Piecing Together the Neutron Star Puzzle: A Multi-Messenger Exploration of Extreme Matter

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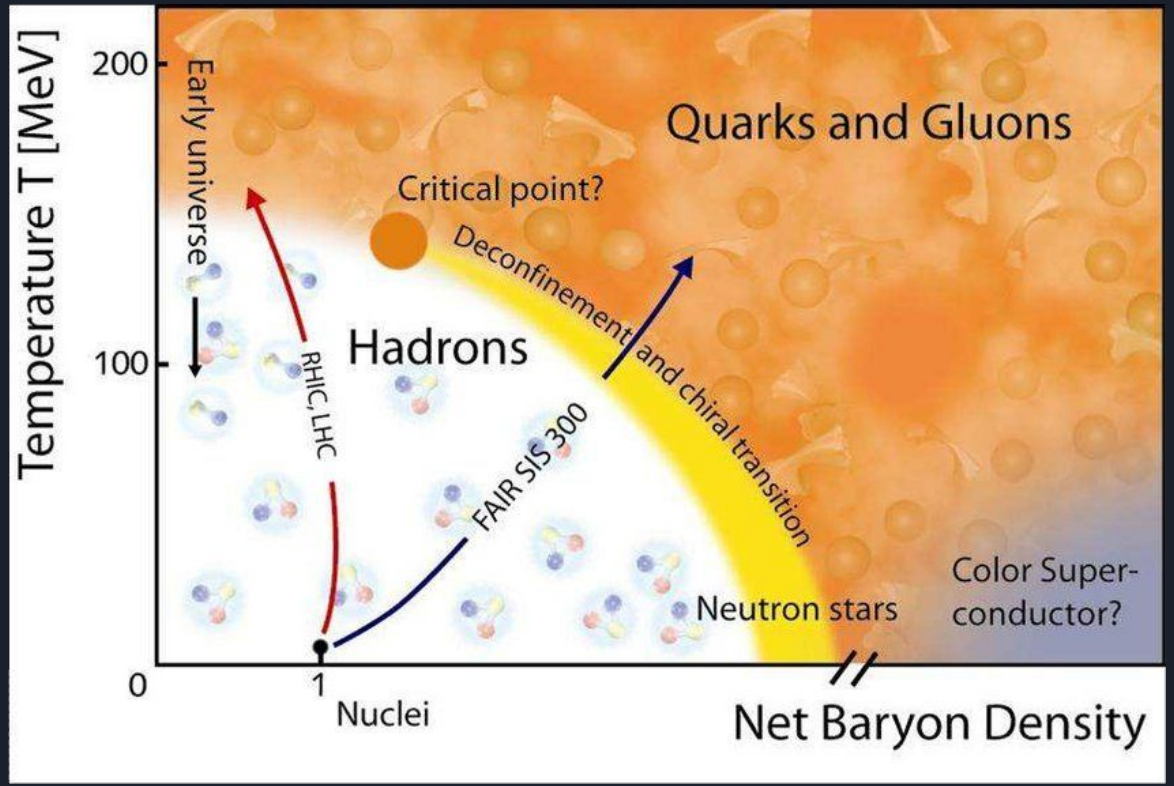
Nikhef

What is a neutron star?

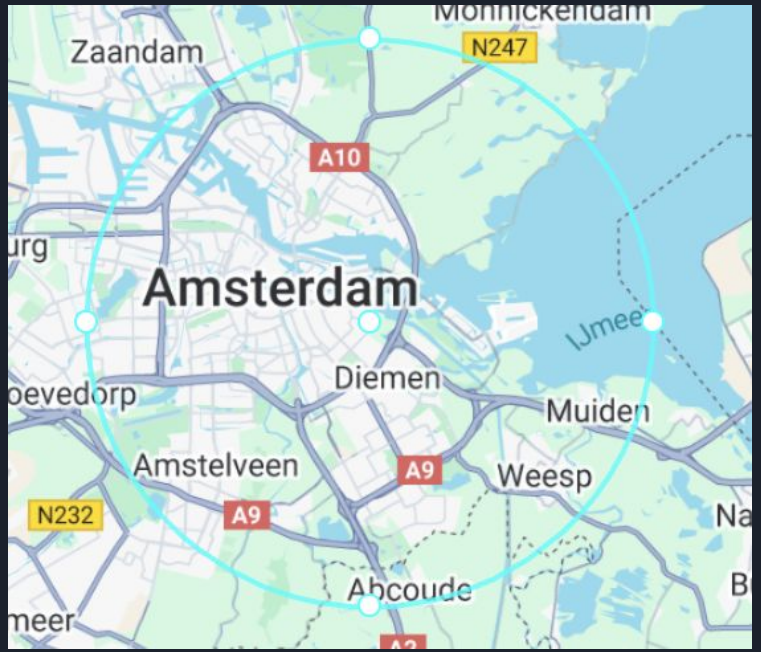


What is a neutron star?

- When a star of 8 - 20 solar masses exhausts its fuel
  - Undergoes a supernova
- The star's core collapses under gravity, and protons and electrons combine to form neutrons.
- Neutron star is on the edge of collapsing into a black hole

What is a neutron star?

- **Incredibly dense**
  - A neutron star packs the Sun's mass into a sphere about 15 km across
  - Supranuclear matter that full of mystery
- **Strong gravity**
  - Most compact object other than black hole
  - Escape velocity up to ~50% of c
- **Not replicable on Earth**



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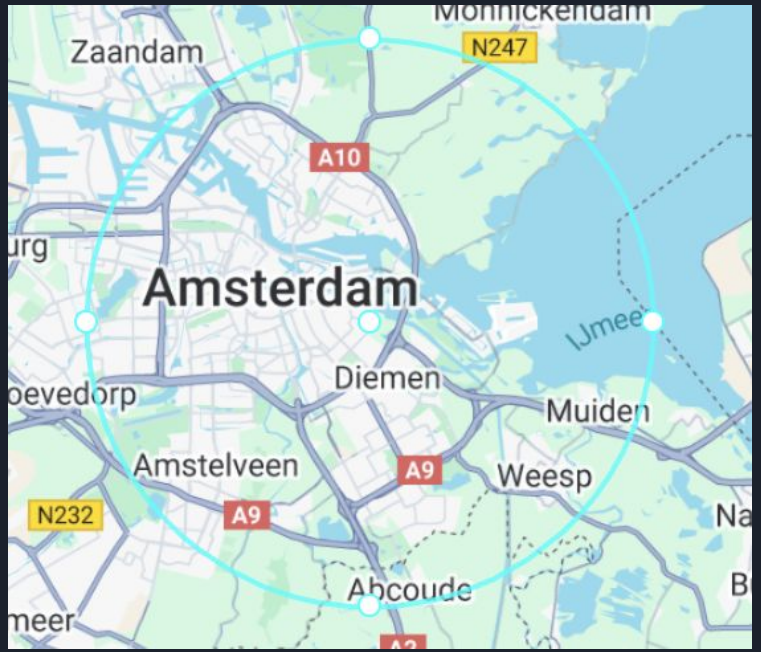

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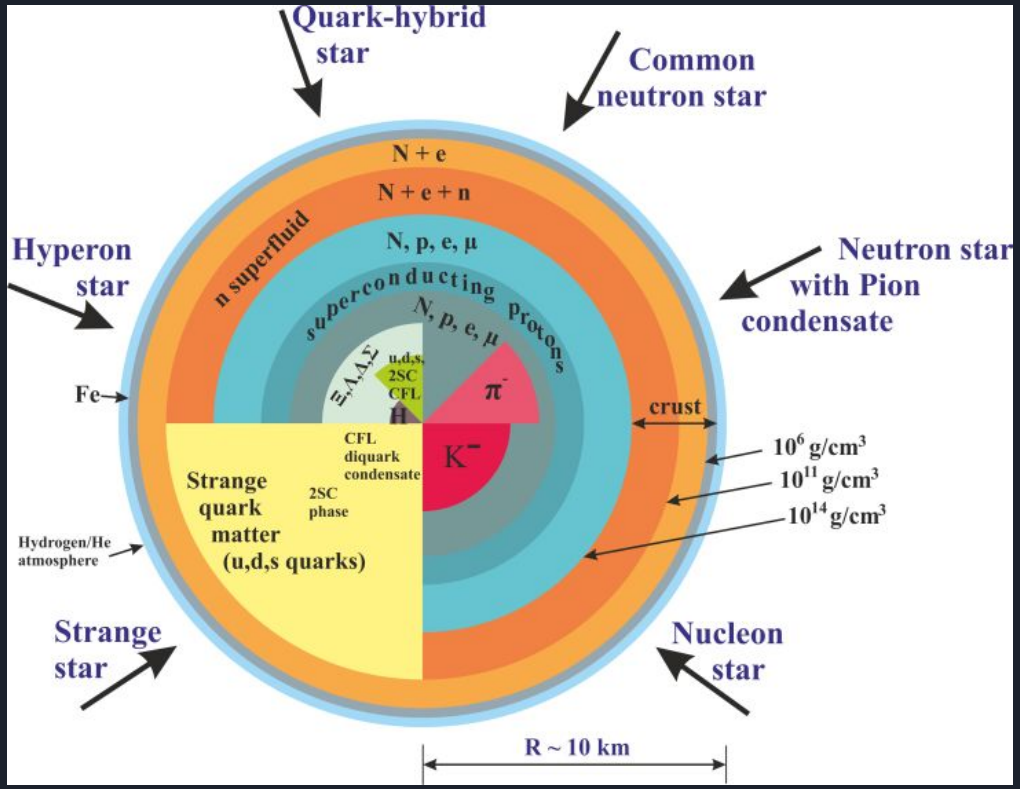
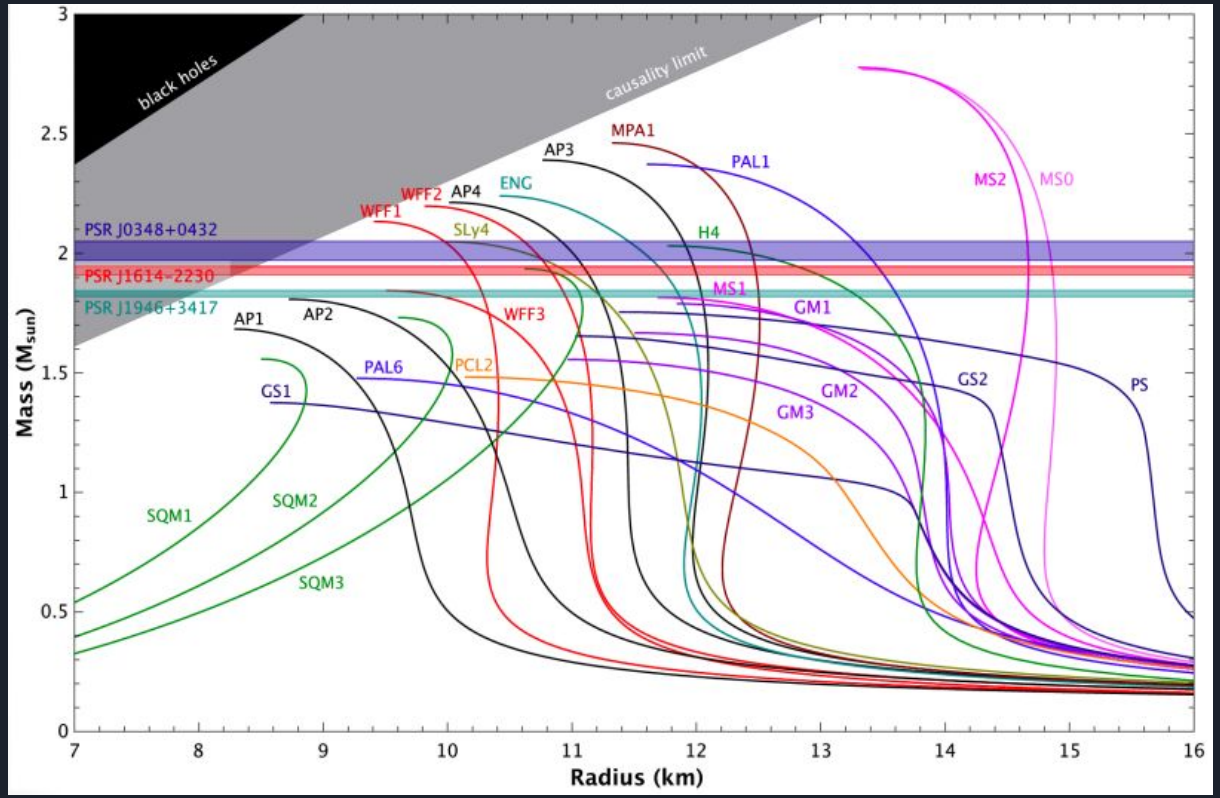


