Spectral and Timing properties of Neutron Star Low-Mass X-ray Binaries

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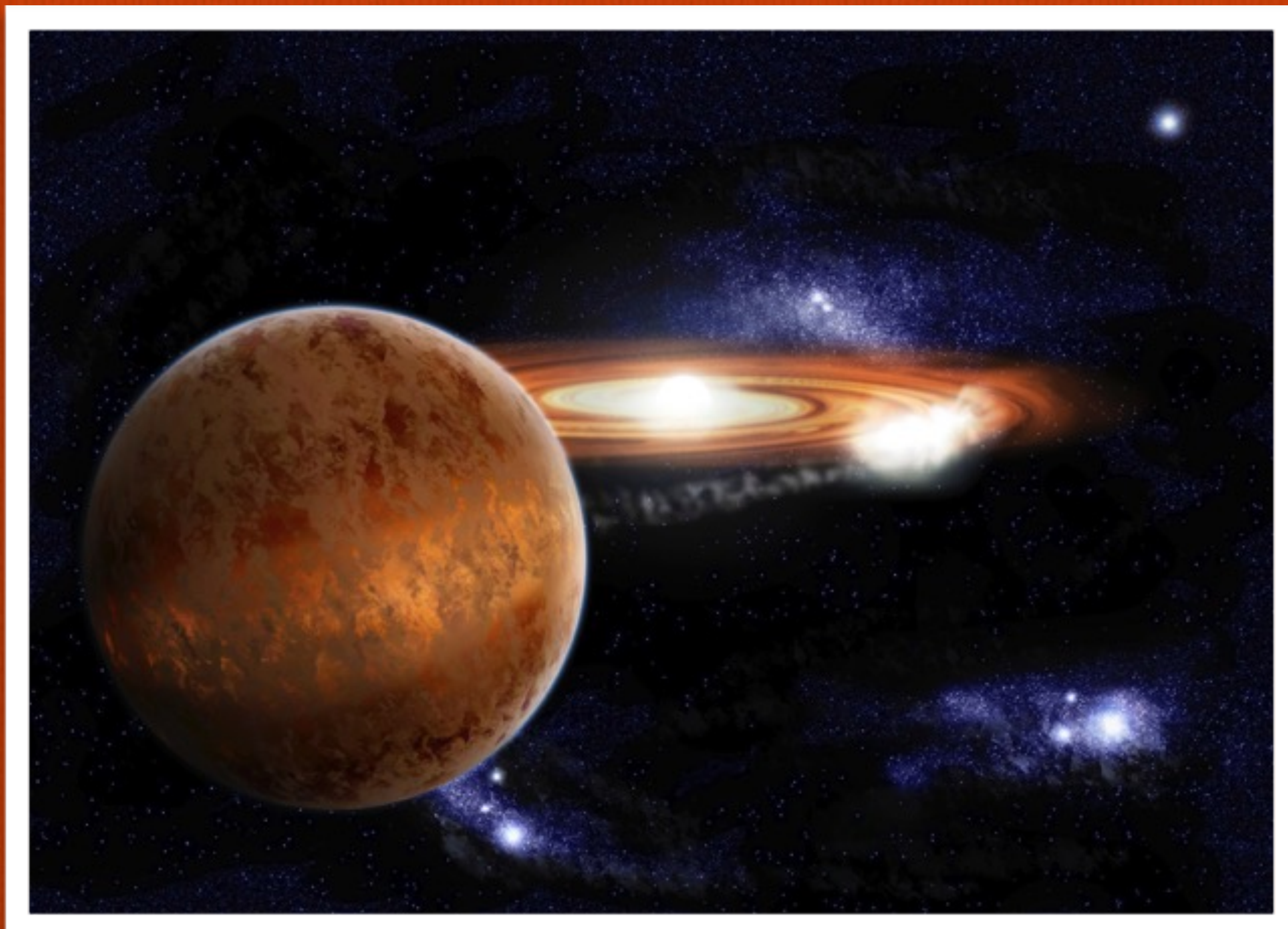
11th Bonn workshop on “Formation and Evolution of NS” - 11th Dec 2017

Low-Mass X-ray Binaries



- late-type star

  $\leq 1\ M_\odot$

- age

  $>$ Gyr

- compact object

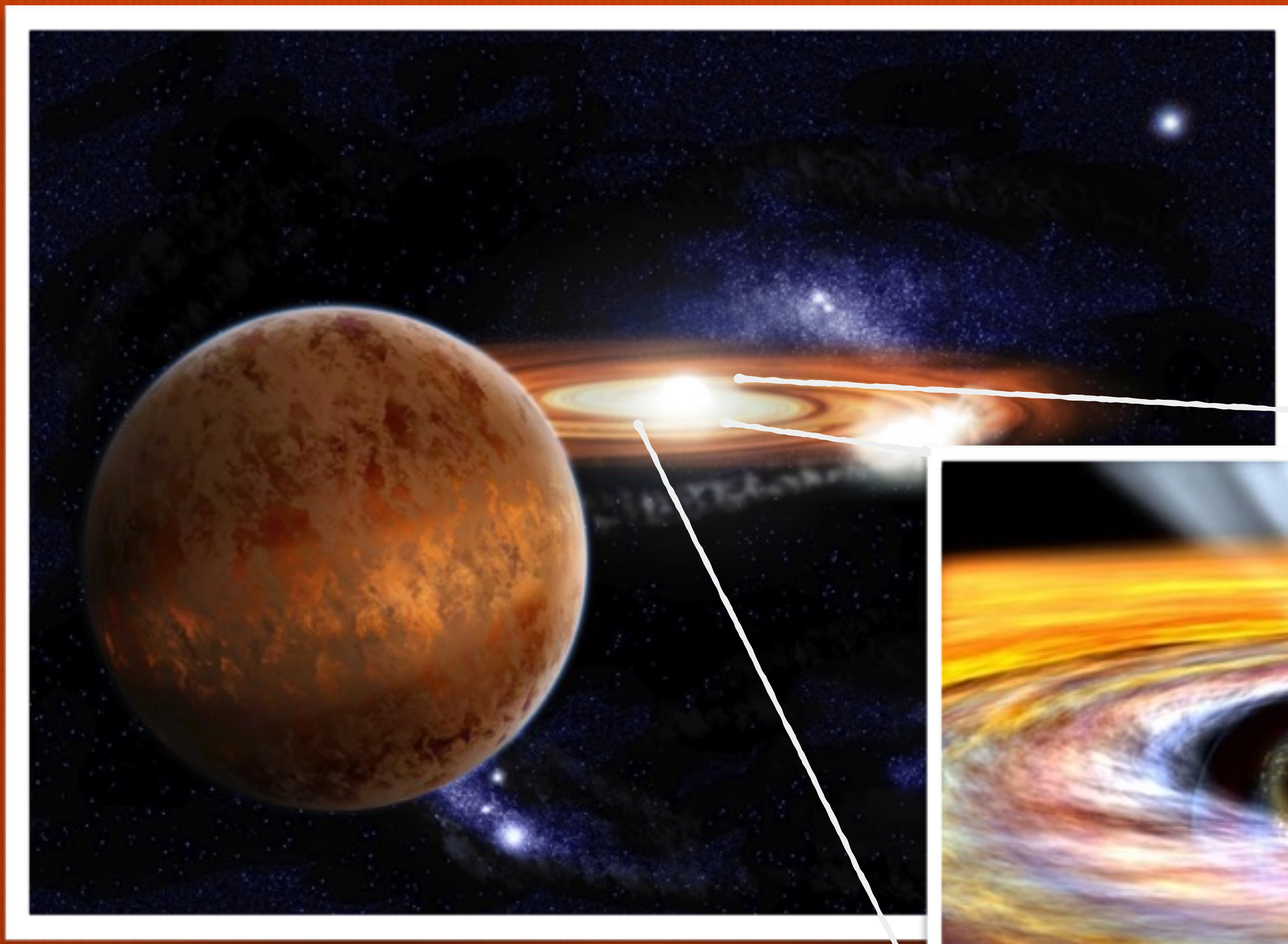
  Neutron Star

  Black Hole

  White Dwarf

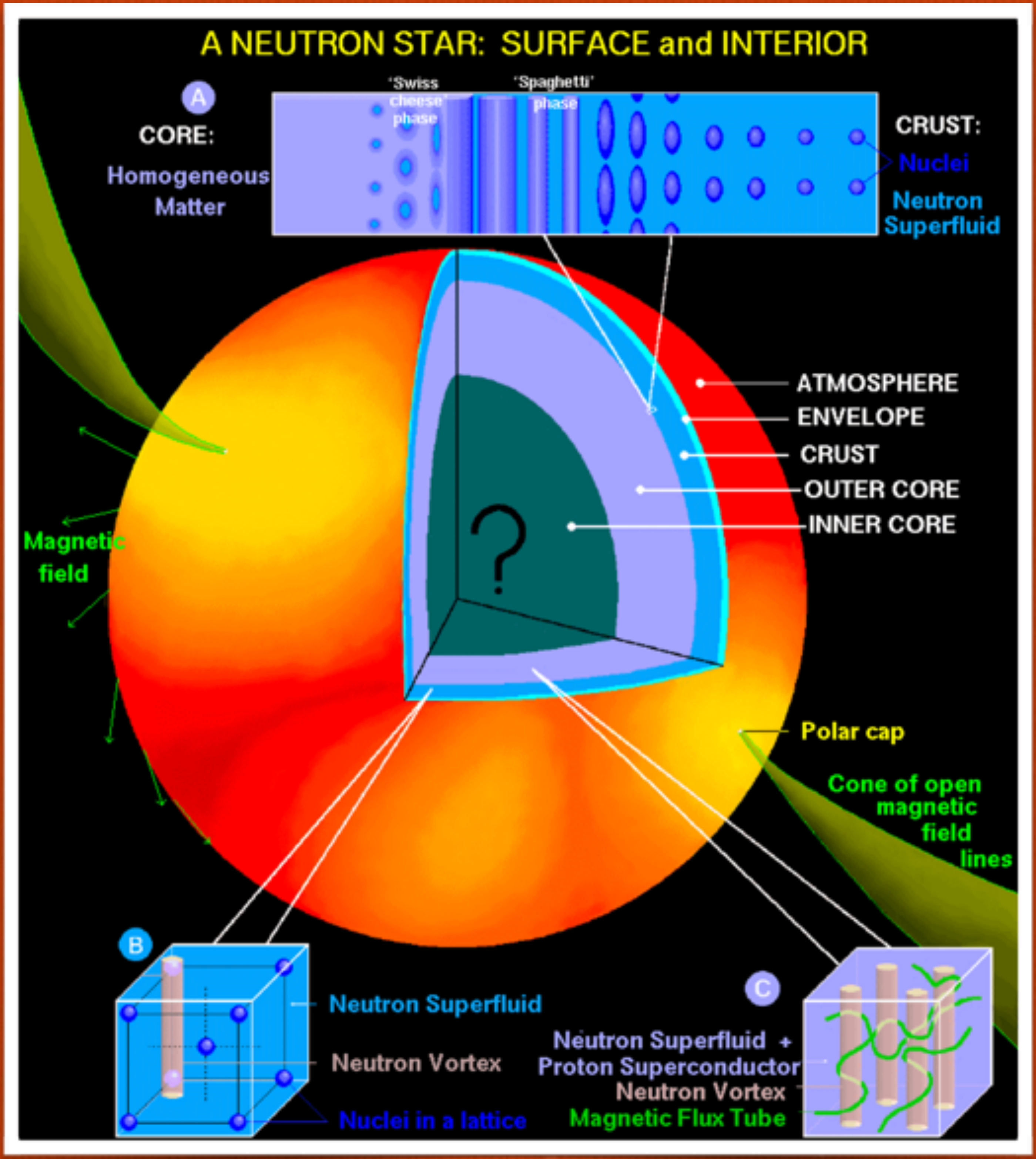
- $L_{opt}/L_x \ll 0.1$

Low-Mass X-ray Binaries



- late-type star
  - $\leq 1\ M_\odot$
- age
  - > Gyr

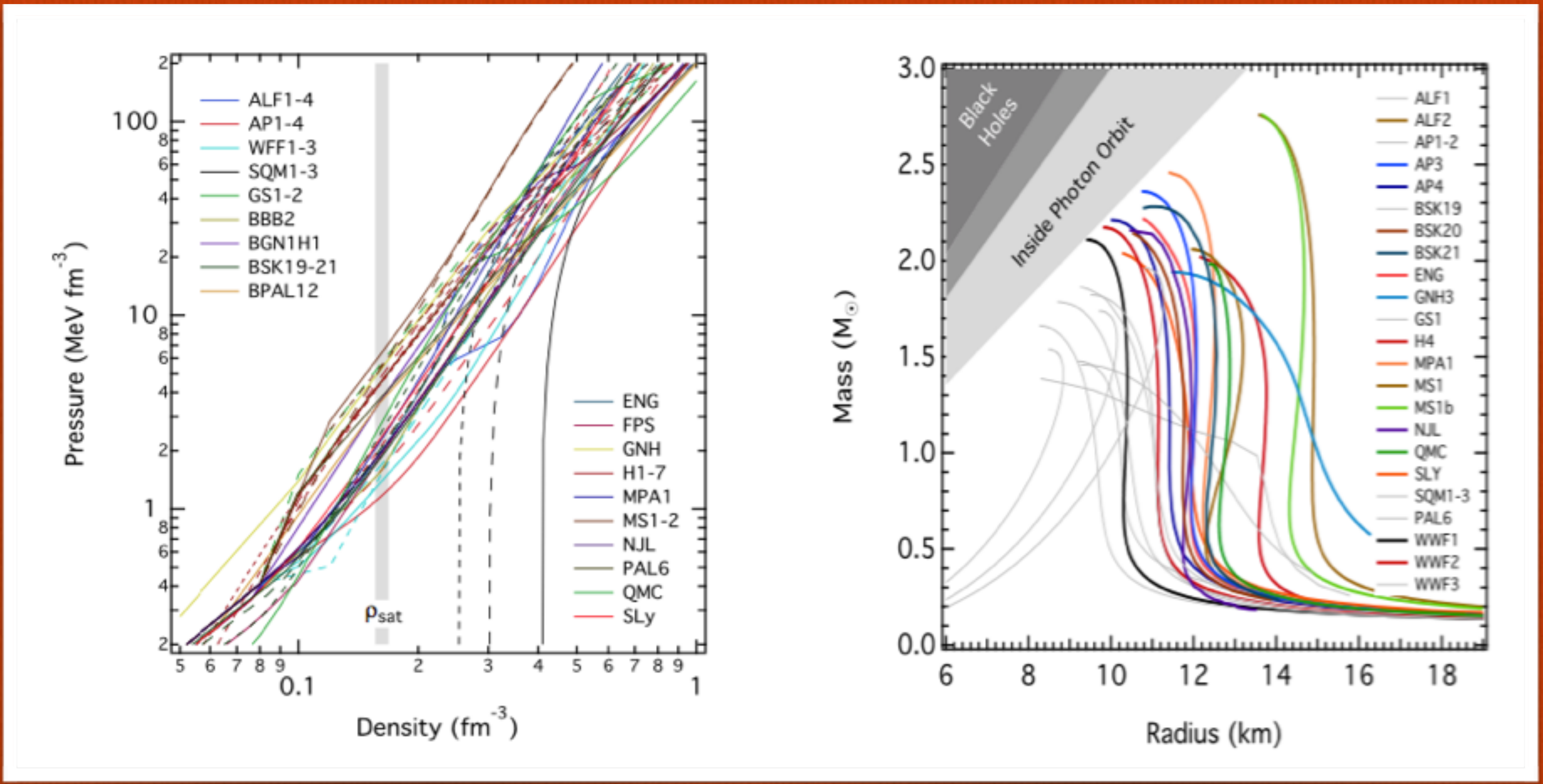
Neutron Stars



- mass ≃ 0.5 – 2.5 M⊙
- radius ≃ 5 – 20 km
- density $\sim 5 - 10\,\rho_{nuc}$
- magnetic field

