Neutron stars as window on dark sectors

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D. McKeen, MP, N. Raj, 2105.09951 (NS heating constraints on mirror sector)

Y. Ema, R. McGehee, MP, A. Ray, 2405.18472 (DM destroying baryons, NS constraints)

MP and S. Roychowdhury, in preparation (NS constraints on freeze-in dark matter)

Y. Liu, Z. Liu, MP, S. Reddy, in preparation (Asymmetric capture of DM in NS)

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Plan

1. *Introduction*. Neutron stars as a unique probe of dark sectors. *Neutron stars as a calorimeter. Neutron stars as a [broken] weight scale.*
2. A new twist of NS→BH story. Asymmetric capture of symmetric DM
3. Neutron portal: a window into interesting phenomenology. Select cosmological bounds. Neutron star bounds on dark/mirror neutrons and neutron portal.
4. Dark matter with baryon number violation and chain reaction in neutron stars.
5. *Freeze-in dark matter in neutron stars. Constraints on neutrino-mediated models.*
6. Conclusions.

Dark Sectors

Typical BSM model-independent approach is to include all possible BSM operators once very heavy new physics is integrated out *plus all possible light states explicitly*

$L_{SM+BSM} = - m_H^2 \, (H^{+}_{SM} H_{SM})$ + all dim 4 terms ($A_{SM}, \ \psi_{SM}, \ H_{SM}$) +

(W.coeff. $/\Lambda^2$) × Dim 6 etc ($A_{SM}, \ \psi_{SM}, \ H_{SM}$) + …

all lowest dimension portals ($A_{SM}, \ \psi_{SM}, \ H, \ A_{DS}, \ \psi_{DS}, \ H_{DS}$) × portal couplings

+ dark sector interactions ($A_{DS}, \ \psi_{DS}, \ H_{DS}$)

SM = Standard Model

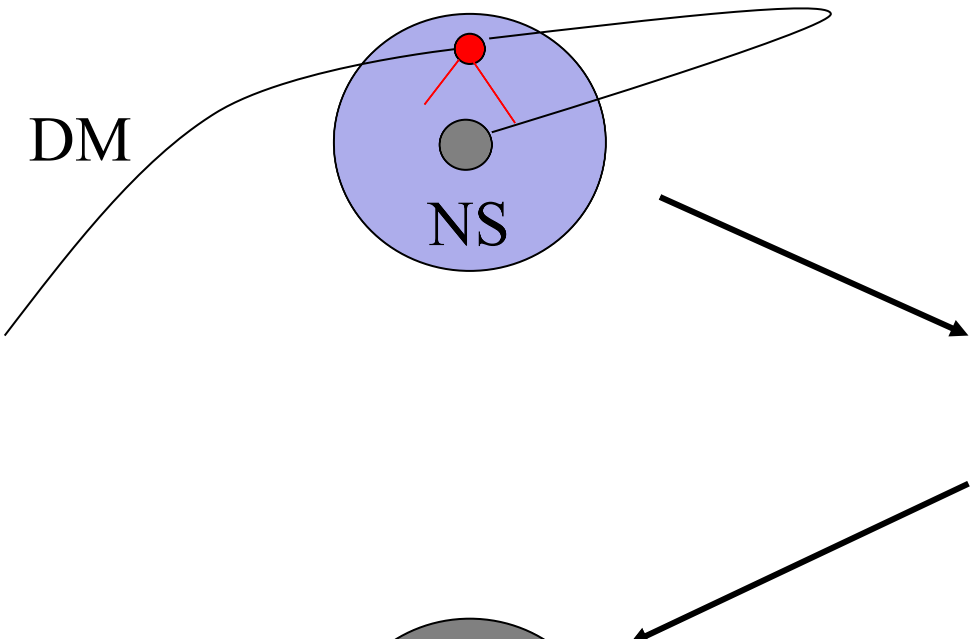
DS – Dark Sector

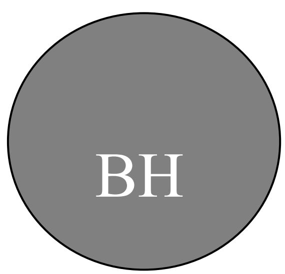
Salient properties of NS relevant for BSM searches

- Born in initially very violent (T ~ 30-50 MeV), and very long (t ~ 10 sec) explosions. Source ν fluxes!
- Due to high density provide a very efficient gravitational potential "trap". (Escape kinetic energy ~ 50% of rest energy)
- Provide a sensitive mass-radius relations and a cooling rate that can be disrupted by BSM. *Can be turned into a BH my DM*.
- Contain very high-density environment, and due to Pauli principle and nuclear medium properties having $E_{NS\ nucleons} > m_{N\ vacuum}$.
- After the neutrino cooling stage shuts down, *old NS cool down* to very small T, from Stefan-Boltzmann surface photon emission. The age and the temperature of coldest NS is observationally $t \sim 10^{15}$ sec; T < 3.5 eV. *Late time calorimeter*.
- Plethora of EM radiation at different stages of NS life.

Neutron Stars as a [broken] weight scale

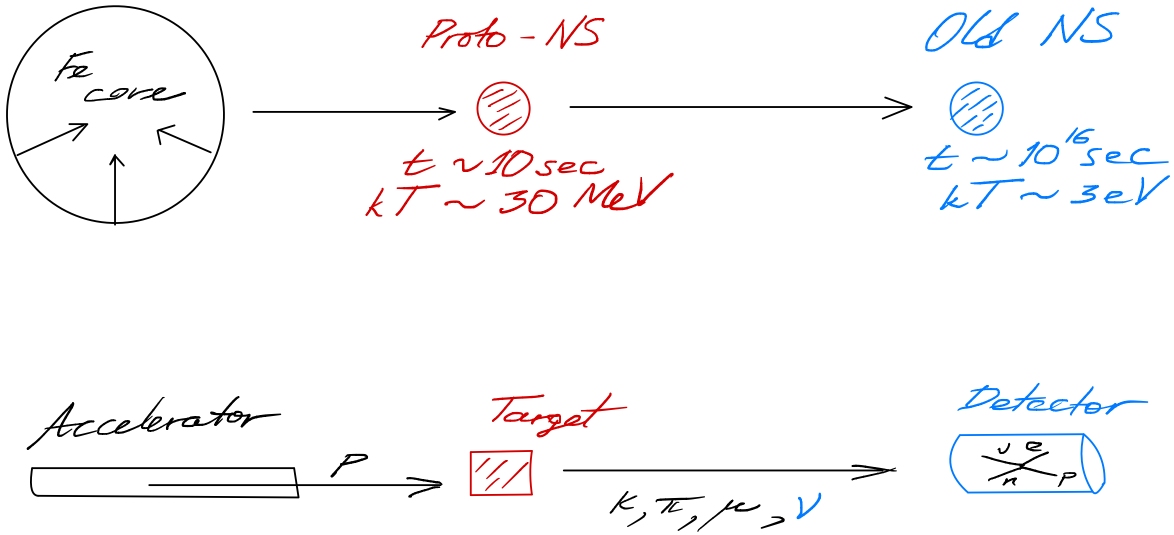
- Capture of external stable particles (e.g. DM) can turn NS into a BH

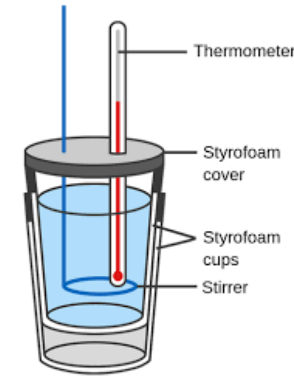




Extensive literature on particle-antiparticle asymmetric DM turning NS into a BH. Particle-antiparticle asymmetry is required to forbid the annihilation, enabling the DM build-up.