What is a neutron star made of?



Solving the neutron star puzzle

Common ground

- What is Bayesian statistics?
- What is an equation of state?
- What are the Tolman-Oppenheimer–Volkoff equations

Bayesian statistics

$$\text{Posterior} \propto \text{Likelihood} \times \text{Prior}$$

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- Astrophysical observations
- Experimental results
- Theoretical calculations

Bayesian statistics

$$\text{Posterior} \propto \text{Likelihood} \times \text{Prior}$$

- Encode prior information / knowledge
- As generic as possible

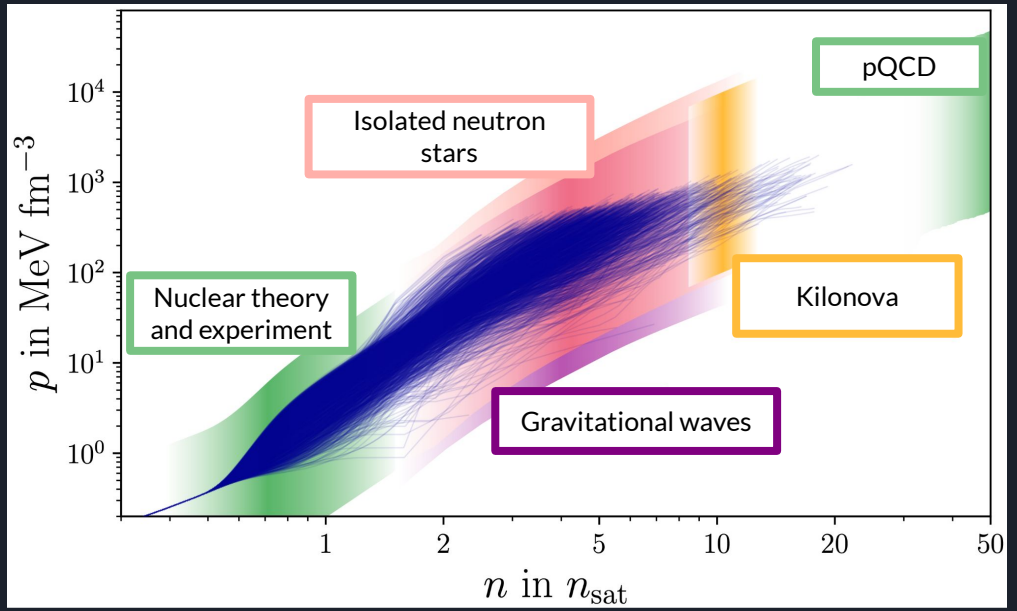
Bayesian statistics

$$\text{Posterior} \propto \text{Likelihood} \times \text{Prior}$$

What we know about the neutron star (so far)

Equation of state

- Thermodynamic equation relating state variables
- Relating pressure and density at zero temperature
- Described by Quantum Chromodynamics (QCD)
- Direct calculation is very difficult



Tolman–Oppenheimer–Volkoff equation

- Relativistic hydrostatic equation
- Assuming a spherical star
- Additional input of $p(\epsilon)$
- Maximum allowed mass

$$\frac{dm}{dr} = 4\pi r^2 \epsilon$$

$$\frac{dp}{dr} = -\frac{m}{r^2}\epsilon \frac{\left(1+\frac{p}{\epsilon}\right)\left(1+\frac{4\pi r^3 p}{m}\right)}{1-\frac{2m}{r}}$$

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Newtonian hydrostatic

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Relativistic corrections

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Pressure also experience gravity

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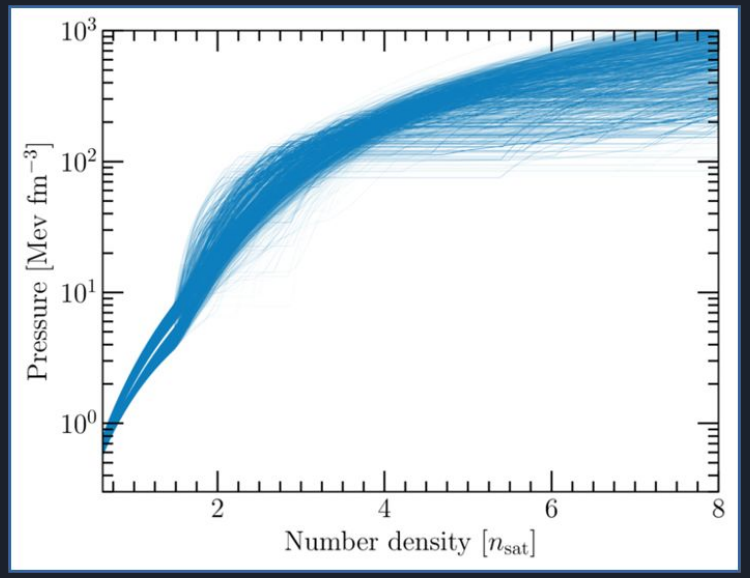
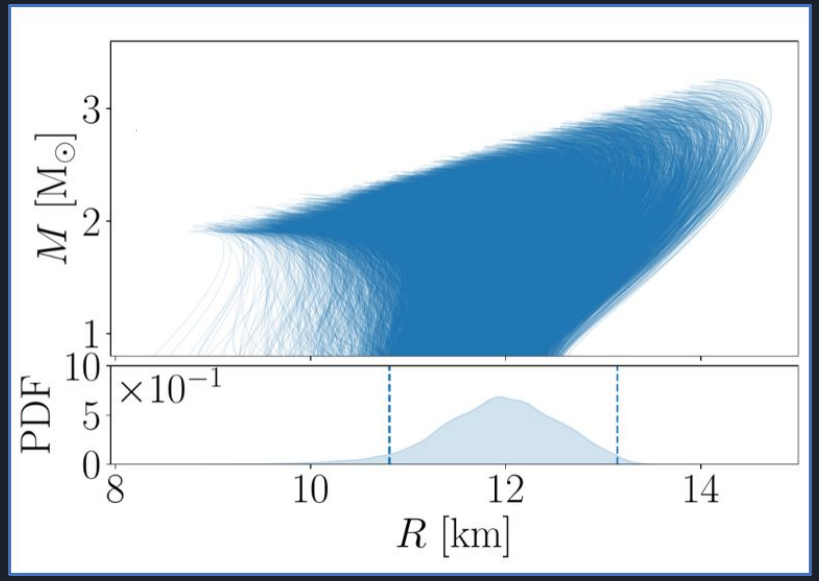
Metric correction due to gravity

