Verifying the failing supernova constraint on dark photons with 2D hydrodynamic simulations

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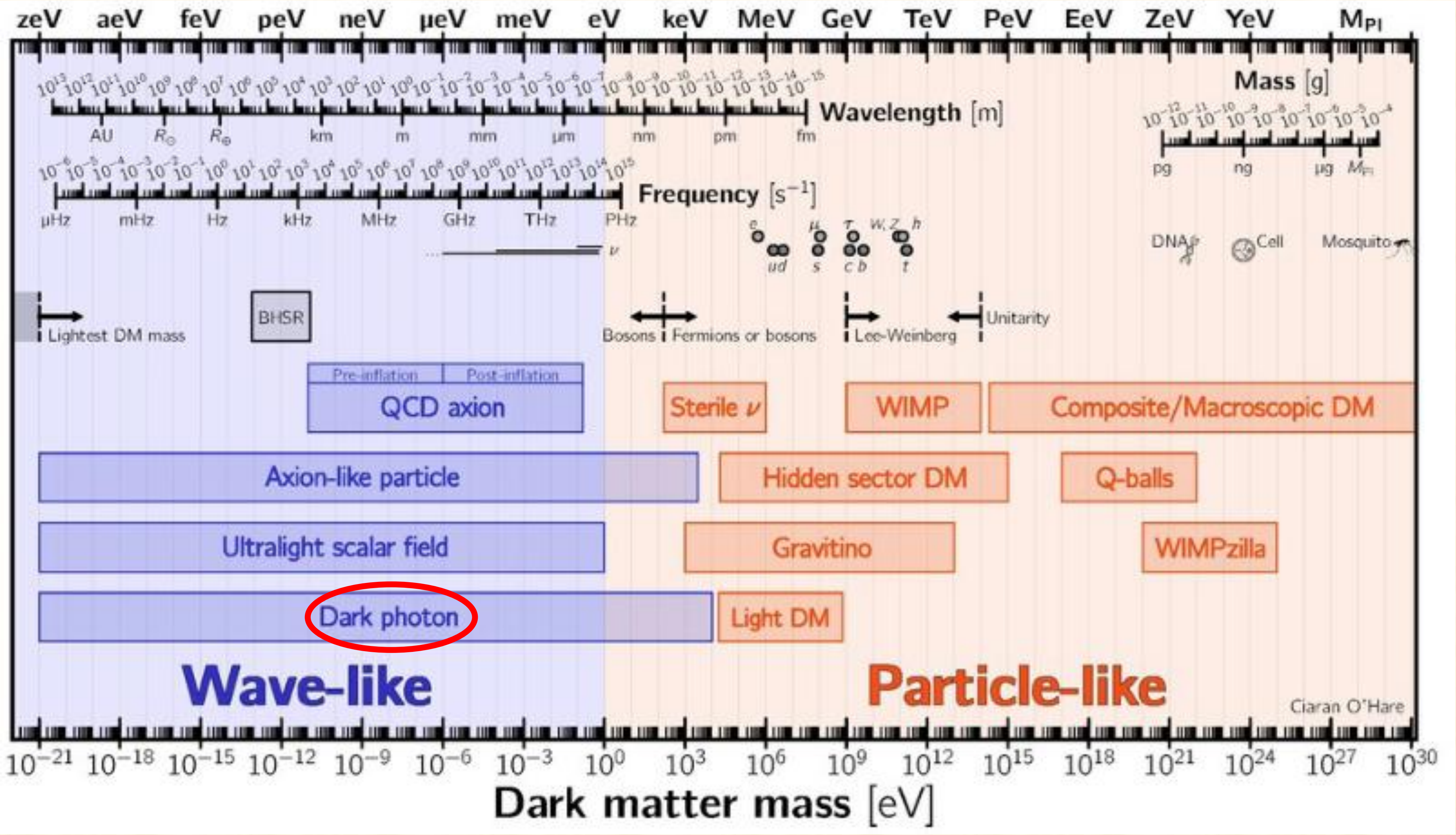
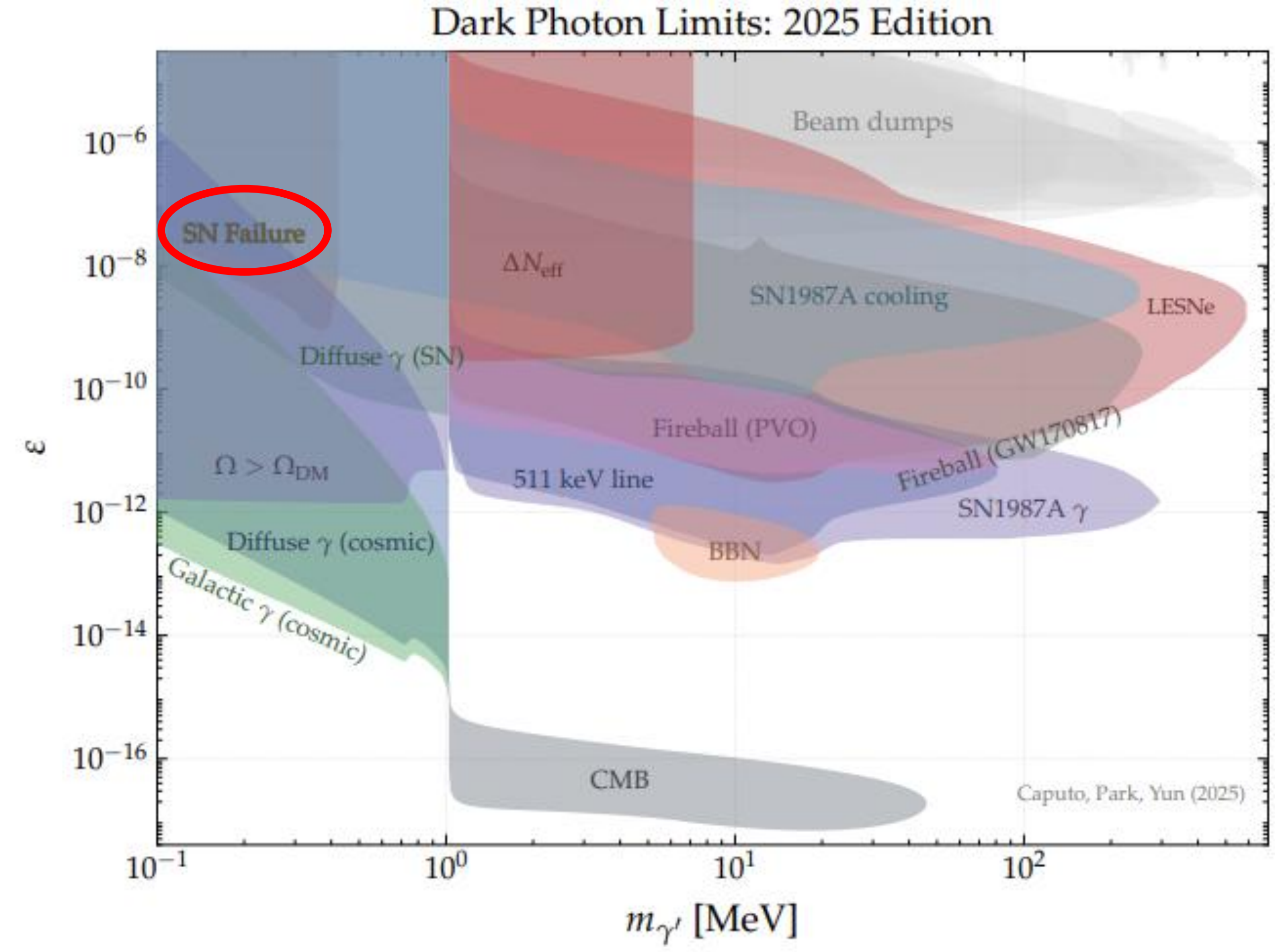
KM, T. Takiwaki, & K. Kohri, PRD, 113, L041303 (2026)

Dark Matter Landscape

https://en.wikipedia.org/wiki/File:Dark_matter_candidates.pdf



Dark Photon



Caputo et al., (2025) arXiv:2511.15785

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

Kinetic mixing

Core-collapse supernova bounds:

- Cooling bound
- γ-ray bound
- Explosion energy bound
- **Failing supernova bound**

Supernova Failure by ~100 keV Dark Photons?

