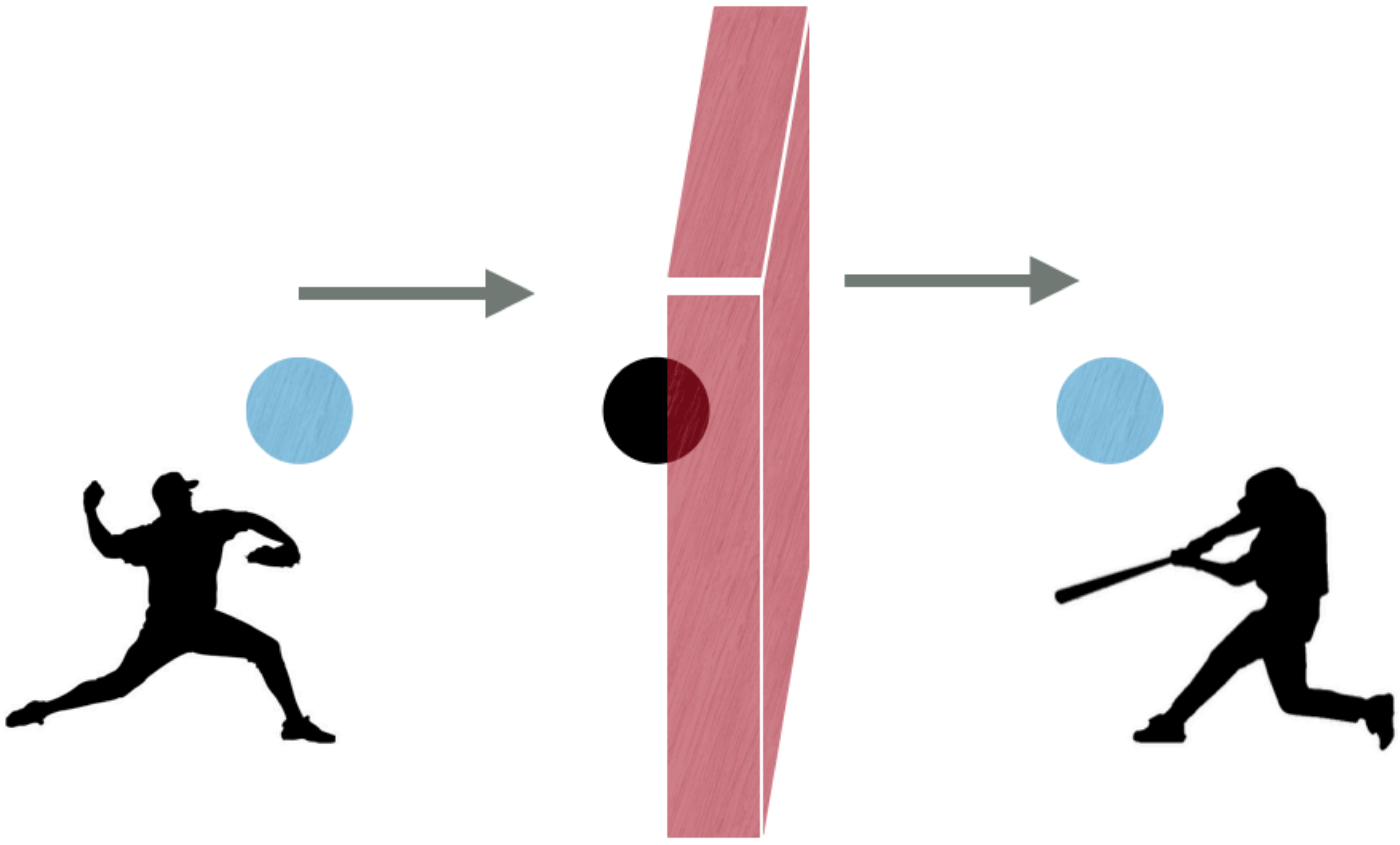
Particle Theory: Dark Neutrons



Nirmal Raj
TRIUMF Science Week
08/17/2021

based on

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

with **David McKeen**
& Maxim Pospelov

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
$939.5654\ \mathrm{MeV}/c^2$	?

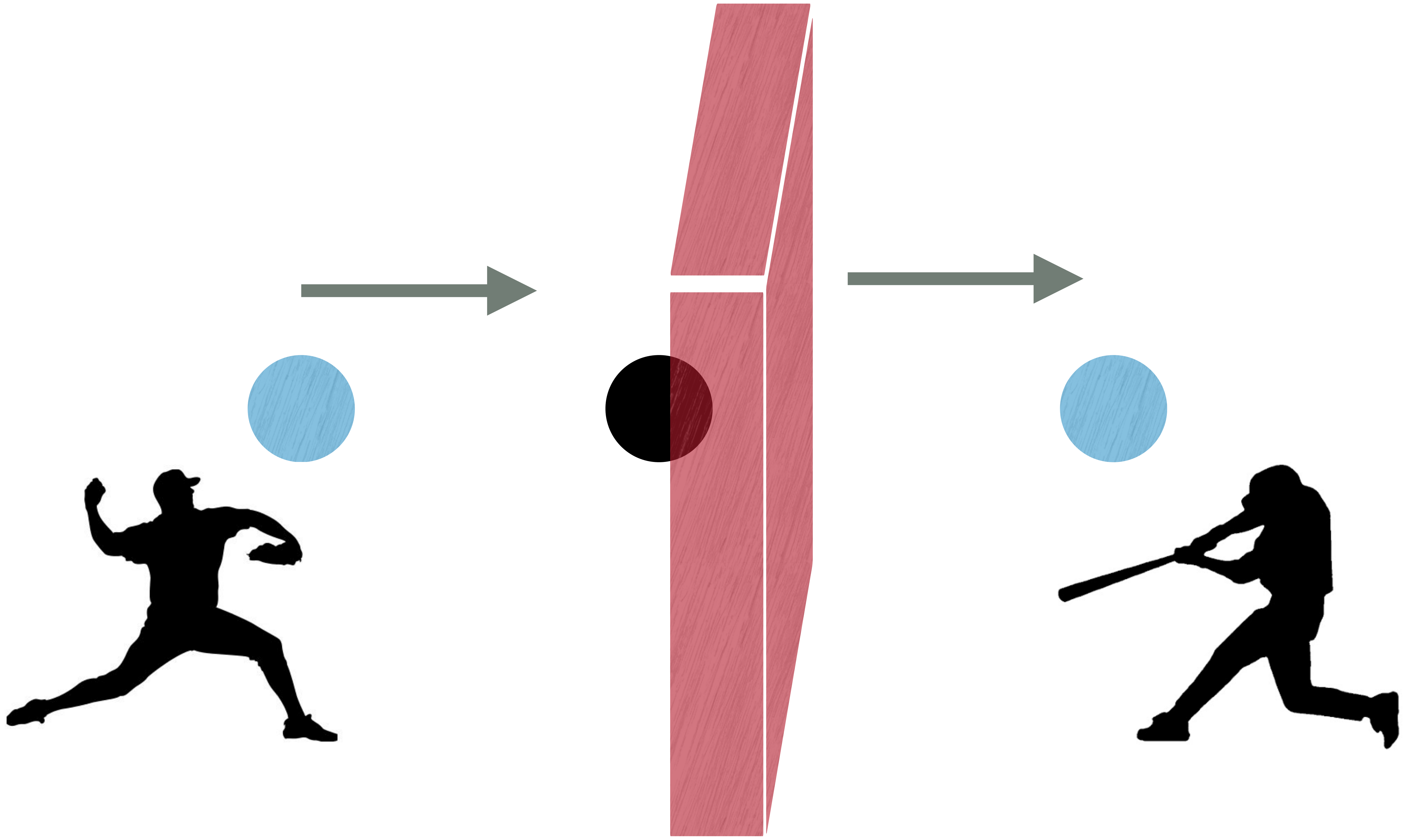
Hamiltonian

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

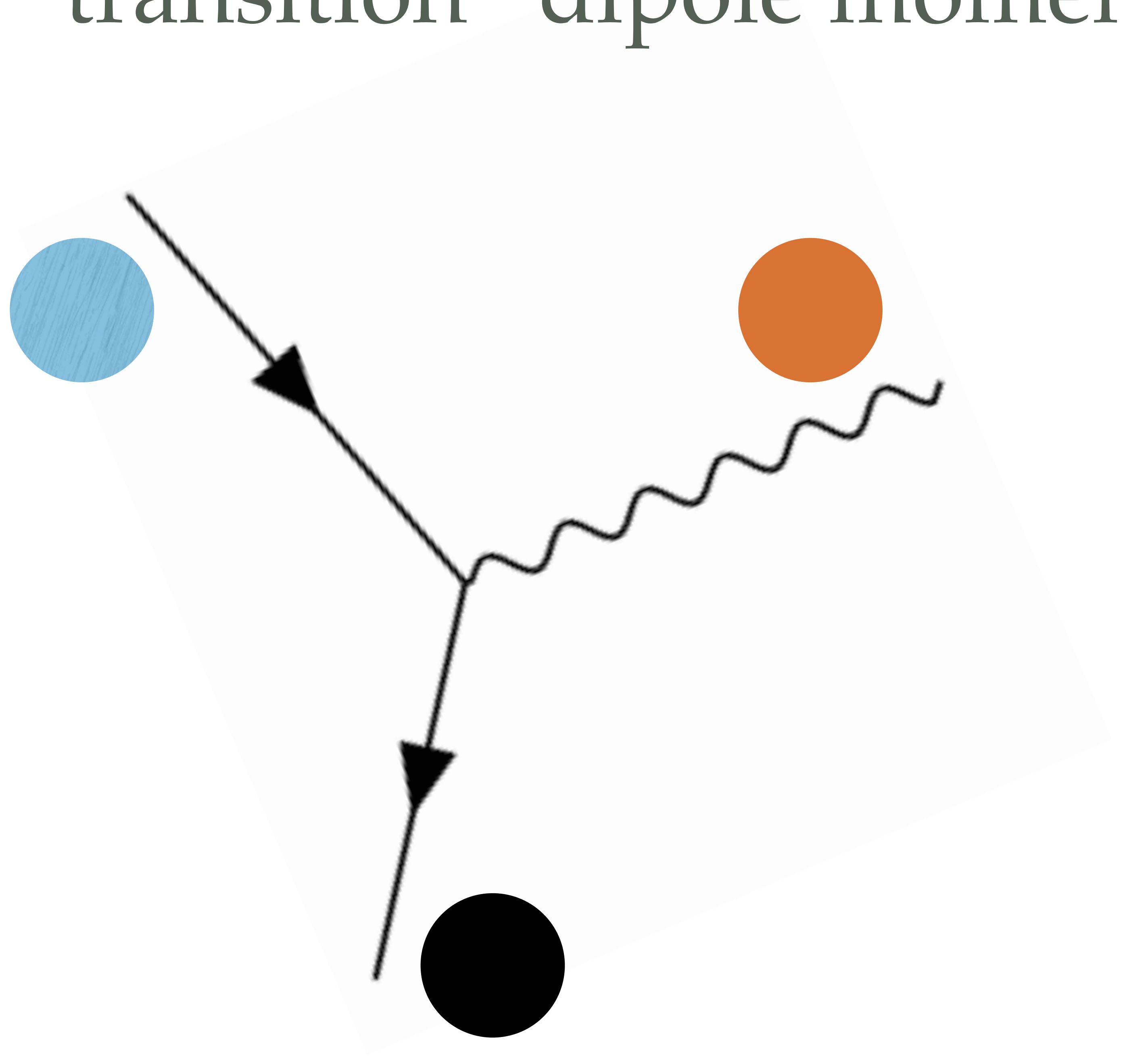
$\epsilon_{n\chi}$ nothing forbids it: compulsory! => *quantum mixing*

Consequences

oscillations



magnetic “transition“ dipole moment



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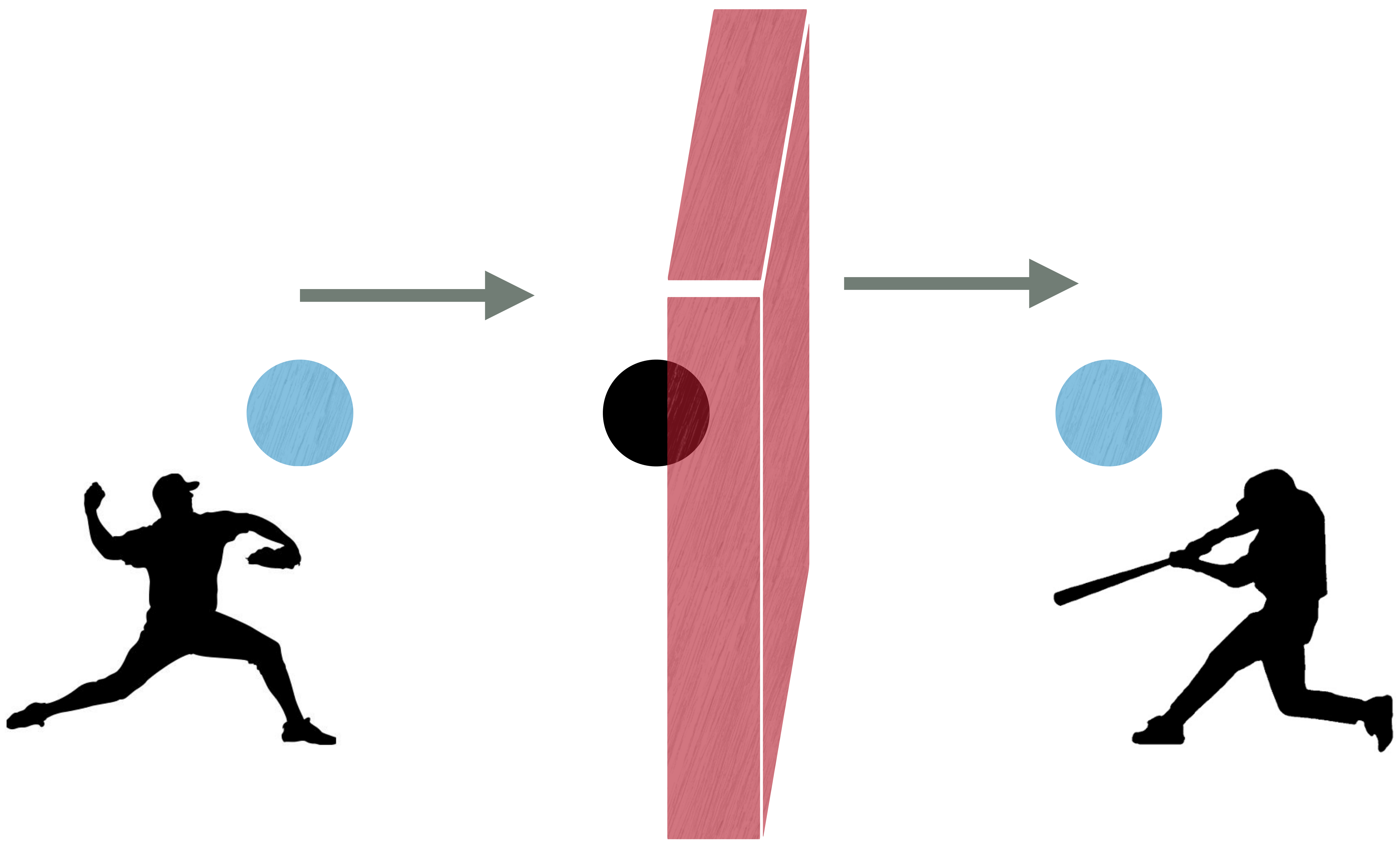

