# *Insights* into **Dark Matter** and **Baryogenesis** from Binary Pulsar Data

arXiv:2409.08178

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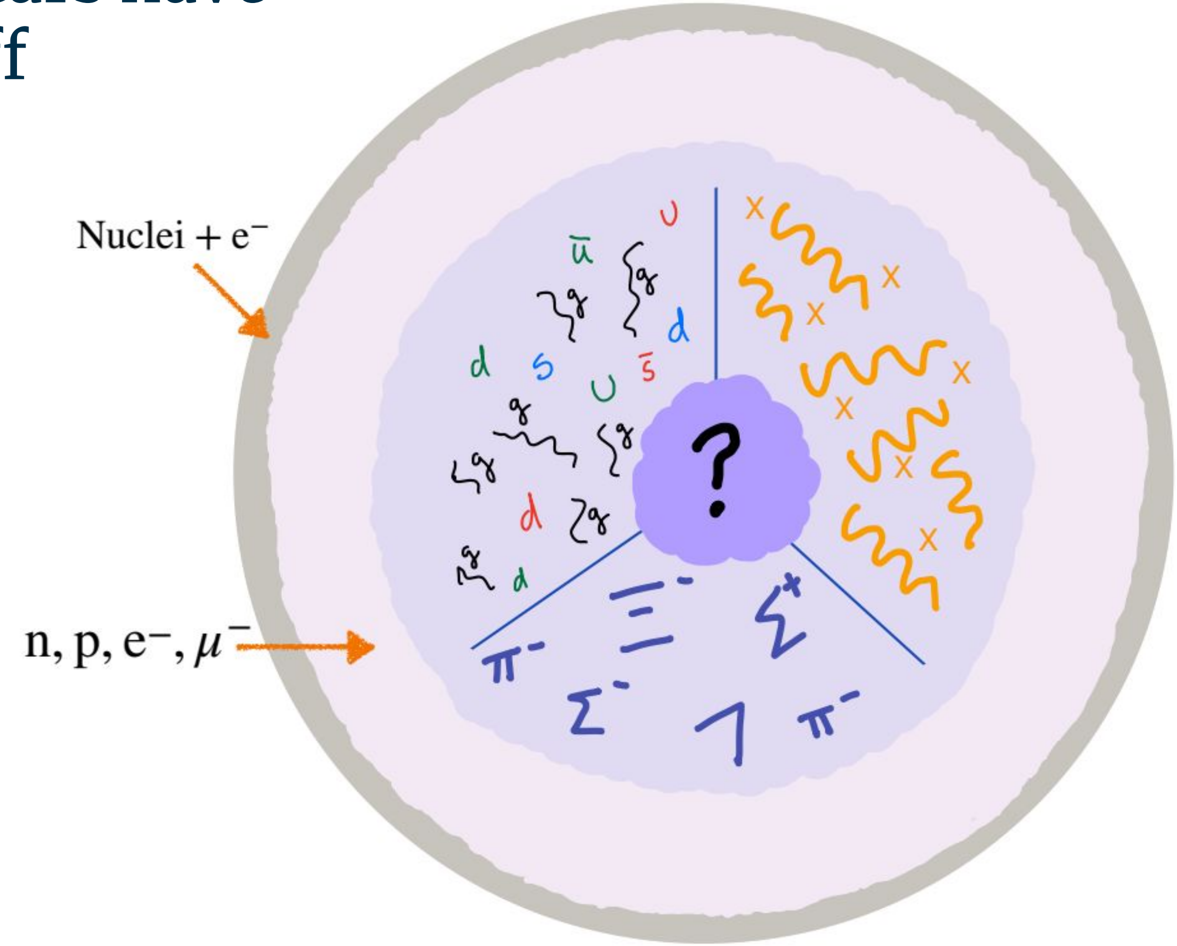
# Motivation

- Baryogenesis and *B* violation
- Dark matter - baryon number coincidence puzzle ($5\Omega_B \sim \Omega_{DM}$)
- N-Nbar oscillations

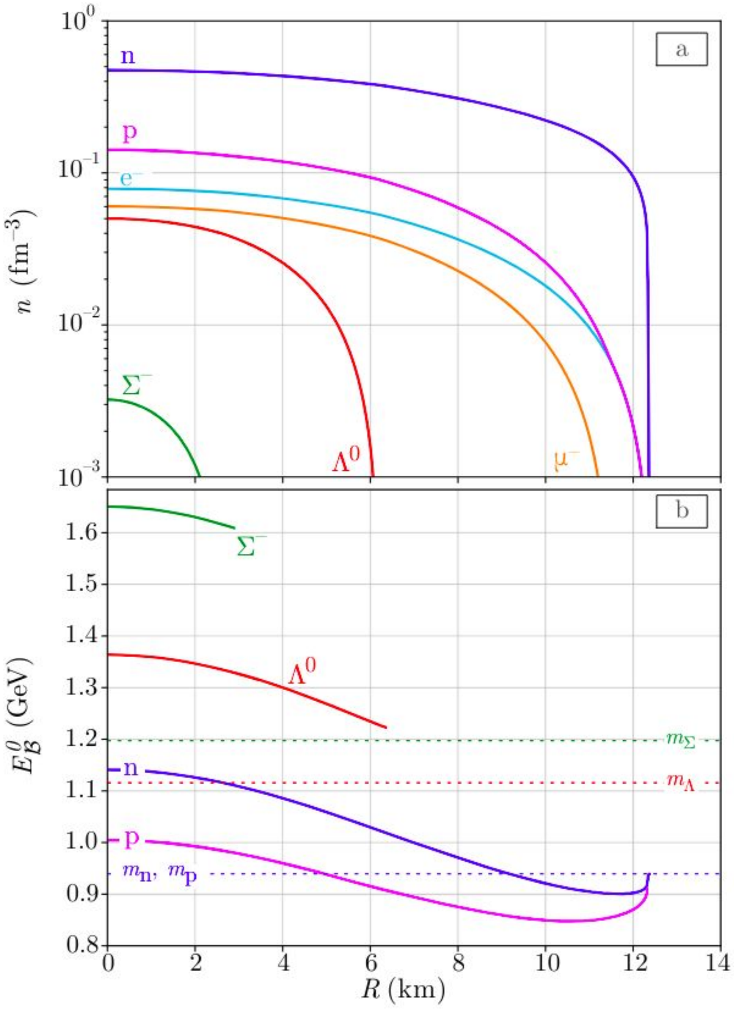
Basic Question: How can neutron stars constrain Baryogenesis models?

Can those constraints motivate complementary searches?

# Neutron Stars have lots of stuff




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




# Neutron Star EoS Example: Hyperonic EoS

- We have a variety of hypothetical neutron star equations of state (EoS) with or without hyperons (“Hyperonic” / “Nucleonic”)
- The zero-point energy in the baryon rest frame is raised by scalar/vector meson VEVs in the dense nuclear matter (e.g. see 2305.13377)

# Our Model: A Majorana fermion + color-triplet scalar

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

(suppressing color indices)

