Probing the Neutron Portal with Neutron Star Internal Heating

Nirmal Raj
TRIUMF

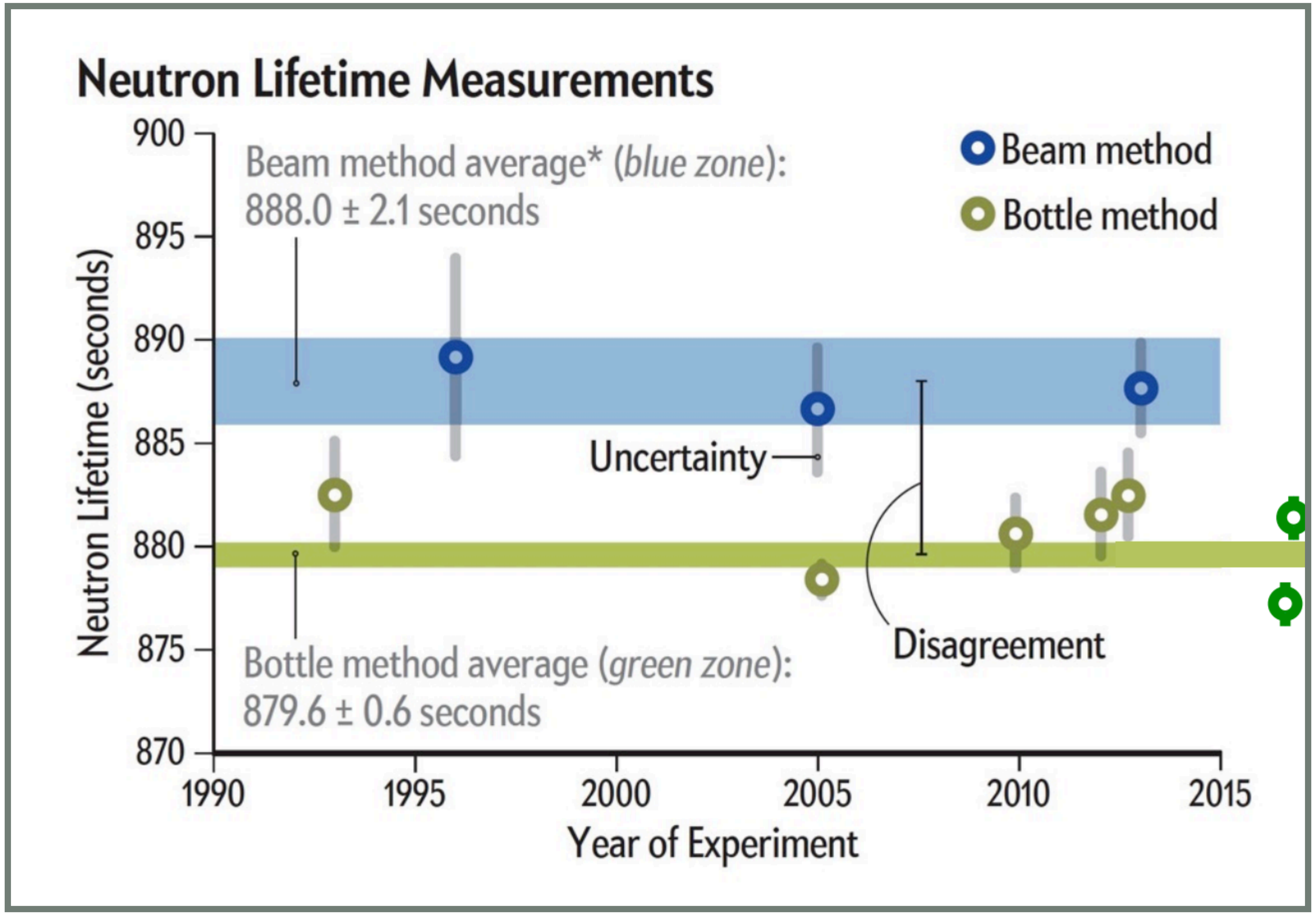
based on **2105.09951**
(submitted to PRL)
& **2012.09865**
(accepted at PRD)
with
David McKeen
& Maxim Pospelov

PHENO 2021
Parallel talk
05/26/2021

Why dark neutrons*?

*BSM states that mix with neutrons

(1)



discrepancy:

$$\boxed{\frac{\Delta\tau_n}{\tau_n} \approx 1\%}$$

explain puzzle with

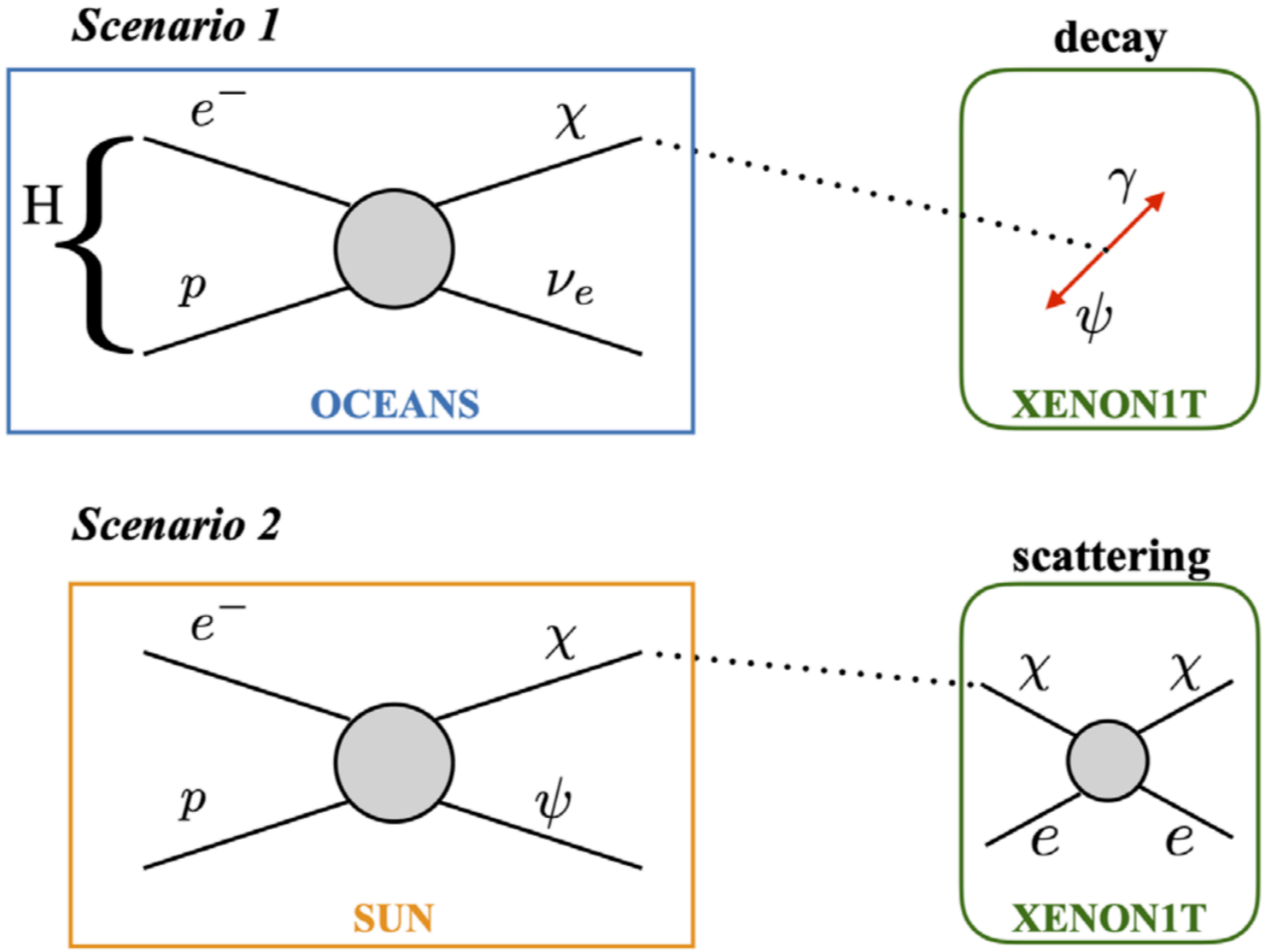
1% branching to
$n \to \chi$ + anything in **bottle**
Fornal, Grinstein (2018)

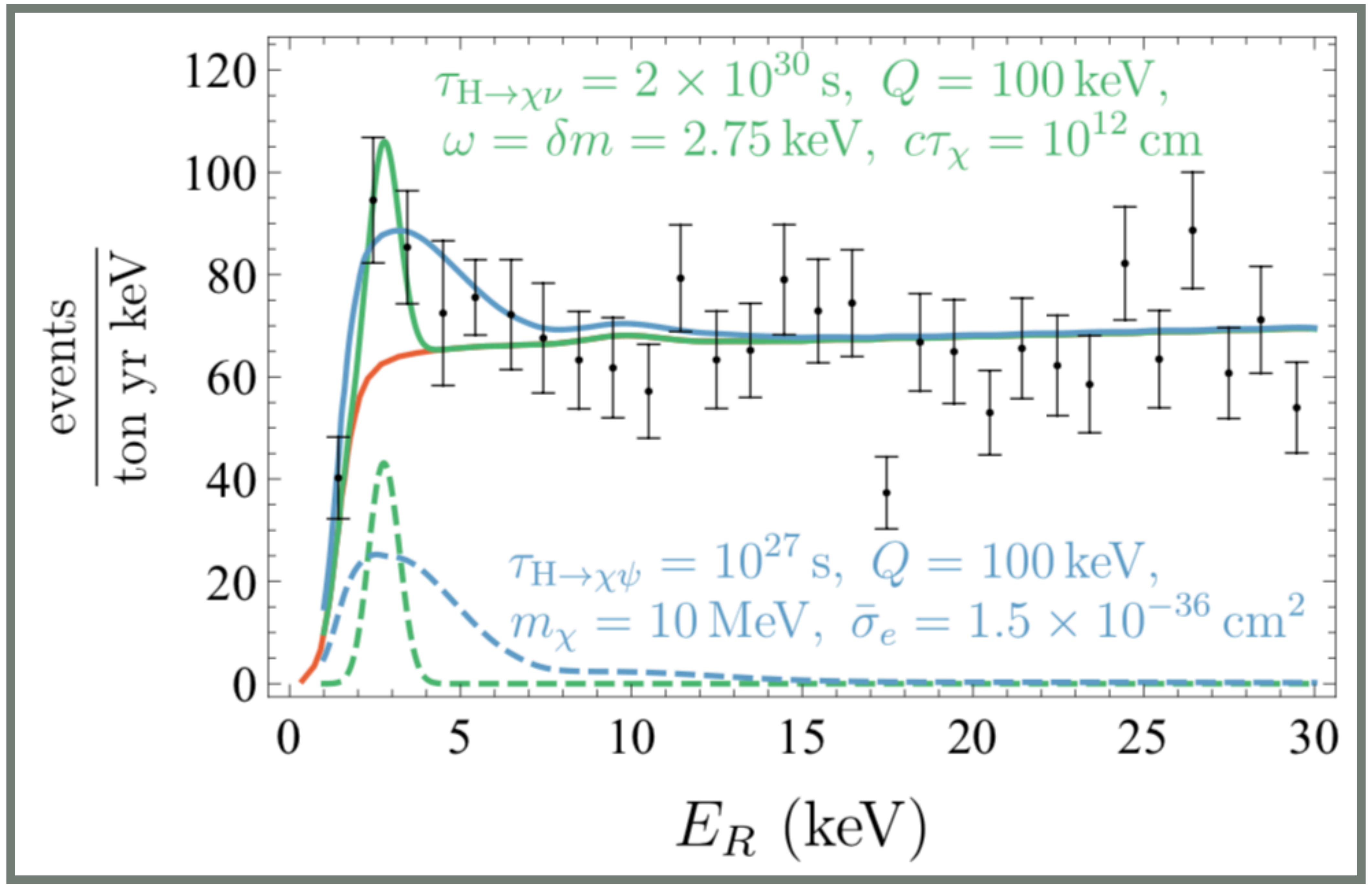
1% probability of
$n \to \chi$ in **beam**
Berezhiani (2018)

Why dark neutrons*?

