How Binary-Pulsar Orbital Period Measurements Constrain Baryon Dark Decays

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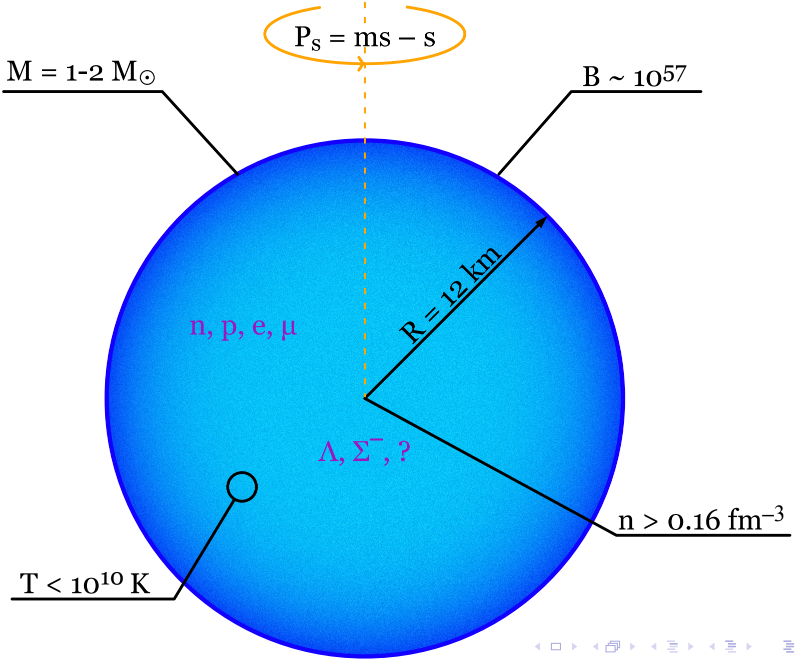
Overview

1. **General Considerations**: Pulsars, Mass loss in binary systems, Quasi-equilibrium baryon number violation (BNV)
2. **Binary Pulsar Candidates**: J1614−2230, J0737−3039A/B, J0348+0432
3. **General Dense Matter Framework**: Relativistic mean-field
4. **Equation of State (EoS)**: Based on non-linear hadronic SU(3) chiral mean-field (CMF)
5. **Particle Physics Model**: Baryon ($\mathcal{B}$) mixing ($\varepsilon_{\mathcal{B}\chi}$) with a dark fermion ($\chi$) leading to $\mathcal{B} \to \chi\gamma$
6. **From Macro to Mirco**: Limits on $\varepsilon_{\mathcal{B}\chi}$ and $\text{Br}(\mathcal{B} \to \chi\gamma)$ in vacuum

General Considerations



$P_s = \text{ms} - \text{s}$

$M = 1\text{-}2\ M_\odot$

$B \sim 10^{57}$

$R = 12\ \text{km}$

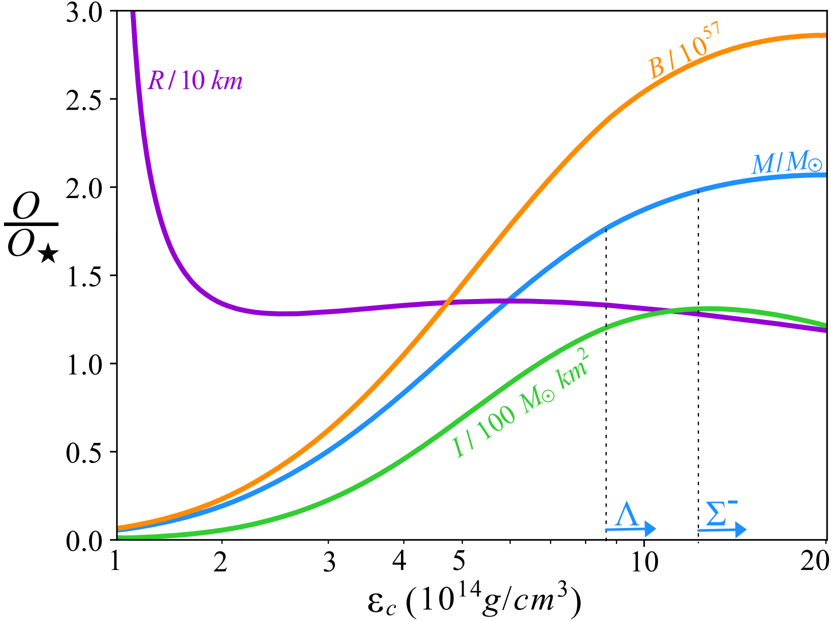
n, p, e, μ

$\Lambda, \Sigma^-, ?$

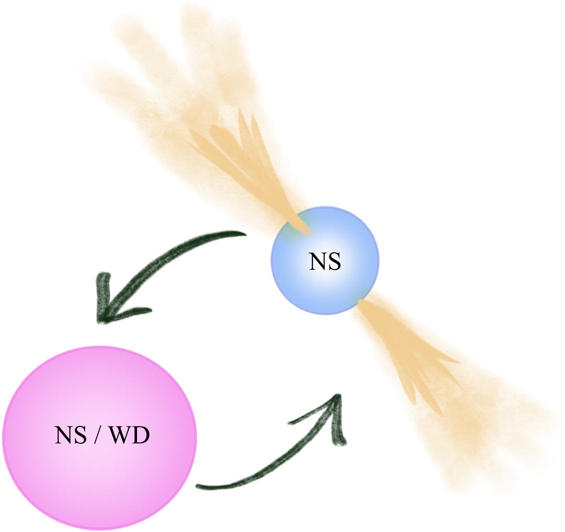
$n > 0.16\ \text{fm}^{-3}$

$T < 10^{10}\ \text{K}$

- Neutron stars cool down to $T \ll E_{\text{Fermi}} \lesssim$ GeV within a few seconds after formation.
- Equation of state (EoS): energy density ($\mathcal{E}$) and pressure (p) as a function of baryon number density (n).
- Structure of static NS ($\mathcal{E}[r], p[r]$) is found by integrating TOV equations with $\mathcal{E}_c \equiv \mathcal{E}[0]$ up to $p[R_\star] = 0$ (surface of the star).
- Given an EoS, there is a unique family (*single parameter sequence*) of stars parameterized by $\mathcal{E}_c$.
- In the case of a rotating neutron star, or a neutron star with a dark matter core, extra parameters in addition to $\mathcal{E}_c$ are needed to describe the star uniquely.


