Nuclear physics with neutron stars:

Transients and non-transient phenomena

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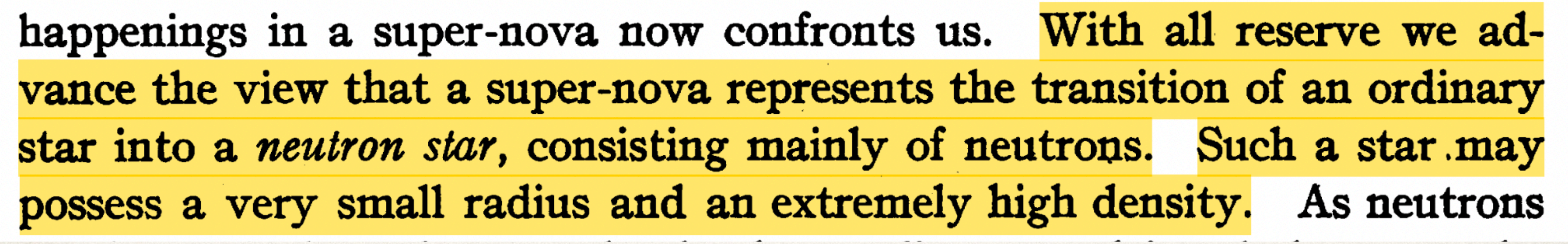
irap
astrophysique & planétologie

Transient
Universe 2023

History
From the neutron to neutron stars

- **Prediction of the neutron** (Rutherford, 1920)
- Suggestion of stars as “*one giant nucleus*” (Landau, 1932)
- **Discovery of the neutron** (Chadwick, 1932)
- 1st description of dense nuclear matter (Sterne, 1933)
- **Predictions of neutron stars** (Baade and Zwicky, 1934)



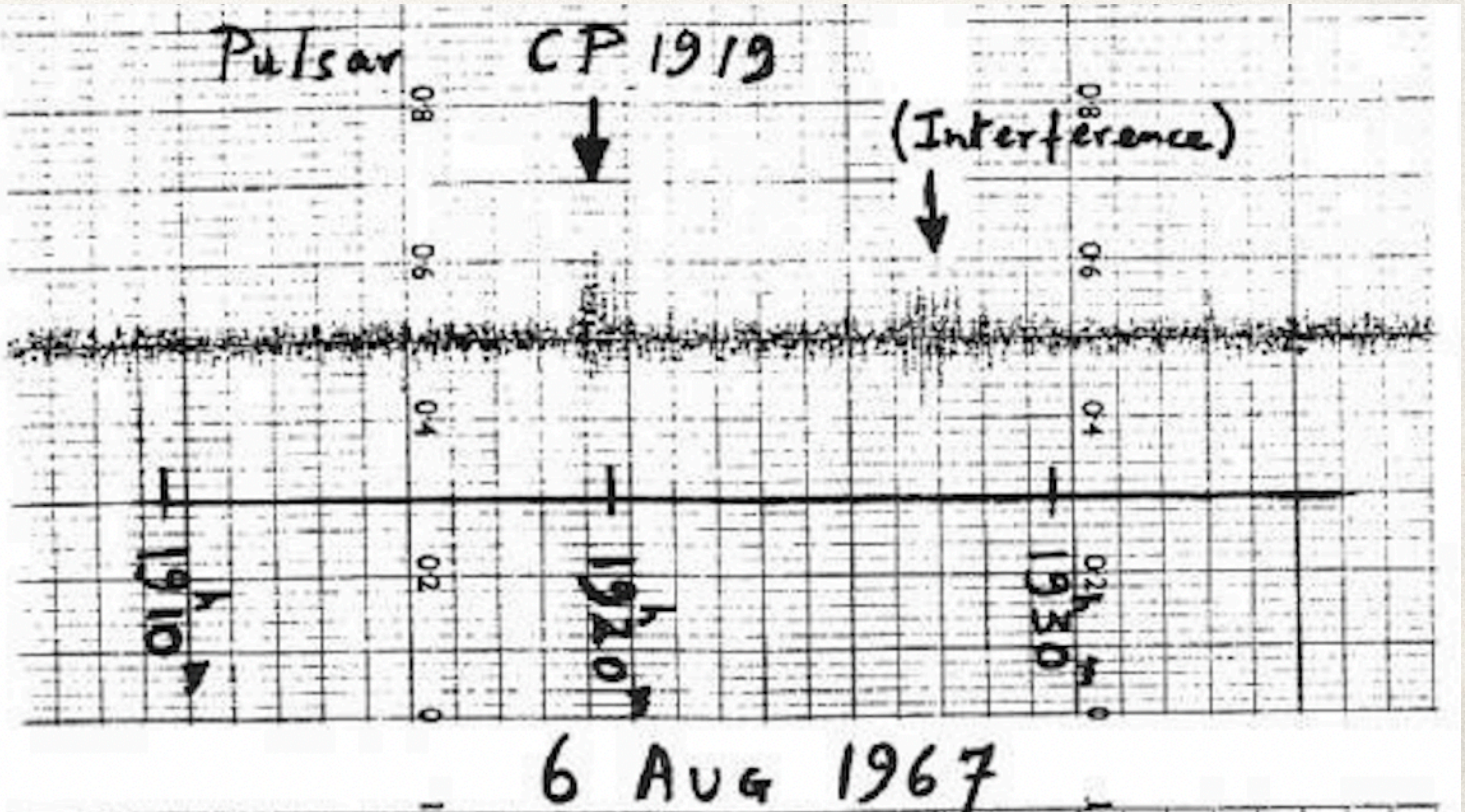
happenings in a super-nova now confronts us. With all reserve we advance the view that a super-nova represents the transition of an ordinary star into a *neutron star*, consisting mainly of neutrons. Such a star may possess a very small radius and an extremely high density. As neutrons

Baade and Zwicky, 1934

- **1st density estimations**: $10^{12} – 10^{15}$ g/cm^3 (Hund, 1936)

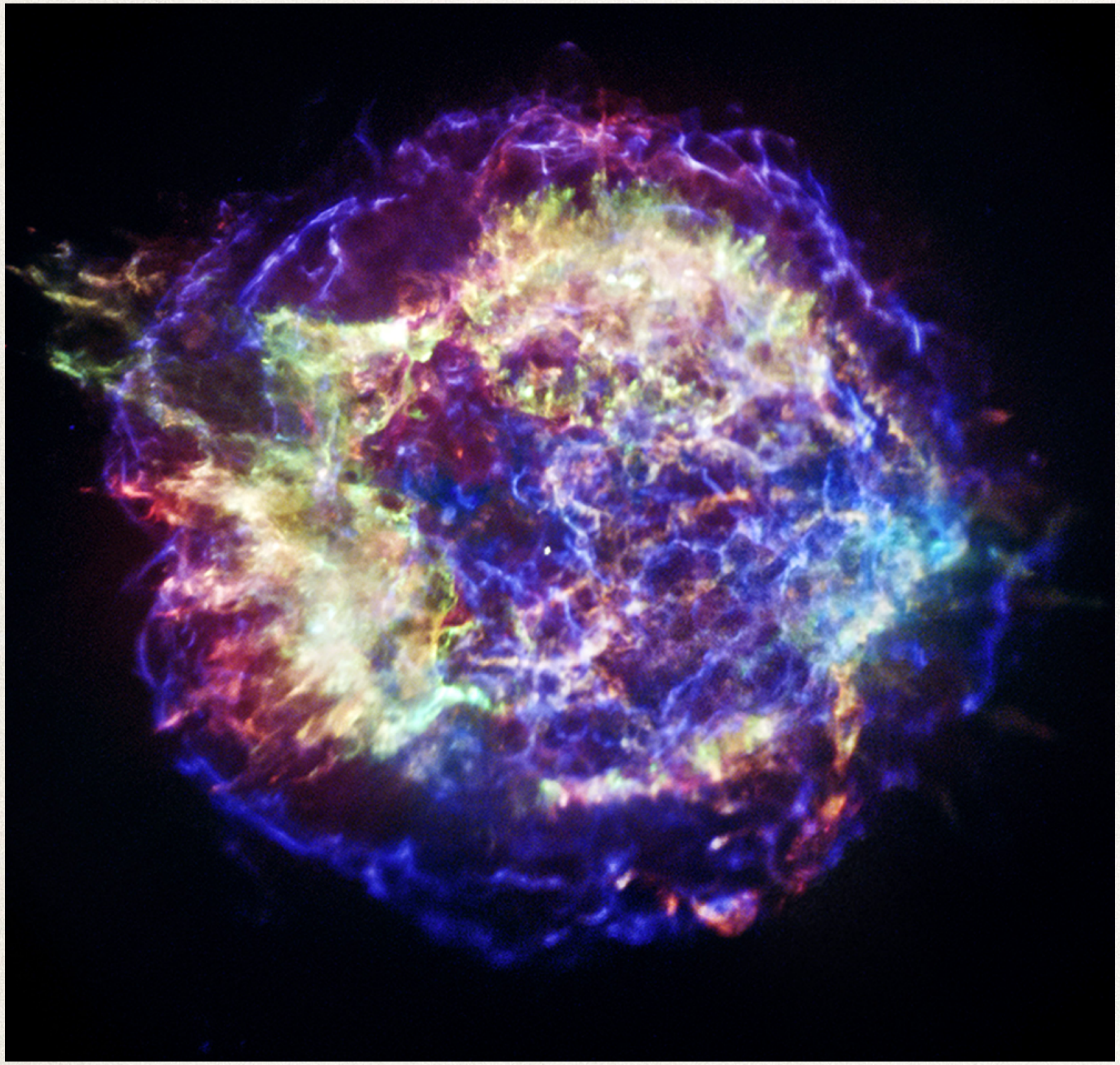
History
From theory to observations

- Equation of relativistic stellar structure
  - Tolman, 1939; Oppenheimer and Volkoff, 1939
- Development of the theory on the Strong force
  - Yukawa, 1935; Skyrme, 1959; Cameron, 1959
- More physics inside neutron stars
  - Superfluidity, Hyperons, Quarks
- Discovery of pulsars in 1967 by J. Bell
  - ~1.337 sec periodicity
- First observation of a neutron star actually precedes the discovery of pulsars (in 1962)



6 AUG 1967

Neutron stars are the remnants of the core-collapse of massive stars.



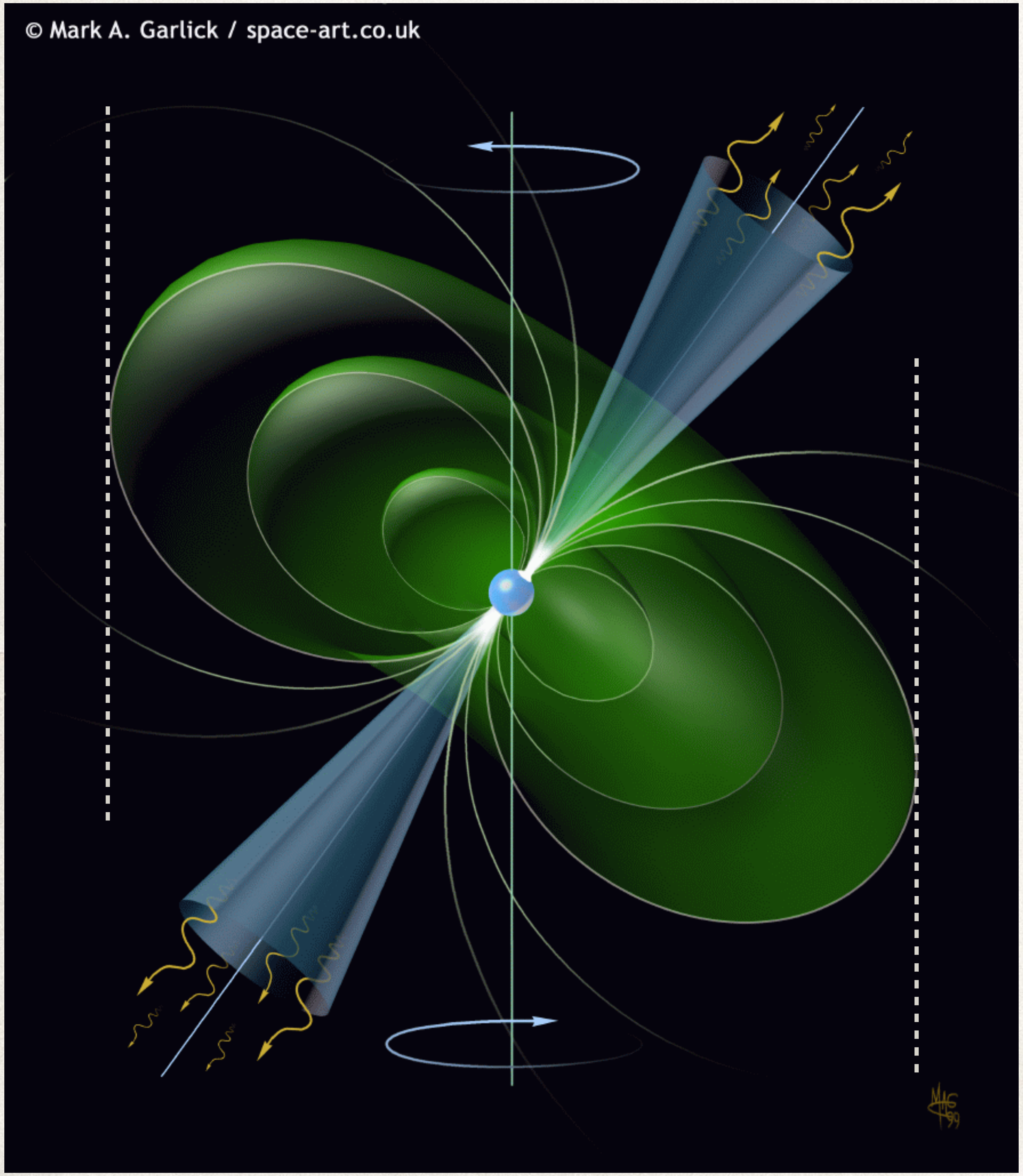
Cassiopeia A
X-ray image

Credits: NASA CXO

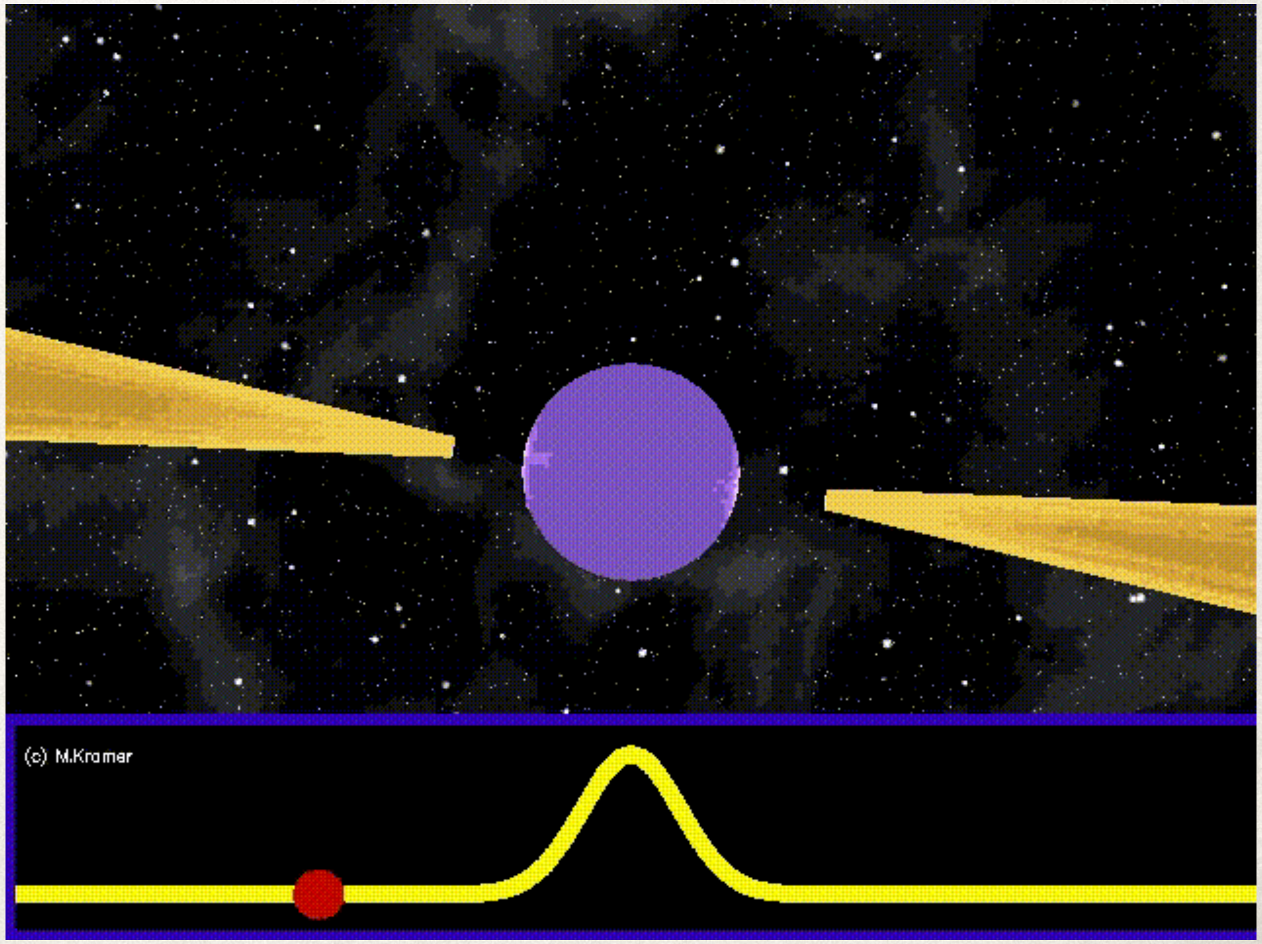
Crab Nebula
Composite X-ray+IR+Opt

Credits: NASA CXC / ESA / JPL

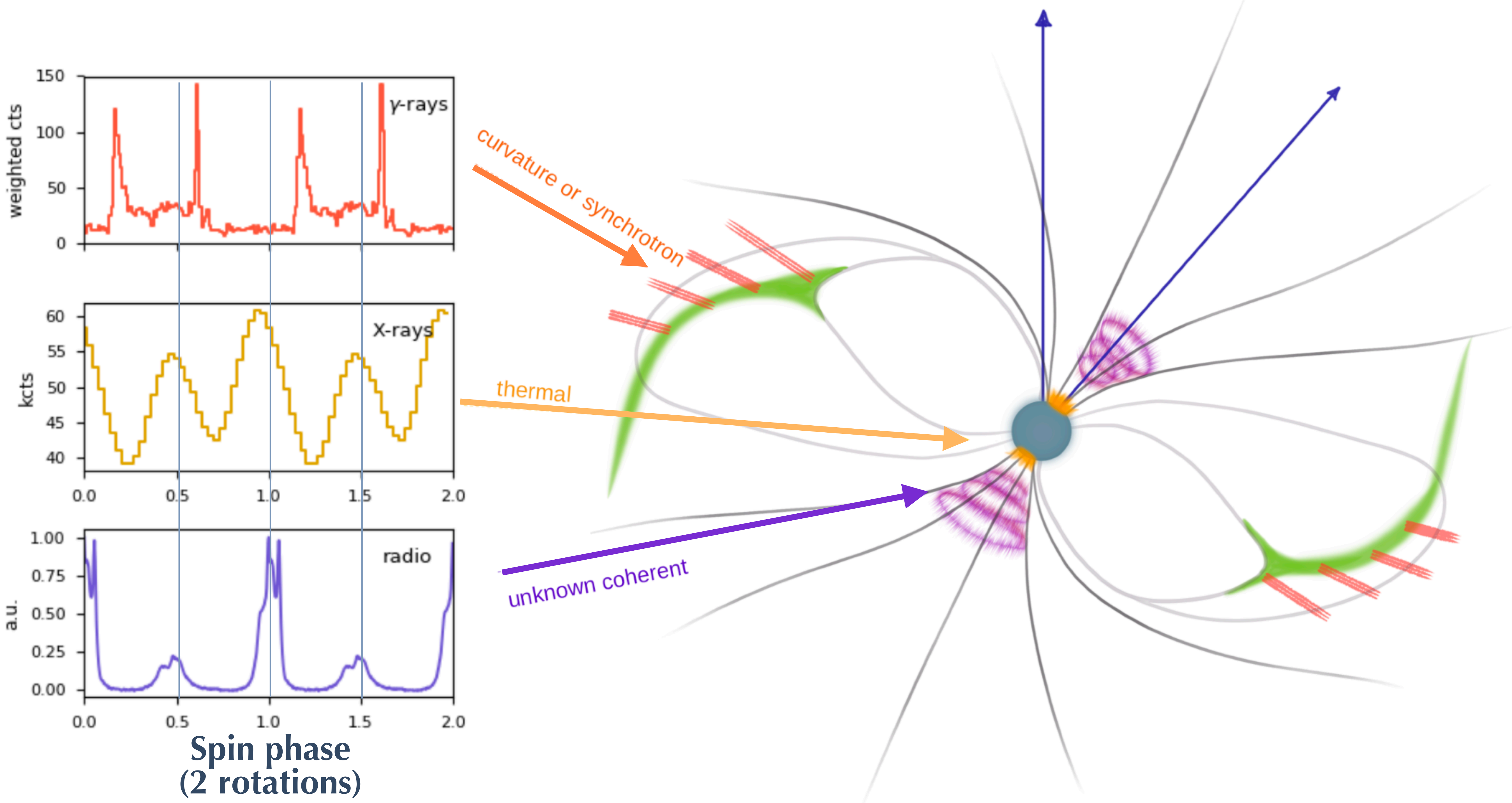
All pulsars are neutron stars, but not all neutron stars are pulsars!


© Mark A. Garlick / space-art.co.uk

R_{NS} ~ 10 – 15 km
M_{NS} ~ 1.0 – 2.0 $M_\odot$
B ~ 10^8 – 10^{15} G
P_{spin} ~ 0.001 – 10 sec


(c) M.Kramer

A variety of pulsations mechanisms at different wavelengths can be observed in pulsars



Spin phase
(2 rotations)

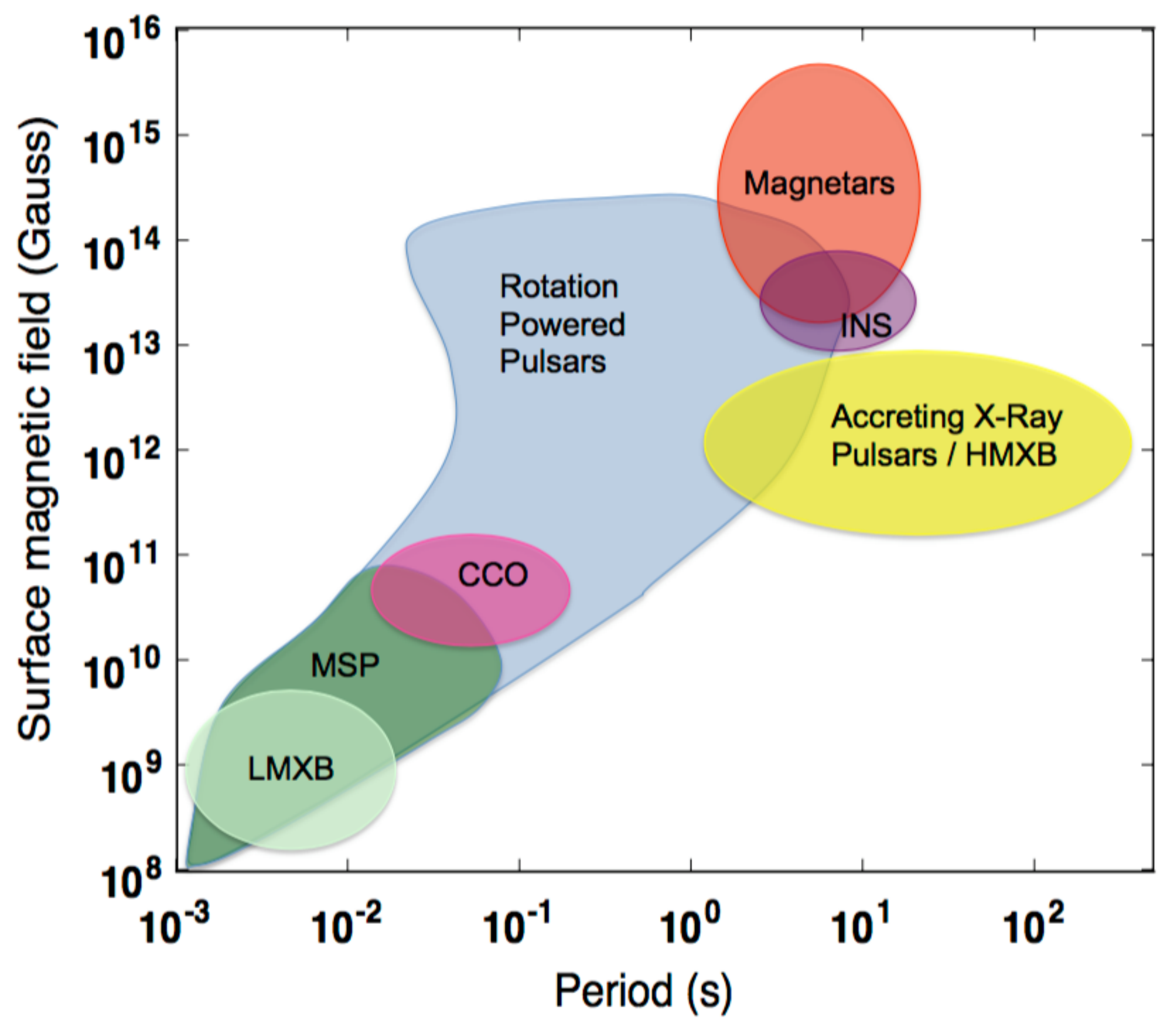
curvature or synchrotron

thermal

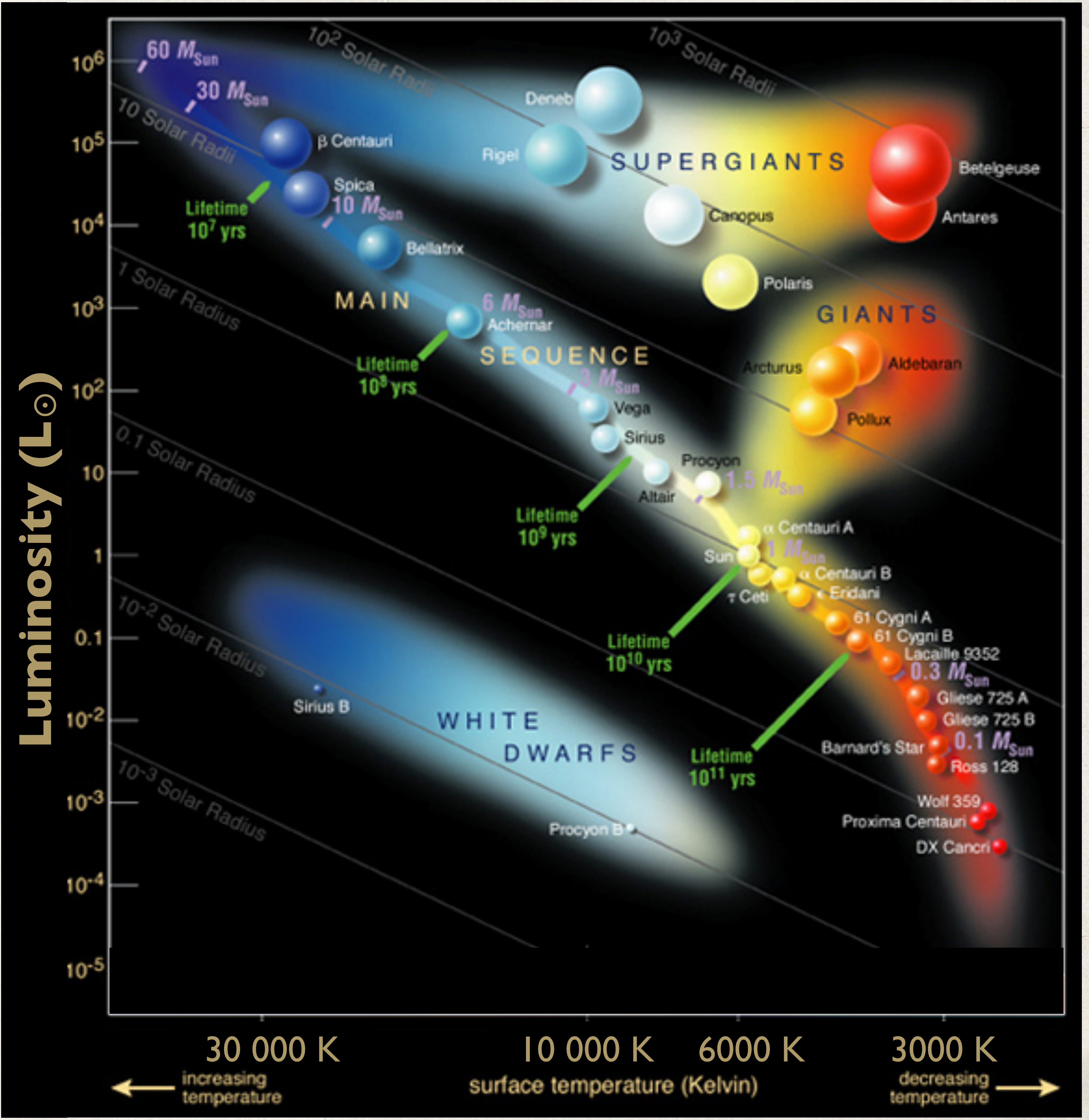
unknown coherent

Credits: A. Bilous

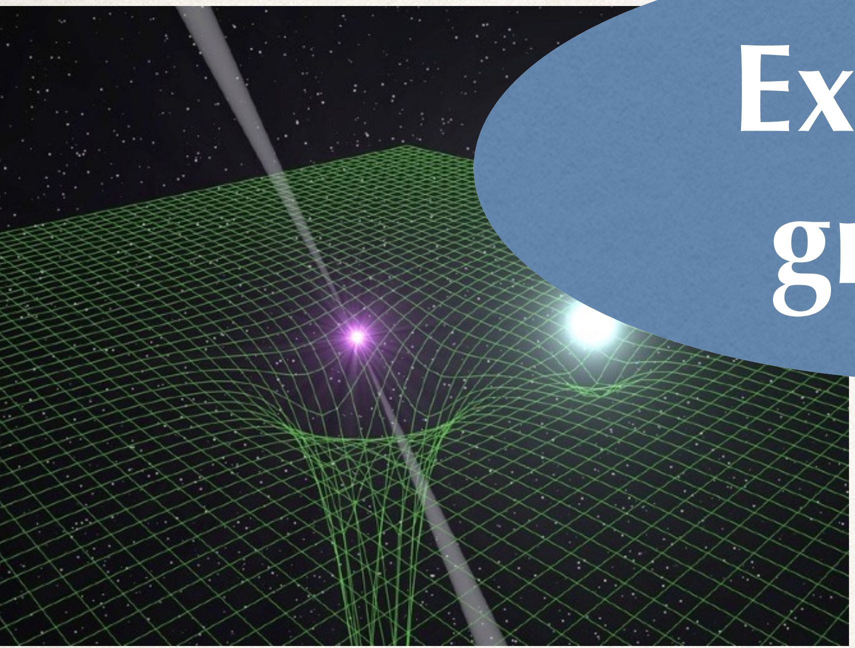
Neutron stars come in a variety of flavours, with different properties and observational signatures.



Question: Where would neutron stars be on the HR diagram?

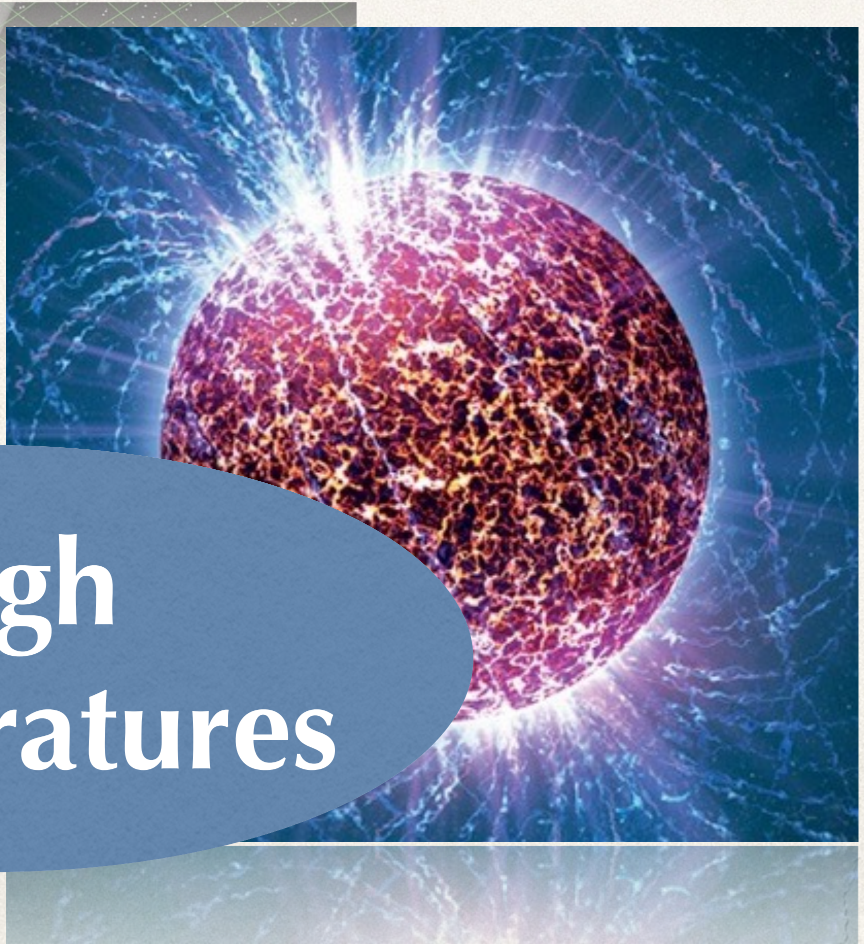


Neutron stars are amazing laboratories for extreme physics.

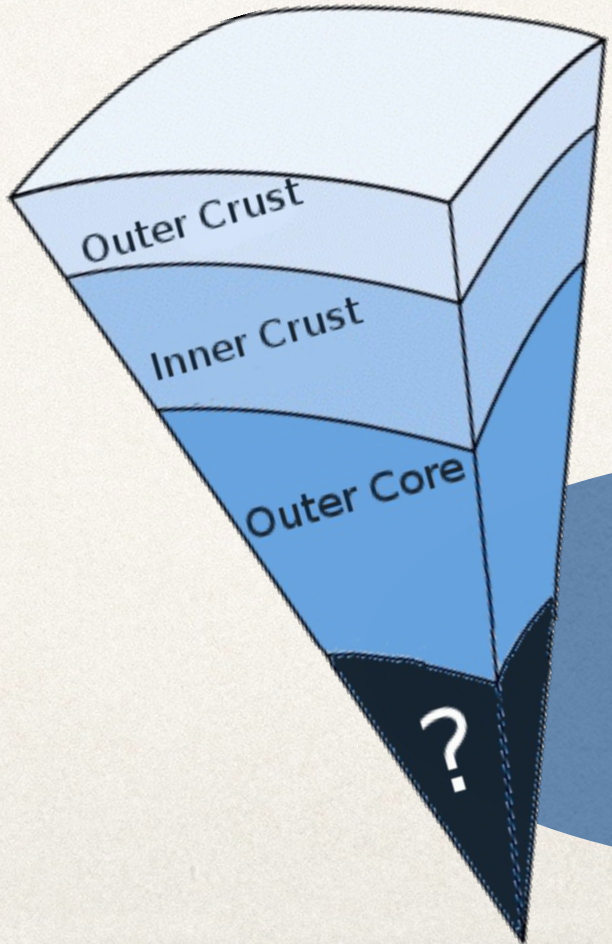


Extreme gravity

Extreme B-fields

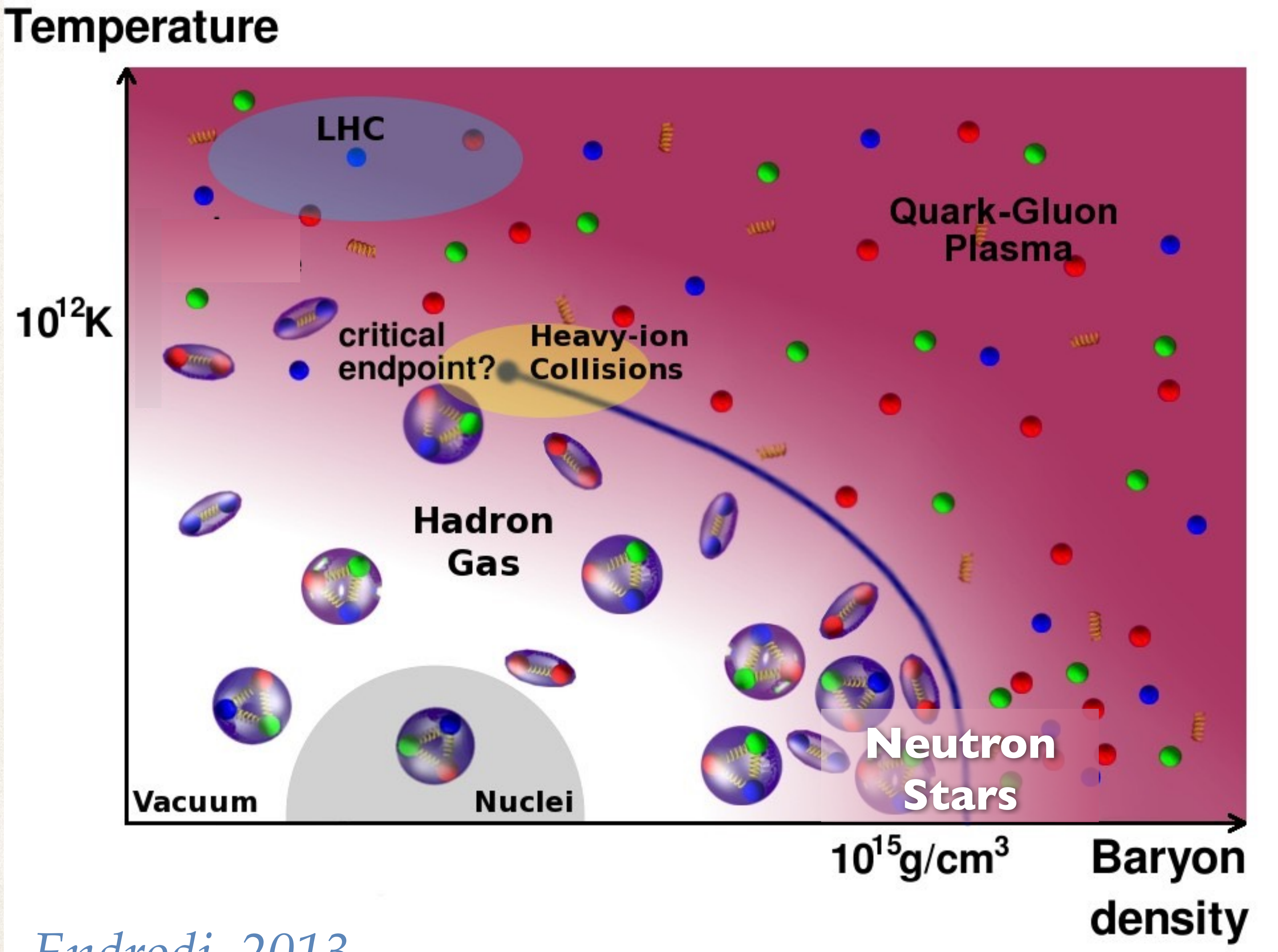


High temperatures



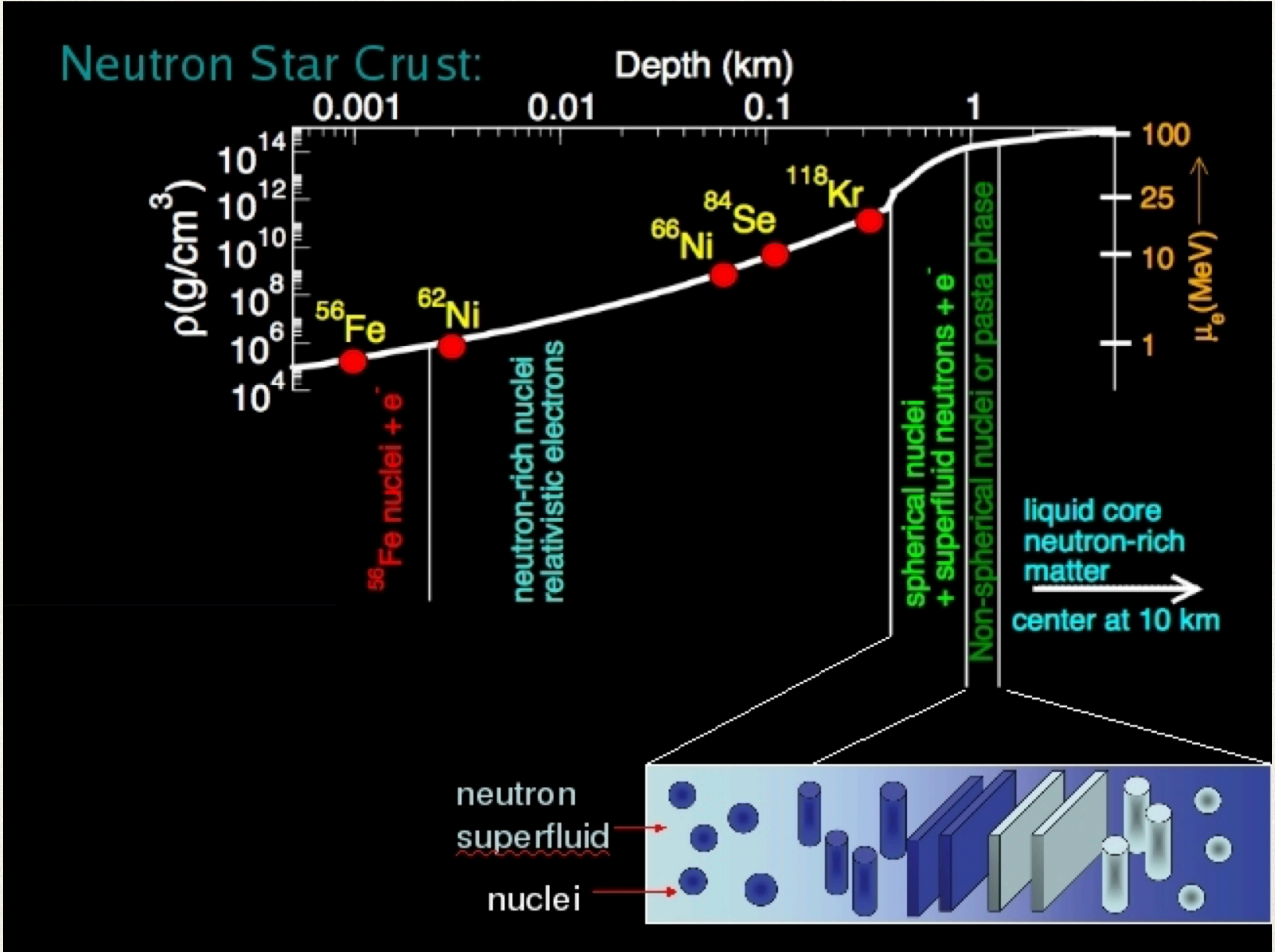
Extreme densities

Neutron stars provide tests of nuclear physics that are out of reach from experiments and calculations.

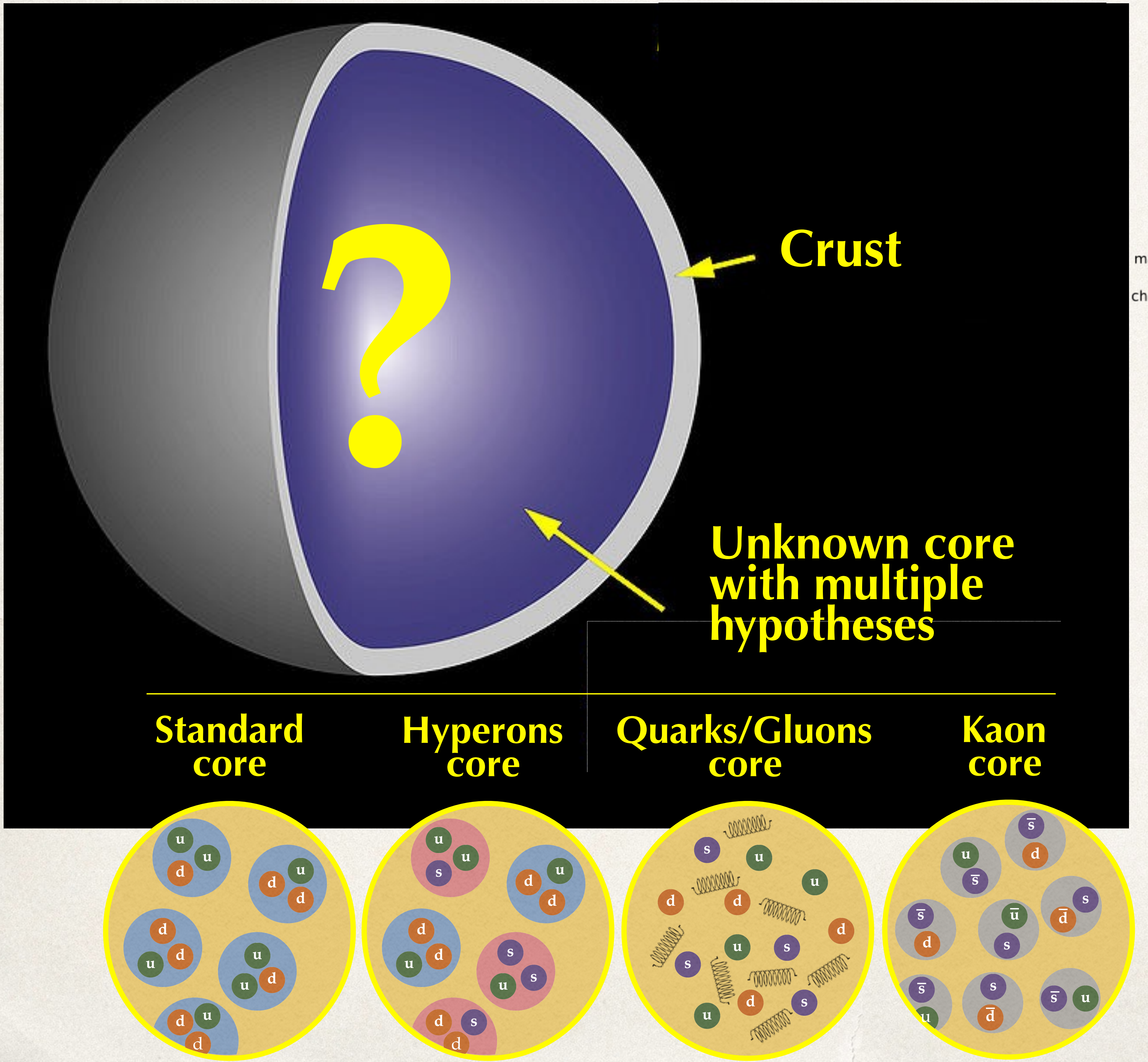


Endrodi, 2013

In the outer layers of neutron stars, the physics is relatively understood.



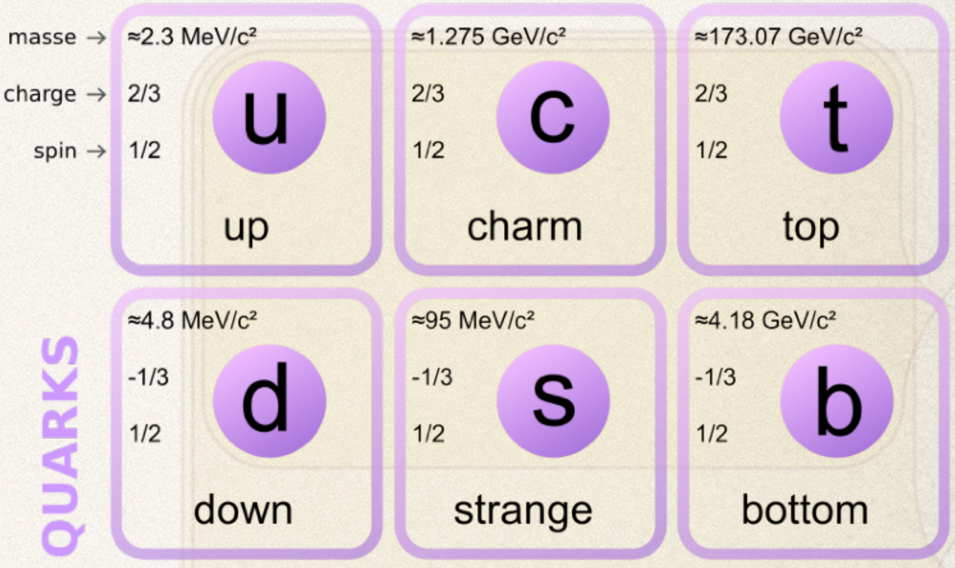
The internal structure of neutron stars is still unknown and numerous theories are proposed.



Crust

Unknown core with multiple hypotheses

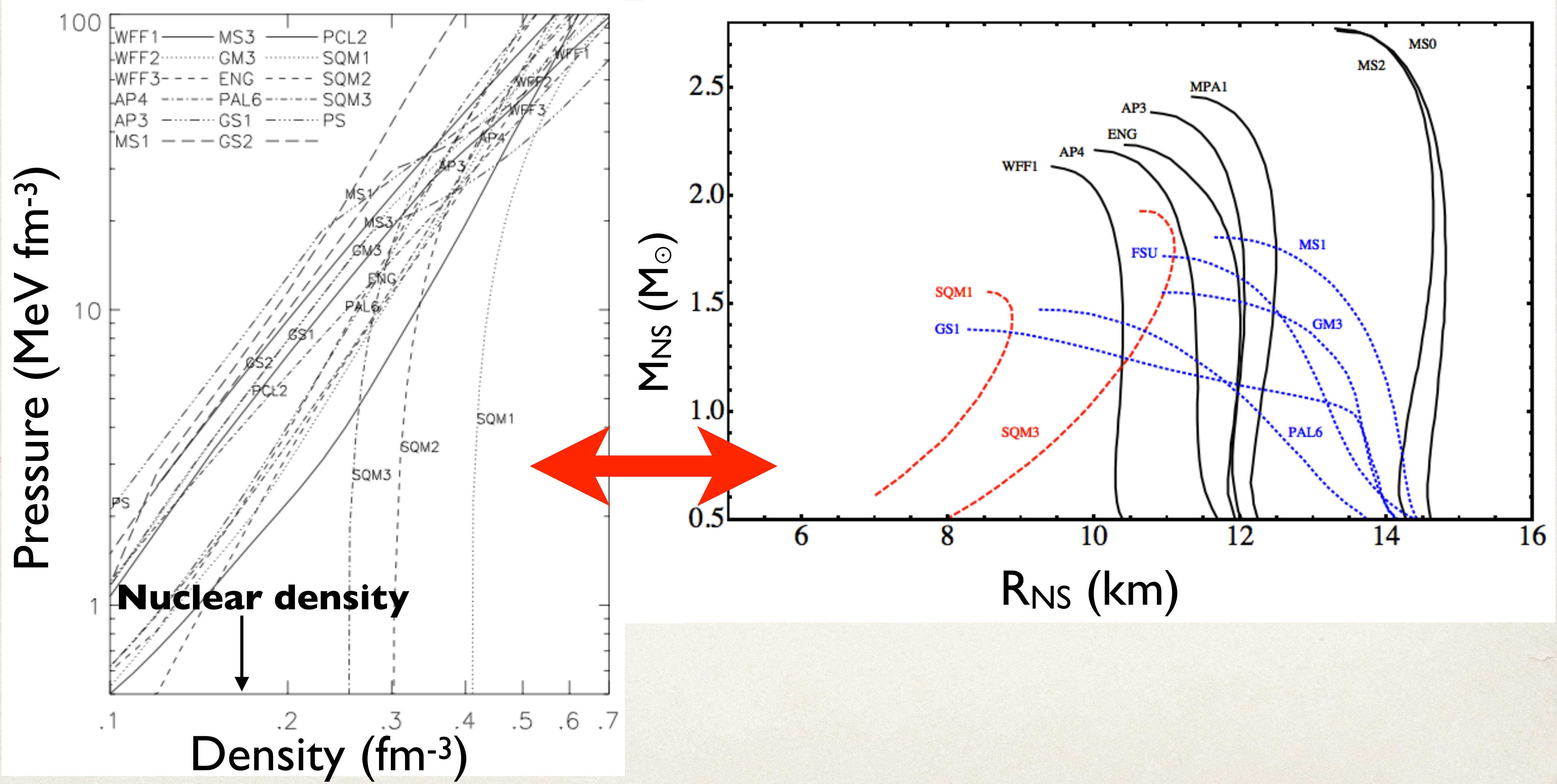
Standard core	Hyperons core	Quarks/Gluons core	Kaon core



QUARKS

masse →	≈2.3 MeV/c²	≈1.275 GeV/c²	≈173.07 GeV/c²
charge →	2/3	2/3	2/3
spin →	1/2	1/2	1/2
	u	c	t
	up	charm	top
	≈4.8 MeV/c²	≈95 MeV/c²	≈4.18 GeV/c²
	-1/3	-1/3	-1/3
	1/2	1/2	1/2
	d	s	b
	down	strange	bottom

Dense nuclear matter is described by an equation of state P(ρ). But what is it?



Lattimer and Prakash 2001

To get $M_{NS}(R_{NS})$ from $P(\rho)$, one must solve the equations of stellar structure.