***BSM states that mix with neutrons**

(2) could explain recent XENON1T excess



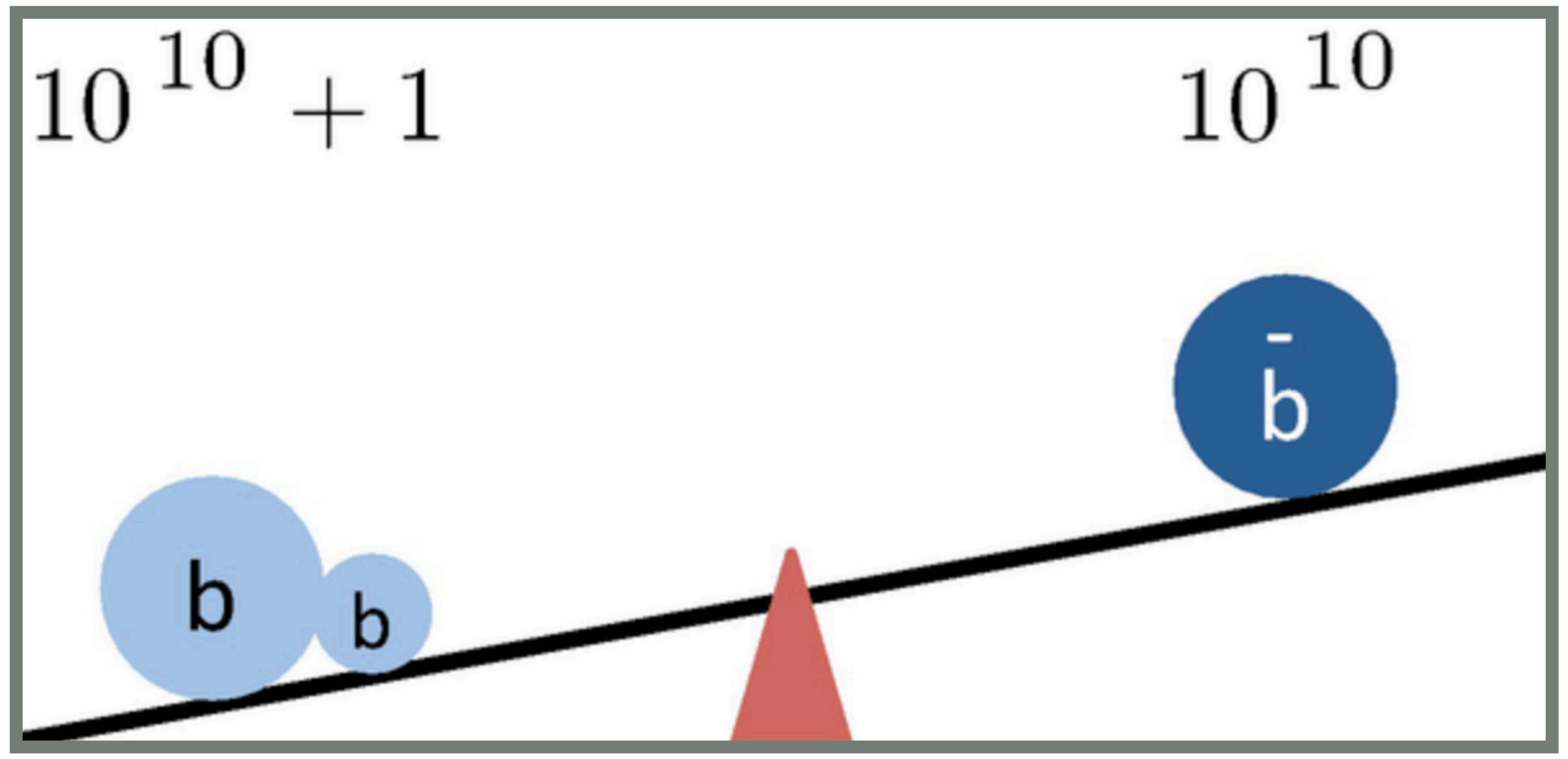


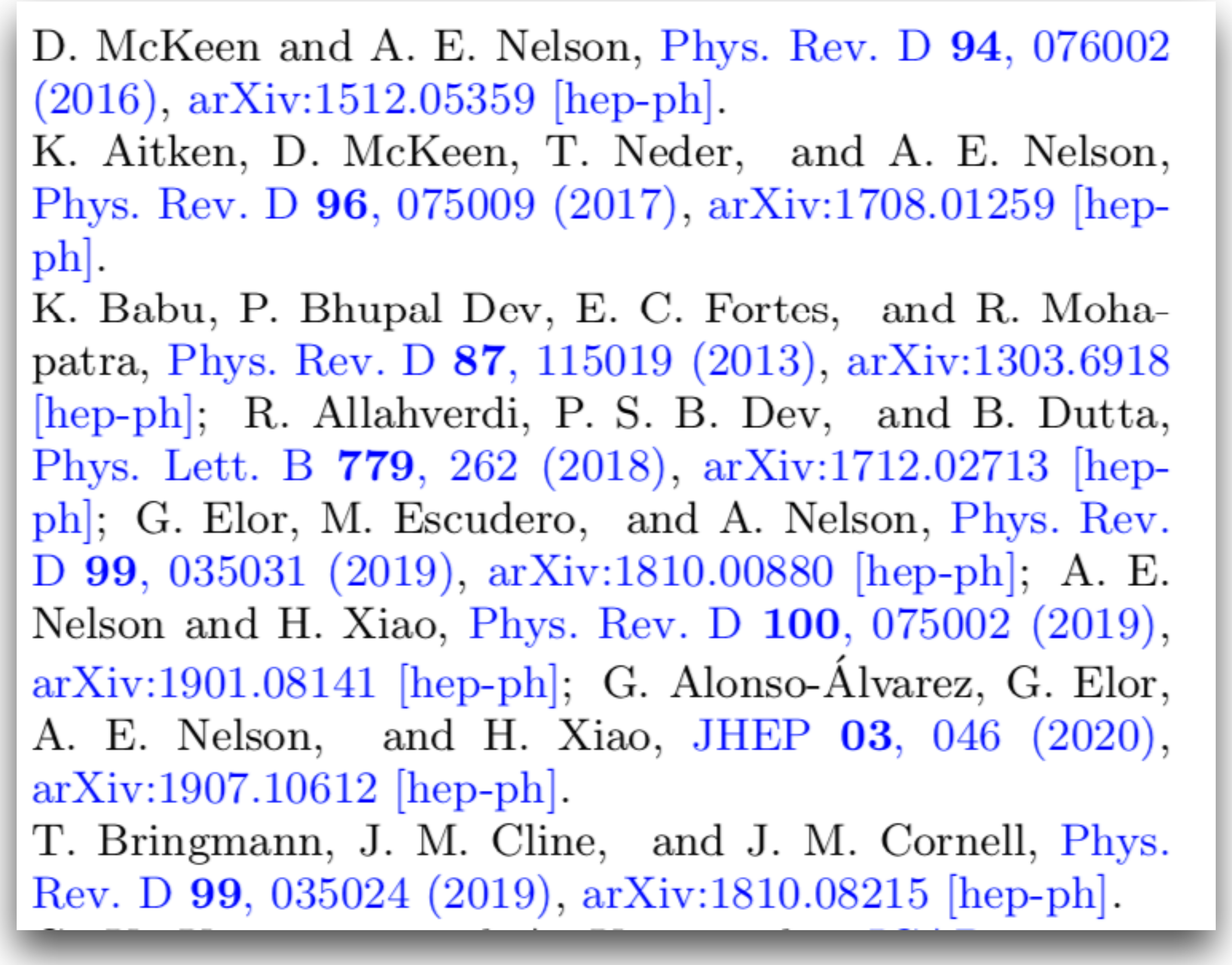
2006.15140 [*PRL* **125**, 231803 (2020)] : McKeen, Pospelov, ***Raj***

Why dark neutrons*?

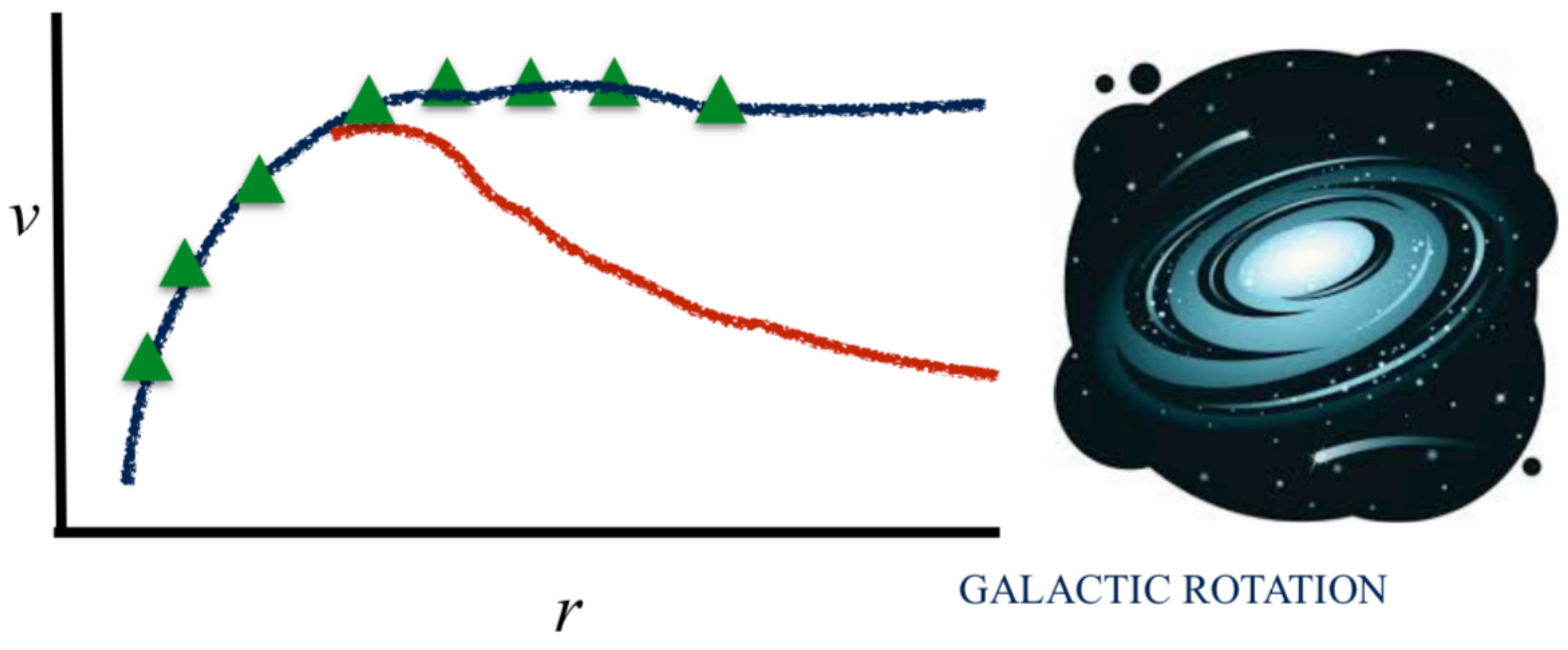
***BSM states that mix with neutrons**

(3) role in baryon asymmetry

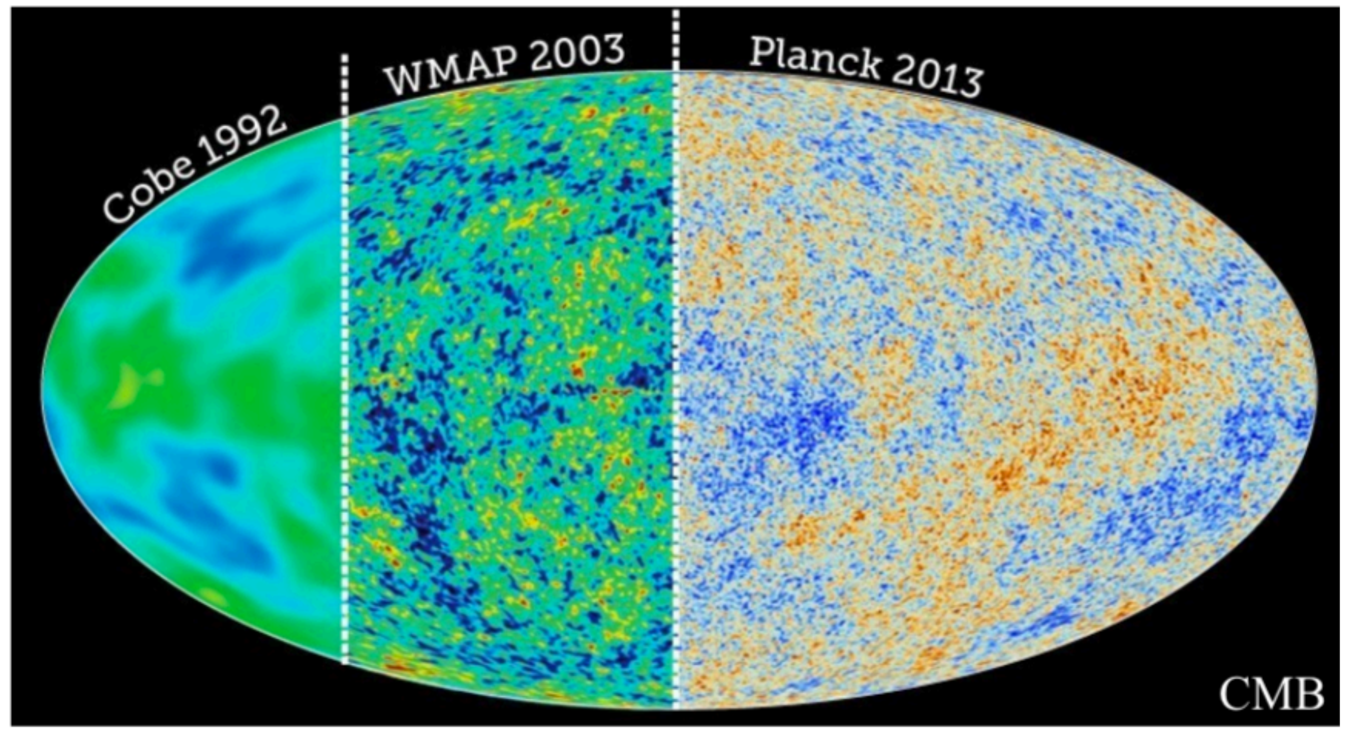



D. McKeen and A. E. Nelson, Phys. Rev. D **94**, 076002 (2016), arXiv:1512.05359 [hep-ph].
K. Aitken, D. McKeen, T. Neder, and A. E. Nelson, Phys. Rev. D **96**, 075009 (2017), arXiv:1708.01259 [hep-ph].
K. Babu, P. Bhupal Dev, E. C. Fortes, and R. Mohapatra, Phys. Rev. D **87**, 115019 (2013), arXiv:1303.6918 [hep-ph]; R. Allahverdi, P. S. B. Dev, and B. Dutta, Phys. Lett. B **779**, 262 (2018), arXiv:1712.02713 [hep-ph]; G. Elor, M. Escudero, and A. Nelson, Phys. Rev. D **99**, 035031 (2019), arXiv:1810.00880 [hep-ph]; A. E. Nelson and H. Xiao, Phys. Rev. D **100**, 075002 (2019), arXiv:1901.08141 [hep-ph]; G. Alonso-Álvarez, G. Elor, A. E. Nelson, and H. Xiao, JHEP **03**, 046 (2020), arXiv:1907.10612 [hep-ph].
T. Bringmann, J. M. Cline, and J. M. Cornell, Phys. Rev. D **99**, 035024 (2019), arXiv:1810.08215 [hep-ph].

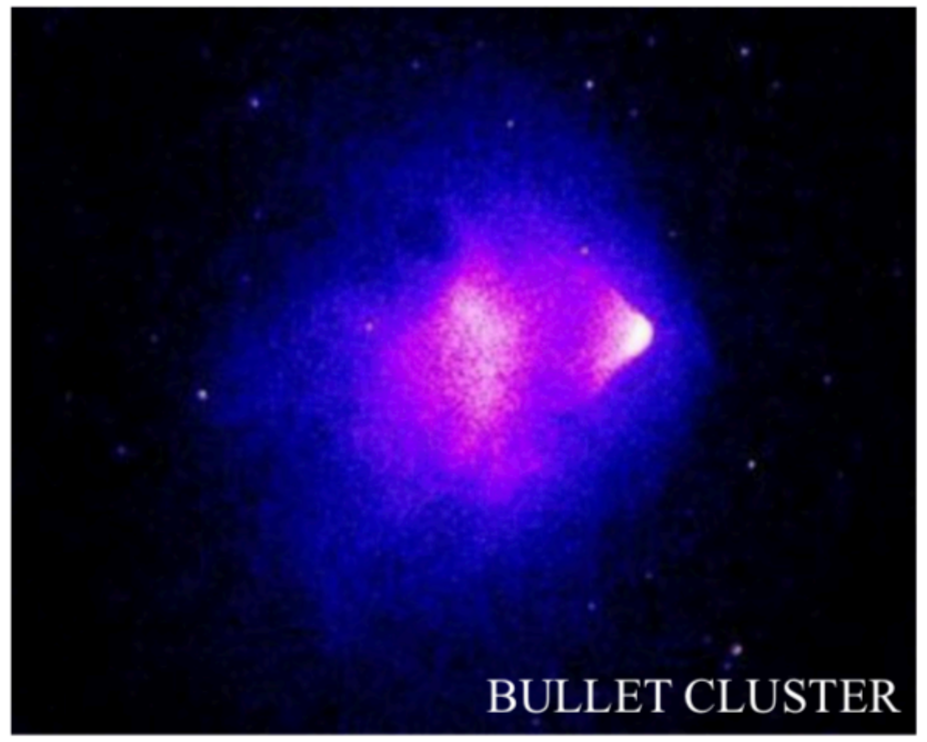
(4) could constitute the **dark matter** of the universe



GALACTIC ROTATION



CMB



BULLET CLUSTER

Why dark neutrons*?

***BSM states that mix with neutrons**

(5)

part of <u>mirror sector</u>:

Kobzarev, Okun, Pomeranchuk 1966

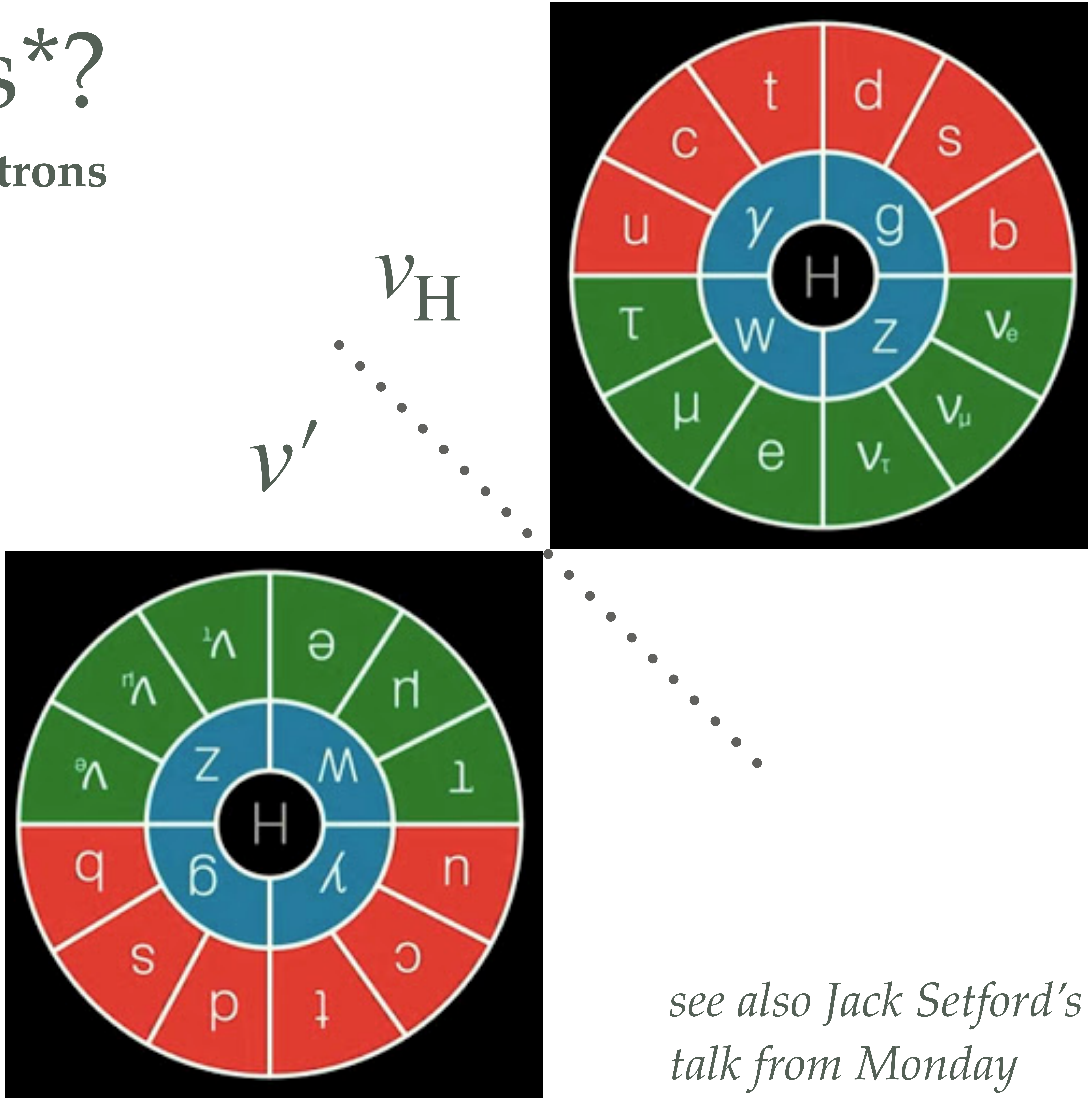
very early idea of “dark sector”,

can address:

+ Why is $v_{\rm H} \ll M_{\rm Planck}$?
(Twin Higgs realization)

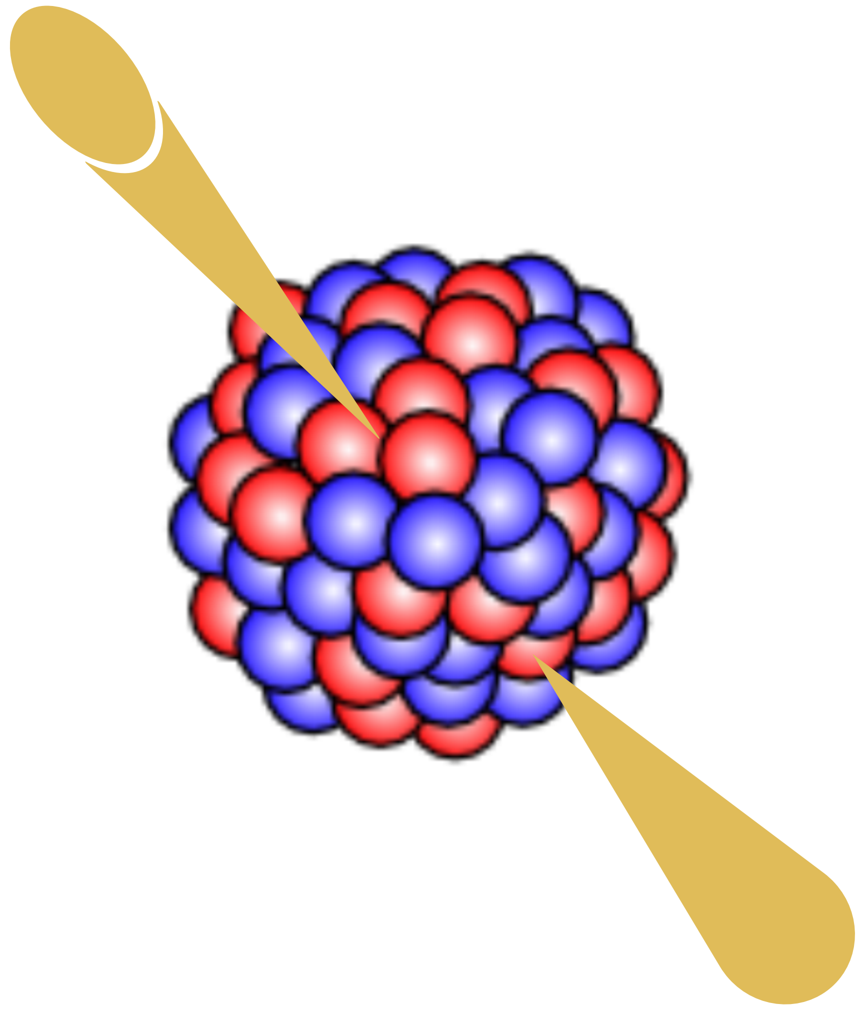
+ dark matter.

