THE DENSE MATTER EQUATION OF STATE

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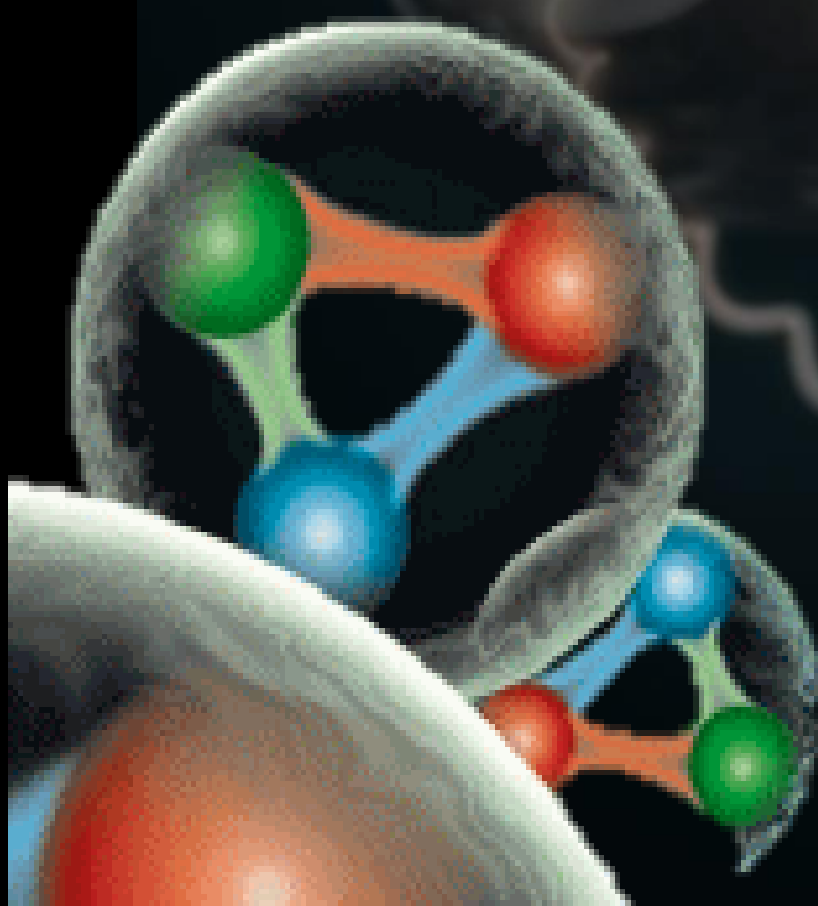
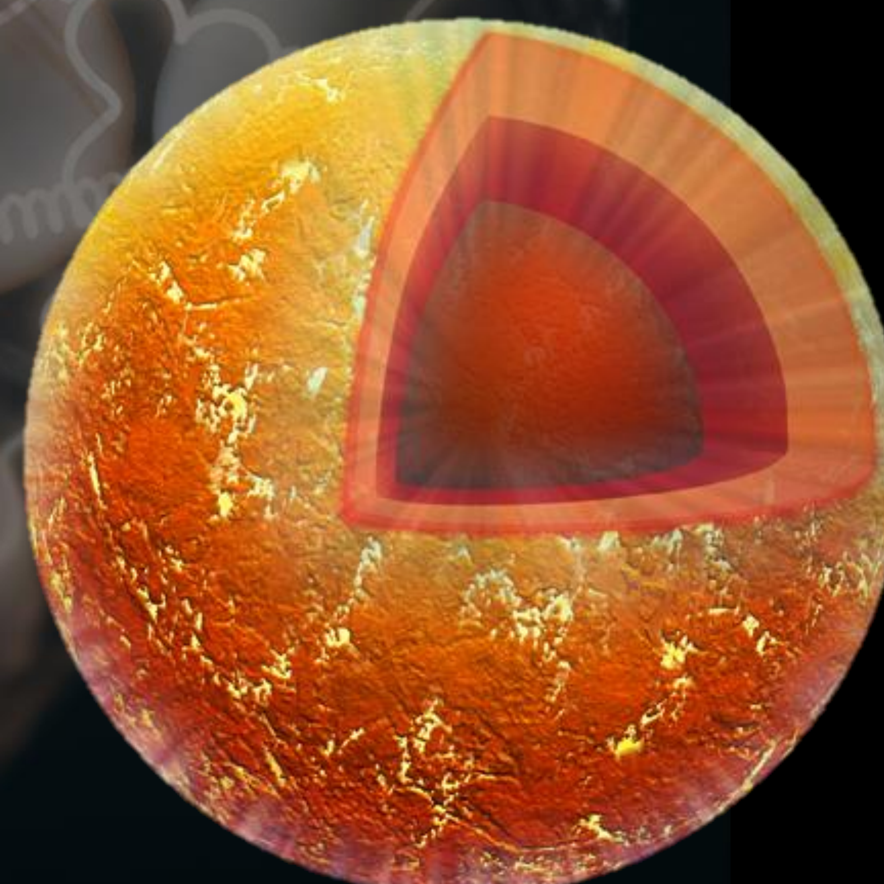
ANTON PANNEKOEK INSTITUTE

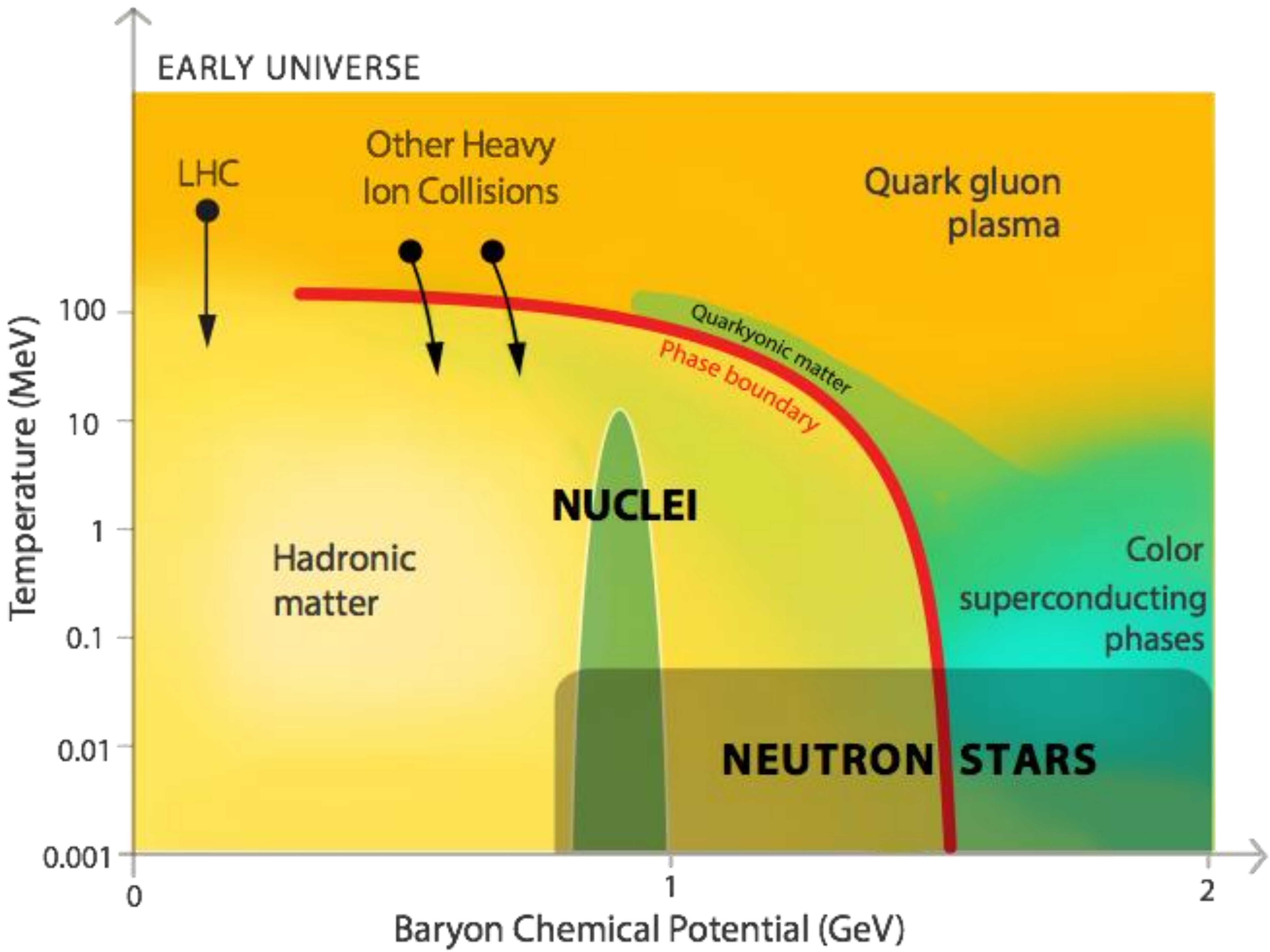
The strong force determines the state of nuclear matter - from atomic nuclei to neutron stars.

It is a major problem within modern physics.

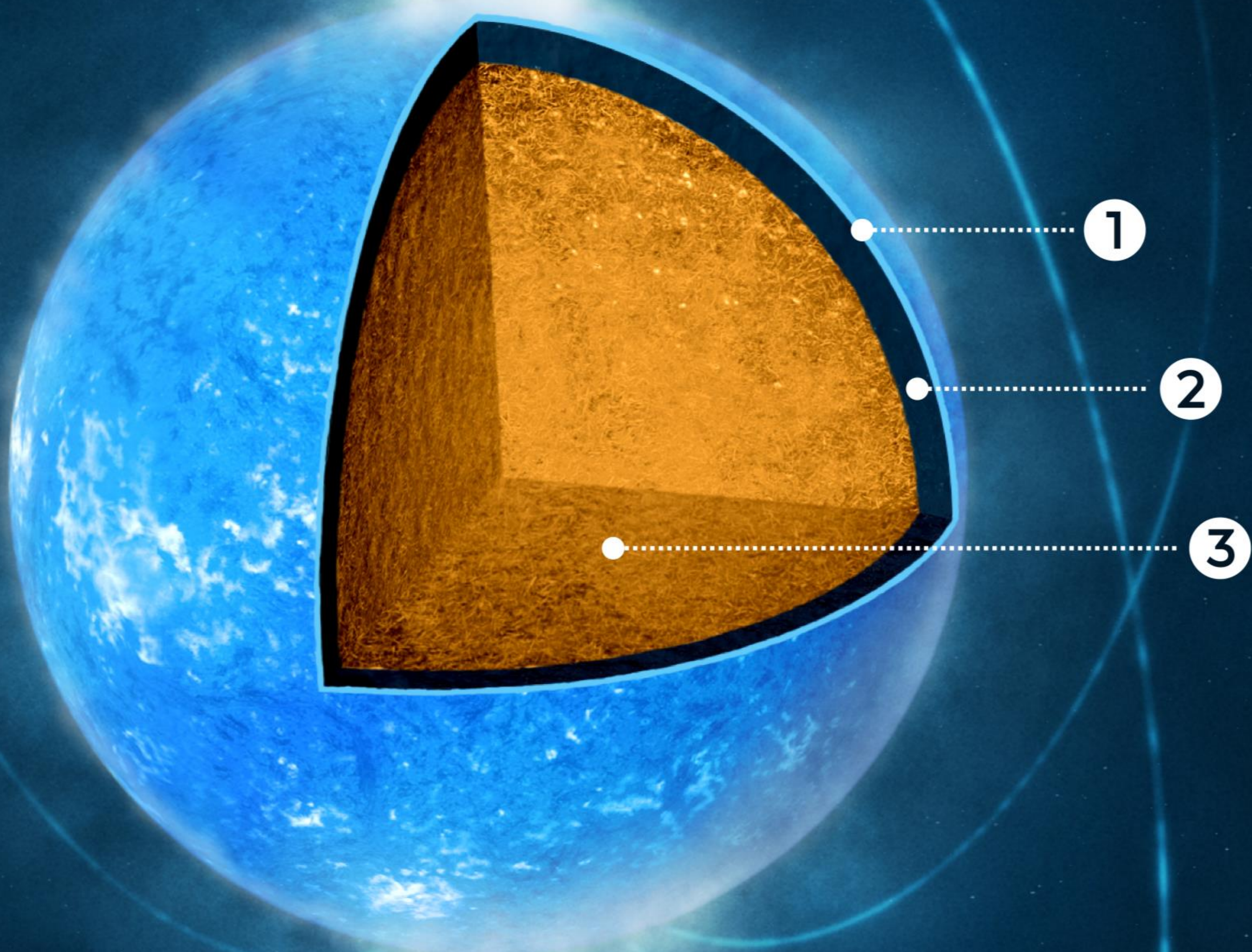


Progress is driven by **experiment** and **observation**.





