

Core-Collapse Supernovae as Laboratories for Neutrino and New Particle Physics

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Most of the work is done in collaboration with
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Question:

Can we use a core-collapse supernova as a laboratory for fundamental physics?

Yes—but only if we understand how new microphysics changes both **the observable signal and the supernova itself**.

New microphysics

Examples beyond the Standard Model

dark photon

A'

ALPs

a

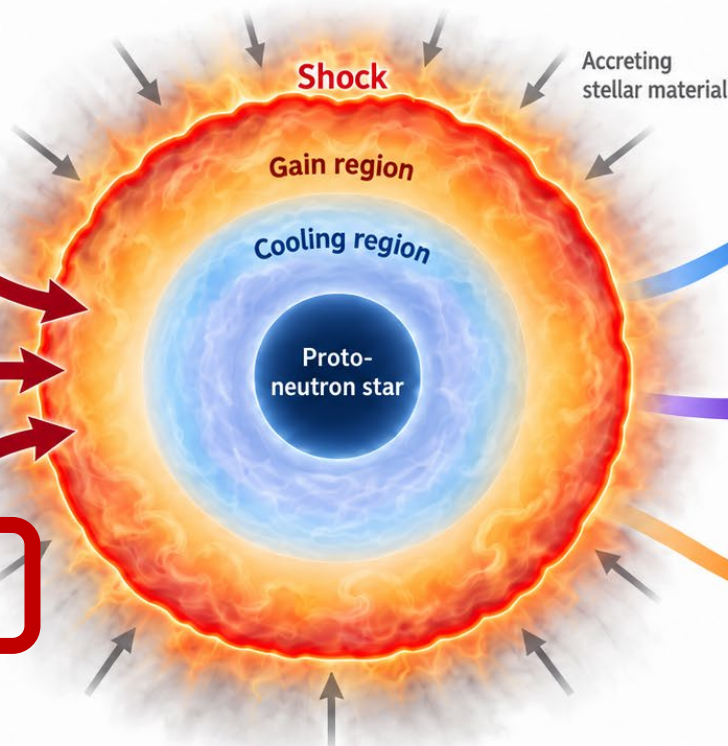
sterile neutrinos

$\nu_s \rightarrow \nu_{e,\mu,\tau}$

Modify
interior physics

Explosion dynamics

Core-collapse supernova as a laboratory



Observable signals

Imprints of the same microphysics

neutrinos

Neutrino detectors

gravitational waves

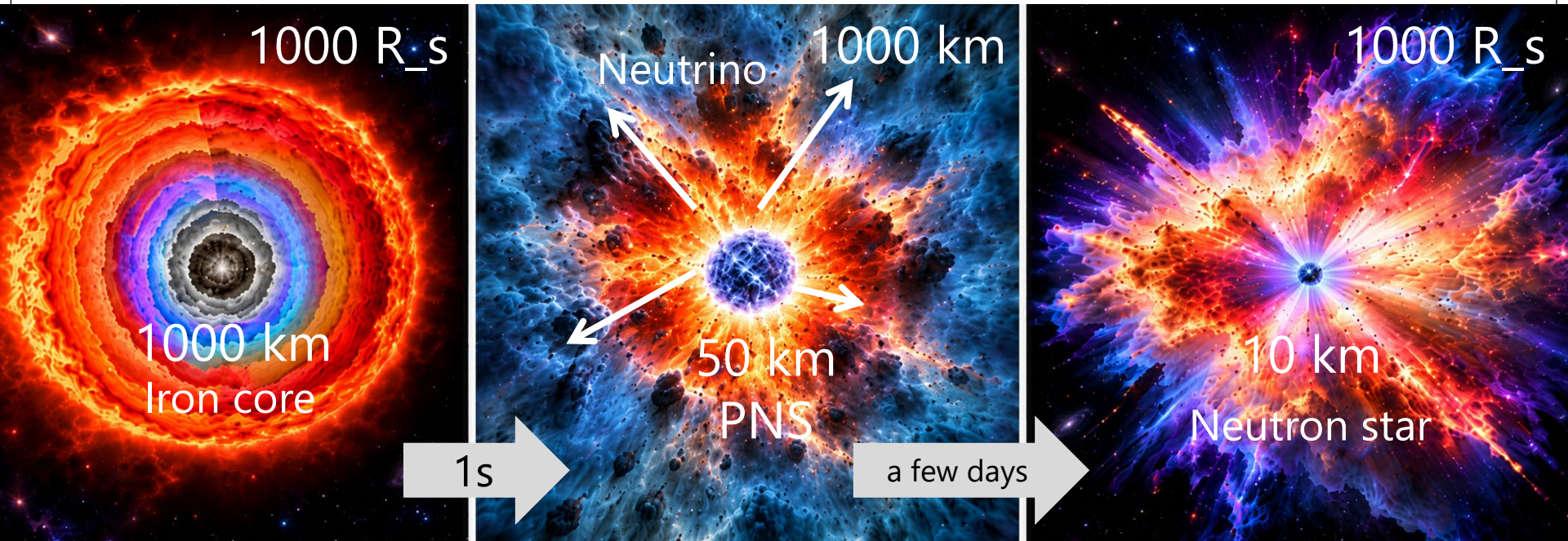
LIGO / Virgo / KAGRA

gamma rays

Fermi / INTEGRAL etc.