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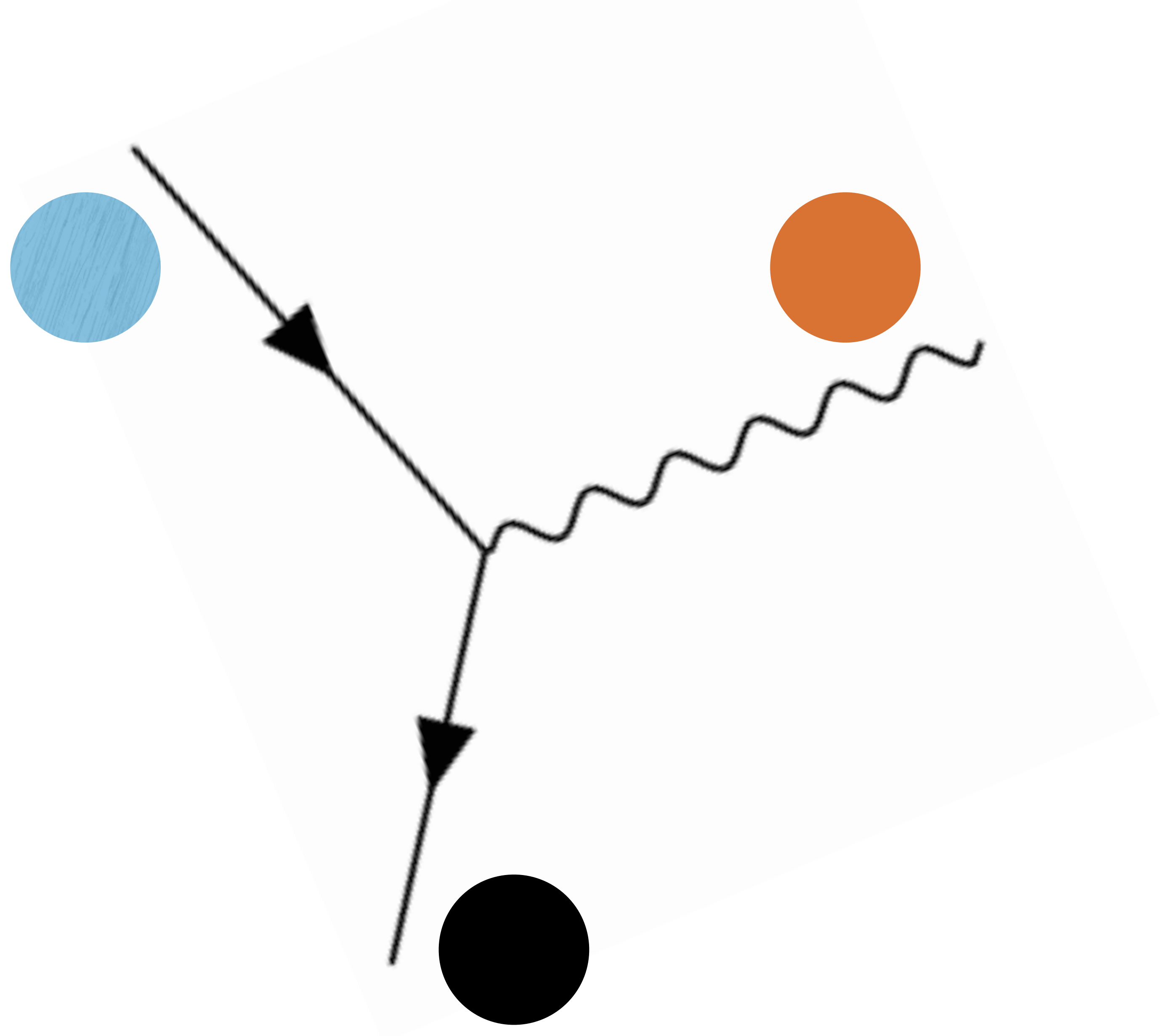
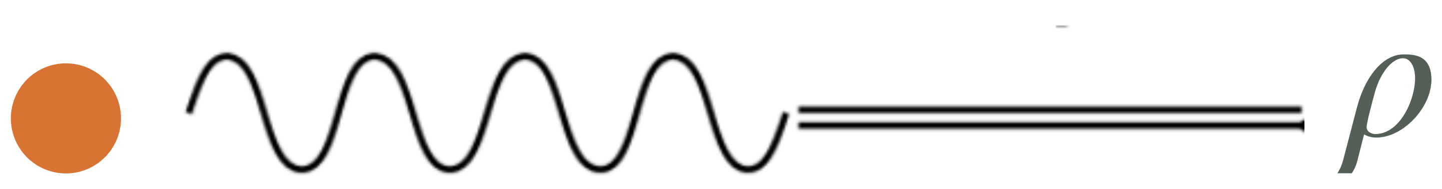
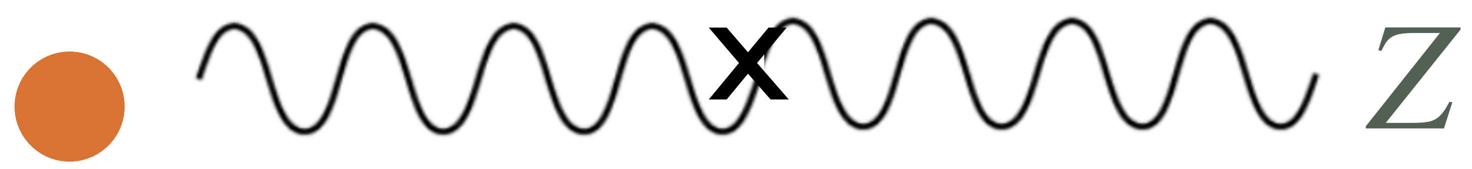


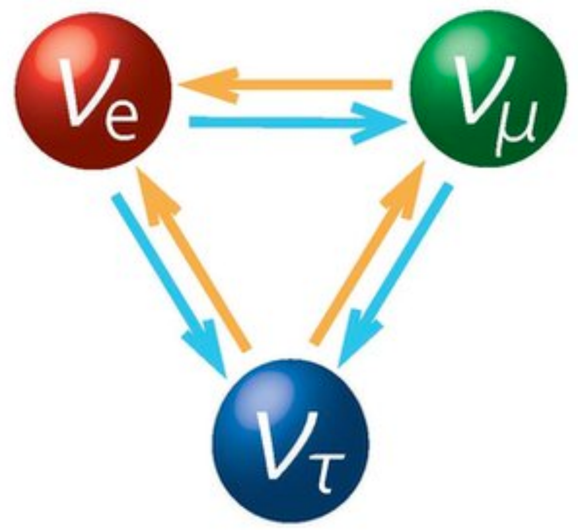
quantum mixing already seen in Nature:



photon - rho meson



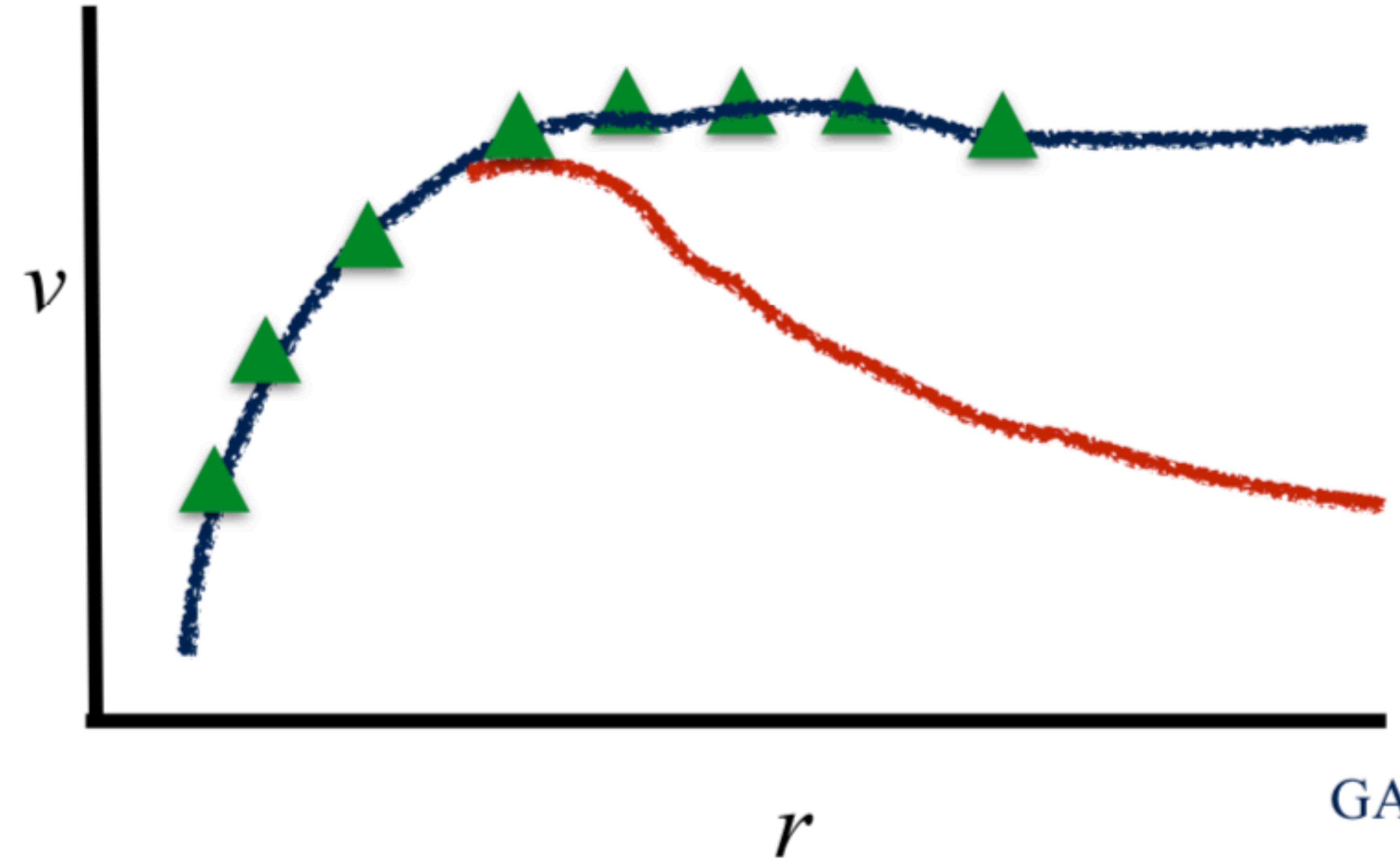
photon - Z boson



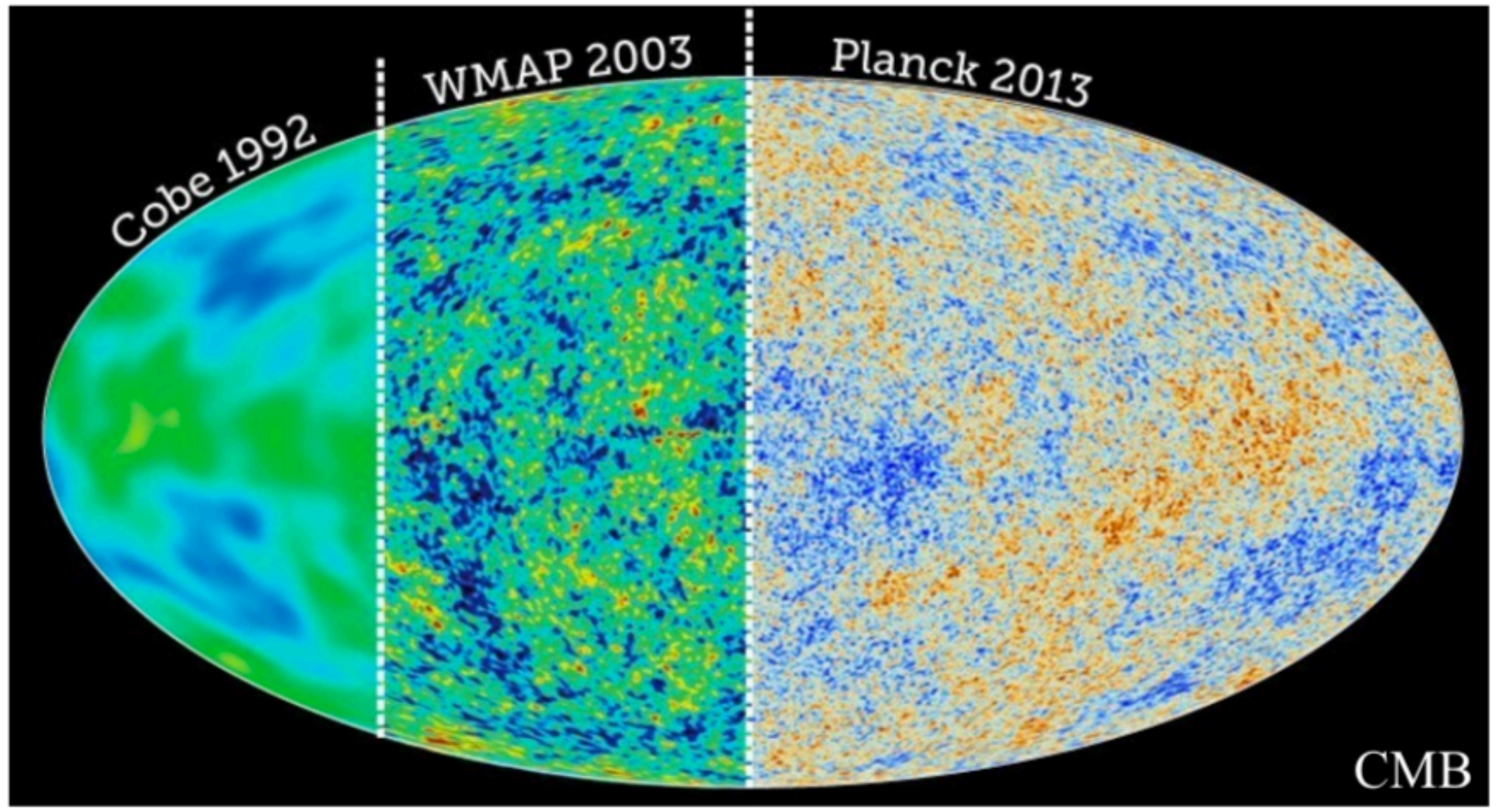
neutrino flavours

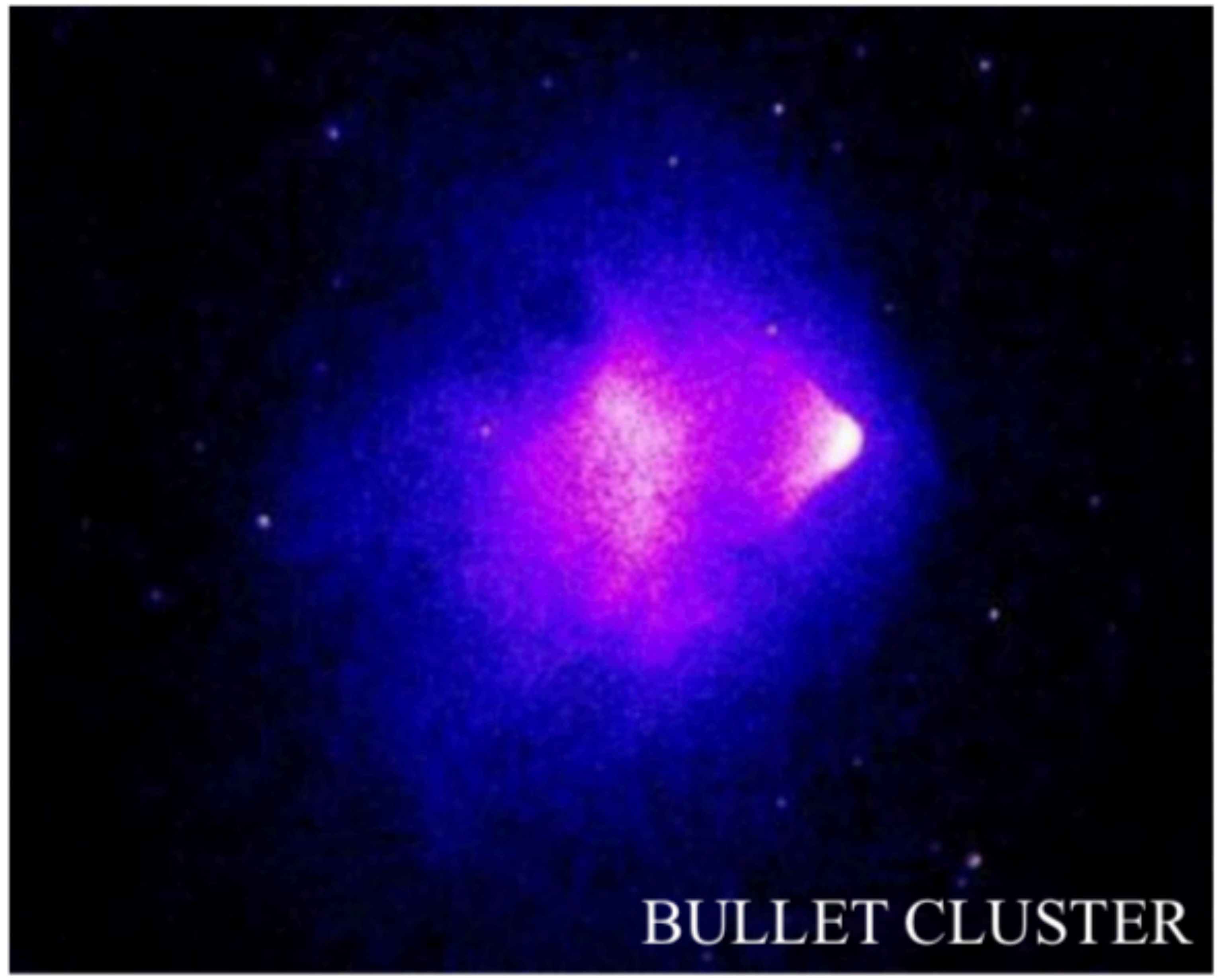
Why care?