Neutron Star as a "calorimeter"/active target

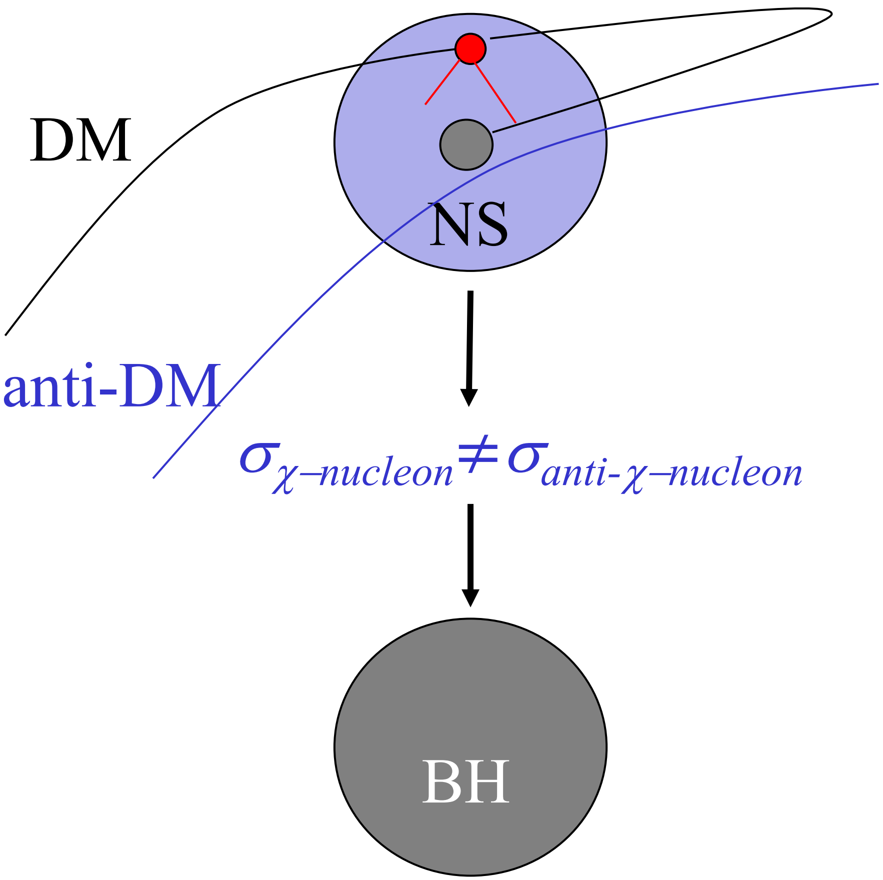




- Long-lived particles that can be produced inside a *young* NS, survive inside neutron star for ~10^{16} seconds, *and* generate heat by decay/annihilation, an *old* neutron star can be used as a type of calorimetric detector.
- Some particles inside NS can do *something strange*: e.g. *n* → *anti-n, n* → *mirror n*; DM + *n* → DM + 1 GeV of energy. NS can be considered as an *"active target"* and a *calorimeter*.
- Notice that current sensitivity is not enough to "sense" the capture and annihilation of DM.

Asymmetric WIMP capture

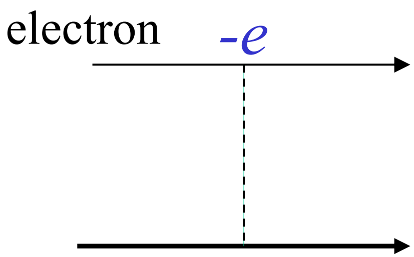
- Capture of external stable particles (e.g. DM) can turn NS into a BH without any need for preexisting DM χ–anti-χ asymmetry.

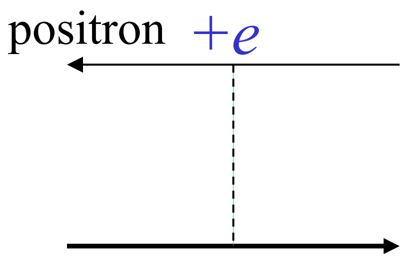


- Any neutron star is particle-antiparticle asymmetric, i.e. made of baryons and leptons
- It is very easy to have a DM-nucleon scattering cross section that has a *different size* for $\chi - n$ and anti-$\chi - n$.
- Therefore, even with no DM particle-anti-particle asymmetry, there is a possibility for χ–anti-χ asymmetric accumulation enabling NS→BH collapse.
- *To appear*, X. Liu, Z. Liu, MP, S. Reddy.

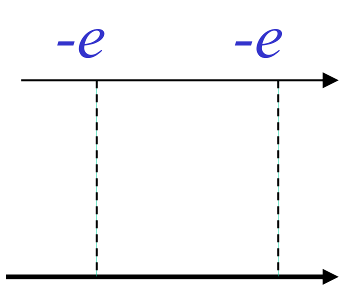
Illustration in QED

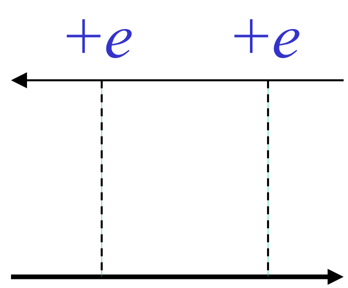
- Consider scattering of an electron and of a positron on a nucleus, in the 1st and 2nd order of perturbation theory/
- First order amplitudes are opposite, giving identical LO cross section, while the second order are the same. Therefore, the *interference* of the 1st and 2nd order gives unequal cross sections between particles and antiparticles.





$$A^{(1)}{}_{electron} = -\,A^{(1)}{}_{positron}$$





$$A^{(2)}{}_{electron} = A^{(2)}{}_{positron}$$

$$Asymmetry = \frac{\sigma(electron)-\sigma(positron)}{\sigma(electron)+\sigma(positron)} = A^{(1)}{}_{electron}\,A^{(2)}{}_{electron} \,/\, (A^{(1)}{}_{electron}\,)^2$$

Criteria for asymmetric DM capture

1. Violation of DM charge conjugation C_χ: $\not{C}_\chi$.

2. Violation of the product of combined parity and C_χ: $\not{C_\chi P}_{combined}$
   (this condition takes care of the vanishing of the asymmetry under spin average of n and χ.)

- *Example:* $\mathcal{L} = G_S(\bar{\chi}\chi)(\bar{n}n) + G_V(\bar{\chi}\gamma_\mu\chi)(\bar{n}\gamma_\mu n)$

$$H_{\chi n} = (G_S + G_V)\delta^{(3)}(\mathbf{r}_n - \mathbf{r}_\chi); \quad H_{\bar{\chi}n} = (G_S - G_V)\delta^{(3)}(\mathbf{r}_n - \mathbf{r}_{\bar{\chi}})$$

