Neutron portal

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3 papers this year

D. McKeen, MP, 2003.02270 (lifetime of H atom, to appear in PRD)

D. McKeen, MP, N. Raj, 2006.15140 (H decaying to interacting particles, PRL)

D. McKeen, MP, N. Raj, 2012.09865 (cosmological constraints)

D. McKeen, MP, N. Raj, 2105.09951 (NS heating constraints)

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Plan

1. *Introduction.* Broad look at dark sectors.
2. Neutron portal: a window into interesting phenomenology.
3. What happens when proton is stable and Hydrogen atom is not.
4. Select cosmological bounds.
5. Neutron star bounds on mirror neutrons.
6. Conclusions.

Dark Sectors = light BSM states

Typical BSM model-independent approach is to include all possible BSM operators once very heavy new physics is integrated out *plus all possible light states explicitly*

$L_{SM+BSM} = - m_H^2 \, (H^+_{SM} H_{SM}) +$ all dim 4 terms $(A_{SM},\ \psi_{SM},\ H_{SM}) +$

(W.coeff. $/\Lambda^2$) $\times$ Dim 6 etc $(A_{SM},\ \psi_{SM},\ H_{SM})$ + …

all lowest dimension portals $(A_{SM},\ \psi_{SM},\ H,\ A_{DS},\ \psi_{DS},\ H_{DS}) \times$ portal couplings

+ dark sector interactions $(A_{DS},\ \psi_{DS},\ H_{DS})$

SM = Standard Model

DS – Dark Sector

Classes of portal interactions

Let us *classify* possible connections between Dark sector and SM

$H^+H\,(\lambda\,S^2 + A\,S)$ Higgs-singlet scalar interactions (scalar portal)

$B_{\mu\nu}V_{\mu\nu}$ "Kinetic mixing" with additional U(1)' group

(becomes a specific example of $J_\mu^i A_\mu$ extension)

$LH\,N$ neutrino Yukawa coupling, N – RH neutrino

$J_\mu^i A_\mu$ requires gauge invariance and anomaly cancellation

It is very likely that the observed neutrino masses indicate that Nature may have used the *LHN* portal…

Dim>4

$J_\mu^A\ \partial_\mu a\,/f$ axionic portal

……….

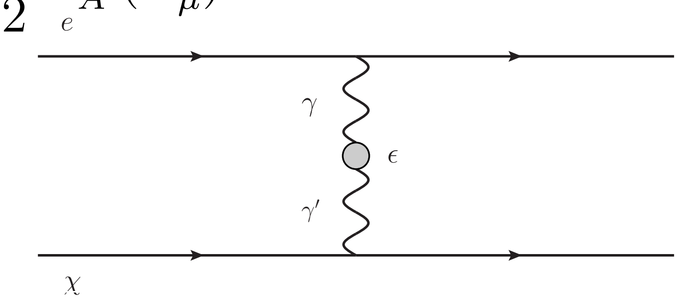
$$\mathcal{L}_{\text{mediation}} = \sum_{k,l,n}^{k+l=n+4} \frac{\mathcal{O}_{\text{med}}^{(k)}\mathcal{O}_{\text{SM}}^{(l)}}{\Lambda^n},$$

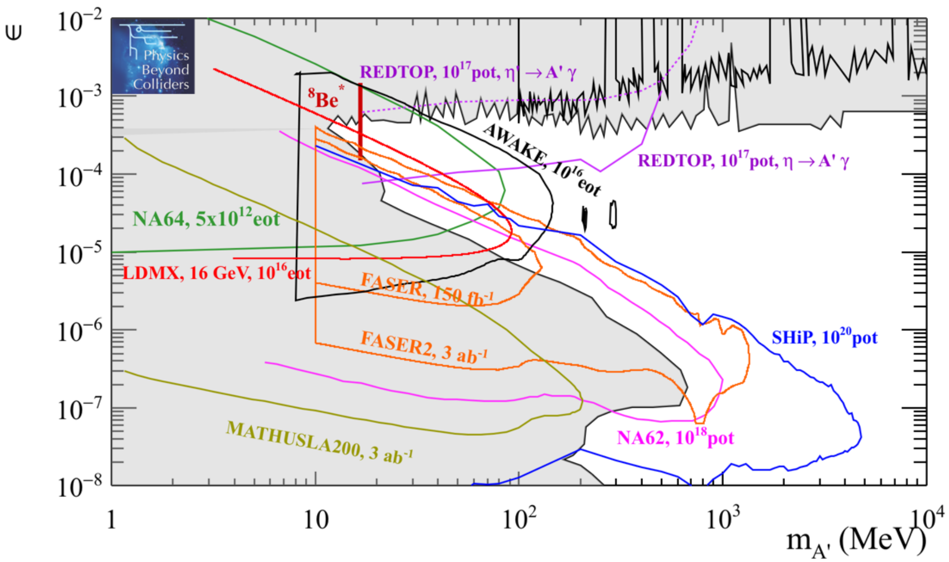
A simple model of dark sector

$$\mathcal{L} = \mathcal{L}_{\psi,A} + \mathcal{L}_{\chi,A'} - \frac{\epsilon}{2} F_{\mu\nu} F'_{\mu\nu} + \frac{1}{2} m_{A'}^2 (A'_\mu)^2.$$

$$\mathcal{L}_{\psi,A} = -\frac{1}{4} F_{\mu\nu}^2 + \bar{\psi}[\gamma_\mu (i\partial_\mu - eA_\mu) - m_\psi]\psi$$

$$\mathcal{L}_{\chi,A'} = -\frac{1}{4} (F'_{\mu\nu})^2 + \bar{\chi}[\gamma_\mu (i\partial_\mu - g' A'_\mu) - m_\chi]\chi,$$



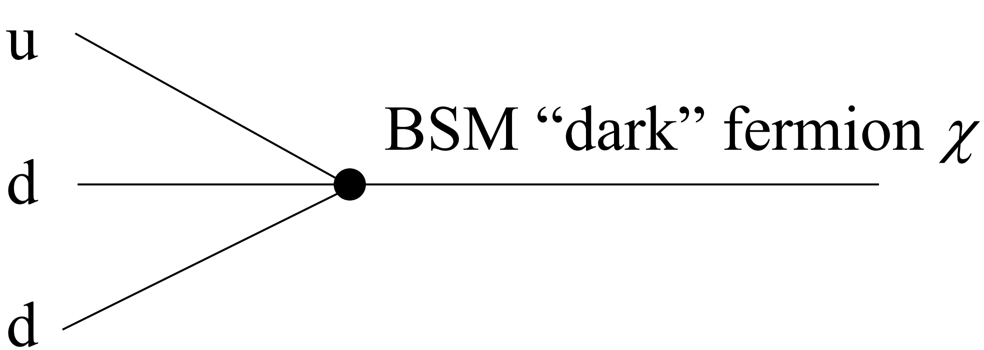


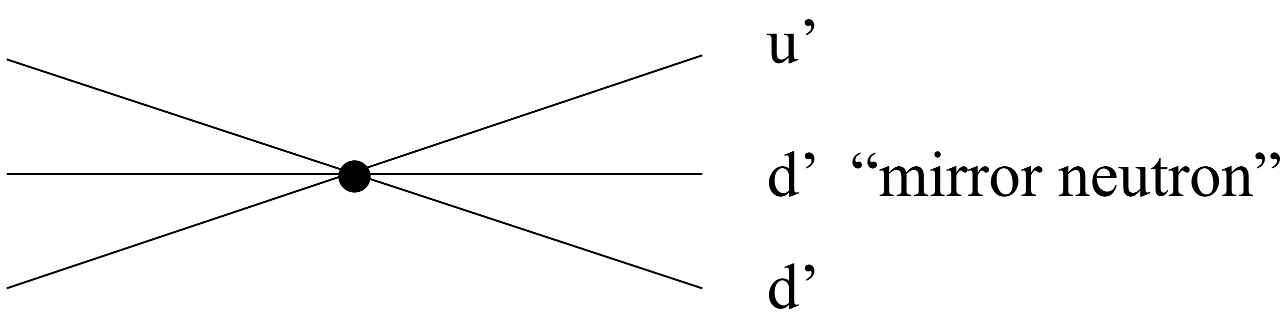
Plot from recent Physics Beyond Colliders review

- Investigation of dark sector parameter space is an active field of research at the moment

A similar model for a baryon portal?

