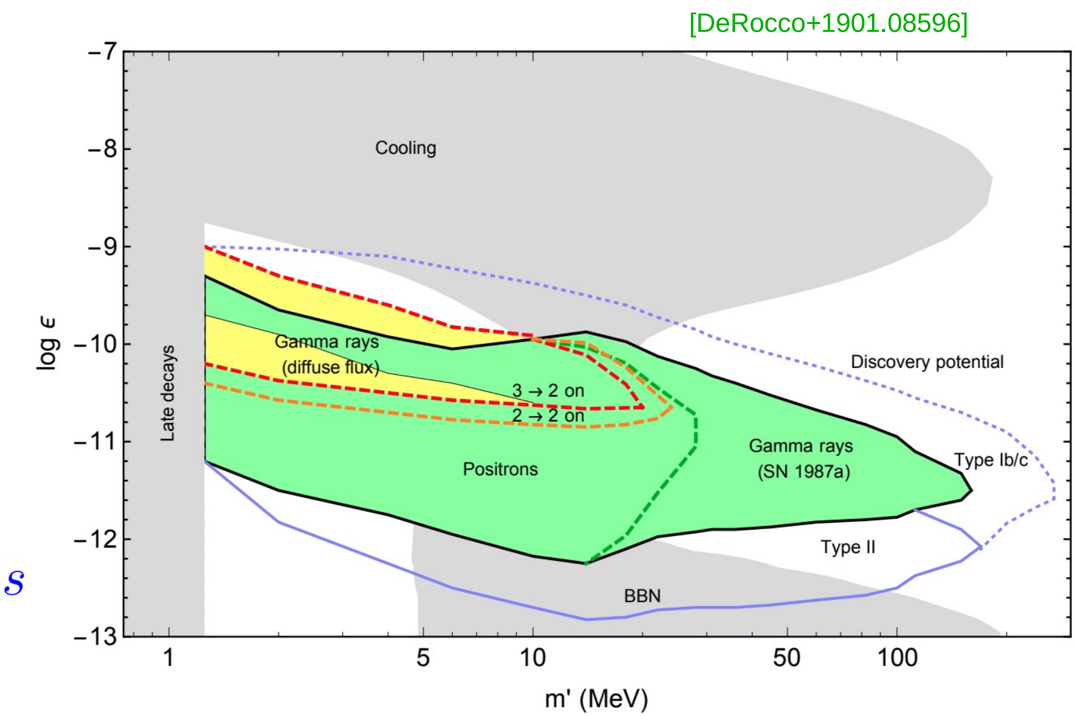
$$A' \to e^+ + e^-$$



bSM v.s. SN: (iii) additional SM signature

bSM particles can also decay to or produce SM photons or neutrinos that arrive Earth