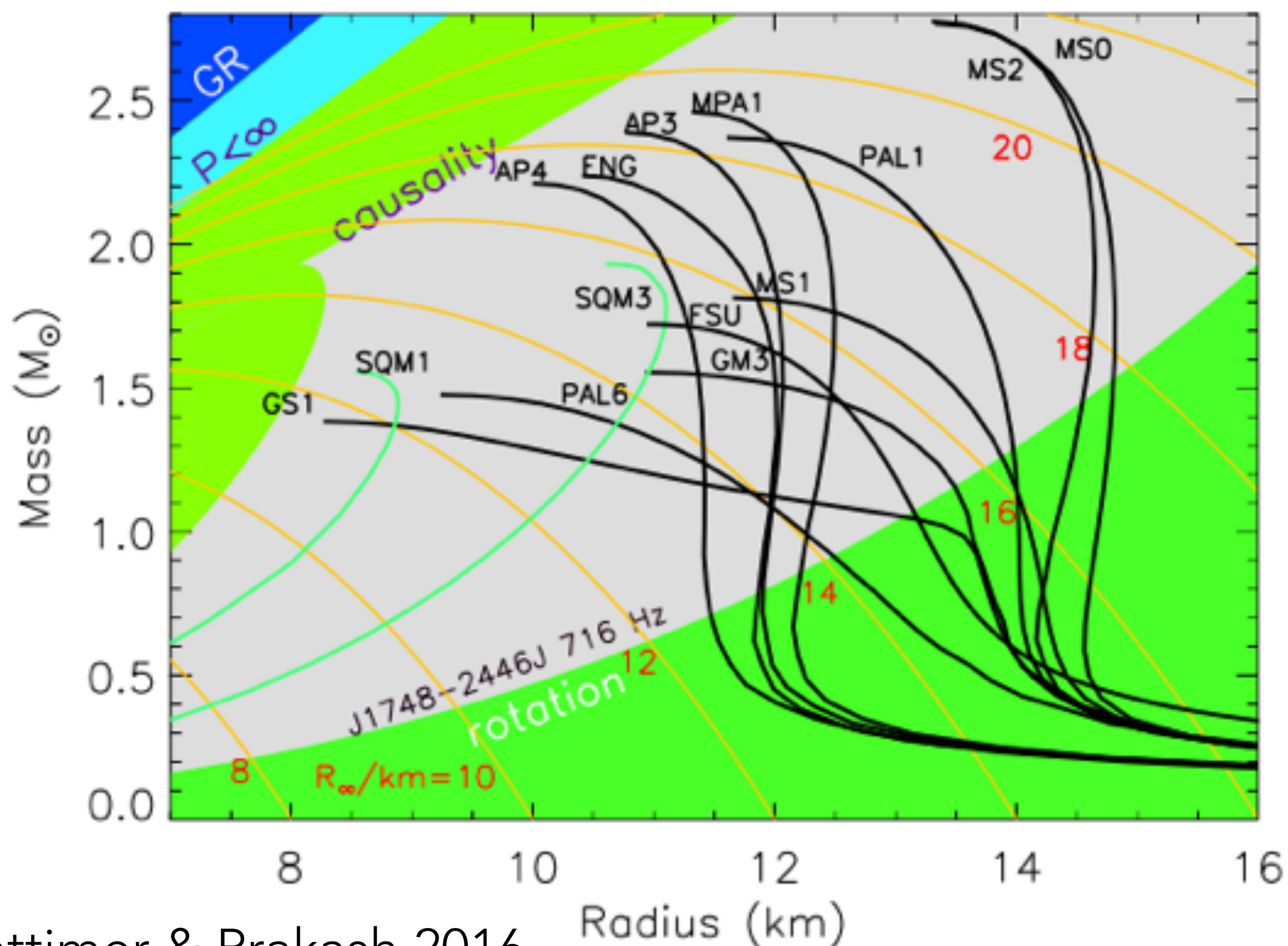
  $10^7 - 10^{15}$ Gauss

Neutron Stars

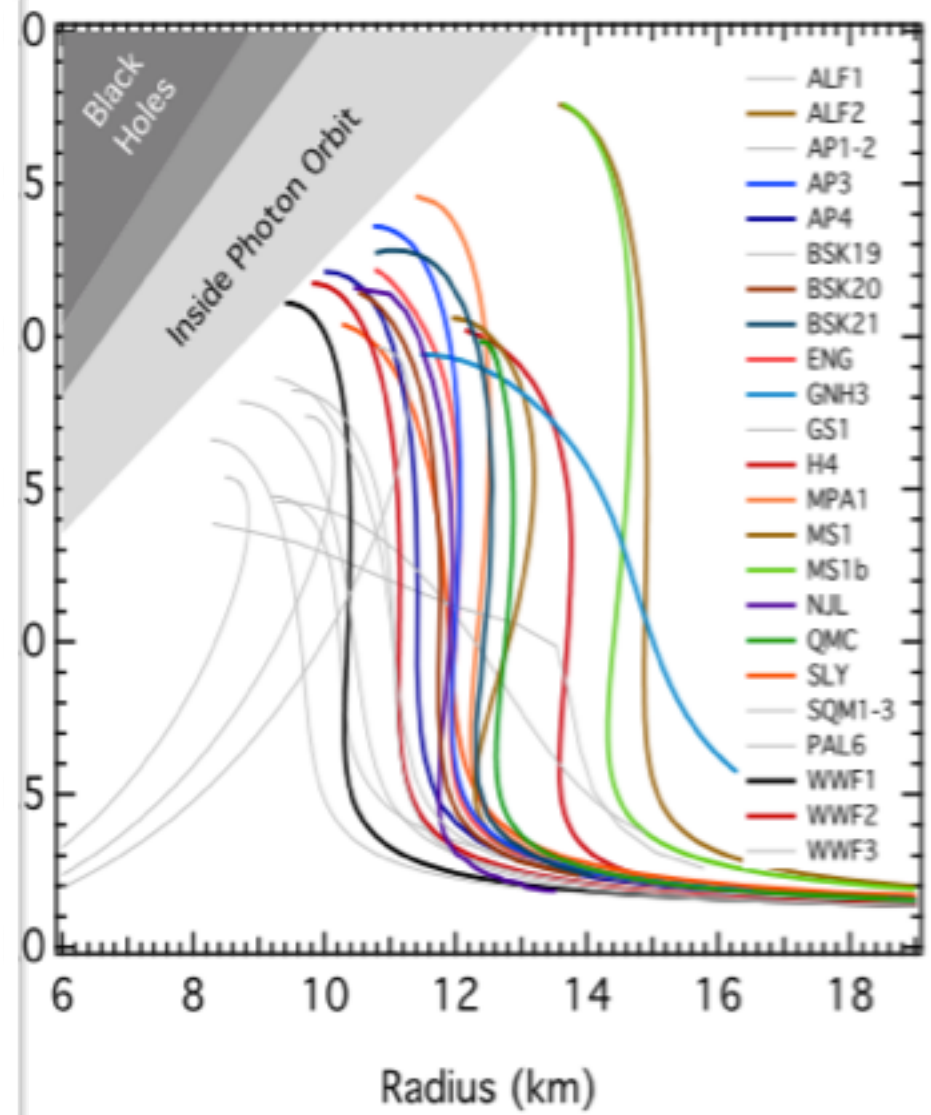


Özel & Freire 2016

Neutron Stars



Lattimer & Prakash 2016

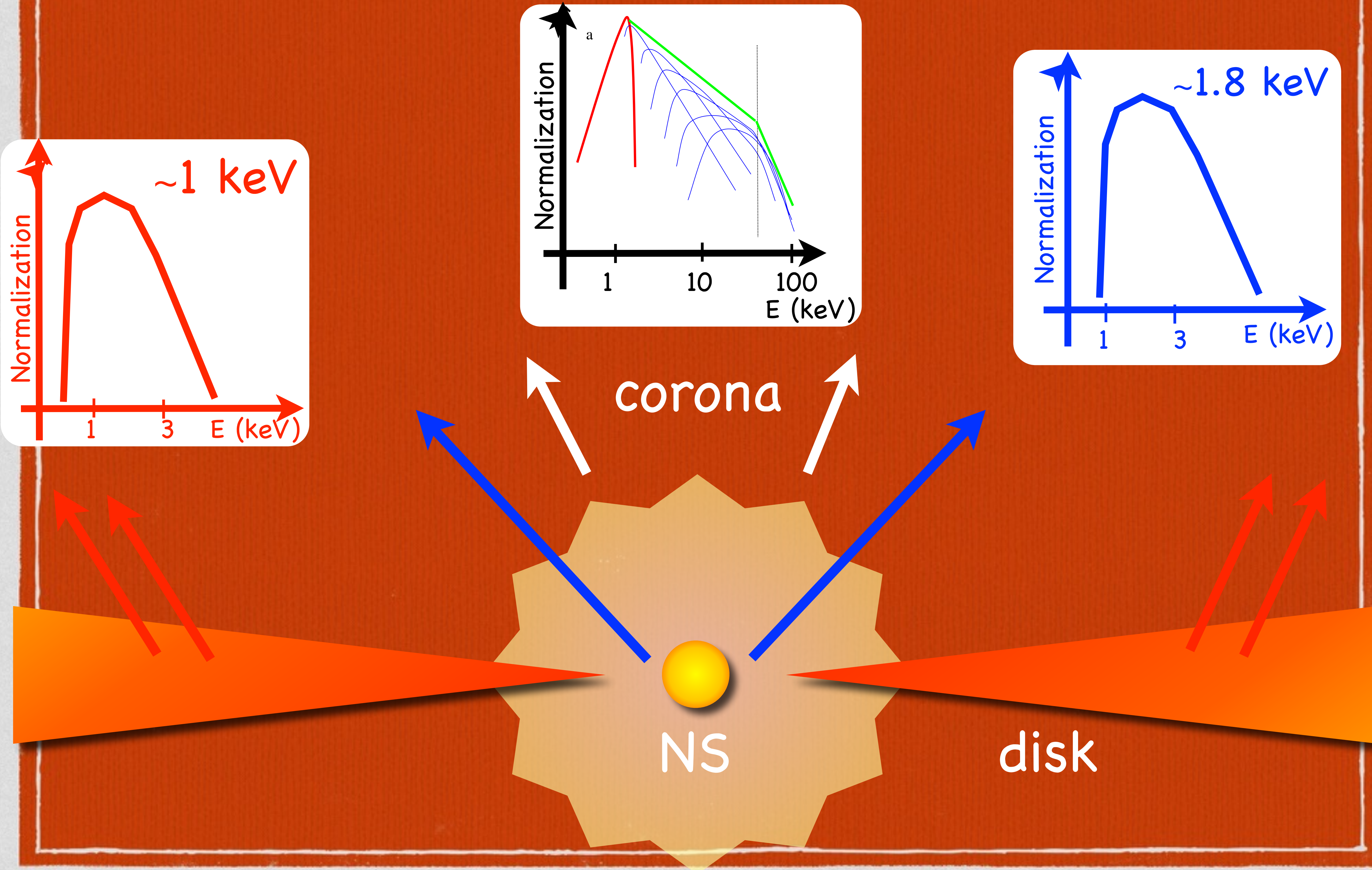


Özel & Freire 2016

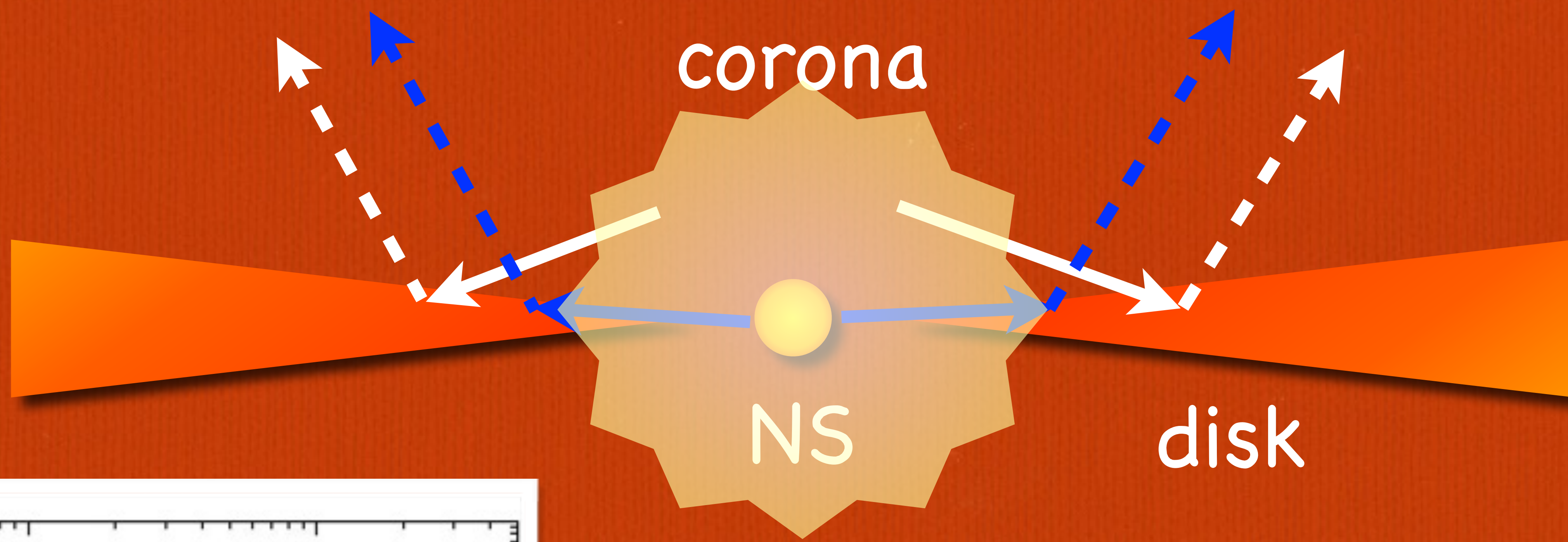
NS M-R measurements

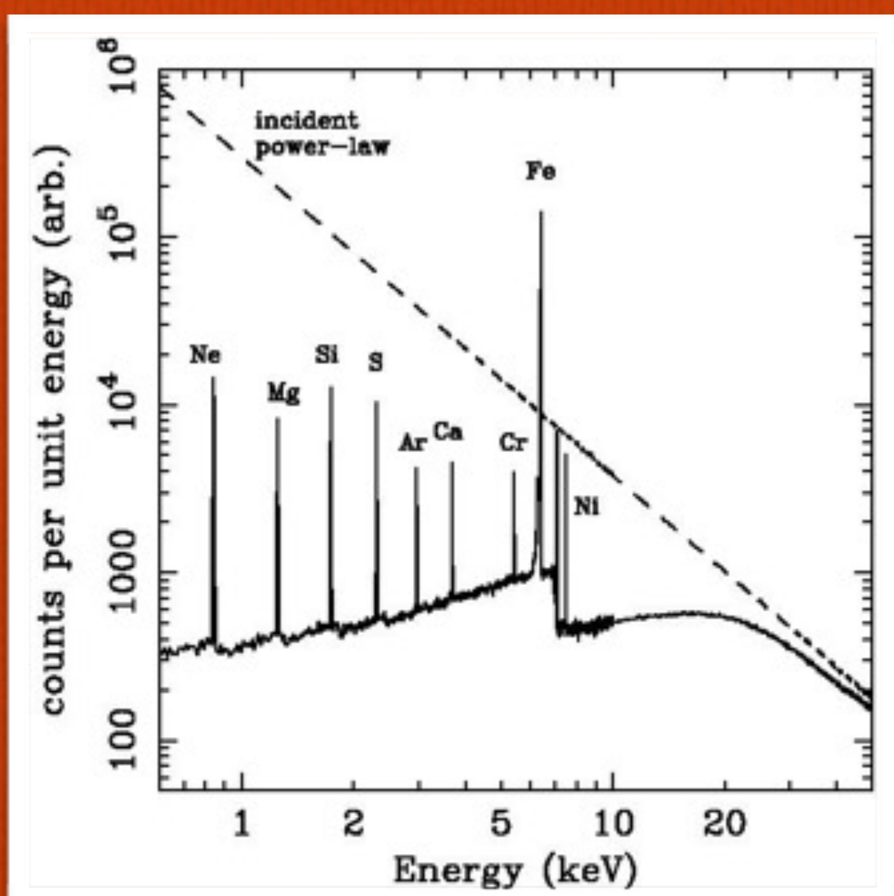
- Thermonuclear X-ray Bursts
- Continuum spectrum method
- Spectral line method
