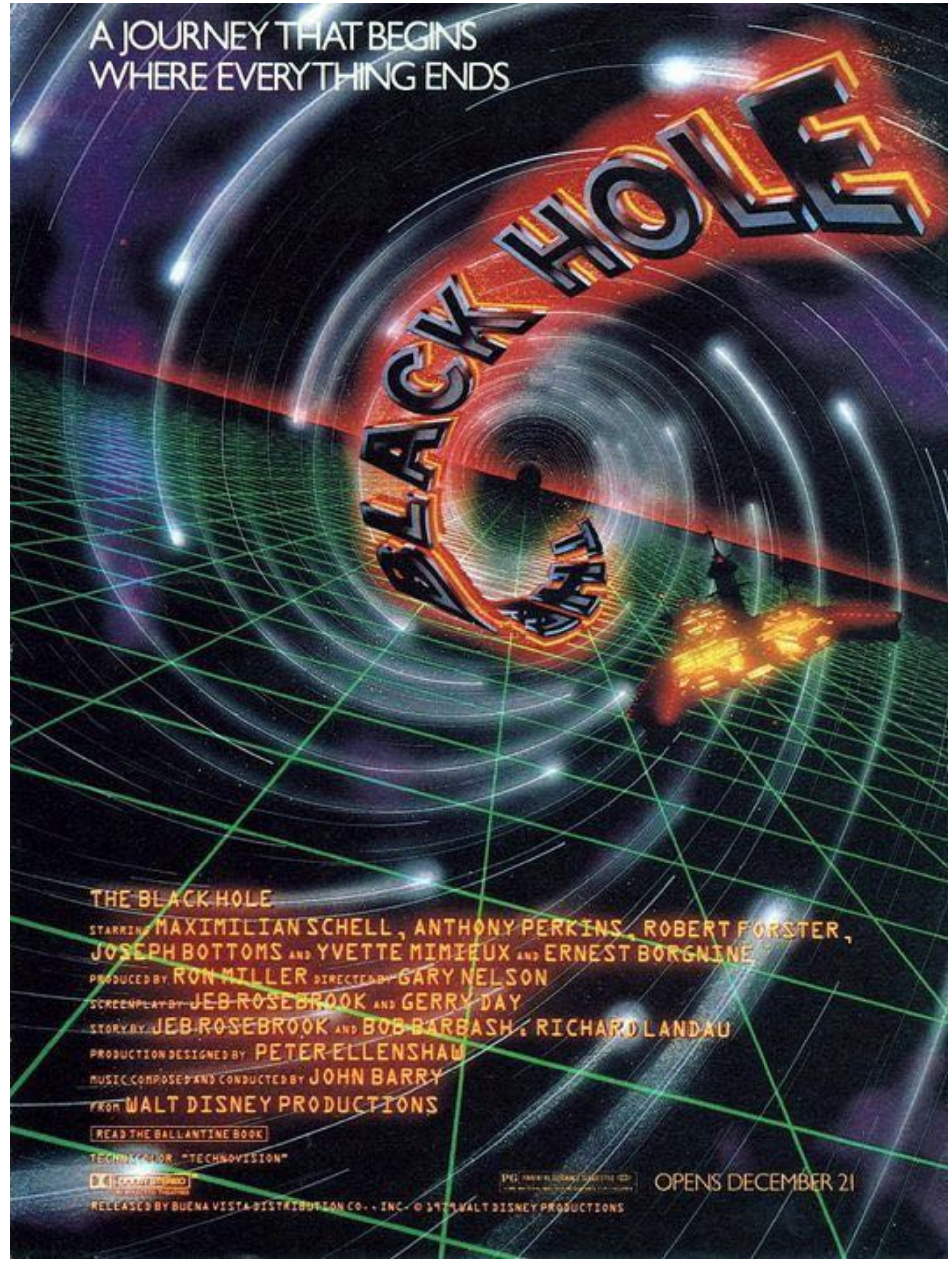
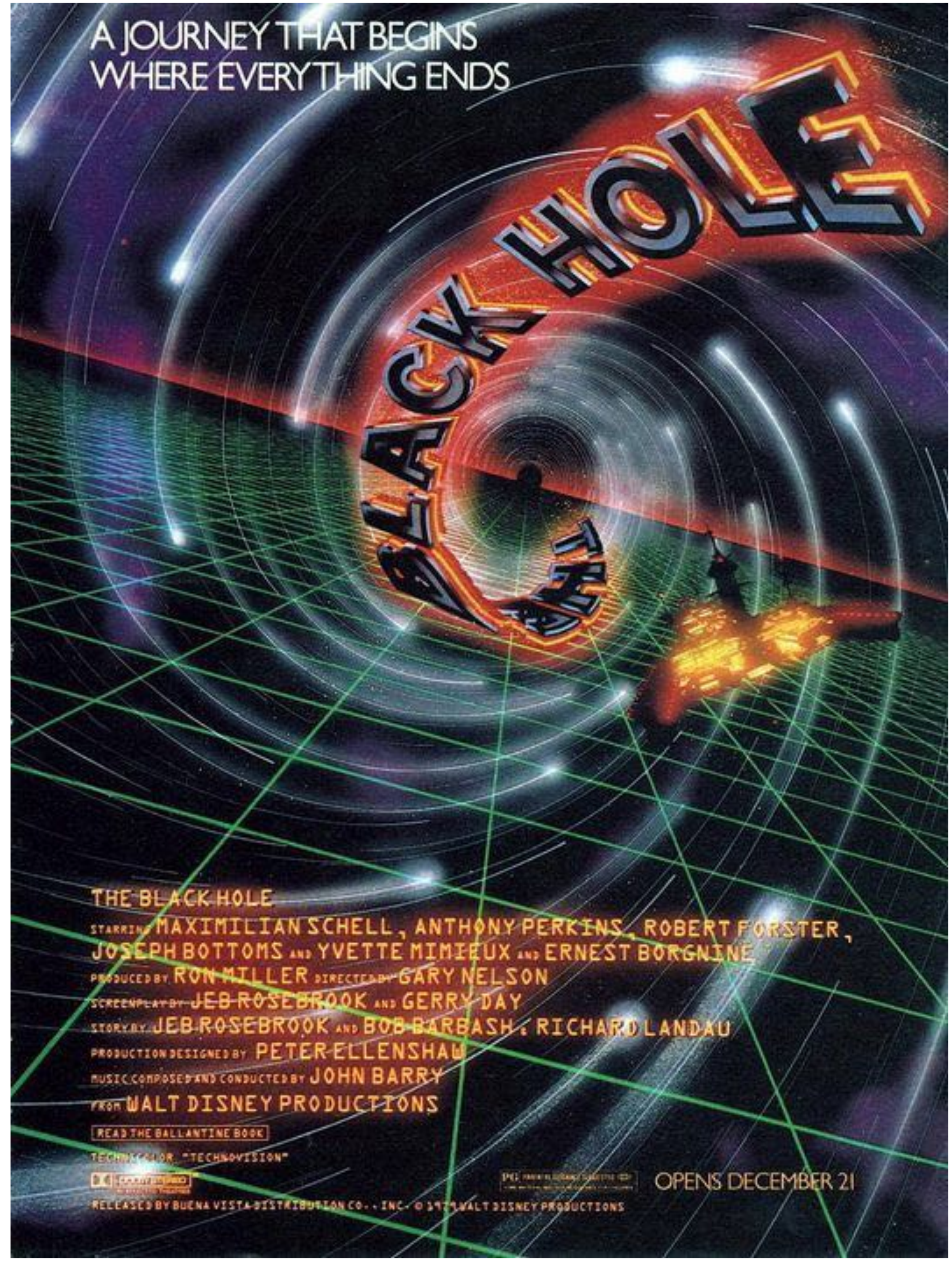
Black Holes!



David Collins, FSU
Quarknet 2018

BLACK HOLES

- Some basic physics
  - Kepler
  - Blackbody
- Cygnus X-1: “First” Black Hole
- Sagittarius A*: Nearest SMBH
- LIGO
- Formation

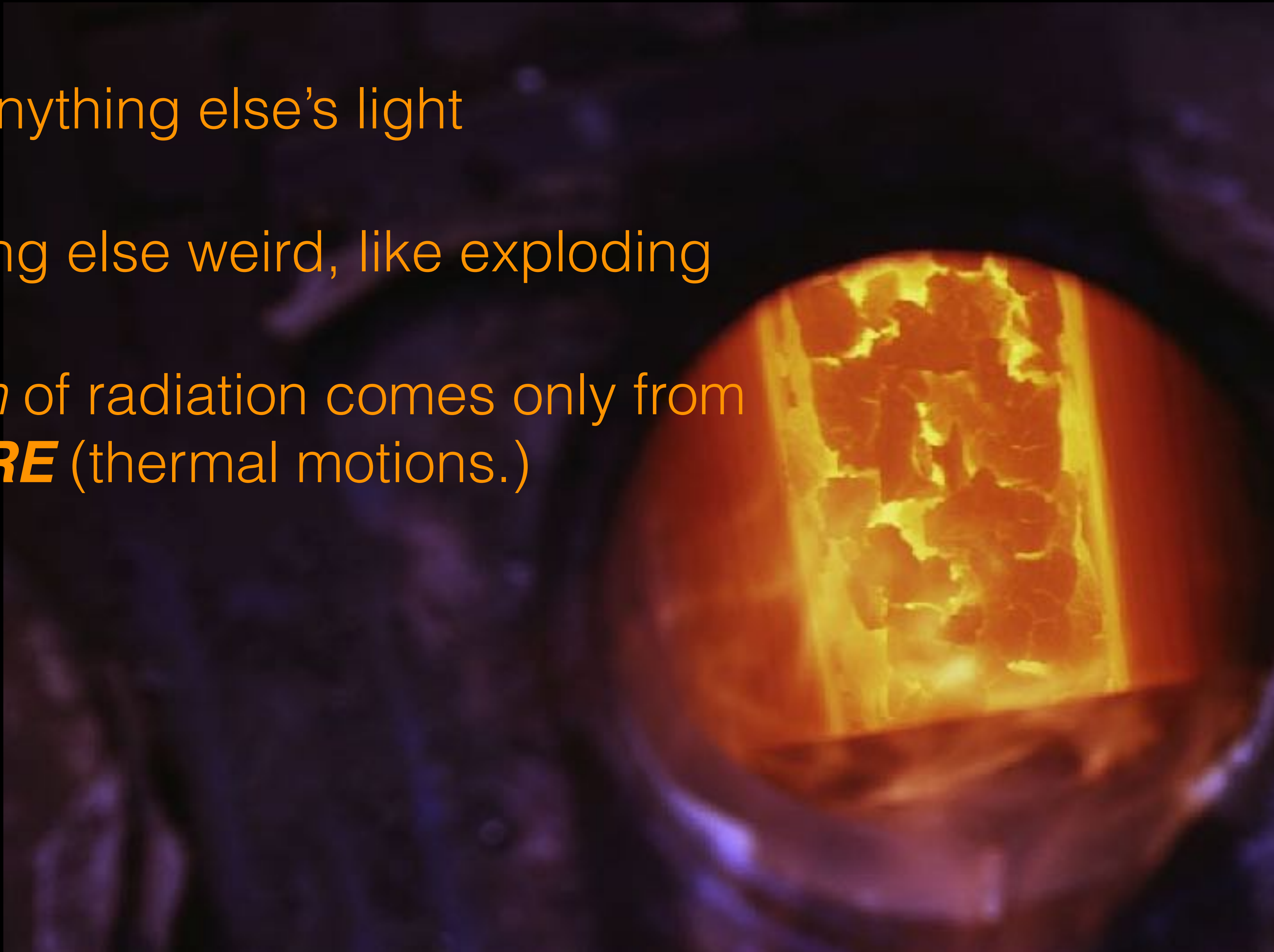


Basic Physics 2:

- The most useful thing in the universe for astronomy:
  Black Body Radiation.

Blackbody

- If I have a thing (blob of gas or whatever) that:
  - Isn't getting hotter or colder (*equillibrium)*
  - Isn't reflecting anything else's light
  - Or doing anything else weird, like exploding
- Then the *spectrum* of radiation comes only from the ***TEMPERATURE*** (thermal motions.)



Black Body

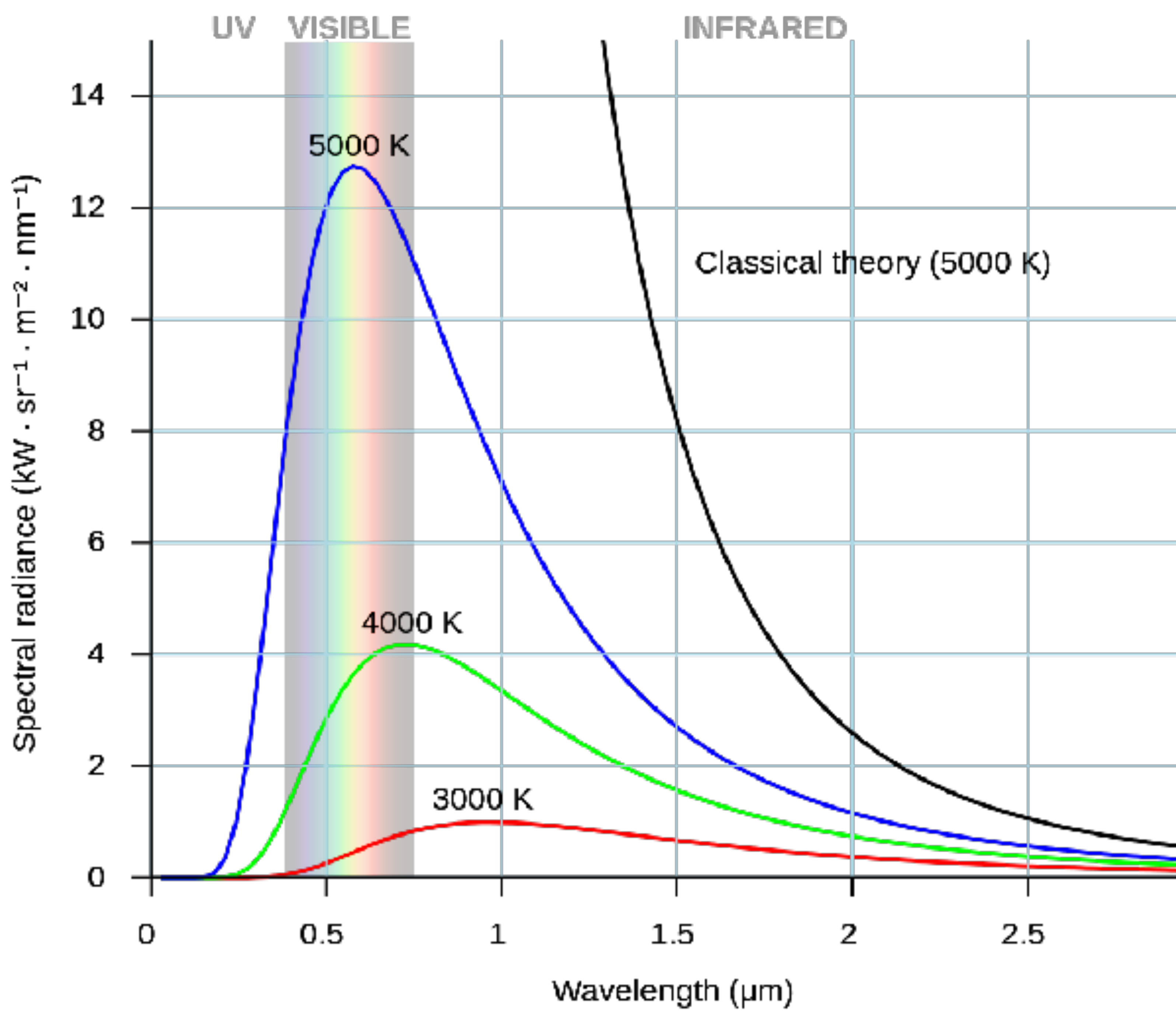
- **ONE** parameter: **TEMPERATURE.**

- Peak wavelength:

$$\lambda_{max} = [2.9/T\ (K)]\ mm$$

- Two fluxes to know the **Temperature** and **Distance** to an object.

(provided it's a perfect black body, which it isn't.)



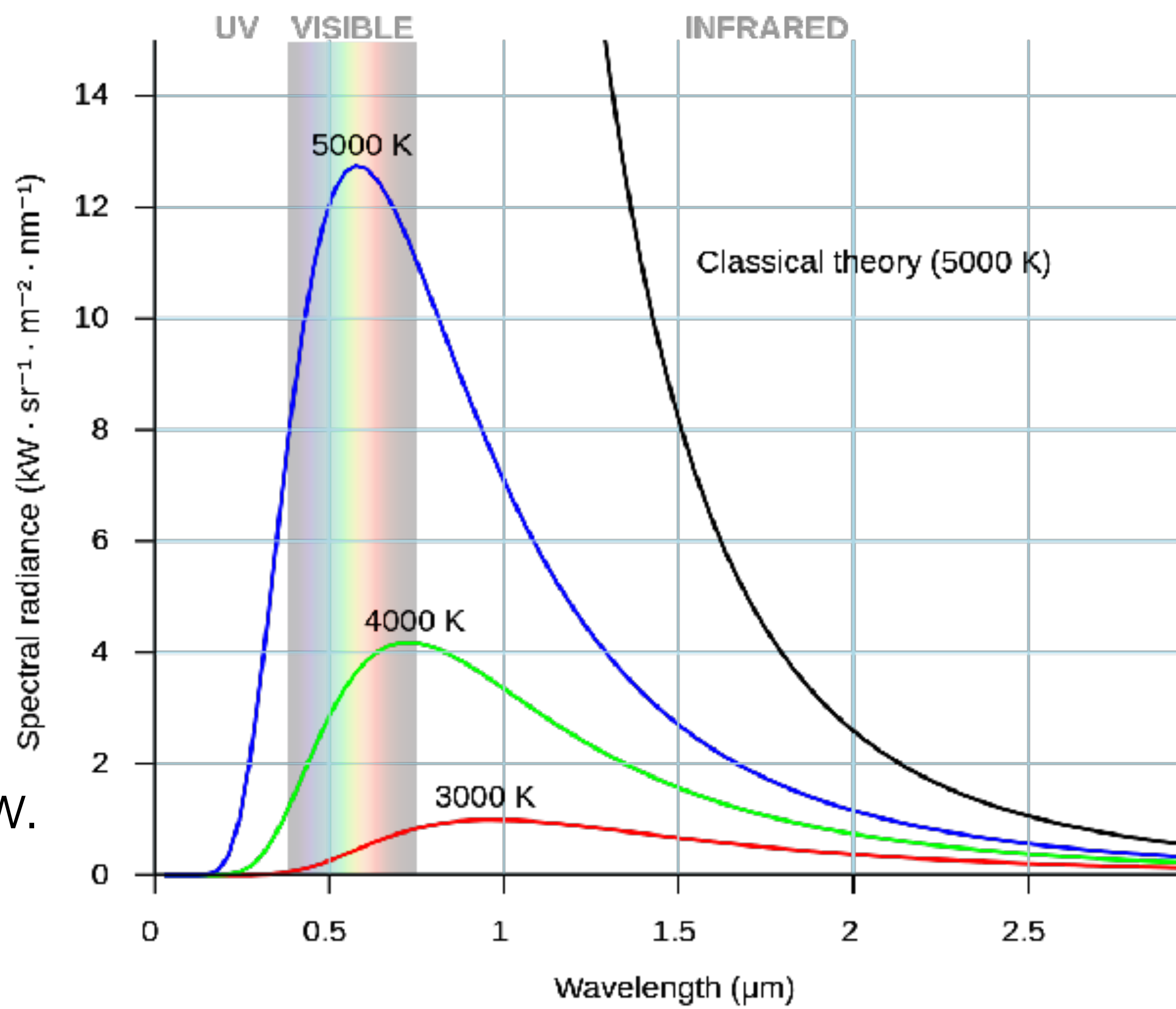
Black Body and X-rays

- Things aren't perfect, but it's a good start.

- The sun peaks in the visible, 700nm, T=6000K.

- X-rays, with $\lambda = 0.1\text{nm}$ would imply a blackbody with $T=10^7$K.
  OR
  something violent is going on.

- Scotch Tape is violent, fwiw.

