Reading (for both Oct 13 and 15 lectures): OpenStax, Chapter 23, Section 23.6 & Chapter 24, all sections

EXAM #2: (Next) Wednesday, October 21 in recitation (just like Exam 1). Review materials (topic lists and sample questions) are now available (bottom of Modules).

Previously: **main sequence to Red Giant to white dwarfs, supernova & neutron stars**

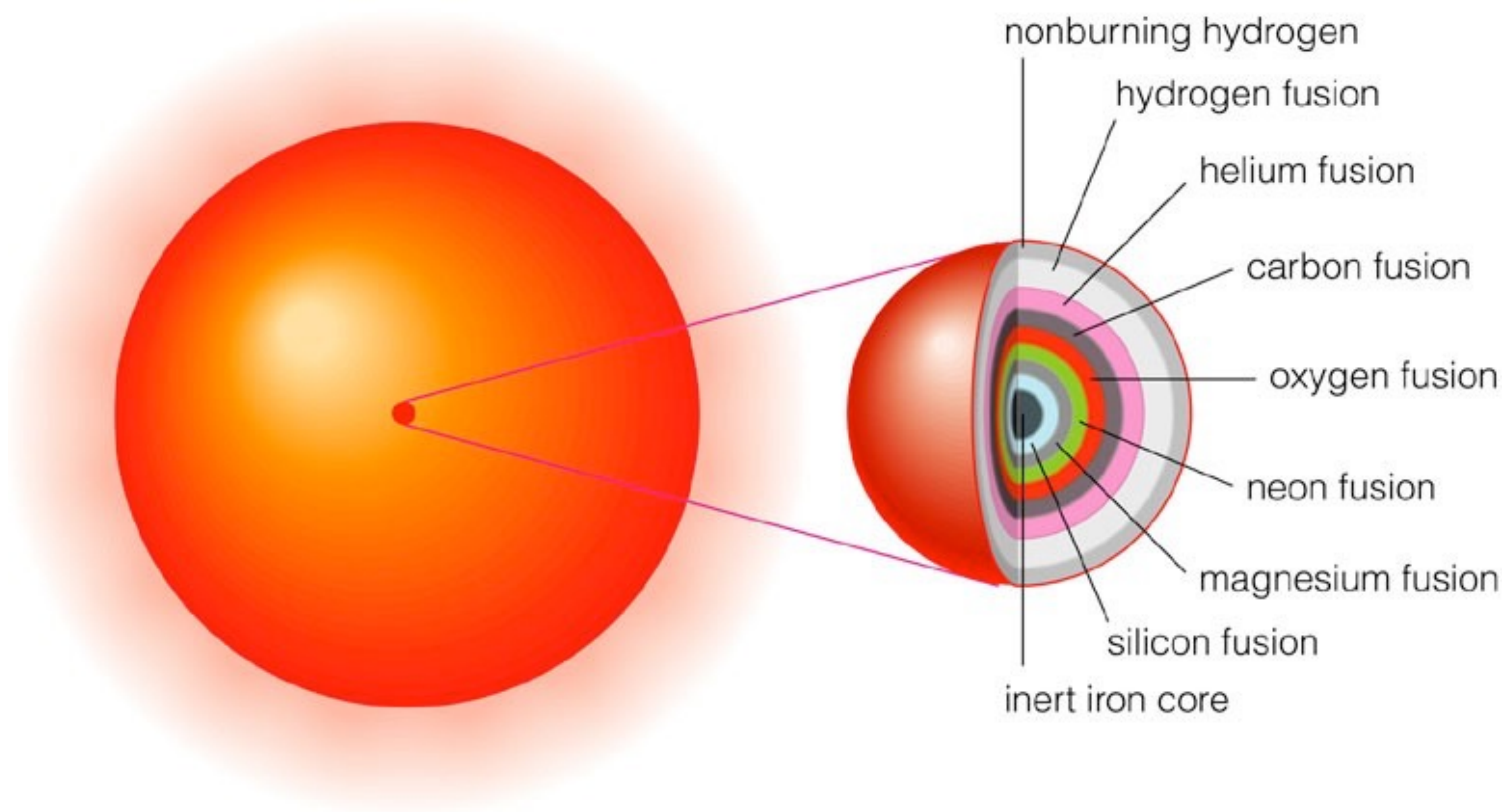
- Main sequence stars differ in their internal structure and their fates
- After hydrogen runs out, new energy sources are needed
- Fusion of heavier elements needs higher temperatures
- After helium burning comes a long slow death as a white dwarf if not massive enough
- massive stars - Supernova explosion! Neutron star!

Today: **Black Holes I: Formation and environment**

- Gamma ray bursts (GRBs) — distant explosions of ENORMOUS energy
- Hypernova (long GRB) — massive stars produce cores that are too massive for neutron degeneracy pressure
- Black holes — why they are black: escape velocity > speed of light
- Types of black holes and how we know they exist

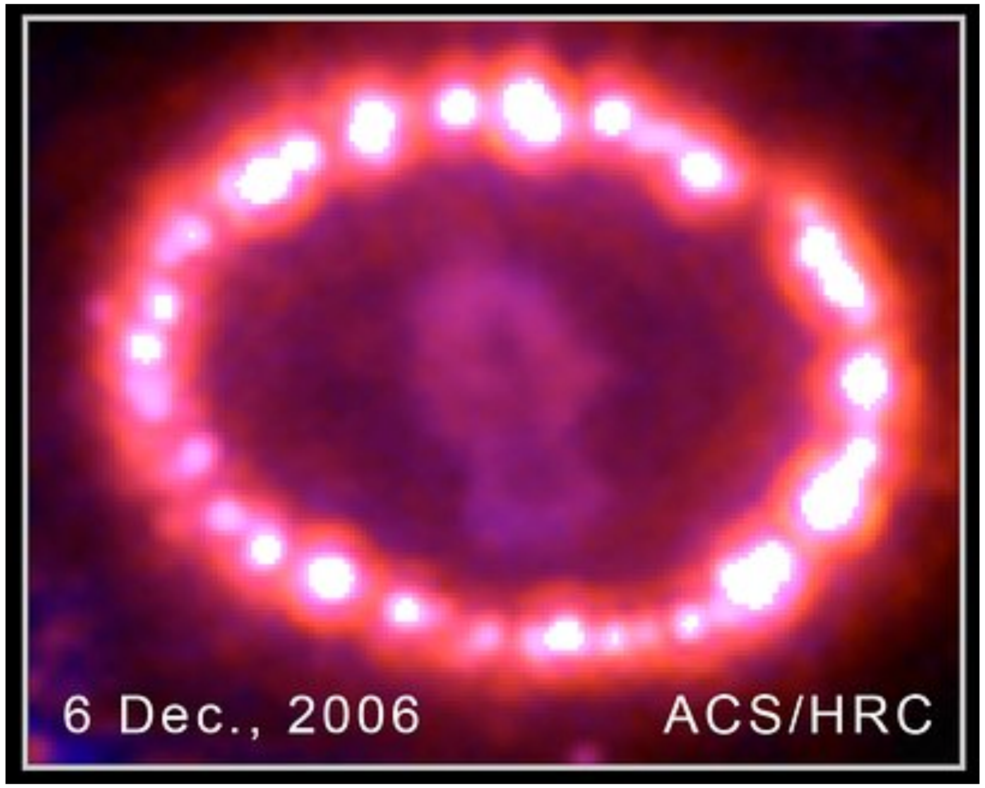
M > 8 M_{sun}: out with a ***BANG***

- can reach higher core temperatures
- C/O fusion for support ... all the way to IRON
- Onion Skin Structure



Supernova

- In the broadest sense, a supernova is an exploding star
- Two main physical mechanisms for exploding stars:
  - Gas is dumped onto a white dwarf from a companion (more on this later!
  - A massive star (M > 8 Solar Masses) explodes



Supernova: 8 M_{Sun} < M < 25 M_{Sun}

Neutron degeneracy prevents star from further collapse

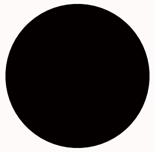
Neutron star is formed

Mass is approx. < 3 M_{Sun}

Supernova: M > 25 M_{Sun}

Neutron degeneracy pressure cannot overcome the weight of the core!!!

This happens when mass of core > 3 M_{Sun}



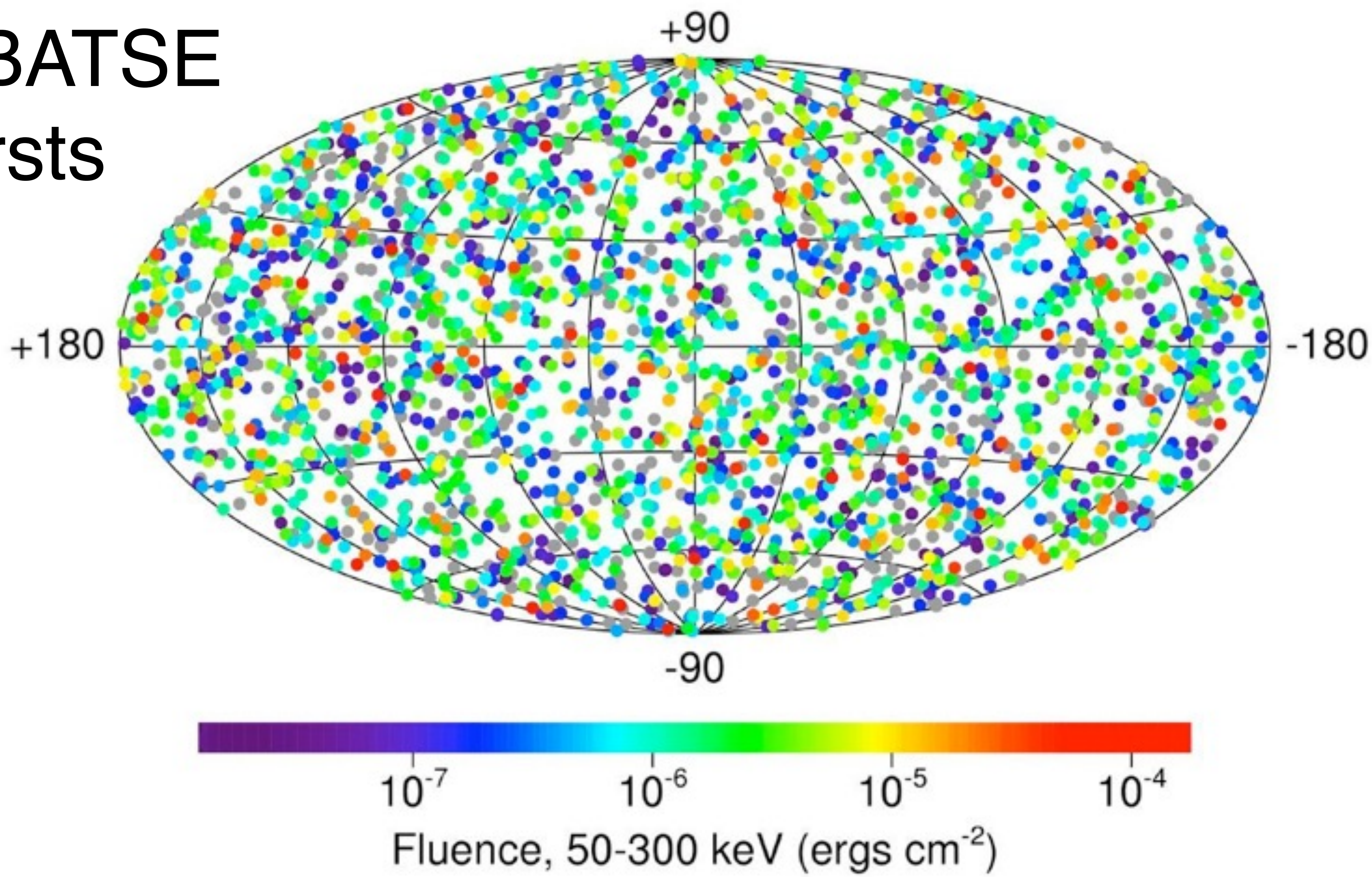
Black hole is formed

This type of explosion is sometimes called a *hypernova or a collapsar*

Gamma-ray Bursts (GRBs)

- short-duration, high energy flashes
- evenly distributed across the entire sky
- cosmological distances - intensely bright supernovae

2704 BATSE bursts

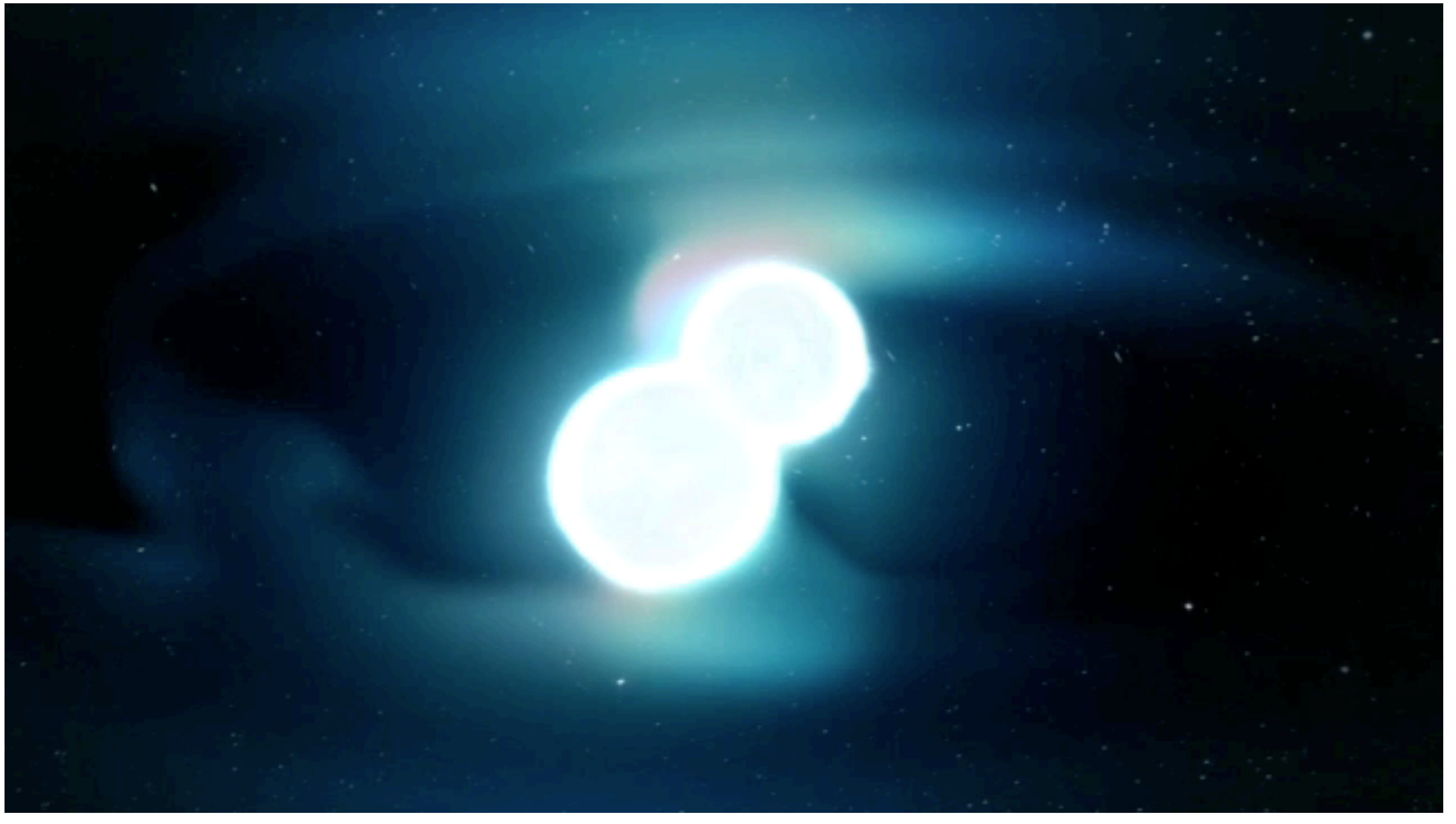


GRBs linked to black holes

1. Long duration GRBs — Hypernova or Collapsar
   - Light from explosion takes a “long” time to fade
   - *VERY* energetic jet slices through outer layers of the star
   - The outer layers are decimated, revealing a rapidly rotating disk of hot gas around a black hole

