Astro 350
Lecture 38
May 4, 2022

Announcements:

- **Thank you for your presentations!**
- **Final Exam** Monday May 9, 1:30–4:30 pm
  information on Canvas
- **Term Paper** due Wed May 11
  information on Canvas
- HW grading is late but will be done soon
  and solutions posted

Last lecture:
antimatter – not science fiction, not a second-class citizen!

Today: the Grand Finale

Inner Space and Outer Space

We have seen in this course that
the nature of matter on microscopic scales
influences the evolution of the cosmos on the grandest scales

- big bang nucleosynthesis: the Universe as nuclear reactor
- cosmic microwave background released when atoms first formed

At very early times: U extremely hot, dense
particle collisions higher energy than we can reproduce in the lab
"the Universe is the poor person's accelerator" – Y. Zel'dovich

Most elementary particle theories predict:

- when $t \ll 1$ sec, primordial "soup" of exotic particles
  can't yet be make in lab: massive, so $E = mc^2$ too high
- at least one type of these exotic particles is stable

Q: and so?

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 discovered!

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 Universe: 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, particles we *can* detect

Q: where are annihilations most likely to occur?

Q: how might we find evidence that this has happened?

WIMP Annihilation Signatures

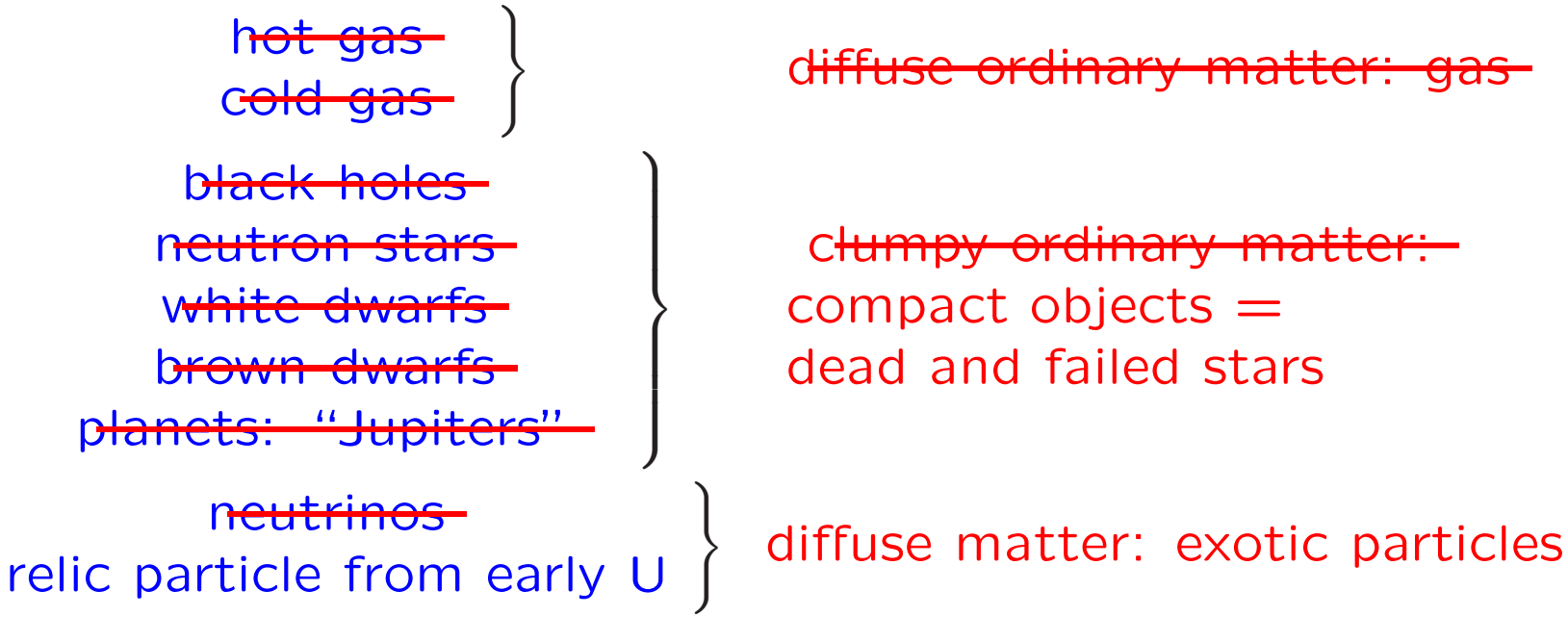
WIMP annihilations most likely where WIMPs most abundant
so that they can most easily collide
$\rightarrow$ regions of highest WIMP concentration
$\rightarrow$ regions of highest dark matter density
$\rightarrow$ *centers of galaxies*

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



relic particles like WIMPs are only candidates left!

Will either be detected soon, or back to drawing board

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

FINALE

The Semester's Silliest iClicker Poll

There seems to be a cosmological comedy show nowadays

Be honest! Answers remain anonymous!

