Dark Light Boson Emission from (proto) Neutron Stars

Chang Sub Shin (CNU)

based on JHEP 02 (2022) 133 [arXiv:2110.0336] CSS, Seokhoon Yun

JHEP 02 (2022) 143 [arXiv:2110.01972] Kiwoon Choi, Hee Jung Kim, Hyeonseok Seong, CSS

The 2022 CERN-CKC workshop on physics beyond the Standard Model

June 06, 2022

Outline

Introduction of Core Collapse SN: e.g. SN1987A & NS1987A

Dark light boson scenarios beyond the Standard Model

- *Axion and U(1) gauge boson*
- *Implications of symmetry and breaking for dark boson emission @ SN*

Revisiting Axion emission at SN

- *Effects of the axion-pion-nucleon contact Interactions*

Revisiting $U(1)_{B-L}$ gauge boson emission at SN

- *Implication of the effective charge of the nucleons on dark Bremsstrahlung*

Discussion

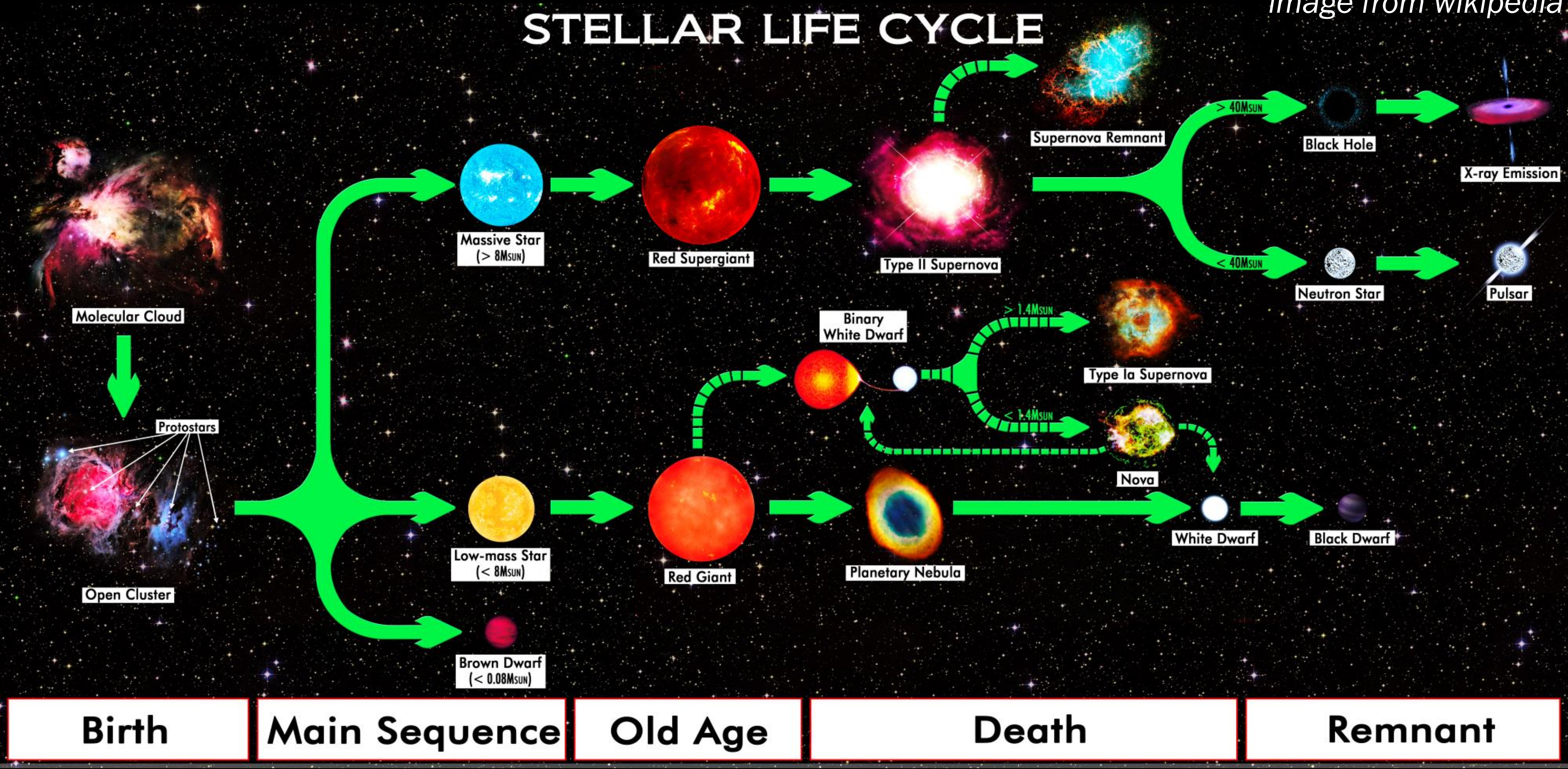
Introduction of
Core collapse SN Explosion & Its remnant

Stellar evolution

Star: an astronomical object consisting of a luminous spheroid of plasma

held together by its own gravity

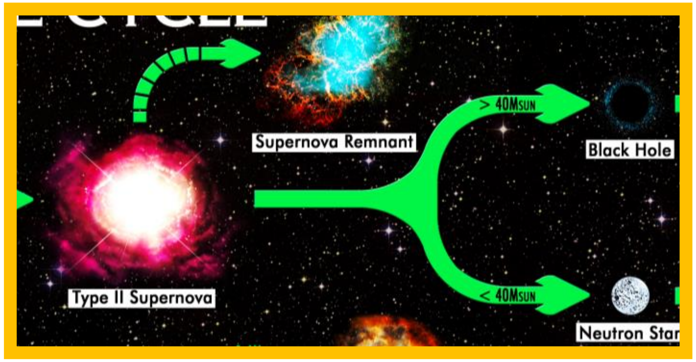
image from wikipedia



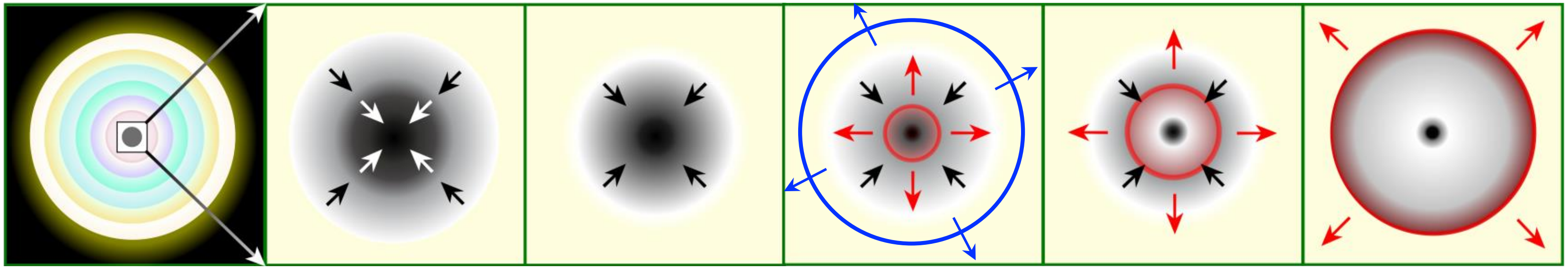
Stellar evolution could be changed if there is an extra energy leakage source

Core-Collapse Supernova(SN) explosion

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

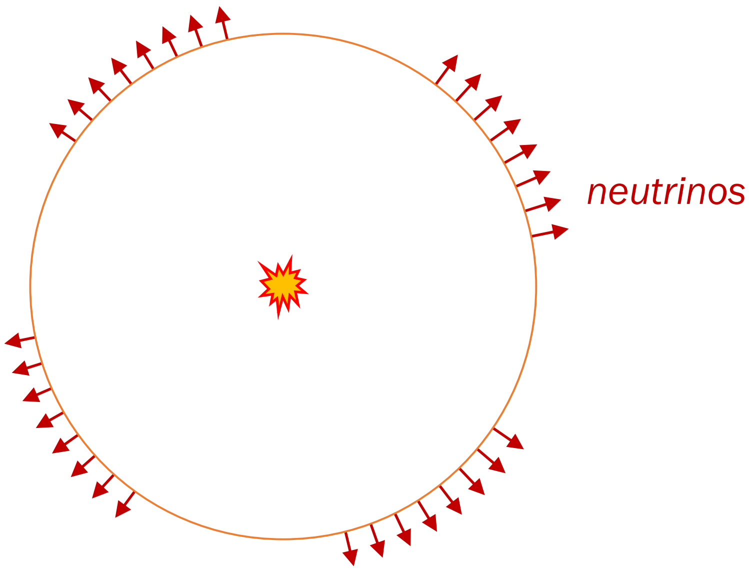


$6-8\ M_{\odot} < M_{\mathrm{star}}$



Explosion: Neutrino first, Visible matter later

SN explosion @ 1987



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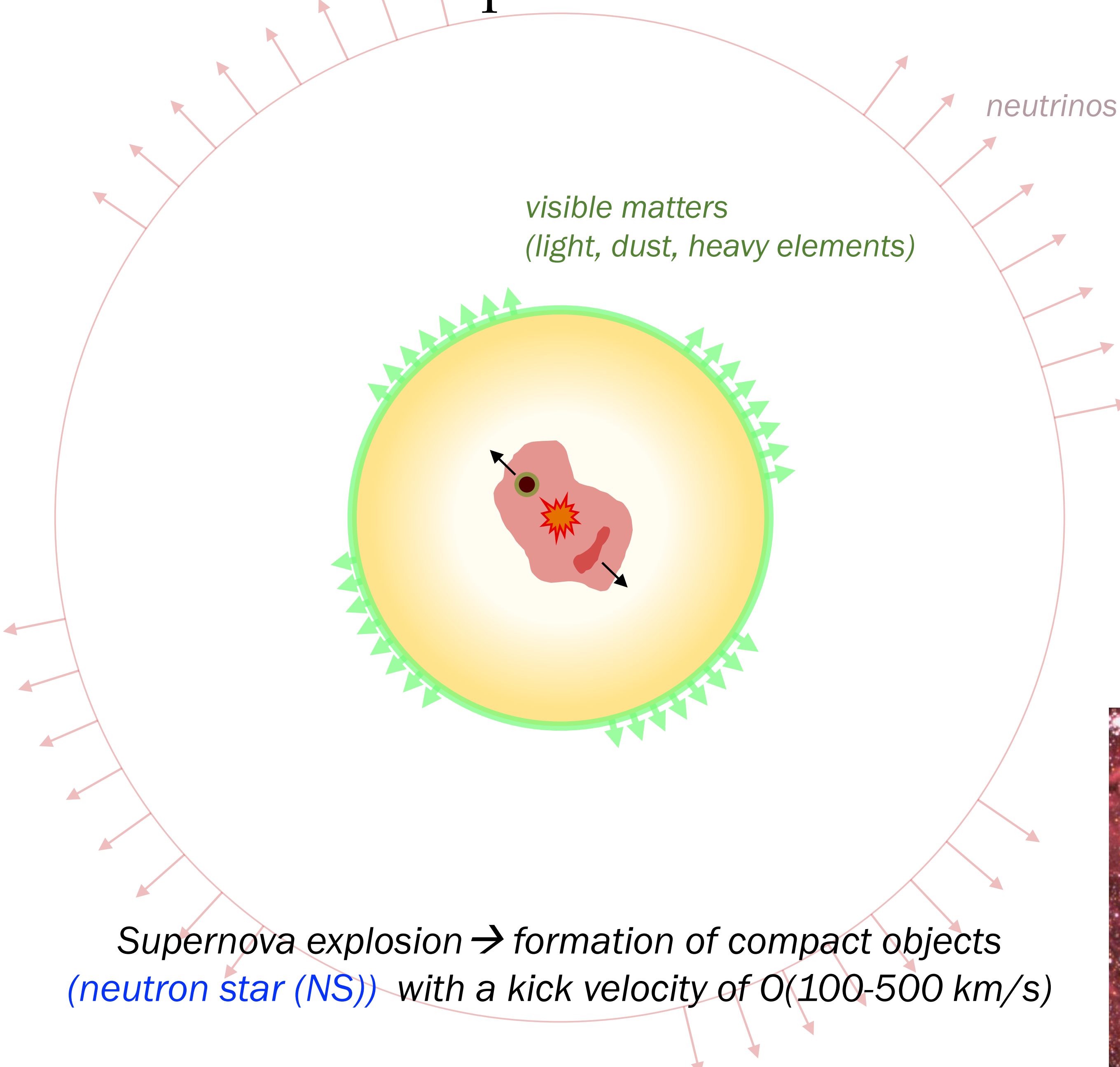
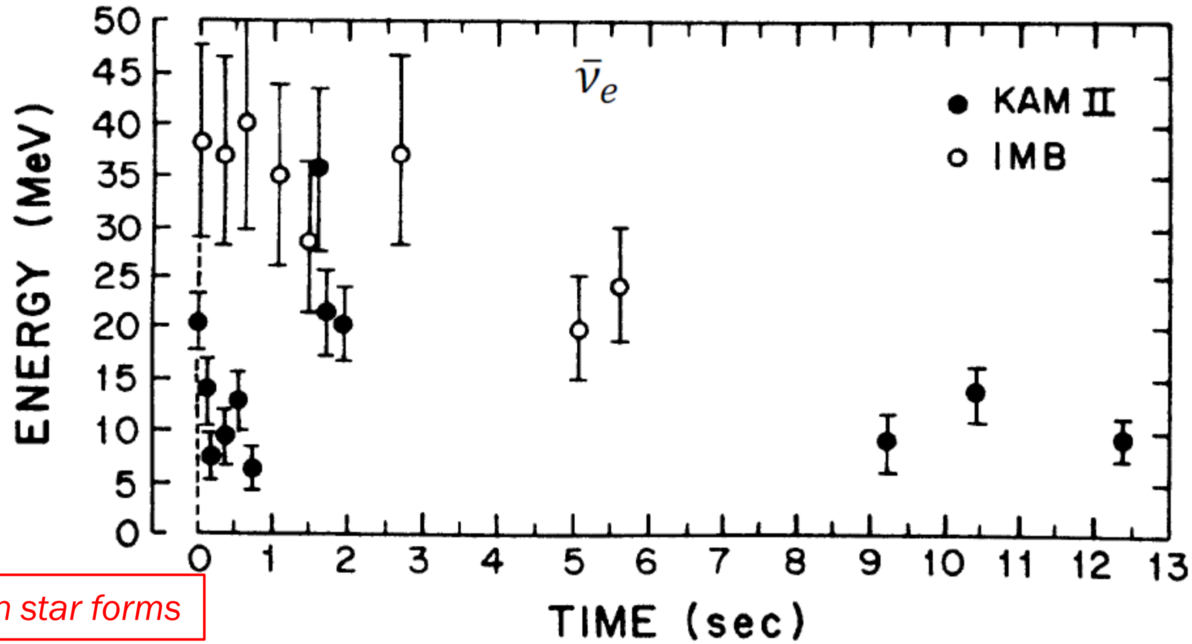


