New Physics with Continuous GWs:

Pulsar Timing Constraints on New Energy Loss Mechanisms in Neutron Stars

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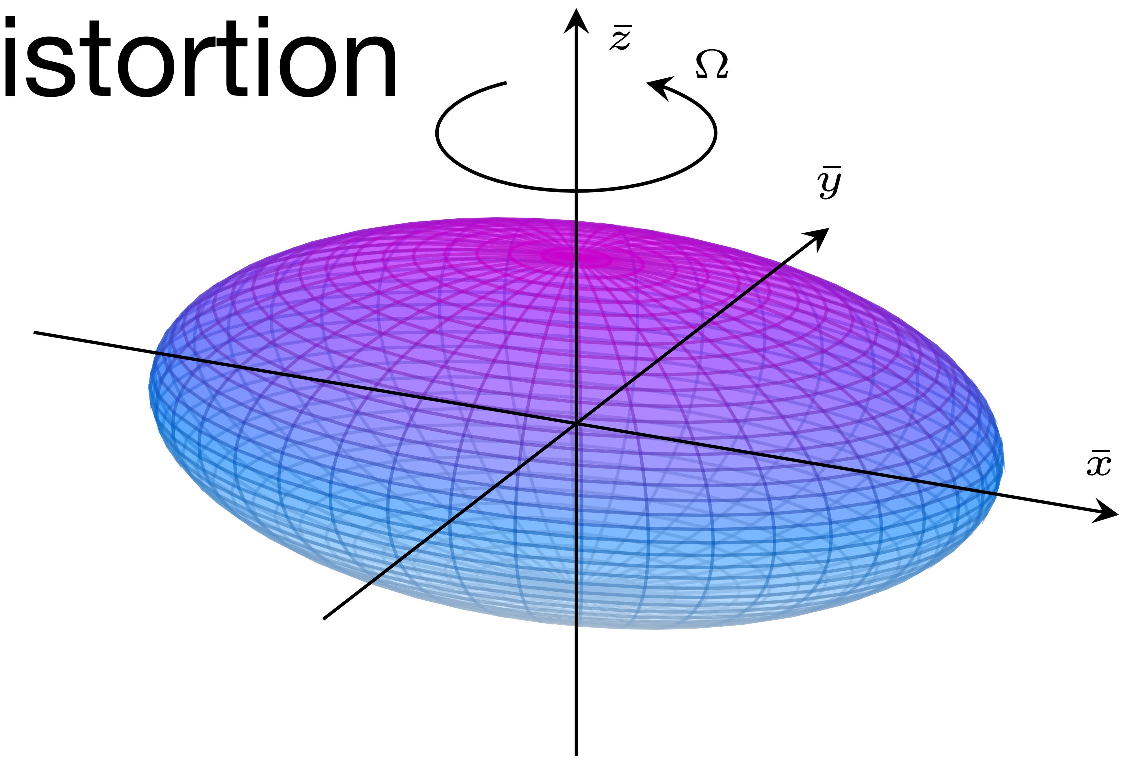
Example: in collaboration with
Mohammadreza “Zaki” Zakeri [UK → EKU] ,
in preparation & 2311.13649 [Universe **2024**, 10, 67]
and
Jeff Berryman [N3AS, VPI → LLNL] & Mohammadreza Zakeri,
2201.02637 [Symmetry **2022**, 14(3), 518] &
2305.13377 [Phys. Rev. D 109, 023021 (2024)]

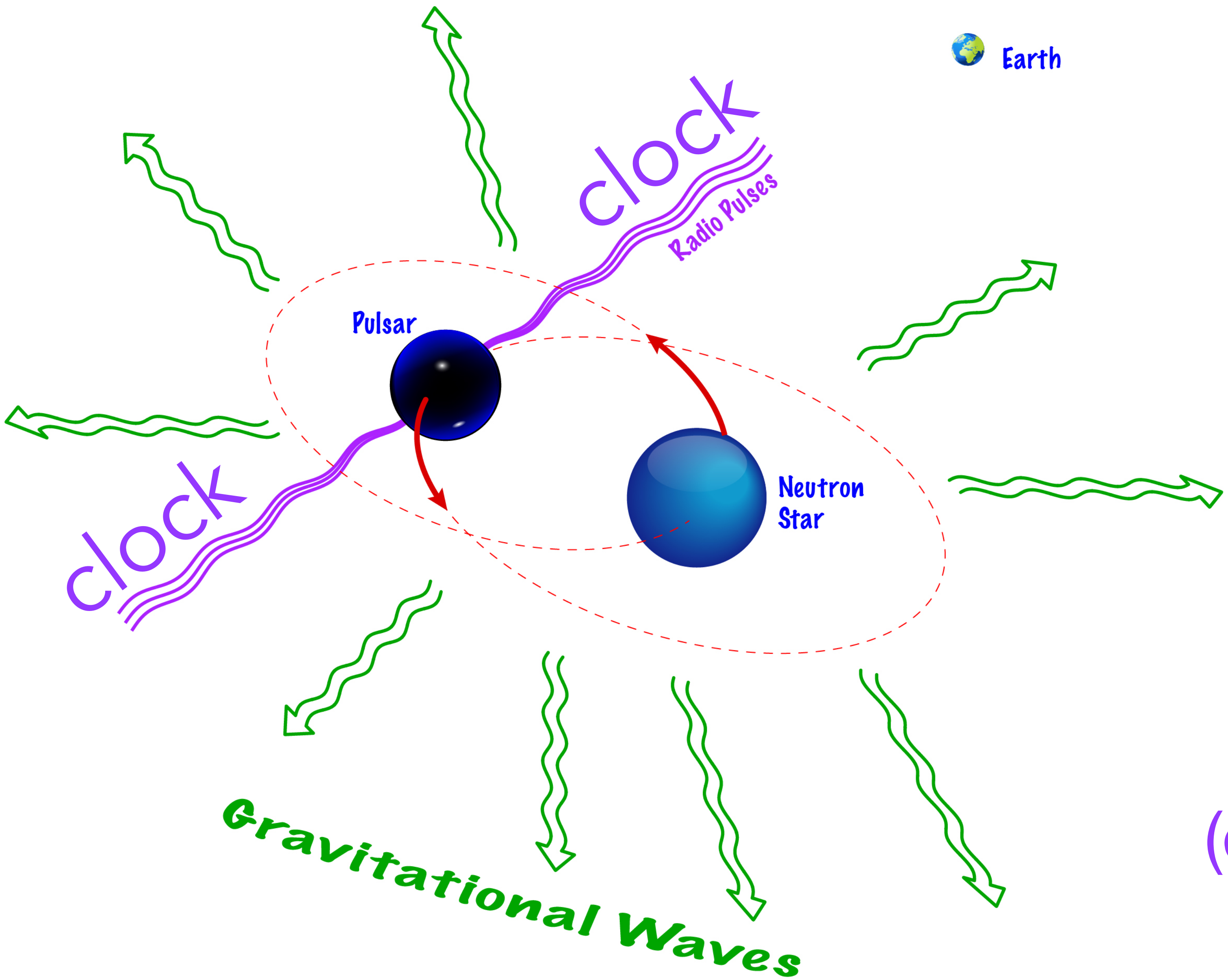
Discovering Continuous GWs with Nuclear, Astro and Particle Physics
INT Workshop — November 18-22, 2024

Continuous GW from Neutron Stars

via a non-axially-symmetric distortion
("Mountains")
(not yet detected)



[Gittins, 2401.01670]



Hulse-Taylor
binary pulsar (1974)
(Nobel, 1993)

