An introduction to

Stellar Remnants

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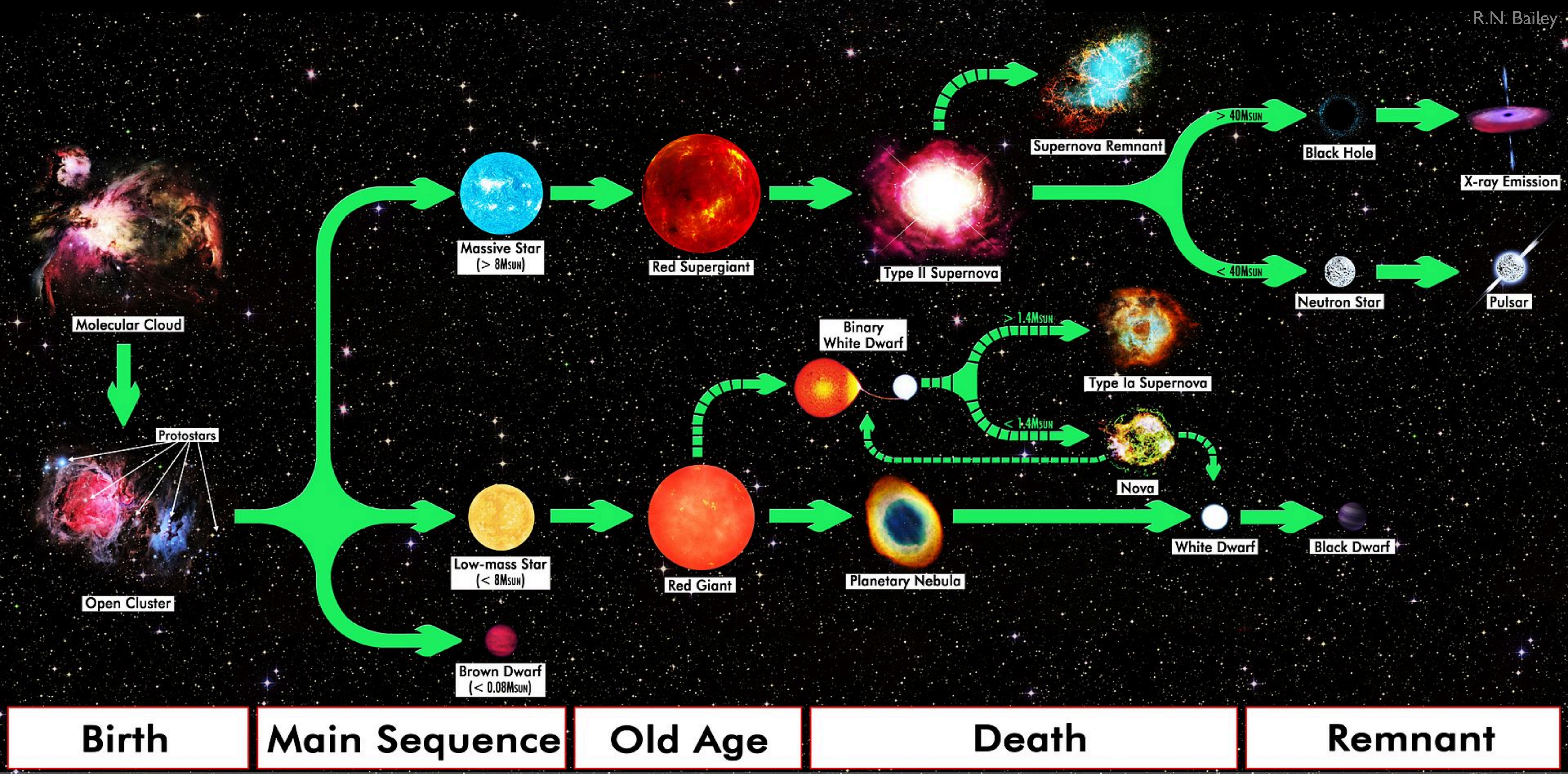
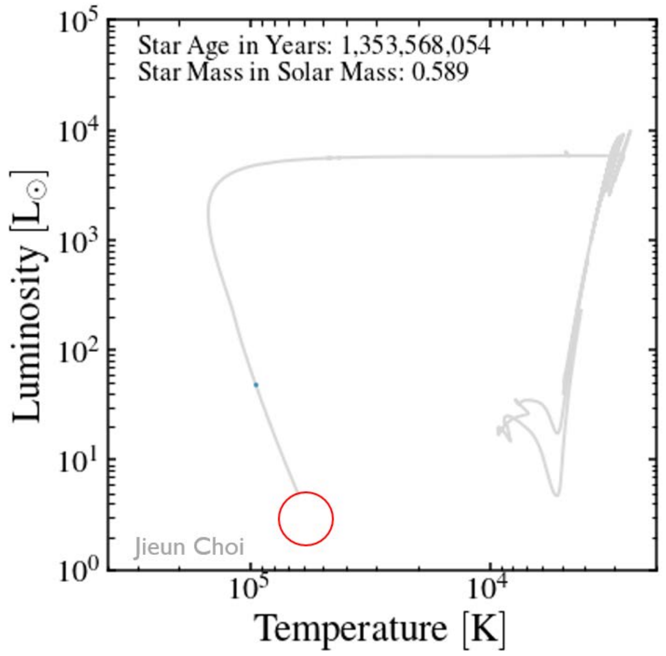
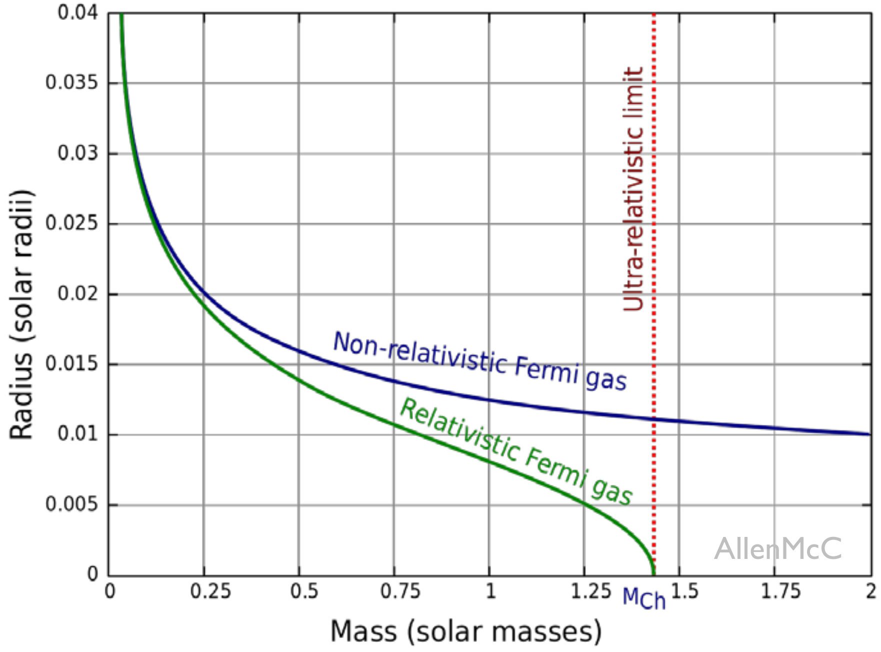
Stellar Evolution Flow Chart *(can be complicated by binary evolution!)*