Simplified view of supernovae

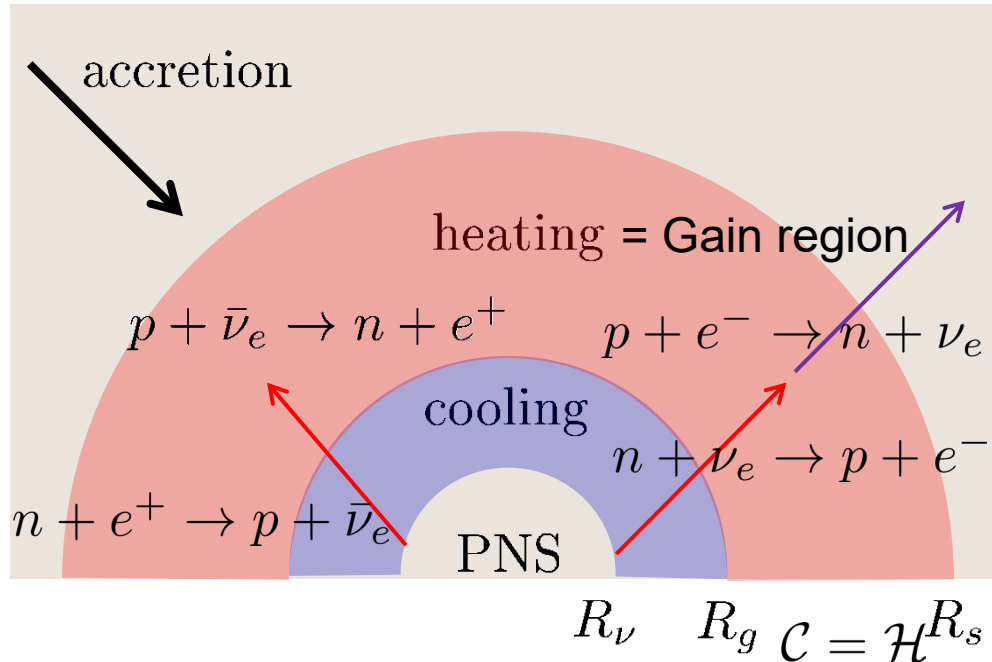
Red supergiant



Huge iron core immediately shrinks to proto-neutron star.
The released gravitational energy blow off the outer layers.
Neutrino helps the explosion.

Neutrino heating mechanism

Janka 01



Cooling: Local temperature

Heating: Radius and central temperature

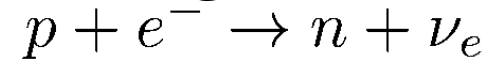
Radial dependence

$$T \propto 1/r$$

$$\mathcal{C} \propto 1/r^6$$

$$\mathcal{H} \propto 1/r^2$$

-Cooling term

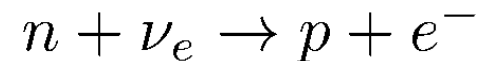


$$Q_\nu^- = (3\alpha^2 + 1) \frac{\pi \sigma_0 c (kT)^6}{(hc)^3 (m_e c^2)^2} \frac{\rho}{m_u} \times [Y_p \mathcal{F}_5(\eta_e) + Y_n \mathcal{F}_5(-\eta_e)]$$

$$\approx 145 \frac{\rho}{m_u} \left(\frac{kT}{2 \text{ MeV}} \right)^6 \left[\frac{\text{MeV}}{\text{s}} \right]$$

$$\rho_{\text{proton}} \times \rho_{\text{electron}} (\propto T^3) \times \sigma (\propto T^2) \times \bar{E} (\propto T)$$

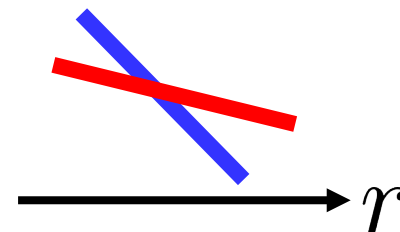
-Heating term



$$Q_\nu^+ = \frac{3\alpha^2 + 1}{4} \frac{\sigma_0 \langle \epsilon_{\nu_e}^2 \rangle}{(m_e c^2)^2} \frac{\rho}{m_u} \frac{L_{\nu_e}}{4\pi r^2 \langle \mu_\nu \rangle} (Y_n + 2Y_p)$$

$$\approx 160 \frac{\rho}{m_u} \frac{L_{\nu_e, 52}}{r_7^2 \langle \mu_\nu \rangle} \left(\frac{kT_{\nu_e}}{4 \text{ MeV}} \right)^2 \left[\frac{\text{MeV}}{\text{s}} \right]$$

$$\rho_{\text{neutron}} \times \rho_{\text{neutrino}} (\propto T_\nu^3 / r^2) \times \sigma (\propto T_\nu^2) \times \bar{E} (\propto T_\nu)$$