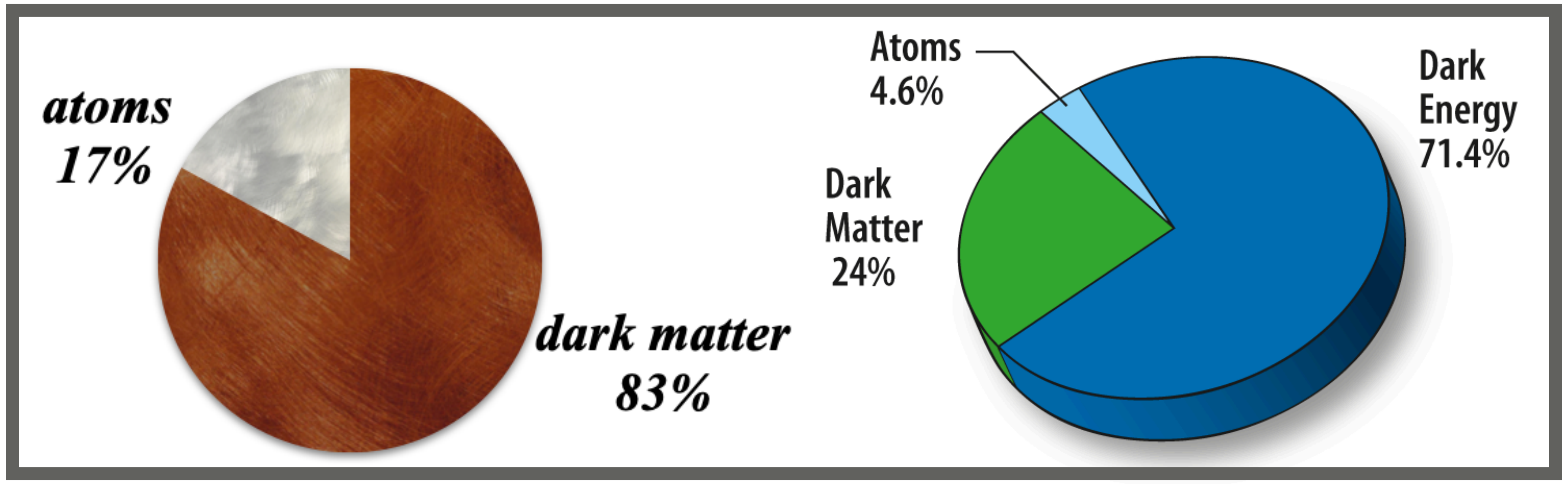
(1) the *dark matter* of the universe



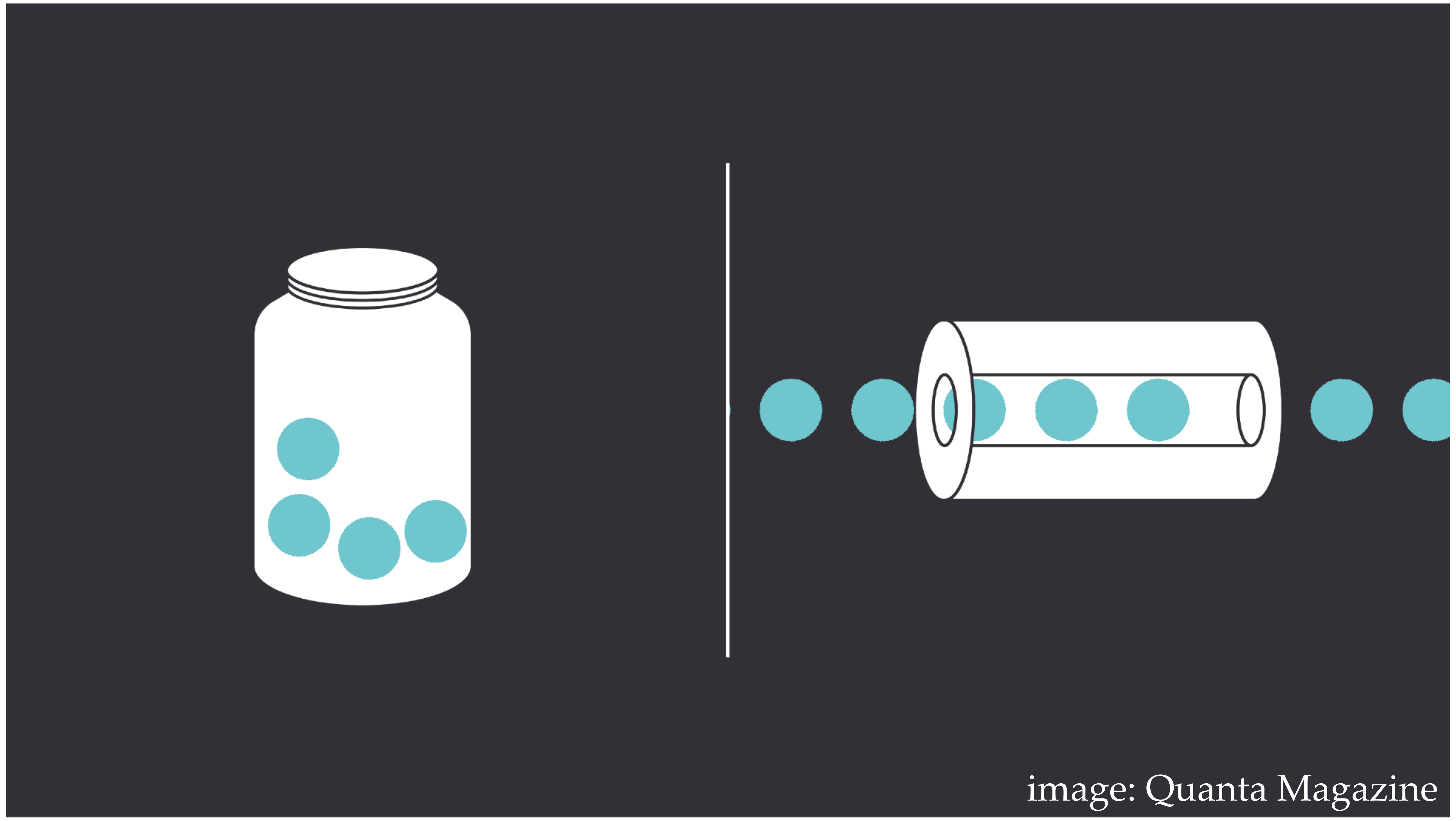
GALACTIC ROTATION

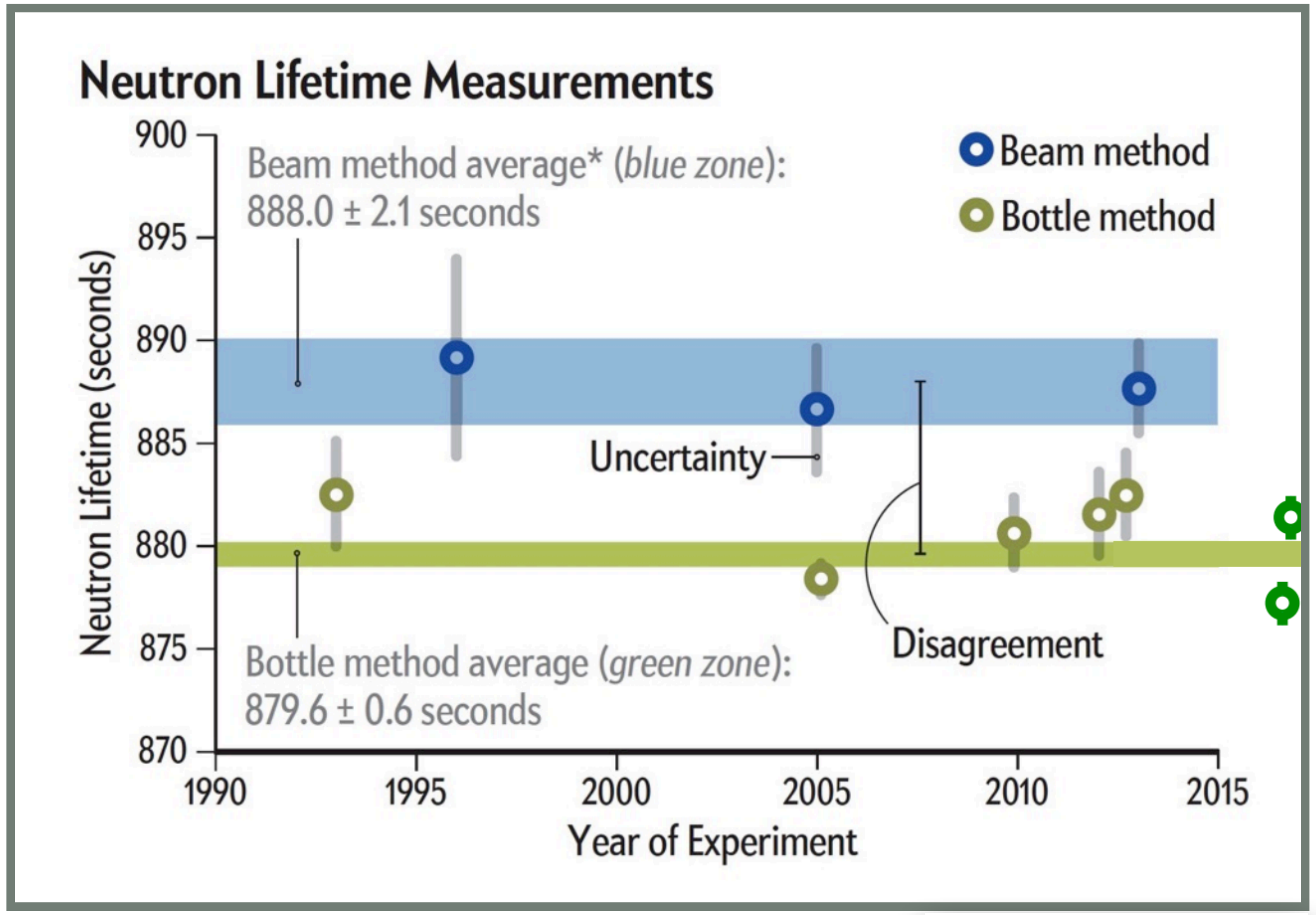






Why care? (2) the *neutron lifetime puzzle*





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

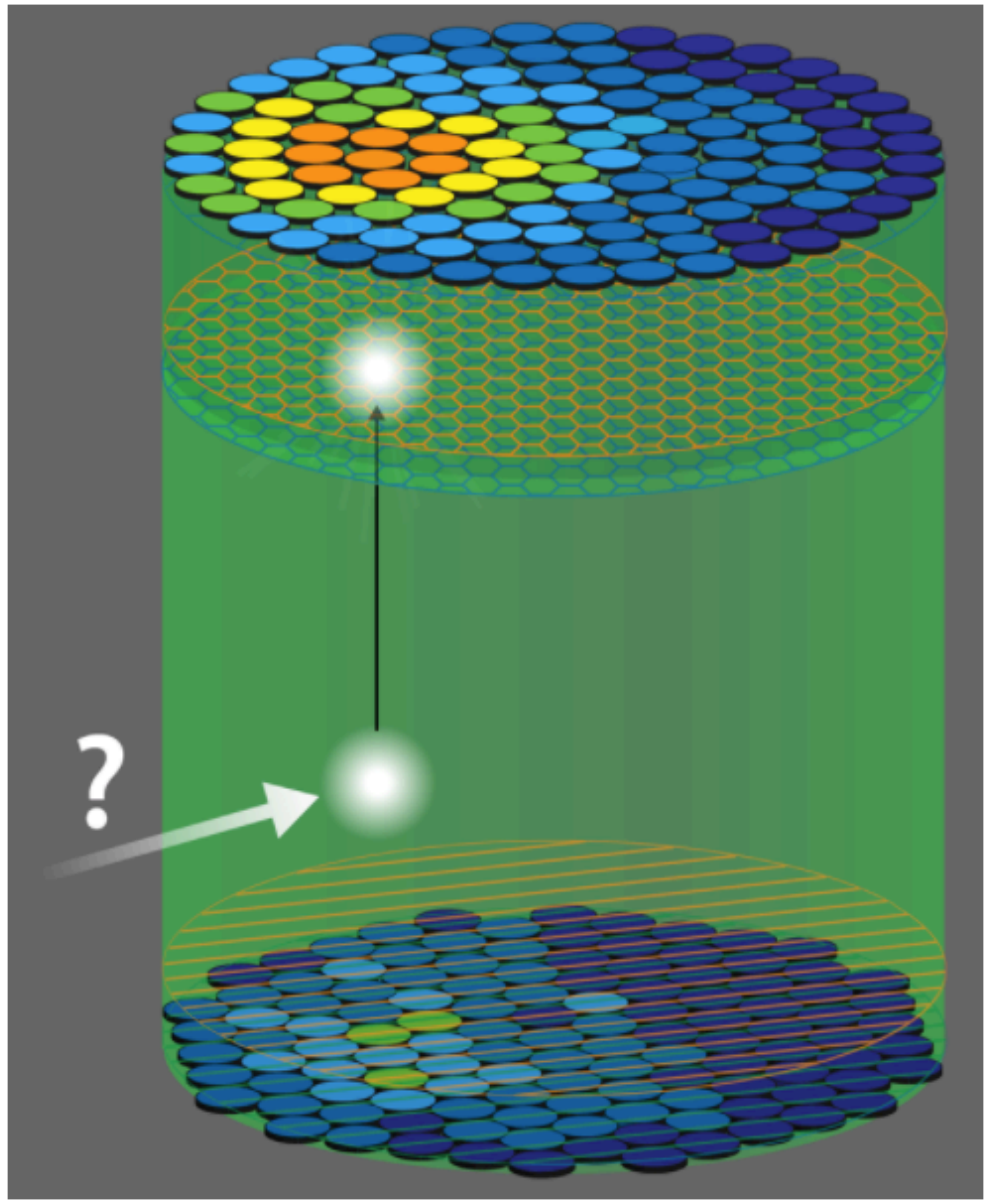
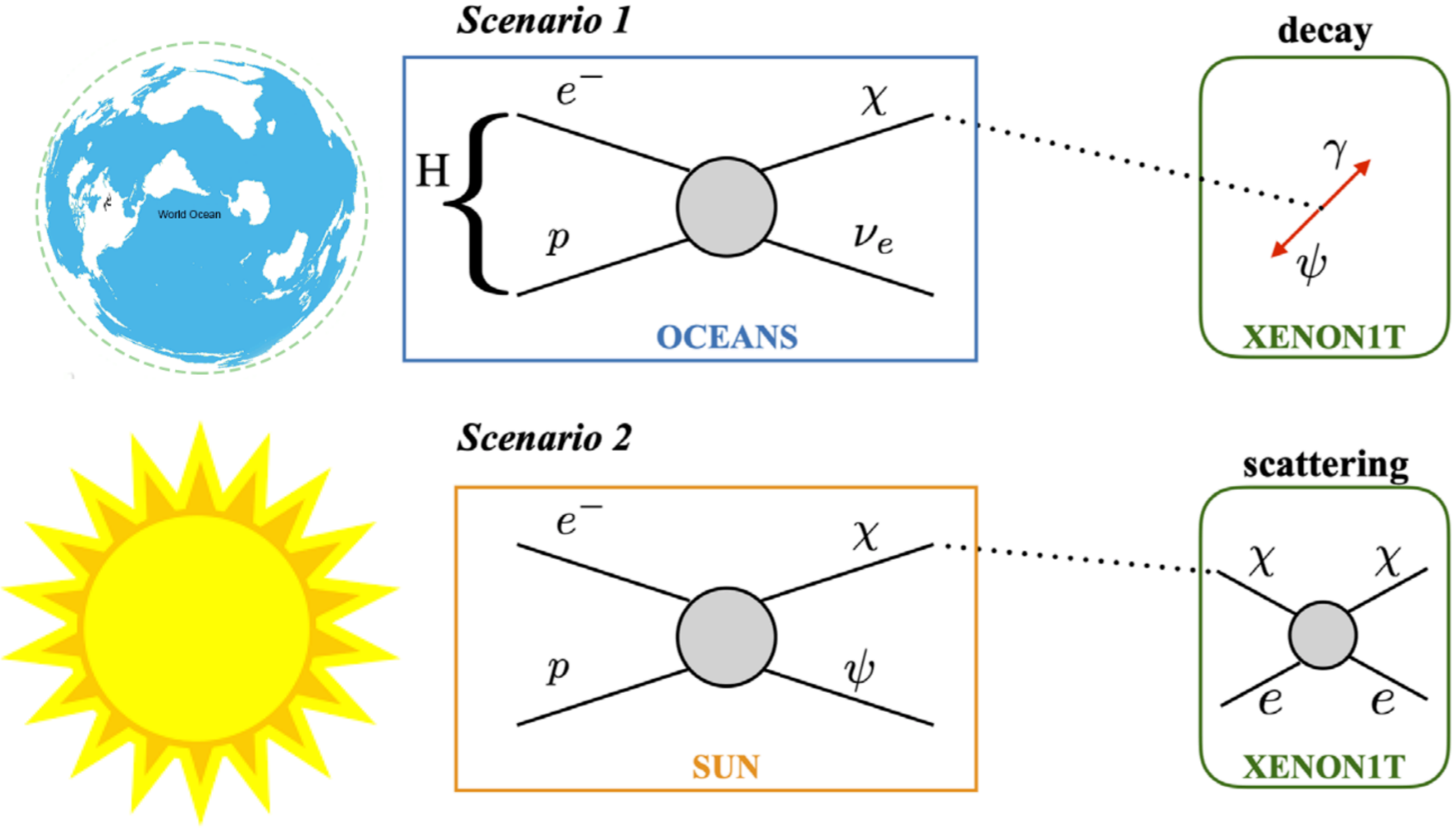


image: APS

arXiv: 2006.09721



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

From where?

