Connecting Nuclear Physics to QCD with the lattice

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Lattice QCD, Hadron Structure and Hadronic Matter

Outline

- Lecture 1: Introduction and Motivation
- Lecture 2: Baryon Chiral Perturbation Theory
- Lecture 3: Two hadrons in a finite Euclidean Volume
- Lecture 4: Matrix Elements (reaction rates) and some results

What are important roles for QCD, nuclear physics and current experimental efforts?

- *QCD is The fundamental theory of the strong interactions*

$$E^{(i)}_{N,Z,S} = \Lambda_{QCD} \times f^{(i)}_{N,Z,S}\left(\frac{m_u}{\Lambda_{QCD}}, \frac{m_d}{\Lambda_{QCD}}, \frac{m_s}{\Lambda_{QCD}}, \frac{e^2}{4\pi}\right)$$

these energy levels range from a few KeV to MeV to many GeV

We would like to understand the spectrum and transitions in nuclear physics directly from QCD

What are important roles for QCD, nuclear physics and current experimental efforts?

- *There are well known fine-tunings in nature that have a significant impact on our existence*

$$M_n - M_p, \quad B_d, \quad \text{triple alpha process and } {}^{12}C, \quad \cdots$$

How sensitive are these fine-tunings to variations of fundamental parameters in the Standard Model?

How sensitive is the Universe as we know it to variations in these fundamental parameters?

→ *need a solution to QCD*

What are important roles for QCD, nuclear physics and current experimental efforts?

- *What is the weak fusion rate*

$$p + p \rightarrow d + \nu_e + e^+$$

  as a function of parameters in the Standard Model?

- *What is the composition and equation of state of dense nuclear matter in neutron stars?*

- ...

What are important roles for QCD, nuclear physics and current experimental efforts?

- These are examples of understanding QCD to connect interesting nuclear physics to the fundamental theory

- There is another very compelling reason - depending on your taste - you will find it more or less compelling (or the same).

What are important roles for QCD, nuclear physics and current experimental efforts?

- *With the discovery of the Higgs boson, the Standard Model (SM) is now complete*
- *However, the LHC has turned up no hints of any physics beyond the Standard Model (BSM)*
- *Further, there is almost NO terrestrial experimental hints for any physics BSM*

the exceptions: *muon anomalous magnetic moment*
proton radius puzzle

What are important roles for QCD, nuclear physics and current experimental efforts?

- muon anomalous magnetic moment

  the numerical size of the discrepancy between theory and experiment is the size of a one-loop SM correction

  This makes it difficult to understand this coming from high-energy BSM physics - as there is no room in any other SM comparison for a correction the size of one-loop (Z. Ligeti @ LBNL)

  could the BSM physics come from weakly coupled light degrees of freedom?

What are important roles for QCD, nuclear physics and current experimental efforts?

- proton radius puzzle

the discrepancy between the quoted value of the proton charge radius $$\langle r_E^2 \rangle \equiv -6 \frac{\partial G_E(Q^2)}{\partial Q^2}\bigg|_{Q^2=0}$$

measured in muonic-hydrogen and e-p scattering is ~7 sigma!

The determinations of this quantity have been put under extreme scrutiny - while the resolution is still a mystery - it is fair to say many people working on this subject suspect the systematics in e-p are underestimated

What are important roles for QCD, nuclear physics and current experimental efforts?

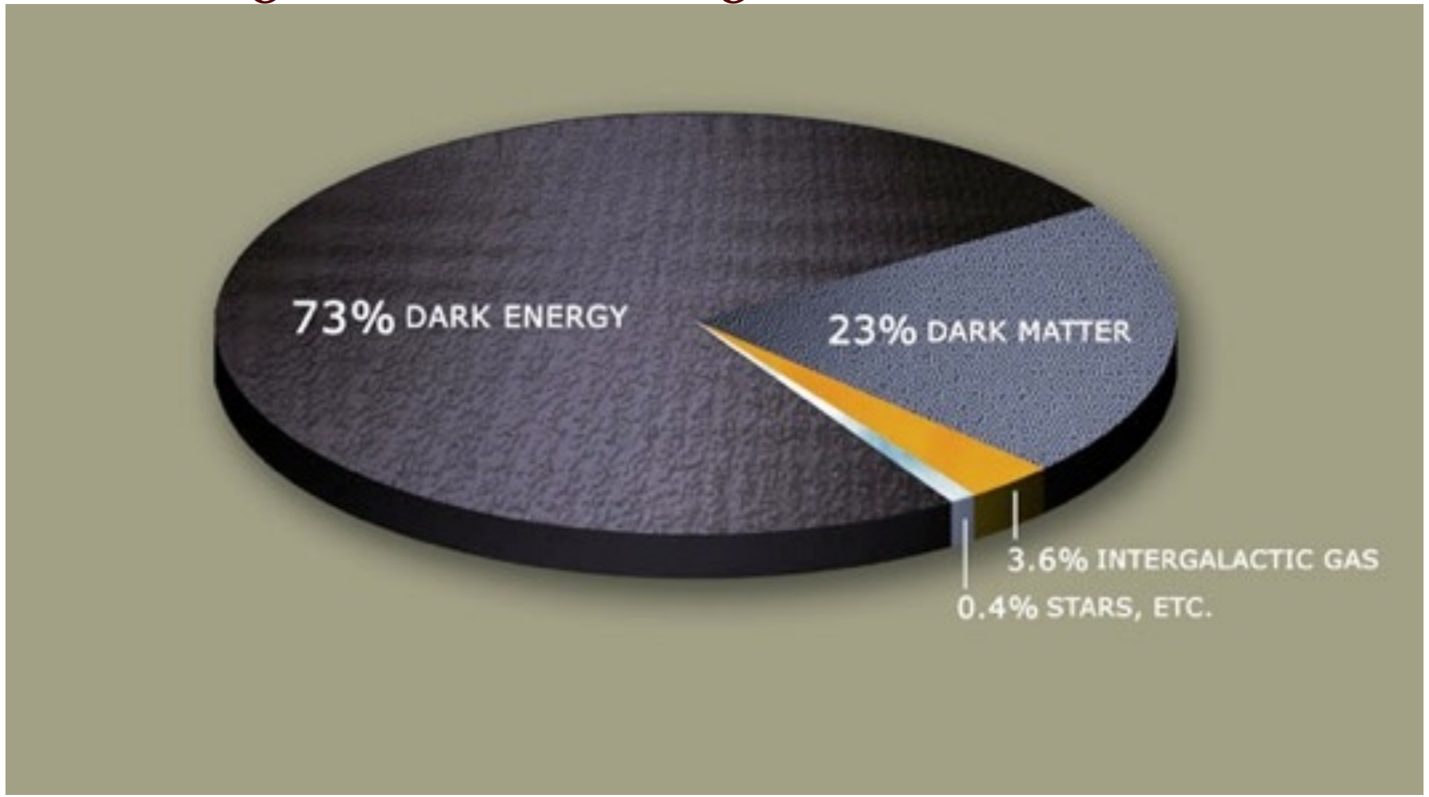
- high-energy physics colliders are one way to search for BSM physics - but it is not clear this will be possible in the near future

  this helps emphasize the important role low-energy precision nuclear physics can play in searching for new physics (in addition to muon g-2 and proton size)

What are important roles for QCD, nuclear physics and current experimental efforts?

- While we have no direct confirmation of any BSM physics - we have very strong indirect evidence:

The SM describes only ~5% of the mass of the Universe
~27% of the mass of the Universe is believed to be Dark Matter
~68% of the mass of the Universe is believed to be Dark Energy

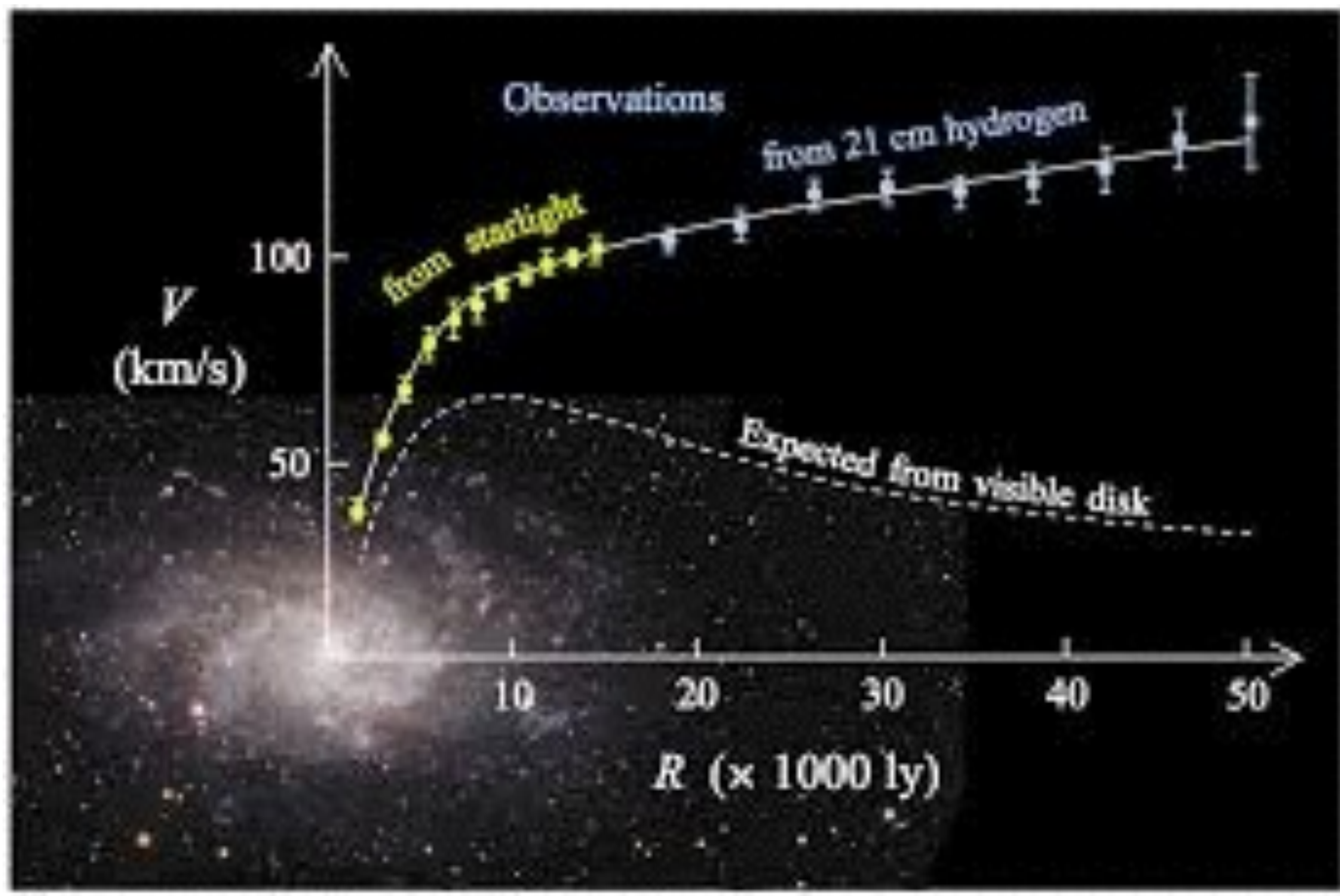


(picture out of date)

What are important roles for QCD, nuclear physics and current experimental efforts?

- *The assumed existence of Dark Matter (DM) comes from several sources:*

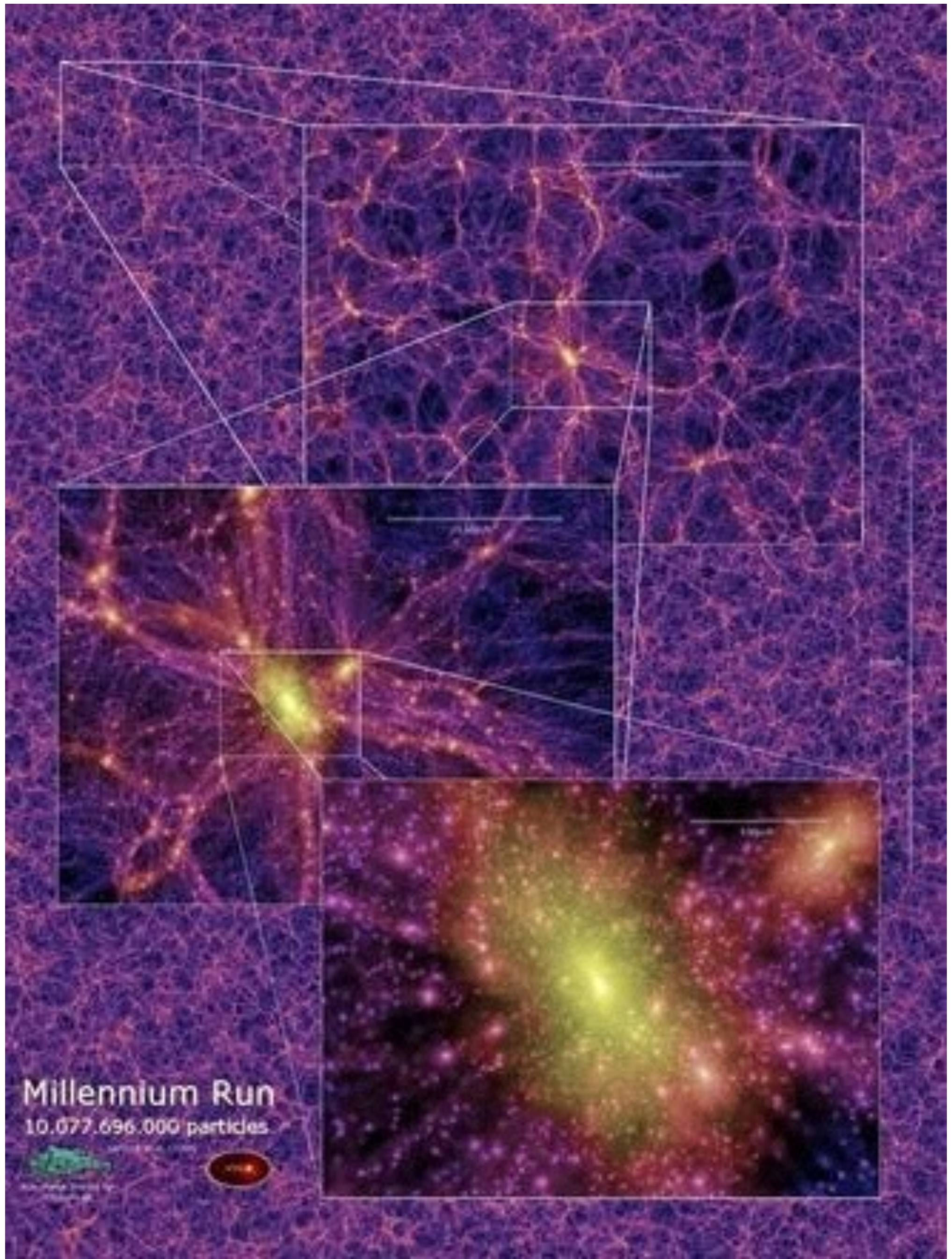
  Velocity curves of rotational galaxies require significantly more gravitating mass than observed



What are important roles for QCD, nuclear physics and current experimental efforts?

- The assumed existence of Dark Matter (DM) comes from several sources:

  N-body simulations of galaxy formation (assuming cold-dark matter)
  DM gives rise to observed structure of galaxies and galaxy clusters (simulations without DM do not)



What are important roles for QCD, nuclear physics and current experimental efforts?

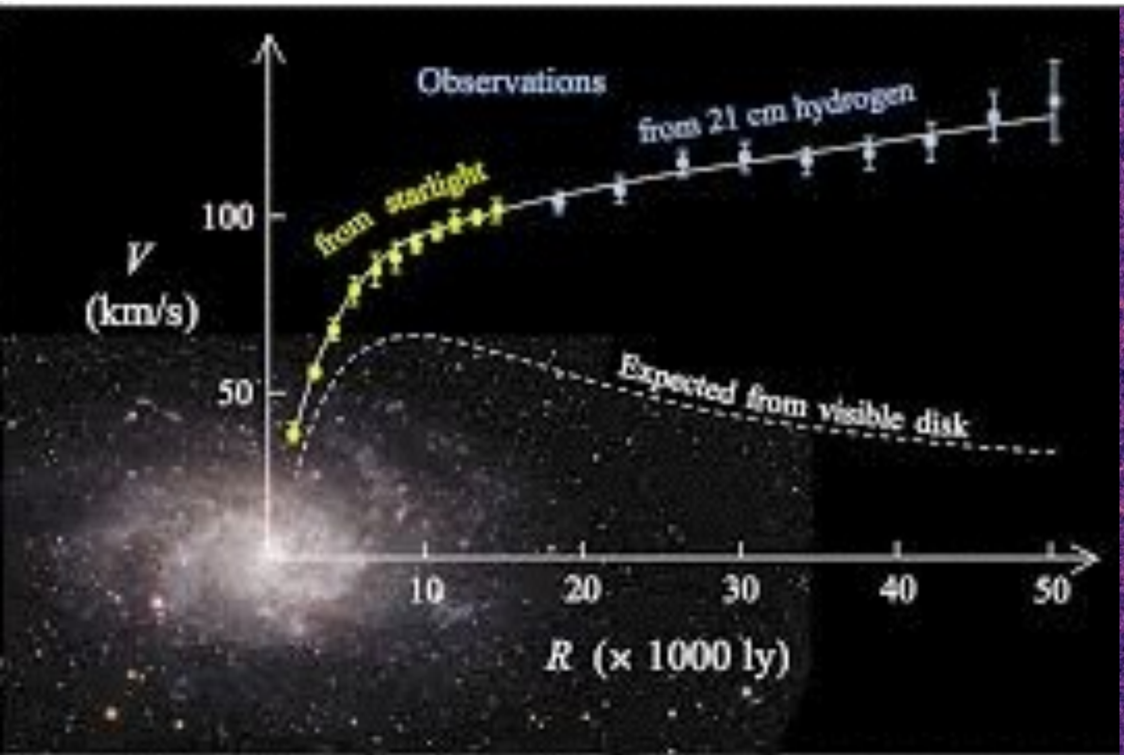
- The assumed existence of Dark Matter (DM) comes from several sources:

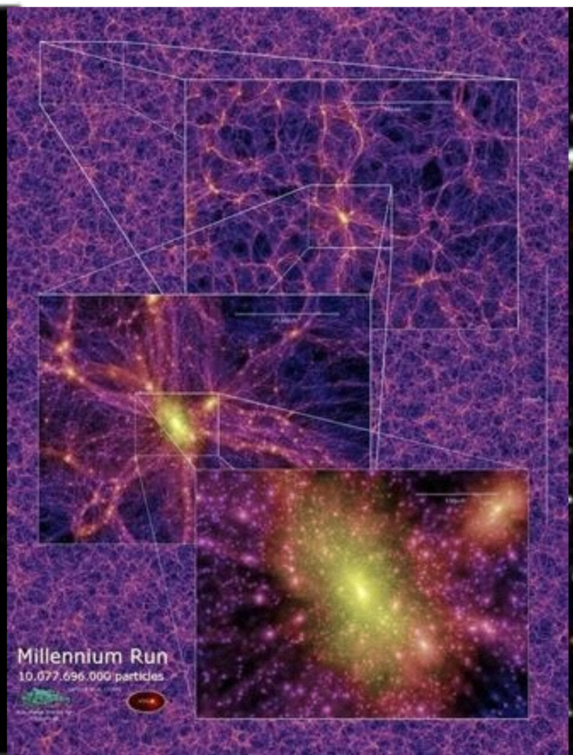
  Bullet-Cluster: two colliding galaxies
  gravitational lensing shows COM moved right through collision and is not observable while visible matter "collided"

What are important roles for QCD, nuclear physics and current experimental efforts?

- The assumed existence of Dark Matter (DM) comes from several sources:

  These three observations, in particular the bullet cluster, are very difficult to explain with modified gravity. Cold Dark Matter is the simplest explanation consistent with all observations





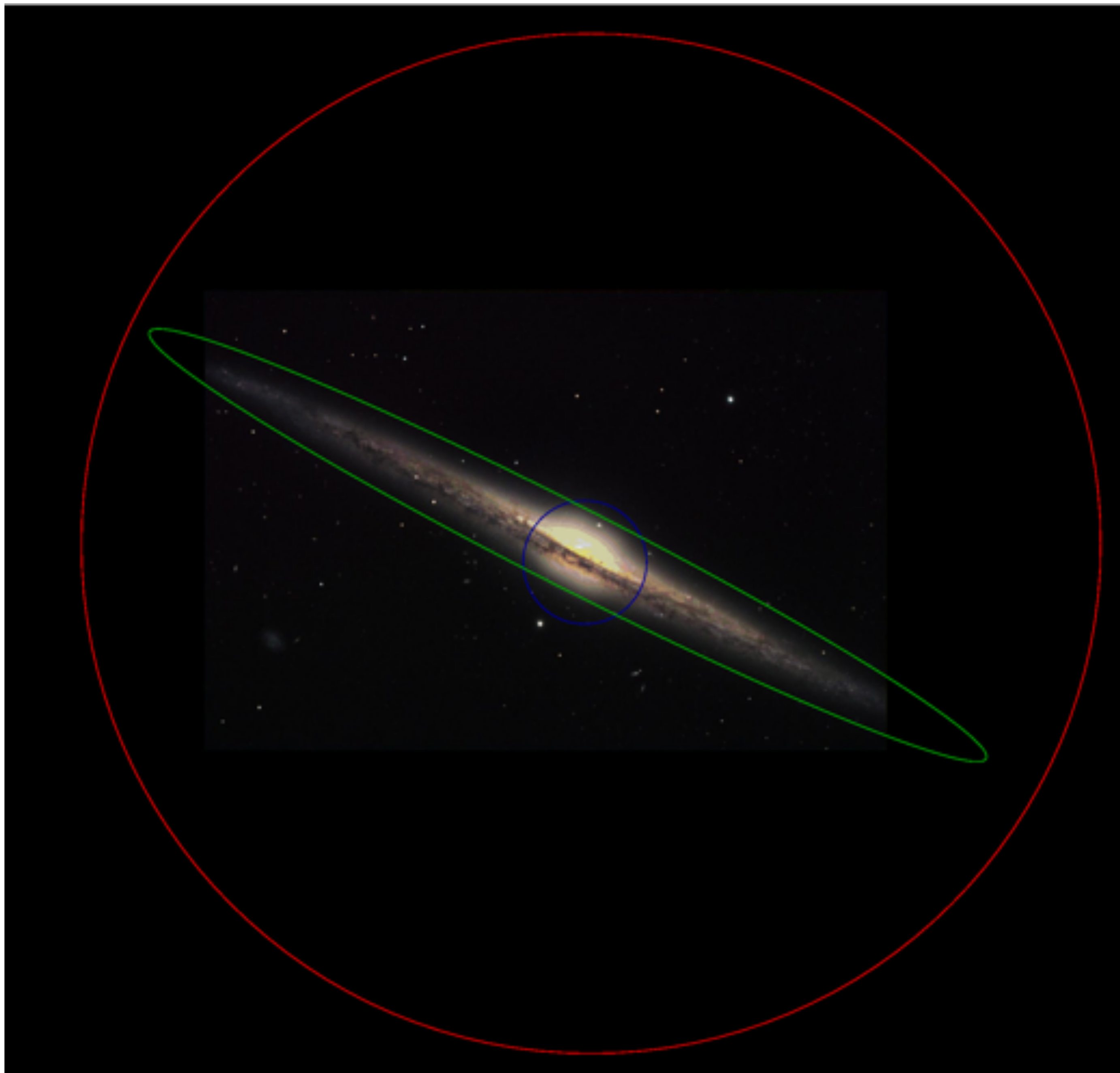
What are important roles for QCD, nuclear physics and current experimental efforts?

