Cooling of young neutron stars and dark gauge bosons

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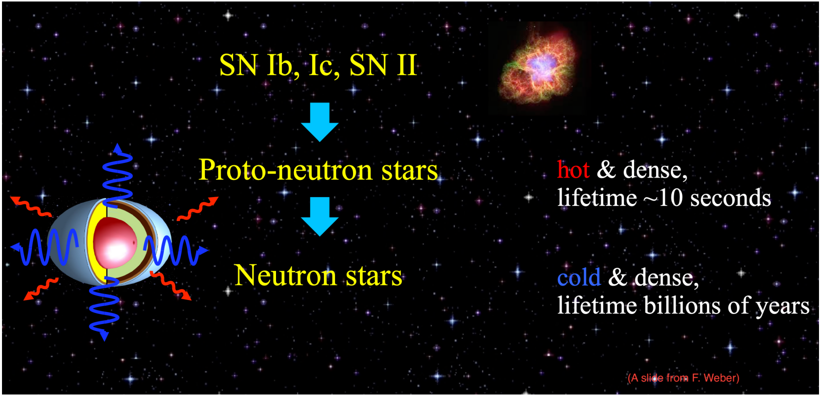
Work done with Seokhoon Yun and Chang Sub Shin

arXiv:2012.05427

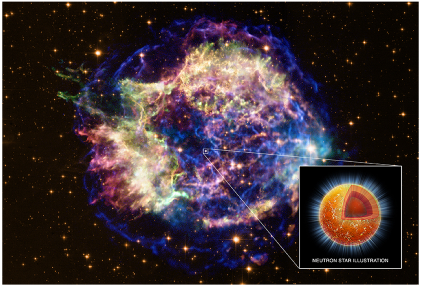
What is neutron star?

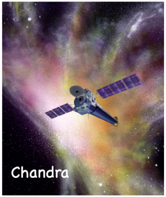
- Neutron star appears as a remnant of supernova explosion



Two young neutron stars: (1) Cas-A

Cas A Neutron Star





images from Chandra's webpage

- In 1999, Chandra found a point source at the center of Cas A.
- X-ray spectrum is consistent with a thermal emission of Neutron Star with a carbon atmosphere, mass M = (1.4±0.3) Msun, and radius R = (11–13) km.

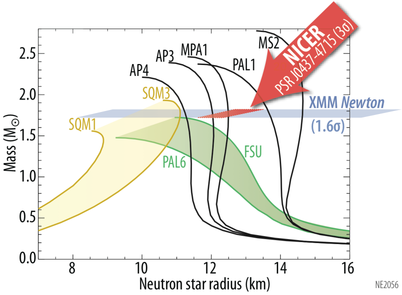
[W.C.G.Ho, C.O.Heinke, '09], [W.C.G.Ho, K.G.Elshamouty, C.O.Heinke, A.Y.Potekhin, '14].

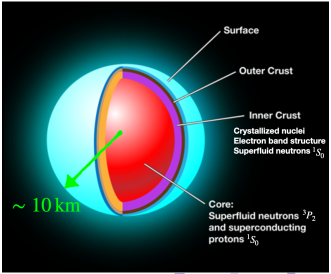
- and,.....

(A slide from Hamaguchi 2019)

Standard cooling scenario of NS

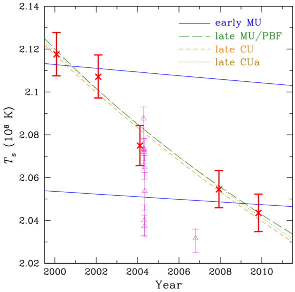
- Inside NS nucleons and electrons are in chemical equilibrium: $n \to p + e^- + \bar{\nu}_e \leftrightarrow p + e^- \to n + \nu_e$
- However neutrinos are not in thermal equilibrium and escape NS, taking energy away by Direct Urca till $T \sim 10^9\ K$.
- Then the modified Urca (MU) takes over till $6 \times 10^5\ K$.