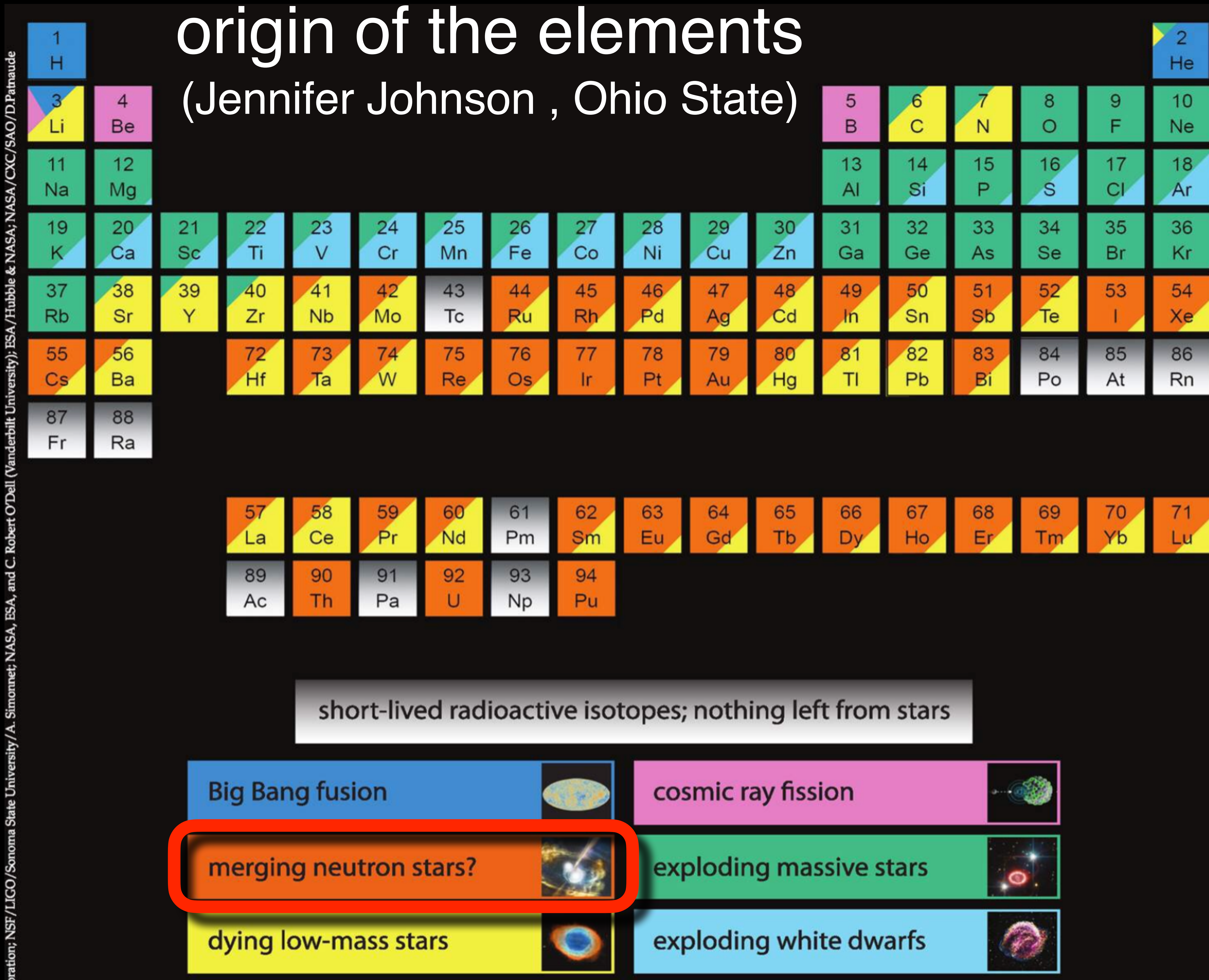
Another type of GRB

2. Short duration GRBs — merging neutron stars, called kilonova
   - Light from explosion takes a “short” time to fade
   - Two neutron stars spiral inward due to the loss of gravitational radiation (more on this next lecture)
   - Immense energy is released when these neutron stars collide
   - Might leave black hole at center, but might not…



origin of the elements

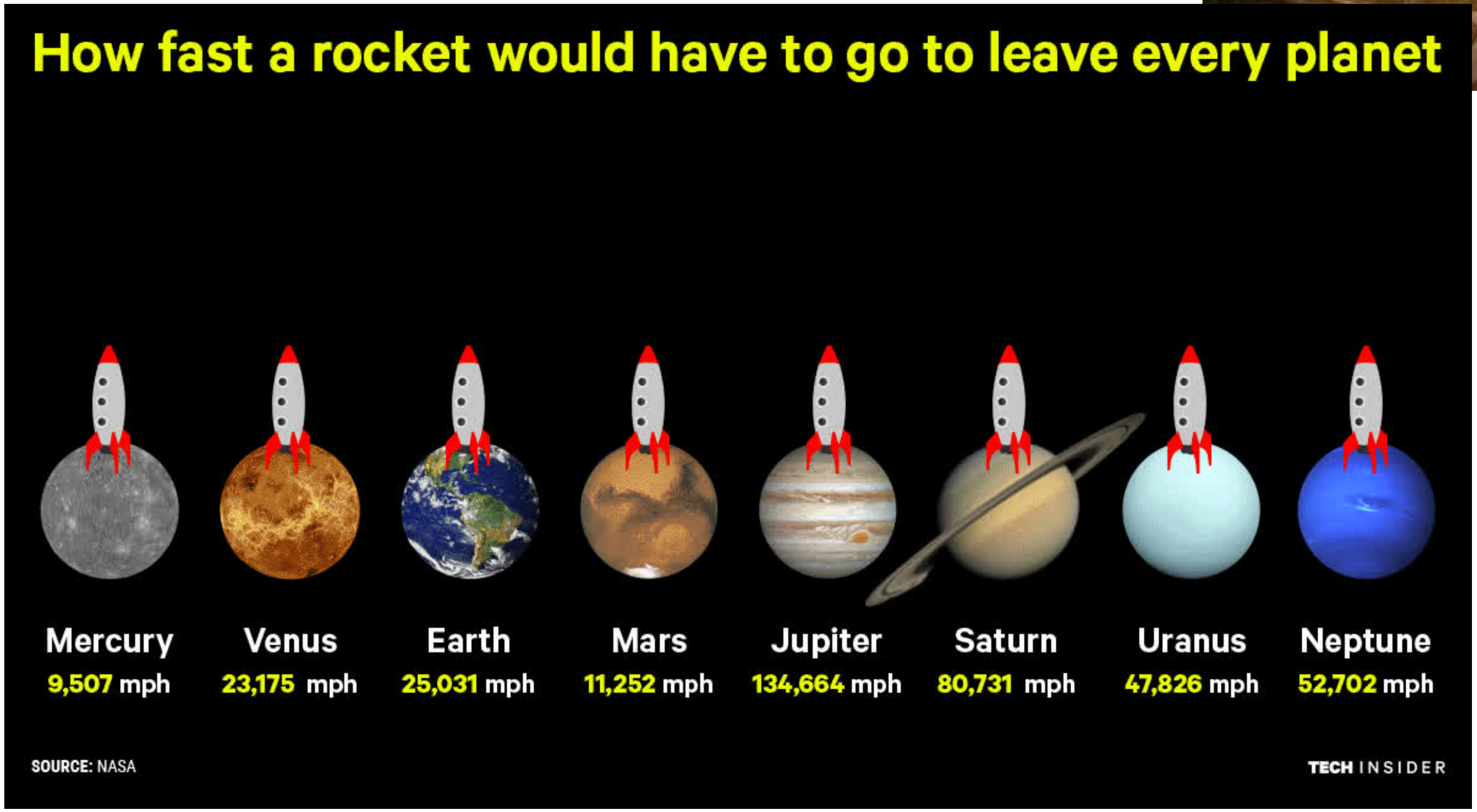
(Jennifer Johnson , Ohio State)



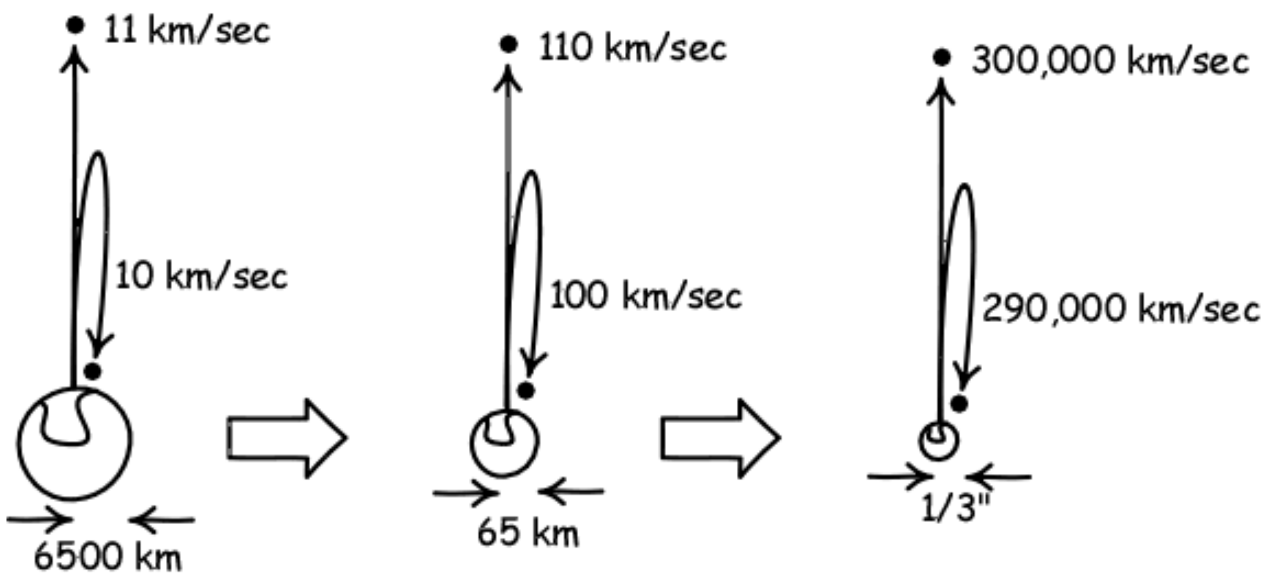
Black Holes

- Gravity is so immense that escape velocity exceeds the speed of light

Escape velocity:

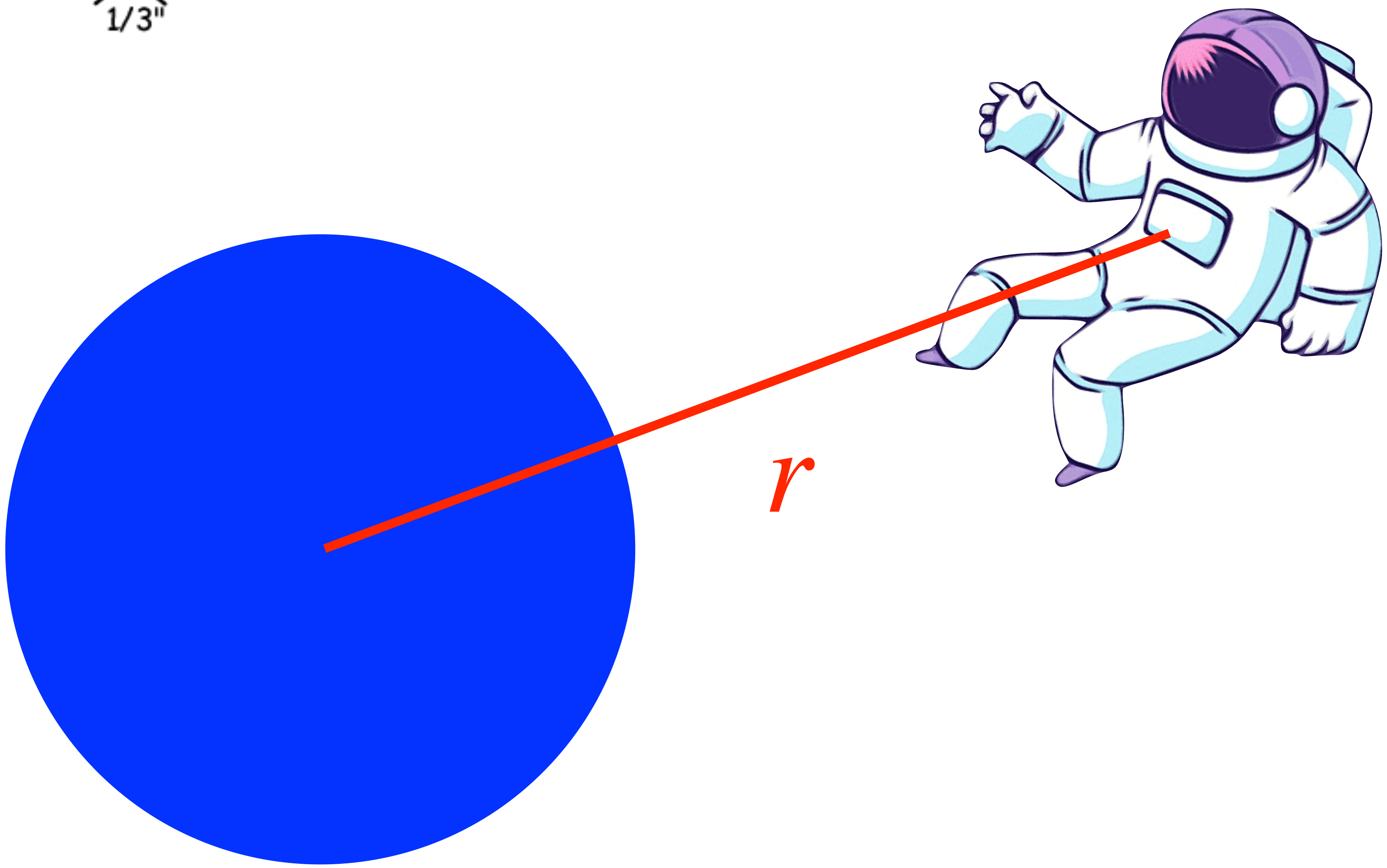


Escape velocity is not just about mass



Inverse square law!

