Black Holes

Kielan Wilcomb

A New Way of Seeing Inside Black Holes

What Are Black Holes?

- Regions of space where nothing, not even *light*, can escape
  - Michell (1783) who set $v = \sqrt{\frac{2GM}{r}}$ to c! leading to:

→The Schwarzschild Radius M_{Earth}

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

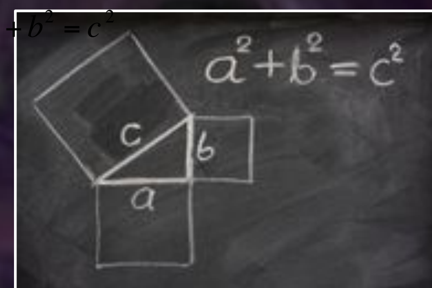
- Requires extremely high density
  - If M= M_{Earth}, r=9mm!

Black holes in General Relativity

- Rediscovered as mathematical solutions of Einstein's theory of General Relativity (1915)
- In General Relativity (GR), ***gravity = curved spacetime***
- Solutions in GR ("metrics") are generalizations of the Pythagorean theorem

$$a^2 + b^2 = c^2$$

$a^2 + b^2 = c^2$



- With 1 time and 3 space dimensions, and allowing for curvature:

$$g_t dt^2 - g_x dx^2 - g_y dy^2 - g_z dz^2 = ds^2$$

"metric" "proper distance"

Event Horizon

- Simplest black hole metric for a non-rotating spherical mass (*polar coordinates*) found by Schwarzchild (1916)

$$ds^2 = \left(\frac{1 - r_s}{r}\right) c^2 dt^2 - \frac{1}{\left(1 - \frac{r_s}{r}\right)} dr^2 - r^2 d\vartheta^2$$

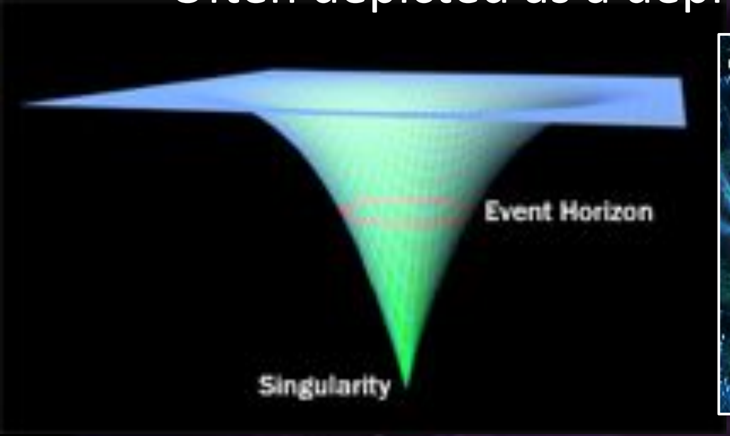
- Spherical surface $r = r_s$ → "event horizon"
- Time and space switch roles (metric coefficients switch signs) as you cross from $r > r_s$ → $r < r_s$
- Metric seems to blow up (∞) as $r \rightarrow r_s$ and $r \rightarrow 0$

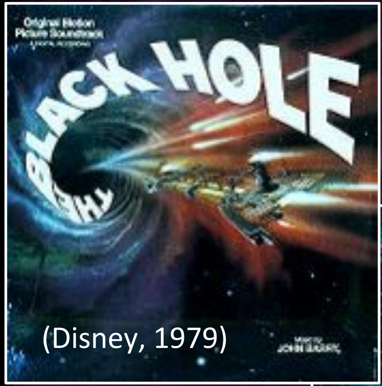
Invariants

- BUT at r = 0 there is a genuine singularity that cannot be removed by *any* choice of coordinates
- To be sure of locating singularities, need to find "invariants" (measures of curvature with values *independent* of coordinates)
- Coordinate-dependent quantities can be misleading!!!

Spacetime Outside the Horizon

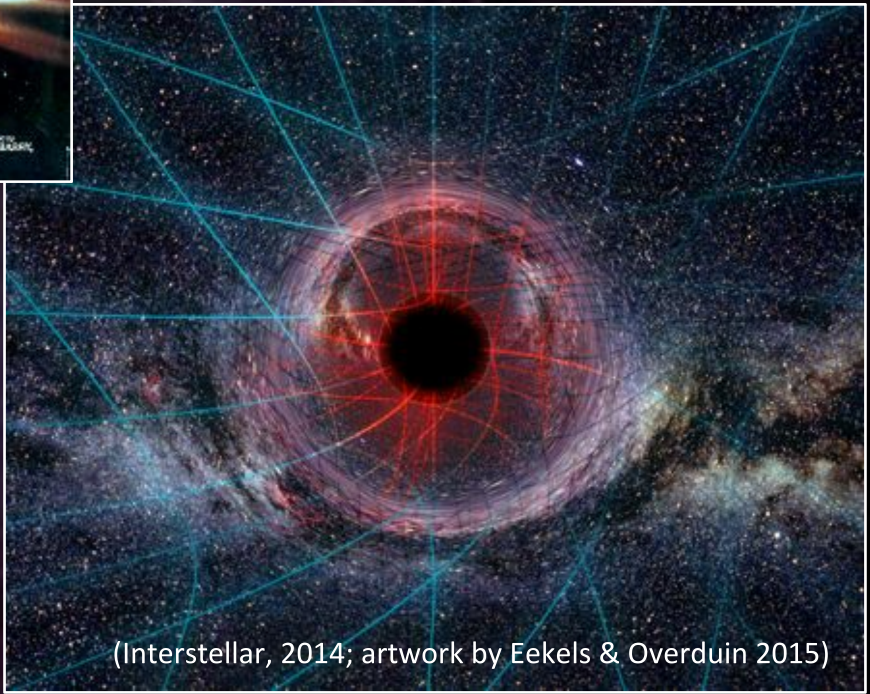
- Often depicted as a depression in 2-dimensional space





(Disney, 1979)

- More closely resembles a 3-dimensional hole *from every direction!*
- Near the horizon, time is dilated, space is compressed, and (if the hole is spinning) both are dragged around in the equatorial plane!

