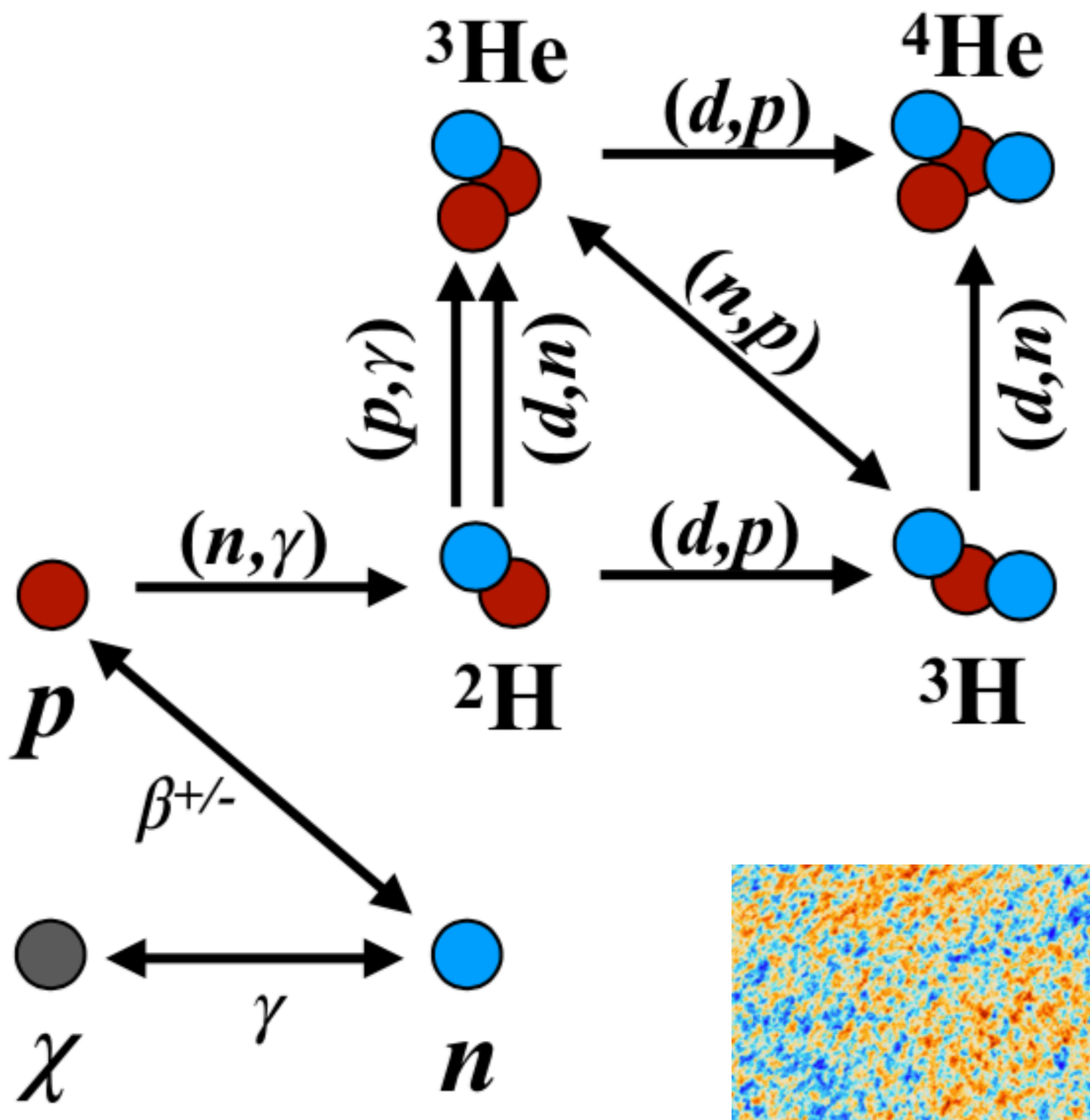
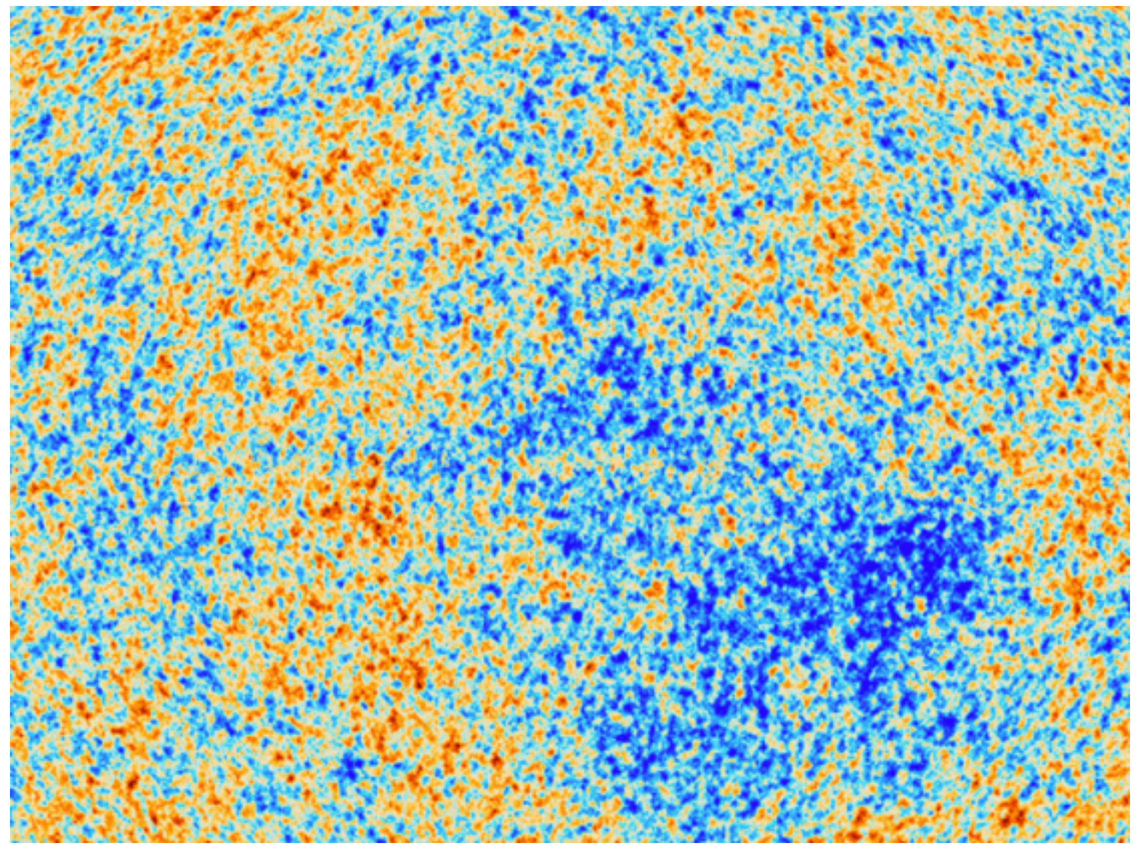
The History and Fate of Dark Neutrons

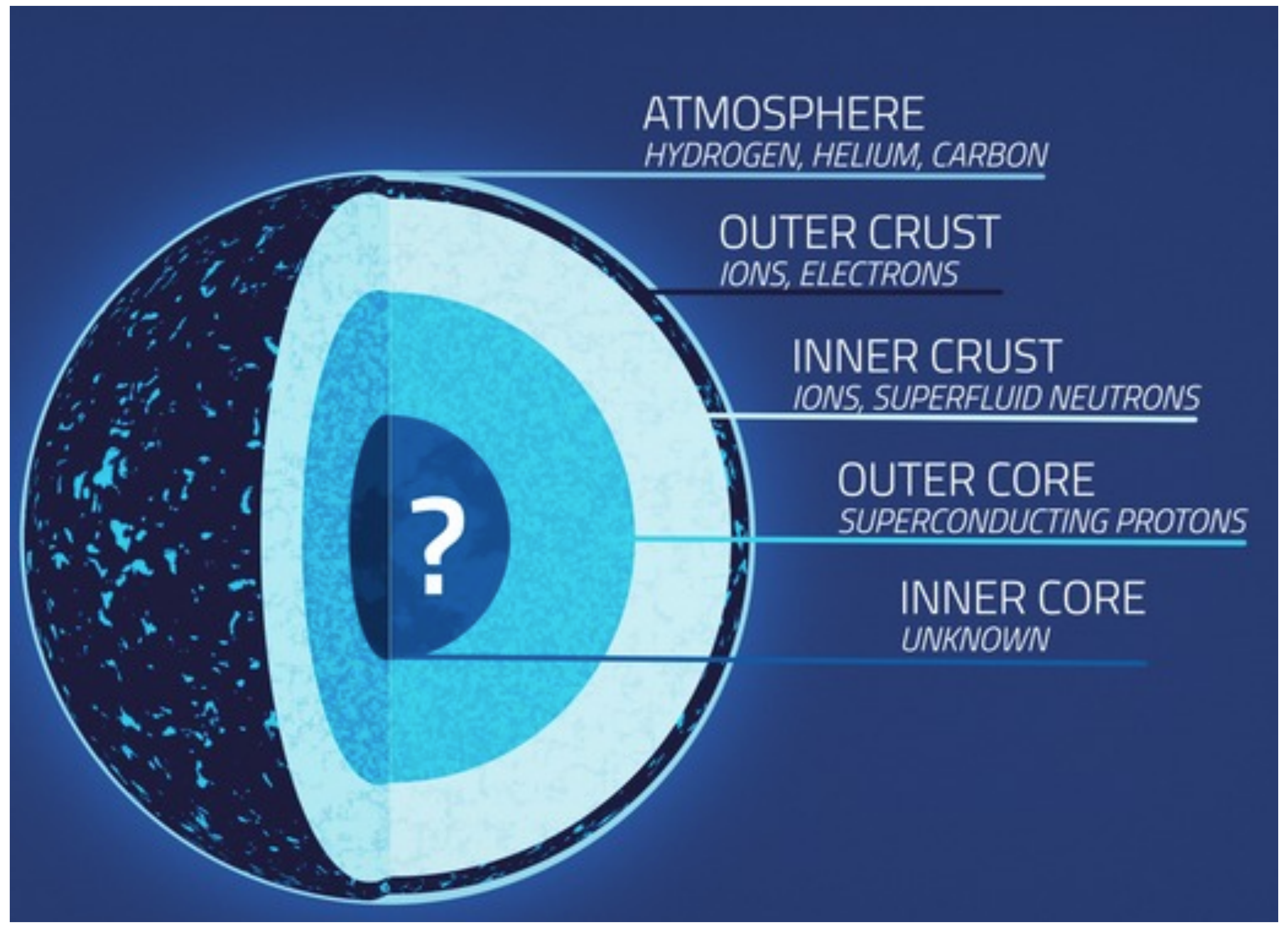
Nirmal Raj

TRIUMF

based on **2012.09865**
(accepted at PRD)
with
David McKeen
& Maxim Pospelov



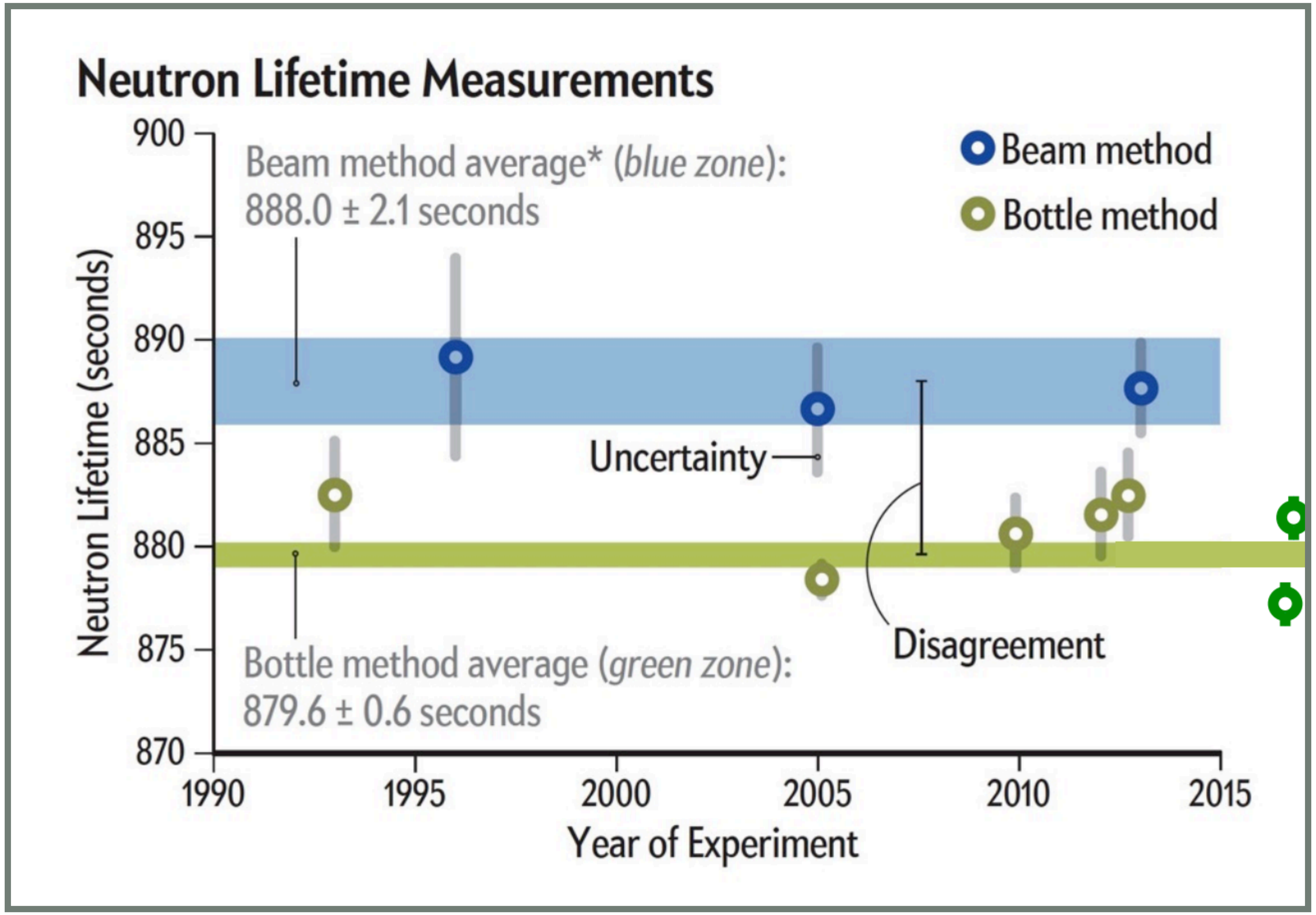




PPC 2021
Parallel talk
05/19/2021

Why dark baryons? [new GeV-mass states carrying *B*]