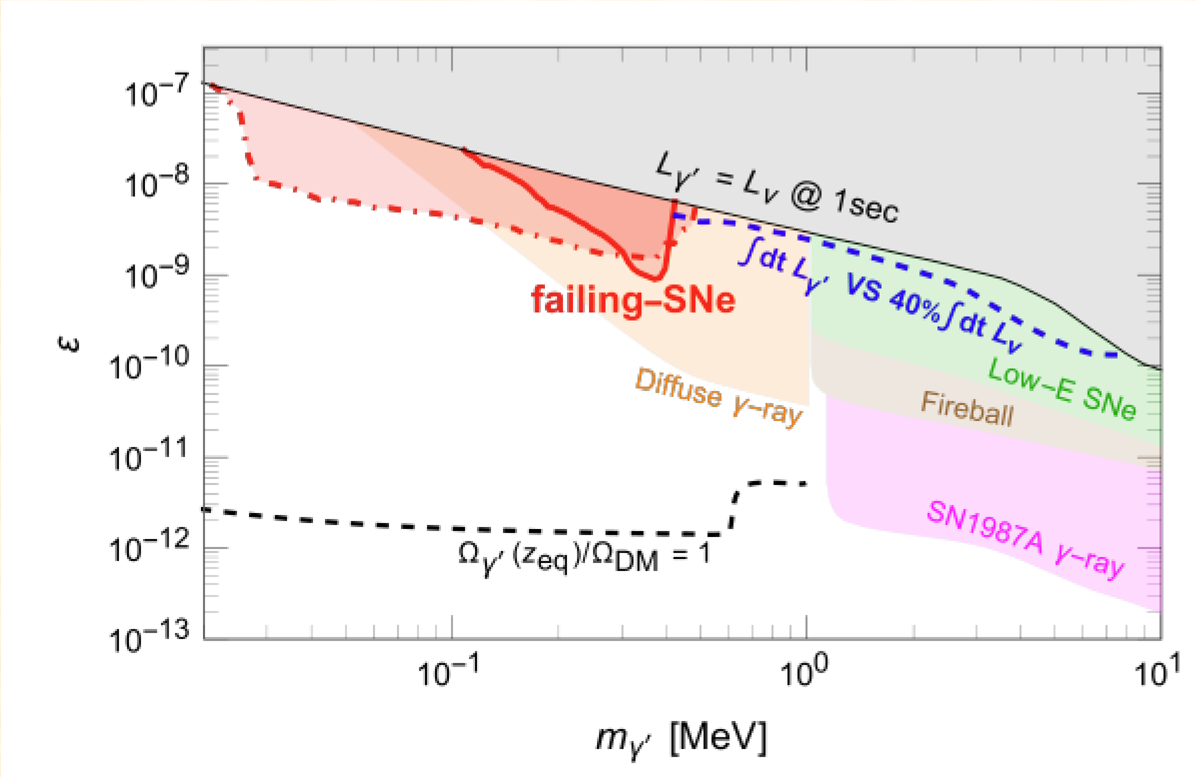
- **Dark photons produced in the stellar core can prevent supernova explosion**.

⇒ a new constraint on dark photons

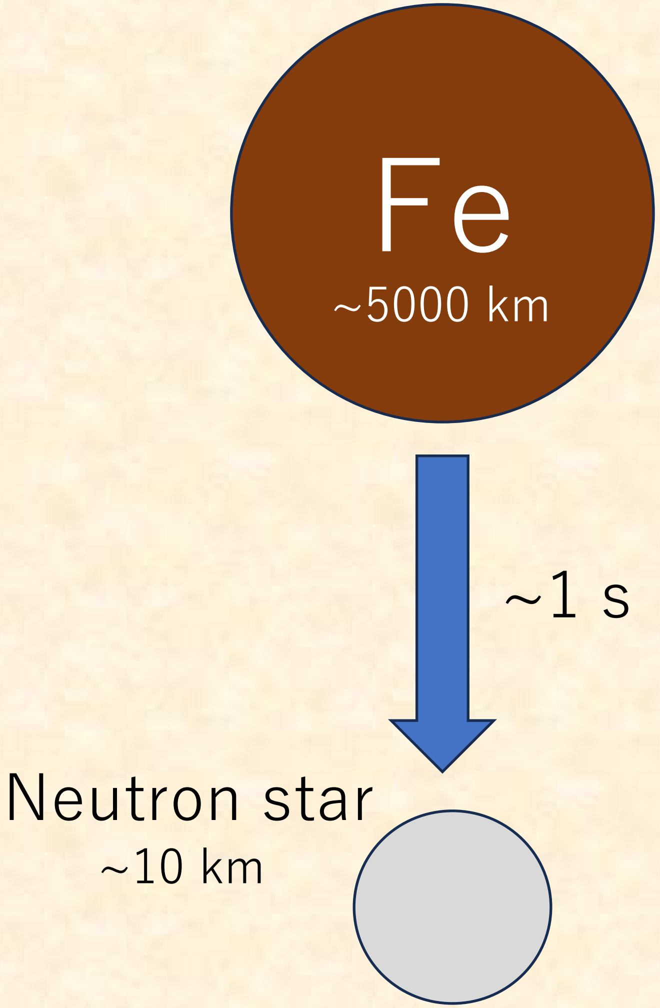
- ***Assumption***: If the exotic cooling rate exceeds 20% of the neutrino heating rate, explosion will be failed.

⇒ **Simulations are needed to verify the idea!**

Caputo et al., PRL 134 (2025) 151002



Neutrino-driven Supernova Explosion



- Gravitational energy release

$$E_g = \left(-\frac{GM^2}{R_{star}}\right) - \left(-\frac{GM^2}{R_{NS}}\right) \approx 10^{53}\ \mathrm{erg}$$