+ baryogenesis.



see also Jack Setford’s talk from Monday

Neutron stars



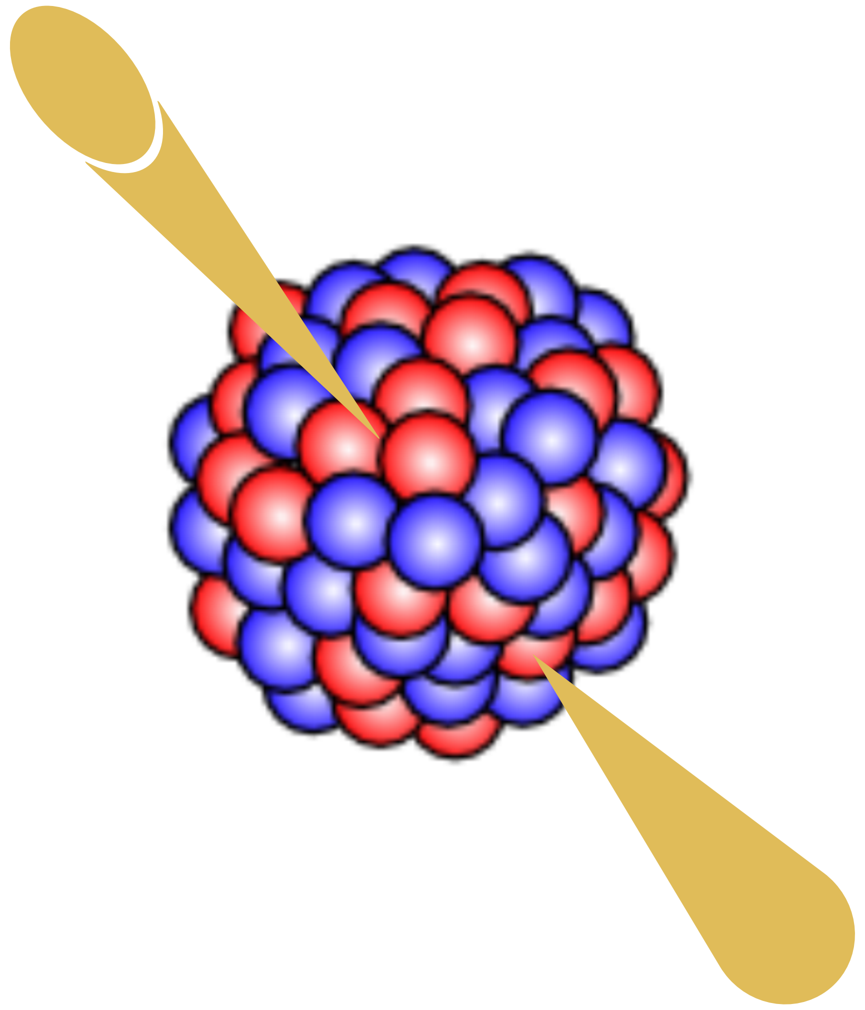
10^{57} neutrons

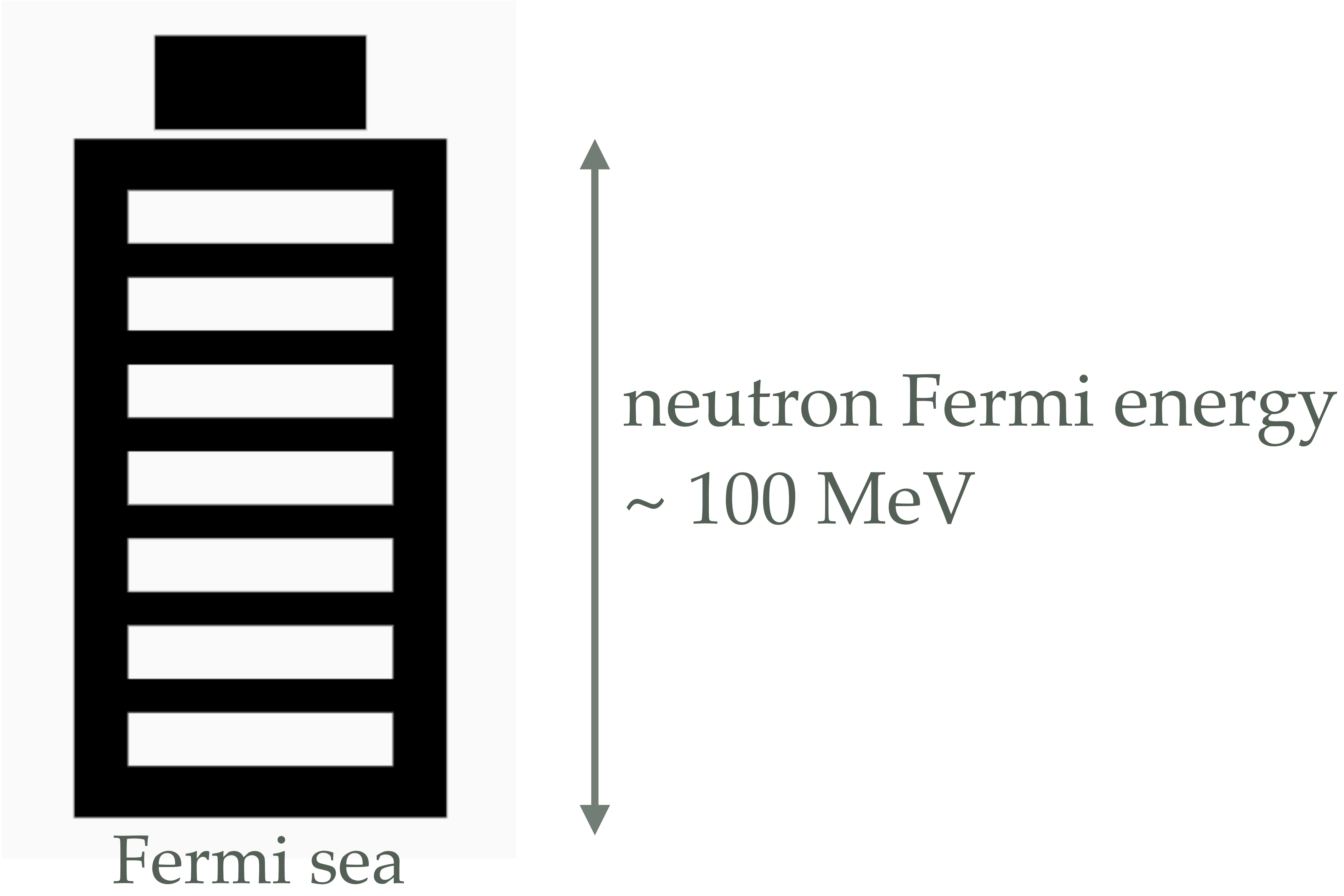
$+$

10^{56} protons, electrons, muons

(β equilibrium products)

Neutron stars = Pauli batteries





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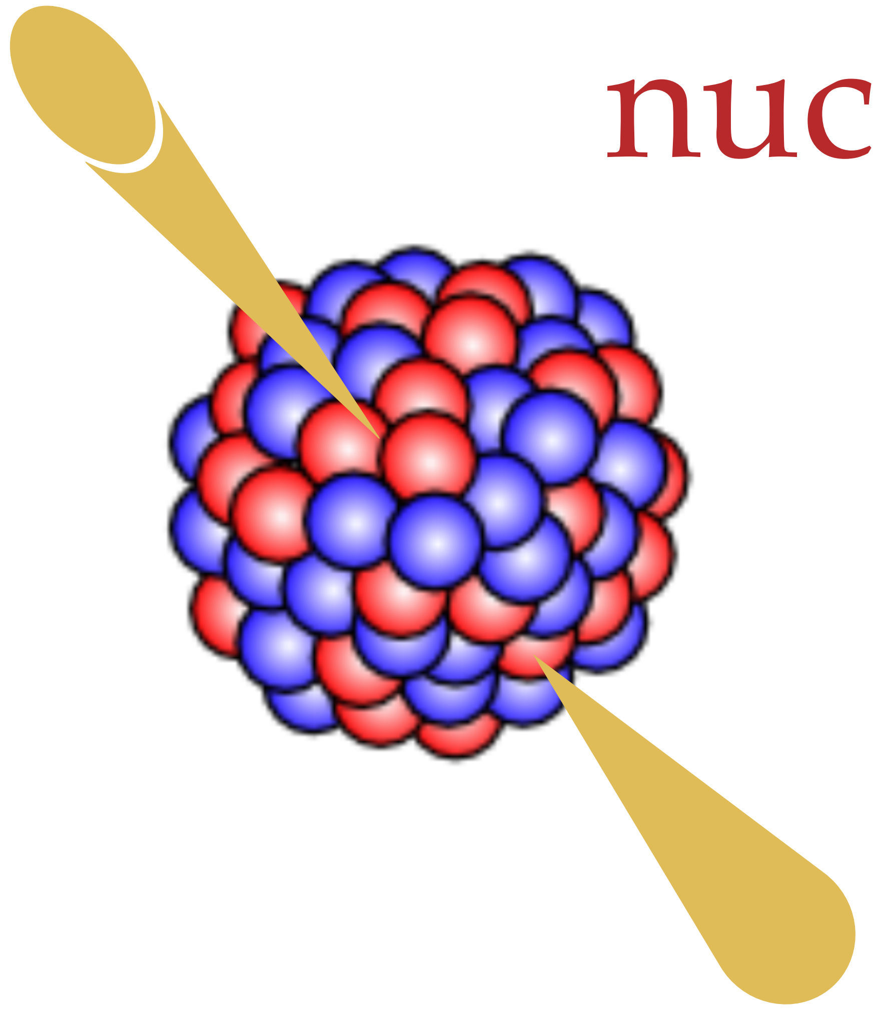
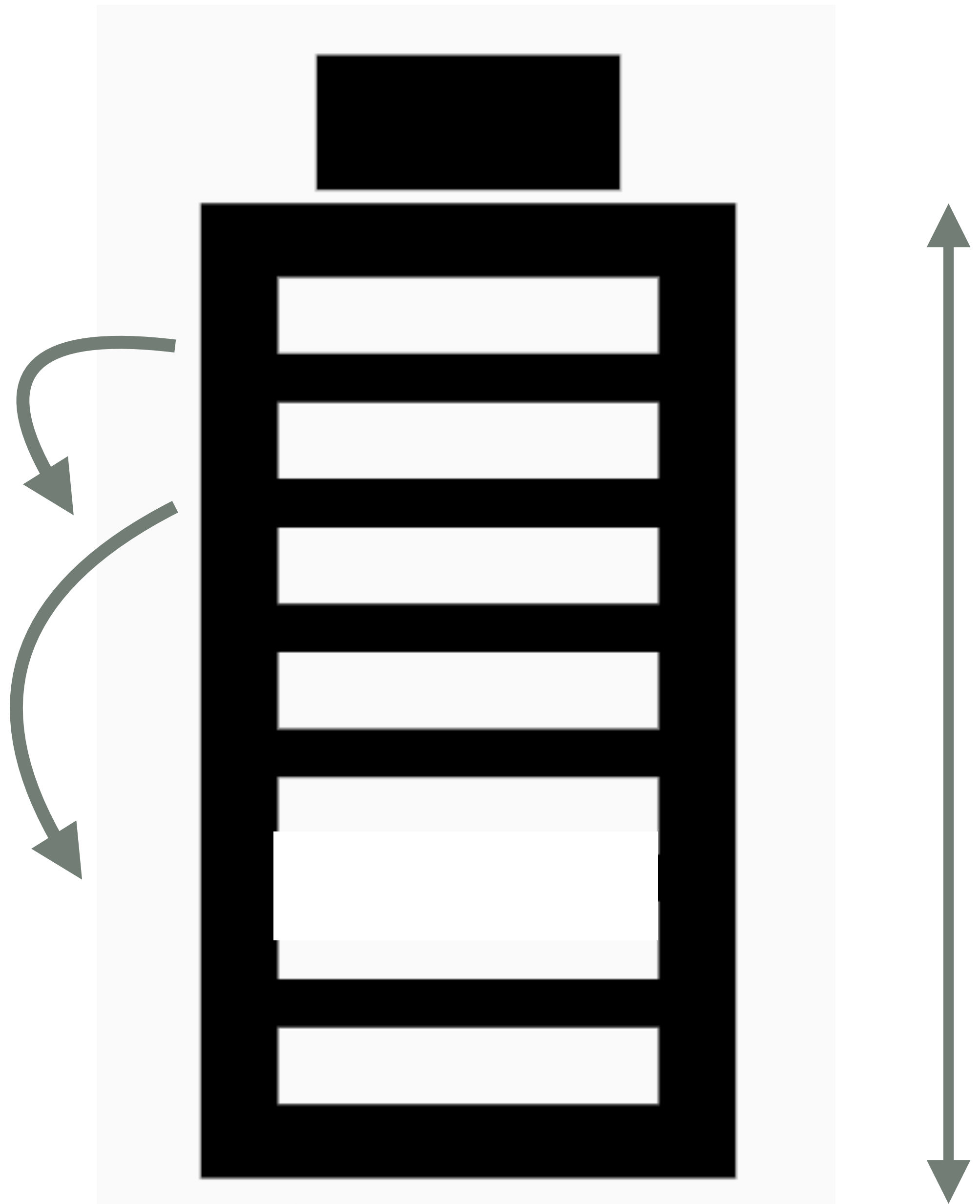


new heating mechanism:
nucleon "Auger effect"

$$\left.\begin{array}{l} n \to \chi + \underline{anything} \\ n\, n \to n\, \chi \\ p\, n \to p\, \chi \end{array}\right\}$$