- What do we know about Dark Matter?

DM interacts very weakly, if at all, with the SM except through gravity

DM is weakly self-interacting: DM exists in halos rather than disks (matter accumulates to a disk through collisions)

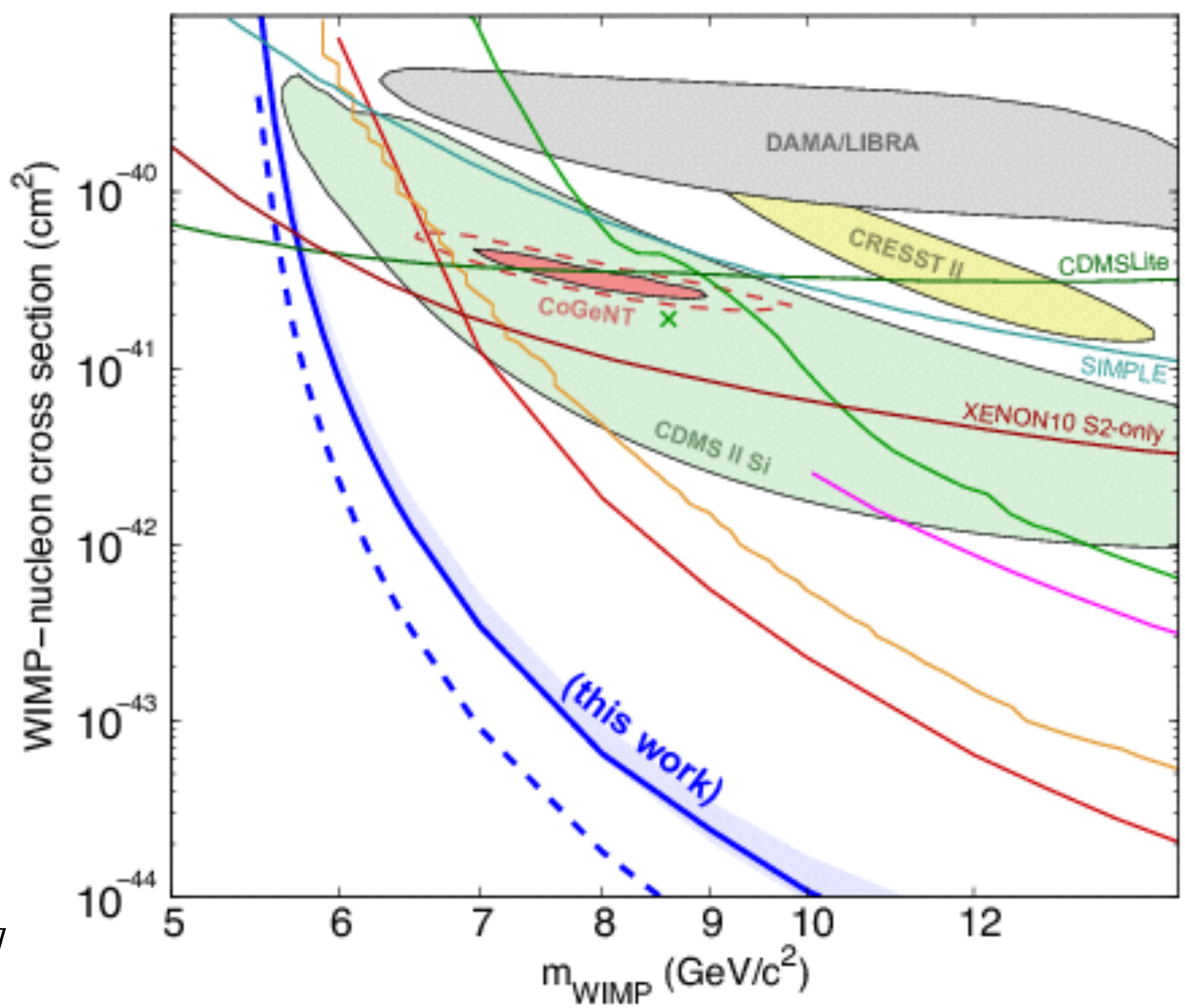
DM is cold (non-relativistic) since it clumps



What are important roles for QCD, nuclear physics and current experimental efforts?

- *There are several significant experimental efforts underway to try and directly detect Dark Matter - through elastic collisions with matter*

These detectors all use nuclei to search for elastic recoil - to interpret constraints/ observations we must understand QCD and possible interactions with DM



LUX exclusion plot [arXiv:1405.5906]

What are important roles for QCD, nuclear physics and current experimental efforts?

- To the best of our knowledge, the SM matter in the Universe is comprised entirely of matter and not anti-matter

A measure of the excess matter in the Universe is given by the primordial ratio of the number of baryons to photons - from the CMB, we know this number to be

$$\eta \equiv \frac{X_N}{X_\gamma} \simeq 6.2 \times 10^{-10}$$

However, the SM is nearly symmetric in matter and anti-matter. While this observed asymmetry is small, it is larger than predicted by the SM, assuming the Universe began in a matter/anti-matter symmetric state

What are important roles for QCD, nuclear physics and current experimental efforts?

- To produce a matter/anti-matter asymmetry, we need the three Sakharov conditions:
  - baryon number violation
  - C-symmetry and CP-symmetry violation
  - interactions out of thermal equilibrium

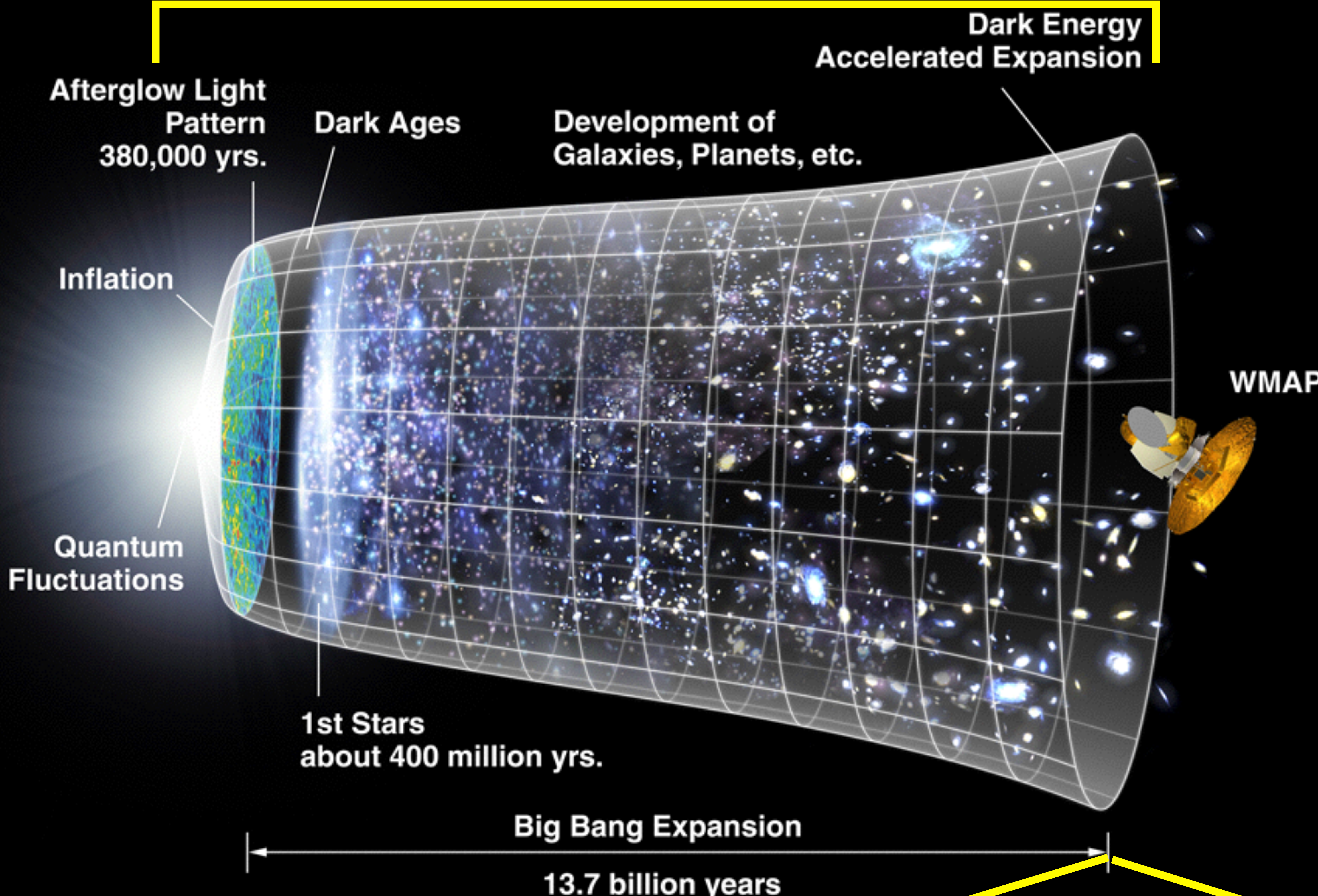
  CP violation implies permanent electric dipole moments (EDMs) for SM fermions. There are significant experimental efforts to search for permanent electric dipole moments in electrons, protons, neutrons, deuterium, … Hg, Pa, Ra

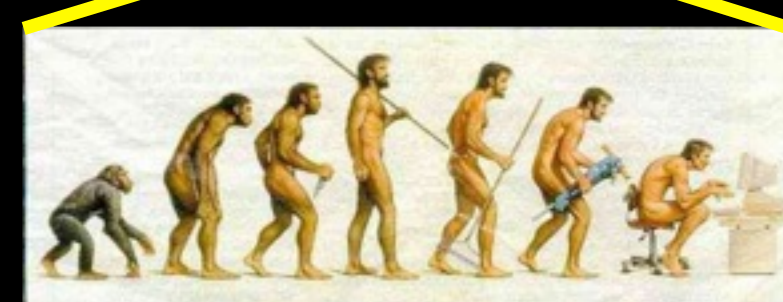
What are important roles for QCD, nuclear physics and current experimental efforts?

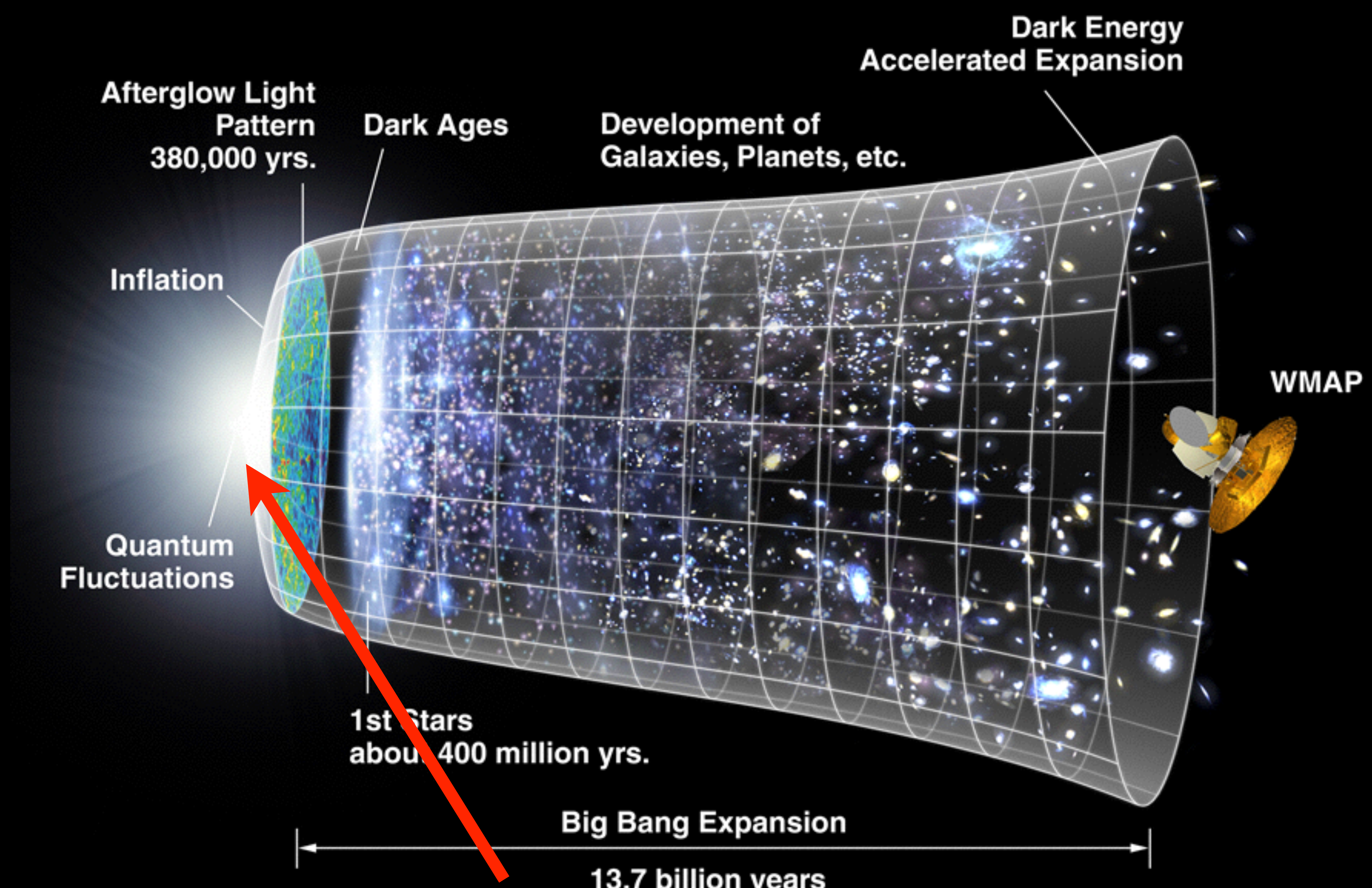
- If we assume the BSM physics is heavy, and can be integrated out, this leaves several higher-dimensional operators that generate CP-violating operators, in example quark bi-linear operators, 4-quark operators, and gluonic operators.

  In order to relate constraints/measurements on permanent EDMs in nucleons/nuclei to BSM physics, we must be able to solve QCD!

QCD


Dark Energy
Accelerated Expansion
Afterglow Light
Pattern
380,000 yrs.
Dark Ages
Development of
Galaxies, Planets, etc.
Inflation
WMAP
Quantum
Fluctuations
1st Stars
about 400 million yrs.
Big Bang Expansion
13.7 billion years



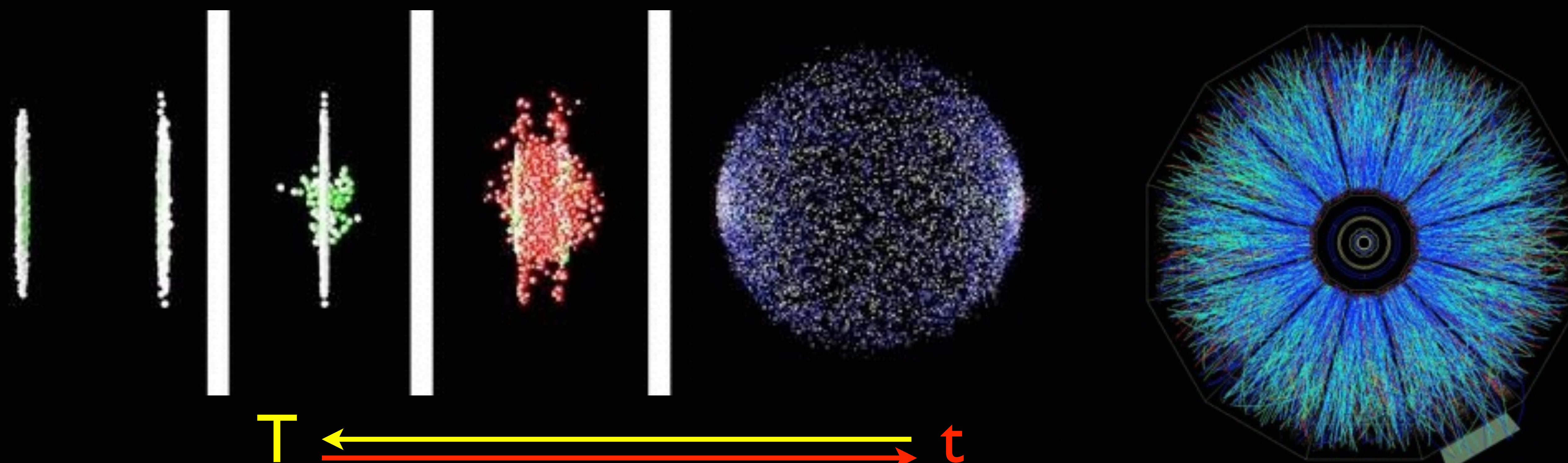


Formation of Matter

$$T \simeq 1 \text{ trillion K} \ \left(10^{12} \text{ K}\right)$$

$$t \simeq 30 \text{ micro seconds} \left(3.0 \times 10^{-5} s\right)$$


12:00 o'clock
Sextant 10/11
Sextant 12/1
PHOBOS
10:00 o'clock
BRAHMS
2:00 o'clock
RHIC
Sextant 2/3
4:00 o'clock
Sextant 6/7
STAR
Sextant 4/5
(First sextant to be tested)
BOOSTER
G-2
LINAC
AGS
TANDEMS


T
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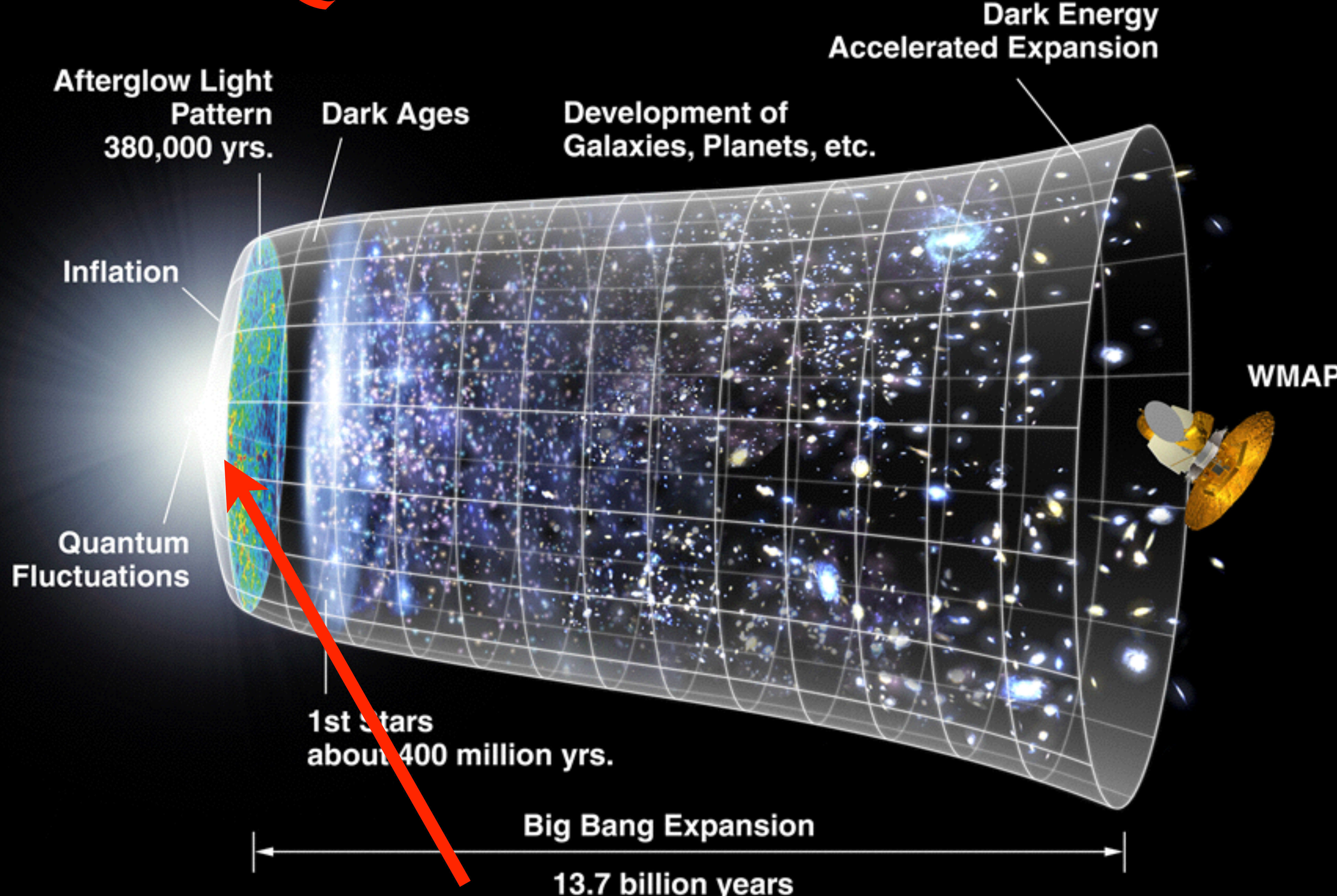
QCD to the rescue!