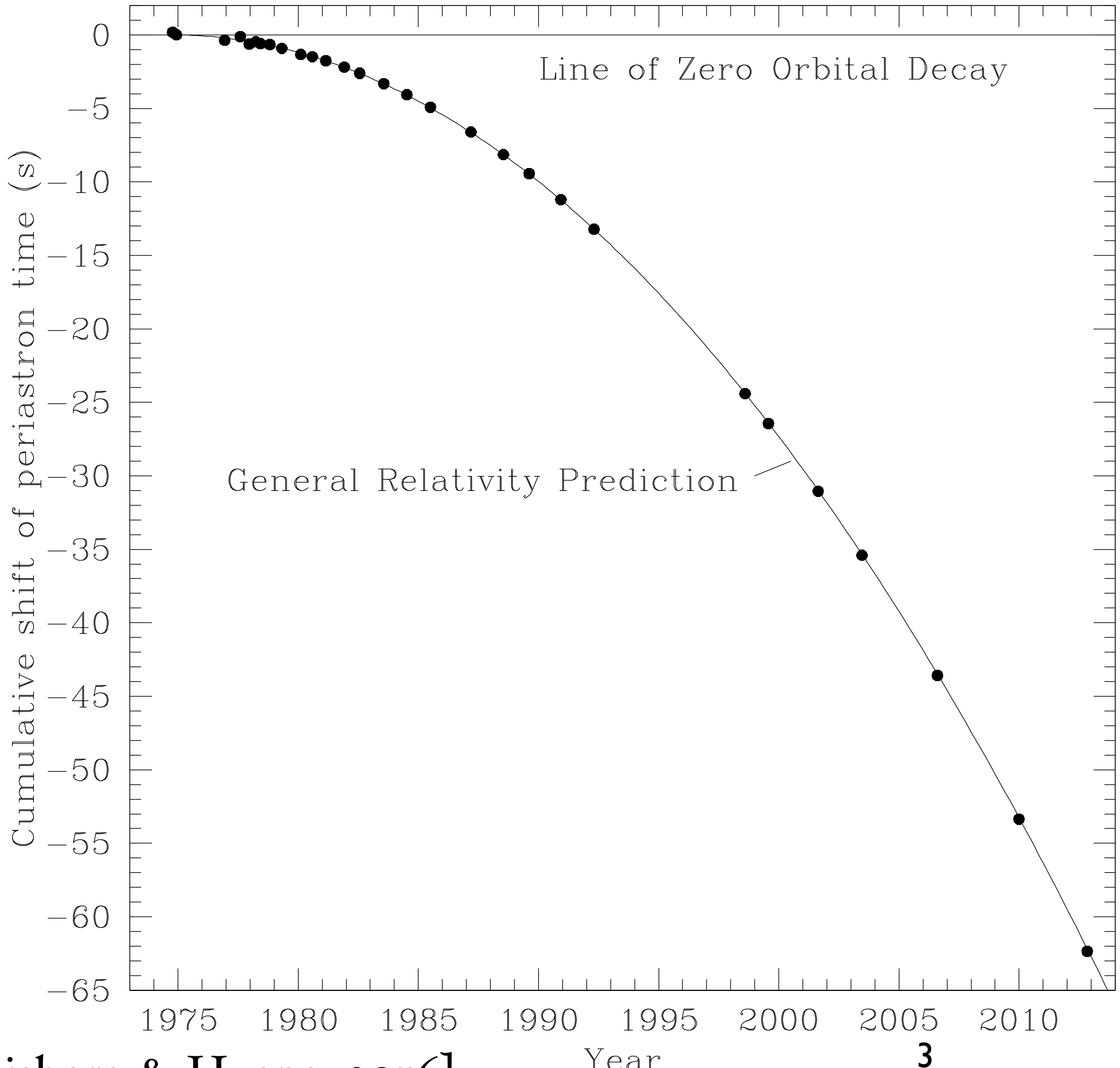
(existence of continuous GWs **inferred**!)

[Figure Credit: Shane L. Larson (NASA)]

Binary Pulsar PSR 1913+16

Discovered by Hulse & Taylor, 1974

Nobel, 1993: "for the discovery of a new type of pulsar, a discovery that has opened up new possibilities for the study of gravitation"



[Weisberg & Huang, 2016]

Precise GR Test!

Now let's use pulsar clocks to look for new physics! e.g.,

$n \to \text{dark} + \ldots$

Observable Signatures

of Baryon Number Violation (BNV)

- **Spin Down:** Change in the moment of inertia (I) could modify the pulsar spin-down rate ($\dot{P}_s$).

- ★ **Binary Orbital Decay:** Changes in the masses and spins of NS components would modify the binary orbital period decay rate ($\dot{P}_b$).

- **Temperature:** BNV would change the cooling history of NS by generating direct and indirect (via chemical disequilibrium) heat.

Pulsar Binary Orbital Decay

Mass-loss induced change in period

The dominant contributions to the observed relative rate of orbital period decay [Damour and Taylor, 1991]:

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

[Lazaridis et al., 2009]

1. Gravitational radiation [Peters, 1964]
2. Mass-energy loss ← BSM (BNV) here!
3. Extrinsic effects such as Doppler effects caused by the relative acceleration a binary pulsar with respect to the solar system

[Cf. galactic acceleration map: Moran, Mingarelli, Van Tilburg, 2023; Donlon et al., 2024]

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

[Jeans, 1924; Huang, 1963]

[Note pulsar timing & n-mirror n mixing: Goldman et al., 2019]

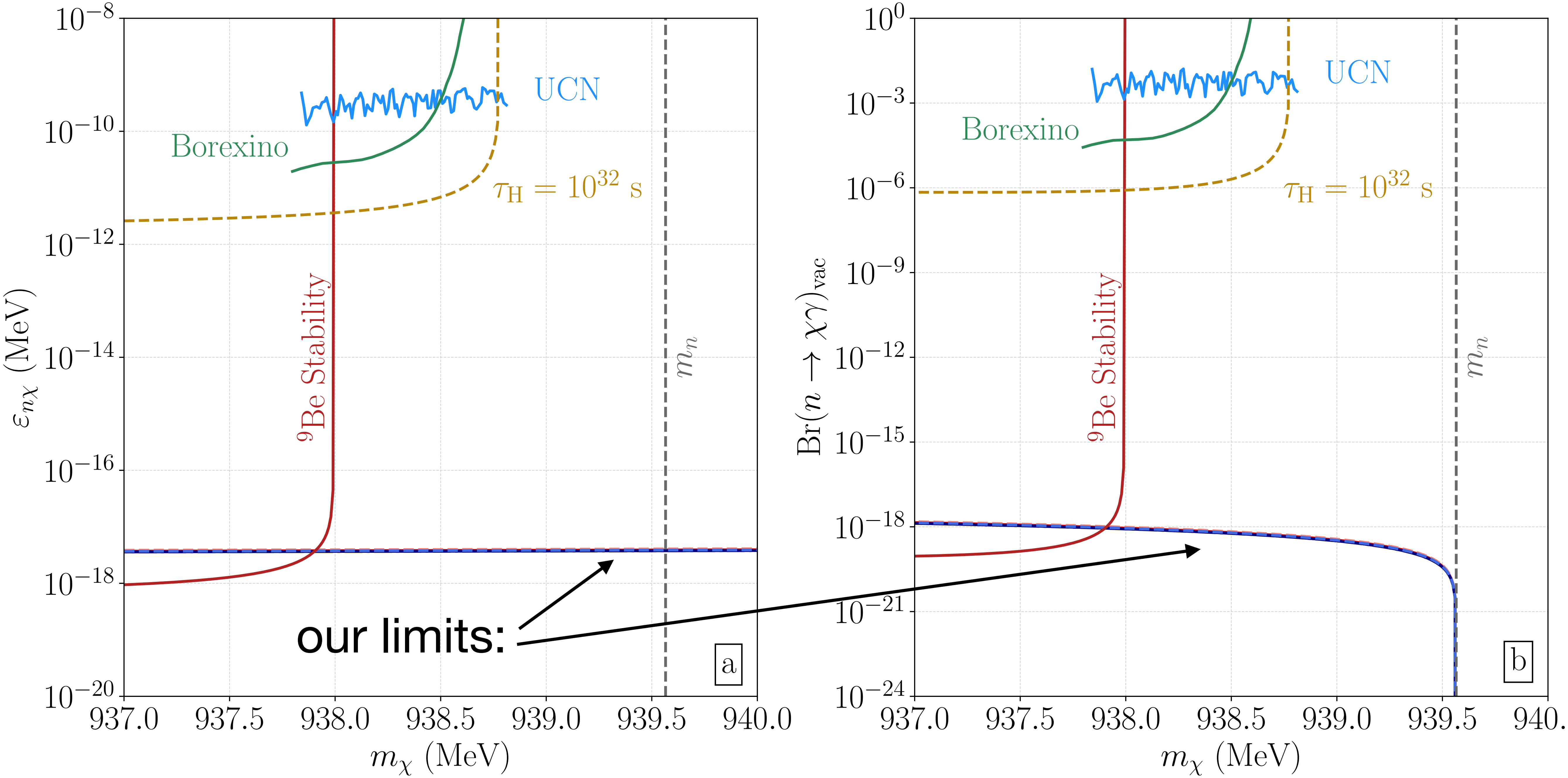
Binary Pulsars to Limit BNV

Use systems without observable mass transfer….

