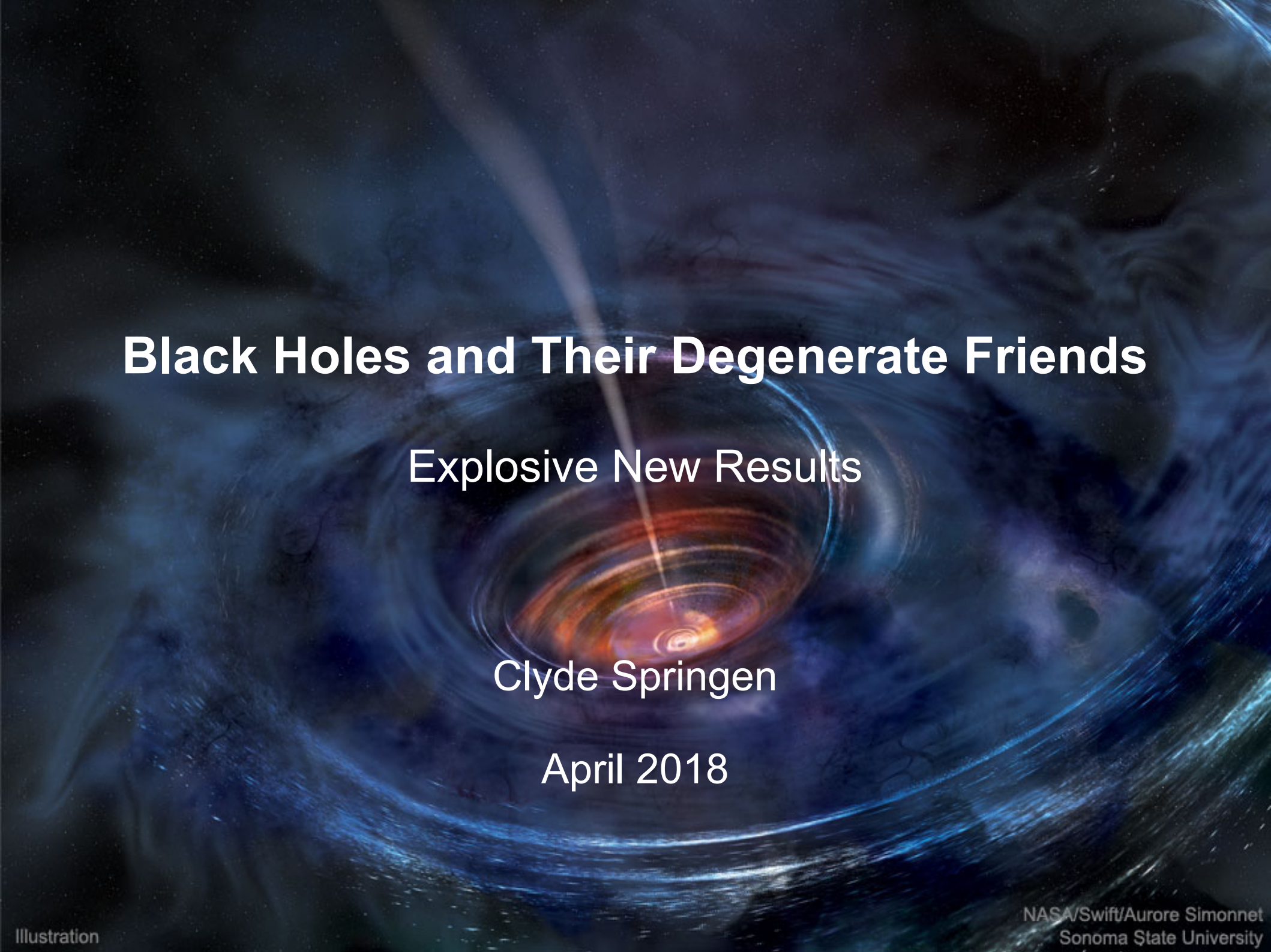


Black Holes and Their Degenerate Friends

Explosive New Results

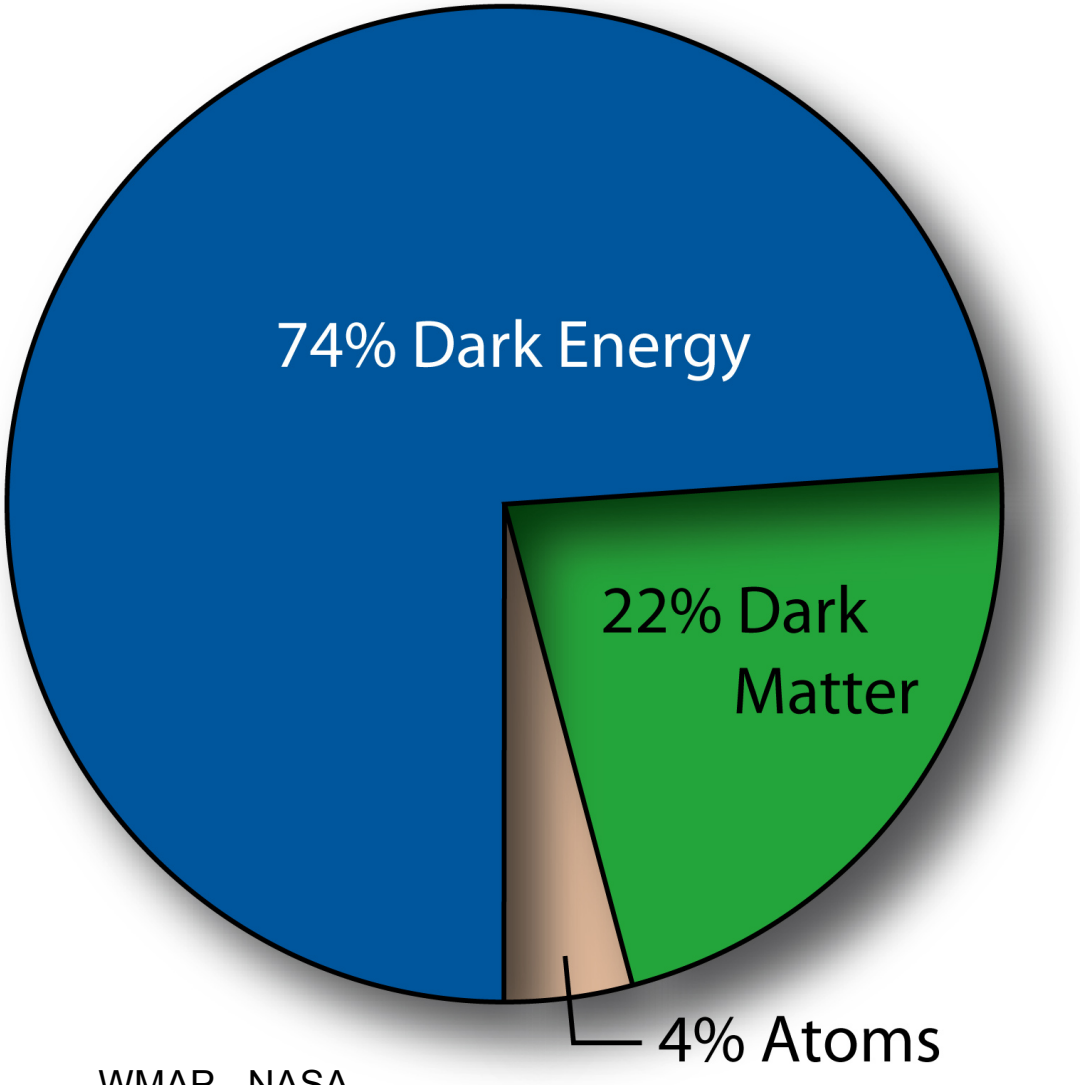
Clyde Springen

April 2018

Extent of Our Astronomical Knowledge

Everything counts – Energy and matter (ie w/mass)

- Accelerating extent of Universe implies Dark Energy
- Dark matter has mass but doesn't react with ordinary matter
- Everything we really know about (4%)
  - Atoms: People, stars, planets, Black Holes...
  - Today's topic contained in this part



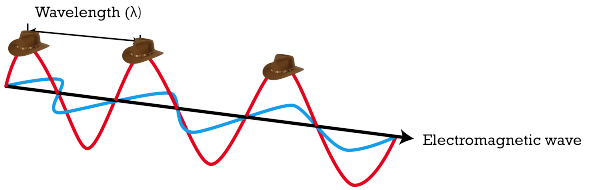
WMAP - NASA

Radiation

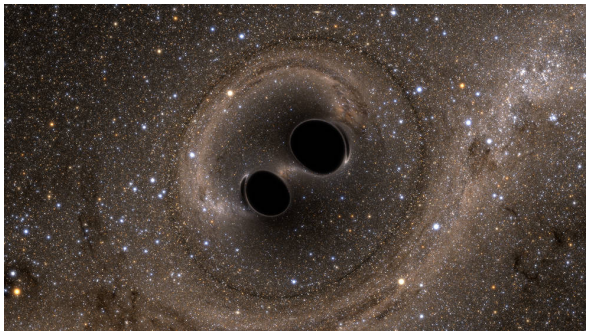
- **Radiation**: The transport of energy, information and sometimes mass from one place to another without direct physical contact

  - Moving particles
    - Have mass & kinetic energy
    - Sub-atomic particles (e.g. protons, electrons, neutrinos)
    - Examples: Solar wind, cosmic rays, radioactive emission