- Due to a composite nature of nucleons, this is a higher-dimensional operator

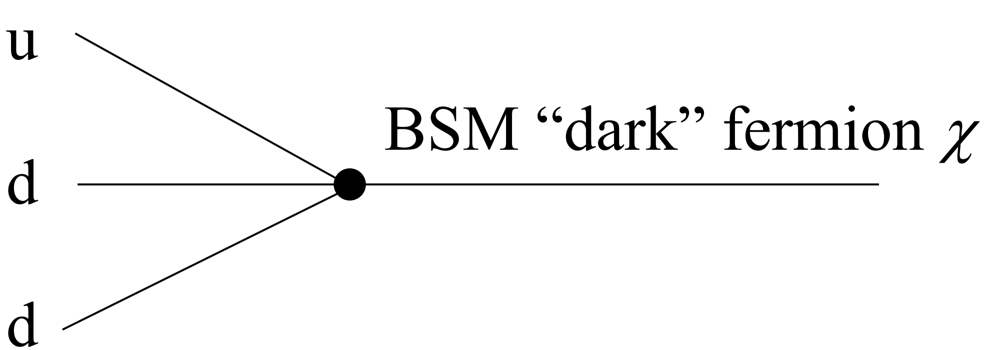




A similar model for a baryon portal?

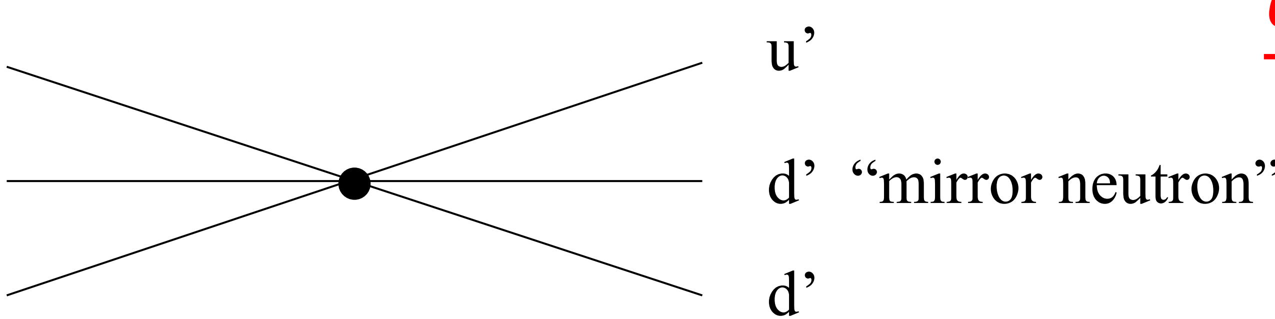
- Due to a composite nature of nucleons, this is a higher-dimensional operator

$$\frac{O^{dim=6}}{\Lambda^2}$$

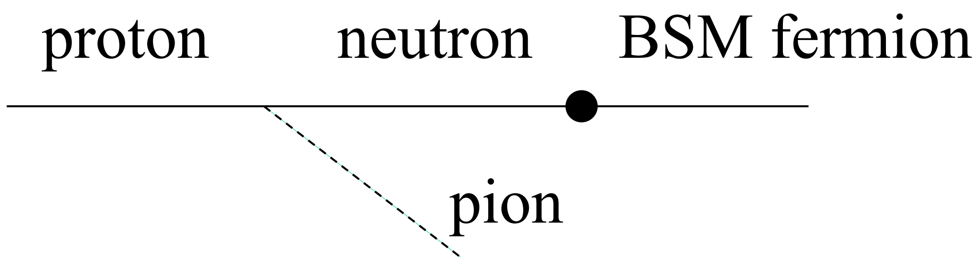


Can be made UV complete above EW scale

$$\frac{O^{dim=9}}{\Lambda^5}$$



Strong constraints at $m_\chi << m_n$



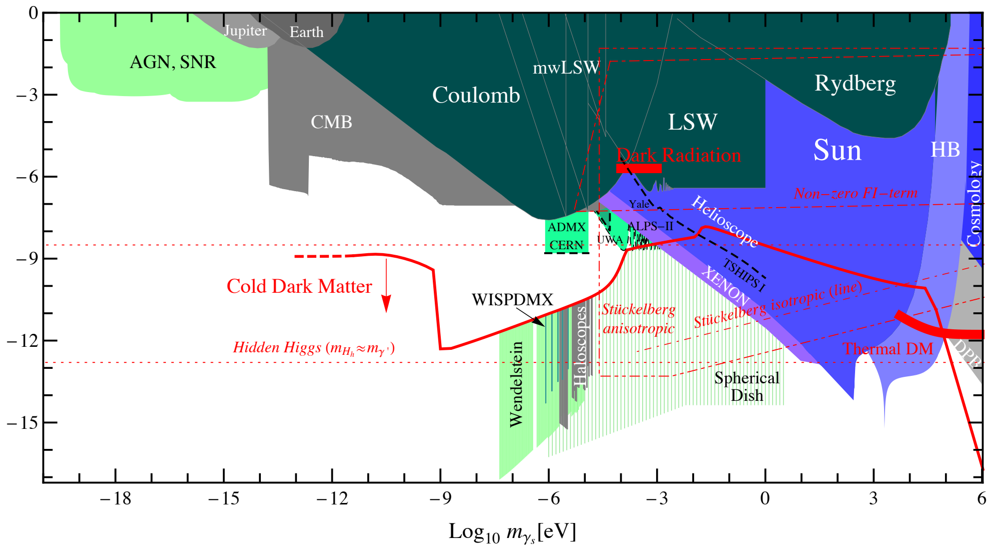
- When $m_\chi << m_n$, strong constraints from proton (nucleon) decay apply.
- If $m_\chi << m_n$ it is not obvious if a model is constrained *at all*.
- When the mass splitting becomes smaller than O(1.8 MeV), $\Delta m = m_n - m_\chi < 1.8$ MeV, the nuclei are stable but neutrons are not. Expect modifications to the physics of free neutrons.
- When the mass splitting is sub-eV, i.e. χ is a mirror neutron, quantum oscillations are expected.
- Investigate the parameter space, identify most interesting physics!