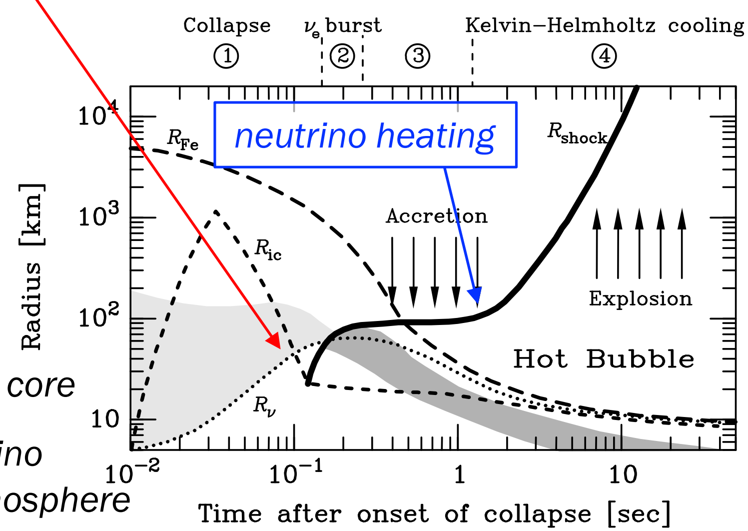
Supernova explosion → formation of compact objects
(neutron star (NS)) with a kick velocity of O(100-500 km/s)

Neutrino spectrum from SN1987A

There is the observation of neutrino flux in 1987



proto-neutron star forms

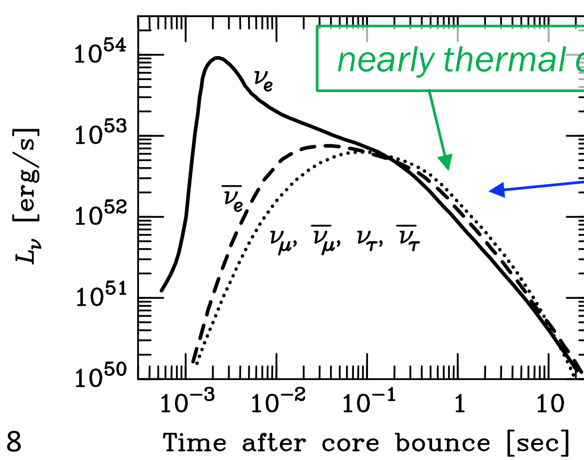


neutrino heating

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

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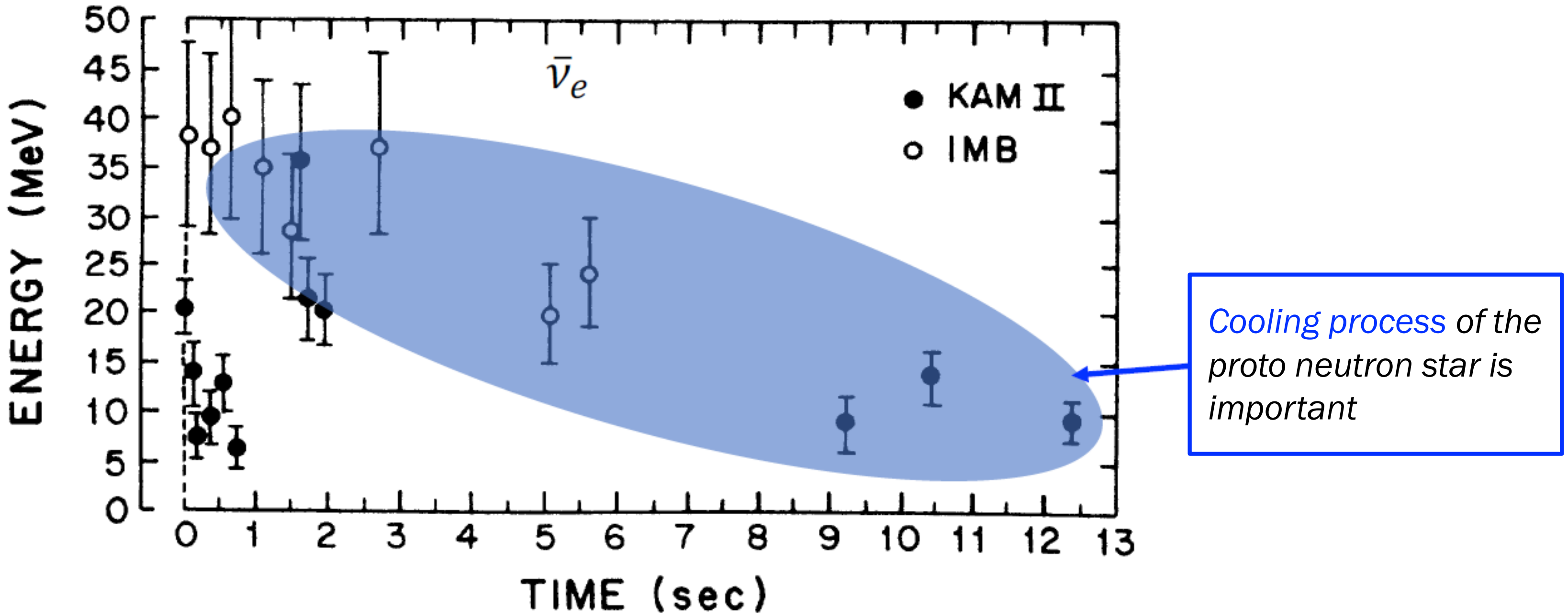
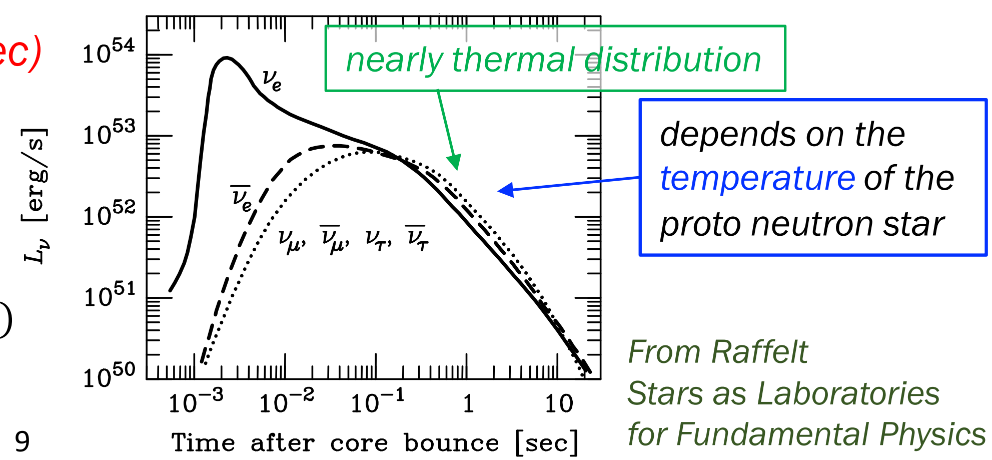


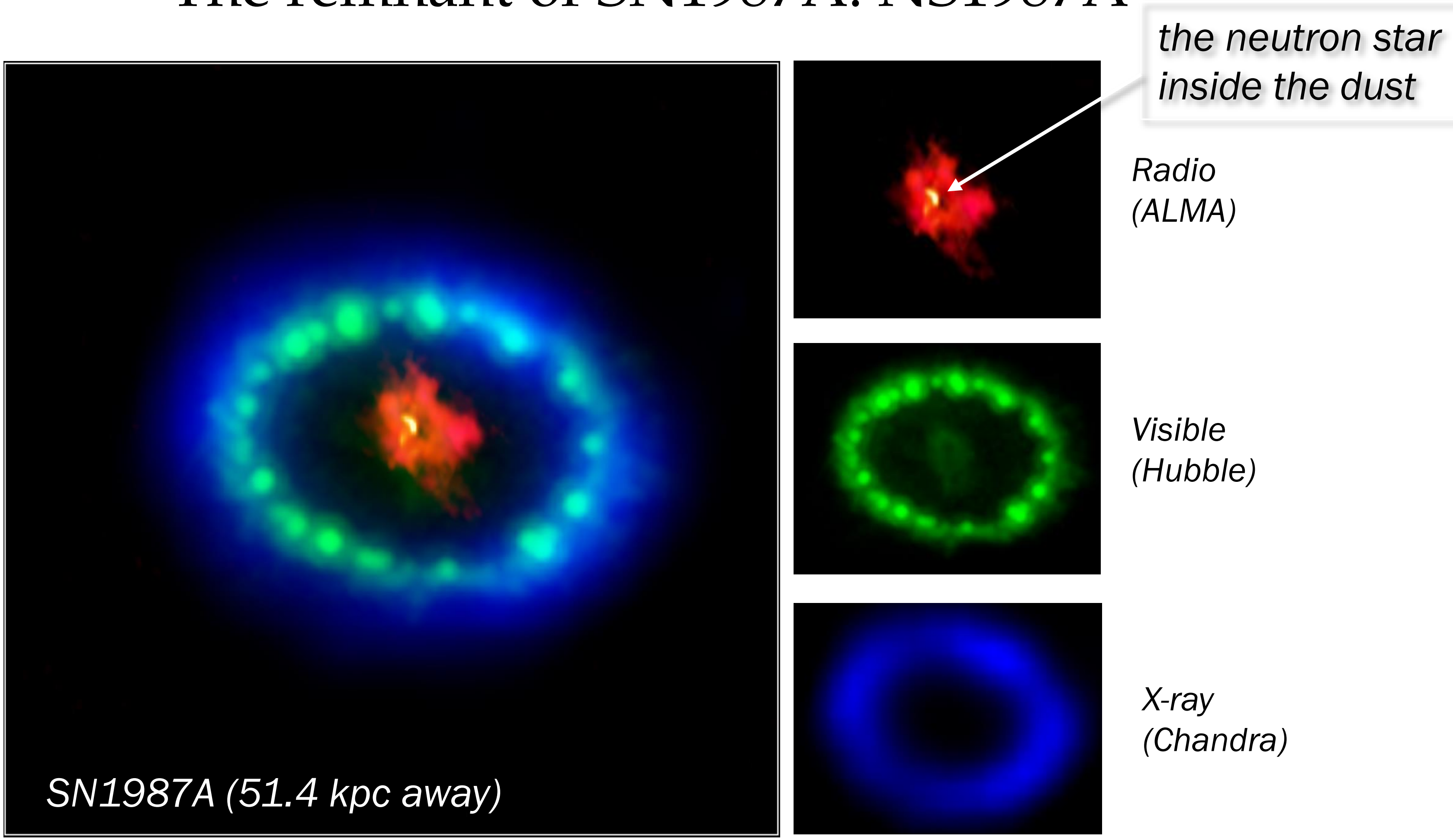
Cooling of PNS by neutrino emissions (t >0.5 sec)

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

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



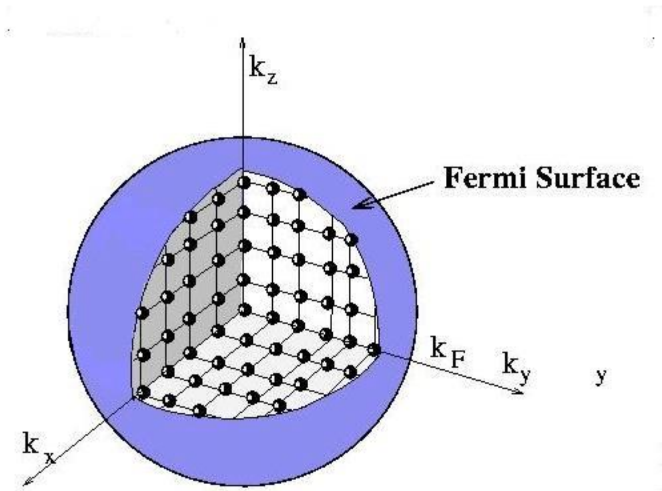
The remnant of SN1987A: NS1987A



The compact object of the remnant of SN1987A is naturally expected to be NS because

1) *SN1987A simulation consistent with the existence of NS ($M < M_{\mathrm{NS\ max}}$)*
2) *Position of the hot blob in the dust consistent with the NS position kicked by the explosion*
3) *Luminosity of the blob consistent with the thermal luminosity of NS around 34 years old*

Neutron Star (degenerate pressure of nucleons ⇔ gravity)



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

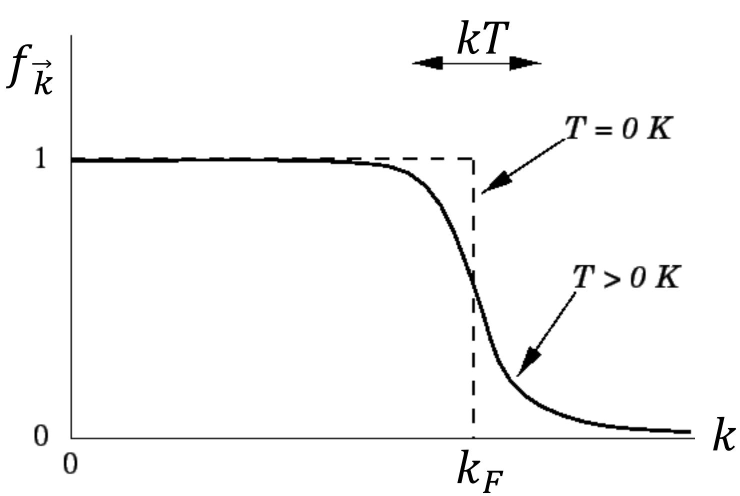
$$
n_f = 2\int \frac{d^3k}{(2\pi)^3} f_f\left(\vec{k}\right)
$$