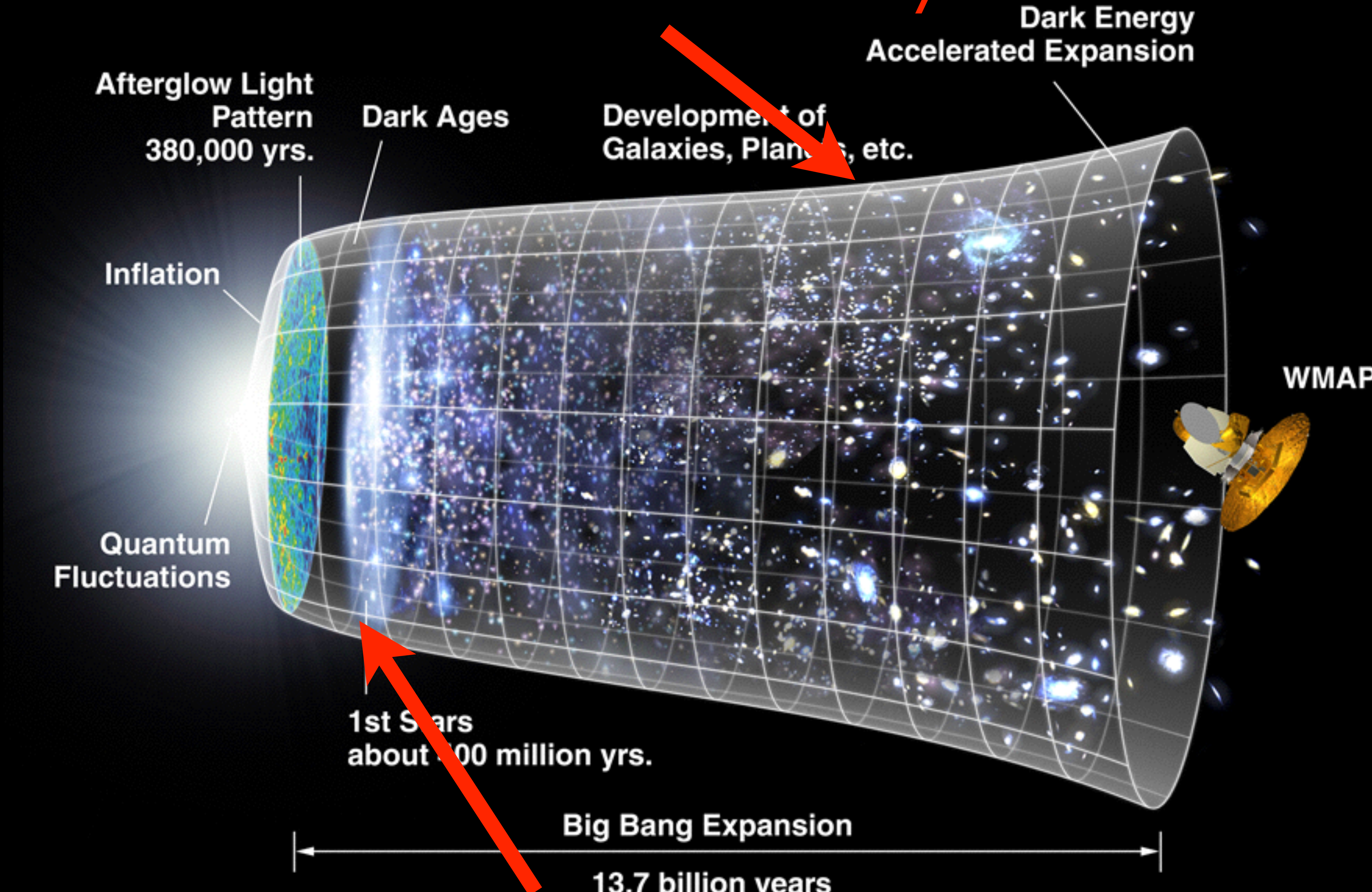


Formation of light nuclei

$T \simeq 1$ billion K $(10^9$ K$)$

$t \simeq 3$ minutes

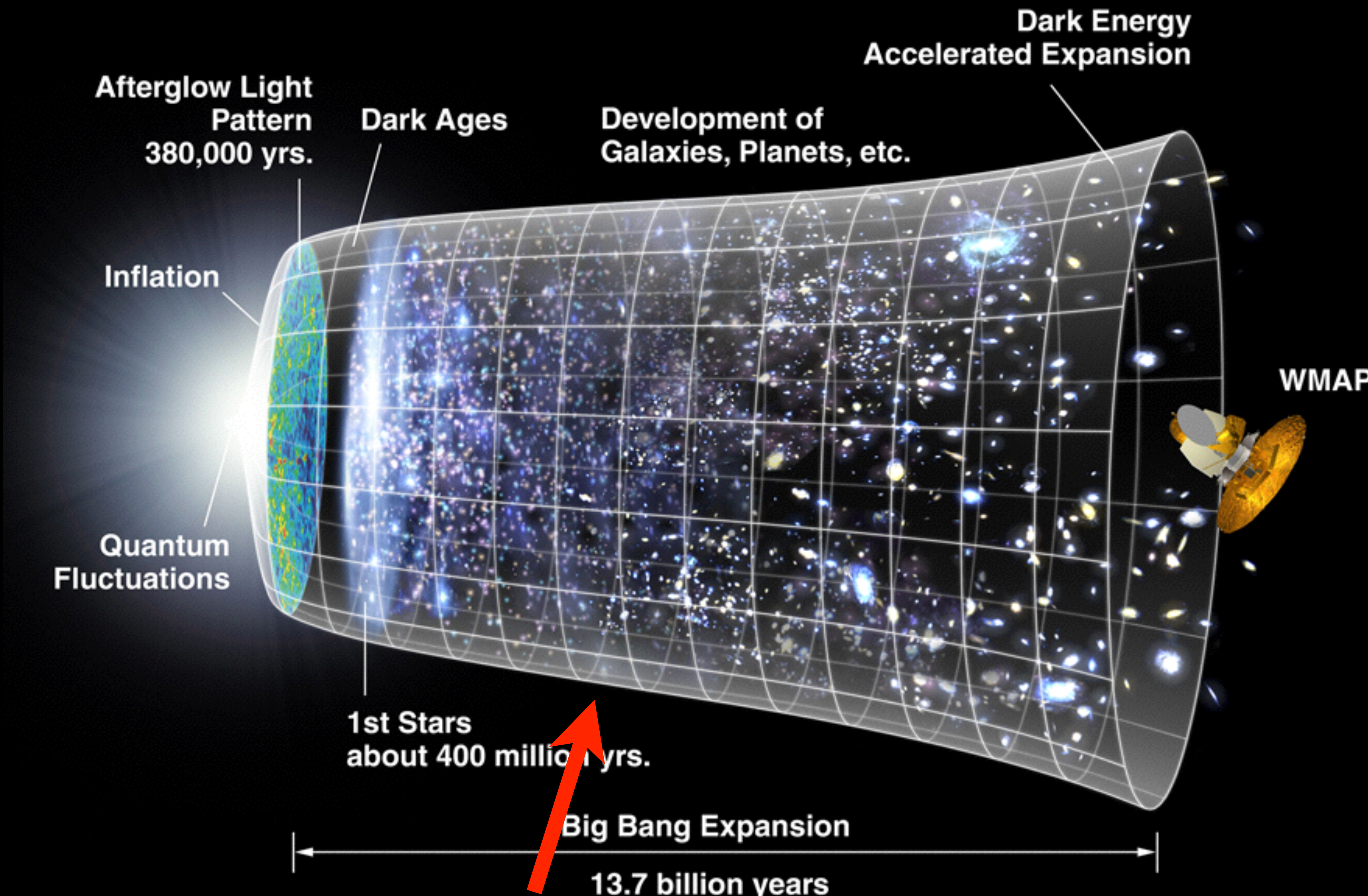
Formation of our solar system



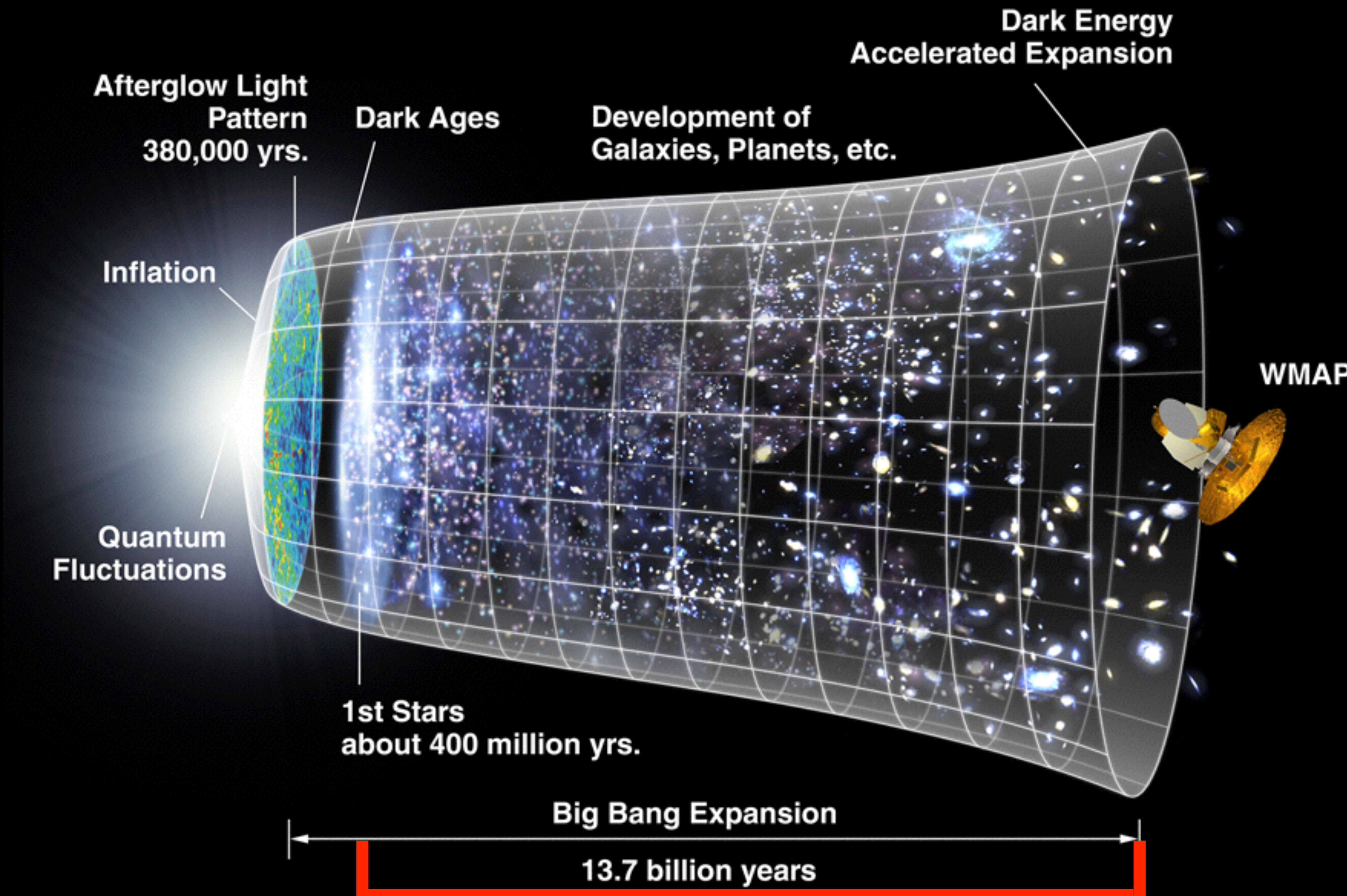
Formation of first stars

$$T \simeq 20 \text{ K}$$

$$t \simeq 200 \text{ Million years}$$



Galaxy formation



Death of stars, creation of heavy nuclei and *life*, creation of new, *ultradense* states of nuclear matter

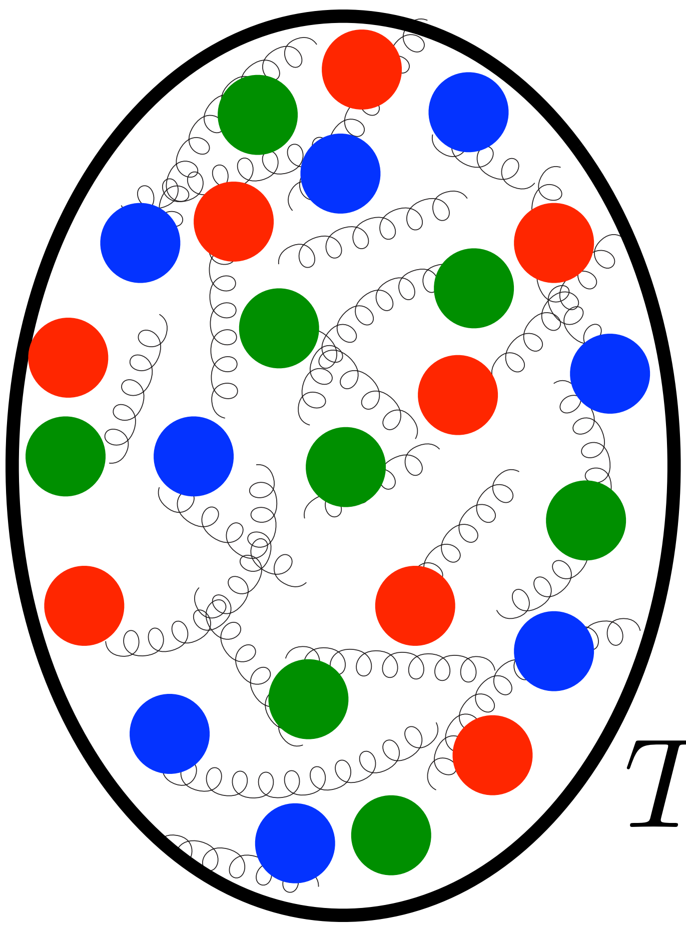
Role of QCD in the Evolution of the Universe

From Quarks to Protons and Neutrons

$$T \simeq 1 \text{ trillion K} \;\; (10^{12} \text{ K})$$

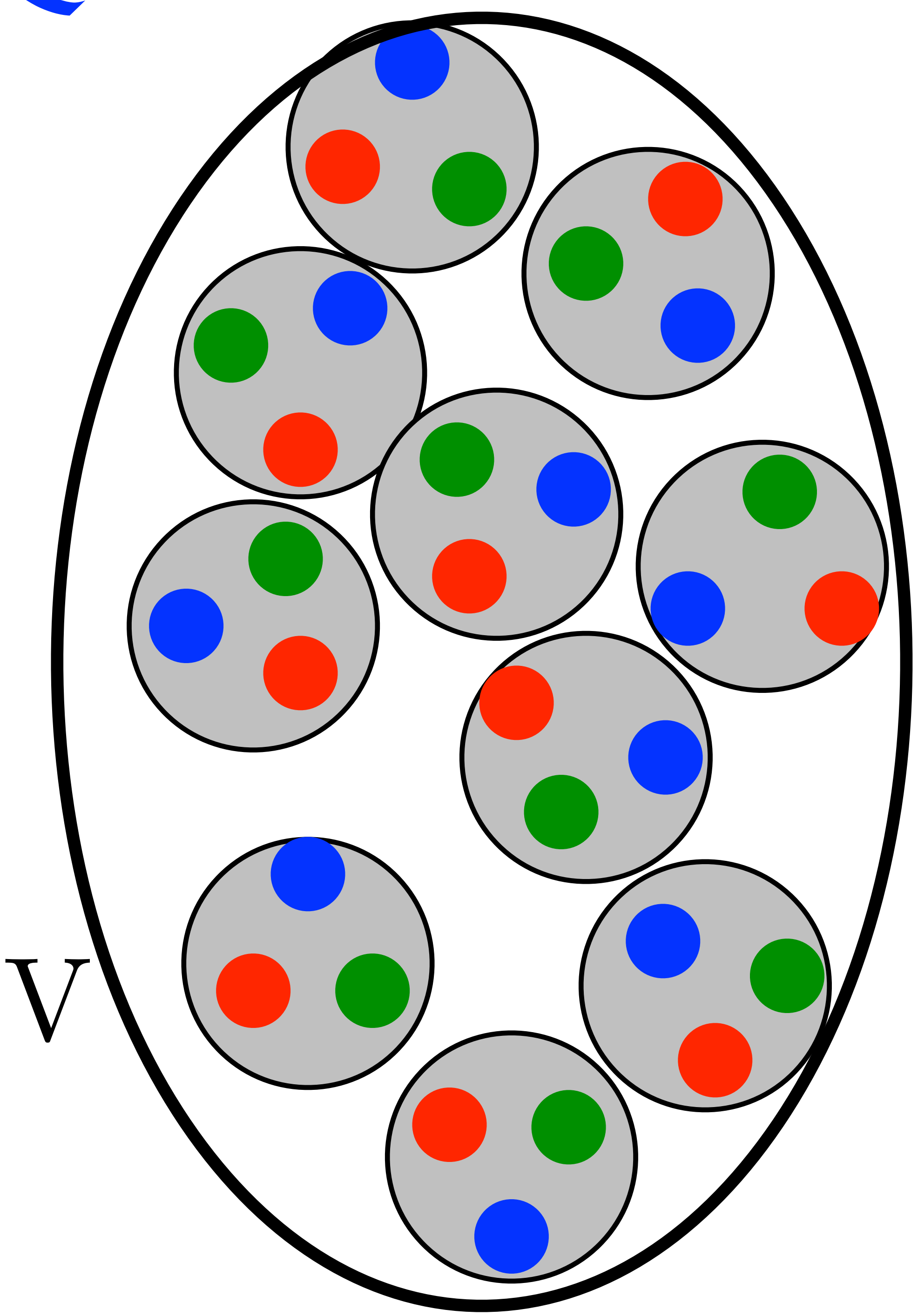
$$t \simeq 30 \text{ micro seconds} \left(3.0 \times 10^{-5} s\right)$$

Confinement of Quarks



cooler

T_c



$$T_c \simeq 145 - 170 \text{ MeV}$$

$$\simeq 10^{12} K$$

QCD: computed by hot-QCD and Budapest-Wuppertal Lattice Collaborations

LHC @ CERN

primary effort is to find the Higgs Boson, responsible for mass of quarks

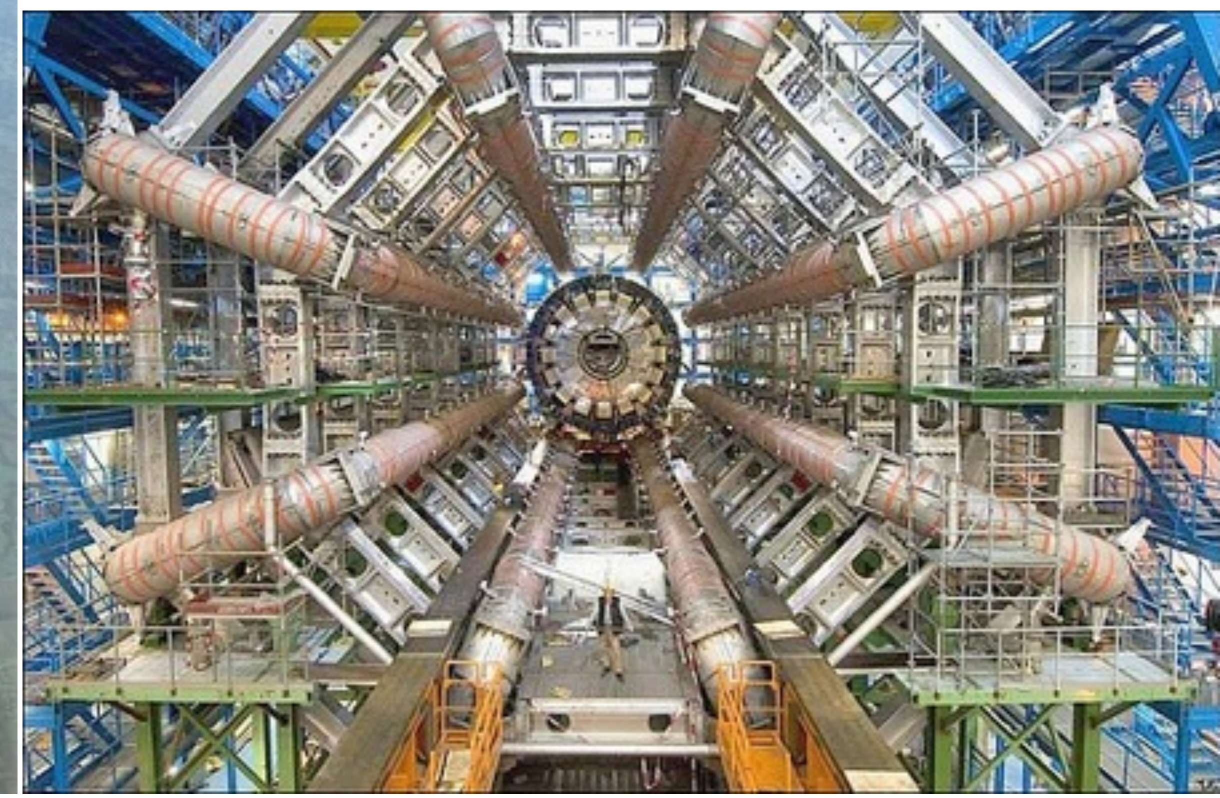
Will also probe conditions similar to big bang

LHC @ CERN

primary effort is to ~~find~~ study the Higgs Boson, responsible for mass of quarks

Will also probe conditions similar to big bang

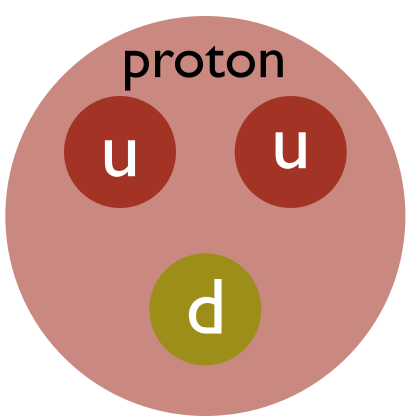
LHC @ CERN



ATLAS

LHC @ CERN

primary effort is to ~~find~~ study the Higgs Boson, responsible for mass of quarks

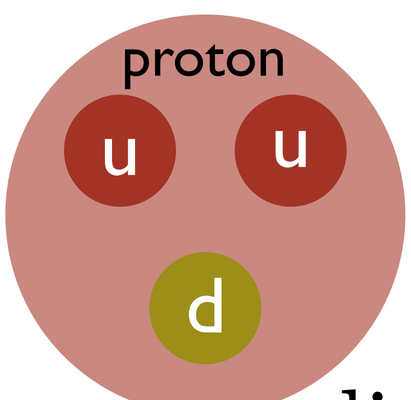


$$m_u \simeq 2 \ \mathtt{MeV}$$
$$m_d \simeq 5 \ \mathtt{MeV}$$

$$m_p \simeq 938 \ \mathtt{MeV}$$

LHC @ CERN

primary effort is to ~~find~~ study the Higgs Boson, responsible for mass of quarks



$$m_u \simeq 2 \ \mathtt{MeV}$$

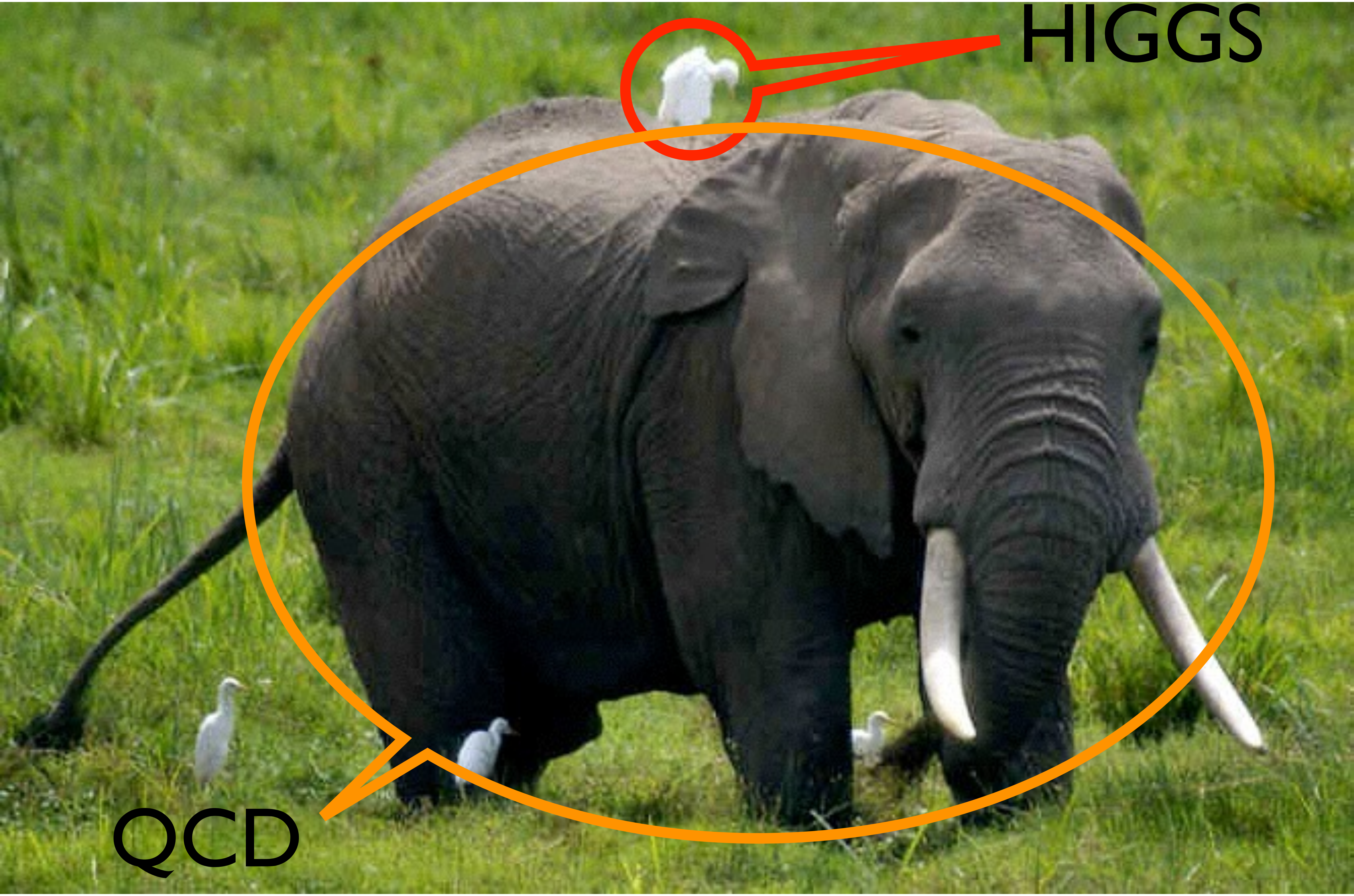
$$m_d \simeq 5 \ \mathtt{MeV}$$

$$m_p \simeq 938 \ \mathtt{MeV}$$

$$\lim_{m_{u,d} \to 0} m_p \simeq 900 \ \mathtt{MeV}$$

95% mass in universe is from the QCD glue!

