

Marco Drewes, Université catholique de Louvain

PRIMORDIAL ANTIMATTER AS A PROBE OF COSMOLOGY AND FUNDAMENTAL PHYSICS

18.10.2019

**Light Anti-Nuclei as a Probe for
New Physics**

Leiden, The Netherlands

Canetti / MaD / Shaposhnikov 1204.4186

Bilnnikov / Dolgov / Postnov 1409.5736

Potential sources of antinuclei

Antimatter in the present universe

Antimatter in the early universe

Standard baryogenesis scenarios

Non-standard baryogenesis and anti-stars

Potential sources of antinuclei

Antimatter in the present universe

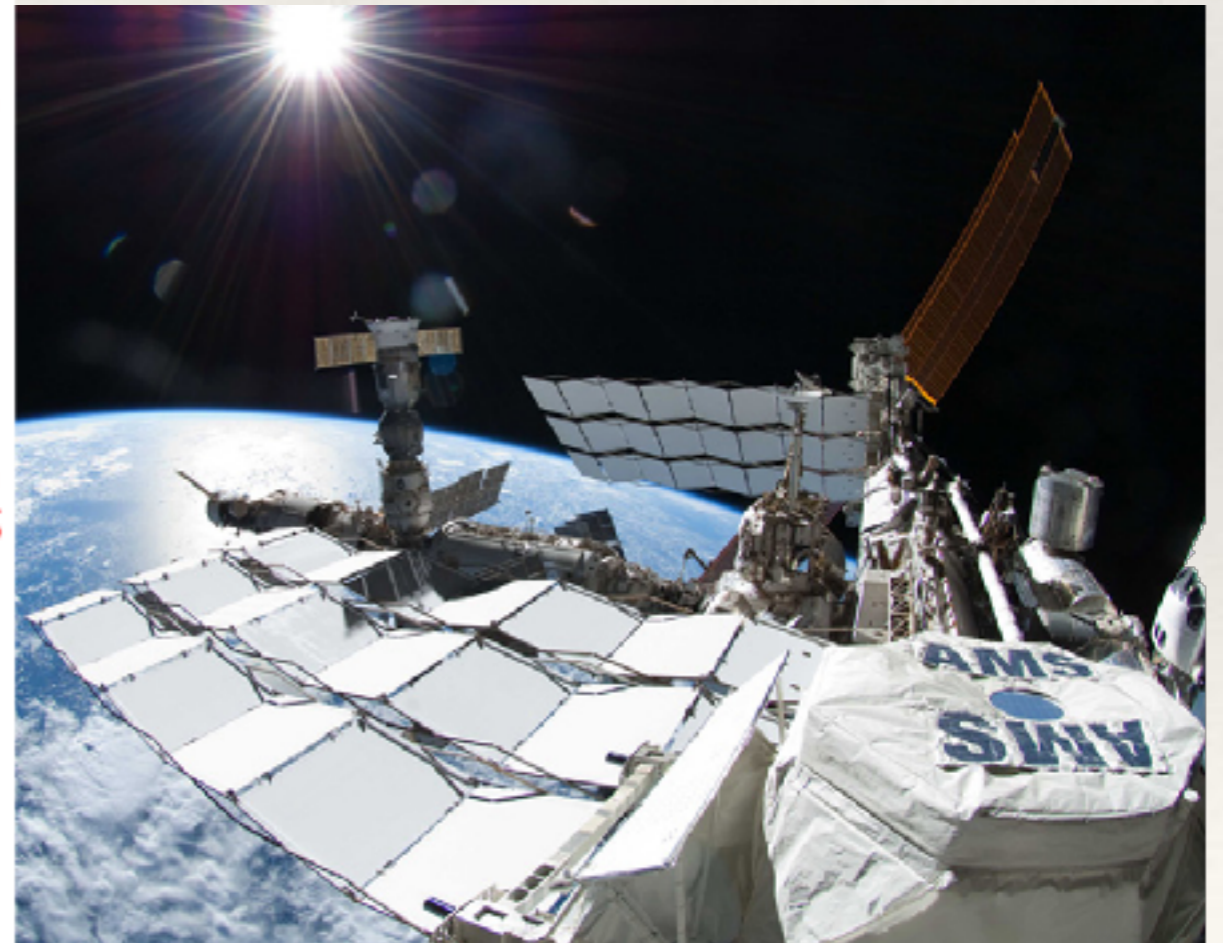
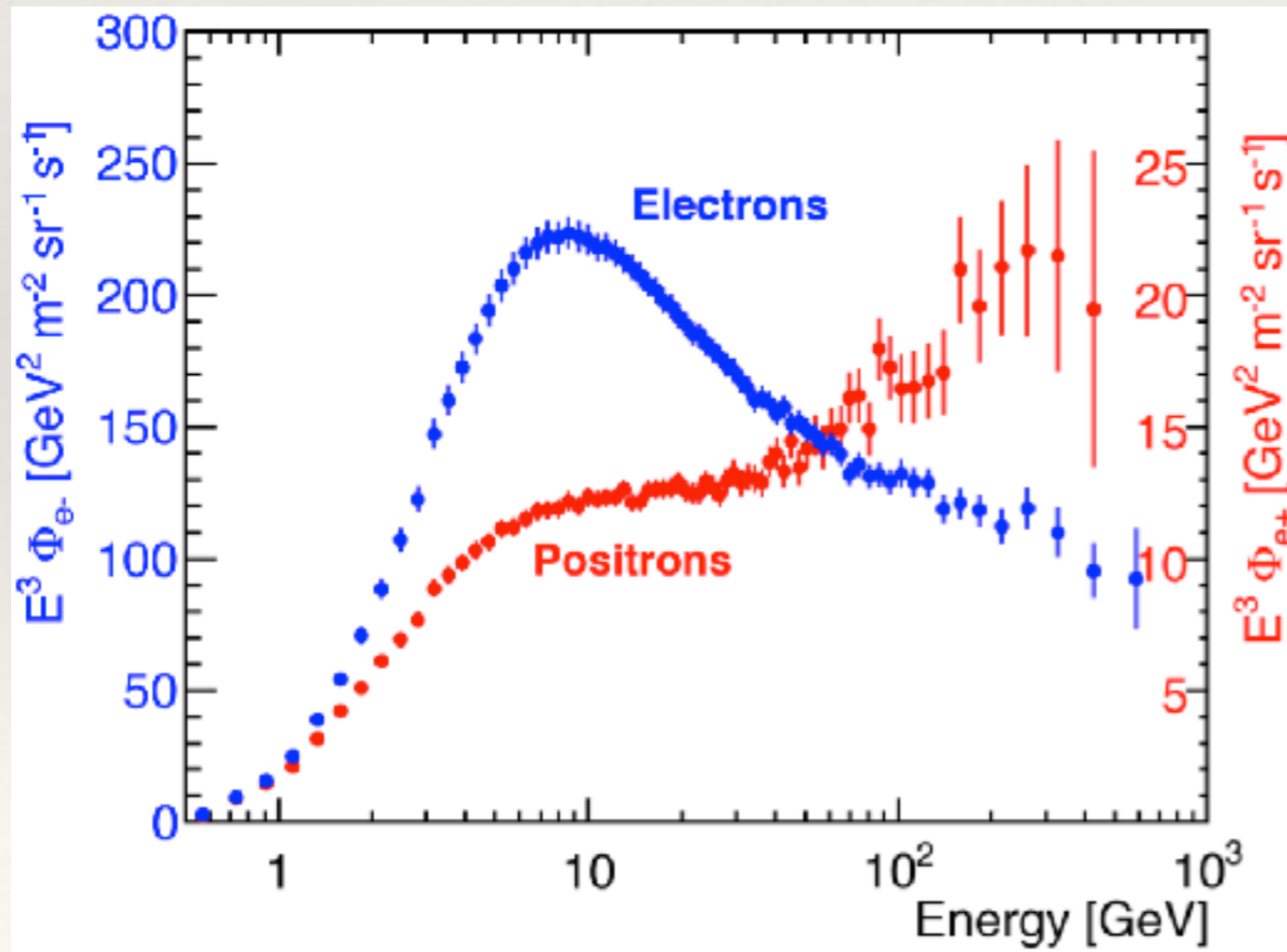
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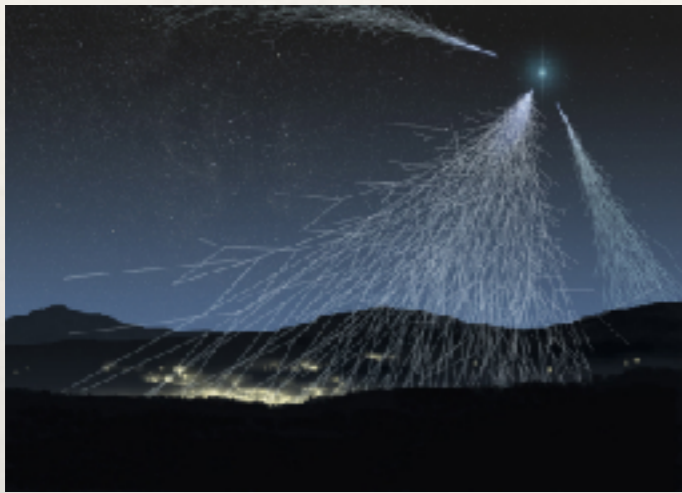
Antimatter in the Universe

