Core–Collapse Supernova Cooling in the Dark Z Model

Ju Hyeong Kang

부산대학교
PUSAN NATIONAL UNIVERSITY

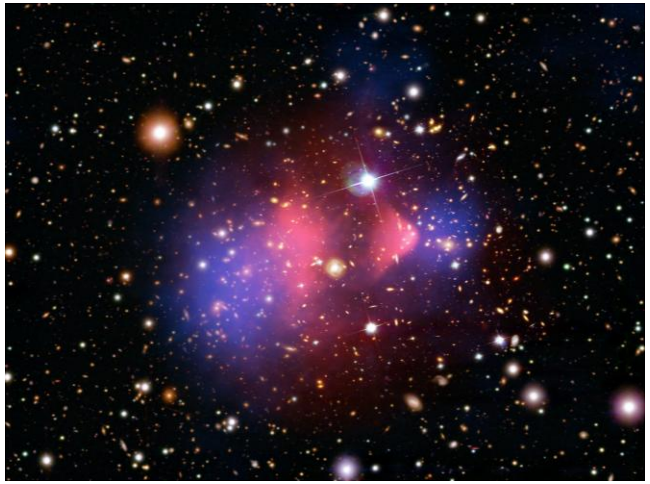
Based on the ongoing work
with Eung Jin Chun, Kwang Sik Jeong, Dong–Won Jung, and Seokhoon Yun

The 5th workshop on Symmetry and Structure of the Universe
24 August 2026

1. Dark Z Model

Physics Beyond the Standard Model

- Standard Model: Excellent explanation of nature up to the TeV $(\sim 10^{-18}\ \mathrm{m})$ scale;
  unresolved problems require BSM physics



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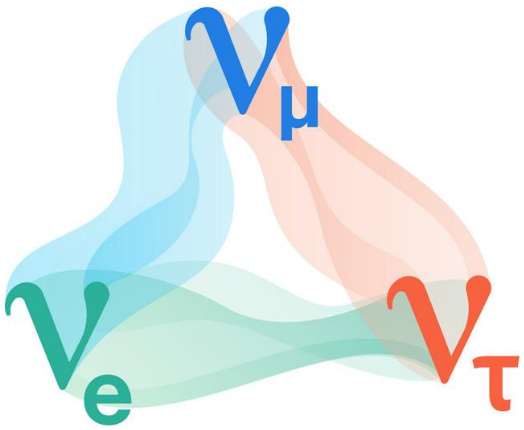

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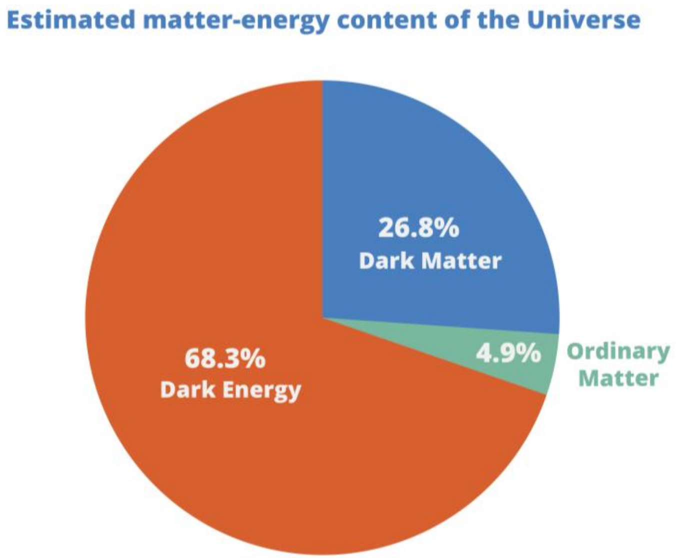


Planck 2018

Dark Sector

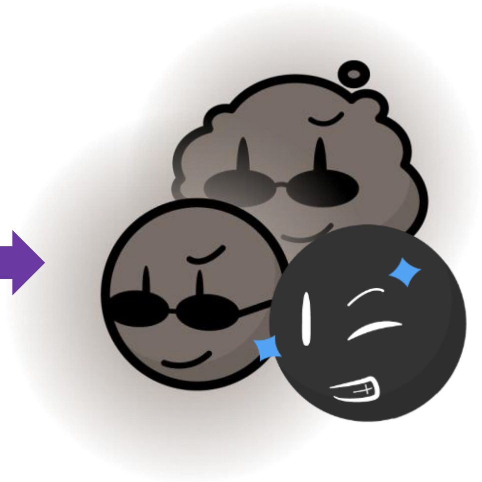
- Dark sector: hidden sector that are neutral under the SM gauge symmetries
- Dark gauge boson: may act as a mediator between the SM sector and dark sector

SM sector

Dark Gauge Boson

Dark photon / Dark Z

Dark sector



Dark matter, dark radiation

pictures from higgstan.com

Dark Z Model

- Dark Z (Z'): Gauge boson of a hidden $U(1)_D$ gauge symmetry

- Couples to the SM currents via kinetic and mass mixing

Kinetic mixing

$$\frac{\varepsilon_0}{2} B^{\mu\nu} X_{\mu\nu} \quad \frac{\varepsilon_3}{2} W_3^{\mu\nu} X_{\mu\nu}$$

