What's the Deal with Dark Matter?

Quarknet 2017
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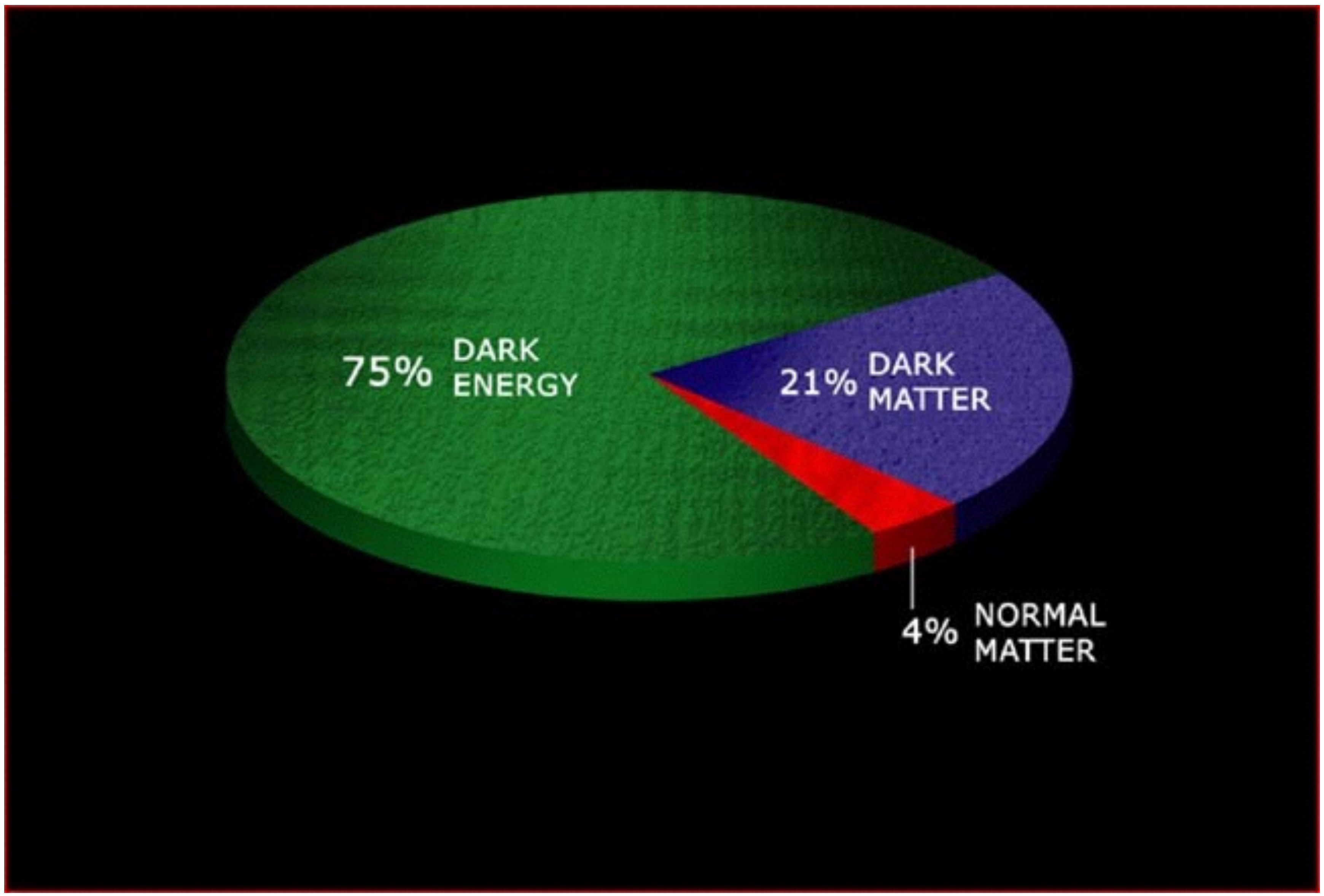
STOP
Me If You Have Questions

Dark Matter

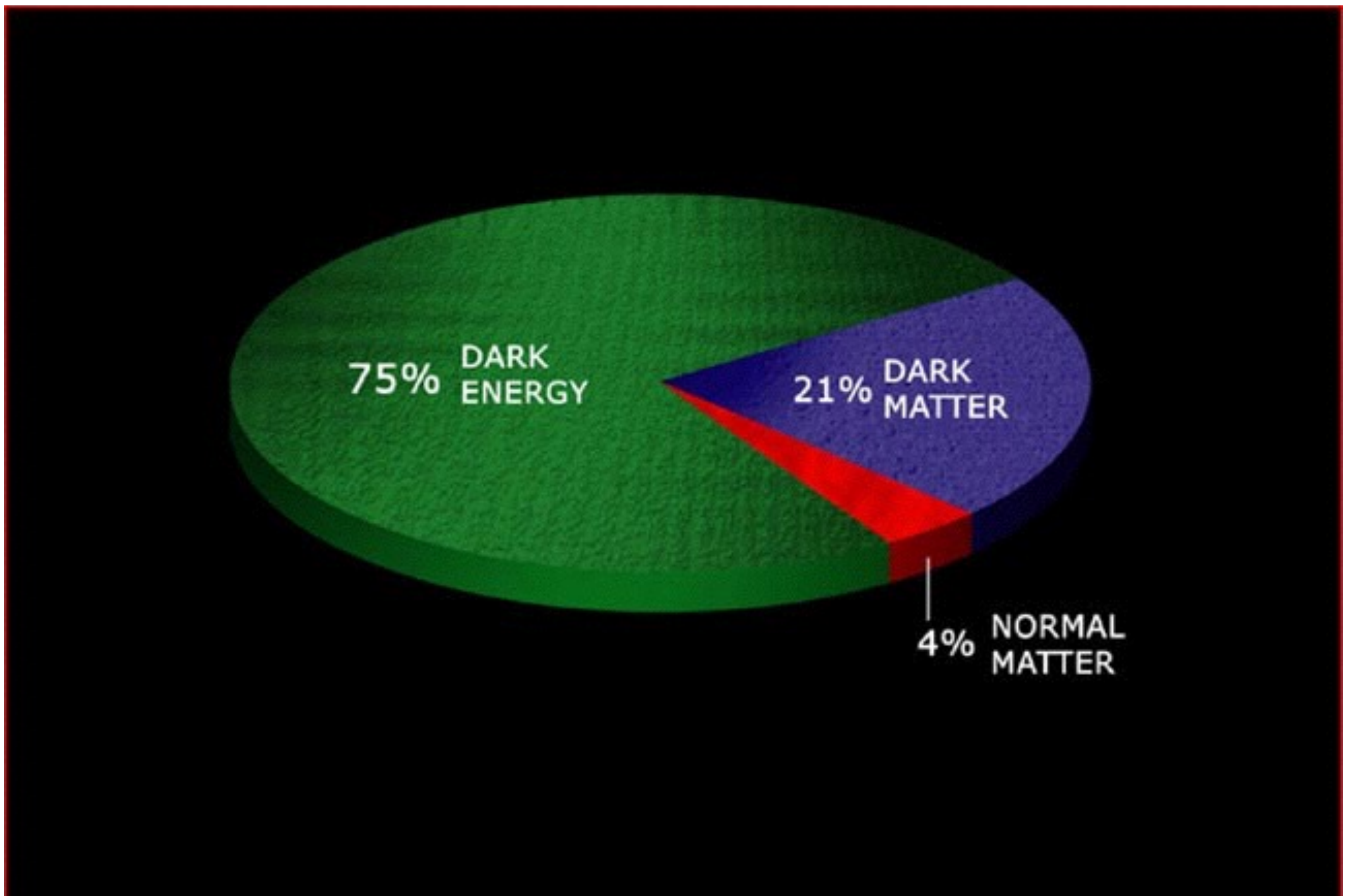
- Have you seen this pie chart, or something like it? This is the Energy Budget of the Universe.



We know basically nothing about what's in the universe.

Dark Matter

- Today I’ll talk about the blue part,
  Dark Matter,
  which we sort of understand.



What I'll Talk About

- Where (and how) we can find Dark Matter.
- What it probably is,
  and almost certainly isn't.

What I'll Talk About

- Where (and how) we can find Dark Matter.
    - Basically anything astronomically large.
    - Measure mass, count protons (baryons), compare.
- What it probably is,
  and almost certainly isn't.
    - It is probably not black holes of any size.
    - It is probably not brown dwarfs or other gas-like thing that we just can't see.
    - It is probably not an error in our understanding of gravity (though there is certainly at least one)

The Hardest Questions in Astronomy:

- How far away is that?

  and related,

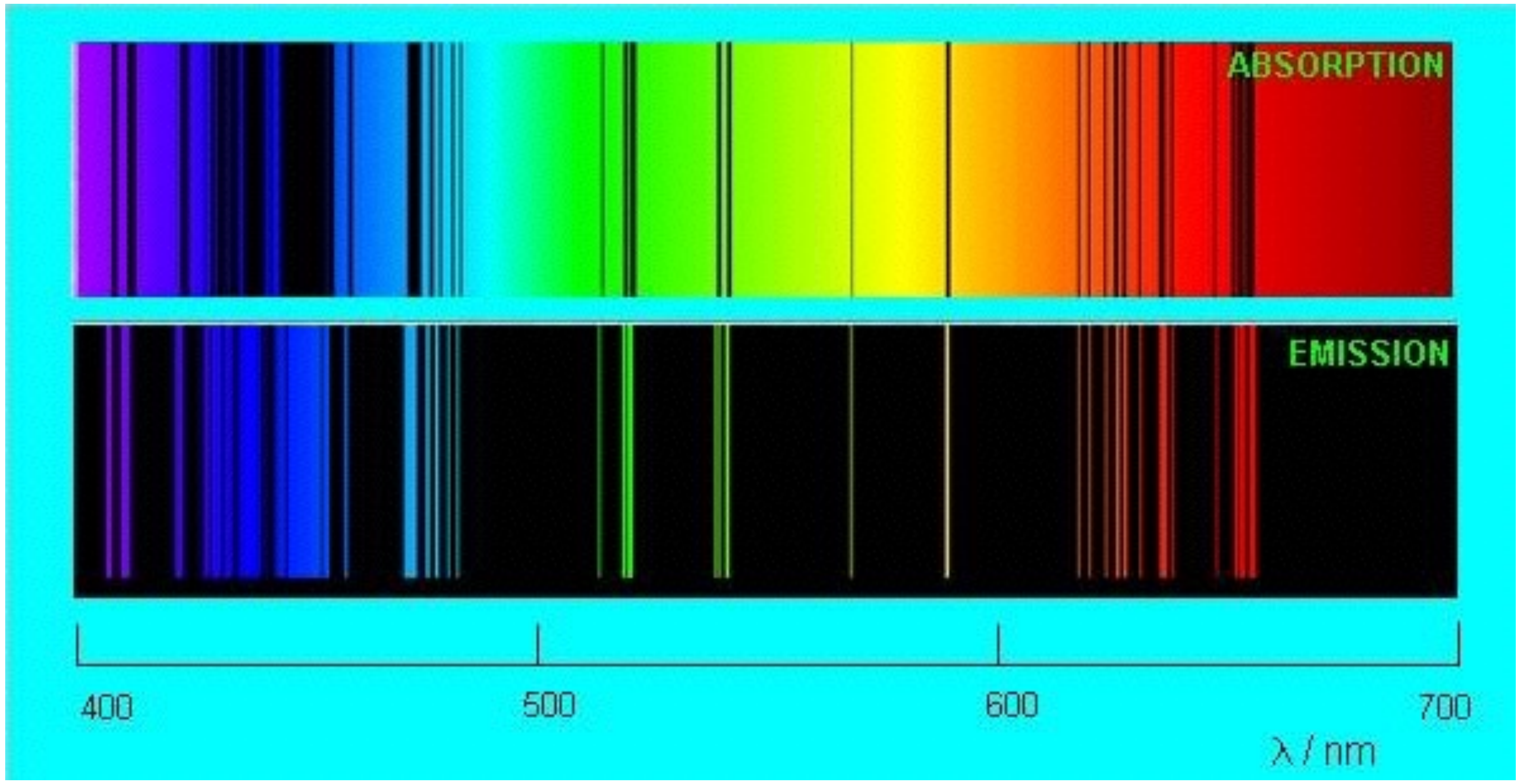
- How massive is that?

Much easier questions in Astronomy

- How hot is that?

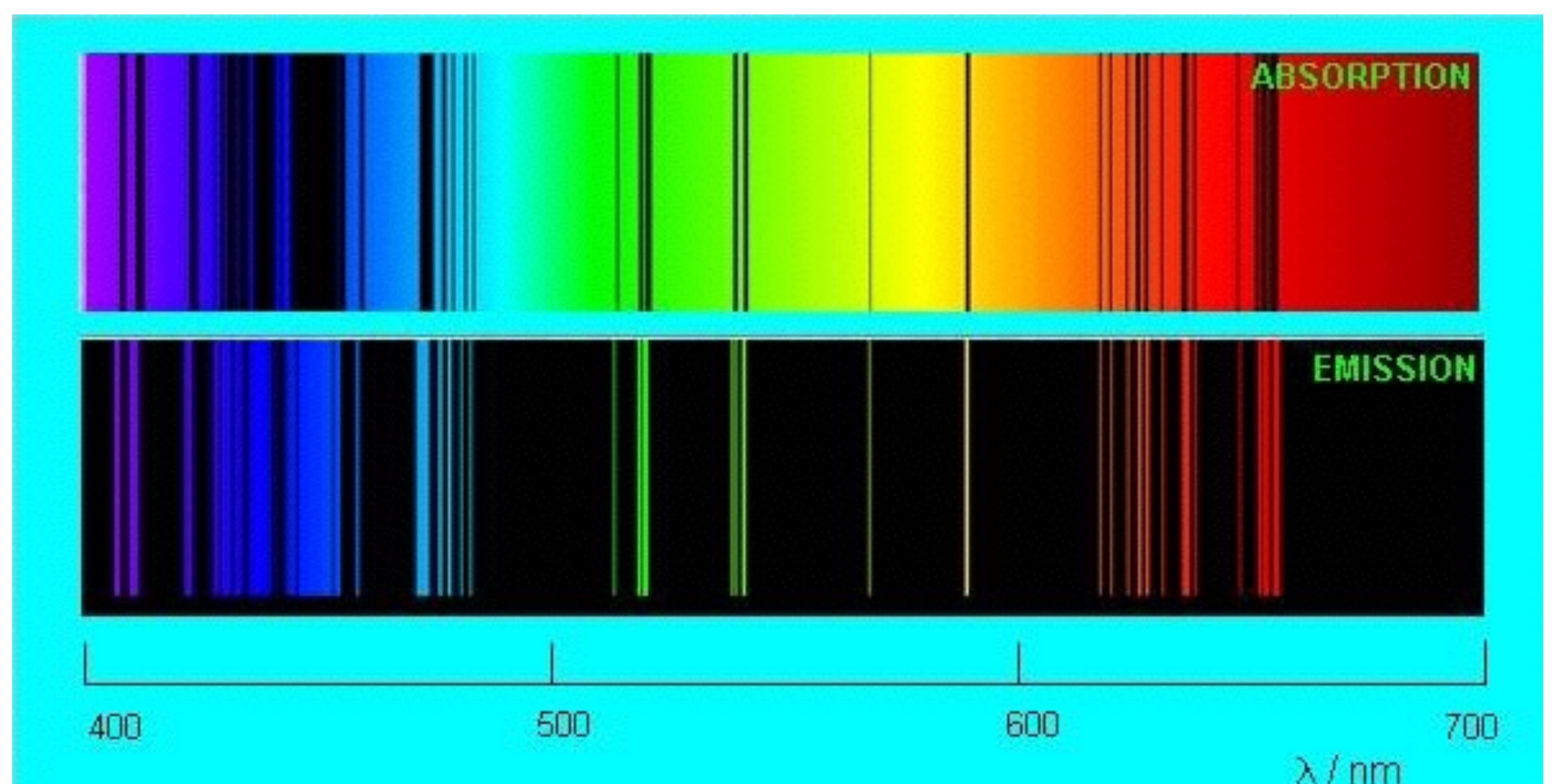
- How fast is that moving?
  (away from me?)