$$F = \frac{GMm}{r^2} \propto \frac{1}{r^2}$$



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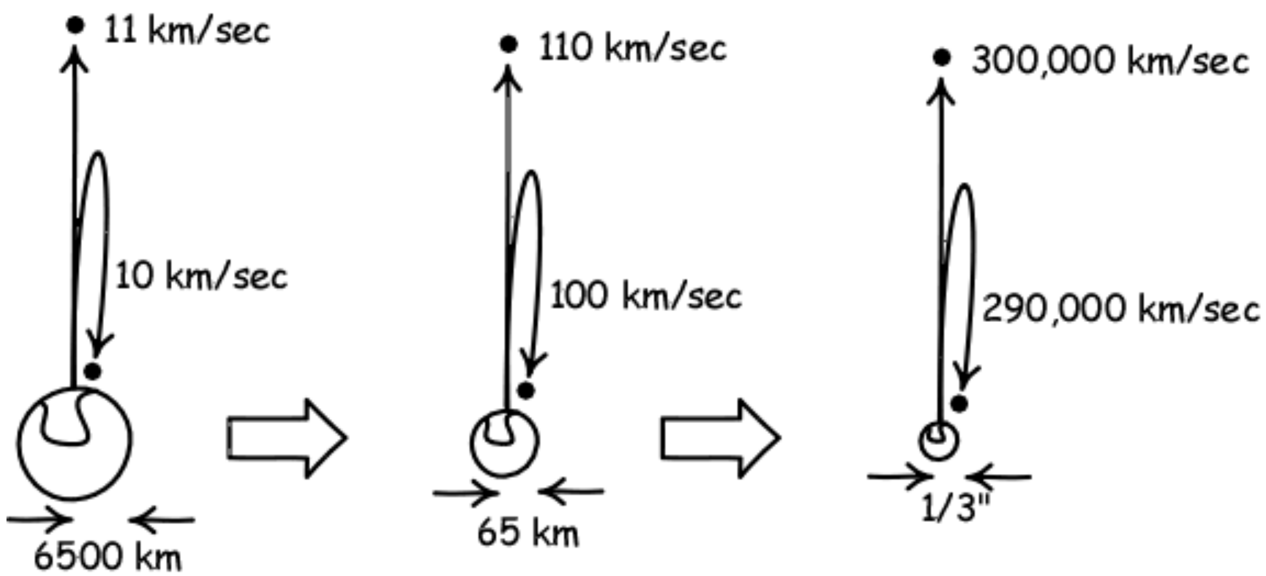

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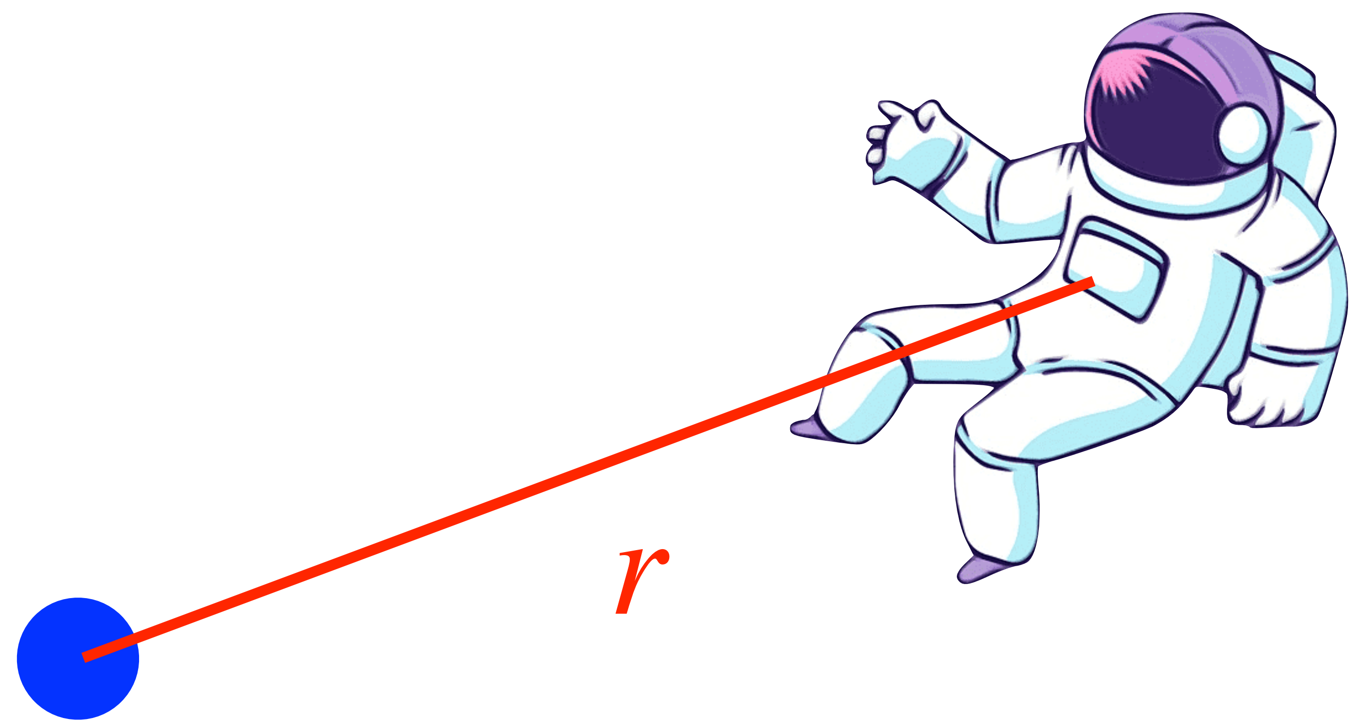

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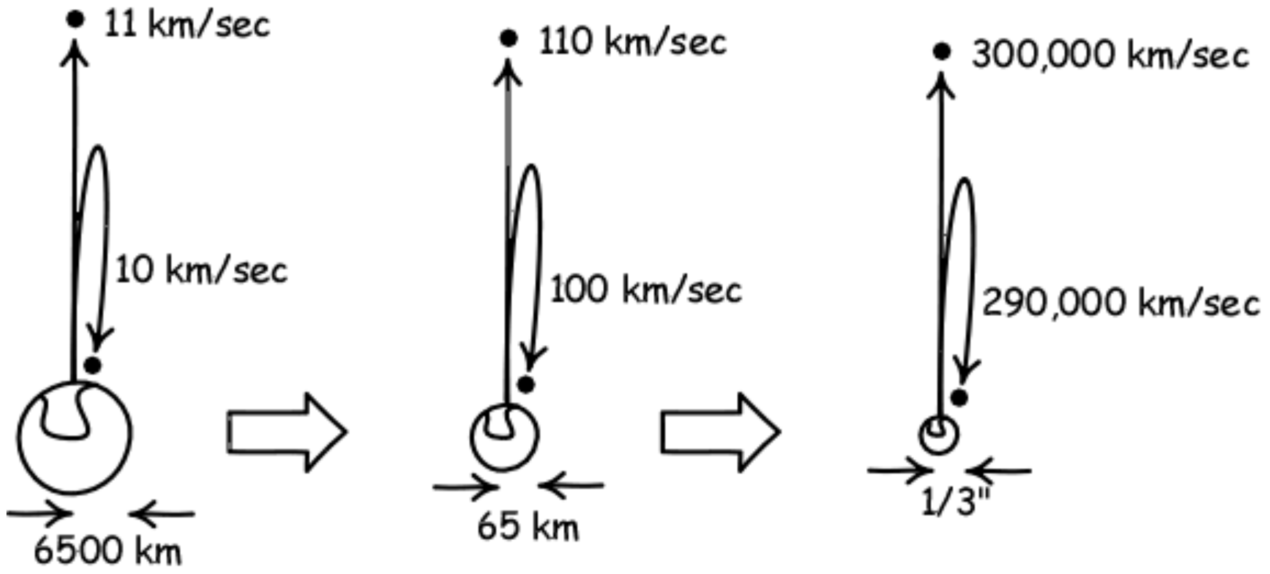

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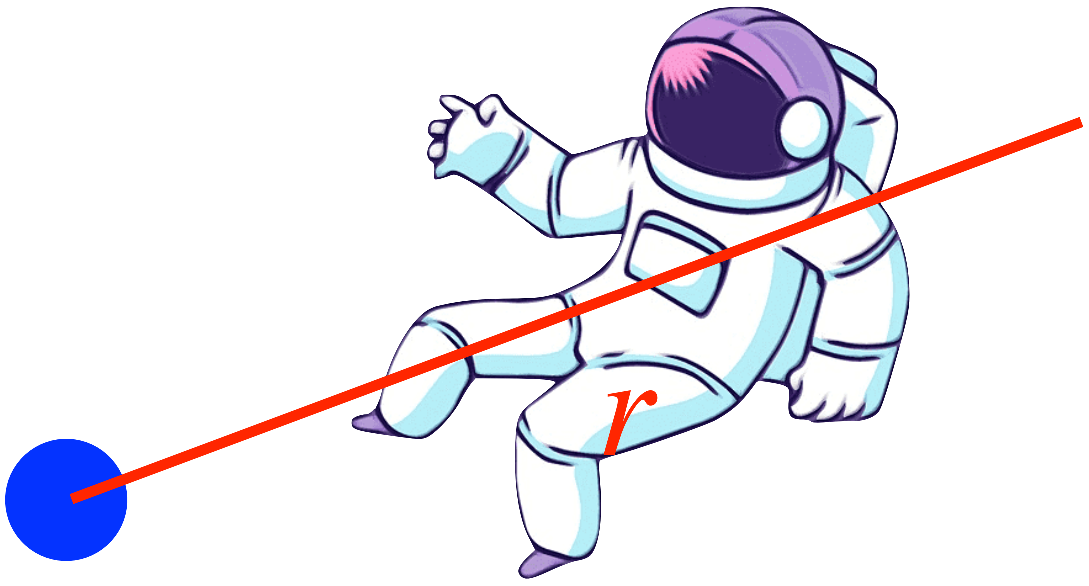

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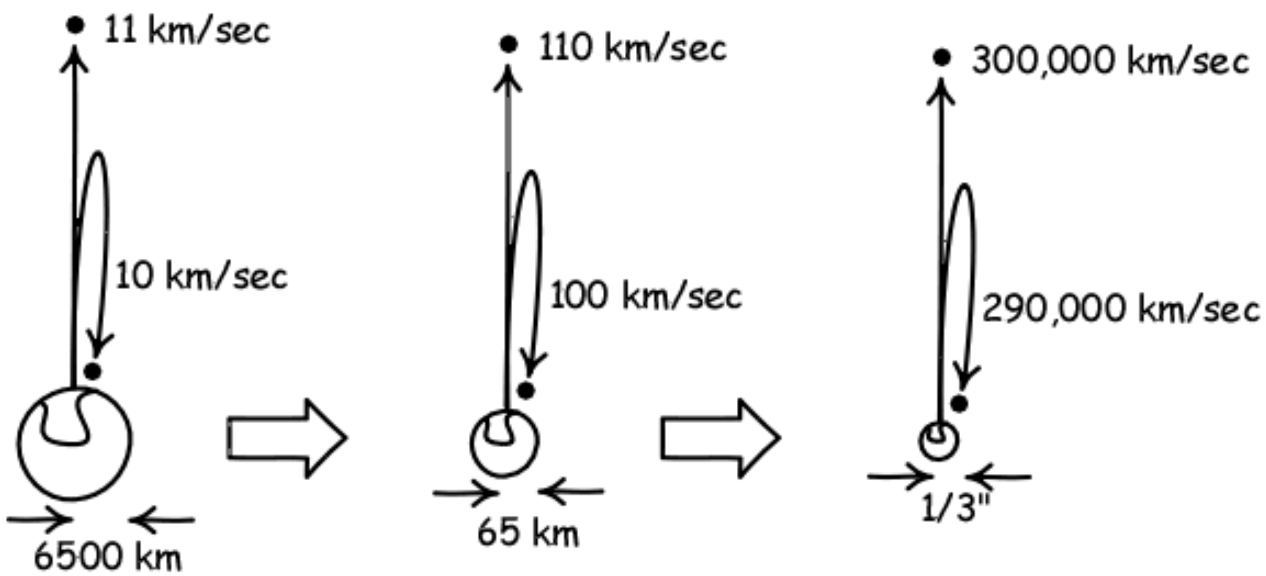
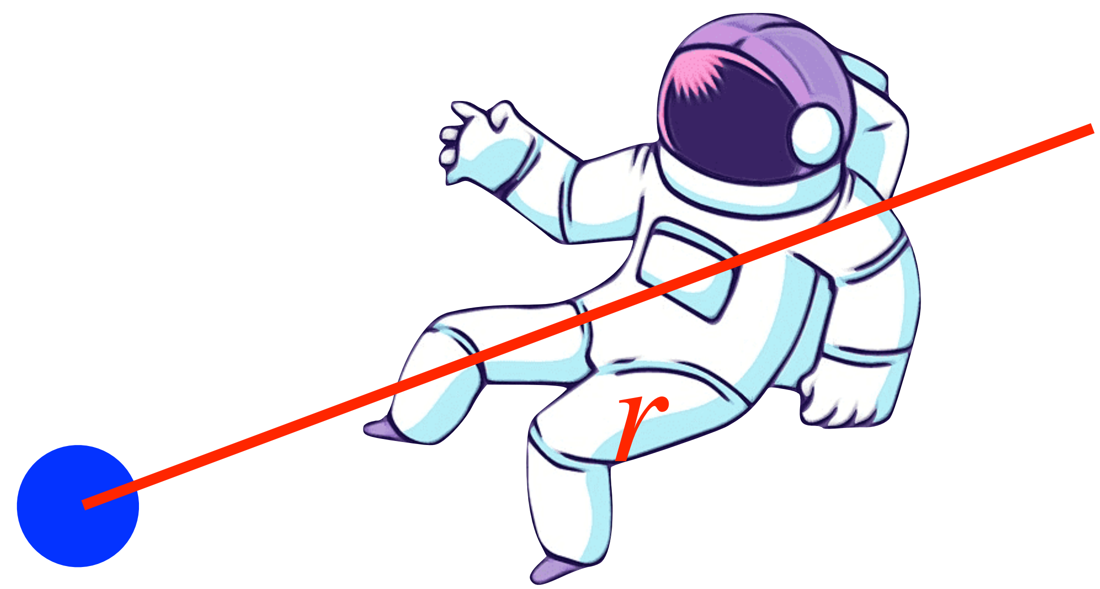


Inverse square law!

