Baryon Number Violation in Neutron Stars and the Lab

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Baryon number violation, Sakharov conditions and baryogenesis

Baryogenesis

$\Omega_{DM} : \Omega_{Baryon} \simeq 5:1$

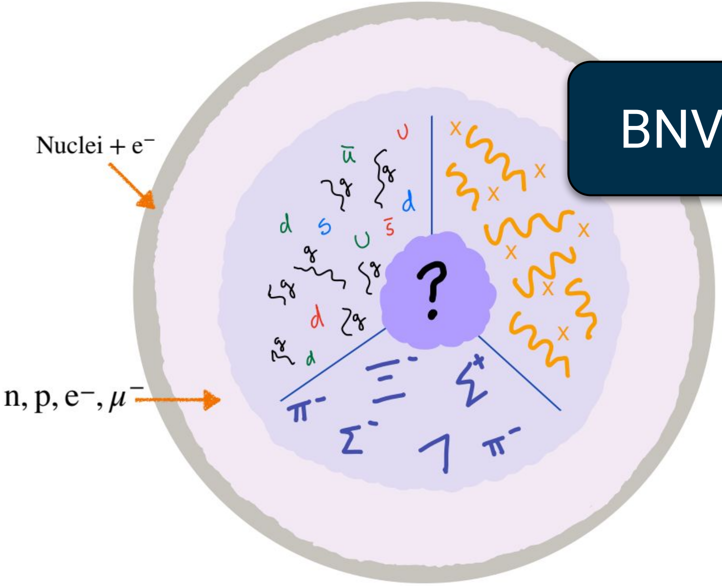
…connection with DM?

Baryon number violating phenomenology below Λ_{QCD}

- Inspired by:
  - B-Mesogenesis scenarios
  - Hyperon decays to dark sector particles
  - neutron anomaly
- Typical setup: Heavy scalar(s) mediator & GeV-scale dark sector particle(s)
- B-violation with chiral perturbation theory

Baryon $\rightarrow \psi\, \gamma$ and other Rare Decays

Alonso-Álvarez, Elor, Escudero, Fornal, Grinstein, Camalich [2111.12712]
also: Davoudiasl, Morrissey, Sigurdson, Tulin [1106.4320]



BNV in Neutron Stars

Berryman, Gardner, Zakeri [2305.13377] [2311.13649] [2201.02637]

Specific Model: A Majorana fermion + color-triplet scalar

	$SU(3)_c$	$SU(2)_L$	$U(1)_Y$
$X^{1,2}$	$\mathbf{3}$	$\mathbf{1}$	$+4/3$
ψ	$\mathbf{1}$	$\mathbf{1}$	0

(suppressing color indices)

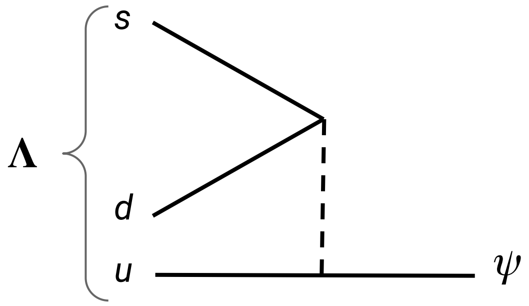
$$\mathcal{L} \supset \lambda_i \left(X \bar{u}_i P_L \psi + X^* \bar{\psi} P_R u_i \right) + \lambda'_{ij} \left(X^* \bar{d}_i P_L d_j^c + X \bar{d}_j^c P_R d_i \right)$$

- If $X^{1,2}$ have CP-violating phases, baryon asymmetry can be explained
- If $(m_p - m_e) < m_\psi < (m_p + m_e)$ ψ can be the DM, proton stable
- λ'=0 for i=j
- $m_\psi \sim 1$ GeV
- $m_X \gtrsim 1$ TeV

See e.g.:
Allahverdi, Dev, Dutta[1712.02713]
Dev, Mohapatra [1504.07196]
Allahverdi, Dutta, Sinha [1005.2804]

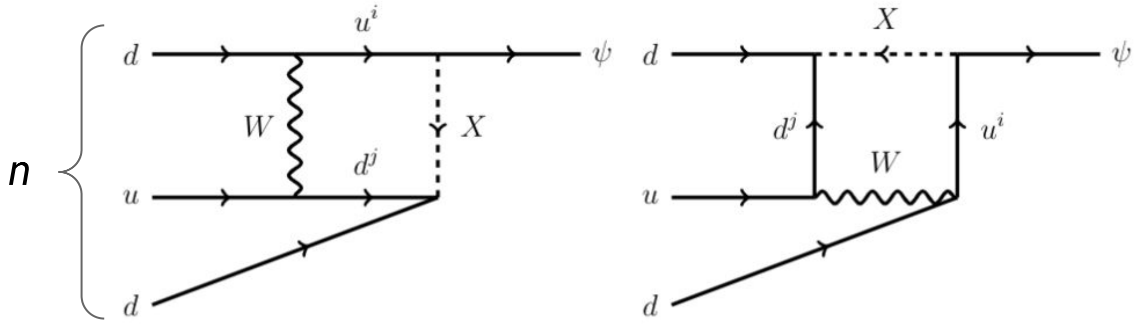
Decays of the Baryons to ψ and a Photon (ΔB=1)

$\Lambda \to \psi$ mixing



ds-u coupling or $\lambda_1\lambda'_{12}$

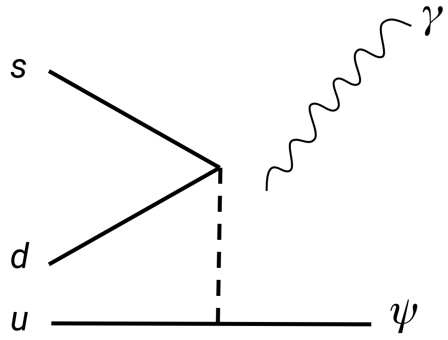
$n \to \psi$ mixing



All higher-generational couplings: $\lambda_k\lambda'_{ij}$

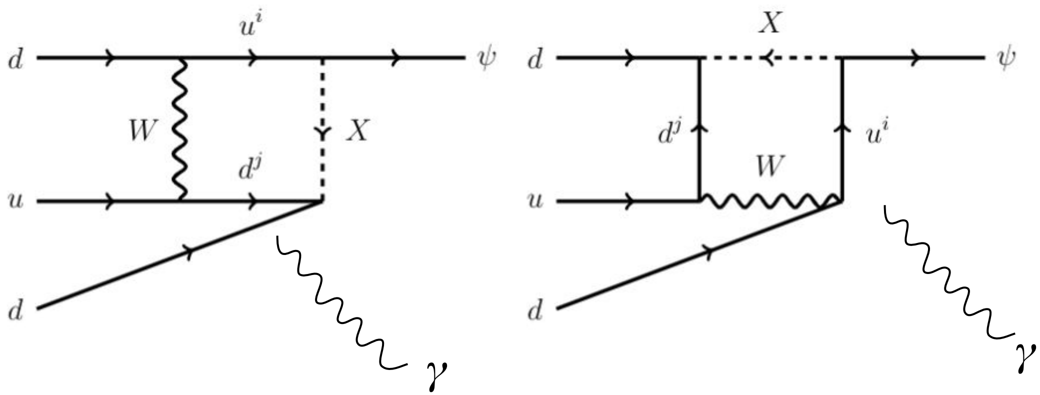
Decays of the Baryons to ψ and a Photon (ΔB=1)

$\Lambda \to \psi\, \gamma$ decay at tree level



ds-u coupling or $\lambda_1 \lambda'_{12}$

$n \to \psi\, \gamma$ decay at loop level



All higher-generational couplings: $\lambda_k \lambda'_{ij}$

Operator Matching to the ChiPT Lagrangian (*d–s–u coupling*)