- ❖ Is there any antimatter in the present universe? **Yes. But little.**

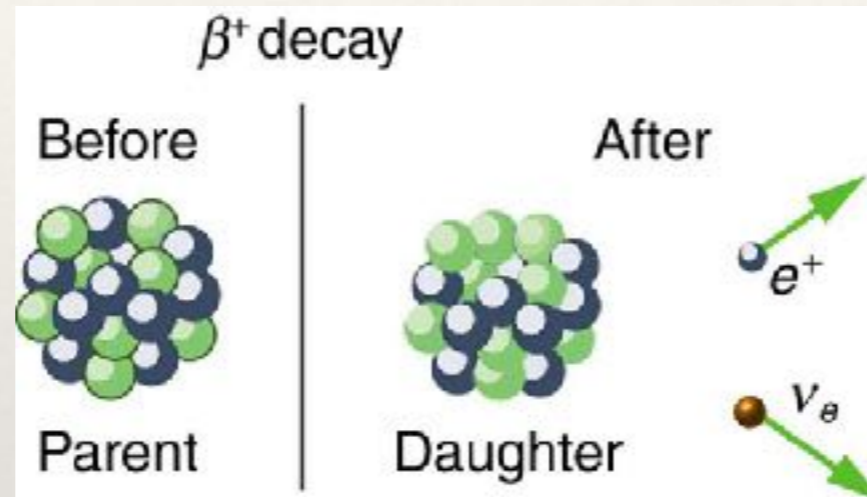


Sources of Antimatter

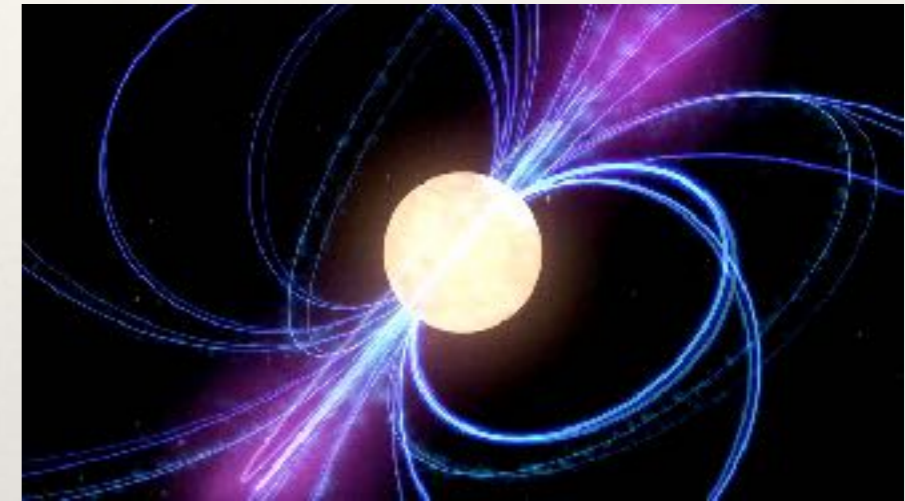
Cosmic rays



Natural radioactivity



Pulsars and black holes



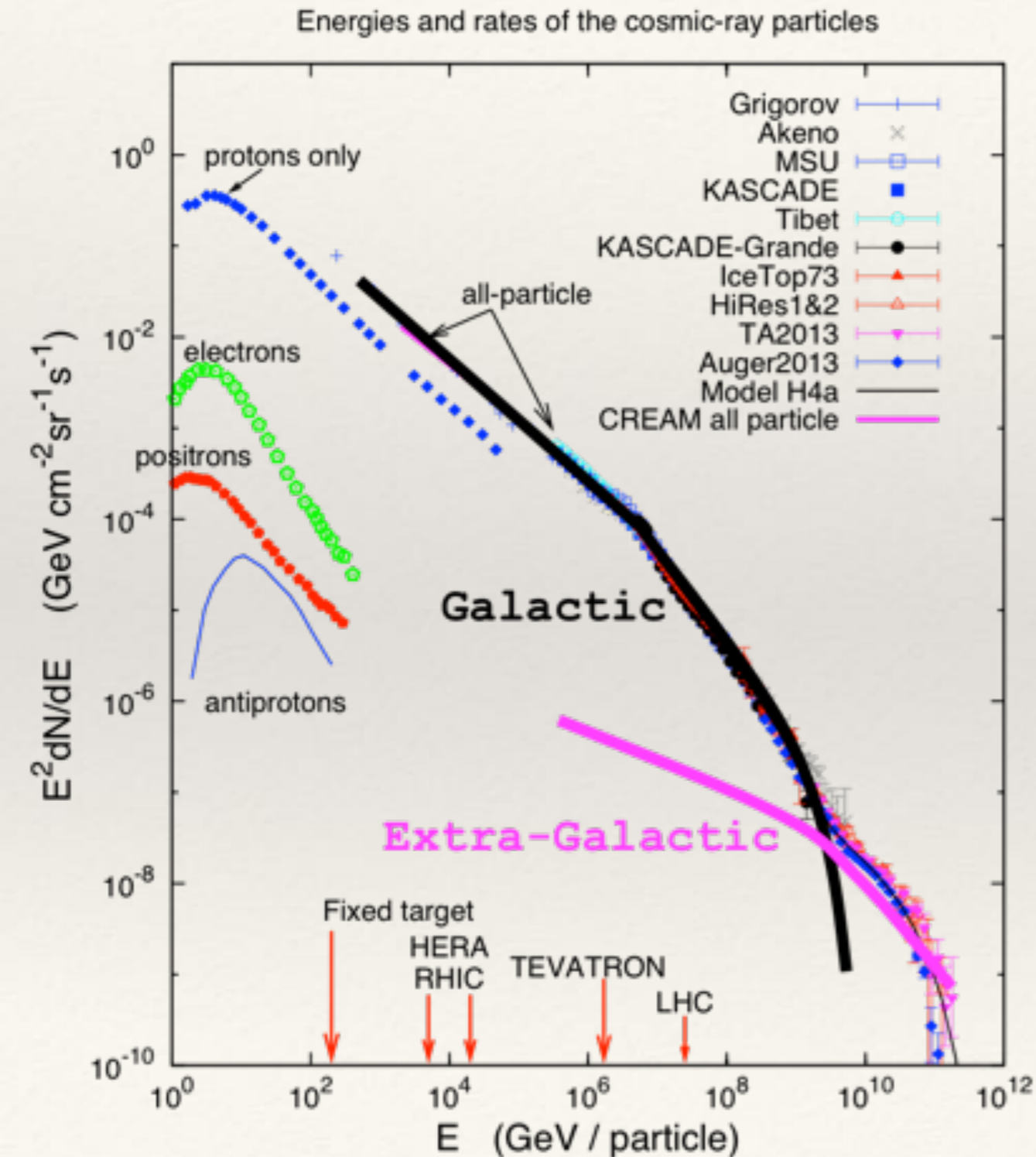
Particle accelerators



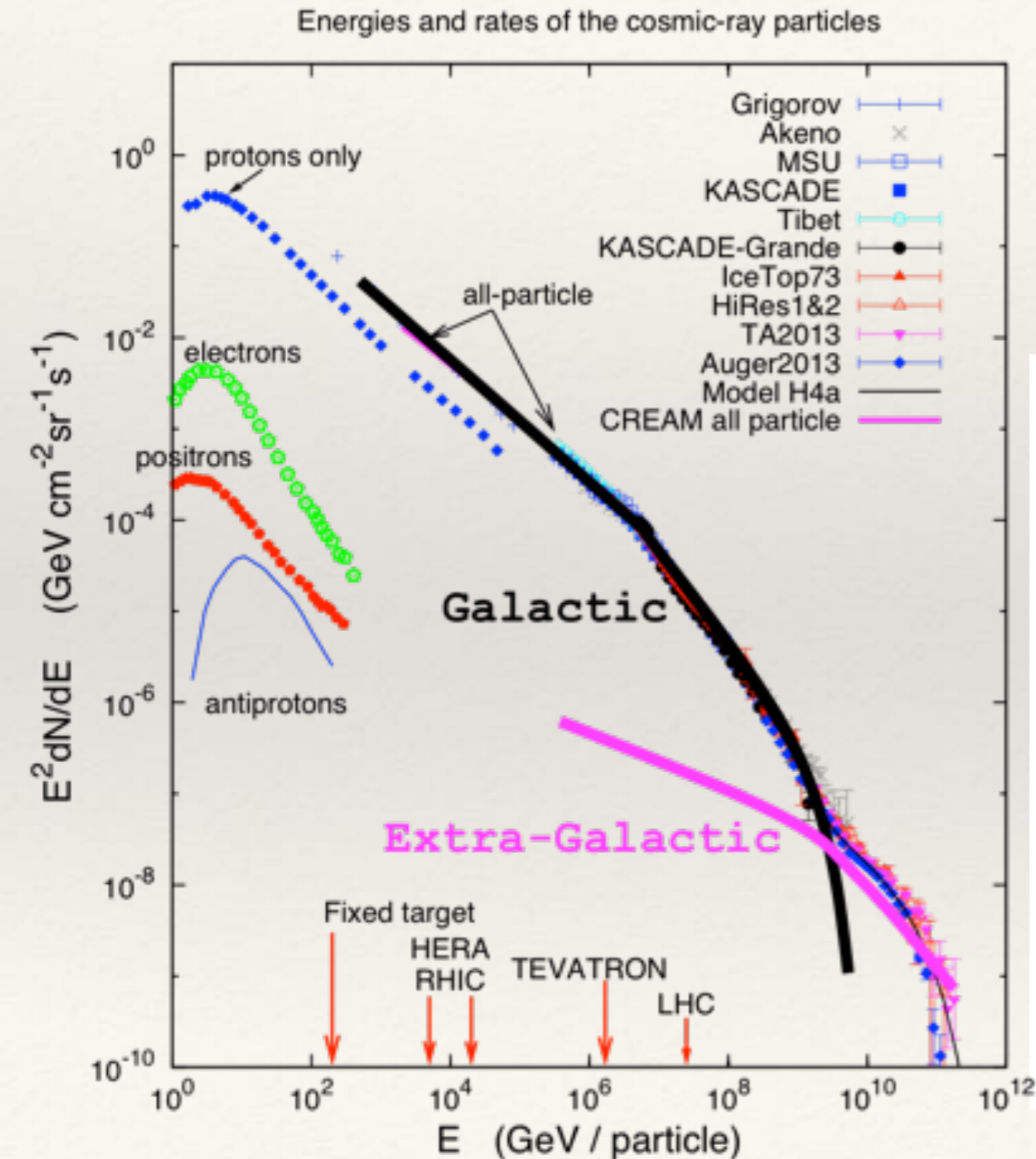
Nuclear medicine



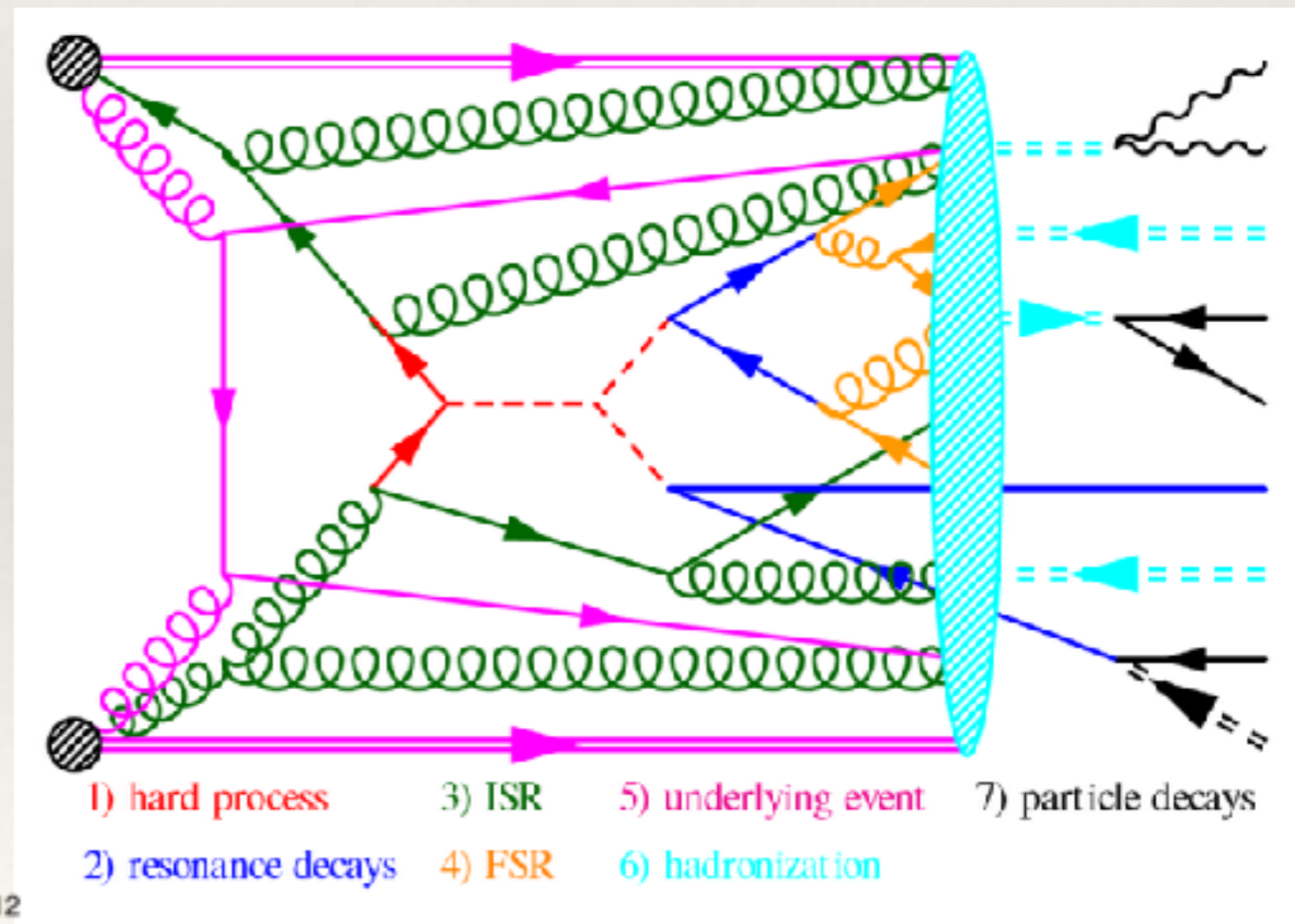
Can Cosmic Rays make an Anti-Nucleus?



Can Cosmic Rays make an Anti-Nucleus?



Extended bound states are extremely unlikely to form

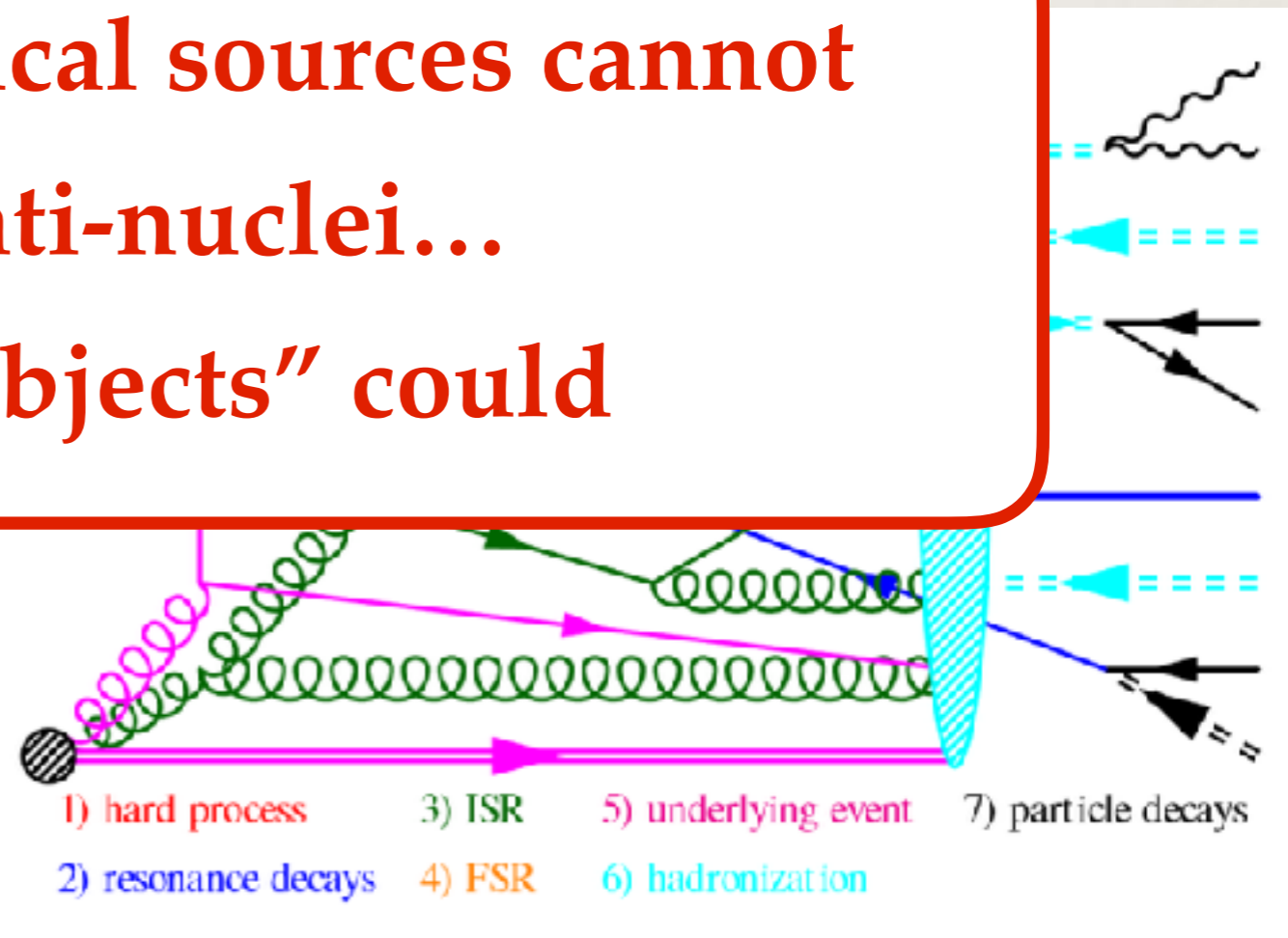
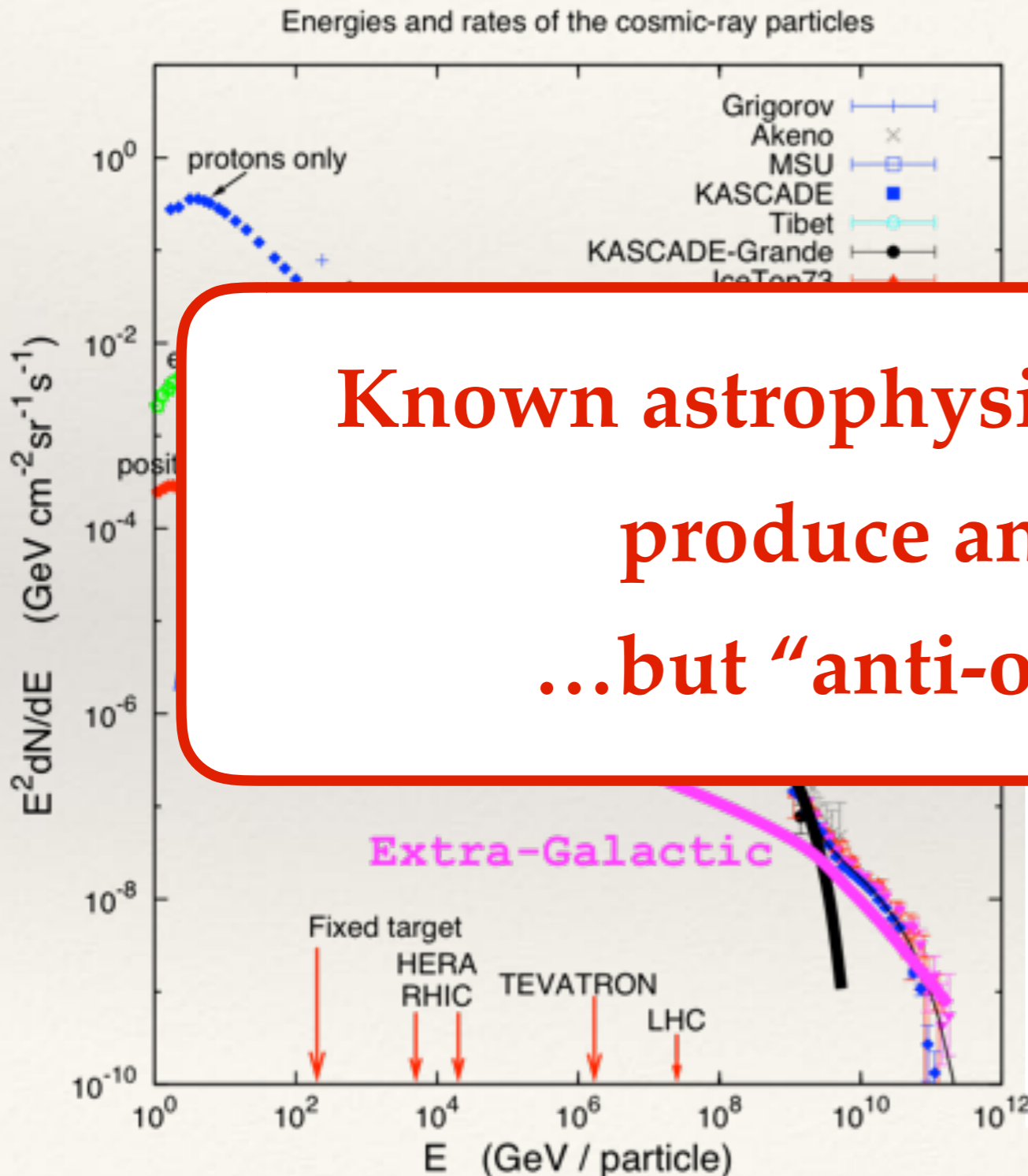


picture Christophe Royon

Can Cosmic Rays make an Anti-Nucleus?