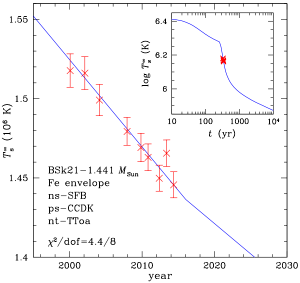




Rapid cooling of Cas-A

- The surface temperature has decreased $\sim 4\%$ for 15 years.
- The rapid cooling might be due to the superfluidity in the core. (Heinke-Ho 2010; Ho et al 2015; others)





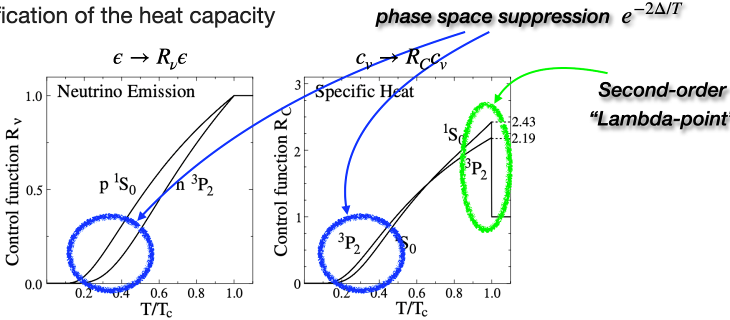
- If confirmed, it is the first evidence of superfluidity in NS, predicted by Migdal (1959) and Baym (1969).

Rapid cooling of Cas-A

(A talk silde by S. Yun)

Effect of pairing for NS cooling

1. Suppression of the emissivity
2. Modification of the heat capacity



3. Triggering of the "pair breaking and formation" (PBF) emission

Two young neutron stars: (2) NS1987a

- SN 1987A was a type II SN in the Large Magellanic Cloud.
- The remnant is consistent with NS of $R = 25\,\mathrm{km}$ and $T \sim 5 \times 10^6\,\mathrm{K}$. (Page et al. arXiv:2004.06078)

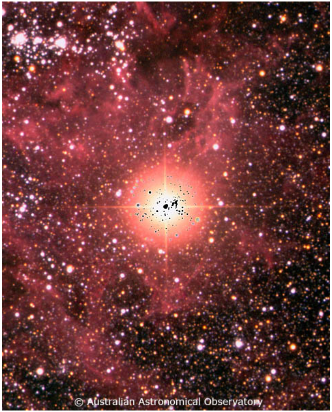


Figure: February 23, 1987

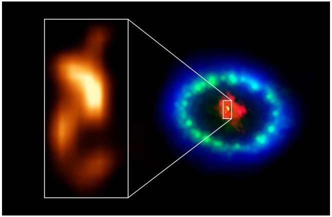


Figure: 2016

Dark gauge bosons from NS

- Light dark gauge bosons that couples weakly to nucleons might upset the ν cooling fit (DKH+Shin+S. Yun, 2020):

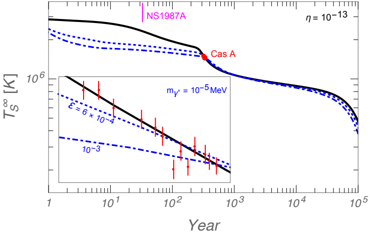


Figure: dark photons

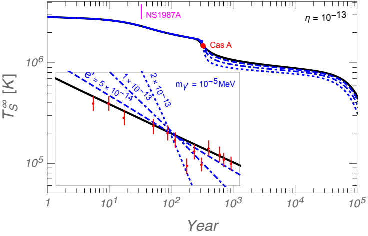


Figure: $U(1)_{\mathrm{B-L}}$ gauge bosons

- Constraints on axions from Cas-A are compatible with SN1987a bounds. (Hamaguchi et al 2018)

Dark gauge bosons from NS

- Global constraints on dark gauge bosons.

