Impact of heavy axion-like particles on neutrino-driven supernova explosions: Dependence on progenitor structure and rotation

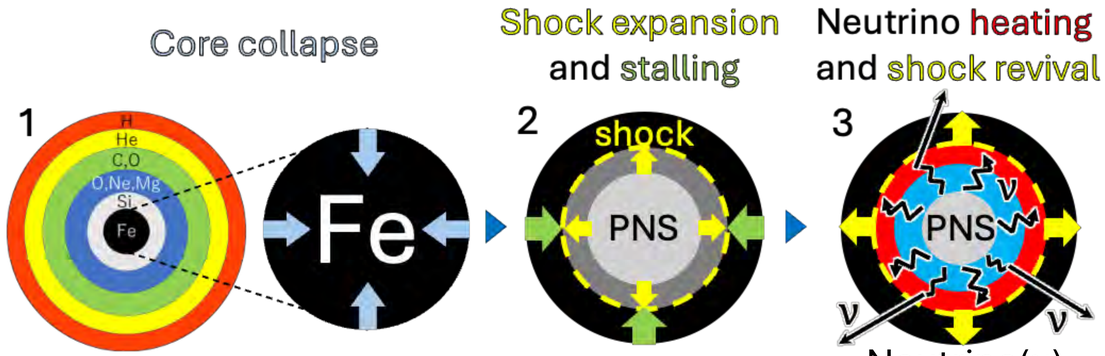
Tsurugi Takata (Fukuoka U.), Kanji Mori (Keio U.), Ko Nakamura (Fukuoka U.), Kei Kotake (Fukuoka U.)

Introduction

Core-collapse supernova (CCSN)

CCSN is a powerful explosion of a massive star, leaving behind a compact object such as a neutron star or a black hole.

Neutrino-driven mechanism



1. The iron core forms via nuclear fusion, and disintegration of iron triggers gravitational collapse.
2. A neutron star forms; accreting matter rebounds, creating a shock wave that then loses energy as it moves outward.
3. But neutrinos heat the matter, leading to the SN explosion.

Axion-like particles (ALPs)

Axion is hypothetical particle solving the strong CP problem. (ALP is more general class particle.)

We employ an ALP scenario interacting with photons.

Impact of ALPs on SN explosions

ALPs can be thermally produced and can decay inside SN

➡ Transporting energy and assisting the explosion.

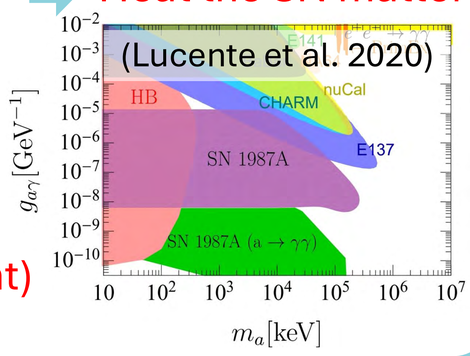
Production process : $\gamma + p \to a + p,\ \gamma + \gamma \to a$

Decay process : $a \to \gamma,\ a \to \gamma + \gamma$ ➡ Heat the SN matter

Constraints on ALP Parameters from SN Observations (SN1987A)

Neutrino/gamma-ray observations

➡ Constraints on ALP parameter (mass, coupling constant)



Motivations & Methods

Motivations

1. Progenitor dependence of ALP production/heating effects in SN.
2. Rotational effects on the constraint of ALP parameter.

Simulation setup (Common for 1D & 2D)

SNcode : 3DnSNe code (Takiwaki et al. 2016)

EOS : LS220 (Lattimer & Swesty 1991)

1D simulation setup (with ALPs)

Progenitor: s11.2 $M_\odot$ model (Woosely, Heger & Weaver 2002)
s20, s25 $M_\odot$ model (Woosely & Heger 2007)

ALP parameter

coupling constant : $g_{a\gamma} = (4, 6, 8, 10)\ [10^{-10}\ \mathrm{GeV}^{-1}]$

ALP mass : $m_a = (100, 150, 200, 300, 400, 600, 800)\ [\mathrm{MeV}]$

2D simulation setup (without ALPs)

Progenitor: s13, s18 $M_\odot$ model (Woosely & Heger 2007)
m14 (14+9 $M_\odot$) model (Urushibata 2018)

Rotation : 0.0, 1.0 [rad/sec]

