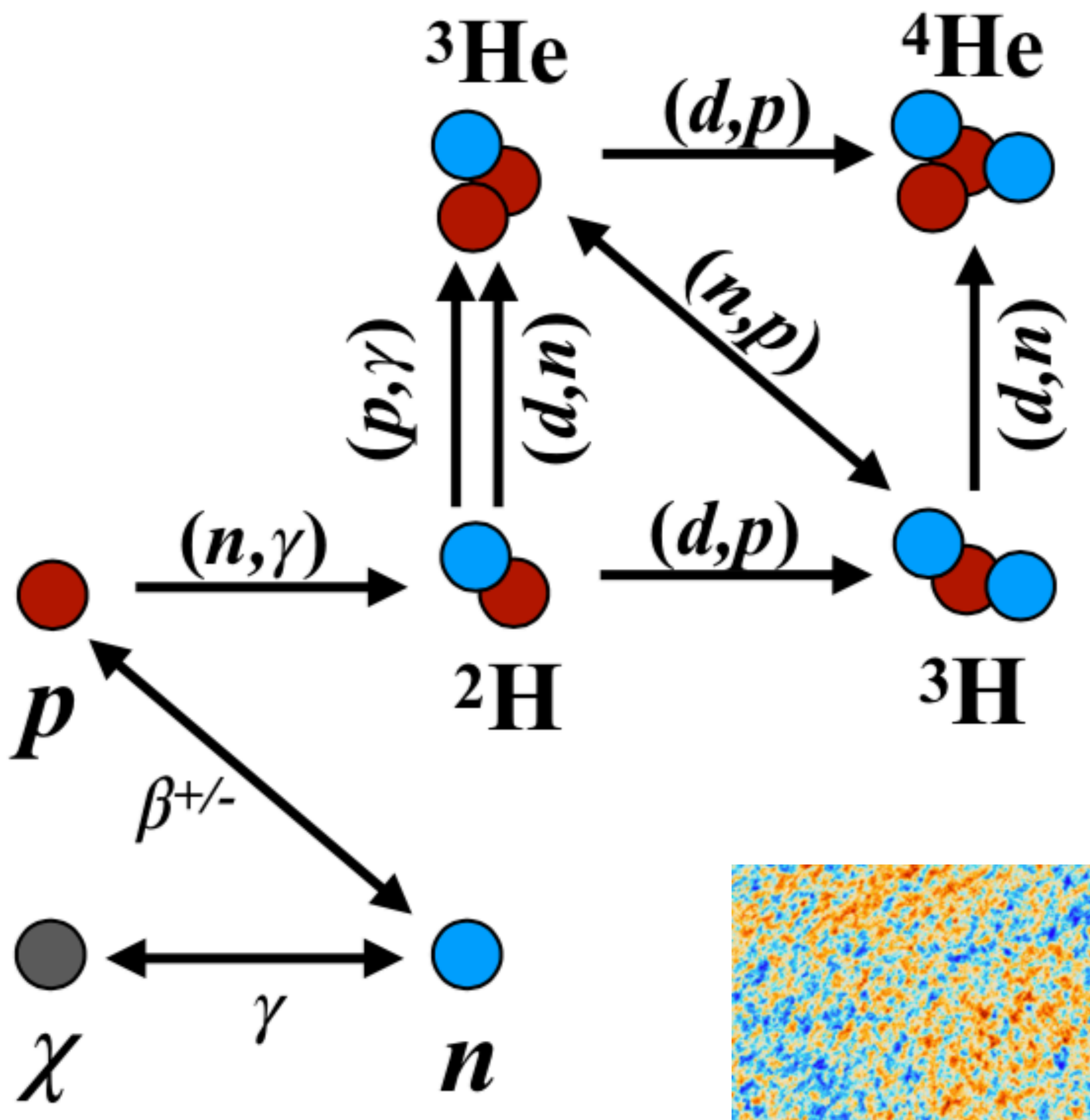
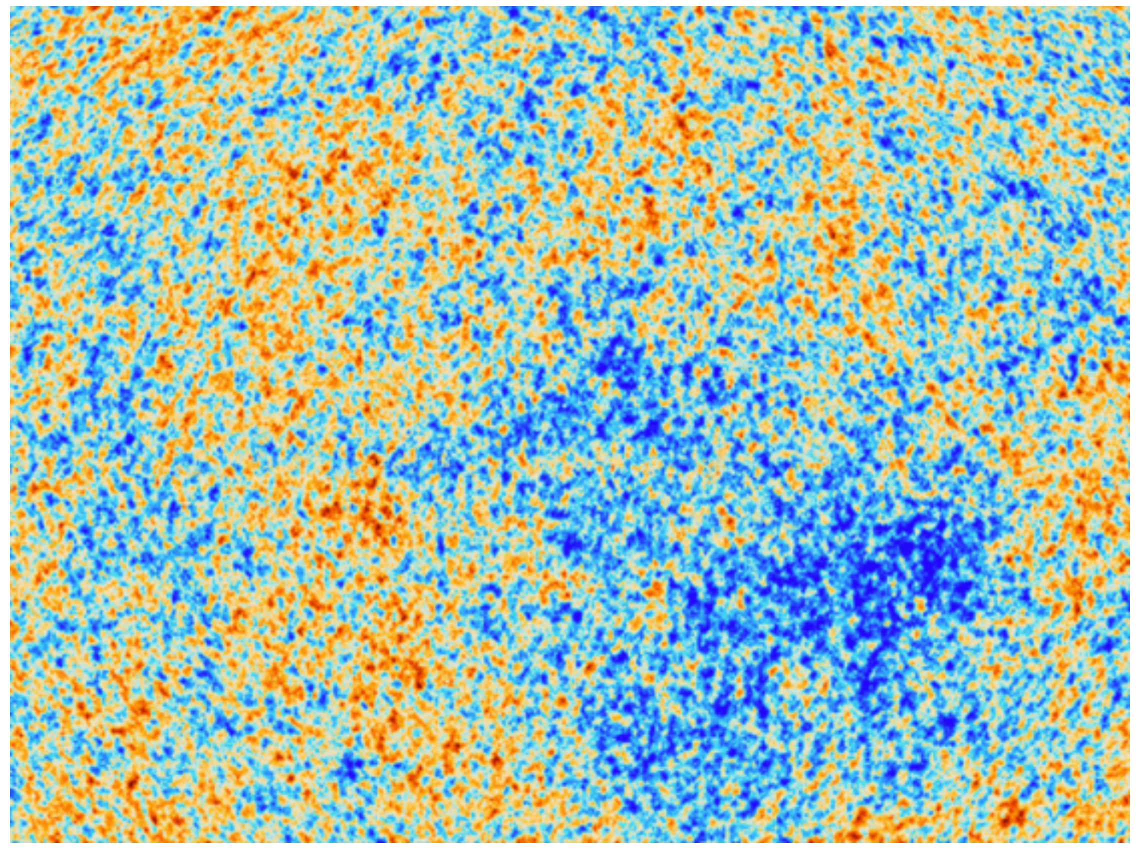


Dark Neutrons:
Cosmology & Astrophysics

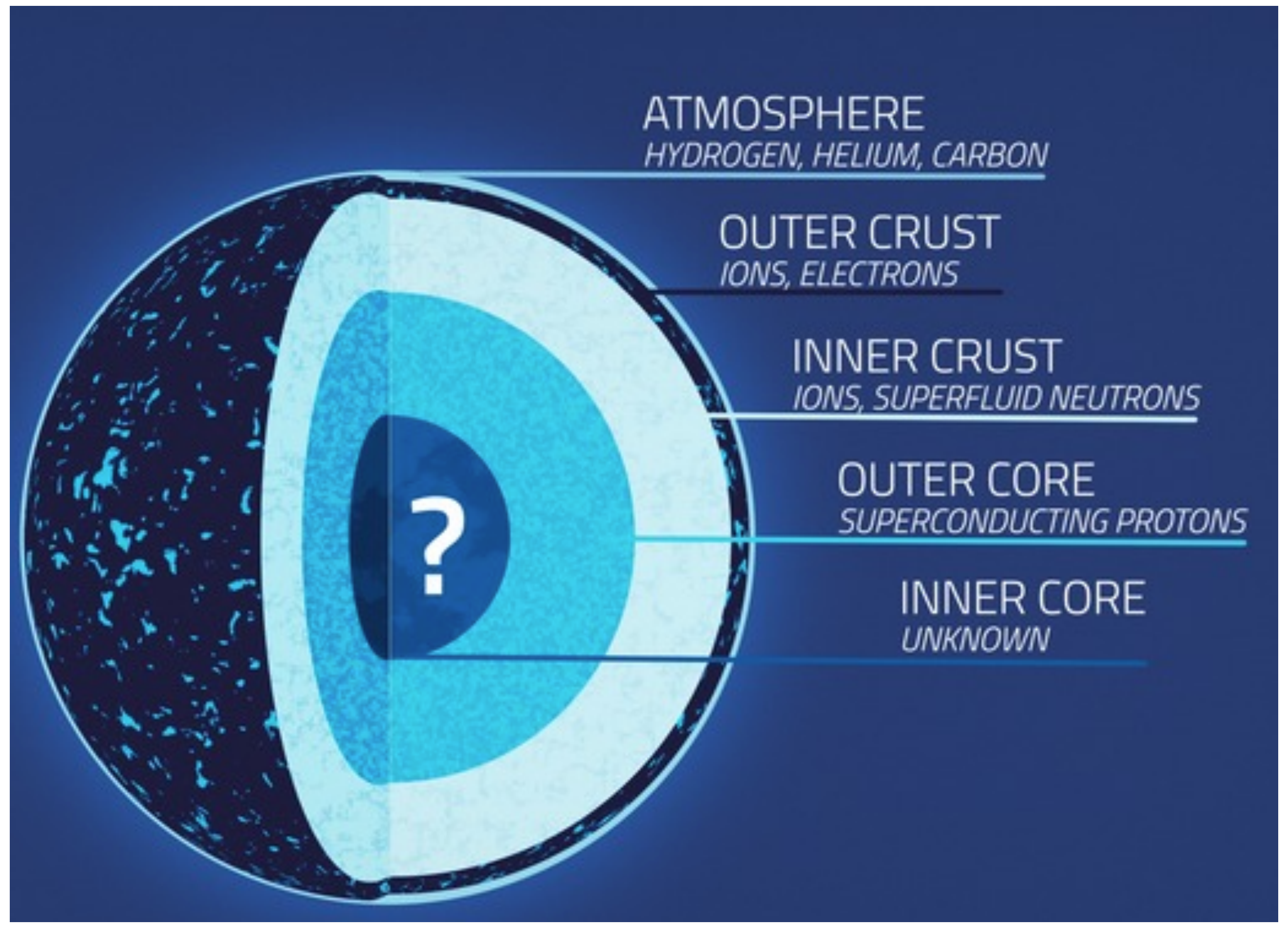
Nirmal Raj
TRIUMF

Phys. Rev. Lett. 125 (2020), 231803,
Phys. Rev. Lett. 127 (2021), 061805,
Phys. Rev. D. (2021) 103.115002



with David McKeen
& Maxim Pospelov

Brookhaven Forum: *Opening New Windows to the Universe*



Nov 03, 2021

Introduction

hypothesis: a new particle "χ"

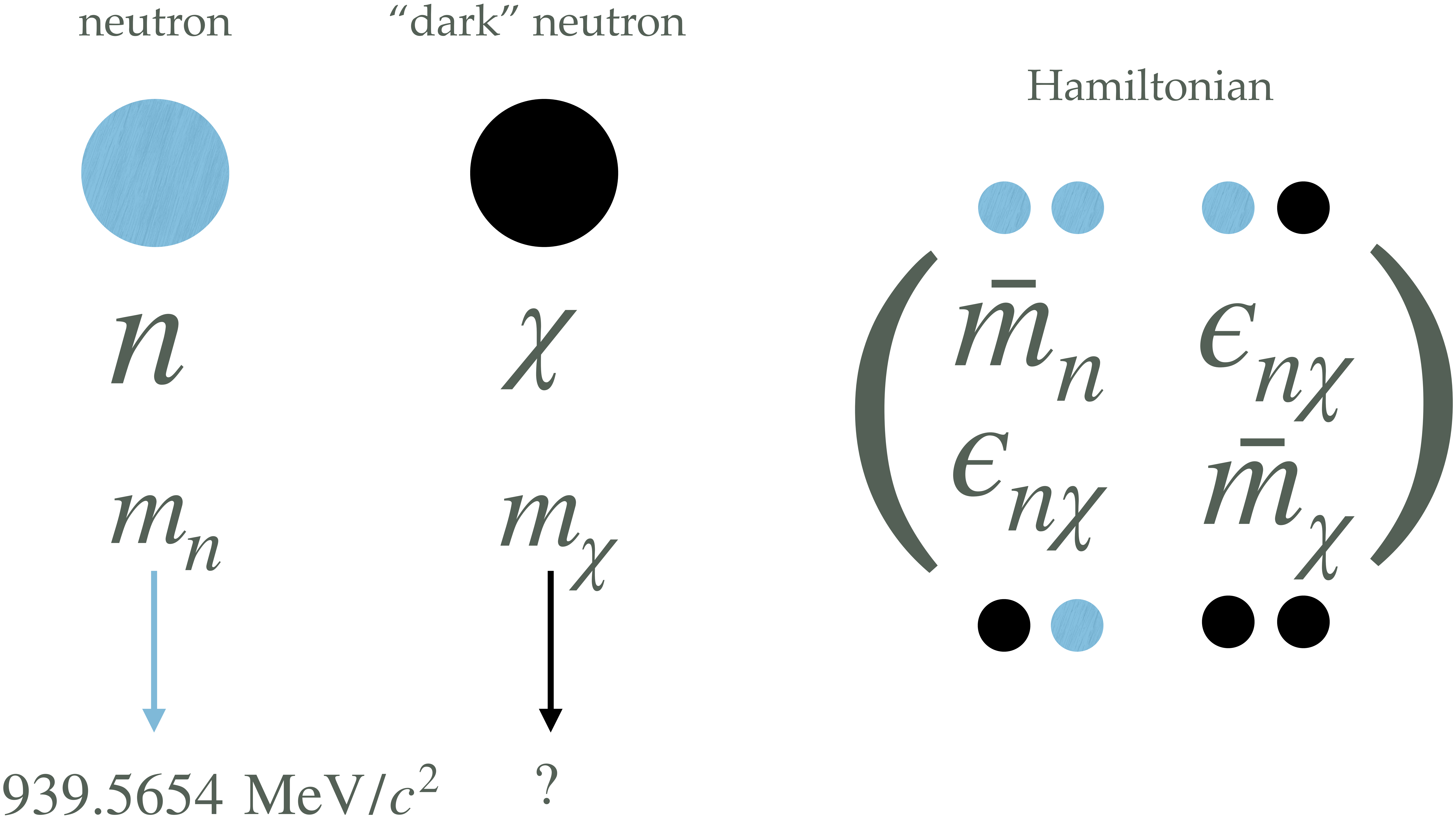
its character:

0 : charge under all fundamental forces
1/2 : spin
1 : baryon number

James Chadwick

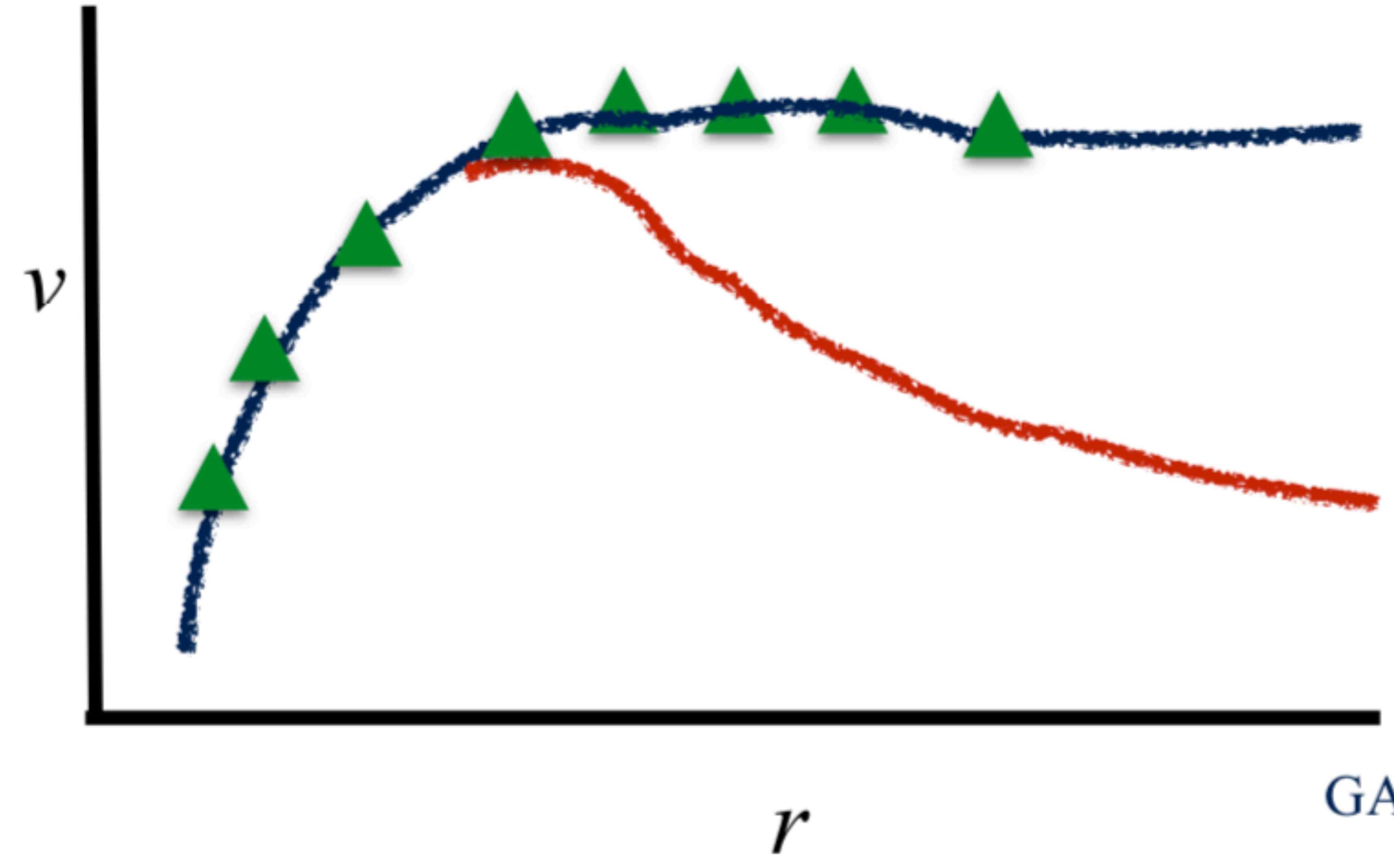
It's called a neutron.
N. E. U. T. R. O. N,
neutron.