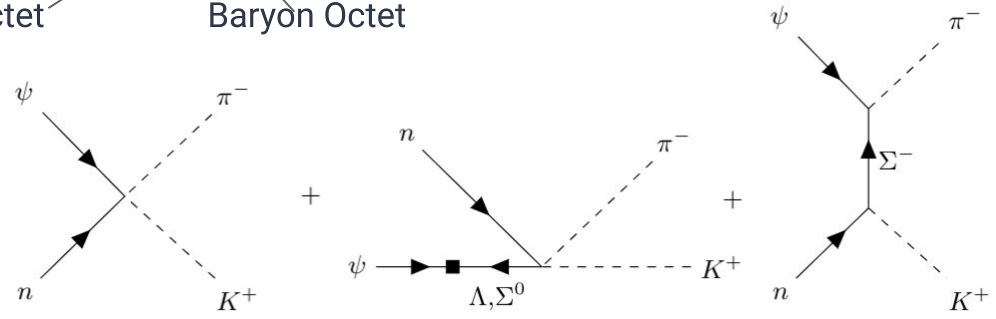
New physics "spurion"

$$O_{ij} \equiv \frac{1}{2}\epsilon_{jkl}(q_k q_l)(q_i \psi) \Longleftrightarrow \mathcal{L}_6 = \mathrm{Tr}[\hat{C}^R O]$$

$$\mathcal{L}^{(0)}_{\mathrm{eff,ChPT}} = \beta \mathrm{Tr}[\hat{C}^R u^\dagger B_R \psi u]$$

Meson Octet   Baryon Octet

1. Match the quark-level operator to the SU(3) representation after integrating out the heavy *X*
2. Write down the SU(3)-invariant interactions between the new physics spurion C^R and the meson octet $u \sim e^{\phi/f}$ and baryon octet *B*



Claudson, Wise, Hall, 1981

The new physics spurion terms

Integrating out *X* and matching the operator $dsu\psi$ gives rise to the spurion C^R:

$$\hat{C}^R[(ds)u] = \frac{\lambda'_{12}\lambda_1}{m_X^2}\begin{pmatrix}1 & 0 & 0\\ 0 & 0 & 0\\ 0 & 0 & 0\end{pmatrix}$$

For the higher generational couplings, the spurion term depends on a loop factor and CKM matrix elements:

$$\hat{C}^R[(ds)u] = \frac{G_F\sqrt{3}}{8\pi^2\, m_W^2}\sum_{i,j\neq 1,l\neq k}\lambda_i\lambda'_{kj}V_{il}V^*_{1j}m_{d_j}m_{u_i}\,F(x_{d_j},x_{u_i},x_X)\times\begin{pmatrix}1 & 0 & 0\\ 0 & 0 & 0\\ 0 & 0 & 0\end{pmatrix}$$

$$\hat{C}^R[(dd)u] = \frac{G_F\sqrt{3}}{8\pi^2\, m_W^2}\sum_{i}\sum_{j\neq 1}\lambda_i\lambda'_{1j}V_{i1}V^*_{1j}m_{d_j}m_{u_i}\,F(x_{d_j},x_{u_i},x_X)\times\begin{pmatrix}0 & 0 & 0\\ 0 & 0 & 0\\ 0 & 1 & 0\end{pmatrix}$$

Expansion of the ChiPT New Physics Lagrangian: Zeroth order

$$\mathcal{L}^{(0)}_{\text{eff,ChPT}} = \beta \text{Tr}[\hat{C}^R u^\dagger B_R \psi u]$$

$$b_R^\dagger \left[-i\sigma^2\right] \psi_R^* = \bar{b} P_L \psi^c \text{ and } u = e^{i\Phi/f_\pi}$$

$$\Phi = \begin{pmatrix} \frac{\pi^0}{\sqrt{2}} + \frac{\eta_8}{\sqrt{6}} & \pi^+ & K^+ \\ \pi^- & -\frac{\pi^0}{\sqrt{2}} + \frac{\eta_8}{\sqrt{6}} & K^0 \\ K^- & \overline{K}^0 & -\frac{2\eta_8}{\sqrt{6}} \end{pmatrix}, \quad B = \begin{pmatrix} \frac{\Lambda^0}{\sqrt{6}} + \frac{\Sigma^0}{\sqrt{2}} & \Sigma^+ & p \\ \Sigma^- & \frac{\Lambda^0}{\sqrt{6}} - \frac{\Sigma^0}{\sqrt{2}} & n \\ \Xi^- & \Xi^0 & -\frac{2\Lambda^0}{\sqrt{6}} \end{pmatrix}$$

Zeroth order expansion:

$$u^\dagger \simeq 1 - i\frac{\phi}{2f_\pi} - \frac{\phi^\dagger \phi}{8 f_\pi^2}$$

$$\mathcal{L}^{(0)}_{\text{eff,ChPT}} = \beta \frac{\lambda_1 \lambda'_{12}}{m_X^2} \left(\frac{1}{\sqrt{6}} \bar{\psi}^c P_R \Lambda + \frac{1}{\sqrt{2}} \bar{\psi}^c P_R \Sigma^0 + \text{h.c.} \right) + \mathcal{O}(1/f_\pi)$$

Expansion of the ChiPT New Physics Lagrangian: First order in $1/f_\pi$

$$\mathcal{L}^{(0)}_{\text{eff,ChPT}} = \beta \text{Tr}[\hat{C}^R u^\dagger B_R \psi u]$$

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First order expansion:

$$u^\dagger \simeq 1 - i\frac{\phi}{2f_\pi} - \frac{\phi^\dagger \phi}{8f_\pi^2}$$

$$\mathcal{L}^{(0)}_{\text{eff,ChPT}} \supset \frac{\beta}{f_\pi} \frac{\lambda_1 \lambda'_{12}}{m_X^2} \left(\frac{iK^- \bar{\psi}^c P_R p}{\sqrt{2}} - \frac{iK^+ \bar{\psi}^c P_R \Xi^-}{\sqrt{2}} + \frac{i\pi^- \bar{\psi}^c P_R \Sigma^+}{\sqrt{2}} - \frac{i\pi^+ \bar{\psi}^c P_R \Sigma^-}{\sqrt{2}} + \text{h.c.} \right)$$

Expansion of the ChiPT New Physics Lagrangian: Second order in $1/f^2_\pi$

$$\mathcal{L}^{(0)}_{\text{eff,ChPT}} = \beta \text{Tr}[\hat{C}^R u^\dagger B_R \psi u]$$