Extended bound states are extremely unlikely to form

Known astrophysical sources cannot produce anti-nuclei...
...but “anti-objects” could



Potential sources of antinuclei

Antimatter in the present universe

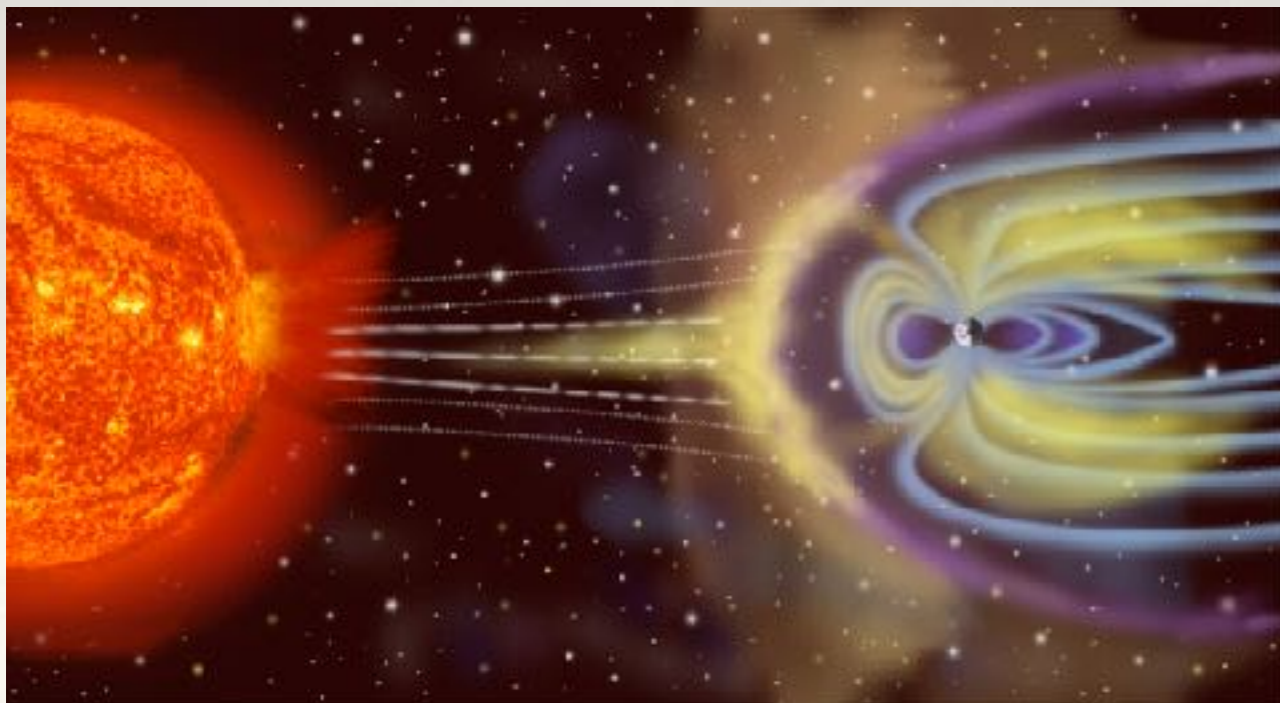
Antimatter in the early universe

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Antimatter in the Solar System

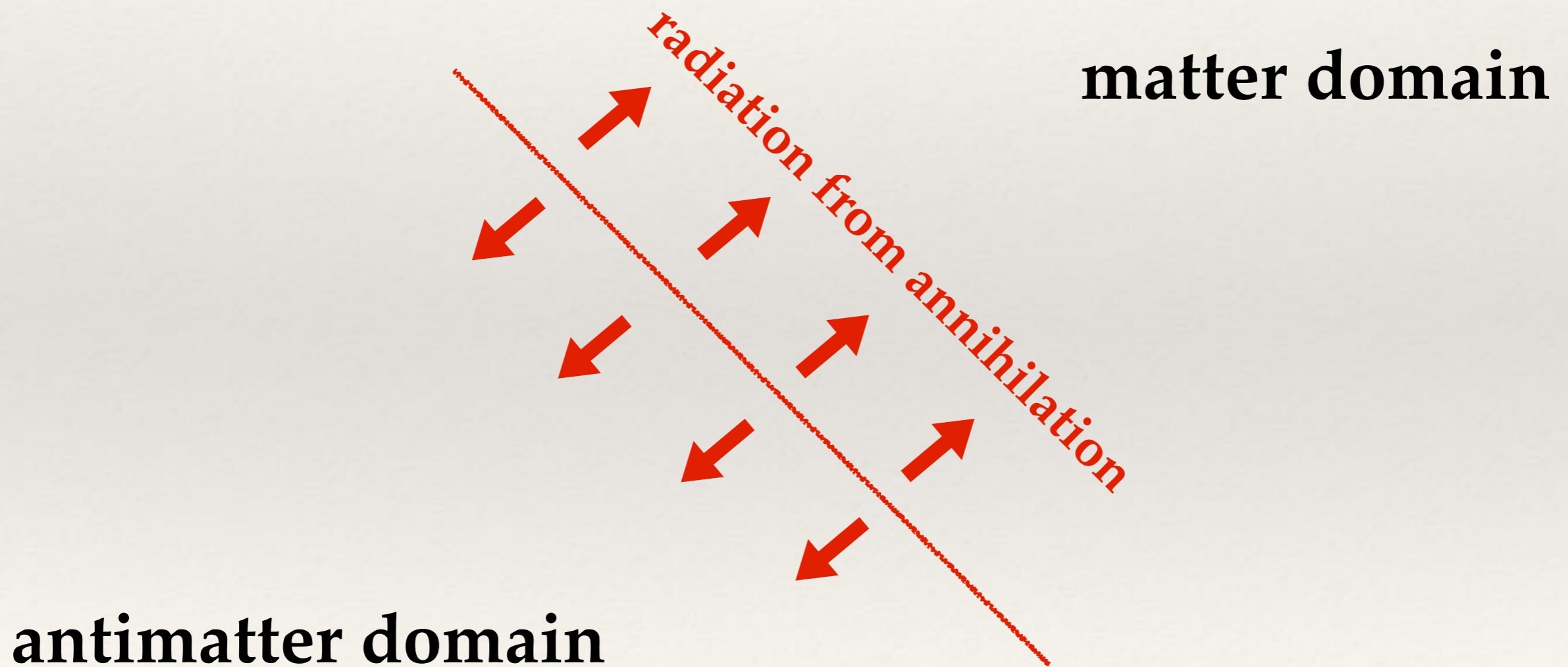
Several celestial bodies have been visited by spacecraft. They are not made of antimatter.



Solar winds would lead to strong annihilation signals when hitting antimatter.

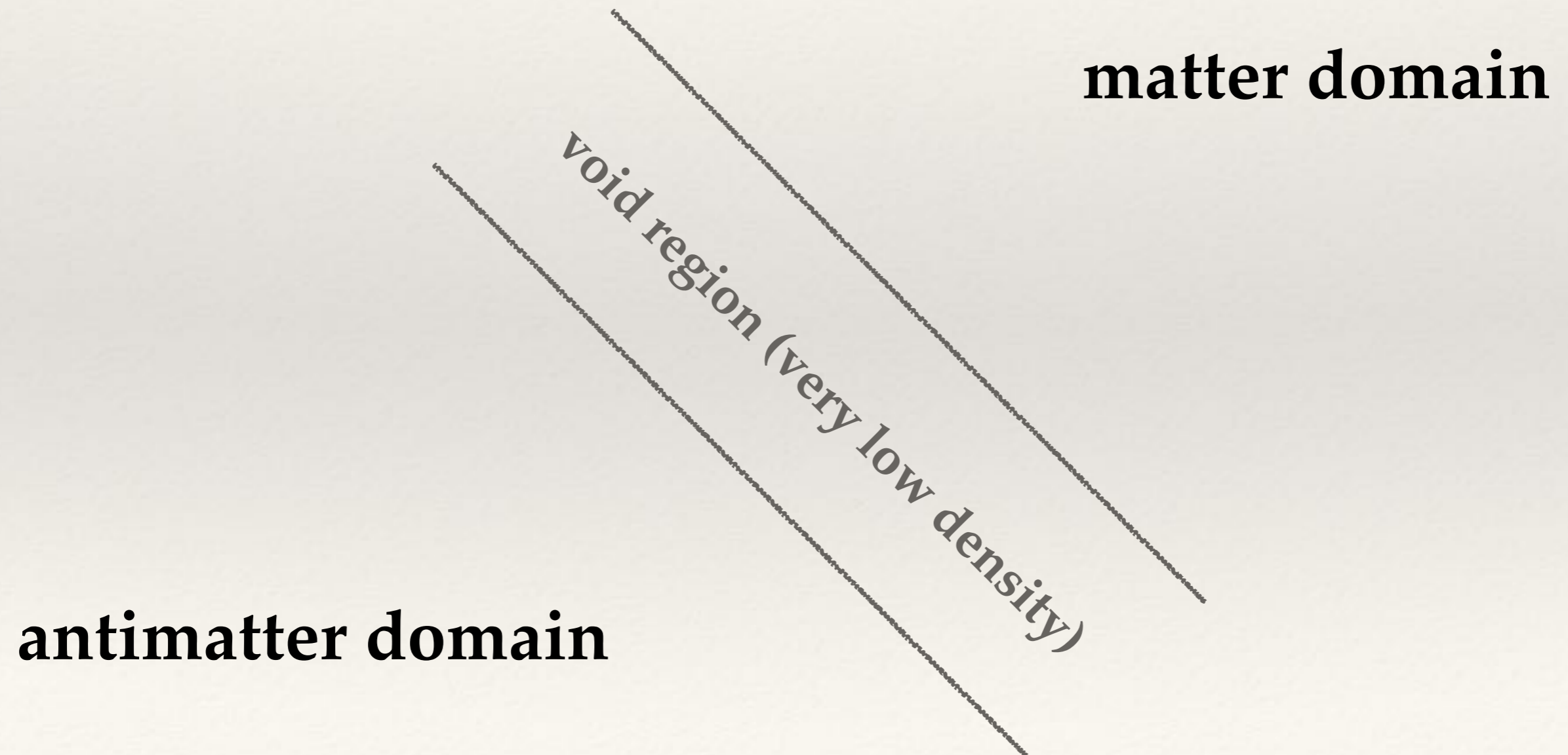
Extragalactic Antimatter

Are there antimatter galaxies?



Extragalactic Antimatter

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Extragalactic Antimatter

Are there antimatter galaxies?

**Direct astronomical observation excludes
“anti - objects” in our local environment**

antimatter domain

Potential sources of antinuclei

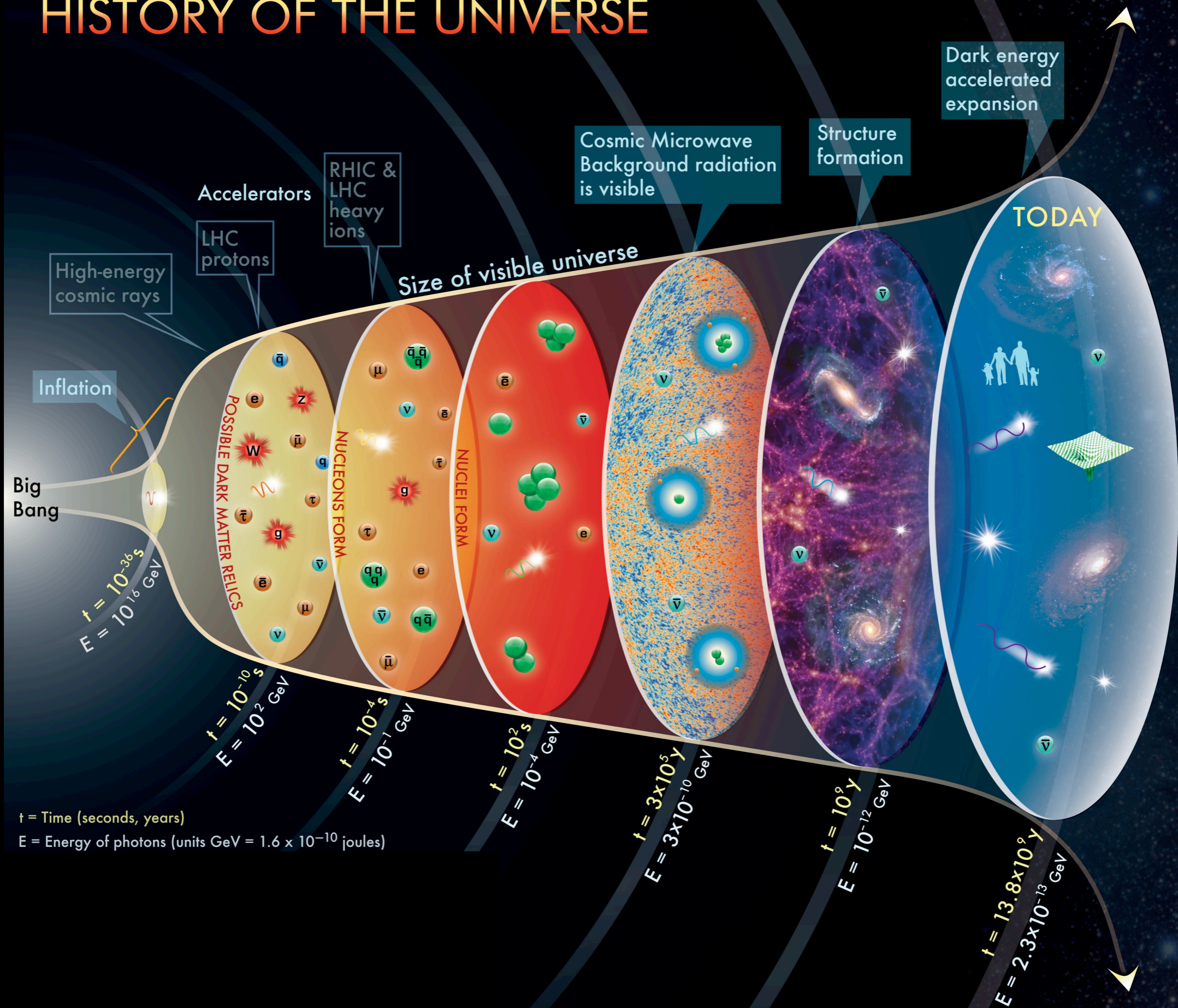
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HISTORY OF THE UNIVERSE



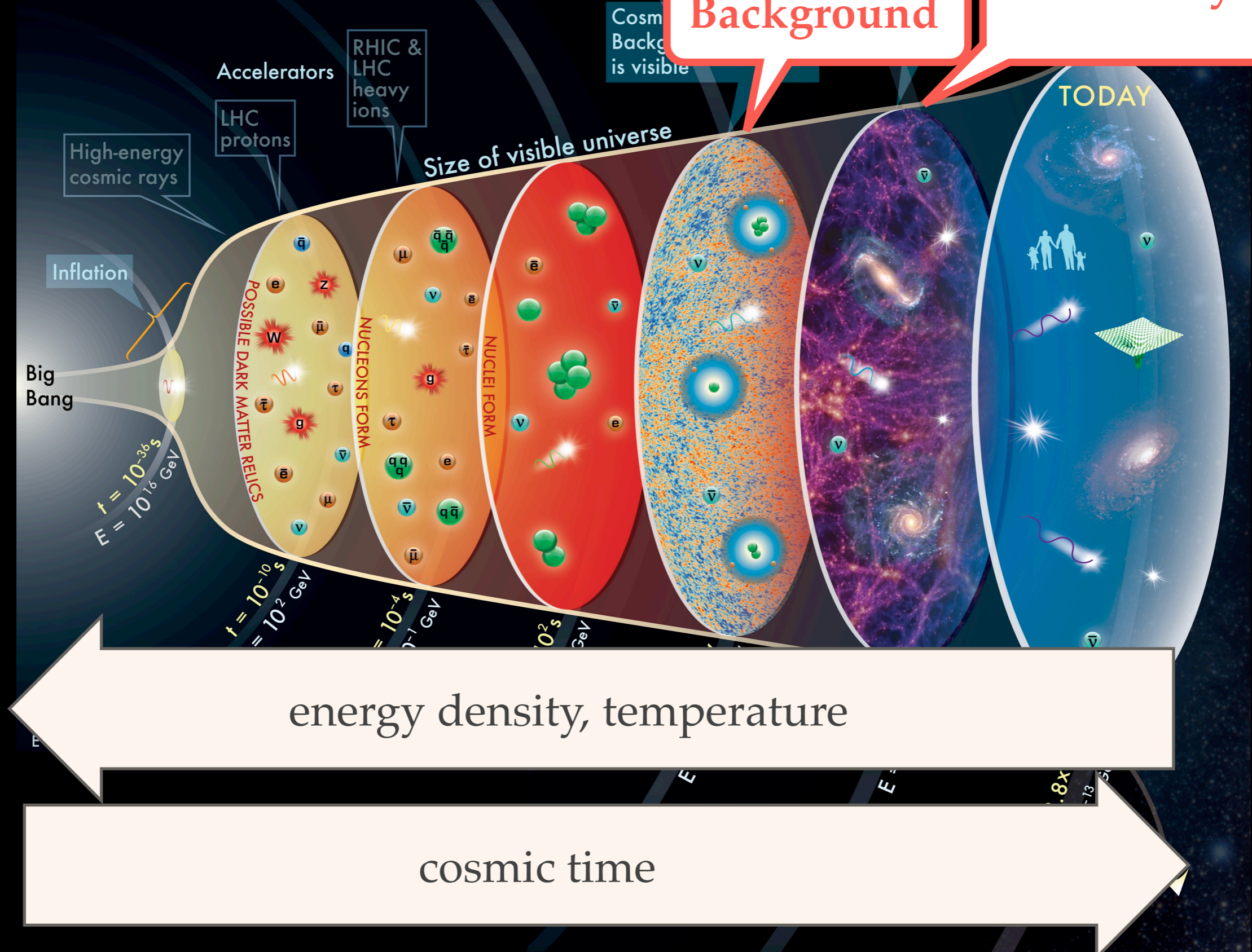
t = Time (seconds, years)

E = Energy of photons (units $\text{GeV} = 1.6 \times 10^{-10}$ joules)