$\frac{O}{O_\star}$
3.0
2.5
2.0
1.5
1.0
0.5
0.0
$R\,/\,10\ km$
$B\,/\,10^{57}$
$M/M_\odot$
$I\,/\,100\ M_\odot\ km^2$
Λ
Σ^-
1
2
3
4
5
10
20
$\varepsilon_c\ (10^{14} g/cm^3)$

Binary Pulsar Systems



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

$$\left(\frac{\dot{P}_b}{P_b}\right)^{\text{obs}} = \underbrace{\left(\frac{\dot{P}_b}{P_b}\right)^{\text{GR}} + \left(\frac{\dot{P}_b}{P_b}\right)^{\dot{E}}}_{\text{intrinsic}} + \left(\frac{\dot{P}_b}{P_b}\right)^{\text{ext}} . \tag{1}$$

1. Gravitational radiation [Peters, 1964]
2. Mass-energy loss
3. Extrinsic effects such as Doppler effects caused by the relative acceleration of the binary pulsar with respect to the solar system

Jean's mode of mass ejection [Jeans, 1924]:

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

$M_{1,2}$: the masses for each of the components in the binary system.

- Pulsar timing is used to limit neutron-mirror neutron mixing [Goldman et al., 2019].
- Here we constrain baryon number violation (BNV) in pulsars that belong to a binary system.
- Examples of BNV: $n \to 3\nu$, $nn \to e^+e^-$, $\Lambda \to \chi\gamma$.
- The mapping between BNV rates and $\dot{M}^{\text{eff}}$ is in general dependent on the specific BNV processes, and also complicated.

Quasi-Equilibrium BNV Formalism

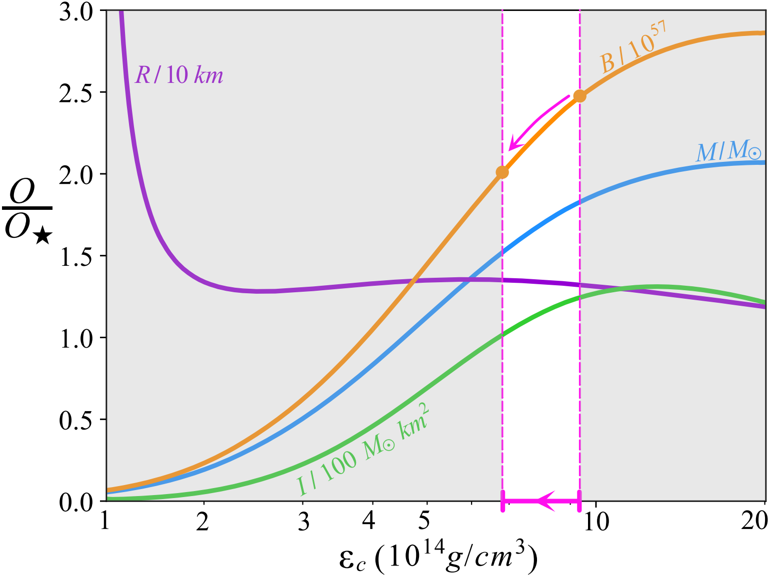
Quasi-equilibrium BNV formalism is a minimal framework for studying BNV in a model-independent way, which requires the following conditions:

1. BNV rate must be slower than the dynamical and chemical responses of the star.
2. No significant accumulation of new particles, beyond those already included in the EoS Lagrangian, within the star.

Quasi-Equilibrium BNV Formalism

Consequently:

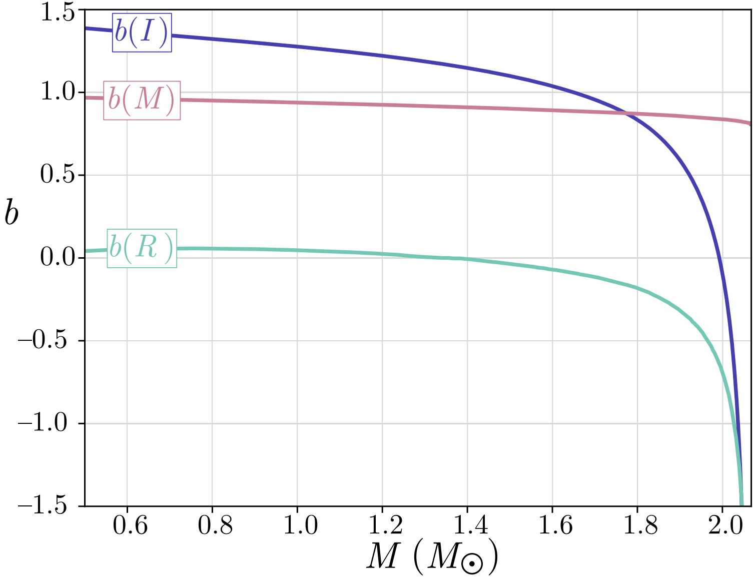
- The instantaneous state of a neutron star is given by the same (baryon number conserving) EoS.
- Neutron star observables ($\mathcal{O}$) will evolve along their equilibrium trajectories, and at a rate determined by the EoS and total baryon number loss rate ($\dot{B}$).



$\frac{O}{O_\star}$
3.0
2.5
2.0
1.5
1.0
0.5
0.0
1
2
3
4
5
10
20
$\varepsilon_c\,(10^{14} g/cm^3)$
$R\,/\,10\ km$
$B\,/\,10^{57}$
$M/M_\odot$
$I\,/\,100\ M_\odot\ km^2$

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

$$\frac{\dot{\mathcal{O}}}{\mathcal{O}} = \underbrace{\left(\frac{B}{\mathcal{O}} \times \frac{\partial_{\mathcal{E}_c}\mathcal{O}}{\partial_{\mathcal{E}_c}B}\right)}_{b(\mathcal{O})} \frac{\dot{B}}{B} \equiv b(\mathcal{O}) \times \frac{\dot{B}}{B} \tag{3}$$


$b(I)$
$b(M)$
$b(R)$
b
$M\ (M_\odot)$
1.5
1.0
0.5
0.0
−0.5
−1.0
−1.5
0.6
0.8
1.0
1.2
1.4
1.6
1.8
2.0

Quasi-equilibrium mass loss:

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

Energy-loss term due to BNV and spin-down:

$$\left(\frac{\dot{P}_b}{P_b}\right)^{\dot{E}} = \left(\frac{\dot{P}_b}{P_b}\right)^{\text{BNV}} + \left(\frac{\dot{P}_b}{P_b}\right)^{\dot{\Omega}}, \tag{5}$$

with each of the contributions given by

$$\left(\frac{\dot{P}_b}{P_b}\right)^{\text{BNV}} = \frac{-2}{M_1 + M_2} \sum_{i=1,2} \left(\frac{\dot{B}_i}{B_i}\right) \left[b_i(M) M_i + b_i(I) \left(\frac{2\pi^2 I_i}{P_{s,i}^2}\right) \right], \tag{6}$$

$$\left(\frac{\dot{P}_b}{P_b}\right)^{\dot{\Omega}} = \frac{8\pi^2}{M_1 + M_2} \left(\frac{I_1 \dot{P}_{s,1}}{P_{s,1}^3} + \frac{I_2 \dot{P}_{s,2}}{P_{s,2}^3}\right). \tag{7}$$