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]
P_s (ms)	39.122 656 901 780 6(5)	3.150 807 655 690 7	22.699 378 986 4727 8(9) [A]
$\dot{P}_s^{\rm obs}(10^{-18})$	0.24073(4)	9.624×10^{-3}	1.7600349(6) [A]
P_b (days)	0.102 424 062 722(7)	8.686 619 422 56(5)	0.102 251 559 297 3(10)
$\dot{P}_b^{\rm obs}(10^{-12})$	−0.273(45)	1.57(13)	−1.247 920(78)
$\dot{P}_b^{\rm ext}(10^{-12})$	$1.6(3) \times 10^{-3}$	1.25(10)	$-1.68(+11, -10) \times 10^{-4}$
$\dot{P}_b^{\rm int}(10^{-12})$	−0.275(45)	0.32(16)	−1.247 752(79)
$\dot{P}_b^{\rm GR}(10^{-12})$	−0.258(+8, −11)	$-4.17(4) \times 10^{-4}$	−1.247827(+6, −7)
$(\frac{\dot{P}_b}{P_b})^{\dot{E}}_{2\sigma}$ (yr^{-1})	2.7×10^{-10}	2.7×10^{-11}	8.3×10^{-13}
$(\frac{\dot{P}_b}{P_b})^{\dot{\Omega}}$ (yr^{-1})	$< 1.4 \times 10^{-13}$	$\approx 4.2 \times 10^{-15}$	$1.04(7) \times 10^{-13}$
$(\frac{\dot{P}_b}{P_b})^{\rm BNV}_{2\sigma}$ (yr^{-1})	2.7×10^{-10}	2.7×10^{-11}	7.3×10^{-13}
$(\frac{\dot{B}}{B})^{\rm BNV}_{2\sigma}$ (yr^{-1})	1.8×10^{-10}	2.0×10^{-11}	4.0×10^{-13}

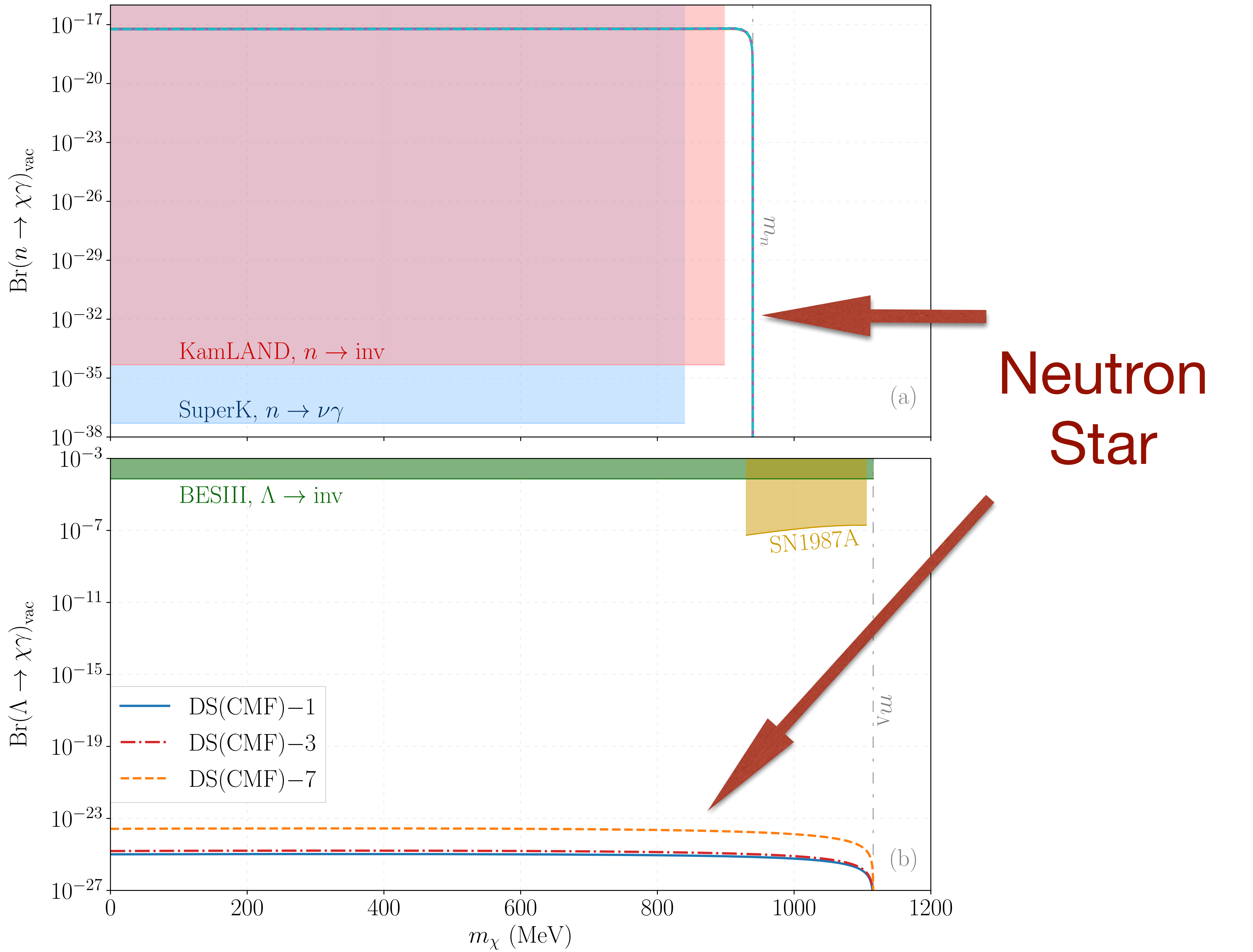
$$\dot{B} = f \times B \times \Gamma_{\rm BNV} \qquad \Gamma_{\rm BNV} < 4 \times 10^{-13}\,{\rm yr}^{-1}\ [95\,\%\ {\rm CL}]$$

Exclusion Limits (at 2σ)



N.B. dark sector choices

Terrestrial vs. Neutron Star Limits



What of Other Pulsar Binaries?

Neutron star-black hole binaries have been discovered (through their GWs), but not ones with pulsars

- Pulsar - black hole binaries should be able to constrain many BSM scenarios (superradiance?)
- Such systems are expected to exist near the Galactic Center [Faucher-Giguere & Loeb, 2011]
- But long-period pulsar binaries (w/ black holes) may remain undetected

[Jones, Kaplan, McLaughlin, Lorimer, 2023]

Summary (for our BNV example)

—Neutron stars contain $\sim 10^{57}$ baryons; energy loss constraints limit BNV rates under weak assumptions…

—Quasi-equilibrium BNV relocates the (static) n star along its one-parameter sequence

—Orbital periods of pulsar binaries lead to stringent constraints for this generic class of BNV: $\Gamma_{\rm BNV} \lesssim 10^{-12}\,{\rm yr}^{-1}$ & microscopic interpretation (flavor structure) thereof limits B-mesogenesis models

—Future studies of neutron star heating may help with identification of non-null results

—BSM models of n lifetime anomaly exist that are insensitive to these constraints (& explain it completely!)

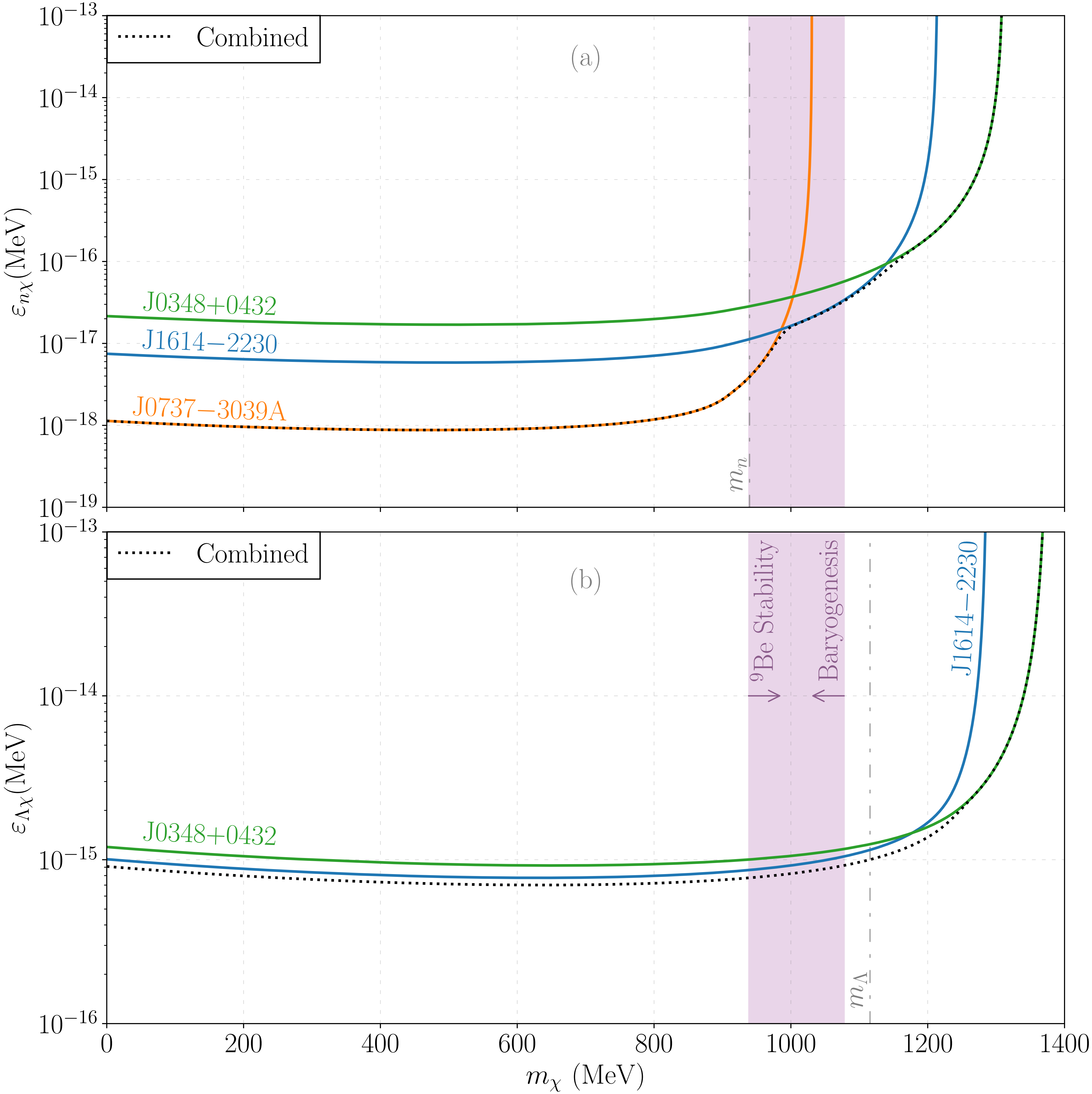
Neutron Stars with Baryon Number Violation, Probing Dark Sectors

