Dark Gauge Boson Emission from Supernova Pions

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based on arXiv:2211.15677 and JHEP 02 (2022) 133

CSS, Seokhoon Yun

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Outline

Introduction of Core Collapse SN

Delayed explosion mechanism

Dark U(1) light boson scenarios beyond the Standard Model

Dark photon and B-L

Effective Lagrangian @ SN

Dark gauge boson emission from SN pions

Highlighting the constraints on heavy gauge boson scenarios

Effects of the gauge boson decay inside and outside the core collapsing star

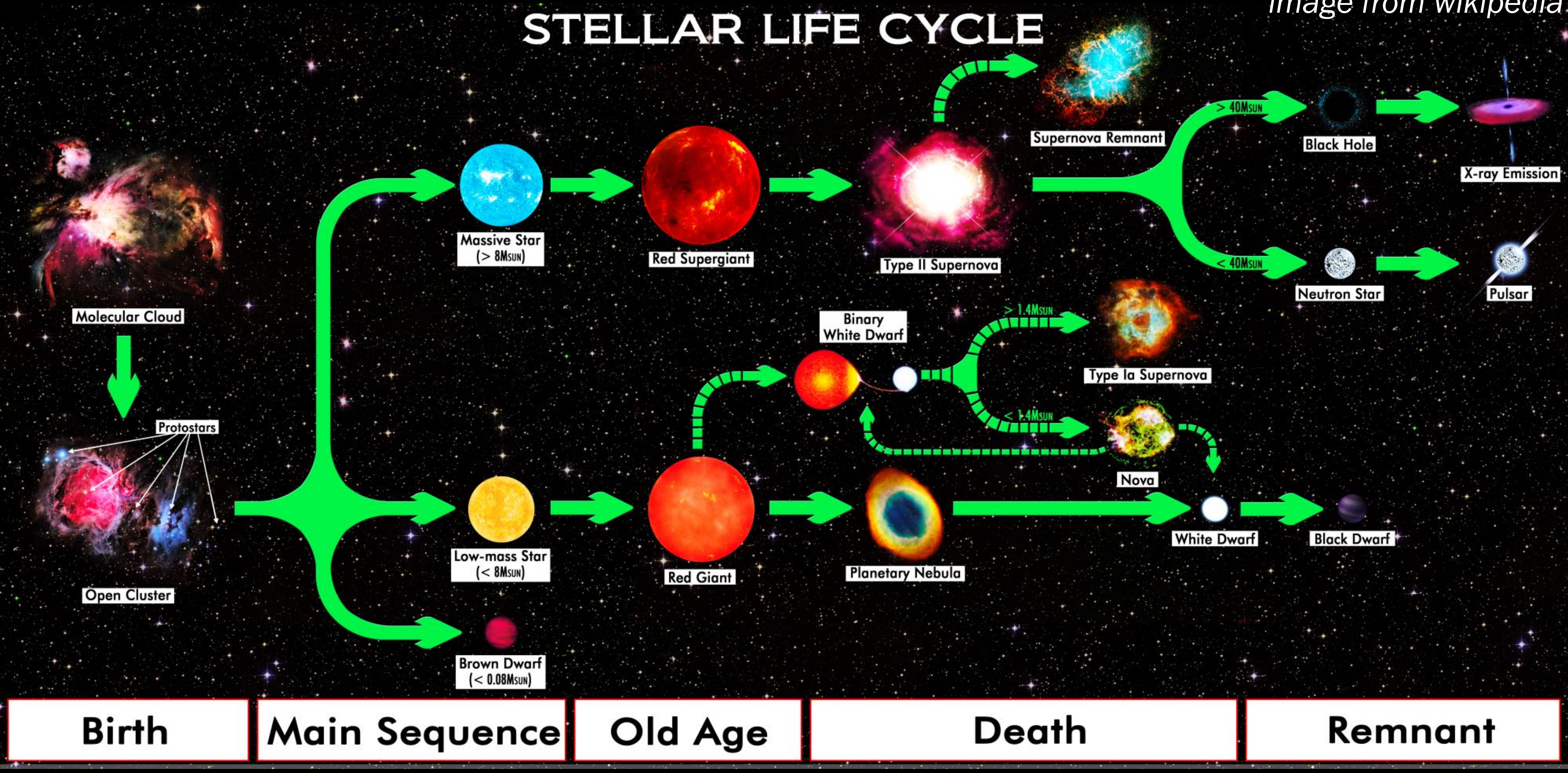
Discussion

Introduction of Core Collapse SN

Stellar evolution

Star: an astronomical object consisting of a luminous spheroid of plasma held together by its own gravity

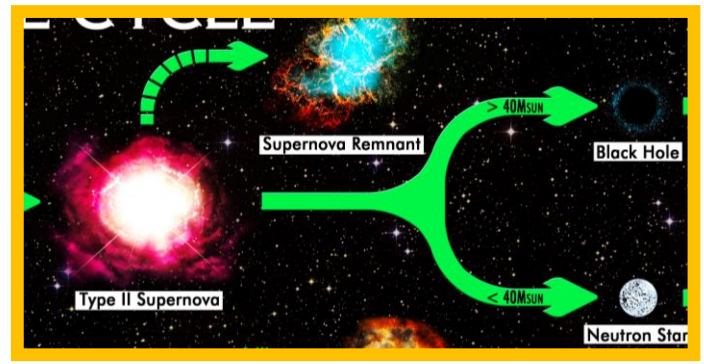
image from wikipedia



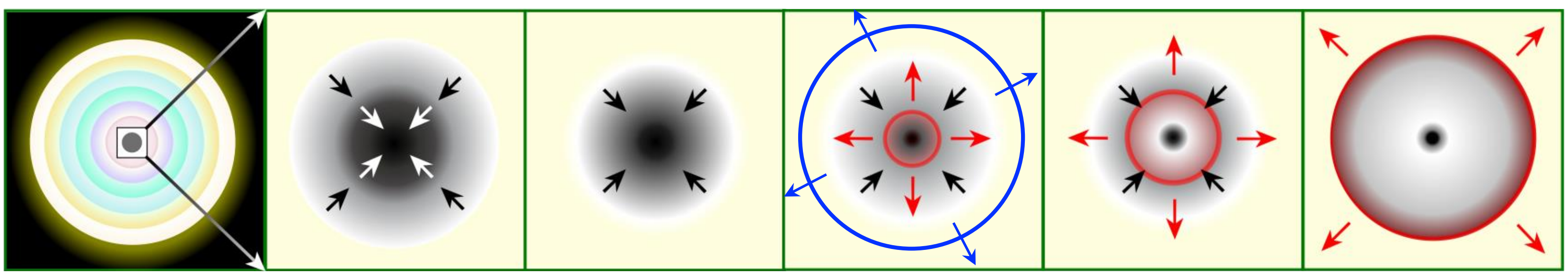
Stellar evolution could be changed if there is an extra energy leakage source

Core-Collapse Supernova(SN) explosion

Star: an astronomical object consisting of a luminous spheroid of plasma held together by its own gravity