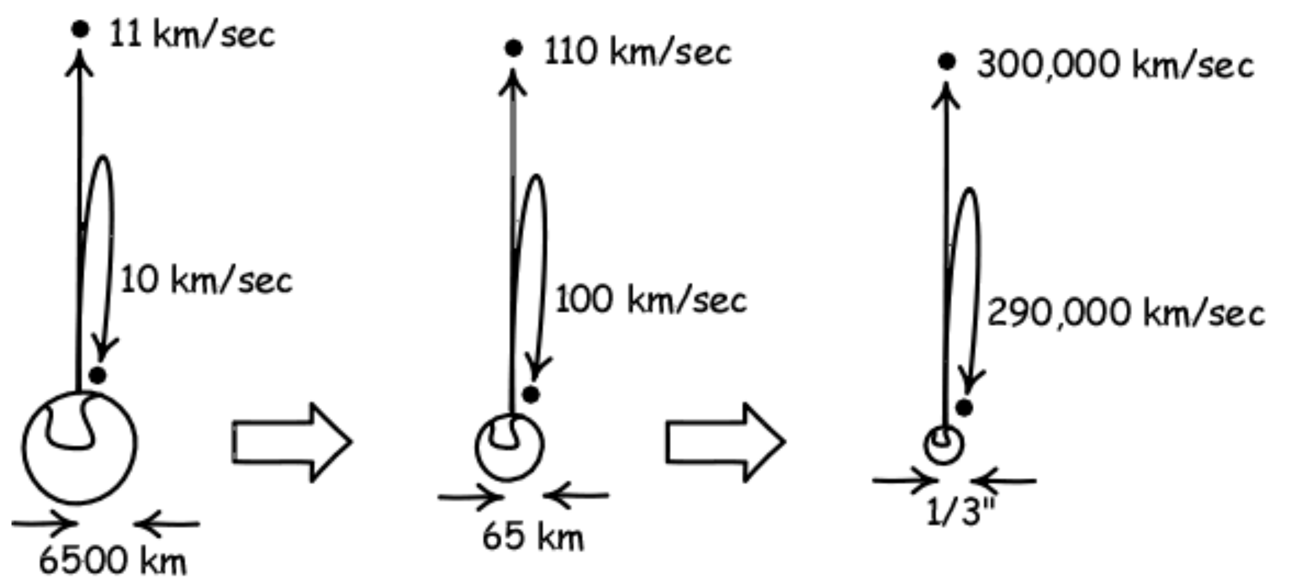
$$F = \frac{GMm}{r^2} \propto \frac{1}{r^2}$$

Astronaut is now closer.
r decreases but M stays the same!

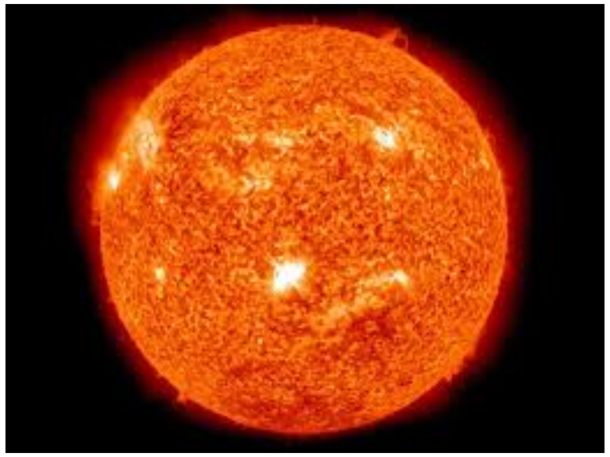


Black holes and escape velocity

- **Escape velocity**
  - from Earth = 11.3 km/s (= 25,000 mph)
  - from Sun = 600 km/s (= 1,350,000 mph)
  - from a WD = 5000 km/s
  - from a NS = 200,000 km/s = **2/3 the speed of light!**
  - from a BH = 300,000 km/s = speed of light!



Since escape velocity increases as F increases, everything can "in effect" be turned into a black hole!



3 km

0.4 inches

0.1 mm (0.004 in)

10^{-23} cm
OR
10^{-11} the size of a proton

Schwarzschild Radius or Event Horizon

Some more examples

Object	Mass: M	Schwarzschild radius: $\frac{2GM}{c^2}$	Schwarzschild density: $\frac{3c^6}{32\pi G^3 M^2}$ or $\frac{3c^2}{8\pi G r^2}$
Observable universe[7]	8.8×10^{52} kg	1.3×10^{26} m (13.7 billion ly)	9.5×10^{-27} kg/m^3
Milky Way	1.6×10^{42} kg	2.4×10^{15} m (~0.25 ly)	0.000029 kg/m^3
TON 618 (largest known black hole)	1.3×10^{41} kg	1.9×10^{14} m (~1300 AU)	0.0045 kg/m^3
SMBH in NGC 4889	4.2×10^{40} kg	6.2×10^{13} m	0.042 kg/m^3
SMBH in Messier 87[9]	1.3×10^{40} kg	1.9×10^{13} m	0.44 kg/m^3
SMBH in Andromeda Galaxy[10]	3.4×10^{38} kg	5.0×10^{11} m	640 kg/m^3
Sagittarius A* (SMBH in Milky Way)	8.2×10^{36} kg	1.2×10^{10} m	1.1×10^{6} kg/m^3
Sun	1.99×10^{30} kg	2.95×10^{3} m	1.84×10^{19} kg/m^3
Jupiter	1.90×10^{27} kg	2.82 meters	2.02×10^{25} kg/m^3
Earth	5.97×10^{24} kg	8.87×10^{-3} m	2.04×10^{30} kg/m^3
Moon	7.35×10^{22} kg	1.09×10^{-4} m	1.35×10^{34} kg/m^3
Human	70 kilograms	1.04×10^{-25} m	1.49×10^{76} kg/m^3
Big Mac	0.215 kilograms	3.19×10^{-28} m	1.58×10^{81} kg/m^3
Planck mass	2.18×10^{-8} kg	3.23×10^{-35} m	1.54×10^{95} kg/m^3

So, can anything be turned into black holes?

NO

Need certain conditions (e.g., a dense core from a dying star)

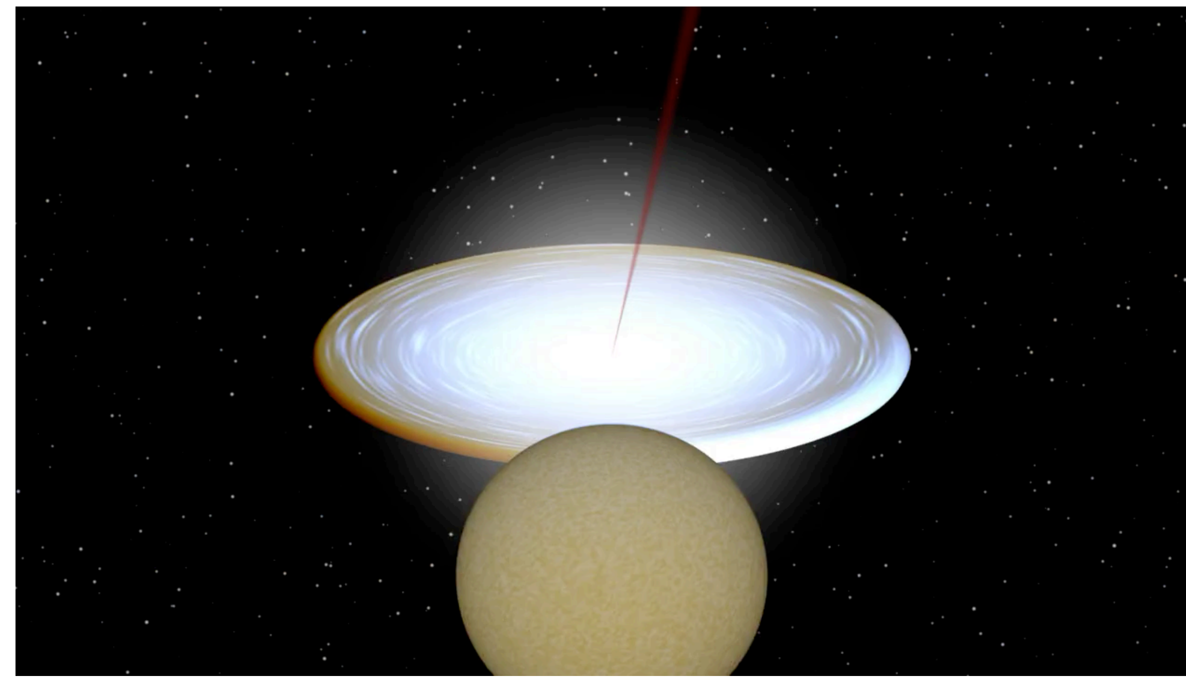
But there are more than just "stellar mass black holes"

Different types of black holes

Type	Mass (M_{Sun})	Detected by obs/exp?
1. Stellar mass black holes	>3-10ish	Yes
2. Supermassive black holes (SMBHs)	10^6-10^9	Yes
3. Intermediate mass black holes (IMBHs)	100-1000	Maybe?
4. Primordial black holes	Very uncertain, but can be as small as 10^{-37} M_{Sun} (10^{-5} grams)	No

Stellar mass black holes

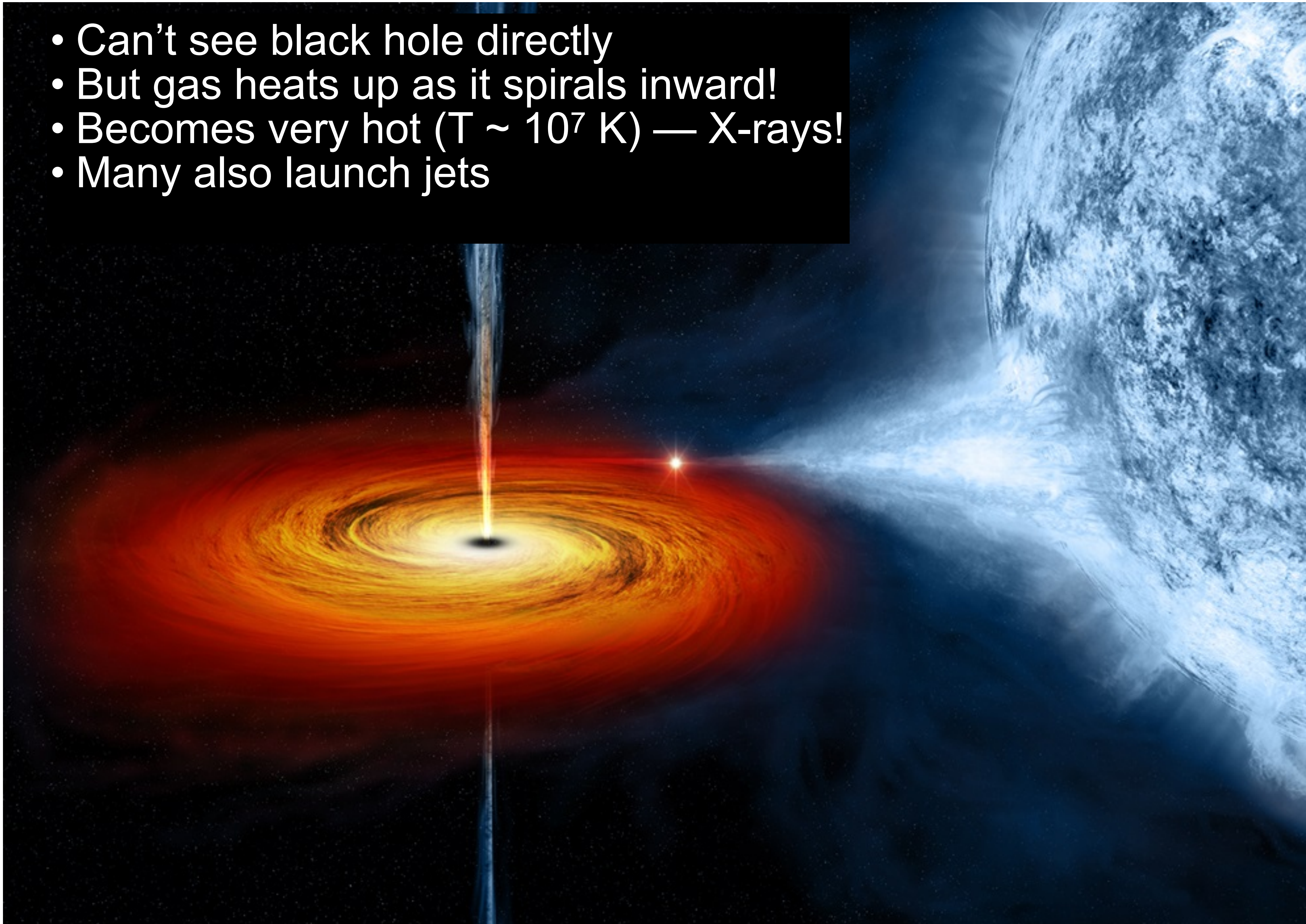
Collapse of core after supernova
(already talked about this)