Tolman–Oppenheimer–Volkoff equation

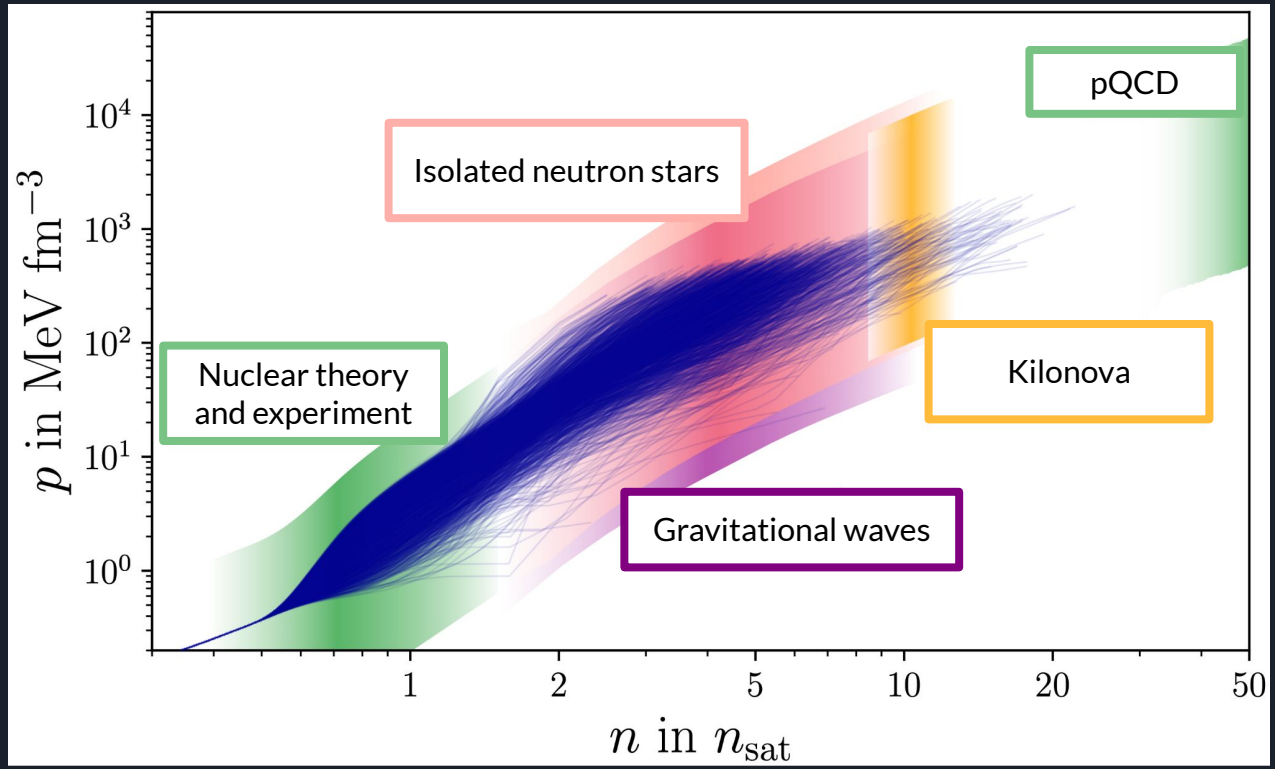


TOV equation

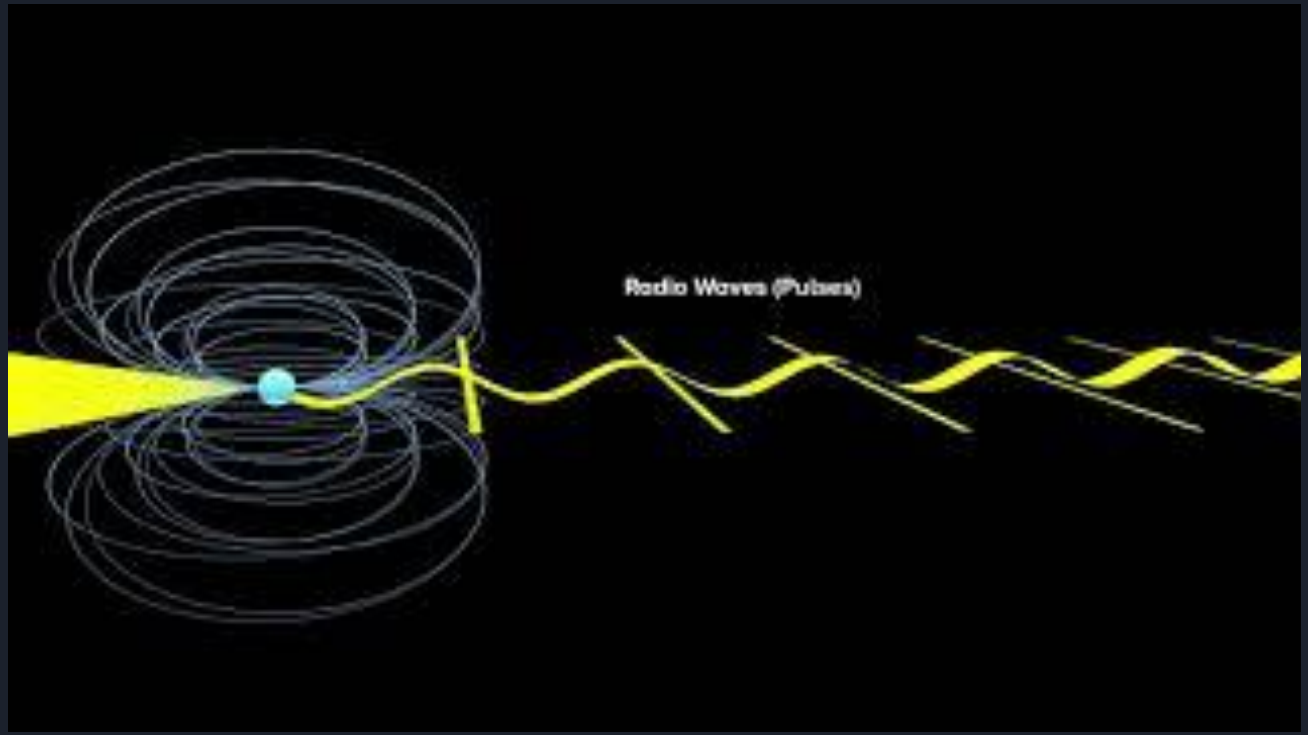


Relating the microscopic properties of neutron star matter to the macroscopic feature of a neutron star

Neutron star puzzle pieces

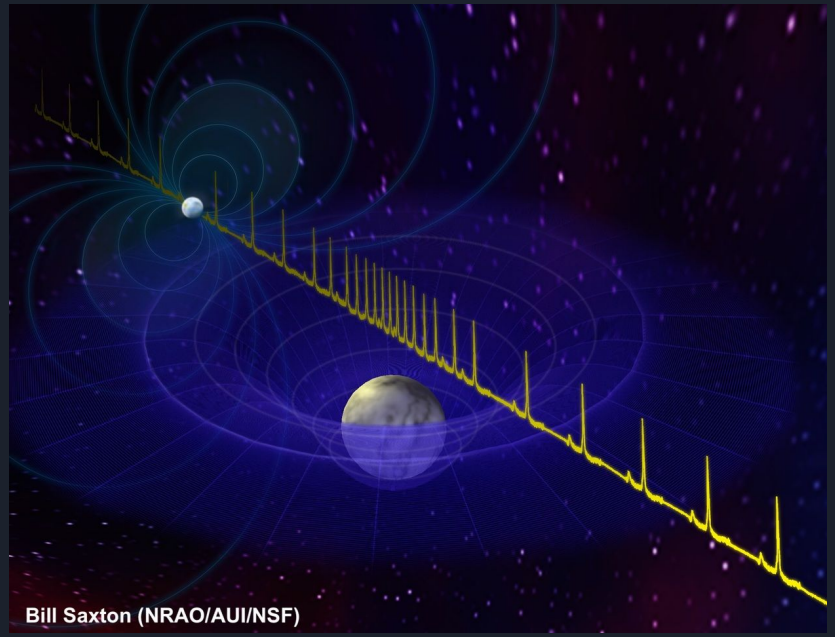


Radio timing



Radio timing

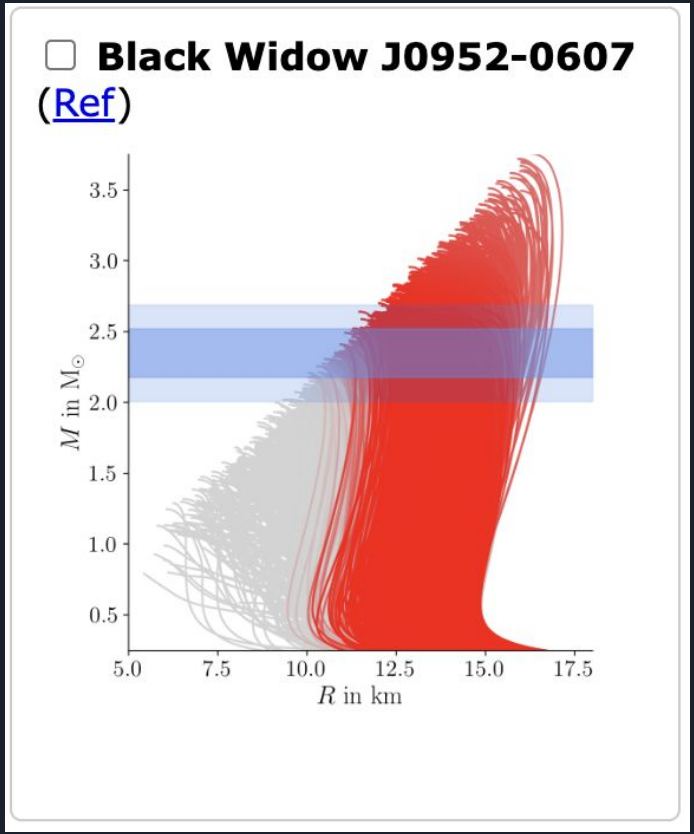
- Measuring the radio signal
  - Shapiro time delay
  - Mass of the neutron star
- Unlike Newtonian gravity
  - Maximum allowed mass
  - Inform us about the neutron star matter