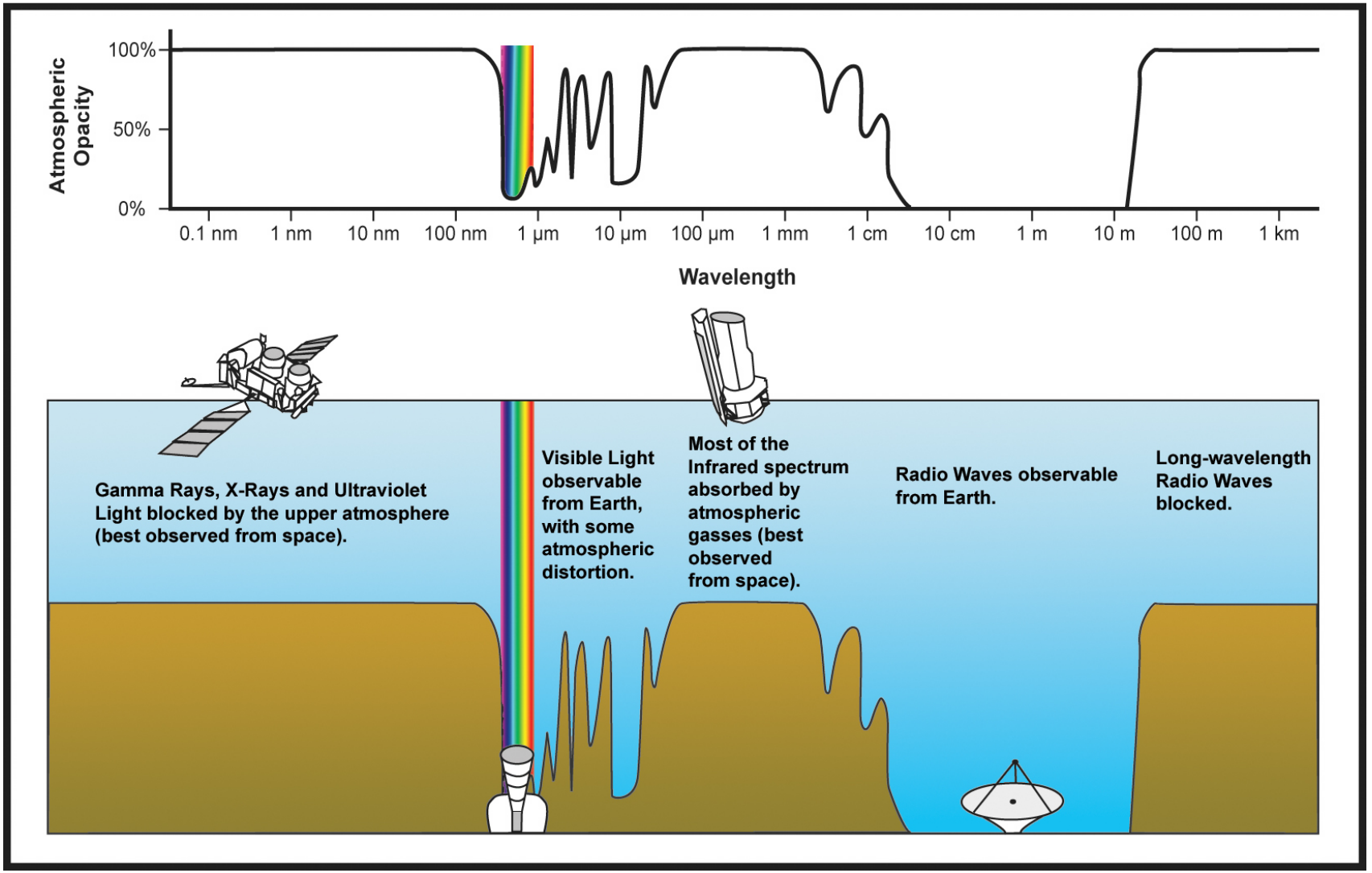
  - Propagating electromagnetic (EM) energy
    - Massless
    - Waves of alternating electric and magnetic fields
    - Examples: light, radio, gamma rays….



  - Gravitational waves (~~Theoretical~~)
    - ~~Not detected yet (Experiments in progress)~~
      - **LIGO Detected! (14 Sept 2015)**
    - Variation in the strength of the gravitational field
    - Examples: black-hole merger



Earth's Atmospheric Electro-magnetic Opacity



The Four Forces

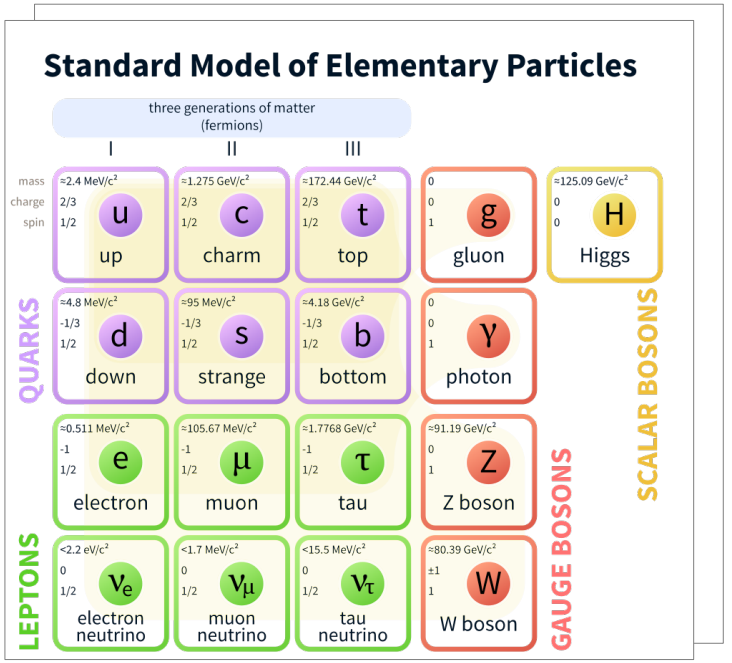
- **Strong Force** – binds elementary particles (e.g. quarks) into nuclear particles (e.g. protons) [$r \approx 10^{-15}$ m, rel-strength =1]
- **Electromagnetic Force** – Magnetic and Electric Fields exert force on electrically charged objects May repel (like) or attract (unlike) charges [$r=\infty$, rel-strength=10^{-2}]
- **Weak Force –** Involved in radioactive decay (fission) [$r=10^{-18}$ m, rel-strength$\approx 10^{-14}$]
- **Gravitational Force** – all objects with mass attract each other (Netwon), follow geodesics (Einstein) [$r=\infty$, rel-strength 10^{-38}]

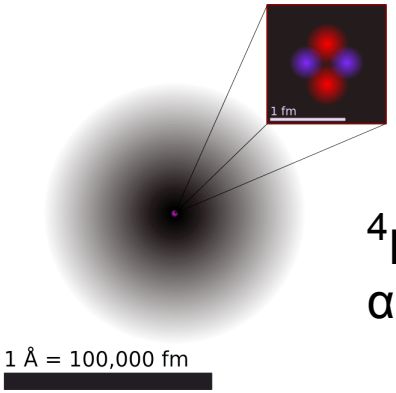
Today's Focus

Increasing Strength

Atoms, Sub-Atomic and Elementary Particles

- Fermions consist of quarks (heavy) and leptons (light). All have spin = 1/2)
- Protons & Neutrons are made from 3 Quarks each
- Electrons and neutrinos are Leptons
- Each elementary particle has a corresponding anti-particle
- Atoms are composed of protons, neutrons & electrons





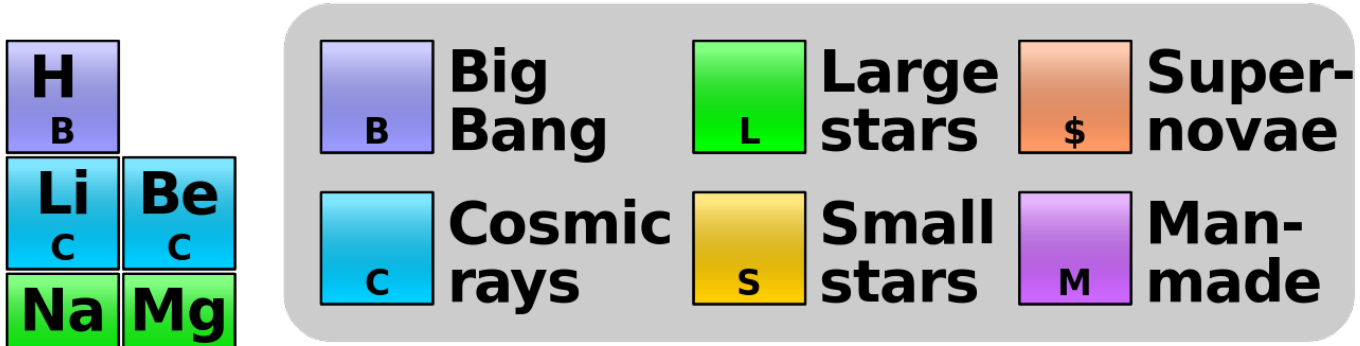
^{4}He Atom
α + 2e

Credit: Creative Commons

Source of Chemical Elements

AAS

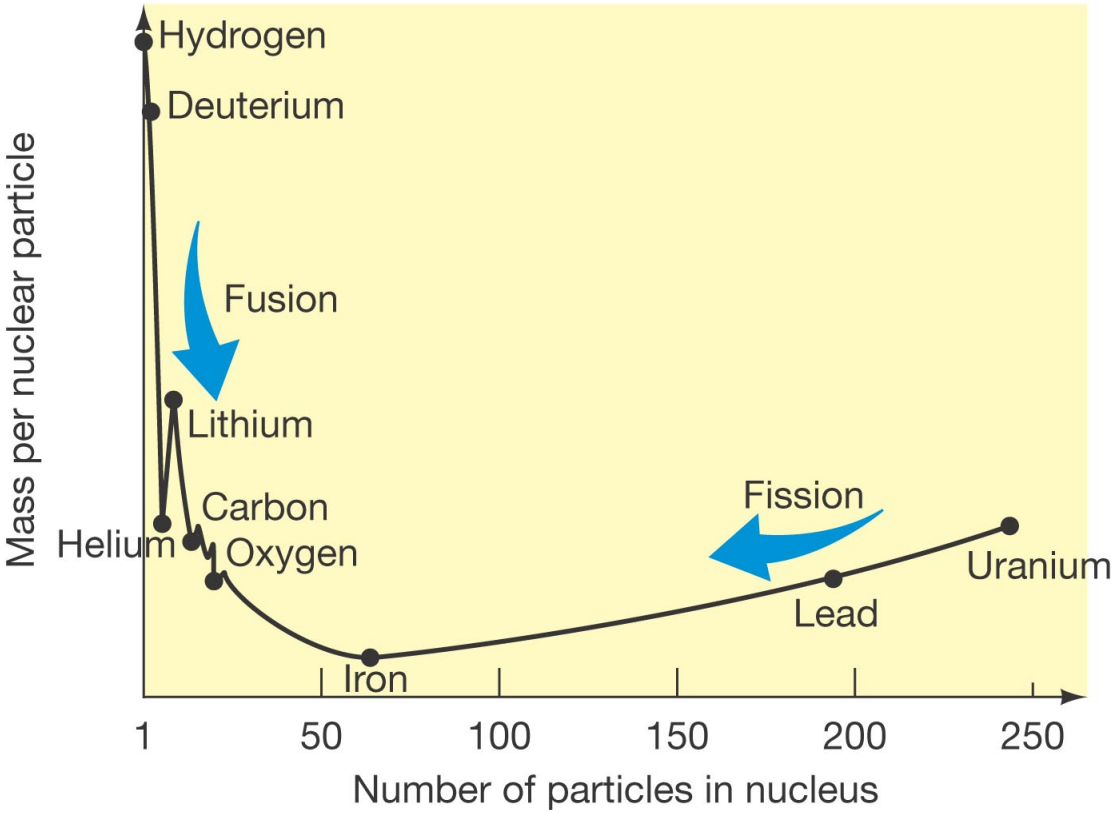
Orange r-process
SN & NS mergers



H B																	He B
Li C	Be C											B C	C S L	N S L	O S L	F L	Ne S L
Na L	Mg L											Al $ L	Si $ L	P L	S S L	Cl L	Ar L
K L	Ca L	Sc L	Ti $ L	V $ L	Cr L	Mn L	Fe $ L	Co $	Ni $	Cu L	Zn L	Ga $	Ge $	As L	Se $	Br $	Kr $
Rb $	Sr L	Y L	Zr L	Nb L	Mo $ L	Tc L	Ru $ L	Rh $	Pd $ L	Ag $ L	Cd $ L	In $ L	Sn $ L	Sb $	Te $	I $	Xe $
Cs $	Ba L		Hf $ L	Ta $ L	W $ L	Re $	Os $	Ir $	Pt $	Au $	Hg $ L	Tl $ L	Pb $	Bi $	Po $	At $	Rn $
Fr $	Ra $																
			La L	Ce L	Pr $ L	Nd $ L	Pm $ L	Sm $ L	Eu $	Gd $	Tb $	Dy $	Ho $	Er $	Tm $	Yb $ L	Lu $
			Ac $	Th $	Pa $	U $	Np $	Pu $	Am M	Cm M	Bk M	Cf M	Es M	Fm M	Md M	No M	Lr M