Binary Pulsar Candidates

We consider three binary systems:

Name	J1614−2230	J0737−3039A/B	J0348+0432
$M_p\,(M_\odot)$	$1.908(16)$	$1.34\ \left[{}^{+0.000012}_{-0.000014}\right]$	$2.01(4)$
$M_c\,(M_\odot)$	$0.172(3)$	$1.25\ \left[{}^{+0.000013}_{-0.000011}\right]$	$0.172(3)$
$P_b\,(\mathrm{h})$	$208.48(\,[\pm1.2\times10^{-9}]$	$2.45\,[\pm2.4\times10^{-11}]$	$2.46\,[\pm1.68\times10^{-10}]$
$\dot{P}_b^{\mathrm{obs}}\,(10^{-12})$	$1.57(13)$	$-1.247920(78)$	$-0.273(45)$
$\left(\frac{\dot{B}}{B}\right)^{\mathrm{BNV}}_{2\sigma}\,(\mathrm{yr}^{-1})$	2.0×10^{-11}	4.0×10^{-13}	1.8×10^{-10}

J1614−2230: [Arzoumanian et al., 2018, Alam et al., 2021]

J0737−3039A/B: [Burgay et al., 2003], [Kramer et al., 2021]

J0348+0432: [Boyles et al., 2013, Lynch et al., 2013], [Antoniadis et al., 2013]

General Dense Matter Framework

Relating Macroscopic and Microscopic Limits

BNV Microphysics

$\Updownarrow$

Rate of change in baryon number $\dot{B}$

Framework for Including the Medium Effects

- High densities in NS: Use relativistic mean-field approximation
- Assume that baryons are in a classical mesonic background and solve the equation of motions.
- The baryon wave-function in uniform medium is

$$\psi(x) = e^{-ik\cdot x} u(k^*, \lambda), \tag{8}$$

in which $k^{*\mu} \equiv k^\mu - \Sigma^\mu = \left\{ E^*(k^*), \vec{k} - \vec{\Sigma} \right\}$ and $u(k^*, \lambda)$ satisfies the Dirac equation:

$$\left(\not{k}^* - m^* \right) u(k^*, \lambda) = 0, \tag{9}$$

in which $m^* \equiv$ effective mass, $\Sigma^\mu \equiv$ baryon self-energy and

$$E(k) = E^*(k) + \Sigma^0 = \sqrt{(m^*)^2 + \left(\vec{k} - \vec{\Sigma} \right)^2} + \Sigma^0. \tag{10}$$

$\Sigma^0 > 0$, $\vec{\Sigma}_{\rm nm} = 0$.

Equation of State (EoS)

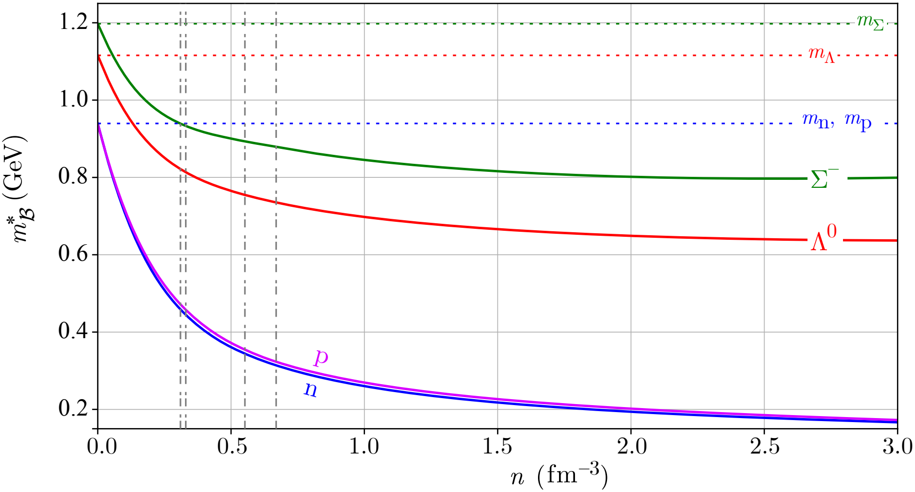
- We choose an EoS based on a non-linear hadronic SU(3) CMF model [Papazoglou et al., 1999, Dexheimer and Schramm, 2008]
- Baryonic degrees of freedom: nucleons (n, p), hyperons (Λ, Σ, Ξ) and the spin-3/2 resonances (Δ, Σ^*, Ξ^*, Ω)
- Baryons interact via exchange of scalar (σ, $\boldsymbol{\delta}$, ζ, χ) and vector mesons ($\boldsymbol{\rho}^\mu$, ω^μ, ϕ^μ).
- Effective masses are generated by the scalar meson VEVs, except for a small explicit mass term $\delta m_i \sim 150$ MeV:

$$m_i^* = g_{i\sigma}\langle\sigma\rangle + 2g_{i\delta}\langle\delta_3\rangle I_{3i} + g_{i\zeta}\langle\zeta\rangle + \delta m_i, \tag{11}$$

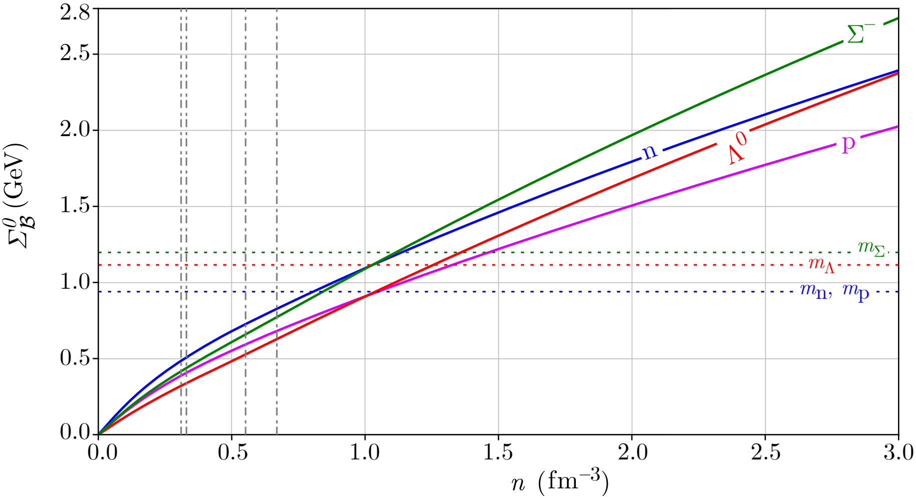
- Baryon self-energy is given by

$$\Sigma_i^0 = g_{i\omega}\langle\omega^0\rangle + g_{i\rho}\langle\rho_3^0\rangle I_{3i} + g_{i\phi}\langle\phi^0\rangle. \tag{12}$$

