Neutron stars and black holes: the relics of massive stars

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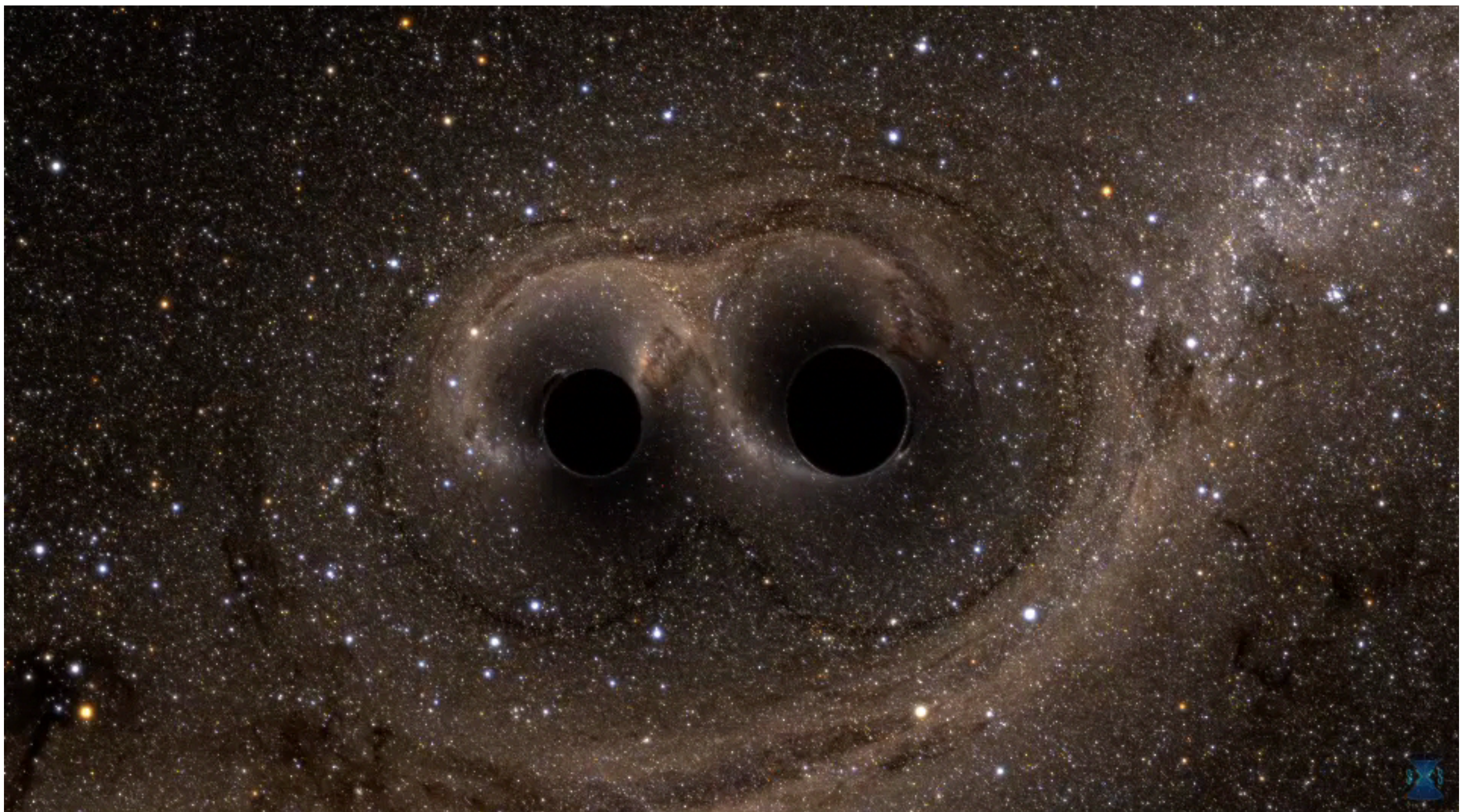
LIGO-G1801452

Some cool things about General Relativity

- Solutions to equations predict orbital motion, bending of light, weird time effects, black holes, etc.
- Spacetime is dynamical: gravitational waves

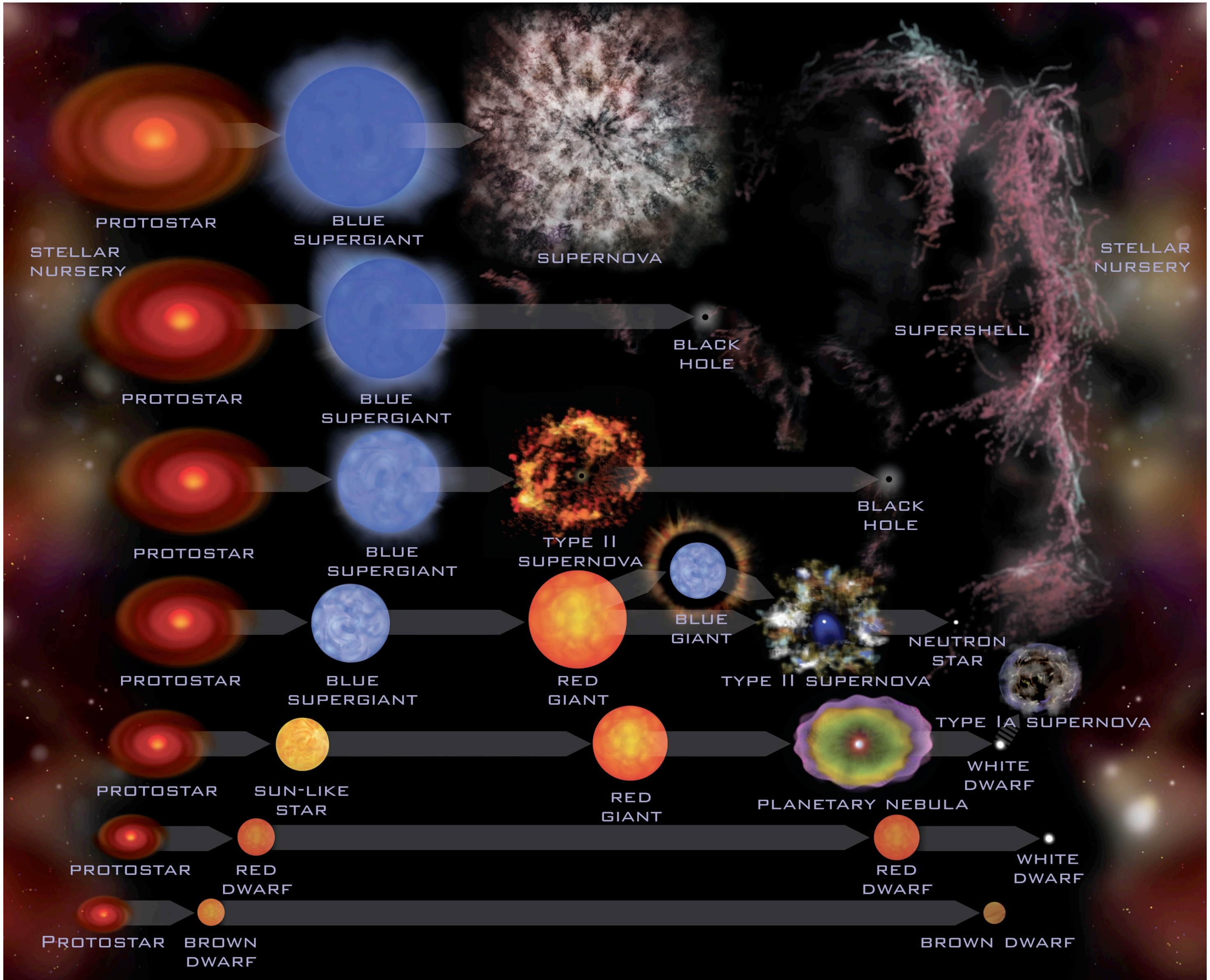


Credit: ligo.caltech.edu

Outline

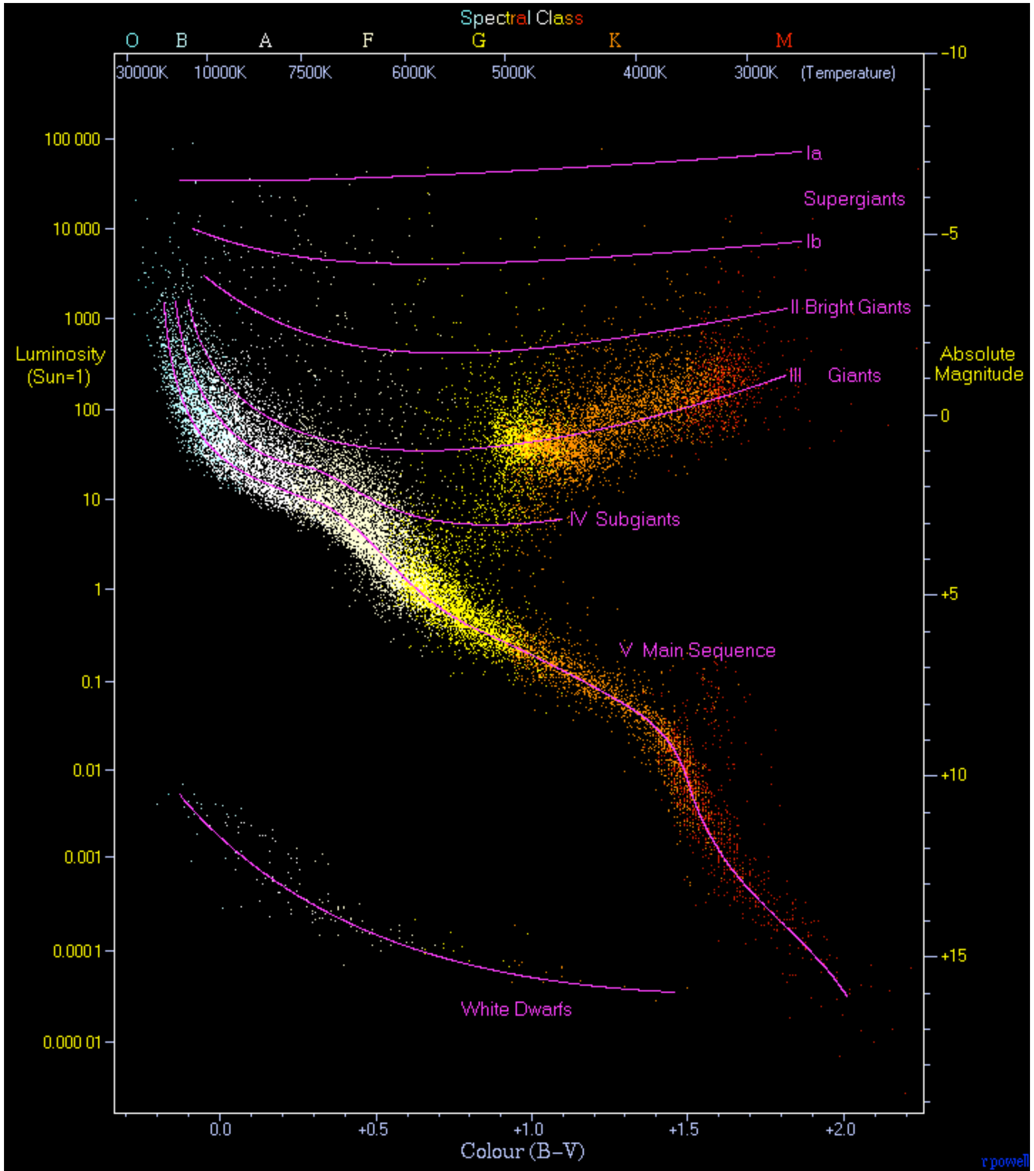
- Stellar evolution
- Neutron stars
- Black holes
- Gravitational waves

