超新星爆発を用いた暗黒光子の制限

シミュレーションに基づく検証

Exploring Dark Photons with Supernova Simulations

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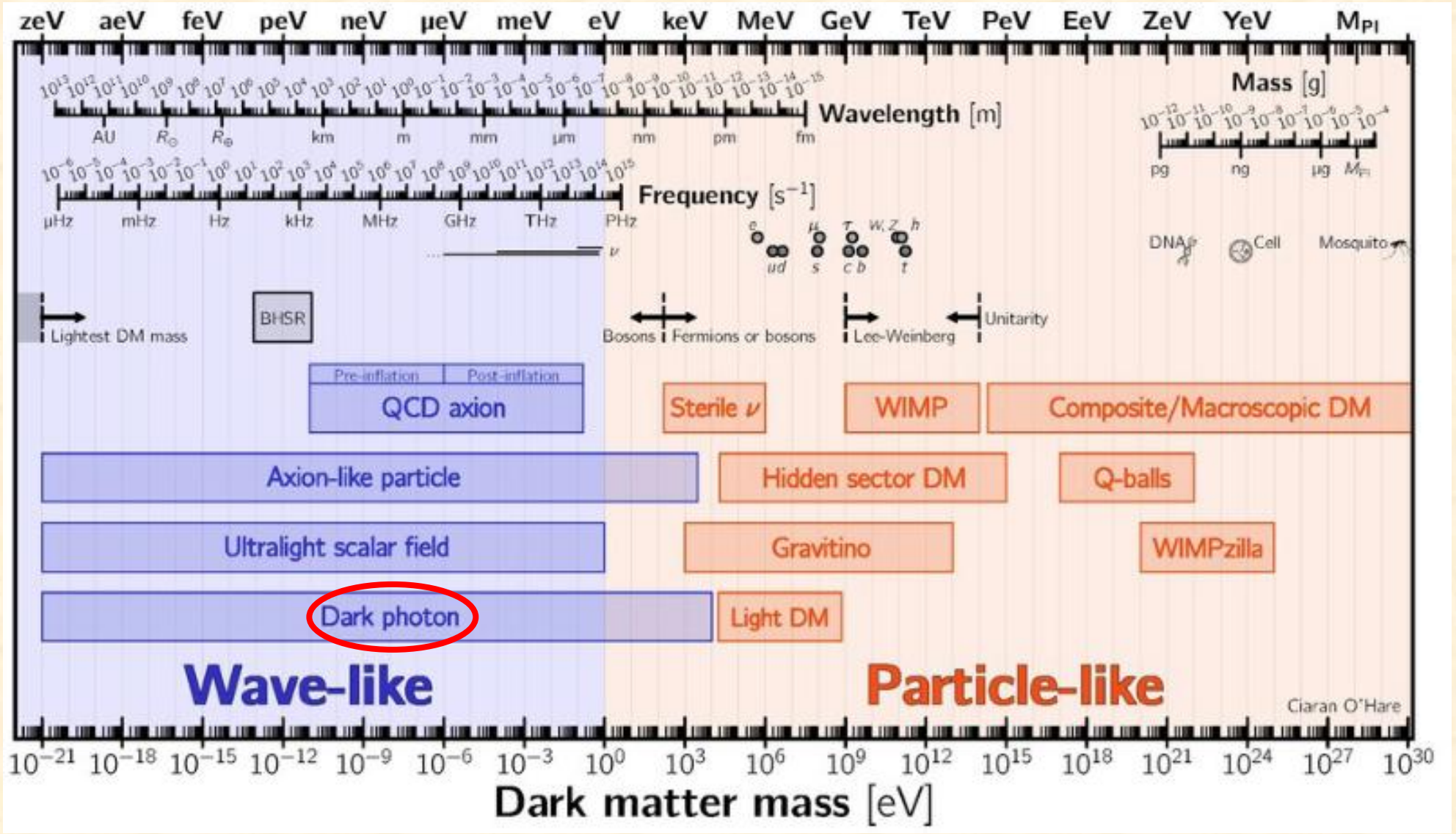
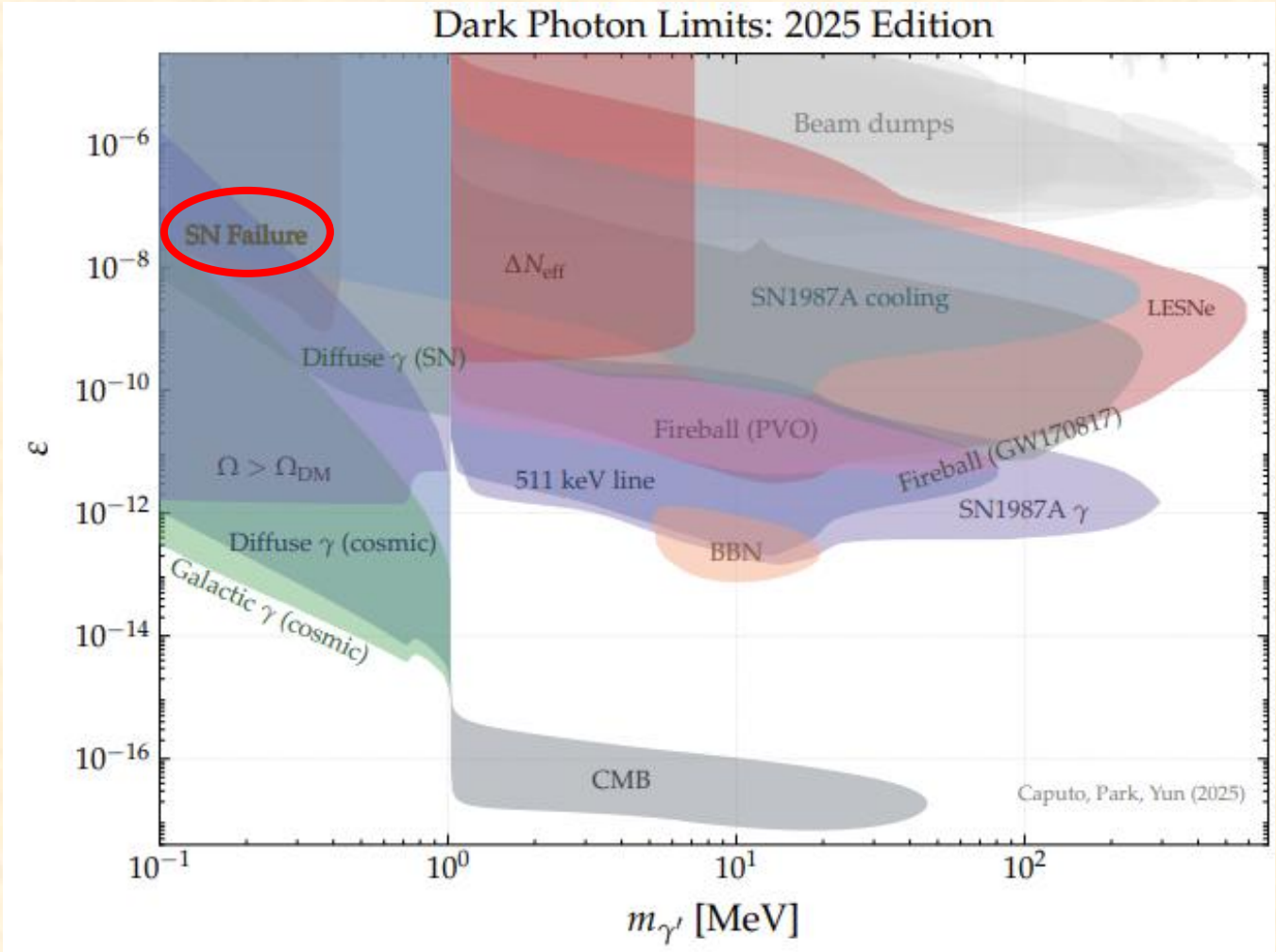
KM, T. Takiwaki, & K. Kohri, PRD, 113, L041303 (2026)