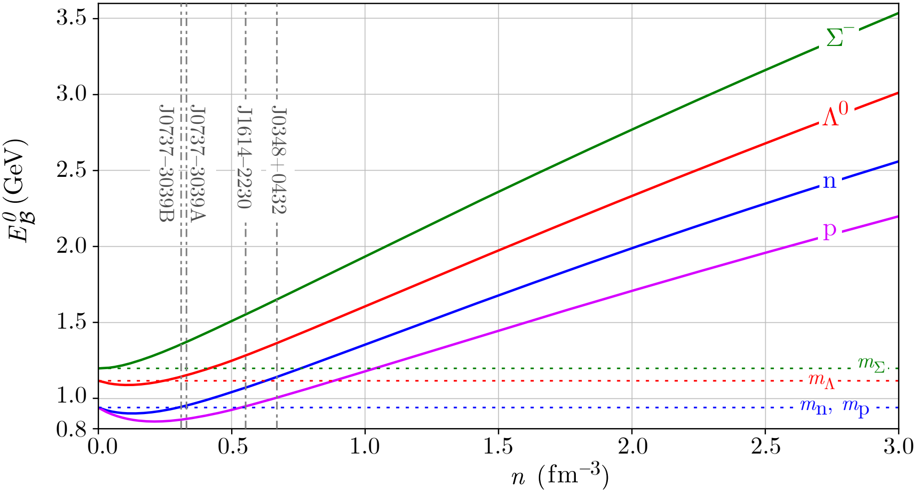
Effective Masses (CMF-1)

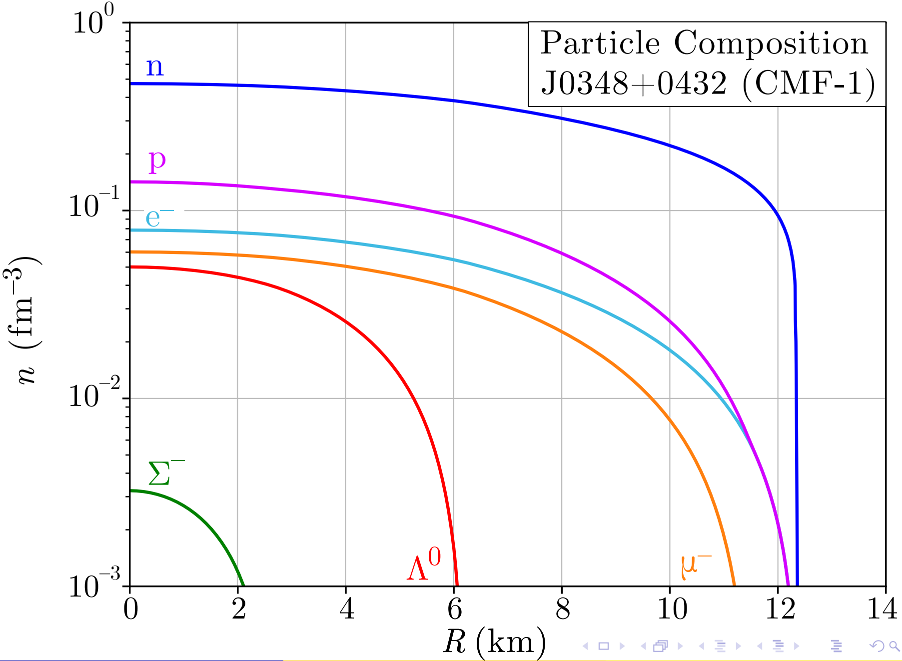


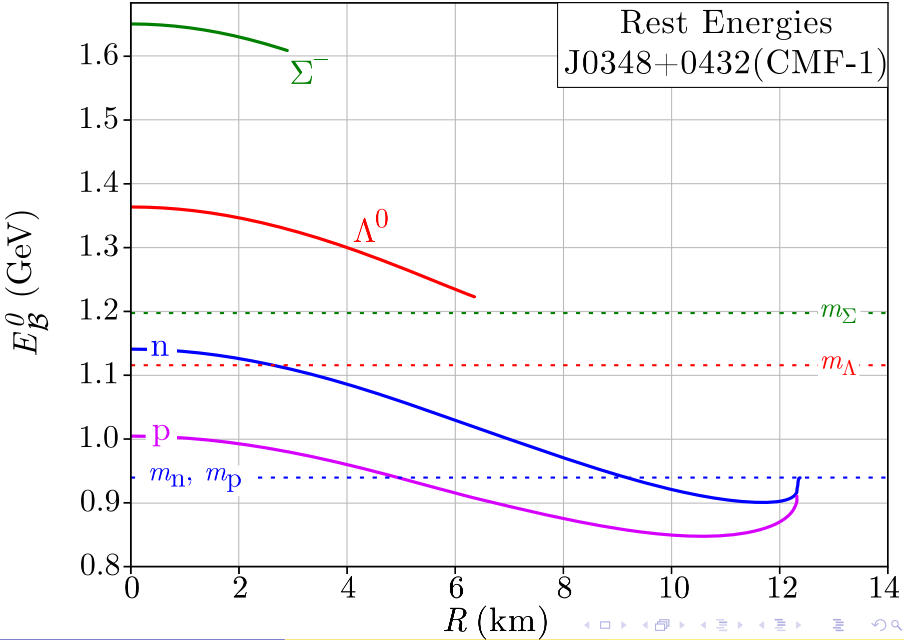
Self-Energies (CMF-1)



Rest Energies (CMF-1)




Particle Composition
J0348+0432 (CMF-1)
n
p
e$^-$
Σ^-
Λ^0
μ^-
n (fm^{-3})
10^0
10^{-1}
10^{-2}
10^{-3}
R (km)
0
2
4
6
8
10
12
14


Rest Energies
J0348+0432(CMF-1)
Σ^-
Λ^0
n
p
m_Σ
m_Λ
m_n, m_p
$E^0_\mathcal{B}$ (GeV)
R (km)
1.6
1.5
1.4
1.3
1.2
1.1
1.0
0.9
0.8
0
2
4
6
8
10
12
14

Particle Physics Model

Baryon Dark Decay Models

- Add a Dirac fermion χ with baryon number $B = +1$ which interacts with SM quarks [Heeck, 2021] :

$$\mathcal{L}_\chi = \bar{\chi}(i\partial\!\!\!/ - m_\chi)\chi + \left(\frac{u_i d_j d_k \chi_L^c}{\Lambda_{ijk}^2} + \frac{Q_i Q_j d_k \chi_L^c}{\tilde{\Lambda}_{ijk}^2} + \text{h.c.} \right) , \qquad (13)$$

- Flavor structure can be introduced in renormalizable models, e.g., [Fornal and Grinstein, 2018, Fajfer and Susič, 2021] with colored scalars $S_1 \sim (\bar{3}, 1, 1/3)$, or $\bar{S}_1 \sim (\bar{3}, 1, -2/3)$.

