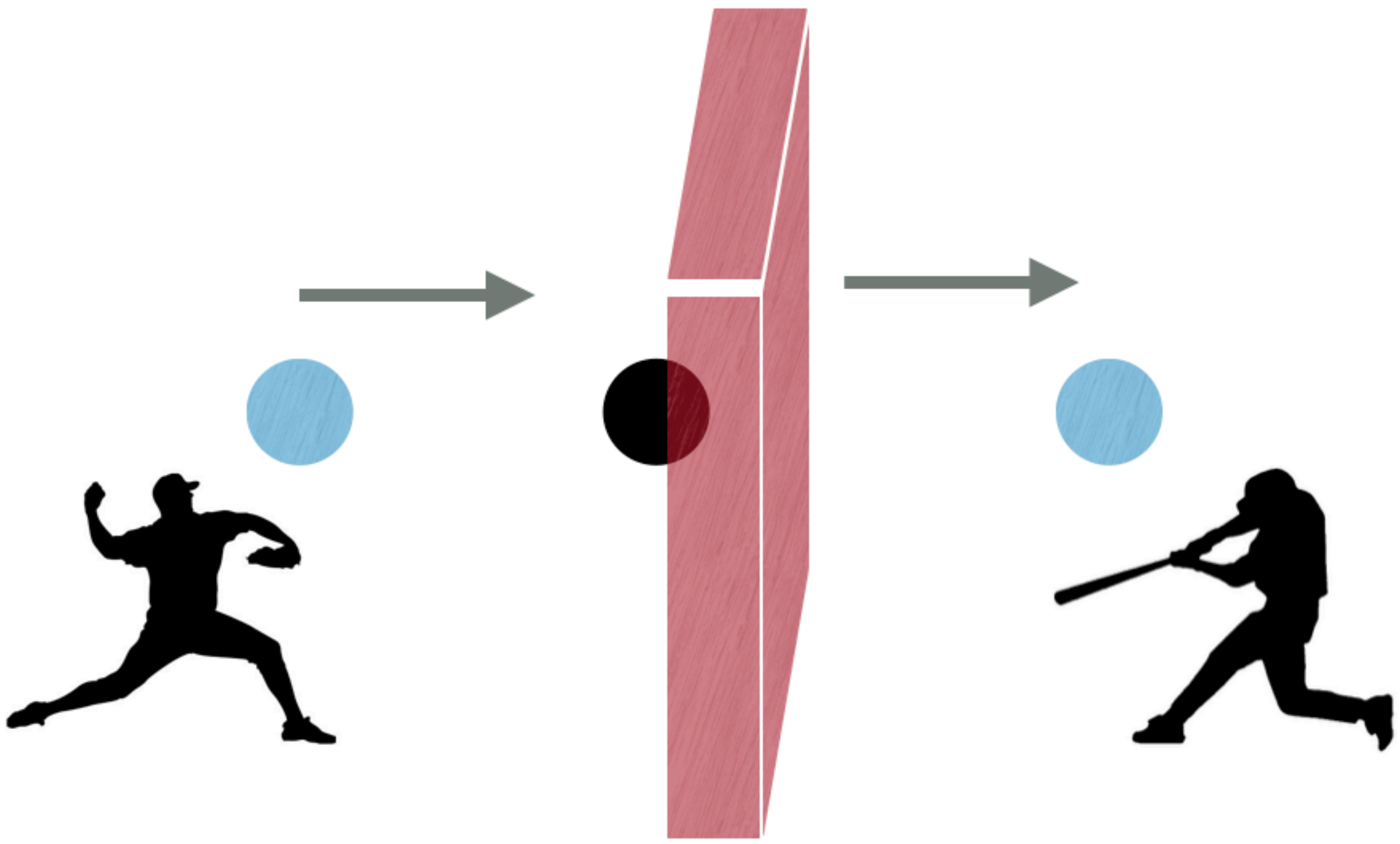
Dark *Neutrons*: Cosmology and Astrophysics

NIRMAL RAJ
TRIUMF National Lab,
Canada
@PhysicsNirmal



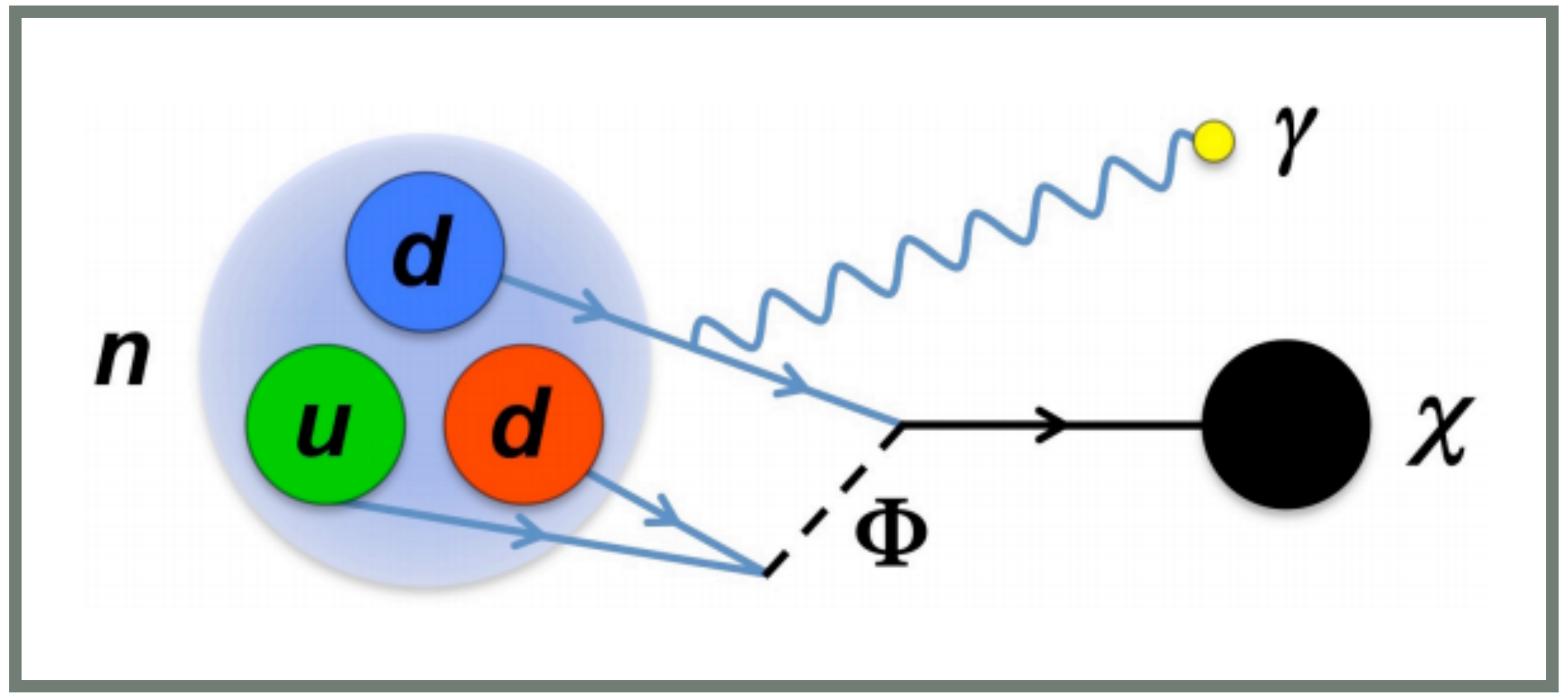
based on

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

with David McKeen
& Maxim Pospelov

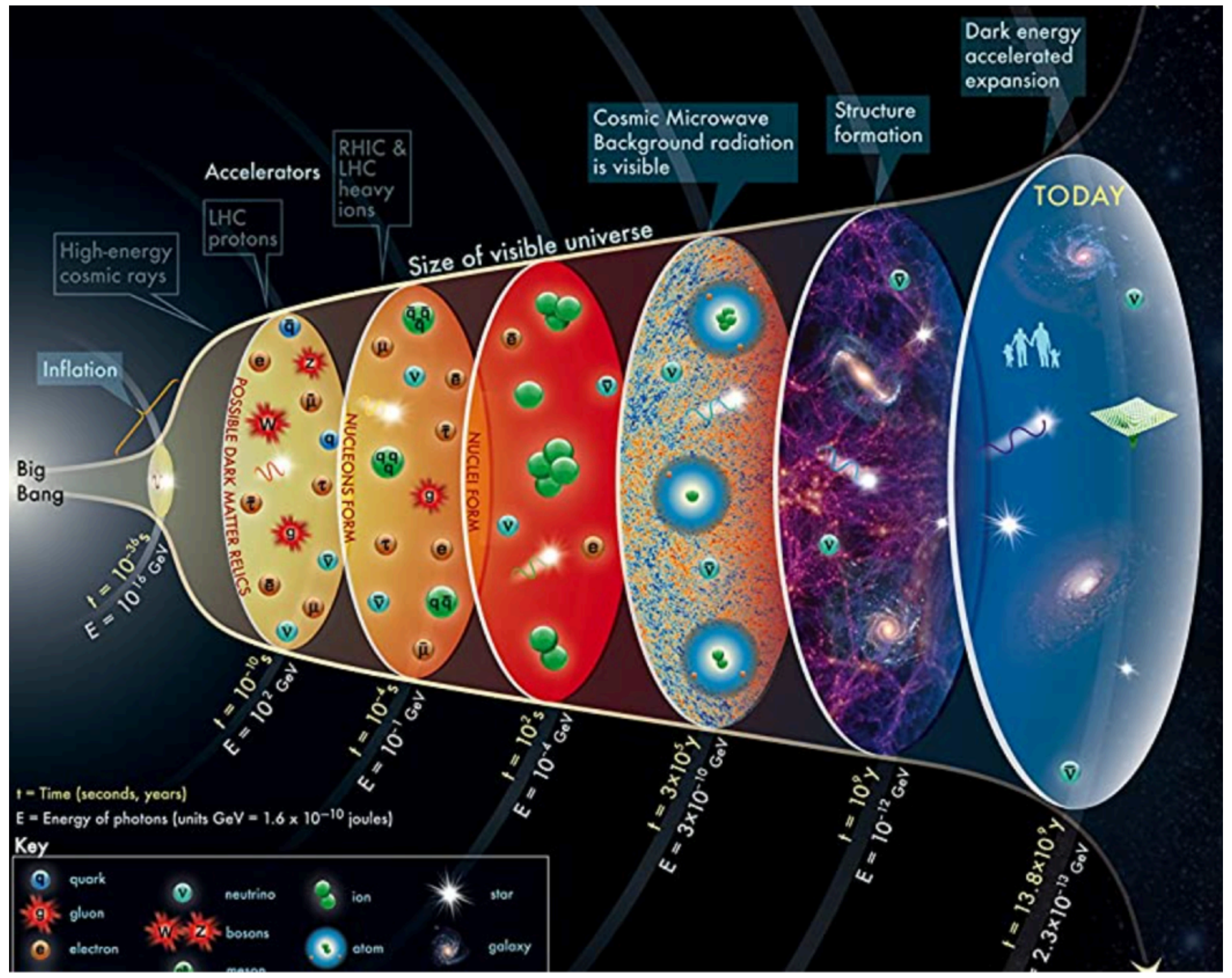
Oklahoma State University
17 Sep 2021

Structure of the talk

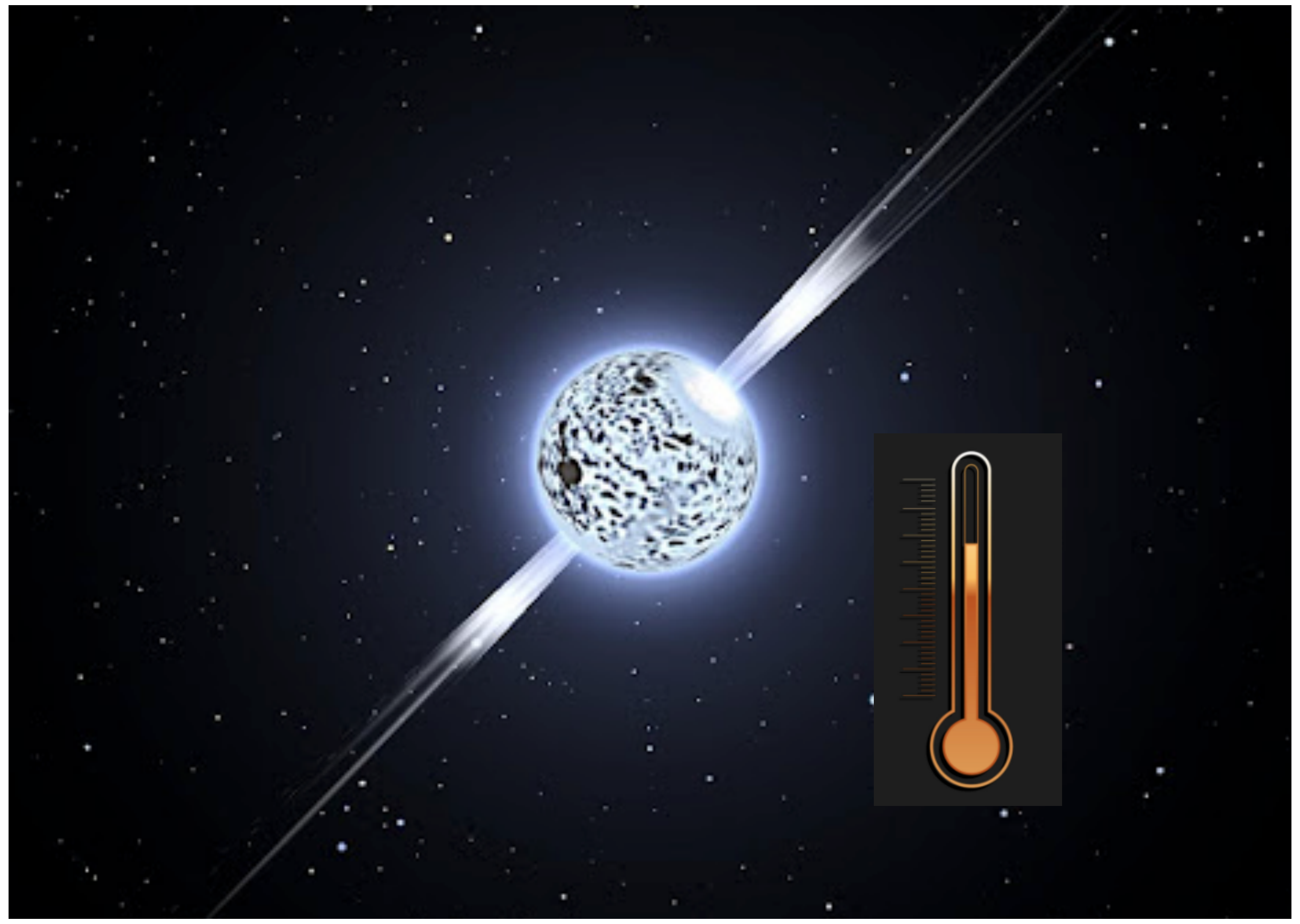


1 What? Whence? Why care?

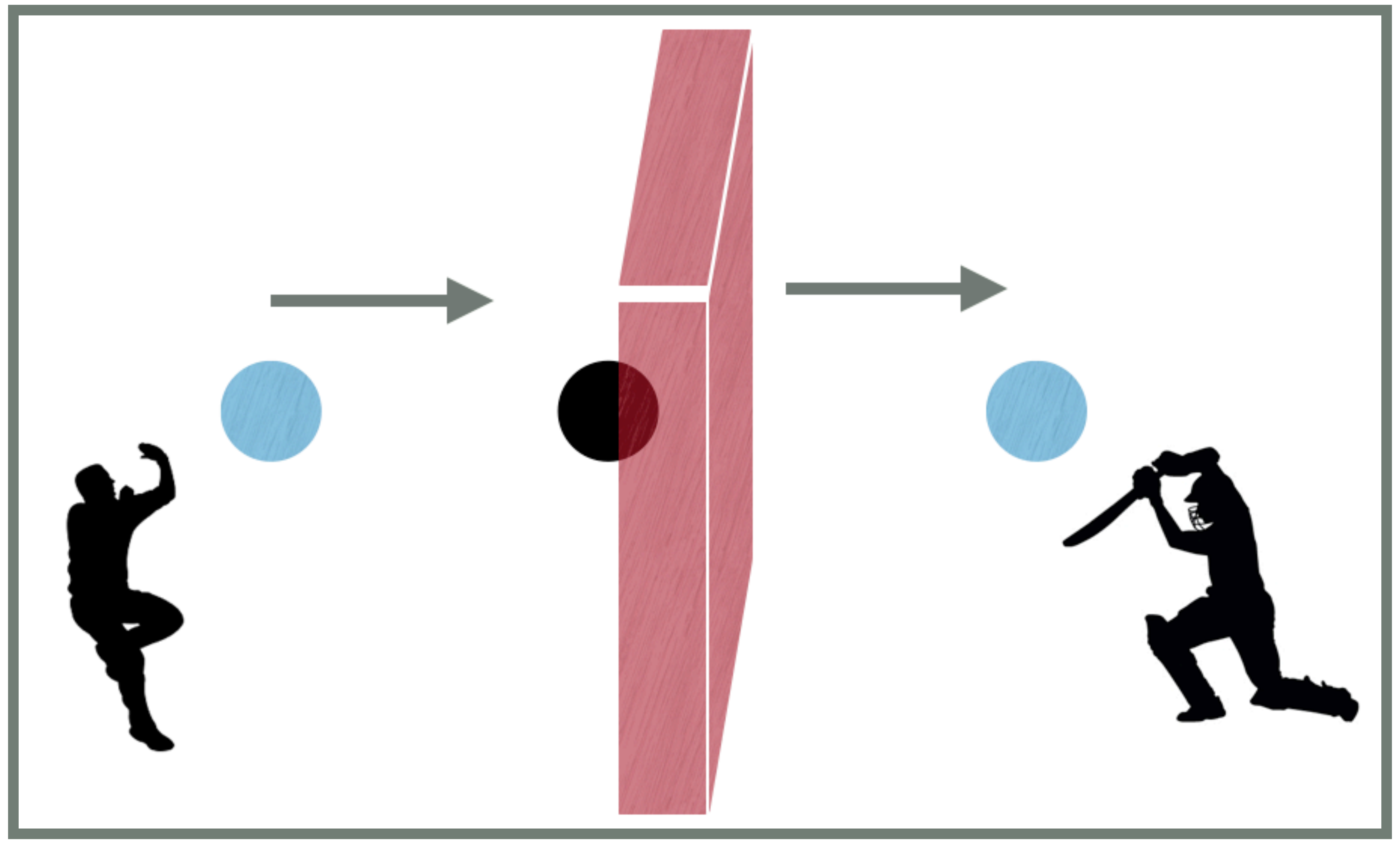
2 Discovering dark neutrons



reshaping early universe



overheating neutron stars



neutrons shining through a wall

Introduction

hypothesis:	a new particle "χ"
its character:	0 : charge under all fundamental forces
	1/2 : spin
	1 : baryon number

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
(hidden)

n

χ

m_n

m_χ

939.5654 MeV/c^2

?

neutron

"dark" neutron

n

χ

m_n

m_χ

939.5654 MeV/c^2

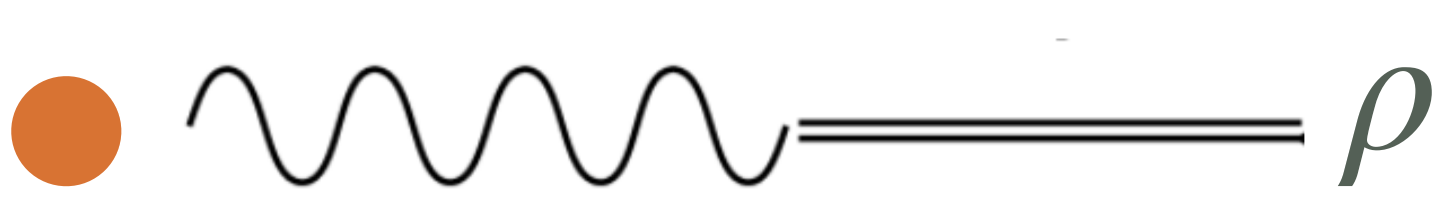
?

Hamiltonian

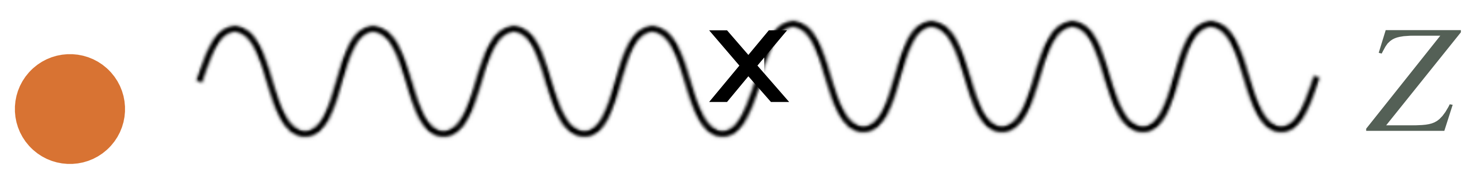
$$\begin{pmatrix} \bar{m}_n & \epsilon_{n\chi} \\ \epsilon_{n\chi} & \bar{m}_\chi \end{pmatrix}$$

$\epsilon_{n\chi}$ nothing forbids it: compulsory! => *quantum mixing*

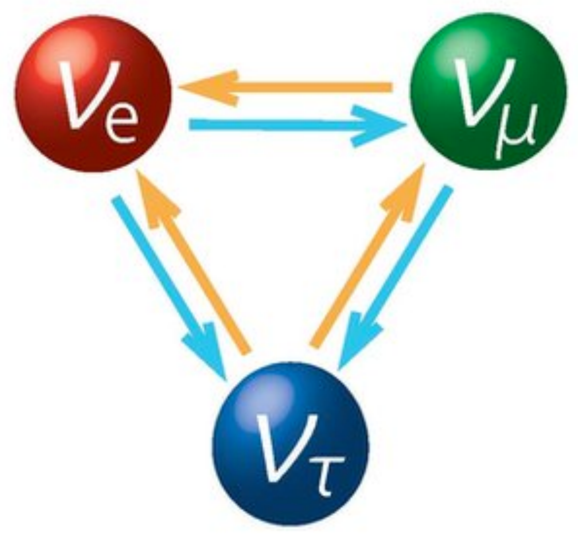
quantum mixing already seen in Nature:



photon - rho meson



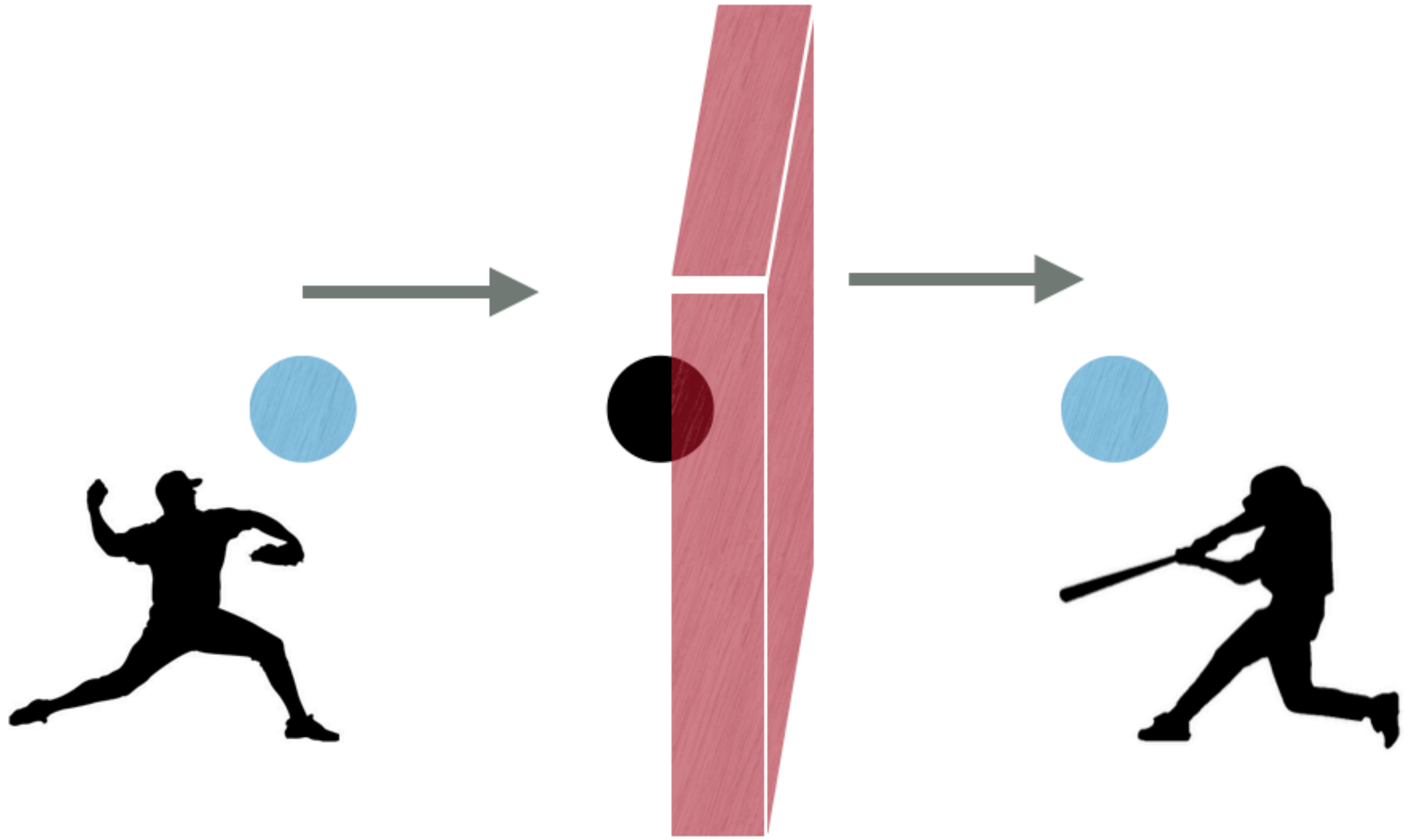
photon - Z boson



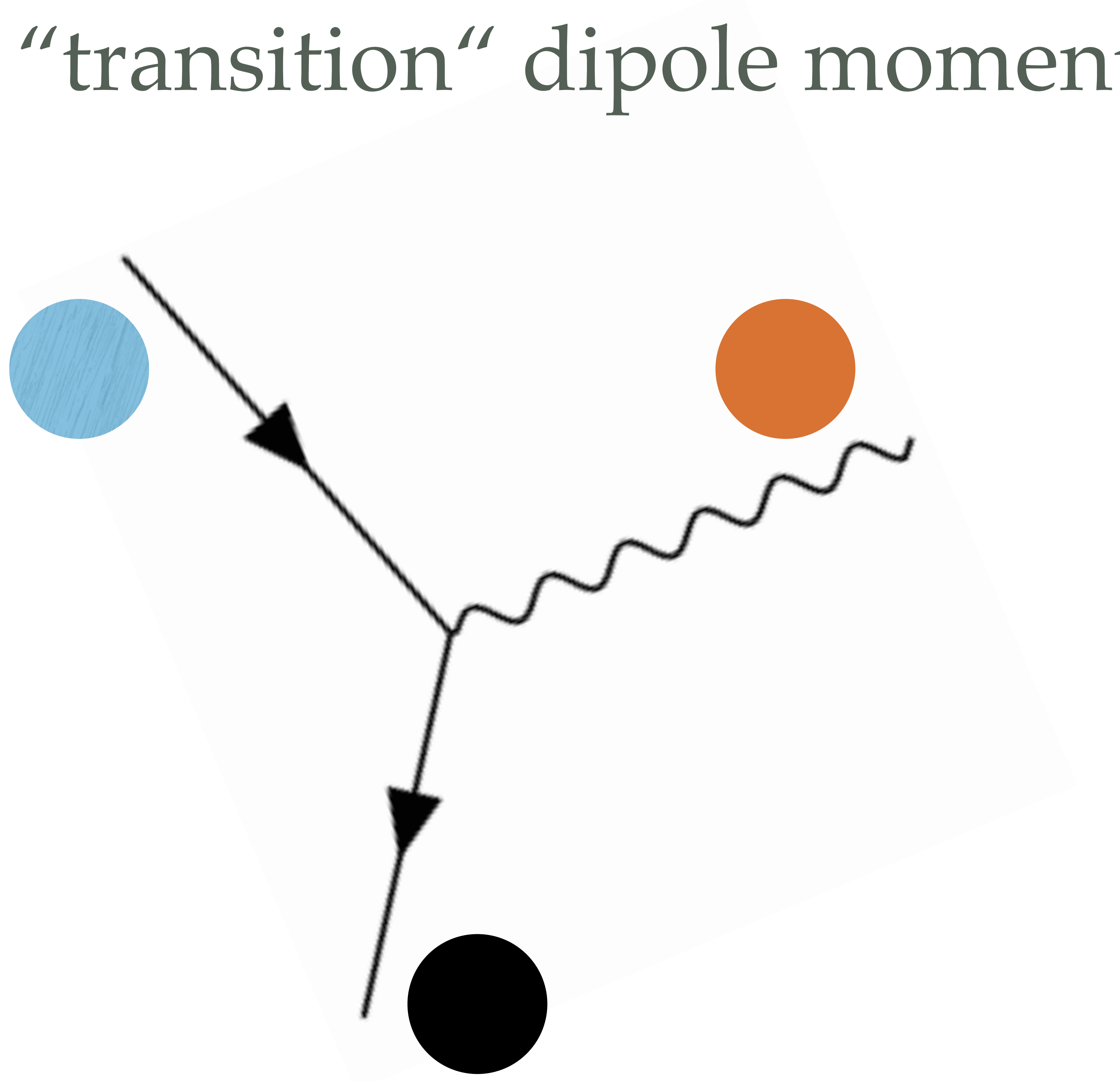
neutrino flavours

Consequences for neutrons

oscillations

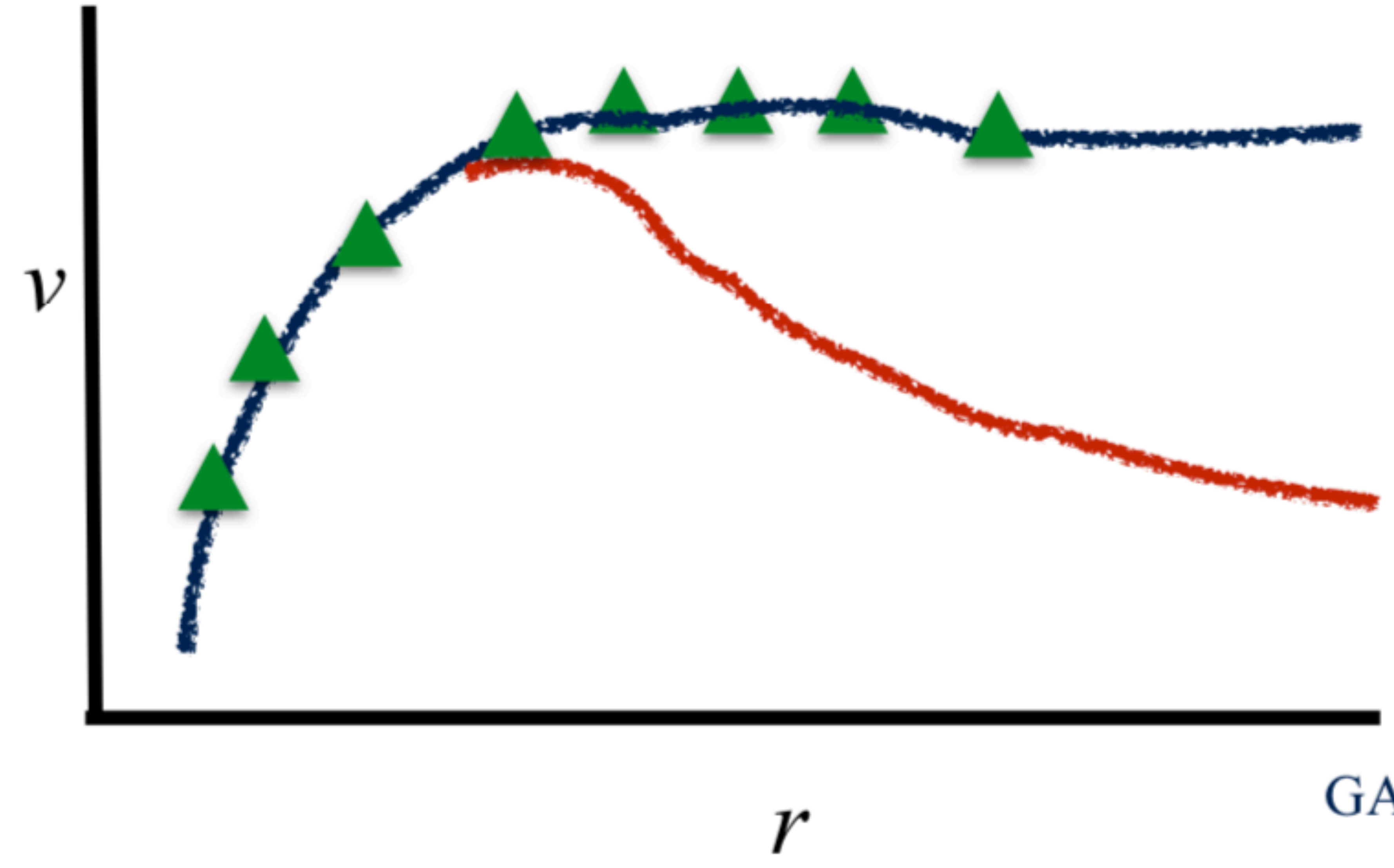


magnetic “transition“ dipole moment

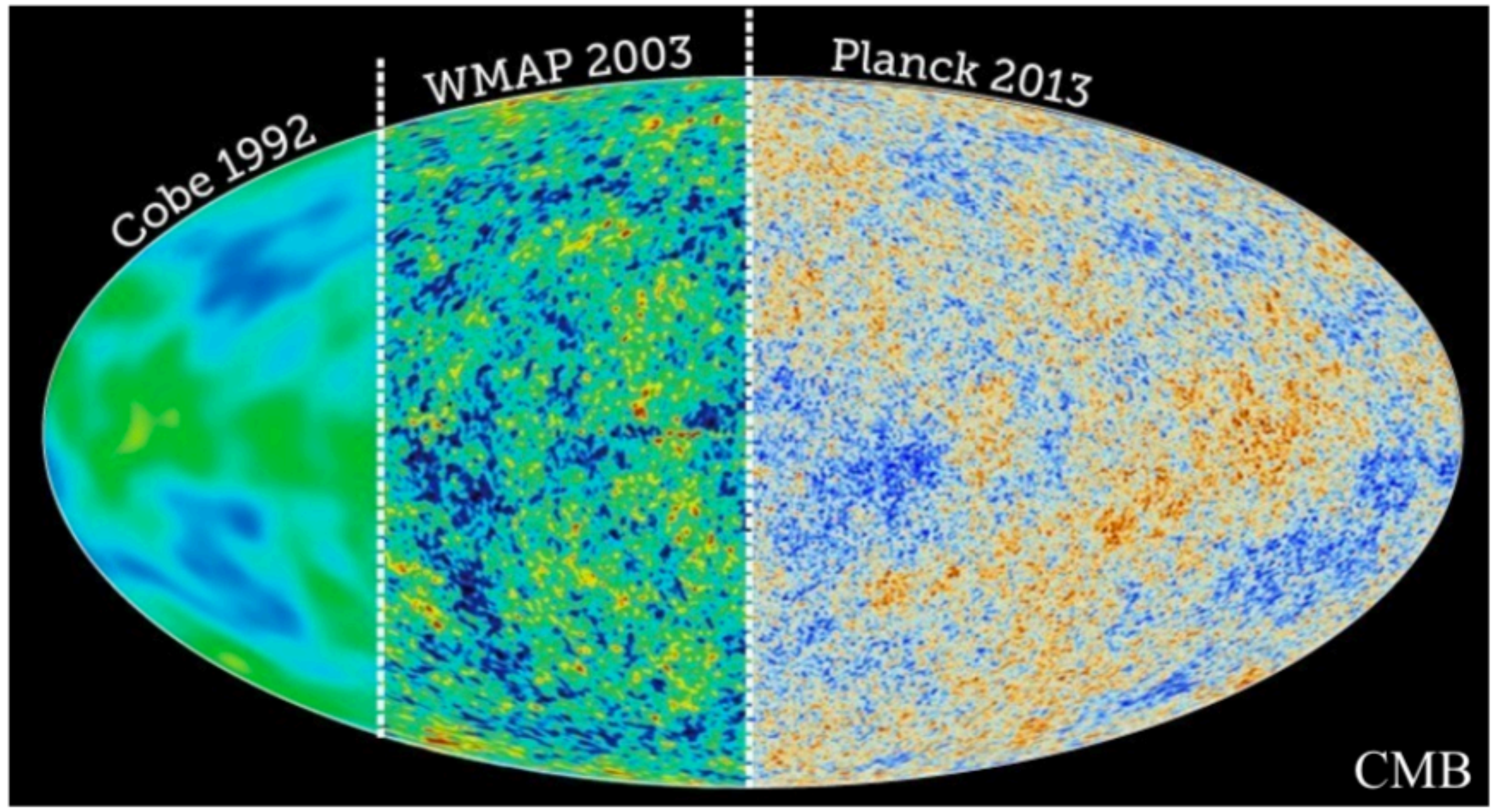


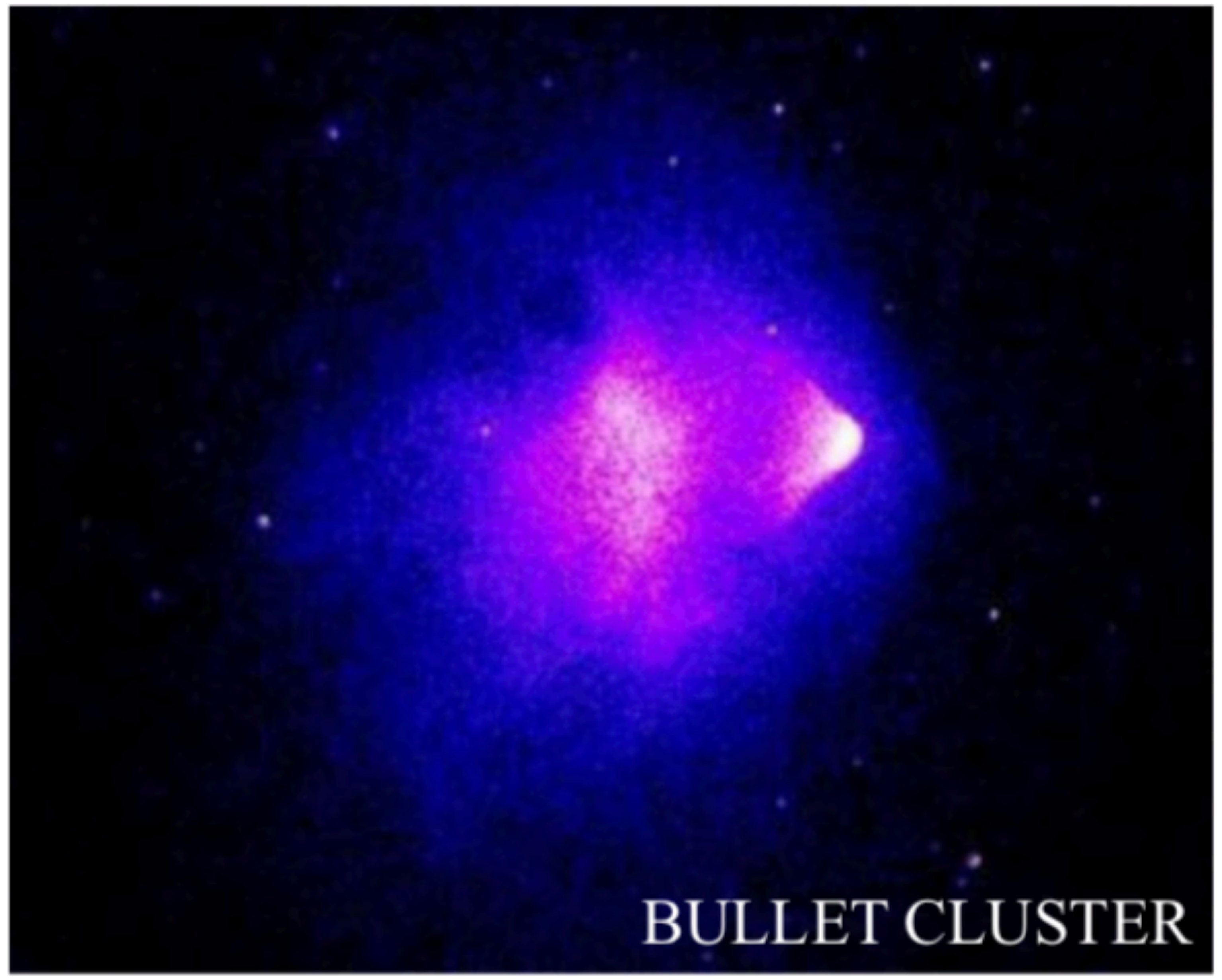
Why care?

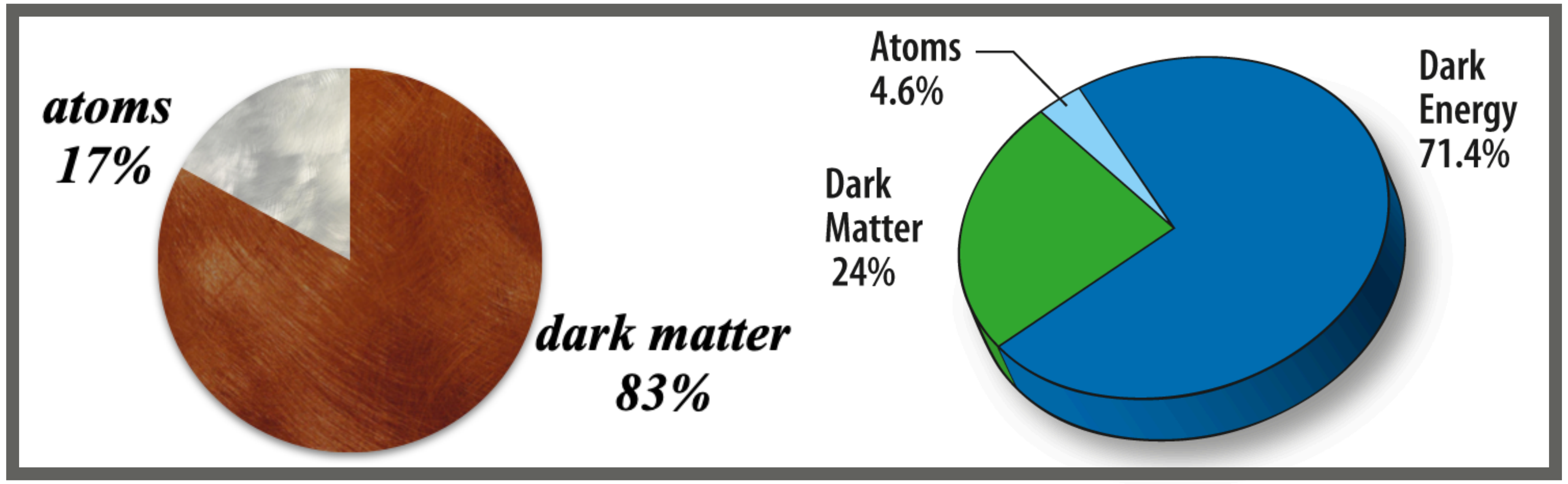
(1) the *dark matter* of the universe



GALACTIC ROTATION







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

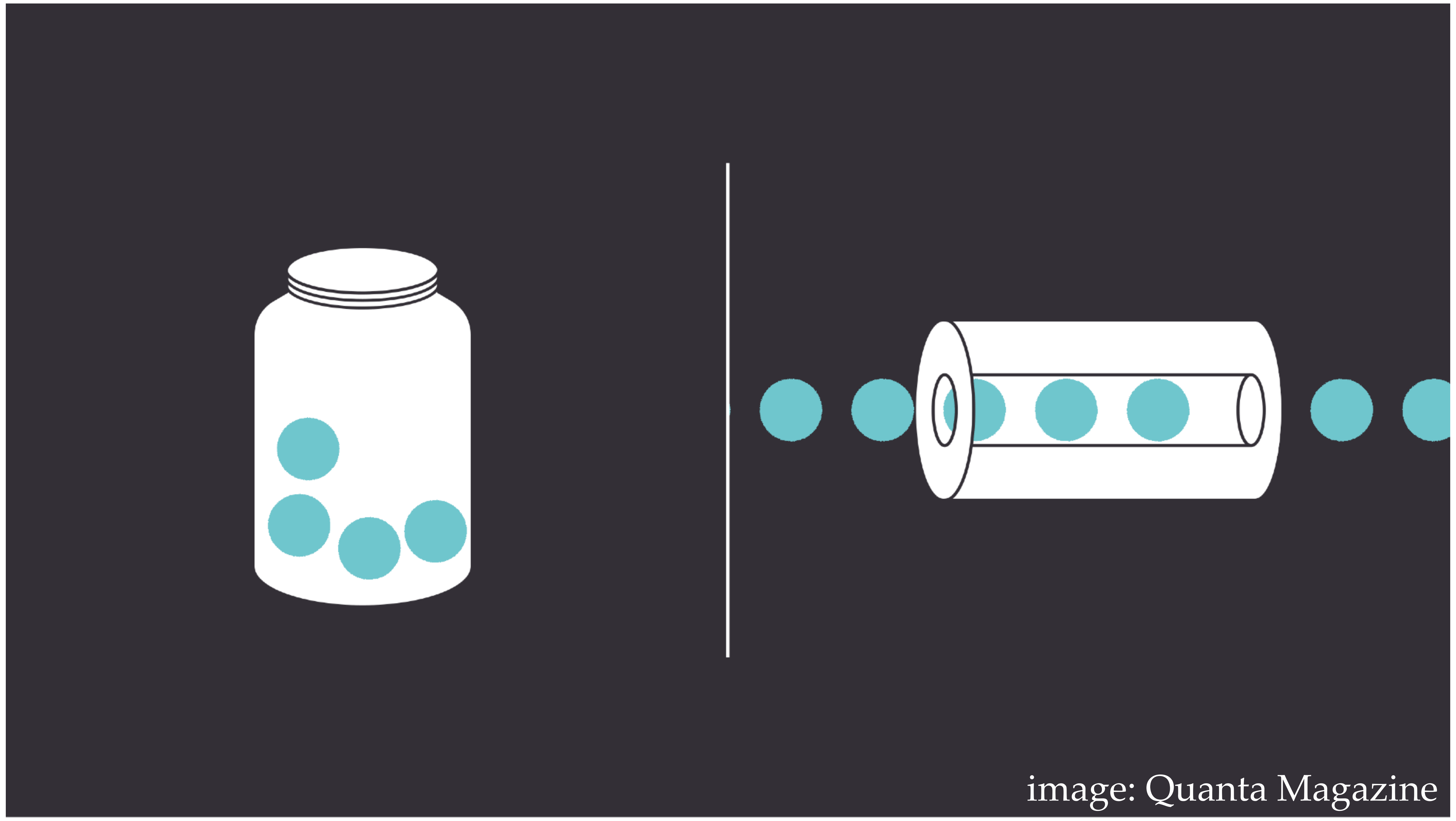
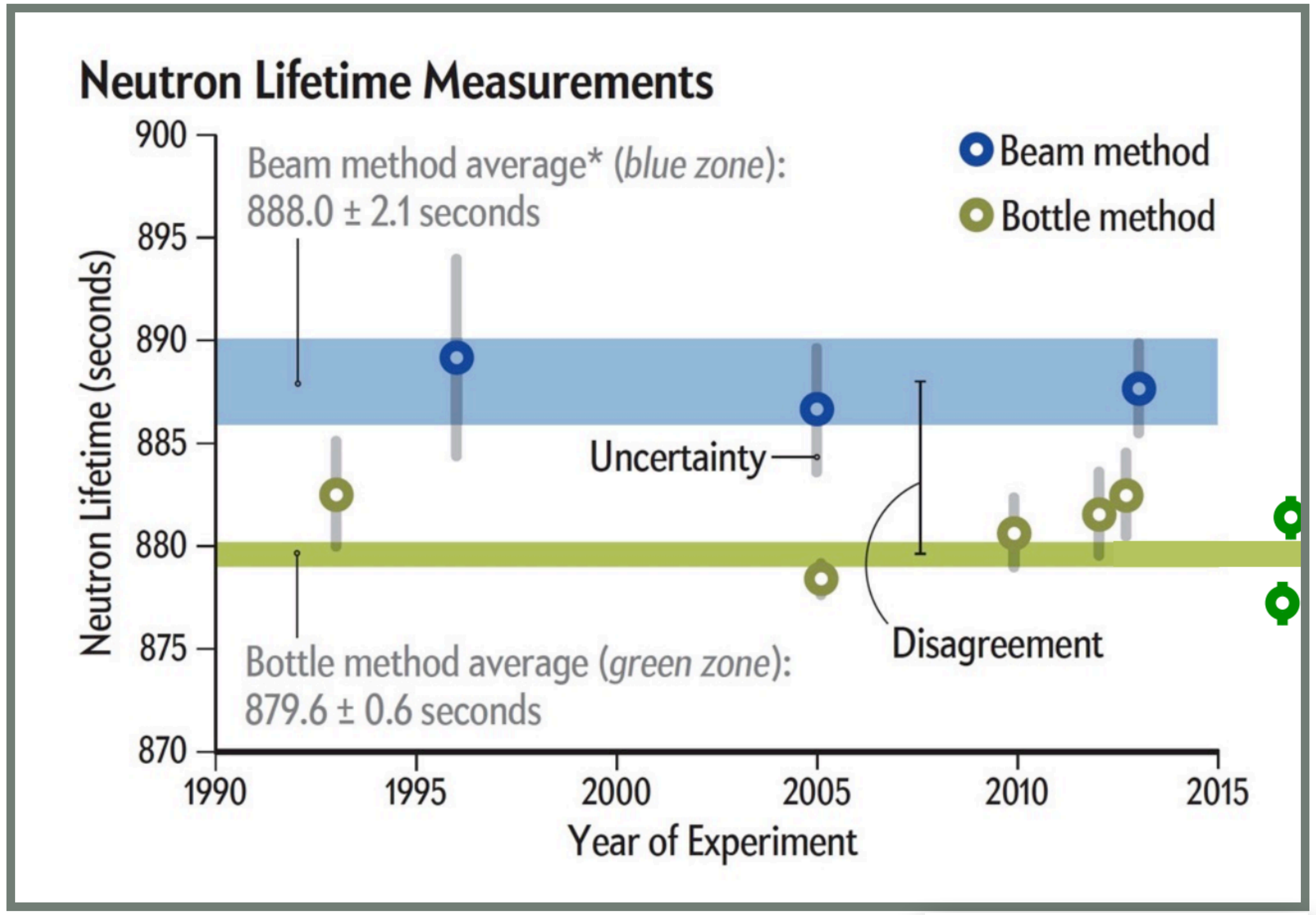


image: Quanta Magazine



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

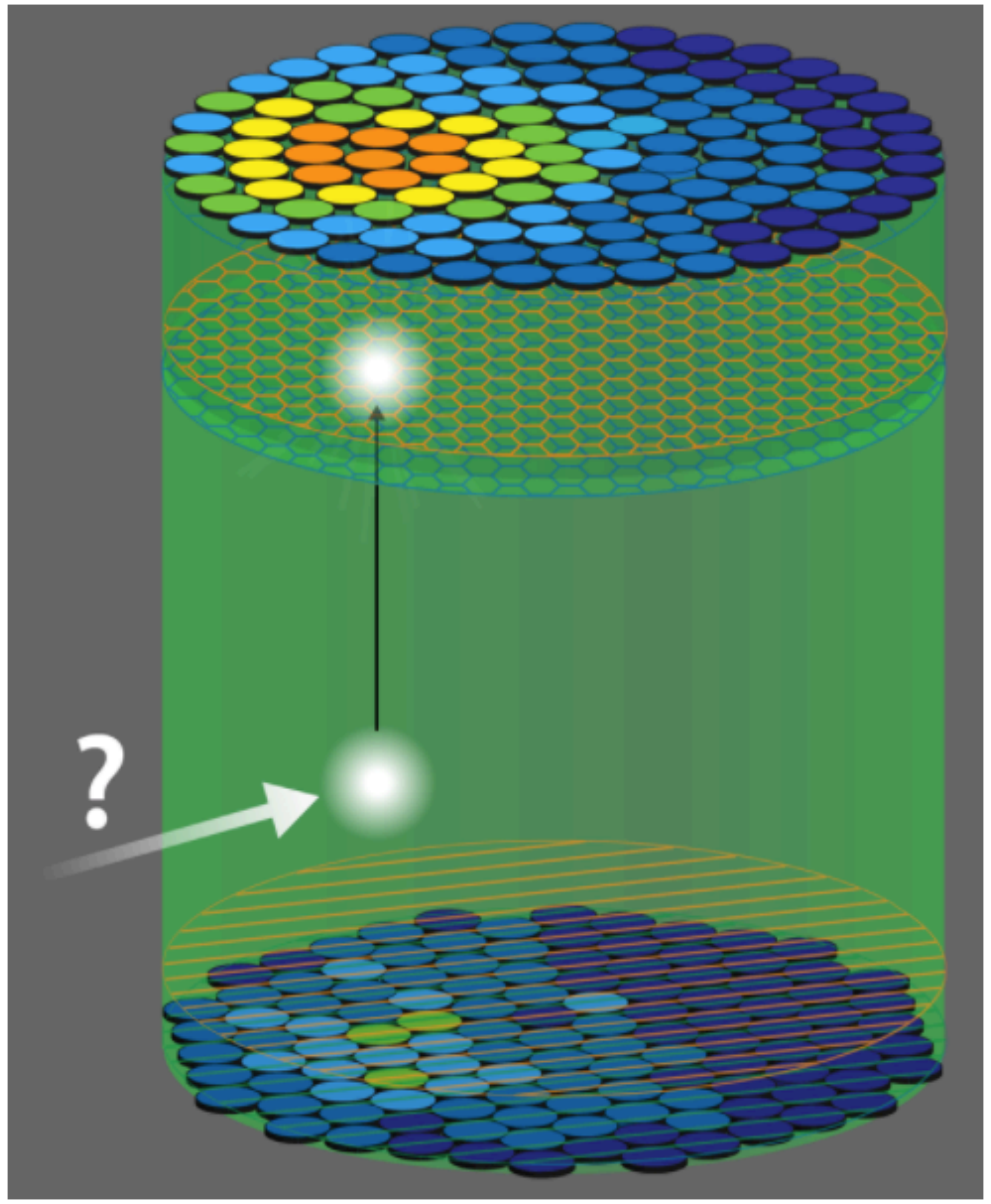
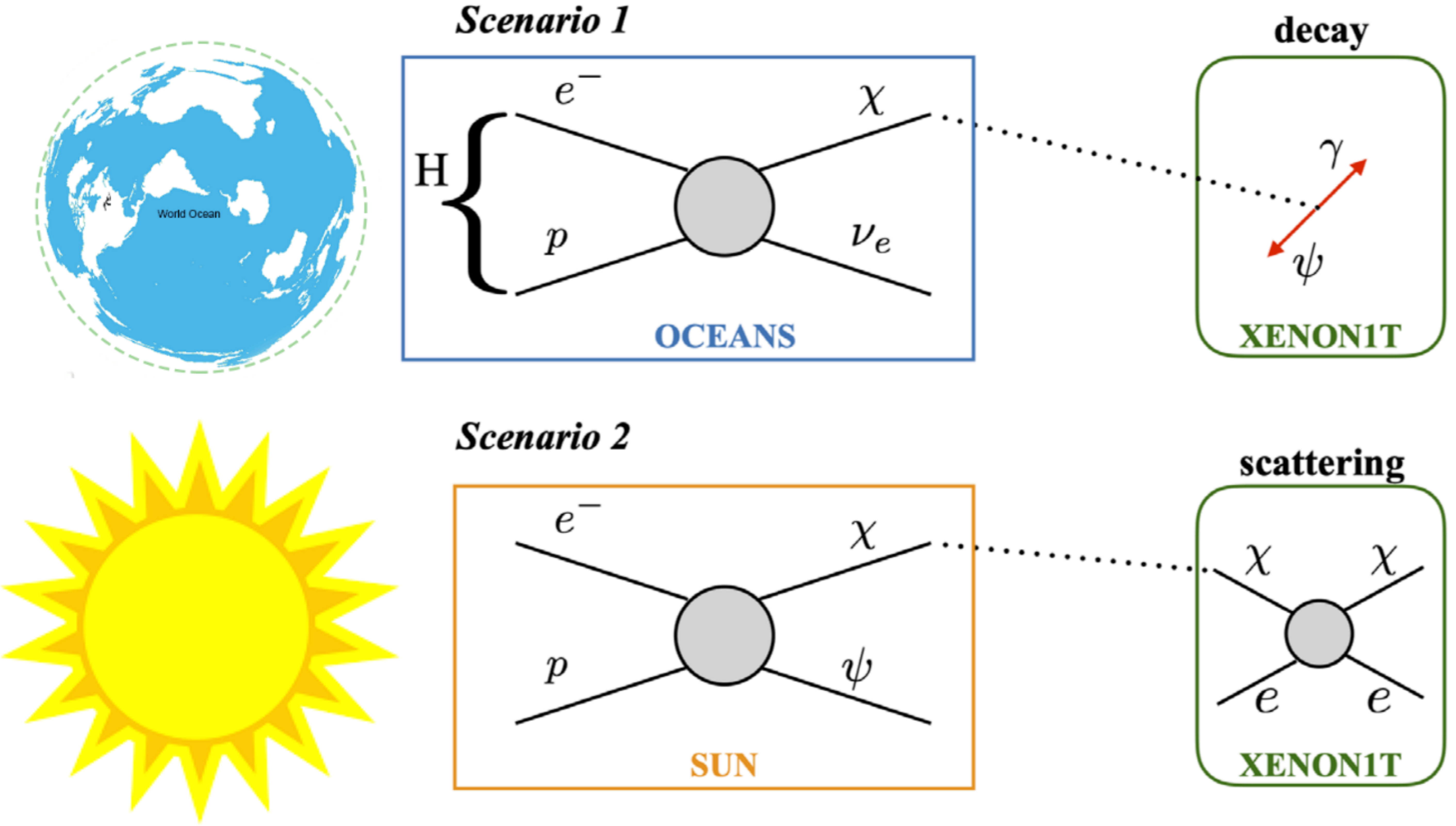