also $\Lambda^0, \Sigma^0, \Delta^0, \ldots$

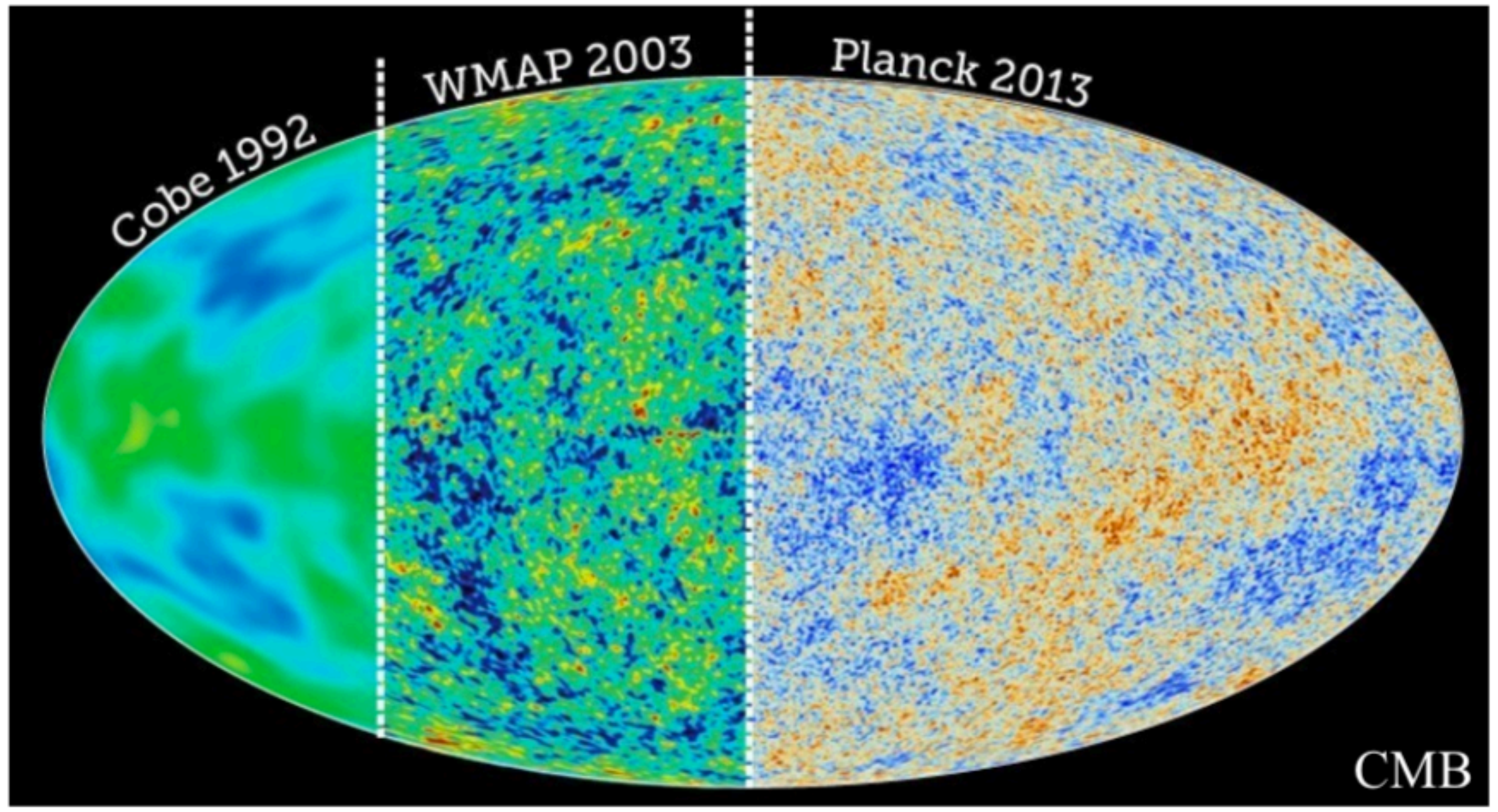

neutron
"dark" neutron
Hamiltonian
n
χ
m_n
m_χ
939.5654 MeV/c^2
?
$\begin{pmatrix} \bar{m}_n & \epsilon_{n\chi} \\ \epsilon_{n\chi} & \bar{m}_\chi \end{pmatrix}$

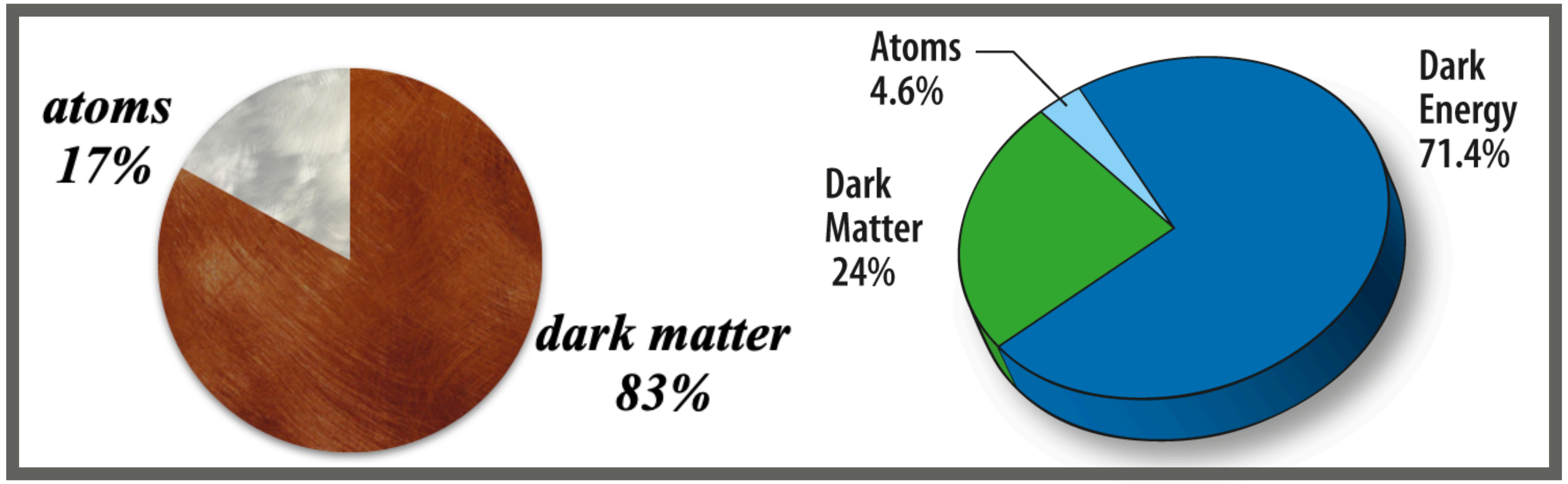
Why care?

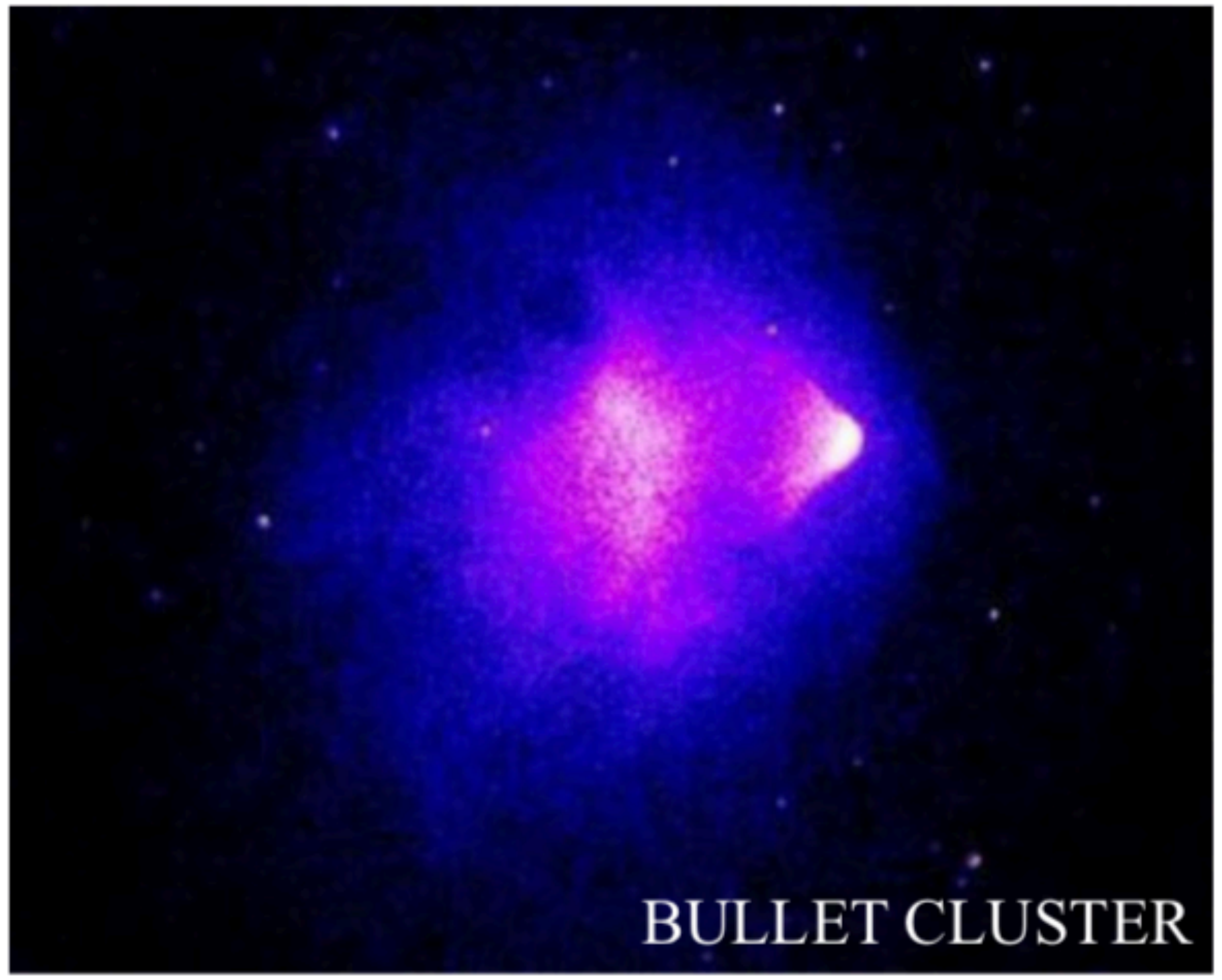
(1) the *dark matter* of the universe



GALACTIC ROTATION







Why care? (2) the *neutron lifetime puzzle*

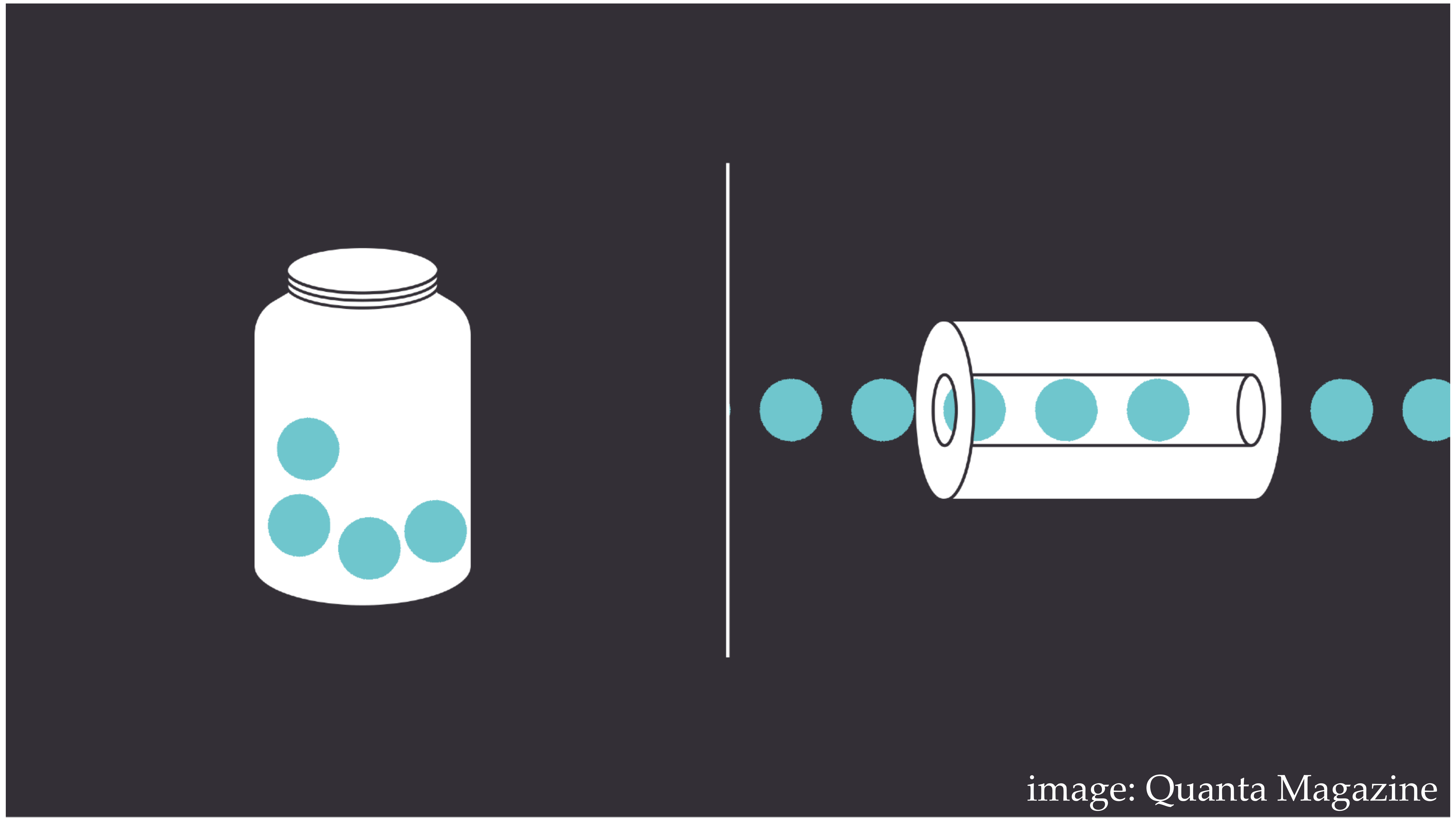
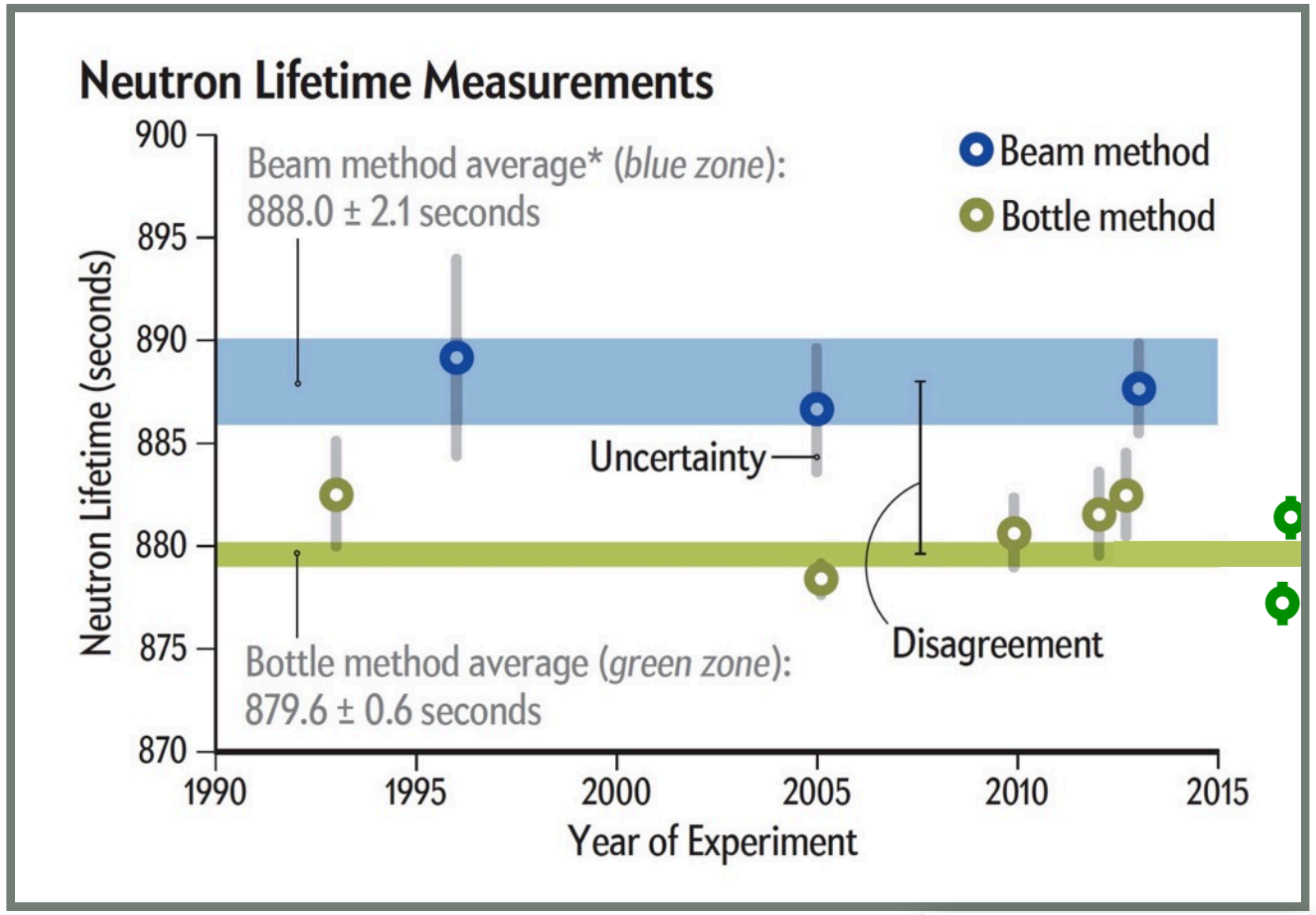


image: Quanta Magazine



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

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 care?

