Light dark sector and core-collapse supernovae

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Dark Matter in Compact Objects, Stars, and Low-Energy Experiments
INT Program 22-2b, Seattle, August 22, 2022

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MOST 科技部
Ministry of Science and Technology

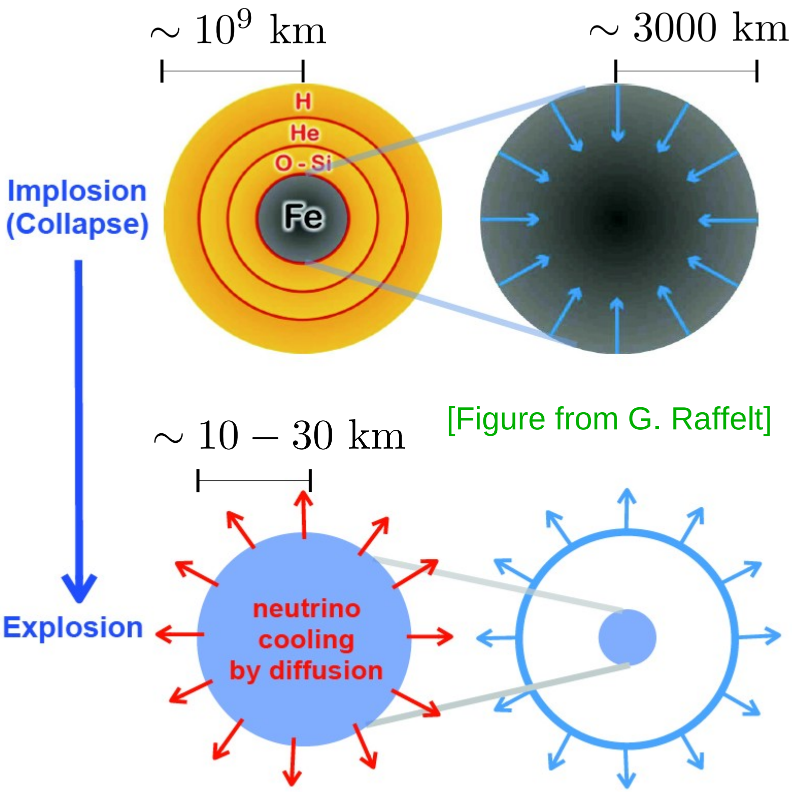
Core-collapse supernovae

- 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

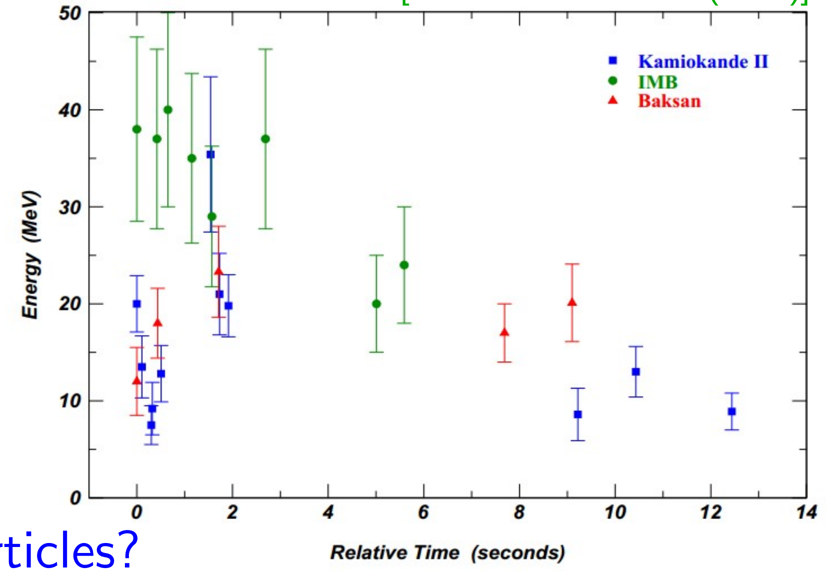
SN1987a (From AAO website)



[Figure from G. Raffelt]

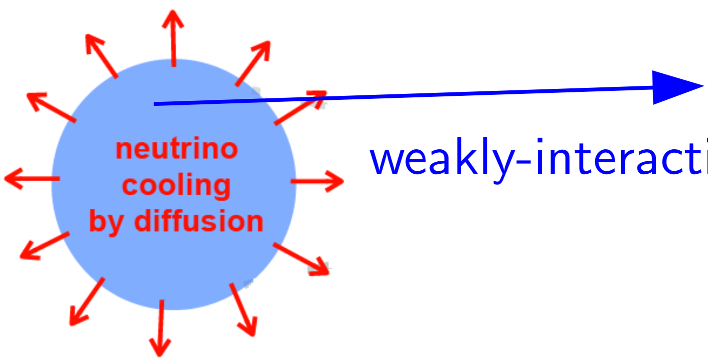
Supernova cooling bound

[J. Heise PhD Thesis (2002)]



~ 20 SN $\bar{\nu}_e$ detected from SN1987a

$L_{\bar{\nu}_e} \sim 5 \times 10^{52}$ erg, $\langle E_{\bar{\nu}_e} \rangle \sim 15$ MeV



weakly-interacting bSM particles?

If the energy carried away by any bSM particles is larger than that by neutrinos predicted within the Standard Model, the cooling timescale of the proto-neutron star becomes shorter than ~ 10 s

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

axions, keV sterile neutrinos, dark photons,...

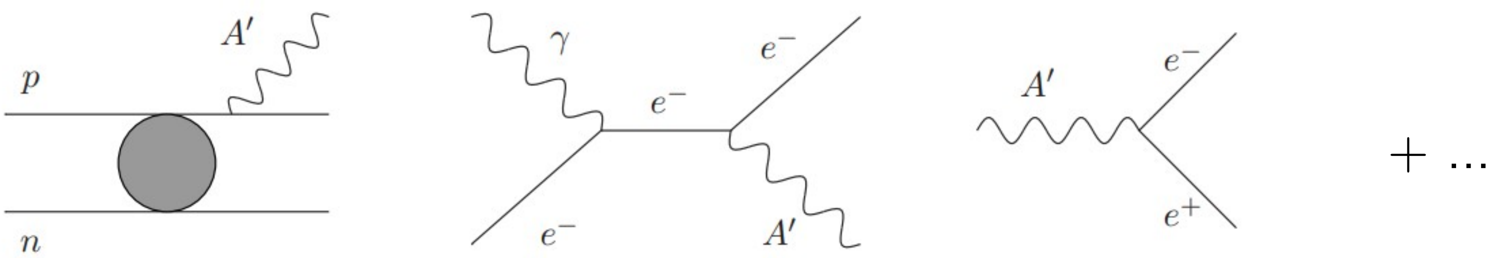
Cooling constraint on dark photon

For dark photon portal dark sector:

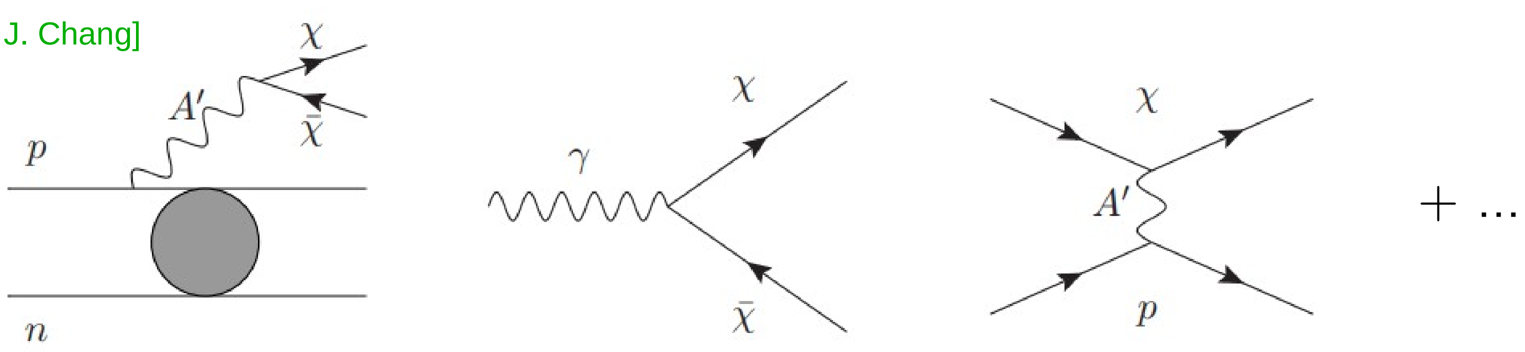
[Holdom 1986, Okun 1982, and many others]

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

They can be produced in PNS via a number of processes, e.g.,



[Adapted from J. Chang]



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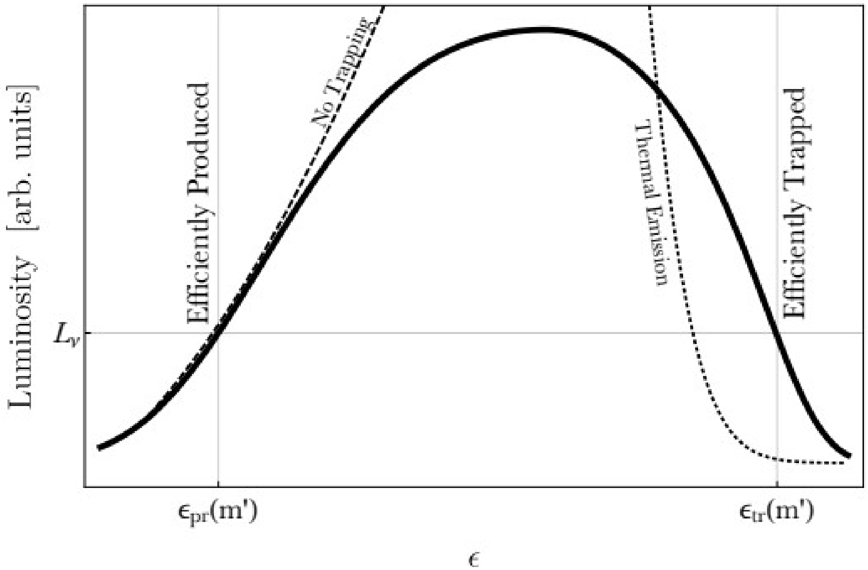
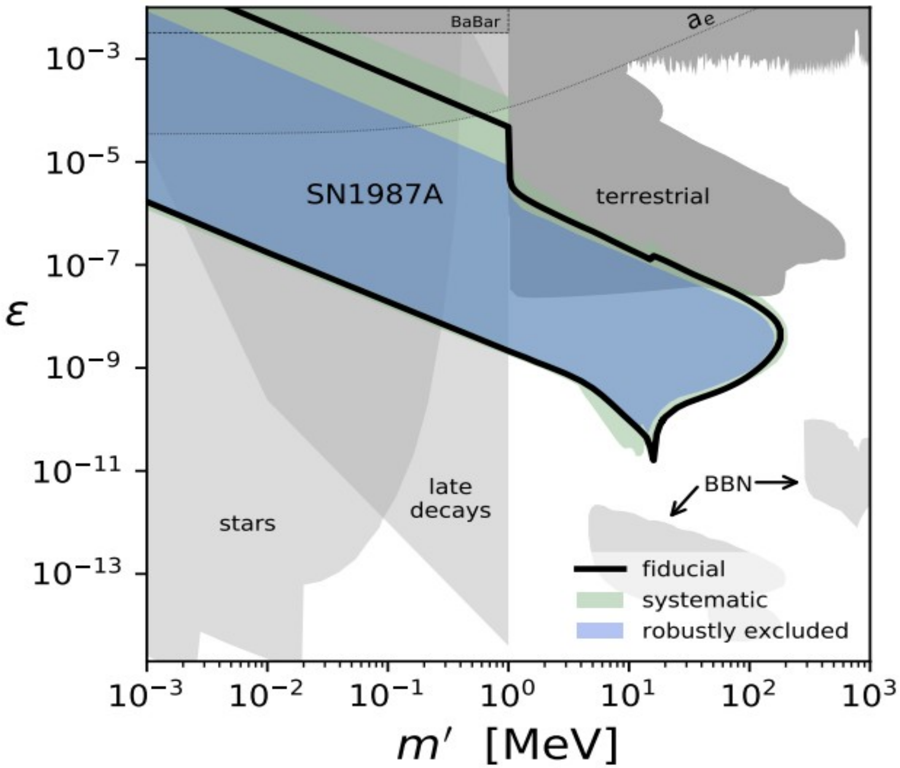
Considering the degree of freedom of dark photon only:

[Chang+ 1611.03864]

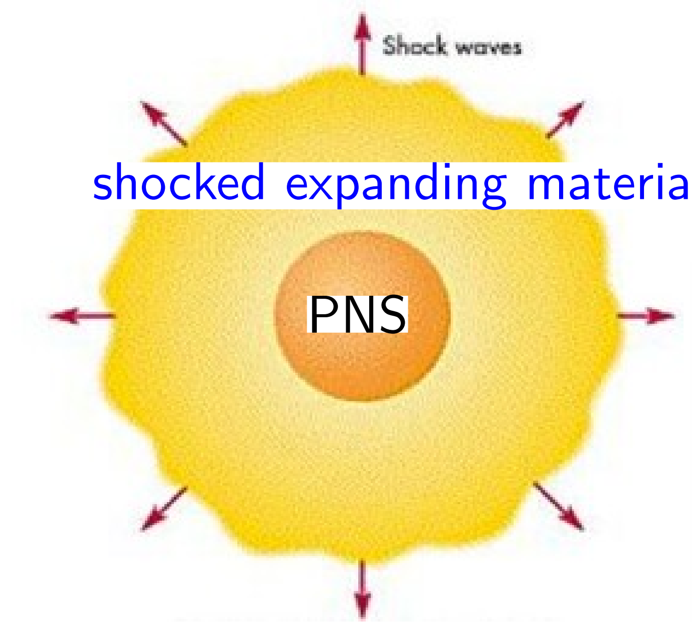


cooling constraint



[See also Dent+, Rrapaj+, Hardy+,...]