EARLY UNIVERSE
LHC
Other Heavy Ion Collisions
Quark gluon plasma
Quarkyonic matter
Phase boundary
NUCLEI
Hadronic matter
Color superconducting phases
NEUTRON STARS
Temperature (MeV)
100
10
1
0.1
0.01
0.001
0
1
2
Baryon Chemical Potential (GeV)



1 | OUTER CRUST

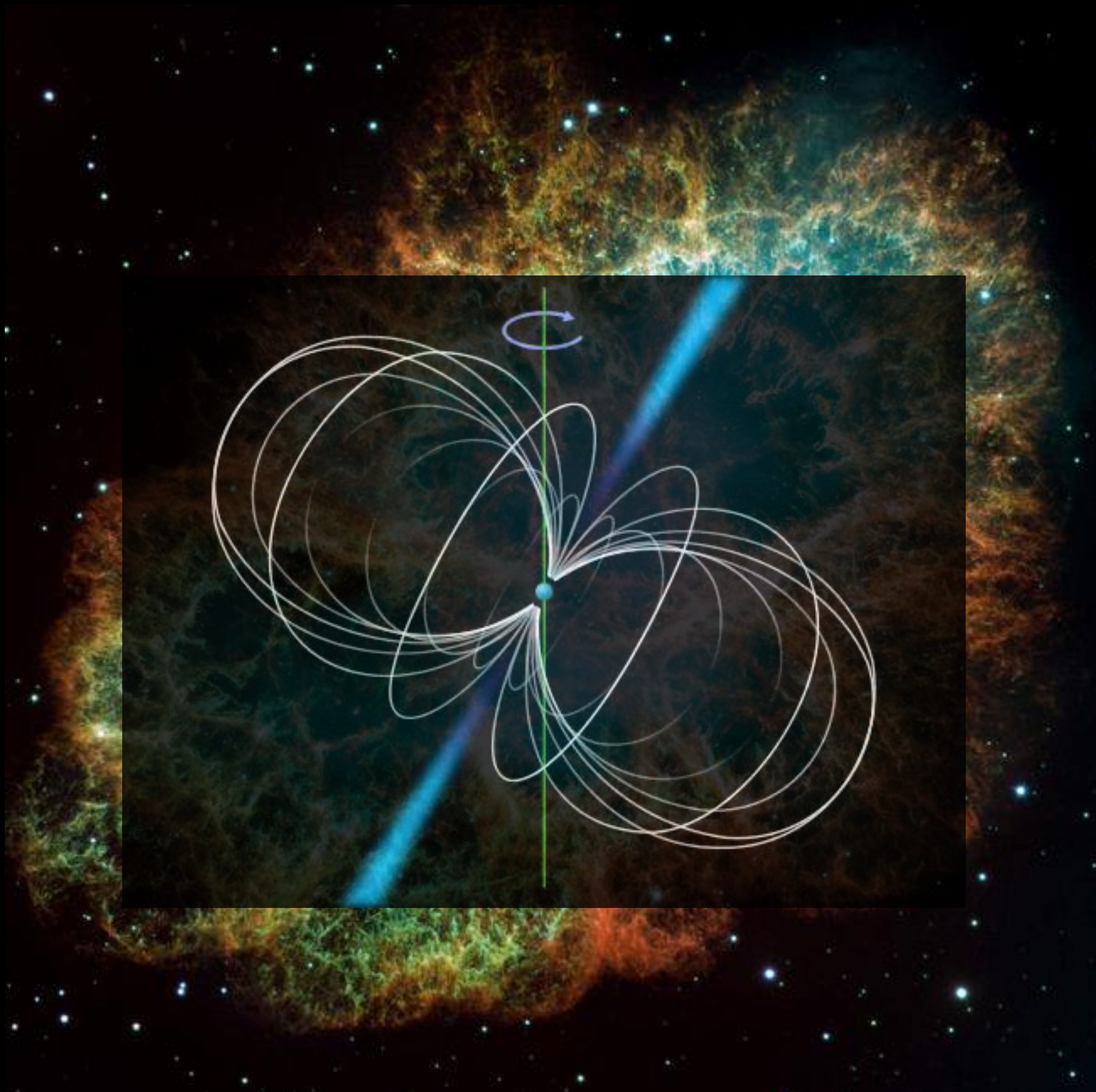
NUCLEI
ELECTRONS

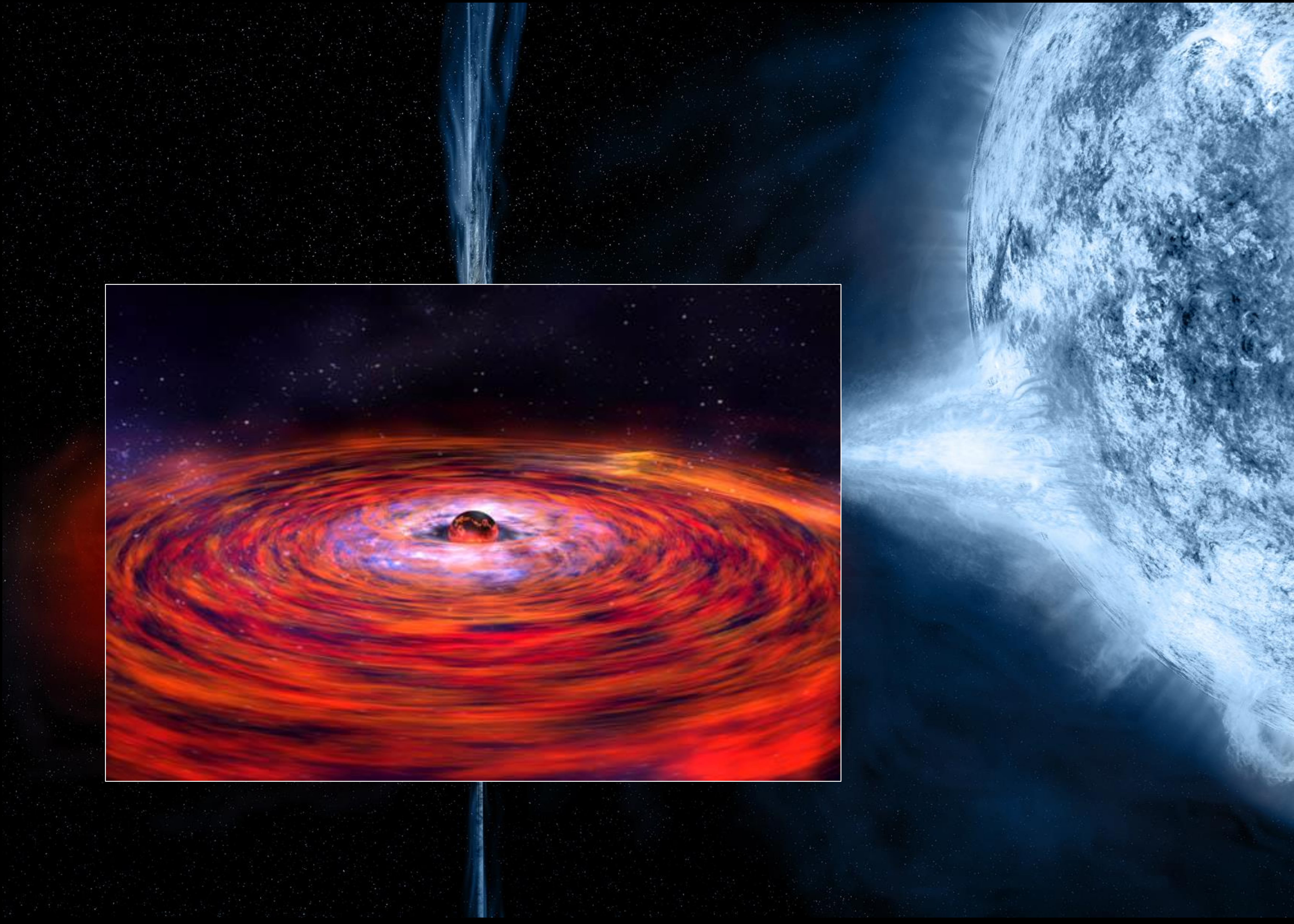
2 | INNER CRUST

NUCLEI
ELECTRONS
SUPERFLUID NEUTRONS

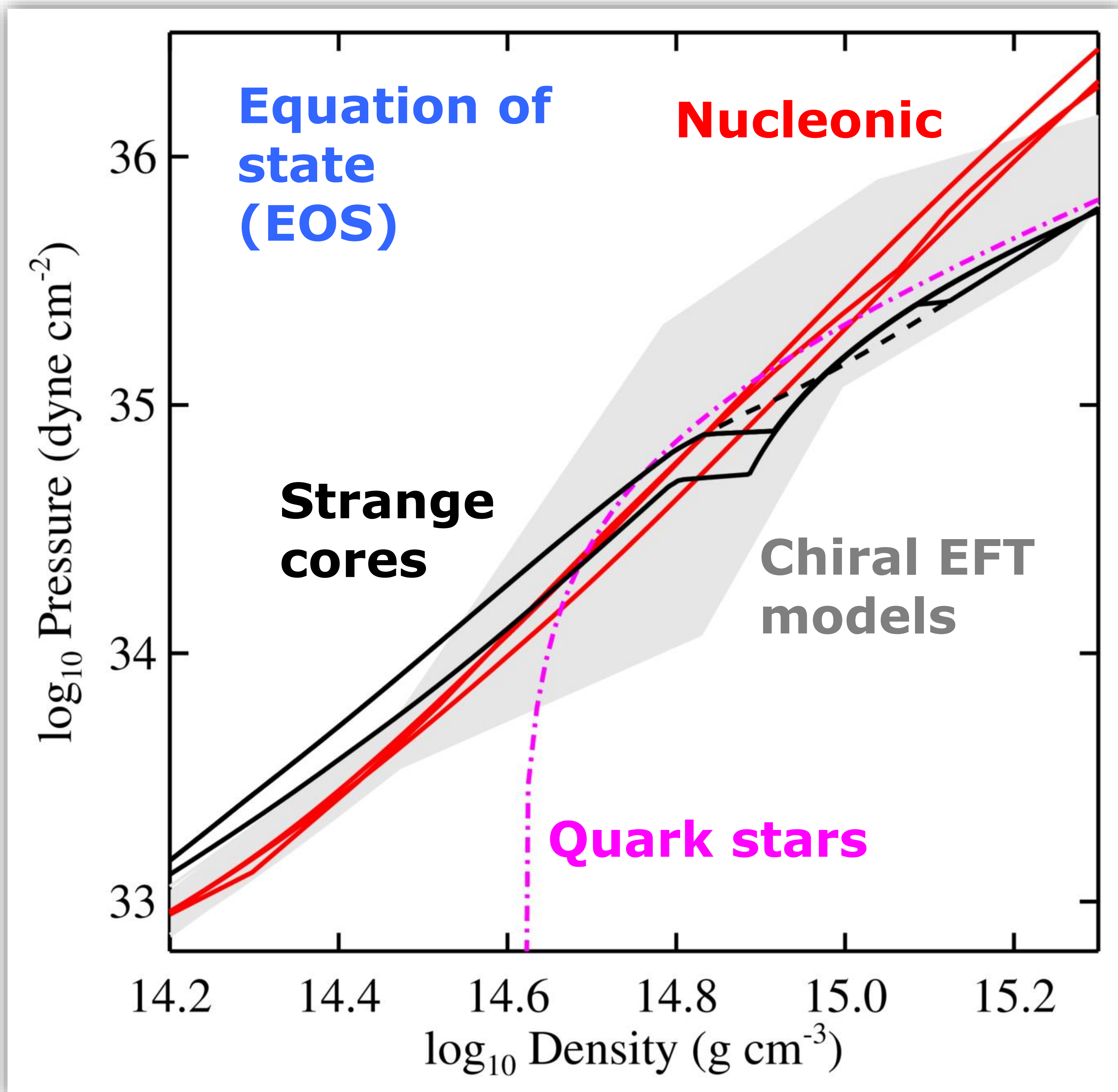
3 | CORE

SUPERFLUID NEUTRONS
SUPERCONDUCTING PROTONS
HYPERONS?
DECONFINED QUARKS?
COLOR SUPERCONDUCTOR?



