TDLI-PKU BSM workshop 2022:
Electroweak lights the way (online)

$n - n'$ oscillation and Neutron star cooling

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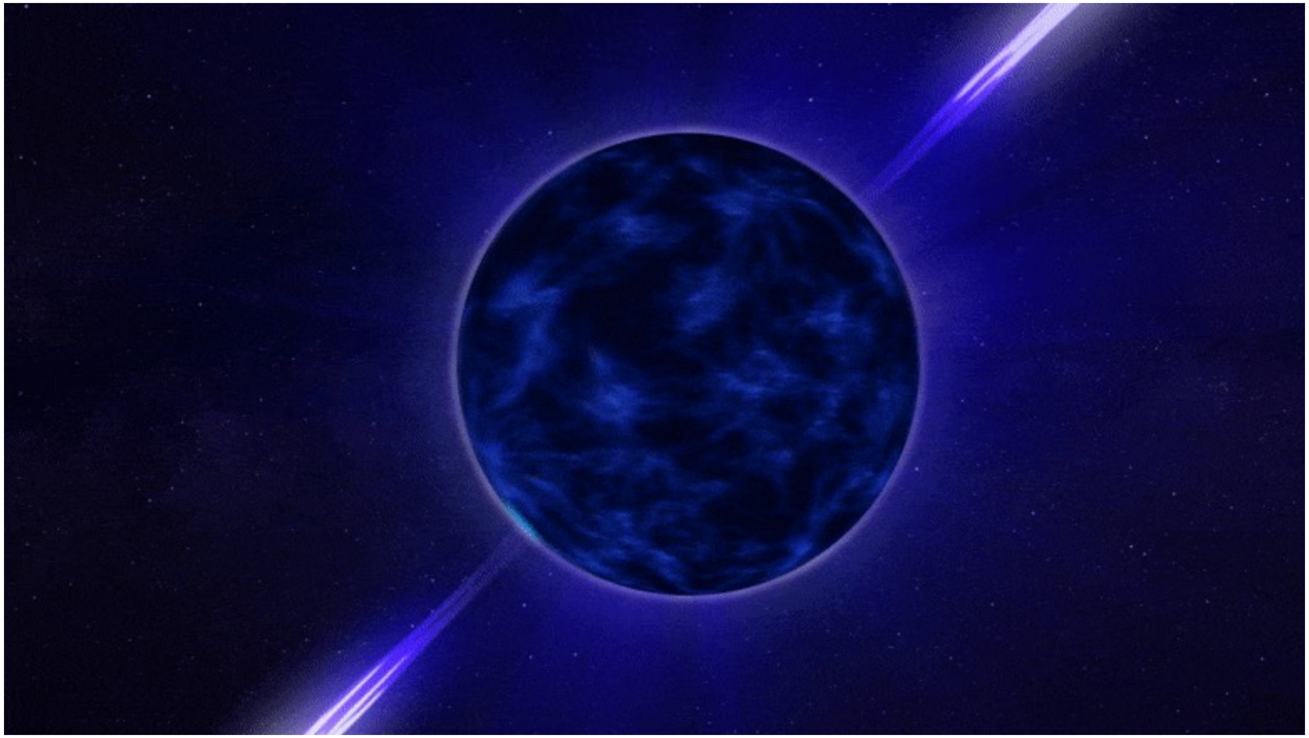
Based on work with Goldman, Mohapatra & Nussinov [2203.08473], accepted by PRL

Neutron star



Neutron star (pulsar in the figure)

- Astronomy
- GW
- Nuclear physics
- Particle physics
- ……

NS limits on BSM physics

- Axion/ALP
  Hook & Huang ’17;
  Huang, Johnson, Sagunski, Sakellariadou & Zhang ’18;
  Dietrich & Clough ’19;
  P. Harris, Fortin, Sinha & Alford ’20;
  Fiorillo & Iocco ’21;
  Fortin, Guo, Harris, Kim, Sinha & Sun ’21;
  Nurmi, Schiappacasse & Yanagida ‘21
- Dark gauge boson
  Croon, Nelson, Sun, Walker & Xianyu ’17;
  Dror, Laha & Opferkuch ’19;
  Diamond & Marques-Tavares ’21
- Dark Higgs
  Dev, Fortin, Harris, Sinha & YCZ ’21
- Lorentz violation
  LIGO, Virgo, Fermi-GBM & INTEGRAL ‘17
- Parity violation
  Alexander & Yunes ‘17
- Hubble constant
  LIGO, Virgo, 1M2H, Dark Energy Camera GW-E, DES, DLT40, Las Cumbres, VINROUGE, MASTER ‘17