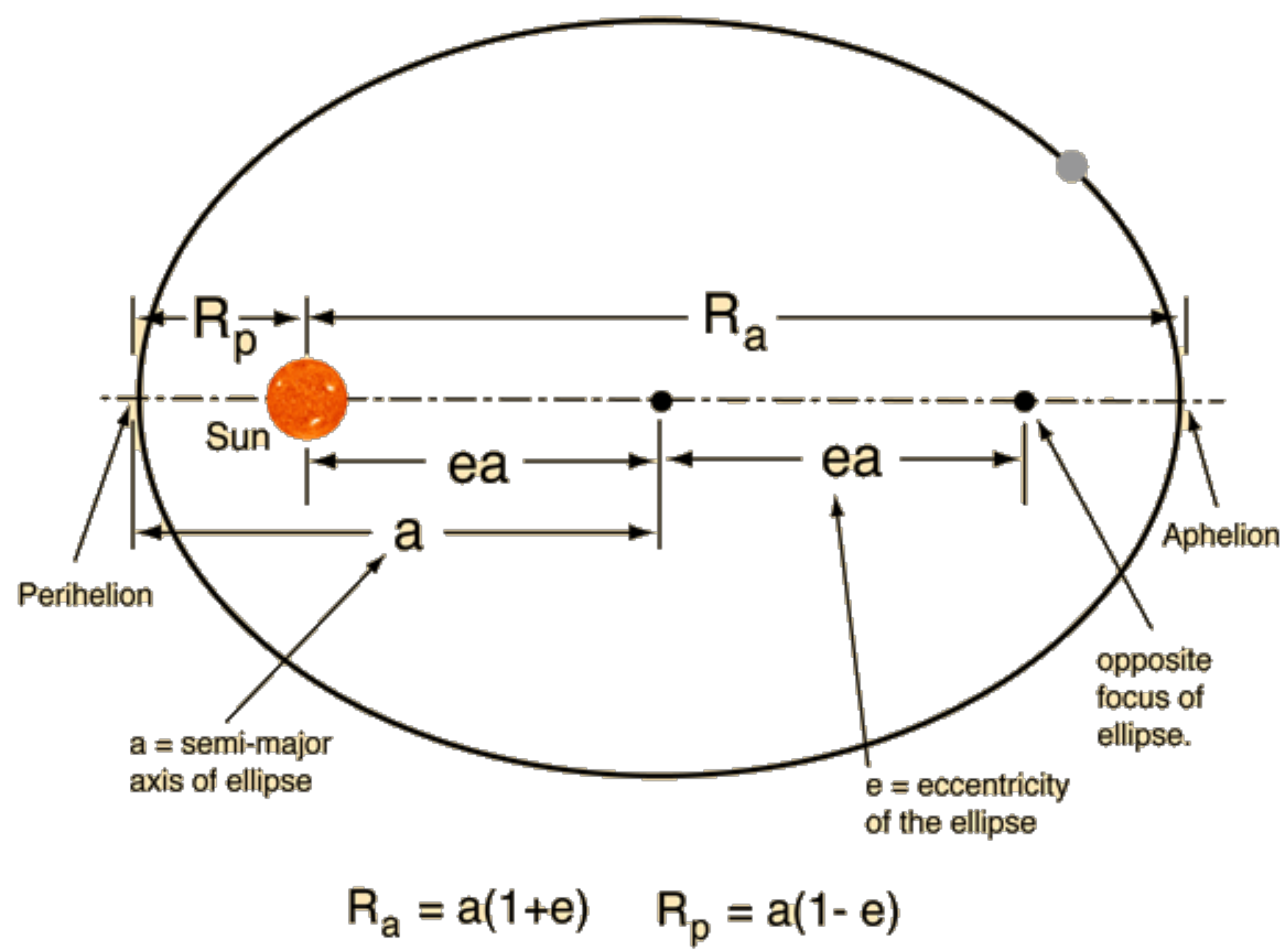


Kepler

- Ellipses, sun at one focus.
- Equal Area for Equal Time (faster closer)
- Period Squared *goes like* Radius Cubed

$$T^2 \propto a^3$$

- So we can get a lot from measuring orbits.

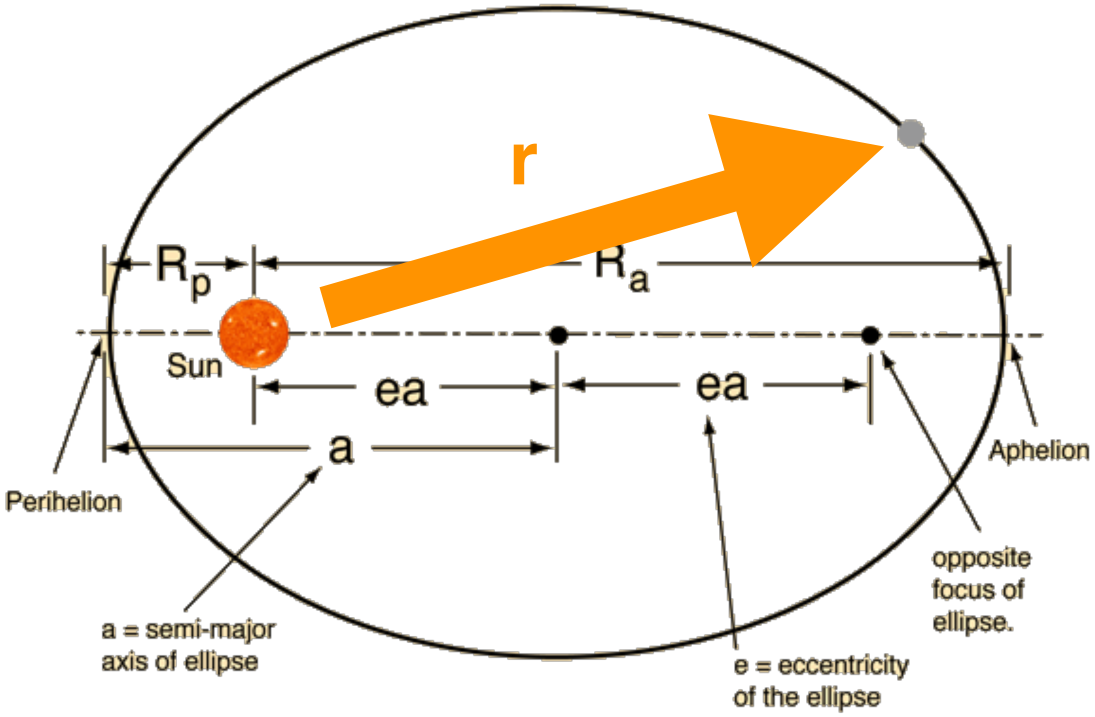


Newton

- Packaged it nicely.

$$\vec{F} = m\vec{a}$$

$$\vec{F} = \frac{-GMm}{r^2}\hat{r}$$



$R_a = a(1+e)$ $R_p = a(1-e)$

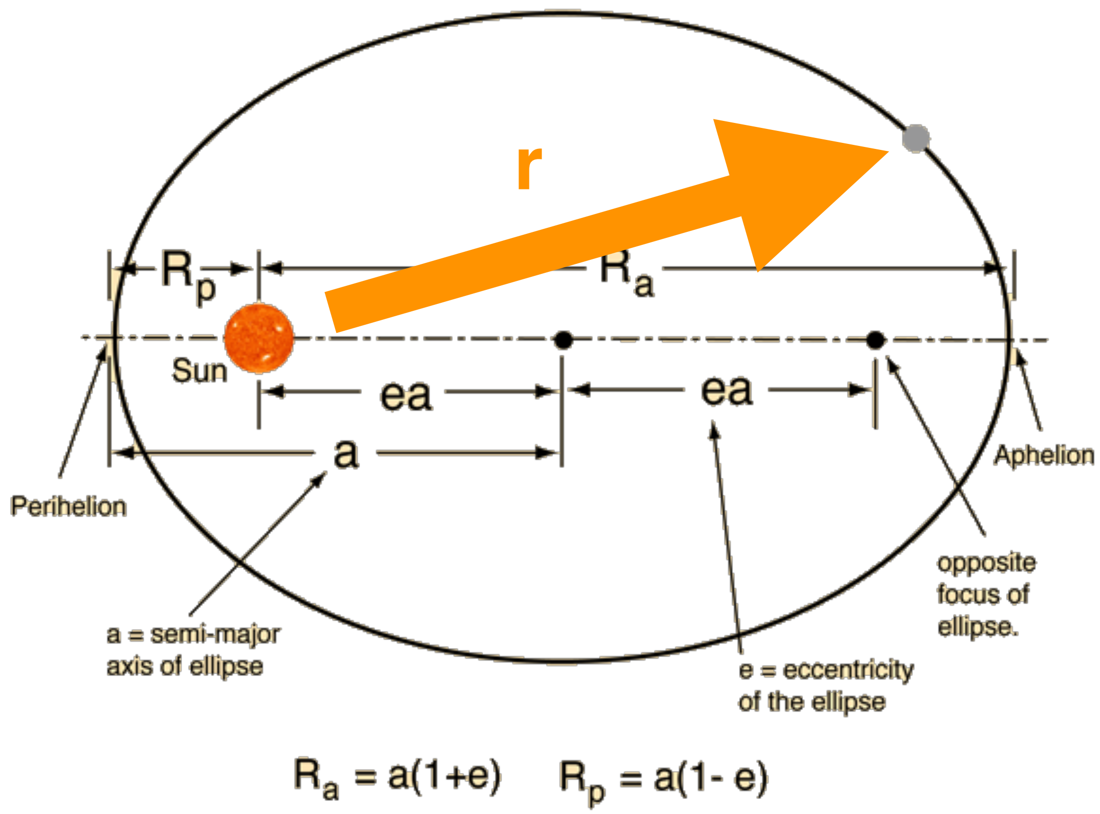
Newton

- The important take-away:
  For Circular Orbits:

$$v^2 = \frac{GM}{r}$$

- $$E = \frac{-GMm}{r}$$

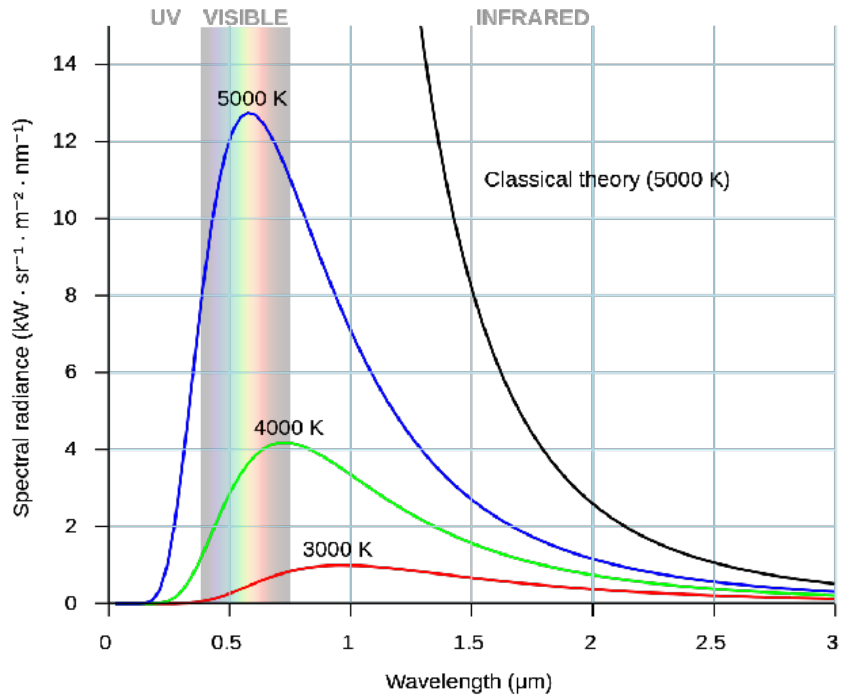
  (think about falling toward the Sun.)

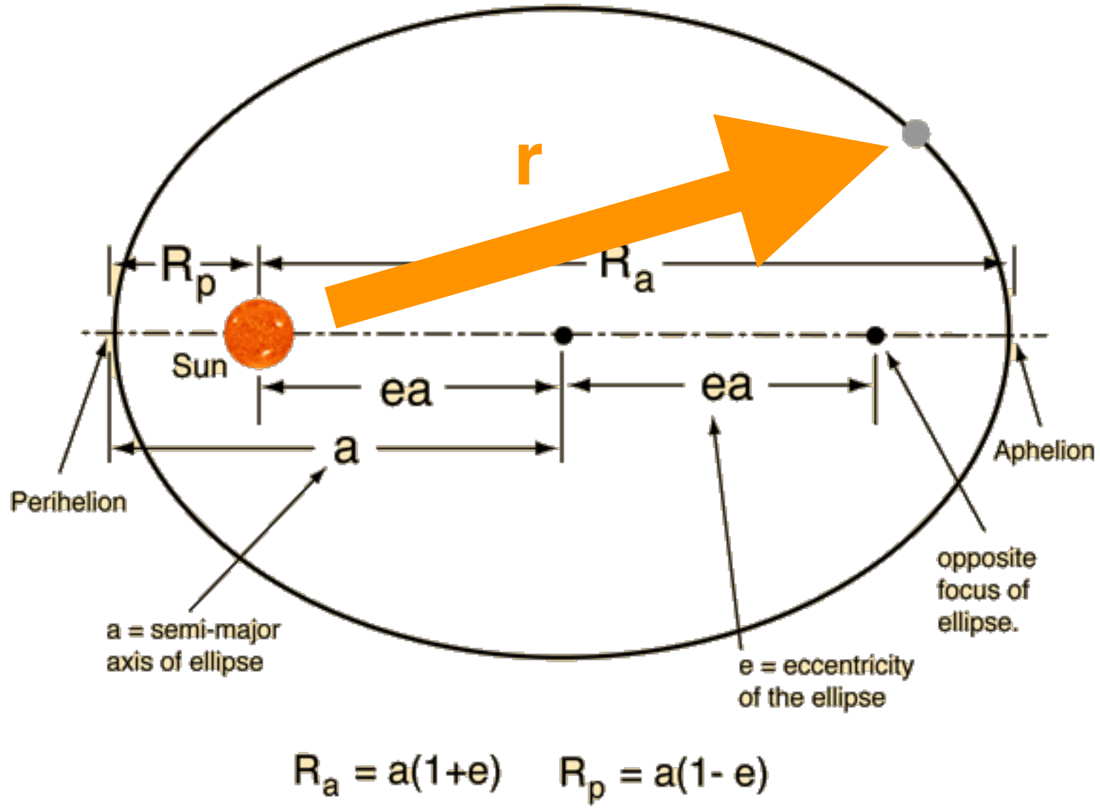


Sum Up

- Black Body:
  Short Wavelength is Large Temperature (Or Violence)

- Kepler:
  Stuff orbiting stuff Using only gravity Is well understood.



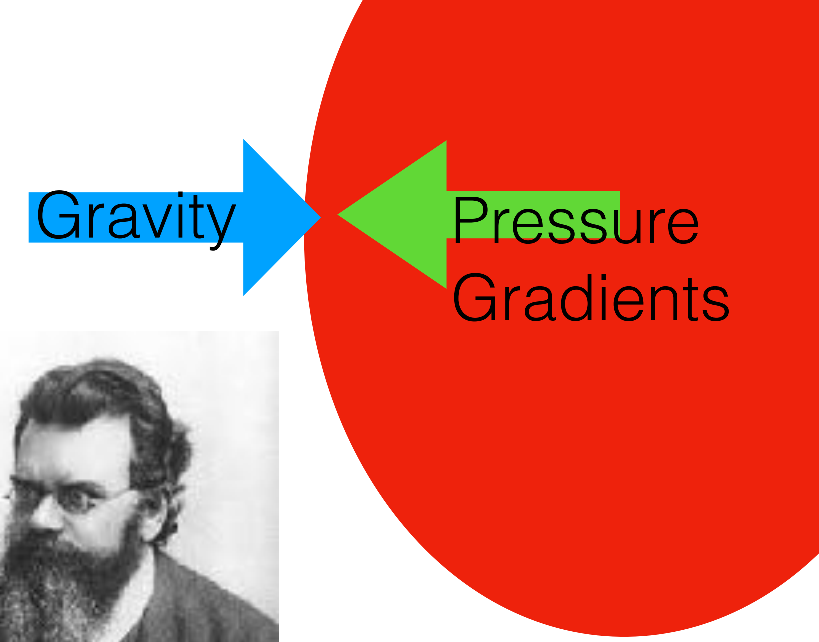


What it is

$$r_s = 2GM/c^2 = 3\text{km}\frac{M}{M\odot}$$

- Energy is $|E| = \frac{GMm}{r} = \frac{1}{2}mv^2$
  - So that gives us $r_{escape} = 2GM/v^2$
- So if v = c, we have a problem.
  - Why is c such a problem? Ask me later.
- 1800s, several people postulated objects too massive for light to escape.
- Schwarzschild, 1916: 
  - Again with General Relativity, same result: If you have some mass, and you are closer than r_s, it will take an infinite time to get away. (You get a *singularity* that looks like this:) $\frac{1}{1 - r_s/r}$
- This is a thing you can write down on paper, but Nature may not actually ever do that. Nature doesn't care about your paper.

How do things fail?



- When the force holding it up
  is smaller than
  the force pushing it down.

- Boltzmann: Pressure is particles bouncing off each other.(1865)

- Pauli: Electrons hate each other. (1925)

- **Tolman, Oppenheimer, Volkoff**: Neutrons can't hold up past a couple solar masses. (1939)

- Thom Yorke: Gravity Always Wins. (1995)

There's a quantum expectation for BH, too.

- Electrons and Neutrons hate each other, but only so much.
- Gravity only goes in one direction.

Much argument.

- Many people didn’t think a BH could exist.
- Because really, this seems like a stupid thing for nature to do.

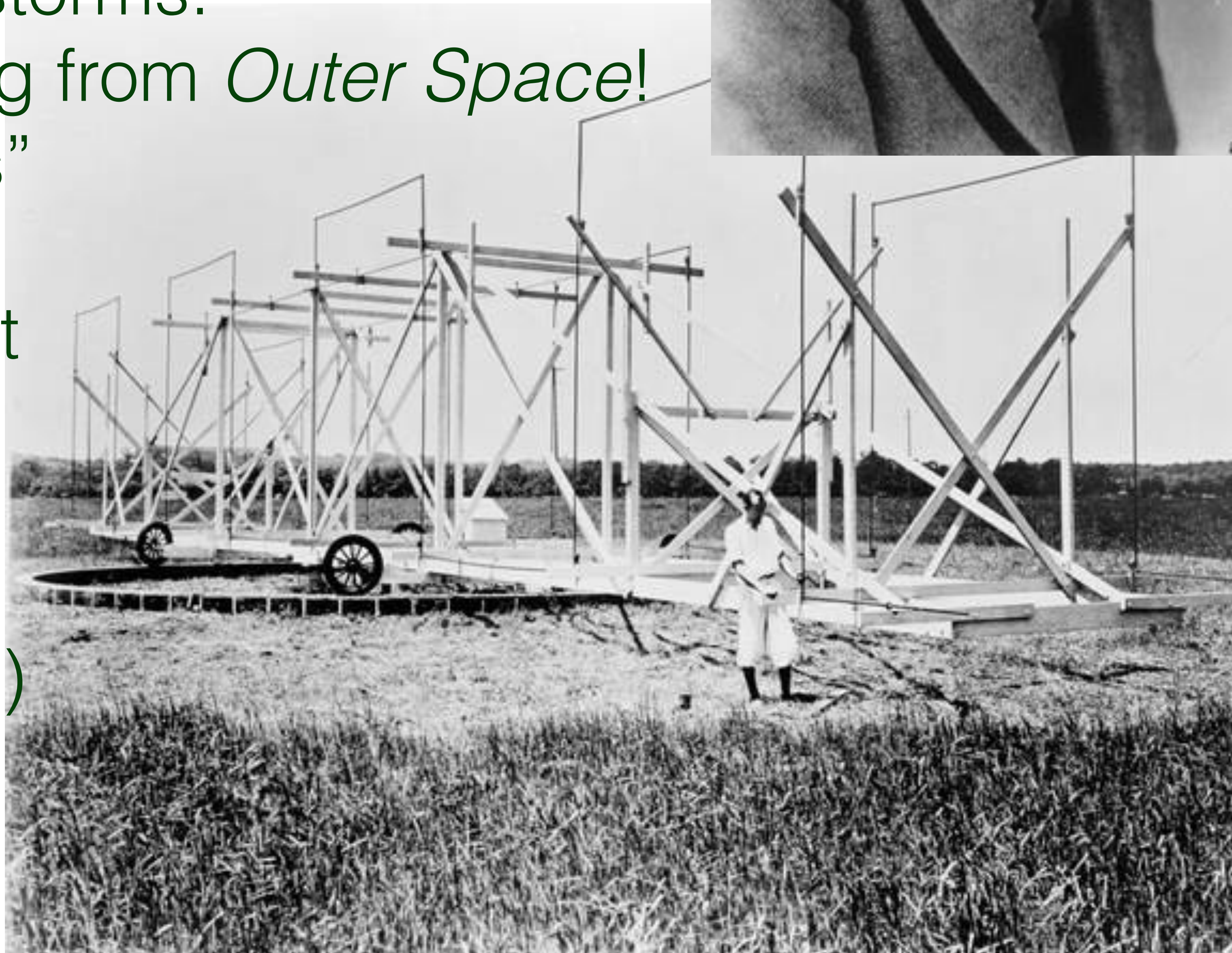
Radio!