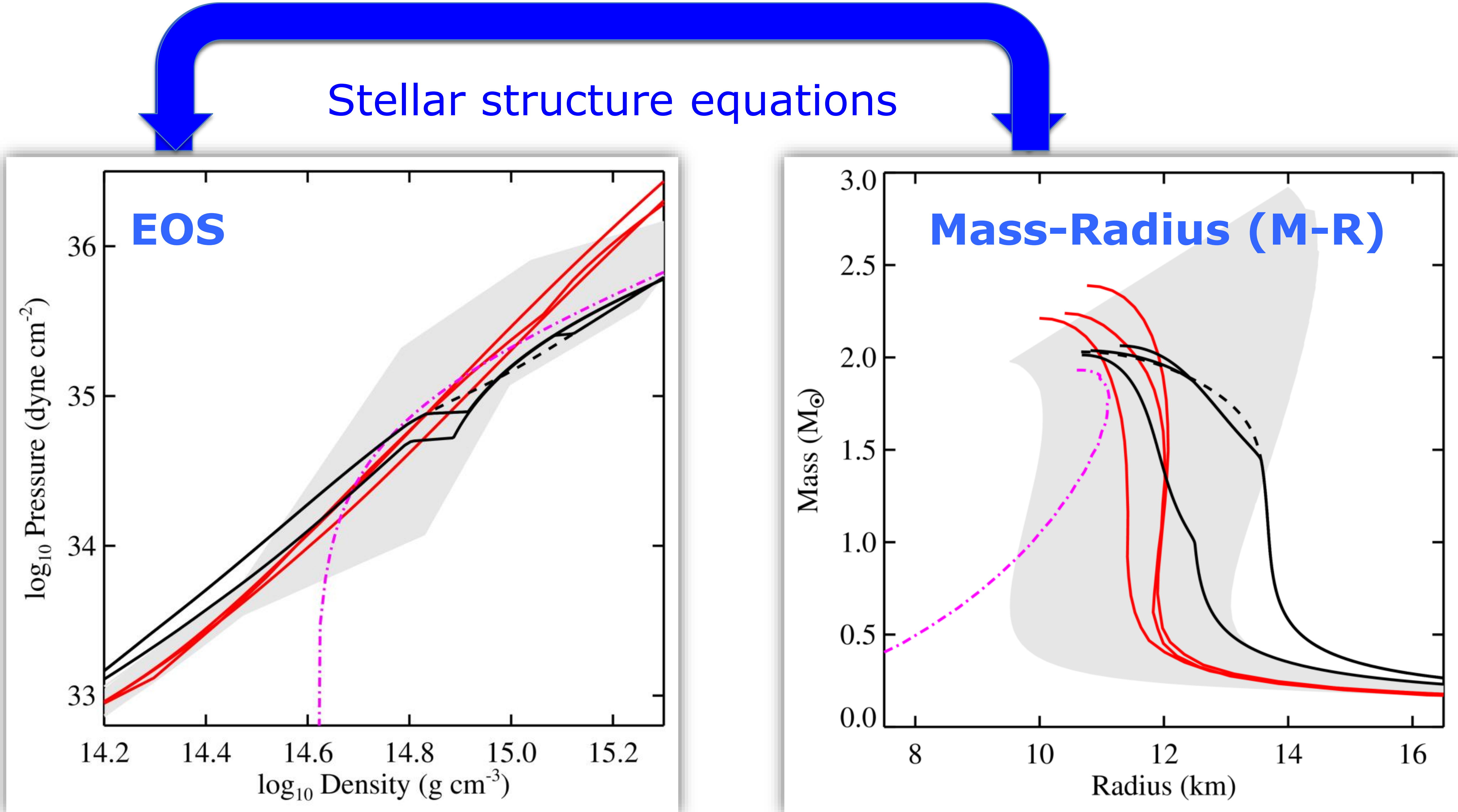


"...upon entering the faculty, each student was issued a set of tools: a pair of pliers, a pair of long-nose pliers, a wire cutter, and a screwdriver..."

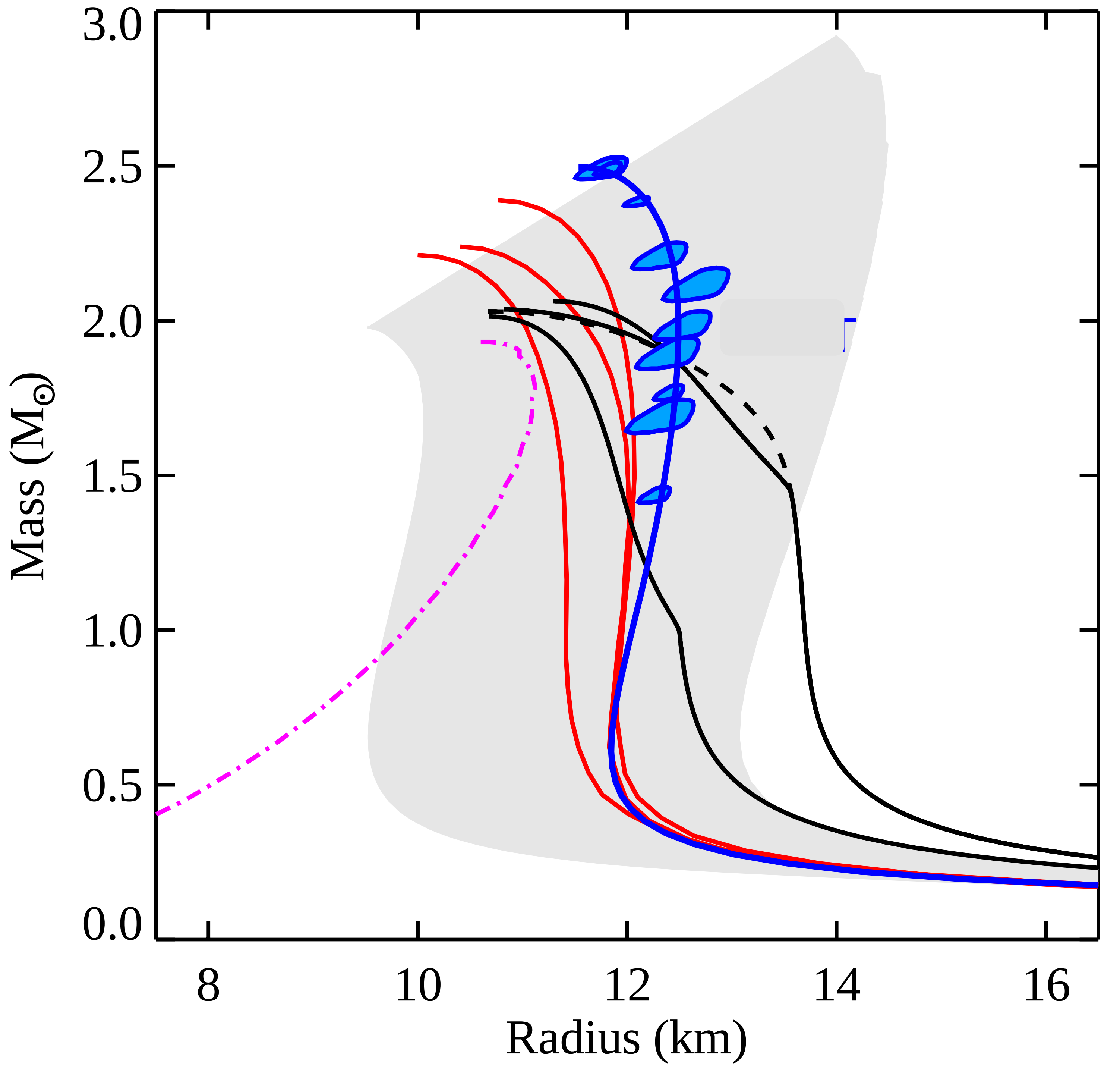


The strong force determines the 'stiffness' of neutron star matter.

This is encoded in the **EQUATION OF STATE**.



Measuring M-R relation uniquely determines the EOS



Ideally, to determine the EOS we would like to measure

both mass and radius,

to high precision

for a range of masses

Measuring masses in binaries

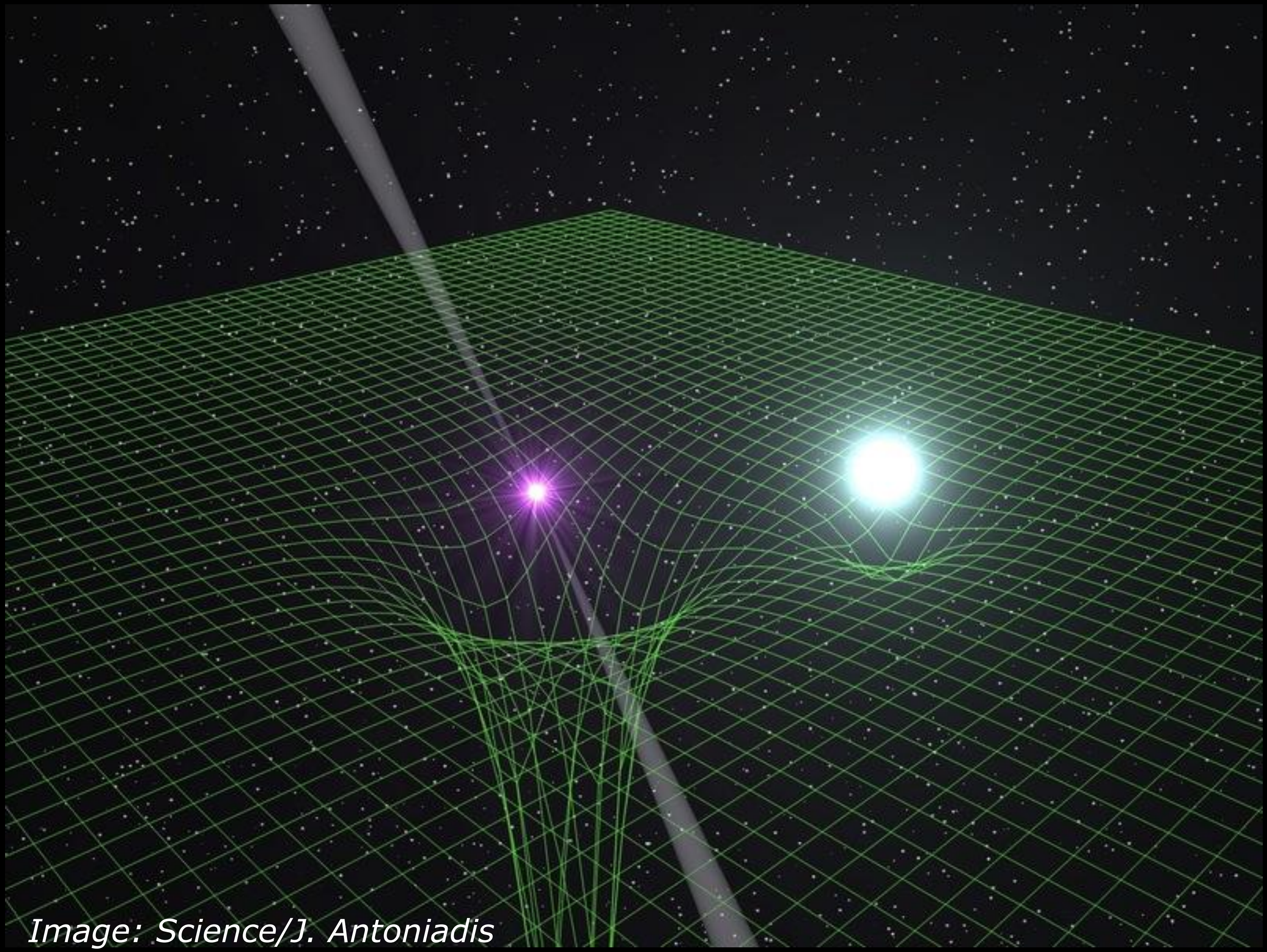
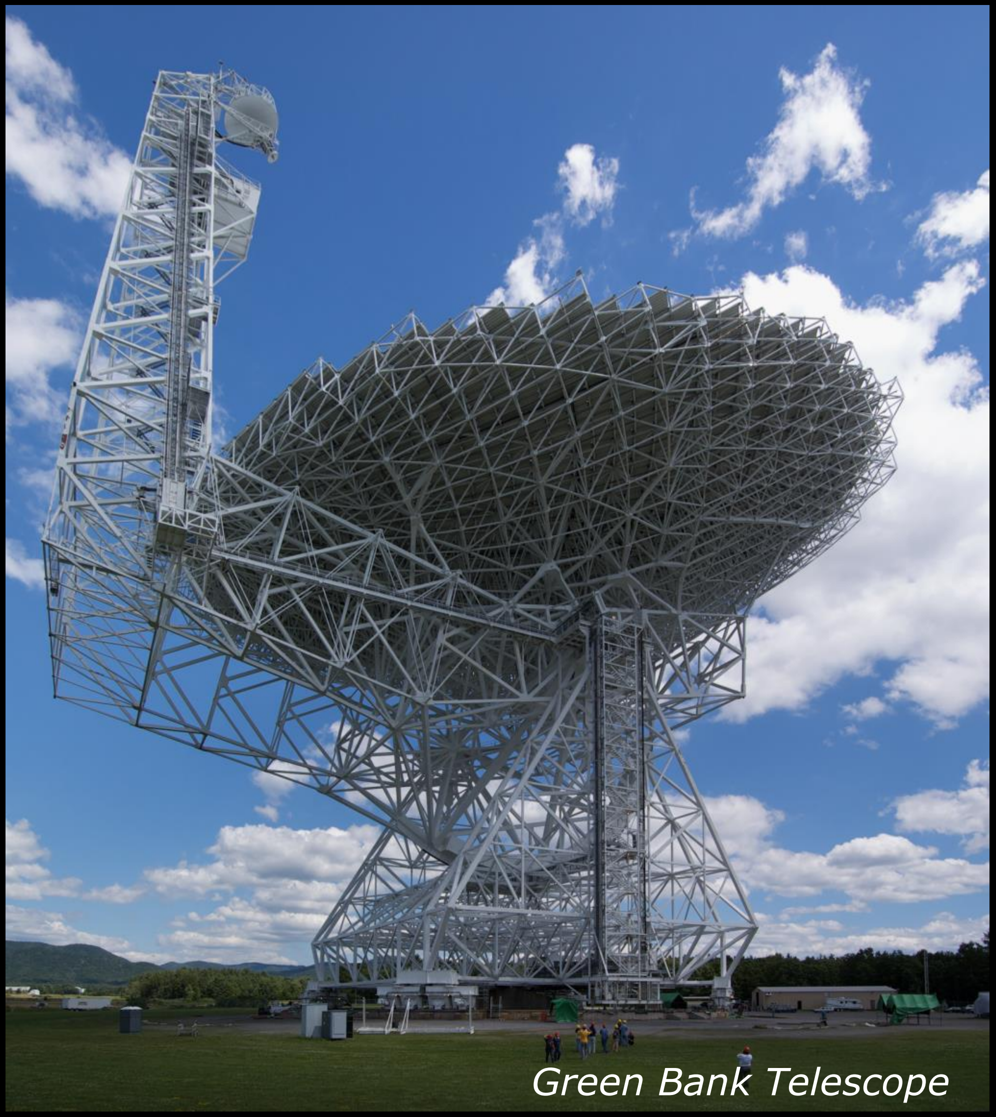