(1)



discrepancy:

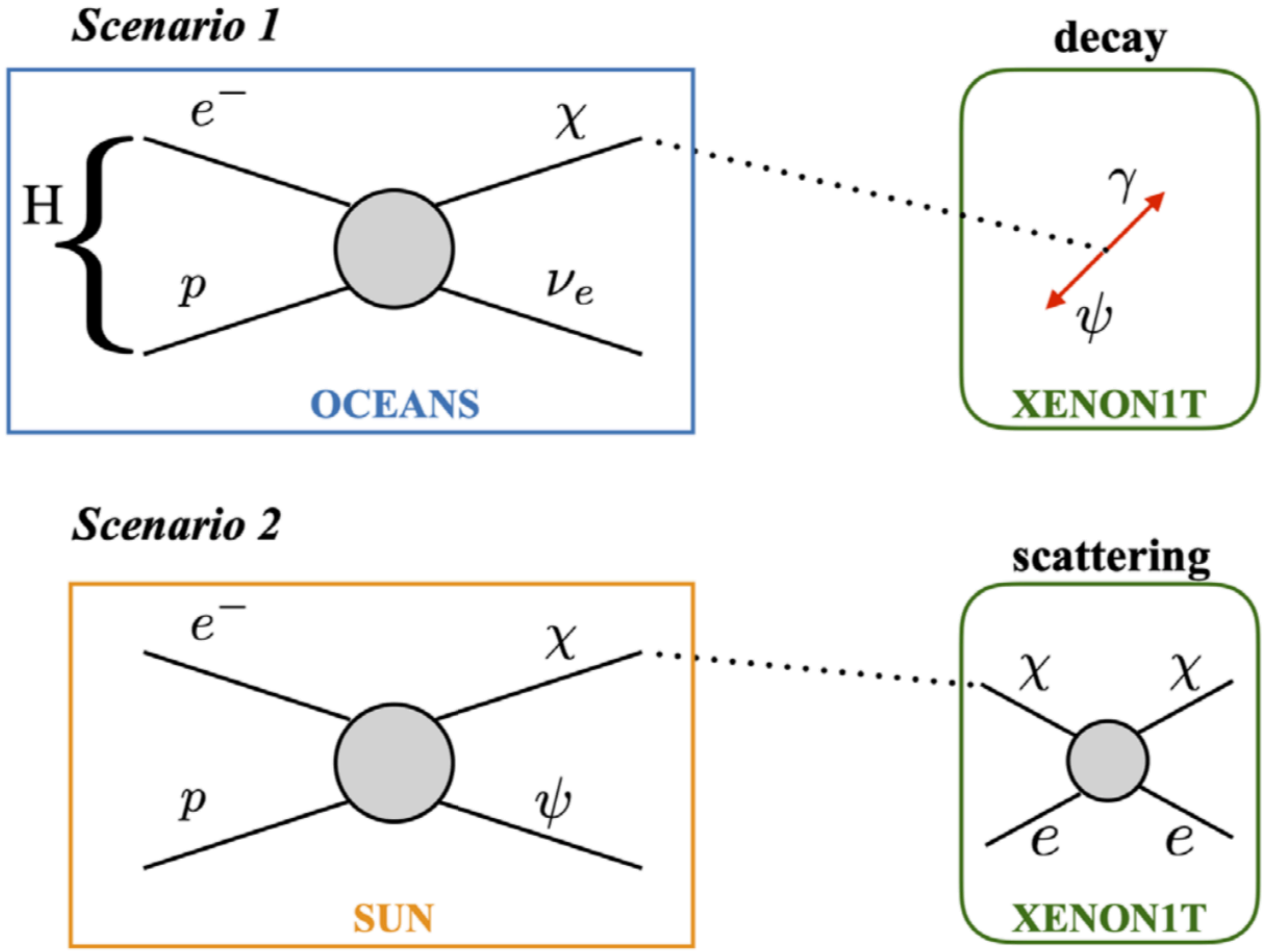
$$\frac{\Delta\tau_n}{\tau_n} \approx 1\%$$

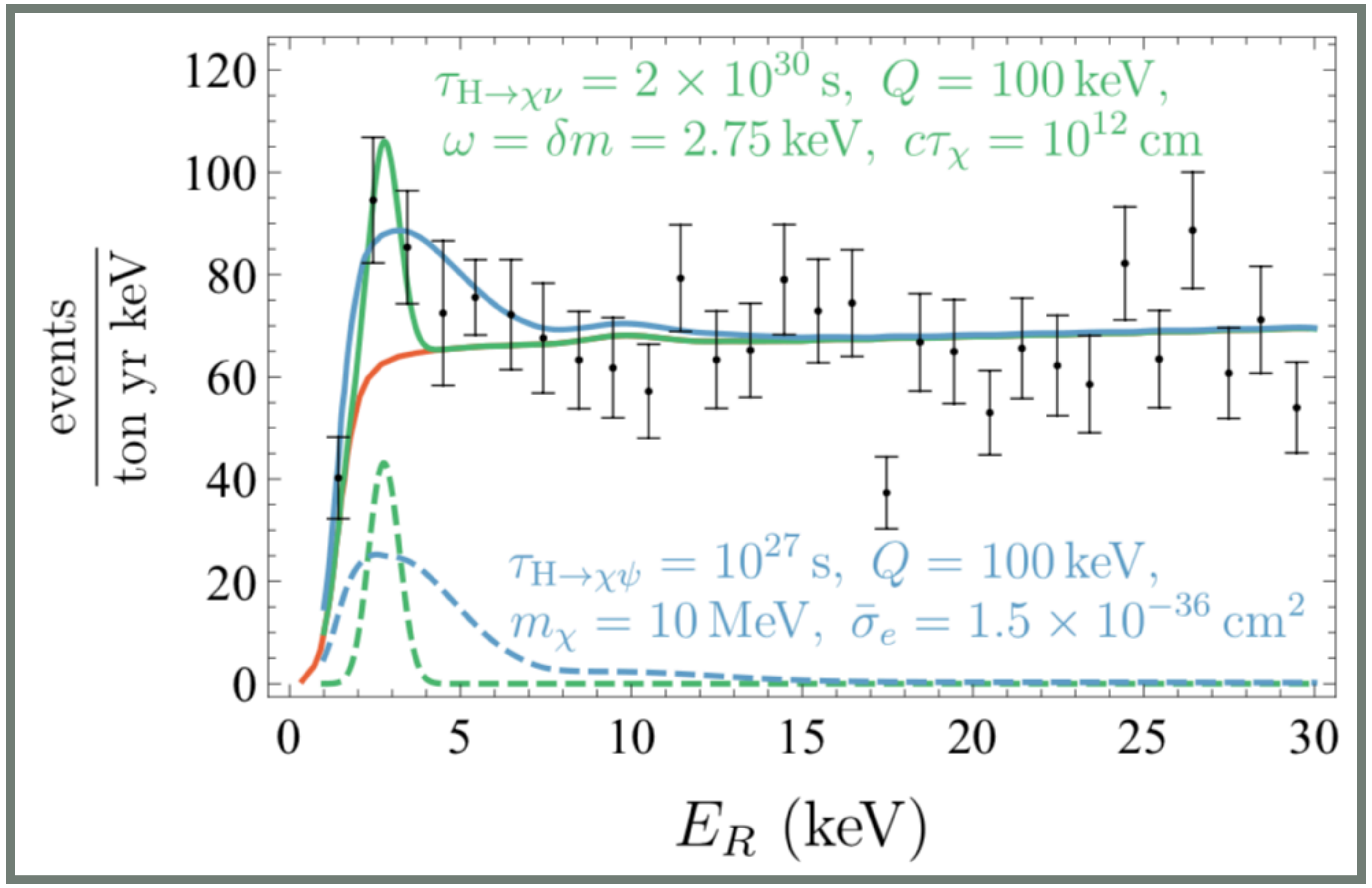
explain *n* lifetime puzzle with 1% branching to $n \to \chi + \text{anything}$

Fornal, Grinstein (2018)

Why dark baryons? [new GeV-mass states carrying B]