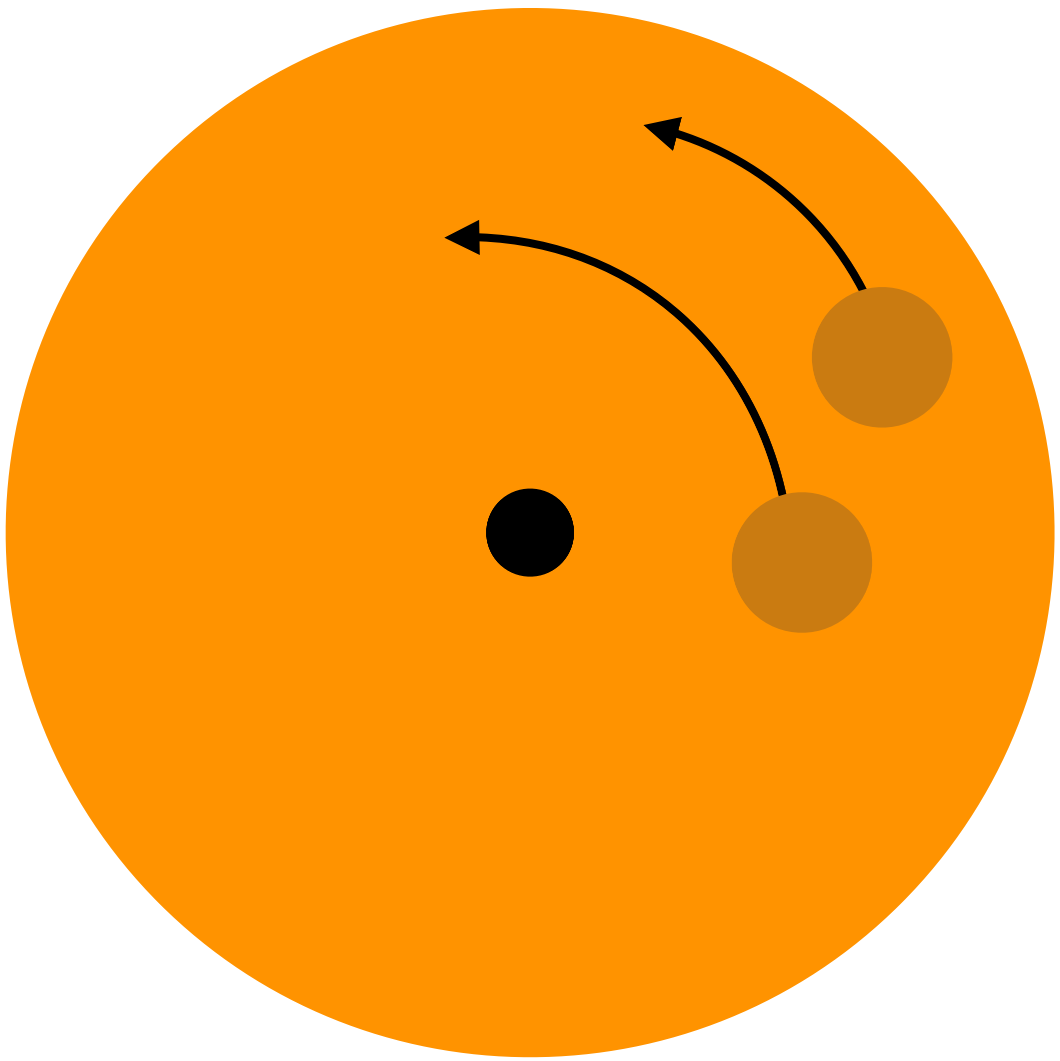
Often in orbit with a companion!

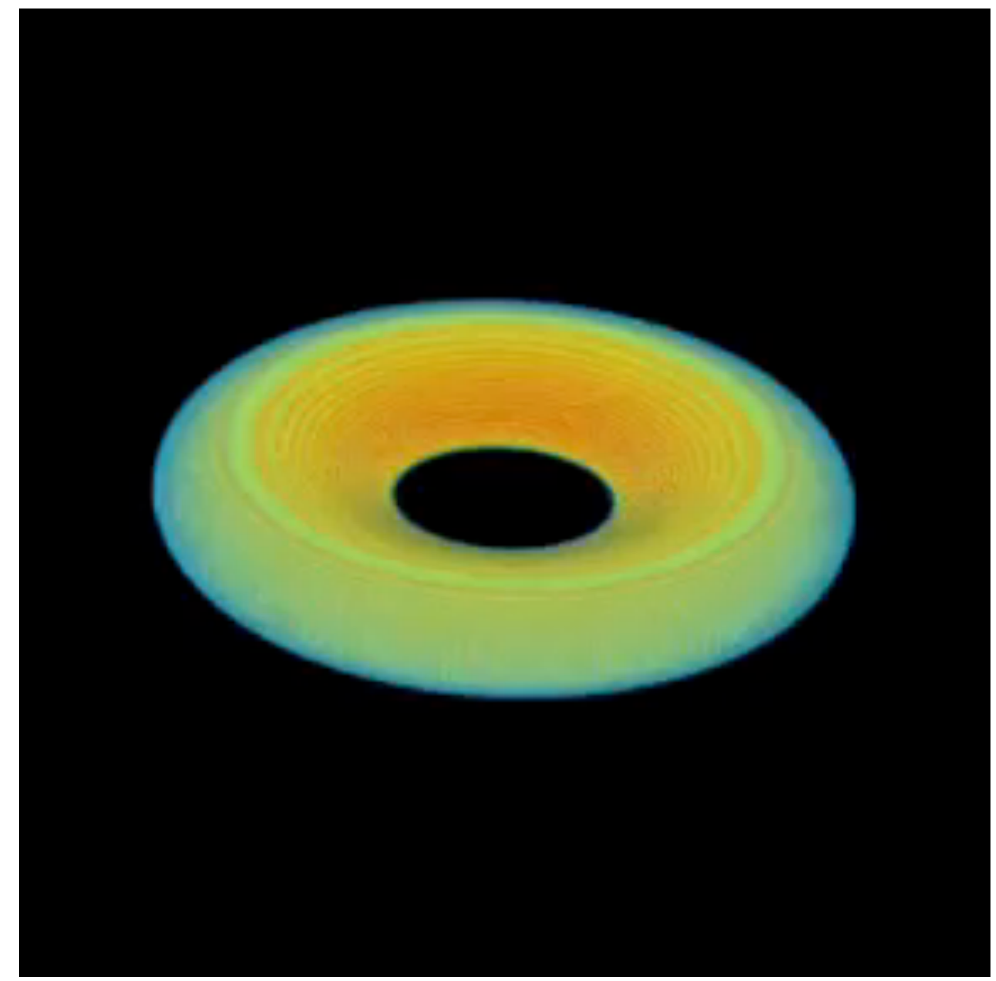
Observing black holes

- Can’t see black hole directly
- But gas heats up as it spirals inward!
- Becomes very hot ($T \sim 10^7$ K) — X-rays!
- Many also launch jets



How does gas accrete if angular momentum is conserved?





- Turbulence causes collisions between gas
- This transports angular momentum away
- Gas then falls inward toward black hole
- Heats up, reaching 10^7 K (X-rays)!

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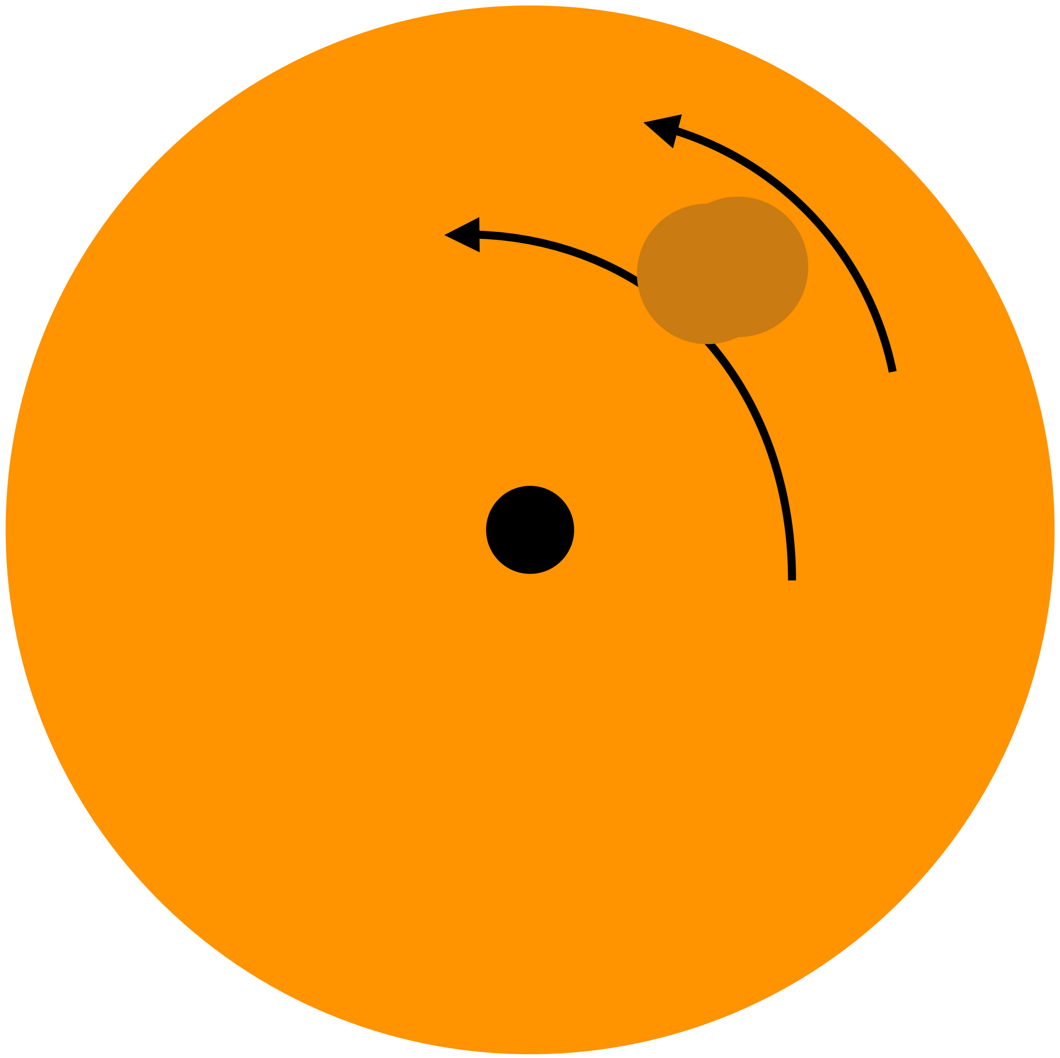