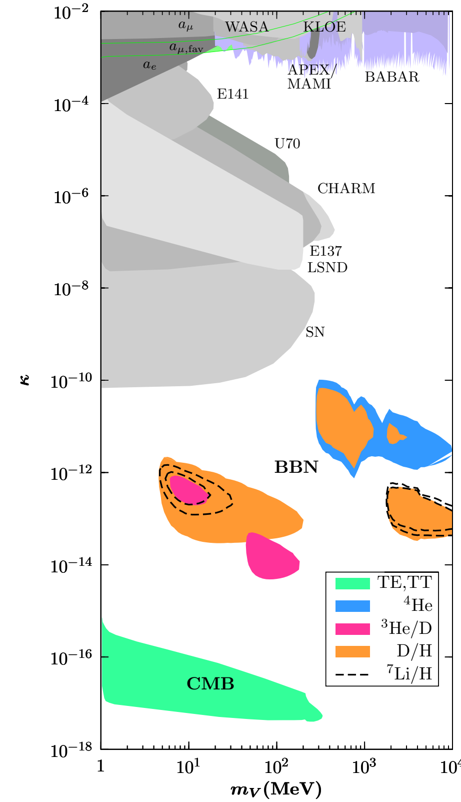
Motivation for studying neutron portal

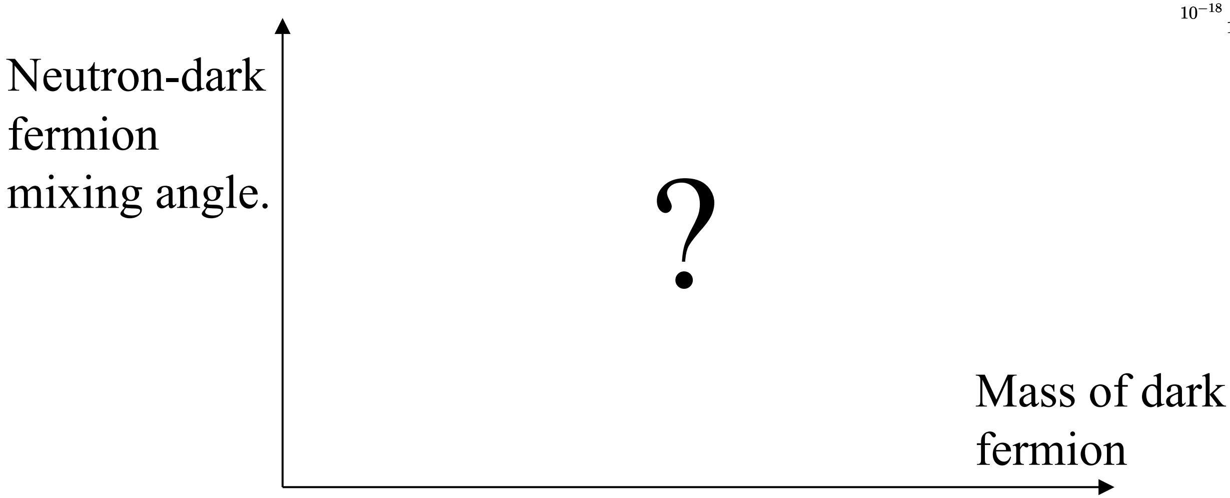
- *Economical new physics*, with implications for high- and low-energy physics experiments
- ”Shared” baryon number provides interesting possibilities for *baryogenesis*.
- A new fermion χ maybe stable, in which case it is an *appealing DM candidate*, and a mass close to m_n maybe also behind $\rho_{DM} \sim \rho_{baryon}$
- New effects in cosmology where neutrons are crucial: *neutron stars*, *Big Bang Nucleosynthesis*.
- Novel effects in neutron physics: new neutron decay channels, oscillations into dark states, oscillations back (regeneration)

Motivation for studying neutron portal

- Dark photons (e.g.) are well studied







Possibility to alter the neutron lifetime

Grinstein, Fornal 2018; Berezhiani 2018 + earlier papers

Speculates whether there is an extra decay channels for neutrons

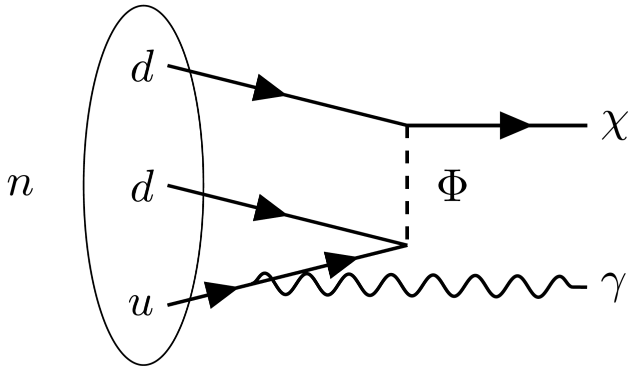
$$\tau_n^{\mathrm{bottle}} = 879.6 \pm 0.6\,\mathrm{s}\,.$$

$$\tau_n^{\mathrm{beam}} = 888.0 \pm 2.0\,\mathrm{s}\,.$$

Beam experiments register protons in the final state. Will miss an "exotic" decay mode. This is why bottle experiments see shorter lifetime (!)

Neutron portal and its UV completions

Grinstein, Fornal 2018, PRL



- In this example, the scale of the UV completion (i.e. the mass of Φ scalar) can be made in the 10's of TeV's, and far outside the current collider reach.
- Neutron lifetime issues can be addressed [maybe]
- *It makes total sense to study exotic channels for neutron decay*.
- Very quickly, new gamma and electron-positron decay channels were investigated! (Tang et al, 2018, 1802.01595)

Simplest low-energy model

- A tantalizing simple model consists of one dark fermion χ.

$$\mathcal{L} = \bar{n}\,(i\,\partial\!\!\!/ - m_n)\,n + \bar{\chi}\,(i\,\partial\!\!\!/ - m_\chi)\,\chi - \delta\,(\bar{n}\chi + \bar{\chi}n)$$

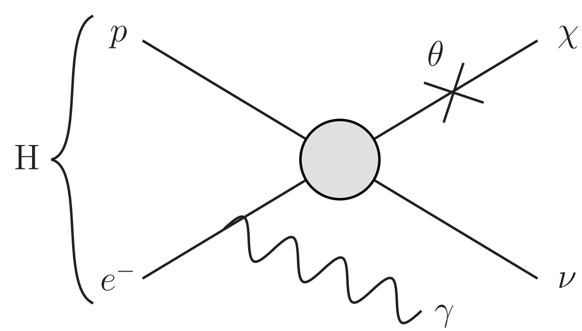
- Two-parameter model: mass-mixing angle $\{\Delta m,\ \theta = \delta/\Delta m\}$
- If we want to "influence" neutron lifetime, but have no other dramatic consequences, m_χ has to be in a narrow ~ 1.8 MeV range.