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 Dark Photons?

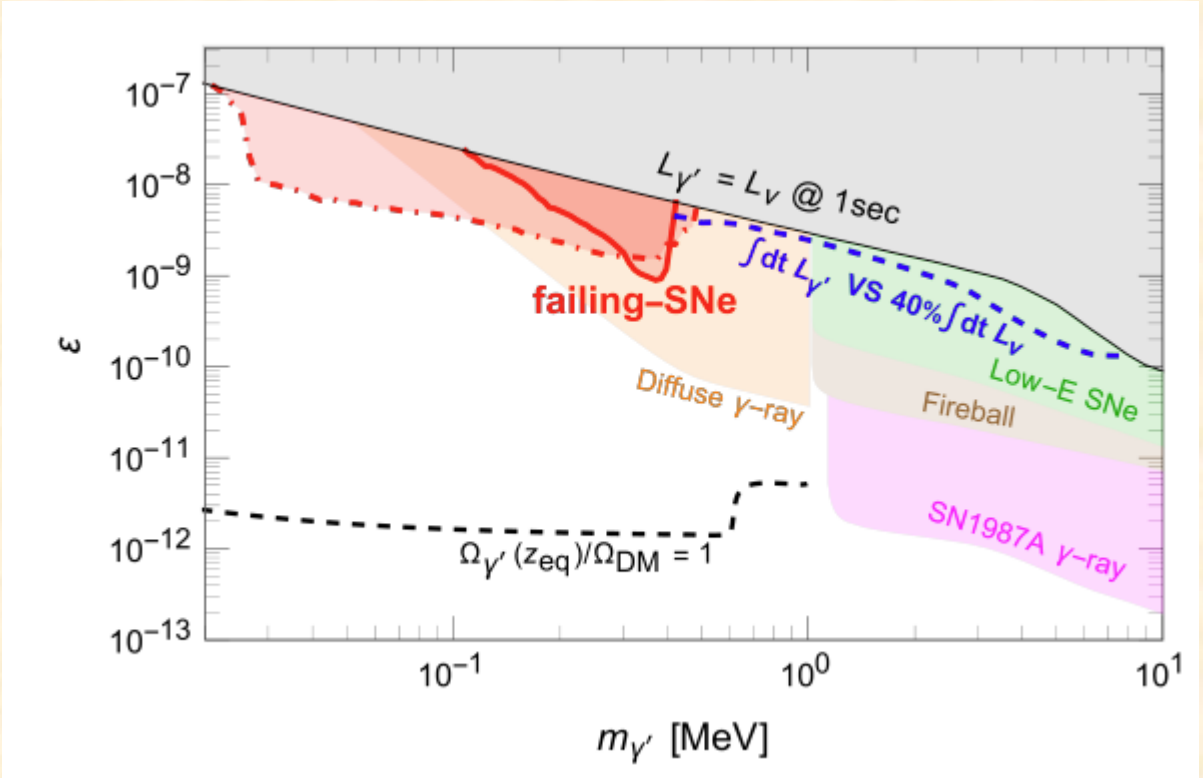
Caputo et al., PRL 134 (2025) 151002

- **Dark photons produced in the gain region 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!**



Dark Photon Production in Supernovae

✓ Effective mixing parameter in plasma:

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

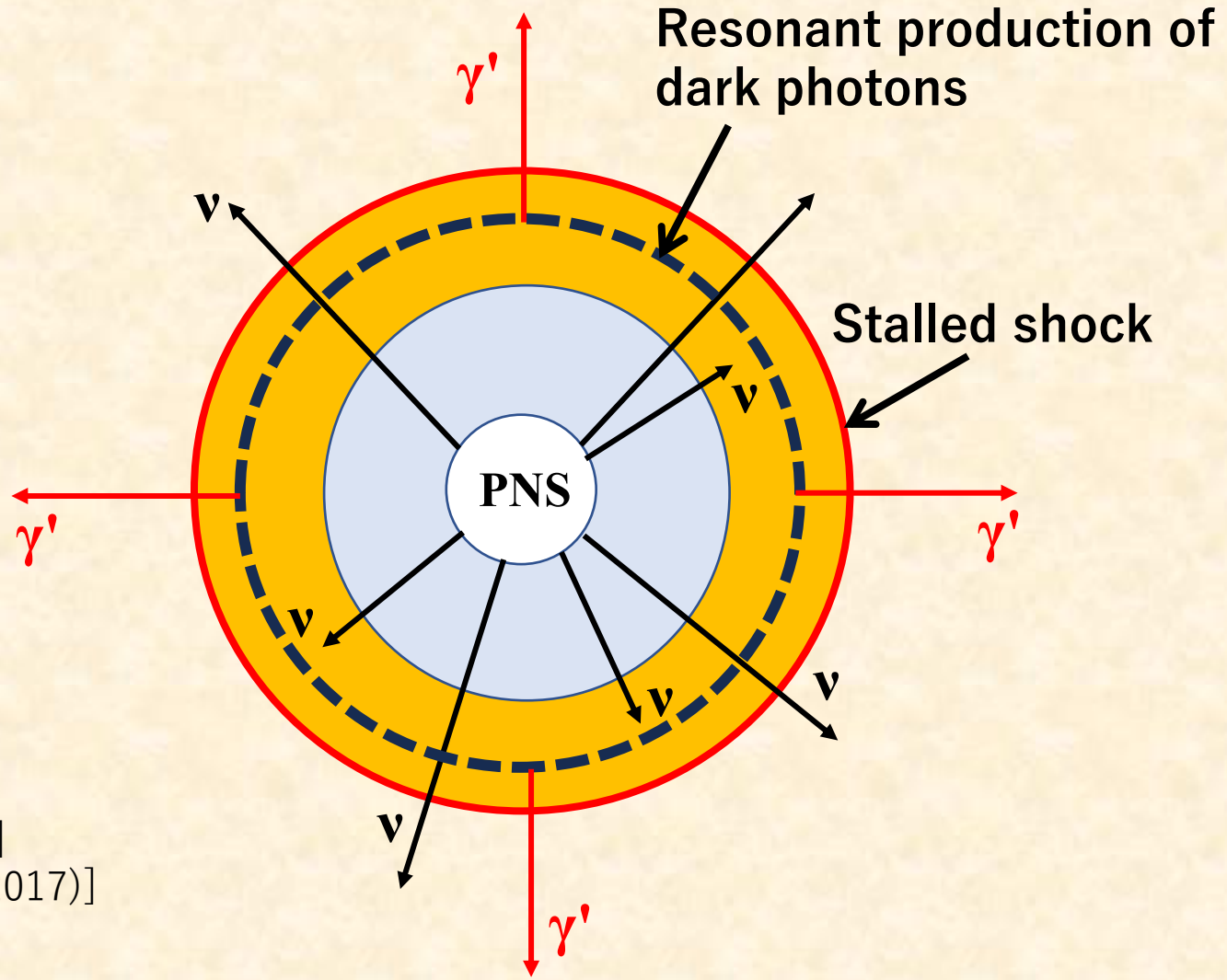
Π: Polarization tensor

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

dark photons are resonantly produced!

✓ When $m_{\gamma'}$~100 keV, the resonance appears in the gain region.

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



SN Simulation 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 **EoS**: LS220

Dark photon production:

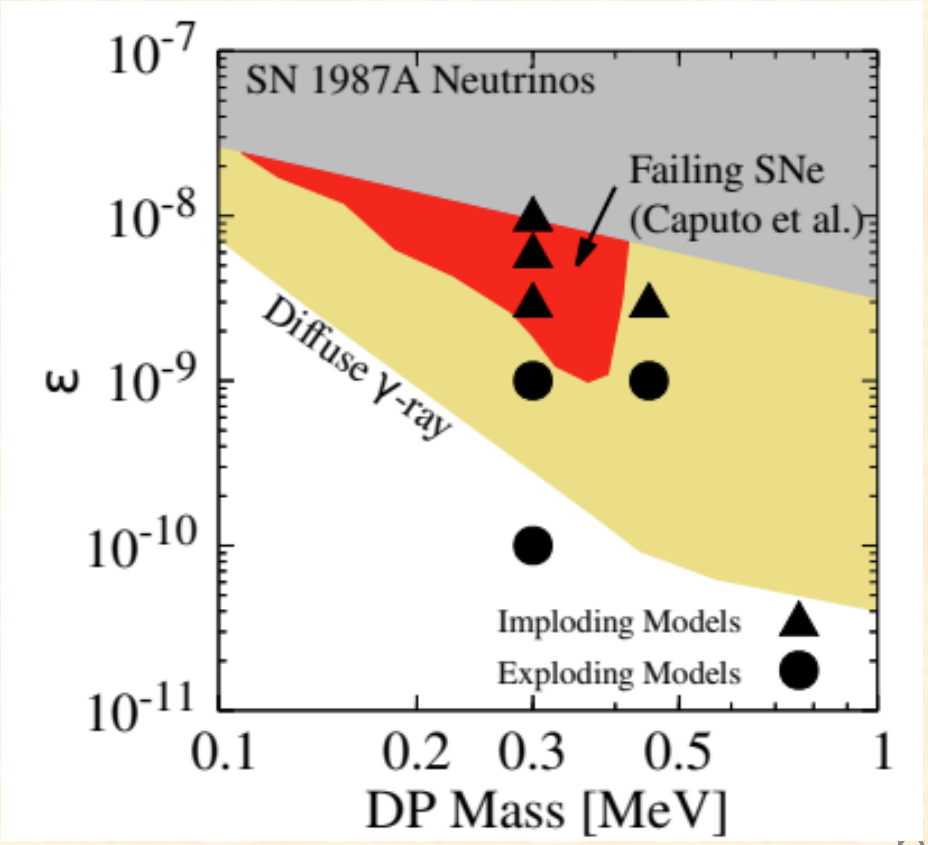
nucleon bremsstrahlung (n+p -> n+p+ γ ')

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

"SN 1987A progenitor model"

