Introduction to Astronomy and Astrophysics I
Lecture 9

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Black Holes: Introduction

- Definition: Region of spacetime where gravity is so strong that nothing, not even light, can escape
- Predicted by Einstein's General Theory of Relativity
- Key properties:
  - Event horizon
  - Singularity (theoretical)
- No direct emission, but detectable through:
  - Effects on surrounding matter
  - Gravitational waves
  - Gravitational lensing

Black Hole Formation and Types

- Stellar-mass black holes:
  - Formed from collapse of massive stars ($M > 20 - 25 M_\odot$)
  - Typical mass: $5 - 50 M_\odot$ (high max. mass due to mergers)
- Supermassive black holes:
  - Found at centers of galaxies
  - Mass range: $10^6 - 10^{10} M_\odot$
  - Formation mechanism still uncertain
- Intermediate-mass black holes:
  - Mass range: $10^2 - 10^5 M_\odot$
  - Evidence growing, but still controversial

Black Hole Properties

- Schwarzschild radius (event horizon for non-rotating black hole):

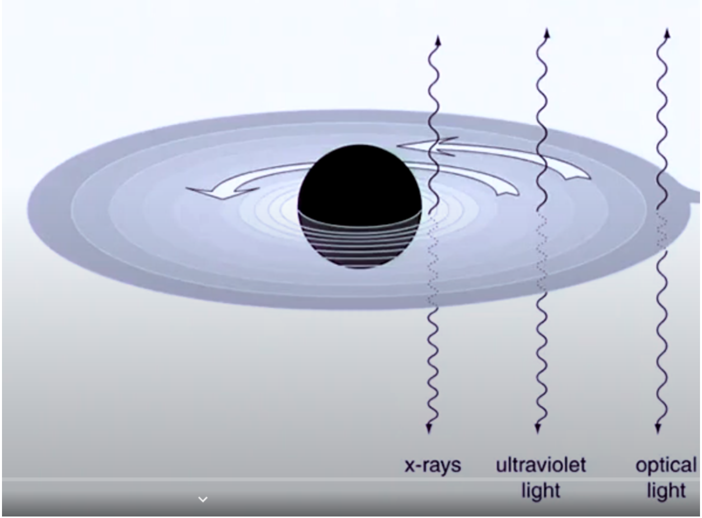
$$R_s = \frac{2GM}{c^2}$$

- No-hair theorem: Black holes characterized by only three parameters:
  - Mass (M)
  - Angular momentum (J)
  - Electric charge (Q) (usually negligible in astrophysical contexts)
- Types based on rotation:
  - Schwarzschild black hole (non-rotating)
  - Kerr black hole (rotating)

Black Hole Anatomy

- Event horizon: "Point of no return"
- Ergosphere (for rotating black holes):
  - Region where spacetime itself is dragged
  - Allows energy extraction (Penrose process)
- Photon sphere: Orbit of light around black hole
- Accretion disk: Infalling matter forms hot, luminous disk
- Jets: High-energy particle outflows (in some cases)

Hot Accretion disk



Spacetime and General Relativity

- Curved spacetime:
  - Mass-energy curves spacetime
  - Objects follow geodesics in curved spacetime
- Gravitational time dilation:

$$\frac{t_f}{t_0} = \sqrt{1 - \frac{2GM}{rc^2}}$$

  where t_f is time in strong field, t_0 is time at infinity
- Gravitational redshift:

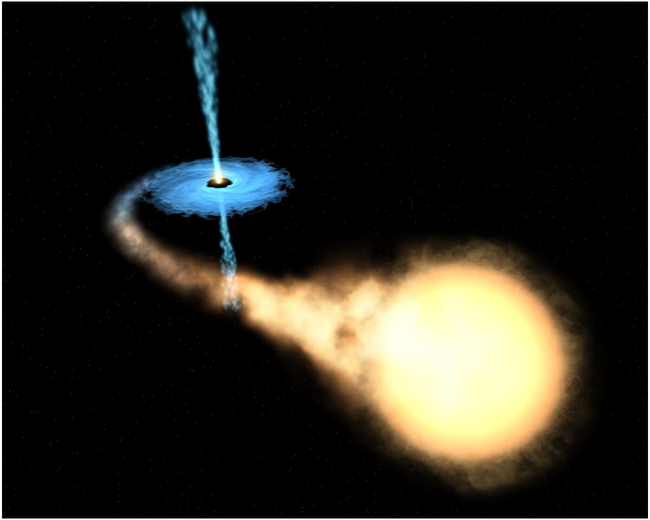
$$z = \frac{1}{\sqrt{1 - \frac{2GM}{rc^2}}} - 1$$