- Burst oscillation method
- Accretion-powered millisecond pulsar method
- Kilohertz Quasi-periodic Oscillation method
- Broad relativistic Iron line method
- Quiescent emission method
- ……

NS LXMB: X-ray emission



NS LXMB: reflection spectrum

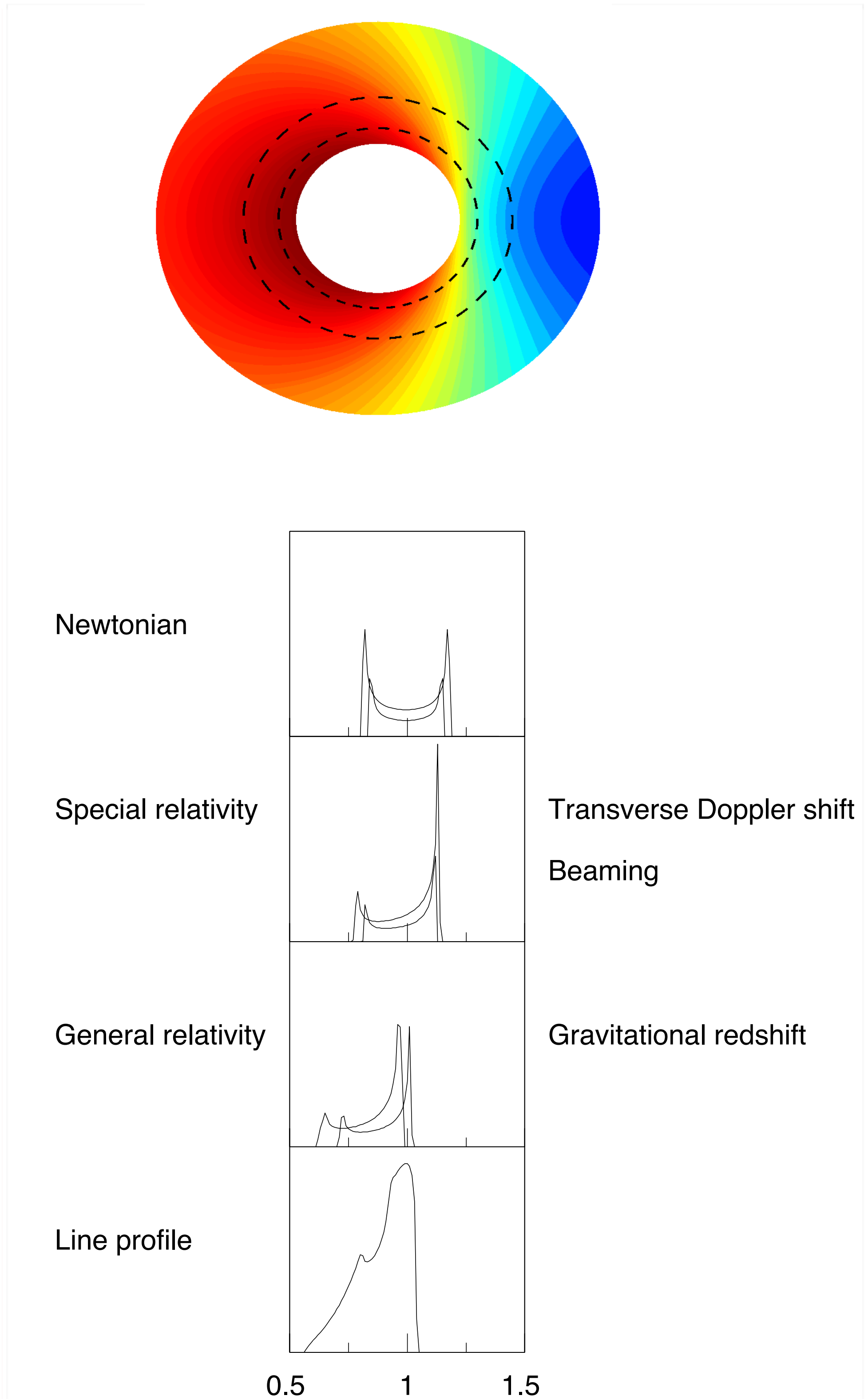




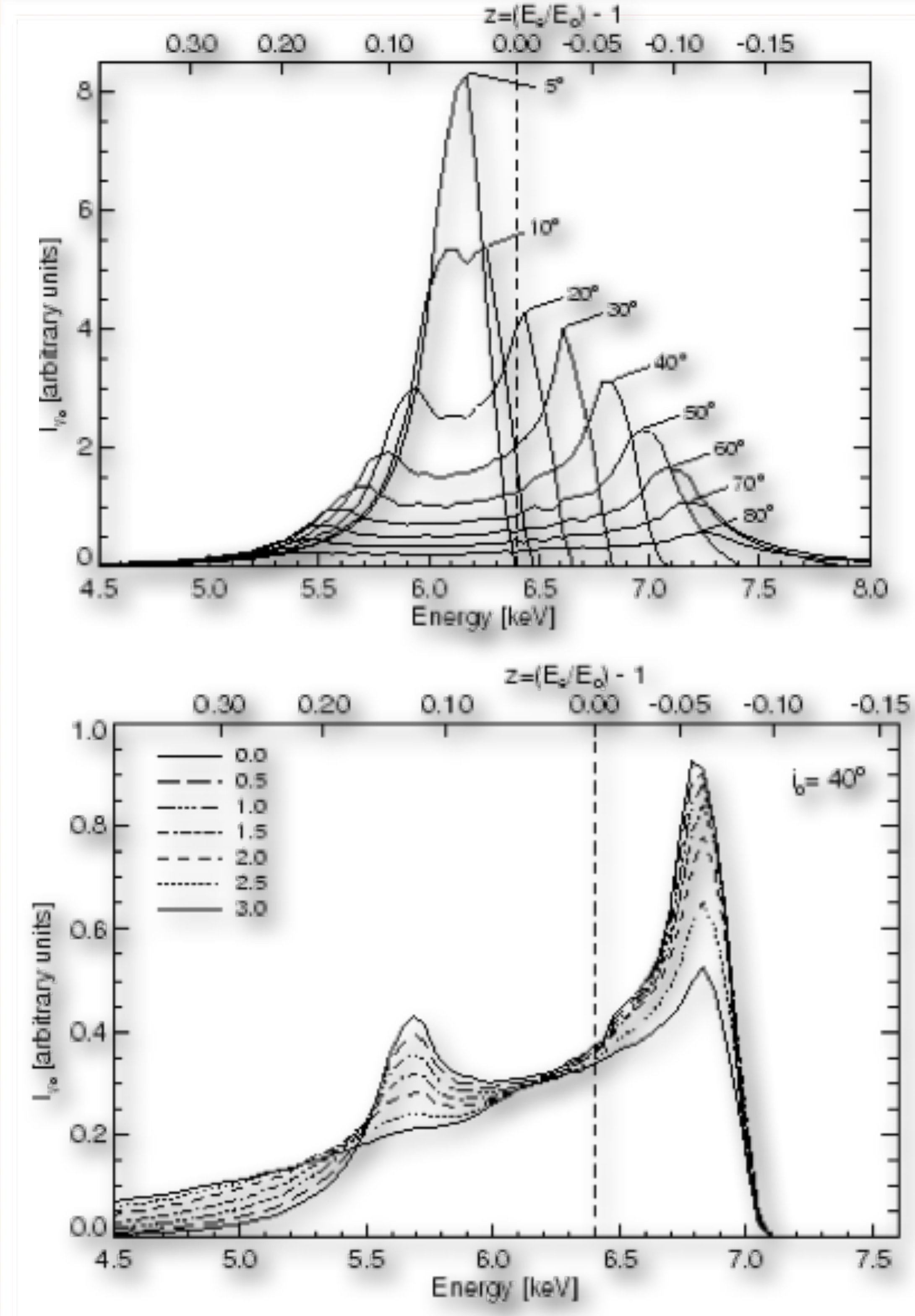
Main reflected features:

- Fe Kα line (6.4 keV)
- Fe absorption edge (7.1 keV)
- Compton hump (~10-30 keV)