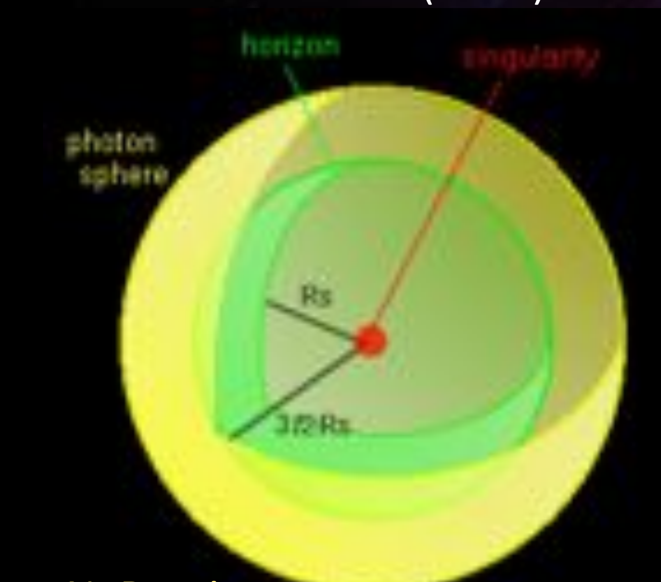


(Interstellar, 2014; artwork by Eekels & Overduin 2015)

Black Holes

- Three properties: Mass, spin, and electric charge

Schwarzschild (1916)



N. Rumiano

Mass M

Reissner-Nordstrom (1918)

N. Rumiano

Mass M, Charge Q

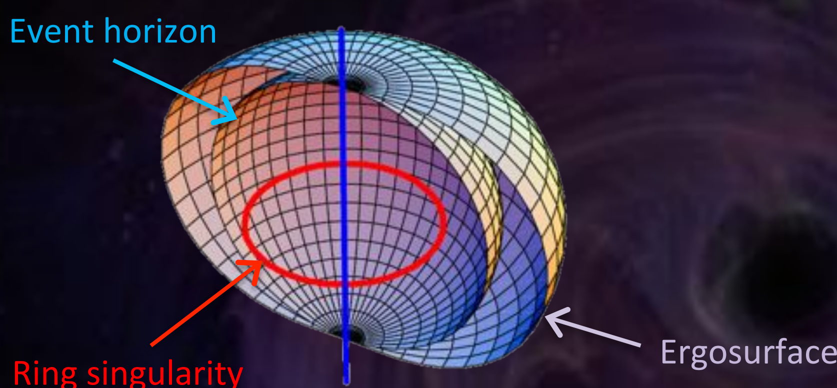
Kerr (1963), Kerr-Newman (1965)

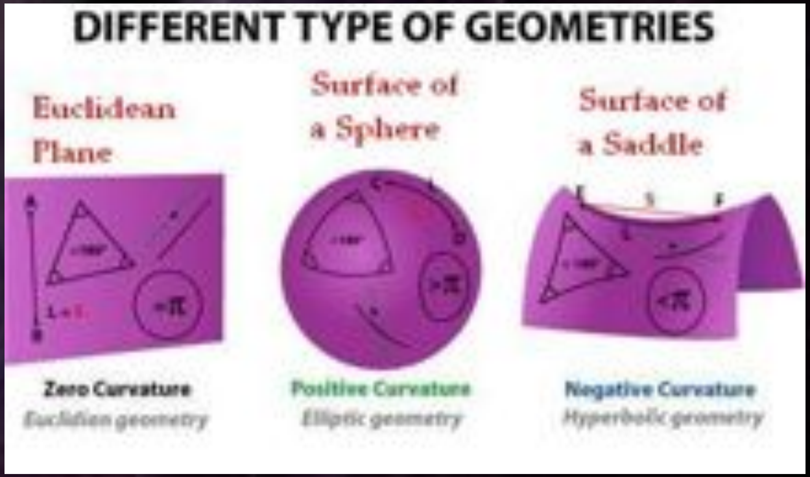
N. Rumiano

Mass M, Charge Q, and Spin J

Curvature Inside Real (Spinning) Black Holes

- Astrophysical black holes may not have significant electrical charge Q (they will discharge themselves quickly) but will certainly have significant spin J
- Described by the **Kerr solution**
- Interior structure usually depicted using "Boyer-Lindquist coordinates", in which curvature appears everywhere (1) *positive,* (2) *constant*, and (3) *uncomplicated*!





- But this appearance may be an artifact of the coordinates---just as Greenland looked larger than Africa in Mercator coordinates!

Curvature Invariants: Definitions

- To *truly* characterize the curvature inside real (spinning) black holes, we have calculated for the first time all the curvature invariants for the most general (Kerr-Newman) case
- In general there are seventeen (including the Kretschmann scalar *K*)
- But only two (the "**Weyl invariants**") are *independent* when

$$I_1 = C_{\alpha\beta}{}^{\gamma\delta} C_{\gamma\delta}{}^{\alpha\beta} = C^{\alpha\beta\gamma\delta} C_{\alpha\beta\gamma\delta} = \frac{8}{(r^2 + a^2 cos^2\theta)^6}$$
$$\times [\ 6\, m^2\, (r^6 - 15 r^4 a^2 cos^2\theta + 15 r^2 a^4 cos^4\theta - a^6 cos^6\theta)$$
$$-12\, m\, Q^2\, r\, (r^4 - 10 r^2 a^2 cos^2\theta + 5 a^4 cos^4\theta)$$
$$+Q^4\, (7 r^4 - 34 r^2 a^2 cos^2\theta + 7 a^4 cos^4\theta)\ ]$$

OBLIGATORY MATH

$$I_2 = -C_{\alpha\beta}{}^{\gamma\delta} C^{*}_{\gamma\delta}{}^{\alpha\beta} = \frac{-\epsilon^{\alpha\beta}{}_{\gamma\delta} C^{\gamma\delta\lambda\mu} C_{\alpha\beta\lambda\mu}}{2\sqrt{g}} = \frac{96\, a\, cos\theta}{(r^2 + a^2 cos^2\theta)^6}$$
$$\times [\ m^2\, r\, (3 r^4 - 10 r^2 a^2 cos^2\theta + 3 a^4 cos^4\theta)$$

[illegible] $a^2 cos^2\theta + a^4 cos^4\theta)$

$$+2\, Q^4\, r\, (r^2 - a^2 cos^2\theta)\ ]$$

- For there is also a "**Ricci invariant**" :

$$I_6 = R_{\alpha}{}^{\beta} R_{\beta}{}^{\alpha} = R_{\mu\nu} R^{\mu\nu} = \frac{4\, Q^4}{(r^2 + a^2 cos^2\theta)^4}$$