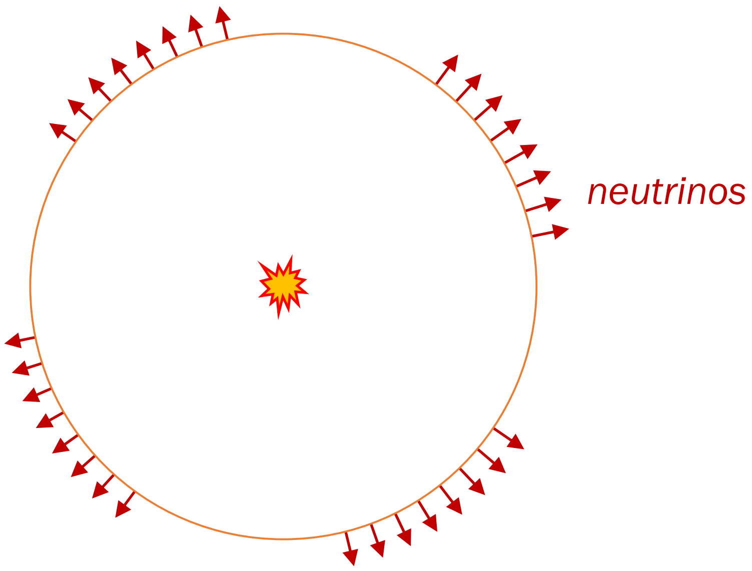


$M_{\text{star}} > 6 - 8\ M_{\odot}$

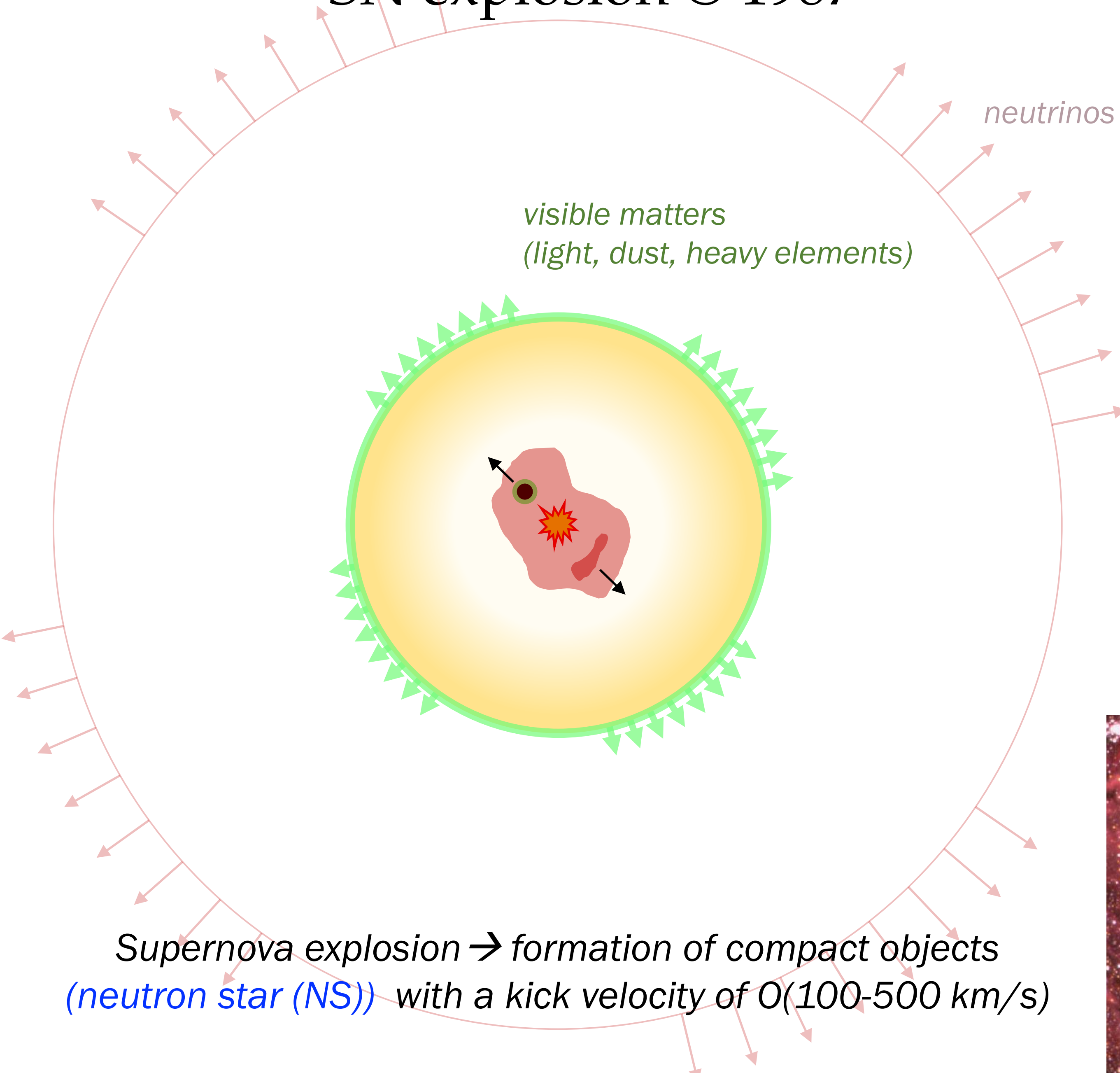


Explosion: Neutrino first, Visible matter later

SN explosion @ 1987



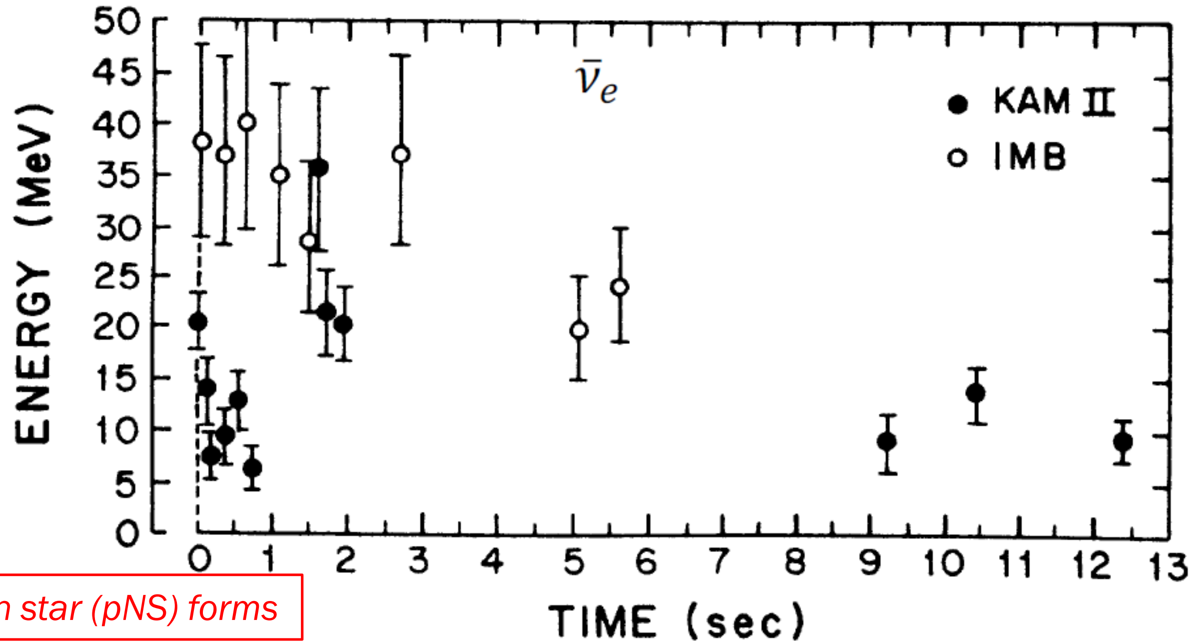
SN explosion @ 1987



Supernova explosion → formation of compact objects
(neutron star (NS)) with a kick velocity of O(100-500 km/s)