NS LXMB: reflection spectrum

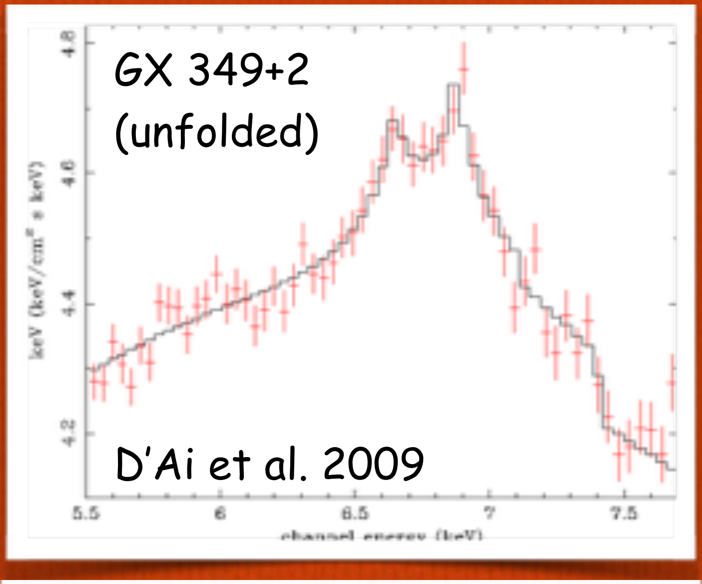


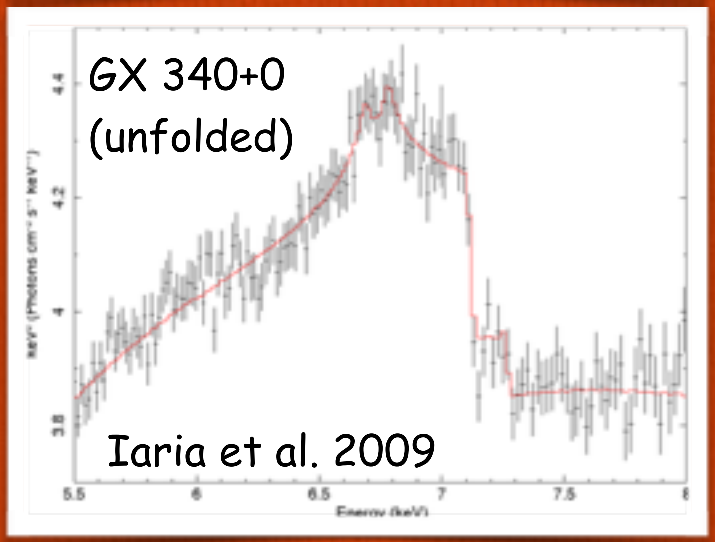
Fabian 2000

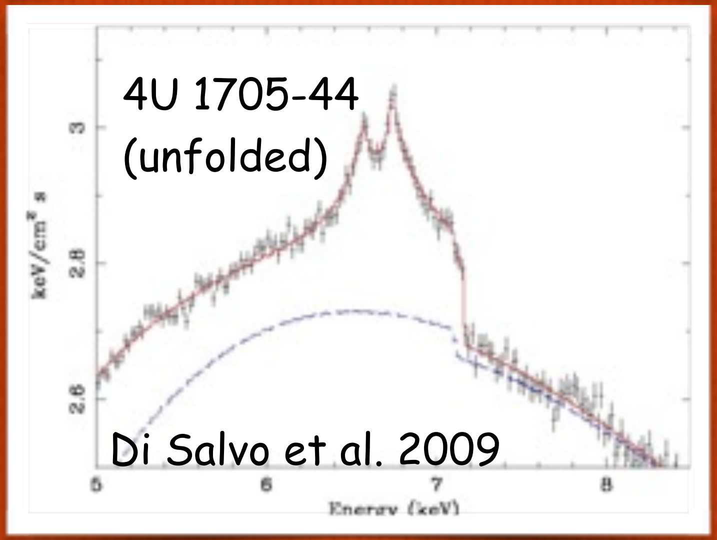


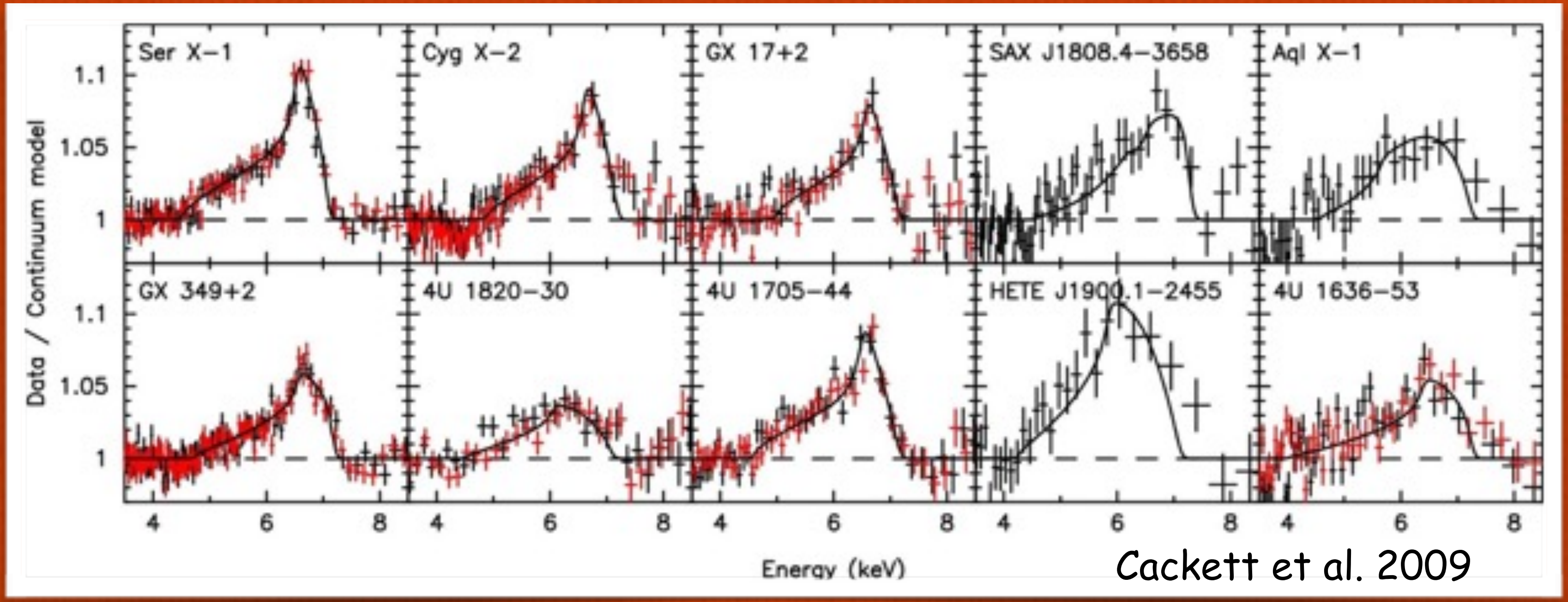
Reynolds & Nowak 2003

NS LXMB: Fe emission lines







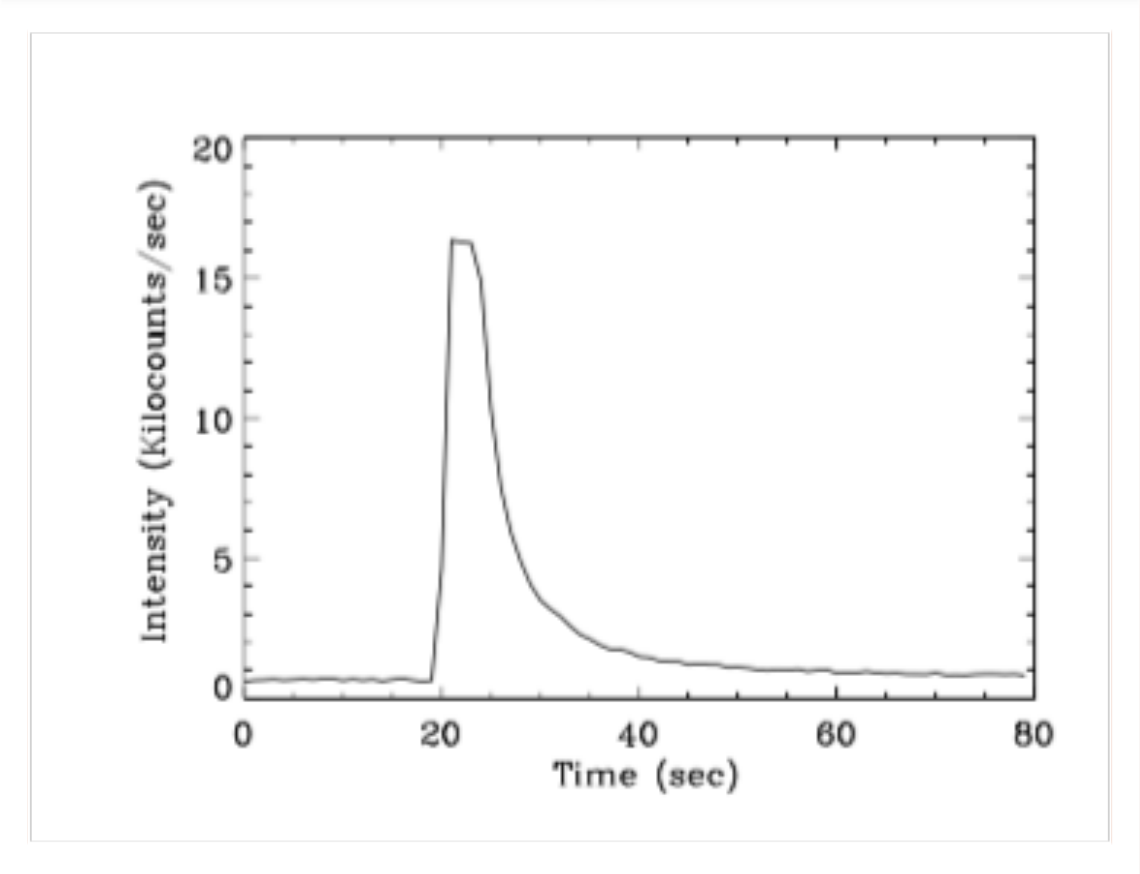


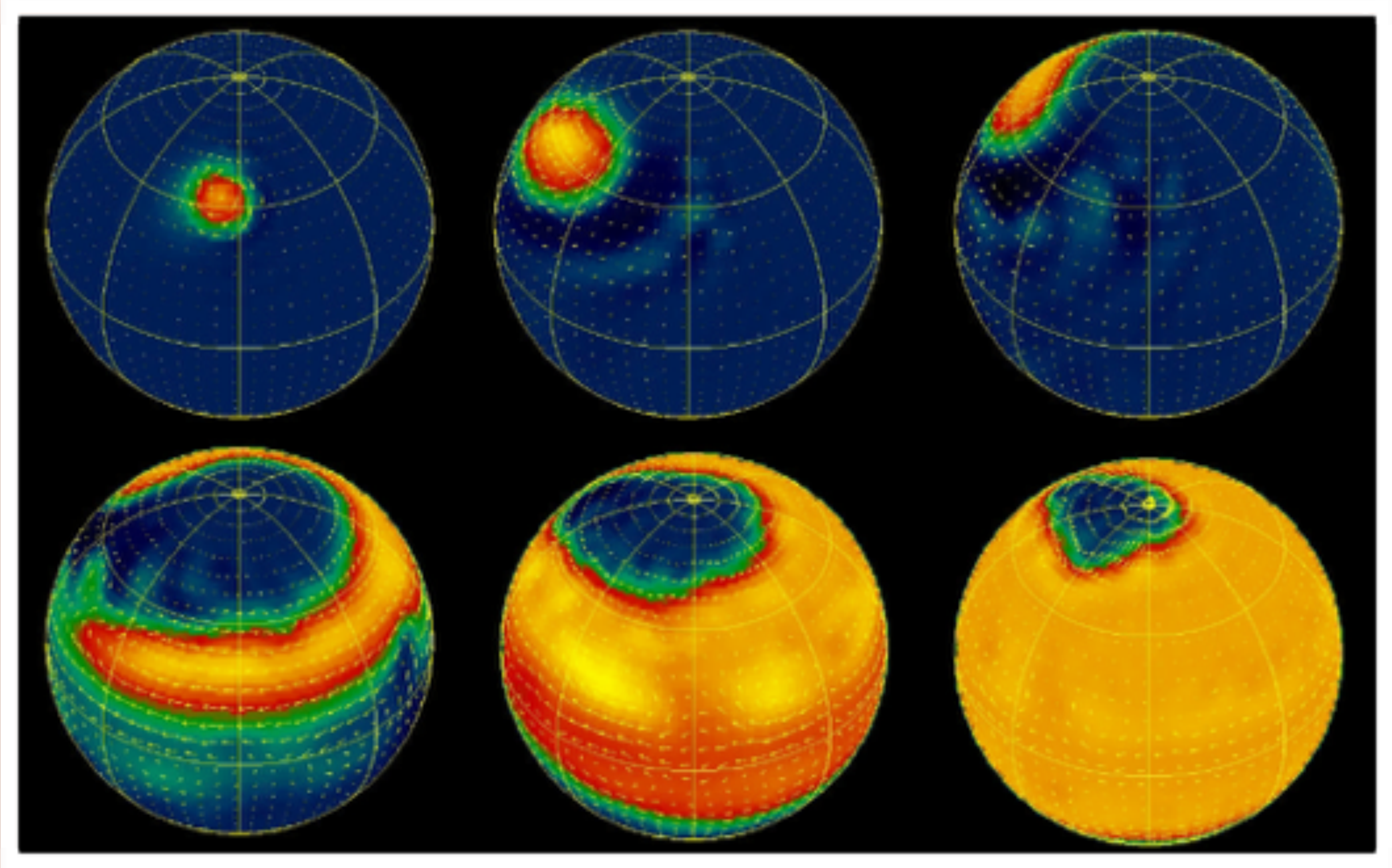
What do we get from them?

- Ionisation parameter and element abundance
- Disk emissivity index
- Inner and outer radii of the disk emitting region

Potentially we could constrain M & R → EoS

NS LXMB: X-ray type-I Bursts



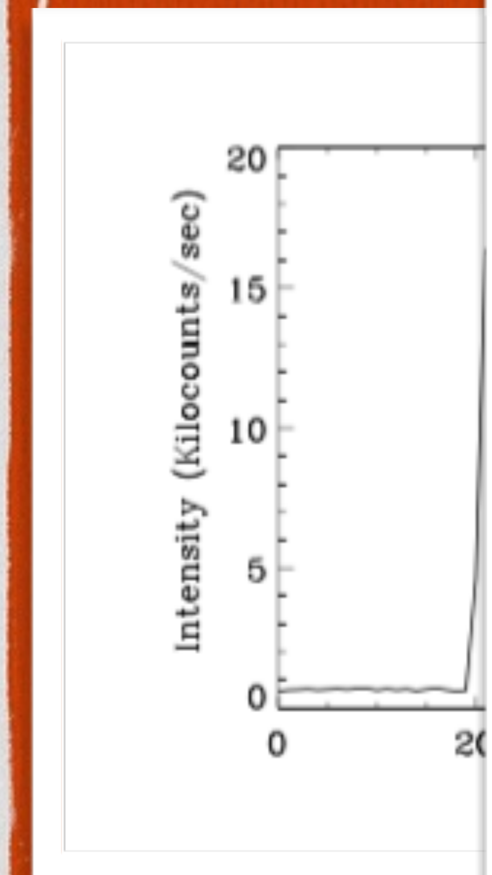


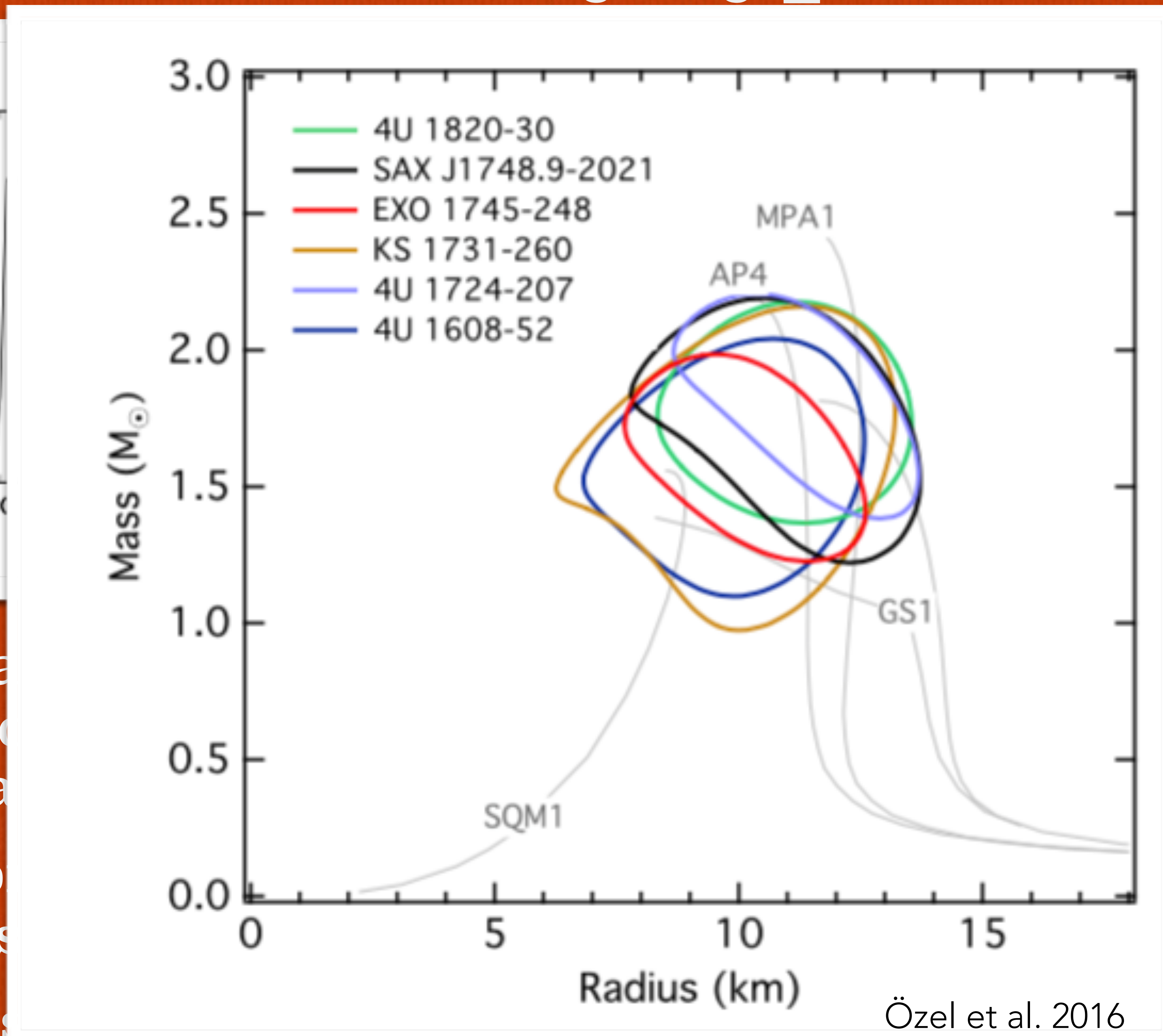
Spitkovsky, Levin, & Ushomirsky (2002)

Why are they useful?