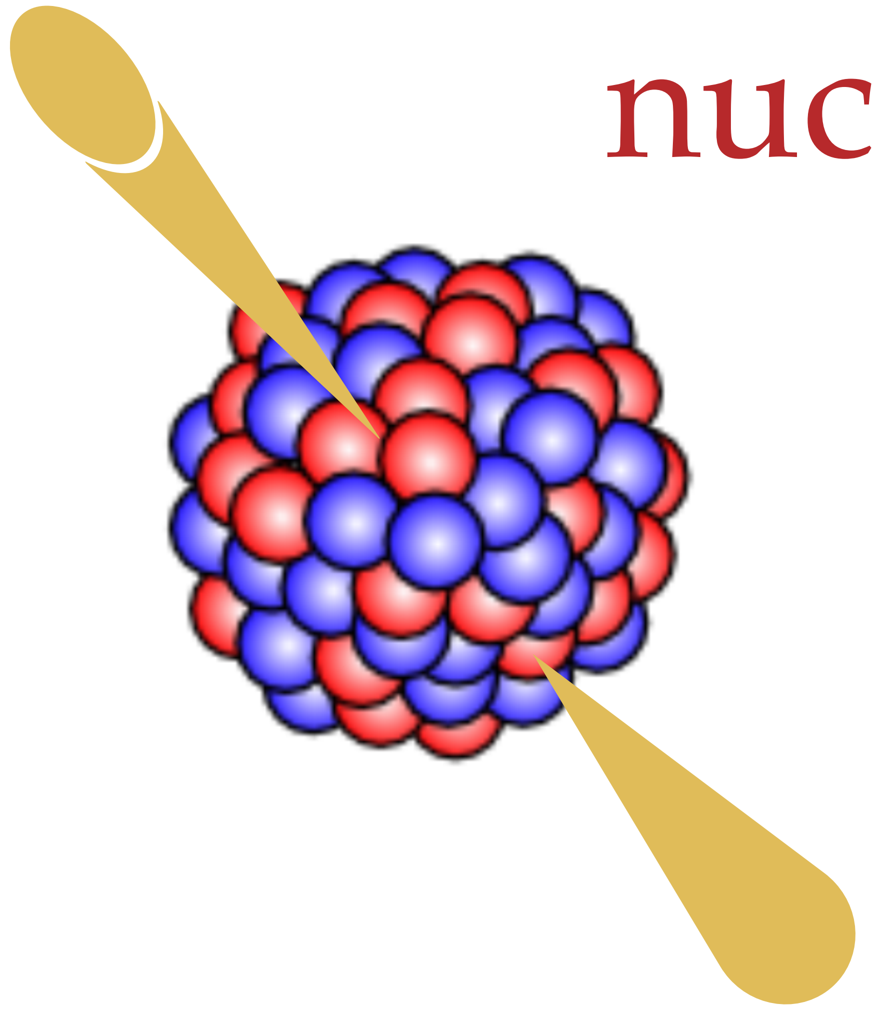
neutron Fermi energy
~ 100 MeV

10^{57} neutrons
+
10^{56} protons

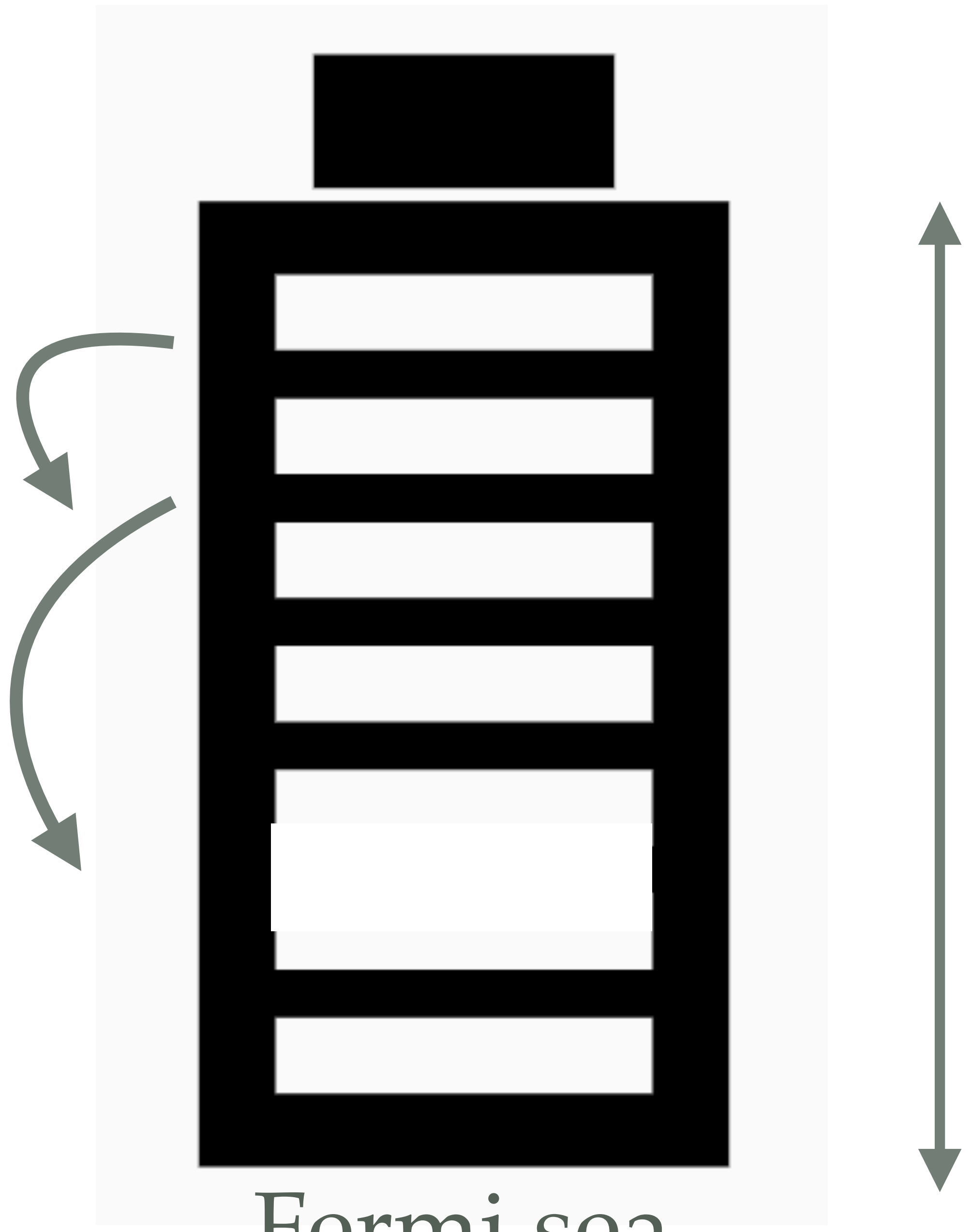
=> **explosive liberation of energy!**

Neutron stars = Pauli batteries

new heating mechanism:
nucleon "Auger effect"



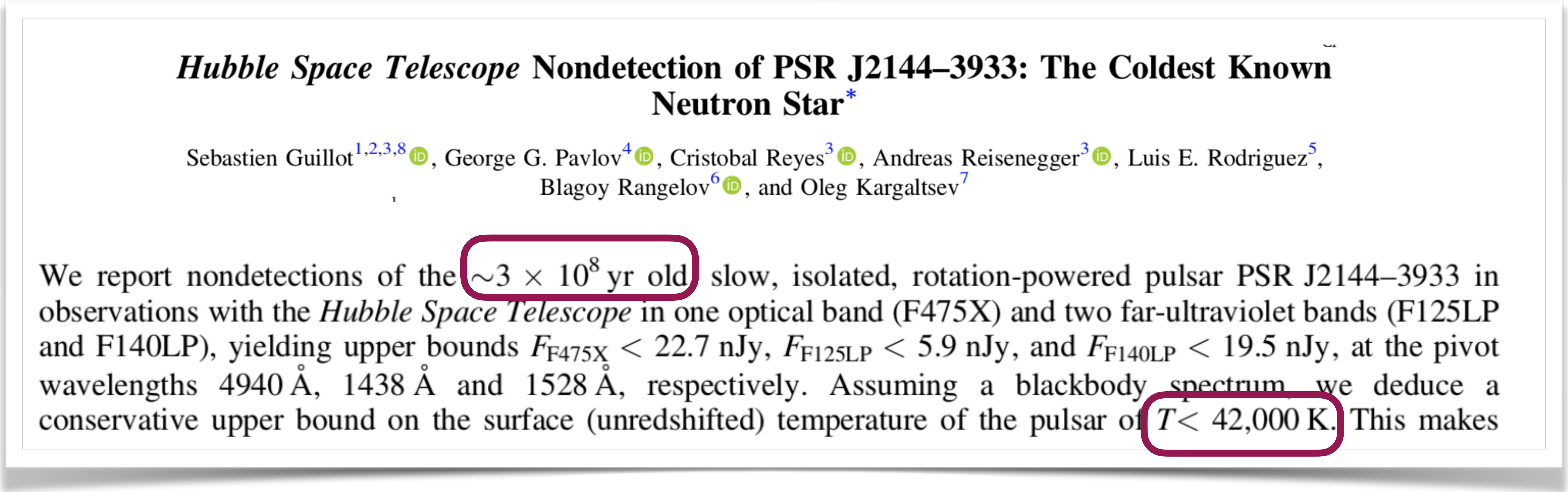
$$\left.\begin{array}{l} n \to \chi + \underline{anything} \\ n\; n \to n\; \chi \\ p\; n \to p\; \chi \end{array}\right\}$$



neutron Fermi energy
~ 100 MeV

Fermi sea

Suitable lab:



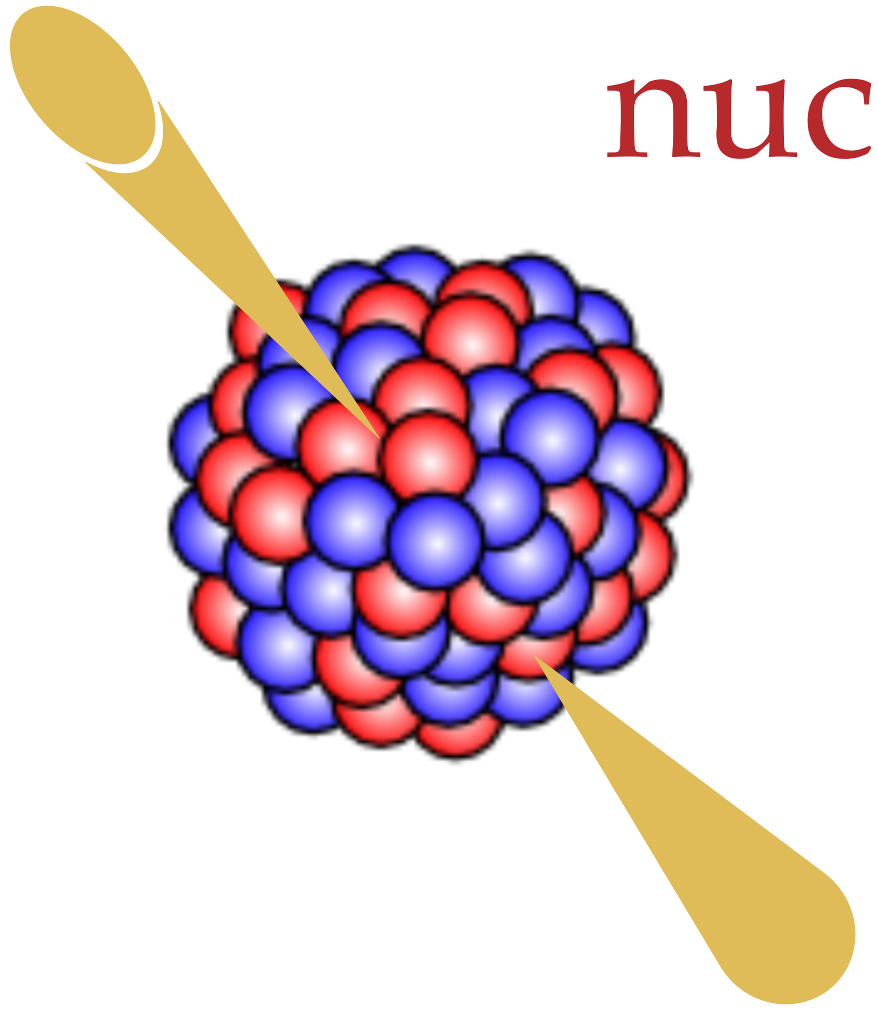
Hubble Space Telescope Nondetection of PSR J2144–3933: The Coldest Known Neutron Star*

Sebastien Guillot[1,2,3,8], George G. Pavlov[4], Cristobal Reyes[3], Andreas Reisenegger[3], Luis E. Rodriguez[5],
Blagoy Rangelov[6], and Oleg Kargaltsev[7]

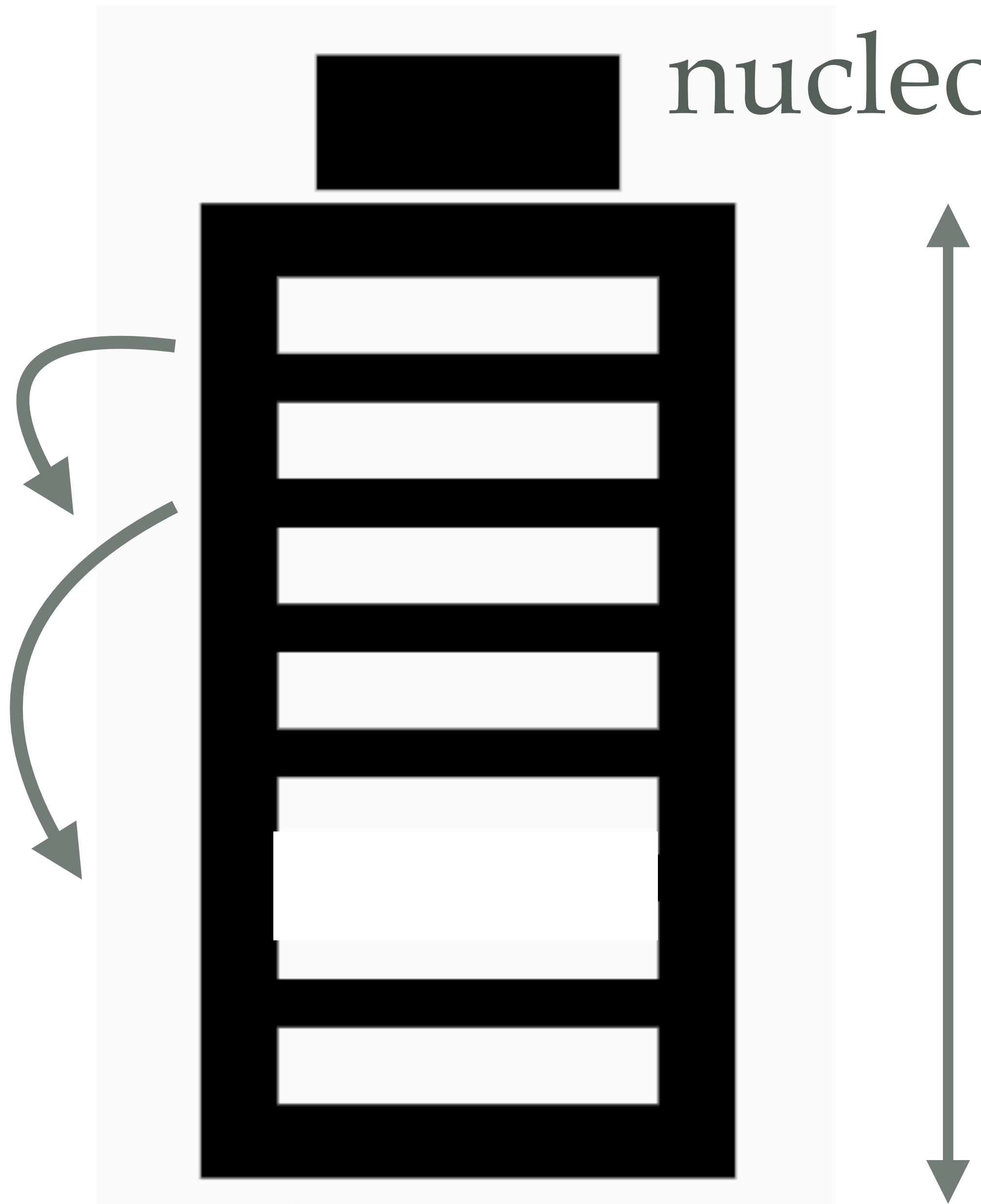
We report nondetections of the ~3 × 10^8 yr old slow, isolated, rotation-powered pulsar PSR J2144–3933 in observations with the *Hubble Space Telescope* in one optical band (F475X) and two far-ultraviolet bands (F125LP and F140LP), yielding upper bounds $F_{\rm F475X} < 22.7$ nJy, $F_{\rm F125LP} < 5.9$ nJy, and $F_{\rm F140LP} < 19.5$ nJy, at the pivot wavelengths 4940 Å, 1438 Å and 1528 Å, respectively. Assuming a blackbody spectrum, we deduce a conservative upper bound on the surface (unredshifted) temperature of the pulsar of $T < 42{,}000$ K. This makes

Neutron stars = Pauli batteries

new heating mechanism:
nucleon "Auger effect"



$$\left.\begin{array}{l} n \to \chi + \underline{\mathit{anything}} \\ n\,n \to n\,\chi \\ p\,n \to p\,\chi \end{array}\right\}$$