(2) could explain recent XENON1T excess

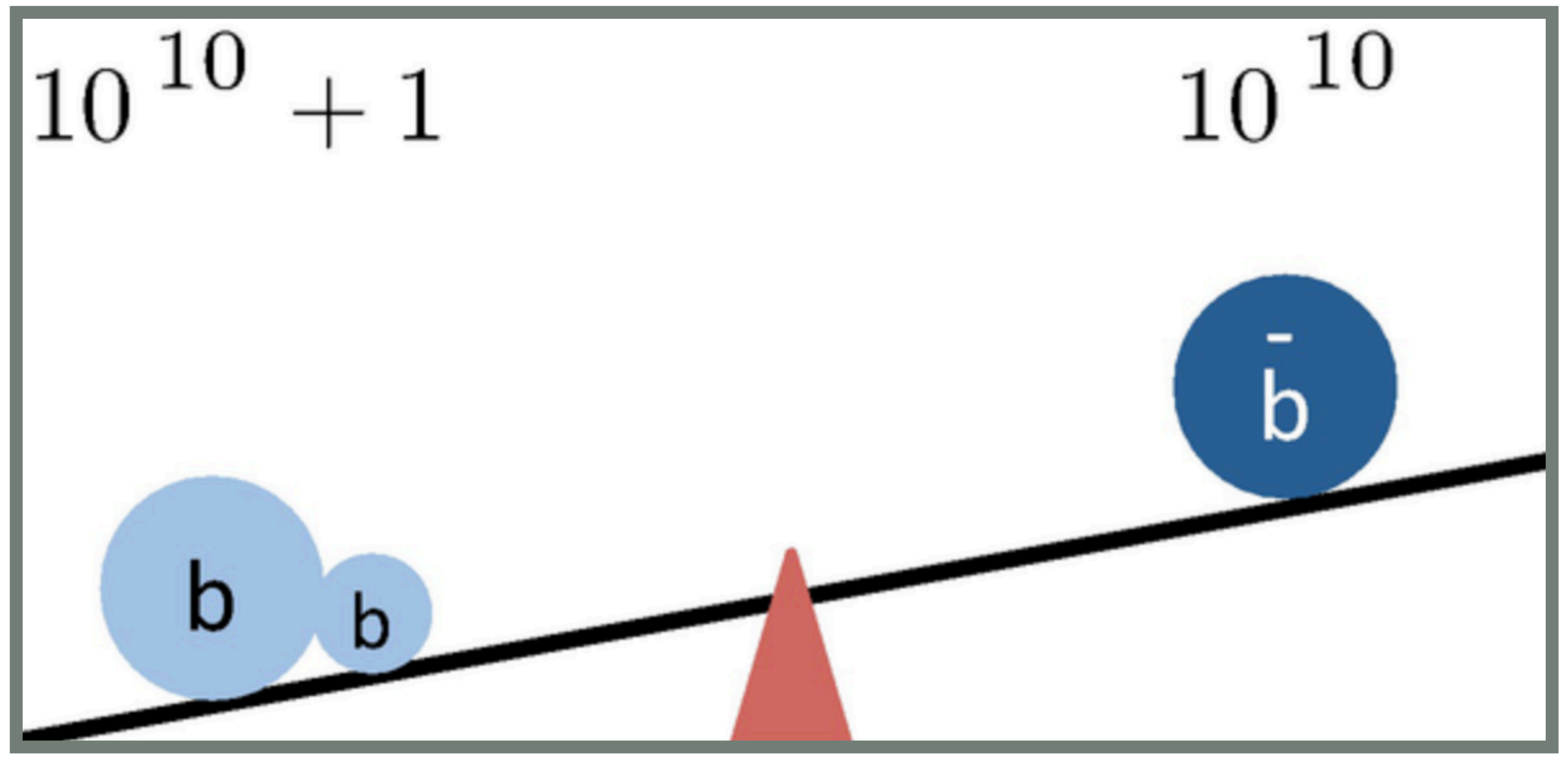


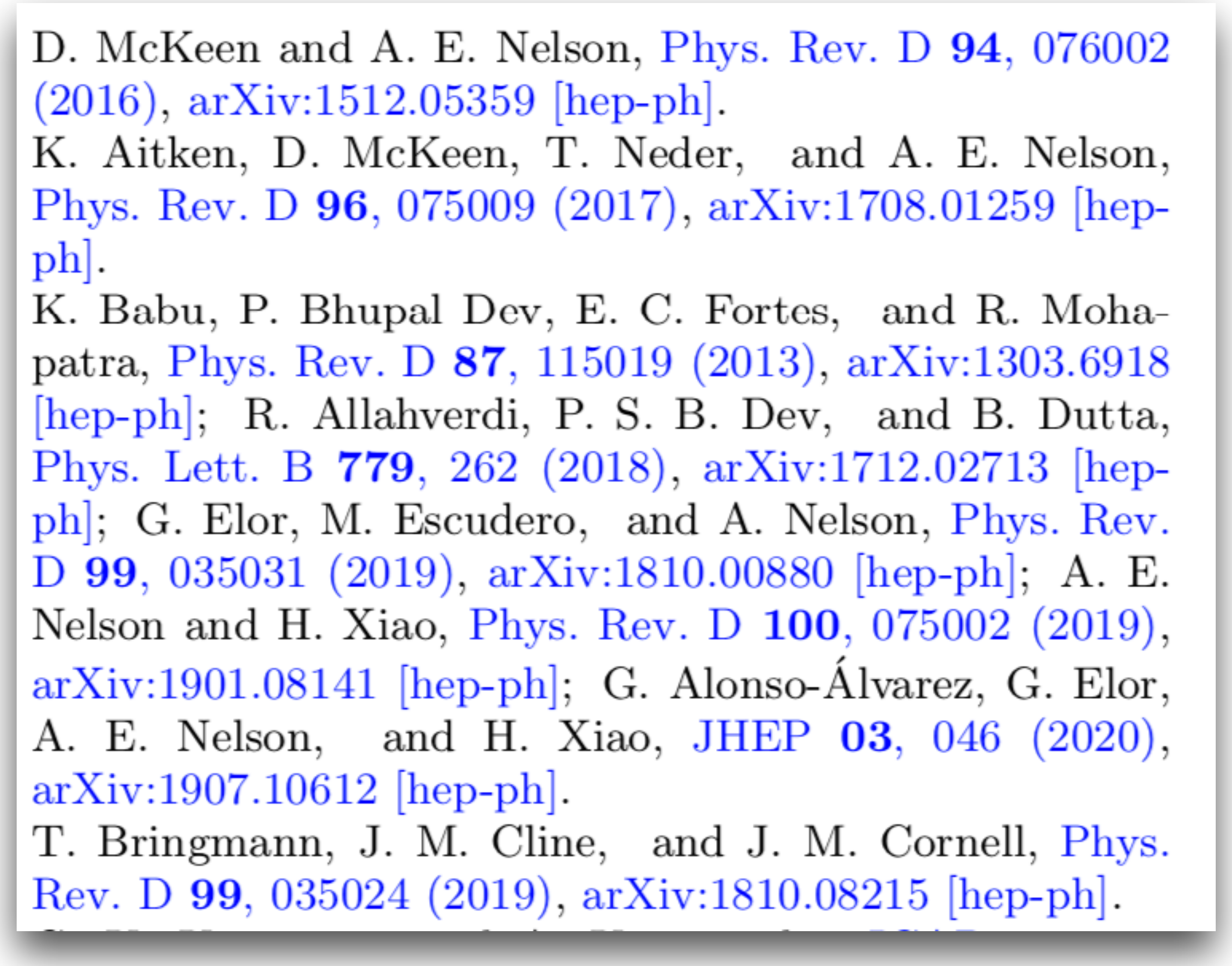


2006.15140 [*PRL* **125**, 231803 (2020)] : McKeen, Pospelov, ***Raj***

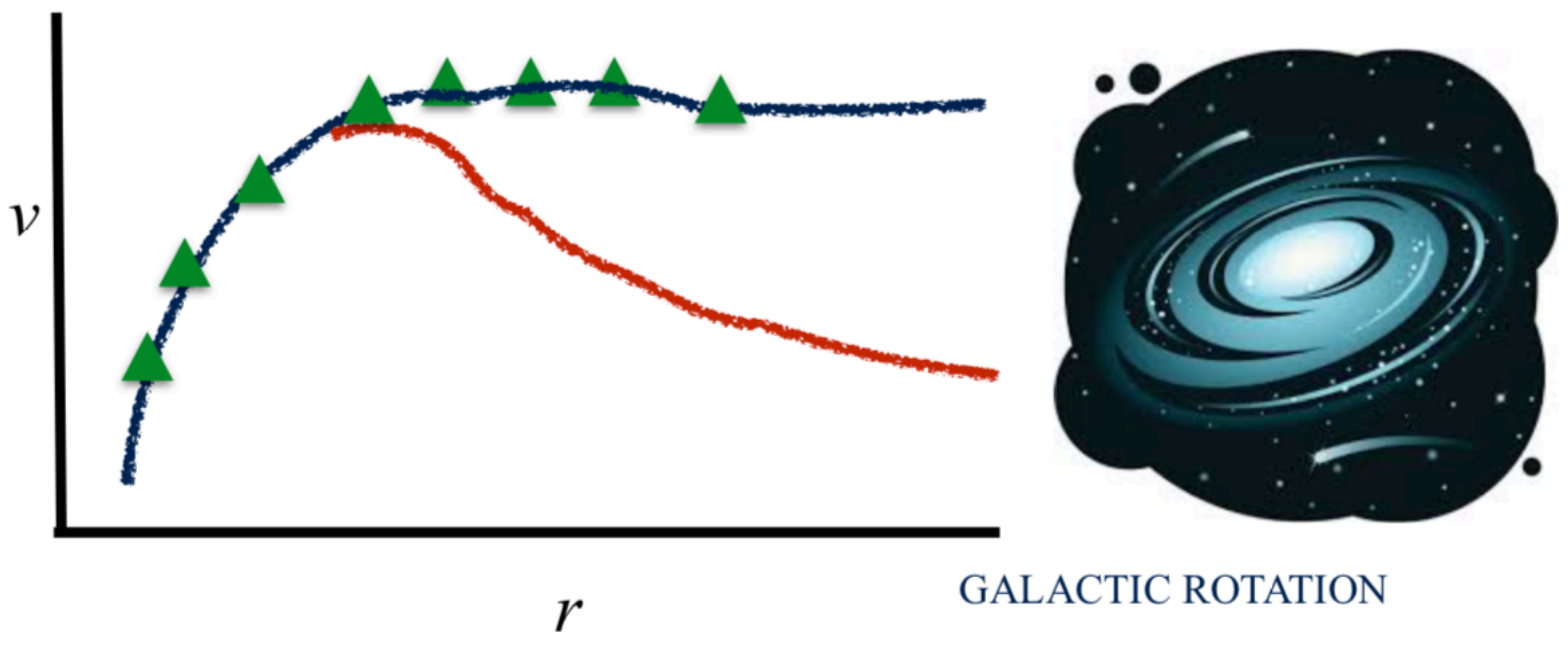
Why dark baryons? [new GeV-mass states carrying B]

(3) role in baryon asymmetry

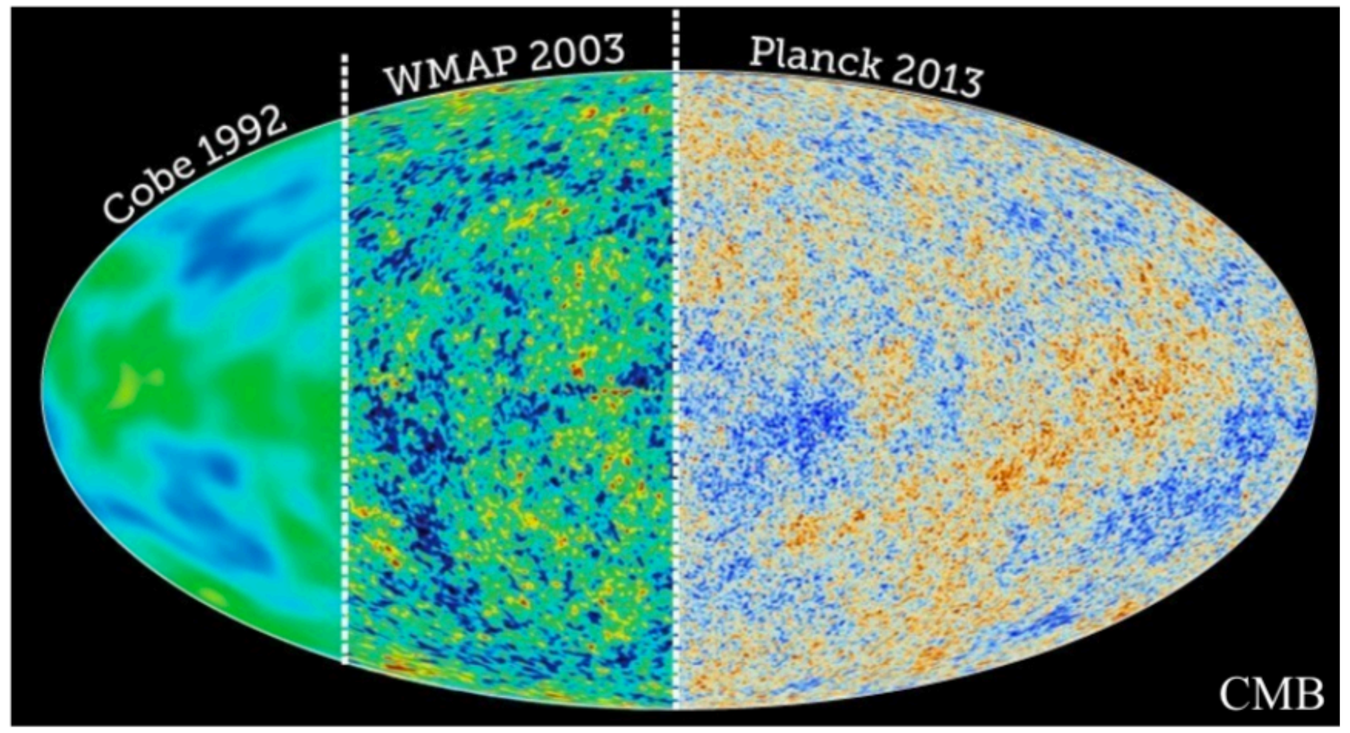


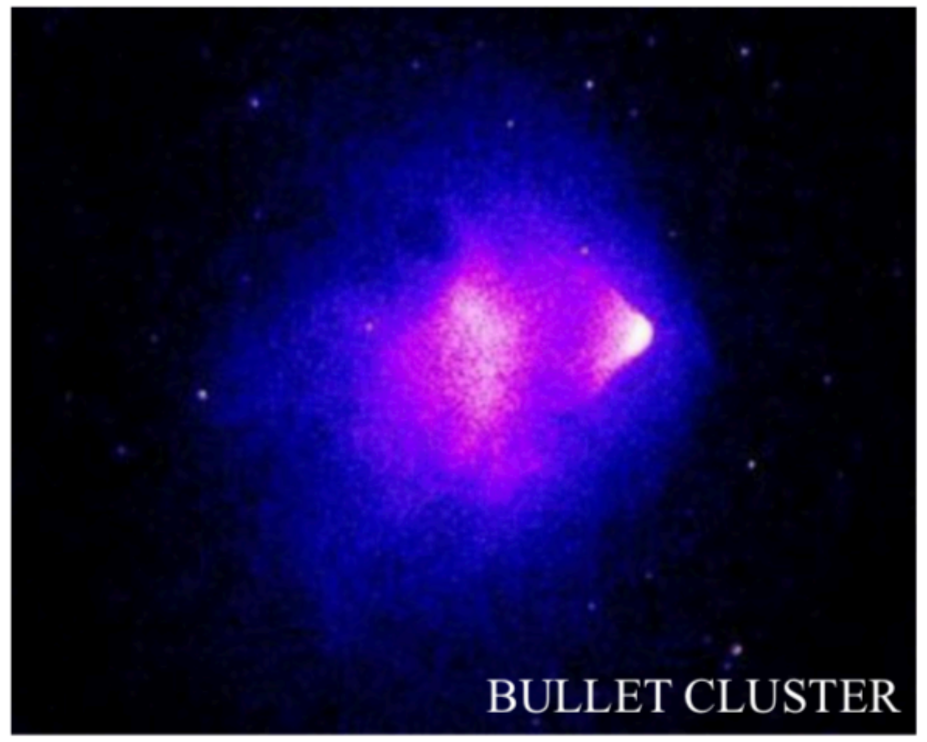

D. McKeen and A. E. Nelson, Phys. Rev. D **94**, 076002 (2016), arXiv:1512.05359 [hep-ph].
K. Aitken, D. McKeen, T. Neder, and A. E. Nelson, Phys. Rev. D **96**, 075009 (2017), arXiv:1708.01259 [hep-ph].
K. Babu, P. Bhupal Dev, E. C. Fortes, and R. Mohapatra, Phys. Rev. D **87**, 115019 (2013), arXiv:1303.6918 [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





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

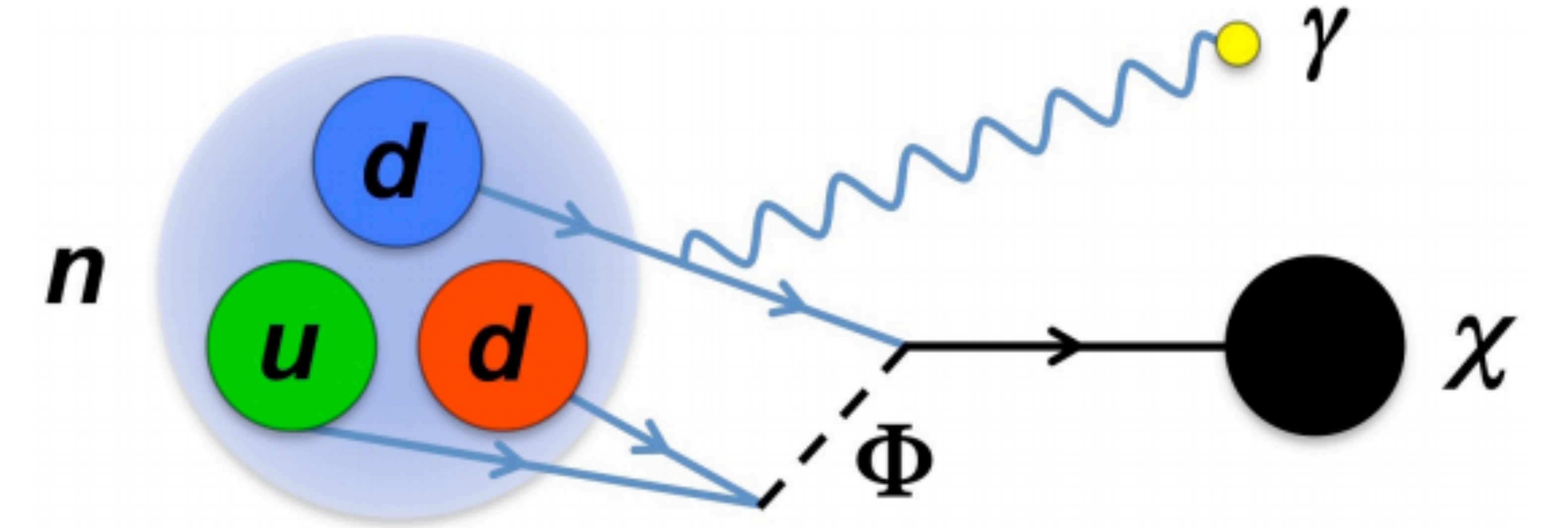


image: Fornal & Grinstein

n lifetime puzzle:

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

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

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

Prehistoric census

Interesting cases:

(i) $n_\chi^0 = 5.4(n_p^0 + n_n^0)$ (χ is the dark matter if $\tau_\chi > t_{\mathrm{U}}$)

(ii) $n_\chi^0 = 0.01(n_p^0 + n_n^0)$ (perhaps never chem eqbm)