HISTORY OF THE UNIVERSE

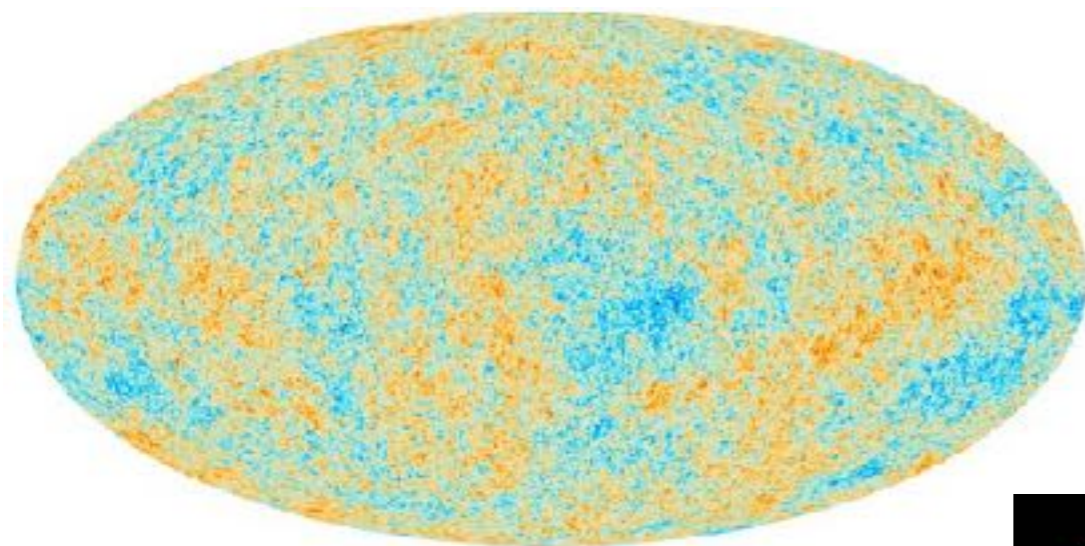
Cosmic
Microwave
Background

optical
astronomy



Extragalactic Antimatter

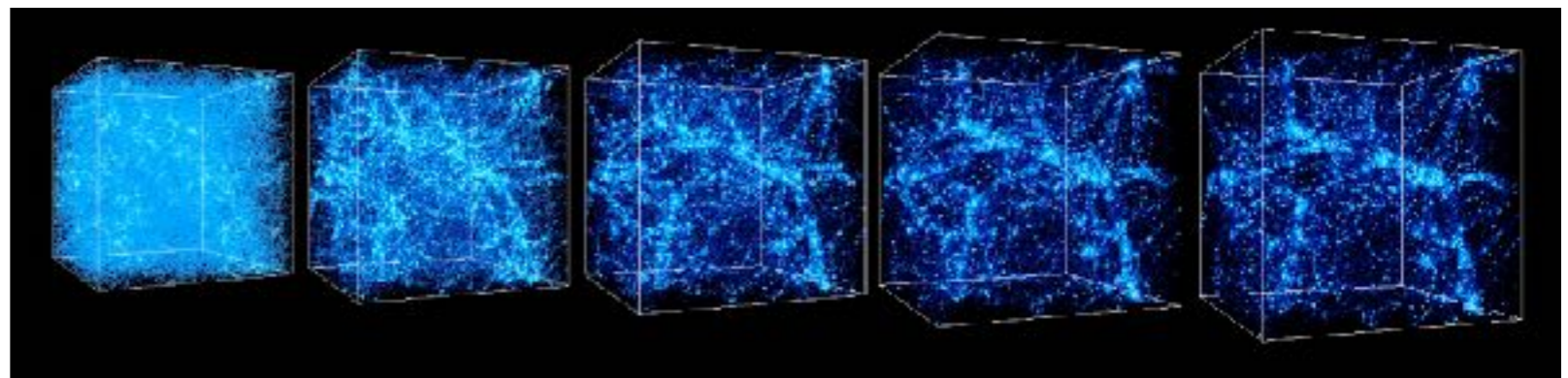
Are there antimatter galaxies?



The early universe was very homogeneous and isotropic...

...so matter and antimatter regions must have been in

touch Cohen/Di Rujula/Gashow 98



With observed CMB anisotropies: Observable universe contains no significant amounts of antimatter.

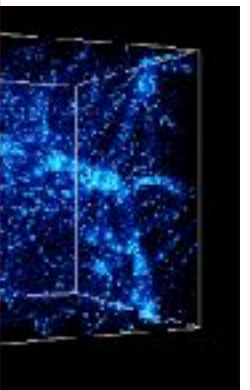
Extragalactic Antimatter

Are there antimatter galaxies?

**CMB and diffuse γ background
observations rule out the existence of
sizeable antimatter regions in the
observable universe**

**(cf also talk by Vivian Poulin
for updated numbers)**

**With
contains no significant amounts of antimatter.**



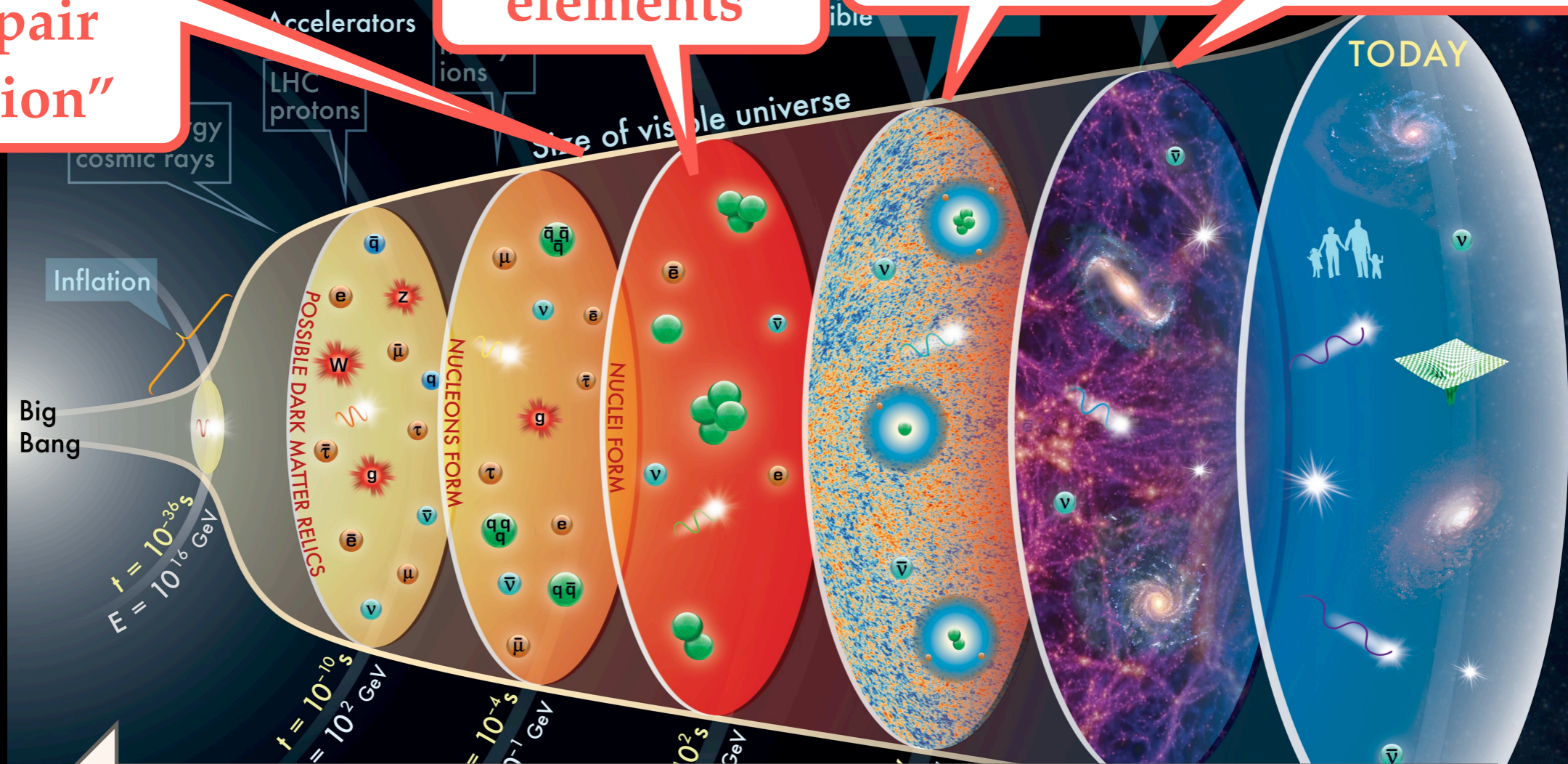
COSMOLOGY OF

Hot enough
to produce
antimatter
in “pair
creation”

nuclear
reactions
form light
elements

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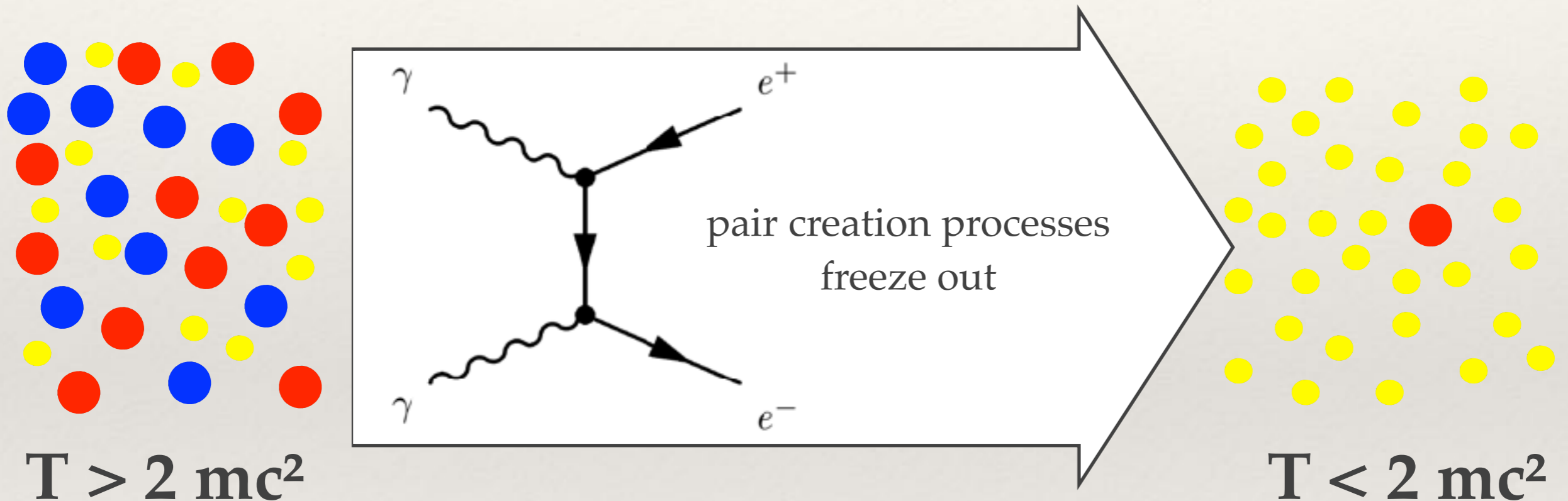


energy density, temperature

cosmic time

Baryon Asymmetry of the Universe

Antimatter was abundant in the early universe, when the temperature was high enough for pair creation



CMB constraint on
baryon-to-photon ratio η :
 $6.03 \times 10^{-10} < \eta < 6.15 \times 10^{-10}$
(Planck Collaboration)

BBN constraint on baryon-to-
photon ratio η :
 $5.8 \times 10^{-10} < \eta < 6.6 \times 10^{-10}$
(PDG)

Baryon-to-Photon Ratio

- ❖ When the temperature was very high, **pair creation processes were in equilibrium.**
- ❖ When the temperature dropped below the positron mass, no new antiparticles could be produced, and **all antiparticles were annihilated.**
- ❖ Obviously, some matter survived - so **there was more matter than antimatter in the early universe!**
- ❖ This “baryon asymmetry of the universe” was very small, it corresponds to today’s “**baryon-to-photon ratio**”
 $\# \text{nucleons} / \# \text{photons} : \sim 1 / 10.000.000.000$

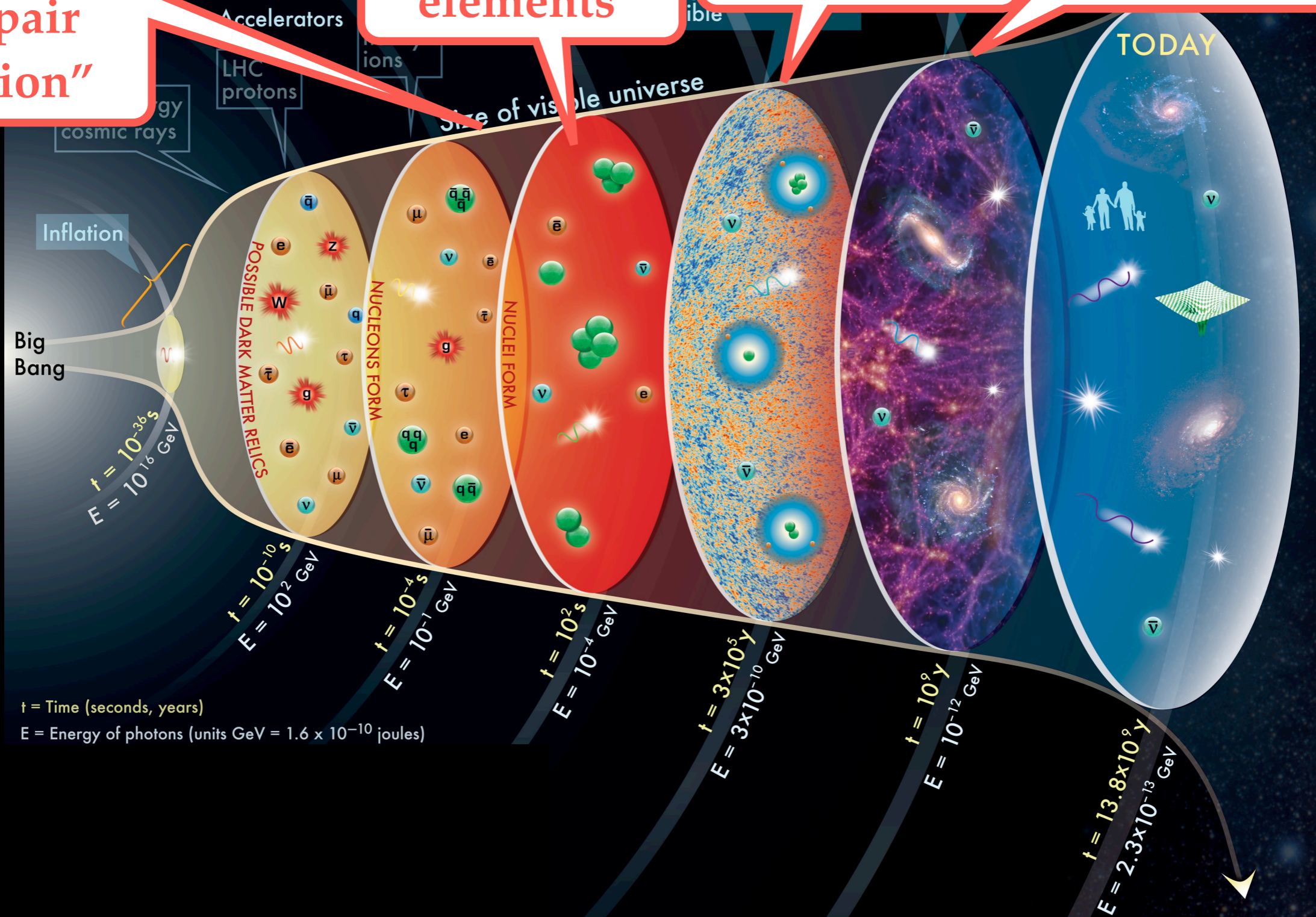
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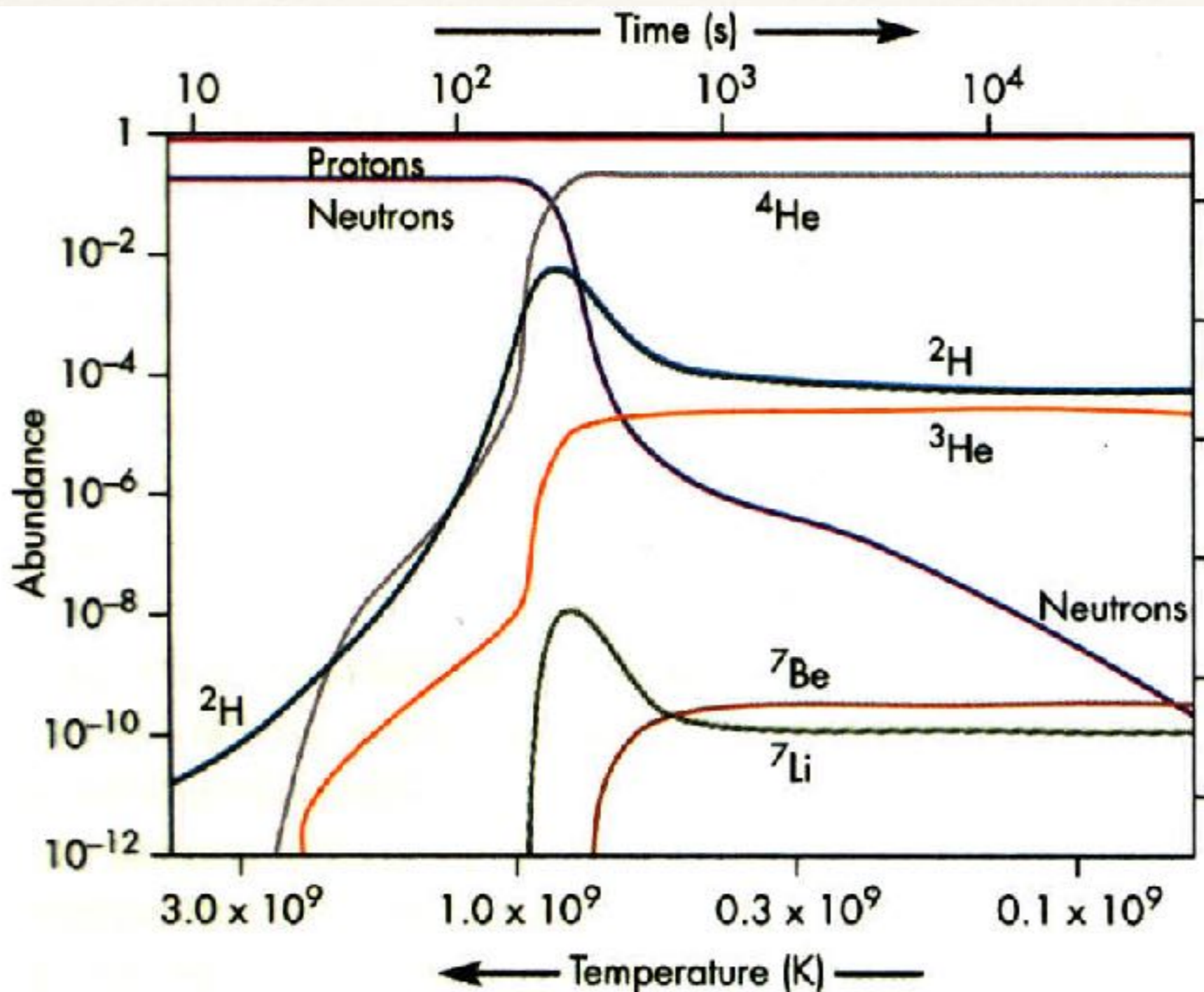
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Big Bang Nucleosynthesis