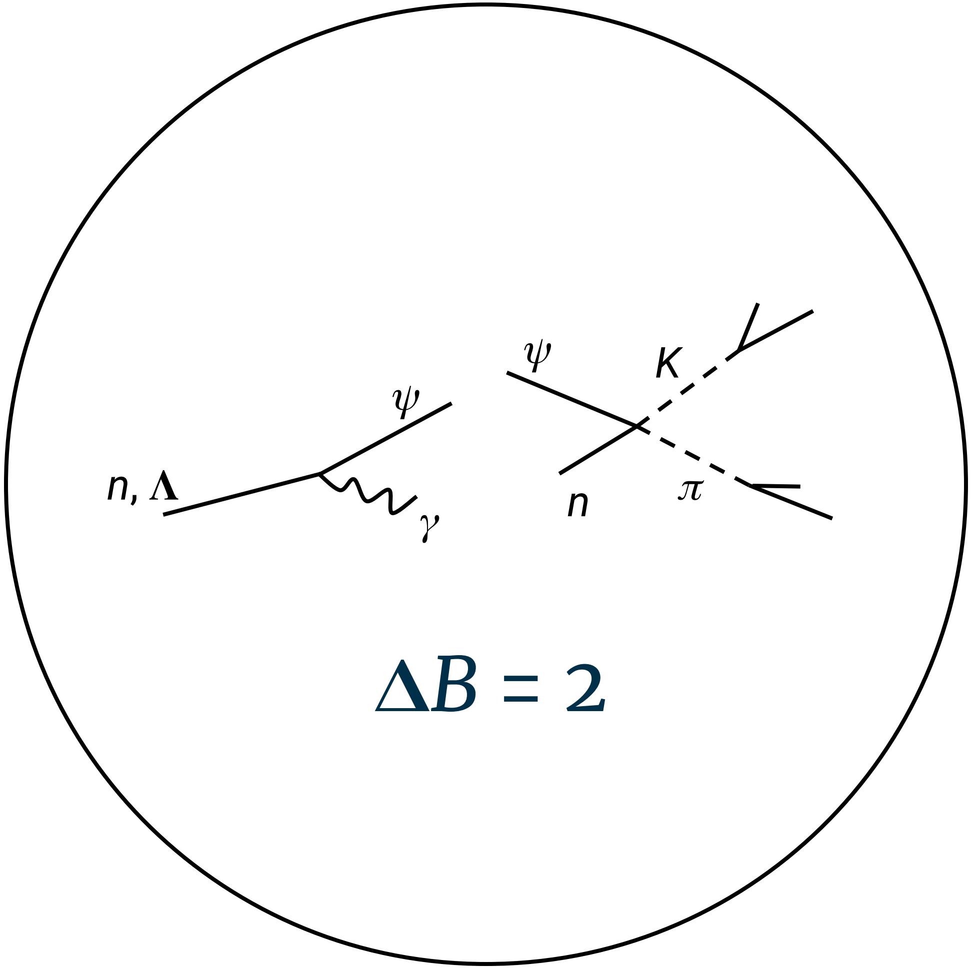
$$b^\dagger_R \left[-i\sigma^2\right] \psi^*_R = \bar{b} P_L \psi^c \text{ and } u = e^{i\Phi/f_\pi}$$

$$u^\dagger \simeq 1 - i\frac{\phi}{2f_\pi} - \frac{\phi^\dagger \phi}{8f_\pi^2}$$

Second order expansion:

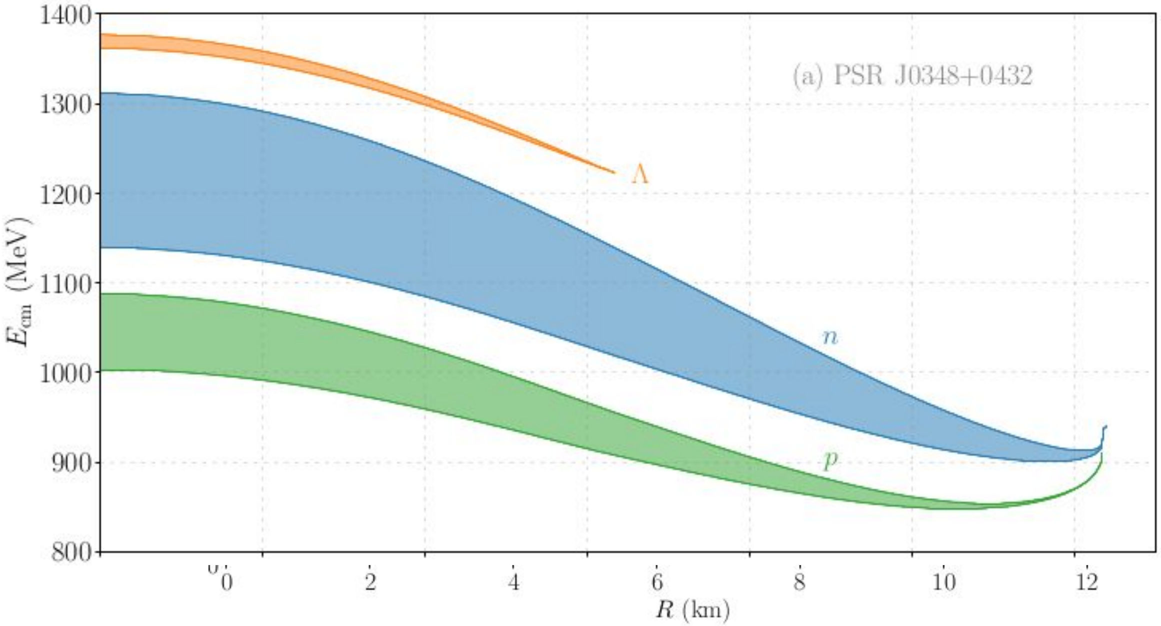
$$\mathcal{L}^{(0)}_{\text{eff,ChPT}} \supset \frac{\beta}{f_\pi^2}\frac{\lambda_1 \lambda'_{12}}{m_X^2}\Bigg(- \sqrt{\frac{3}{8}} K^- K^+ \bar{\psi}^c P_R \Lambda - \frac{K^- K^+ \bar{\psi}^c P_R \Sigma^0}{2\sqrt{2}} + \frac{\pi^+ K^- \bar{\psi}^c P_R n}{2} + \sqrt{\frac{3}{2}}\frac{\eta^8 K^- \bar{\psi}^c P_R p}{4} + \frac{\pi^0 K^- \bar{\psi}^c P_R p}{4\sqrt{2}}$$
$$+ \sqrt{\frac{3}{2}}\frac{\eta^8 K^+ \bar{\psi}^c P_R \Xi^-}{4} + \frac{\pi^- K^+ \bar{\psi}^c P_R \Xi^0}{2} + \frac{\pi^0 K^+ \bar{\psi}^c P_R \Xi^-}{4\sqrt{2}} - \frac{K^0 \pi^+ \bar{\psi}^c P_R \Xi^-}{4F^2}$$
$$+ \frac{\pi^0 \pi^- \bar{\psi}^c P_R \Sigma^+}{2\sqrt{2}} + \frac{\pi^0 \pi^+ \bar{\psi}^c P_R \Sigma^-}{2\sqrt{2}} - \frac{K^+ \overline{K^0} \bar{\psi}^c P_R \Sigma^-}{4} - \frac{\pi^- \overline{K^0} \bar{\psi}^c P_R p}{4}$$
$$- \frac{K^0 K^- \bar{\psi}^c P_R \Sigma^+}{4} - \frac{1}{\sqrt{2}} \pi^- \pi^+ \bar{\psi}^c P_R \Sigma^0 + \text{h.c.} \Bigg) + \mathcal{O}(1/f_\pi^3)$$