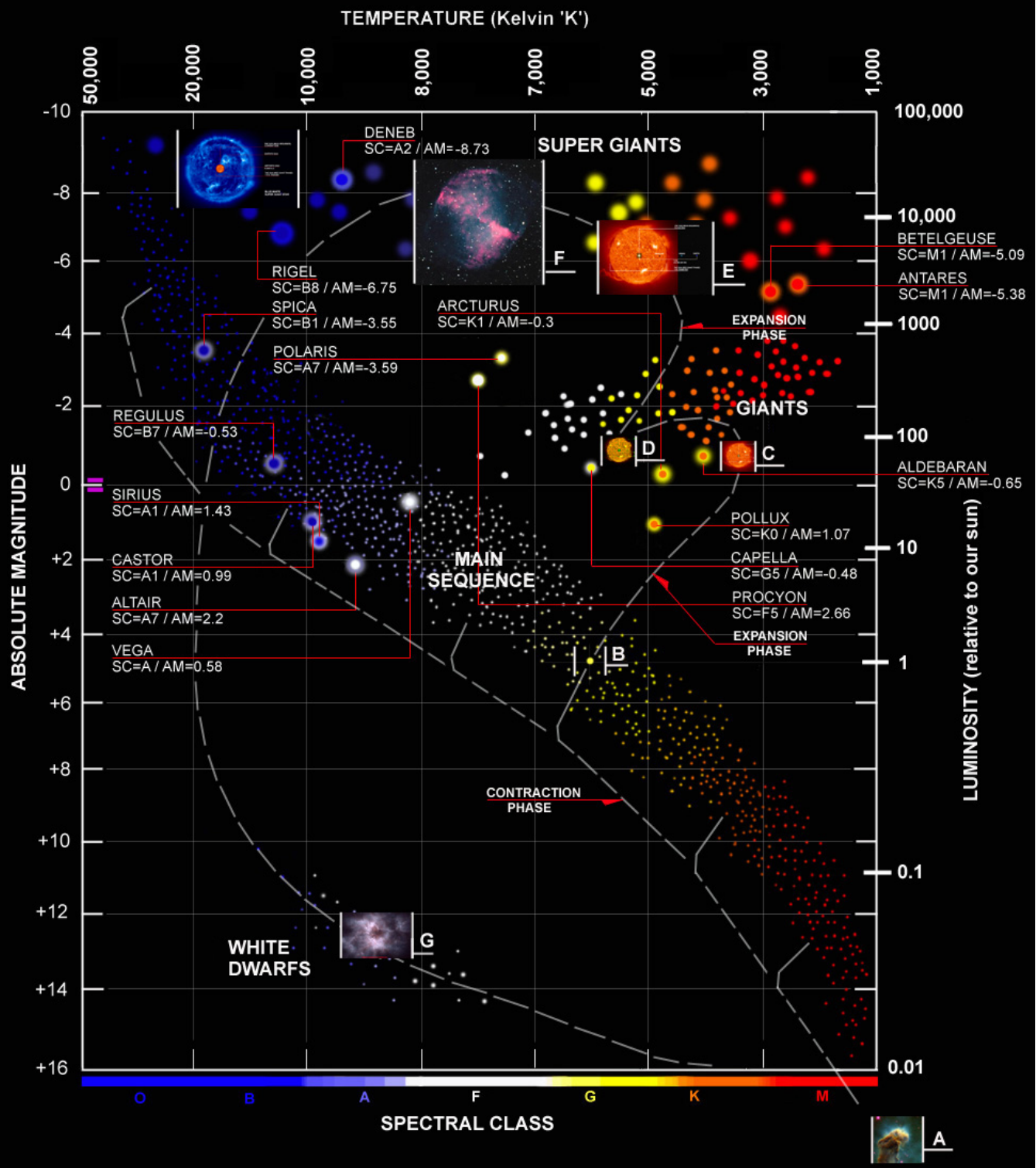
Stellar Nuclear Energy

- Losing mass in nuclear reactions becomes energy ($E=mc_0^2$)
- Fusion releases energy (heats) below Fe
- Fusion consumes energy (cools) above Fe