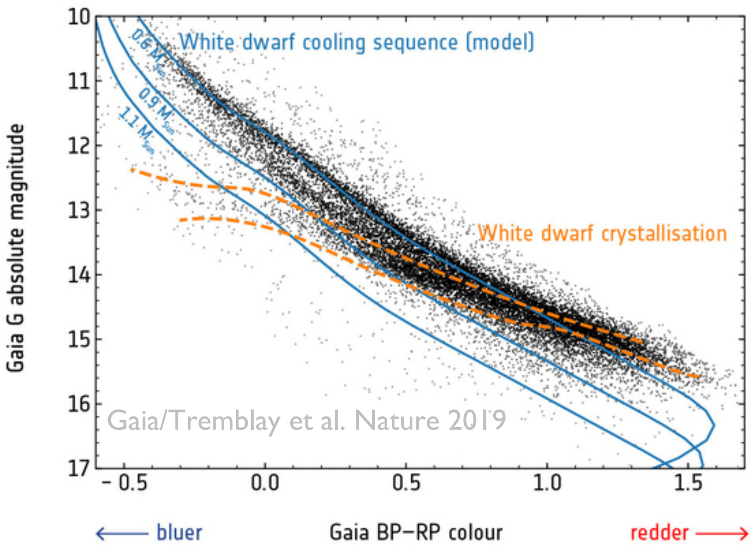
White Dwarf: *the low-mass stellar remnant*



- An earth-sized object (R~6x10^6 m) around the mass of the sun
- Matter is "degenerate"
  - the pressure generated from packing electrons so close is what repels gravity (see Introduction to Stellar Equilibrium)
- Degeneracy leads to an interesting mass-radius relationship: adding mass would shrink the star!

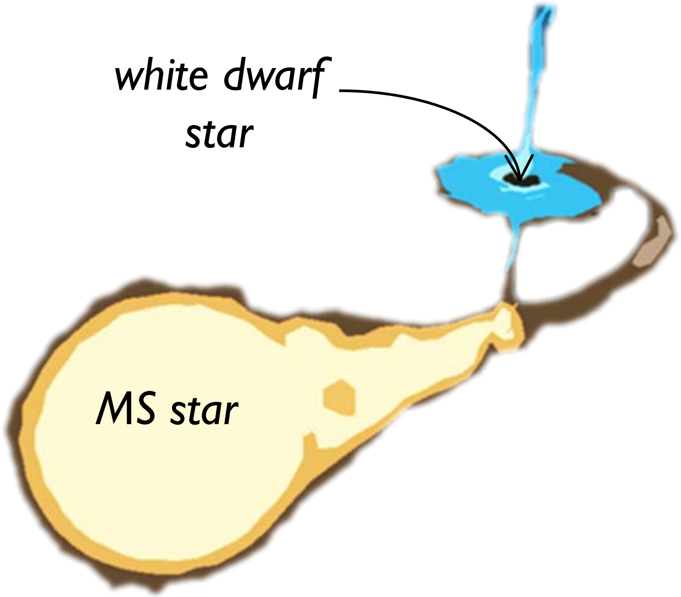


- Over time, the white dwarf continues to cool, becoming dimmer & redder on the HR-diagram
- Cooling is delayed at the point of crystallization

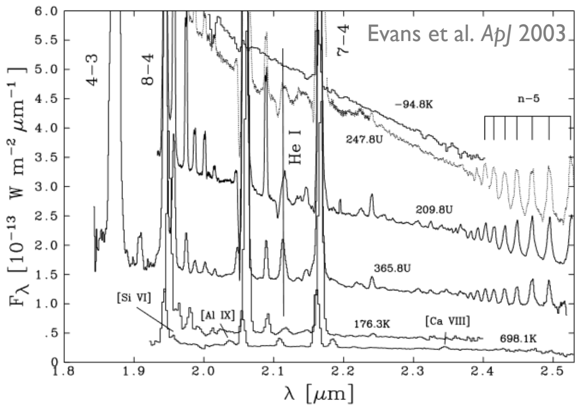


White dwarfs in binaries: *Novae*

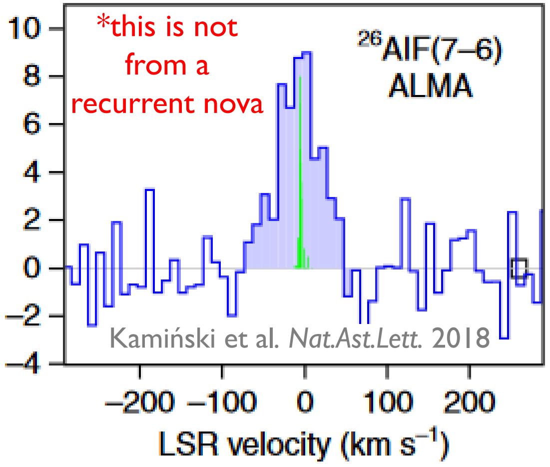
Recurrent explosions synthesize up to ^{40}Ca (and beyond?) with a potentially rich set of observables



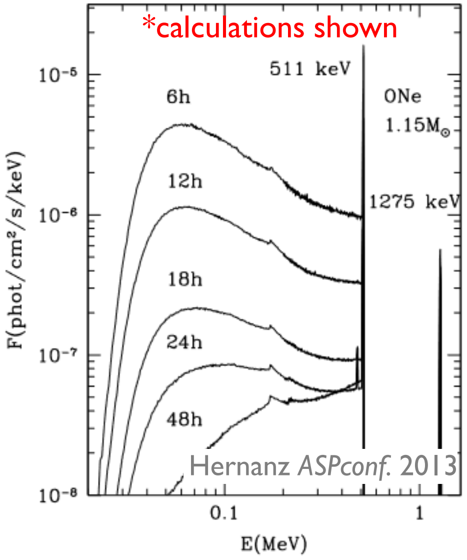
Atomic spectra:



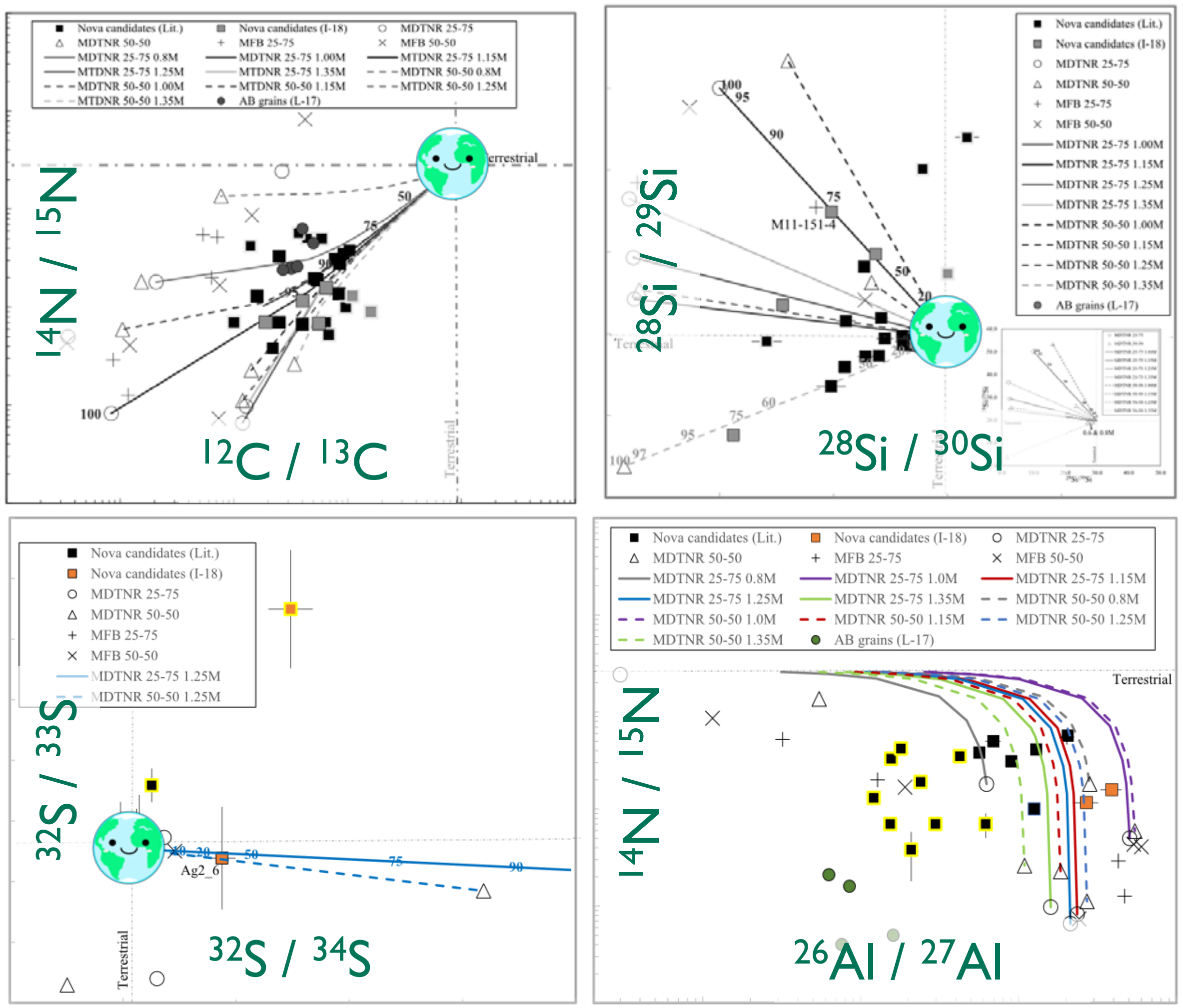
Maybe* molecular spectra:



Maybe* γ-rays:



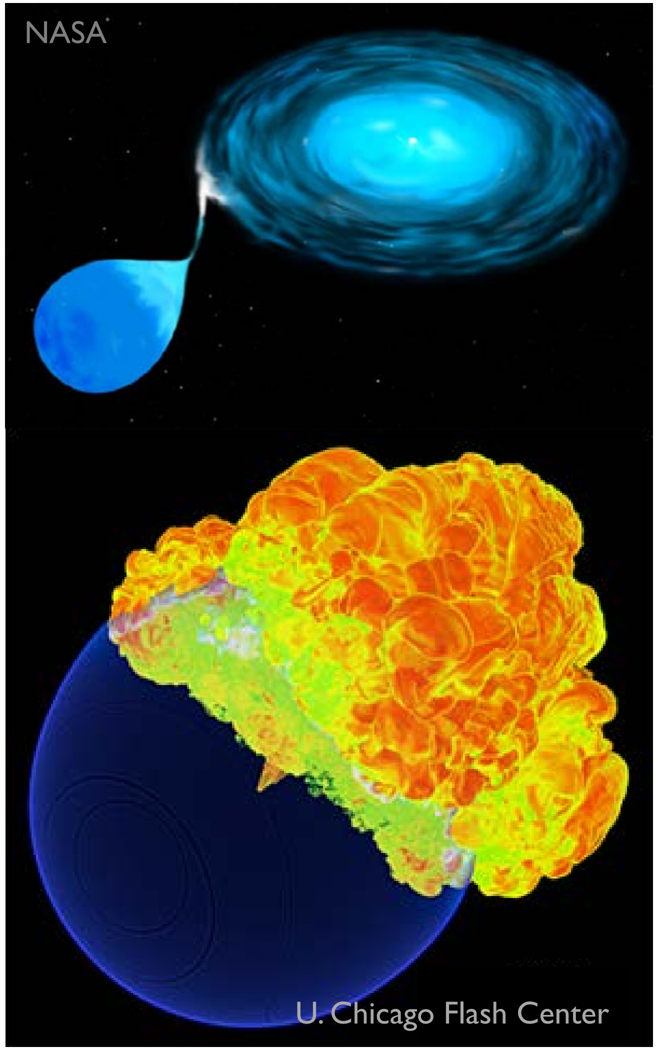
Pre-solar grains:

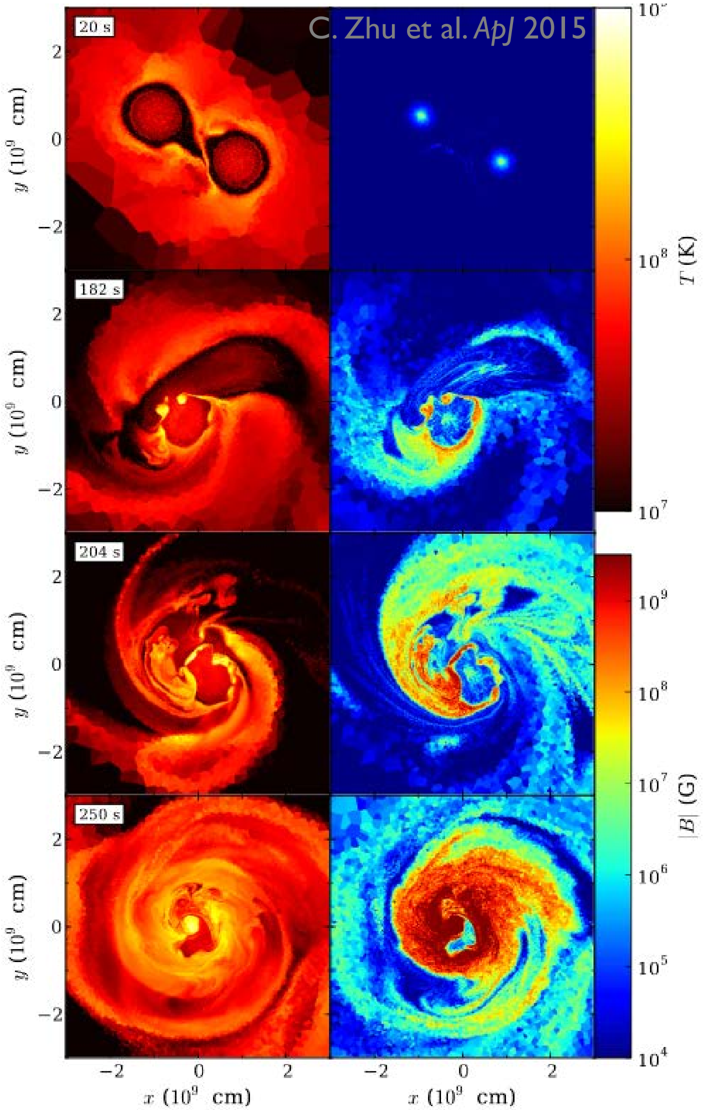


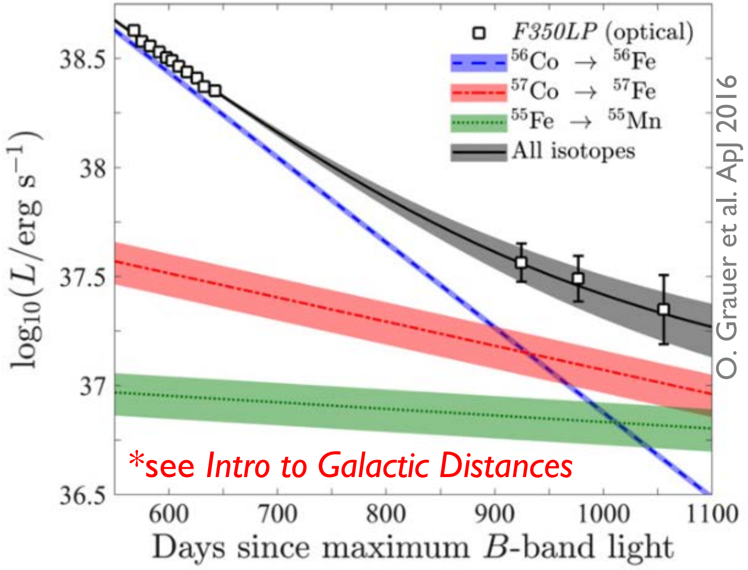
Bose & Starrfield *ApJ* 2019

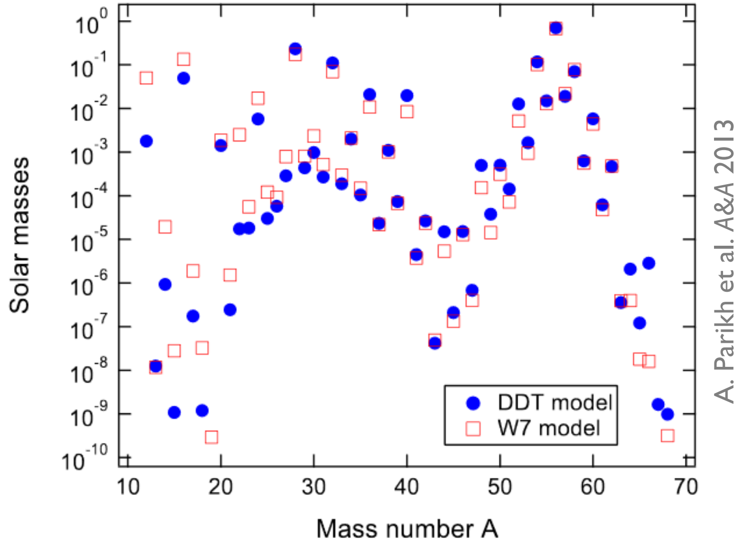
White dwarfs in binaries: *Thermonuclear Supernovae (a.k.a. Type-Ia)*

Single or double degenerate (or both) scenarios give similar results



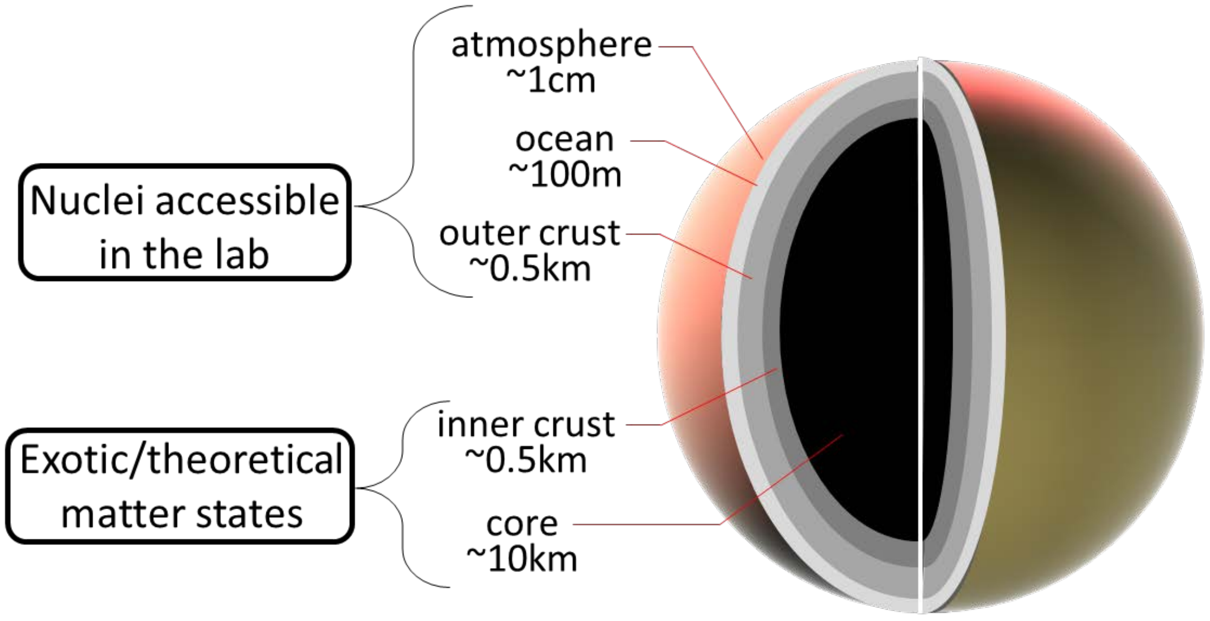






Neutron Star: *a high-mass stellar remnant*

- A city-sized object (R~10km wide) around the mass of the sun
- They are not a "ball of neutrons"! The structure is much more interesting.
- Because of the compactness, the surface gravity is extreme. (~10^{11}x on Earth's surface)