- Both of these from Spectra



What's a Spectrum?

- A fingerprint of the stuff, in photons.
- **Thermal** motion gives a broad distribution of light.
  - The peak wavelength decreases with T. **More hot is more blue**
- Energy **transitions** give very narrow lines of exactly one frequency.
- Doppler shift of that frequency lets us measure velocity.



What's Mass?

- The m in

$$F = ma$$

- The m in

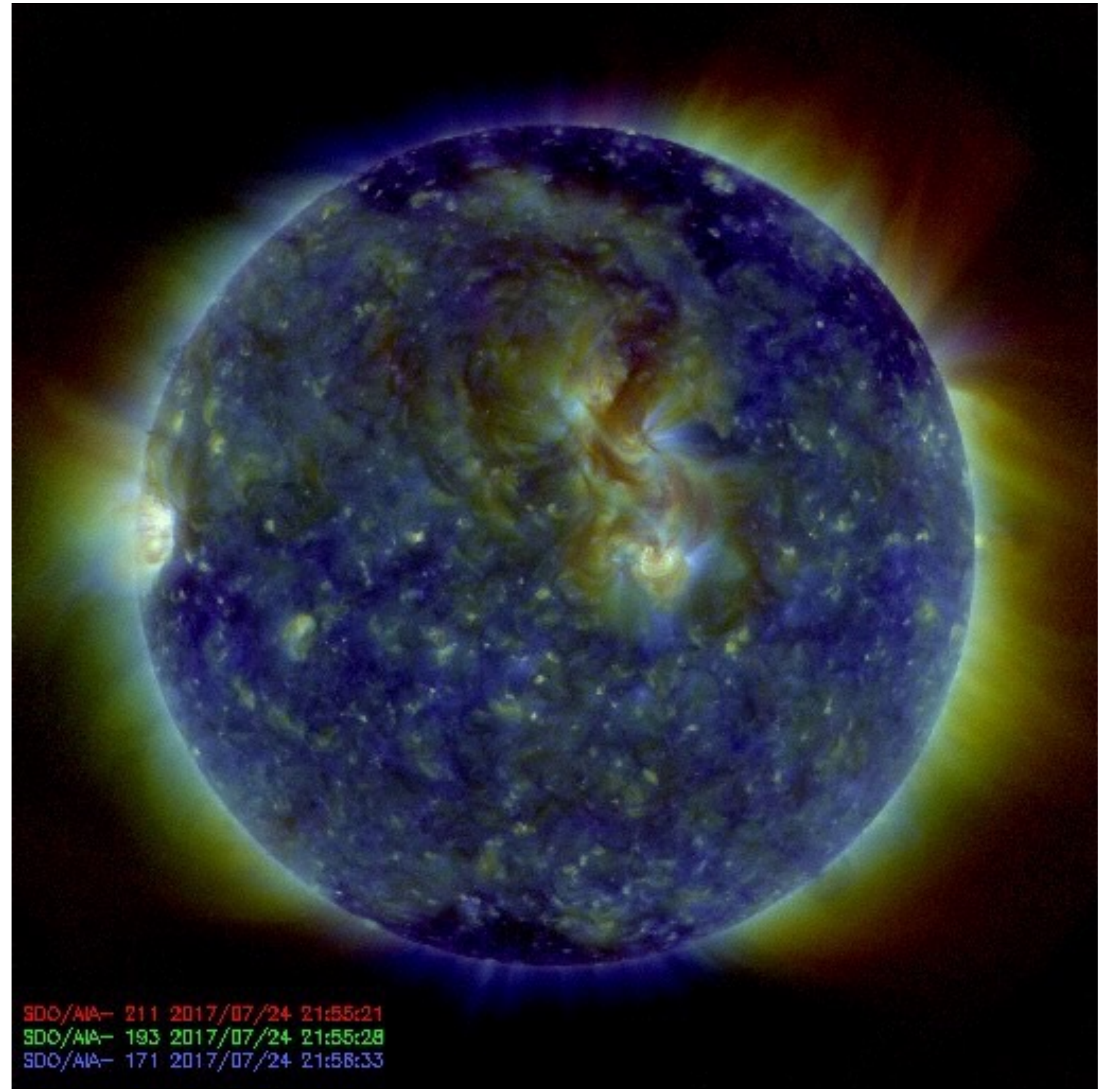
$$F = \frac{Gm_1m_2}{r^2}$$

- The energy contained in the system.
  (Loosely, the number of protons and what they're doing)

- We're going to assume they're all the same.
  (Rather, to the extraordinary limits of human measurement, they're the same.)

Gravity

$$F = \frac{Gm_1m_2}{r^2}$$

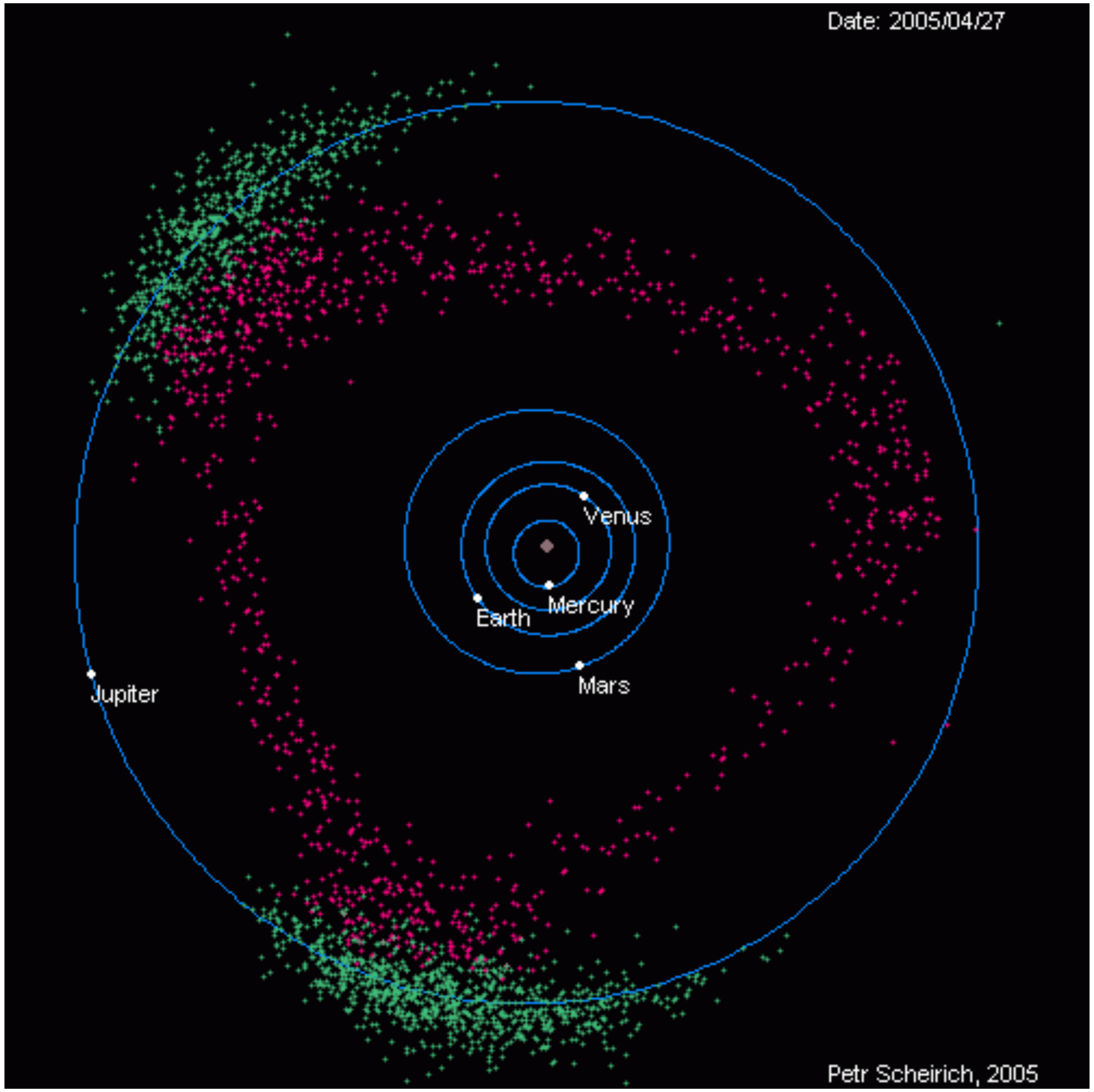


(the sun as of 6:20 pm last night)
(Solar Dynamics Observatory is cool)

Gravity

- To stay on a circular orbit,

$$F = \frac{\mathrm{m}\, v^2}{r}$$



Gravity

- so we can use Newton to relate
  MASS AND VELOCITY
  for objects moving around each other

$$\frac{G m_{\mathrm{stuff}}}{r^2} = \frac{v^2}{r}$$

$$m_{\mathrm{stuff}} = \frac{v^2 r}{G}$$

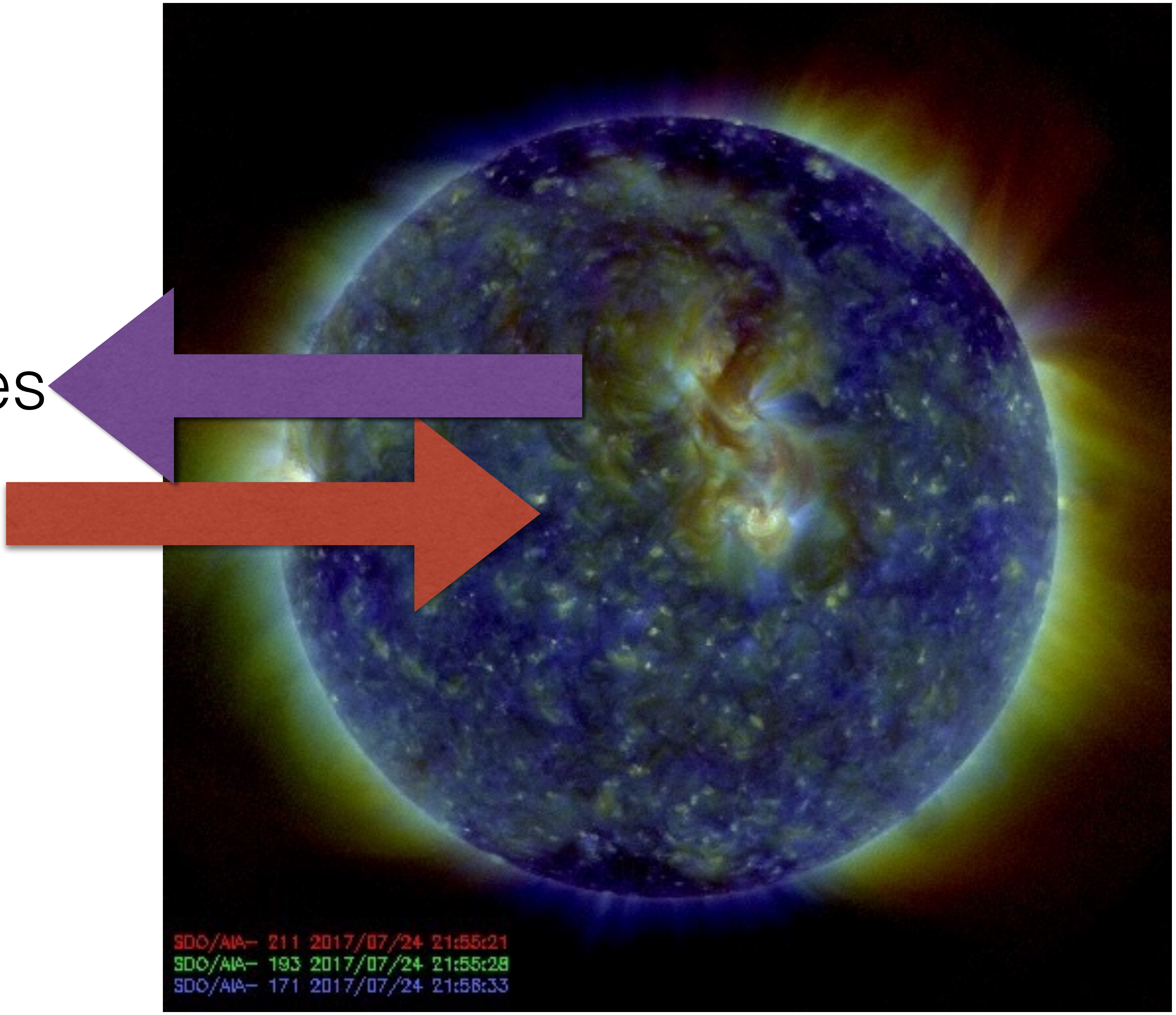
Light from Stars.