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

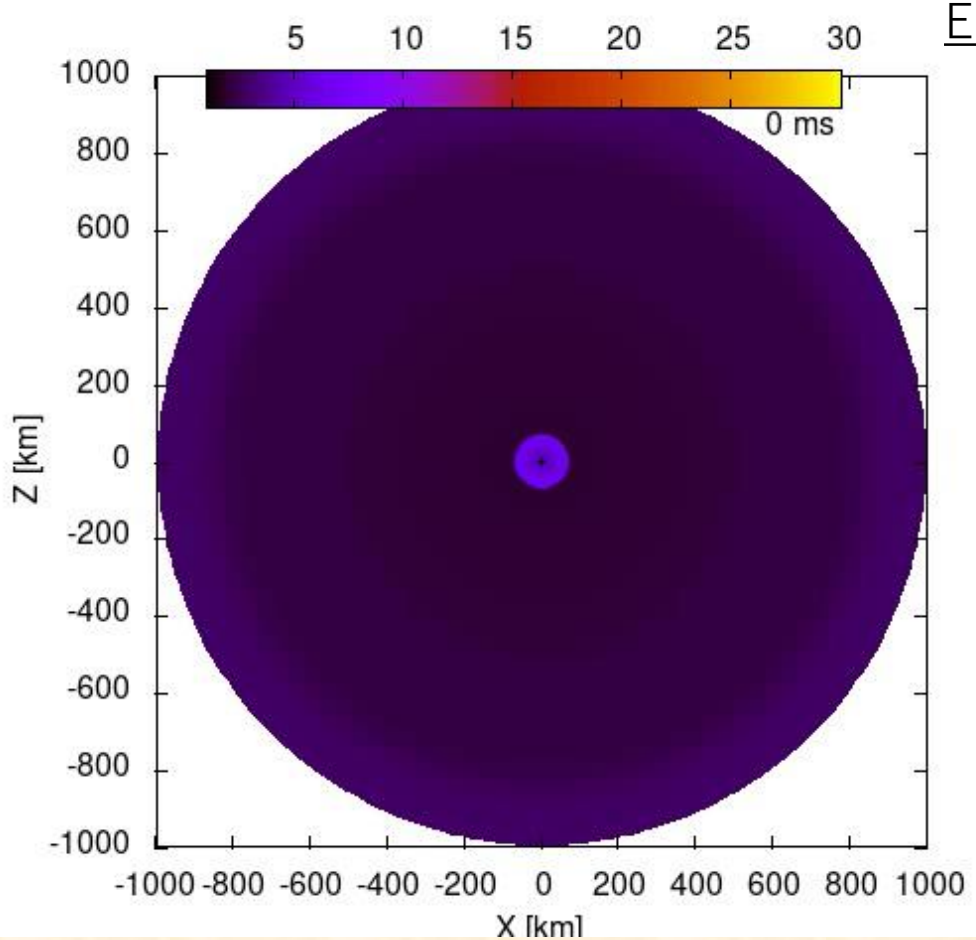
Resolution: $N_r \times N_\theta = 512 \times 128$