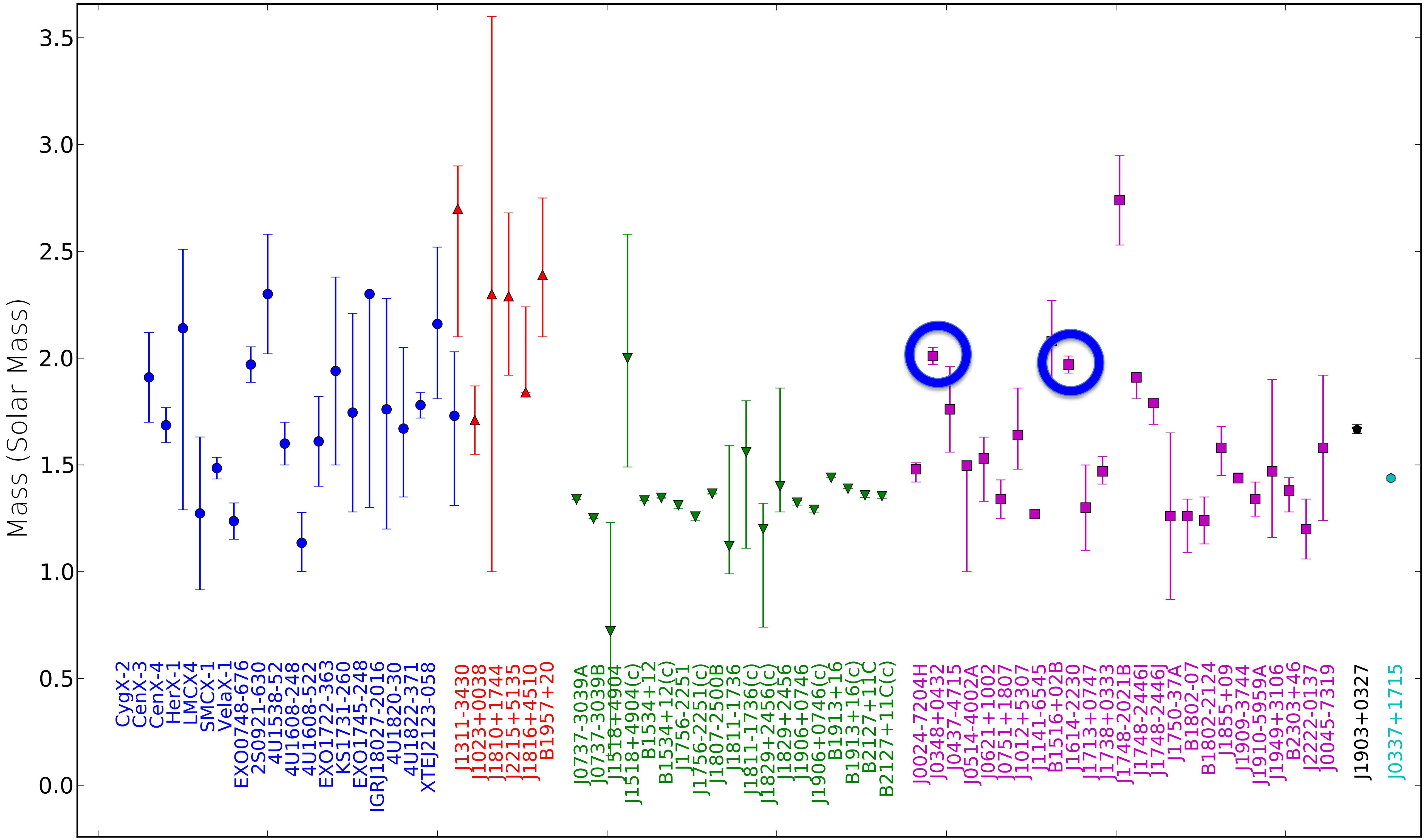
Image: Science/J. Antoniadis



Green Bank Telescope

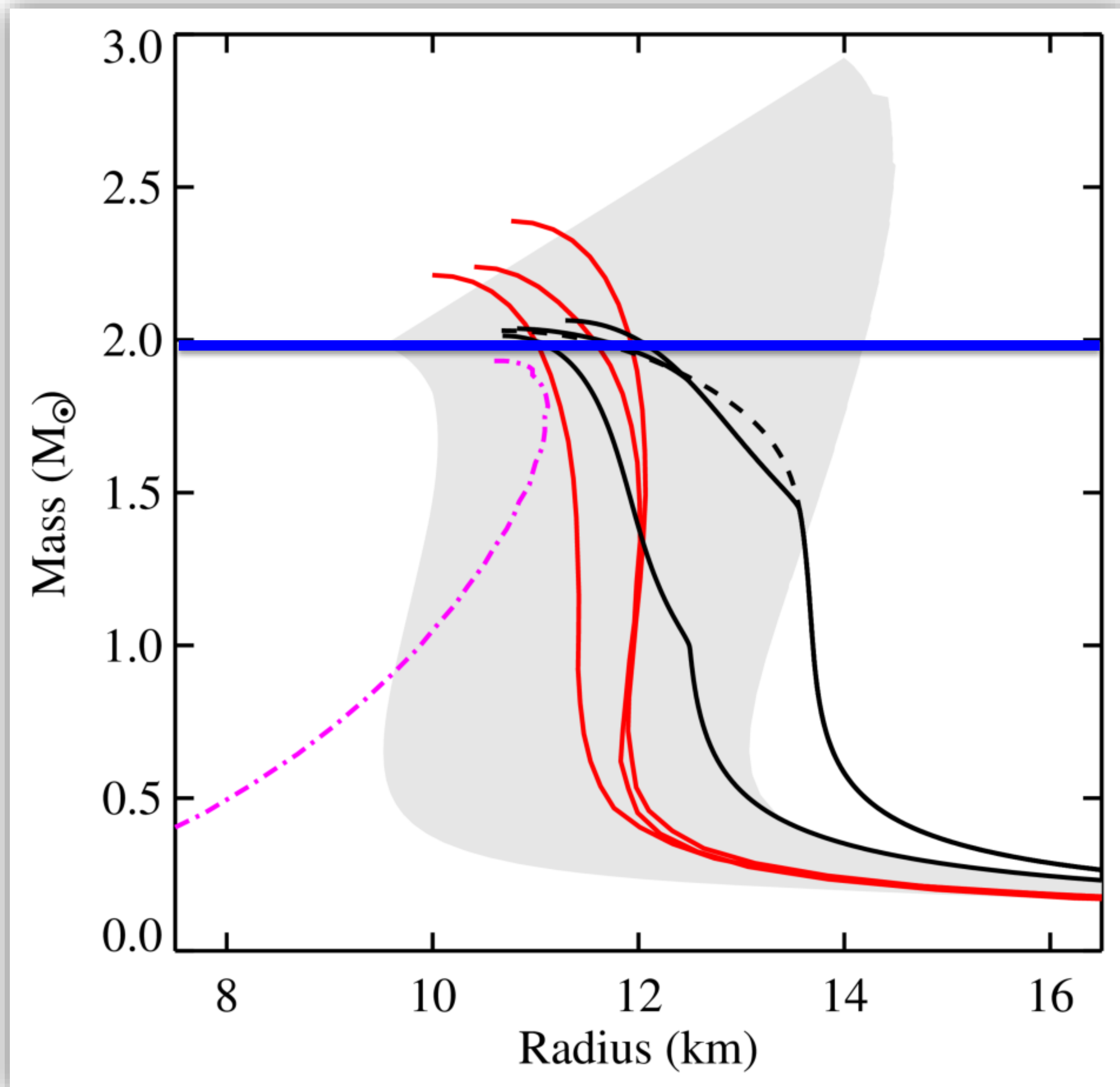
Masses can be measured very precisely for radio pulsars in relativistic binaries (if geometry is favourable), using Post-Keplerian parameters such as Shapiro delay.