Baryon Dark Decay Models

Neutron decay anomaly	$\mathcal{O}_d = u\,d\,d\,\chi$	$m_{\mathrm{DS}} \lesssim m_n$
Hyperon dark decay	$\mathcal{O}_s = u\,d\,s\,\chi$	$m_{\mathrm{DS}} \lesssim m_\Lambda$
B-Mesogenesis	$\mathcal{O}_b = u\,d\,b\,\chi$	$m_{\mathrm{DS}} \lesssim m_B$

- $\mathcal{O}_s$ can be constrained by the duration of the neutrino pulse from SN1987A [Alonso-Álvarez et al., 2021]: $\mathrm{Br}\,(\Lambda \to \chi\gamma) < 1.6 \times 10^{-7}$
- We consider the effects of $n \to \chi\gamma$ and $\Lambda \to \chi\gamma$ induced by

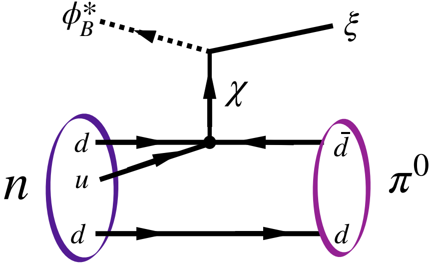
$$\mathcal{L}_{\mathrm{n}} = \bar{n}\left(i\partial\!\!\!/ - m_n + \frac{g_n e}{8m_n}\sigma^{\alpha\beta}F_{\alpha\beta}\right)n + \bar{\chi}(i\partial\!\!\!/ - m_\chi)\chi + \varepsilon_{n\chi}(\bar{n}\chi + \bar{\chi}n)\,, \tag{14}$$

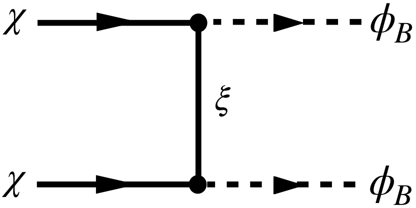
$g_n = -3.826$, $g_\Lambda = -1.226$ [Workman et al., 2022]

A minimal dark sector that avoids χ accumulation in the star, and induced nucleon decays [Elor et al., 2019]:

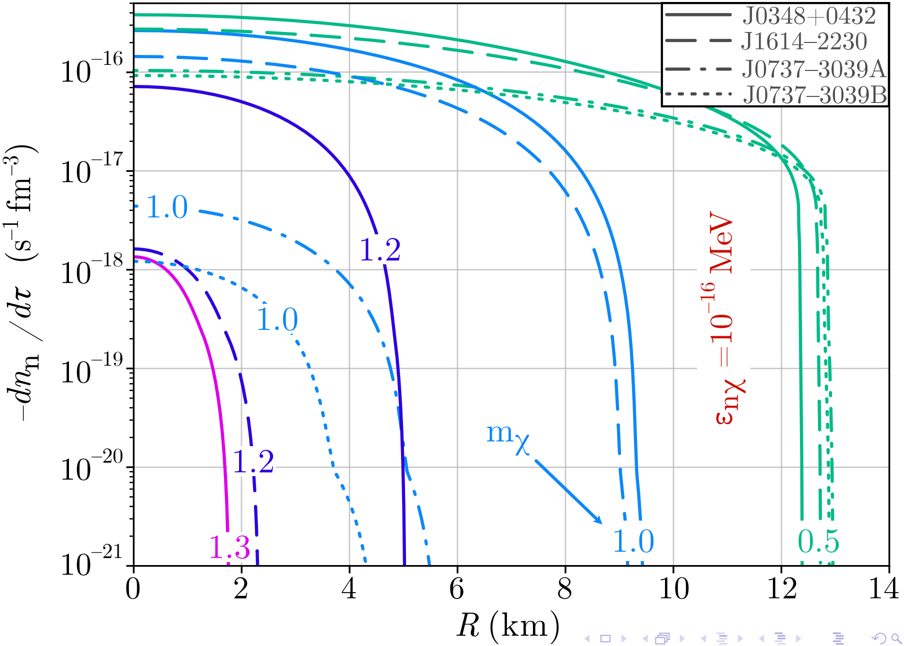
$$\mathcal{L}_{\text{dark}} \supset y_d \bar{\chi} \phi_B \xi + \text{h.c.}\,, \tag{15}$$

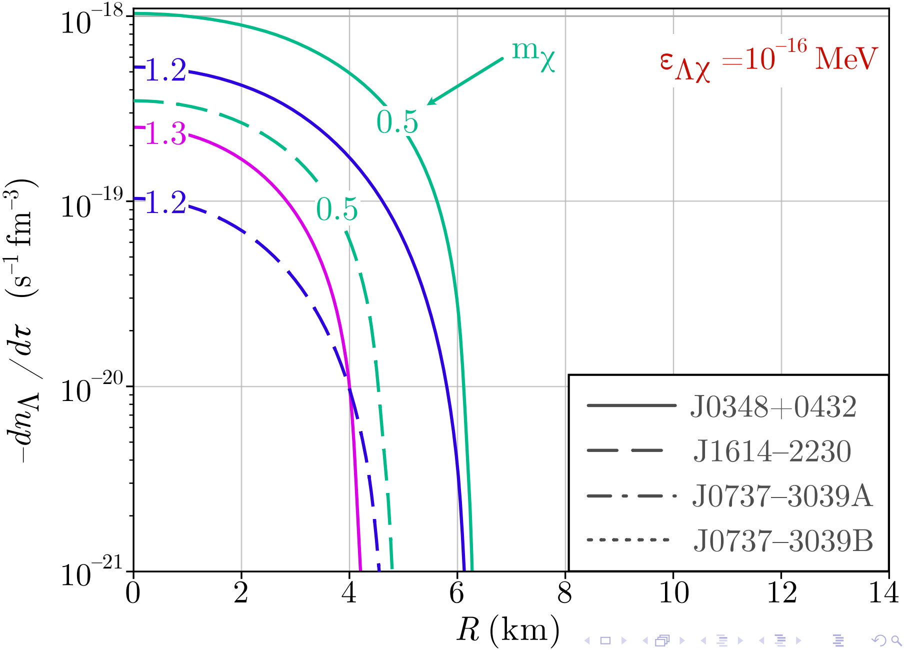
- ϕ_B: complex scalar with $B = +1$, Z_2 odd
- ξ: Majorana fermion, Z_2 odd, $m_\xi > m_n$
- χ, n, and p: Z_2 even