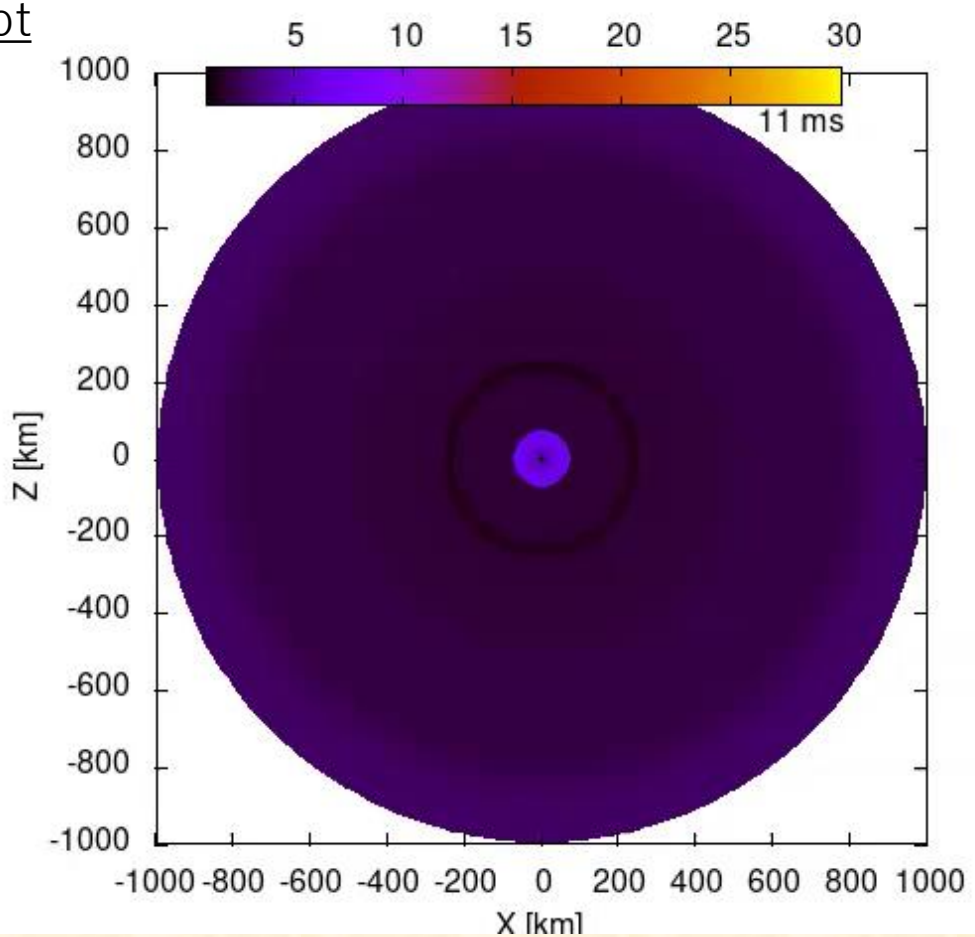


Model without dark photon

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

Entropy plot

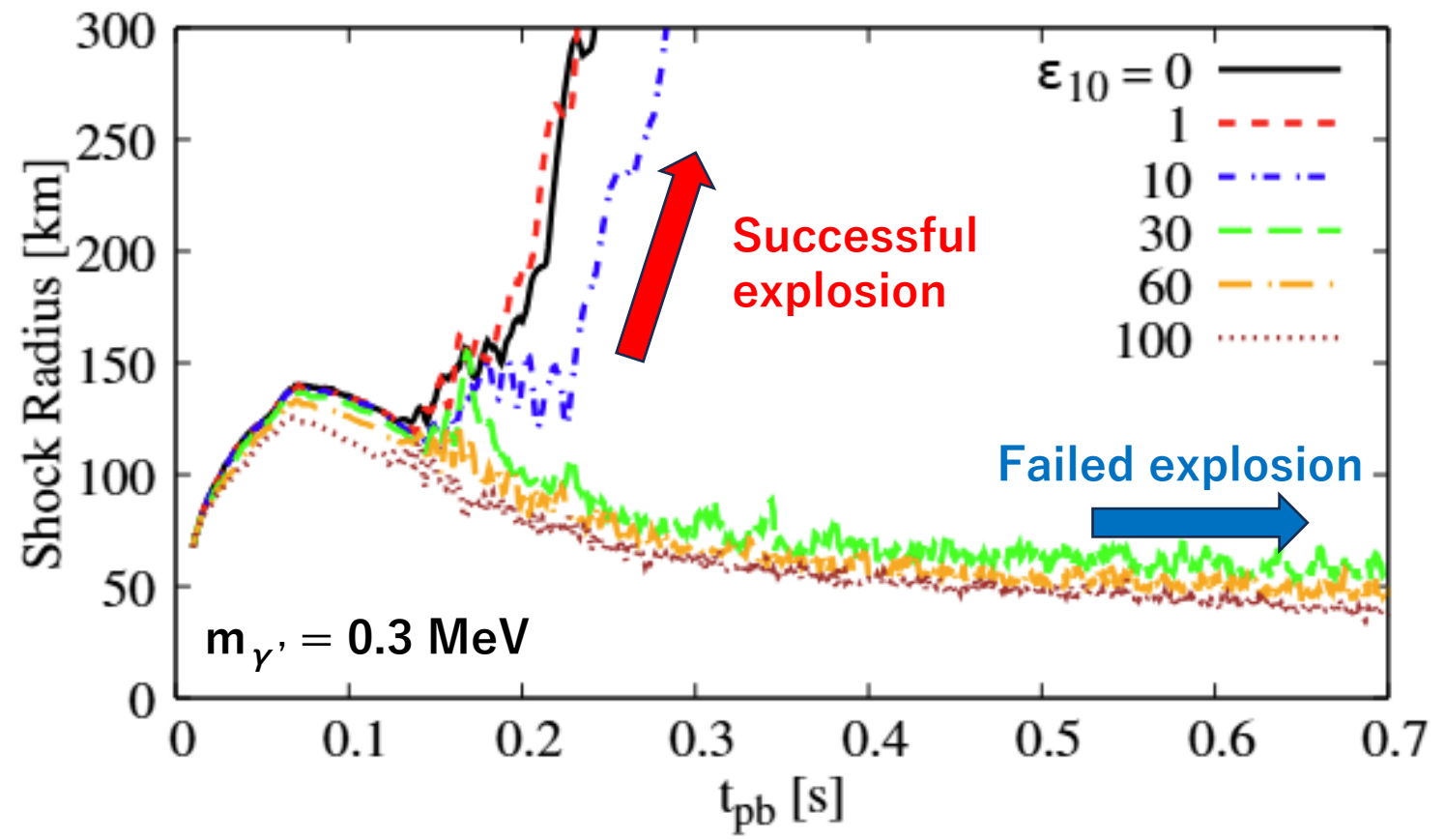




Dark photons hinder SN explosion!

Shock Radius

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



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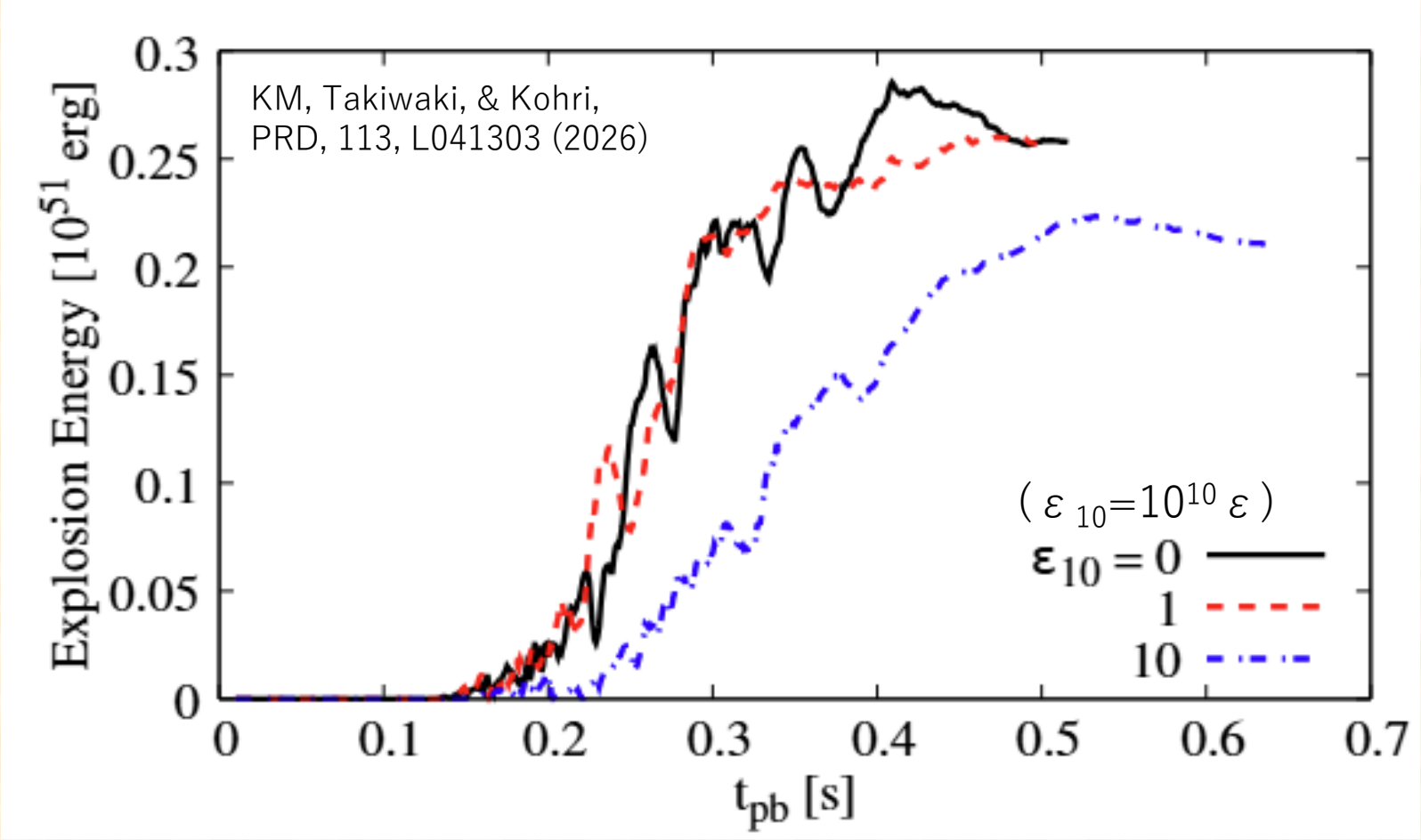
- ✓ When dark photons are considered, the shock revival is delayed.
- ✓ When ε is sufficiently large, the shock is not revived until the end of the simulations.