Stellar evolution



www.jpl.nasa.gov

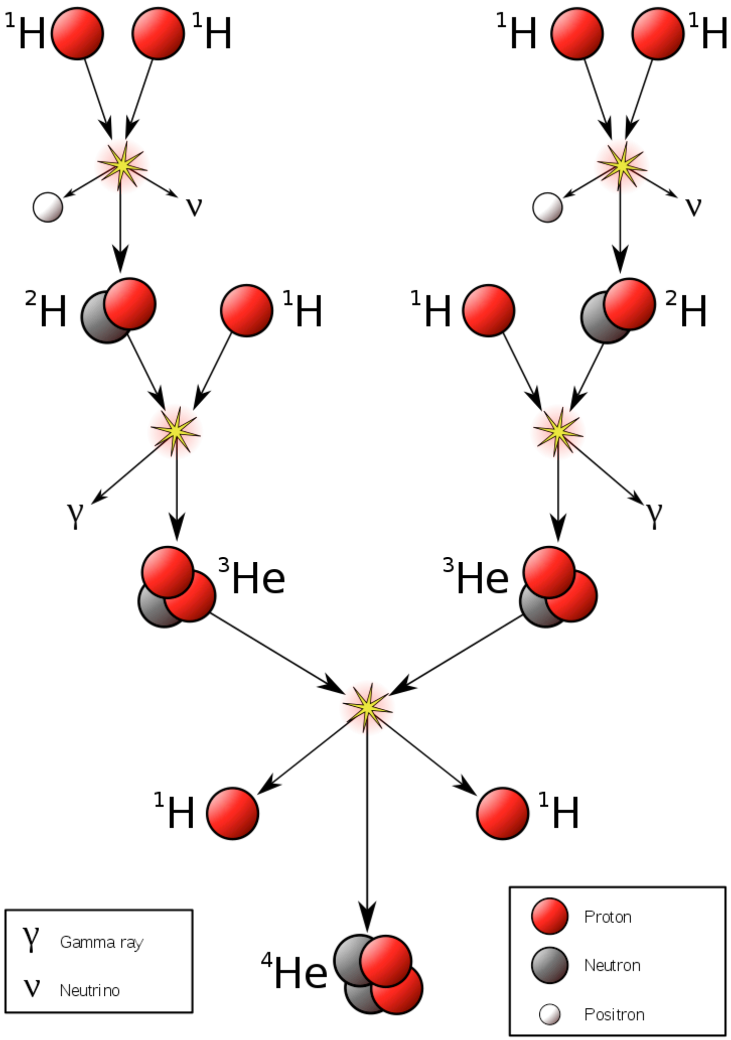
HR diagram



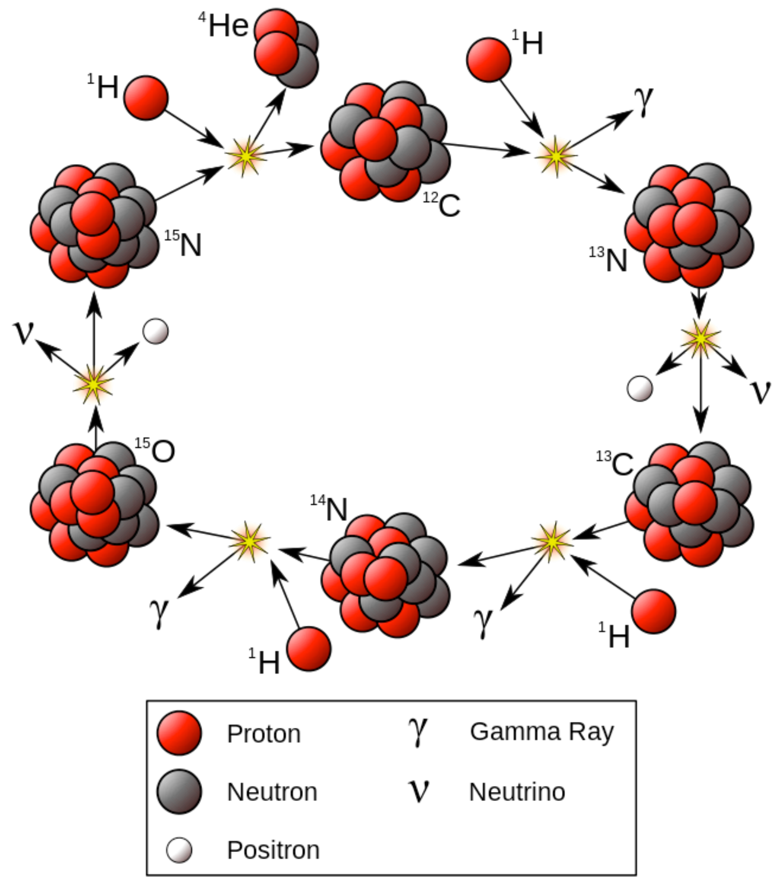
wikipedia.org

Nuclear fuel burning

p-p chain fusion (low mass stars)



CNO cycle fusion (higher mass stars)

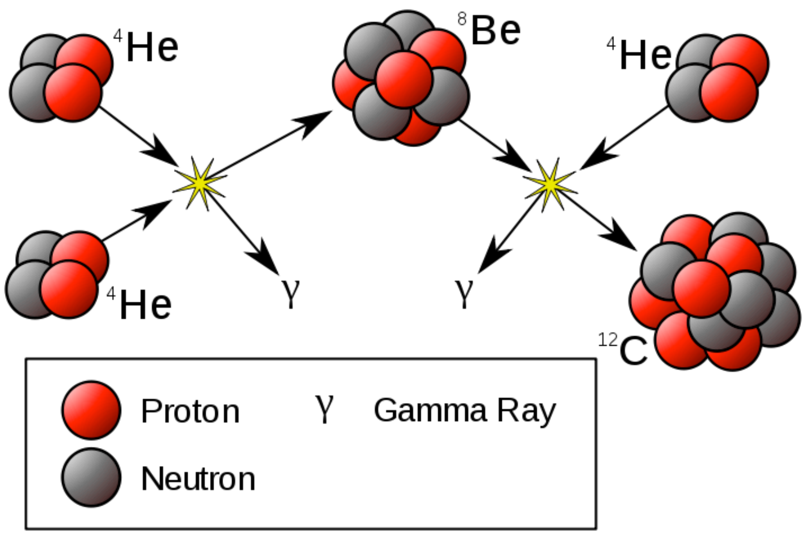


Just examples, many other nuclear pathways…

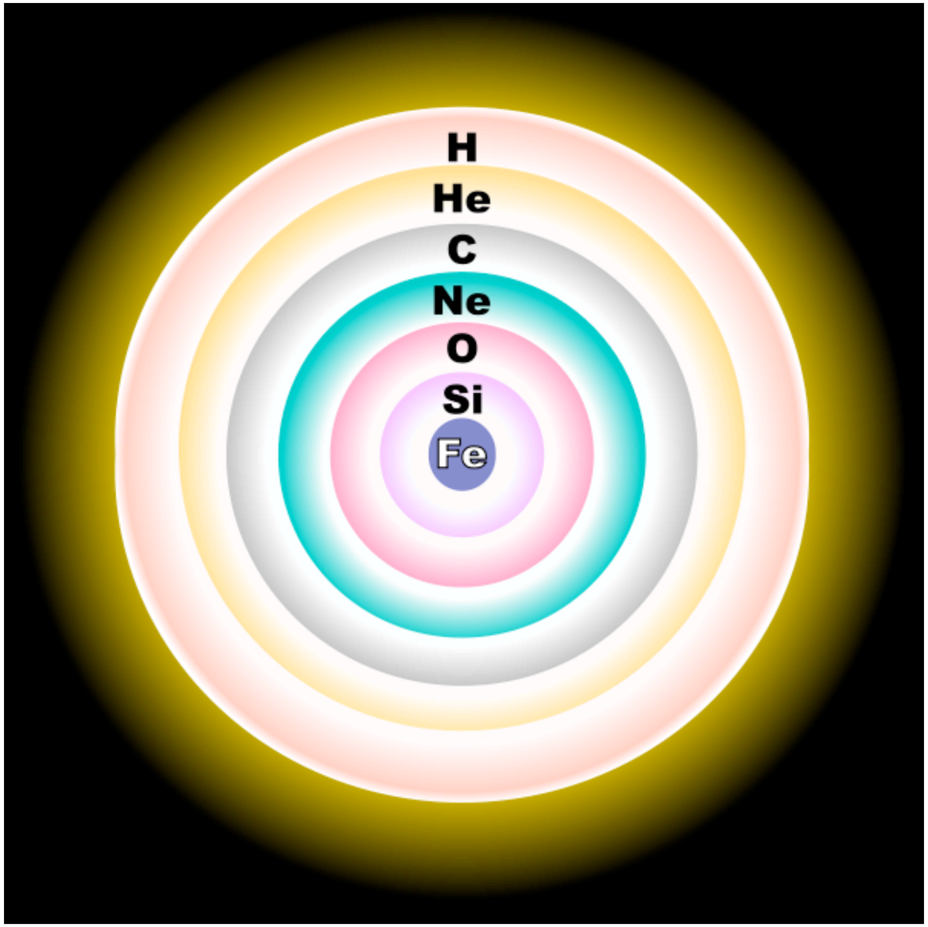
wikipedia.org

Life of a star goes on

Triple-alpha process
(near end of low mass star)