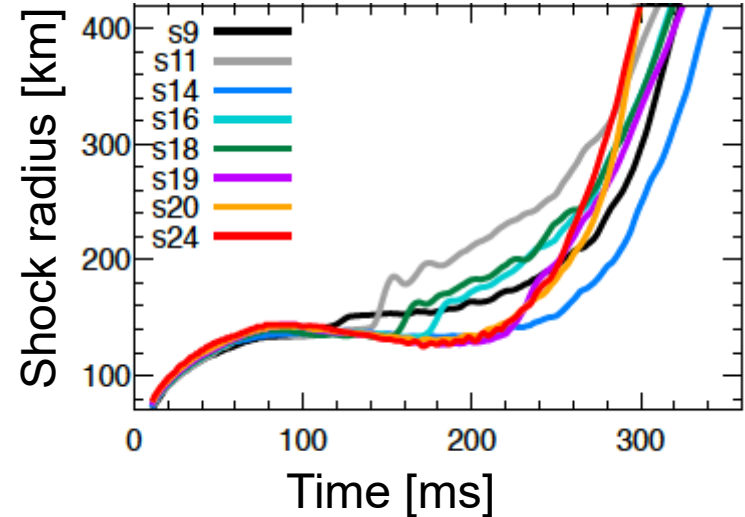
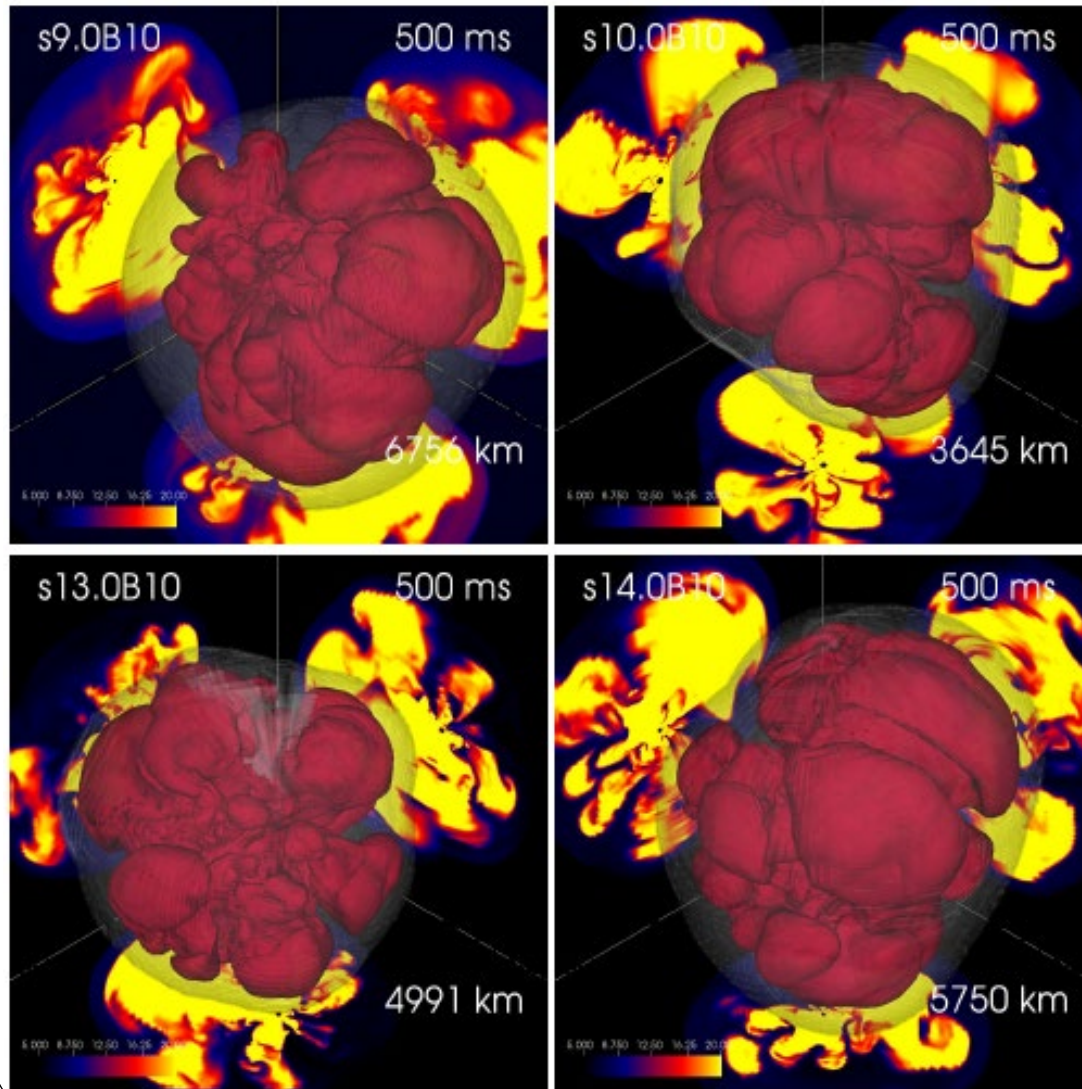


Heating
dominate
outside

From 1D to 3D

Achievements of supernova simulations

We obtain successful explosions in 3D simulations.



We now have a quantitative baseline for neutrino-driven explosions.

Supernovae as Laboratories for Neutrino and New Particle Physics

Now we can use a supernova as a lab for the new particles.

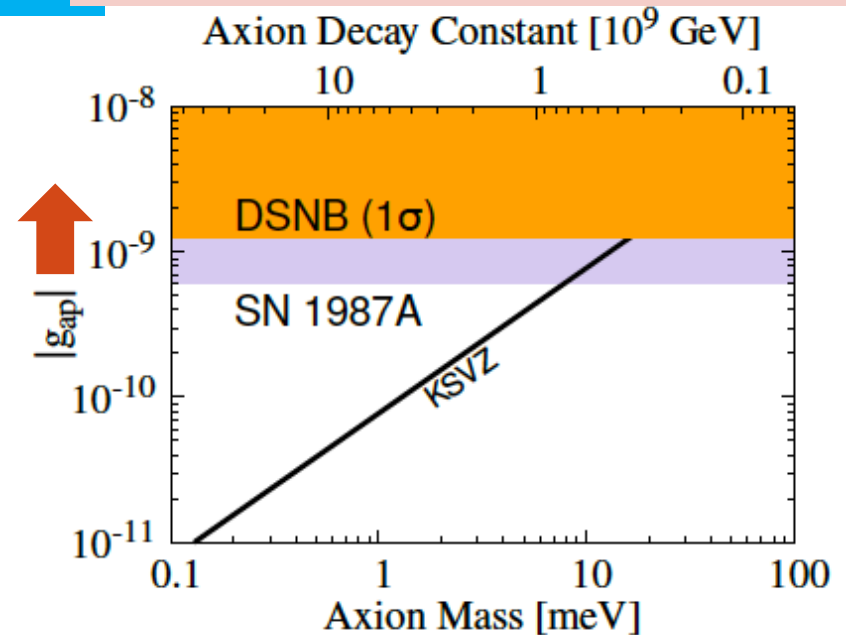
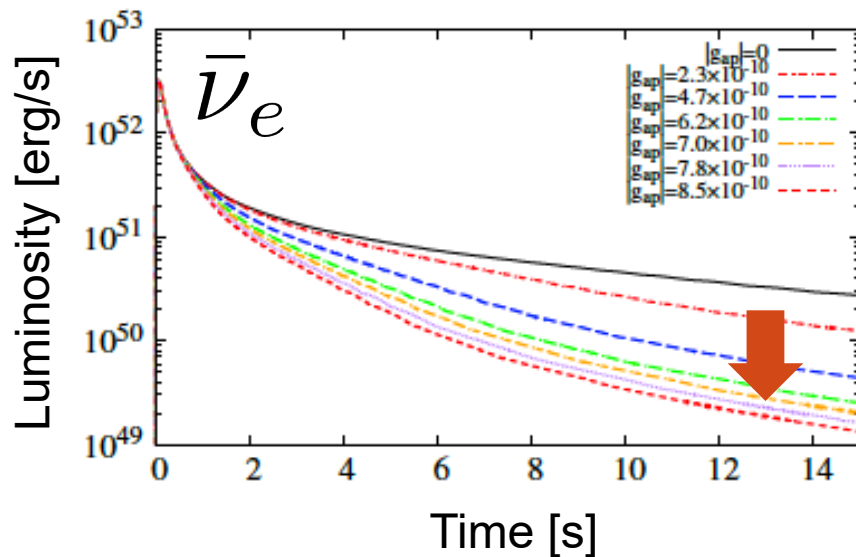
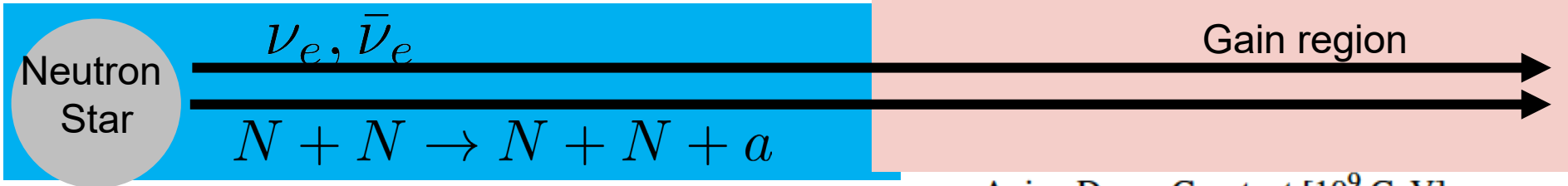
Here we classify the effect of the new particles:

- **PNS cooling**
energy escapes $\rightarrow$ lower neutrino luminosity
e.g., meV QCD axion, Axion-Like Particles
- **Cooling / loss of heating in the gain region**
less energy available for shock revival $\rightarrow$ explosion suppressed
e.g., eV sterile ν , dark photon
- **Energy transport and deposition outside the PNS**
decay / absorption $\rightarrow$ explosion enhanced
e.g., heavy ALP / heavy sterile ν

Cooling by QCD axion

meV QCD axions cool the proto-neutron star.

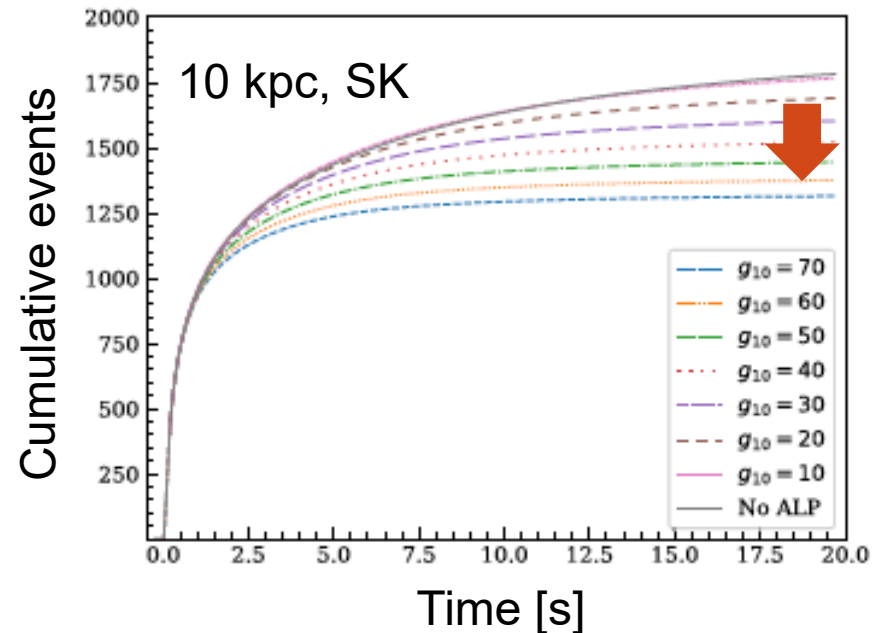
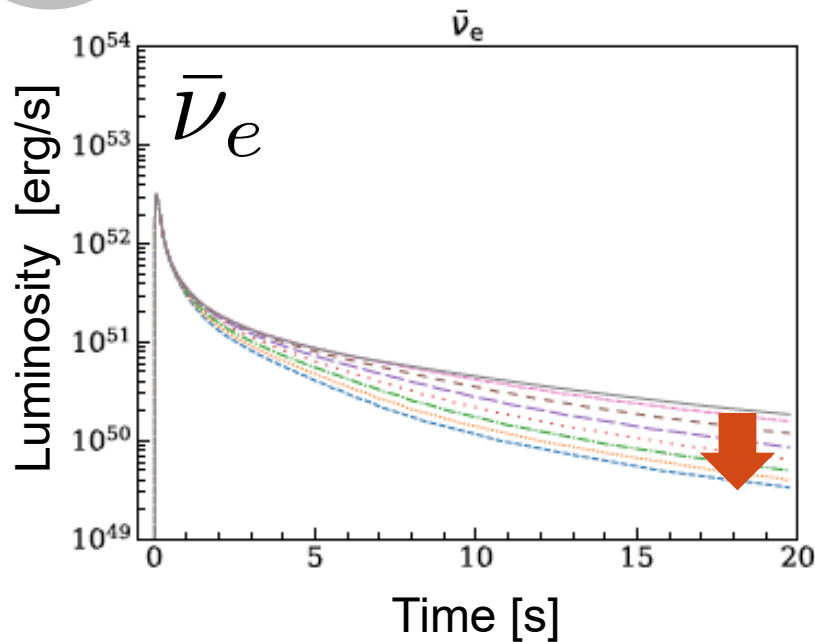
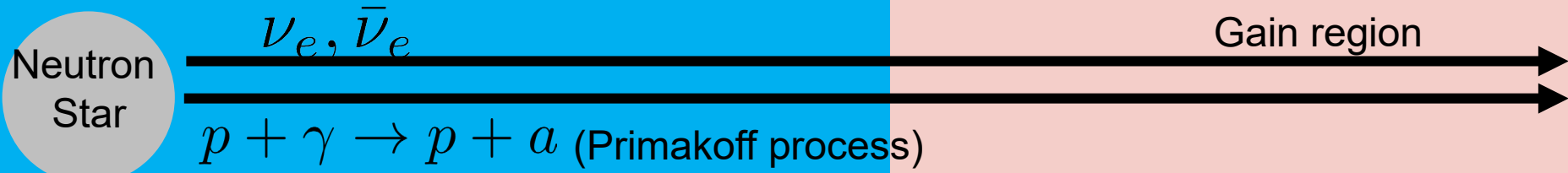
Temperature of PNS decreases and neutrino emission is suppressed.