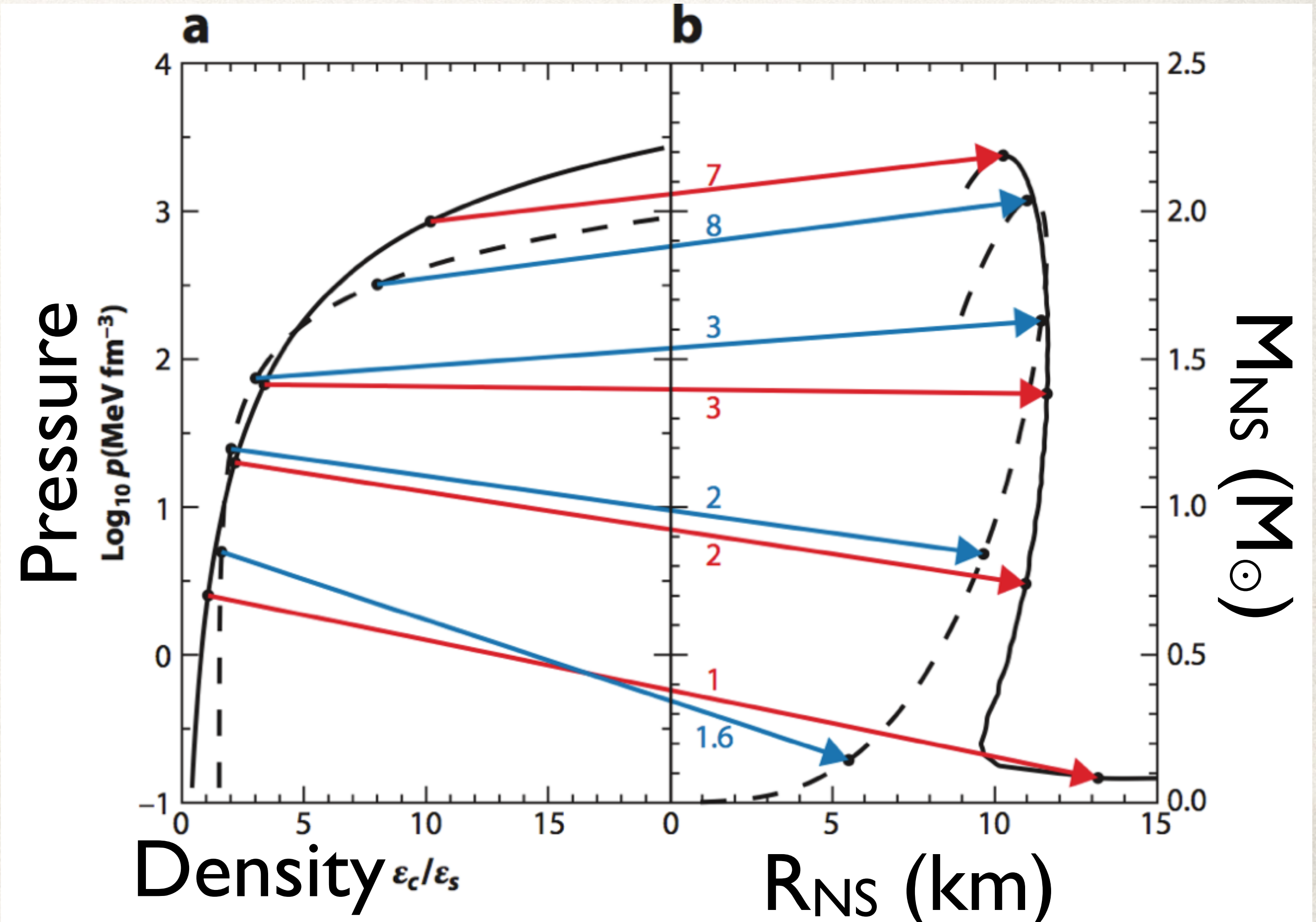
Hydrostatic equilibrium

$$\frac{dP}{dr} = -G\frac{\rho(r)M(r)}{r^2}\overbrace{\left(1+\frac{P(r)}{\rho(r)}\right)\left(1+\frac{4\pi r^3 P(r)}{M(r)}\right)\left(1-\frac{2GM(r)}{r}\right)^{-1}}^{\text{relativistic corrections}}$$

Mass continuity

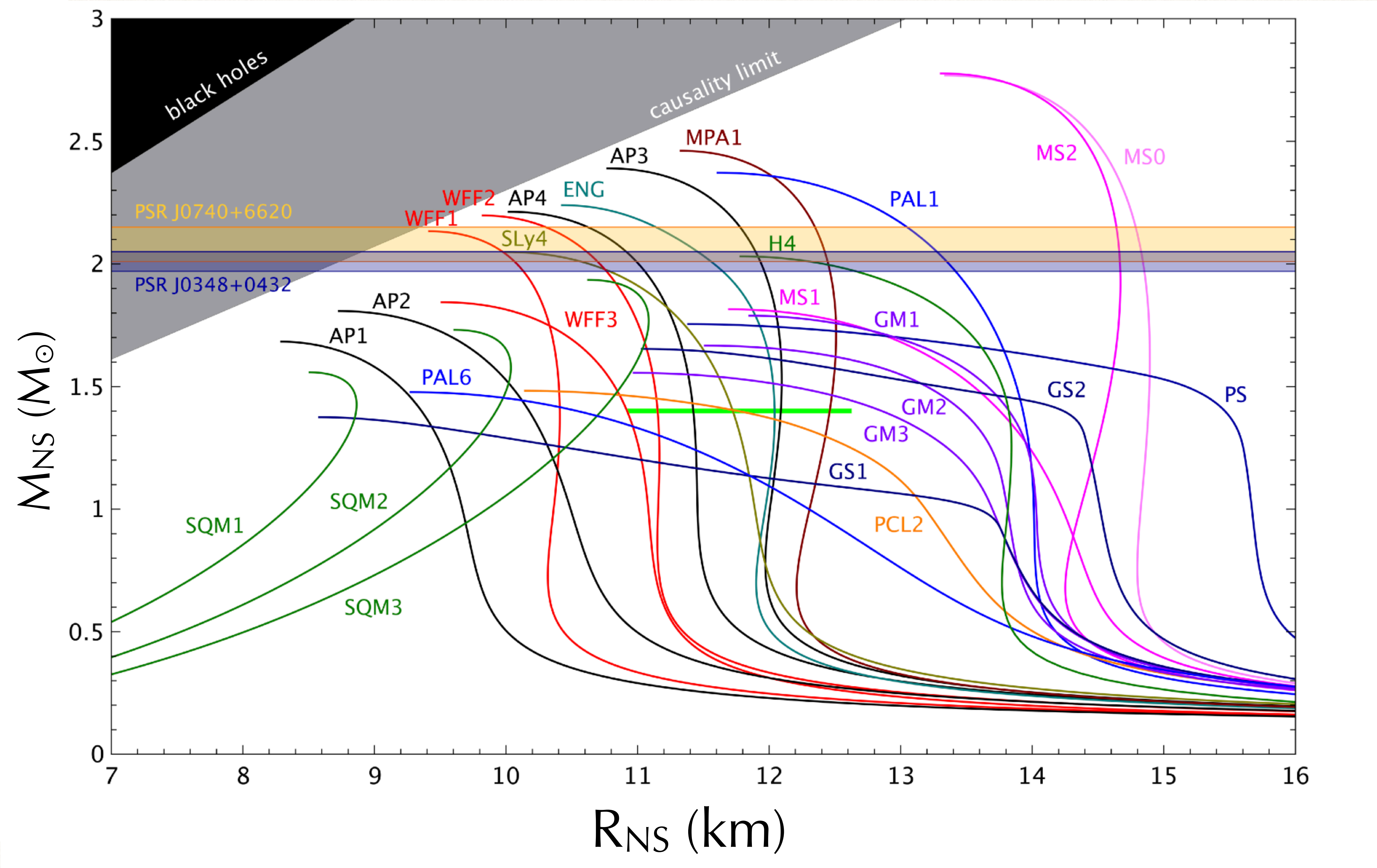
$$\frac{dM}{dr} = 4\pi r^2\rho(r)$$

Tolman-Oppenheimer-Volkoff equations



J. Lattimer, 2012

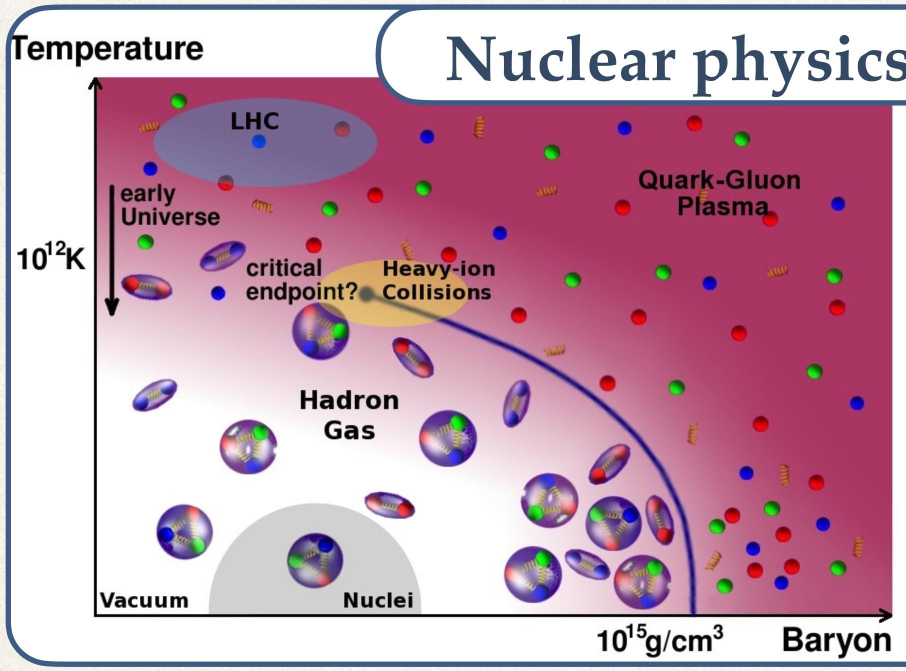
To determine the equation of state P(ρ), one needs to measure M_{NS} and/or R_{NS}.

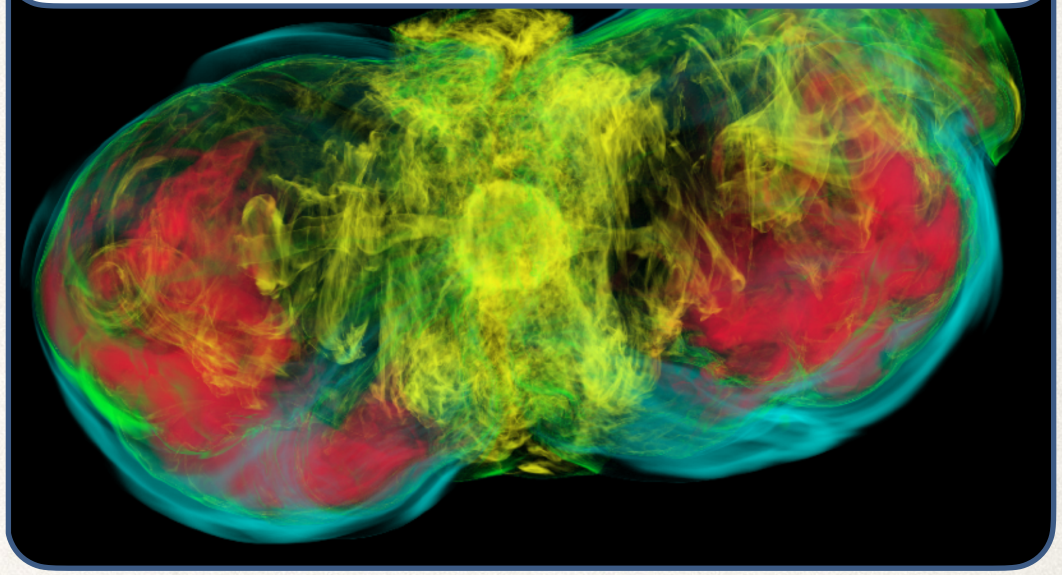


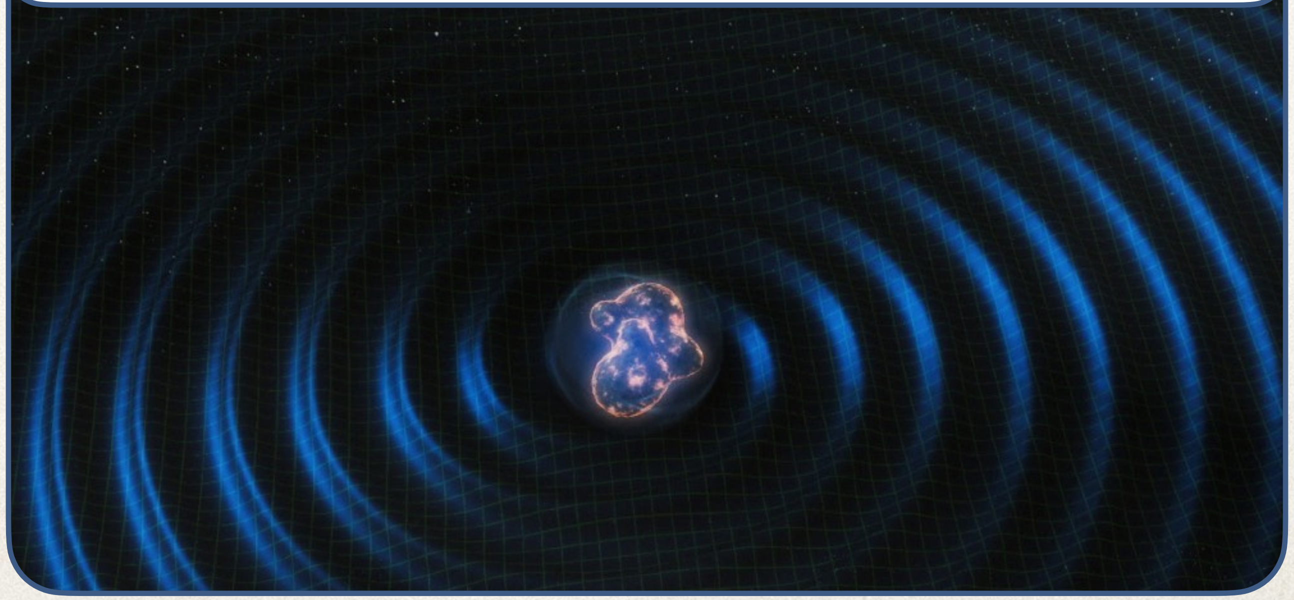
I will show a lot of these M-R diagram!

Credits: N. Wex

The dense matter equation of state is a key question of fundamental physics and astrophysics


Nuclear physics


Supernovae mechanisms

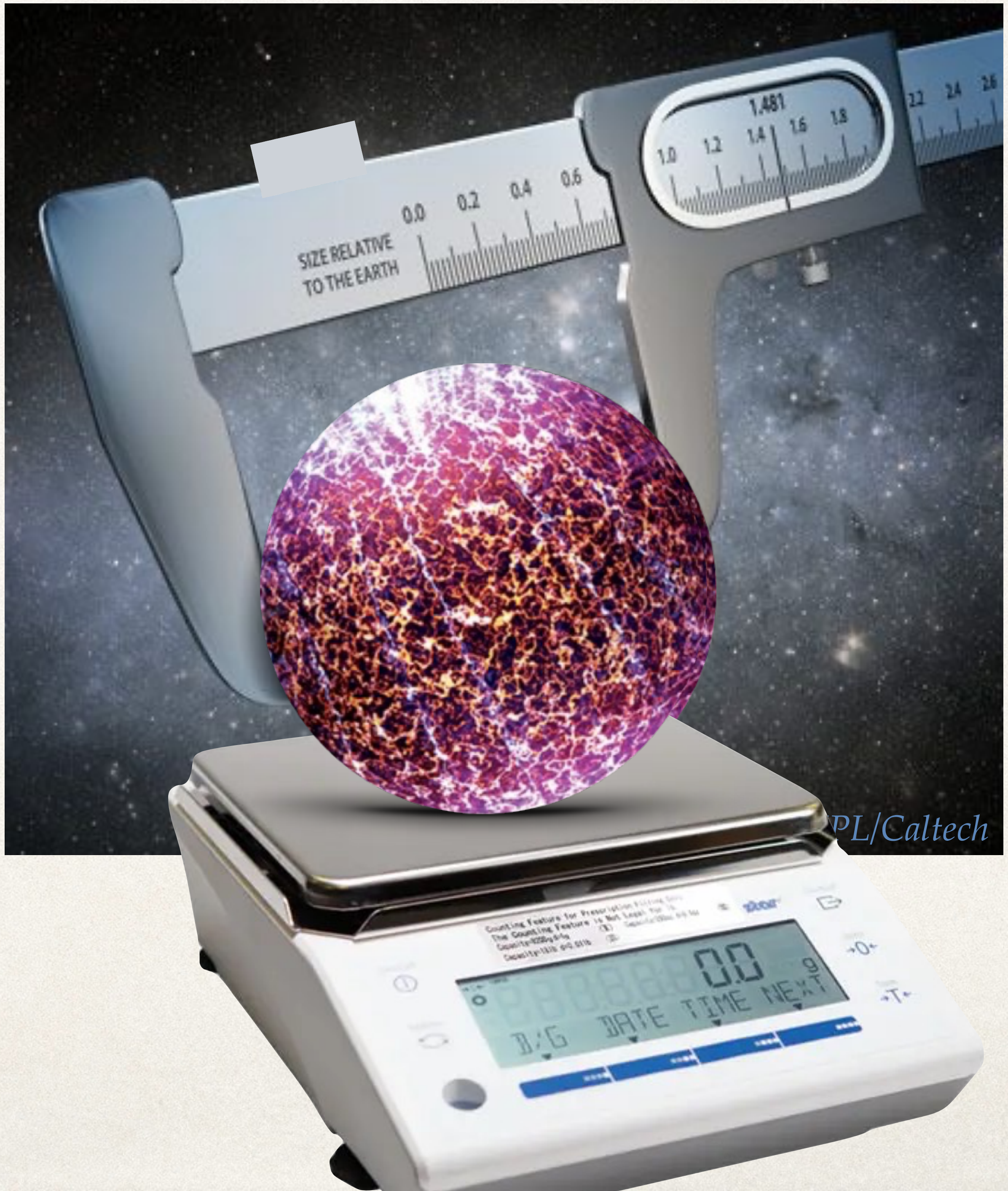

Mergers of compact objects

A brief outline

1. **Generalities on measurements of masses M_{NS} and radii R_{NS}**
2. **Measurements of M_{NS} and R_{NS}:**
    1. **with transient phenomena (surface explosions, i.e., X-ray bursts)**
    2. **with non-transient neutron stars**
3. **Measurement of M_{NS} and R_{NS} with gravitational waves**
4. **Combining observations to understand dense matter**

PART 1

Generalities on M_{NS} and R_{NS} measurements

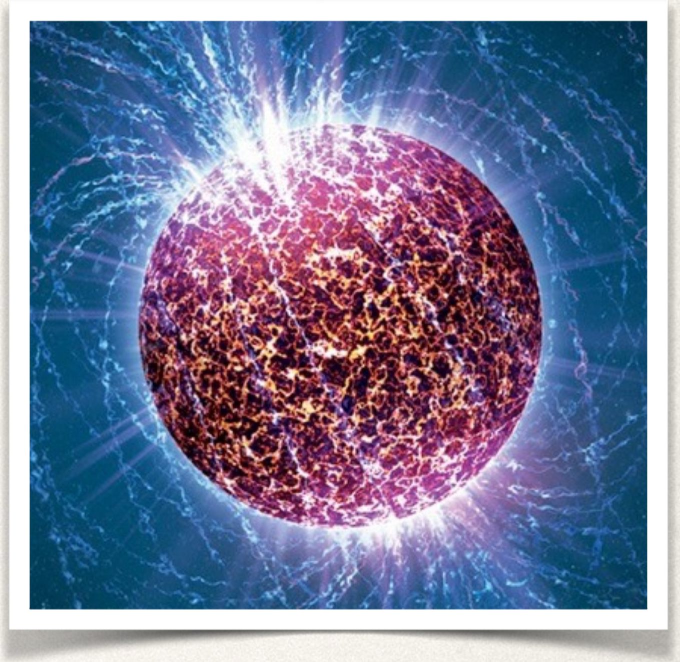


PL/Caltech

Measuring with precision the radius from surface thermal emission is rather difficult.

To measure the radius, we need to:

- observe the surface thermal emission,
- correctly model this emission,
- know the distance independently.



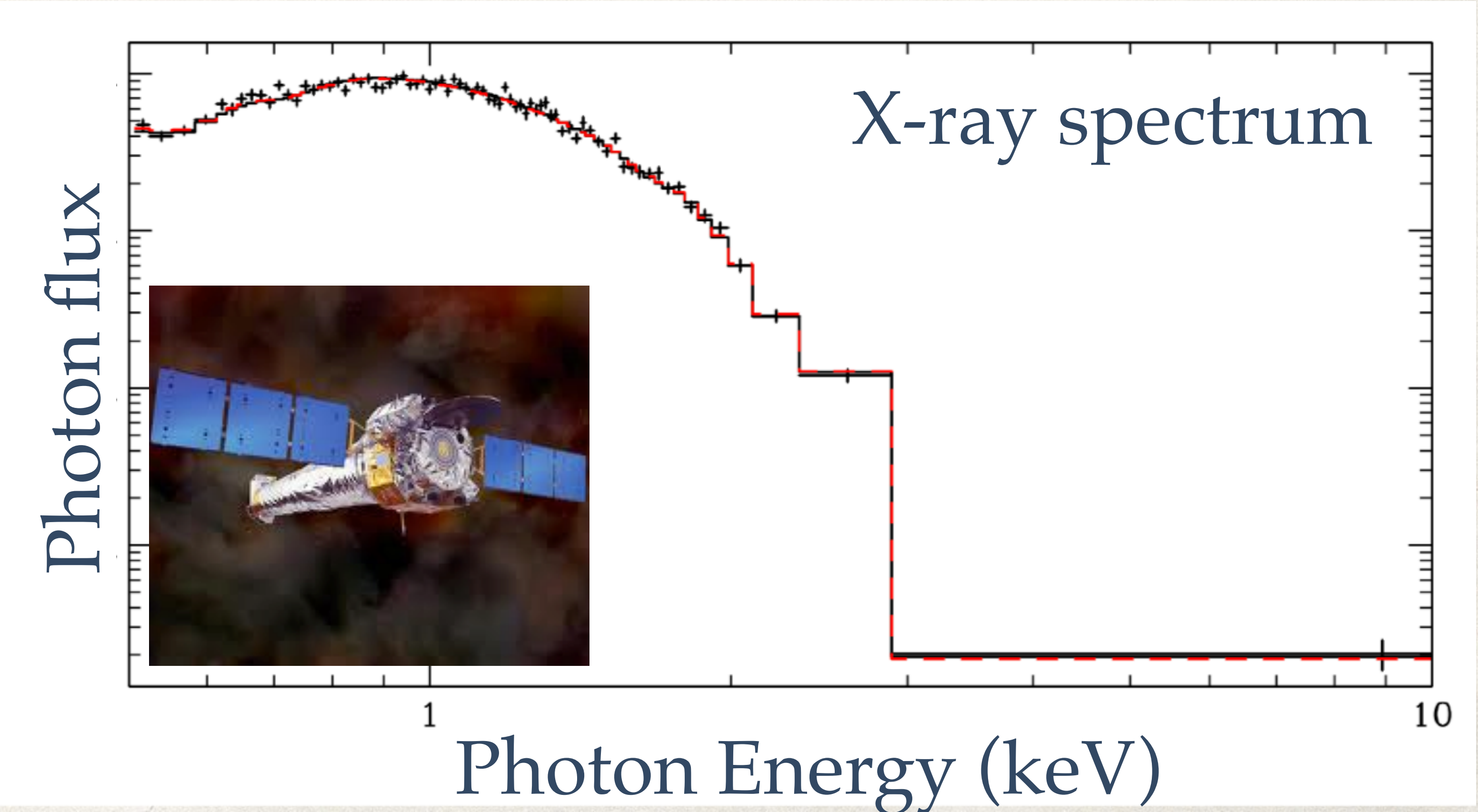
Luminosity

$$L = 4\pi R^2 \sigma T_{\rm eff}^4$$

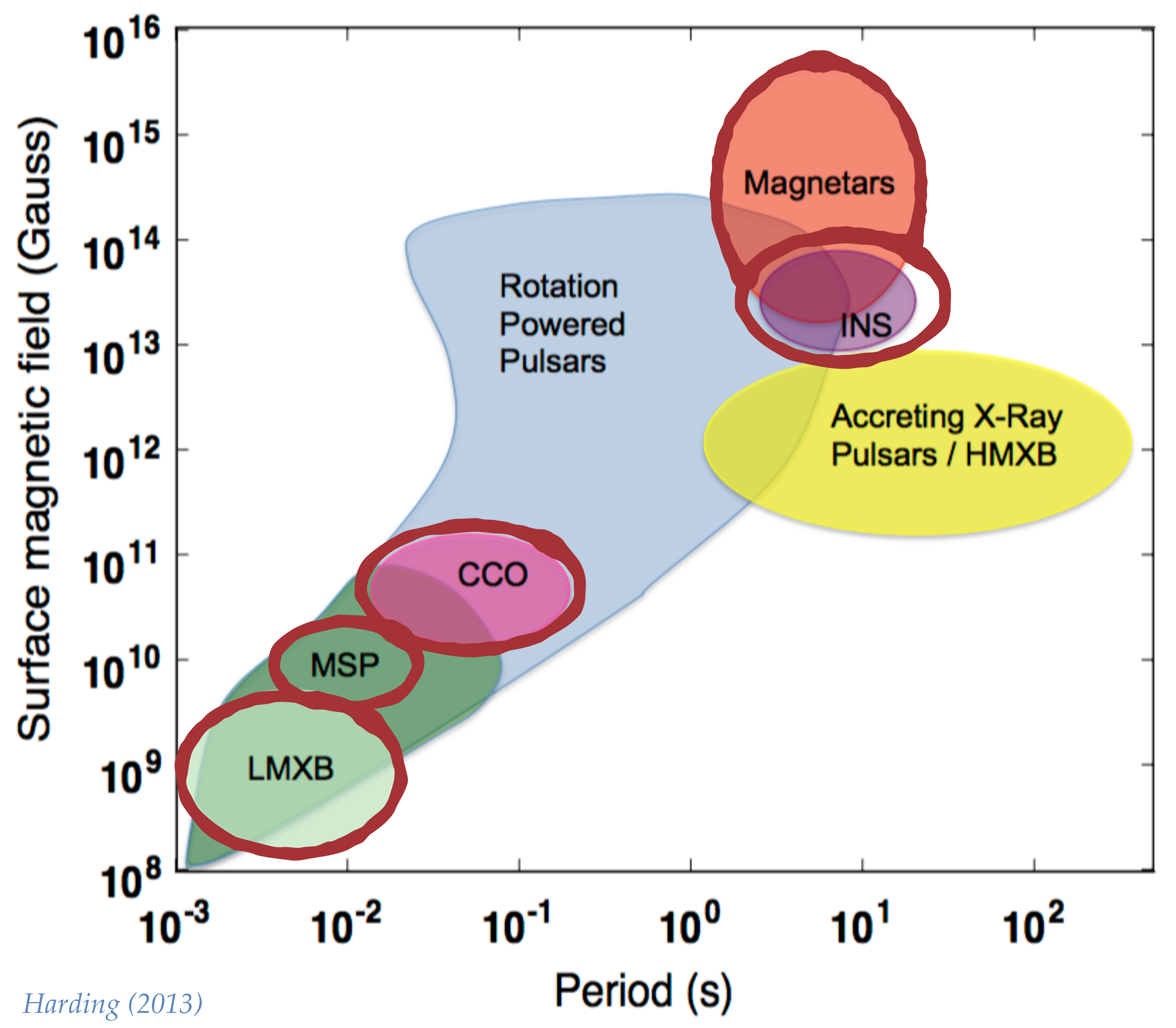
$$\Big\downarrow$$

Flux

$$F = \left(\frac{R}{D}\right)^2 \sigma T_{\rm eff}^4$$



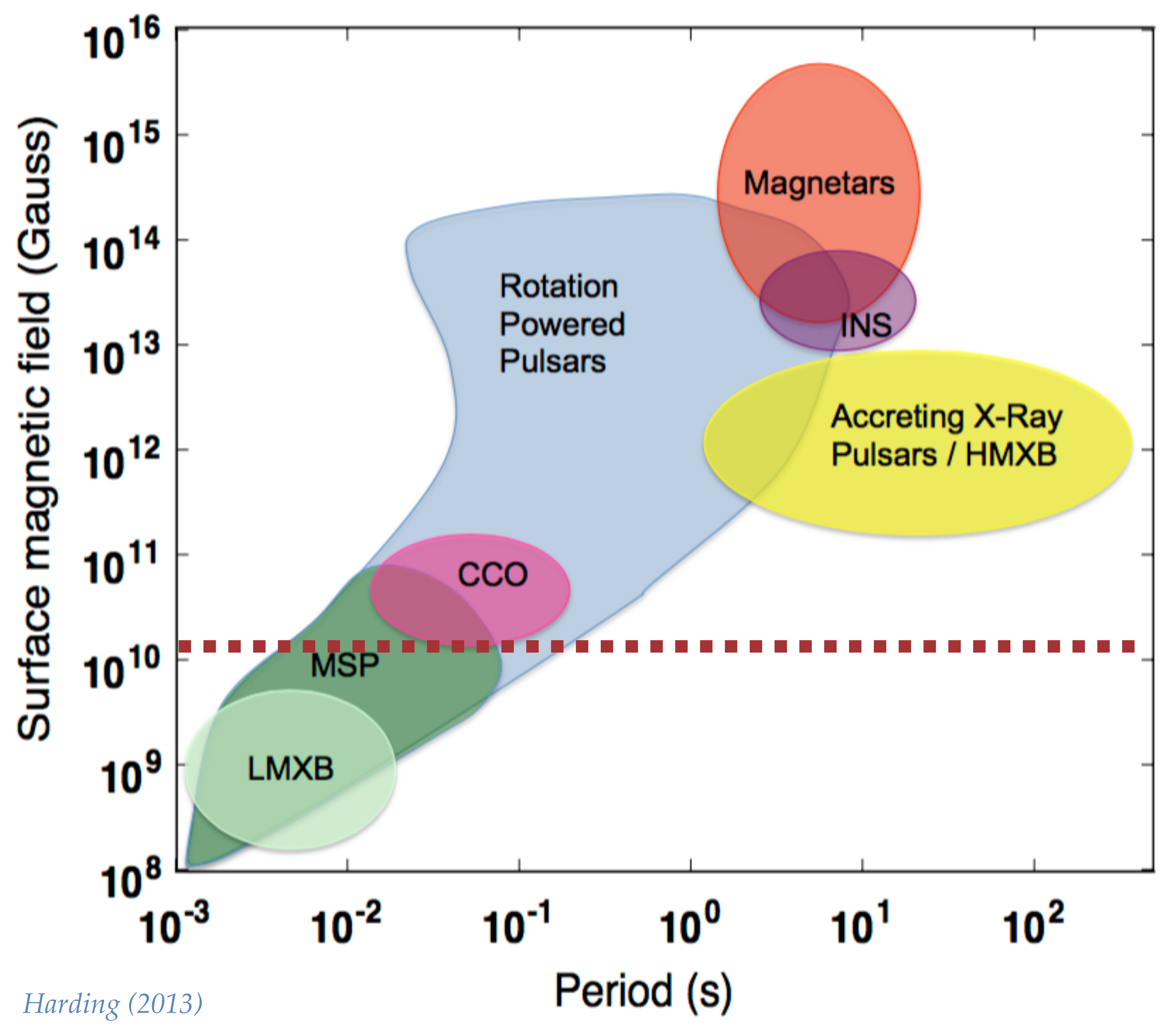
Measuring M_{NS} and/or R_{NS} requires understanding the observational properties. Not all classes of neutron stars are useful for this purpose.



Harding (2013)

The emission from the entire surface needs to be visible

Measuring M_{NS} and/or R_{NS} requires understanding the observational properties. Not all classes of neutron stars are useful for this purpose.



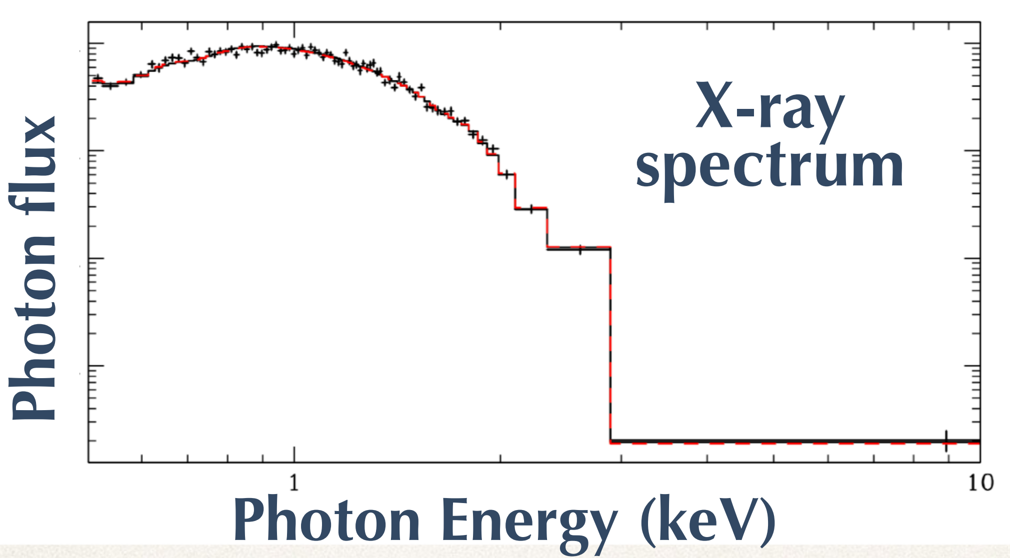
Harding (2013)

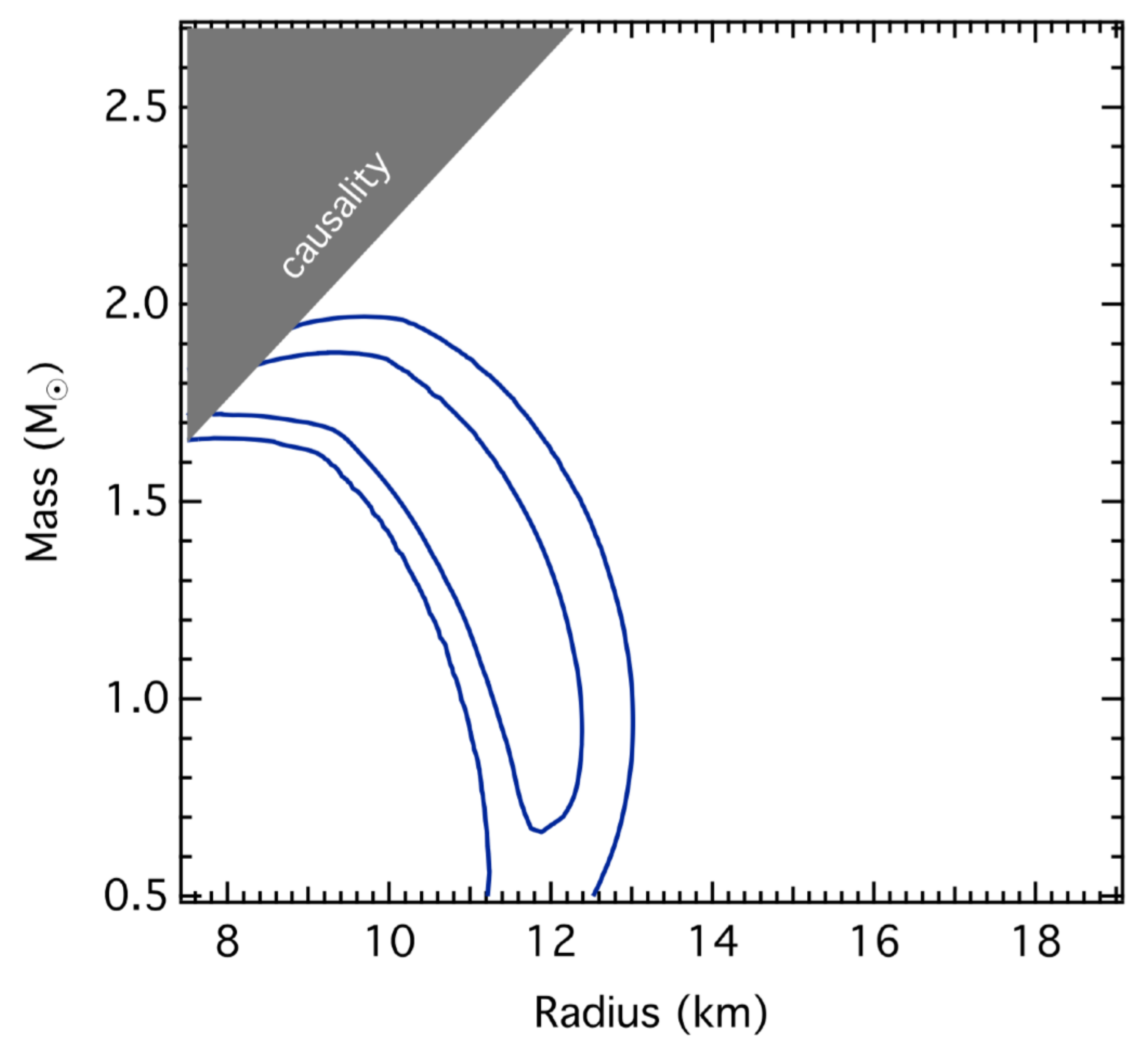
Highly magnetised atmospheres are difficult to model

For $B \lesssim 10^{10}$ G, opacities of free-free processes in 10^{6} K atmosphere are unaffected

Because of gravitational redshift, the radius is degenerate with the mass.

$$R_\infty = R_{\rm NS}\,(1+z) = R_{\rm NS}\left(1 - \frac{2GM_{\rm NS}}{R_{\rm NS}\;c^2}\right)^{-1/2}$$



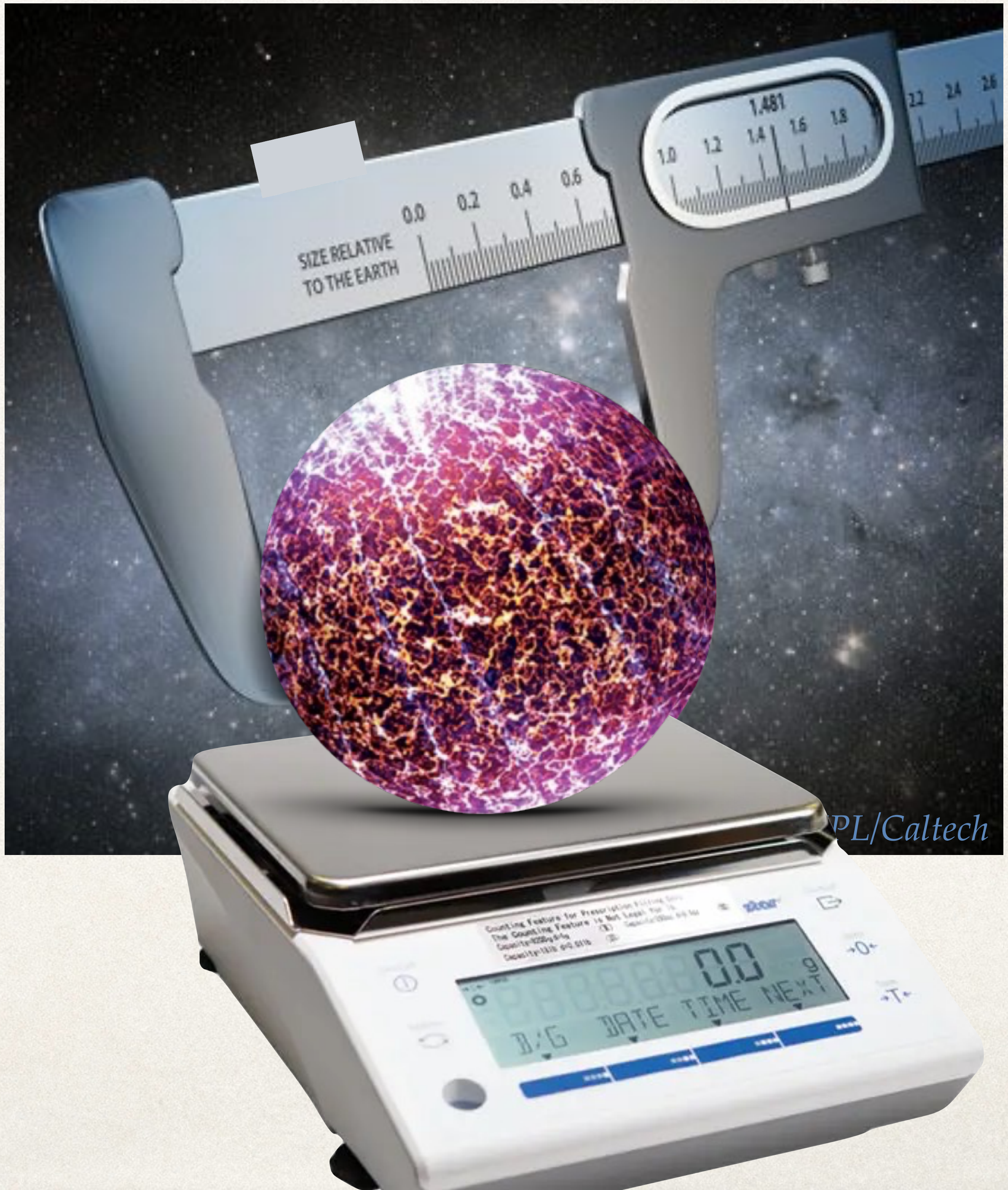


Bogdanov et al. 2016

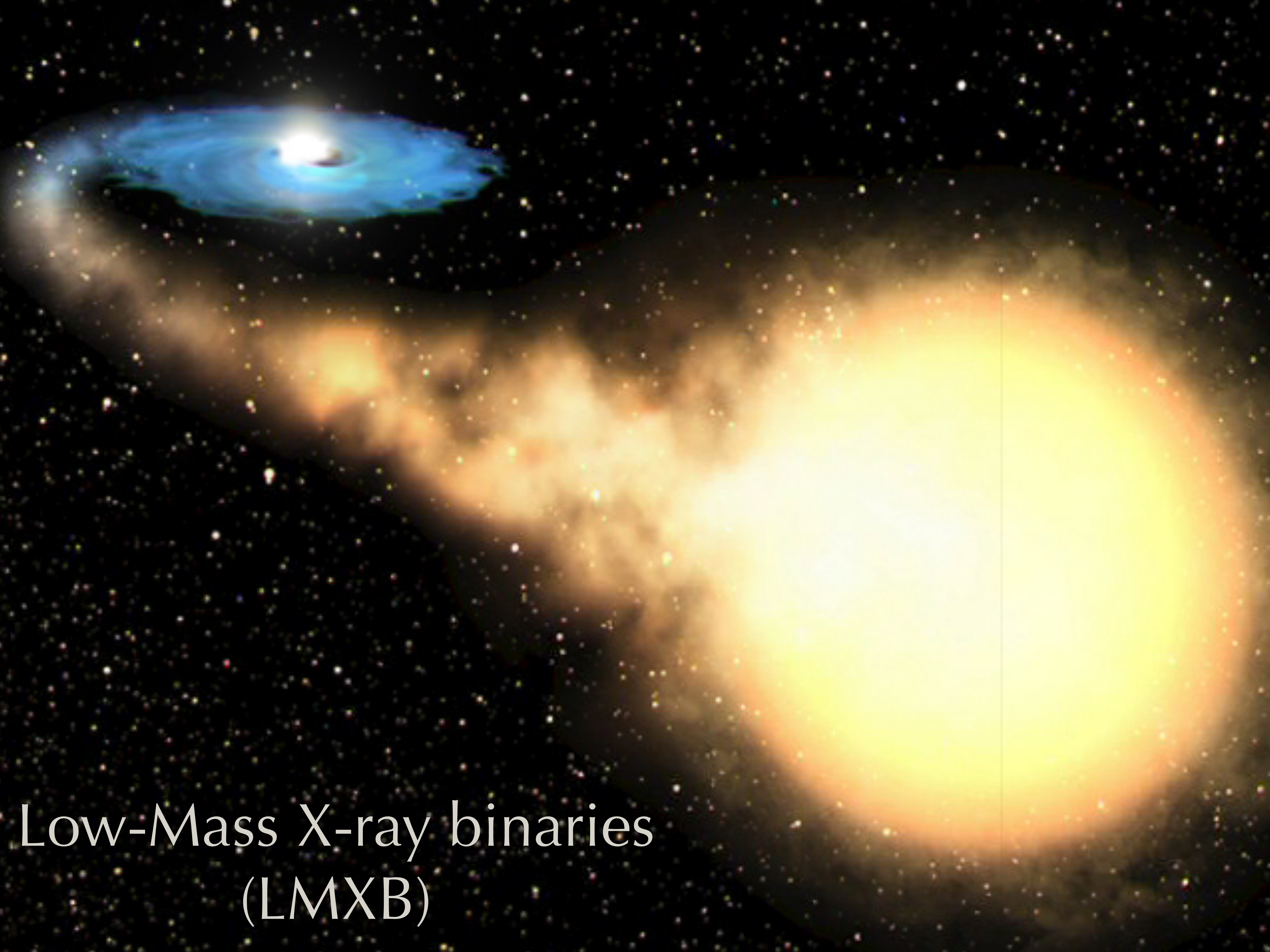
$$F_{\rm X} \propto \left(\frac{R_\infty}{D}\right)^2 \sigma T^4_{\rm eff,\infty}$$

PART 2A

Measuring M_{NS} and R_{NS} with transient phenomena

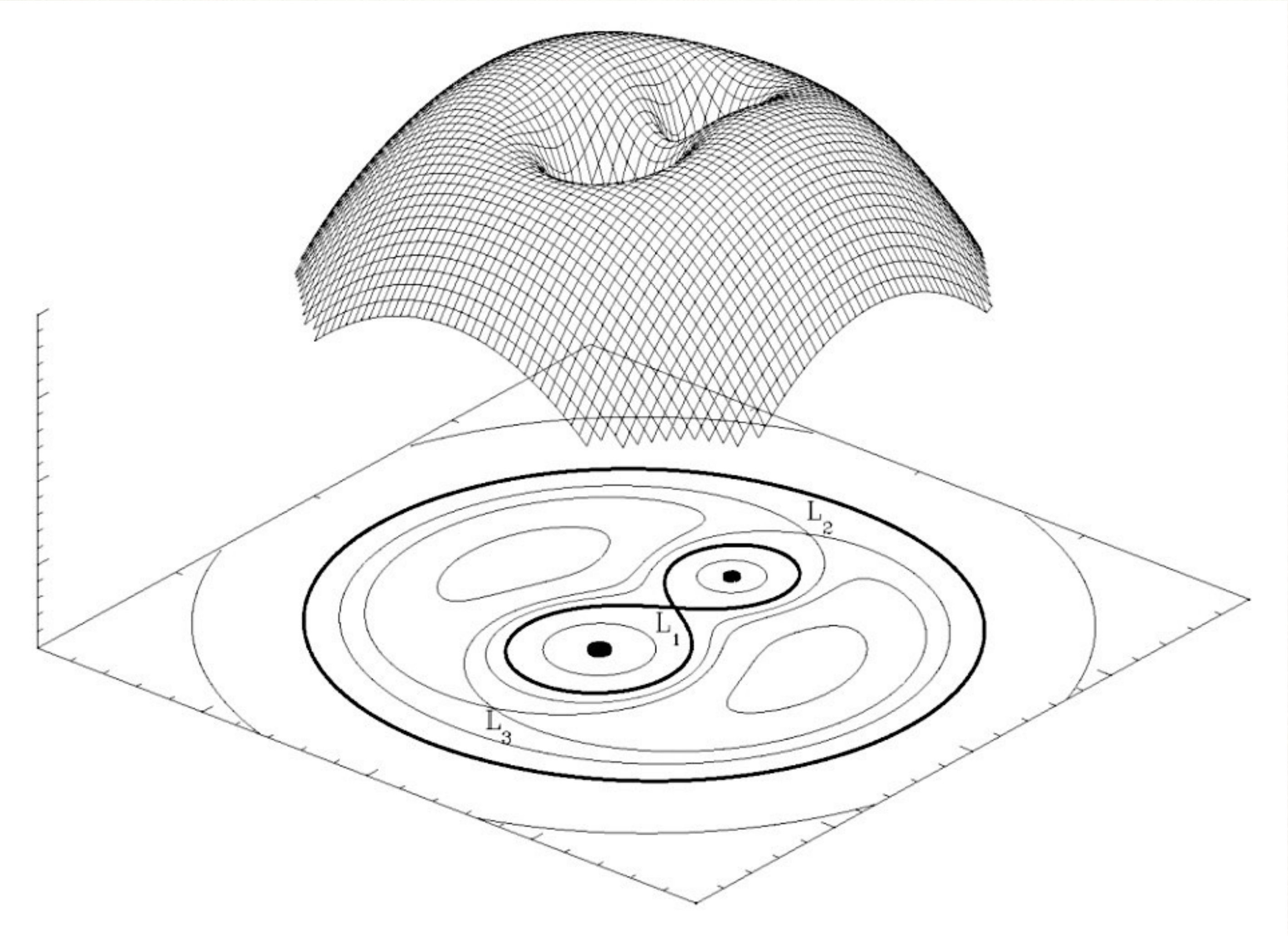


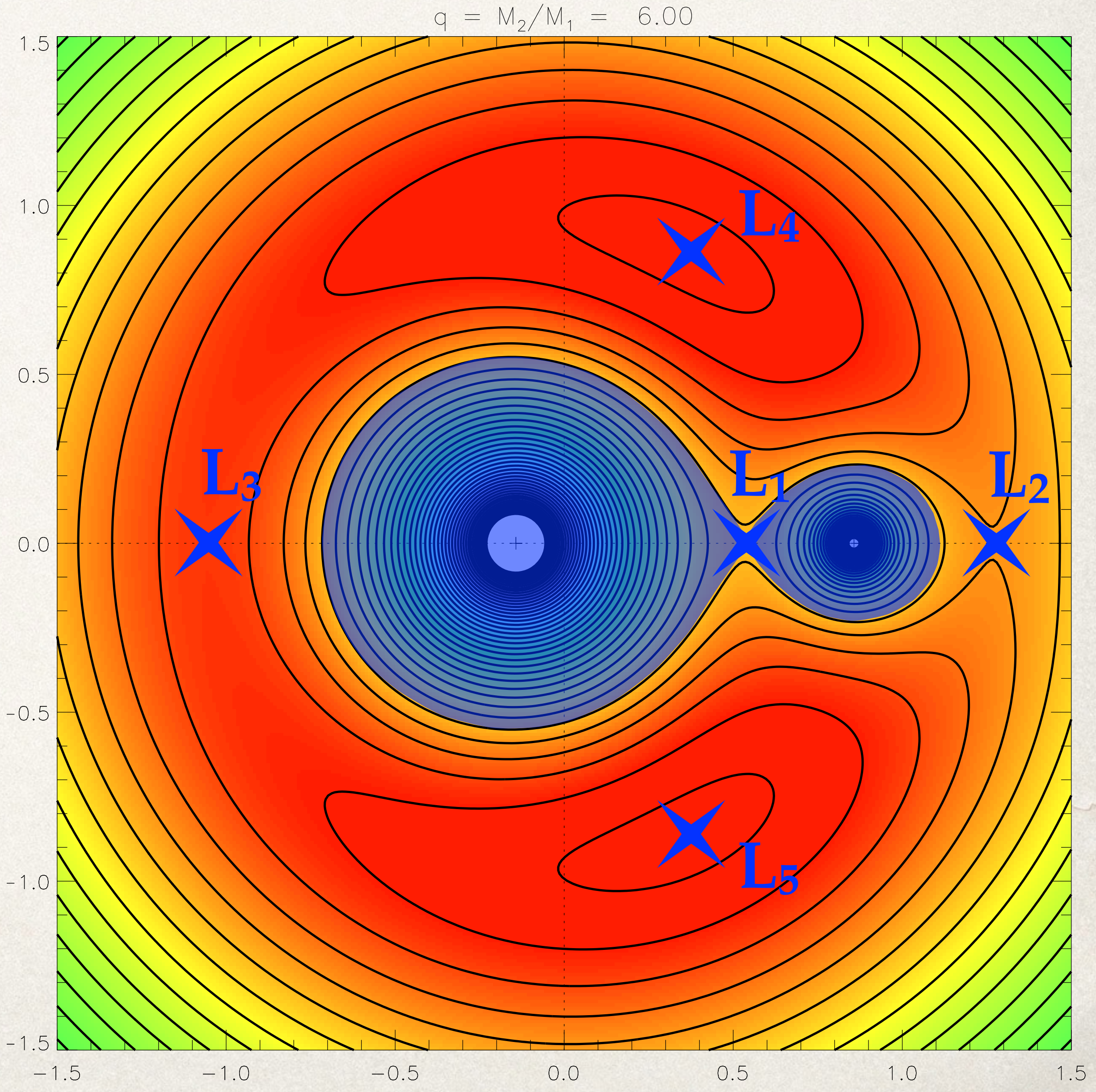
PL/Caltech



Low-Mass X-ray binaries
(LMXB)

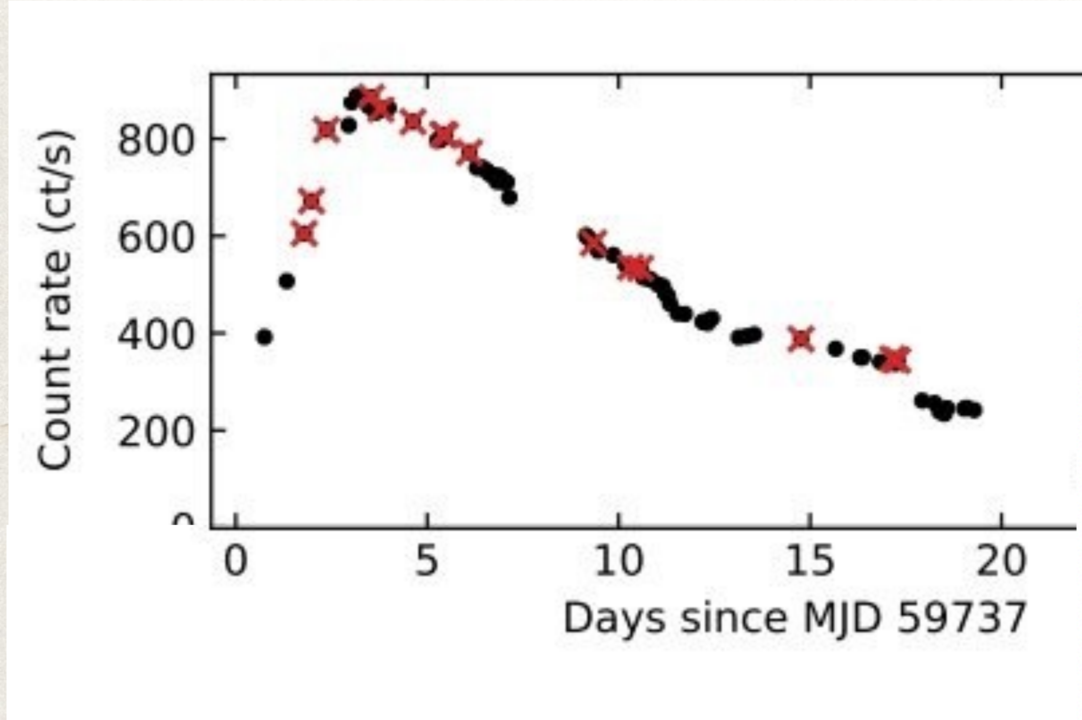
Matter accumulates in the disk via Roche lobe overflow





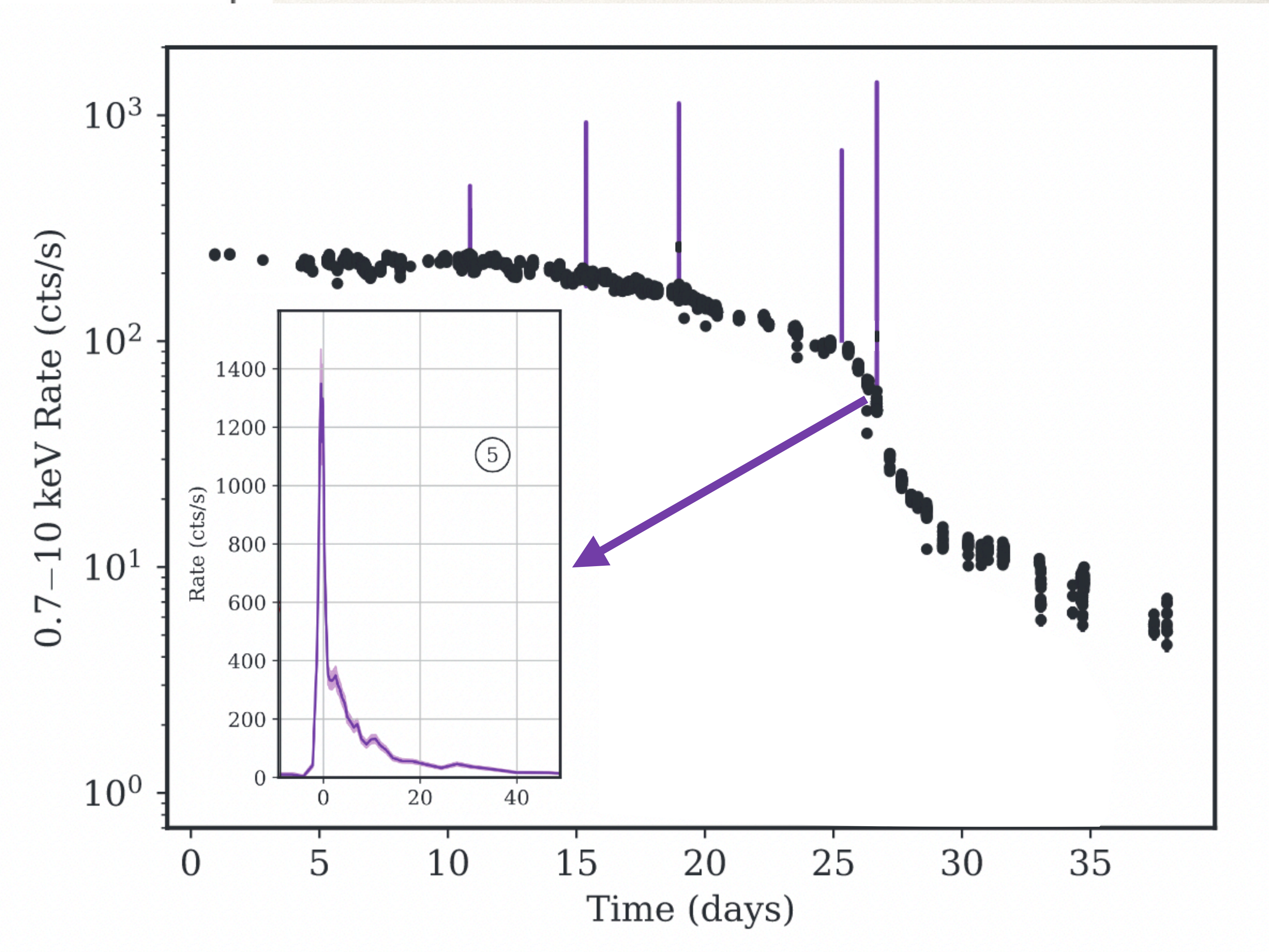
See talk by J. Wilms

Accretion outbursts can last from a few days to several months, with recurrence of a few months or decades

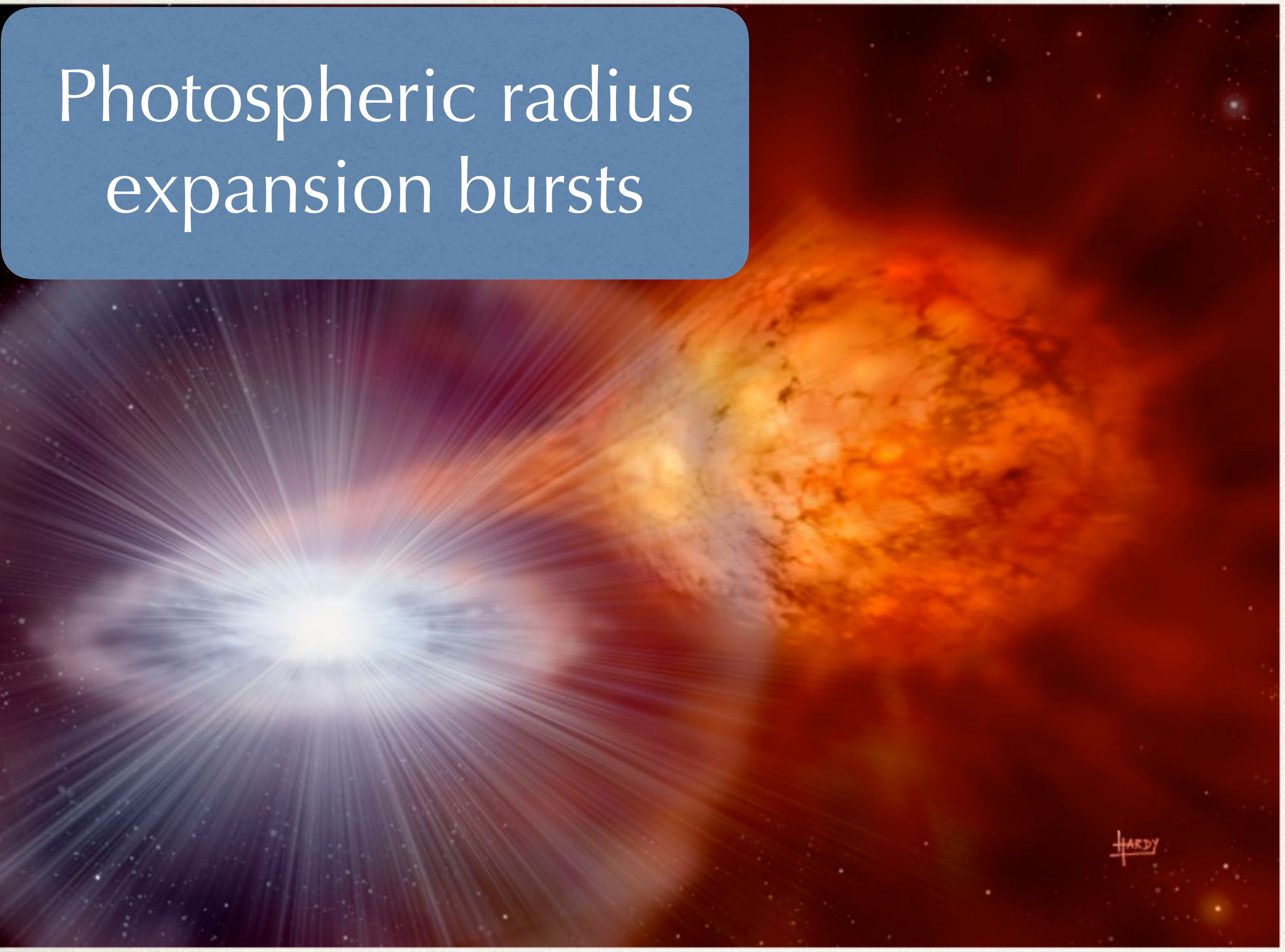


- Instabilities in the disk
- Matter transfers inward
- Disk brightens

Matter accumulates
at the surface



Some LMXBs exhibiting thermonuclear bursts bright enough to push the neutron star photosphere out.