~10 km

- Neutrino energy

$$E_\nu = 10^{53}\ \mathrm{erg}$$

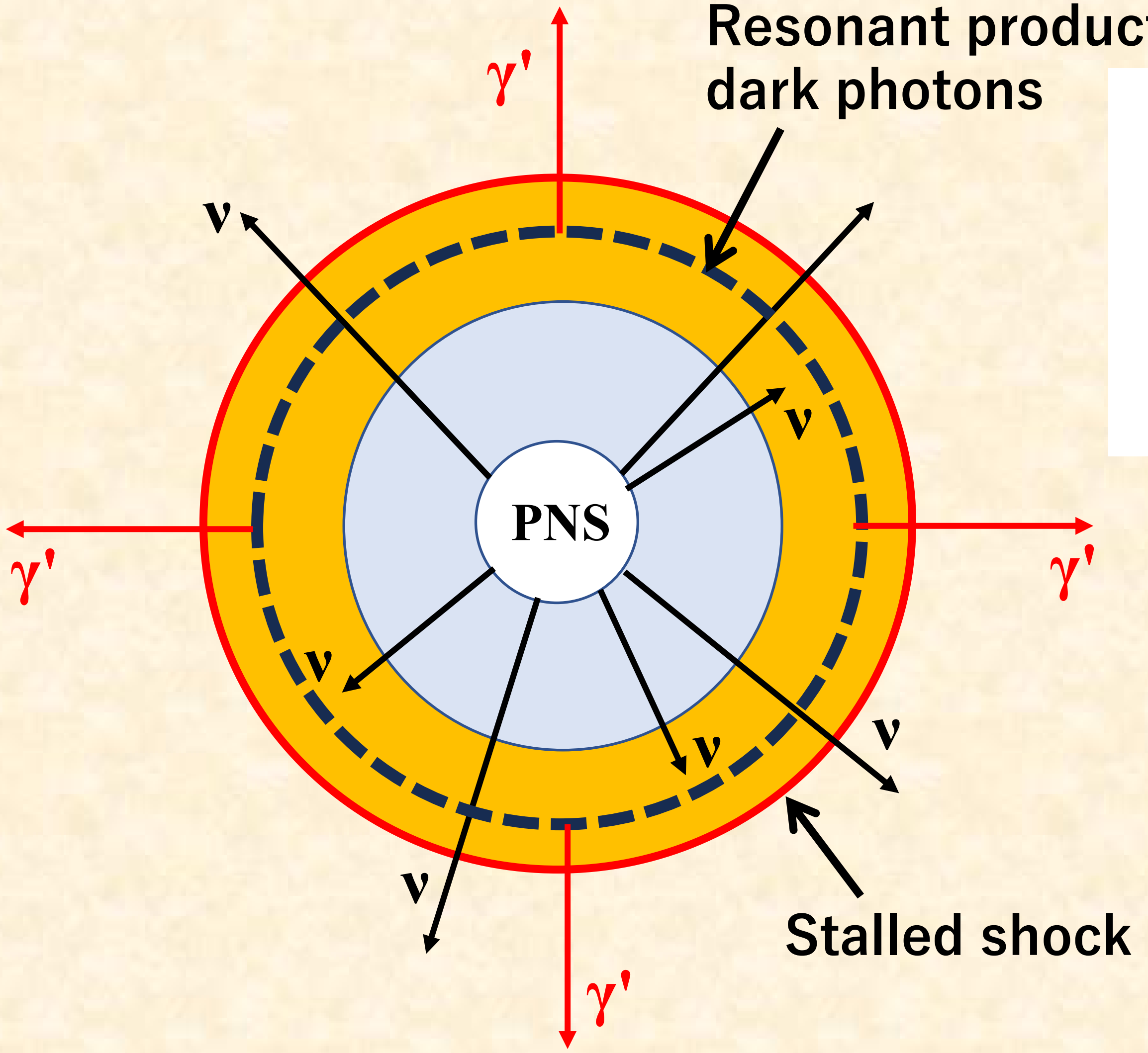
- Kinetic energy of ejecta

$$E_{\mathrm{exp}} = 10^{51}\ \mathrm{erg}\ (= 1\ \mathrm{Bethe})$$

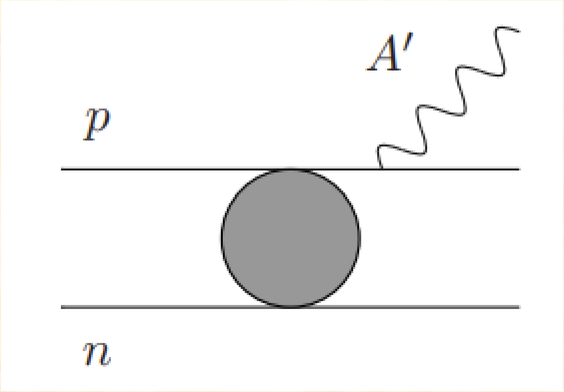
1% energy transfer through neutrino-nucleon interactions

Neutrino heating is essential for successful supernova explosion

Dark Photon (DP) Production in Supernovae



Chang, Essig & McDermott, JHEP (2017)



- ✓Since DPs freely escape from the star, DP production leads to **an additional cooling process**.
- ✓DPs may cancel neutrino heating and prevent supernova explosion.

[Caputo et al., PRL 134 (2025) 151002]

Neutrino-radiation Hydrodynamic Simulations Coupled with Dark Photons

Code: 3DnSNe [Takiwaki, Kotake & Suwa MNRAS 461 (2016) L112]

Neutrino transport: IDSA [Liebendörfer, Whitehouse, & Fischer ApJ 698 (2009) 1174]

Dimension: 2D (axisymmetric)

EoS: LS220

Dark photon production:

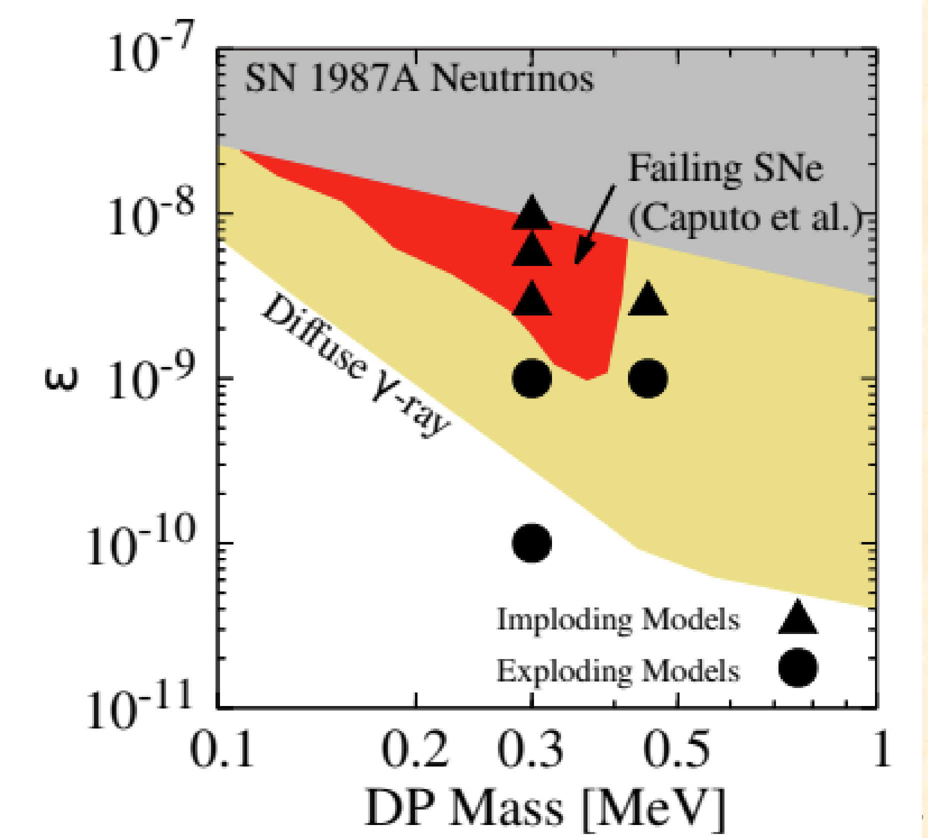
nucleon bremsstrahlung (n+p -> n+p+γ')

Progenitor: 14+9$M_\odot$ merger model

"SN 1987A progenitor model"

[Urushibata et al., MNRAS 473 (2018) L101]

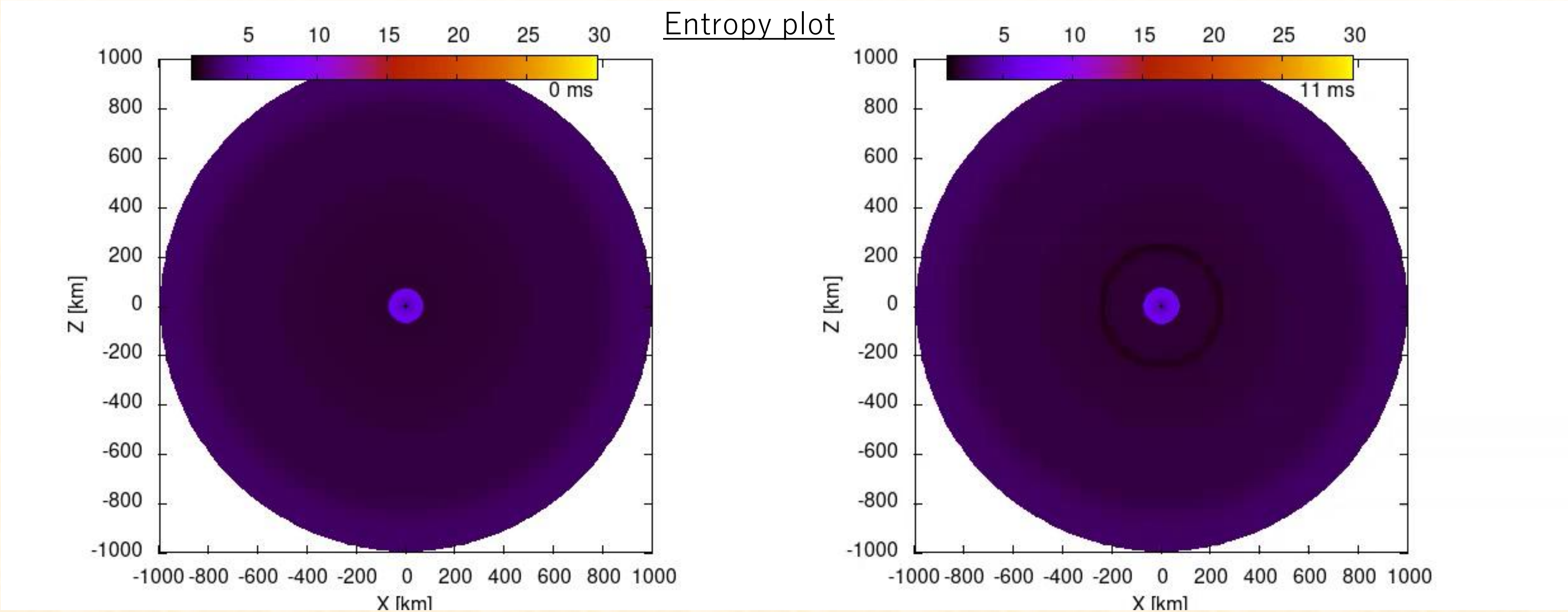
Resolution: $N_r \times N_\theta = 512 \times 128$