- Karl G. Jansky, (1905-1950)

- Working at Bell Labs. 1932. “Karl, what’s this radio noise? It’s messing up our stuff”
  “Some of it is thunder storms.
  But some of it is coming from *Outer Space*!
  Specifically, Sagittarius”

- Wanted to do more, but his boss said no.

- Now we know it’s a black hole! (more soon)



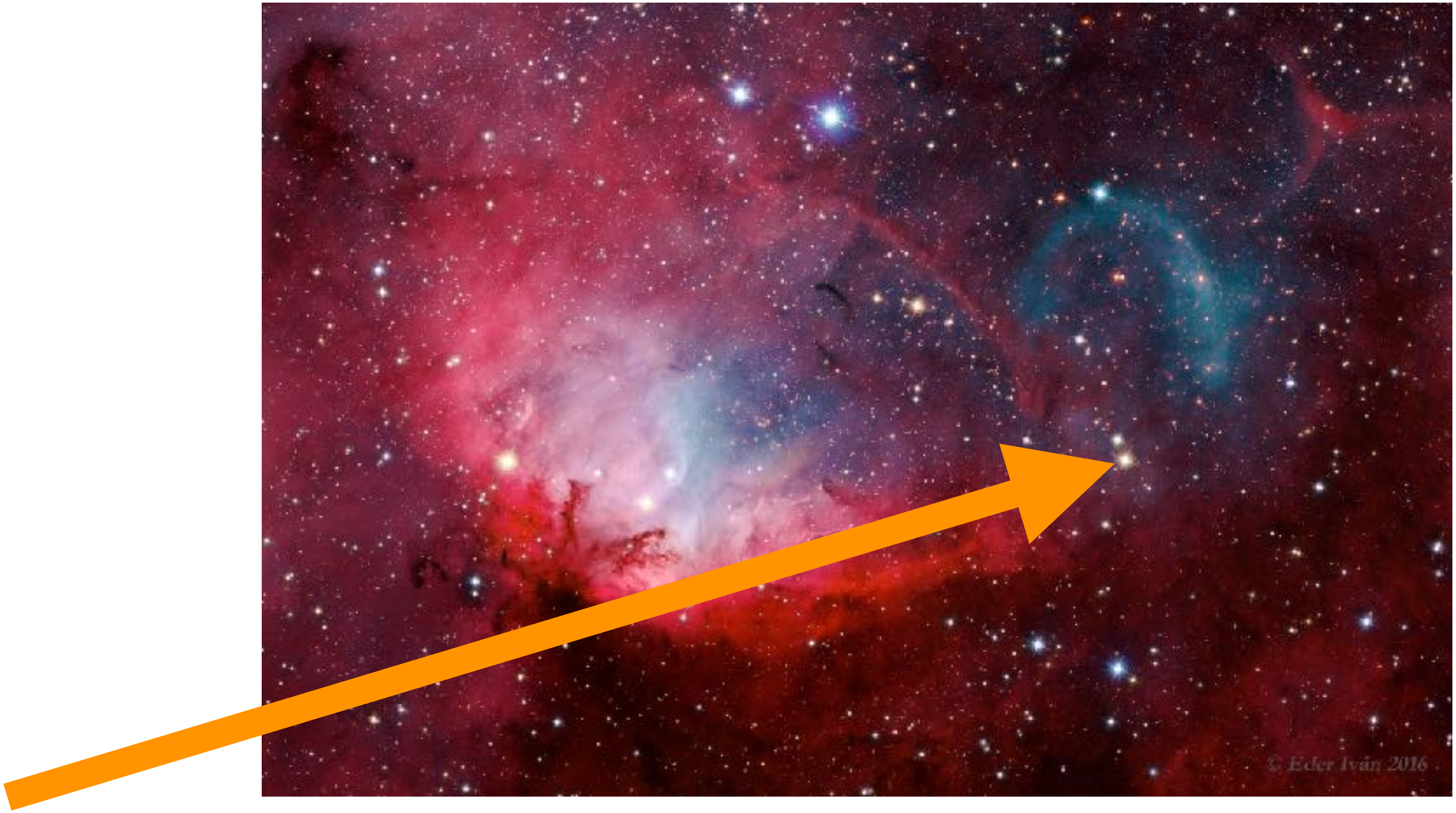
1960s

- Sub-orbital sounding rockets:
  - X-ray sources!
  - In Cygnus, Sagittarius, Ophiuchus, several others.
- (needs a rocket, x-rays don't go very far in air.)

Cygnus X-1

- Is not pictured here.

  But its companion is.



Cygnus X-1

- The "first" black hole was Cygnus X1.
    - First seen in 1965; measurements in 1974. Kip Thorne is convinced in 2011.

- HUGE source of X-rays.
- Binary with O-star
- 15 Msun.
- About 6,000 lyr from Earth.
- Thorne vs. Hawking

Cygnus X-1: useful things

- In a binary: KEPLER'S LAWS tell us masses.
- Close enough for Parallax Distance with the VLBA.
  Accurate fluxes & masses (2011)
- BH:14 $M_{\odot}$
- Ostar:19 $M_{\odot}$

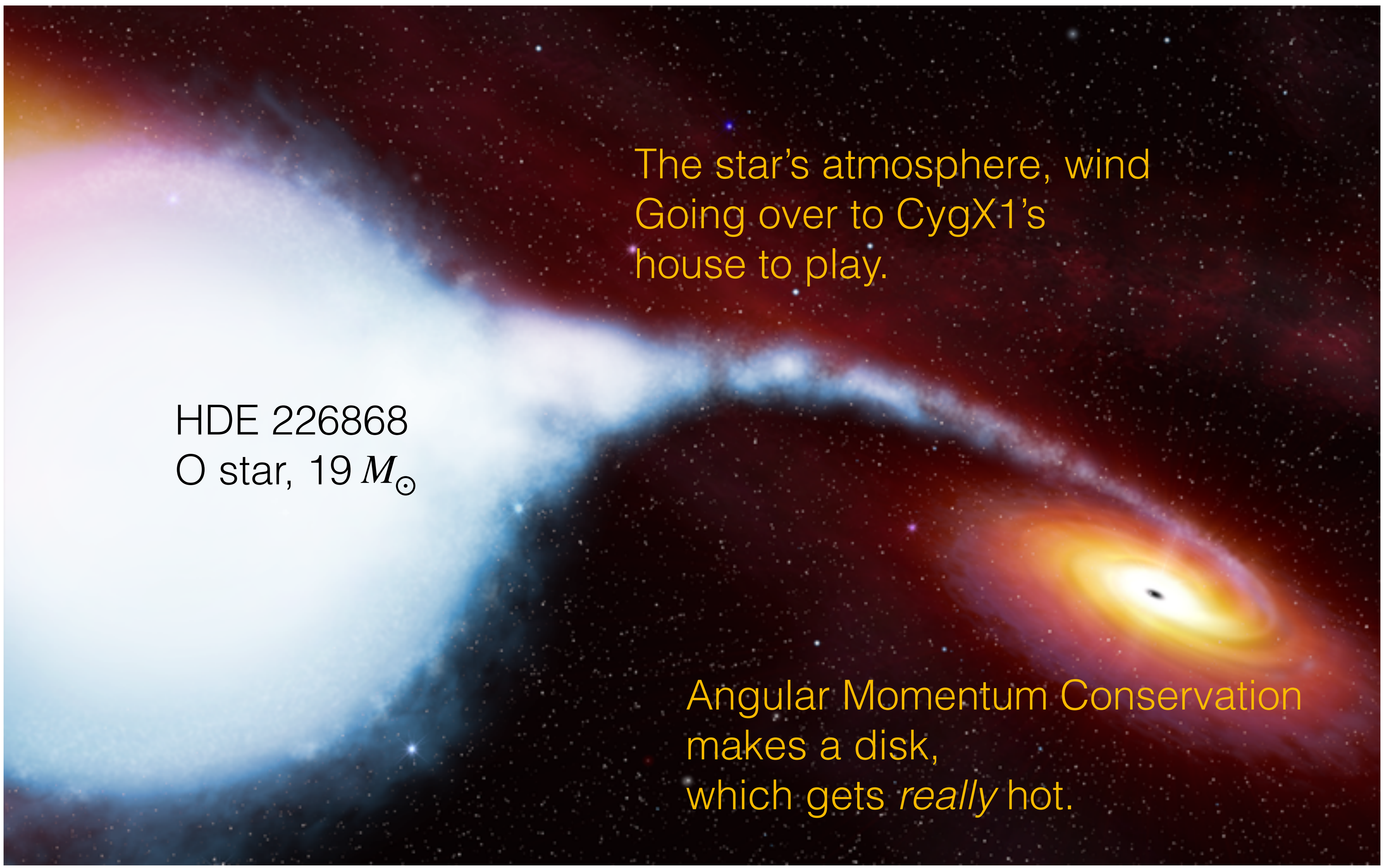
Still not convinced it's a BH.

- Something in this pair is producing a lot of X-rays.
- It's not the O-star, they're not hot enough.
- Why would a Black Hole produce X-rays?
  They're, uh, black.

How do you make X-rays?

- Gas from the atmosphere of the O-star blows off in a wind.

- Then it accretes onto the BH.



Why does it get hot?

- Gravitational Energy

$$E = -\frac{GMm}{r}$$

  is Negative.

- As r gets small, *E* gets ***more negative.***

- So to get closer to any gravitating thing, one has to *get rid of energy.*

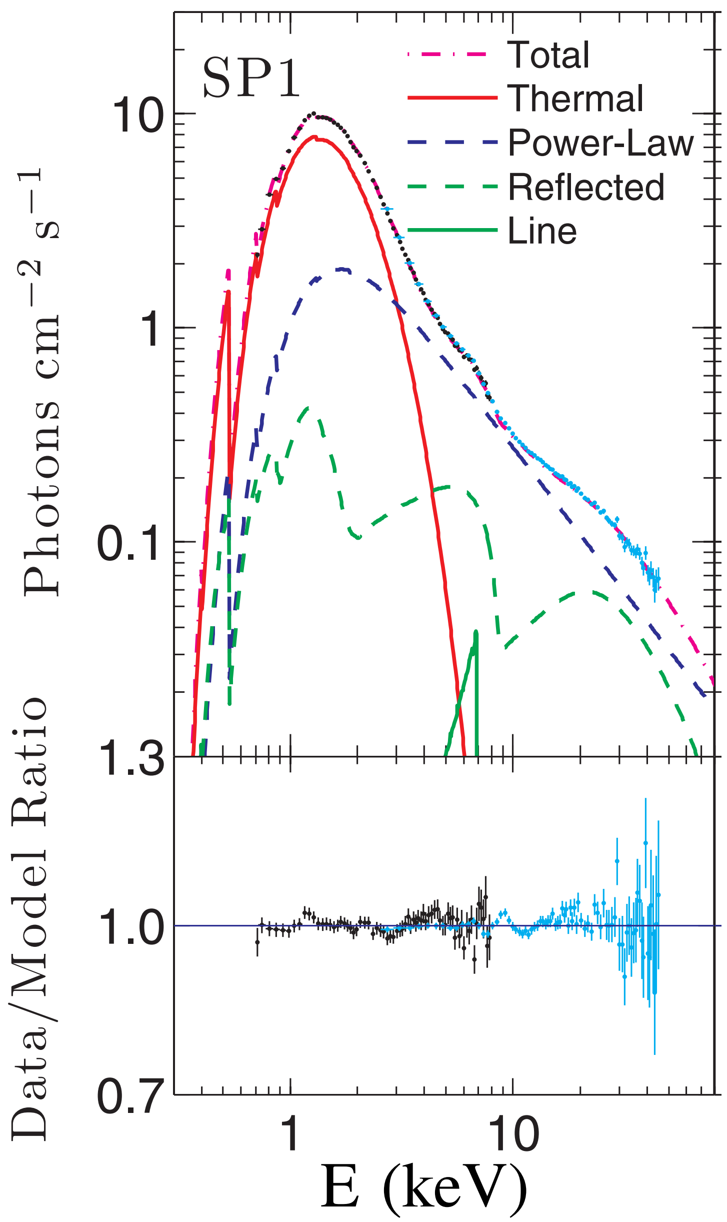
  - For example, the ISS is traveling at 17,150 mph. Sometimes the astronauts want to land.

- Specifically, **Kinetic** energy turns into **Thermal** energy. Then gets radiated away.

One more time with feeling.

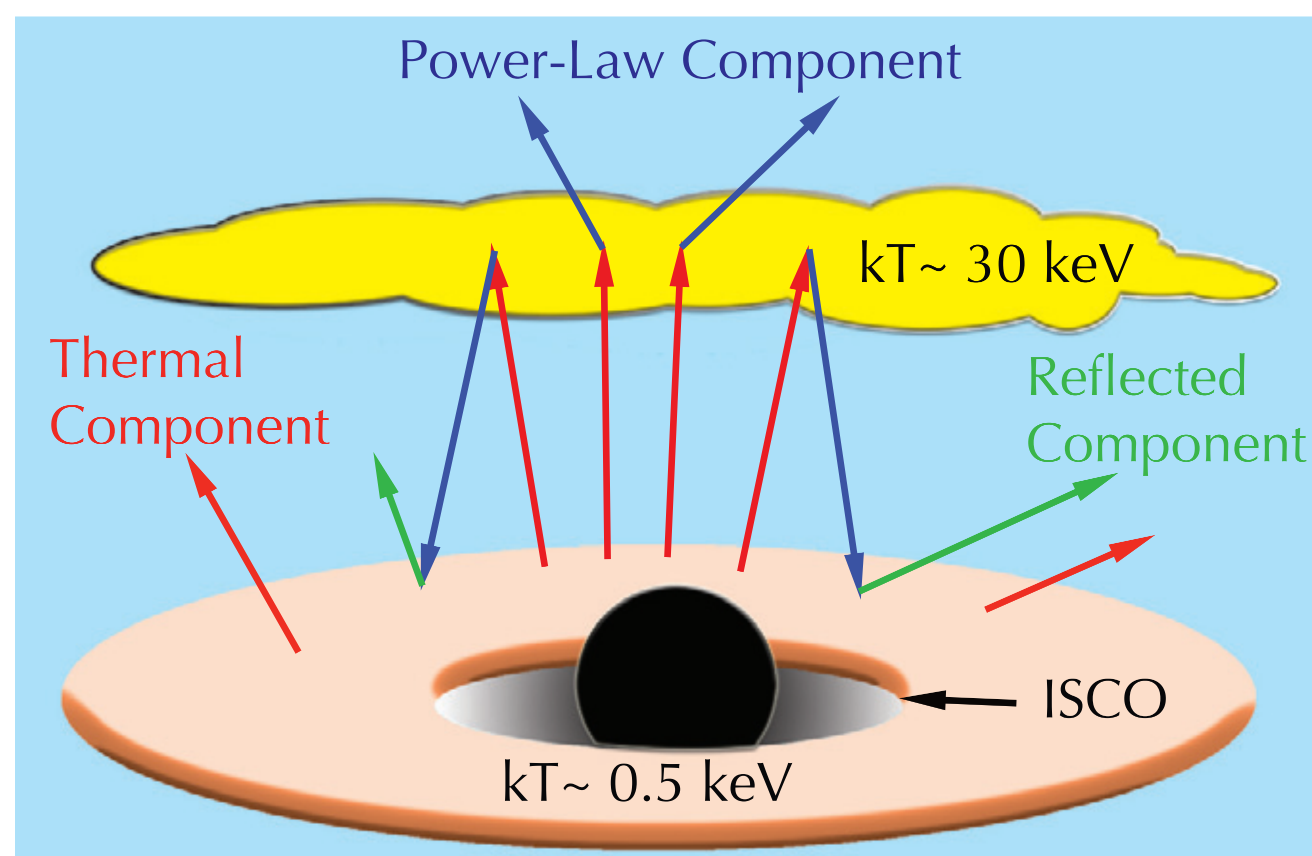
Given the **mass**, we can understand the **spectrum**. $E = -\frac{GMm}{r}$

- Too many to go into today, but blackbodies, GMM/r², and energy conservation reproduce these spectra very well.
  (and some atomic physics)(ok, the details needs GR, but not a lot)



$r_{inner} < 30\text{km}$

(Gou et al 2011, “Extreme Spin of the Black Hole in Cyg X-1”)

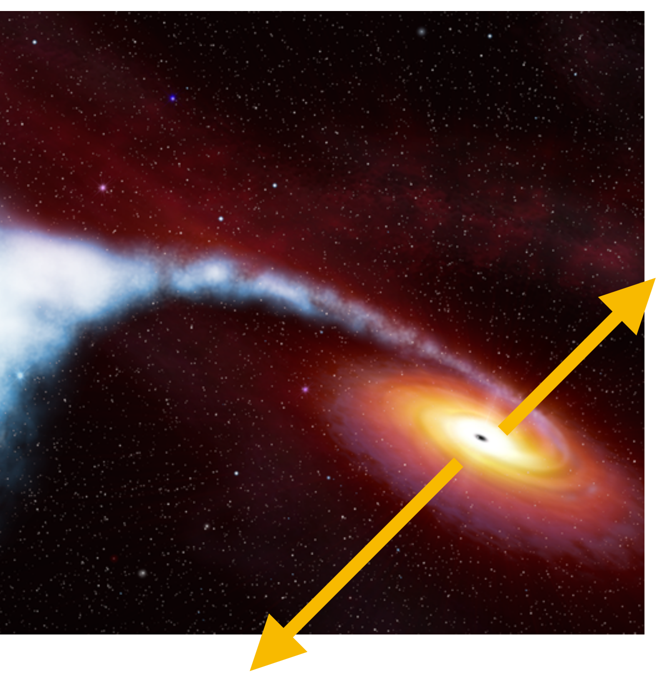


So?