(3) the *"XENON1T excess"* from last summer

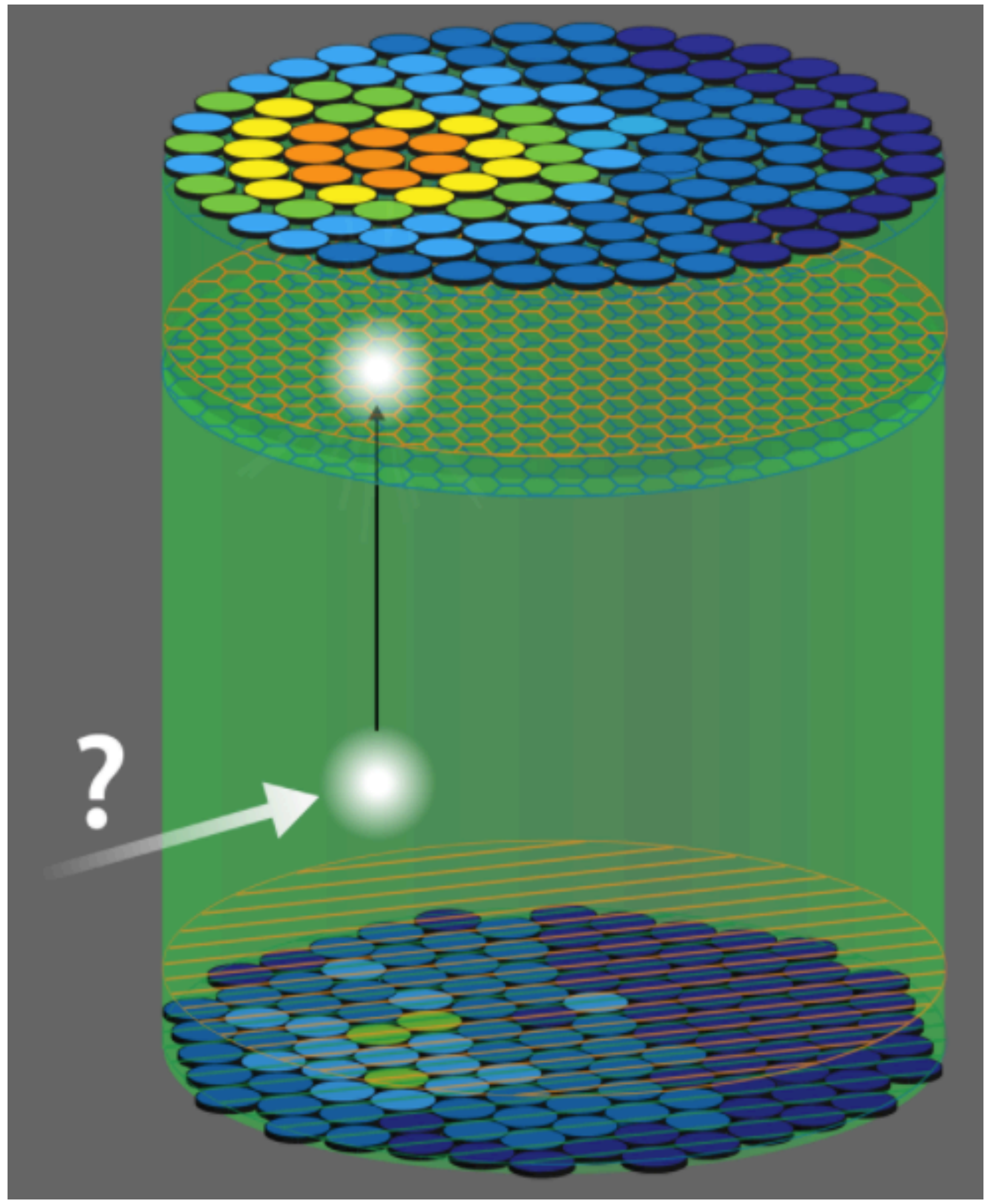
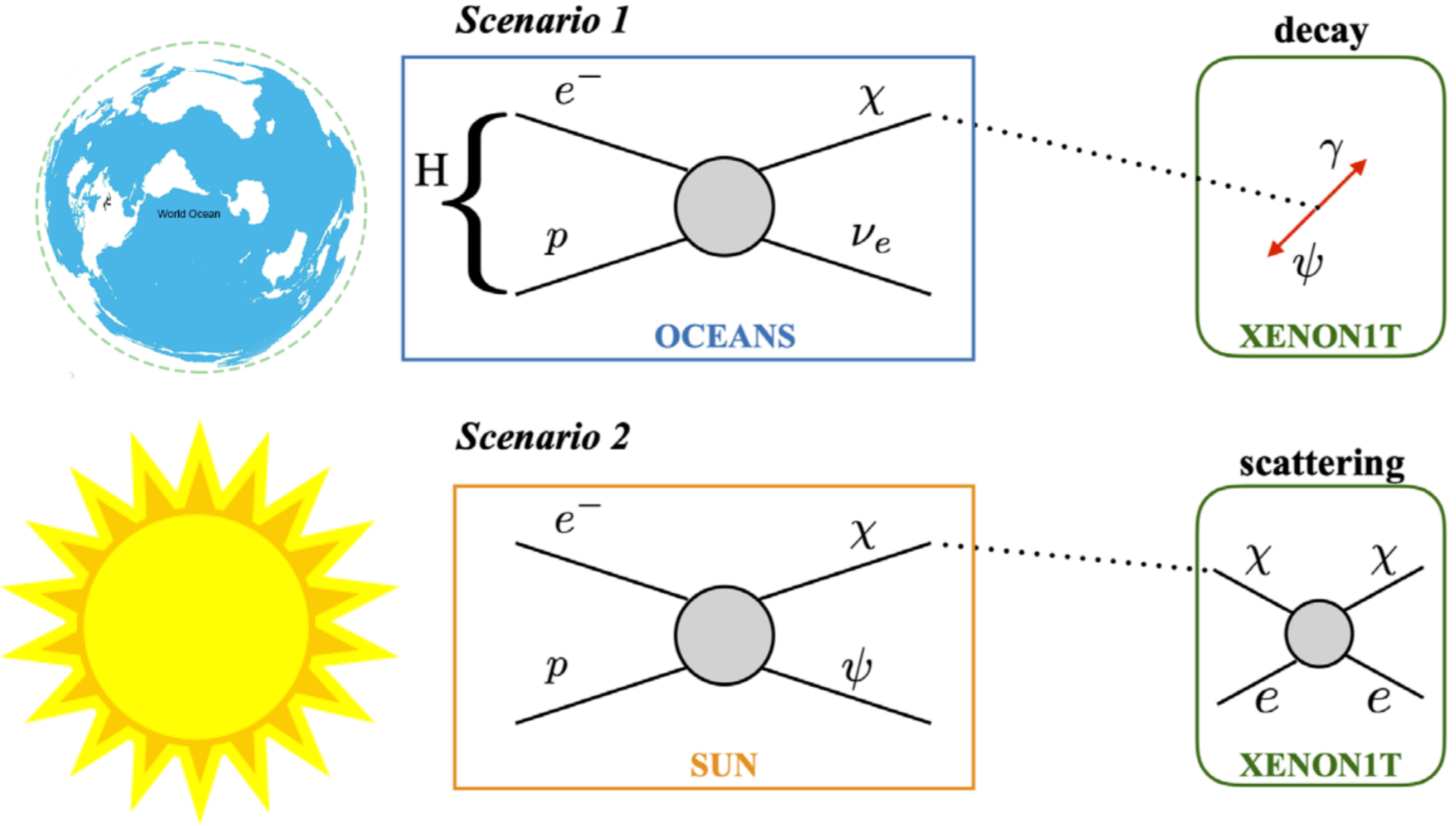


image: APS

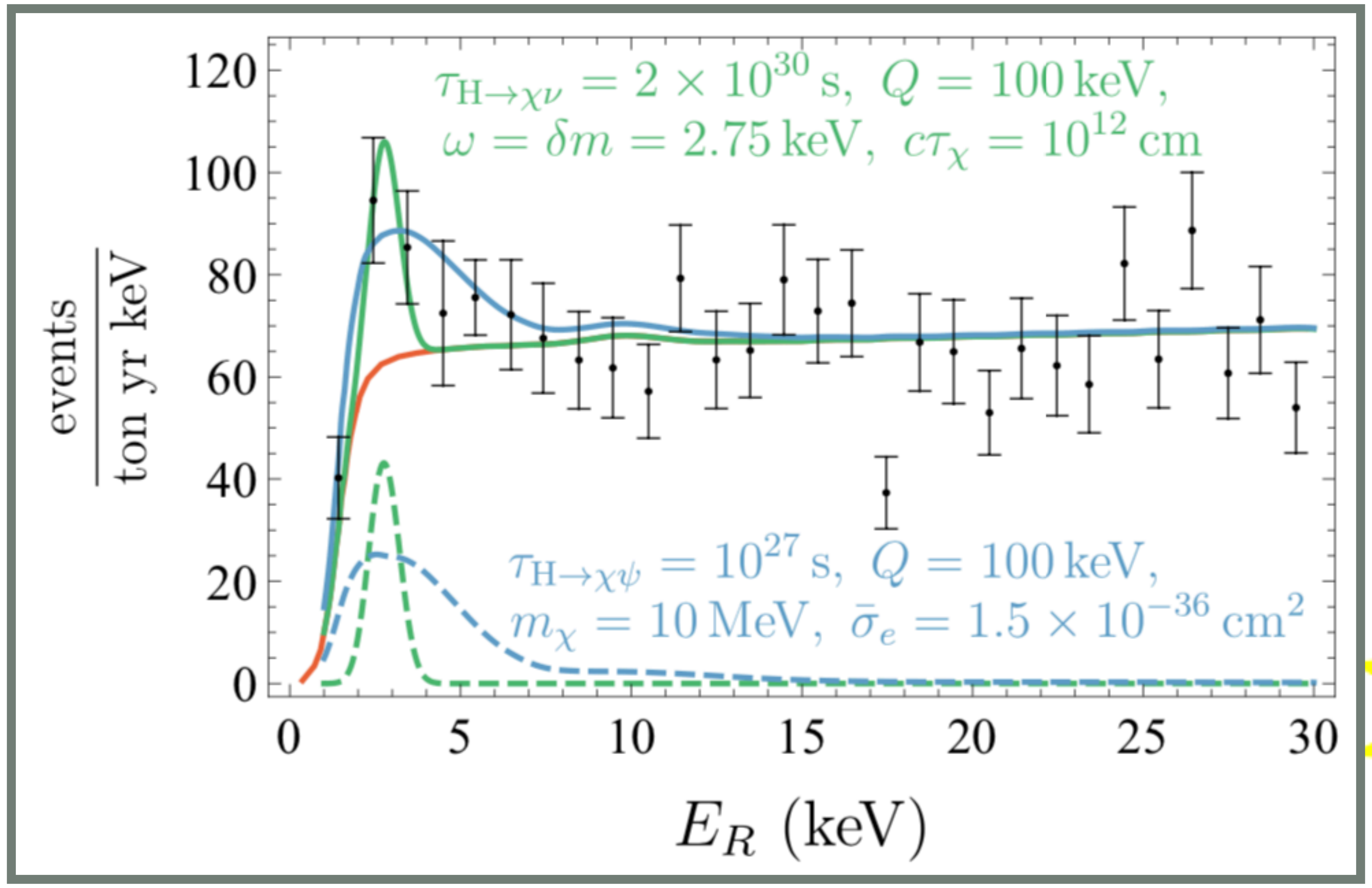
arXiv: 2006.09721

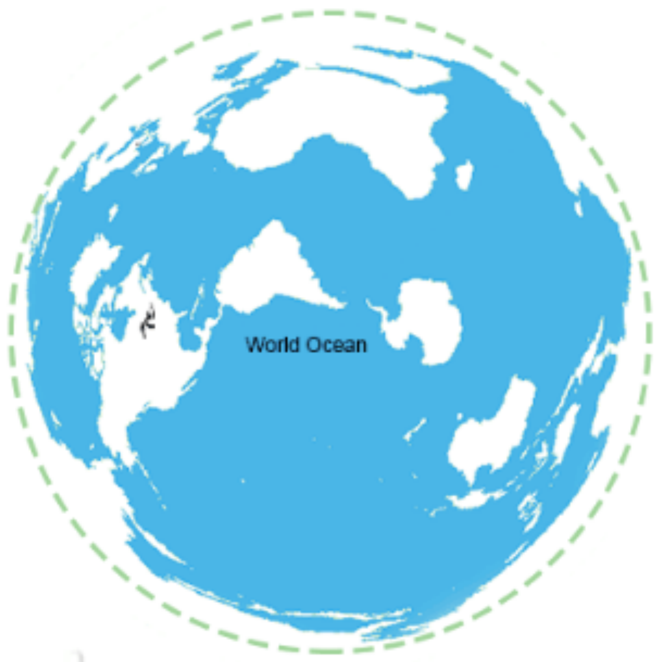


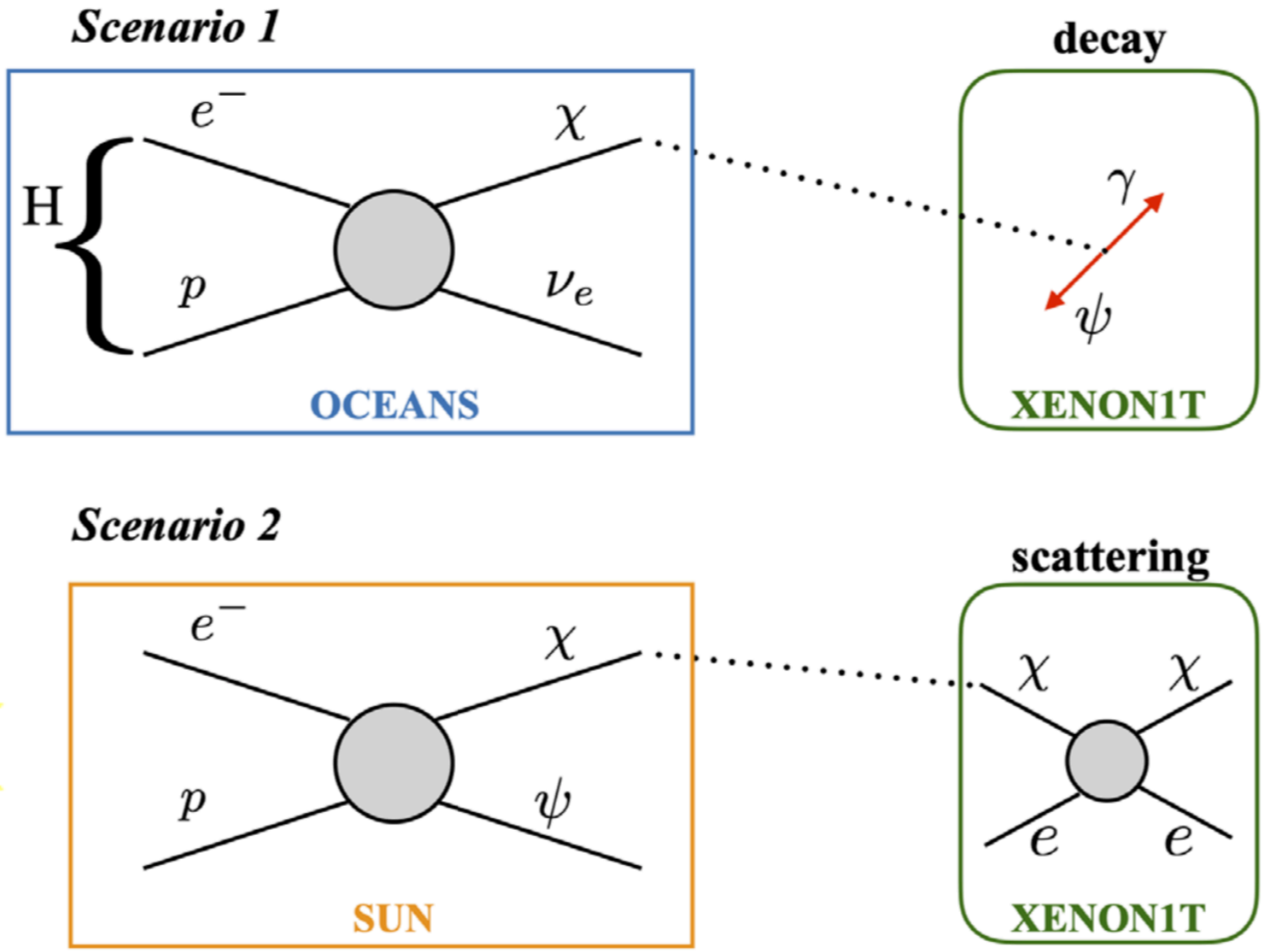
[*Phys. Rev. Lett.* **125**, 231803 (2020)] : McKeen, Pospelov, ***Raj***

Why care?

(3) the *"XENON1T excess"* from last summer



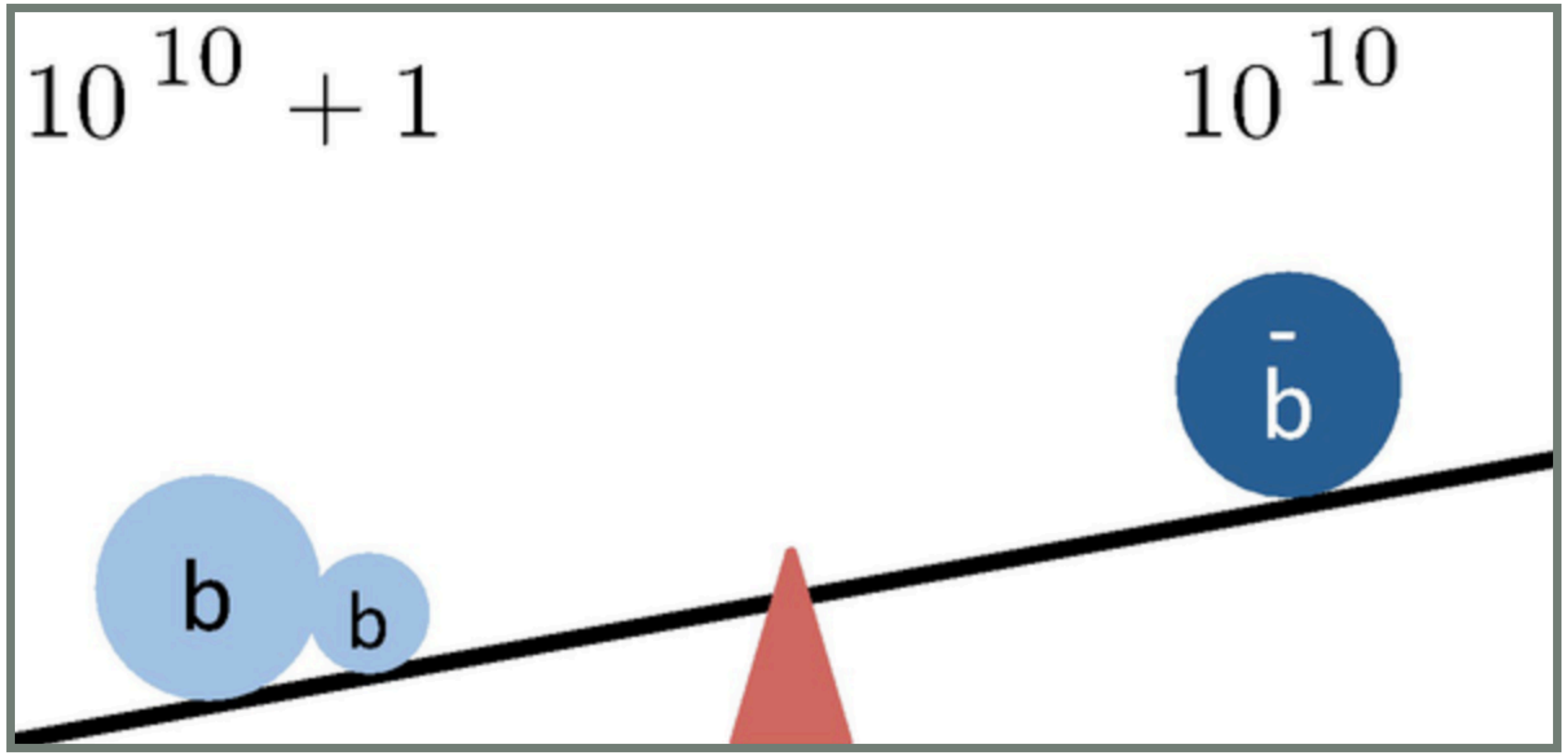




[*Phys. Rev. Lett.* **125**, 231803 (2020)] : McKeen, Pospelov, ***Raj***

Why care?

(4) 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].