image: APS

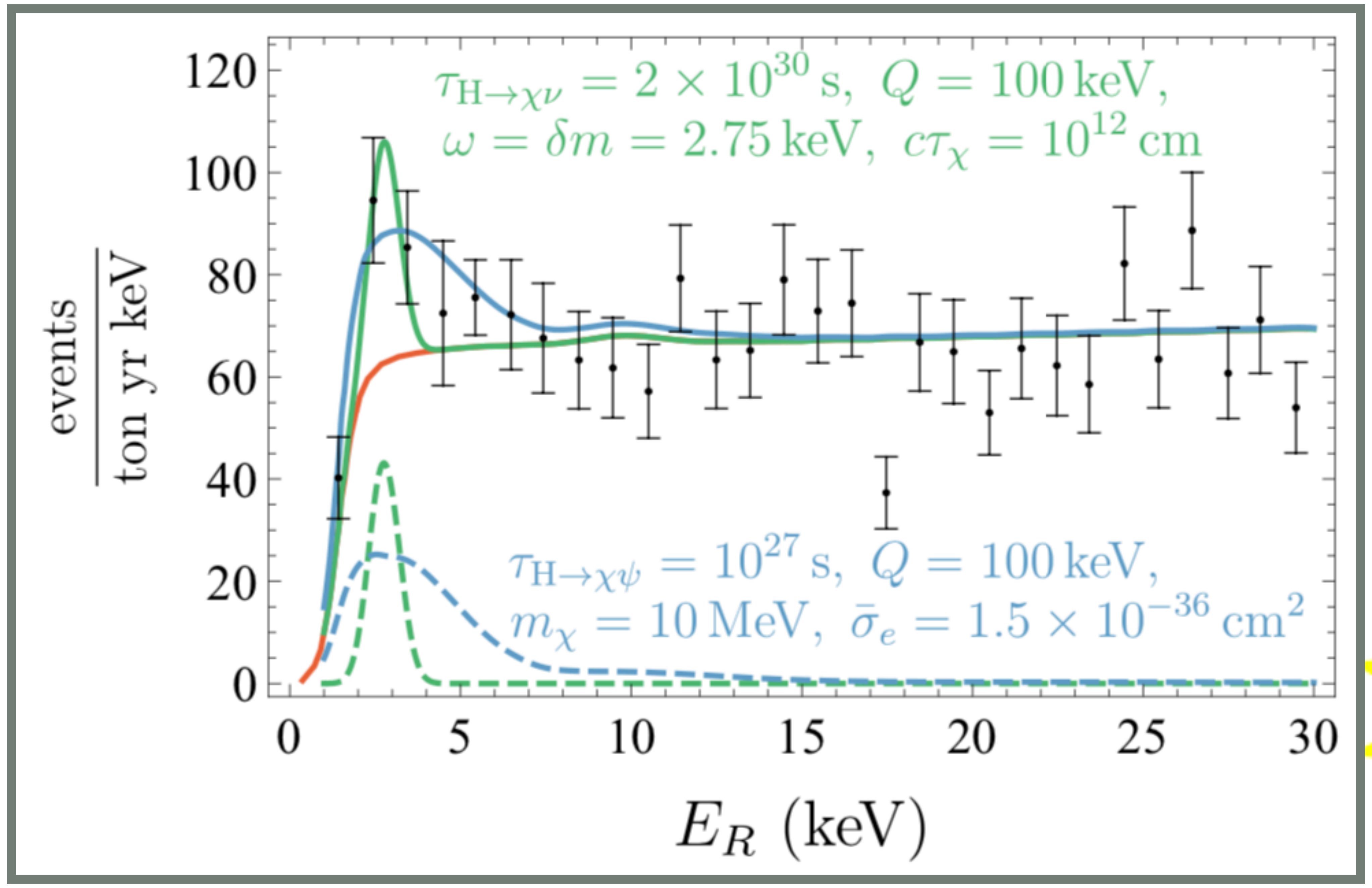
arXiv: 2006.09721

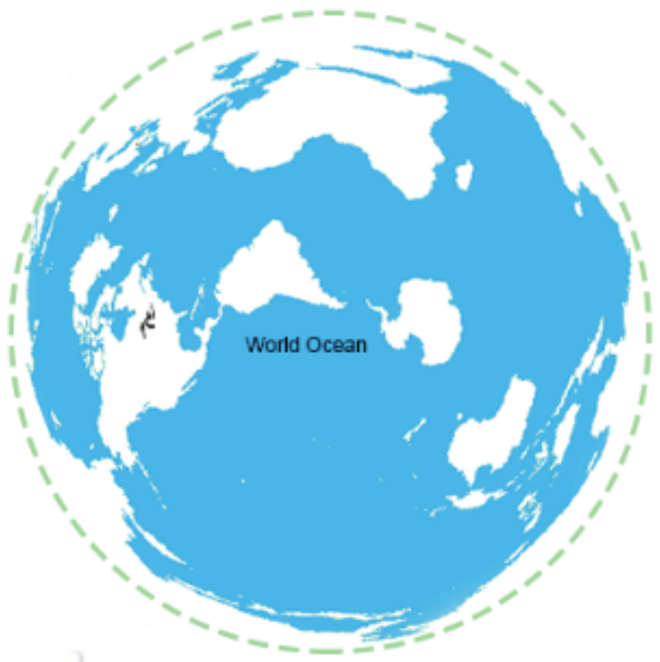


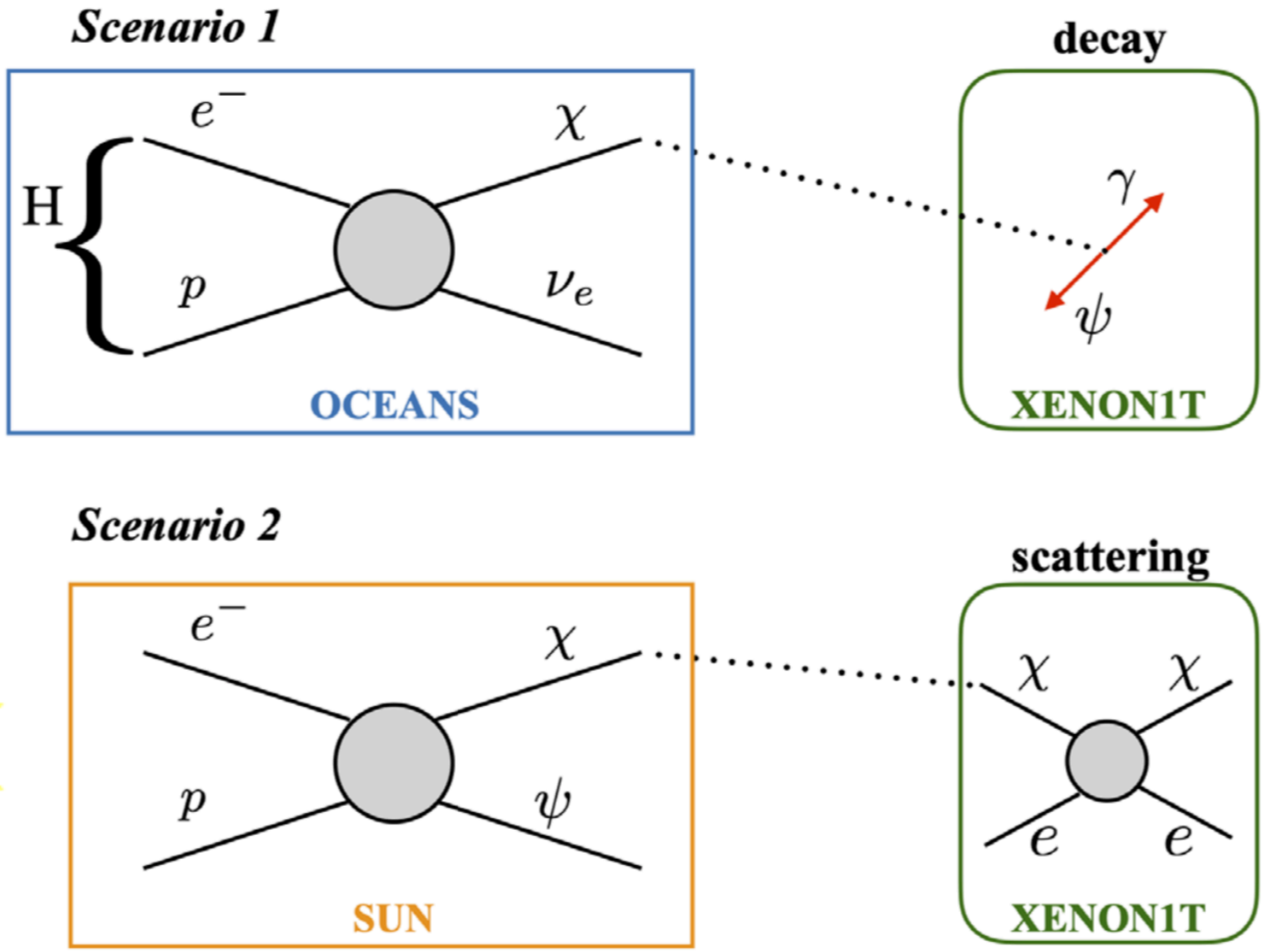
[*Phys. Rev. Lett.* **125**, 231803 (2020)] : McKeen, Pospelov, ***Raj***

Why care?

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



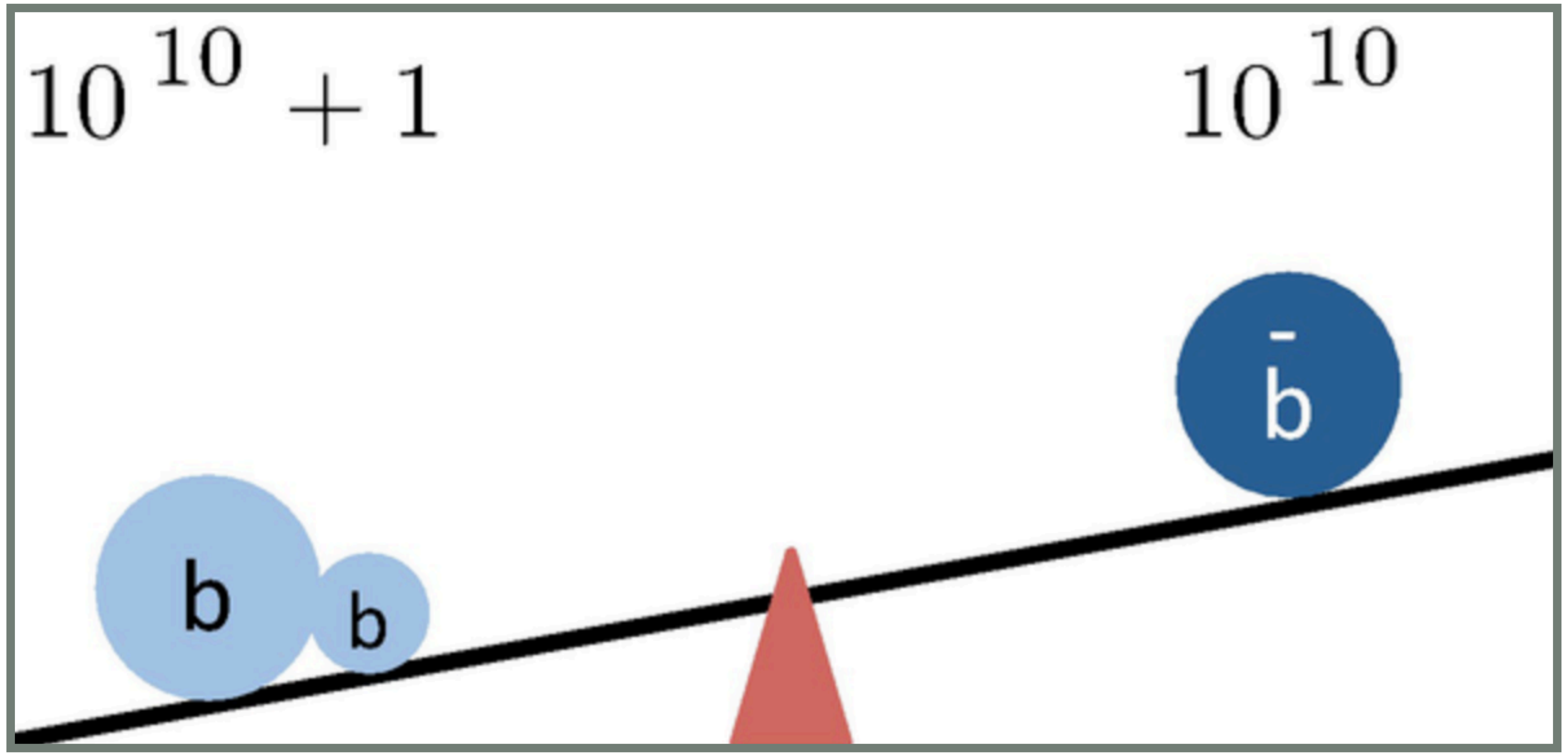




[*Phys. Rev. Lett.* **125**, 231803 (2020)] : McKeen, Pospelov, ***Raj***

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].

From where?

elementary

@ hadron level :

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

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

$\mu_n = -1.91 \mu_N$

neutron magnetic moment

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

($\mu_N = e/(2m_n) \simeq 0.1\ e\,\text{fm}$
nuclear magneton)

From where?

elementary

@ hadron level :

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

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

$$\mu_n = -1.91 \mu_N$$

neutron magnetic moment

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

($\mu_N = e/(2m_n) \simeq 0.1\ e\,\text{fm}$
nuclear magneton)

exotic neutron decay

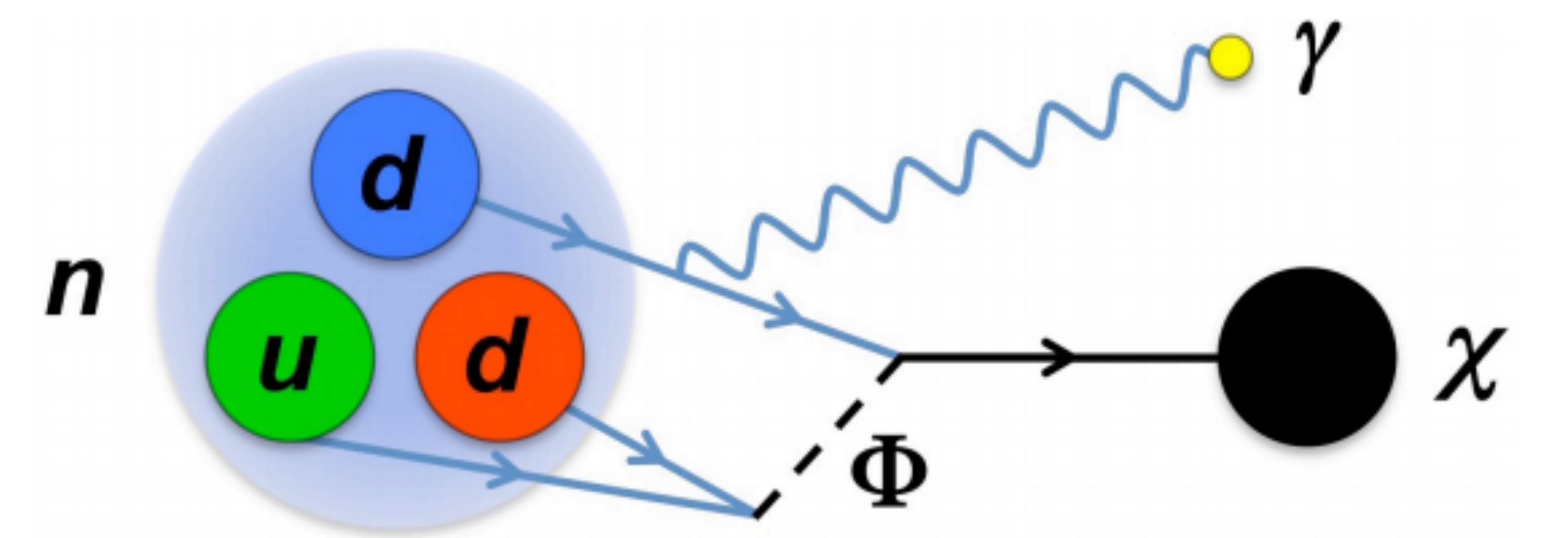


image: Fornal & Grinstein

n lifetime puzzle:

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

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

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

From where?

composite

from *mirror sector*

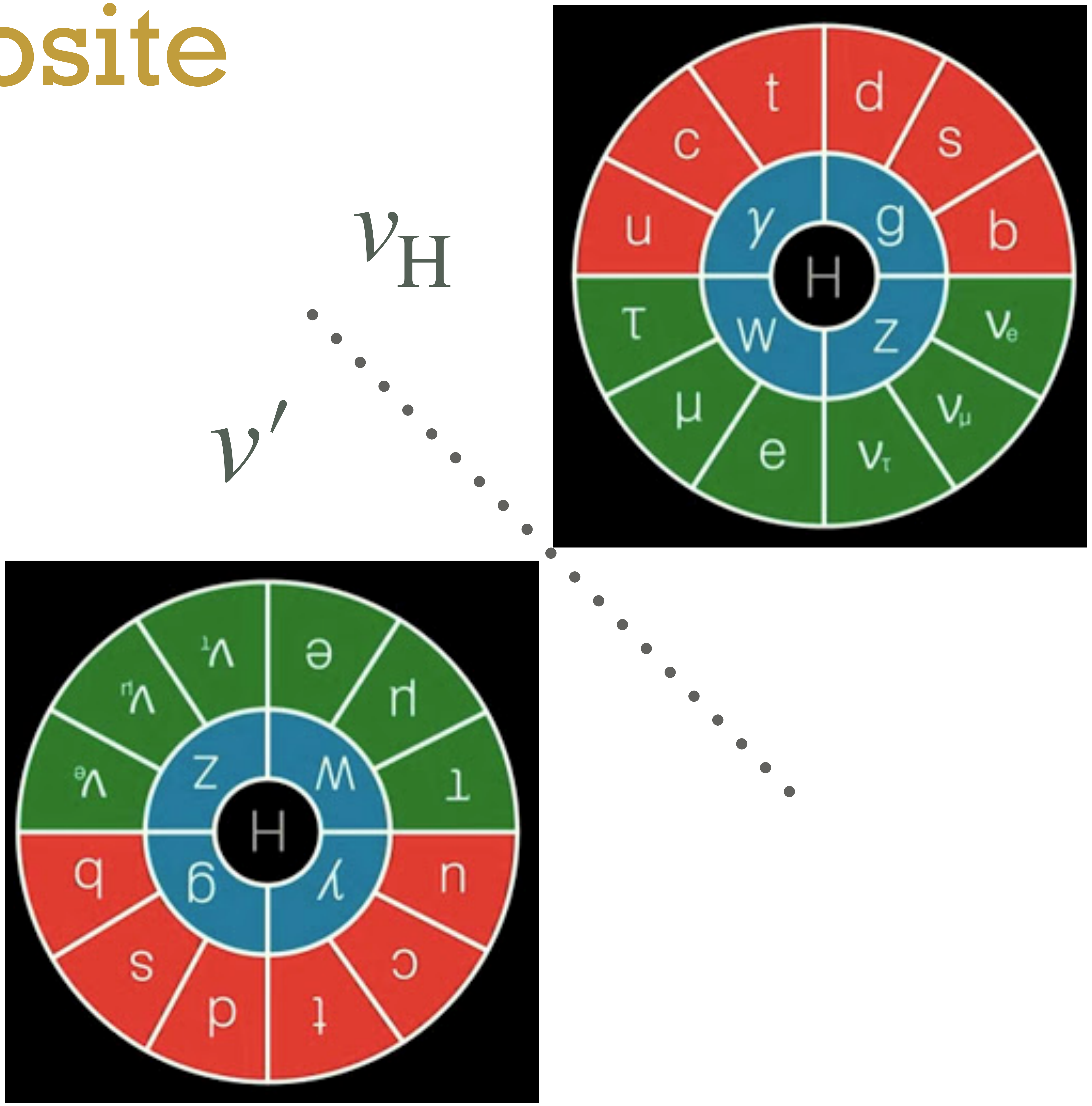
very early idea of "dark sector",

can address:

+ Why is $v_H \ll M_{\text{Planck}}$?
(Twin Higgs realization)

+ dark matter

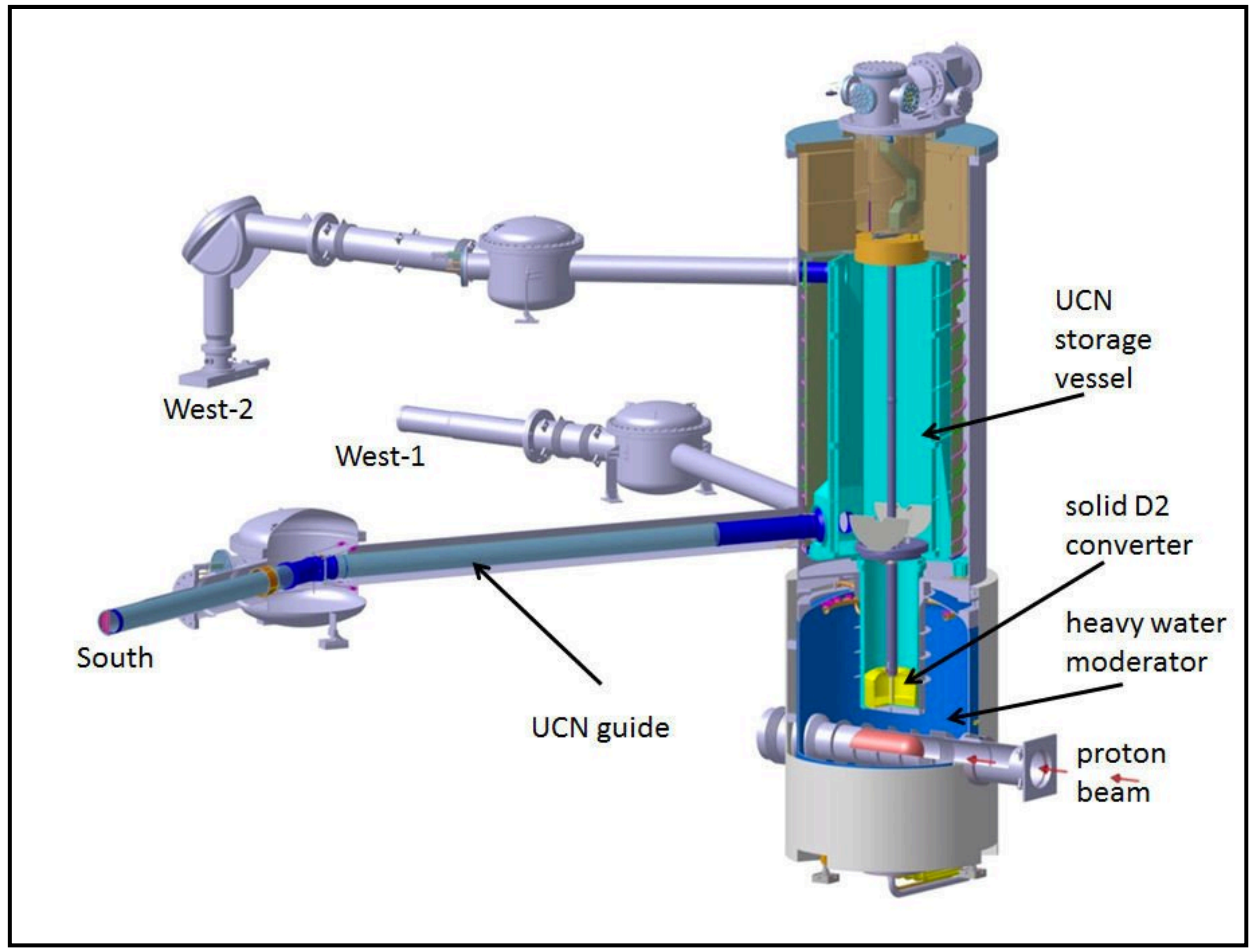
+ baryogenesis

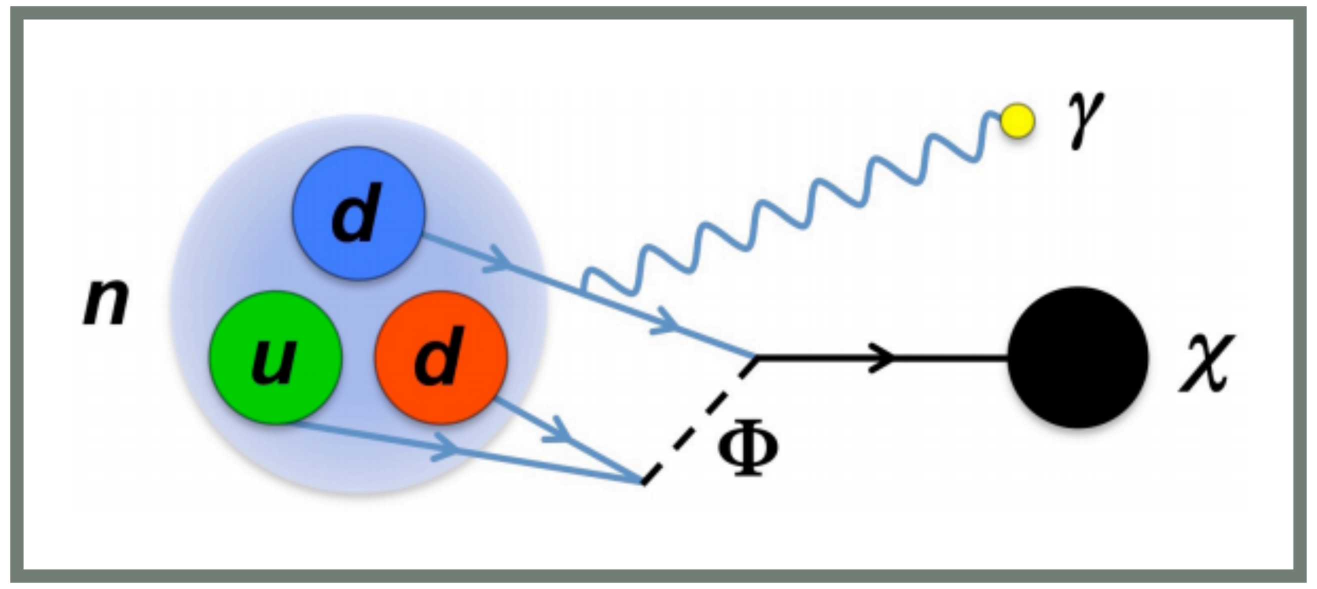


Kobzarev, Okun, Pomeranchuk 1966

Where to find?