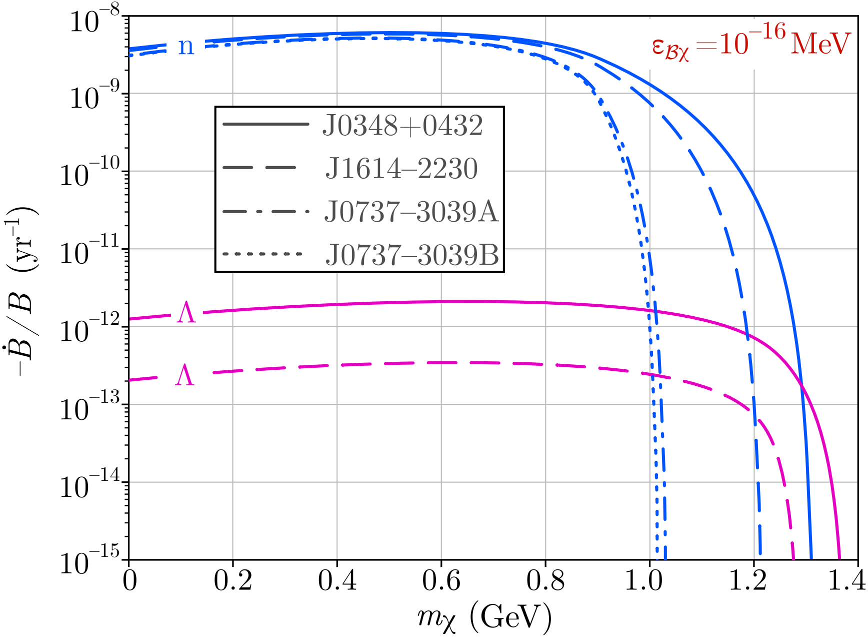


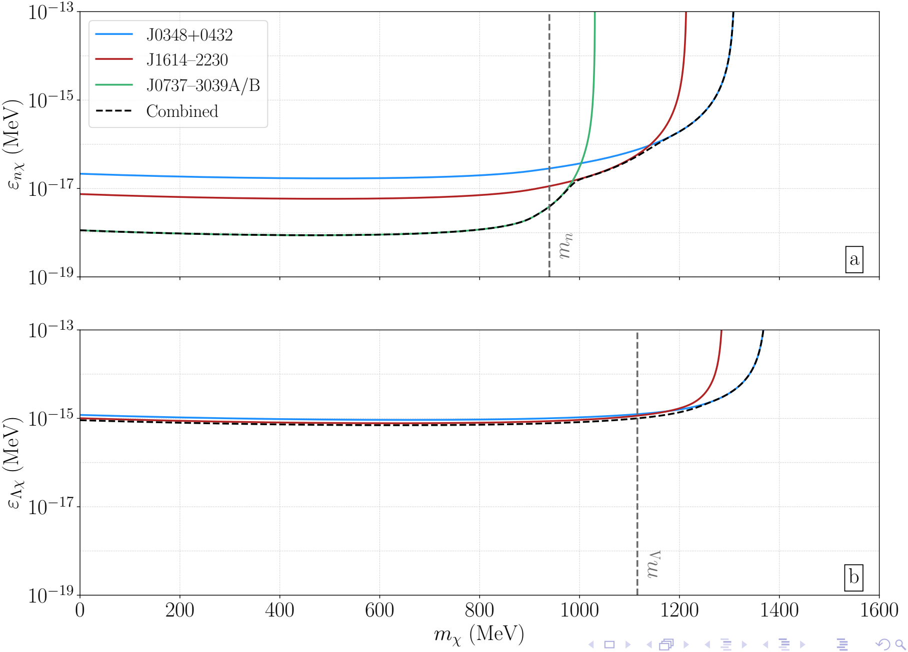


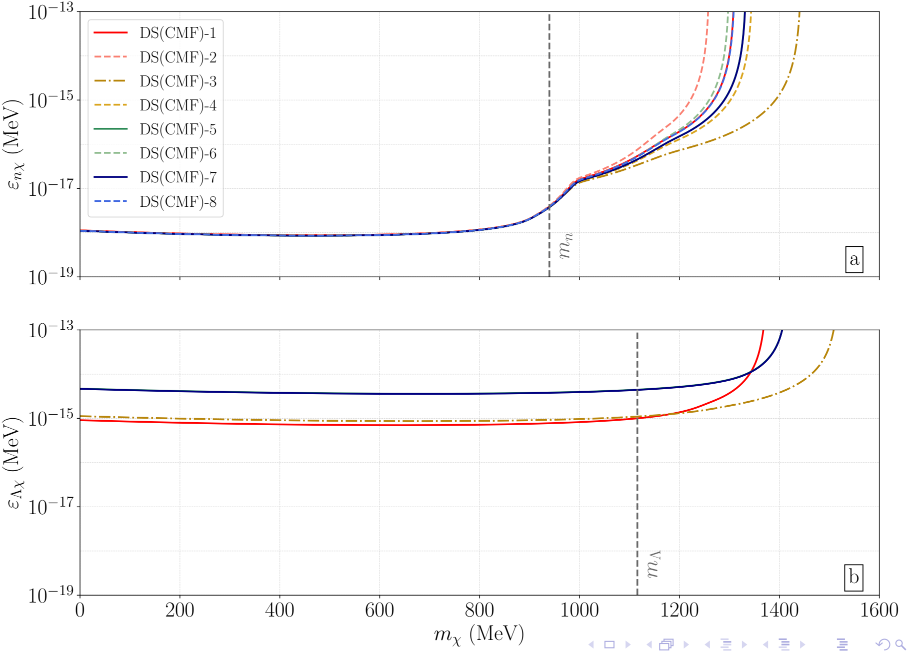
From Macro to Mirco

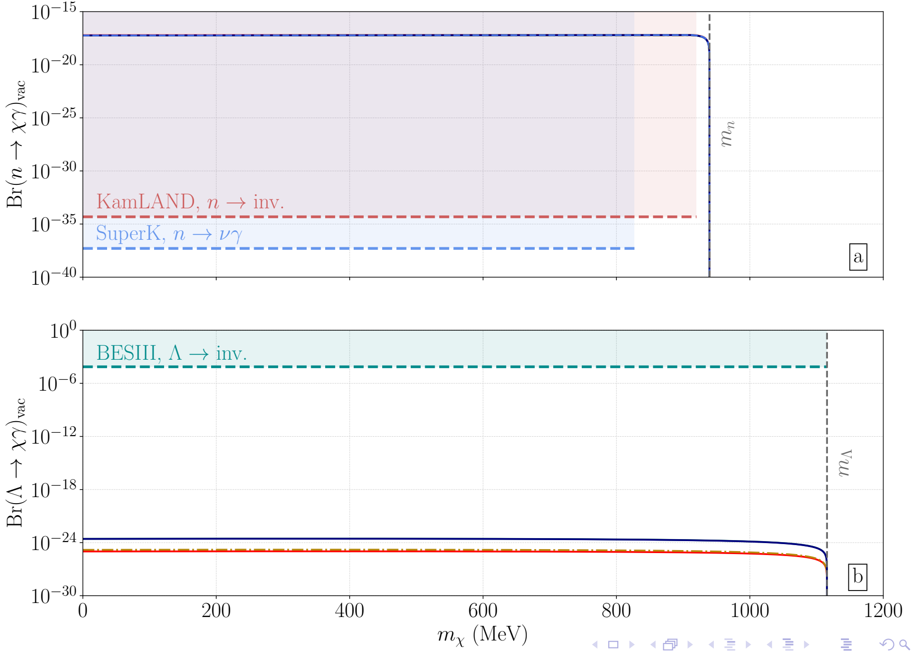

J0348+0432
J1614–2230
J0737–3039A
J0737–3039B
$-dn_{\mathrm{n}}/d\tau$ ($\mathrm{s}^{-1}\,\mathrm{fm}^{-3}$)
R (km)
10^{-16}
10^{-17}
10^{-18}
10^{-19}
10^{-20}
10^{-21}
0
2
4
6
8
10
12
14
1.0
1.2
1.0
1.2
1.3
m_χ
1.0
0.5
$\varepsilon_{n\chi} = 10^{-16}$ MeV

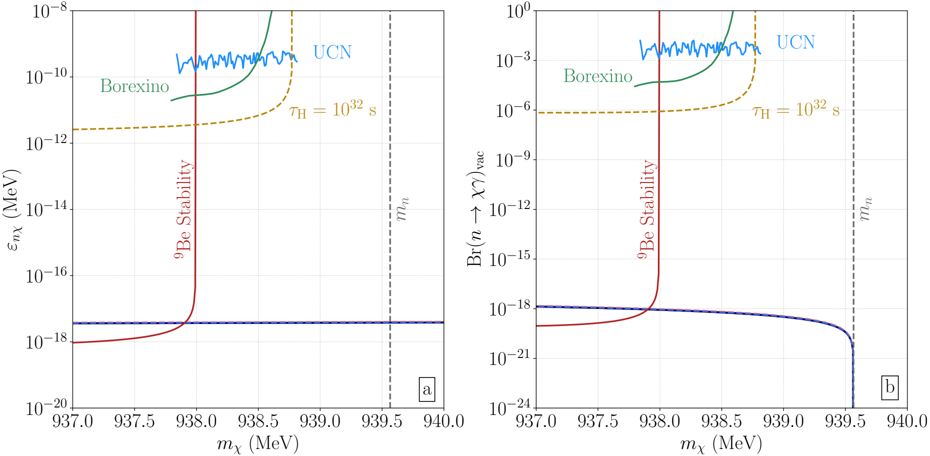

$\varepsilon_{\Lambda\chi} = 10^{-16}$ MeV
m_χ
1.2
1.3
1.2
0.5
0.5
$-dn_\Lambda/d\tau$ (s^{-1} fm^{-3})
R (km)
10^{-18}
10^{-19}
10^{-20}
10^{-21}
0
2
4
6
8
10
12
14
J0348+0432
J1614–2230
J0737–3039A
J0737–3039B


10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^{-12}
10^{-13}
10^{-14}
10^{-15}
$-\dot{B}/B$ (yr^{-1})
0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
m_χ (GeV)
n
Λ
Λ
$\varepsilon_{\mathcal{B}\chi} = 10^{-16}$ MeV
J0348+0432
J1614–2230
J0737–3039A
J0737–3039B


J0348+0432
J1614–2230
J0737–3039A/B
Combined
$\varepsilon_{n\chi}$ (MeV)
10^{-13}
10^{-15}
10^{-17}
10^{-19}
m_n
a
$\varepsilon_{\Lambda\chi}$ (MeV)
m_Λ
b
0
200
400
600
800
1000
1200
1400
1600
m_χ (MeV)


DS(CMF)-1
DS(CMF)-2
DS(CMF)-3
DS(CMF)-4
DS(CMF)-5
DS(CMF)-6
DS(CMF)-7
DS(CMF)-8
$\varepsilon_{n\chi}$ (MeV)
10^{-13}