The DSNB can constrain the axion mass and coupling

Cooling by Axion-like particle

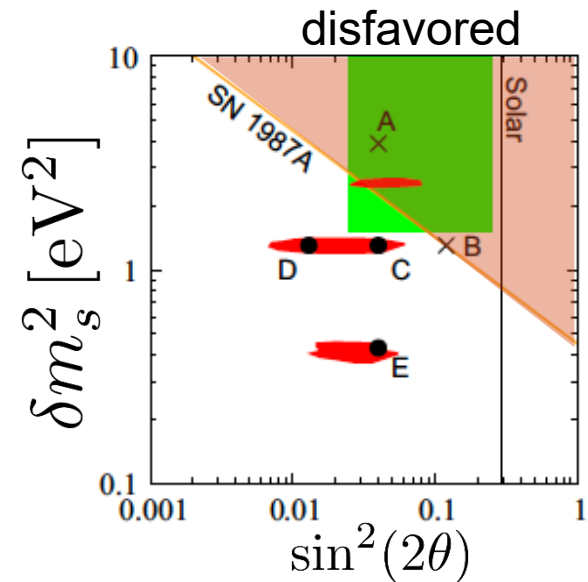
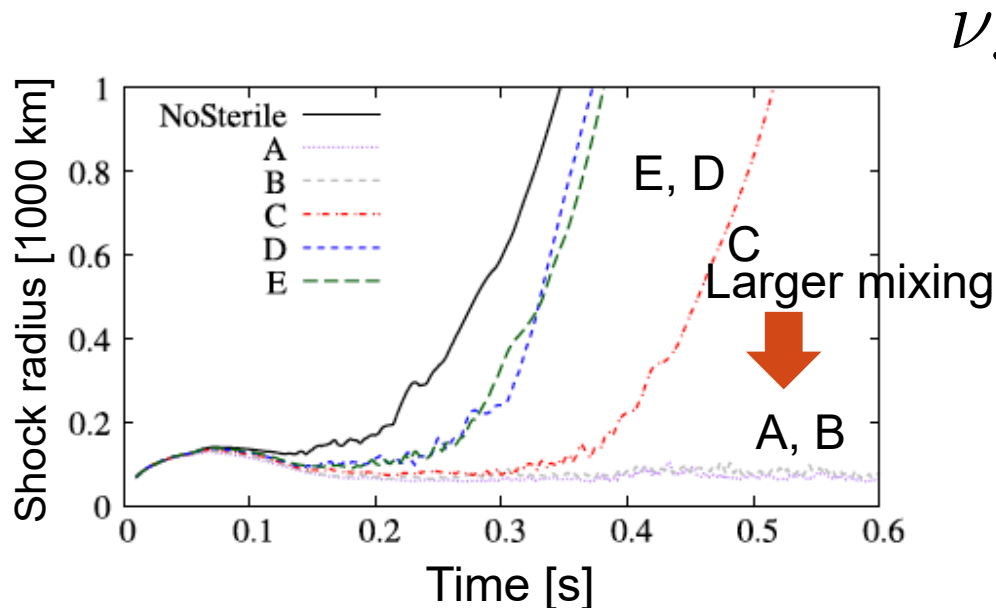
More generally, axion-like particles (ALP) can have independent masses and couplings. Here we consider a 10MeV ALP.



The same basic effect appears: additional PNS cooling reduces the neutrino signal.