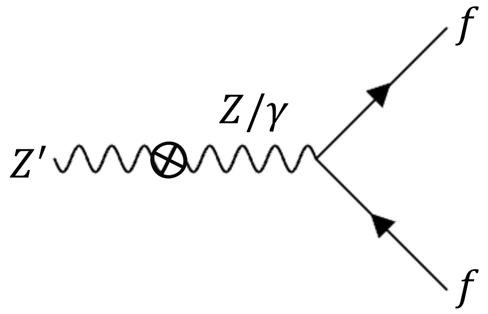
($\varepsilon_0, \varepsilon_3$: Kinetic mixing parameters)

Mass mixing

$$m_{ZX}^2 Z^\mu X_\mu$$

(m_{ZX}^2: Mass mixing parameter)

$$\Rightarrow$$



$$\mathcal{L}_{\text{int}} = Z'_\mu \left(e\theta_A J^\mu_{\text{EM}} + g_Z \theta_Z J^\mu_{\text{NC}} \right)$$

- Low mass limit: $m_{Z'} \ll m_Z$

J^μ_{NC} coupling $\theta_Z \sim (\varepsilon_0 - \varepsilon_3) \frac{m_{Z'}^2}{m_Z^2} - \frac{m_{ZX}^2}{m_Z^2}$