- Singularity: Point of infinite density (according to classical GR)
- quantum gravity effects expected to resolve singularity

Black Hole Observations: Accretion and X-ray Binaries

- X-ray binaries:
  - Black hole accreting from companion star
  - Strong X-ray emission from hot accretion disk
- Accretion disk spectra:
  - Thermal component from disk
  - Power-law component from corona
- Quasi-periodic oscillations (QPOs)
- Examples: Cygnus X-1, GRS 1915+105

X-ray binary or microquasar



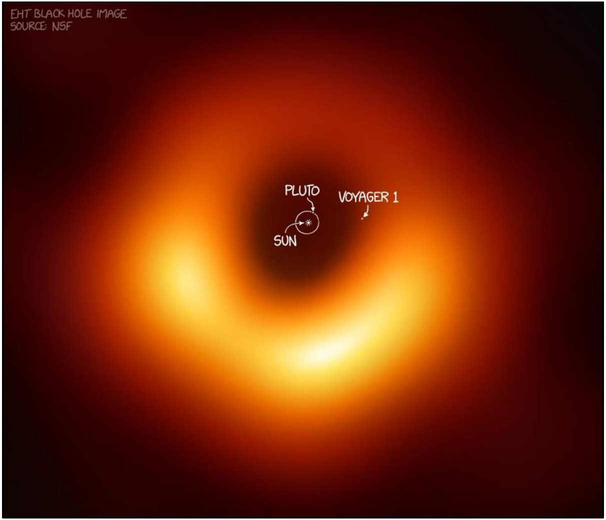
Black Hole Observations: Gravitational Waves

- First direct detection: GW150914
- Typical sources:
  - Binary black hole mergers
  - Neutron star - black hole mergers
- Stages of a merger:
  1. Inspiral
  2. Merger
  3. Ringdown
- Provides information on:
  - Masses of merging objects
  - Spins of black holes
  - Distance to source

Black Hole Observations: Event Horizon Telescope

- Global network of radio telescopes
- Very Long Baseline Interferometry (VLBI)
- First image of a black hole shadow: M87* (2019)
- Observable features:
  - Photon ring
  - Black hole shadow
  - Asymmetry due to relativistic beaming
- Confirms predictions of General Relativity

EHT image of M87 black hole



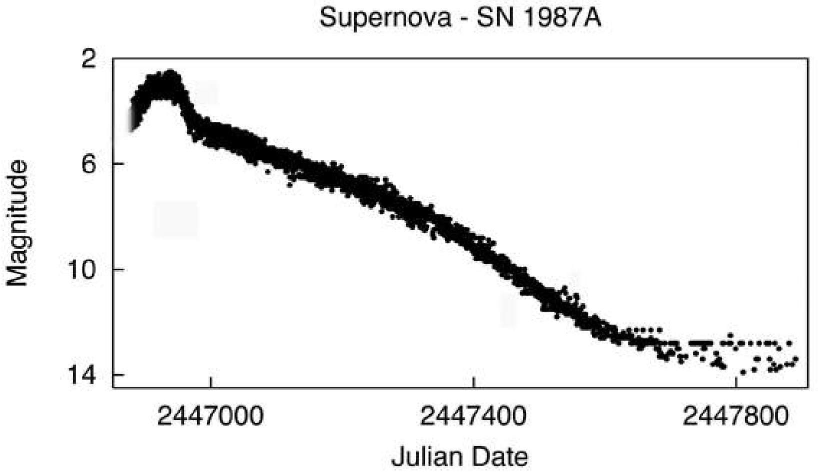
Astrophysical Importance of Black Holes

- Galaxy evolution:
  - M-σ relation: correlation between SMBH mass and galaxy bulge velocity dispersion
  - AGN feedback regulating star formation
- Active Galactic Nuclei (AGN):
  - Powered by accretion onto supermassive black holes
  - Various types: Seyfert galaxies, quasars, blazars
- Tests of General Relativity:
  - Strong-field regime
  - Gravitational waves
- Connection to fundamental physics:
  - Hawking radiation
  - Information paradox
  - Potential link to quantum gravity