J. Berryman, SG, M. Zakeri
arXiv: 2201.02637 & 2305.13377
SG, M. Zakeri, 2311.13649

Jeff

Zaki

Backup Slides



Combined
(a)
J0348+0432
J1614−2230
J0737−3039A
m_n
$\varepsilon_{n\chi}$(MeV)
Combined
(b)
^{9}Be Stability
Baryogenesis
J1614−2230
J0348+0432
m_Λ
$\varepsilon_{\Lambda\chi}$(MeV)
m_χ (MeV)

Dark Decay Models

Minimal ingredients, considered broadly

At lower energies…

[Alonso-Alvarez et al., 2022]

$$\mathcal{O}_{abc} = u_a d_b d_c \chi$$

— to induce visible-dark baryon mixing

Dark Decays of Hadrons

Neutron decay anomaly	$\mathcal{O} = u\,d\,d\,\chi$	$m_{\rm DS} \lesssim m_n$
Hyperon dark decays (this work)	$\mathcal{O} = u\,d\,s\,\chi$	$m_{\rm DS} \lesssim m_\Lambda$
B-Mesogenesis	$\mathcal{O} = u\,d\,b\,\chi$	$m_{\rm DS} \lesssim m_B$

CLAS, BESIII, SN1987A

largest dark sector mass

$$\mathcal{L}_1^{\rm eff} = \bar{n}\left(i\partial\!\!\!/ - m_n + \frac{g_n e}{2m_n}\sigma^{\mu\nu}F_{\mu\nu}\right)n + \bar{\chi}(i\partial\!\!\!/ - m_\chi)\chi + \varepsilon(\bar{n}\chi + \bar{\chi}n)$$

mediates $n \to \chi\gamma$ (or $\Lambda \to \chi\gamma$)

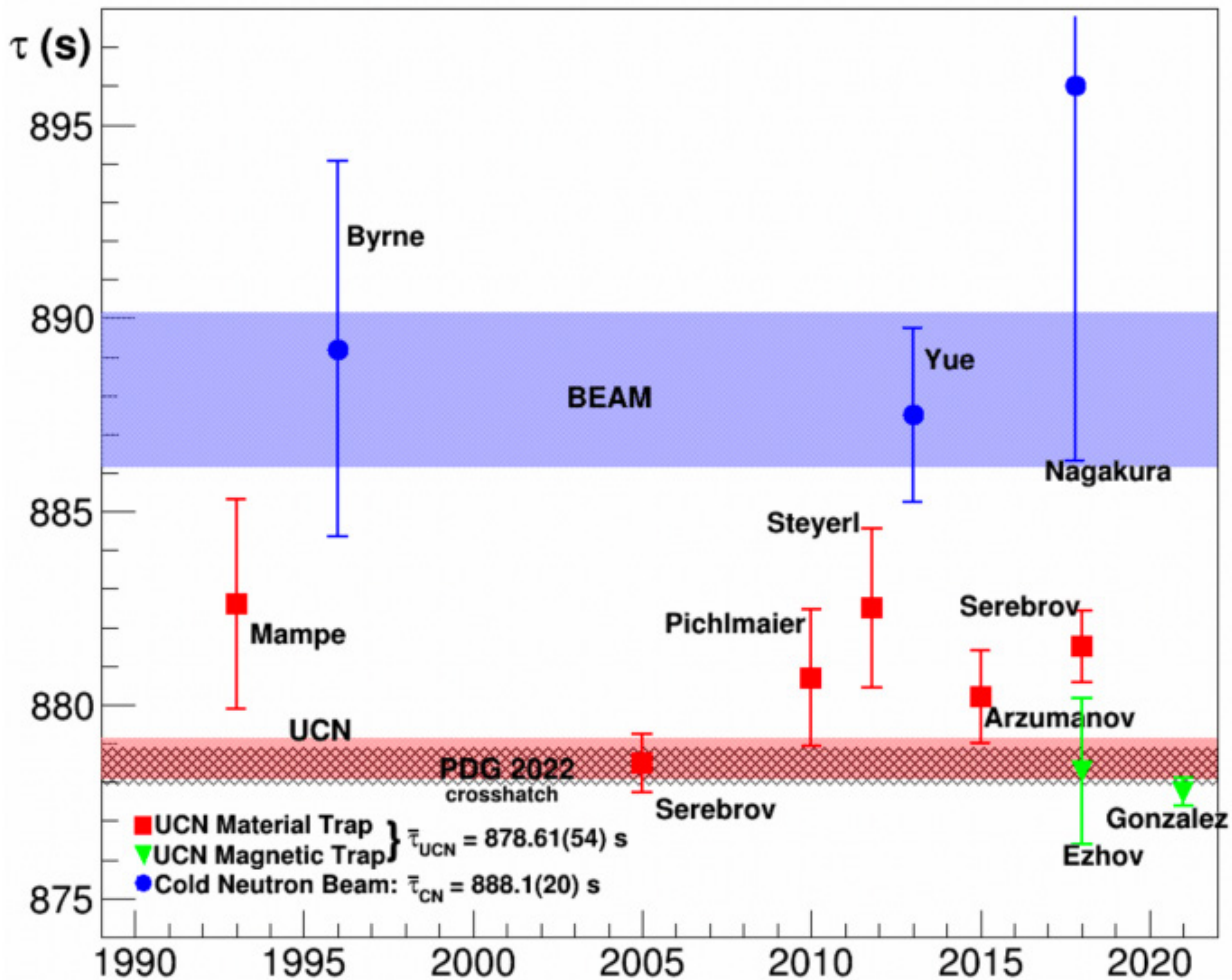
limits from duration of SN1987A ν burst

$\mathrm{Br}(\Lambda \to \chi\gamma) < 1.6 \times 10^{-7}$

The Neutron Lifetime Puzzle

What if neutrons were to decay invisibly?

[Recall early suggestion: Z. Berezhiani & "mirror neutrons" & 2019; note Broussard et al., 2022!]



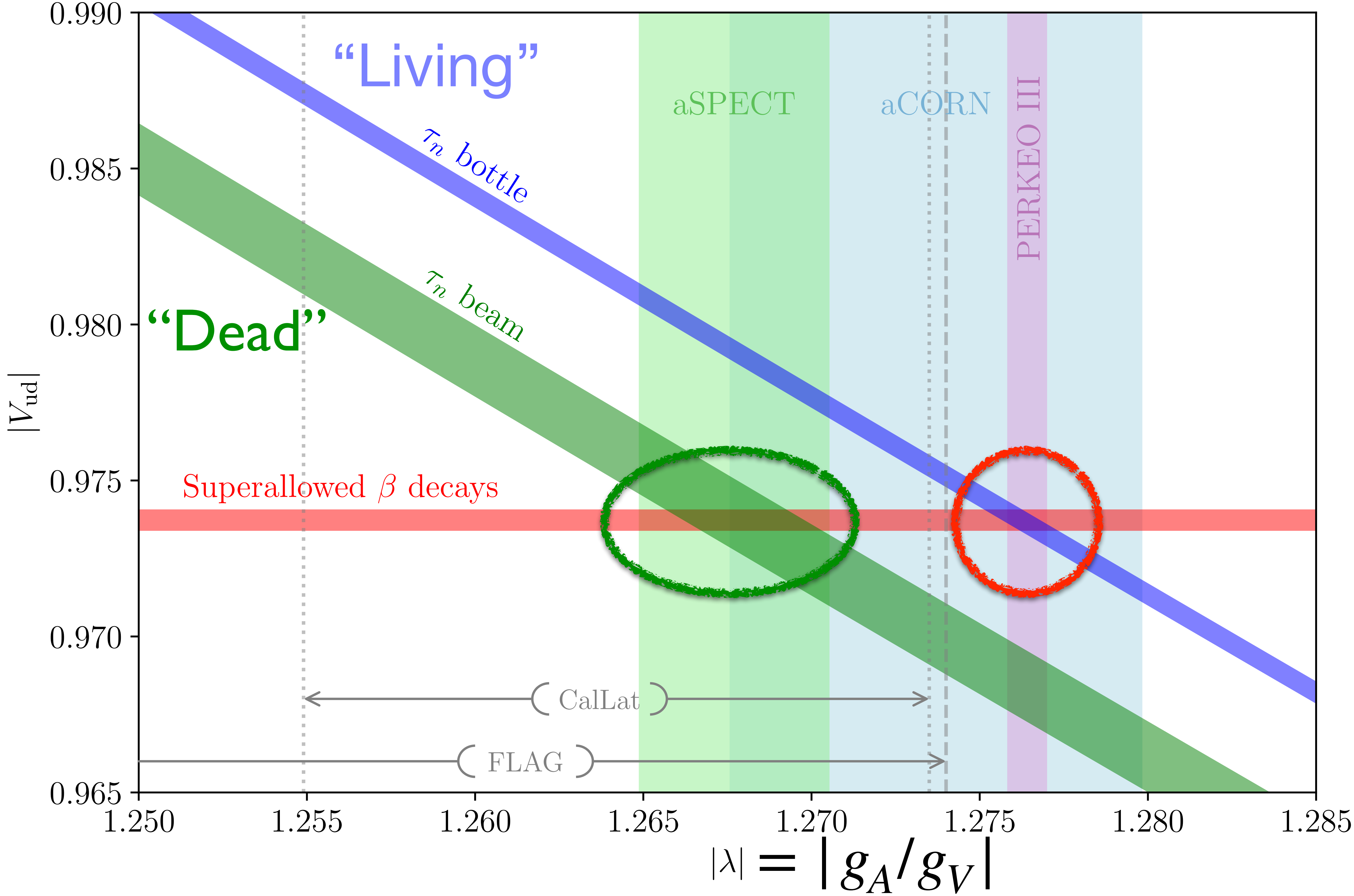
(9.5 s, (>)4σ)