eV sterile neutrino hinders explosion

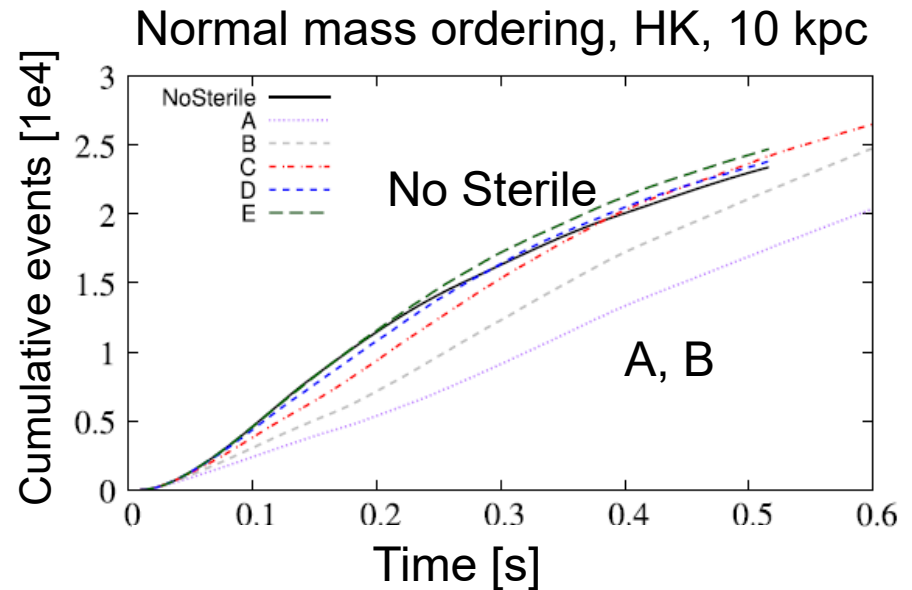
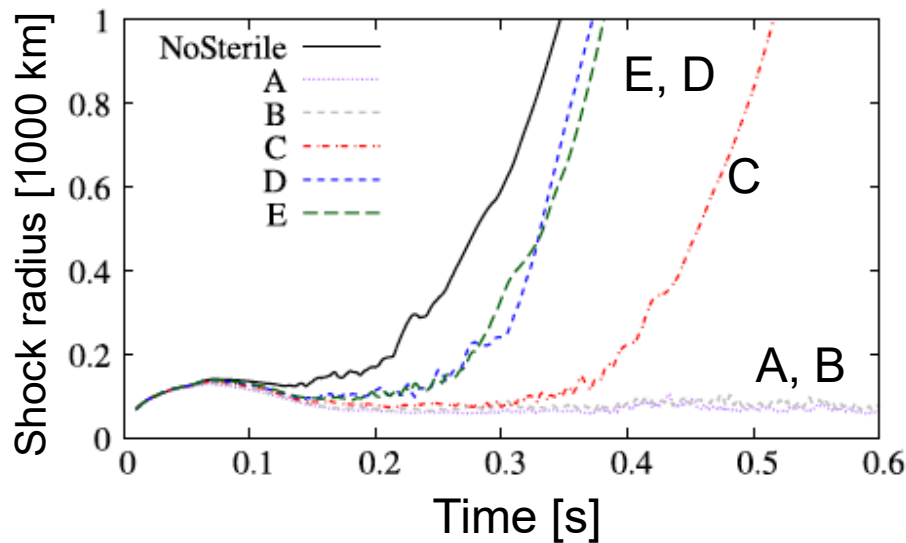
eV-scale sterile neutrinos are discussed in connection with reactor neutrino anomalies.



Active-sterile conversion reduces neutrino heating and can hinder shock revival.

eV sterile neutrino hinders explosion

eV-scale sterile neutrinos are discussed in connection with reactor neutrino anomalies.



In the case of A and B, active neutrino is significantly reduced. The event number in HK is also reduced.

Sub-MeV dark photon hinders explosion

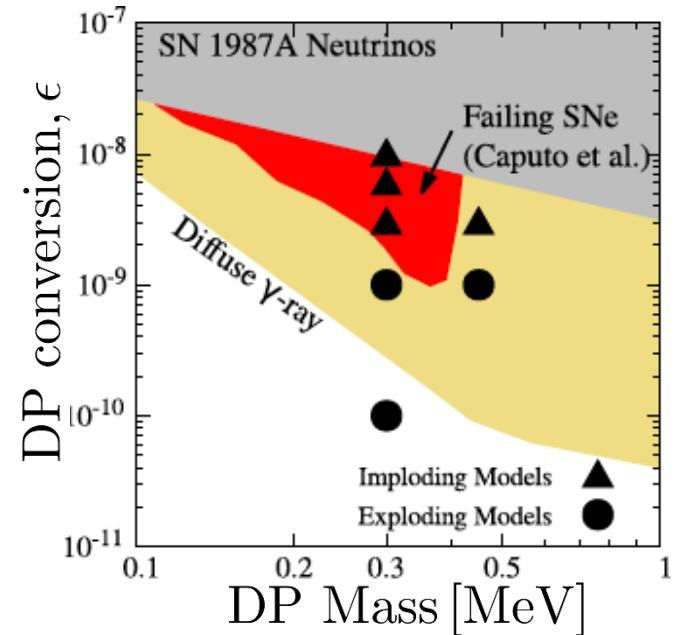
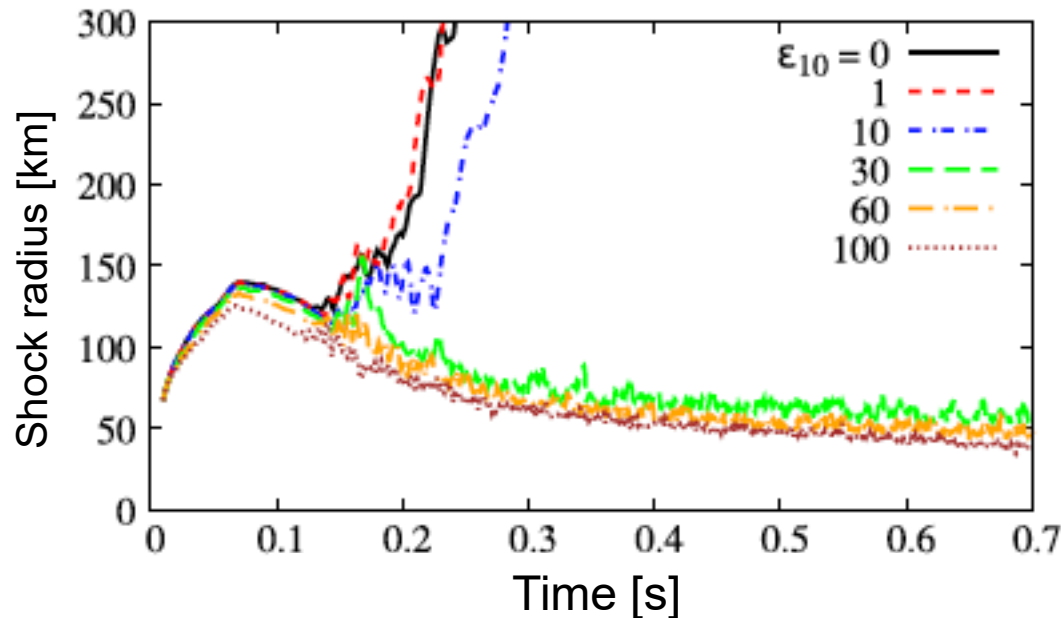
A dark photon is a simple portal connecting the Standard Model to a hidden dark sector.