- Stars are really well understood. (They're spheres, and not evolving very fast.) There are 4 bits.
  - Pressure vs. Gravity
  - Mass vs. Density and Size
  - Energy production
  - Thermal conduction

Υ

Light from Stars

- **Gravity** pulls in, **pressure** gradients push out.
  They balance.
  More pressure makes **more temperature**



Light from Stars

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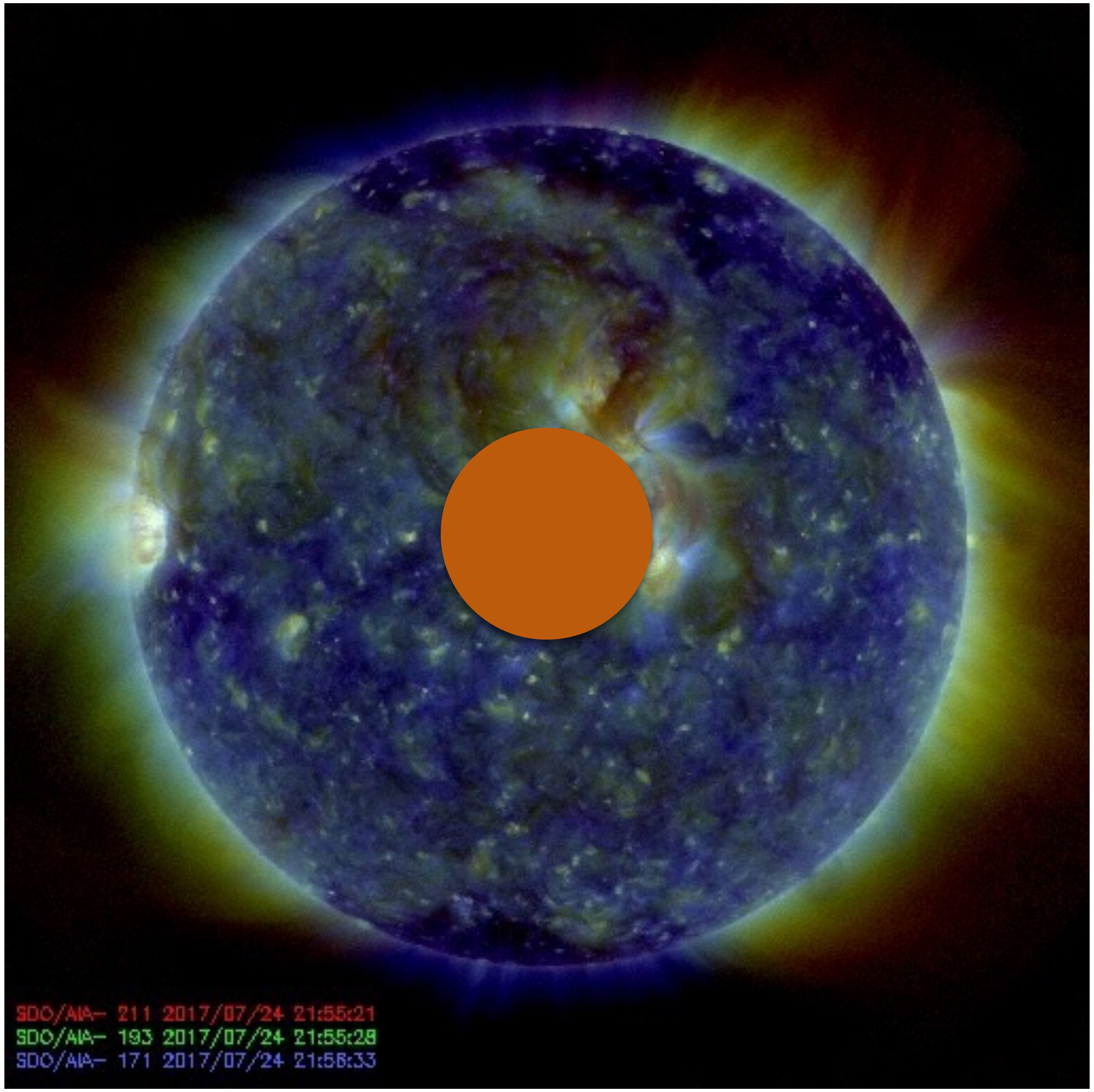
- **Nuclear Fusion** produces energy in the core



Light from Stars

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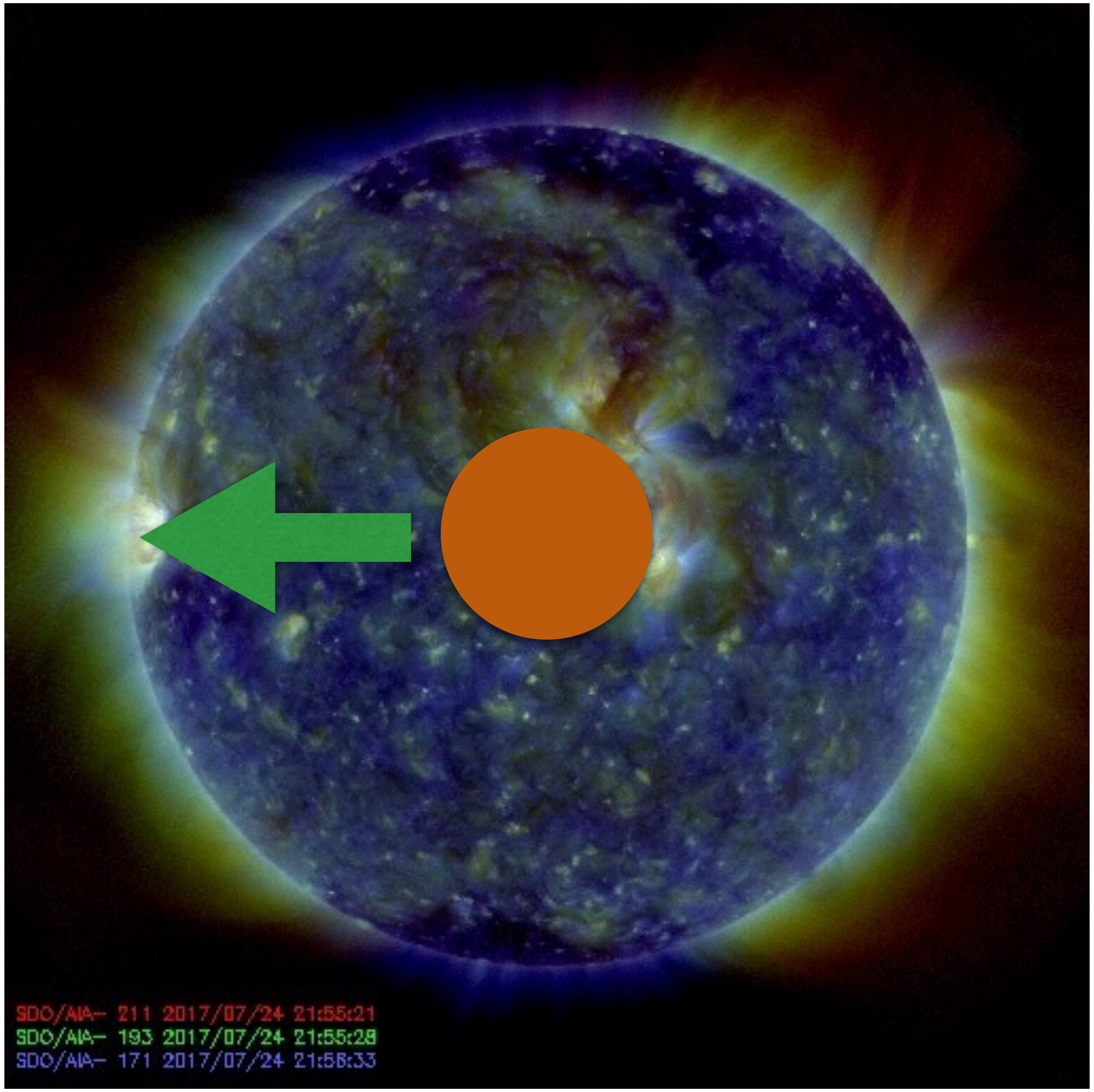

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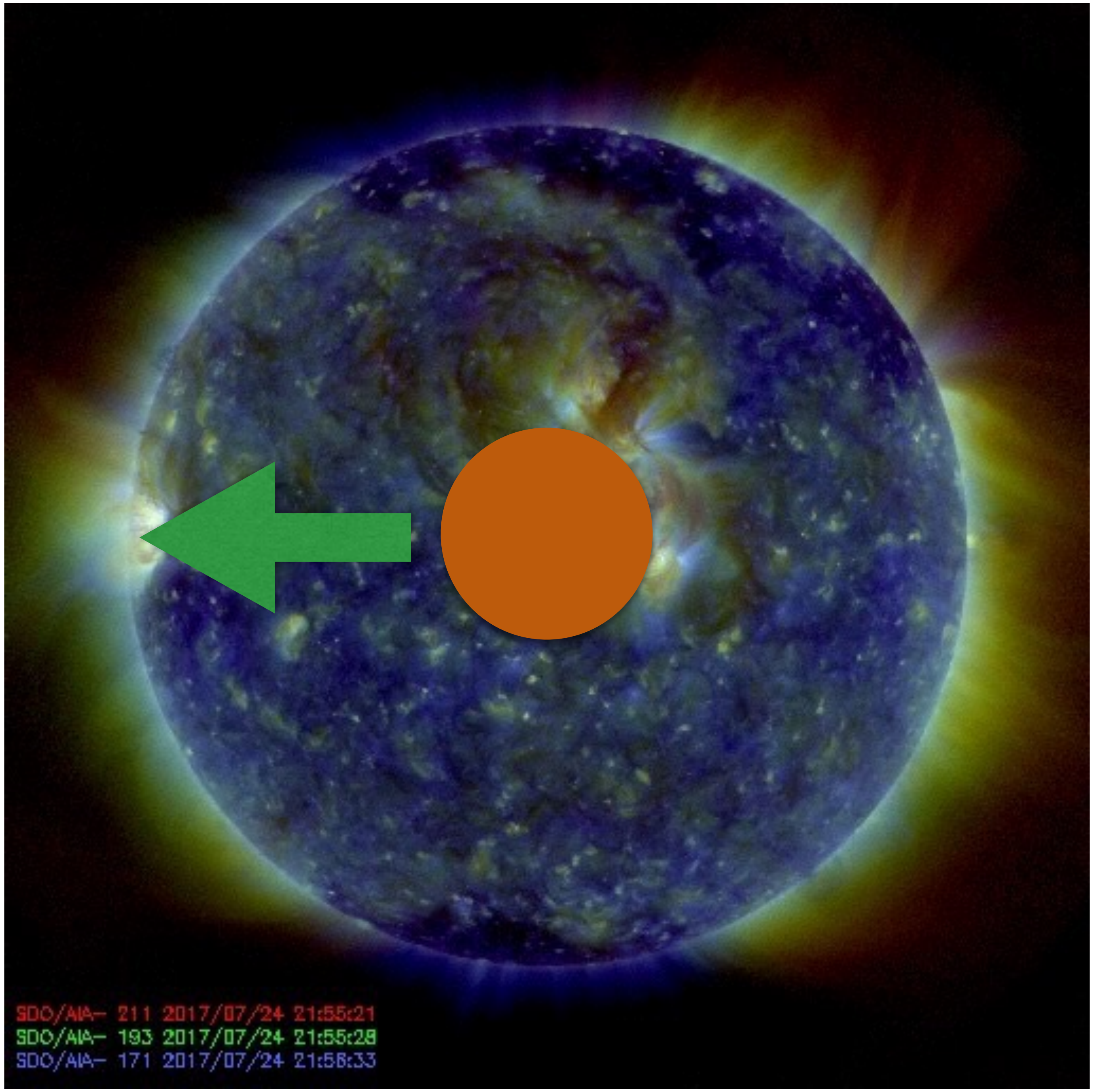
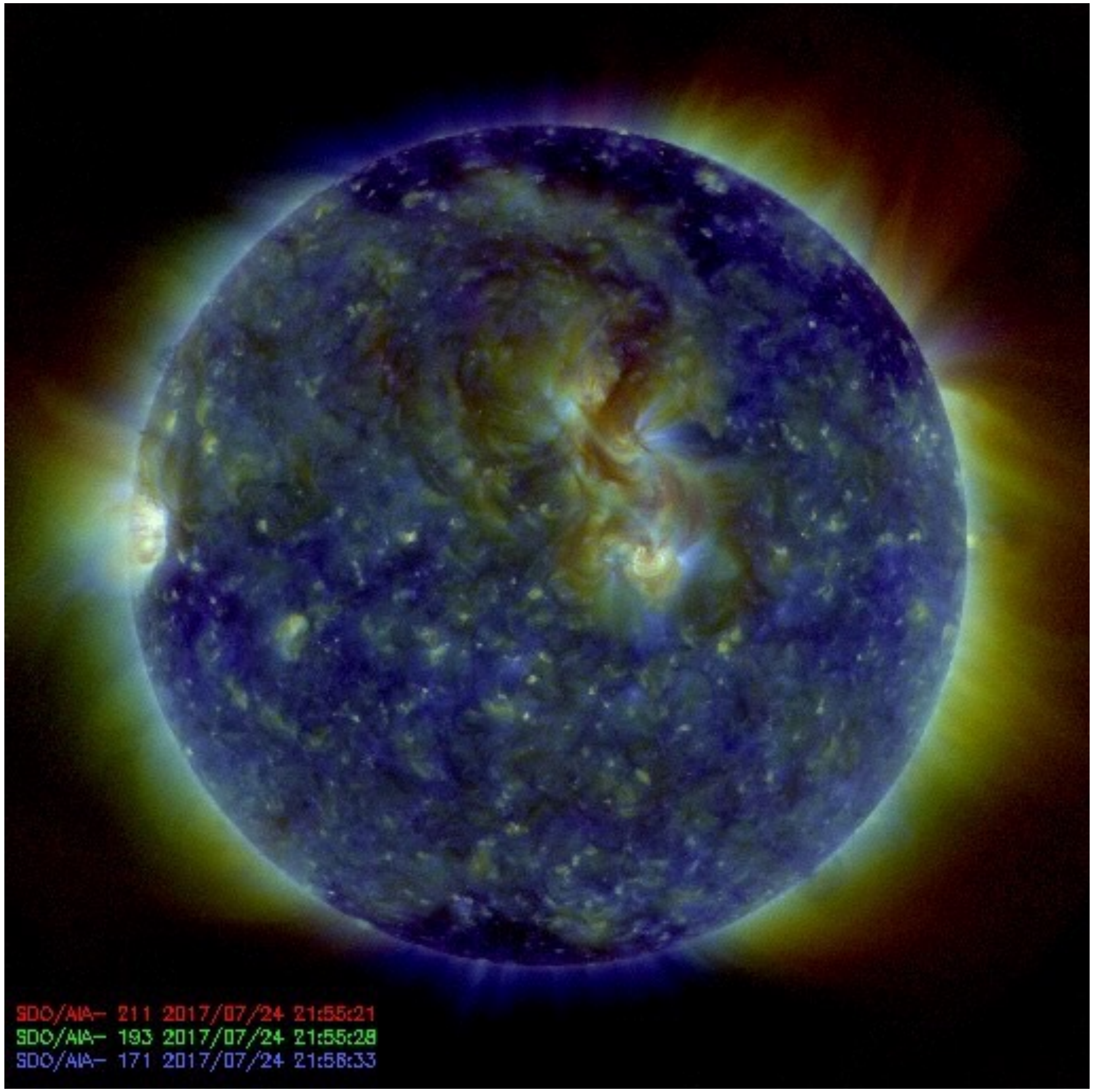


- **Photons** leave the star, and we can get its Temperature.

