Astro 350
Lecture 13
February 16, 2022

Announcements:

- **Discussion 3** due today
- **Homework 4** due Friday
- Office Hours after class today or by appointment

Last time: hot gas as dark matter?
Q: why is hot gas a good DM candidate? how hot?
Q: how to test for hot gas DM? results? lessons?

Recap: Hot Gas as Dark Matter?

exceedingly useful fact:
everything glows if temperature above absolute zero!
blackbody radiation:
- color ↔ peak $\lambda \propto 1/T$: warmer=bluer, cooler=redder
- brightness/intensity/flux $F \propto T^4$

hot gas?
- if very hot, $T \gg 10,000$ K, peak λ is X-ray!
- not bright in optical/visible wavelengths!
- optically invisible!

Look with “X-ray vision” at clusters of galaxies
- hot gas found between galaxies!
- intracluster gas has more mass than the galaxies!

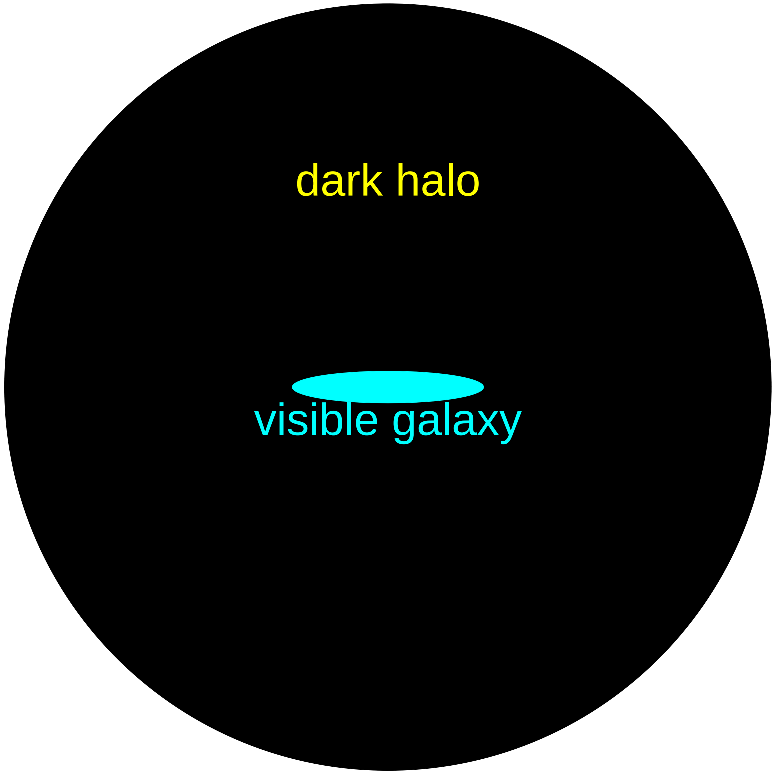
⇒ *hot gas* is *a form of dark matter!* (optically invisible)
- but :still find $M_{\text{galaxies}} + M_{\text{gas}} \ll M_{\text{gravitating}}$

⇒ the *majority of dark matter is* not *hot gas*! mystery remains!

Lineup of Dark Matter Suspects

~~hot gas~~ cold gas	diffuse ordinary matter: gas
black holes neutron stars white dwarfs brown dwarfs planets: "Jupiters"	clumpy ordinary matter: compact objects = dead and failed stars
neutrinos relic particles from big bang	diffuse matter: exotic particles

- Next stop: cold gas



Imagine the dark halo is made of cold gas

how can we detect it?

Cold Gas as Dark Matter?

recall Wien's law–thermal radiation color: $\lambda_{\text{peak}} \propto 1/T$
hotter $\leftrightarrow$ bluer, colder $\leftrightarrow$ redder (not faucet pattern!)

if gas has $T \ll 3000$ K, then λ_{peak} in IR or radio
$\Rightarrow$ very dim at optical wavelengths

suggests obvious test: look for cold gas halos of galaxies
$\Rightarrow$ search for thermal infrared or radio

But: thermal emission depends strongly on T
for object at temperature T, of fixed size
emitted blackbody radiation (i.e., luminosity) $L_{\text{therm}} \propto T^4$
$\rightarrow$ hot objects hugely luminous, but cold objects not
$\rightarrow$ if gas very *cold*, also very *dim*–too dim to see!
$\rightarrow$ so lack of IR or radio signal does not prove lack of cold gas
Q: how else can we test for cold gas?