Neutron
Star

Gain region

$$n + p \rightarrow n + p + \gamma^*$$

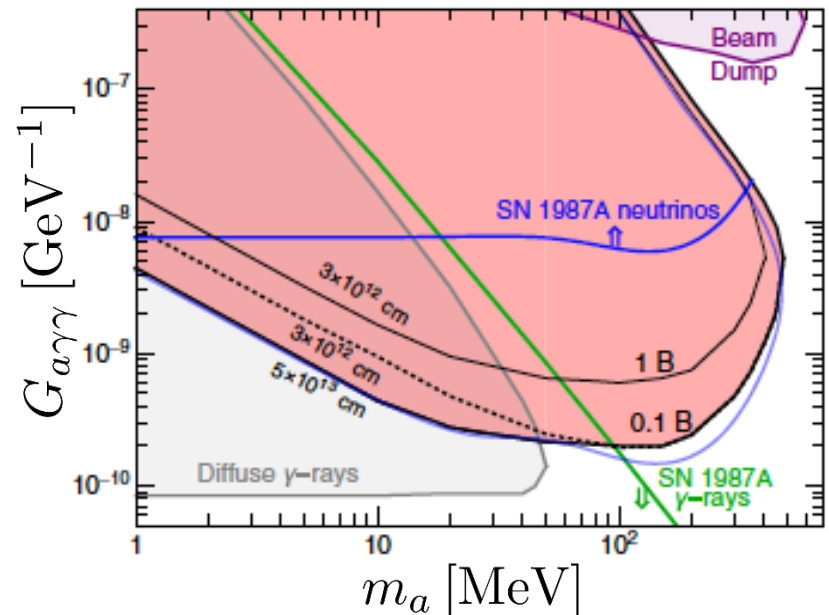
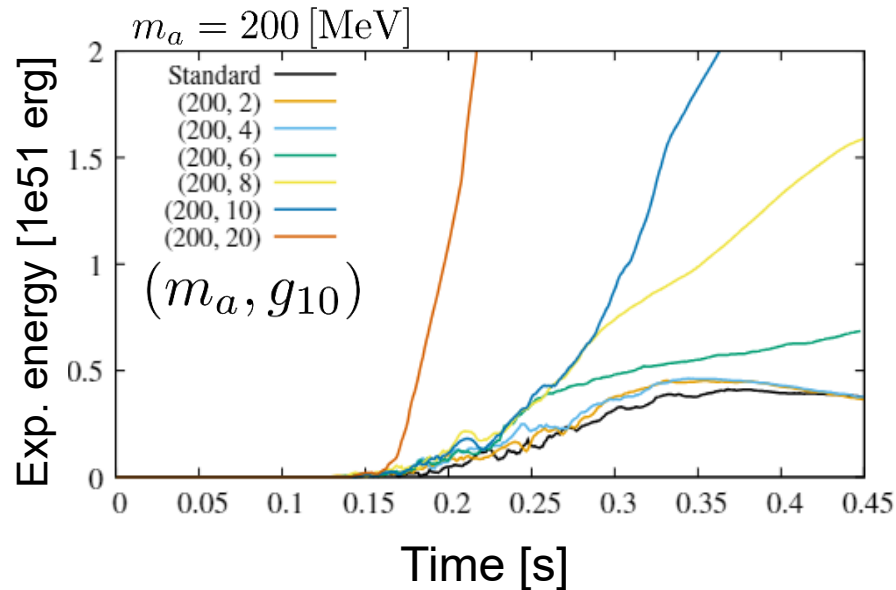
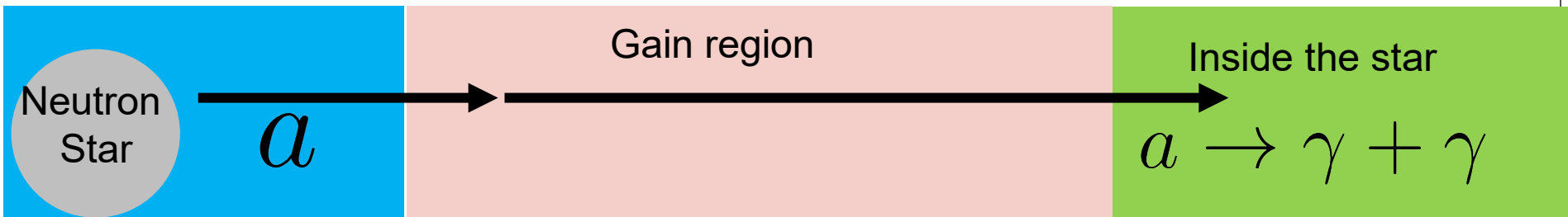
$$\gamma^* \rightarrow A'$$



Sub-MeV dark photon is selectively produced in the gain region and that cool it. Strong coupling fails the explosion.