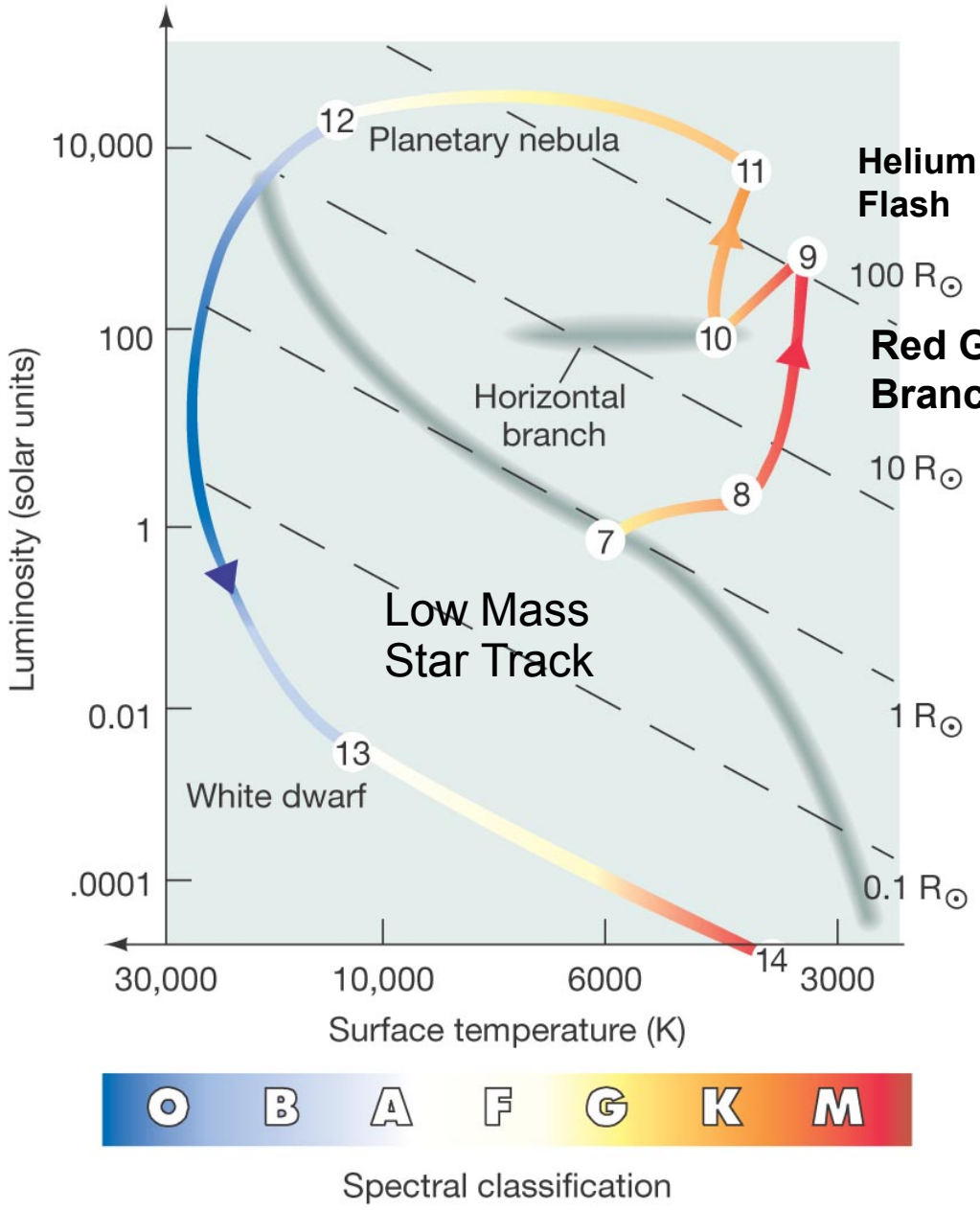


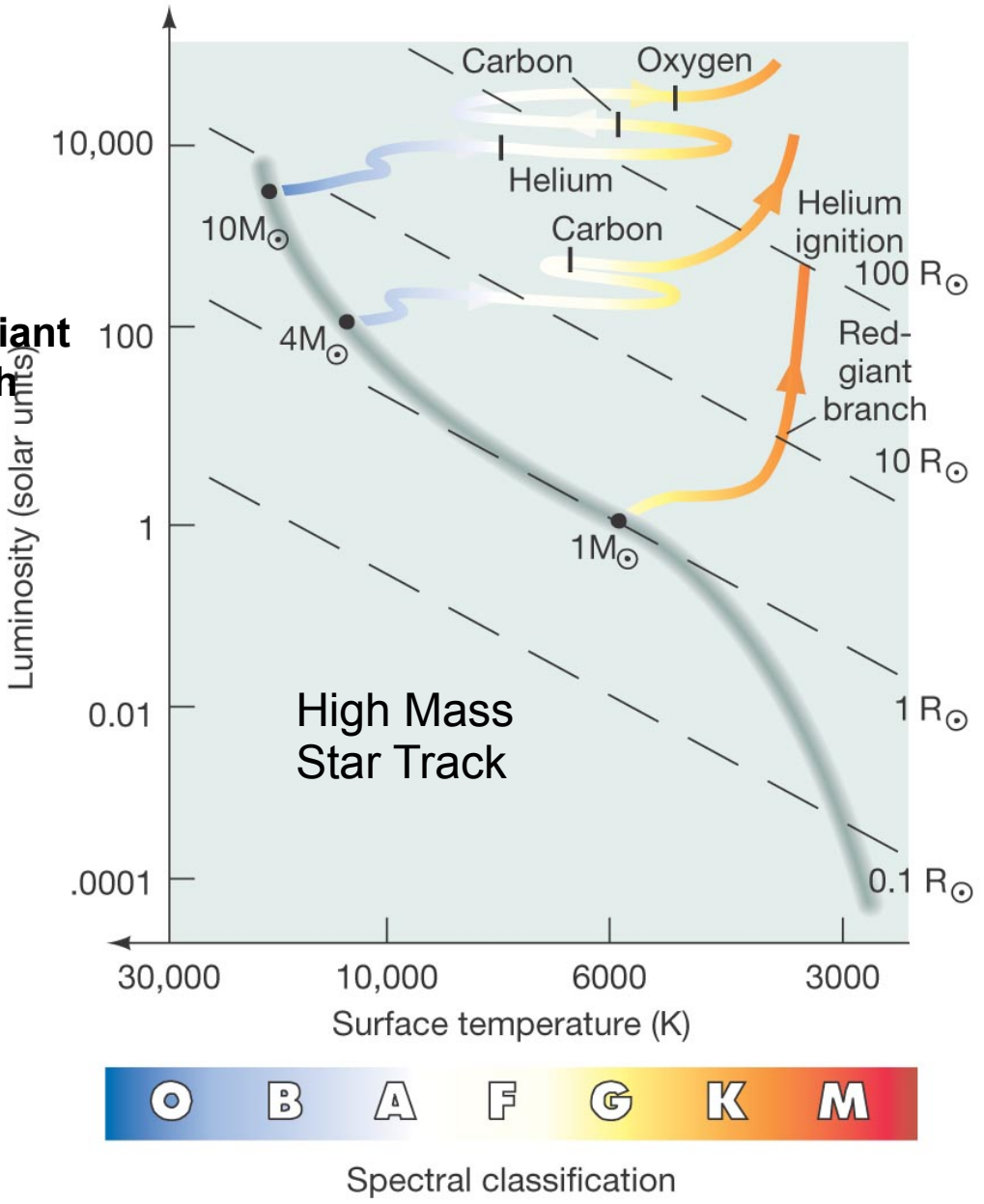
Hertzsprung-Russel (HR) Diagram

- Classification
- Evolution

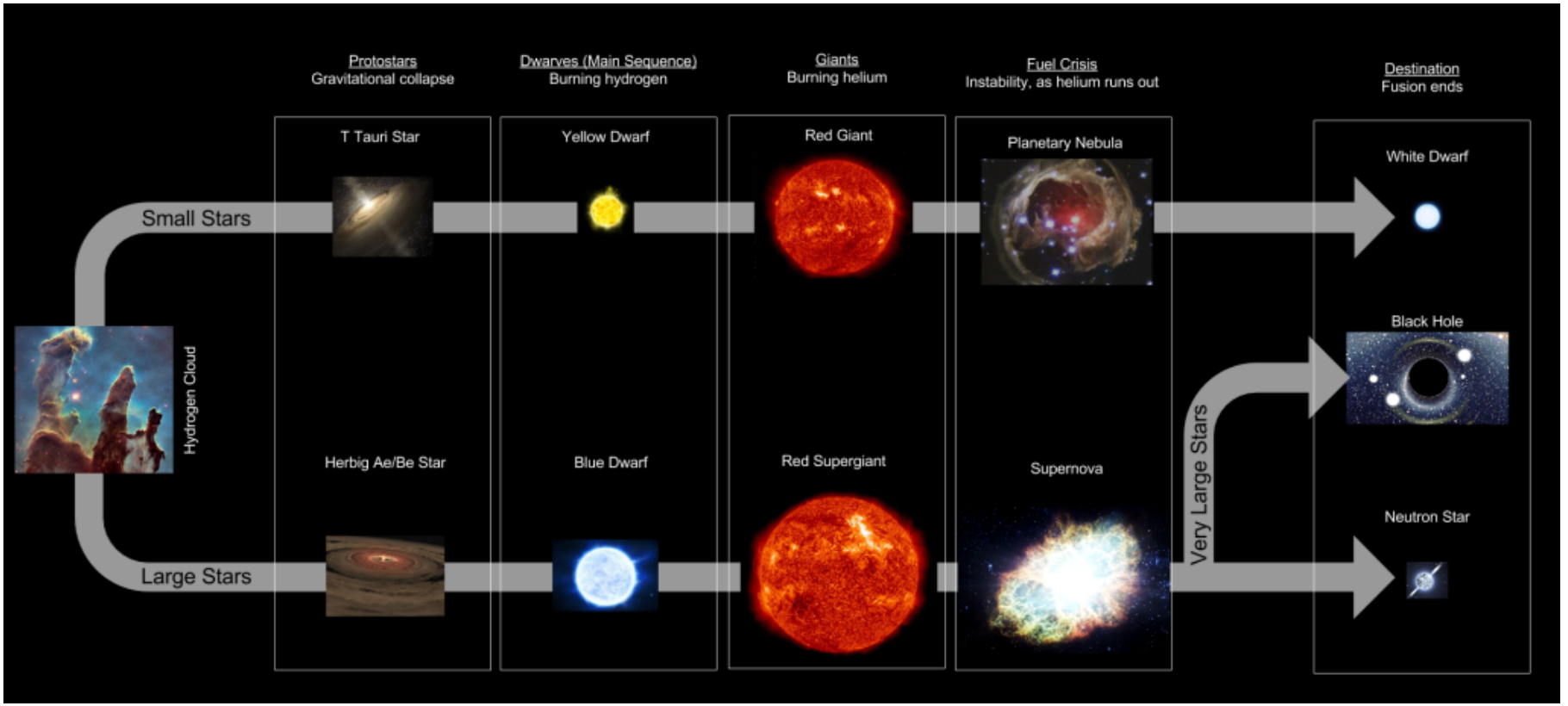


Low and High Mass Evolution





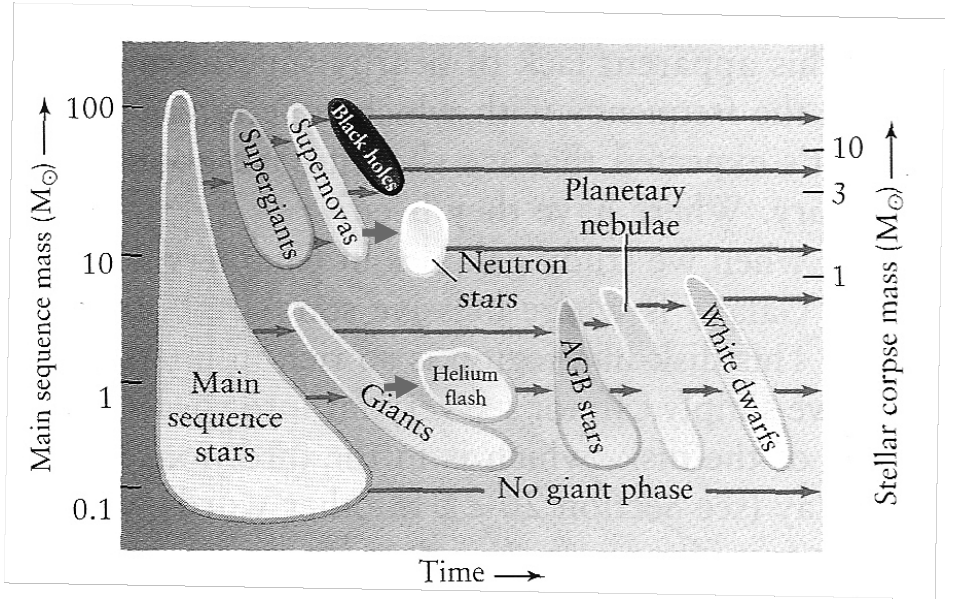
Stellar Outcomes – Three Options



Mass Determines the Final Outcome of Star's Core

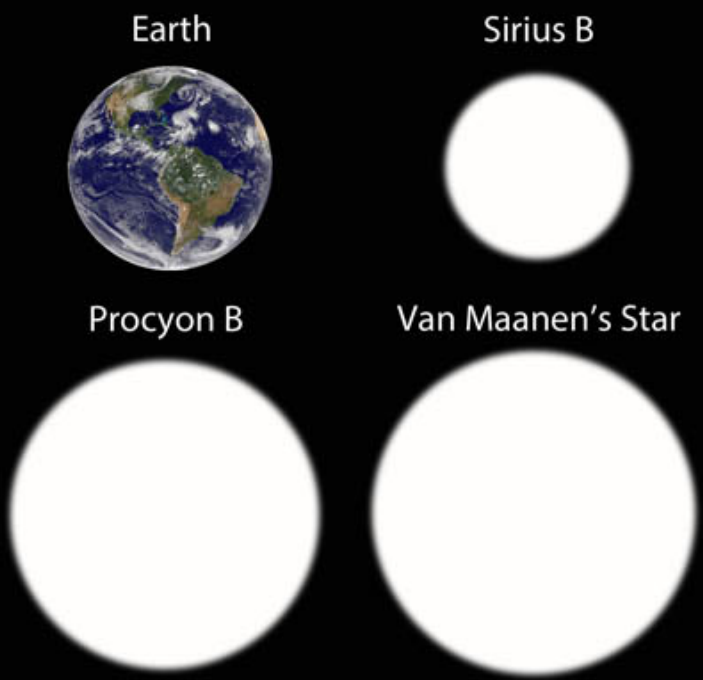
- Small stars (like the Sun) go out without a bang → **White Dwarf**.
  - *Electron degeneracy*
- Larger stars go supernova & collapse to **Neutron "Stars"**

  M_{core}>1.4 $M_{\odot}$ (Chandrasekhar Limit)
  - *Neutron degeneracy*
- High mass stars M_{MS}>25 $M_{\odot}$ go supernova & collapse to **Black Holes** M_{core} > 3 $M_{\odot}$
  - *Singularity*



White Dwarfs

- Small, Earth sized +/-
- Massive ~$M_{\odot}$
- Dense ~10^{9} kg/m^{3}
- Electron degenerate
- No fusion
- Initially hot (white) then cool to Black Dwarf & crystallizes



NGC 4526 inVirgo Cluster

Type Ia Supernova 1994D

Neutron Stars

Neutron stars:

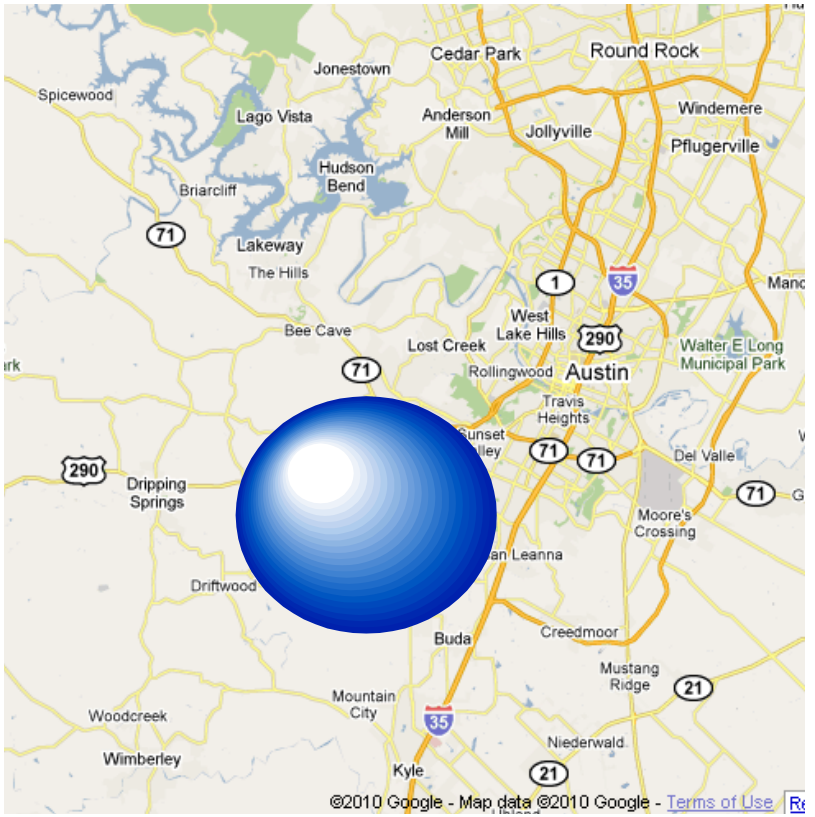
1.4–3 $M_{\odot}$, are so dense that they are very small

Density ≈ 3 x 10^{17} kg/m^3 – as dense as atomic nuclei

Neutron degenerate – holds up NS against gravity

This image shows a 1-solar-mass neutron star, about 10 km in radius, compared to City of Austin