$\frac{\mu_n}{2}\theta\bar{\chi}\sigma^{\mu\nu}nF_{\mu\nu} \longrightarrow$ number-changing rate

$$\Gamma_{\Delta\chi} \sim \theta^2\mu_n^2T^3 \gtrsim H \text{ for } T \gtrsim 100\ \text{MeV}\left(\frac{10^{-9}}{\theta}\right)^2$$

above QCD transition => quark level description required

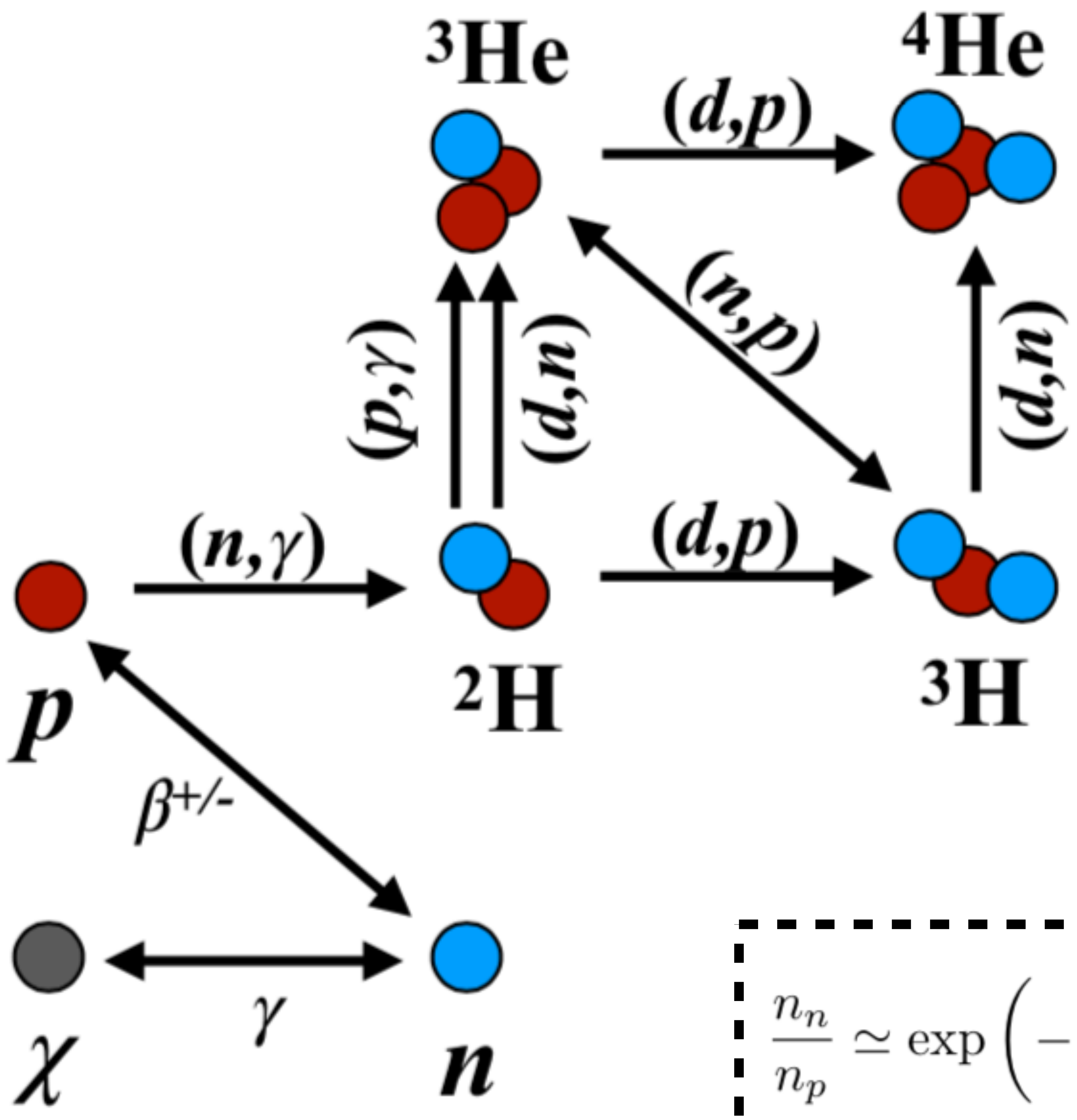
$-\delta(\bar{\chi}n + \bar{n}\chi) \longleftarrow \bar{\chi}qqq/\Lambda^2$ => $\Gamma_{\Delta\chi} \sim T^5/\Lambda^4$

chemical equilbrium keepable down to T ~ GeV—PeV

for $\theta \sim 10^{-20}$ — 10^{-10} and Δm ~ 1—100 MeV

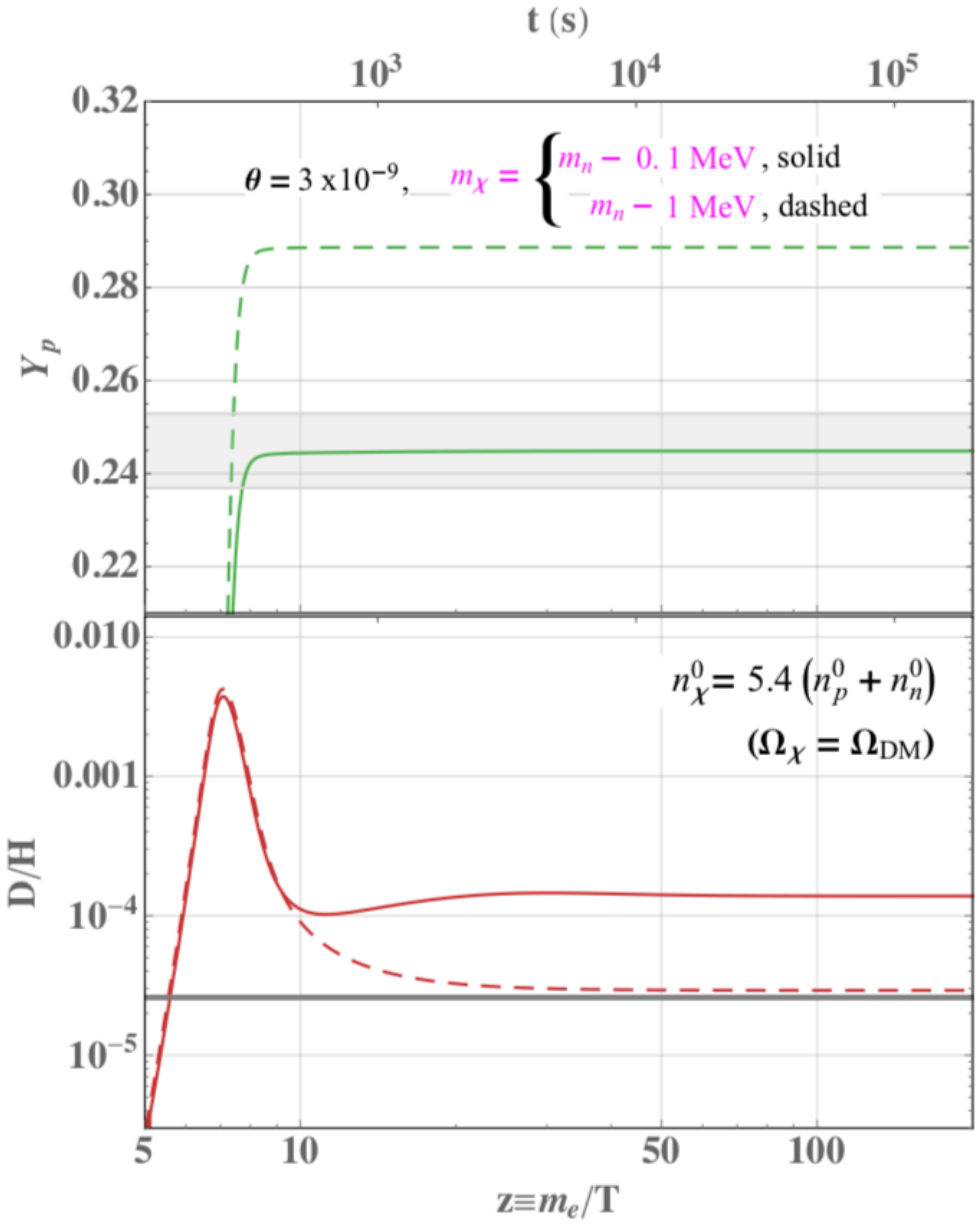
$\dashrightarrow$ $n_\chi \sim n_p = n_n$ reasonable since universe was probably that hot

Probes: [1] primordial nucleosynthesis

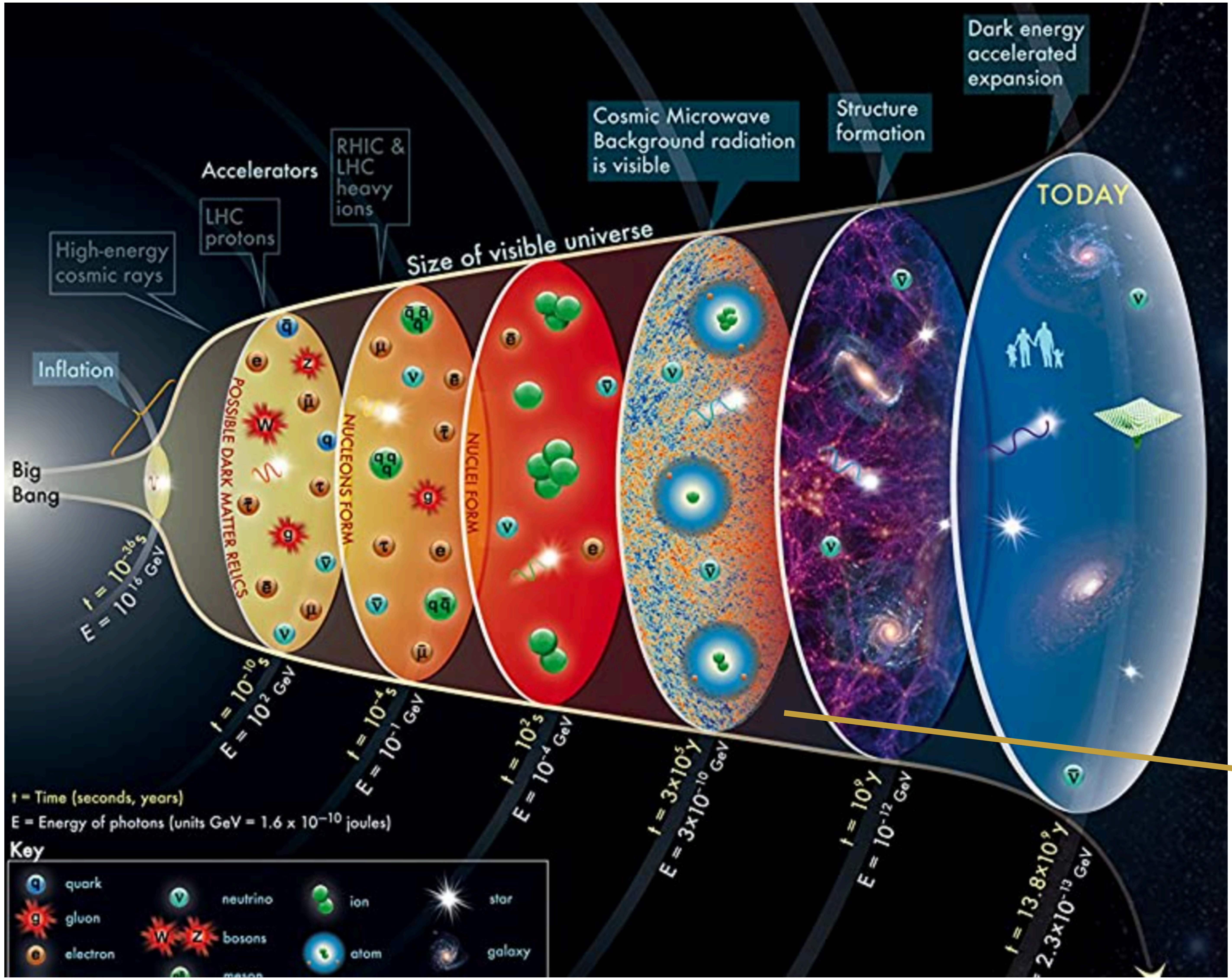


$$\frac{n_n}{n_p} \simeq \exp\left(-\frac{Q_{np}}{T_{np}}\right) \simeq \exp\left[-\frac{Q_{np}}{T_{np}}\left(1-\frac{\mathrm{Br}_{n\to\chi}}{3}\right)\right]$$

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



Probes: [2] relic radiation



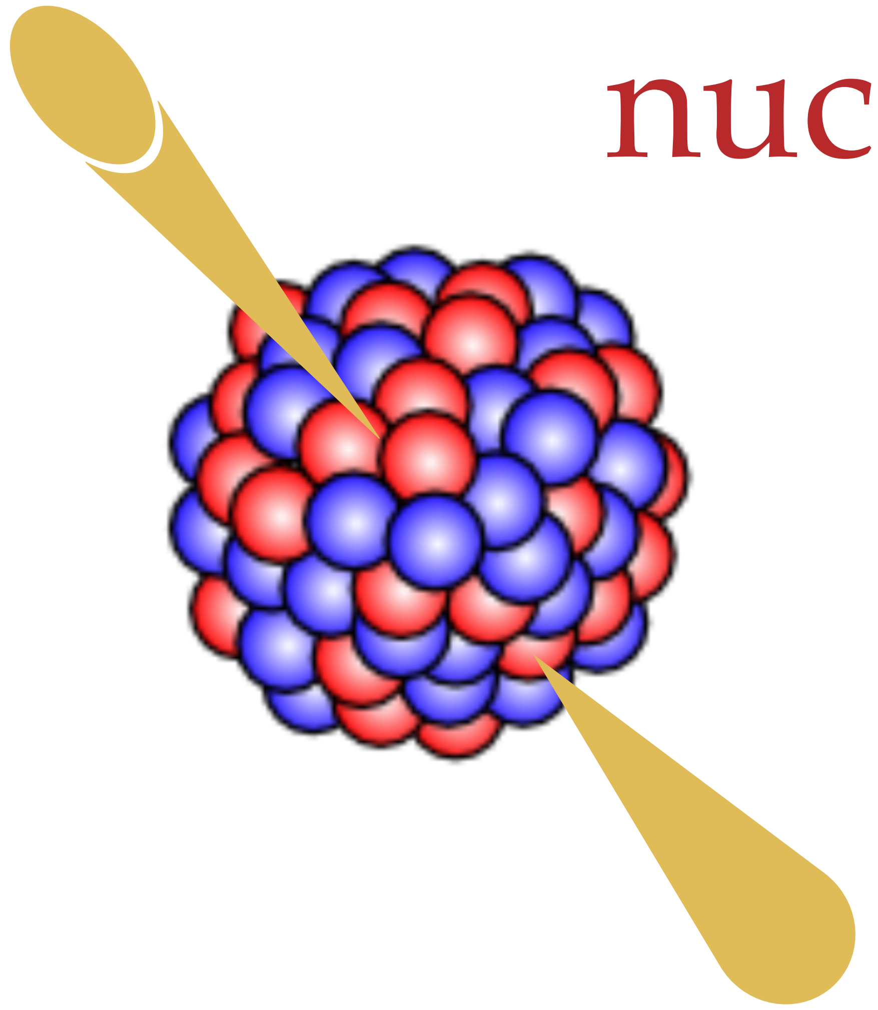
When kinematically open:

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

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

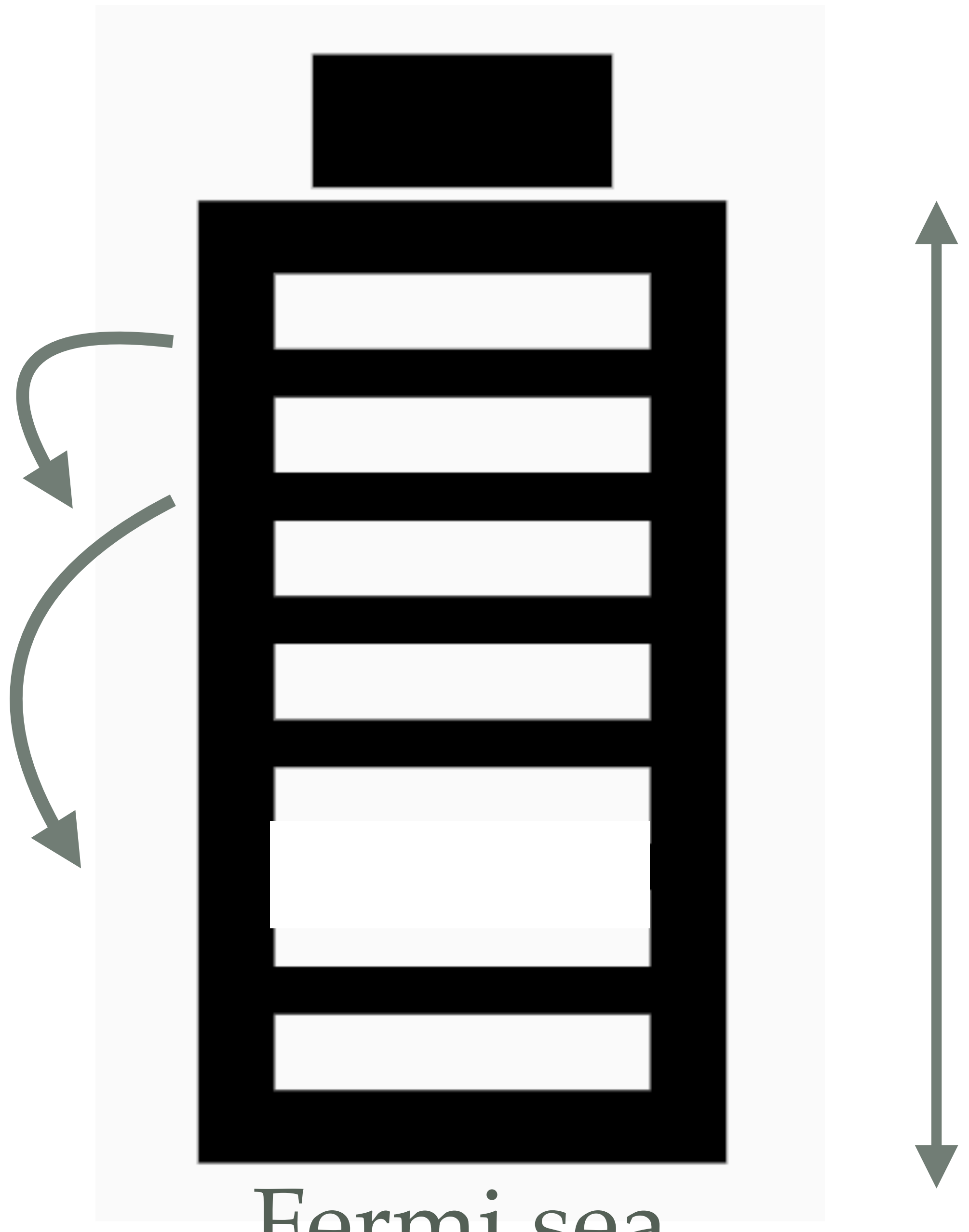
e or γ could "rewrite" reionization history by dumping EM energy in Dark Ages
(i.e. modify optical depth)

Probes: [3] neutron star temperatures



new heating mechanism:
nucleon "Auger effect"

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



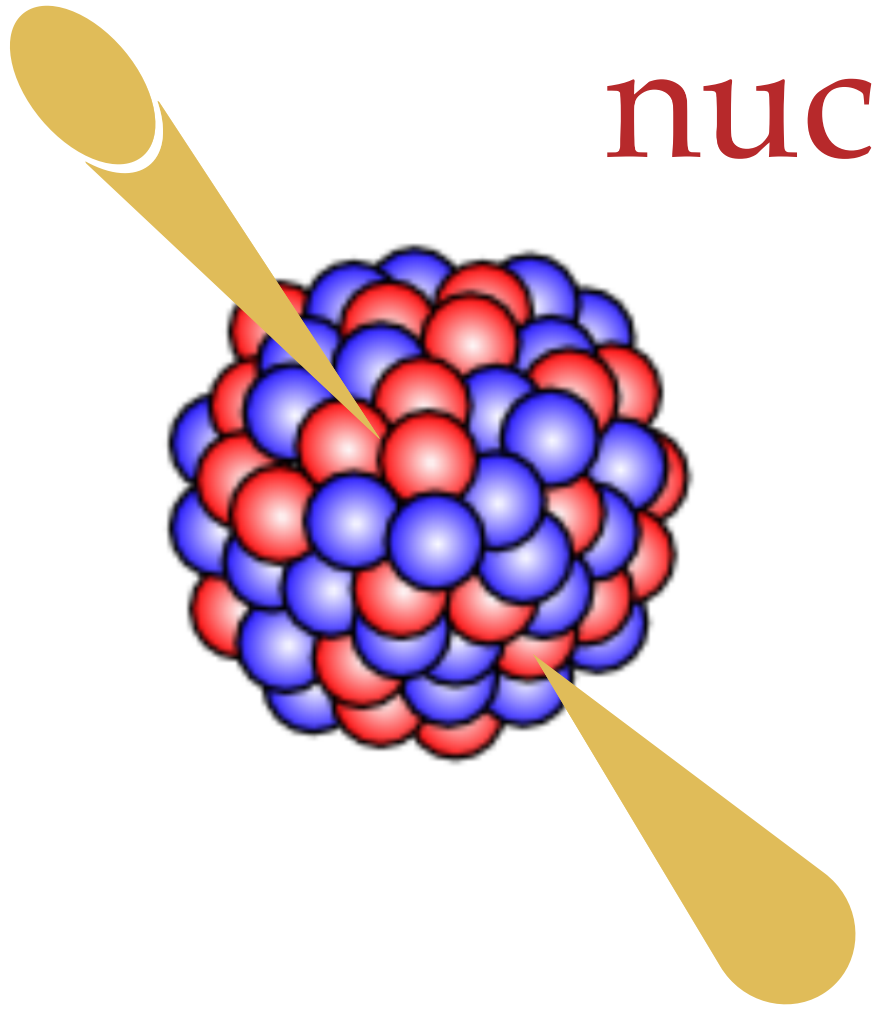
Fermi sea

neutron Fermi energy
~ 100 MeV

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

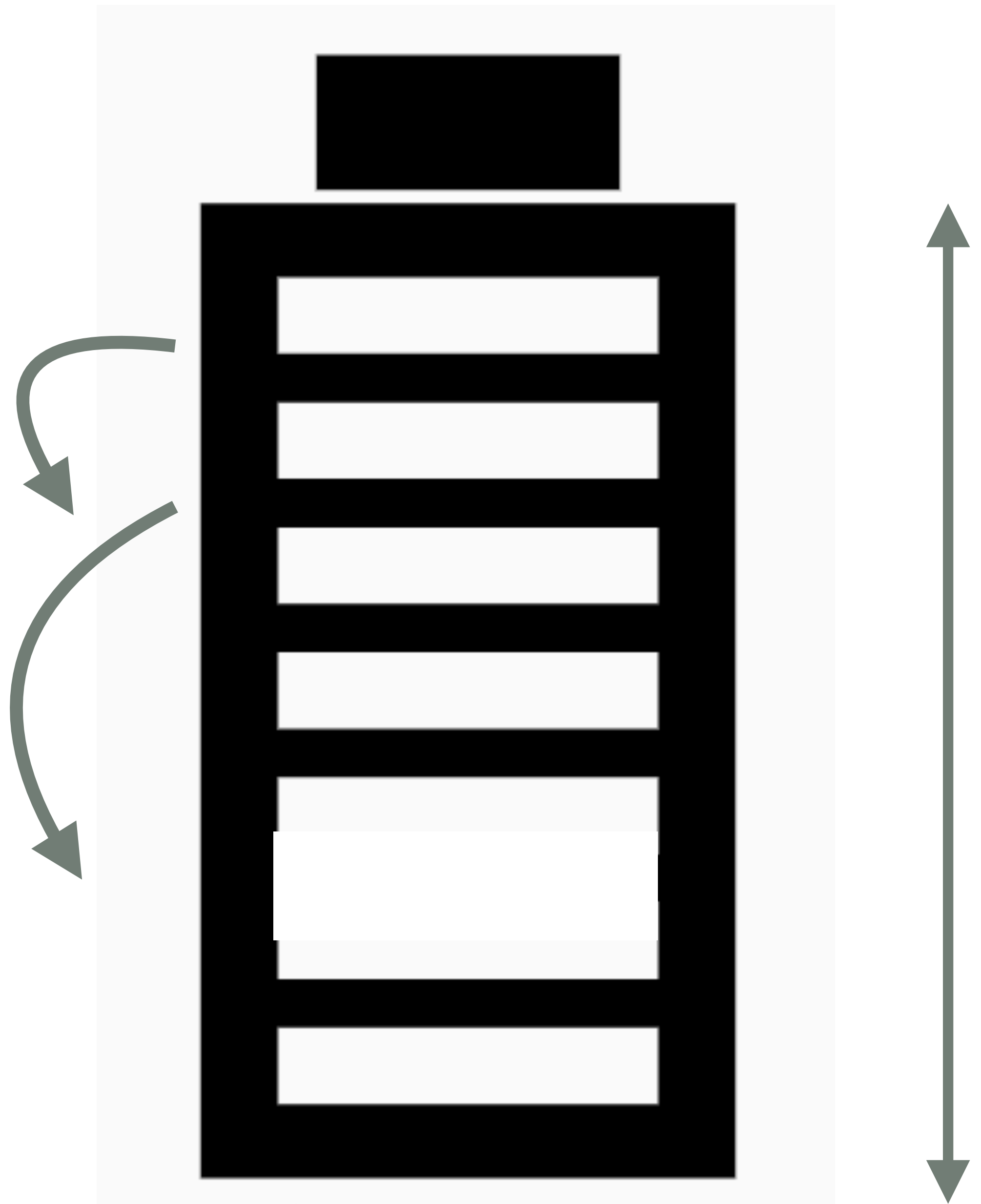
=> **explosive liberation of energy!**

Probes: [3] neutron star temperatures



new heating mechanism:
nucleon "Auger effect"

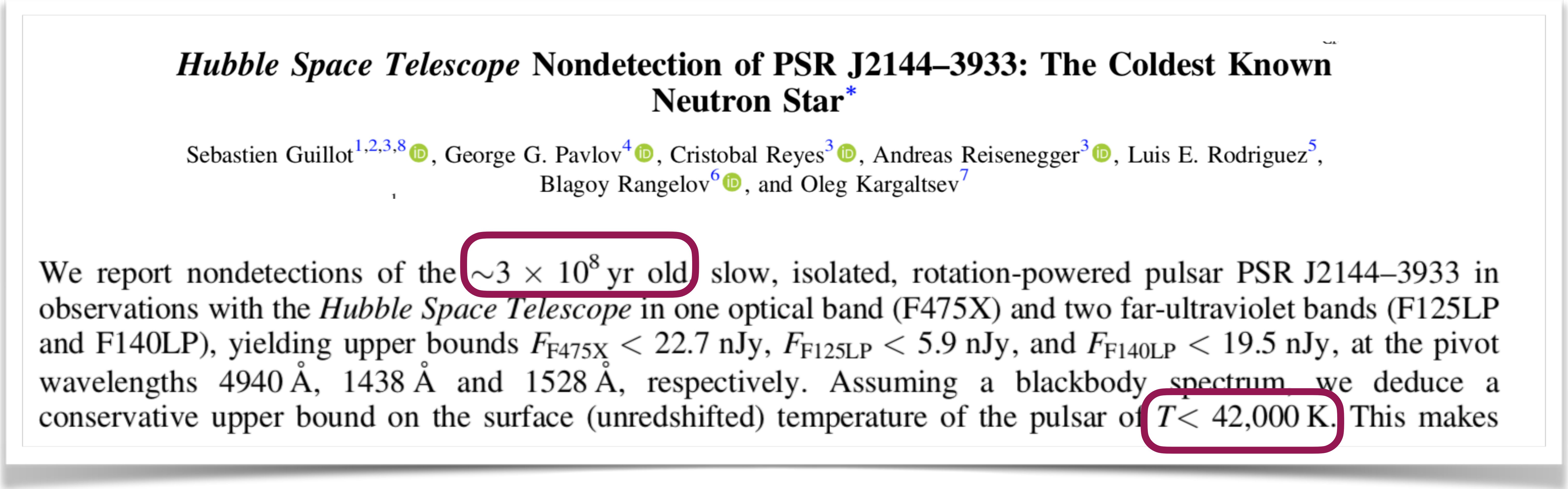
$$\left.\begin{array}{l} n \to \chi + \underline{anything} \\ n\, n \to n\, \chi \\ p\, n \to p\, \chi \end{array}\right\}$$