What do you think of *The Big Bang Theory*?

A People still watch TV?

B Seen it. Love it. Must-see TV.

C Seen it. Watch it as a guilty pleasure. Don't tell!

D Seen it. Meh. What else is on?

E Seen it. Hate it, hate it, hate it. I really do.

A Brief History of Time

The Very Early Universe & Ultra-High-Energy Physics

Planck Epoch: $t \lesssim 10^{-43}$ s

extrapolating back to this time:
general relativity invalid – quantum effects large
$\Rightarrow$ need quantum GR theory: **quantum gravity**
...which we do not have!

which means the one thing we *can* be sure of is that
we aren't yet "qualified" to go back earlier
to the big bang itself $t = 0$ sec!
$\rightarrow$ the nature of the big bang itself intimately tied
to the unification of gravity and quantum mechanics
the ultimate inner space/outer space connection!

A Brief History of the Universe II

Speculations on the High-Energy Frontier: Underlying Physics Unkown

Inflation: $t \sim 10^{-38}$ s **(???)**

exponential expansion: the original dark energy

quantum fluctuations $\rightarrow$ seeds of structure

Baryogenesis: $t \sim 10^{-37}$ s **(???)**

matter-antimatter asymmetry created

must occur after inflation

Dark Matter Created: $t \sim 10^{-20}$ s **(???)**

particles born in high-energy collisions

stable remains are in galaxy halos today

A Brief History of the Universe III

The Early Universe: Underlying Physics Known

Big Bang Nucleosynthesis: $t \sim 1$ s, $z \sim 10^{10}$

neutrinos freeze out, remain as cosmic neutrino background

light elements created

Matter-Radiation Equality: $t \sim 30$ kyr, $z \sim 3200$

matter density begins to exceed radiation density

$\rho_{\rm matter} > \rho_{\rm rad}$

expansion slows, structures begin to grow

Recombination: $t \sim 380$ kyr, $z \sim$**1100**

plasma $\rightarrow$ neutral gas

opaque $\rightarrow$ transparent

CMB photons free stream

A Brief History of the Universe IV

The Growth of Structure

The First Stars: $t \sim 100$ Myr, $z \sim 30$ **(???)**

very massive ($> 100 M_\odot$) $\rightarrow$ die as supernovae?

reionization of the universe?

Star Formation Peaks: $t \sim few$ Gyr, $z \sim 3$ **(??)**

elliptical galaxies, spheroids formed

Matter–Dark Energy Equality: $t \sim 4$ Gyr, $z \sim 1$

$\rho_{\text{dark energy}} > \rho_{\text{matter}}$

structure formation tails off

exponential expansion begins

A Brief History of the Universe V

To Infinity and Beyond

Sun Born: $t \sim 9$ Gyr, $z \sim 0.5$

Planets formed soon thereafter

Today: $t \sim 14$ Gyr, $z \equiv 0$

You take Astronomy 350

The Far Future: $t \gg 14$Gyr, $z < 0$

the Universe meets its final fate

big crunch? big chill? big rip? other?

Final iClicker Poll: Cosmic Surprises

Of the following aspects of modern cosmology

Which of these seems the most likely to be overturned?

A matter-antimatter difference due to early universe particle reactions

B dark matter as fossil exotic particles

C dark energy as origin of cosmic acceleration

Which of these seems the most likely to be confirmed?

NEW VIEWS OF THE COSMOS

New experiments and observations coming in the next few years
Likely to answer some questions, raise new ones

⋆ Gravitational wave detectors reawaken: LIGO/Virgo/KAGRA
upgraded: higher sensitivity – reach farther across the cosmos
mergers of stellar-mass black holes, neutron star. Kilonovae?

⋆ *James Webb Space Telescope* infrared telescope
new views of high-redshift Universe: first galaxies and stars

⋆ Vera Rubin/LSST and Nancy Grace Roman Telescopes
surveys of the sky from the ground and space
map galaxy evolution and cosmic expansion over time

⋆ CERN Large Hadron Collider upgraded to highest energy
potentially creating dark matter particles in the lab

OPEN QUESTIONS

⋆ Why do most (all?) galaxies have black holes at their centers? What does this have to do with galaxy formation?

⋆ What is the origin of spiral, elliptical galaxies? What role do mergers, dark matter play?

⋆ What is the nature of the dark matter in the Milky Way? Can we detect it?

⋆ What is the nature of the dark energy? Is it related to inflation?

⋆ What is the fate of the U.? Are we doomed to exponential expansion and the cosmic "tunnel vision" of a shrinking horizon?

⋆ What does the Milky Way's supermassive black hole look like? How does it change with time?
Good news: answer revealed next Thursday May 12

⋆ Is the dark matter a relic particle leftover from the early U.?

⋆ Did the universe undergo a singularity at $t = 0$? What is the nature of quantum gravity and what does this mean for the origin of the U.?

⋆ Will all of this be on the final?

Thank You!

Director's Cut Extras

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?