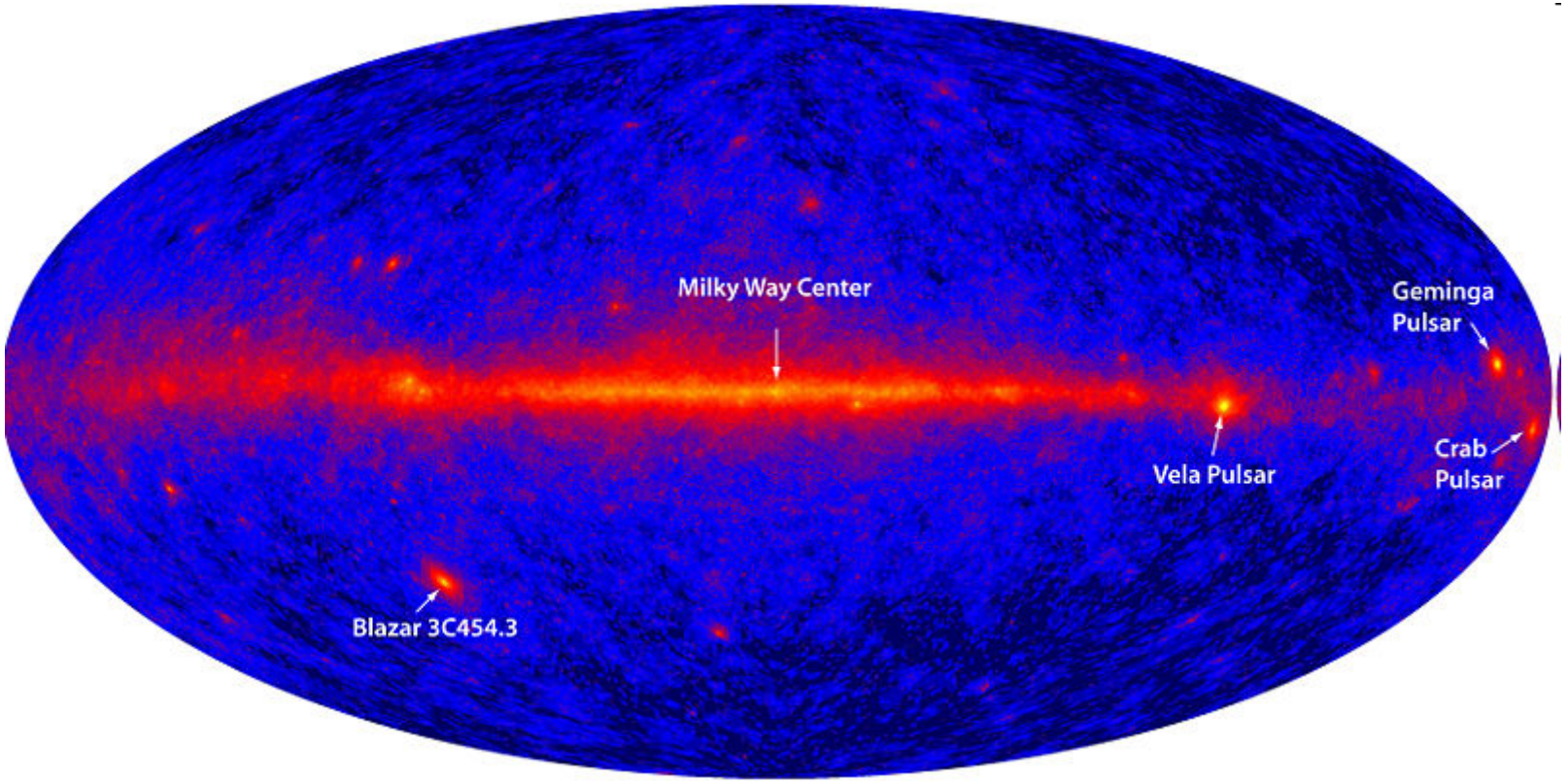
The Sun has about 330,000 x M_{Earth}



LGM-1 - 1967

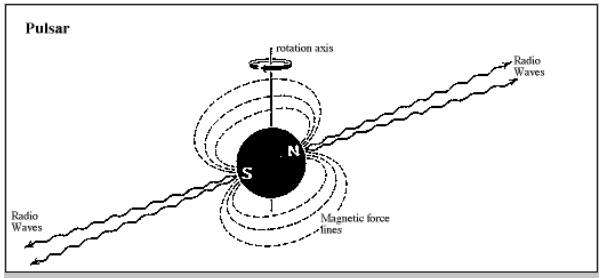
- **1st pulsar (rotating neutron star that radiates at radio frequencies)**
- **Discovered by Dame Jocelyn Bell Burnell** - a Postgraduate student at Cambridge at the time
  - (Her thesis advisor Anthony Hewish and others got the Nobel Prize)

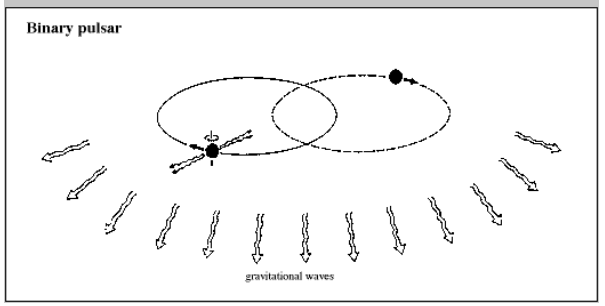
Bright Pulsars in Milky Way



Indirect Evidence of Gravitational Waves

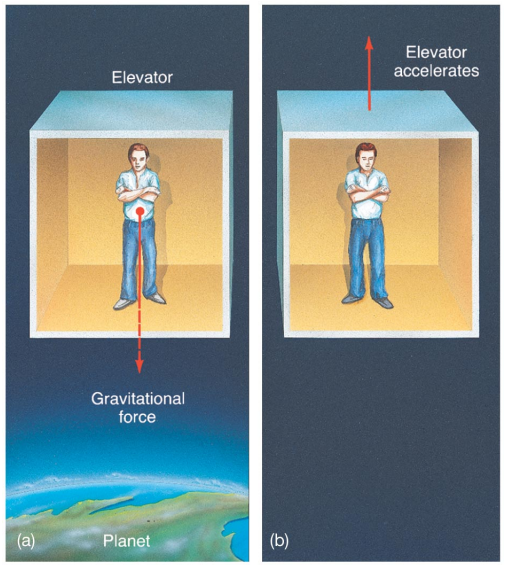
Joe Taylor & Russel Hulse
Nobel Prize in 1993



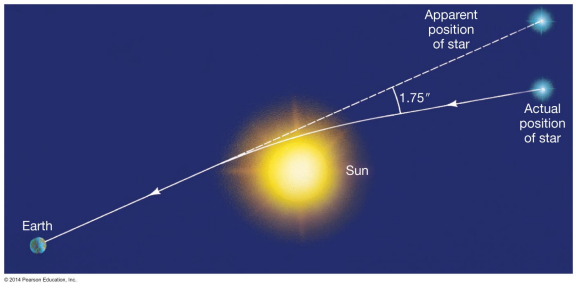


Orbital decay of a binary pulsar consistent with prediction by General Relativity theory

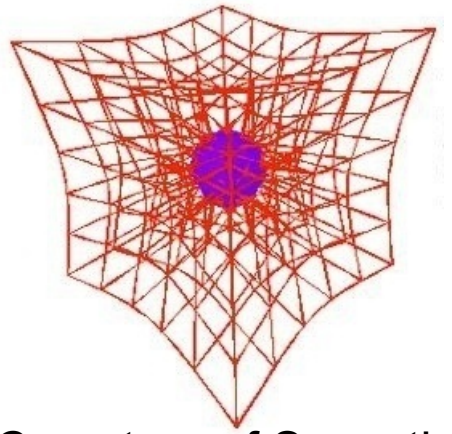
Relativity Principles & Effects



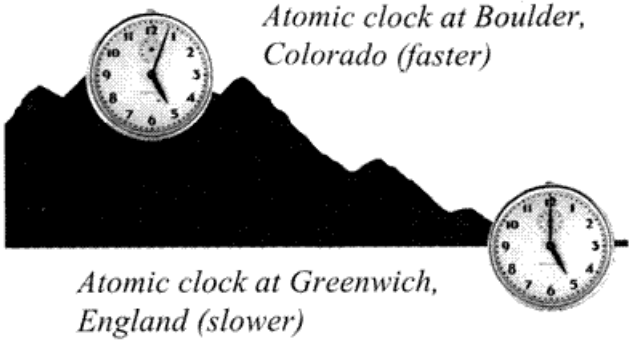
Gravity & Acceleration Equivalence



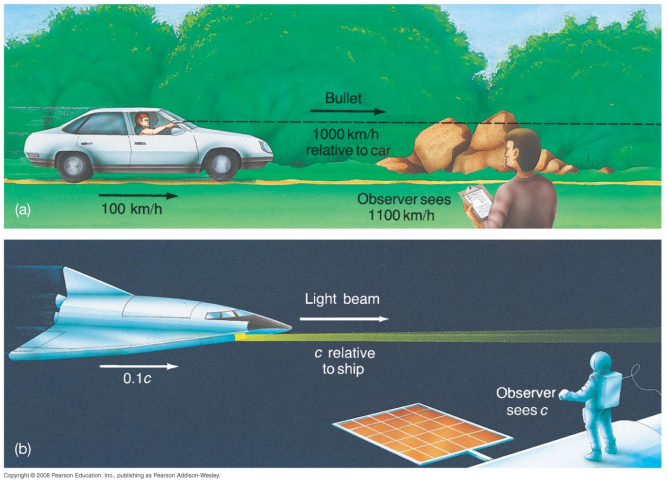
Spacetime Refraction



Curvature of Spacetime



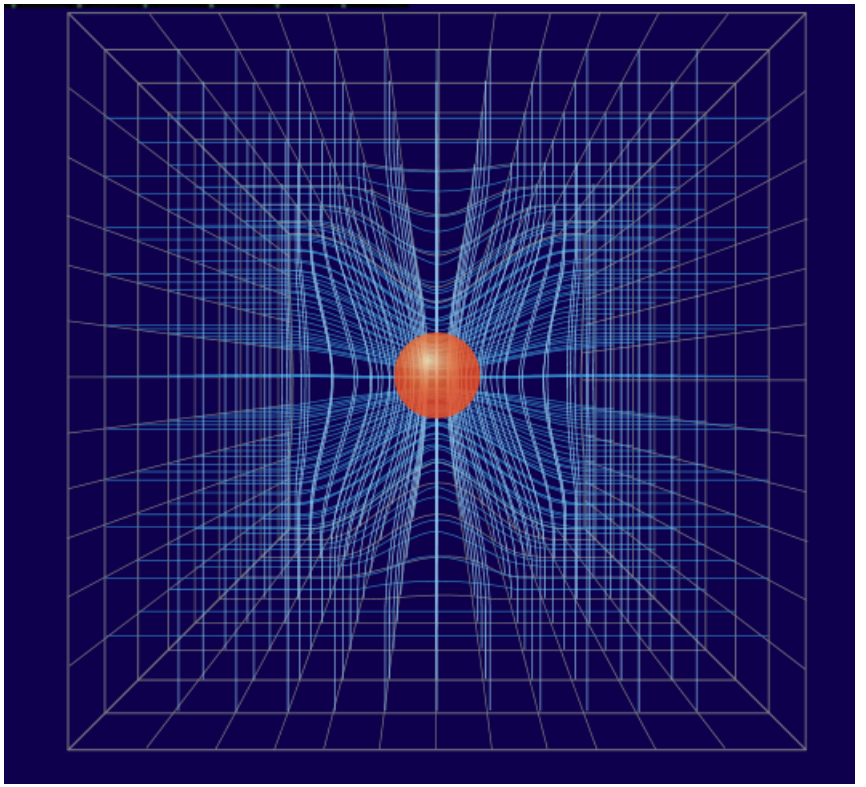
Gravitational Time Dilation: *The rate at which an atomic clock records time is diminished as gravity increases.*



