Astro 350
Lecture 36
Nov. 30, 2012

Announcements:

- **Homework 10** due now
- **Discussion 11** – last one! Due next Wednesday
- **Homework 11** – last one! Due next Friday
- Check syllabus: lowest HW and Discussion score dropped but you are still responsible for all of the material
- **ICES** available online – please do it!
  I do read and use comments!

Last time: origin of the elements–primordial nucleosynthesis
Q: qualitative predictions? quantitative preditions?
Q: Cosmologist Dr. Phil asks: how's that working out for us?
Q: implications of theory-observation comparison?
Q: how does this give the amount of ordinary matter in the U?

BBN: Implications

Qualitatively

extrapolated big bang to $t = 1$ s

predicted lite elts $\rightarrow$ agreement with observations

big bang working well back to 1 sec!

Quantitatively

observed lite elements select baryon density

$\Rightarrow 0.040 \lesssim \Omega_B \lesssim 0.050$

1. $\Omega_B \ll 1$: baryons don't close the U.

2. $\Omega_{lum} \sim 0.007 \ll \Omega_B$

baryonic dark matter hot (10^{6-7} K) intergalactic gas?

3. $\Omega_{\text{matter}} \approx 0.3 \gg \Omega_B$:
non-baryonic dark matter

confirms: **most dark matter** is **not**
made of atoms of any kind in any arrangement!
$\rightarrow$ must be exotic form of matter!

known matter = anything on the periodic table
is a tiny fraction of the makeup of the cosmos!

4. Note: Big bang nuke theory assumed early Universe
was filled with a sea of **neutrinos**
- needed to set the initial amounts of n and p
- huge numbers! about as abundant as CMB photons!

$\rightarrow$ these neutrinos should be leftover today!
Q: why is this a big deal?

Neutrinos as Dark Matter

Neutrinos have mass and interact weakly
if they are everywhere: *neutrinos could be the dark matter*

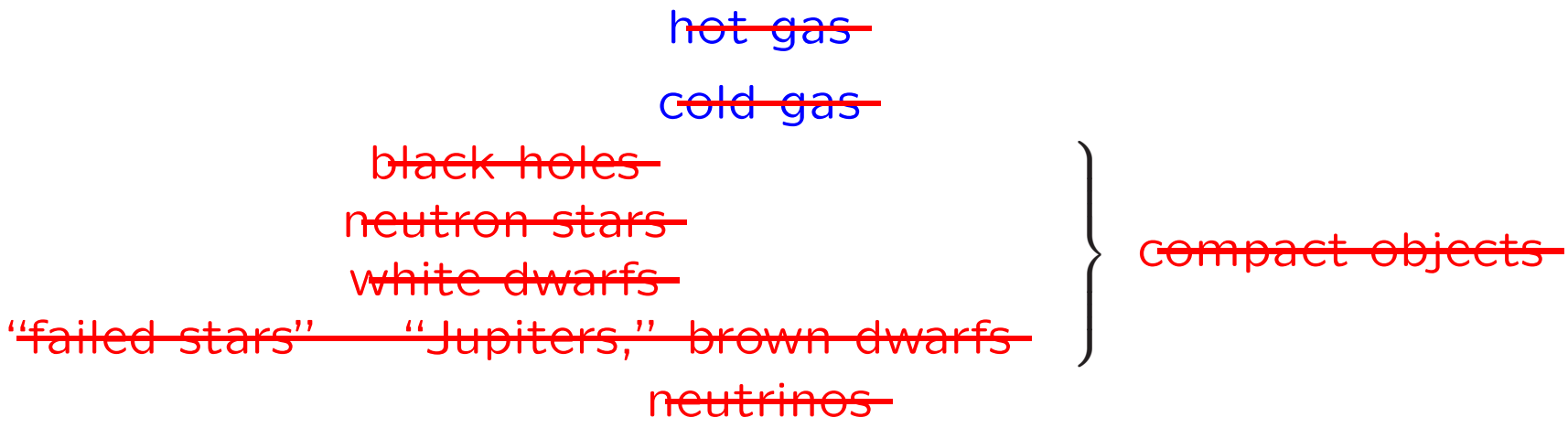
And using big bang nuke we can predict precisely
the amount (number) of neutrinos today

but what counts is the gravity from neutrinos, set by
their *mass density* today
$\rightarrow$ need to know masses of neutrinos!
...which we don't know!

But: we know enough! Experiments show
- neutrinos do have mass
- each neutrino's mass is less than $0.000001 m_e$

this gives $\Omega_\nu \leq 0.01 \approx \Omega_{\rm luminous} \ll \Omega_{\rm matter}$
Q: and so?

Lineup of Dark Matter Suspects



List is getting short!

Early Universe Cosmology Scorecard

Recall strategy:

- inventory universe today
- extrapolate back to early epochs
- apply known laws of nature to expanding, cooling U
- identify observable consequences ("fossils") persisting today
- measure fossils $\rightarrow$ learn about early U!

Cosmo Report Card

Epoch	Recombination	Big Bang Nuke
cosmic time t	$\sim 400,000$ yr	~ 1 sec–3 min
micro-processes	nuclei+$e \rightarrow$ atoms	p+$n \rightarrow$ nuclei
predicted fossils	thermal radiation	baryons $\rightarrow$ H, He, Li
observed?	Yes! $\rightarrow$ CMB	Yes! $\rightarrow$ primordial abundances
grade	A	A

The Very Early Universe

CMB success $\Rightarrow$ understand Univ at $t \sim 400,000$ yr
$z \sim 1100$ and $T \sim 3000$ K

BBN success $\Rightarrow$ understand Universe at $t \sim 1$ s
$z \sim 10^{10}$ and $T \sim 10$ billion K

success gives confidence:
boldly extrapolate to $t \ll 1$ s
and $T \gg 1$ MeV

Q: what are conditions like?