Proto-neutron star

Core density: $\rho_{\mathrm{PNS}} = (0.5-2)(2.8\times 10^{14}\mathrm{g/cm^3})$

Core temperature: $T_{\mathrm{PNS}} = 30-50\ \mathrm{MeV}$

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



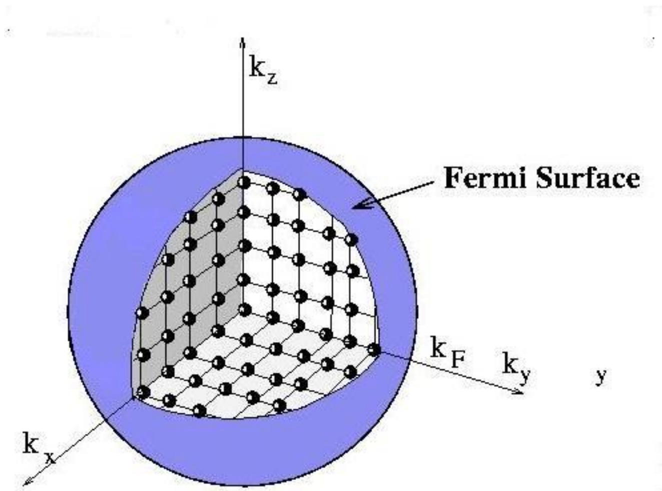
- ▷ *Chemical equilibrium for the beta process of the hadrons and charged leptons*

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

- ▷ *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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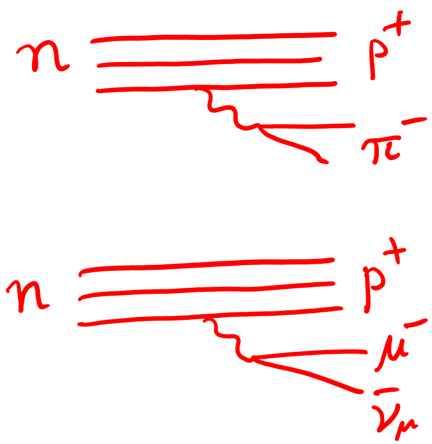

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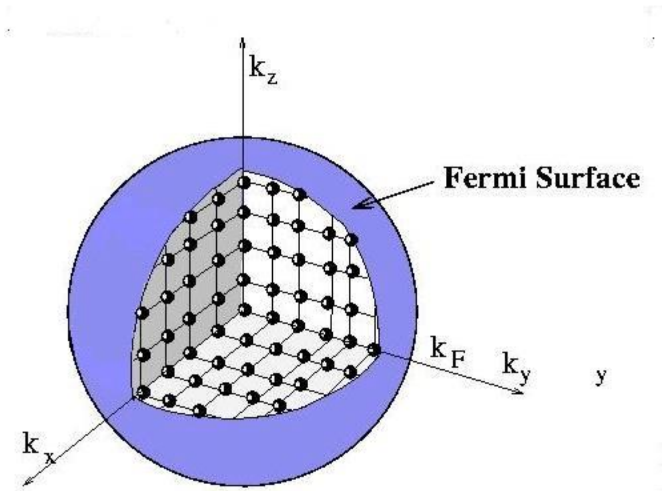

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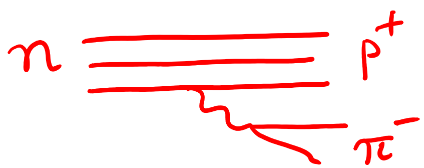
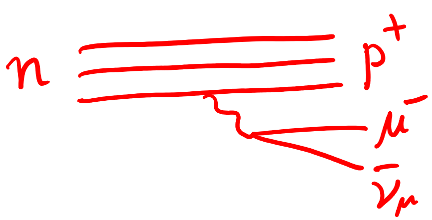
e.g. for neutrons with $\rho_n = 10^{14-15}\mathrm{g/cm^3}$

$$\rho_n \simeq m_n n_n \to k_{Fn} = 300 - 500\ \mathrm{MeV}$$

$$\rho_p \simeq (0.1 - 0.2)\rho_n \to k_{Fp} = 100 - 250\ \mathrm{MeV}$$



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

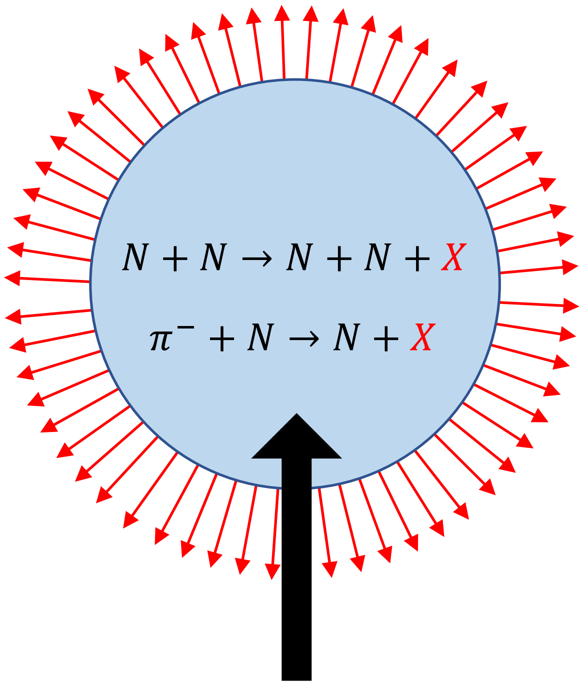


$$f_{\pi^-}(p) \sim \frac{1}{\exp\left(\frac{m_{\pi^-} - \mu_{\pi^-}}{T}\right) - 1} = 0.04 - 0.4$$

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

Neutron Star (degenerate pressure of nucleons ⇔ gravity)

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



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

B. Fore and S. Reddy 1911.02632

$$n_f \simeq \frac{k_{Ff}^3}{3\pi^2} \qquad \text{for } \frac{3}{2}T \lesssim \frac{k_{Ff}^2}{2m_f}$$
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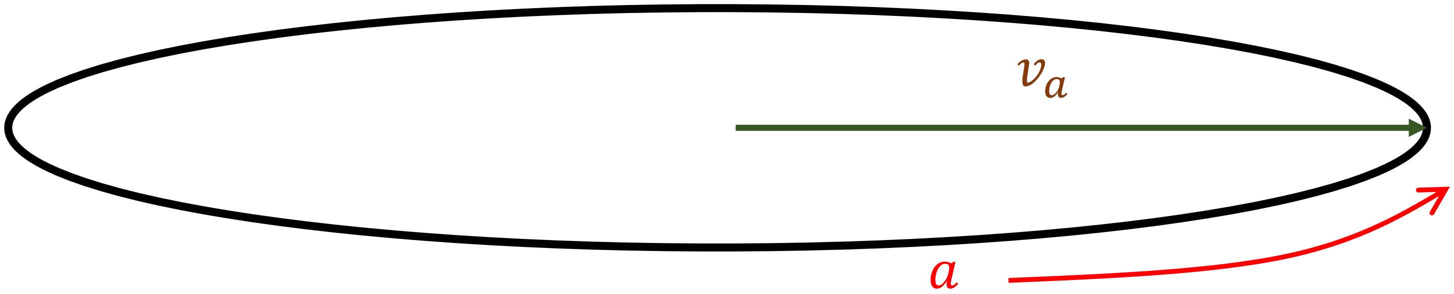
Dark Light Boson Scenarios

Axion (Axion Like Particle)

The axion is a SM singlet pseudo-scalar degree of freedom with a period $2\pi v_a$

1) *The axion is well described in a theory with a cut-off* $\Lambda_{\mathrm{eff}} \ll v_a$
2) *Under the Parity and Time reversal operations* $P: a \to -a\,, T: a \to -a$
3) *Perturbative continuous shift symmetry* $U(1)_{\mathrm{PQ}}\!: a \to a + c v_a,\ c \in \mathbb{R}/2\pi\mathbb{N}$



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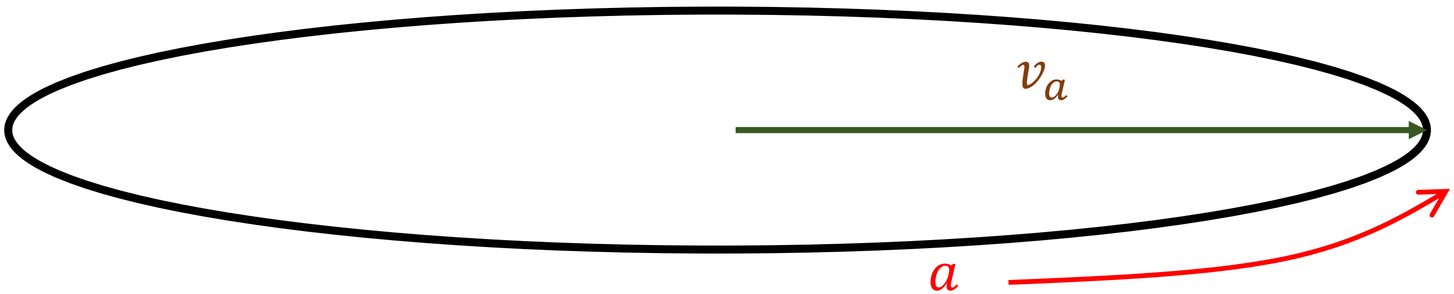

At low energies (above the QCD scale), considering light quarks, gluons and axion couplings

$$L_{\text{eff}} = \frac{1}{2}\left(\partial_\mu a\right)^2 + V_{\text{NP}}(a) - \frac{1}{4} G^a_{\mu\nu} G^{a\mu\nu} + i\left(\bar{u}\gamma^\mu D_\mu u + \bar{d}\gamma^\mu D_\mu d\right) - \left(m_u \bar{u} u + m_d \bar{d} d\right)$$
$$+ \frac{g_s^2}{32\pi^2}\frac{a}{f_a} G^a_{\mu\nu}\tilde{G}^{a\mu\nu} + \frac{\partial_\mu a}{2 f_a}\left(\left(c_u^0 + \delta c_u^0\right)\bar{u}\gamma^\mu\gamma_5 u + \left(c_d^0 + \delta c_d^0\right)\bar{d}\gamma^\mu\gamma_5 d\right)$$

$f_a = v_a / N_{\text{DW}}$ *is usually called "the axion decay constant"* $(N_{\text{DW}} \in \mathbb{N})$

N_{DW} , c_d^0 , c_d^0 *are axon model parameters,* $\delta c_{u,d}^0$ *are RG running induced corrections*

Dark gauge bosons

One of the natural extensions of the Standard Model is to introduce dark U(1) gauge symmetry:

$$SU(3)_C \times SU(2)_L \times U(1)_Y \rightarrow SU(3)_C \times SU(2)_L \times U(1)_Y \times U(1)_X$$

Anomaly free (including right-handed neutrinos), flavor universal extension of the SM:

Dark Photon (DP) & B-L gauge symmetry (including RH neutrinos)

At low energies, considering photon, nucleon, electron, neutrino, and dark gauge boson

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

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

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

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

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

Absence of the dark gauge boson mass $m_{\gamma'}^2 \to 0$ ➔ symmetry enhancement
➔ a small mass is technically natural
(although its origin needs a further explanation beyond the effective theory).

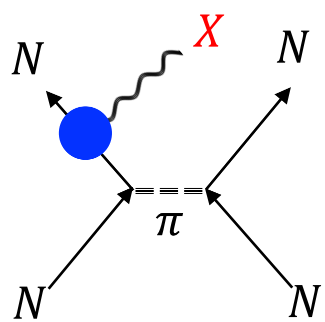
There are also many interesting studies regarding flavor dependent dark gauge symmetries

New Light Boson Emissions

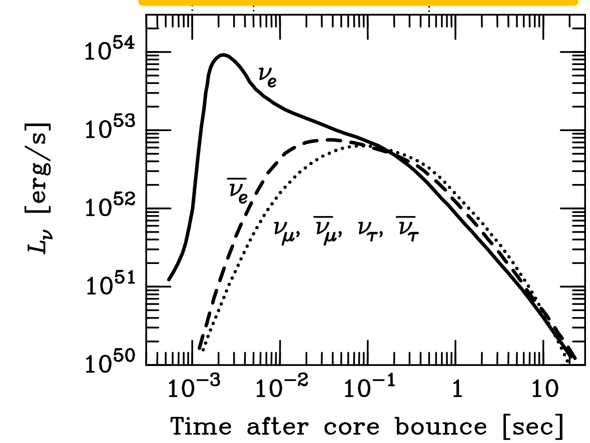
When the light boson mass is smaller than the temperature of the NS core, they could be produced enormously from the (proto) neutron stars, contributing the cooling rate.

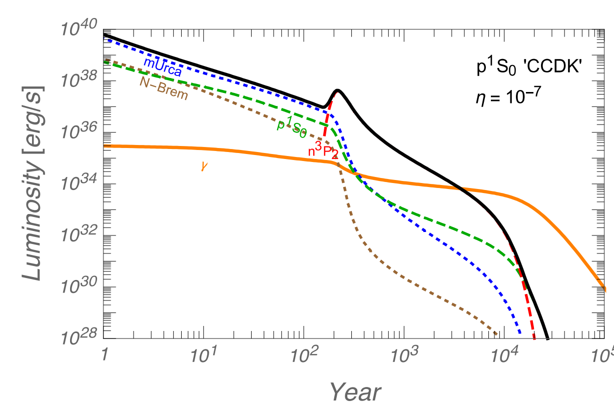
$$C\frac{dT}{dt} = -L_\nu(T) - L_\gamma(T) - L_X(T) + H_{\text{environment}}$$

$$L_{\text{new}}(T) < L_{\text{SM}}(T)$$



Bremsstrahlung





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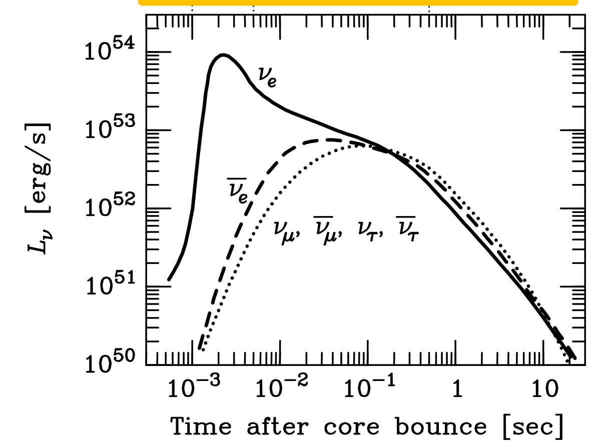