Count **protons** that appear

Count **neutrons** that persist

 [Figure Credit: NSAC LRP, 2023 [Albert Young]]

SM Tests & Neutron Dark Decays

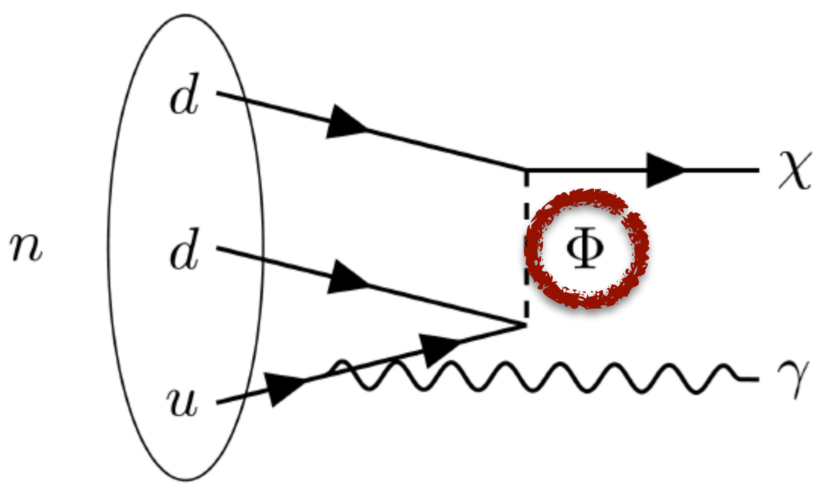


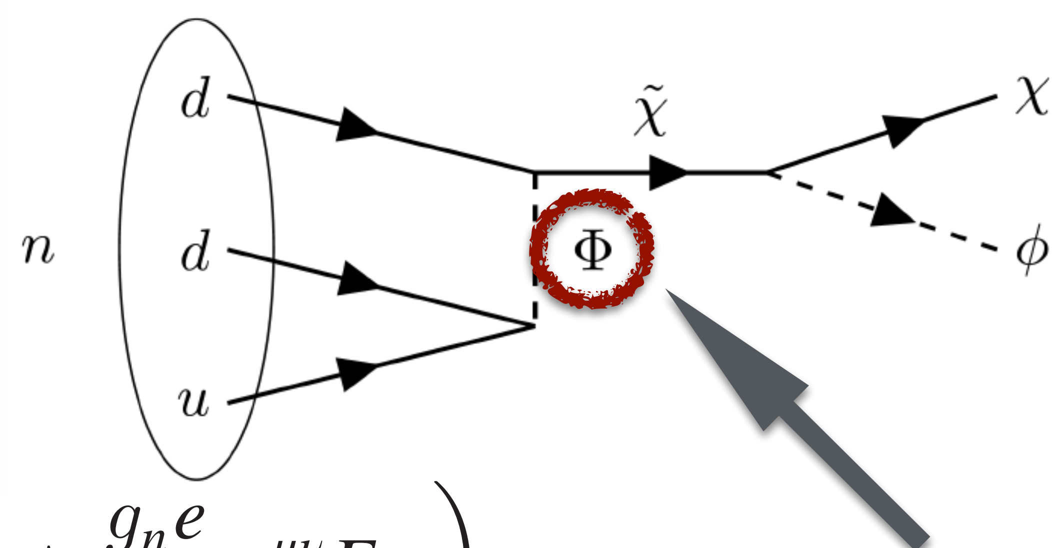
Neutron Dark Decays

Modeled to solve the n lifetime puzzle

[Fornal & Grinstein, 2018]

★ Enter $n \to \chi\gamma$; also $n \to \chi(\phi \to e^+e^-)$





$\phi \to e^+e^-$

B-carrying scalar!

At low E: $$\mathcal{L}_1^{\text{eff}} = \bar{n}\left(i\partial\!\!\!/ - m_n + \frac{g_n e}{2m_n}\sigma^{\mu\nu}F_{\mu\nu}\right)n + \bar{\chi}(i\partial\!\!\!/ - m_\chi)\chi + \varepsilon(\bar{n}\chi + \bar{\chi}n)$$

Select χ mass window to avoid **proton decay** ($|\Delta B| = 1$)

& nuclear stability constraints: $937.993\,\text{MeV} < m_\chi < 939.565\,\text{MeV}$

Thus $\tau_n^{\text{beam}} = \tau_n^{\text{bottle}}$ / Br(n→p + anything)

Many constraints! But $\Gamma_{n\,\text{dark}} \gg \Gamma_{|\Delta B|=1}$ still possible!

N.B. connection to low-scale cosmic baryogenesis!

A Cosmic Baryon Asymmetry

via dark sector co-genesis — an "EDM safe" mechanism!

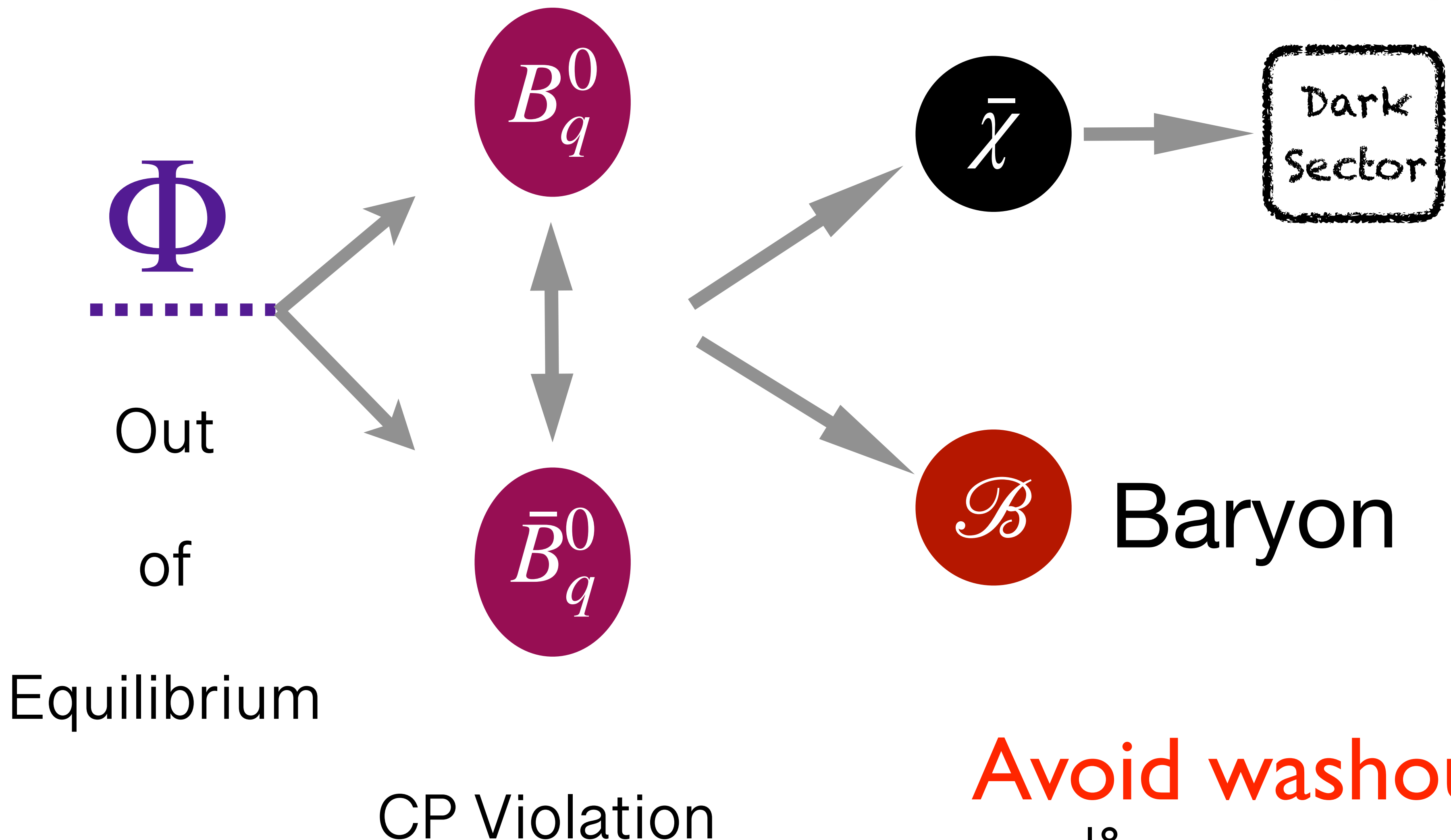
Visible & dark sectors have opposite B charge

E.g., new dark sector fermion ψ_B [$\bar{\chi}$] with $B = -1 \ldots$

[N.B. Davoudiasl & Mohapatra, 2012]

"B-Mesogenesis"

[Elor, Escudero, Nelson, 2019; Elor & McGehee, 2021;...]