Model

@ hadron level :

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

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

$$\mu_n = -1.91\mu_N \qquad \delta/(m_n - m_\chi)$$

neutron magnetic moment

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

exotic neutron decay

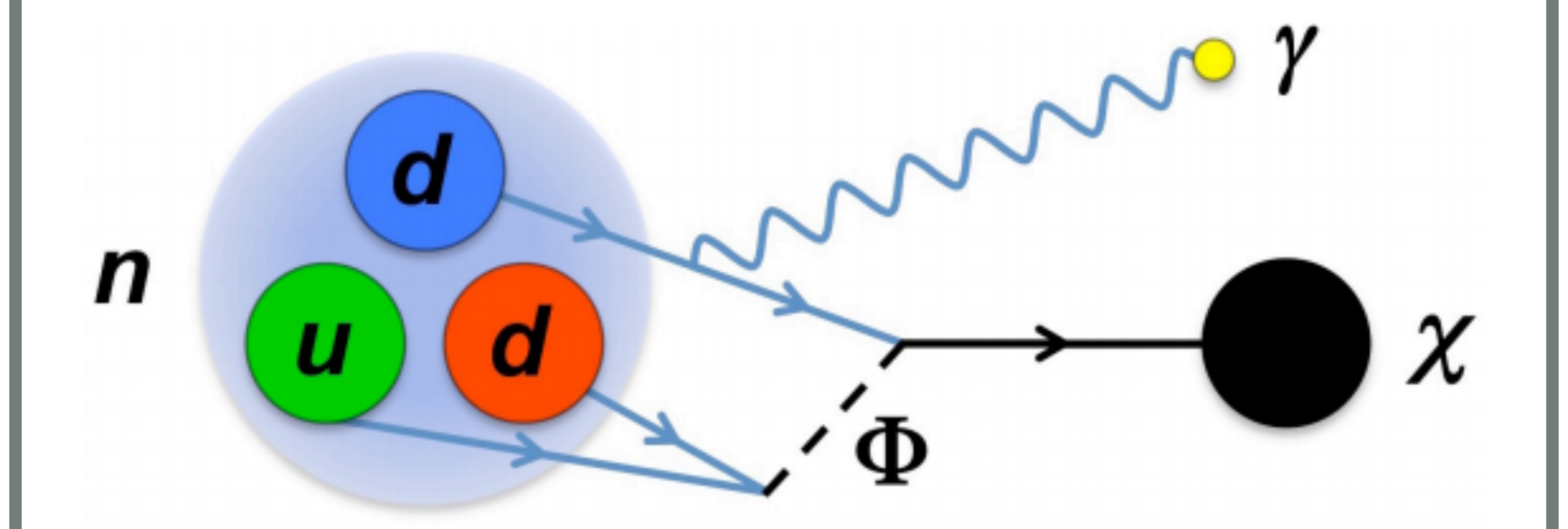


image: Fornal & Grinstein

n lifetime puzzle:

$$\text{Br}_{n\to\chi\gamma} \simeq 0.01\left(\frac{\theta}{5\times10^{-10}}\right)^2\left(\frac{\Delta m}{\text{MeV}}\right)^3$$

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

$$\Gamma_{\chi\to pe^-\bar{\nu}} = \frac{1}{9\times10^{22}\ \text{s}}\left(\frac{\theta}{10^{-10}}\right)^2\frac{F(Q_\chi/m_e)}{F(Q_n/m_e)}$$

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)

above QCD transition => quark level description required

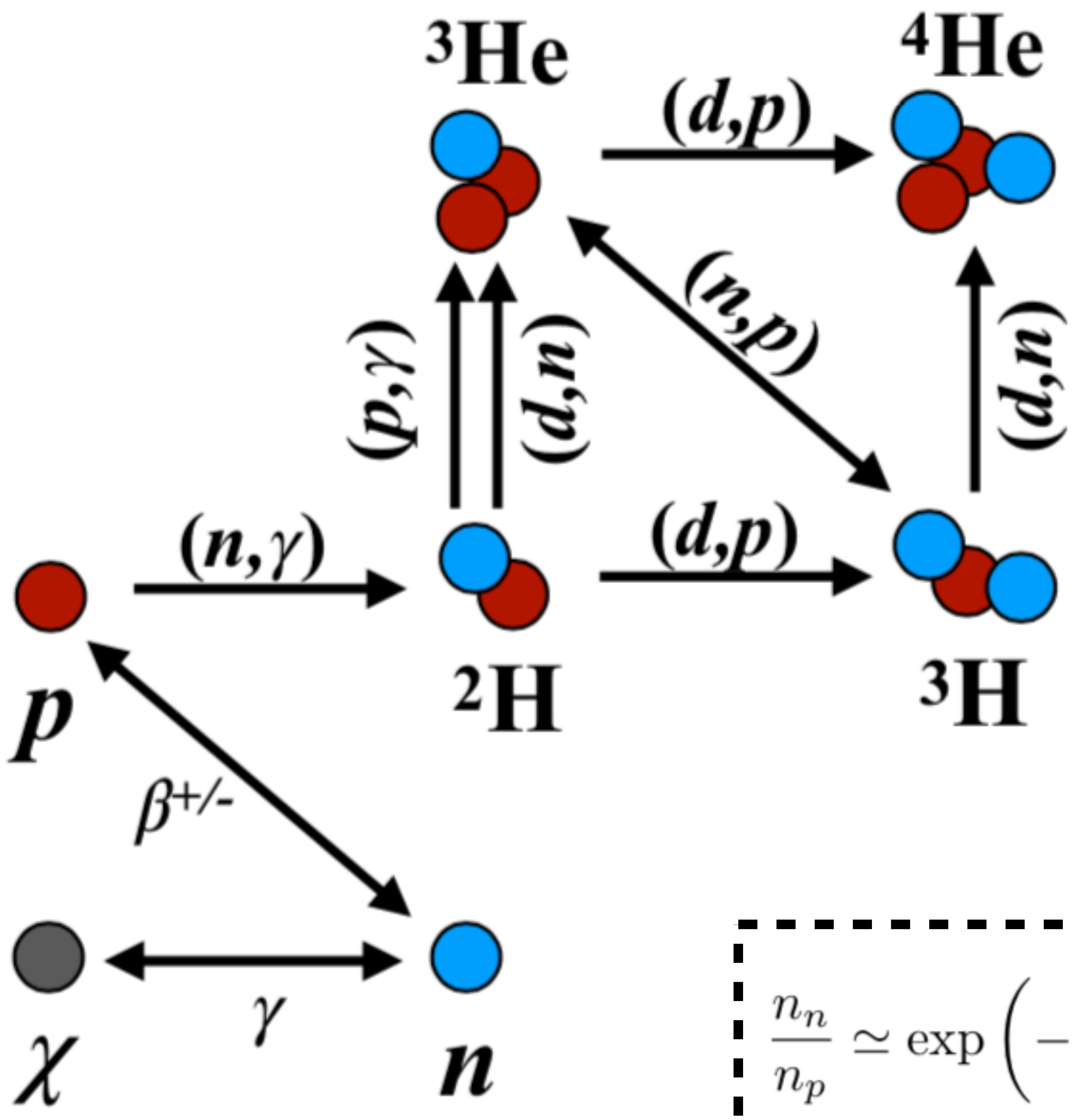
$$-\delta(\bar{\chi} n + \bar{n}\chi) \longleftarrow \bar{\chi} q q q/\Lambda^2 \quad \Rightarrow \quad \Gamma_{\Delta\chi} \sim T^5/\Lambda^4$$

chemical equilbrium keepable down to T ~ GeV—PeV

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

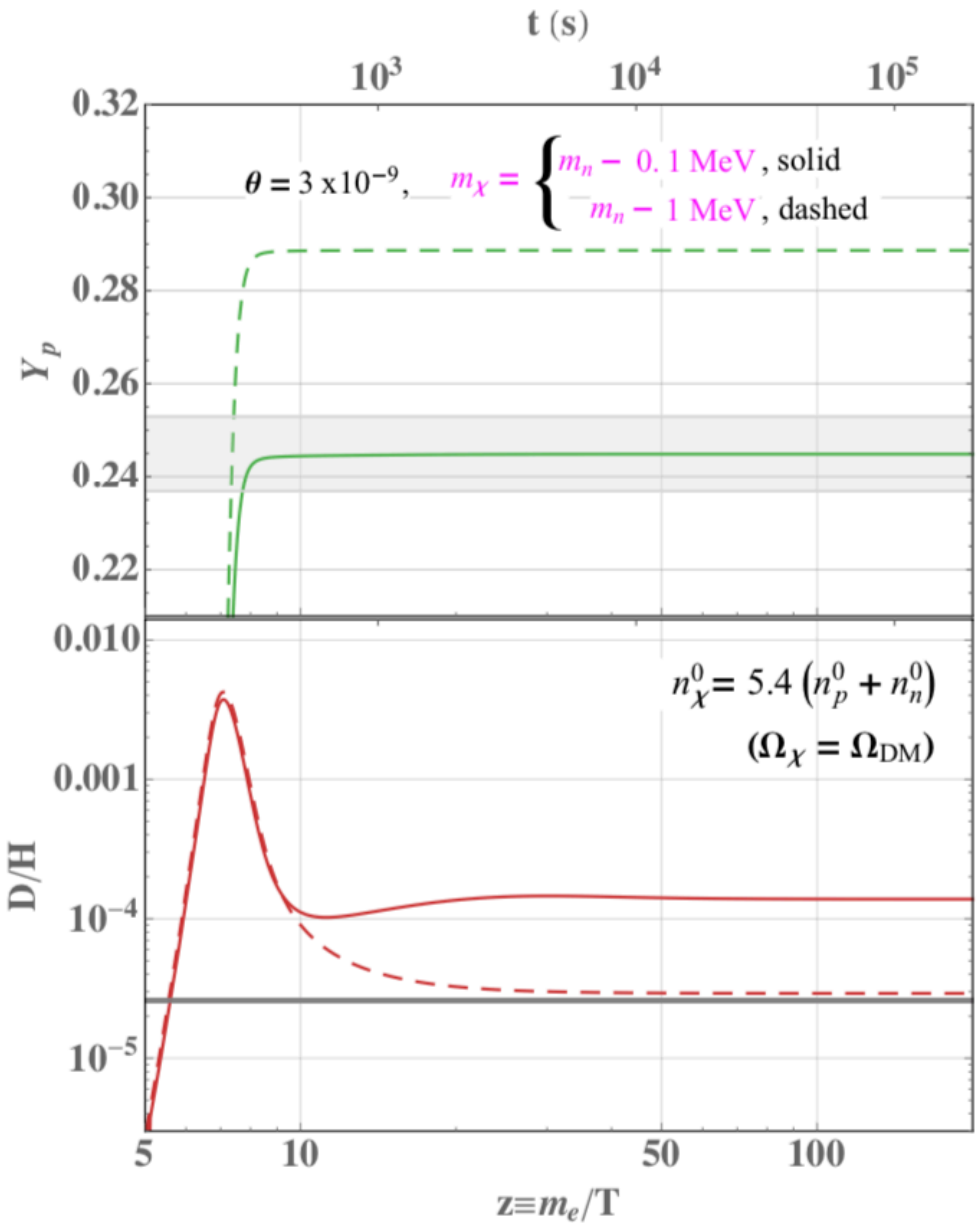
$n_\chi \sim n_p = n_n$ reasonable since universe was probably that hot

Probes: [1] primordial nucleosynthesis

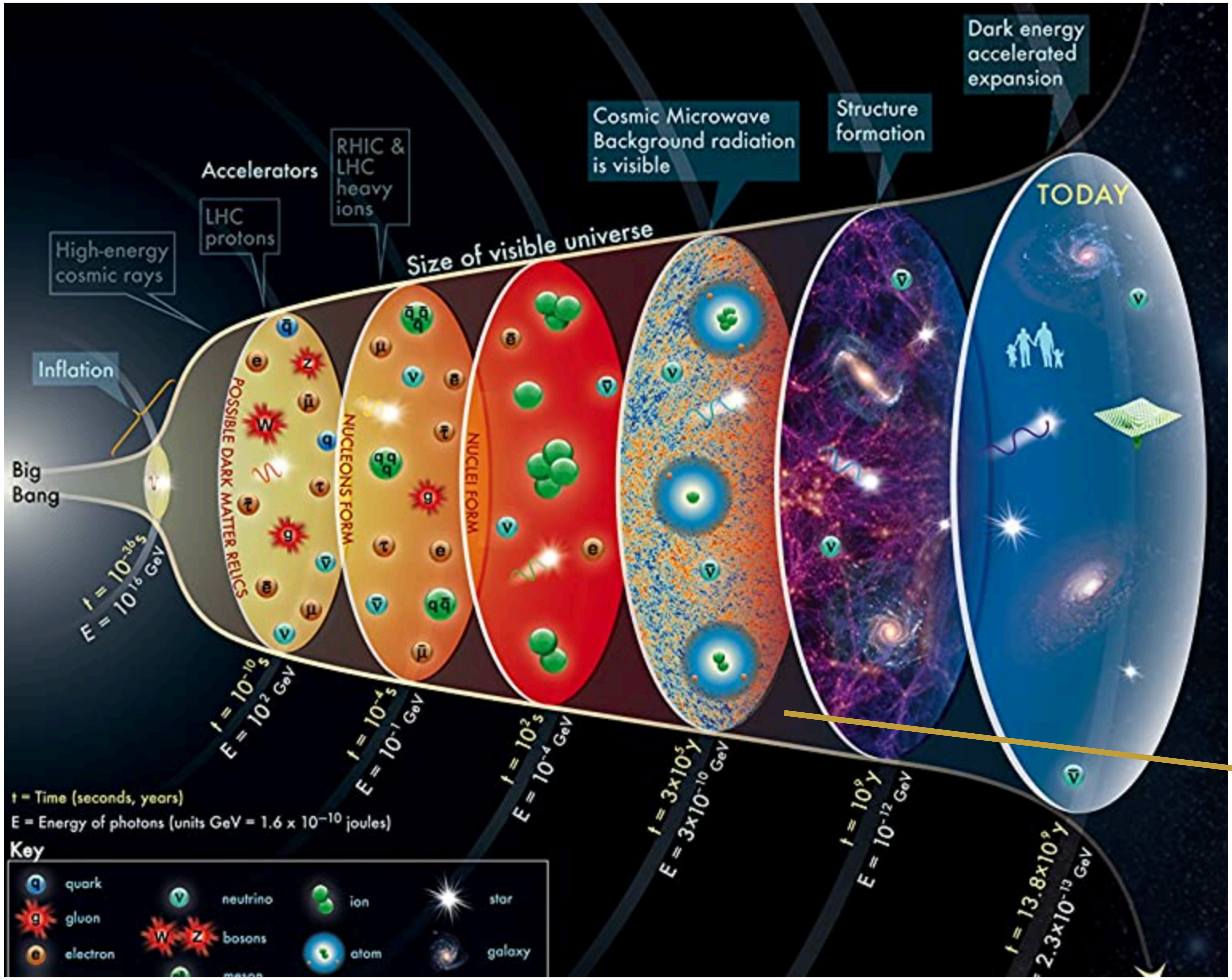


$$\frac{n_n}{n_p} \simeq \exp\left(-\frac{Q_{np}}{T_{np}}\right) \simeq \exp\left[-\frac{Q_{np}}{T_{np}}\left(1-\frac{\mathrm{Br}_{n\to\chi}}{3}\right)\right]$$

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



Probes: [2] relic radiation



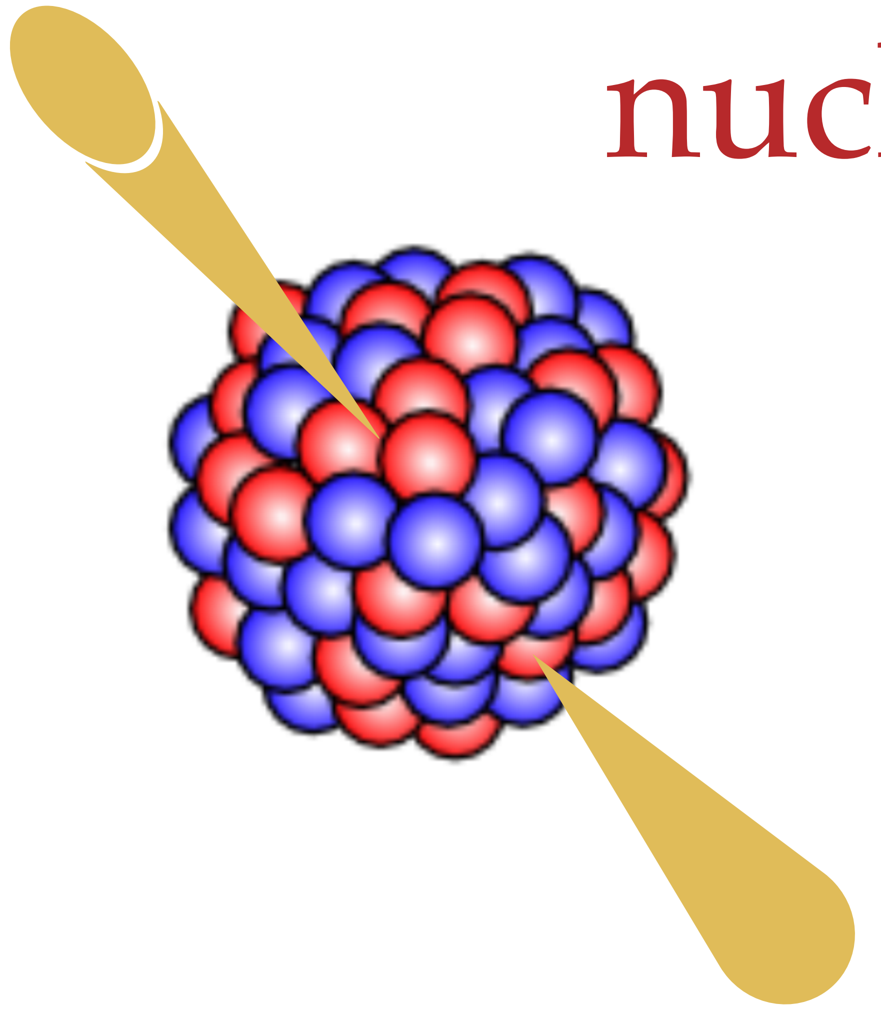
When kinematically open:

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

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

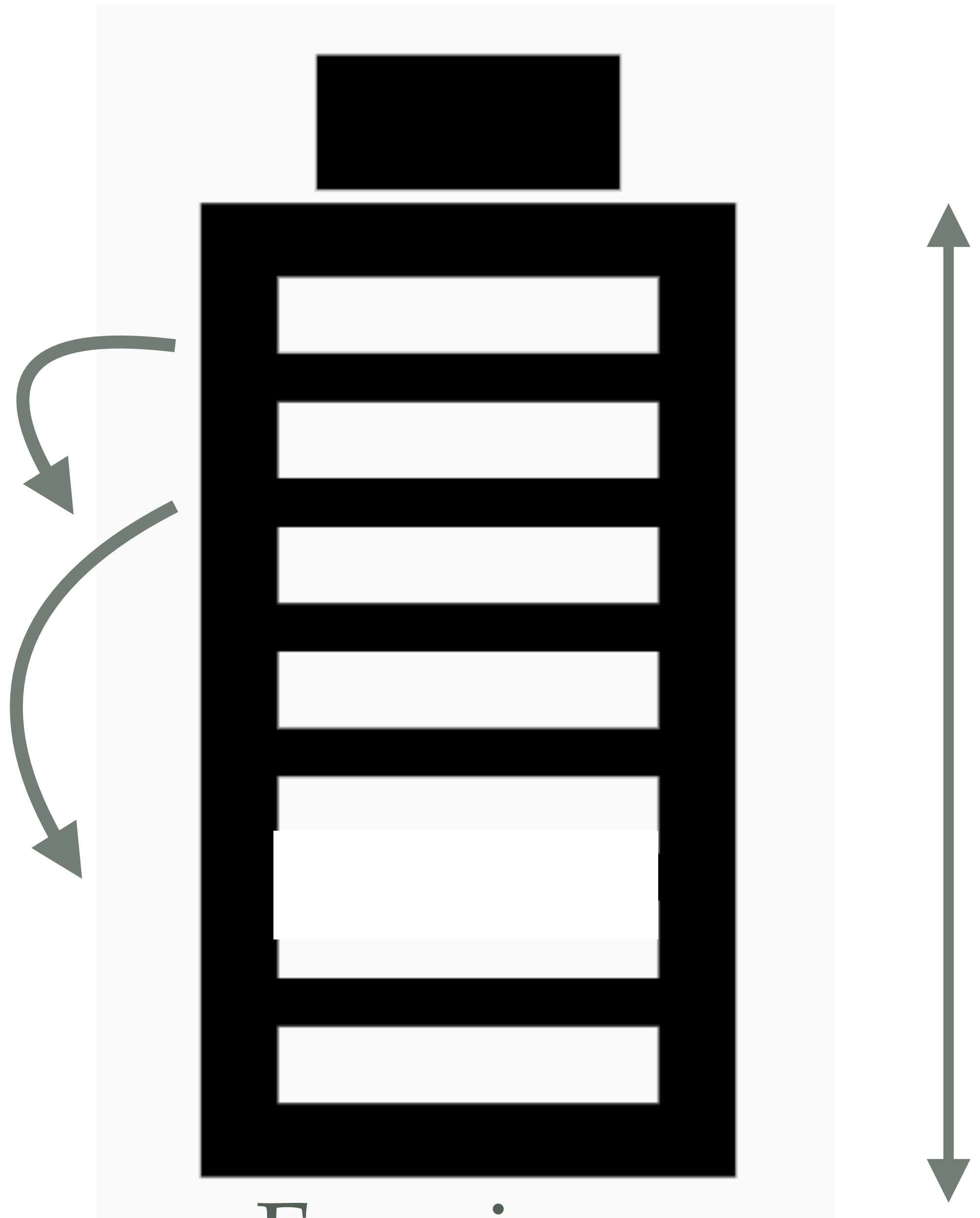
e or γ could “rewrite” reionization history by dumping EM energy in Dark Ages
(i.e. modify optical depth)

Probes: [3] neutron star temperatures



new heating mechanism:
nucleon "Auger effect"