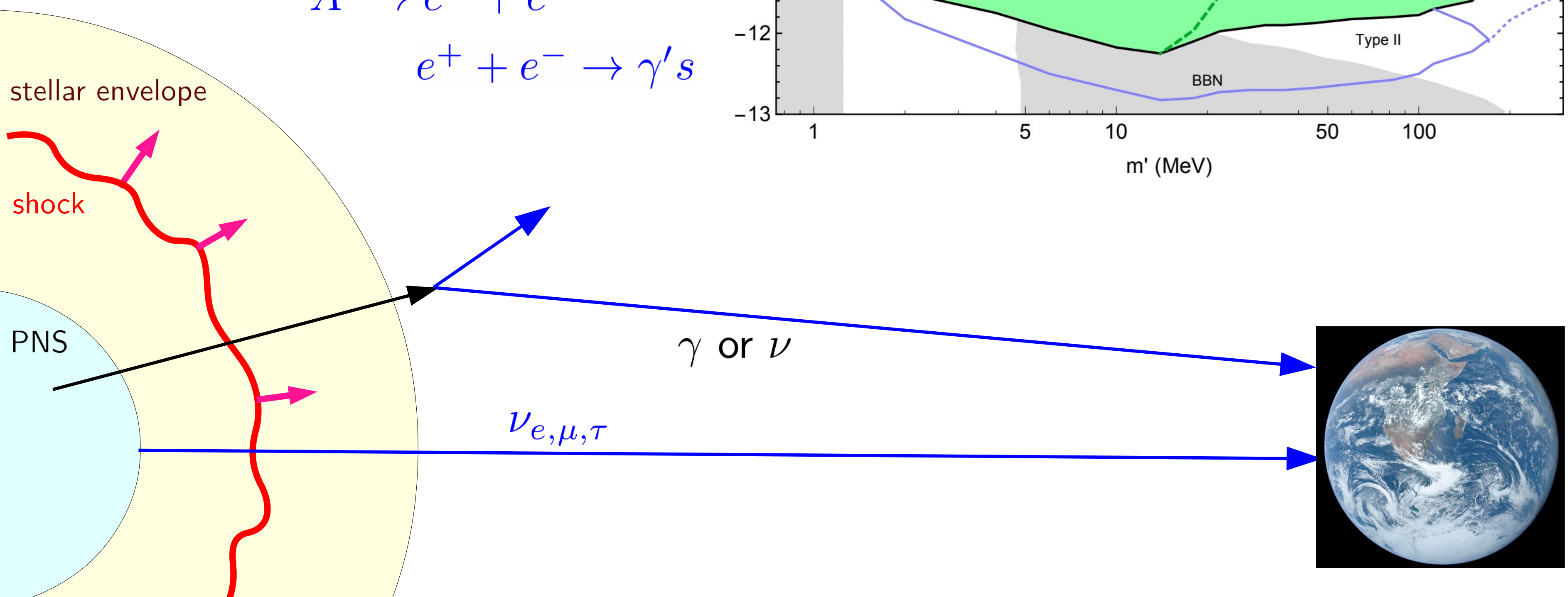
$\rightarrow$ additional signature



for dark photon

$A' \rightarrow e^+ + e^-$

$e^+ + e^- \rightarrow \gamma' s$



bSM v.s. SN: (iii) additional SM signature

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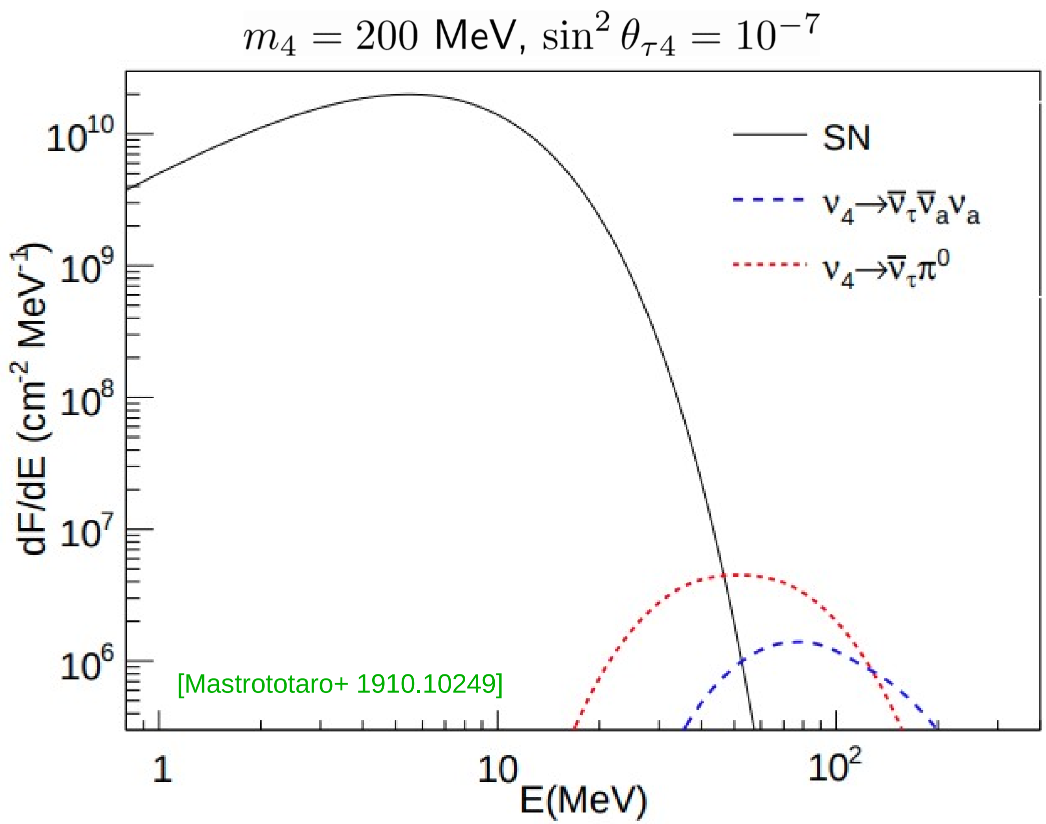
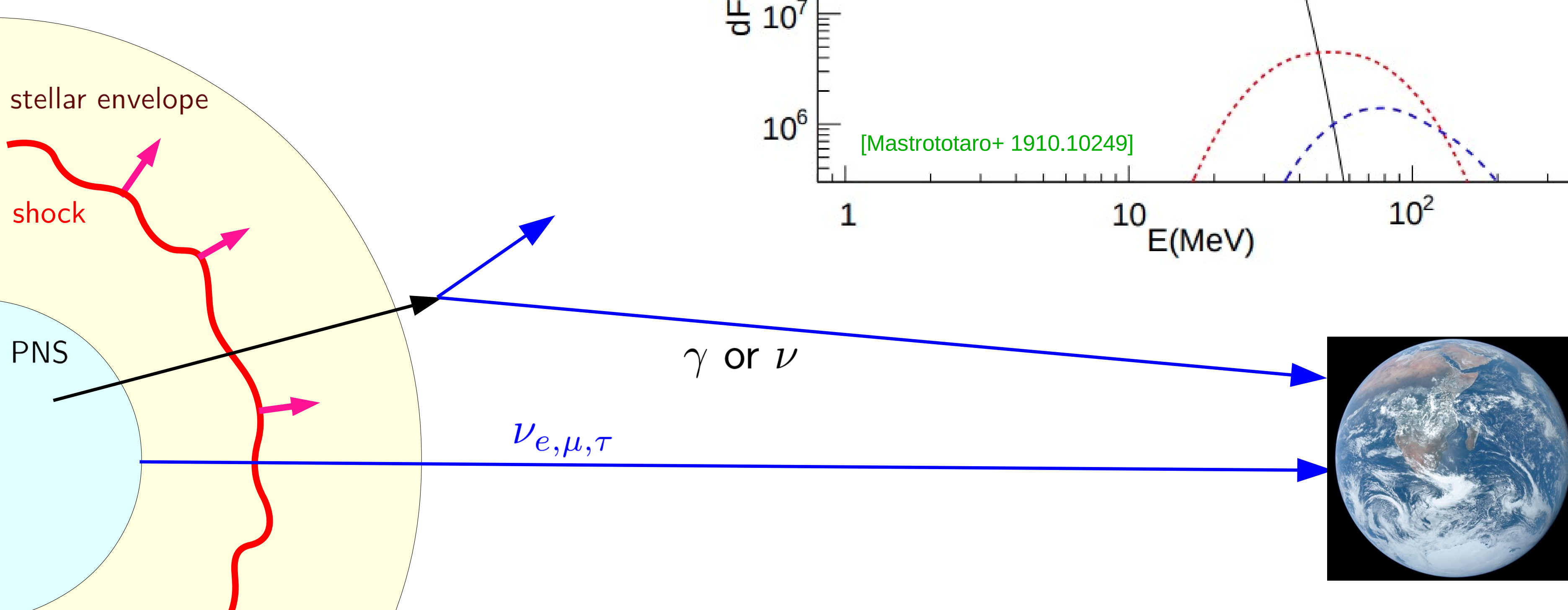
$\rightarrow$ additional signature