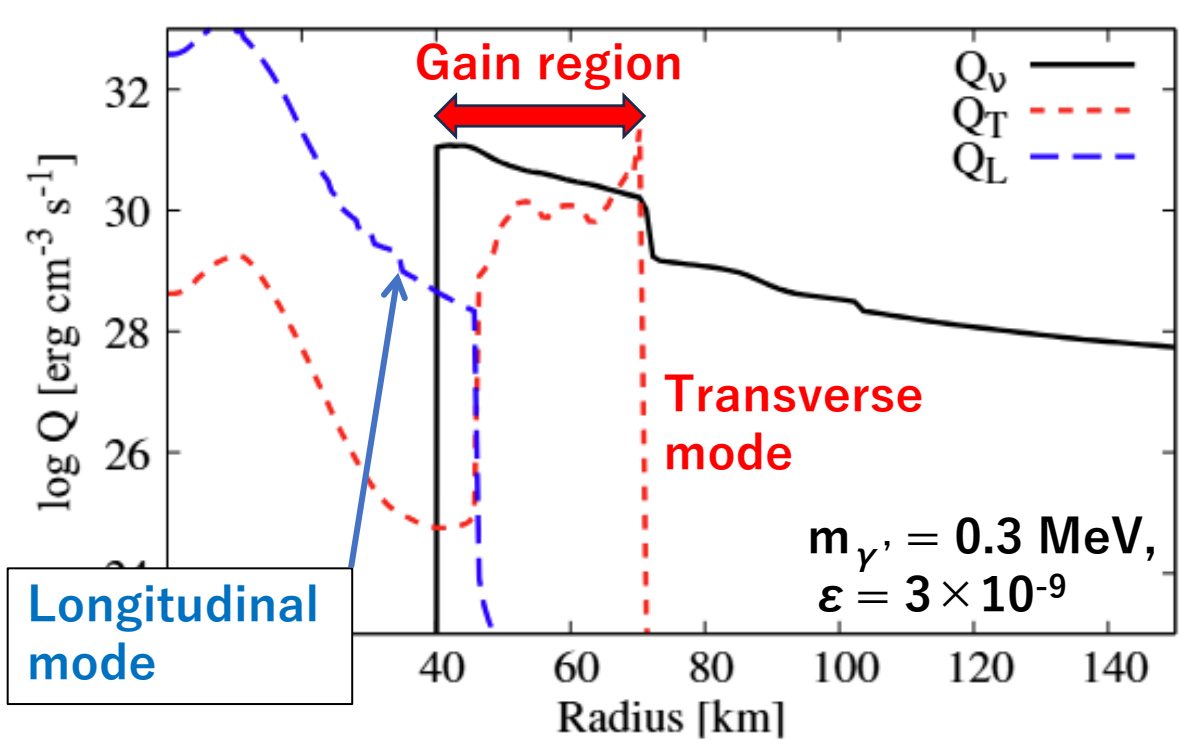
Explosion Energy



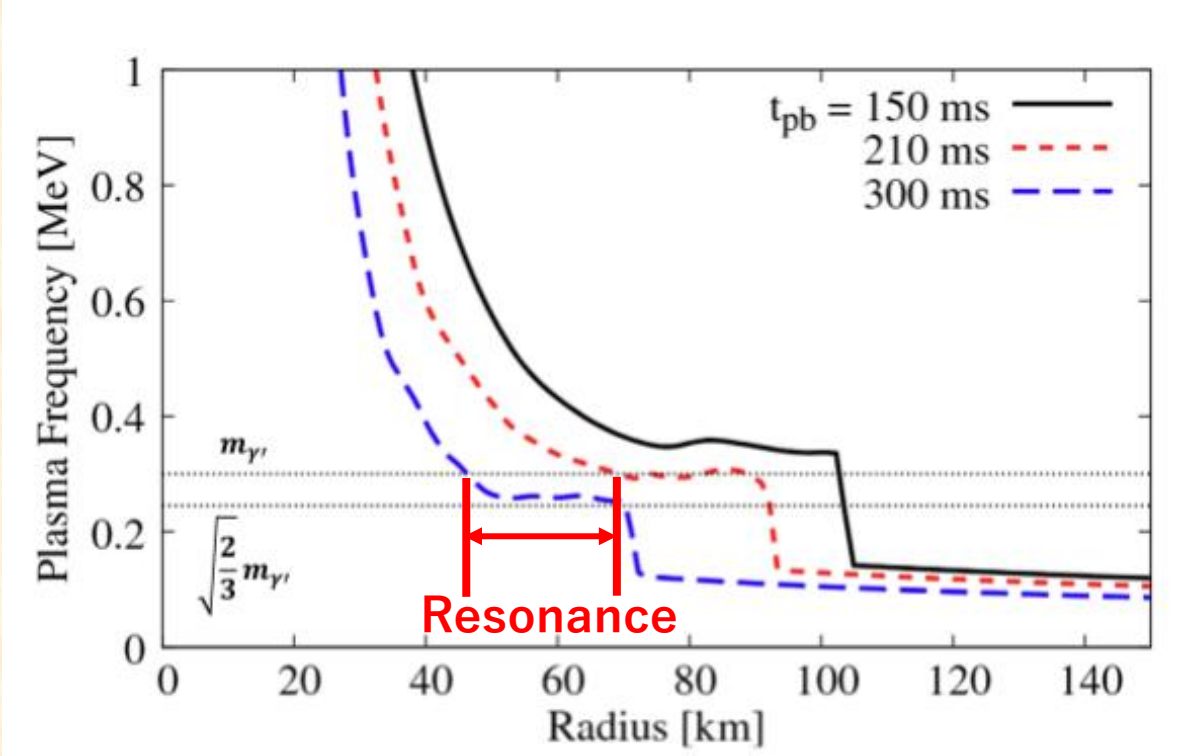
When dark photons are considered, **the explosion energy is reduced**.