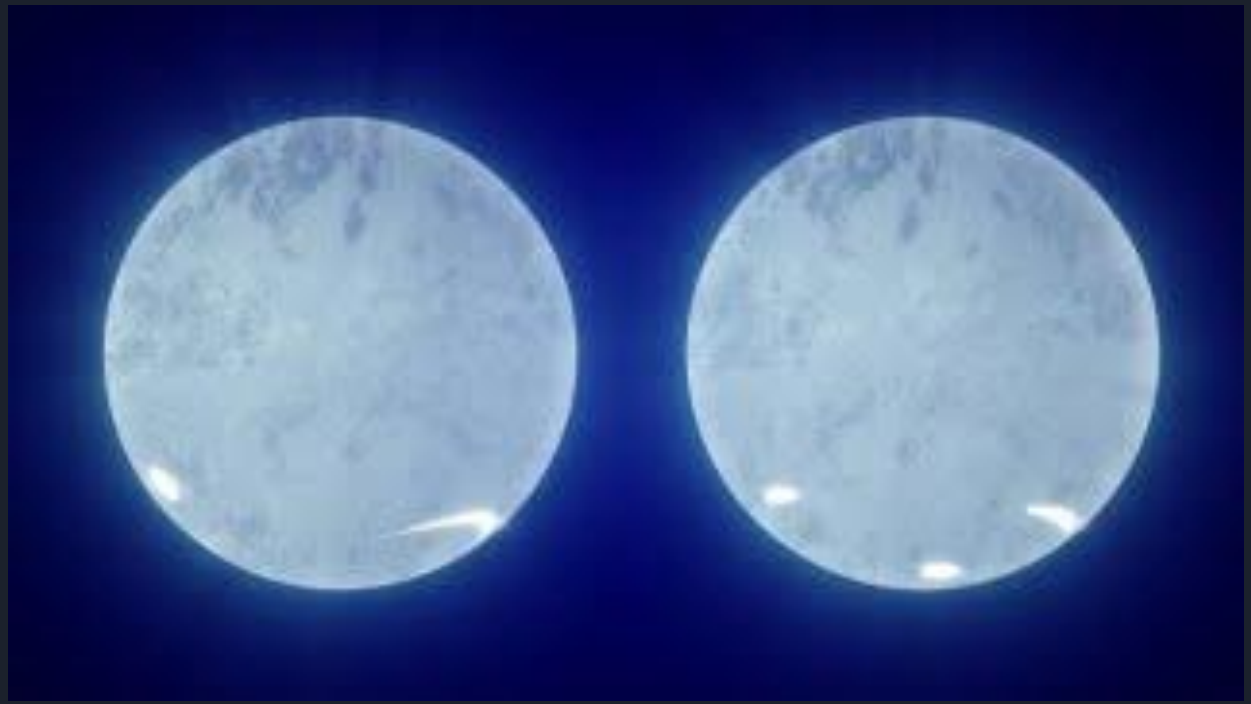
Black widow J0952-0607

- Most massive neutron star ever observed
- Low-mass companion’s outer atmosphere is evaporated by the pulsar's radiation.
- Uncertainties from heat transport and temperature variations on the companion’s surface

Black widow J0952-0607



The Neutron Star Interior Composition Explorer Mission



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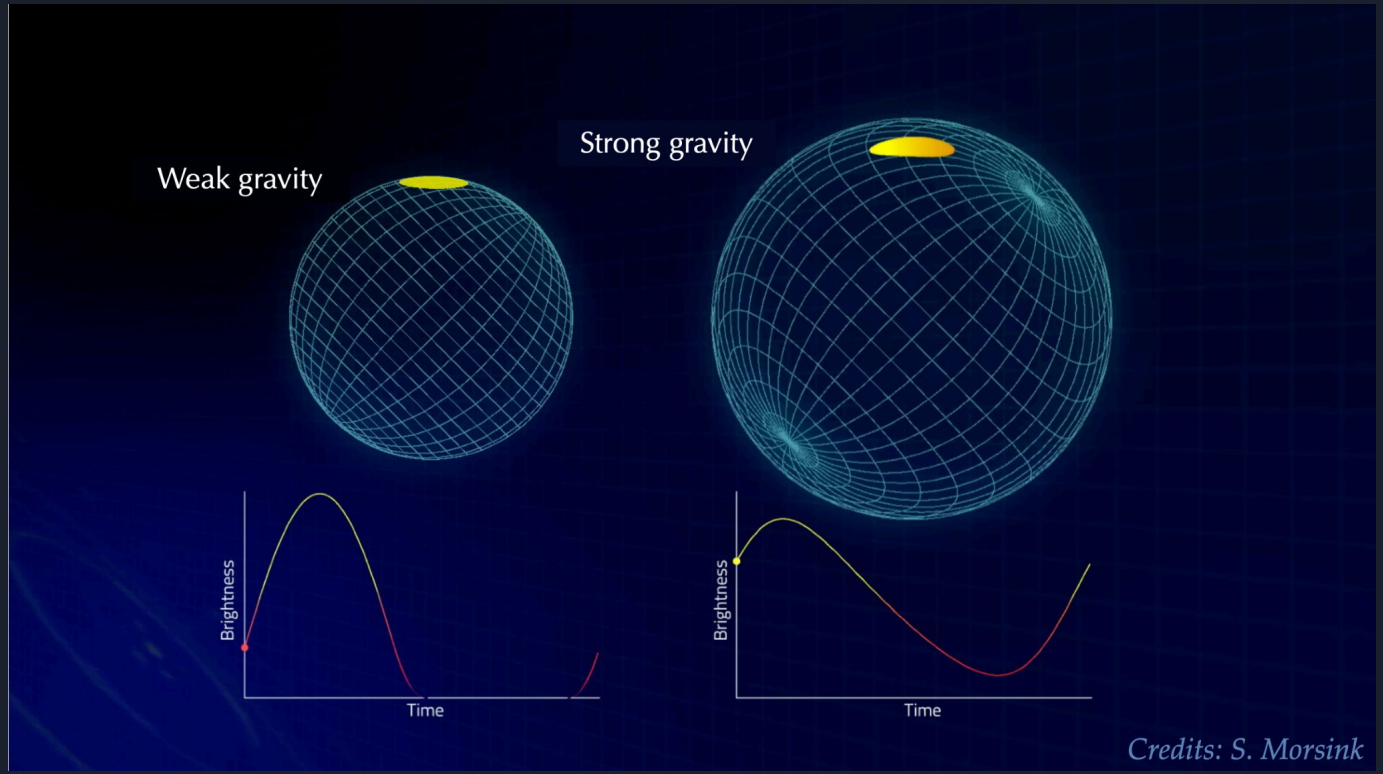

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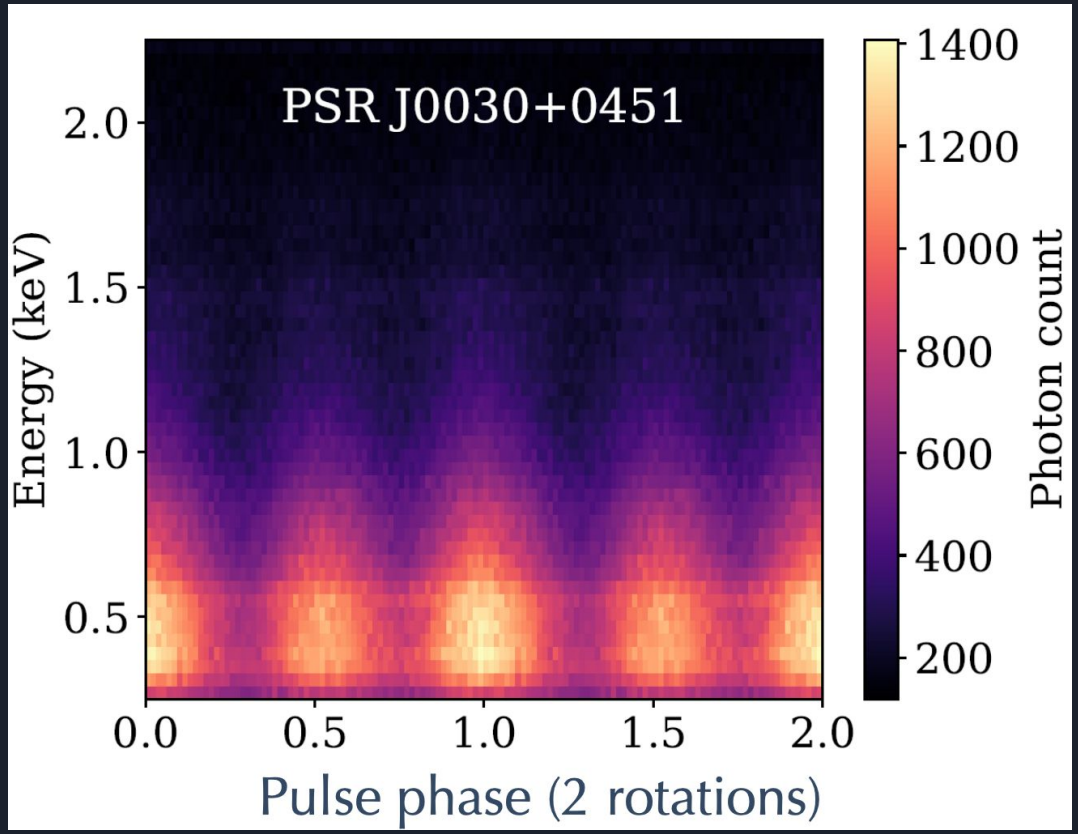