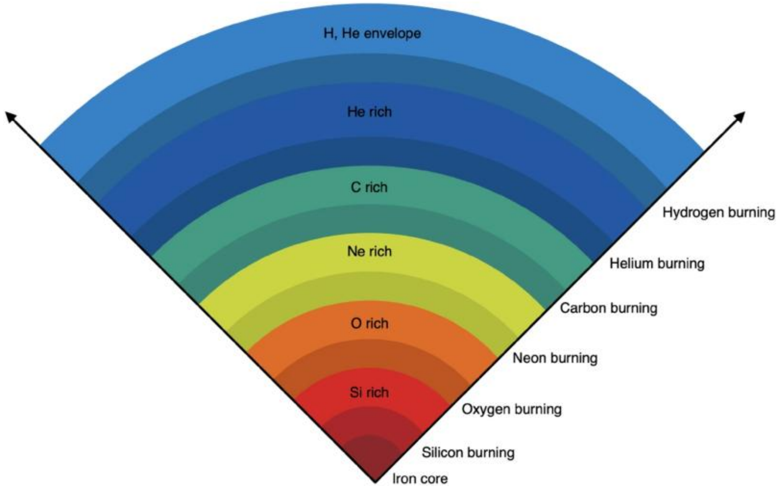
Suppressed

No $m_{Z'}^2/m_Z^2$ suppression

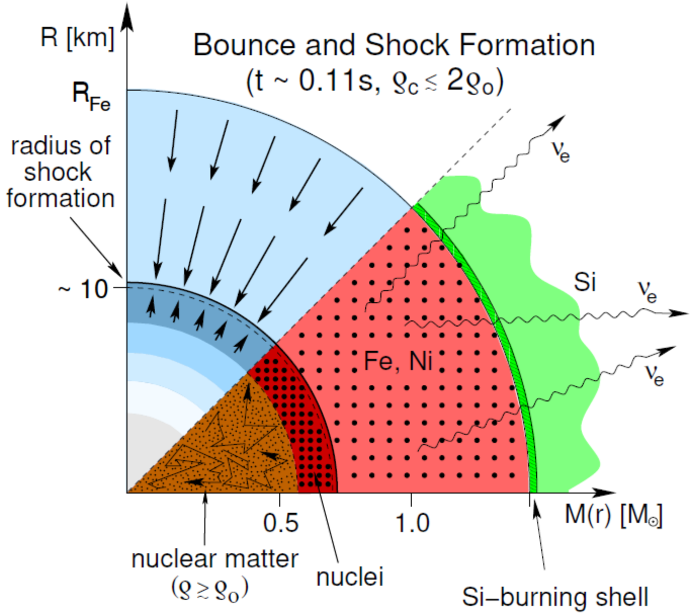
2. Core-Collapse Supernova

Initial Phase of Core−Collapse Supernova

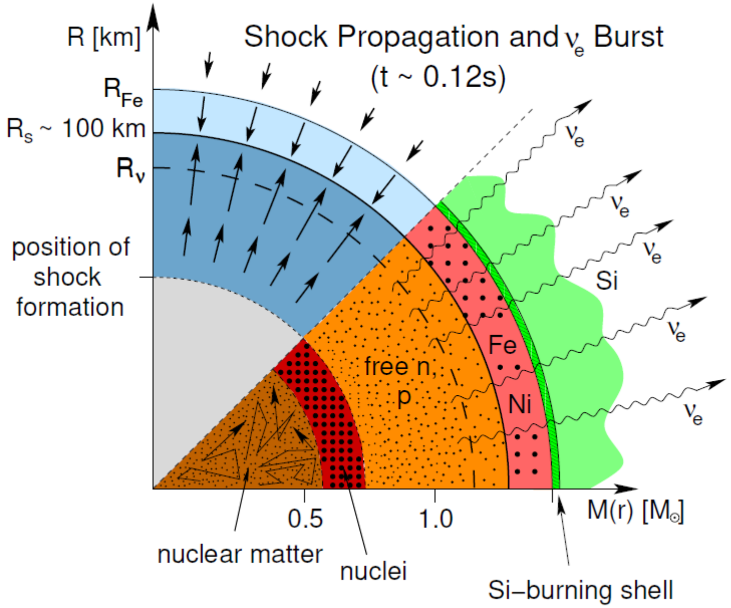
- At the final stage of stellar evolution, an Fe core forms and nuclear fusion ceases
- Upon reaching nuclear saturation density, core bounce occurs and a shock forms
- Shock dissociates heavy nuclei and generates a ν_e burst



A. Arcones and F. Thielemann, 2022



H.T. Janka et al., 2007



H.T. Janka et al., 2007

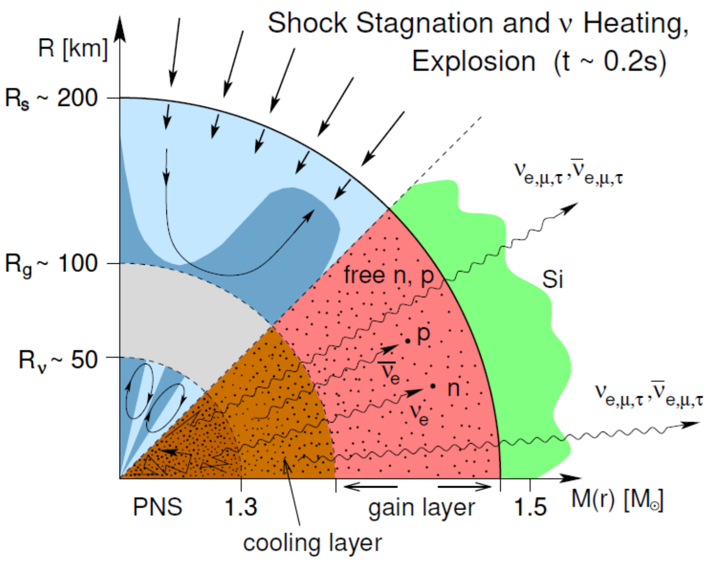
PNS Formation and Shock Revival

- Hot and dense proto-neutron star (PNS) formed; $T \sim \mathcal{O}(10)$ MeV, $\rho \sim \mathcal{O}(10^{14})$ g/cm^3
- Neutrinos from the PNS deposit energy into the shock