Dark Photon Production

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



Plasma frequency ("photon mass")



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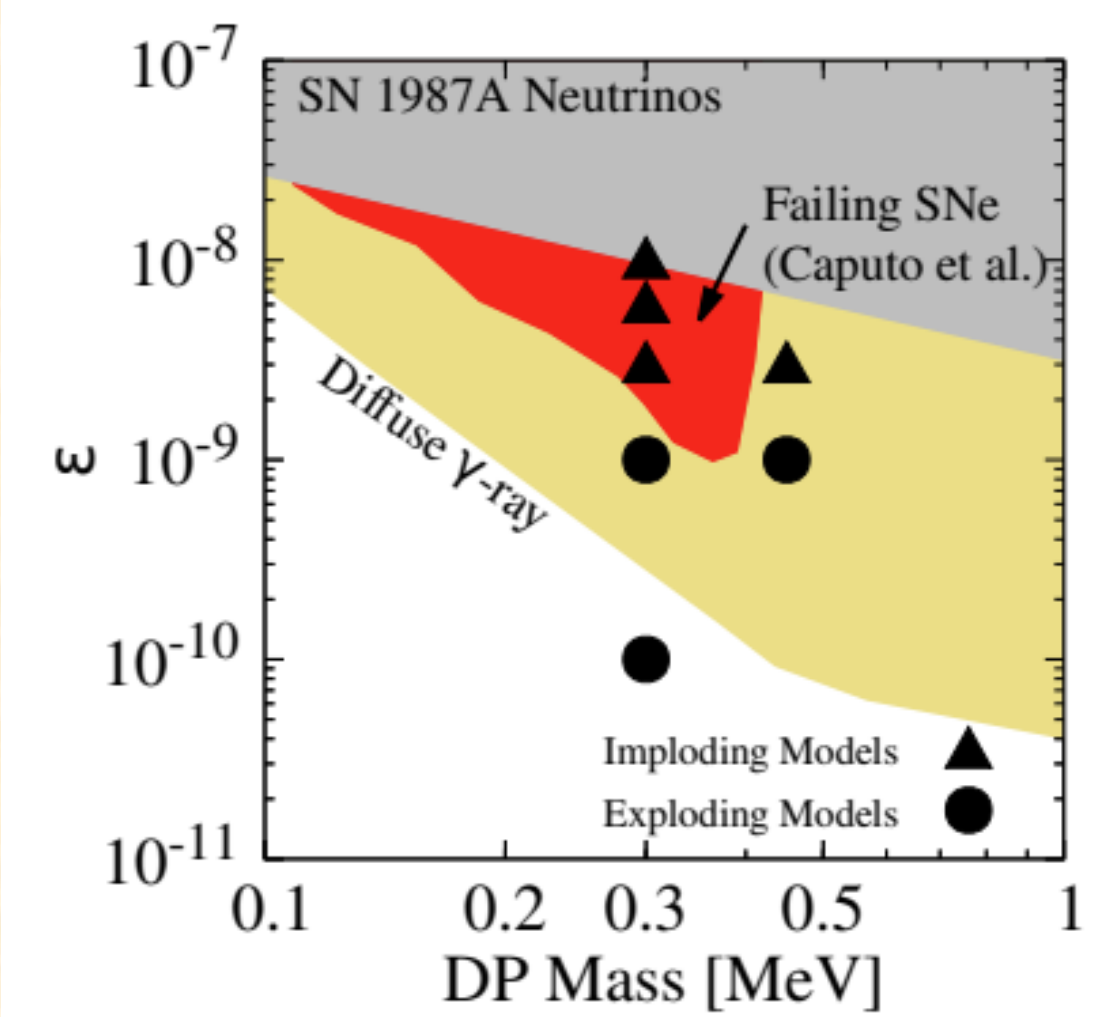
- ✓ The (transverse-mode) resonance appears when $m_{\gamma'}$ is close to plasma frequency.
- ✓ **Production of dark photons in the gain region!**

SN 1987A Explosion Condition



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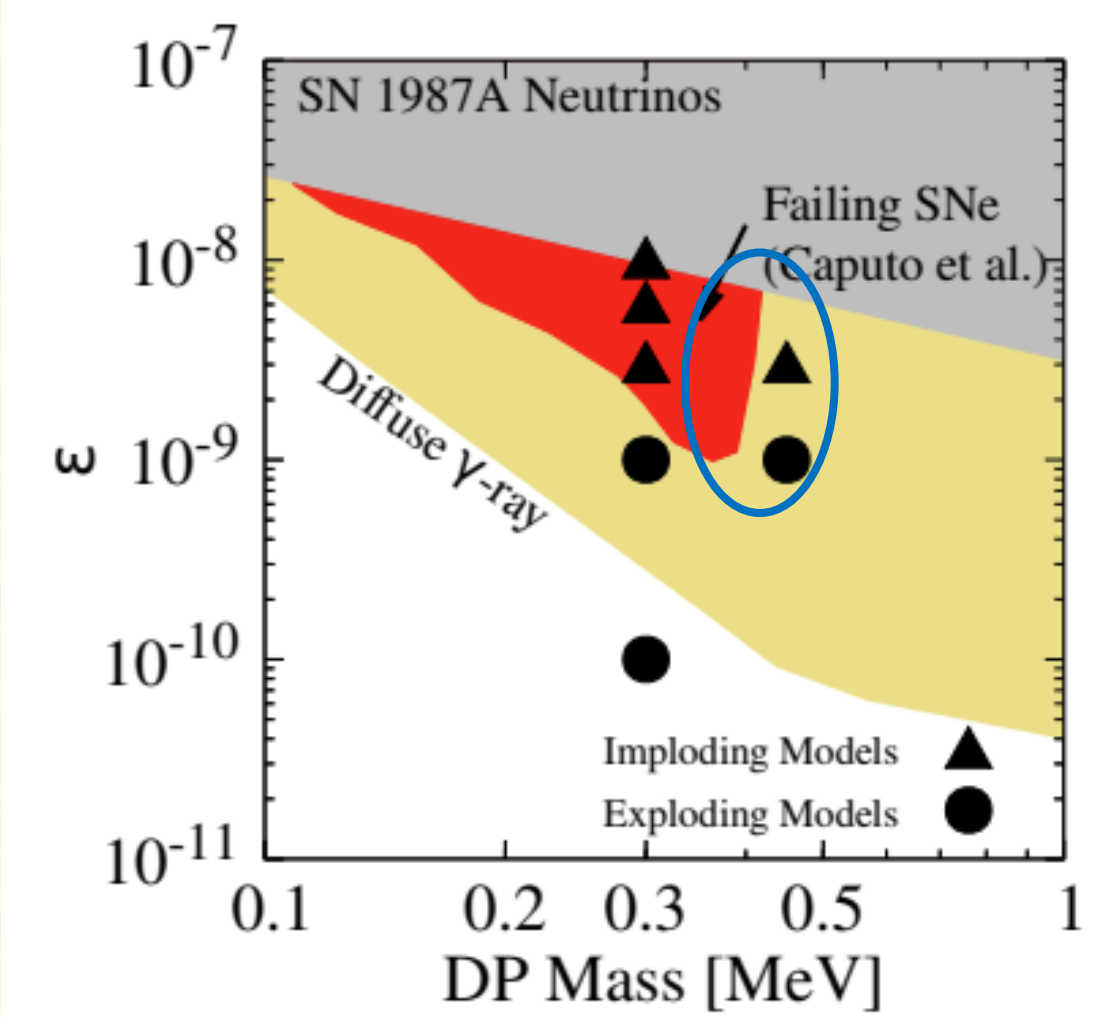
Condition for successful SN 1987A explosion:

$\varepsilon \lesssim 3 \times 10^{-9}$ for $m_{\gamma'} = 0.30\text{-}0.45$ MeV

- ✓ **SN explodability can provide a new constraint on dark photons!**
- ✓ Sensitivity studies on uncertain factors (e.g. EoS) are, of course, important.