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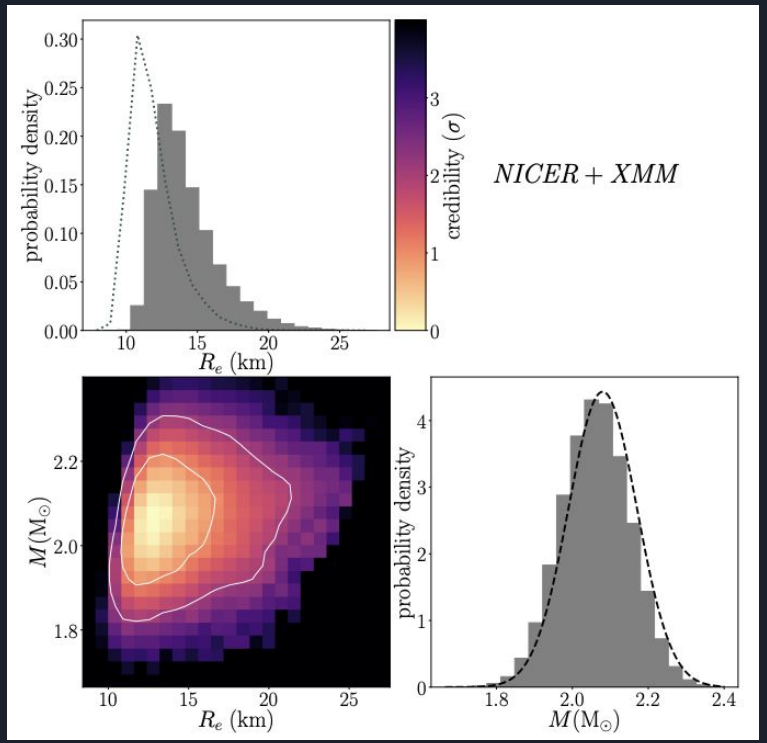
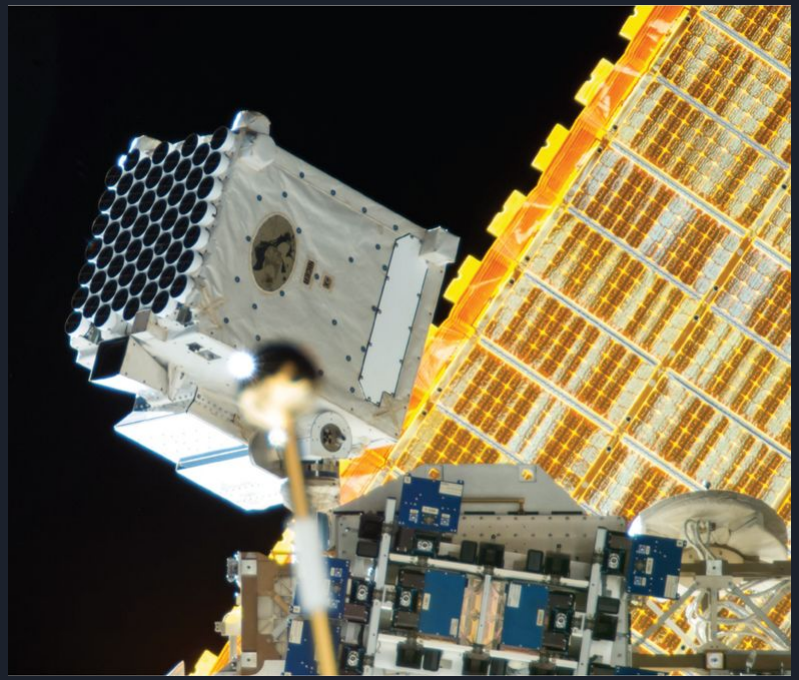
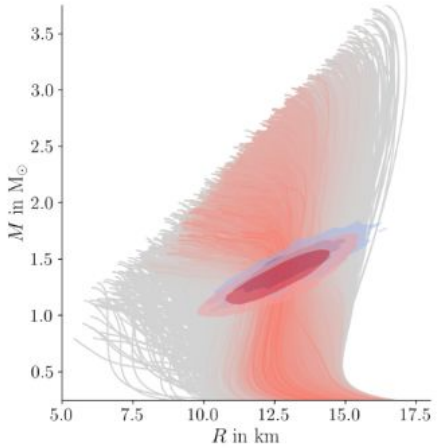


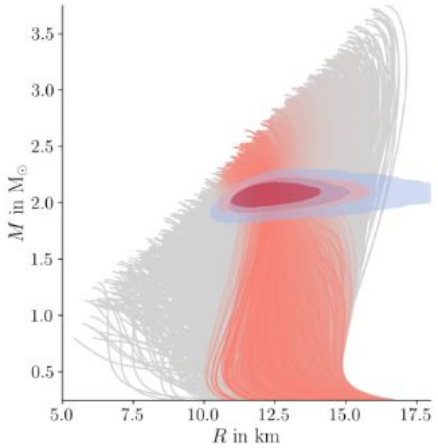


NICER

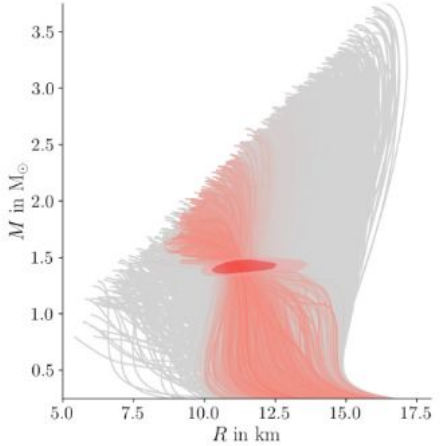
☐ **NICER J0030+0451** (Ref, Ref)



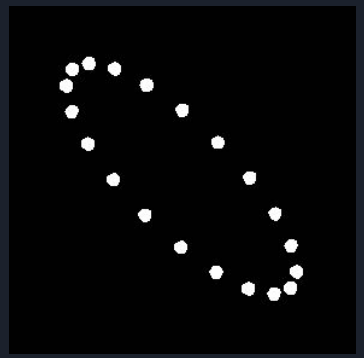
☐ **NICER J0740+6620** (Ref, Ref)

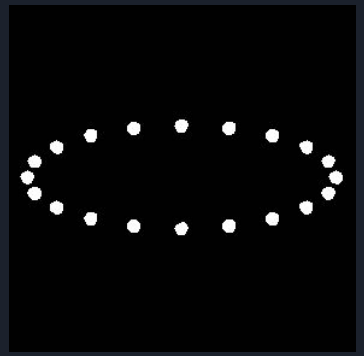


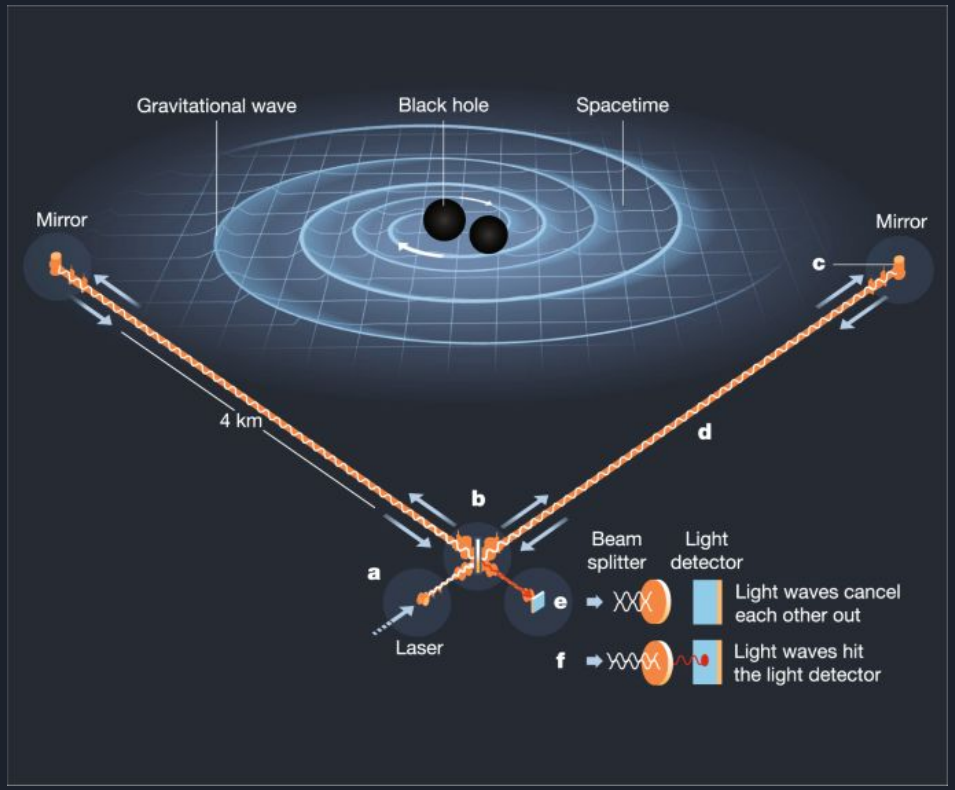
☐ **NICER J0437-4715** (Ref)



Gravitational waves







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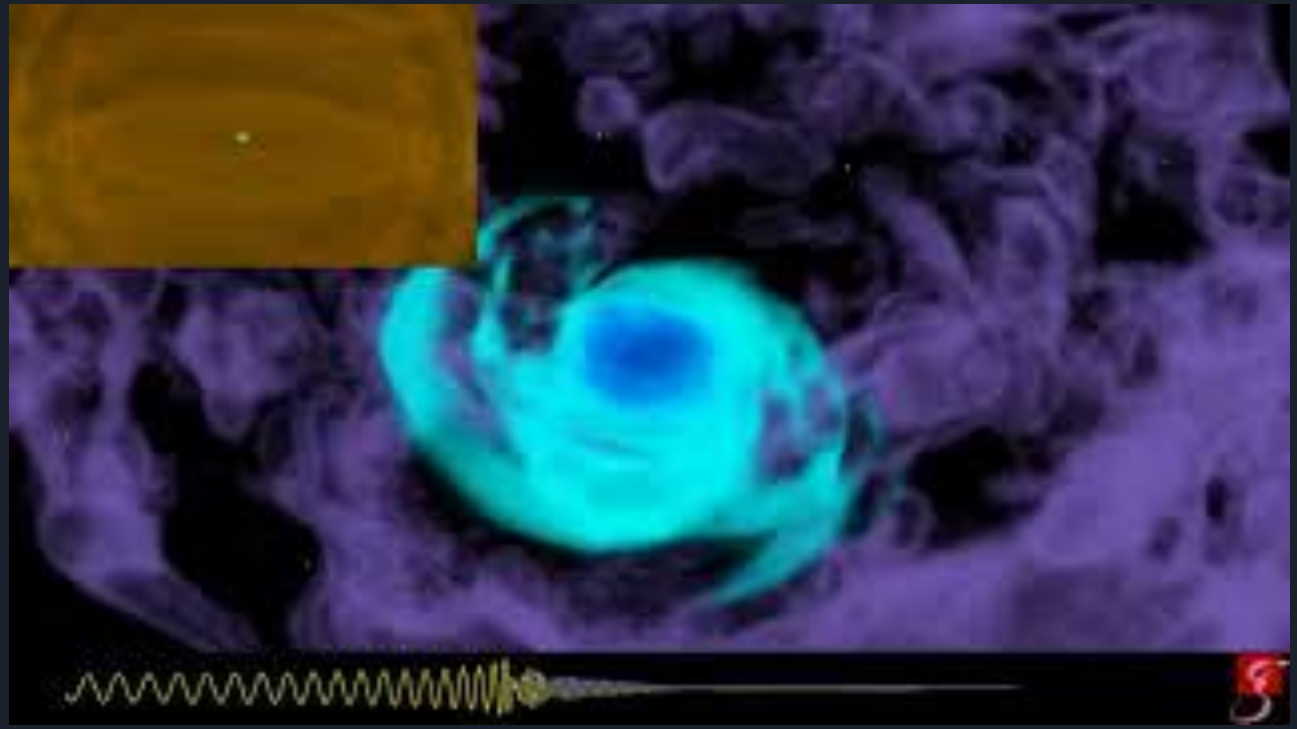