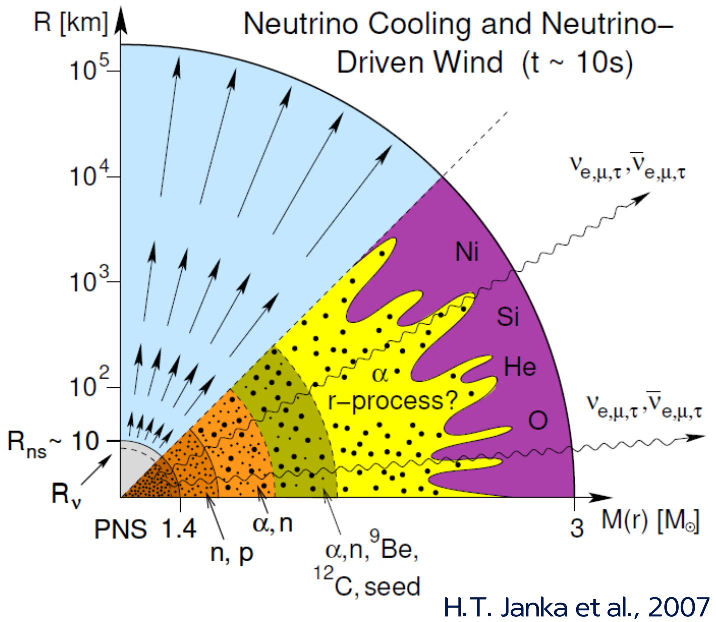
  Revival success → Neutron star

  failure → Black hole

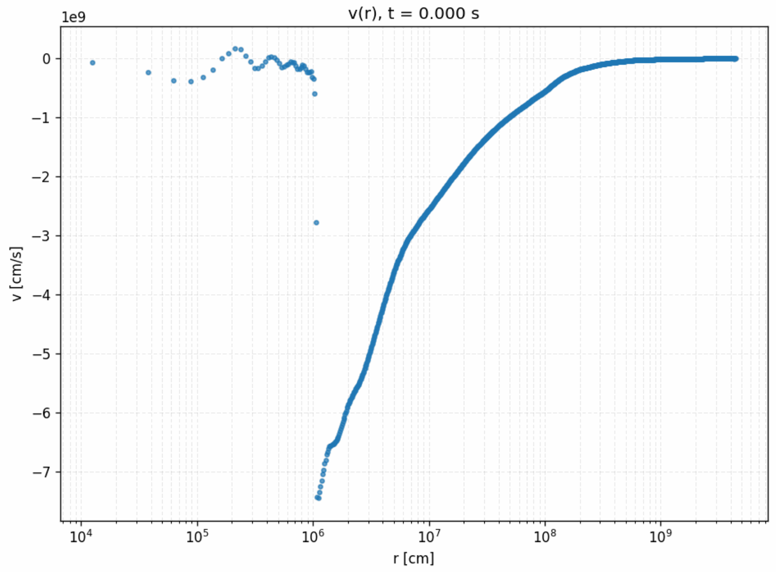
Simulation result: velocity profile



H.T. Janka et al., 2007



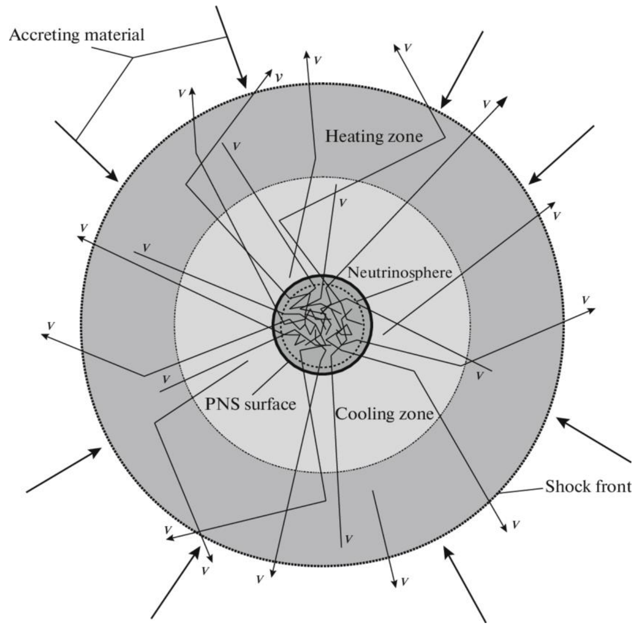
H.T. Janka et al., 2007



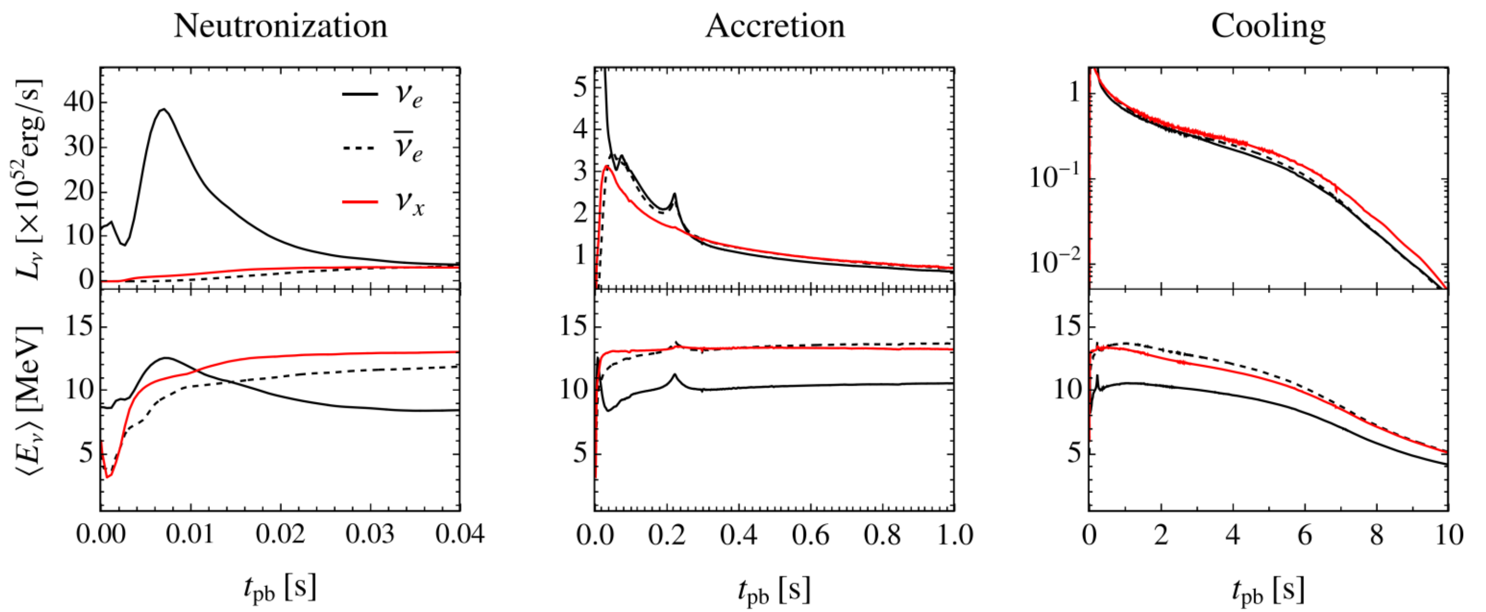
Neutrino Cooling

- About 99% of the gravitational binding energy is released through neutrinos of all flavors

$$L_\nu \sim 10^{52}\ \mathrm{erg/s}, \quad \langle E_\nu \rangle \sim \mathcal{O}(10)\ \mathrm{MeV}, \quad t_{\mathrm{diff}} \sim 10\ \mathrm{s}$$