elementary

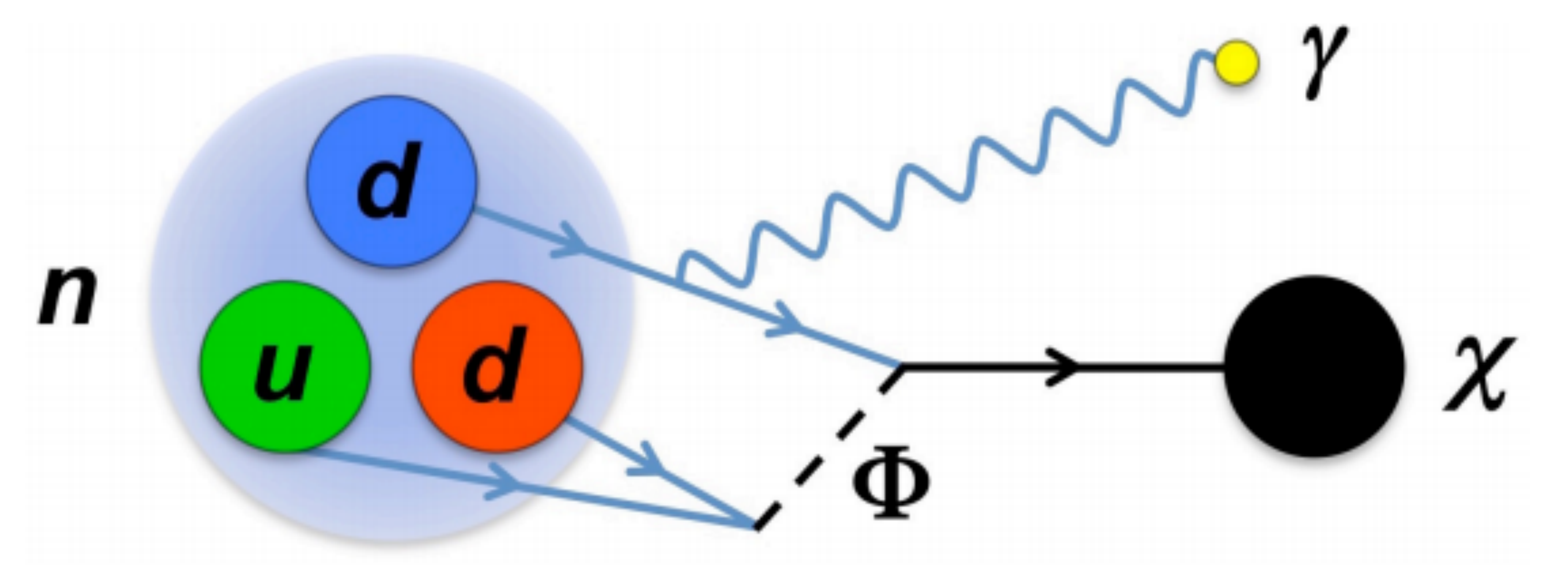
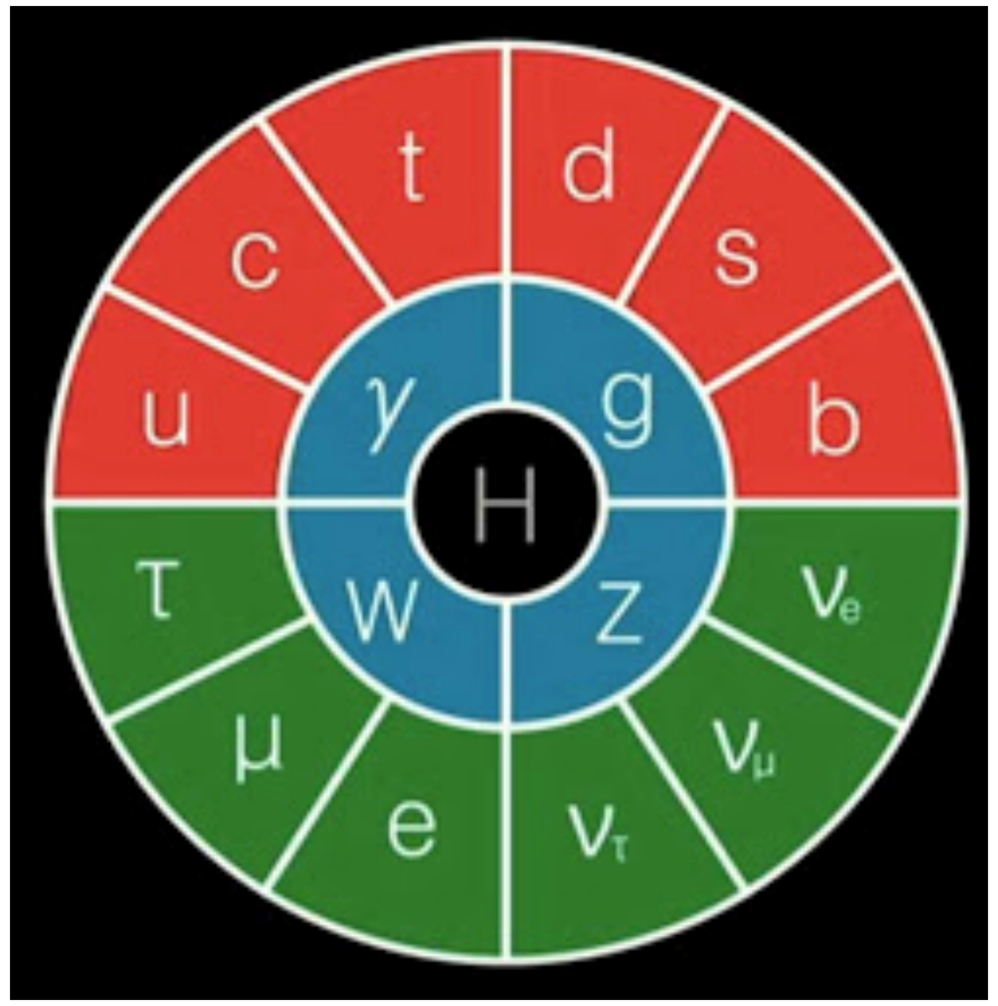
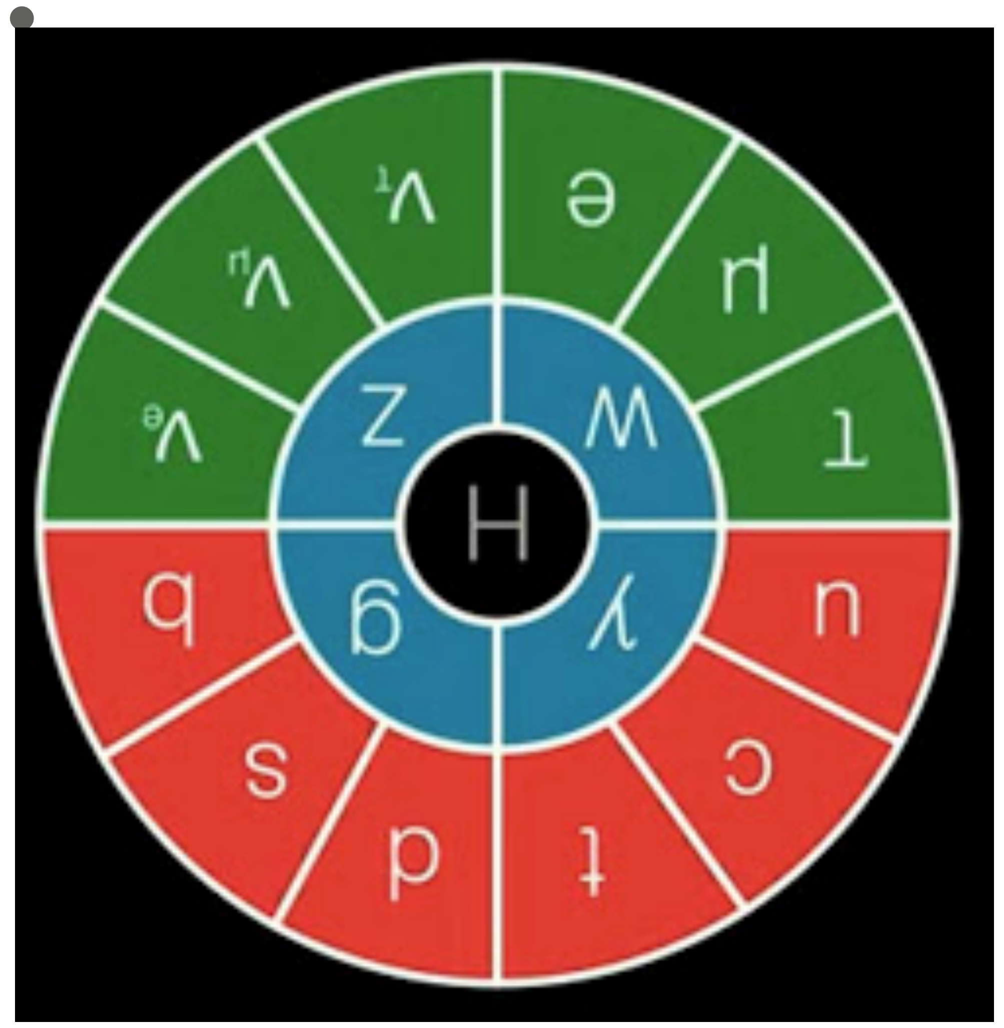


image: Fornal & Grinstein

composite



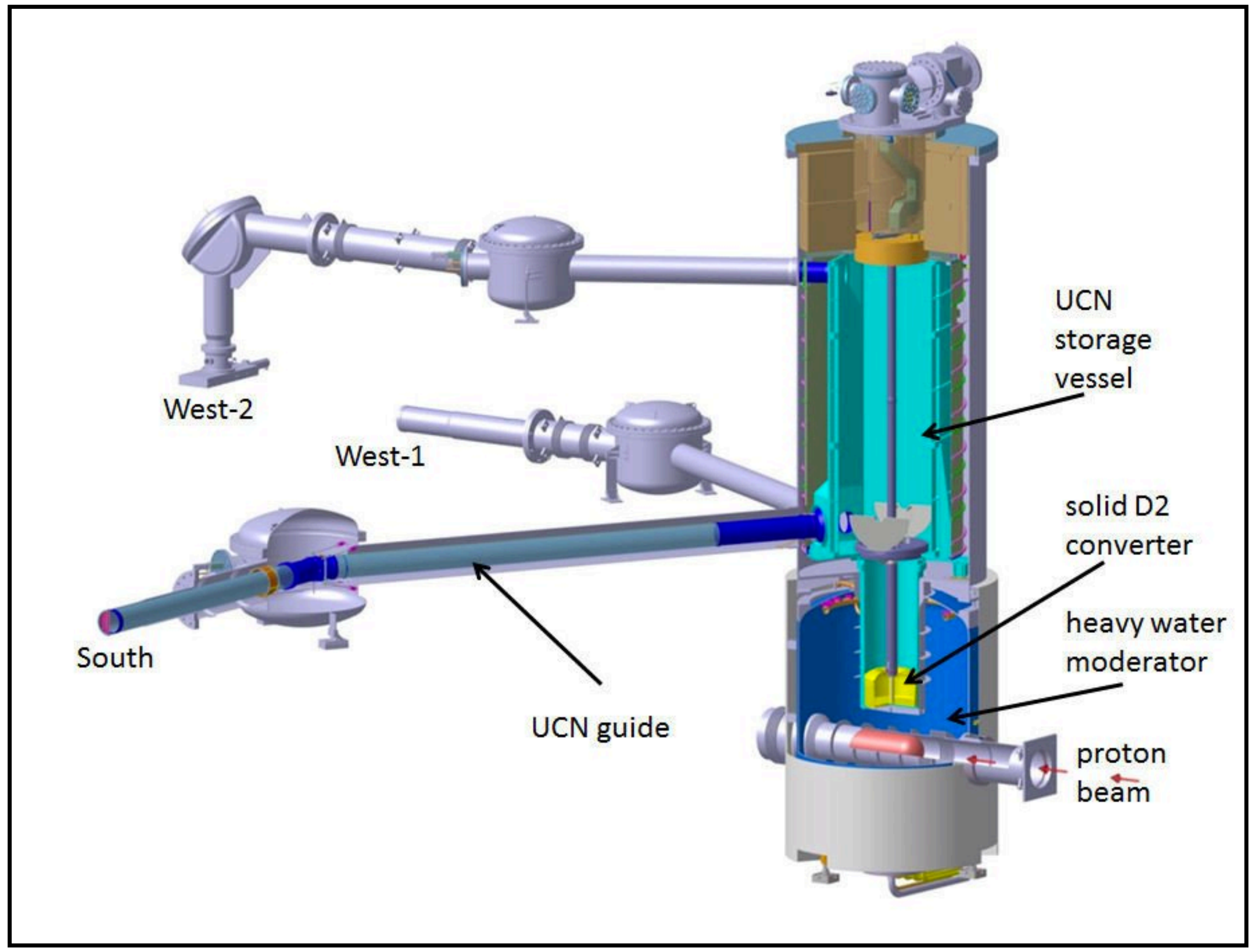
from a ***mirror sector***

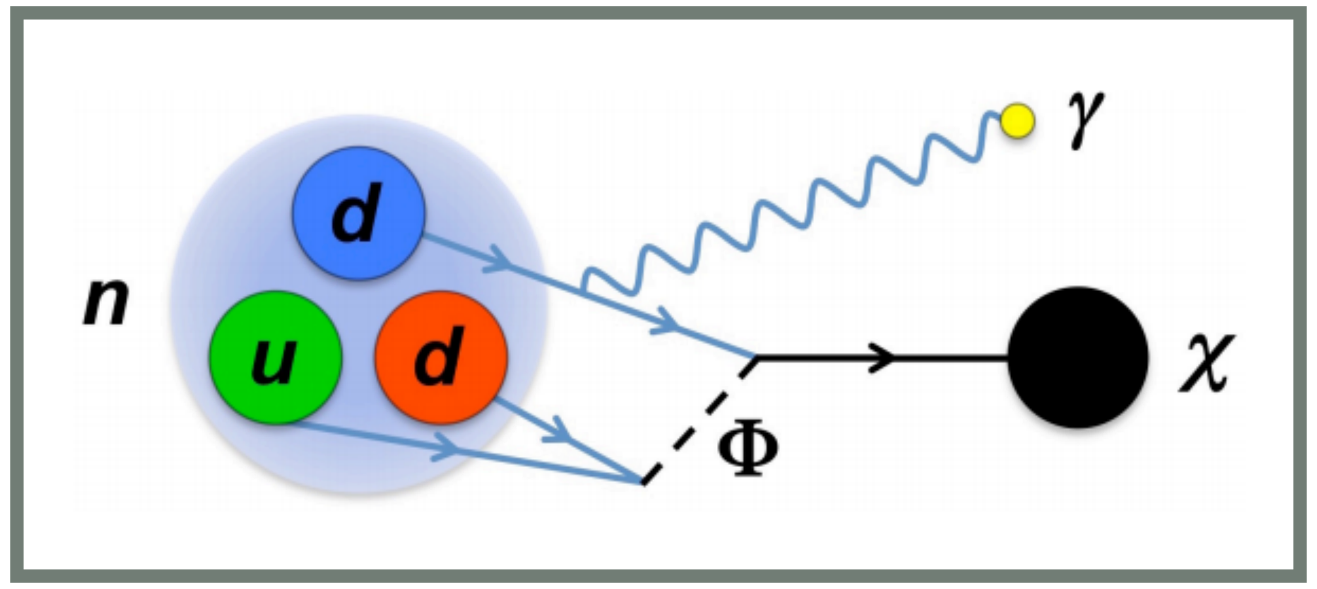


Kobzarev, Okun, Pomeranchuk 1966

Where to find?