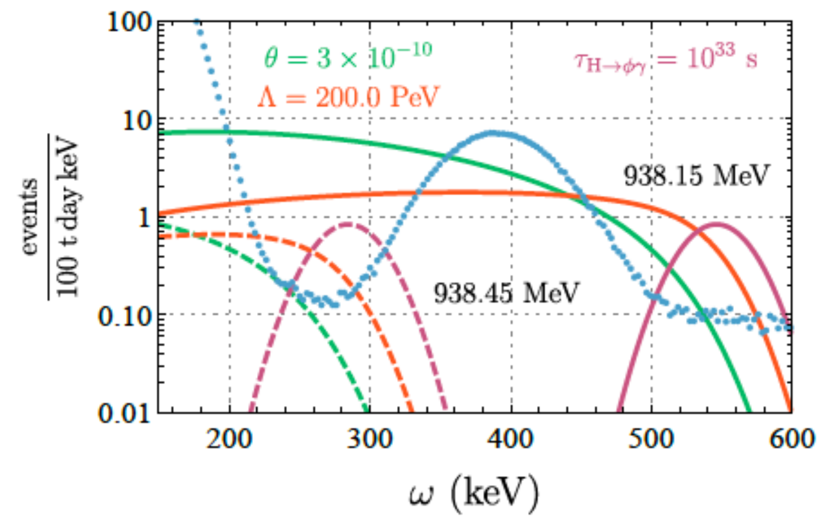
$$\mathrm{Br}_{n\to\chi\gamma} \simeq 0.02\left(\frac{\theta}{10^{-9}}\right)^2\left(\frac{\Delta m}{\mathrm{MeV}}\right)^3$$

- Roughly 1% Br is interesting for the neutron lifetime controversy
- Astrophysics provide strong constraints on this possibility (McKeen, Nelson, Reddy, Zhou; Baym et al, Motta et al, 2018). Mass-radius relation imply some mechanism that generates extra pressure in the dark sector → self interaction etc (e.g. Cline, Cornell 2018)

Proton and nuclei maybe stable by H-atom can decay

- If $m_\chi < m_p + m_e$, there is a possibility for H → $\chi + \nu$ decay.
- It looks like a "completely dark" decay.
- Radiative hydrogen decay is discoverable, however, via the energy release associated with ~ 100's keV photon.



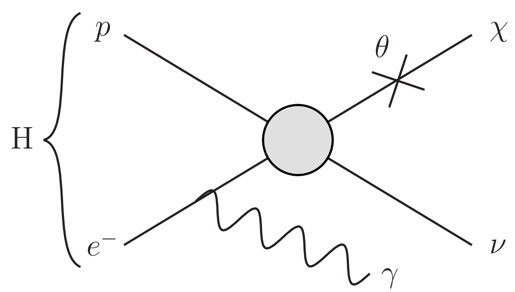


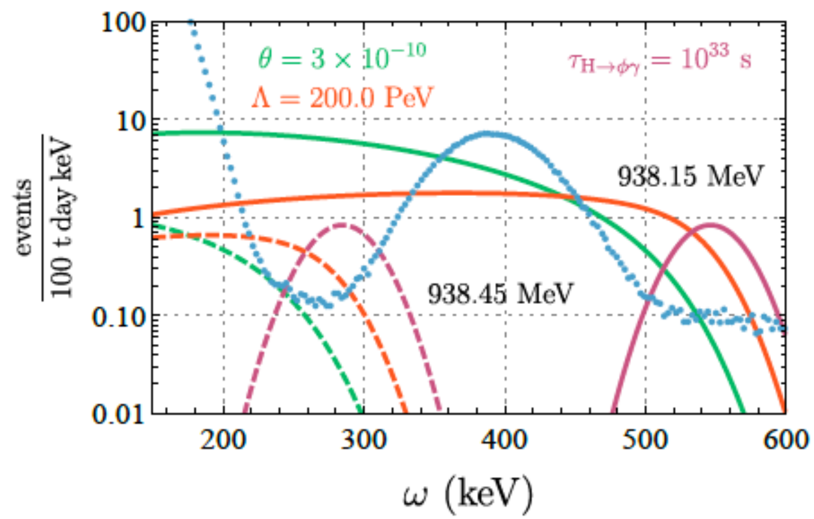
Radiative decays of H can be probed down to ~ 50 keV energy release through Borexino data on "e decays", and by Borexino test facility results from the 1990s

Investigation of limits on H lifetime

- McKeen and MP, this year

- Large hydrocarbon-containing detectors are being used for the solar neutrino studies: Borexino, SNO+, etc. Lots of H.





- Radiative decays of H can be probed down to ~ 50 keV energy release through Borexino data on "e decays", and by Borexino test facility results from the 1990s

Investigation of limits on H lifetime

- Radiative branching in the mixing model:

$$\Gamma_{H\to\nu\chi} = \frac{1}{\tau_H} \simeq |\psi(0)|^2 \frac{G_F^2 |V_{ud}|^2 \theta^2}{2\pi} \left(1+3g_A^2\right) Q^2$$
$$= \frac{1}{10^{27}\ \mathrm{s}} \left(\frac{\theta}{10^{-9}}\right)^2 \left(\frac{Q}{m_e}\right)^2,$$

- Photon spectrum

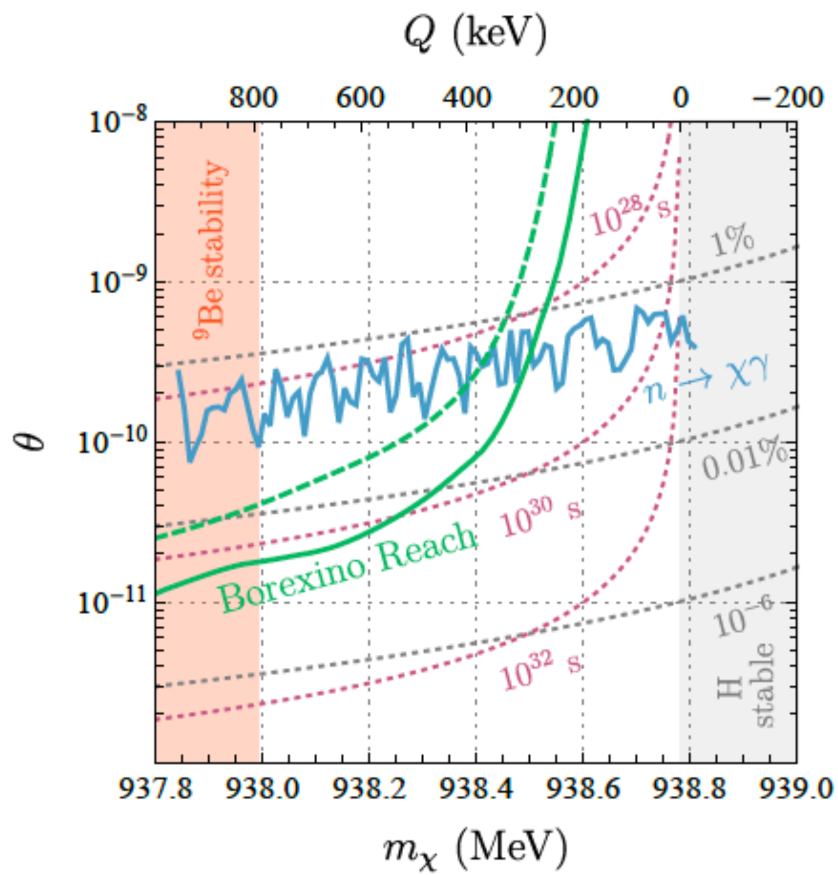
$$\frac{d}{d\omega}\mathrm{Br}_{H\to\nu\chi\gamma} = \frac{\alpha}{\pi}\frac{\omega}{m_e^2}\left(1-\frac{\omega}{Q}\right)^2 + \mathcal{O}\left(\frac{m_e}{m_p}\right)$$
$$\simeq \frac{5\times 10^{-6}}{\mathrm{keV}}\frac{\omega}{m_e}\left(1-\frac{\omega}{Q}\right)^2.$$

- Total radiative branching

$$\mathrm{Br}_{H\to\nu\chi\gamma} \simeq \frac{\alpha}{12\pi}\frac{Q^2}{m_e^2} \simeq 2\times 10^{-4}\left(\frac{Q}{m_e}\right)^2.$$