Model without dark photon

Model with dark photon

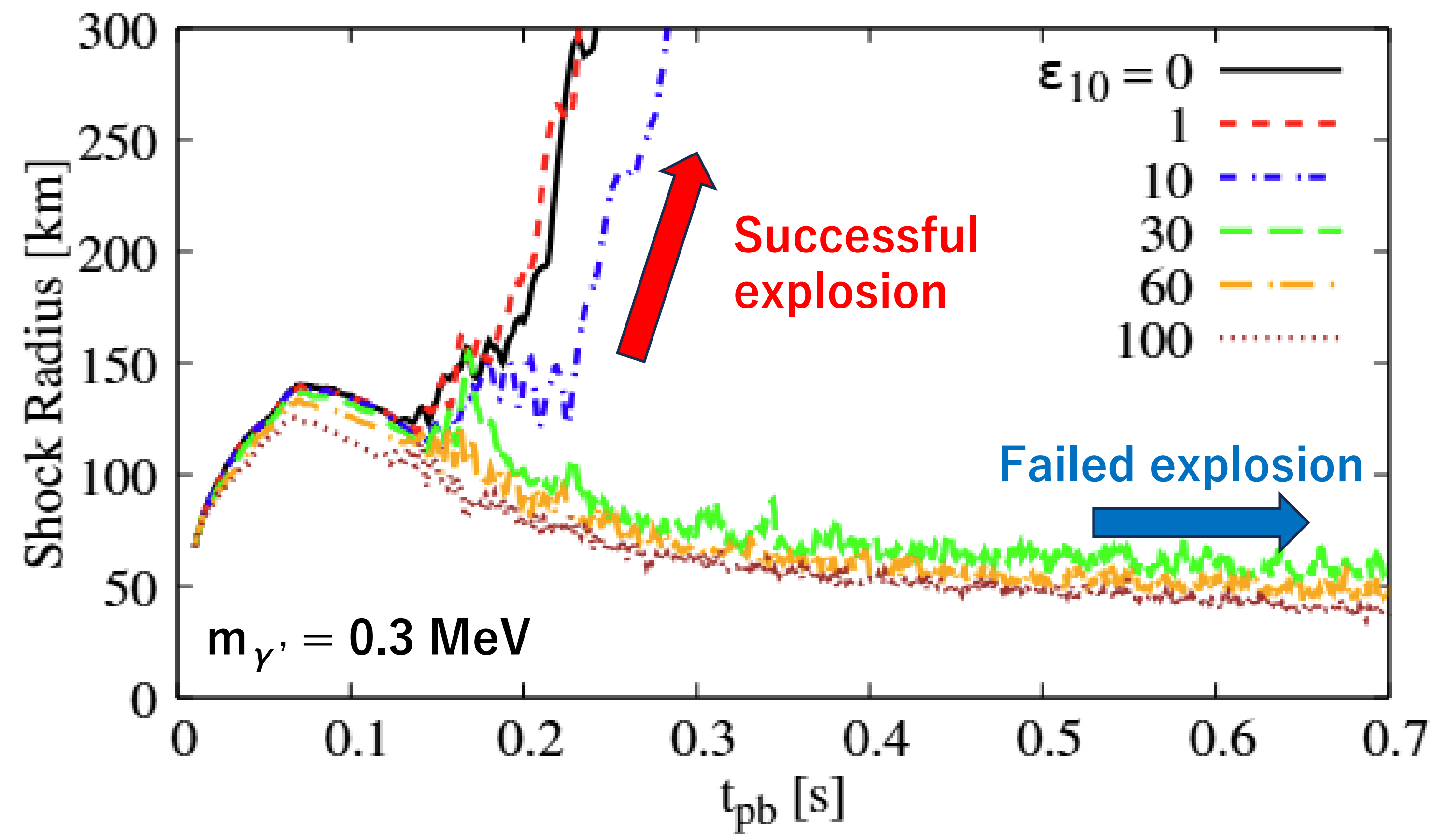
($m_{\gamma'} = 0.3$ MeV, $\varepsilon = 3 \times 10^{-9}$)



Dark photons hinder SN explosion!

Shock Radius

($\varepsilon_{10} = 10^{10}\,\varepsilon$)



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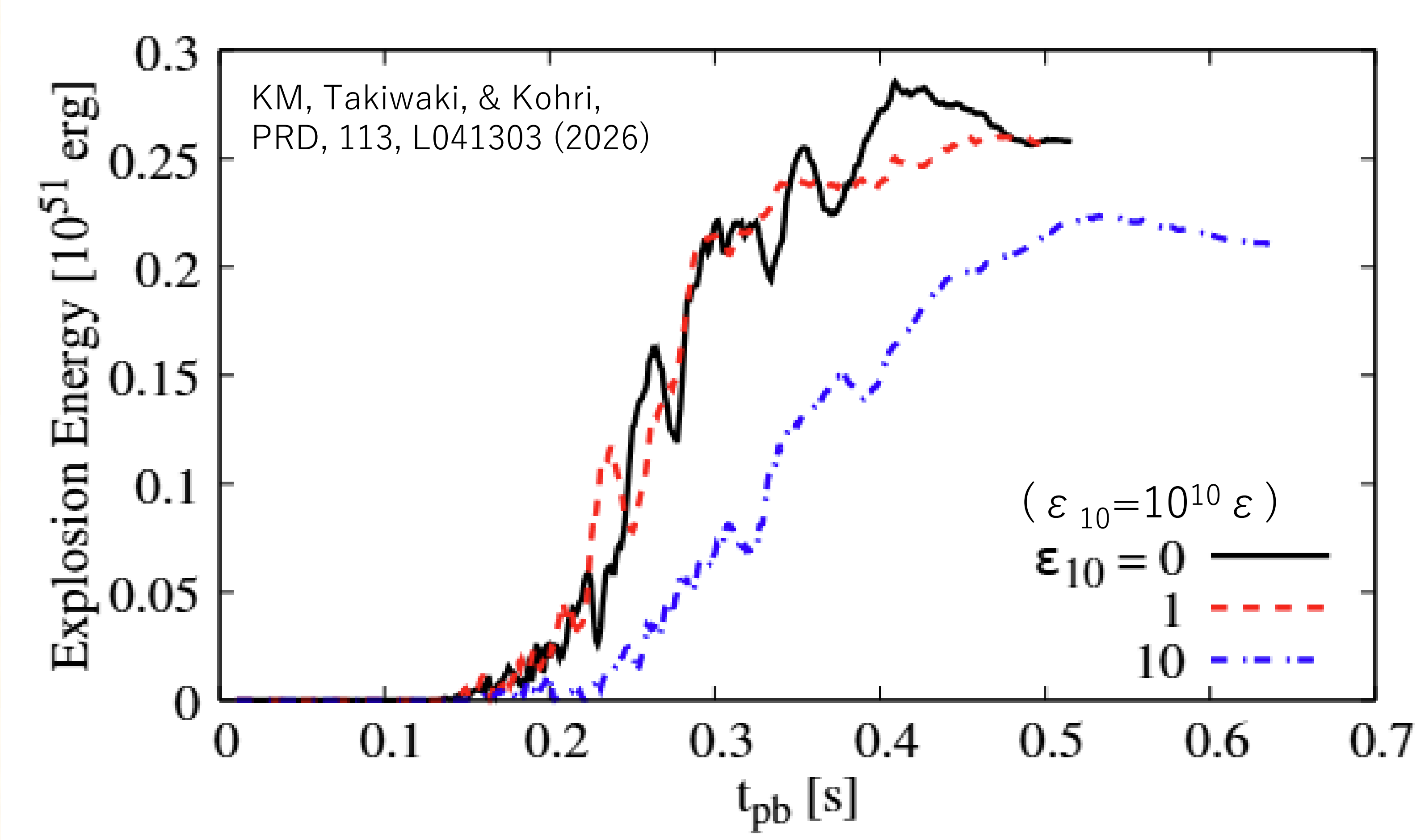
- ✓ When dark photons are considered, the shock revival is delayed.
- ✓ **When ε is sufficiently large, the shock is not revived until the end of the simulations.**