(0) *ultra-cold neutron facilities*





UCN @ TRIUMF

Where to find?

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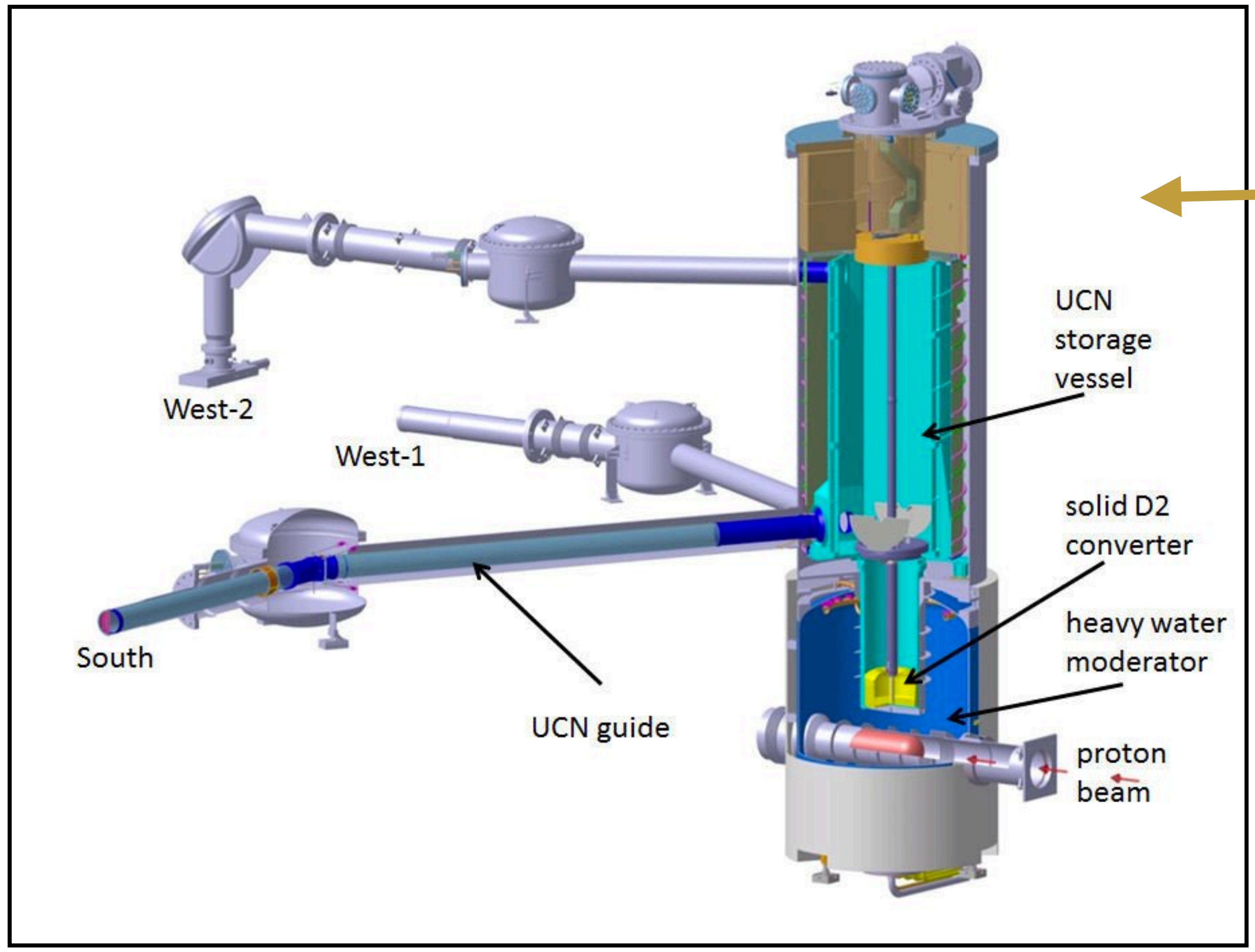
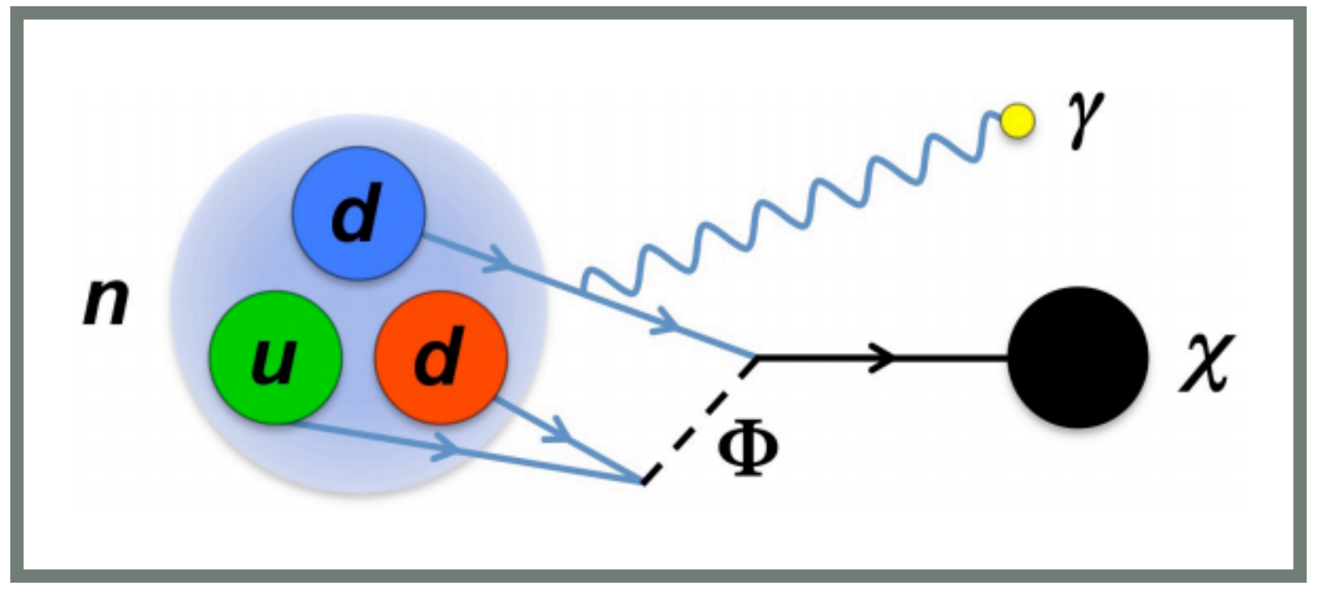
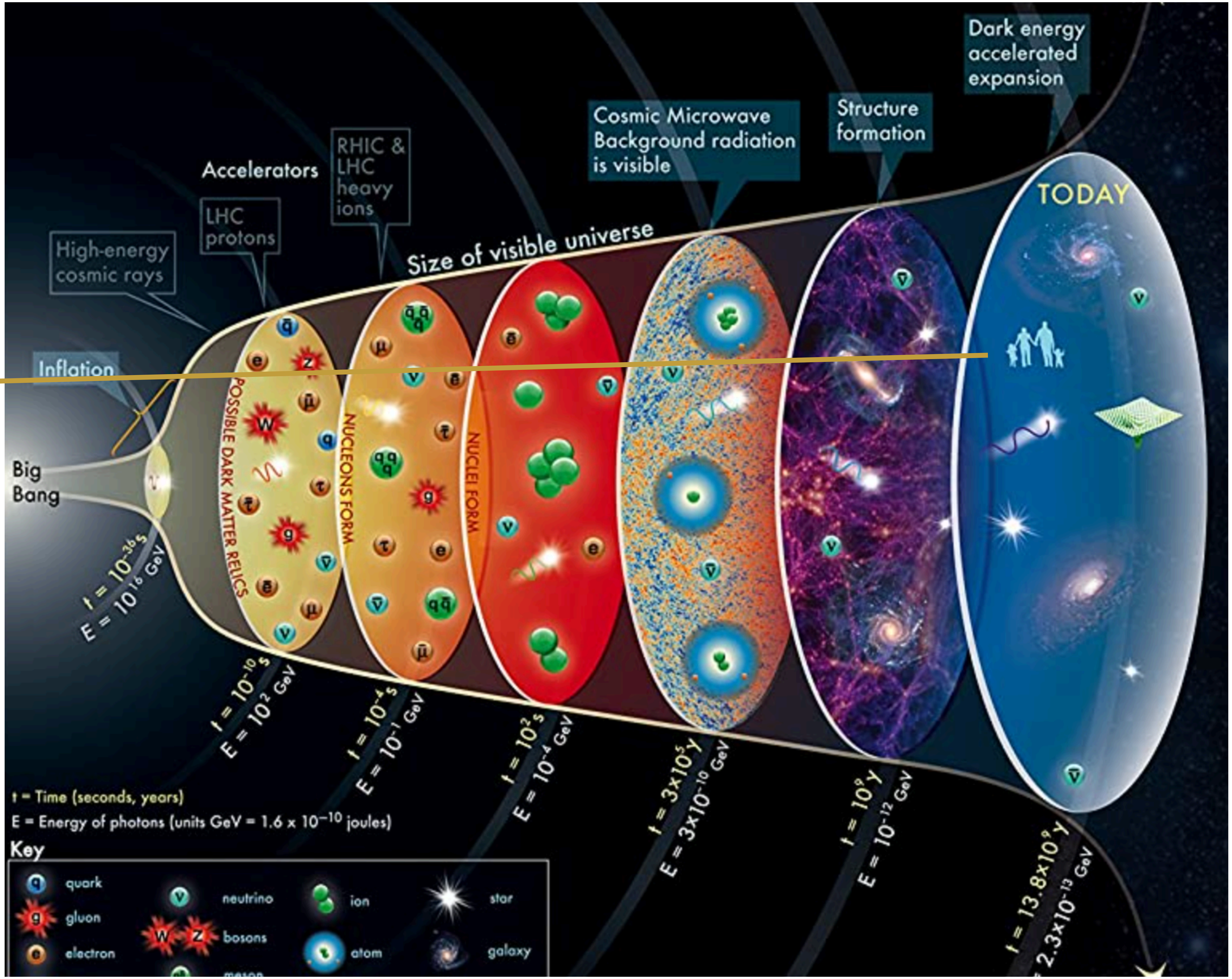


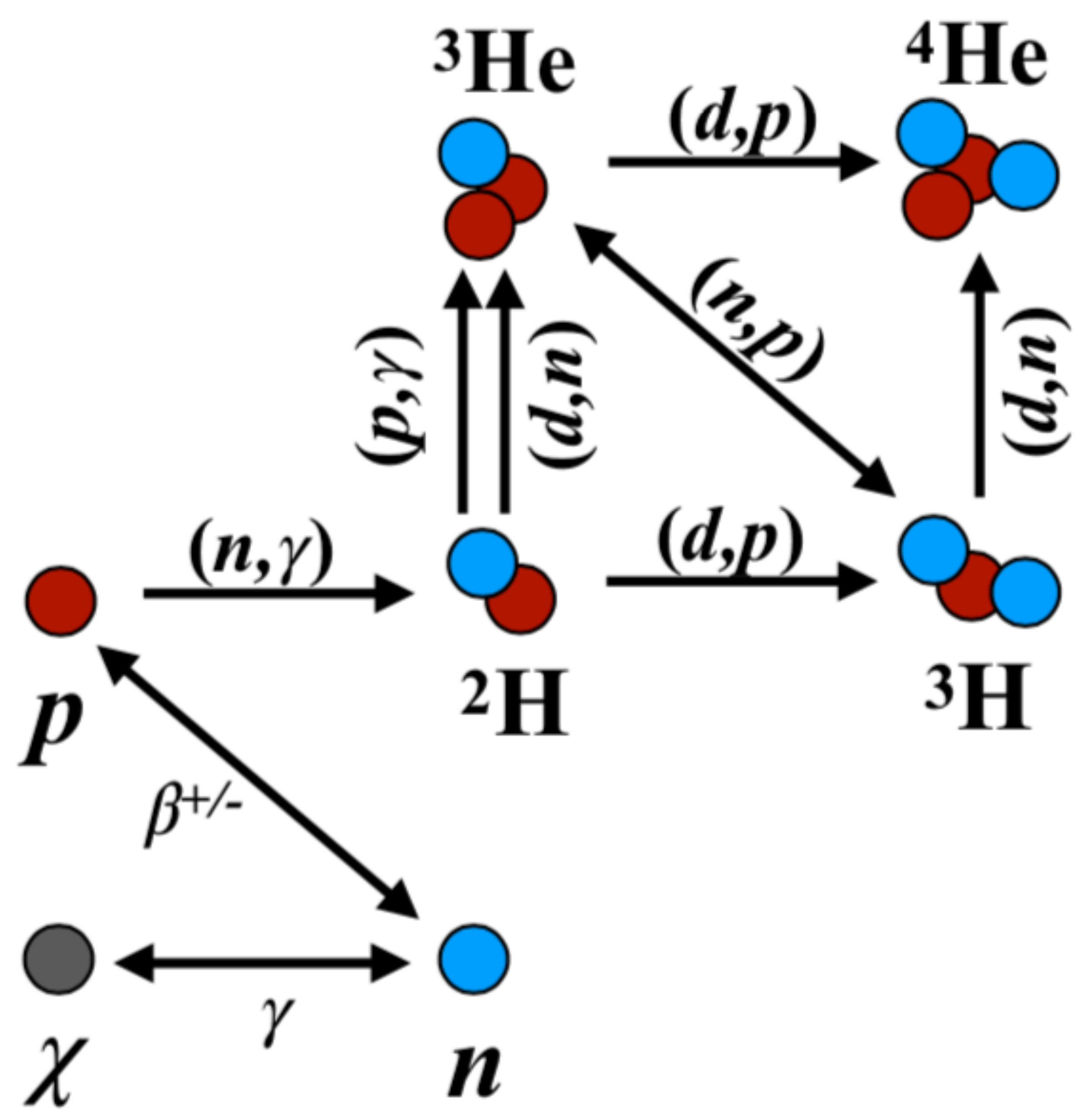


timeline of the universe

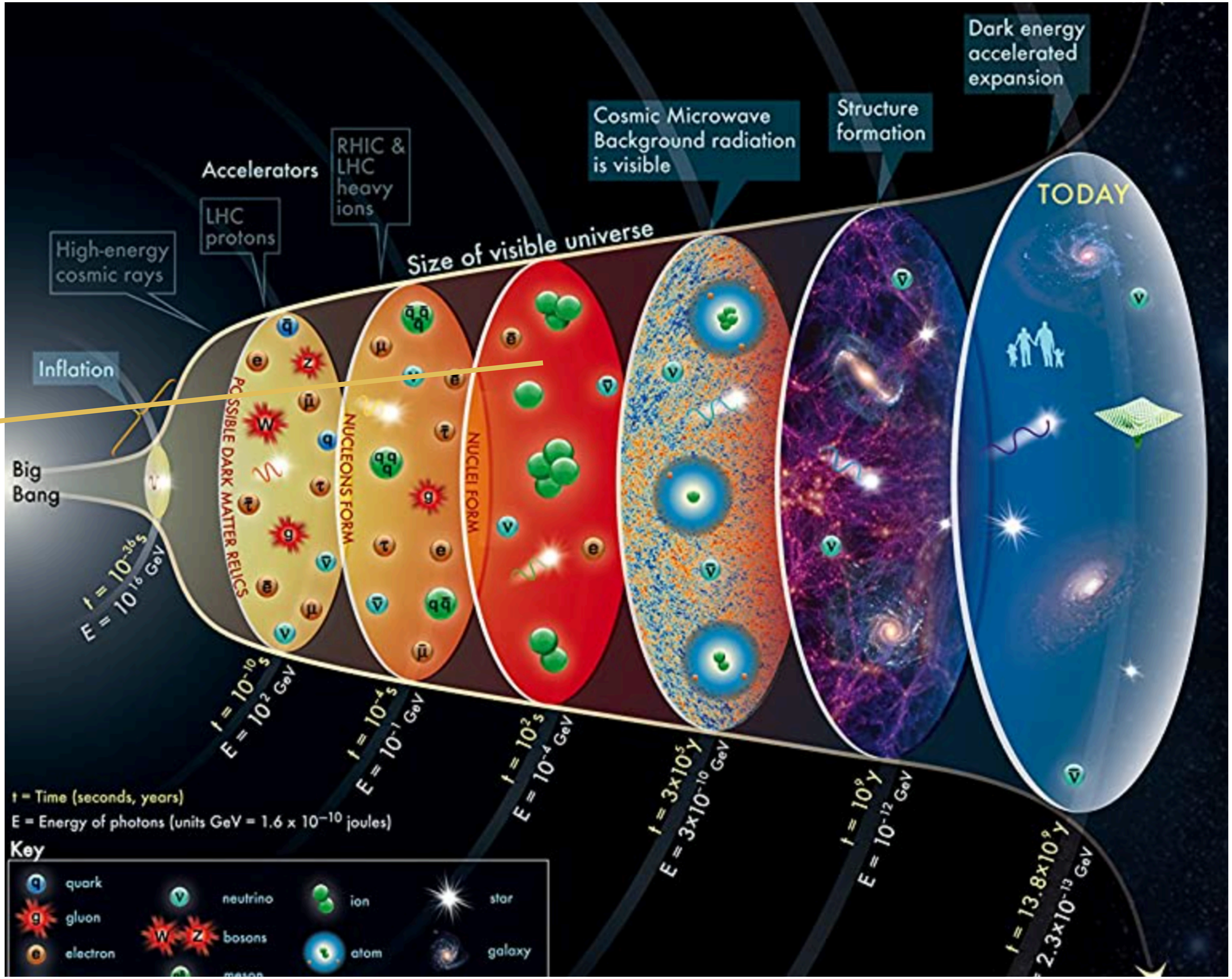


Where to find?