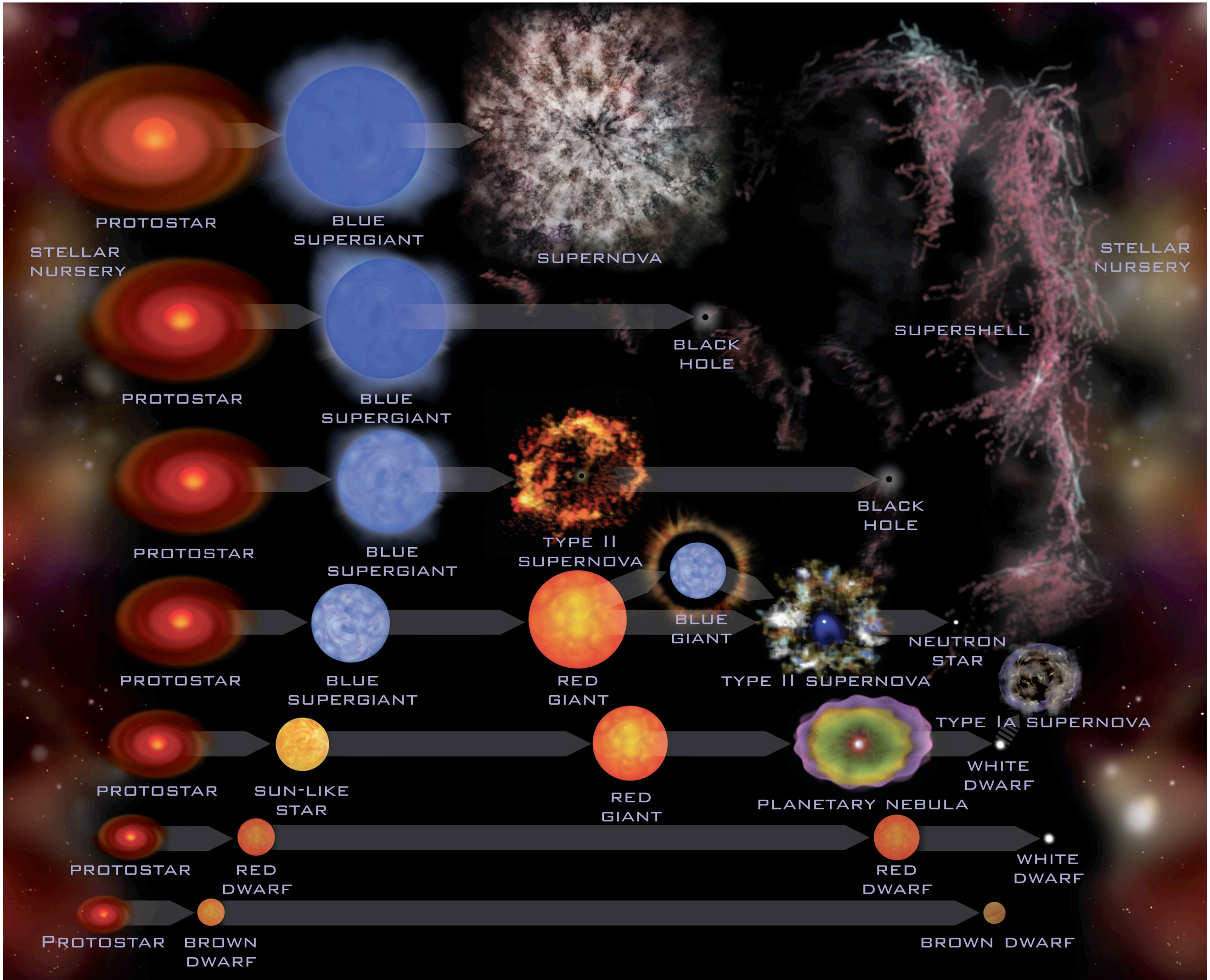


Late stages of a high mass star



wikipedia.org

End of life

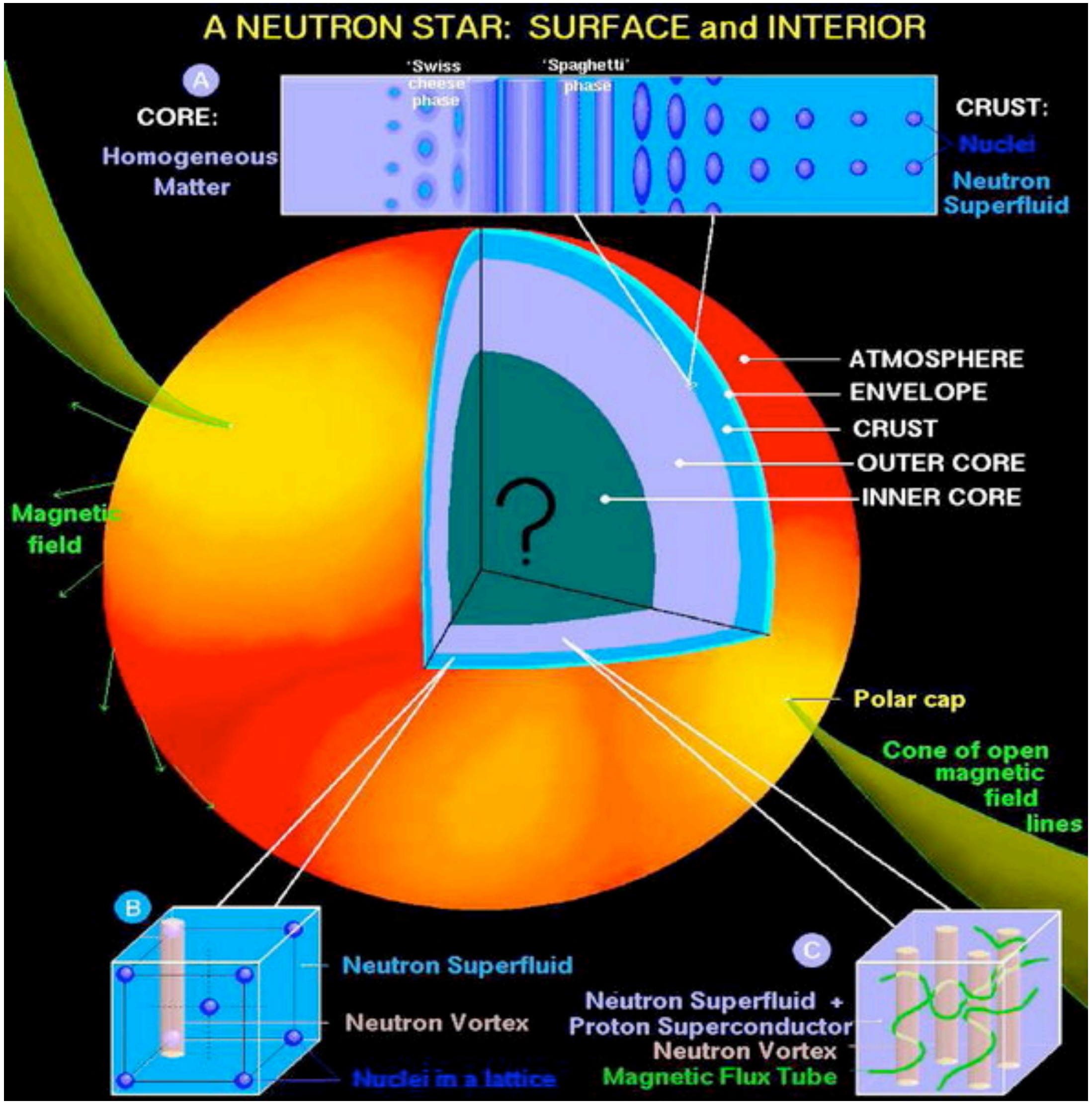


www.jpl.nasa.gov

Tale of a massive star end of life

- Exact physics of collapse/SN is very complicated!
- "Useless" iron core of star
- Hydrostatic equilibrium fails and star collapses
- Inverse beta decay as core collapses $p + e^- \to n + \nu_e$
- Shock wave results in supernova explosion
- Collapsing core may halt because of neutron degeneracy pressure – neutron star $10M_\odot \lesssim M \lesssim 30M_\odot$
- Collapse may continue – black hole $M \gtrsim 30M_\odot$