Y. Krivosheyev and G. Kogan, 2018

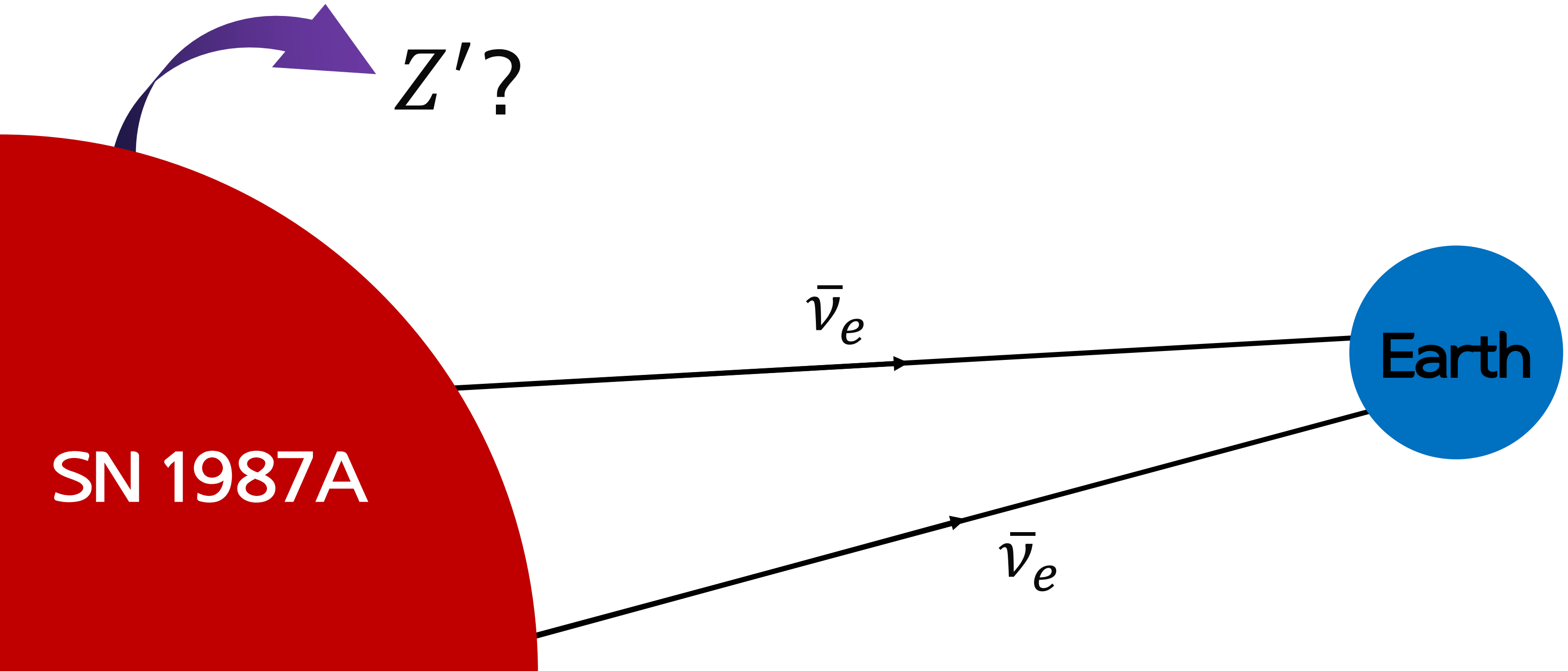


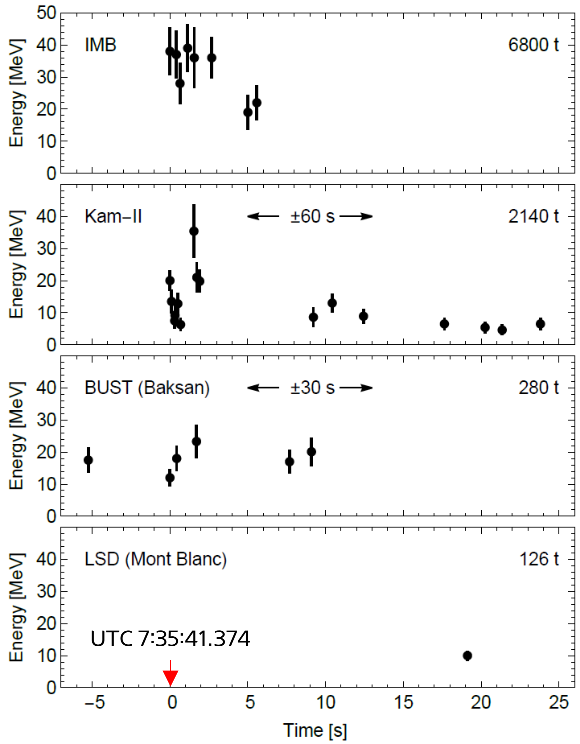
P. Carenza et al., 2024

3. Supernova Cooling

SN 1987A Cooling Bounds

- Electron antineutrinos were observed from SN 1987A
- Excessive energy loss through Z' emission would shorten the observed neutrino signal
- This requires $L_{Z'} \lesssim \mathcal{O}(10^{52})\ \mathrm{erg/s}$ at $t_{\mathrm{pb}} \sim 1\ \mathrm{s}$





