Astro 350
Lecture 36
Nov. 18, 2011

Announcements:
- HW10 due now
- HW11 due Friday after break (Dec 2)
- Discussion Question 11 available
- Check syllabus: lowest HW and Discussion score dropped but you are still responsible for all of the material

Breaking news on OPERA "speedy neutrino" experiment
original paper updated yesterday with new tests
$\rightarrow$ faster-than-light result persists!
$\rightarrow$ no pizza payoff yet! but stay tuned...

Today: pre-break change of pace
special topic: antimatter cosmology

Antimatter

Fundamental result of Special Relativity + Quantum Physics

every particle has an antiparticle

e.g., $\bar{e^-} = e^+$ positron

e.g., $\bar{p}$ = antiproton

Fermilab: $p\bar{p}$ collisions

mass $m(\bar{x}) = m(x) \geq 0$

electric charge $Q(\bar{x}) = -Q(x)$

combine $x + \bar{x} \rightarrow$ energy $\rightarrow$ other particles: annihilation

energy release: $E = m_x c^2 + m_{\bar{x}} c^2 = 2m_x c^2$!

Q: apply to universe–what happens when T so high that $E_{\text{avg,particle}} > 2m_e c^2$?

when $E_{\text{avg,particle}} > 2m_e c^2$
particle collisions violent enough to create e^+e^- pairs

So: early universe a particle soup!
full of matter and antimatter
we see the cooled-off remains

Cosmic Matter vs Antimatter

so far: assumed that universe only had normal matter

But we know:

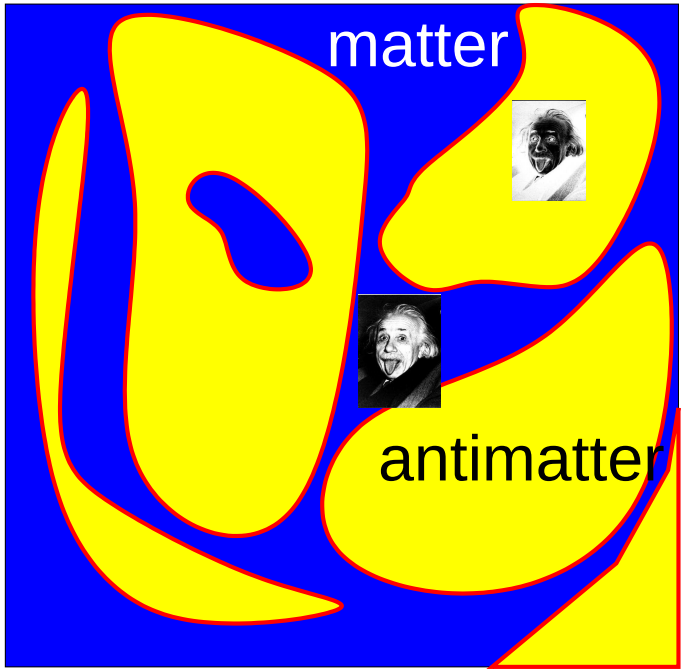
- antimatter exists
- the U went through a hot big bang

$\rightarrow$ antimatter should have been created abundantly!

Major question: where is it?

in other words–particle physics + cosmology forces choice:

- ▷ is the universe only matter–and if so, why?
- ▷ is the universe made of "domains" of matter and antimatter ...and if so, why?

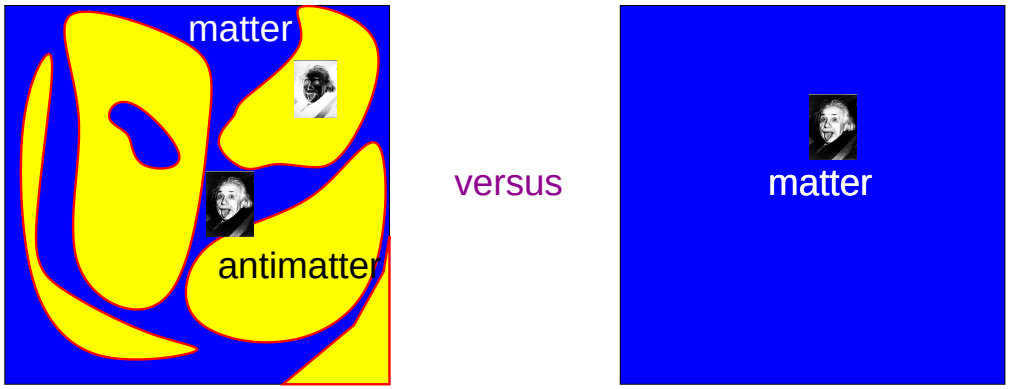


versus

iClicker Poll: Antimatter

Vote your conscience!