Photospheric radius expansion bursts

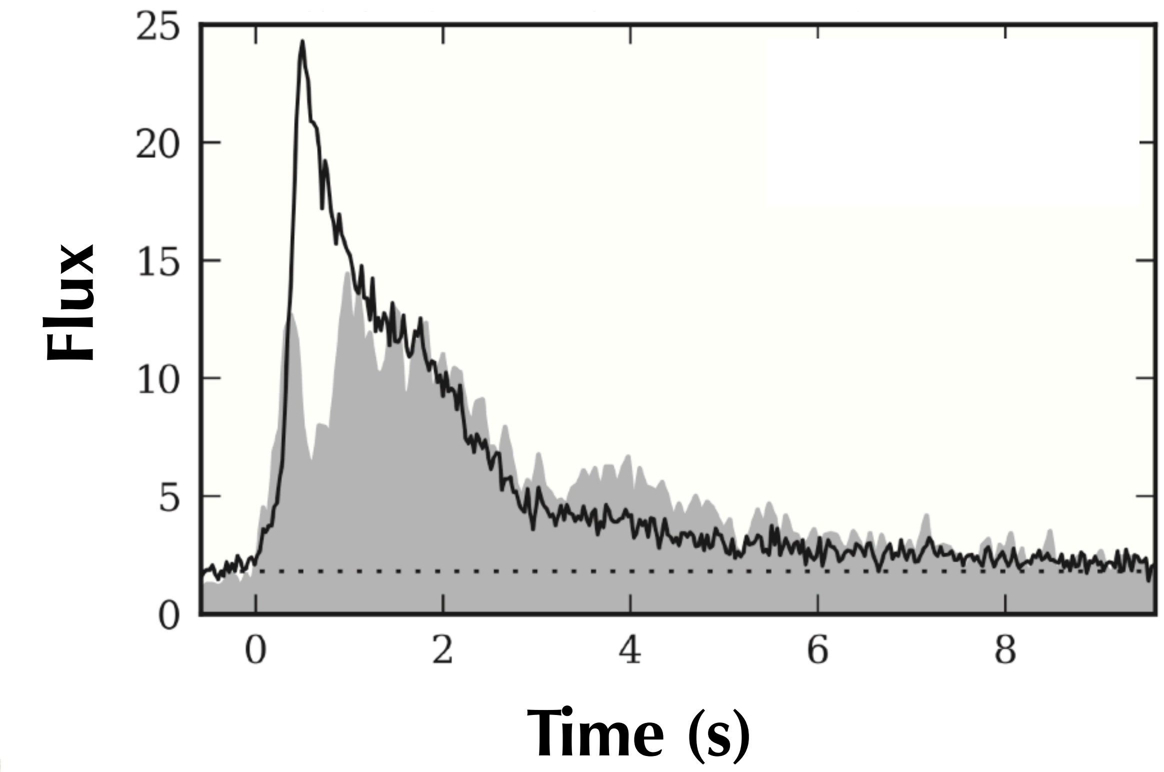
Balance between gravity

$$F_g = -m_p \frac{GM}{r^2}$$

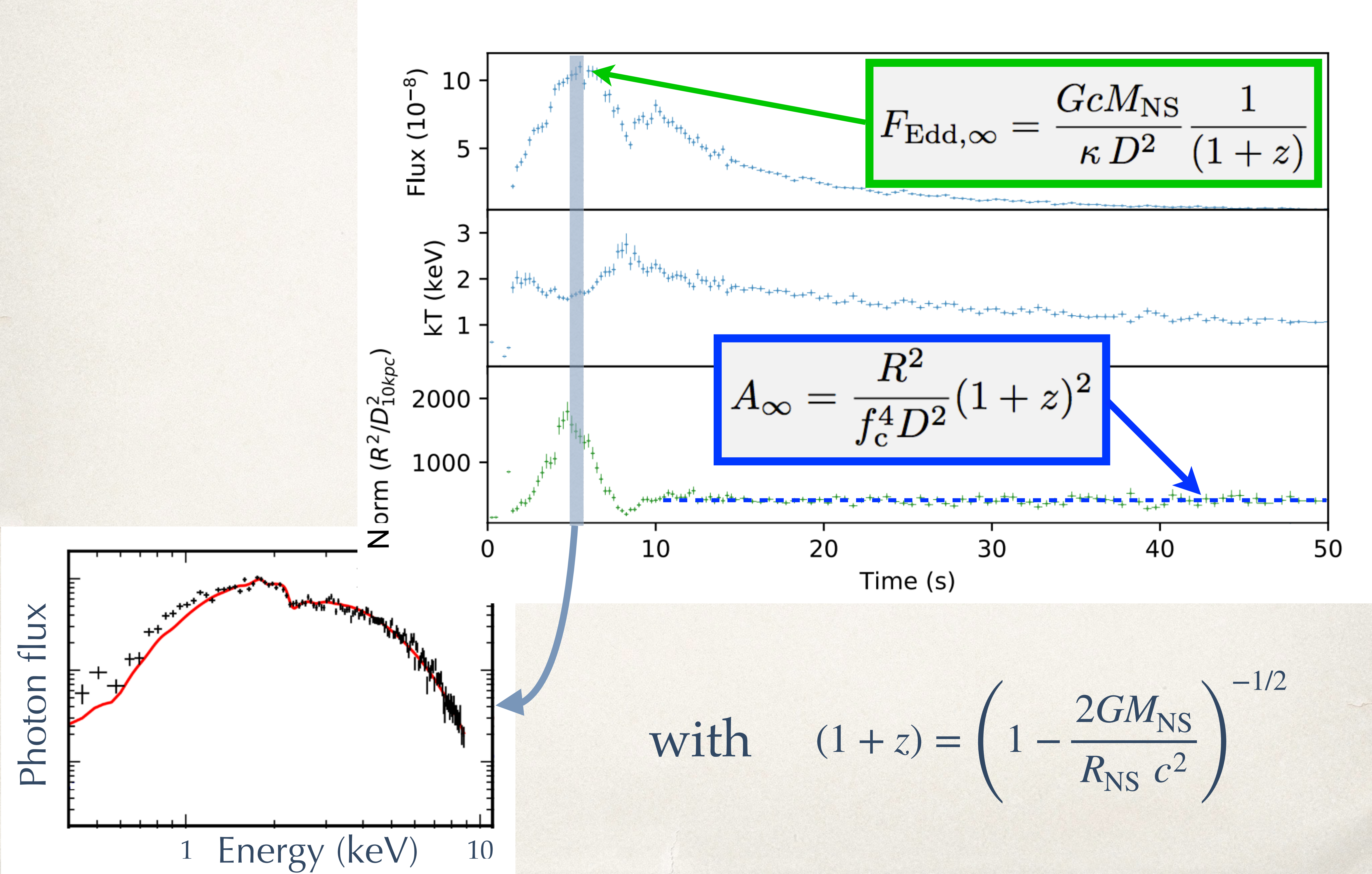
and radiation pressure

$$F_{rad} = +\frac{\sigma_T}{c} \frac{L}{4\pi r^2}$$

$$\boxed{L_{\mathrm{Edd}} = \frac{4\pi G c M_{\mathrm{NS}}}{\kappa}}$$



The peak flux correspond to the Eddington flux, and the cooling tail gives the size of the emitting area.

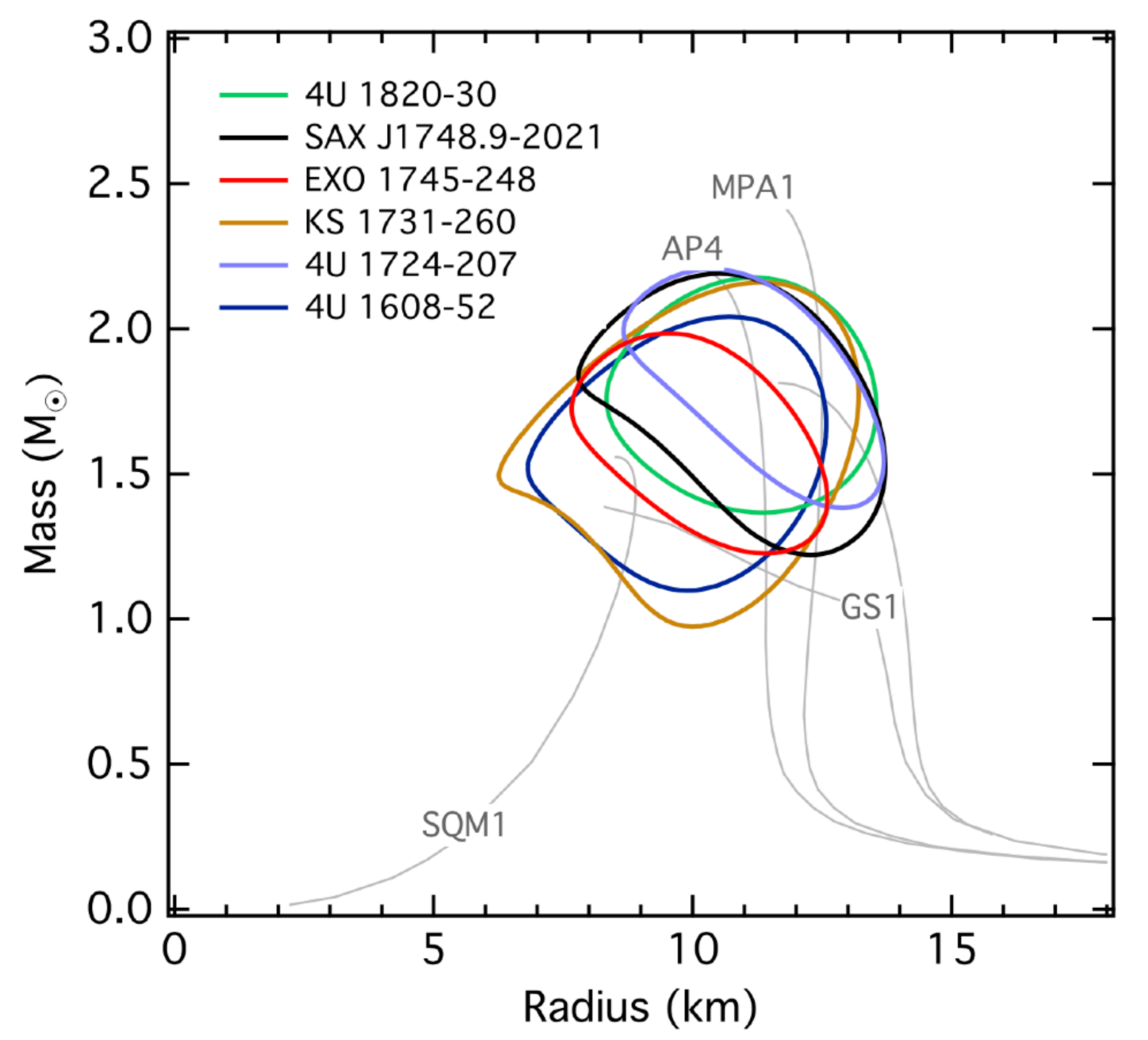


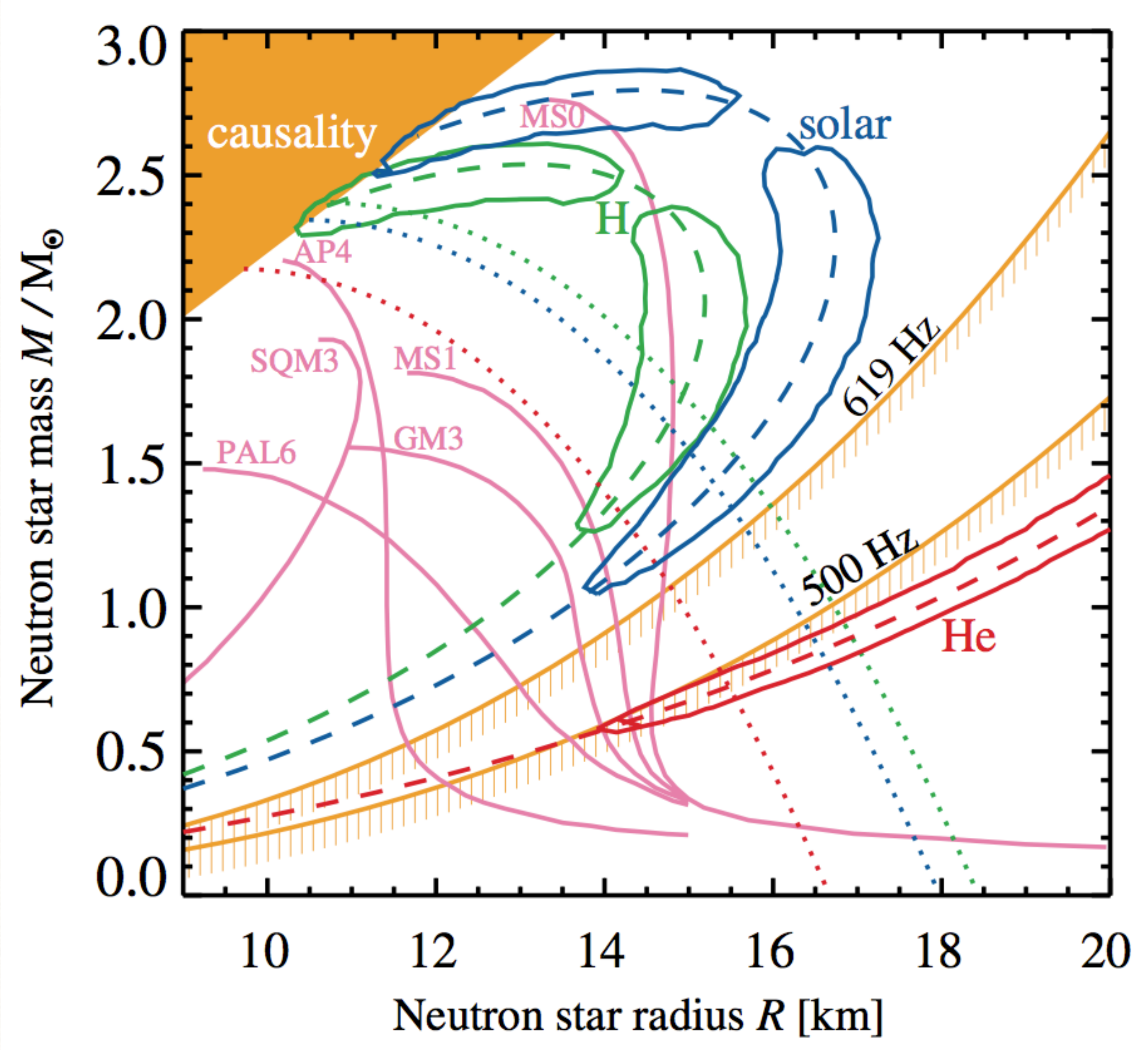
$$F_{\mathrm{Edd},\infty} = \frac{GcM_{\mathrm{NS}}}{\kappa\, D^2} \frac{1}{(1+z)}$$

$$A_\infty = \frac{R^2}{f_\mathrm{c}^4 D^2}(1+z)^2$$

with $$(1+z) = \left(1 - \frac{2GM_{\mathrm{NS}}}{R_{\mathrm{NS}}\ c^2}\right)^{-1/2}$$

Different analysis method and LMXB spectral states result in different constraints.





Identification of F_{edd} and A_∞ normalisation at touchdown

Fit of theoretical curves to tracks of F–$A_\infty^{-1/4}$

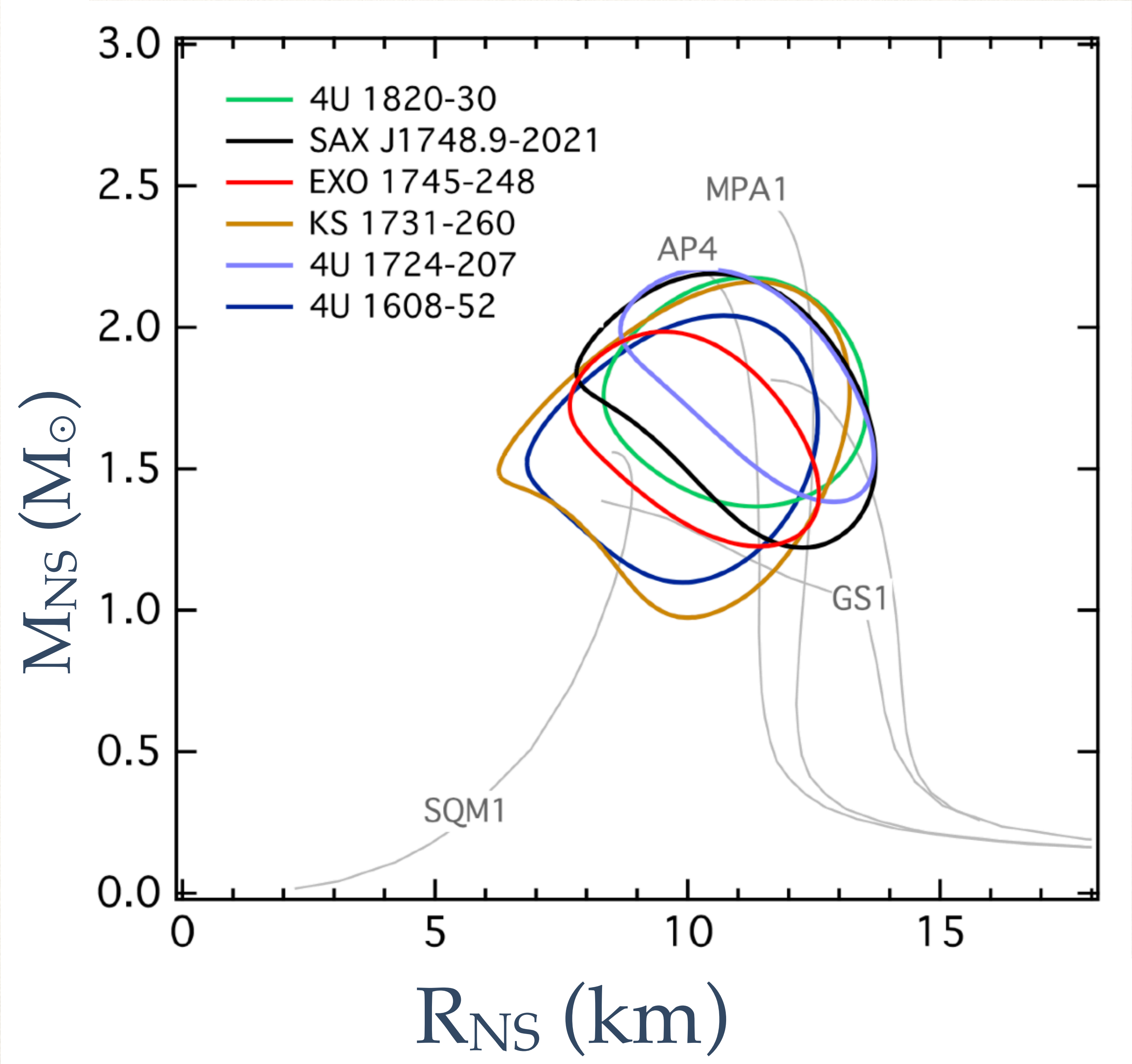
Özel et al. 2016

Suleimanov et al. 2011

A lot of uncertainties remain and make the measurements poorly constrained.

$$F_{\mathrm{Edd},\infty} = \frac{GcM_{\mathrm{NS}}}{\kappa\, D^2}\frac{1}{(1+z)}$$

$$A_\infty = \frac{R^2}{f_{\mathrm{c}}^4 D^2}(1+z)^2$$



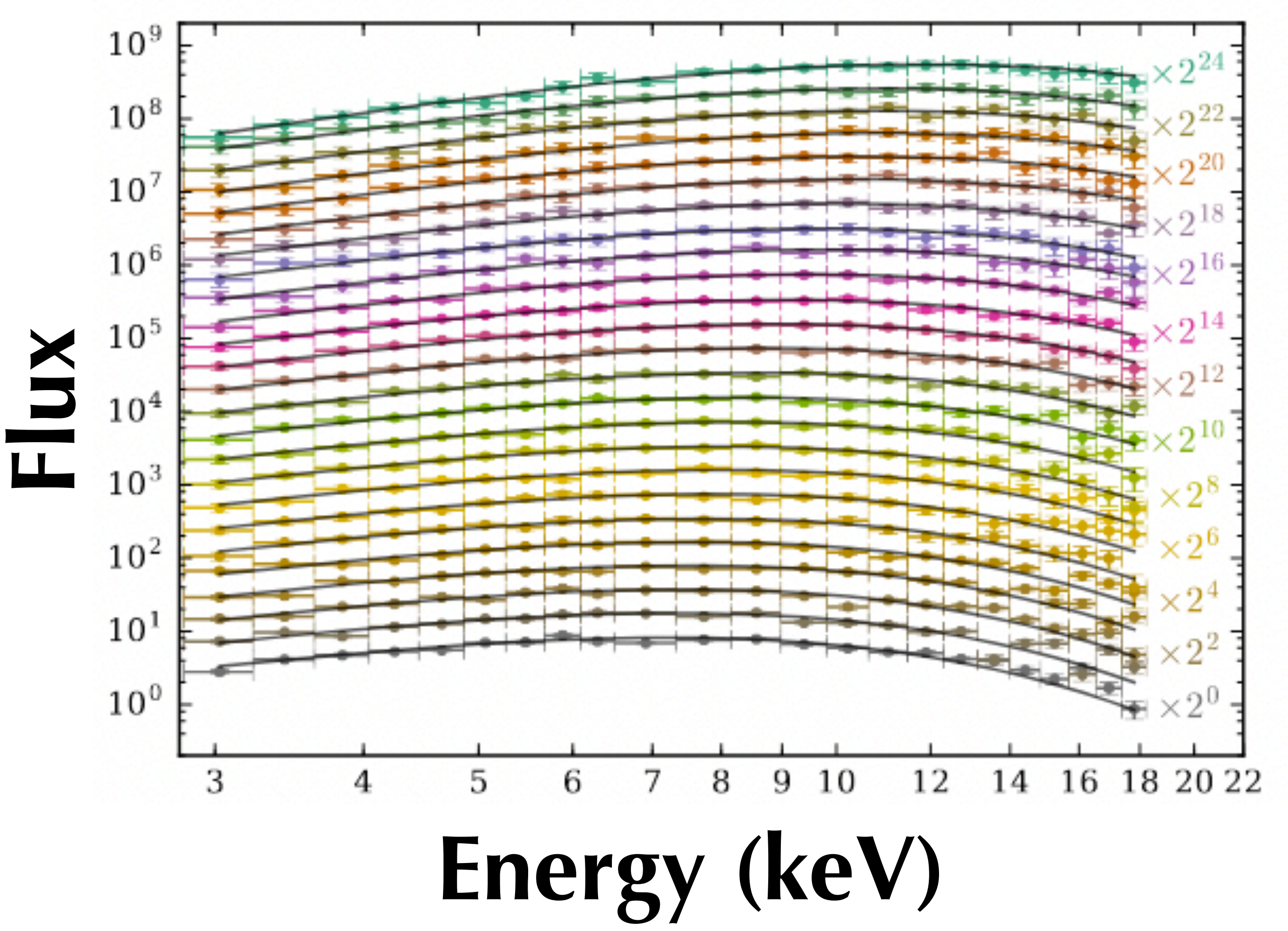
<u>Sources of uncertainty:</u>

- Distance
- Atmospheric composition (via $\boldsymbol{\kappa}$)
- Atmospheric modelling (via f_{c})
- Effects of the spectral state

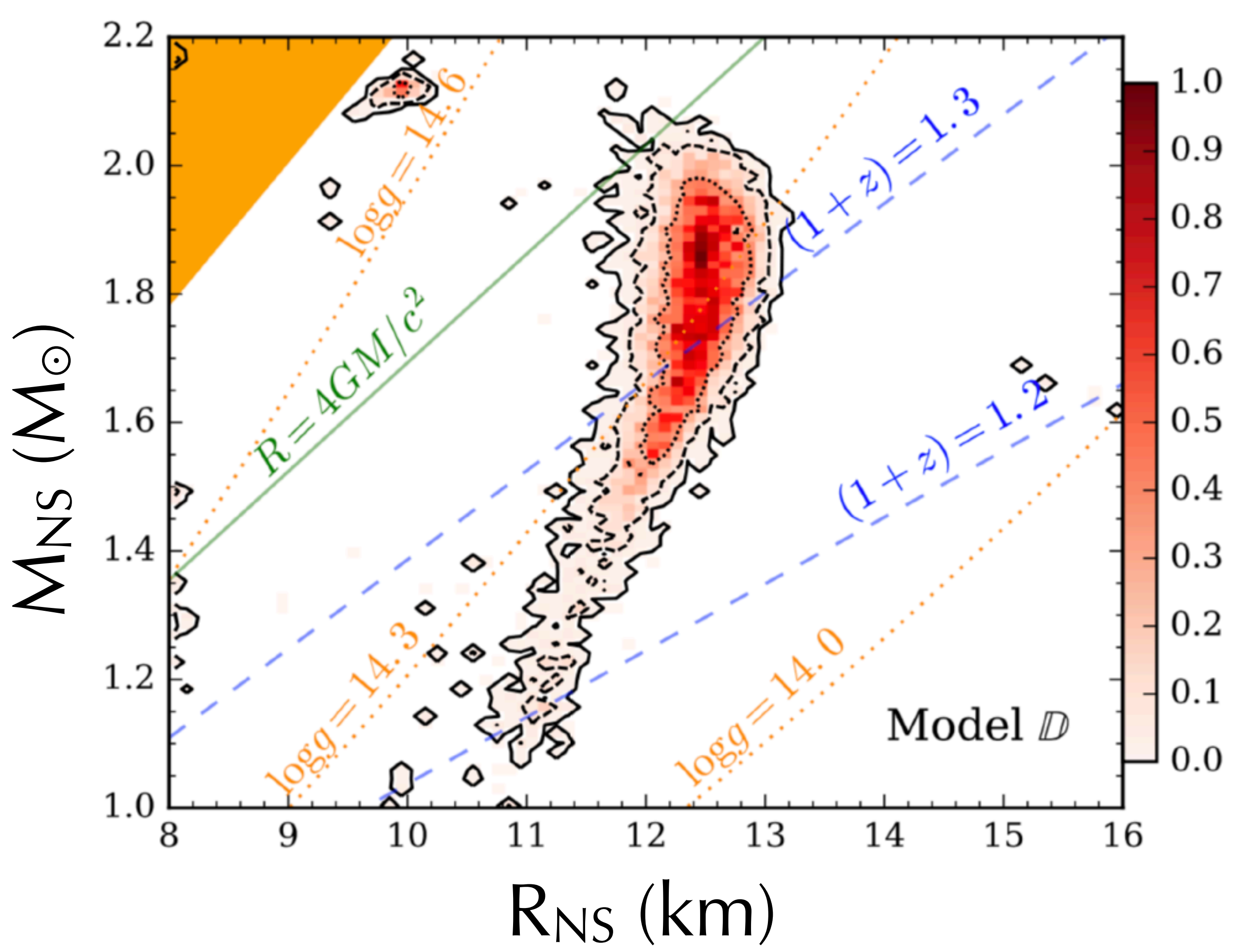
Recent developments in the field of Type I X-ray bursts ?

1. **A new method**

The direct spectral fits with realistic models during the burst evolution avoids using color-correction factors.



Burst from 4U 1702–429



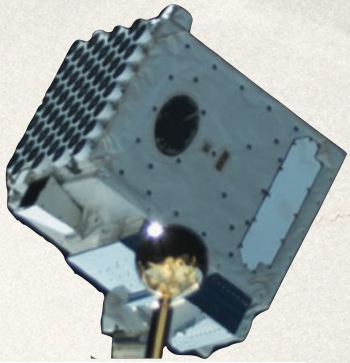
Nattila et al. 2017

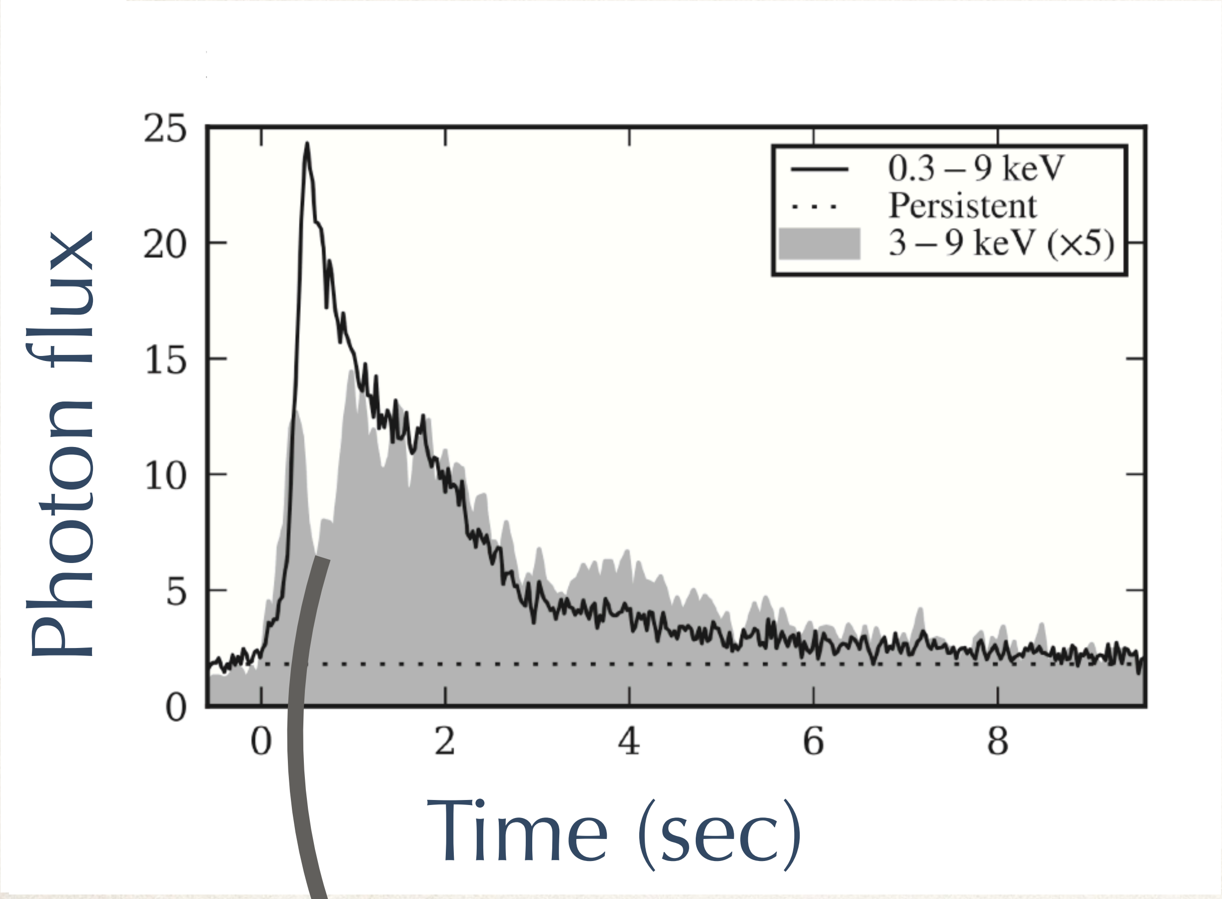
Recent developments in the field of Type I X-ray bursts ?

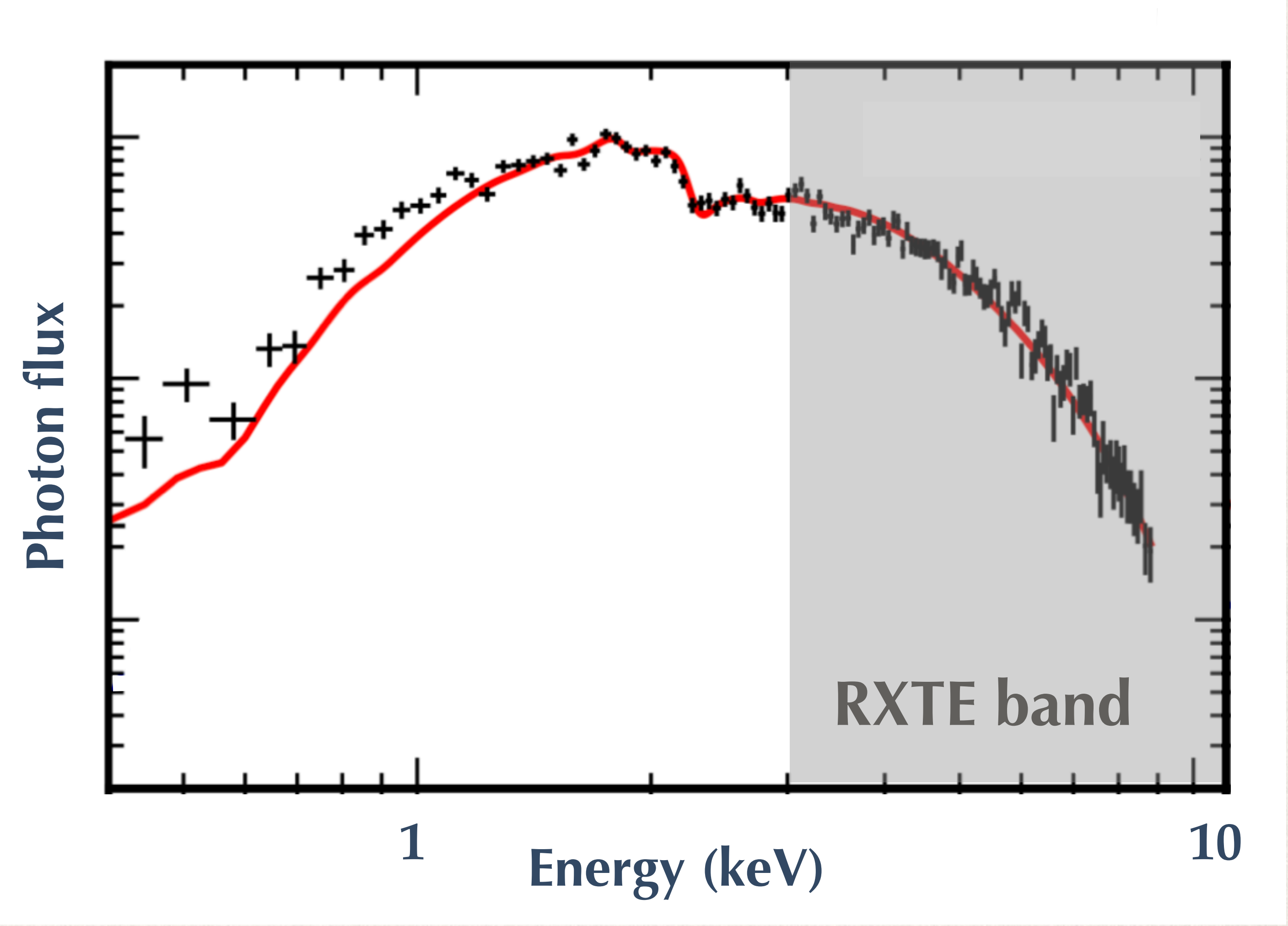
1. **A new method**

2. **A new instrument**

The observation of type I X-ray bursts with NICER shows the whole burst evolution in the soft X-ray band.







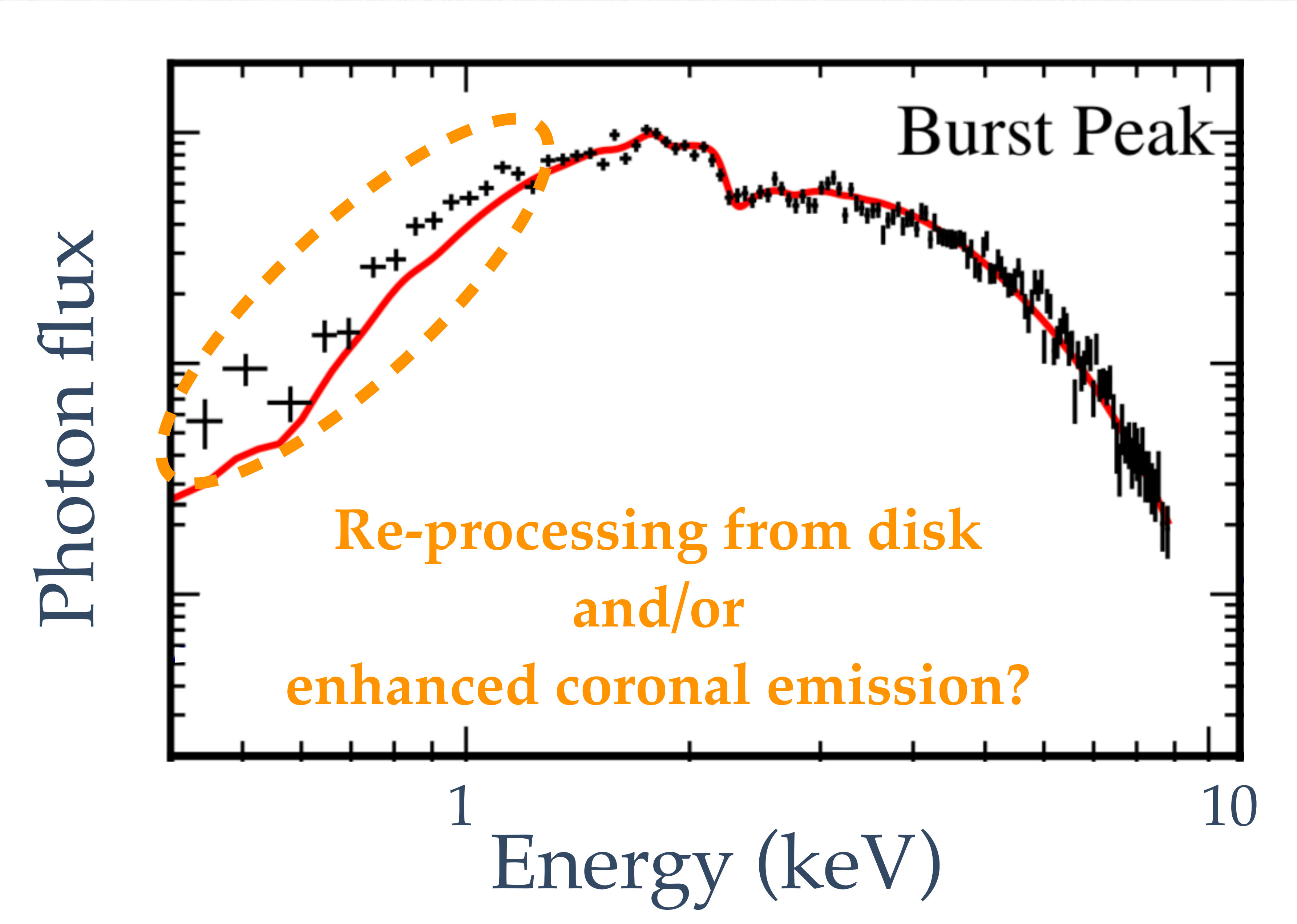
Keek et al. (2018)

In the RXTE band, the drop in flux comes from the temperature drop as the photosphere expands. With its 0.3–10 keV range, NICER sees the full evolution

Recent developments in the field of Type I X-ray bursts ?

1. **A new method**
2. **A new instrument**
3. **A new problem**

But NICER observations of type I X-ray burst also showed the presence of a un-modelled excess at low energies.



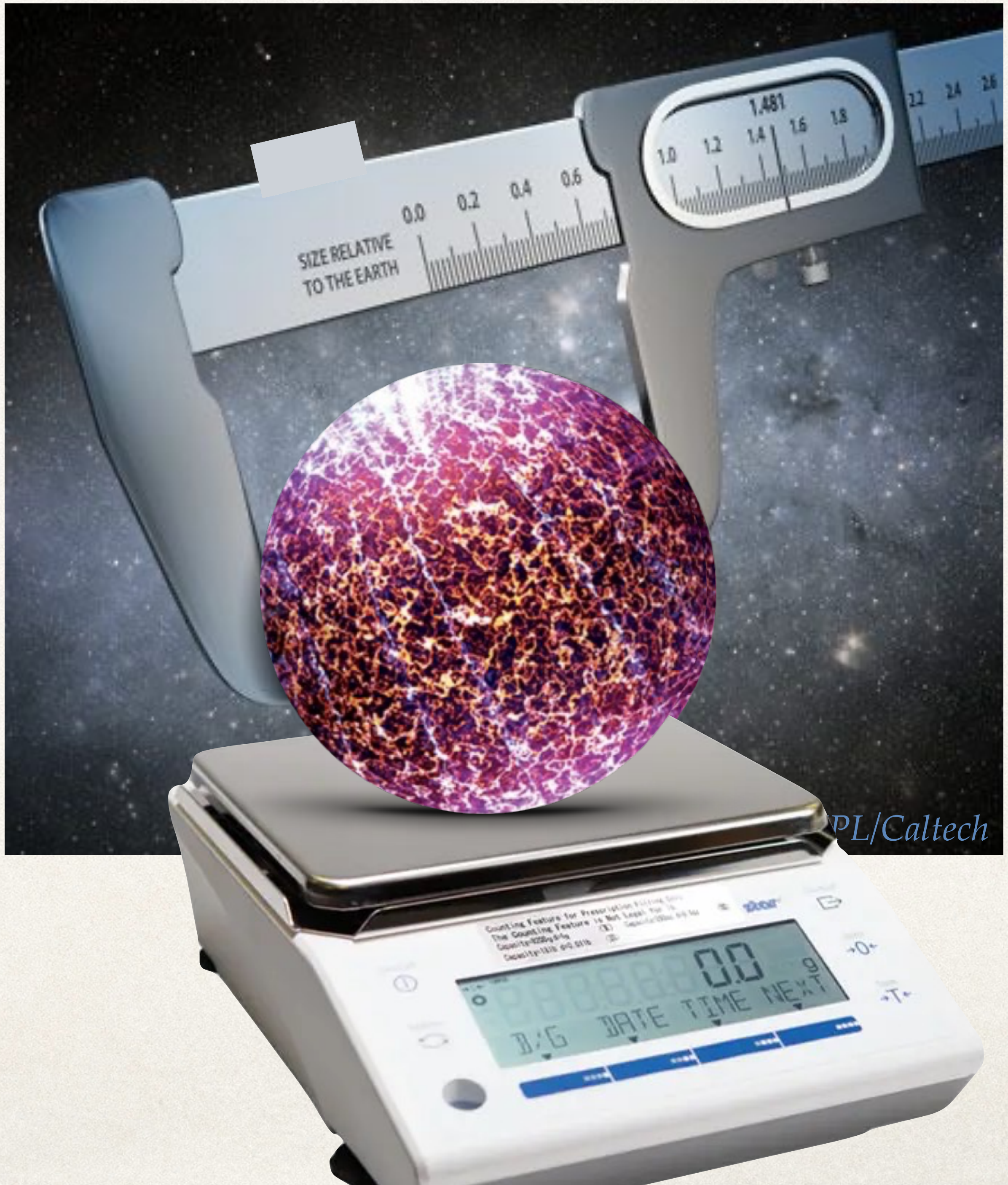
Re-processing from disk
and/or
enhanced coronal emission?

Keek et al. 2018

Güver et al. 2021, 2022

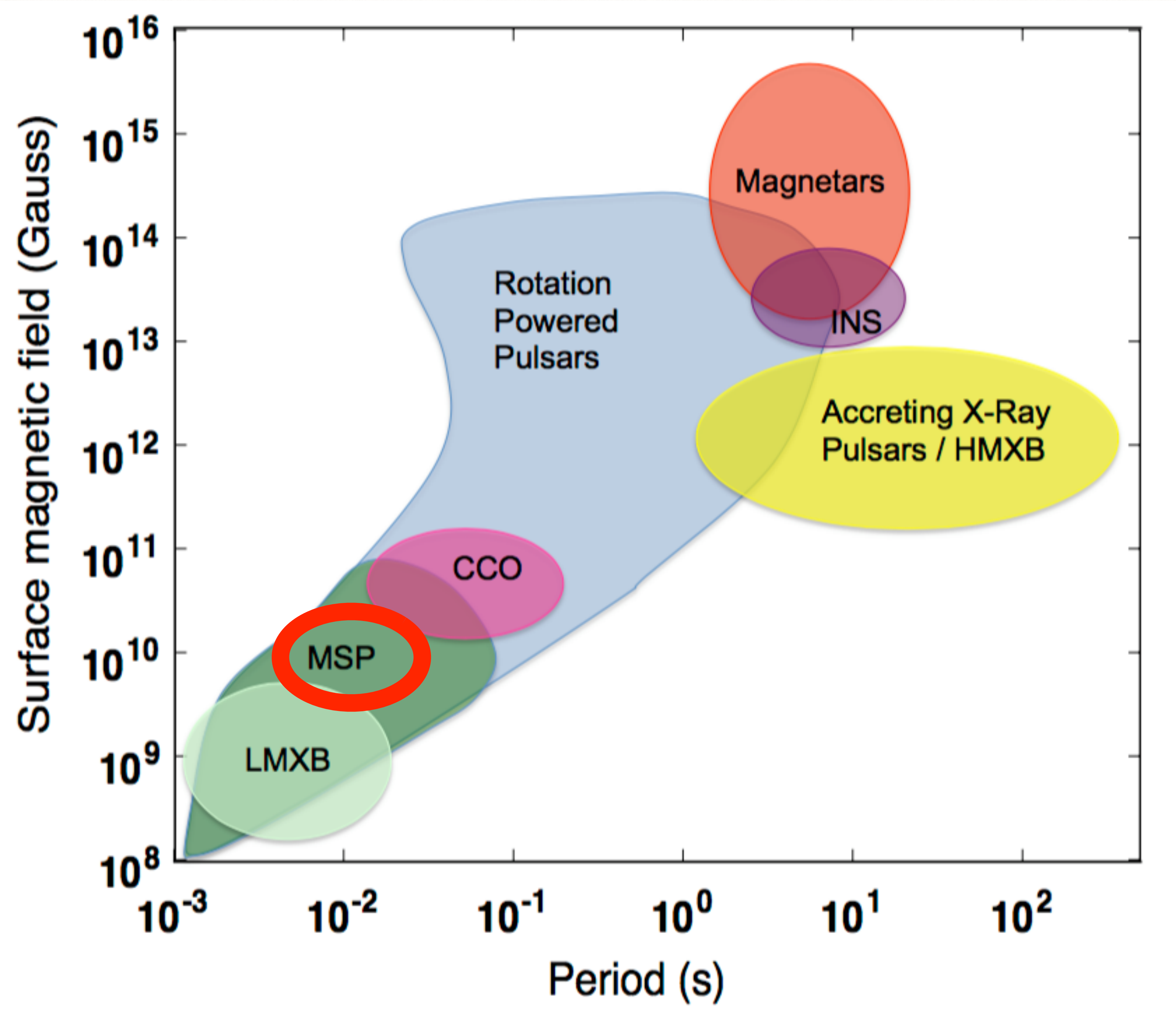
PART 2B

Measuring M_{NS} and R_{NS} with non-transient neutron stars

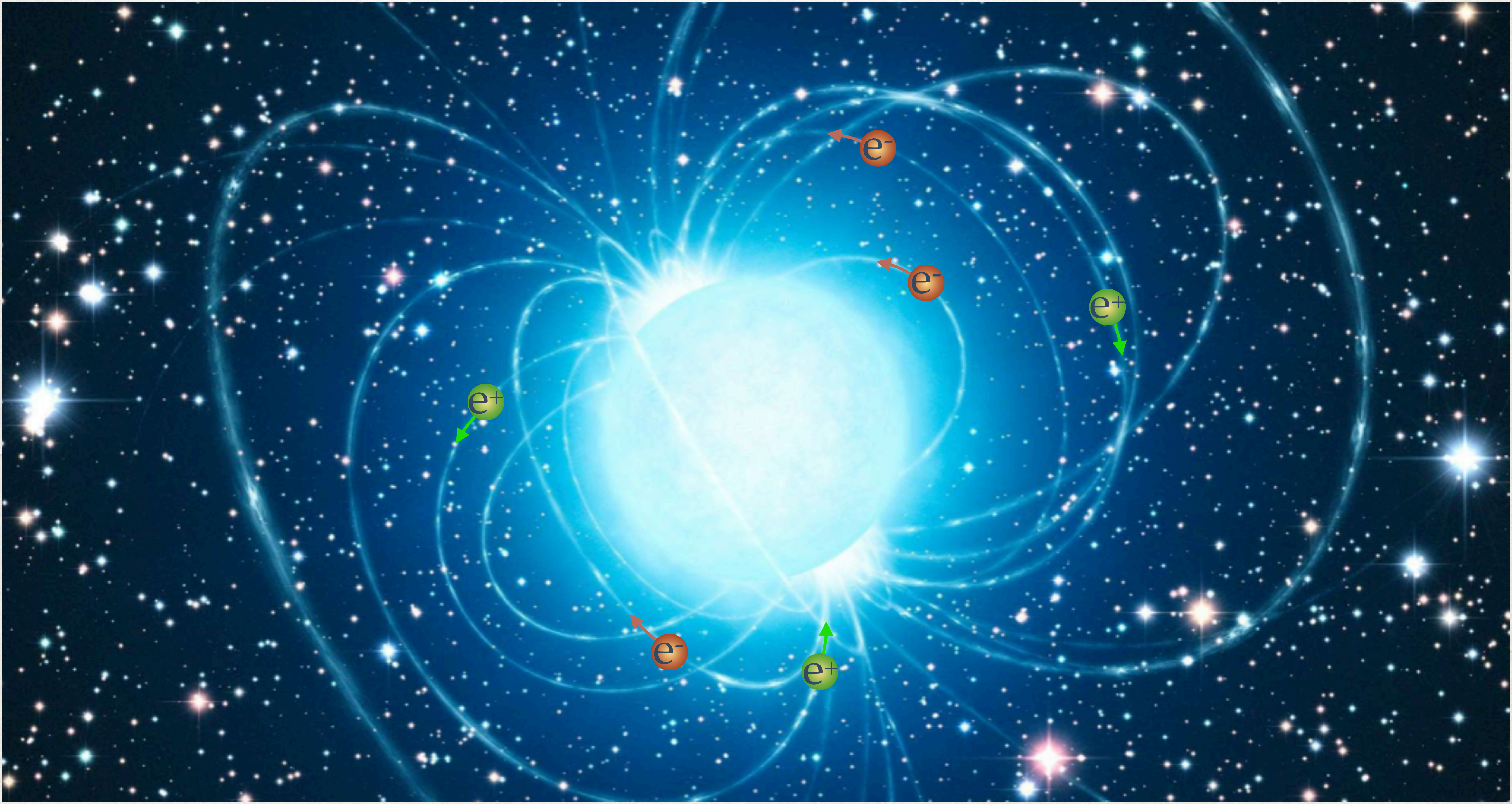


PL/Caltech

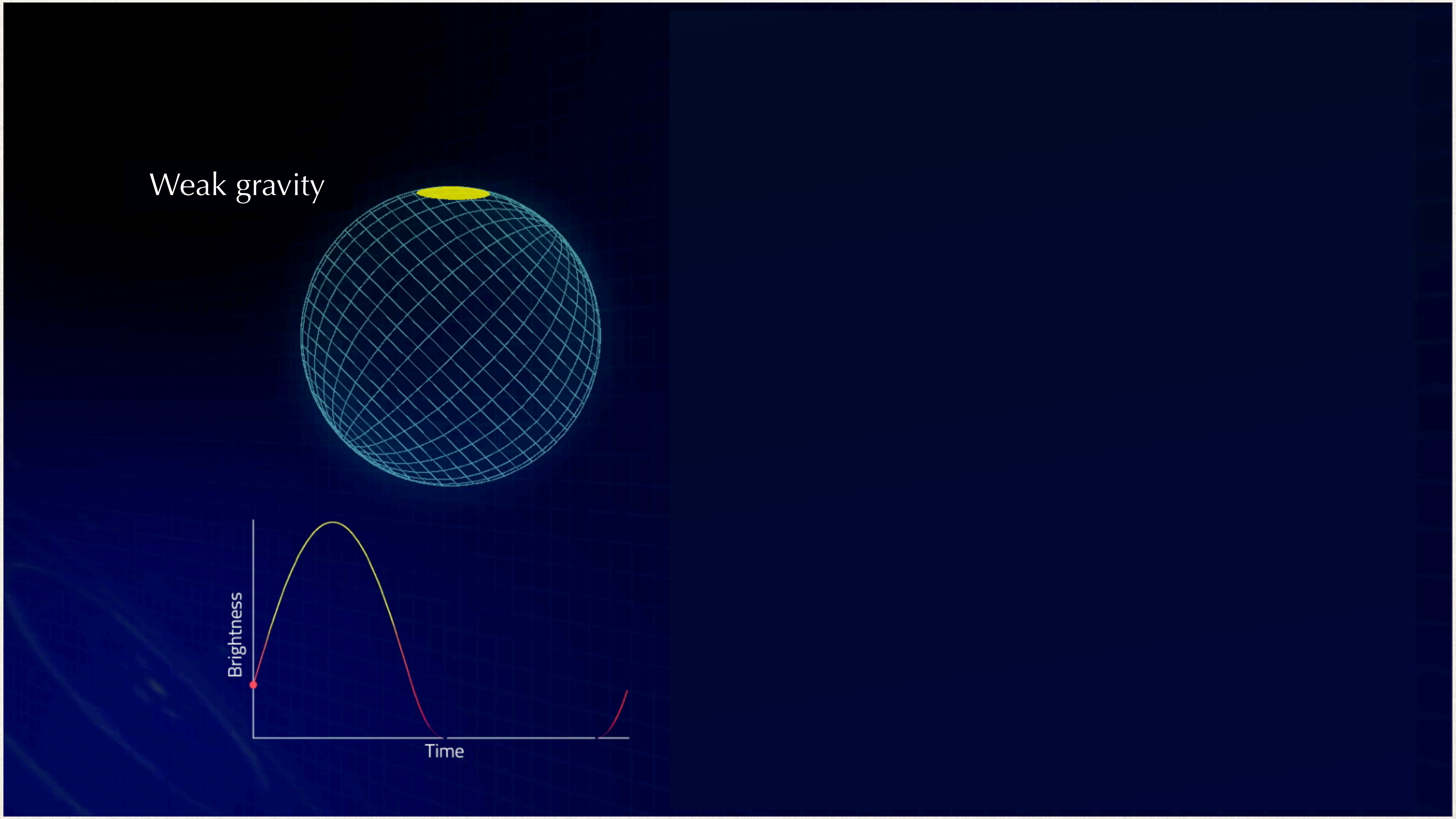
Millisecond pulsars offer a very different method to measure the radius.