for $\mathcal{O}(100)$ MeV sterile neutrinos





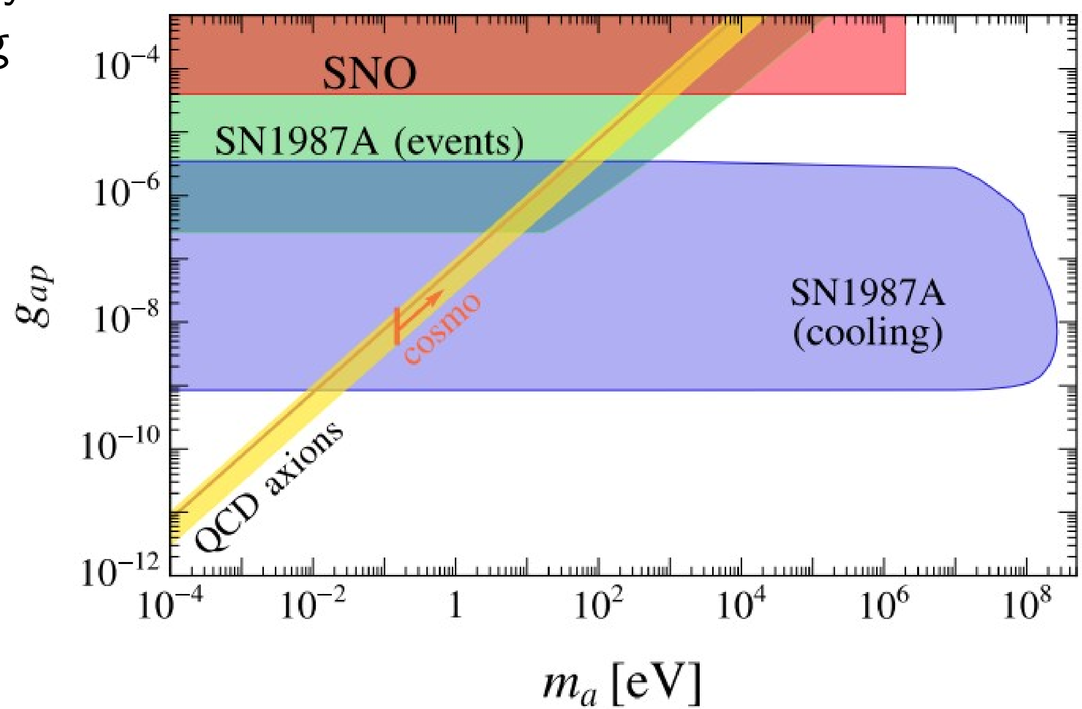
bSM v.s. SN: (iv) direct bSM signature

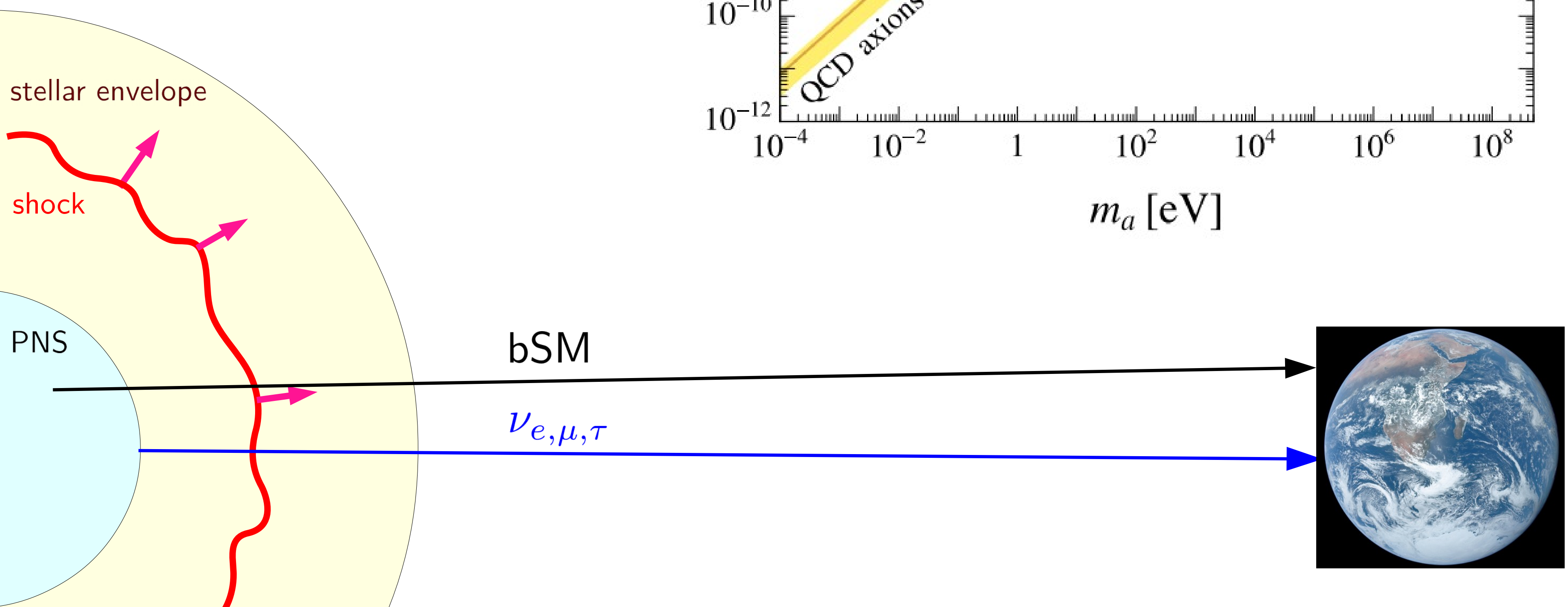
bSM particles that arrive directly at Earth may also be interesting

for axion & axion-like particle

e.g., ALP + ^{16}O $\rightarrow ^{16}$O$^* \rightarrow ^{16}$O$+\gamma$

[Lella+ 2306.01048]





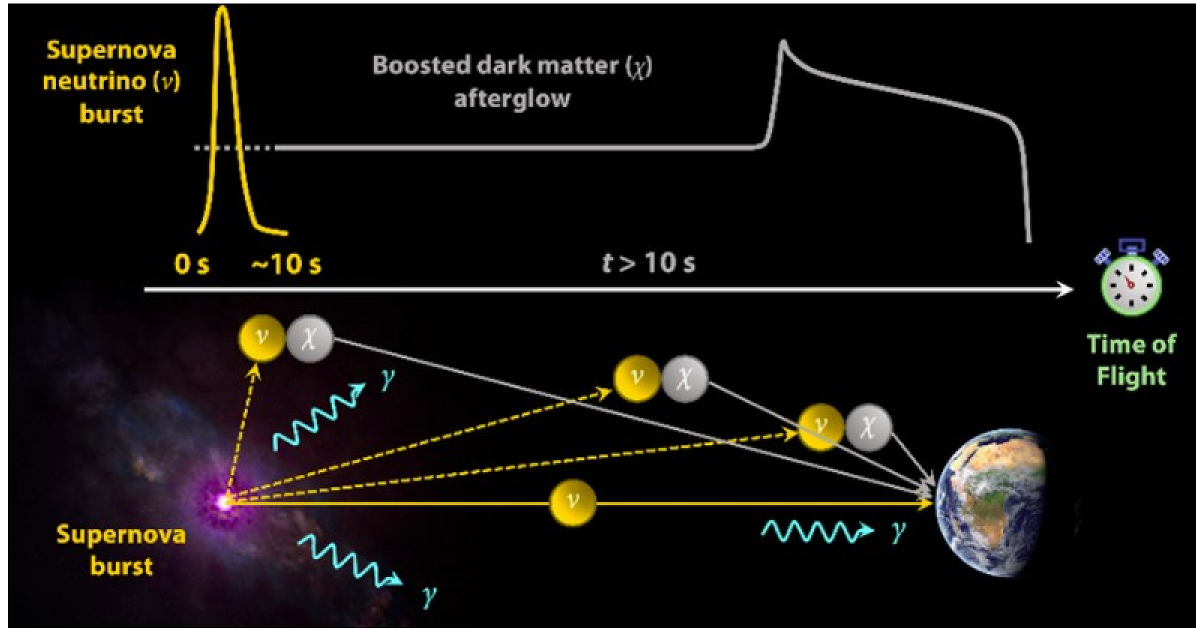
if neutrinos interact with dark matter...

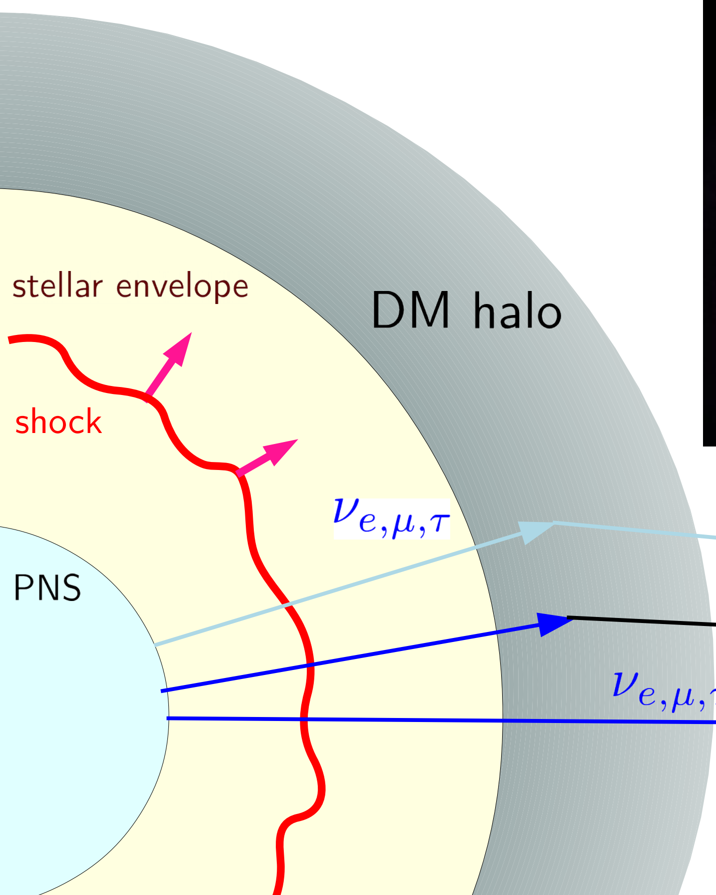
bSM v.s. SN: (ν) interaction with DM

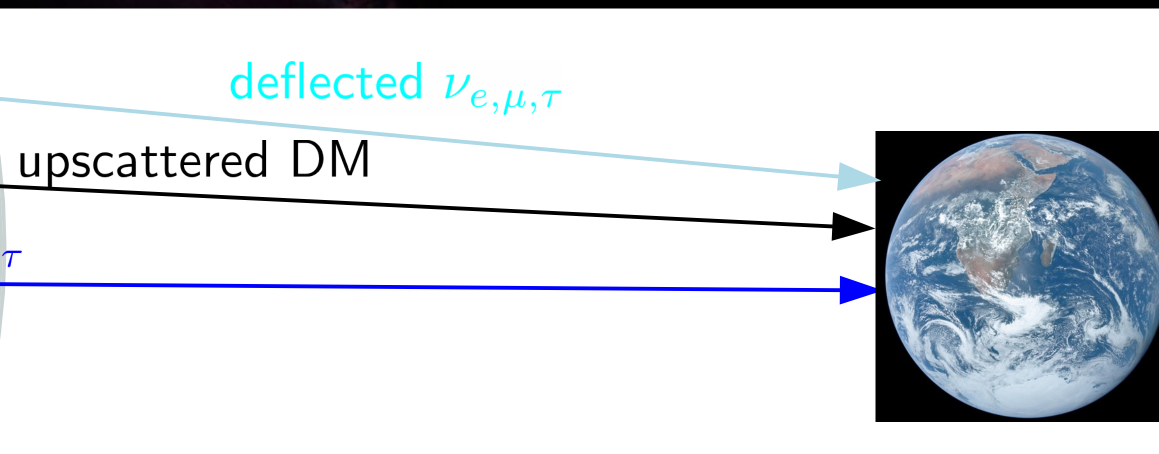
If SNν interact with DM, they may:

a. upscatter the DM and produce “afterglow” events

[Lin, Wu, MRW, Wong, 2206.06864]