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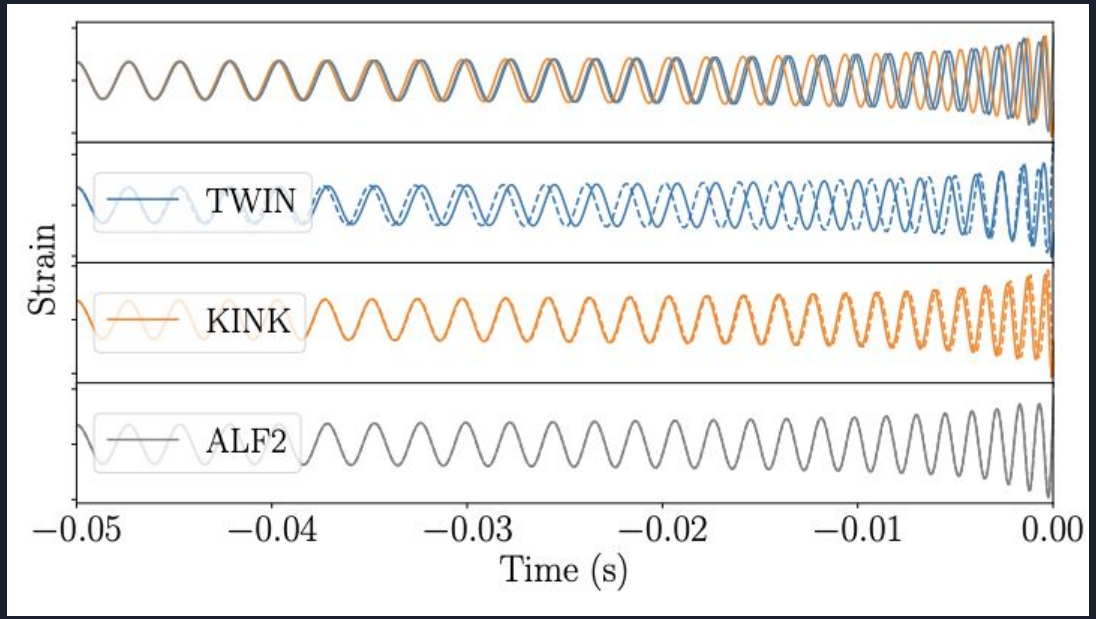

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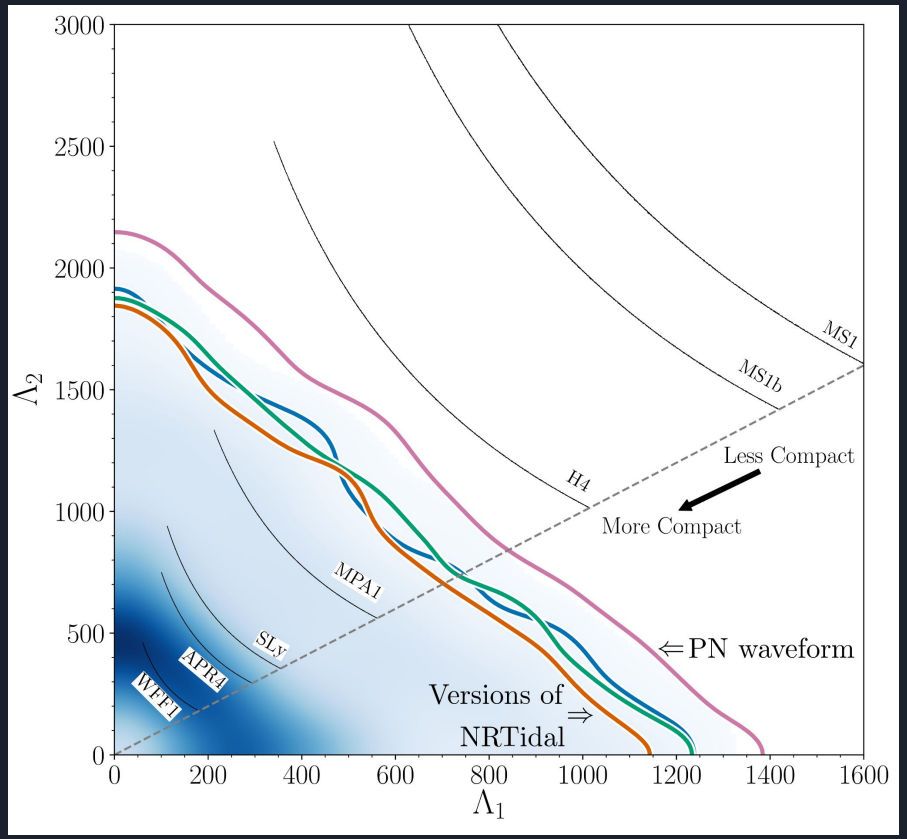

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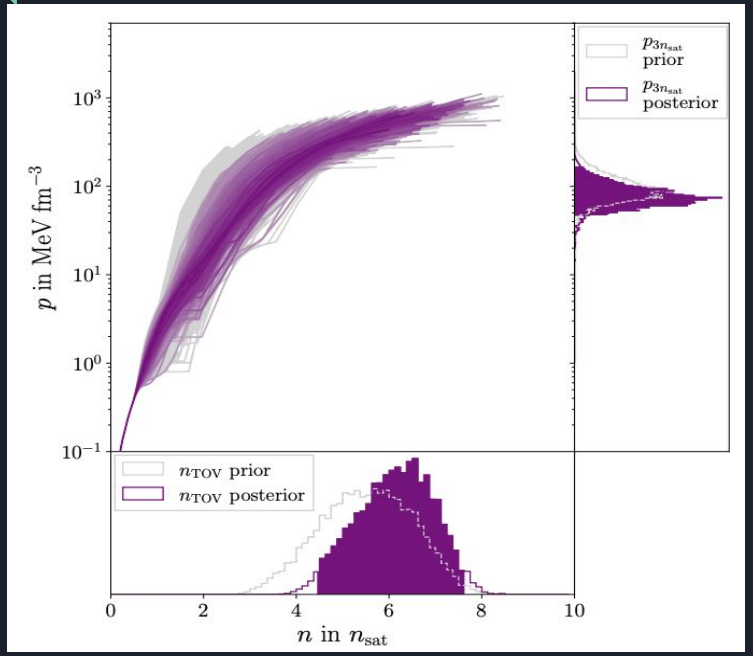
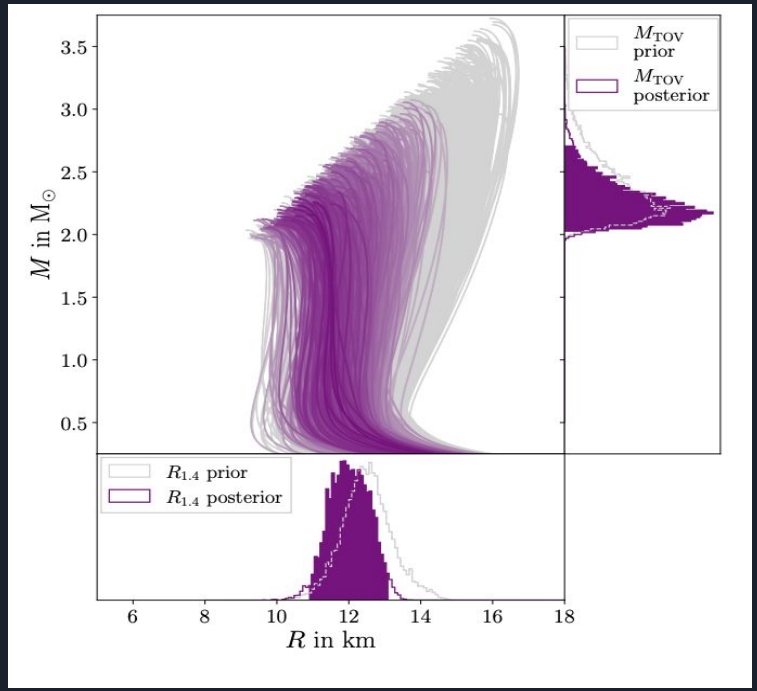
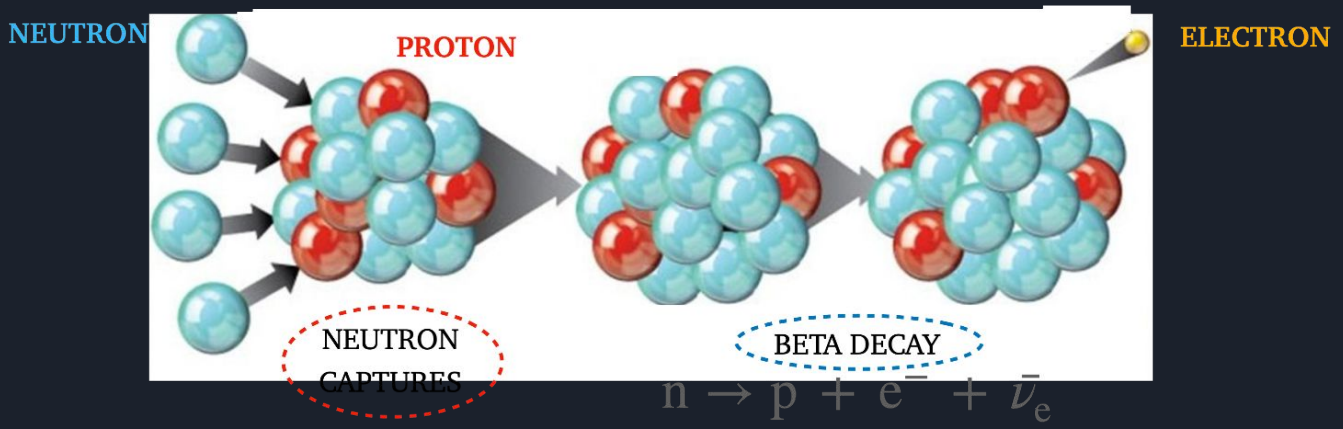
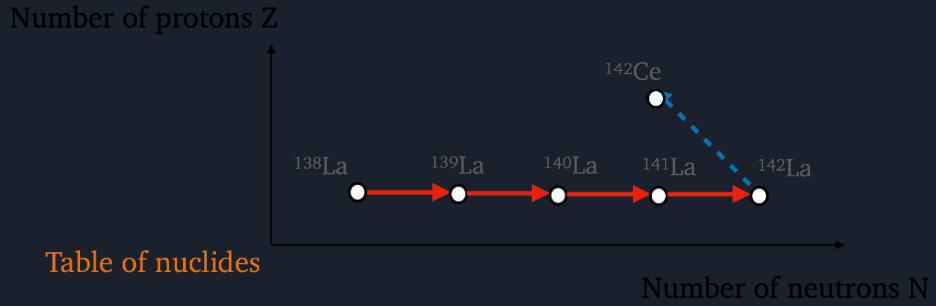