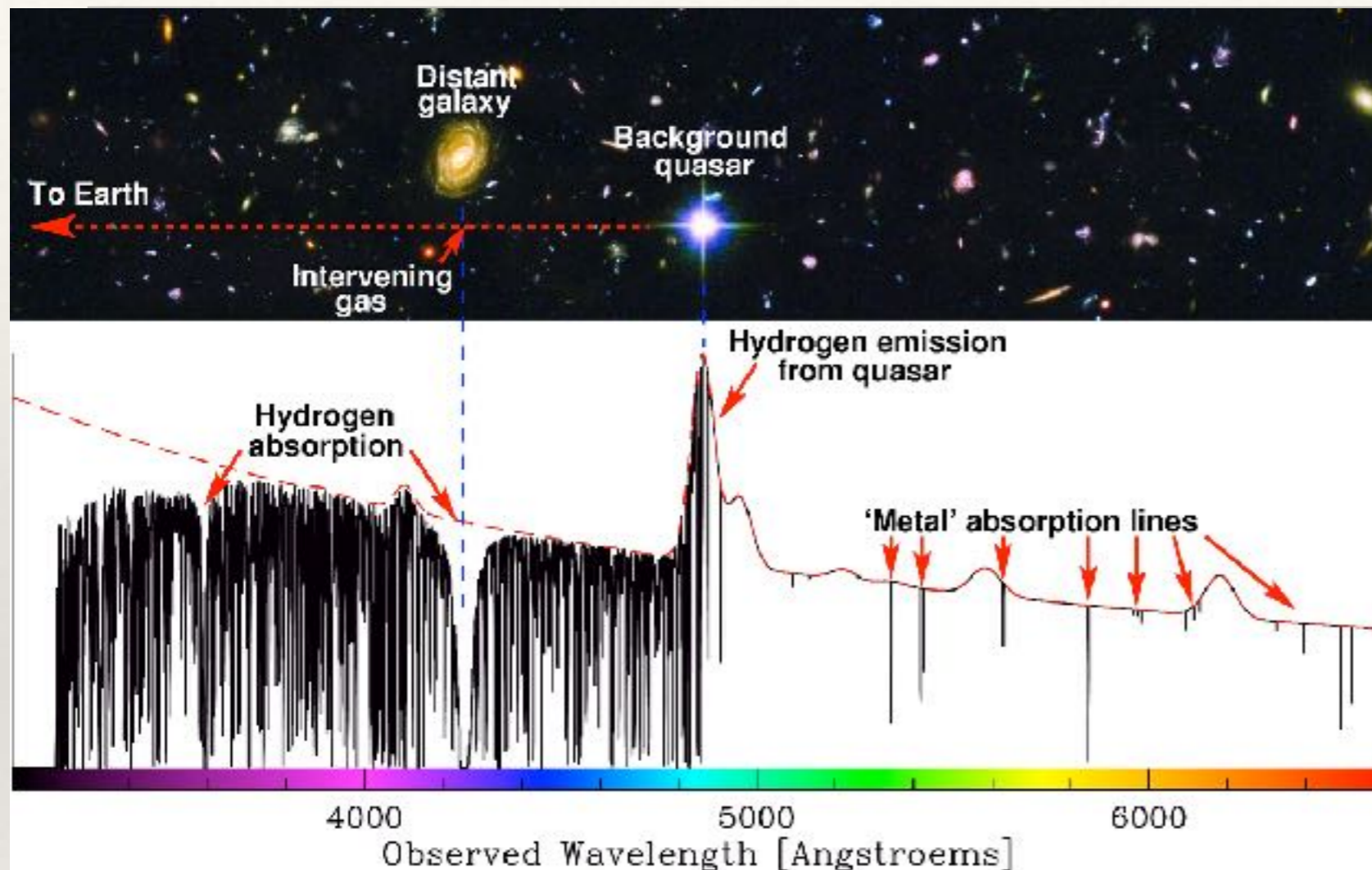


Light elements are produced in a chain of nuclear reactions.

The only unknown parameter is the baryon-to-photon ratio

Primordial light element abundances measure the baryon asymmetry!

Big Bang Nucleosynthesis

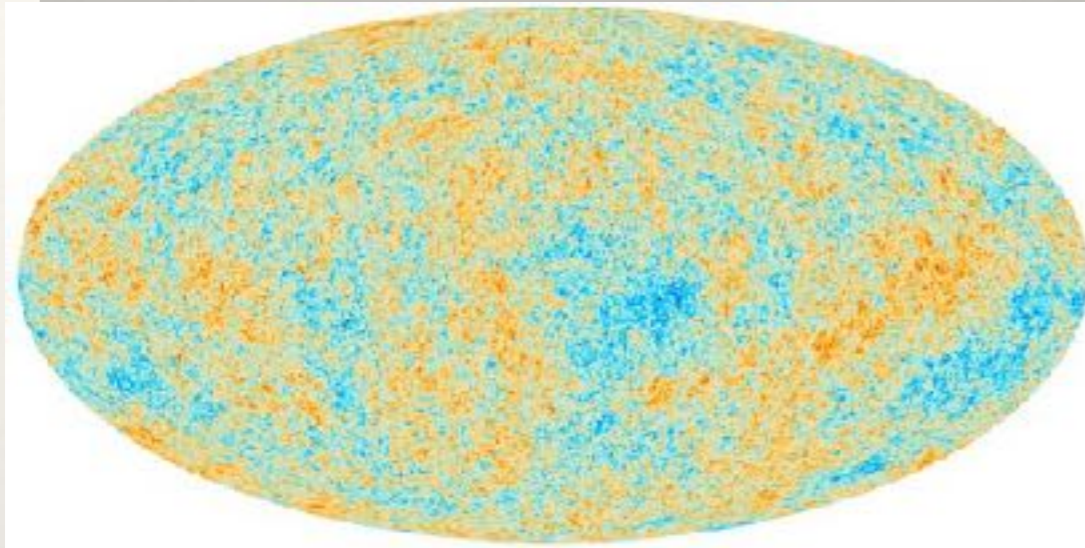


- ❖ light element abundances in intergalactic medium can be measured in quasar spectra
- ❖ Deuterium is sensitive to baryon asymmetry and not produced in stars

Constraint on baryon-to-photon ratio η :

$$5.8 \times 10^{-10} < \eta < 6.6 \times 10^{-10} \quad \text{PDG 2016}$$

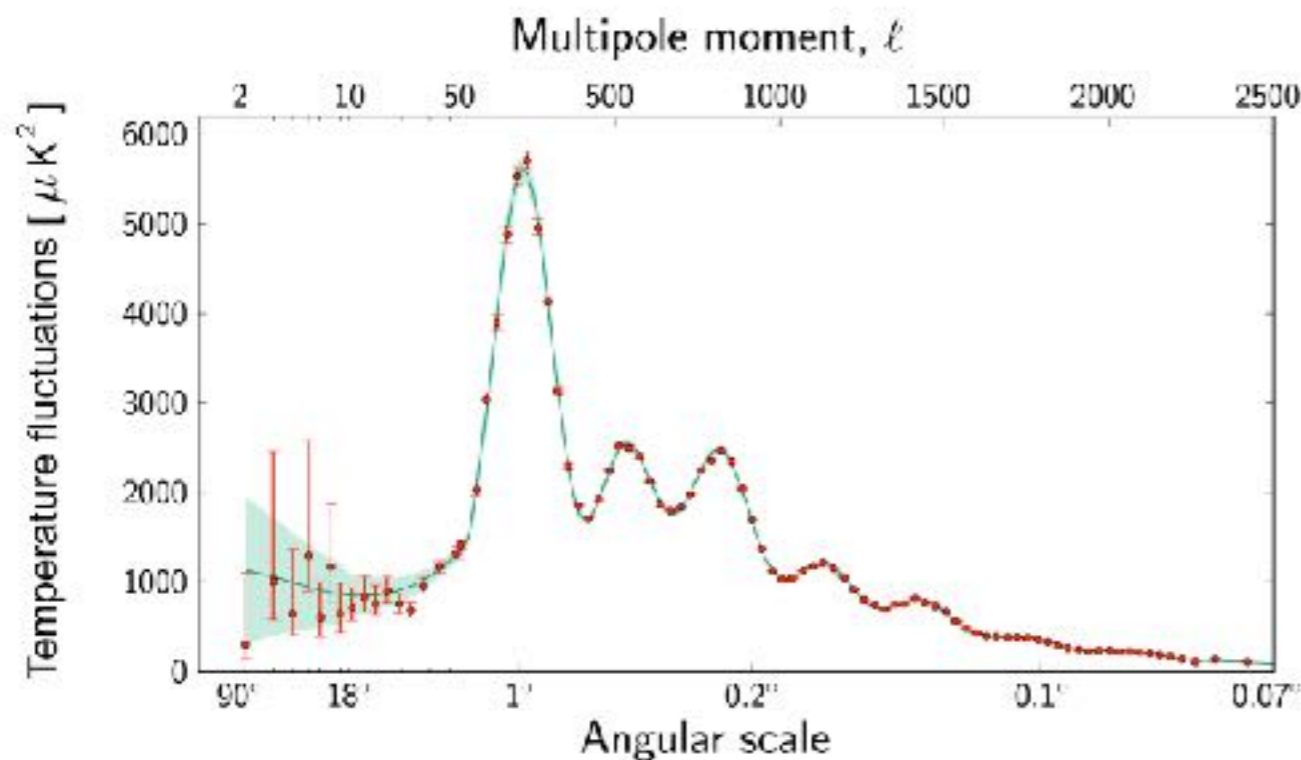
Cosmic Microwave Background



**Constraint on
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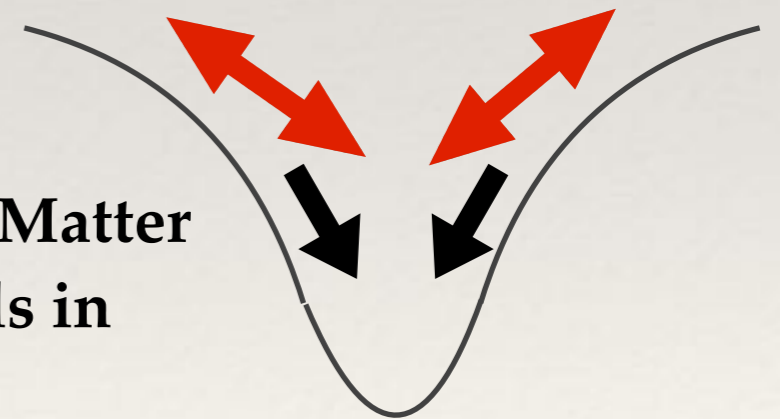
PDG 2016



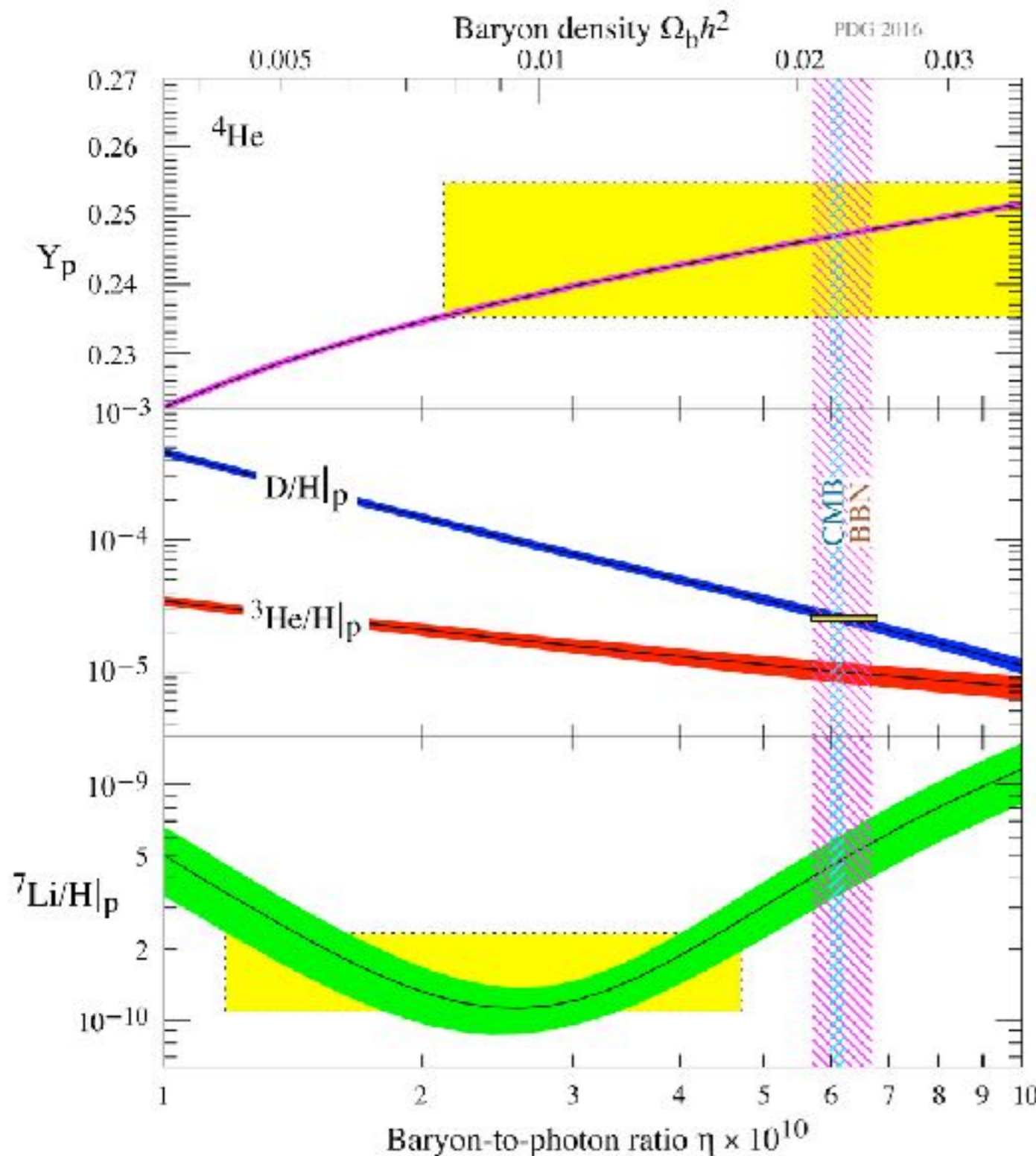
**ordinary matter/radiation oscillates
due to radiation pressure**