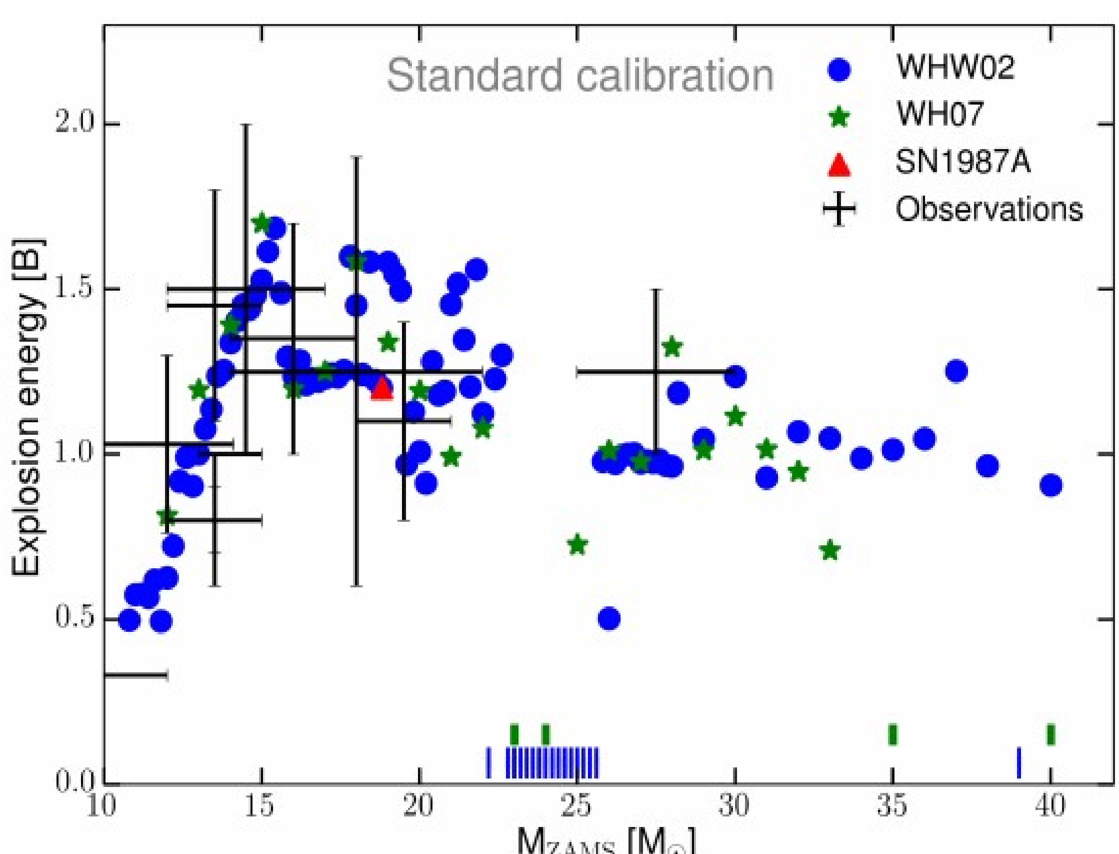
Supernova ejecta and explosion energy



$M_{\mathrm{ej}} \sim 10\ M_{\odot},\ \ v_{\mathrm{ej}} \sim 0.01\ \mathrm{c}$

$$
\begin{aligned}
E_{\mathrm{expl}} &\sim \text{K.E. of ejecta} \\
&\sim \tfrac{1}{2} M_{\mathrm{ej}} v_{\mathrm{ej}}^2 \\
&\sim 10^{51}\ \mathrm{erg} \equiv 1\ \mathrm{B(ethe)}
\end{aligned}
$$

more observations than just SN1987a!



[Ebinger+, 1804.03182]

Explosion energy constraints on radiative dark particle

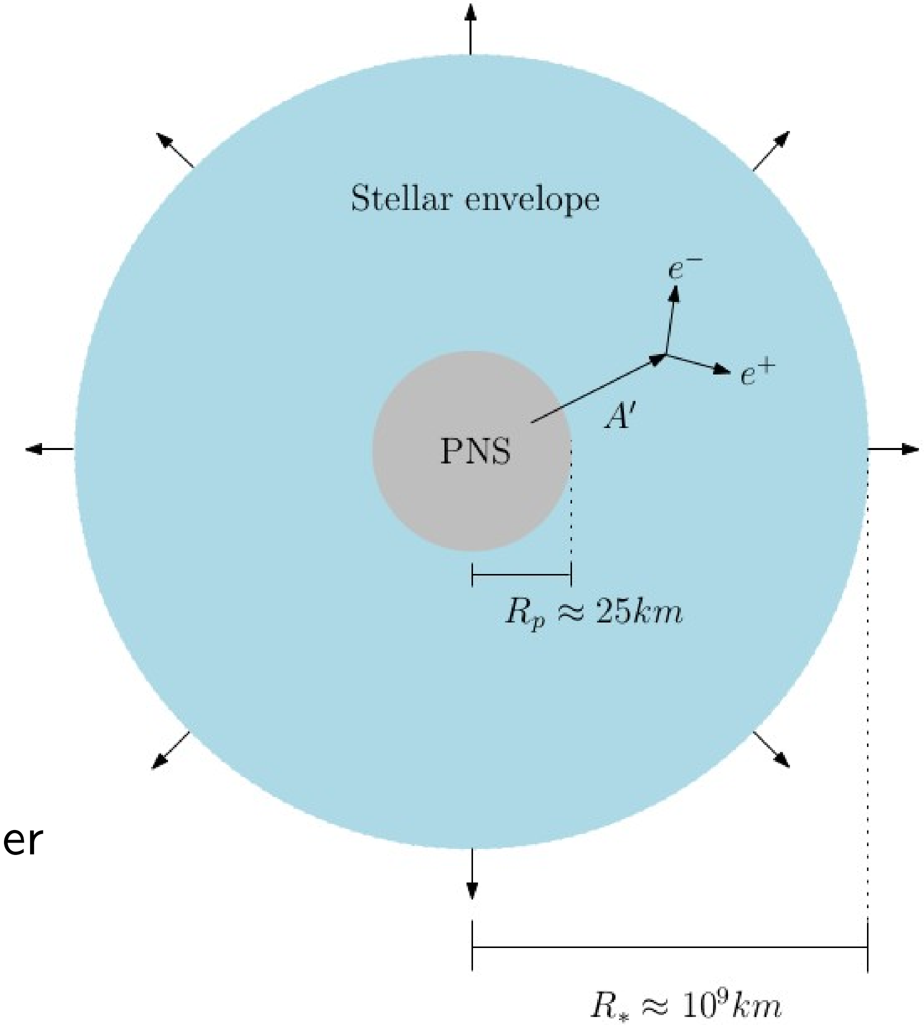
[A. Sung, H. Tu, MRW, PRD 99 (2019) 121305, arXiv: 1903.07923]