(universe would be very different)

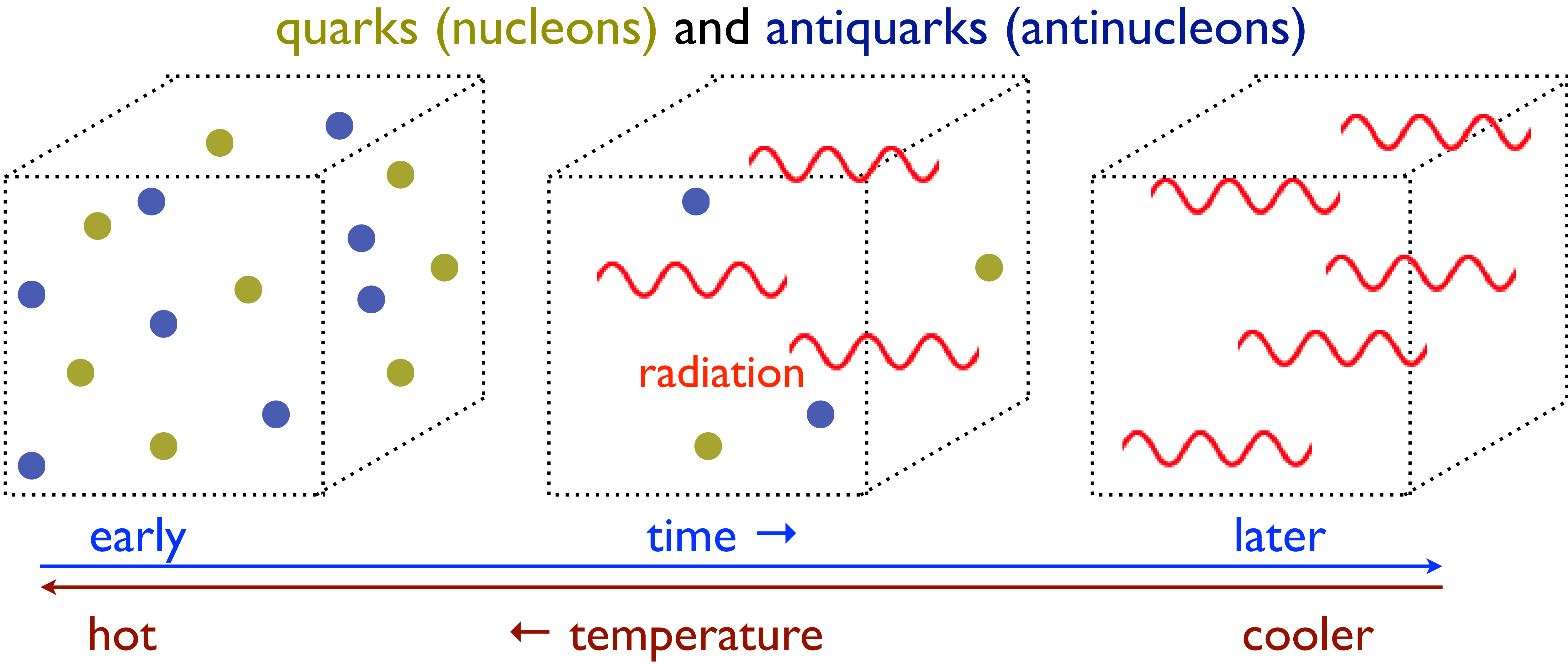

HIGGS
QCD

Big Bang Nucleosynthesis

$$T \simeq 1 \text{ trillion K} \rightarrow 1 \text{ billion K}$$

$$t \simeq 3 \times 10^{-5} s \rightarrow 3 \text{ min}$$

Why is there matter?



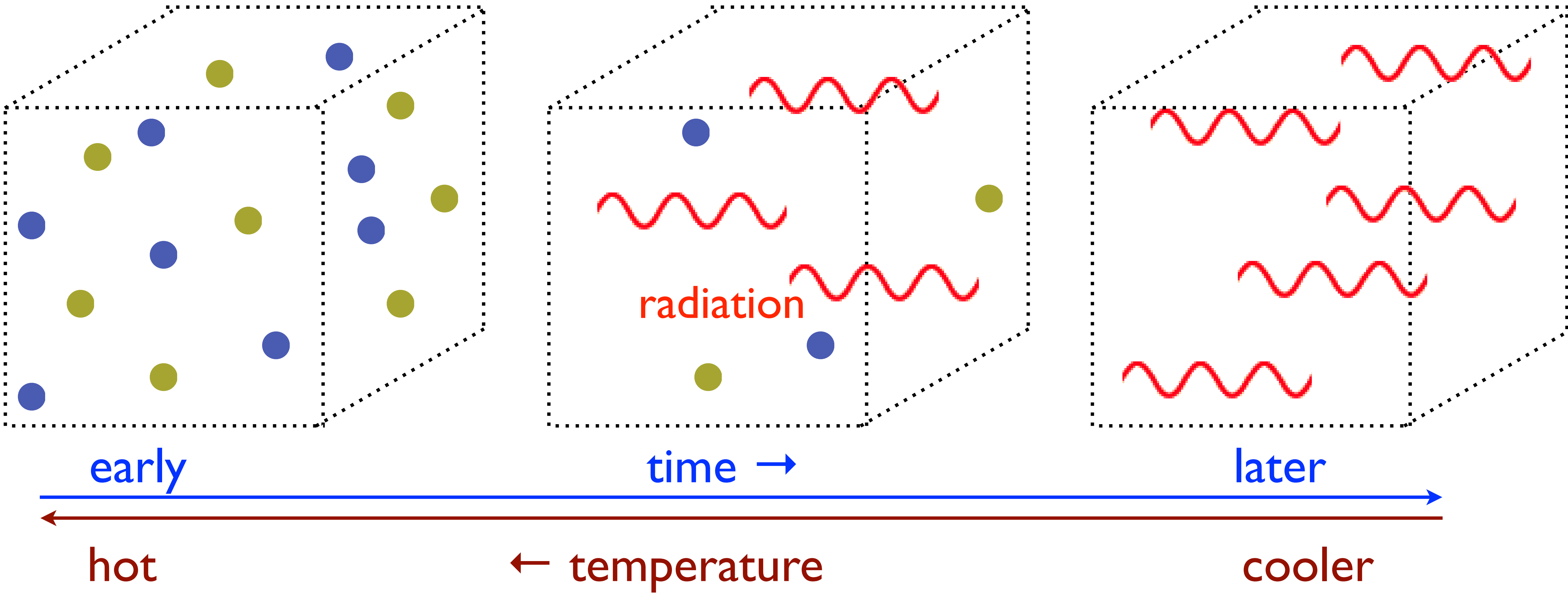
We would have expected the very early universe to be matter/antimatter symmetric, and thus to annihilate completely into radiation as the universe cooled

But we -- matter -- exist

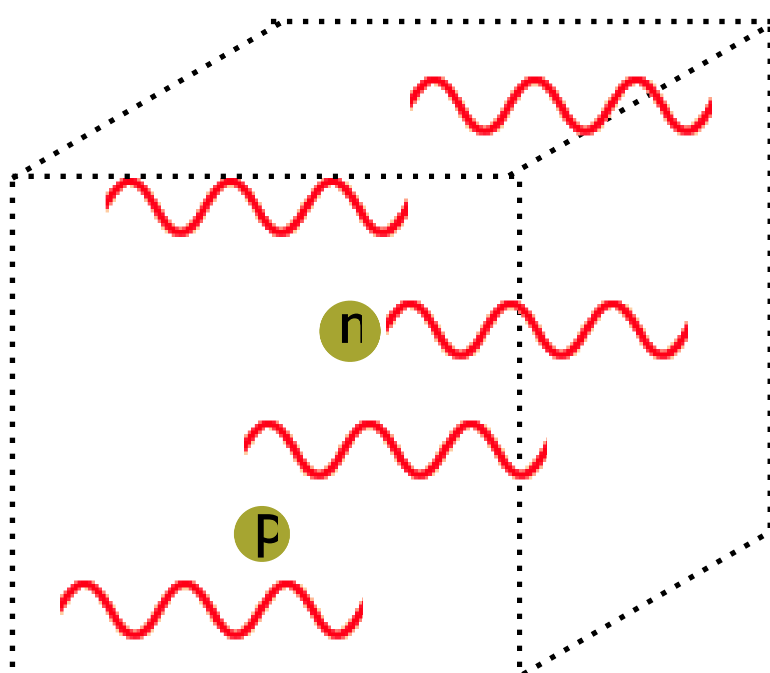
answer most likely from beyond Standard Model Physics

Why is there matter?

quarks (nucleons) and antiquarks (antinucleons)

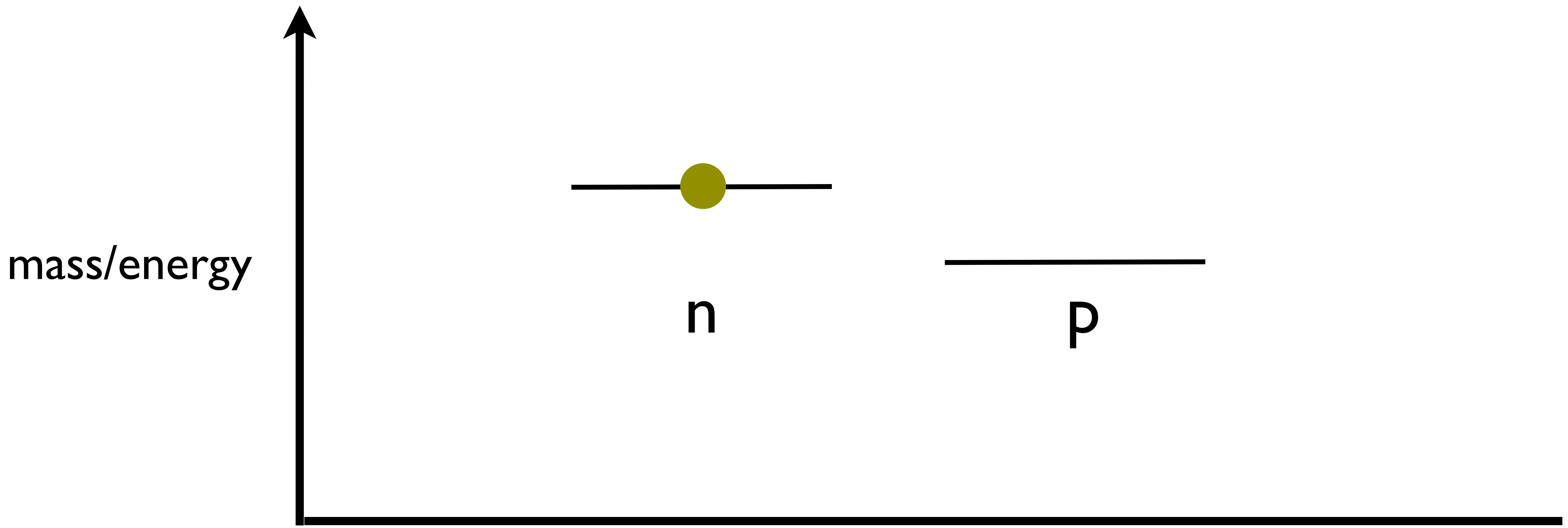


$$\eta \equiv \frac{n_B}{n_\gamma} \sim 10^{-9}$$



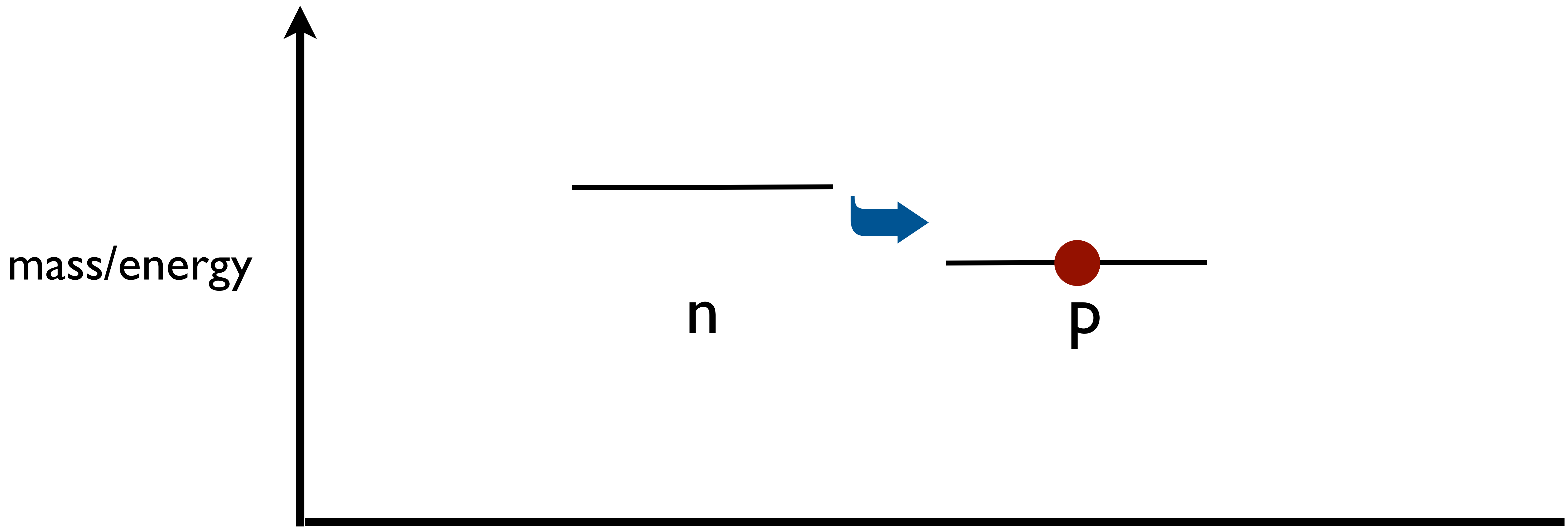
~equal number of protons and neutrons

when systems cool, they settle into the lowest energy state



$\tau_n \sim 15 \text{ min}$

when systems cool, they settle into the lowest energy state

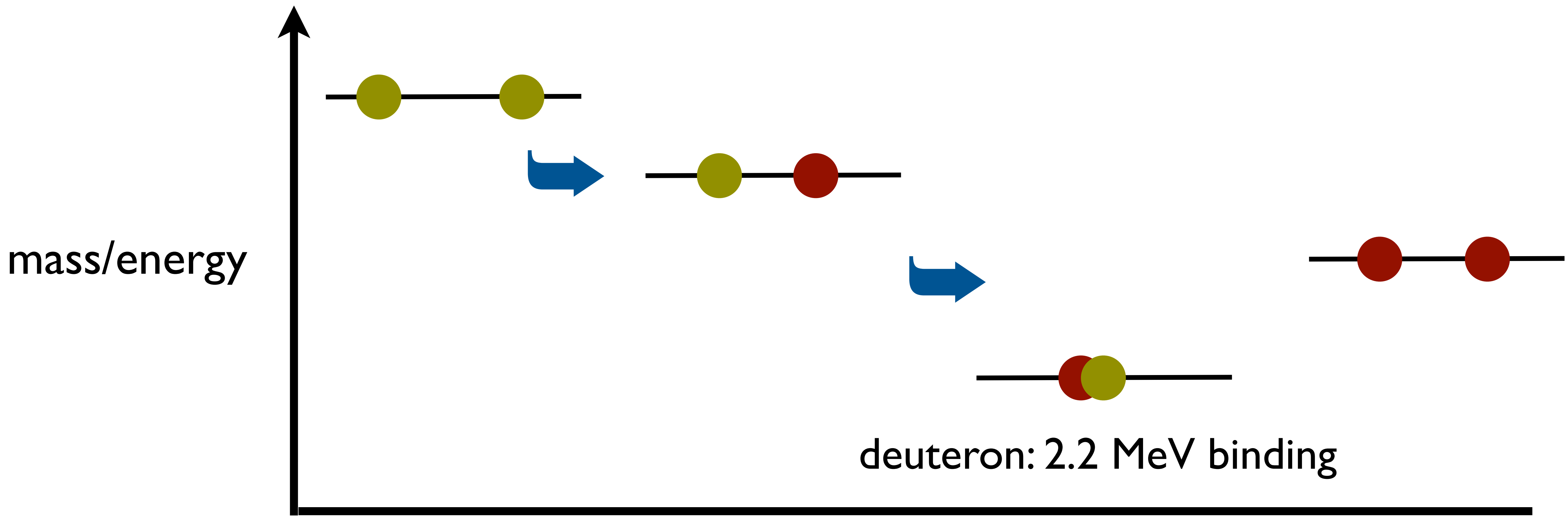


$$\tau_n \sim 15 \text{ min}$$

what prevented this from destroying all the neutrons?

if nothing else were to happen in the next few minutes, our universe would be full of only Hydrogen

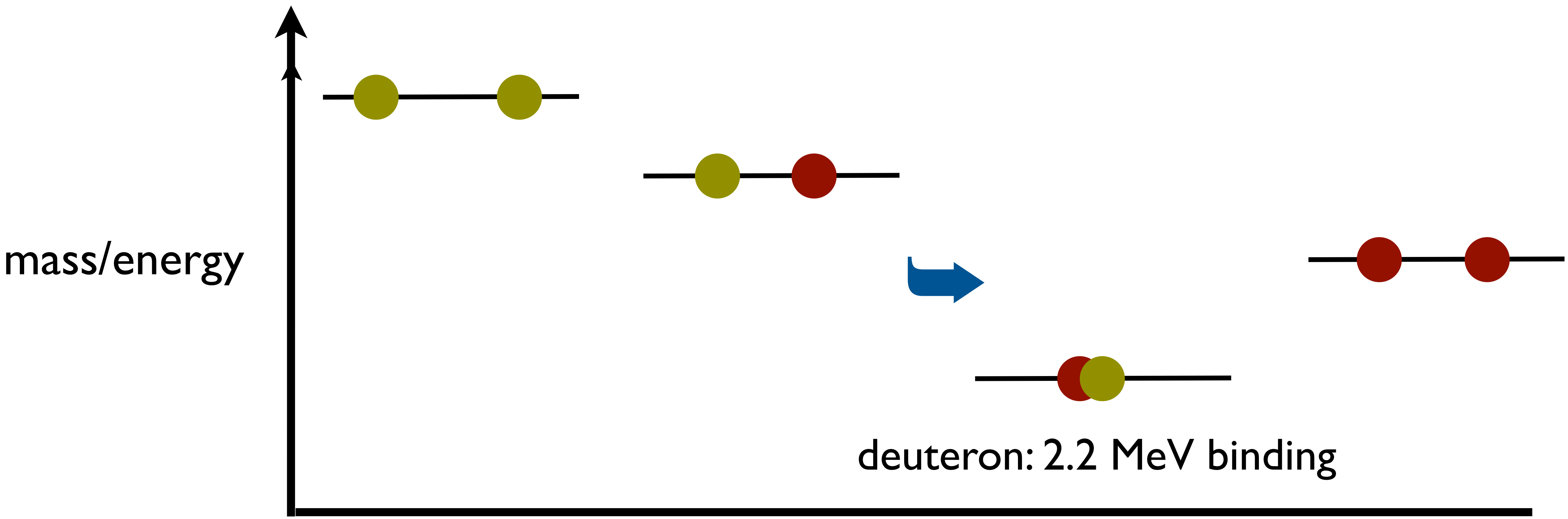
when systems cool, they settle into the lowest energy state

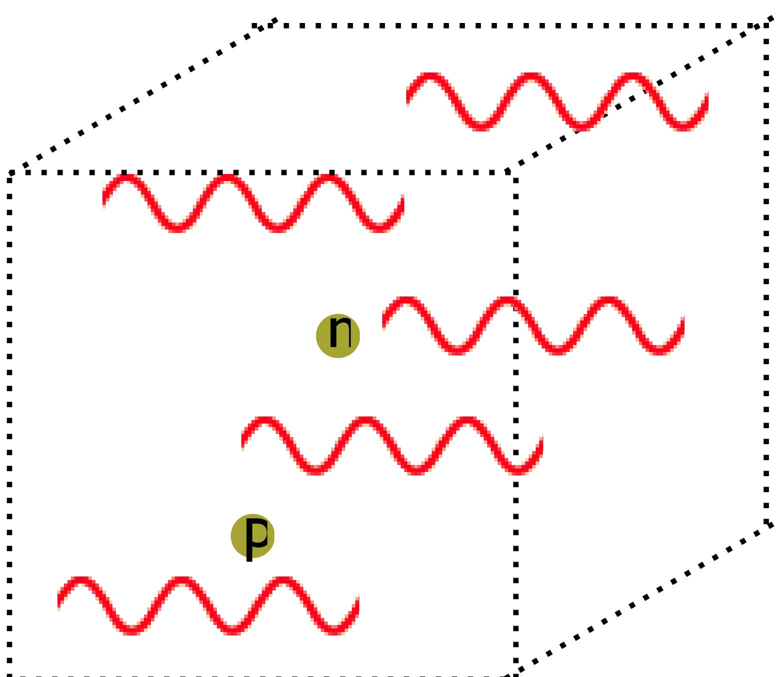


Answer: formation of nuclei

a system with protons and neutrons can collapse to a compact bound state, the deuteron: the attractive binding of a neutron and proton allows neutrons to survive when embedded in nuclei

The deuterium "bottleneck"