**Dark Matter
falls in**

gravitational potential well



Cosmic Microwave Background

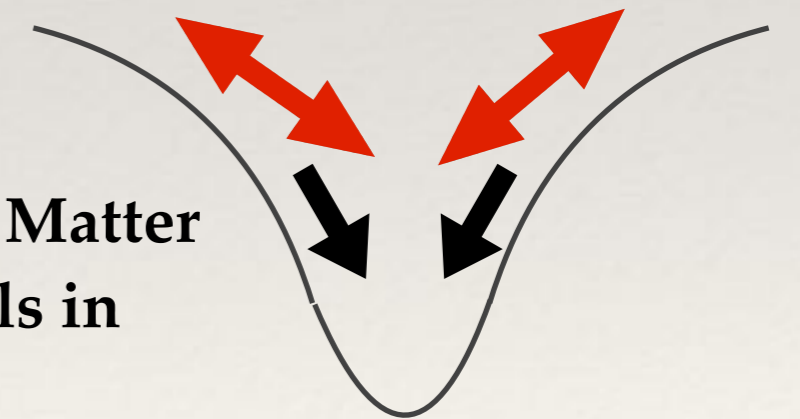


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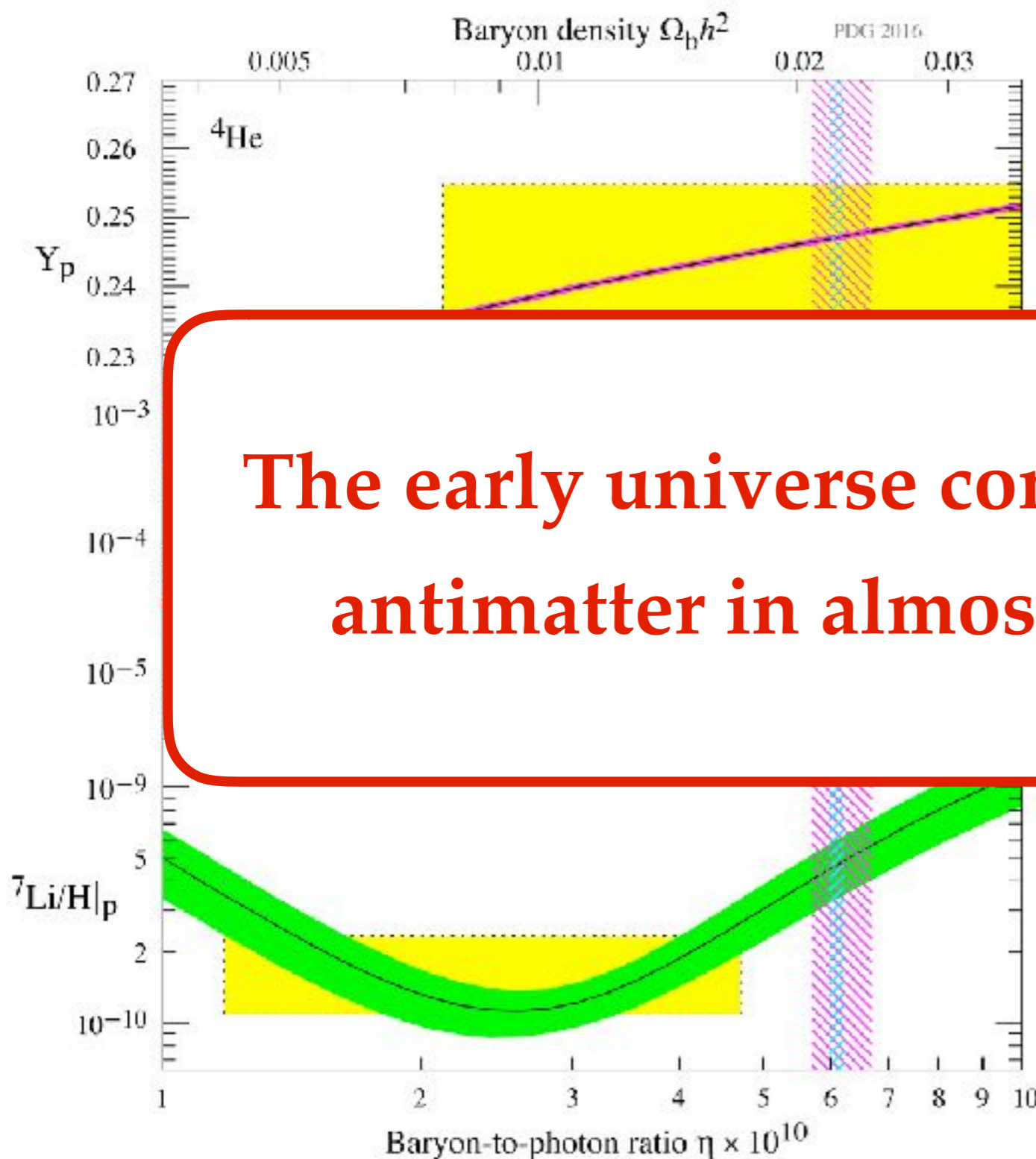
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Cosmic Microwave Background



**Constraint on
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$$6.02 \times 10^{-10} < \eta < 6.15 \times 10^{-10}$$

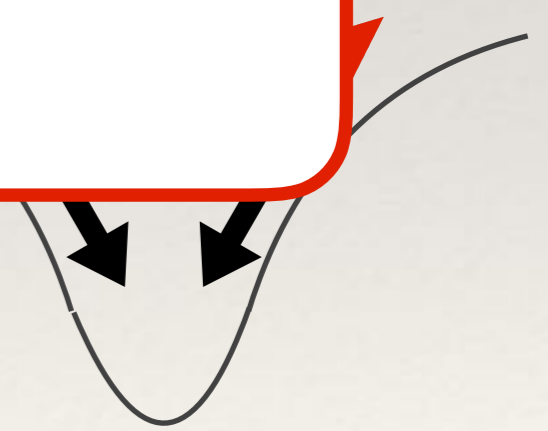
PDG 2016

**The early universe contained matter and
antimatter in almost equal amounts**

plates

**Dark Matter
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gravitational potential well



Potential sources of antinuclei

Antimatter in the present universe

Antimatter in the early universe

Standard baryogenesis scenarios

Non-standard baryogenesis and anti-stars

Where does the asymmetry come from?

Sakharov Conditions (1967)

- ❖ Baryon number violation
- ❖ C and CP violation
- ❖ Deviation from thermal equilibrium



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Exists in Standard Model
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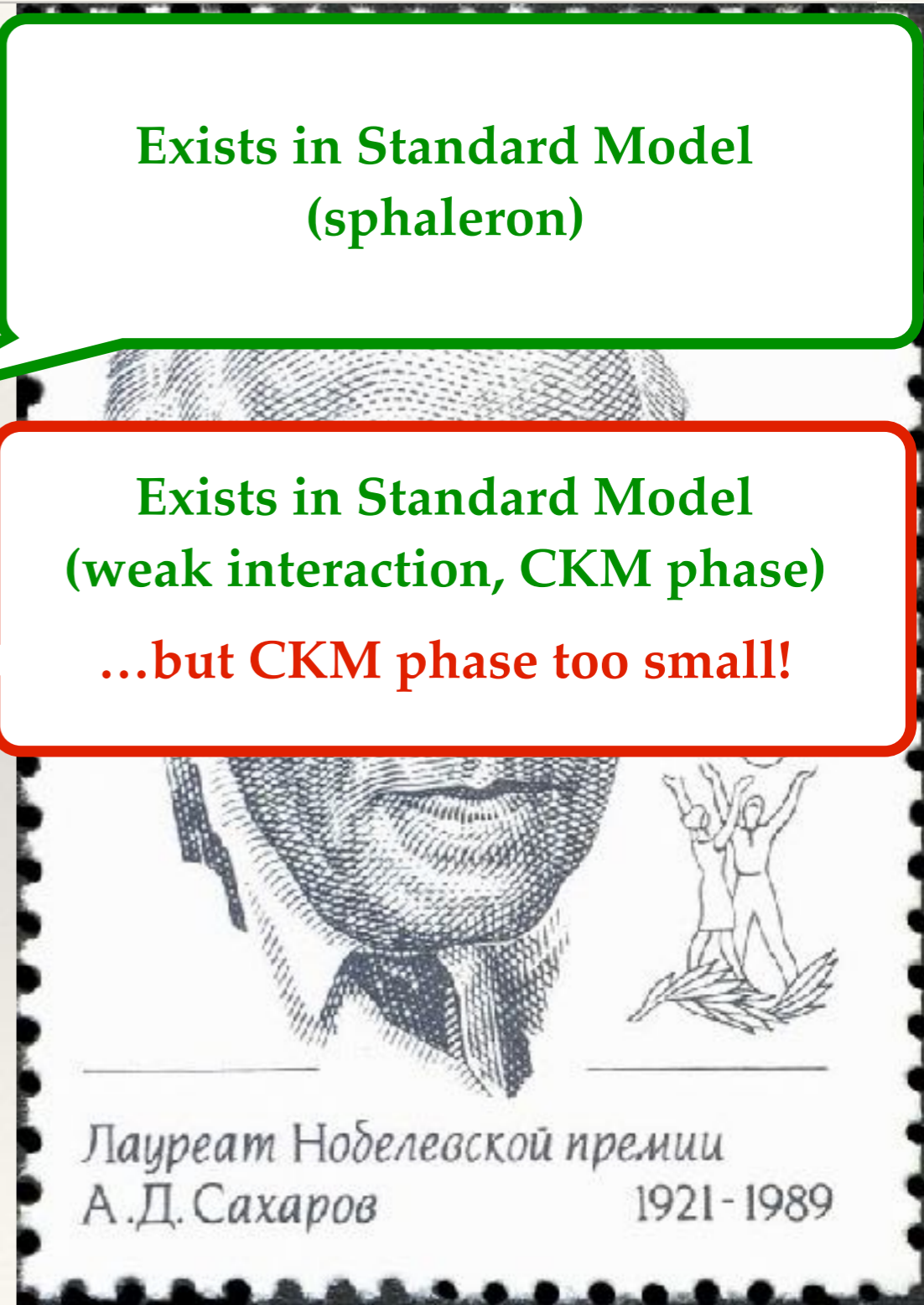
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Exists in Standard Model
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Exists in Standard Model
(weak interaction, CKM phase)

...but CKM phase too small!



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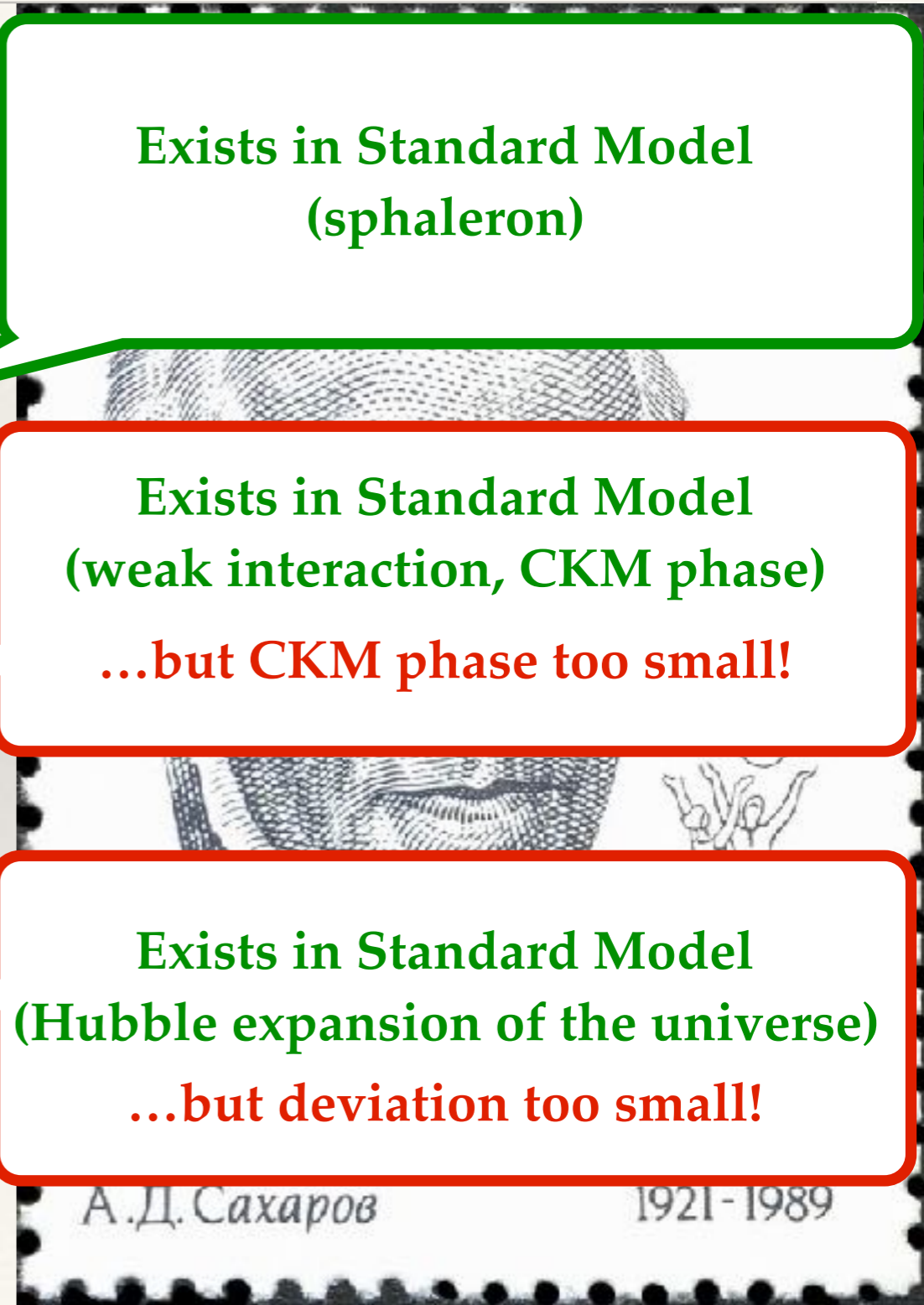
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- ❖ C and CP violation
- ❖ Deviation from thermal equilibrium

Exists in Standard Model
(sphaleron)

Exists in Standard Model
(weak interaction, CKM phase)
...but CKM phase too small!

Exists in Standard Model
(Hubble expansion of the universe)
...but deviation too small!