Light from Stars

- **The light from stars, and the relationship to mass, is very well understood.**



Light from Stars

- Stars are really well understood.
  - Gravity pulls in, drives fusion, photons come out.
  - Υ = Mass/Light
- For the sun, 5133 kg/W (bit smaller for bigger stars)

$$\Upsilon$$

(At 2000 Cal/day, I emit about 100 W,
so my mass/light is about 0.53 kg/W)
(or I used to be)

So!

- Discuss with your neighbor:
  - What’s Mass-To-Light ratio for a trillion solar-mass stars (in units of Solar mass-to-light)?

Light

- Mass from Light is pretty easy:
  L is the Luminosity of the objects

$$m_{\mathrm{stuff}} = L\Upsilon$$

They should give us the same answer.

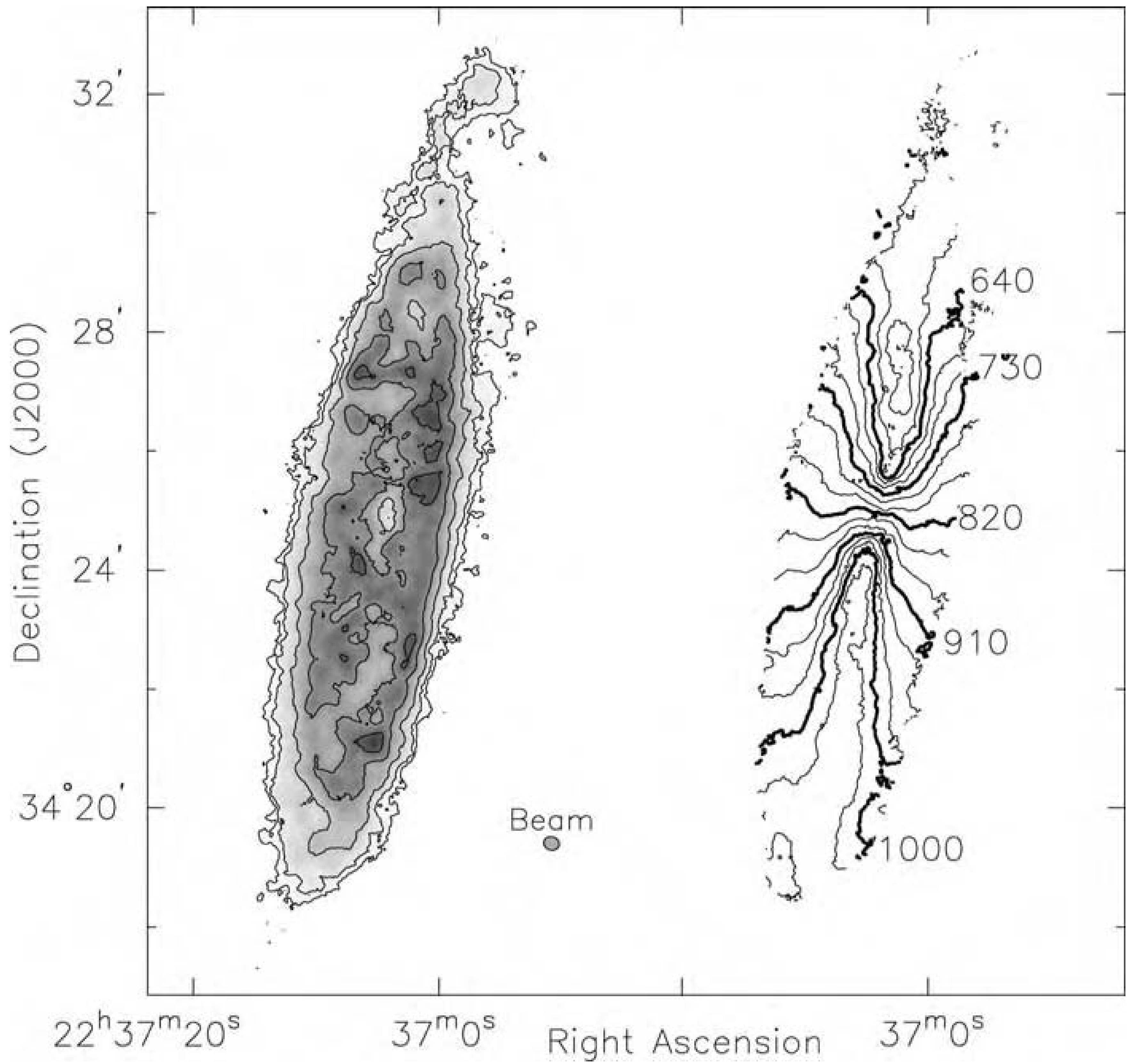
$$m_{\mathrm{stuff}} = L\Upsilon$$

$$m_{\mathrm{stuff}} = \frac{v^2 r}{G}$$

(I've glossed over a couple integrals for clarity, ask me later if you want more details.)

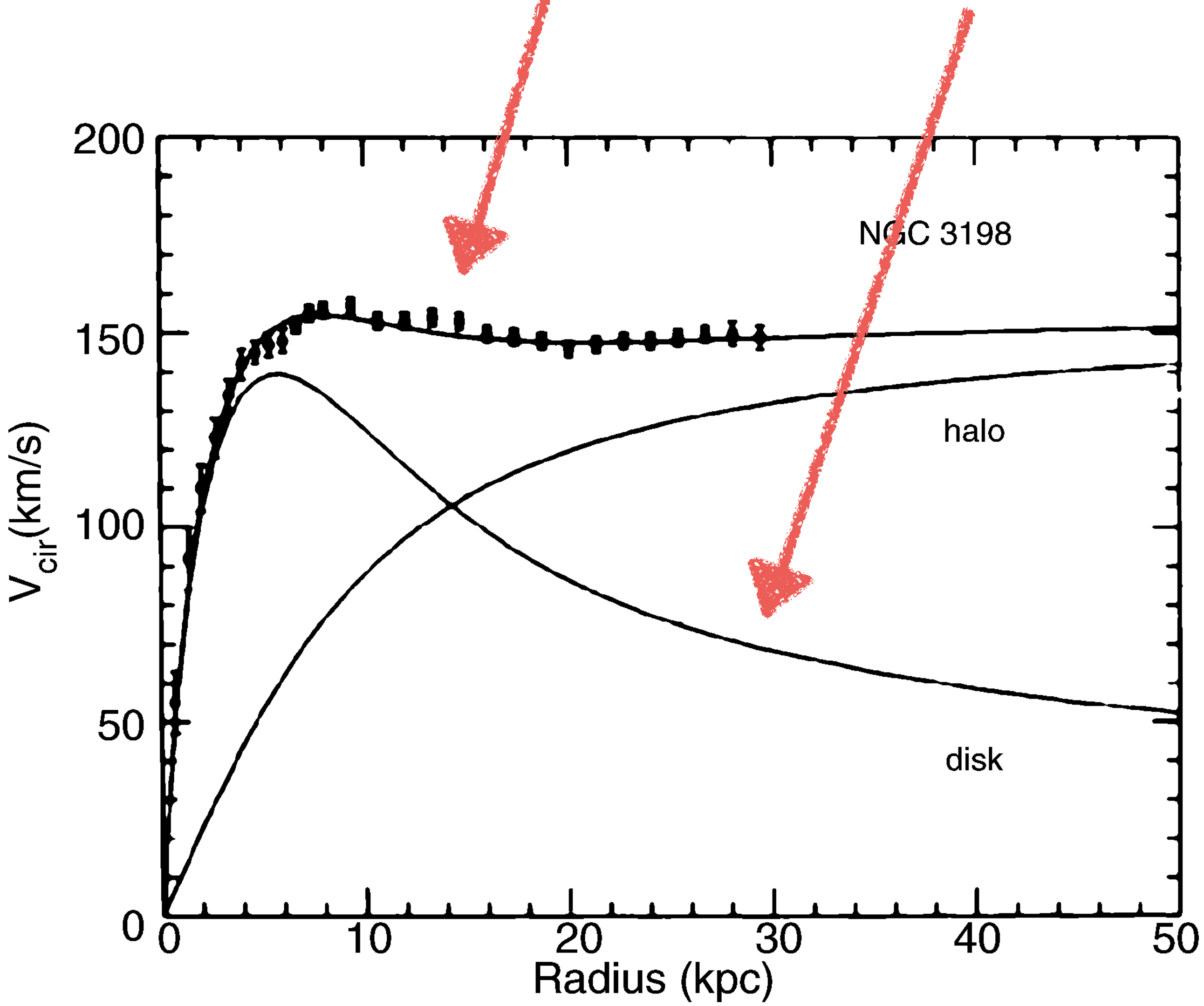

NGC7331

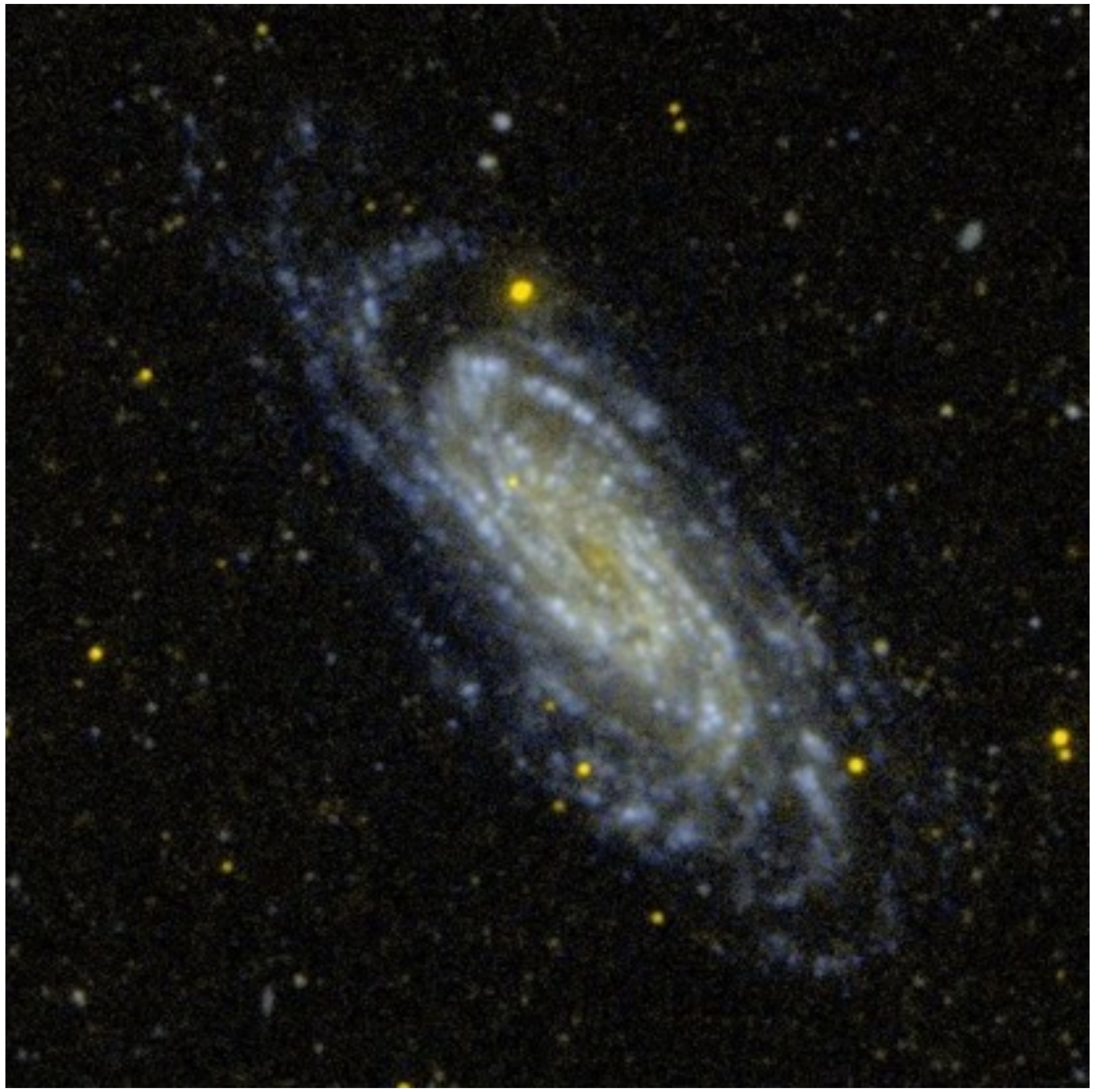
- NGC 7331 in 21 cm, with velocity contours
- 21 cm is a radio line that comes from Hydrogen.
- Looking at the side of a galaxy gets you its rotation.



Lets put all this together.