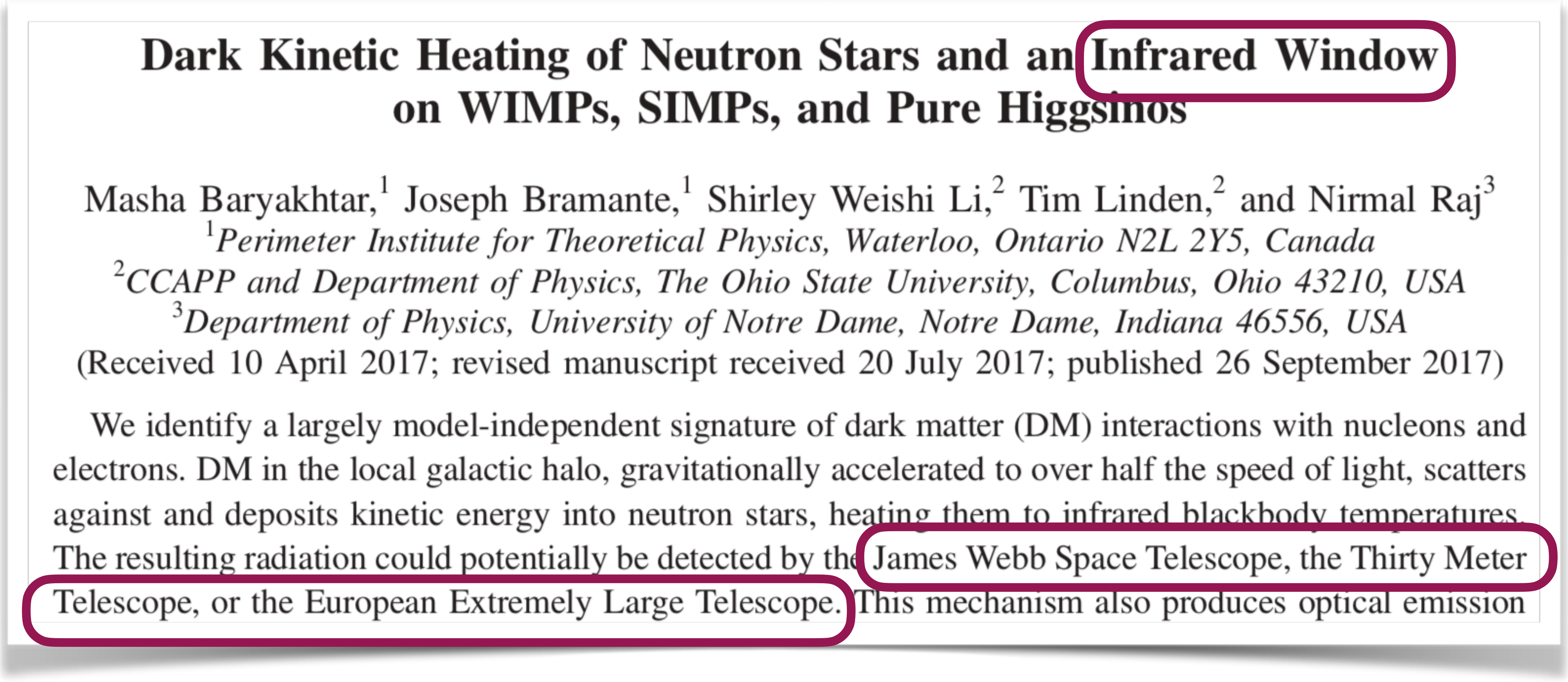


nucleon Fermi sea

neutron Fermi energy
~ 100 MeV

Fermi sea

Future lab:



Dark Kinetic Heating of Neutron Stars and an Infrared Window on WIMPs, SIMPs, and Pure Higgsinos

Masha Baryakhtar,[1] Joseph Bramante,[1] Shirley Weishi Li,[2] Tim Linden,[2] and Nirmal Raj[3]
[1]*Perimeter Institute for Theoretical Physics, Waterloo, Ontario N2L 2Y5, Canada*
[2]*CCAPP and Department of Physics, The Ohio State University, Columbus, Ohio 43210, USA*
[3]*Department of Physics, University of Notre Dame, Notre Dame, Indiana 46556, USA*

(Received 10 April 2017; revised manuscript received 20 July 2017; published 26 September 2017)

We identify a largely model-independent signature of dark matter (DM) interactions with nucleons and electrons. DM in the local galactic halo, gravitationally accelerated to over half the speed of light, scatters against and deposits kinetic energy into neutron stars, heating them to infrared blackbody temperatures. The resulting radiation could potentially be detected by the James Webb Space Telescope, the Thirty Meter Telescope, or the European Extremely Large Telescope. This mechanism also produces optical emission

see also next talk by Aniket Joglekar!

optimized for
~2000 K

Constraining neutron conversions

heating rate

$$\int_{\mathrm{NS}} d^3r\, n_n(\mathbf{r})\dot{E}_{n'}(\mathbf{r})$$

neutron number density

energy release rate

$$\leq$$

cooling rate
(blackbody emission)

$$4\pi R_{\mathrm{NS}}^2 \sigma_{\mathrm{SB}} T_{\mathrm{NS}}^4$$

Conversions to mirror neutrons

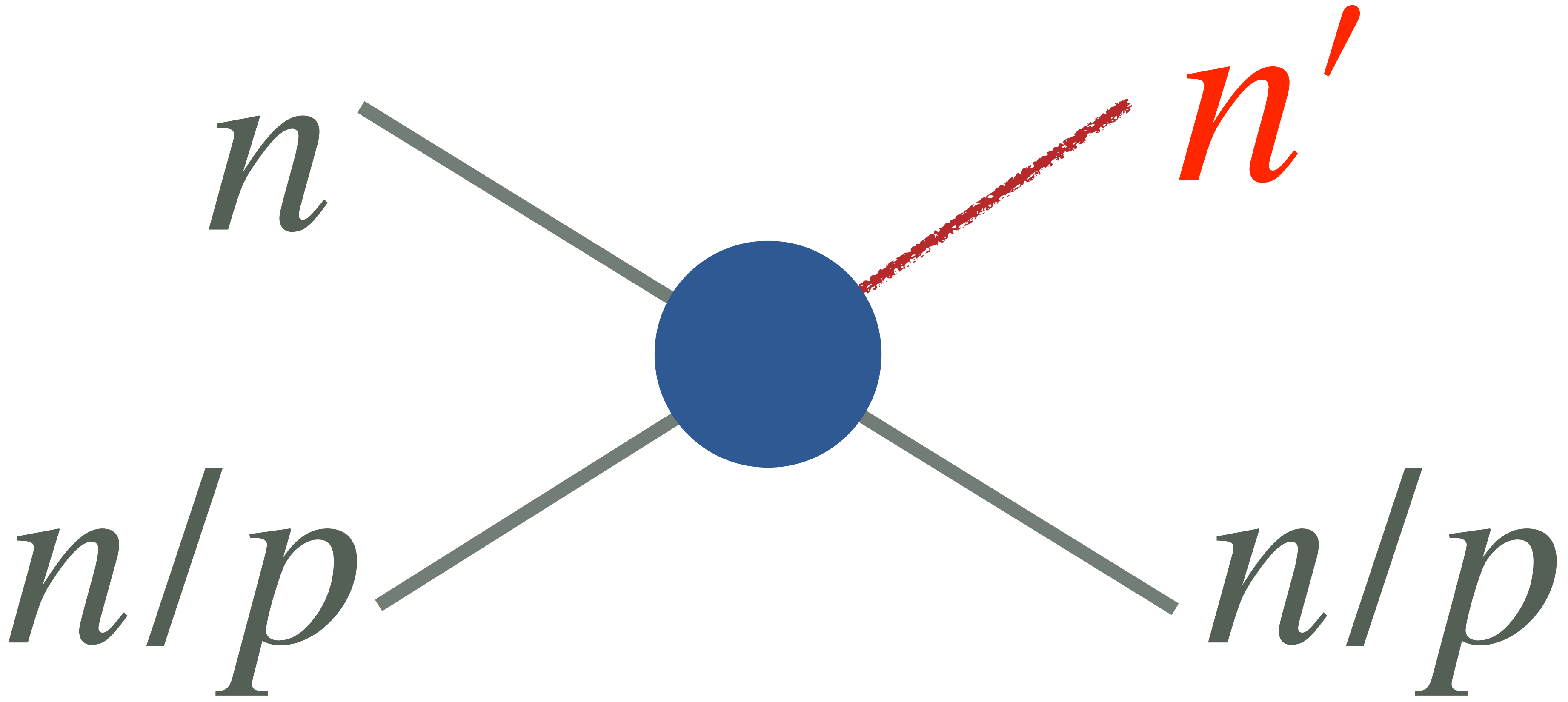
medium-dependent splitting

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

e.g. neutron star nuclear
self-energies, 10—100 MeV

$$\boxed{\sigma_{n'N} \simeq g_N \left(\frac{\epsilon_{nn'}}{\Delta E}\right)^2 \sigma_{nN\to nN}}$$

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



energy-dependent
phase shifts
from nuclear potential models
(https://nn-online.org/)

Conversions to mirror neutrons

symmetry factor

neutron chemical potential*

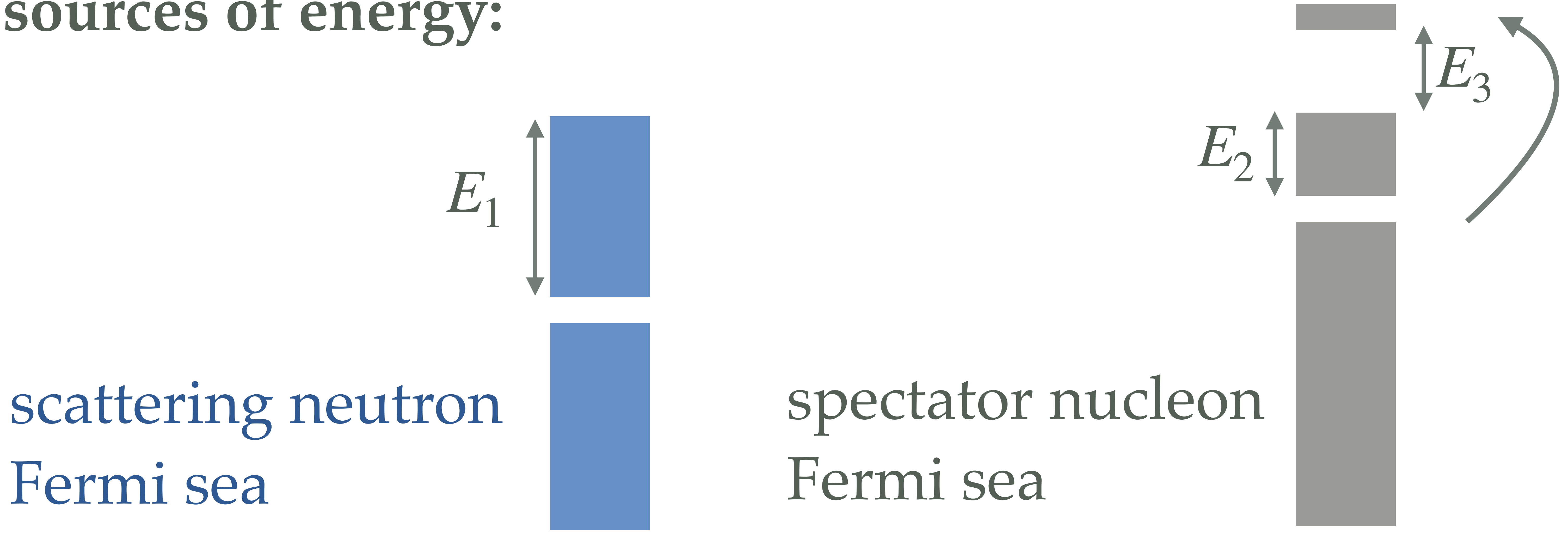
$$\dot{E}_{n'} = \sum_{N=n,p} f_N n_N \left\langle \left(\widetilde{\mu}_n - \frac{p_{n'}^2}{2m_{n'}} \right) \sigma_{n'N} v \right\rangle_{p_N > p_{F_N}}$$

energy release rate

number density*

Pauli blocking condition

3 sources of energy:



scattering neutron
Fermi sea

spectator nucleon
Fermi sea

Amusement

proton spectators
(~ 10% of NS nucleons)
supply more heat!

less Pauli-blocked,
greater cross section

---

* determined from high-density equation of state + NS mass & radius,
in practice used Brussels-Montreal BSk24 with $M_{\rm NS} = 1.5\ M_\odot$, $R_{\rm NS} = 12.6$ km

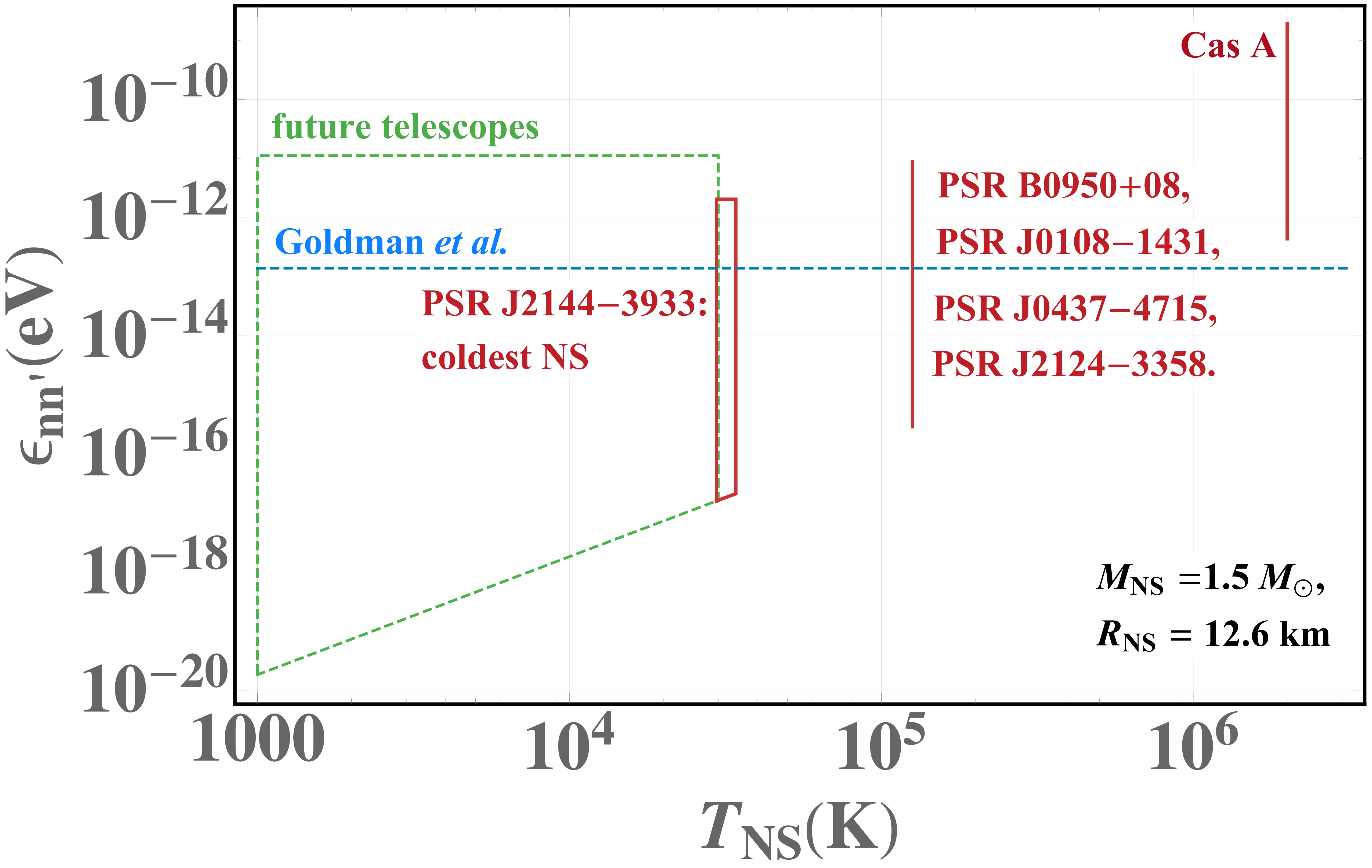
2105.09951 *McKeen, Pospelov, Raj*

Constraints

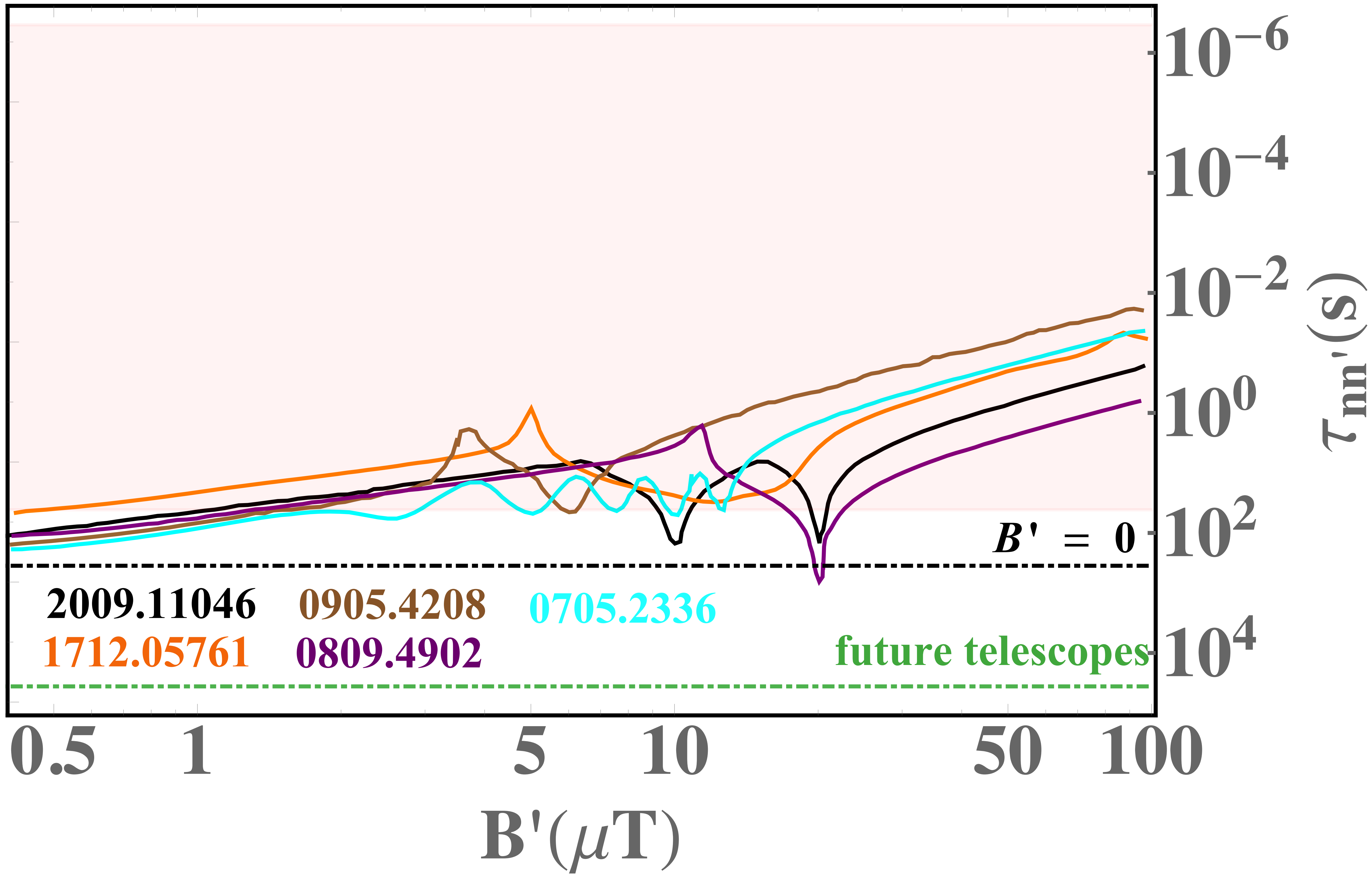
NS energy per baryon

Zeeman from Earth's B field

neutron star heating: $|m_n - m_{n'}| \lesssim \mathcal{O}(10\ \text{MeV})$



UCN searches: $|m_n - m_{n'}| < 10^{-18}$ MeV



ceilings: neutron conversions stop within NS lifetime

NB. neutron lifetime anomaly explained by $\epsilon_{nn'} \sim 10^{-8}$ eV *(Berezhiani 2018)*