The gravitational binding energy of the stellar envelope outside the proto-neutron star radius is

$$E_b \lesssim 10^{51}\ \text{erg}$$

The observed explosion energy is

$$E_{\text{expl}} \lesssim 2 \times 10^{51}\ \text{erg}$$



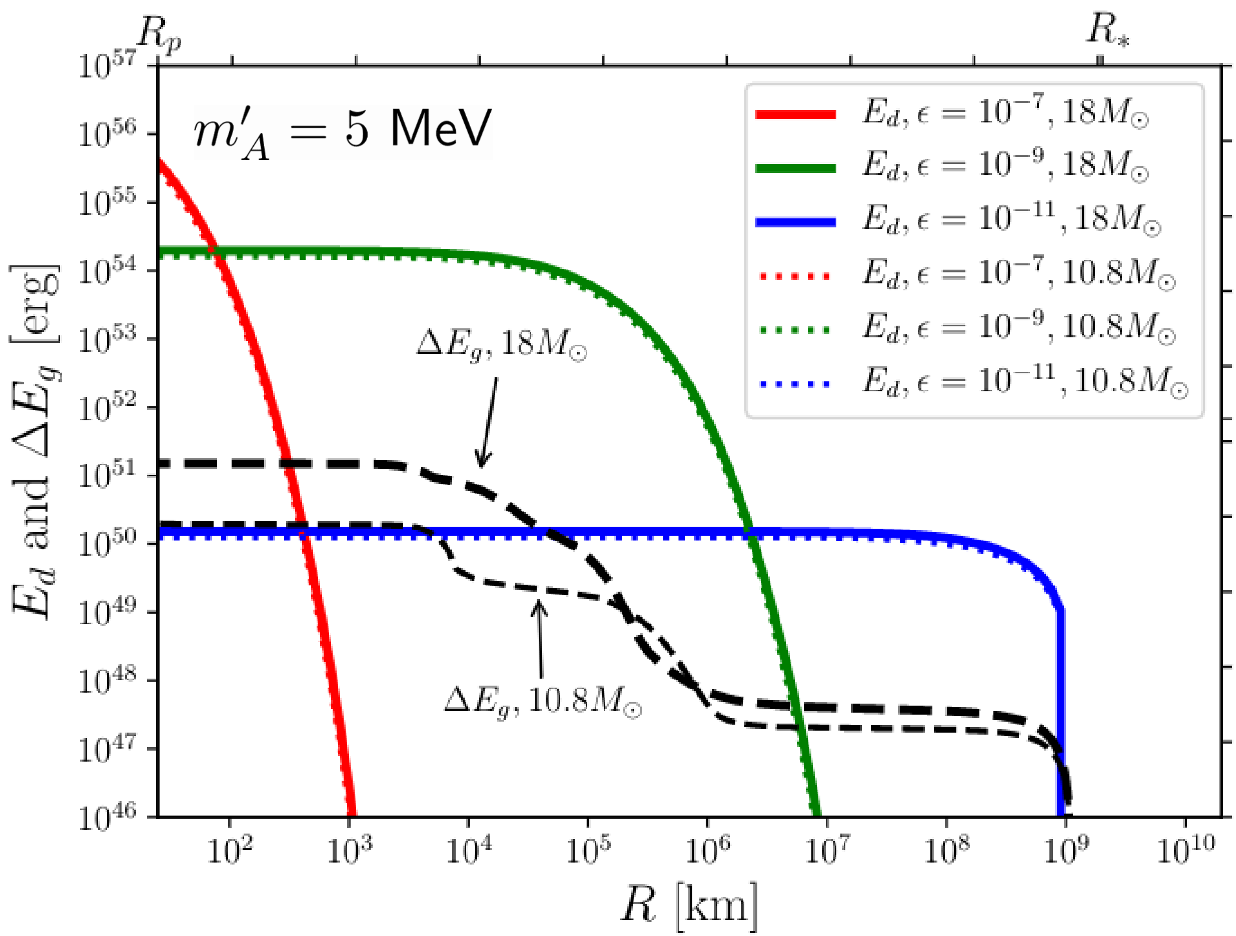
$\rightarrow$ new particles that can deposit energy more than $\simeq 3 \times 10^{51}$ erg into the stellar enevelope & expanding material is NOT consistent with observation

$\rightarrow$ can improve the constraint on exotic particle to smaller coupling by $\sim$ one order of magnitude

Decay of dark photons outside PNS

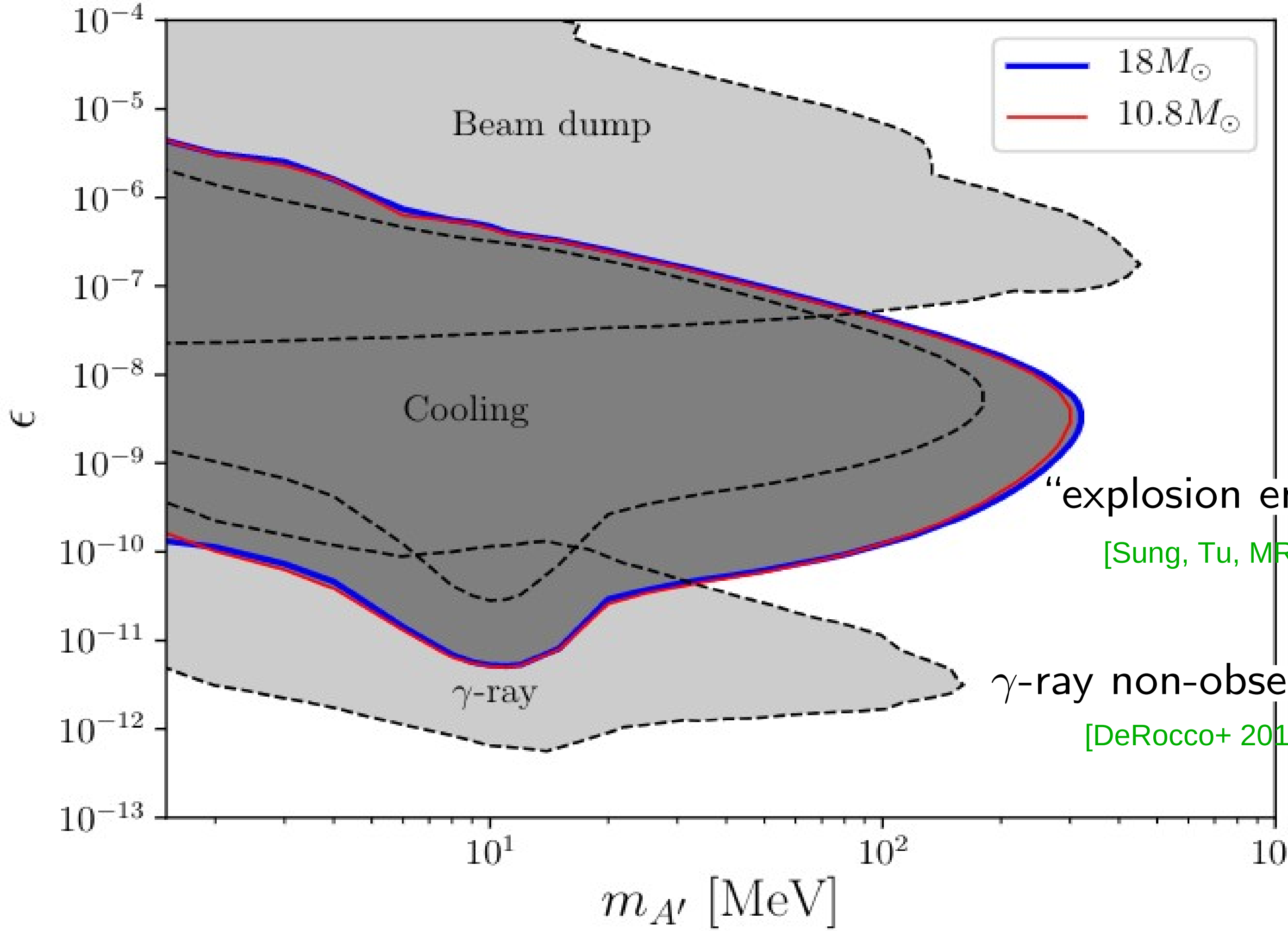
E_d: cumulative energy deposition above a stellar radius R