Approach to ALP parameter constraint

Neutrinos were observed for ~12 seconds from SN 1987A.

excessive ALP cooling ➡ Accelerate core cooling ➡ Shorten the neutrino duration

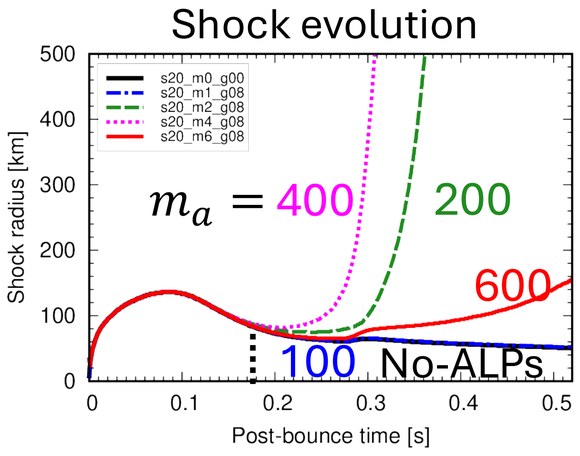
Excessive-cooling ALPs parameter are excluded

Simple condition: ALP emission < neutrino luminosity (Raffelt 2008).

Progenitor dependence of ALP effects in SN

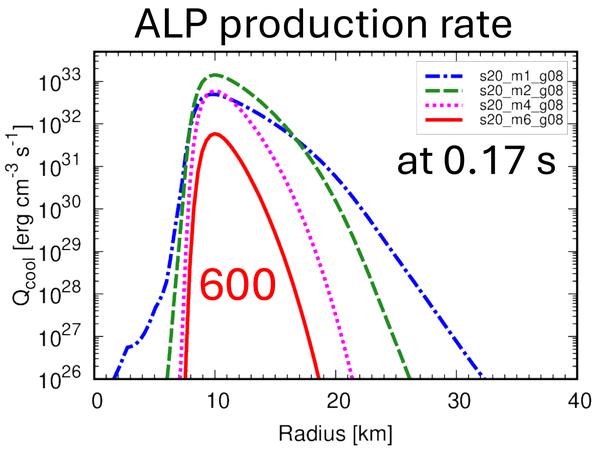
1D supernova with ALPs (10.1103/PhysRevD.111.103028)

Shock evolution



1. For m_a = **100 – 400** MeV, heavier ALPs ➡ earlier shock revival.
2. For m_a = **600** MeV, the shock expand more slowly.

ALP production rate

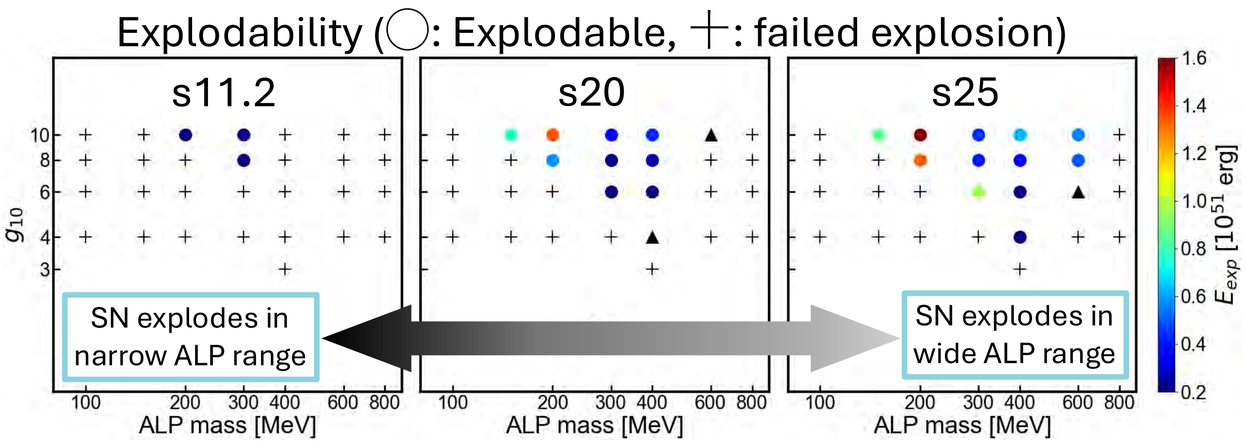


1. For m_a = **100 – 400** MeV, the production rate is comparable, heavier ALPs ➡ more effective heating.
2. For m_a = **600** MeV, the production rate is decreased.

causes

The SN temperature is insufficient for production.