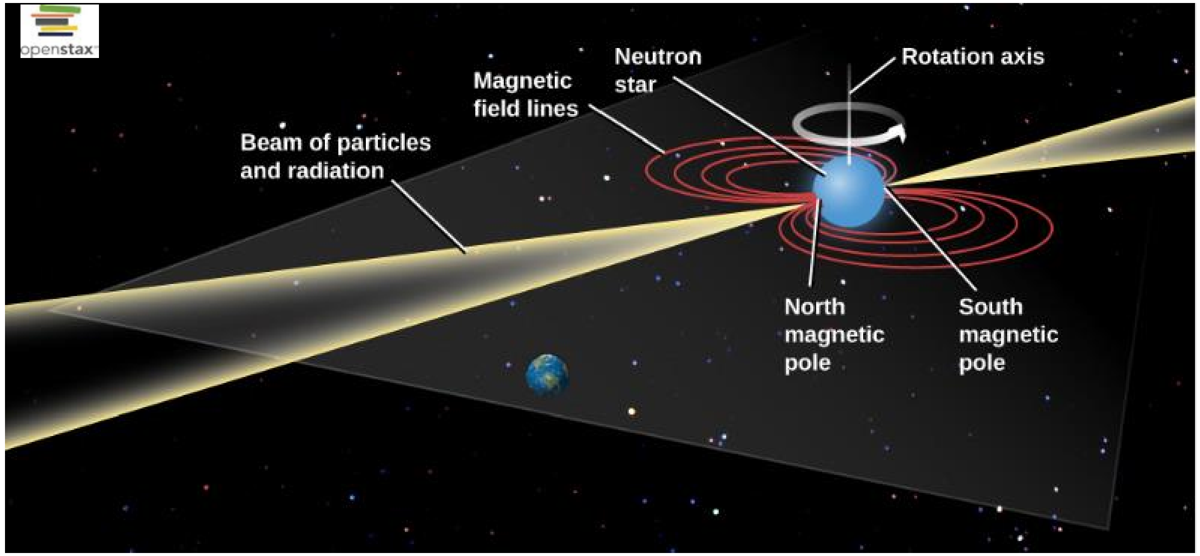


- The gradient in the force is also extreme
  - Consider the force of gravity on your head, which we'll say weighs 5kg
    - $F_{head} = \frac{GMm}{R^2} \approx \frac{\left(6.67\times10^{-11}\frac{\mathrm{m}^3}{\mathrm{kg}\cdot\mathrm{s}^2}\right)(2\times10^{30}\mathrm{kg})(5\mathrm{kg})}{(1\times10^4\ \mathrm{m})^2} \approx 6.670 \times 10^{12}\ \mathrm{N}$
  - Now consider the force on your lower 5kg, which is ~1m lower (R→(R-1m)): $F_{feet} \approx 6.671 \times 10^{12}\ \mathrm{N}$
  - The force difference $F_{head} - F_{feet} \approx 10^9\mathrm{N}$

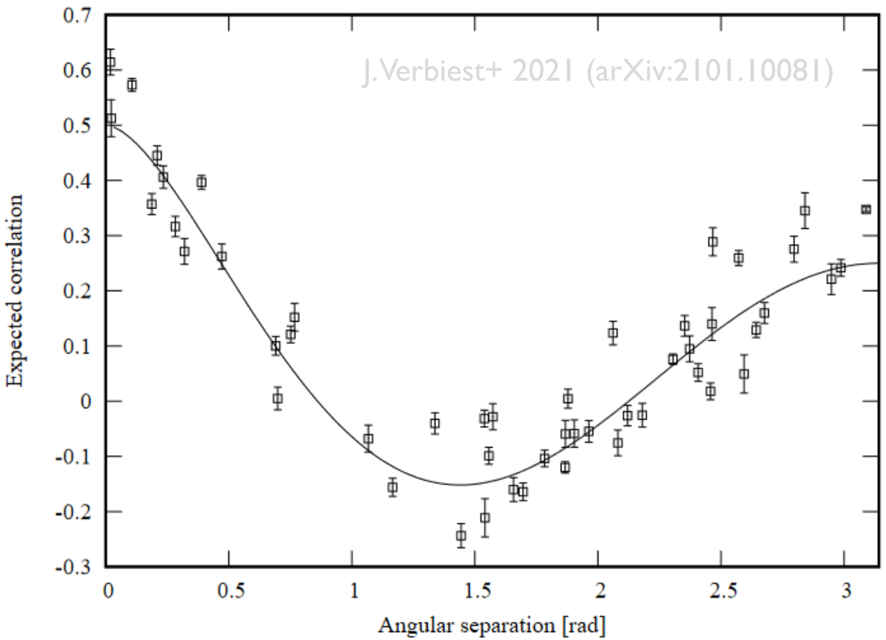
A human tendon has a tensile strength of ~10^3 N

Pulsars

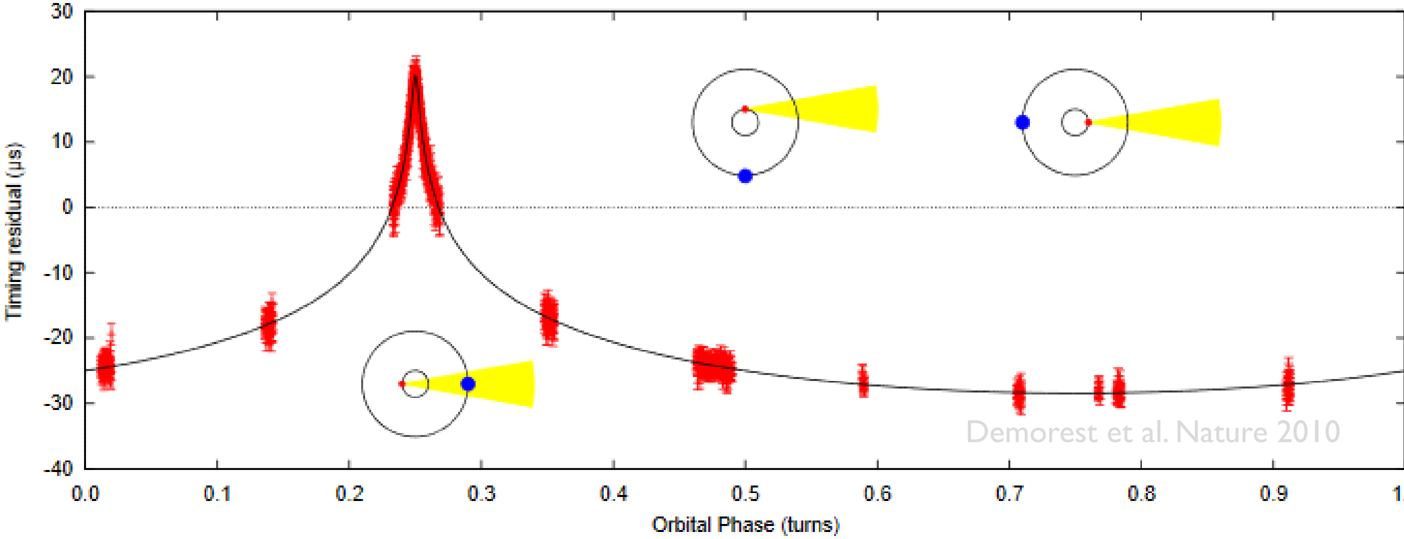
- Neutron stars are often rotating at high rates and with high magnetic fields, which results in a jet of radiation
- When the jet is pointed towards earth, we see a signal with a repeating pulse
- These can be used as very accurate clocks