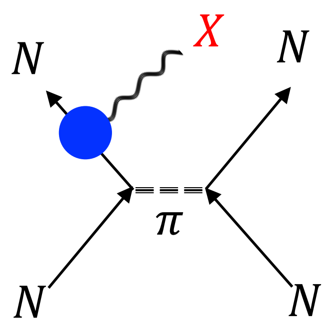

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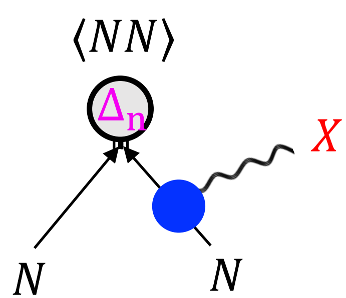
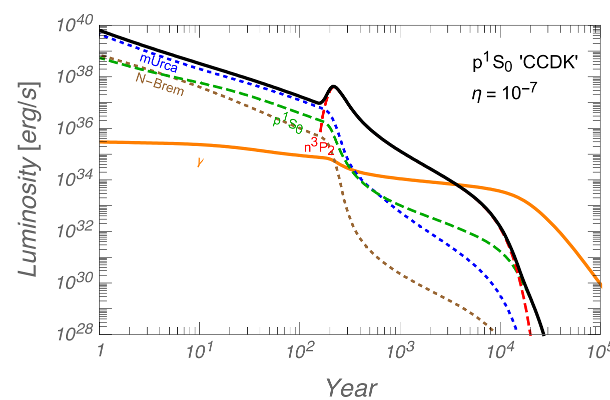


Pair Breaking Formation



Relevant for NSs with ages of 200~300 yrs
For axion [arXiv:1405.6873, 1806.07151, etc.]
For dark gauge boson [**arXiv:2012.05427**]

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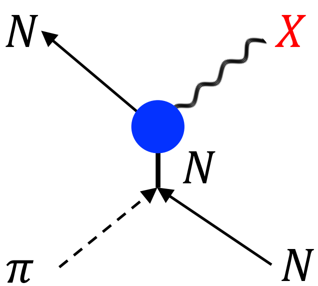
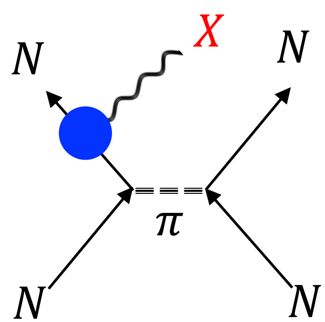


Compton-like Scattering

Relevant for NSs around SN explosion period
For axion [arXiv:2010.02943] [arXiv:2022.00268]
For dark gauge boson
[CSS, S. Yun work in progress]



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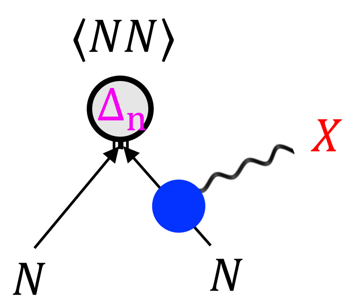

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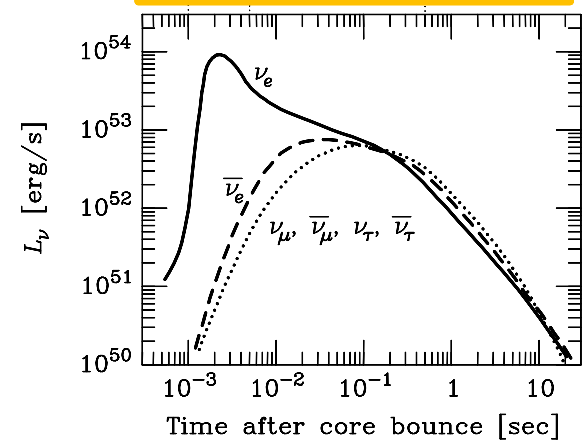

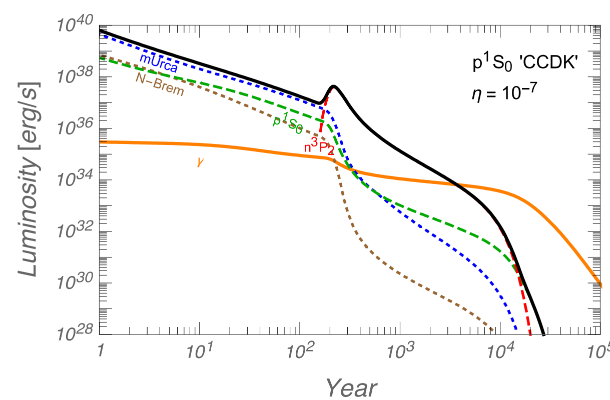

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For axion, [PRD 40 (1982) 652], [**arXiv:2110.01972**]

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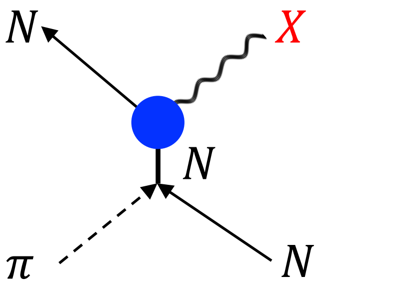

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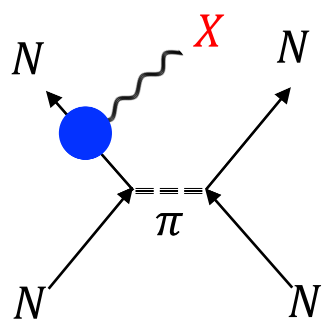

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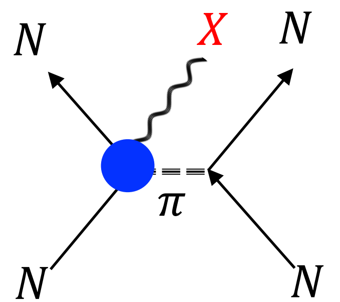
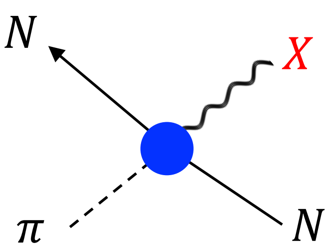


Contact Interactions



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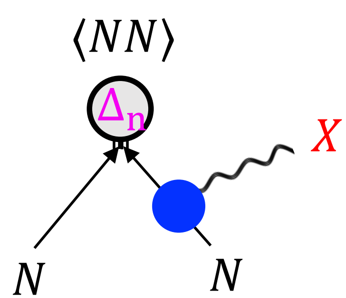
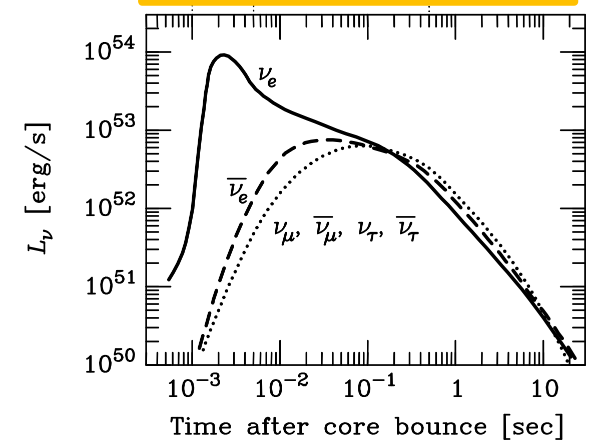
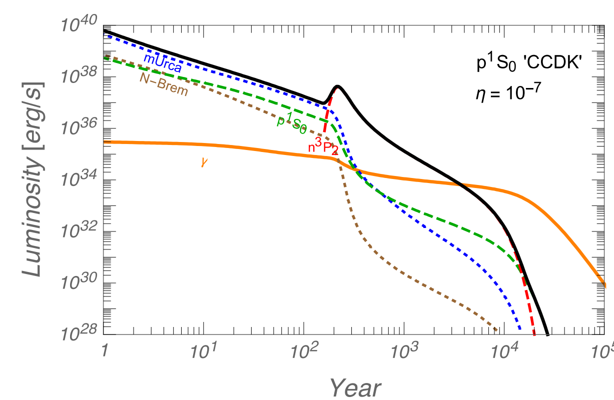
For axion [**arXiv:2110.01972**]



Pair Breaking Formation



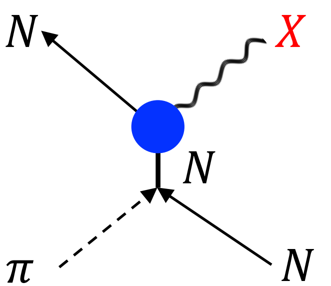


New Light Boson Emissions

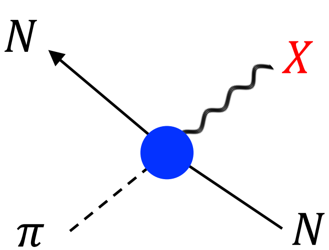
When the light boson mass is smaller than the temperature of the NS core, they could be produced enormously from the (proto) neutron stars, contributing the cooling rate

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

$$L_{\text{new}}(T) < L_{\text{SM}}(T)$$

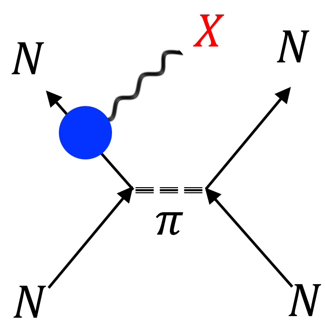


Compton-like Scattering

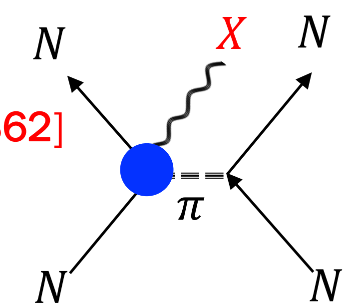


Contact Interactions

For dark gauge boson Bremsstrahlung revisited [arXiv:2110.03362]



Bremsstrahlung



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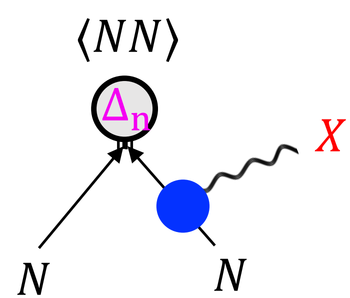

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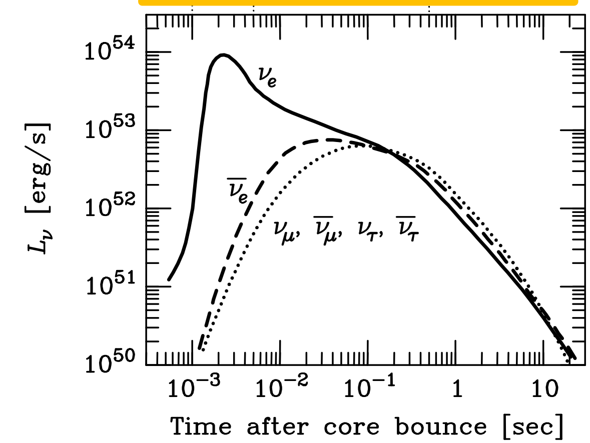

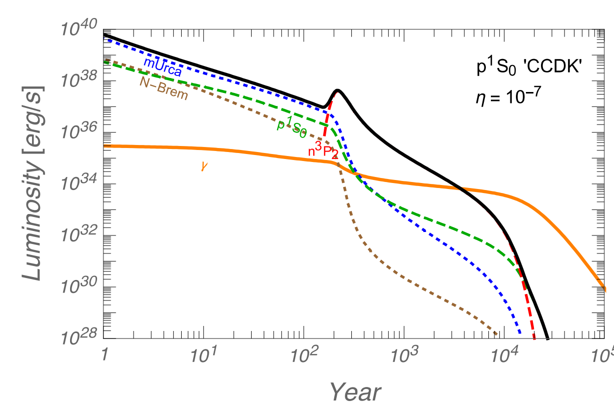

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$$L_{\text{new}}(T) < L_{\text{SM}}(T)$$

For dark gauge boson Bremsstrahlung

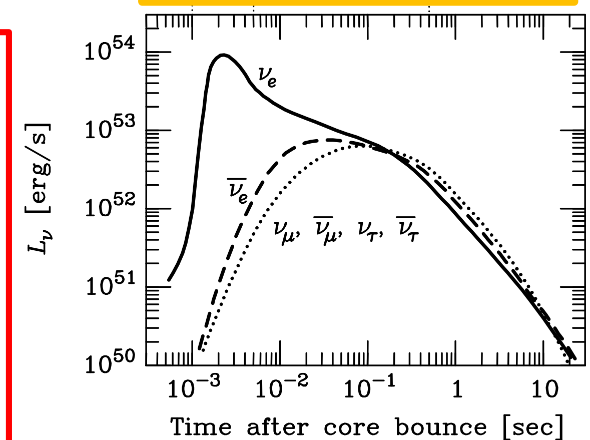
The emission rate of the new particles can be constrained or provide new hints/predictions depending on the size of couplings specified by symmetry structure

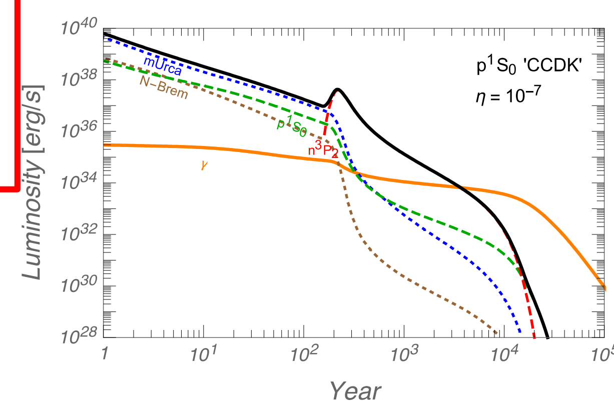
In this talk, I introduce

1) *axion emission at SNs including contact interactions [2110.01972]*
2) *dark gauge boson emission, revisiting Bremsstrahlung process at SN1987A and NS1987A [2110.03362]*