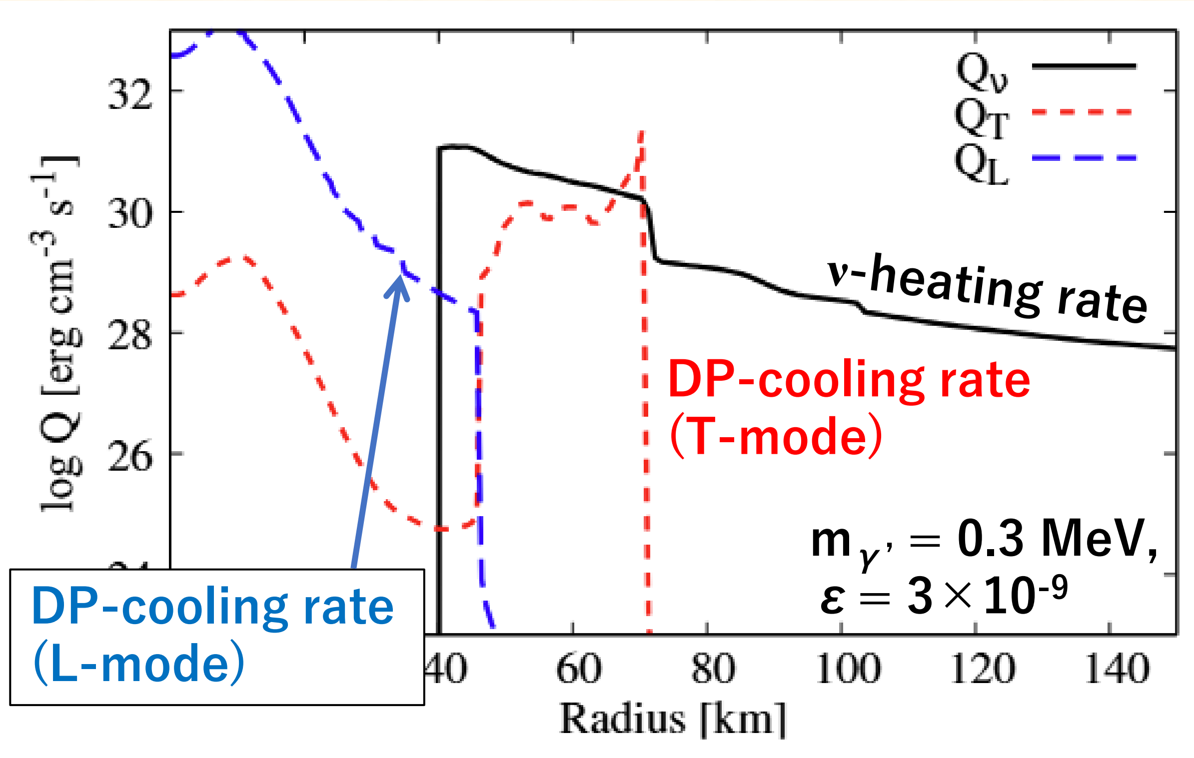
Explosion Energy
(~ kinetic energy of supernova ejecta)



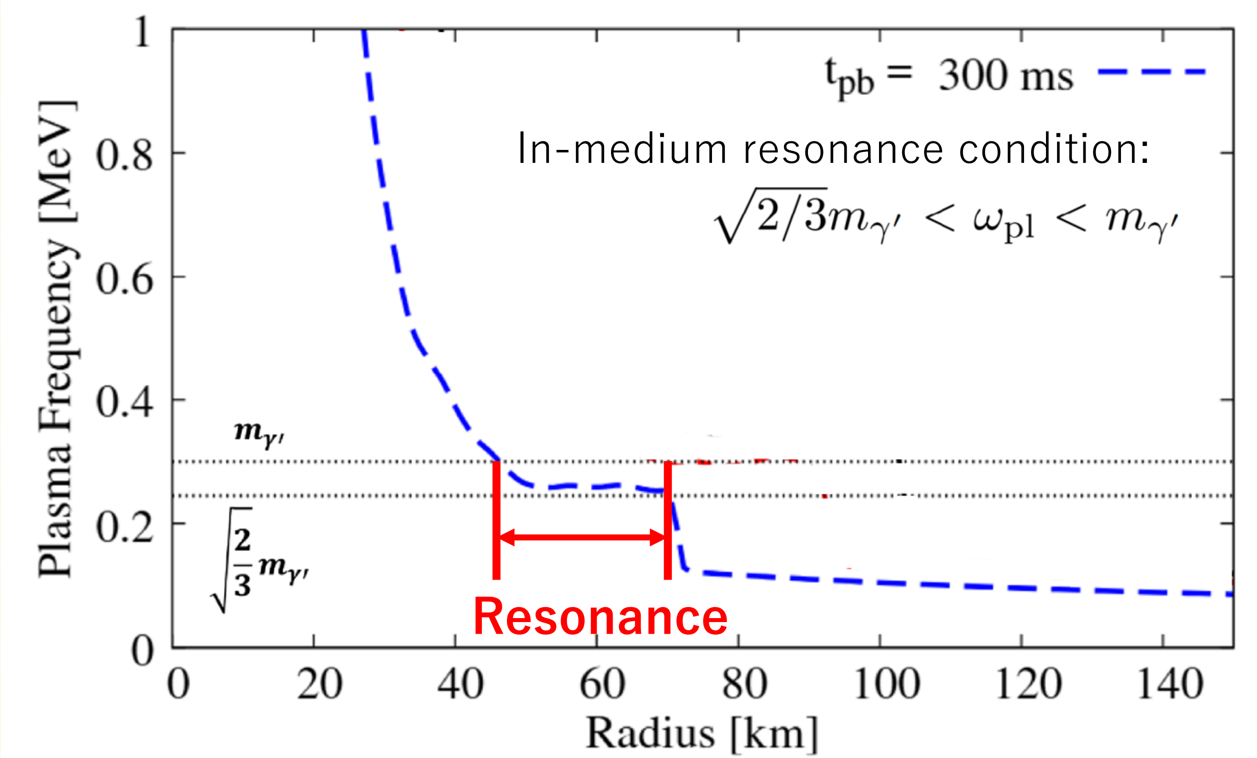
When dark photons are considered, **supernova explosion becomes weaker.**

Dark Photon Production

Heating & cooling rates @ t_{pb}=300 ms



Plasma frequency ("photon mass")