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

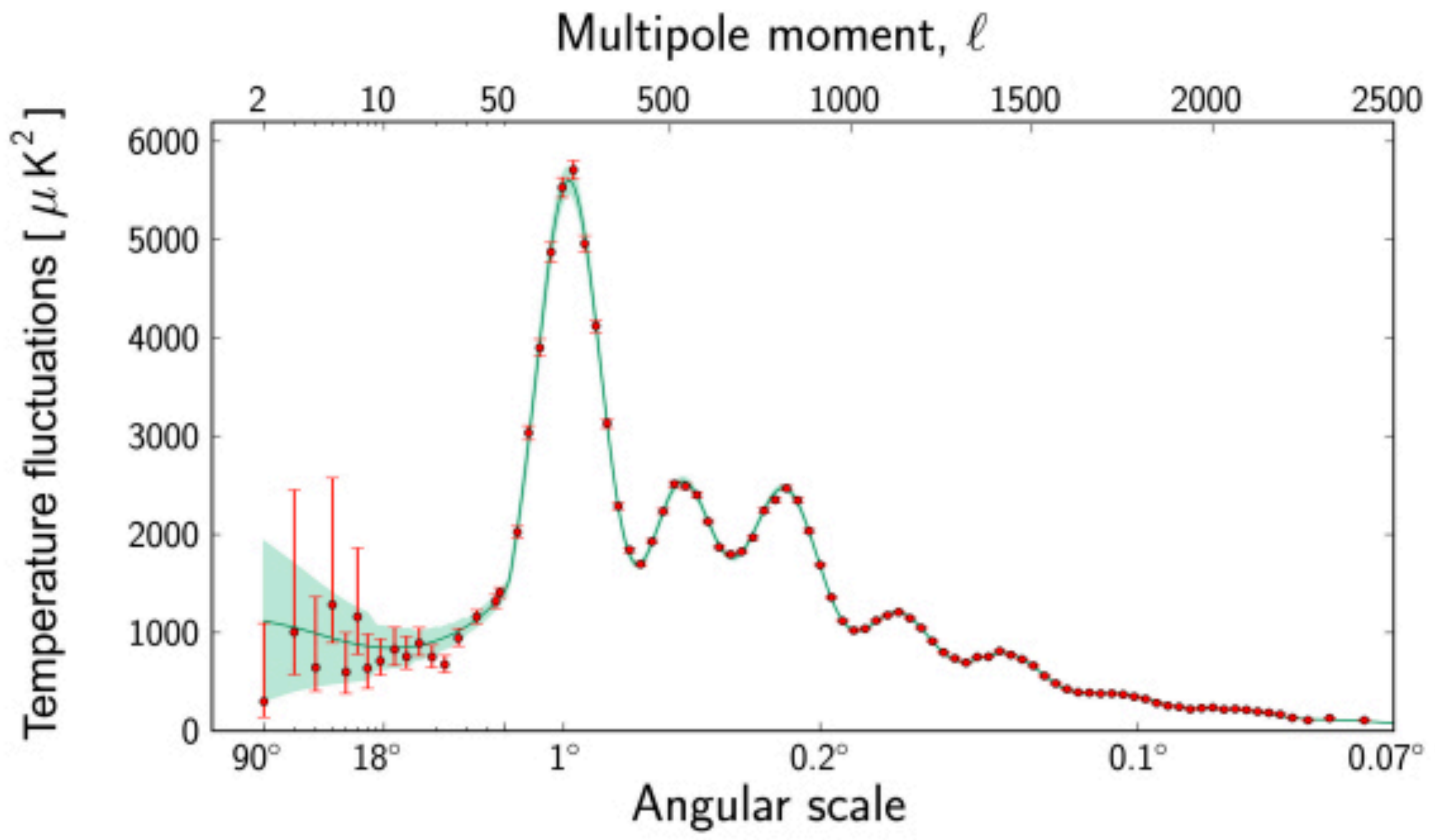


timeline of the universe



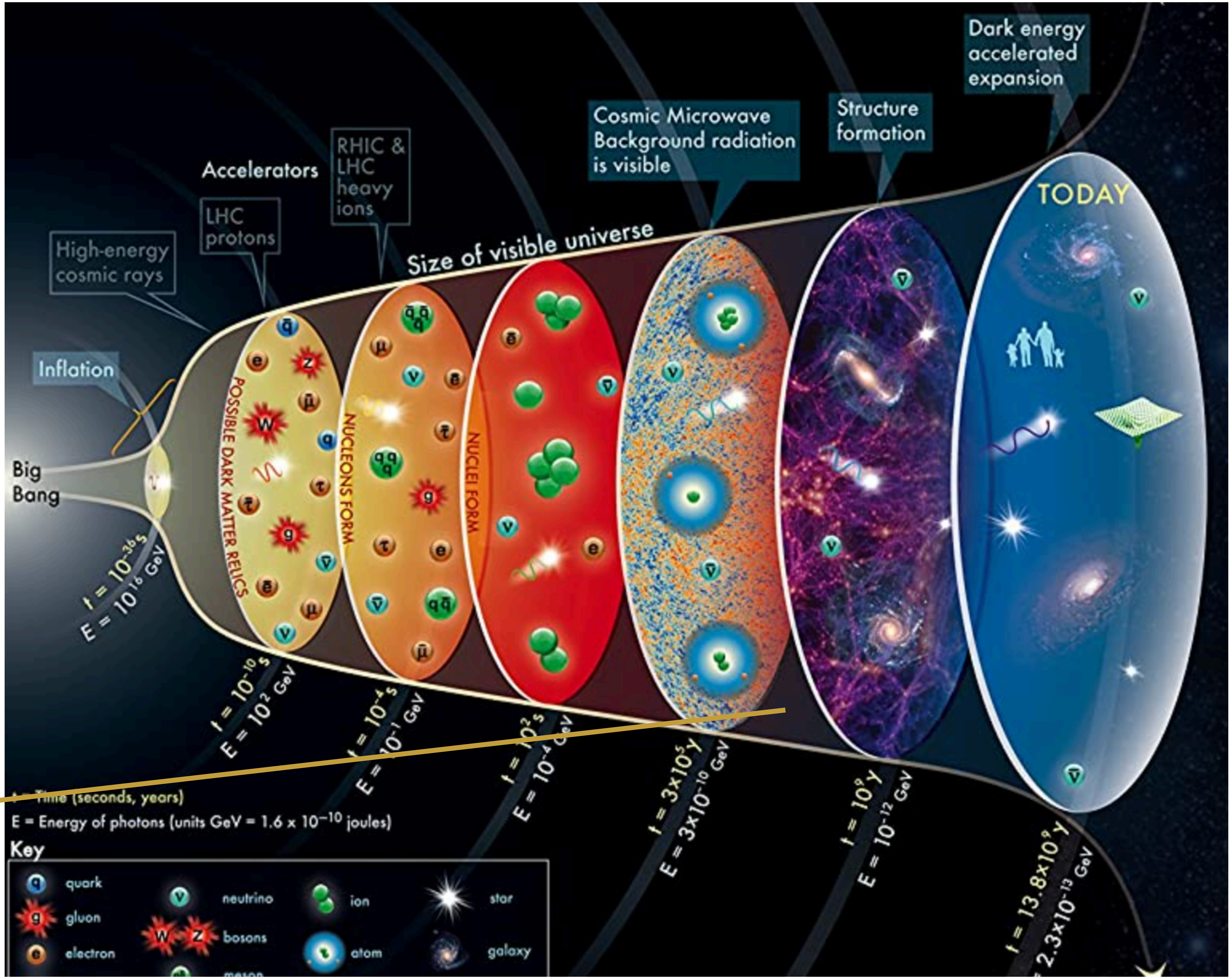
Where to find?

(2) *relic radiation*



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

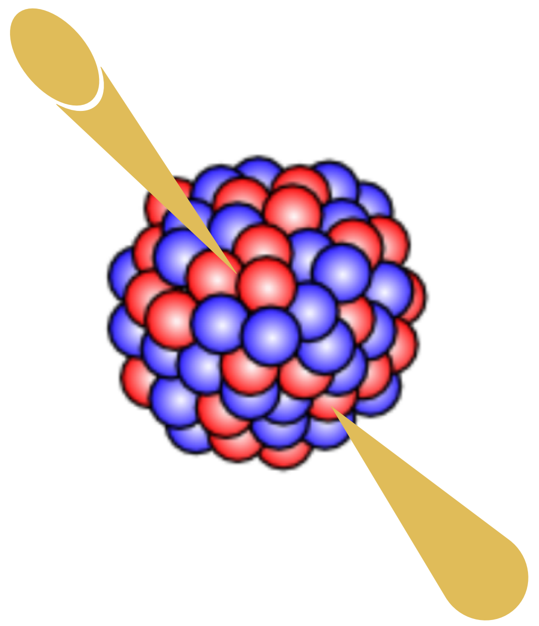
e or γ could "rewrite" reionization history by dumping EM energy in Dark Ages



Where to find?

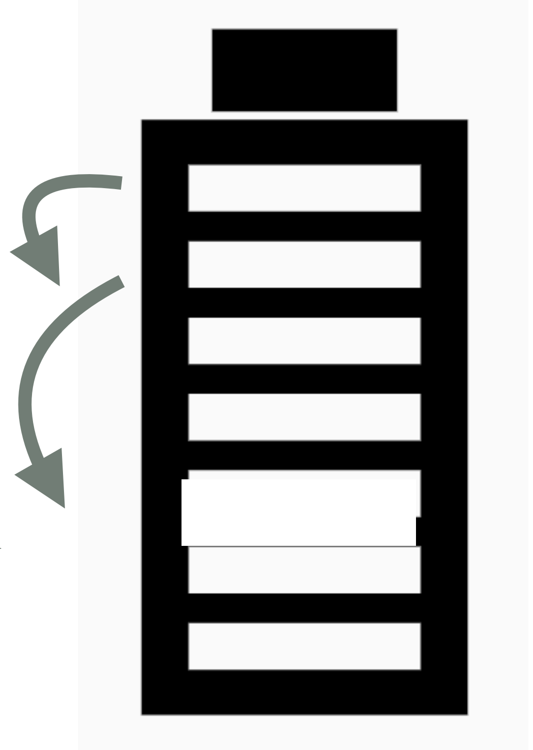
timeline of the universe

(3) *ancient neutron stars*



new heating mechanism:
nucleon "Auger effect"

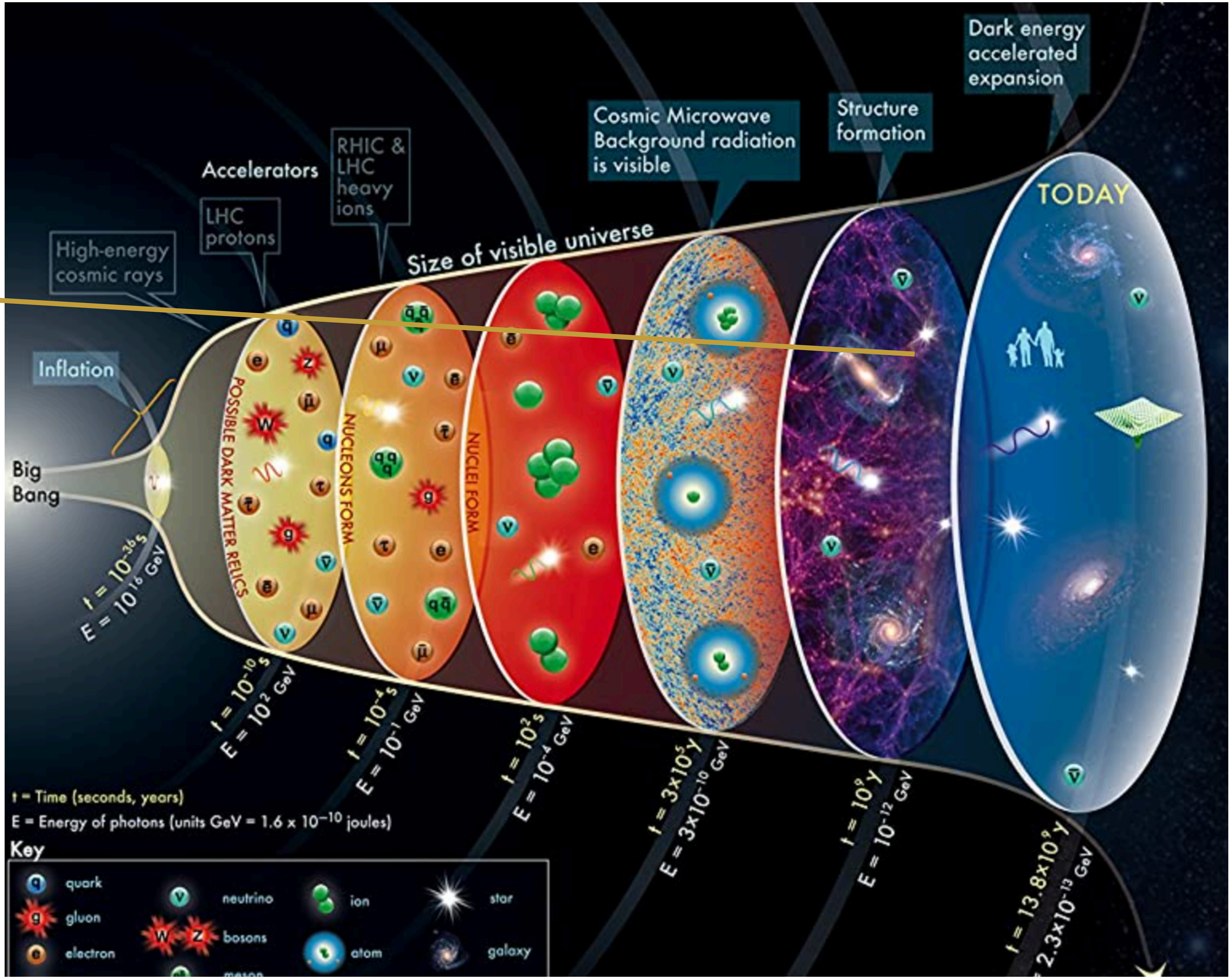
$n\, n \rightarrow n\, \chi$
$p\, n \rightarrow p\, \chi$



Fermi sea

=>

explosive liberation of energy!