Contact Interactions

Pair Breaking Formation

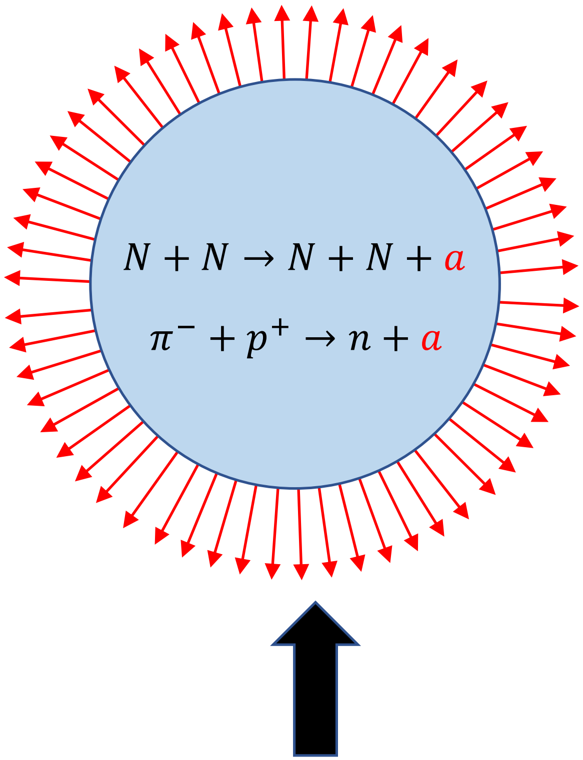




Axion emission from Contact Interactions

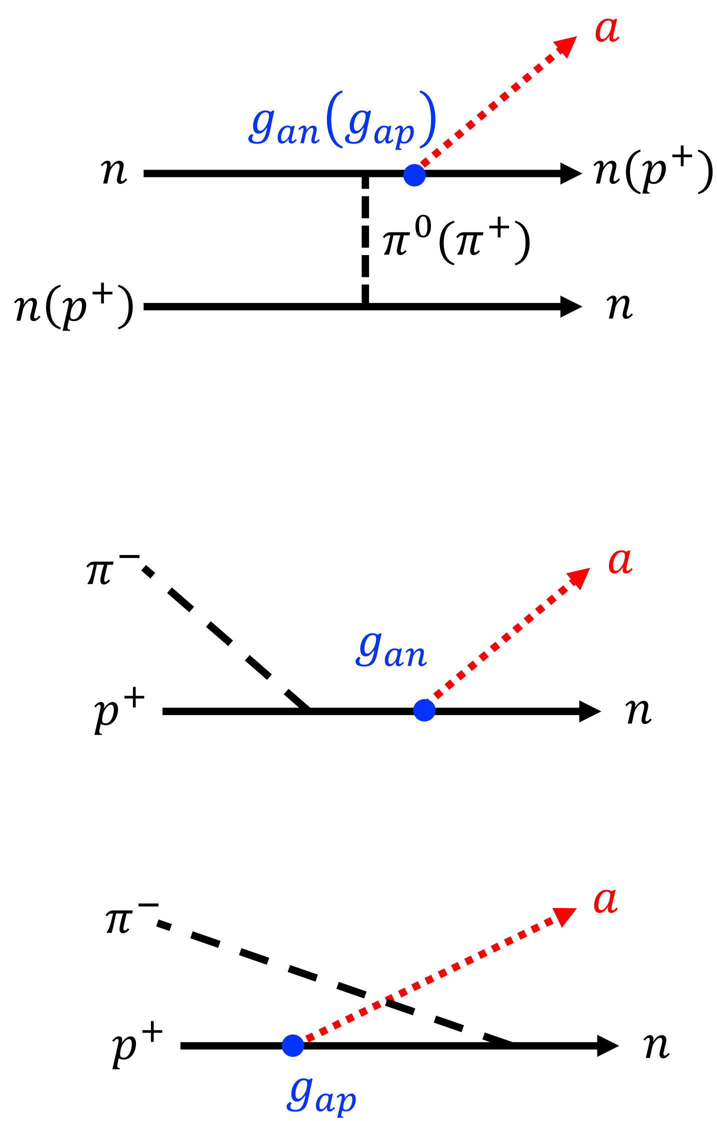
Neutron Star Cooling by Axion Emission

Impacts on cooling of proto-neutron stars by axion emissions



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

B. Fore and S. Reddy 1911.02632



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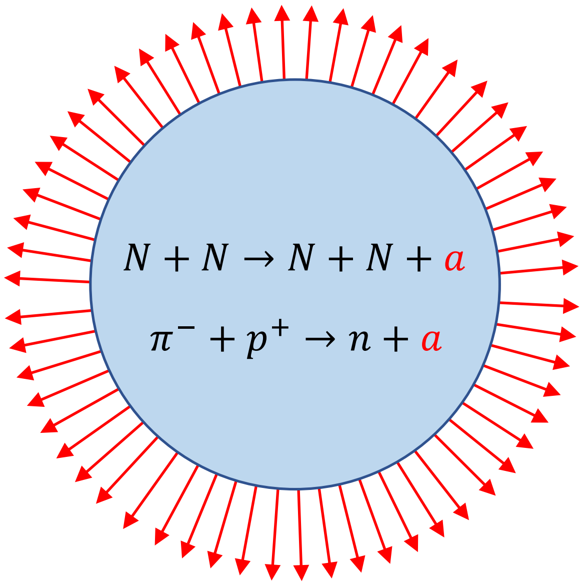

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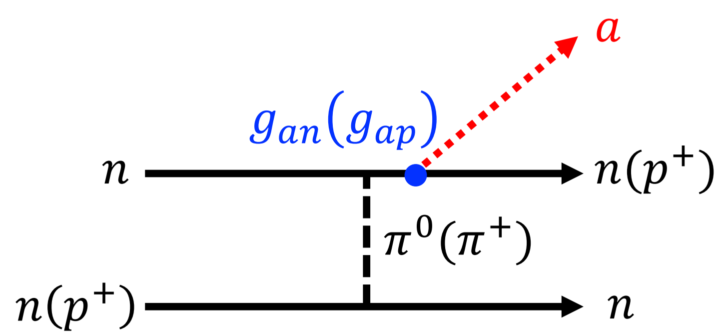
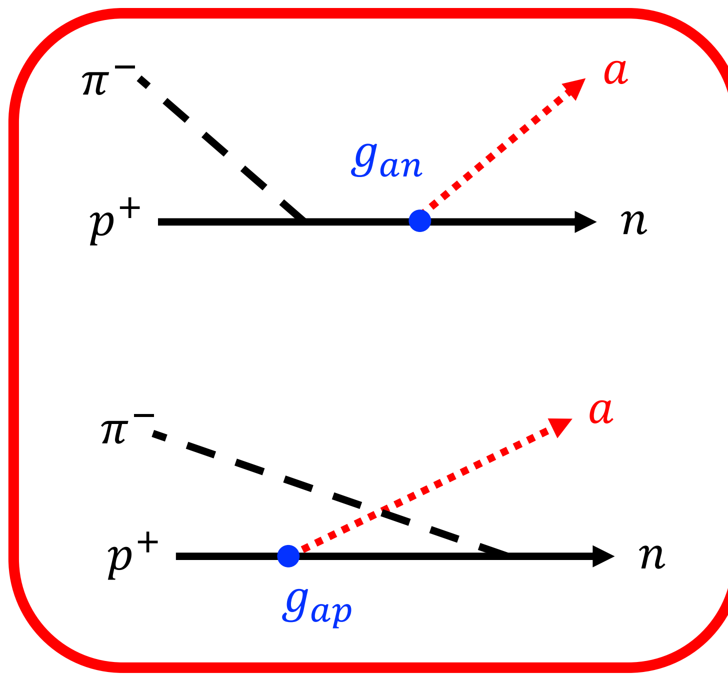


The revisited contribution from arXiv:2010.02943 could be more important than the axion-Bremsstrahlung



P. Carenza, B. Fore, M. Giannotti, A. Mirizzi, S. Reddy 2010.02943

QCD axion interactions at low energies

The QCD axion, gluon and light quarks (u&d) Lagrangian:

$$L = \frac{1}{2}\left(\partial_\mu a\right)^2 - \frac{1}{4} G^a_{\mu\nu} G^{a\mu\nu} + i\left(\bar{u}\gamma^\mu \partial_\mu u + \bar{d}\gamma^\mu \partial_\mu d\right) - \left(m_u \bar{u}u + m_d \bar{d}d\right)$$

$$+ \frac{g_s^2}{32\pi^2}\frac{a}{f_a} G^a_{\mu\nu}\tilde{G}^{a\mu\nu} + \frac{\partial_\mu a}{2f_a}\left(\left(c_u^0 + \delta c_u^0\right)\bar{u}\gamma^\mu\gamma_5 u + \left(c_d^0 + \delta c_d^0\right)\bar{d}\gamma^\mu\gamma_5 d\right)$$

where $\delta c_u^0, \delta c_d^0 = O(0.01)$ *are radiative corrections from RG running.*

After confinement, the relevant interactions become

$$L_{\text{eff}} = \frac{1}{2}\left(\partial_\mu a\right)^2 + i\left(\bar{p}\gamma^\mu \partial_\mu p + \bar{n}\gamma^\mu \partial_\mu n\right) + m_N(\bar{p}p + \bar{n}n) + \frac{1}{2}(\partial_\mu \vec{\pi})(\partial^\mu \vec{\pi})$$

$$+ \frac{g_A}{2f_\pi}\left[\left(\partial_\mu \pi^0\right)(\bar{p}\gamma^\mu\gamma_5 p - \bar{n}\gamma^\mu\gamma_5 n) + \left(\sqrt{2}\left(\partial_\mu \pi^-\right)\bar{n}\gamma^\mu\gamma_5 p + h.c.\right)\right]$$

$$+ \frac{\partial_\mu a}{2f_a}\left[C_{ap}\,\bar{p}\gamma^\mu\gamma_5 p + C_{an}\,\bar{n}\gamma^\mu\gamma_5 n - \frac{C_{a\pi N}}{f_\pi}(i\,\pi^-\bar{n}\gamma^\mu p + h.c.)\right]$$

$$+ \frac{\partial_\mu a}{2f_a}\left[\frac{C_{a\pi}}{f_\pi}\left(\pi^0\pi^+\partial_\mu\pi^- + \pi^0\pi^-\partial_\mu\pi^+ - 2\pi^+\pi^-\partial_\mu\pi^0\right)\right]$$

QCD axion interactions at low energies

$$C_{ap} + C_{an} = \left(c_u^0 + c_d^0 - 1 + \delta c_u^0 + \delta c_d^0\right)(\Delta u + \Delta d)$$

$$C_{ap} - C_{an} = \left(c_u^0 - c_d^0 - \frac{m_d - m_u}{m_d + m_u} + \delta c_u^0 - \delta c_d^0\right)(\Delta u - \Delta d)$$

$$C_{a\pi N} = \frac{1}{\sqrt{2}}\left(c_u^0 - c_d^0 - \frac{m_d - m_u}{m_d + m_u} + \delta c_u^0 - \delta c_d^0\right) = \frac{C_{ap} - C_{an}}{\sqrt{2} g_A}$$

S. Chang and K. Choi hep-ph/9306216

$$S_\mu \Delta f \equiv \langle p | \bar{f} \gamma_\mu \gamma_5 f | p \rangle$$

$\Delta u = 0.897(27)$ $\Delta d = -0.376(27)$ $g_A = \Delta u - \Delta d = 1.27$ $\frac{m_u}{m_d} = 0.48(3)$ at $\mu = 2\text{GeV}$

$$+\frac{\partial_\mu a}{2 f_a}\left[C_{ap}\, \bar{p}\gamma^\mu \gamma_5 p + C_{an}\, \bar{n}\gamma^\mu \gamma_5 n - \frac{C_{a\pi N}}{f_\pi}(i\, \pi^- \bar{n}\gamma^\mu p + h.c.)\right]$$

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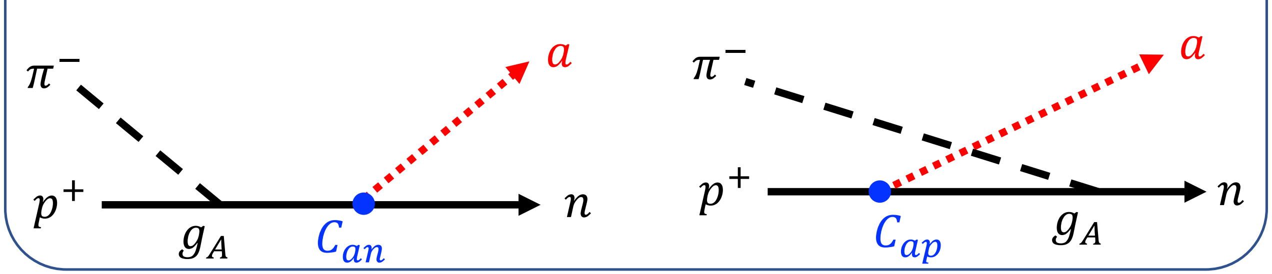
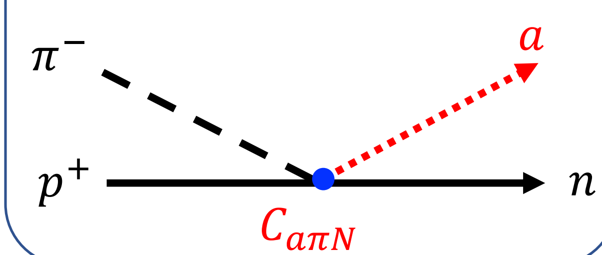


Missing contributions



Implications of contact Interactions

The contribution of contact interactions for new particle emission is usually ignored. Why?