Neutron stars



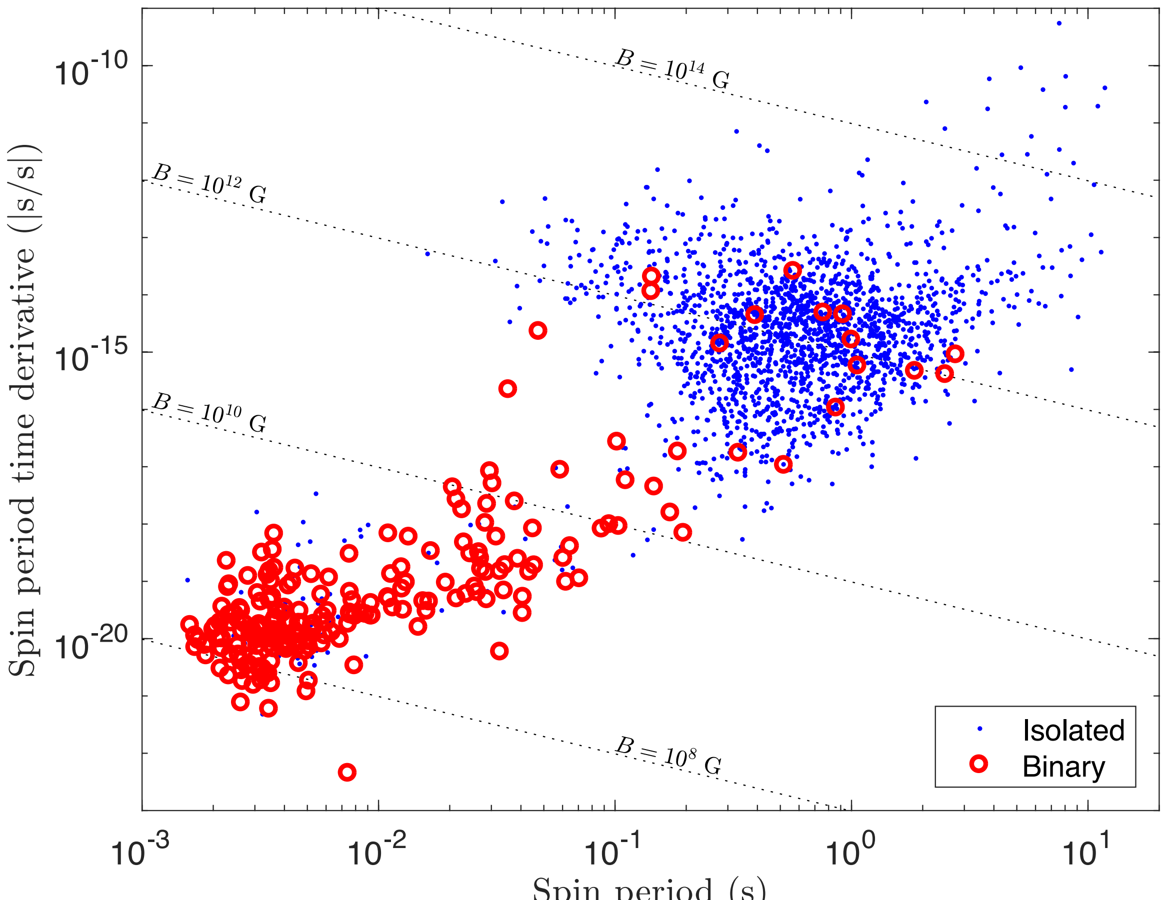
- Proposed in 1933 by Baade and Zwicky
- Dense, relic of massive star
- Supported by neutron degeneracy pressure
- Made up of mostly neutrons
- Very strong magnetic fields
- Interesting: an isolated neutron decays to a proton in approx. 11 min.; why doesn't a NS decay?

http://www.mpifr-bonn.mpg.de/research/fundamental/forces

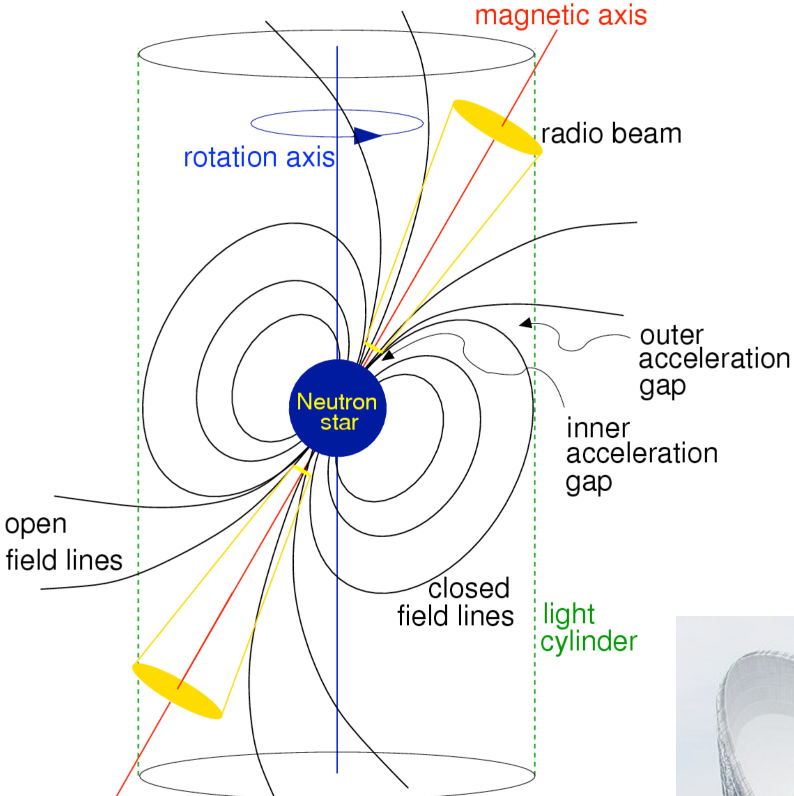
Known neutron stars (pulsars)

First pulsar discovered in 1967 in Jocelyn Bell and Antony Hewish

ATNF catalog: 2636 pulsars (July 2018) and counting!



Observing pulsars (EM)



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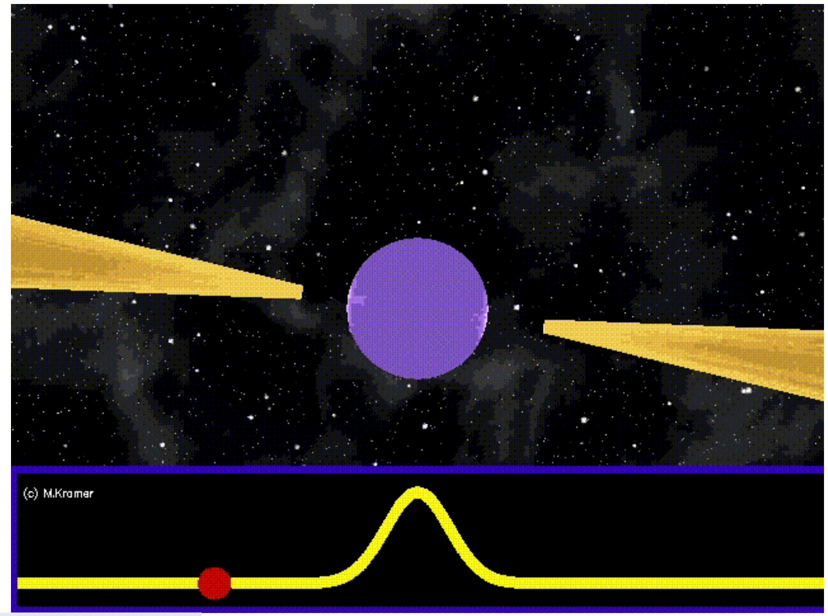
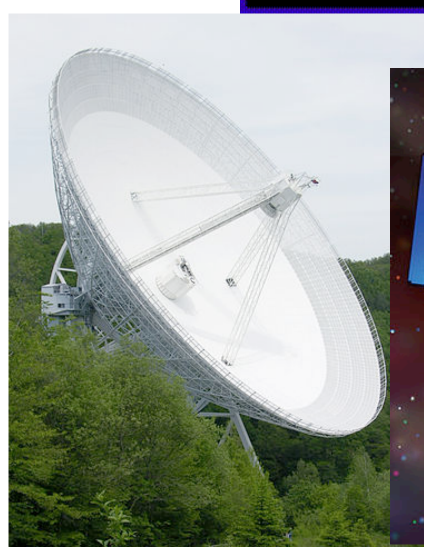
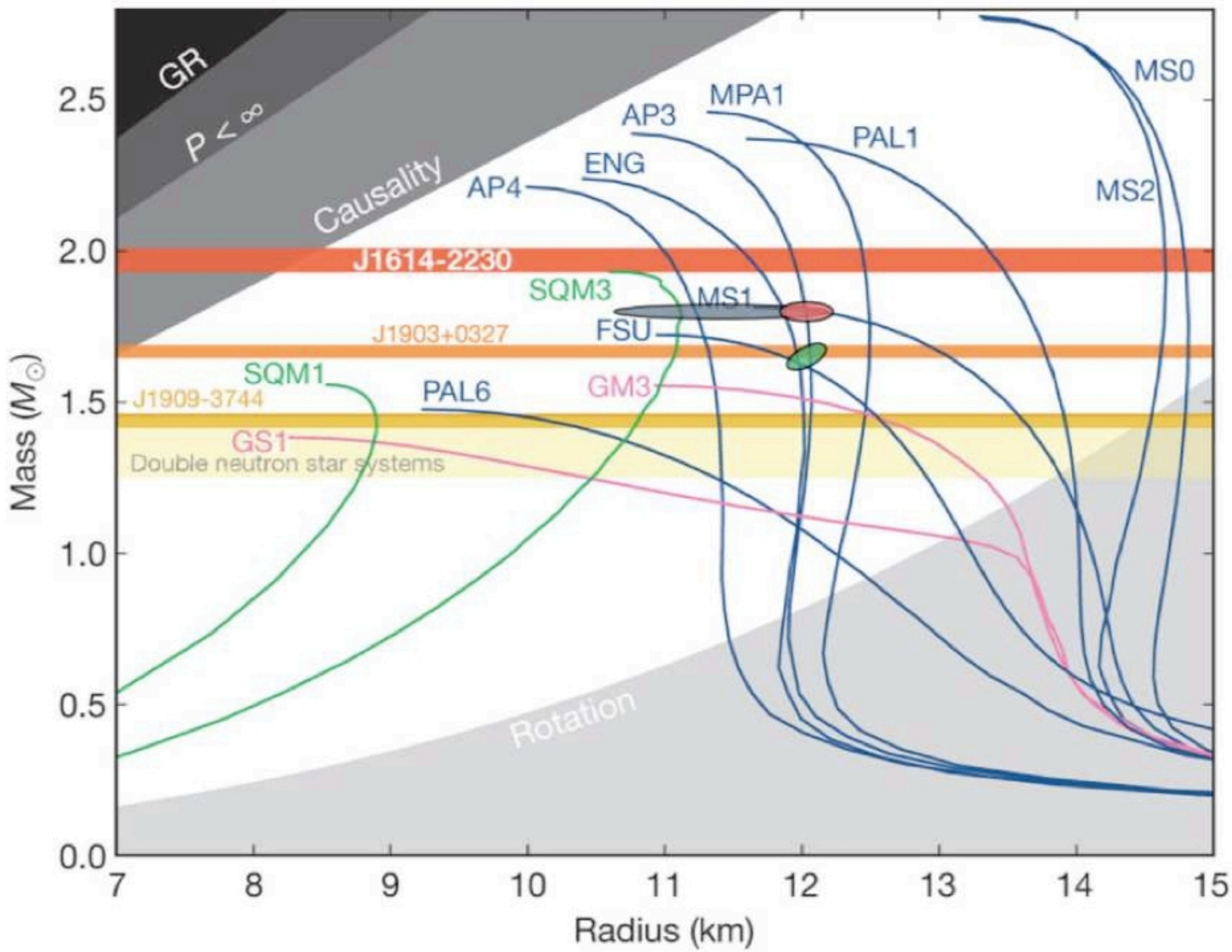