Neutron Star



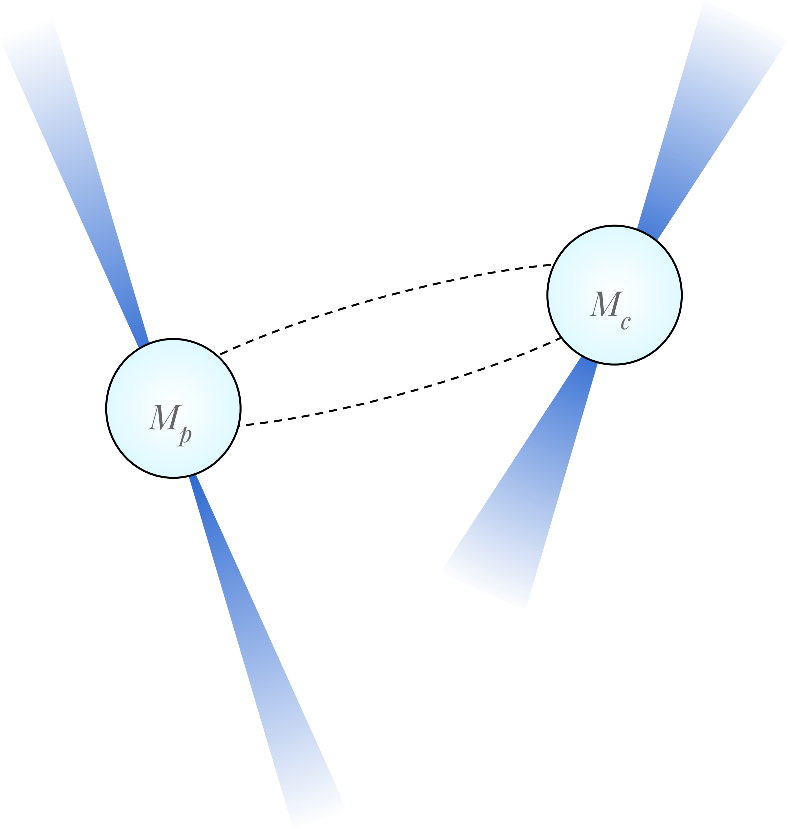
Enhancement of the Baryon CM Energy in Dense Matter

- Dense nuclear matter: baryons get a kinetic mass → lifts the CM frame energy
- Allows us to probe decays that would otherwise be kinematically forbidden in vacuum!
  - → We can decay to ψ with masses up to ~1.4 GeV



Impact of ΔB processes on Binary Pulsars

Berryman, Gardner, Zakeri [2305.13377]
[2311.13649] [2201.02637]



$$\frac{\dot{B}}{4\pi} = -\int e^{\nu(r)} \left[1 - \frac{2M(r)}{r}\right]^{-\frac{1}{2}} \Gamma_{\rm nm}(r)\, n(r)\, r^2\, dr$$

Impact of ΔB processes on Binary Pulsars

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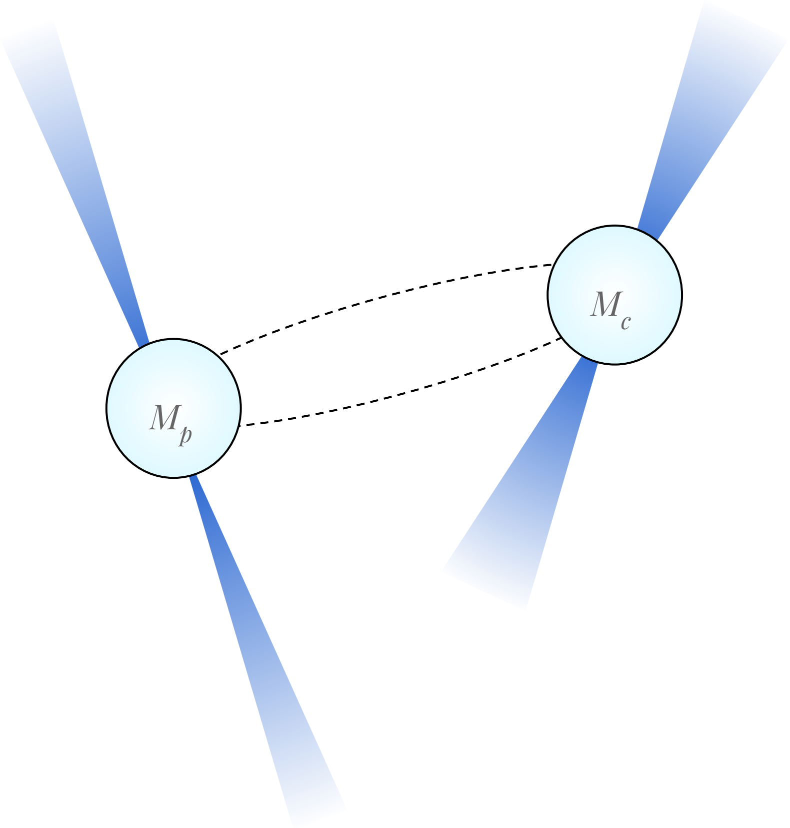

$$\frac{\dot{B}}{4\pi} = -\int e^{\nu(r)} \left[1 - \frac{2M(r)}{r}\right]^{-\frac{1}{2}} \Gamma_{\rm nm}(r)\, n(r)\, r^2\, dr$$

$$\dot{M}^{\rm eff} = \left(\partial_{\mathcal{E}_c} M + \left(\frac{\Omega^2}{2}\right) \partial_{\mathcal{E}_c} I\right) \left(\frac{\dot{B}}{\partial_{\mathcal{E}_c} B}\right)$$

Impact of ΔB processes on Binary Pulsars

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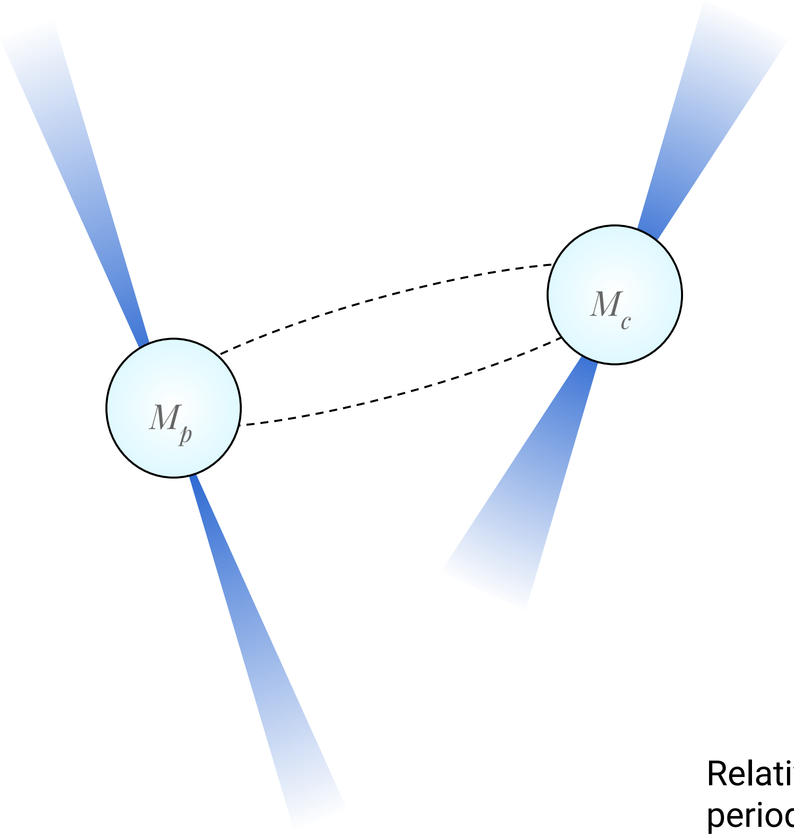


$$\frac{\dot{B}}{4\pi} = -\int e^{\nu(r)} \left[1 - \frac{2M(r)}{r}\right]^{-\frac{1}{2}} \Gamma_{\rm nm}(r)\, n(r)\, r^2\, dr$$