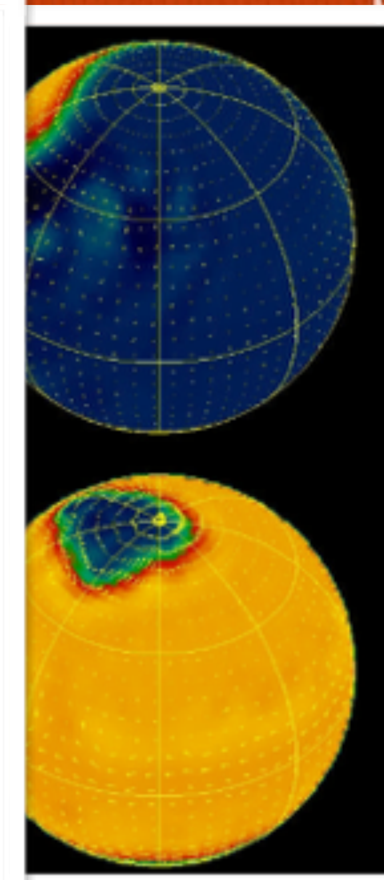
1. They originate from the NS surface, hence mass, radius and spin freq. influence their properties;
2. Very bright with respect to the continuum emission. Very easy to isolate the surface emission;
3. Large sample in more than 80 sources.

NS LXMB: X-ray type-I Bursts





Özel et al. 2016



omirsky (2002)

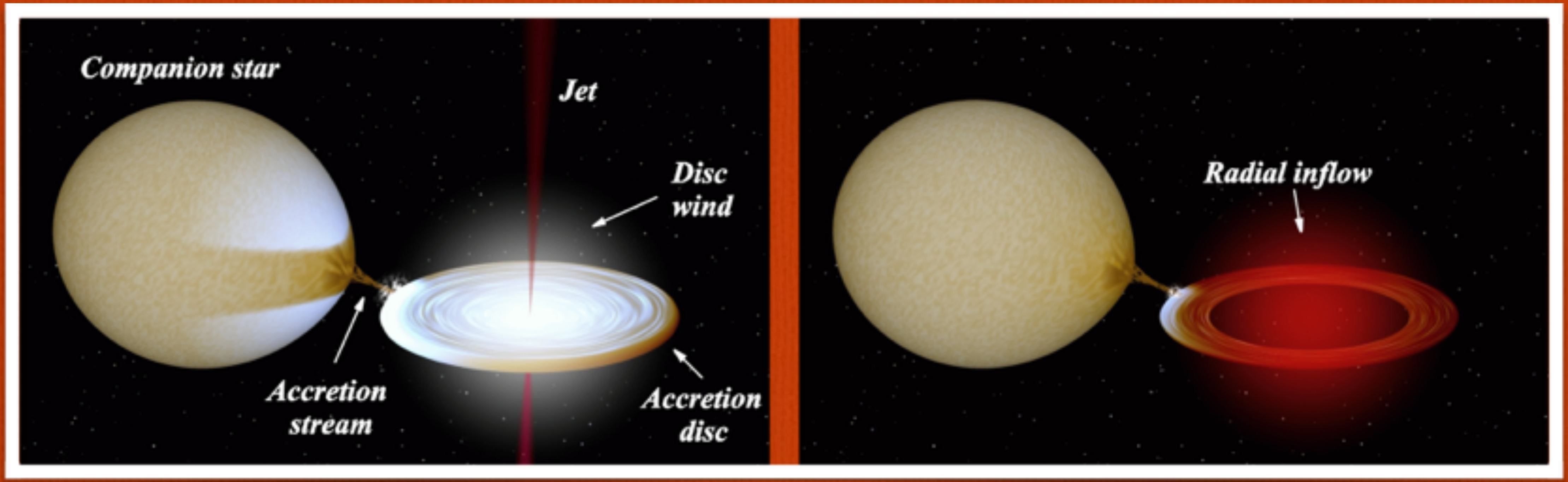
Why a

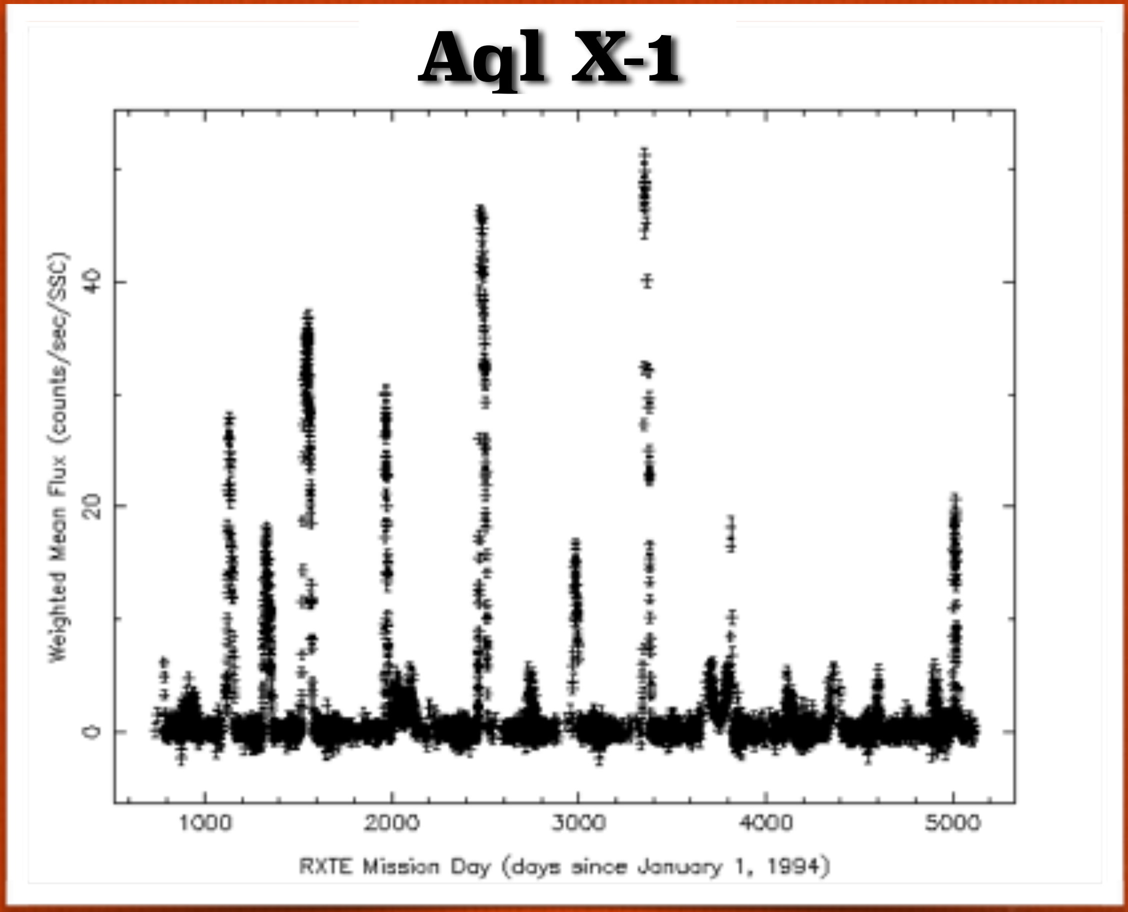
1. They c … e mass, radius a … s;

2. Very b … nission. Very eas

3. Large s

NS LXMB variability

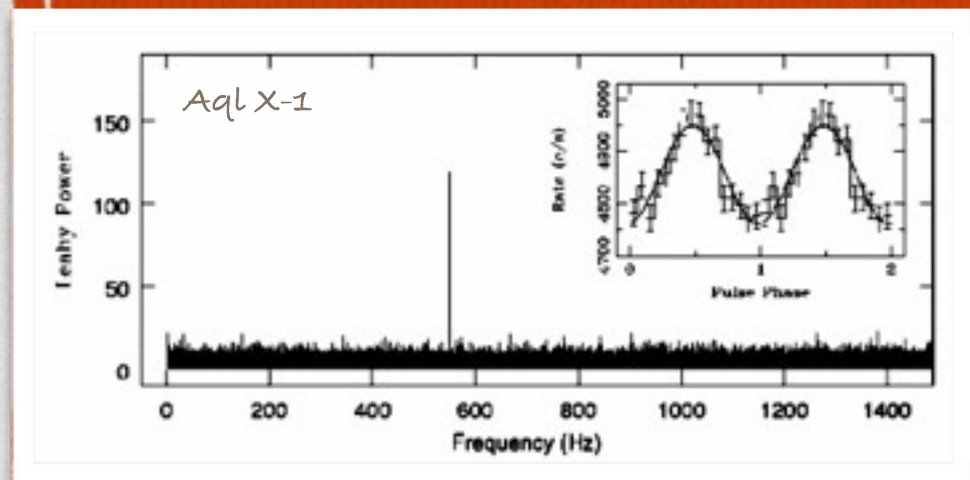




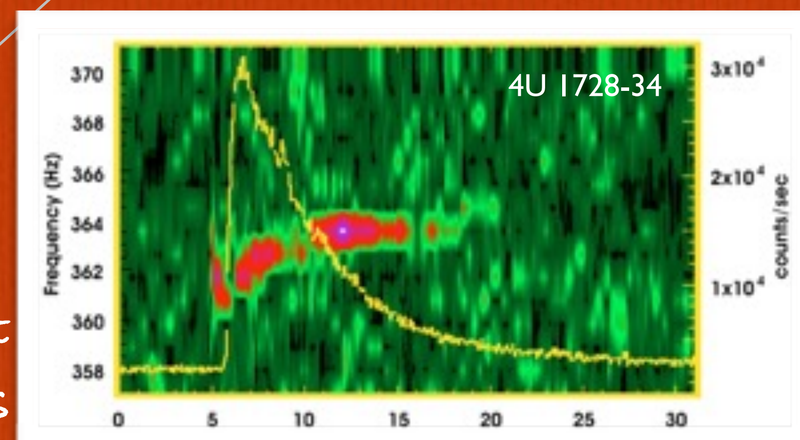
X-ray transients:

- Outburst phase (day-months) $L_X=10^{36}$-10^{38} erg/s
- Quiescence phase (months-years) $L_X=10^{32}$-10^{34} erg/s