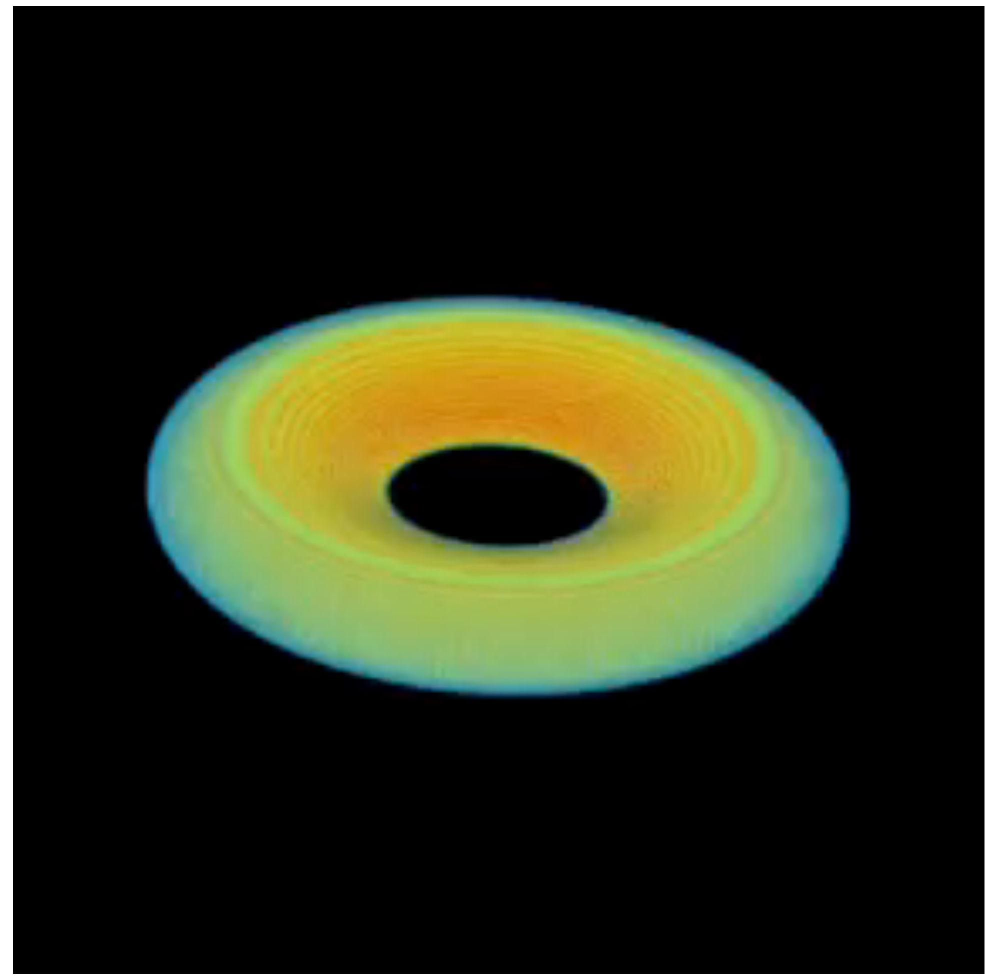

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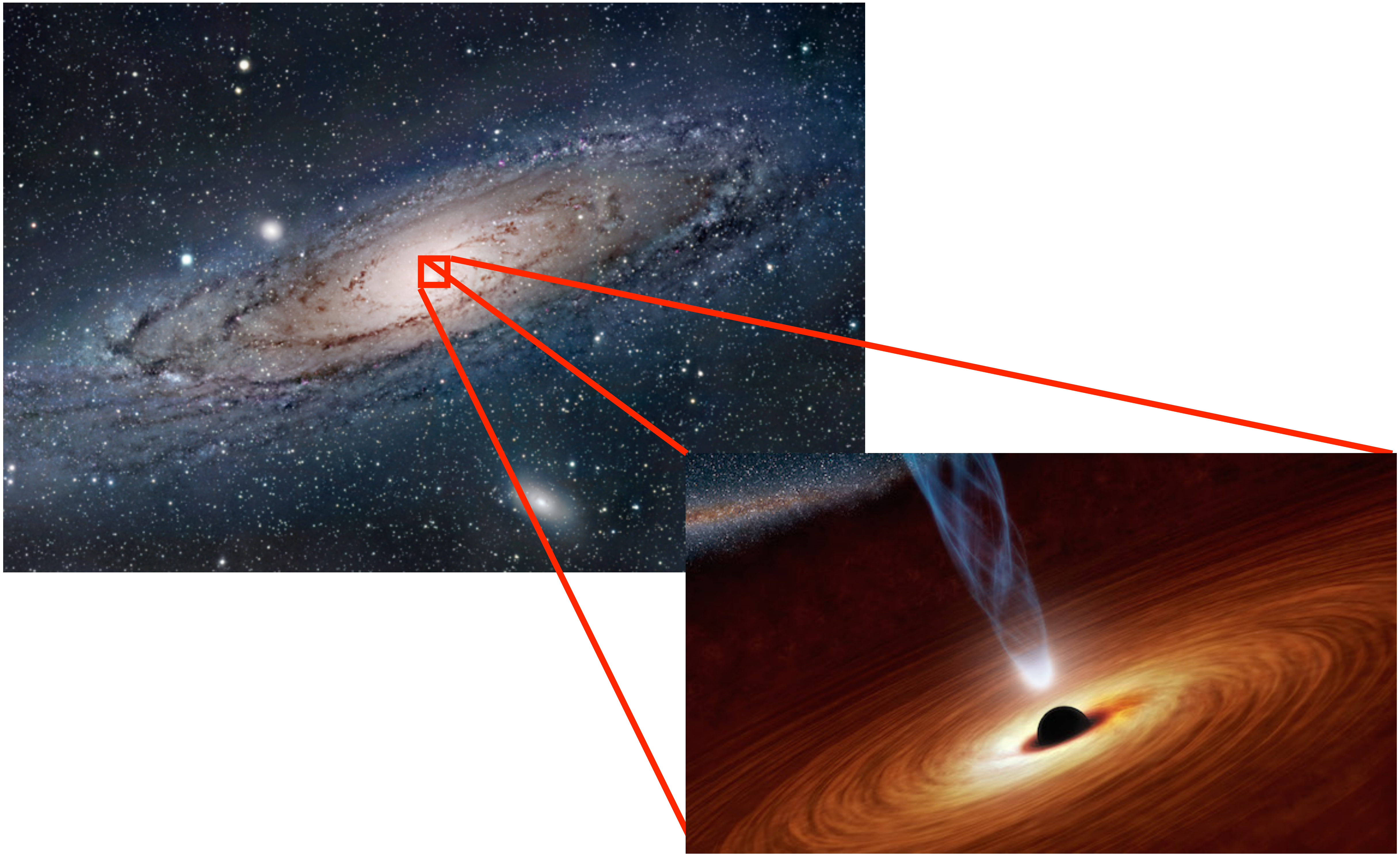
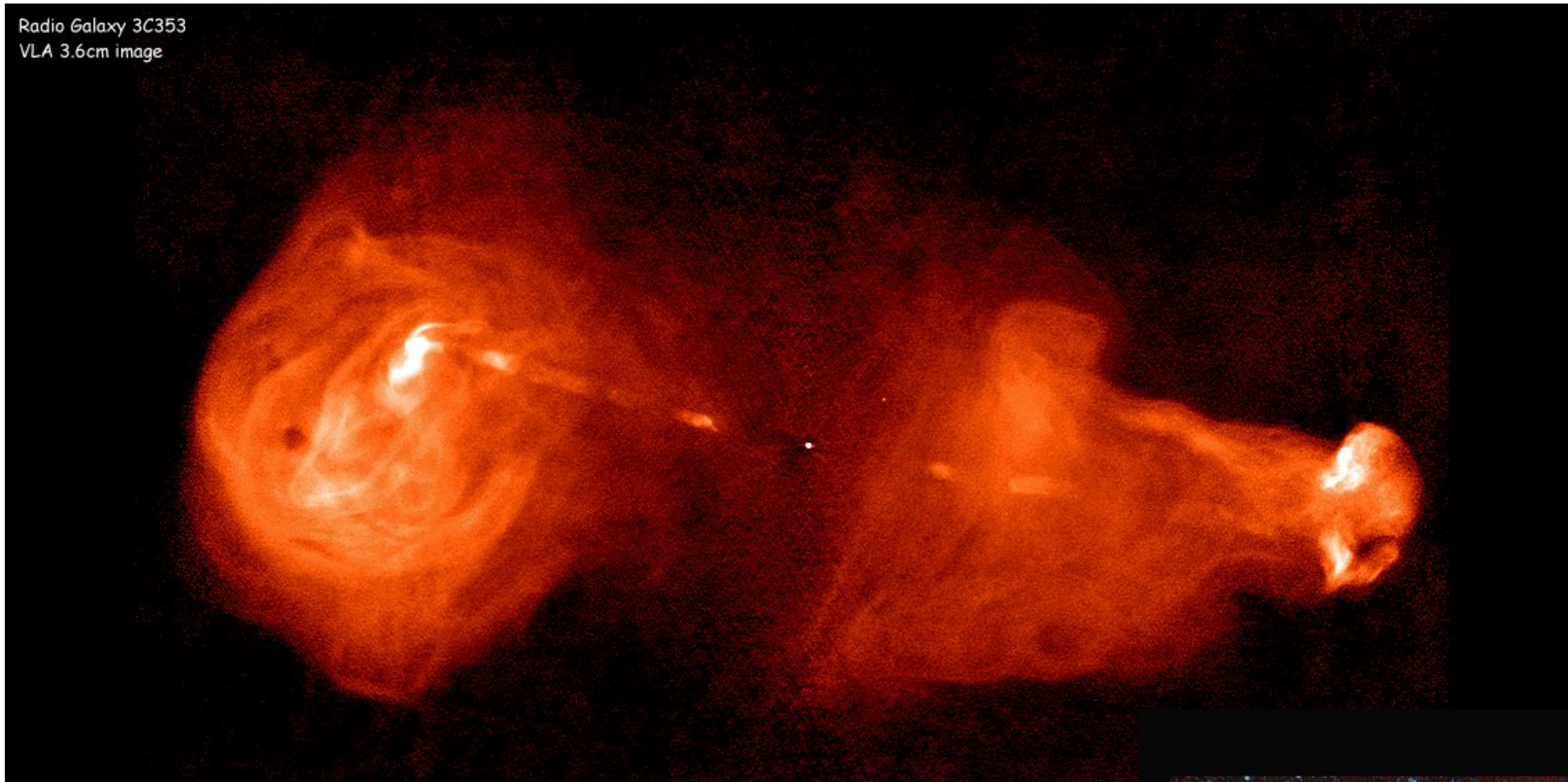
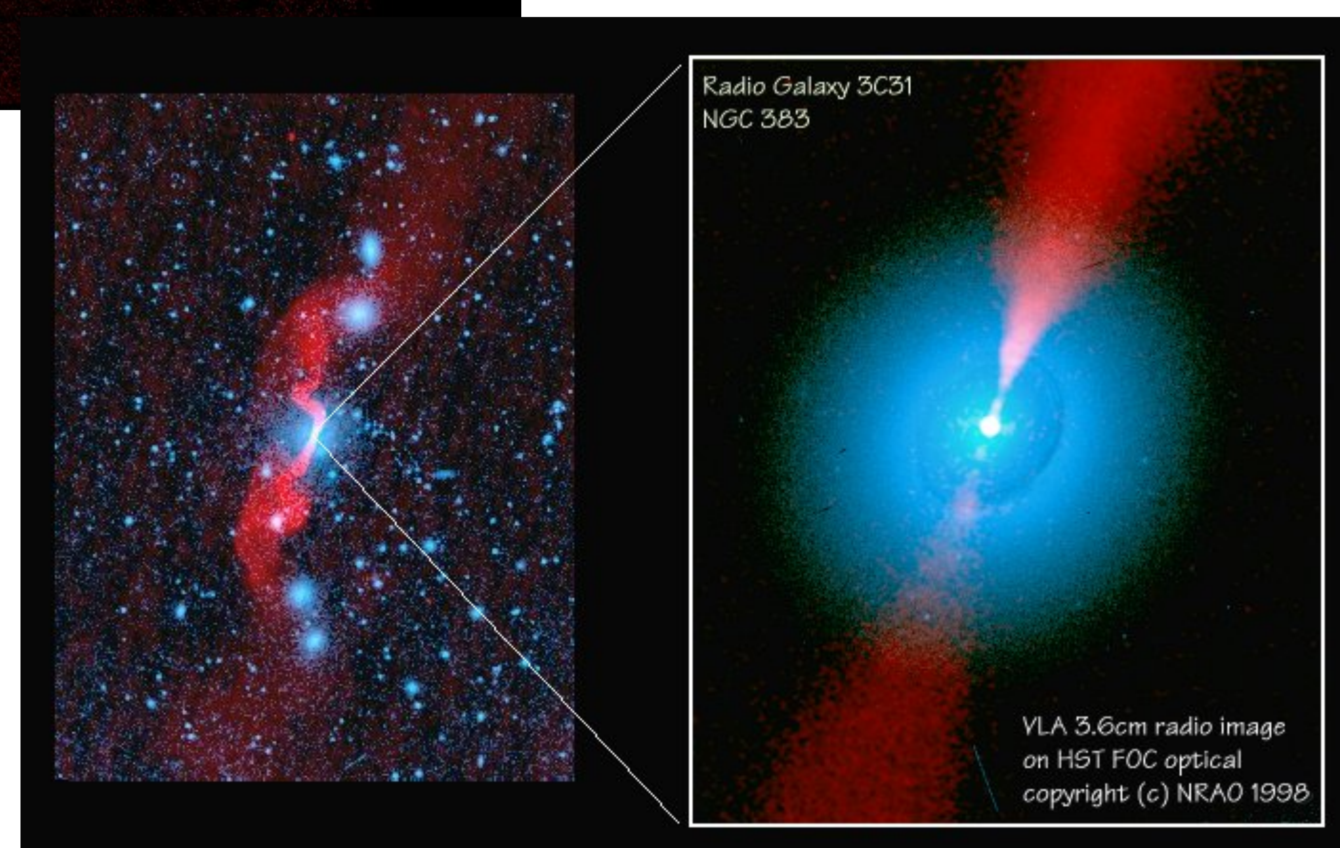
Supermassive black holes exist at the centers of galaxies

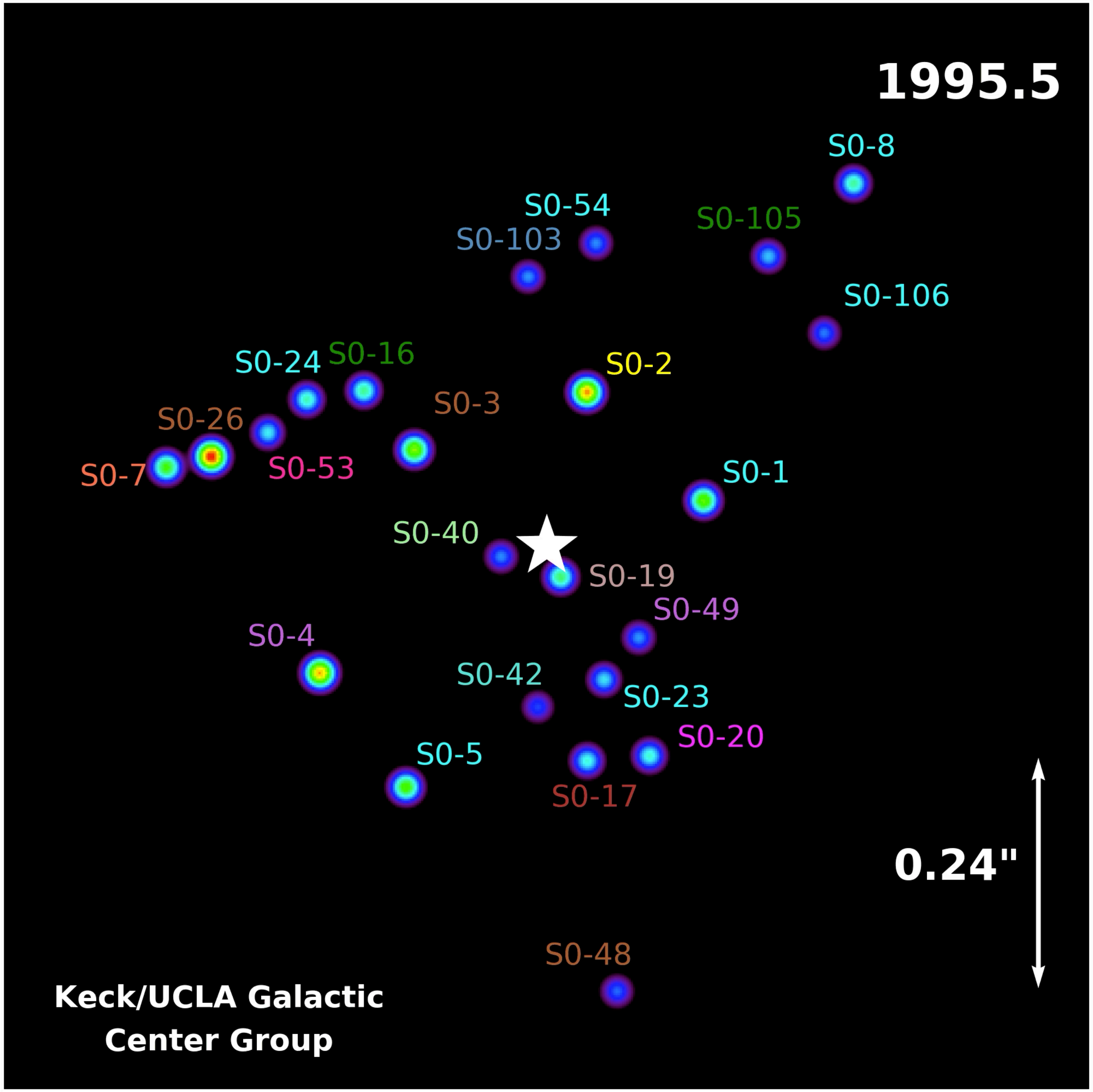


Accreting gas heats up in these disks and powers some of the most luminous objects in the Universe!