NS limits on BSM physics

- DM

Goldman, Nussinov '89;
Kouvaris '07;
Bertone & Fairbairn '08;
de Lavallaz & Fairbairn '10;
Kouvaris & Tinyakov '10;
Brito, Cardoso, Okawa '15 PRL;
Cermeño, Pérez-García, Silk '17;
Bezares, Viganò & Palenzuela '19;
McKeen, Nelson, Reddy & Zhou '18 PRL
Kain '21;
Emma, Schianchi, Pannarale, Sagun & Dietrich '22
……

- $n - \bar{n}$ oscillation

Krishan & Sivaram '82;
Buccella, Gualdi & Orlandini '87;
Berryman, Gardner & Zakeri '22;
Arun '22

- $n - n'$ mixing

Goldman, Mohapatra & Nussinov '19;
Berezhiani, Biondi, Mannarelli & Tonelli '20
McKeen, Pospelov, Raj '21 PRL
Goldman, Mohapatra, Nussinov & YCZ '22 PRL

Mirror model

Parity violation in SM
→ mirror model

T. D. Lee, C.-N. Yang ’56;
Kobzarev, Okun, Pomeranchuk ’66;
Blinnikov, Khlopov ’83;
Foot, Lew, Volkas ‘91;
Hodges ’93;
Berezhiani, Mohapatra ‘95;
Berezhiani, Comelli, Villante ’01;
Ignatiev, Volkas ’03;
……

Mirror neutron $\boldsymbol{n}'$

SM particles				
u	c	t	γ	H
d	s	b	W	
ν_e	ν_μ	ν_τ	Z	
e	μ	τ	g	

mirror particles				
u'	c'	t'	γ'	H'
d'	s	b	W'	
ν'_e	ν'_μ	ν'_τ	Z'	
e'	μ'	τ'	g'	

neutron $\boldsymbol{n} = (\boldsymbol{udd})$

Mirror neutron
$\boldsymbol{n}' = (\boldsymbol{u}'\boldsymbol{d}'\boldsymbol{d}')$

Mirror model: degenerate case

- SM couplings ≅ mirror couplings
- SM fermion masses ≅ mirror fermion masses
  $m_n \cong m_{n'}$ & $m_p \cong m_{p'}$ & $m_e \cong m_{e'}$ & $m_\nu \cong m_{\nu'}$
- β decay $\sim \beta'$ decay

- Mirror photon mass

$$m_{\gamma'} \leq \sqrt{4\pi\alpha^{-1}\delta_{nn'}\Lambda_{\mathrm{QCD}}} \sim 10^{-3}\ \mathrm{eV}\left(\frac{\delta_{nn'}}{10^{-17}\ \mathrm{eV}}\right)^{1/2}$$

- Milli-charge scenario:
  couplings of mirror particles to SM particles $\propto \epsilon$

- Cosmological limits: asymmetric inflation
  reheating temperature in the mirror sector smaller by $\sim$3.

Berezhiani, Dolgov & Mohapatra '95

$n - n'$ mixing (oscillation)

Berezhiani, Bento '05 PRL

- From $D = 9$ operators:
  (quantum number $\Delta\mathcal{B} = B - B'$ conserved)

$$\mathcal{O}_9 \sim \frac{1}{\mathcal{M}^5}(udd)(u'd'd') + \frac{1}{\mathcal{M}^5}(qqd)(q'q'd')$$