What if dark photons are heavier?



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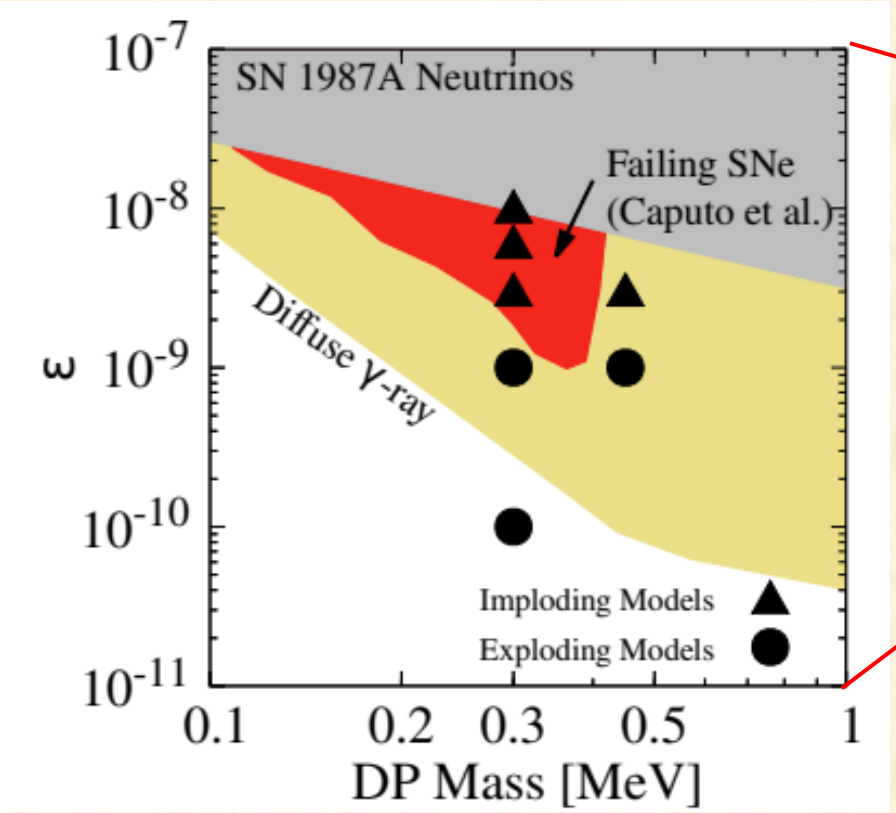
- ✓ The constraint disappears when dark photons are heavier, because the resonance appears in the cooling region.
- ✓ Impact on PNS convection?

What if dark photons are heavier?



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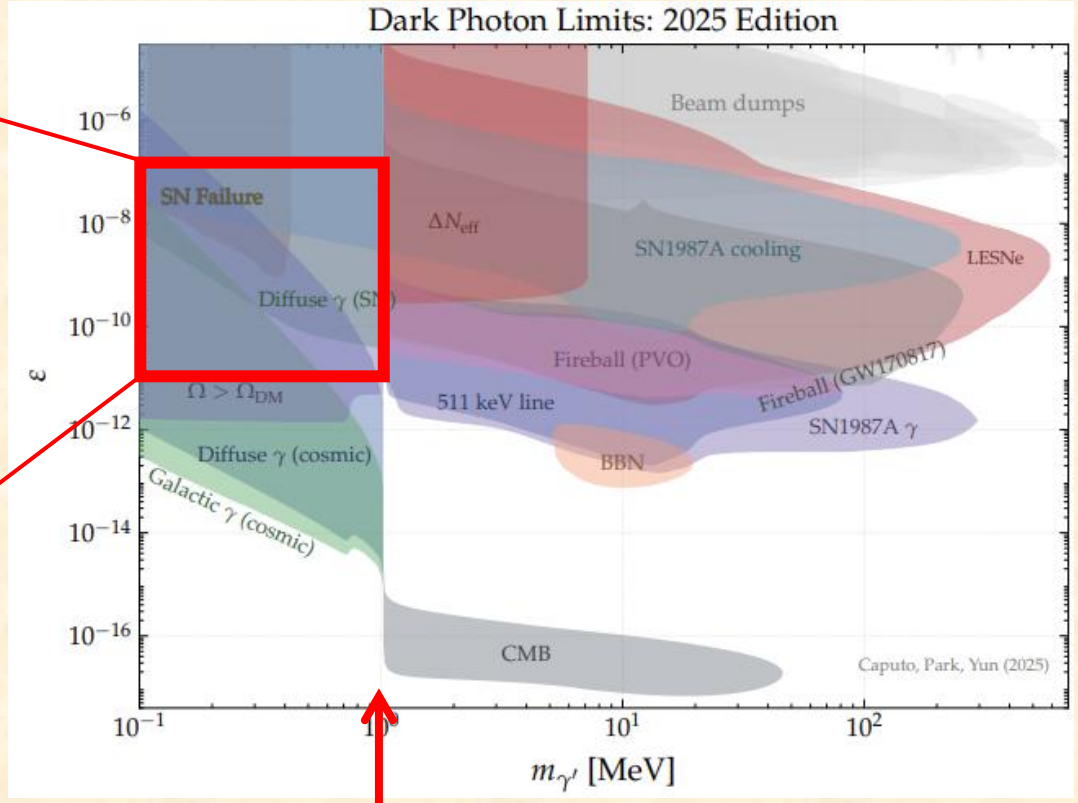

e-e+ mass

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.
→ They may look similar to heavy axion-like particles.

Summary

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

- Production of dark photons in the gain region causes cooling.
- A new constraint can be obtained based on explodablity.
- We verified the argument with self-consistent simulations.
- Investigating heavier dark photons will be interesting.