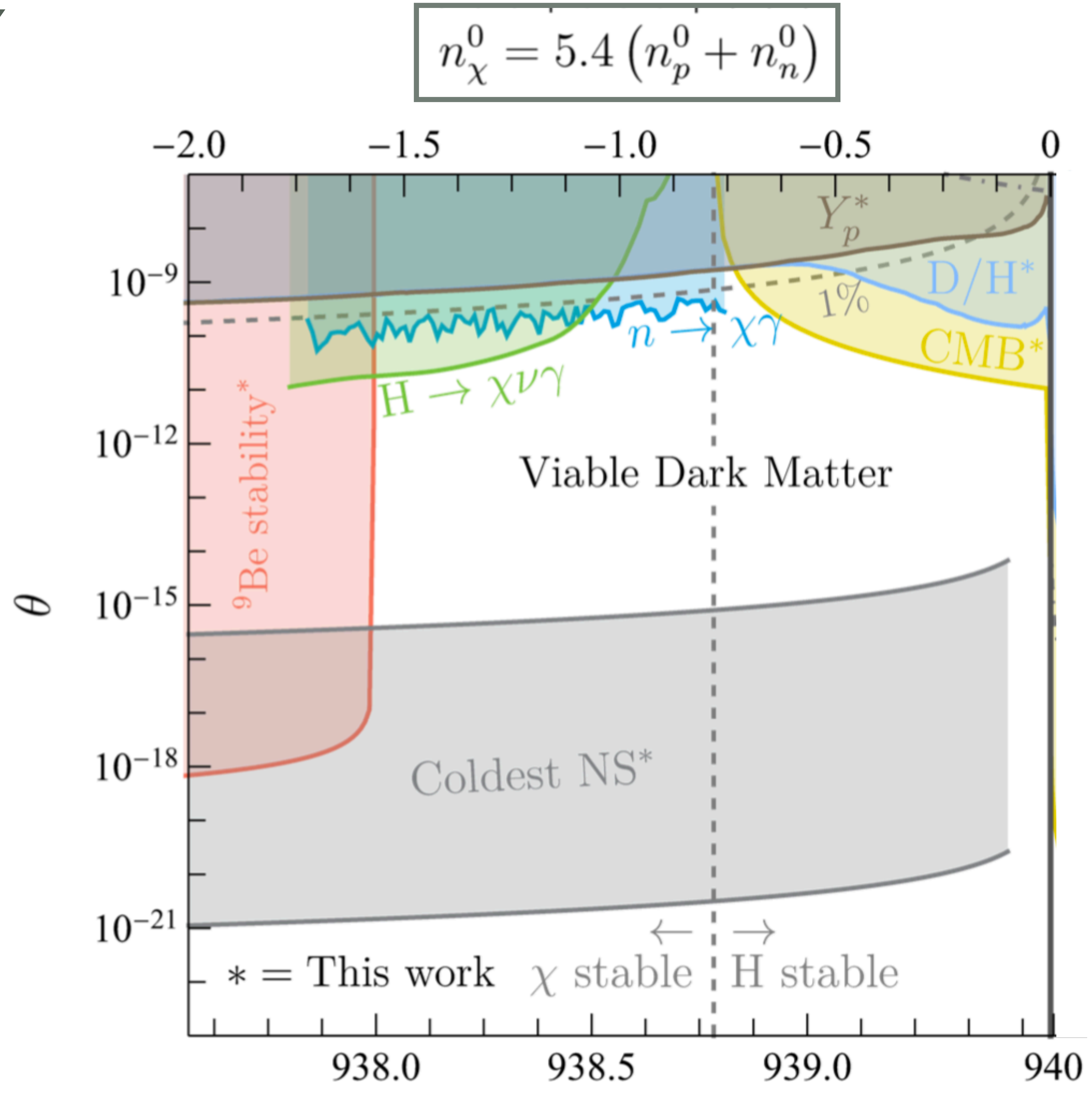


Constraints

2012.09865 *McKeen, Pospelov,* Raj

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

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

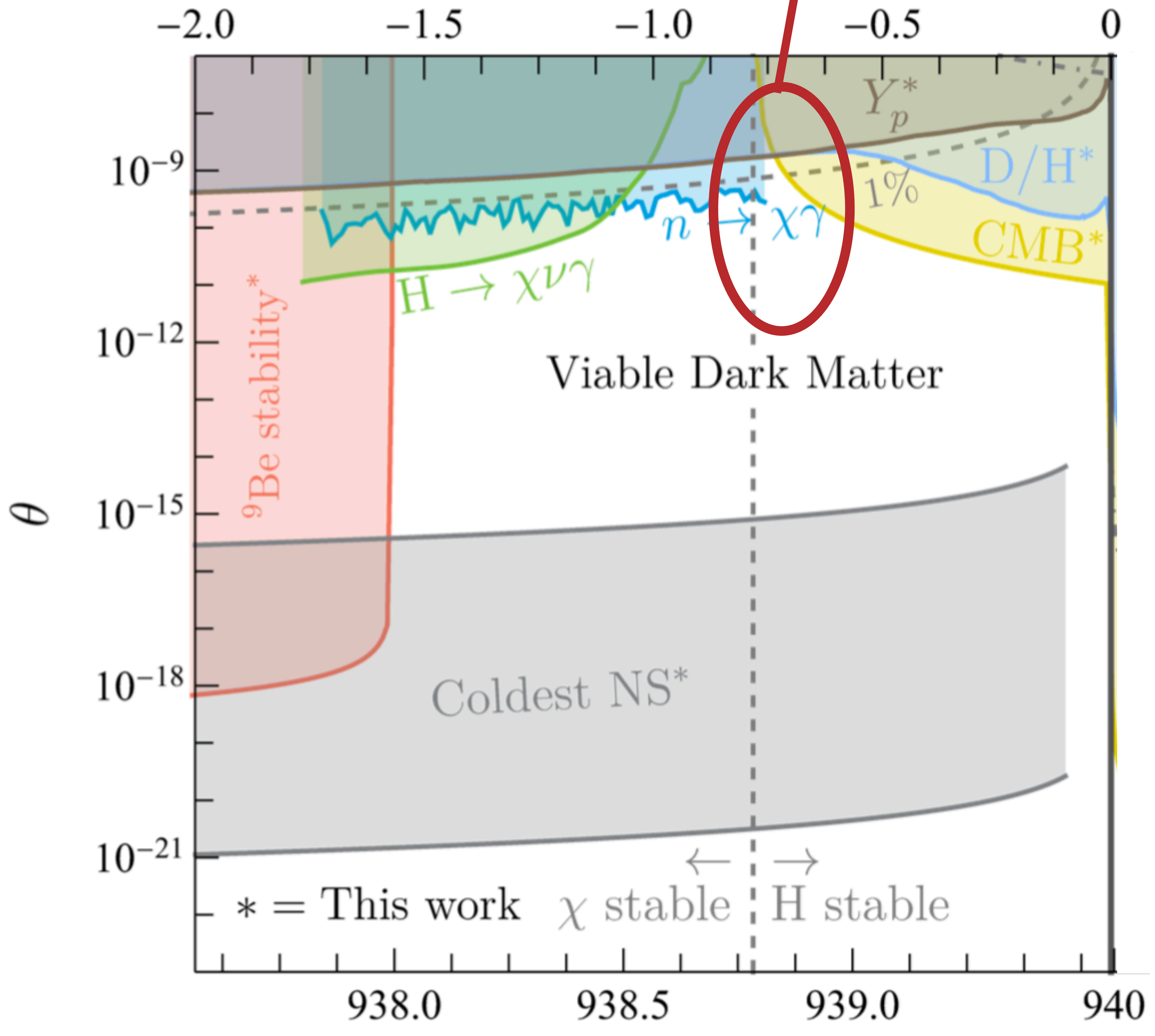
2012.09865 *McKeen, Pospelov, Raj*

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

$n \to \chi\gamma$ open

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

- BBN limits: $Y_p = 0.245 \pm 0.004$, $D/H = (2.55 \pm 0.03) \times 10^{-5}$, $^3He/H = (1.0 \pm 0.5) \times 10^{-5}$,



longer life

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Highlights

- 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

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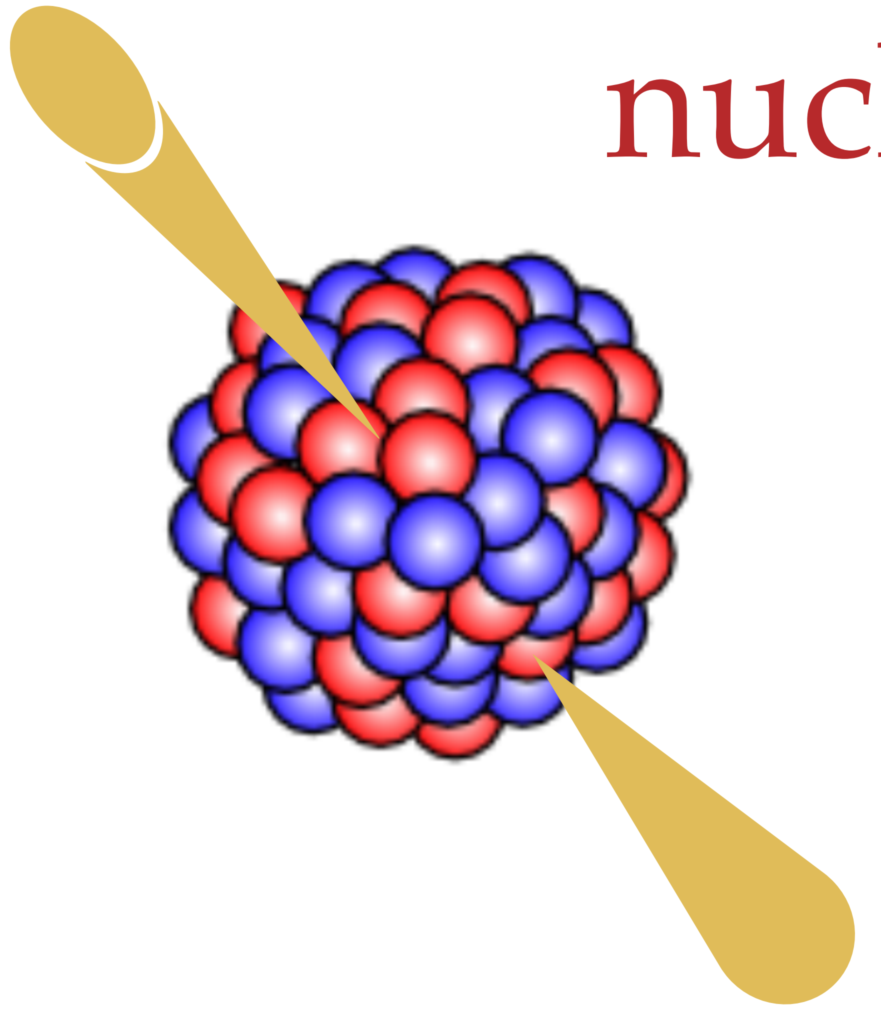
Thank you! Questions?

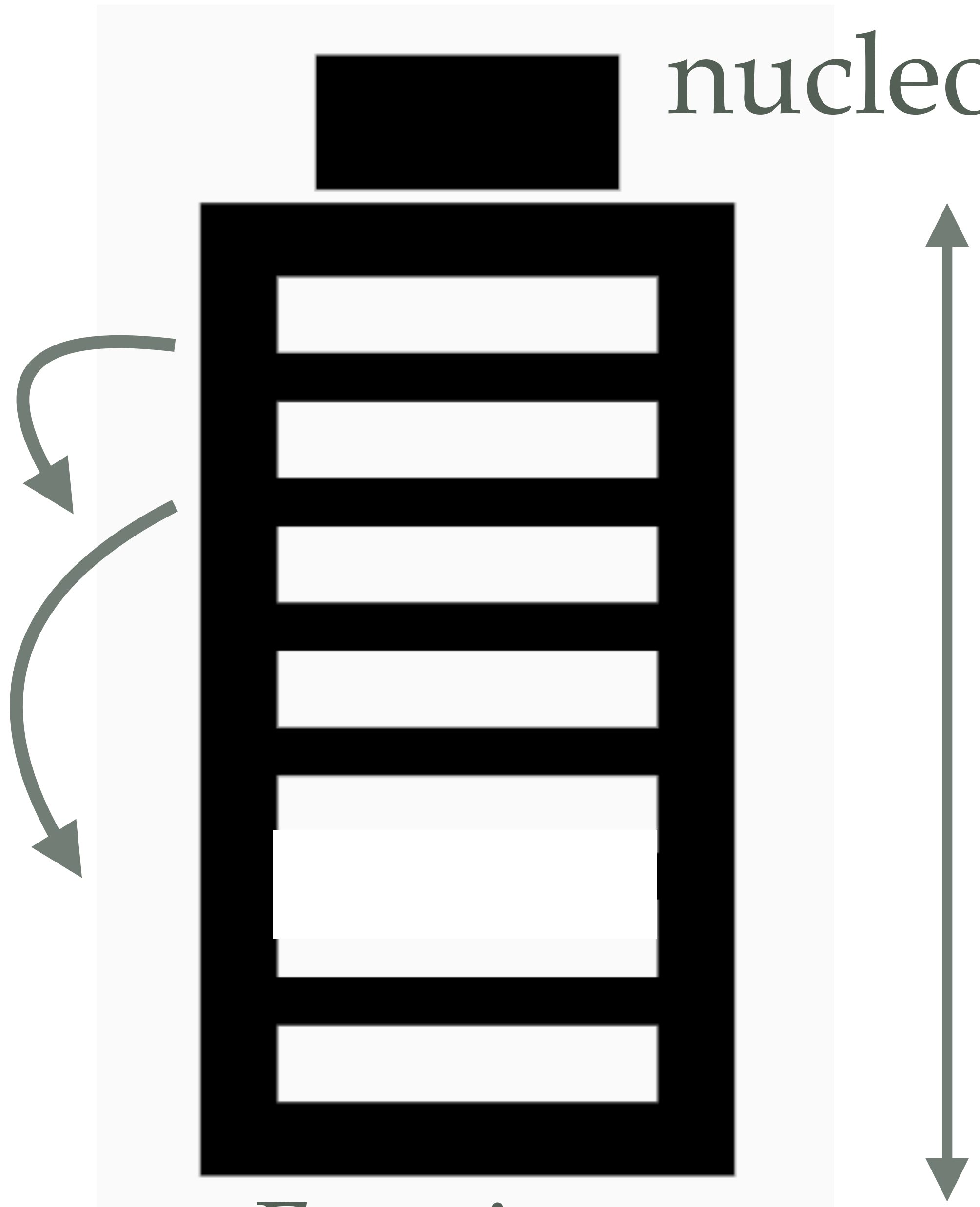
Back-up slides

Neutron stars = Pauli batteries



new heating mechanism:
nucleon "Auger effect"

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



Future lab:

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

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[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

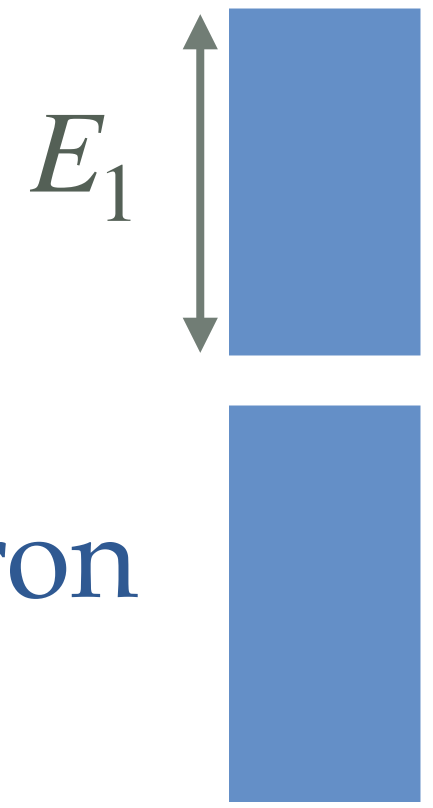
optimized for
~2000 K

Conversions to dark neutrons in NS

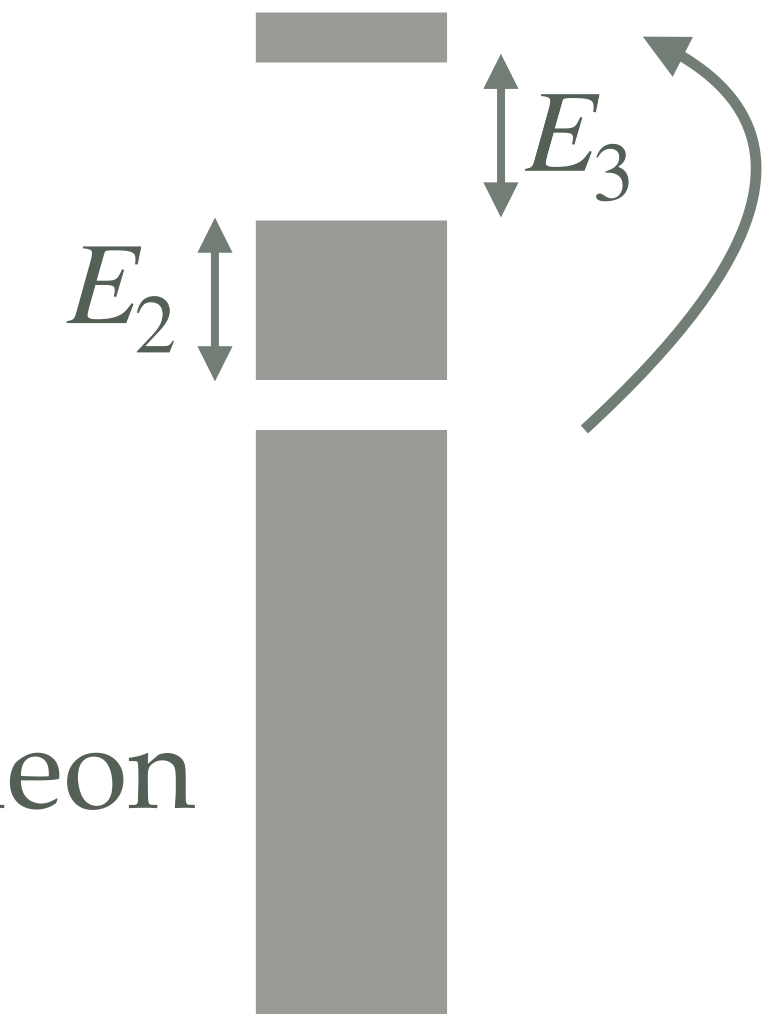
$$\dot{E}_{n'} = \sum_{N=n,p} f_N n_N \left\langle \left(\tilde{\mu}_n - \frac{p_{n'}^2}{2m_{n'}} \right) \sigma_{n'N} v \right\rangle_{p_N > p_{F_N}}$$