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

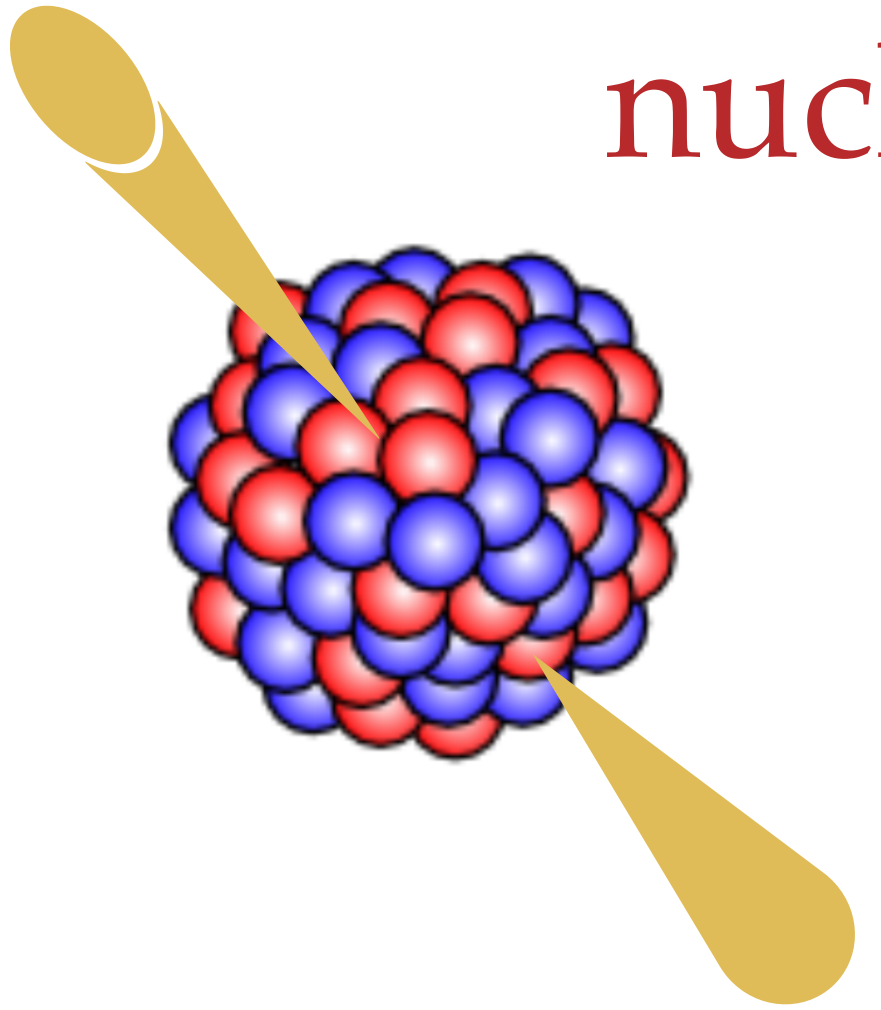


10^{57} neutrons
$+$
10^{56} protons

=> **explosive liberation of energy!**

Probes: [3] neutron star temperatures

new heating mechanism:
nucleon "Auger effect"



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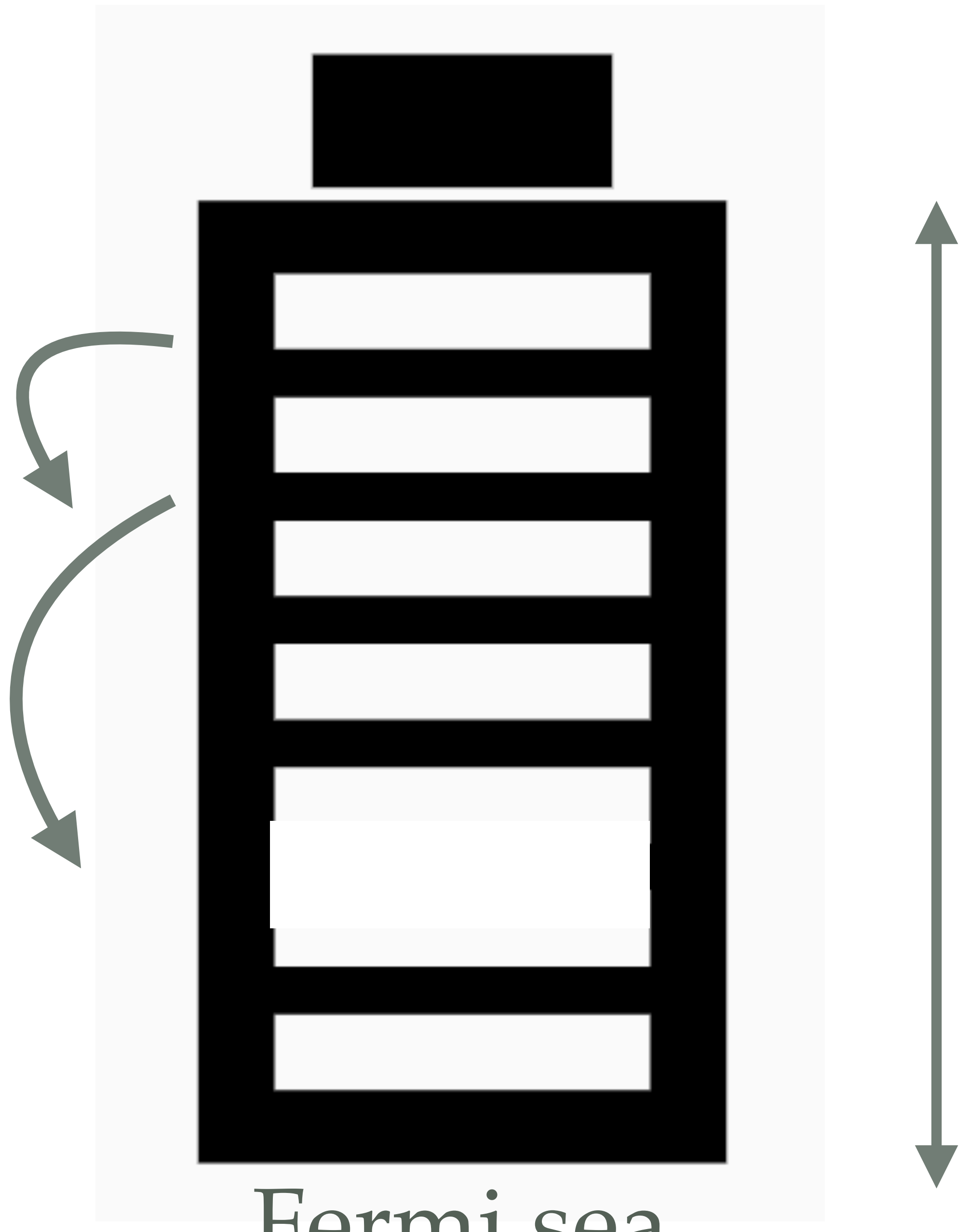


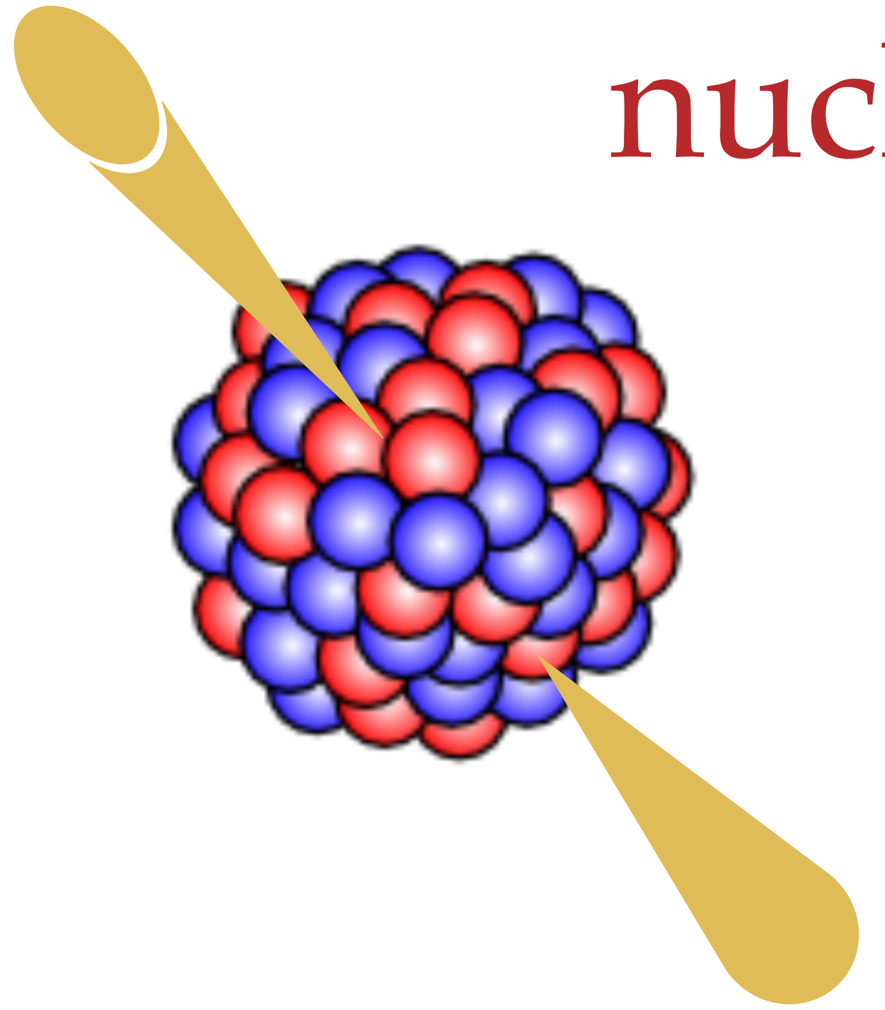
Suitable lab:

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 $\sim 3 \times 10^8$ 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

Probes: [3] neutron star temperatures



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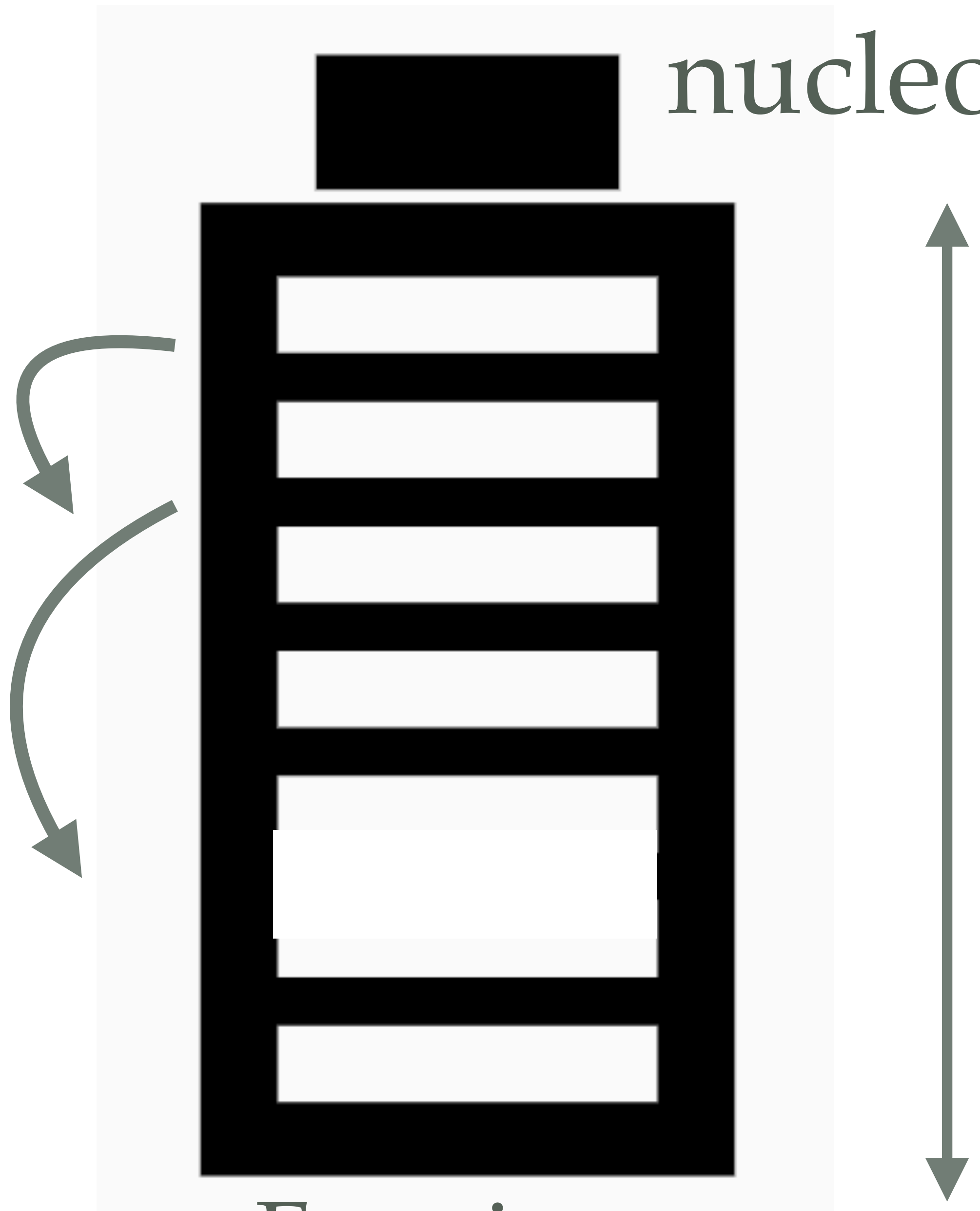

Future lab:

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

Aside: more fundamental physics with UV, optical, IR telescope missions

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]

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31801 (2017) PHYSICAL REVIEW LETTERS wee 29 SEPT

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Scattering searches for dark matter in subhalos: neutron stars, cosmic rays, and old rocks

Joseph Bramante,[1, 2, *] Bradley J. Kavanagh,[3, †] and Nirmal Raj[4, ‡]

submitted to PRL,
arXiv: 2109.04582

see also:

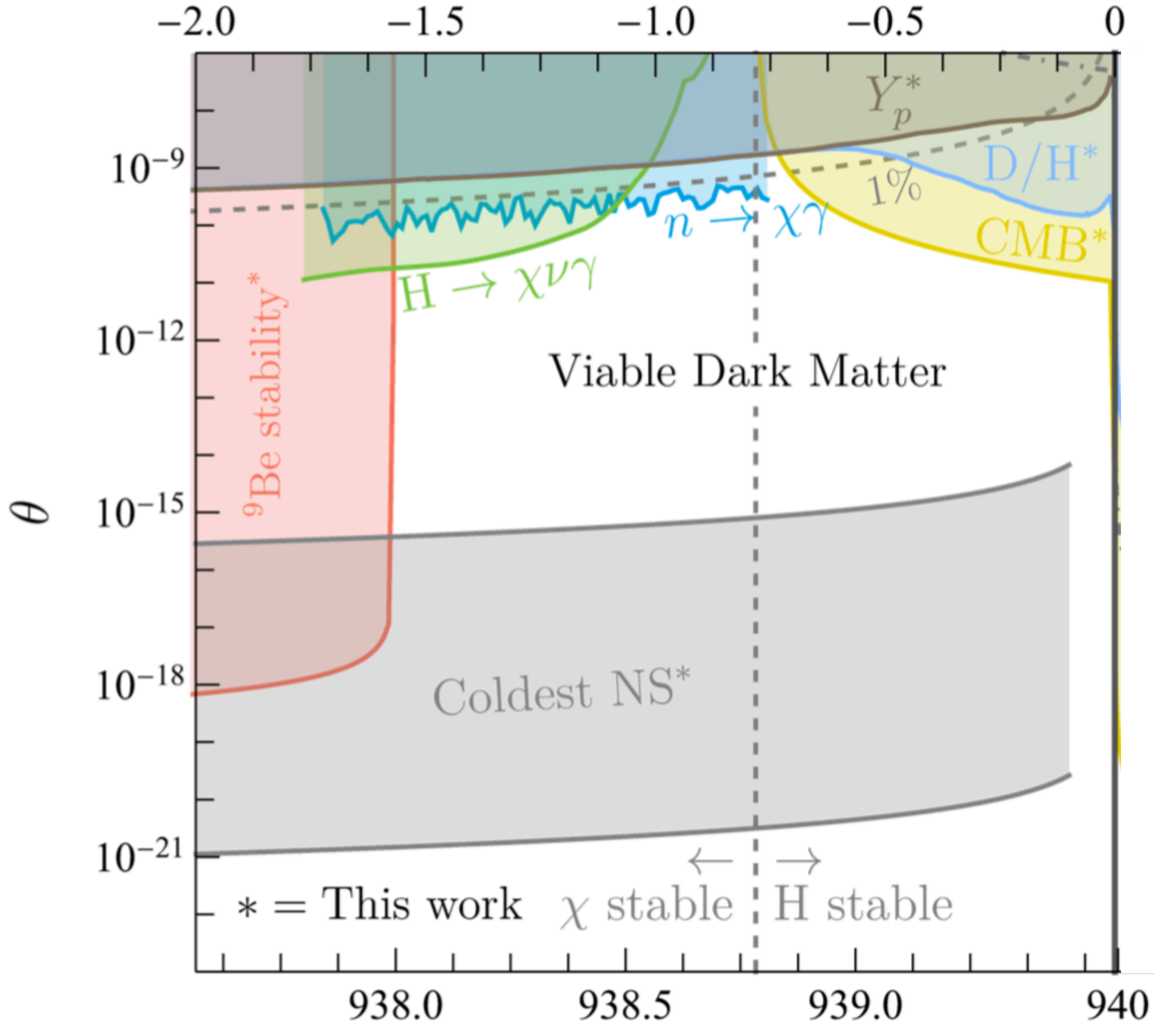
N. Raj, P. Tanedo, H-B. Yu **PRD 2017**	EFT
J. Acevedo, J. Bramante, R. Leane, *N. Raj*, **JCAP 2020**	NS crust/pasta
A. Joglekar, *N. Raj*, P. Tanedo, H-B. Yu **PLB 2020**	NS electrons
A. Joglekar, *N. Raj*, P. Tanedo, H-B. Yu **PRD 2020**	NS electrons EFT
R. Garani, A. Gupta, *N. Raj*, **PRD 2021**	DM refrigeration

Constraints

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

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

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

Constraints

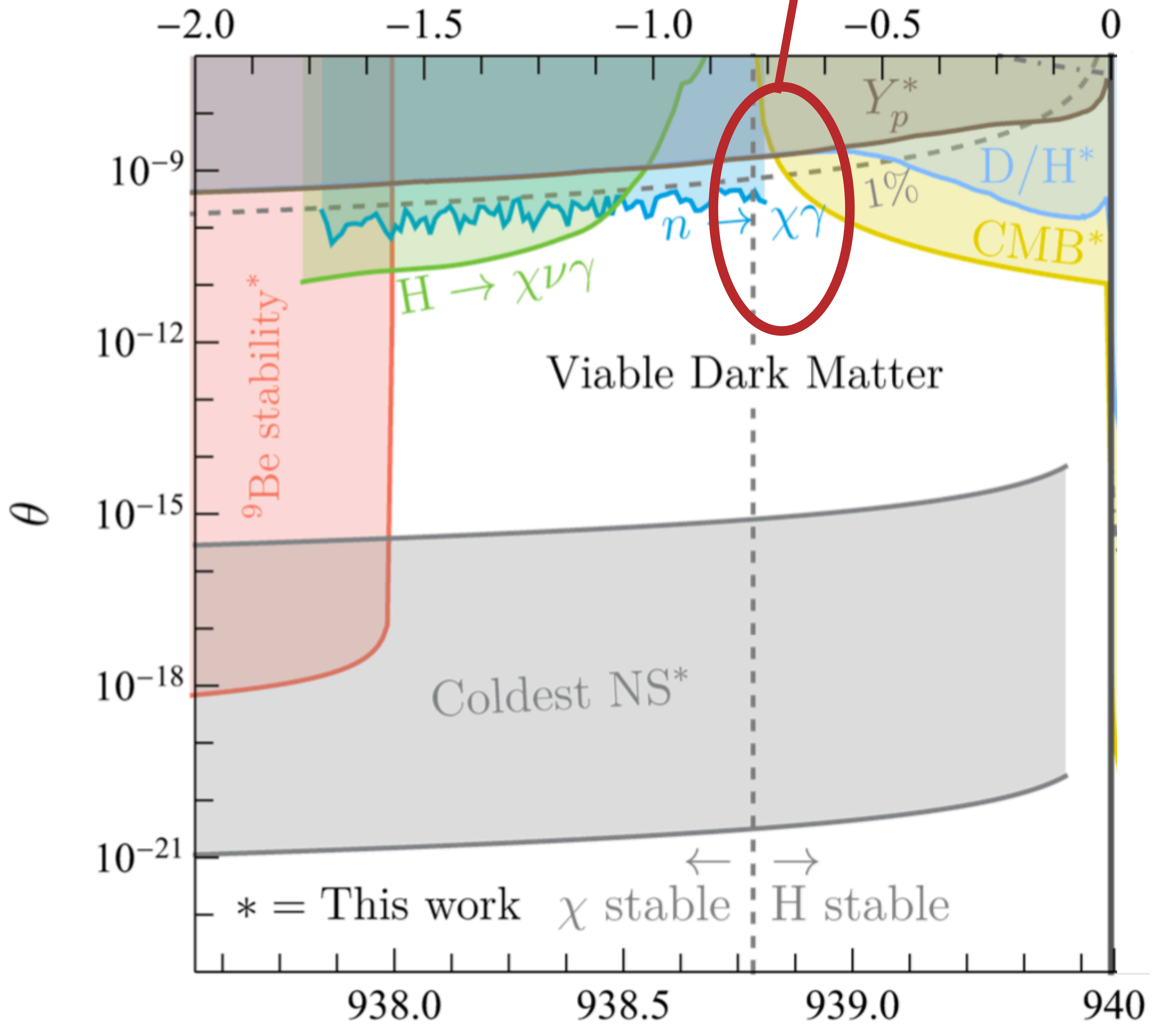
100 keV "neutron lifetime puzzle" window for UCN experimentalists to target!