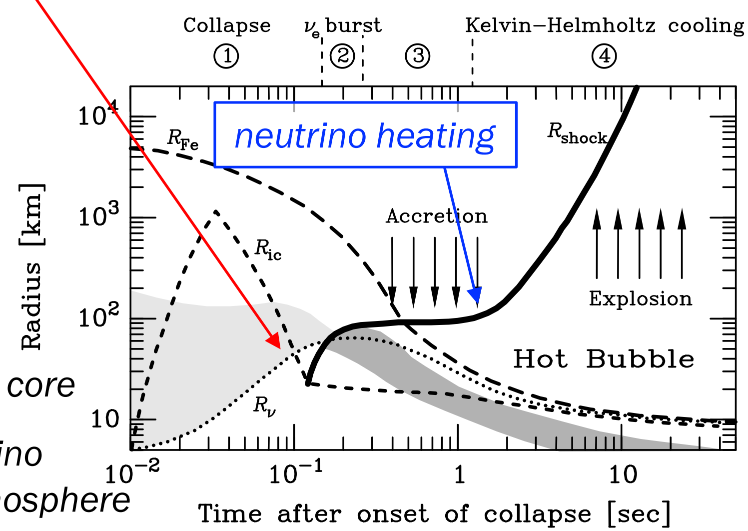
Neutrino spectrum from SN1987A

There is the observation of neutrino flux in 1987



proto-neutron star (pNS) forms

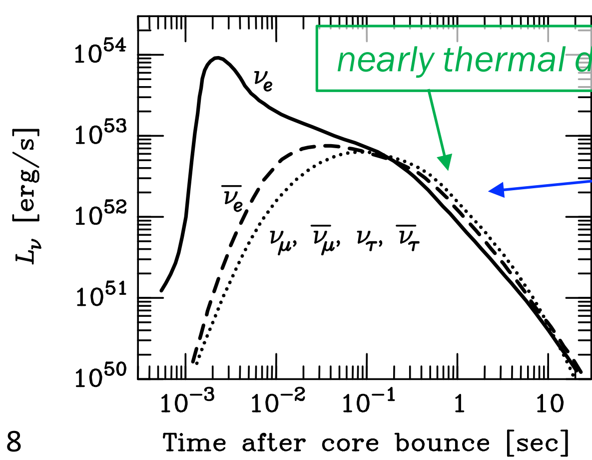
neutrino heating



R_{ic}: inner core

R_ν: neutrino thermosphere

nearly thermal distribution



depends on the temperature of the proto neutron star

From Raffelt
Stars as Laboratories for Fundamental Physics

Neutrino spectrum from SN1987A

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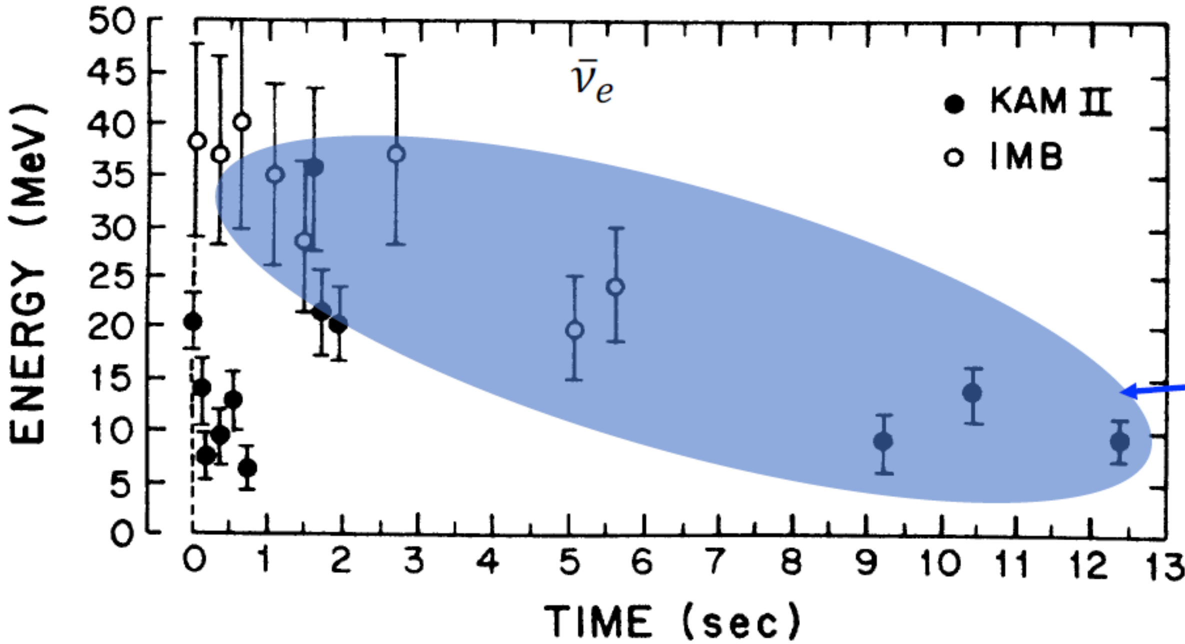


Cooling process of the proto neutron star is important

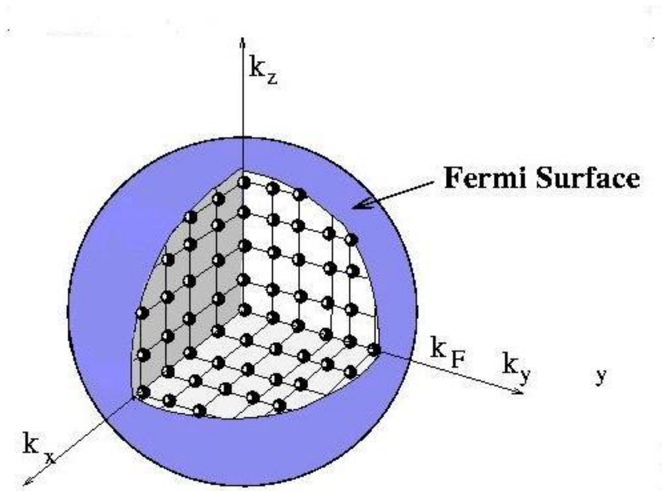
SN explosion energy is expected as

$$L_\nu(T = 30 - 50\ \mathrm{MeV}) = O(1-10) \times 10^{51} \mathrm{erg/s}$$

$$\left(\rho_{\mathrm{pNS}} = O(1-10) \times 10^{14} \mathrm{g/cm^3}, R_{\mathrm{PNS}} \simeq 10\ \mathrm{km}\right)$$

The Gamma-Ray Spectrometer (GRS) of the Solar Maximum Mission (SMM) satellite was operative and didn't observe a gamma-ray signal at the time of the neutrino burst of SN 1987A : There is a sizable time difference between the neutrino and gamma-ray signals

Neutron Star (degenerate pressure of nucleons ⇔ gravity)



$$n_f \simeq \frac{k_{Ff}^3}{3\pi^2} \qquad \text{for} \quad \frac{3}{2}T \lesssim \frac{k_{Ff}^2}{2m_f}$$
$$\mu_f = \sqrt{m_f^2 + k_{Ff}^2}$$

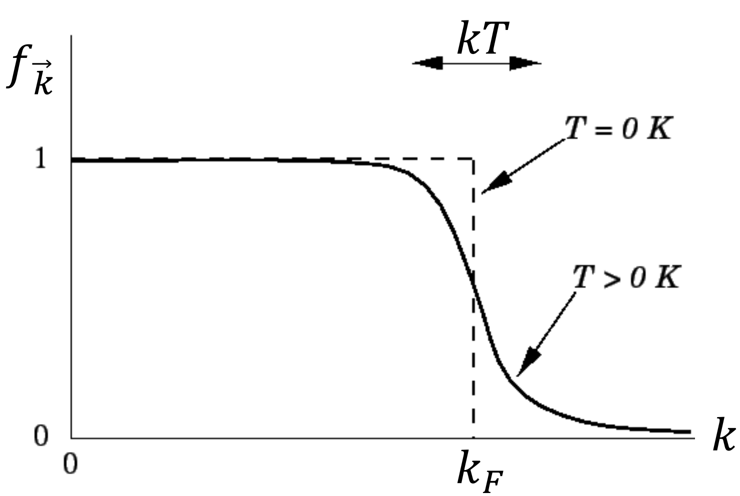
$$n_f = 2\int \frac{d^3k}{(2\pi)^3} f_f\left(\vec{k}\right)$$

Proto-Neutron Star

Core density: $\rho_{\rm pNS} = (0.5-2)(2.8\times10^{14}\,{\rm g/cm^3})$

Core temperature: $T_{\rm pNS} = 30-50\ {\rm MeV}$

(*semi-degenerate, neutrinos are trapped in the bulk*)



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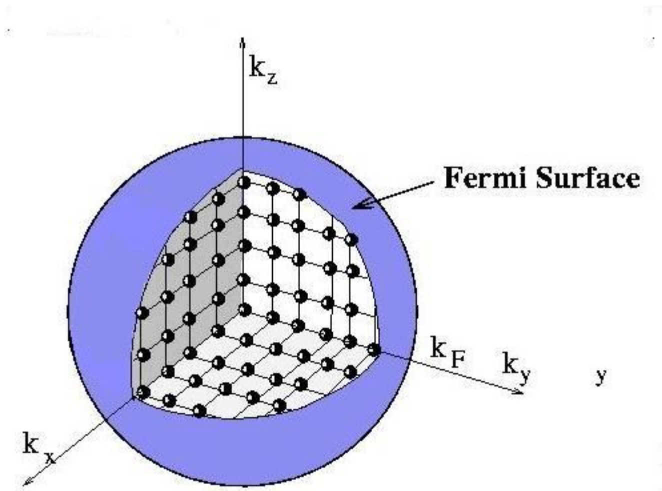

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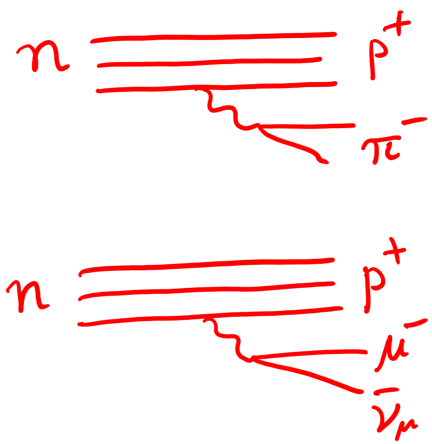


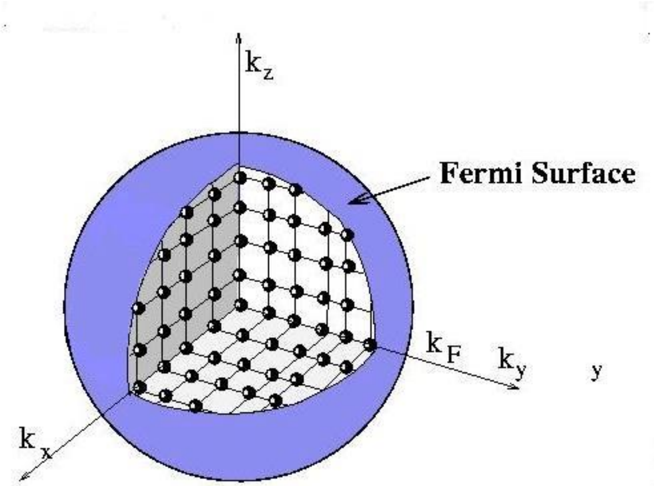
- *Chemical equilibrium for the beta process of the hadrons and charged leptons*

$$\mu_{\pi^-} = \mu_{e^-} - \mu_{\nu_e} = \mu_{\mu^-} - \mu_{\nu_\mu} = \mu_n - \mu_p$$

- *Sizable amount of negatively charged pions and muons inside the NS core*

$$f_X = \frac{1}{\exp\left(\frac{E_X - \mu_X}{T}\right) \pm 1}$$

Neutron Star (degenerate pressure of nucleons ⇔ gravity)



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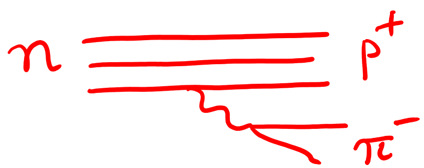
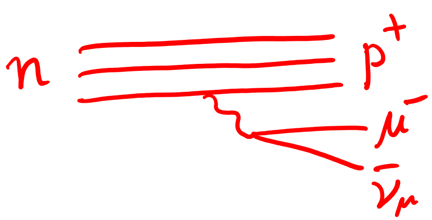
e.g. for neutrons with $\rho_n = 10^{14-15}\mathrm{g/cm^3}$

$$\rho_n \simeq m_n n_n \rightarrow k_{Fn} = 300 - 500 \text{ MeV}$$

$$\rho_p \simeq (0.2 - 0.3)\rho_n \rightarrow k_{Fp} = 100 - 250 \text{ MeV}$$



$$\mu_{\pi^-} = \mu_n - \mu_p \simeq \frac{k_{Fn}^2 - k_{Fp}^2}{2m_N} = 40 - 90 \text{ MeV}$$