NS LXMB: very rapid variability

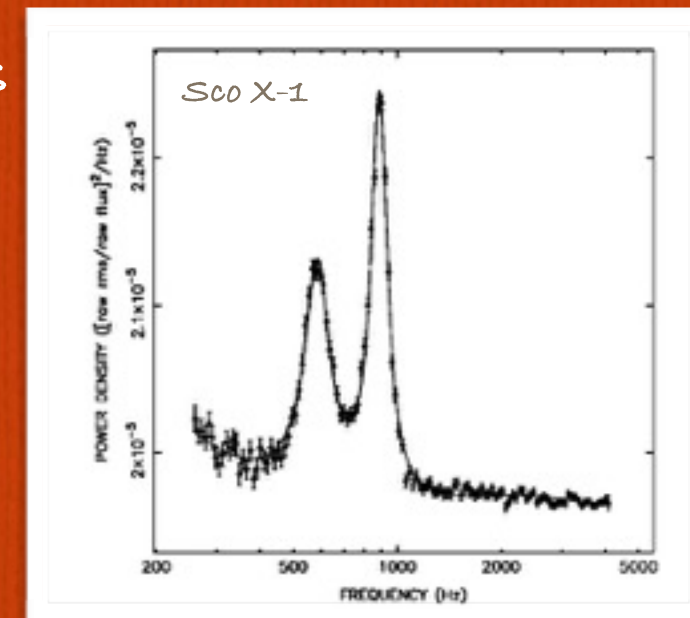


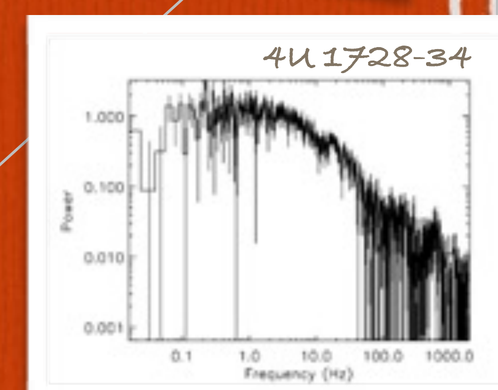
Pulses from accreting X-ray pulsars



Burst Oscillations

kHz QPOs



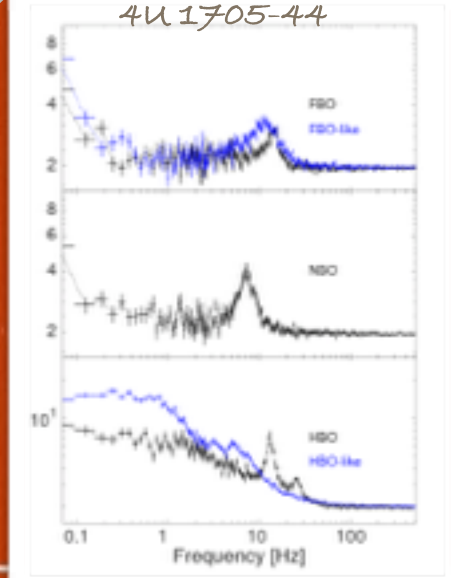


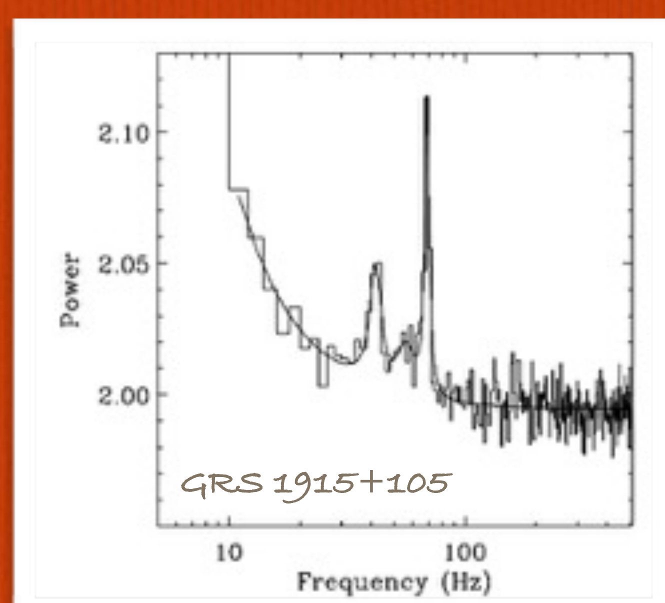
Periodic variability

Quasi periodic variability

Aperiodic variability

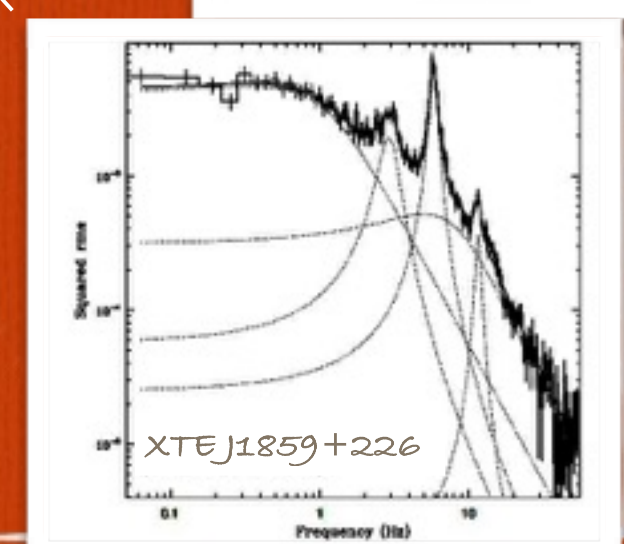
Low Frequency QPOs





High Frequency QPOs

Broad band Noise

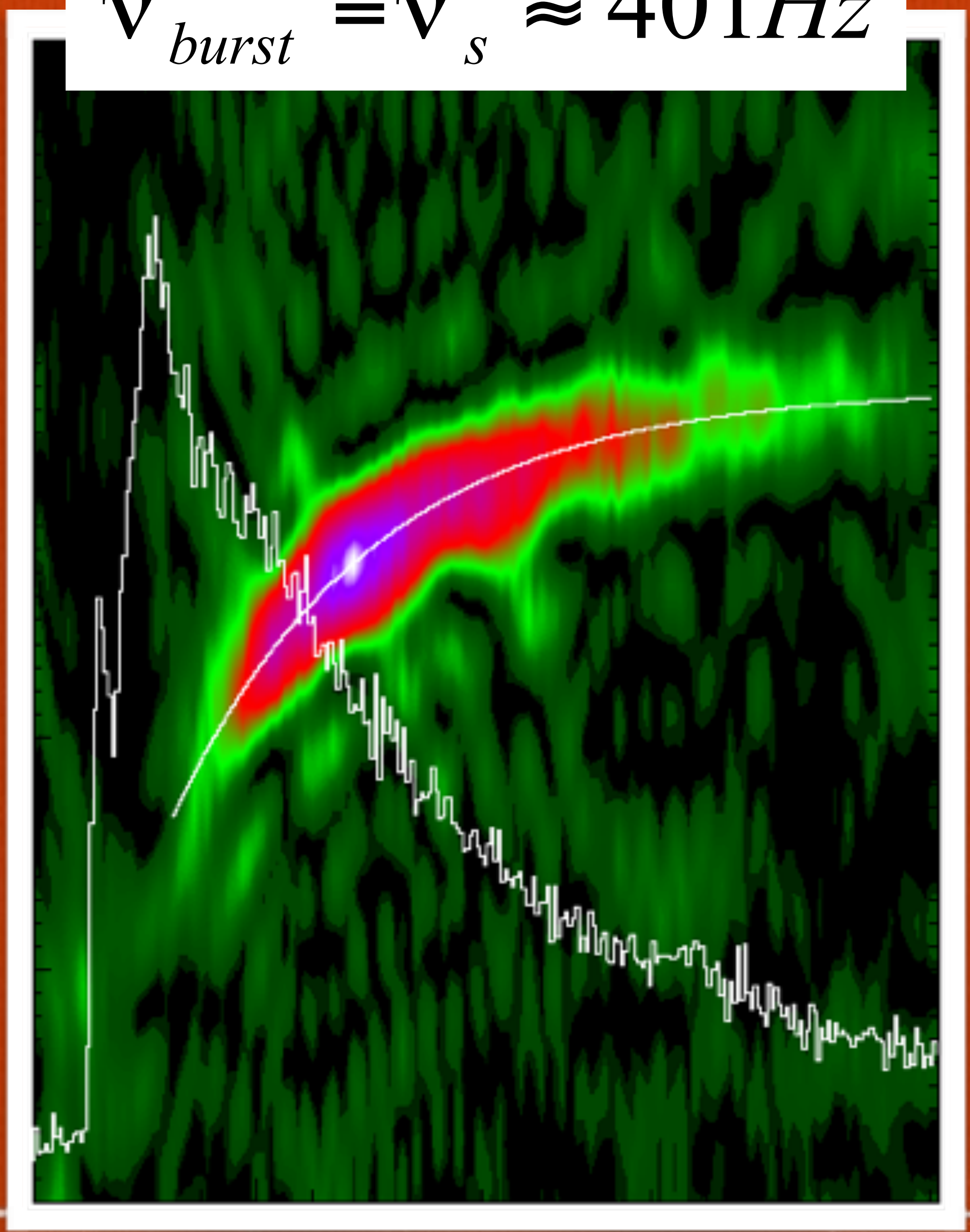


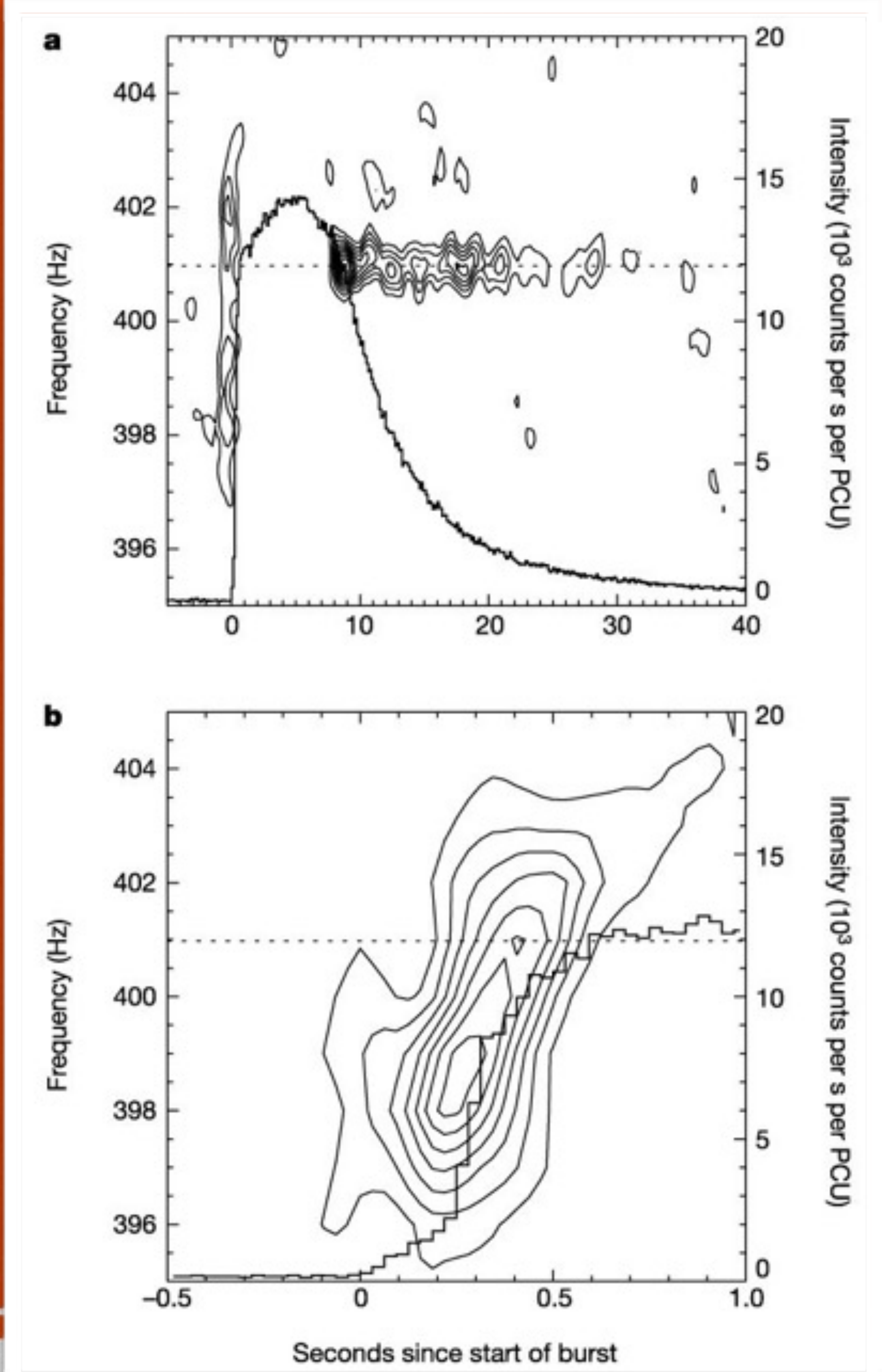
credit: S. Motta

NS LXMB: Bursts oscillations

SAX J1808.4-3658 confirms that the asymptotic frequency of burst oscillations is the spin frequency of the NS