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

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

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- If $X_{1,2}$ have CP-violating phases, baryon asymmetry can be explained after non-thermal production of $X_{1,2}$
- If $(m_p - m_e) < m_\psi < (m_p + m_e)$ $\psi$ can be the DM, proton stable
- $\lambda'$=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]
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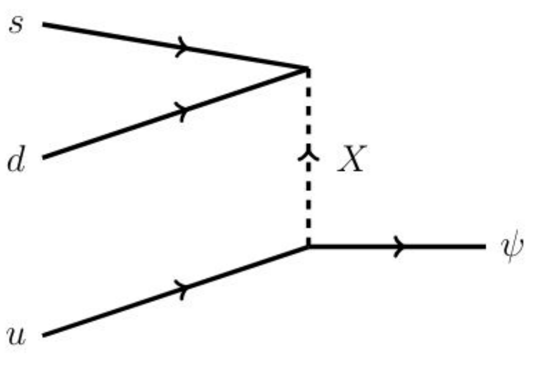
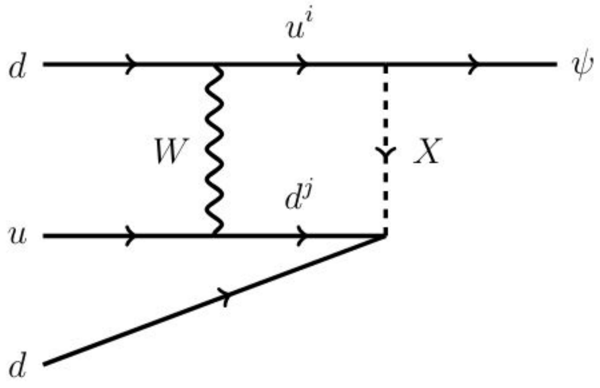
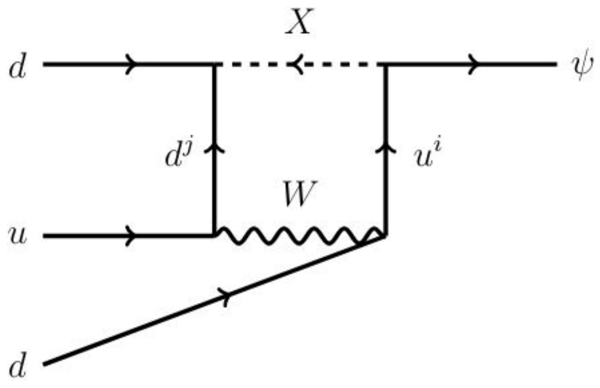
# Generating a Baryon Mixing to $\psi$ ($\Delta B$=1)

**$\Lambda \leftrightarrow \psi$ mixing**




**$n \leftrightarrow \psi$ mixing**



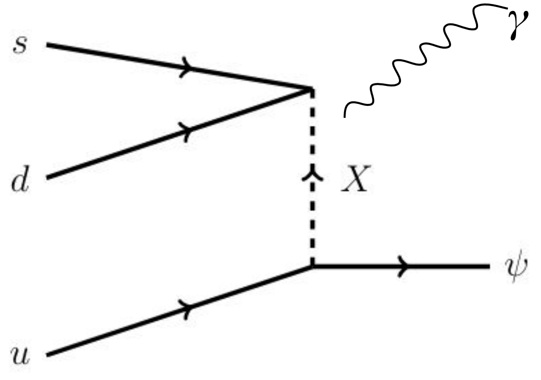




Baryon ($n$,$\Lambda$,...) ⇔ Dark Matter ($\psi$) Mass Mixing

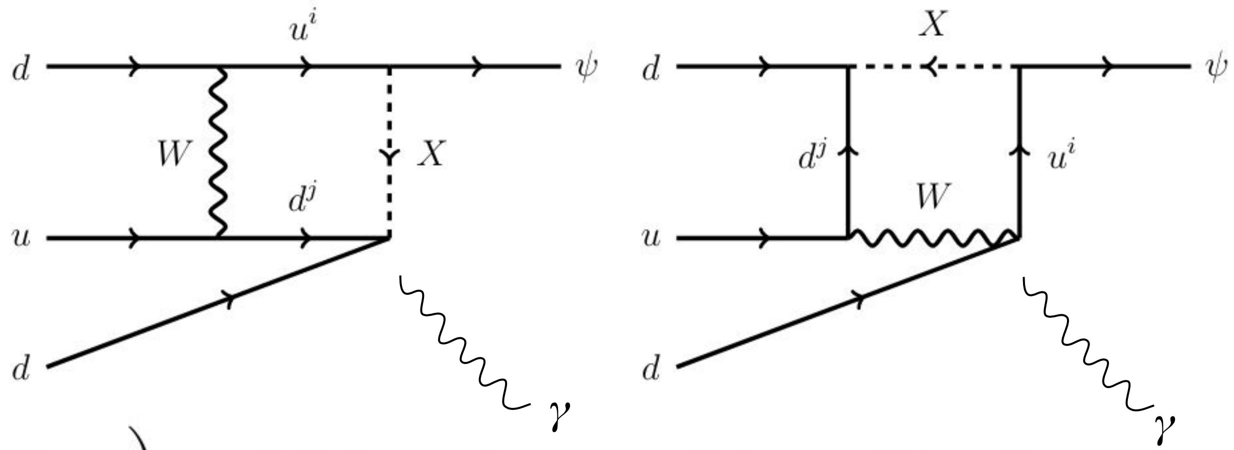
See also Fajfer, Susič 2010.08367 for example
Alonso-Álvarez *et al* (2022)[2111.12712]

# Decays of the Baryons to $\psi$ and a Photon ($\Delta B$=1)

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




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




$$\mathcal{L} = \overline{\mathcal{B}}\left(i\partial\!\!\!/ - \Sigma\!\!\!/_{\mathcal{B}} - m_{\mathcal{B}}^{*} + \frac{g_{\mathcal{B}}e}{8m_{\mathcal{B}}^{*}}\sigma^{\alpha\beta}F_{\alpha\beta}\right)\mathcal{B} + \overline{\psi}\left(i\partial\!\!\!/ - m_{\psi}\right)\psi - \varepsilon_{\mathcal{B}\psi}\left(\overline{\mathcal{B}}P_L\psi + \overline{\psi}P_R\mathcal{B}\right) .$$

$$\varepsilon_{\Lambda\psi}^{\text{tree}} = \beta\frac{\lambda_1\lambda'_{12}}{\sqrt{6}m_X^2}$$

$$\varepsilon_{n\psi} = \frac{G_F\,\gamma_n^L}{\sqrt{2}\,4\pi^2\,m_W^2}\sum_i\sum_{j\neq 1}\lambda_i\lambda'_{1j}V_{i1}V_{1j}^{*}m_{d_j}m_{u_i}\,F(x_{d_j}, x_{u_i}, x_X)$$

# 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

**Expand in $1/f_\pi$**

$$u = e^{i\Phi/f_\pi}$$

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

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:

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

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

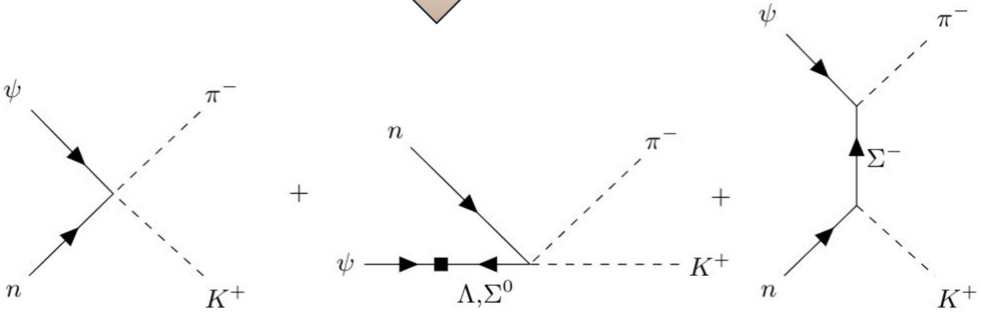
# "Induced Nucleon Decay"

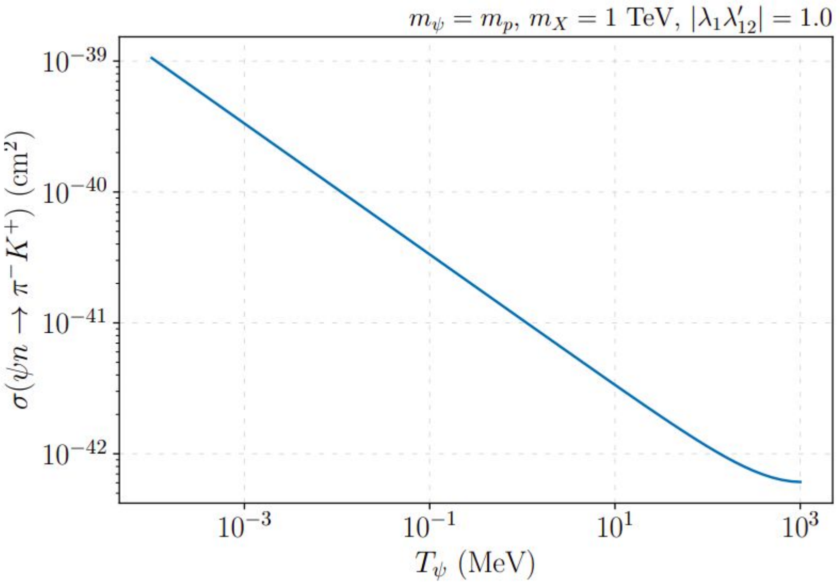
$$\mathcal{L}^{(0)}_{\text{eff,ChPT}} = \beta \text{Tr}[\hat{C}^R u^\dagger B_R \psi u]$$