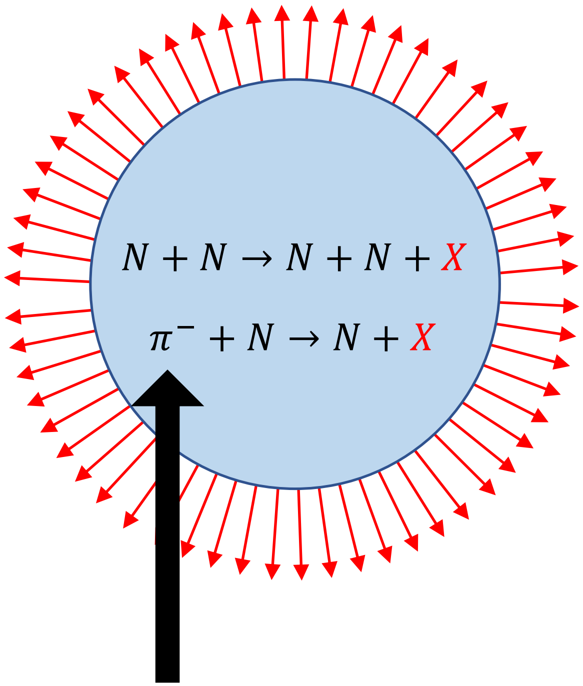


$$f_{\pi^-}(p) \sim \frac{1}{\exp\left(\frac{m_{\pi^-} - \mu_{\pi^-}}{T}\right) - 1} = 0.04 - 0.4$$

for $T = 30 - 50 \text{ MeV} \ (m_{\pi^-} = 139 \text{ MeV})$

Neutron Star (degenerate pressure of nucleons ⇔ gravity)

Impacts on cooling of proto-neutron stars by new particle (X) emissions



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for $T = 30 - 50\ \mathrm{MeV}$ $(m_{\pi^-} = 139\ \mathrm{MeV})$

$$Y_\pi \equiv \frac{n_{\pi^-}}{n_n} = 1\,\% - 5\,\%$$

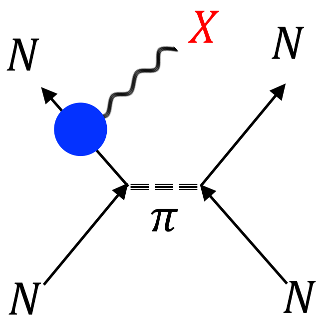
B. Fore and S. Reddy 1911.02632

New Light Particle Emissions

When the light particle mass is smaller than the temperature of the NS core, they could be produced enormously from the (proto) neutron stars, contributing the cooling rate

$$C\frac{dT}{dt} = -L_\nu(T) - L_\gamma(T) + H_{\text{eat}} - \boldsymbol{L_X(T)}$$

$$\boldsymbol{L_X(T)} < L_{\text{SM}}(T)$$



Bremsstrahlung

$\langle E_X \rangle \sim T$

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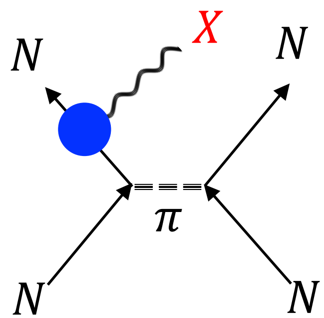

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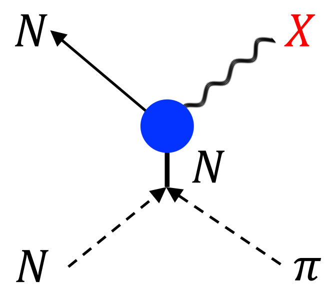


Thomson-like Scattering

$$\langle E_X \rangle \sim m_\pi + \frac{3}{2}T \gg T$$

For the pion mediated production, the higher mass of dark particles can be easily produced.

The deviation from the SN explosion energy and the observed gamma-ray spectrum can provide the further interesting implications.

Dark Gauge Boson Production at SN

Dark gauge boson effective couplings

From the couplings between (nucleon, electron, neutrino) and dark gauge boson,

$$L_{eff} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} - \frac{\varepsilon}{2}F_{\mu\nu}F'^{\mu\nu} - \frac{1}{4}F'_{\mu\nu}F'^{\mu\nu} - \frac{1}{2}m^2_{\gamma'}A'_\mu A'^\mu$$

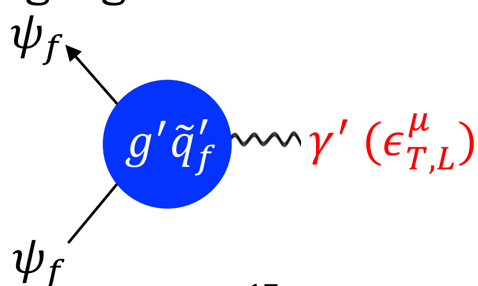
$$+ \sum_{f=n,p,e,\nu} \bar{\psi}_f i\gamma^\mu \partial_\mu \psi_f + eA_\mu J^\mu_{EM} + g' A'_\mu J'^\mu_X + \cdots$$

$U(1)_{DP}$:
$q'_\psi = 0$

$U(1)_{B-L}$:
$q'_e = q_e = -1$
$q'_p = q_p = 1$
$q'_n = 1$

we have to calculate the medium dependent effective couplings

between a dark gauge boson and nucleons at (P)NS core



(T : transverse mode,
L : longitudinal mode)

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$$+ \sum_{f=n,p,e,\nu} \bar{\psi}_f i\gamma^\mu \partial_\mu \psi_f + eA_\mu J^\mu_{EM} + g' A'_\mu J'^\mu_X + \cdots$$

The effective interactions between the gauge boson and nucleons & pions are given as

$$A'_\mu \sum_{N=p,n} c_N \, \bar{N}\gamma^\mu N + i(c_p - c_n)A'_\mu(\pi^-\partial^\mu\pi^+ - \pi^+\partial_\mu\pi^-)$$

$$+i(c_p - c_n)A'_\mu \frac{g_A}{\sqrt{2}f_\pi}(\pi^-\bar{n}\gamma^\mu\gamma^5 p \; - \pi^+\bar{p}\gamma^\mu\gamma^5 n)$$

where $c_{p,n,l}$ are the effective coupling in medium

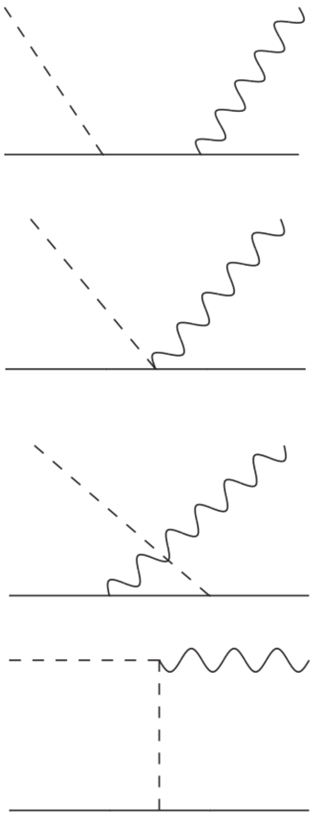
$$c_p = g'\tilde{q}'_p, \qquad c_n = g'\tilde{q}'_n$$

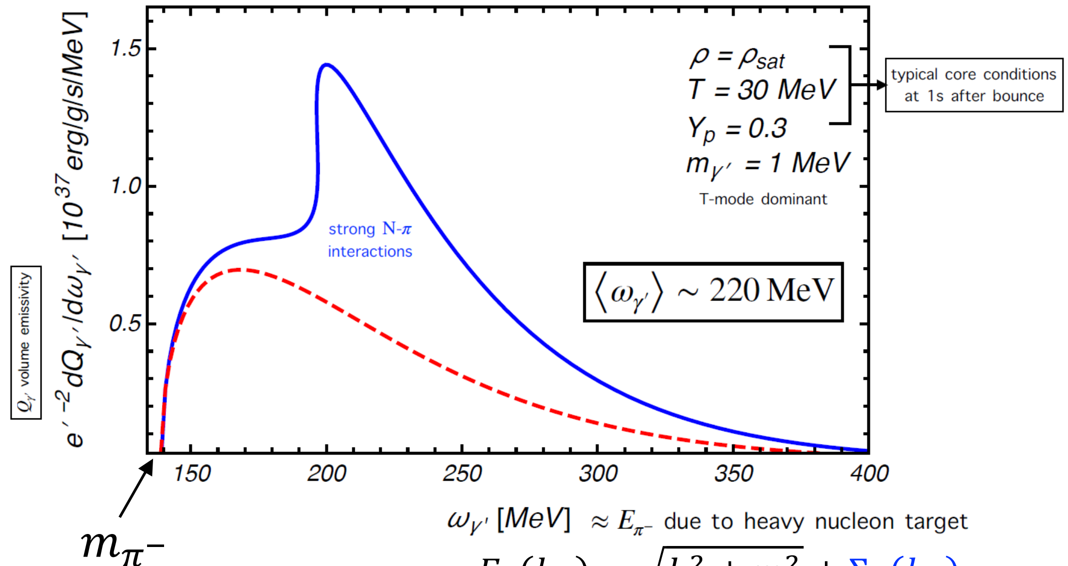
and (q_f is the EM charge: $q_e = -1, q_p = 1, q_n = 0$)

$$g'\tilde{q}'_f = g'(q'_e q_f - q_e q'_f) + (\varepsilon e - g' q'_e) q_f \frac{m_{\gamma'}^2}{m_{\gamma'}^2 - \pi_{\mathrm{T,L}}}$$

Pion-induced emission processes

The emitted dark gauge boson energy could be greater from the pion-induced emission process.





$$E_\pi(k_\pi) = \sqrt{k_\pi^2 + m_\pi^2} + \Sigma_\pi(k_\pi)$$

$$\langle\omega_{\gamma'}\rangle \sim 220\ \text{MeV} \gg T \sim 30\ \text{MeV}$$

Therefore, the pionic Thomson scattering provides the constraints on the higher mass range.