Note!

Different variants!

Here

$0.937993\,\mathrm{GeV} < m_\chi < 1.07784\,\mathrm{GeV}$

Avoid washout: no $\bar{\chi} \to \bar{p}\pi^-$

Simple, "UV-Complete" Models of B-Mesogenesis

Contain a B-carrying scalar or vector

[Elor, Escudero, Nelson, 2019; Alonso-Alvarez et al., 2022;...]
[N.B. leptoquark models: Fajfer & Susic, 2021]

Supposing low-scale, out-of-equilibrium B production

Enter: $Y_{\frac{2}{3}}: \quad \left(\bar{3}, 1, \frac{2}{3}\right)$ (SU(3) x SU(2)$_L$ x U(1)$_Y$)

$$\mathscr{L}_{Y_{\frac{2}{3}}} \supset -y_{d_a d_b}\epsilon_{\alpha\beta\gamma}Y^{\alpha}_{\frac{2}{3}}d^{\beta}_a d^{\gamma}_b - y_{\chi u_c}Y^{\alpha\,*}_{\frac{2}{3}}\chi^c u^{\alpha}_c + \mathrm{h.c.},$$

Or: $Y_{-\frac{1}{3}}: \quad \left(\bar{3}, 1, -\frac{1}{3}\right)$ ← ! τ_n anomaly

$$\mathscr{L}_{Y_{-\frac{1}{3}}} \supset -y_{u_a d_b}\epsilon_{\alpha\beta\gamma}Y^{\alpha}_{-\frac{1}{3}}u^{\beta}_a d^{\gamma}_b - y_{\chi d_c}Y^{\alpha\,*}_{-\frac{1}{3}}\chi^c d^{\alpha}_c + \mathrm{h.c.}$$

Or....

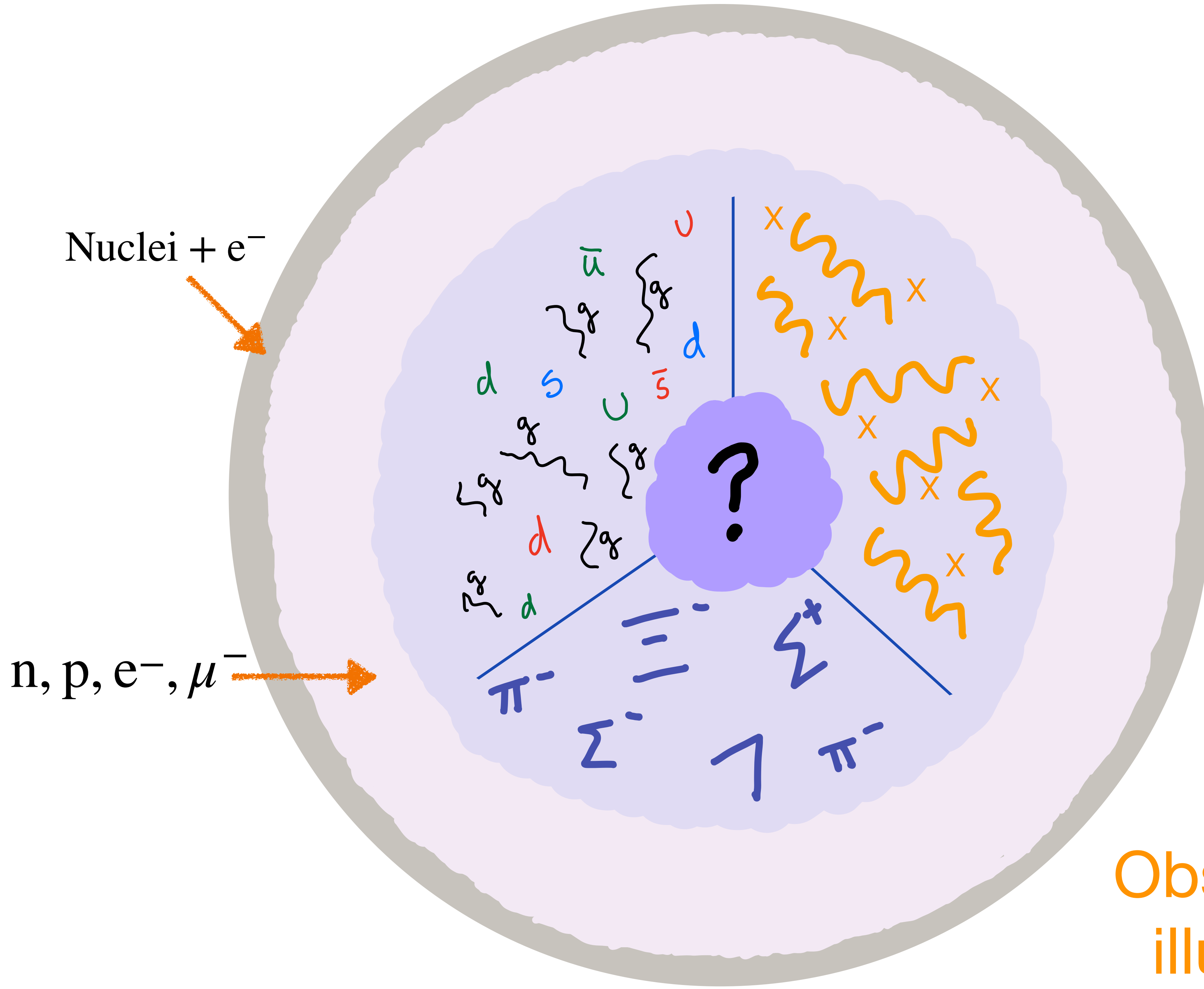
proton decay $p \to e^+\pi^0$

Plus: $\mathscr{L}_{\mathrm{dark}} \supset y_d \bar{\chi}\phi_B\xi + \mathrm{h.c.}$

How to constrain the couplings? Enter neutron stars!

Neutron Star Schematic

Observed neutron stars limit neutron dark decay models



Here: impact of **energy-loss** constraints

Enormous baryon ($\sim 10^{57}$) reservoir!

Observational studies illuminate structure & dynamics….

[Berryman, SG, & Zakeri, 2022; after Baym & Pethick, 1975]

Neutron Stars to Limit BNV

Neglecting rotation & χ that does not accumulate

For a given EoS, the structure of a n star $[\varepsilon(r), p(r)]$ is fixed by its central energy density ε_c as per the solution to the TOV equations & b.c.

Supposing $\Gamma_{\rm BNV} << \Gamma_{\rm weak}$ (quasi-equilibrium)

BNV implies that ε_c changes, yet the resulting structure is fixed by BNC physics