$\eta_{B/\gamma} \sim 10^{-9}$

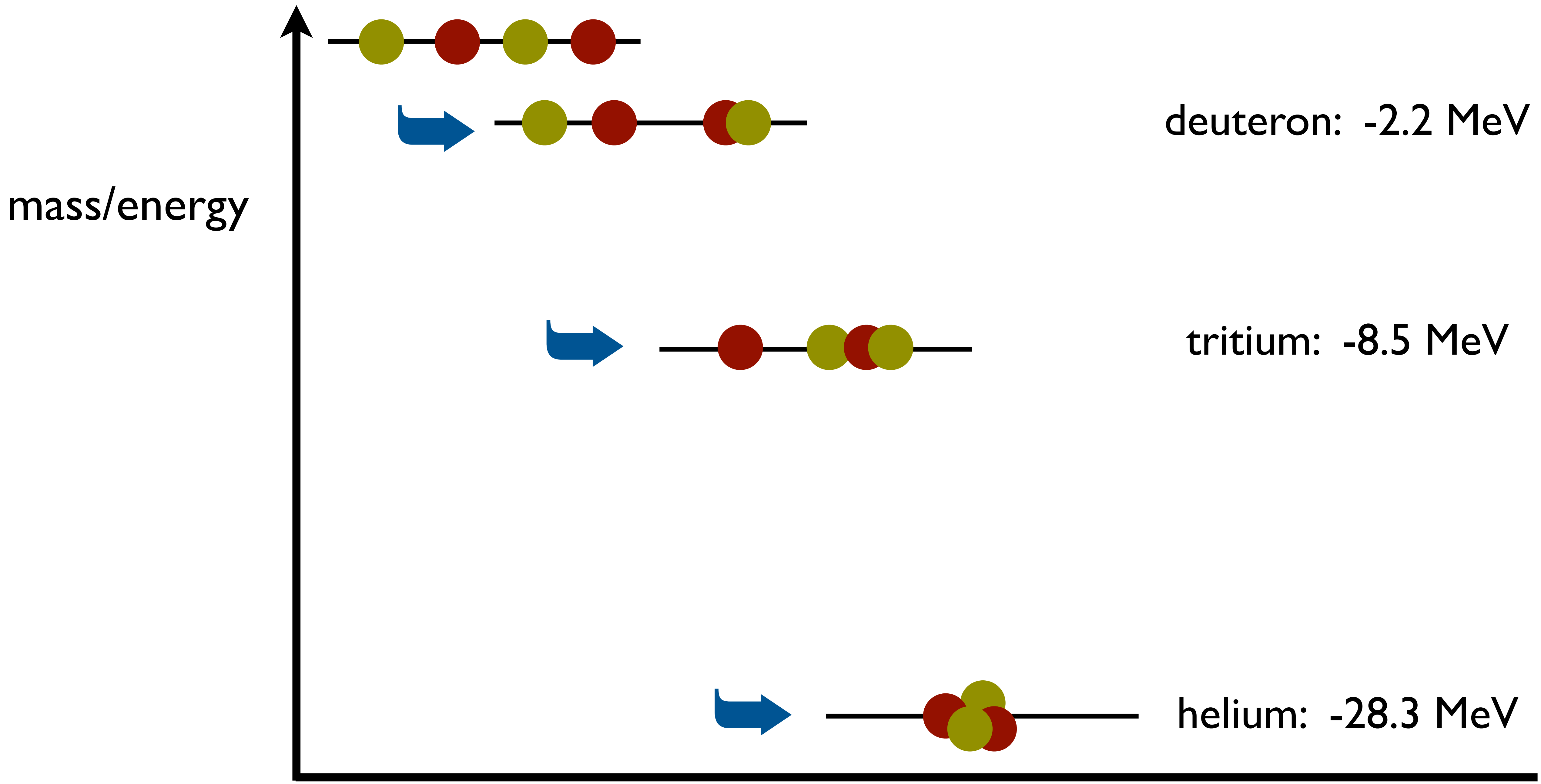
$$p + n \longleftrightarrow d + \gamma$$

until T ≃ 100 keV (1 billion K),

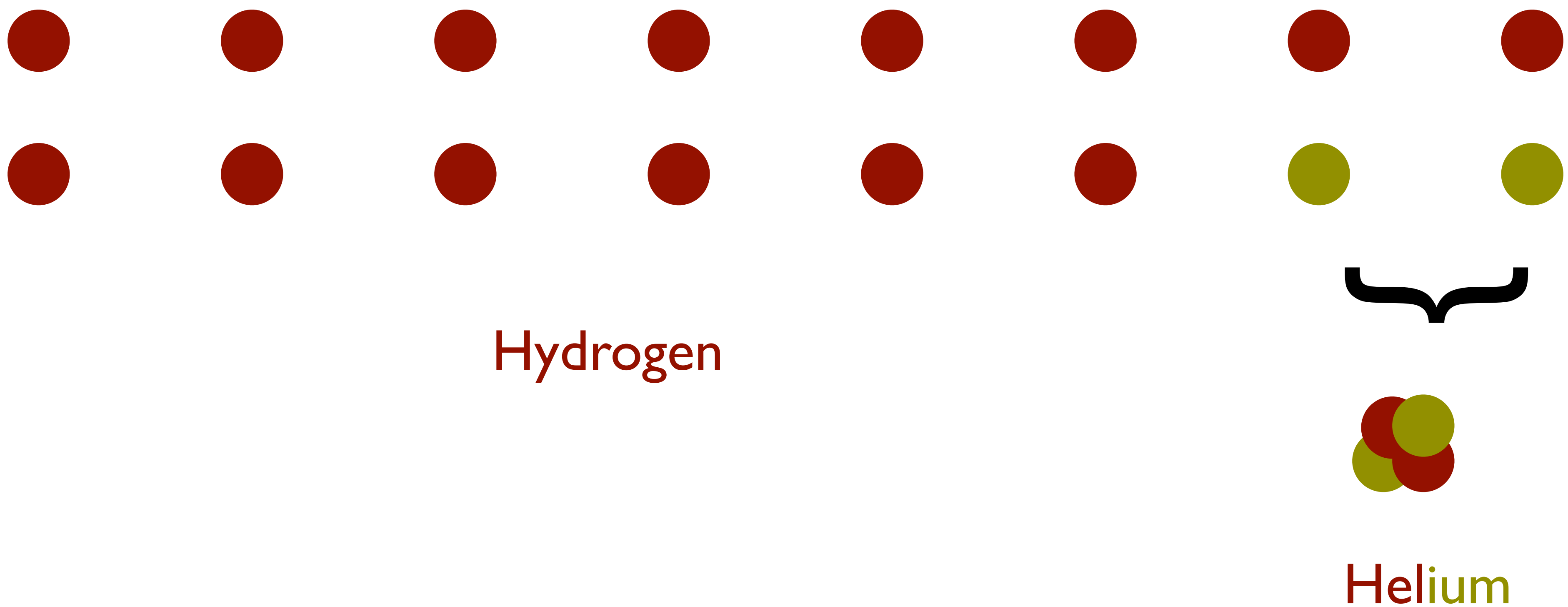
t ≃ 3 min

$$p + n \longrightarrow d + \gamma$$

The deuterium "bottleneck" is broken, neutrons flow into He



He stability: ↑,↓ protons and ↑,↓ neutrons can be packed together



The early universe contains 75% H and 25% ^{4}He by mass fraction

("all" deuterium converted to ^{4}He)

this picture very sensitive to binding energy of deuterium which is finely tuned (most nuclei have ~8 MeV binding per nucleon)!

$$B_d = 2.22 \ \texttt{MeV}$$

What if

$B_d \ll 2.22$ MeV

more finely tuned

all neutrons decay - no helium

mostly hydrogen stars?

$B_d \gg 2.22$ MeV

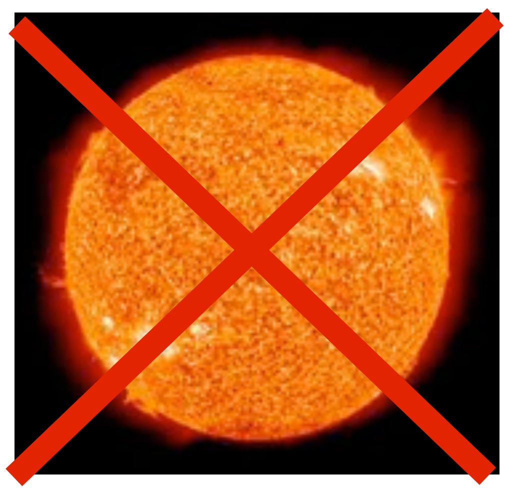
natural scenario

all neutrons captured in deuterium and helium - no hydrogen

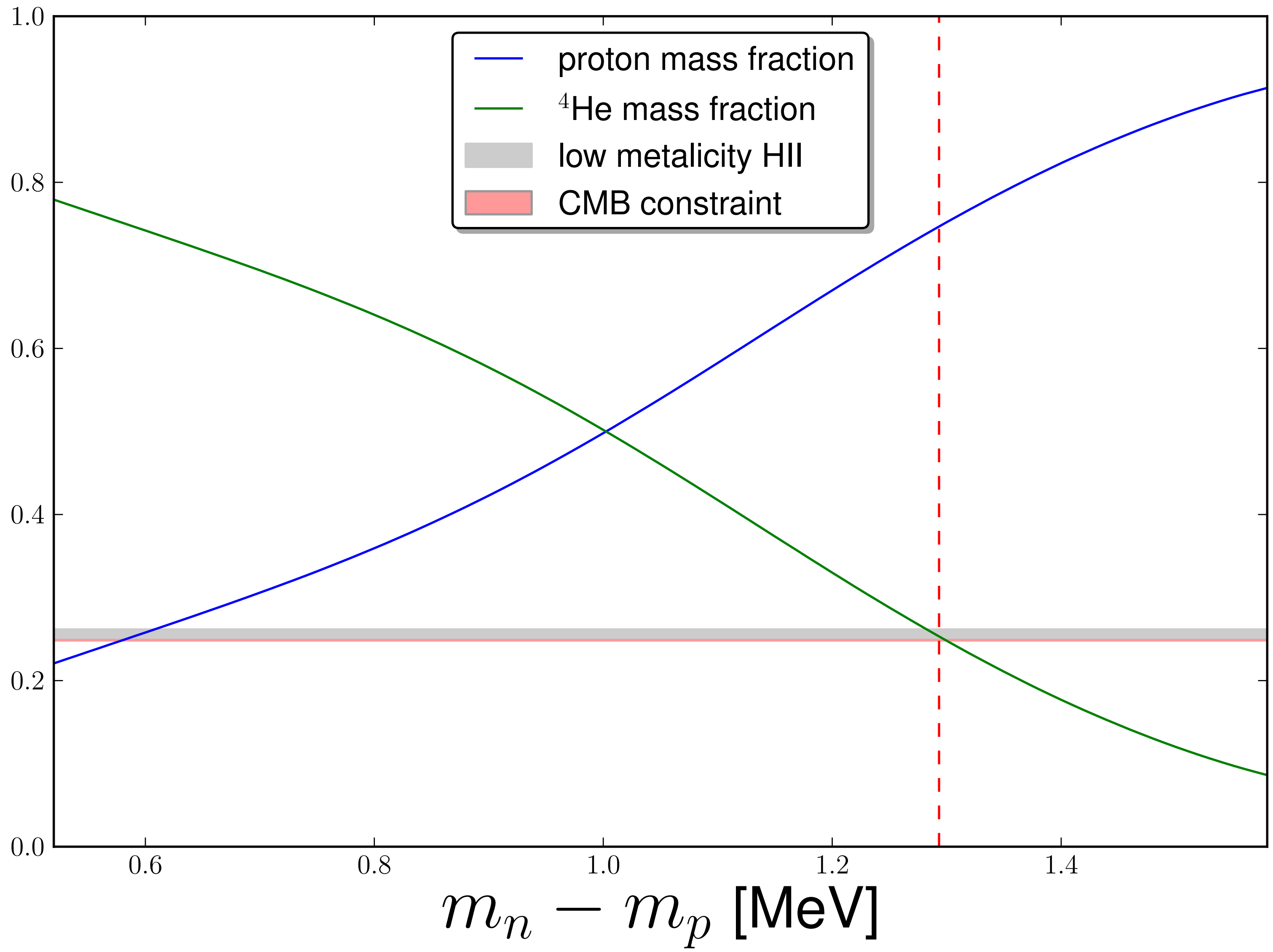
no stars like ours!

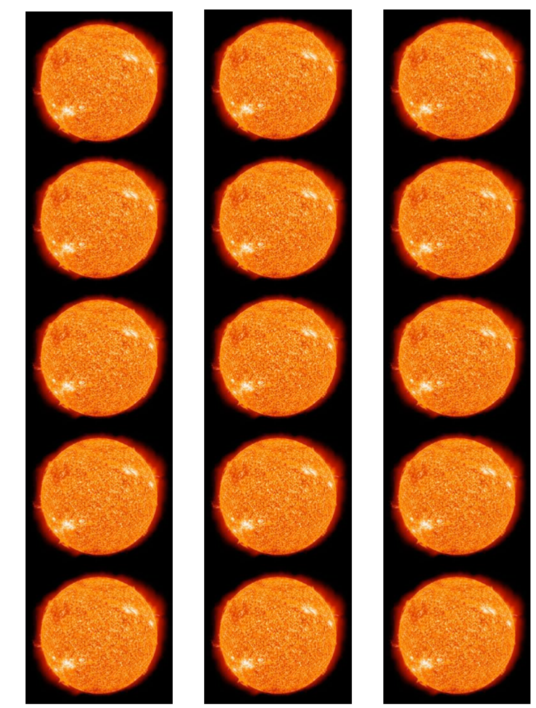
Turns out BBN abundances are also very sensitive to

$$m_n - m_p \propto \begin{cases} m_d - m_u \\ e^2/4\pi \end{cases}$$



No Sun!



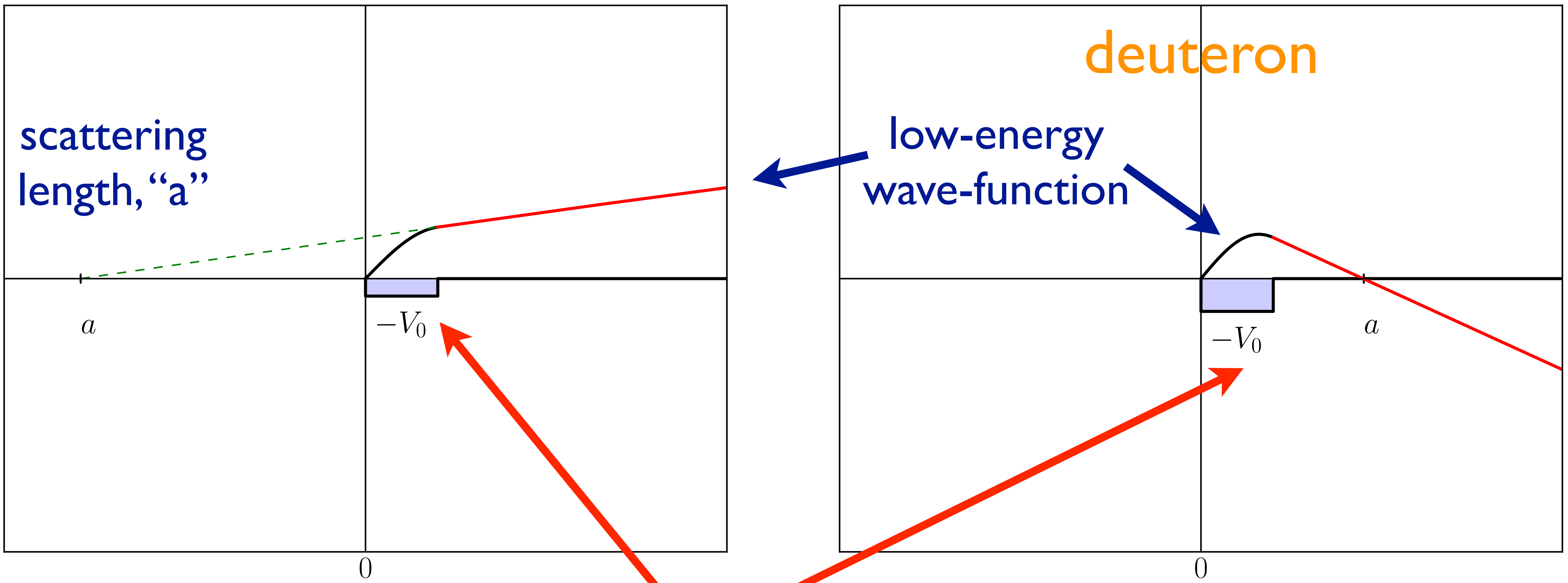


Too many suns?

How does QCD impact light element synthesis in the early Universe? (Will come back to this later)

proton-neutron scattering at low energies

$^1S_0 : a \simeq -24\ \mathtt{fm}$ $\quad$ $^3S_1 : a \simeq 5.5\ \mathtt{fm}$

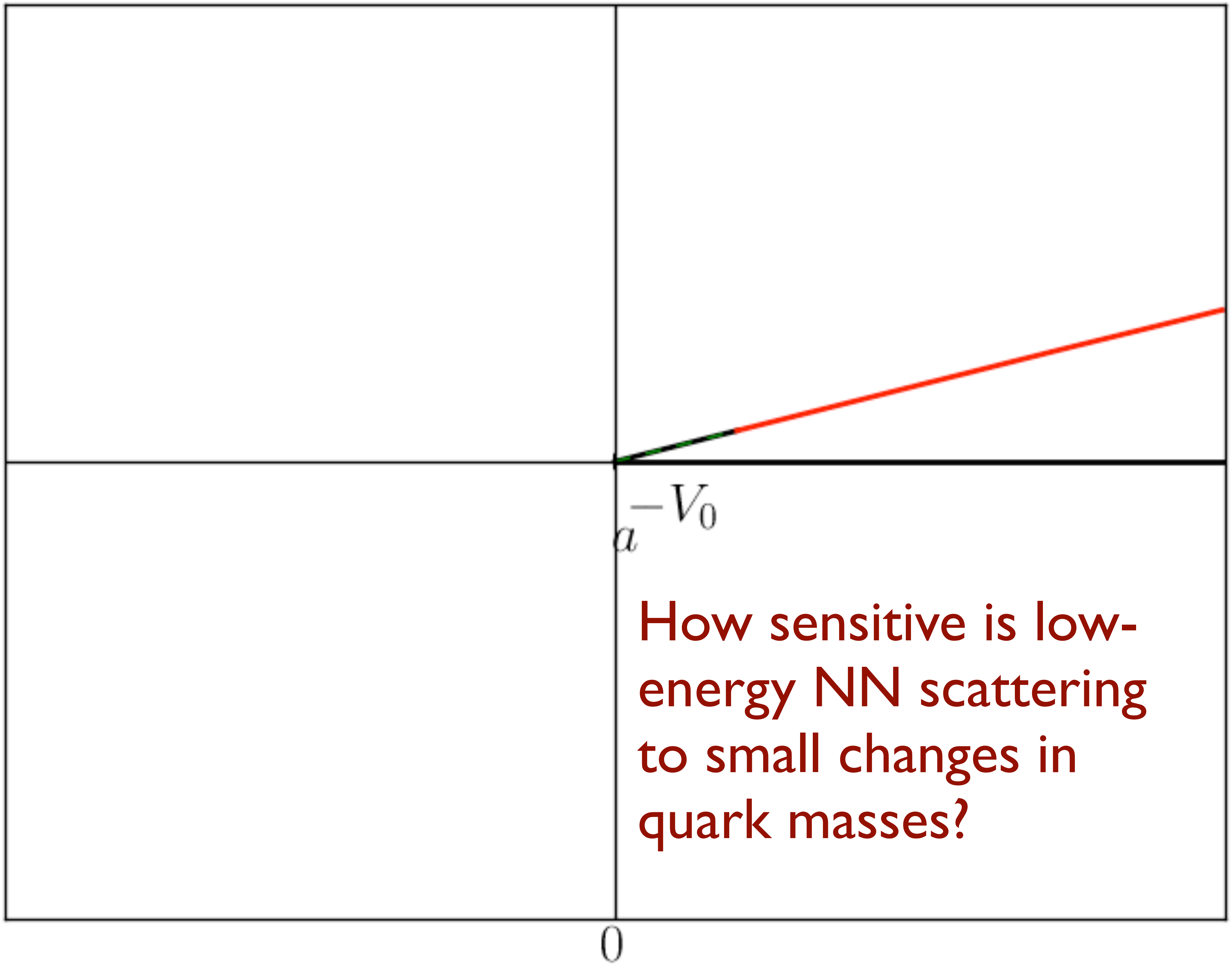


$$R_{NN} \sim 1.4\ \mathtt{fm}$$

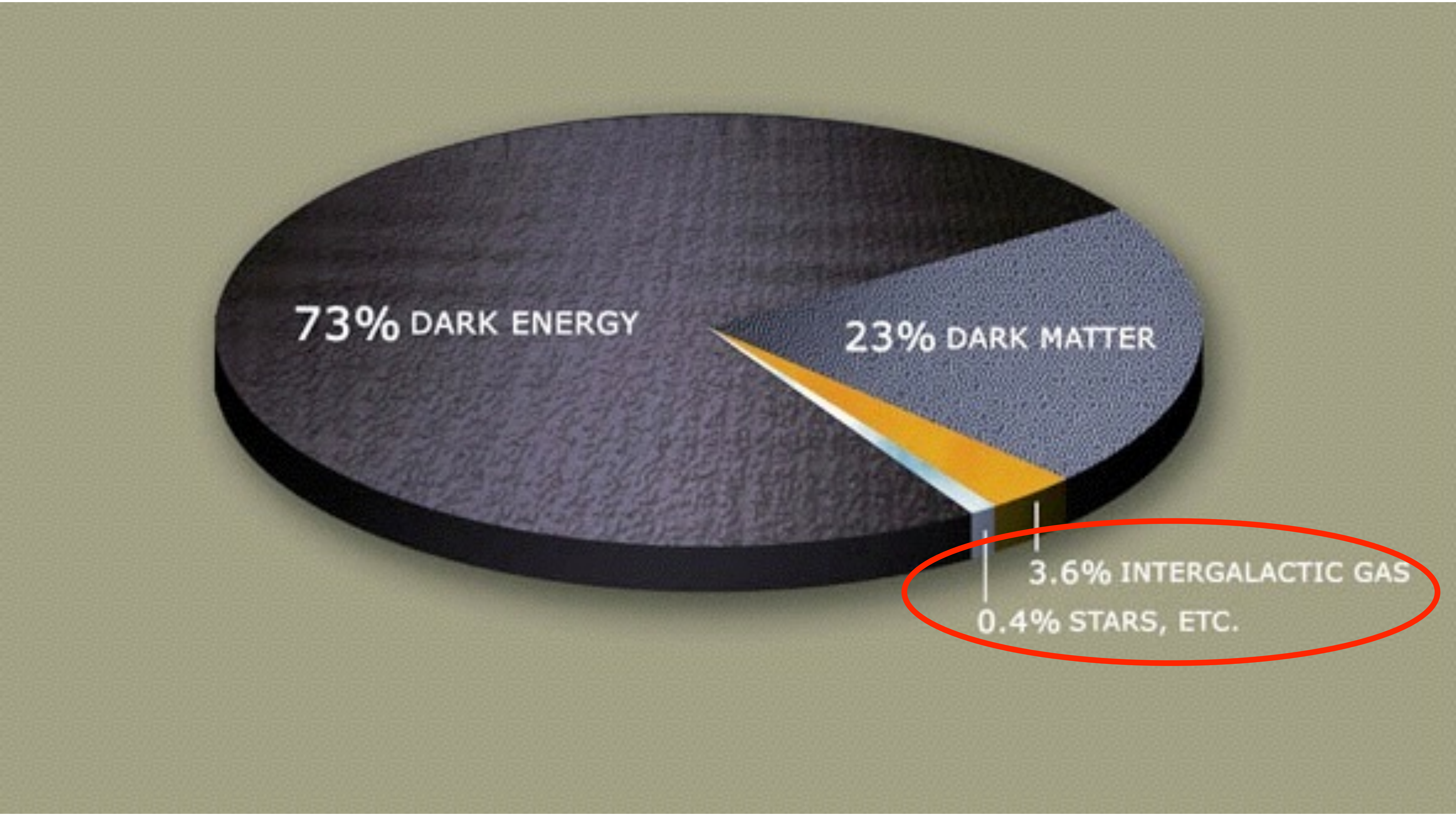
Fine tuning gives small deuteron binding energy