Peering towards the center of the Milky Way



This work won this year’s Nobel Prize!

The Nobel Prize in Physics 2020

Roger Penrose

Prize share: 1/2

Reinhard Genzel

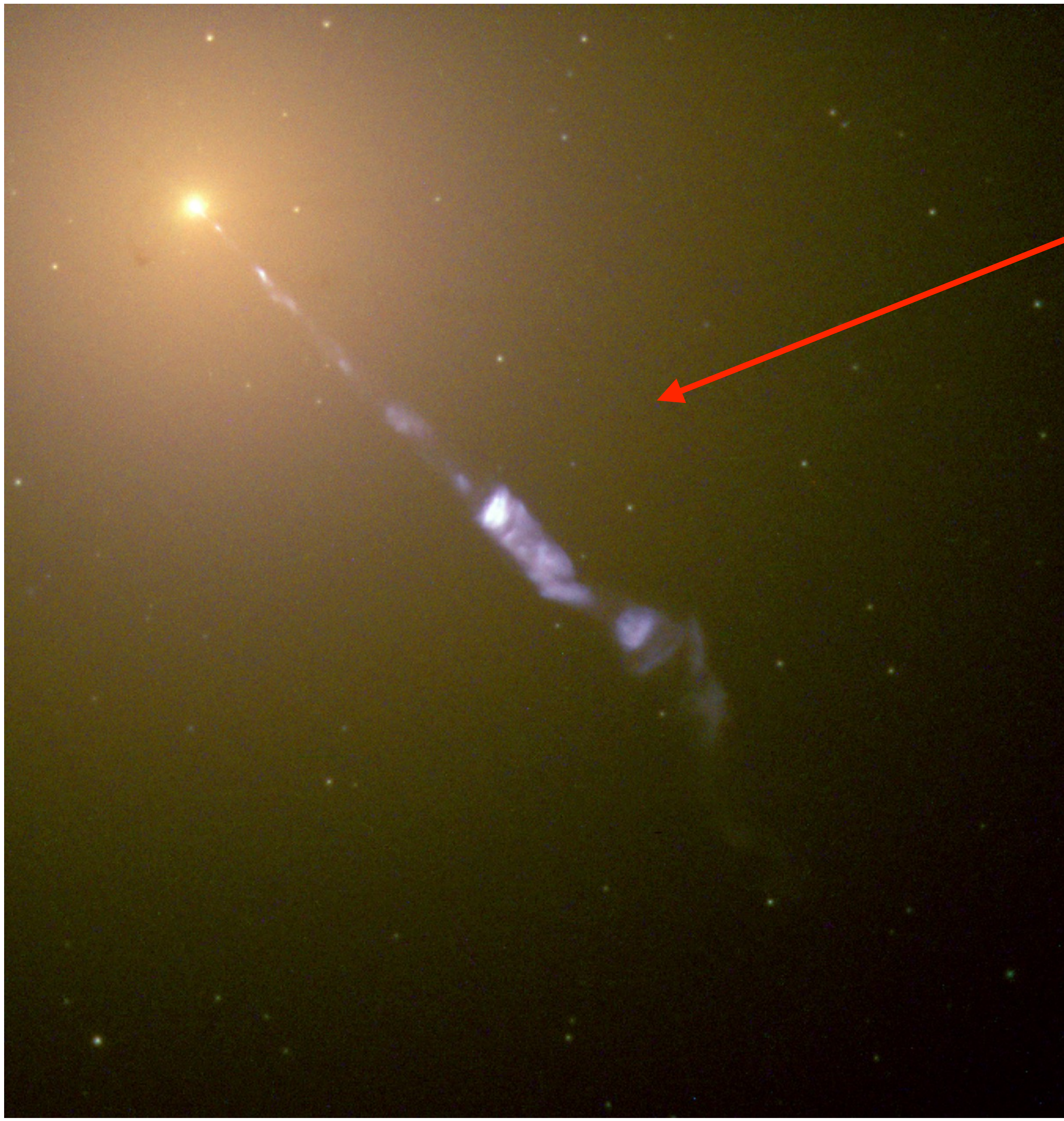
Prize share: 1/4

Andrea Ghez

Prize share: 1/4

The Nobel Prize in Physics 2020 was divided, one half awarded to Roger Penrose "for the discovery that black hole formation is a robust prediction of the general theory of relativity", the other half jointly to Reinhard Genzel and Andrea Ghez "for the discovery of a supermassive compact object at the centre of our galaxy."

Even more recently, we have been able to "see" black holes!

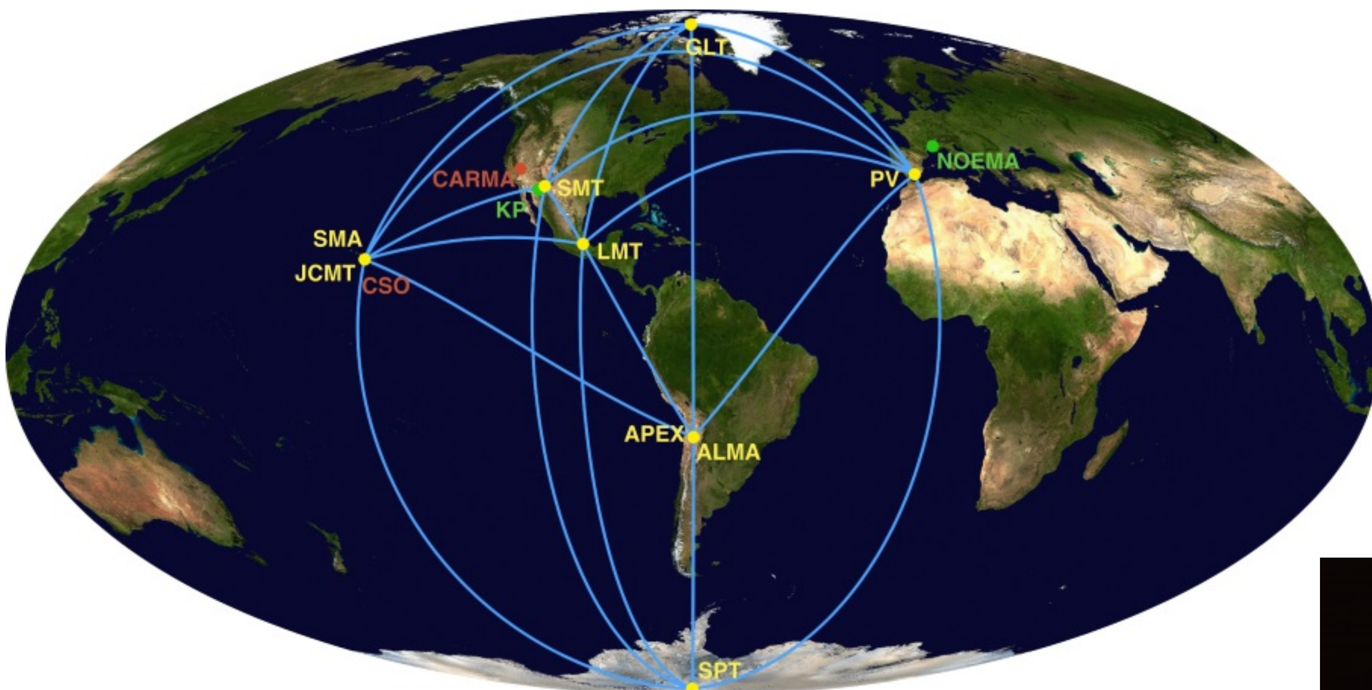


NASA

Highly energetic jet!

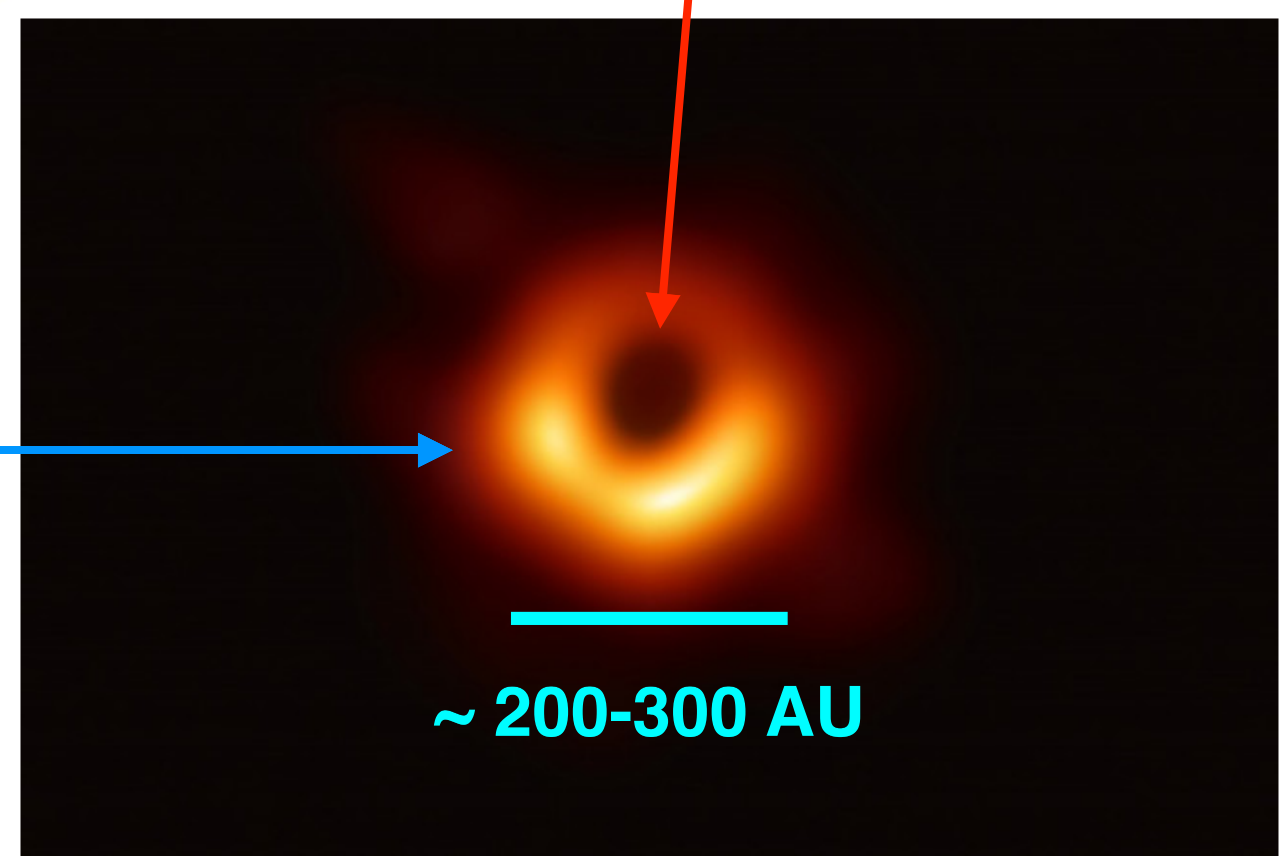
Even more recently, we have been able to "see" black holes!

Event Horizon Telescope (EHT)



Black hole itself!

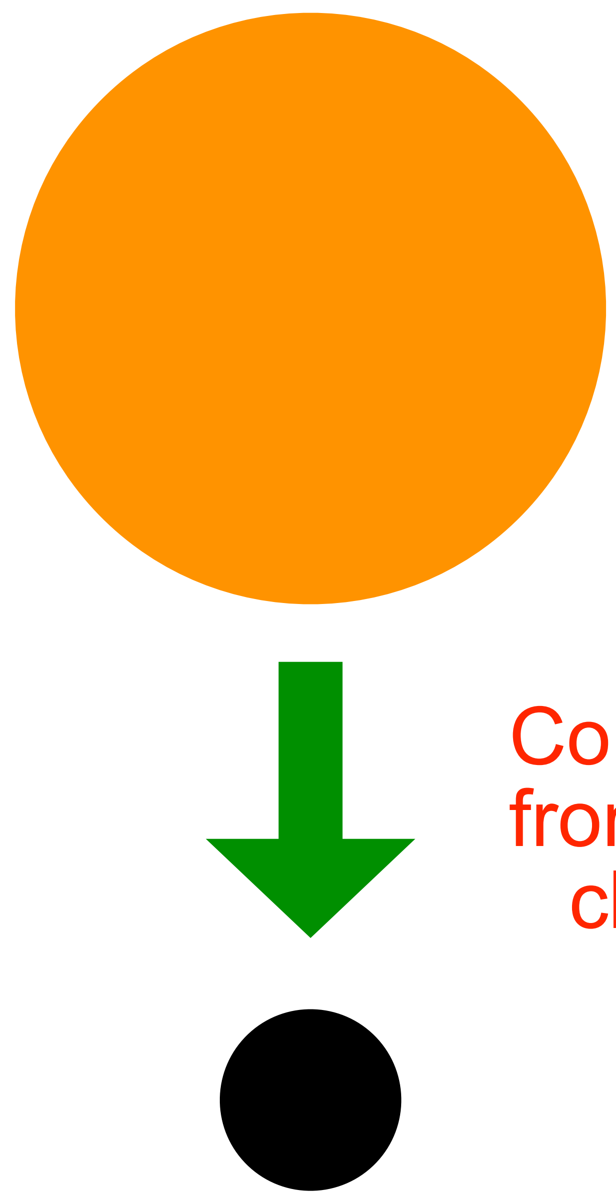
Disk immediately next to black hole



How do SMBH's form?