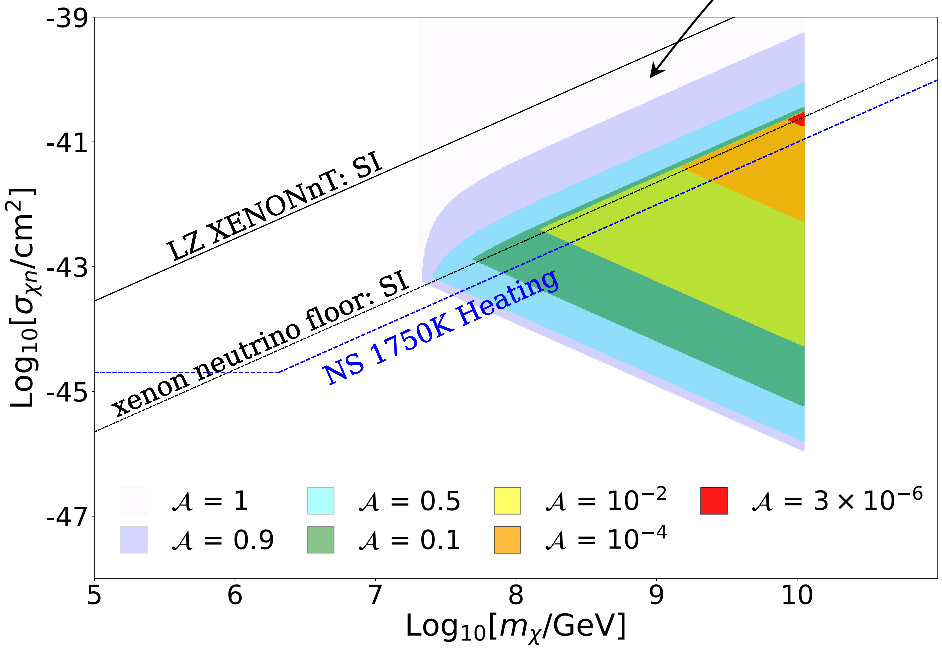
$$\sigma_{\chi n} = \frac{1}{\pi}(G_S + G_V)^2\mu^2_{\chi n}; \quad \sigma_{\bar{\chi}n} = \frac{1}{\pi}(G_S - G_V)^2\mu^2_{\bar{\chi}n}: \quad A = \frac{G_S G_V}{G_S^2 + G_V^2}$$

- *Another example:* $\mathcal{L} = G_T(\bar{\chi}\sigma_{\mu\nu}\chi)(\bar{n}\sigma_{\mu\nu}n) + G_A(\bar{\chi}\gamma_\mu\gamma_5\chi)(\bar{n}\gamma_\mu\gamma_5 n)$

$$H_{\chi n} = (G_A + G_T)(\vec{\sigma}_n\vec{\sigma}_\chi)\delta^{(3)}(\mathbf{r}_n - \mathbf{r}_\chi); \quad H_{\bar{\chi}n} = (G_A - G_T)(\vec{\sigma}_n\vec{\sigma}_{\bar{\chi}})\delta^{(3)}(\mathbf{r}_n - \mathbf{r}_{\bar{\chi}})$$

Sensitivity to asymmetry and cross section

- *Preliminary* sensitivity plot

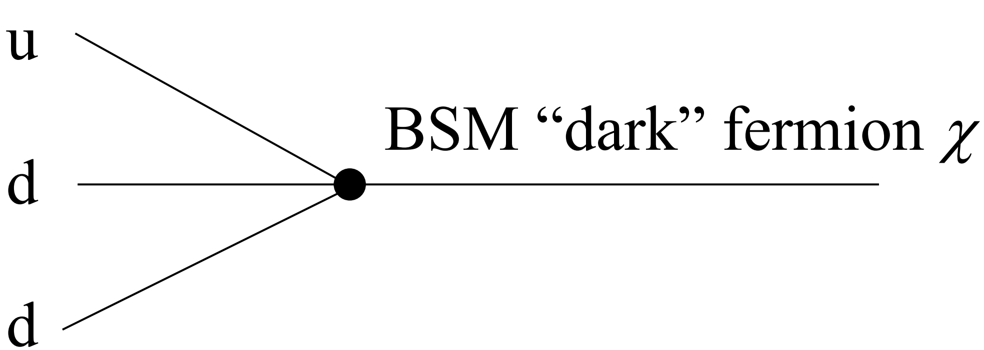


Here the cross sections are too high, and both DM and anti-DM get captured.

- *Inside colored regions NS is turned into a BH.*
- *We built some models that realize sizeable asymmetries.*
- *New sensitivity for a new [wider class of models].*
- *Outside of reach of other probes!*

The neutron portal

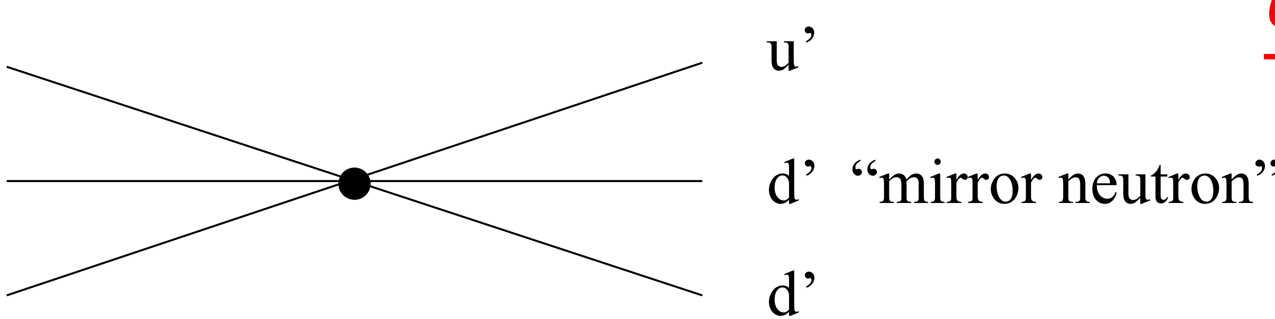
- Due to a composite nature of nucleons, this is a higher-dimensional operator



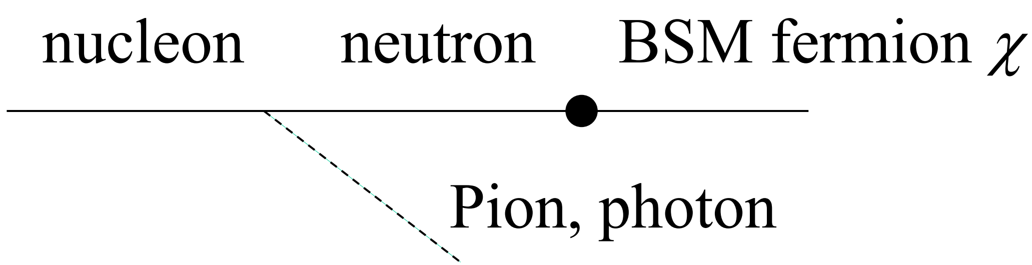
$$\frac{O^{dim=6}}{\Lambda^2}$$

Can be made UV complete above EW scale

$$\frac{O^{dim=9}}{\Lambda^5}$$



Strong constraints at $m_\chi << m_n$



- When $m_\chi << m_n$, strong constraints from proton (nucleon) decay apply.
- If $m_\chi << m_n$ it is not obvious if a model is constrained *at all*.
- When the mass splitting becomes smaller than O(1.8 MeV), $\Delta m = m_n - m_\chi < 1.8$ MeV, the nuclei are stable but neutrons are not. Expect modifications to the physics of free neutrons.
- When the mass splitting is sub-eV, i.e. χ is a mirror neutron, quantum oscillations are expected.
- Investigate the parameter space, identify most interesting physics!