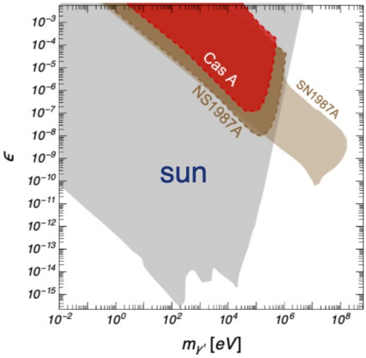


Figure: dark photons

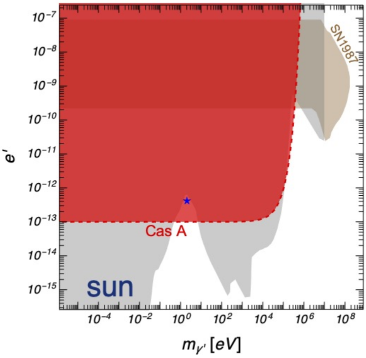


Figure: $U(1)_{\mathrm{B-L}}$ gauge bosons

Dark gauge bosons from NS

- The effective Lagrangian for dark gauge bosons:

$$\mathcal{L}_{\rm eff} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} - \frac{1}{4}F'_{\mu\nu}F'^{\mu\nu} - \frac{1}{2}m^2_{\gamma'}A'_\mu A'^\mu + \frac{\varepsilon}{2}F_{\mu\nu}F'^{\mu\nu} + eA_\mu J^\mu_{\rm EM} + e'A'_\mu J'^\mu \,,$$

- Photons have medium effects:

$$\Pi_{\rm T} = \omega_{\rm P}^2\left[1 + \frac{1}{2}G\left(v_*^2 k^2/\omega^2\right)\right] \equiv \pi_{\rm T},$$

$$\Pi_{\rm L} = \omega_{\rm P}^2\frac{k^2}{\omega^2}\frac{1 - G\left(v_*^2 k^2/\omega^2\right)}{1 - v_*^2 k^2/\omega^2} \equiv \frac{k^2}{\omega^2 - k^2}\pi_{\rm L}\,,$$

where $\omega_{\rm P}$ is the plasma frequency, v_* denotes the typical electron velocity in the medium, and $G(x)$ is given as

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

Dark gauge bosons from NS

- The effective couplings of dark gauge bosons in cold medium:

Model	$e^{\mathrm{e}}_{\mathrm{eff}}$	$e^{\mathrm{p}}_{\mathrm{eff}}$	$e^{\mathrm{n}}_{\mathrm{eff}}$
Dark photon	$\varepsilon e m^2_{\gamma'}/\pi_{\mathrm{T,L}}$	$-\varepsilon e m^2_{\gamma'}/\pi_{\mathrm{T,L}}$	-
$U(1)_{B-L}$	$e' m^2_{\gamma'}/\pi_{\mathrm{T,L}}$	$-e' m^2_{\gamma'}/\pi_{\mathrm{T,L}}$	e'

- Pair formation and pair breaking (PBF) by dark gauge bosons:

$$\psi + \psi \to X \quad \text{or} \quad \psi \to \psi_c + X\,.$$

Dark gauge bosons from NS

- The dark gauge boson emissivity from PBF:

$$Q_V^{\mathrm{PBF}} = 2\int \frac{\mathrm{d}^3\vec{k}}{2\omega(2\pi)^3}\mathrm{d}W_{i\to f}\,\omega f_F\left(\frac{\epsilon_p}{T}\right) f_F\left(\frac{\epsilon_{p'}}{T}\right)$$

with the transition rate

$$\mathrm{d}W_{i\to f} = \frac{\mathrm{d}^3\vec{p}}{(2\pi)^3}\frac{\mathrm{d}^3\vec{p}'}{(2\pi)^3}\,|M|^2\times(2\pi)^3\delta(\epsilon_p+\epsilon_{p'}-\omega)\delta^3(\vec{p}+\vec{p}'-\vec{k})$$