Light dark matter boosted by supernova neutrinos

For SN at the galactic center of the Milky Way:

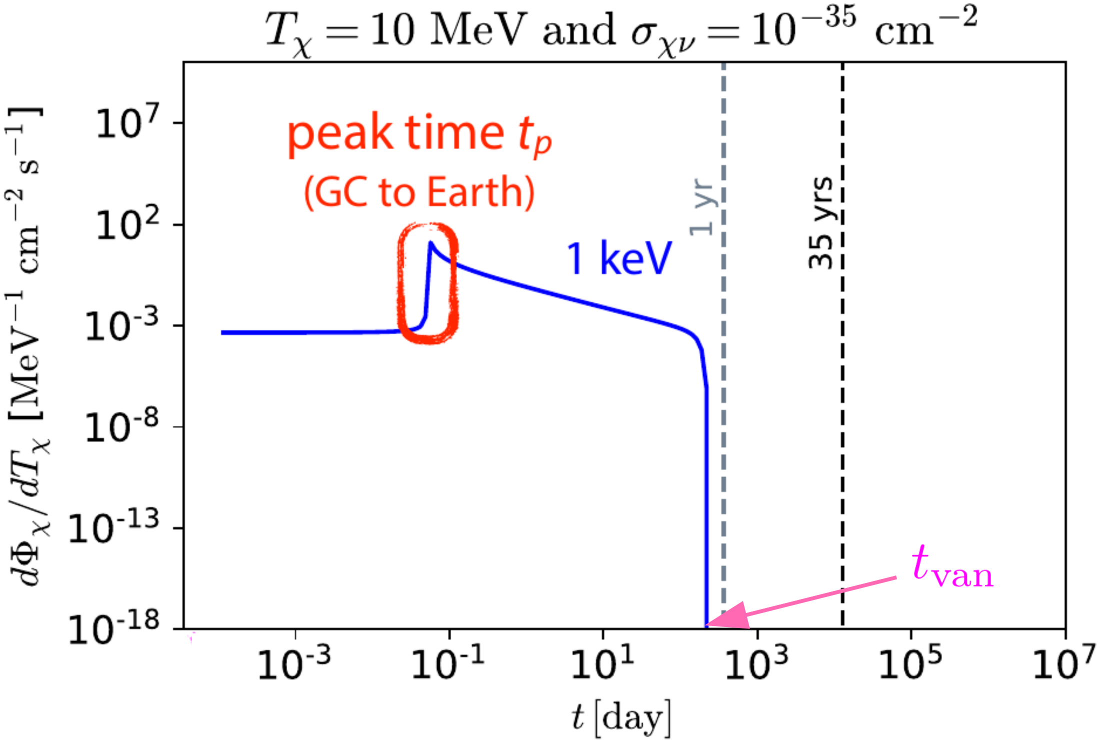
$\rightarrow$ upscattered DM arrives the Earth at
~ 10 days $\times [d/(8\ \text{kpc})][m_\chi/(10\ \text{keV})]^2[E_\chi/(10\ \text{MeV})]^{-2}$ after the arrival of SNν

- Time-dependent feature:

t_p and $t_{\rm van}$ determined by the distance and m_χ, *independent* of $\sigma_{\chi\nu}$

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

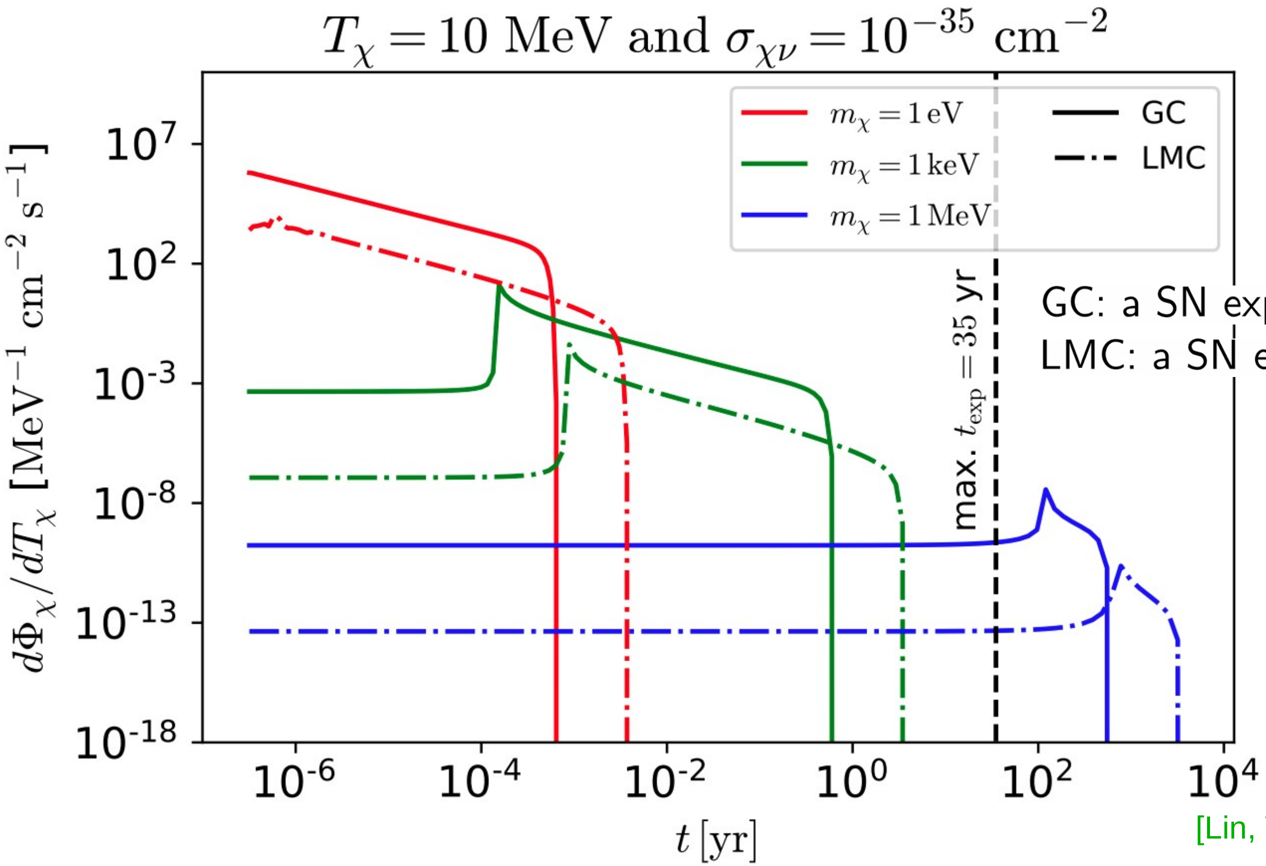
[Lin, Wu, MRW, Wong, 2206.06864]



t: time relative to SNν arrival time

Light dark matter boosted by supernova neutrinos

For SN at GC or at the Large Magellanic Cloud, with different m_χ:



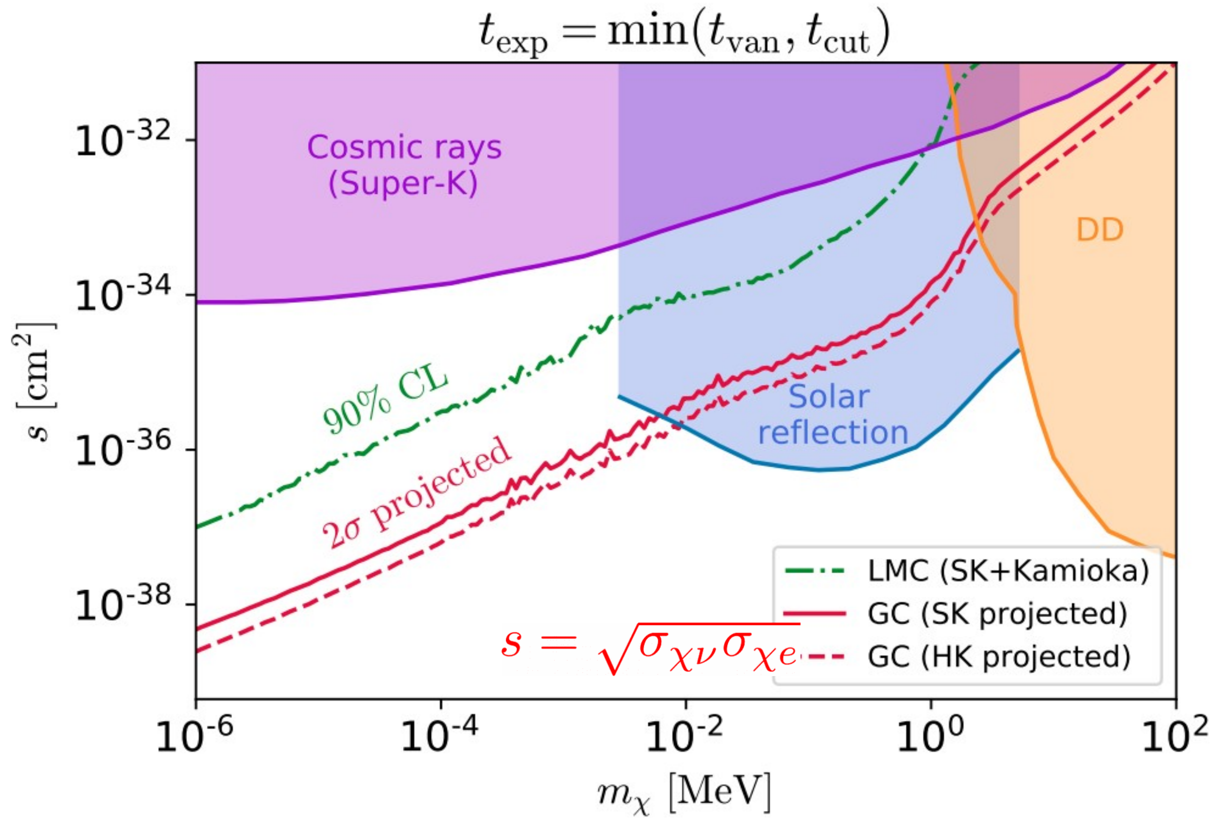
GC: a SN exploded in the MW center
LMC: a SN exploded in the LMC center

[Lin, Wu, MRW, Wong, 2206.06864]

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

SNν boosted DM events and constraints

Consider total event numbers 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 $\sigma_{\chi\nu} \lesssim 10^{-6}\sigma_{\chi e}$

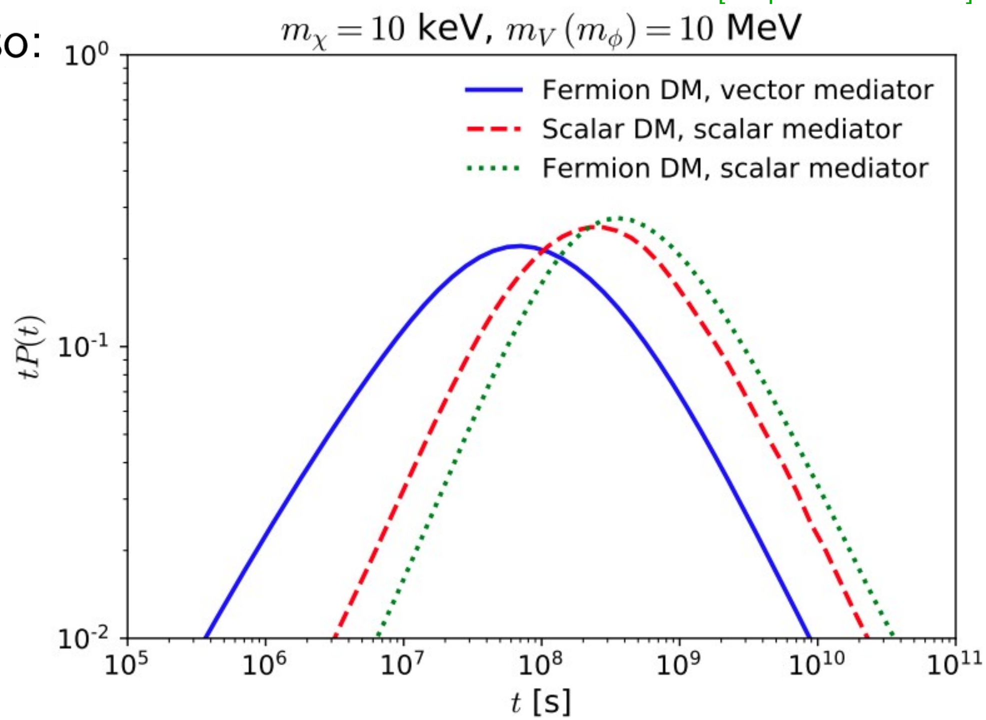
(generalization to arbitrary SN location and $U(1)_{L_\mu - L_\tau}$ model in Lin+, 2307.03522)

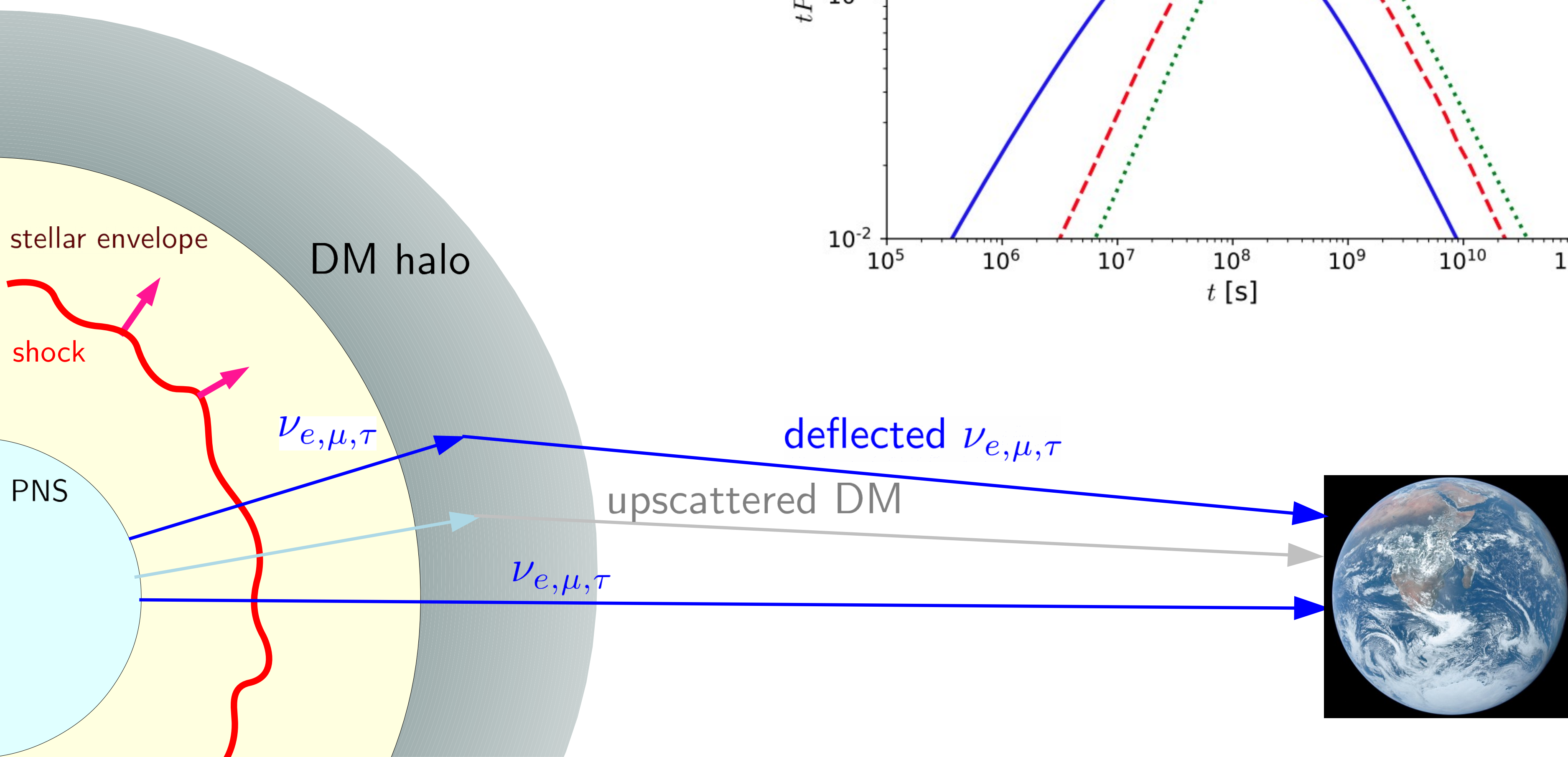
bSM v.s. SN: (v) interaction with DM

If SNν interact with DM, they may also:

b. be deflected and lead to "neutrino echo"

[Carpio+ 2204.09650]





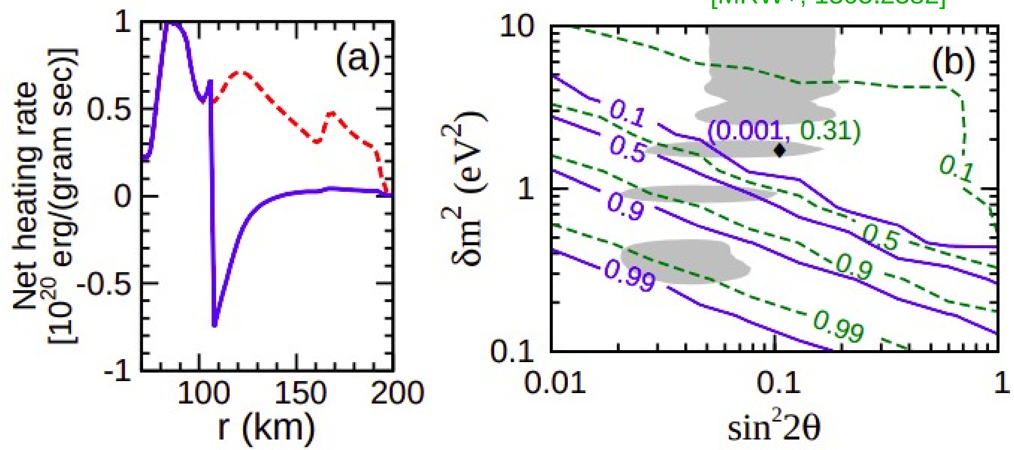
Can bSM physics simply lead to reduction of SNν event without affecting (much) SN evolution?

bSM v.s. SN: (iv) reduce decoupled SNν

e.g., for eV sterile neutrinos:

if ν_e-ν_s mixing exists, ν_e and $\bar{\nu}_e$ can be converted to ν_s and $\bar{\nu}_s$ at $Y_e \simeq 1/3$ (behind the SN shock)

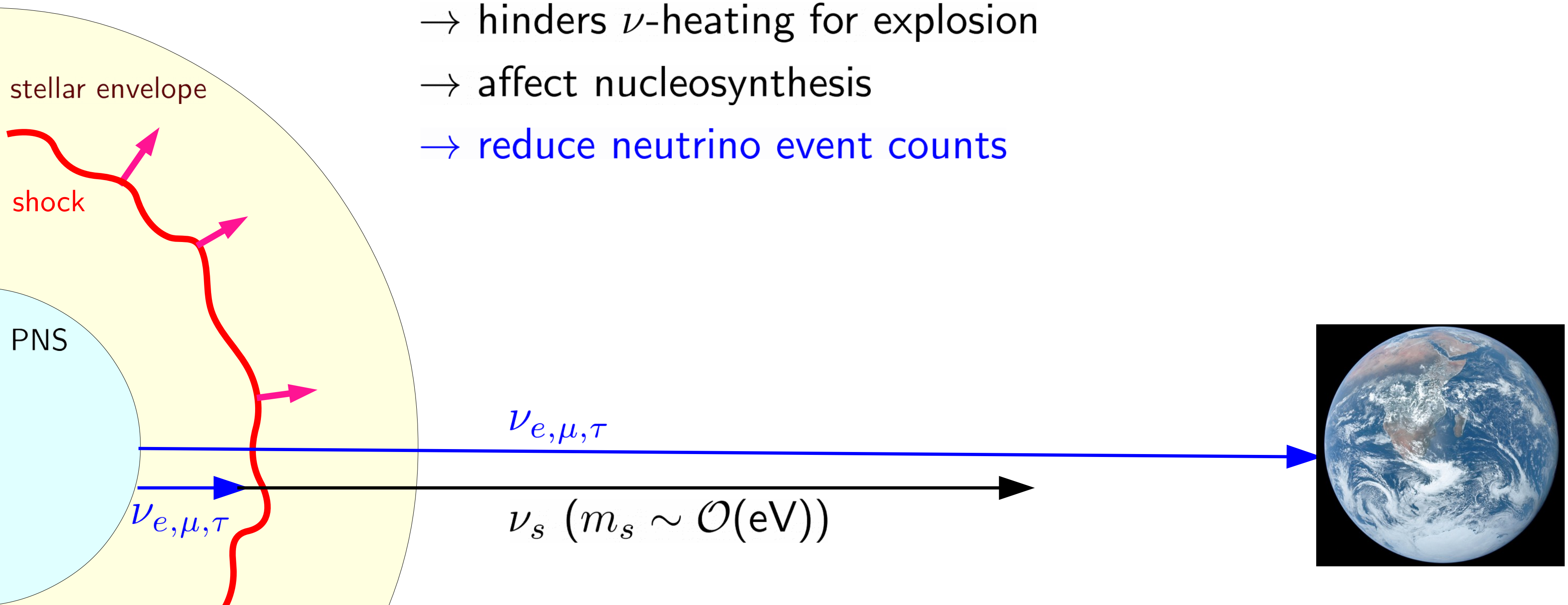
[MRW+, 1305.2382]



$\rightarrow$ hinders ν-heating for explosion

$\rightarrow$ affect nucleosynthesis

$\rightarrow$ reduce neutrino event counts



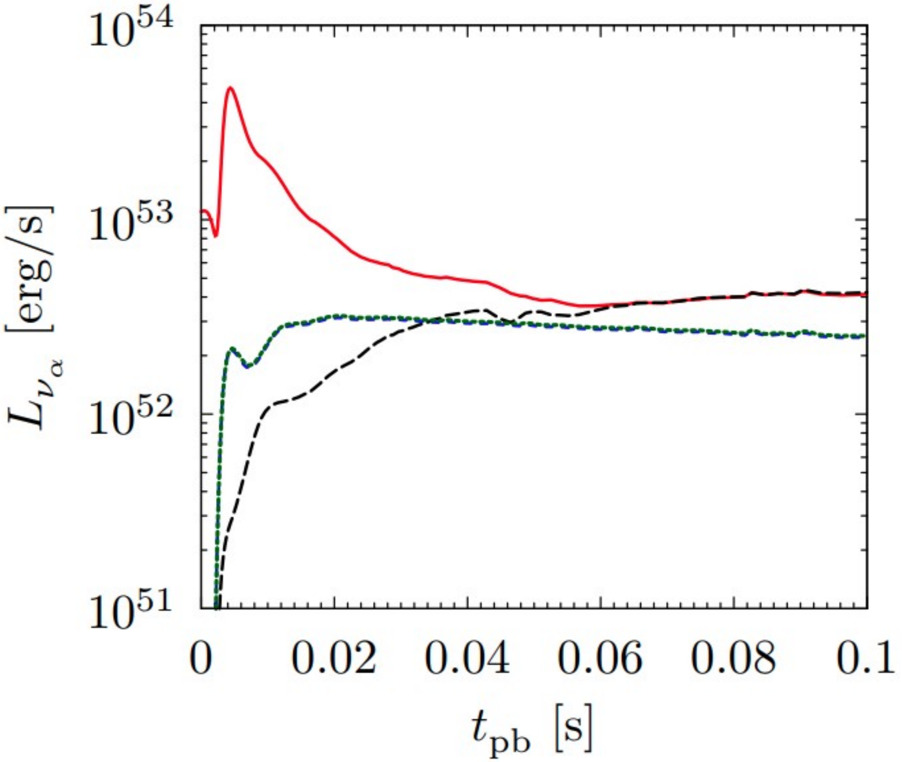
Neutronization burst and eV sterile neutrinos