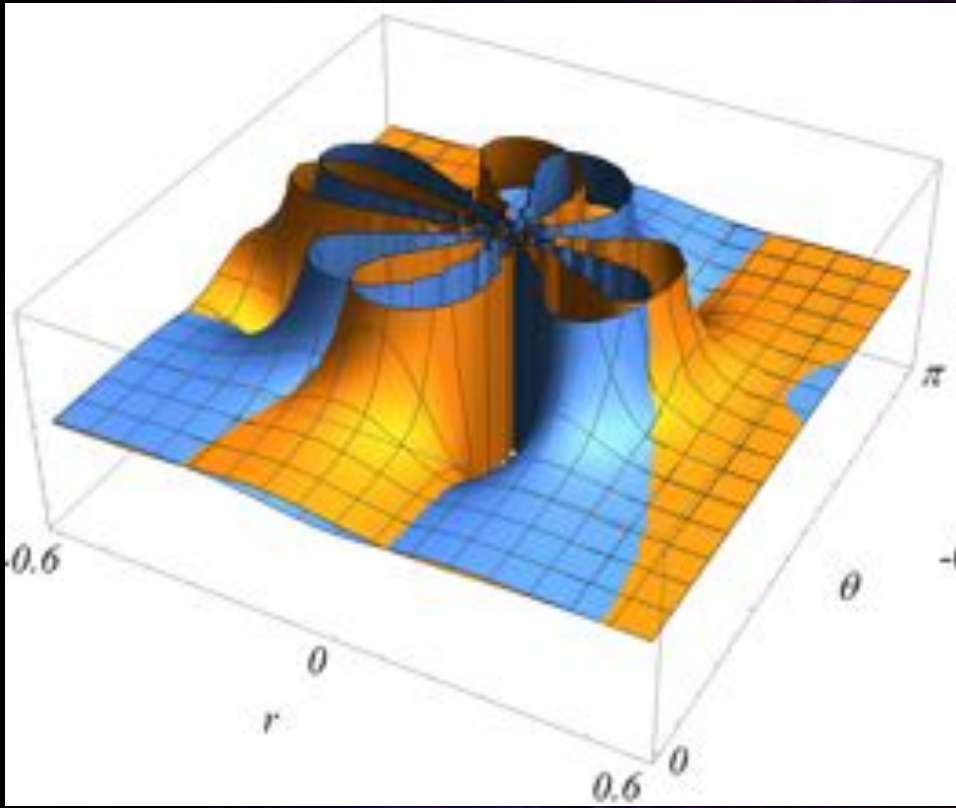
- And the "**mixed invariants**" :

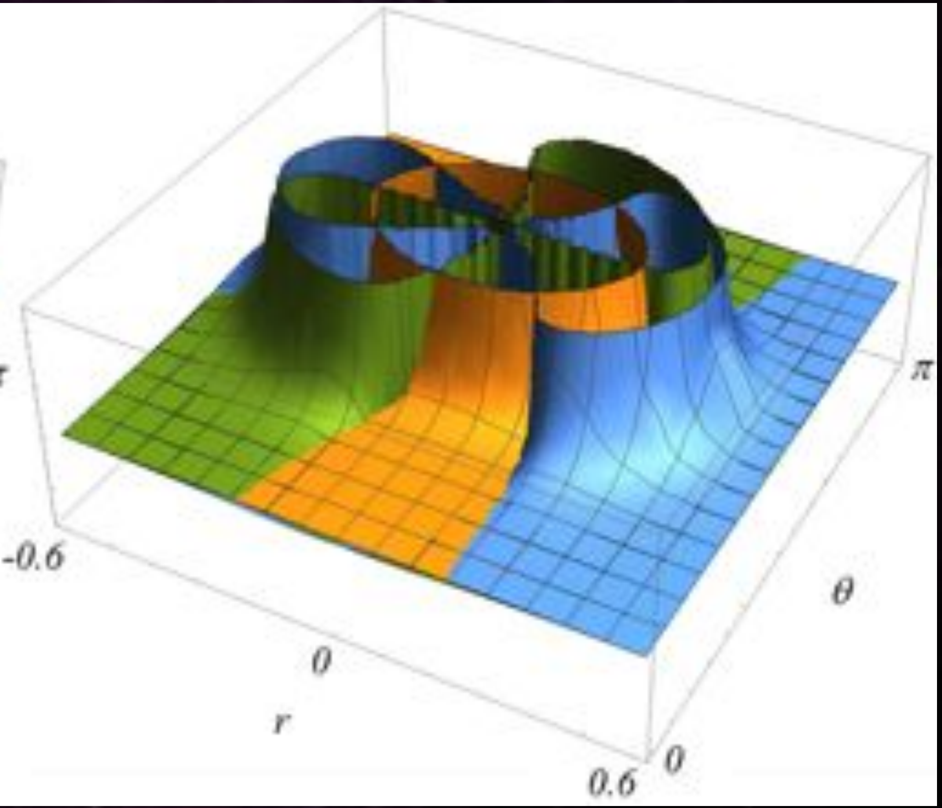
$$I_9 = C_{\alpha\delta\epsilon}{}^{\beta} R^{\delta\epsilon} R_{\beta}{}^{\alpha} = \frac{16\, Q^4\, [r^2 (Q^2 - m r) - a^2 (Q^2 - 3 m r) cos^2\theta]}{(r^2 + a^2 cos^2\theta)^7}$$

$$I_{10} = -C^{*}_{\alpha\delta\epsilon}{}^{\beta} R^{\delta\epsilon} R_{\beta}{}^{\alpha} = \frac{16\, a\, Q^4\, cos\theta [r (3 m r - 2 Q^2) - a^2\, m\, cos^2\theta]}{(r^2 + a^2 cos^2\theta)^7}$$

Curvature Invariants: Results!