**+**

$$\mathcal{L}^{(1)}_{\phi B} = \frac{D}{2}\text{Tr}\left(\overline{B}\gamma^\mu\gamma_5\{u_\mu, B\}\right) + \frac{F}{2}\text{Tr}\left(\overline{B}\gamma^\mu\gamma_5[u_\mu, B]\right)$$

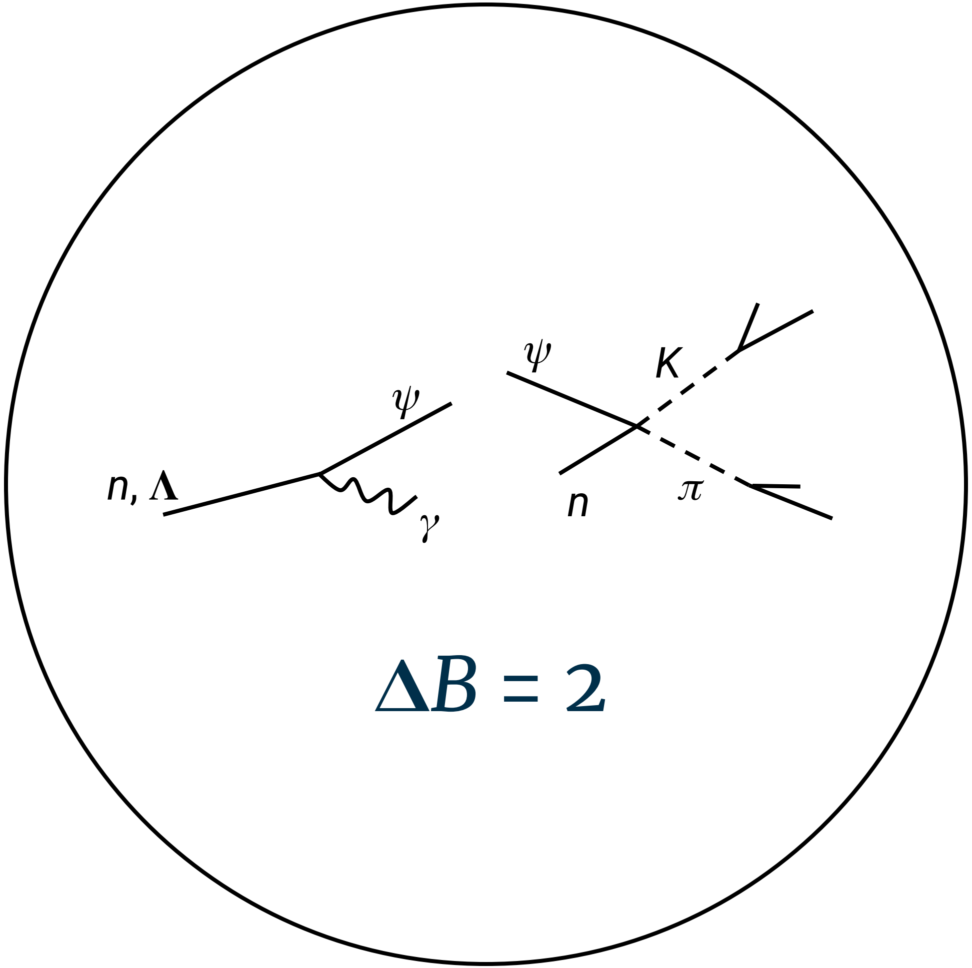
***(ds)uψ***




See e.g. Davoudiasl *et al* (2011)
Alonso-Álvarez *et al* (2022)

Neutron Star



# Several ways baryon loss can be constrained in the NS

Mass Loss in Neutron Star (Pulsar) Binary Systems, e.g. [2201.02637]

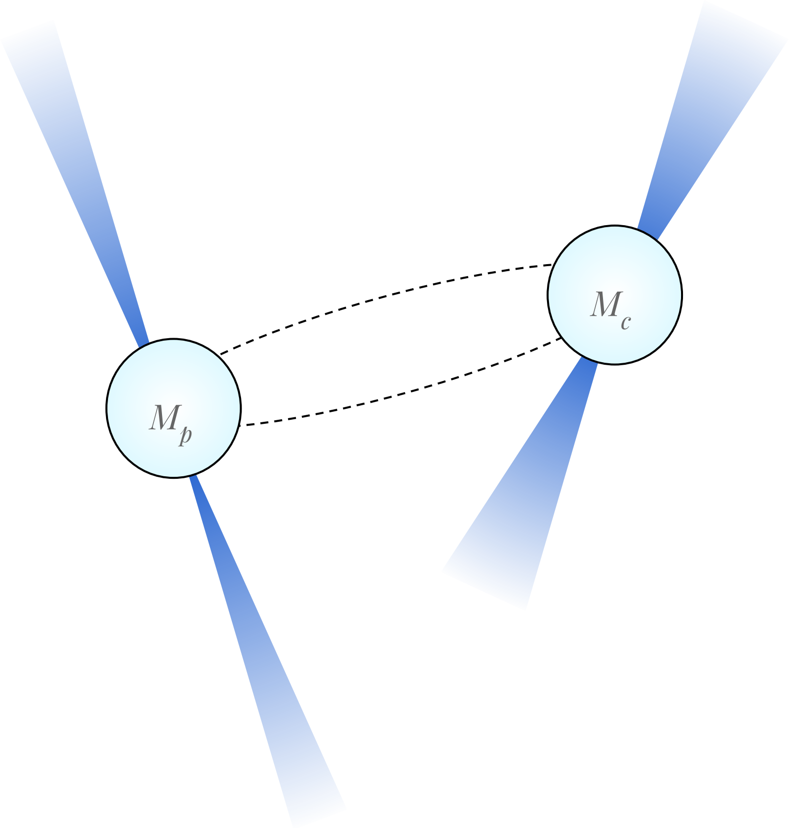
Perturb the Equation of State (EoS) and lower the NS mass limit, e.g. [1802.08244]

Heating of the Neutron Star, e.g. [2405.18472], [2407.03450]

etc…

# Impact of $\Delta B$ processes on Binary Pulsars

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




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

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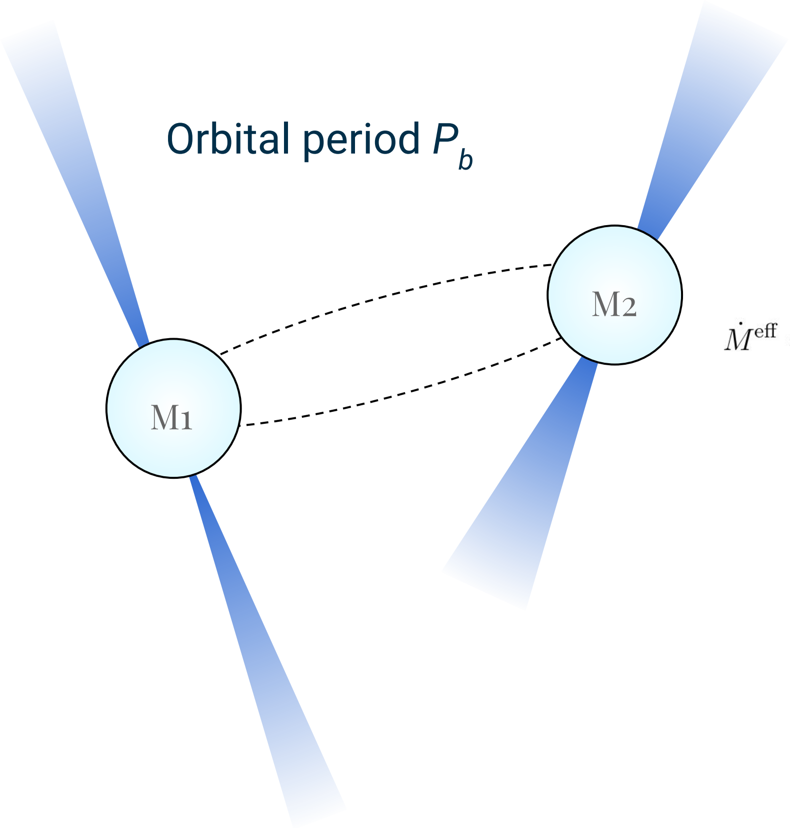