What is the matter/antimatter layout of our Universe?



A *equal* amount of regions with matter or with antimatter
on average, matter/antimatter symmetric and "democratic"

B *entirely matter*, *no* regions of antimatter
"bias" against antimatter

Antimatter in Our Universe

A democratic universe:
Imagine U made of domains of matter (protons & electrons) and antimatter (antiprotons and positrons)
Q: what would life be like in the anti-regions? How would it differ from life here?

Searching for antimatter:
what **observable evidence** tells us:

- *Are there antimatter domains in this room?*
- *...on the Earth?*
- *Is the Moon matter or antimatter?*
- *...the Sun?*
- *...other solar system bodies?*
- *Is the local solar neighborhood matter or antimatter?*
- *Are there domains in our Galaxy?*
- *Are galaxy clusters matter/antimatter combinations?*
- *What about the observable universe?*

Observed Matter (Baryon) Asymmetry of the Universe

cosmic asymmetry: matter dominates over antimatter

Matter-only System	Evidence
Solar system	landings, meteors/comets, solar wind, proto-$\odot$ n
Cosmic rays	direct detection
MW Galaxy	cosmic rays, no annihilation γs
Galaxy clusters	no γ from galaxy-intracluster gas interface $\Rightarrow$ all matter or all antimatter
Hubble volume	too few 1–10 MeV γ, no CMB distortion

if antimatter domains, exit they must segregated from matter
on mass scales $\gtrsim 10^{14} M_\odot$
and probably length $> d_H = c/H \sim 3$ Gpc

∞

Conclude: the universe is made of matter only!

The Matter Excess–How Much?

More particle physics:
baryons n, p not elementary–made of quarks!
in fact: baryon=3 quark system
$p = uud$, $n = udd$, $u, d =$ "up, down" quarks

Early universe was quark/antiquark soup
where quarks slightly outnumbered antiquarks

$$\frac{n_q - n_{\bar{q}}}{n_q + n_{\bar{q}}} \sim \frac{n_B}{n_\gamma} \sim 6 \times 10^{-10} \qquad (1)$$

for every 6 billion $\bar{q}$, there were 6 billion + 1 q
excess tiny –but crucial!

annihilation $\rightarrow$ baryons today
Q: what about the photons?
where are they now?

annihilation photons are CMB today!

$\rightarrow$ tiny baryon-to-photon ratio a result of
tiny matter/antimatter asymmetry in early U!

Transp: *fortune cookie cosmology*

Q: what are implications for early universe, particle physics?

Baryogenesis: Origin of Baryons

A. Sakharov (1967)
brilliant but completely cryptic paper

Assume: initially, $n_B = n_{\bar{B}}$
$\rightarrow$ begin with matter/animatter symmetry and democracy
under the right conditions,
the U can generate asymmetry spontaneously
$\rightarrow$ end up with $n_B > n_{\bar{B}}$

Q: what conditions needed for this to happen?

Conditions for Baryogenesis

the game: start with $n_B = n_{\bar{B}}$
end with $n_B > n_{\bar{B}}$

1. **Baryon number non-conservation**

but B conservation "protects" p against decay
$\rightarrow$ if *not* conserved: protons *can* decay!
not yet observed:
e.g., proton lifetime $\tau_p > 10^{33}$ yr
but theoretically expected!

2. Matter/Antimatter Reaction Differences

if identical quantum probabilities for matter, antimatter rxns,
then make and destroy each at the same rate
no net gain or loss of one over the other!
need different probabilities!

1964: diff probabilities for decay of one particle
$K^0, \bar{K}^0$ decay differently
2001: diff probabilities for another particle
$B^0, \bar{B}^0$ decays ($K = \bar{s}d$, $B = \bar{b}d$)

`www: Jim Cronin`

3. Departure from thermal equilibrium

in equilibrium: production, destruction rates equal!

so again can't generate a net excess

but we know the U leaves eq. sometimes (e.g., recombination)

Putting the pieces together:

Baryogenesis models have been constructed

with high-energy particle theories

can get $\eta \sim 10^{-10}$: encouraging!

Matter/Antimatter Lessons

- present observed U is only matter
  this innocent fact alone has profound implications for
  - ▷ cosmology (had to achieve matter excess)
  - ▷ fundamental physics:
    baryon number not conserved: protons will decay!
    matter/antimatter not perfect mirror images!

- our existence as matter traces back to very early U

- need more particle physics data to test

Ongoing! Fermilab and successors!

stay tuned...

Have a good break!