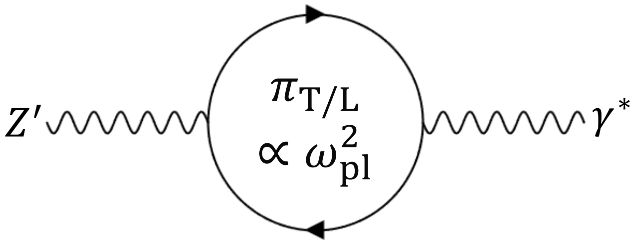
D. F. G. Fiorillo et al, 2023

Dark Z in the PNS Medium

- PNS environment: Strongly degenerate electrons

$$\omega_{\rm pl} \sim \mathcal{O}(10)\ \mathrm{MeV}$$

- In-medium plasma effect induced by $Z'e^-$ coupling

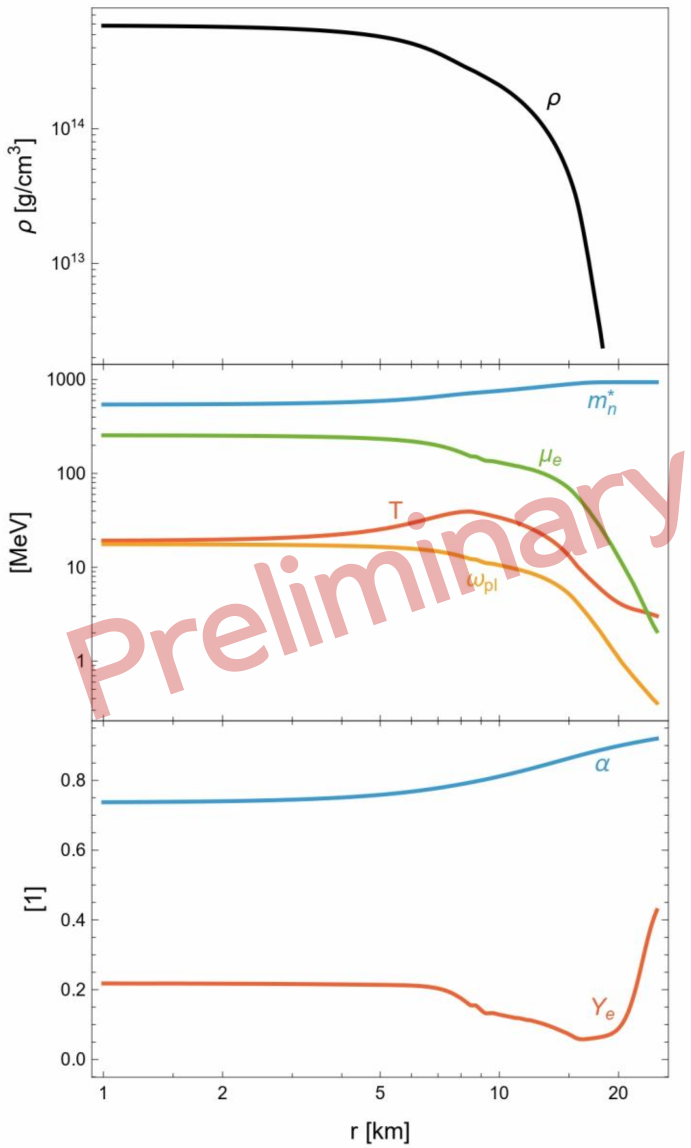


In-medium mixing with the photon

$$q^V_{\rm eff,\,T/L} = q^V \frac{m^2_{Z'}}{m^2_{Z'} - \pi_{\rm T/L}}$$

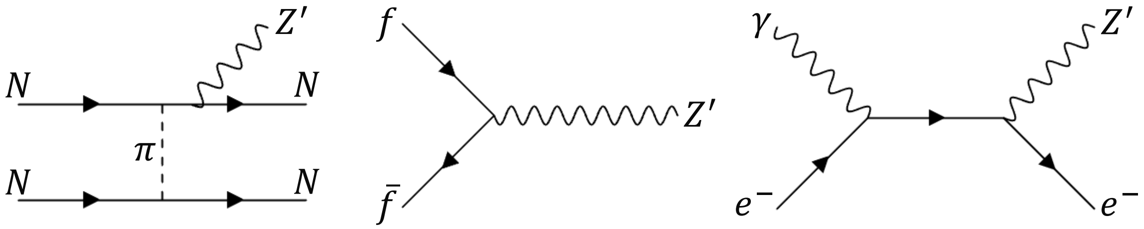
Vector coupling is modified for charged particles