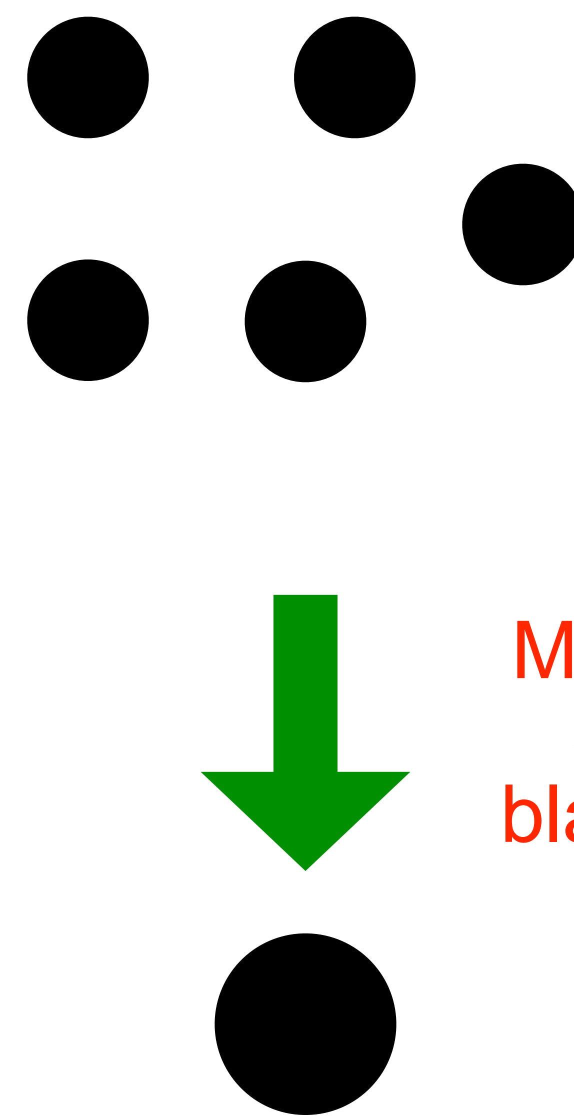
Two possibilities:

(1)



Collapse from gas cloud

(2)



Merging of smaller black holes

Intermediate Mass Black Holes

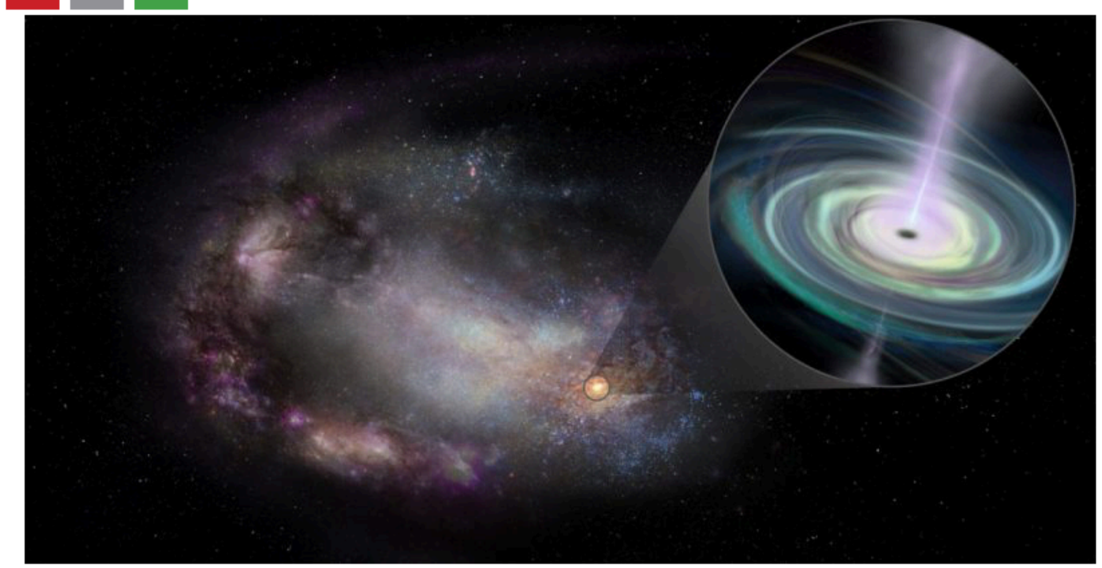
- Masses between 100 and 1000 M_{Sun}
- Some evidence that they exist, but still not clear
- They may be present in dwarf galaxies
- Also may be present at the centers of globular clusters

Astronomers find wandering black holes in dwarf galaxies

Posted by **Eleanor Imster** *in* **SPACE** | January 10, 2020

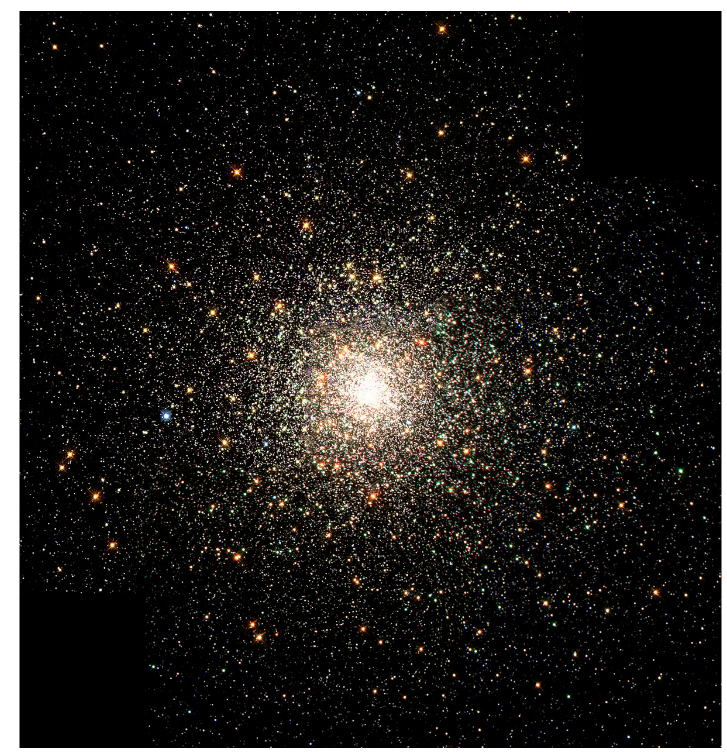
They found massive black holes in 13 dwarf galaxies, which are now among the smallest galaxies known to host such massive black holes. In roughly half the galaxies, the black hole isn't at the galactic center, but instead is "wandering."

Sharing is caring!

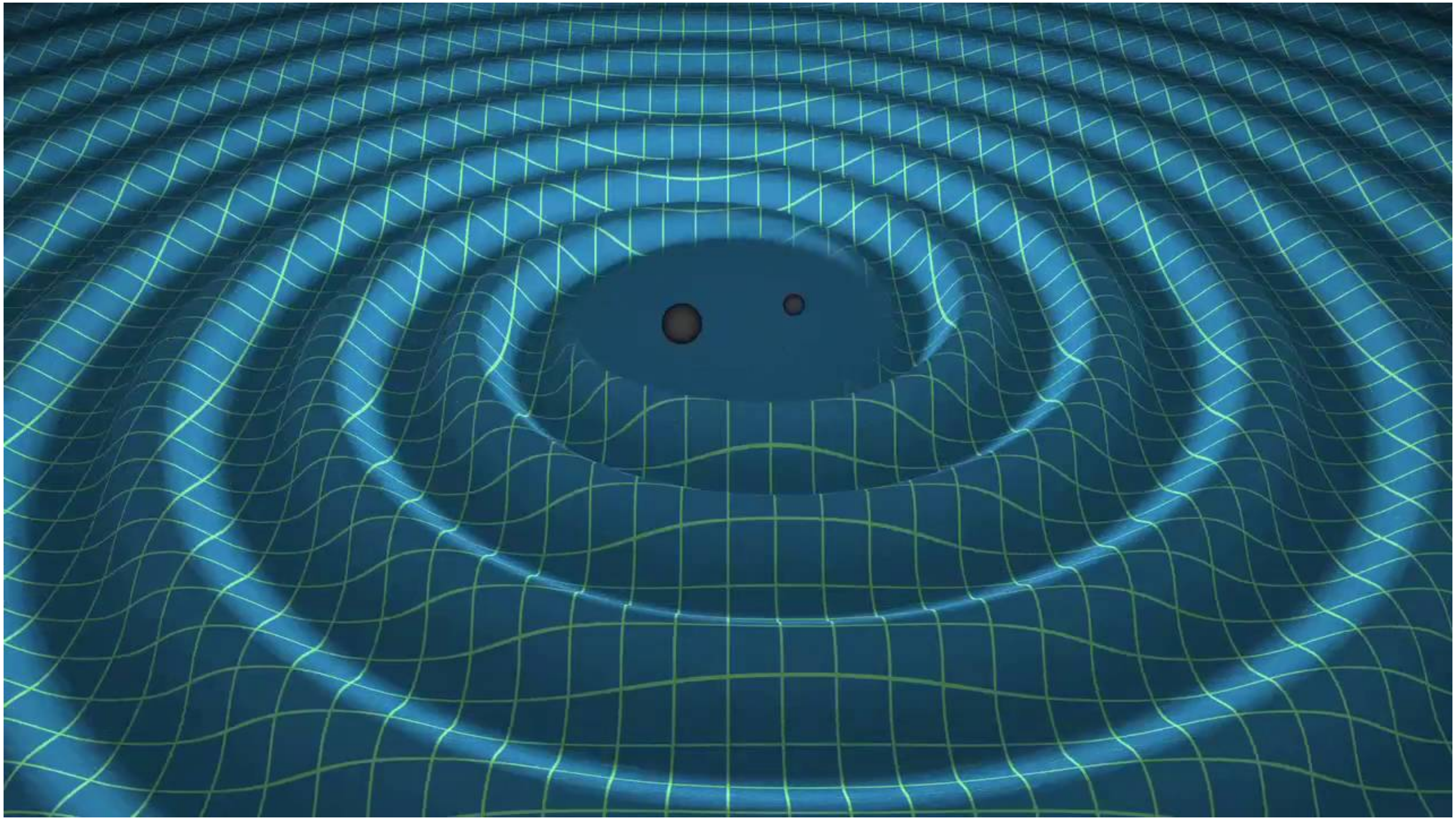


Artist's concept of a dwarf galaxy, its shape distorted, most likely by a past interaction with another galaxy, and a massive black hole in its outskirts (bright spot, far right). Image via Sophia Dagnello/ NRAO/ AUI/ NSF.

It's an amazing aspect of our knowledge of the modern universe that – everywhere we look – large galaxies have supermassive black holes at their centers. Now a team of astronomers has spotted 13 massive black holes in dwarf galaxies, located less than a billion light-years from Earth. All 13 galaxies are more than 100 times less massive than our own Milky Way. That makes them among the smallest galaxies known to host massive black holes. The astronomers announced the discovery at the American Astronomical Society's recent meeting in Honolulu, Hawaii (January 4-8, 2020).

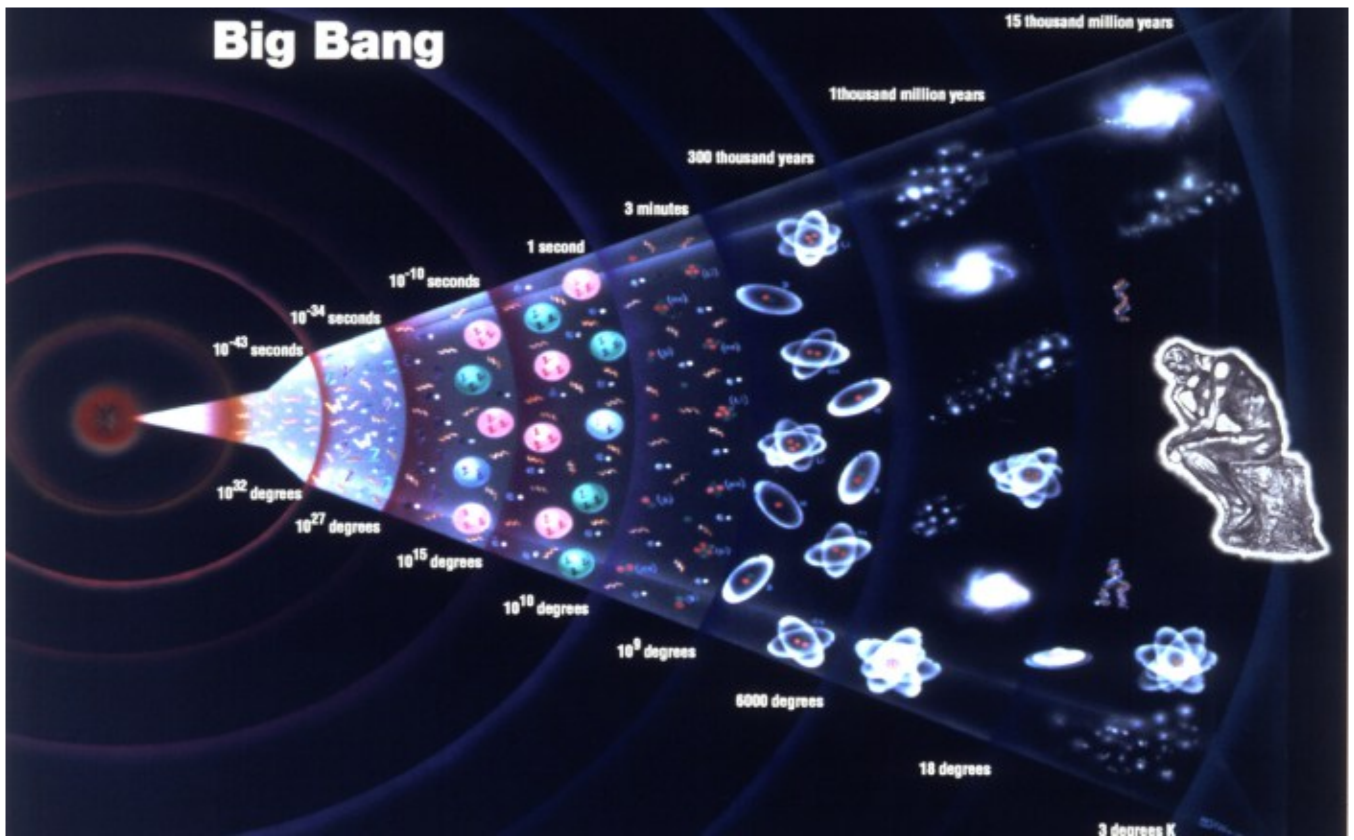


Intermediate Mass Black Holes



- Recent detection of gravitational wave emission from two black holes (more on gravitational waves next time!)
- The masses of the black holes were ~50-100 M_{Sun}
- Not sure how these objects form — much more research needed

Primordial black holes may have formed in the Big Bang



- High densities present at the very beginning of the Universe may have “squeezed” matter into black holes.
- No observational evidence of these objects (yet).

Next time:

The weird nature of black holes