- Top line: velocity I measured.
- Bottom line: velocity I'd get if I only used the light

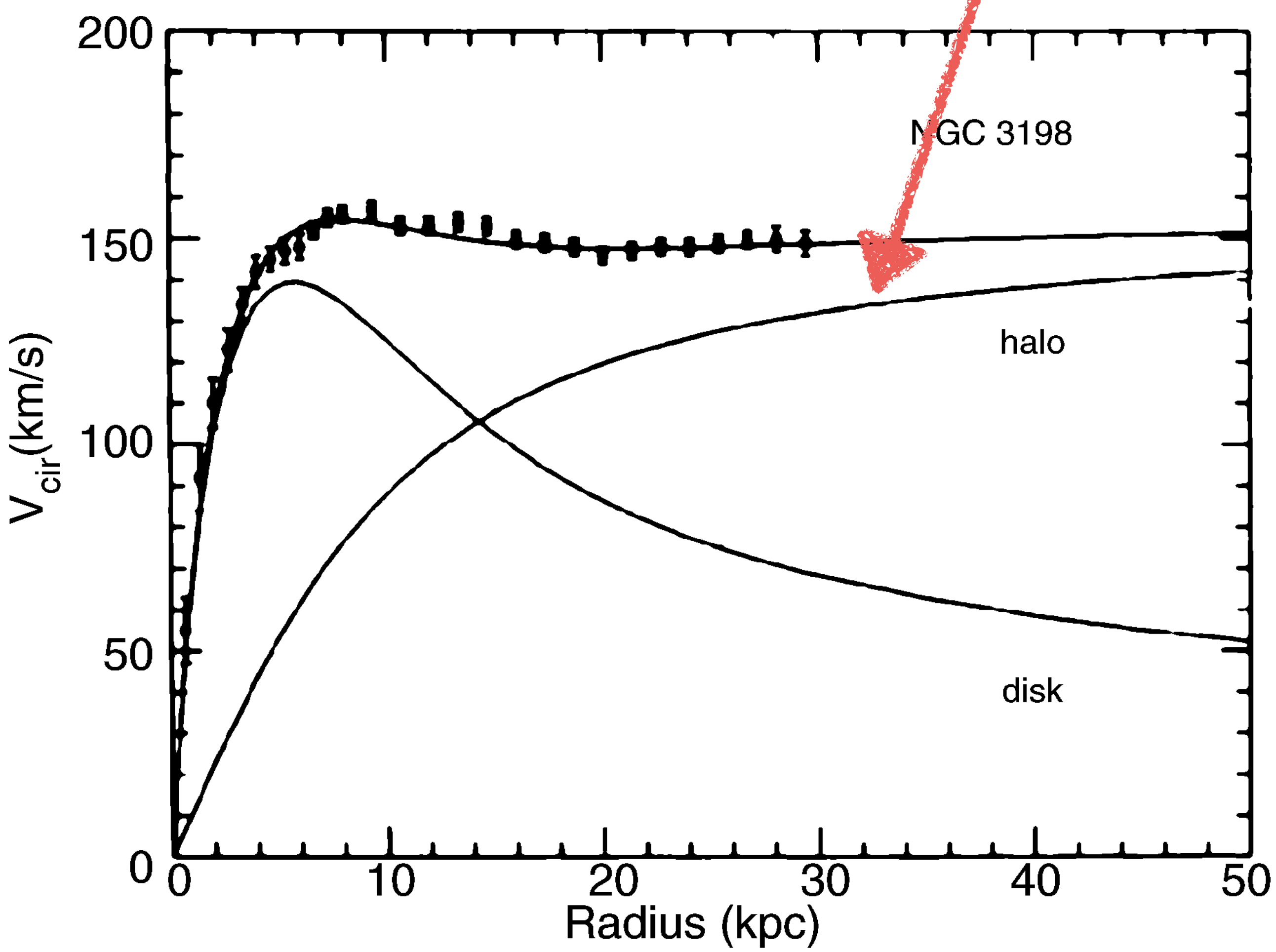




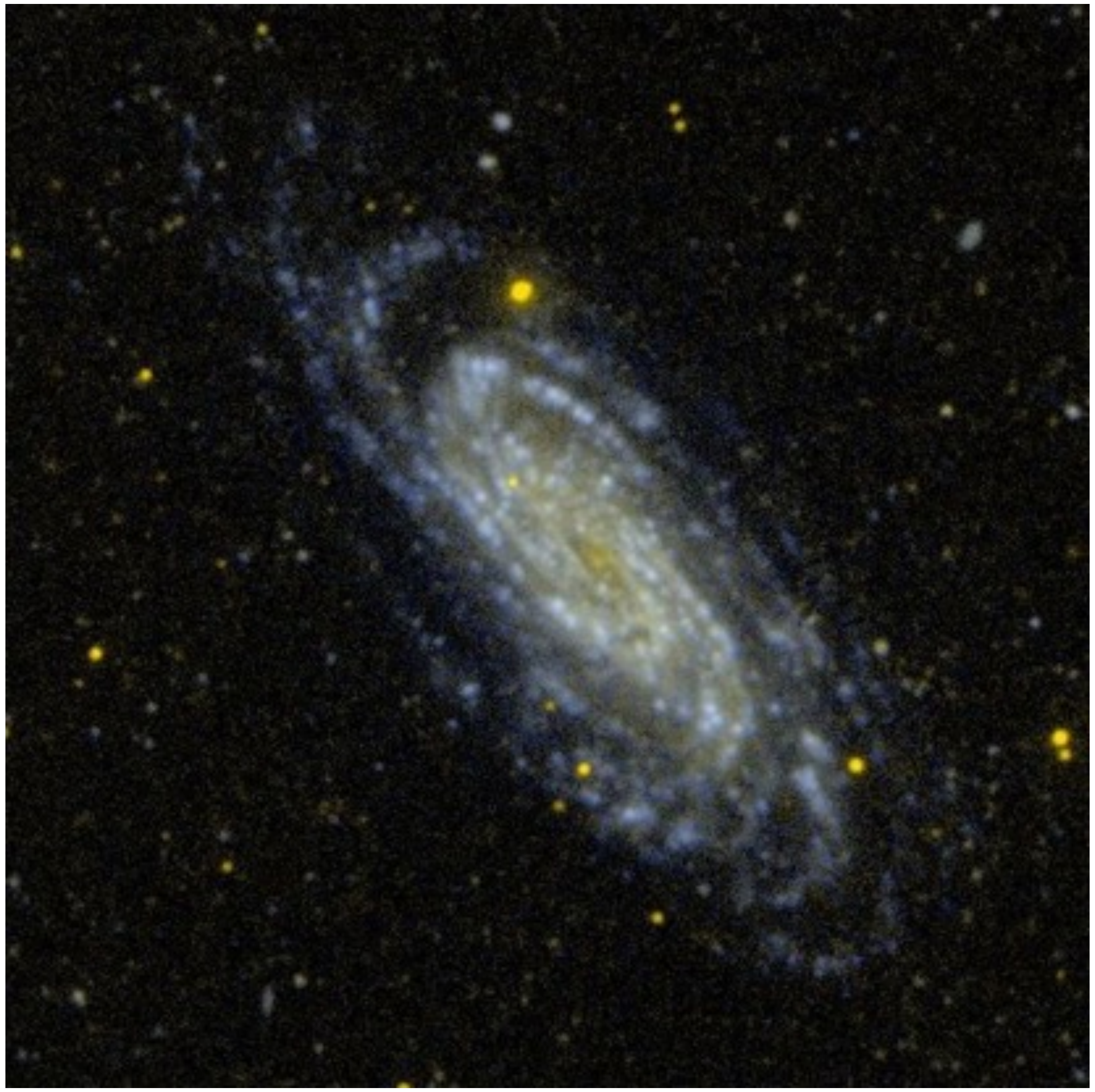
$$m_{\mathrm{stuff}} = \frac{v^2 r}{G} \quad = L\Upsilon$$

Lets put all this together.

- We need this much to make up the difference.
- And it gets FLAT.



$$m_{\rm stuff} = \frac{v^2 r}{G} \quad = L\Upsilon$$

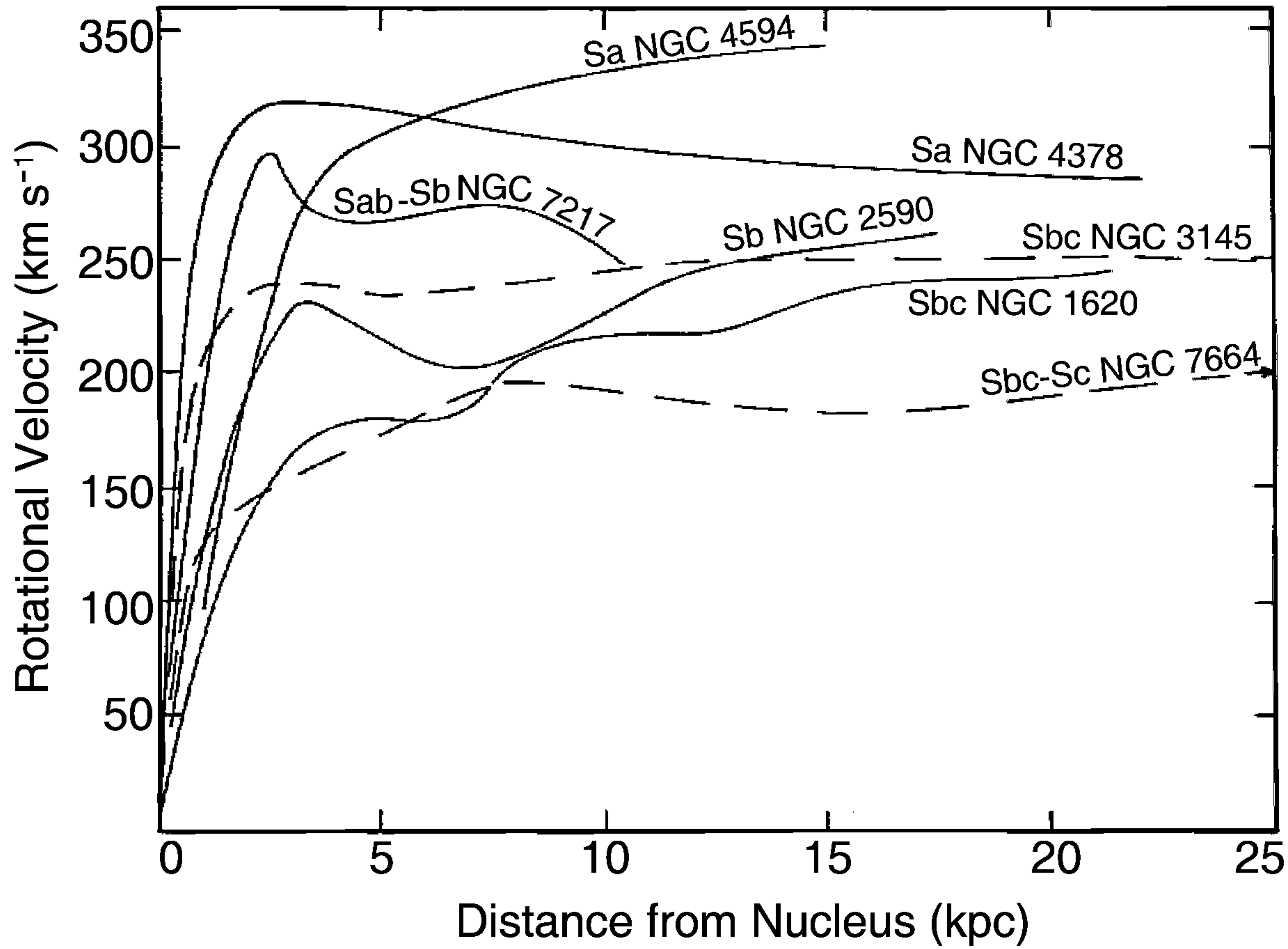


This is in basically all of them.

- It looks like v is constant, so

$$m_{\text{stuff}} = \frac{v^2 r}{G}$$

$$m_{\text{stuff}} \propto r$$



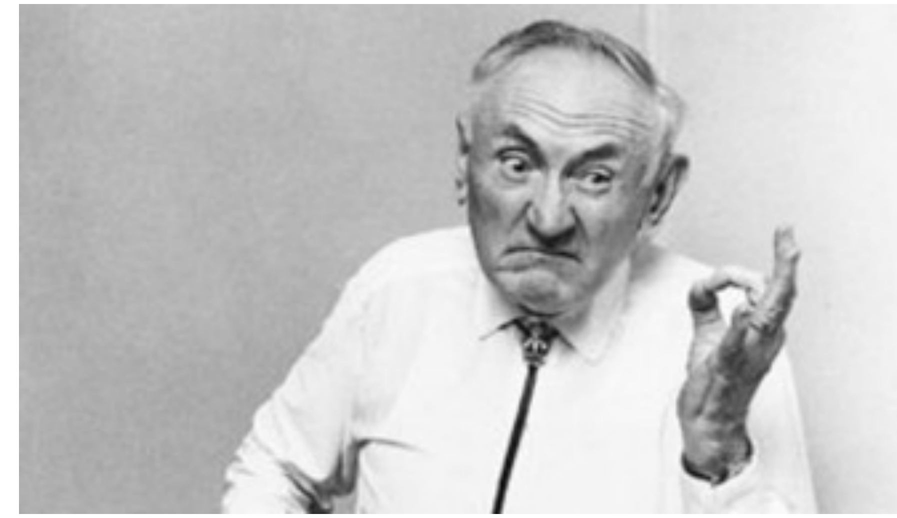

It’s clear that stars don't in crease with radius.
This isn’t just a calibration issue, the whole behavior is bizarre.

It’s not just spiral galaxies.

- Galaxy clusters!
- Really Huge Structure!
- The amount of Hydrogen in the Universe!

Galaxy Clusters

(Fritz Zwicky, 1937)



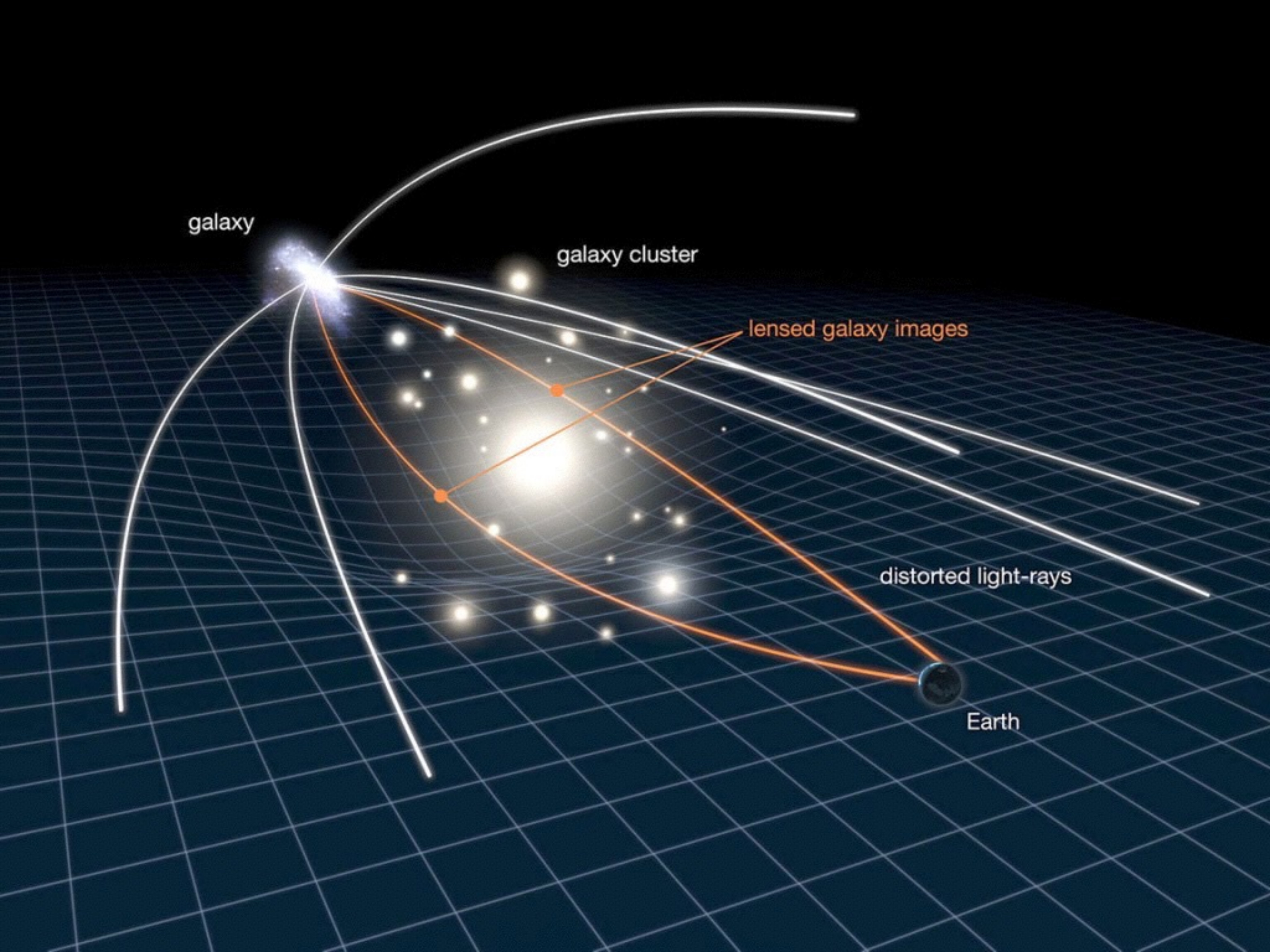
- Huge groups of galaxies
- Again, the galaxies are MOVING TOO FAST for the amount of for the light. $\Upsilon=300$