Light-speed Constant in all Inertial frames

Spacetime Curvature

- Mass and energy increase curvature of spacetime
- Mass tells space how to curve
- Curved space tells mass how to move

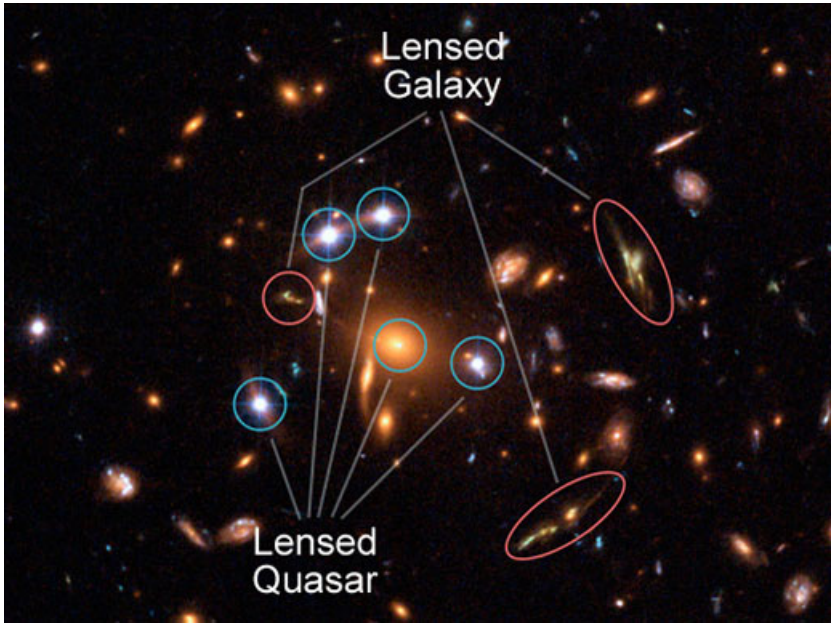


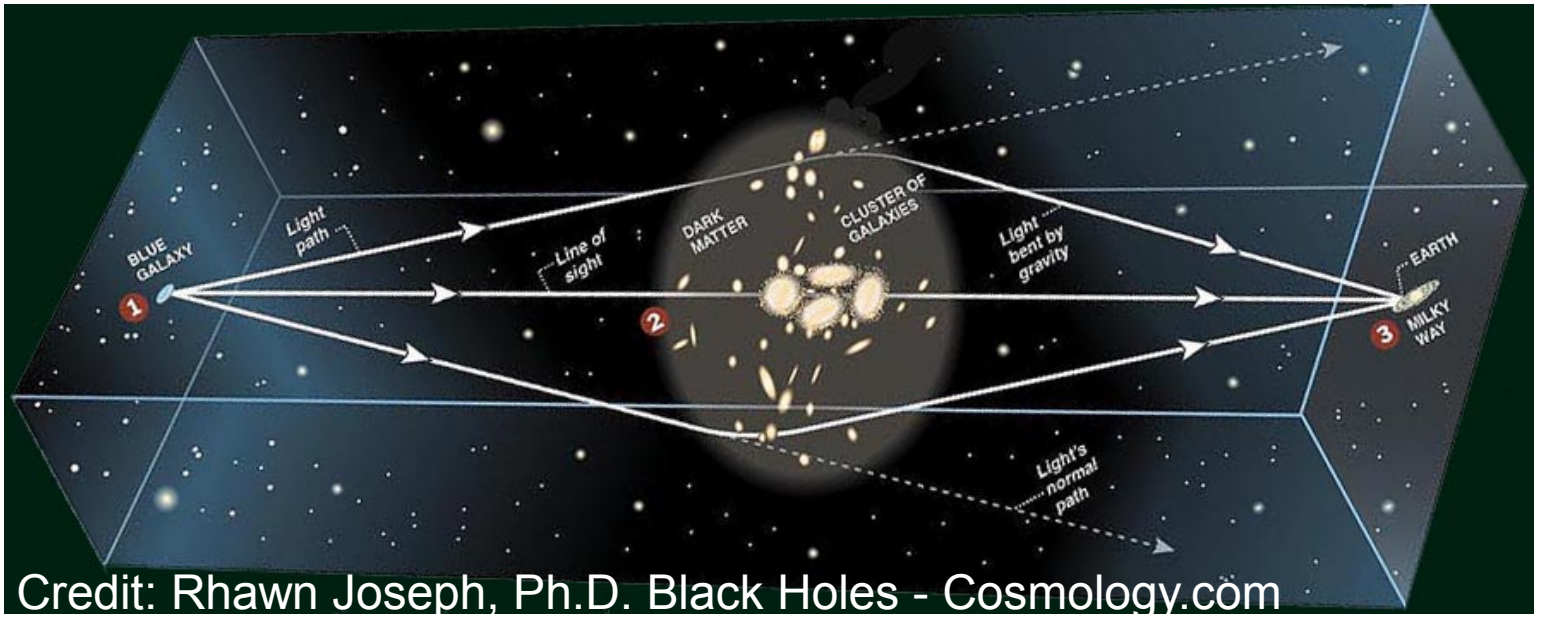
Relativity

- Validation
  - Gravitational refraction - (A. Eddington 1919)
  - Frame dragging - Gravity Probe B
  - Gravitational time dilation (Pound–Rebka 1959) (Hafele–Keating 1971)
  - Gravitational red-shift (Popper 1954)

Galactic Lensing

- Gravitation of large structures is used to observe objects that are too far away to see otherwise



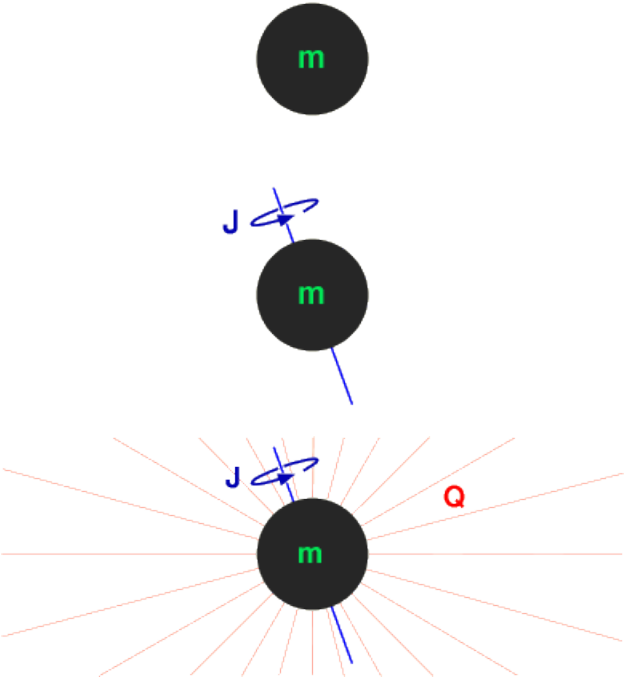


Credit: Rhawn Joseph, Ph.D. Black Holes - Cosmology.com

Bald Black Hole Types

"No-Hair Theorem"

- Completly characterized by 3 parameters: energy, angular momentum & electric charge
  - Swartzchild BH
    - Vacuum
  - Kerr BH
    - Rotating
  - Kerr-Newman BH
    - Rotating & charged



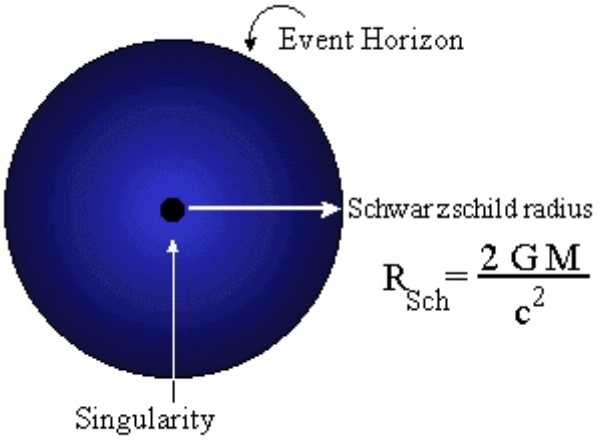
The Ultimate Escape Velocity
The Schwartzchild Radius

- We learned in Ch. 2 that the escape velocity of any mass is:

$$v = \sqrt{(2GM/r)}$$

$$r = 2GM/v^2$$

(notice that the radius is directly proportional to mass)



Simple Schematic of a Vacuum Black Hole

- Substituting the mass of the Sun and speed of light

$$r = \sqrt{((2(6.67\text{x}10^{-11}\,N\,m^2/kg^2)(2\text{x}10^{30}\,kg))/(3\text{x}10^{8}\,m/s)^2)}$$

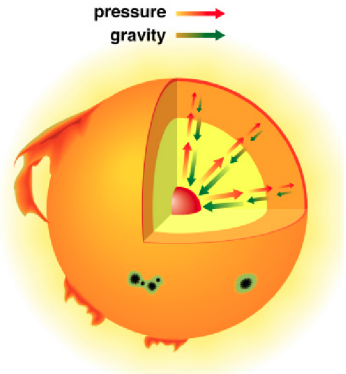
$$r = 2964\,m$$

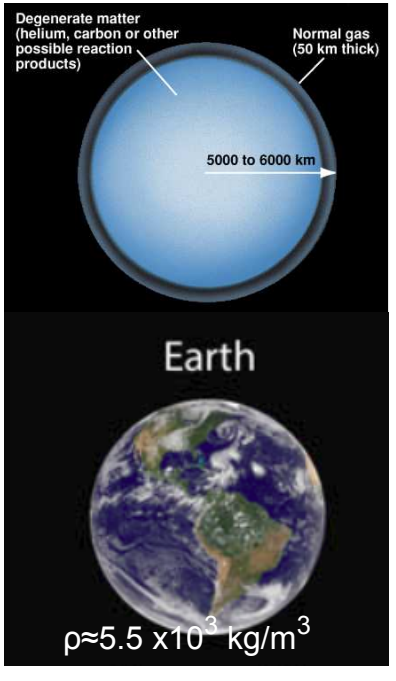
$$r = 3\,km$$

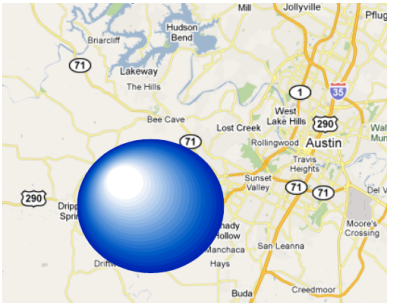
- The Event Horizon is just a mathematical boundary where nothing (even light) can escape