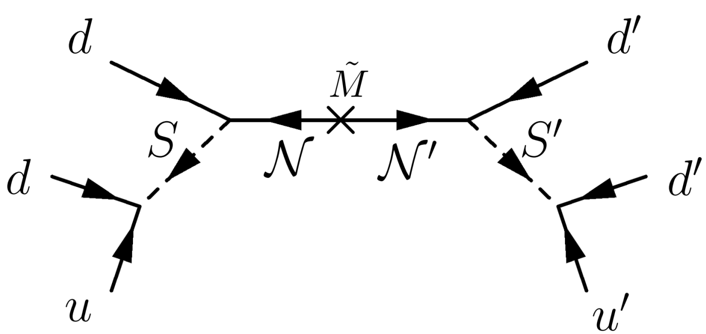
$$\Rightarrow \quad \delta m \sim \left(\frac{\mathcal{M}}{1\ \text{TeV}}\right)^{-5} \times 10^{-10}\ \text{eV}$$

- From renormalizable interactions

$$\mathcal{L} = uds + qqS + S^* d\mathcal{N} + u'd'S' + q'q'S' + S'^* d'\mathcal{N}'$$

S: color-triplet scalar

$\mathcal{N}$: gauge singlet fermion



$n - n'$ system

- Hamiltonian for the $n - n'$ system:

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

$\epsilon_{nn'}$: mixing parameter
ΔE: medium-dependent energy difference

- $n - n'$ transition:

$\epsilon_{nn'} \neq 0$ ⇒ $n \to n'$ transition

$n - n'$ transition vs. $n - \bar{n}$ transition

- $n - n'$: masses can be different;
  $n - \bar{n}$: masss the same (CPT conservation).

- $n \to n'$ transition: $\Delta\mathcal{B} = B - B'$ conserved;
  $n \to \bar{n}$ transition: $\Delta\mathcal{B} = B - B'$ violating.
  ($\Delta B = 2$, possibly connected to $\Delta L = 2$ & neutrino mass generation)

- $n \to n'$ transition: can **NOT** happen inside nuclei;
  (neutrons are bound in nuclei by ~ 8 MeV)
  $n \to \bar{n}$ transition: can happen inside nuclei.

$$\tau_{n\bar{n}} > 8.6\times 10^{7}\ \mathrm{s} \quad \Rightarrow \quad \boxed{\epsilon_{n\bar{n}} < 7.6\times 10^{-24}\ \mathrm{eV}}$$

Baldo-Ceolin et al ‘94

Ultracold neutron (UCN) experimental limits

- Transition probability:

$$P_{nn'} = (\epsilon_{nn'} t)^2 = \left(\frac{t}{\tau_{nn'}}\right)^2$$

$m_n = m_{n'}$
$\Delta E = 0$ (vanishing mirror magnetic field)

nEDM@PSI '21 $\tau_{nn'} > 352\ \mathrm{s}$ ⇒ $\epsilon_{nn'} < 1.9\times10^{-18}\ \mathrm{eV}$

Serebrov et al '09 $\tau_{nn'} > 448\ \mathrm{s}$ ⇒ $\epsilon_{nn'} < 1.5\times10^{-18}\ \mathrm{eV}$

condition: $|m_n - m_{n'}| \lesssim 10^{-12}\ \mathrm{eV}$ ($\Delta E = 0$)

$n \to n'$ transition in NSs

- $n \to n'$ transition occurs in a NS via the process

$$n + N \to n' + N$$

- The holes left by n & N are filled quickly by higher energy nucleons. → releasing energy!

- Black-body radiation of cold NS:

$$\mathcal{L}_\gamma = 4\pi\sigma_{\rm SB}R^2T^4$$

$\sigma_{\rm SB}$: Stefan-Boltzmann constant

- Luminosity limit due to $n \to n'$ transition: $\mathcal{L}_{n\to n'} < \mathcal{L}_\gamma$ (from coldest NS PSR J2144−3933)

McKeen, Pospelov, Raj '21 PRL

$$\epsilon_{nn'} < 1.6\times10^{-17}\ \text{eV}$$

⇒ $\tau_{nn'} > 10\ \text{s}$

condition: $|m_n - m_{n'}| \lesssim \text{MeV}$

$n \to n'$ transition in NSs

Goldman, Mohapatra, Nussinov '19

- Orbital period measurements in binary pulsars (decreasing NS mass → decreasing orbital period)