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$$\dot{M}^{\rm eff} = \underbrace{\eta^{(M)} \left(\frac{\dot{B}}{B}\right) M + \eta^{(I)} \left(\frac{\dot{B}}{B}\right) \left(\frac{2\pi^2 I}{P_s^2}\right)}_{\rm BNV} - \frac{4\pi^2 I \dot{P}_s}{P_s^3}$$

$$\left(\frac{\dot{P}_b}{P_b}\right)^{\dot{E}} = -2 \left(\frac{\dot{M}_1^{\rm eff} + \dot{M}_2^{\rm eff}}{M_1 + M_2}\right)$$

# Impact of $\Delta B$ processes on Binary Pulsars

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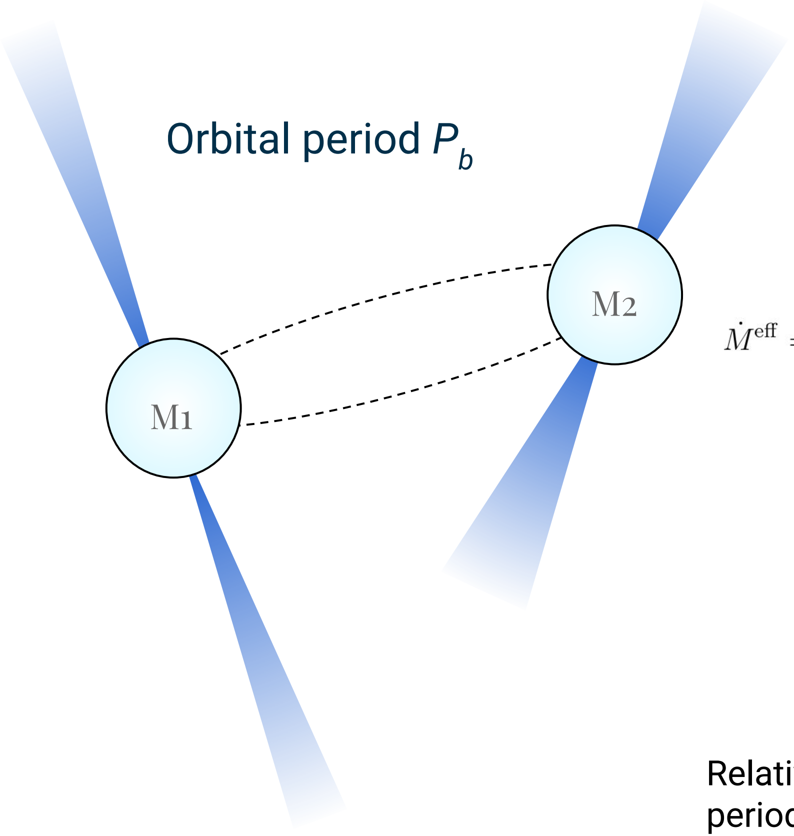


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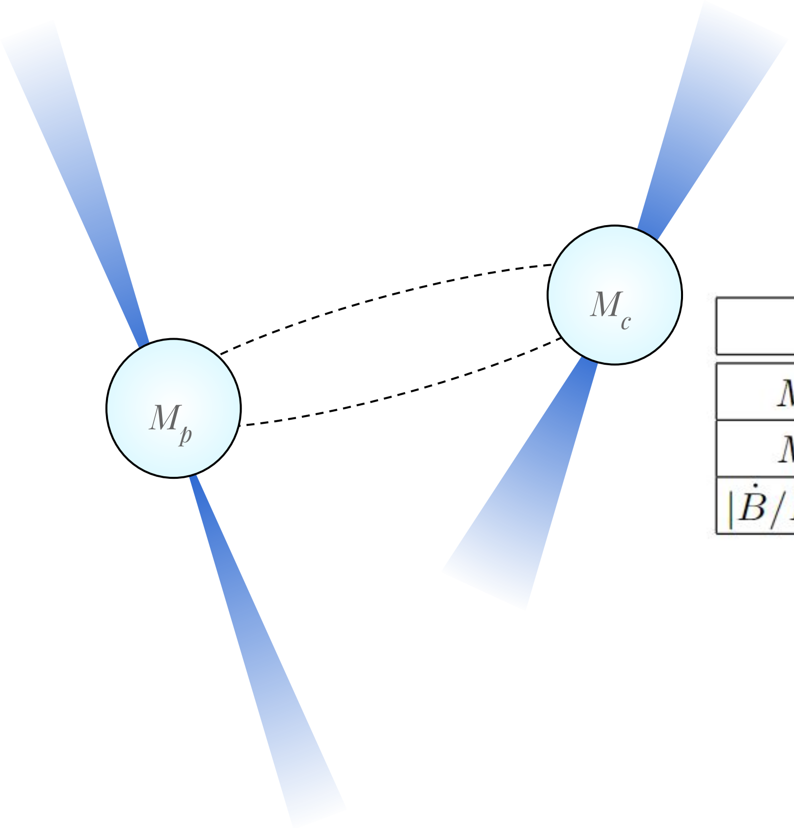
$$\left(\frac{\dot{P}_b}{P_b}\right)^{\rm obs} = \underbrace{\left(\frac{\dot{P}_b}{P_b}\right)^{\rm GR} + \left(\frac{\dot{P}_b}{P_b}\right)^{\dot{E}}}_{\rm intrinsic} + \left(\frac{\dot{P}_b}{P_b}\right)^{\rm ext}$$