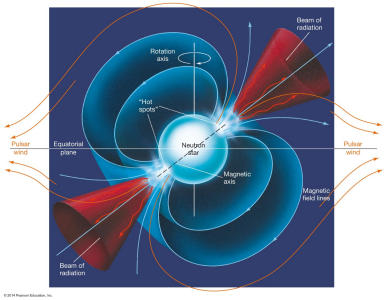
Equilibrium - the Balance of Forces

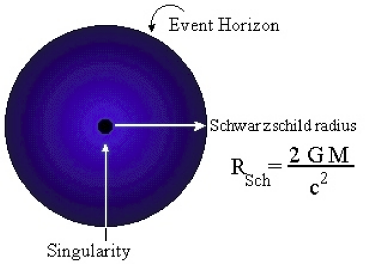
Ideal Gas Law	Pauli Exclusion Principle		TBD Physics
Hydrostatic Equilibrium	Electron Degeneracy	Neutron Degeneracy	Singularity Quark degeneracy?
Main sequence & giant stars	White Dwarfs	Neutron Stars	Black Holes
R= M≈0.1-200 $M_\odot$ $\rho \approx 10^3$ kg/m^3	R≈6x10^3 km M≈1 $M_\odot$ $\rho = 10^9$ kg/m^3	R≈10 km 1.4<M<3 $M_\odot$ $\rho = 10^{17}$ kg/m^3	R_s=3*M km 3<M<10^9 $M_\odot$ $\rho = \infty$





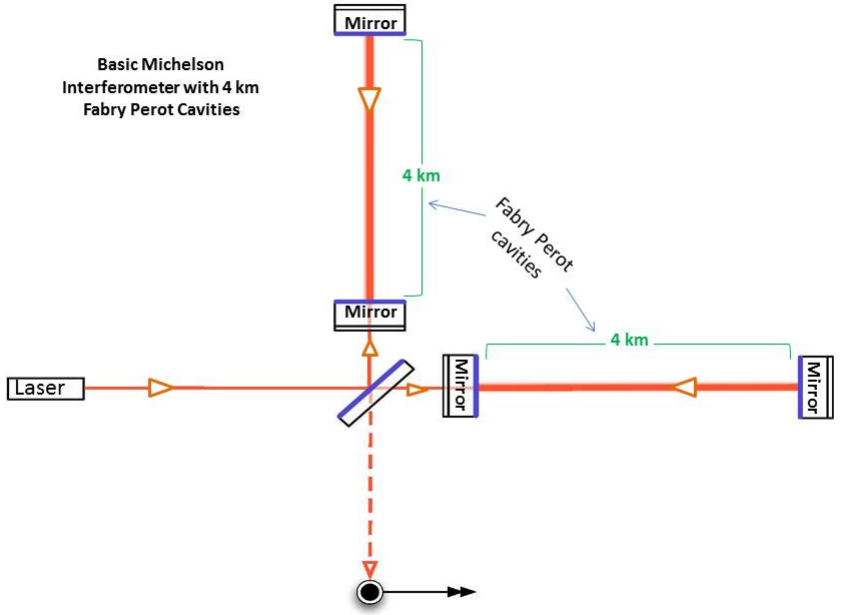






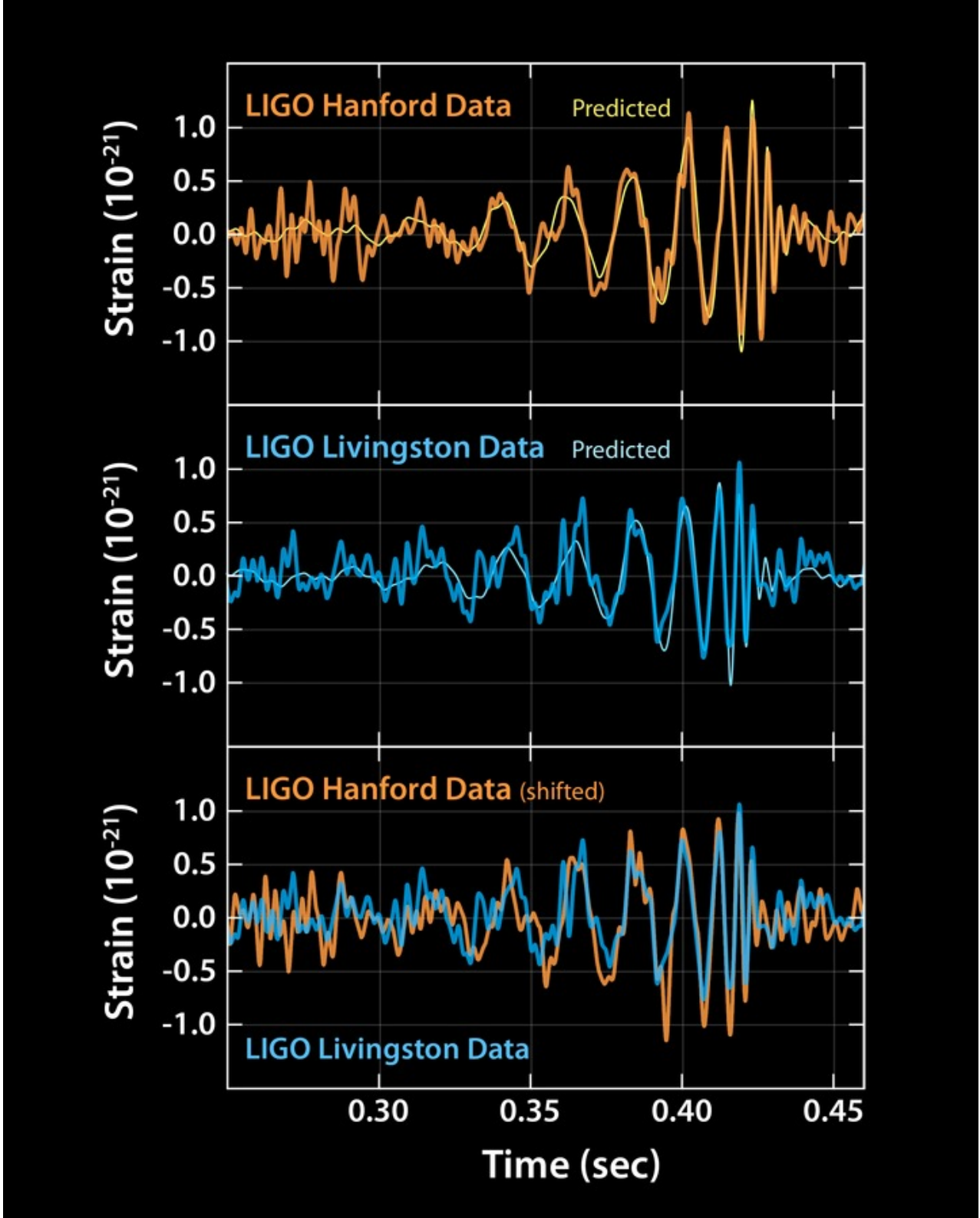
LIGO

- Laser Interferometer Gravitational-Wave Observatory
- Michelson Interferometer
- Arms 4 km long (x280)
- Livingston LA & Hanford WA
  - two observatories w/3002 km separation allows differential measurement
- Null output port
- Ultra high vacuum tunnels
- Cryogenic instruments
- Extreme vibration & noise suppression