Fascination with neutron stars

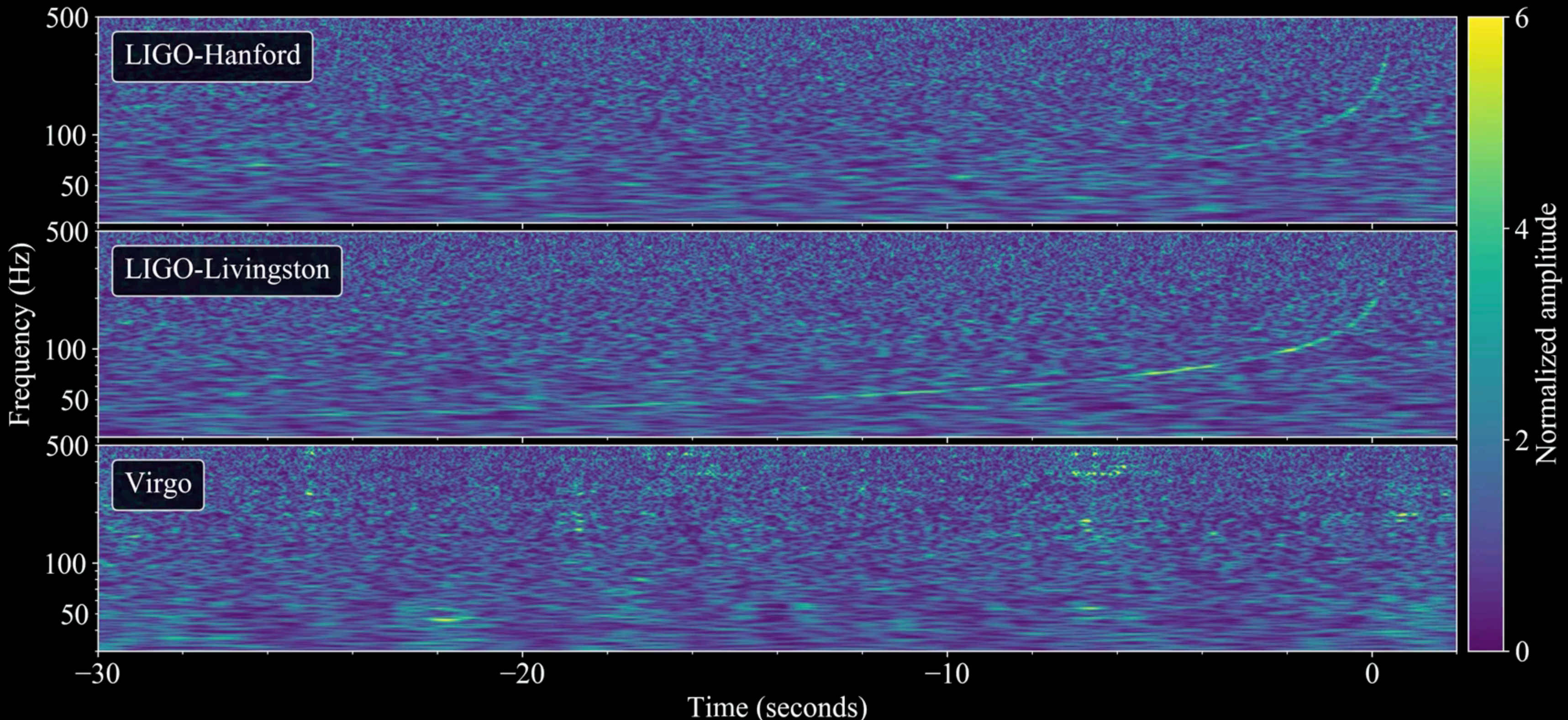
- Matter under extreme conditions
- Probe fundamental physics
- Structure of neutron star
- Equation of state
  - Pressure vs density
  - Mass vs radius

Equation of state



http://sci.esa.int/loft/49338-equation-of-state-for-neutron-stars/

August 17, 2017, 5:41 am PDT



Credit: LSC-Virgo Collaboration

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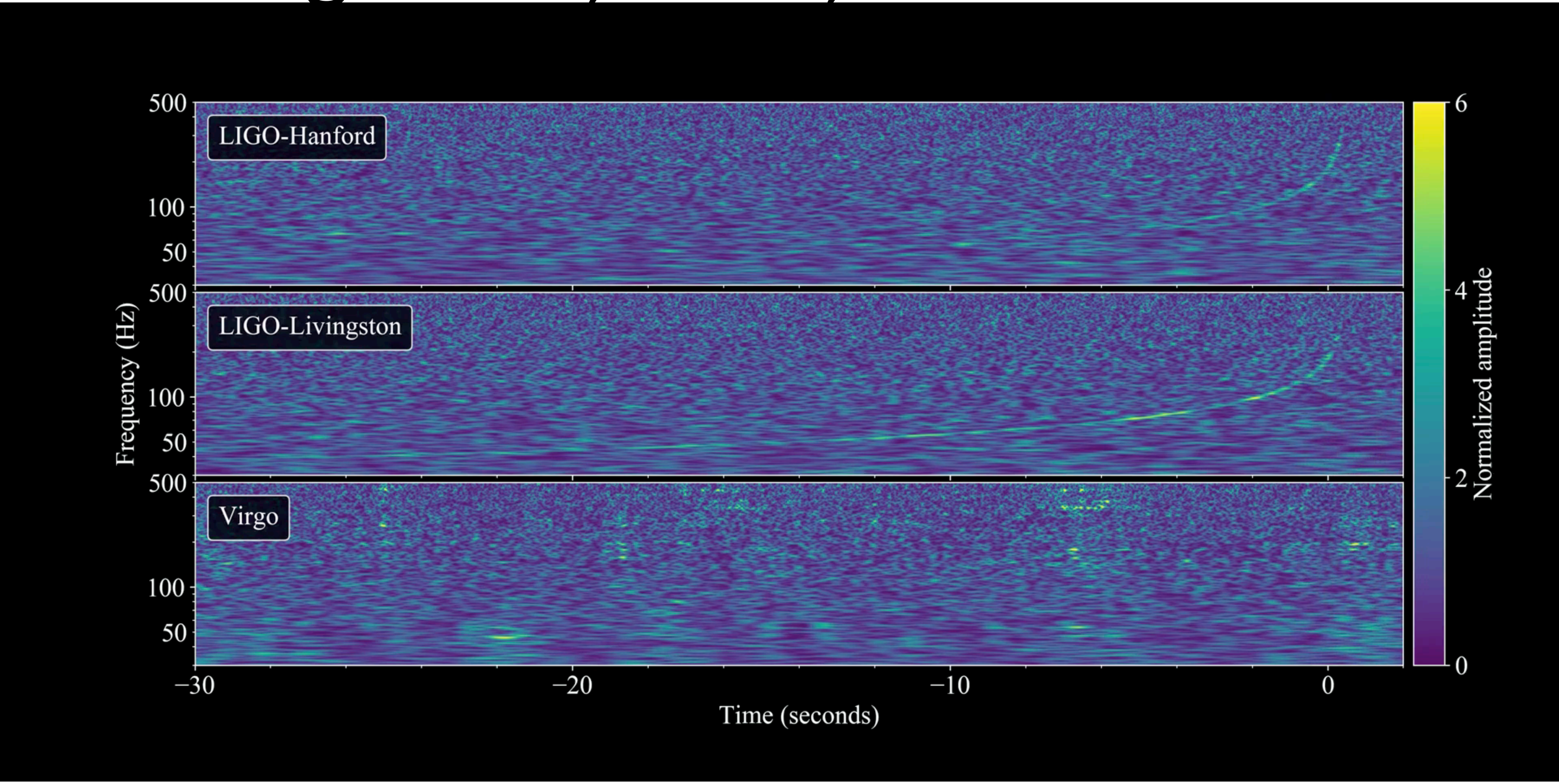
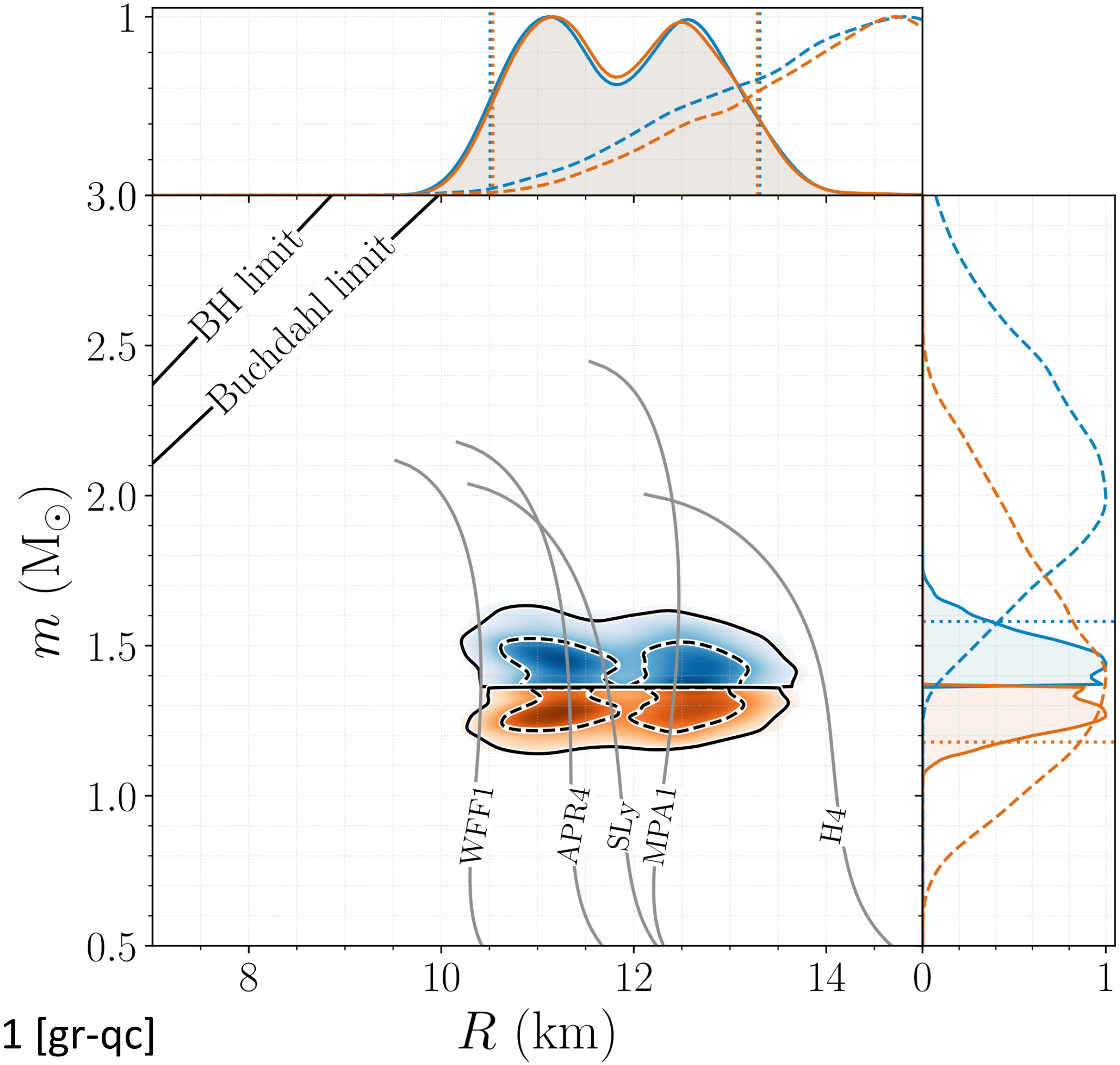