- Kerr-Newman black hole with $M = 1$, $Q = 0.8$, $J = 0.6$

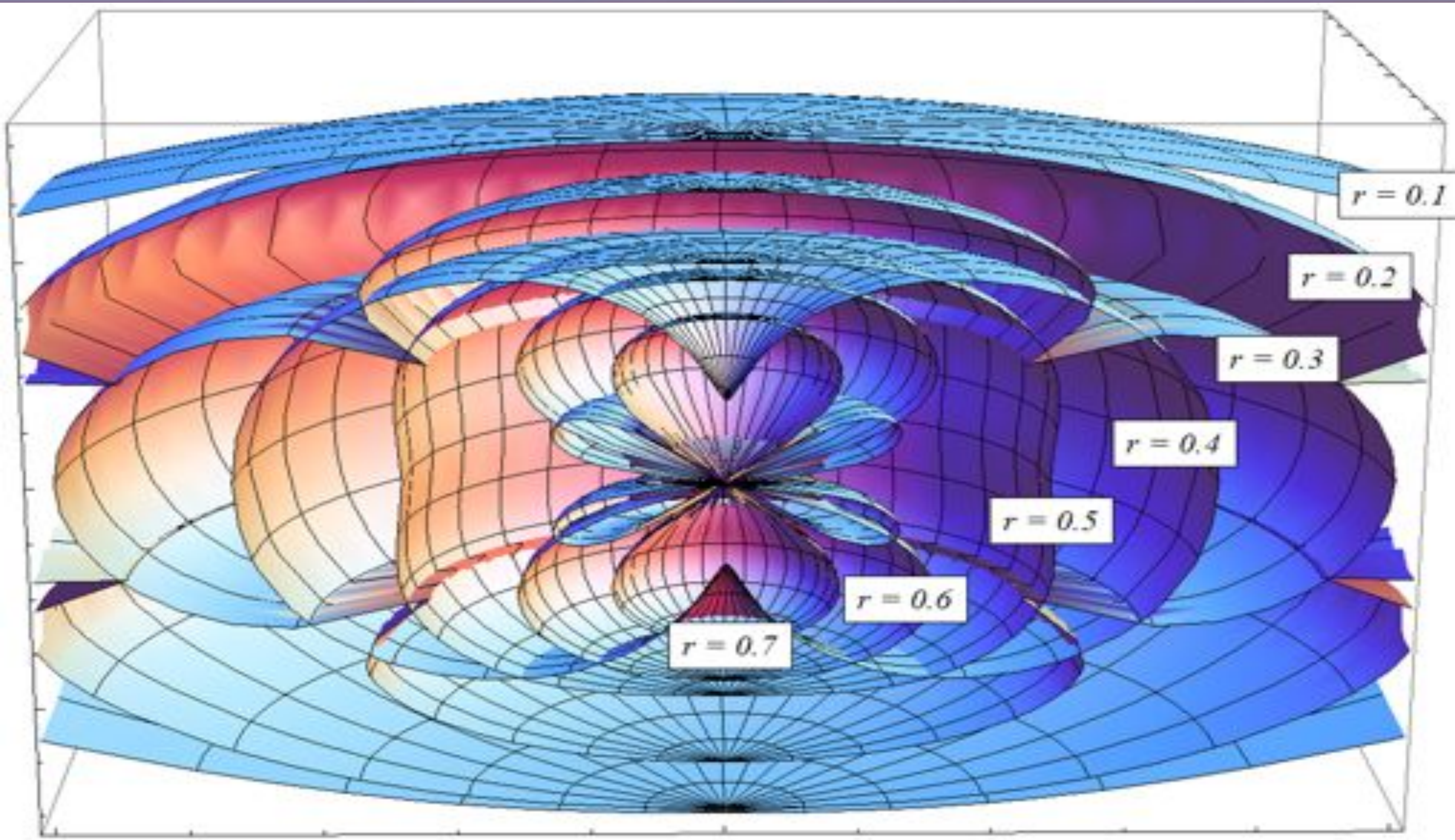




Weyl invariants I_1 (yellow), I_2 (blue)

Ricci, mixed invariants I_6 (yellow), I_9 (blue) I_9 (green)

Weyl Invariant "Unpacked"



Conclusions

- Curvature inside realistic black holes is (1) both positive *and negative*, (2) definitely *not constant*, and (3) *ridiculously complex!*
- The Weyl invariants are especially contorted! Interesting since this expression is associated with *gravitational waves*
- Regions of positive/negative curvature thought to be associated with dominance of “gravito-electric” (=warping) vs. “gravito-magnetic” (=twisting) fields
- Much more remains to be understood about the physical importance of these invariants
- But before that, it is necessary to find the invariants, and that is what we have done!

- *Credits: Prof. Richard Henry (Hopkins), James Overduin (Towson)*

Physics of Black Holes

Types of Black Holes

1. Stellar Mass Black Holes (3-20 Msun)
2. Supermassive Black Holes (10^6 - 10^9 Msun)
3. Intermediate Mass
   Black Holes (100-1000 Msun)
   … or maybe even greater

Stellar Mass Black Holes


The Lifecycle of a Star
Globule
Brown Dwarf
Main Sequence Star
Dust Cloud
Red Giant
Nebula
White Dwarf
Black Hole
Black Dwarf
Neutron Star
Supernova

Core Collapse Supernova

Stellar Mass Black Holes

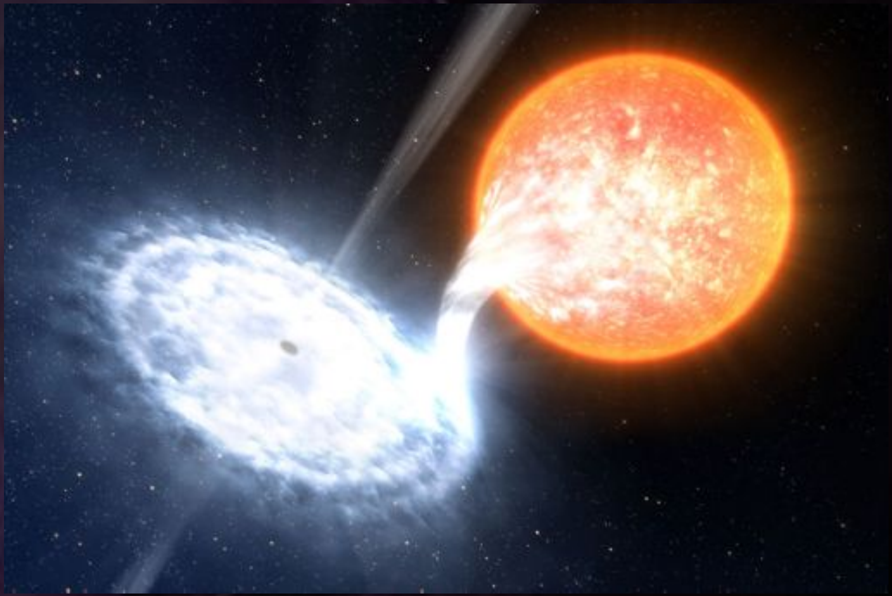
- Mass: 3 – 20 Msun
- A massive star (*>25 Msun*) goes Supernova
  – Core-collapse supernova
    (Type Ib, Ic, and II)
  – Must be compressed below the
    Schwarzschild Radius

$$R_s = \frac{2MG}{c^2}$$

Stellar Mass Black Holes

Mass accretion of companion

- Neutron star binary:
  Star's self-gravity exceeds the degeneracy pressure to support it
- Evolution of two massive stars (>25Msun) together