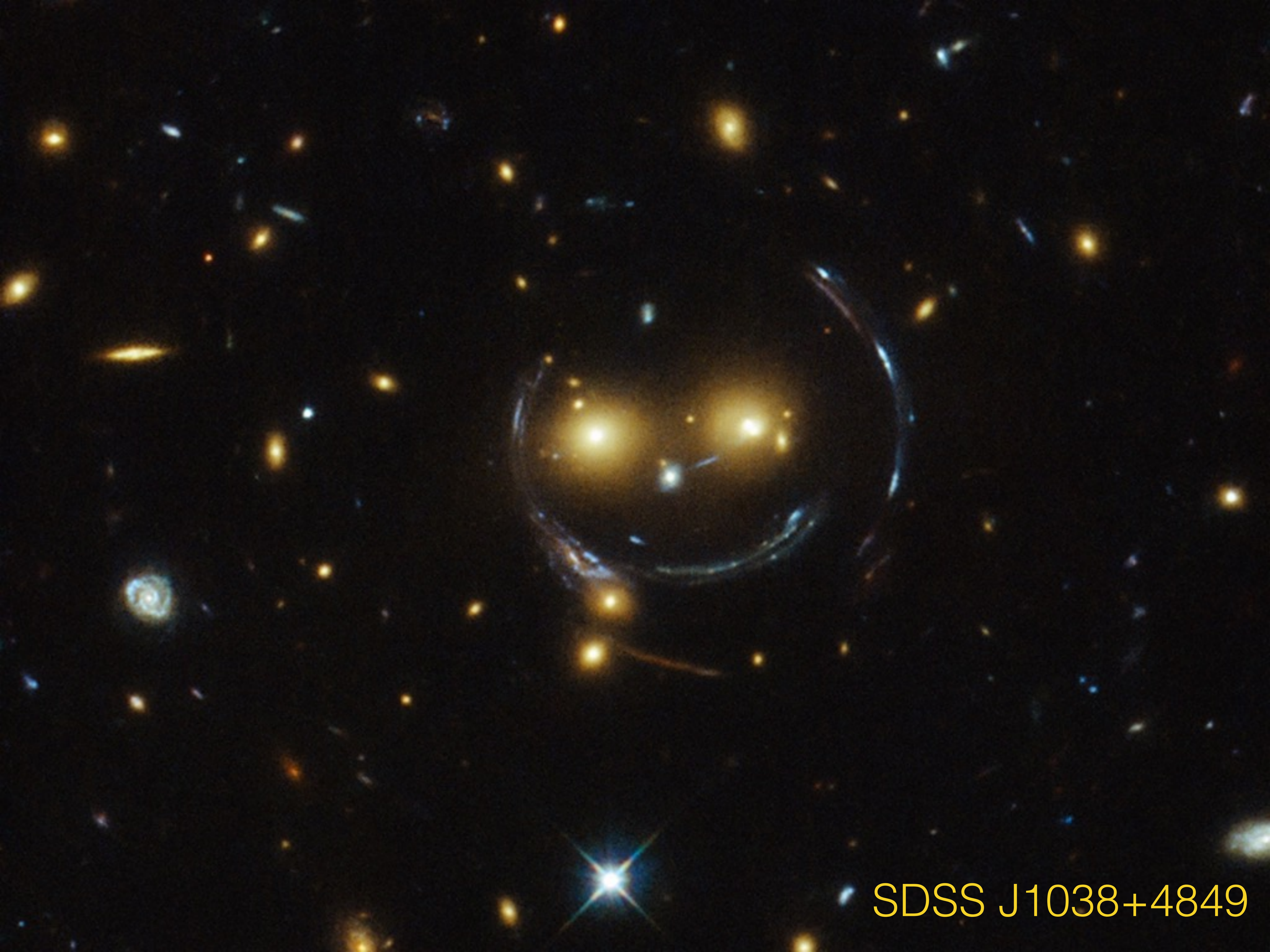
(Abell 2218)

More ways to measure Gravitational Mass vs. Baryonic Mass

- Gravitational Mass from Velocity of Galaxies
- Gravitational Mass from Lensing (instead of velocity)
- Both Gravitational Mass *and* Baryon mass from X-Rays
- Collisions of Clusters

Another way to measure Mass: Gravitational Lensing


galaxy
galaxy cluster
lensed galaxy images
distorted light-rays
Earth

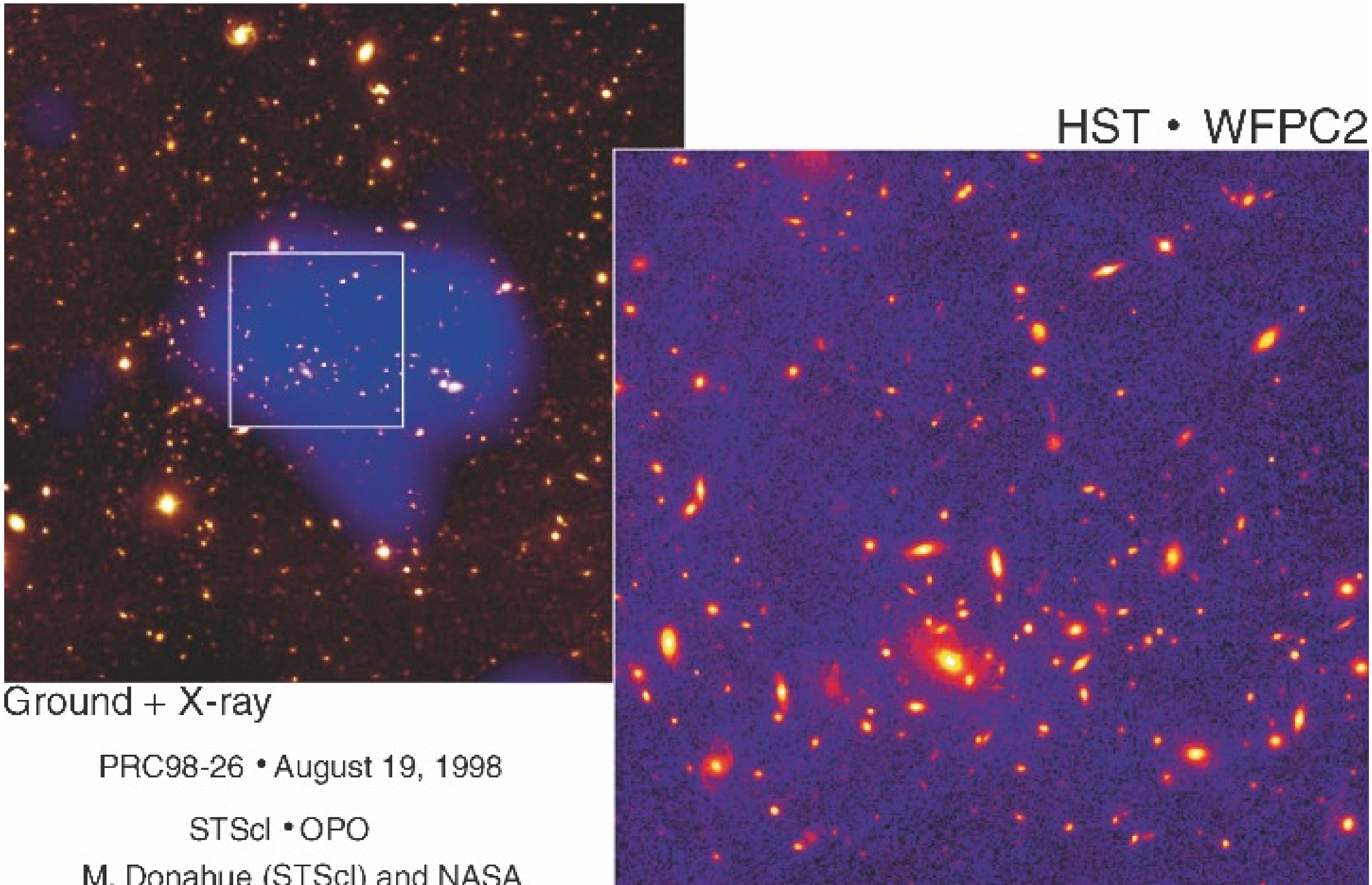

SDSS J1038+4849

We can measure the mass of things with this.

Υ =440

$10^{14} M_\odot$

Huge amount of x-ray



How do you make 10 million degree gas?

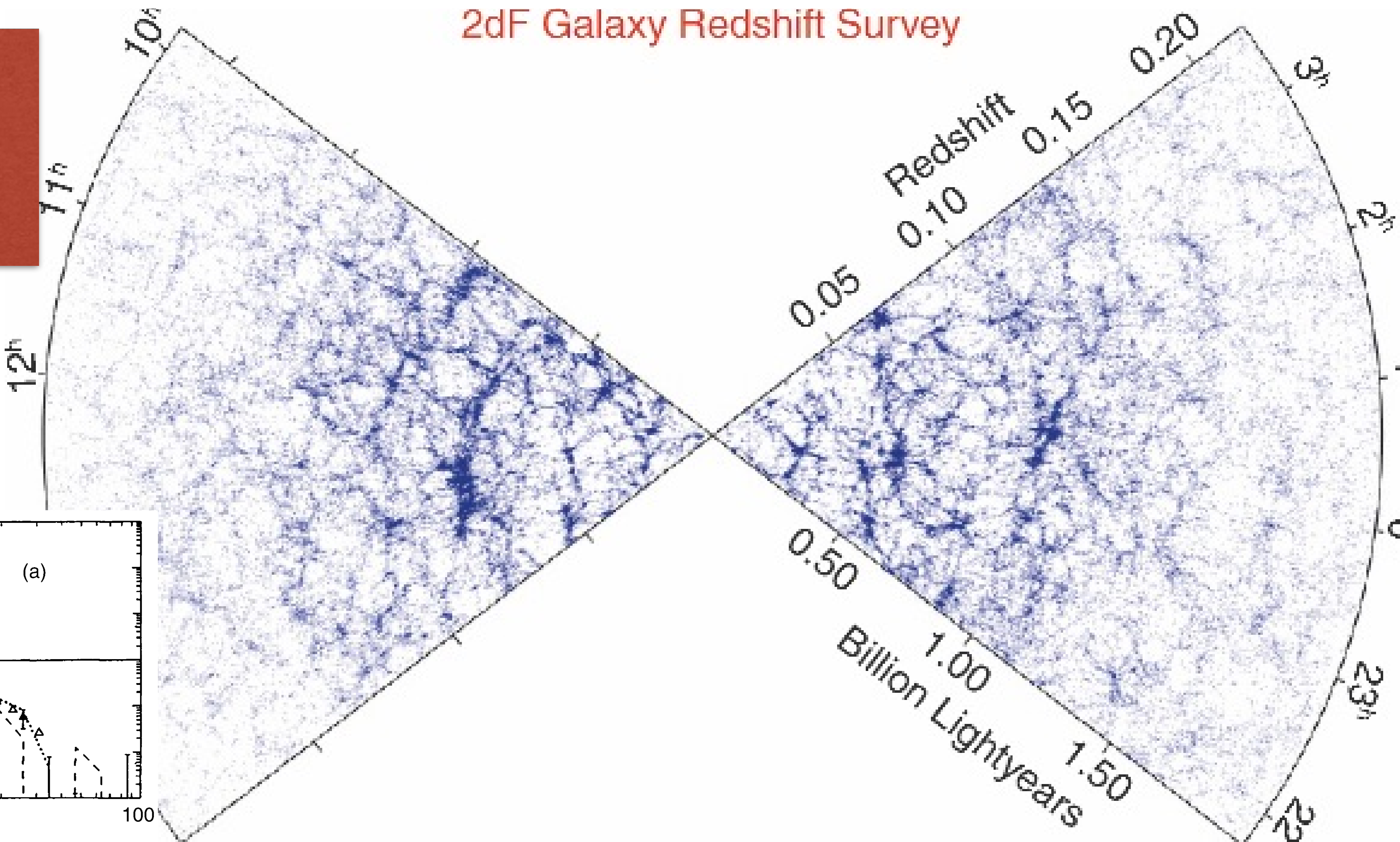
- $$F = \frac{G m_1 m_2}{r^2}$$
- In a gas, this creates **Pressure** which is related to **Temperature** (PV=nRT)
- How much mass do we need to make all of this x-ray gas?
  - about 20x what we see in galaxies.
  - That's still not 400!

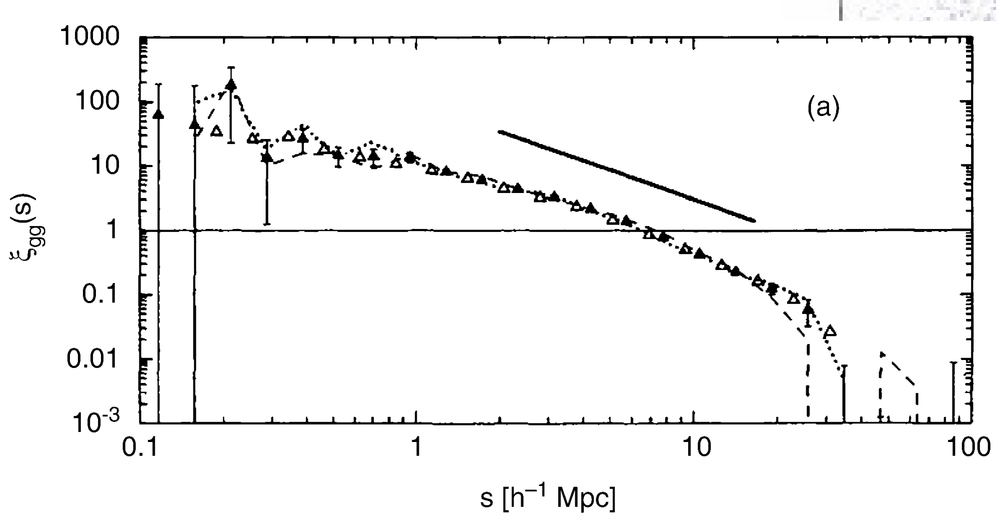
Bullet Cluster

Large Scale Structure

- Very large structures!
- Measures not just the mass, but where it is.