Relative rate of orbital period decay

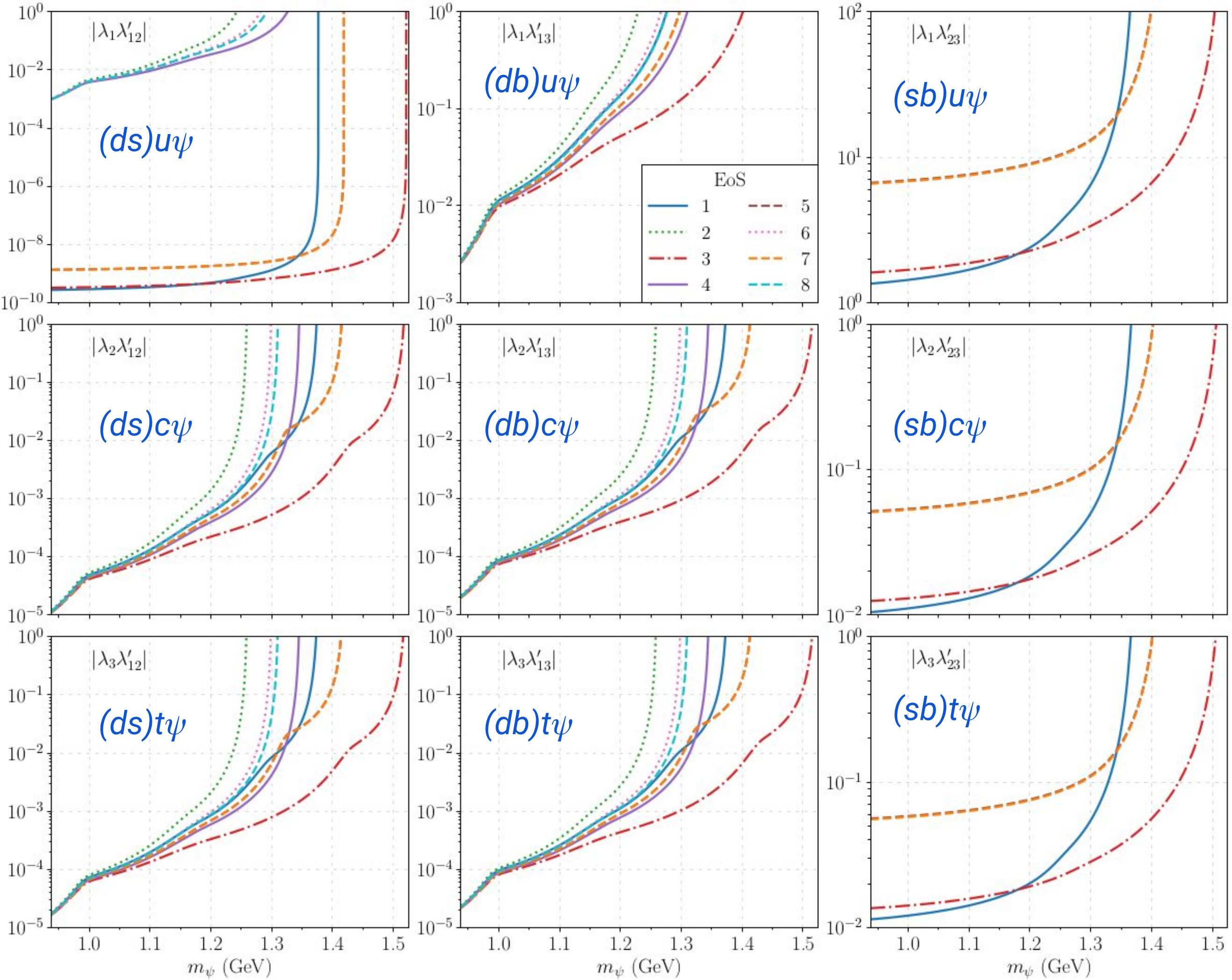
BNV perturbs the energy loss term

# Systems in this study




**White dwarf / pulsar binaries** | **Double pulsar**

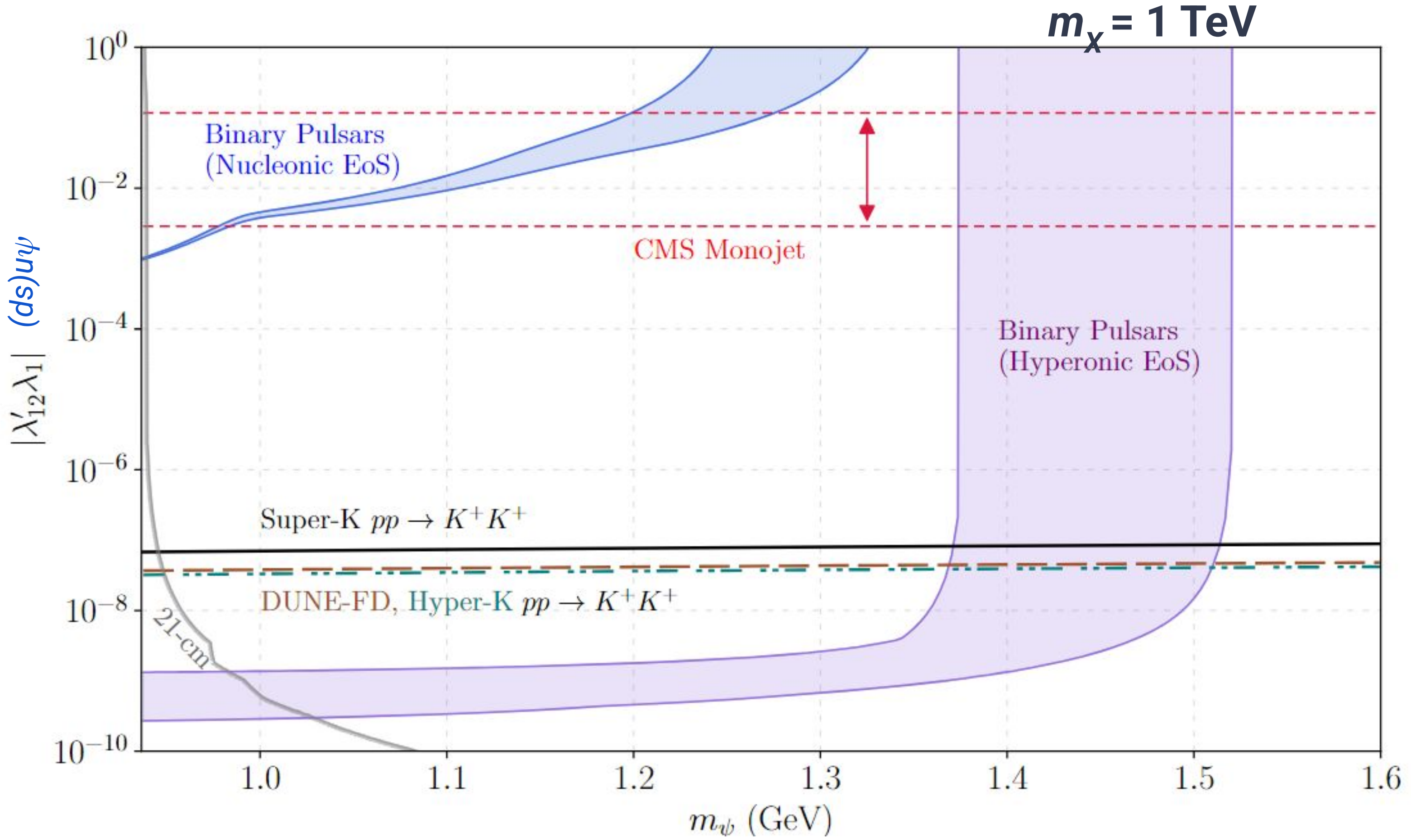
| Name | J0348+0432 | J1614−2230 | J0737−3039A/B |
|---|---|---|---|
| $M_p\,(M_\odot)$ | 2.01(4) | 1.908(16) | 1.338 185(+12, −14) [A] |
| $M_c\,(M_\odot)$ | 0.172(3) | 0.493(3) | 1.248 868(+13, −11) [B] |
| $\lvert\dot{B}/B\rvert_{2\sigma}\,(\mathrm{yr}^{-1})$ | $1.8 \times 10^{-10}$ | $2.0 \times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




- 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!