Light and Atoms

Experiment: tube with hydrogen gas under high voltage
$\rightarrow$ high-energy electrons accelerated, collide with gas atoms
atoms receive energy from collisions, emit light

Vote your conscience!
What will spectrum of tube look like?

A continuous: all visible colors = all λs

B bands of colors = λs in only some ranges

C only a few *single* colors = a few individual λ

New experiment: view blackbody source,
with cold hydrogen gas between source and us
What will the spectrum look like?

The Quantum Atom

at small distances (size of atoms) Newton's laws *fail*!
atoms, light obey new & different rules: **quantum mechanics**

electron orbits

nucleus + e: like solar system?
No! QM $\rightarrow$ e not like planet
in atom, acts like wave !?!

▷ *most* orbits *forbidden*!
▷ only special orbit distances allowed $\rightarrow$ "quantized" in steps

special allowed orbits $\rightarrow$ special allowed distances and speeds
and thus *special energies*
list of all allowed orbit energies: **energy levels**
lowest energy $\rightarrow$ stable orbit, closest to nucleus
"ground state" `www: hyrdogen atom simulation`

Photons

just as matter (like e) can sometimes act like waves
light can sometimes act like particles...

on small lengthscales or low intensities
light acts like *particle*: "**photon**," symbol γ

photon is discrete "lump" or "packet" of energy
different colors $\leftrightarrow$ different photon energies
smaller λ $\rightarrow$ higher E:

$$E_{\text{photon}} \propto \frac{1}{\lambda} \tag{1}$$

blue photons have shorter λ than red photons
$\rightarrow$ blue photons have more energy
Q: what kind of photons have the most energy? the least?

Light-Atom Interactions

If light hits atom **and** photon energy = atom energy level

1. atom absorbs photon
2. e jumps to higher level
3. atom in "excited" state

but excited = unstable

after time,

1. e spontaneously jumps back to ground state
2. emits photon whose energy = excited − ground *difference*

Atoms and Light: Cosmologist's Barcode

Atoms absorb/emit light

atom structure sets energies, and $\lambda \propto 1/E$

...which is different for different atoms

so energy level spacings different for different atoms

light spectrum gives atom "fingerprint" or "barcode"

spectrum $\rightarrow$ composition

Measuring the Composition of the Cosmos

Example: The Sun

Sun, stars hotter, denser in center cooler, less dense at surface

so: sunlight/starlight shows *Q: what kind of spectrum?*

`www: Sun spectrum`

amount absorbed in each line → amount of atoms

→ **composition** of Sun; works for other stars too!

Example: interstellar gas in our Galaxy

look at stars in our own Galaxy

light passes thru space between us and the star

Q: if interstellar gas, what should we see?

`www: starlight spectrum`

interstellar gas revealed! and composition found!

→ mostly hydrogen and helium, about 2% heavy elements

Dark Matter as Cold Gas Halos?

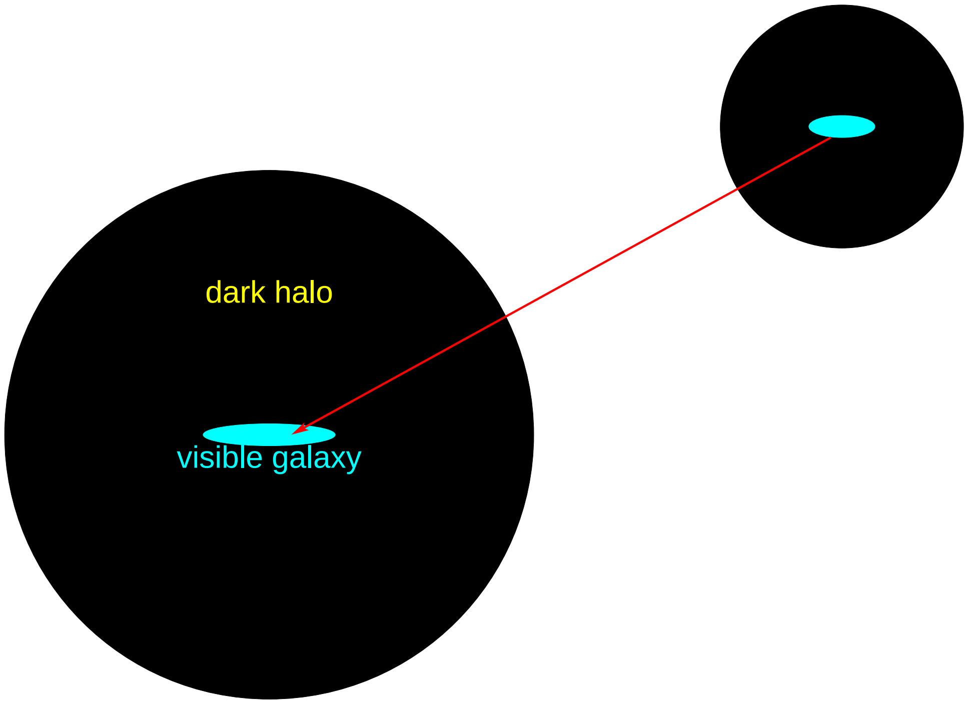
What if dark matter is in the form of cold gas?