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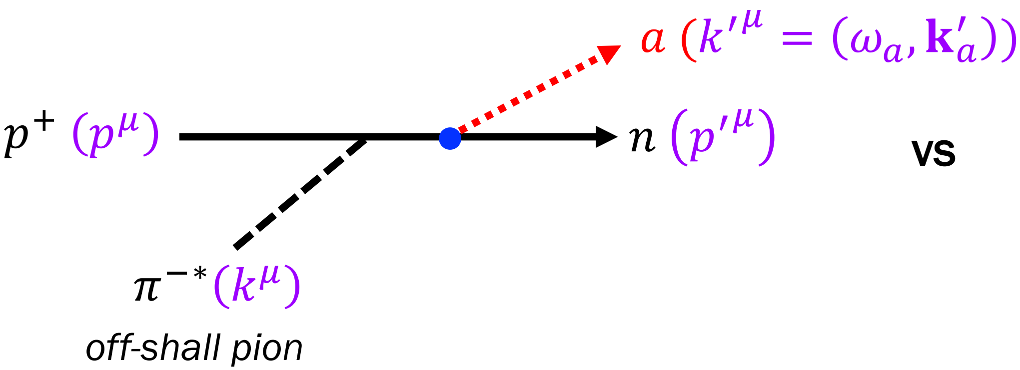
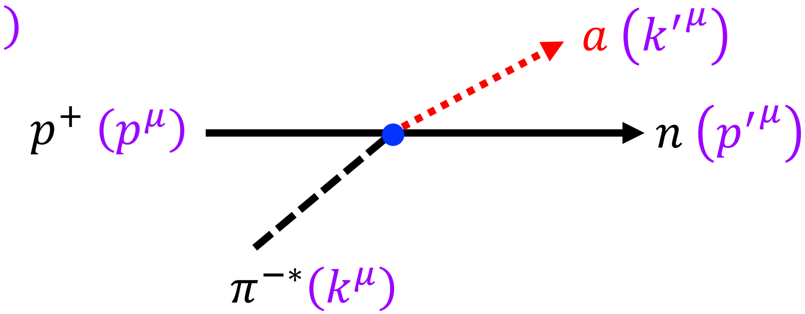
Let us consider Bremsstrahlung case with $m_N \gg T \sim \omega_a \approx |\mathbf{k}'_a| \gg m_a$



vs



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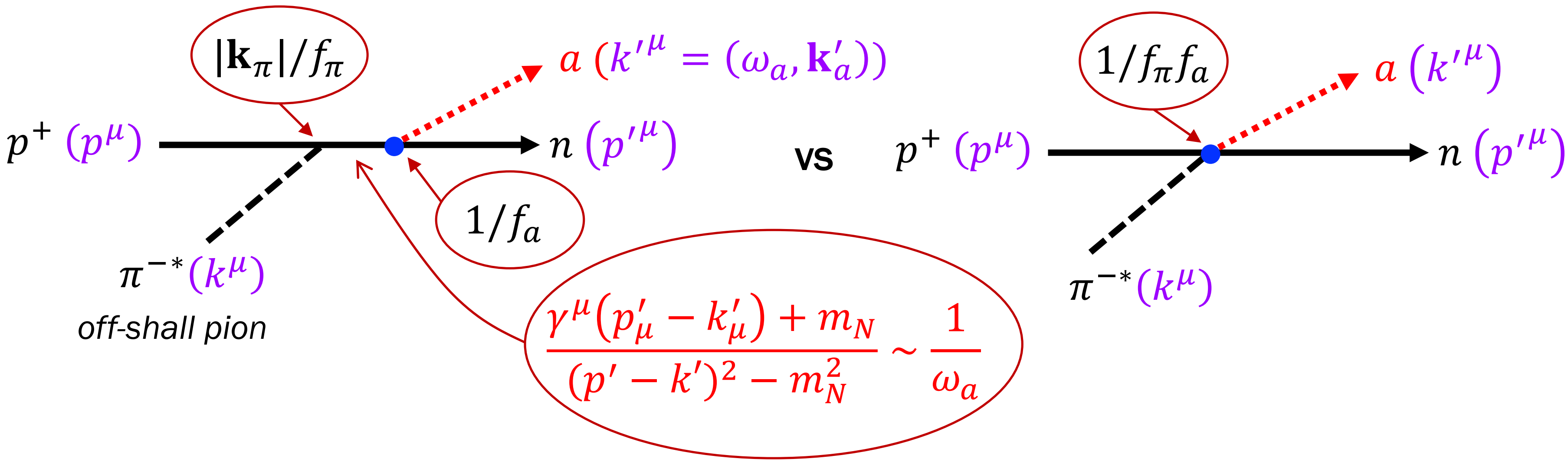


There is a relative enhancement from the propagator of the nucleon when the axion energy is much smaller than the nucleon energy (soft Bremsstrahlung – IR divergence)

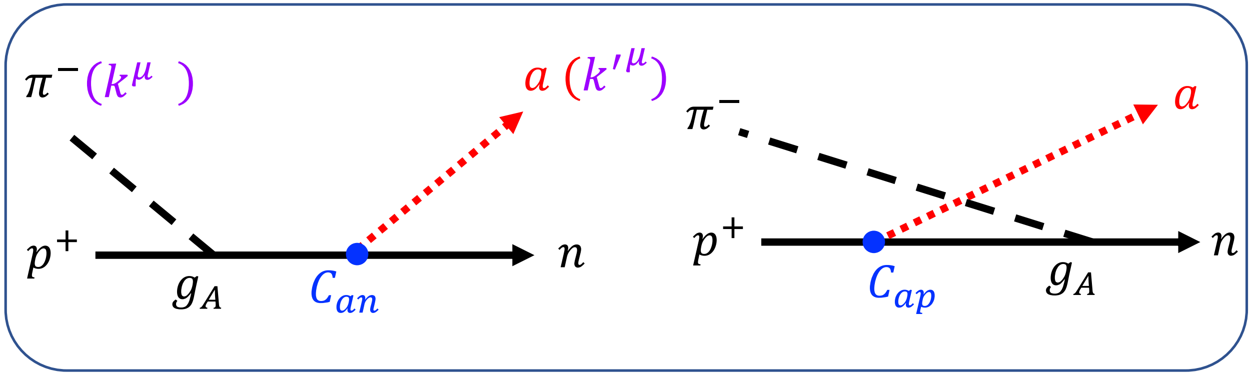
$$(p' - k')^2 - m_N^2 = -2p' \cdot k' \simeq -2m_N\omega_a$$

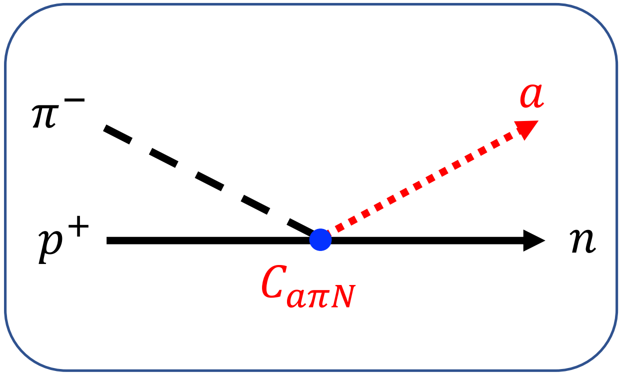
Therefore, a matrix amplitude square from the non-contact interaction is enhanced compared to that from the contact interaction by the factor

$$\frac{|\mathbf{k}_\pi|^2}{\omega_a^2} \sim \frac{|\mathbf{p}_p - \mathbf{p}_n|^2}{T^2} \sim \frac{m_N T}{T^2} \sim \frac{m_N}{T} \gg 1 \ \textit{(semi−degenerate case)}$$

Implications of contact Interactions

HOWEVER, no such an enhancement for on-shall pion-nucleon scattering





$k^\mu = (E_\pi, \mathbf{k}_\pi), k'^\mu = (\omega_a, \mathbf{k}'_a)$ $\qquad \dfrac{|\mathbf{k}_\pi|^2}{\omega_a^2}$ **vs** 1

Because 1) the pions are in thermal equilibrium: $\frac{|\mathbf{k}_\pi|^2}{2m_\pi} \simeq \frac{1}{2} m_\pi v_\pi^2 \sim T$,

2) the axion energy is greater than the pion mass: $\omega_a \sim E_\pi = \sqrt{m_\pi^2 + |\mathbf{k}_\pi|^2}$

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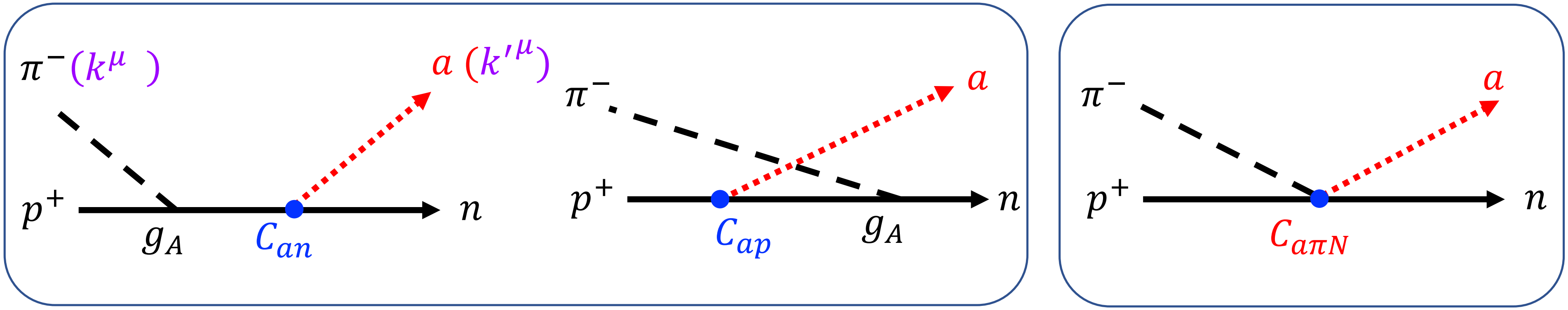

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Therefore,

$$\frac{|\mathbf{k}_\pi|^2}{\omega_a^2} \sim \frac{|\mathbf{k}_\pi|^2}{E_\pi^2} \sim v_\pi^2 \sim \frac{T}{m_\pi} \ \text{ for } T < m_\pi$$

The contact interaction could be more important than the non-contact contributions!

Implications of contact Interactions

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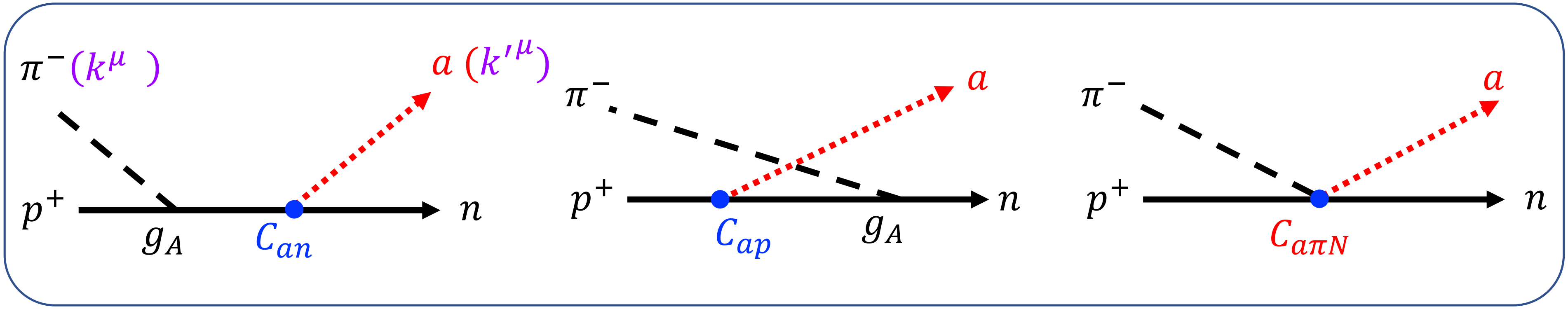

$$\int d\Omega_{\pi^-} \sum_{s_p, s_n} |\mathcal{M}_{\pi^- + p \to n + a}|^2 = \frac{8\pi m_N^4}{f_a^2 f_\pi^2} \mathcal{C}_a^{p\pi^-}$$

$$\mathcal{C}_a^{p\pi^-} \simeq \frac{2}{3} g_A^2 \left(\frac{|\mathbf{p}_\pi|}{m_N}\right)^2 (2C_+^2 + C_-^2) + \left(\frac{E_\pi}{m_N}\right)^2 C_{a\pi N}^2 + \sqrt{2} g_A \left(\frac{E_\pi}{m_N}\right)^3 \left(1 - \frac{1}{3}\left(\frac{|\mathbf{p}_\pi|}{E_\pi}\right)^2\right) C_{a\pi N} C_-,$$

$$C_\pm = \frac{1}{2}(C_{ap} \pm C_{an}), \quad E_\pi = \sqrt{m_{\pi^-}^2 + |\mathbf{p}_\pi|^2}.$$

K. Choi, H. Kim, H. Seong, CSS 2110.01972

Implications of contact Interactions

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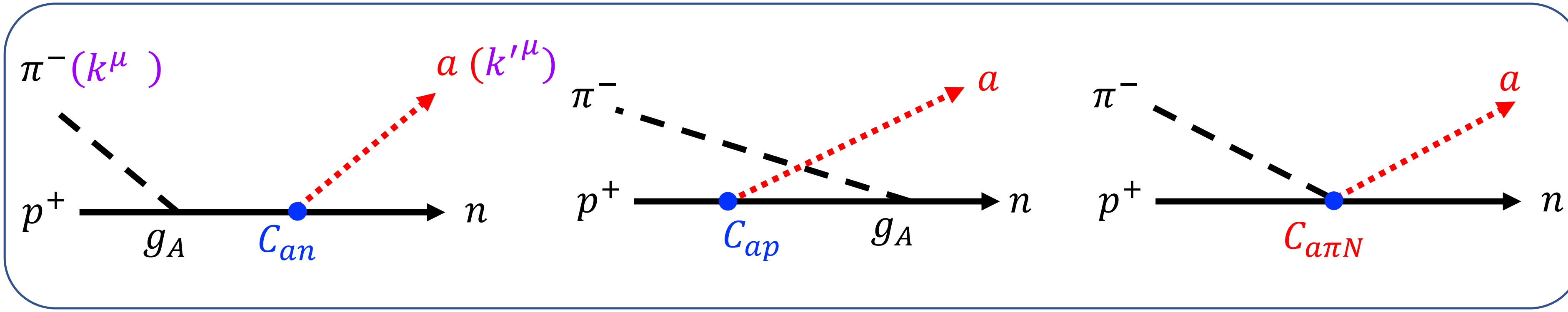


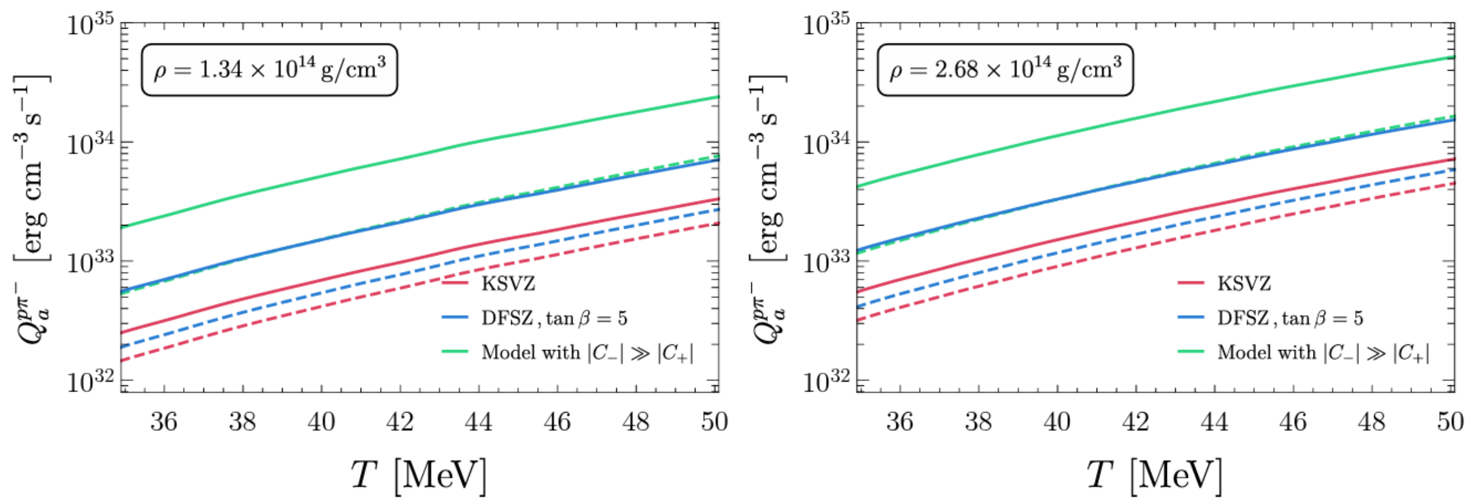


Figure 3. Axion emissivities of $\pi^- + p \to n + a$ for the KSVZ, DFSZ, and a model with $|C_-| \gg |C_+|$. All models are assumed to have $f_{a9} \equiv (f_a/c_G)/10^9\,\mathrm{GeV} = 1$. The solid curves represent the total emissivity including the effect of the contact interaction $C_{a\pi N}$, while the dashed curves are the emissivity without including the contribution from $C_{a\pi N}$.