$$\epsilon_{nn'} \lesssim 10^{-13}\ \mathrm{eV}$$

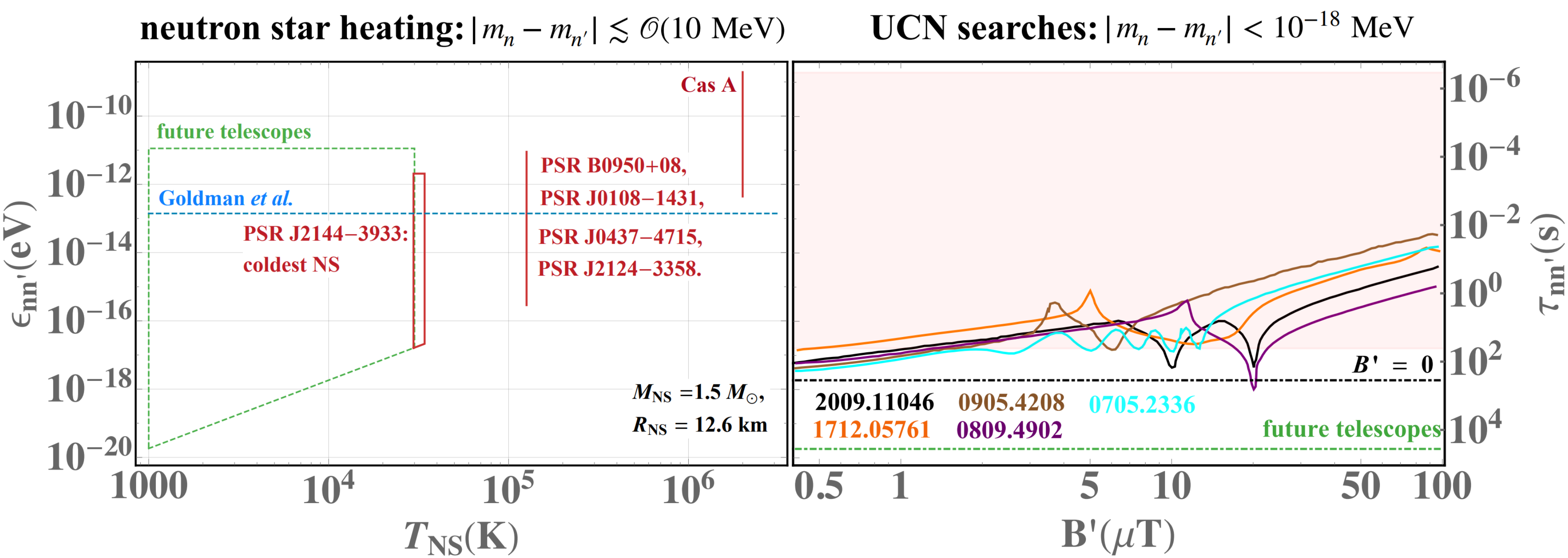
- GW observations: mixed stars → smaller radii → changes of GW signals

$$\frac{dW}{dt} = \frac{32 G_N}{5c^5} \mu^2 \Omega_{\mathrm{orb}}^6 a^4 \propto a^{-5}$$