(0) *ultra-cold neutron facilities*

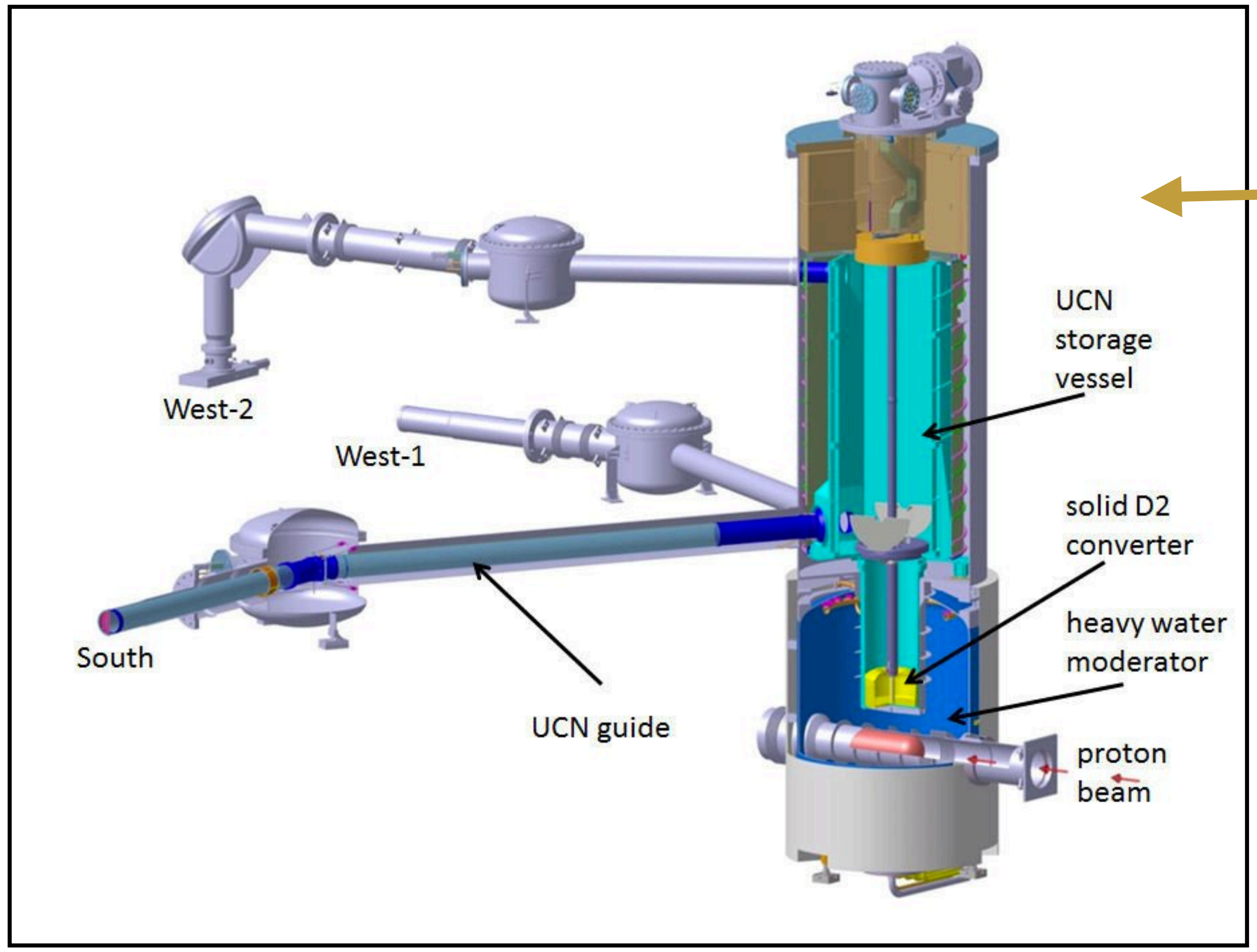


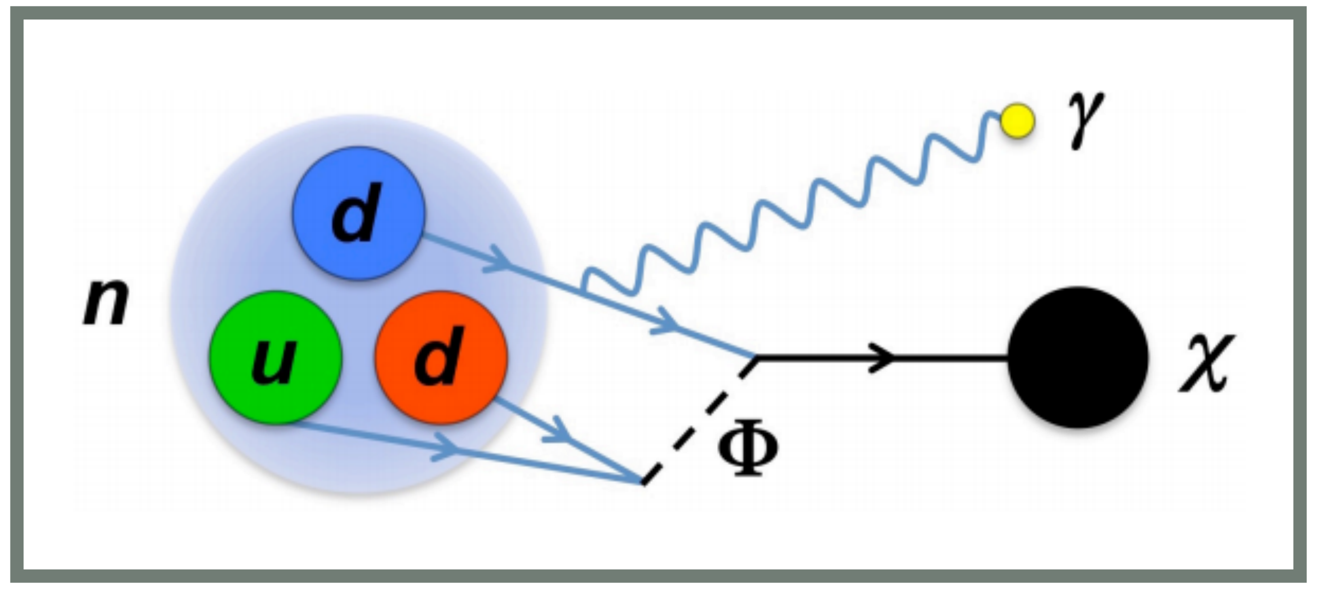


UCN @ TRIUMF

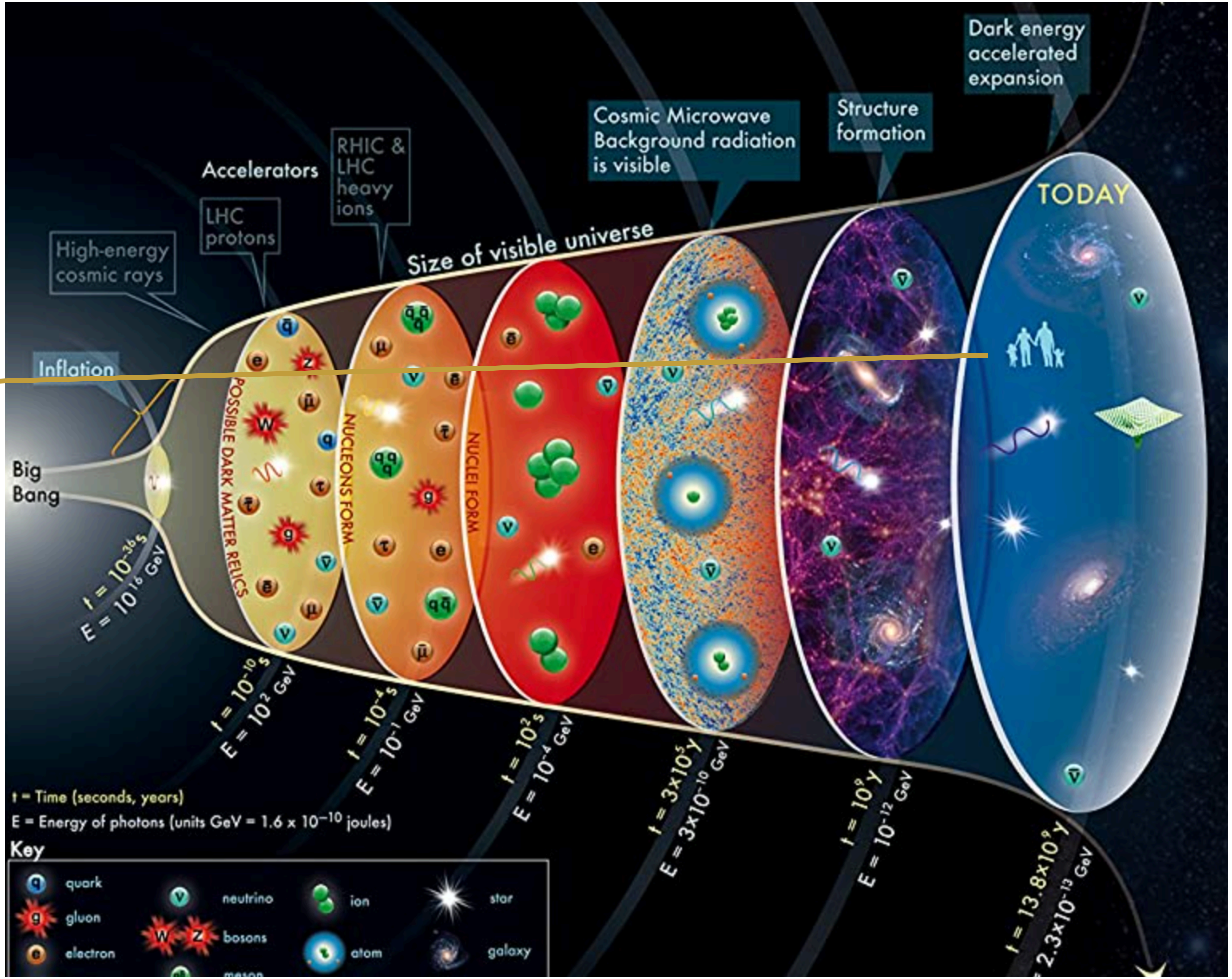
Where to find?

(0) *ultra-cold neutron facilities*





timeline of the universe



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)

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

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

above QCD transition => quark level description required

Prehistoric census

Interesting cases:

(i) $n_\chi^0 = 5.4(n_p^0 + n_n^0)$ (χ is the dark matter if $\tau_\chi > t_U$)

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

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

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

above QCD transition => quark level description required

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

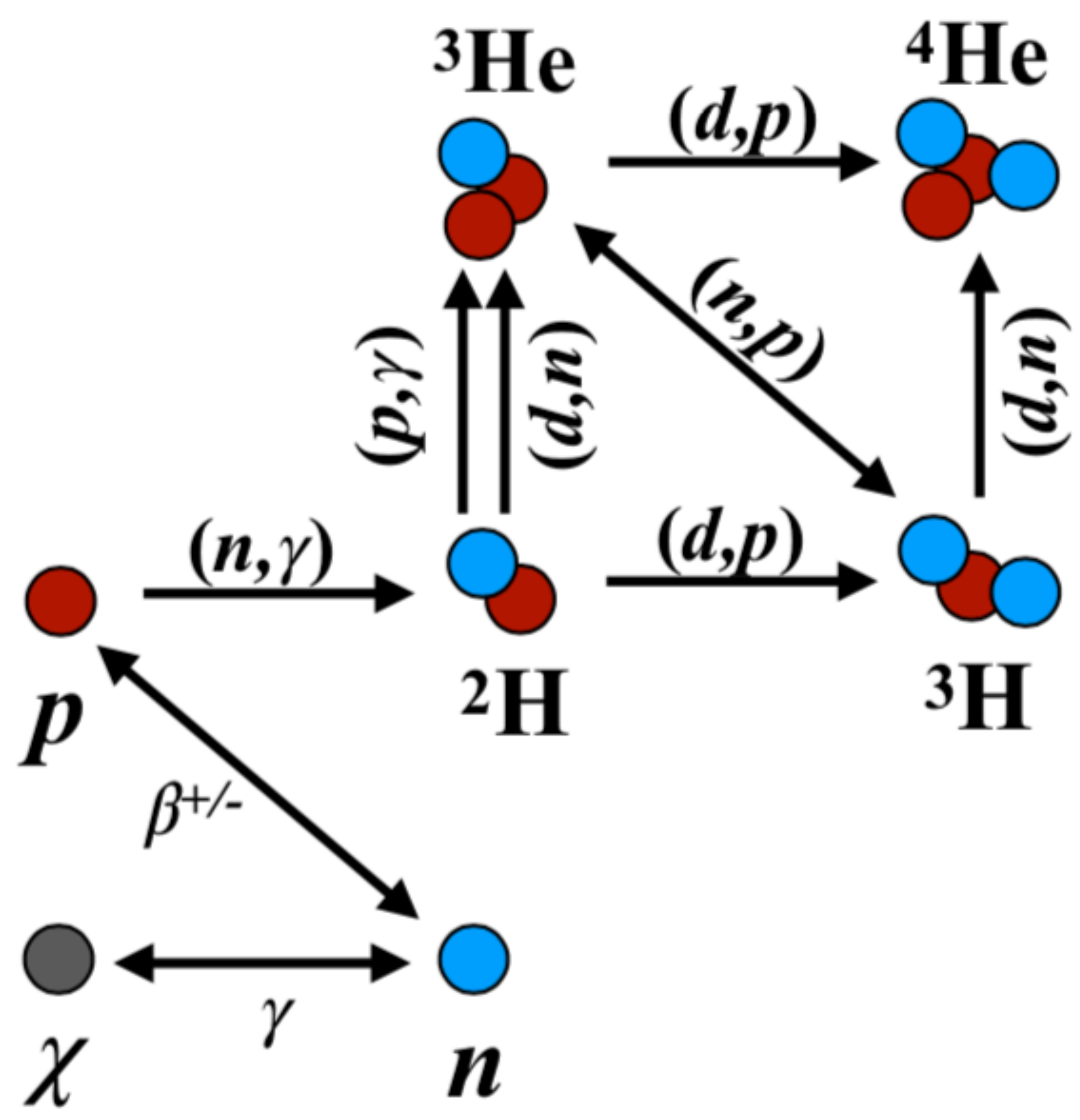
chemical equilbrium keepable down to T ~ GeV—PeV

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

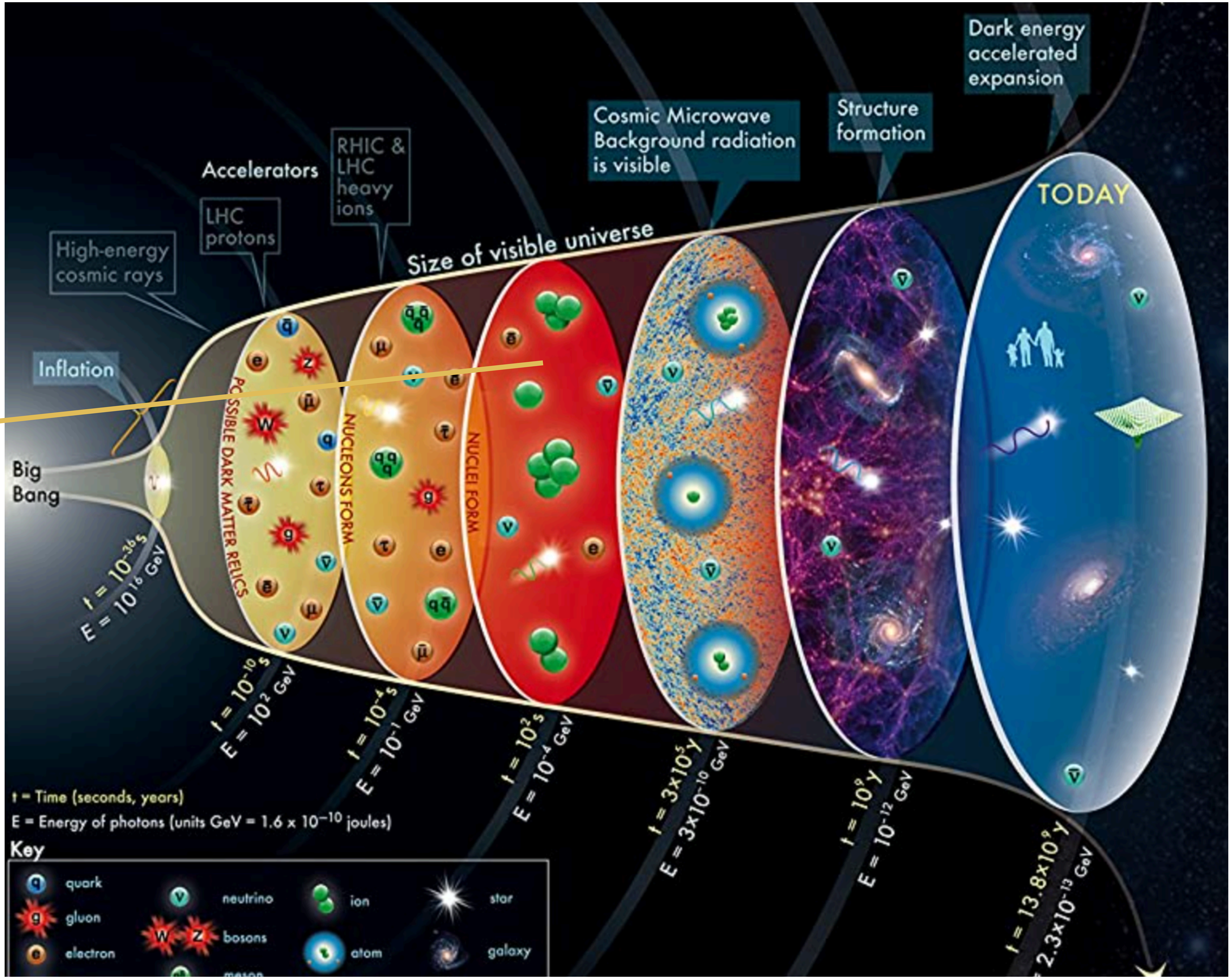
⇢ $n_\chi \sim n_p = n_n$ reasonable since universe was probably that hot

Where to find?

(1) *synthesis of nuclei*:
earliest epoch of
Big Bang cosmology



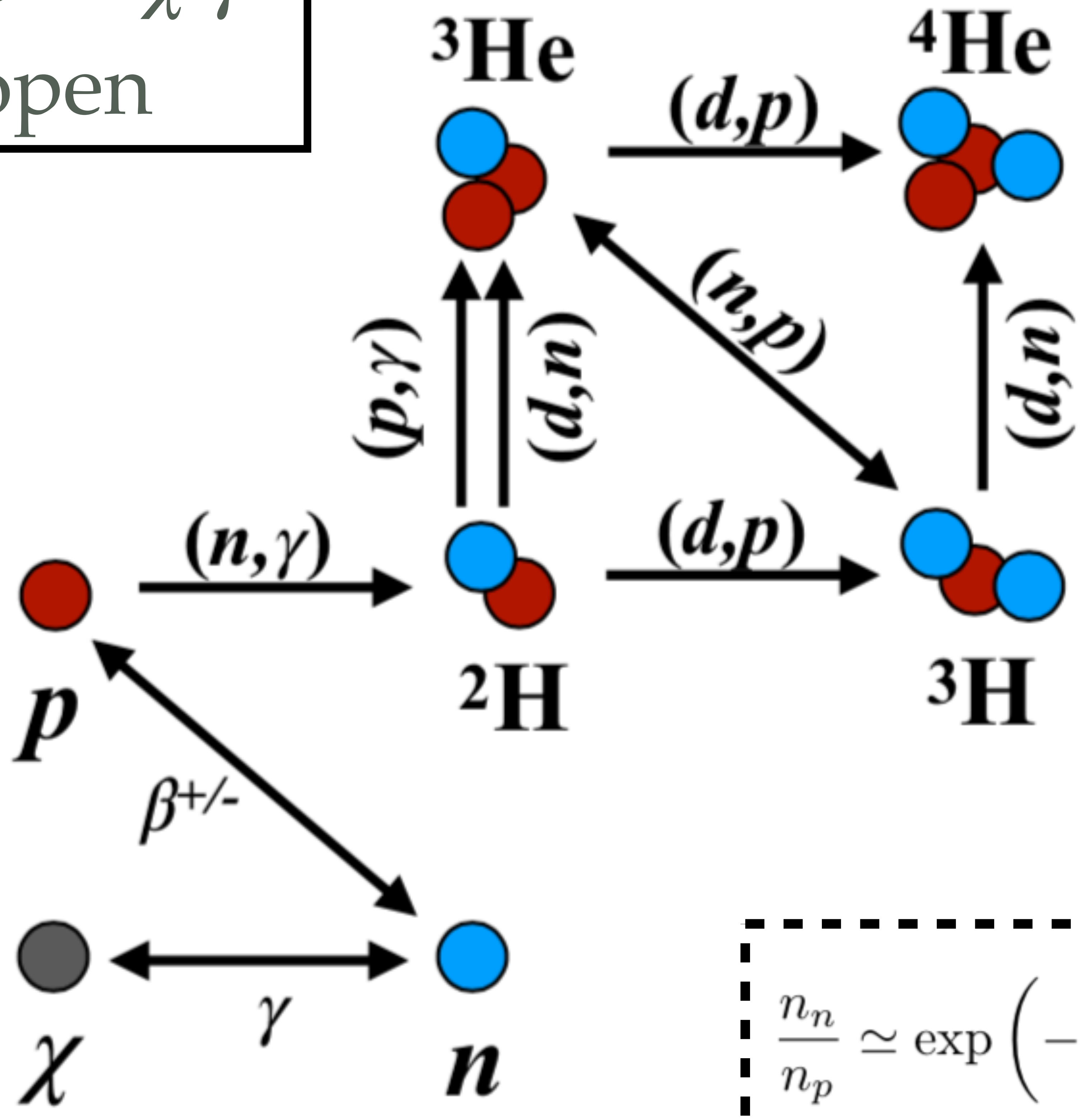
timeline of the universe



PRD 2021 *McKeen, Pospelov, Raj*

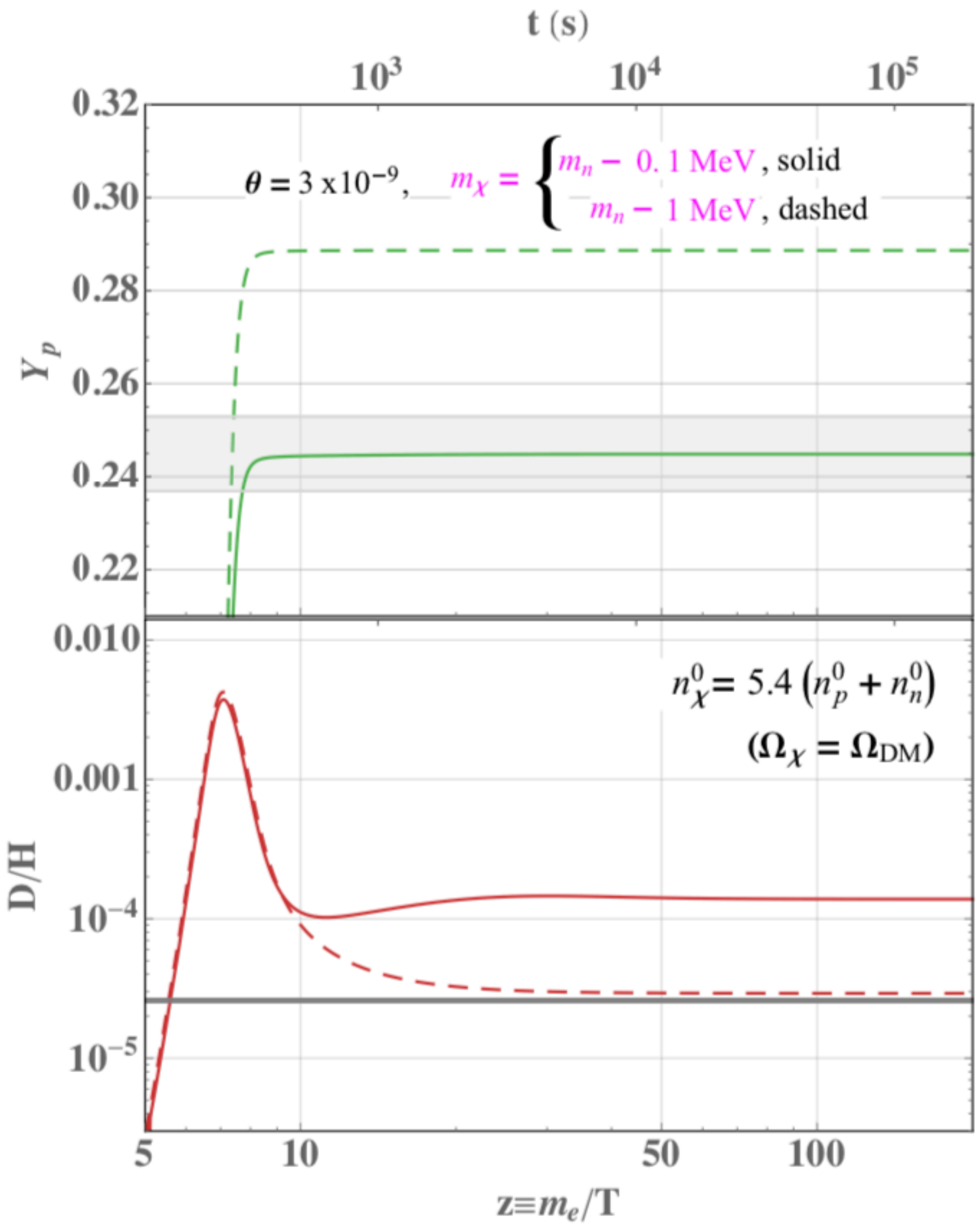
Primordial nucleosynthesis

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



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

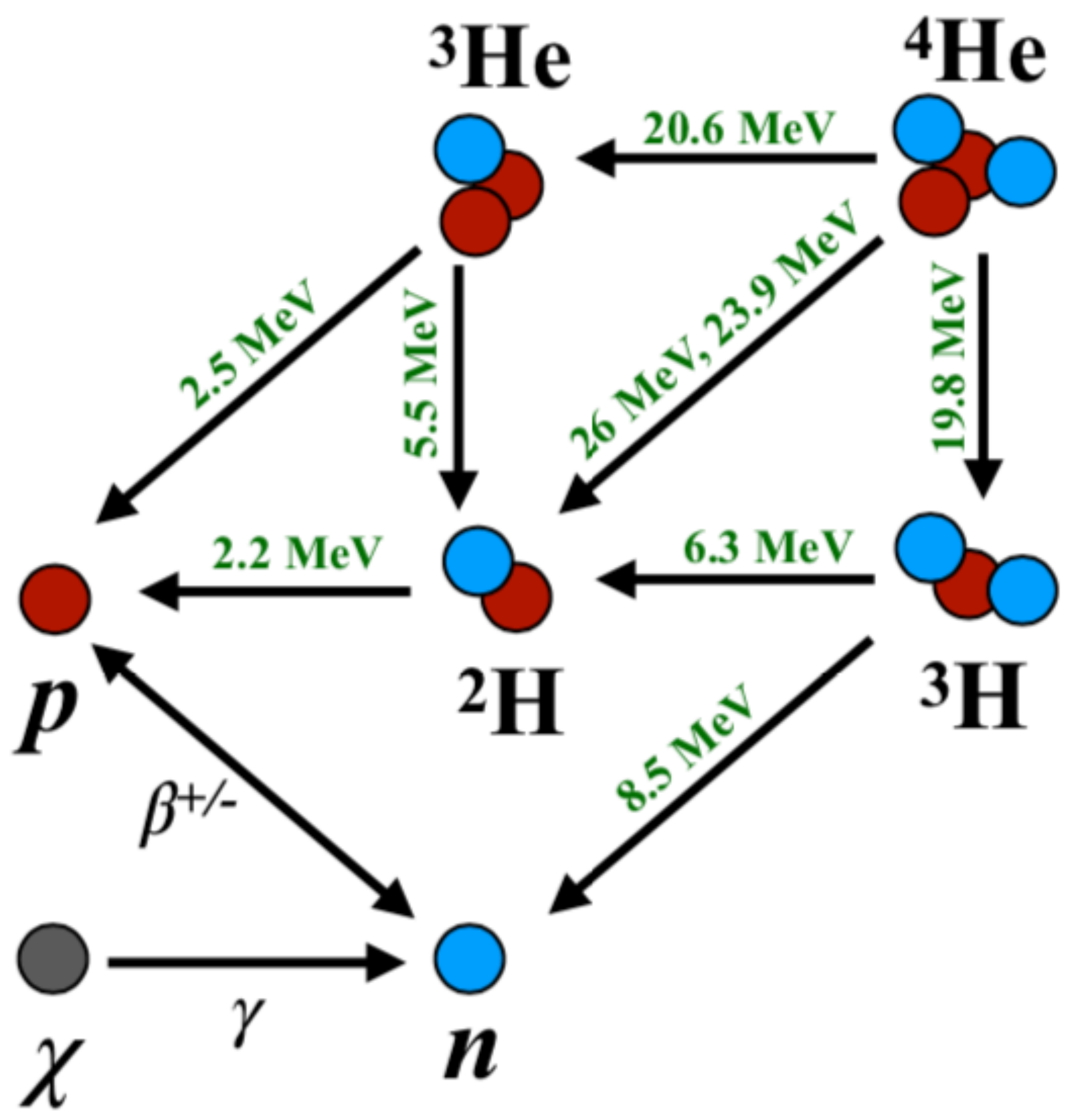
$$\frac{\delta Y_p}{Y_p} \simeq \frac{\delta(n_n/n_p)}{n_n/n_p} \times \frac{1}{1+n_n/n_p} \simeq 0.4\% \left(\frac{\mathrm{Br}_{n\to\chi}}{1\%}\right).$$