2012.09865 *McKeen, Pospelov, Raj*

$n \to \chi\gamma$ open

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

longer life



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T. R. Slatyer, Physical Review D 87 (2013), 10.1103/physrevd.87.123513.
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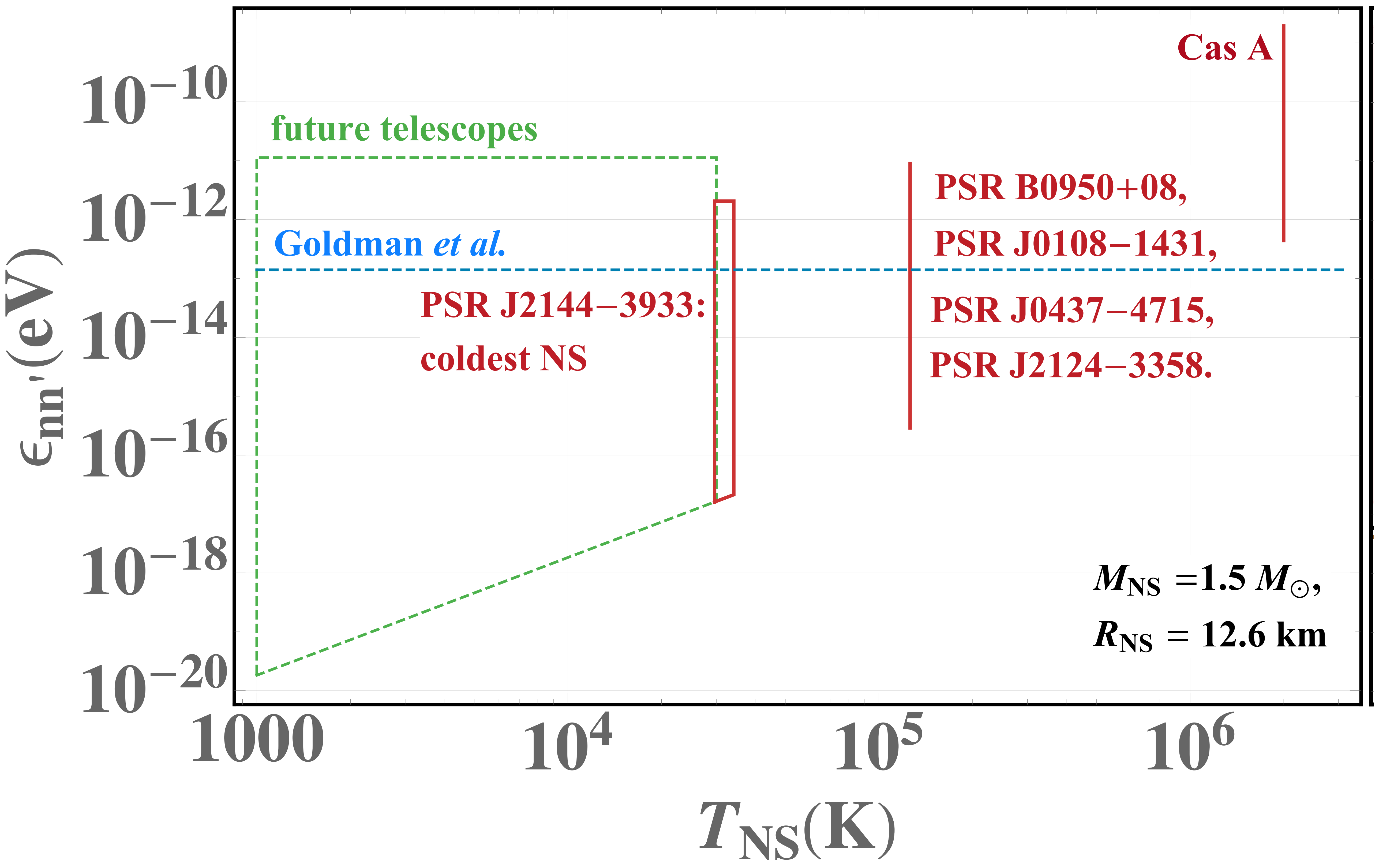
$< 3 \times 10^9$ yr in metal-poor stars

- NS: J2144-3933

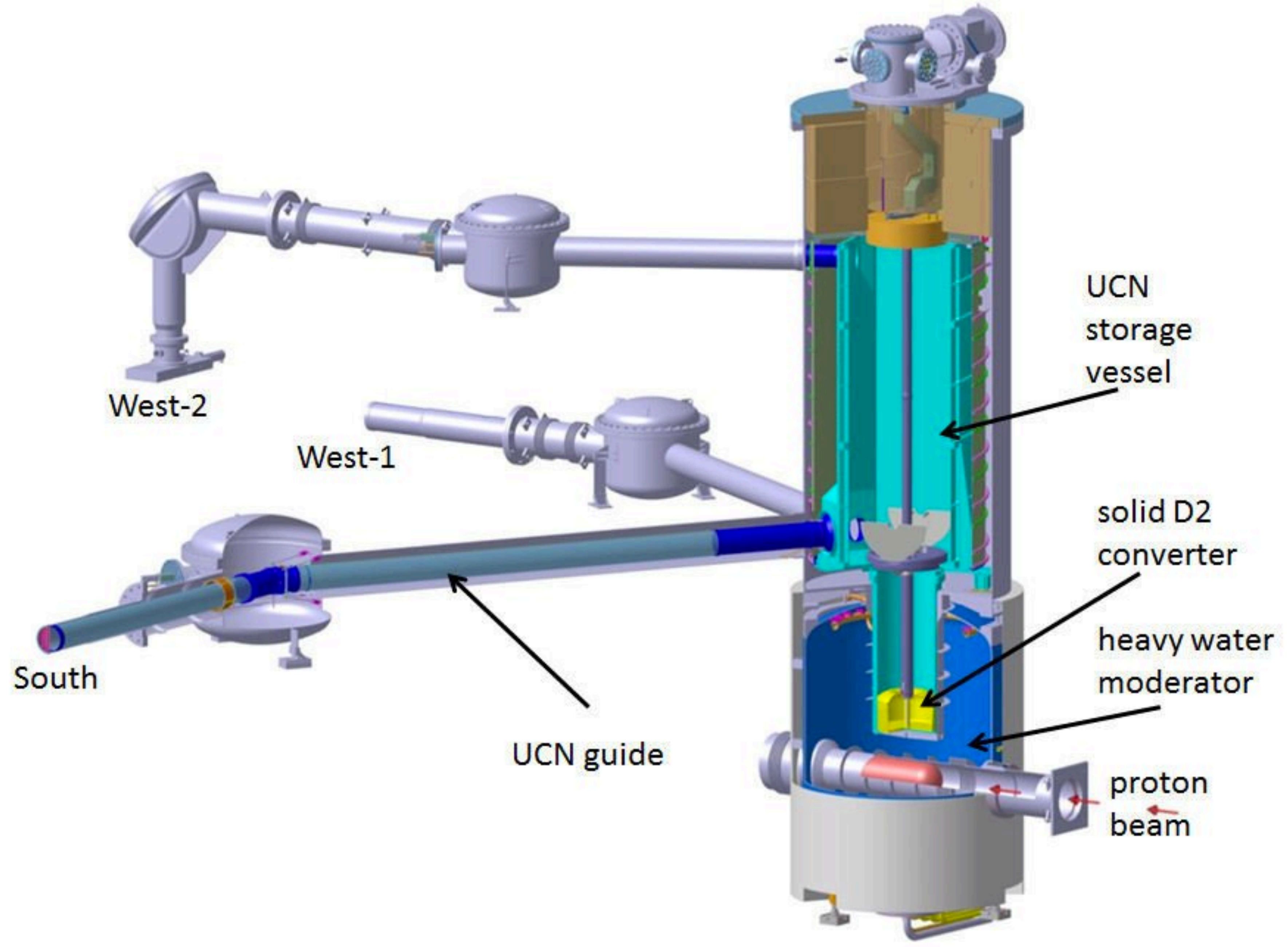
Constraints: NS heating

NS energy per baryon

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



What about terrestrial ultra-cold neutron searches?



ceilings: neutron conversions stop within NS lifetime

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

PRL 2021 *McKeen, Pospelov, Raj*

Constraints: NS heating

NS energy per baryon

Zeeman from Earth's B field

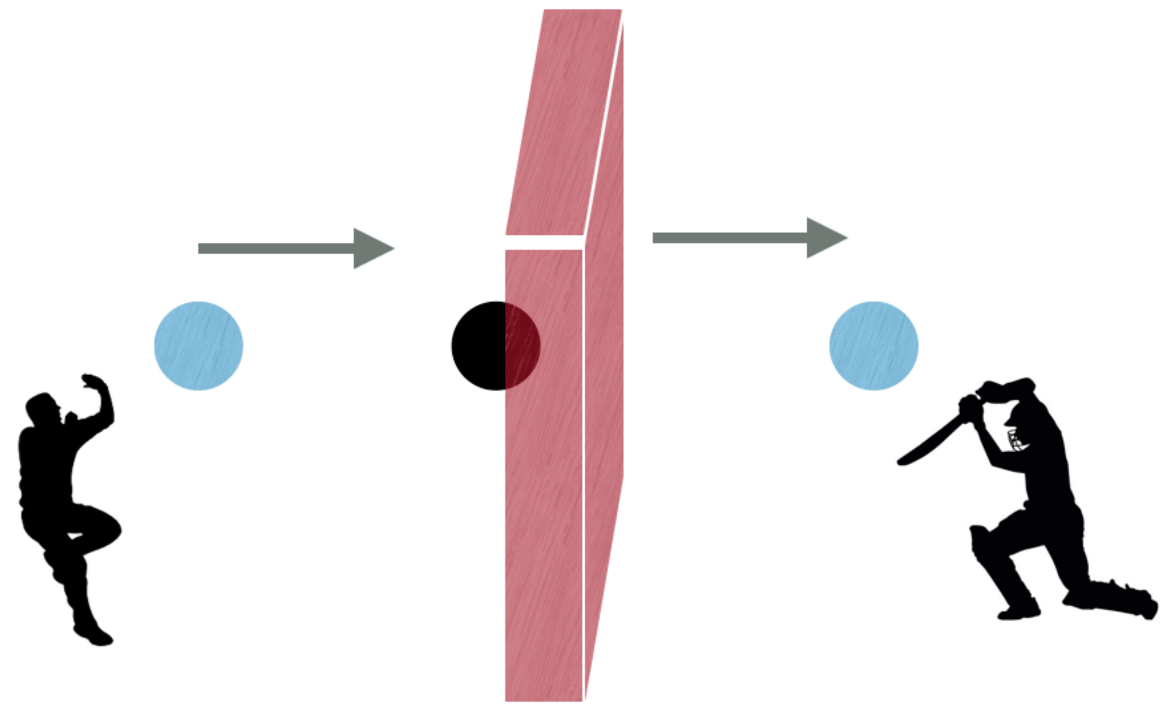
neutron star heating: $|m_n - m_{n'}| \lesssim \mathcal{O}(10\ \text{MeV})$

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

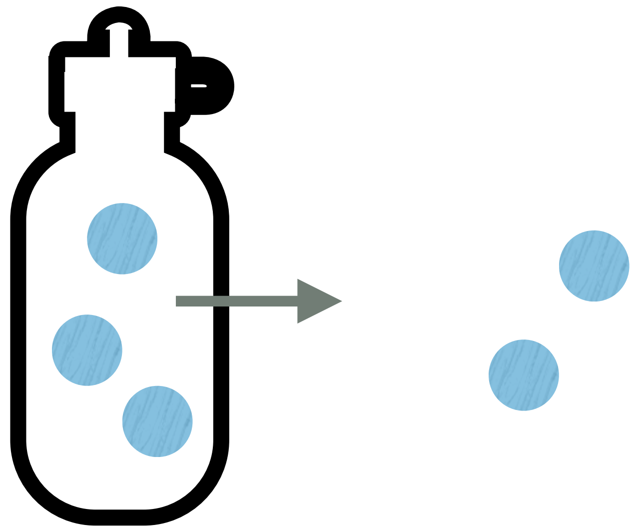
ceilings: neutron conversions stop within NS lifetime