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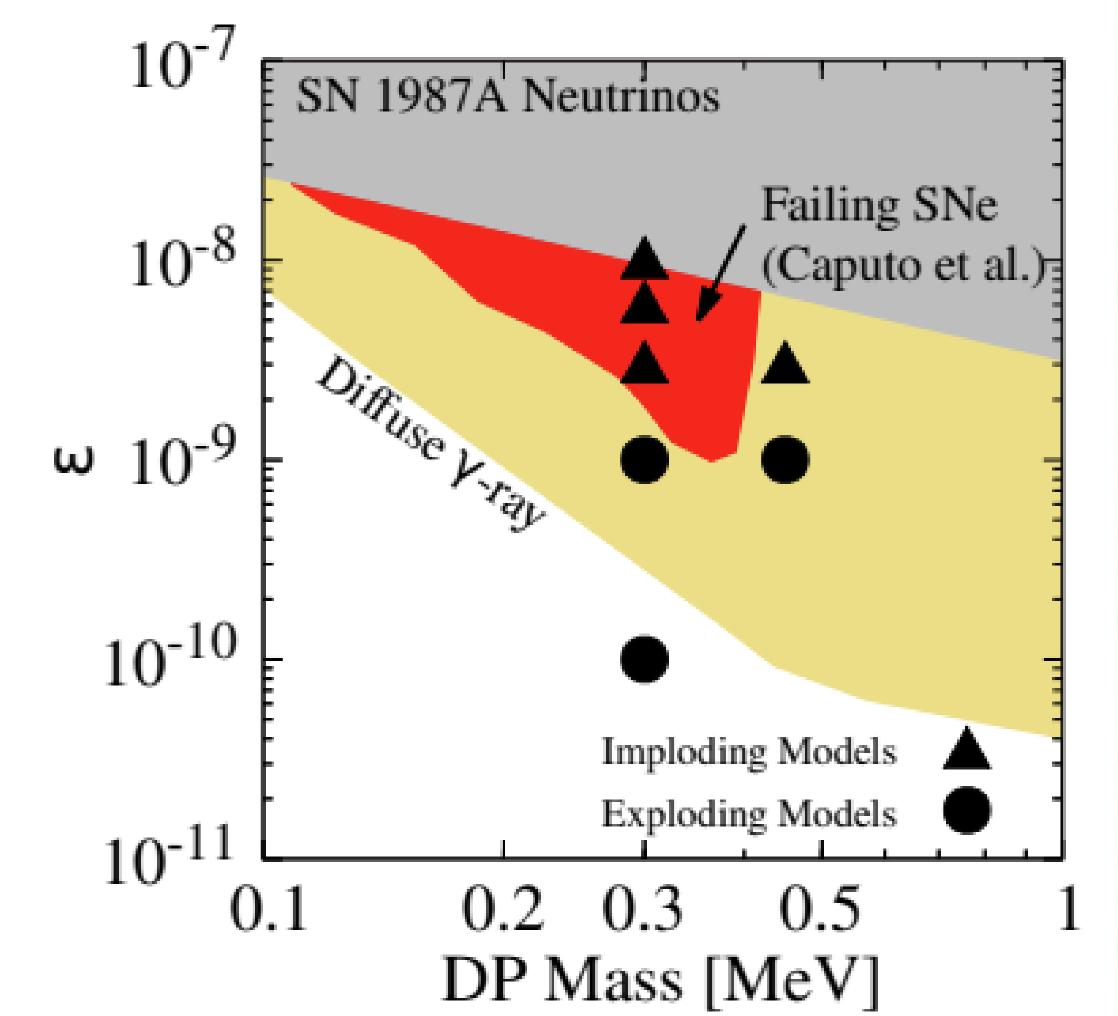
- ✓ The (T-mode) resonance appears when $m_{\gamma'}$ is close to plasma frequency.
- ✓ **Production of dark photons in the neutrino heating region!**

SN 1987A Explosion Condition



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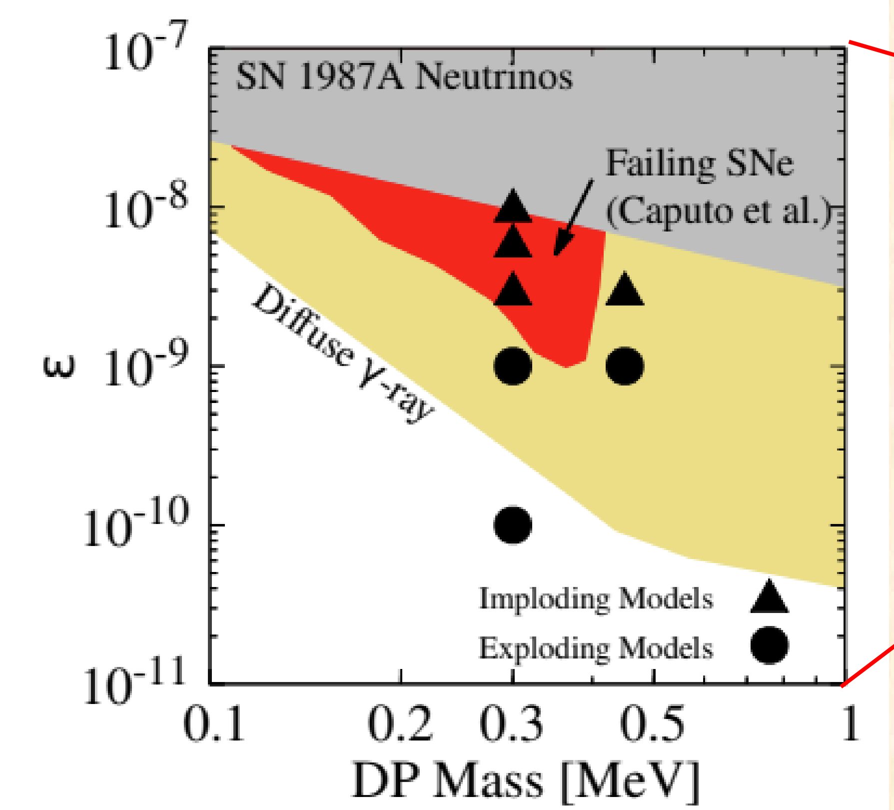
Condition for successful SN 1987A explosion:

$$\boxed{\varepsilon \lesssim 3\times10^{-9} \text{ for } m_{\gamma'} = 0.30\text{-}0.45 \text{ MeV}}$$

- ✓ **SN explodability can provide a new constraint on dark photons!**
- ✓ Qualitatively consistent with post-processing in Caputo et al., but we find a model that shows a different fate

What if dark photons are heavier?



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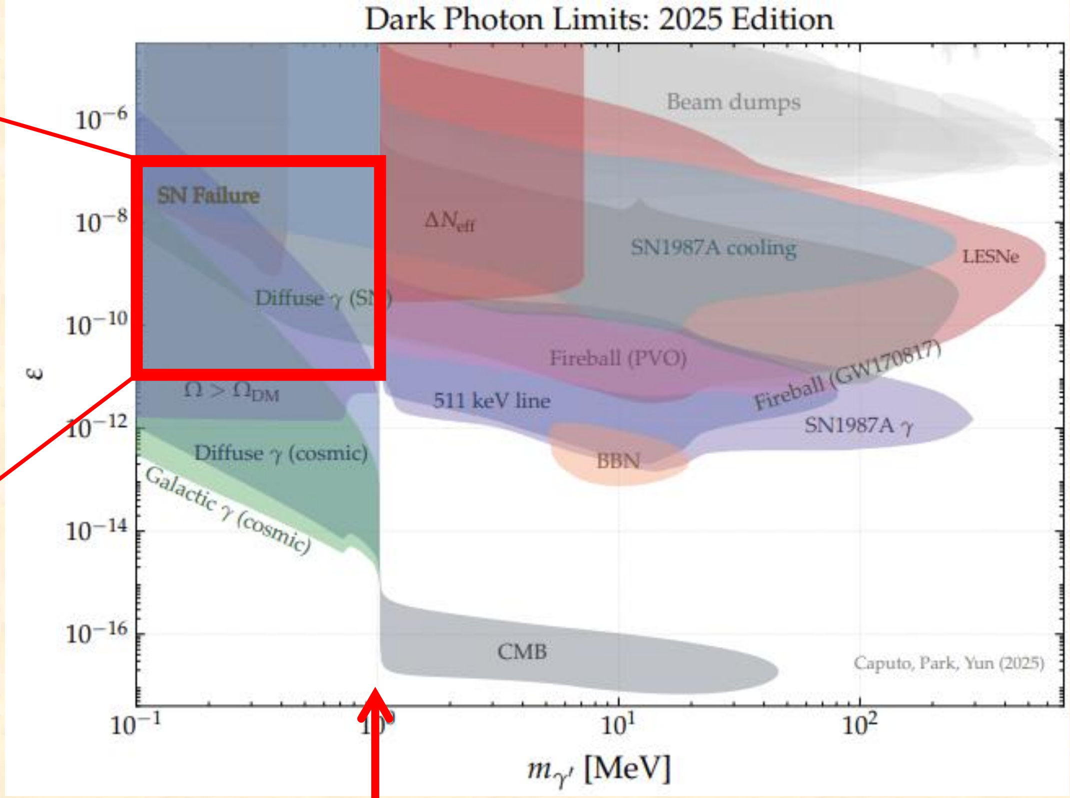