Constraints

Cooling argument:

$$\frac{Q_{\gamma'}}{\rho} e^{-\Gamma r_{\rm far}} < 10^{19}\ \mathrm{erg\,g^{-1}s^{-1}} \quad (@\ 1\ \mathrm{sec}, r_{\rm far} \sim 10^3\mathrm{km})$$

Supernovae explosion energy: *(explosion energy from simulations & observations* ~ $10^{51}\mathrm{erg}$*)*

$$\frac{Q_{\gamma'}}{\rho}\left(e^{-\Gamma r_{\rm far}} - e^{-\Gamma r_{\rm env}}\right) < 10^{17}\ \mathrm{erg\,g^{-1}s^{-1}} \quad (r_{\rm env} \sim 10^9\mathrm{km})$$

Diffused gamma-rays from positron injections: *(INTEGRAL satellite < $O(10^{43})e^+\mathrm{s}^{-1}$ focusing on 511keV line, COMPTEL telescope < $O(10^{42})e^+\mathrm{s}^{-1}$ for higher energies)*

$$\left(\frac{Q_{\gamma'}}{\rho} m_{\rm pNS}\right)\frac{\Delta t}{\langle\omega\rangle} e^{-\Gamma r_{\rm esc}} < 10^{52} e^+ \quad \text{for} \quad \Delta t = 10\ \mathrm{sec} \quad (r_{\rm esc} \sim 10^9\mathrm{km})$$

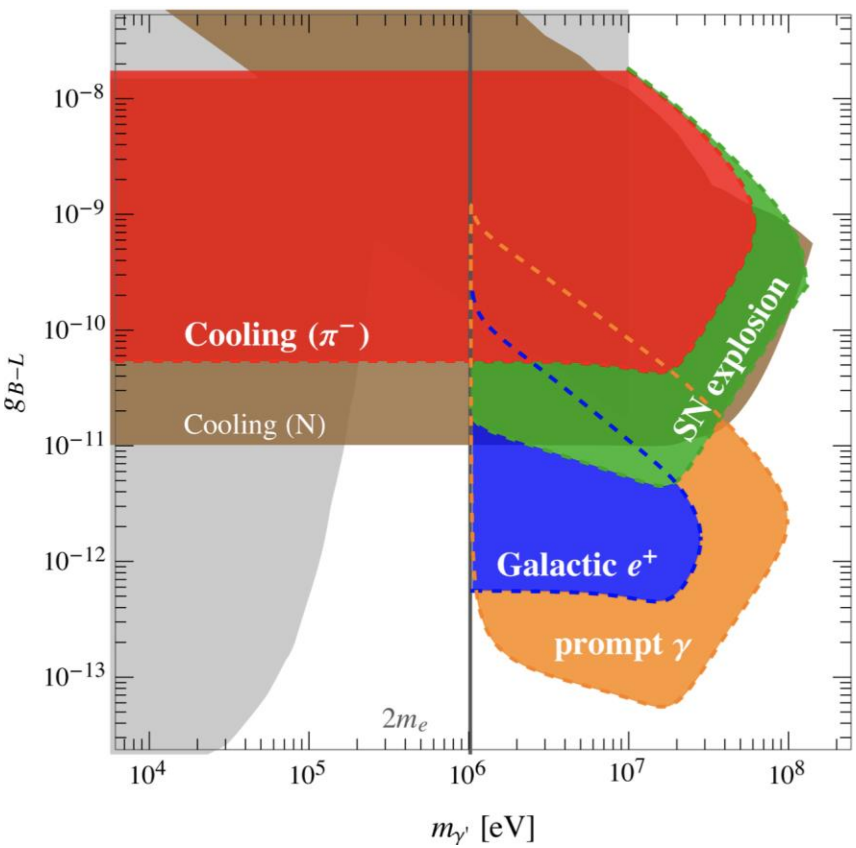
Absence of prompt gamma-rays: *(SMM satellite : the gamma-ray fluence $\mathcal{F}_\gamma < 10\mathrm{cm}^{-2}$ for 4~100MeV within 200 sec after the neutrino burst of SN1987A)*

$$\left(\frac{Q_{\gamma'}}{\rho} m_{\rm pNS}\right)\frac{\Delta t}{\langle\omega\rangle} e^{-\Gamma r_{\rm esc}} \mathrm{Br}(\gamma' \to e^- e^+ \gamma) < 4 \times 10^{48}$$

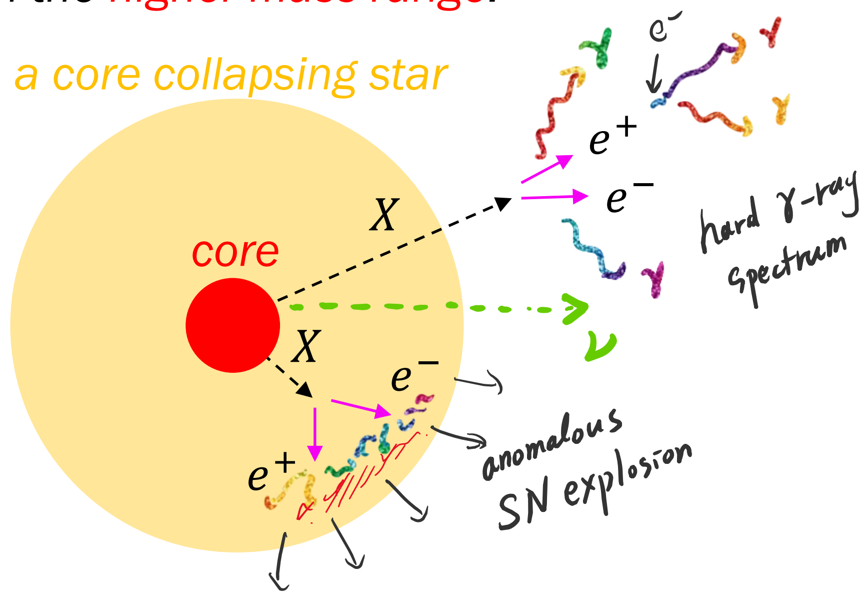
Constraints including pion-induced emission process

The emitted dark gauge boson energy could be greater from the pion-induced emission process. This could provide the constraints on the higher mass range.

CSS, Seokhoon Yun **2211.15677**



$U(1)_{B-L}$



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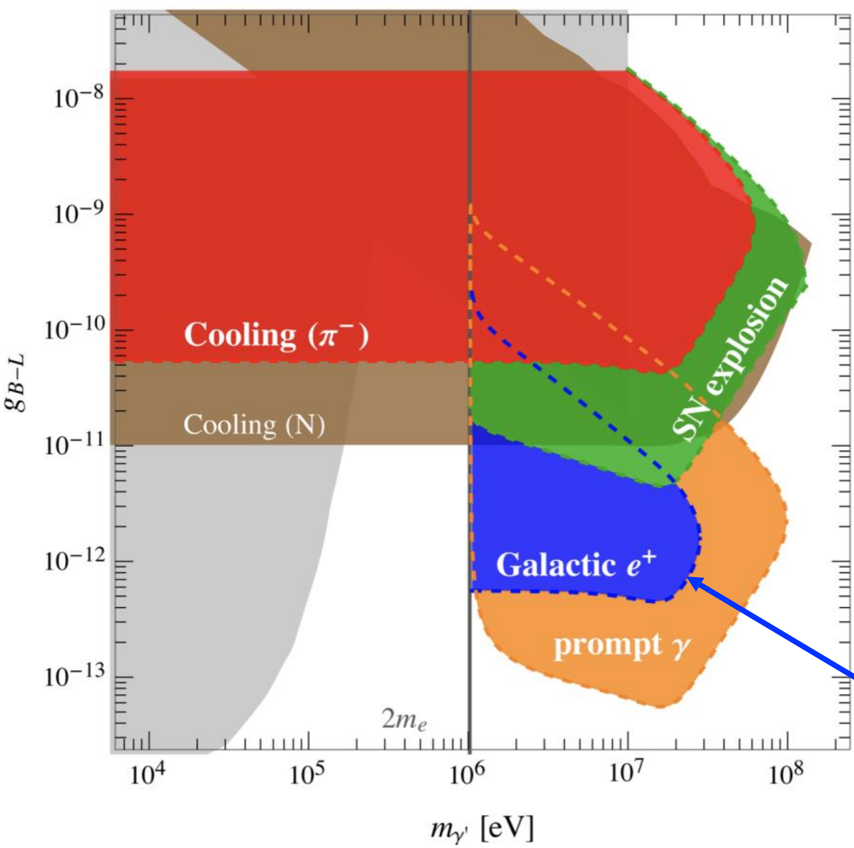