ΔE_g: gravitational binding energy above R



The radiative decay of dark particle can deposit much more energy than the binding energy energy of stellar envelope + the explosion energy

Supernova bounds on dark photon



"explosion energy"

[Sung, Tu, MRW, 2019]

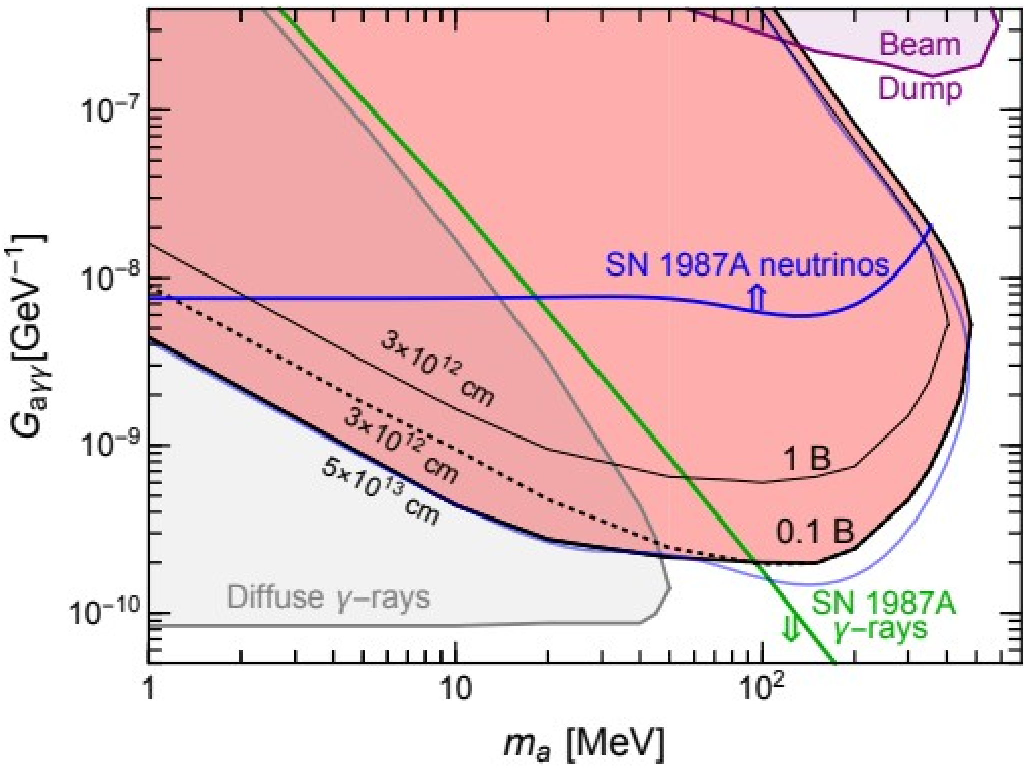
γ-ray non-observation

[DeRocco+ 2019]

Some discussions...

- low-energy supernovae (observed $E_{\rm expl} \simeq 0.1 B$)

[Caputo+ 2201.09890]



Some discussions...

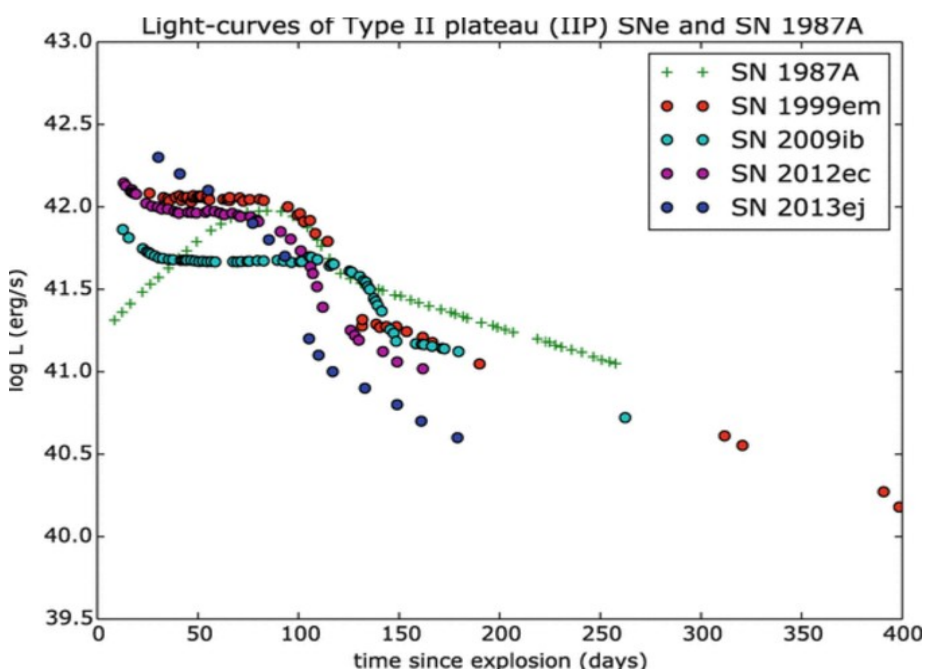
- low-energy supernovae [Caputo+ 2201.09890]

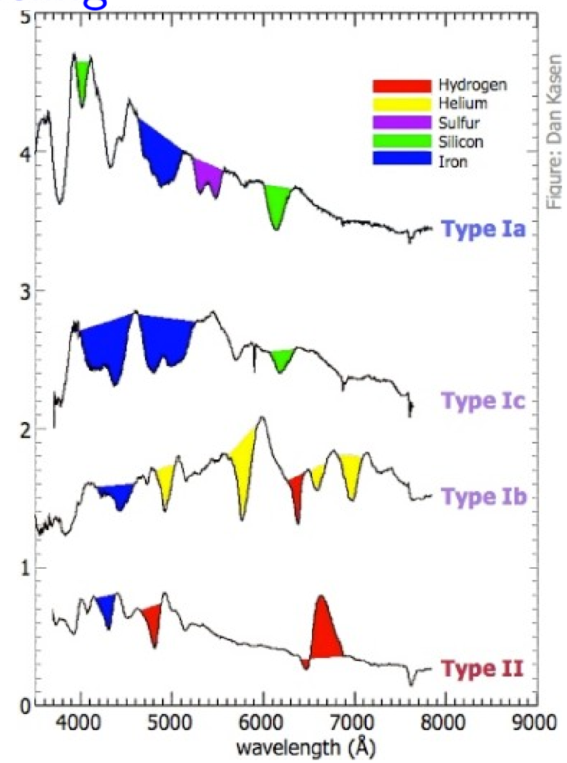
  (observed $E_{\rm expl} \simeq 0.1B$)

- modification of lightcurve and spectrum?

  e.g., altered ejecta structure, collision between bSM-driven & shock driven components, change of absorpton feature,...