$$\Omega_{\mathrm{orb}} \backsim a^{-3/2}$$
$$a = R_1 + R_2$$

Limits on $n \to n'$ transition

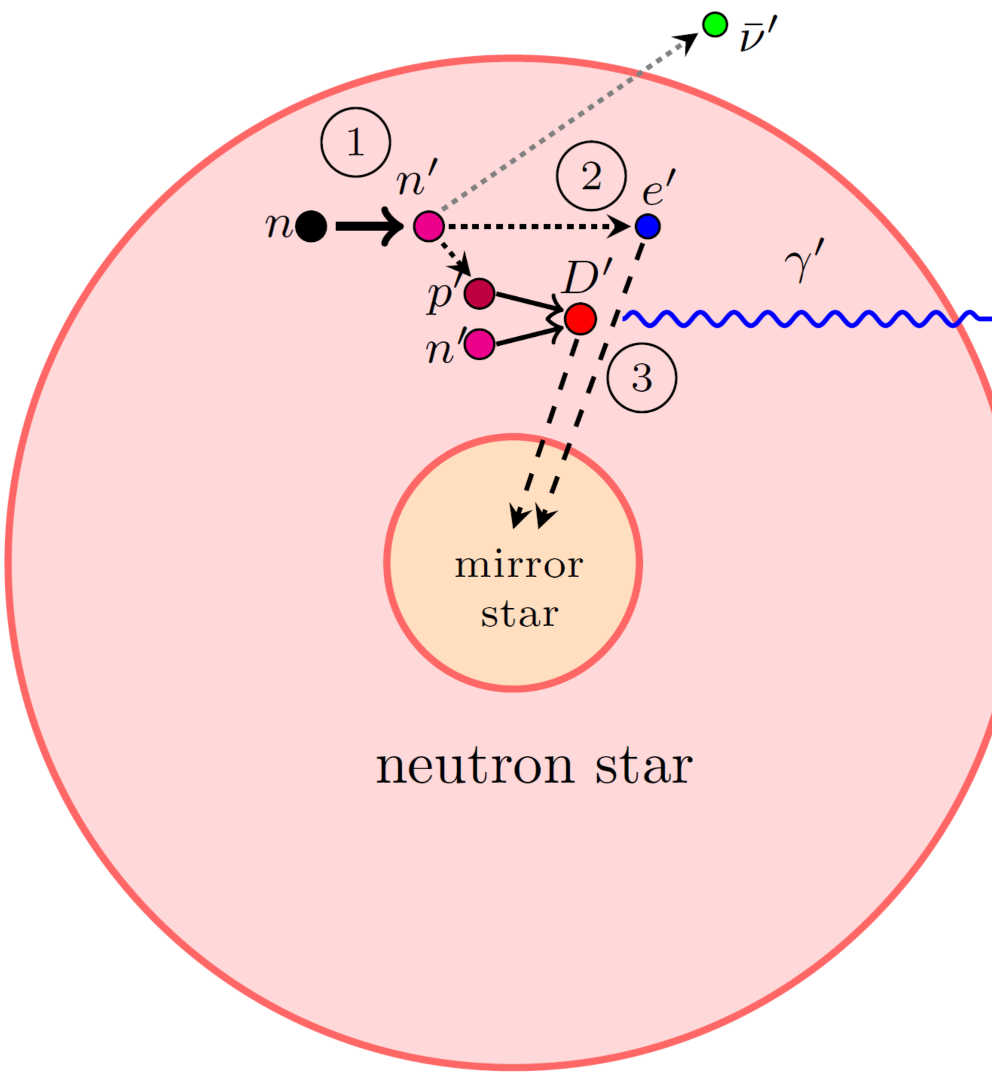
McKeen, Pospelov, Raj '21 PRL



- NS limits on $n \to n'$ transition via γ emission exclude (most of) sensitivity ranges of $\epsilon_{nn'}$ in current and future experiments.
- Current and near future UV, optical and IR survey telescopes: **LUVOIR, Rubin/LSST, Dark Energy Survey, Roman/WFIRST.**

Rescuing the experiments!

Adventure of n' in NSs



1. $n \to n'$ transition
2. Decay $n' \to p' + e' + \bar{\nu}'$
   $p' + n' \to D' + \gamma'$
3. D' & e' falling into center forming mirror star

- $p' + n' \to D' + \gamma'$ faster than $e' + p' \to n' + \nu'$ such that all p' are eaten.
- Charge neutrality
  → $n_{e'}(r) = n_{D'}(r)$

Profiles of e' & D'

- $e' - D'$ fluid in the star:

degenerate pressure of e' ⟺ gravity (mass of D')

- Pressure of e'

$$P_{e'} = \frac{8\pi}{3 m_{e'} \hbar^3} \int_0^{p_F} \mathrm{d}p \frac{p^4}{\sqrt{1 + (p/m_{e'}c)^2}}$$