Correlations between arrival time changes for an "array" of pulsars would occur for gravitational waves

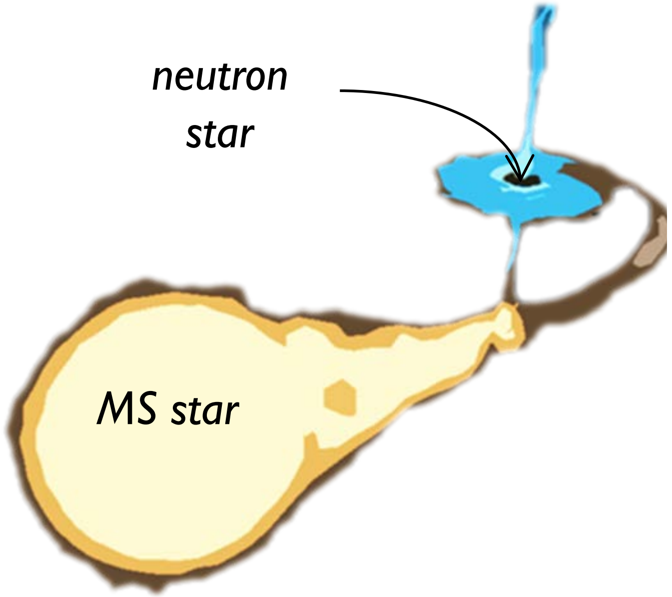


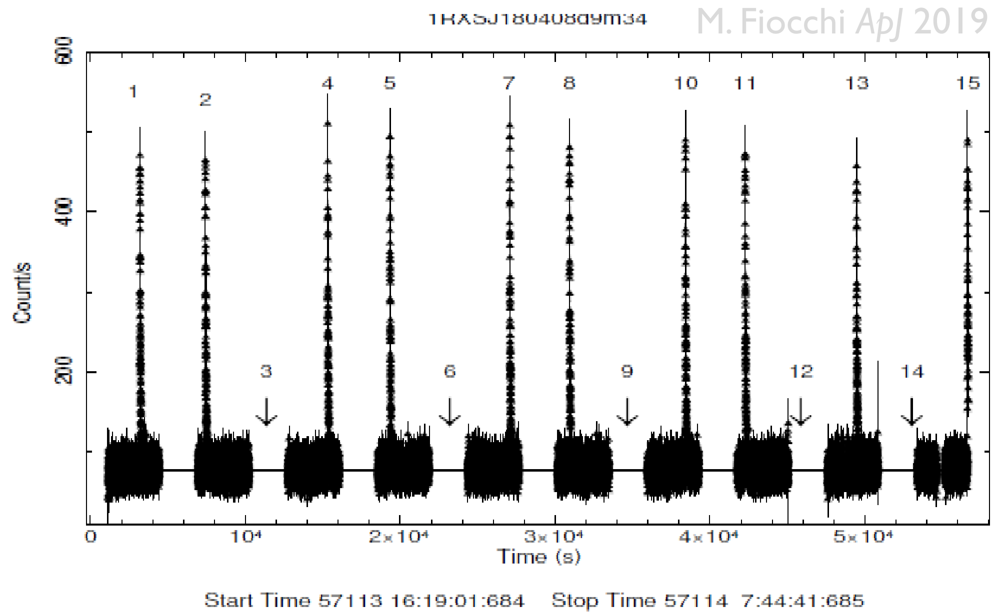
"Shapiro delay" of a pulsar signal due to gravitational time dilation provides the most accurate mass for neutron stars

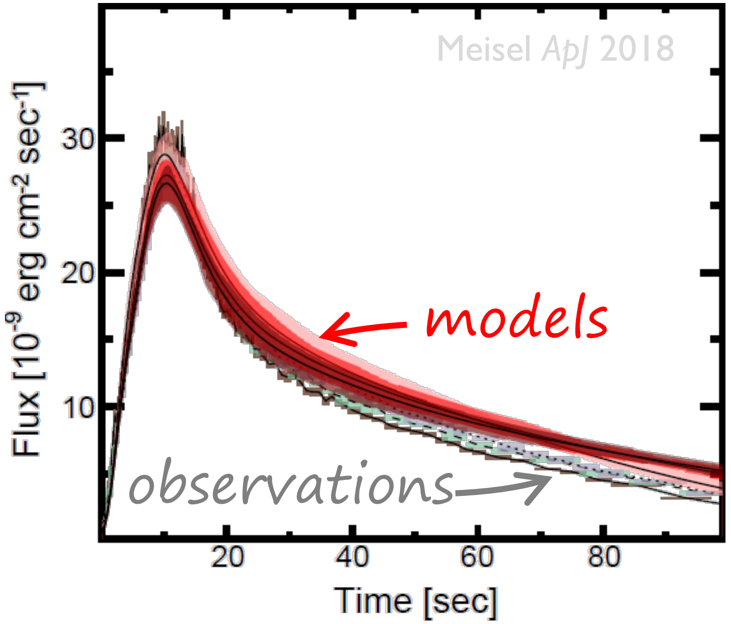


Neutron stars in binaries: *X-ray bursts*

Recurrent explosions that release as much energy in 100s as the sun does in an entire day