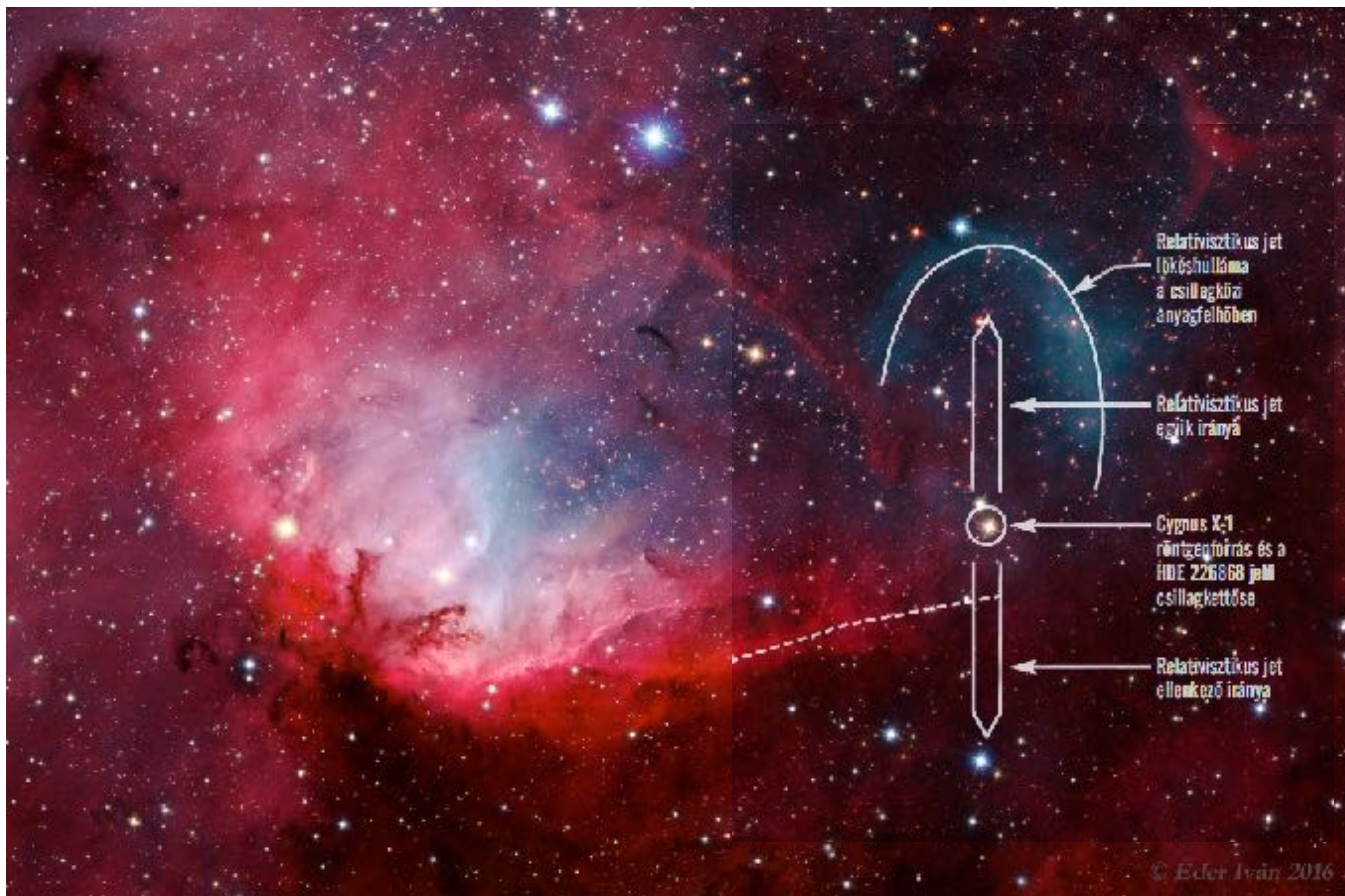
- So we have 14.8 $M_{\odot}$ $r = 30\text{km}$
- $r_s = 45\text{km}$
- So any way light can't get out from the object itself, whatever it is.
- It's either a **Black Hole**, or something much more difficult to understand.
- But it certainly isn't something simple.

Cygnus X-1: The Jet.

- Also stuff squirts out the top and bottom of the disk! Makes a jet that runs into the Inter-Stellar Medium



(why is there a jet? Probably magnetic fields)



More Things that are Obviously Black Holes.

- Sgr A*
- M87

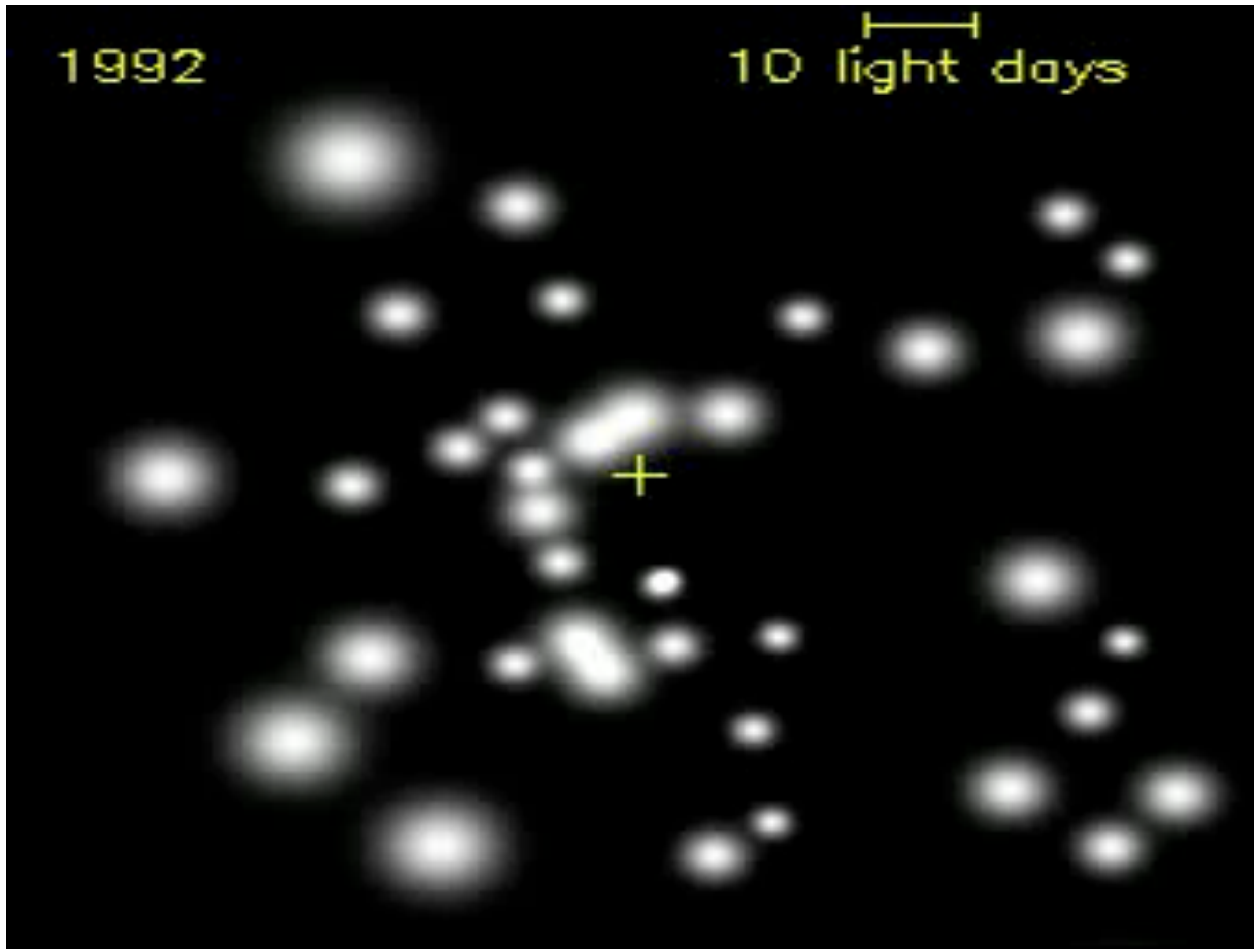
Sgr A*

- Galactic Center. Very bright in X-ray, Radio.
- Short flares in X-ray

Sgr A*

- R. Genzel

- These are stars in the center of the MW.

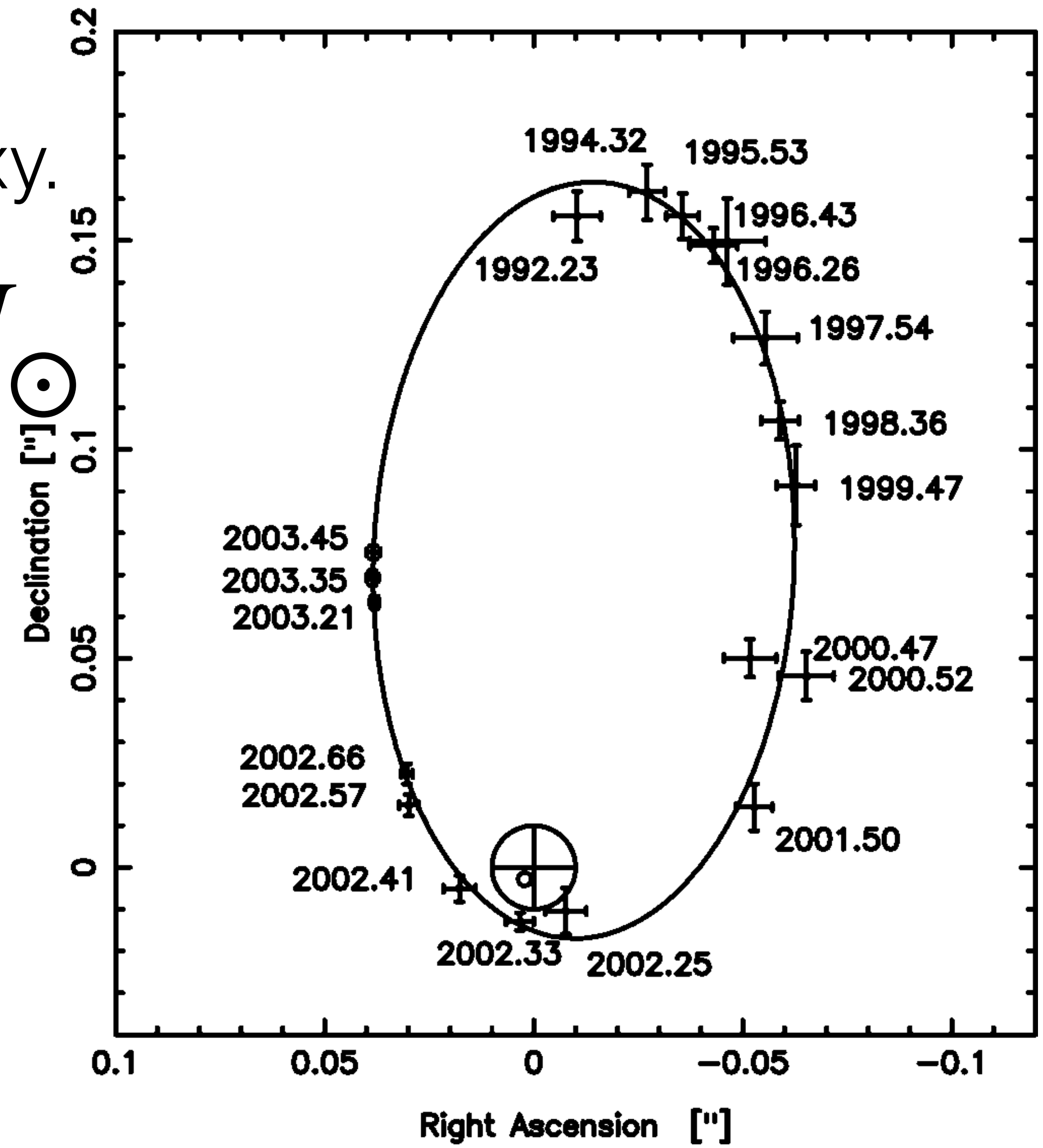


Kepler's Laws get us really far.

- Distance to the center of the galaxy.
- Mass of Sgr A*. $4.6 \times 10^6 M_\odot$

BEST-FIT KEPLER ORBIT FOR S2

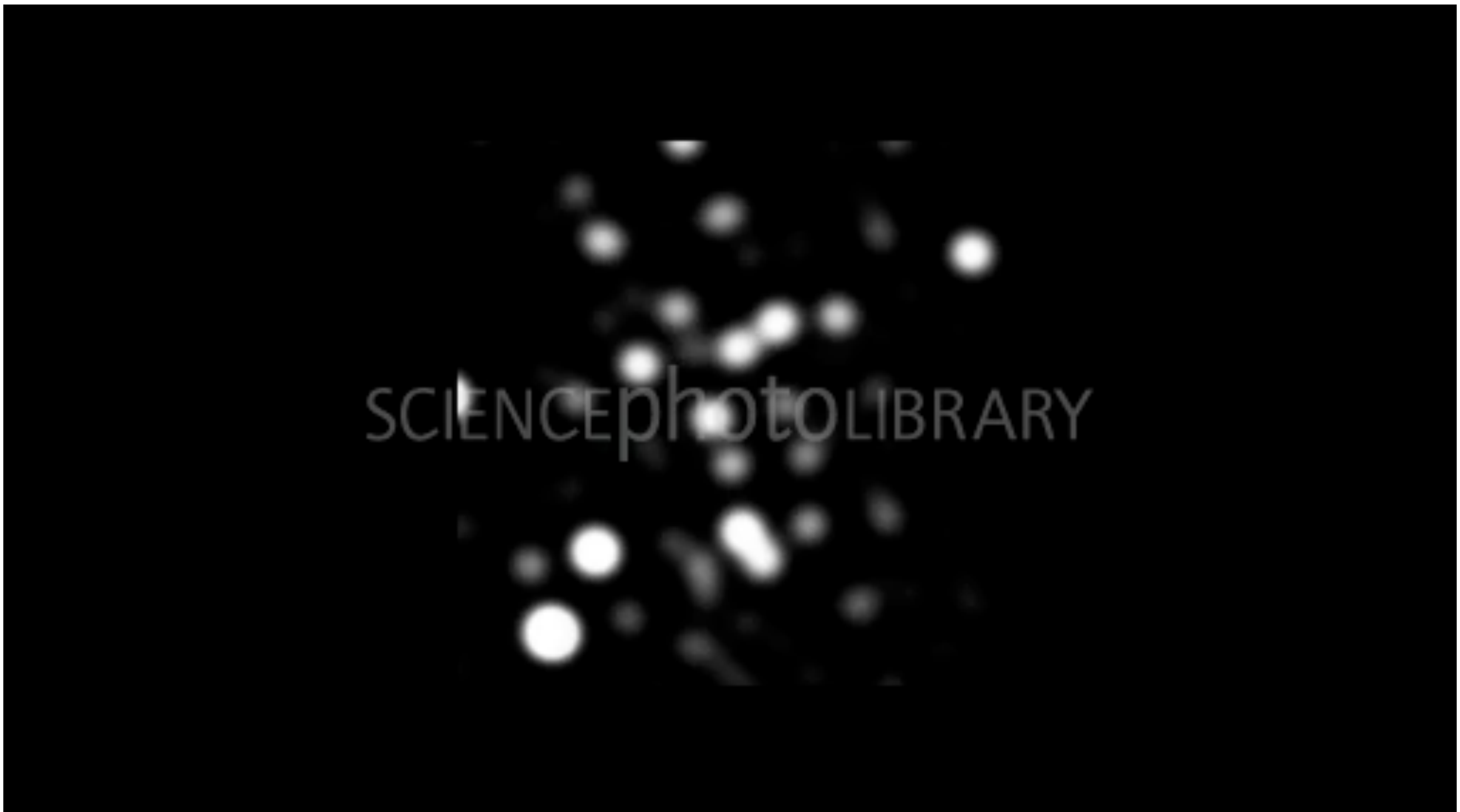
Parameter	Value
Semimajor axis a	$0''.1203 \pm 0''.0027$
Eccentricity e	0.881 ± 0.007
Orbital period P	15.56 ± 0.35 yr
Time of pericenter approach T_{peri}	2002.331 ± 0.012 yr
Inclination i	$-48^\circ.1 \pm 1^\circ.3$
Angle of line of nodes Ω	$45^\circ.0 \pm 1^\circ.6$
Angle of nodes to pericenter ω	$245^\circ.4 \pm 1^\circ.7$
x_0	$0''.0023 \pm 0''.0012$
y_0	$-0''.0031 \pm 0''.0012$
R_0	7.94 ± 0.38 kpc



(Eisenhauer + 2003)

Without Adaptive Optics.

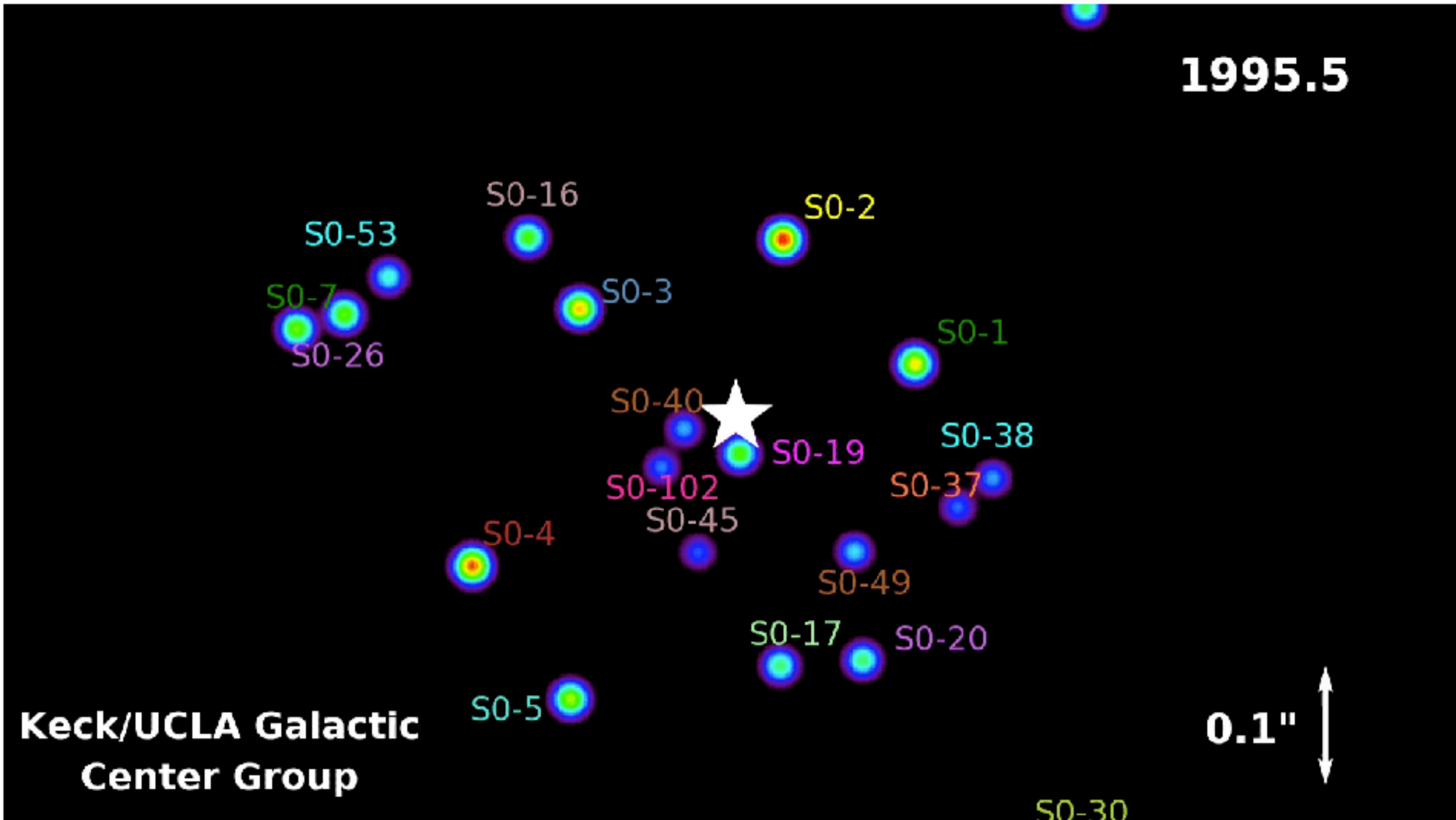
- Very cool techniques were developed to get this measurement right.



http://www.sciencephoto.com/media/247366/view/s2-star-orbiting-milky-way-black-hole

Andrea Ghez

- More data from the LA group.



Sgr A*

- From the stellar orbits, we know
  - How massive it is: $4 \times 10^6 M_\odot$
  - How close S2 gets: 950 AU
- It cannot be:
  - A star: it wouldn't survive, we'd see it
  - A cluster of (brown dwarfs, small stars) it would fly apart.
- It's either a black hole, or something much stranger that we haven't dreamed up yet. But it isn't something simple.

We (the Sun) aren't orbiting Sgr A*.

- Sgr A* is really large, but the bulge+disk of the galaxy are 20000x larger.

Also, it’s not very *active*.