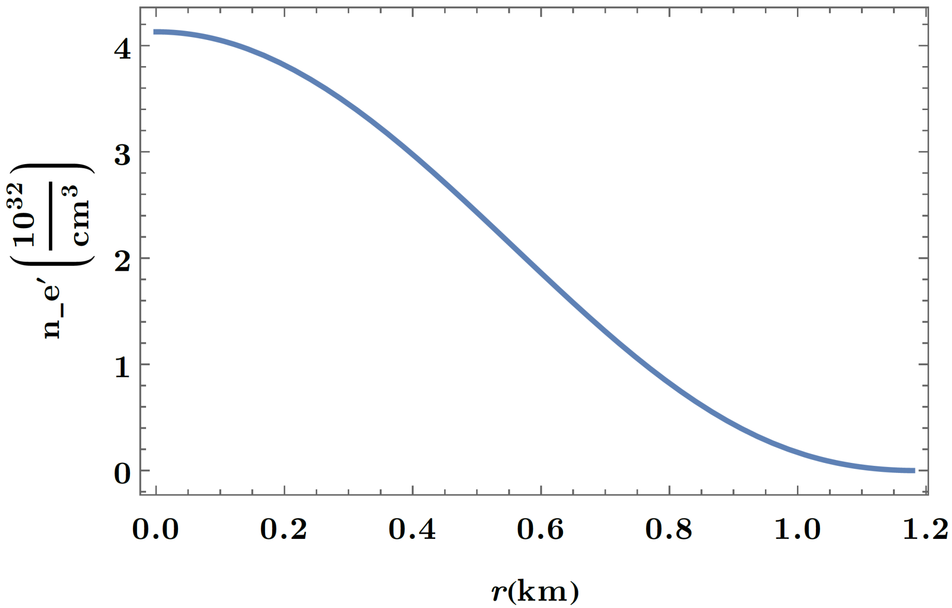
- Hydrostatic equation

$$\frac{\partial}{\partial r} P_{e'}(r) = -\rho(r) g(r)$$

$$g(r) = \frac{G_N M(r)}{r^2} = \frac{4\pi}{3} G_N \rho_0 r \qquad \rho_0 = 10^{15}\,\mathrm{gr/cm^3}$$

- Relativistic modifications are very small ($\sim 10^{-3}$).

Profiles of e' & D'



$$n_{e'}(r) = \frac{8\pi}{3m_{e'}^3 c^3 \hbar^3}\left[\left(\sqrt{X_F^2(0)+1} - \frac{r^2}{2r_0^2}\right)^2 - 1\right]^{3/2}$$

$$\mathcal{N}_{e'}(r) = \mathcal{N}_{D'}(r) = \int_0^r 4\pi n_{e'}(x) x^2 \mathrm{d}x$$

$$r_0 = \sqrt{\frac{3m_{e'}c^2}{4\pi G_N \rho_0 m_{D'}}} \simeq 0.296 \text{ km}$$

$$X_F \equiv p_F / m_{e'} c$$

Number of n'

- Assuming $n - n'$ is the only energy source in a NS. ($\Delta E \sim 30$ MeV is the energy gained in each transition)

$$\frac{\mathrm{d}\mathcal{N}_{n'}}{\mathrm{d}t} = \frac{\mathcal{L}_{\mathrm{NS}}}{\Delta E}$$