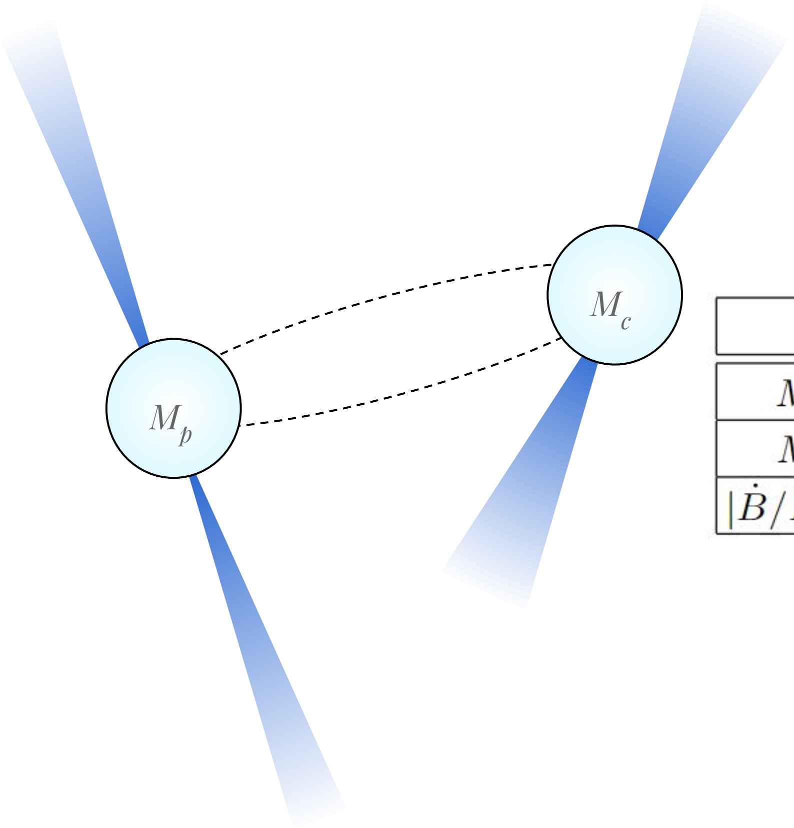
$$\dot{M}^{\rm eff} \equiv \frac{d}{dt}\left(M + \frac{1}{2}I\Omega^2\right) = \underbrace{b(M)\left(\frac{\dot{B}}{B}\right)M + b(I)\left(\frac{\dot{B}}{B}\right)\left(\frac{2\pi^2 I}{P_s^2}\right)}_{\rm BNV} - \frac{4\pi^2 I \dot{P}_s}{P_s^3}$$

$$\left(\frac{\dot{P}_b}{P_b}\right)^{\rm obs} = \underbrace{\left(\frac{\dot{P}_b}{P_b}\right)^{\rm GR} + \left(\frac{\dot{P}_b}{P_b}\right)^{\dot{E}}}_{\rm intrinsic} + \left(\frac{\dot{P}_b}{P_b}\right)^{\rm ext}$$

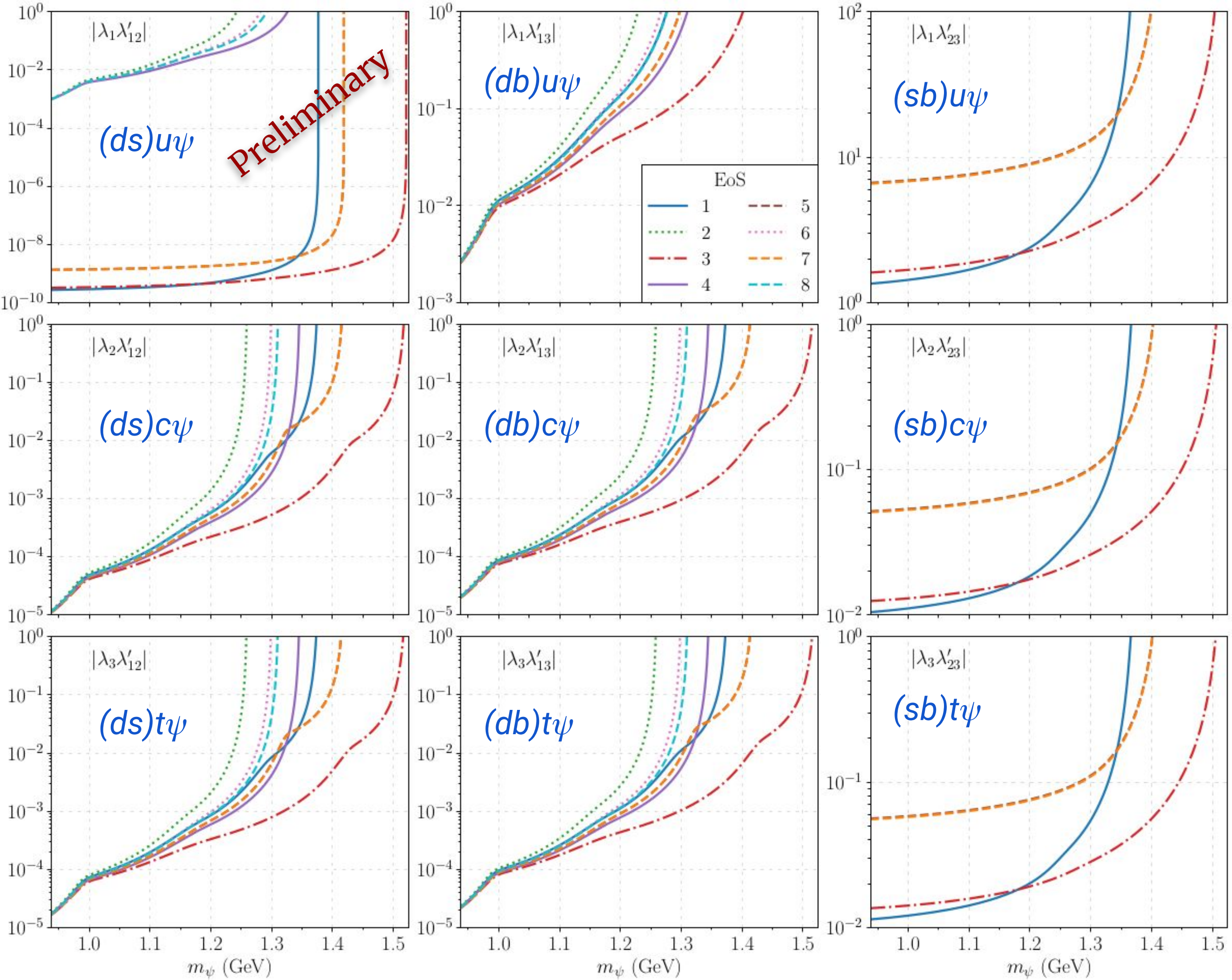
Relative rate of orbital period decay

BNV perturbs the energy loss

Systems in this study



Name	J0348+0432	J1614−2230	J0737−3039A/B
$M_p\,(M_\odot)$	2.01(4)	1.908(16)	1.338 185(+12, −14) [A]
$M_c\,(M_\odot)$	0.172(3)	0.493(3)	1.248 868(+13, −11) [B]
$\lvert\dot{B}/B\rvert_{2\sigma}\,(\mathrm{yr}^{-1})$	1.8×10^{-10}	2.0×10^{-11}	4.0×10^{-13}



- We looked at constraints on the coupling product

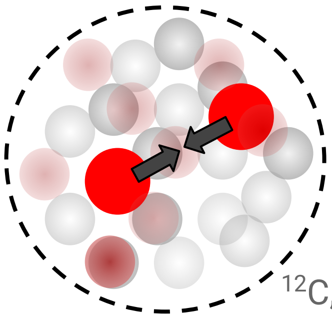
$$|\lambda_k \lambda'_{ij}|$$

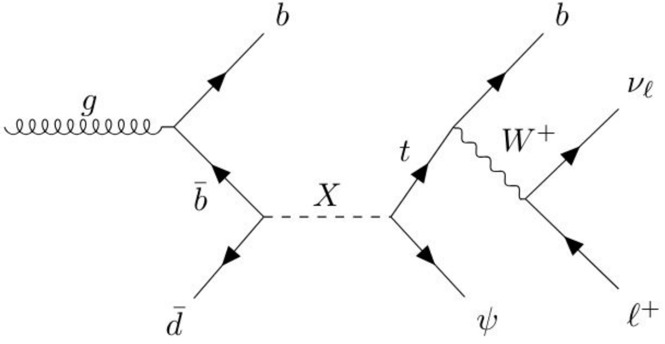
- We find stringent constraints from binary pulsars down to the 10^{-5} level (nucleonic Equation of State or EoS)
- Potentially as low as 10^{-9} if we have hyperonic EoS!