Millisecond pulsar exhibits hot thermal emission originating from the surface at the magnetic poles

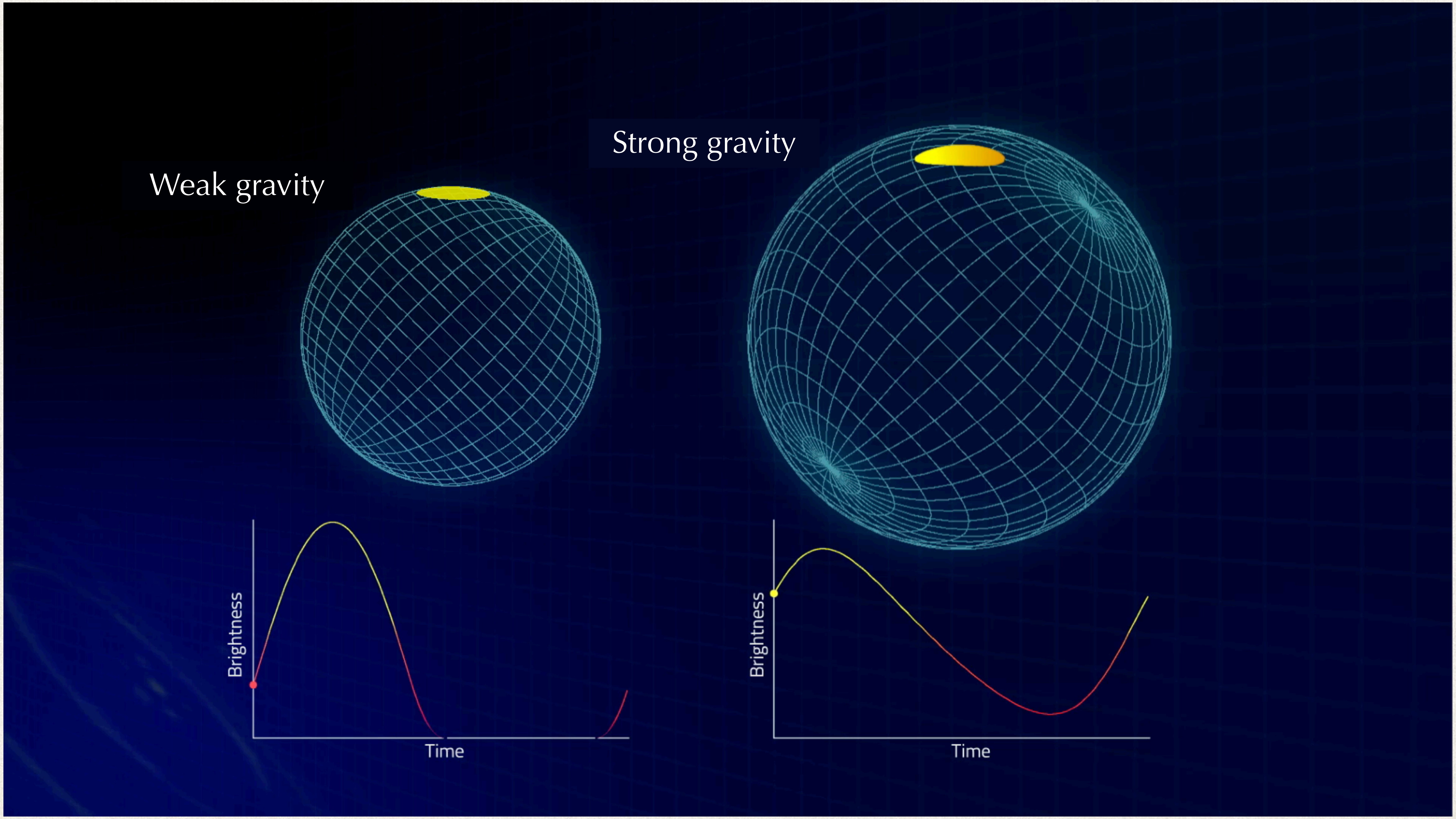


Credits: ESO



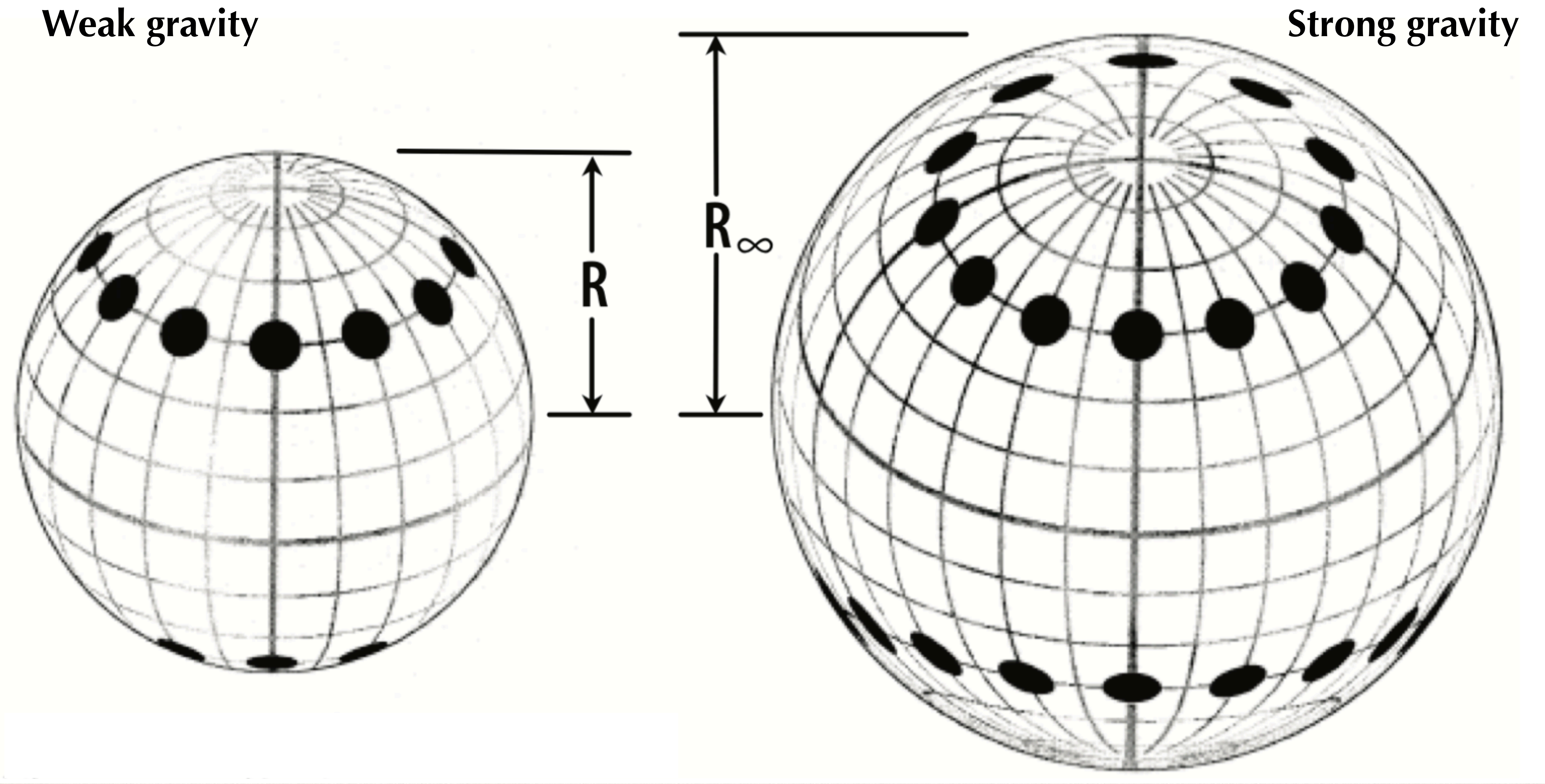
Credits: S. Morsink

Strong gravity permits seeing beyond the hemisphere of the neutron star.



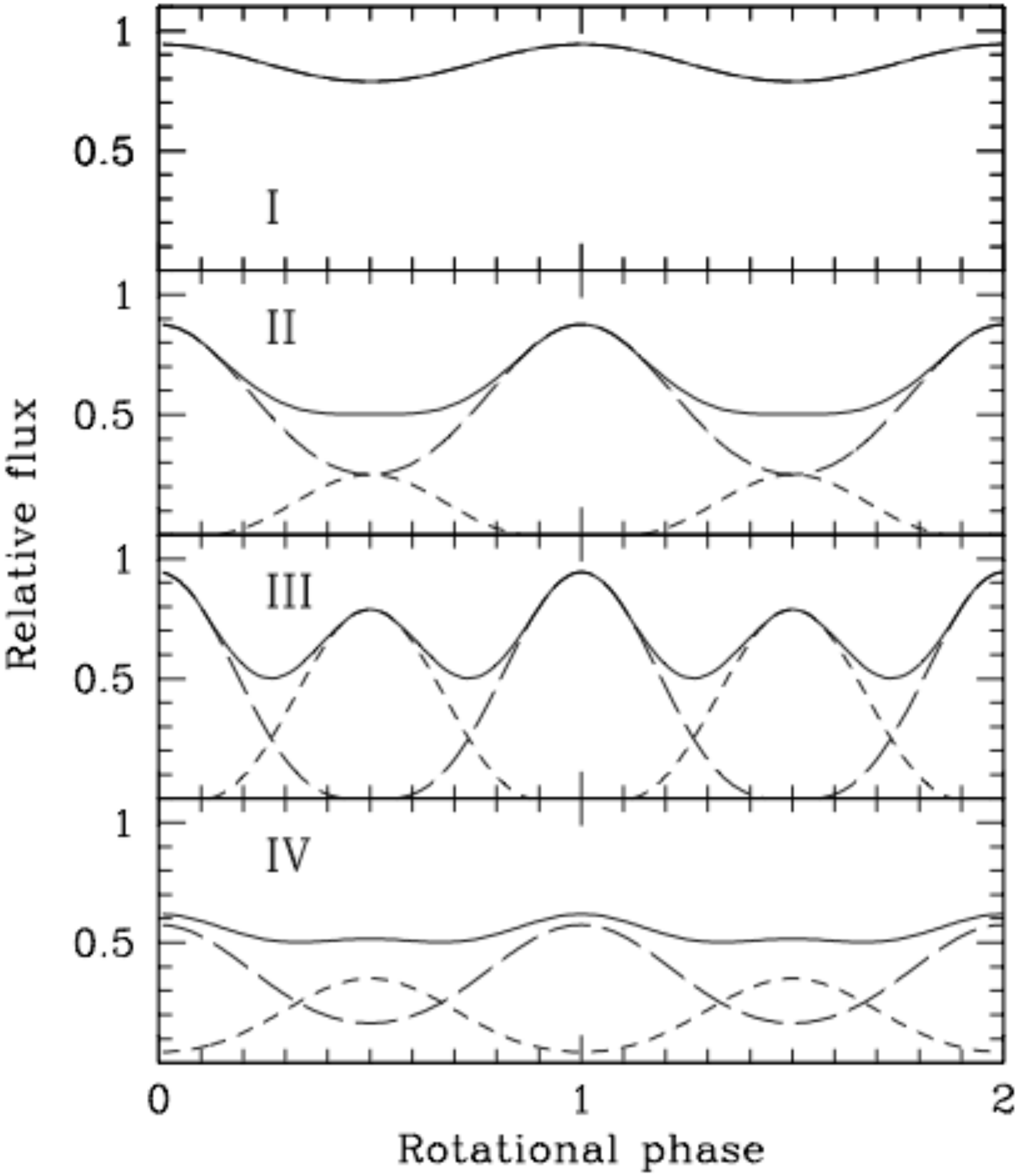
Credits: S. Morsink

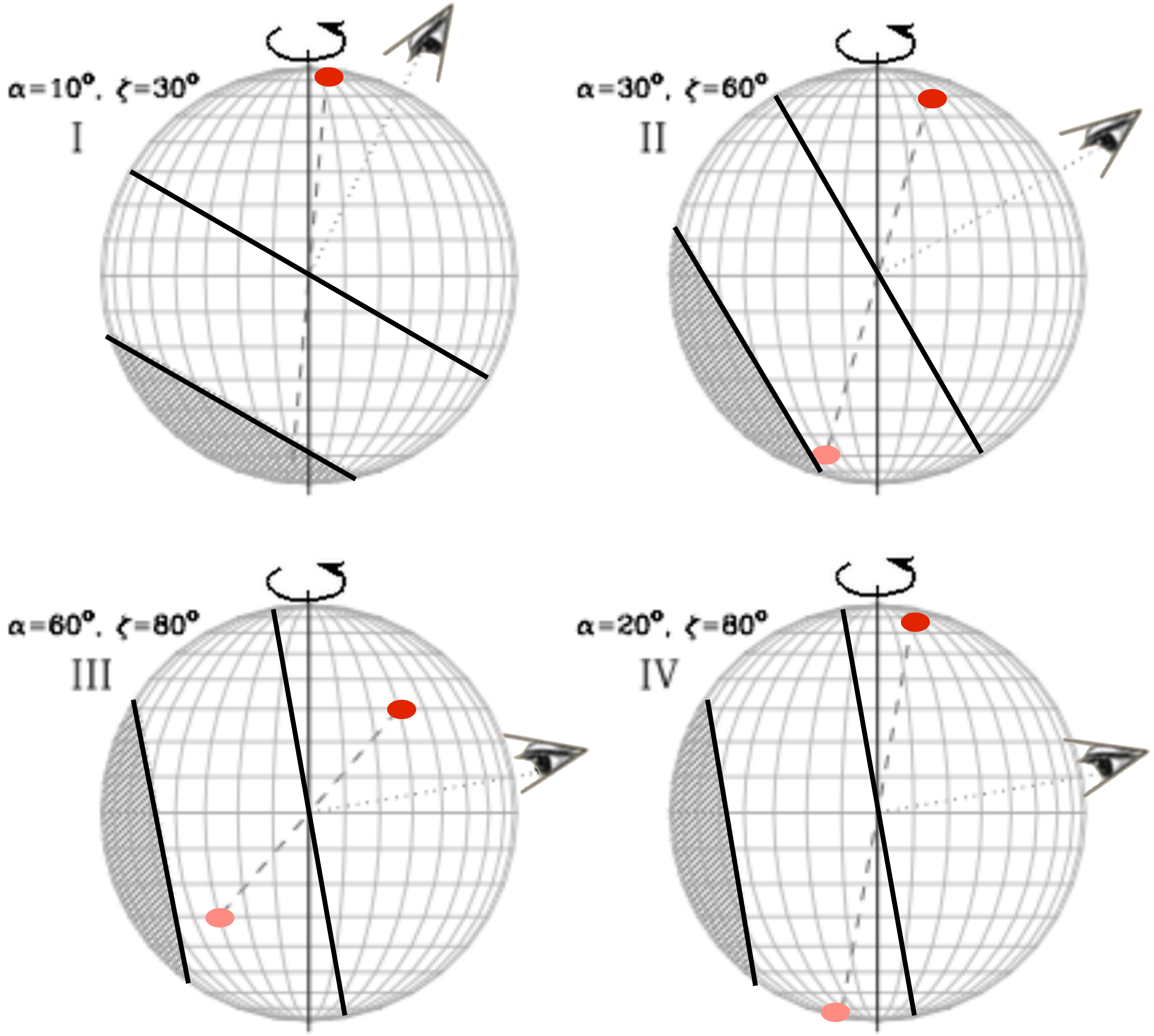
Strong gravity permits seeing beyond the hemisphere of the neutron star.



Same neutron star, with the same physical mass and radius

… but this also depends on the system geometry.





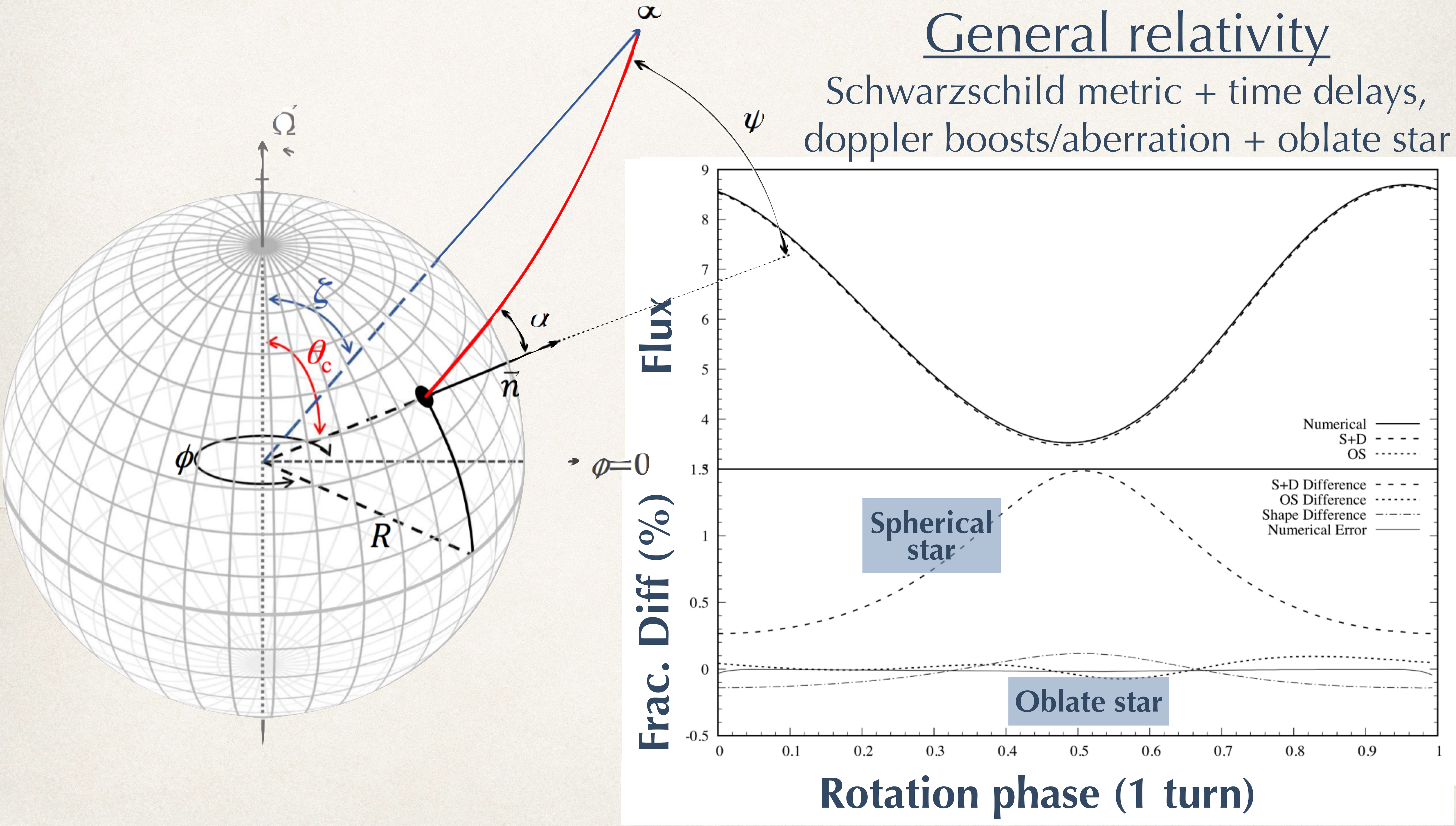
$M_{NS} = 1.4\ M_{\odot}, \quad R_{NS} = 10\mathrm{km}$

(Bodganov et al. 2008)

The modelling of the light curve requires a relativistic ray-tracing model.

General relativity

Schwarzschild metric + time delays, doppler boosts/aberration + oblate star

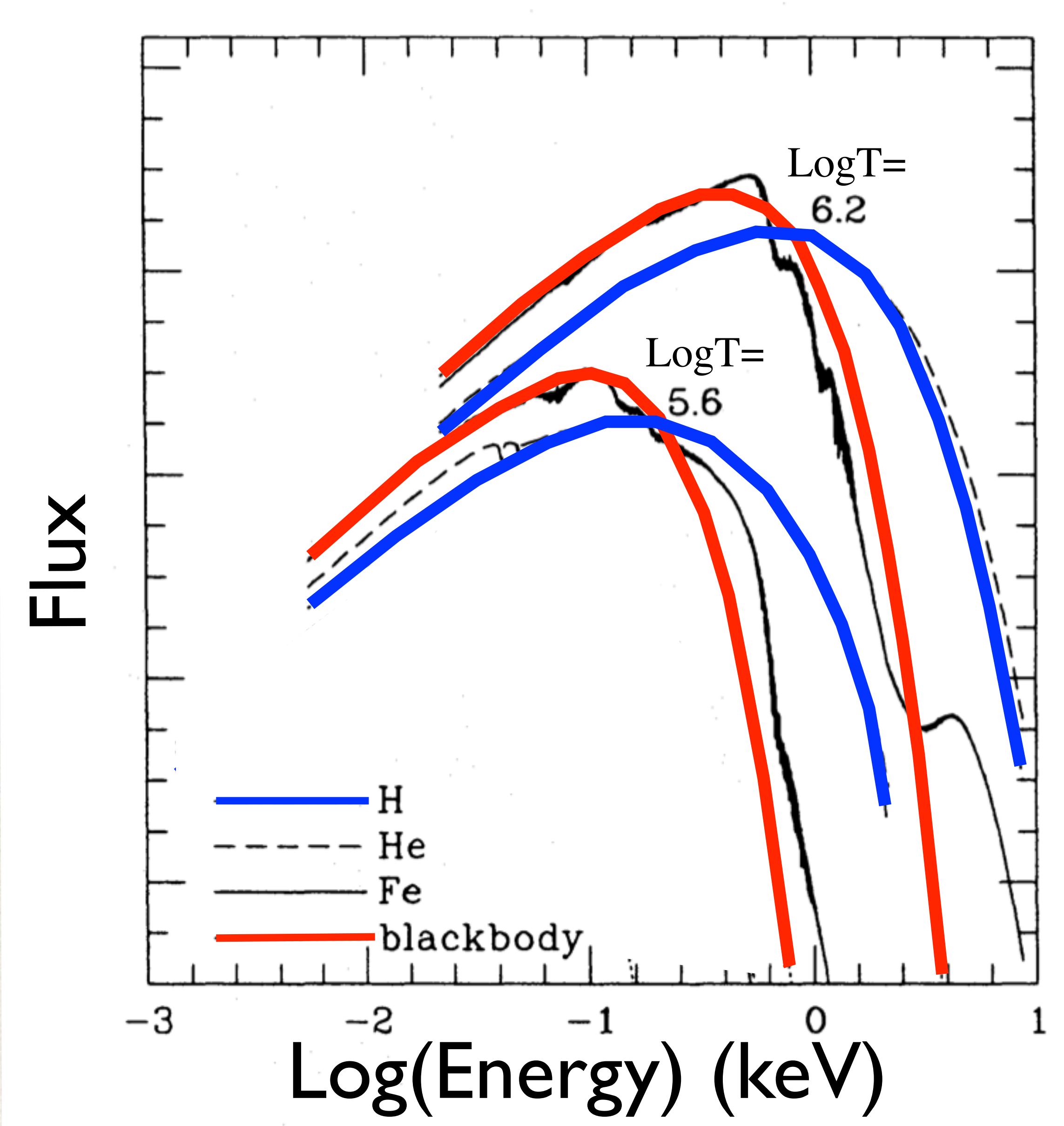


Bogdanov, …, SG et al. (2019b)

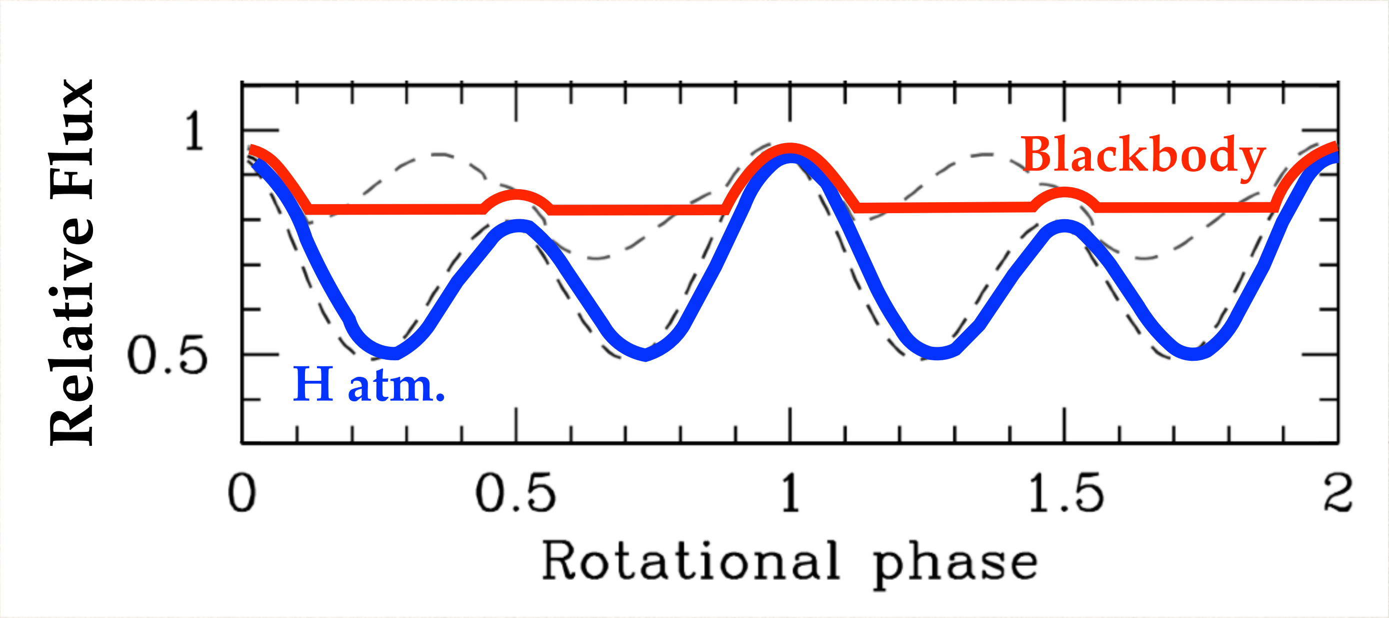
The surface thermal emission is modelled with a NS atmosphere, not a black body.

$$F = \left(\frac{R_\infty}{D}\right)^2 \sigma T_{\mathrm{eff}}^4$$

Zavlin et al. (1996)



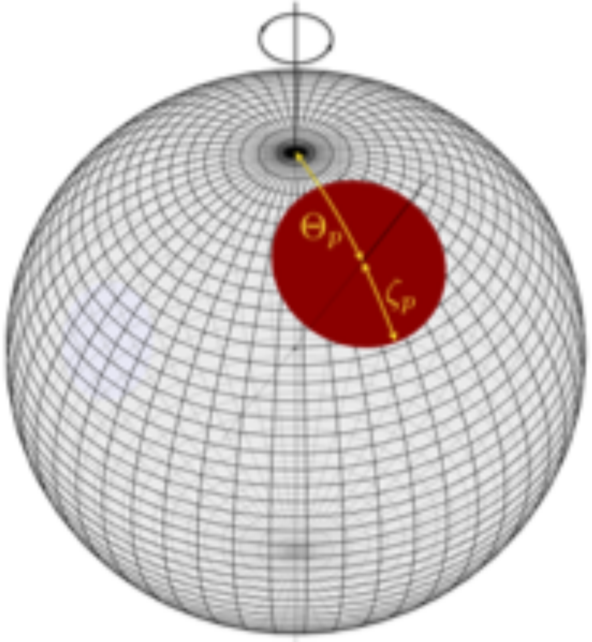
Blackbody and NS atmosphere generate different pulse profile shapes



Bogdanov et al. (2007)

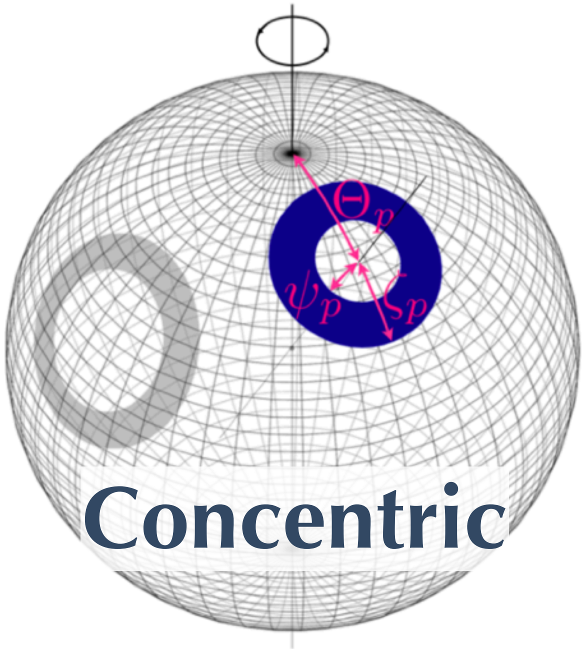
The surface patterns (shape, size, etc.) of the hot spots must also be modelled.

Single Temperature

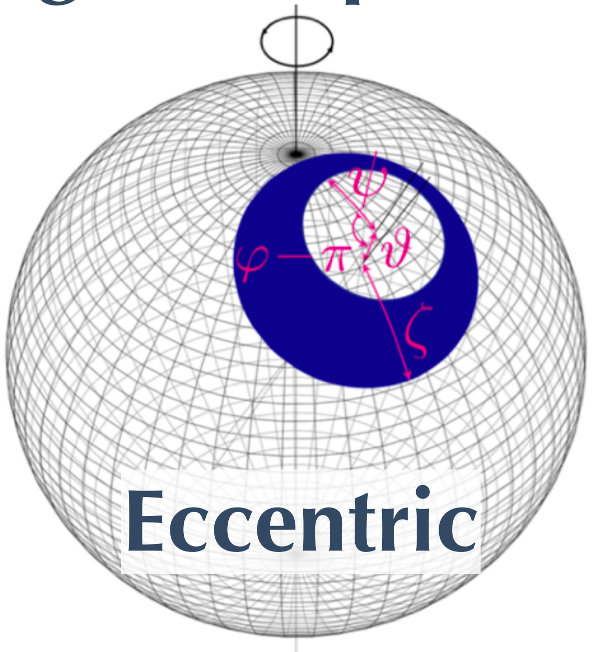


Circular

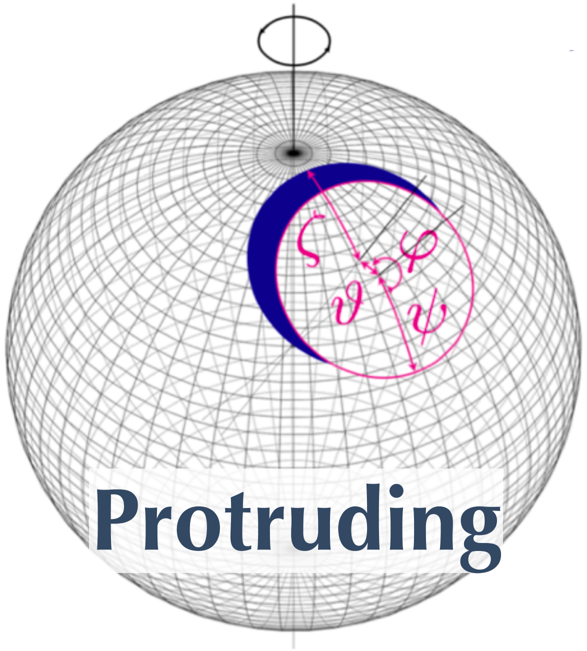
Single Temperature



Concentric

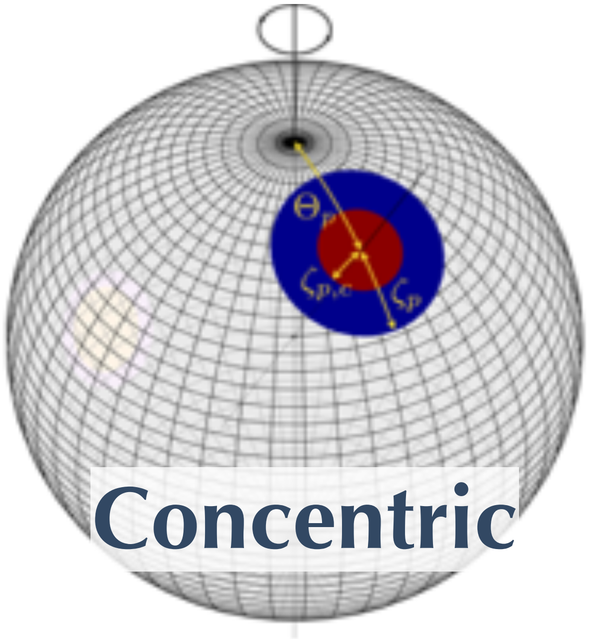


Eccentric

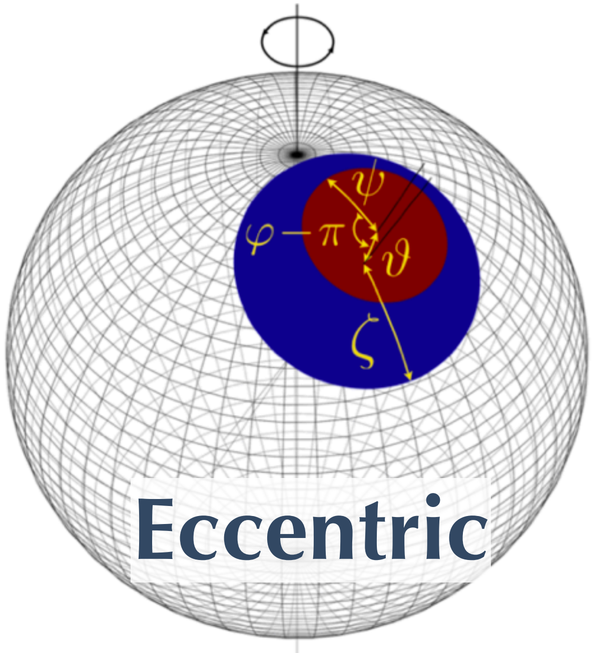


Protruding

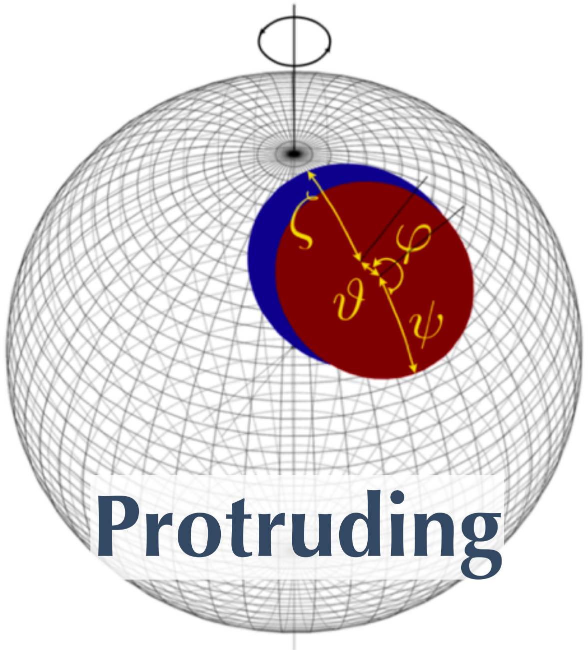
Dual Temperature



Concentric

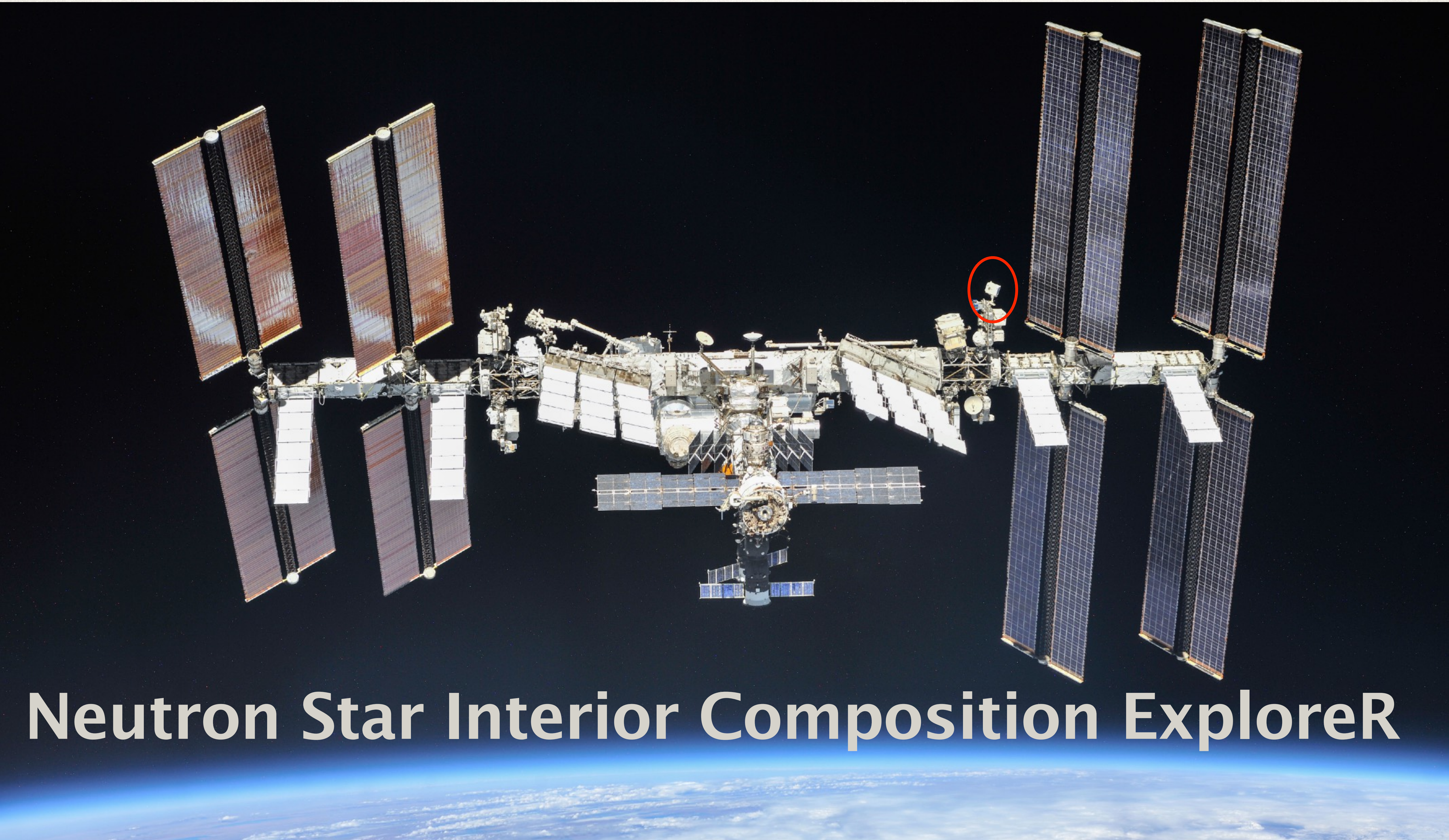


Eccentric

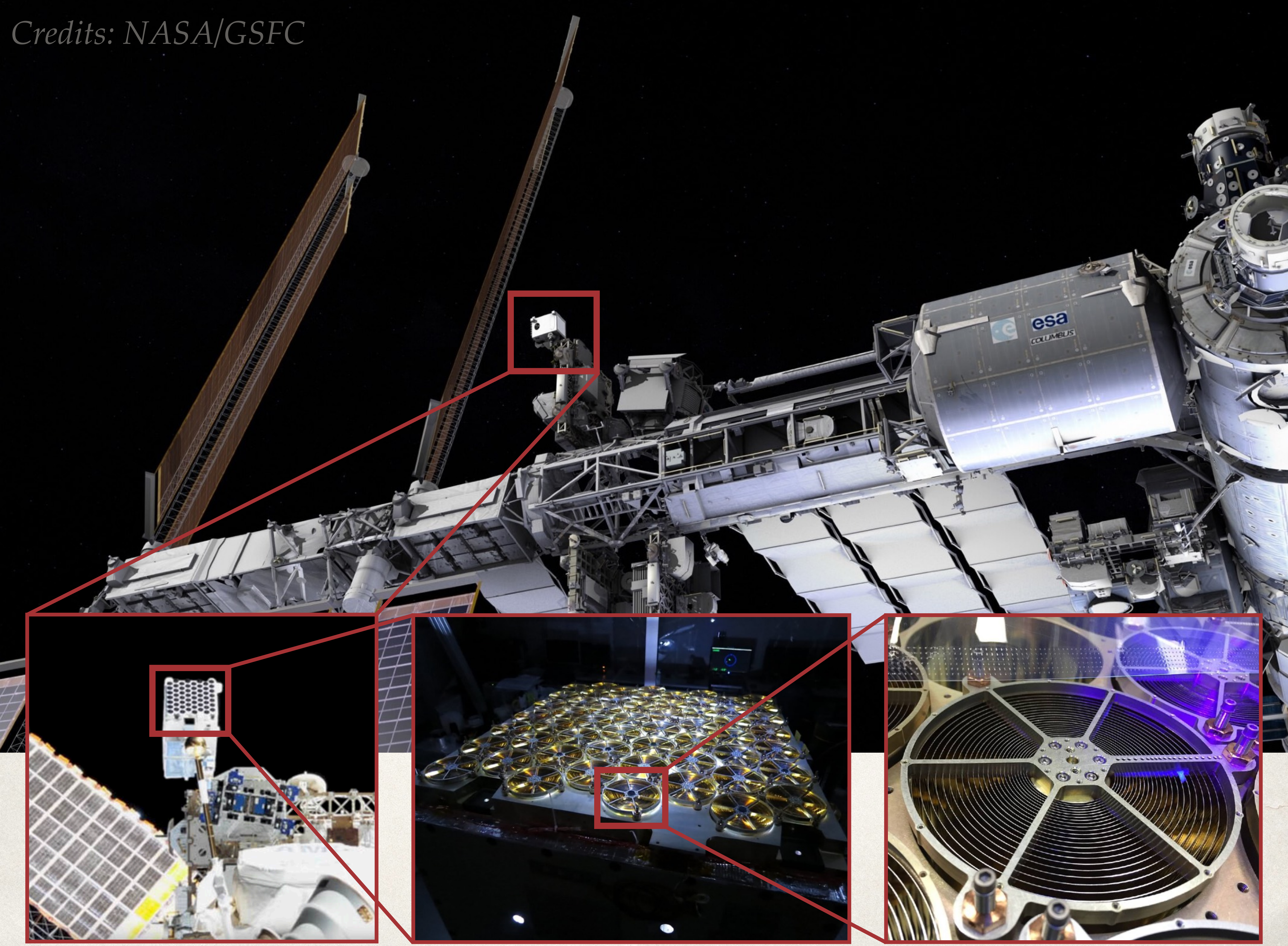


Protruding

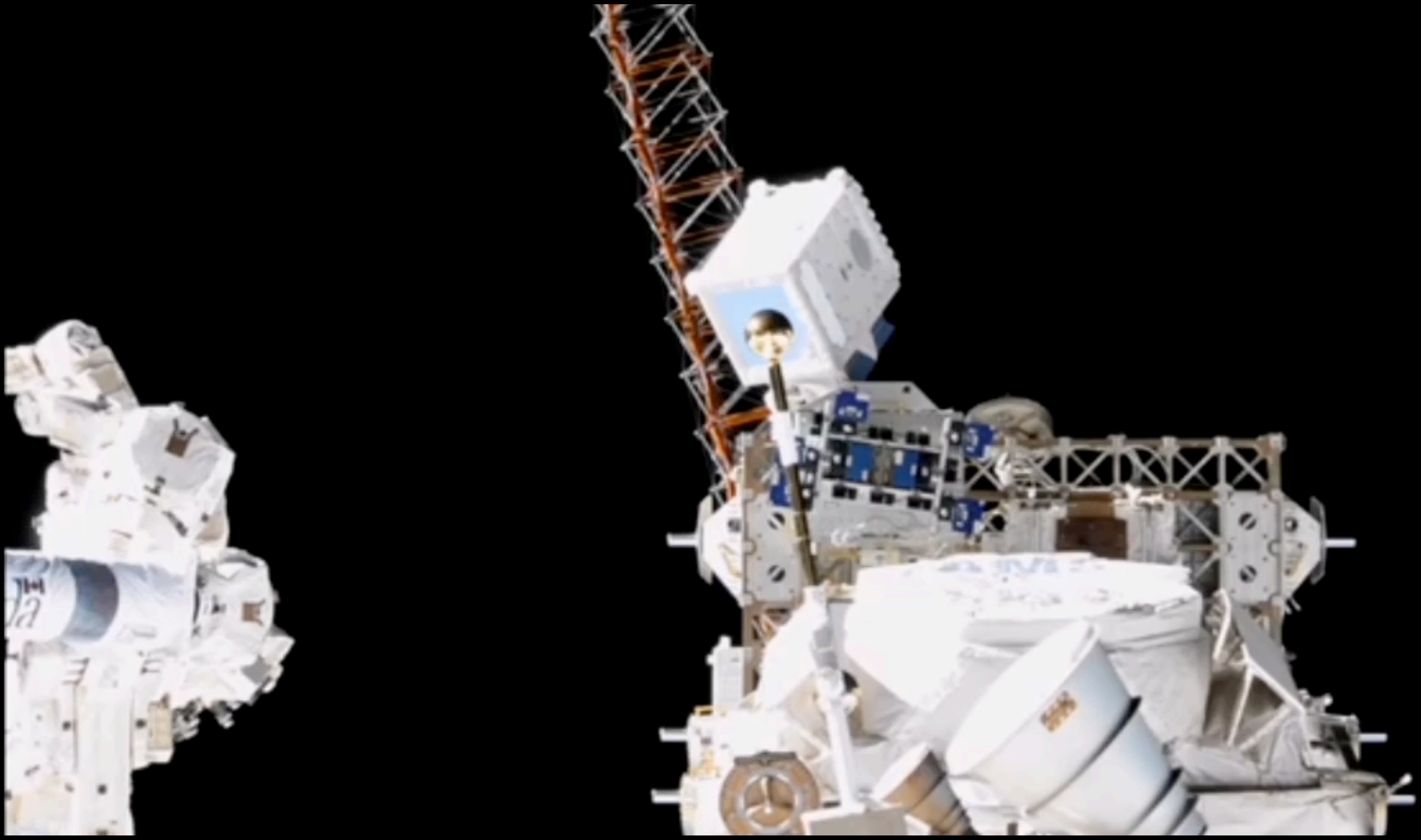
Since June 2017, NICER has been used to perform (almost) exclusively the observations needed for this technique.



Neutron Star Interior Composition ExplorеR

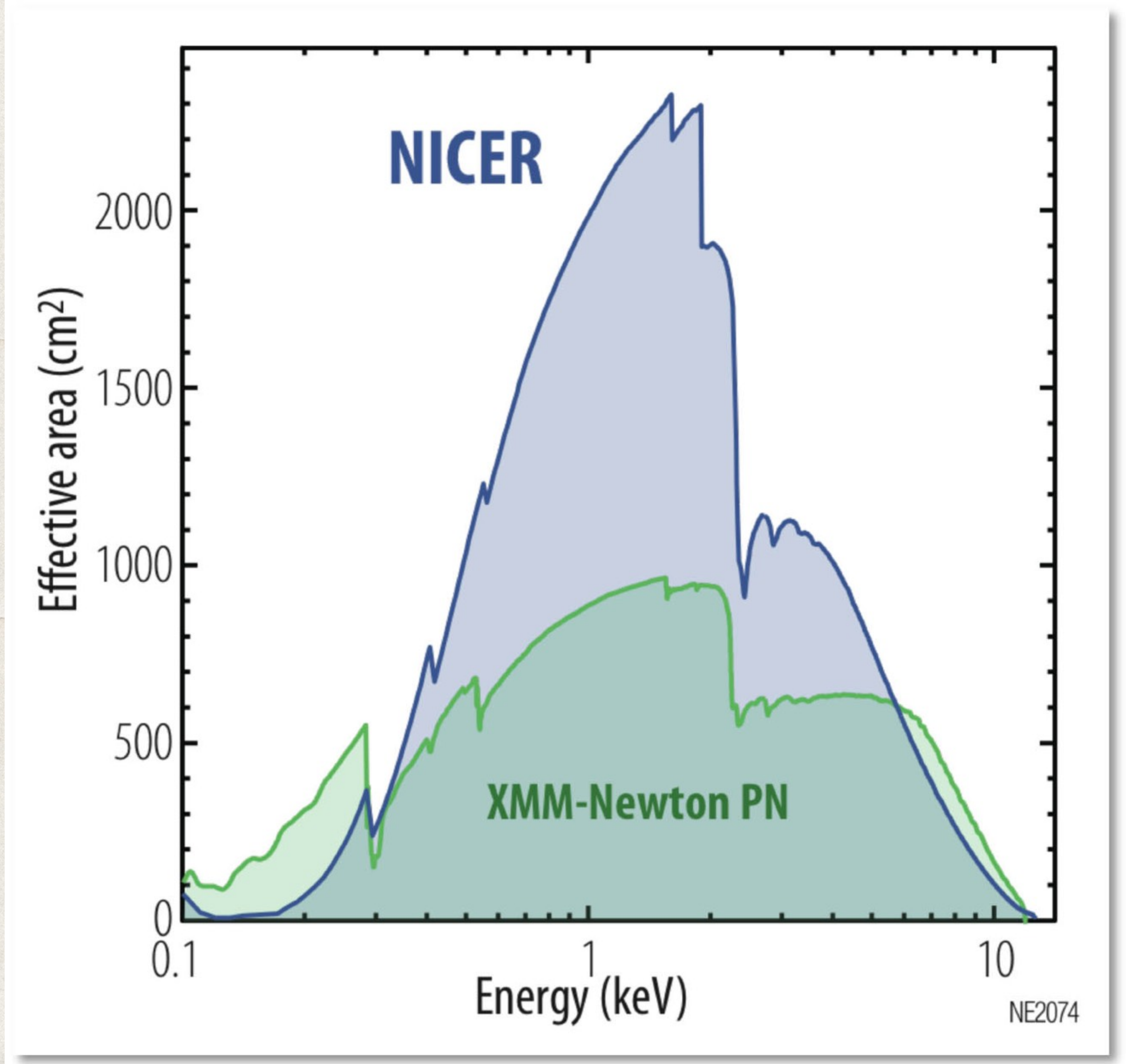


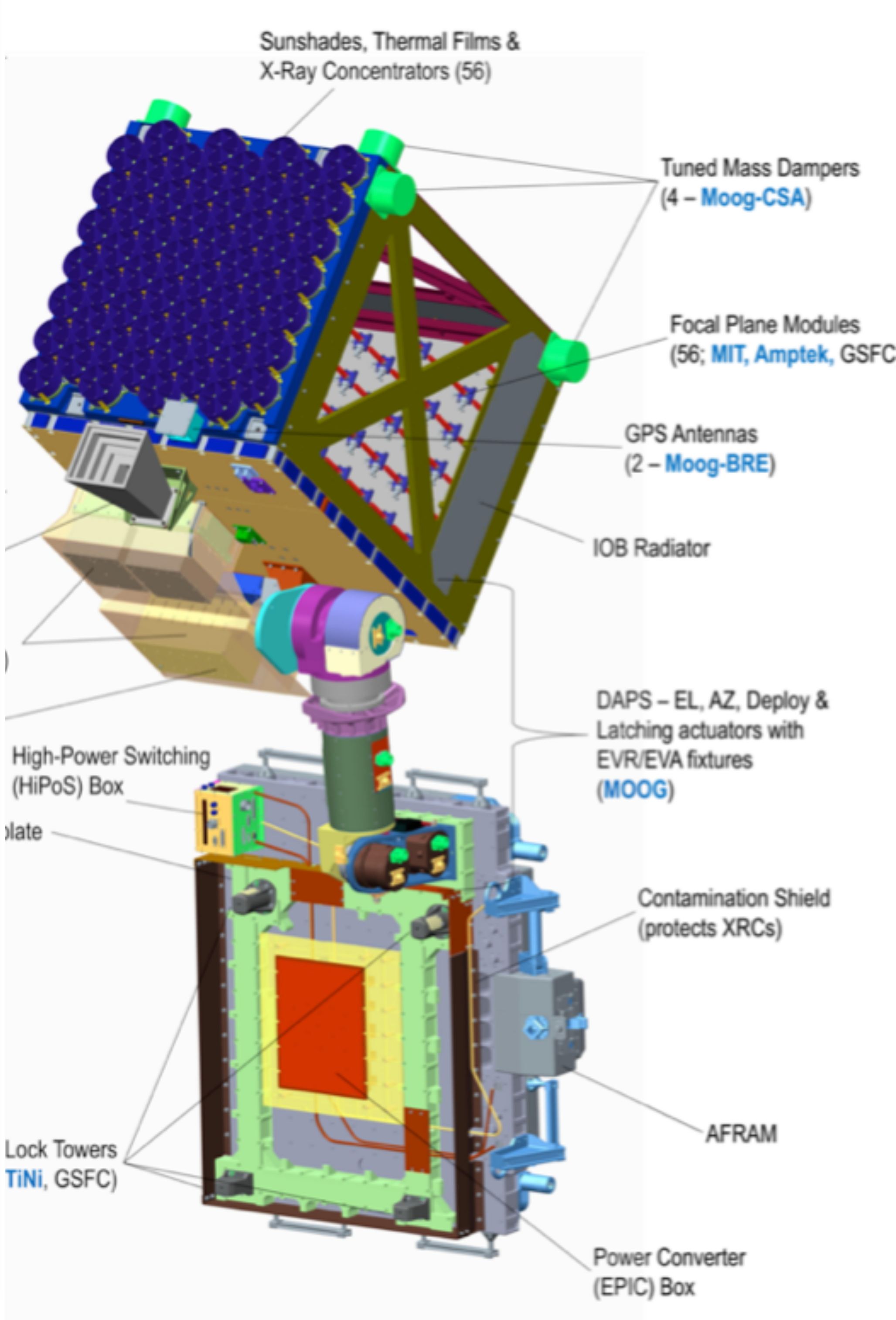
Credits: NASA/GSFC



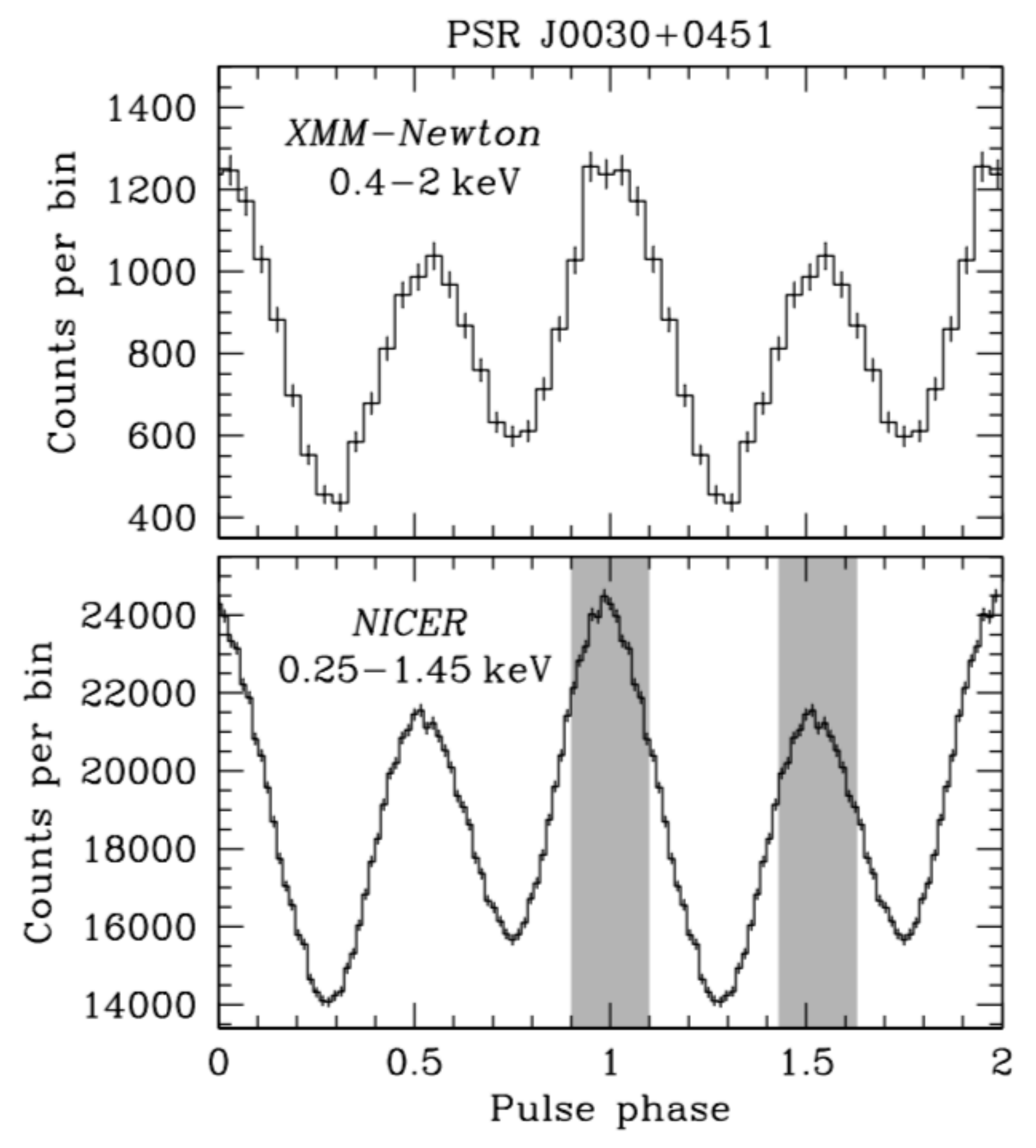
Credits: NASA/NICER

NICER is NASA’s X-ray photon counting machine.