10^{-15}
10^{-17}
10^{-19}
m_n
a
$\varepsilon_{\Lambda\chi}$ (MeV)
m_Λ
b
0
200
400
600
800
1000
1200
1400
1600
m_χ (MeV)


10^{-15}
10^{-20}
10^{-25}
10^{-30}
10^{-35}
10^{-40}
$\mathrm{Br}(n \to \chi\gamma)_{\mathrm{vac}}$
m_n
KamLAND, $n \to$ inv.
SuperK, $n \to \nu\gamma$
a
10^{0}
10^{-6}
10^{-12}
10^{-18}
10^{-24}
10^{-30}
$\mathrm{Br}(\Lambda \to \chi\gamma)_{\mathrm{vac}}$
BESIII, $\Lambda \to$ inv.
m_Λ
b
0
200
400
600
800
1000
1200
m_χ (MeV)



- UCN: $n \to \chi\gamma$ [Tang et al., 2018]
- Borexino: $H \to \nu\chi\gamma$ [McKeen and Pospelov, 2020]
- ^{9}Be: Metal-poor stars [Rich and Boesgaard, 2009] ($\tau \gtrsim 3 \times 10^9$ yrs [McKeen et al., 2021])

Conclusion

- Neutron star observations are complementary to terrestrial studies of BNV:
  - Huge reservoir of baryons
  - Heavy NS may contain hyperons (e.g., Λ^0, Σ^-)
  - Higher kinematical reach due to extreme repulsion (compared with rates in vacuum and within nuclei)

- Quasi-equilibrium BNV relocates the neutron star along its one-parameter sequence.

- Orbital periods of pulsar binaries can lead to stringent constraints on this generic class of BNV: $\Gamma_{\mathrm{BNV}} \lesssim 10^{-13}\,\mathrm{yr}^{-1}$.

- Our hyperonic limits are 20 orders of magnitude better than the terrestrial bounds.

Thank You!