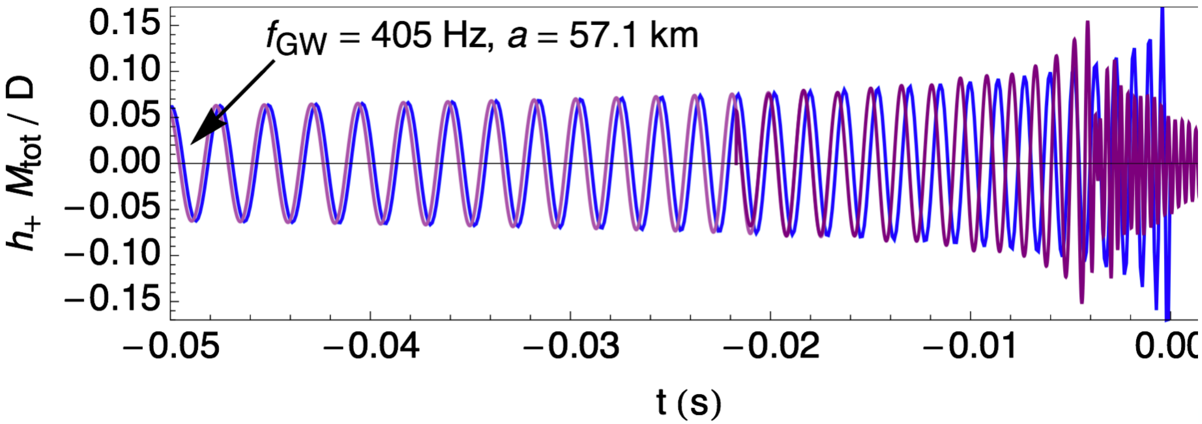
Credit: LSC-Virgo Collaboration

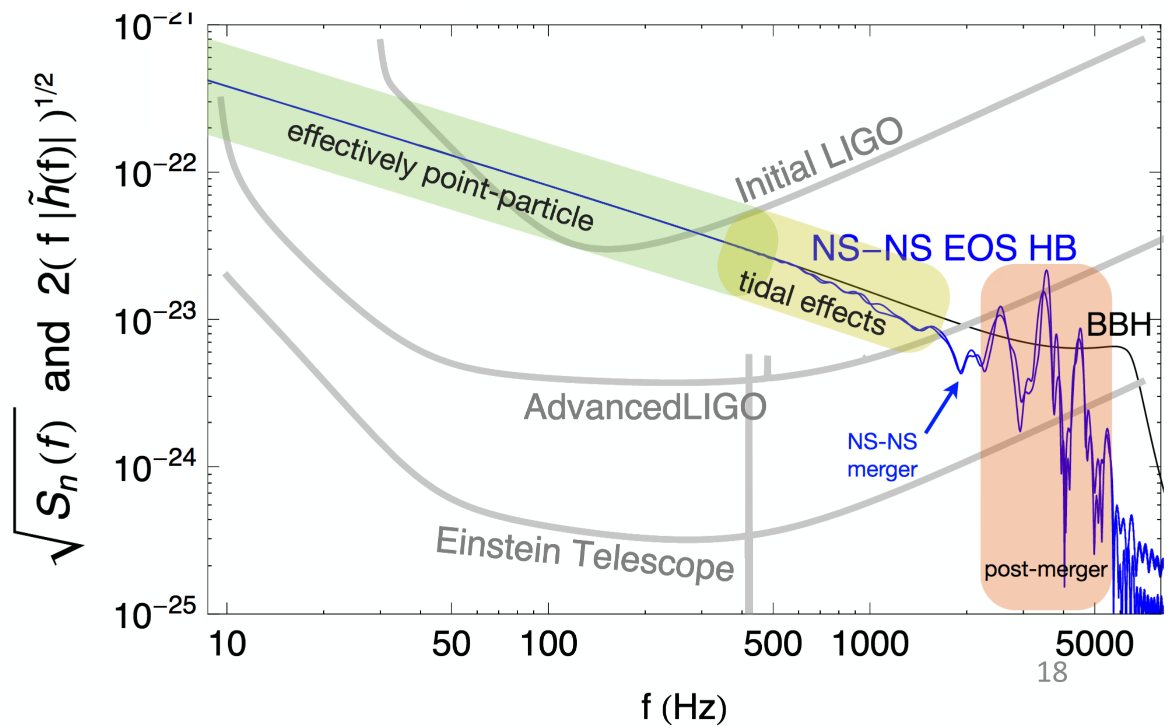
Equation of state measured in GWs



arXiv:1805.11581 [gr-qc]

Tidal deformations impact GW waveform



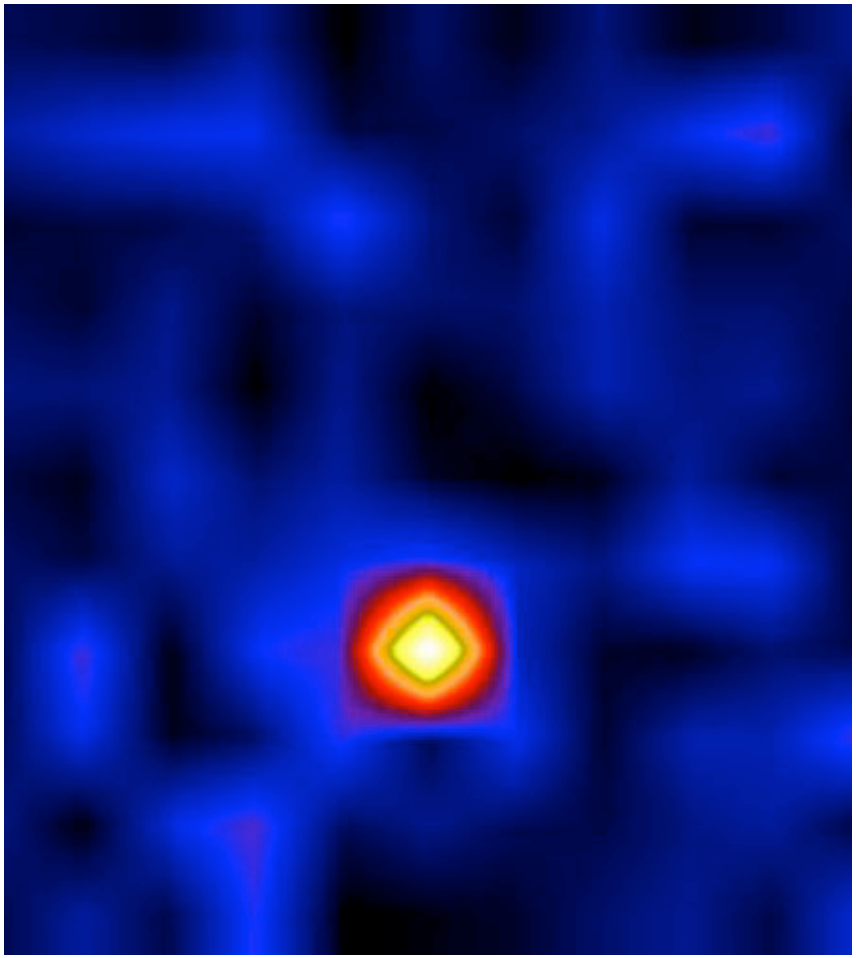


J. Read LIGO-G1702037

Black holes

- Understood early on from mathematics of GR
- Completely described by 3 physical values:
  - Mass, angular momentum, electric charge
- At first, the idea seemed crazy: singularities?!
- Does nature really create such objects?