Simplest low-energy model

- A tantalizing simple model consists of one dark fermion χ.

$$\mathcal{L} = \bar{n}\,(i\,\partial\!\!\!/ - m_n)\,n + \bar{\chi}\,(i\,\partial\!\!\!/ - m_\chi)\,\chi - \delta\,(\bar{n}\chi + \bar{\chi}n)$$

- Example $\Delta m = 10\ keV$, $\delta = 10^{-16} eV$, $\theta = \delta/\Delta m = 10^{-20}$ ← hard to exclude
- If we want to "influence" neutron lifetime, but have no other dramatic consequences, m_χ has to be in a narrow ~ 1.8 MeV range.

$$\mathrm{Br}_{n\to\chi\gamma} \simeq 0.02\left(\frac{\theta}{10^{-9}}\right)^2\left(\frac{\Delta m}{\mathrm{MeV}}\right)^3$$

- Roughly 1% Br is interesting for the neutron lifetime controversy
- Astrophysics provide strong constraints on this possibility (McKeen, Nelson, Reddy, Zhou; Baym et al, Motta et al, 2018). Mass-radius relation imply some mechanism that generates extra pressure in the dark sector → self interaction etc (e.g. Cline, Cornell 2018)

Possibility to alter the neutron lifetime

Grinstein, Fornal 2018; Berezhiani 2018 + earlier papers

Speculates whether there is an extra decay channels for neutrons

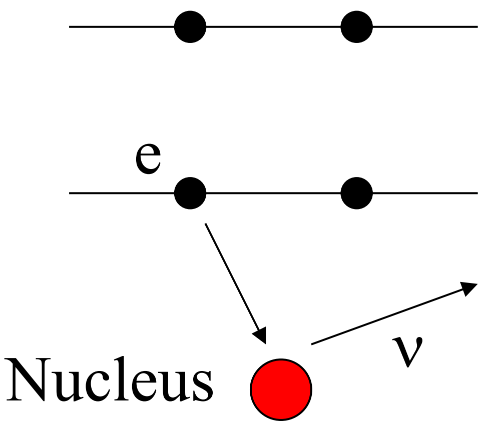
$$\tau_n^{\rm bottle} = 879.6 \pm 0.6 \, {\rm s} \; .$$

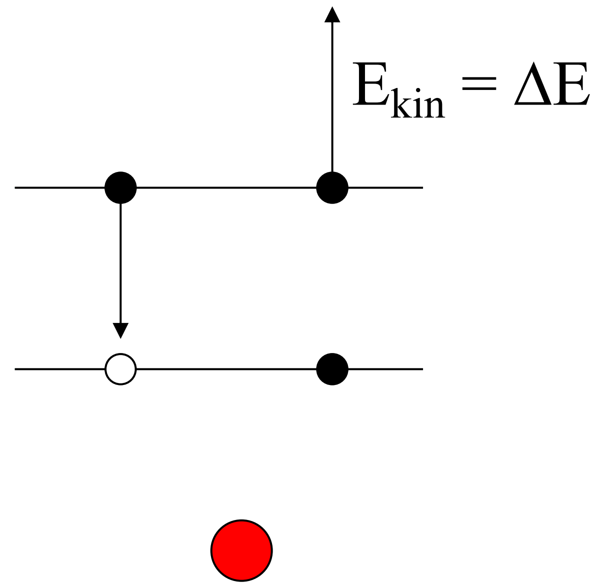
$$\tau_n^{\rm beam} = 888.0 \pm 2.0 \, {\rm s} \; .$$

Beam experiments register protons in the final state. Will miss an "exotic" decay mode. This is why bottle experiments see shorter lifetime (!)

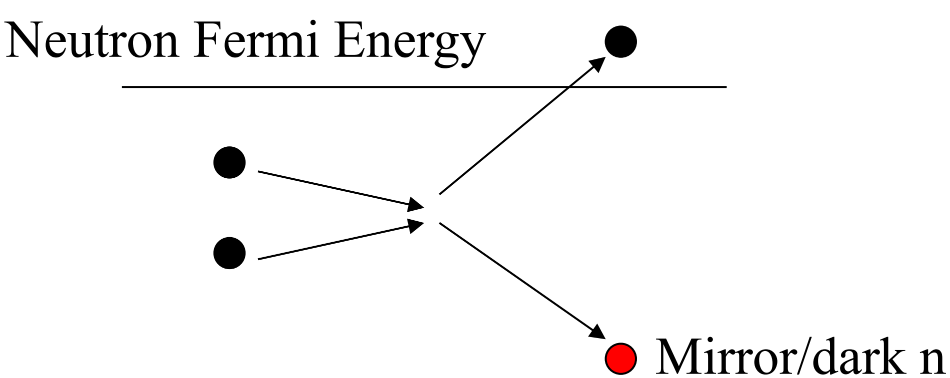
Energy generation mechanism in NS

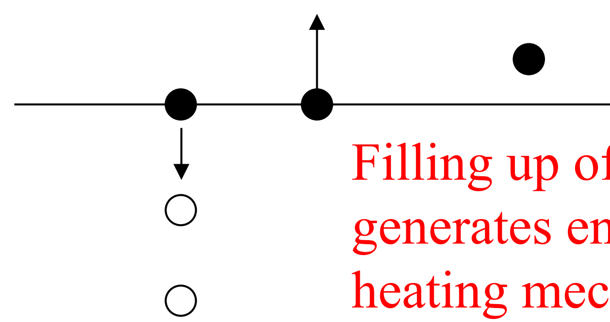
Electron capture in atoms + Auger effect





n → n' transfer in neutron stars

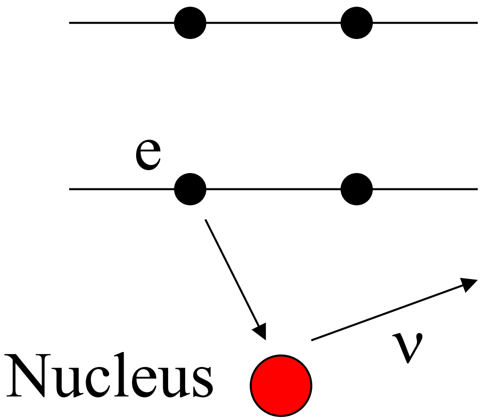


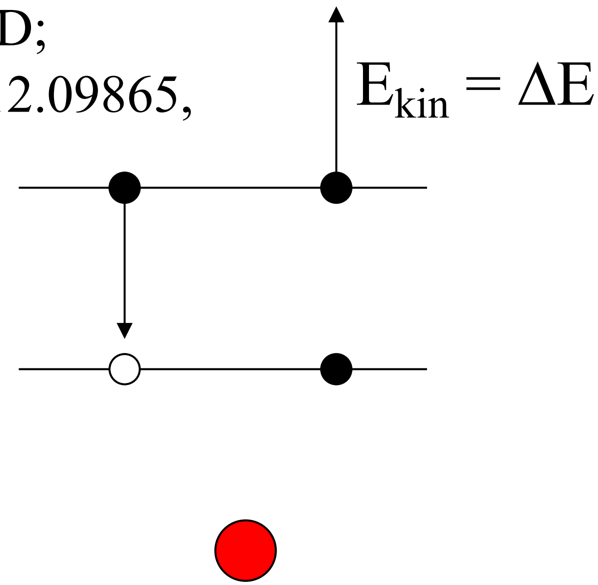


Filling up of holes generates energy = heating mechanism for neutron stars

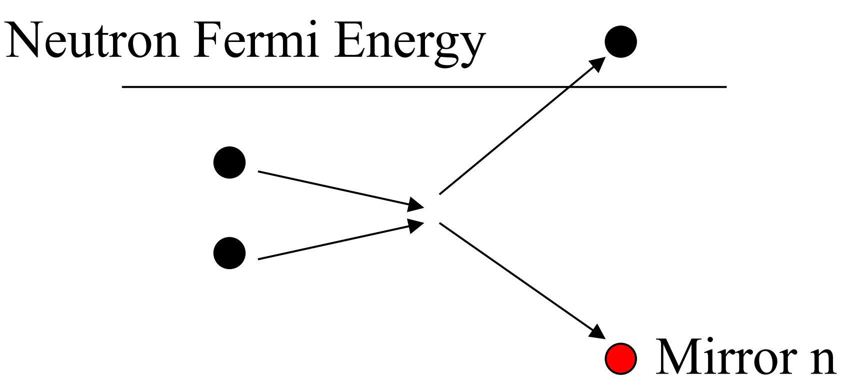
Energy generation mechanism in NS

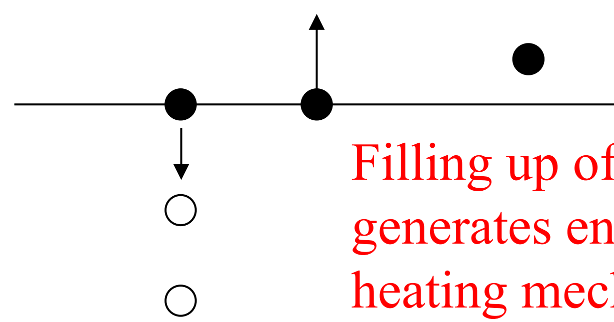
This interesting mechanism of heat generation was pointed out in
Goldman, Mohapatra, Nussinov, 19011.07077, PRD;
Berezhiani et al. 22012.15233; McKeen, MP, Raj, 2012.09865, 2105.09951