Fermi sea

neutron Fermi energy
~ 100 MeV

Suitable lab:



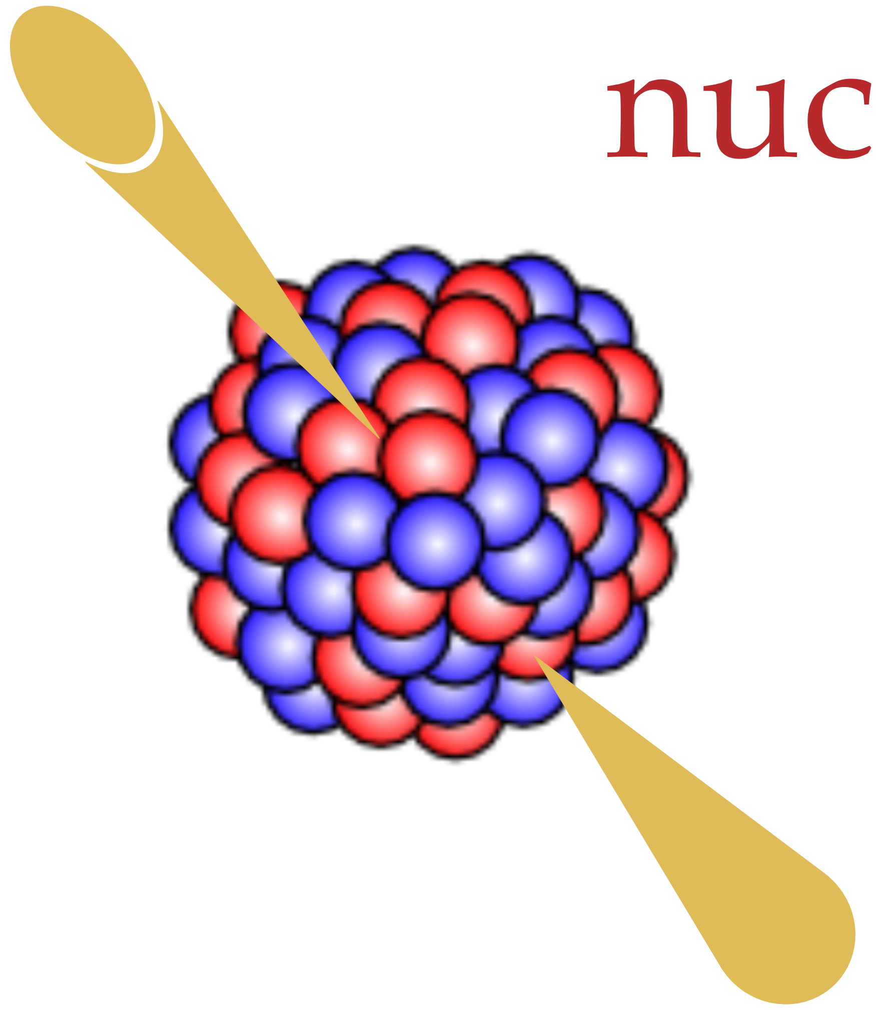
Hubble Space Telescope Nondetection of PSR J2144–3933: The Coldest Known Neutron Star*

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]

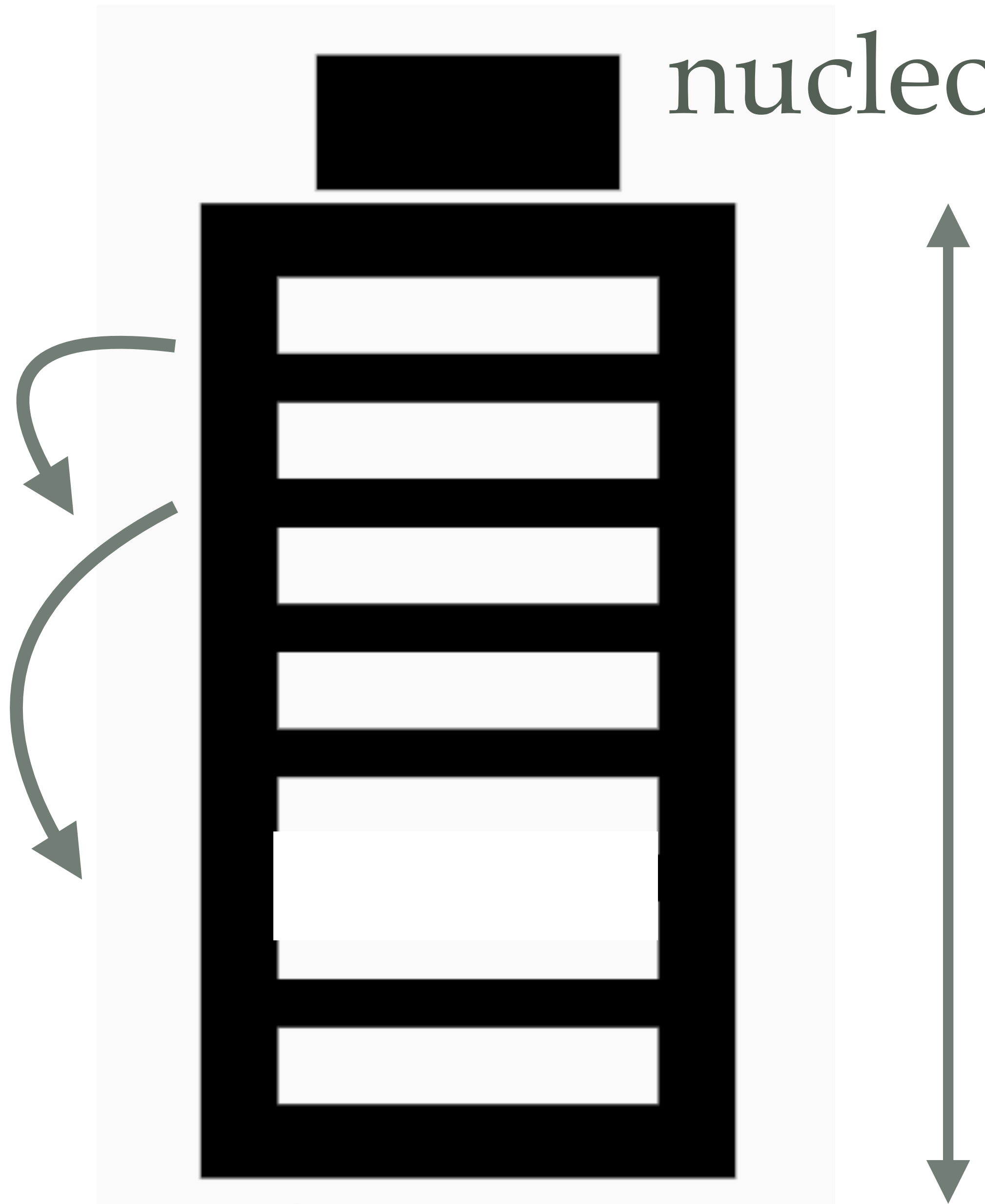
We report nondetections of the $\boxed{\sim 3 \times 10^8\ \text{yr old}}$ slow, isolated, rotation-powered pulsar PSR J2144–3933 in observations with the *Hubble Space Telescope* in one optical band (F475X) and two far-ultraviolet bands (F125LP and F140LP), yielding upper bounds $F_{\text{F475X}} < 22.7$ nJy, $F_{\text{F125LP}} < 5.9$ nJy, and $F_{\text{F140LP}} < 19.5$ 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 $\boxed{T < 42{,}000\ \text{K}}$. This makes

Probes: [3] neutron star temperatures

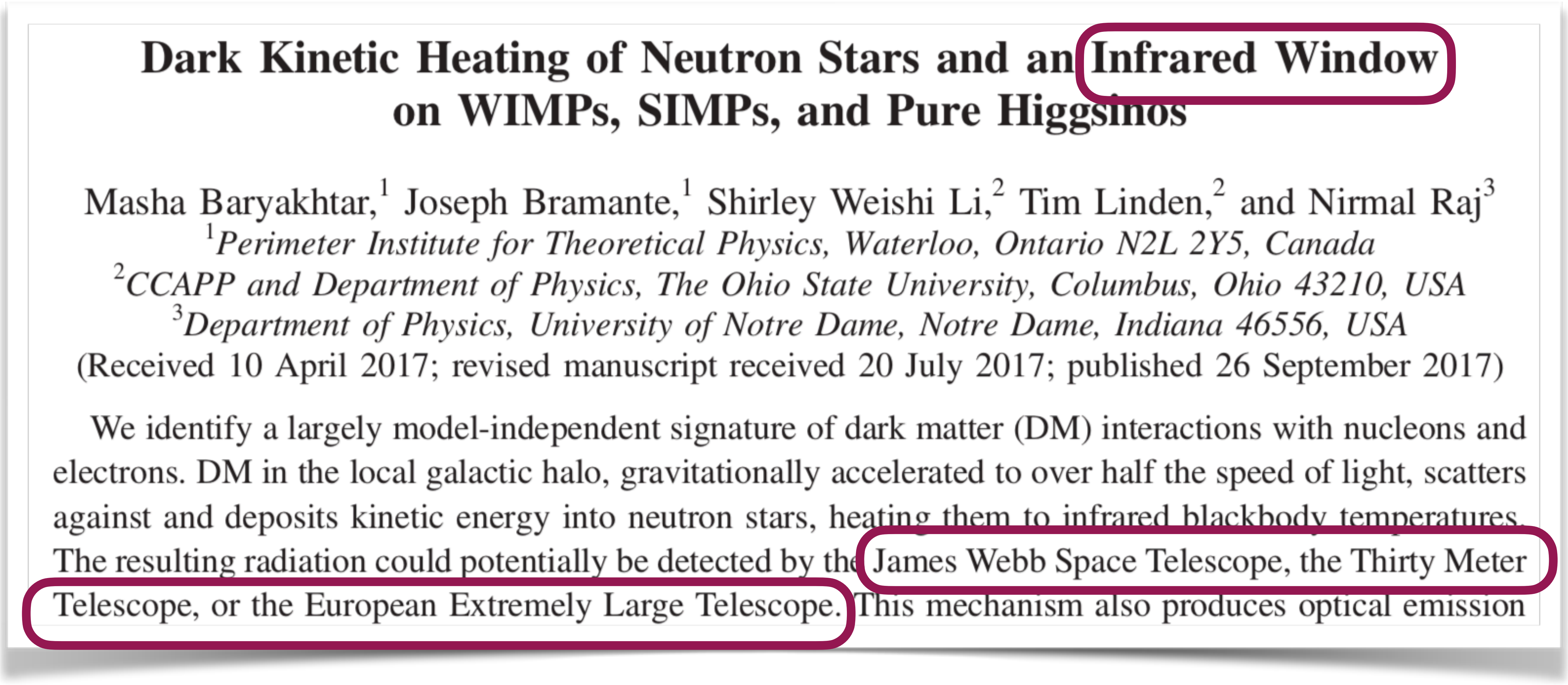
new heating mechanism:
nucleon "Auger effect"



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



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)

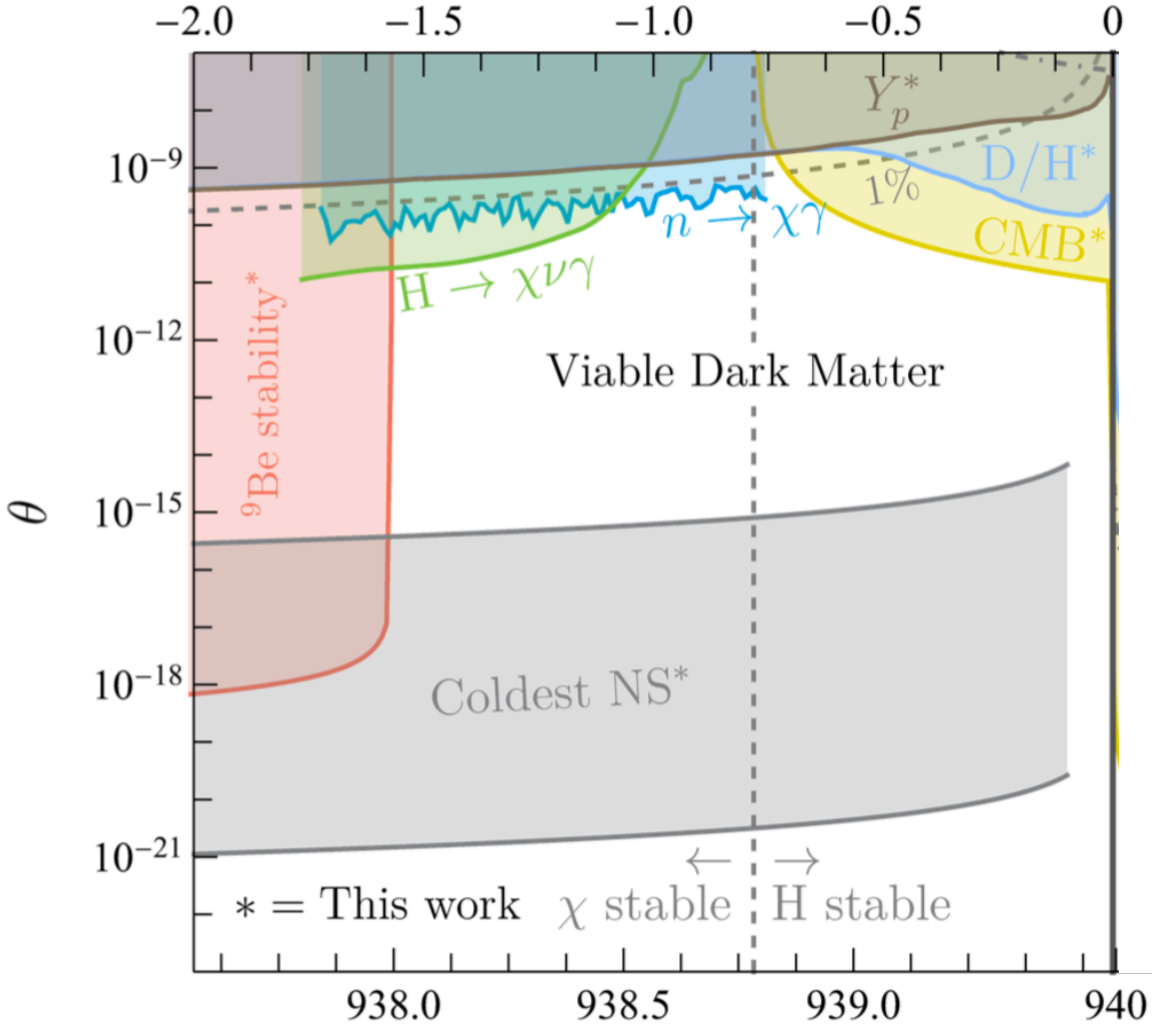
We identify a largely model-independent signature of dark matter (DM) interactions with nucleons and electrons. DM in the local galactic halo, gravitationally accelerated to over half the speed of light, scatters against and deposits kinetic energy into neutron stars, heating them to infrared blackbody 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

optimized for
~2000 K

Constraints

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

$$\boxed{n_\chi^0 = 5.4\left(n_p^0 + n_n^0\right)}$$



longer
life

- BBN data: $$Y_p = 0.245 \pm 0.004\,,$$ $$\mathrm{D/H} = (2.55 \pm 0.03) \times 10^{-5}\,,$$ $$^3\mathrm{He/H} = (1.0 \pm 0.5) \times 10^{-5}\,,$$
- 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]
- $\mathrm{H} \to \chi\nu\gamma$: 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

Highlights

- Cosmology (BBN + CMB) stringently limits dark neutron explanation of neutron lifetime puzzle.
  - small 100 keV-ish window left for UCN experiments to target!