  $\rightarrow$ requires further hydro+radiative transfer modeling





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- disfavor SN explosions helped by bSM energy deposition

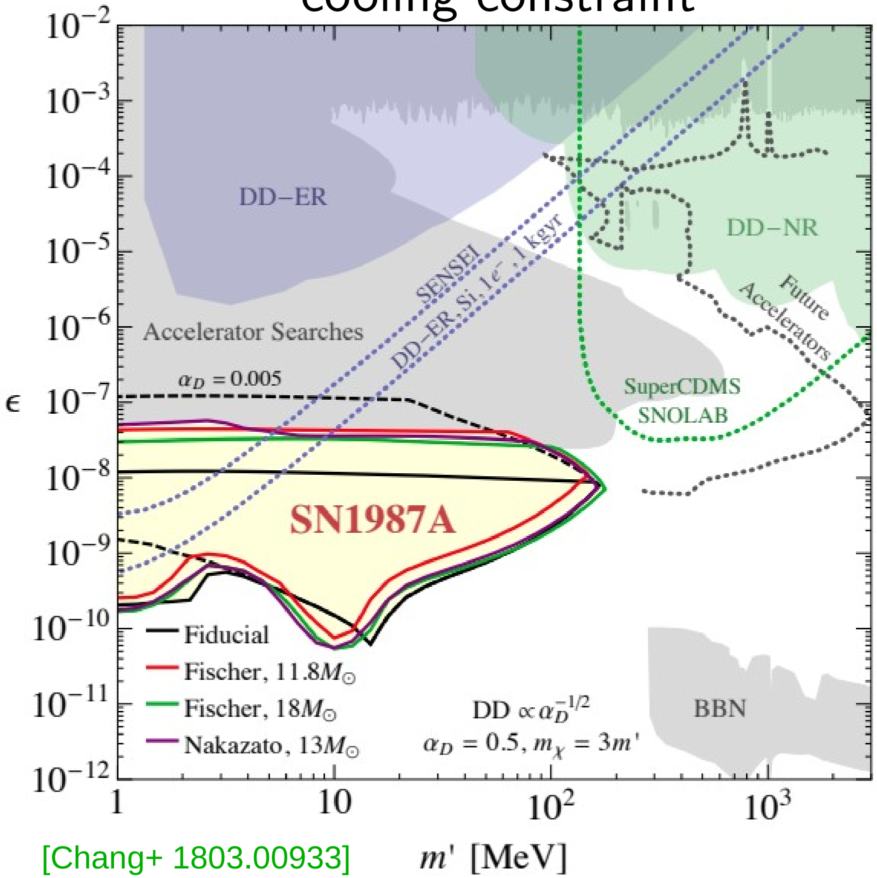
  Such scenario typically requires a sustained energy deposition rate of $\gtrsim 10^{51}$ erg/s during the accretion phase

SN constraints on light dark sector?

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

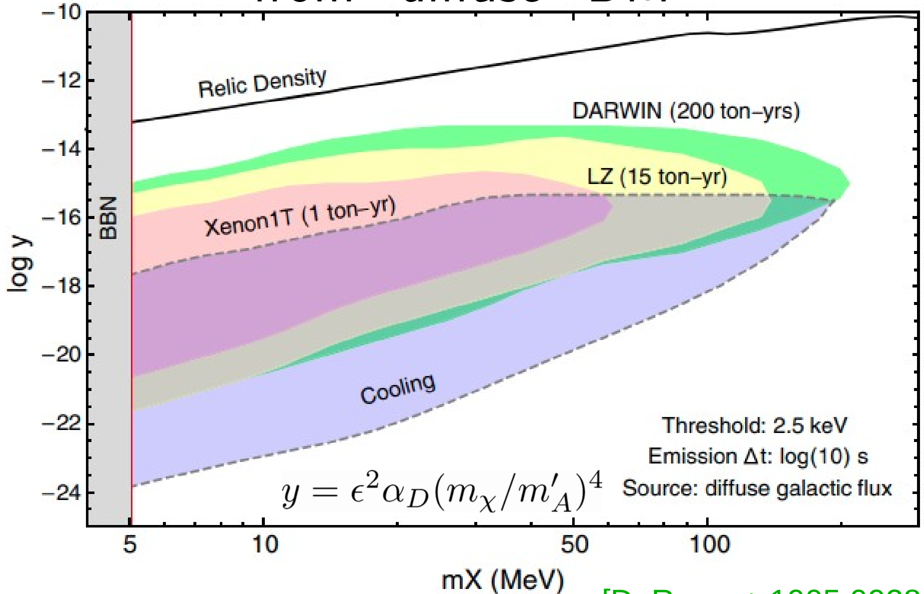
Including both light dark fermion & dark photon

cooling constraint



[Chang+ 1803.00933]

from "diffuse" DM



[DeRocco+ 1905.09284]

Effect of dark sector self-interaction?

Diffuse luminosity

For light & neutral particles, they can diffuse out from stars even if they are in thermal contact with matter (e.g., photons, neutrinos)

Diffusion luminosity across a surface (let's take the neutrinosphere):

$$L_i = -\frac{2g_i R_\nu^2 T_\nu^3}{3\pi} \left.\frac{dT}{dr}\right|_{R_\nu} \frac{1}{\langle \lambda_i^{-1}(R_\nu)\rangle} \times \int_{m_i/T_\nu}^{\infty} \xi^3 \sqrt{\xi^2 - \left(\frac{m_i}{T_\nu}\right)^2} \frac{e^\xi}{(e^\xi \pm 1)^2} d\xi$$