n → n' transfer in neutron stars





Filling up of holes generates energy = heating mechanism for neutron stars

Mirror neutrons and old neutron stars

Taking a simply Hamiltonian as before,

$$H = \begin{pmatrix} m_n + \Delta E & \epsilon_{nn'} \\ \epsilon_{nn'} & m_{n'} \end{pmatrix}$$

we evaluate n→n' conversion. (ΔE comes from matter effects in NS). Taking into account nn->nn' and np ->n'p processes, while using

$$\sigma_{nn\to nn} \simeq \frac{1}{4} \times \frac{16\pi}{m_N^2 v^2} \sin^2 \delta_S,$$
$$\sigma_{np\to np} \simeq \frac{1}{4} \times \frac{16\pi}{m_N^2 v^2} (\sin^2 \delta_S + 3 \sin^2 \delta_T)$$

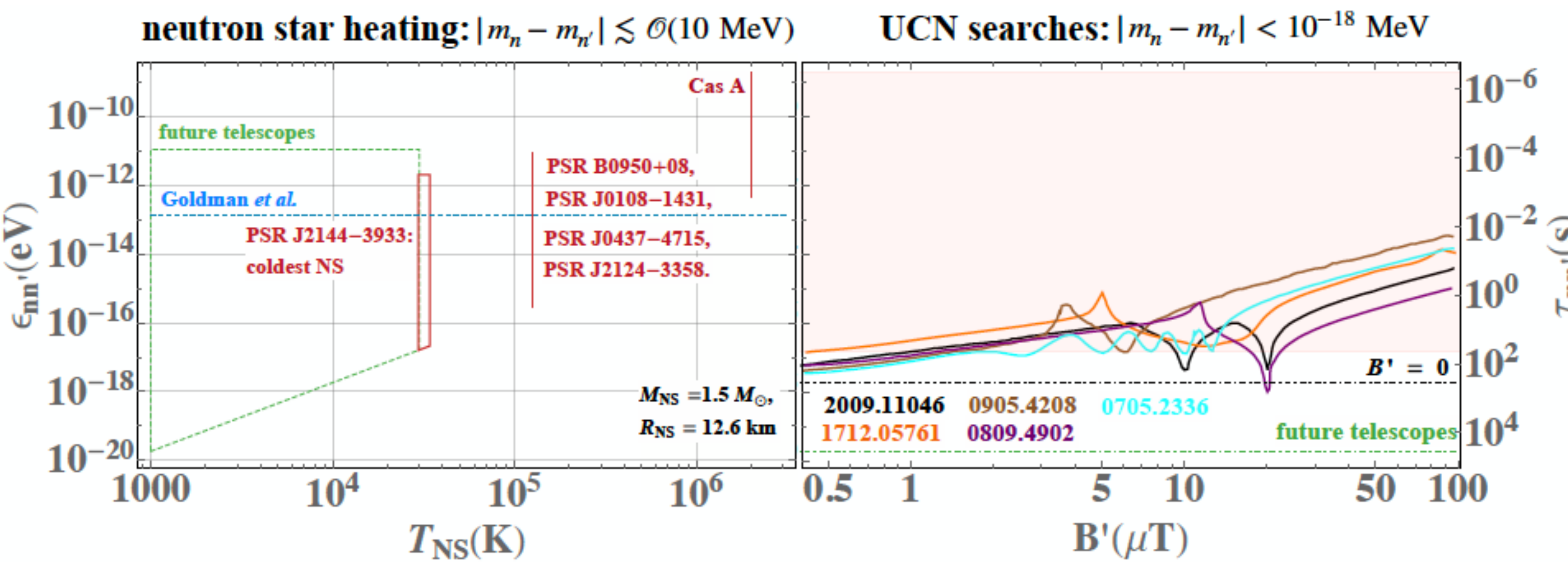
as input, we derive numerically the heating rate that scales as

$$\Gamma_{n'} = \frac{1}{1.2 \times 10^{11}\ \mathrm{yr}} \left(\frac{\epsilon_{nn'}}{10^{-17}\ \mathrm{eV}}\right)^2 \left(\frac{n_{\mathrm{nuc}}}{0.3\ \mathrm{fm}^{-3}}\right)$$

In the oldest NS, when surface emission from photons dominates, additional heating mechanism generates *minimum* temperature

$$T_{\min}^4\, 4\pi R^2 > \mathrm{O}(1)\ \text{number} \times \Gamma_{n'} * E_F.$$

Mirror neutrons and old neutron stars

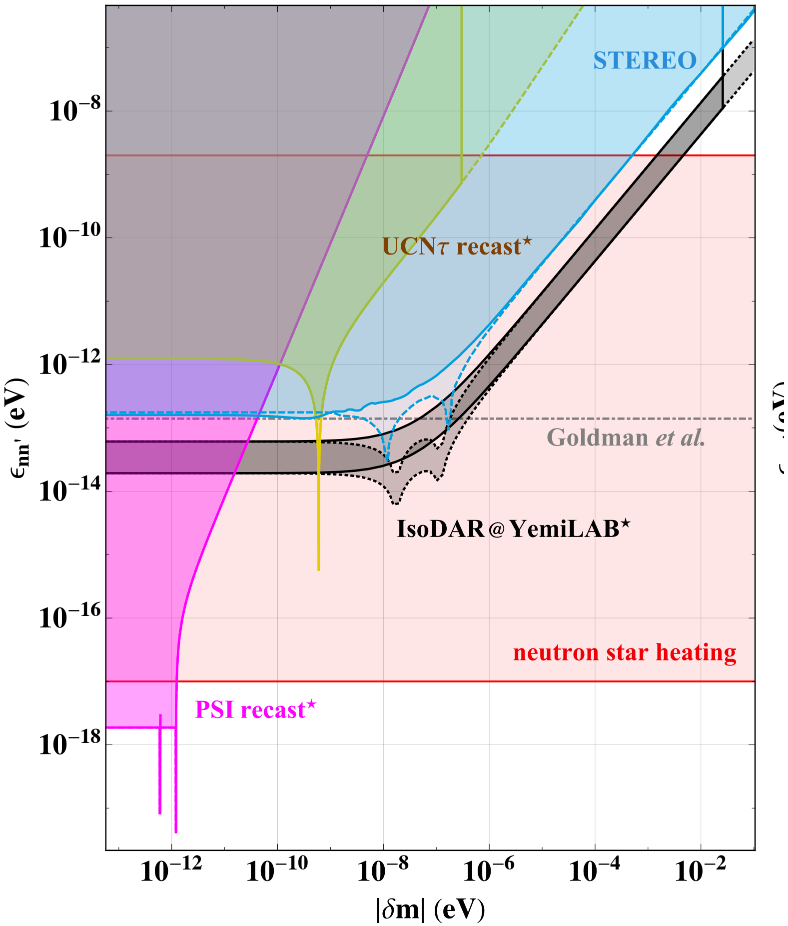


From McKeen, MP, Raj, 2105.09951

- The coldest pulsar, J2144-3933, T < 40,000K implies the bound for the off-diagonal matrix element $\varepsilon_{nn'} = \delta < 10^{-17}$ eV.
- Above 10^{-9} eV there are no limits from NS heating – happens too fast.
- Very competitive with lab limits. Can further improve if colder T_{NS} found