Supermassive Black Holes

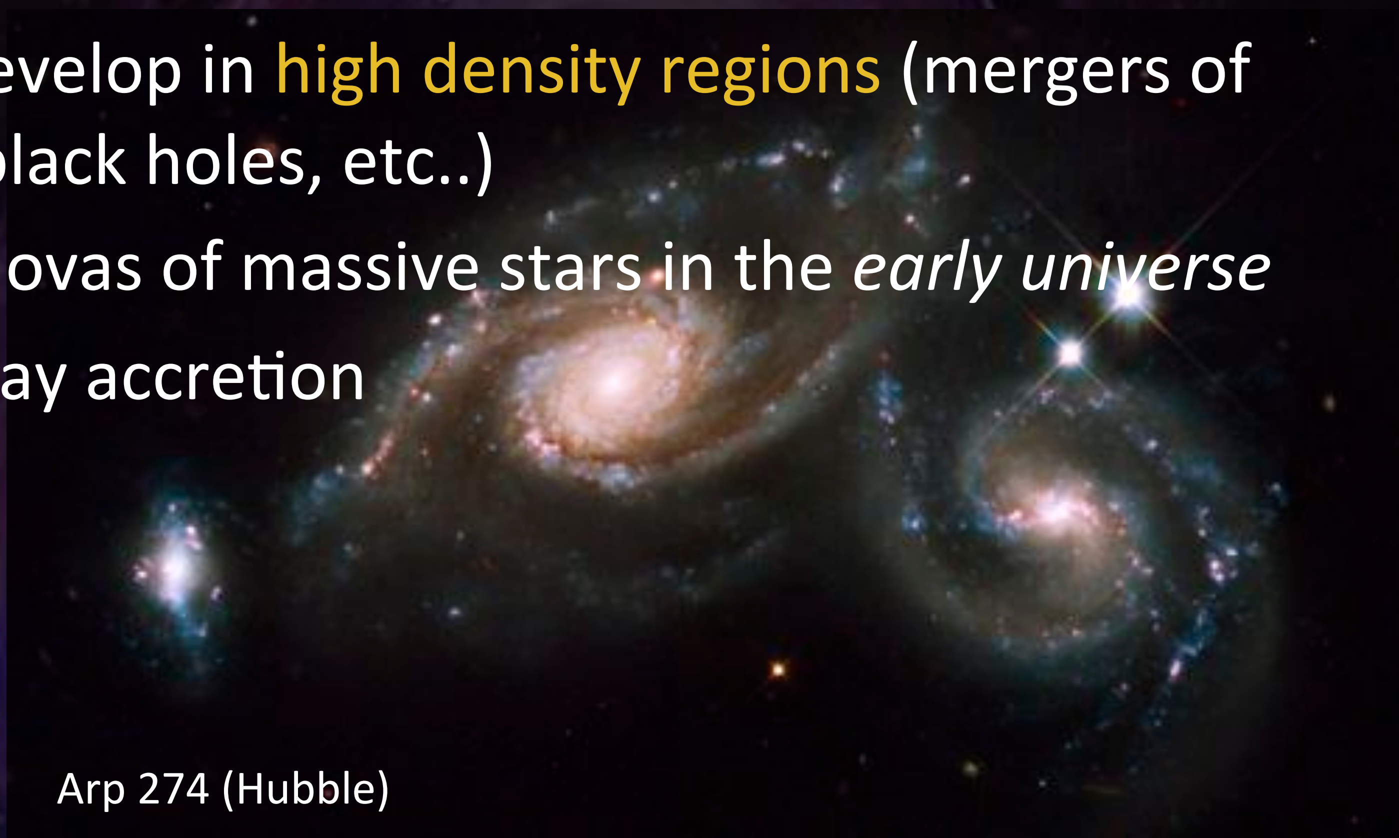
Supermassive Black Holes

- Mass: 10^6 - 10^9 Msun
- Known to exist at the center of most galaxies, including our own Milky Way!
- We do not know how they formed, but we know they *exist!*

Sombrero Galaxy

Supermassive Black Holes

- Popular ideas:
  - Collisions between galaxies
  - May develop in high density regions (mergers of stars, black holes, etc..)
  - Supernovas of massive stars in the *early universe*
  - Runaway accretion