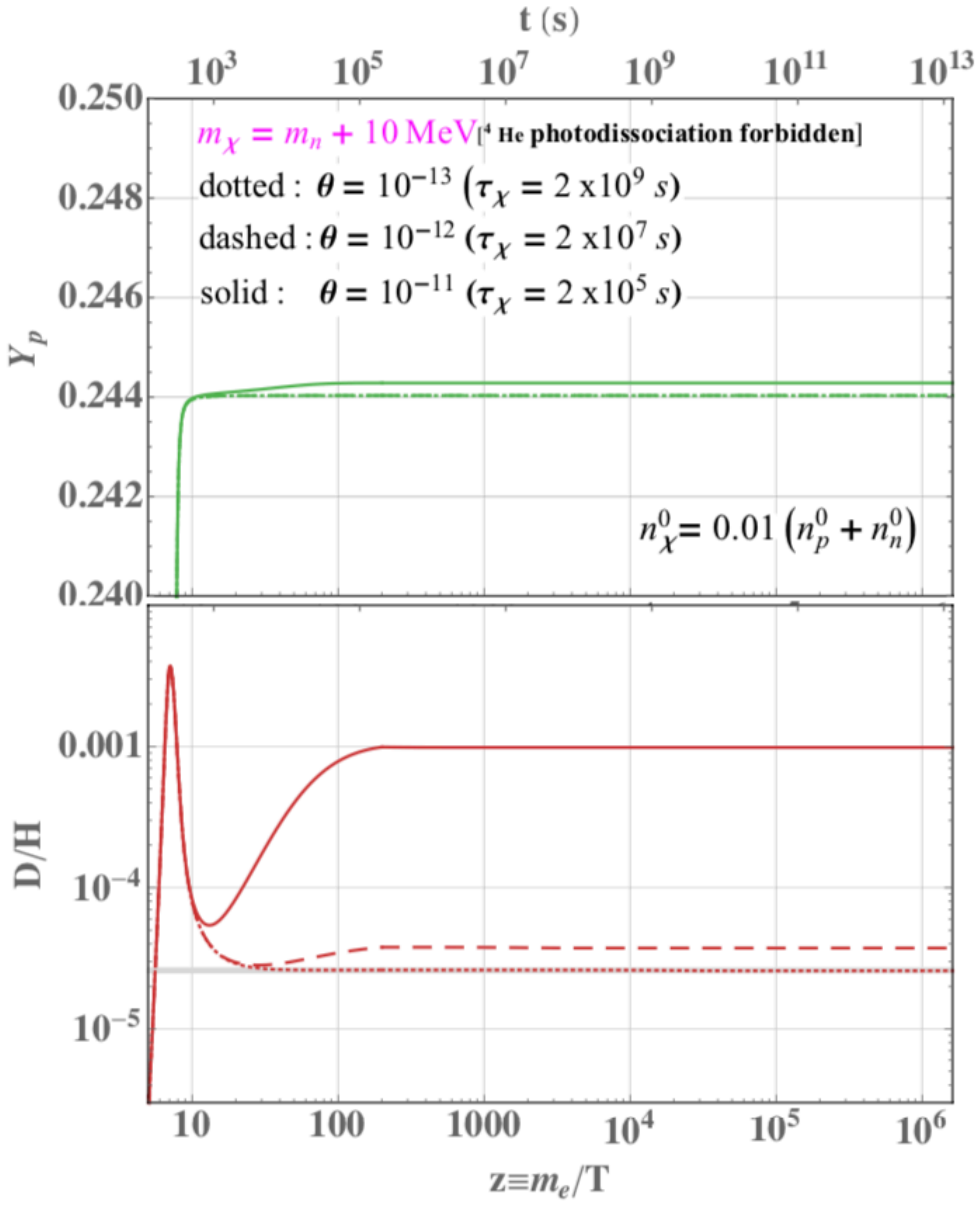


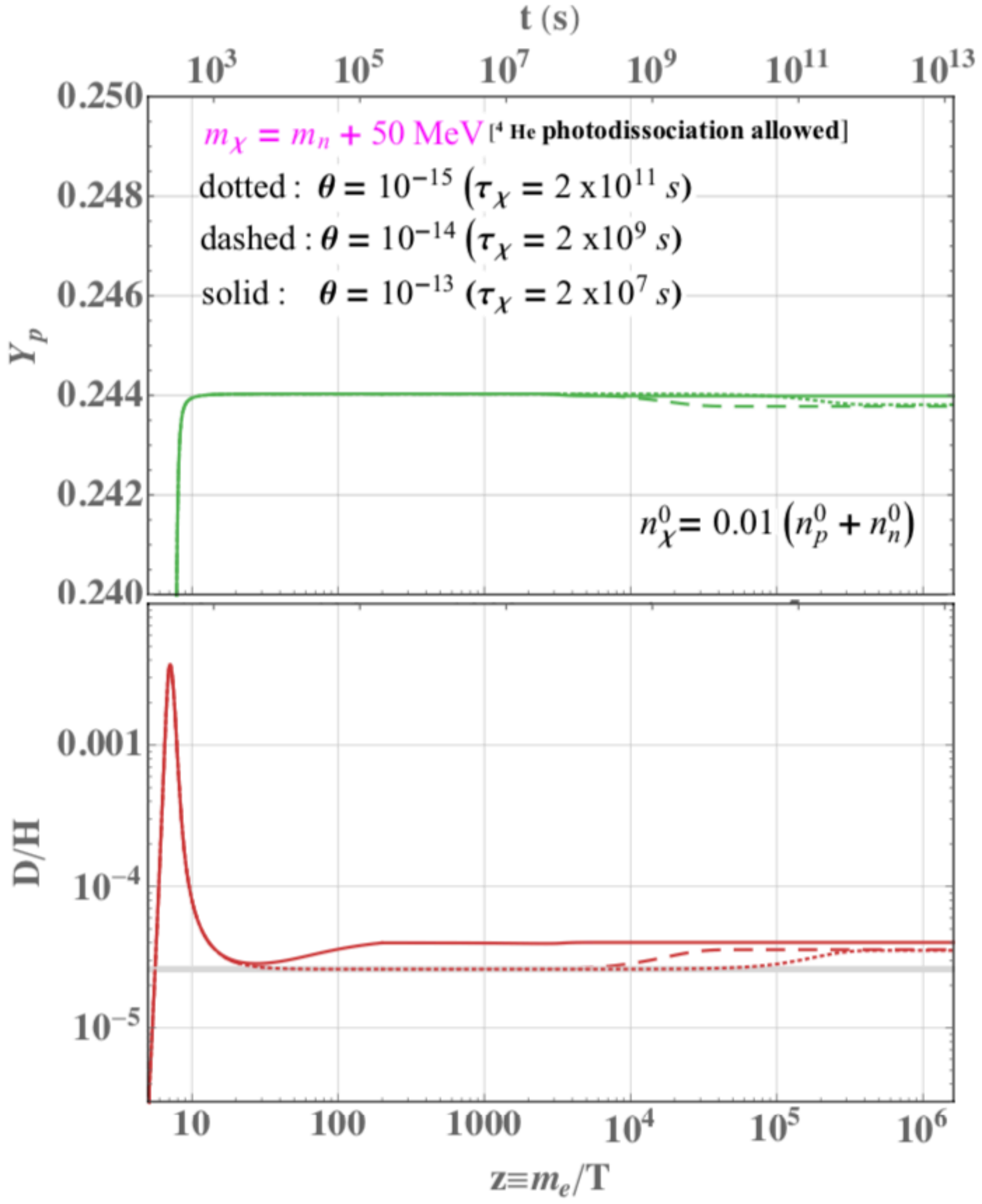
PRD 2021 *McKeen, Pospelov, Raj*

Photodissociation post-nucleosynthesis

$\chi \rightarrow n\,\gamma$
open

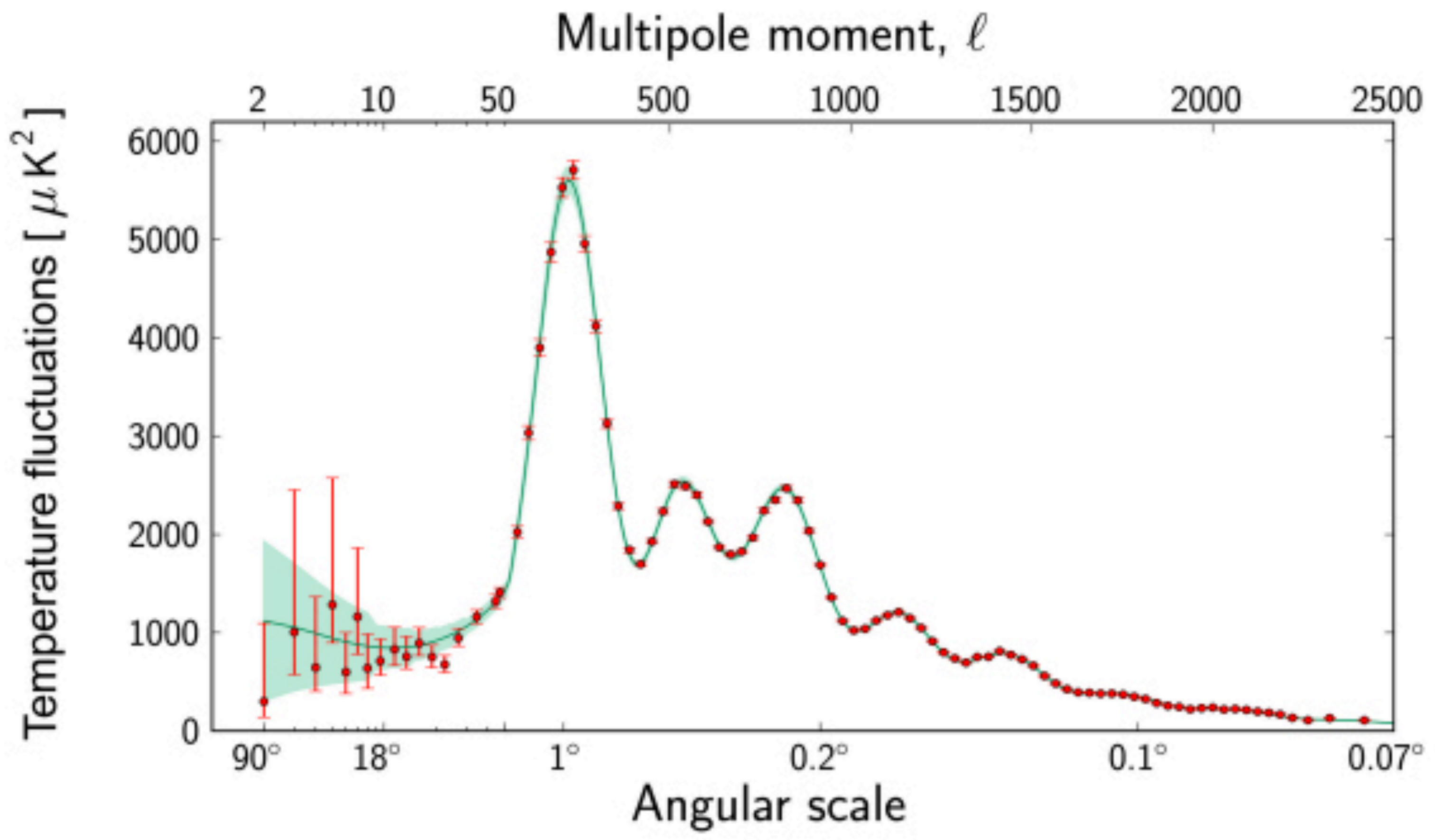






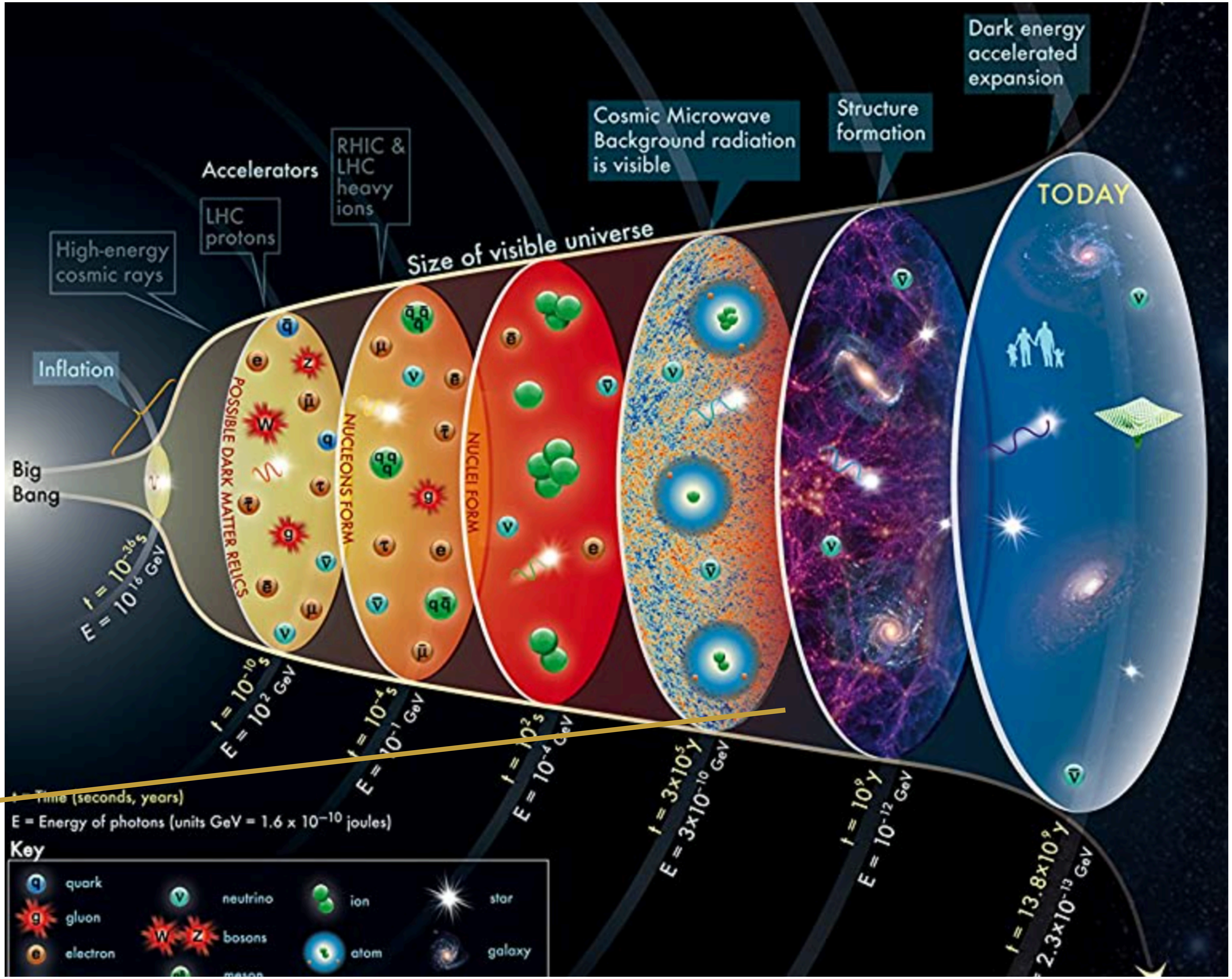
Where to find?

(2) *relic radiation*



Via $\chi \to pe\nu$, $\chi \to n\gamma$

e or γ could "rewrite" reionization history by dumping EM energy in Dark Ages



Where to find?

(2) *relic radiation*

When kinematically open:

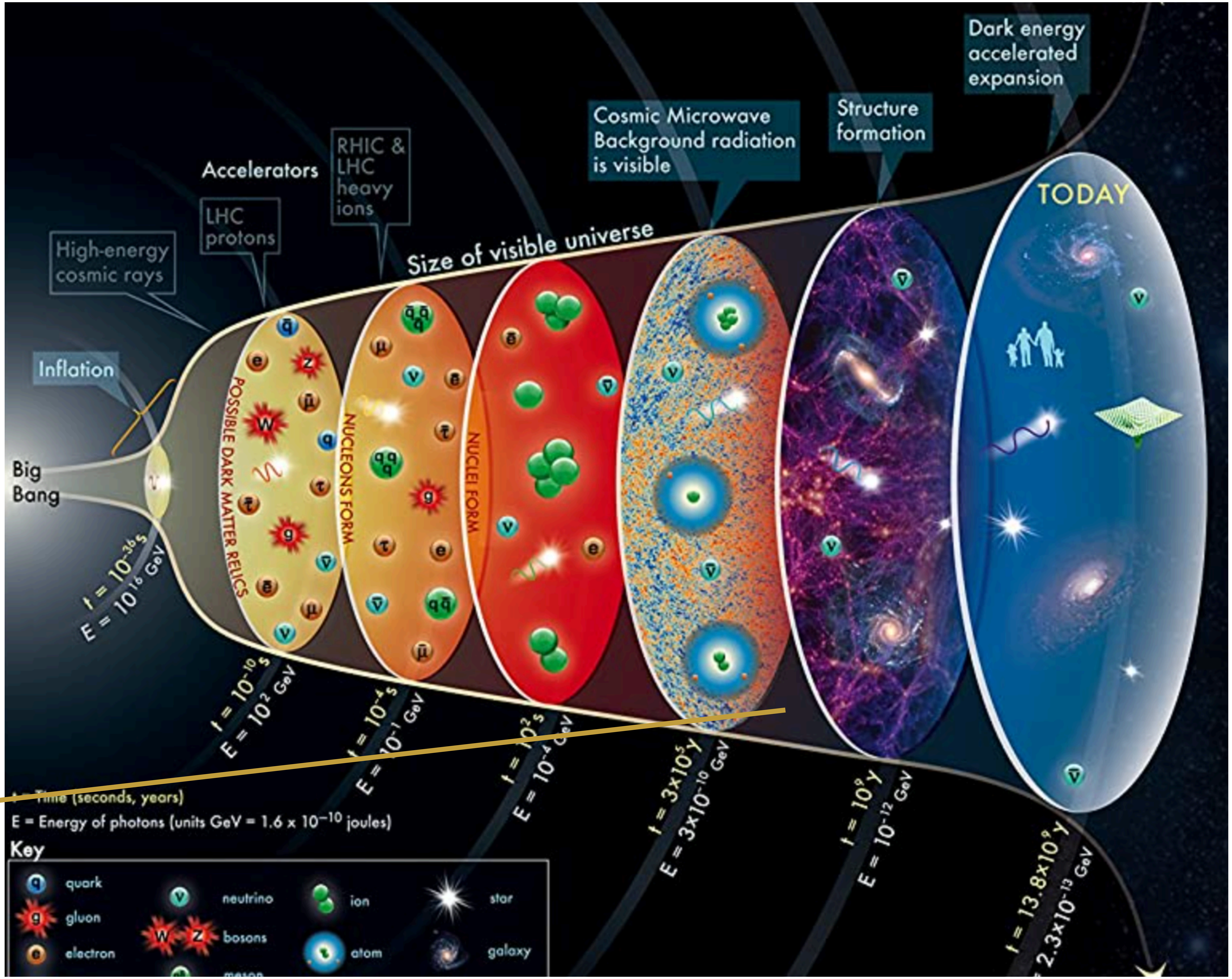
$$\Gamma_{\chi\to pe^-\bar{\nu}} = \frac{1}{9\times 10^{22}\ \mathrm{s}}\left(\frac{\theta}{10^{-10}}\right)^2 \frac{F(Q_\chi/m_e)}{F(Q_n/m_e)}$$

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

Via $\chi \to pe\nu$, $\chi \to n\gamma$

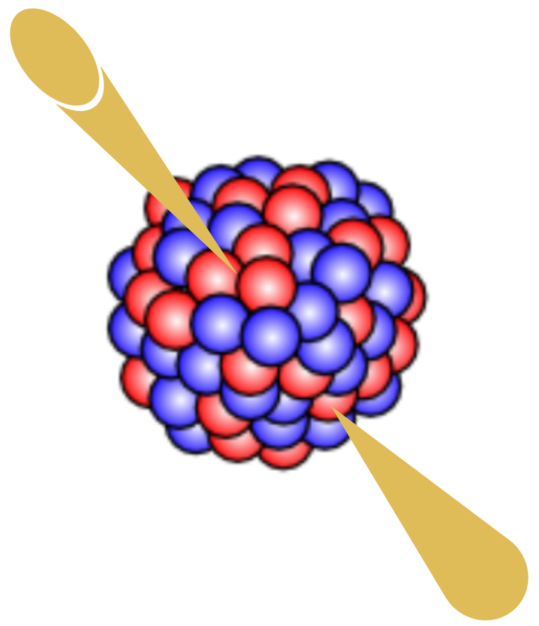
e or γ could "rewrite" reionization history by dumping EM energy in Dark Ages

timeline of the universe



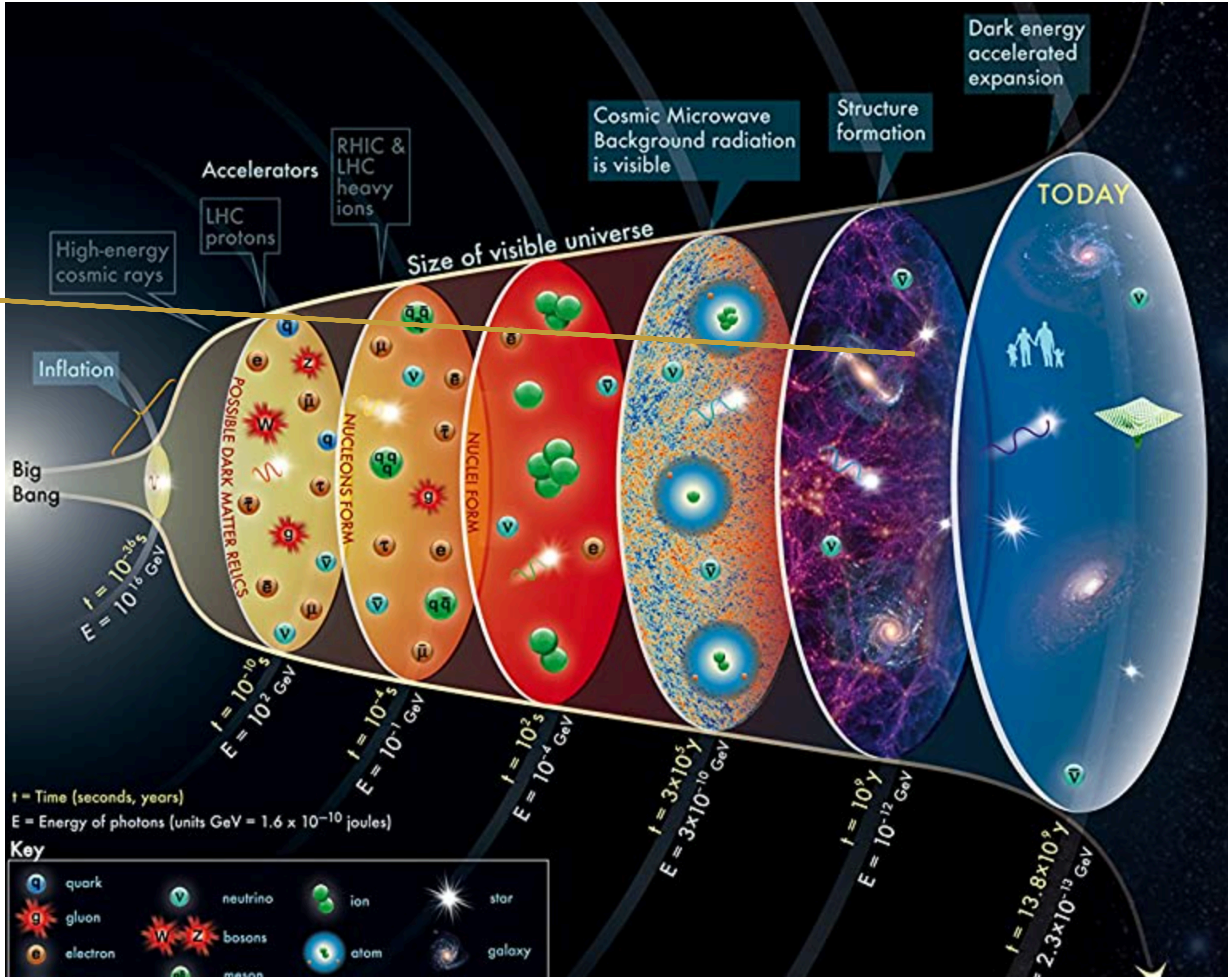
Where to find?

(3) *ancient neutron stars*

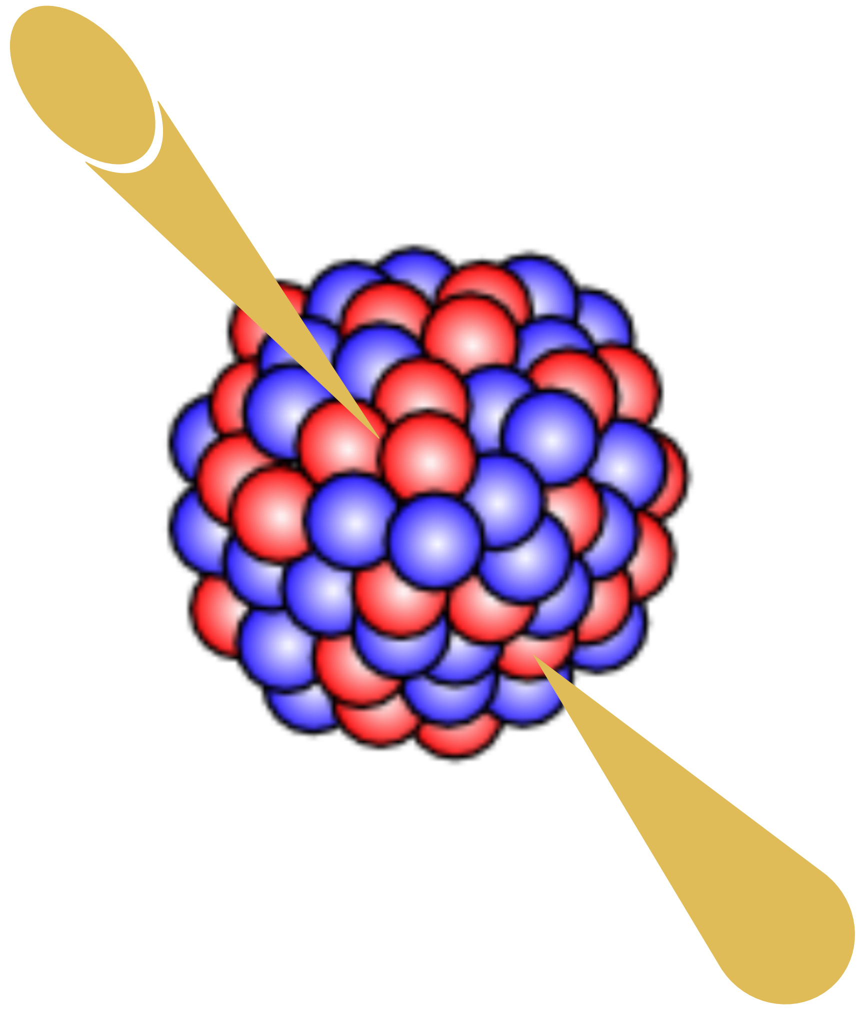


new heating mechanism:
nucleon "Auger effect"

timeline of the universe



Neutron stars



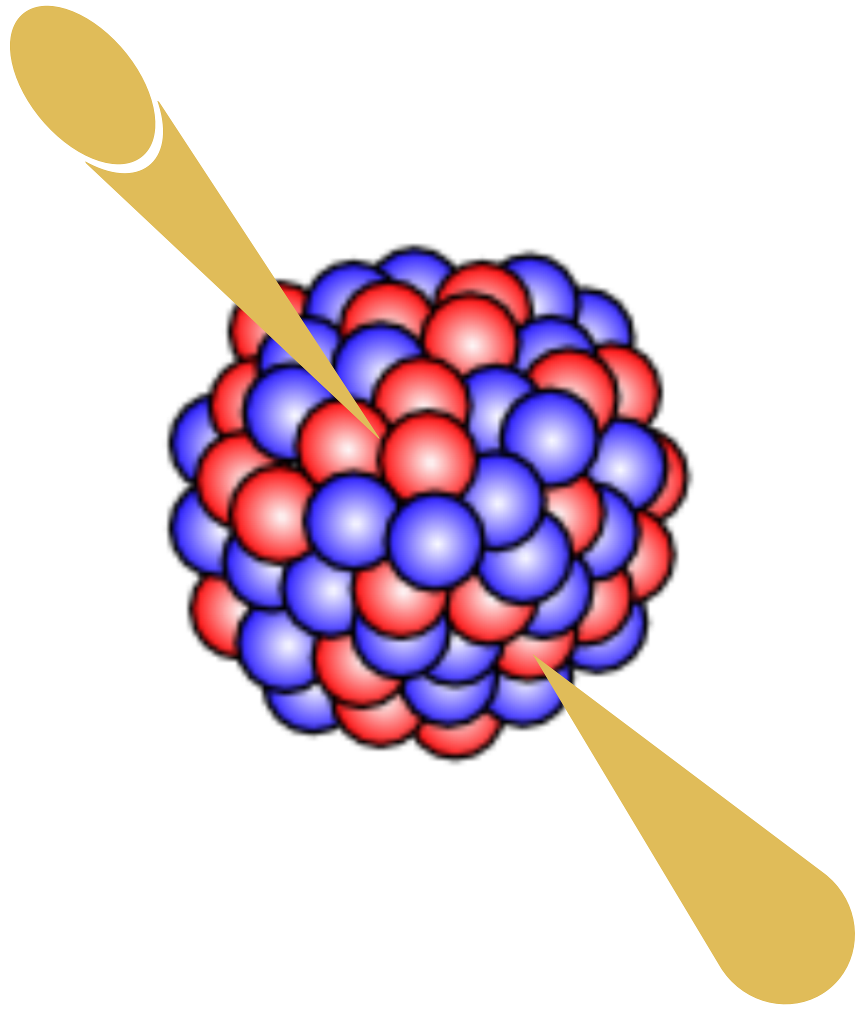
10^{57} neutrons

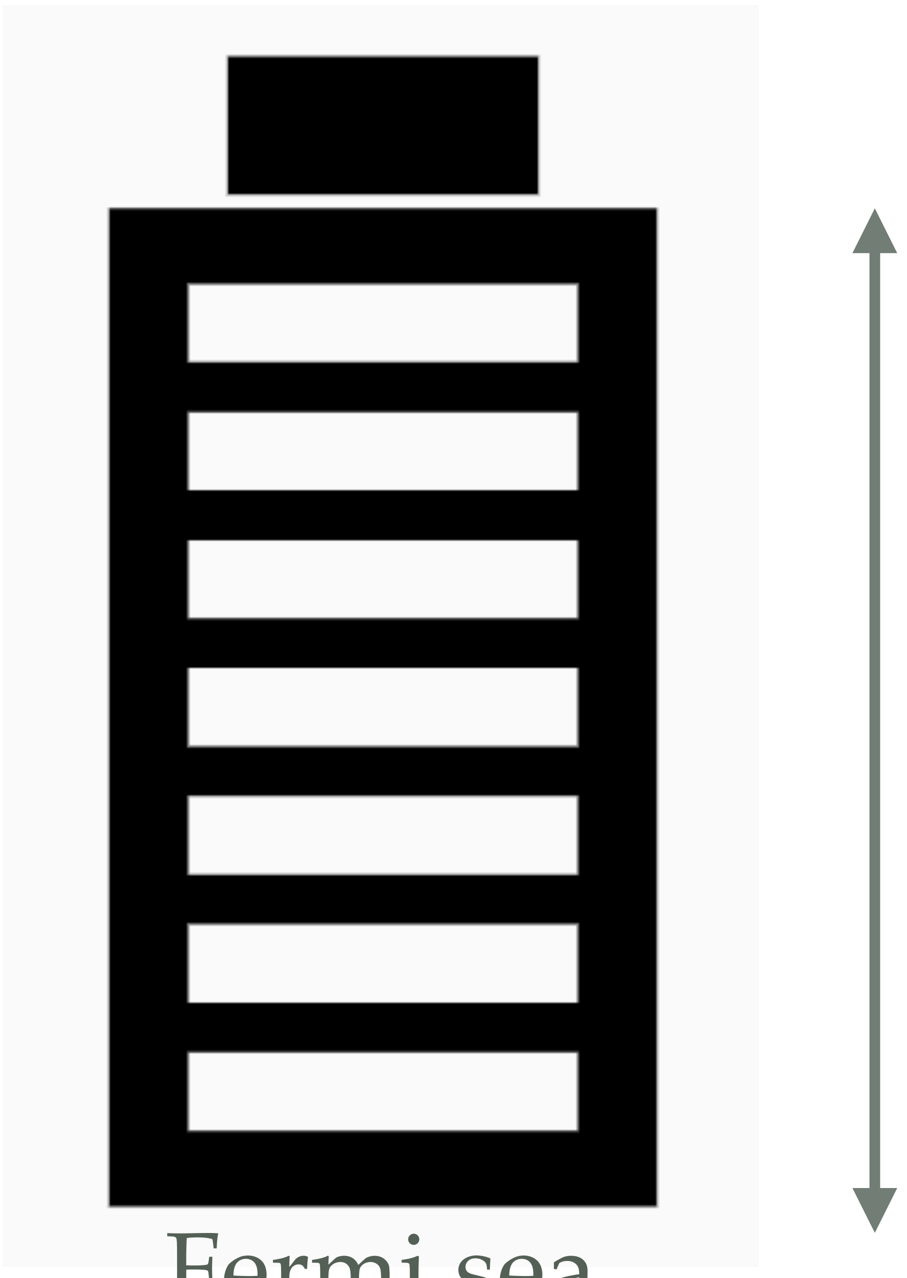
$+$

10^{56} protons, electrons, muons

(β equilibrium products)