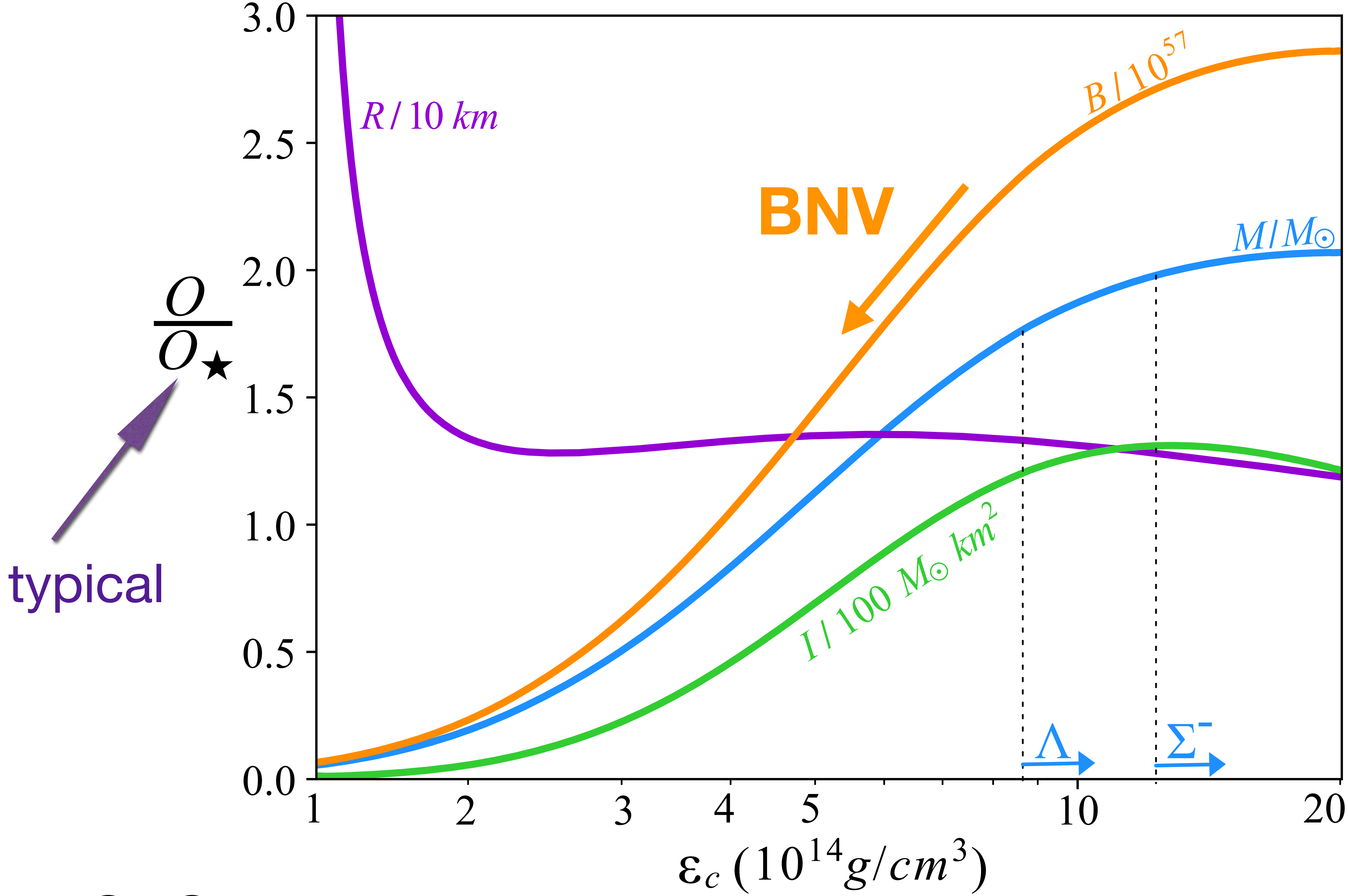
Given a rate of change in B, we can predict changes in the macroscopic parameters of the star

Given these, we can limit microscopic (dark decay) models using relativistic mean-field theory….

[Berryman, SG, & Zakeri, 2022 & 2023]

Neutron Stars (with BNV)

Their structure moves along a one-parameter sequence



EoS: CMF-1 [Dexheimer & Schramm, 2008]

Neutron Stars to Limit BNV

Parameterize the quasi-equilibrium change in an observable ($\mathcal{O}$) as a result of a change in B by

$$\frac{\dot{\mathcal{O}}}{\mathcal{O}} = \left(\frac{B}{\mathcal{O}} \times \frac{\partial_{\mathcal{E}_c} \mathcal{O}}{\partial_{\mathcal{E}_c} B} \right) \frac{\dot{B}}{B} \equiv b(\mathcal{O}) \times \frac{\dot{B}}{B}$$

Quasi-equilibrium mass loss:

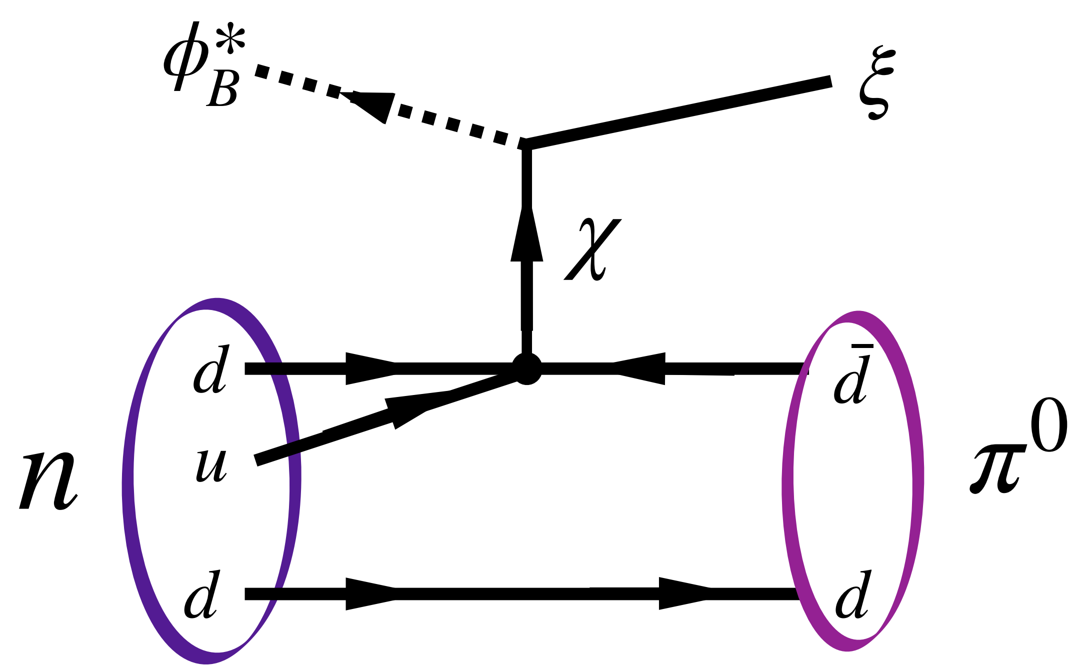
negligible

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

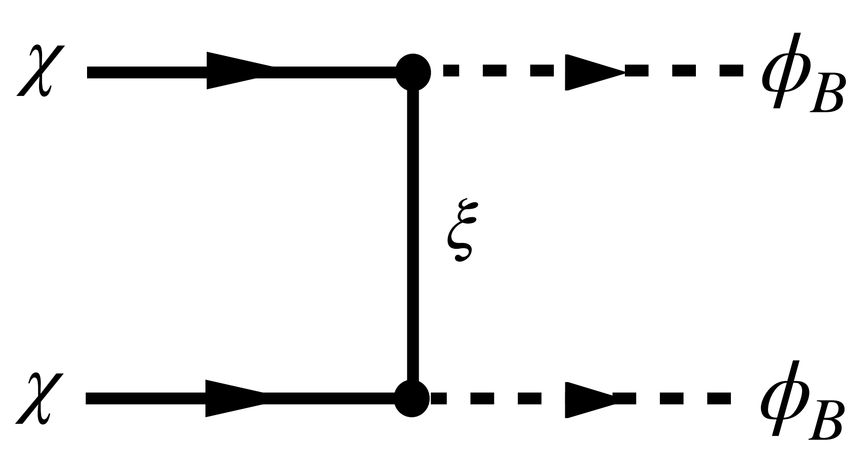
Dark Sector Processes

Choose masses judicially

Induced nucleon decay ← Suppress!



χχ Annihilation ← Let ϕ_B escape!