If galaxy dark halos are made of cold gas

- all galaxies embedded in huge clouds of (neutral) atoms including our own!
- cold $\to L \propto T^4$ small – thermal glow dim, maybe missed! could "hide" from IR and radio telescopes!

But note: when we observe other galaxies
their light must pass through the halo of our own!

Q: how to test for cold gas in our own halo?



If dark halos are cold gas: halo atoms will absorb light

we should see absorption lines:

- from halo gas in our Galaxy
- from halo gas surrounding luminous parts of other galaxies

Poll: Dark Matter as Cold Gas–Lay Your Bets

Look at **spectrum** of light from distant galaxies
if cold gas fills our dark halo
atoms will absorb photons if match energy levels $\rightarrow$ spectral lines

Vote you conscience!

What will we find in the spectra?

A strong absorption lines from our halo
cold gas is the dark matter!

B no/weak absorption lines
cold gas is not the dark matter!

C none of the above

Cold Halo Gas?

galaxy spectra show *no lines*
as light passes *into* our own dark halo
$\rightarrow$ our Galaxy not surrounded by cold gas!

also: *no lines* from cold gas reservoirs
as light passes *out* of distant galaxies
$\rightarrow$ other galaxies also not surrounded by cold gas!

Conclude: *cold gas is not the dark matter*
mystery persists! must look elsewhere!

Lineup of Dark Matter Suspects

~~hot gas~~ ~~cold gas~~	diffuse ordinary matter: gas
black holes neutron stars white dwarfs brown dwarfs planets: "Jupiters"	clumpy ordinary matter: compact objects = dead and failed stars
neutrinos relic particles from big bang	diffuse matter: exotic particles

diffuse (non-clumpy) ordinary matter ruled out!

what about clumpy ordinary matter: compact objects

$\rightarrow$ all arise from birth and death of stars

Stars and Cosmology

The Facts of Life for Stars

Fact: stars constantly radiates energy
and at a huge rate!
the Sun: a lightbulb with wattage $L_\odot = 4 \times 10^{26}$ Watts!

Fact: stars have a finite ($\neq \infty$) mass
and thus a finite fuel supply (whatever that fuel may be)

Fact: Energy is conserved
no free lunch!

Q: therefore?

Star Lives and the Consequences of Energy Conservation

the Sun and all stars:

- are constantly releasing energy to the rest of the universe, and
- require fuel, and are unable to "refuel" out of nothing, and
- thus must eventually run of out fuel

Thus:

- all stars – including the Sun – must eventually "burn out"
  = run out of fuel: *all stars are doomed to die*
  Q: important followup question?
- stars do not live forever

And thus:

- stars alive today were not alive forever
- *all stars must be born* as well as die

stars have life cycles

Director's Cut Extras

Kirchhoff's Laws

some gas absorbs light, some emits
which is which?
$\Rightarrow$ depends on gas **density**, T

Kirchhoff:

1. if solid or dense gas is hot
   emits **continuous** spectrum: blackbody

2. if thin, rarefied gas is hot
   emits **emission line** spectrum

3. if continuous spectrum passes thru cool gas
   atoms absorb light $\rightarrow$ **absorption line** spectrum