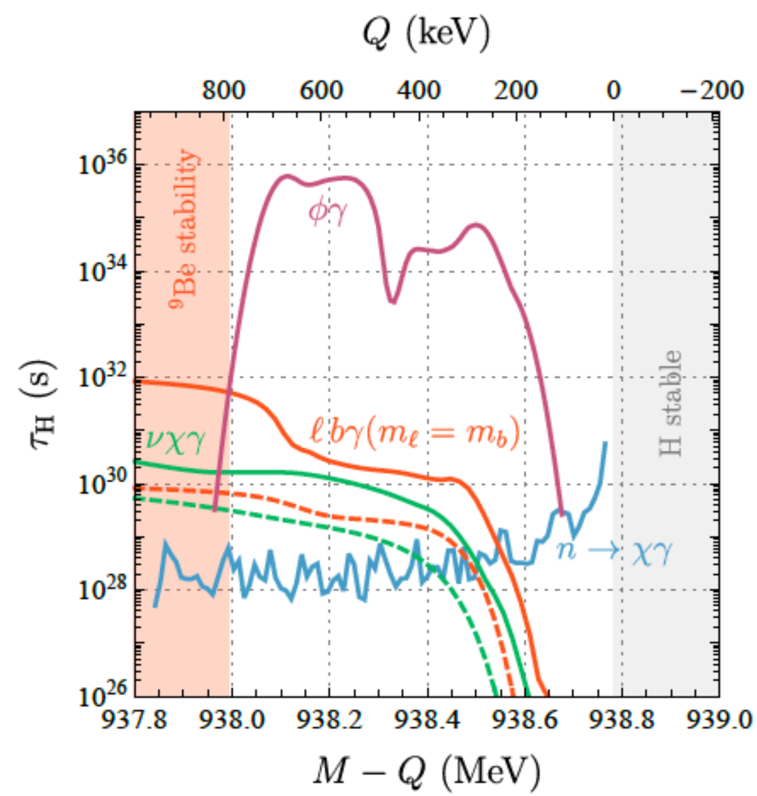
Investigation of limits on H lifetime

- McKeen and MP, 2003.02270
- Adding constraints on mass-mixing parameter space.



Investigation of limits on H lifetime

- McKeen and MP, 2003.02270
- Limits on H lifetime in various models



- Typical constraints are at ~ 10^{30} seconds level.
- This is ~ several orders of magnitude less tight than p decay limits

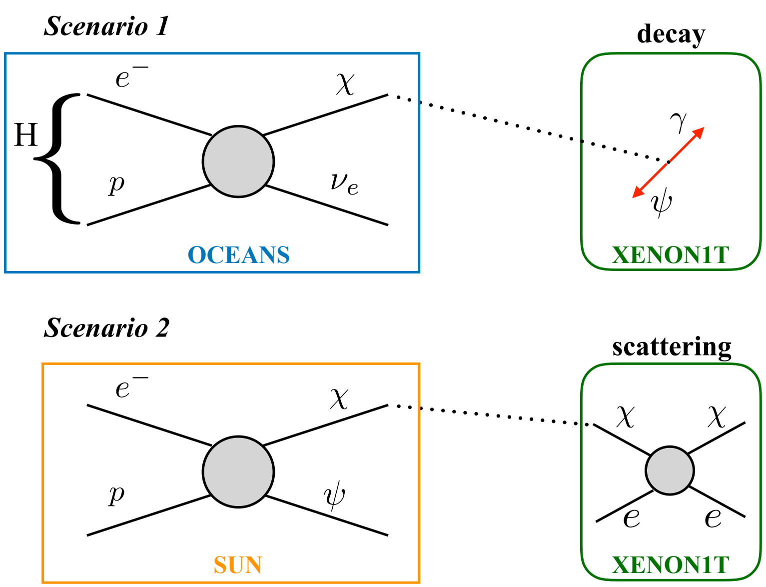
Could H decay to a more interacting species than neutrino + χ?

$$\Phi^{\text{global+MW}}_{\text{DM decay}} \sim 10^4\ \text{cm}^{-2}\text{s}^{-1}\left(\frac{10\,\tau_{\text{U}}}{\tau_{\text{DM}}}\right)\left(\frac{1\,\text{GeV}}{m_{\text{DM}}}\right),$$

$$\Phi^{\odot}_{\text{proton decay}} \sim 10^{-8}\ \text{cm}^{-2}\text{s}^{-1}\left(\frac{10^{30}\,\text{yr}}{\tau_p}\right),$$

$$\Phi^{\odot}_{\text{H decay}} \sim 10^{3}\ \text{cm}^{-2}\text{s}^{-1}\left(\frac{10^{28}\,\text{s}}{\tau_{\text{H}}}\right),$$

$$\Phi^{\oplus}_{\text{H decay}} \sim 1\ \text{cm}^{-2}\text{s}^{-1}\left(\frac{10^{28}\,\text{s}}{\tau_{\text{H}}}\right).$$



We (McKeen, MP, Raj) have considered two speculative scenarios vs Xenon1T electron excess, that could conceivably come from this exotic source

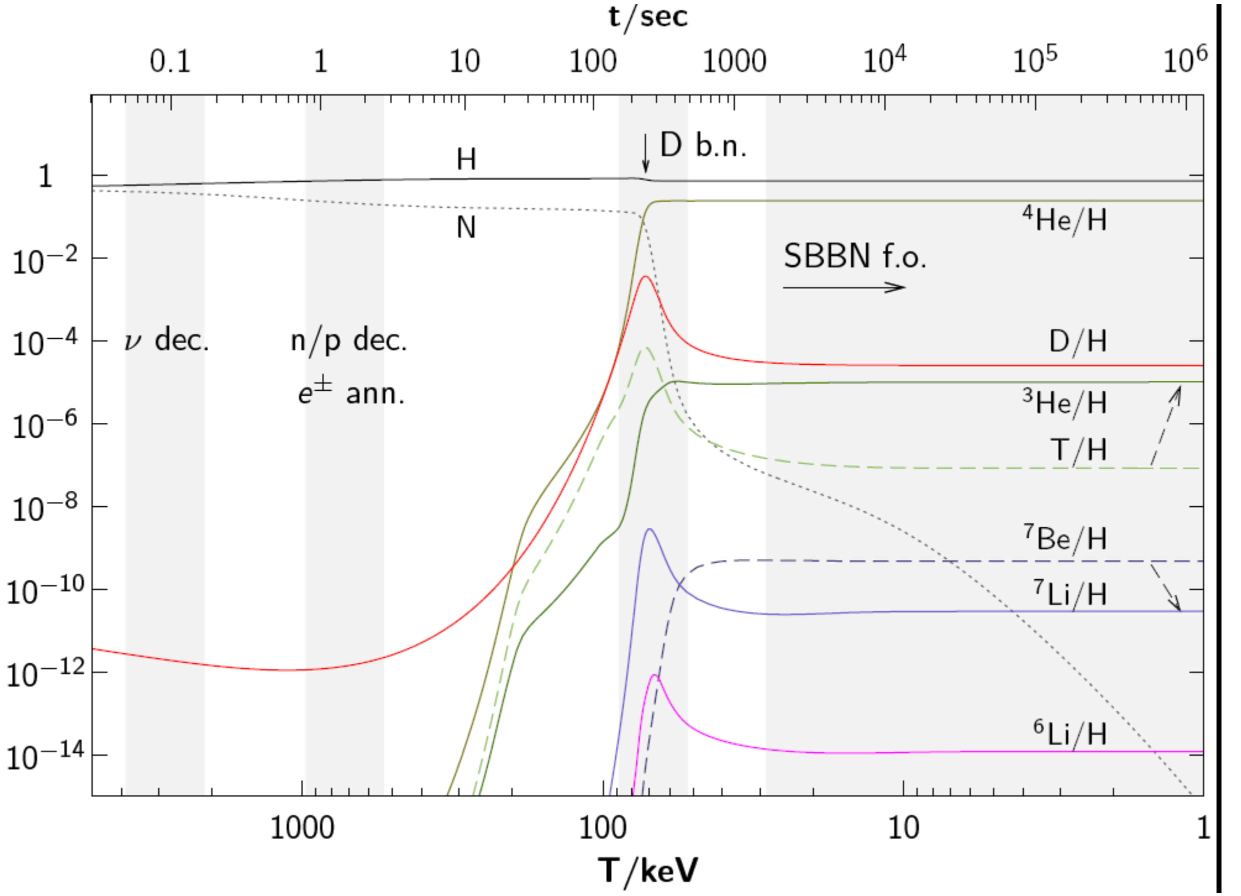
Cosmological bounds

(McKeen, Raj, MP, 2012.09865)