Structure formation from Dark Matter predictions match observations extremely well.

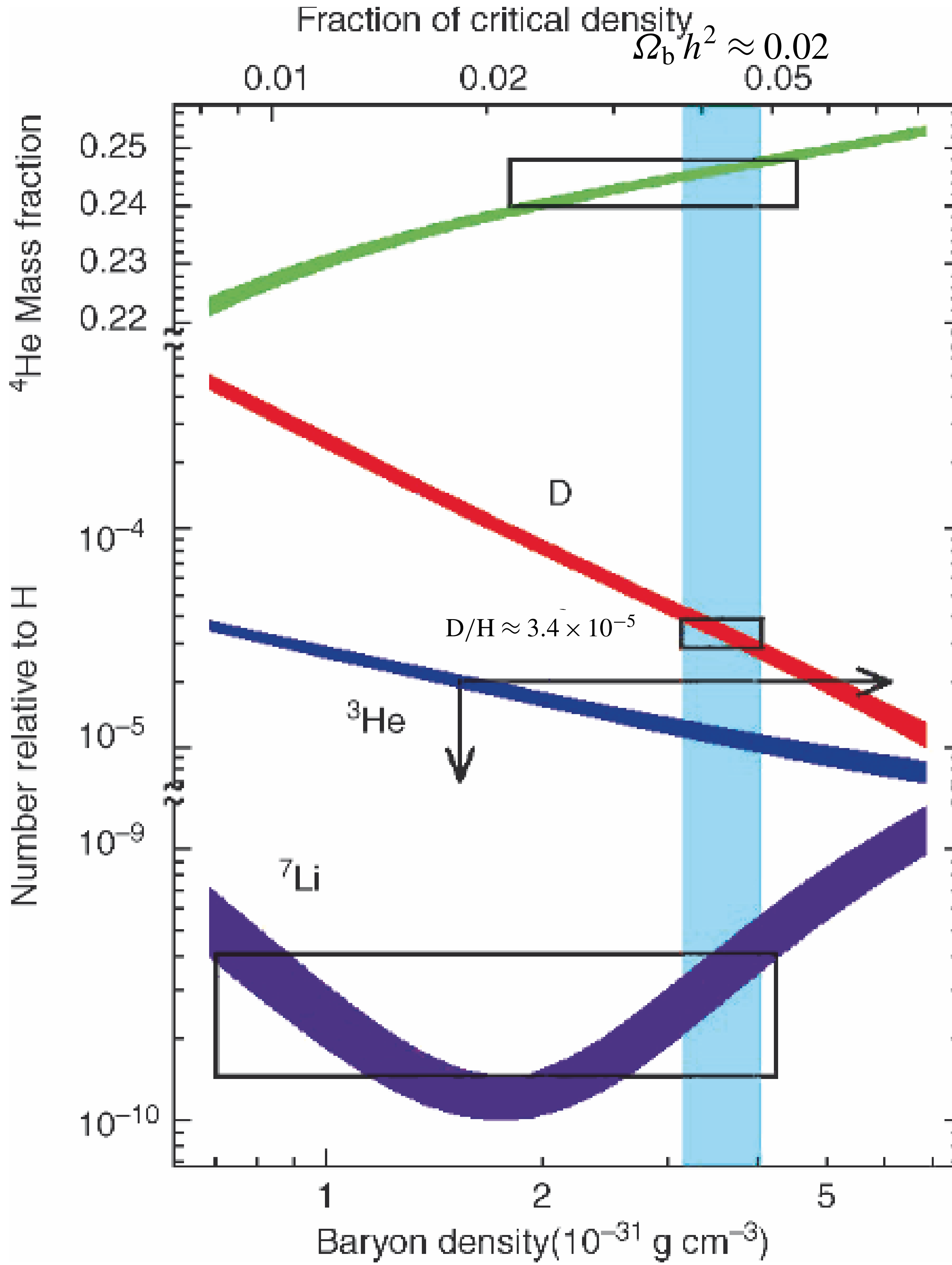




Hydrogen/Deuterium

- Are there non-gravity measurements?
- Big Nucleosynthesis!
    - Photons turn into
    - Protons and Neutrons which turn into
    - Deuterium and Helium
- Very sensitive to the temperature and **proton** density.

- D and He^4 trace Ω_b
- Increase in Ω_b means more baryons per photon, less D destruction, higher n/p, Y increases
- Higher Ω_b, more D converted to He^4, less D
- Ly Alpha from QSO absorption lines



Many Measurements

- Galaxy Rotation Curves
- Cluster Dynamics, X-Rays
- Bullet Cluster
- Large Scale Structure
- H/D/He ratios

- ALL show that the **gravitational** mass and **baryonic** mass in the universe are different.
- Any solution has to cover all of these.
(It would be nice if it were consistent with other things)

So we either have to:

- Fix Gravity
- Find some missing mass

Fix Gravity

- People are trying. Really hard.
- Turns out it doesn’t work all that well.
  - MOND (Modified Newtonian Dynamics)

$$F = ma\frac{1}{1+\frac{a_0}{a}}$$

  - can get galaxy rotations ok, but doesn’t do galaxy clusters, large scale structure, or D/H

Find the Missing Stuff

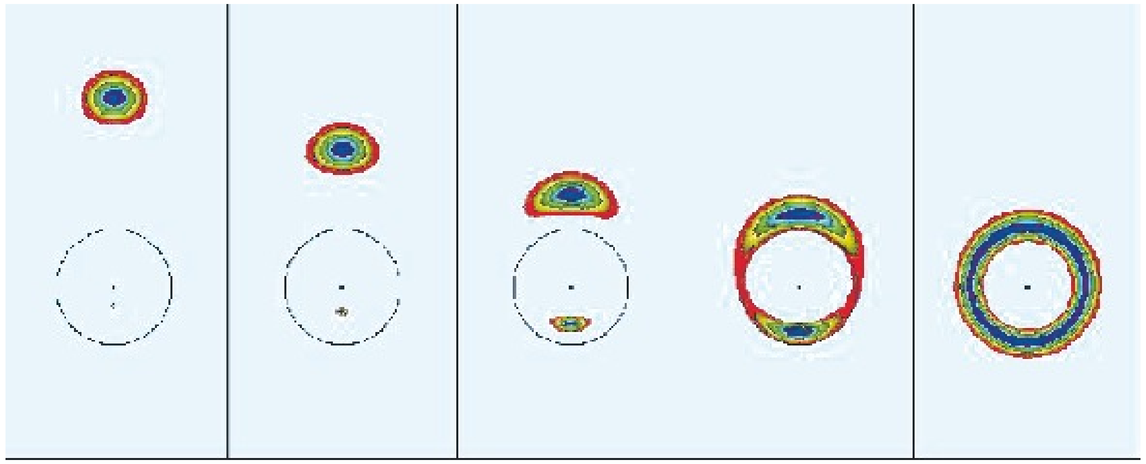
- Has to be one of two things:
  - Something we already know about, but doesn’t show up in most galaxy images.
  - Something we haven’t found yet, but we hope it exists.

Stuff we already know about pt. 1: MACHOS

- Massive Compact Halo Objects
- Brown Dwarfs (tiny stars with really high Υ)
- Small Black Holes ($1M_\odot$)
- Supermassive Black Holes $10^4 - 10^9 M_\odot$
  (these would be pretty obvious)
- Intermediate Mass Black Holes $100M_\odot$

Dark Matter Candidates: MACHOS

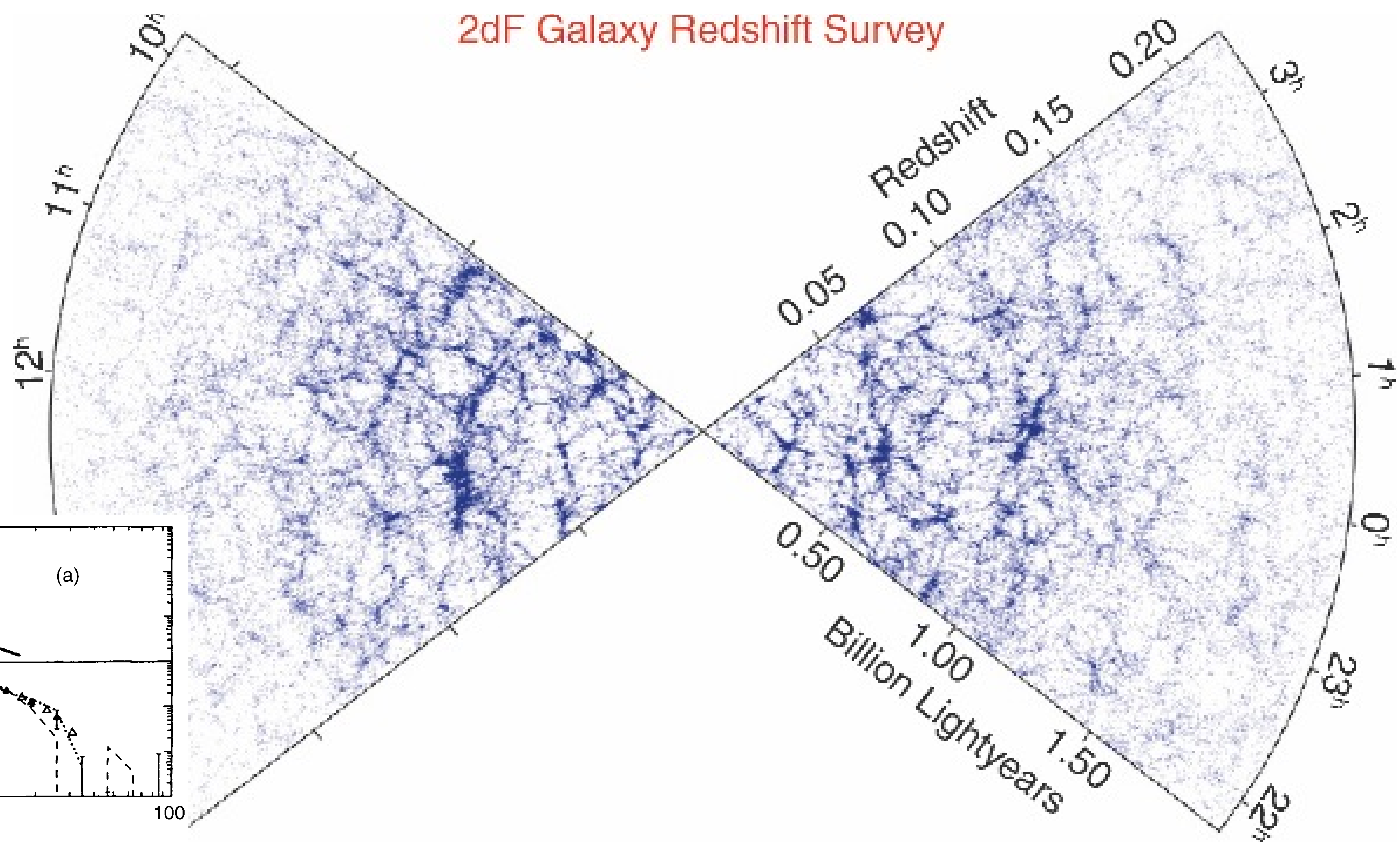
- Lower mass MACHOS
  - MACHO and EROS surveys: **micro lensing.**
  - 1992-1999 survey, MW Bulge and LMC, for microlensing events.
    - 100 events towards bulge
    - 13 towards LMC
    - Might be 20% of the MW DM halo.

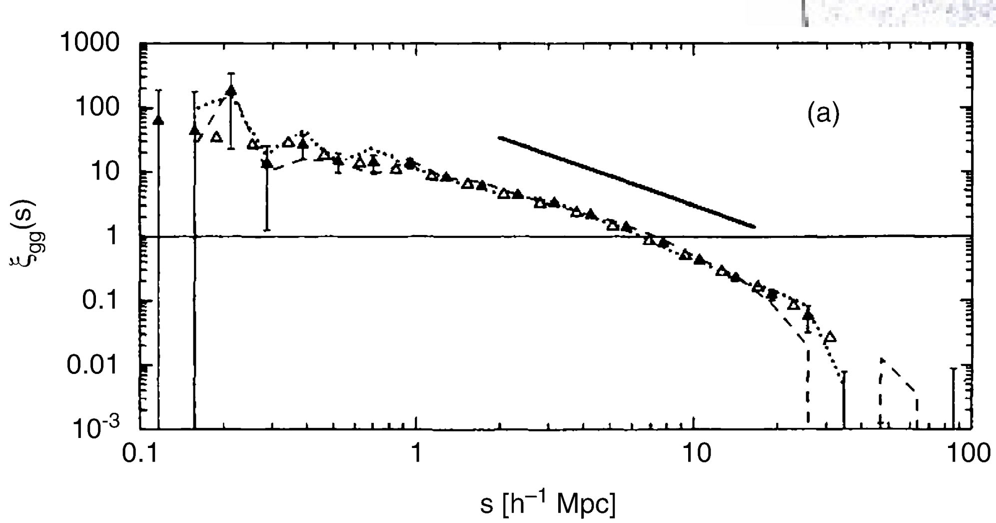


Stuff we already know about pt. 2: neutrinos

- They totally throw off the statistics of very large structures. They're so fast, they just leave.

Neutrinos have a hard time staying bound to small objects





Find the Missing Stuff

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  - ~~Something we already know about~~
  - Something we haven't found yet.