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

3 sources of energy:



scattering neutron Fermi sea



spectator nucleon Fermi sea

Amusement

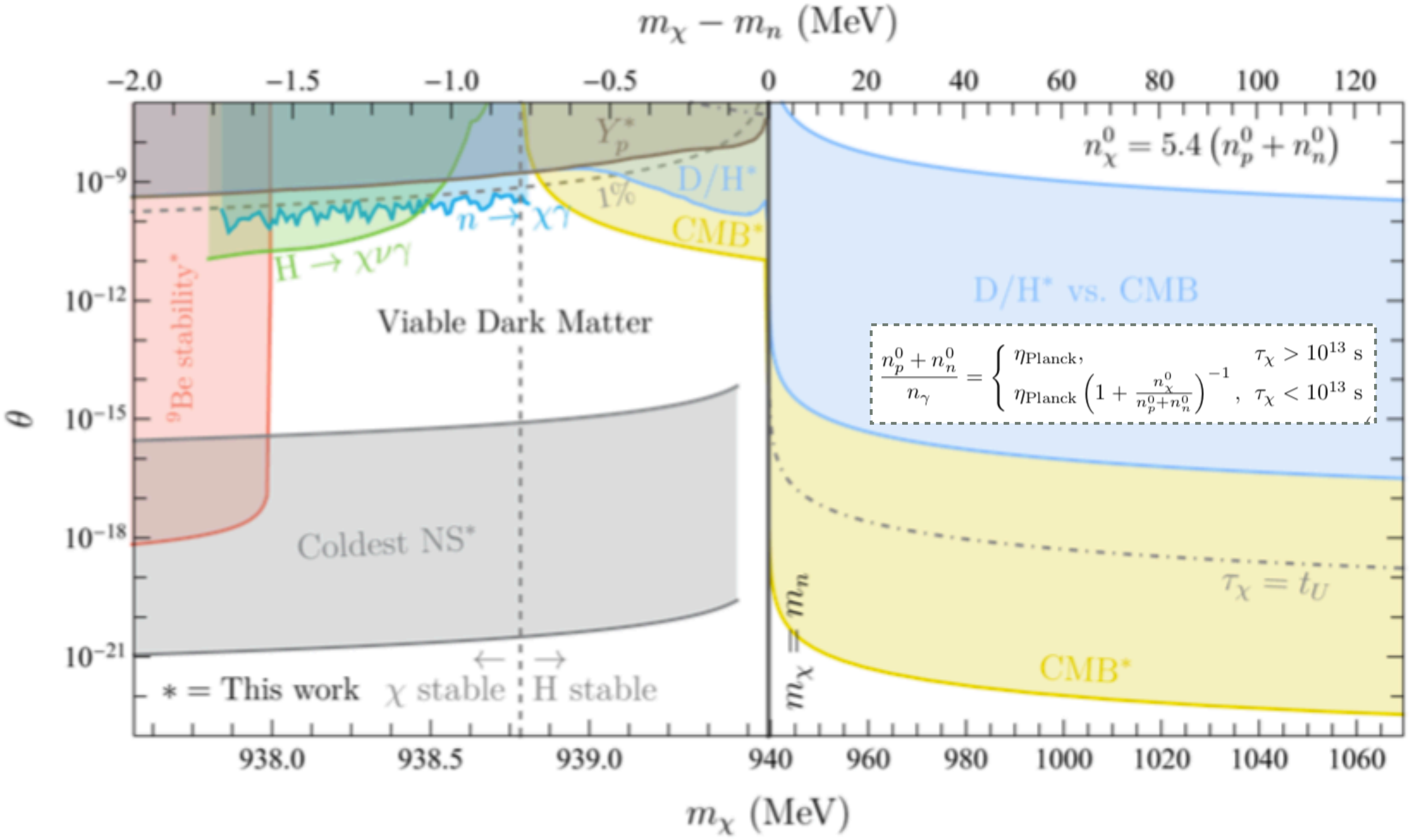
proton spectators (~ 10% of NS nucleons) supply more heat!

less Pauli-blocked, greater cross section

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

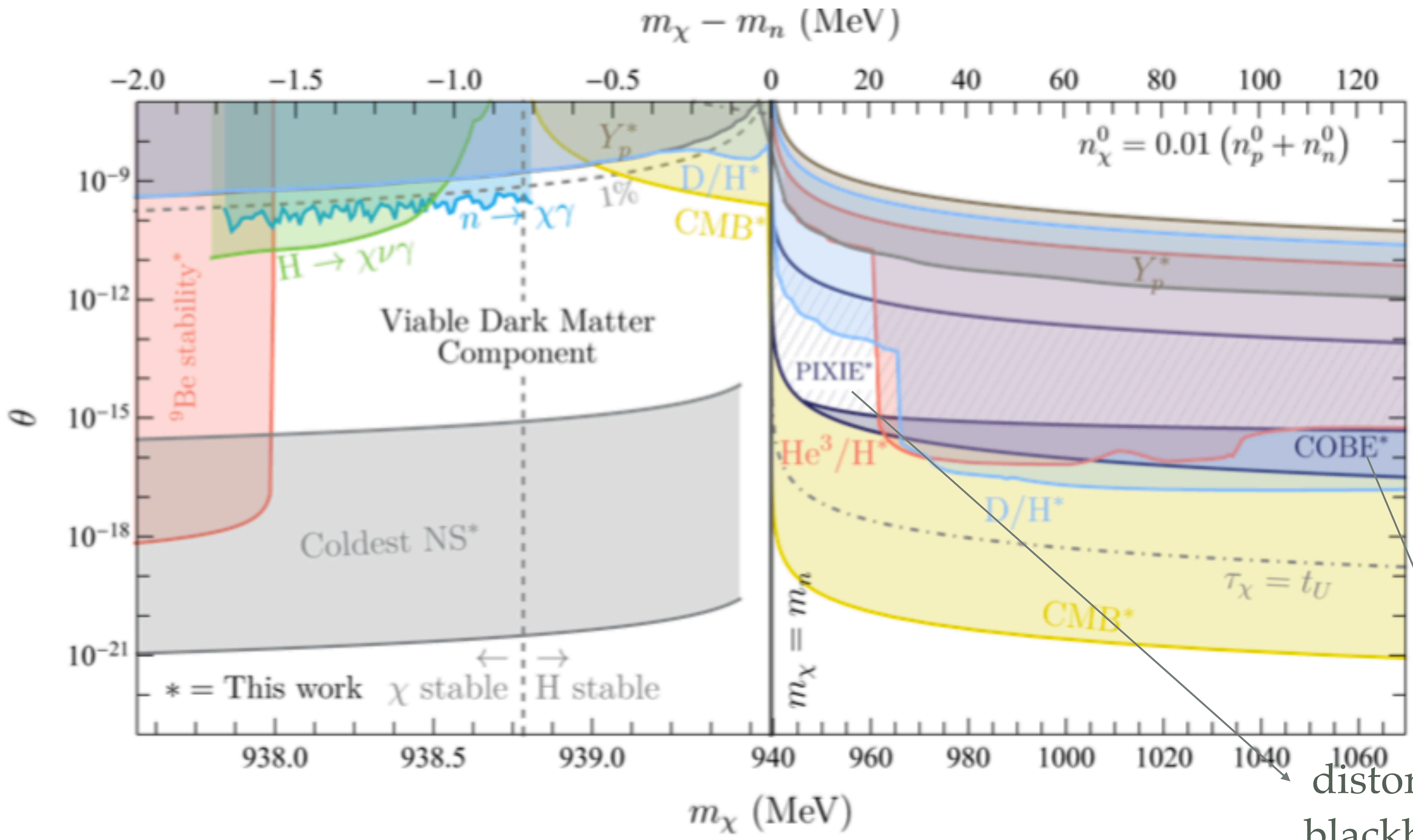
Constraints: χ all the dark matter

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



2012.09865 *McKeen, Pospelov,* Raj

Constraints: χ percent-level dark matter



distortions of CMB blackbody spectrum

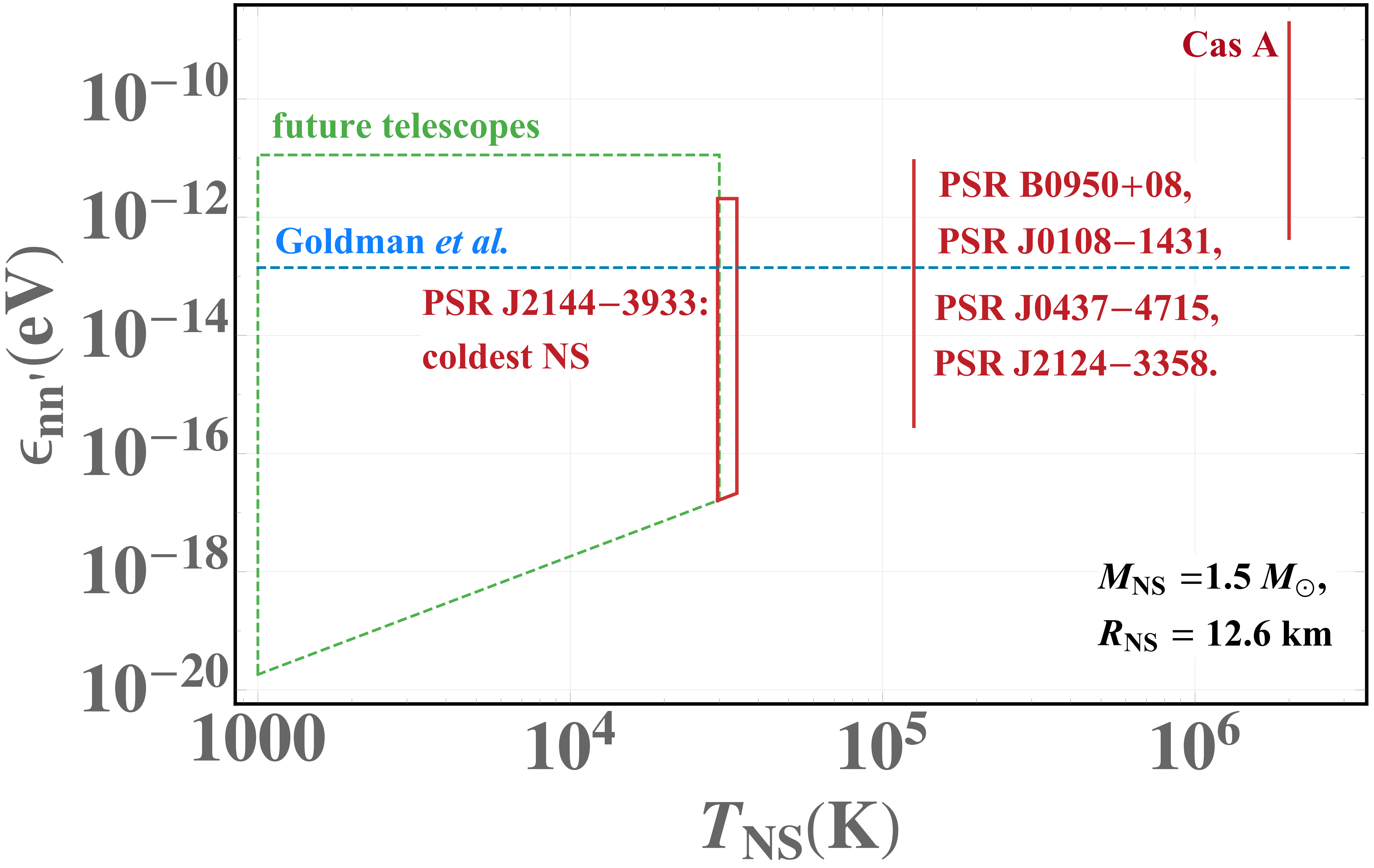
Constraints: NS heating

2105.09951 *McKeen, Pospelov, Raj*

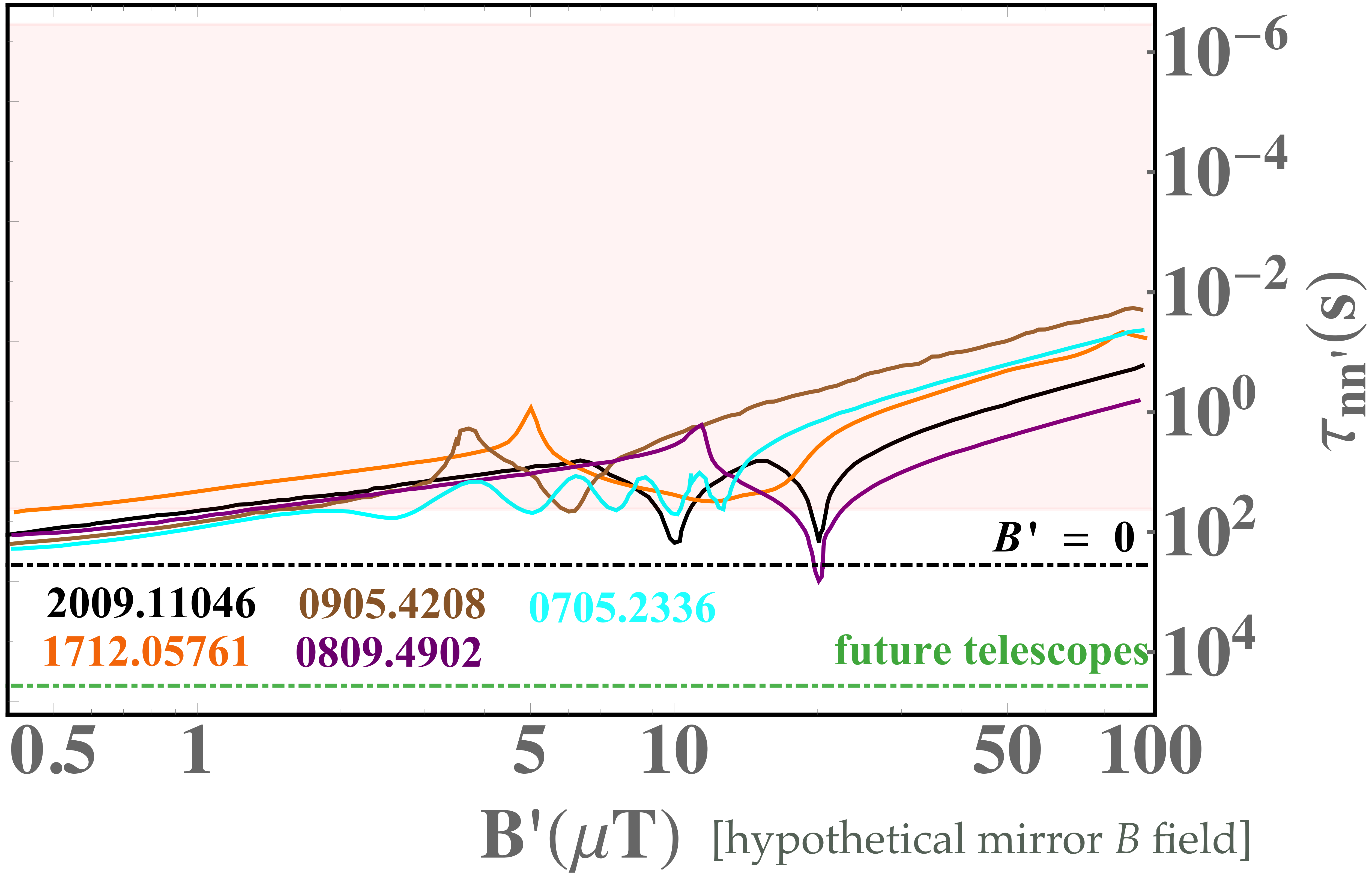
NS energy per baryon

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)*