Q: what physics needed to describe?

Particle Physics Today: Success and Its Discontents

Current theory of elementary particles:
"the Standard Model of Particle Physics"

all known particles explained in terms of

- matter particles in "families" of quarks and "leptons" (e, ν and cousins)
- interacting with four fundamental forces: gravity, electromagnetism, and the nuke and weak forces
- with forces "carried" by another set of particles i.e., photons and cousins

The Standard Model: Report Card

How does this stack up against experiment?
extremely (annoyingly!) successful theory $\Rightarrow$ *no* known disagreement with experiment!

- all expected particles discovered after Higgs found July 2012

  ...more on Higgs soon...

- all measured particle properties behave as expected
  e.g., e^- magnetic moment $(g-2)$ measurement
  agrees with theory to 1 part in 10^{10}!

- But: Standard Model only tested in lab
  to LHC energies $E = 8\,\mathrm{TeV} = 8 \times 10^{12}\,\mathrm{eV} = 8000 m_p c^2$
  roughly the kinetic energy of a housefly...but all in one particle

- And: Standard Model begs the questions:
  why the patterns of particles we see?
  why four forces are they unified (like E&M are)?
  where does mass come from?
  why is matter one class of particles (fermions)
  and force carriers another (bosons)?

Standard Model a "victim of its own success"
carries the seeds of its destruction/supplanting

To address these questions: *new particle theories proposed*
that go beyond the Standard Model
to give possible answers to these questions

as a by-product, new theories *postulate/invent new particles*:

- almost always high-mass ($m \gtrsim 1$ TeV $= 1000\ m_{\text{proton}}$)
- almost always weakly interacting
  (at "low" energies = Fermilab/CERN)
- note: invented to fix particle problems,
  not with cosmology in mind (no ulterior motive!)

Today: new particles hard to make
But in early U: created everywhere!
Q: possible fossils today? what conditions needed?

The Heavenly Accelerator and Dark Matter

If exotic massive particles exist
$\rightarrow$ created in early universe

If stable: remain today
$\rightarrow$ natural candidates for **dark matter**
bonus: naturally weakly interacting

"just what the doctor ordered"
Weakly Interacting Massive Particles: WIMPs!
key point: not invented for cosmology
but for particle physics reasons

So: if particle theorists are right:
can't *avoid* a U filled with crazy WIMPs

iClicker Poll: WIMP Status

Many cosmologists (including your instructor) believe
dark matter = weakly interacting massive particles: WIMPs

Vote your conscience!

Right now do we have any real evidence for WIMP particles?

A No–and there never will be because weakly interacting particles are impossible to detect.

B No, but it is possible to detect WIMPs, so maybe they don't exist.

C Maybe!? There are conflicting claims and hints of WIMPs

D Yes! WIMPs have been disocvered!

Direct Detection of WIMPs

Difficult! ...but not impossible

weakly interacting $\rightarrow$ experiments similar to ν detection
- go underground
- expect small count rate ($\lesssim$ few events/month)

`www: WIMP experiments`

WIMP-nucleus collisions: nucleus recoils with ~ 1 keV
measure recoil energy: cryogenic detectors

strategy: look for annual variations
$\vec{v}_{\text{WIMP}} = \vec{v}_{\odot} + \vec{v}_{\text{Earth,orbit}}$
$\rightarrow$ velocity has time change due to earth orbit
$\rightarrow$ modulation in 1-year period, amplitude $v_{\text{Earth}} \sim 10\% v_{\odot}$

Direct WIMP Search Results

1998: Italian experiment (DAMA) claims evidence!

by now: claim evidence is strong

- very controversial result!
- most competing groups don't see signal
- could be different WIMP interactions for different nuclei
- ...or could be false alarm

How to resolve dispute? Better experiments

- will be coming online
- either will find WIMPs, or rule out favorite theories
- stay tuned!

Indirect WIMP Searches

In early Universse: WIMPs expected to be created in pairs

energy $\rightarrow$ WIMP + anti-WIMP

actually, in many theories anti-WIMP = WIMP: their own antiparticle!

today: if WIMPs and anti-WIMPs meet
they annihilate, and produce Standard Model particles
that is, paricles we *can* detect

Q: where are annihilations most likely to occur?
Q: how might we find evidence that this has happened?

WIMP Annihilation Signatures

WIMP annihilations most likely where WIMPs most abundant
so that they can most easily collide
$\rightarrow$ regions of highest WIMP concentration
$\rightarrow$ regions of higest dark matter density
$\rightarrow$ *centers of galaxies*

So: look for WIMP annihilation products at centers of galaxies!
$\rightarrow$ high-energy particles

2012: *Fermi* gamma-ray space telescope
claimed to see unexplained gamma-ray signal!
- coming from our Galactic center
- at energy 130 GeV $\approx 150 m_p c^2$

Controversial claim! Possibly an instrumental problem!
not clear what is going on! stay tuned

Lineup of Dark Matter Suspects

WIMPs are the only candidate left standing!

Will either be detected soon, or back to drawing board

$\rightarrow$ *these are exciting times for dark matter!*