Solving QCD can help us determine the nature of this fine tuning

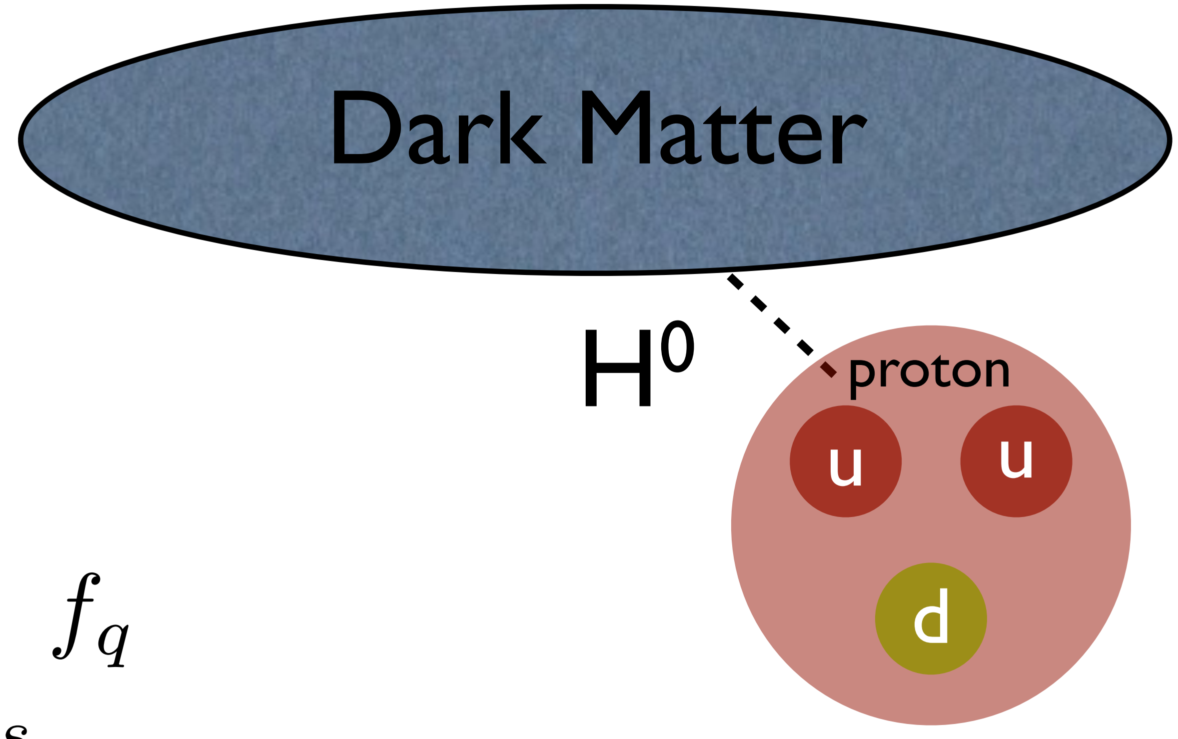
Finely tuned interactions (like in AMO systems)



Energy Budget of the Universe



If Dark Matter couples to the scalar current of the nucleon (eg via Higgs) Spin Independent cross section



$$\sigma \propto |f|^2 \qquad f = \frac{2}{9} + \frac{7}{9} \sum_{q=u,d,s} f_q$$

$$f_q \equiv \frac{\langle N|m_q \bar{q} q|N\rangle}{m_N}$$

see eg. Cheung, Hall, Pinner, Ruderman arXiv:1211.4873

with enhancement of A^2 for nucleus (Xenon)

scalar current difficult to measure experimentally

$f_{u,d}$ estimated from pion-nucleon scattering

f_s uncertainty dominates estimates of cross section

Ellis, Olive, Savage
Phys.Rev. D77 (2008)

If Dark Matter couples to the scalar current of the nucleon (eg via Higgs) Spin Independent cross section

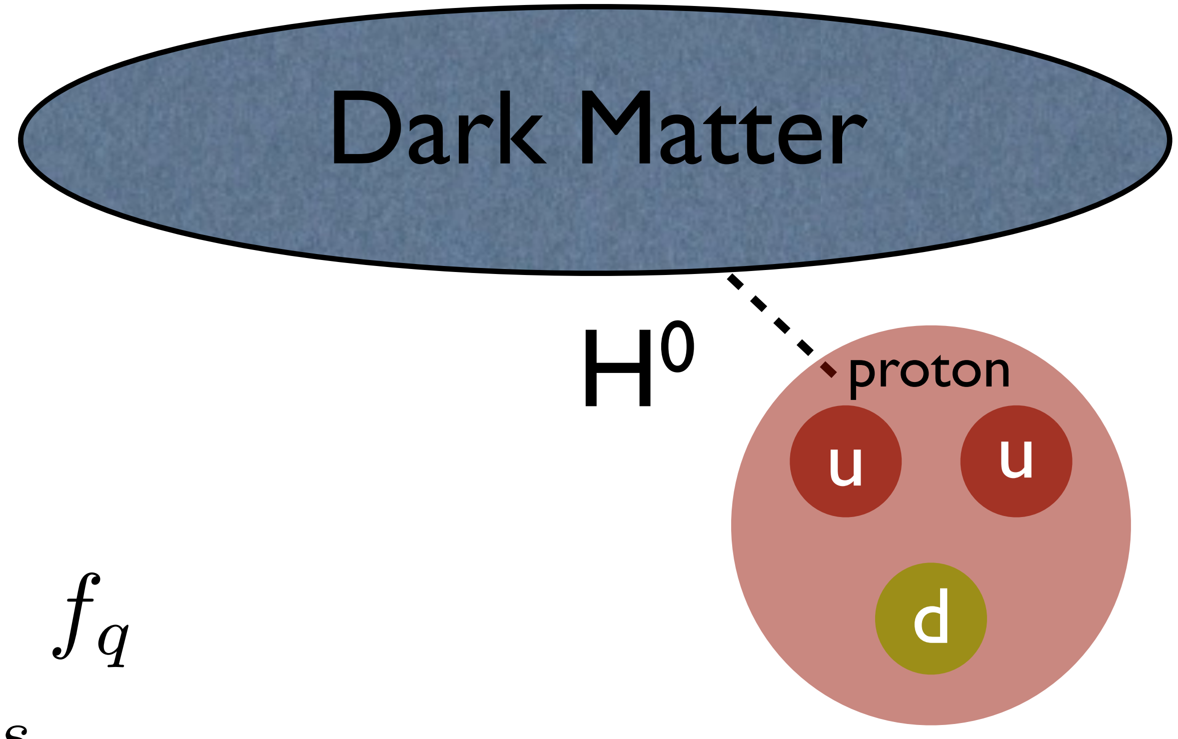


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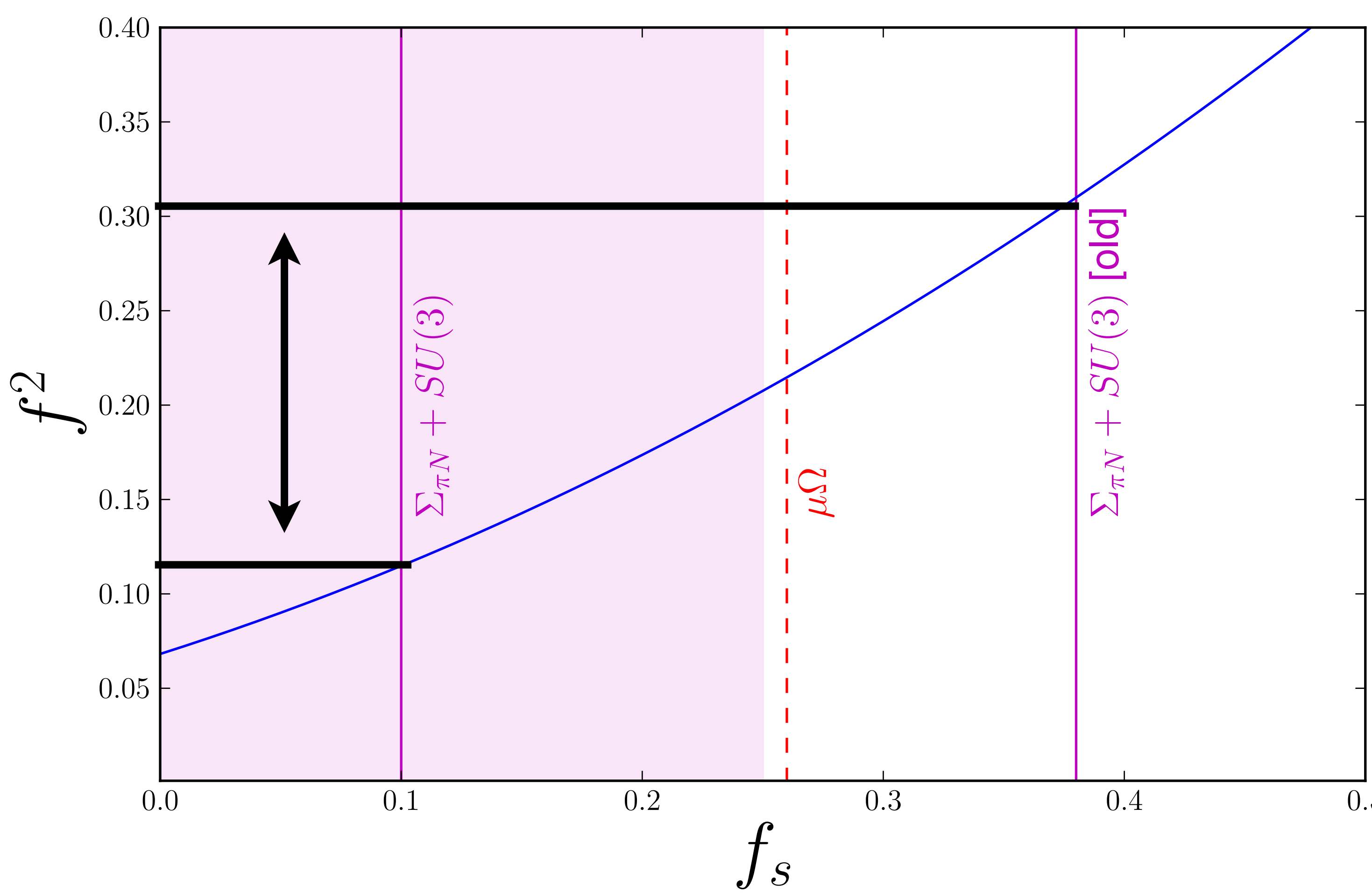
figure adapted from arXiv:1211.4873
thanks to J. Ruderman and collaborators



Feynman-Hellman Theorem

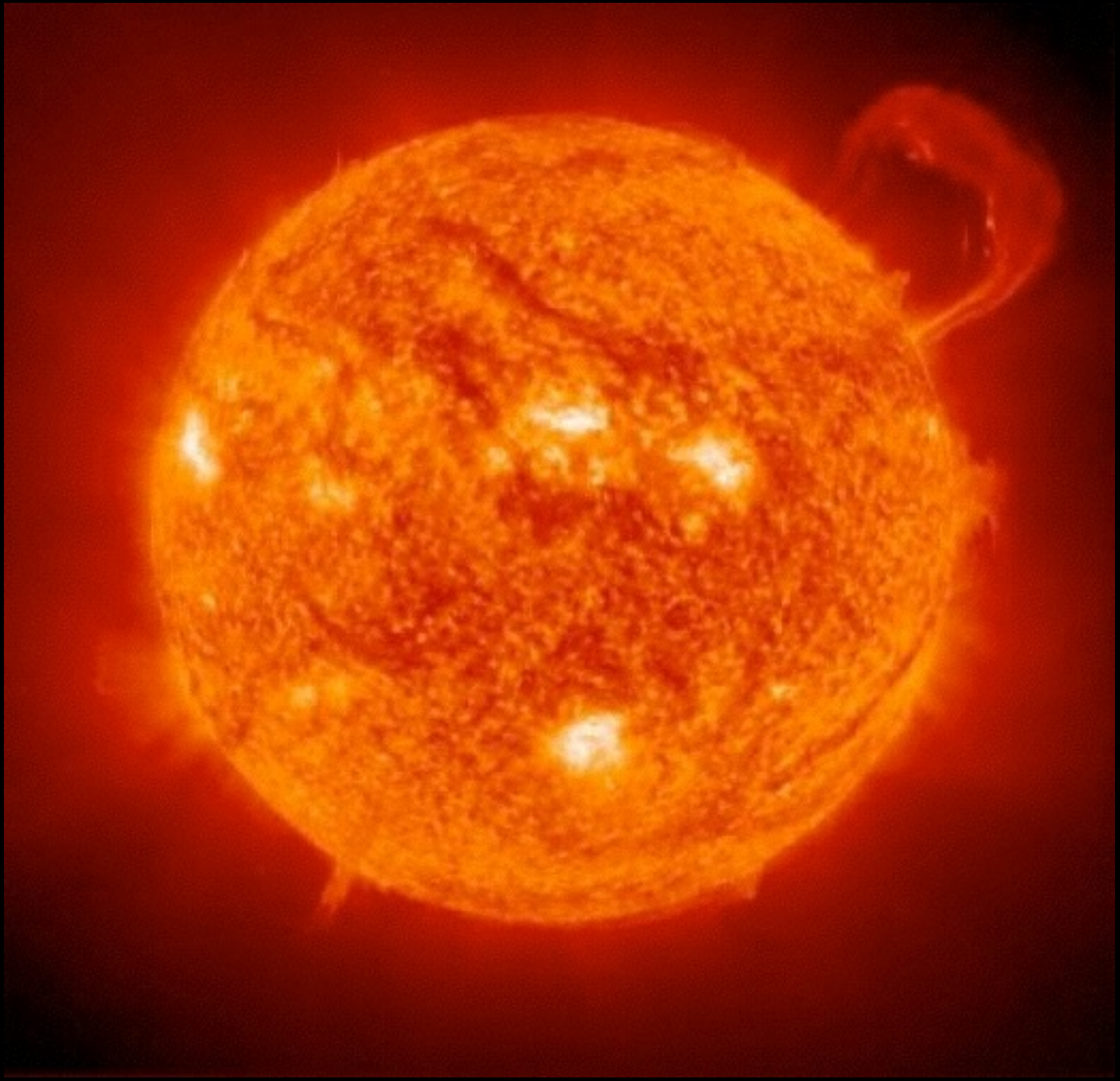
$$H = H_0 + \lambda H_1 \quad \Rightarrow \quad \frac{\partial E_n}{\partial \lambda} = \langle n | \frac{\partial H}{\partial \lambda} | n \rangle$$

In our lattice QCD calculations, we can study the quark mass dependence of the nucleon and infer these matrix elements

$$m_q \frac{\partial m_N}{\partial m_q} = \langle N | m_q \bar{q} q | N \rangle$$

By understanding the quark mass dependence of the nucleon - we can determine these important matrix-elements

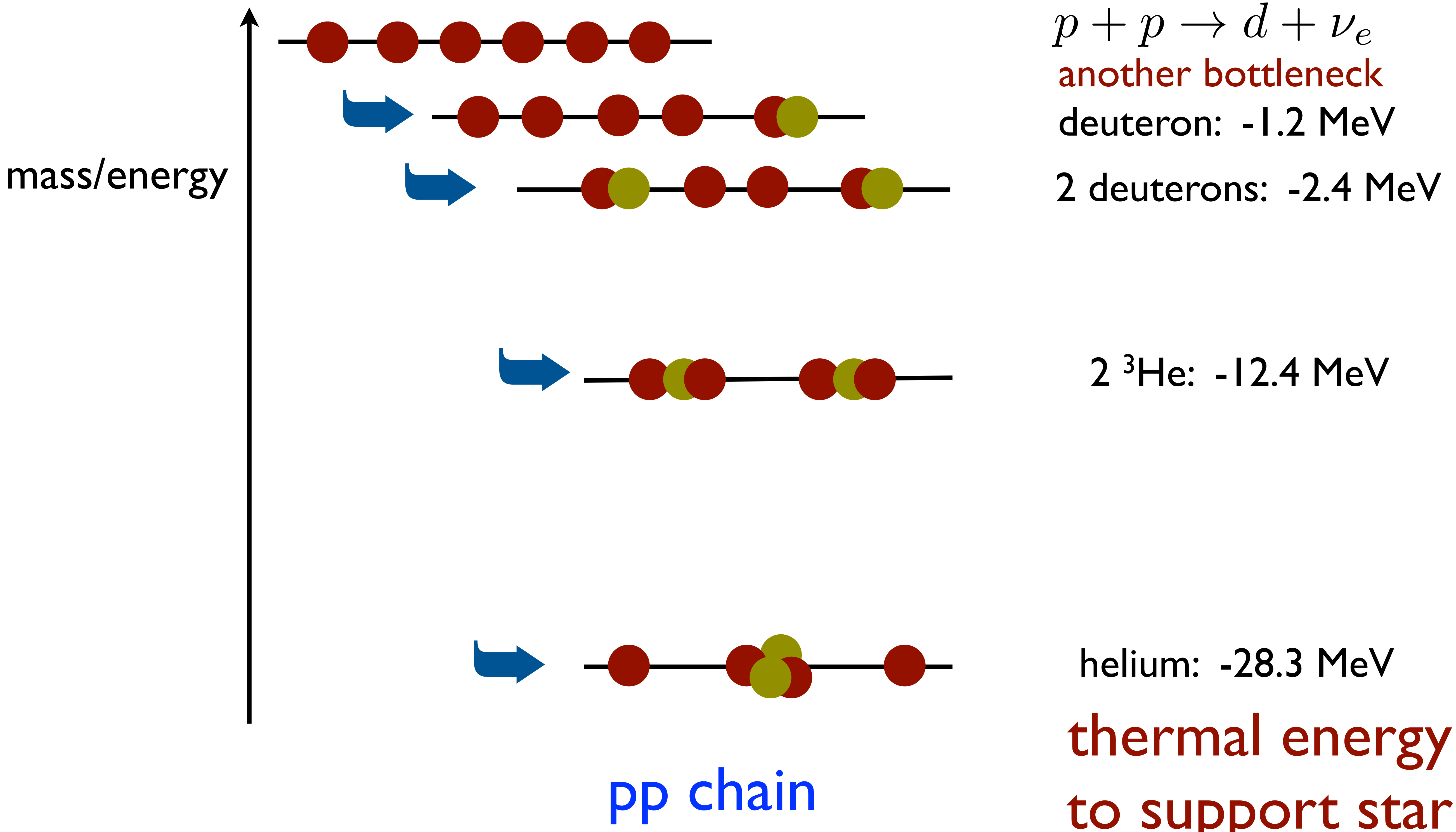
Solar Fusion



$$T \simeq 20\ \mathrm{K}$$
$$t \simeq 200\ \text{Million years}$$

One needs neutrons and protons to make new nuclei.

Small stars burn protons only, manufacturing the needed neutrons



This is how our Sun generates its energy

80% of all stars generate their energy by hydrogen burning

At its very center the Sun generates 275 watts/m^3 - similar to the energy generated by a compost (garbage) heap (of the same size)!

And this is why the Sun has burned for 4.6 b.y., and will burn for 5 b.y. more, fortunately -- a very big, very slow reactor

$$p + p \to d + \nu_e + e^+$$

This fundamental reaction can not be measured!
(Coulomb Repulsion)

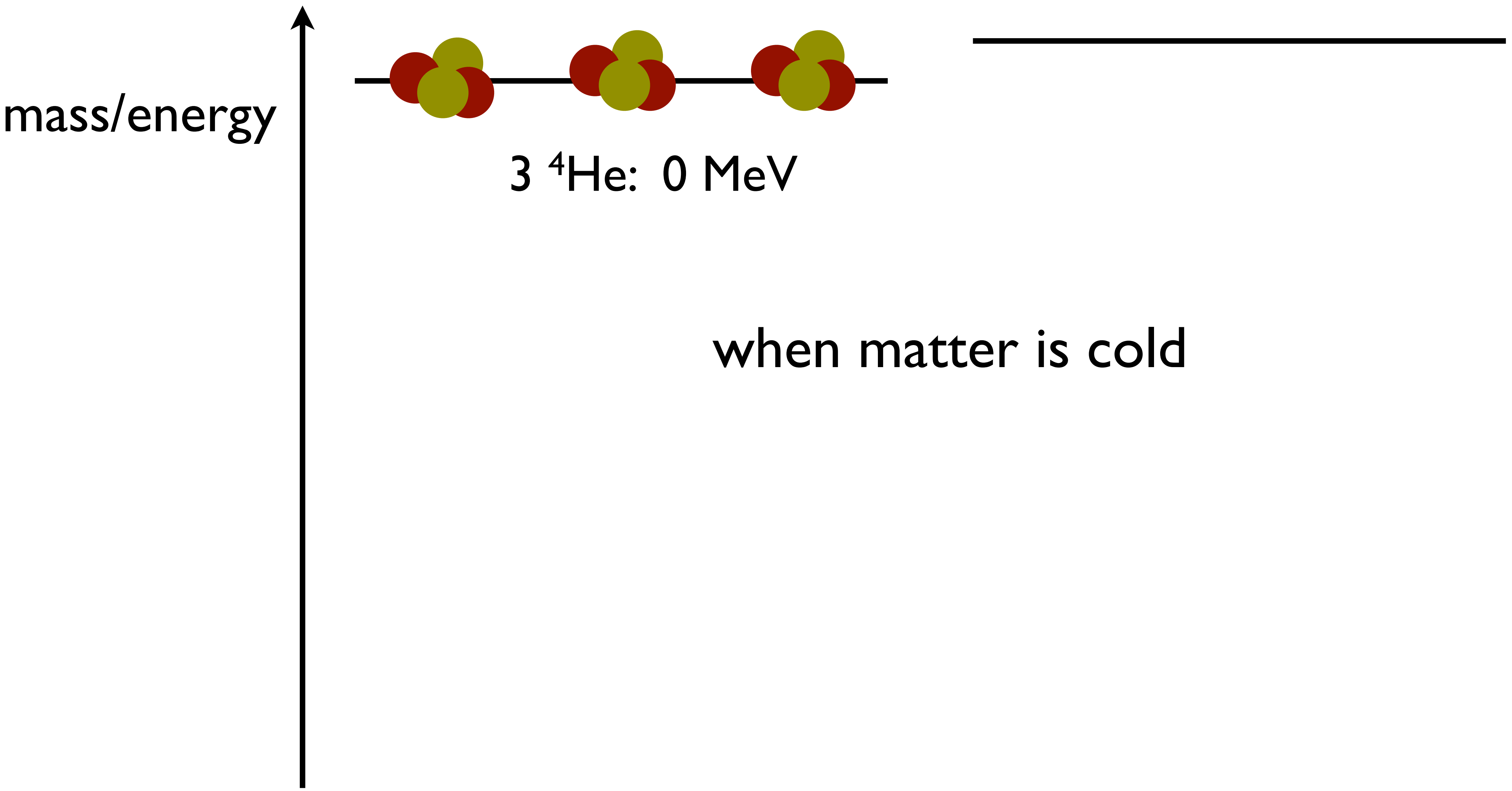
We believe we know the value,
but based upon model calculations
or Effective Field Theory with limited constraints

Soon, with numerical QCD, we will be able to
calculate this from first principles