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

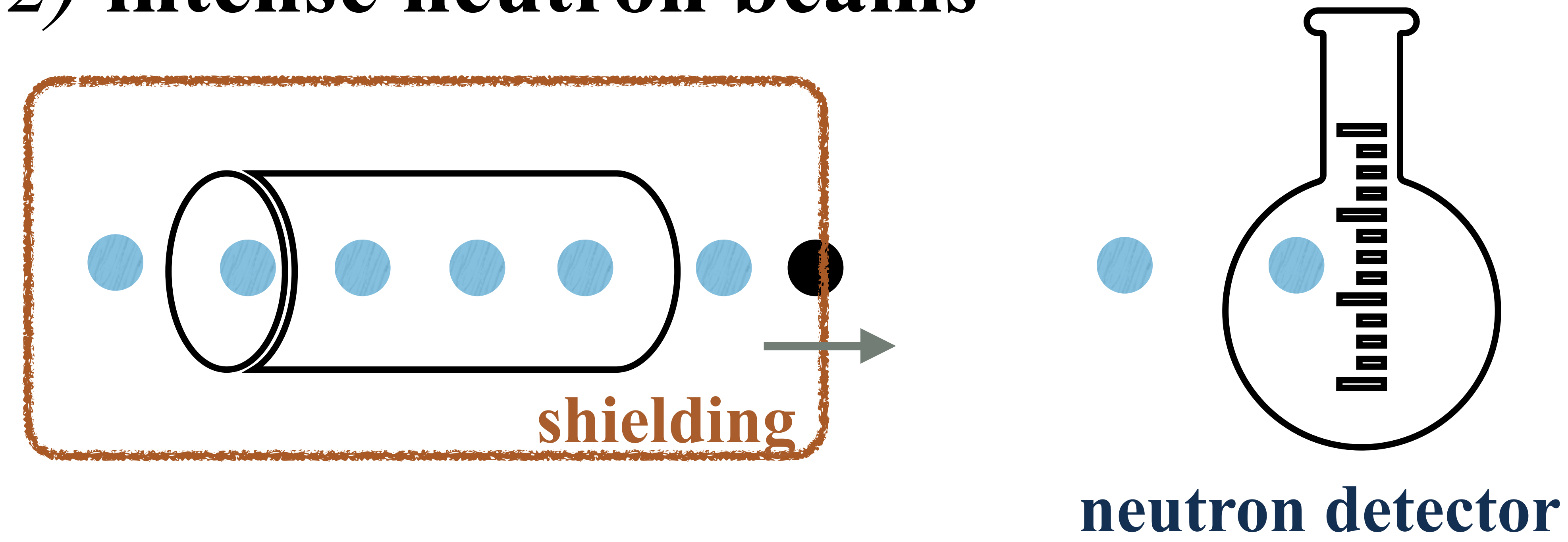
Neutrons shining through a wall



(1) **UCN disappearance**

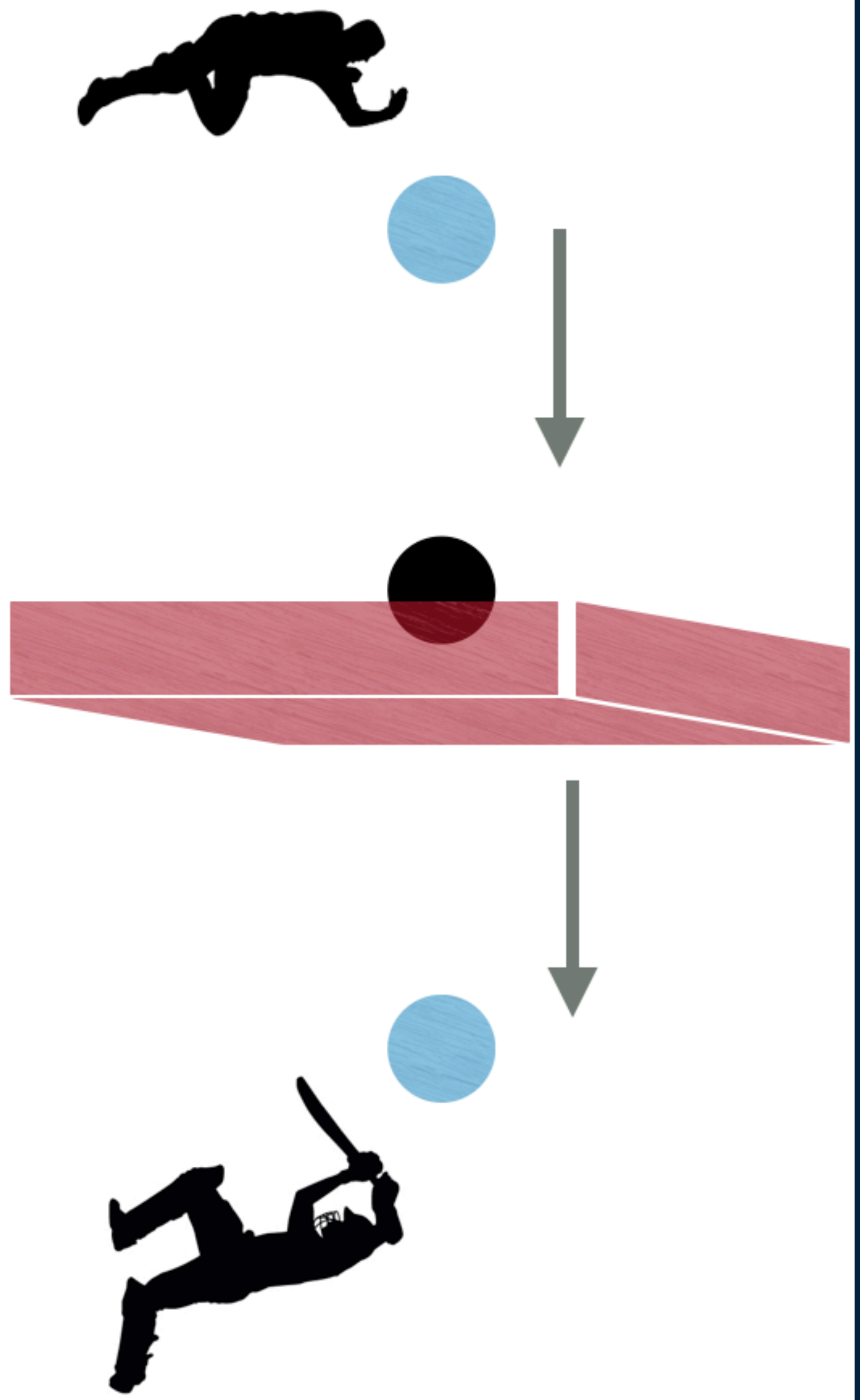


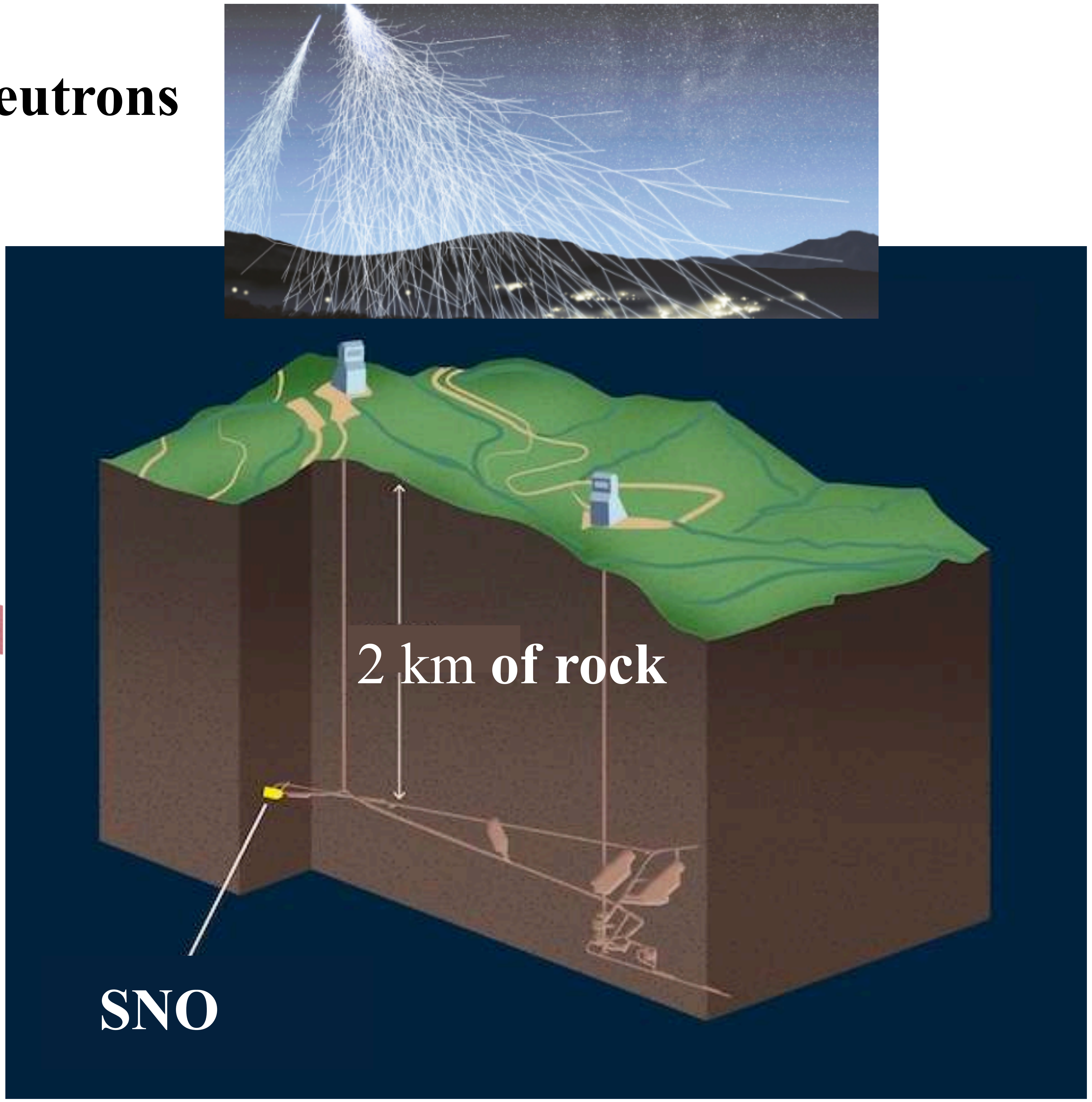
(2) **intense neutron beams**



e.g., IsoDAR at Yemilab:
Conrad, *et al.*, 2110.10635

(3) **cosmic ray neutrons**





ongoing work with
M. Hostert, D. McKeen, M. Pospelov

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

Constraining neutron conversions

neutron number density

heating rate

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

energy release rate

$$\leq$$

cooling rate
(blackbody emission)

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

Conversions to dark neutrons

medium-dependent splitting

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

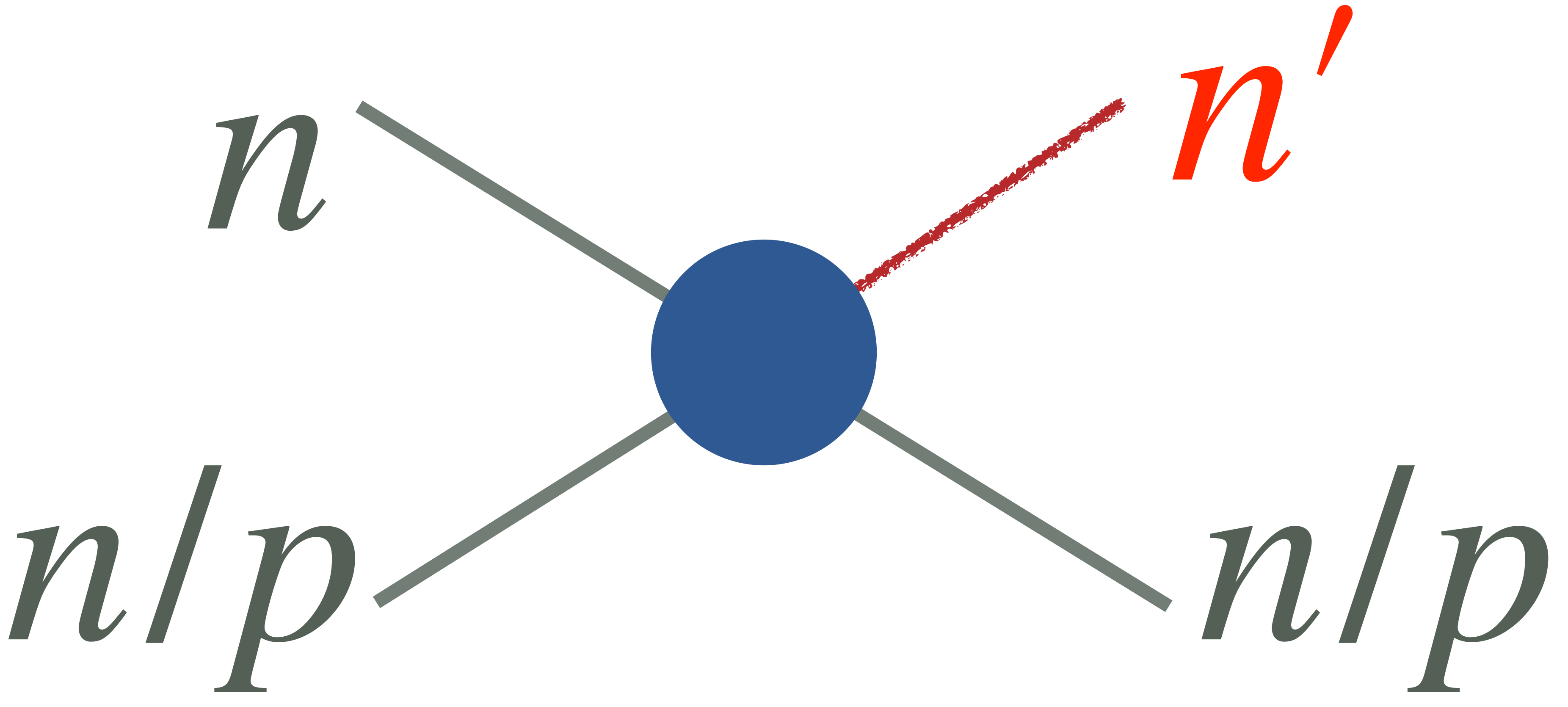
e.g. neutron star nuclear self-energies, 10—100 MeV

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

$$\sigma_{nn\to nn} \simeq \frac{1}{4} \times \frac{16\pi}{m_N^2 v^2} \sin^2 \delta_S ,$$

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

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



Conversions to dark neutrons

symmetry factor

neutron chemical potential*

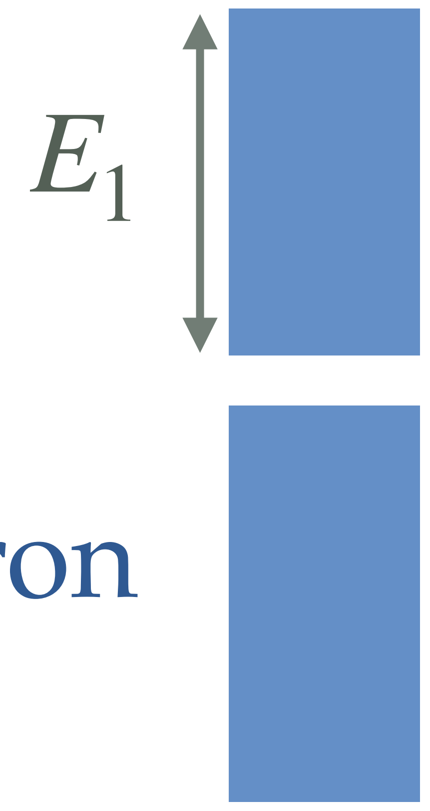
$$\dot{E}_{n'} = \sum_{N=n,p} f_N n_N \left\langle \left(\widetilde{\mu}_n - \frac{p_{n'}^2}{2m_{n'}} \right) \sigma_{n'N} v \right\rangle_{p_N > p_{F_N}}$$

energy release rate

number density*

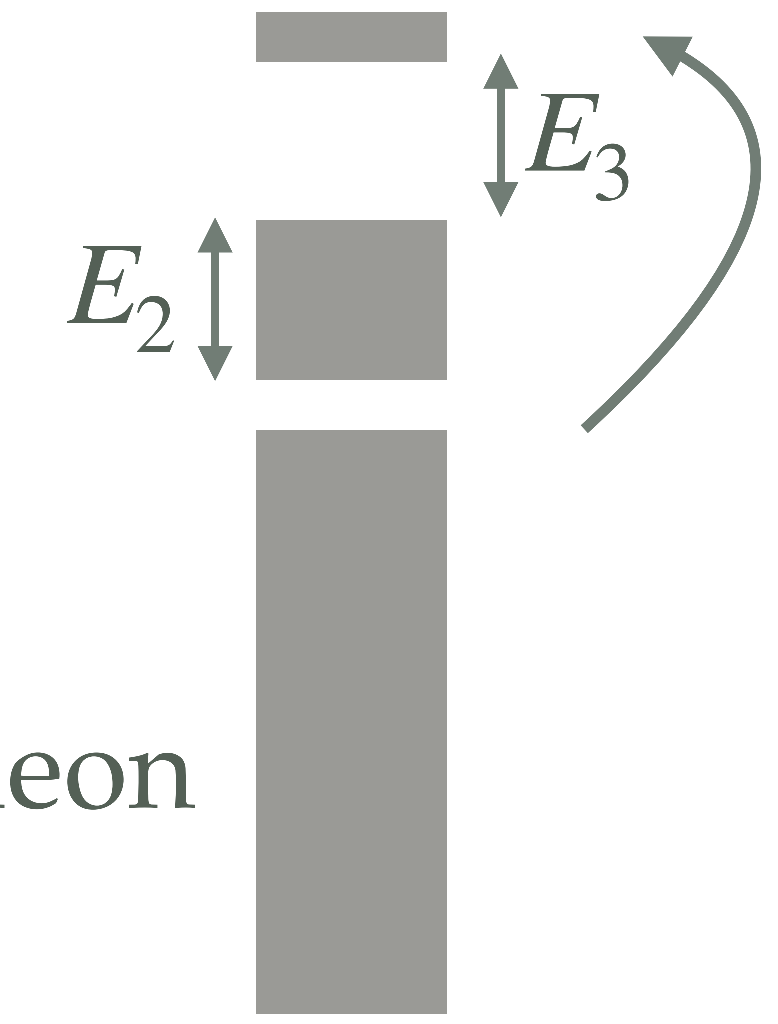
Pauli blocking condition

3 sources of energy:



scattering neutron
Fermi sea

spectator nucleon
Fermi sea



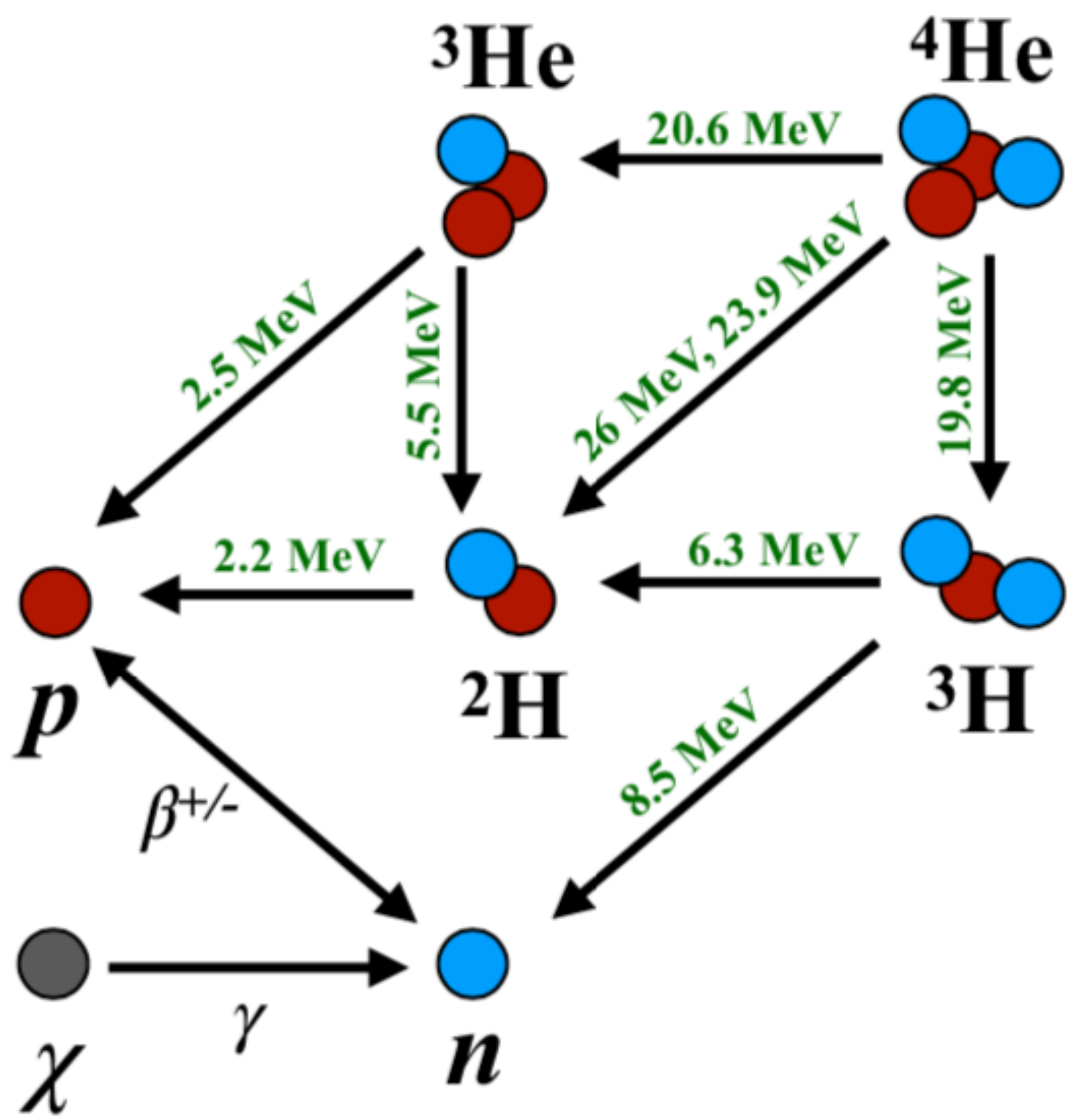
Amusement

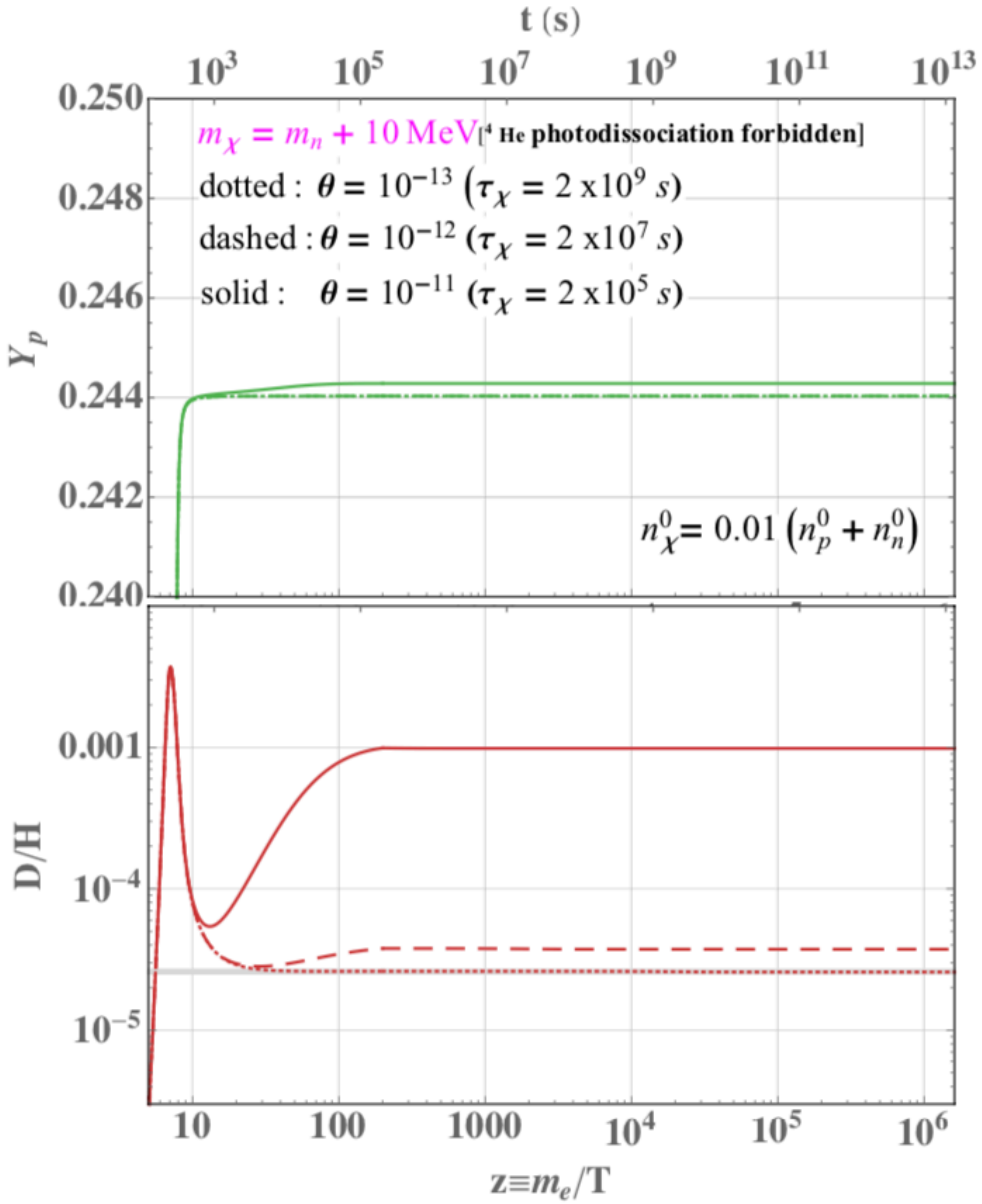
proton spectators
(~ 10% of NS nucleons)
supply more heat!