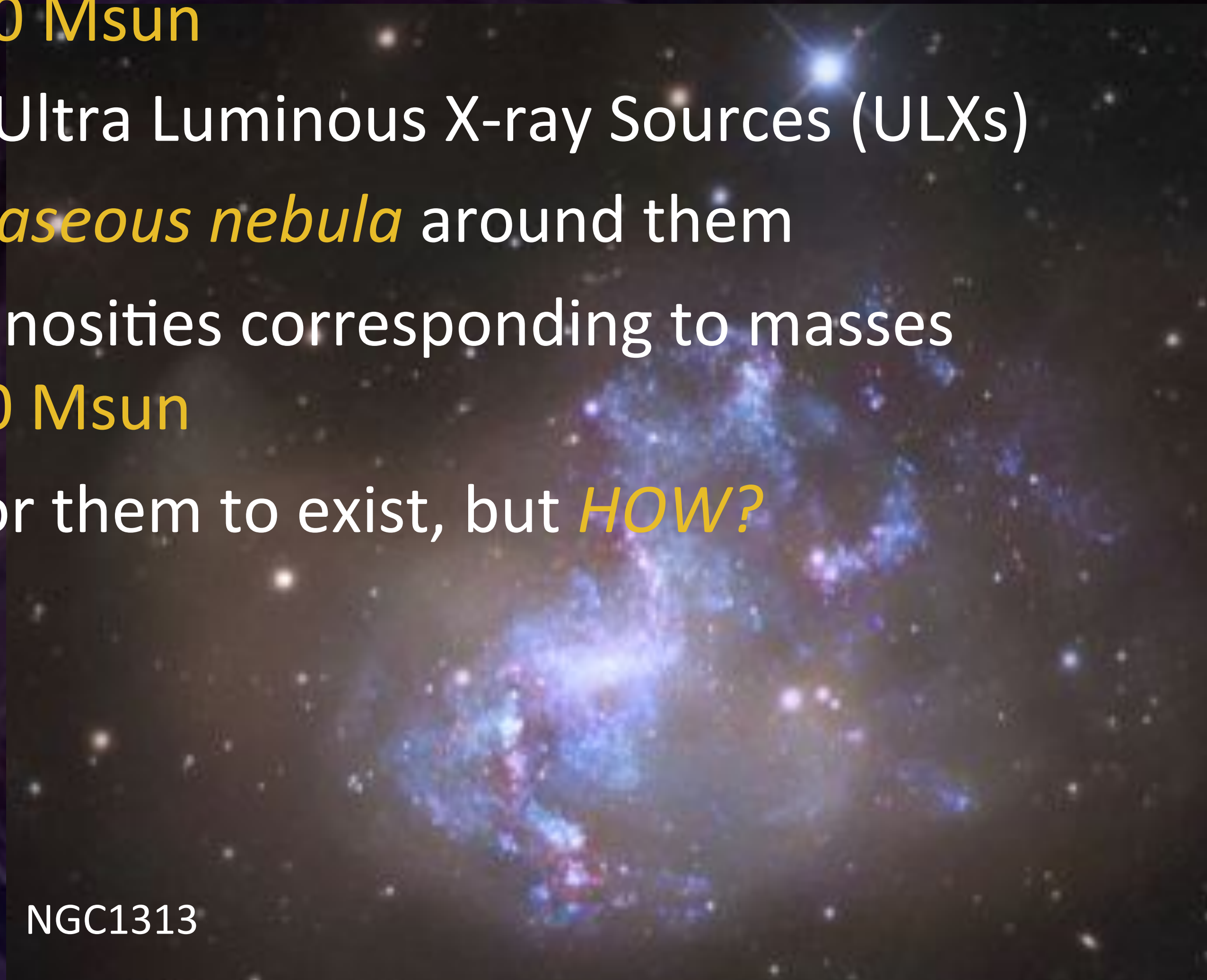
Arp 274 (Hubble)

Galaxy Mergers

Intermediate Mass Black Holes

IMBH: The Missing Link

- Mass: 100-1000 Msun
- Referred to as Ultra Luminous X-ray Sources (ULXs)
- Tend to have *gaseous nebula* around them
- Eddington luminosities corresponding to masses greater than 20 Msun
- Makes sense for them to exist, but *HOW?*



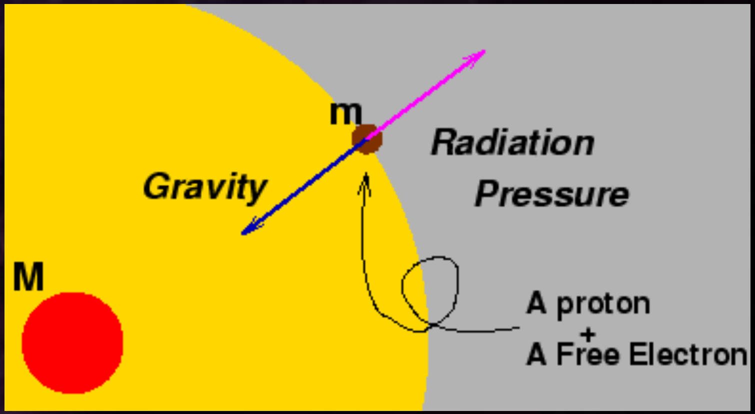
NGC1313

Eddington Luminosity Limit

- Emit at L > 10^{40} ergs/s
- Eddington Luminosity of a 10 – 20 Msun object

$$L_{Edd} = \frac{4\pi G M m_p c}{\sigma_T} = \frac{4\pi c G M}{\bar{\kappa}}$$

- Stars in the current universe do not evolve to black holes of greater than *20 Msuns*
- Are they beaming? *NO*
- ...So how do they form?



Eddington Luminosity Limit

- Super-Eddington accretion
- Supermassive Black Holes emitting below their Eddington Luminosity? *NO*
- Are they beaming? *NO*
- …So how do they form?

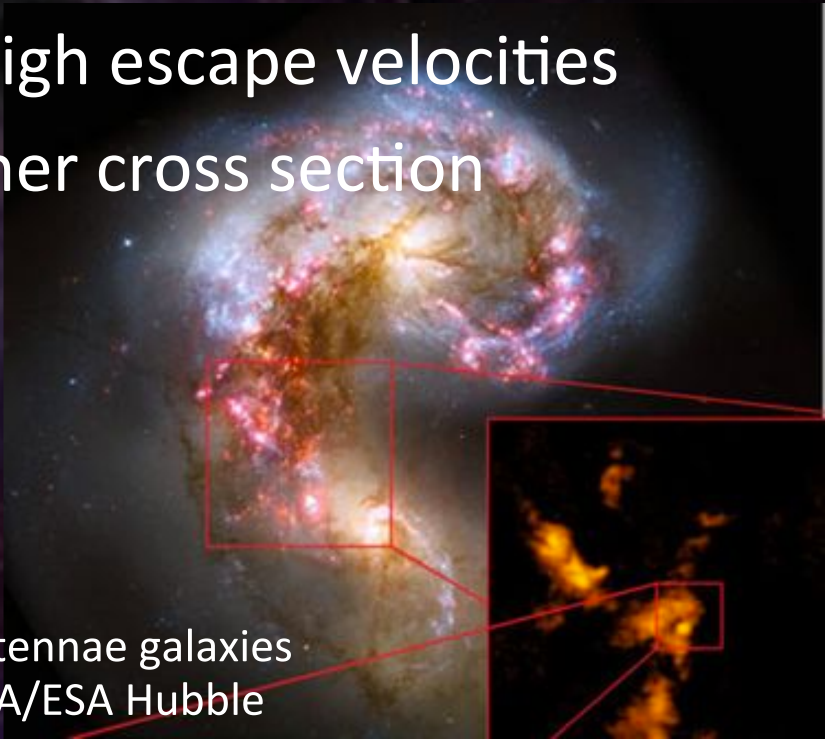
Formation Theories

1. Evolution of Population III stars
   - In a Hydrogen-Helium universe…
     - Small masses → unbind, large masses → collapse (High Jeans Mass)
     - Cooling is less efficient → higher T and M
     - Mass loss is less significant