- T and L modes are modified differently
- Resonance for $m^2_{Z'} \simeq \mathrm{Re}\,\pi_{\rm T/L}$
- Axial coupling is unaffected



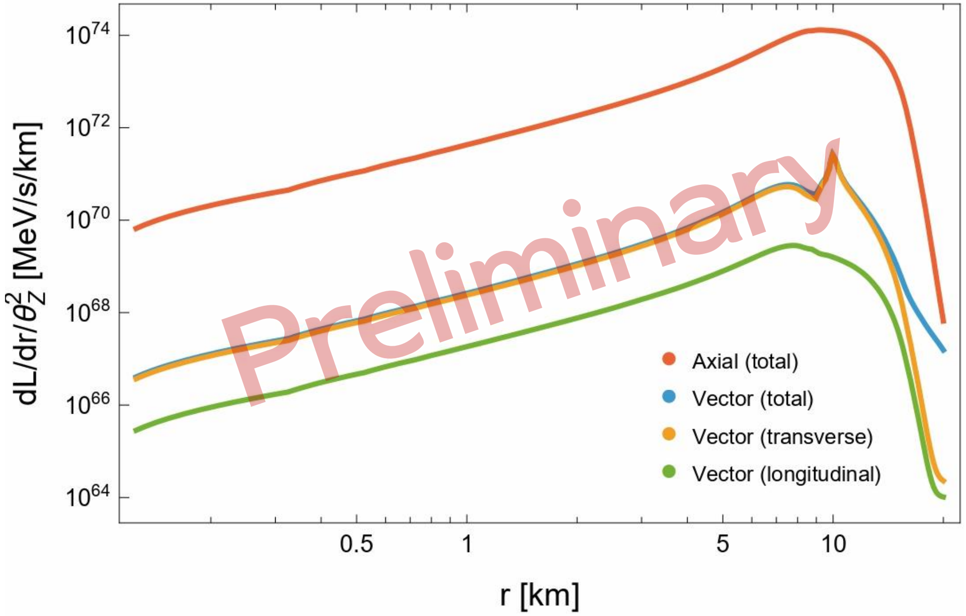
Dark Z Production inside the PNS

- Production channels



Axial	nn brem. dominant	ν inverse decay subdominant	
Vector	pn brem. dominant	ν/e inverse decay subdominant	Sizable near resonance

Differential luminosity for $m_{Z'} = 9.8\ \mathrm{MeV}$



(ν inverse decays are omitted in vector T/L)

- NN bremsstrahlung channels are modified by multiple coherent scatterings in dense medium

Dark Z Absorption and Transport

- Absorption occurs via the inverse processes of production

$$\tau = \int_{\text{path}} dl \, \frac{\Gamma_{\text{abs}}}{v_{Z'}}$$

$\tau \gg 1$: Trapped inside the PNS

$\tau \ll 1$: Freely-streams

$$\langle P_{\text{esc}} \rangle_\mu = \langle e^{-\tau} \rangle_\mu$$

- NN bremsstrahlung gives a dominant contribution, while decays into neutrinos are sizable for massive Z'