K. Choi, H. Kim, H. Seong, CSS 2110.01972

$U(1)_{B-L}$ Gauge Boson Bremsstrahlung at SN

Dark gauge bosons

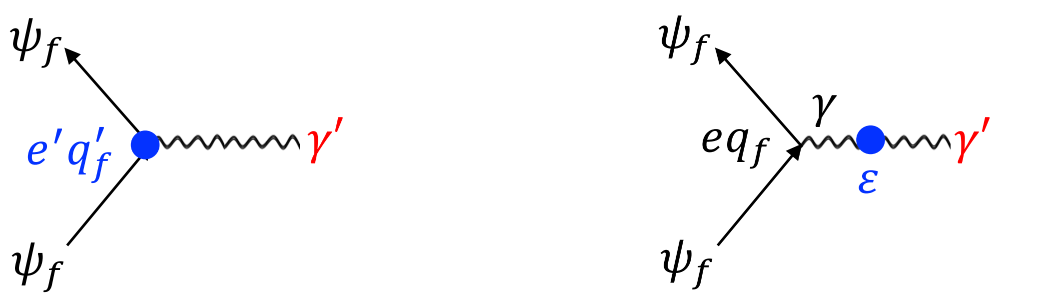
From the couplings between (nucleon, electron, neutrino) and dark gauge boson,

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

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

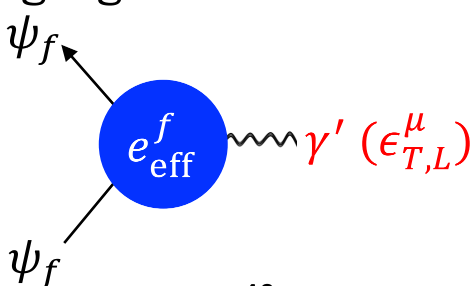
$U(1)_{DP}$:
$q'_\psi = 0$

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



we have to calculate the medium dependent effective couplings

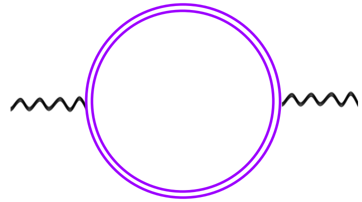
between a dark gauge boson and nucleons at (P)NS core



(T : transverse mode,
L : longitudinal mode)

Dark gauge boson couplings in dense medium

The photon propagator is modified mostly by the highly degenerate electron plasma:



Electron thermal loop

$$\omega_P = \sqrt{\frac{4\pi\alpha n_e}{E_e}} \simeq \left(\frac{k_{F,e}}{100\ \mathrm{MeV}}\right) O(10)\mathrm{MeV}$$

Roughly speaking, a gauge boson coupled to the electron becomes heavy in the medium

(In the basis in which kinetic mixing is removed, ignoring O(ε^2))

$$\Pi^{\mu\nu}_{\mathrm{EM}} = \langle J^{\mu}_{\mathrm{EM}} J^{\nu}_{\mathrm{EM}} \rangle = \pi_T \sum \epsilon^{\mu}_{T} \epsilon^{\nu}_{T} + \pi_L \epsilon^{\mu}_{L} \epsilon^{\nu}_{L}$$

$$\pi_T = \omega_P^2 \left(1 + \frac{1}{2} G(v_*^2 k^2/\omega^2)\right) \qquad \pi_L = \omega_P^2 \frac{\omega^2 - k^2}{\omega^2} \frac{1 - G(v_*^2 k^2/\omega^2)}{1 - v_*^2 k^2/\omega^2}$$

$$G(x) = \frac{3}{x}\left(1 - \frac{2x}{3} - \frac{1-x}{2\sqrt{x}} \ln \frac{1+\sqrt{x}}{1-\sqrt{x}}\right)$$

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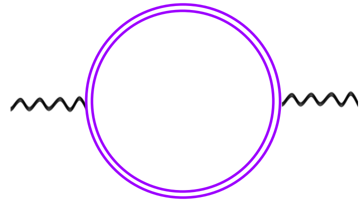

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$$L_{DP} \simeq -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} - \frac{1}{4}F'_{\mu\nu}F'^{\mu\nu} - \frac{1}{2}m^2_{\gamma'}A'_\mu A'^\mu$$
$$-\left(eA_\mu - e\varepsilon A'_\mu\right)\bar{e}\gamma^\mu e + \left(eA_\mu - e\varepsilon A'_\mu\right)\bar{p}\gamma^\mu p$$

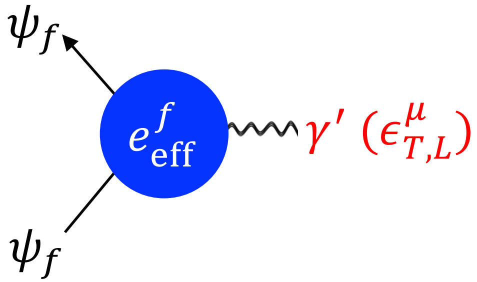
gets an effective mass from the plasma waves of the medium

$$L_{B-L} \simeq -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} - \frac{1}{4}F'_{\mu\nu}F'^{\mu\nu} - \frac{1}{2}m^2_{\gamma'}A'_\mu A'^\mu$$
$$-\left(eA_\mu + (e' - e\varepsilon)A'_\mu\right)\bar{e}\gamma^\mu e + \left(eA_\mu + (e' - e\varepsilon)A'_\mu\right)\bar{p}\gamma^\mu p + \left(e'A'_\mu\right)\bar{n}\gamma^\mu n$$

Dark gauge boson couplings in dense medium

If $m_{\gamma'} = 0$*, the electron and proton are totally decoupled from the dark gauge boson with a proper field redefinition, while the neutron coupling is insensitive to* $m_{\gamma'}$.

** The effective coupling between the current and the dark gauge boson:*



$$e^f_{\rm eff} = e'\left(q'_e q_f - q'_f q_e\right) + (\varepsilon e - e' q'_e) q_f \frac{m^2_{\gamma'}}{m^2_{\gamma'} - \pi_{T,L}}$$

$$\pi_T \simeq \frac{3\omega_P^2}{2}$$

$$\pi_L \simeq 3\omega_P^2 \frac{m^2_{\gamma'}}{T^2} \ln \frac{T}{m_{\gamma'}}$$

for $m'_\gamma \ll T, \omega_P$

$$\begin{pmatrix} T_{\rm core} \sim 0.1 - 50{\rm MeV} \\ \omega_P \sim 10{\rm MeV} \end{pmatrix}$$

(T : transverse mode, L : longitudinal mode)

** The polarization tensors from the current conservation*

$$\epsilon^\mu_T \epsilon^{\nu *}_T \sim -\eta^{\mu\nu}, \qquad \epsilon^\mu_L \epsilon^{\nu *}_L \sim \frac{m'^2_\gamma}{T^2} \eta^{\mu 0}\eta^{\nu 0}$$

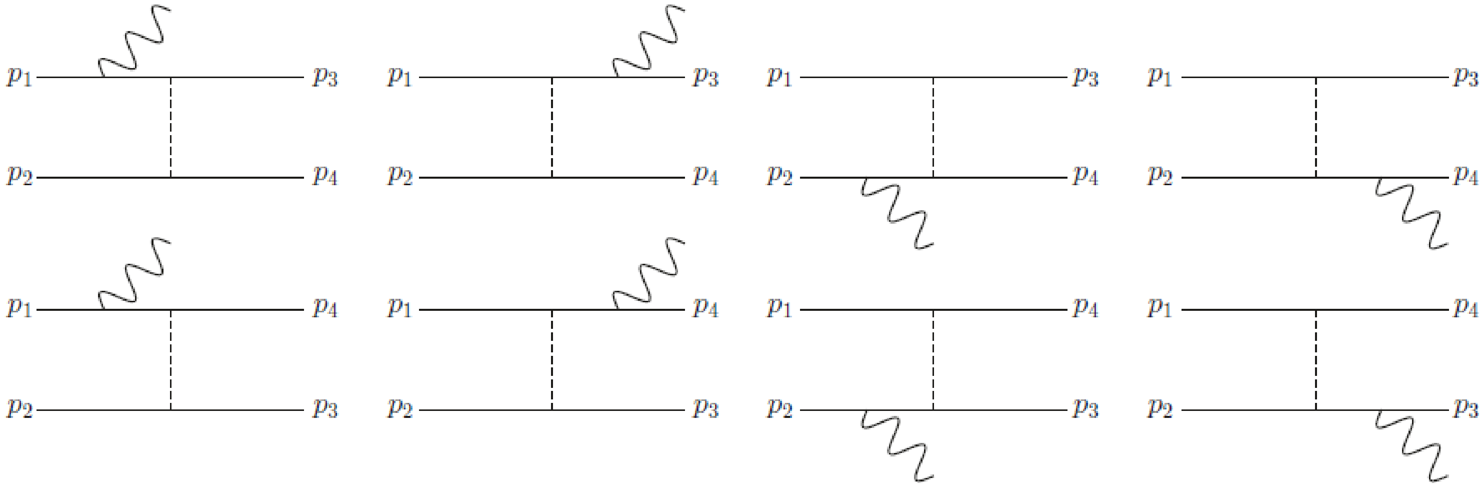
1) Production rates of DP and B-L gauge bosons are different for different polarizations

2) For B-L, the effective coupling of proton and that of neutron are different ($e^p_{\rm eff} \ll e^n_{\rm eff}$)

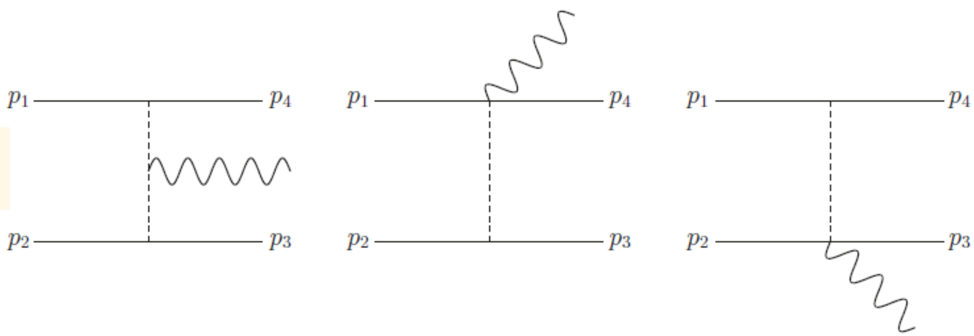
Nucleon-Nucleon Bremsstrahlung

There are many diagrams for $N + N \to N + N + \gamma'$

$A'_\mu \bar{N} \gamma^\mu N$

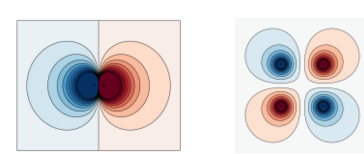


$A'_\mu \pi^- (\partial^\mu \pi^+)$



$A'_\mu \pi^+ \bar{p} \gamma^\mu \gamma^5 n$

In the limit of $m_p = m_n \gg T$, *we can take a velocity of the nucleon* ($v_N \sim \sqrt{T/m_N}$) *as the expansion parameter* ➔ *Multipole expansion of dark radiation*



Multipole radiation

Soft radiation approximation (SRA) is usually taken in the literature for multipole expansion of radiation. However, this captures only classical limit of Bremsstrahlung, i.e. independent of the spin of dark charged particles.

We note that there are also spin dependent contributions (quantum contribution) as

$$\mathcal{M}_{\text{multipole}}(\text{spin}) \sim O\left(\frac{T}{m_N v_N^2}\right)\mathcal{M}_{\text{multipole}}(\text{SRA})$$

which could be relevant for SN environment (semi-degenerate: $m_N v_N^2 \sim T$)

$$H = \frac{1}{2m_N}\left(\vec{\sigma}\cdot\left(\vec{p}_N - q_N\vec{A}'\right)\right)^2$$

$$= \frac{p_N^2}{2m_N} - q_N\frac{p_N}{m_N}\cdot\vec{A}' + \frac{q_N^2}{2m_N}\vec{A}'\cdot\vec{A}' - \frac{g_N q_N}{2m_N}\vec{S}_N\cdot\vec{B}' \qquad \left(\vec{S}_N = \frac{\hbar}{2}\vec{\sigma}, g_N = 2, \vec{B}' = \nabla\times\vec{A}'\right)$$

classical current — magnetic moment

Dipole from classical current = $O(v_N)$ × (Monopole) = $O(v_N^2)$

Dipole from magnetic moment = $O\left(\frac{\omega_{\gamma'}}{m_N}\right) = O\left(\frac{\omega_{\gamma'}}{m_N v_N^2}\right)$ × (Dipole from classical current)

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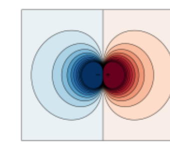
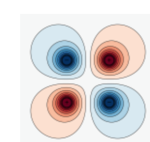
** Dipole radiation*



- *Leading order of v_N expansion*
- $\mathcal{M}_{\text{dipole}} \propto \left(e_{\text{eff}}^{N_1} - e_{\text{eff}}^{N_2}\right)$ *for* $m_{N_1} = m_{N_2}$ *so only* $n + p \to n + p + \gamma'$ *could be relevant*
- *Generally when center of charge = center of mass, dipole contribution is vanishing!*
- *Becomes important only when* $e_{\text{eff}}^{n} \neq e_{\text{eff}}^{p}$

** Quadrupole radiation*



- *Next leading order* $\mathcal{M}_{\text{quadrupole}} \sim O(v_N)\,\mathcal{M}_{\text{dipole}}$ *,*
- *Becomes important when center of charge = center of mass*