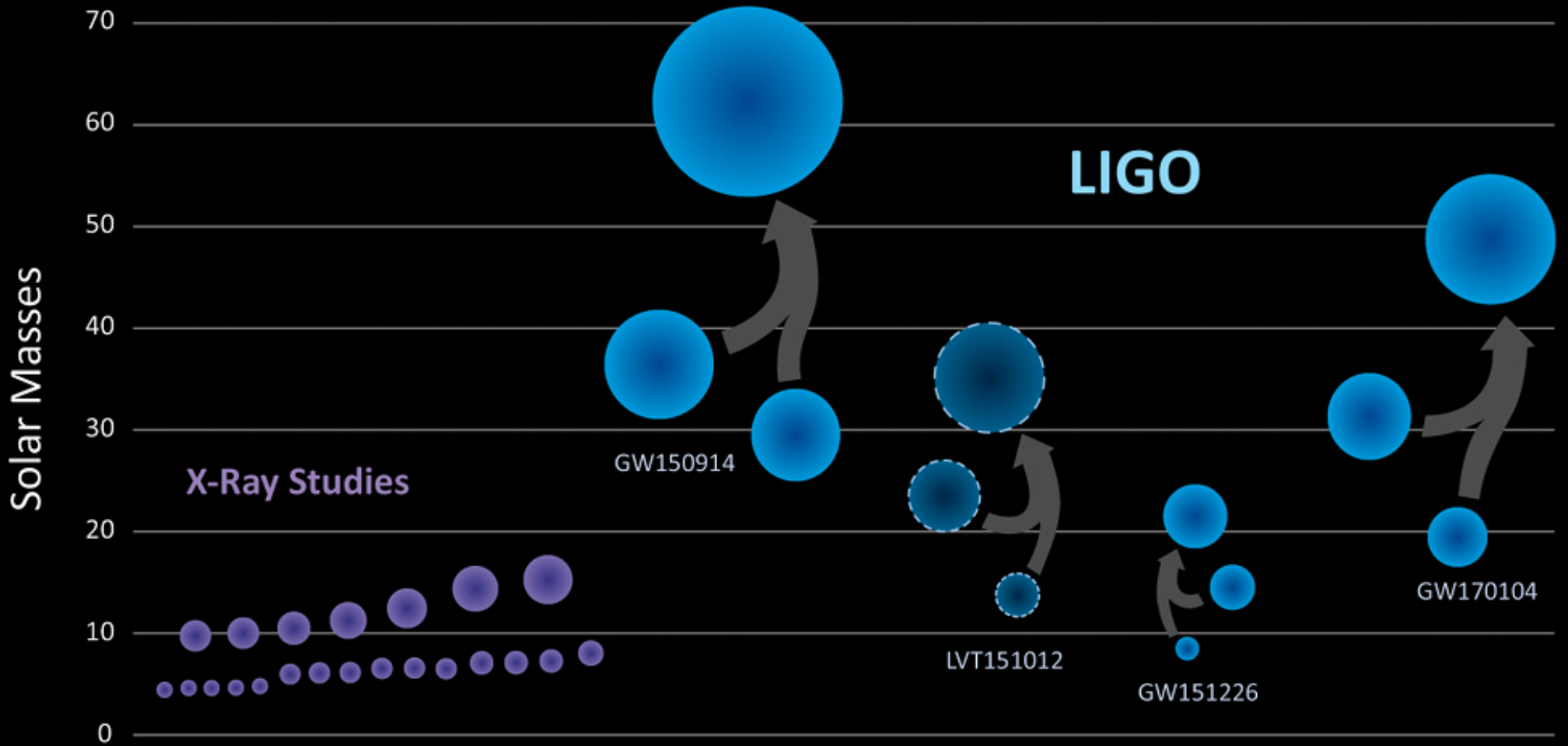


Event Data

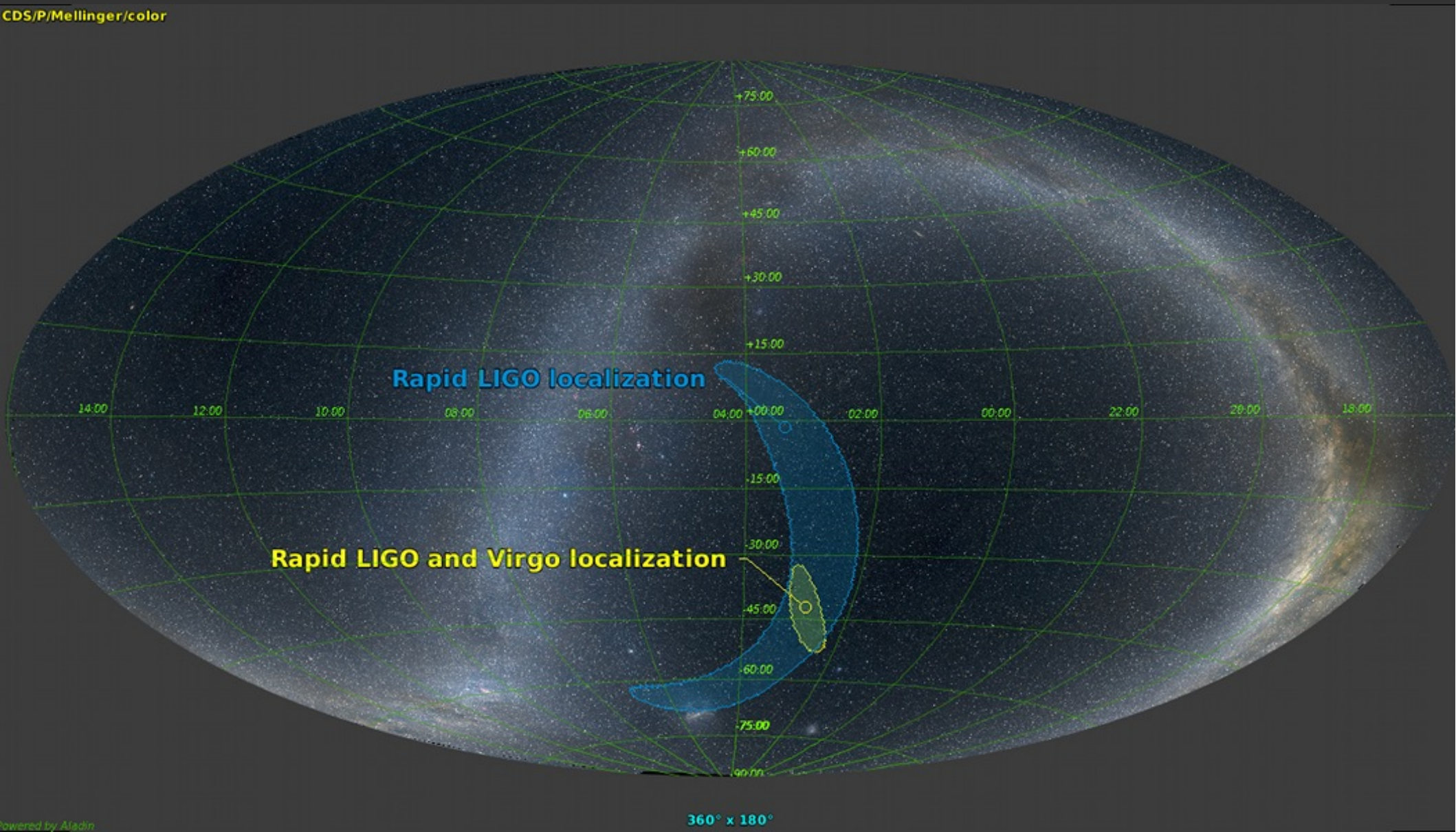
- Both sites saw same event
- Event matched templates from simulations
- Delay allows determination of the region of sky where event occurred



Black Holes of Known Mass

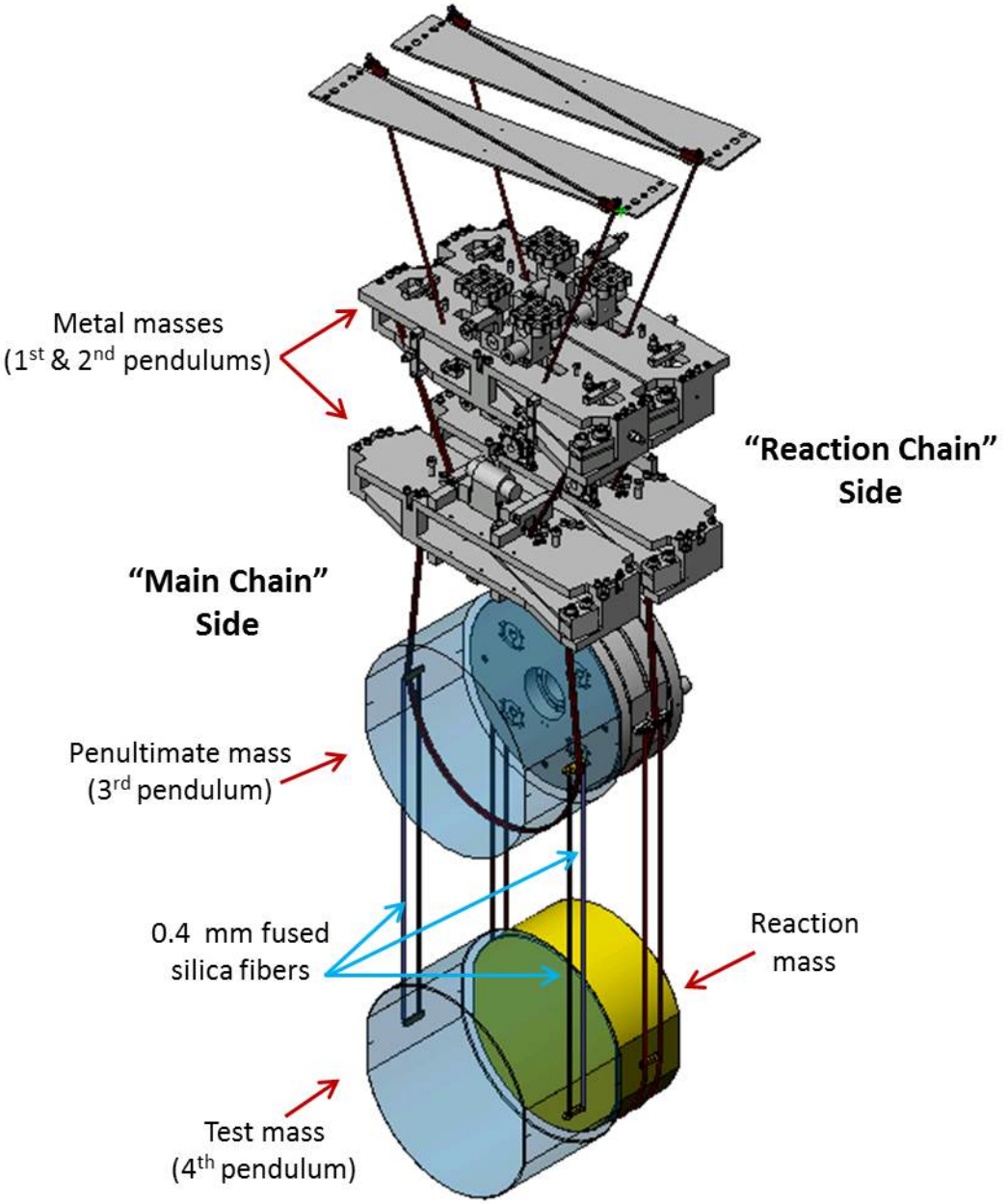


Three Observatory Localization of Event GW 170814



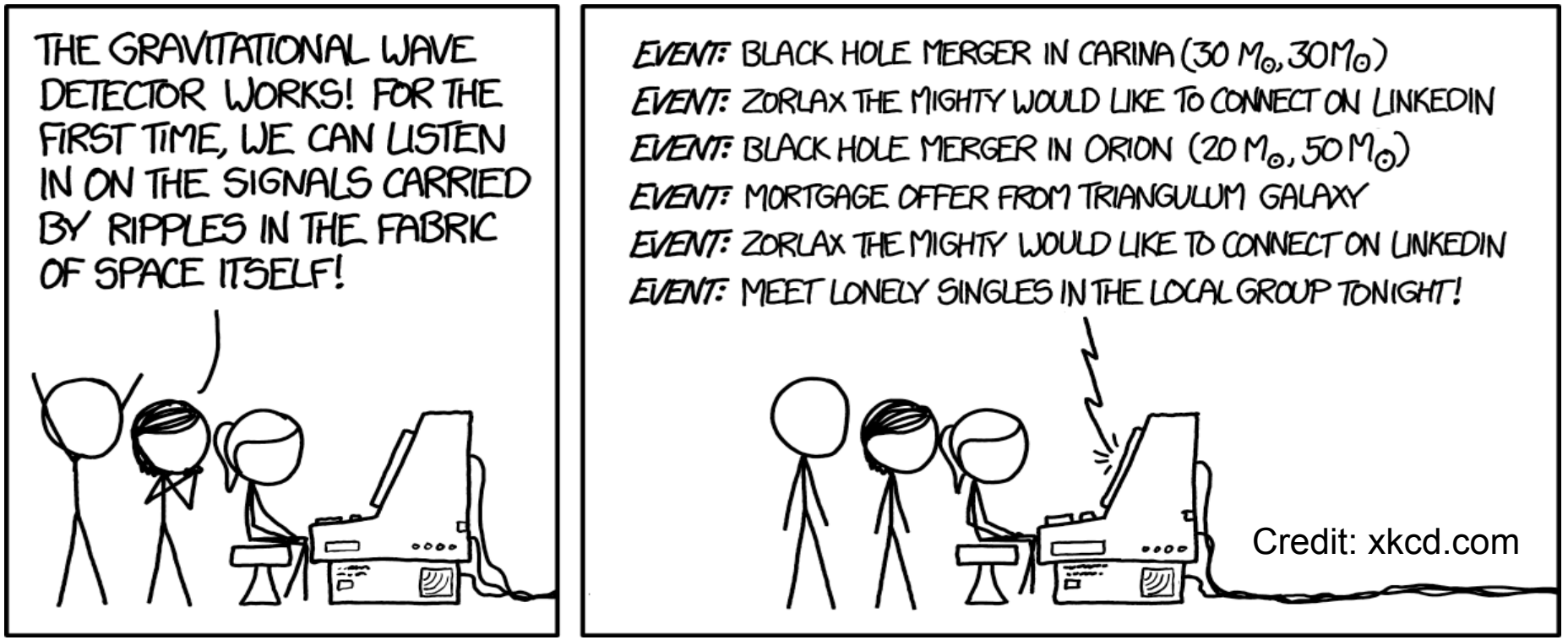
LIGO Technology

- Four stage mirror assembly (test mass)
- Active seismic noise cancellation
- Passive (inertial) quieting w/40 kg mirror



LIGO Simulation of Events

- Detection of merger event
  LIGO Merger Sim




The End