“Dark baryon” model

@ hadron level :

$$\boxed{\mathcal{L} \supset -\delta(\bar{\chi} n + \bar{n} \chi)}$$

$$\boxed{\mathcal{L}_{\text{eff}} \supset \frac{\mu_n}{2} \theta \bar{\chi} \sigma^{\mu\nu} n F_{\mu\nu} + \text{h.c.}}$$

$$\mu_n = -1.91 \mu_N$$

neutron magnetic moment

$$\delta/(m_n - m_\chi)$$

$$\left(\begin{array}{c} \mu_N = e/(2m_n) \simeq 0.1\, e\,\text{fm} \\ \text{nuclear magneton} \end{array} \right)$$

exotic neutron decay

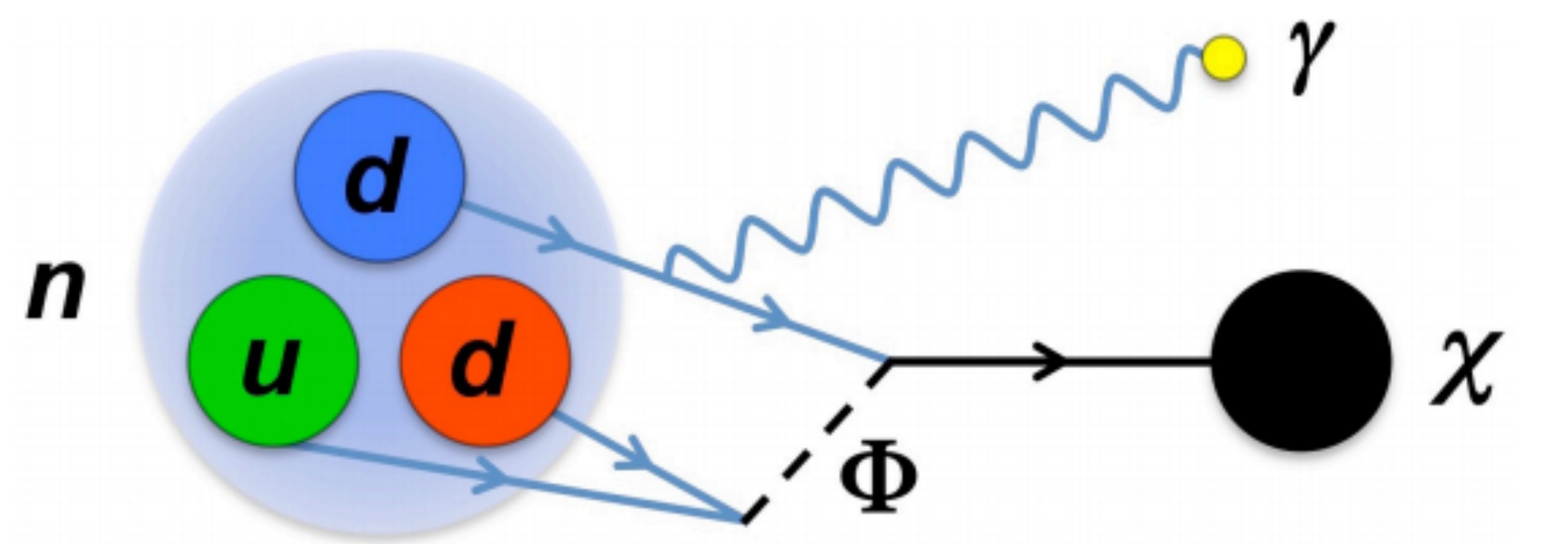


image: Fornal & Grinstein

n lifetime puzzle:

$$\text{Br}_{n\to\chi\gamma} \simeq 0.01 \left(\frac{\theta}{5\times 10^{-10}} \right)^2 \left(\frac{\Delta m}{\text{MeV}} \right)^3$$

$$\Gamma_{\chi\to n\gamma} \simeq \frac{1}{2200\ \text{s}} \left(\frac{\theta}{10^{-10}} \right)^2 \left| \frac{\Delta m}{10\ \text{MeV}} \right|^3$$

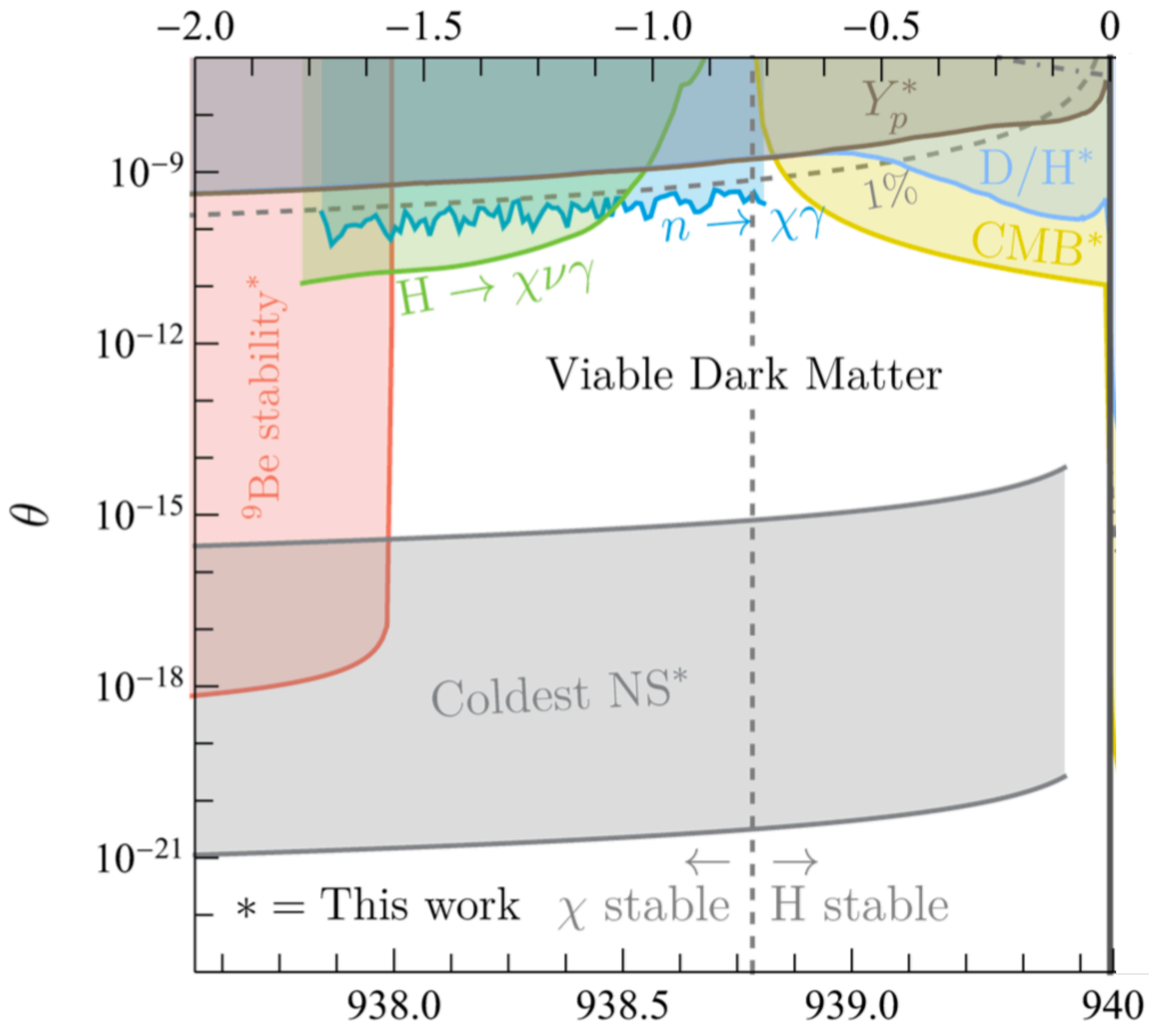
$$\Gamma_{\chi\to p e^- \bar{\nu}} = \frac{1}{9\times 10^{22}\ \text{s}} \left(\frac{\theta}{10^{-10}} \right)^2 \frac{F(Q_\chi/m_e)}{F(Q_n/m_e)}$$

2012.09865 *McKeen, Pospelov,* Raj

Constraints

$n \to \chi\,\gamma$
open

$$n_\chi^0 = 5.4\,(n_p^0 + n_n^0)$$



longer life

- BBN data: $$Y_p = 0.245 \pm 0.004\,, \quad \mathrm{D/H} = (2.55 \pm 0.03) \times 10^{-5}\,, \quad {}^3\mathrm{He/H} = (1.0 \pm 0.5) \times 10^{-5}\,,$$
- CMB limit: $f_\chi/\tau_\chi \lesssim 10^{-25}\ \mathrm{s}^{-1}$

  T. R. Slatyer, Physical Review D **87** (2013), 10.1103/physrevd.87.123513.
  J. M. Cline and P. Scott, JCAP **03**, 044 (2013), [Erratum: JCAP 05, E01 (2013)], arXiv:1301.5908 [astro-ph.CO].
- $n \to \chi\gamma$ direct search: 1802.01595 [nucl-ex]
- $H \to \chi\nu\gamma$: Borexino recast by McKeen, Pospelov (2003.02270)
- $^9\mathrm{Be} \to 2\,{}^4\mathrm{He} + \chi$:

  Limited by: $\tau_{^9\mathrm{Be}} \sim 4 \times 10^{10}\ \mathrm{yr} \left(\frac{10^{-19}}{\theta}\right)^2 \left(\frac{1\,\mathrm{MeV}}{Q_{^9\mathrm{Be}}}\right)^{3/2}$

  $< 3 \times 10^9$ yr in metal-poor stars
- NS: J2144-3933

Future directions

- Pauli battery contribution to NS heating via **dark matter capture.**
- Do dark and visible fluids in neutron star **thermalize** rapidly?
- $\Delta(B+L) = \pm 4$ processes?

Thank you! Questions?