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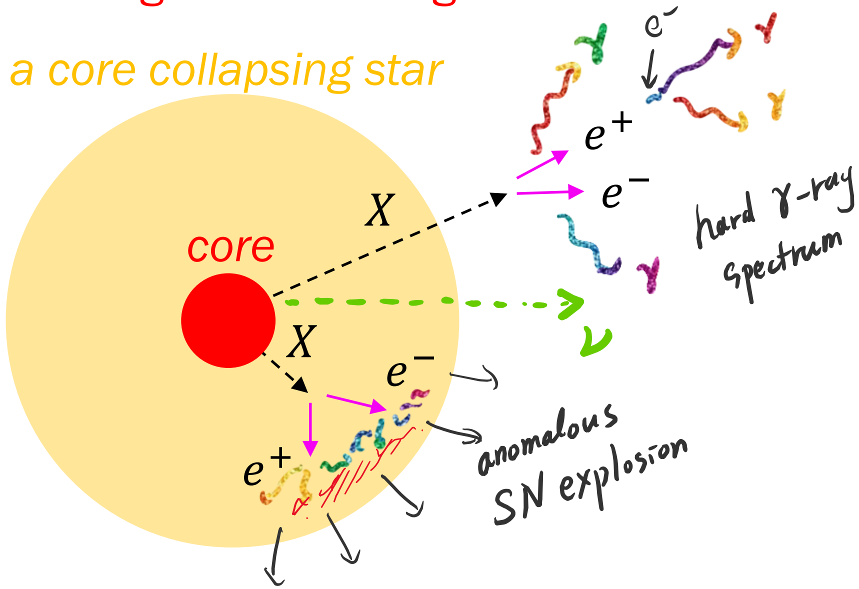

The decay of dark gauge bosons after escaping the star leads to the injection of high energetic galactic positrons, producing high energetic gamma-ray signals (decaying outside the star)

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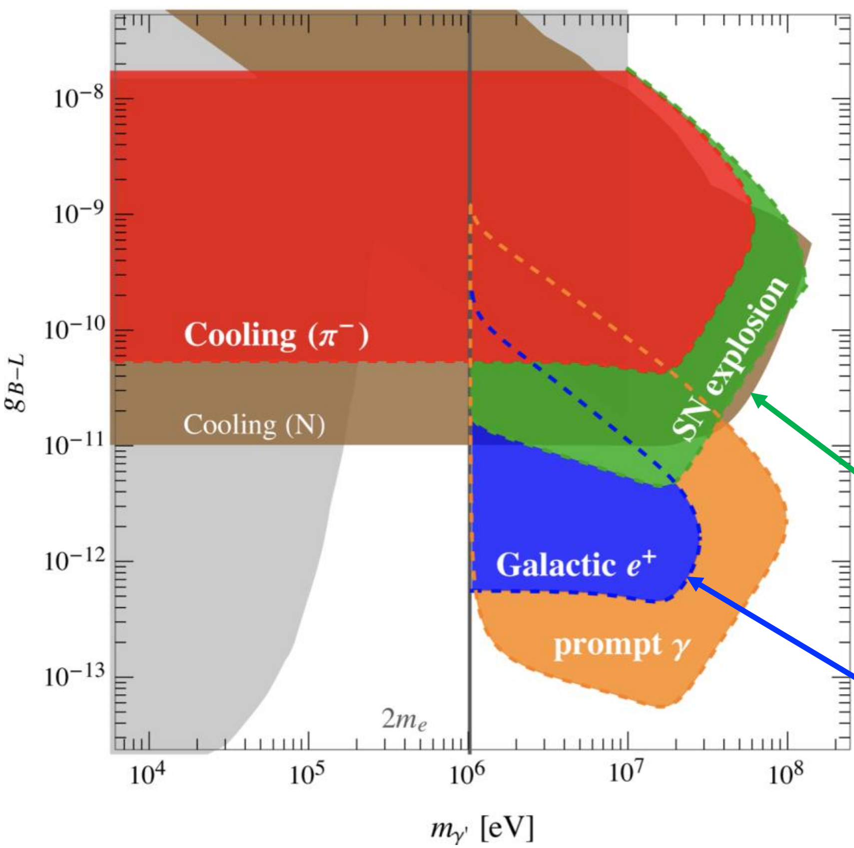

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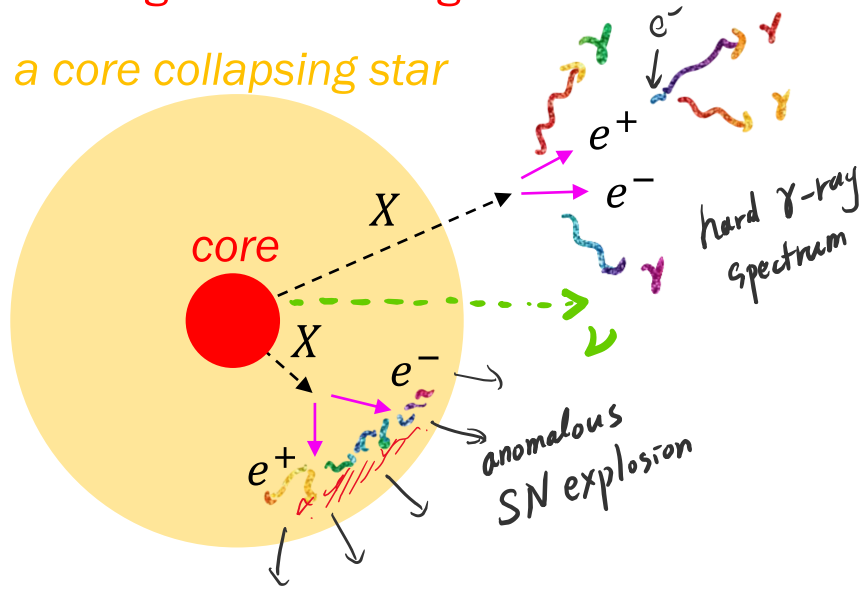

Transfers energy from the core to the surrounding material "too" efficiently compared to neutrinos (decaying inside the star)

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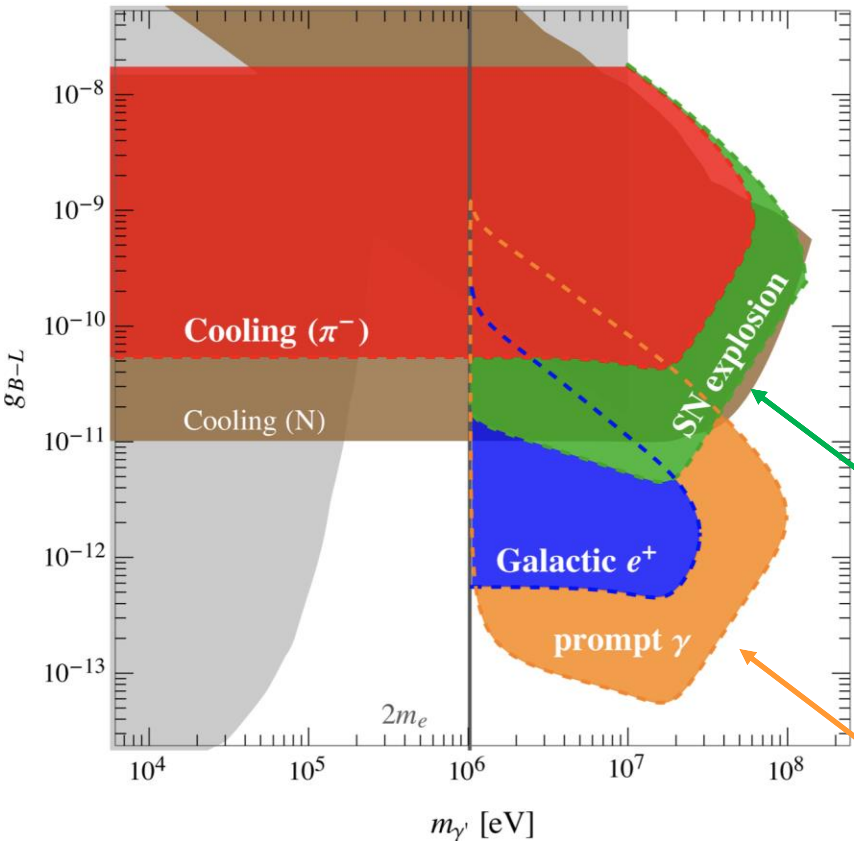
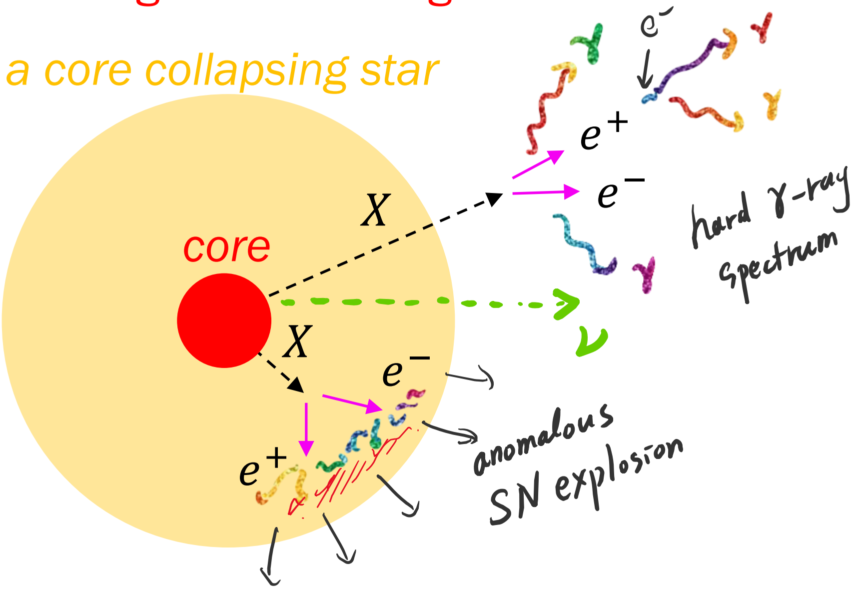