Constraints on mirror neutrons

From Hostert, McKeen, MP, Raj, 2023



$$H = \begin{pmatrix} m_n + \Delta E & \epsilon_{nn'} \\ \epsilon_{nn'} & m_n + \delta m \end{pmatrix}$$

ΔE – matter induced potential

$\varepsilon_{nn'}$ – mixing matrix element

δm – diagonal mass splitting

NS heating provides the most robust constraint over vast parameter space, independent of diagonal mass splitting

Parameter point I showed earlier is excluded

Disclaimer

- Late-time heating of Neutron Stars is good at setting limits on exotic physics, if $T_{SM+New\ Physics} > T_{observed}$.

- At this point coldest NS cannot be used as a “discovery”. One would need considerable statistical samples of coldest NS to be able to e.g. discover “a floor” to the lowest temperature and claim non-standard heating mechanisms.

DM violating baryon number

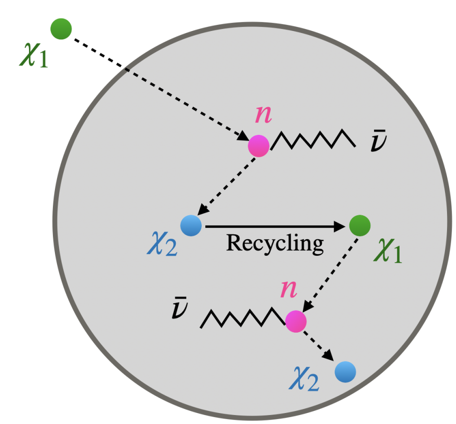
- Particle Dark Matter could break baryon number. Typical (e.g. Xenon etc) experiments limit the elastic scattering on nuclei.

- One can use neutrino detectors (Super-K, SNO, etc) to set constraints on baryon-number-violating (BNV) scattering of dark matter:

$$\chi + n \to \chi + \bar{\nu} \quad \text{and/or} \quad \chi + p \to \chi + e^{+}$$

- In neutron stars, where DM can accumulate, the BNV scattering can repeat itself, generating chain destruction of baryons:

- Loops of DM will lead to baryon decays ← needs further studies



NS star

A representative DM model

$$\mathcal{L} = \mathcal{L}_1 + \mathcal{L}_2 + \mathcal{L}_3,$$

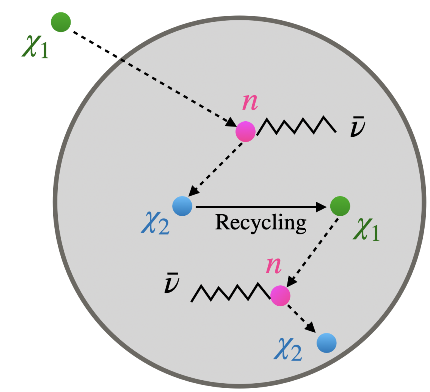
where at the effective field theory level we have

BNV parameter

$$\mathcal{L}_1 = G_{\rm BNV}\bar{\chi}_2\gamma_\mu\chi_1 \times \left(\overline{e^+}\gamma^\mu p + \bar{\nu}\gamma^\mu n\right) + ({\rm h.c.}),$$

$$\mathcal{L}_2 = G_\chi\left(\bar{\chi}_1\gamma_\mu\chi_1 + \bar{\chi}_2\gamma_\mu\chi_2\right)\left(\bar{p}\gamma^\mu p + \bar{n}\gamma^\mu n\right),$$

$$\mathcal{L}_3 = -\frac{\Delta m_\chi}{2}\bar{\chi}_2\chi_1 + ({\rm h.c.}).$$



Capture of χ generates a BNV cycle in the star

Loop-induced baron number is suppressed

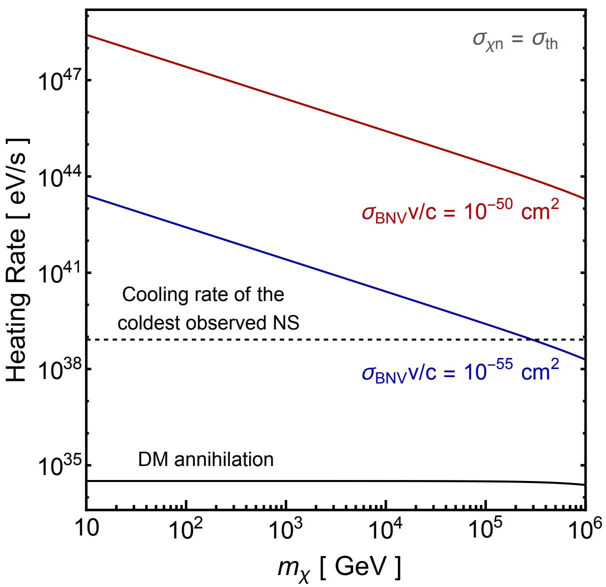
$$v\sigma(nn \to n\bar{\nu}) = \frac{3^2}{2^{15}\pi^5}\left(\frac{\Delta m_\chi}{m_\chi}\right)^2 G_{\rm BNV}^2 G_\chi^2 m_n^6.$$

$$\frac{\Delta m_\chi}{m_\chi} \lesssim 10^{-7}\left(\frac{10^{-50}\,{\rm cm}^2}{\sigma_{\rm BNV}v/c}\right)^{1/2}\left(\frac{10^{-45}\,{\rm cm}^2}{\sigma_{\chi n}}\right)^{1/2}.$$

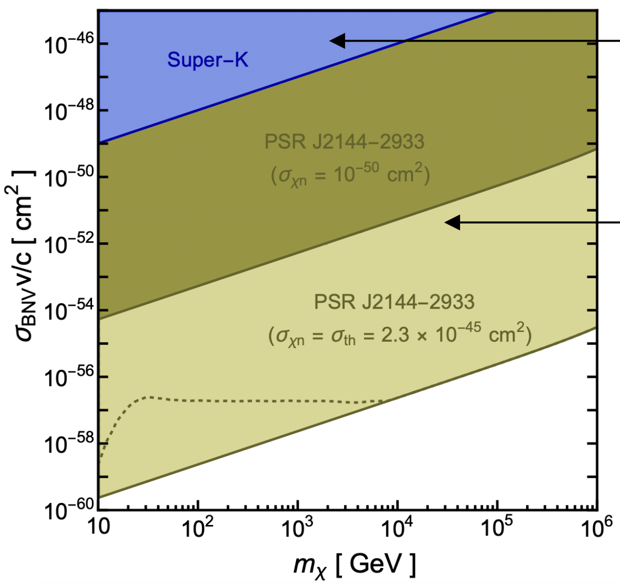
Loop-induced processes are under control.