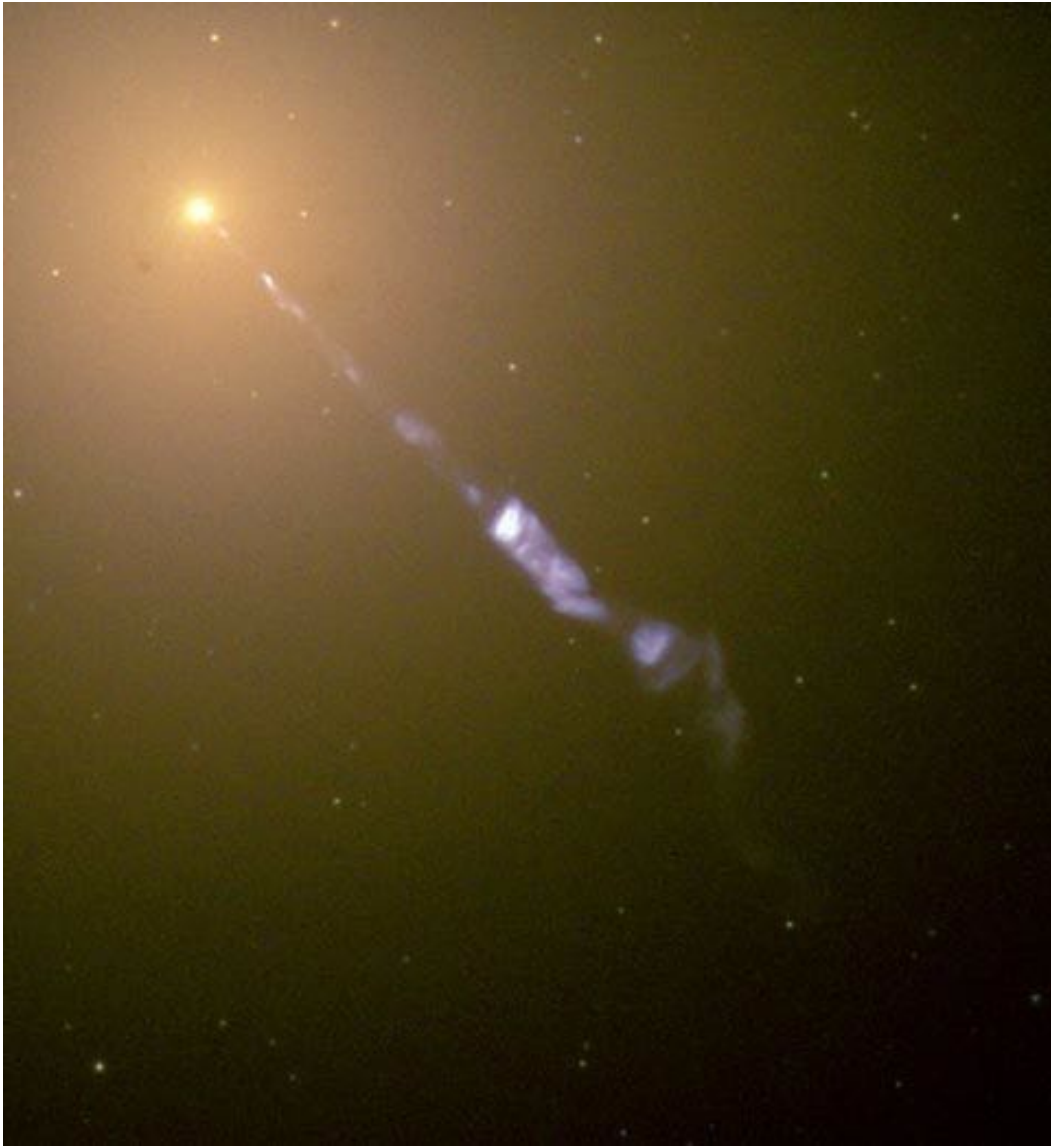
- Remember those X-Rays from Cyg X-1?
- Sgr A* isn’t spitting out photons like that, because it isn’t *accreting* much.

Outside the Milky Way

- Sgr A* is pretty mellow for a SMBH.
- Also not all that large.

M87

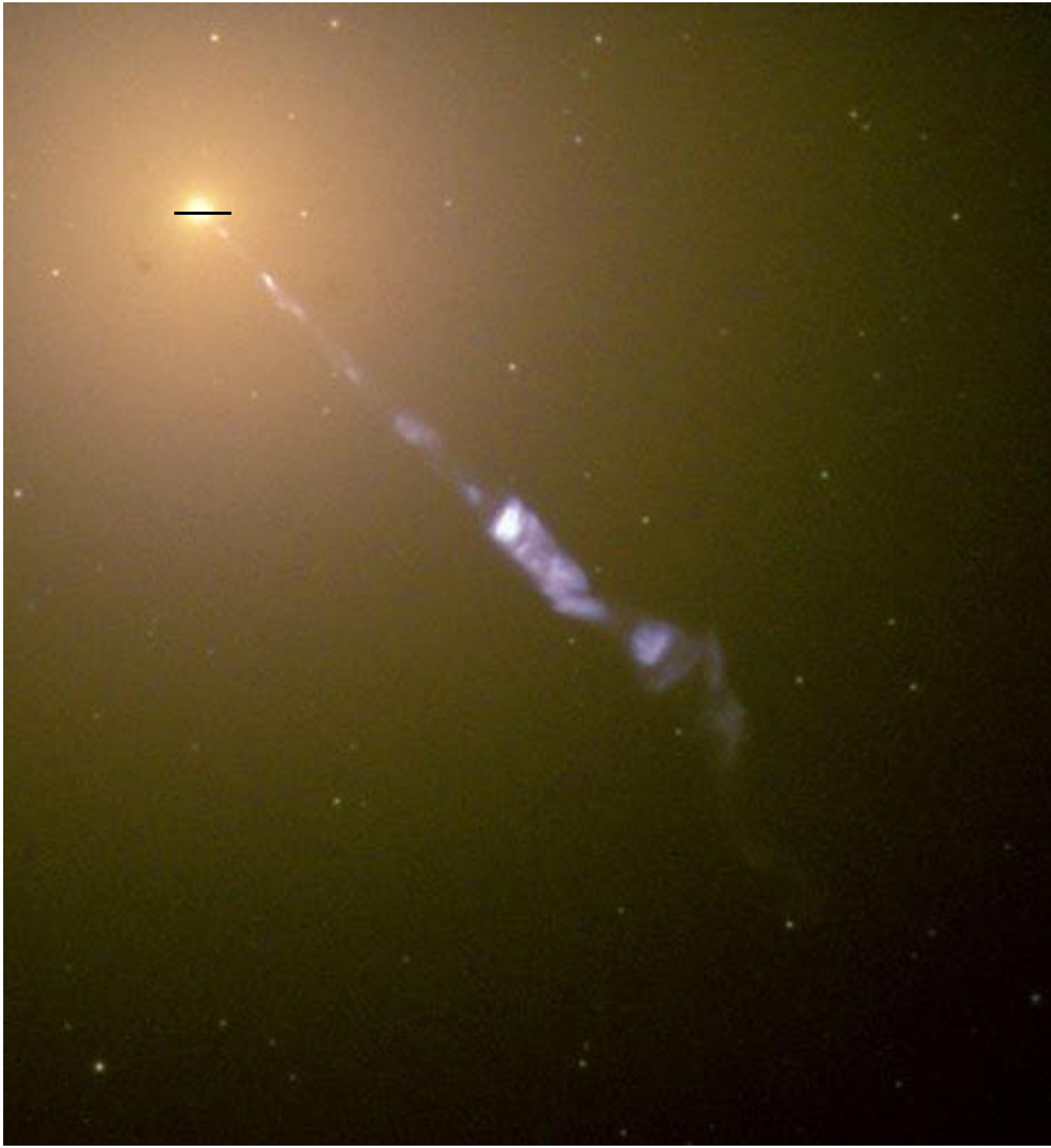
- Next closest (?) SMBH
- E0,
  16 Mpc from us
- Jet is 2.5kpc
  (8000 lyr)
  long.
- Near c.
- Very straight.
- Much energy.
- Wow.



M87

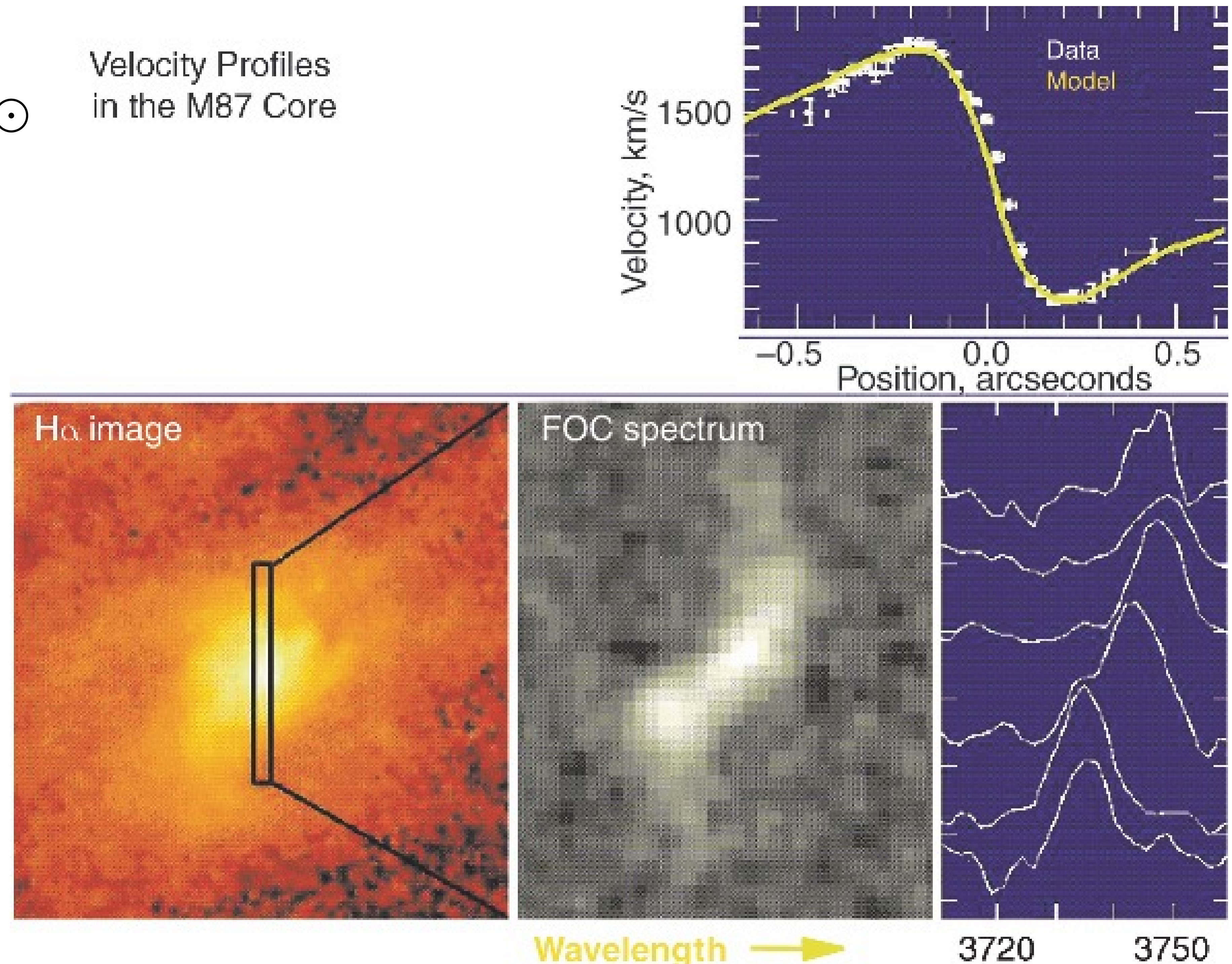
- Let's measure velocities in the middle.

  Use Kepler.



M87

- Again with Keplerian motion, but this time with a whole bunch of stars.
- $M_{BH} \sim 3 \times 10^9 M_\odot$
- That. Is. Huge.



Remember those X-Rays?

- A. Billion. Solar. Masses.

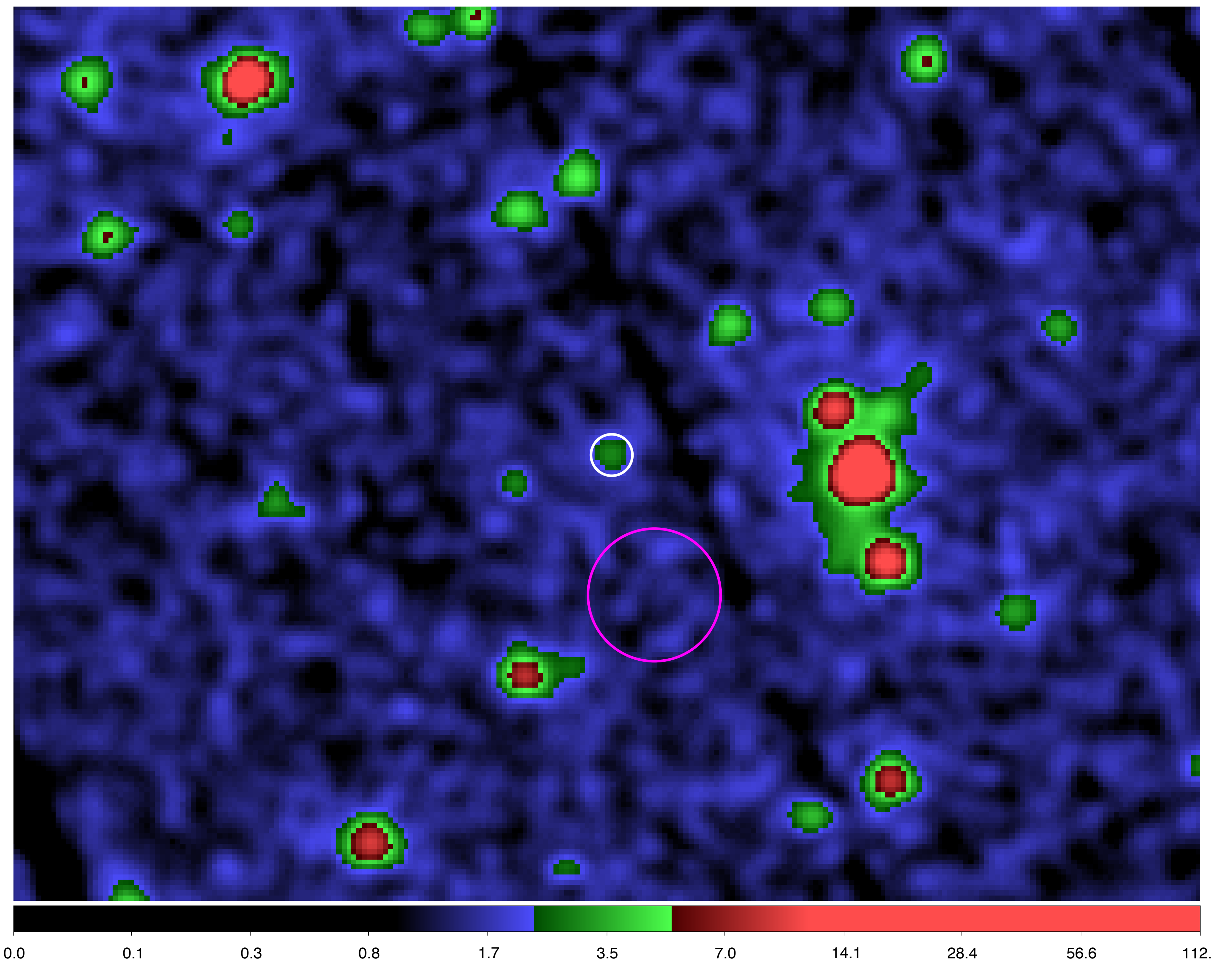
- Active Galactic Nuclei (AGN):
  Quasar/QSO
  Huge zoo of other things.

Most Distant QSO ULAS J1120+0641

- *(z=7.085)*
- t=766 Myr
- R=8.8 Gpc

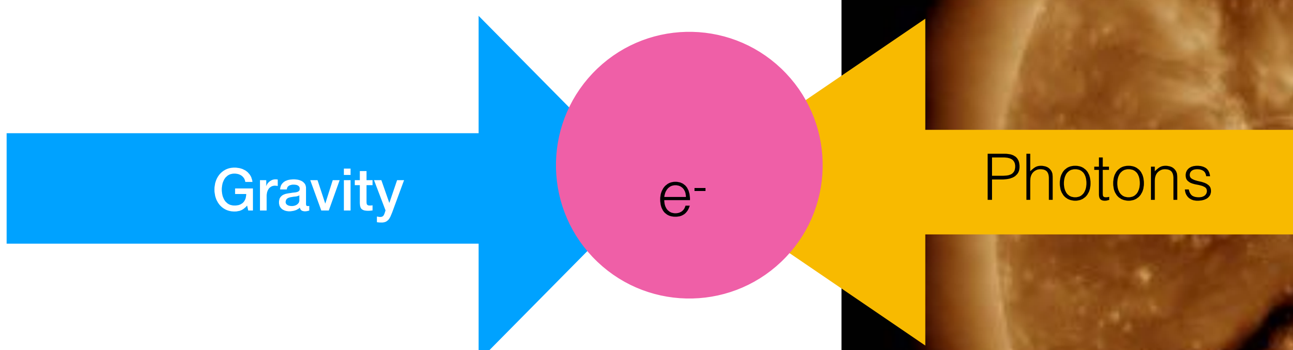
$2.0^{+1.5}_{-0.7} \times 10^{9}\ M_{\odot}$

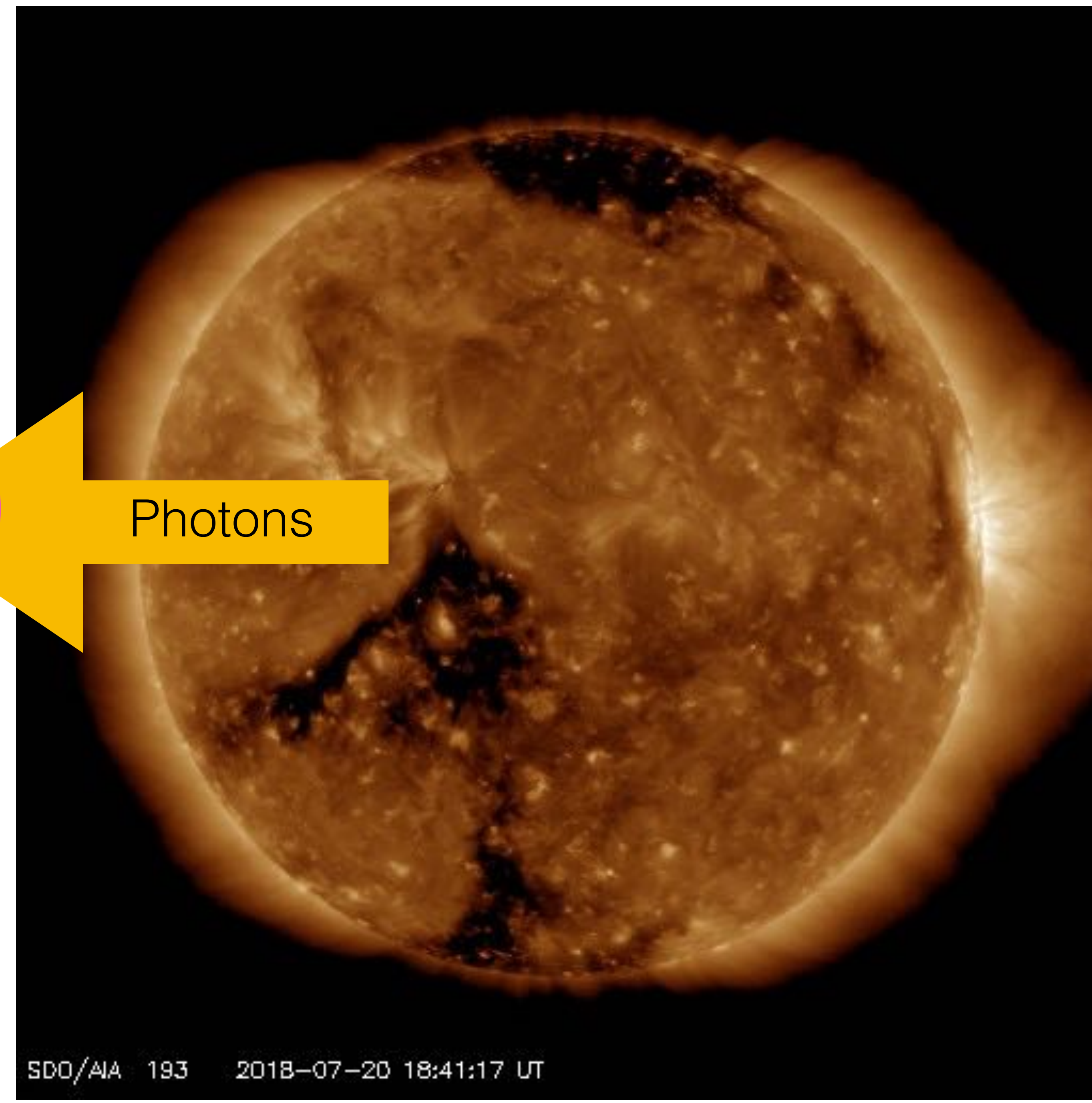
- Mortlock+ 2011



How do we weigh that?