$U(1)_{B\text{-}L}$

a core collapsing star



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Unlike the delayed explosion mechanism, there is no time gap between the neutrino signal and the gamma-ray signal

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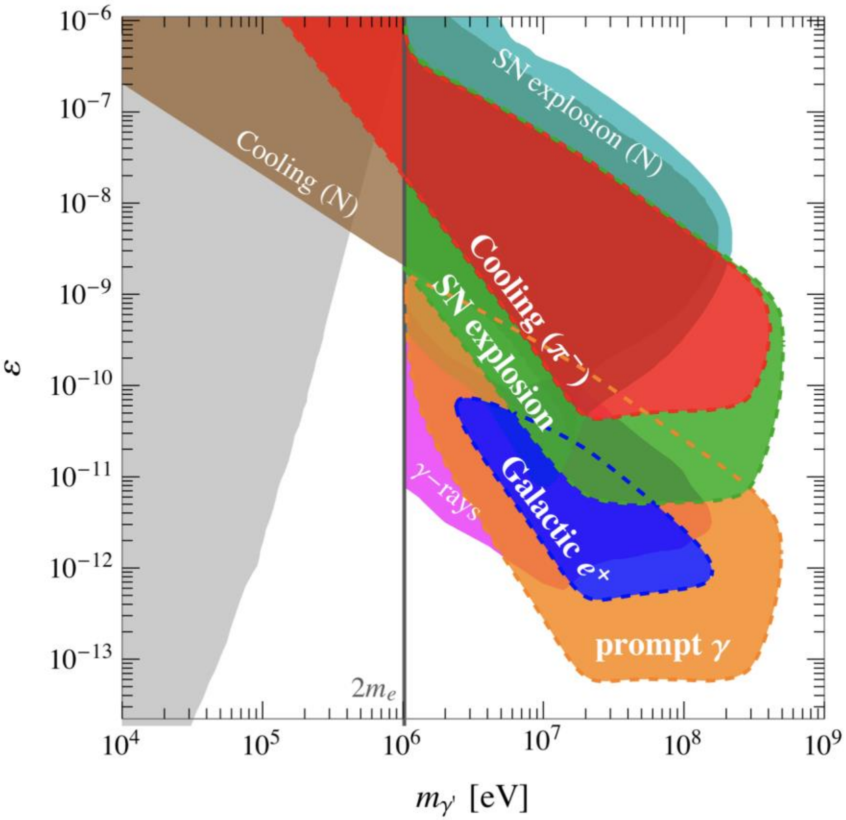

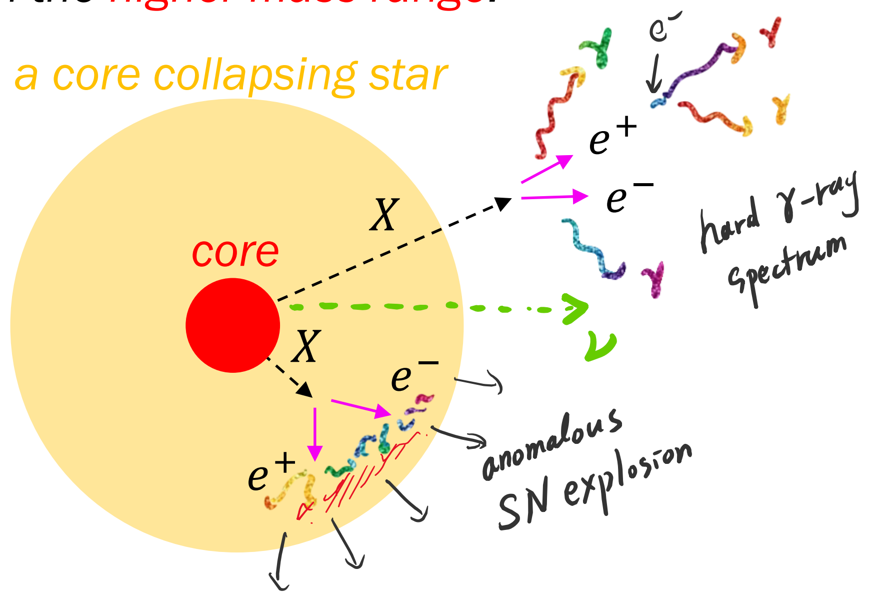

$U(1)_{\text{dark photon}}$

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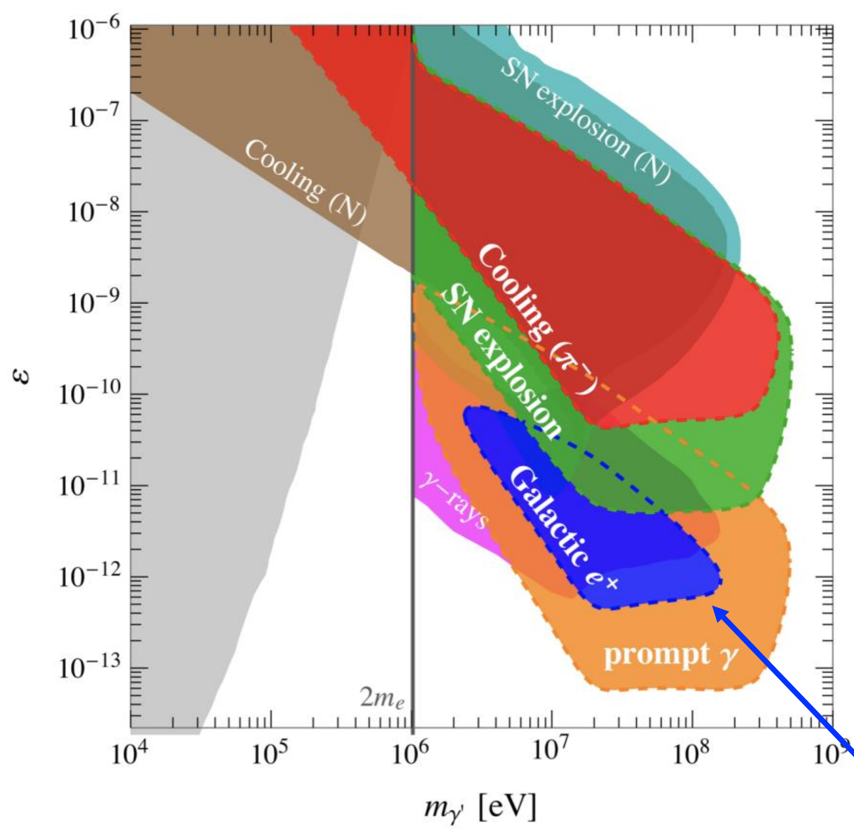
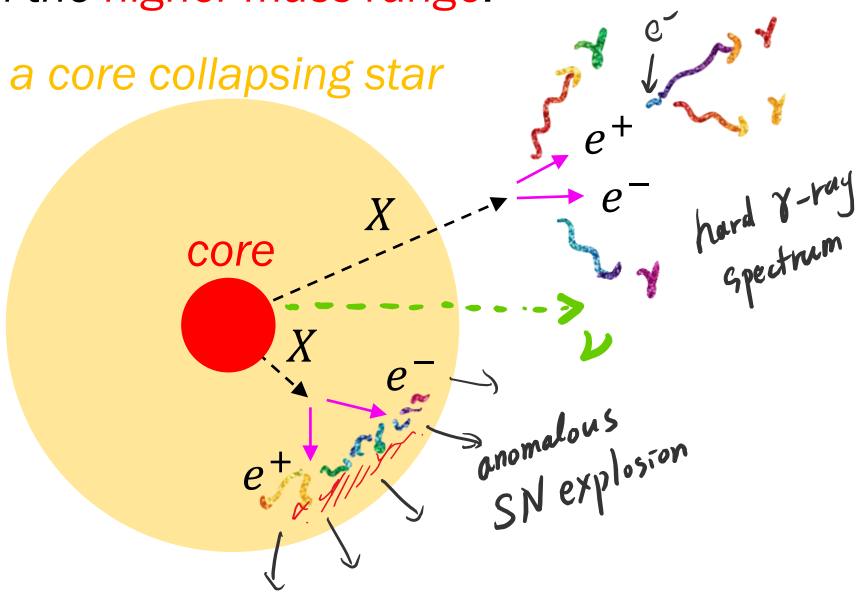