(*back to the minimal model*)

- Early Universe can lead to new bounds.
- Equilibration n ← → χ at early times is inevitable.
- Subsequent decay dumps energy via n → $\chi+\gamma$ or χ → n+γ. (CMB and BBN implications)
- Extra neutrons can be supplied at late times (e.g. $\sim 10^4$ seconds) affecting BBN outcomes.

BBN chronology

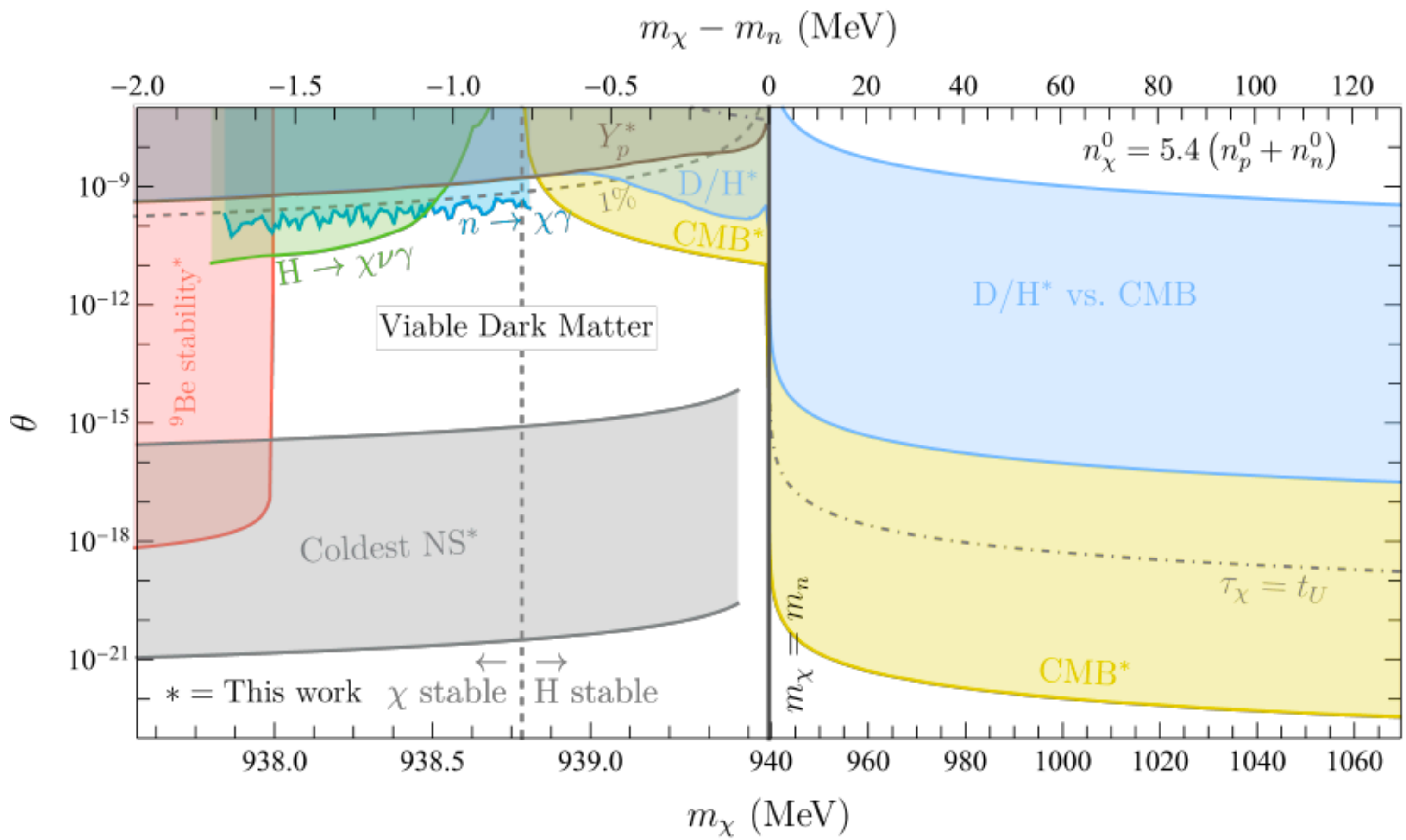


- Late stages of BBN occur in "neutron starvation" regime. Any new addition of n will be reflected in elevated D/H.

- "Dark neutrons" can be converted to normal neutrons via $\chi+\gamma\rightarrow n$. This will work well for smaller mass splittings!