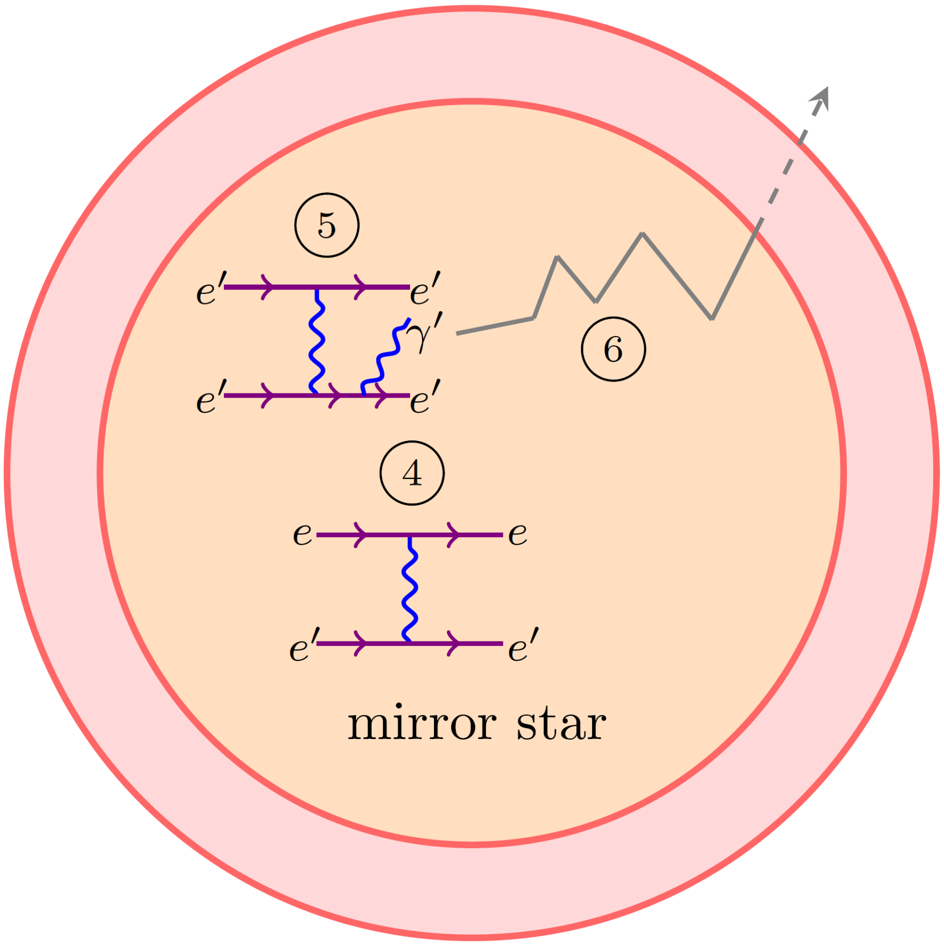
- For PSR J2144-3933 with lifetime of 330 million years:

$$\mathcal{L}_{\mathrm{NS}} \simeq 3 \times 10^{27} \ \mathrm{erg/sec} \quad \Rightarrow \quad \mathcal{N}_{n'} \sim 10^{48}$$

- Tiny fraction of mirror-neutron not affecting gravity fields and of the local density profile of NS.

$$\mathcal{N}_{n'}/\mathcal{N}_{n} \sim 10^{-9}$$

Cooling via γ' emission



4. Energy transfer
$$e + e' \to e + e'$$
5. Mirror photon production
$$e' + e' \to e' + e' + \gamma'$$
6. Energy emission dominated by γ'.

- For sufficiently large ϵ, dominant energy emission is due to γ'.

Cooling via γ' emission

- Heat emission from the mirror sector is much faster than heat transfer between the two sectors.
- Any amount of heat in the mirror sector will be emitted rather than go back to the normal sector.
- Temperature $T' < T$.

- Black-body radiation of γ':

$$\boxed{\mathcal{L}' = 4\pi\sigma_{\mathrm{SB}} R_c^2 T'^4}$$

$$\left.\begin{array}{l} R_c \geq 1\,\mathrm{km} \\ T' \geq 100 T_s \end{array}\right. \Rightarrow \mathcal{L}' \gg \mathcal{L}$$

There is a $\sim$100 meter thick nuclear "thermal blanket" just under the surface, causing the internal temperature to drop dramatically by a factor of $\sim$100.

Beznogov, Potekhin, Yakovlev, '21

$e \to e'$ scattering

- $e - e'$ collision rate (#/sec):

$$\dot{\mathcal{N}}_{\rm col} = \frac{c f f' \mathcal{N}_e(r < R_c) \mathcal{N}_{e'} \sigma_{ee'}}{(4\pi/3) R_c^3}$$

Fractions of active electrons and mirror electrons:
$f = kT/E_F \sim 10^{-5}$ & $f' = kT'/E_F' \sim 10^{-4}$

- Comparing total energy transferring rate with NS luminosity:

$$\dot{\mathcal{N}}_{\rm col} \Delta T \gg \mathcal{L}_{\rm NS} \sim 2 \times 10^{36} \ {\rm keV/sec}$$

$$\Delta T \sim 0.35\,{\rm keV} \quad R_c = 1.2 \ {\rm km}$$

$$\Rightarrow \dot{\mathcal{N}}_{\rm col} \gg 10^{37} \ {\rm sec}^{-1}$$

$$\Rightarrow \sigma_{ee'} \simeq \epsilon^2 \sigma_{ee} \gg 10^{-50} \ {\rm cm}^2$$

$$\Rightarrow \epsilon^2 \gg 10^{-27}$$

$e \to e'$ scattering

- $e - e'$ scattering very similar to $e - e$ Møller scattering, only in the t-channel:

$$\frac{d\sigma}{d\Omega} = \frac{\alpha^2 \epsilon^2}{4E_1E_2}\left[1 - \frac{2}{\sin^2(\theta/2)} + \frac{2}{\sin^4(\theta/2)}\right]$$