Neutron stars = Pauli batteries





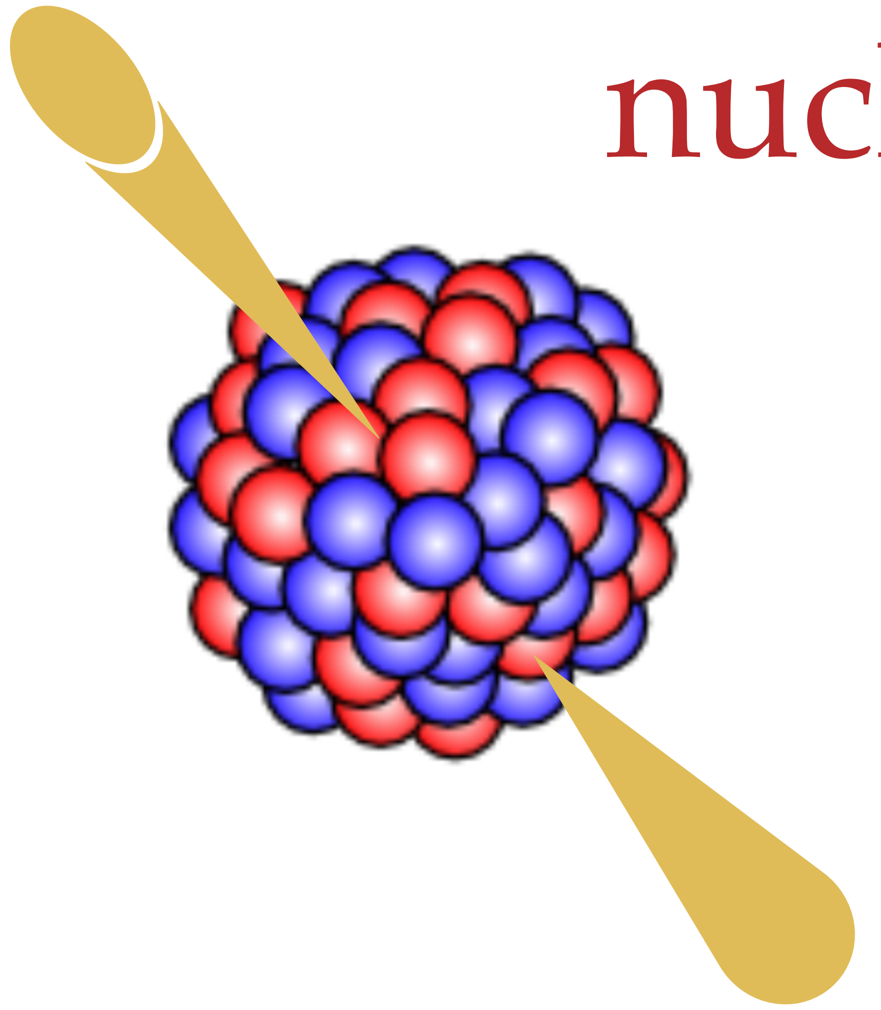
10^{57} neutrons

+

10^{56} protons, electrons, muons

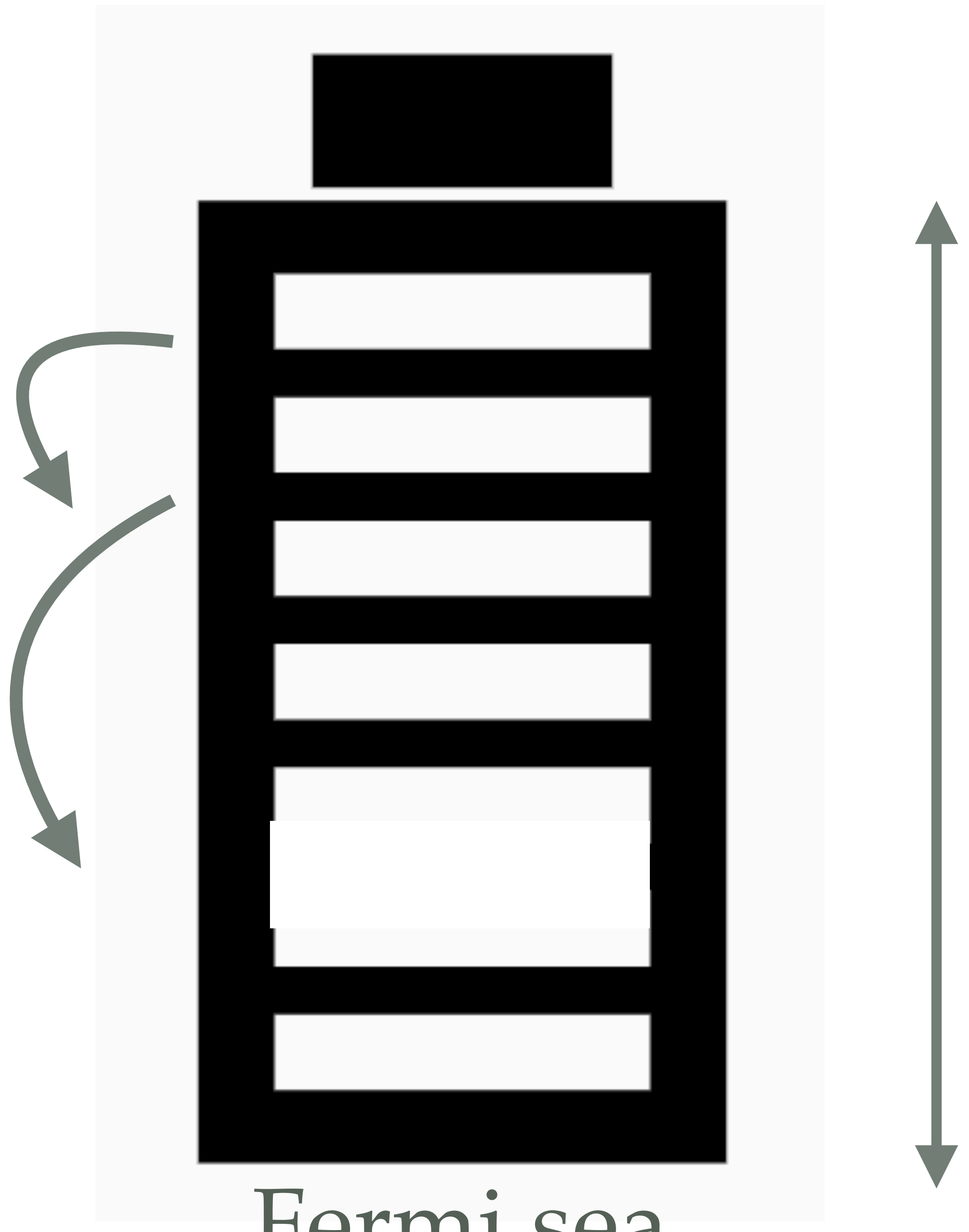
(β equilibrium products)

Neutron stars = Pauli batteries



new heating mechanism:
nucleon "Auger effect"

$n \to \chi + \underline{anything}$
$n\, n \to n\, \chi$
$p\, n \to p\, \chi$

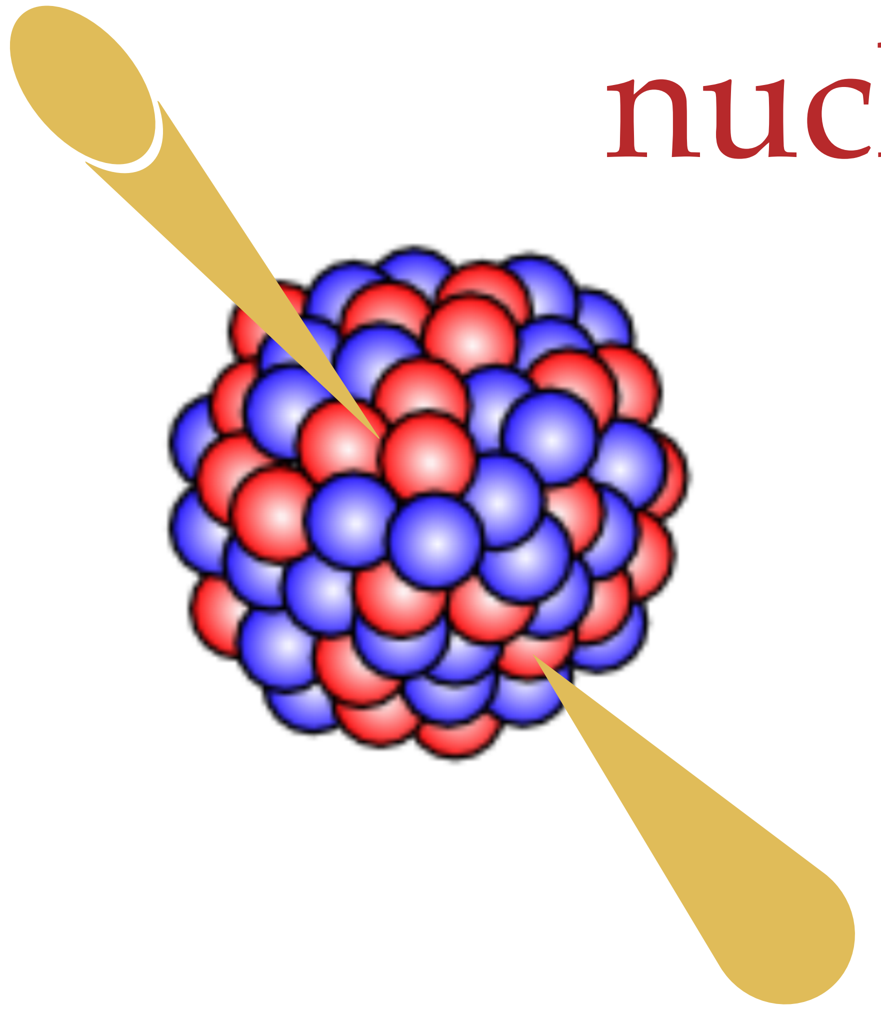


neutron Fermi energy
~ 100 MeV

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

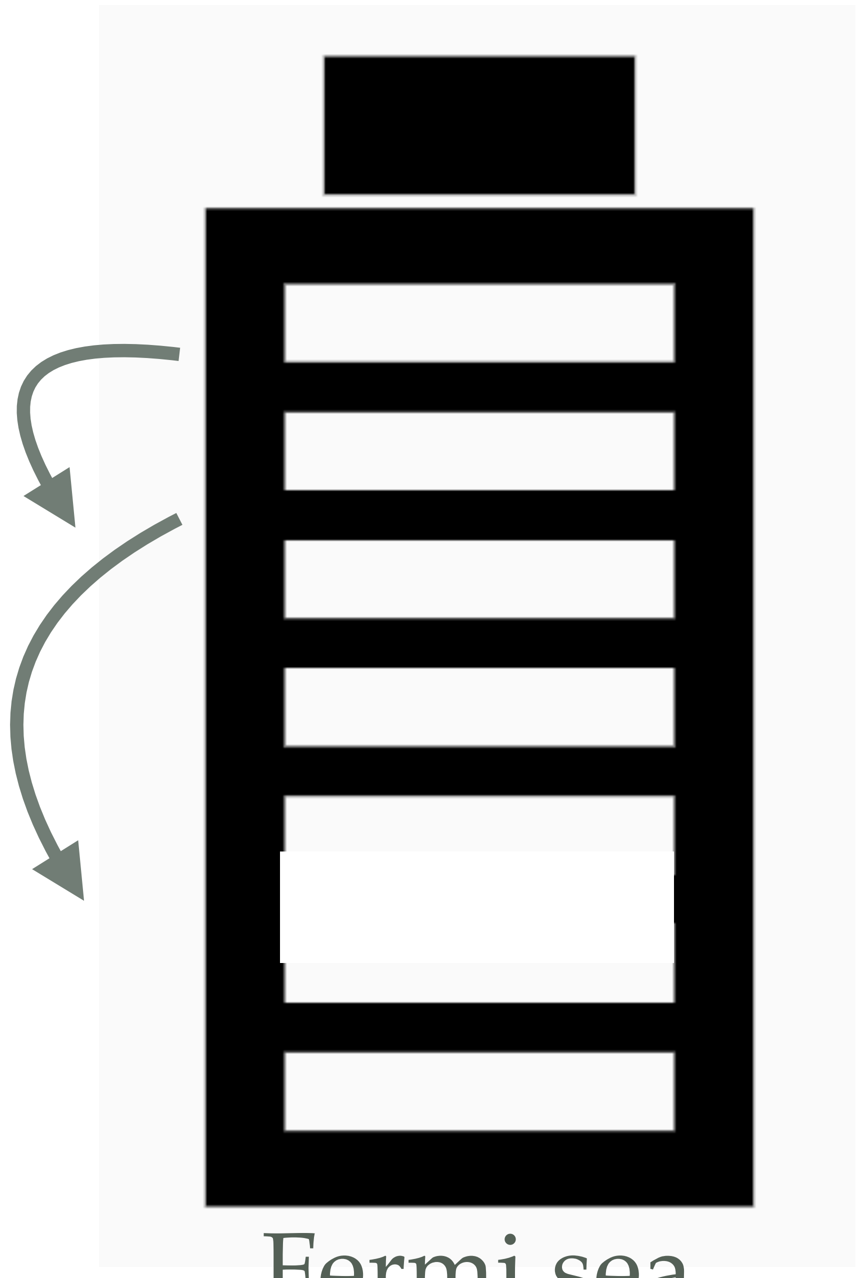
=> **explosive liberation of energy!**

Neutron stars = Pauli batteries



new heating mechanism:
nucleon "Auger effect"

$$n \to \chi + \underline{anything}$$
$$n\, n \to n\, \chi$$
$$p\, n \to p\, \chi$$



neutron Fermi energy
~ 100 MeV

Suitable lab:

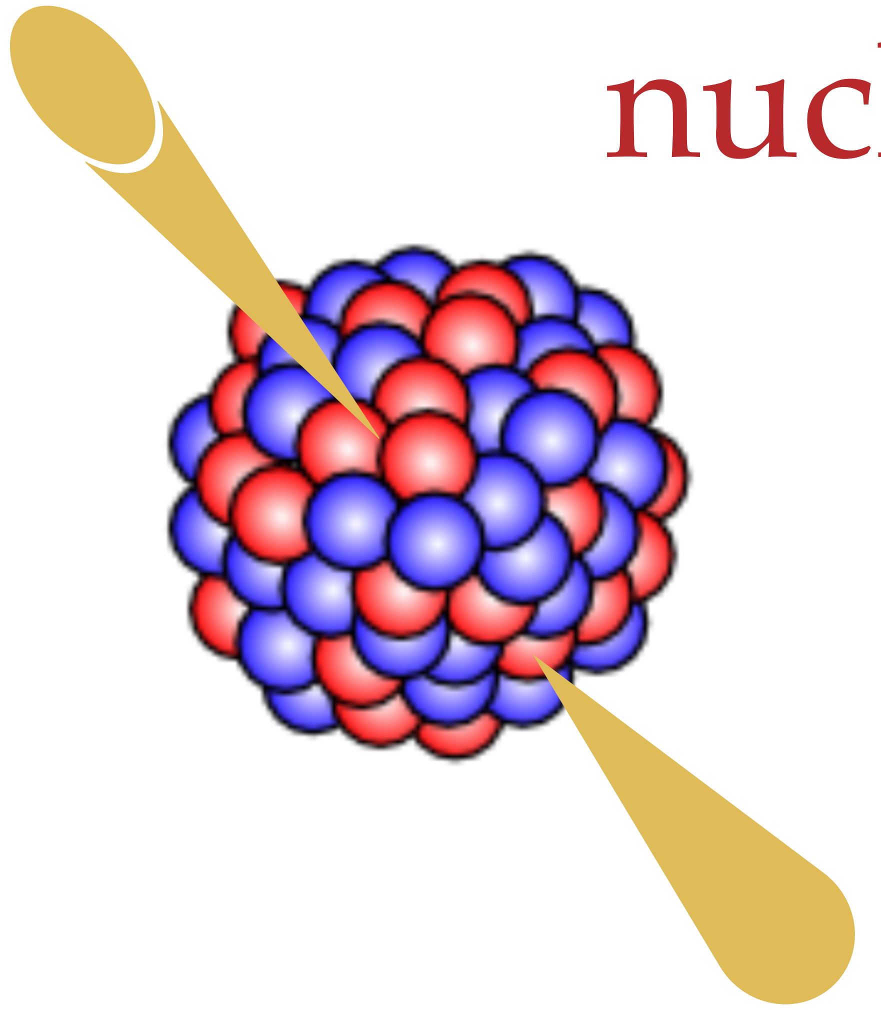
Hubble Space Telescope Nondetection of PSR J2144–3933: The Coldest Known Neutron Star*

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 ~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 $F_{F475X} < 22.7$ nJy, $F_{F125LP} < 5.9$ nJy, and $F_{F140LP} < 19.5$ 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

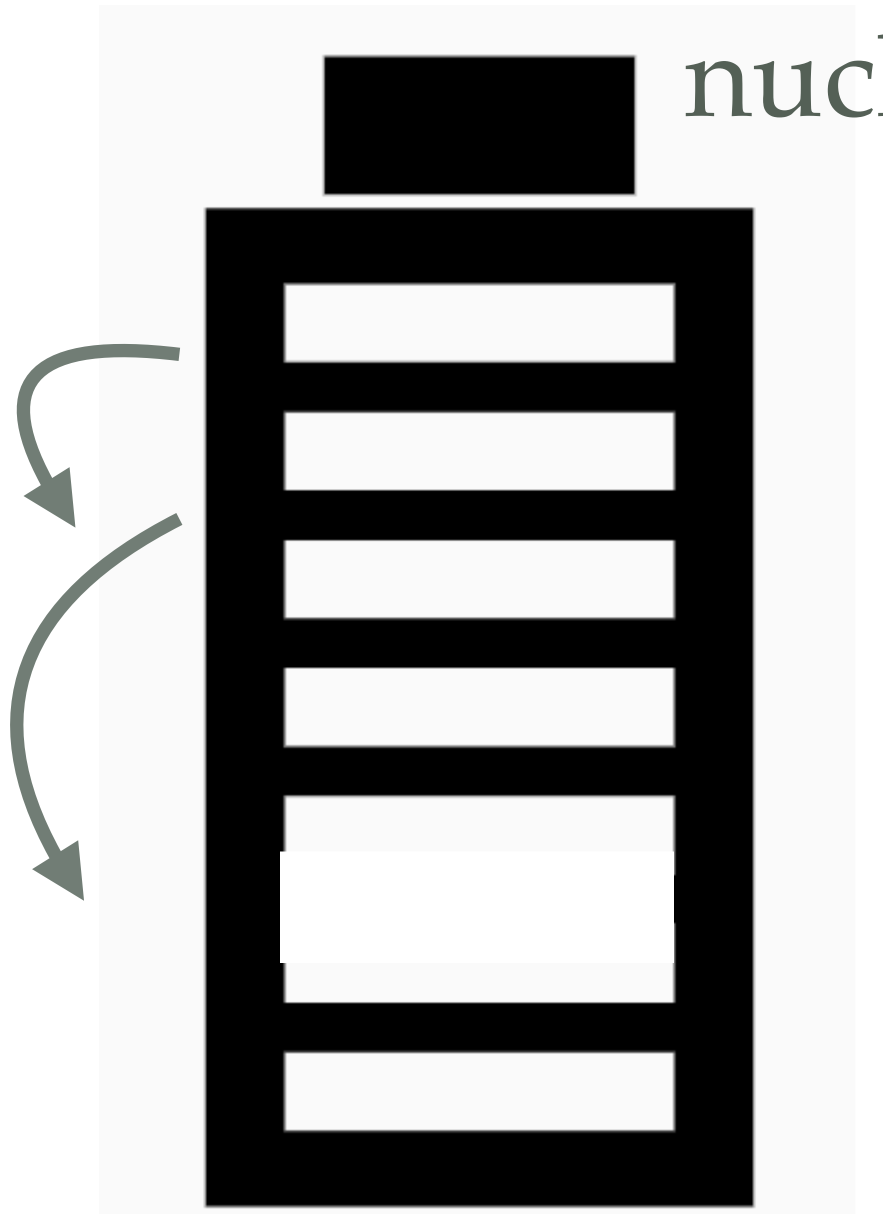
Neutron stars = Pauli batteries

new heating mechanism:
nucleon "Auger effect"



$$n \to \chi + \underline{anything}$$
$$n\, n \to n\, \chi$$
$$p\, n \to p\, \chi$$

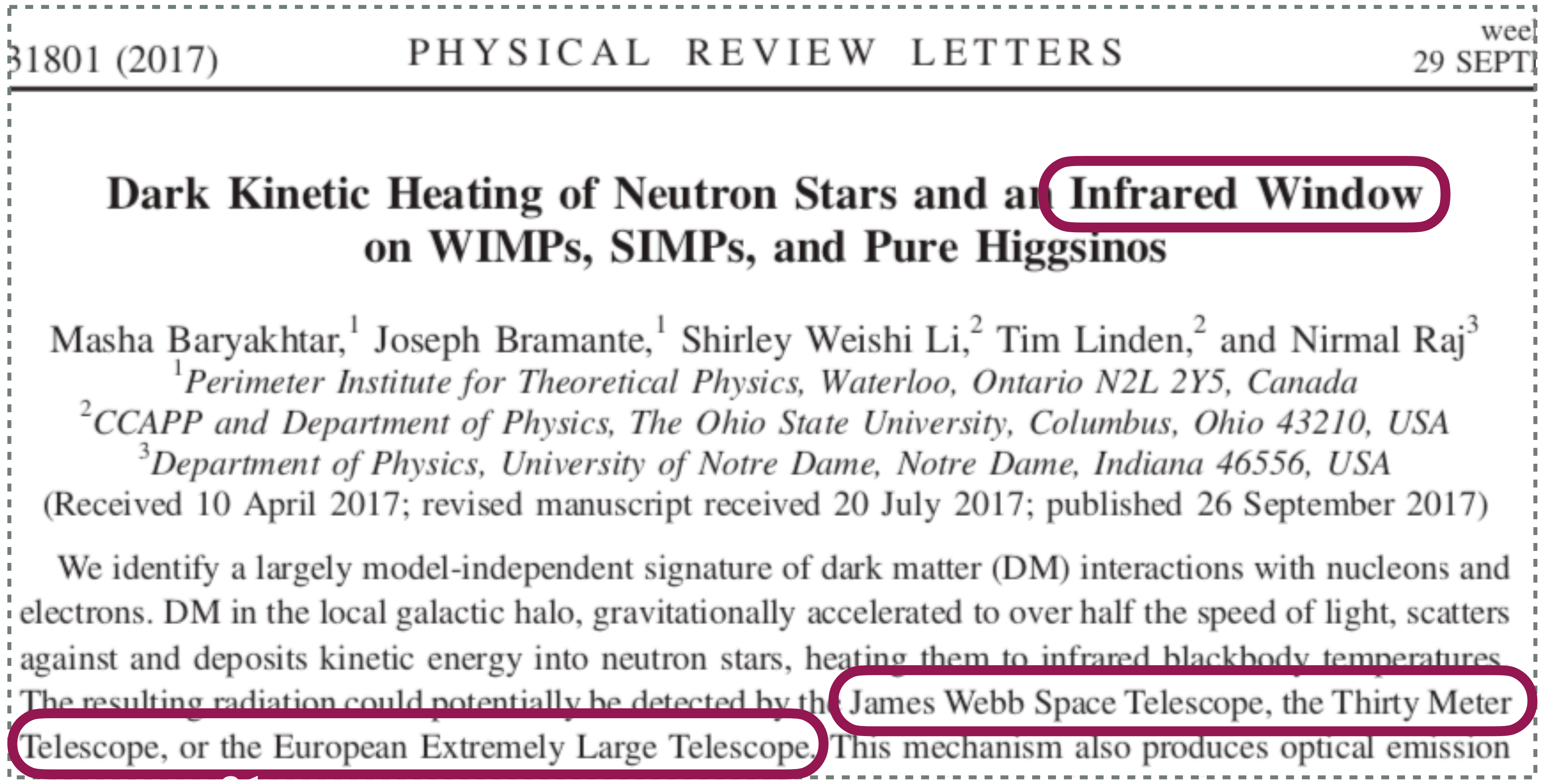
nucleon Fermi sea



Fermi sea

neutron Fermi energy
~ 100 MeV

Future lab:



31801 (2017) PHYSICAL REVIEW LETTERS wee 29 SEPT

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

see also:

N. Raj, P. Tanedo, H-B. Yu **PRD 2017**

J. Acevedo, J. Bramante, R. Leane, *N. Raj*, **JCAP 2020**

A. Joglekar, *N. Raj*, P. Tanedo, H-B. Yu **PLB 2020**

A. Joglekar, *N. Raj*, P. Tanedo, H-B. Yu **PRD 2020**

R. Garani, A. Gupta, *N. Raj,* **PRD 2021**

J. Bramante, B. Kavanagh, *N. Raj*, **submitted to PRL 2021**

J. Bramante, *N. Raj*, **Physics Reports 2022**

31801 (2017) PHYSICAL REVIEW LETTERS wee 29 SEPT

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

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)

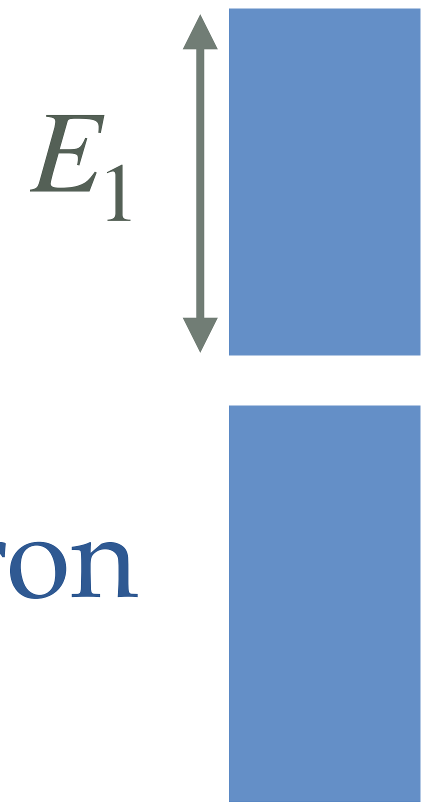
$$4\pi R_{\mathrm{NS}}^2 \sigma_{\mathrm{SB}} T_{\mathrm{NS}}^4$$

Conversions to dark neutrons

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

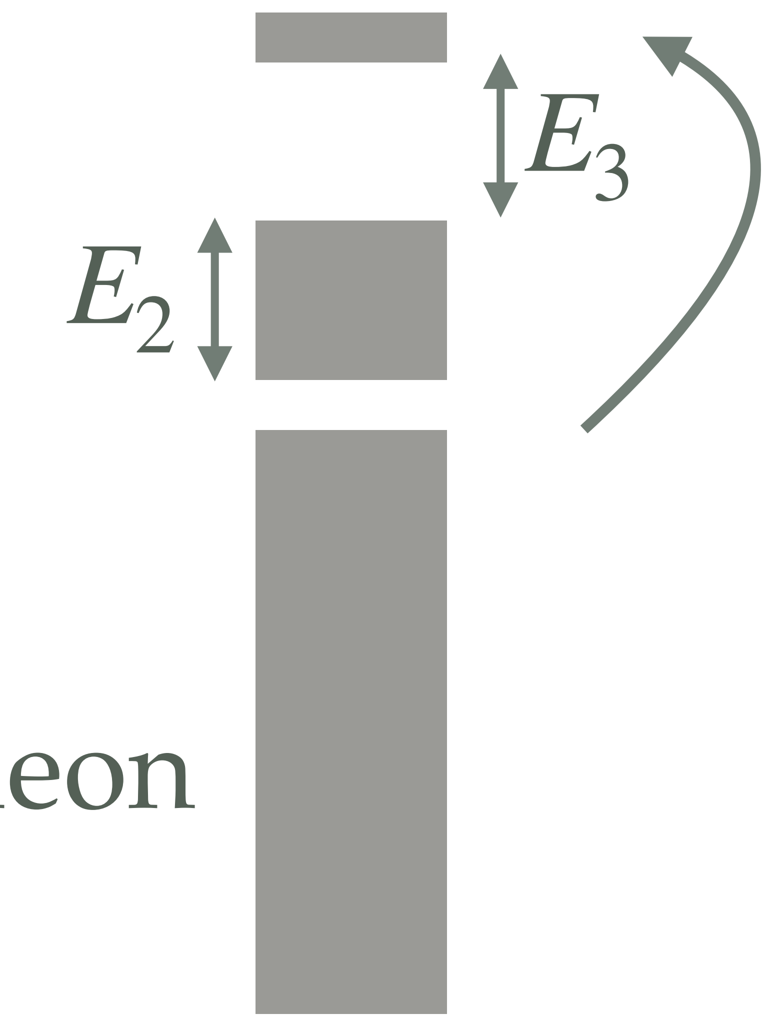
- $\dot{E}_{n'}$: energy release rate
- f_N: symmetry factor
- n_N: number density*
- $\widetilde{\mu}_n$: neutron chemical potential*
- $p_N > p_{F_N}$: Pauli blocking condition

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

Conversions to dark neutrons

medium-dependent splitting

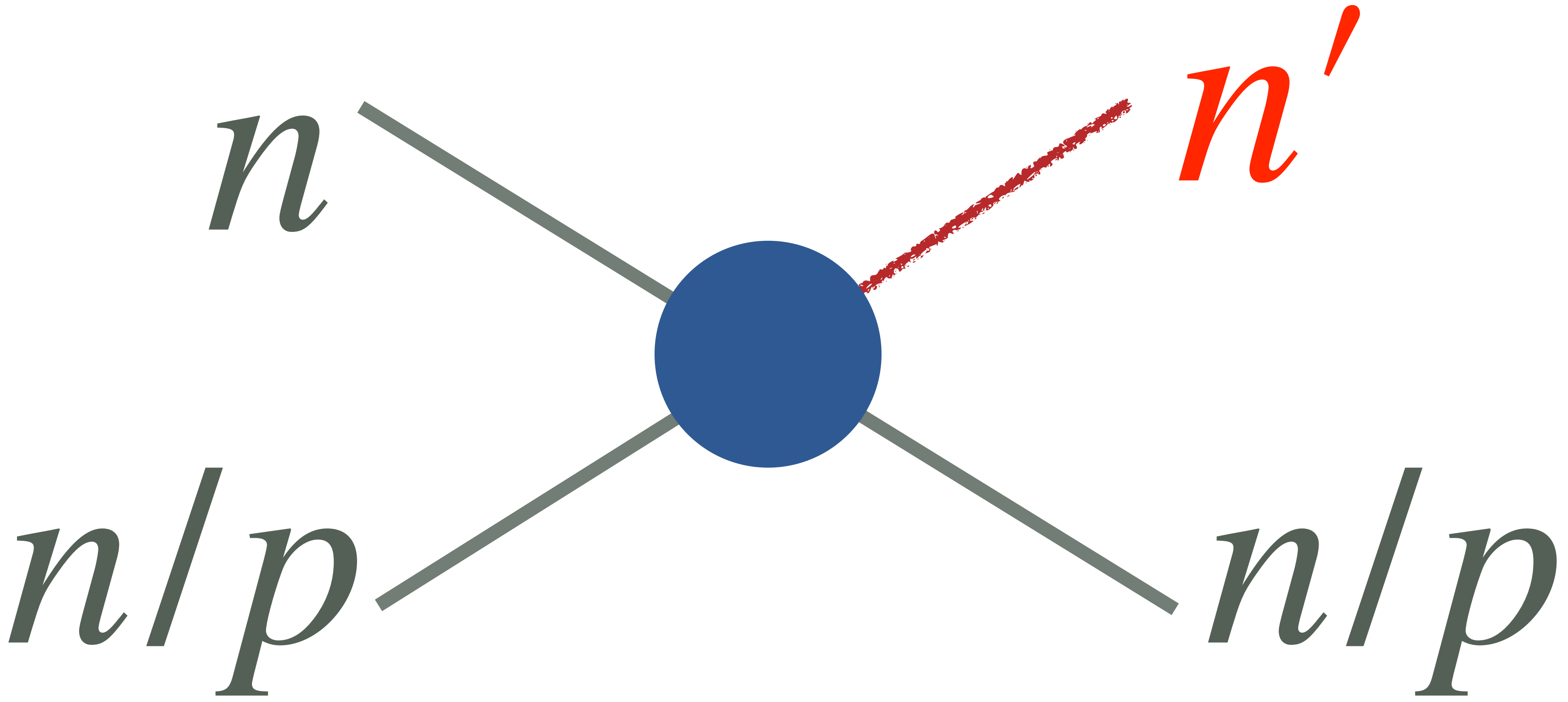
$$H = \begin{pmatrix} m_n + \Delta E & \epsilon_{nn'} \\ \epsilon_{nn'} & m_{n'} \end{pmatrix}$$

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

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

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

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



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

Where to find?