Cosmological bounds

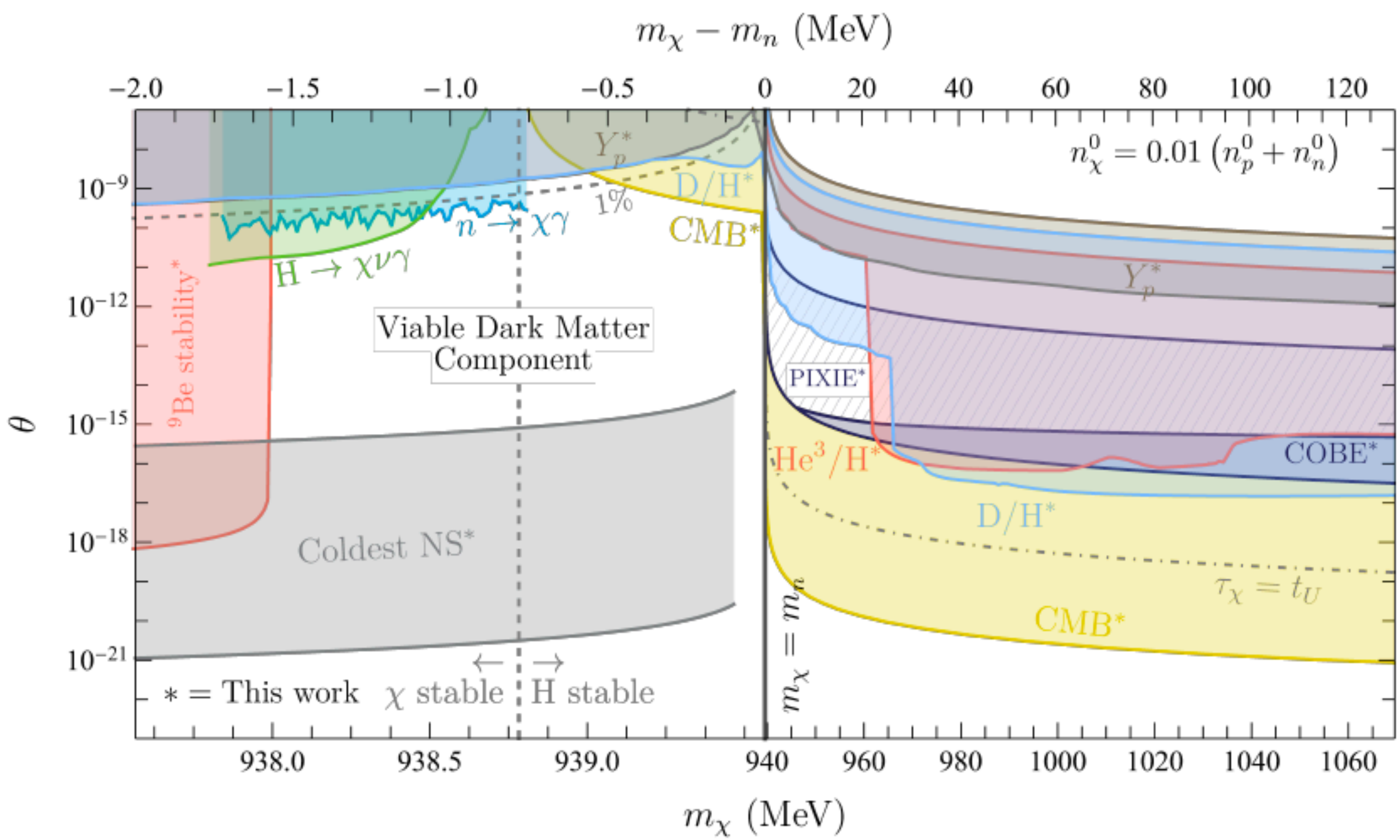
Assuming χ abundance = DM abundance



- Small sliver of parameter space still exists for neutron lifetime!
- CMB limits on the left come from χ → p + e + ν decays at late times.

Cosmological bounds

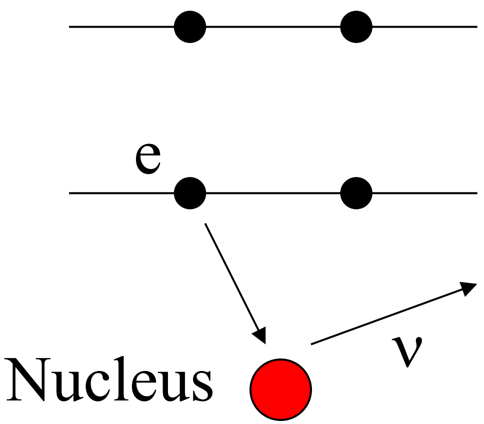
Same for small abundance, 1% from the baryon abundance.

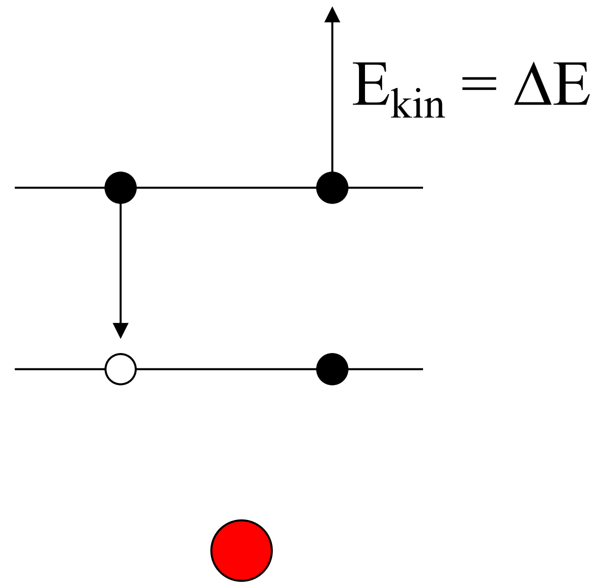


- NS constraints at small angle follow from n→χ conversion and do not rely on chi being dark matter

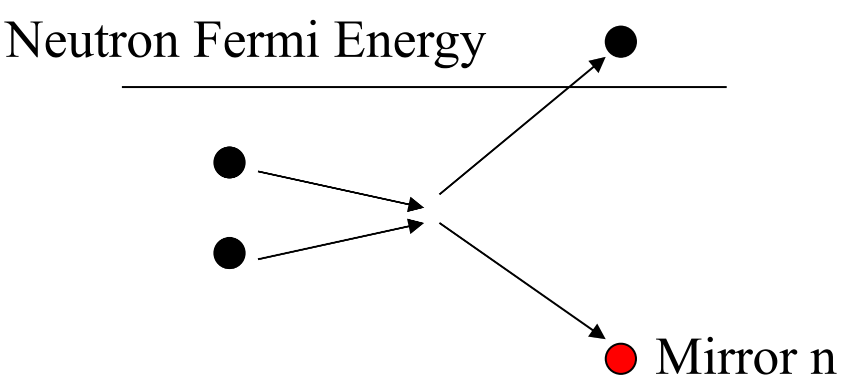
Energy generation mechanism in NS

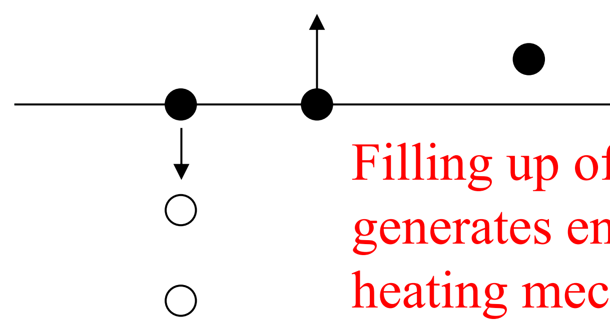
Electron capture in atoms + Auger effect





n → n’ transfer in neutron stars

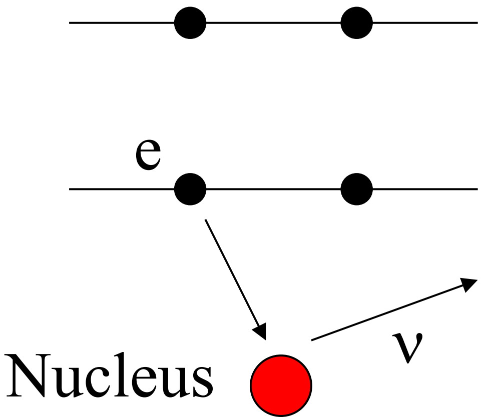


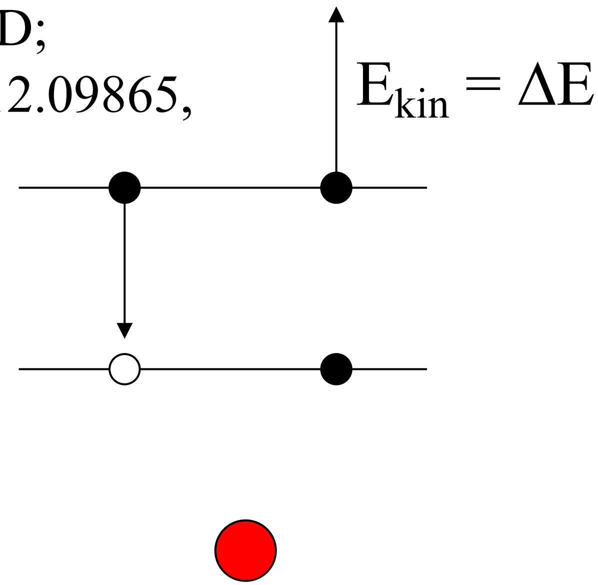


Filling up of holes generates energy = heating mechanism for neutron stars

Energy generation mechanism in NS

This interesting mechanism of heat generation was pointed out in
Goldman, Mohapatra, Nussinov, 19011.07077, PRD; Berezhiani et al. 22012.15233; McKeen, MP, Raj, 2012.09865, 2105.09951