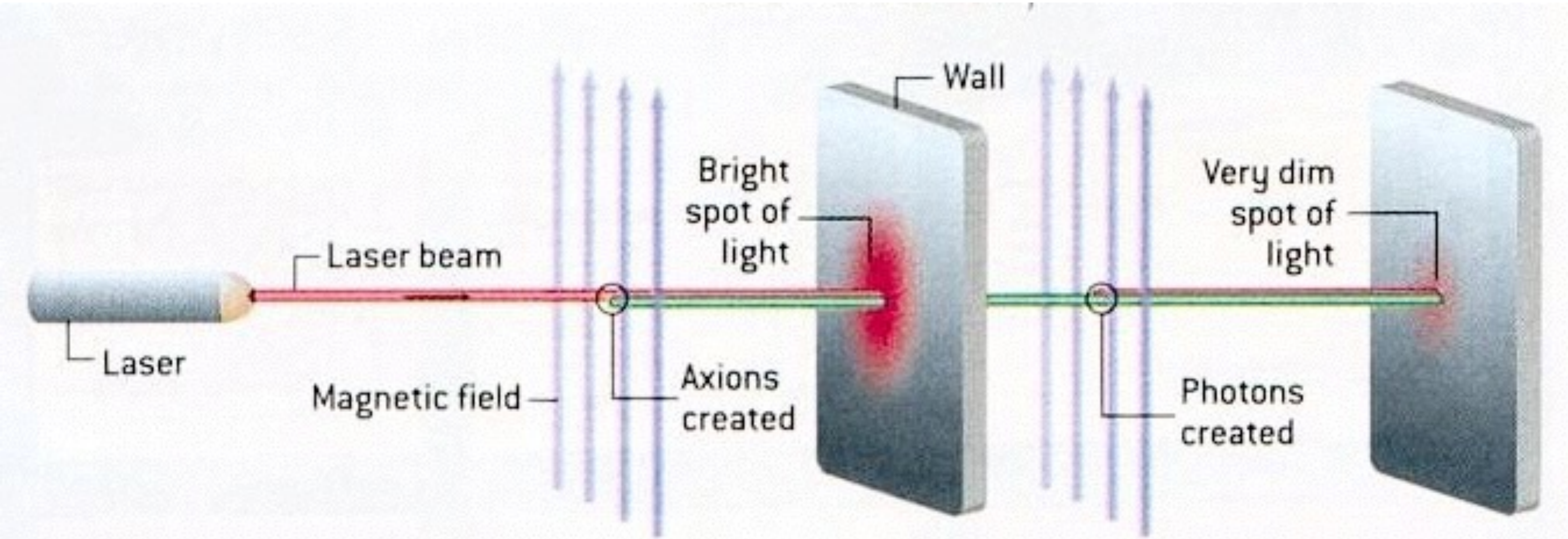
What forces can DM interact with?

- **Gravity** (clearly)
- **Strong** (No: we would see this)
- **Electromagnetic** (No, that's light, its the whole problem)
- **Weak** (Gosh I hope so.)(Also necessary for formation of DM in the first place, ask me later)

Stuff we Don't Yet Know About

- **Axions**
  - Very small (10^{-6} the mass of an electron)
- **WIMPS** (Weakly Interactive Massive Particles)
  (as opposed to Machos)(particle physicists are hilarious)(These actually were named first)
  - There are many predicted candidates for these from the zoo of particle physics

Looking for Axions



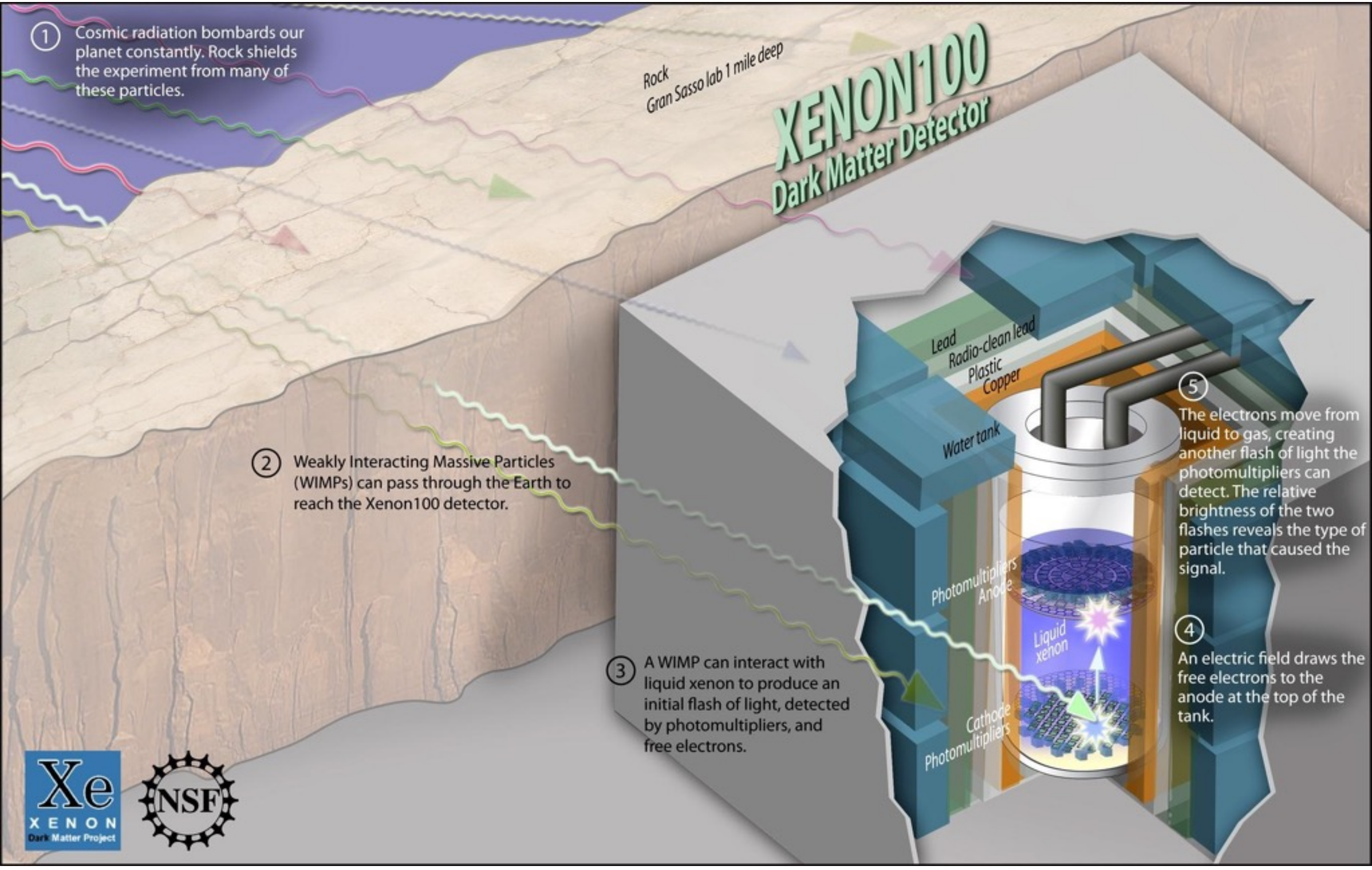
LIGHT BEAM experiment that would confirm the existence of axions passes a laser beam through a strong magnetic field, converting some photons to axions (*green beam*). The axions penetrate a wall before passing through another magnetic field that converts some of the particles back to photons, which form an extremely faint spot on the far wall.

Looking for WIMPS

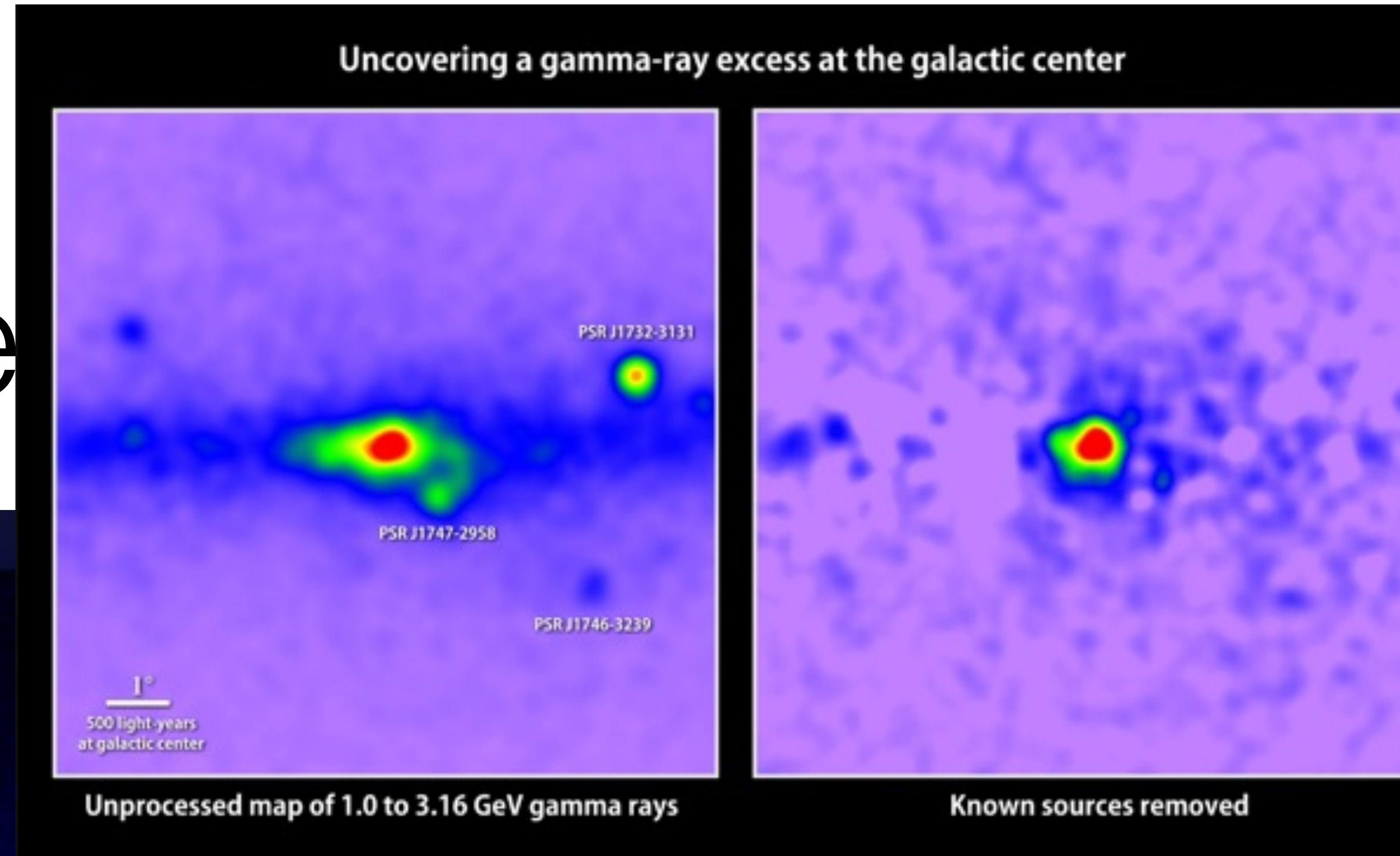
- Let’s hope a Dark Matter particle bounces off some stuff.

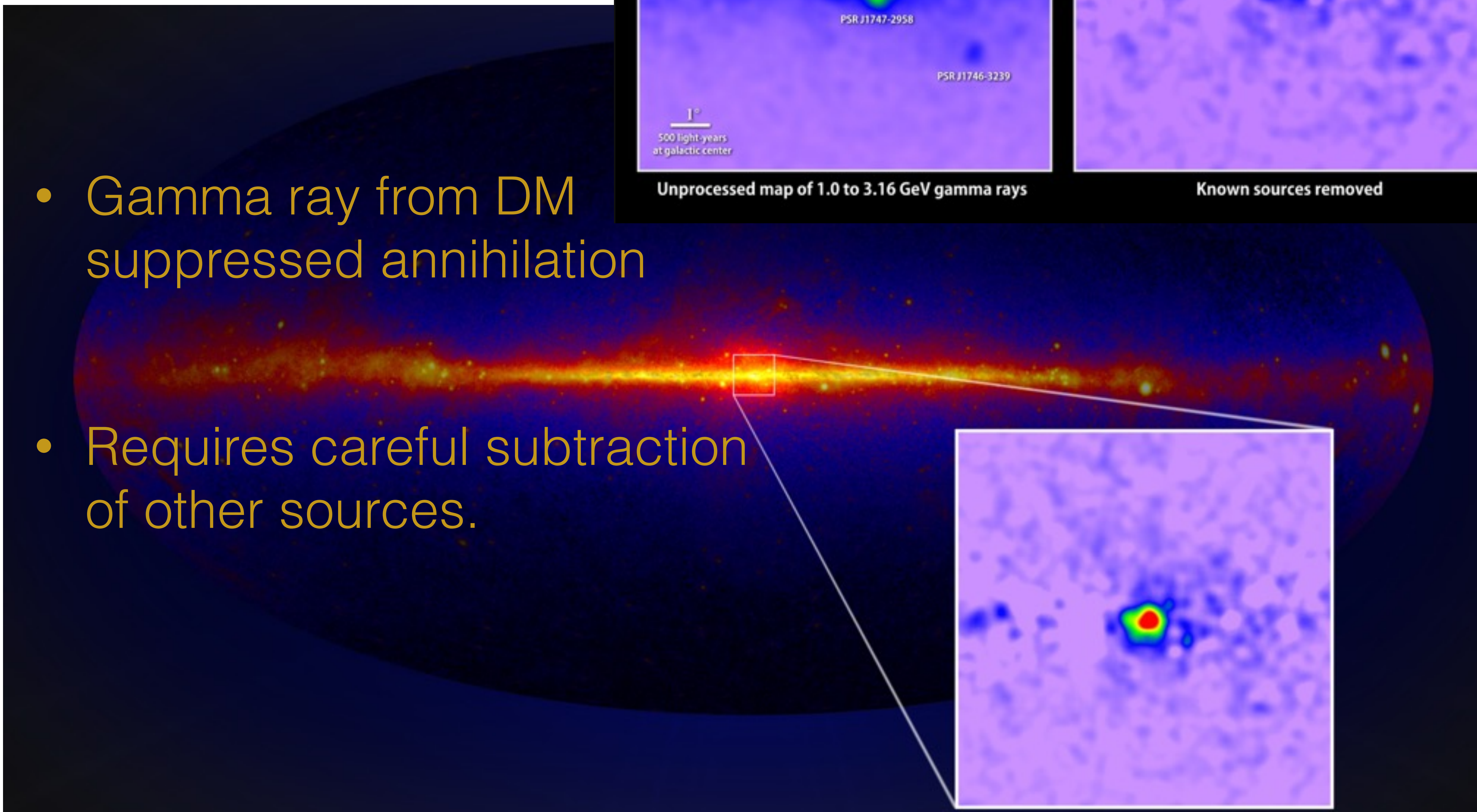
- Very careful book keeping, very careful shielding.

Looking for WIMPS



In Space? Fermi Satellite





- Gamma ray from DM suppressed annihilation
- Requires careful subtraction of other sources.

Huston, we have a problem. (Summary)

- Two ways to measure the mass should give us the same result.
- They Don’t.
    - Galaxies
    - Clusters
    - Large Scale Structure
- Probably not bad physics
- Probably a missing particle