NICER now routinely observes a few key target millisecond pulsars to give us unprecedented signal-to-noise data.



Before ***NICER***
100 ksec

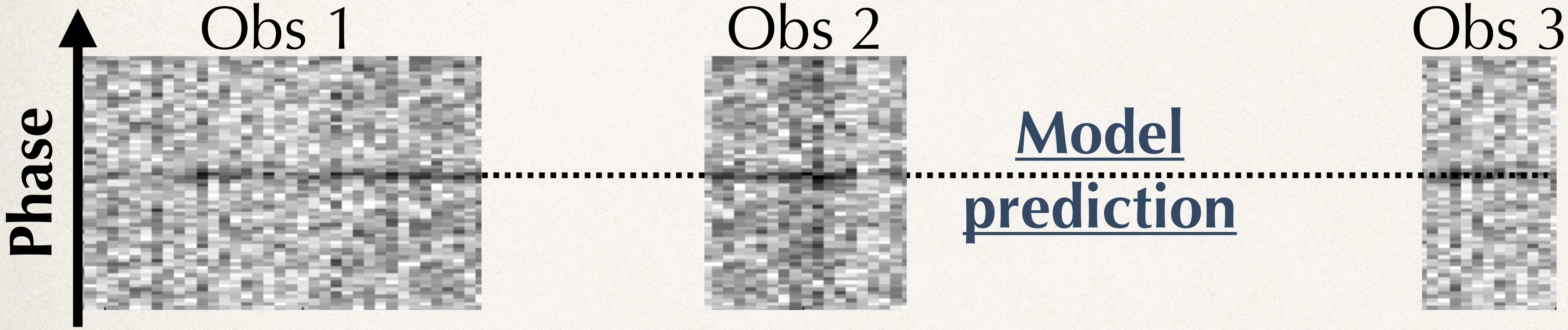
With ***NICER***
2000 ksec

Bogdanov, Guillot et al. 2019

How do we go know the phases of each X-ray photon ?

Pulsar timing

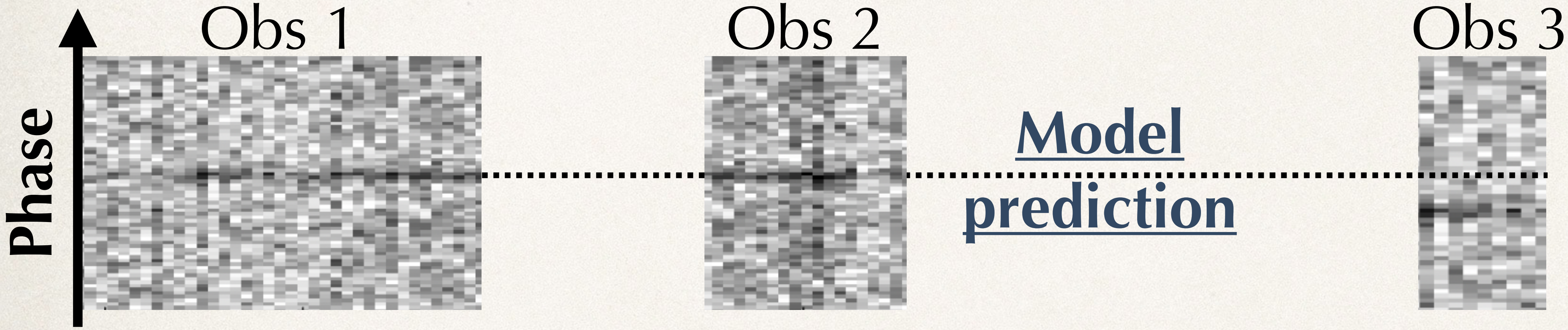
The art of accounting for accounting for
every rotation of a pulsar over the years



How do we go know the phases of each X-ray photon ?

Pulsar timing

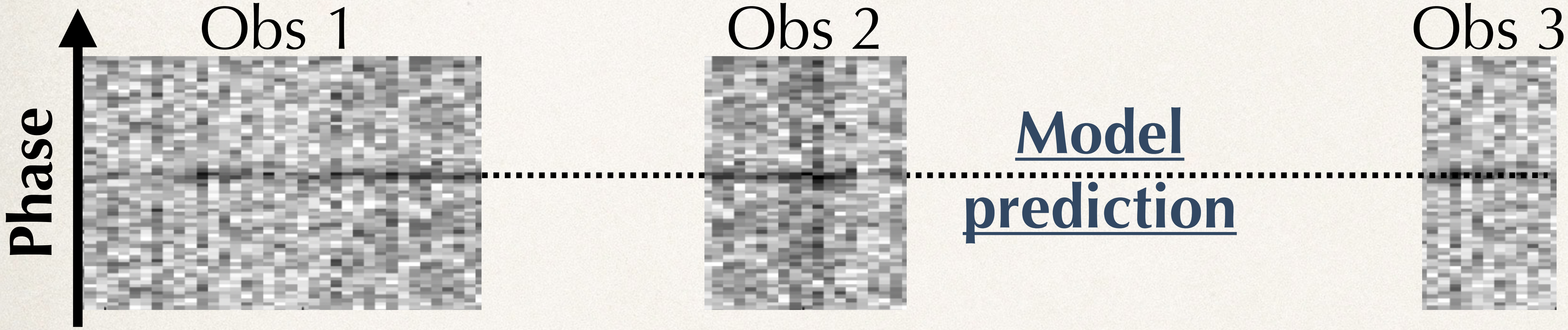
The art of accounting for accounting for every rotation of a pulsar over the years

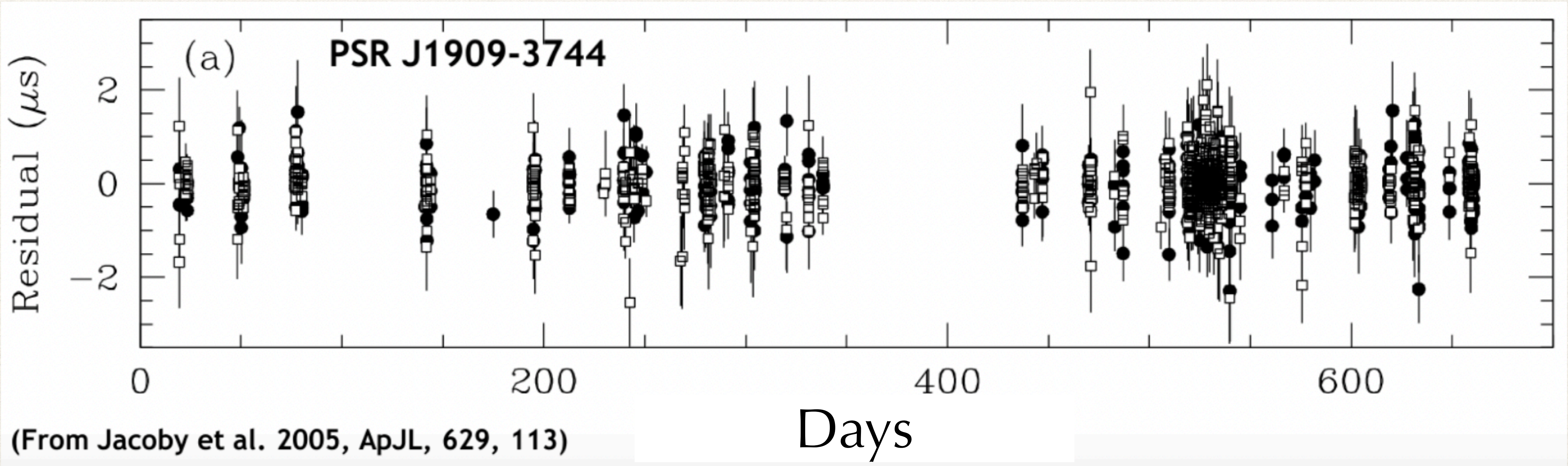


How do we go know the phases of each X-ray photon ?

Pulsar timing

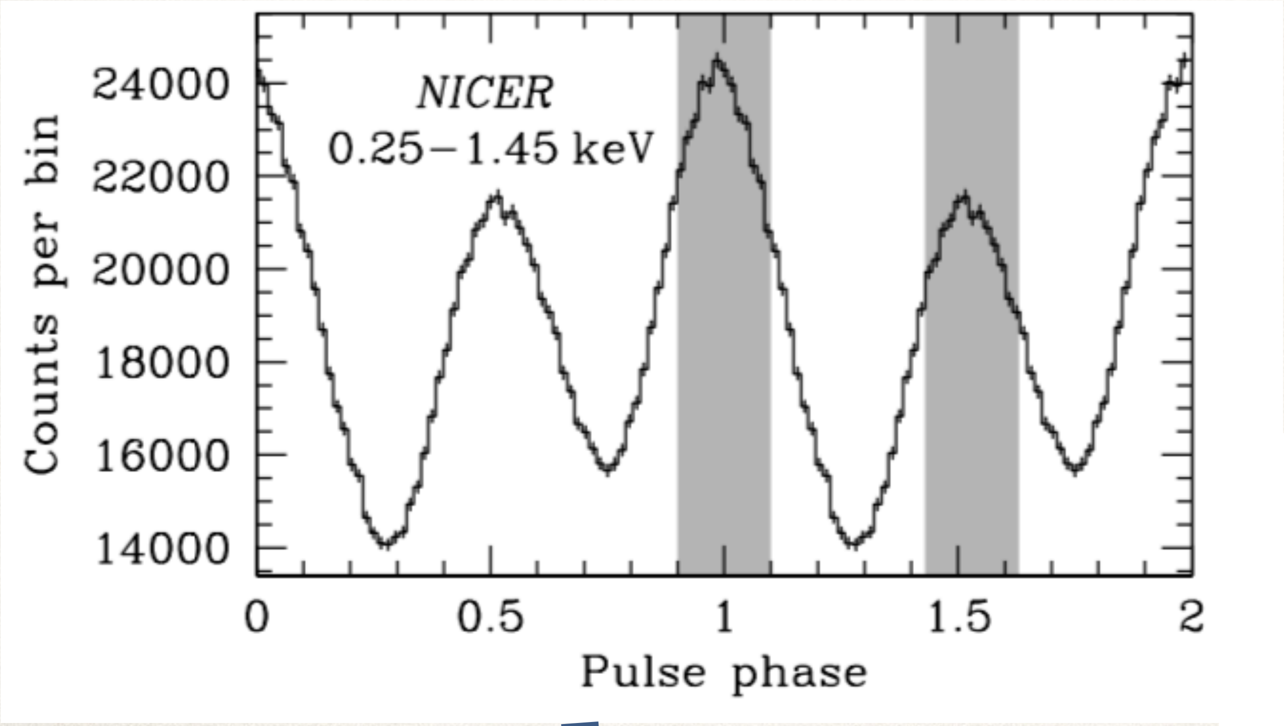
The art of accounting for accounting for every rotation of a pulsar over the years



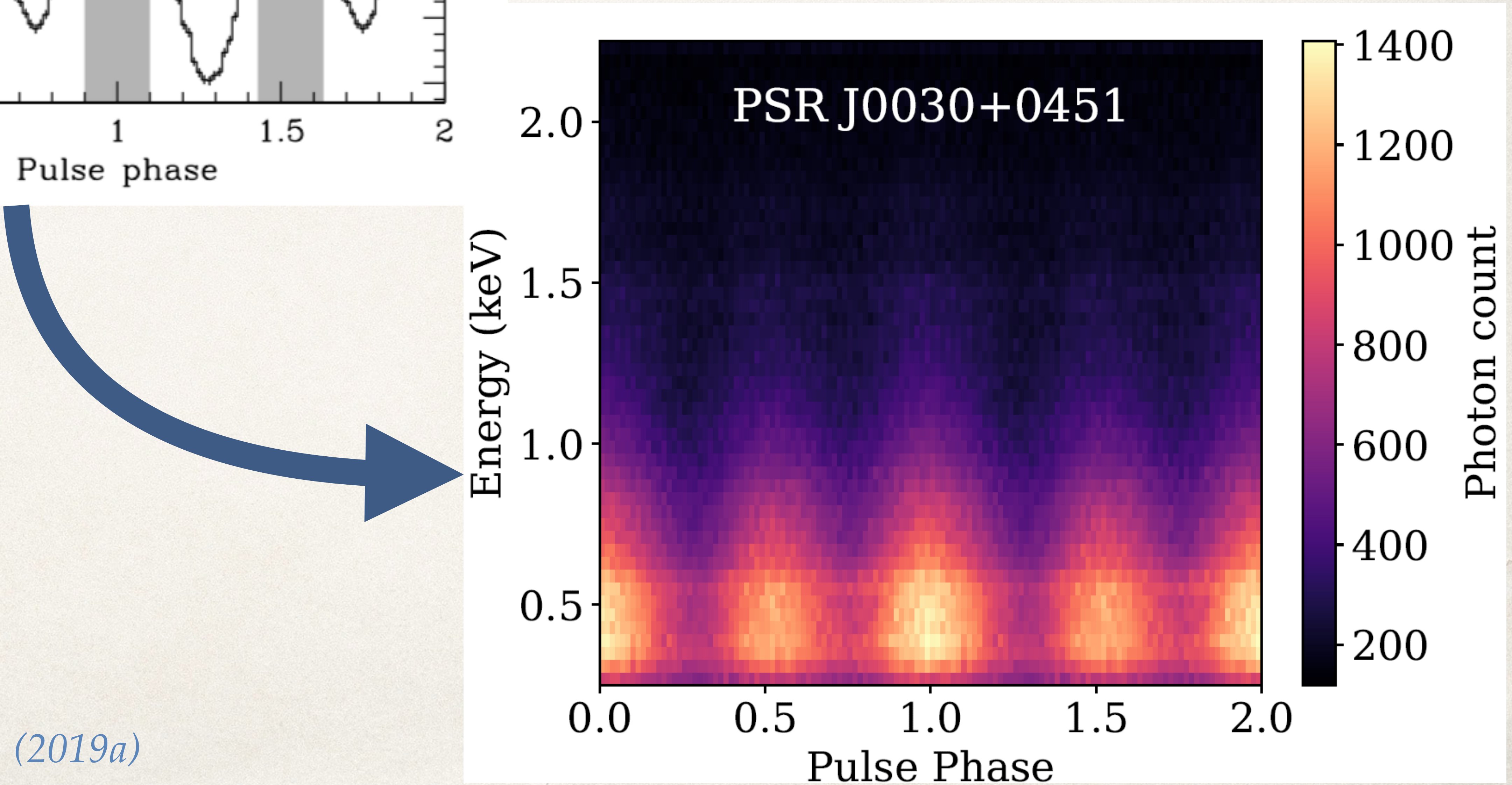


(From Jacoby et al. 2005, ApJL, 629, 113)

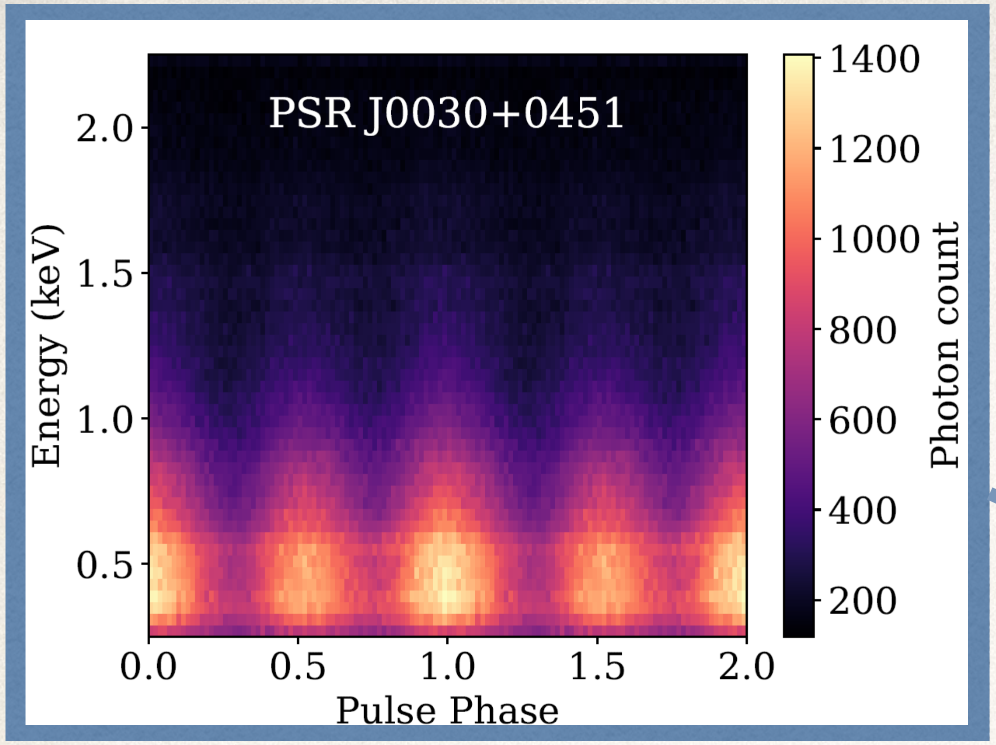
NICER observations provide the pulsed information in phase-energy space.

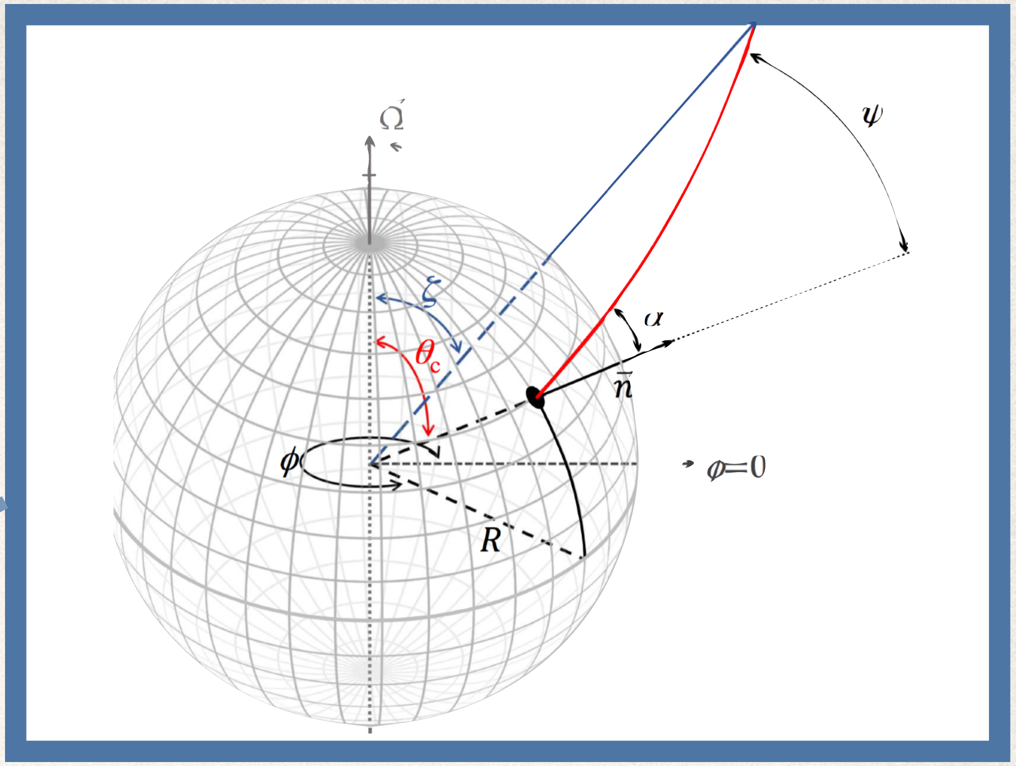


PSR J0030+0451



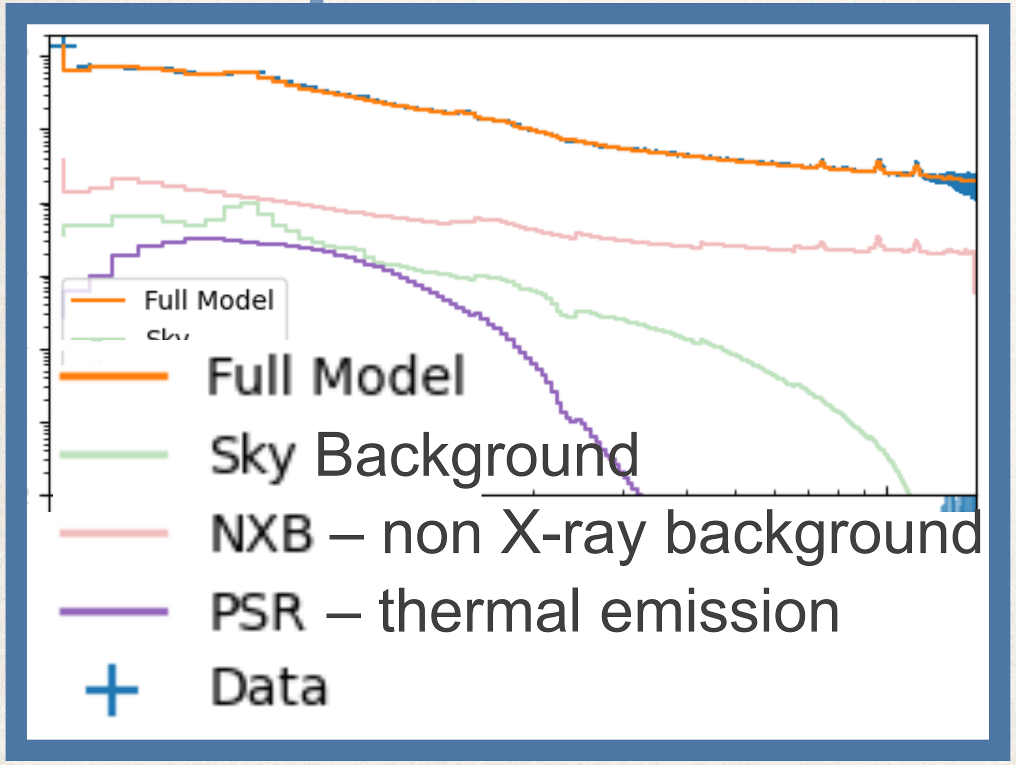
Bogdanov, SG et al. (2019a)

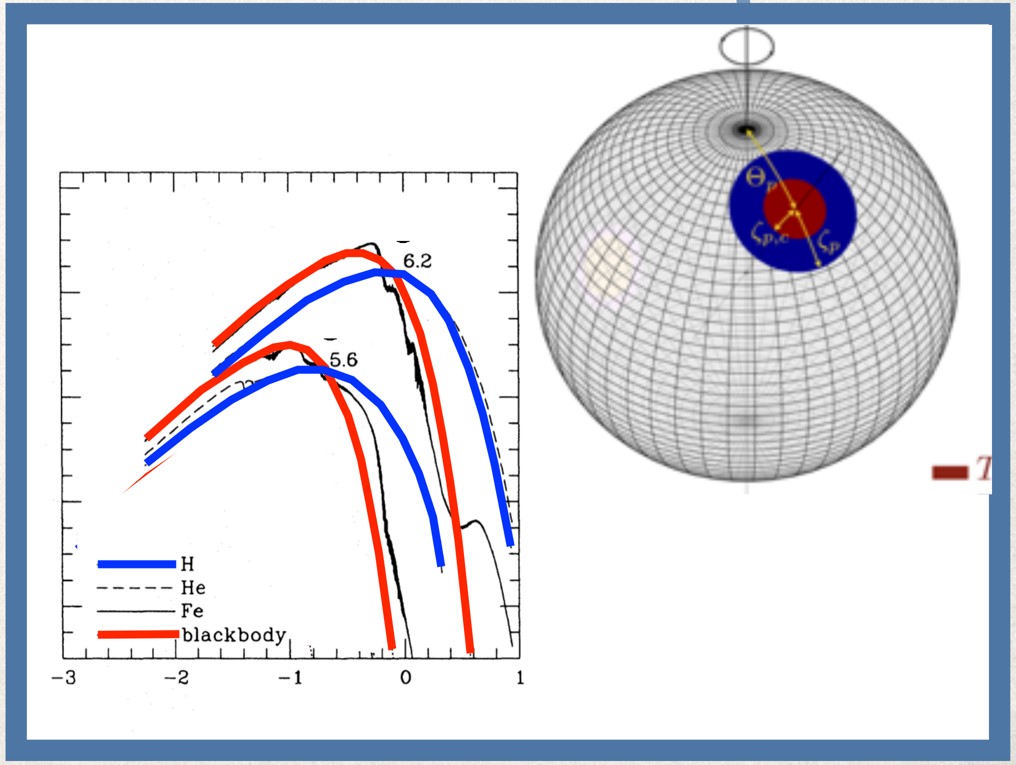




NS properties inference
(Likelihood statistical sampling)

Mass, Radius, EOS

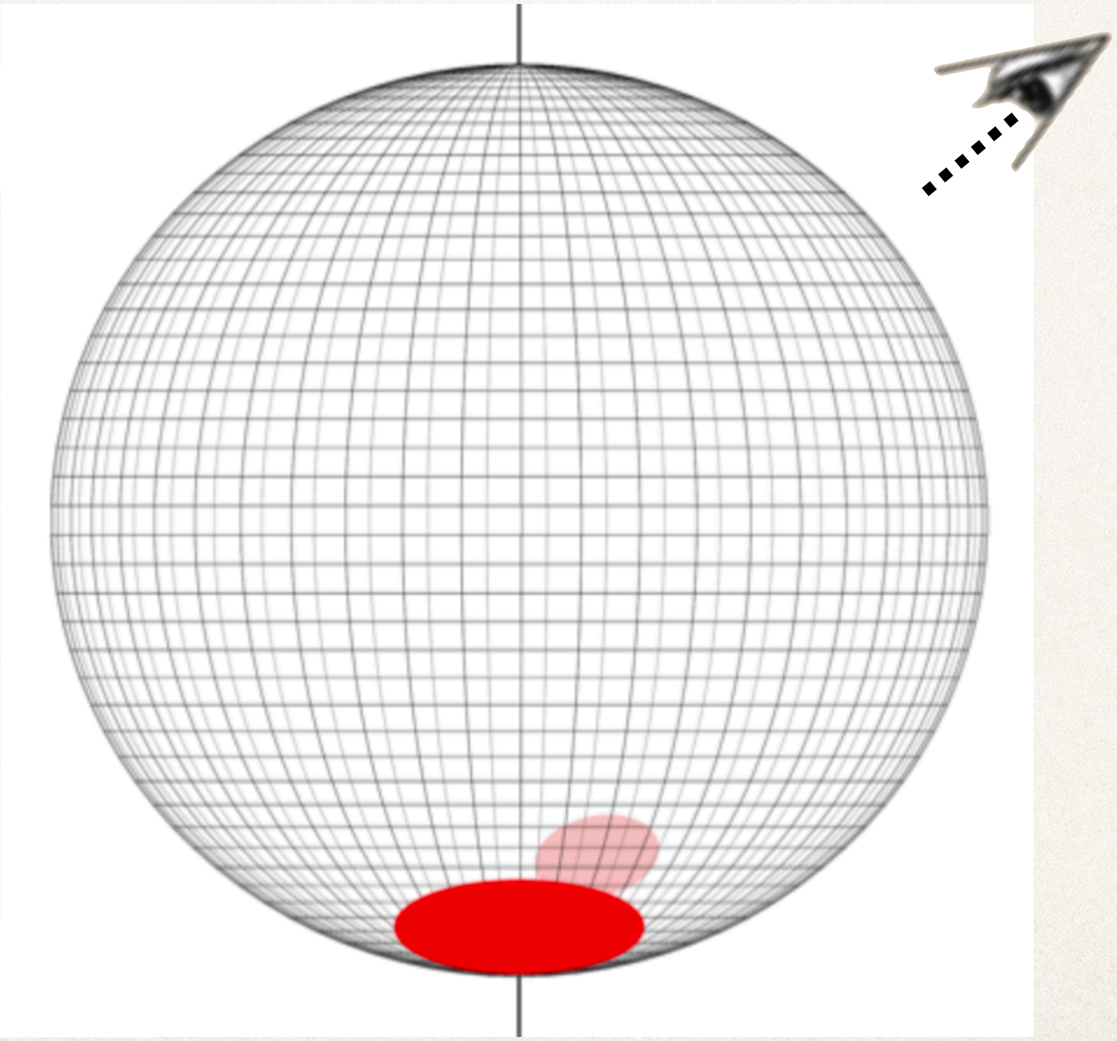


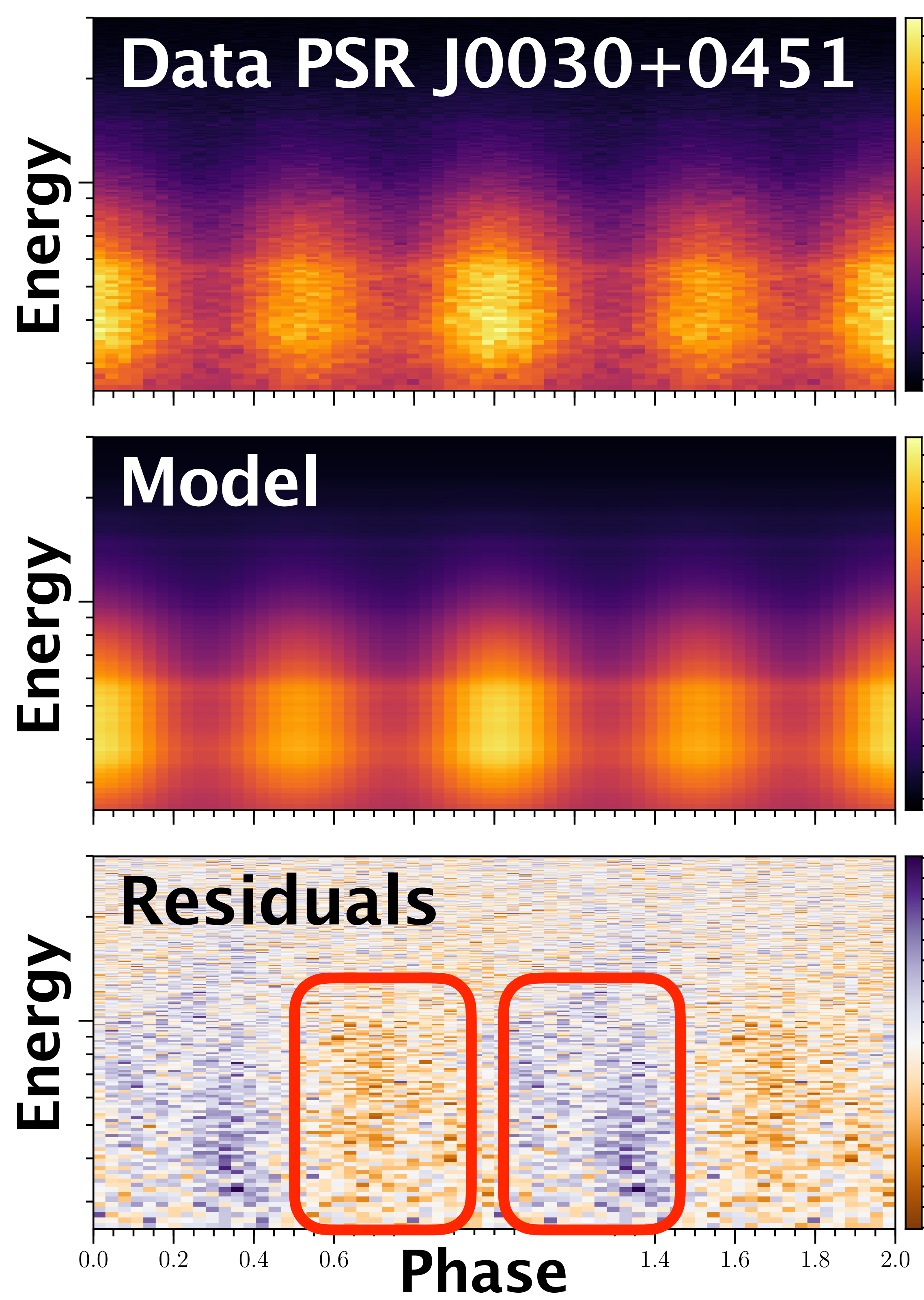


The simplest model shows clear residuals between the model and the data.

ST+ST

Single Temperature +
Single Temperature

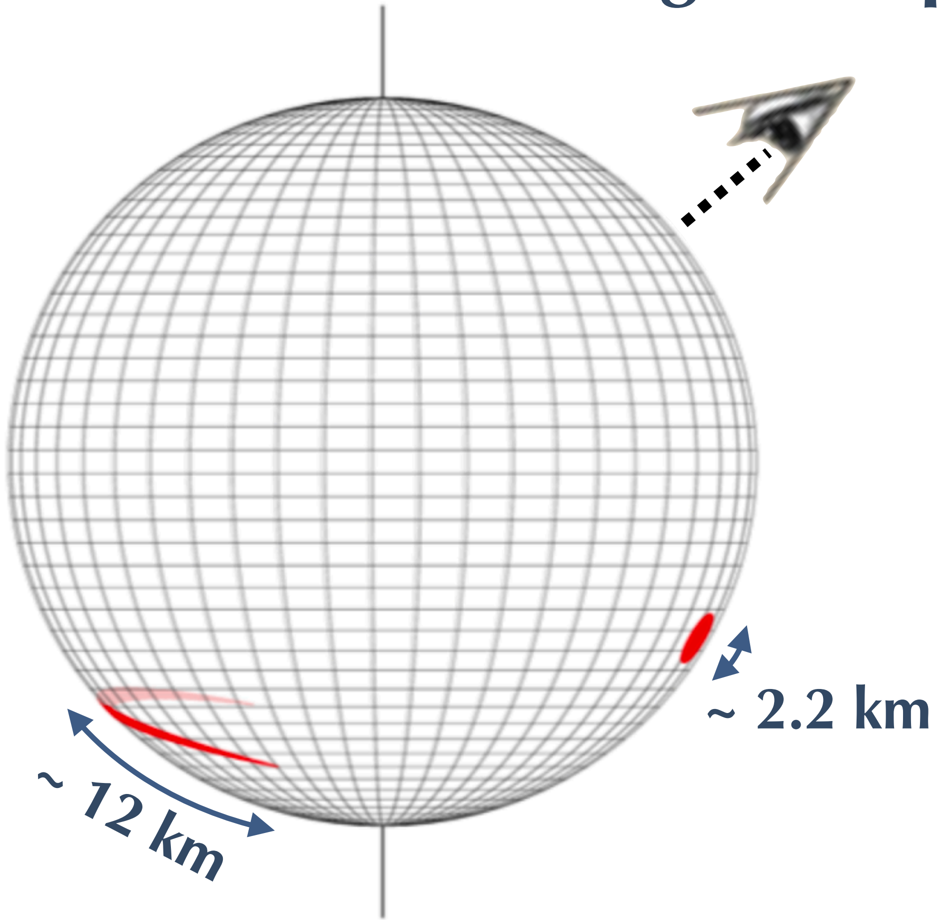


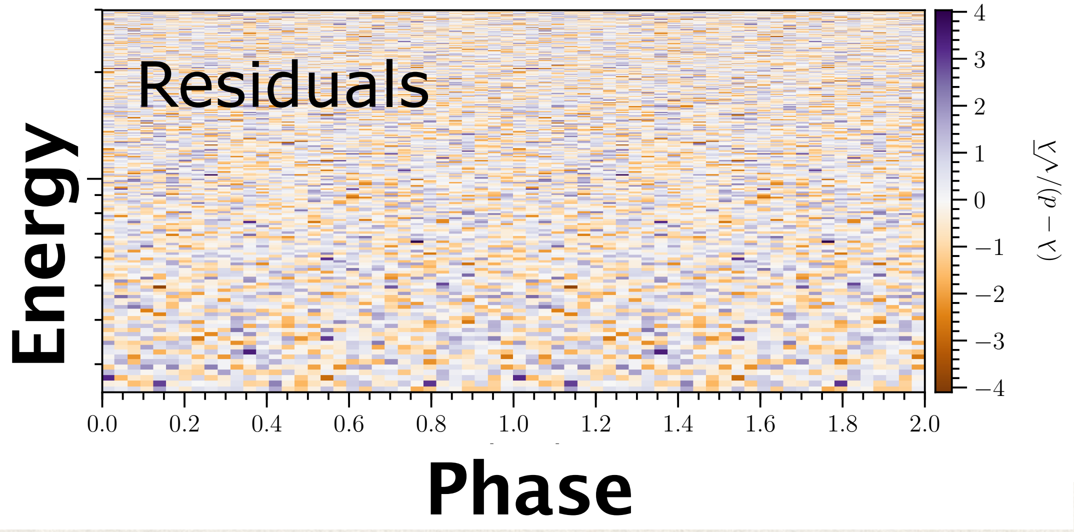


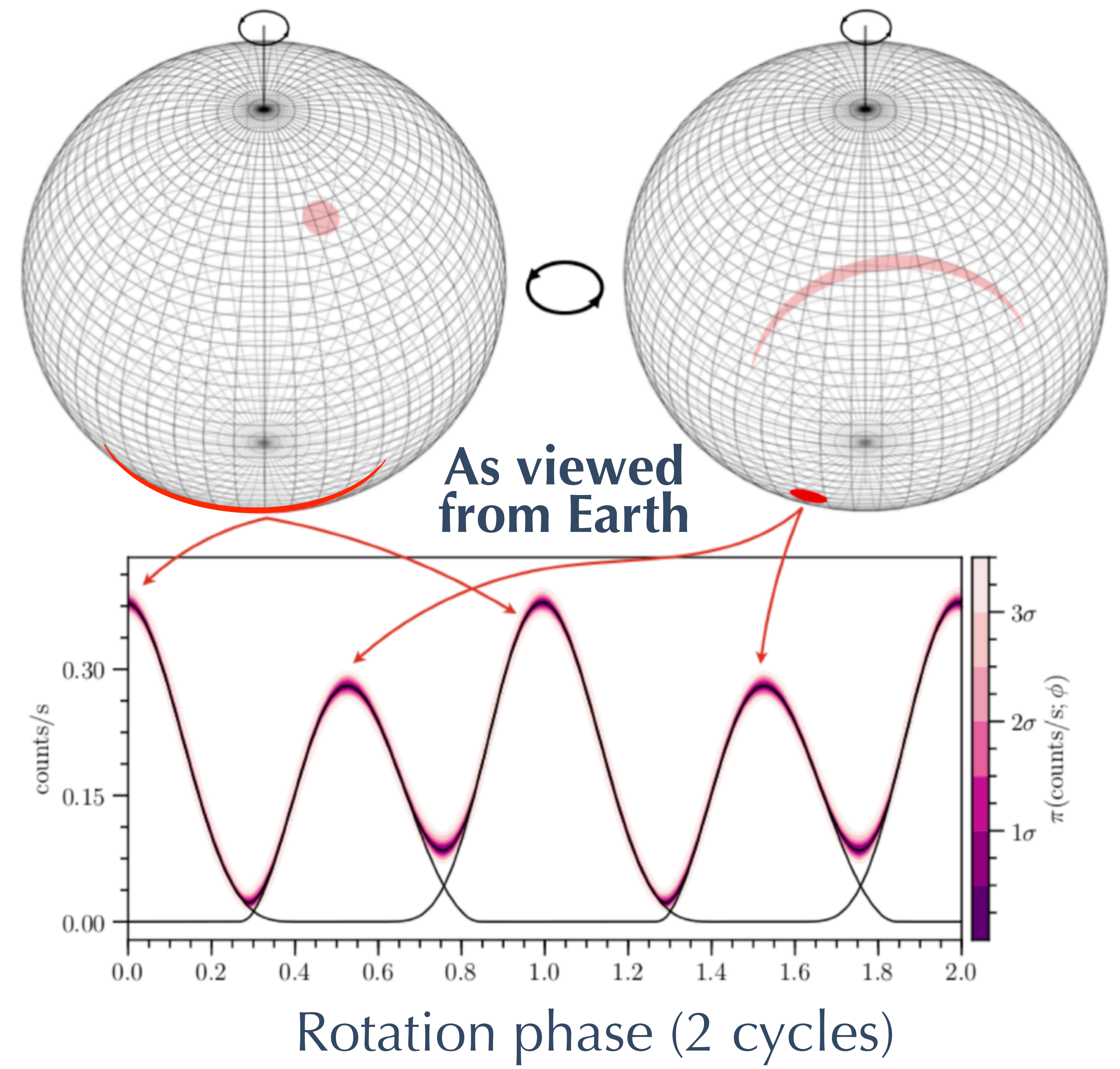
Riley, …, SG et al. (2019)

The preferred model consist in a small circular spot and an elongated crescent.

Single Temperature + Protruding Single Temp.

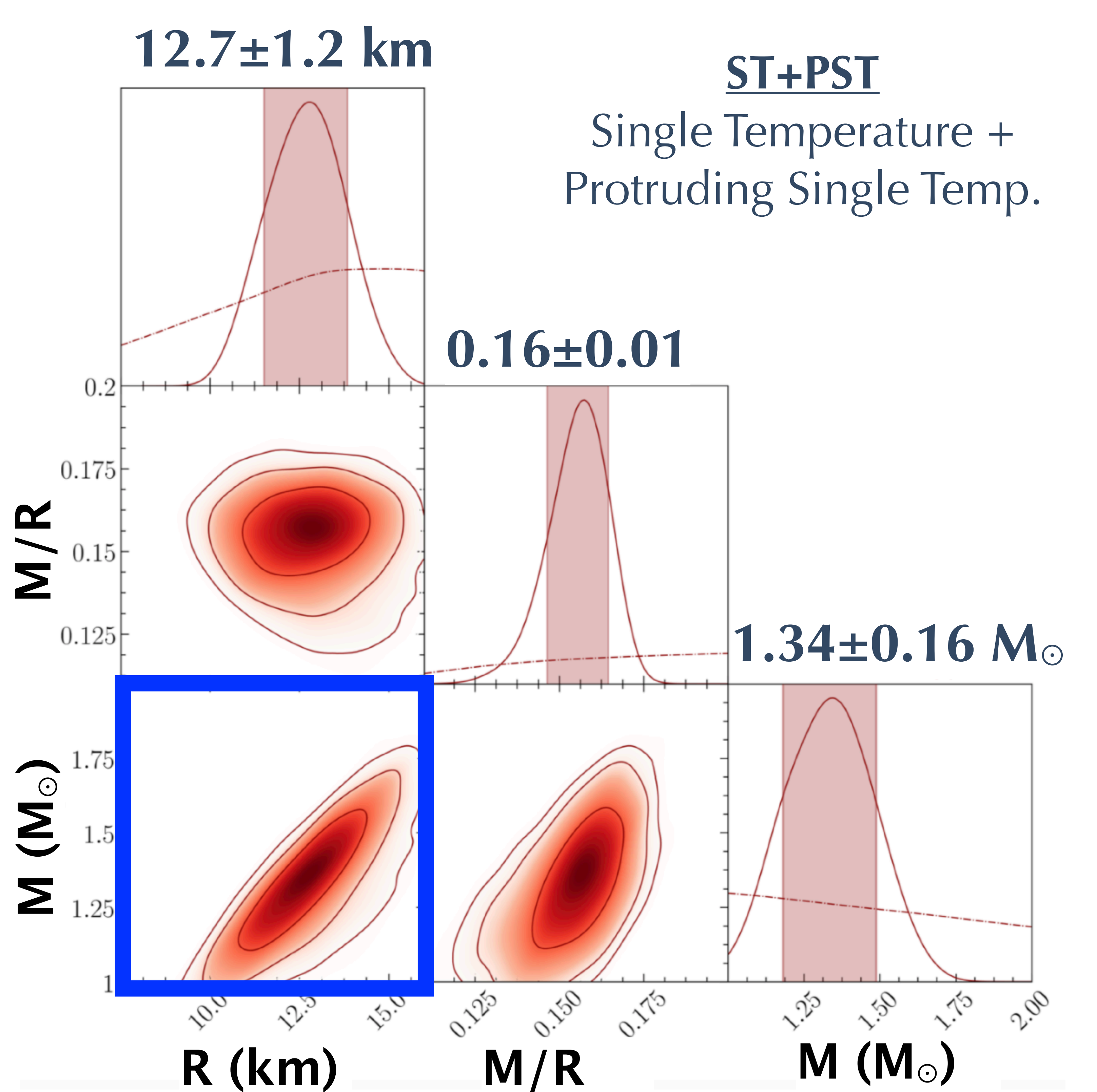





As viewed from Earth

Riley, …, SG et al. (2019)

In addition to the unexpected geometry, we also constrain M and R.

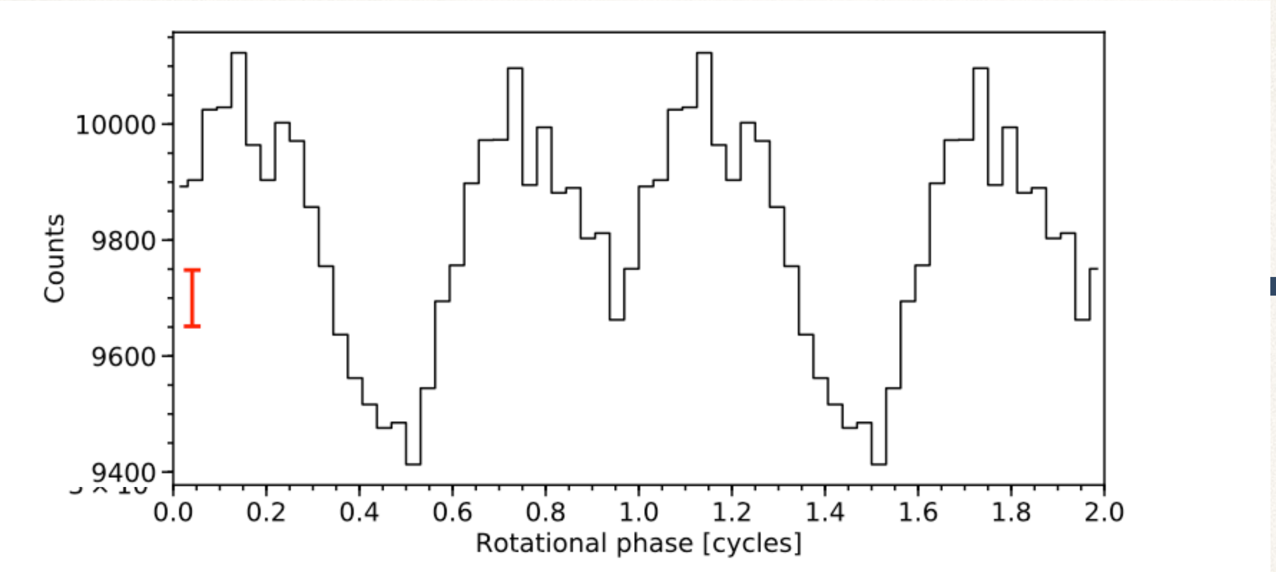


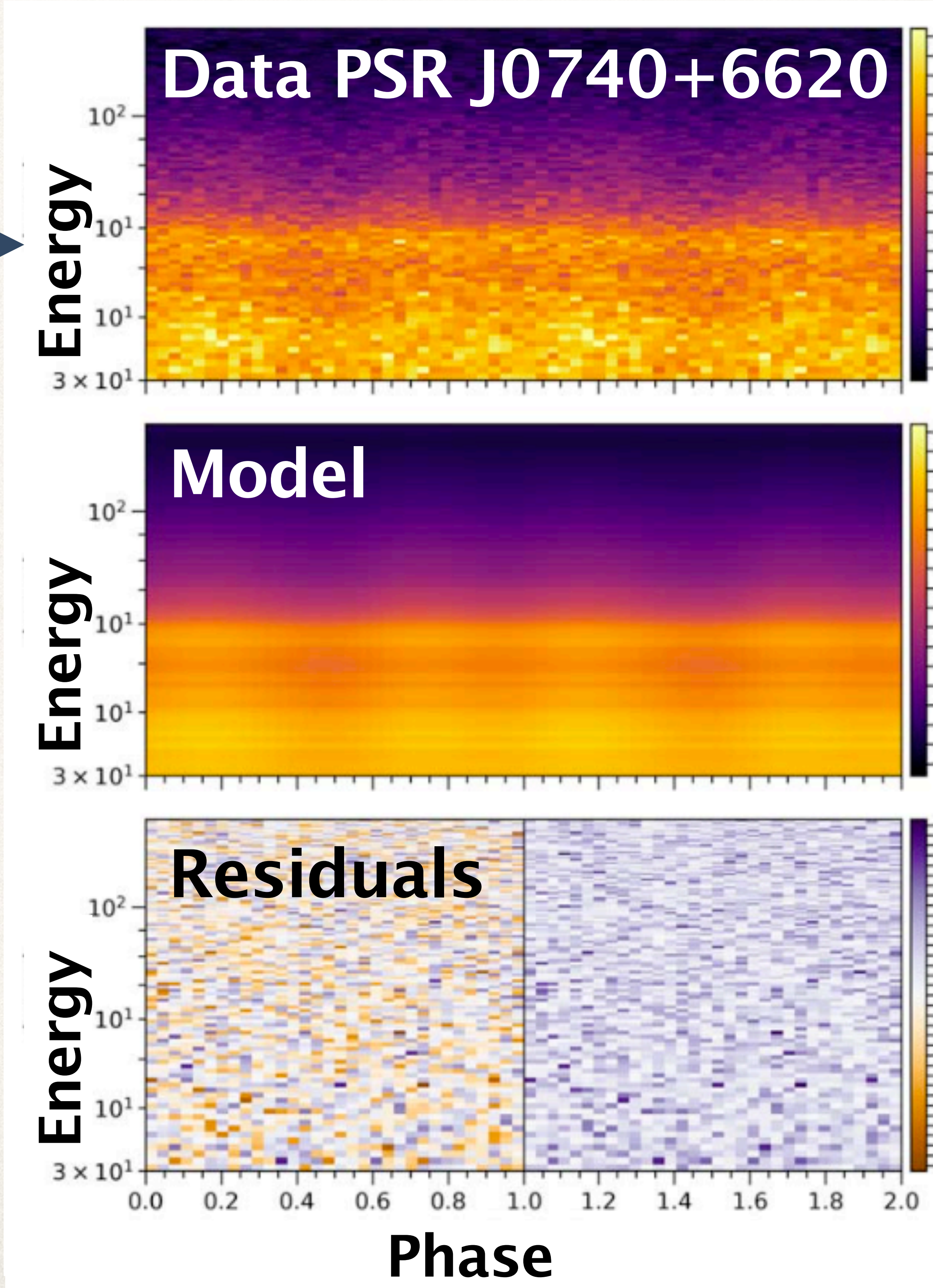
R = 12.7 ± 1.2 km

M = 1.34 ± 0.16 Msun

Riley, …, SG et al. (2019)
See also Miller, …, SG et al. (2019)

Another pulsar is well described by the simplest model (two circular spots)

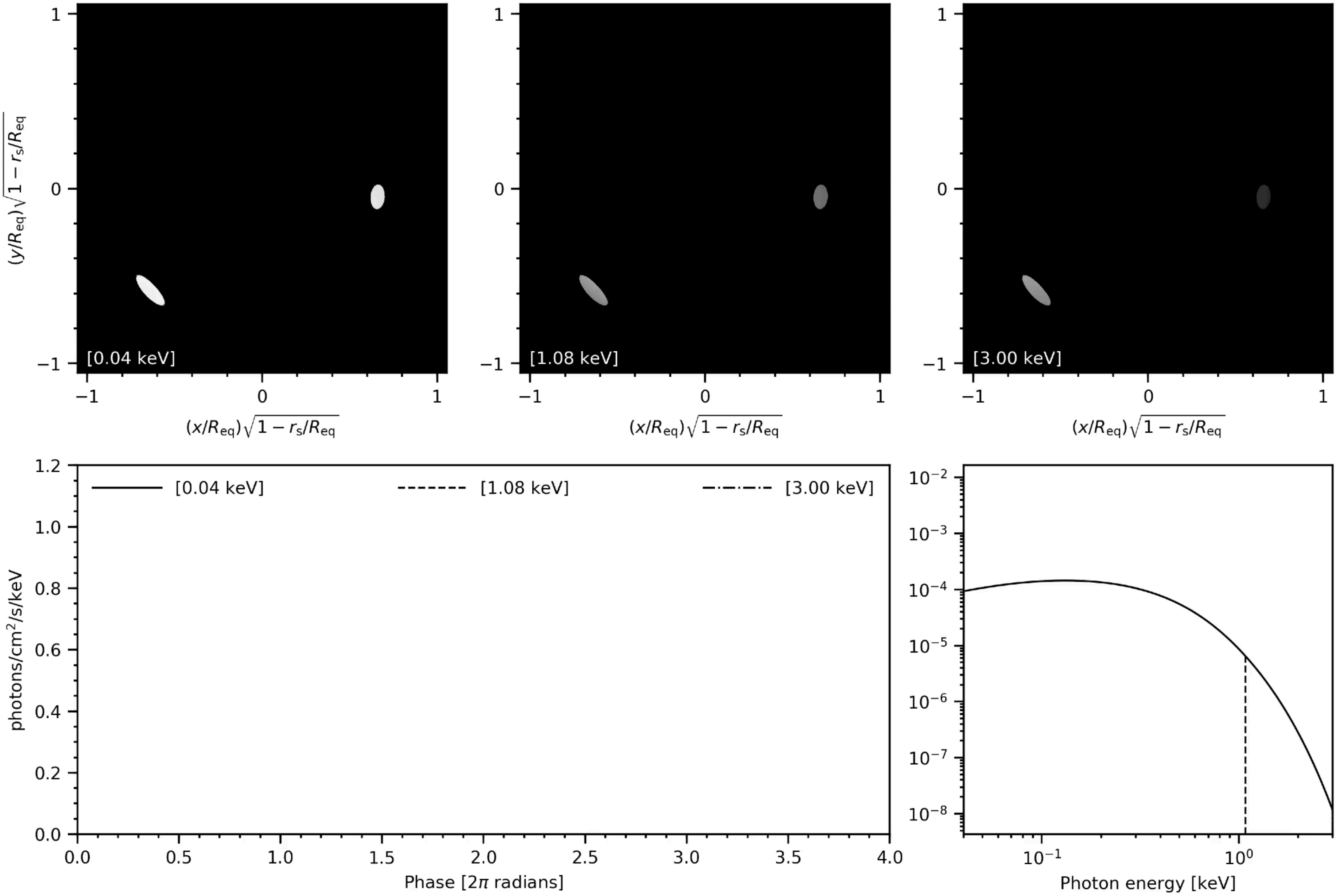




ST+ST

Single Temperature +
Single Temperature

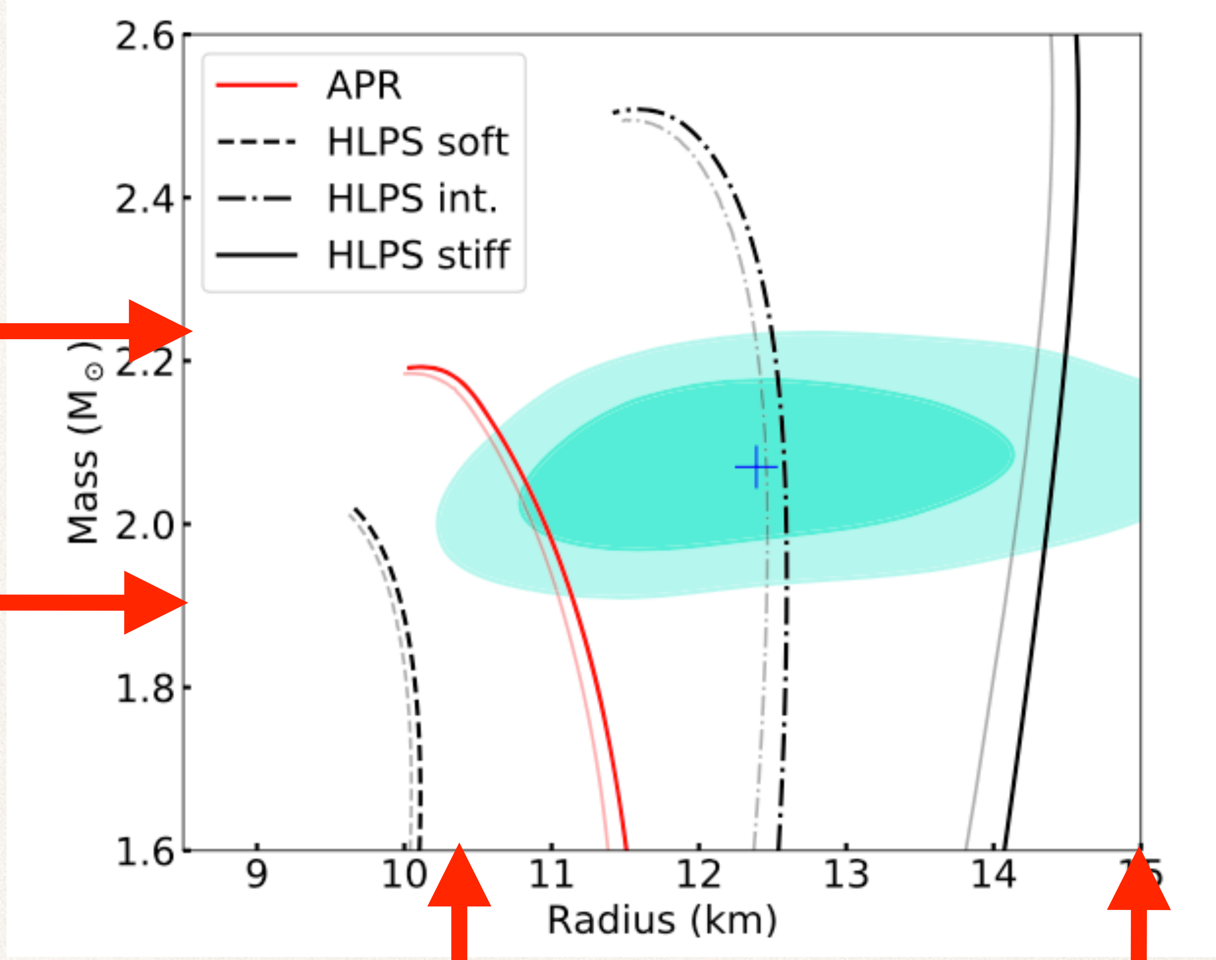
Riley, …, SG et al. (2021)


[0.04 keV]
[1.08 keV]
[3.00 keV]
$(y/R_{\rm eq})\sqrt{1 - r_{\rm s}/R_{\rm eq}}$
$(x/R_{\rm eq})\sqrt{1 - r_{\rm s}/R_{\rm eq}}$
1
0
−1
photons/cm^2/s/keV
Phase [2π radians]
0.0
0.2
0.4
0.6
0.8
1.0
1.2
0.5
1.5
2.0
2.5
3.0
3.5
4.0
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-1}
10^{0}
Photon energy [keV]

The M-R constraints from PSR J0740+6620 are useful thanks to its independently measured high mass.