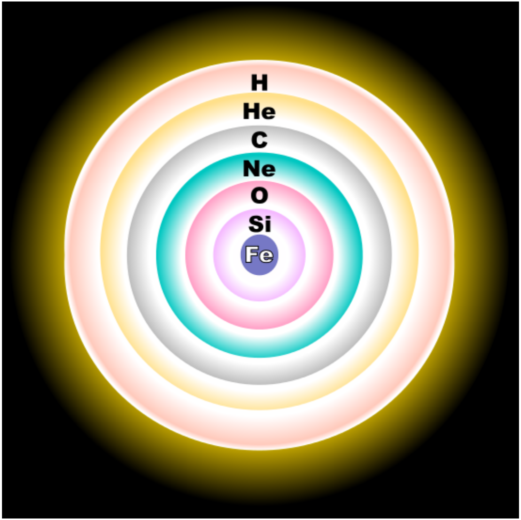
To learn more

Shapiro & Teukolsky (Wiley) *Black holes, white dwarfs and neutron stars. The physics of compact objects*

Type 2 Supernova light curve



Core collapse supernova



Pair instability supernova

When a star is very massive, the gamma rays produced in its core can become so energetic that some of their energy is drained away into production of particle and antiparticle pairs. The resulting drop in pressure causes the star to partially collapse under its own huge gravity. After this violent collapse, runaway thermonuclear reactions (not shown here) ensue and the star explodes, spewing the remains into space.

Pair-instability supernovae can only happen in stars with a mass range from around 130 to 250 solar masses and low to moderate metallicity. Note that due to mass loss a star of <130 solar masses will leave a black hole of about 50 solar masses. What has LIGO really discovered?

What is the ISM?

All the stuff between the stars

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- cosmic rays
- dark matter: interacts little with baryonic matter, influences galaxy kinematics and dynamics.

There is no definite boundary to a galaxy. So most of what happens in the ISM also happends in the intergalactic medium.

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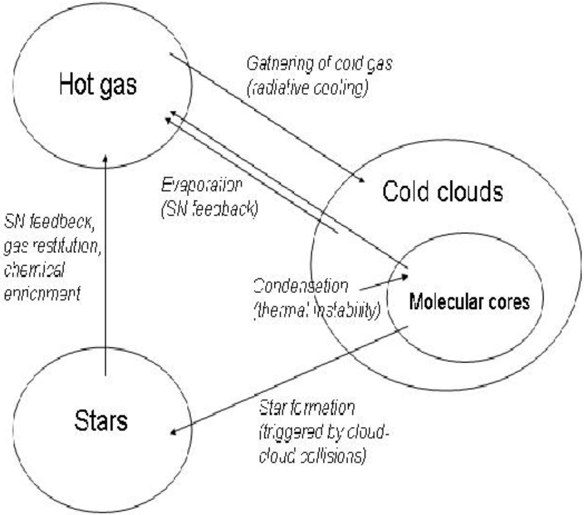
- this fraction was much larger at earlier epochs. As time went by, more and more gas was converted into stars.
- Volume of the ISM is enormous - $>$99.9999% of the Universe is ISM or IGM
- Consequently, its average density is extremely low.

ISM interactions make the ISM very dynamic



Energy content of the ISM

- thermal energy $u = (3/2)nkT$
- bulk kinetic energy $(1/2)\rho v^2$
- cosmic ray energy
- magnetic energy $B^2/8\pi$
- electromagnetic energy

Energy flow in the ISM

The ISM is never in thermodynamic equilibrium. It is continuously being injected with “free energy” mostly in the form of UV photons from stars and high velocity ejecta from supernovae.

Stars $\Rightarrow$ ISM $\Rightarrow$ Extragalactic cold sky