Laboratory Probes

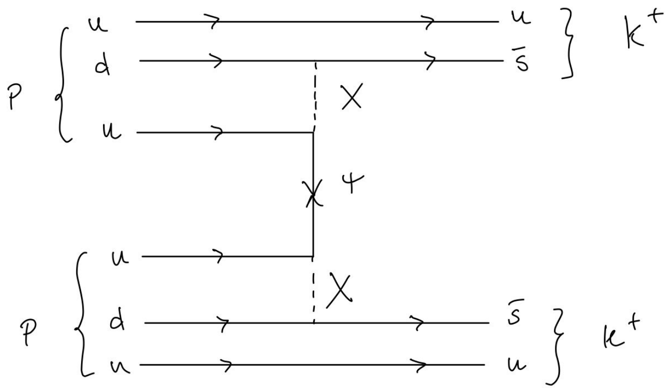
See Denis' talk e.g.: [2404.14844]

- Collider searches:
  - Monotop, Monojet, and missing energy searches
- BES-III, LHCb: see [2111.12712]
- Di-nucleon decay searches:
  - Super-K: large volume search for spontaneous di-proton decay
  - DUNE-FD? Hyper-K?

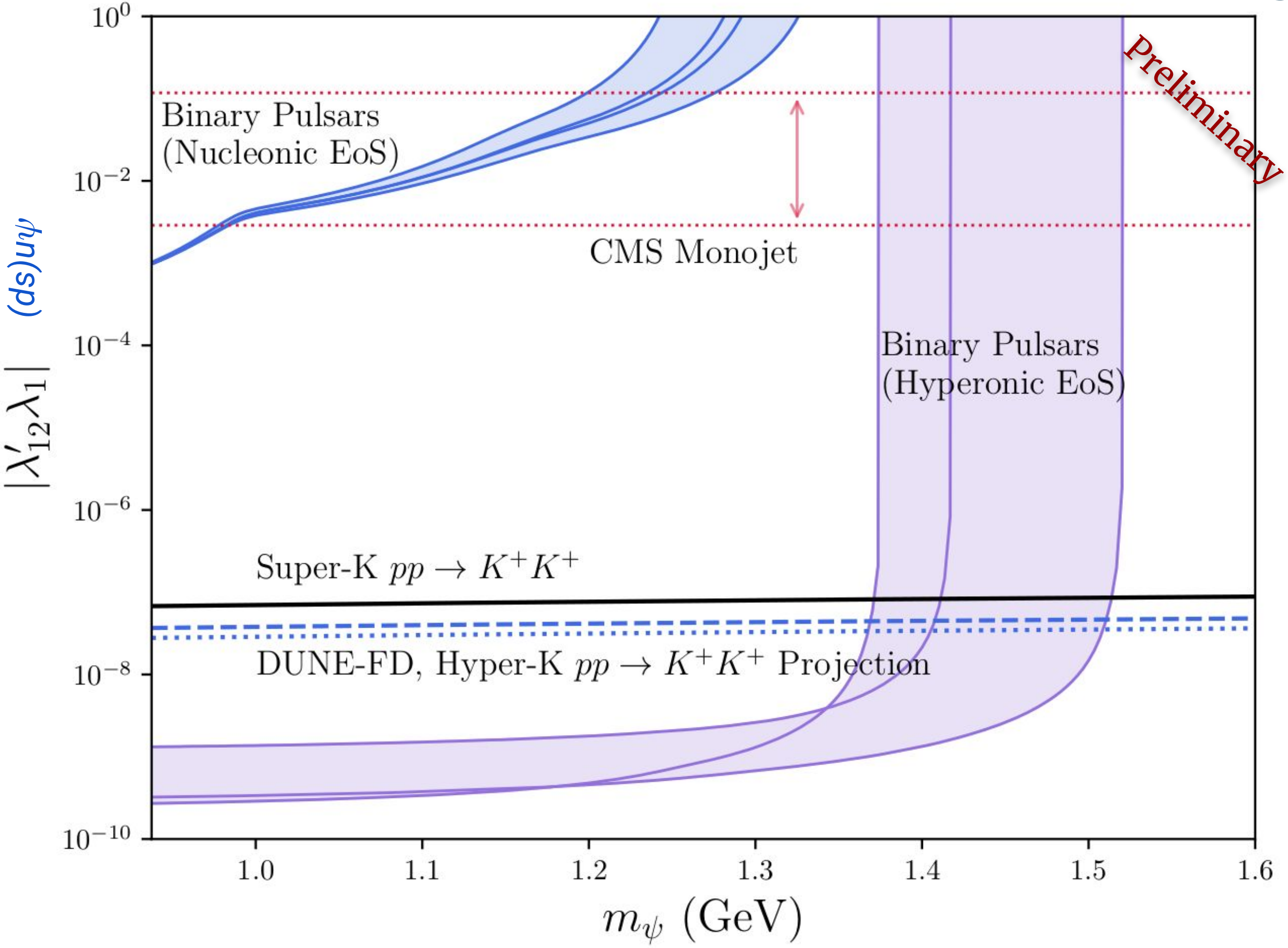




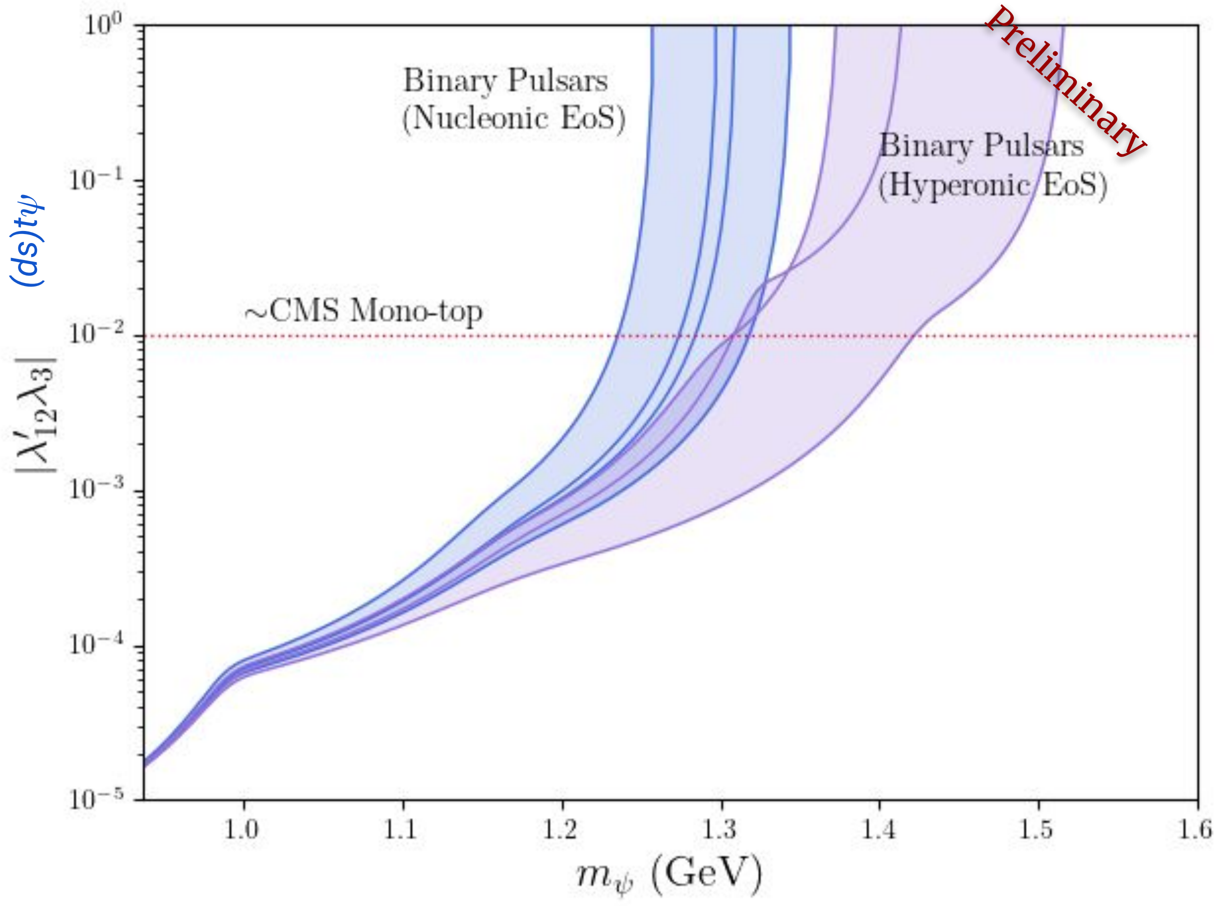
$$\tau(pp \to K^+K^+) = \frac{8}{\pi}(\lambda_1\lambda'_{12})^4 \frac{\Lambda_{\rm QCD}^{10}\rho_N}{m_p^2 m_\psi^2 m_X^8}$$