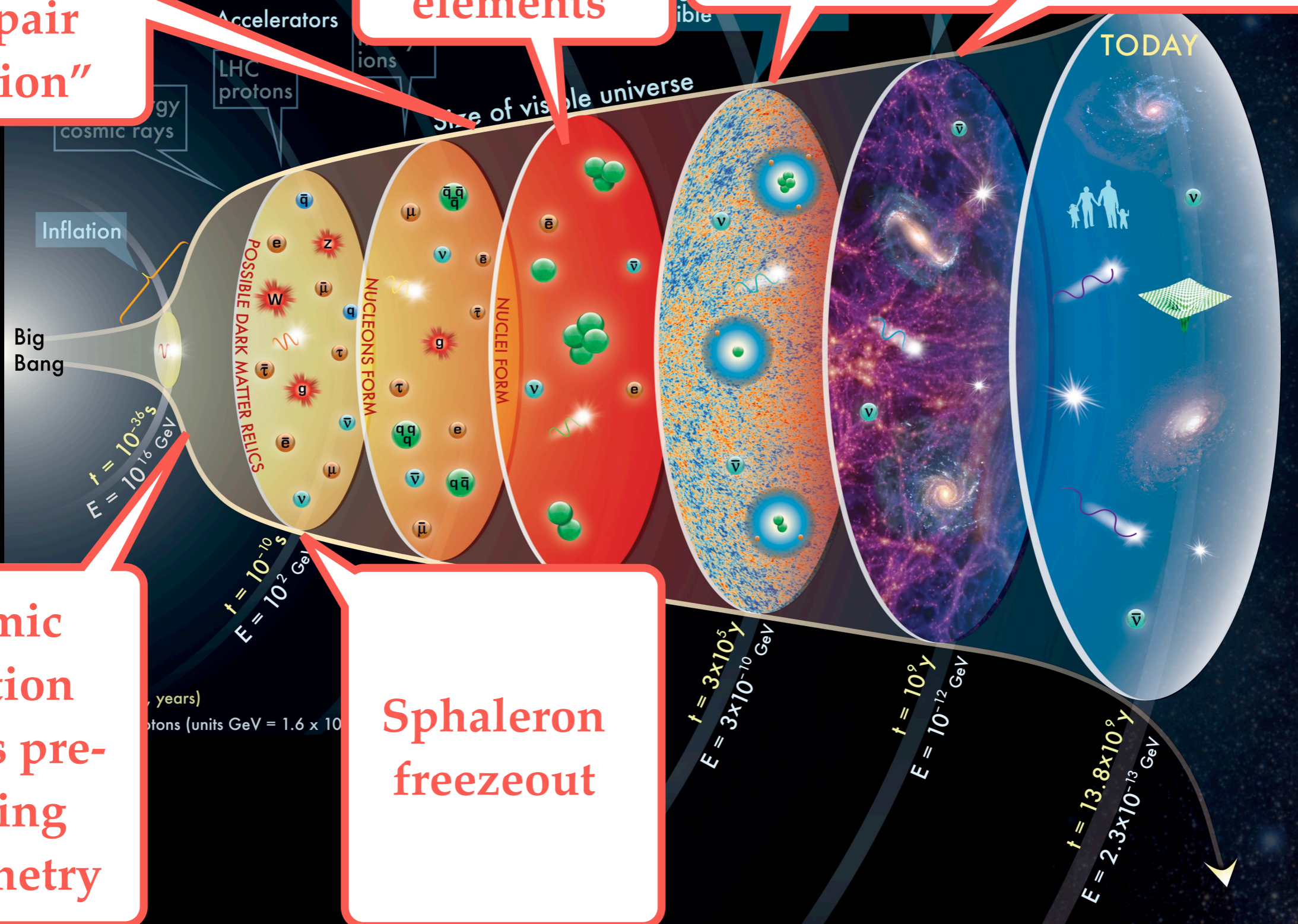
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**Baryon
number
diluted
by inflation**

Baryon number conserved

Cosmic
Inflation
dilutes pre-
existing
asymmetry

Sphaleron
freezeout

ORY OF

Hot enough
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Cosmic
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**Baryon
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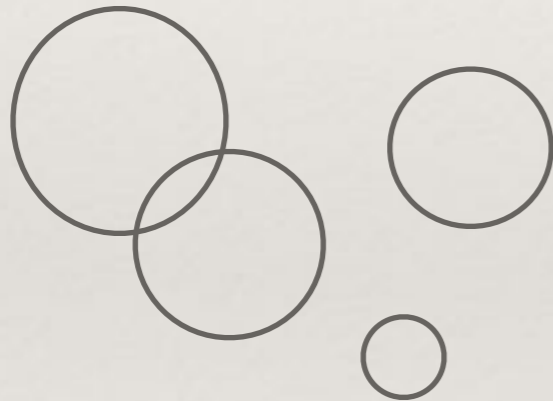
Cosmic
Inflation
dilutes pre-
existing
asymmetry

**Baryon asymmetry generated
("Baryogenesis")**

Where does the asymmetry come from?

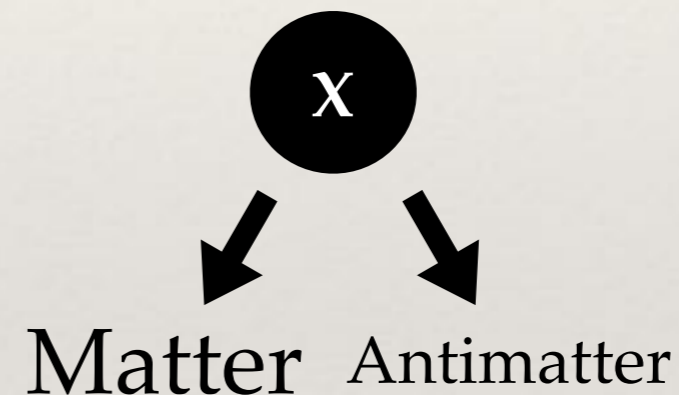
Baryogenesis requires New Physics!

Cosmic phase transition?



Electroweak baryogenesis,
...

Decay of a heavy particle?



GUT baryogenesis,
leptogenesis,
...

Where does the asymmetry come from?

Baryogenesis requires New Physics!

Cosmic phase transition?

Decay of a heavy particle?

**Standard baryogenesis scenarios predict
that there are no “anti-objects” in the
present universe**

Electroweak baryogenesis,

...

GUT baryogenesis,

leptogenesis,

...

Potential sources of antinuclei

Antimatter in the present universe

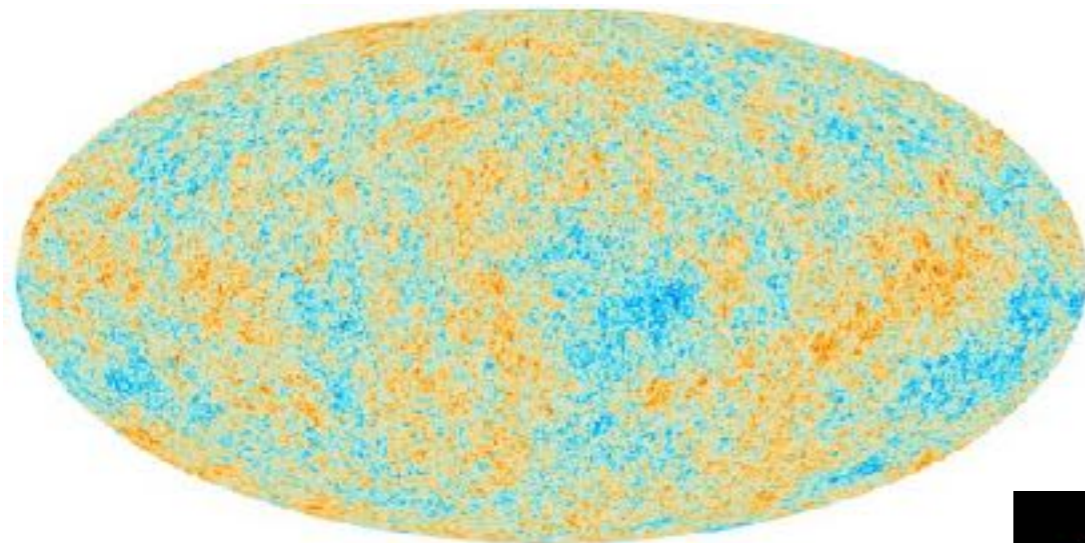
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How robust is the CMB argument?

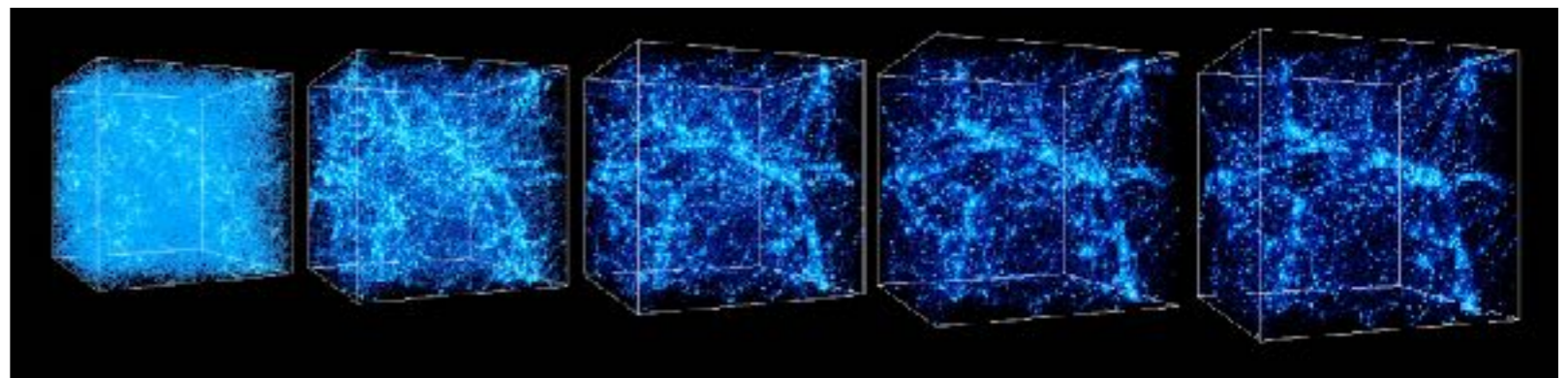
Can there be antimatter objects at some scale?



The early universe was very homogeneous and isotropic...

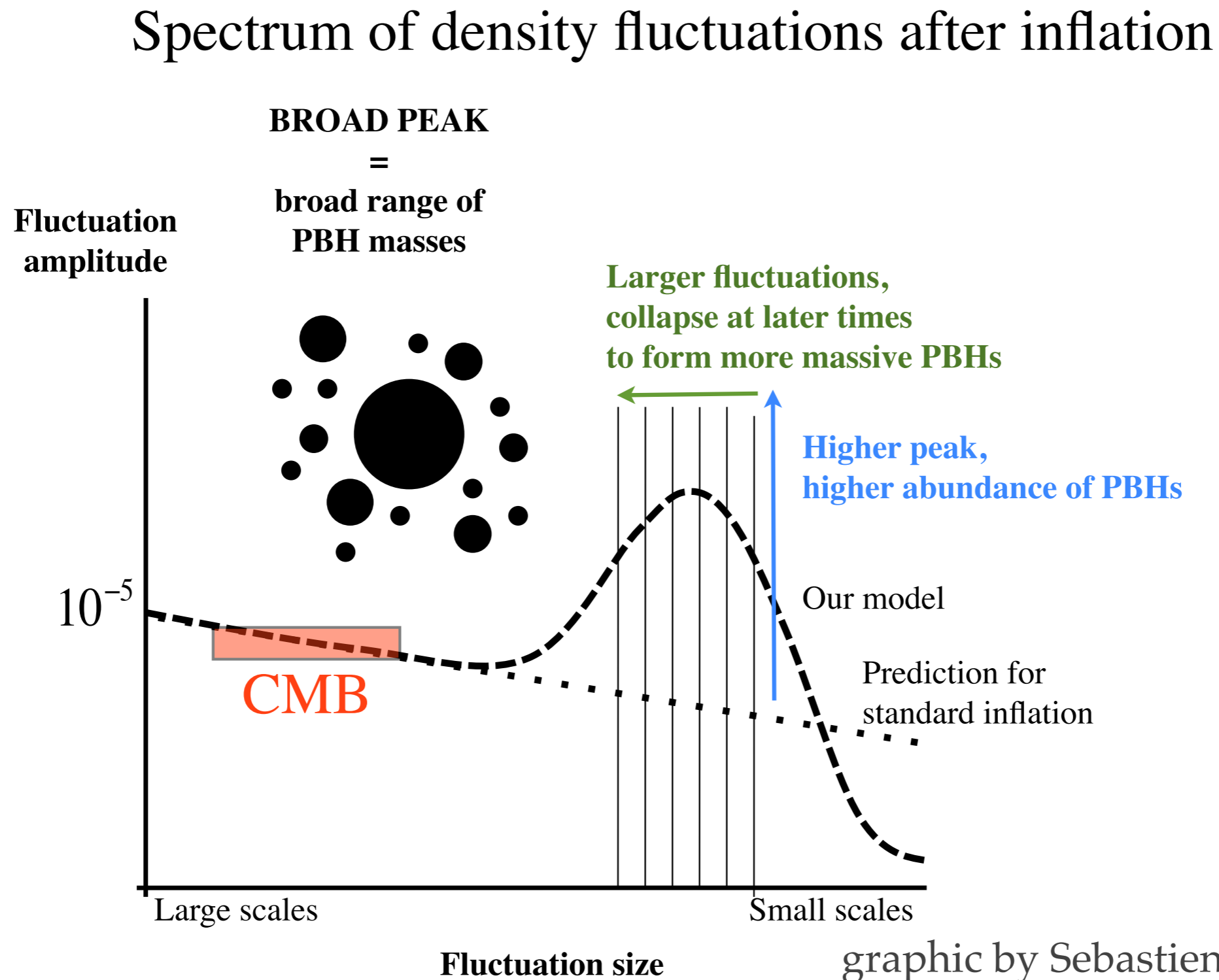
...so matter and antimatter regions must have been in

touch Cohen/Di Rujula/Gashow 98



Argument assumes that density perturbations are tiny at all scales... but the CMB only probes a small range of scales!

Can there be large fluctuations at small scales?



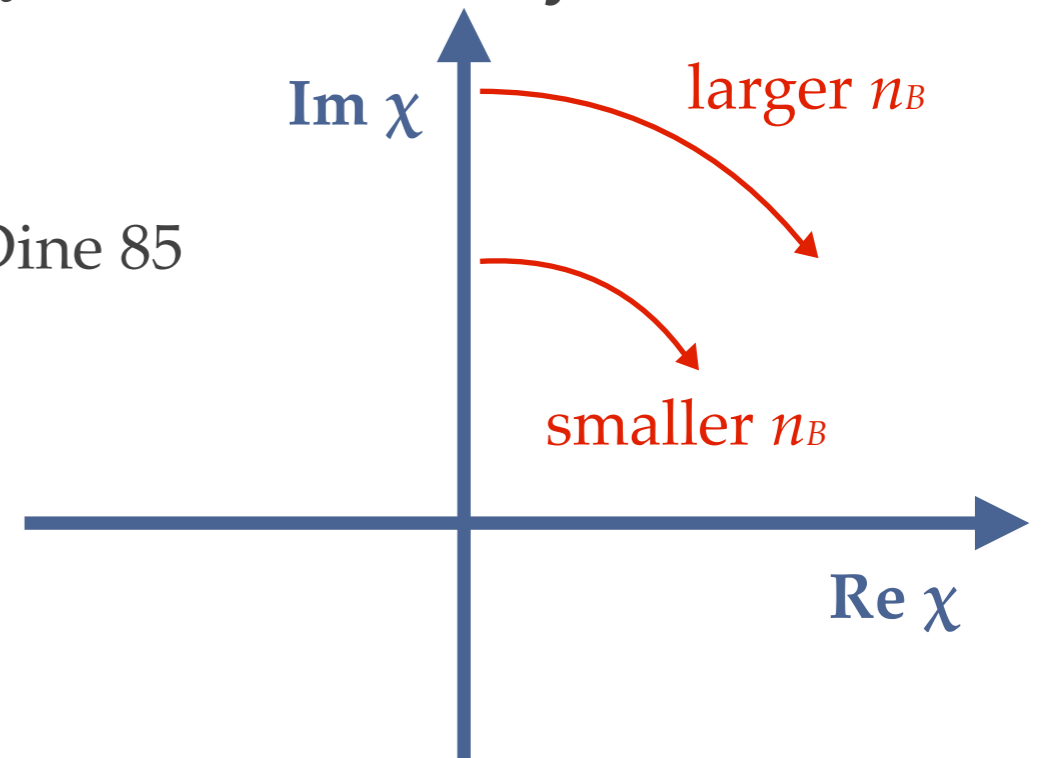
Affleck Dine Baryogenesis

- SUSY models contain scalar superpartner χ that carries baryon number

$$n_B(\chi) = i[\chi^*(\partial_t\chi - (\partial_t\chi^*)\chi)]$$

Affleck / Dine 85

- baryon number corresponds to “angular momentum” in field space, i.e., a time dependent phase



- Scalar potential can have “flat directions”

$$U(\chi) = \lambda (2|\chi|^4 + \chi^4 + \chi^{*4}) + (m_1^2\chi^2 + h.c.) + m_2^2|\chi|^2 ;$$

- Misalignment of flat directions in quartic and quadratic term can give field large “angular momentum” during inflation, i.e., large baryon number
- Subsequent decay into baryons preserves that baryon number