$m_X$ = 1 TeV

# Comparison with Laboratory Limits: lowest quark generation couplings



# Comparison with Laboratory Limits: lowest quark generation couplings

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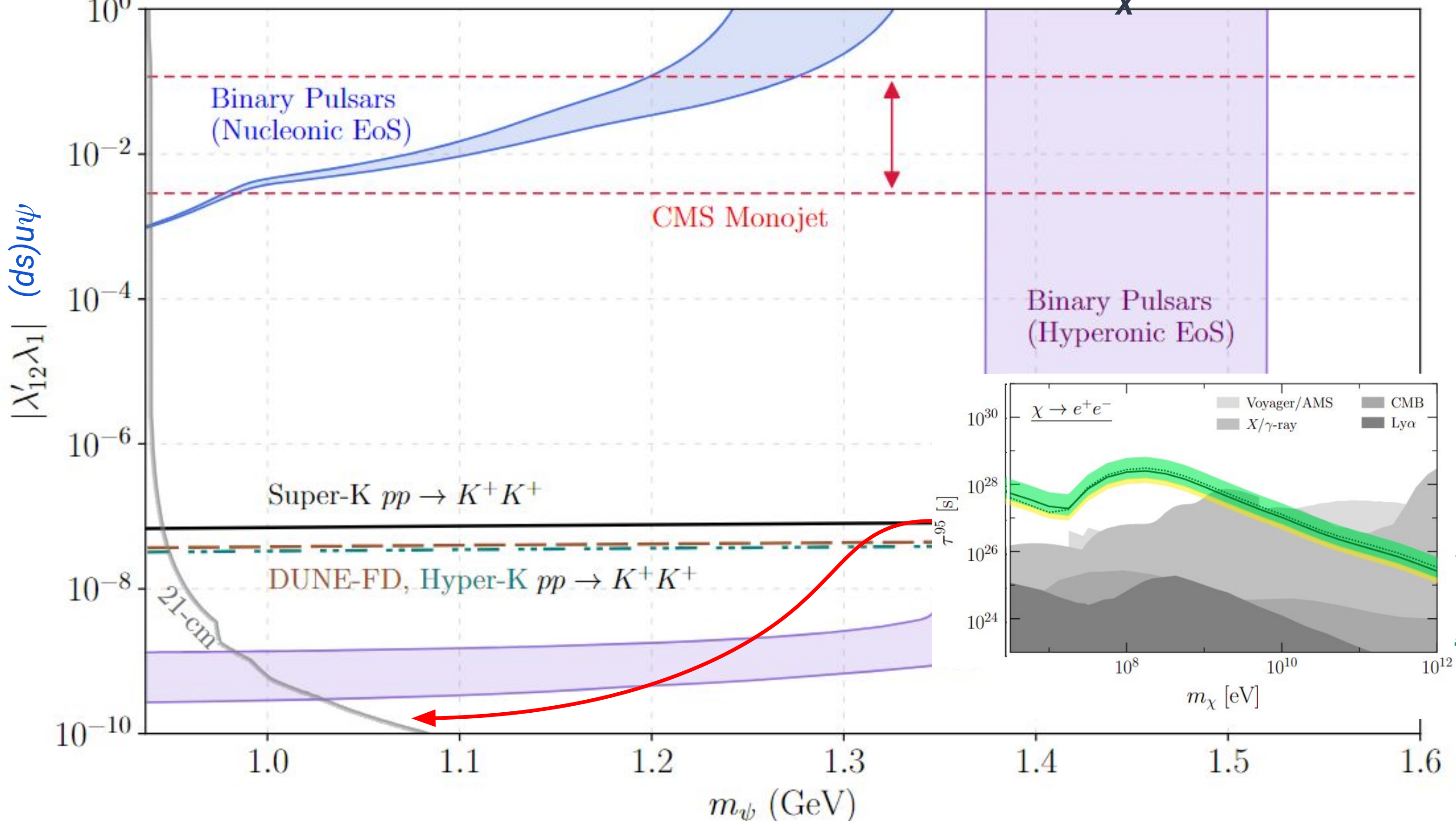
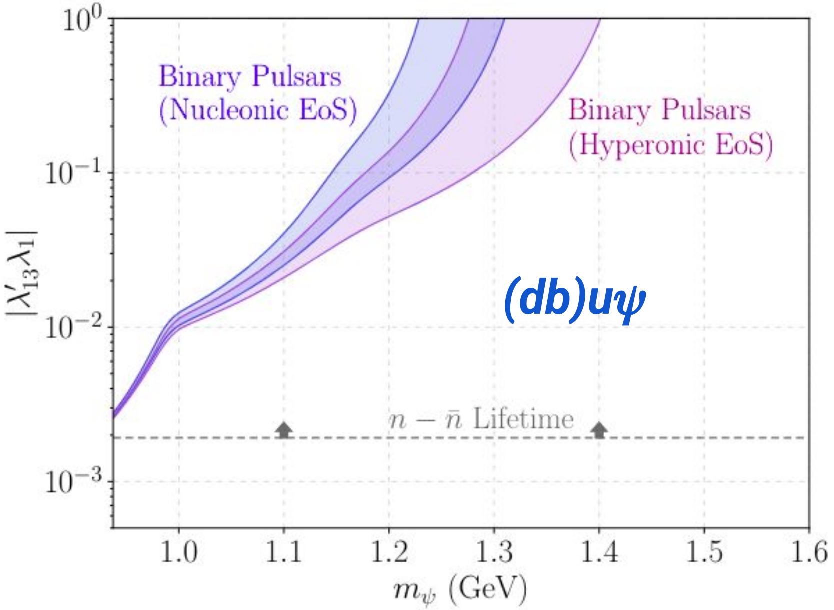


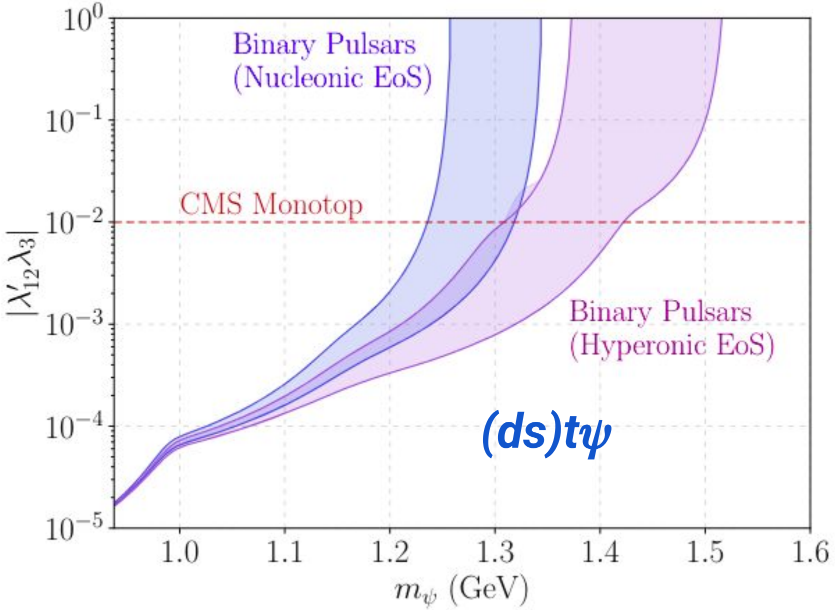

$\psi \to p\, e^- \nu$

Recast of 21-cm decaying DM limits, e.g. 2312.11608

# Other Flavor Combination Couplings

$m_X = 1$ TeV




$$\mathcal{L}_{n\bar{n}} = \frac{(\lambda'_{1j})^2\lambda_1}{m_X^2}[\psi^\dagger u_R][d_R^T(i\sigma_2)d_R^j][d_R^T(i\sigma_2)d_R^j]^\dagger, \qquad \Gamma_{n\bar{n}} \simeq \Lambda_{\rm QCD}^6 \frac{\lambda_1^2(\lambda'_{1j})^4 m_\psi}{16\pi^2 m_X^6} \ln\left(\frac{m_X^2}{m_\psi^2}\right)$$

(Dev, Mohapatra 2015)

# What about dark matter laboratory searches?

$\psi$ can be the dark matter if:

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

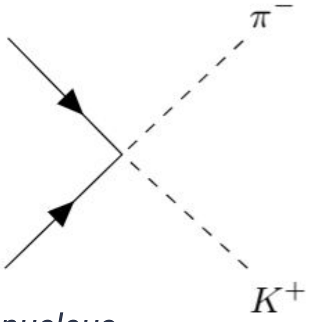
Consider the Earth-captured ambient DM flux through a large detector:

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

Then look for $\psi\, n \to \pi^- K^+$ in the detector

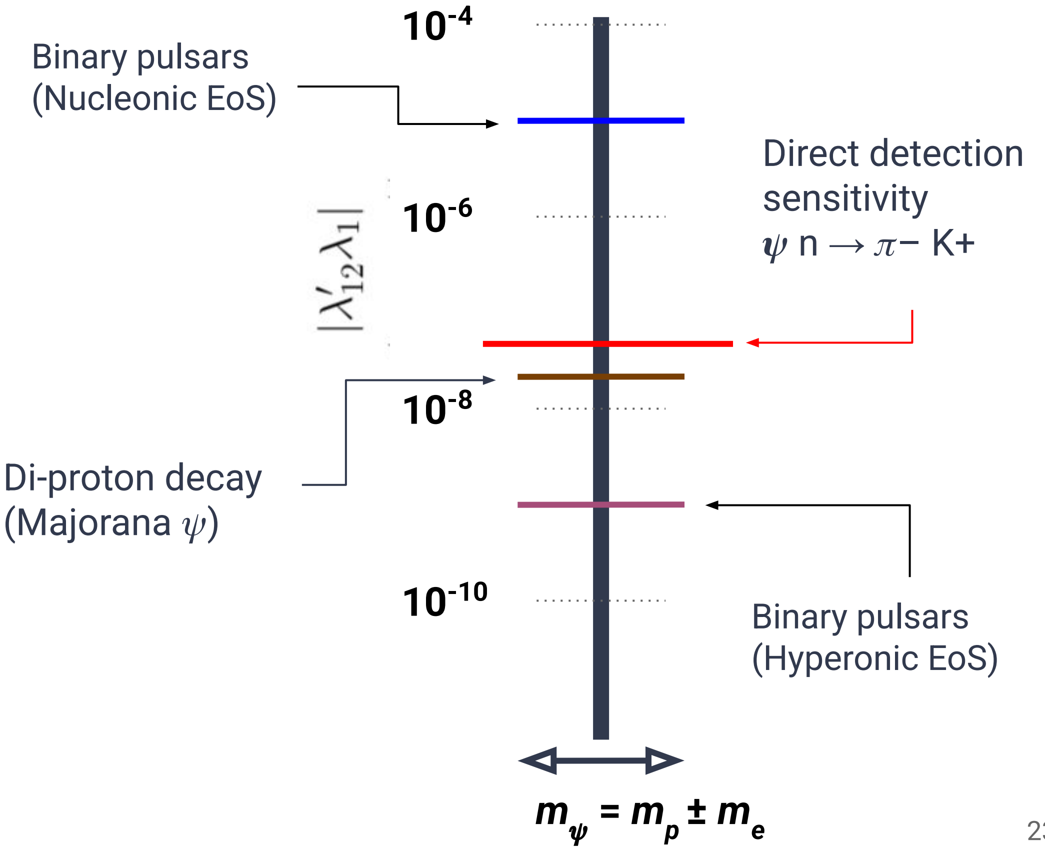
E.g. DUNE Far Detector (FD):

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



# What about dark matter laboratory searches?

- Alternatively, $\psi$ 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 $\psi$, the di-proton decay channel vanishes

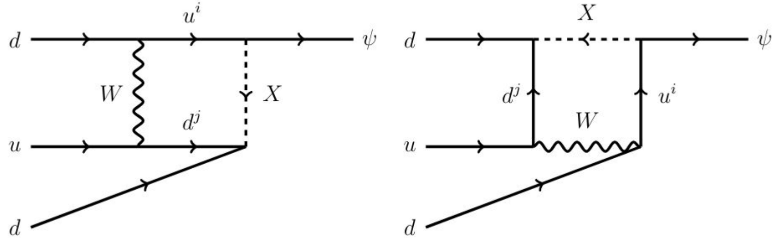


# Outlook

- Neutron stars are extremely sensitive probes of baryon number violation; sensitive to TeV scale mediators
- Hyperonic/Nucleonic EoS can have very different impact
- Laboratory probes (colliders, rare decay searches, nnbar etc..) probe complementary parts of the parameter space
- Thank you!

# *Backup Deck*

# Example: Neutron Decay Rate in the Nuclear Matter Frame




$$\gamma_n^L P_R u_n \equiv \langle 0 | \left[\epsilon_{\alpha\beta\gamma}\, u^{\alpha T} C P_L d^\beta\right] \left[P_R d^\gamma\right] | n \rangle$$

In the nuclear matter frame:

$$\frac{dn_{\mathcal{B}}}{d\tau} = -\frac{\varepsilon_{B\psi}^2 g_{\mathcal{B}}^2 e^2}{128\pi^3}(m_{\mathcal{B}}^*)^2 \int_1^{x_F} dx\,\sqrt{x^2-1} \times \frac{1+2x\sigma+\sigma^2-\mu^2}{(1+2x\sigma+\sigma^2)^2}$$
$$\times \left[(1+2x\sigma+\sigma^2)(1+x\sigma+2\mu)+\mu^2(1+x\sigma)\right]$$

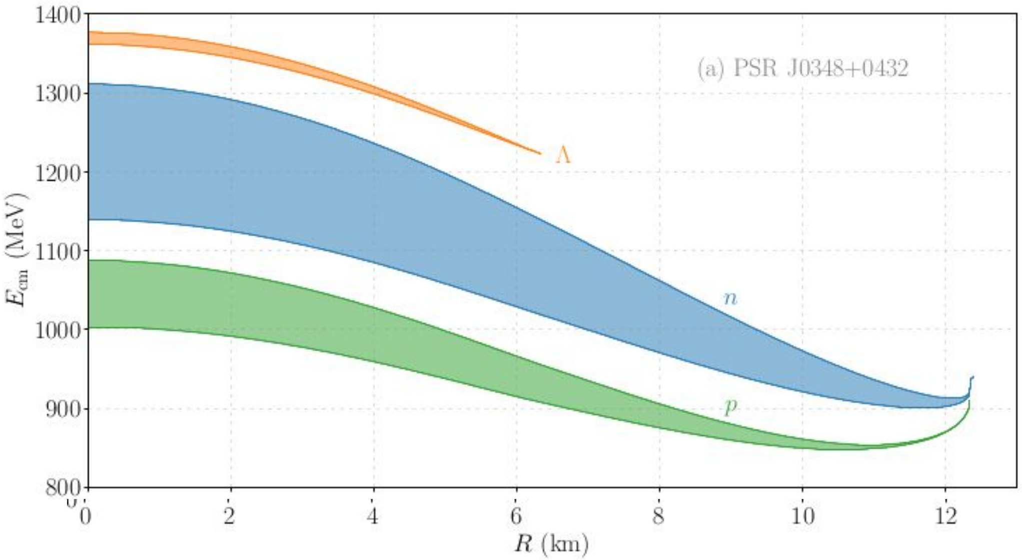
$$x \equiv \frac{E_{\mathcal{B}}^{*,(\mathrm{n.m.})}}{m_{\mathcal{B}}^*}, \qquad x_F \equiv \frac{E_{F,\mathcal{B}}^{*,(\mathrm{n.m.})}}{m_{\mathcal{B}}^*}, \qquad \sigma \equiv \frac{\Sigma_{\mathcal{B}}^{(\mathrm{n.m.}),0}}{m_{\mathcal{B}}^*}, \qquad \mu \equiv \frac{m_\psi}{m_{\mathcal{B}}^*}$$

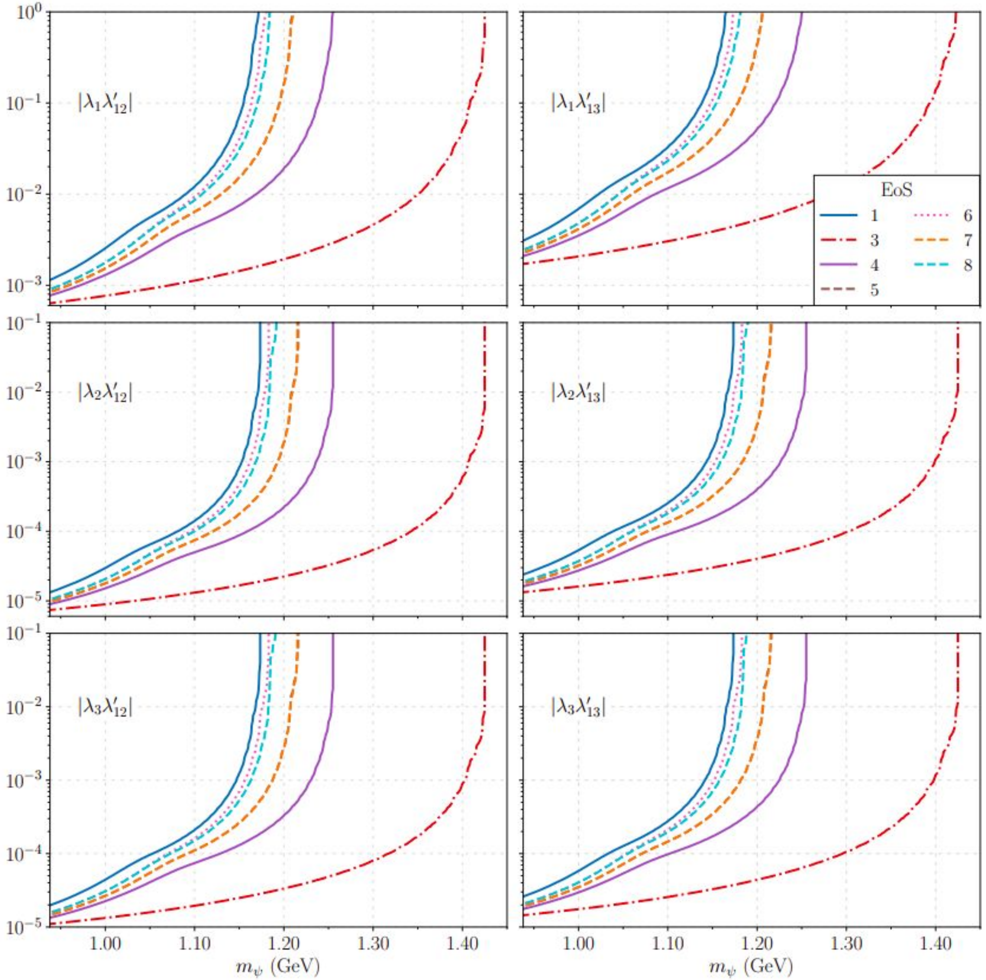
# Enhancement of the Baryon CM Energy in Dense Matter