- Way to far for Kepler.
- Use Eddington: *Photon Pressure* stops *Gravity.*
- Gives a maximum *Luminosity* for a given *Mass.*

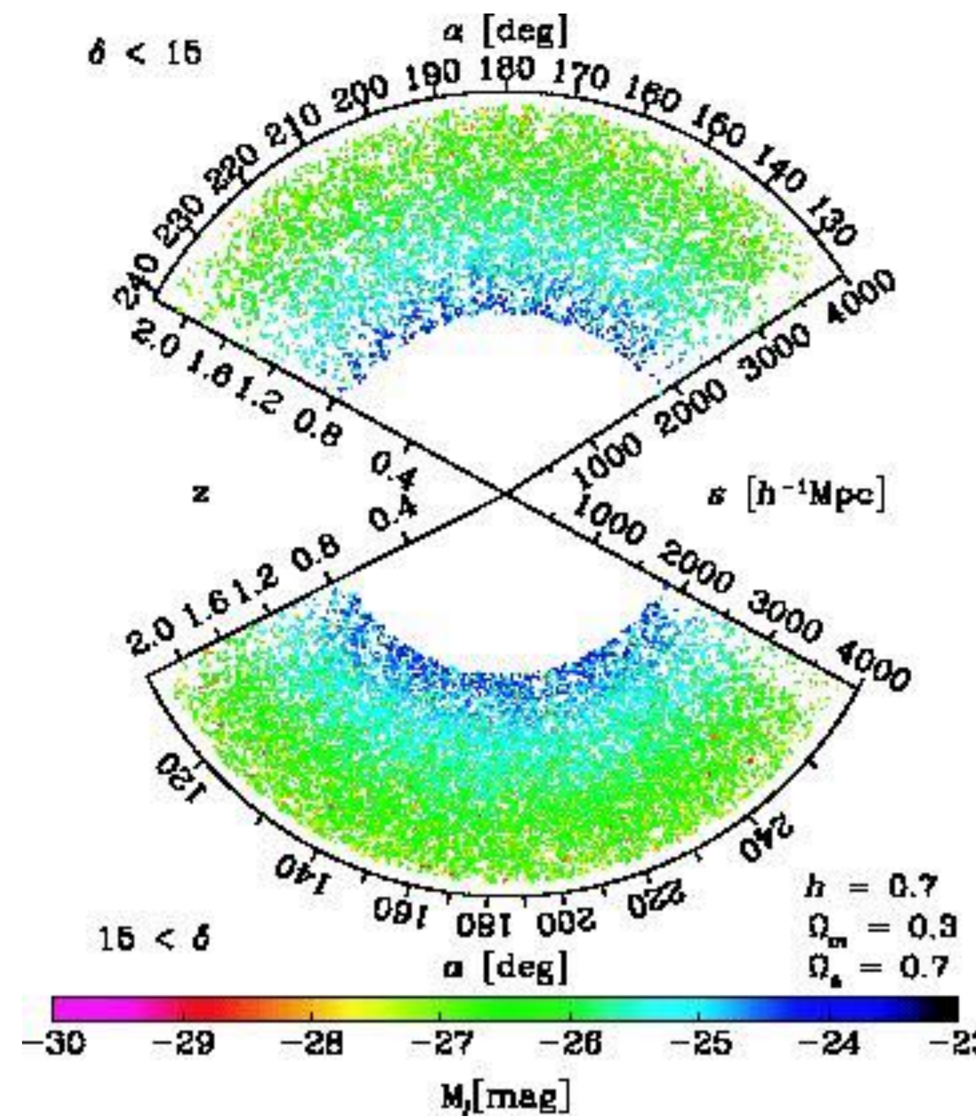




- Given the *Luminosity* we have a *MINIMUM* mass.

Every Galaxy Has a SMBH.

- These are very useful.
- More if I have time at the end.
- Sloan Digital Sky Survey:
  19,986 QSOs
  between 500 and 4000 Mpc/h
  $0.72<z<2.24$



The Newest Awesome.

- The first Nobel Prize in Grant writing.

- Given an *inertia* and a *force* that depends on *space*
(e.g. guitar string; has mass, tension depends on plucking)

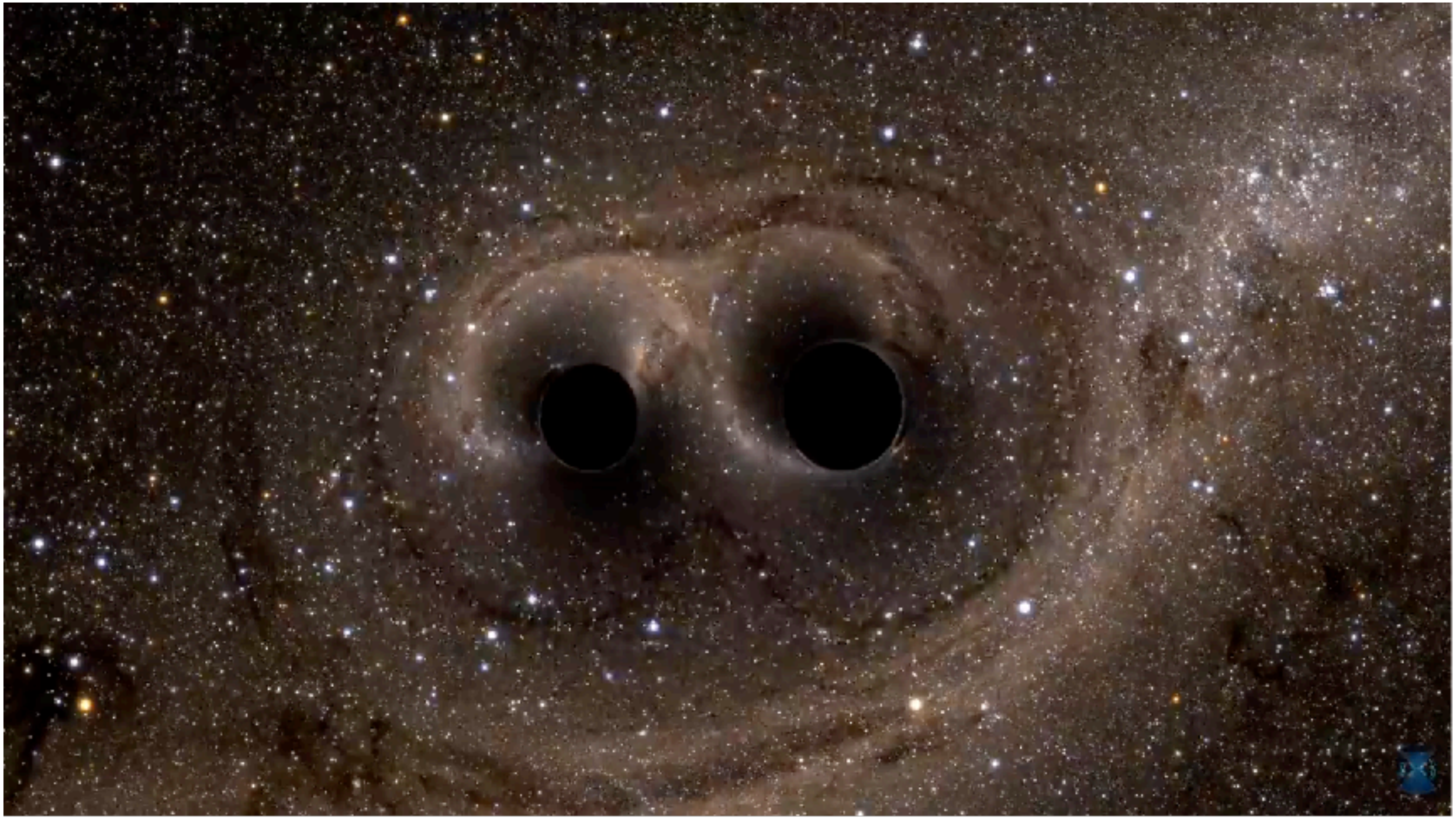
- ALSO General Relativity: ***Curvature = Energy*** (plus a thing everyone hates)

$$G_{\mu\nu} = 8\pi T_{\mu\nu} + \Lambda g_{\mu\nu}$$

- Space is *Really Stiff.*

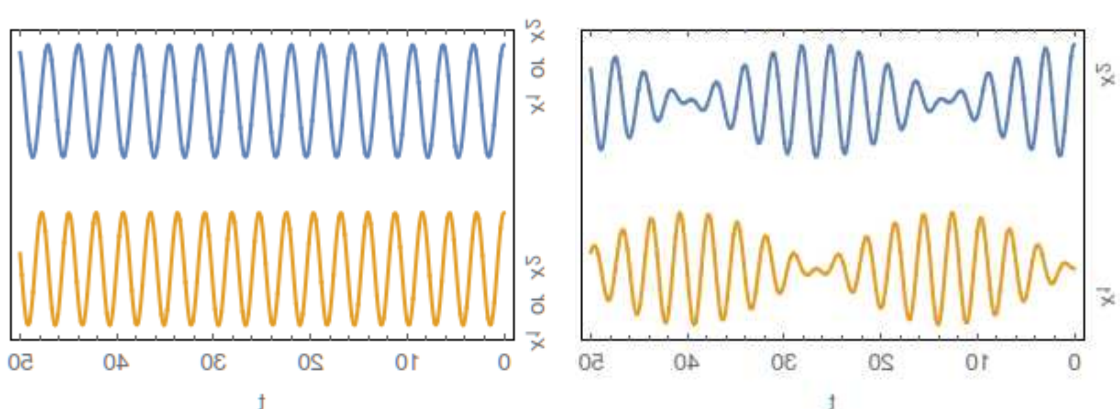
2016

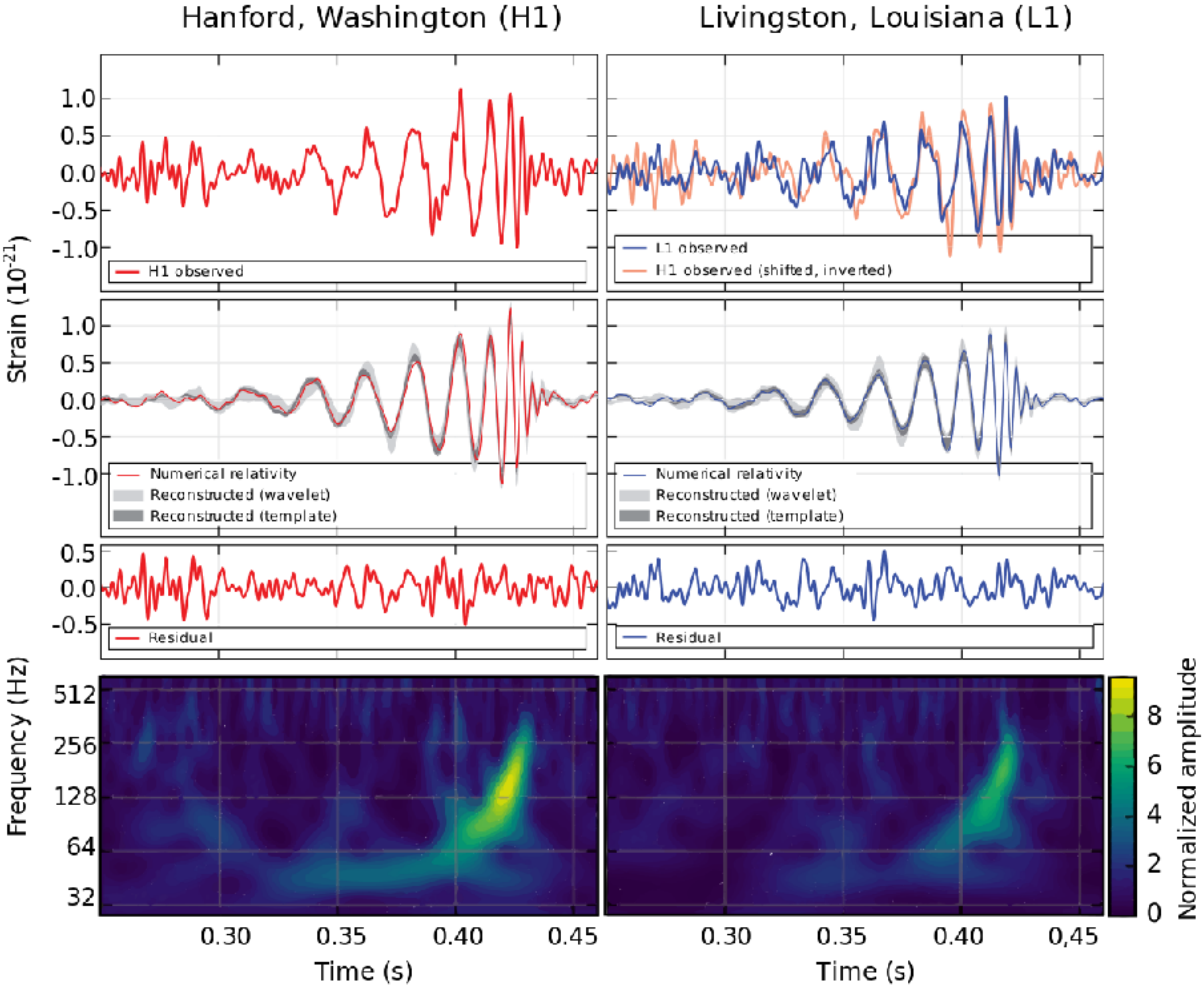
- It takes some serious violence to make waves **IN SPACE-TIME.**



The Newest Awesome.

- Ligo measures the length of these two 4km tubes to within less than the size of a proton.
- No it doesn't. It does something much more clever.
- It measures the relative **Interference** of two Waves of Light: Beat Frequencies.
- One of these waves is just a smidge longer:

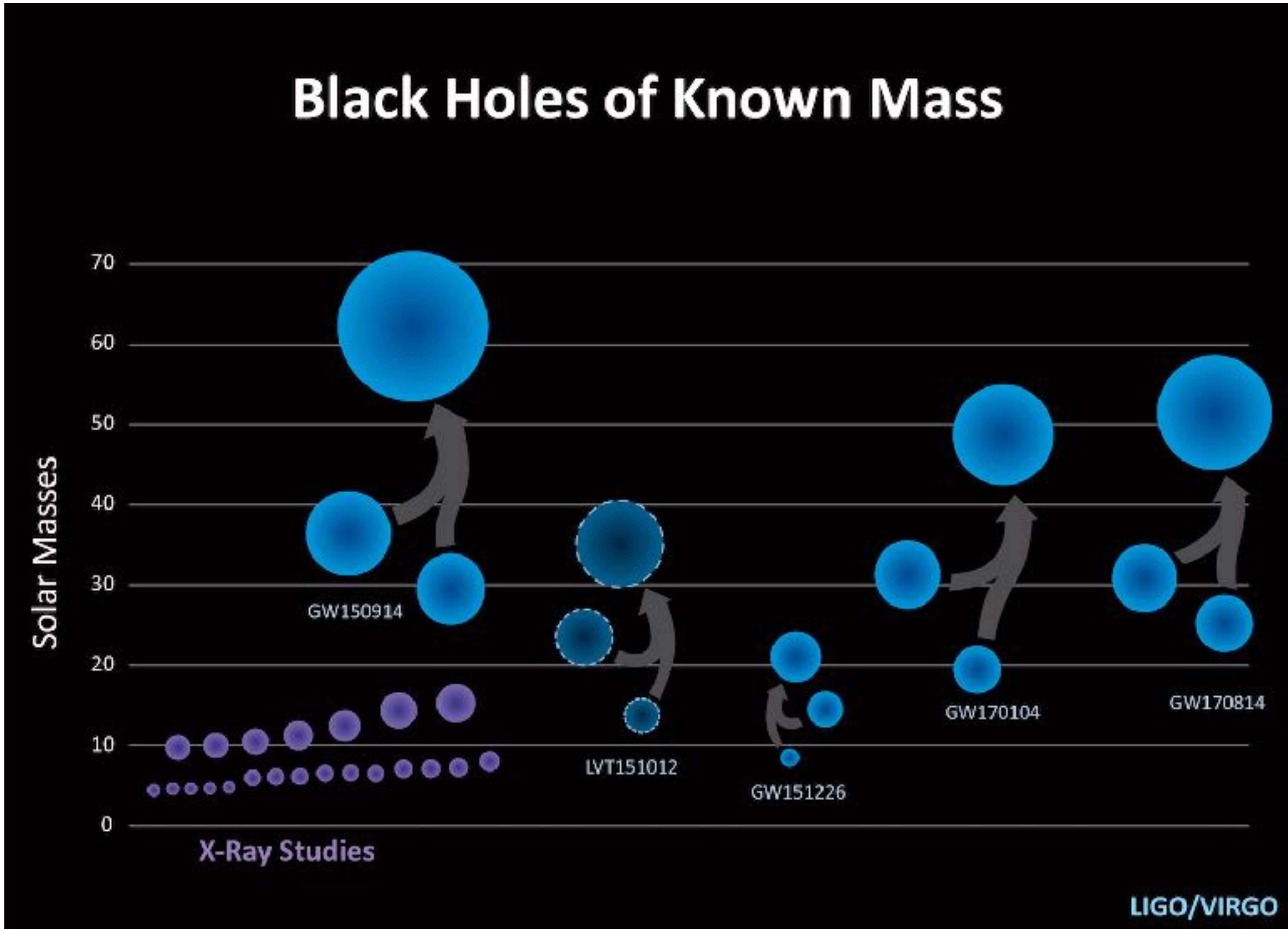




Hanford, Washington (H1)
Livingston, Louisiana (L1)
Strain (10^{-21})
1.0
0.5
0.0
-0.5
-1.0
H1 observed
L1 observed
H1 observed (shifted, inverted)
Numerical relativity
Reconstructed (wavelet)
Reconstructed (template)
Residual
Frequency (Hz)
512
256
128
64
32
0.30
0.35
0.40
0.45
Time (s)
Normalized amplitude
0
2
4
6
8

Five mergers.