e-e+ mass

Caputo et al., (2025) arXiv:2511.15785

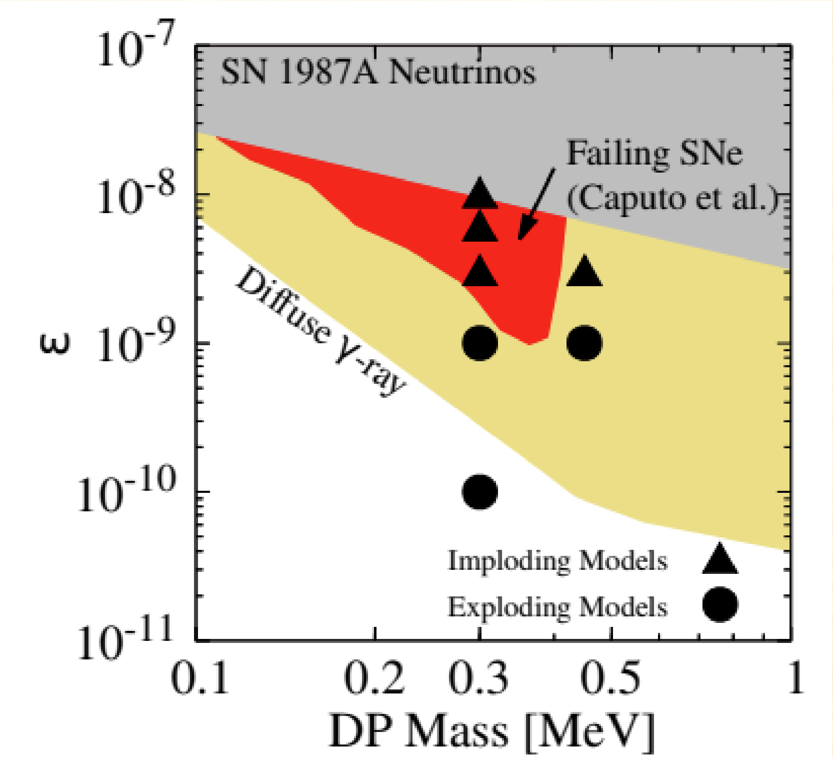
If dark photons are heavier than 1 MeV, they can decay into e-e+.

→ **Dark photons can energize supernovae.**

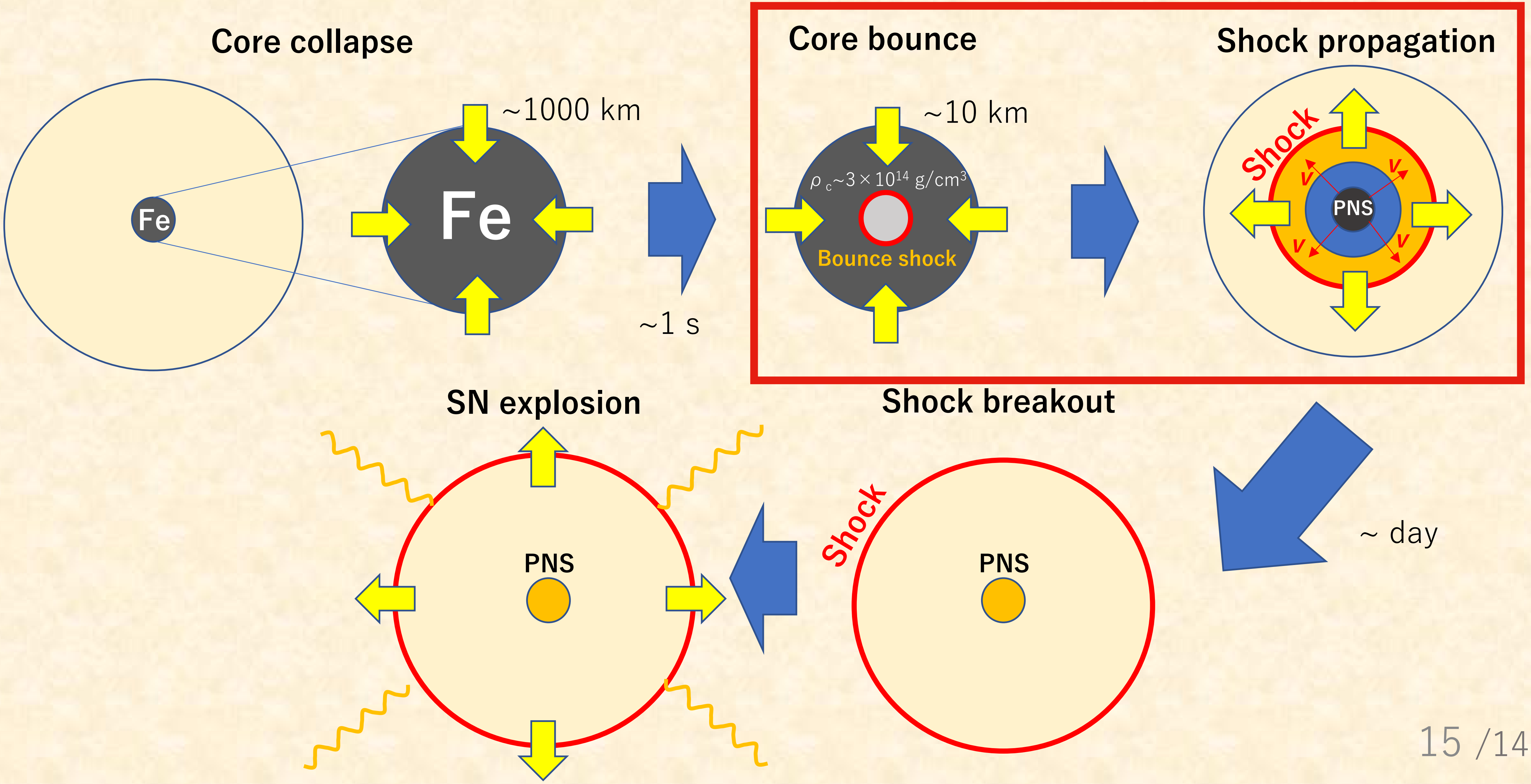
Summary

Dark photons ($m_{\gamma'}$~0.3 MeV) will hinder SN explosion.