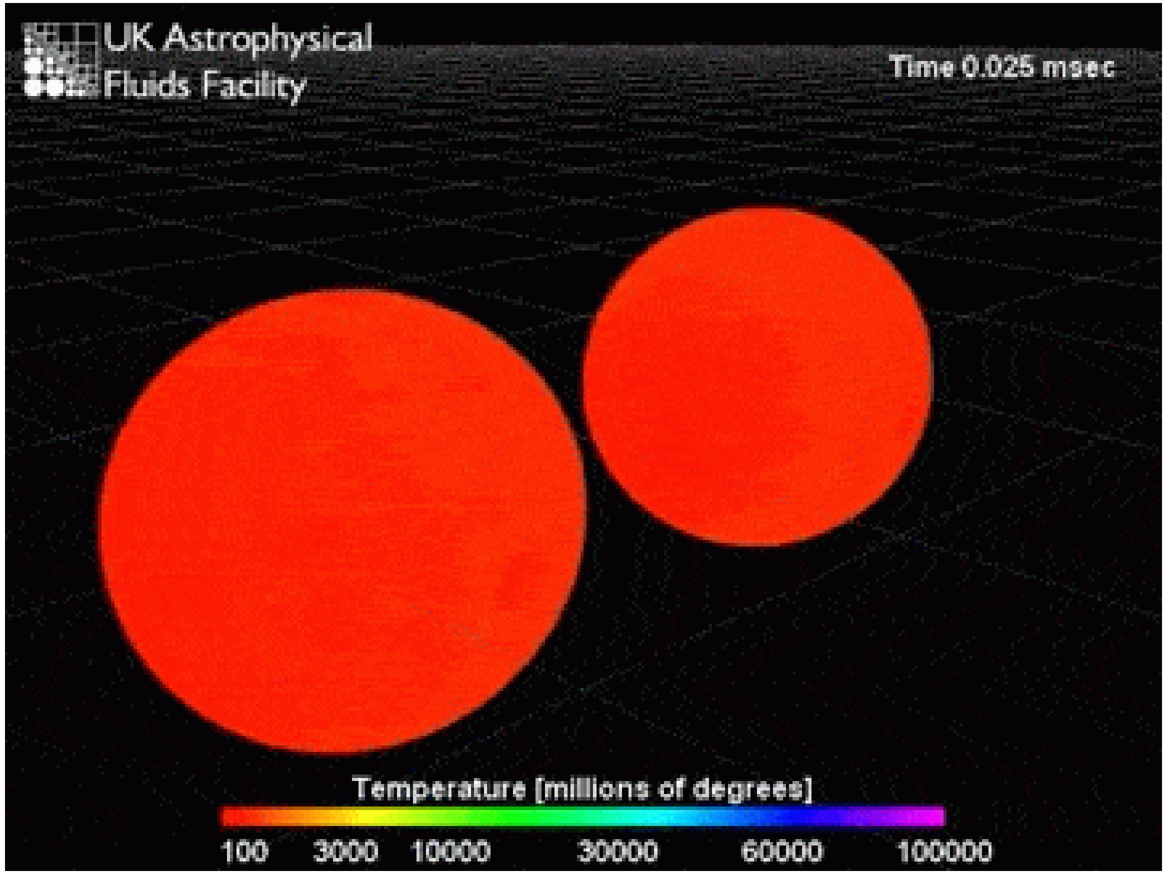




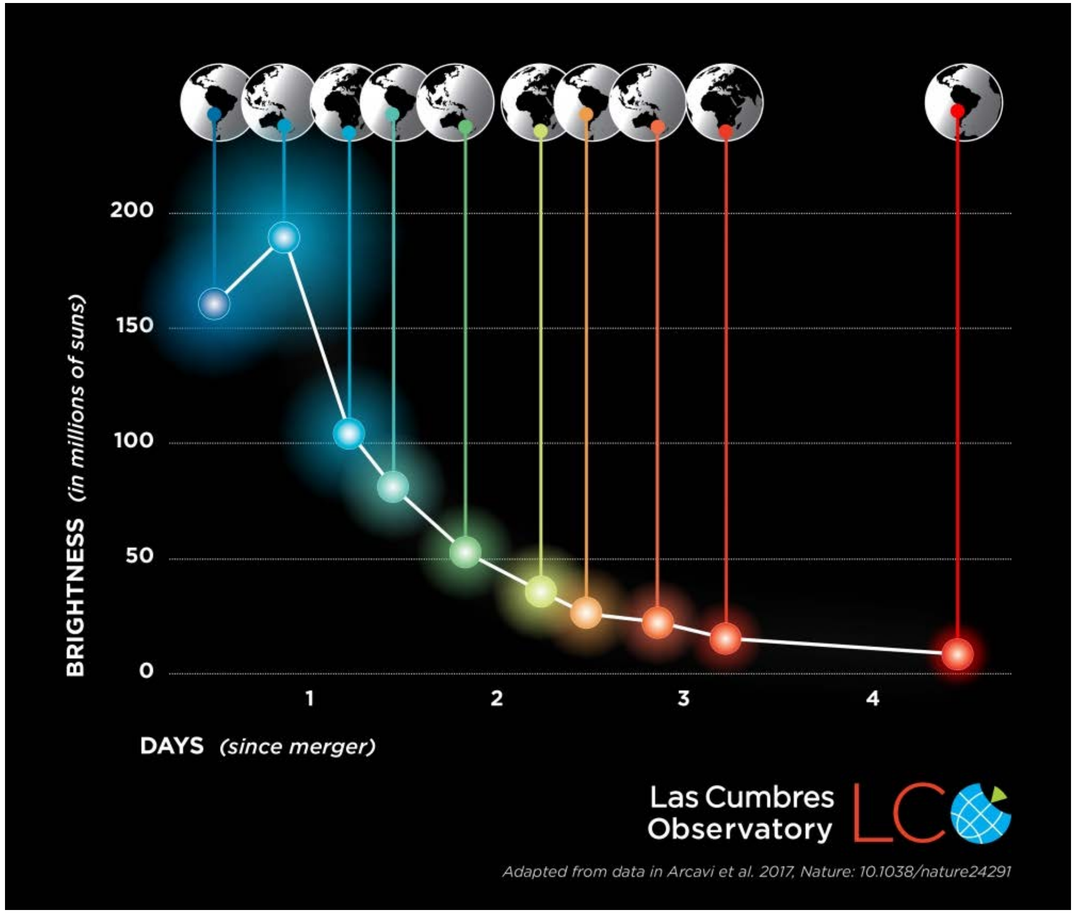
- X-ray burst light curves can teach us about how matter behaves at extreme density
- Matter does not escape:
  - Gravitational binding: $U = \frac{GMm}{R} \approx \frac{\left(6.67\times10^{-11}\frac{\mathrm{m}^3}{\mathrm{kg}\cdot\mathrm{s}^2}\right)\left(2\times10^{30}\mathrm{kg}\right)\left(1.66\times10^{-27}\mathrm{kg}\right)}{\left(1\times10^{4}\ \mathrm{m}\right)} \approx 3\times10^{-11} J$
  - Nuclear reactions release ~ $2\times10^{-13}\ J$ …so not enough energy to power escape
  - These objects do not contribute to elemental abundances in the universe

Neutron stars in binaries…with other neutron stars

- Two massive stars in a binary pair will wind up as neutron stars, which can eventually merge
- This results in gravitational wave and electromagnetic signals and synthesizes a large fraction of elements heavier than iron in the "rapid" neutron-capture (r-)process