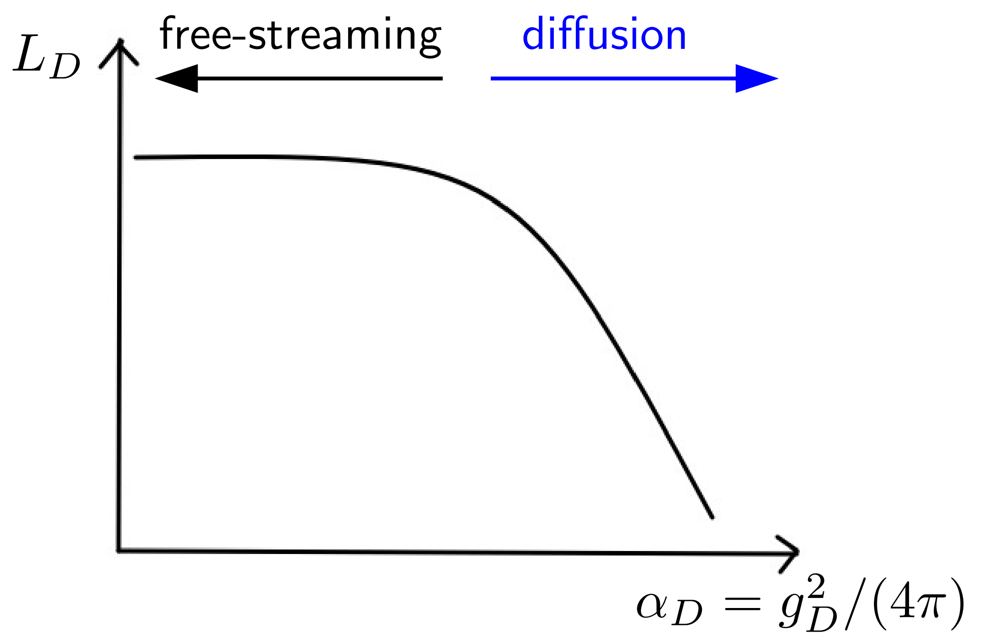
$\propto$ mean-free-path

larger dark sector coupling

$\rightarrow$ smaller mean-free-path

$\rightarrow$ smaller diffuse luminosity

diffusion due to self-trapping affects supernova (or in general, stellar) cooling bound!



When to switch to diffusion limit?

Computing precisely the amount of dark sector particle emission from PNS is difficult and requires solving non-equilibrium transport equations

[Sung, Guo, MRW, 2102.04601]

We estimate this by:

i) estimate whether dark particles can be abundantly produced in PNS within characteristic time scale

$$\Delta t_i = \begin{cases} t_{\rm free}, \text{ if } t_{i,\rm diff} \leq t_{\rm free}, \\ t_{i,\rm diff}, \text{ if } t_{\rm free} < t_{i,\rm diff} < t_{\rm cool}, \\ t_{\rm cool}, \text{ if } t_{\rm cool} \leq t_{i,\rm diff}. \end{cases}$$

ii) if so and if particle mean-free-path is smaller than the radius of neutrinosphere

$$N_i > N_i^{\rm eq}, \text{ and } \langle \lambda_i^{-1}(R_\nu) \rangle > R_\nu^{-1}$$

$\rightarrow$ diffusion limit

Mass	Interaction	Type	Particle	Coupling
$m_{A'} < 2m_\chi$	$A'np \to np$	Abs.	SM	ϵ^2
	$A'e^- \to e^-\gamma$	Abs.	SM	ϵ^2
	$A' \to e^-e^+$	Abs.	SM	ϵ^2
	$A'A' \to \chi\bar{\chi}$	Abs.	DS	α_D^2
	$A'\chi \to \chi A'$	Sca.	DS	α_D^2
$m_{A'} > 2m_\chi$	$A'np \to np$	Abs.	SM	ϵ^2
	$A'e^- \to e^-\gamma$	Abs.	SM	ϵ^2
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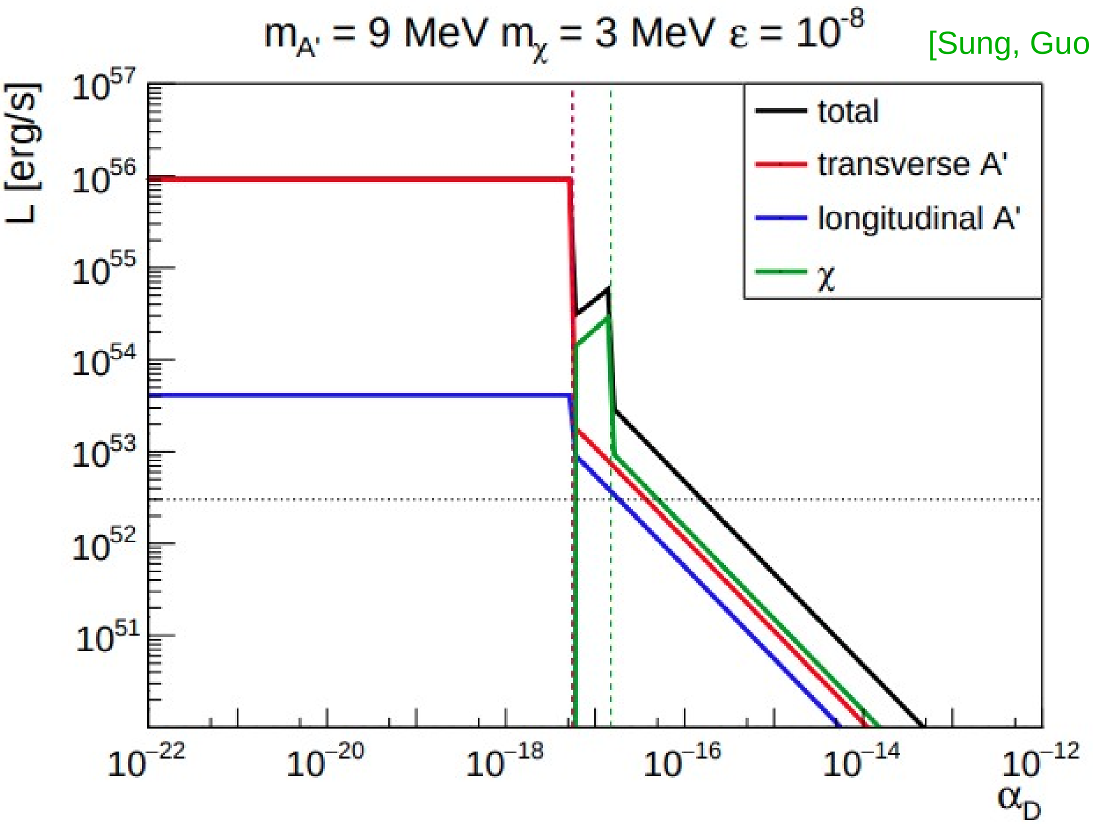
	$A' \to \chi\bar{\chi}$	Abs.	DS	α_D

Mass	Interaction	Type	Particle	Coupling
$m_{A'} < 2m_\chi$	$\chi\bar{\chi}np \to np$	Abs.	SM	$\epsilon^2\alpha_D$
	$\chi\bar{\chi} \to e^-e^+$	Abs.	SM	$\epsilon^2\alpha_D$
	$\chi\bar{\chi} \to \gamma^*$	Abs.	SM	$\epsilon^2\alpha_D$
	$\chi p \to \chi p$	Sca.	SM	$\epsilon^2\alpha_D$
	$\chi e^- \to \chi e^-$	Sca.	SM	$\epsilon^2\alpha_D$
	$\chi\bar{\chi} \to A'A'$	Abs.	DS	α_D^2
	$\chi\chi \to \chi\chi$	Sca.	DS	α_D^2
	$\chi\bar{\chi} \to \chi\bar{\chi}$	Sca.	DS	α_D^2
	$\chi A' \to A'\chi$	Sca.	DS	α_D^2
$m_{A'} > 2m_\chi$	$\chi p \to \chi p$	Sca.	SM	$\epsilon^2\alpha_D$
	$\chi e^- \to \chi e^-$	Sca.	SM	$\epsilon^2\alpha_D$
	$\chi\bar{\chi} \to A'$	Abs.	DS	α_D