Catalytic destruction of baryons in NS

Heating rate in stars:



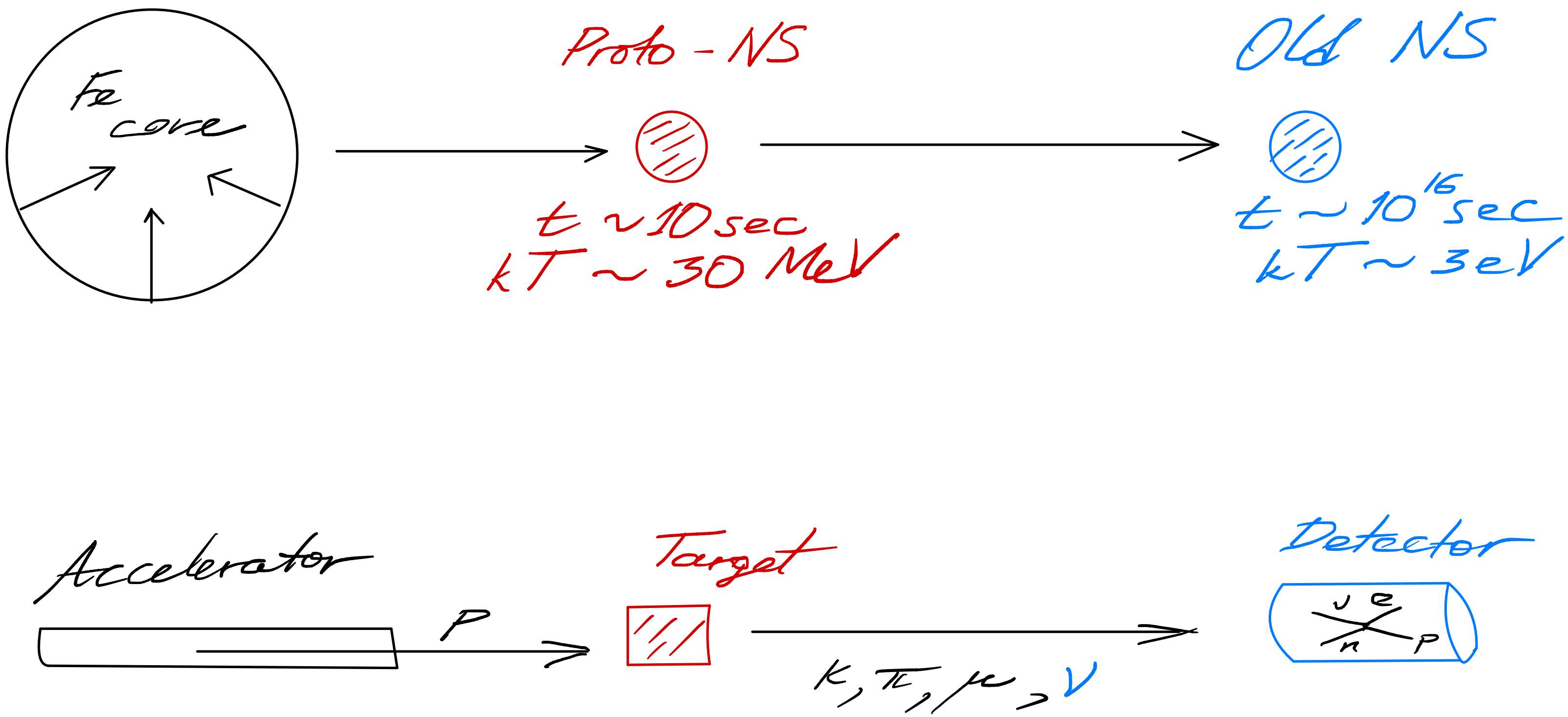
Heating rates from BNV can be much larger than from the DM self-annihilation



Constraints from SK on DM-induced BNV

Constraints on neutron star heating from BNV dark matter (for two representative values of cross section)

Neutron Star as a "astrophysical beam dump"

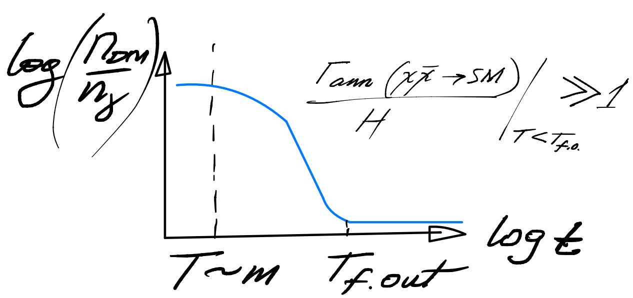


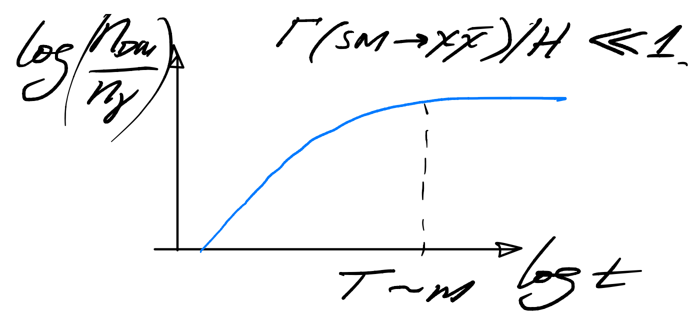
If there are long-lived particles that can be produced inside a *young* NS, survive inside neutron star for ~10^{16} seconds, *and* generate heat by decay/annihilation, an *old* neutron star can be used as a type of calorimetric detector.

Freeze-in and freeze-out dark matter

Two popular scenarios for particle dark matter. At some early cosmological epoch, T >> DM mass, the abundance of these particles relative to a species of SM (e.g. photons) was

- *Abundant:* Sizable interaction rates ensure thermal equilibrium, $N_{DM}/N_\gamma = 1$. Stability of particles on the scale $t_{Universe}$ is required. *Freeze-out* calculation gives the required annihilation cross section for DM -> SM of order ~ 1 pbn, which points towards weak scale. These are **WIMPs**. (asymmetric WIMPs are a variation.) *Residual annihilation continues post-freeze out (CMB or astro constraints apply, m_{DM}> 10 GeV)*





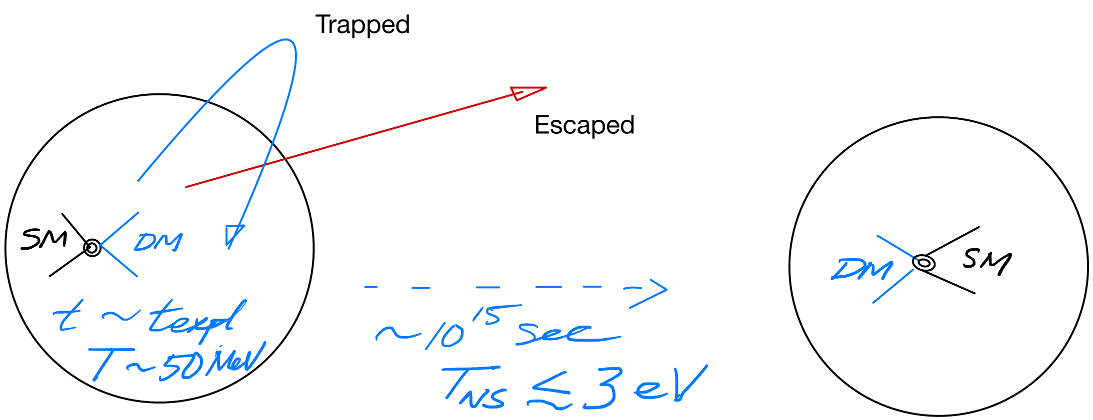
- *Very small:* Very tiny interaction rates (e.g. 10^{-10} couplings from WIMPs). Never in thermal equilibrium. Populated by thermal leakage of SM fields with sub-Hubble rate (*freeze-in*) or by decays of parent WIMPs.

If particles are stable, there is no residual cosmological annihilation (rates are small), but there is residual annihilation in neutron stars. MP and S. Roychowdhury.