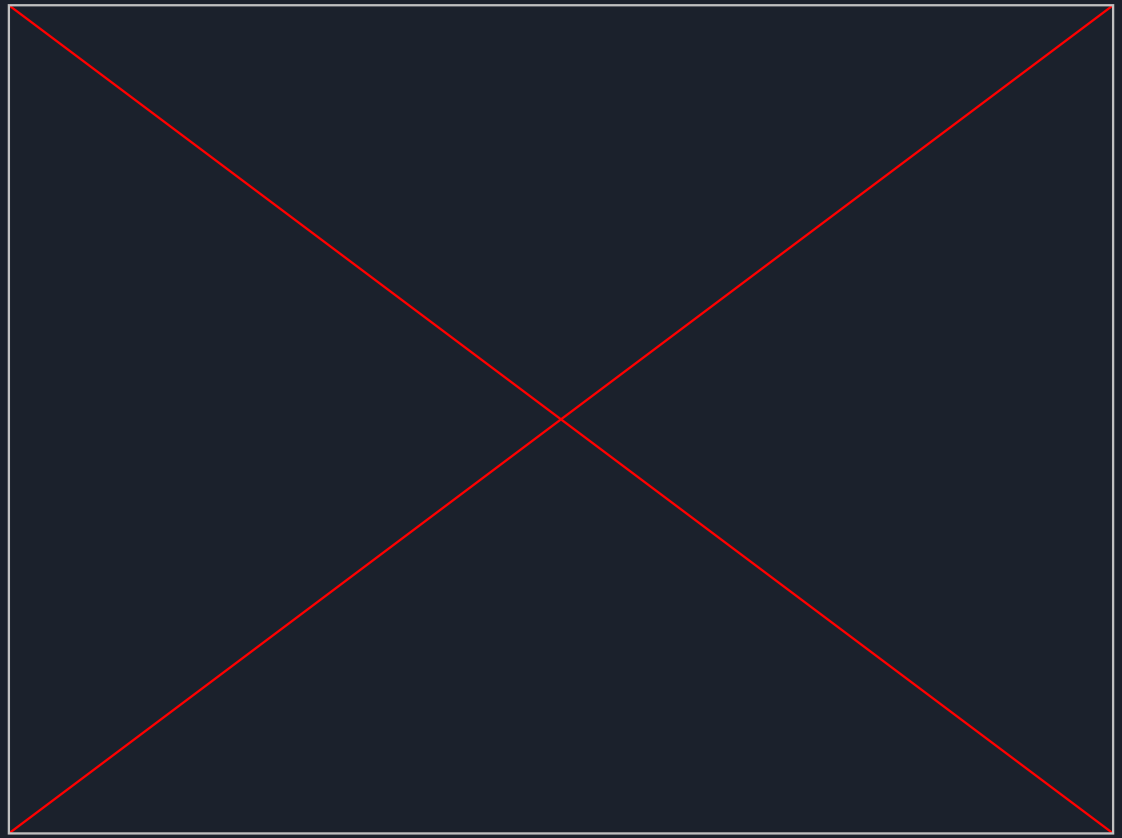
Kilonova

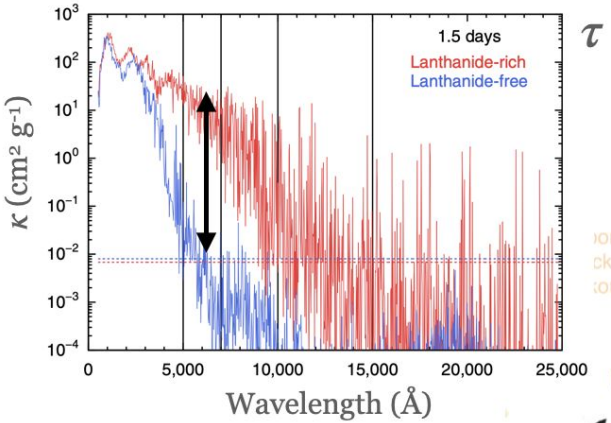
r-process


NEUTRON
PROTON
ELECTRON
NEUTRON CAPTURES
BETA DECAY
$n \rightarrow p + e^- + \bar{\nu}_e$

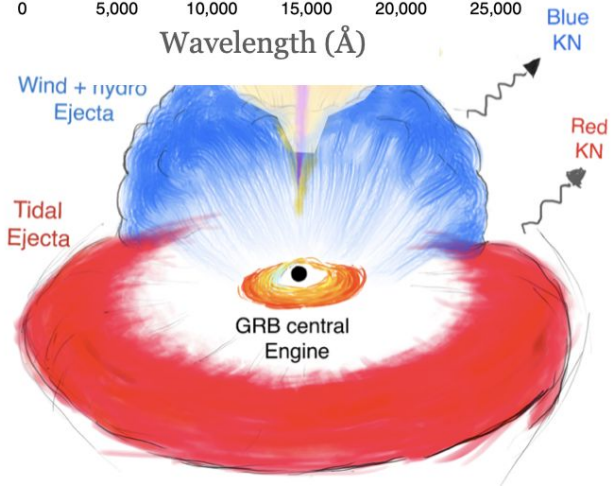

Number of protons Z
^{142}Ce
^{138}La
^{139}La
^{140}La
^{141}La
^{142}La
Table of nuclides
Number of neutrons N

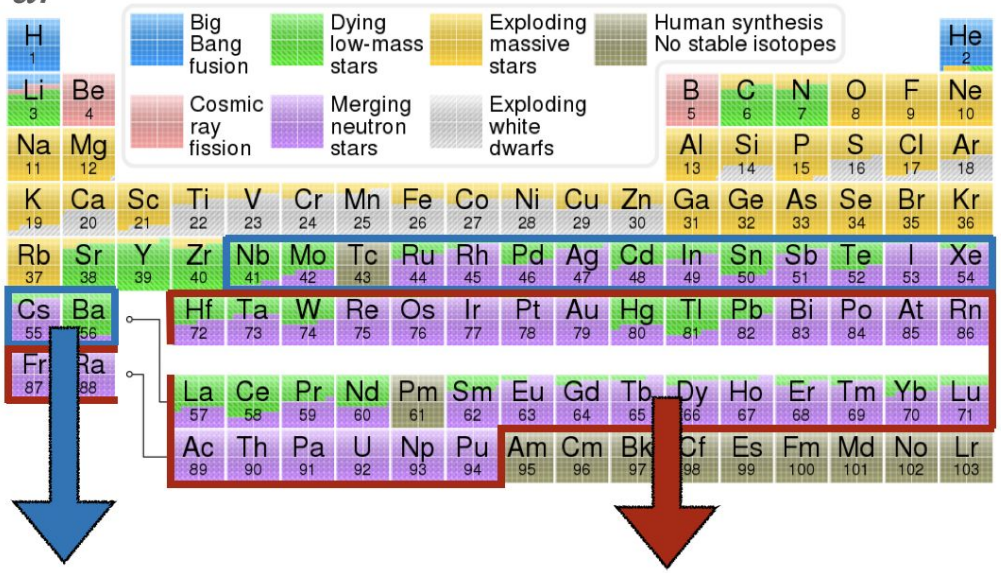
r-process





$$\tau = \int \kappa \rho \, dr$$





$Y_e \gtrsim 0.25$

Low opacities

Blue KN

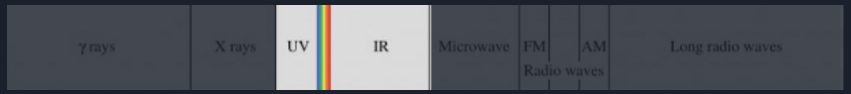
$Y_e \lesssim 0.25$

High opacities

Red KN

Kilonova

- Transient events that last from days to weeks
- They similar profile as supernovae but shorter
- Powered by the radioactive decay of heavy, neutron-rich elements
- These elements are synthesized in the expanding ejecta from a neutron star merger though r-process