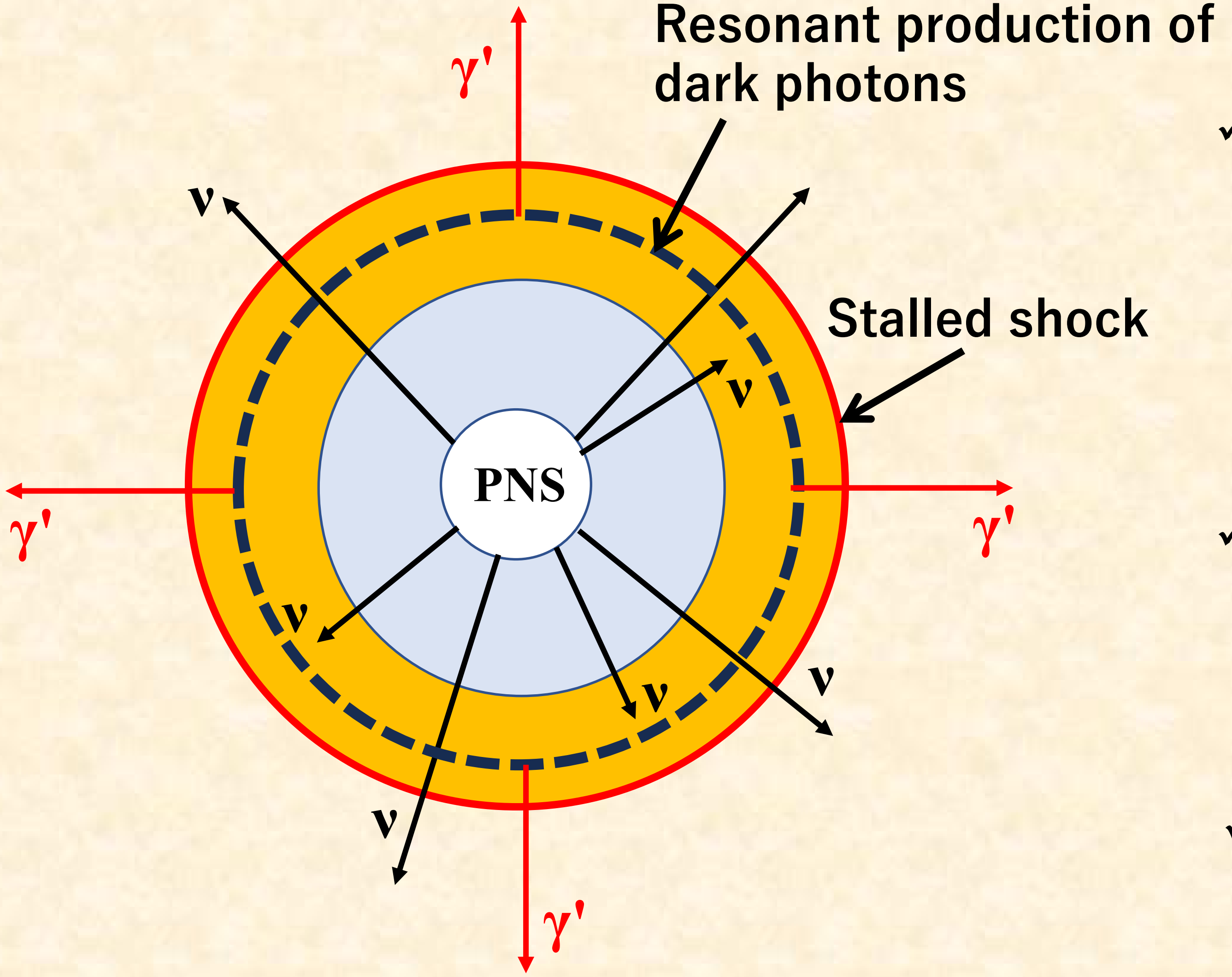
- Production of dark photons in the neutrino heating region causes cooling.
- A new constraint can be obtained based on SN explodablity.
- We verified the argument with self-consistent simulations.
- Sensitivity studies on simulation uncertainties would be important.



Explosion Mechanism of Core-collapse SNe



Dark Photon Production in Supernovae



✓ Effective mixing parameter in plasma:

$$\epsilon_{\rm m}^2 = \frac{\epsilon^2}{\left(1 - \frac{{\rm Re}\,\Pi}{m_{\gamma'}^2}\right)^2 + \left(\frac{{\rm Im}\,\Pi}{m_{\gamma'}^2}\right)^2}$$

Π: Polarization tensor

✓ If ${\rm Re}\,\Pi_i = m_{\gamma'}^2$,

dark photons are resonantly produced!

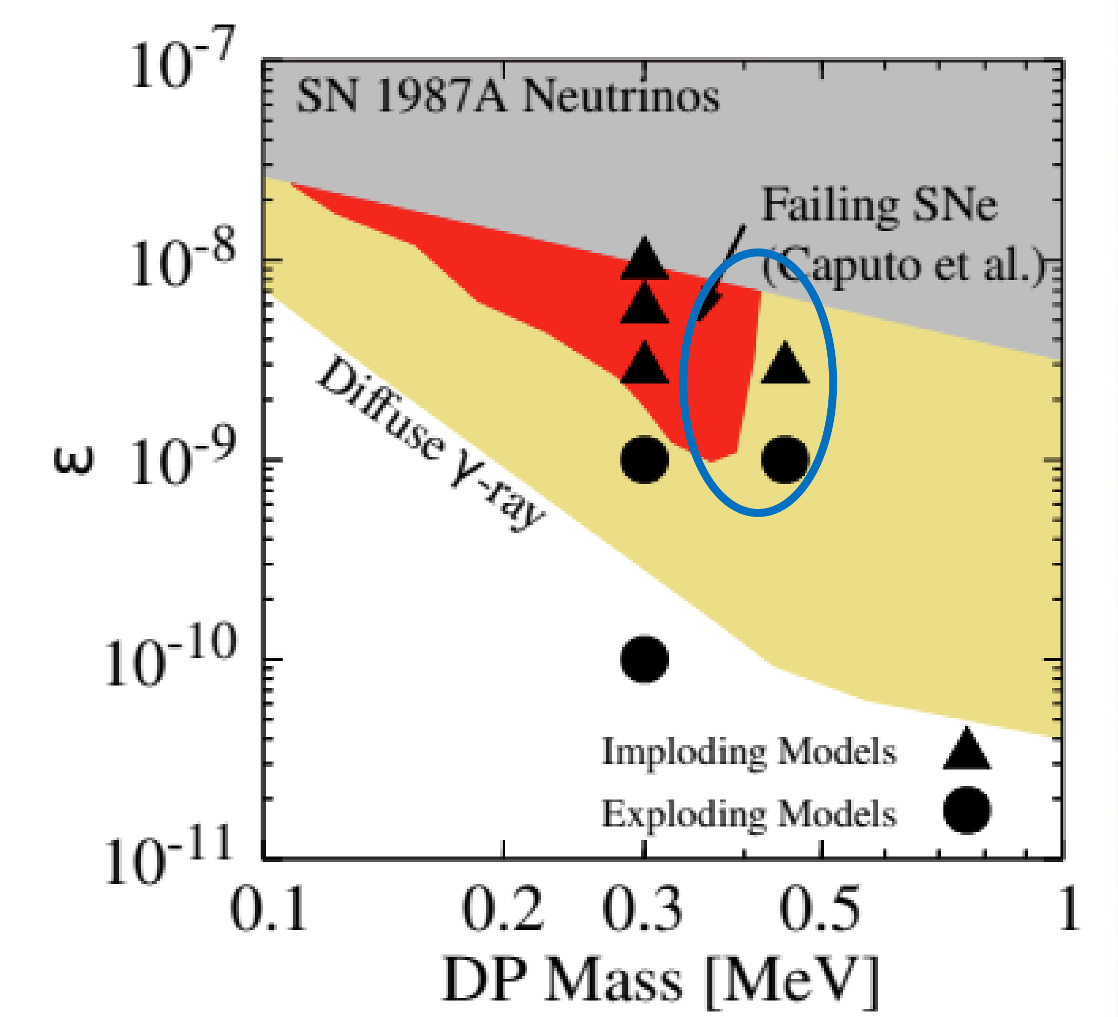
[An, Pospelov & Pradler, PLB (2013)]
[Chang, Essig & McDermott, JHEP (2017)]

✓ DP cooling may cancel neutrino heating

and prevent supernova explosion.

[Caputo et al., PRL 134 (2025) 151002]

What if dark photons are heavier?



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- ✓ The constraint disappears when dark photons are heavier, because the resonance appears in the cooling region.
- ✓ Impact on PNS convection?