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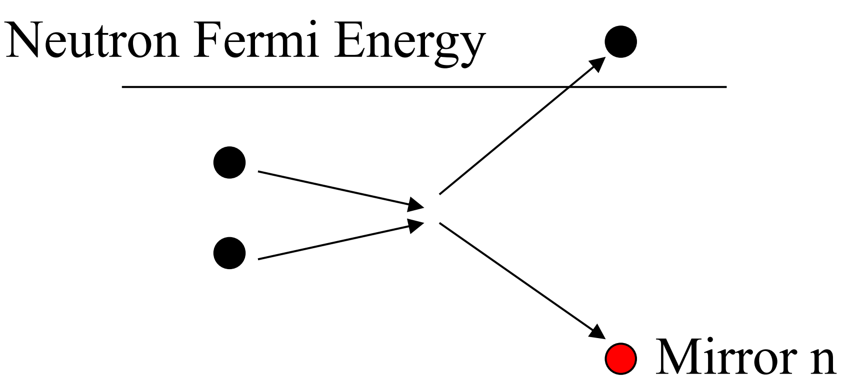
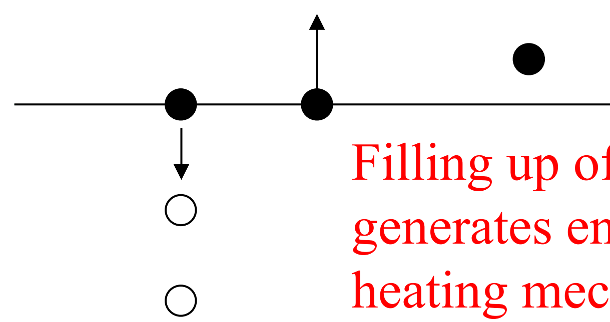




Filling up of holes generates energy = heating mechanism for neutron stars

Mirror neutrons and old neutron stars

Taking a simply Hamiltonian as before,

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

we evaluate n→n' conversion. (ΔE comes from matter effects in NS). Taking into account nn->nn' and np ->n'p processes, while using

$$\sigma_{nn\to nn} \simeq \frac{1}{4} \times \frac{16\pi}{m_N^2 v^2} \sin^2 \delta_S,$$
$$\sigma_{np\to np} \simeq \frac{1}{4} \times \frac{16\pi}{m_N^2 v^2} (\sin^2 \delta_S + 3 \sin^2 \delta_T)$$

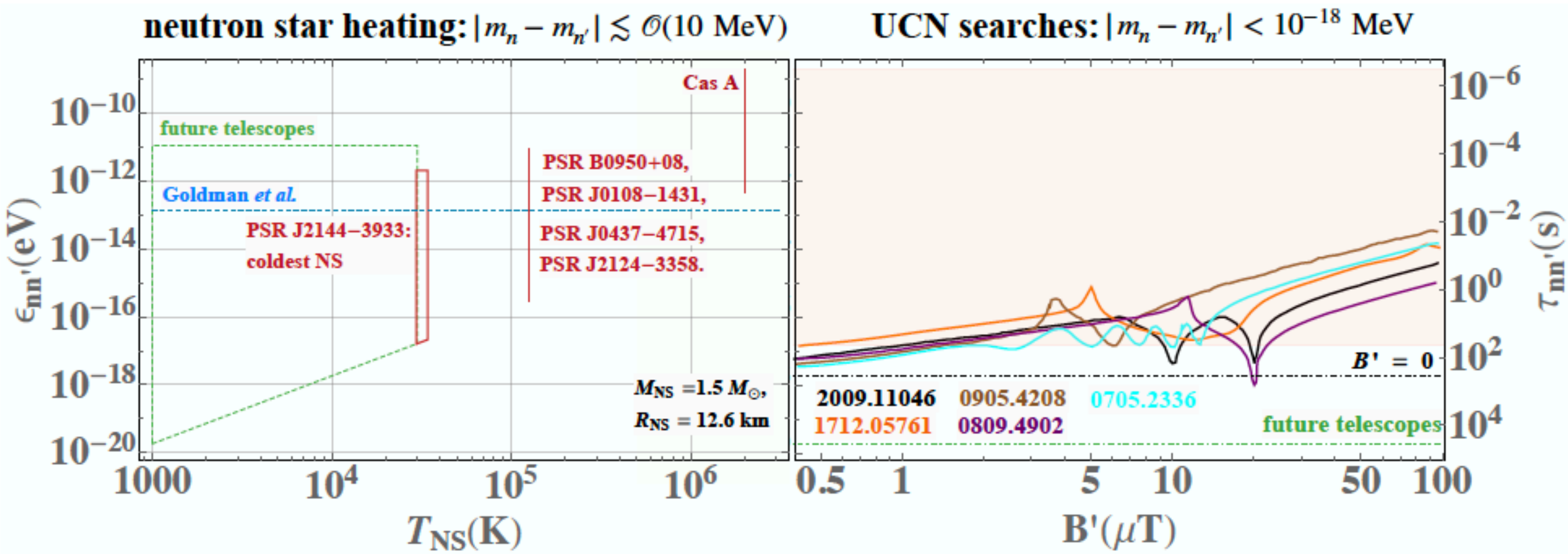
as input, we derive numerically the heating rate that scales as

$$\Gamma_{n'} = \frac{1}{1.2 \times 10^{11}\ \mathrm{yr}} \left(\frac{\epsilon_{nn'}}{10^{-17}\ \mathrm{eV}} \right)^2 \left(\frac{n_{\mathrm{nuc}}}{0.3\ \mathrm{fm}^{-3}} \right)$$

In the oldest NS, when surface emission from photons dominates, additional heating mechanism generates *minimum* temperature

$$T_{\min}^4\ 4\pi R^2 \sim \mathrm{O}(1)\ \text{number} \times \Gamma_{n'}\ E_F.$$

Mirror neutrons and old neutron stars



From McKeen, MP, Raj, 2105.09951

- The coldest pulsar, J2144-3933, T < 3000K implies the bound for the off-diagonal matrix element $\varepsilon_{nn'} = \delta < 10^{-17}$ eV.
- Above 10^{-9} eV there are no limits from NS heating – happens too fast.
- Very competitive with lab limits. Can further improve if colder T_{NS} found

Conclusions

1. Neutron portal is an example of "economical new physics" at low energy. (However, unlike dark photon or neutrino portal, this is a higher-dimensional operator.) *Needs to be explored!*

2. We set a number of new limits on the "minimal model" in that context: through radiative H-decays and cosmology. New constraints "almost entirely" exclude model of $n \to \chi\, \gamma$ correcting neutron lifetime.

3. If H can decay to χ, typically we get $\tau_H > 10^{30}$ seconds.

4. $n \to n'$ conversion offers an interesting heating mechanism for old NS. Taking at face value the constraint of $T_{NS} < 4000$ K for the oldest pulsar results in a very restrictive bound for $\delta < 10^{-17}$ eV.