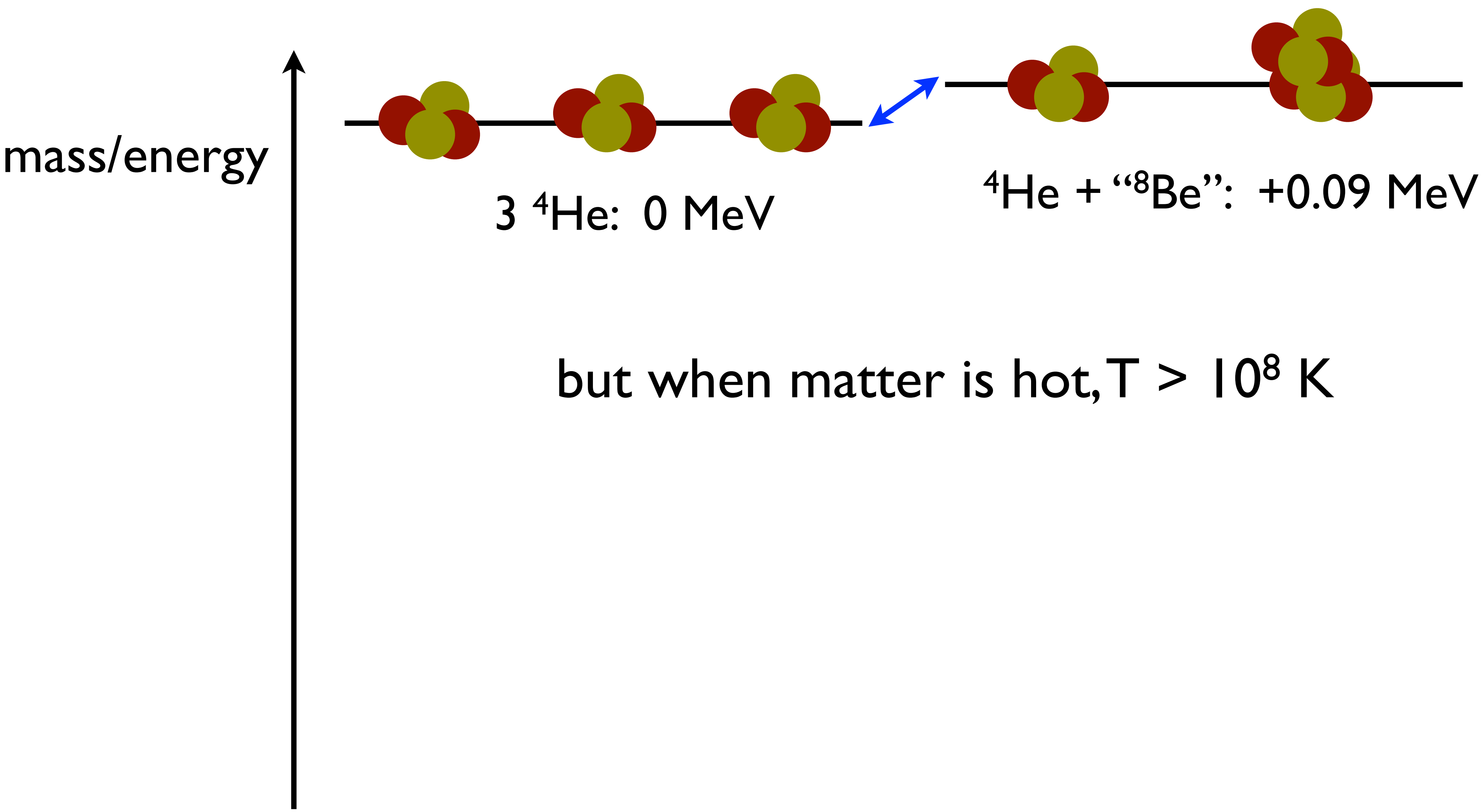
Large stars use He and neutrons to build new nuclei.

Higher temperatures and higher densities are needed.

The Big Bang could not do this because the density was too low.



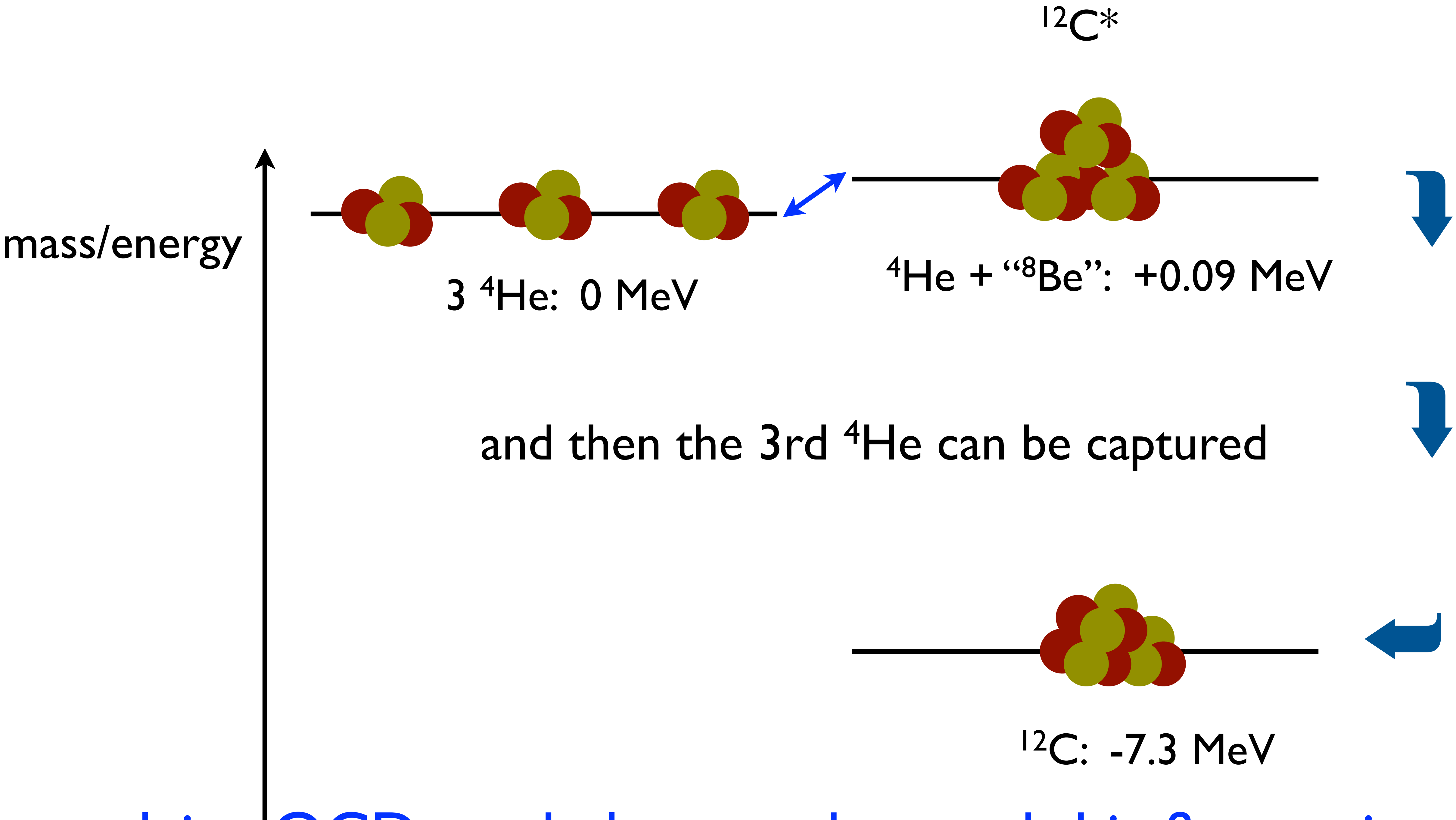
even more finely tuned



but when matter is hot, $T > 10^8$ K

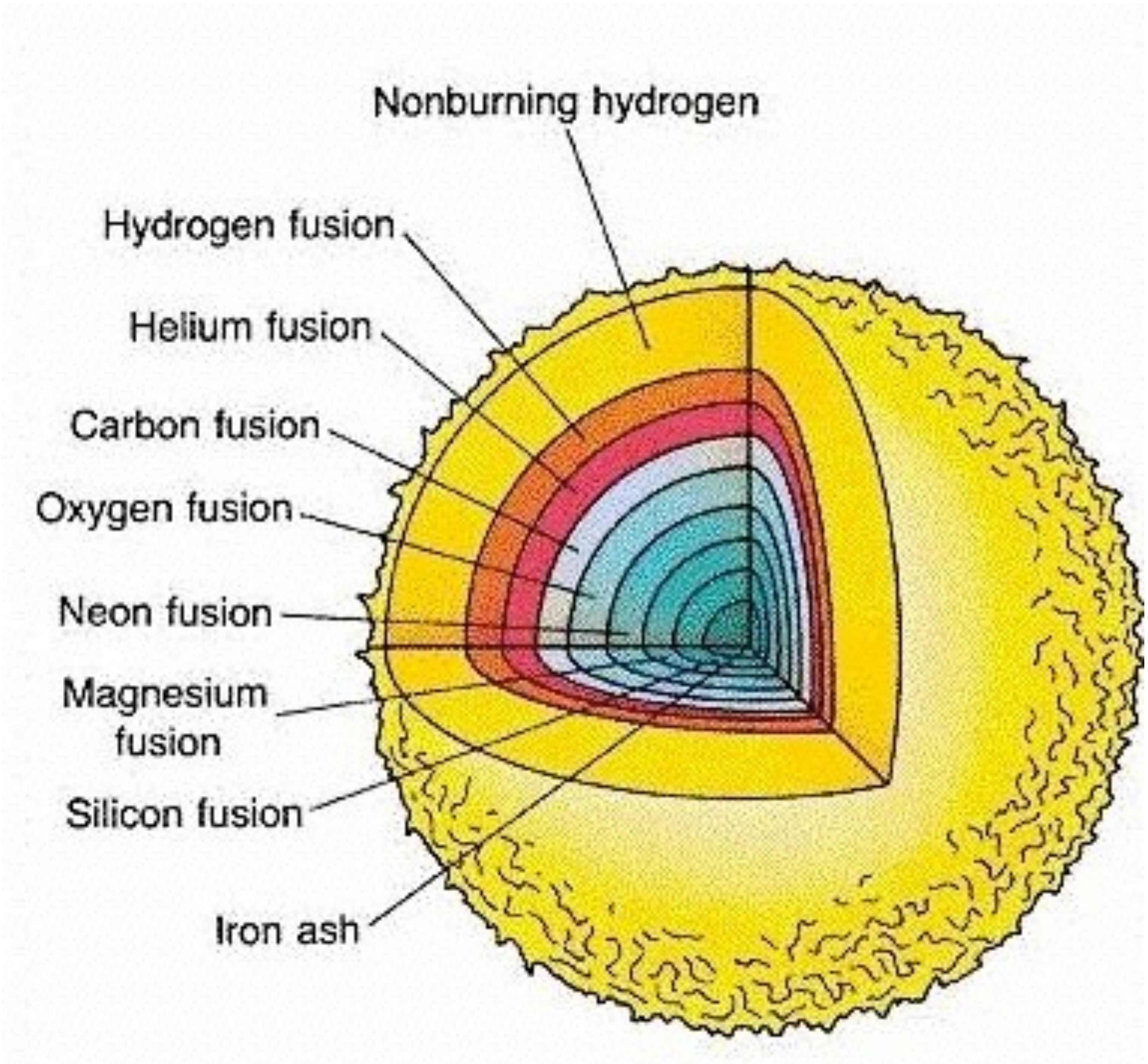
even more finely tuned - source of complex life

the triple-α process Hoyle State

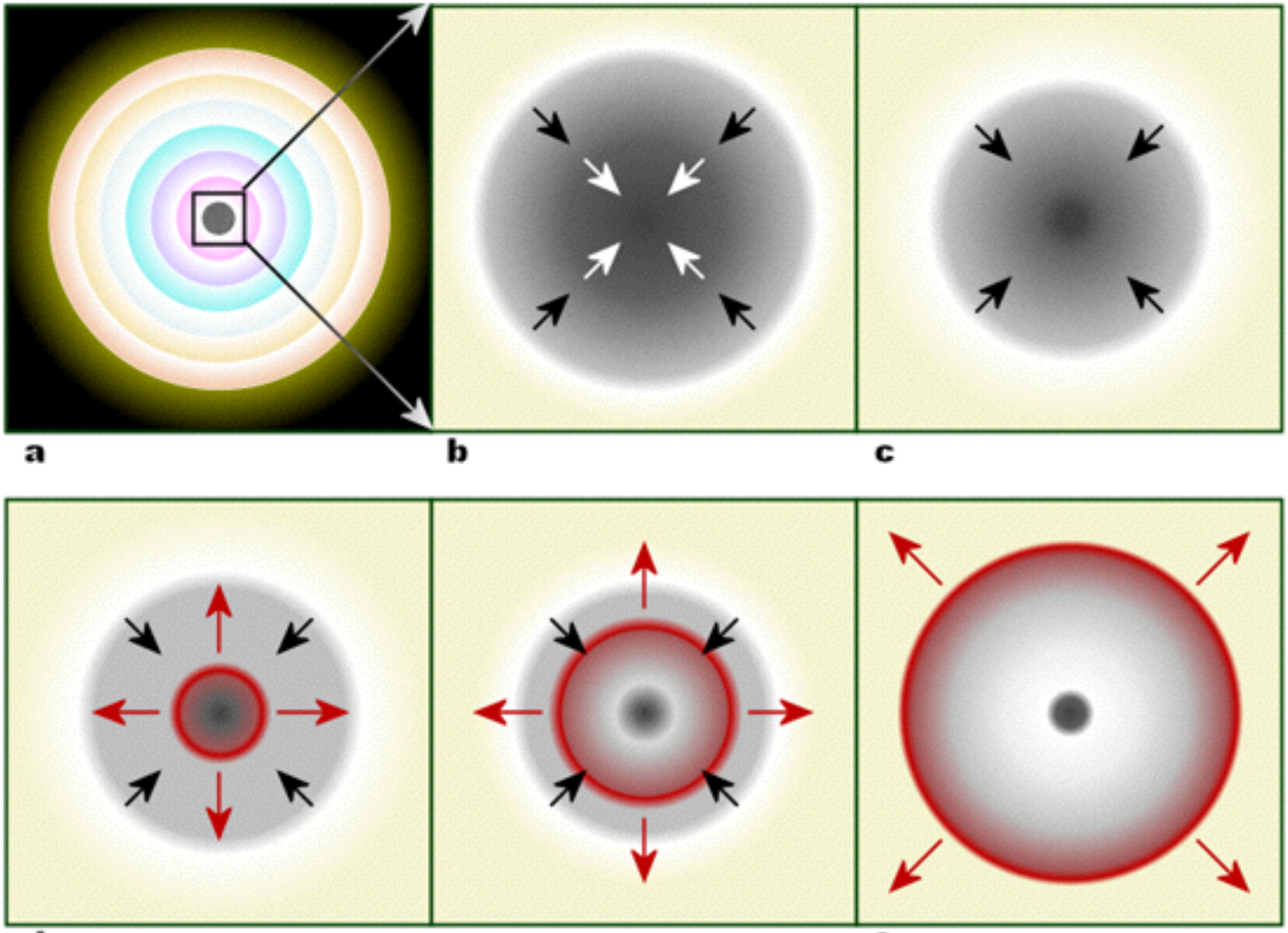


solving QCD can help us understand this fine tuning:

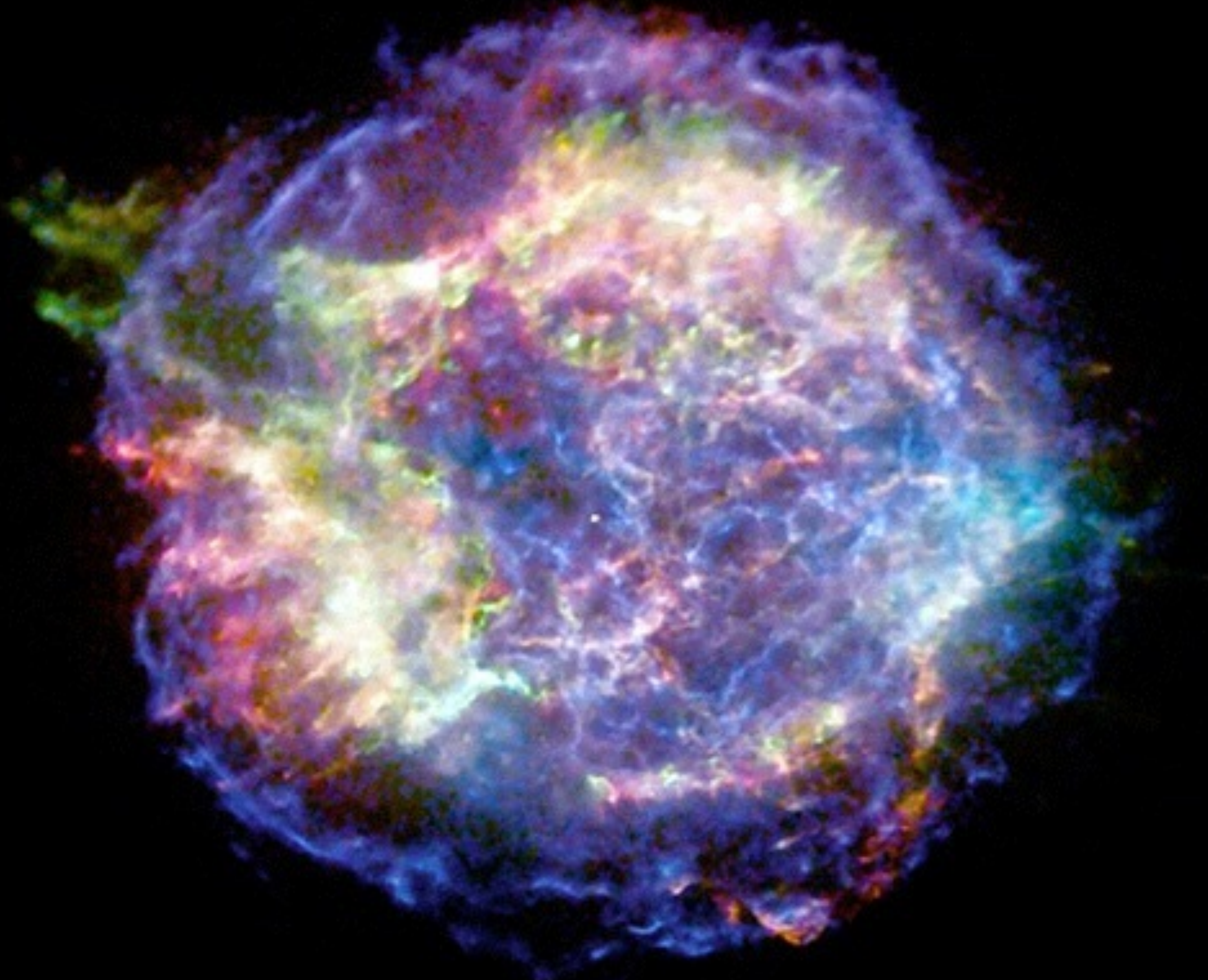
chance? fundamental?



He, C, O, ... Si burning produces energy until Iron (Fe)



core collapse supernova, shock-wave-aided ejection of mantel

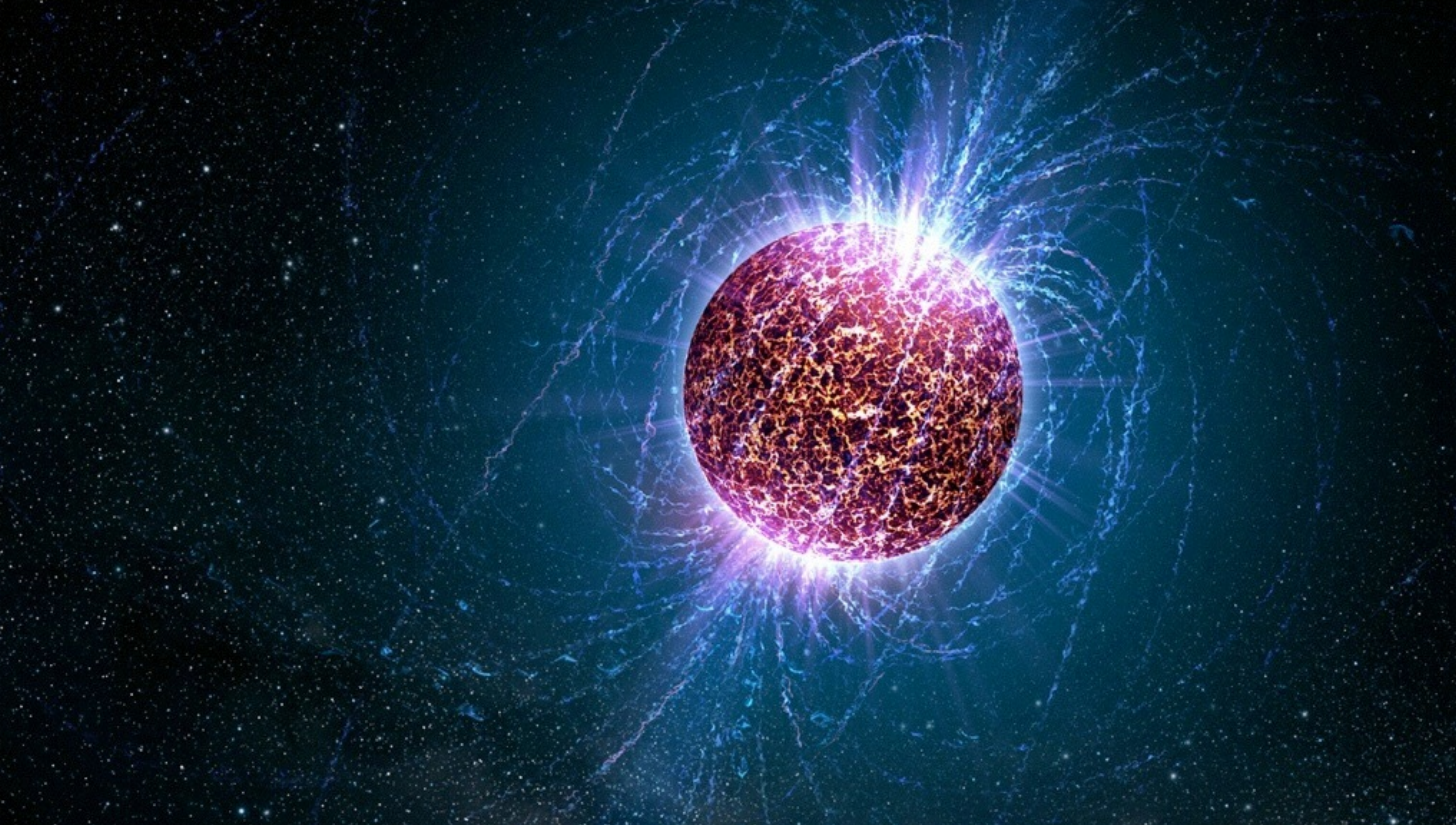


Supernova

"We are all made of star stuff"