Painting by Adolf Schaller • STScI-PRC02-02

Formation Theories

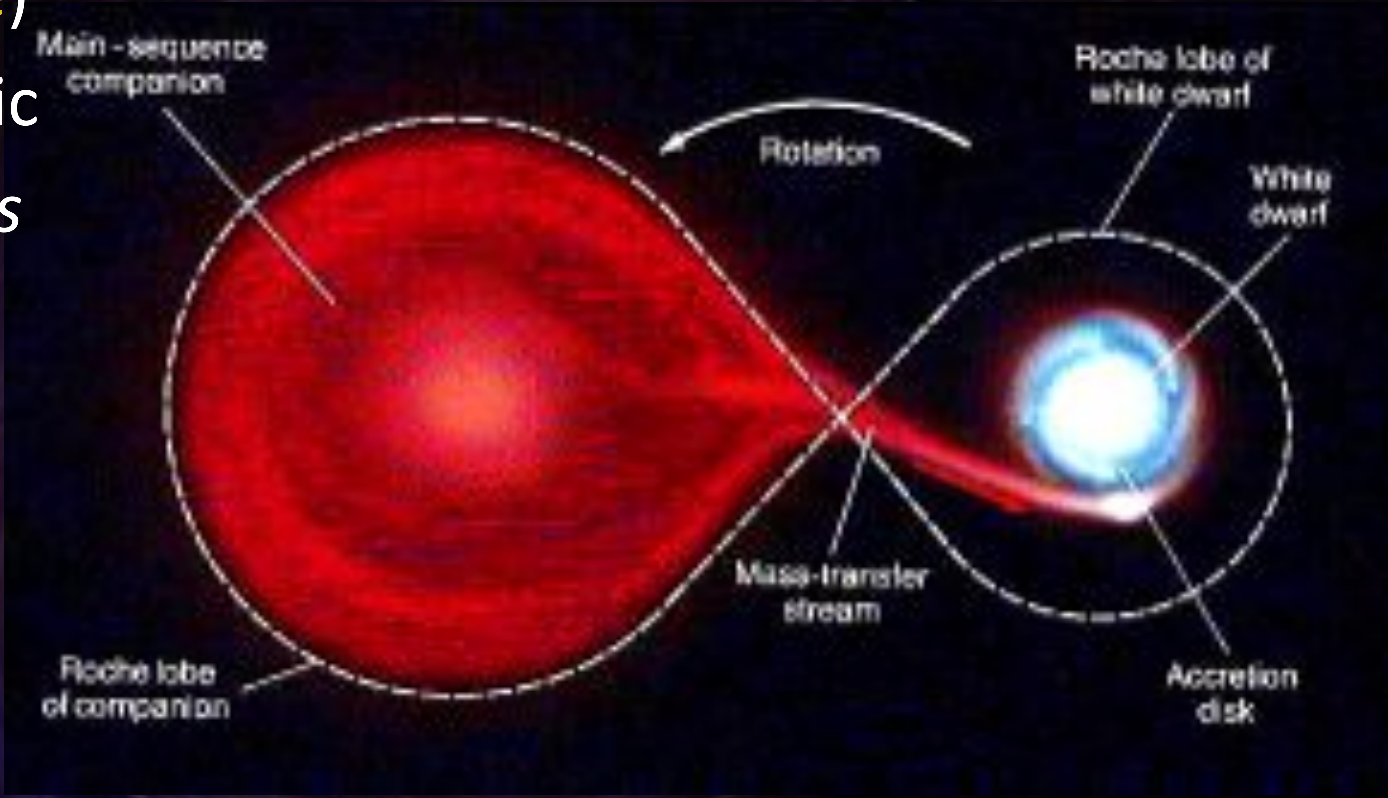
2. Direct collisions of massive stars in a young, dense star cluster ("Super star clusters")
   – Physically collide before evolving off MS
   – Stick together because of high escape velocities
   – New star: higher mass, higher cross section
   – *RUNAWAY ACCRETION*



The Antennae galaxies
NASA/ESA Hubble

Other Formation Theories

- Mass transfer to drive high Luminosity (overflow of Roche Lobe)
- Extragalactic
  BH binaries
- Three Body
  collisions



IMBH Candidates

Chandra

Detecting Black Holes

Detecting Black Holes

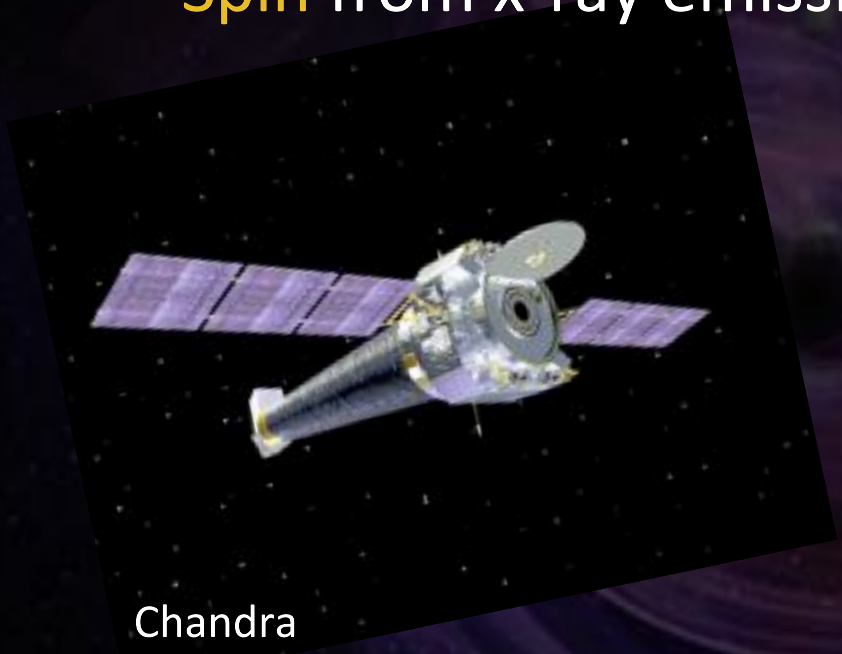
- General Relativity *predicts* their existence

BUT: How do we *know* they're there?