(4) *ancient metal-poor stars*
(~3 Gyr old; ^{9}Be observed)

Via

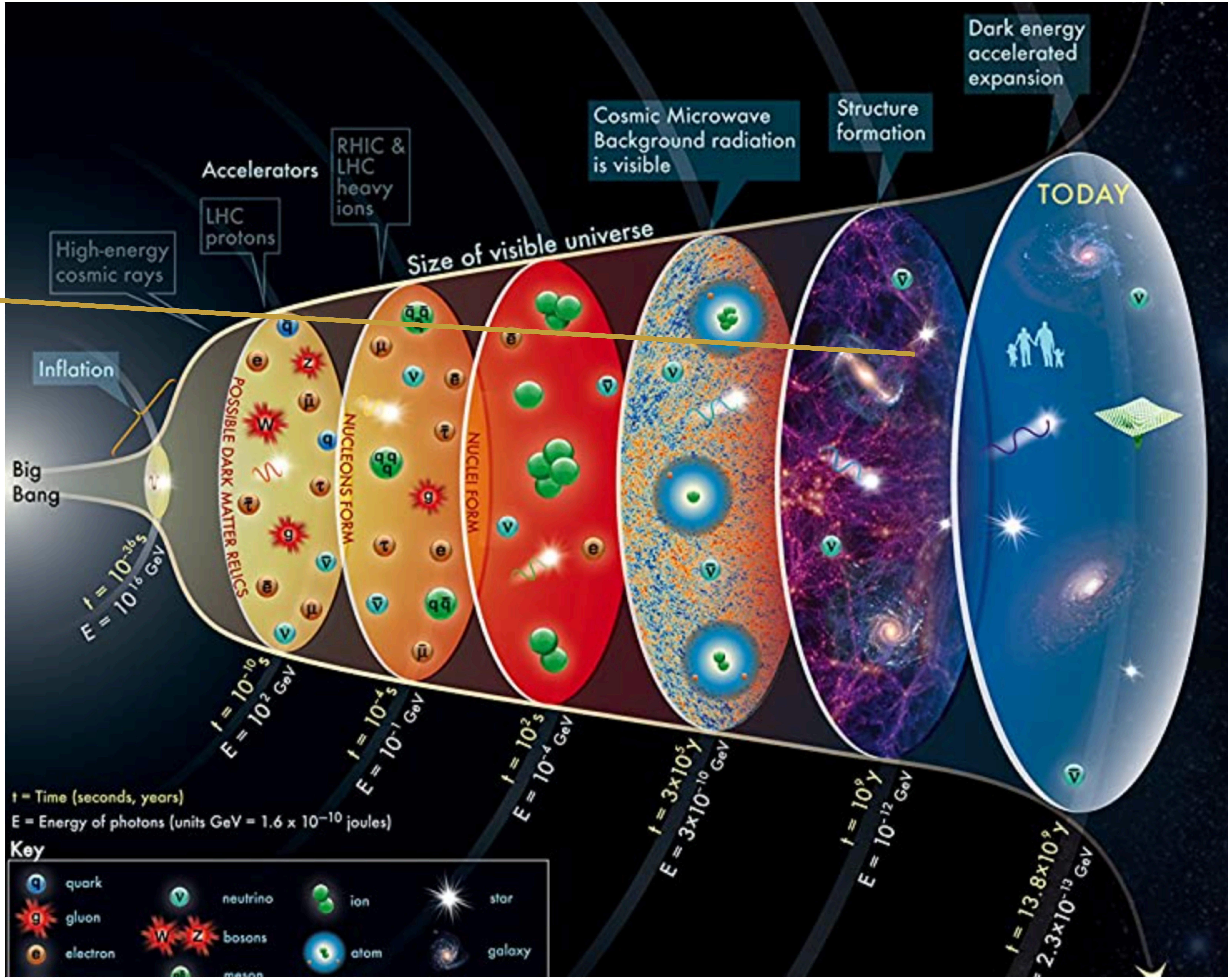
$$^9\mathrm{Be} \to 2\,^4\mathrm{He} + \chi$$

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

beryllium-9 lifetime:

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

timeline of the universe



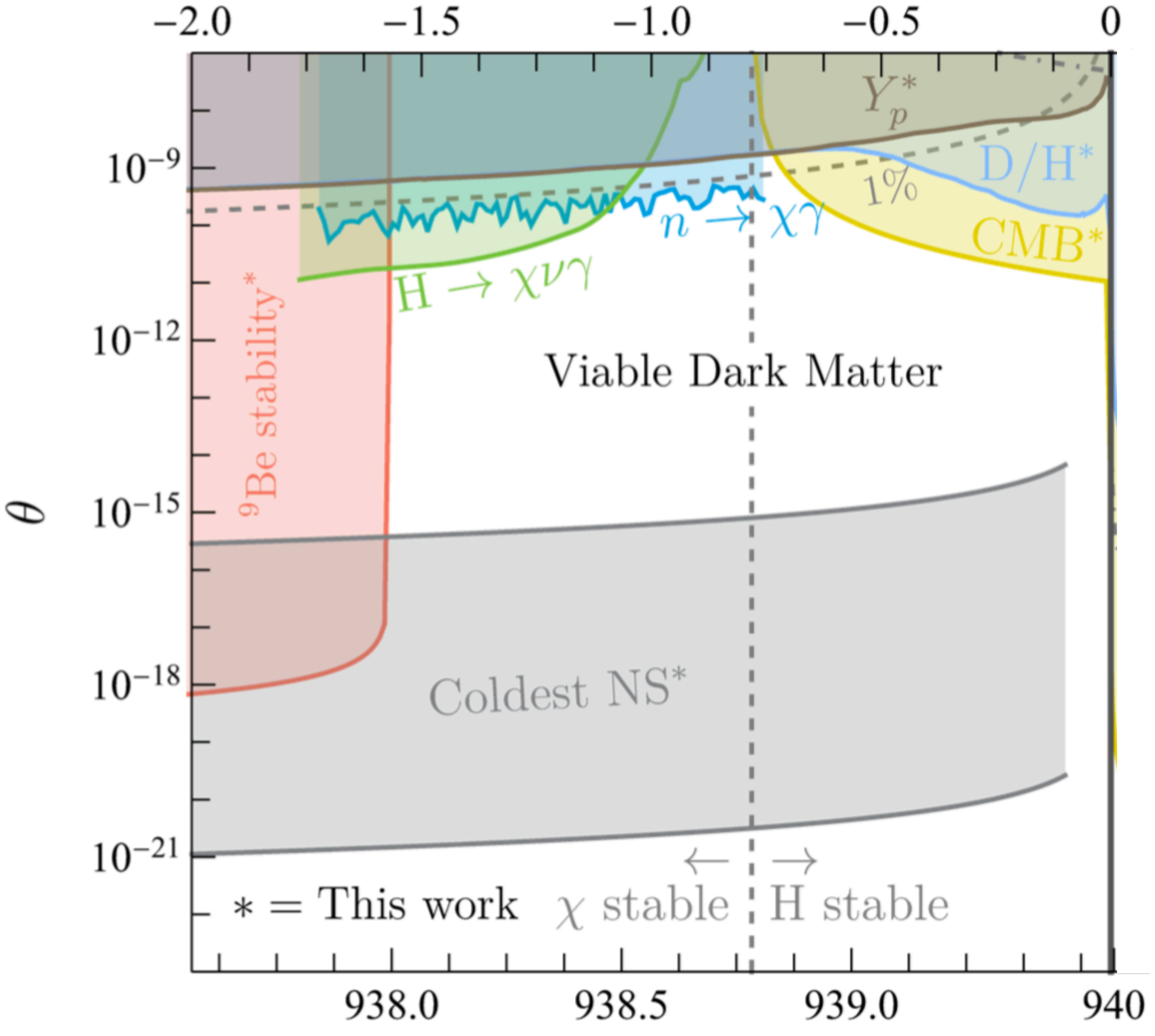
Constraints

PRD 2021 *McKeen, Pospelov,* Raj

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

longer
life

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



- 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)
- $^9\mathrm{Be} \to 2\ ^4\mathrm{He} + \chi$:

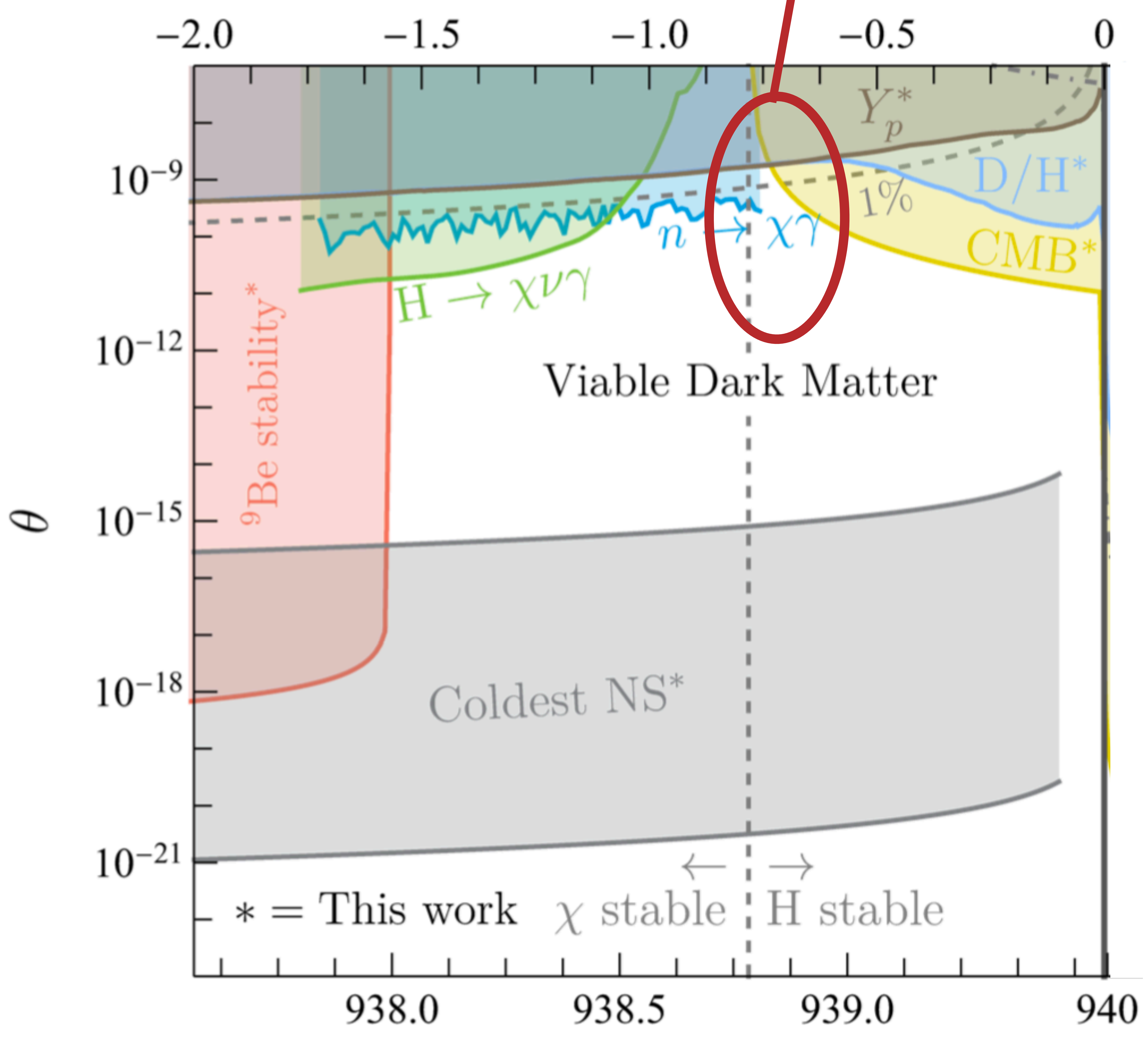
Limited by: $\tau_{^9\mathrm{Be}} \sim 4 \times 10^{10}\ \mathrm{yr} \left(\frac{10^{-19}}{\theta}\right)^2 \left(\frac{1\,\mathrm{MeV}}{Q_{^9\mathrm{Be}}}\right)^{3/2}$

$< 3 \times 10^9$ 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

$D/H = (2.55 \pm 0.03) \times 10^{-5}$,

$^3He/H = (1.0 \pm 0.5) \times 10^{-5}$,

- CMB limit: $f_\chi/\tau_\chi \lesssim 10^{-25}\ s^{-1}$

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)
- $^9Be \to 2\ ^4He + \chi$:

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

$< 3 \times 10^9$ yr in metal-poor stars

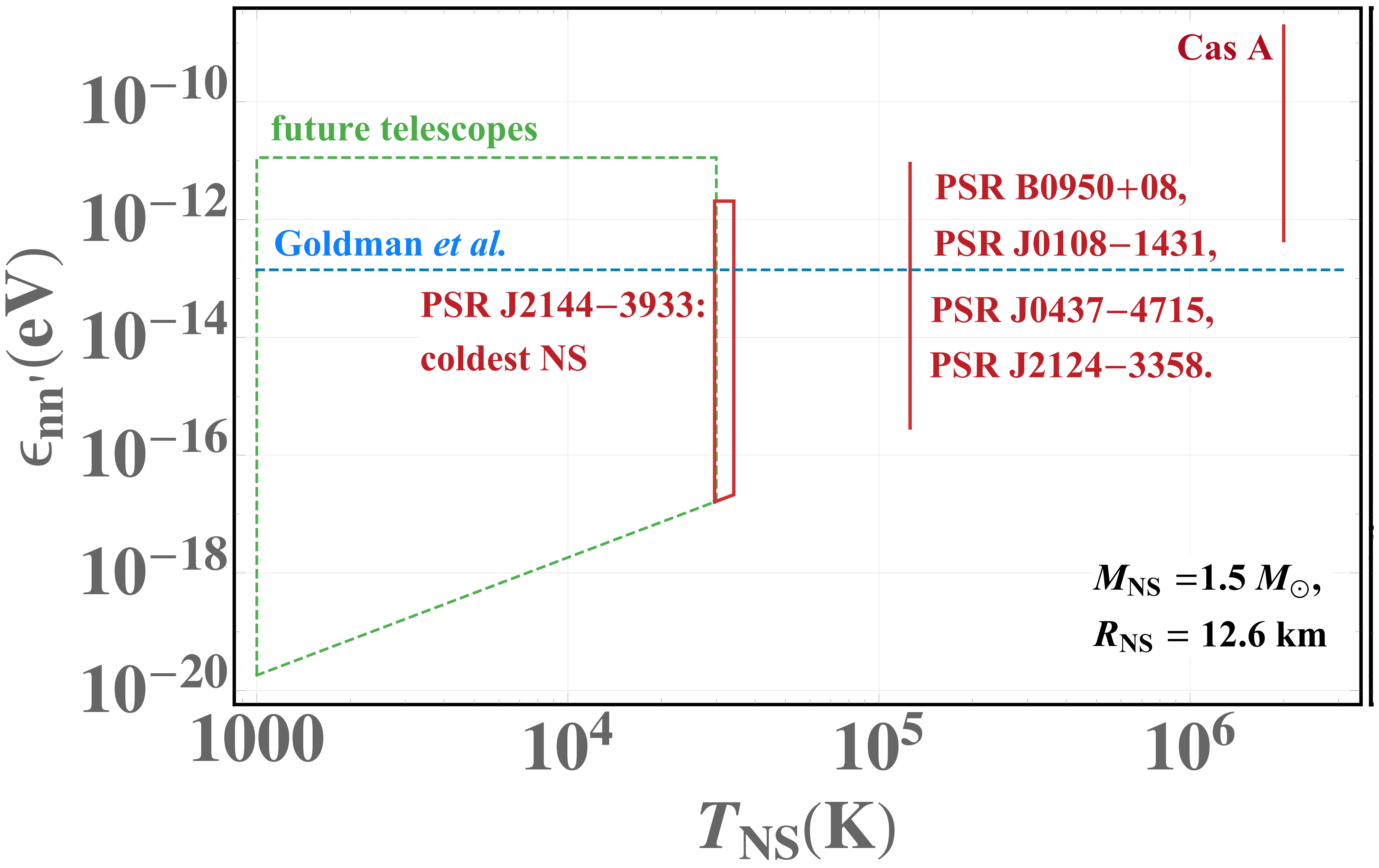
- NS: J2144-3933

PRD 2021 *McKeen, Pospelov, Raj*

Constraints: NS heating

NS energy per baryon

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



ceilings: neutron conversions stop within NS lifetime

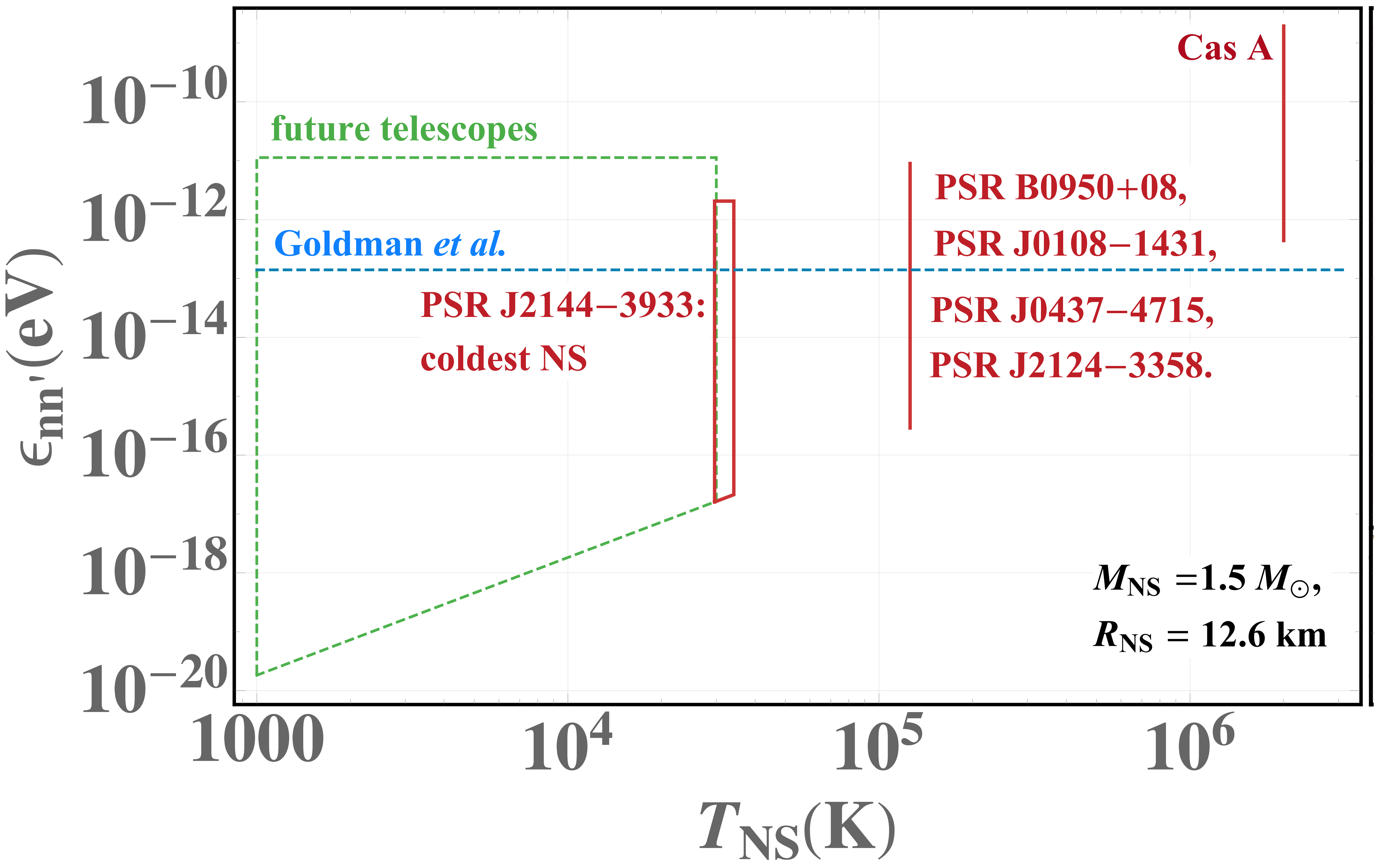
NB. neutron lifetime anomaly explained by $\epsilon_{nn'} \sim 10^{-8}$ eV (*Berezhiani 2018*)

PRL 2021 *McKeen, Pospelov, Raj*

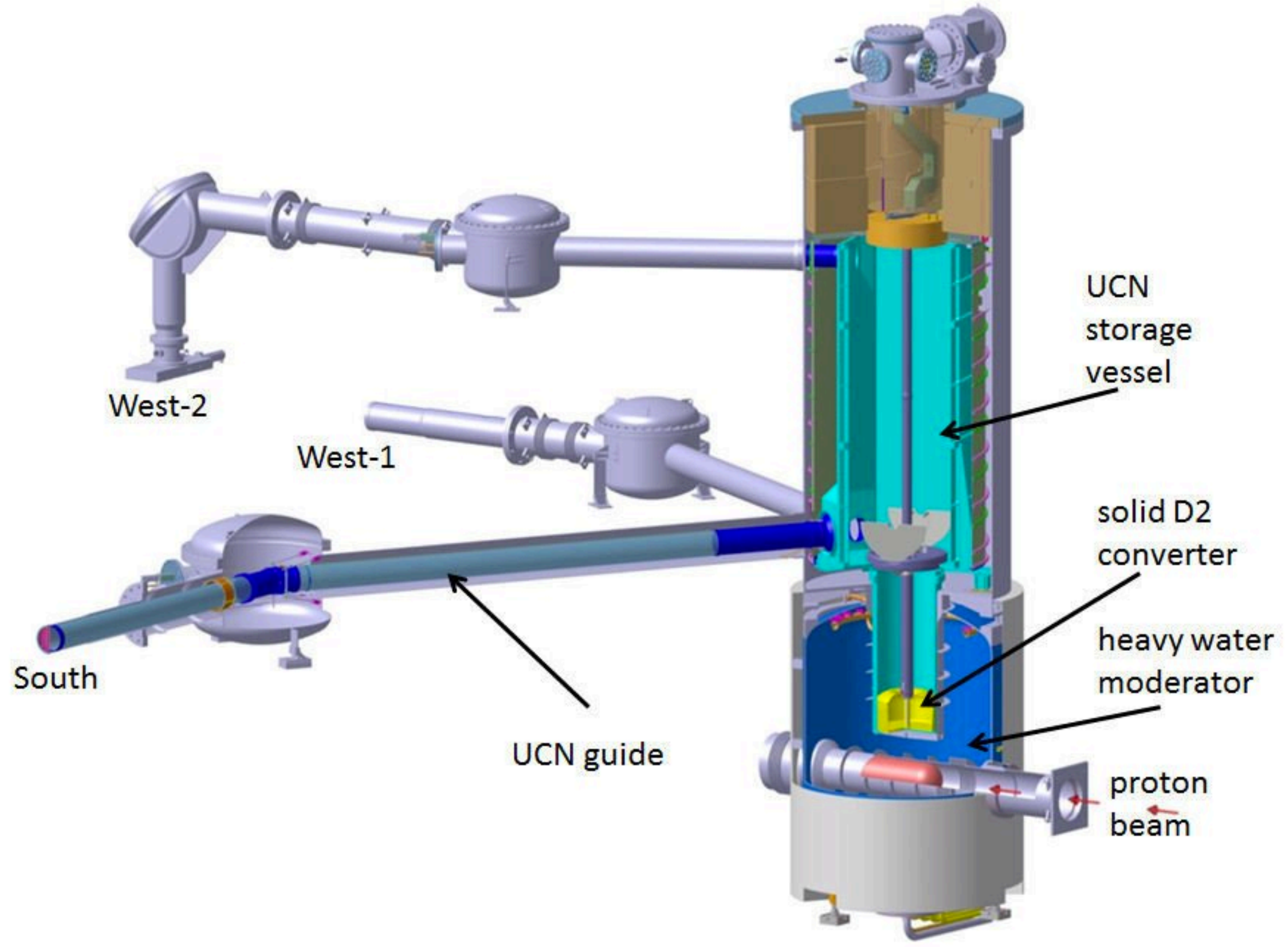
Constraints: NS heating

NS energy per baryon

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

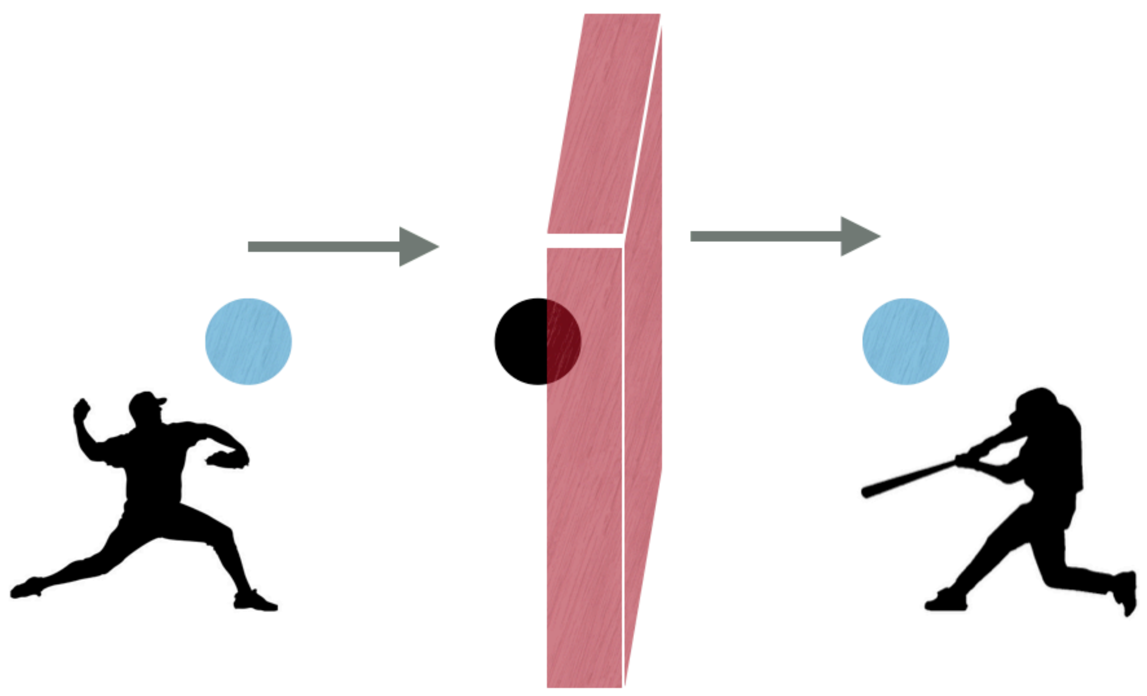
Zeeman from Earth's B field

[hypothetical mirror B field]

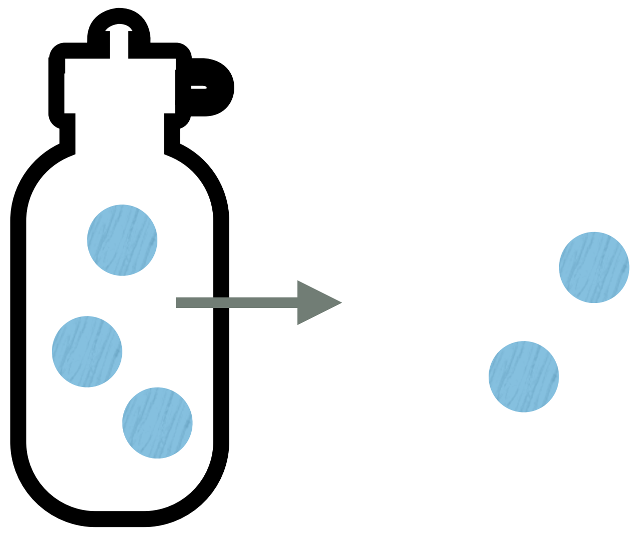
ceilings: neutron conversions stop within NS lifetime