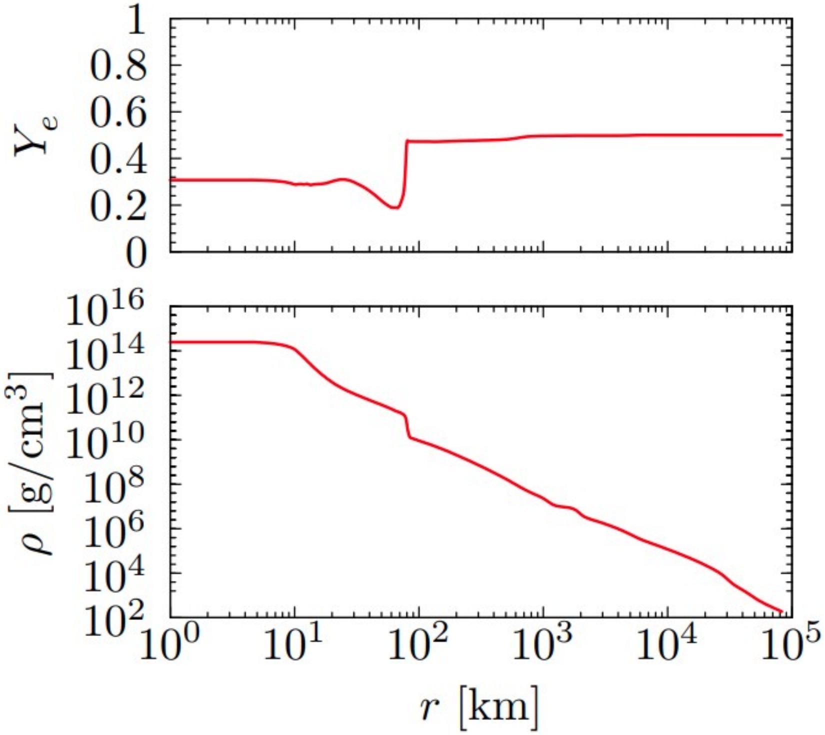
MSW resonance condition for ν_e–ν_s mixing:

$$\frac{\delta m^2}{2E_\nu}\cos\theta_{\rm v} = V_{\rm eff} = \pm\sqrt{2}G_F n_b \left[\frac{3Y_e - 1}{2} + 2Y_{\nu_e} + Y_{\nu_\mu} + Y_{\nu_\tau}\right]$$

$(+$: neutrino, $-$: antineutrino, $Y_i = (n_i - n_{\bar{i}})/n_b)$

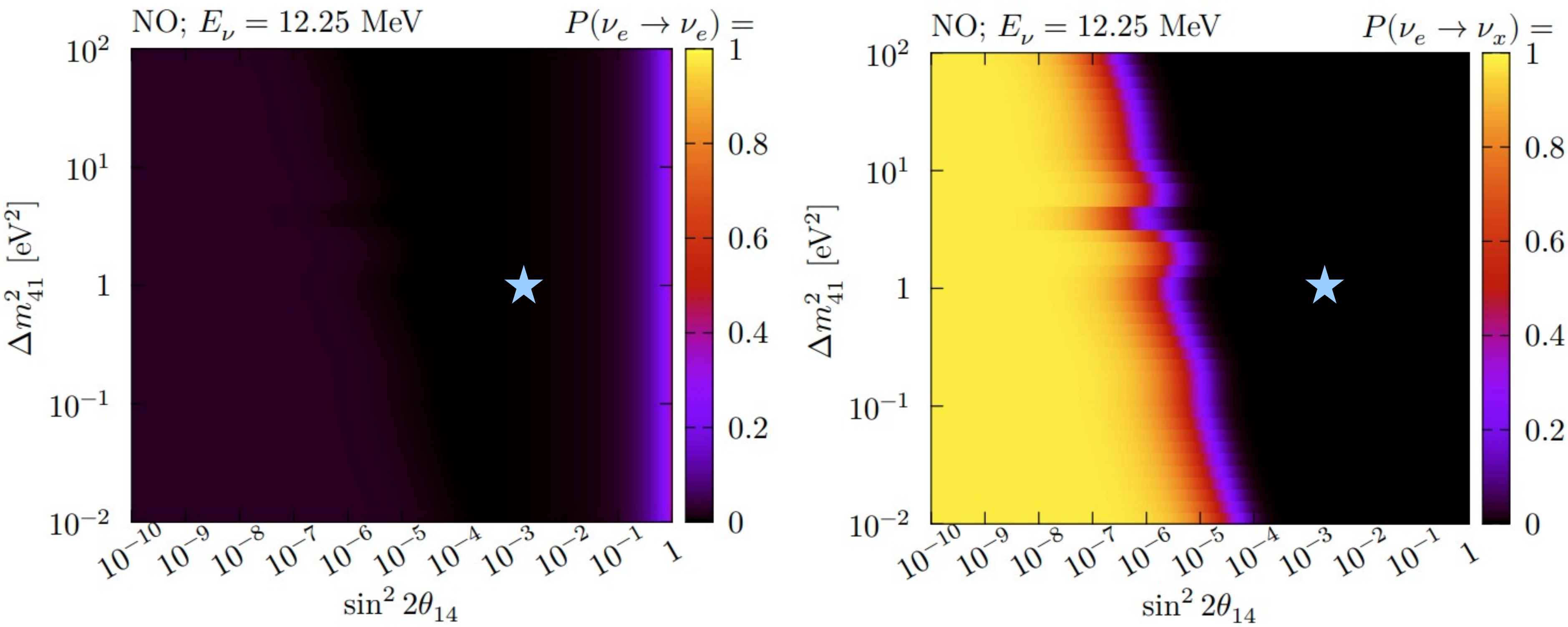
[Tang, Wang, MRW, 2005.09168]





Neutronization burst and eV sterile neutrinos

[Tang, Wang, MRW, 2005.09168]



ν-e scattering in detectors is the most important channel for probing light sterile neutrinos in neutronization burst for normal ordering (NO)

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)