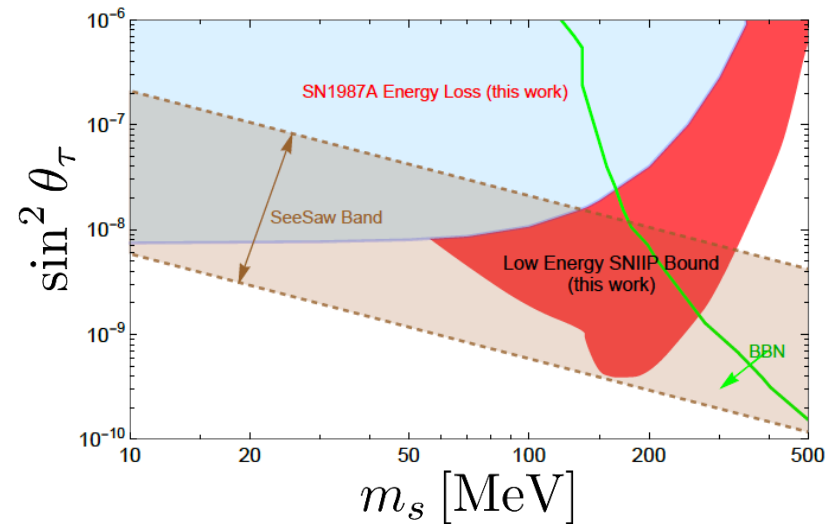
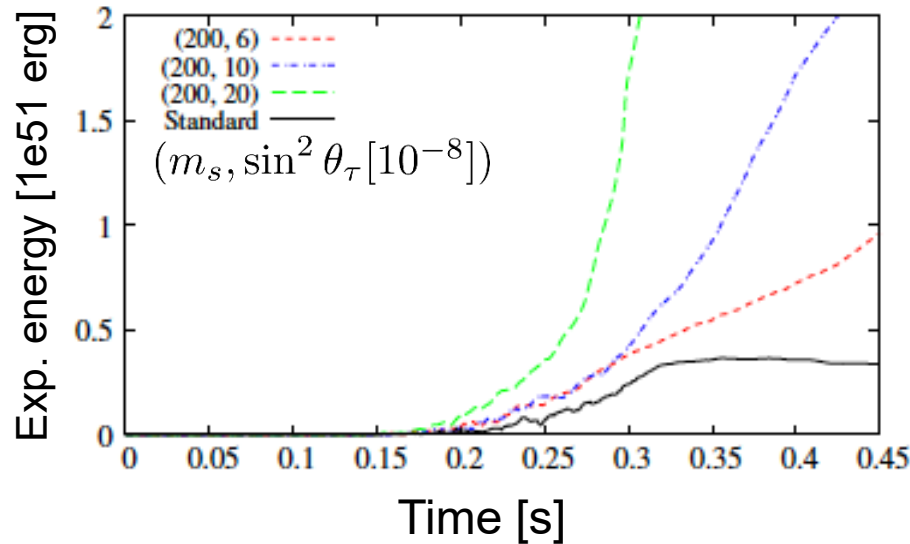
Mori et al. 2025

Heavy ALPs enhance explosion energy



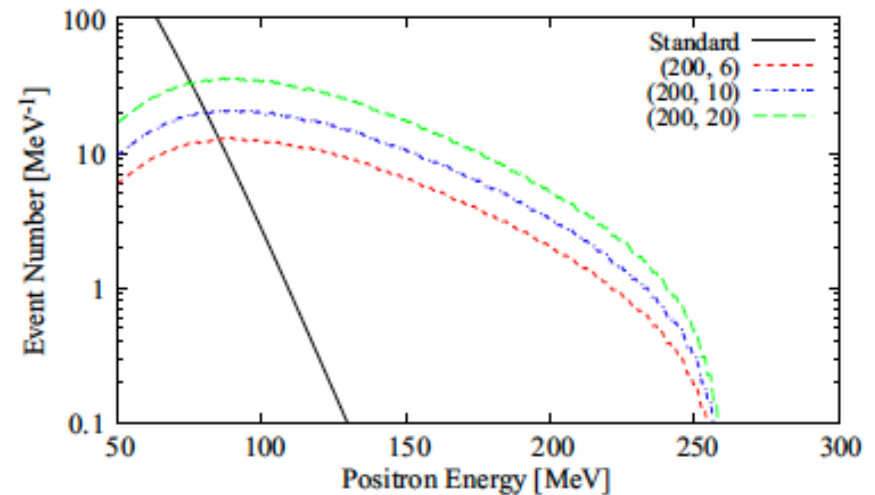
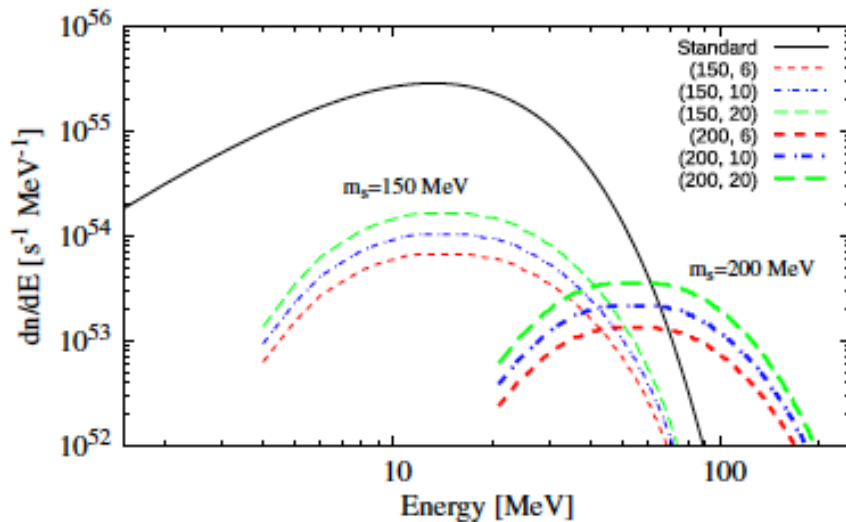
Heavy ALPs transport energy outward and deposit it inside the star. Too much heating can overproduce the explosion energy.

Heavy sterile neutrinos enhance explosion energy



Heavy sterile neutrinos carry energy out of the core and deposit it farther out through their decay, enhancing the explosion.

Heavy sterile neutrinos change spectrum



Their decay can produce a distinctive high-energy neutrino signal.

Summary

Modern core-collapse supernova simulations provide a quantitative baseline.

New particles can cool the core, suppress neutrino heating, or deposit energy farther out.

They can therefore change both the explosion and the neutrino signal.

The quantitative impact depends on progenitor structure, neutrino transport, and the treatment of new-particle production and transport, but this energy-flow picture would be robust.