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

Neutrons shining through a wall



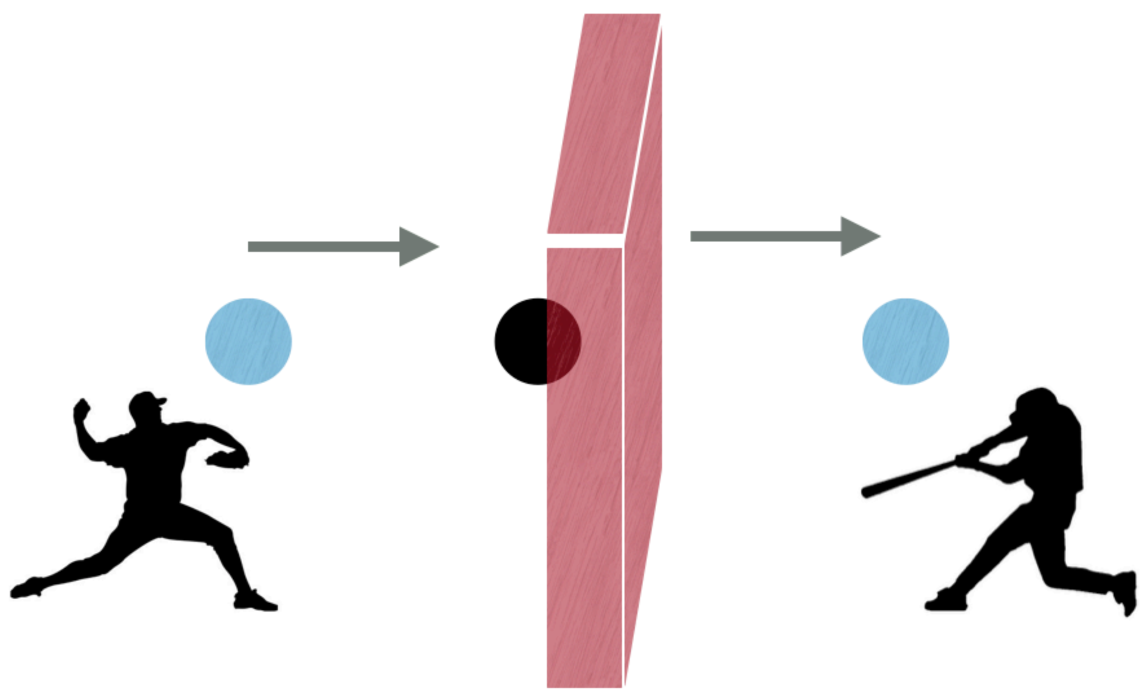
(1) **UCN disappearance**



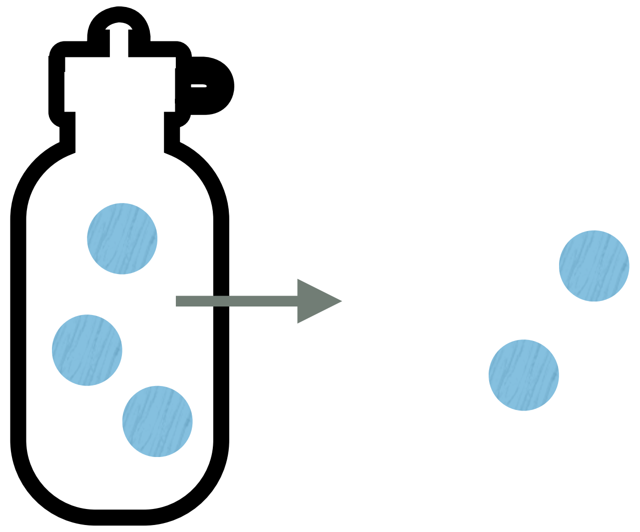
ongoing work with

M. Hostert, D. McKeen, M. Pospelov

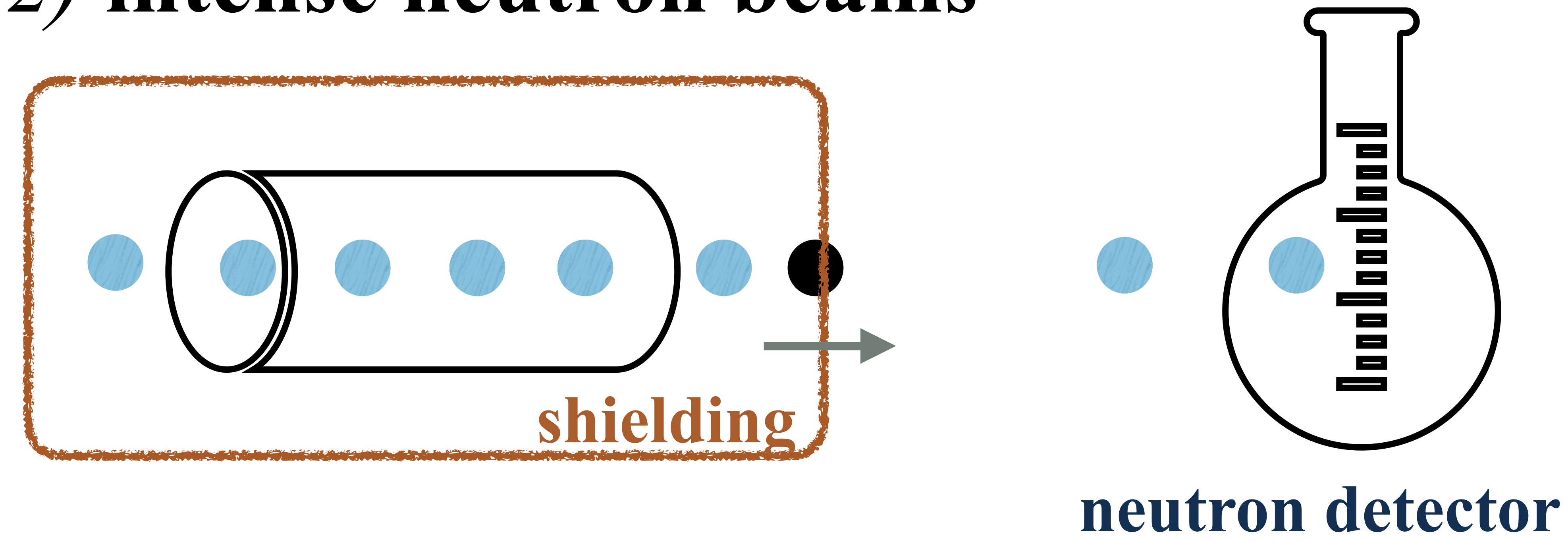
Neutrons shining through a wall



(1) **UCN disappearance**



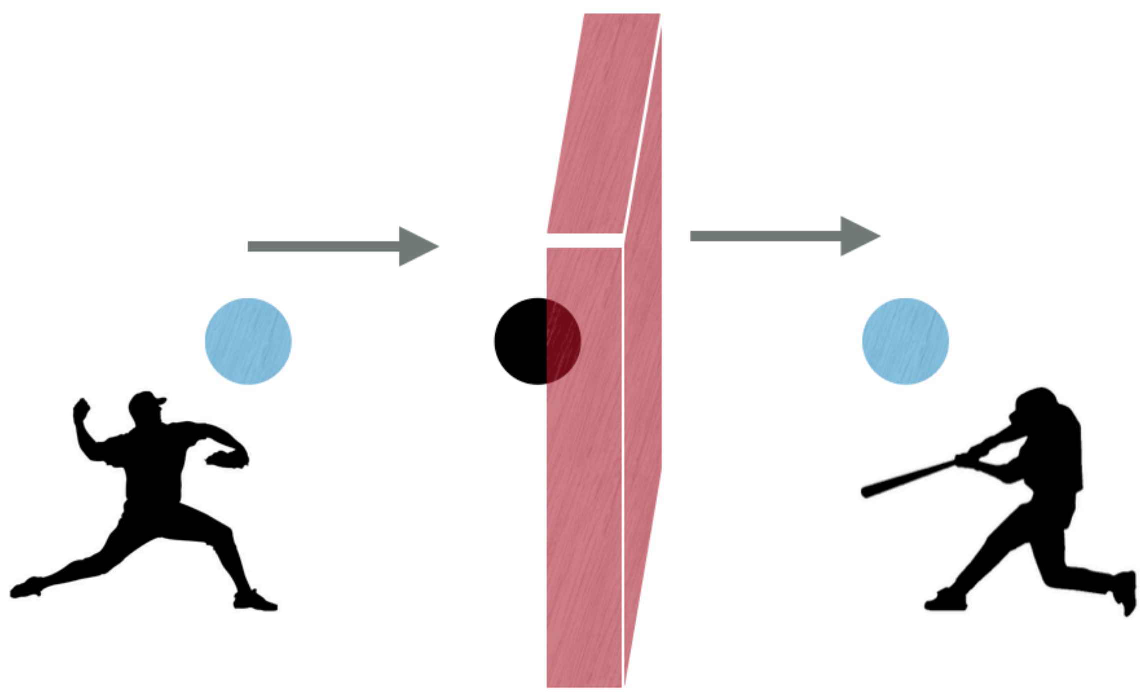
(2) **intense neutron beams**



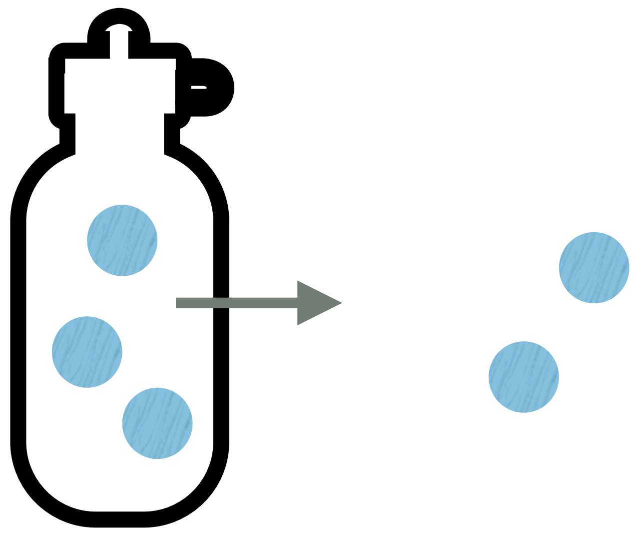
e.g. IsoDAR at Yemilab, Korea

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

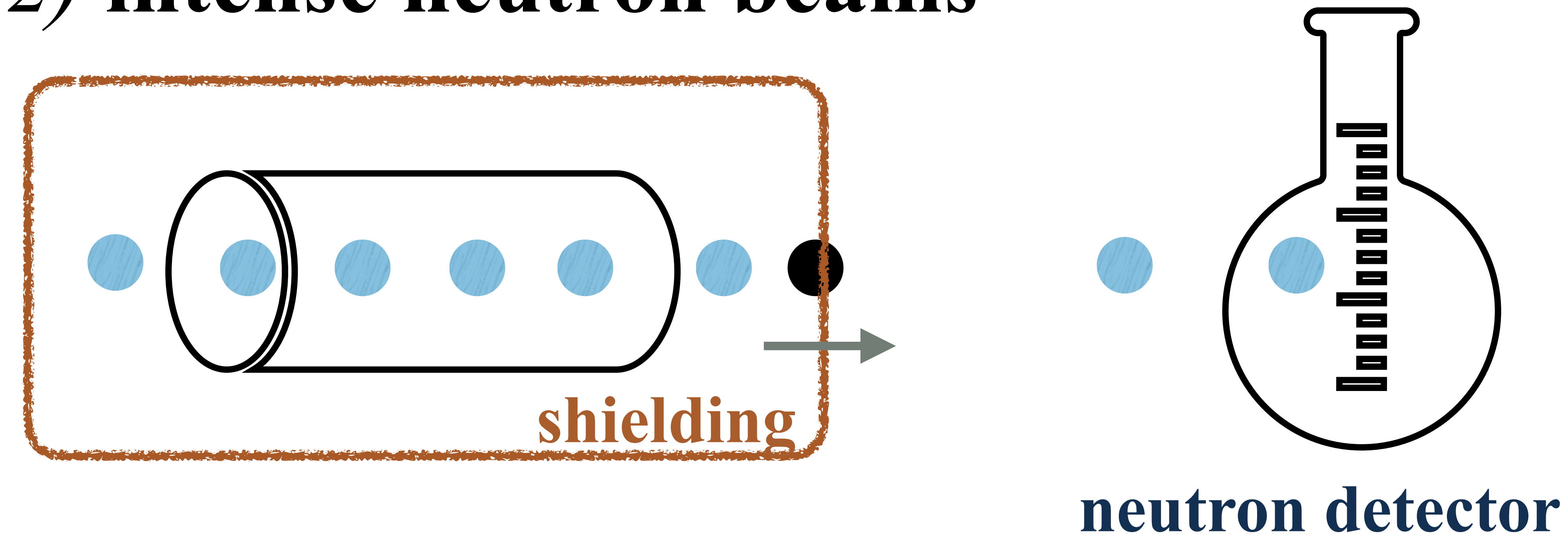
Neutrons shining through a wall



(1) **UCN disappearance**

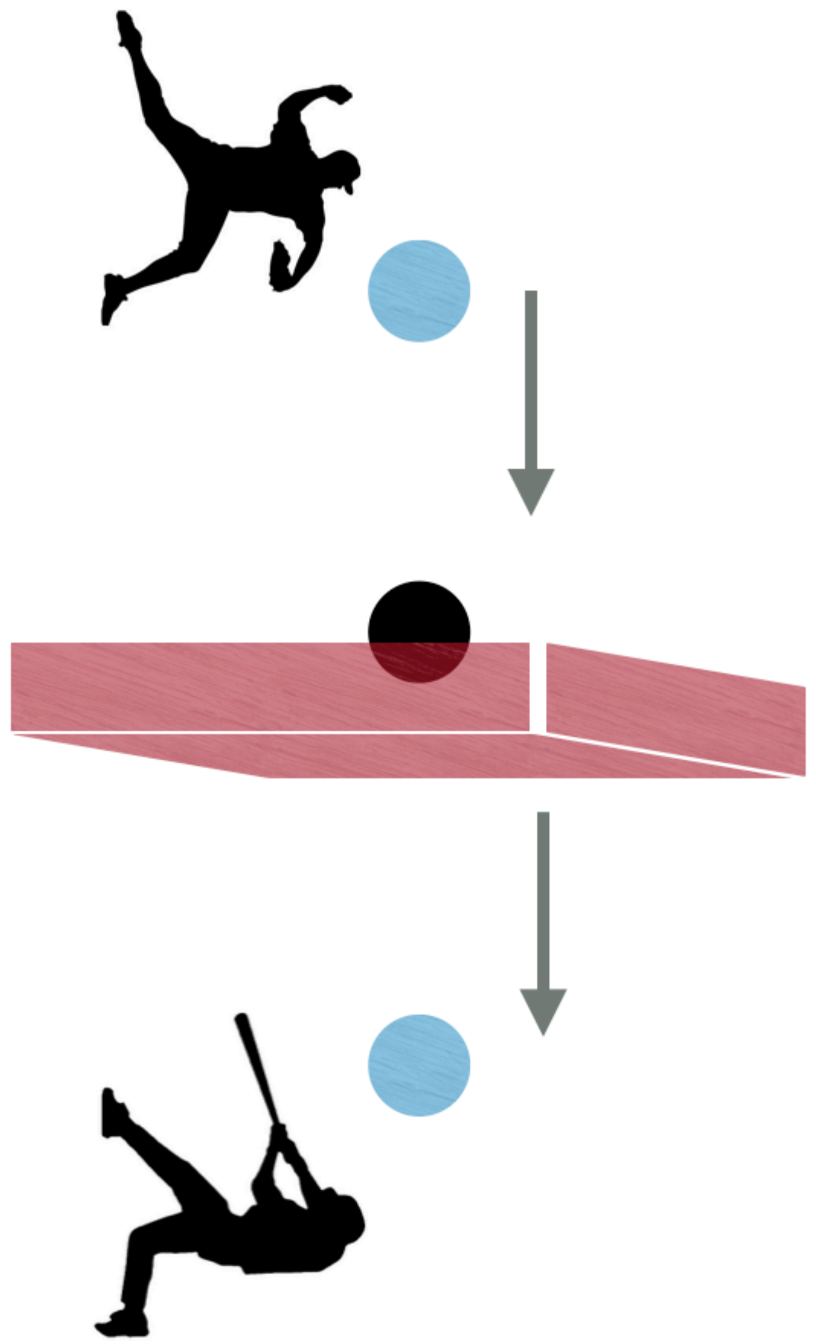


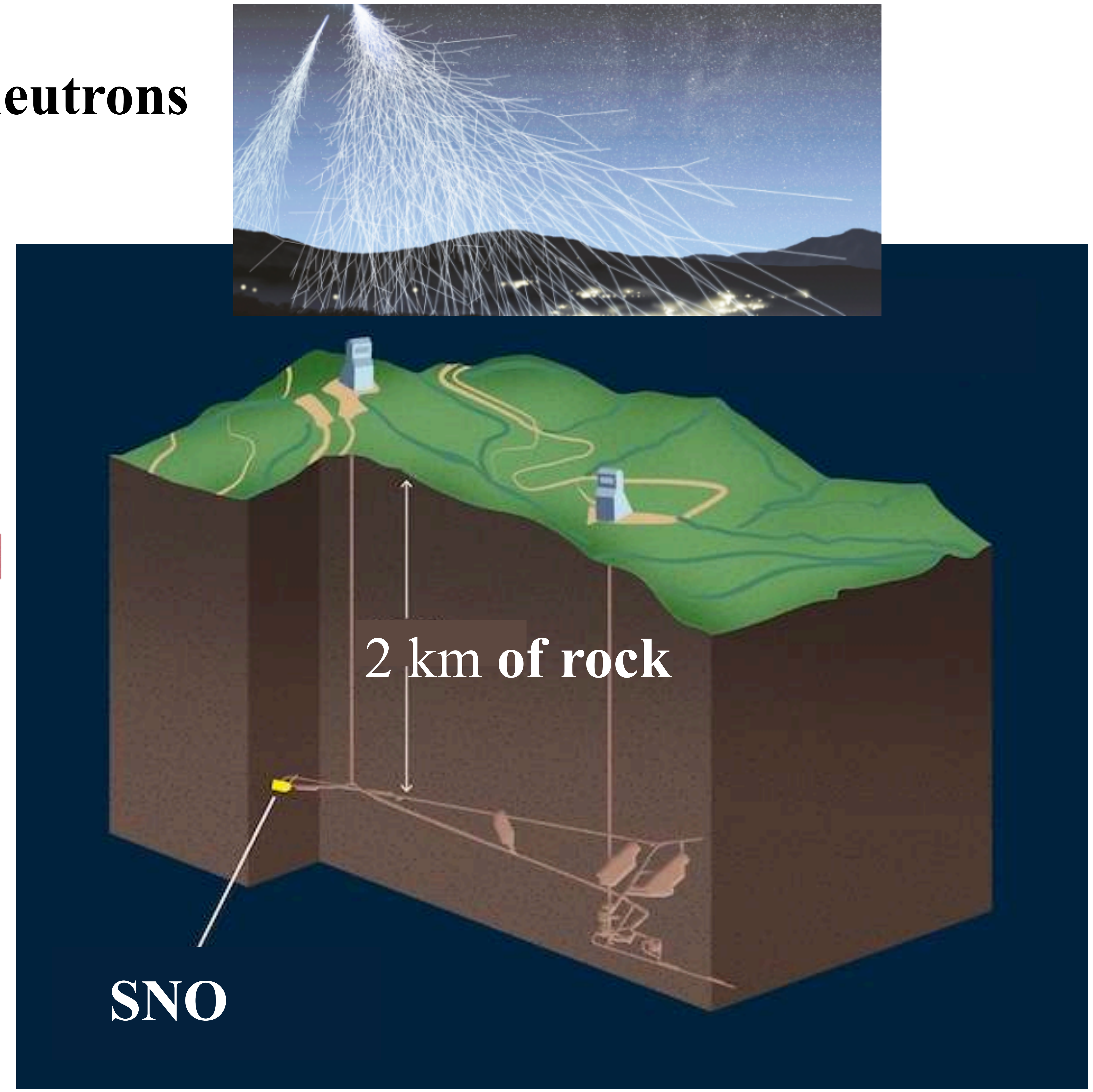
(2) **intense neutron beams**



e.g. IsoDAR at Yemilab, Korea

(3) **cosmic ray neutrons**

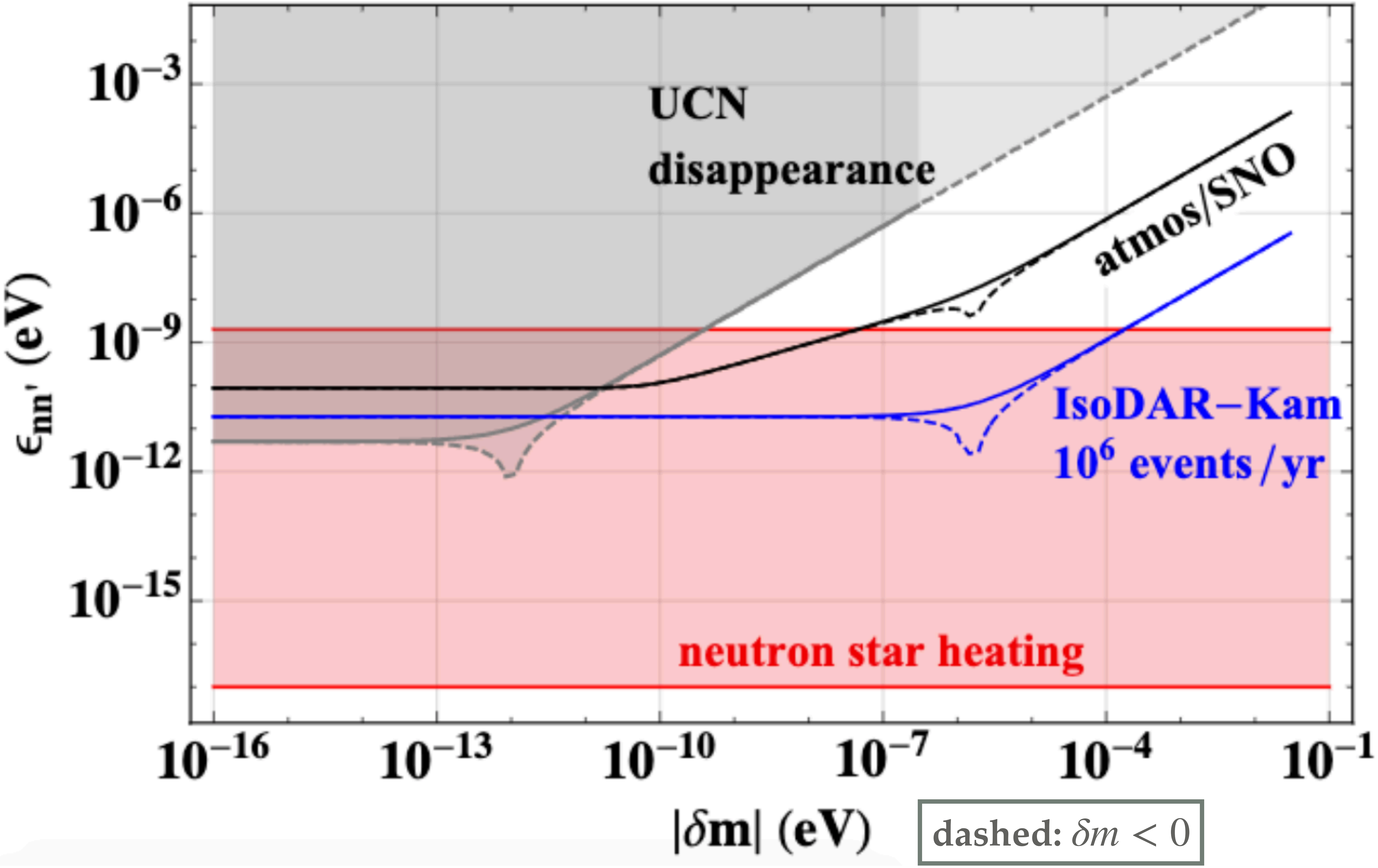




ongoing work with
M. Hostert, D. McKeen, M. Pospelov

Neutrons shining through a wall

preliminary



dashed: $\delta m < 0$

Summary

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

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

- very slow dark neutron production => explosive heating of neutron stars.
  - constrains 19 orders of mass splitting more than UCN searches
  - motivation for future astronomy: direct probe of neutron's quantum properties

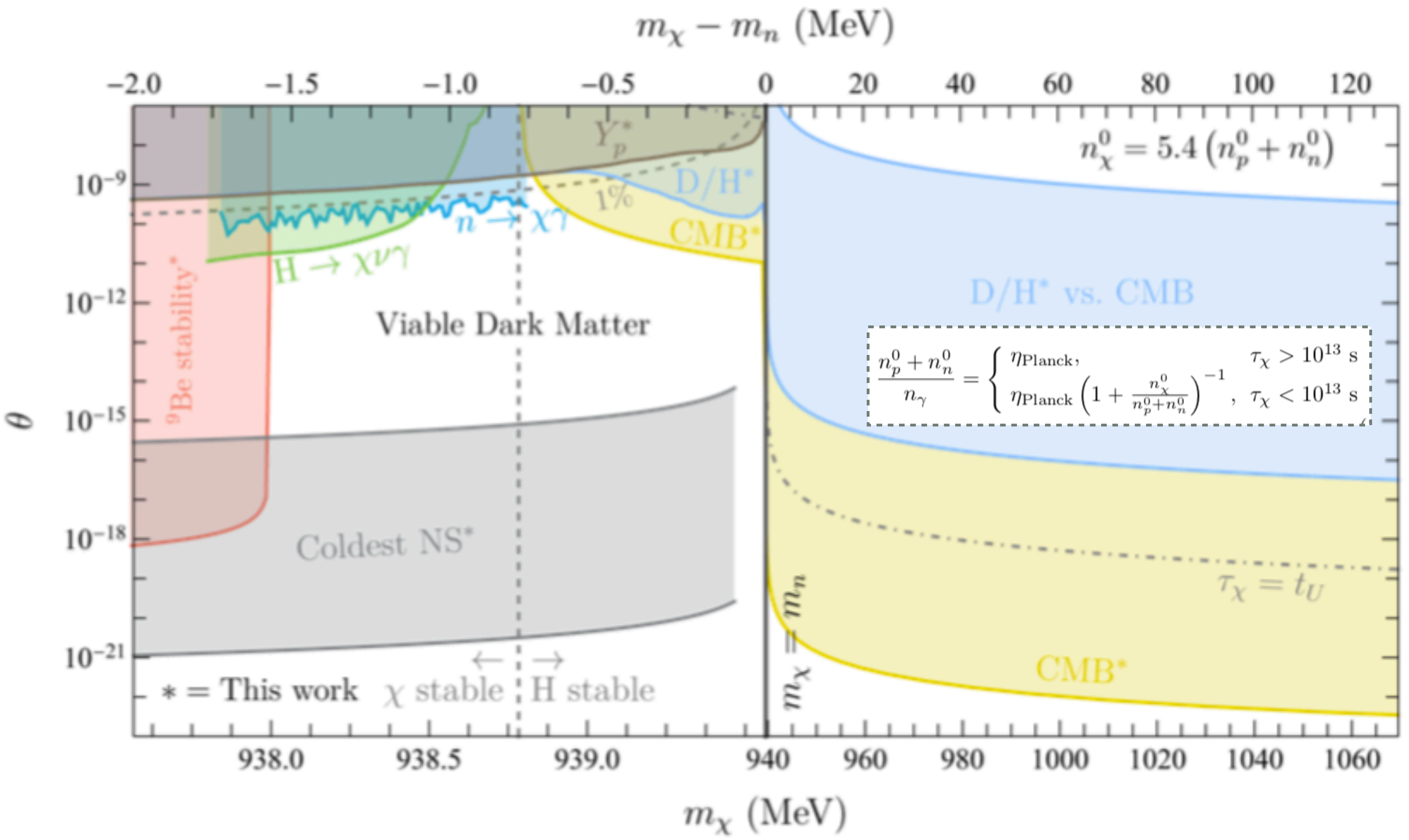
---

Thank you! Questions?

Back-up slides

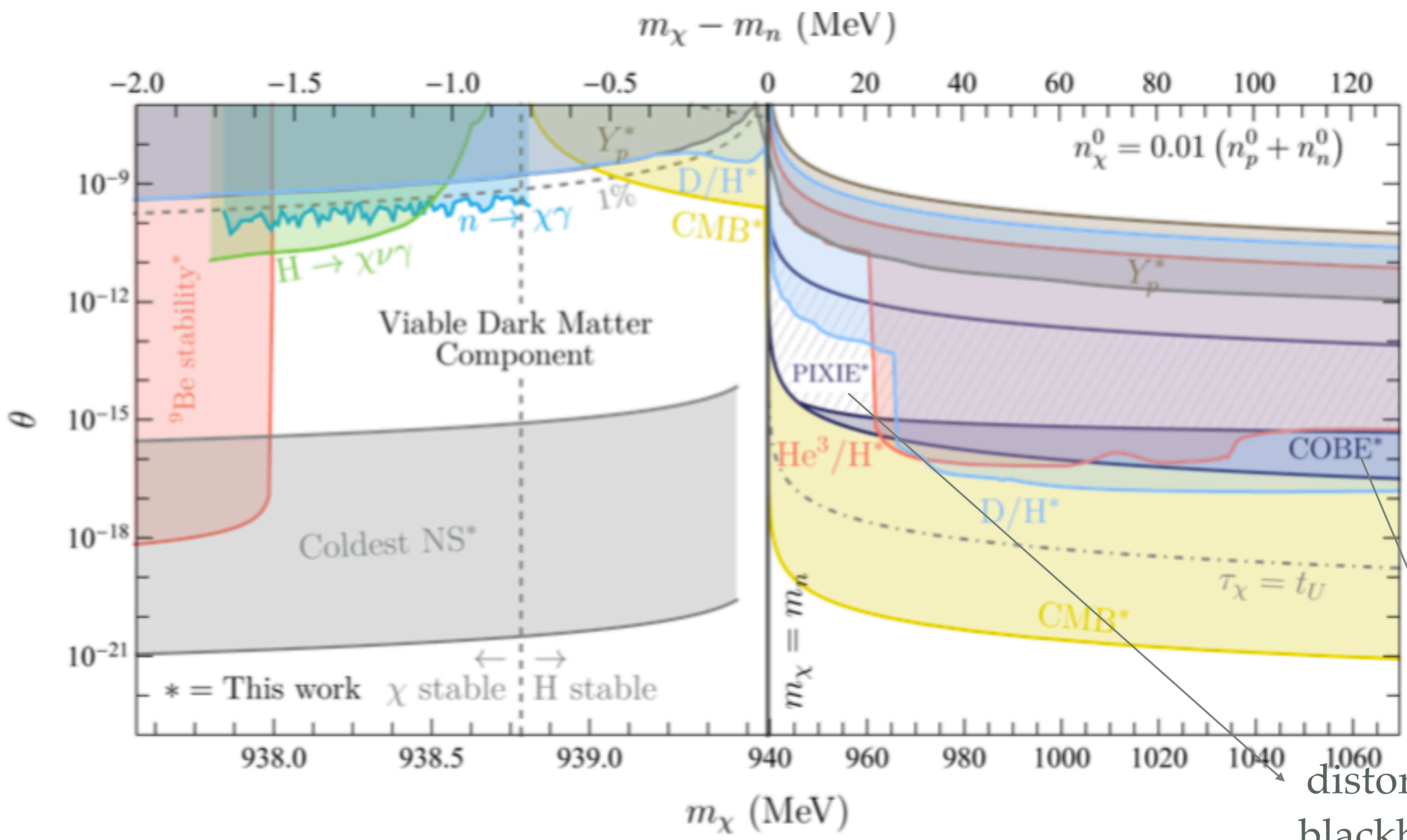
2012.09865 *McKeen, Pospelov,* Raj

Constraints: χ all the dark matter



Constraints: χ percent-level dark matter

2012.09865 *McKeen, Pospelov,* Raj



distortions of CMB blackbody spectrum