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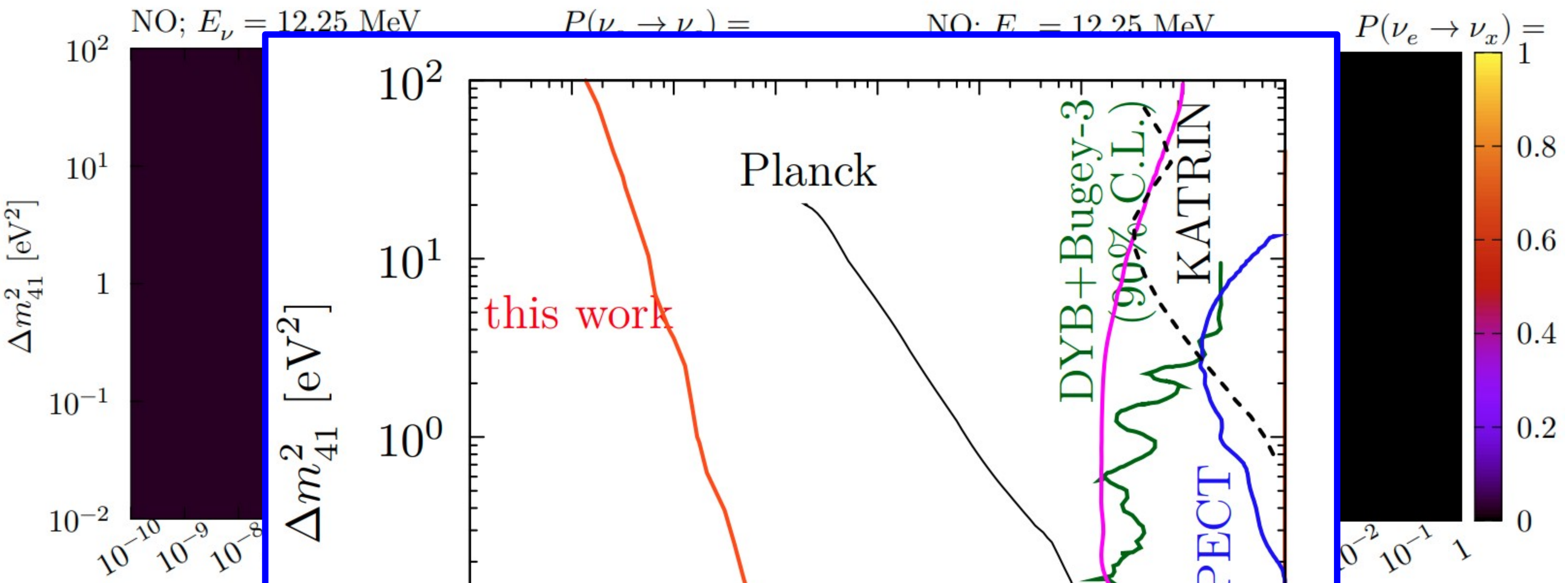


ν-e scatte… light

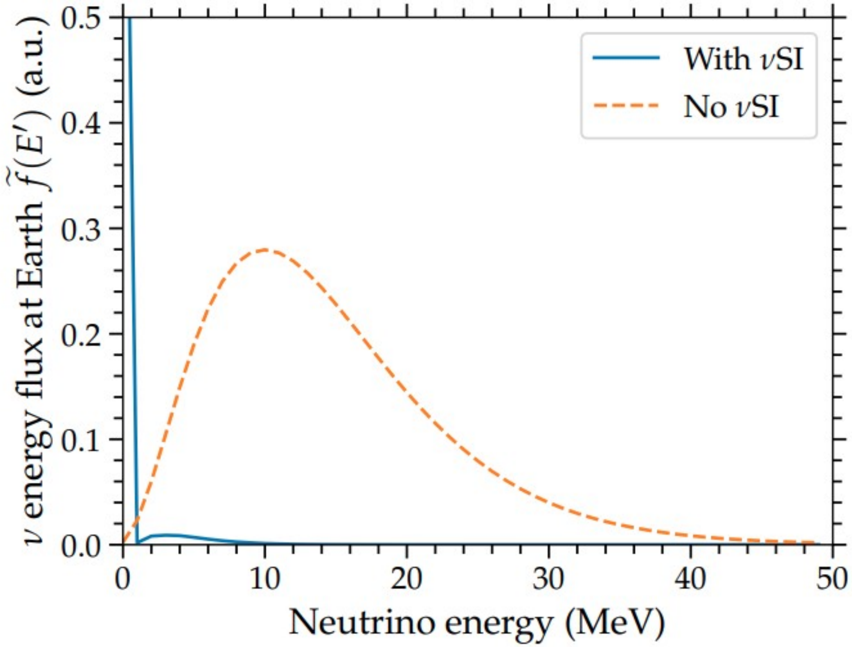
sterile neu…

ν_e; @1…	JUNO pES
3-ν…	9.1
$\sin^2 2\theta_{14} = 1$…	3.3

(for IO, both CC and eES are important)

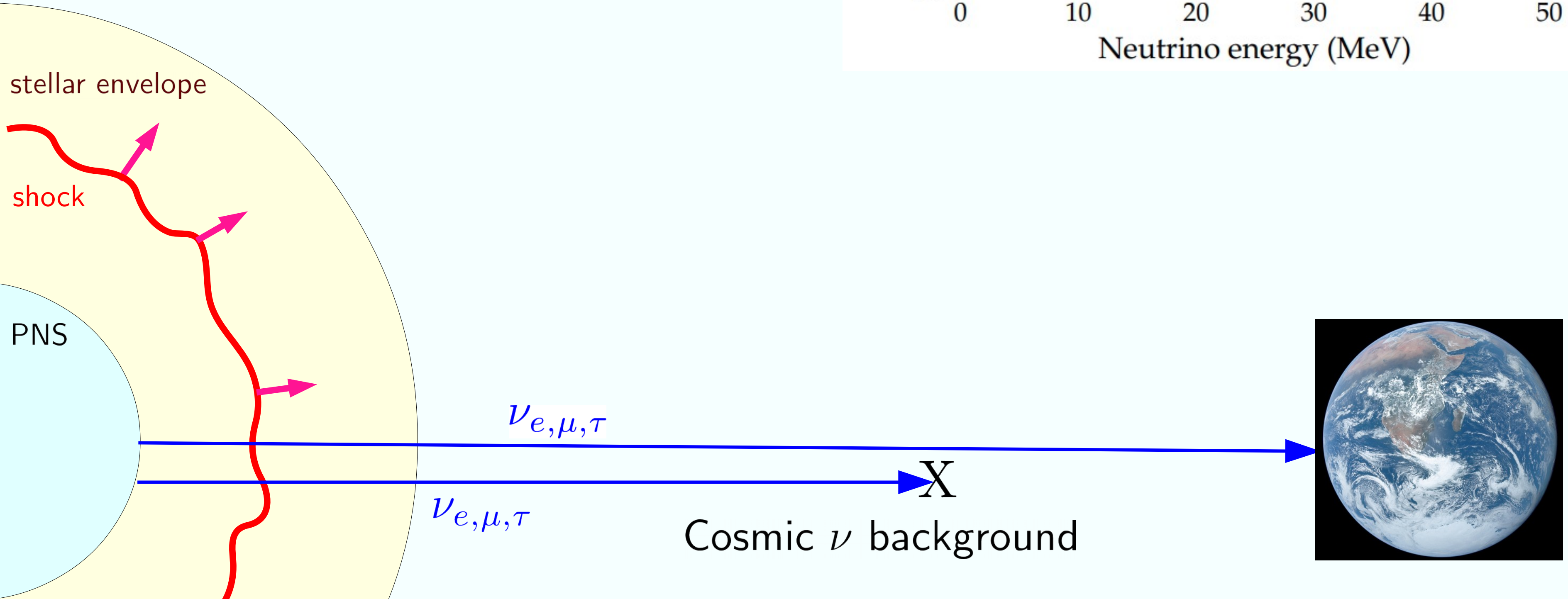
bSM v.s. SN: (iv) reduce decoupled SNν

[Shalgar+1912.09115]



If non-Standard neutrino self-interaction exists, SNν can be downscattered by CνB on its way to Earth

However, when introducing NSI/NSSI, one expects that strong effect on SN dynamics, neutrino decoupling, and oscillations! [see e.g., Chang+ 2206.12426]



Summary & discussions

- Supernova provides a variety of means to probe/constrain bSM physics

Mechanism	applicability	Smoking-gun signature?	Feedback effect?
Cooling	Very wide	X	important
Explosion	Need decay / reconversion	X	Perhaps not
Additional neutrinos or gammas	Need decay / reconversion	Maybe?	no
Direct bSM signals	wide	Maybe?	depends
Interaction with DM	X	V	depends
Disappearing of SNv	restricted	X	no

- For scenarios that affect neutrino emissions, detailed treatment of feedback effect on bSM particle production is critically important. Including them in simulations are needed to obtain robust results.

Summary & discussions

• Effects due to self-interaction among bSM particles (or neutrinos with strong non-standard self-interaction) need to be clarified

• Improved modelings on bSM particle production in thermal environment were carried in recent years, which can significantly affect the bounds

• How do they modify the subsequent evolution of (proto)neutron star and the remnant phase?