Current mass measurements



Watts et al. 2015, see J.Antoniadis website for updates

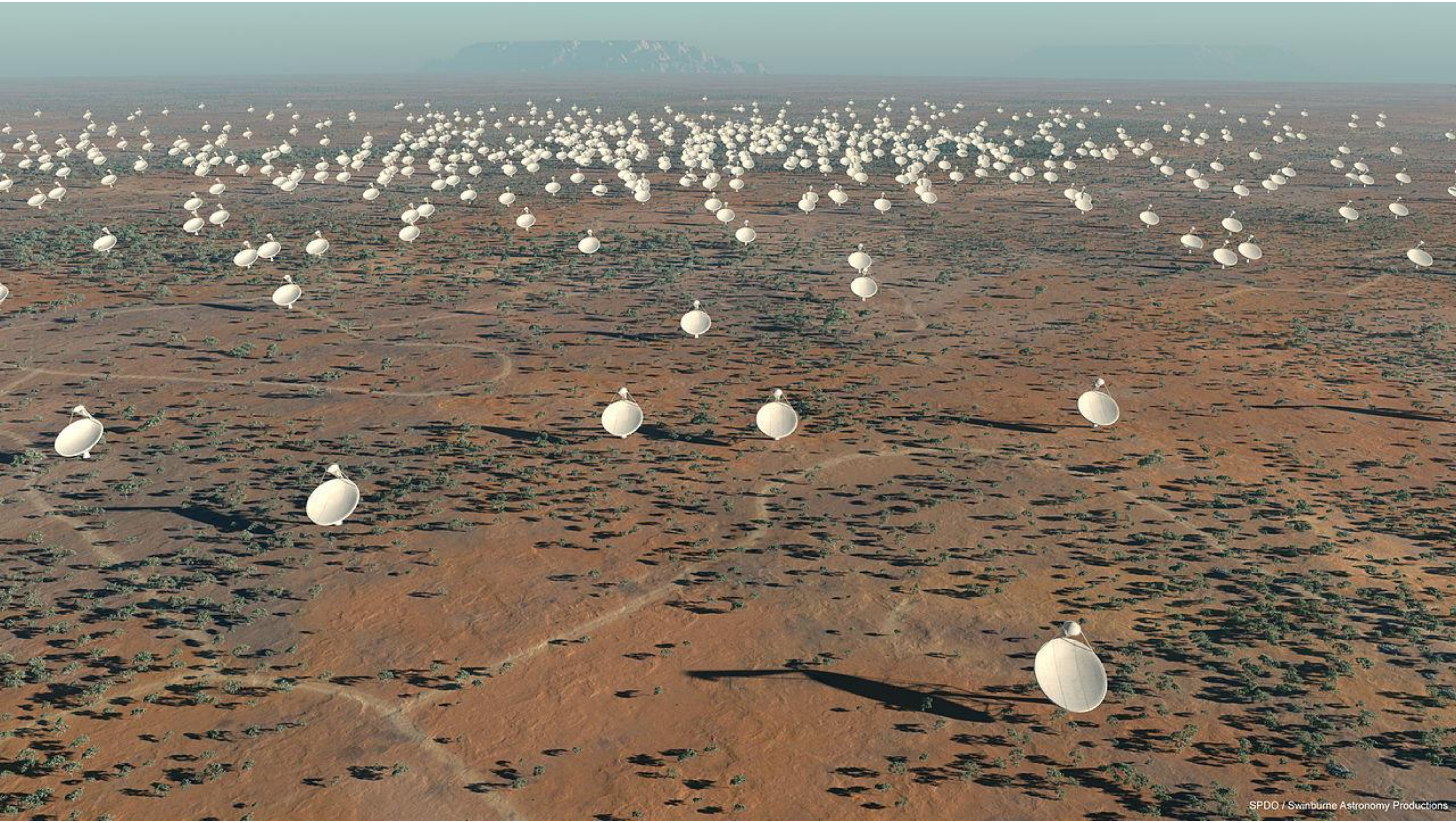
Limits from maximum mass



Demorest et al. 2010, Antoniadis et al. 2013

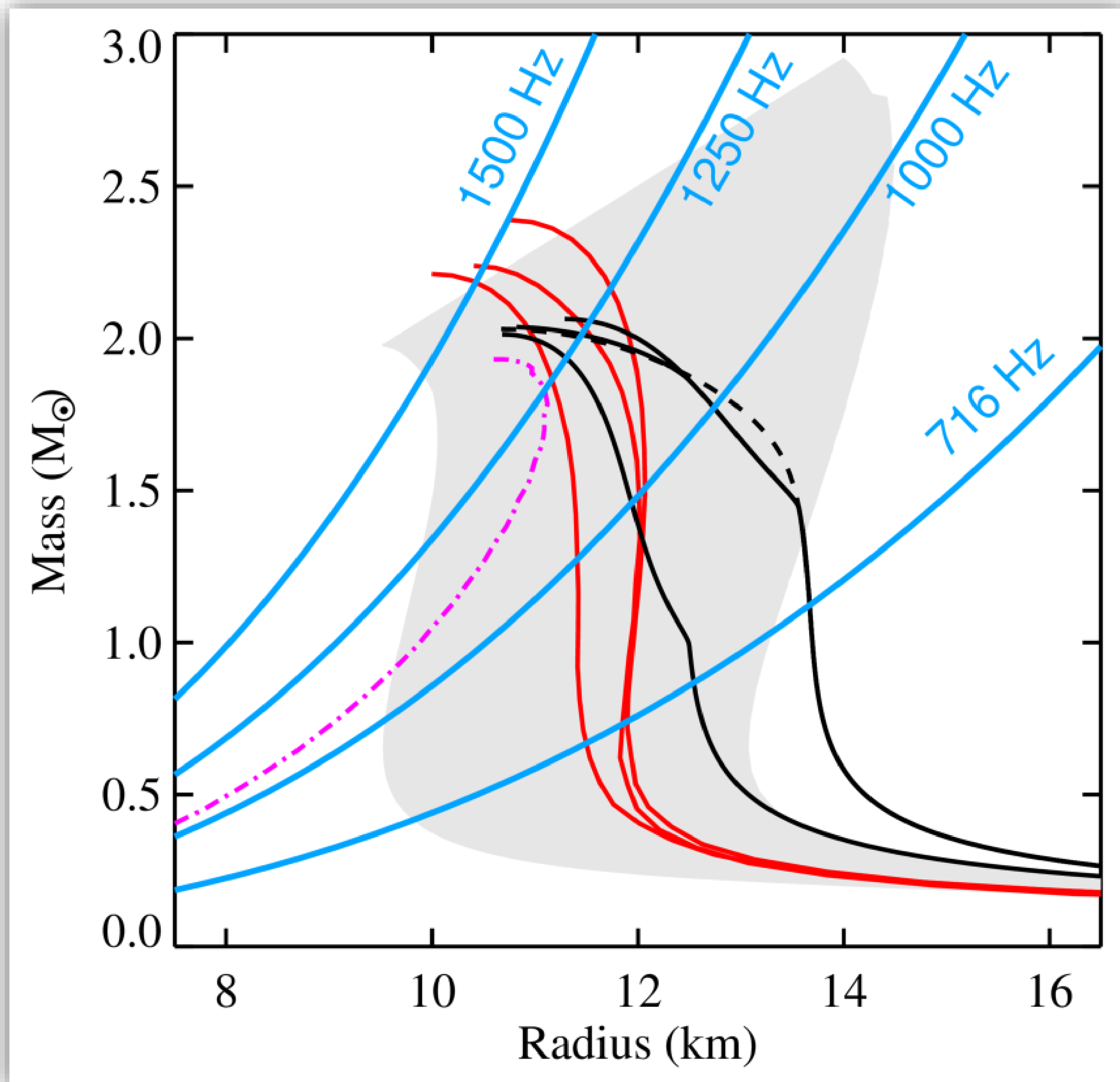
- Two 2 solar mass neutron stars now discovered (Demorest et al. 2010, Antoniadis et al. 2013).
- ‘Hyperon problem’: hyperons are energetically probable but would soften EOS too much (Chen et al. 2011, Weissenborn et al. 2012).
- Additional repulsive interactions (Takatsuka et al. 2008, Logoteta et al. 2013)?
- Phase transition to quark matter?

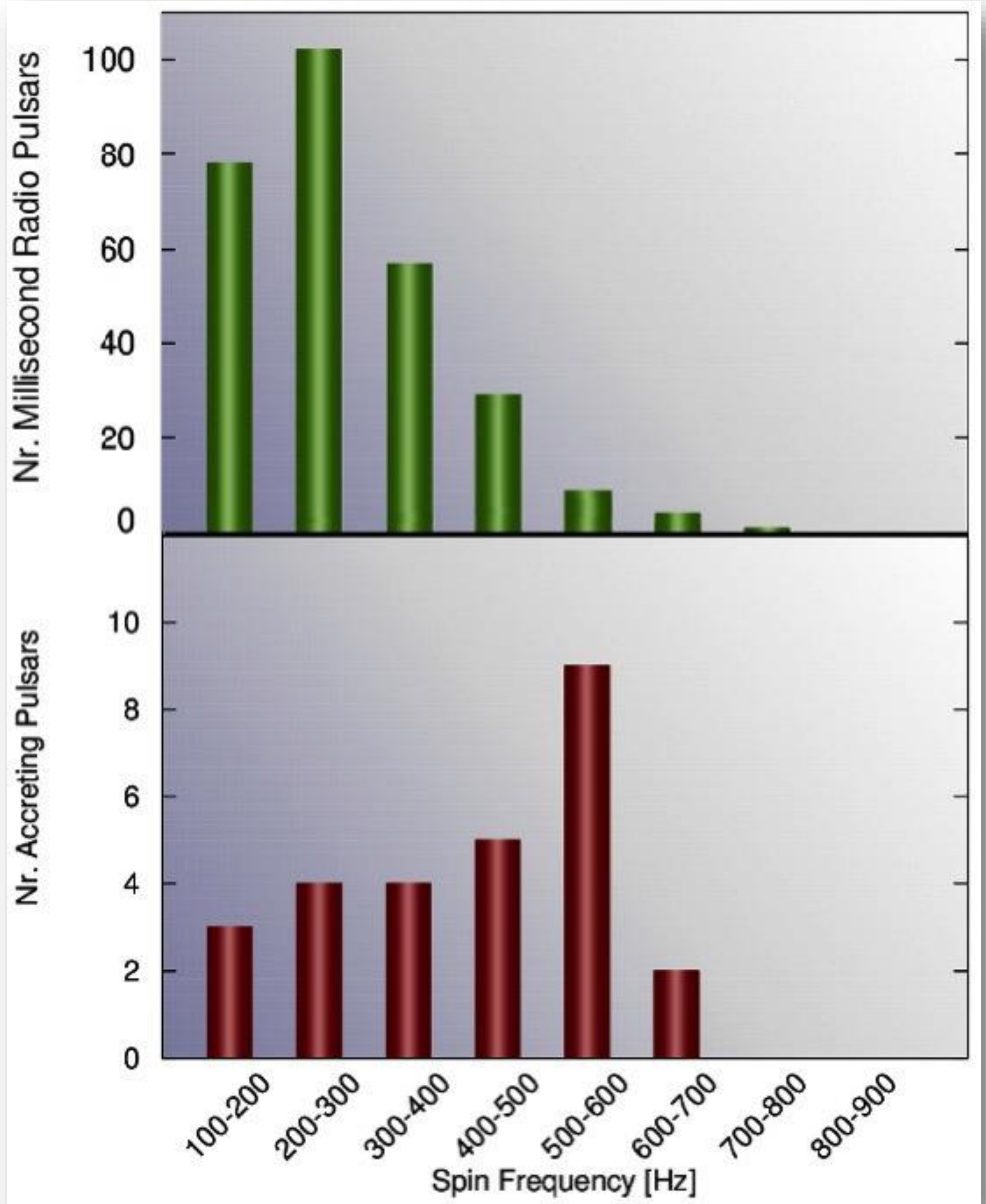
The future: Square Kilometer Array



Watts et al. 2015, *Probing the NS interior and the EOS of cold dense matter with the SKA*, arXiv:1501.00042

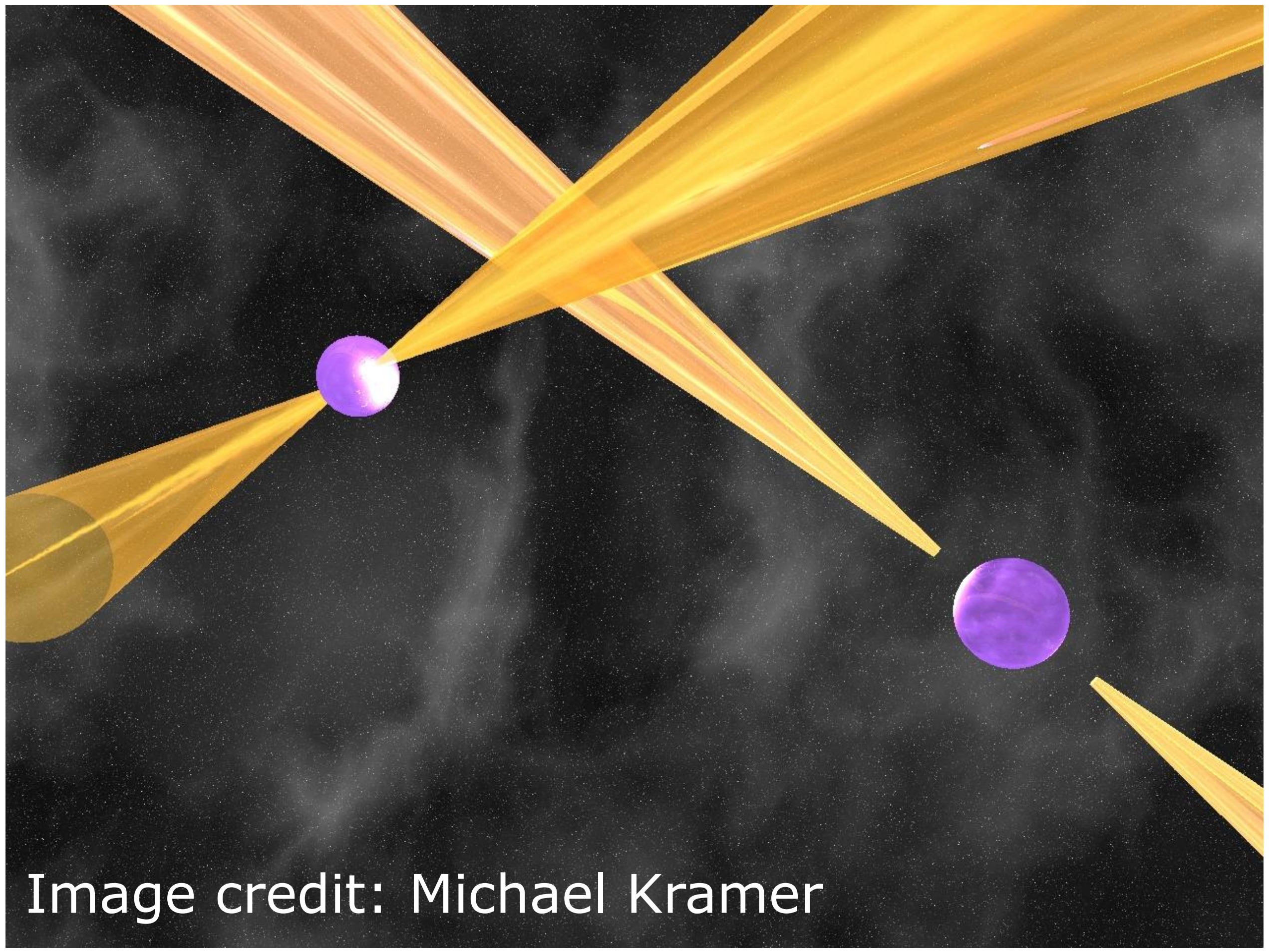
Constraints from rapid spin





Spin rates can be measured for isolated and accreting pulsars. Break-up spin constrains M and R.