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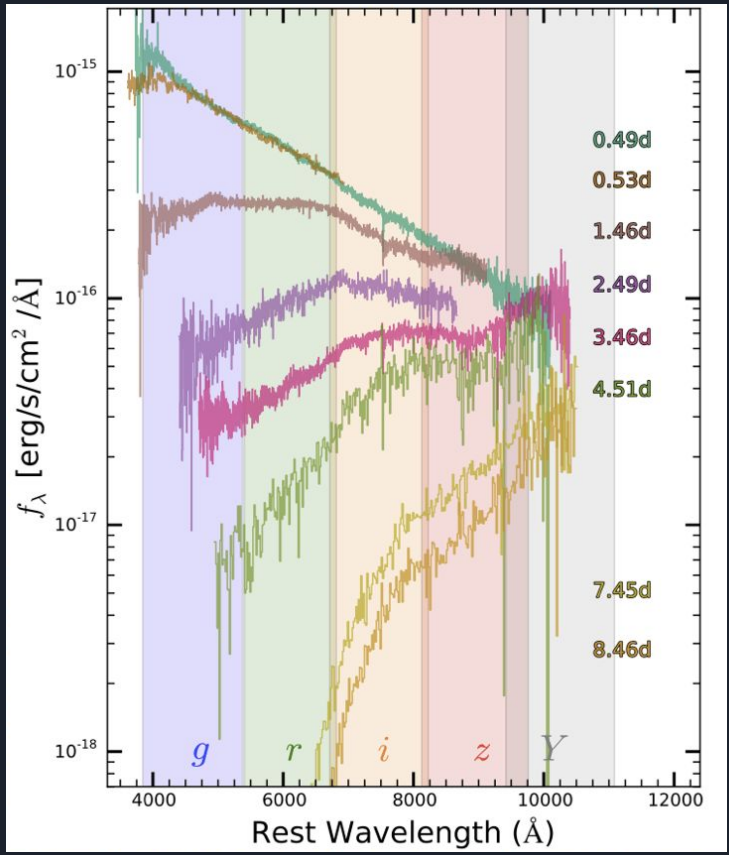
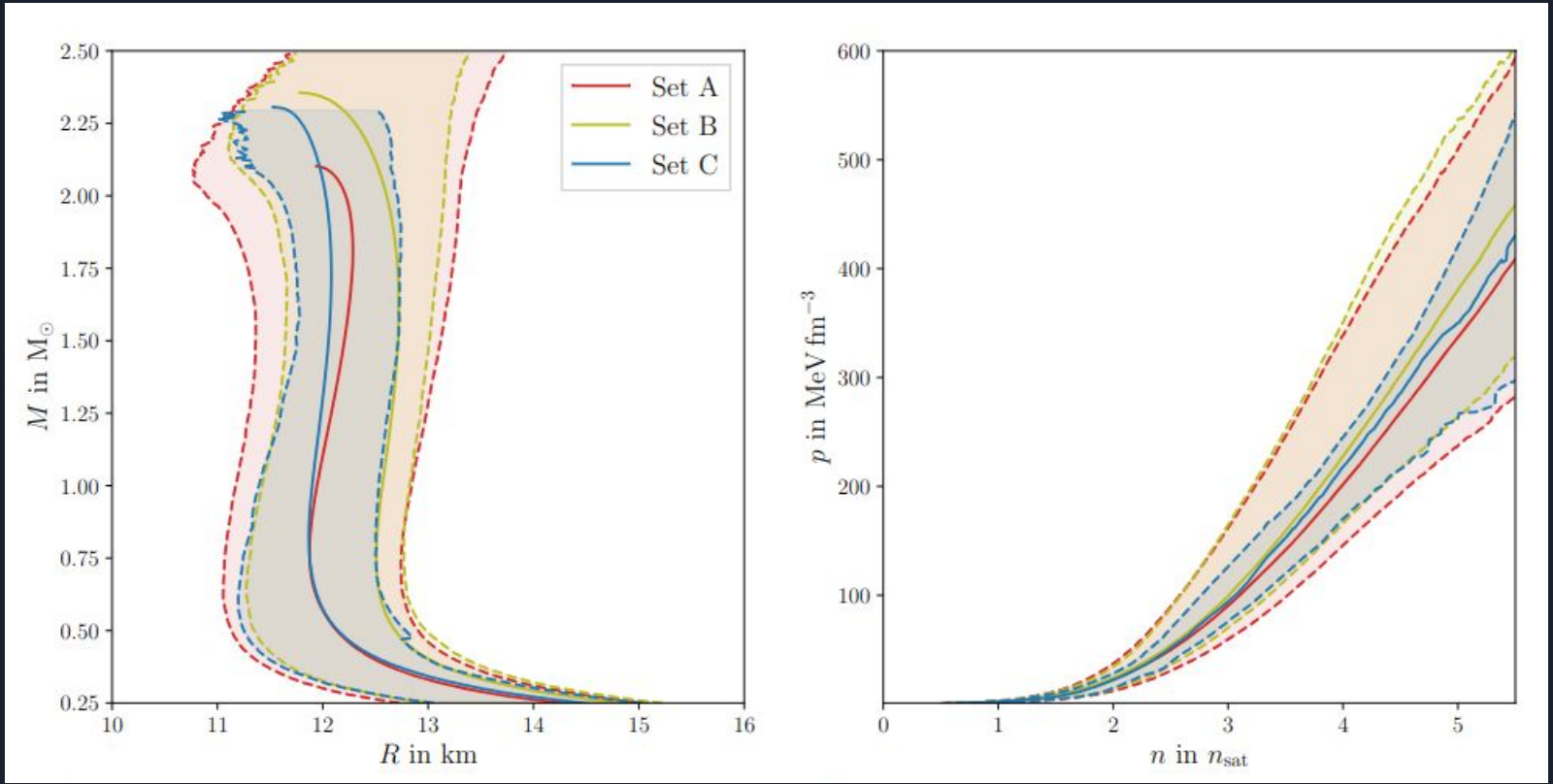
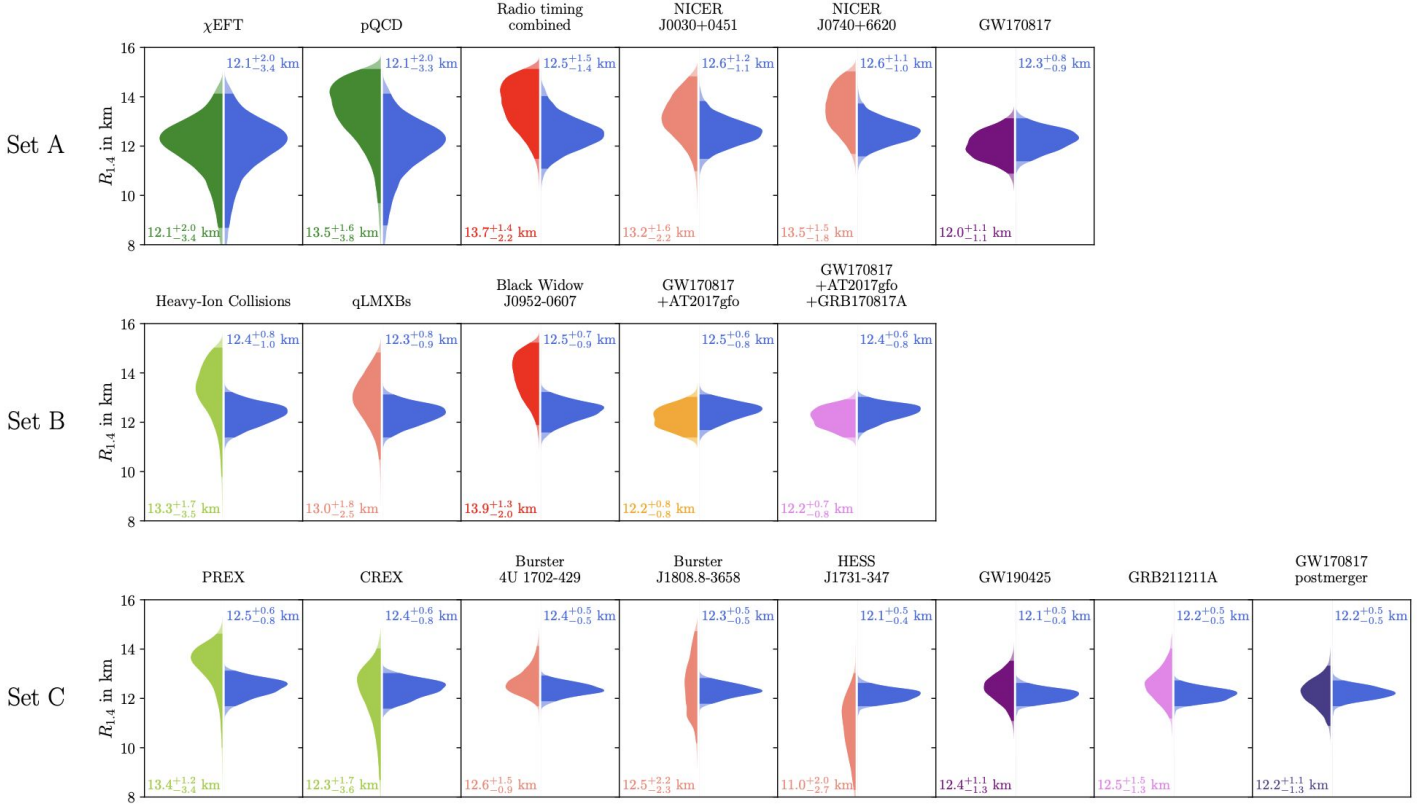


Neutron star puzzle pieces

Nuclear experiment / theory	Isolated neutron star	Binary neutron star
Chiral EFT	Radio timing	GW170817 + AT2017gfo + GRB170817A
pQCD	NICER	
PREX-II	Black widow	GW190425
CREX	qLMXBs	GRB211211A
Heavy ion collision	Thermonuclear accretion bursts	Post-merger of GW170817


Set A
Set B
Set C
M in $M_\odot$
R in km
p in MeV fm^{-3}
n in n_{sat}


Set A
Set B
Set C
$R_{1.4}$ in km
χEFT
pQCD
Radio timing combined
NICER J0030+0451
NICER J0740+6620
GW170817
Heavy-Ion Collisions
qLMXBs
Black Widow J0952-0607
GW170817 +AT2017gfo
GW170817 +AT2017gfo +GRB170817A
PREX
CREX
Burster 4U 1702-429
Burster J1808.8-3658
HESS J1731-347
GW190425
GRB211211A
GW170817 postmerger

Set	A	B	C
$R_{1.4}$ in km	$12.27^{+0.83}_{-0.94}$	$12.43^{+0.56}_{-0.8}$	$12.20^{+0.53}_{-0.50}$
M_{TOV} in $\mathrm{M}_{\odot}$	$2.26^{+0.45}_{-0.22}$	$2.37^{+0.36}_{-0.24}$	$2.31^{+0.08}_{-0.20}$
$p_{3n_{\mathrm{sat}}}$ in $\mathrm{MeV\,fm^{-3}}$	92^{+78}_{-33}	104^{+70}_{-34}	97^{+29}_{-22}
n_{TOV} in n_{sat}	$5.88^{+1.39}_{-1.41}$	$5.55^{+1.15}_{-1.05}$	$5.71^{+0.95}_{-0.80}$

Conclusion

- Multi-messenger approach on studying neutron star
- Some of the most interesting yet challenging puzzle
- Each pieces of information compliment each other
- Arrived the state-of-the-art understanding
- More work to be done…