Medium Effects

EOS: DS (CMF)-1

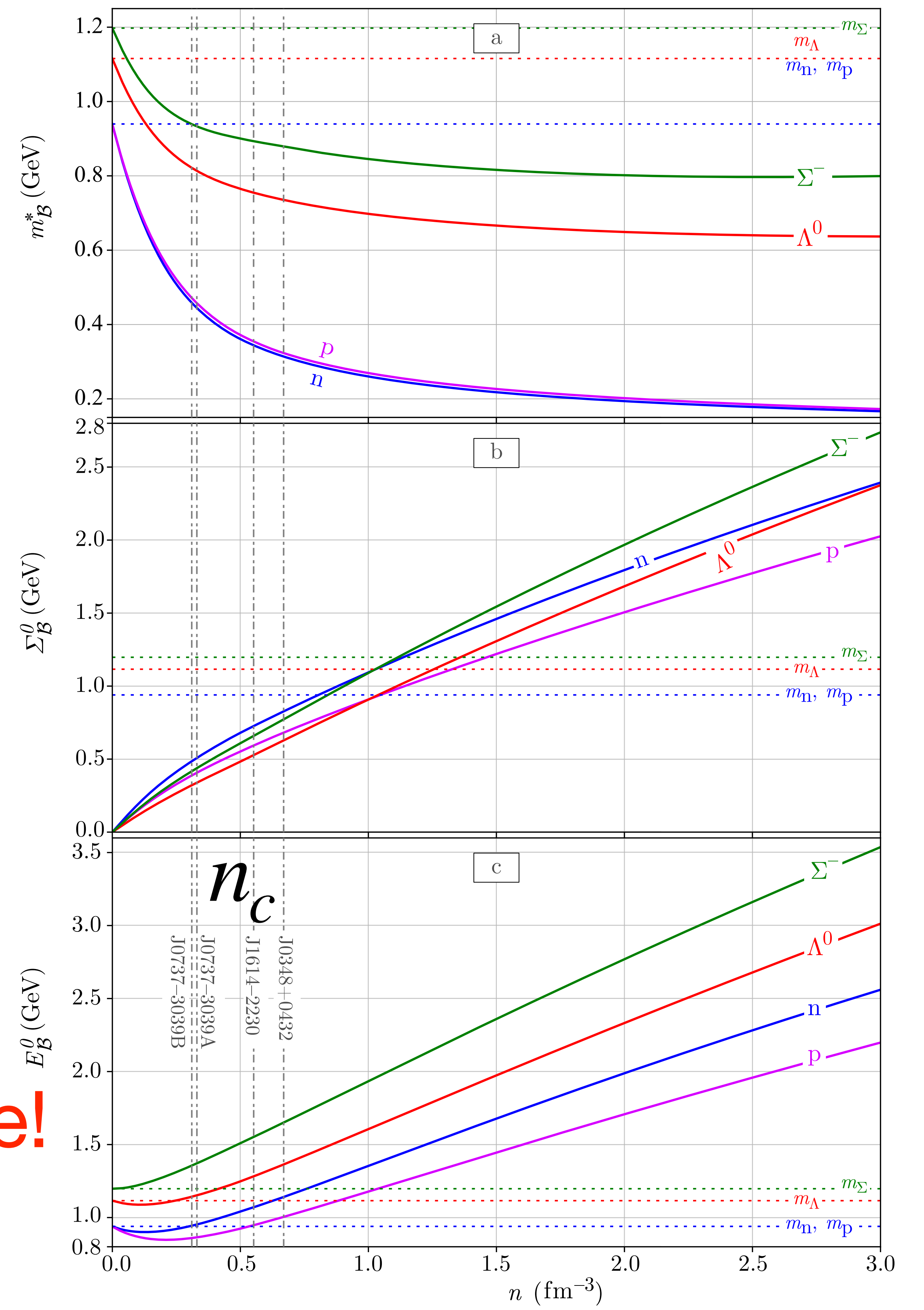
Effective mass

Vector Self Energy

Energy

In the dense medium,
new processes are possible!

Broader constraints!



Modelling Dense Matter

The Walecka Model

[Walecka, 1974;
Serot & Walecka, 1986]

$$\mathscr{L}_{\varphi/V} = \bar{\psi}[(i\gamma_\mu\partial^\mu - g_V\gamma_\mu V^\mu) - (m_N - g_s\varphi)]\psi$$
$$+\frac{1}{2}(\partial_\mu\varphi\partial^\mu\varphi - m_s^2\varphi^2) - \frac{1}{4}F^{\mu\nu}F_{\mu\nu} + \frac{1}{2}m_V V_\mu V^\mu + \delta\mathscr{L}$$

~massive QED with a scalar extension; $\mathscr{B}$ cons. charge

captures basic features of the NN force

$$\left(\partial^2 + m_s^2\right)\varphi(x) = g_s\bar{\psi}\psi$$

$$\partial_\nu F^{\nu\mu} + m_V^2 V^\mu = g_V\bar{\psi}\gamma^\mu\psi$$

$$\left\{\left[i\gamma_\mu\partial^\mu - g_v\gamma_\mu V^\mu(x)\right] - \left[m_N - g_s\varphi(x)\right]\right\}\psi(x) = 0.$$

The mean-field limit $\varphi(x) \to \bar{\varphi}$ & $V_\mu(x) \to \delta_{\mu 0}\bar{V}_0$ in the n.m. frame is grossly simplifying & is apropos to dense matter.

Modelling Dense Matter

The Walecka Model

In static, uniform nuclear matter, the mean fields depends only on density n

Under $k_\mu \to k^*_\mu \equiv k_\mu - g_V \delta_{\mu 0} \bar{V}_0 \quad ; \quad m \to m^* \equiv m - g_s \bar{\varphi}_0$

we can solve a suitably modified free Dirac equation for $\psi(x)$

In nuclear matter with a nucleon we thus have

$$k^{*\mu} \equiv k^\mu - \Sigma^\mu = \left\{ E^*(k^*), \vec{k} - \cancelto{0}{\vec{\Sigma}} \right\}$$

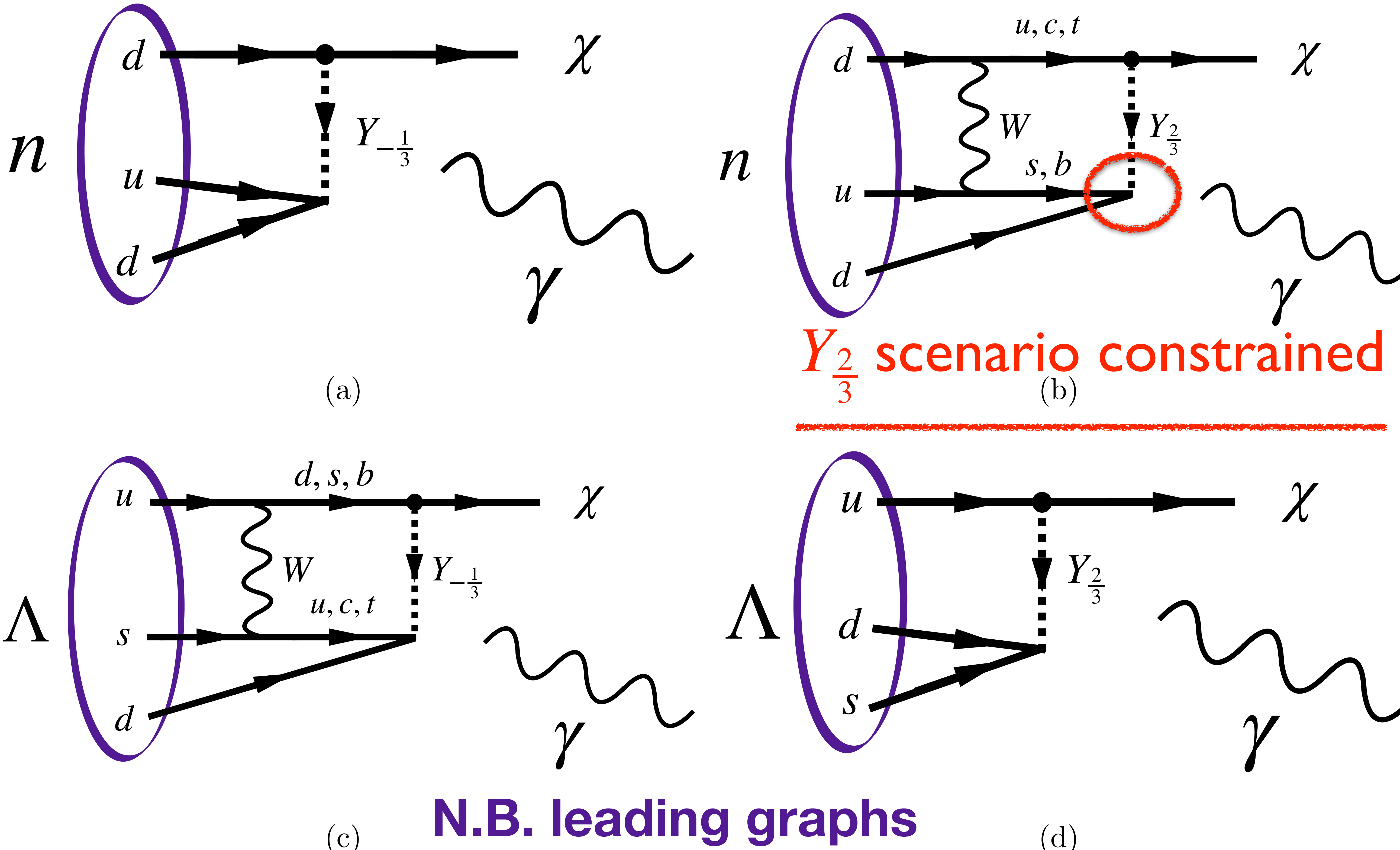
We can generalize thus to baryon species & include additional contributions to m_i^*, Σ_i^0

Enter RMFT with these parameters fixed by the EOS

Future?! e.g., Alford et al., 2205.10283

Interpretation (re B-mesogenesis)

Neutron star results can limit flavor couplings severely



$Y_{\frac{2}{3}}$ scenario constrained

N.B. leading graphs

Decay Rates in the Medium

RMFT provides a covariant framework

We exploit our freedom to pick a frame to simplify our analysis.

We compute the decay matrix element in a background field, e.g., of uniform neutron matter

$$\mathscr{B}(p_{\mathscr{B}}) \to \chi(k_\chi) + \gamma(k_\gamma)$$

$$|\mathscr{M}|^2 = \frac{\varepsilon^2_{\mathscr{B}\chi} g^2_{\mathscr{B}} e^2}{2(m^*_{\mathscr{B}})^2} \left[(p^*_{\mathscr{B}} \cdot k_\chi) + m^*_{\mathscr{B}} m_\chi \right],$$

N.B. integration over phase space non-trivial