Using mass prior from radio timing observations:

M = 2.07±0.07 Msun

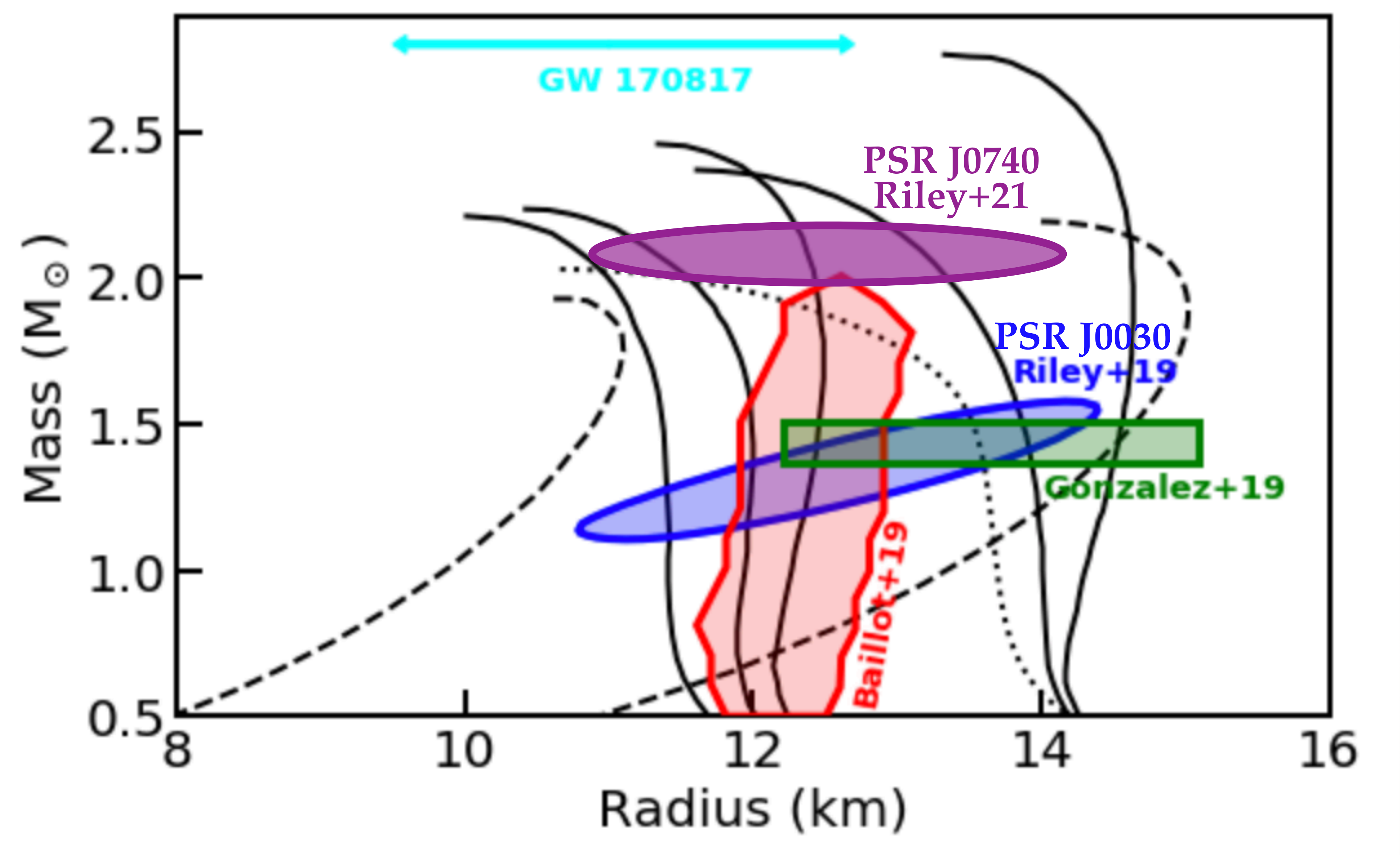


Constraints on radius from NICER+XMM data

R = 12.4 ± 1.3 km

Riley, …, SG et al. (2021)
See also Miller, …, SG et al. (2021)

The NICER Science Team published the results for two pulsars.



Two independent analyses for each target

- PSR J0030+0451
  - Riley et al. 2019
  - Miller et al. 2019 (not shown on figure)
- PSR J0740+6620
  - Riley et al. 2021
  - Miller et al. 2021 (not shown on figure)

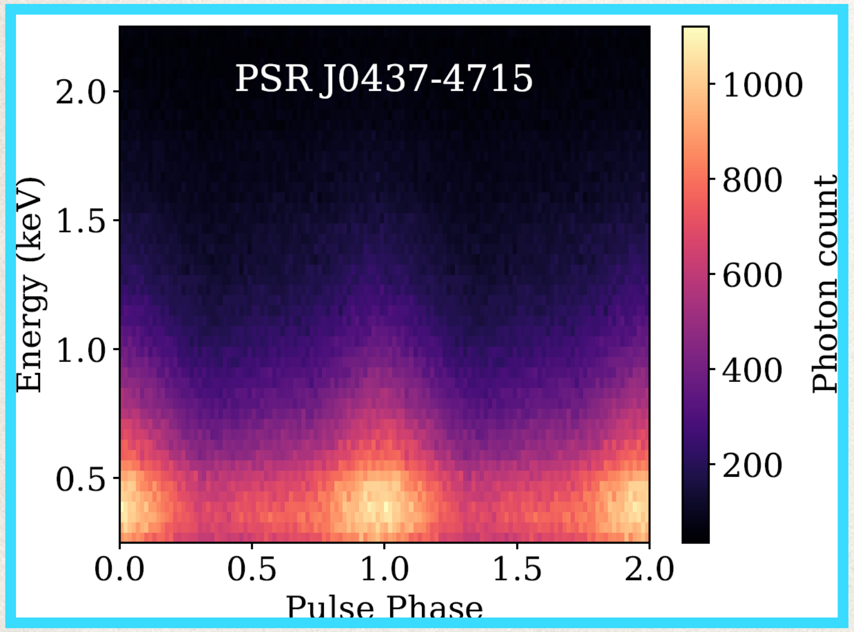
See also a third independent re-analysis of PSR J0030+0451 by Afle et al. 2023 finding results consistent with Riley et al. 2019

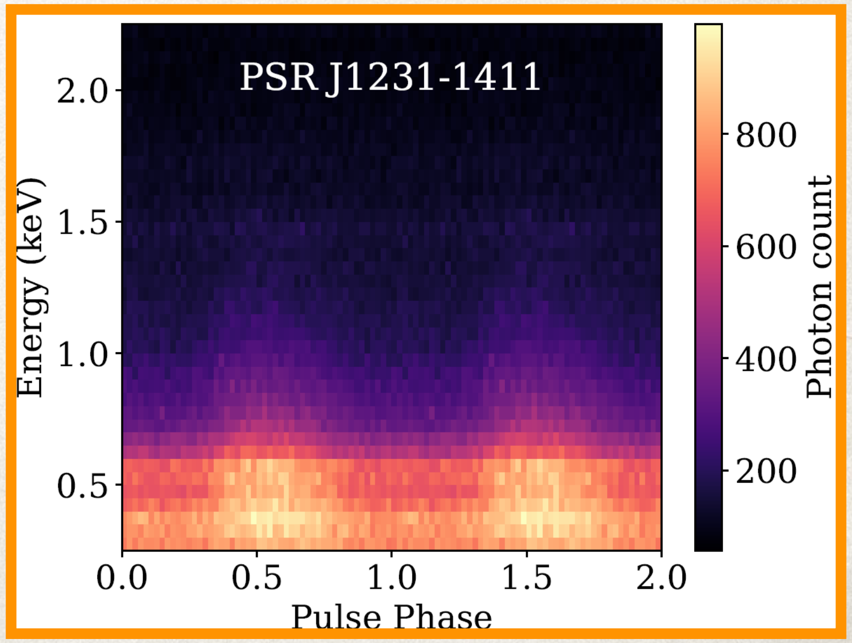
Part 2B – conclusion

NICER observations provided precise radius measurements for **two millisecond pulsars**

We have more data sets to analyse.

Target	Total time
PSR J1231	2.9 Msec
PSR J0437	2.6 Msec
PSR J2124	1.9 Msec
PSR J0614	1.1 Msec
PSR J1614	1.0 Msec

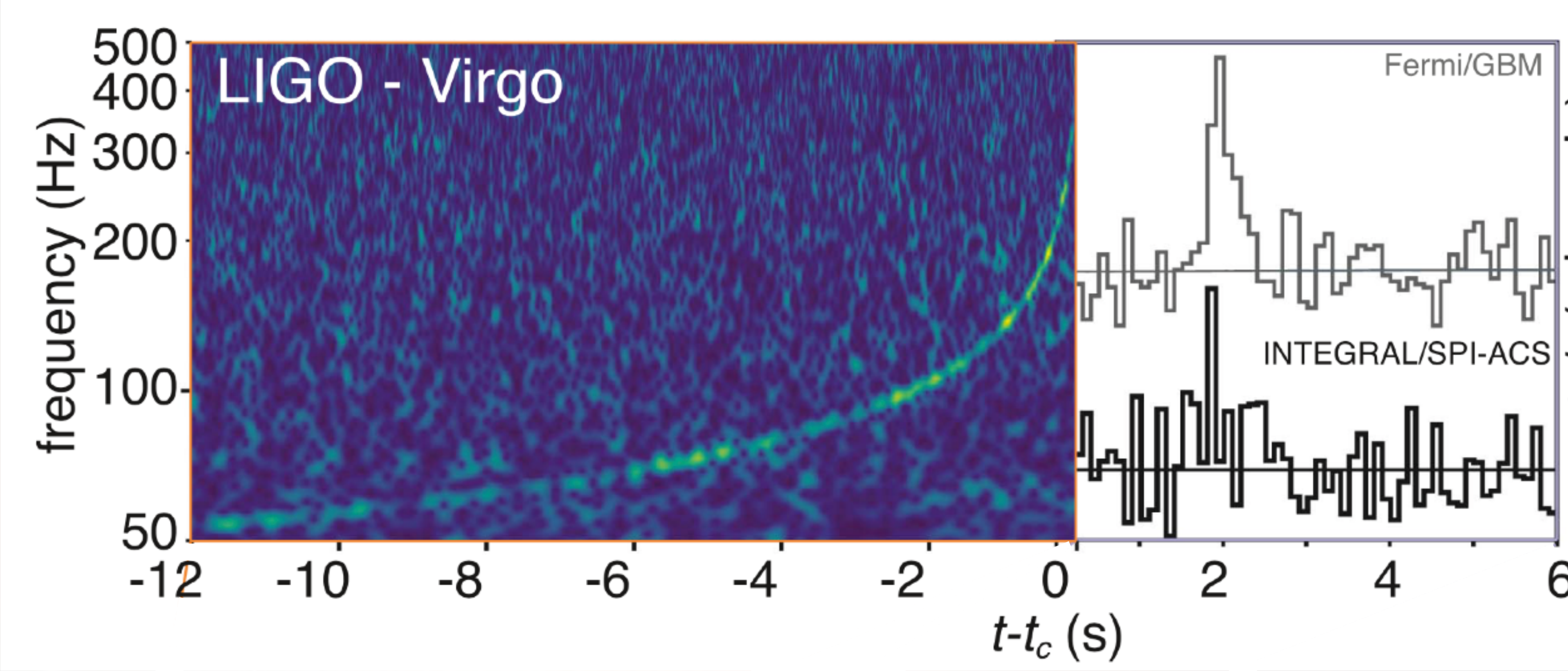


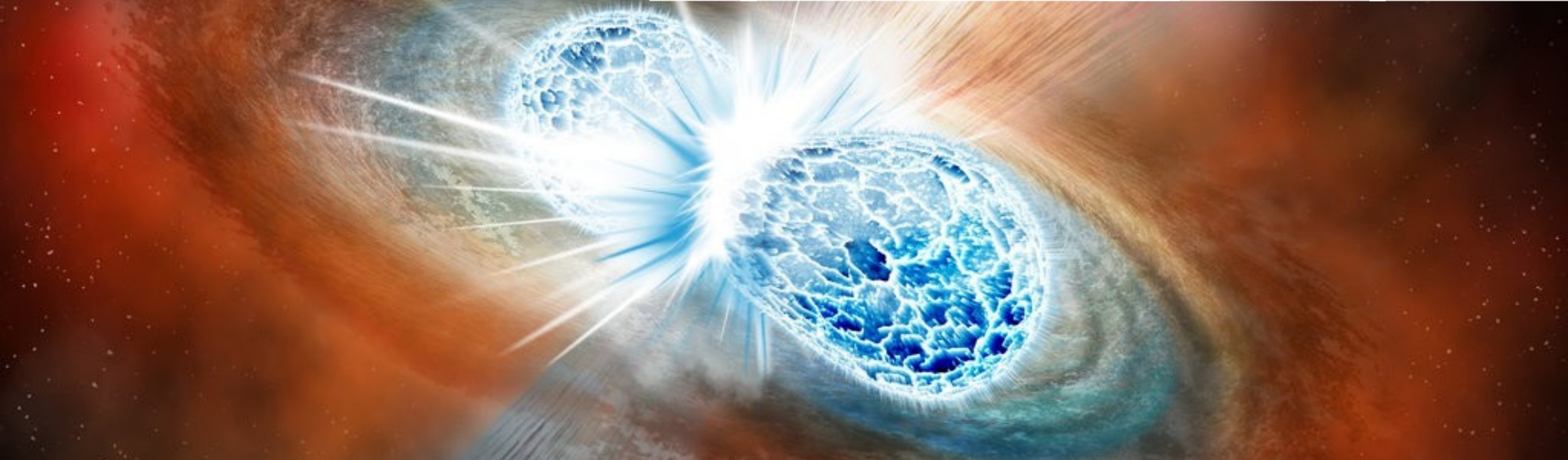


PART 3

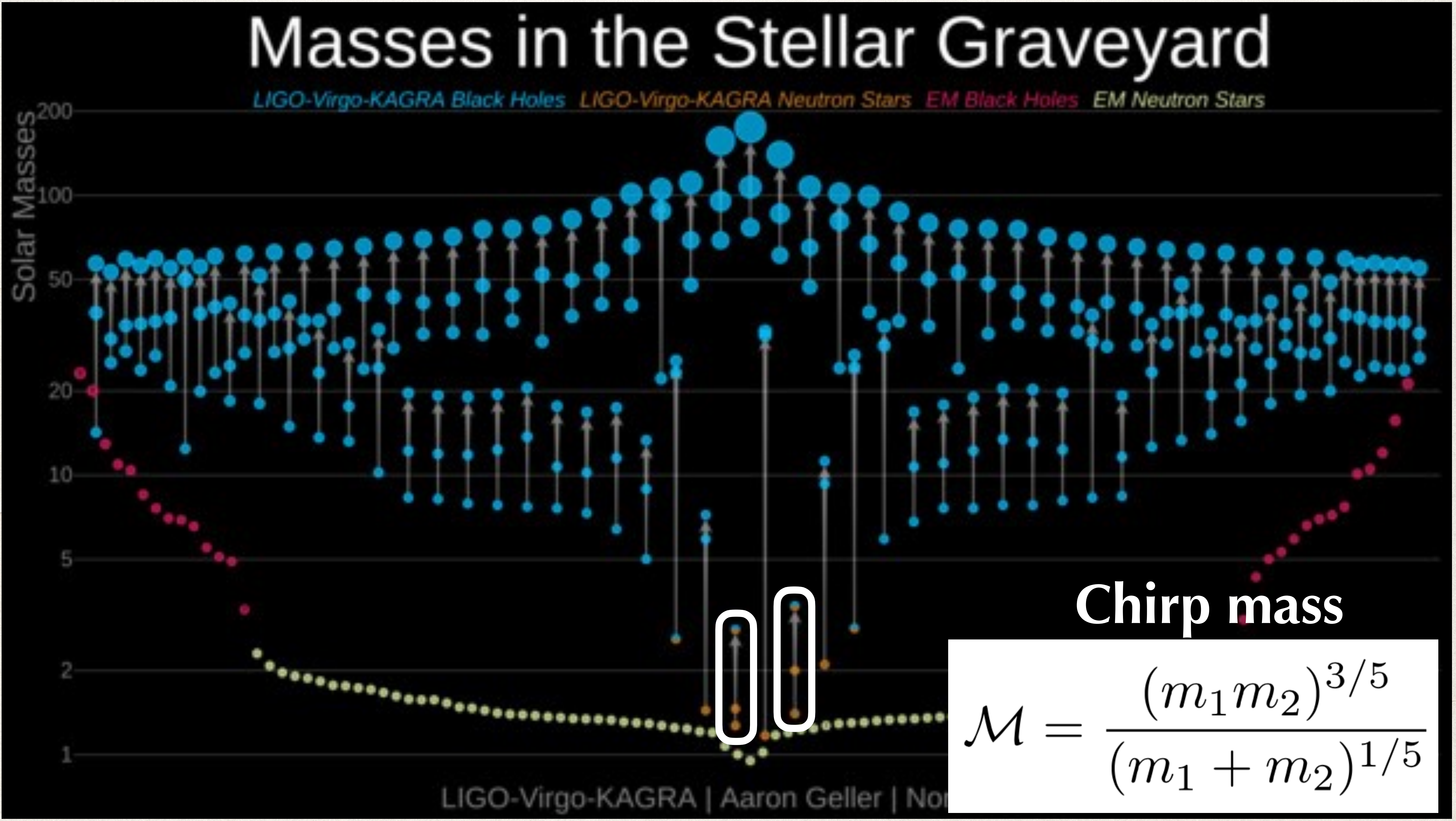
Measuring M_{NS} and R_{NS} with NS-NS mergers

GW 170817





Gravitation wave detections permit measuring the masses of the two merging objects.

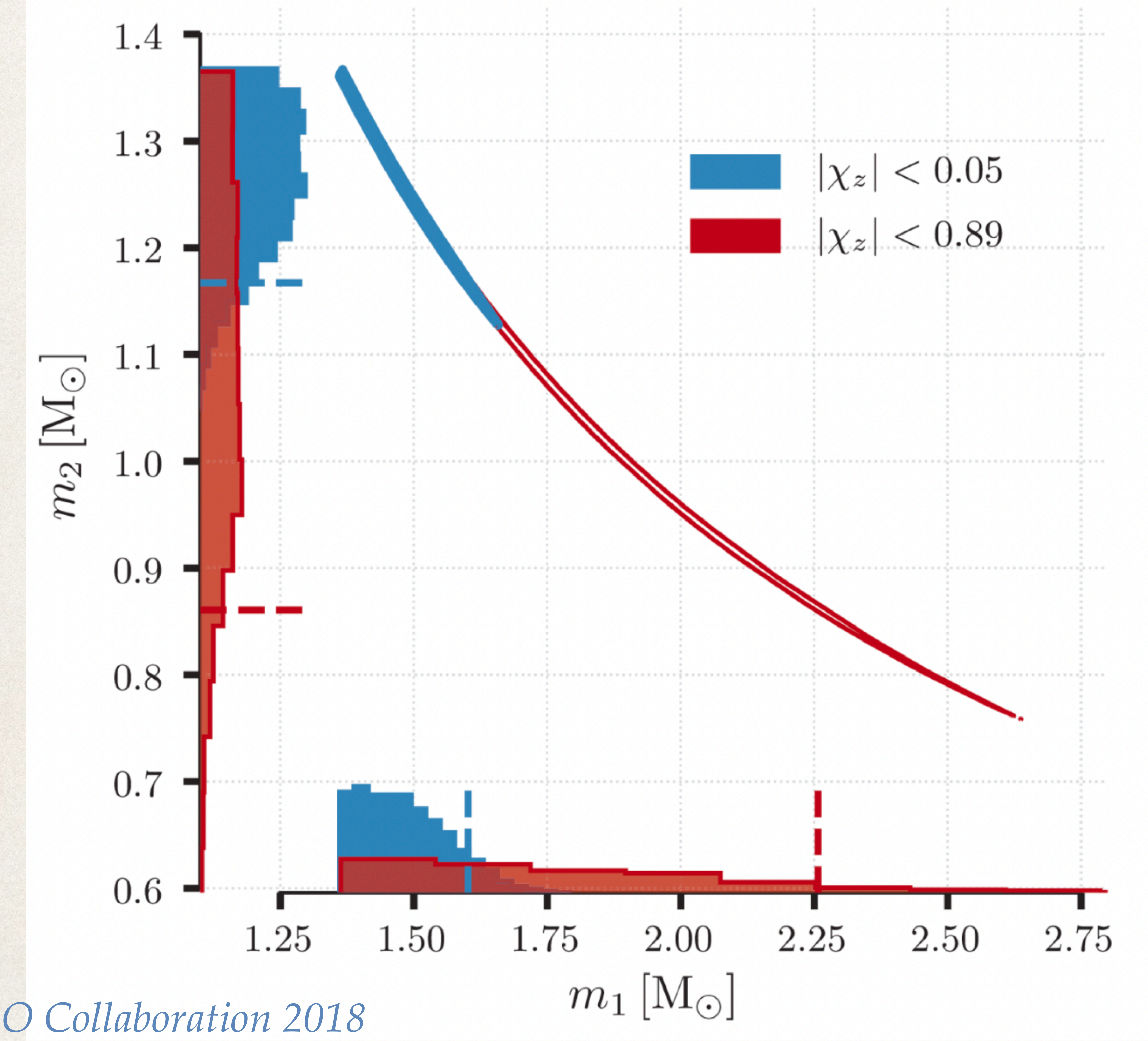


Chirp mass

$$\mathcal{M} = \frac{(m_1 m_2)^{3/5}}{(m_1 + m_2)^{1/5}}$$

LIGO Collaboration

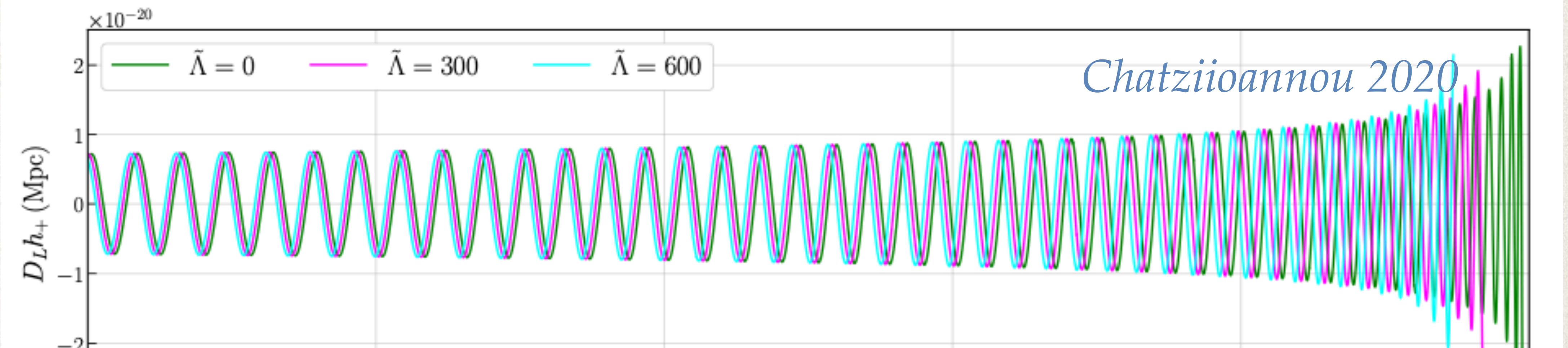
The chirp mass is measured from the gravitational wave signal of a compact objects merger.



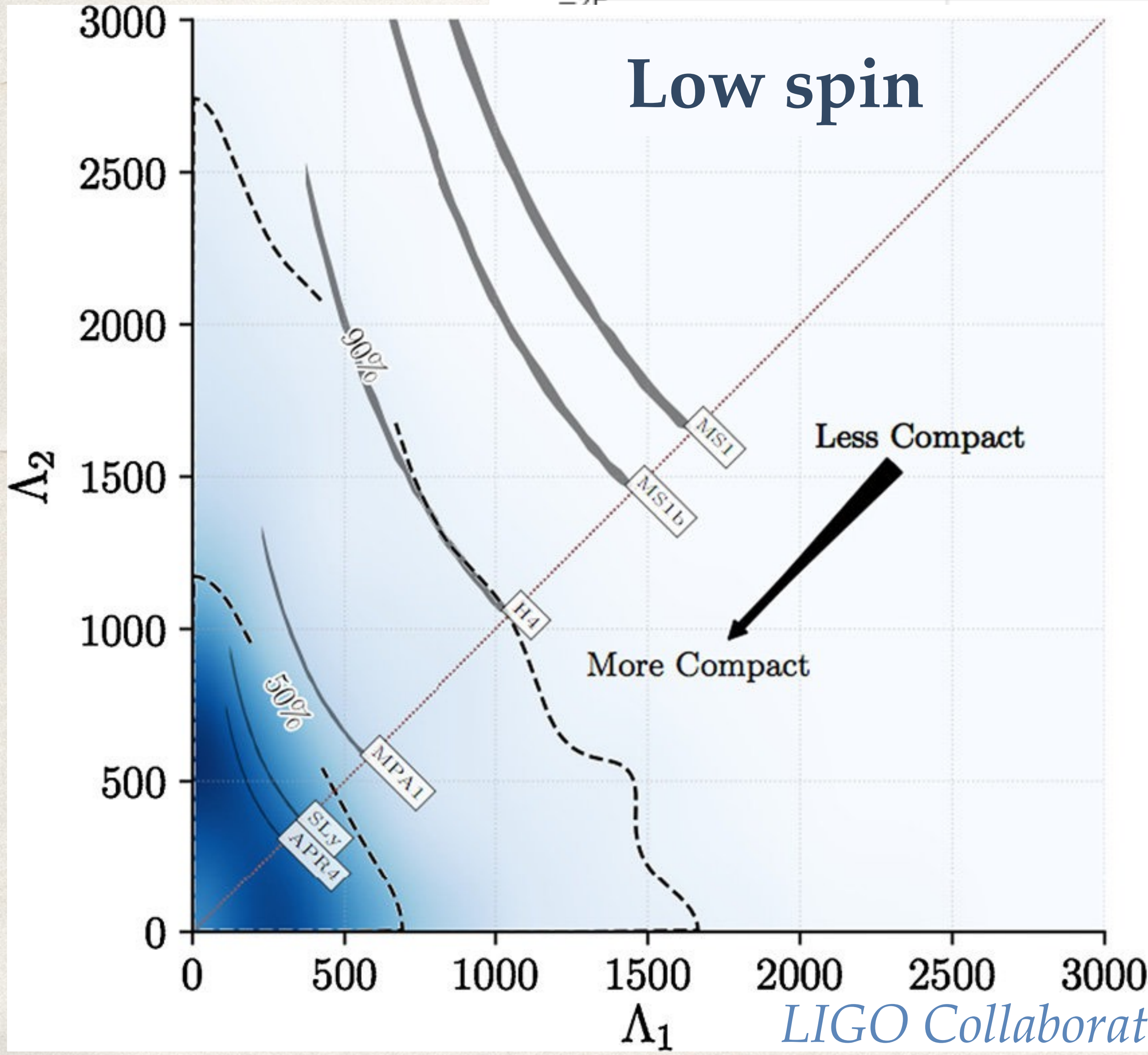
$$\mathcal{M} = \frac{(m_1 m_2)^{3/5}}{(m_1 + m_2)^{1/5}}$$

LIGO Collaboration 2018

In addition to the masses, the GW signals hides information about the tidal deformability.

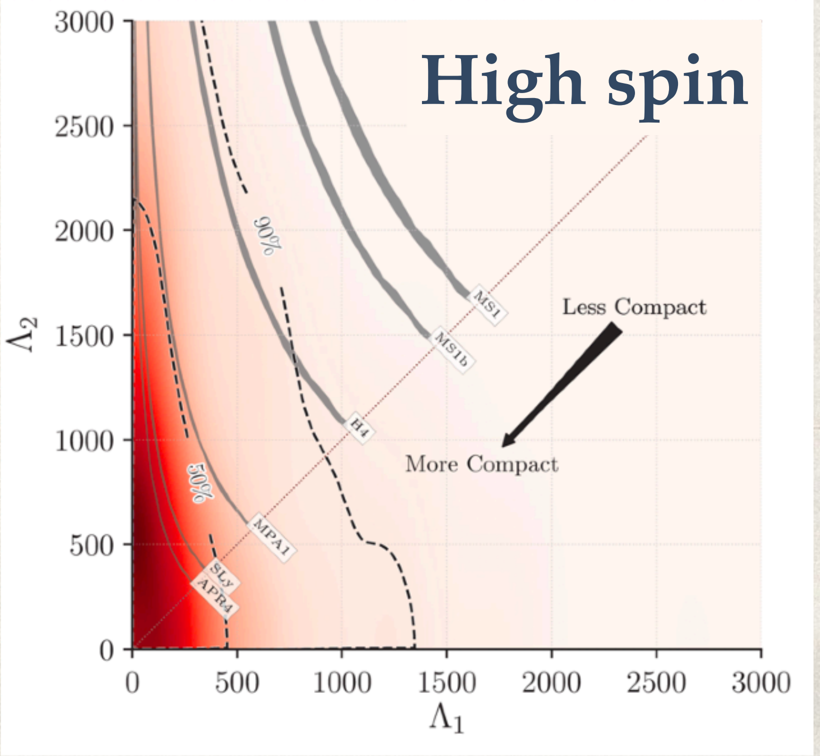


Chatziioannou 2020

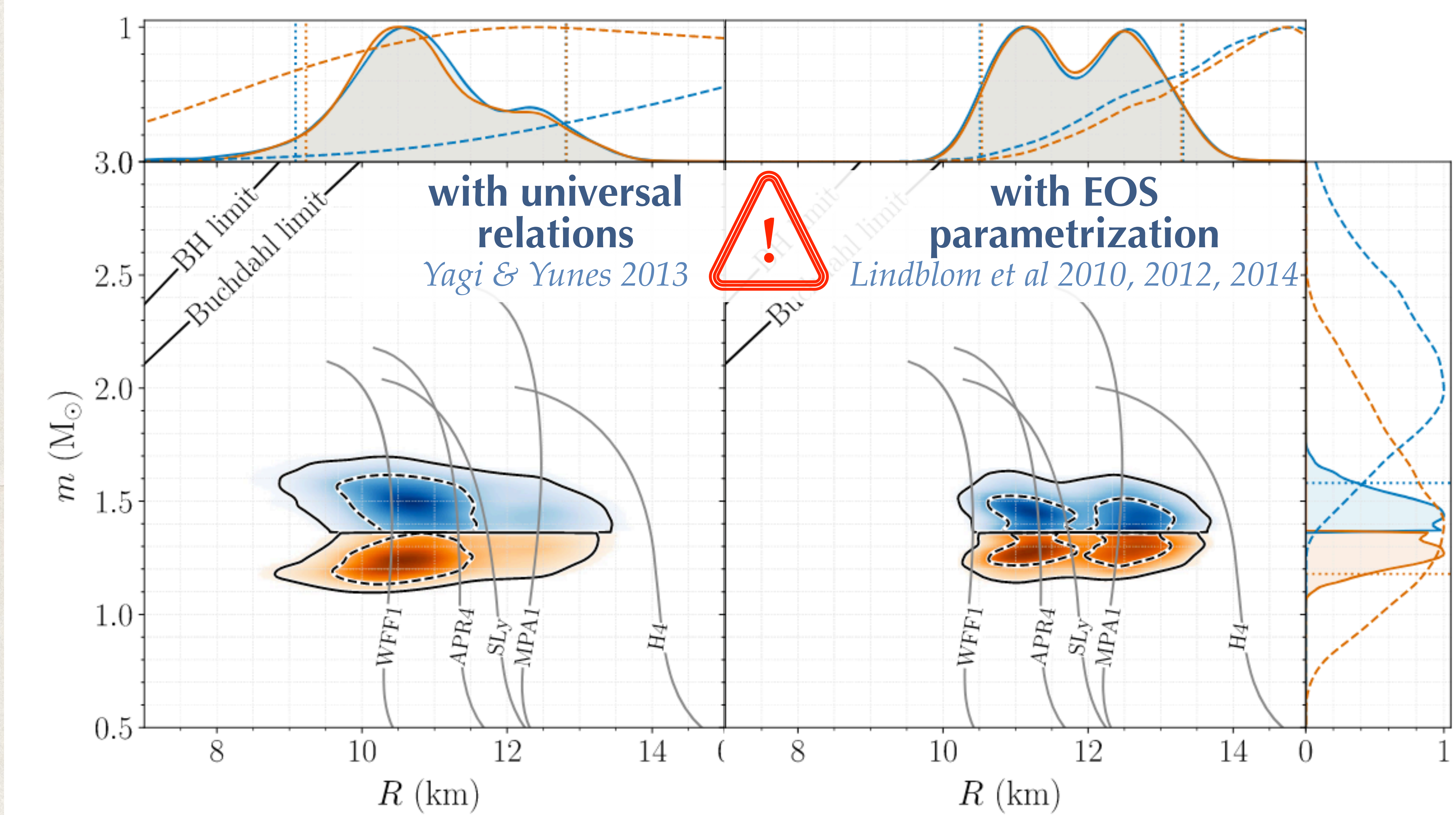

Low spin

LIGO Collaboration 2018

The pre-merger frequency increases faster for large $\tilde{\Lambda}$


High spin

The tidal deformability can results on constraints on the NS radius, but watch out…



with universal relations

Yagi & Yunes 2013

with EOS parametrization

Lindblom et al 2010, 2012, 2014

LIGO Collaboration 2018

The EM signal can also provide information on dense matter (together with the binary mass)

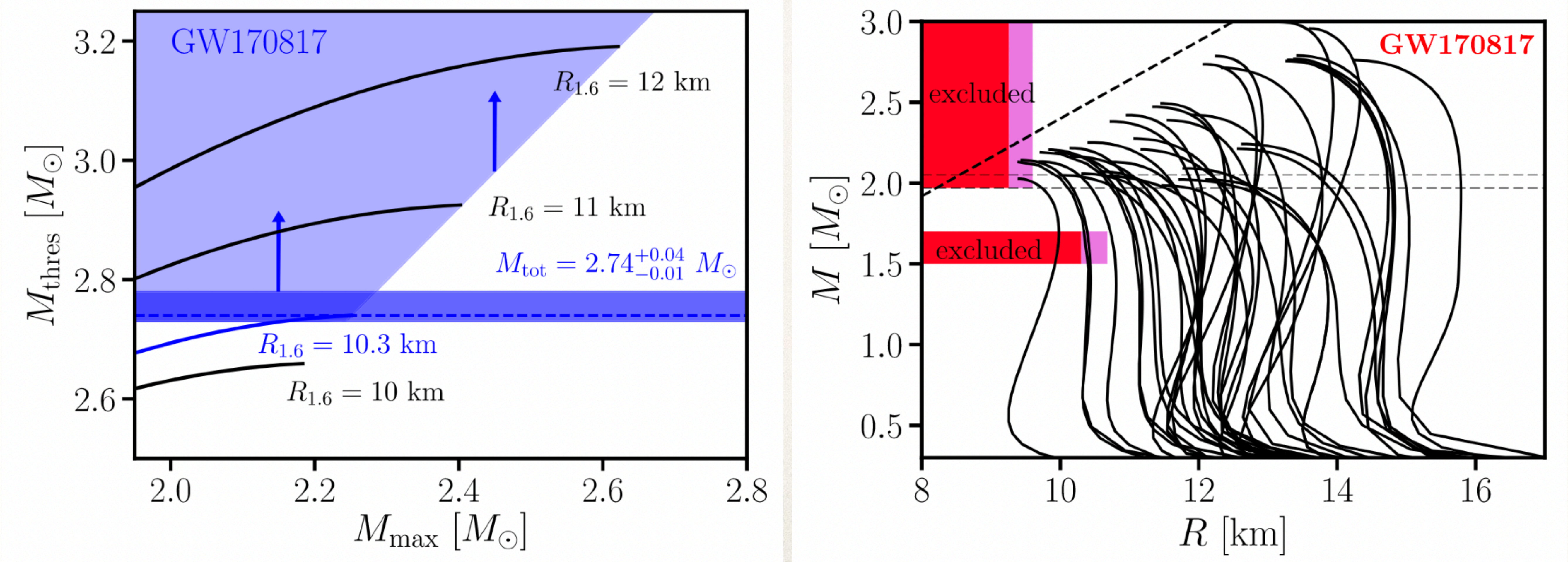
- Assumption: if EM emission —> delayed or no collapse
- Binary mass is a lower limit on M_{thres} for direct BH

$$M_{\rm thres} > M_{\rm tot}^{\rm GW170817} = 2.74^{+0.04}_{-0.01}\, M_\odot$$

Hydrodynamical simulations of mergers

$$M_{\rm thres} = \left(-3.606\frac{GM_{\rm max}}{c^2 R_{1.6}} + 2.38\right) \cdot M_{\rm max}$$

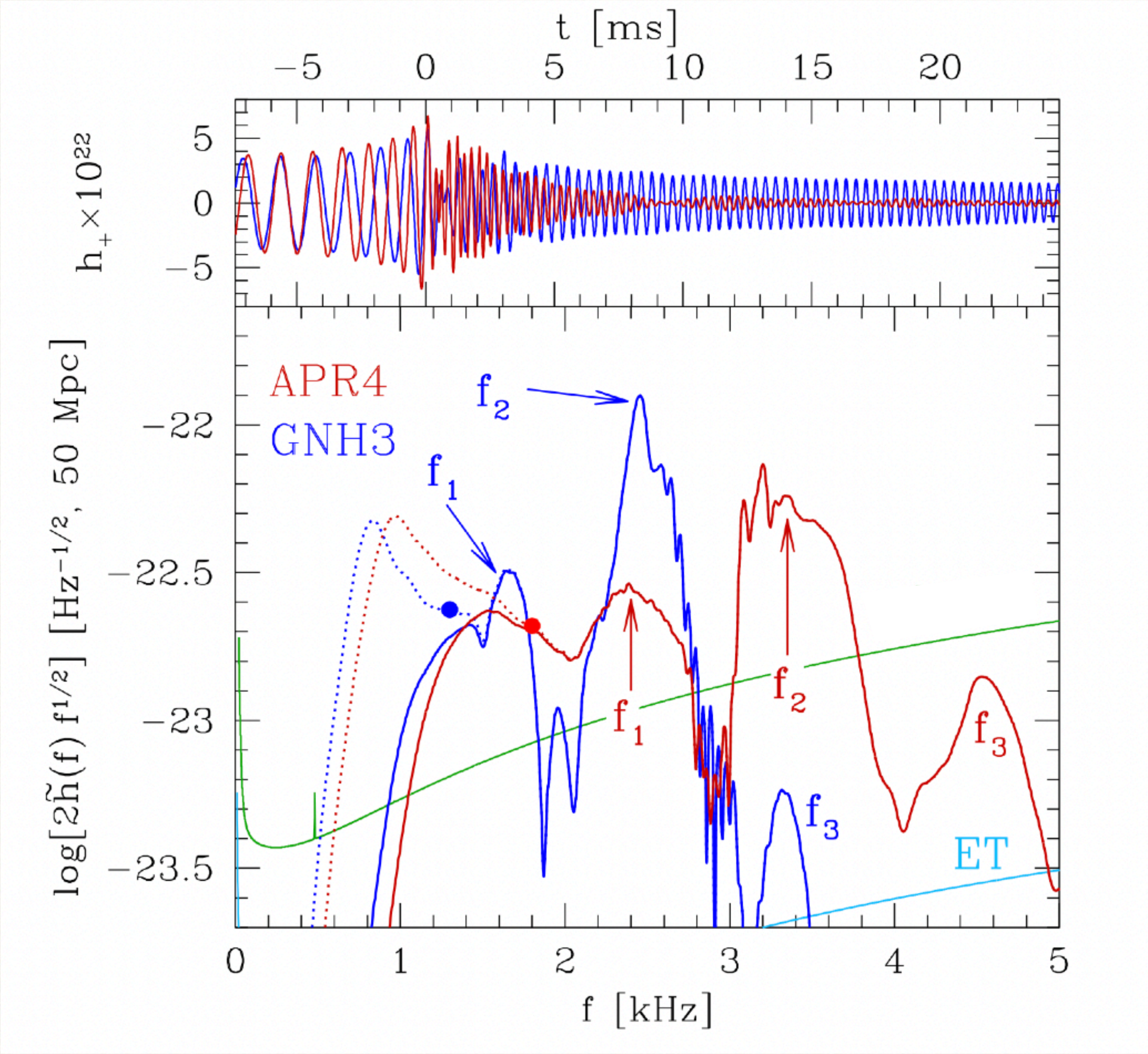
Bauswein et al. 2013



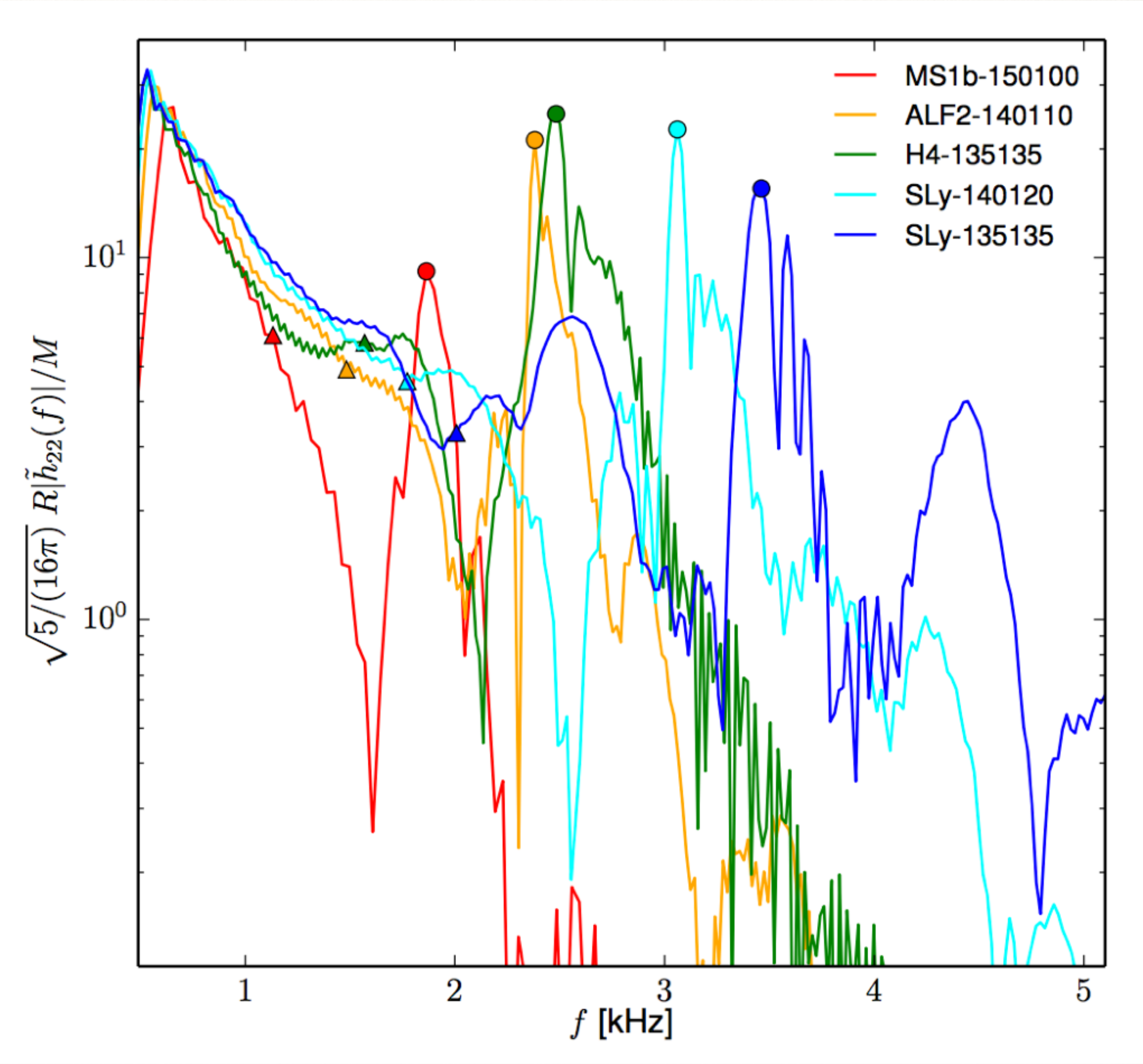
Bauswein et al. 2018

The post-merger GW signal of NS-NS mergers contains “more” info on dense matter.