- Some of these are pretty large…



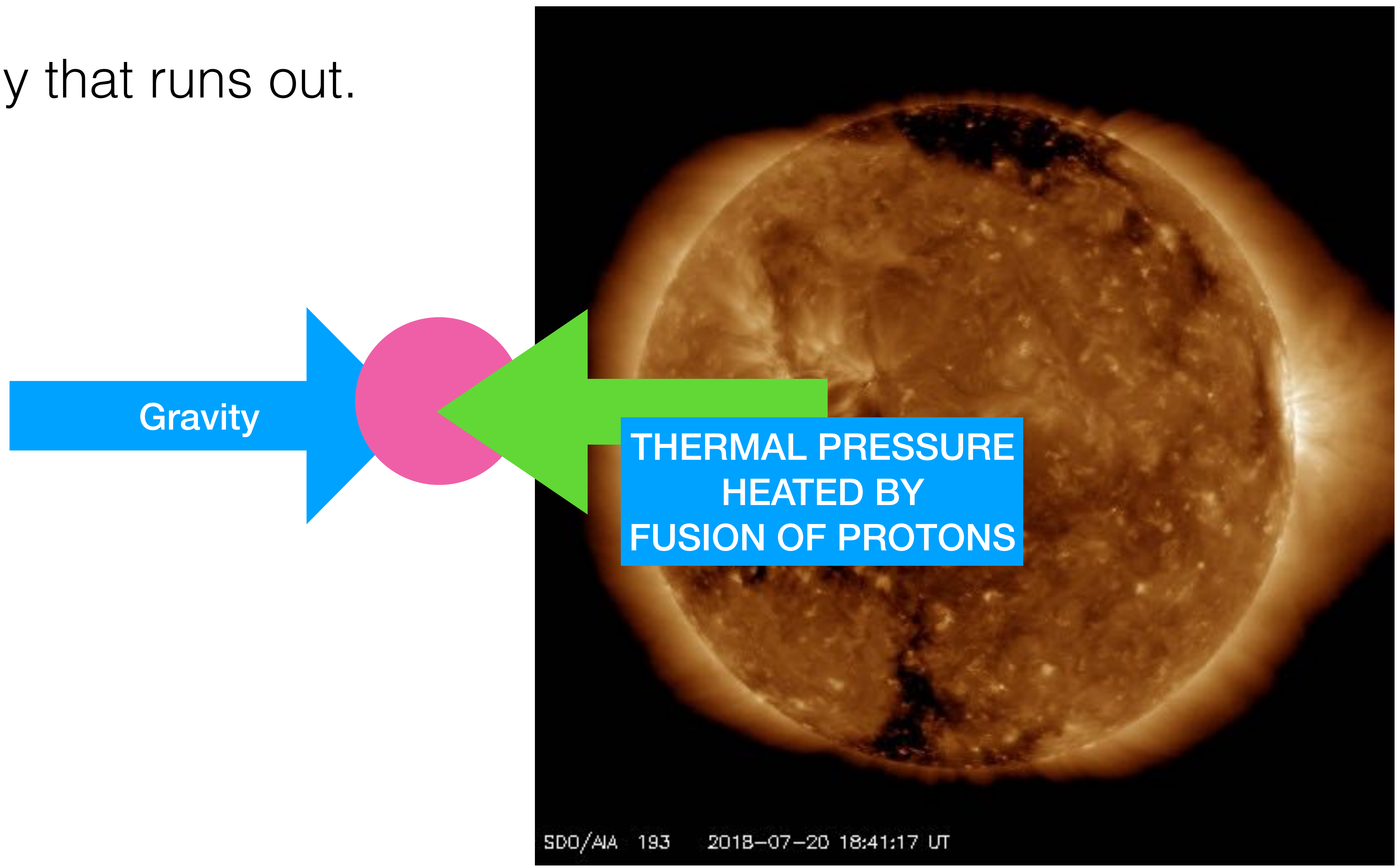
Formation!

- Stellar Mass (easy peasy).
- Intermediate Mass (harder parder).
- Supermassive (impossible pimpossible).

Formation!

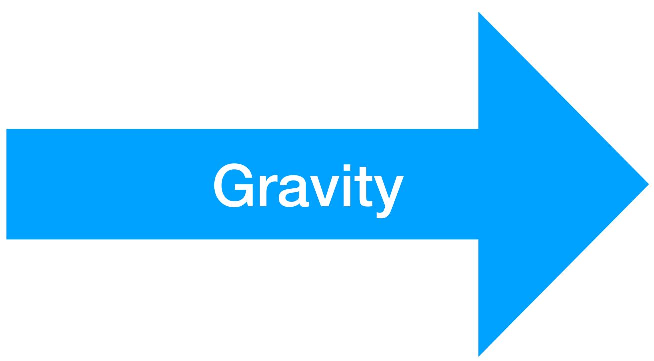
- H+H=
  He+Heat
  + The Star Not Collapsing.

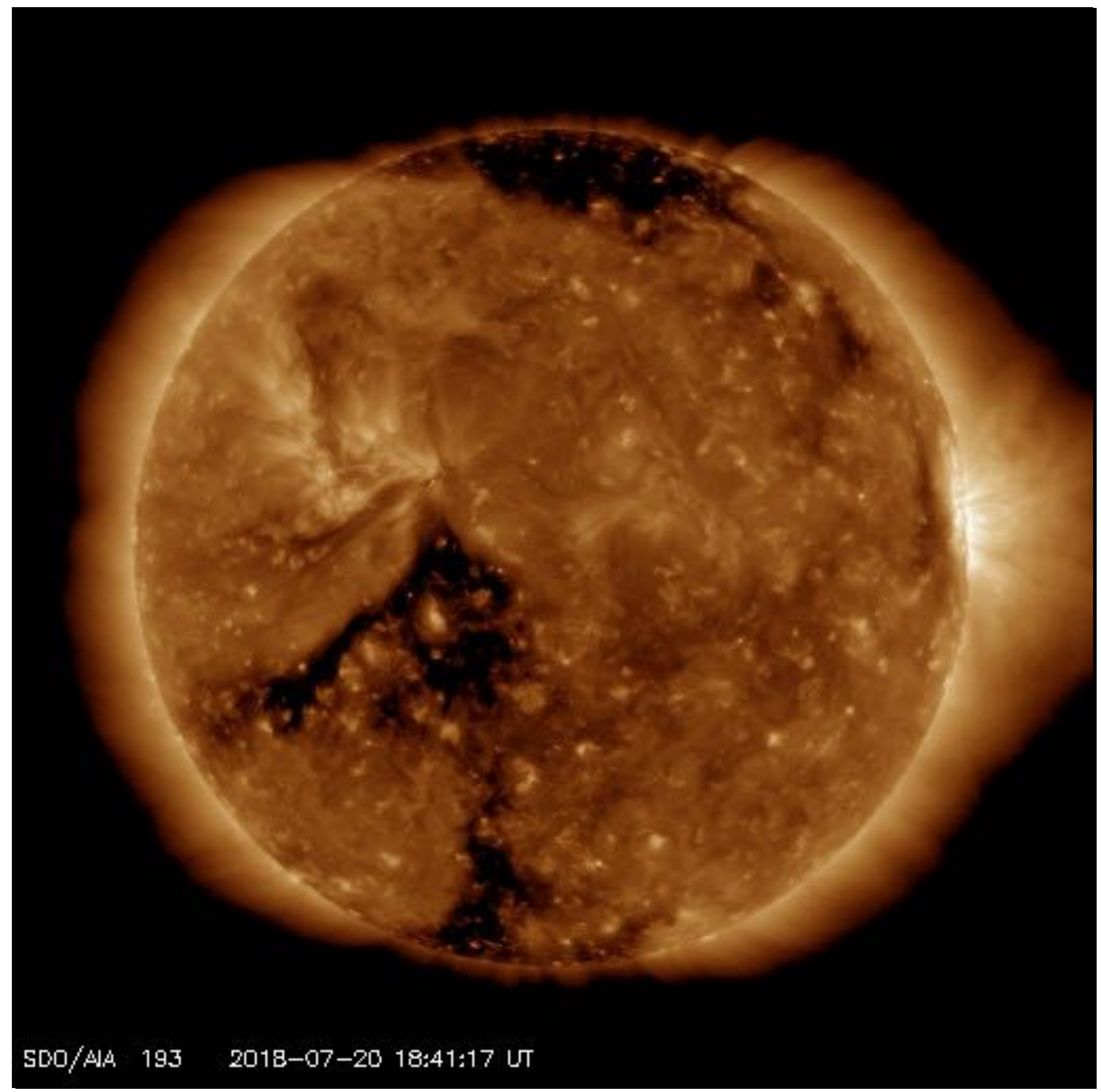
- Eventually that runs out.



Formation!

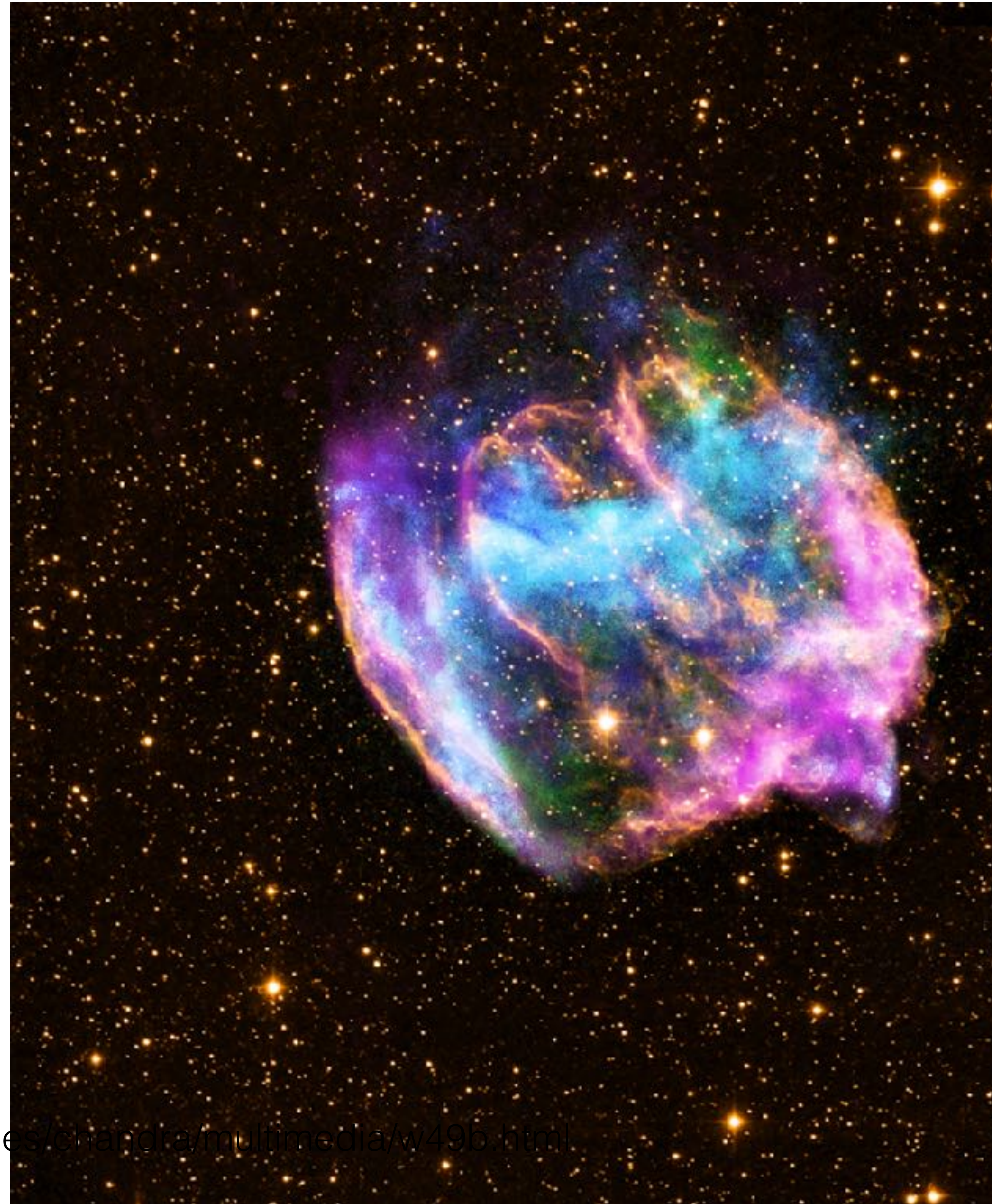
- For large stars >8Msun, the central bits collapse, and the outer bits
  ….
  maybe blow off?





Formation!

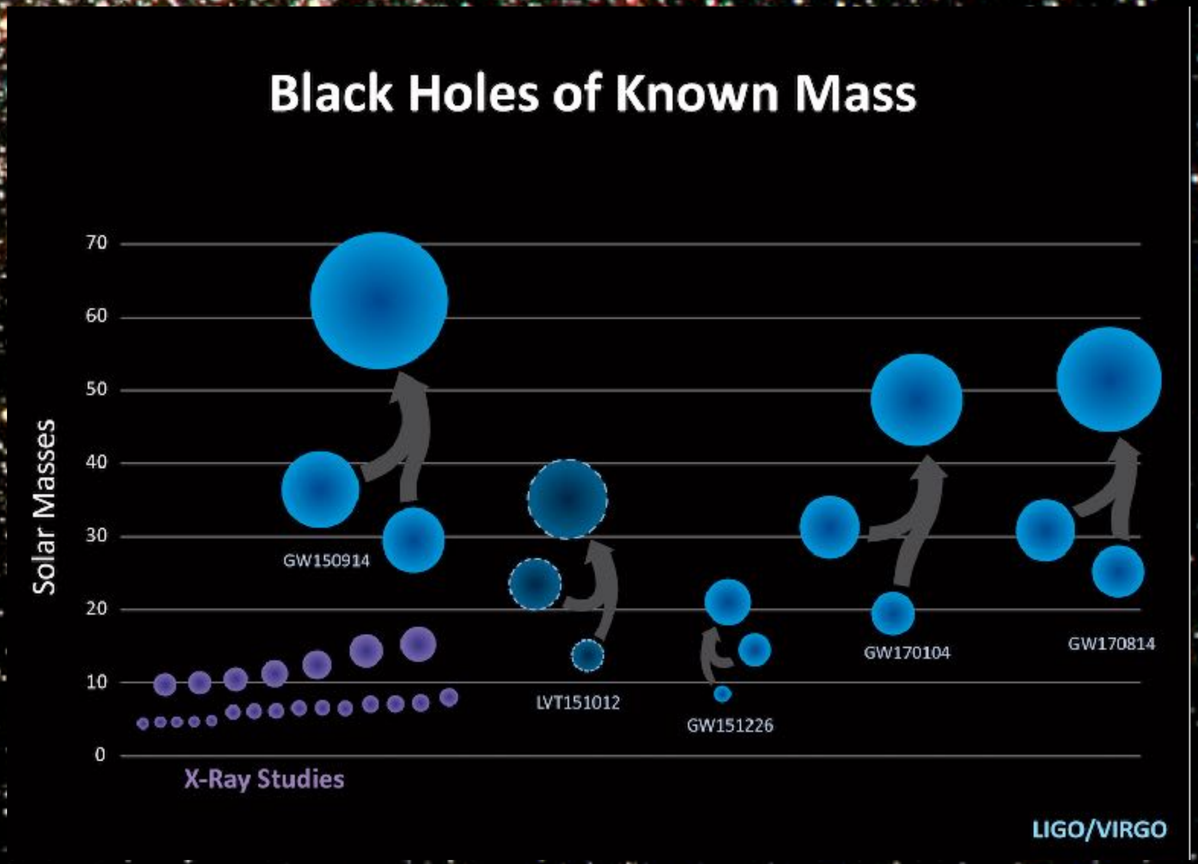
- These details are the subject of much study.
- Sometimes there's a neutron star.
- Sometimes there's …. not…
- Good for M_{BH}~10 Msun.



https://www.nasa.gov/mission_pages/chandra/multimedia/w49b.html

IMBH?

- How did we get 30 Msun?
- Most stars are binary stars. Some stars are in *very* dense environments. Mergers?

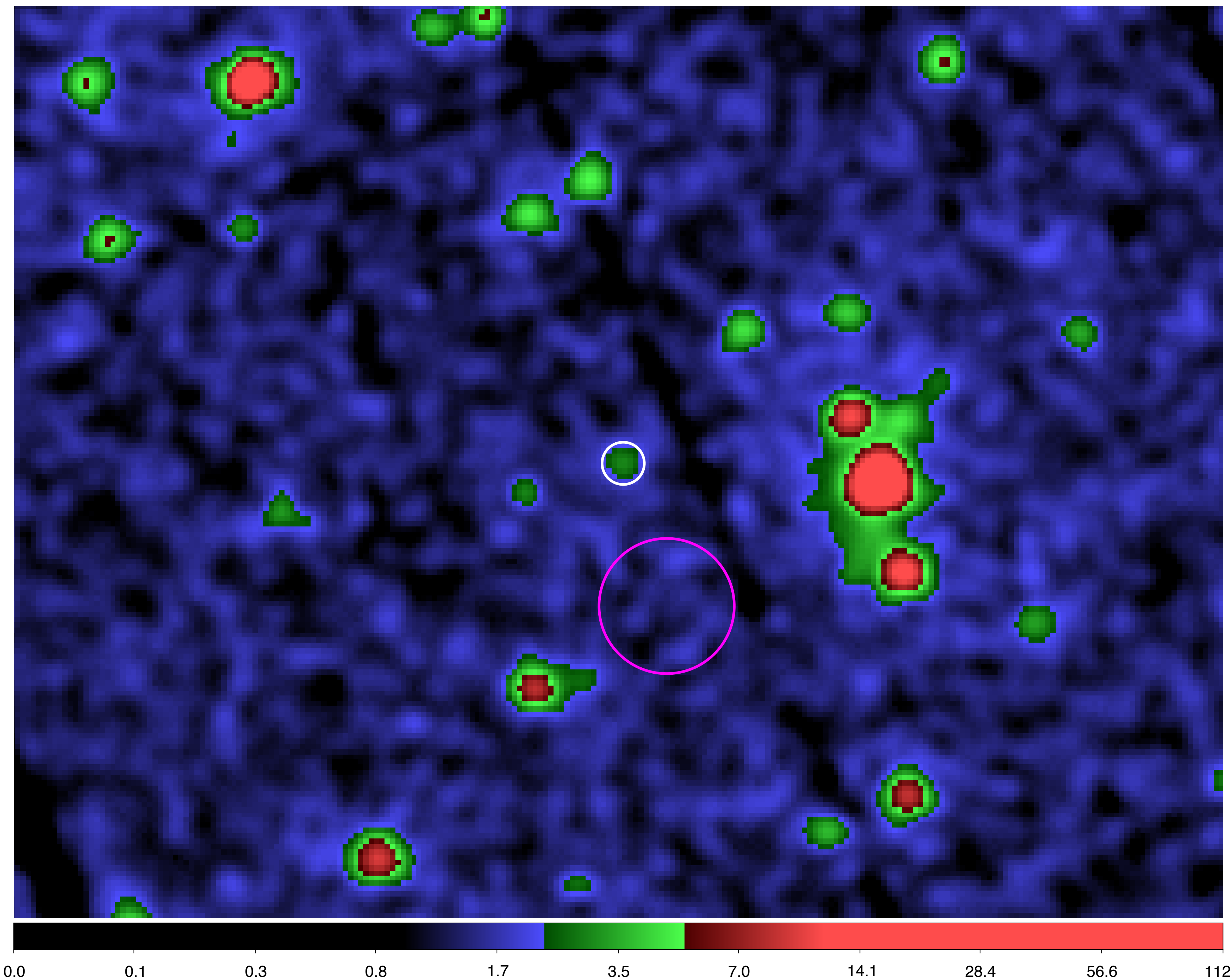


What about these huge things?

- $2x10^9$ Msun
  in
  t=766 Myr

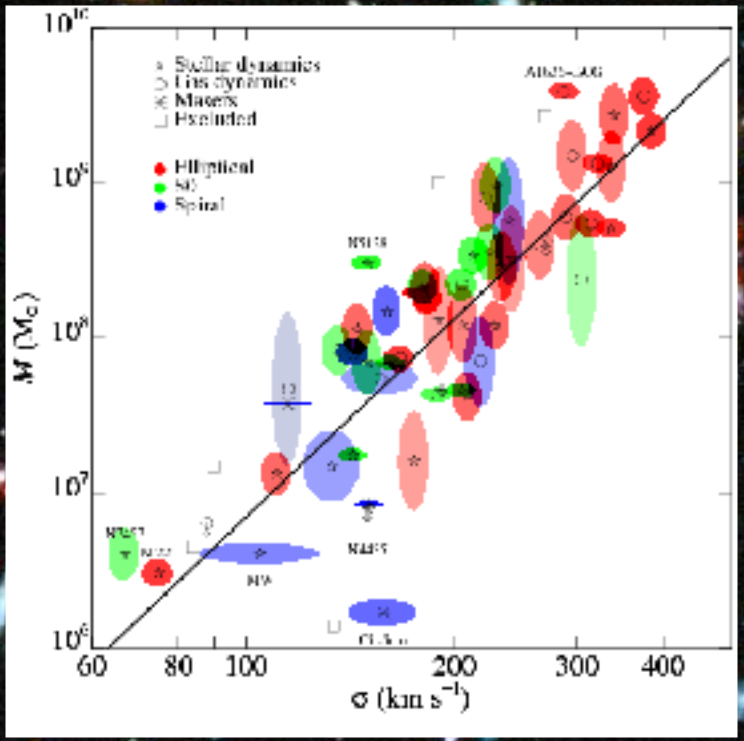
- That sounds like
  a lot of time,
  but it's a HUGE
  amount of mass.