- very slow exotic neutron decays => explosive heating of neutron stars.

- Heavier-than-neutron dark neutrons (see back-up slides): cosmology sole probe.

Thank you! Questions?

Back-up slides

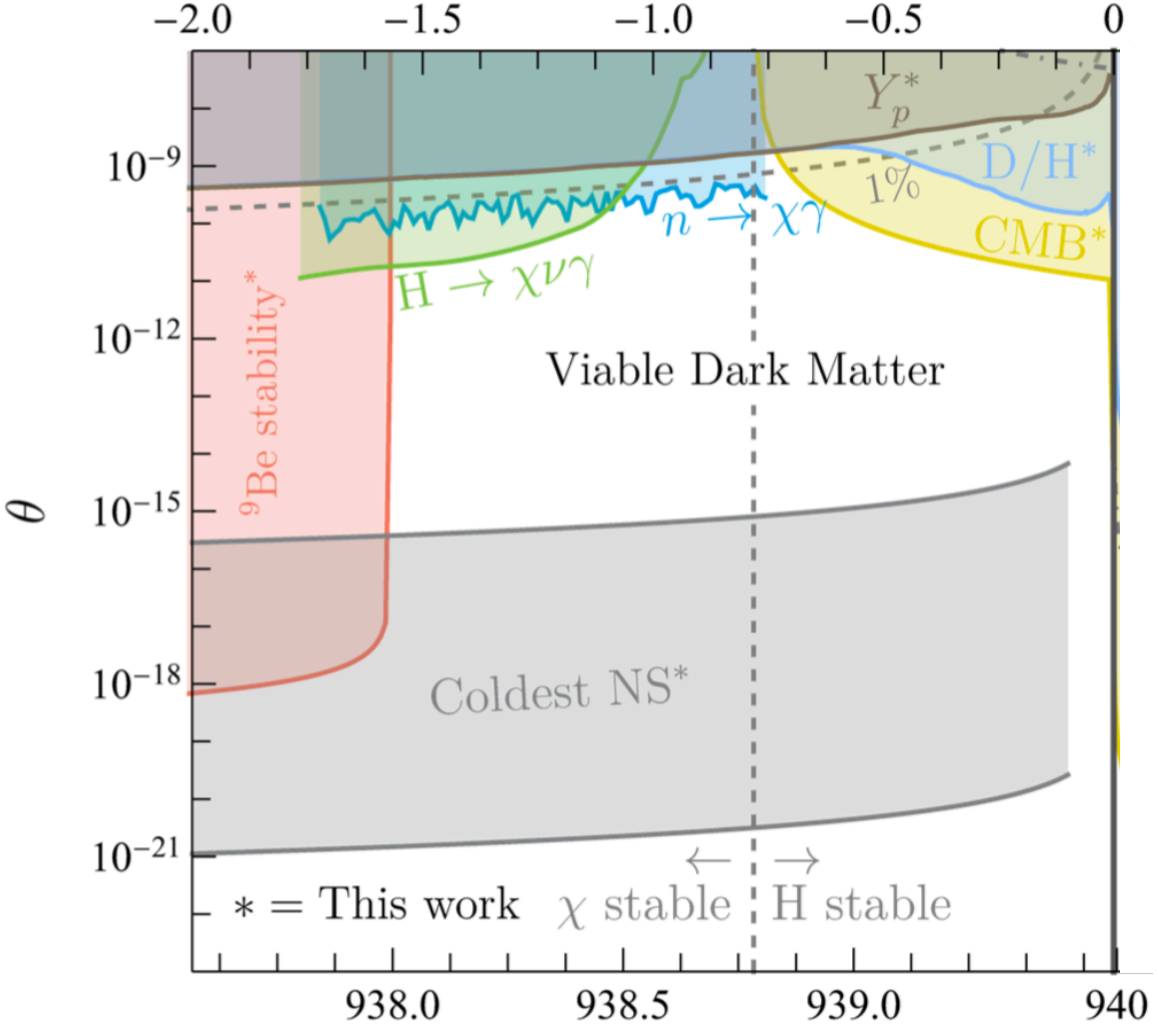
Constraints

$n \to \chi\gamma$

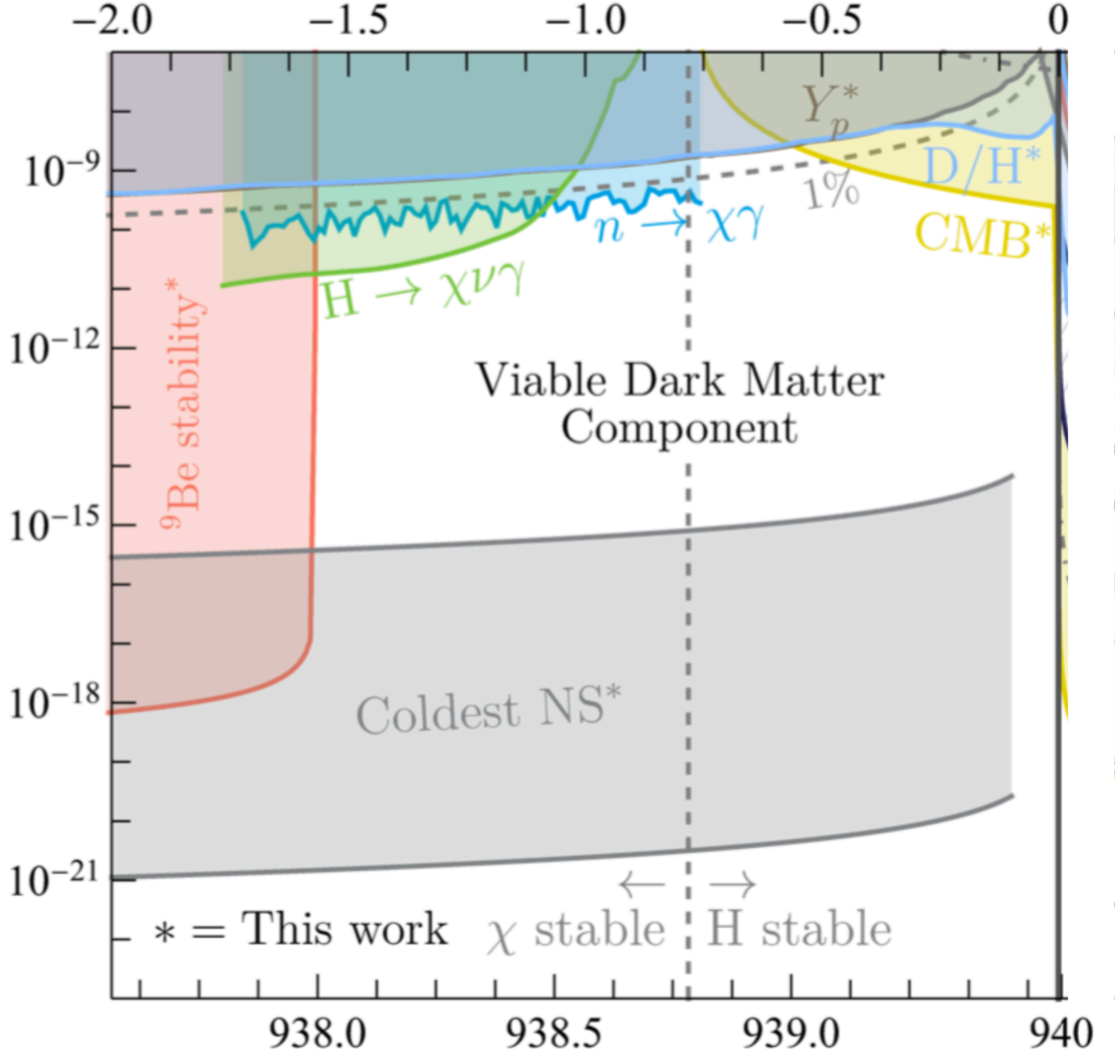
open

longer life

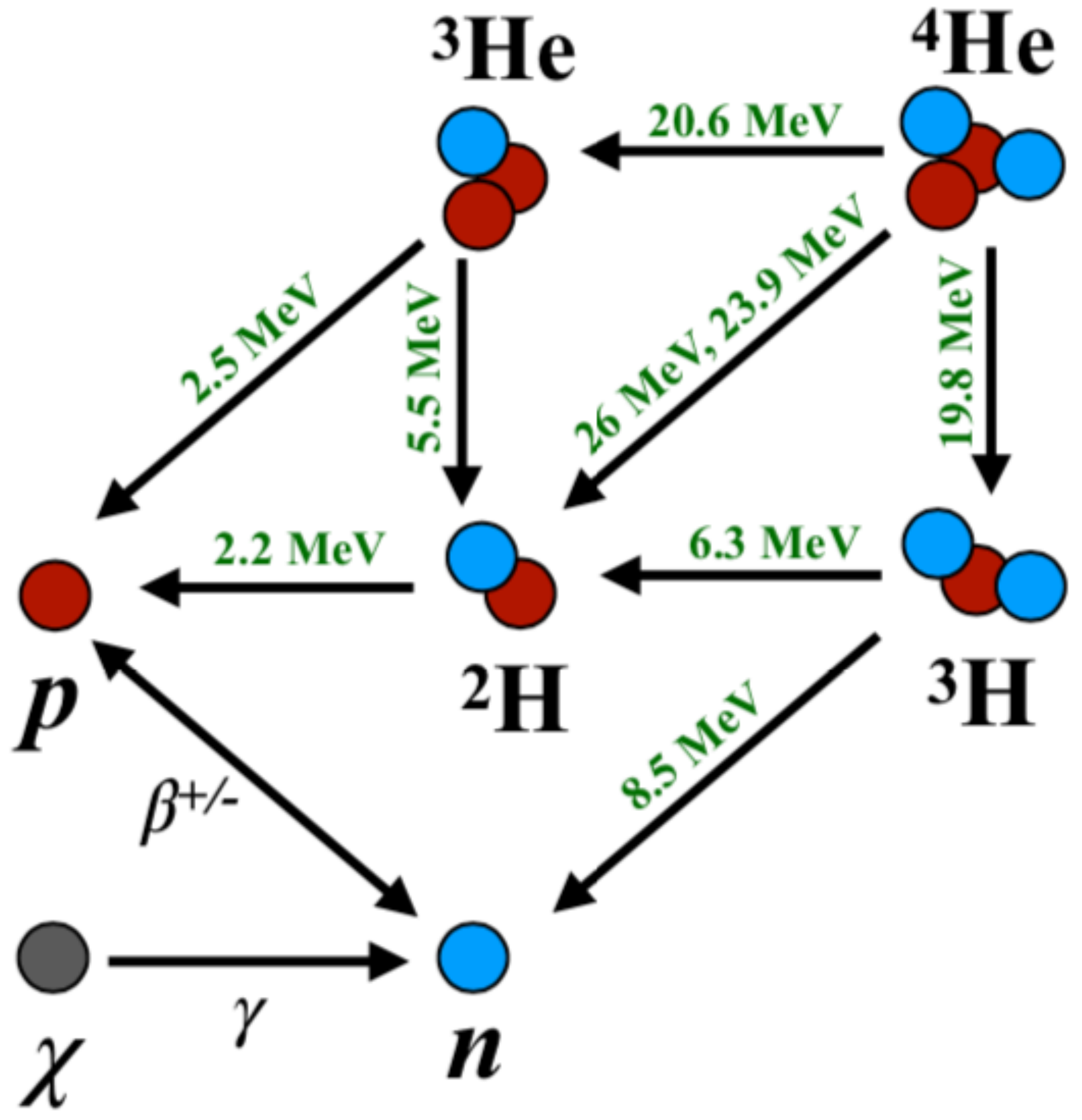
$n_\chi^0 = 5.4\,(n_p^0 + n_n^0)$

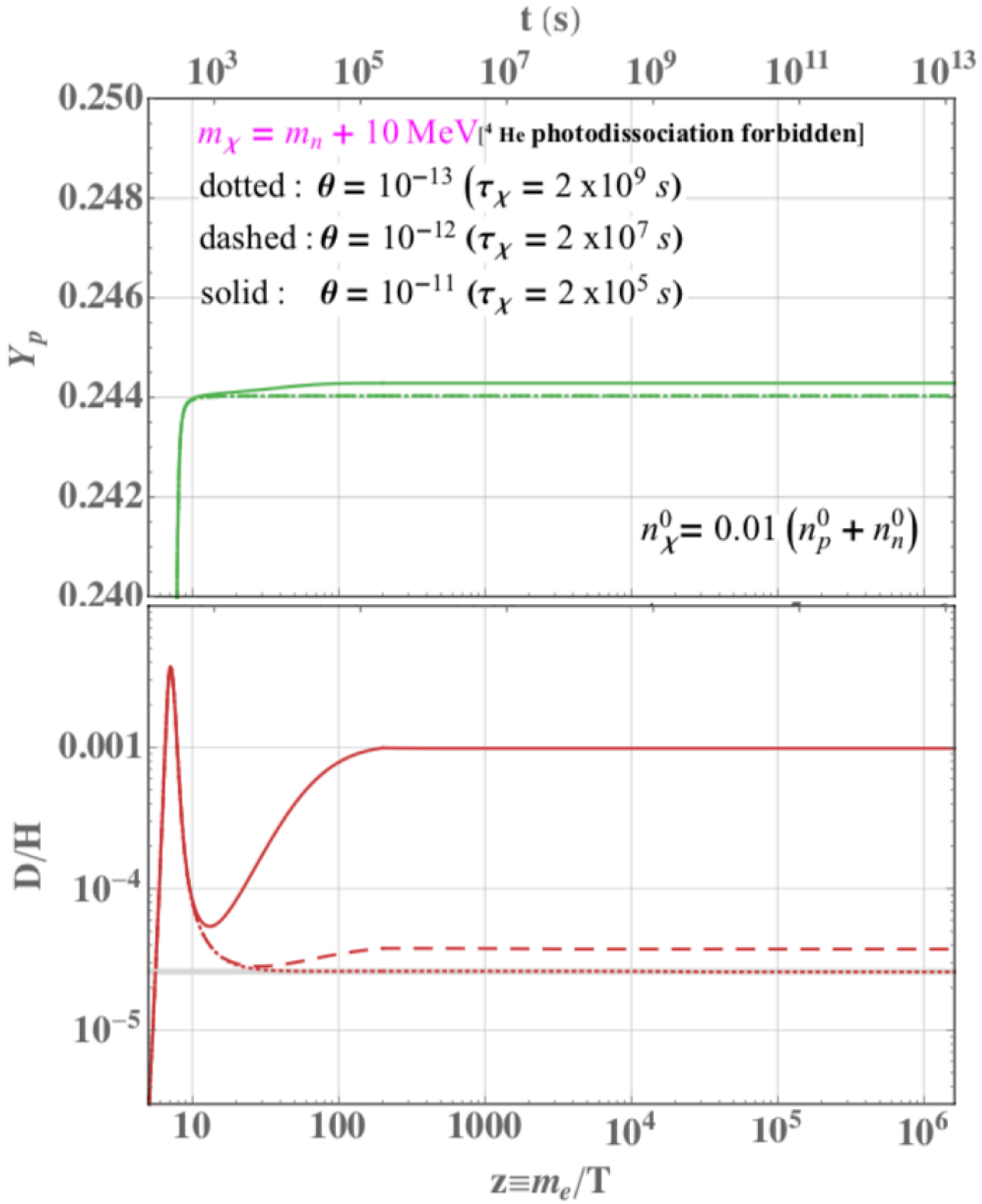


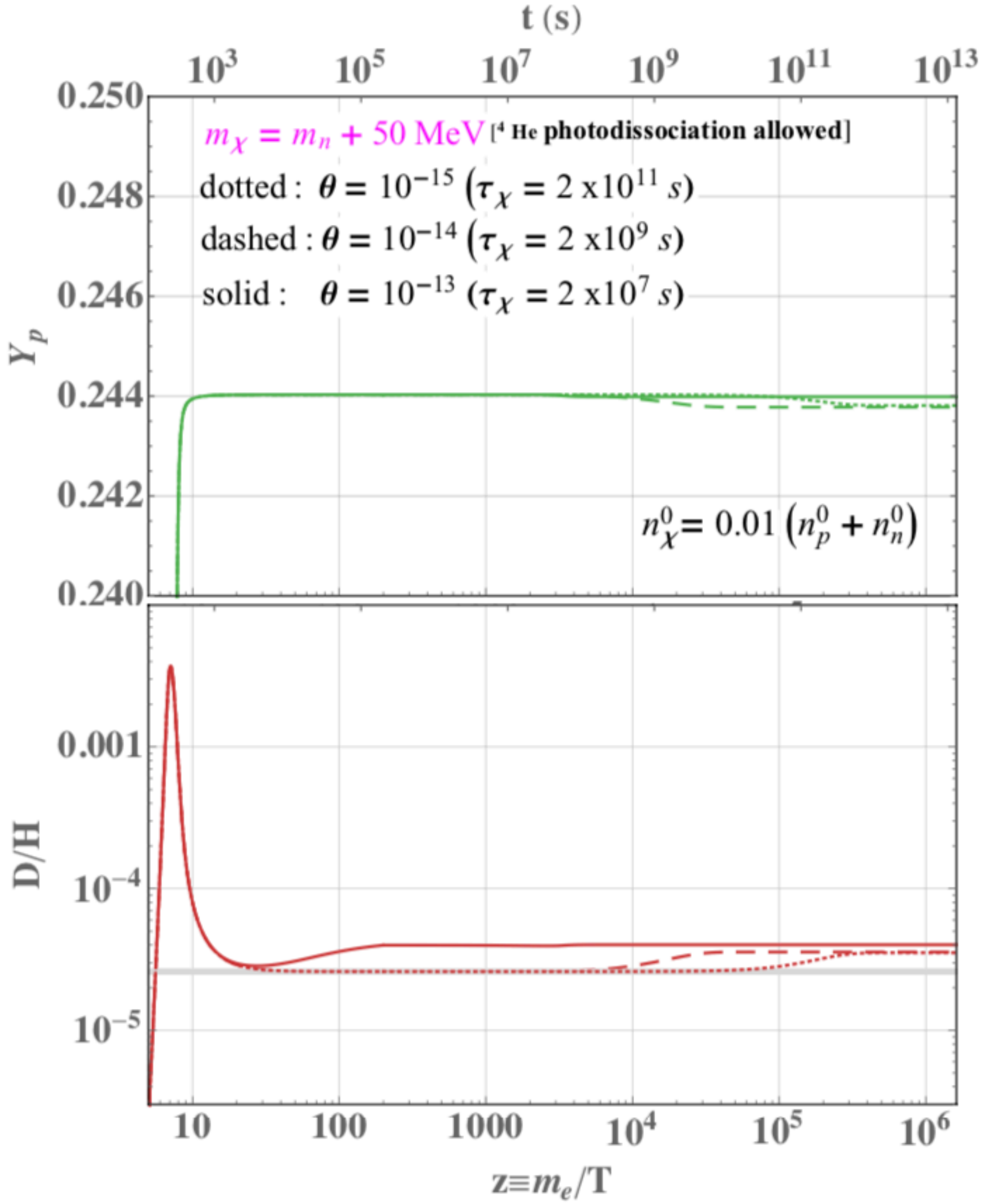
$n_\chi^0 = 0.01\,(n_p^0 + n_n^0)$