Moment of inertia measurements



Highly relativistic systems like the Double Pulsar (PSR J0737-3039, Burgay et al. 2003) required for effects of I on pulsar timing to be detectable.

- Moment of inertia I yields R if M can be determined independently.
- Three different routes to measuring I (Kramer & Wex 2009)
- With SKA, expect 10% measurement of I for Double Pulsar within 20 years, which gives 5% uncertainty in R.
- SKA will discover ~100-180 new Double NS systems, candidates for measurements of I.

Gravitational wave constraints

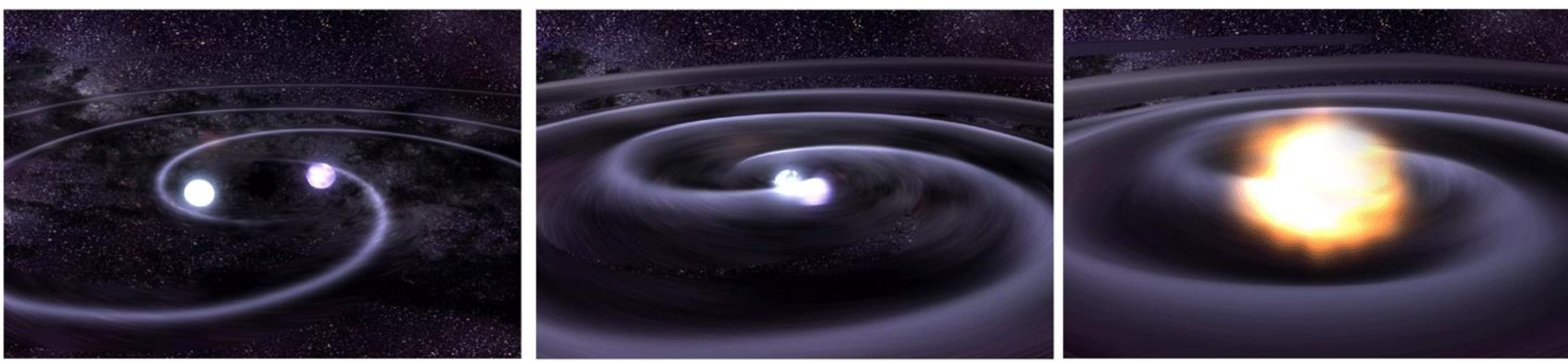


Image credits: LIGO

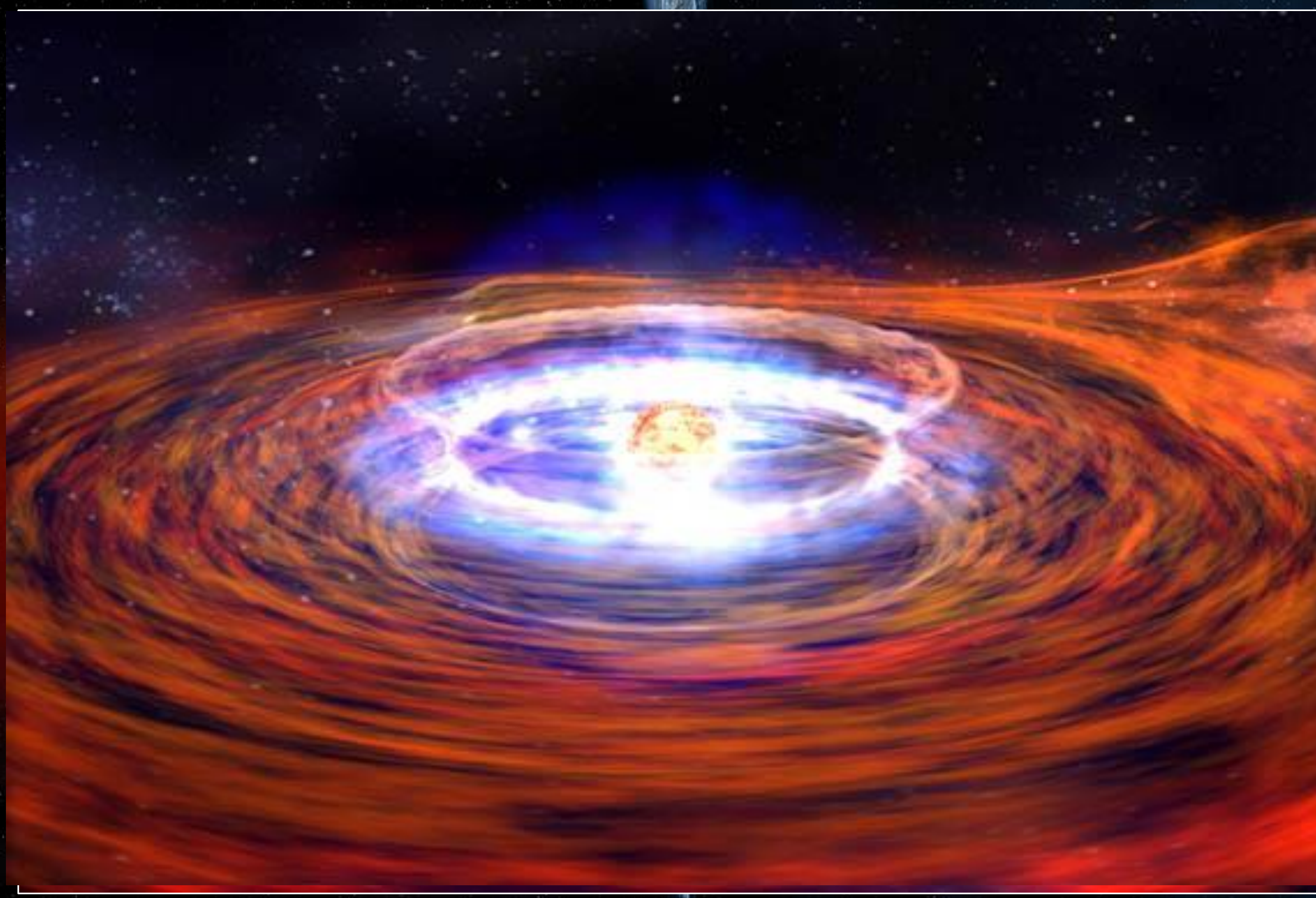
Magnetar asteroseismology

Magnetars: Extreme high magnetic field neutron stars that emit repeated bursts of gamma-rays.

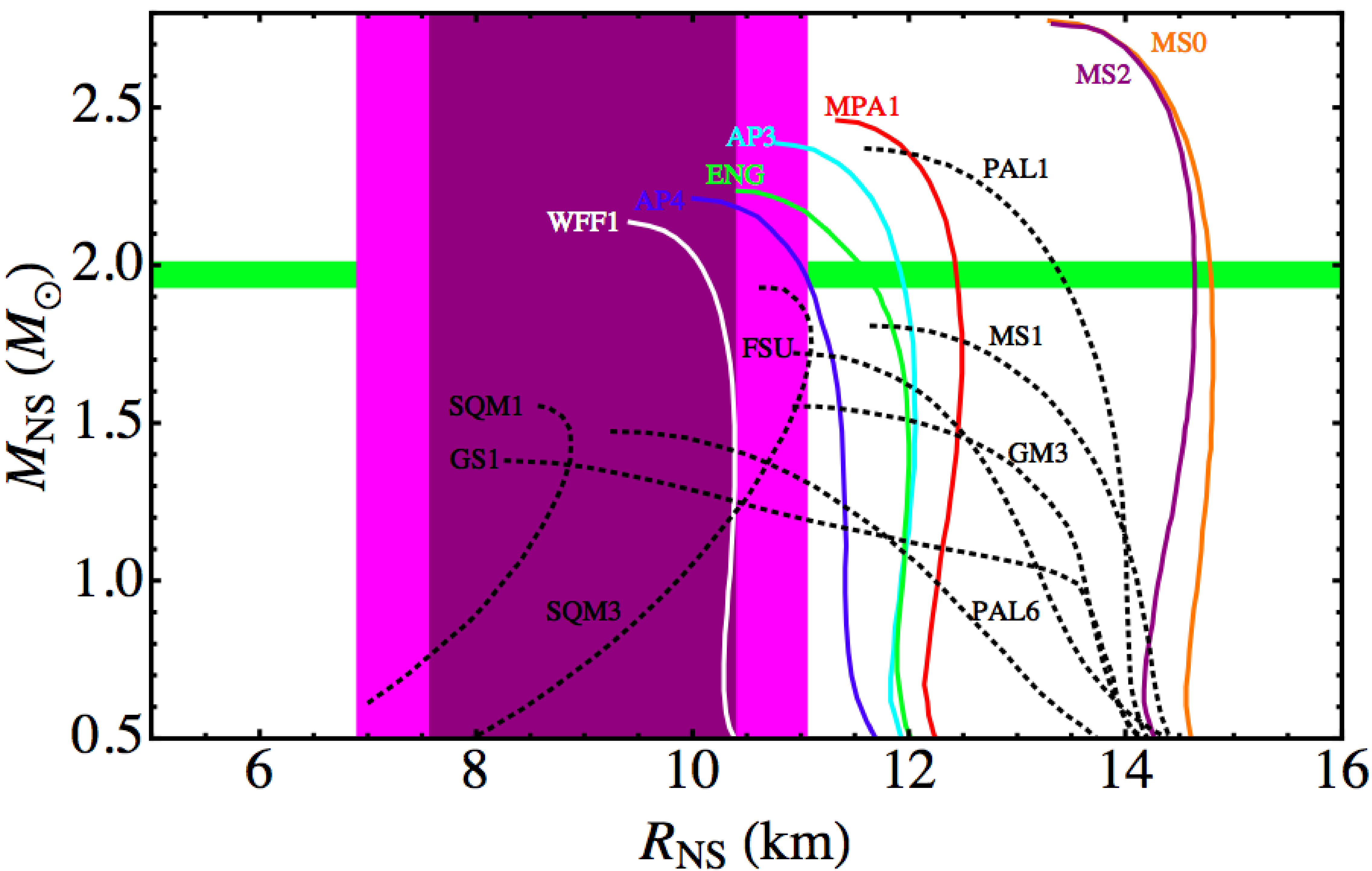
Model: Magnetic reconnection and associated starquakes as strong field decays (Thompson & Duncan 1995)

- Magnetar giant flares: harmonic sequences of oscillations in 18-1800 Hz range (Israel et al. 2005, Strohmayer & Watts 2005,6, WS06)
- Also seen in ‘small’ burst storms (Huppenkothen et al. 2014a, b)
- Interpretation: global magneto-elastic oscillations.
- Frequencies depend on M, R, superfluidity, crust composition, magnetic field.
- Excitation, emission mechanisms still unclear.