Back-up slides

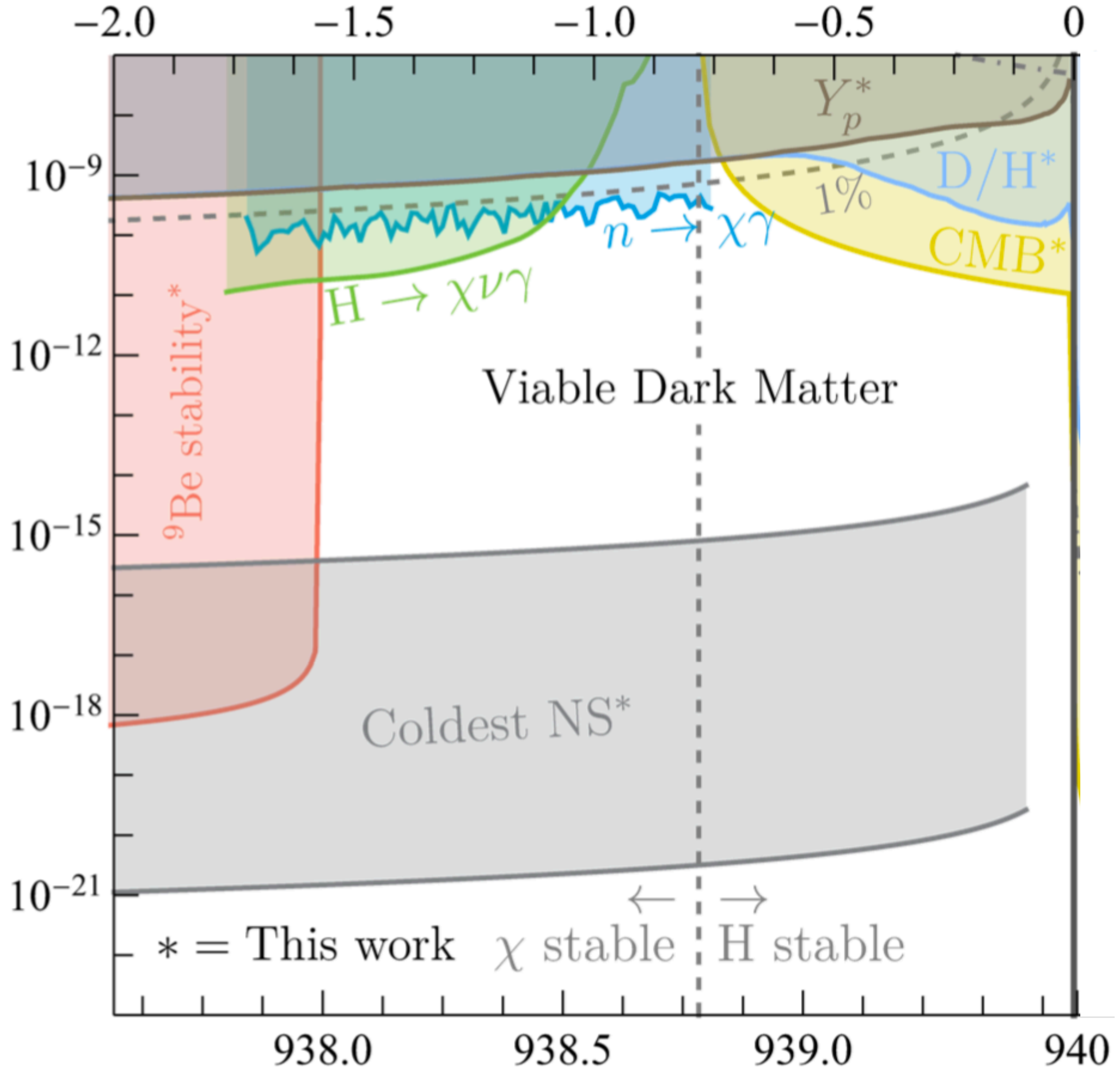
2012.09865 *McKeen, Pospelov, Raj*

Constraints

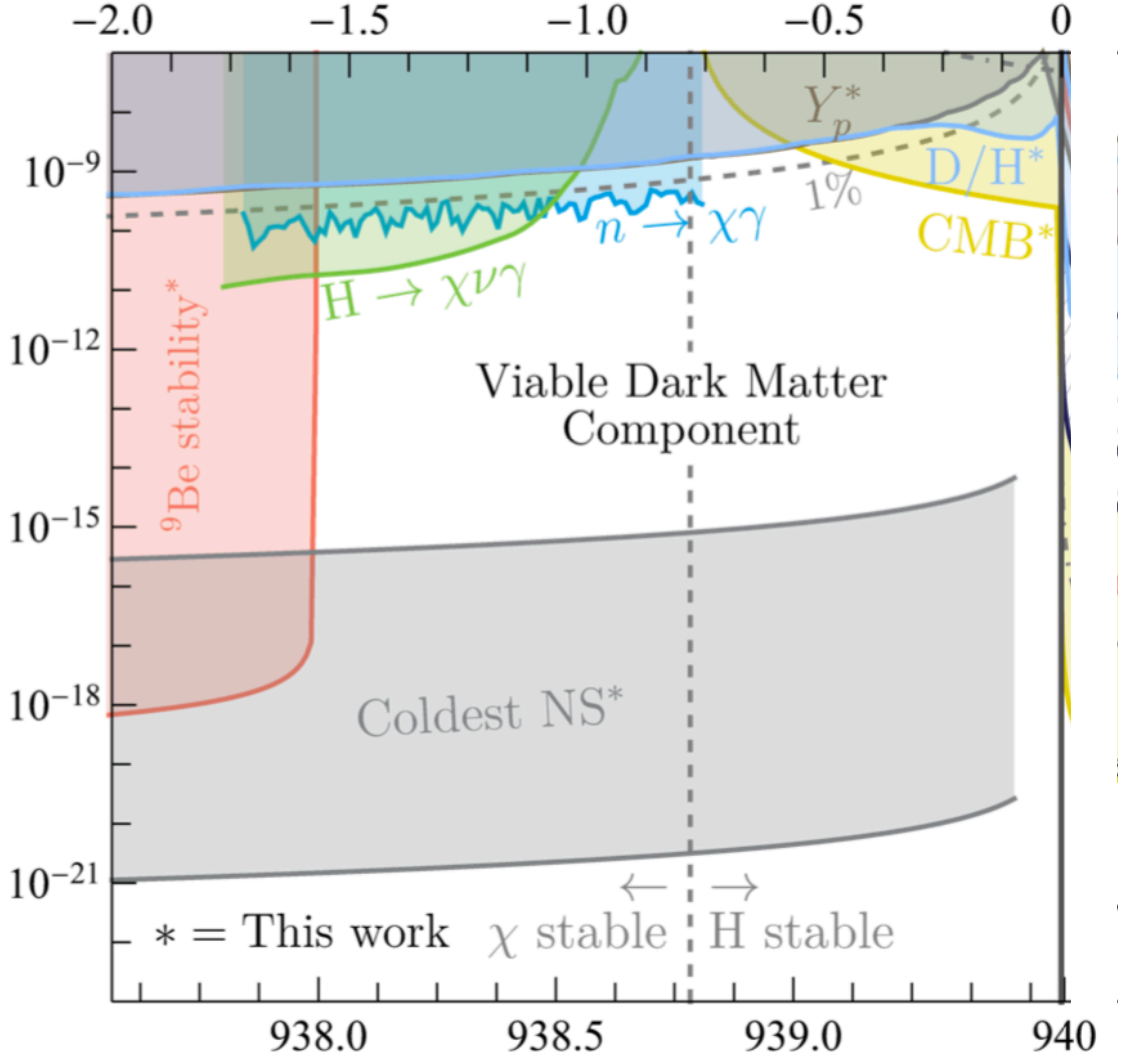
$n \to \chi\,\gamma$
open

longer
life

$n_\chi^0 = 5.4\,(n_p^0 + n_n^0)$



$n_\chi^0 = 0.01\,(n_p^0 + n_n^0)$



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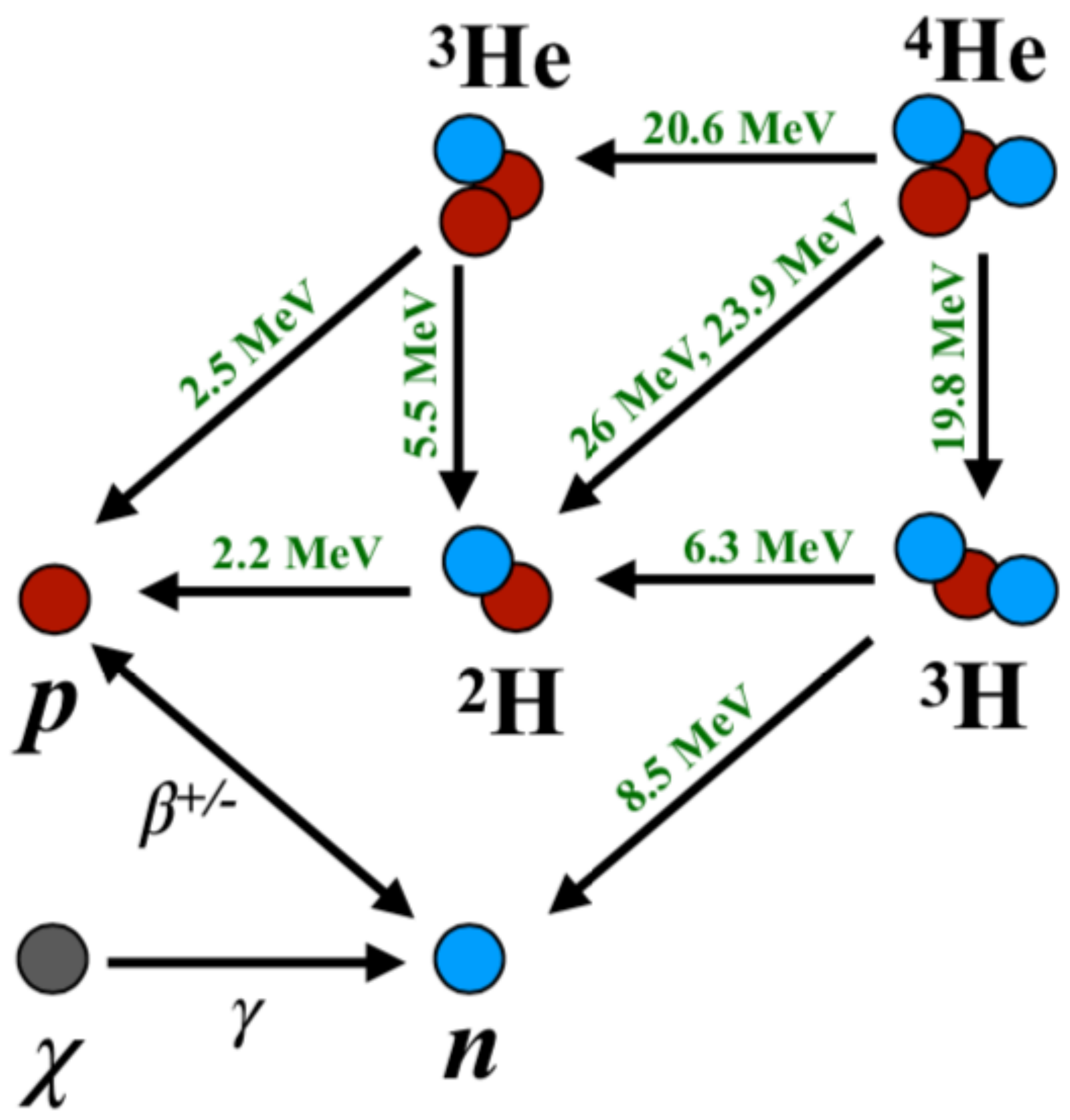
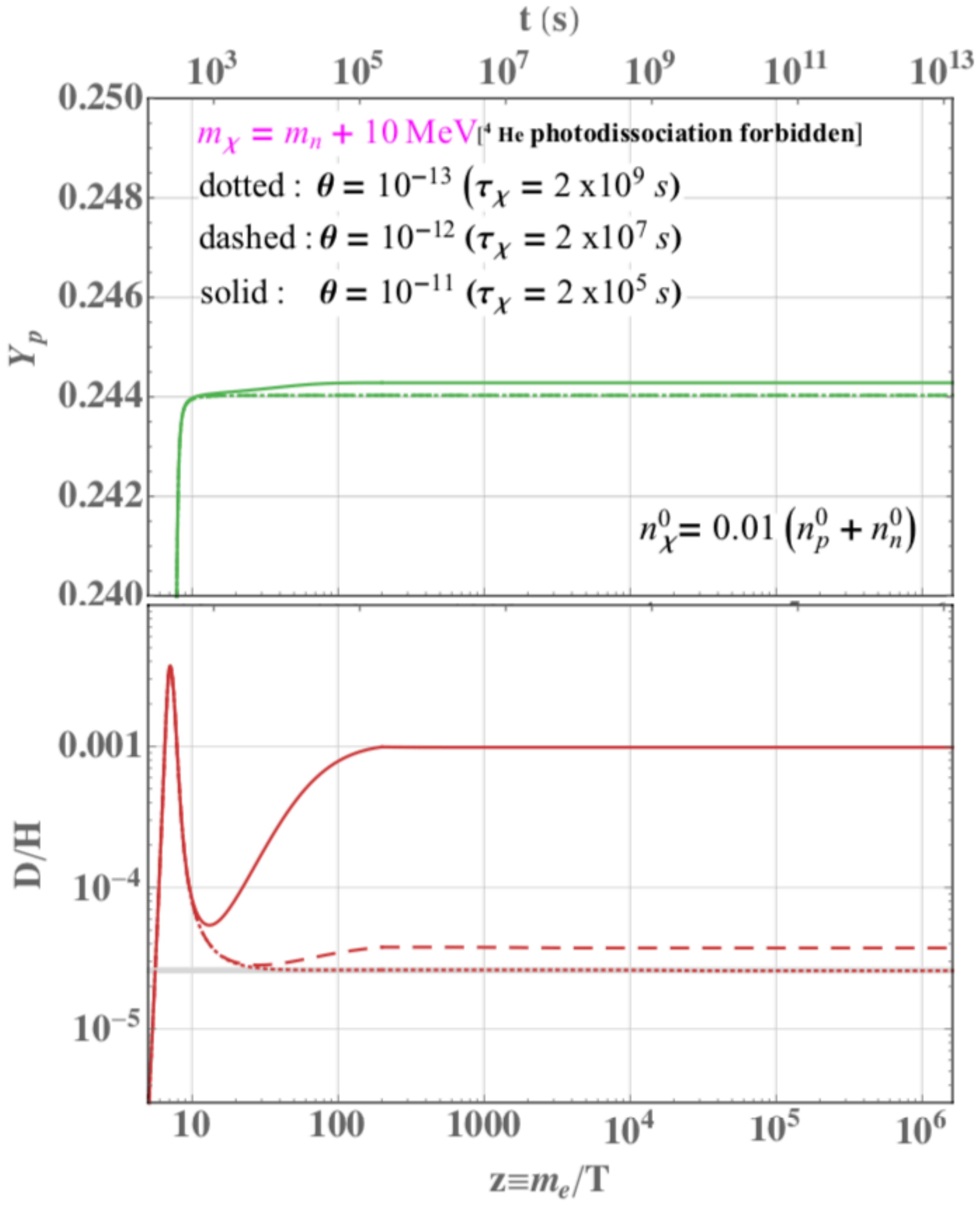
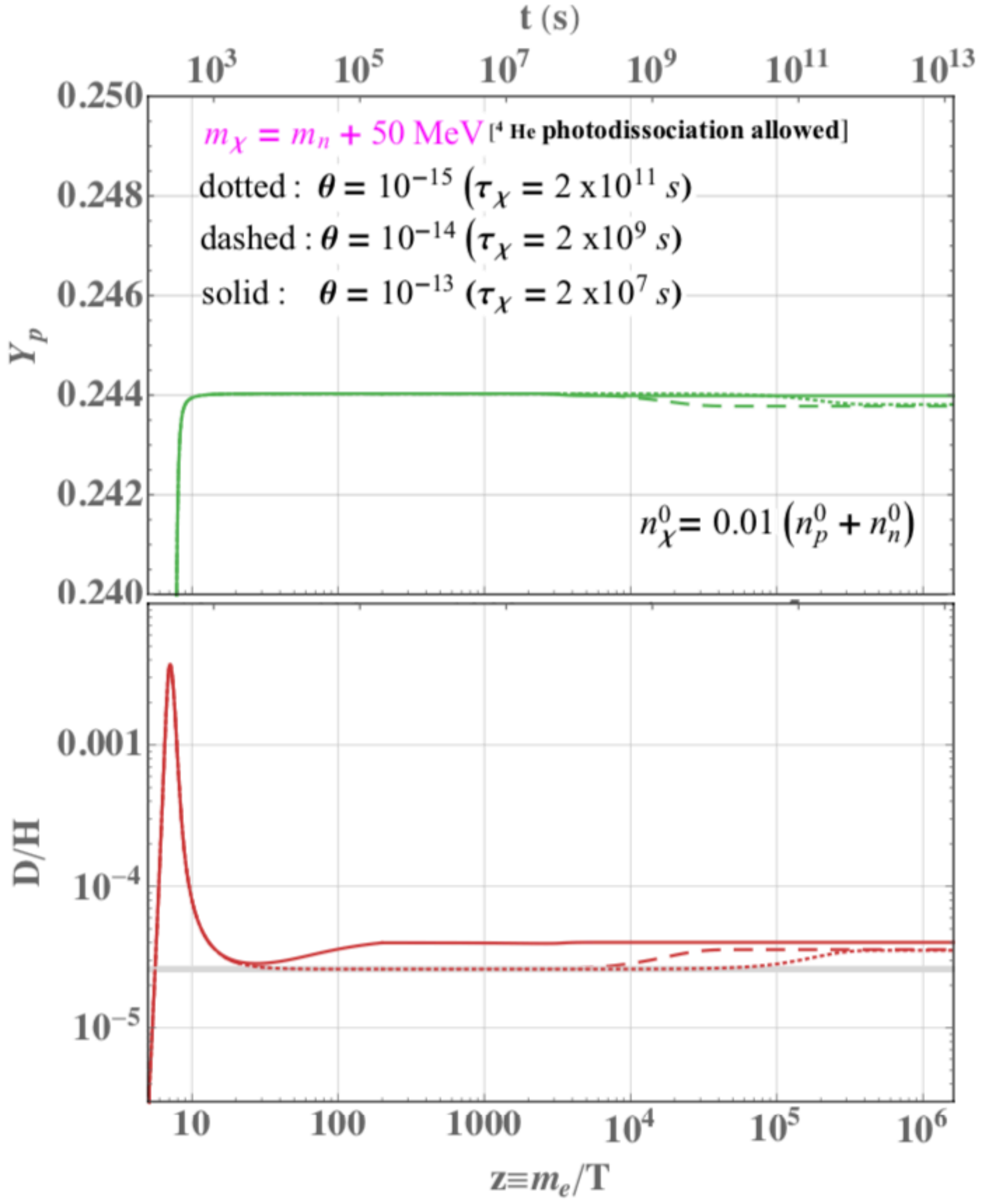
Signals: photodissociation post-nucleosynthesis