U(1)dark photon



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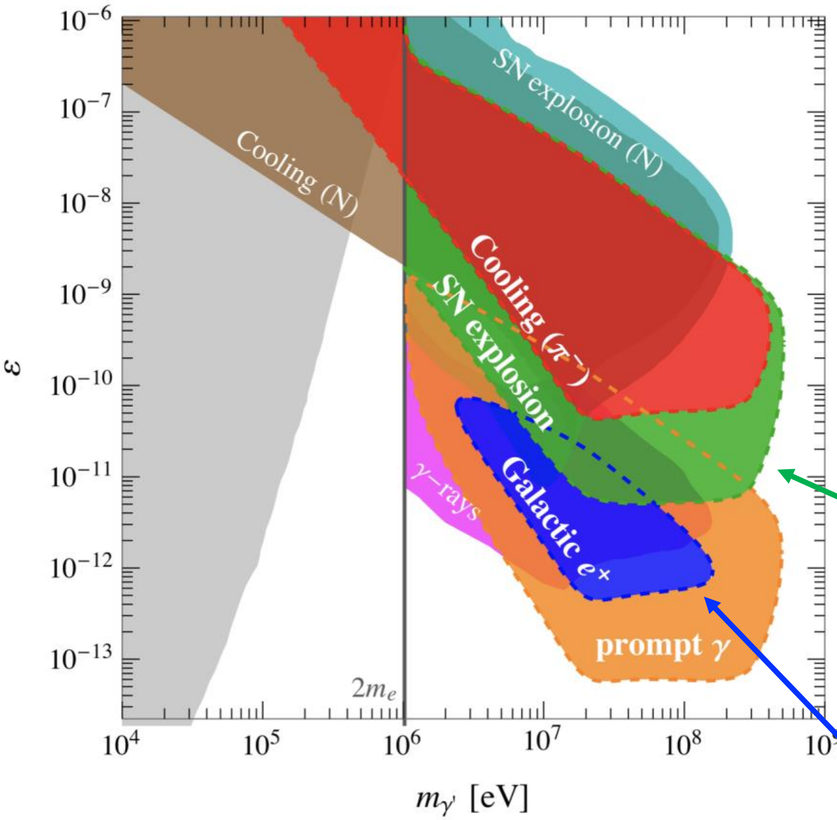

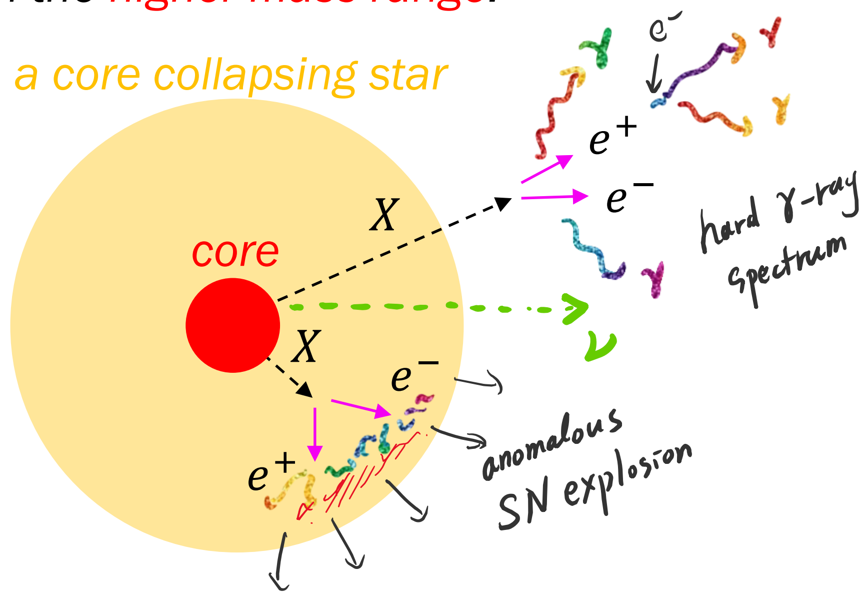

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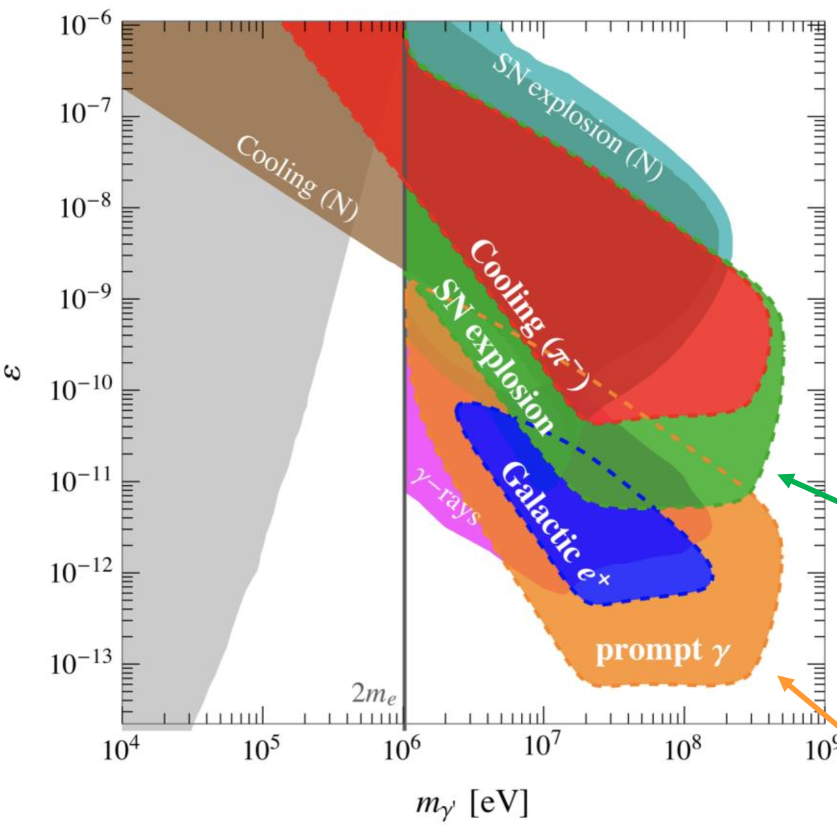
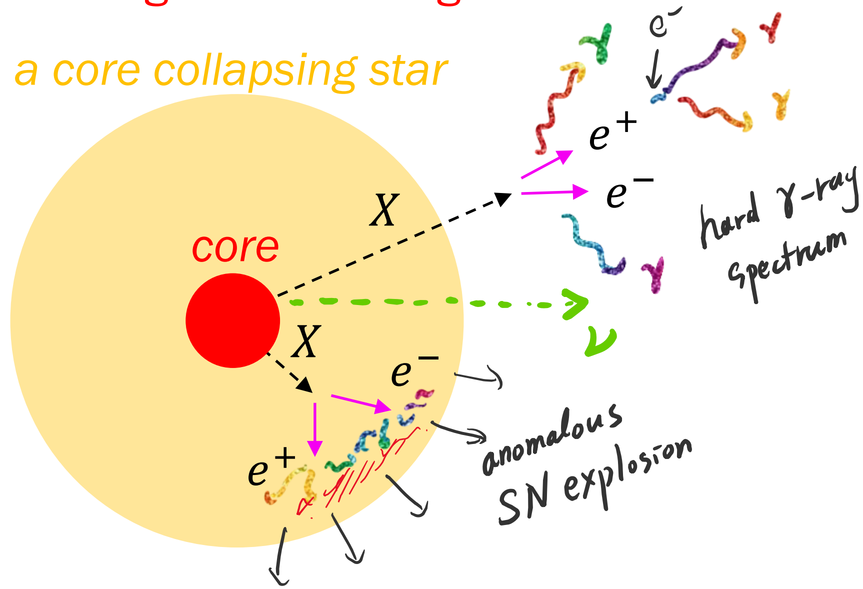
The emitted dark gauge boson energy could be greater from the pion-induced emission process. This could provide the constraints on the higher mass range.

CSS, Seokhoon Yun **2211.15677**





Transfers energy from the core to the surrounding material "too" efficiently compared to neutrinos *(decaying inside the star)*

Unlike the delayed explosion mechanism, there is no time gap between the neutrino signal and the gamma-ray signal

$U(1)_{\text{dark photon}}$

Discussion

We discuss a part of implications of supernova explosion for dark gauge boson scenarios beyond the SM.

In this talk, we highlight the role of the pion abundance in the proto-neutron star core during the SN period, and provide the further constraints on the mass of the dark gauge boson for a given coupling and the mixing parameter from "SN cooling argument, gamma-ray background, SN explosion energy, the time gap between the neutrino and photon signals".