Dark gauge bosons from NS

- The emissivity in the HDL approximation:

$$Q_{\gamma',\mathrm{L}}^{\mathrm{p}^1S_0} \simeq g'^2 m_{\mathrm{p}}^* |\vec{p}_{F,\mathrm{p}}| T^3 \left(\frac{m_{\gamma'}^6}{\pi_{\mathrm{L}}^2 T^2} \right) \left(\frac{8 v_{F,\mathrm{p}}^4 F_3 \left(z_{\mathrm{p}^1S_0} \right)}{9\,\pi^3} \right),$$

- For $U(1)_{\mathrm{B-L}}$ gauge bosons

$$Q_{B-L}^{\mathrm{n}^3P_2} \simeq e'^2 m_{\mathrm{n}}^* |\vec{p}_{F,\mathrm{n}}| T^3 \left(\frac{4 v_{F,\mathrm{n}}^4 F_1 \left(z_{\mathrm{n}^3P_2} \right)}{15\pi^4} \right),$$

- From the phase space integration

$$F_n(z_i) = \int \frac{\mathrm{d}\Omega}{4\pi} \int_1^\infty \mathrm{d}y \, \frac{z_i^{n+2} y^n}{\sqrt{y^2-1}} f_F(z_i y)^2$$

with $z_i = \Delta_i / T$.

Dark gauge bosons from NS

- In the crust the bremsstrahlung emission is dominant and comparable:

$$Q_{\gamma'}^{\mathrm{eZ}} \simeq g'^2 |\vec{p}_{F,\mathrm{e}}| T^4 \left(\frac{m_{\gamma'}^6}{16\pi^4 T^2 \pi_L^2} \right) \sum_{\vec{K}} G\left(v_\parallel, t\right)$$

where G is the lattice function.

Dark gauge bosons from NS

- Core and crust, each channel contributions (DKH+Shin+S. Yun, 2020):

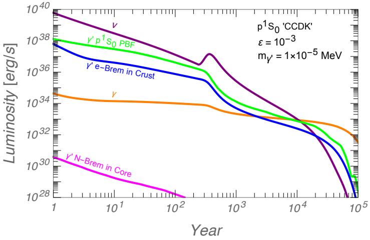


Figure: dark photons

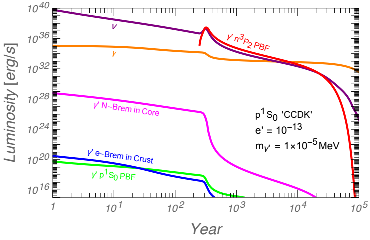


Figure: $U(1)_{\mathrm{B-L}}$ gauge bosons

Conclusions

- Light dark gauge bosons do have an interesting contraints from the rapid cooling of Cas-A:
- When $m < \mathcal{O}(0.1)\,\mathrm{MeV}$, we find for the dark photons

$$\varepsilon m_{\gamma'} < 1.5 \times 10^{-8}\,\mathrm{MeV}$$

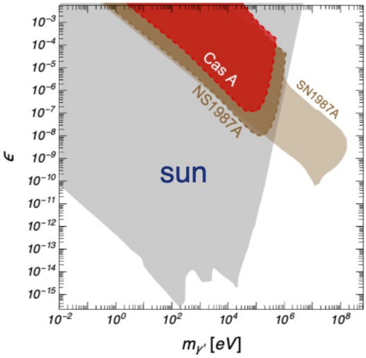
- For the $U(1)_{B-L}$ gauge boson of mass $< \mathcal{O}(0.1)\,\mathrm{MeV}$ its couplings should be

$$e' < 10^{-13}$$

- Our fitting with Cas-A is consistent with another young neutron star, NS1987.

Conclusions

- Constraints on dark gauge bosons from Cas-A



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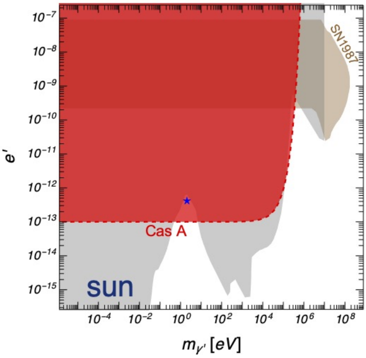

Figure: $U(1)_{\mathrm{B-L}}$ gauge bosons