- – Behaviors of stars' orbits (SMBH), and velocities of gas orbiting the region (SMBH)
- – Emission from material around the BH (x-rays, highly ionized elements… [OIII])
- – *Gravitational radiation and gravitational waves*

Detecting Black Holes

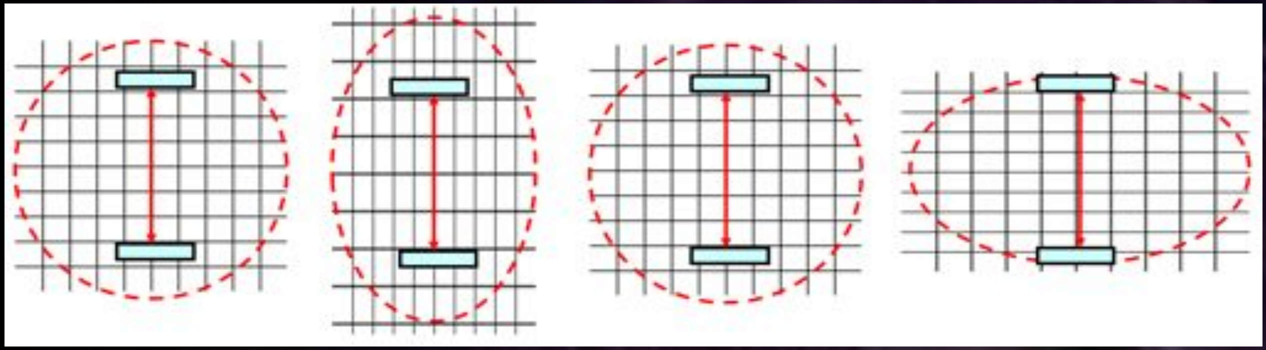
- Hubble: Space Telescope Imaging Spectrograph (STIS) → speed of gas and stars! (Mass)
- Chandra X-Ray Observatory and XMM-Newton
  – Spin from x-ray emission of in-falling material

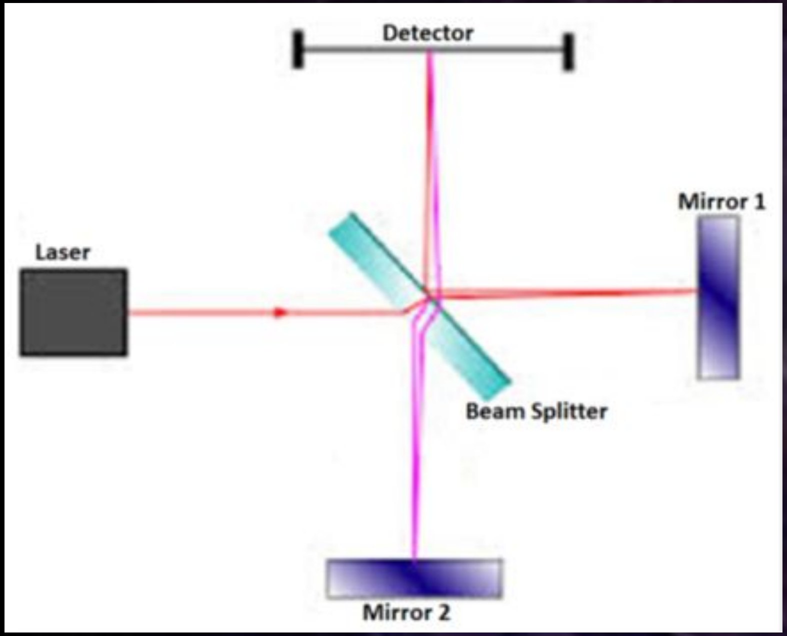


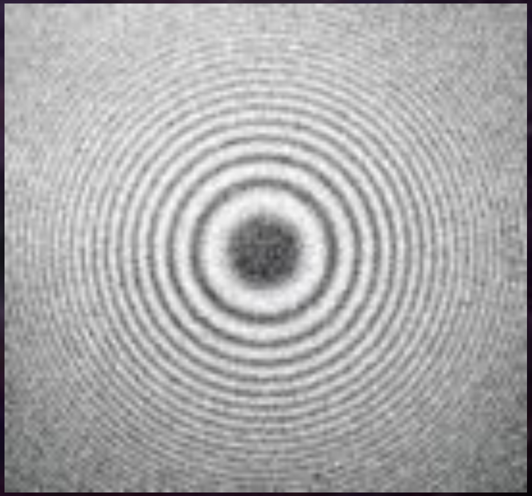
Chandra

XMM-Newton

Detection: Gravitational Waves







- Gravitational waves acting on an interferometer arm
- Differences appear in interference patterns when a wave goes by

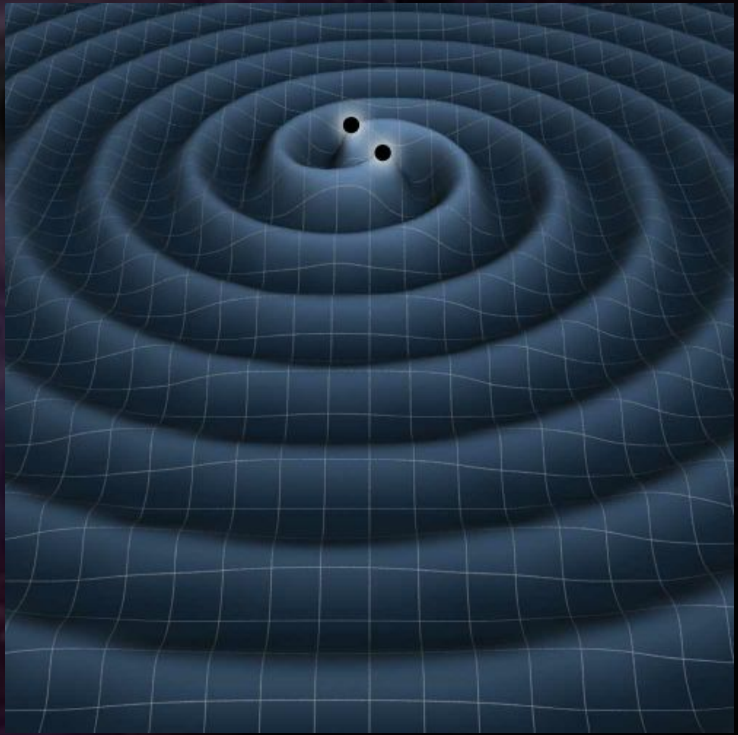
Gravitational Waves and LIGO

LIGO

The strain equation

$$\frac{\Delta L}{L} = \frac{h}{2} \approx 10^{-21}$$

- The larger the L, or distance, the larger the detectable change or *"strain"* caused by gravitational waves
- LIGO is trying to detect the most powerful gravitational waves that are theorized to come from black hole mergers



Thank you for listening!