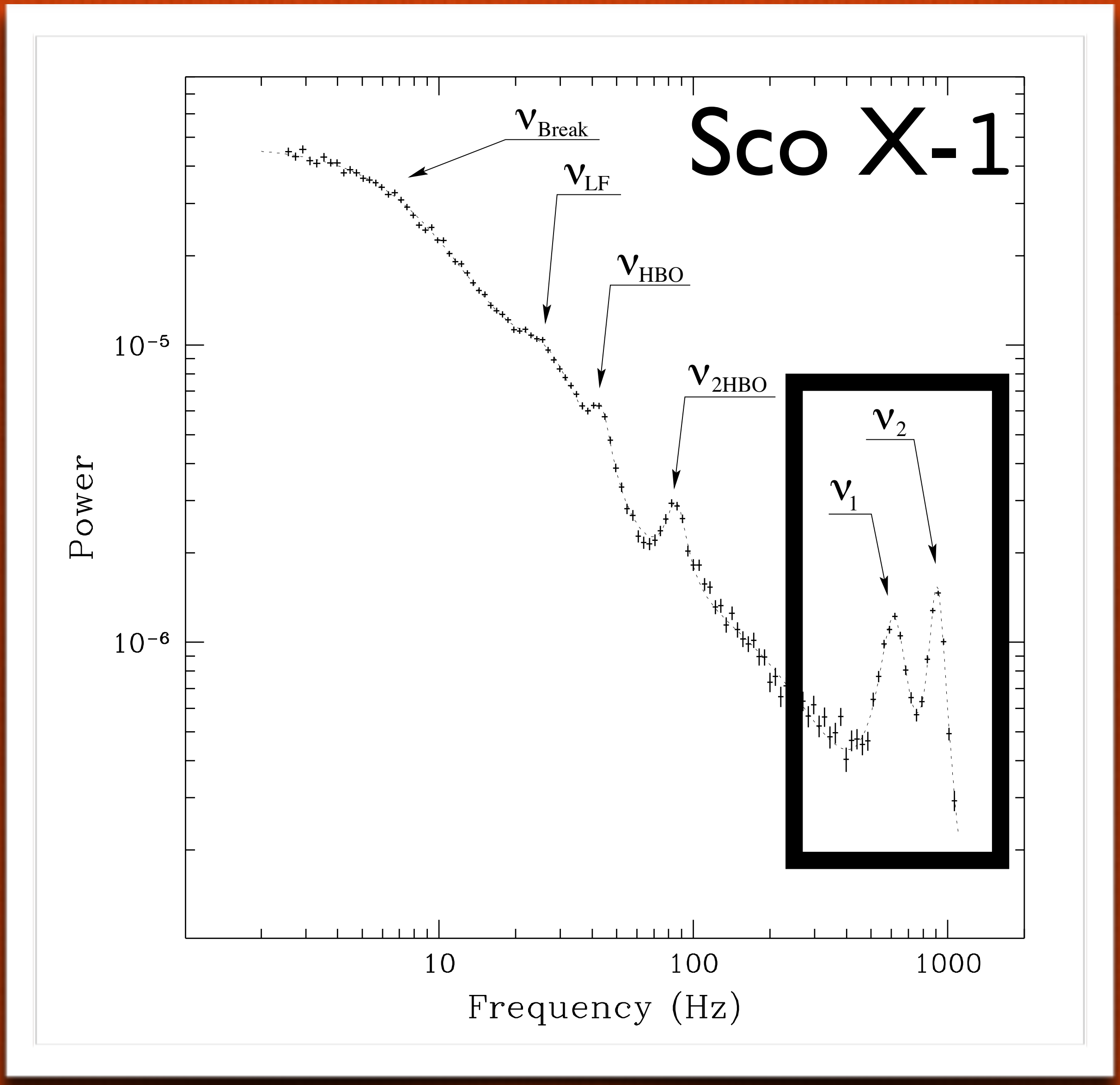
$$\nu_{burst} = \nu_s \approx 401 Hz$$



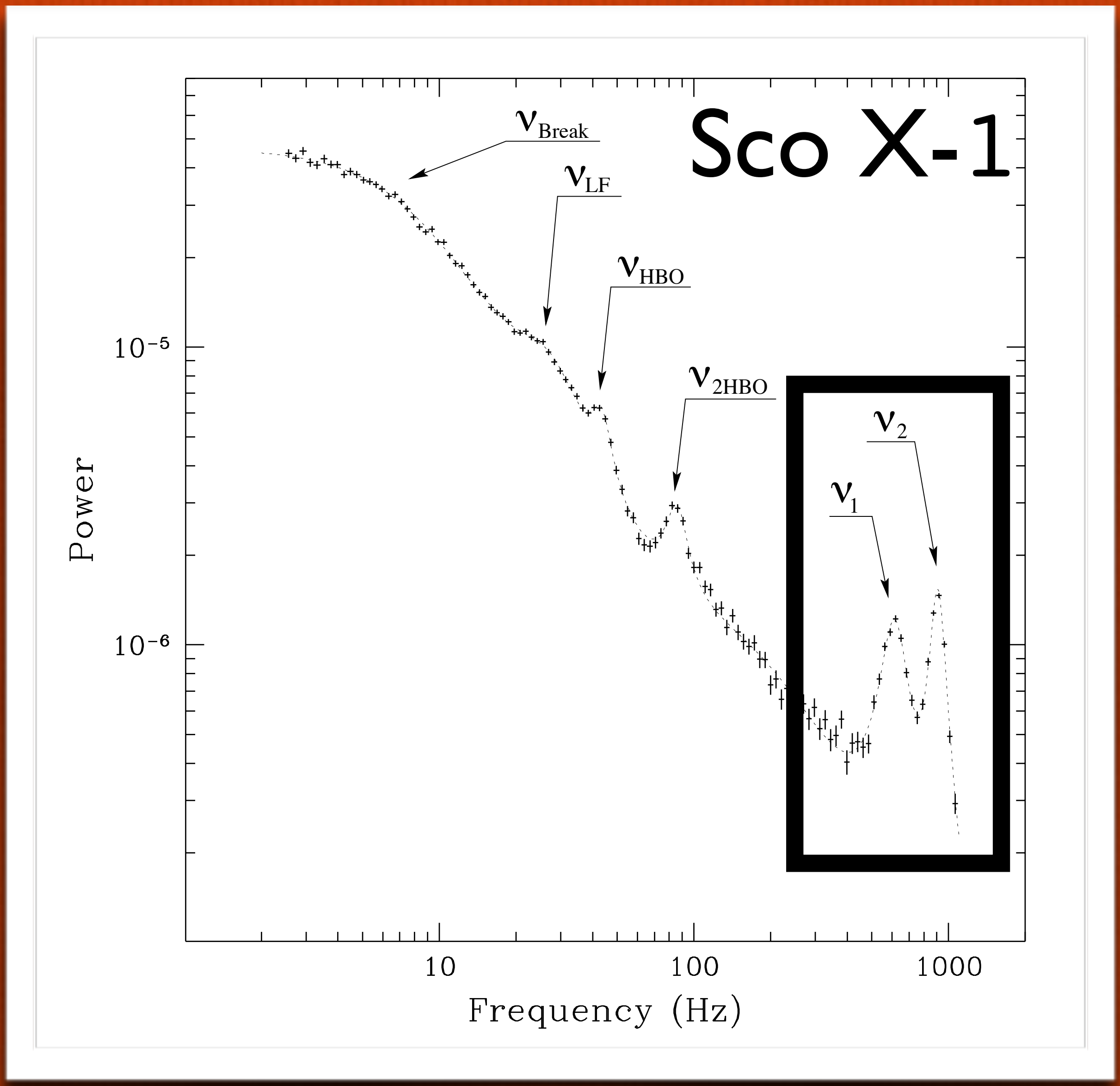


NS LXMB: kHz QPOs

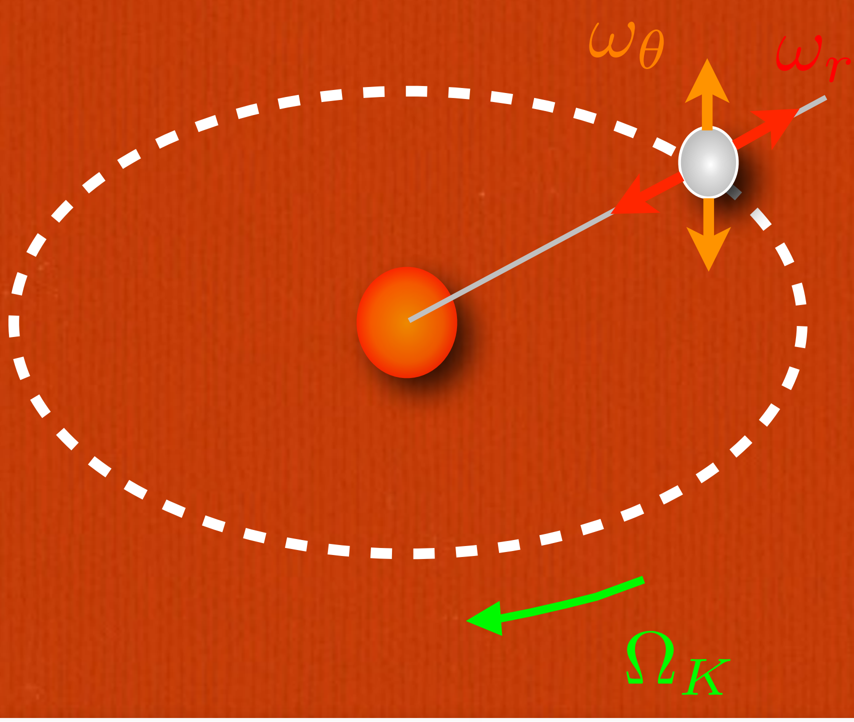
Kuznetsov 2002

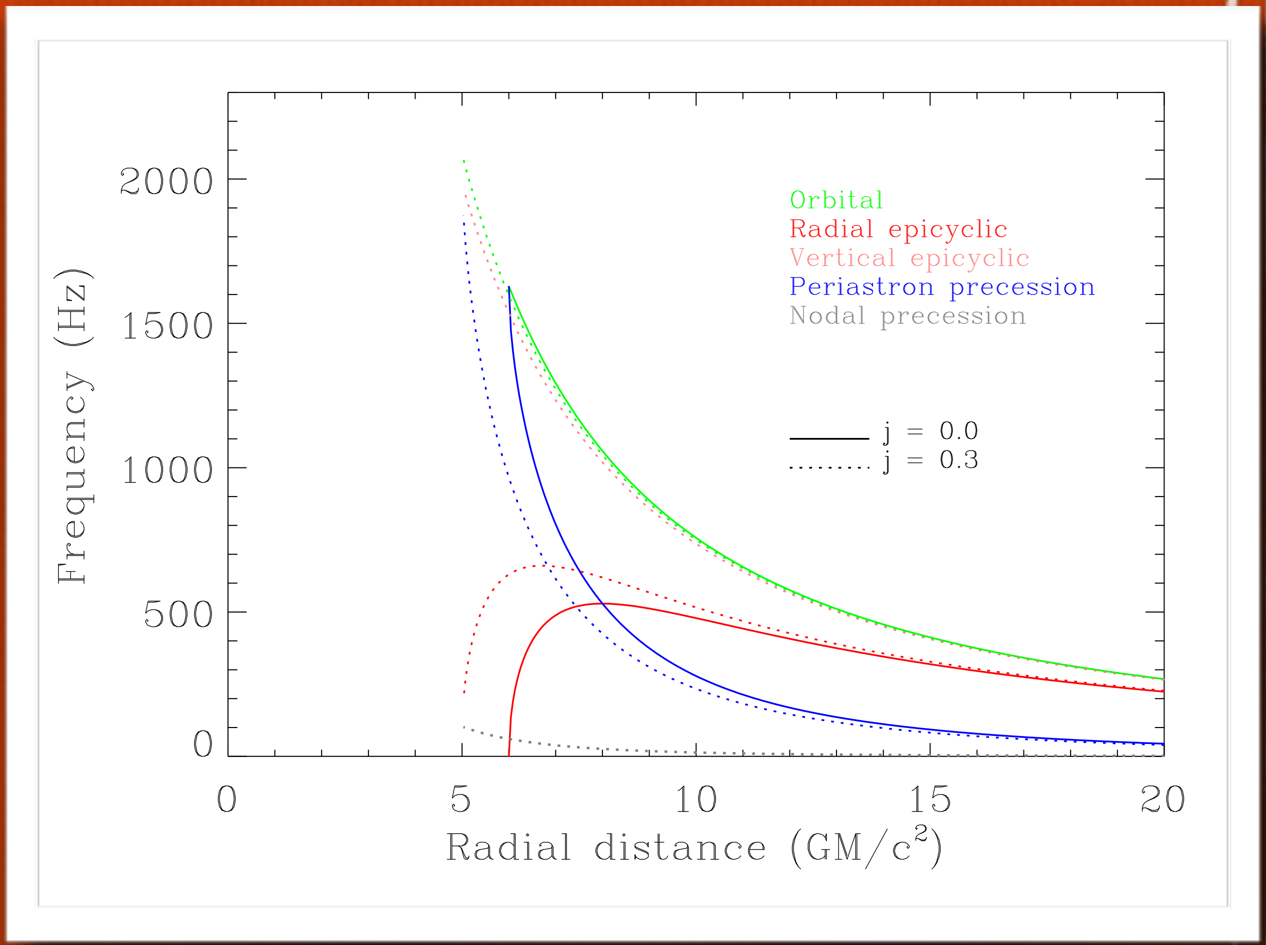


NS LXMB: kHz QPOs



Kuznetsov 2002





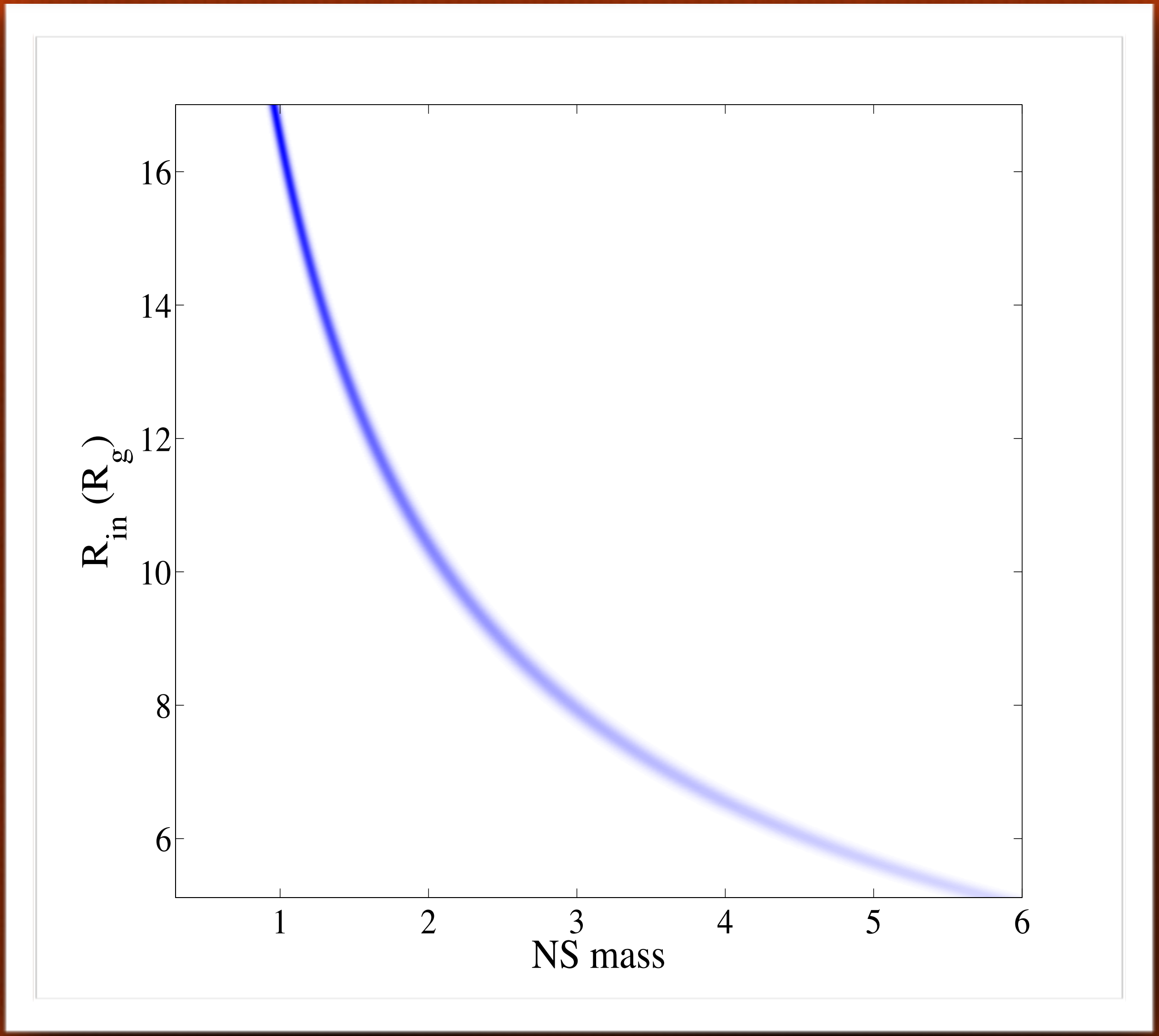
NS LXMB: kHz QPOs

4U 1636-53

- shows strong broad iron emission line
- shows plenty of kHz QPOs
- simultaneous high-time resolution (RXTE) and moderate-energy resolution (XMM-Newton) observations