Comparison with Laboratory Limits: lowest quark generation couplings



Comparison with Laboratory Limits: Higher generational couplings



- Di-nucleon decays $pp \to K^+K^+$ highly suppressed for higher generational couplings (CKM + loop suppressed)
- Binary pulsar constraints no longer benefit from pure tree-level couplings to Λ-baryons
- Binary pulsar set leading bounds below m_ψ < 1.3 GeV → collider searches probe higher masses

What about dark matter laboratory searches?

ψ can be the dark matter if:

$$m_p - m_e < m_\psi < m_p + m_e$$

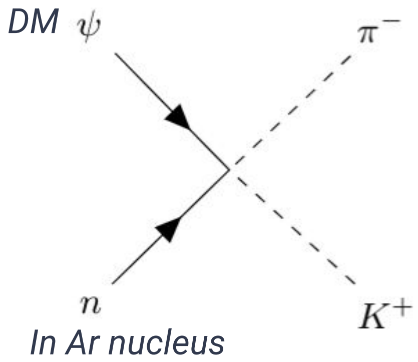
Consider the Earth-captured ambient DM flux through a large detector:

$$f_\psi(\vec{v}) = \frac{1}{N_{\rm esc}\pi^{3/2}v_0^3} \exp\left(-\frac{(\vec{v}+\vec{v}_\oplus)^2}{v_0^2}\right)\Theta(v_{\rm esc} - |\vec{v}+\vec{v}_\oplus|)$$

Then look for $\psi\, n \rightarrow \pi^- K^+$ in the detector; <u>a very unique final state!</u>

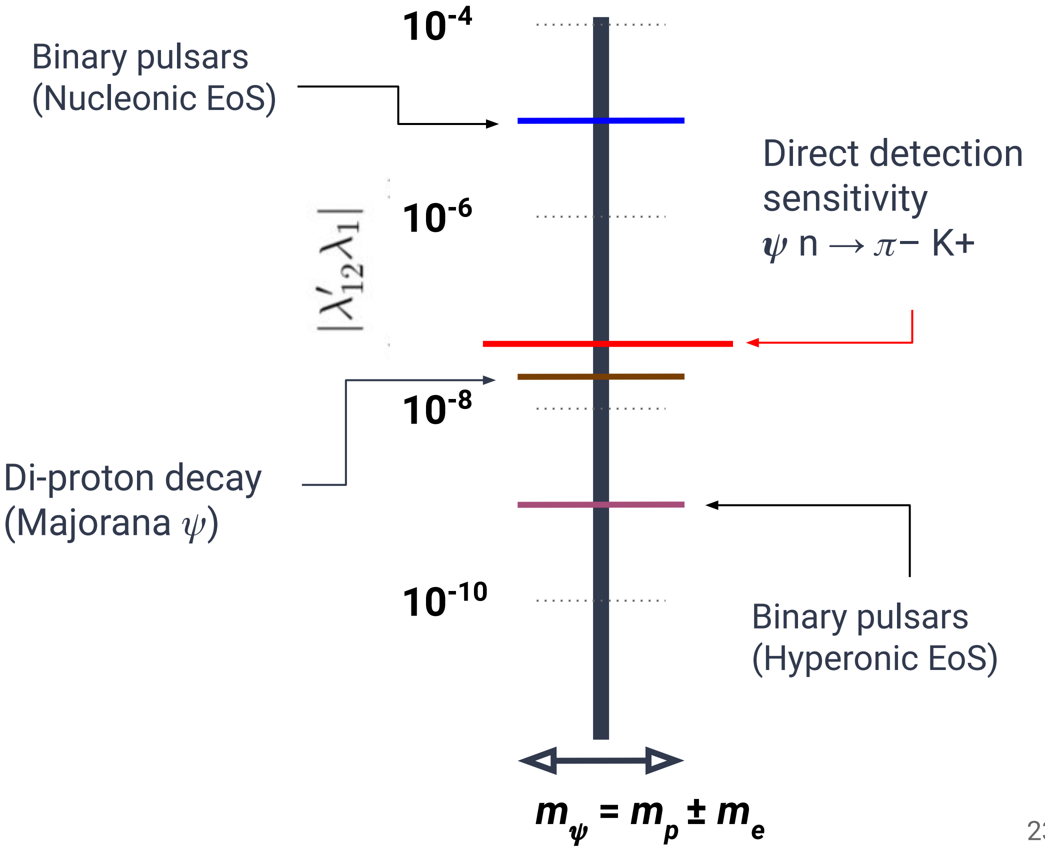
E.g. DUNE Far Detector (FD):

$$|\lambda_1 \lambda'_{12}| > 2.69 \times 10^{-7} \left(\frac{m_X}{\rm TeV}\right)^2 \quad \text{DUNE-FD sensitivity to DM, 90\% CL}$$



What about dark matter laboratory searches?

- Alternatively, ψ could be Dirac with *B=+1* and assign *B=-⅔* for the heavy *X* mediator
- In this case, B is conserved…but hidden away in the dark sector
- For Dirac ψ, the di-proton decay channel vanishes



Outlook

- Neutron stars are extremely sensitive probes of baryon number violation; sensitive to TeV scale mediators
- Whether or not NS have hyperonic EoS makes a huge difference – a good motivation to study nuclear matter and strange physics!
- Laboratory probes and colliders complimentary to these bounds for larger masses of the Majorana fermion > GeV, and for higher-generational couplings