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Back-up

Back-up Slides

GR Formalism of NS

- Line element for a static spherically symmetric system

$$d\tau^2 = g_{\mu\nu} dx^\mu dx^\nu = e^{2\nu(r)}\, dt^2 - e^{2\lambda(r)}\, dr^2 - r^2\, d\theta^2 - r^2\, \sin^2\theta\, d\phi^2 \tag{16}$$

- Static perfect fluid:

$$T_0^{\,0} = \mathcal{E}, \quad T_i^{\,i} = -p \qquad (i = 1, 2, 3). \tag{17}$$

- $g_{11}(r) = -\exp(2\lambda(r)) = -(1 - 2M(r)/r)^{-1}$, with $M(r)$ being the total mass included within radius r:

$$M(r') = 4\pi \int_0^{r'} \mathcal{E}(r) r^2 dr. \tag{18}$$

- Tolman-Oppenheimer-Volkoff (TOV):

$$\frac{dp}{dr} = -\frac{\left[p(r) + \mathcal{E}(r)\right]\left[M(r) + 4\pi r^3 p(r)\right]}{r\left[r - 2M(r)\right]}. \tag{19}$$

Baryon Number in Neutron Star

- The baryon number current is given in terms of the fluid velocity (u^μ) and the baryon number density (n) by $j^\mu(r) = n(r)u^\mu$.
- The invariant 4-volume is given by $\sqrt{-g}\,d^4x$ ($g \equiv \det[g_{\mu\nu}]$)
- The total baryon number in a static, spherically symmetric neutron star is given by

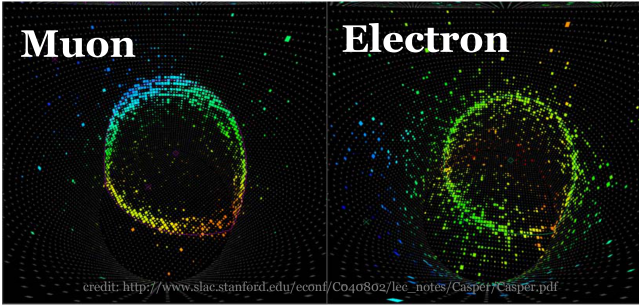
$$B = \int j^0(r)\,\sqrt{-g}\,d^4x = 4\pi \int_0^R \left[1 - \frac{2M(r)}{r}\right]^{-\frac{1}{2}} r^2 n(r) dr, \qquad (20)$$

in which we used $\sqrt{-g} = \exp(\nu(r) + \lambda(r))\,r^2 \sin\theta$.

Experiments

Super-Kamiokande

- A Cherenkov neutrino detector filled with water ($\sim 10^{34}$ nucleons).
- Can probe interactions with the electrons or nuclei of water via detection of Cherenkov radiation by its PMTs.



credit: http://www.slac.stanford.edu/econf/C040802/lec_notes/Casper/Casper.pdf

Example:

- $\tau\,(n \to \nu\gamma) > 5.5 \times 10^{32}$ yr [Takhistov et al., 2015]
- Electron-like ring (γ) with $100\,\text{MeV} < E < 1000\,\text{MeV}$.

Limits are at 90% C.L.

Kamioka Liquid Scintillator Antineutrino Detector

- Antineutrino detector via inverse-β decay
- Liquid scintillator (hydrocarbon)
- Search for nuclear deexcitation signals from neutron (two-neutron) disappearance (^{12}C):
    - $\tau\,(n \to \mathrm{inv}) > 5.8 \times 10^{29}$ yr [Araki et al., 2006]
    - $\tau\,(nn \to \mathrm{inv}) > 1.4 \times 10^{30}$ yr [Araki et al., 2006]
- Correlated triple signal to eliminate background:
    - Neutron scattering ($E_1 \subset 0.9$–25 MeV)
    - Neutron capture ($\tau \sim 210\,\mu s, E_2 \subset 1.8$–$2.6$ MeV)
    - β^+ decay of the residual nuclei (^{10}C, ^{9}C, or ^{8}B, $E_3 \subset 1.5$–3.8 MeV)

Limits are at 90% C.L.

Experiments with Hyperons

- Hyperons are less abundantly produced and short-lived.
- CLAS @ Jefferson Lab [McCracken et al., 2015]:
    - Λ produced by a photon beam incident on a liquid hydrogen target through $\gamma p \to K^+\Lambda$.
    - $\mathrm{Br}\left(\Lambda \to M^\pm l^\mp\right) \lesssim 10^{-7} - 10^{-6} \qquad [M^\pm \equiv \pi^\pm, K^\pm,\ l^\mp \equiv e^\mp, \mu^\mp]$
    - $\tau\left(\Lambda \to M^\pm l^\mp\right) \gtrsim 10^{-12} - 10^{-11}\ \ \mathrm{yr}$
- Invisible decays of the Λ produced in $J/\Psi \to \Lambda\bar{\Lambda}$ at Beijing electron-positron collider (BESIII [Ablikim et al., 2021]):
    - $\bar{\Lambda}$ is explicitly constructed $(\bar{\Lambda} \to \bar{p} + \pi^+)$
    - $\mathrm{Br}\left(\Lambda \to \text{invisible}\right) < 7.4 \times 10^{-5}$
    - $\tau\left(\Lambda \to \text{invisible}\right) \gtrsim 10^{-13}\ \ \mathrm{yr}$

Limits are at 90% C.L., and $\tau_{\mathrm{Decay}}(\Lambda) \sim 10^{-17}$ yr.

Supernova SN1987A Bounds

Constraining hyperon dark decays (apparent BNV) via $\mathcal{O} = u\,d\,s\,\chi$ with SN1987A [Alonso-Álvarez et al., 2021]:

- Dark particles produced in Λ decays that are energetic enough to escape the gravitational potential drain energy from the PNS.

  ⟶ Leads to a new cooling mechanism.

- Constrained by [Alonso-Álvarez et al., 2021] the duration of the neutrino pulse from SN1987A:
  - $\mathrm{Br}\,(\Lambda \to \chi\gamma) < 1.6 \times 10^{-7}$
  - $\mathrm{Br}\left(\Lambda \to \chi\pi^0\right) < 1.1 \times 10^{-7}$
  - $\mathrm{Br}\,(\Lambda \to \xi\phi) \lesssim 4 \times 10^{-9}$

Hyperons in NS?

- Hyperons (Y) are naturally expected to show up at high densities ($n \sim 2\text{-}3\, n_0$) as the baryon chemical potential increases.
- Need measurements of Y-N, Y-Y and Y-N-N interactions.
- Kaon and pion beams can be used to produce hypernuclei via

$$K^- + {}^{A}Z \to {}^{A}_{\Lambda}Z + \pi^-, \tag{21}$$

$$\pi^+ + {}^{A}Z \to {}^{A}_{\Lambda}Z + K^+. \tag{22}$$

- We know that $U_\Lambda(n_0) \approx -30$ MeV, $U_{\Sigma^-}(n_0) \approx +30 \pm 20$ MeV, $U_\Xi(n_0) \approx -15$ MeV. [Gal et al., 2016]
- More data on double hypernuclei (e.g., ${}^{6}_{\Lambda\Lambda}\mathrm{He}$) needed to understand Λ-Λ interaction: Japan Proton Accelearator Research Complex (J-PARC), PANDA experiment at FAIR in Germany.