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






## $n \to \pi^0 \psi$

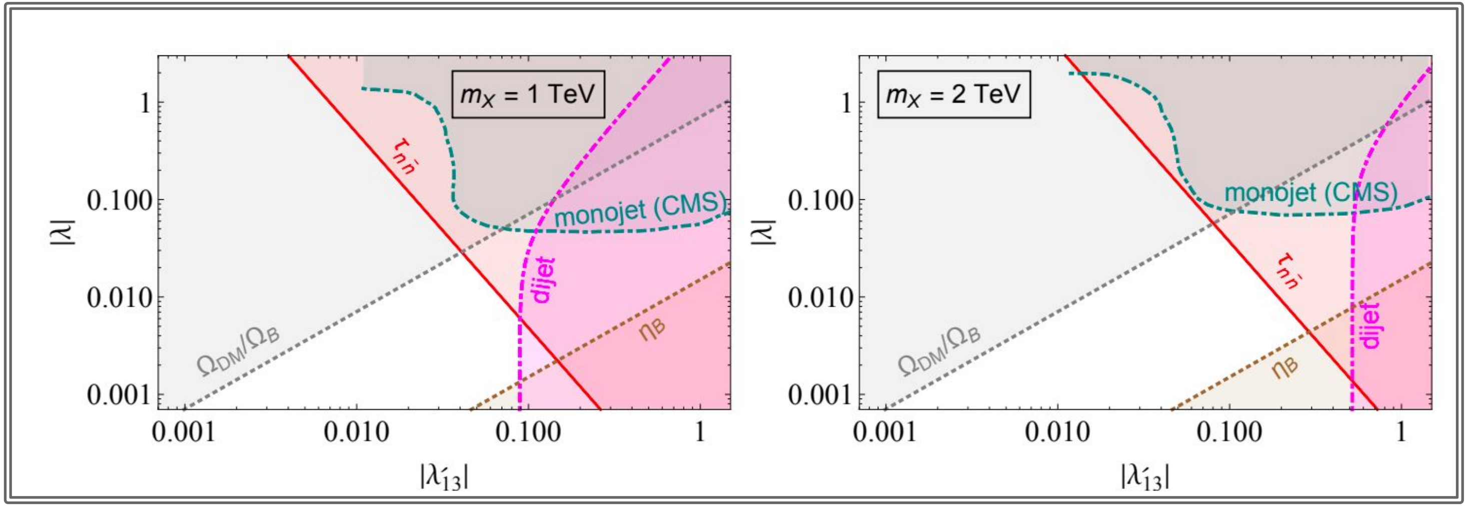
$$\mathcal{M}_m = \frac{iG_F}{\sqrt{2}\, 8\pi^2 m_W^2} \sum_i \sum_{j\neq 1} \lambda_i \lambda'_{1j} V_{i1} V^*_{1j} m_{d_j} m_{u_i} F(x_{d_j}, x_{u_i}, x_X) \times \bar{u}_\psi P_R \left[W^L_{n0}(q^{*2}) - \not{q}^* W^L_{n1}(q^{*2})\right] u_n,$$

$$W^{L,\text{pole}}_{n0}(q^{*2}) = \left(\frac{-\beta b_n}{f}\right) \frac{q^{*2} + m_n^{*2}}{m_n^{*2} - q^{*2}} - \frac{\beta}{f} c_n,$$

$$W^{L,\text{pole}}_{n1}(q^{*2}) = \left(\frac{-\beta b_n}{f}\right) \frac{2m_n^*}{m_n^{*2} - q^{*2}},$$

# Baryogenesis Parameter Space

From [1712.02713]




$$
\epsilon_\alpha = \frac{1}{8\pi} \frac{\sum_{ijk} \mathrm{Im}(\lambda^*_{\alpha k} \lambda_{\beta k} \lambda'^*_{\alpha ij} \lambda'_{\beta ij})}{\sum_i |\lambda_{\alpha i}|^2 + \sum_{ij} |\lambda'_{\alpha ij}|^2} \times \frac{(m^2_{X_\alpha} - m^2_{X_\beta}) m_{X_\alpha} m_{X_\beta}}{(m^2_{X_\alpha} - m^2_{X_\beta})^2 + m^2_{X_\alpha} \Gamma^2_{X_\beta}}
$$

# 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:**

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

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

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

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

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

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

***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 $1/f_\pi^2$

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

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

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

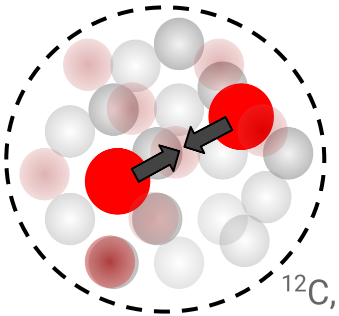
***Second order expansion:***

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

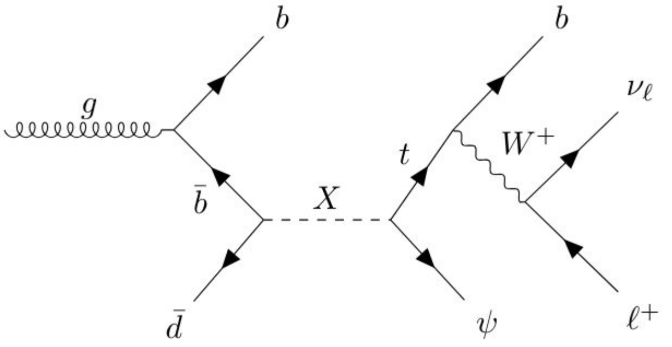
# Laboratory Probes

See [2404.14844]

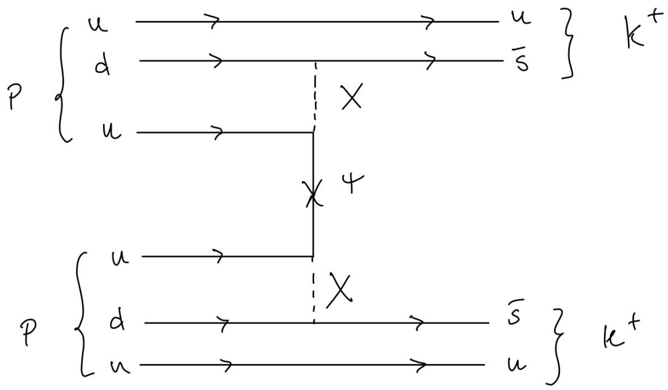
- Collider searches:
    - Monotop, Monojet, and missing energy searches
- BES-III, LHCb: see [2111.12712]
- Di-nucleon decay searches:
    - Super-K: large volume search for spontaneous di-proton decay
    - DUNE-FD, Hyper-K



$^{12}$C, $^{40}$Ar ...




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



# Possibility of dark sector states escaping the star?