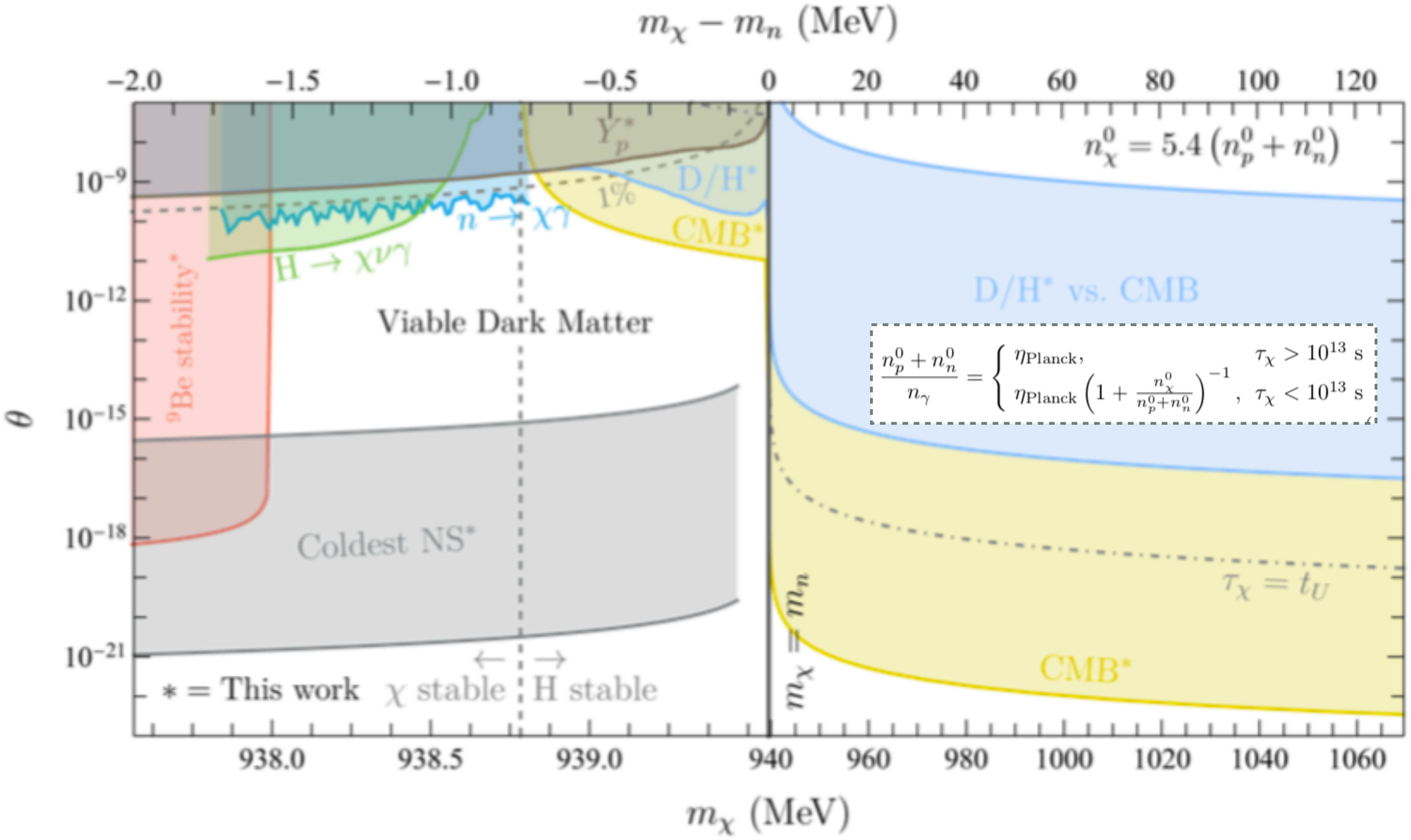
Signals: photodissociation post-nucleosynthesis





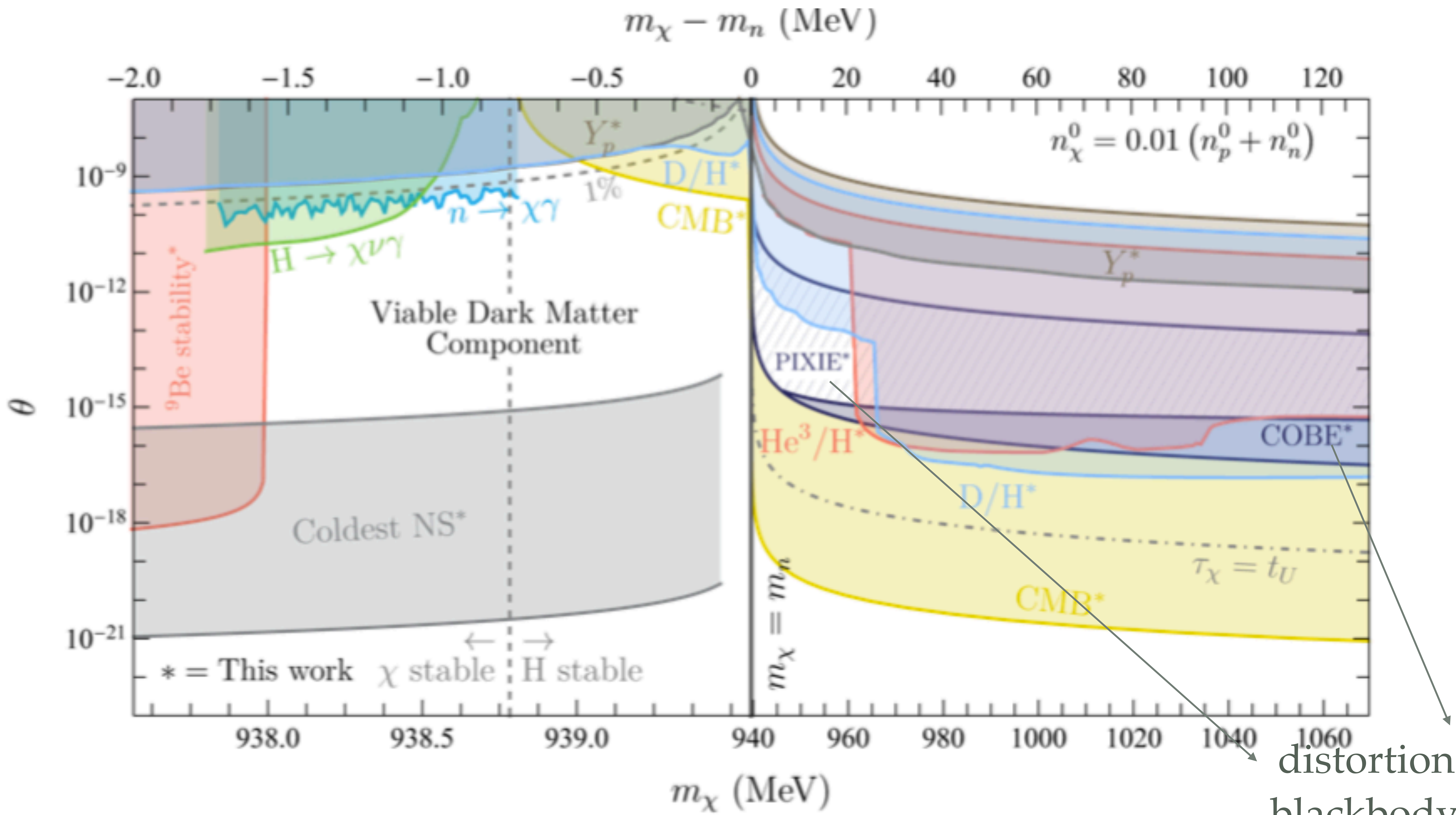


Constraints: χ all the dark matter



$$\frac{n_p^0 + n_n^0}{n_\gamma} = \begin{cases} \eta_{\mathrm{Planck}}, & \tau_\chi > 10^{13}\ \mathrm{s} \\ \eta_{\mathrm{Planck}} \left(1 + \frac{n_\chi^0}{n_p^0 + n_n^0}\right)^{-1}, & \tau_\chi < 10^{13}\ \mathrm{s} \end{cases}$$

Constraints: χ percent-level dark matter



distortions of CMB
blackbody spectrum