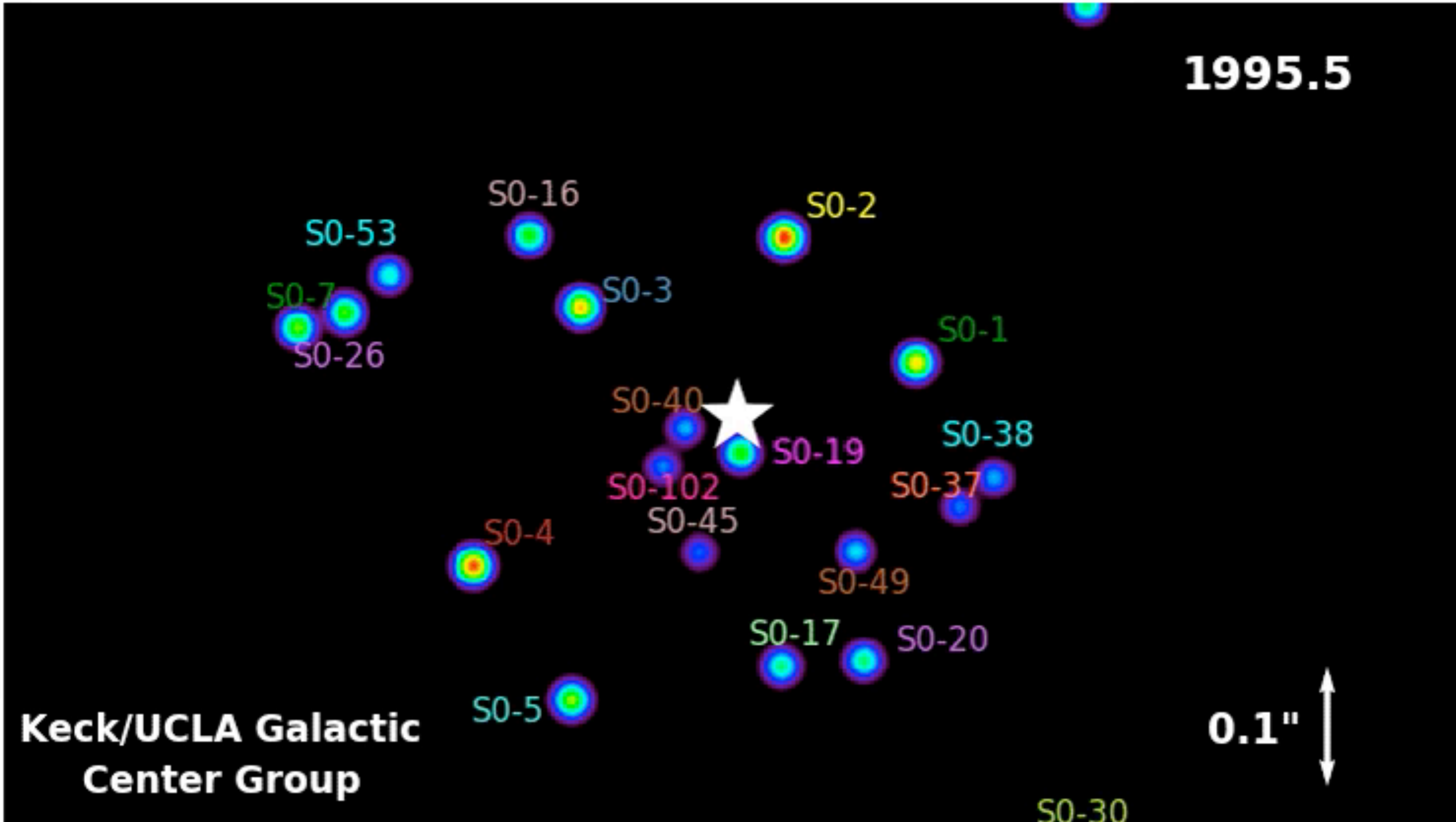
First evidence: Cygnus X-1



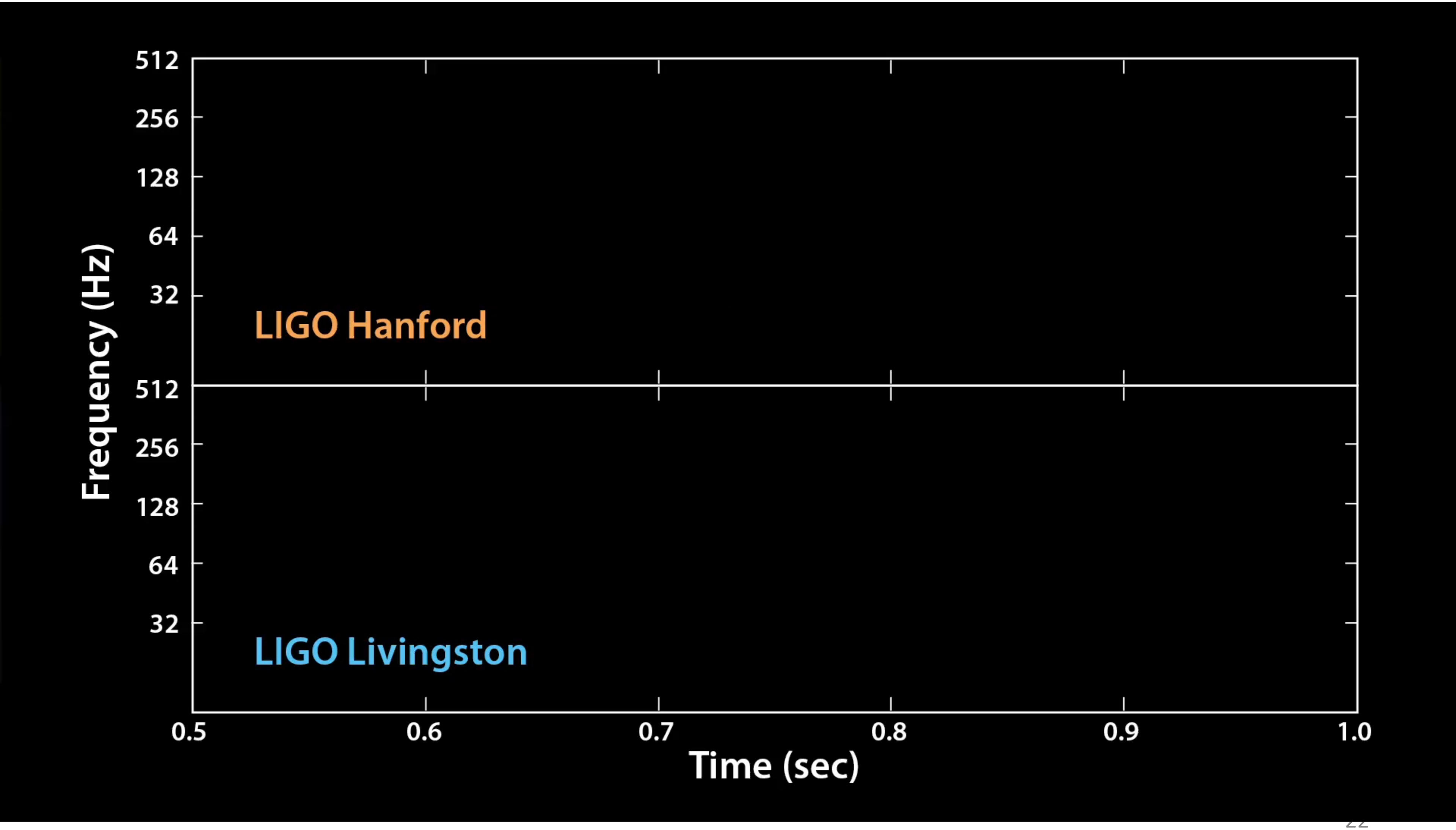
- X-ray source discovered in 1964
- Few years later found to be in a binary
- Rapid x-ray variability (few times per second)
- Implies small size (light crossing time)
- Because $M \sim 14 M_{\odot}$ the object has to be a BH

Cyg X-1 was the subject of the infamous Hawking-Thorne bet; Hawking conceded the bet ☺