Modified Affleck Dine Baryogenesis

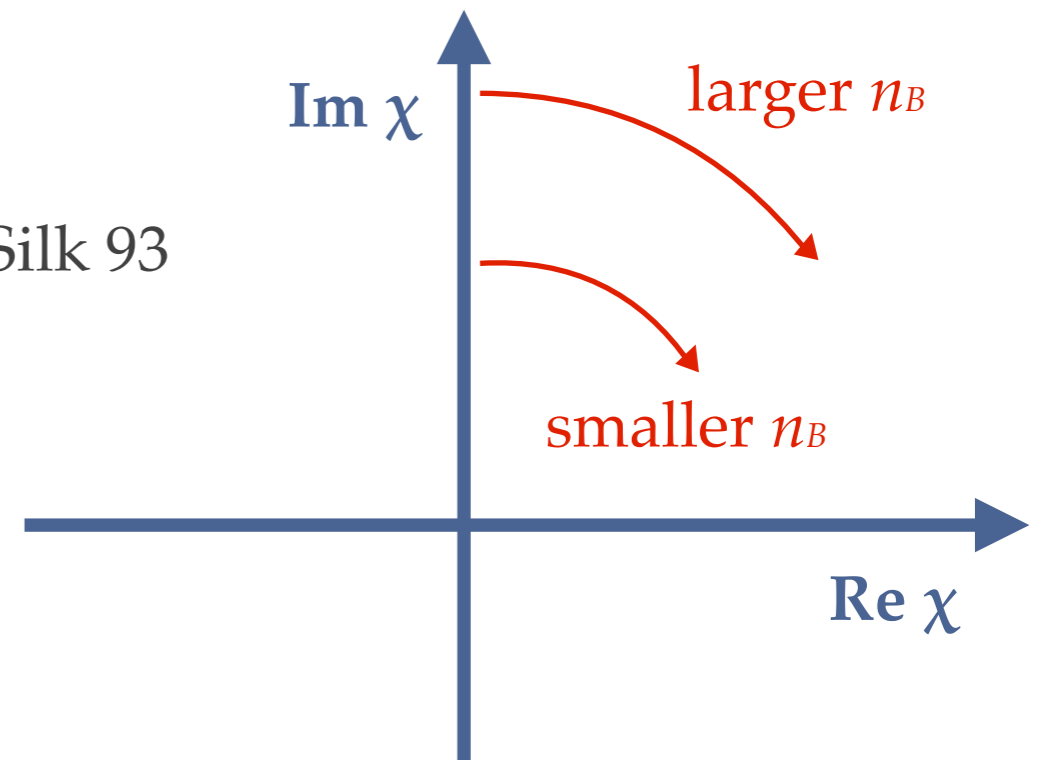
- Add to the scalar potential a coupling to the inflaton that gives a time dependent mass term

$$n_B(\chi) = i[\chi^*(\partial_t\chi - (\partial_t\chi^*)\chi)]$$

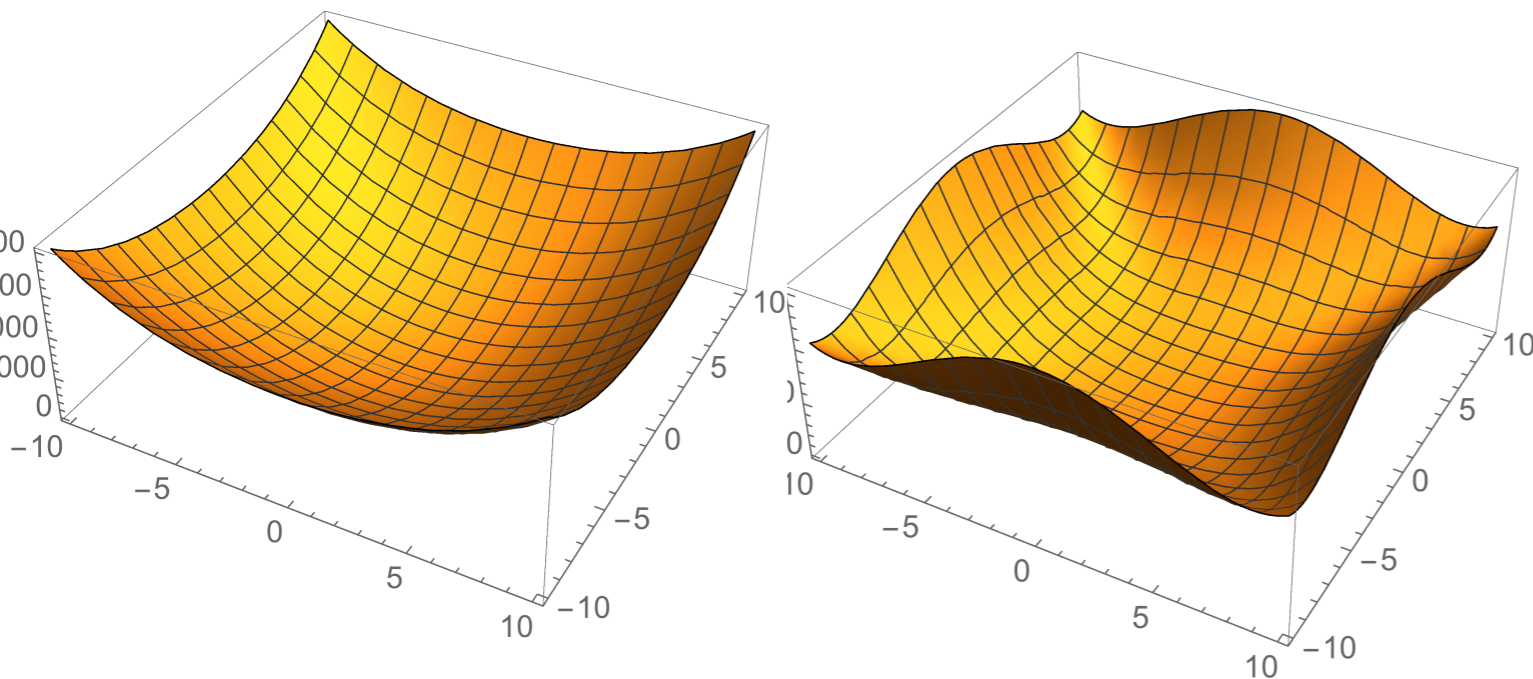
Dolgov / Silk 93

$$\delta U(\chi, \Phi) = g|\chi|^2(\Phi - \Phi_1)^2$$

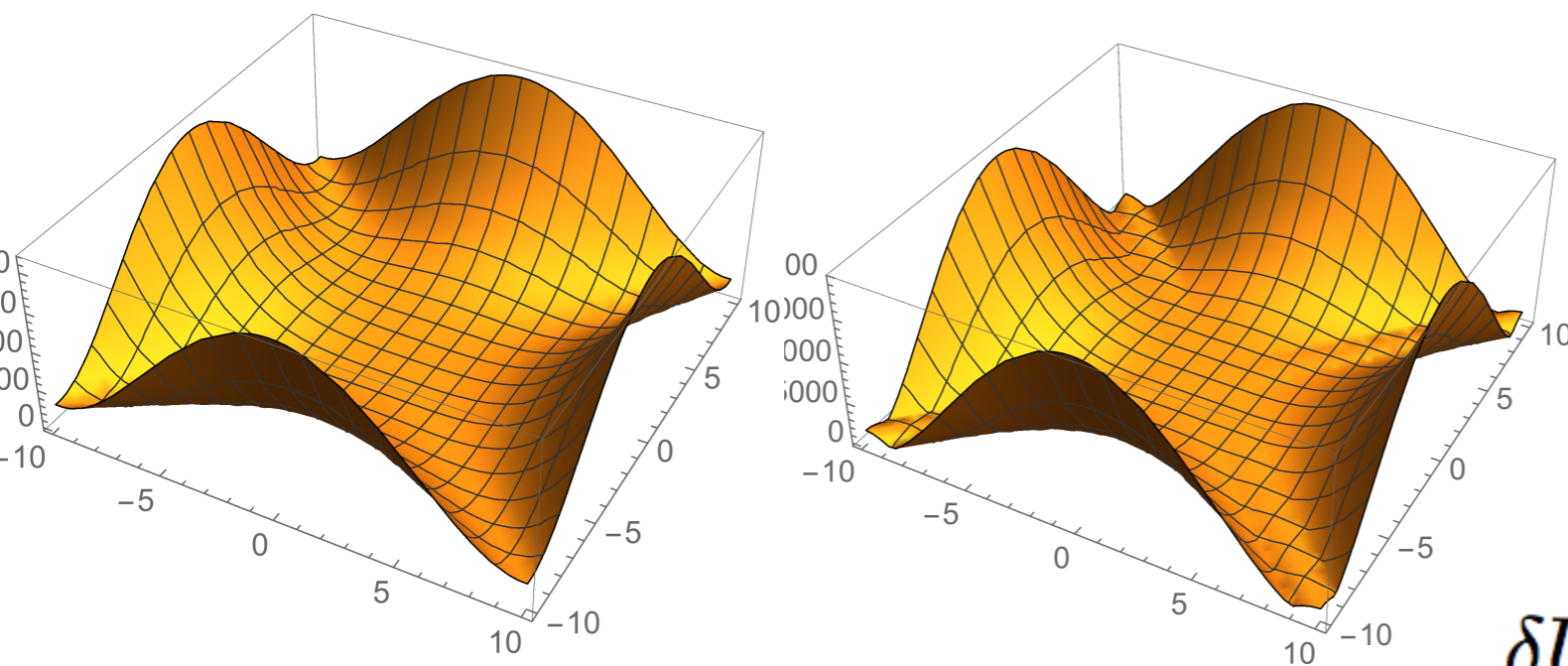
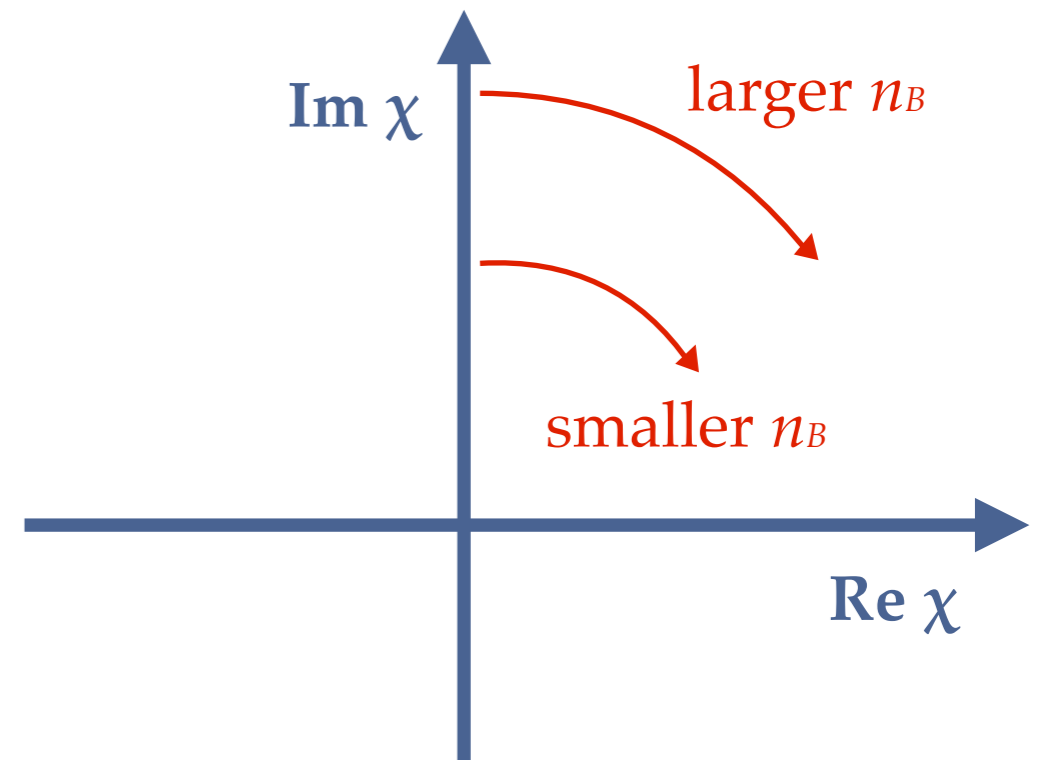
- “flat directions” are removed, they only appear for a short moment as the inflaton crosses the critical value
- It is very unlikely (=rare) that a quantum fluctuation creates a large $|\chi|$, i.e., a large baryon number...
- ...and therefore happens only in a few isolated places in space



Modified Affleck Dine Baryogenesis

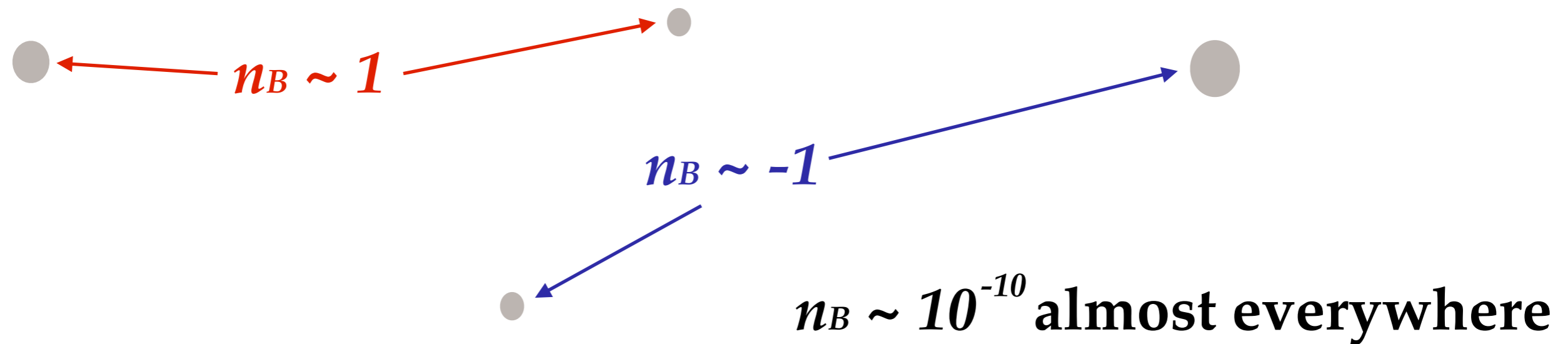


$$n_B(\chi) = i[\chi^*(\partial_t \chi - (\partial_t \chi^*)\chi)]$$



$$\delta U(\chi, \Phi) = g|\chi|^2(\Phi - \Phi_1)^2$$

Formation of Anti-Stars



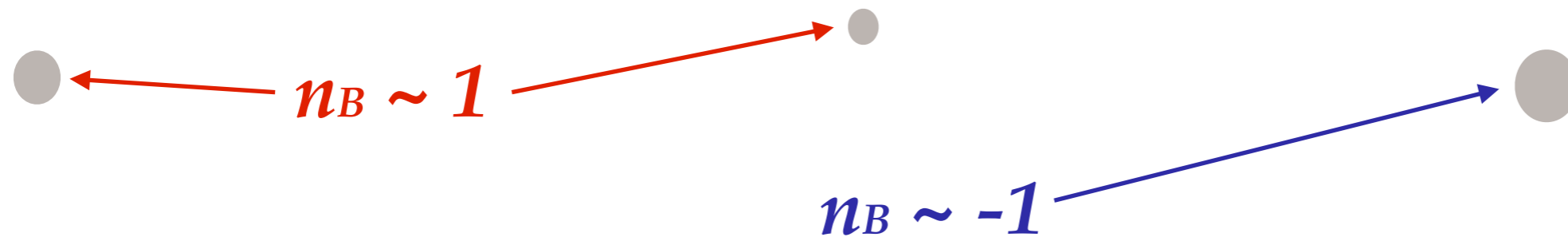
- Leads to small “pockets” of large baryon or anti-baryon number
- Initially those have same density as average...
- ...but during QCD transition heavy baryons form that redshift like matter

Formation of compact matter and antimatter objects at $T \sim 100$ MeV!

log-normal mass distribution

$$\frac{dN}{dM} = C_M \exp[-\gamma \ln^2(M/M_0)]$$

Formation of Anti-Stars



**Non-standard baryogenesis scenarios
can accommodate the possibility
of “anti-objects”**

where

- Lea
- Ini
- ...but during QCD transition heavy baryons form that redshift like matter

Formation of compact matter and antimatter objects at $T \sim 100$ MeV!

log-normal mass distribution $\frac{dN}{dM} = C_M \exp [-\gamma \ln^2 (M/M_0)]$

Conclusions

- **Direct observation rules out sources of anti-nuclei in our local environment**
- **The cosmological standard model and popular particle physics theories predict no sources of anti-nuclei**
- **Non-standard scenarios can accommodate sources of anti-nuclei**
- **Observation of anti-nuclei would provide a hint how to embed the Standard Model of particle physics in a more fundamental theory of nature**