- Accreting at
  Eddington
  Forever
  Still Doesn't Do It.



SMBH Formation

- In the early universe, galaxies are small.
- Larger ones form through repeated mergers.
- It seems that SMBH masses are related to Host Properties, but the connection isn't clear.

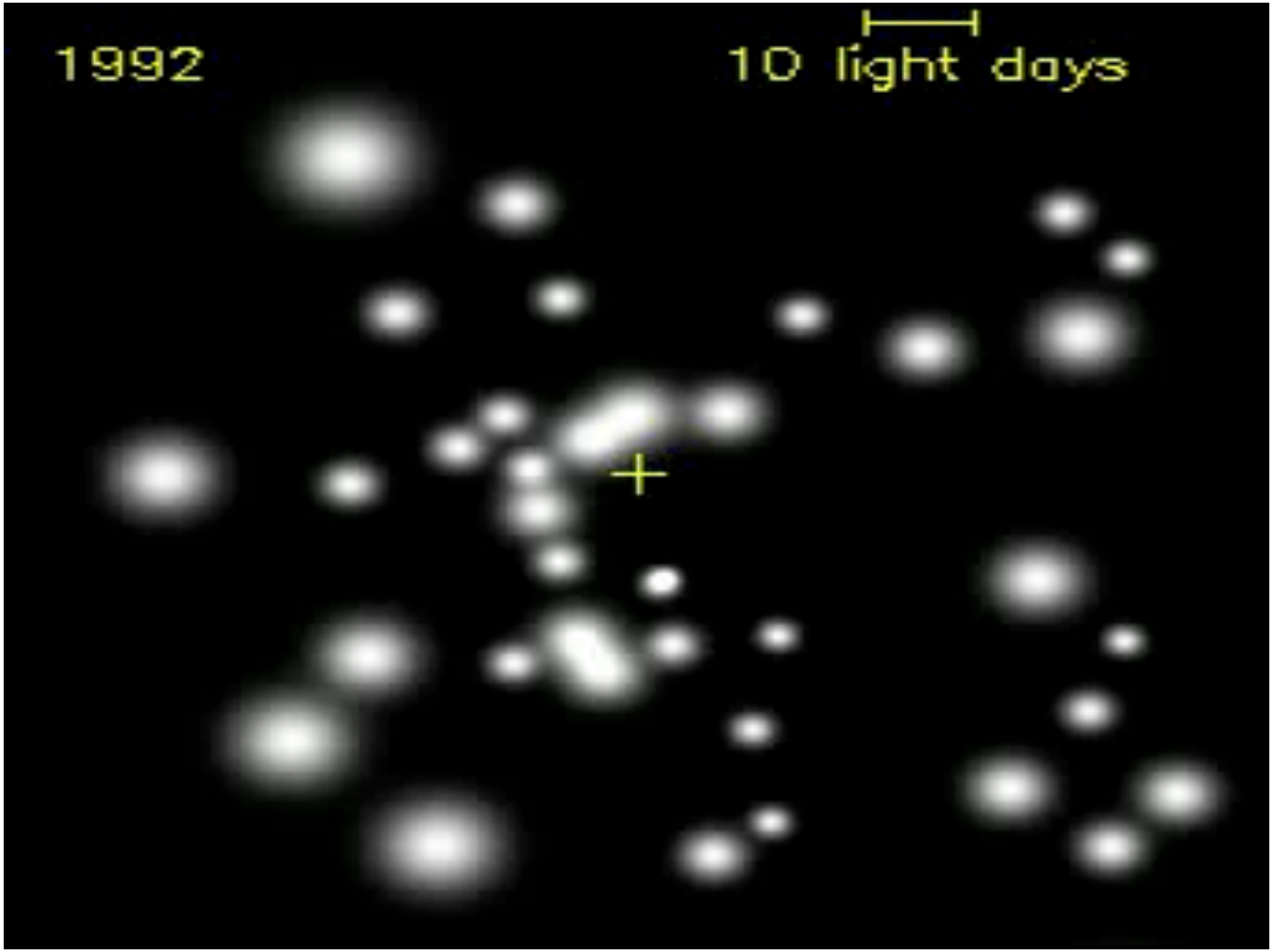


Sum Up.

- Black holes are a giant amount of mass in a very small space.
- There is very clear evidence for their existence in many places in the universe.
- Small ones in X-Ray Binaries
- Medium ones from Gravitational Waves (and way more than expected!)
- Supermassive ones at the center of every galaxy, back to the beginning of the universe.
- Where did they come from? Open questions!

Clearly there are black holes.

- .

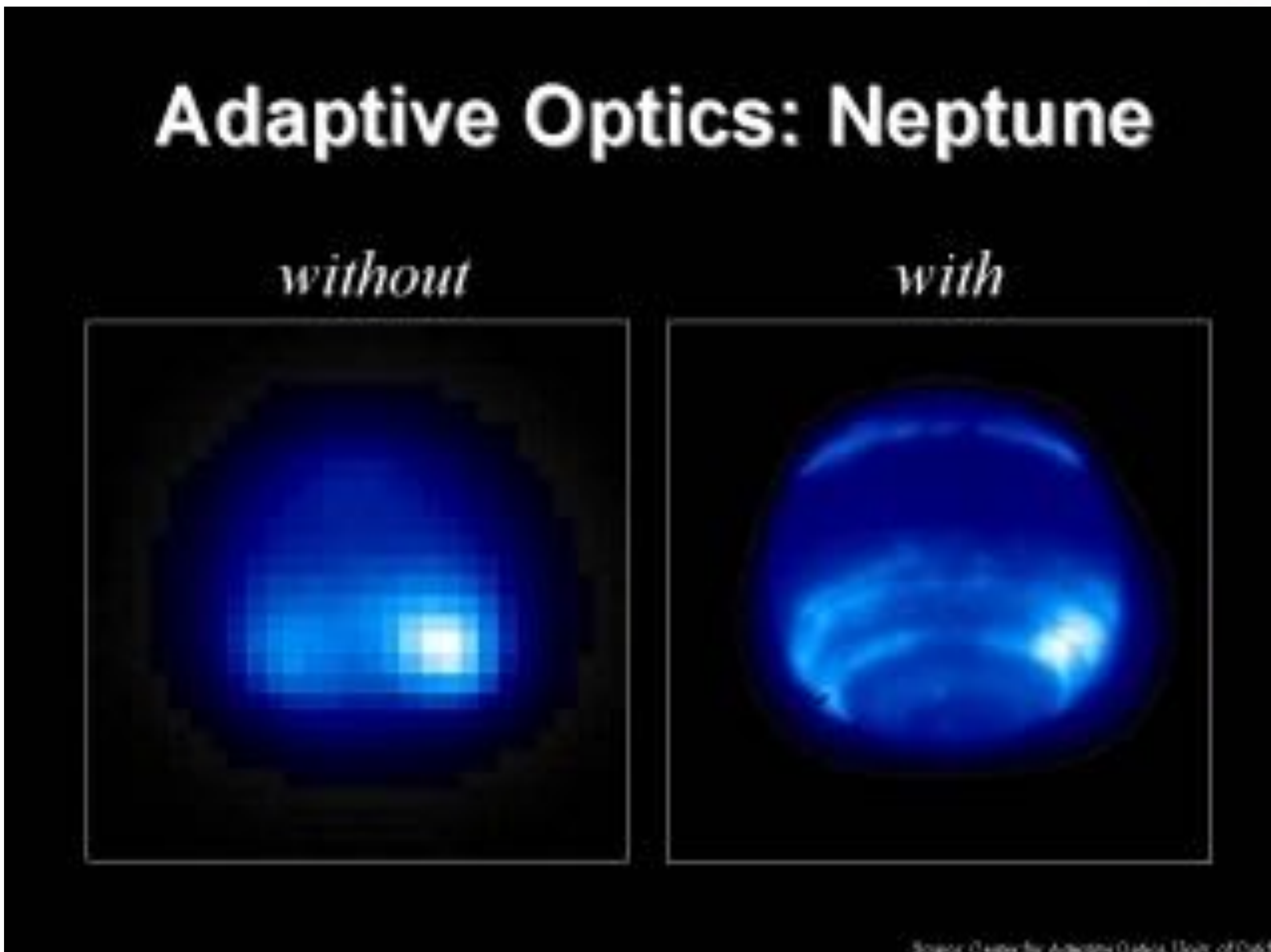


The Central Star Cluster

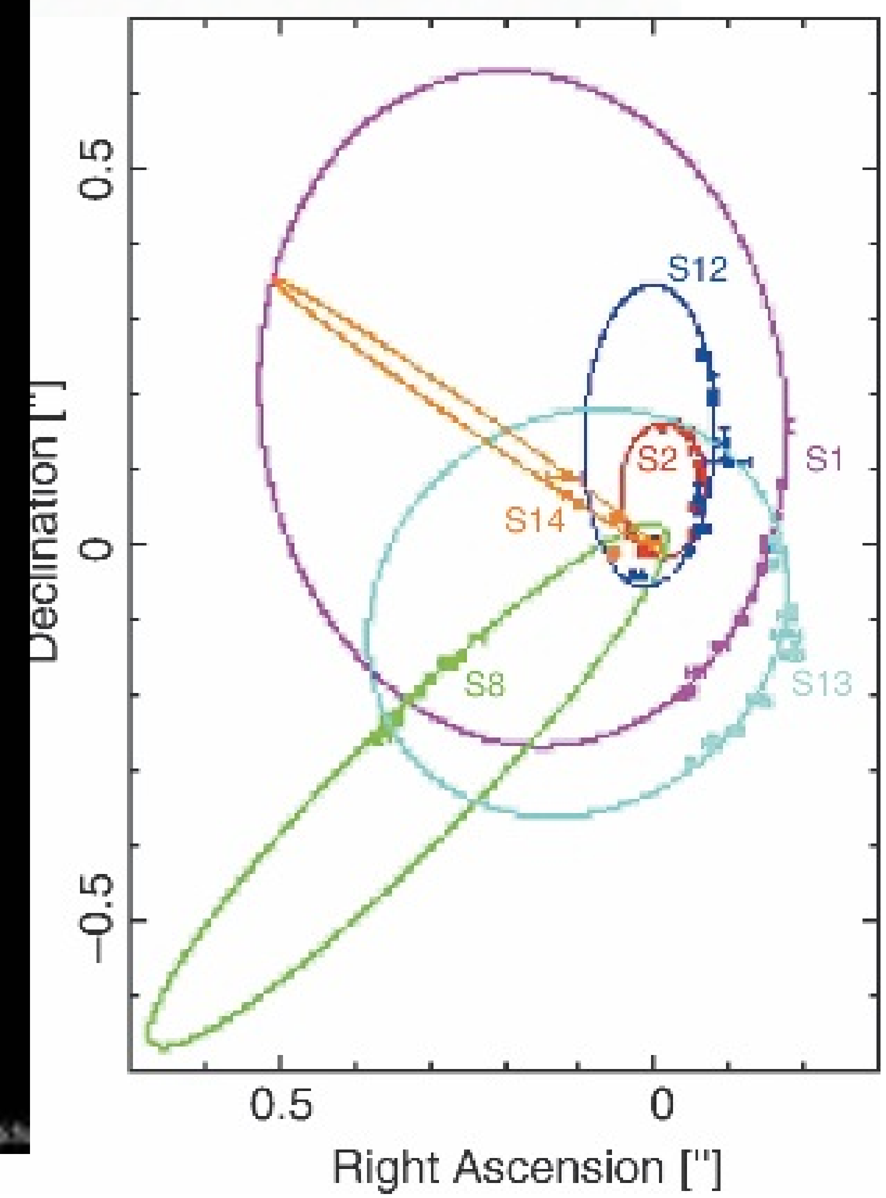
- $n \propto r^{-2}$
- Implies a “relaxed” system: high frequency of encounters implies “isothermal,” or equal energy everywhere.
- Except for the central 0.5 pc. From 55 km/s at 5 pc to 180 km/s at 0.15 pc. What?

Sgr A* stellar mc

- Infrared Speckle Interferometry



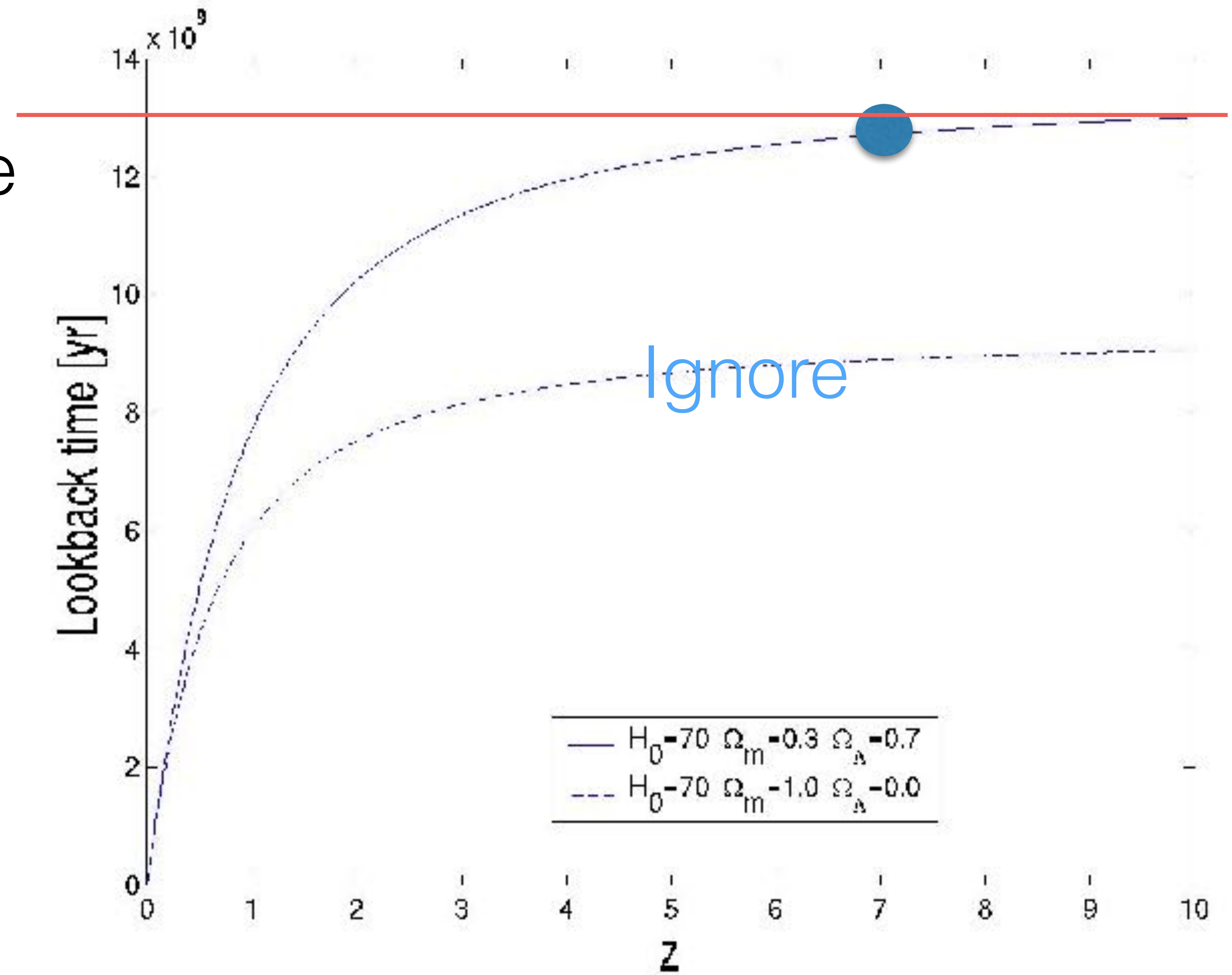
Right Ascension ["]



Lookback time vs. Redshift

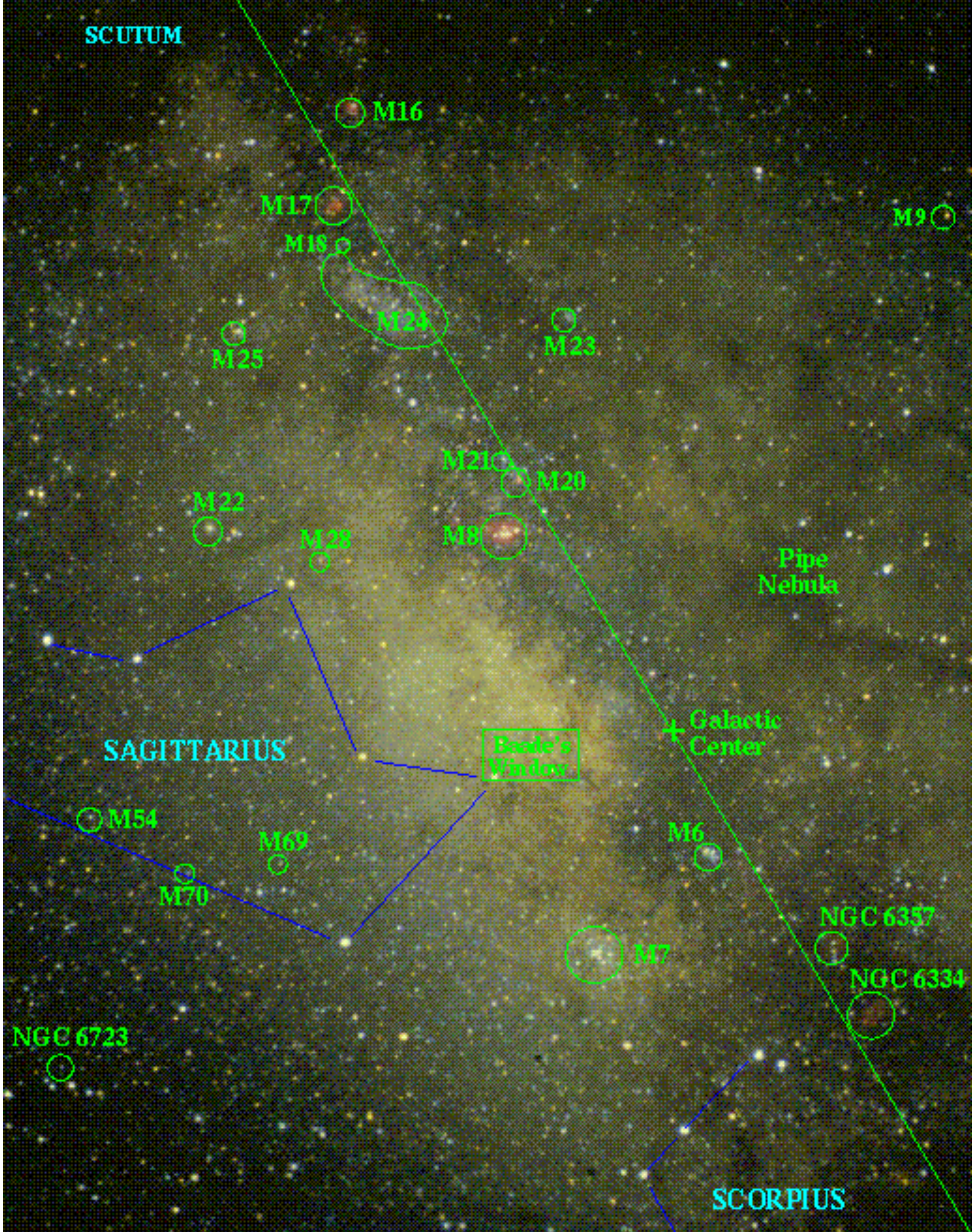
- More on this later, but here's the relationship between age of the photons (lookback time) and redshift.

- Age of the universe is the distance to the red line



The Galactic Center

- Av = 28 mag.
- Convenient holes
- 10% of SF activity in 500 pc x 60 pc
- Most of the 100+ Msun stars



The Center and Sgr A

- Molecular ring, R=(2,8) pc, 20 deg. to disk
  - 110 km/s, solid body
- Sgr A east (synchrotron source). SNR.
- Sgr A west, spiral HII region
- Sgr A* the hole. L_{radio} = 2e34 erg/s. <3au
  - Relatively quiet relative to other SMBH
  - No Jets?
- Stars, $r^{-1.8}$
- Why are the stars B stars?