Constraints from SN1987A

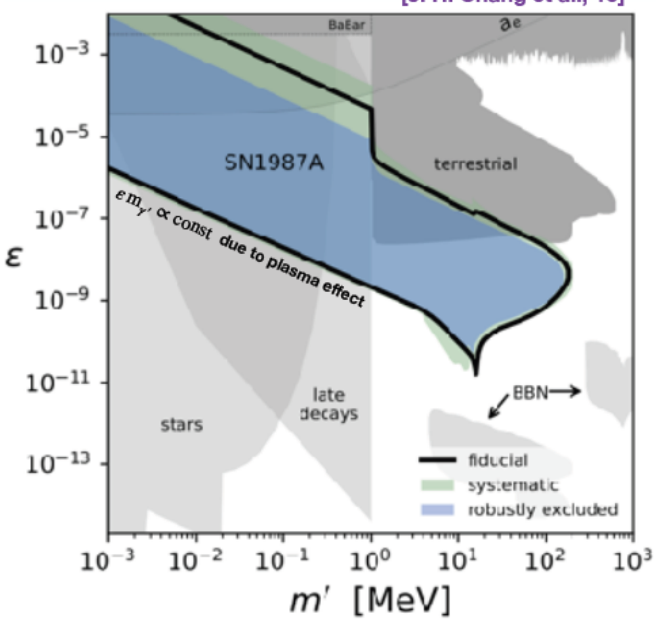
From Seokhoon's slides

✦ Dark photon

$e^n_{\rm eff} = 0$

$e^p_{\rm eff} = \varepsilon e \dfrac{m^2_{\gamma'}}{m^2_{\gamma'} - \pi_{\rm T,L}}$ ➡ Dipole radiation

[J. H. Chang et al., 16]

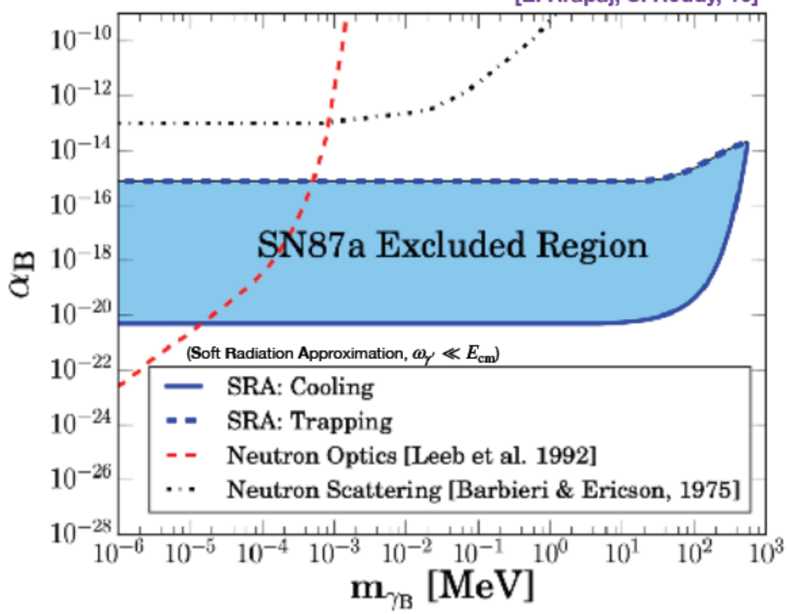


✦ $U(1)_{\rm B}$

$e^n_{\rm eff} = 1$

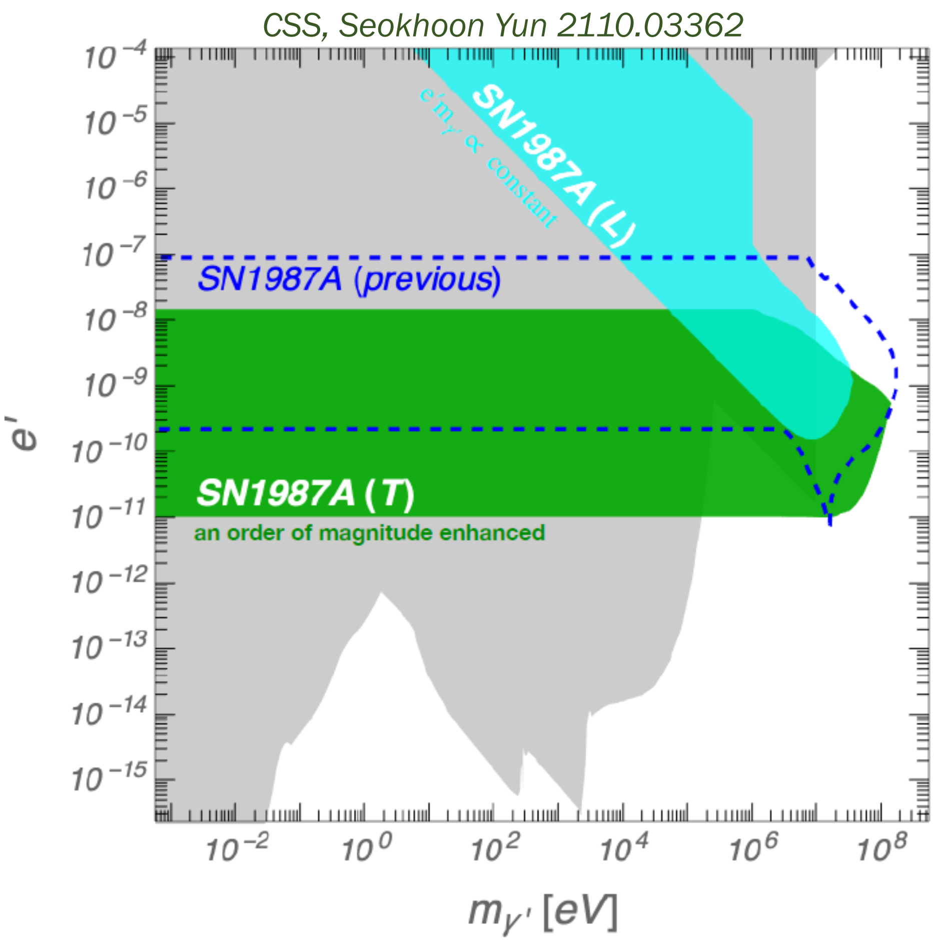
$e^p_{\rm eff} = 1$ ➡ Quadrupole radiation

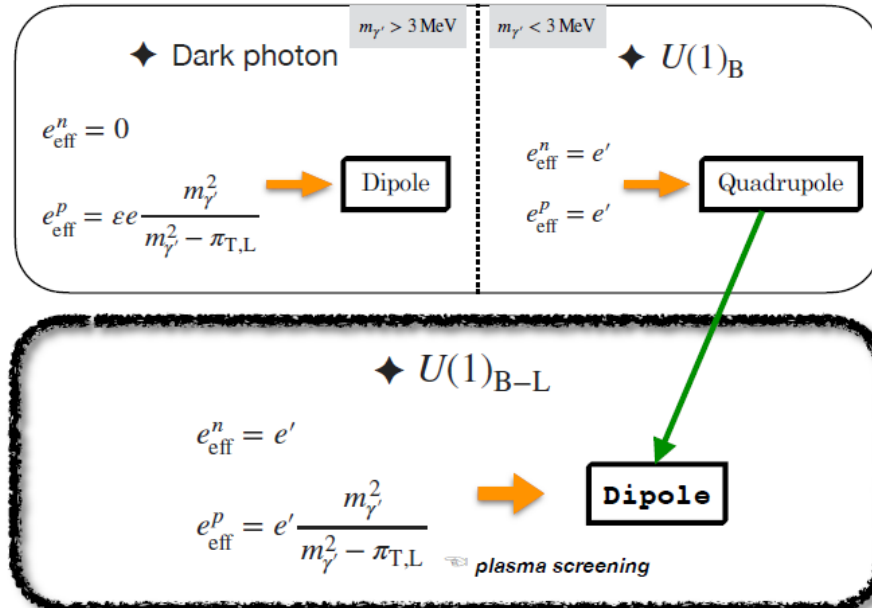
[E. Rrapaj, S. Reddy, 16]

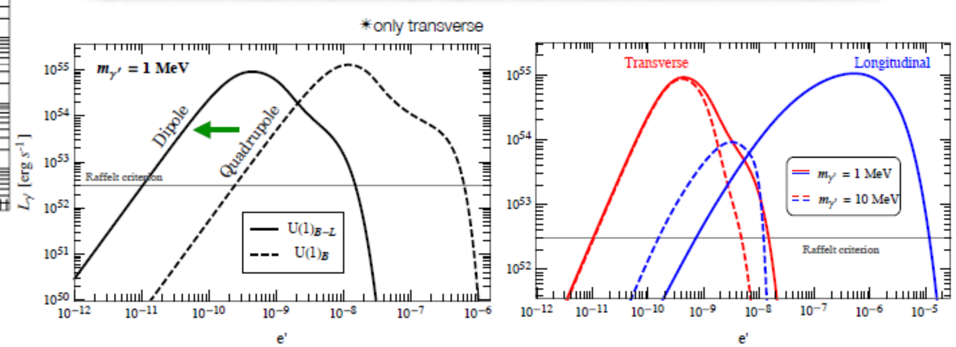


Constraints from SN1987A

From Seokhoon's slides



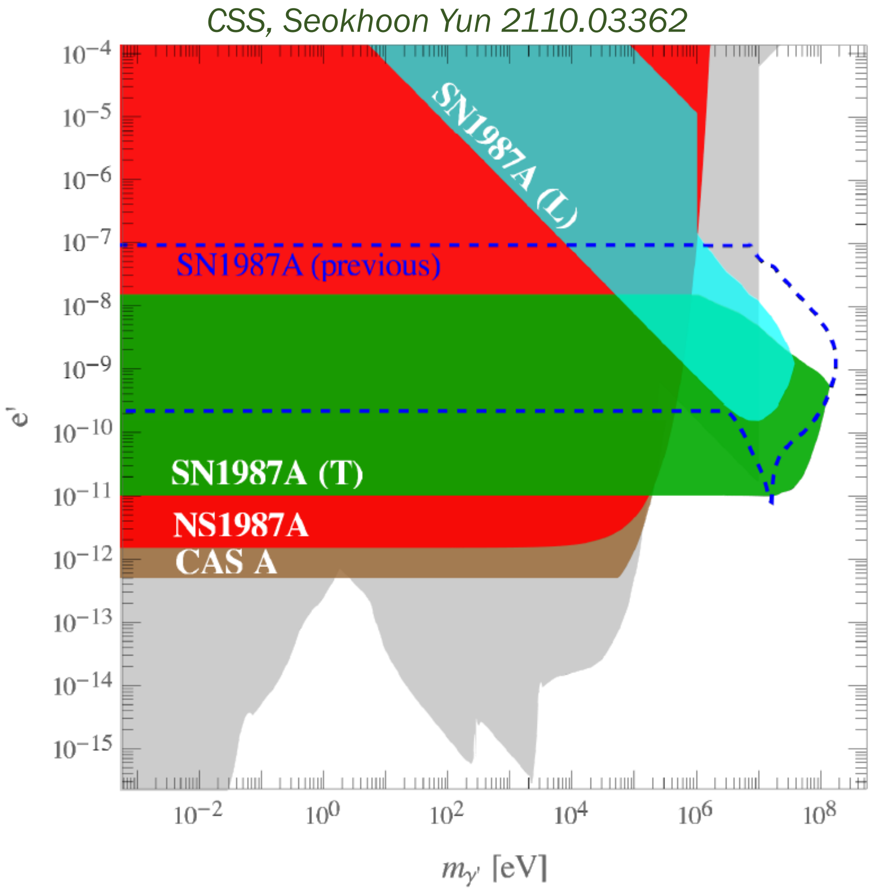


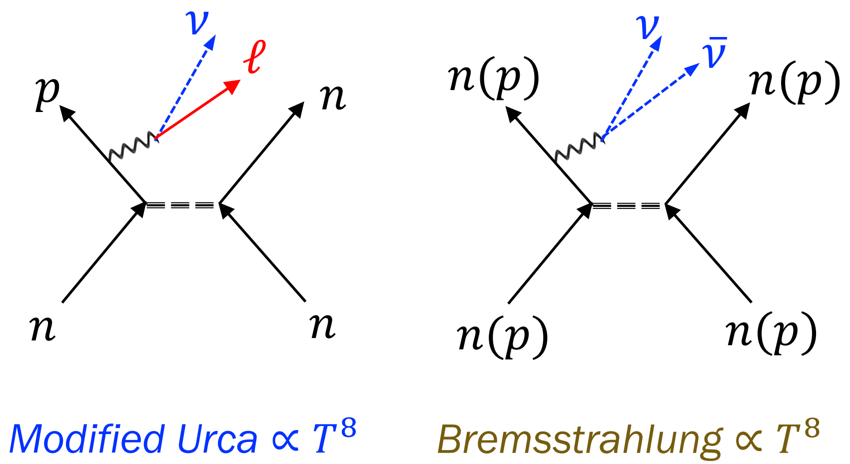


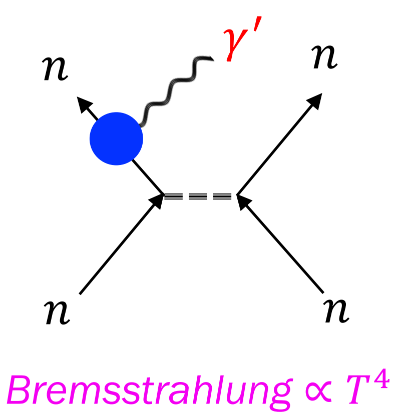
The previous works didn't consider in-medium effects for nucleons carefully
: no difference between $U(1)_B$ & $U(1)_{B\text{-}L}$

Constraints from SN1987A & NS1987A

Dark gauge boson Bremsstrahlung could become more important as the temperature of NS decreases (less sensitive to the temperature of NS compared to the neutrino emission in the limit of degenerate nucleons in the SN) before the superfluid transition







Discussion

We discuss a part of implications of supernova explosion for new particle scenarios beyond the SM, especially for new light bosons (dark gauge bosons and axion scenarios).

It is found that for quantitative calculation of new light particle emissions, the effects of "contact interactions", "spin dependent multipole radiations", "correct treatment of the effective charge of SM fermions in the medium" could be important depending on models.

Since stellar objects are quite complicated, we need a better understanding of nuclear physics and low energy effective theory to get more concrete predictions for given parameter space of the model.

What are the further implications of SN and NS for new physics beyond the standard model?