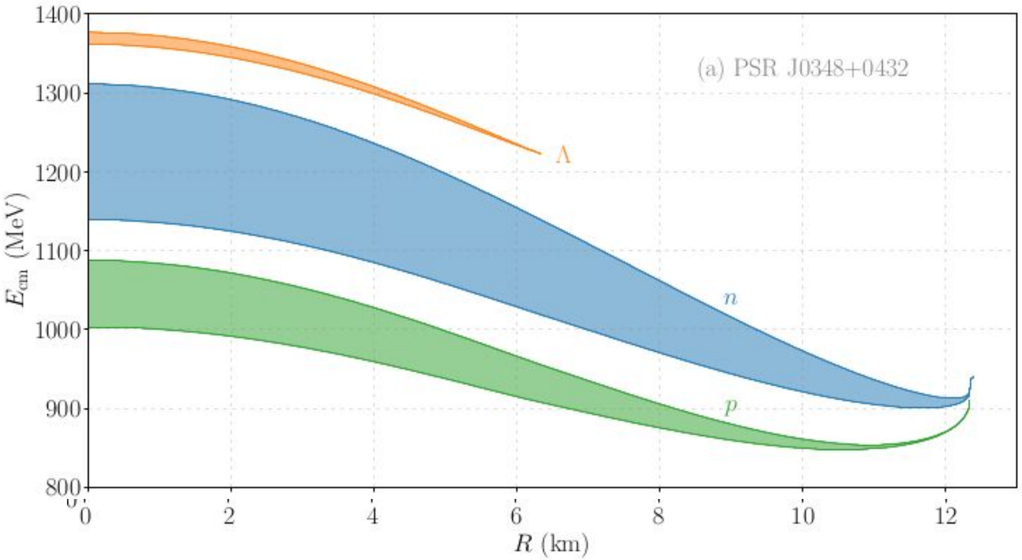
Backup Deck

Enhancement of the Baryon CM Energy in Dense Matter

Vector meson self-energy

$$k^{*\mu} \equiv k^{\mu} - \Sigma^{\mu} = \left\{ E^{*}(k^{*}), \vec{k} - \vec{\Sigma} \right\}$$

- In the dense nuclear matter, baryons get a kinetic mass which lifts the available energy in the CM frame
- This allows us to probe decays that would otherwise be kinematically forbidden in vacuum!
  - → We can decay to ψ with masses up to ~1.5 GeV



Impact of ΔB processes on the Star's spin rate

Berryman, Gardner, Zakeri [2305.13377]
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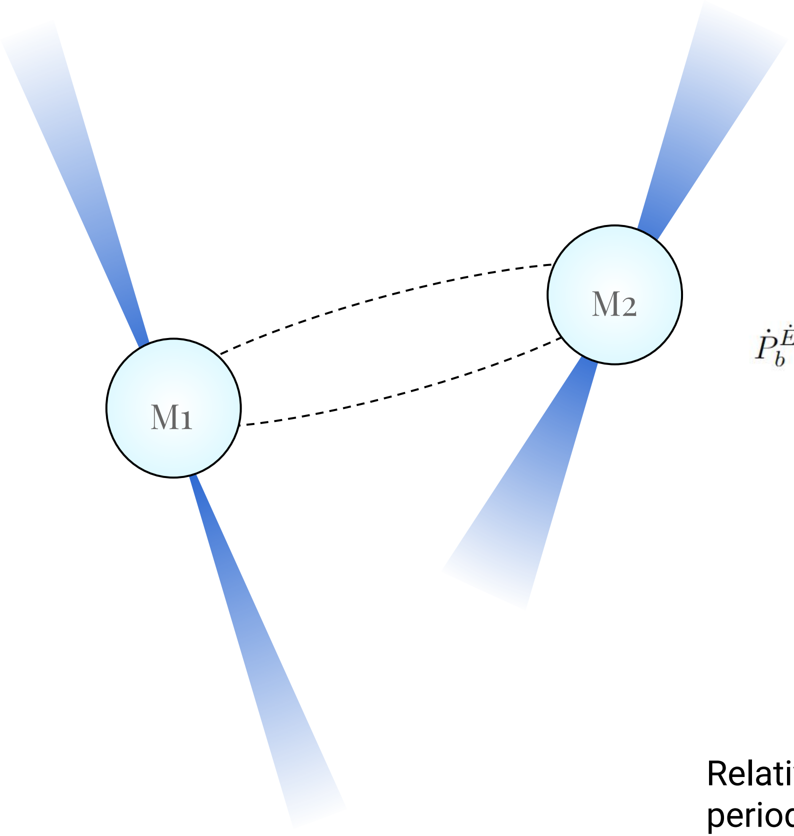


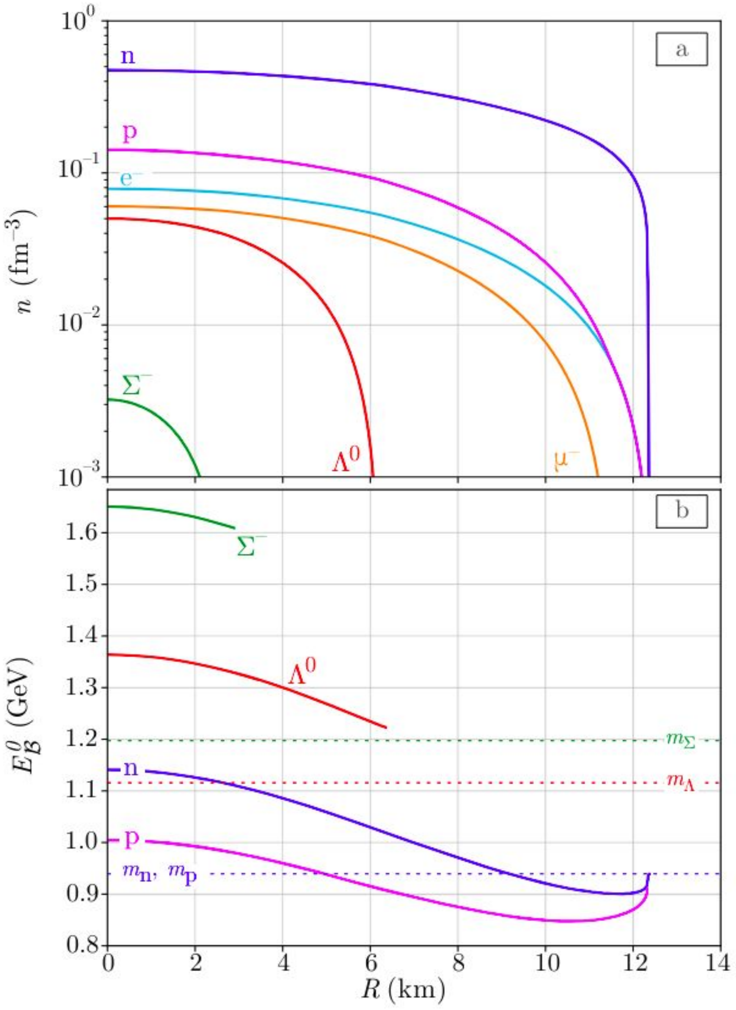
$$\frac{\dot{B}}{4\pi} = -\int e^{\nu(r)} \left[1 - \frac{2M(r)}{r}\right]^{-\frac{1}{2}} \Gamma_{\rm nm}(r)\, n(r)\, r^2\, dr$$

$$\dot{P}_b^{\dot{E}} = -2\left(\frac{\dot{M}_1^{\rm eff} + \dot{M}_2^{\rm eff}}{M_1 + M_2}\right) P_b; \qquad \dot{M}^{\rm eff} = \left(\partial_{\mathcal{E}_c} M + \left(\frac{\Omega^2}{2}\right)\partial_{\mathcal{E}_c} I\right)\left(\frac{\dot{B}}{\partial_{\mathcal{E}_c} B}\right)$$

$$\left(\frac{\dot{P}_b}{P_b}\right)^{\rm obs} = \underbrace{\left(\frac{\dot{P}_b}{P_b}\right)^{\rm GR} + \left(\frac{\dot{P}_b}{P_b}\right)^{\dot{E}}}_{\rm intrinsic} + \left(\frac{\dot{P}_b}{P_b}\right)^{\rm ext}$$

Relative rate of orbital period decay

BNV perturbs the energy loss term



Neutron Star Hyperonic EoS