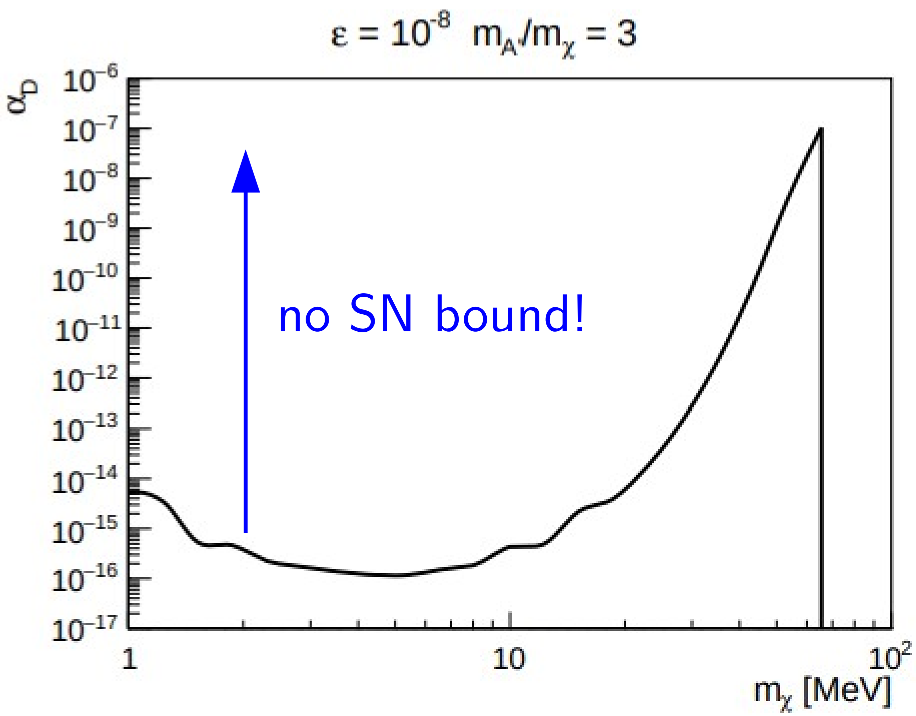
Self-trapping and dark luminosity



[Sung, Guo, MRW, 2102.04601]

- self-trapping effect can evade the SN bound for $\alpha_D \gtrsim 10^{-16}$
- the corresponding $\sigma_{\chi\bar{\chi}}$ (or equavalent) is $\sim \mathcal{O}(10^{-40})$ cm^2

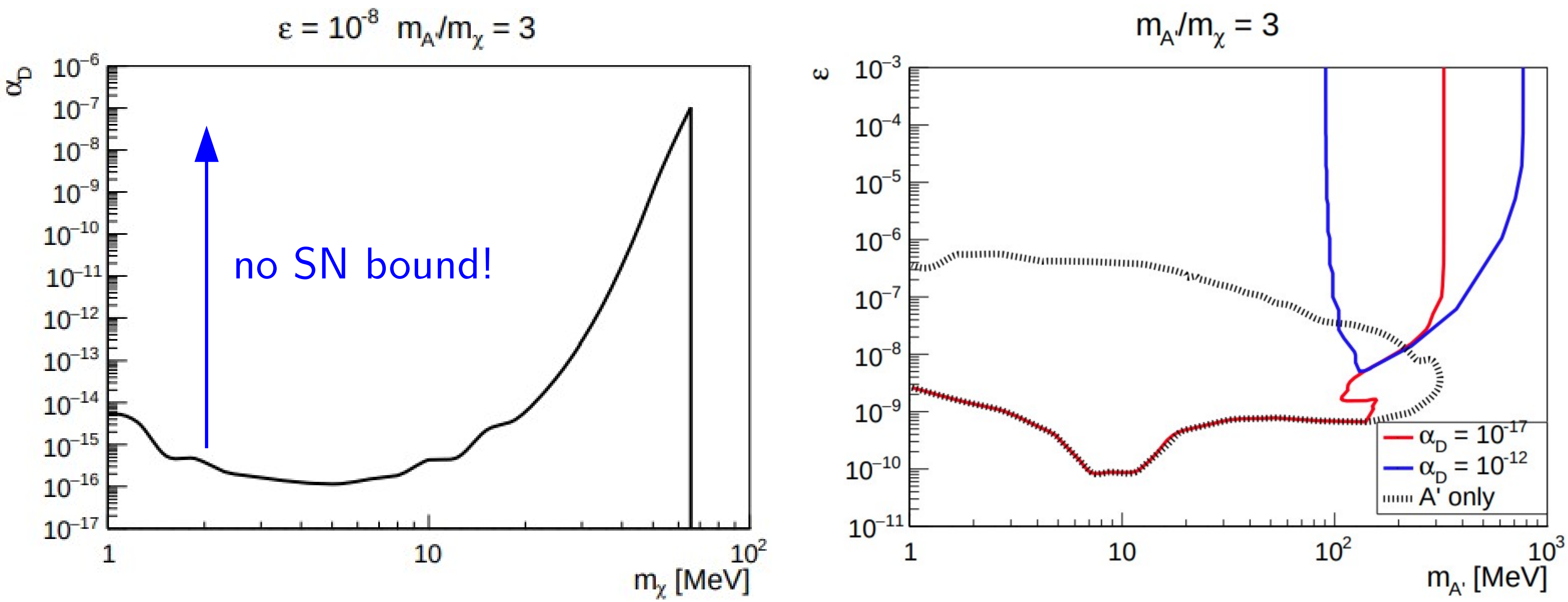
Self-trapping effects on supernova bound



[Sung, Guo, MRW, 2102.04601]

- erase bounds for $m_{A'} \lesssim 30$ MeV if $\alpha_D \gtrsim 10^{-16}$

Self-trapping effects on supernova bound



[Sung, Guo, MRW, 2102.04601]

- erase bounds for $m_{A'} \lesssim 30$ MeV if $\alpha_D \gtrsim 10^{-16}$
- may extend SN bounds to large ϵ for small α_D, due to the decay of $A' \to \chi\bar{\chi}$

Some discussions...

If these light dark sector particles got trapped...

- How do they modify the subsequent evolution of (proto)neutron star?

- Any potential asymmetry to seed a compact dark component inside NS to be probed by GW?

- Can the same mechanism work (in a meaningful way) to evade other stellar cooling bounds?

- A transient phase of "dark matter" burst (which may not be actually trapped)?