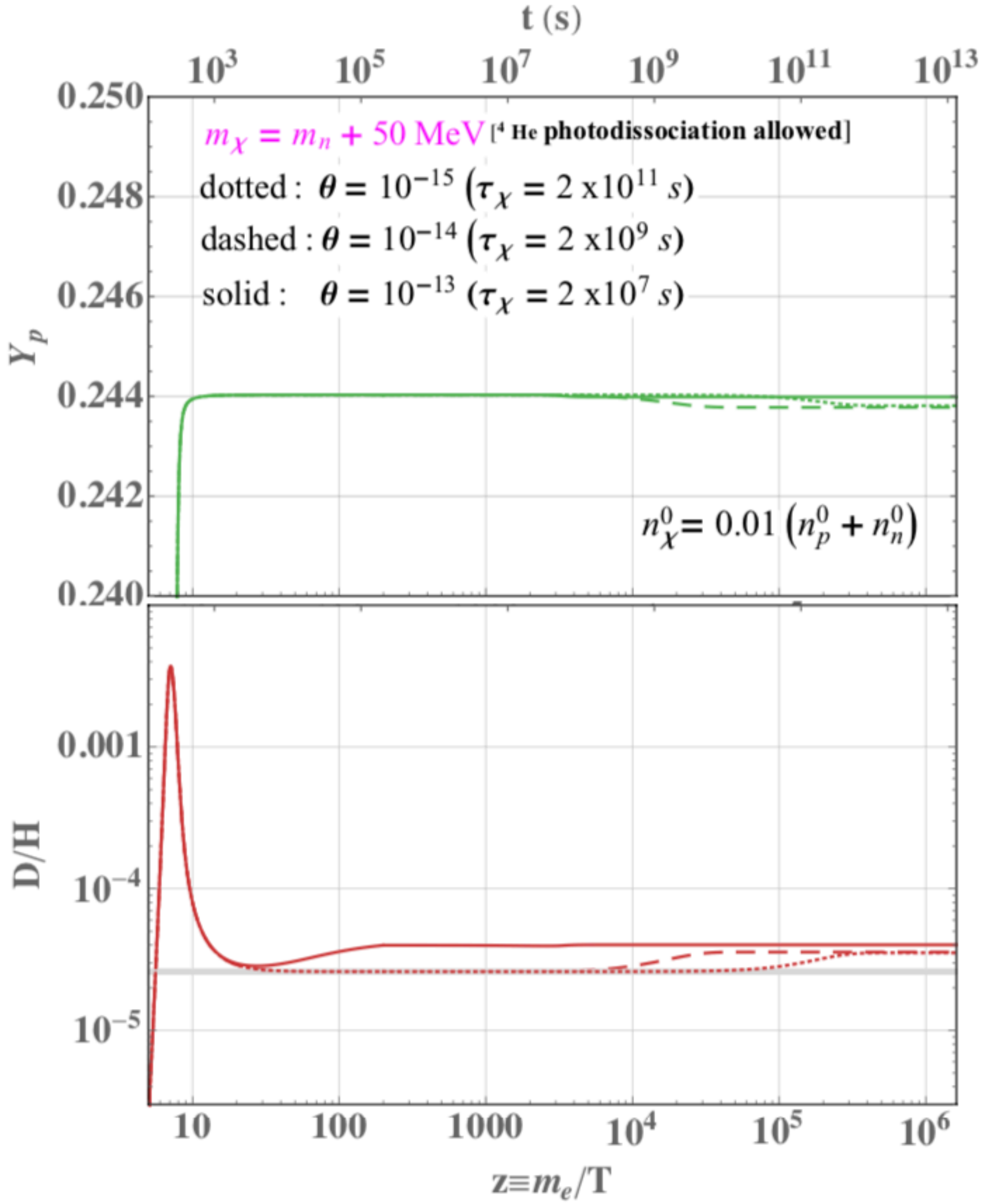
less Pauli-blocked,
greater cross section

* 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

Signals: photodissociation post-nucleosynthesis







Probes

(4) *ancient metal-poor stars*

(~3 Gyr old; ^{9}Be observed)

Via

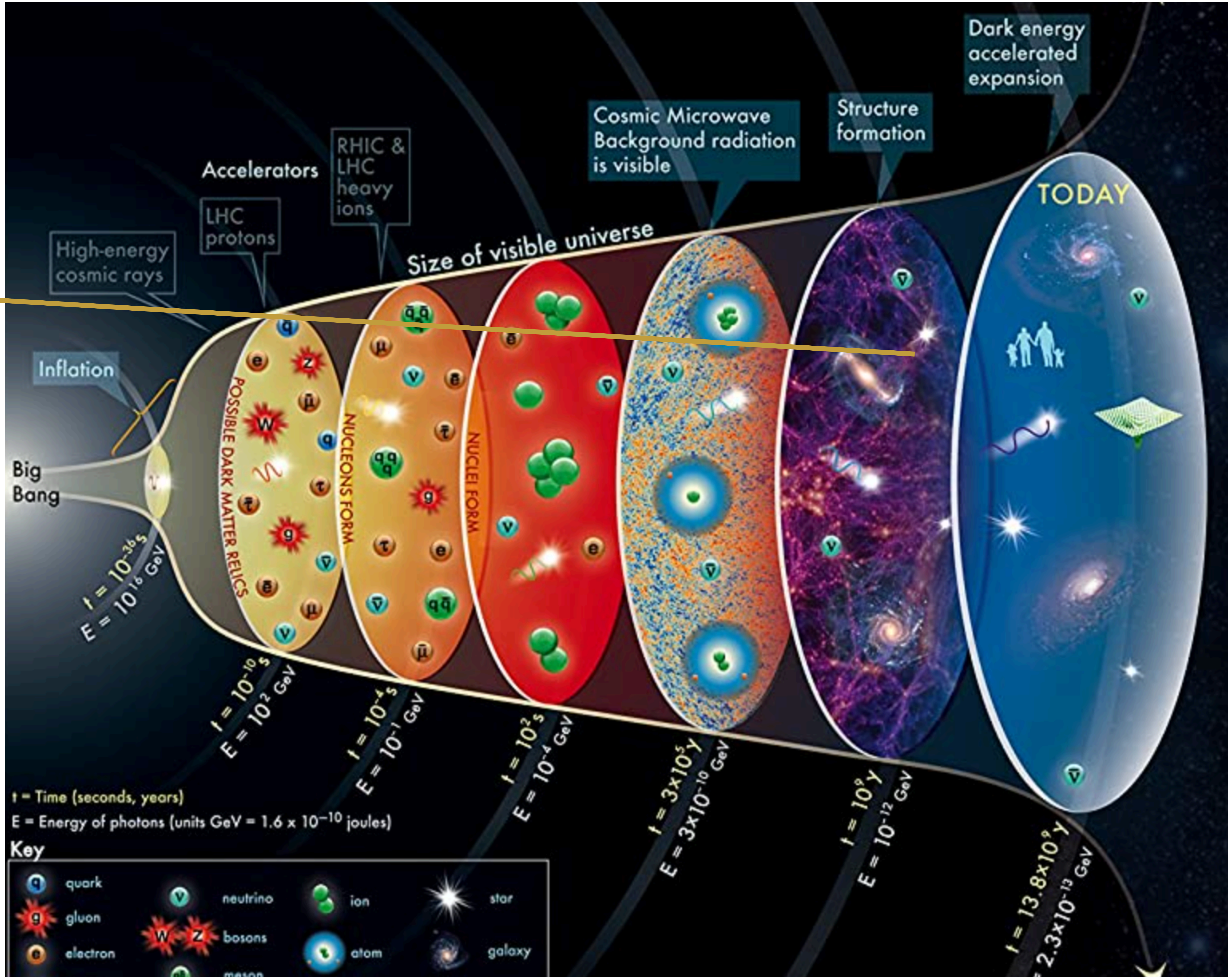
$$^9\mathrm{Be} \to 2\,^4\mathrm{He} + \chi$$

$$^9\mathrm{Be} \to 2\,^4\mathrm{He} + \chi + \gamma$$

beryllium-9 lifetime:

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

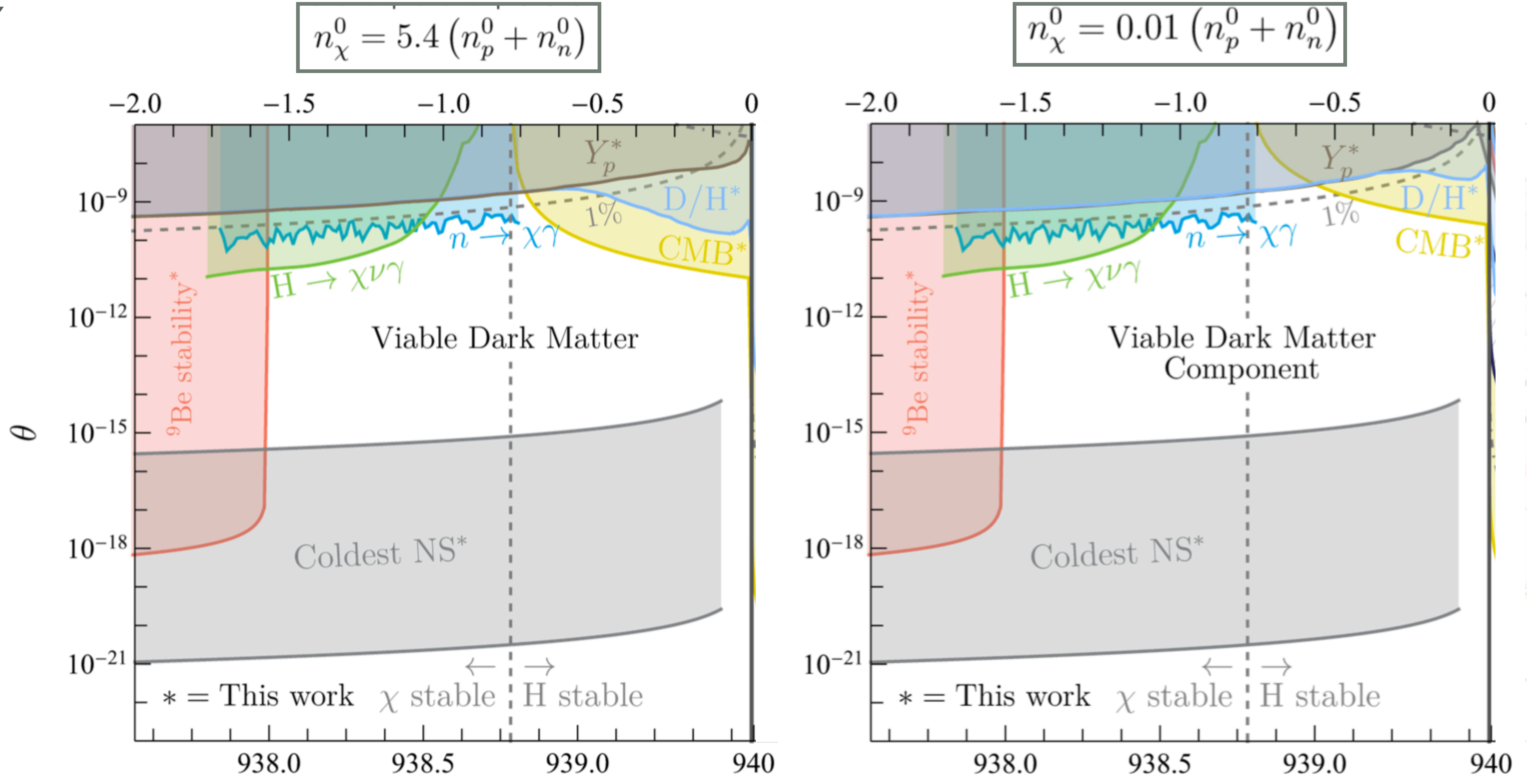
timeline of the universe



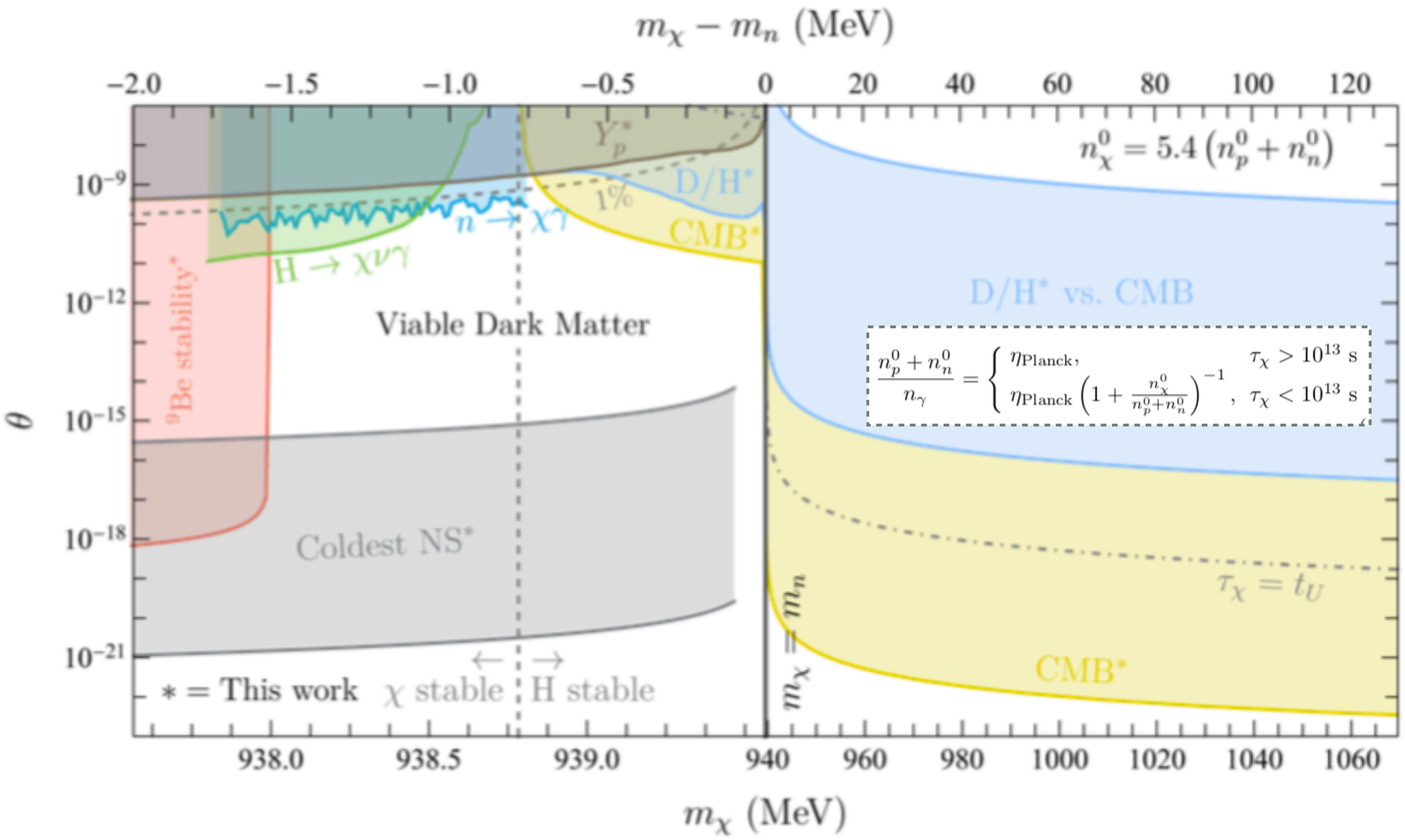
Constraints

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

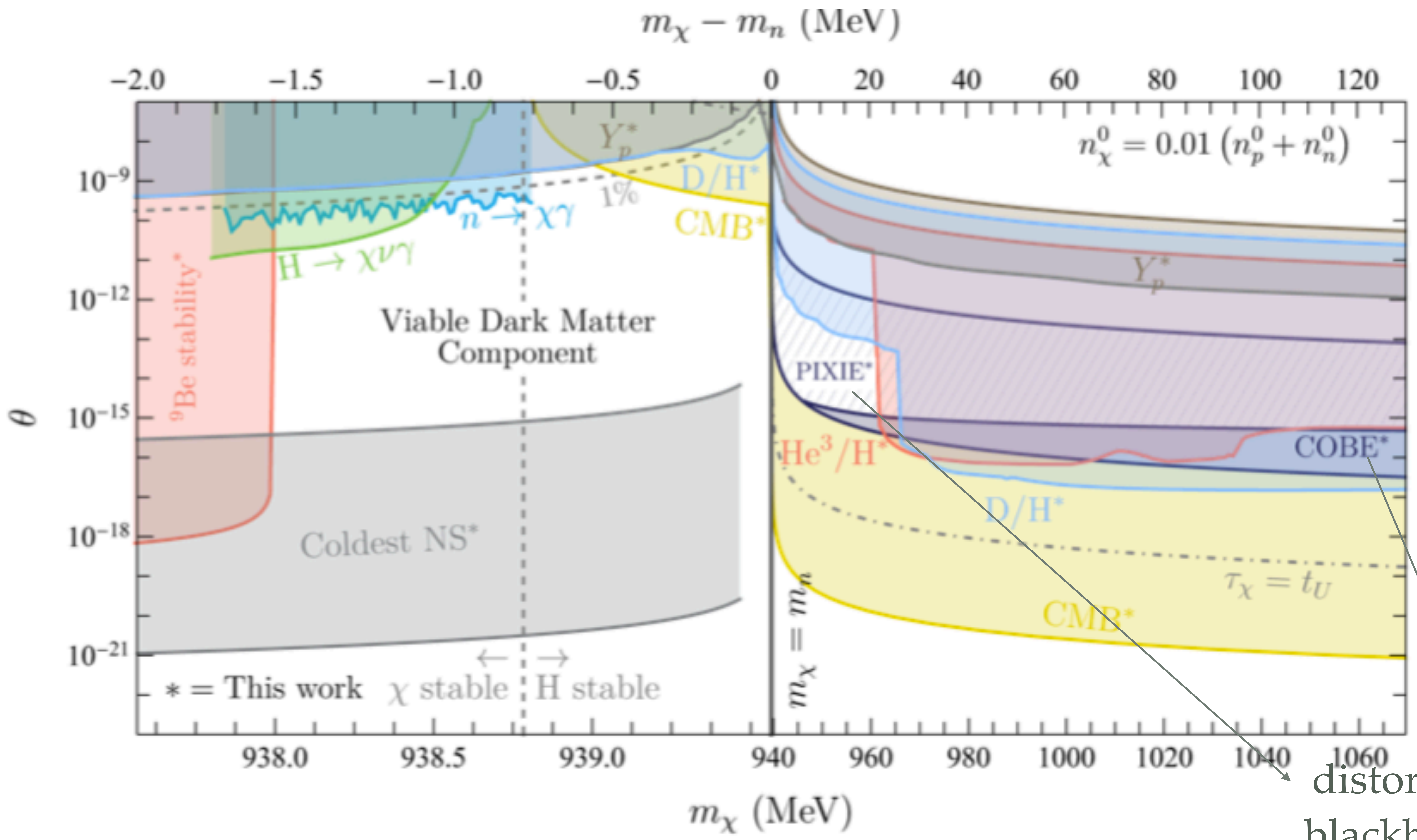
longer
life



Constraints: χ all the dark matter



Constraints: χ percent-level dark matter



distortions of CMB blackbody spectrum