Explodability (◯: Explodable, ┼: failed explosion)



Heavier progenitor has higher temperature

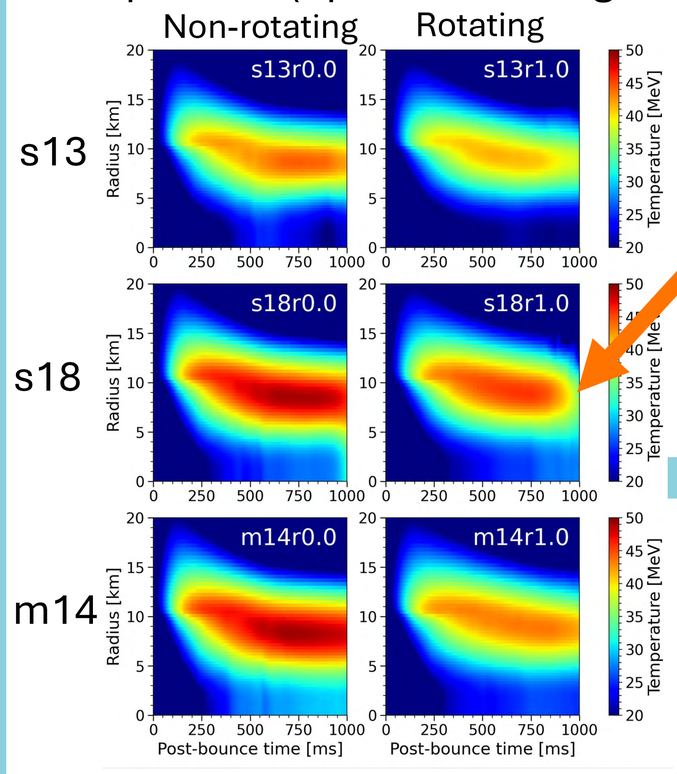
➡ heavier ALPs are produced more efficiently

➡ broader range of explodable ALP parameters in heavier progenitors.

Rotational Effects on the ALP constraint

2D supernova without ALPs (work in progress)

Temperature(Space-time diagram)

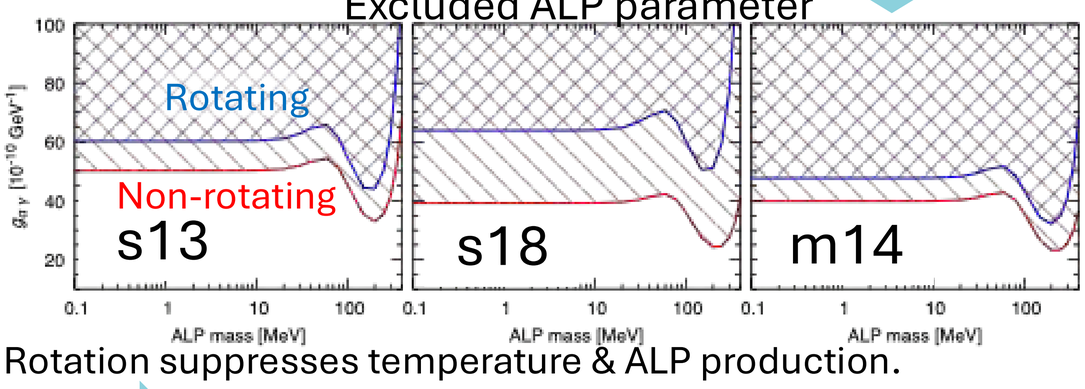


1. Temperature (central core) Non-rotating model > Rotating model
2. At 1 s, rotating s18 model: significant temperature drops.
3. To obtain ALP constraints

➡ Estimate ALP cooling rate

➡ Constraint-imposing condition: $L_a < L_\nu$ at 1 s

Excluded ALP parameter



Rotation suppresses temperature & ALP production.

➡ Rotation relaxes of ALP parameter constraint.

This effect is significant in the high-compactness s18 model.

Summary

- ✓ ALPs can enhance SN explosions, with heavier progenitors showing an effective contribution from heavier ALPs.
- ✓ Rotation lowers the SN core temperature, reducing ALP cooling and thereby relaxing ALP constraints.