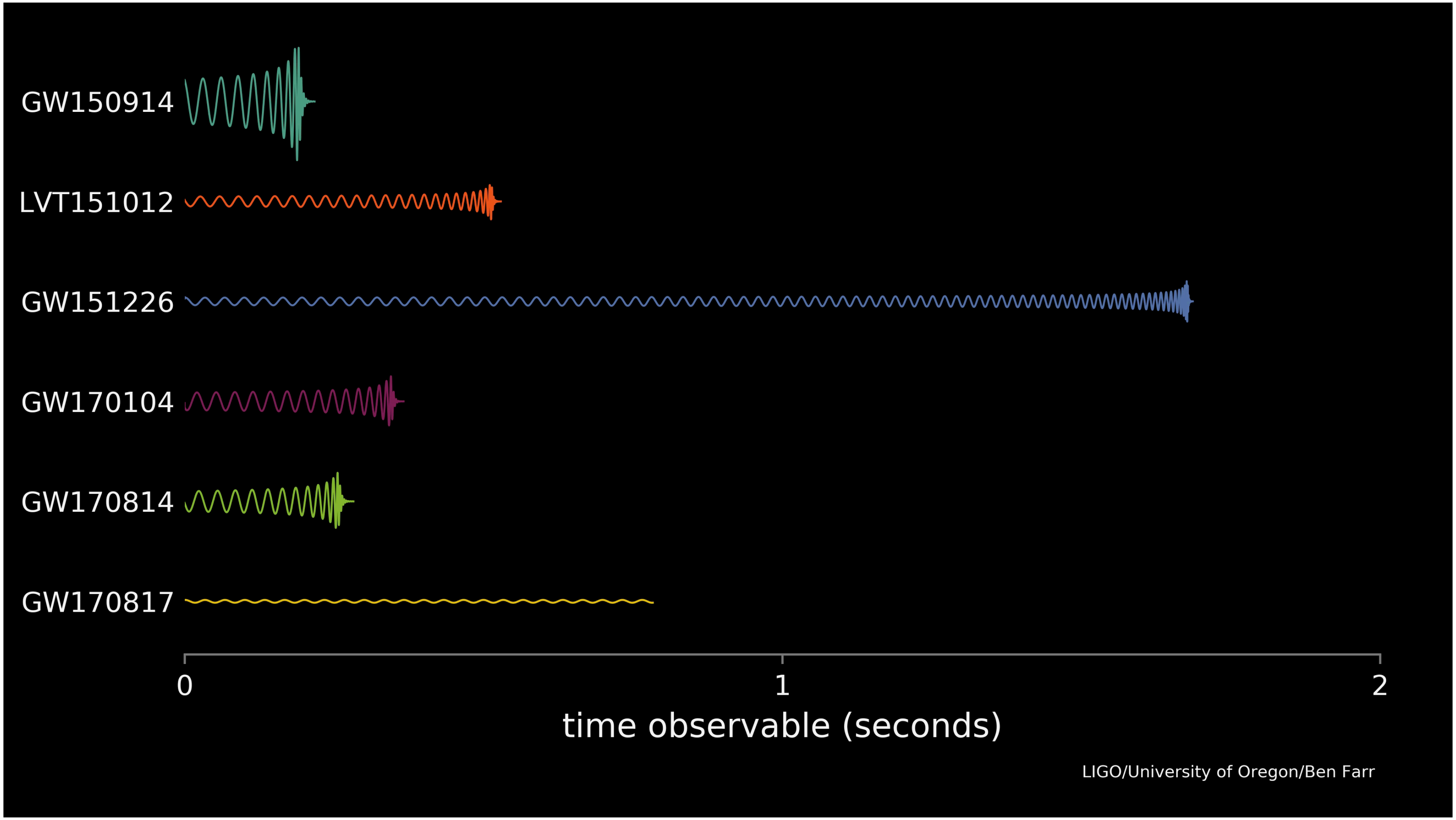
Supermassive black holes



Direct evidence: GW150914



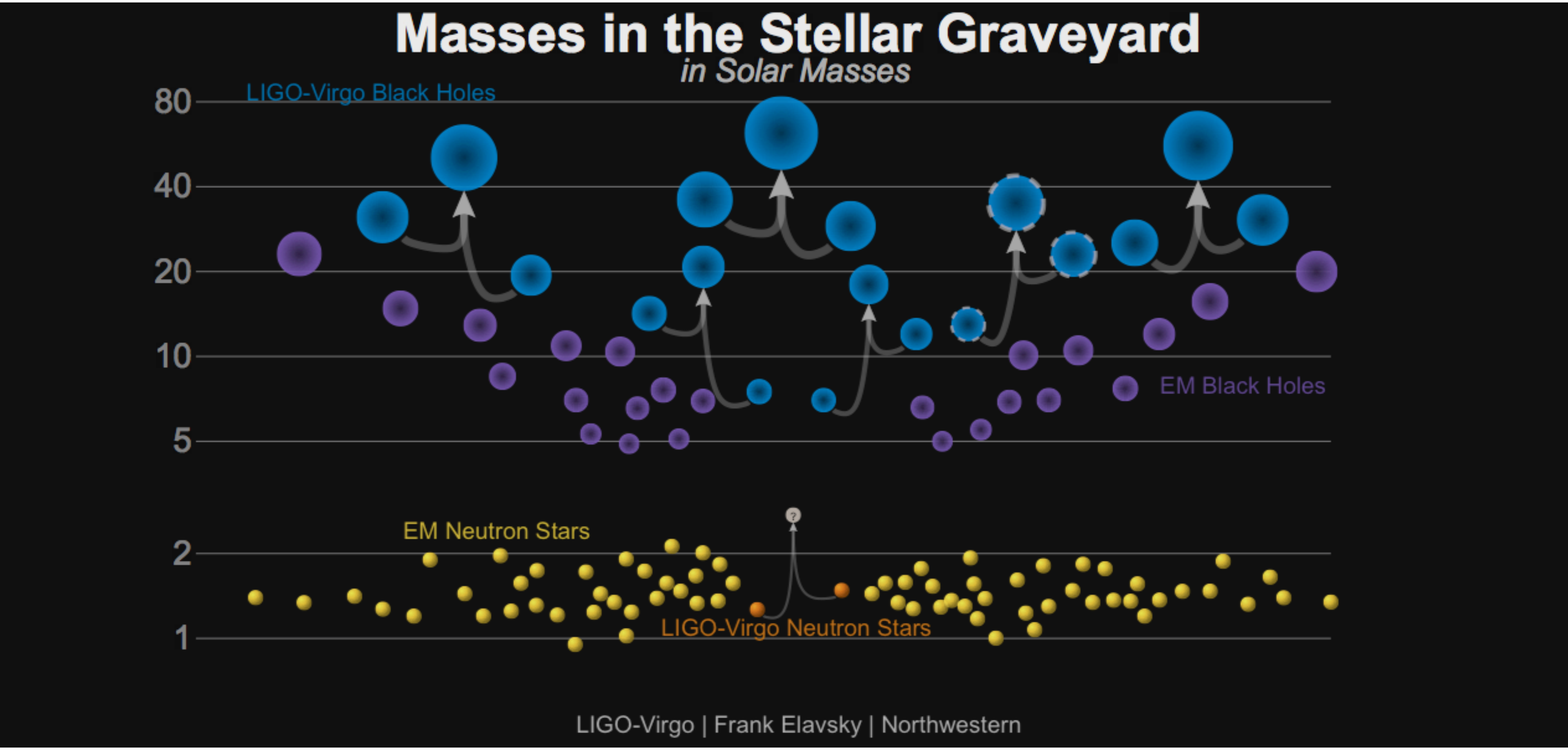
Colliding neutron stars and black holes



Compact binary coalescence GW waveform

- Rich, detailed information carried in the inspiral, merger, and ringdown
- Inspiral:
  - Distance to source, spin of components, precession, masses, tidal distortion
- Merger:
  - Total mass, tidal distortion, progenitor of remnant
- Ringdown:
  - Final mass, remnant formation

Stellar remnants and mergers



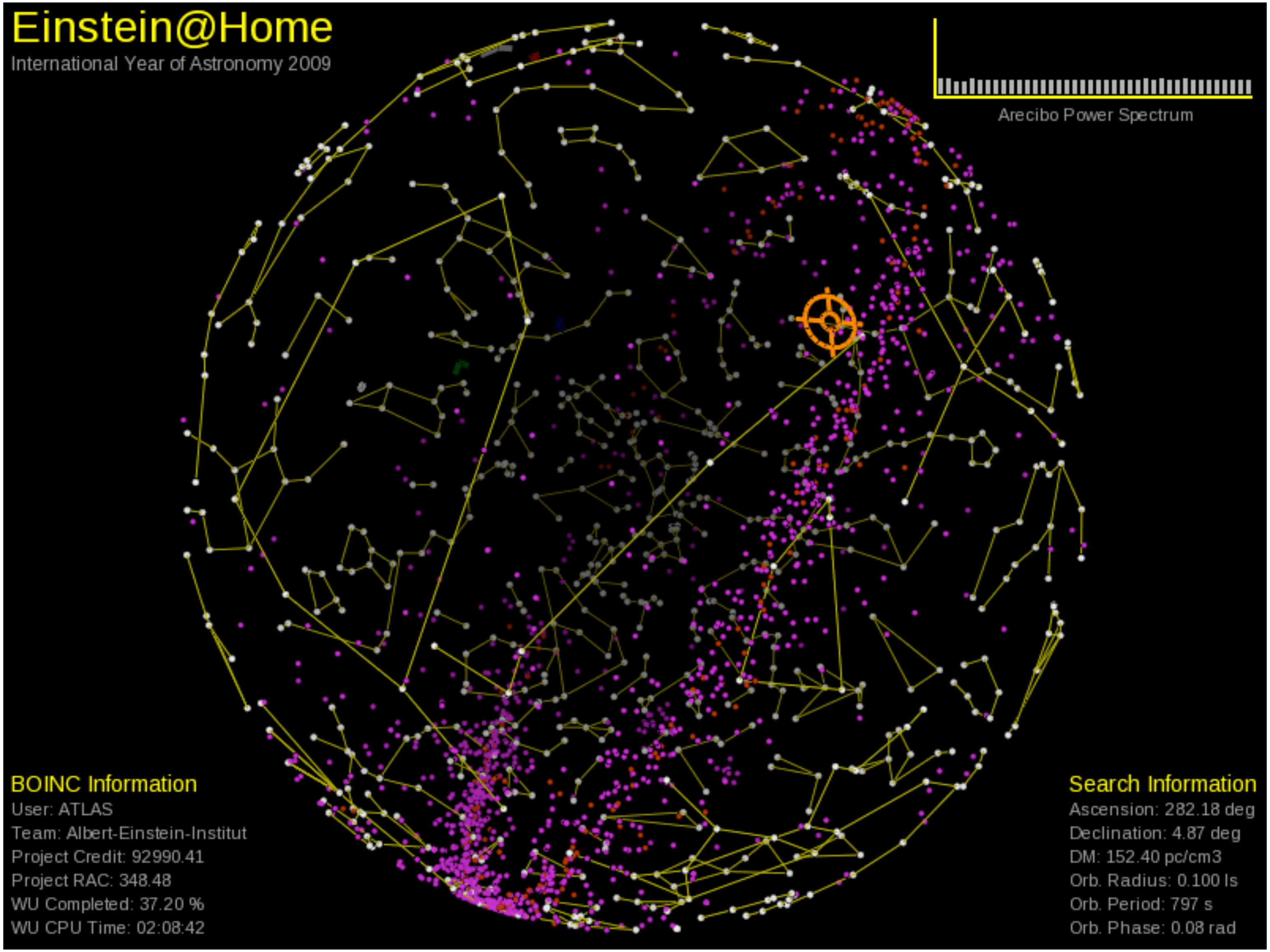
Open questions

- Narrowing in on NS equation of state − more observations will help; continuous GWs?
- Merging NSs can provide an alternative measurement of the Hubble constant; will it resolve the tension from current EM measurements?
- How do supermassive BHs form? Are there intermediate mass BHs?
- Can GWs help answer fundamental questions about the nature of BHs?

Other really cool things about GR

- Physicists are using the accurate pulse arrival times of several pulsars to create a galactic-scale GW detector (Pulsar Timing Array)
- Black holes obey the laws of thermodynamics and can "evaporate" (Hawking radiation)
- When compact objects merge, a DC shift in gravitational potential may be observed (gravitational memory)

Volunteer computing: Einstein@home



Summary

- Death of a massive star is not the end of scientific study
- Neutron stars and black holes provide rich environment of studying extremes physics not achievable in the lab
- GWs provide unique insight and complement EM observations
- Era of multi-messenger astronomy is here and you can get involved!

Thank you!