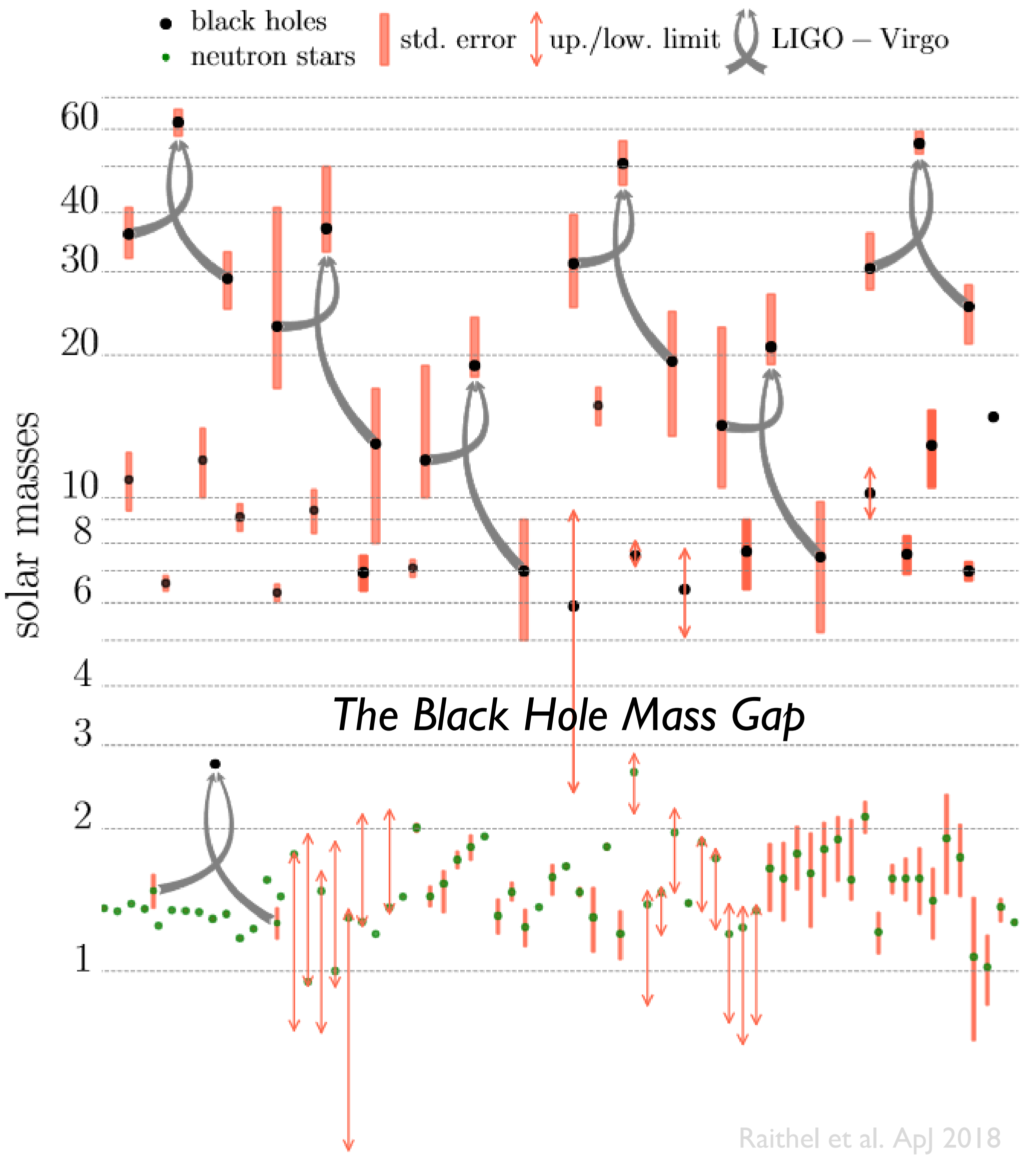


Kilanova light curve



Black Holes

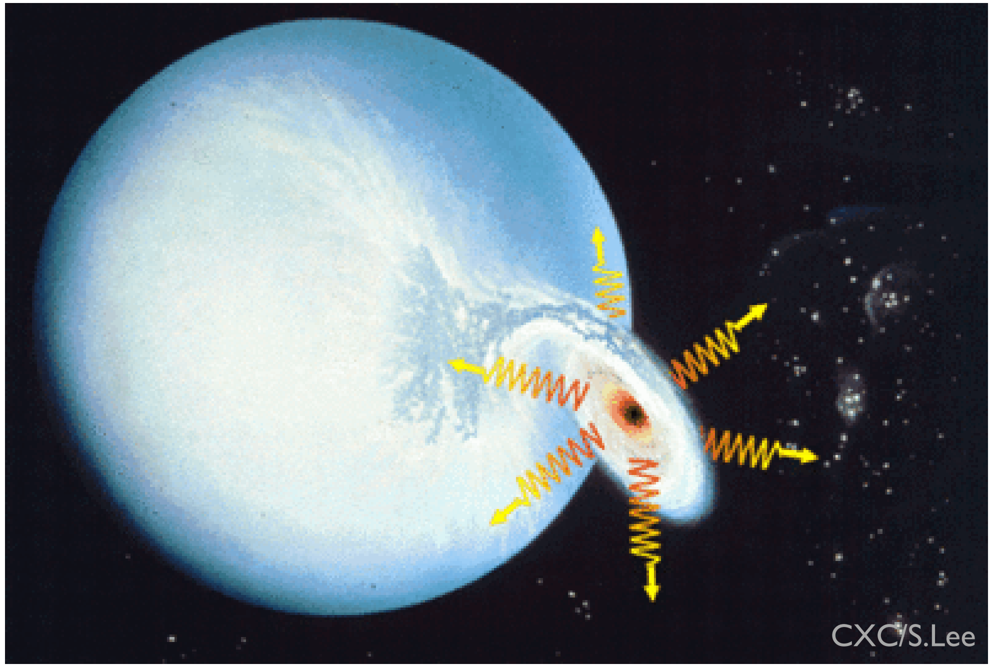
- The most compact objects in the universe are black holes, of which the stellar mass variety are created in massive star death
  (and neutron star mergers)
- The escape velocity of these objects is larger than the speed of light
- The size can be defined by the Schwarzschild radius, which is the radius at which the escape velocity is equal to the speed of light
  - $R_s \approx 2.95 \frac{M}{M_\odot}$ km
- There is a conspicuous gap between the highest-mass neutron stars we know of and the lowest-mass black holes. This is known as the (lower) black hole mass gap



Raithel et al. ApJ 2018

Black holes in binaries: *accreting black holes*

- Since black holes do not give off light, we see them from the absence of light in a region
- This is easiest when the black hole is accreting material from a companion star.
- In that case, there is also the benefit of the impact on the orbit of the black hole on the companion star, which results in the black hole mass *(see Introduction to the HR Diagram)*
- The X-ray signature from the accretion disk can tell us the black hole spin



Black holes in binaries…with other black holes

- Two massive stars in a binary pair will wind up as black holes, which can eventually merge
- This results in gravitational wave signals …but nothing else escapes
    - *This is a (relatively) new probe into general relativity*