Freeze-in dark matter in NS

- Strong constraints on MeV scale KK towers; Hannestad, Raffelt, 2004.
- Weak-scale (i.e. heavy) freeze-in dark matter is not constrained – never produced and hardly captured.
- O(1- 100 MeV) freeze in DM can be produced in SN explosion, and the reverse annihilation is delayed – can be a source of NS heating. Importantly, time scale for annihilation is much longer

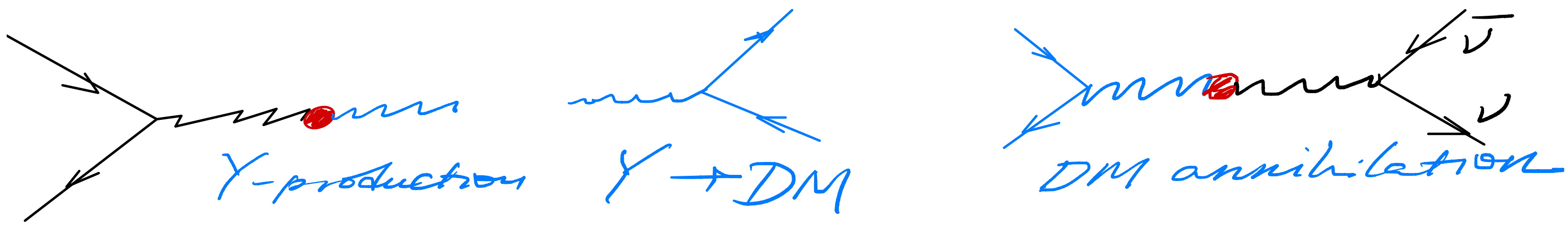
$$\Gamma_{prod} \sim n_{SM} \times \langle \sigma_{SM \to \chi\bar{\chi}} v \rangle \gg \Gamma_{ann} \sim n_{DM} \times \langle \sigma_{\chi\bar{\chi} \to SM} v \rangle$$



- *** O(100 MeV) bosonic DM (produced in-situ) can also turn neutron star into a BH.

Model example

$$
\begin{aligned}
\mathcal{L} &= \mathcal{L}_{L_\mu - L_\tau} + \mathcal{L}_{dark} + \mathcal{L}_{portal}, \\
\mathcal{L}_{L_\mu - L_\tau} &= \bar{L}_{(\mu)}\gamma_\alpha(i\partial_\alpha + g_X X_\alpha)L_{(\mu)} + \bar{L}_{(\tau)}\gamma_\alpha(i\partial_\alpha - g_X X_\alpha)L_{(\tau)} \\
\mathcal{L}_{dark} &= \bar{\chi}(\gamma_\alpha(i\partial_\alpha + g_Y Y_\alpha) - m_\chi)\chi \\
\mathcal{L}_{portal} &= \varepsilon \frac{1}{2} X_{\mu\nu} Y_{\mu\nu}
\end{aligned}
$$



$$
\begin{aligned}
\text{Production :} &\quad \nu\bar{\nu} \to Y(\text{on} - \text{shell}); \quad Y \to \chi\bar{\chi}; \quad \sigma \propto (g_X\varepsilon)^2 \\
\text{Self} - \text{thermalization :} &\quad \chi\bar{\chi} \to \chi\bar{\chi} \\
\text{Annihilation :} &\quad \chi\bar{\chi} \to Y(\text{off} - \text{shell}) \to \nu\bar{\nu}; \quad \sigma \propto (g_X\varepsilon)^2 \times g_Y^2
\end{aligned}
$$

Self-thermalization leads to partial evaporation of DM, and cooling of DM fluid. Annihilation to neutrinos inject energy to neutron star.

Constraints on the parameter space

Let us choose: $m_Y = 30\ MeV;\ m_\chi = 10\ MeV.$

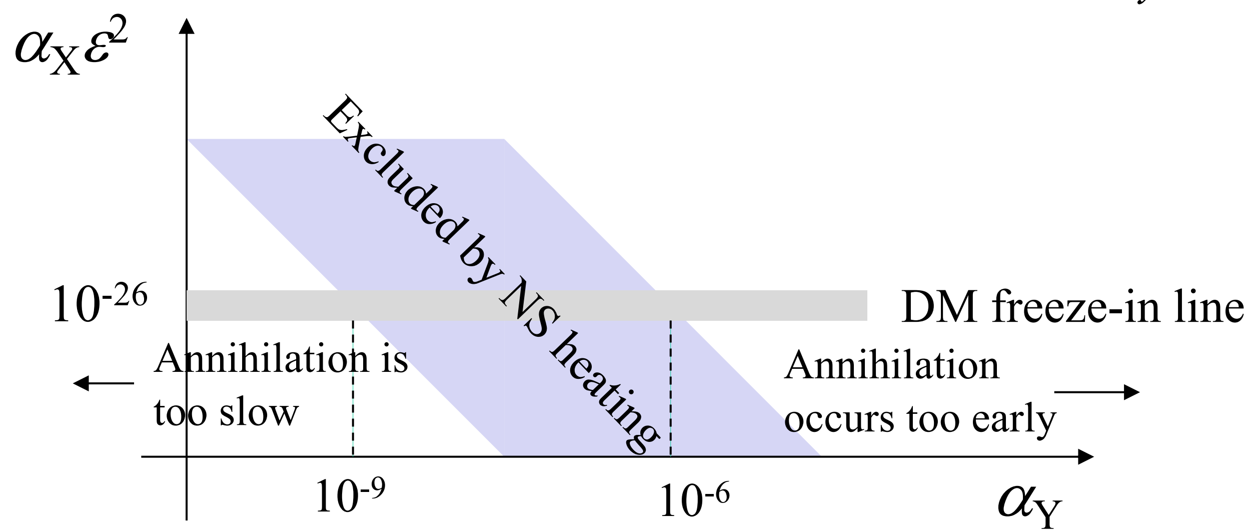
- Early Universe: Freeze-in abundance $\frac{n_{\chi+\bar{\chi}}}{s} \simeq \alpha_X \epsilon^2 \times \frac{30\,\mathrm{MeV}}{m_Y} \times 7.4 \times 10^{18}$

matches the DM abundance $\Omega_{\bar{\chi}+\chi} = \Omega_{\mathrm{DM}} \rightarrow \frac{n_{\chi+\bar{\chi}}}{s} \simeq 4.3 \times 10^{-8} \times \frac{10\,\mathrm{MeV}}{m_\chi}$ if $\alpha_X \varepsilon^2 = 10^{-26}$

- Since $t_{expl}/t_{Hubble} \sim 10^4$, abundance of SN freeze-in DM is larger than in the early Universe at the same temperature. $n_{DM} \sim 10^{-4}\ T_{SN}^3$.
- Annihilation back to neutrinos ($\Gamma \sim \alpha_Y \times \alpha_X \varepsilon^2$), and the heating of neutron star is delayed to parametrically ~ $10^9\ sec \times (\alpha_Y)^{-1}$.

Preliminary

The coupling constants and mass range probed by heating of old NS corresponds to DM-SM scattering cross section ~ $10^{-53}\ cm^2$.



Conclusions

1. Neutron stars provide a unique *calorimetric* way of probing new physics. *DM-induced NS→BH process is important even for symmetric DM, with asymmetric DM-nucleon cross section.*

1. *n→n'* conversion offers an interesting heating mechanism for old NS. Taking at face value the constraint of $T_{NS} < 40000$ K for the oldest pulsar results in a very restrictive bound for $\delta < 10^{-17}$ eV for mirror neutron models.

2. For some models, NS can limit baryon-number-violating interactions of DM better than any other probes, such as neutrino detectors.

3. NS provide *unique* probes of stable freeze-in DM in the mass range MeV - 100MeV. Initial SN production of DM leads to gravitationally trapped population. The late time annihilation is limited by the temperature of the coldest neutron stars.