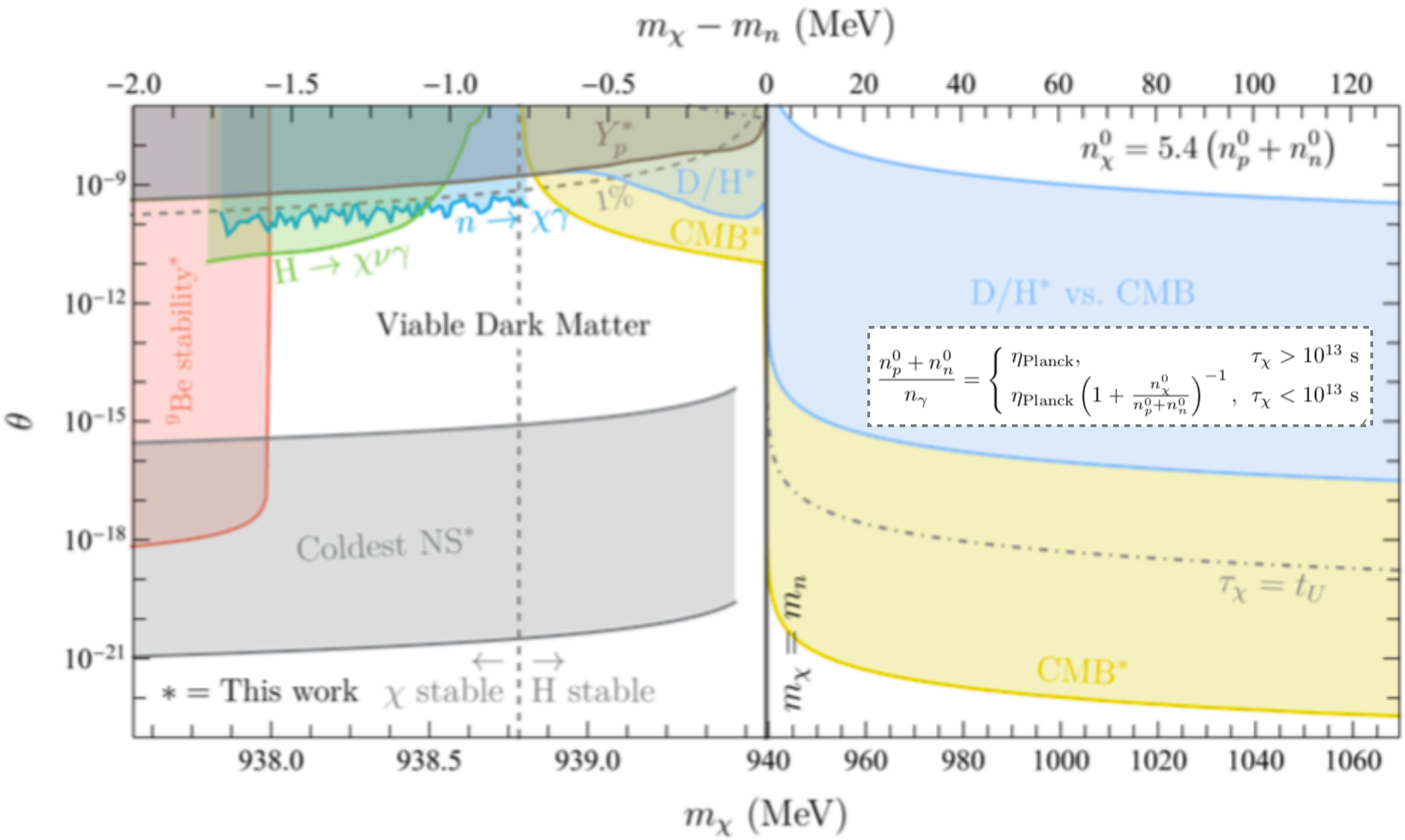






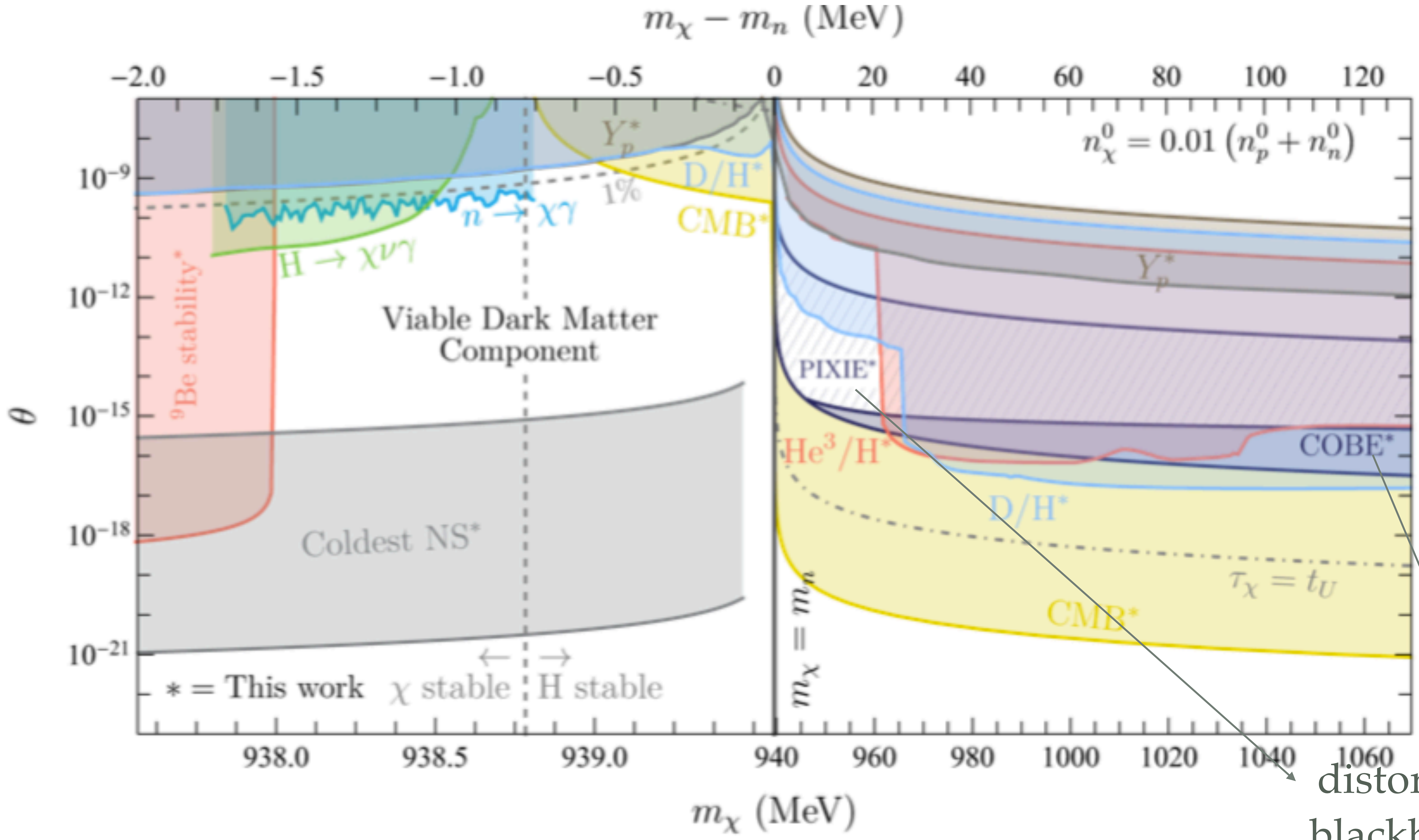
2012.09865 *McKeen, Pospelov,* Raj

Constraints: χ all the dark matter



2012.09865 ***McKeen, Pospelov,*** **Raj**

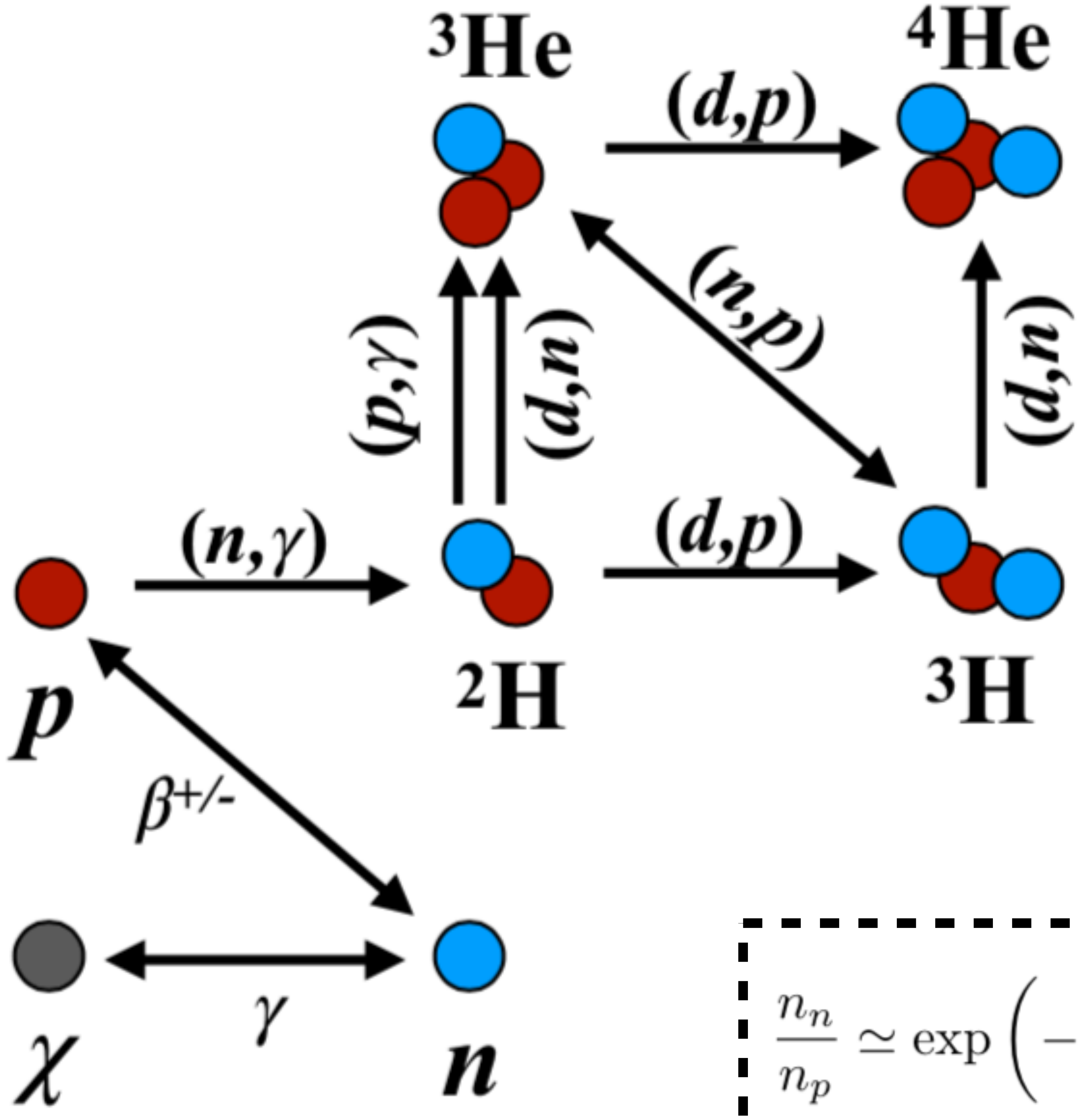
Constraints: χ percent-level dark matter



distortions of CMB blackbody spectrum

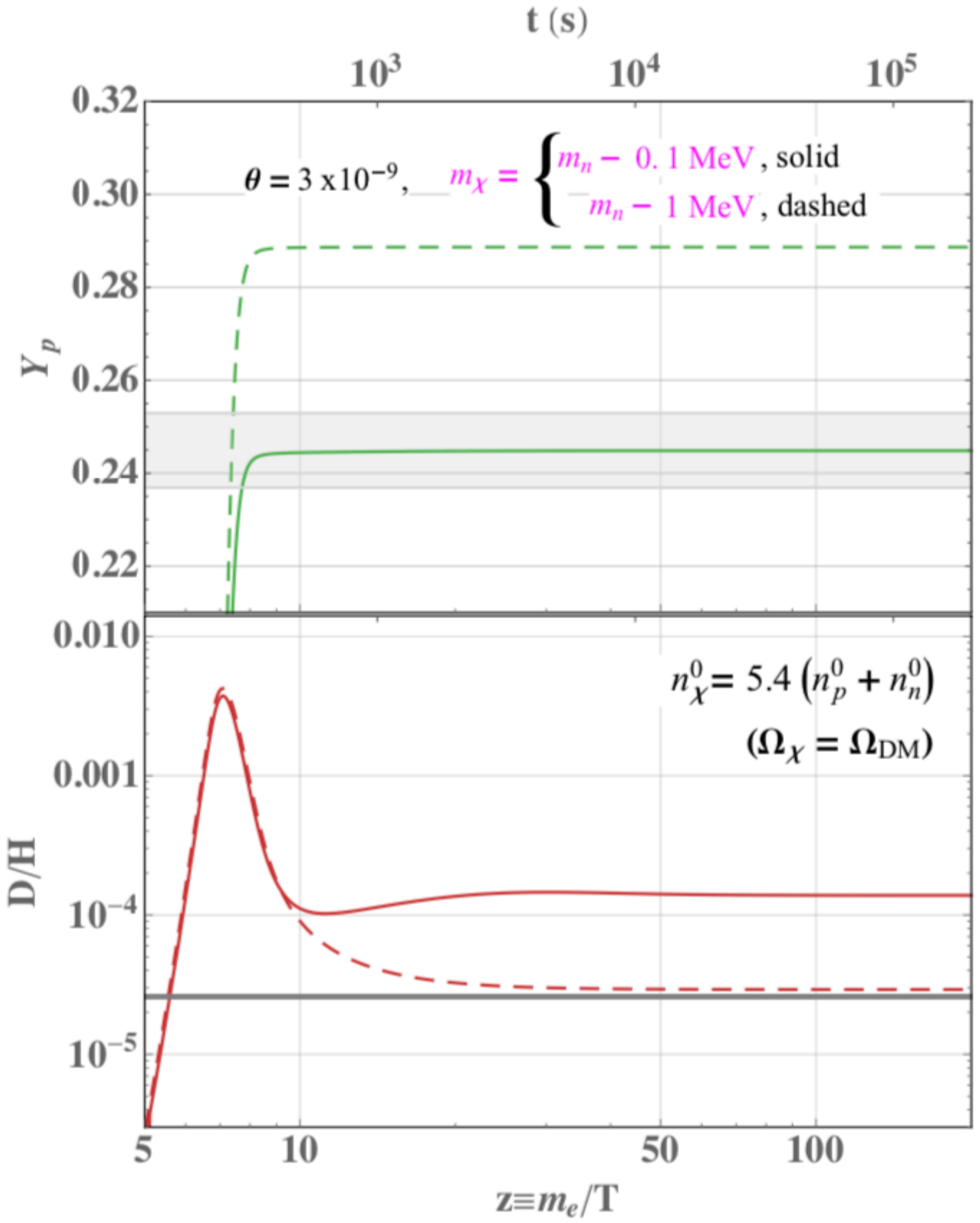
2012.09865 ***McKeen, Pospelov,*** **Raj**

Probes: primordial nucleosynthesis

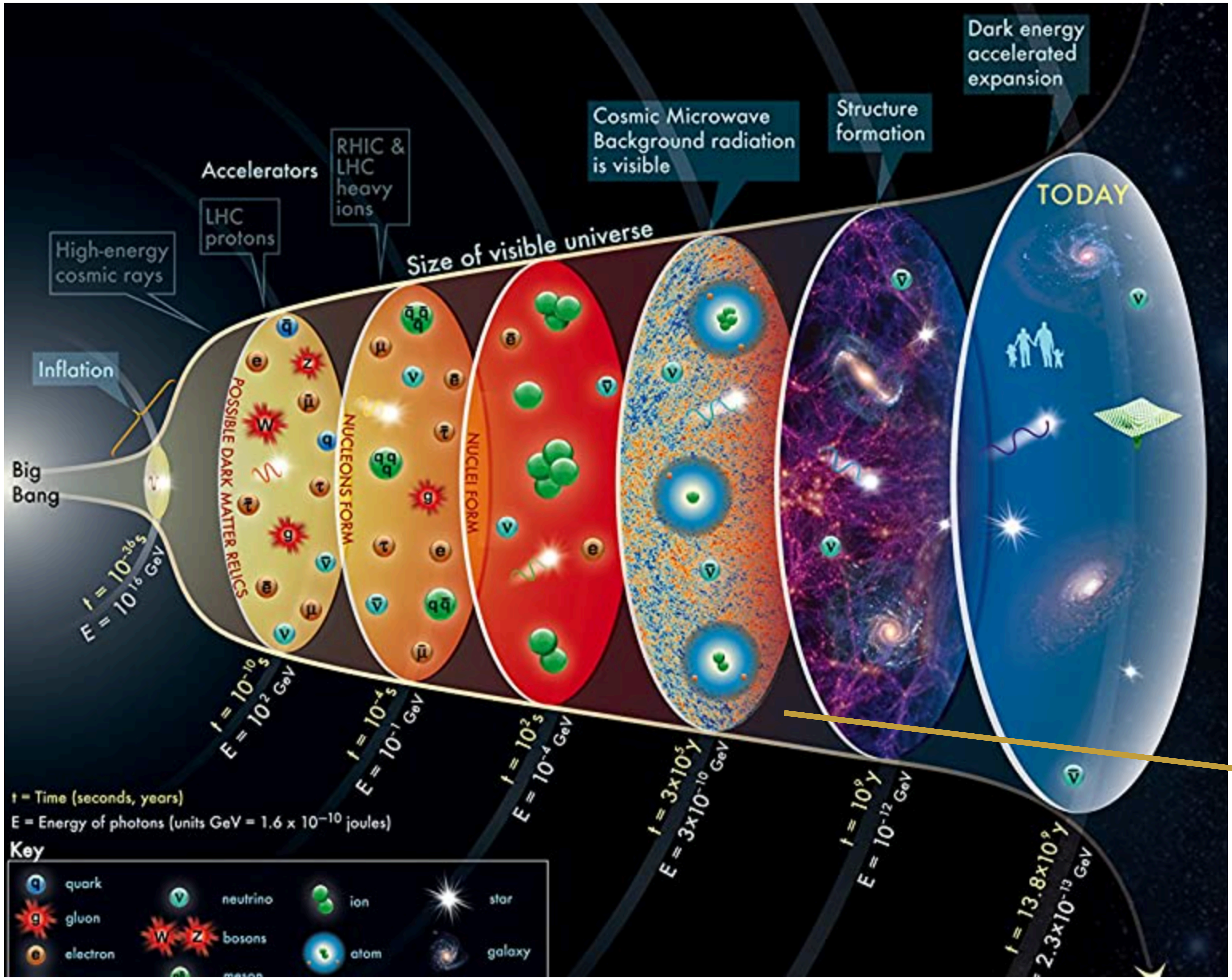


$$\frac{n_n}{n_p} \simeq \exp\left(-\frac{Q_{np}}{T_{np}}\right) \simeq \exp\left[-\frac{Q_{np}}{T_{np}}\left(1-\frac{\mathrm{Br}_{n\to\chi}}{3}\right)\right]$$

$$\frac{\delta Y_p}{Y_p} \simeq \frac{\delta(n_n/n_p)}{n_n/n_p} \times \frac{1}{1+n_n/n_p} \simeq 0.4\% \left(\frac{\mathrm{Br}_{n\to\chi}}{1\%}\right).$$



Probes: relic radiation



When kinematically open:

$$\Gamma_{\chi\to pe^-\bar{\nu}} = \frac{1}{9\times 10^{22}\ \mathrm{s}}\left(\frac{\theta}{10^{-10}}\right)^2 \frac{F(Q_\chi/m_e)}{F(Q_n/m_e)}$$

$$\Gamma_{\chi\to n\gamma} \simeq \frac{1}{2200\ \mathrm{s}}\left(\frac{\theta}{10^{-10}}\right)^2 \left|\frac{\Delta m}{10\ \mathrm{MeV}}\right|^3$$

e or γ could “rewrite” reionization history by dumping EM energy in Dark Ages
(i.e. modify optical depth)