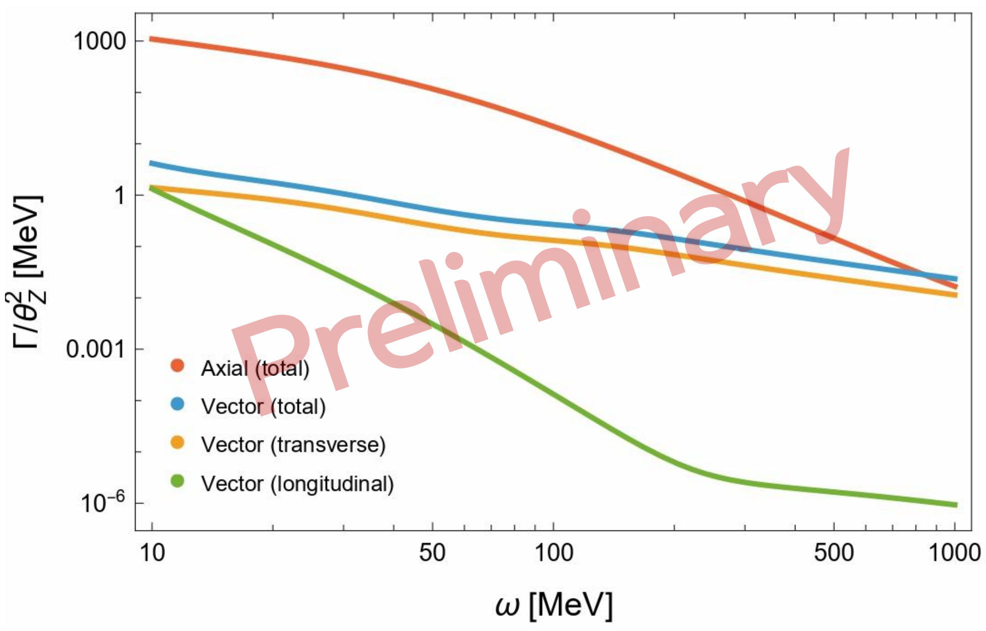
- Gravitational effects

  Gravitational trapping: low-energy Z' cannot escape

  Gravitational redshift: energy decreases during propagation

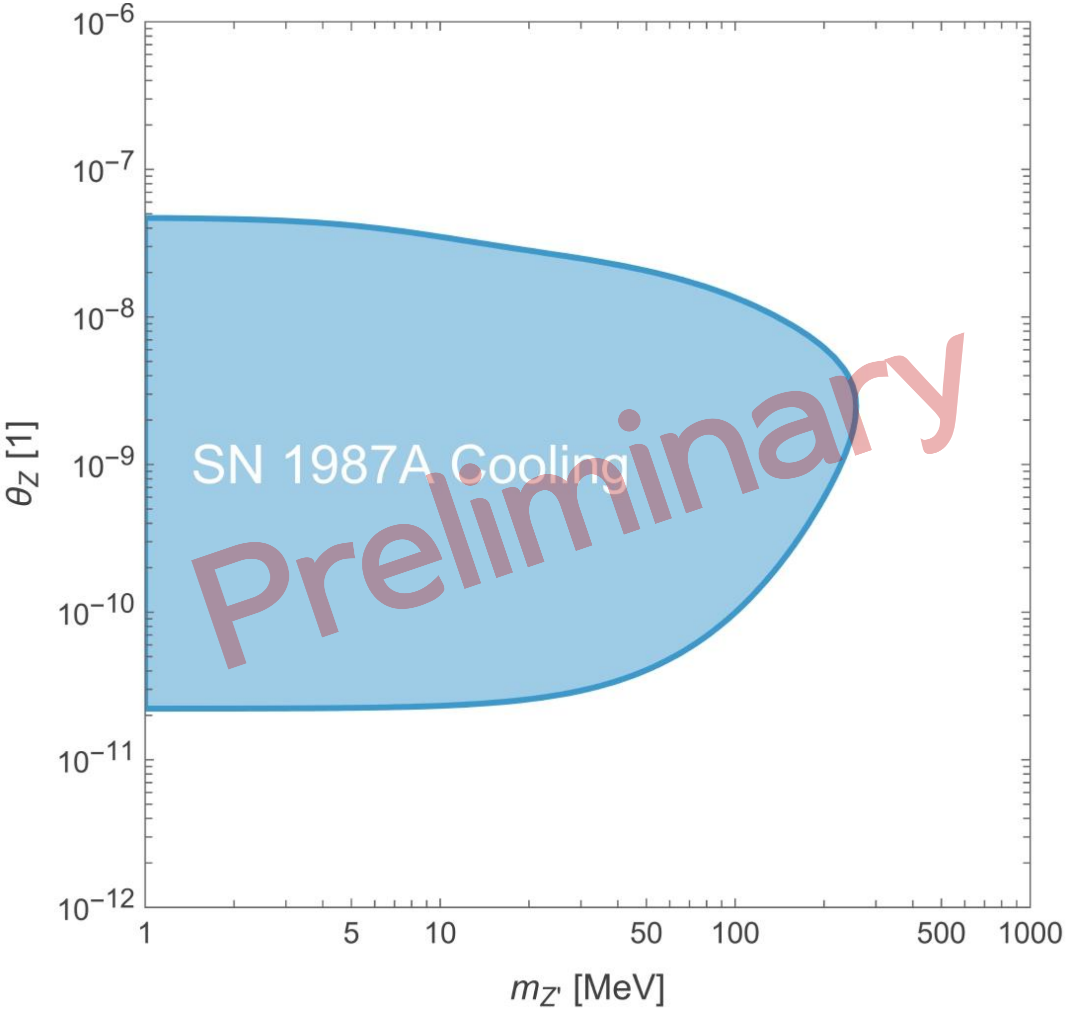
  Time dilation: luminosity at infinity is reduced

Absorption rate at 10 km for $m_{Z'} = 9.8$ MeV



(ν inverse decays are omitted in vector T/L)

SN 1987A Cooling Bounds on the Z'



- Cooling bound

$$L_{Z'}^{\infty} = 4\pi \int_0^{R_\nu} dr\, r^2 \alpha^2(r) \int_{m_{Z'}/\alpha(r)}^{\infty} d\omega \left(\frac{dQ_{Z'}}{d\omega}\right)_{\mathrm{T/L}} \langle e^{-\tau_{\mathrm{T/L}}} \rangle_\mu$$

$$\leq L_\nu \simeq 4.4 \times 10^{52}\ \mathrm{erg/s}$$

- Cooling bound is mainly controlled by the axial coupling
- Vector contribution is subdominant despite resonant plasma enhancement

4. Conclusions

Conclusions

- Dark Z boson can couple to the SM neutral current through mass mixing
- PNS plasma modifies the vector interaction differently for T/L modes, while the axial interaction does not receive this in-medium mixing correction
- Dark Z production is dominated by axial nn bremsstrahlung although vector channels receive enhanced contributions near resonance
- SN 1987A cooling constrains the dark Z parameter space, the resulting bound is strongly controlled by the axial coupling