- Cutoff at the plasmon mass in the forward direction:

$$\omega^2 = 4\pi e^2 n_e/m_e$$

$$n_{e,\,\mathrm{active}} = f \times \frac{4E_F^3}{9\pi} = \frac{4E_F^2 T}{9\pi}$$

$$E_F$$

$$m_\gamma^2 = \omega^2 = \frac{16}{9}E_F T$$

Limits on ϵ

- Cosmological BBN limits:
  $\epsilon \lesssim 10^{-9}$ for exact mirror parity,
  weaker for asymmetric mirror models.

  Berezhiani, Lepidi '08

- Consistency of asymmetric inflation:
  $\epsilon \lesssim 10^{-7}$.

  Babu & Mohapatra '21

- Some limits are not applicable here, e.g.
  $\epsilon \lesssim 10^{-12}$ with fermion DM.

  Vogel & Redondo '13

- There is enough parameter space for $\epsilon^2 \gg 10^{-27}$

Some comments

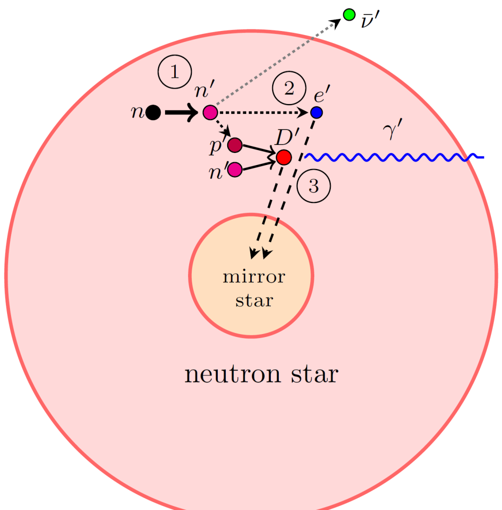
- Heating up argument here applies in principle to all pulsars.
- Orbital period limits requires binary pulsars.

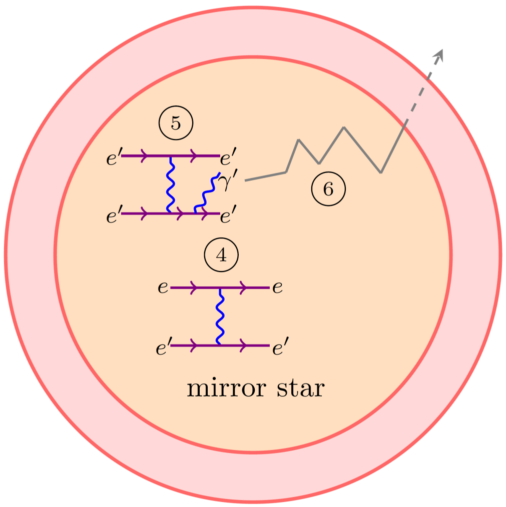
- Measurements of spinning period changes of single pulsars are very accurate; however they can not be used, due to relatively large and incalculable changes due to magnetic braking.

- Cooling of NSs via γ leads to reliable limits on $n - n'$ transition:
  - Nearly exact mirror symmetry with $\epsilon \lesssim 10^{-13}$;
  - Asymmetric mirror model with $m_{p'} \geq m_{n'}$, β' decay is forbidden and n' is DM;
  - No milli-charge portal connection between the ordinary and mirror sectors.

Conclusion

- Neutron stars can be used to set limits on BSM, e.g. $n \rightarrow n'$ transition.
- In nearly exact mirror models, for wide range of milli-charge $\epsilon^2 \gg 10^{-27}$, the luminosity of cold NSs could be dominated by emission of γ'.
- This will invalidate the stringent NS limit $\delta_{nn'} \lesssim 10^{-17}$ eV from photon emission, and rescue the terrestrial experiments looking for $n \rightarrow n'$ oscillations.





Thank you！