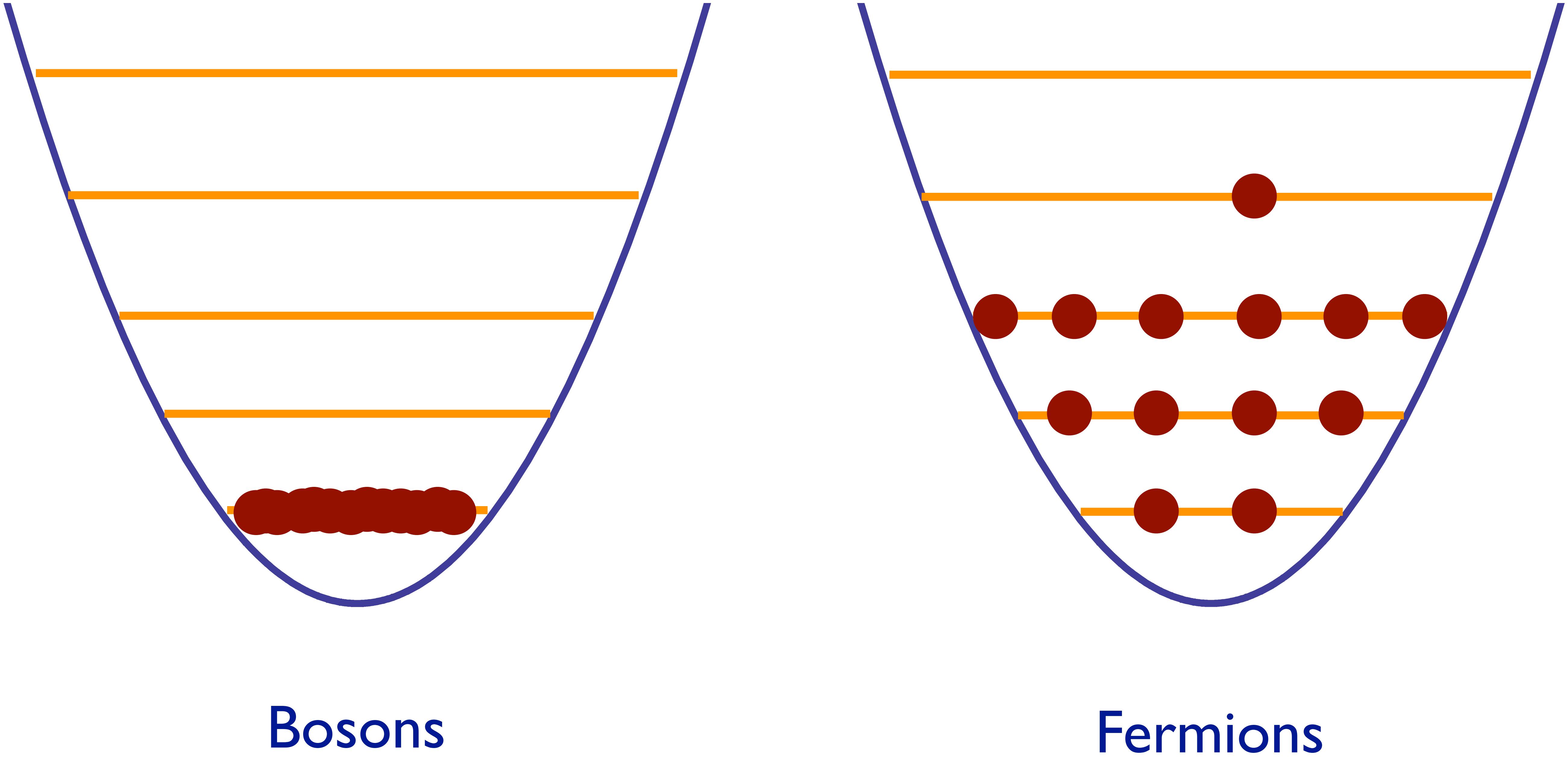
much coming from the ejecta of supernova

Neutron Star

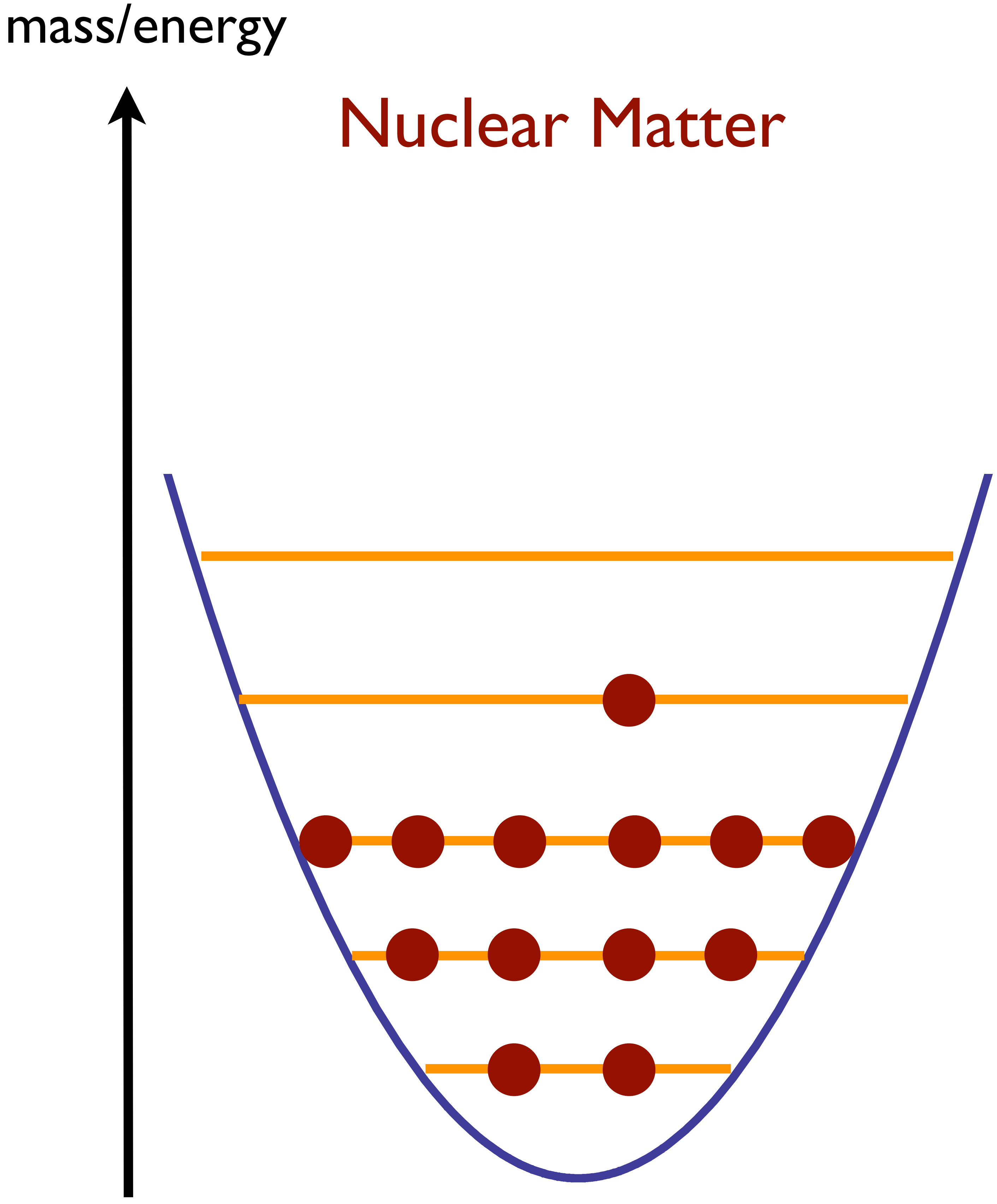


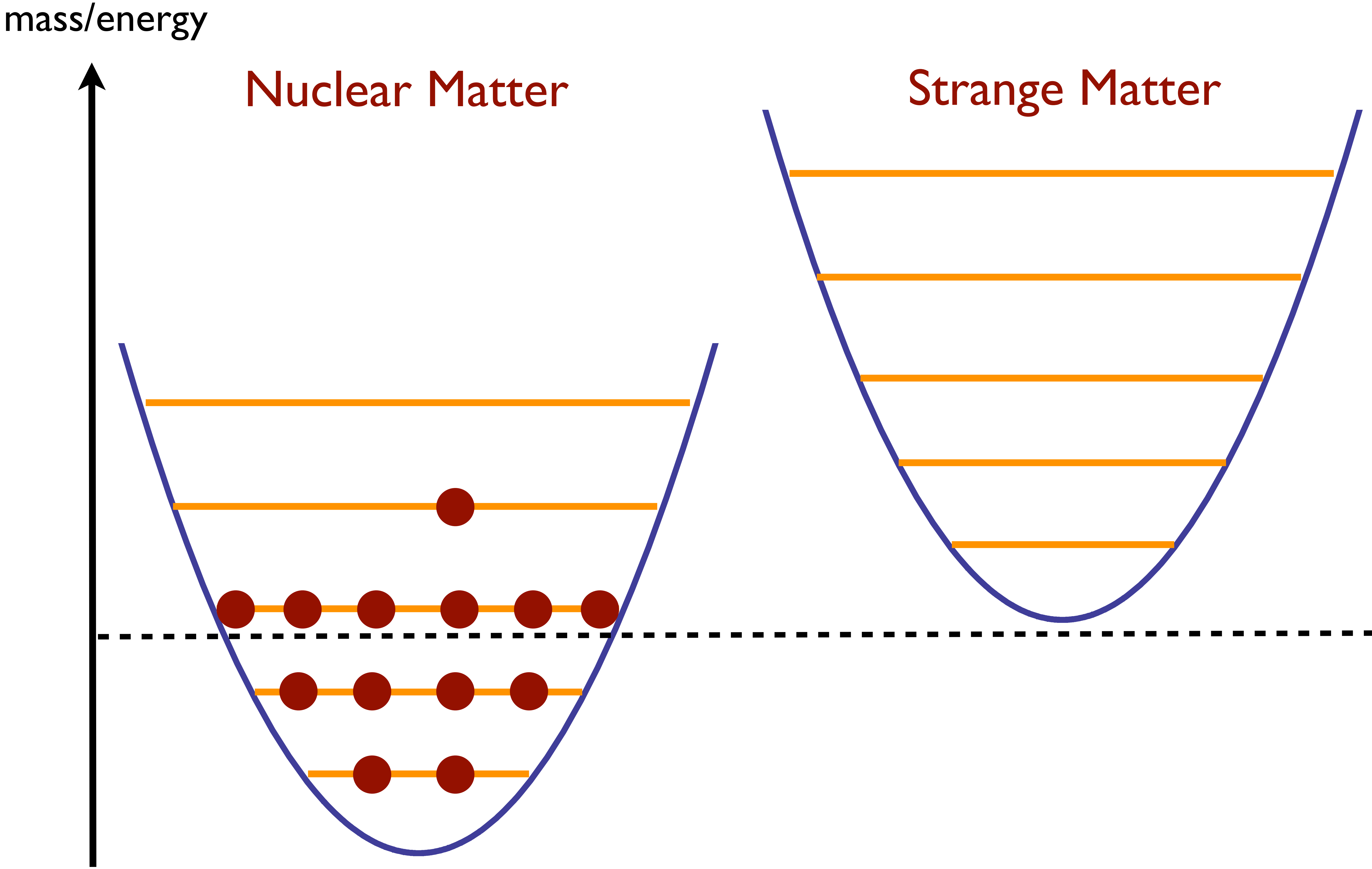
both supernova and neutron stars they leave behind depend on properties of very dense nuclear matter - a QCD problem

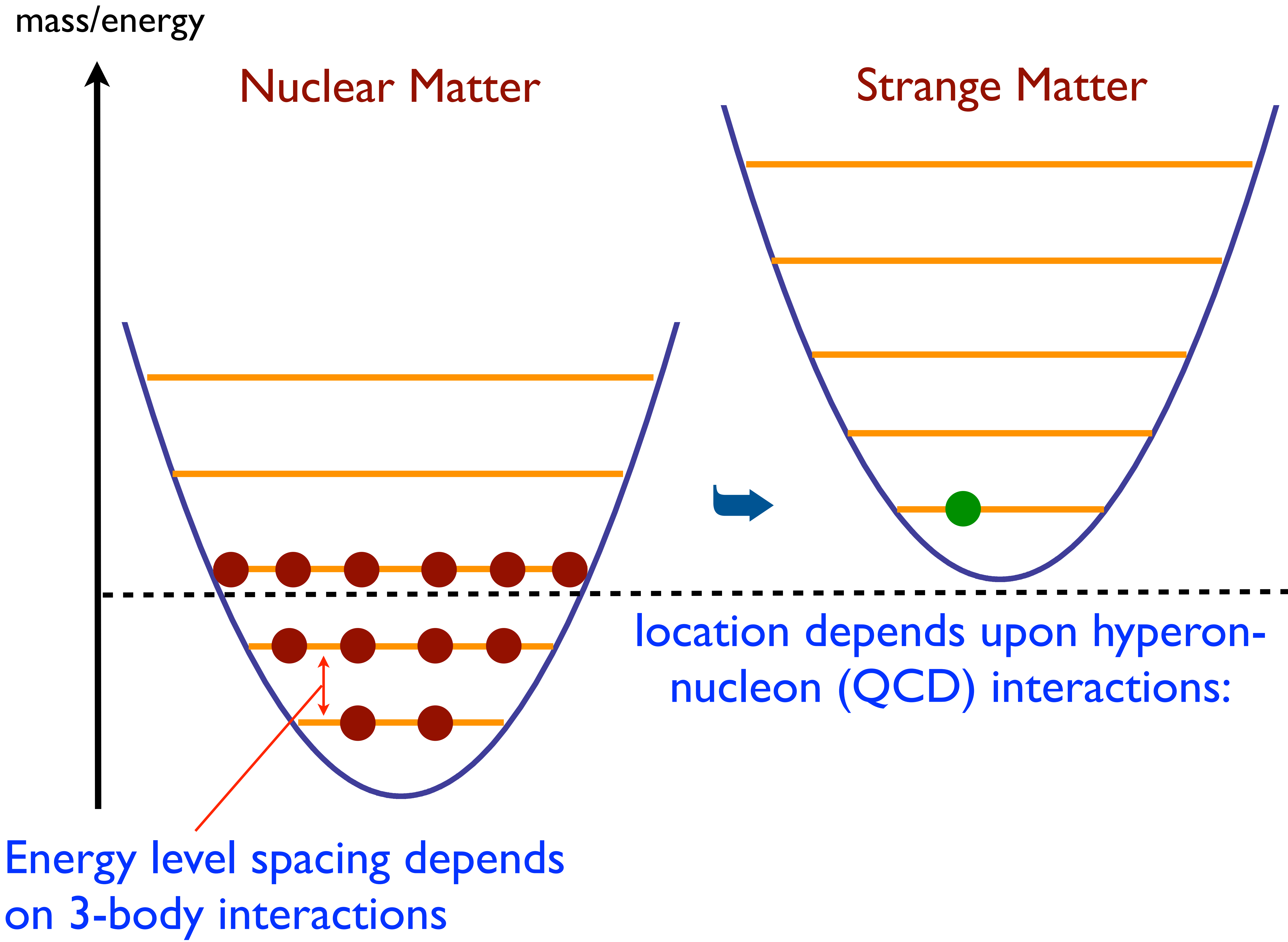
Pauli Exclusion Principle



Nuclear Matter



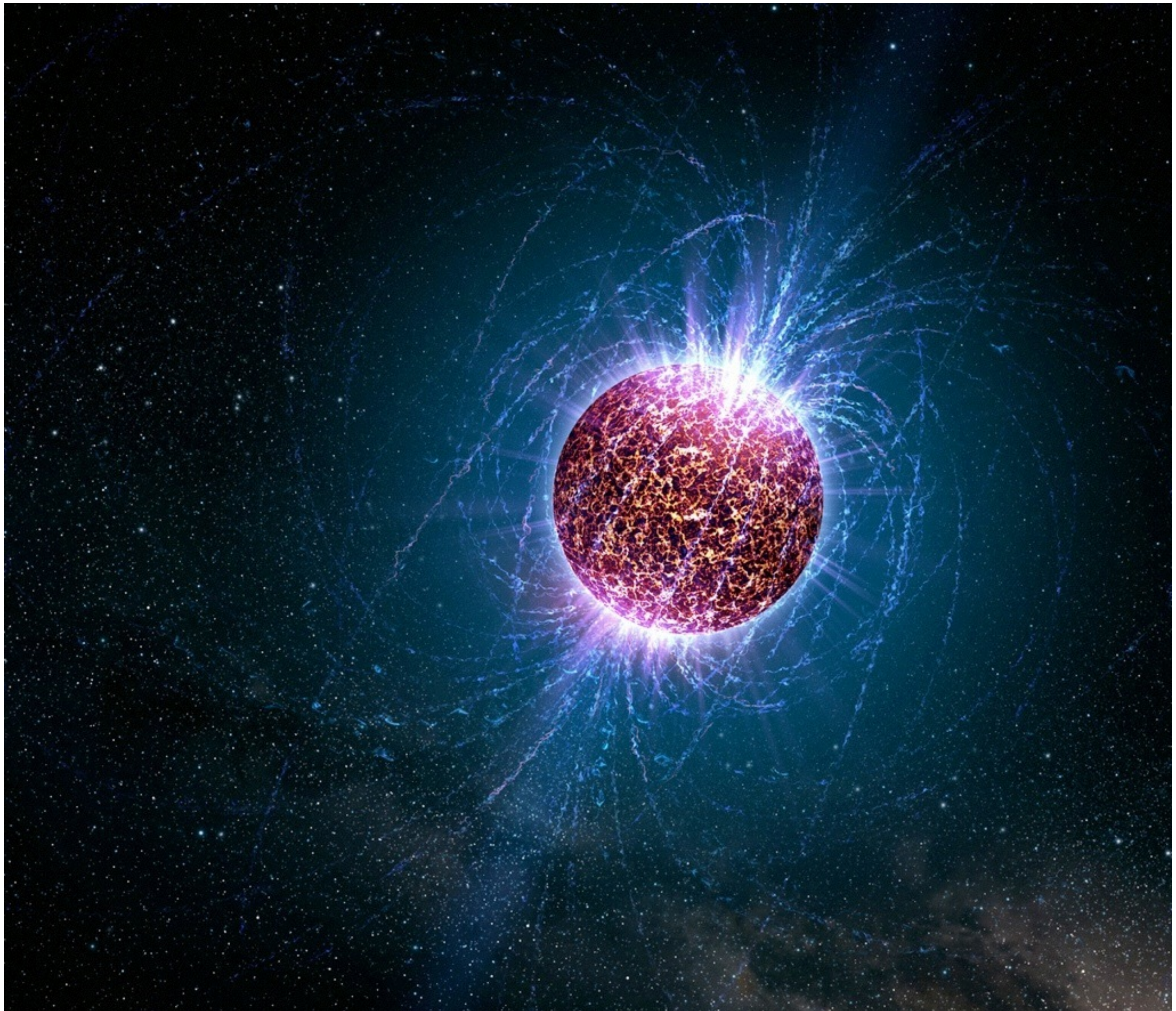

mass/energy
Nuclear Matter
Strange Matter

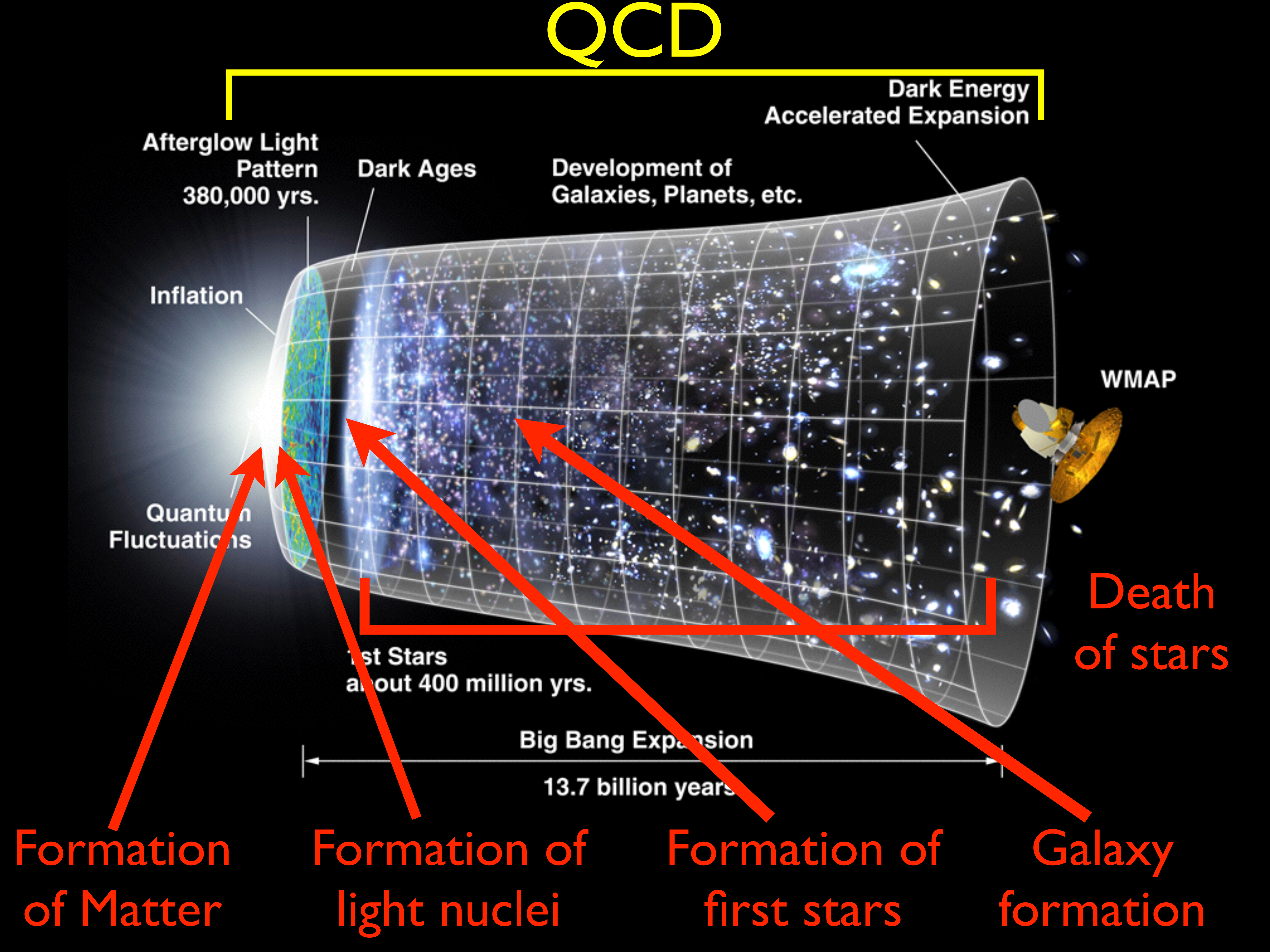

mass/energy
Nuclear Matter
Strange Matter
location depends upon hyperon-nucleon (QCD) interactions:
Energy level spacing depends on 3-body interactions

Recent measurement of a 2 solar mass neutron star

Demorest et al. Nature 467 1081 (2010)

has re-invigorated interest in hyper-nuclear matter at high densities





QCD
Dark Energy Accelerated Expansion
Afterglow Light Pattern 380,000 yrs.
Dark Ages
Development of Galaxies, Planets, etc.
Inflation
WMAP
Quantu n Fluctuatio ns
st Stars a out 400 million yrs.
Big Bang Exp nsion
13.7 billion years
Death of stars
Formation of Matter
Formation of light nuclei
Formation of first stars
Galaxy formation

Conclusions

- Understanding nuclear physics from the fundamental theory of strong interactions, QCD, is exciting and important for these and other reasons:
  - Quantitative connection between QCD and the rich nuclear phenomenology
  - Understanding precision low-energy nuclear physics to constrain the SM and searches for BSM physics
- The growth of computing power and algorithms means that TODAY is the beginning of a renaissance in nuclear physics where these exciting things are just becoming possible!

Thank You