GW frequency spectrum and equation of state



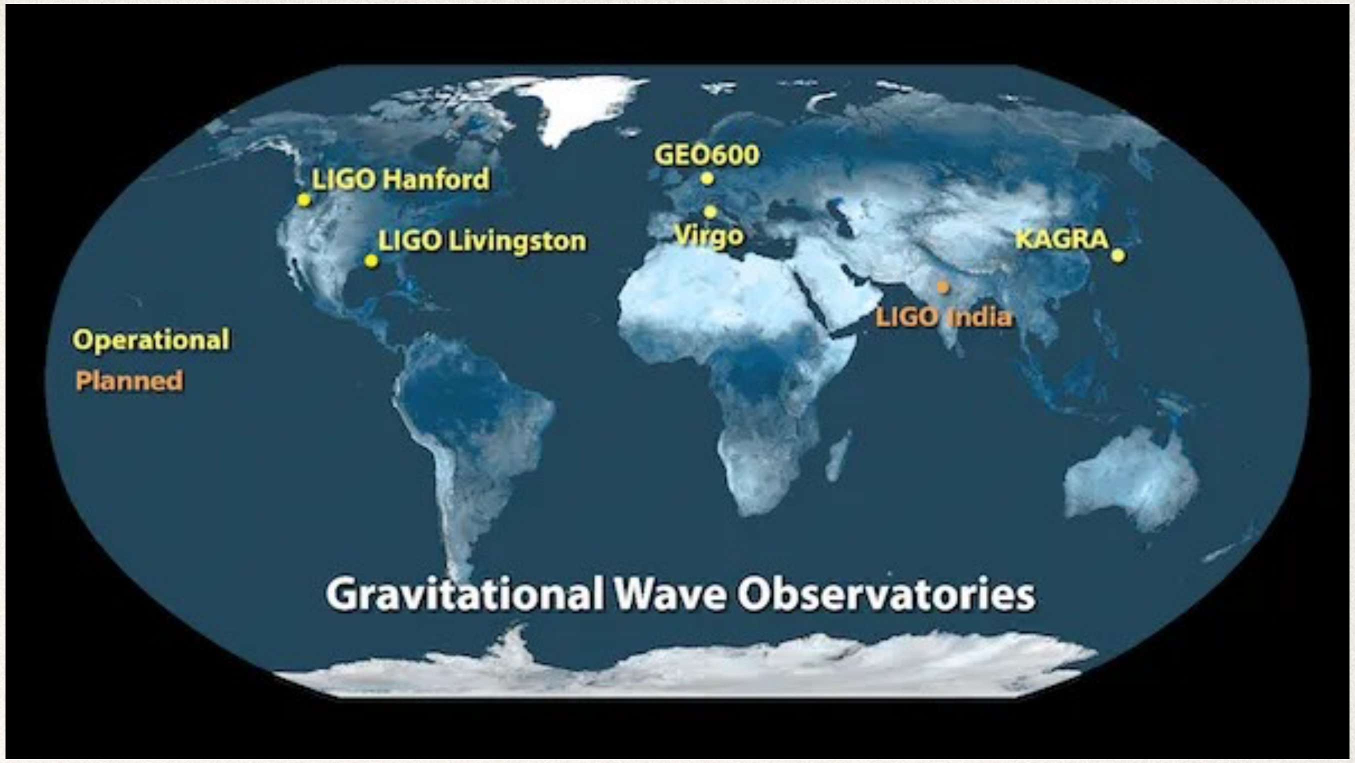
Takami et al. 2014

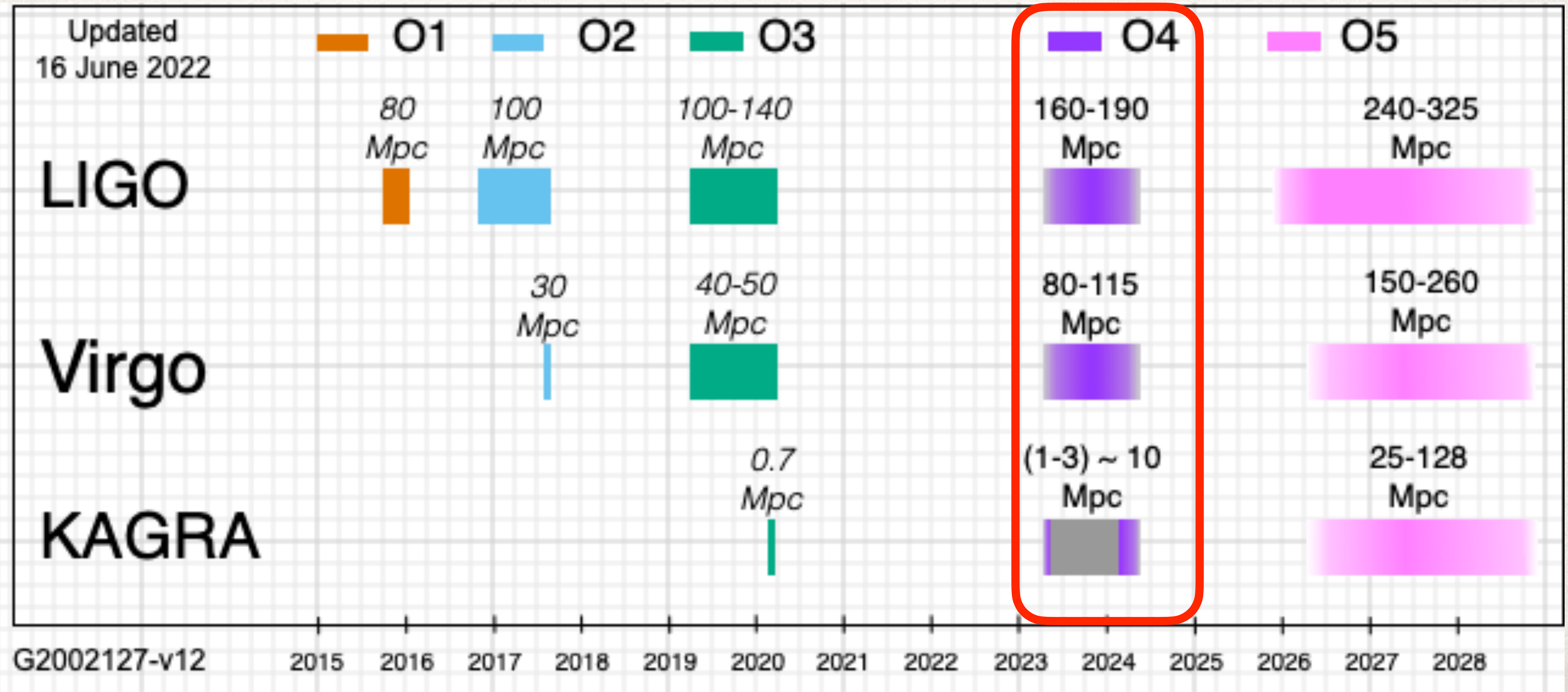


Bernuzzi et al. 2015

Part 3 – conclusion

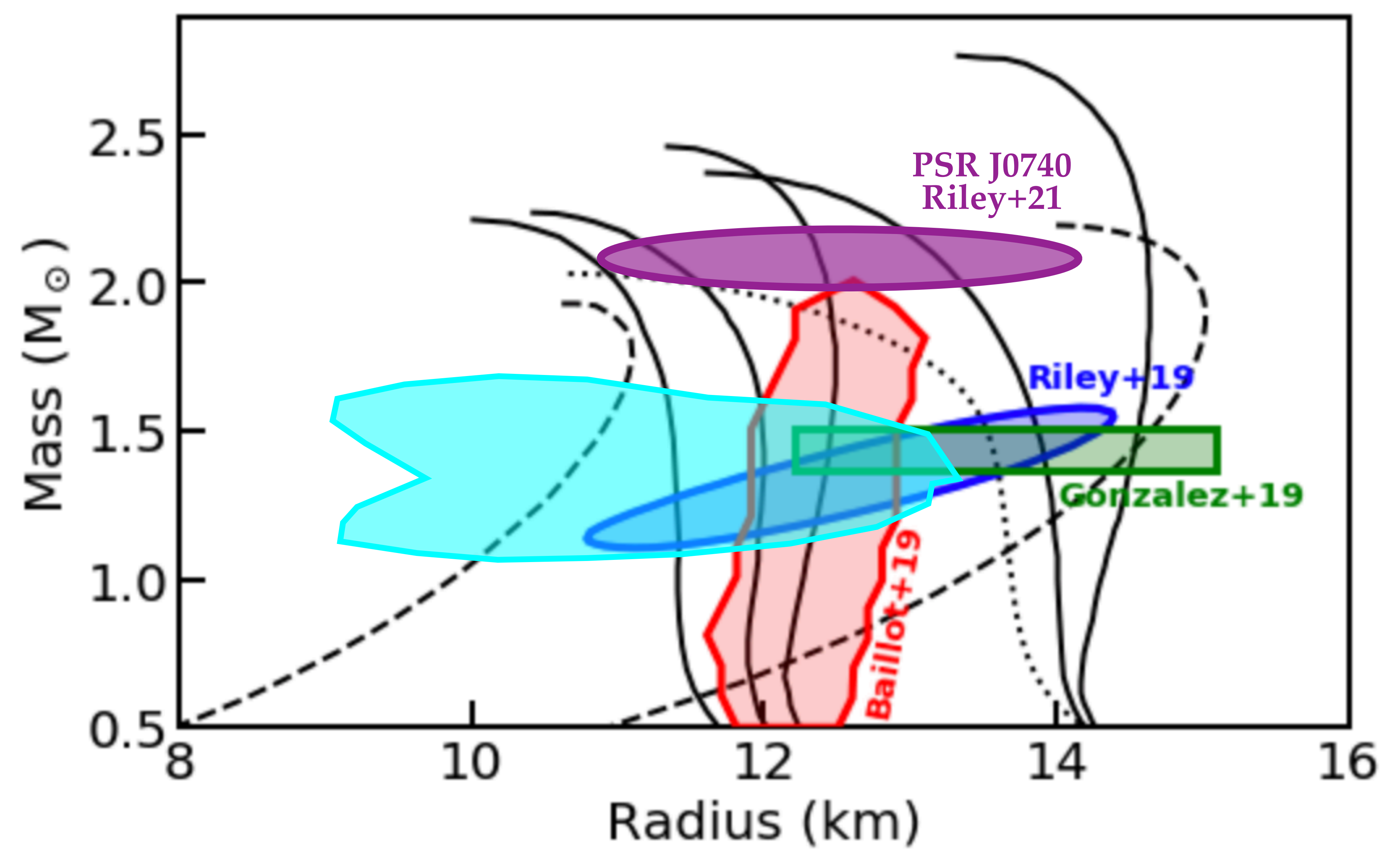
Future NS-NS mergers will give us a new way to study dense matter



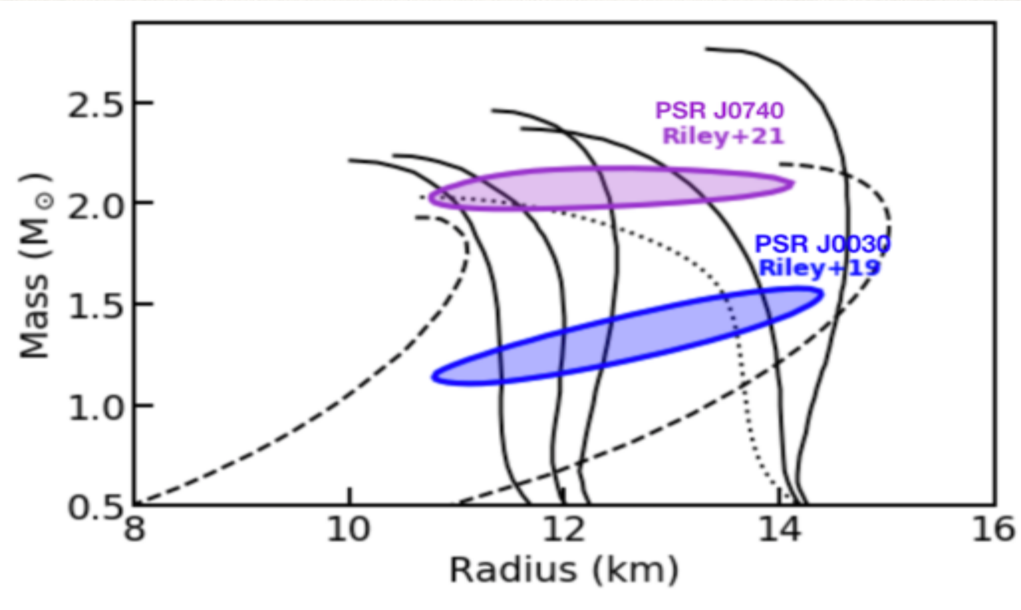


PART 4

Combining observations to understand dense matter



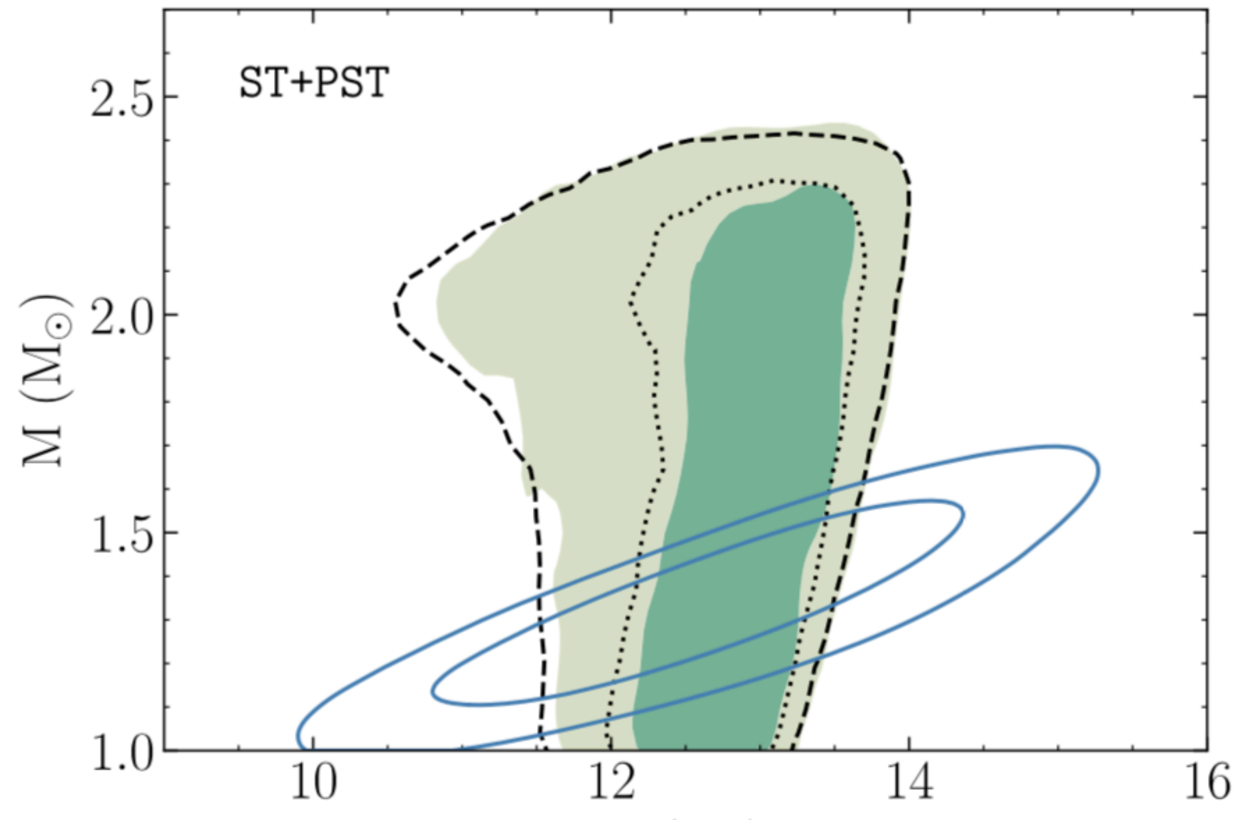
The NICER results for these two pulsars bring some additional constraints on equation of state models.



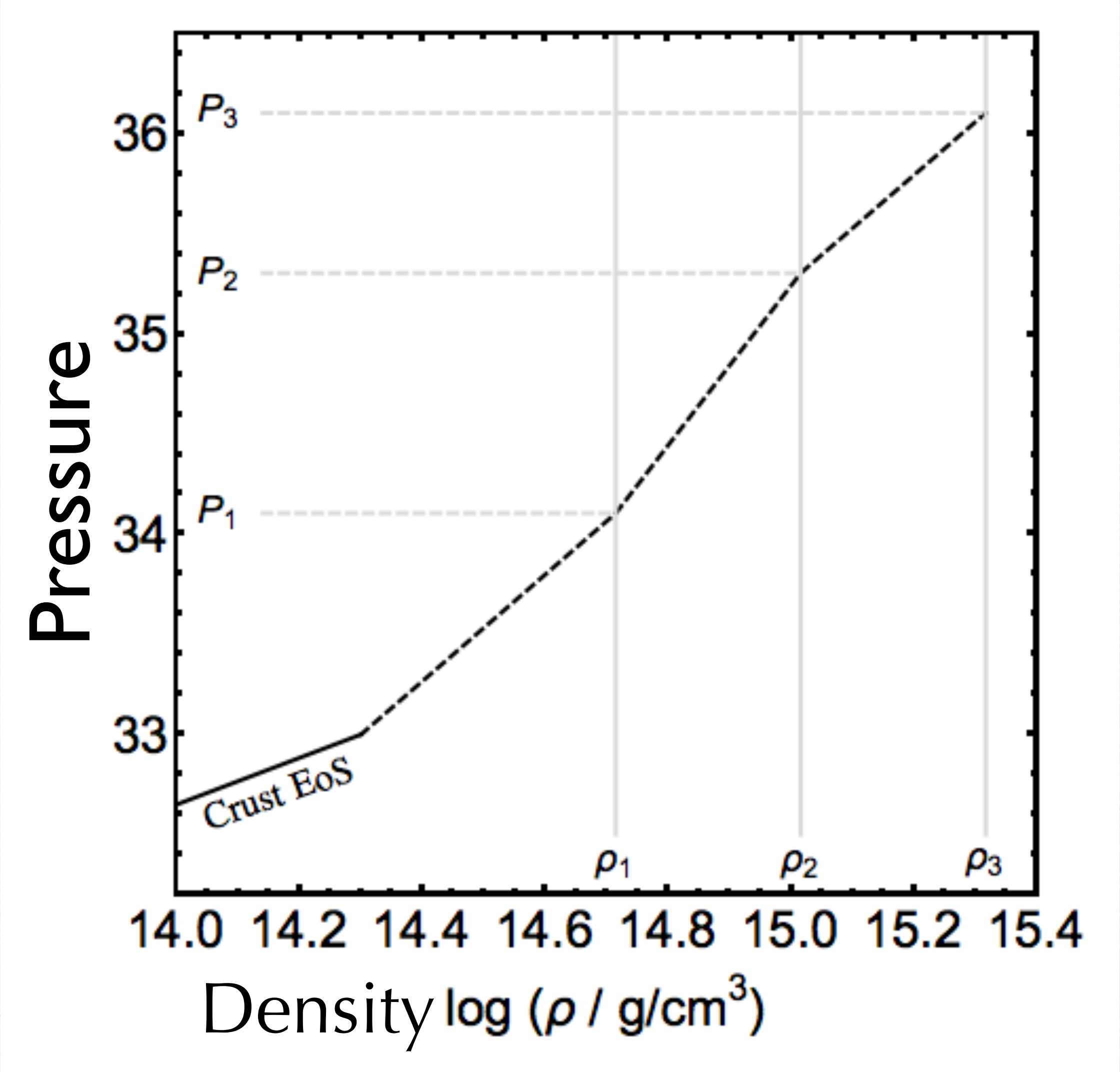
PSR J0030+0451 brings little additional information on EoSs parametrization (polytropes)

┈┈┈ **Nucl. Phys. + GW170817**

🟩 **+ PSR J0030**



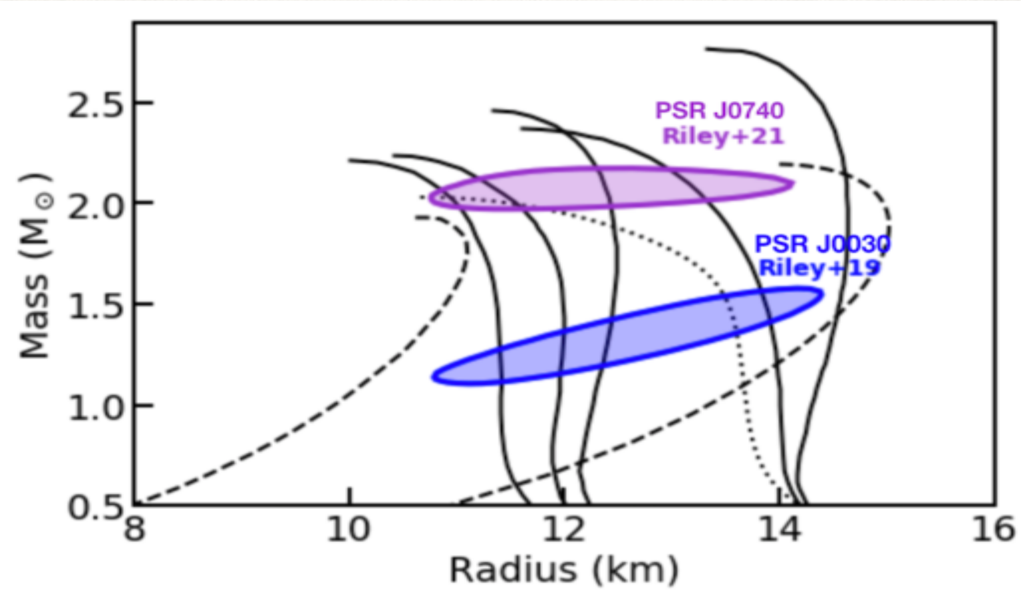
Raaijmakers et al. (2019)



Piecewise polytropes

Read et al. 2009
Özel et al. 2016

The NICER results for these two pulsars bring some additional constraints on equation of state models.



<u>PSR J0030+0451</u> brings little additional information on EoSs parametrization (polytropes)

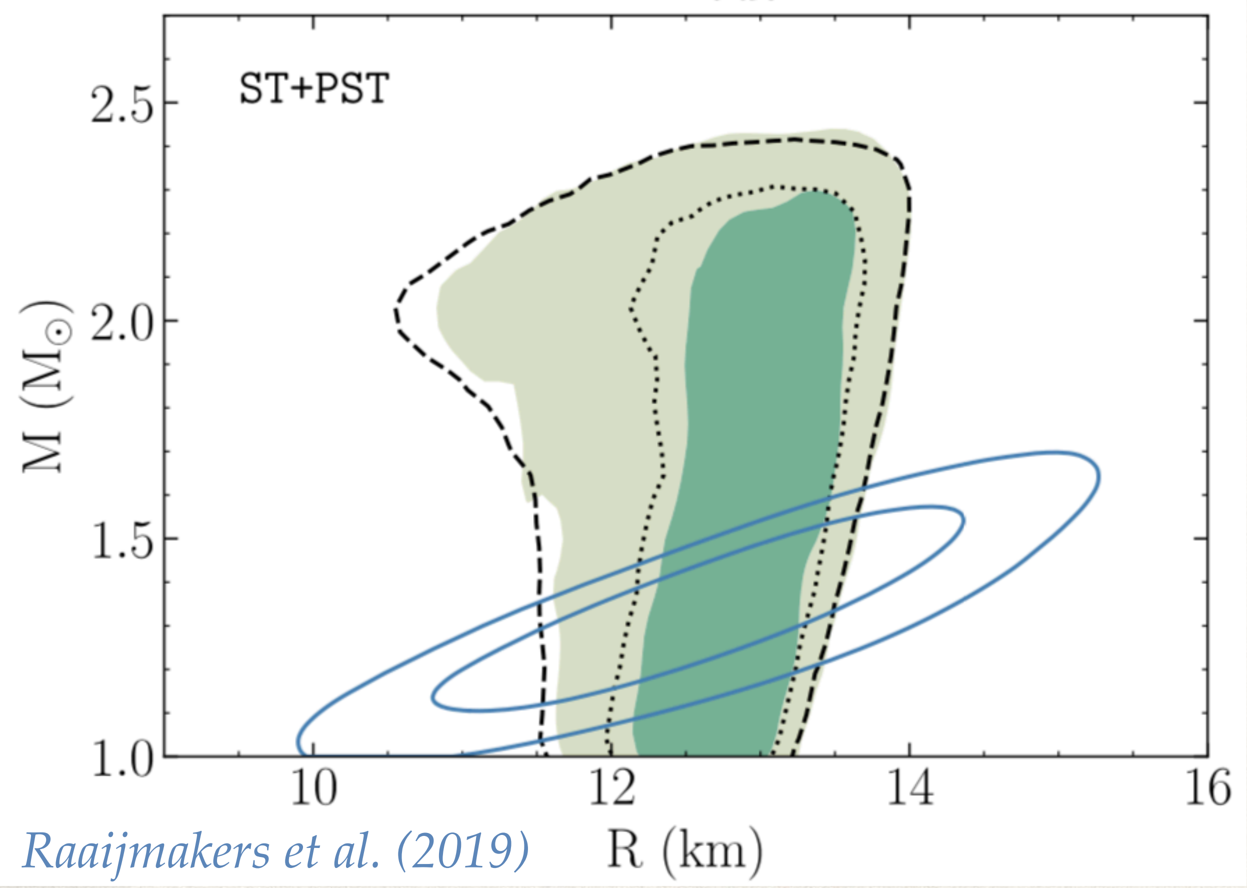
<u>PSR J0740+6620</u> adds some improvement on the EoSs models, thanks to its high mass.

⋯⋯ **Nucl. Phys. + GW170817**

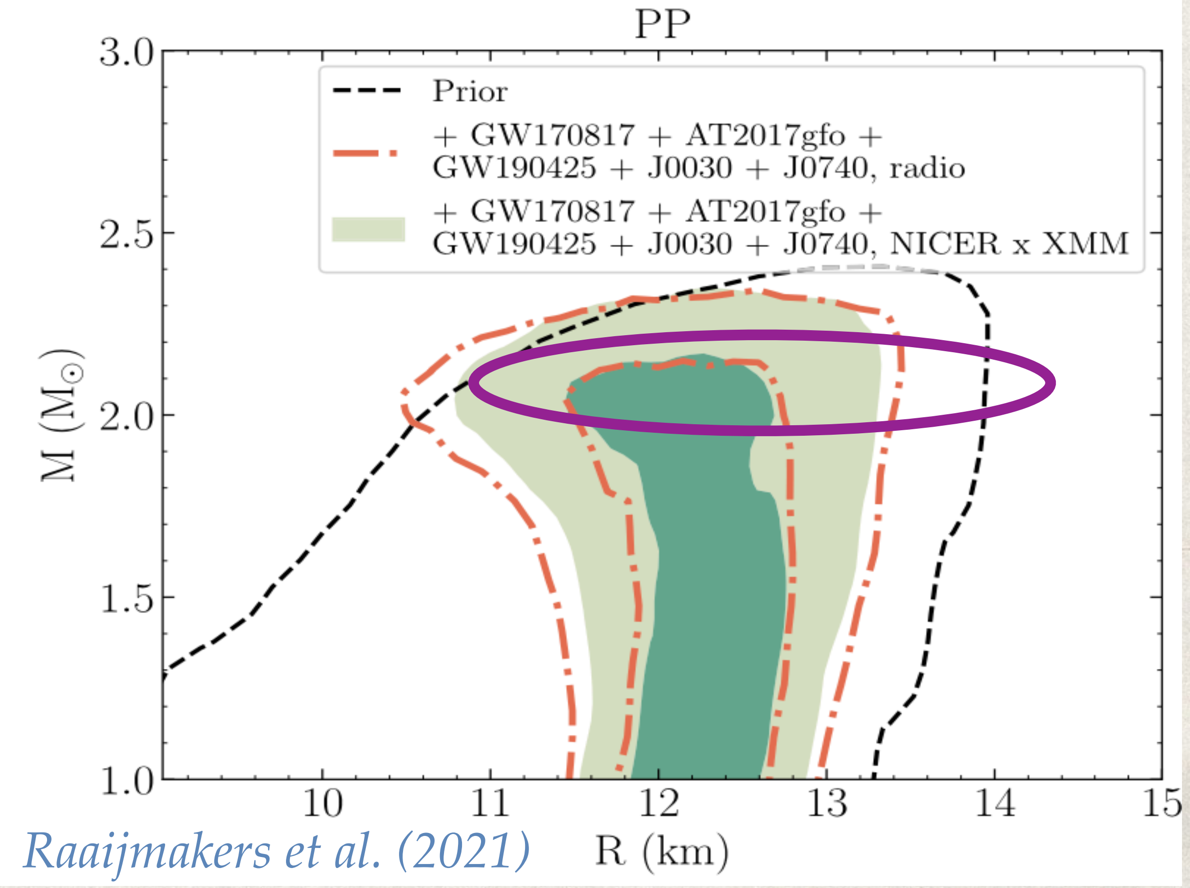
🟩 **+ PSR J0030**

- - - **+ mass of PSR J0740**

🟩 **+ PSR J0740**



Raaijmakers et al. (2019)



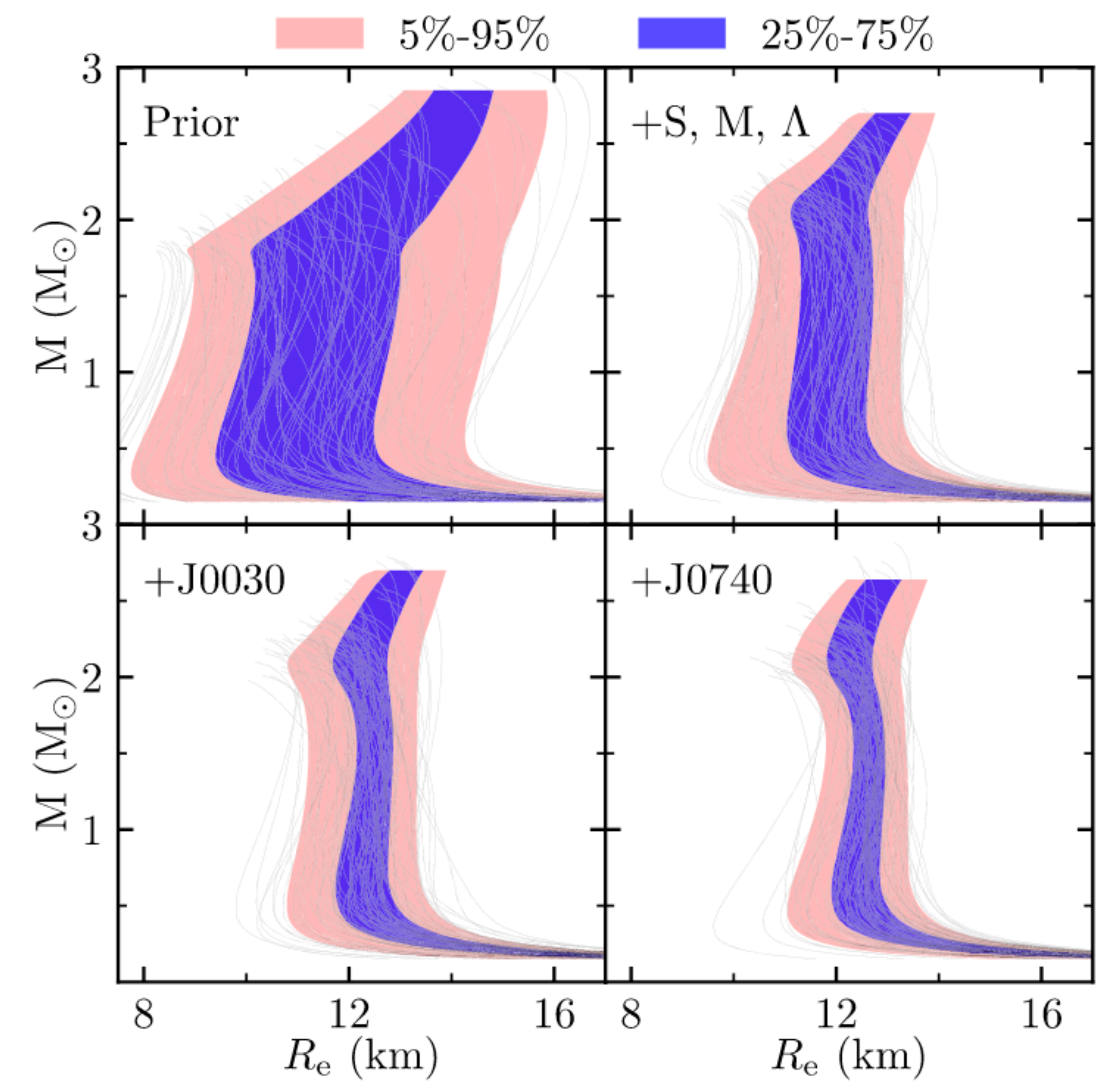
Raaijmakers et al. (2021)

Different approaches use different ways to model the equation of state.

Miller et al. (2019)

Gaussian processes approach for EOS modelling

Landry & Essick (2019)



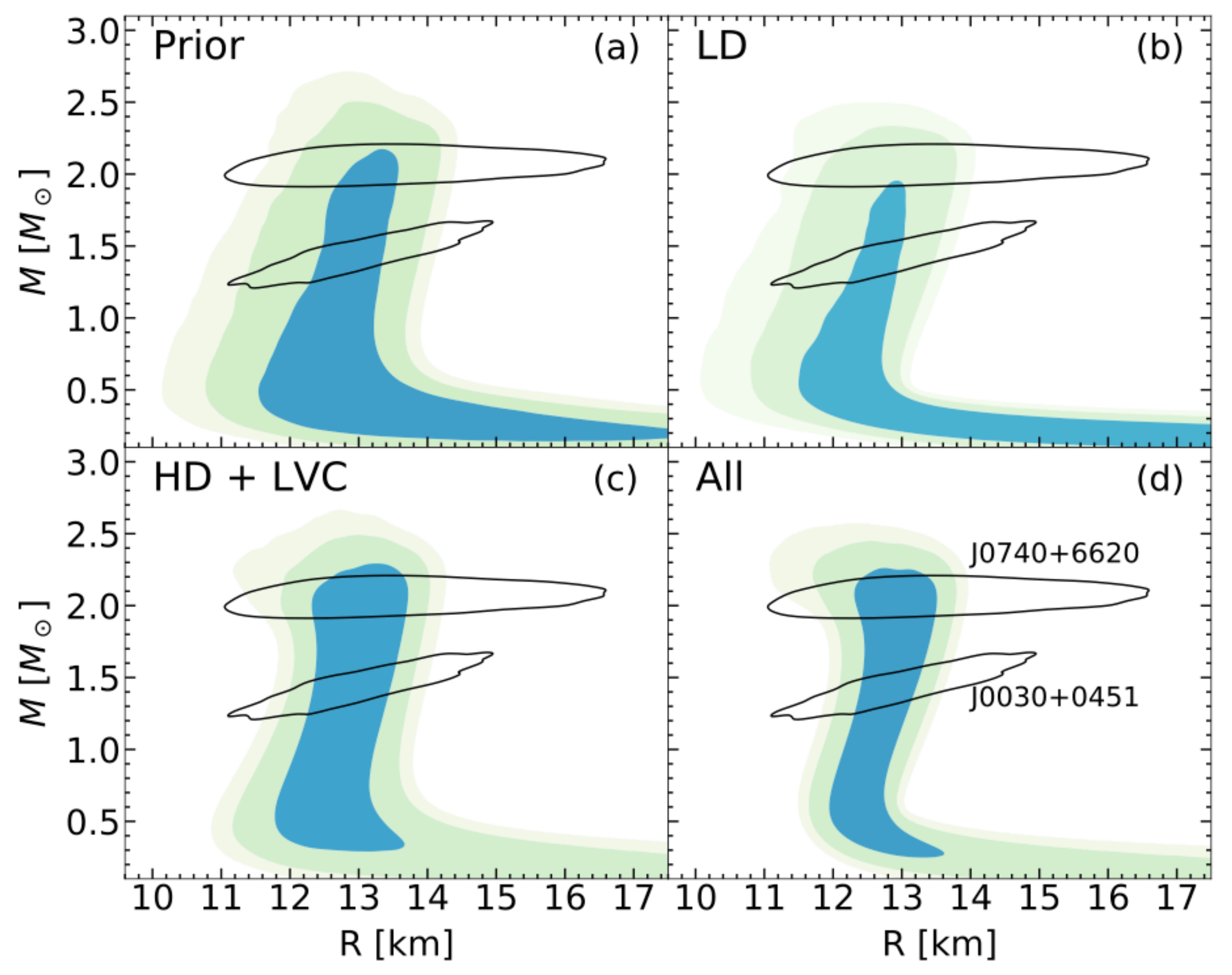
Different approaches use different ways to model the equation of state.

Dinh Thi et al. (2021)

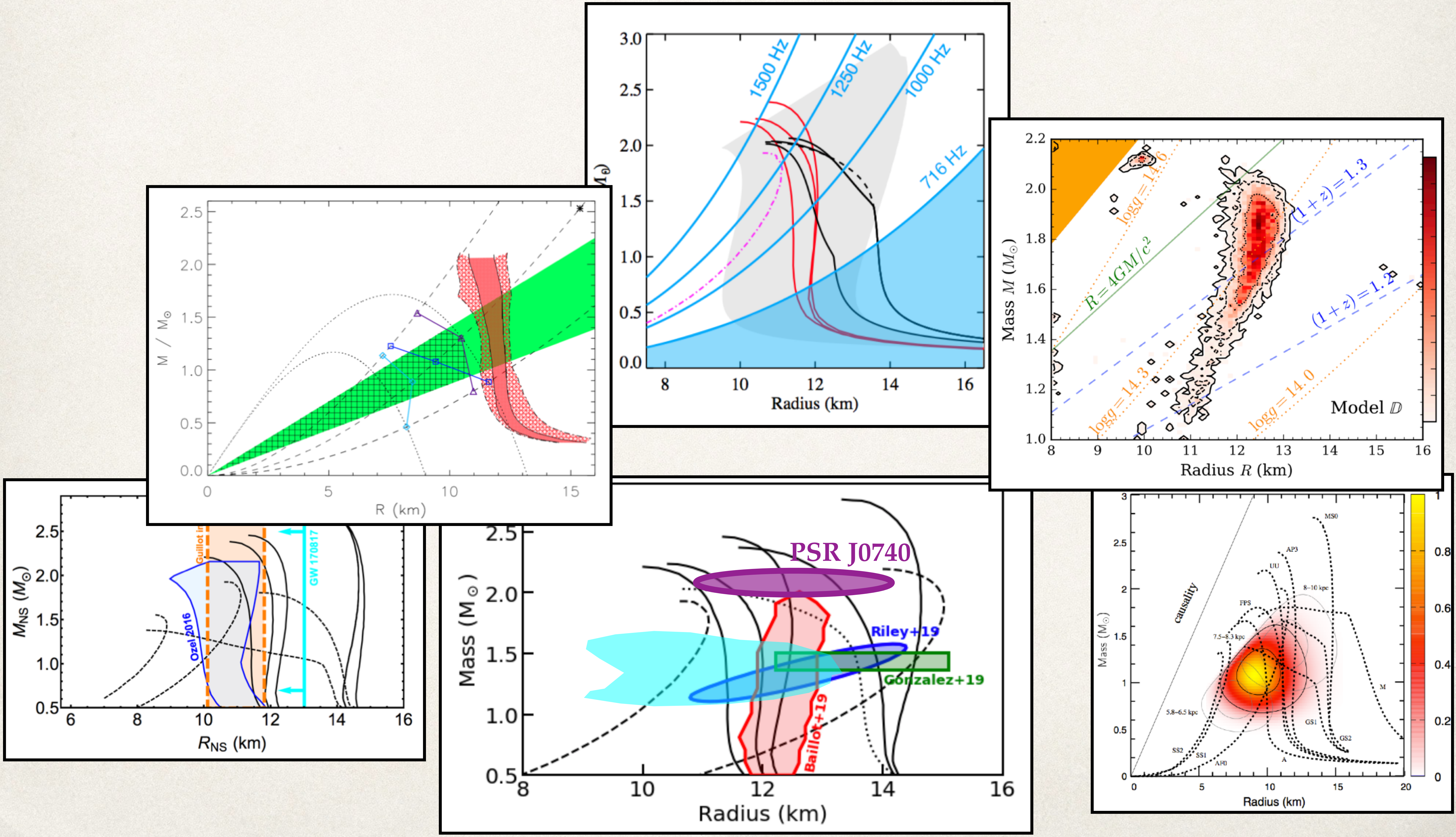
Meta-modelling of the EOS

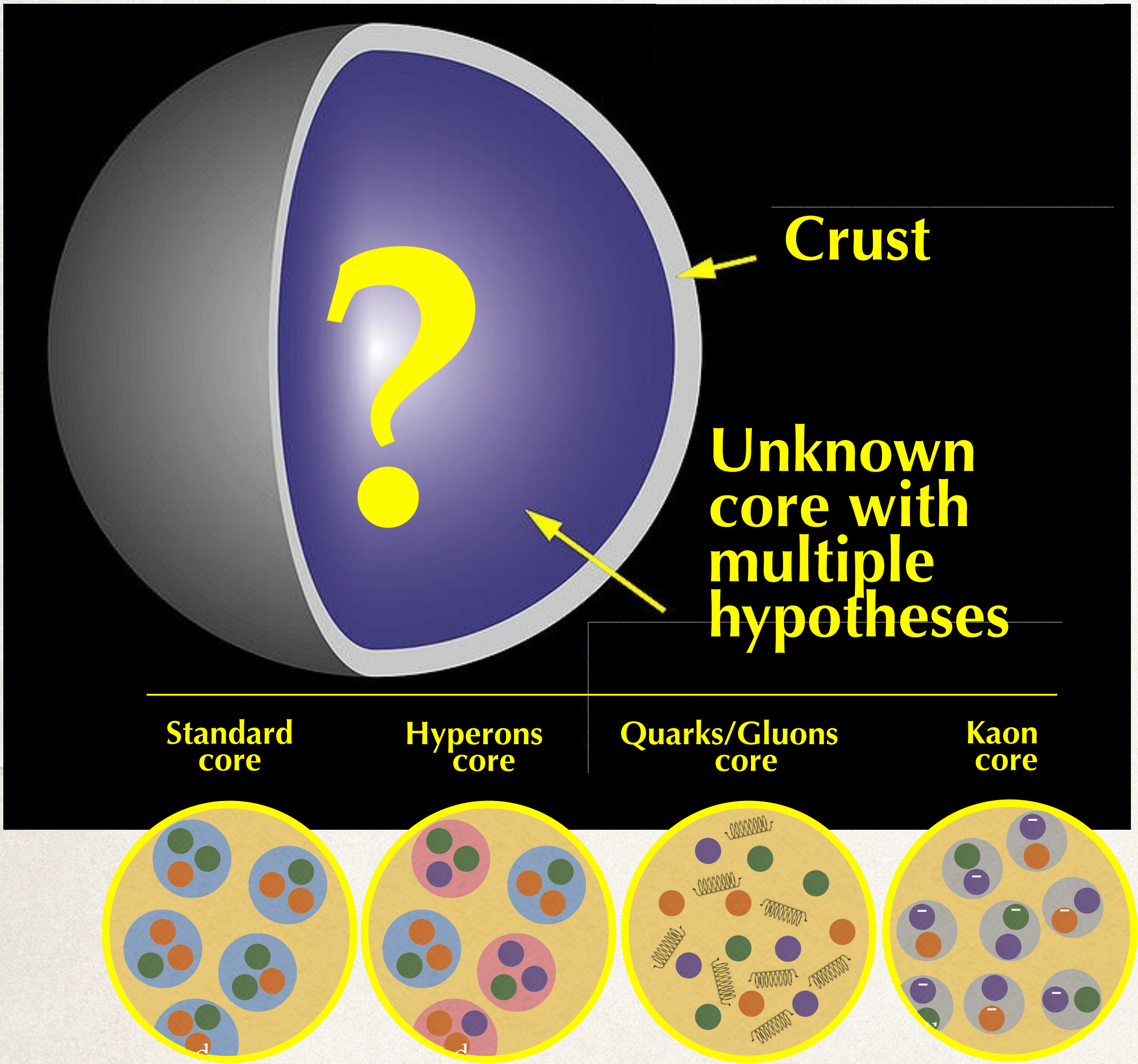
Margueron et al. (2018)

Taylor expansion of the energy density around the saturation density



There are several other methods to measure M_{NS}, R_{NS}, or Λ_{NS}, and still a long way to determine the EoS of dense matter.





Crust

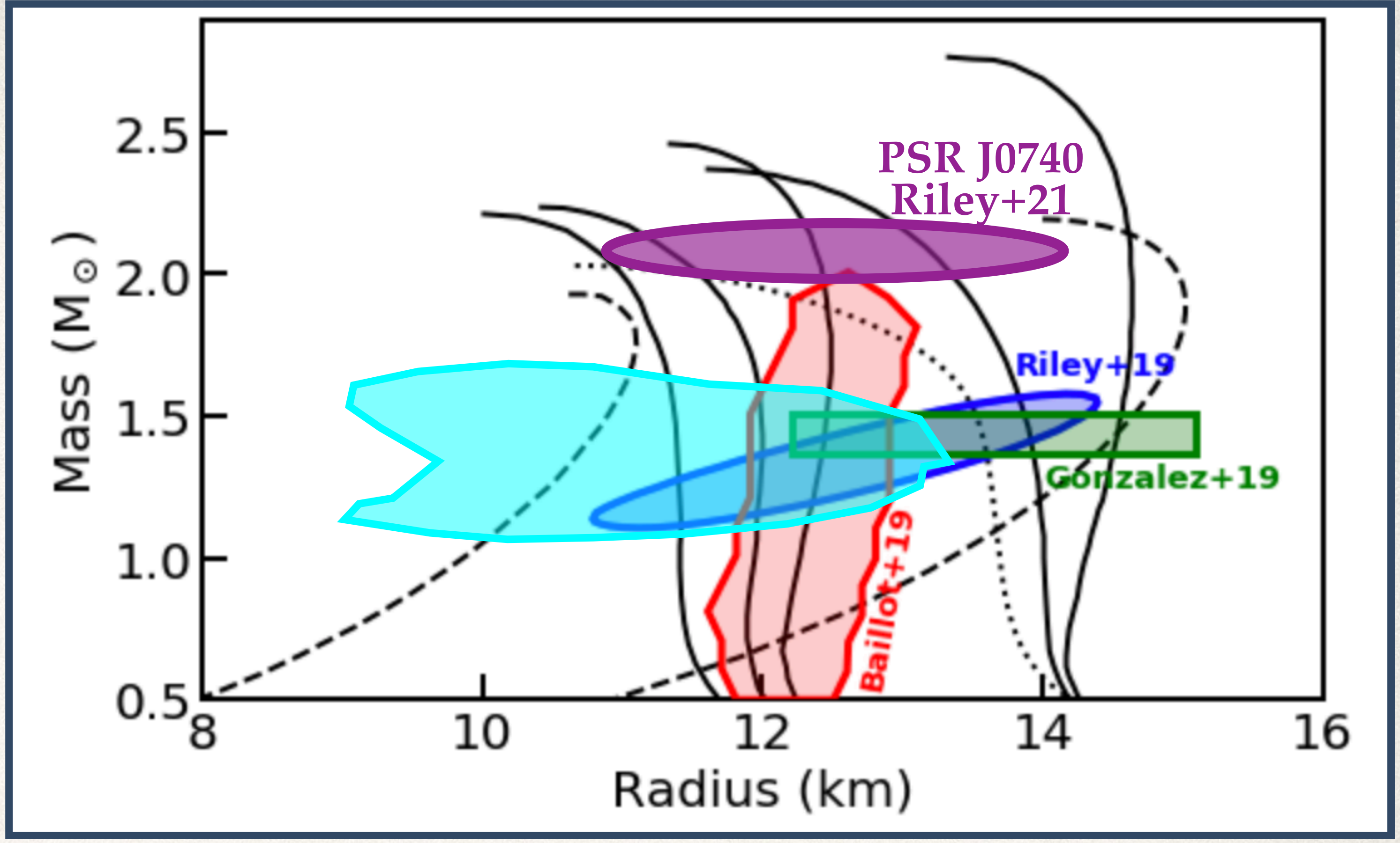
Unknown core with multiple hypotheses

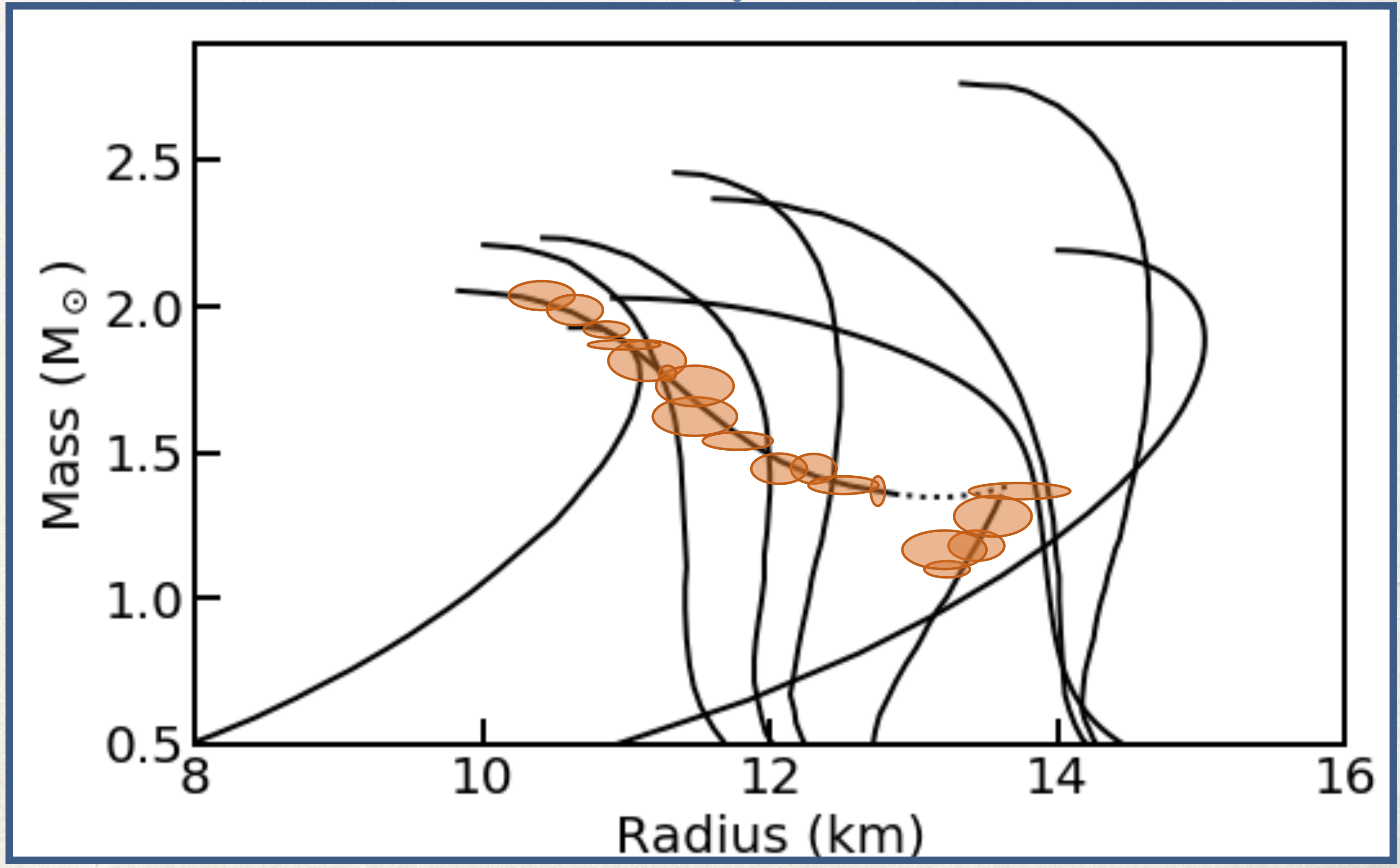
Standard core

Hyperons core

Quarks/Gluons core

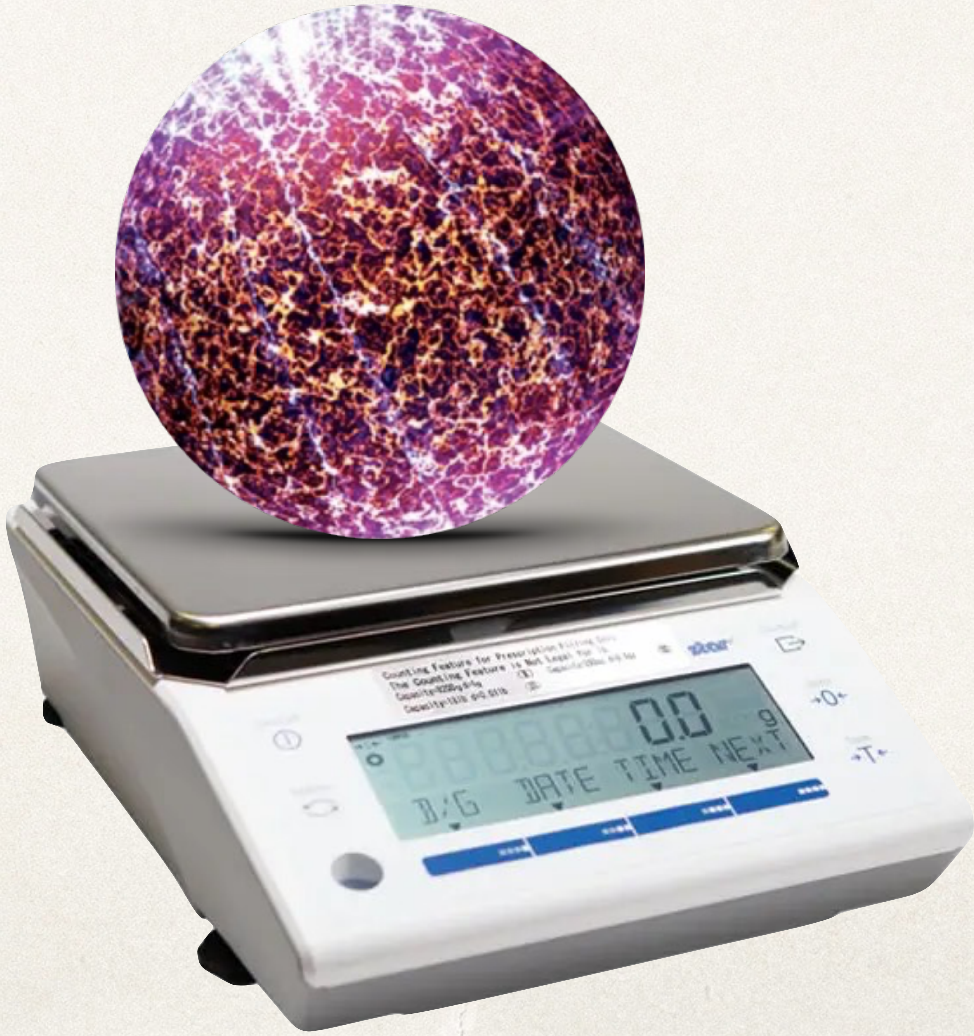
Kaon core



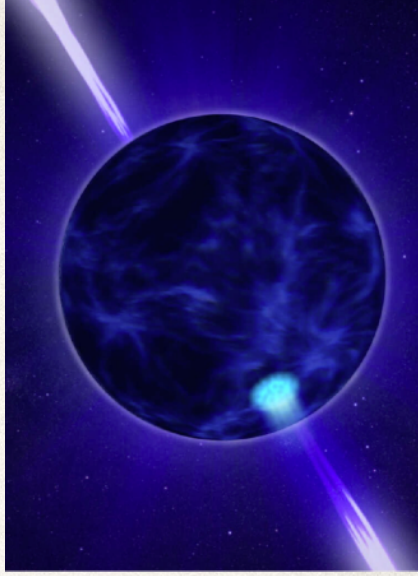


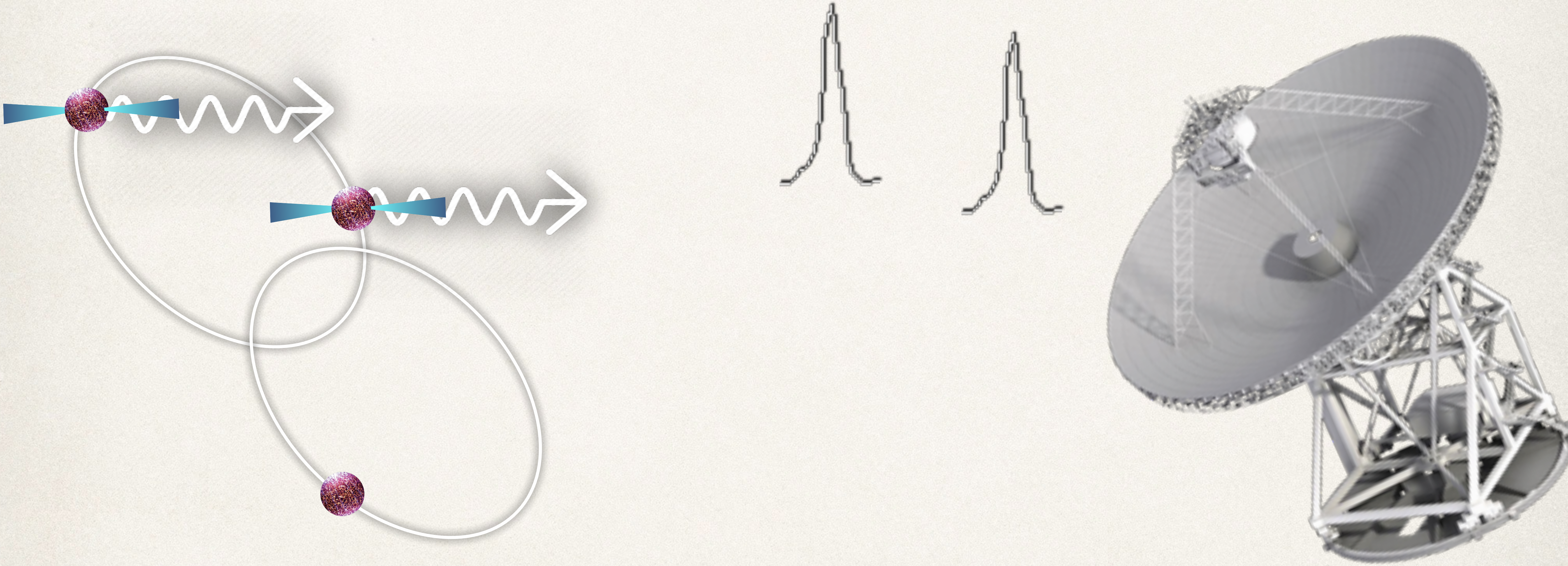
PART 5

Measuring neutron star masses



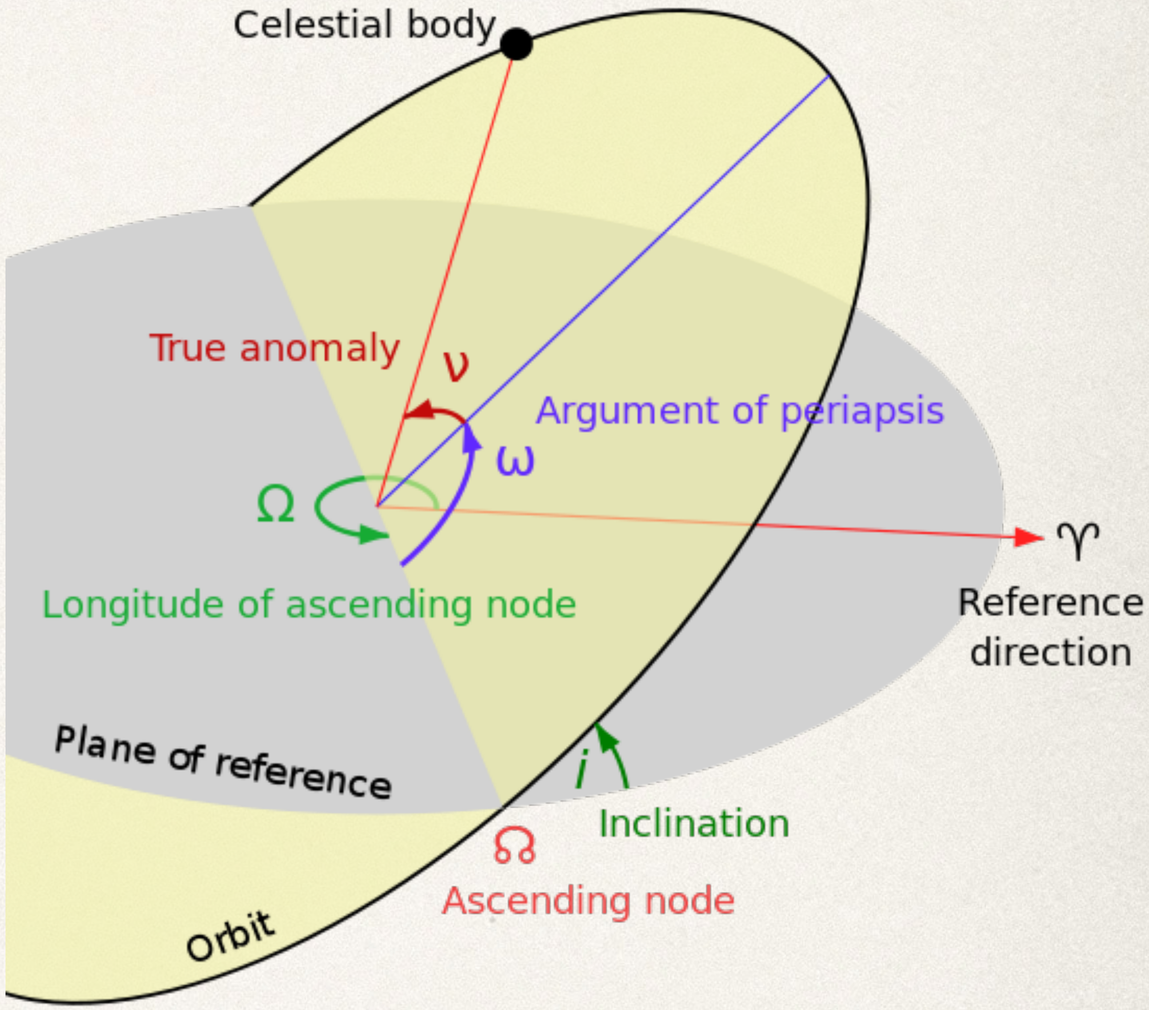
Radio timing of pulsars in binary systems permits measurements of orbital parameters.





The orbital parameters give us some information, but not all!