Spectral modelling

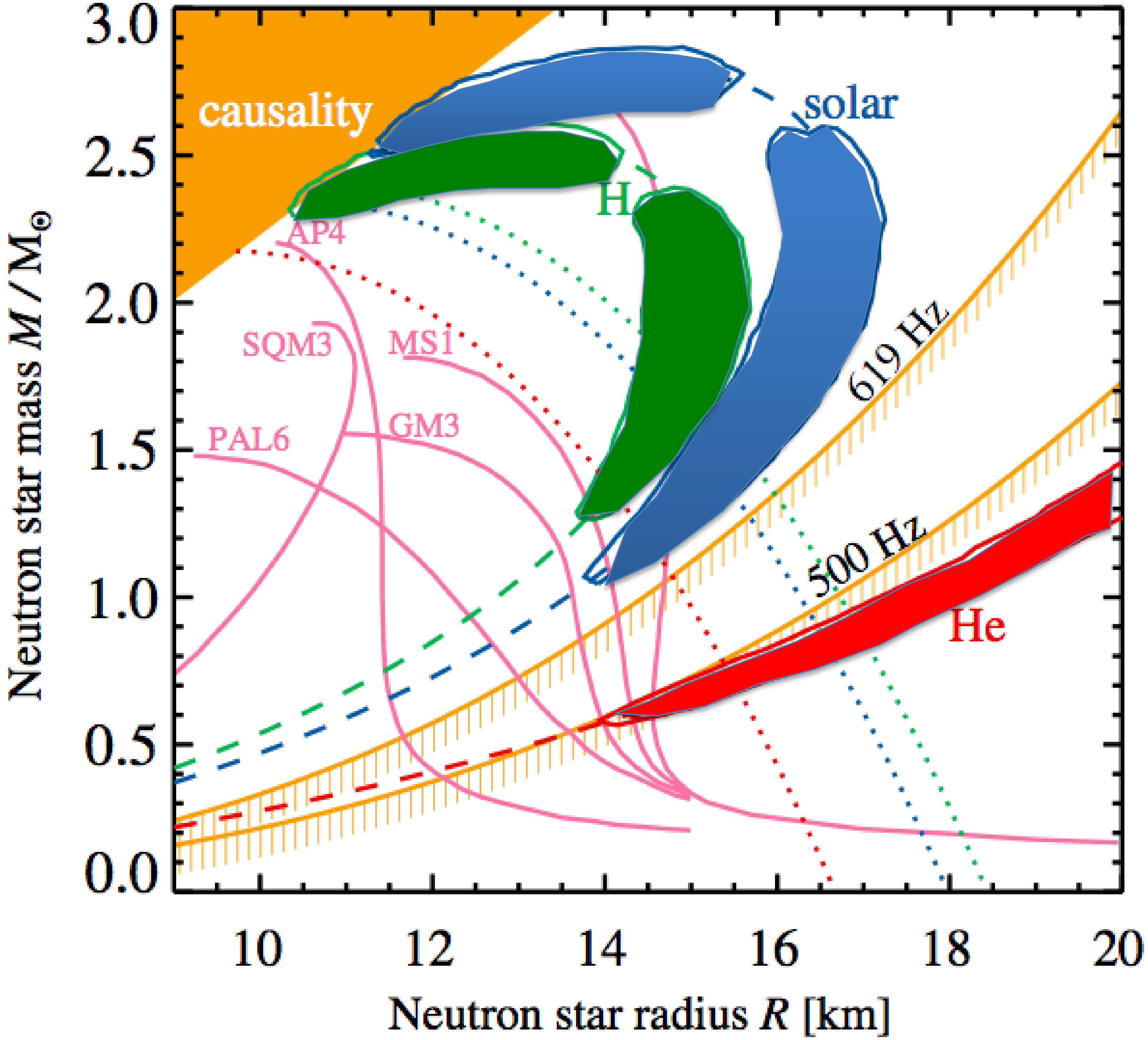


Example: quiescent NS



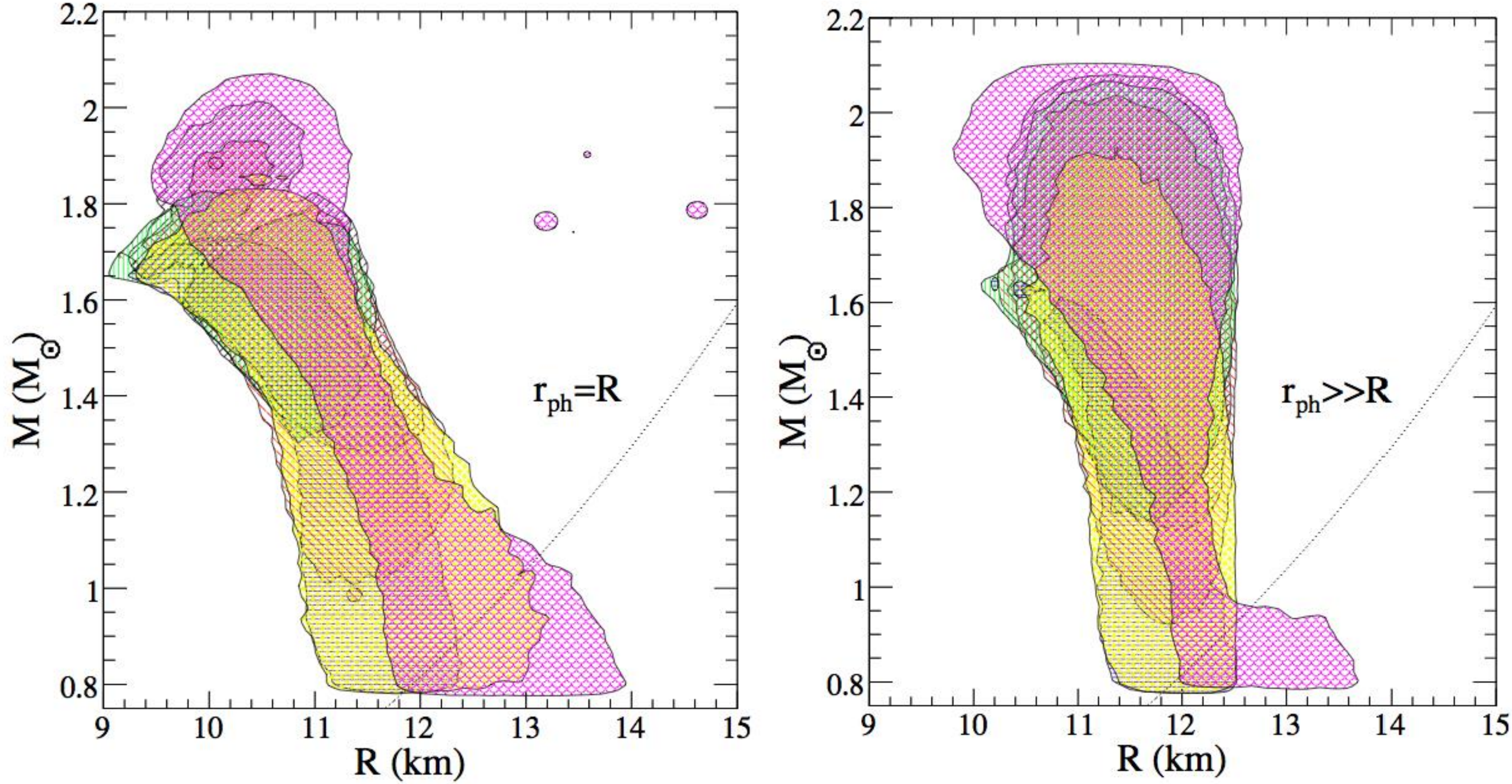
Guillot et al. 2013

Example : bursts



Suleimanov et al. 2011

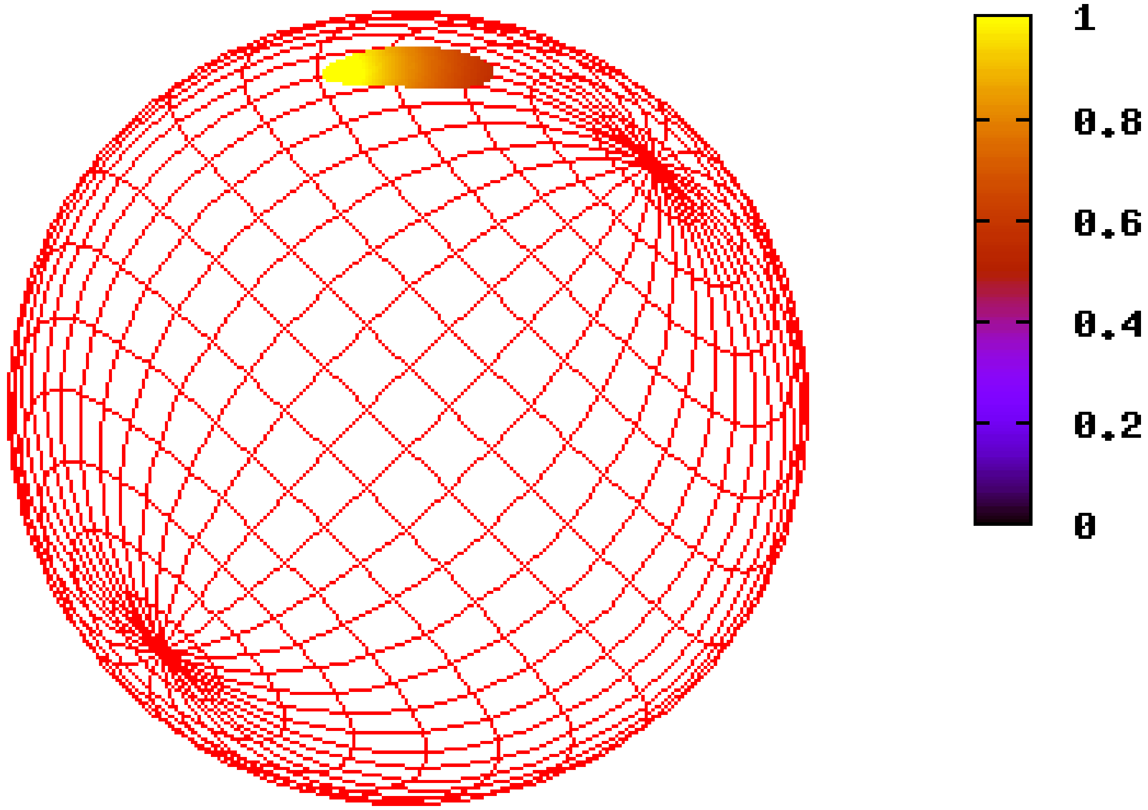
Example: combined sample



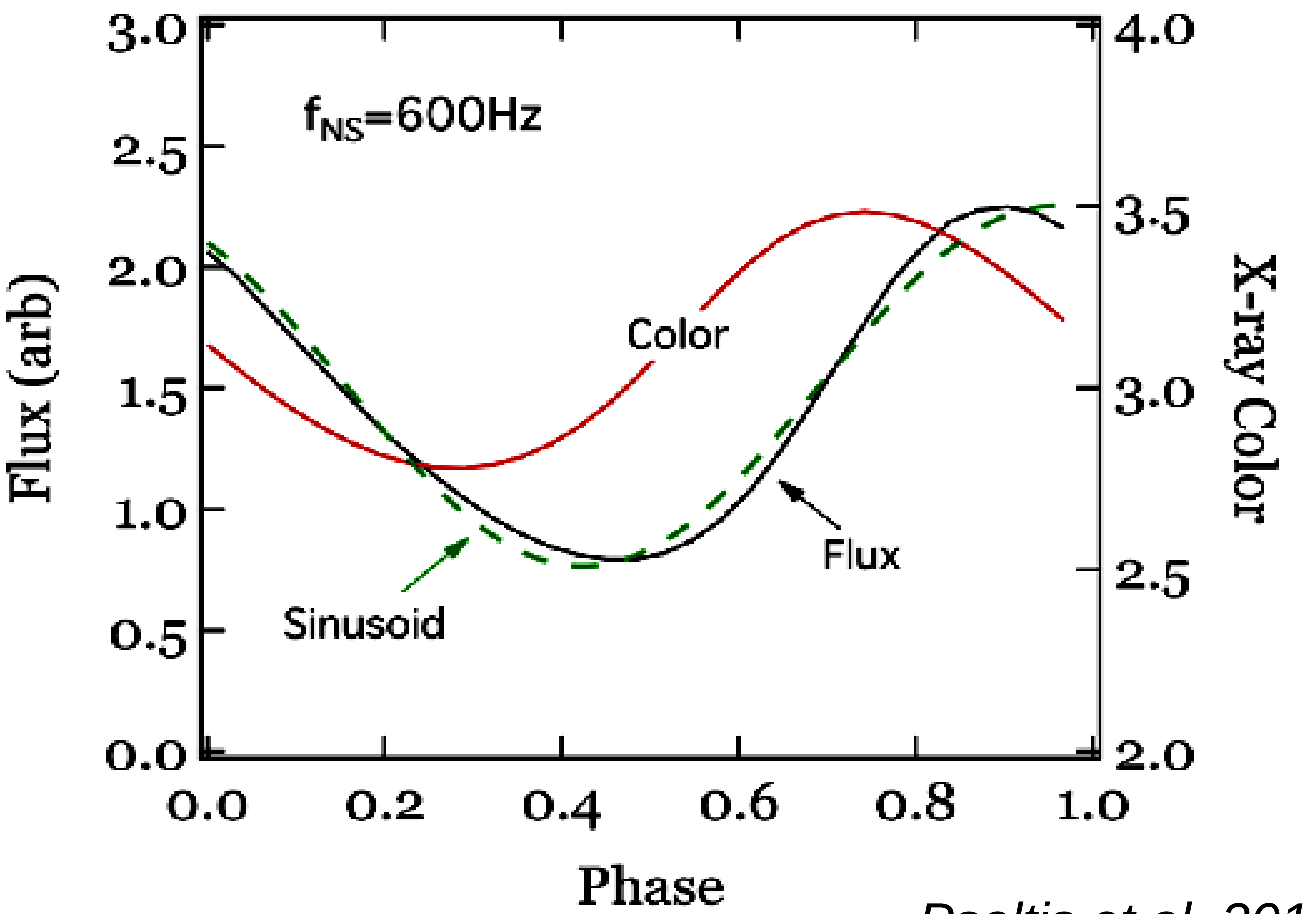
Steiner et al. 2013

The future: Athena

Pulse profile modelling



Animation courtesy of Sharon Morsink

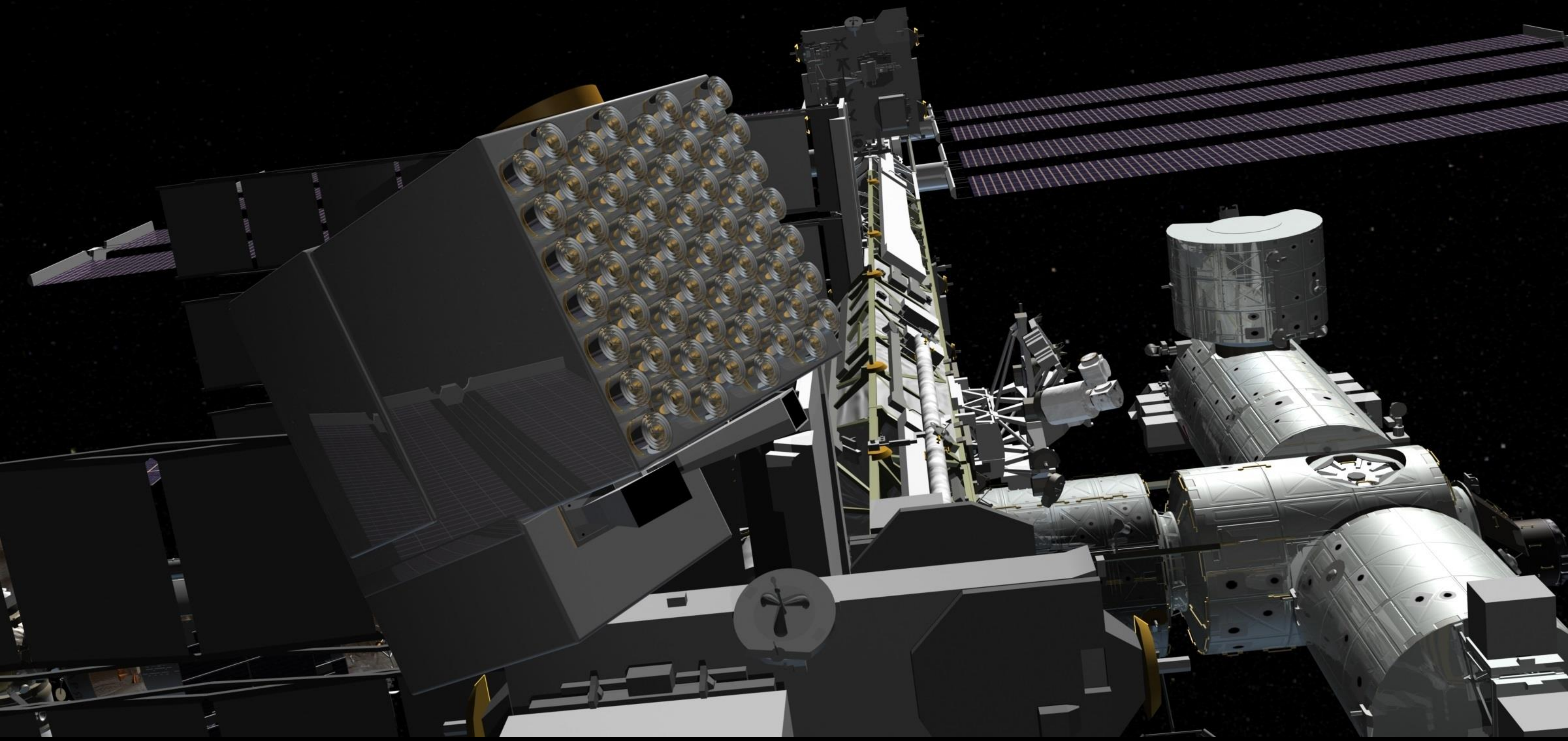


Psaltis et al. 2014

- Relativistic effects on a hotspot (light-bending, redshifts, aberration) encode information about M and R in the observed pulse profile.
- M and R can be recovered from the energy-dependent pulse profile .

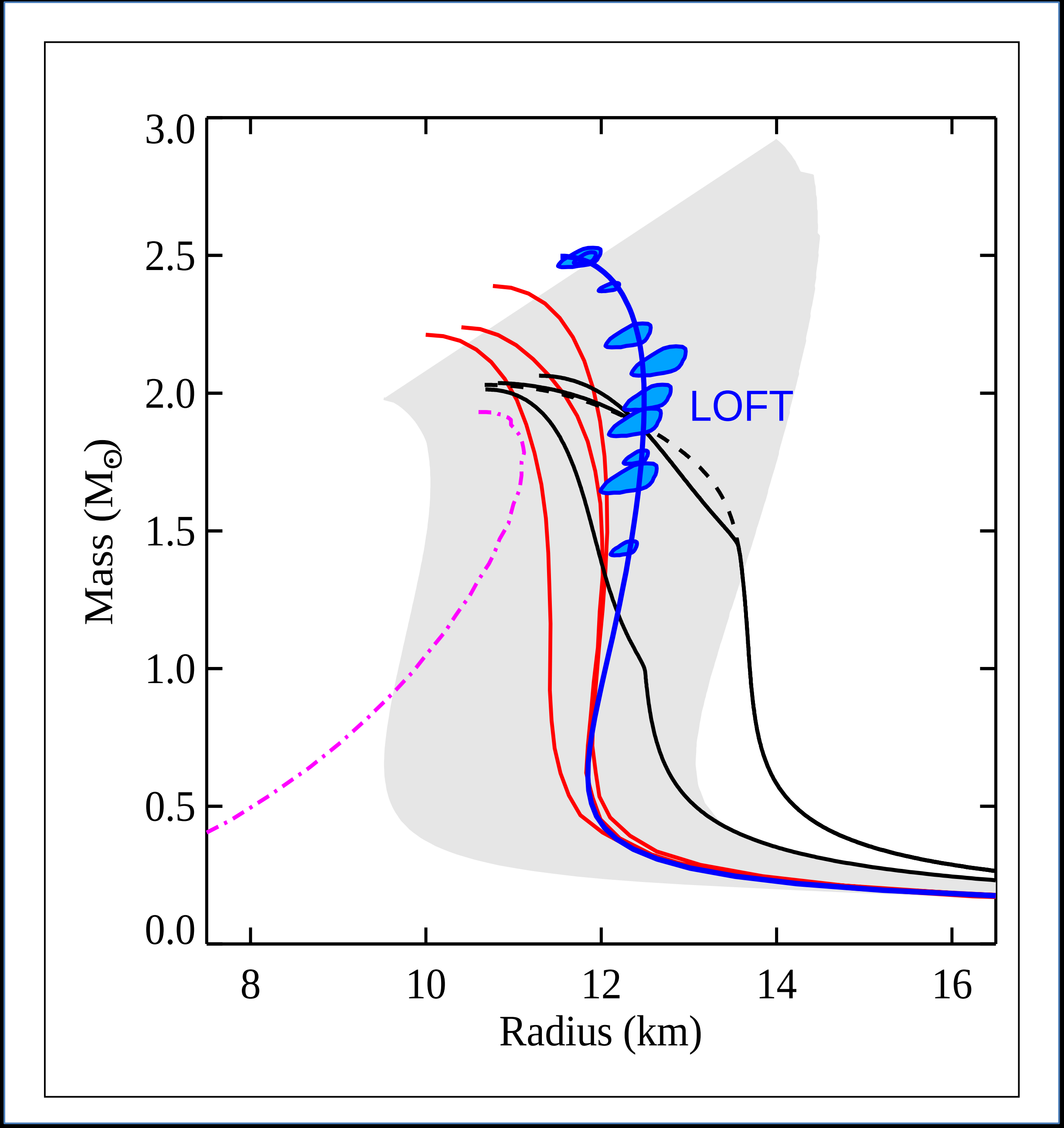
Pechenick et al. 83,Miller & Lamb 98, Braje et al. 00, Beloborodov 02, Poutanen & Gierlinski 03, Poutanen & Beloborodov 06, Cadeau et al. 07, Morsink et al. 07, Bogdanov et al. 07, 08, Baubock et al. 12, 13, Lo et al.13, Al-Gendy & Morsink 14, Psaltis et al. 14, Miller & Lamb 15

NICER – soft X-ray PPM