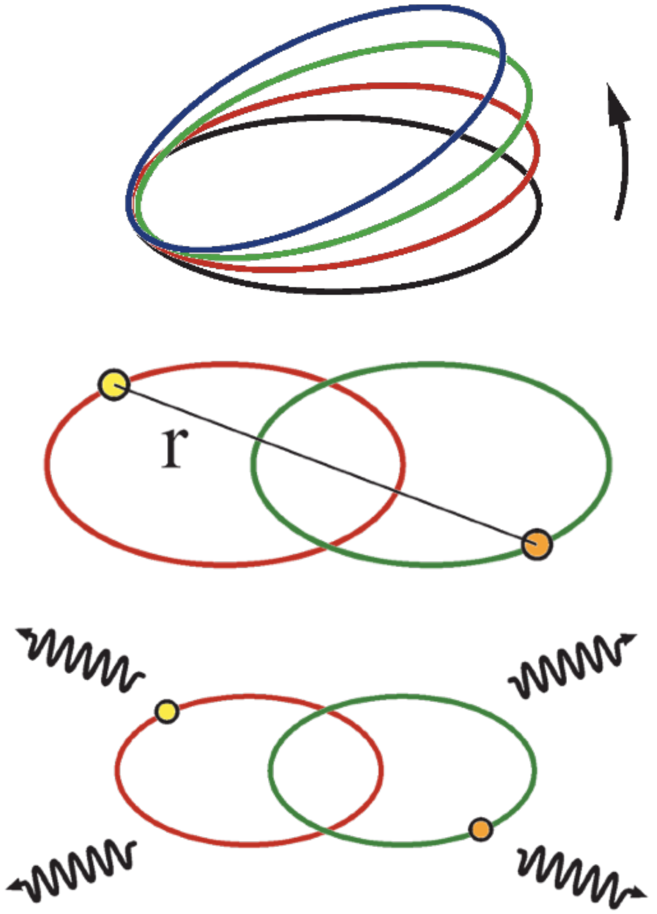
- Orbital period – P_{orb}
- Eccentricity – *e*
- Semi-major axis and inclination – *a* sin(*i*)
- The orientation of the orbit – T_0, ω_0

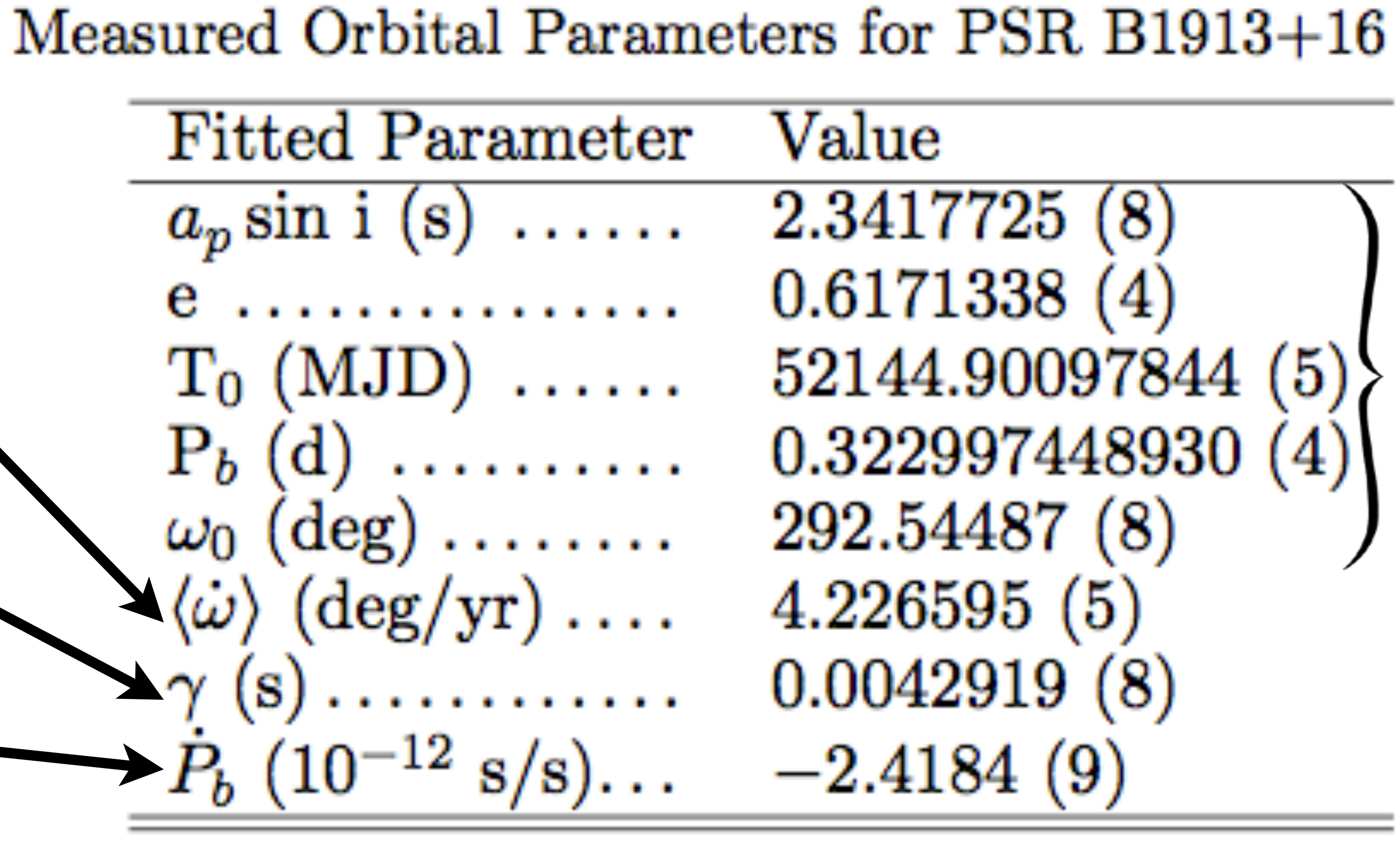


Mass function relates the masses to measured parameters

$$f = \frac{M_2^3 \sin^3 i}{(M_1 + M_2)^2} = \frac{P_{\rm orb}\, K^3}{2\pi G}$$

Long term monitoring of binary pulsars results in precise determination of “post-Keplerian” parameters

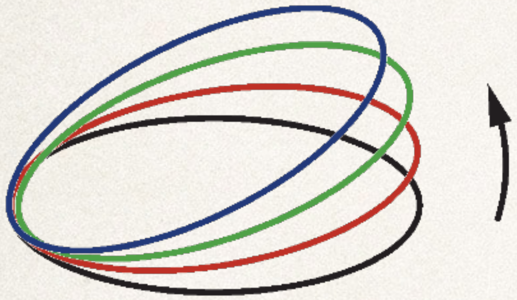



Measured Orbital Parameters for PSR B1913+16

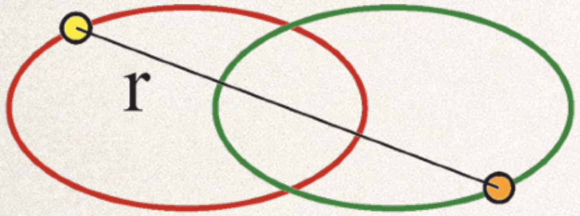
Fitted Parameter	Value
$a_p \sin i$ (s)	2.3417725 (8)
e	0.6171338 (4)
T_0 (MJD)	52144.90097844 (5)
P_b (d)	0.322997448930 (4)
ω_0 (deg)	292.54487 (8)
$\langle\dot{\omega}\rangle$ (deg/yr)	4.226595 (5)
γ (s)	0.0042919 (8)
$\dot{P}_b$ (10^{-12} s/s)...	−2.4184 (9)

Keplerian parameters

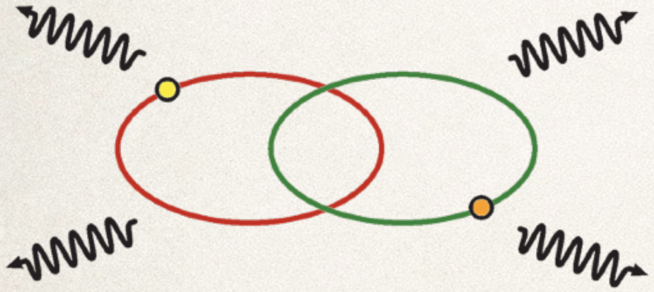
The PK parameters are dependent on the Keplerian parameters and the masses M_1 and M_2.



$$\dot{\omega} = 3 \left(\frac{P_b}{2\pi}\right)^{-5/3} \left(T_\odot M_\text{tot}\right)^{2/3} \left(1 - e^2\right)^{-1}$$



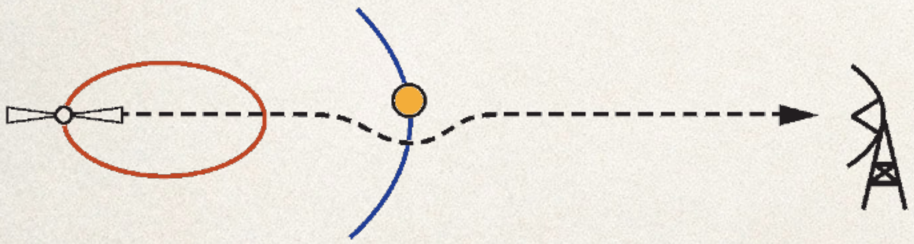
$$\gamma = e \left(\frac{P_b}{2\pi}\right)^{1/3} T_\odot^{2/3} M_\text{tot}^{-4/3} M_2 \left(M_1 + 2M_2\right)$$



$$\dot{P}_b = -\frac{192\pi}{5} \left(\frac{P_b}{2\pi}\right)^{-5/3} \left(1 + \frac{73}{24}e^2 + \frac{37}{96}e^4\right) \left(1 - e^2\right)^{-7/2} T_\odot^{5/3} M_1 M_2 M_\text{tot}^{-1/3}$$

with $T_\odot = \dfrac{GM_\odot}{c^3}$

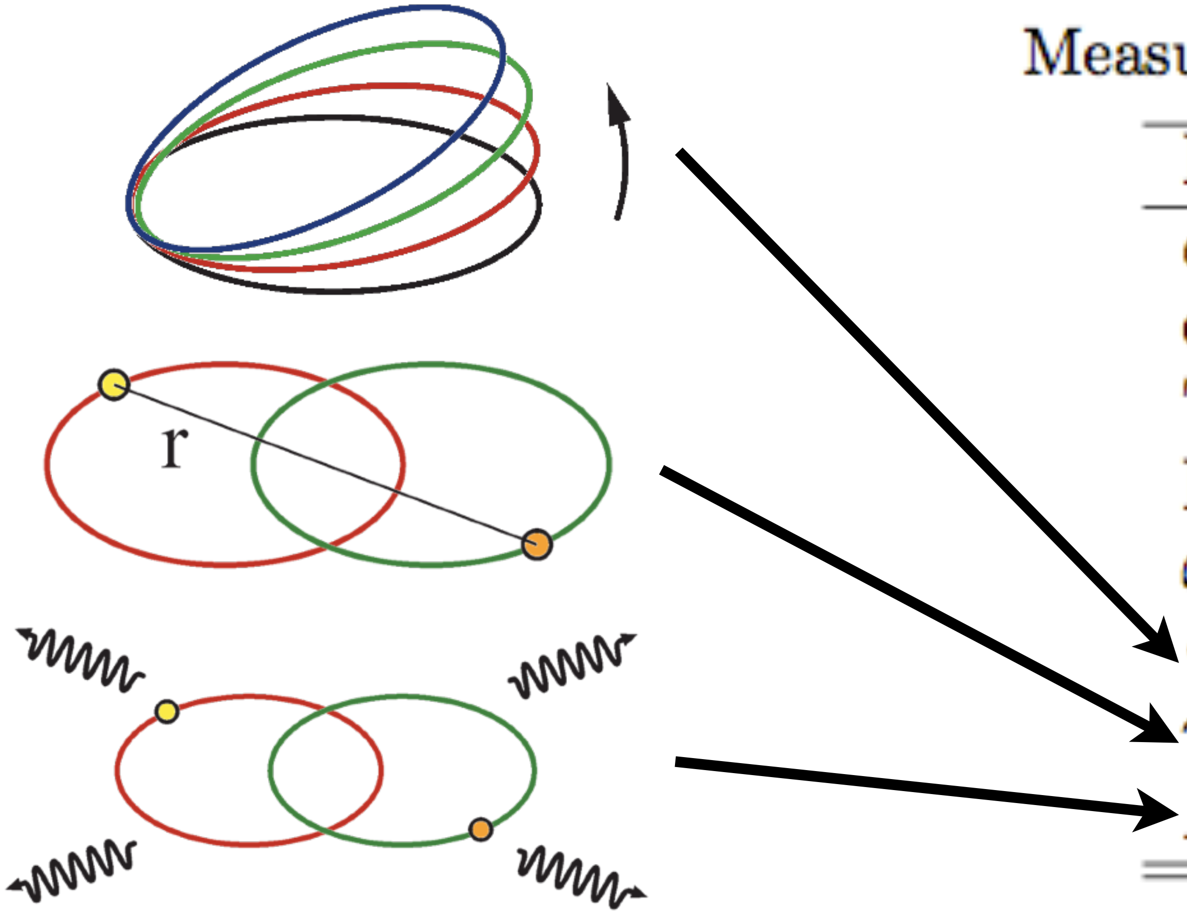
$$r = T_\odot M_2$$



$$s = x \left(\frac{P_b}{2\pi}\right)^{-2/3} T_\odot^{-1/3} M_\text{tot}^{2/3} \; M_2^{-1}$$

Shapiro Delay

Long term monitoring of binary pulsars results in precise determination of “post-Keplerian” parameters



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$\dot{P}_b$ (10^{-12} s/s)...	−2.4184 (9)

depend on M_1 and M_2

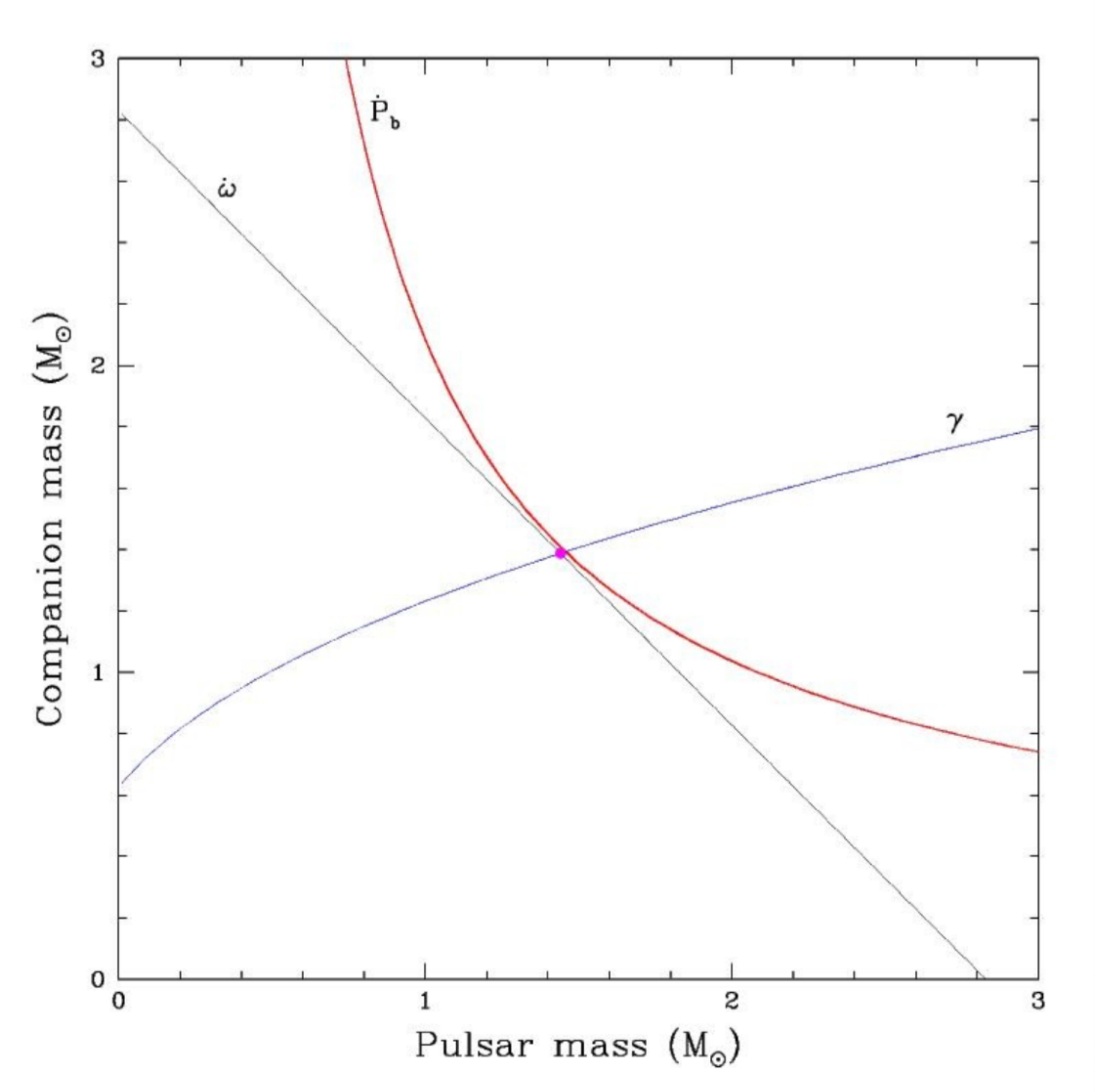
Double-NS system PSR B1913+16

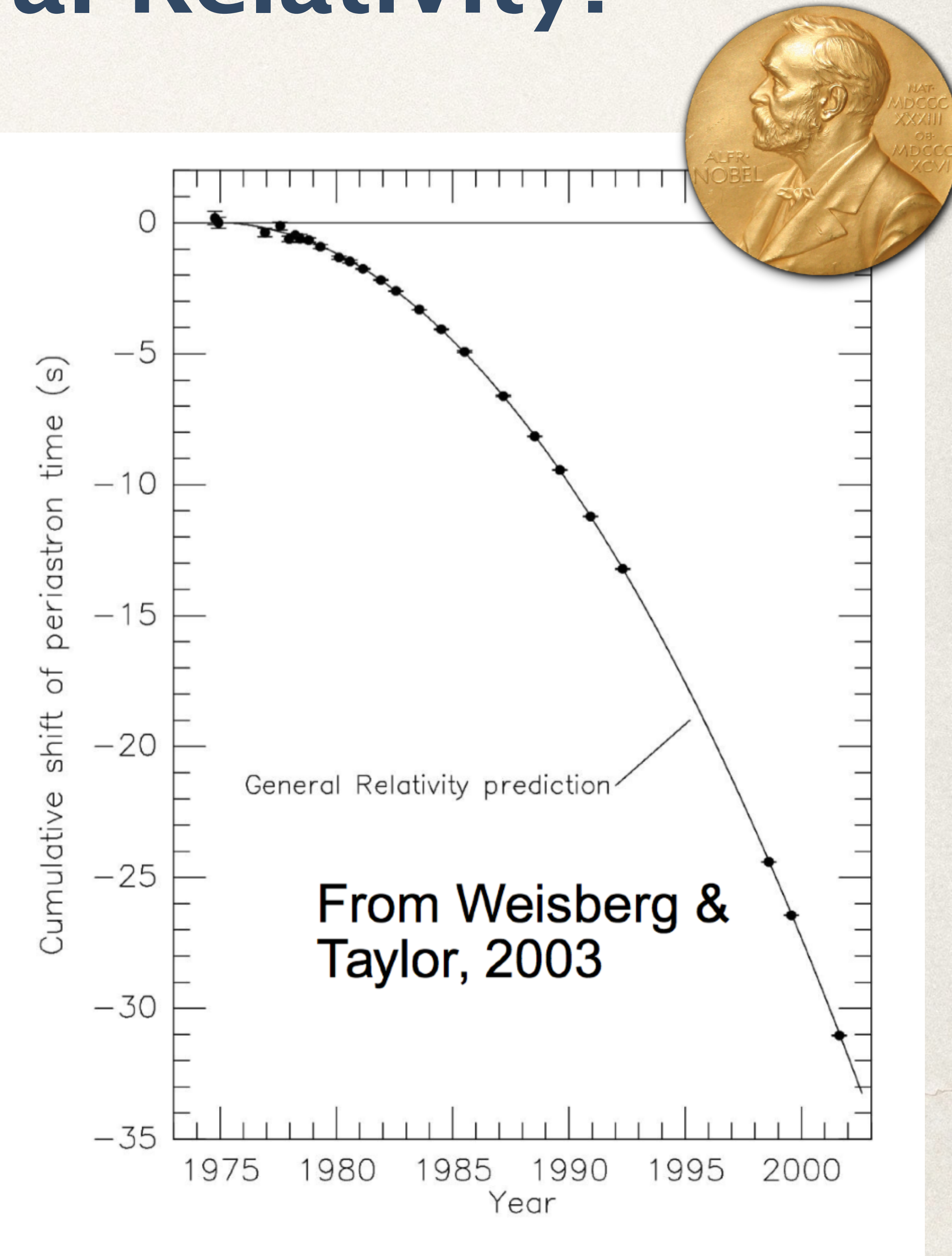
Best M_{NS} measurement

$M_{PSR} = 1.4414 \pm 0.0002\ M_\odot$

Weisberg et al. 2005

Measuring more than two PK parameters provides tests of General Relativity!

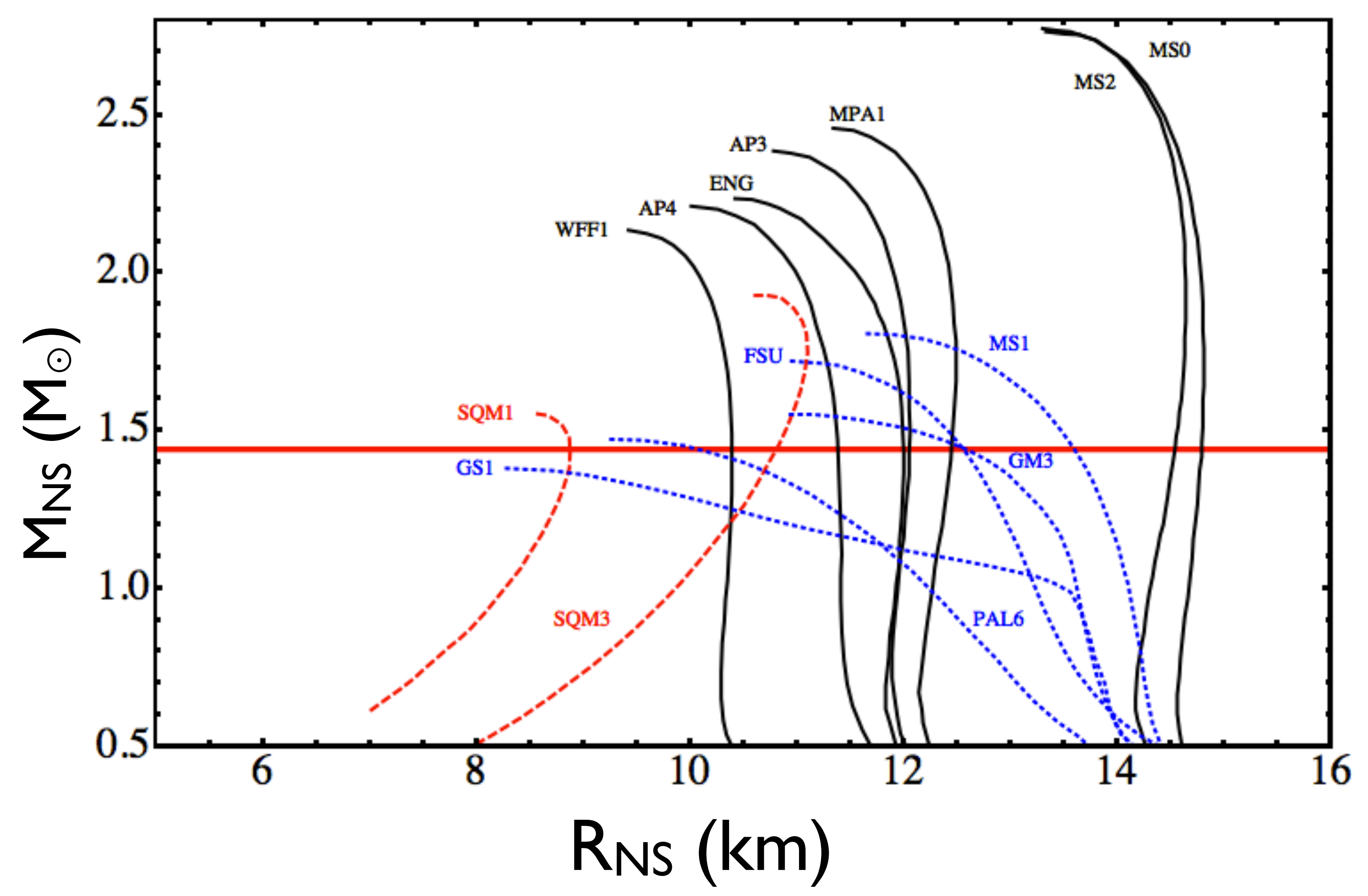




From Weisberg & Taylor, 2003

Double NS system PSR B1913+16

The most precise mass measurement for a pulsar is not constraining enough. Why ?



Not constraining enough!!

Double-NS system PSR B1913+16

Best M_{NS} measurement

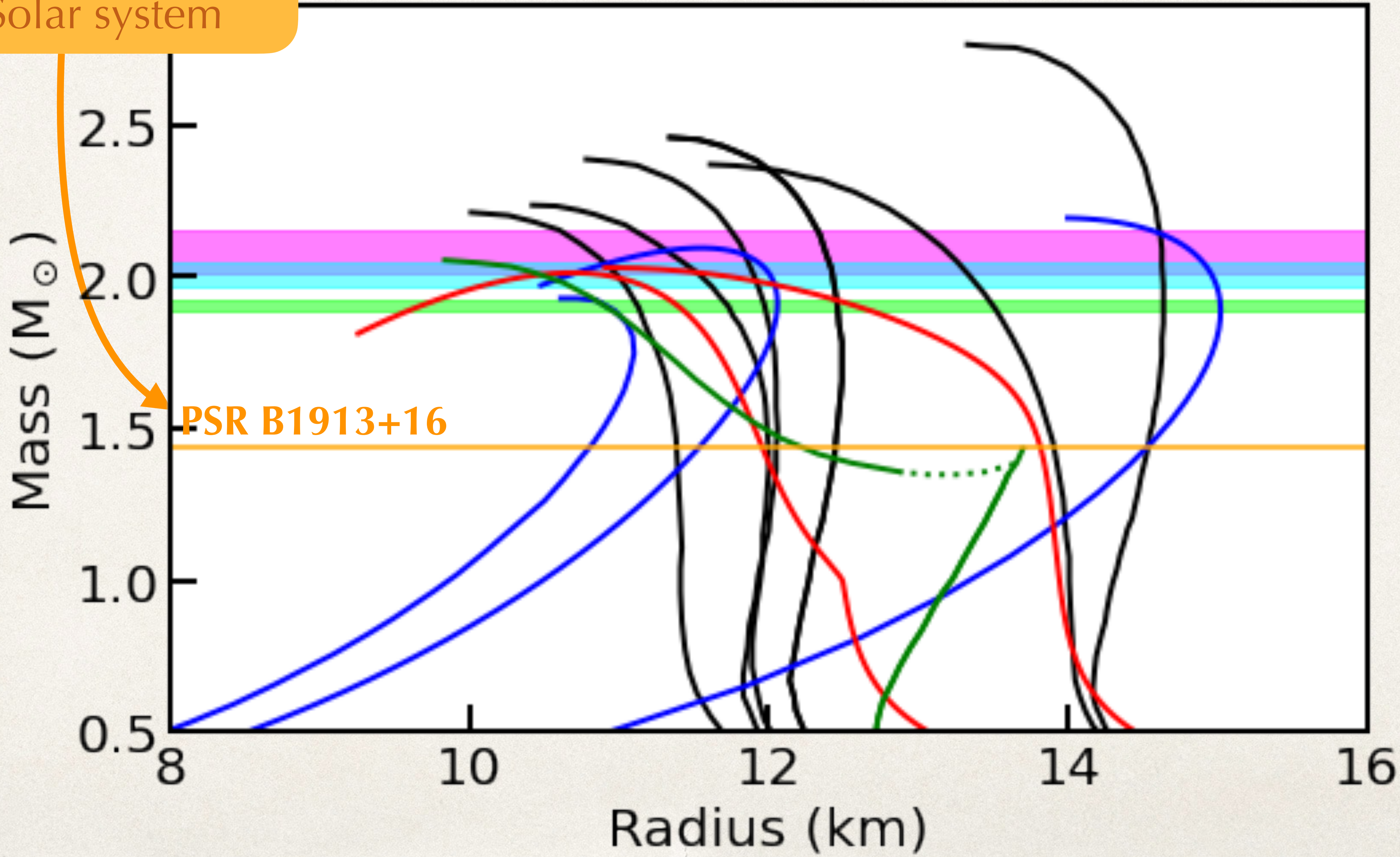
$M_{PSR} = 1.4414 \pm 0.0002\ M_\odot$

Weisberg et al. 2005

Many measurements of the mass M_{NS} exist, but only high-M_{NS} are useful.

Demorest et al. 2010
Antoniadis et al. 2013
Cromartie et al. 2019

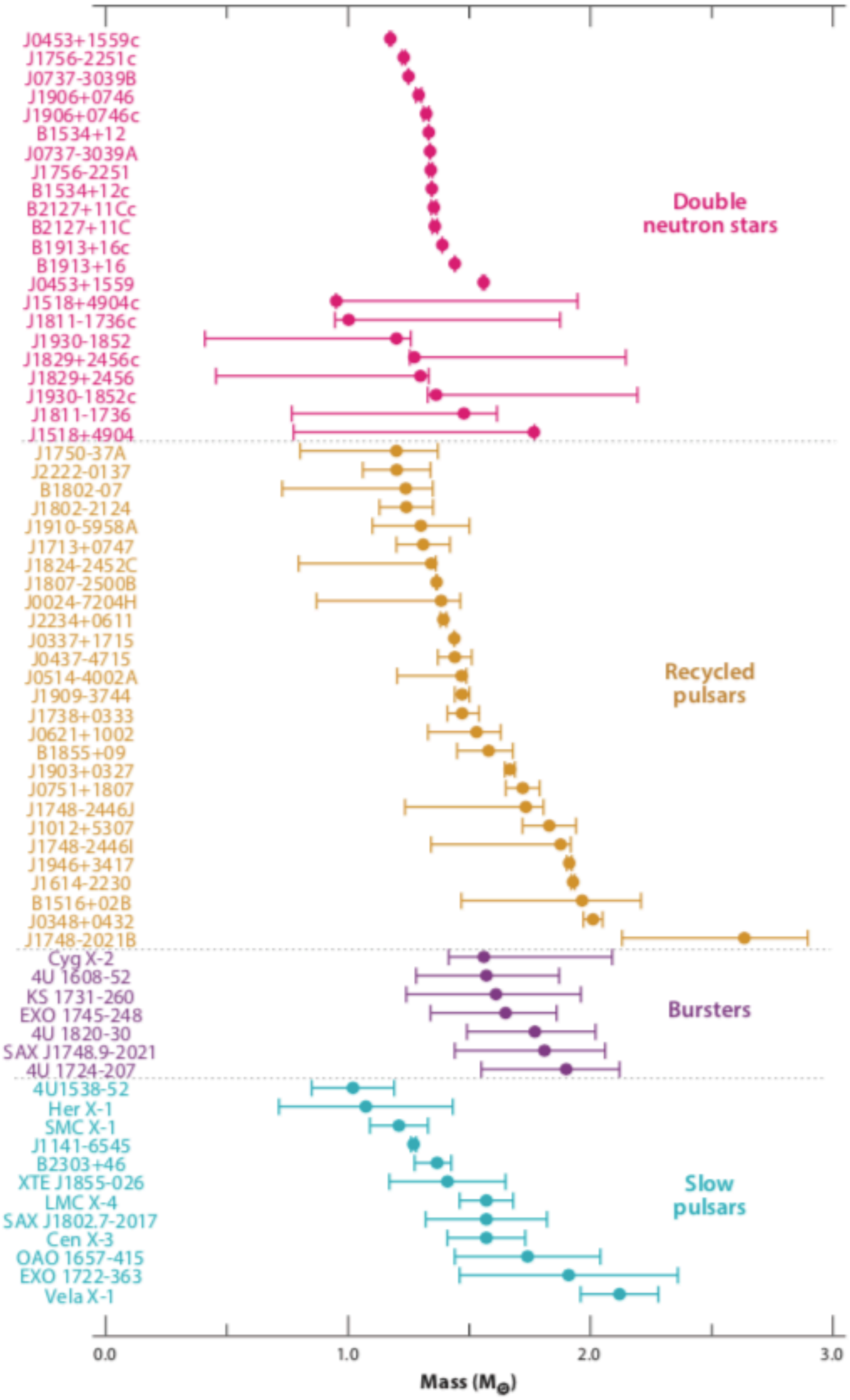
Most precise mass measurement outside the Solar system



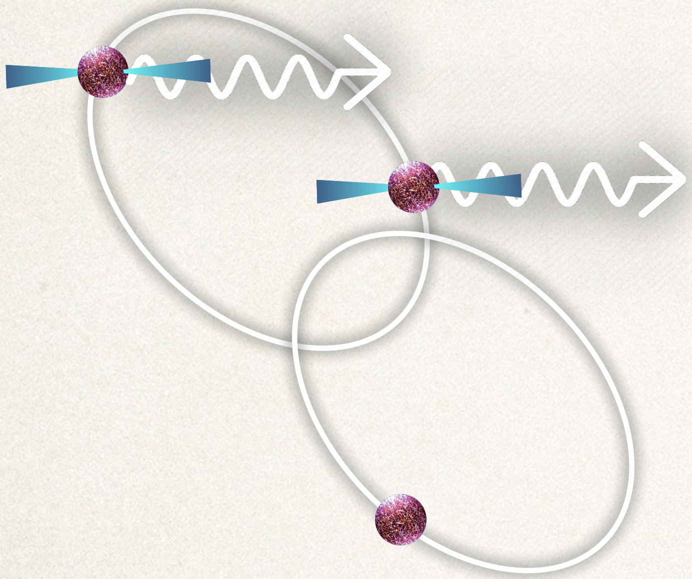
Part 5 – conclusion

Neutron star mass measurements are the most precise from double neutron star systems.

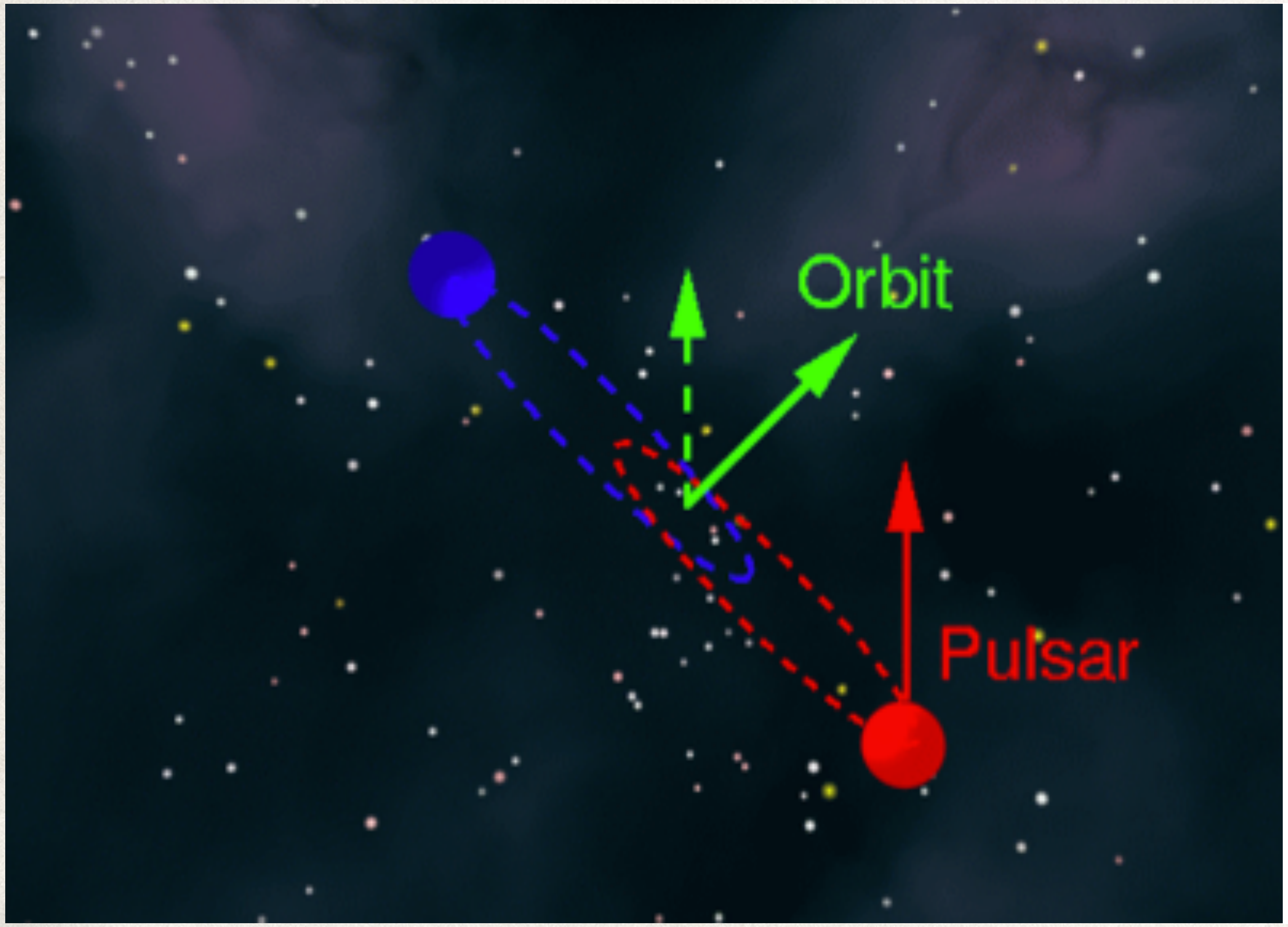
Only the neutron star masses higher than all previously known masses are useful to constrain dense matter

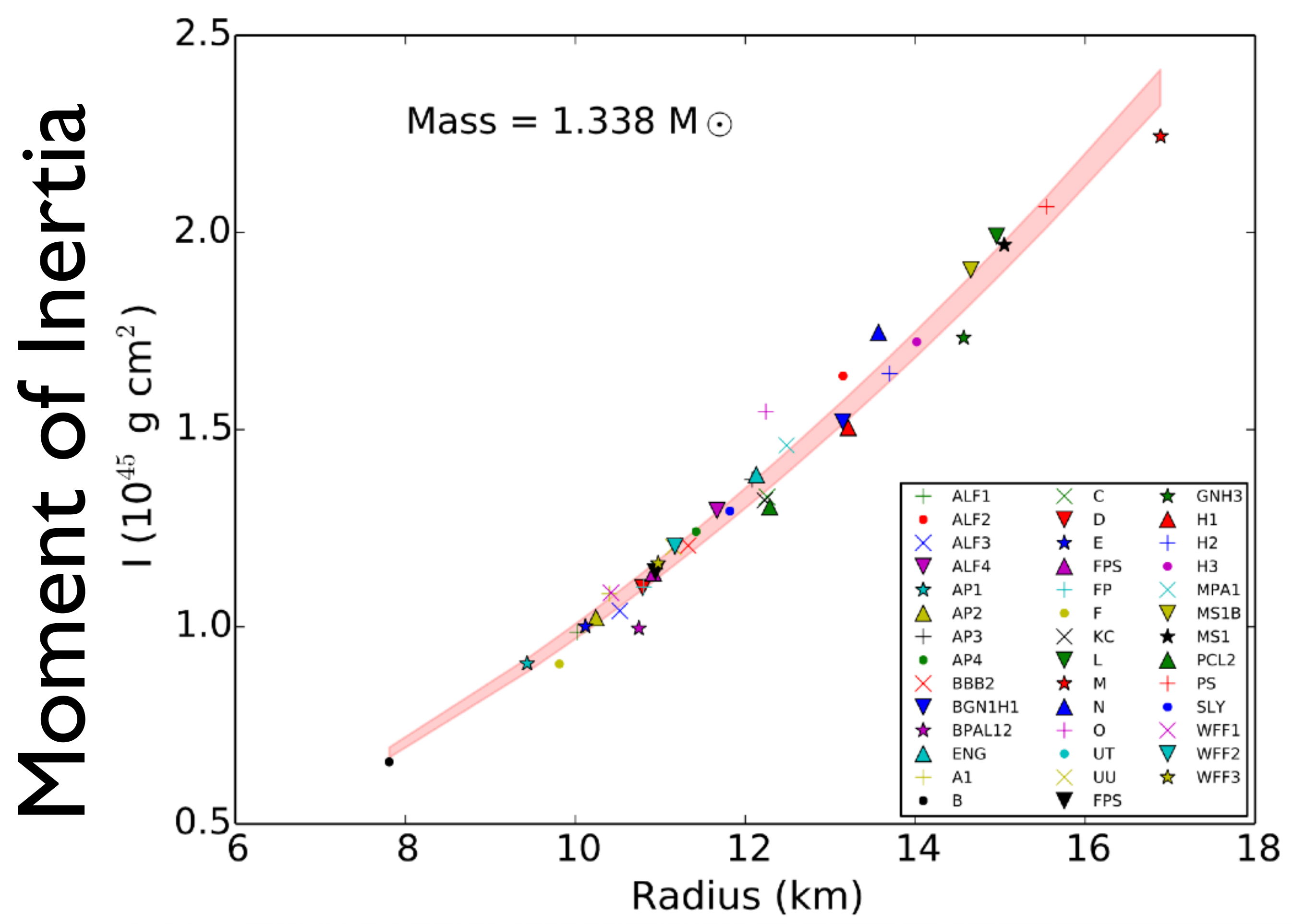


1) The moment of inertia of neutron stars is difficult to measure.



Highly relativistic binary NS system can exhibit the effects of spin-orbit coupling, which depends on the NS moment of inertia.

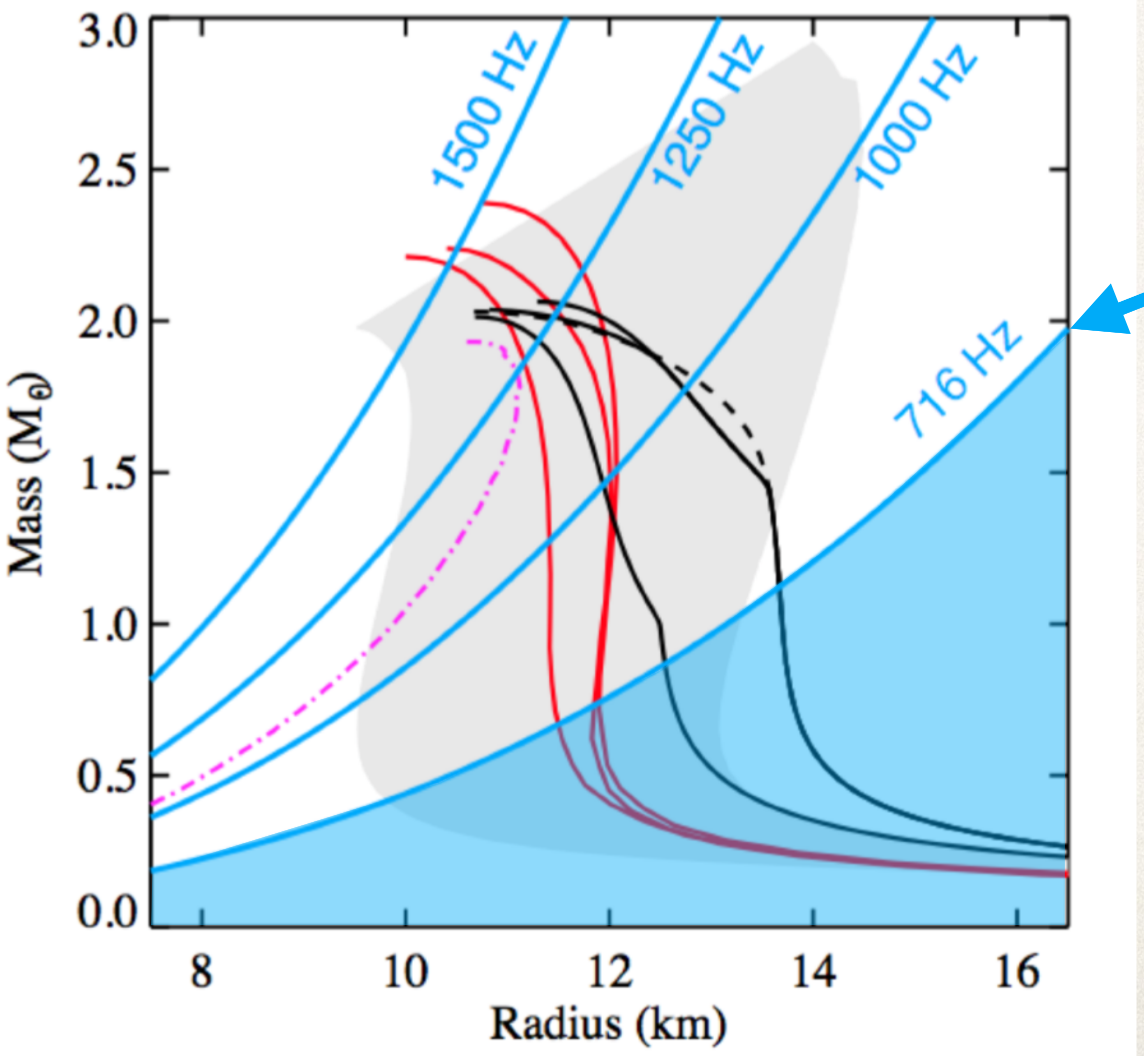




2) Neutron stars would break appart if they spin too fast. This constrains the matter inside them.

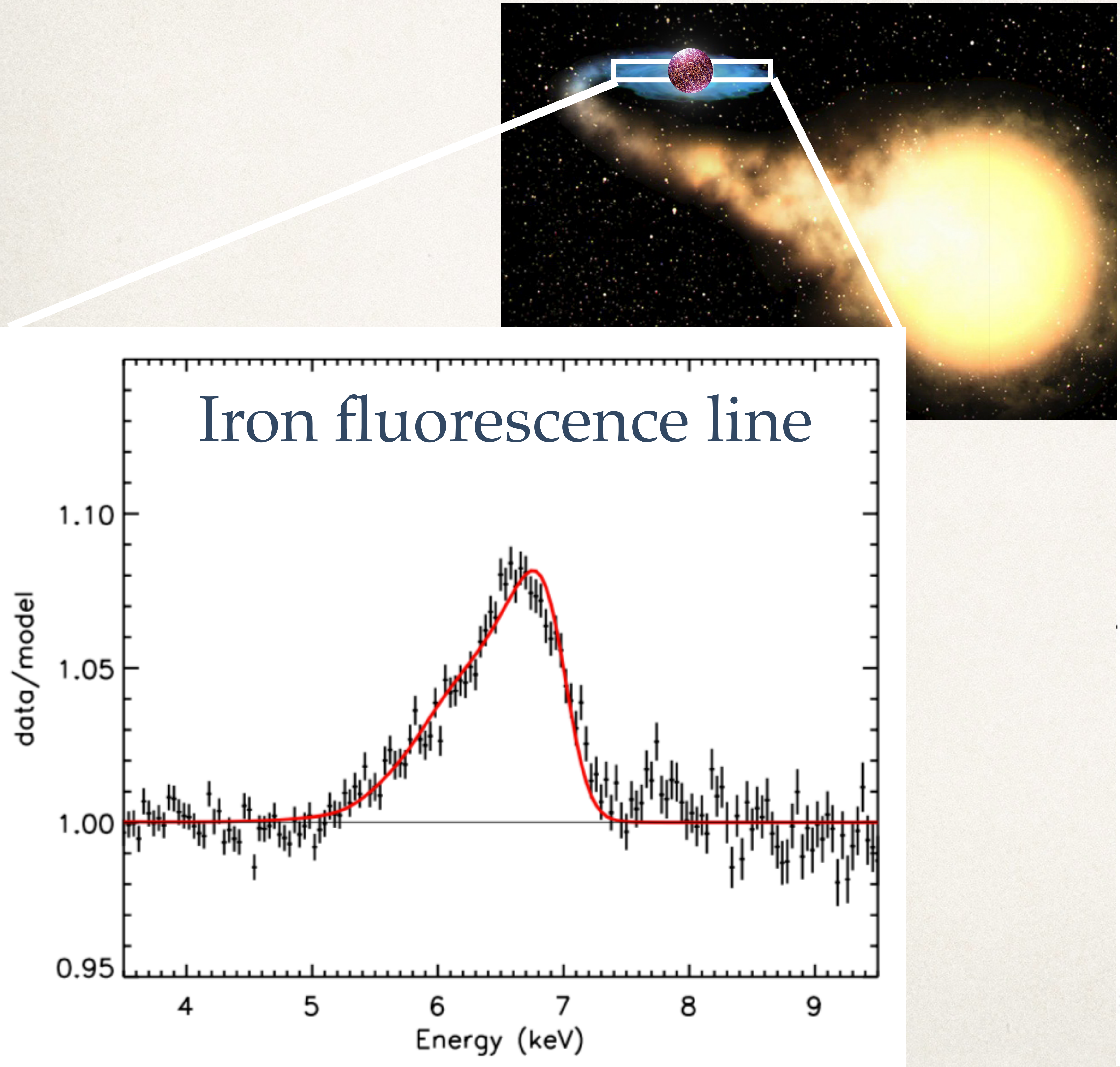
The maximum spin of a NS is determined by the Keplerian frequency at the equator

$$f \leq f_{\mathrm{K}} = \frac{1}{2\pi}\left(\frac{2}{3}\right)^{3/2}\left(\frac{GM}{R^3}\right)^{1/2}$$

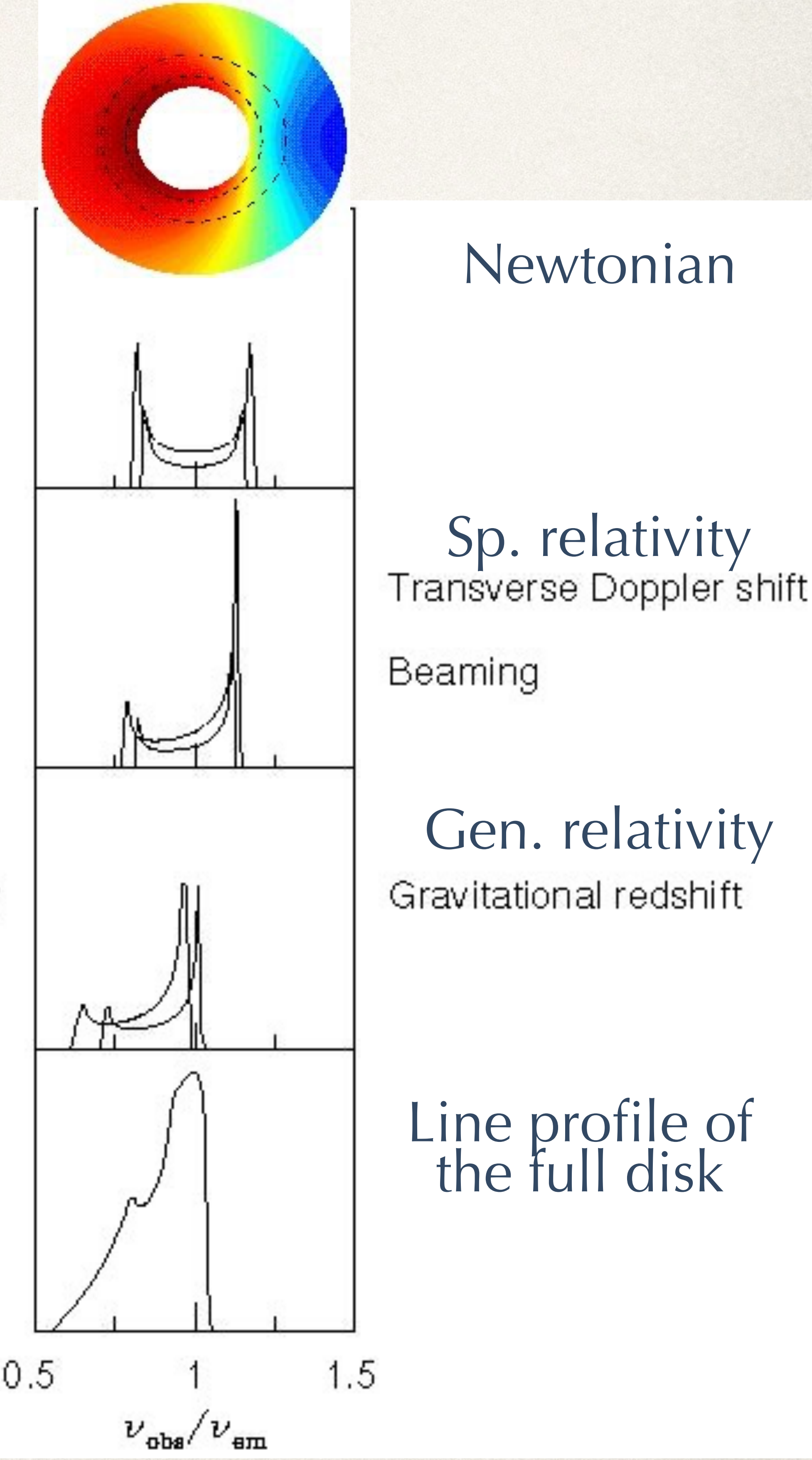


The fastest spinning known neutron star

3) The dynamics of the accretion disk around a compact object broadens disk lines and gives us the inner extent of an accretion disk



Iron fluorescence line



Newtonian

Sp. relativity
Transverse Doppler shift

Beaming

Gen. relativity
Gravitational redshift

Line profile of the full disk

We used a physically-driven, parameterisation of the equation of state is preferable.

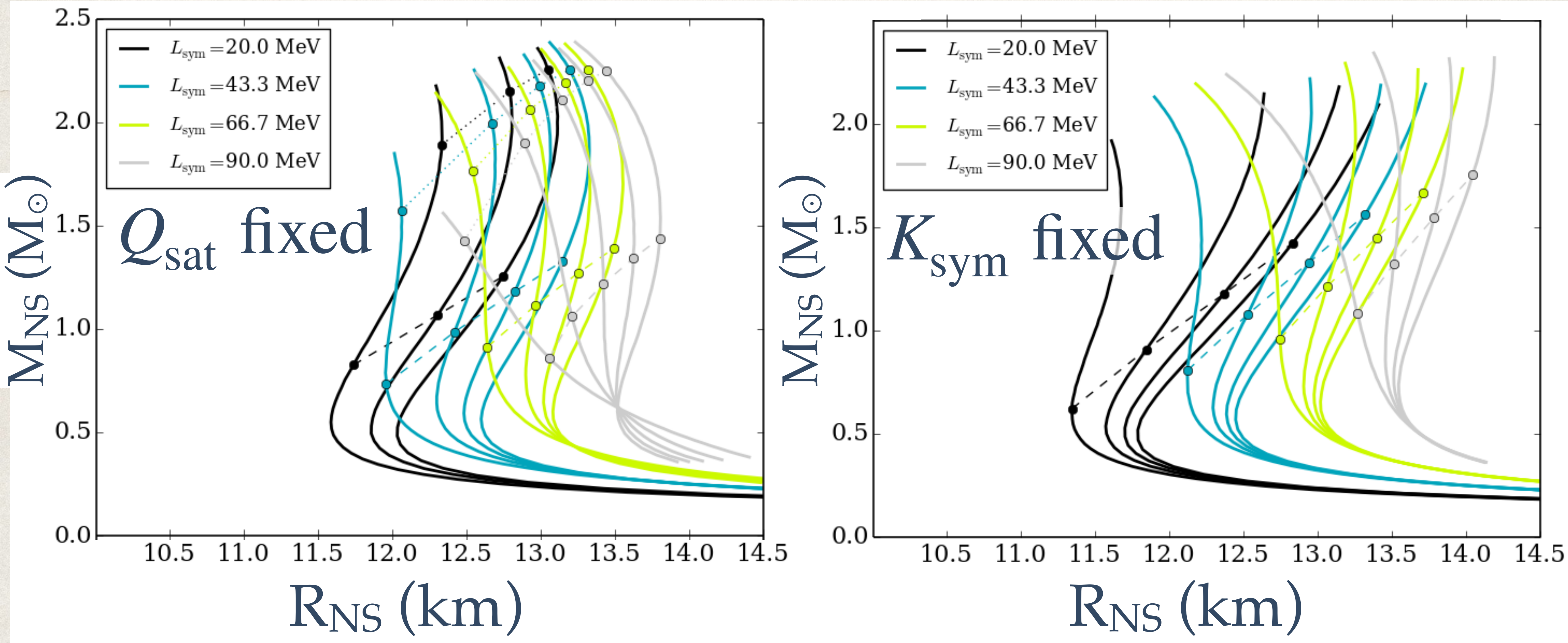
Meta-model of
J. Margueron et al.

$$e_{\rm sat} = E_{\rm sat} + \frac{1}{2}K_{\rm sat}x^2 + \frac{1}{3!}\underline{Q_{\rm sat}}x^3 + \frac{1}{4!}Z_{\rm sat}x^4 + \dots$$

$$e_{\rm sym} = E_{\rm sym}+\underline{L_{\rm sym}}x+\frac{1}{2}\underline{K_{\rm sym}}x^2+\frac{1}{3!}Q_{\rm sym}x^3+\frac{1}{4!}Z_{\rm sym}x^4+\dots,$$

with

$$x = \frac{n - n_{\rm sat}}{3n_{\rm sat}}$$



Margueron et al. 2018
Baillot d'Etivaux, SG et al. 2019