Hard X-ray mission concepts

Hard X-ray opens up new source classes with reduced systematics, and more options for cross-checks.

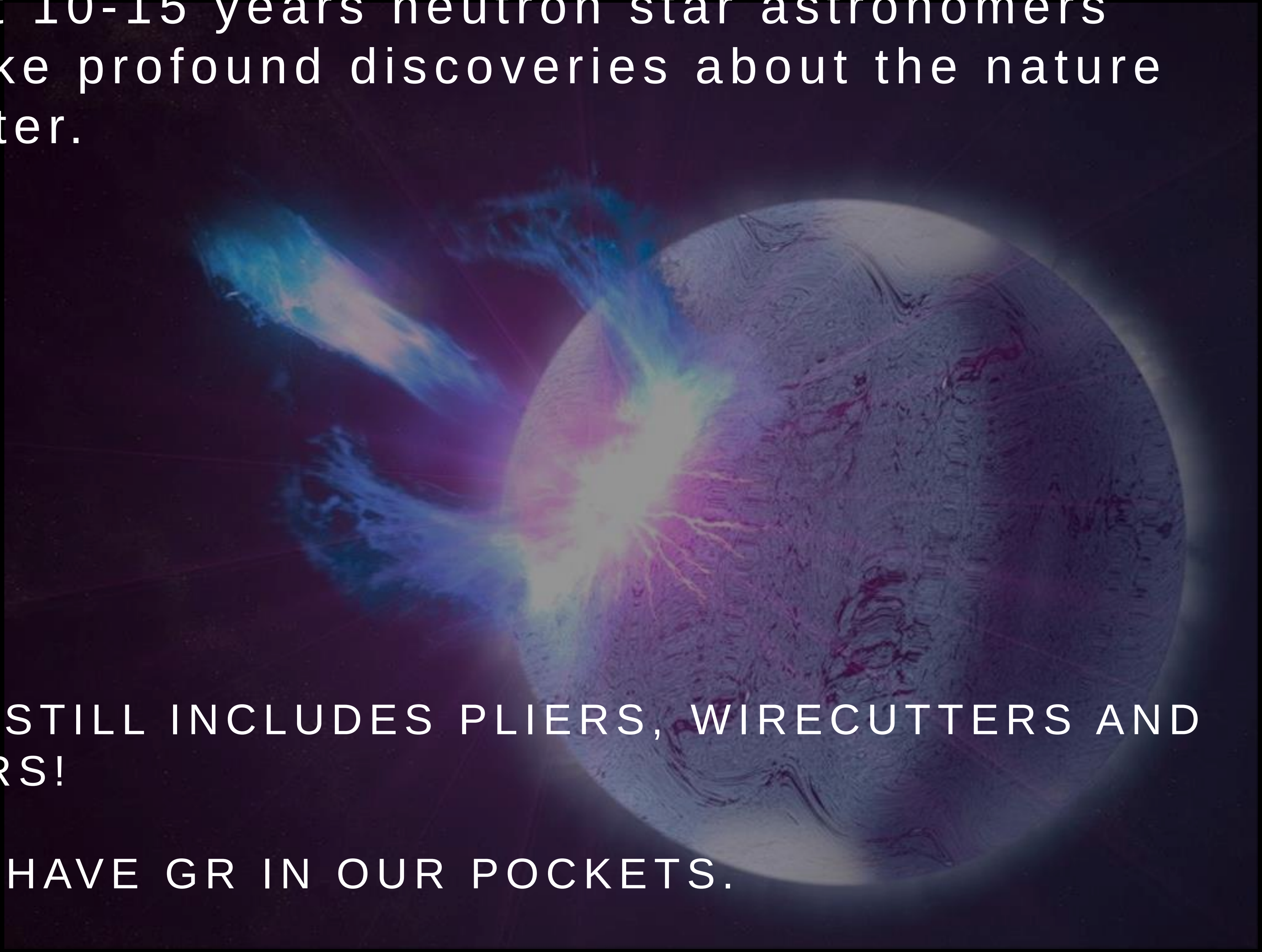


- Large Observatory for X-ray Timing (LOFT), ESA M-class candidate
  - ~10 m^2 hard X-ray
  - Targets burst oscillation sources
- Enhanced XTP – Chinese Academy of Sciences/Europe concept
  - ~1m^2 soft X-ray + polarimeter
  - ~3m^2 hard X-ray
  - Polarimeter helps to offset impact of area reduction
  - Targets accretion-powered millisecond pulsars, especially those with burst oscillations

Watts et al. 2016, Measuring the neutron star equation of state using X-ray timing

The cores of neutron stars reach densities far higher than anything we can achieve on Earth, conditions where we expect to encounter new states of matter.

Over the next 10-15 years neutron star astronomers expect to make profound discoveries about the nature of dense matter.



OUR TOOLKIT STILL INCLUDES PLIERS, WIRECUTTERS AND SCREWDRIVERS!

BUT WE ALSO HAVE GR IN OUR POCKETS.