NS LXMB: kHz QPOs

kHz QPO

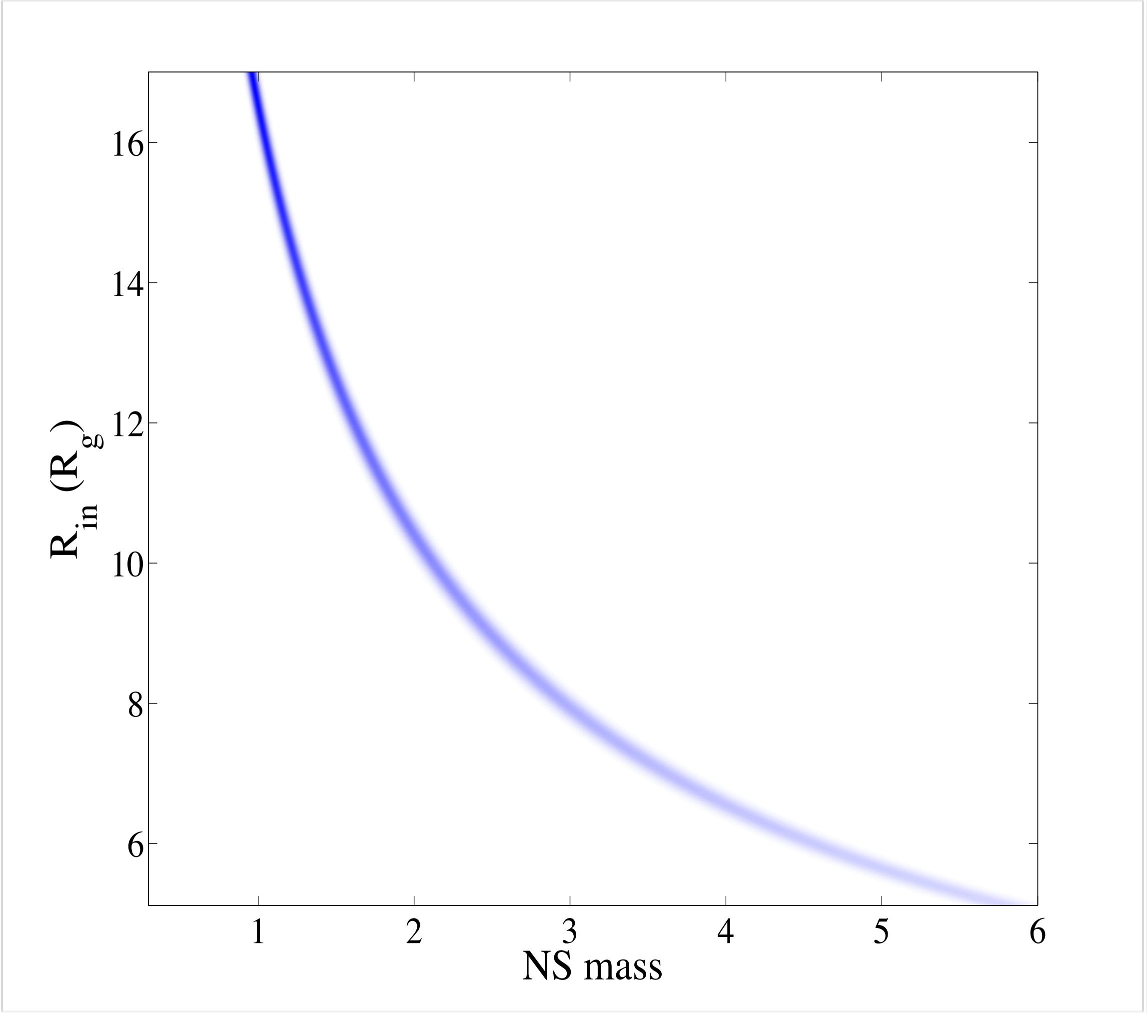


Sanna et al. 2014

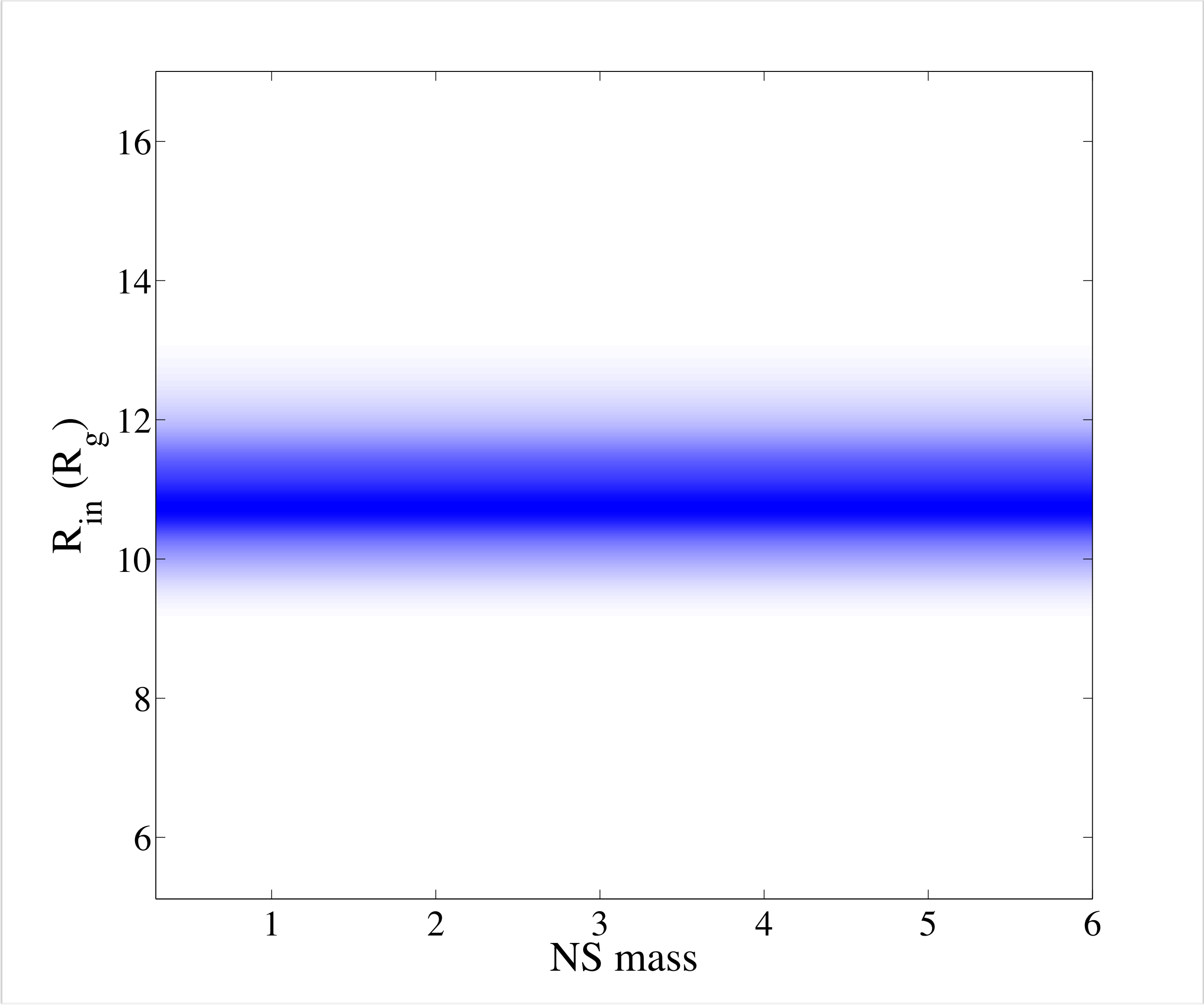
Assumption:
kHz QPO frequency reflects the orbital frequency

NS LXMB: kHz QPOs

kHz QPO

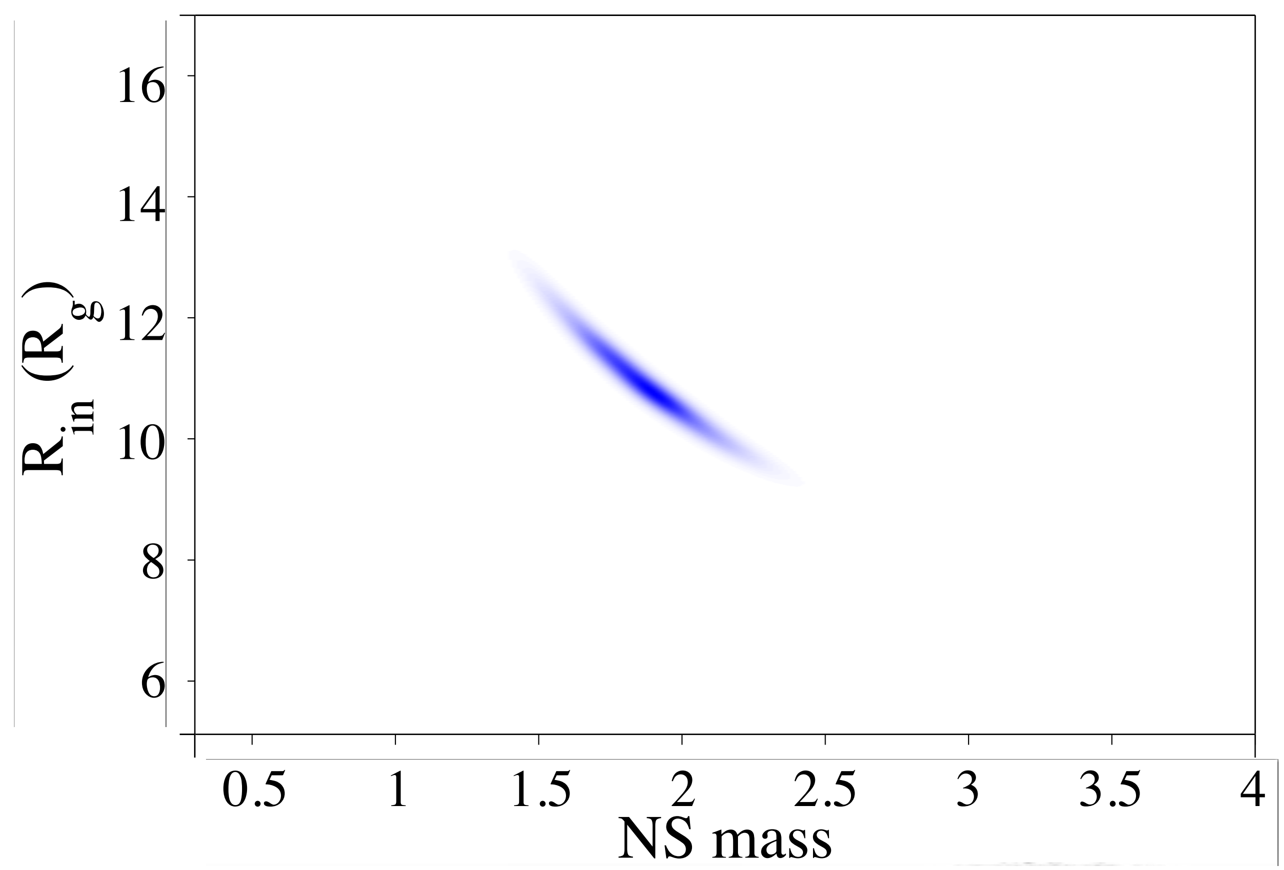


Fe line

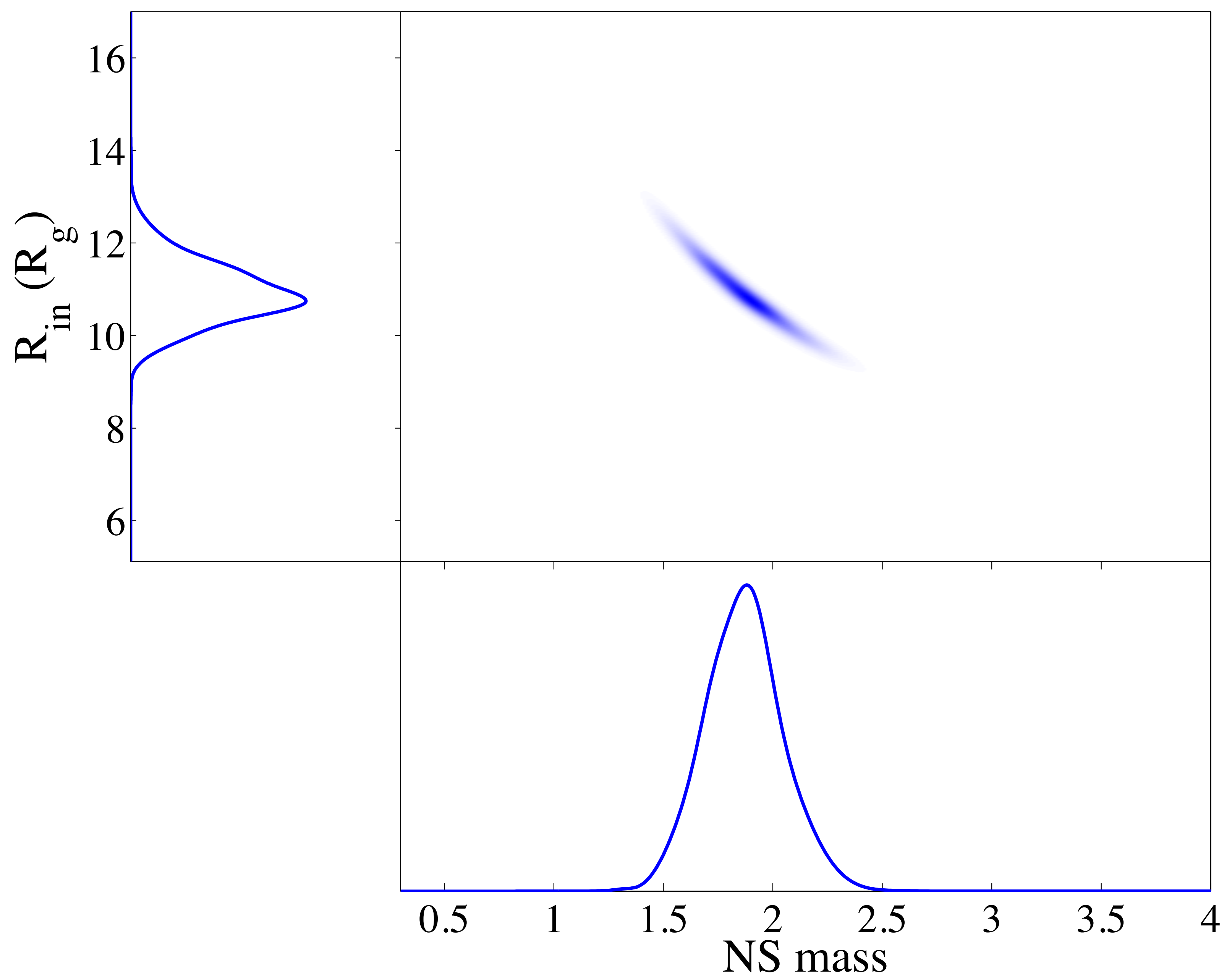


Sanna et al. 2014

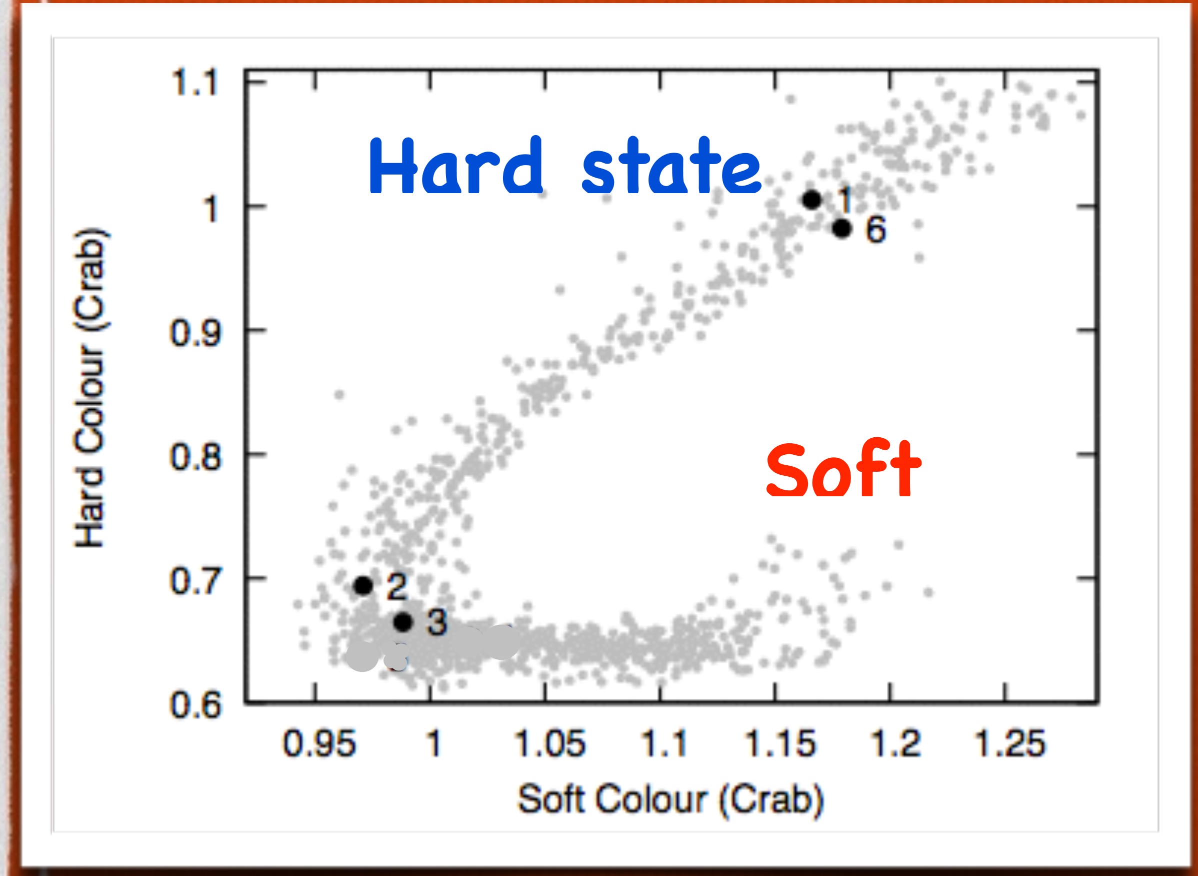
NS LXMB: kHz QPOs



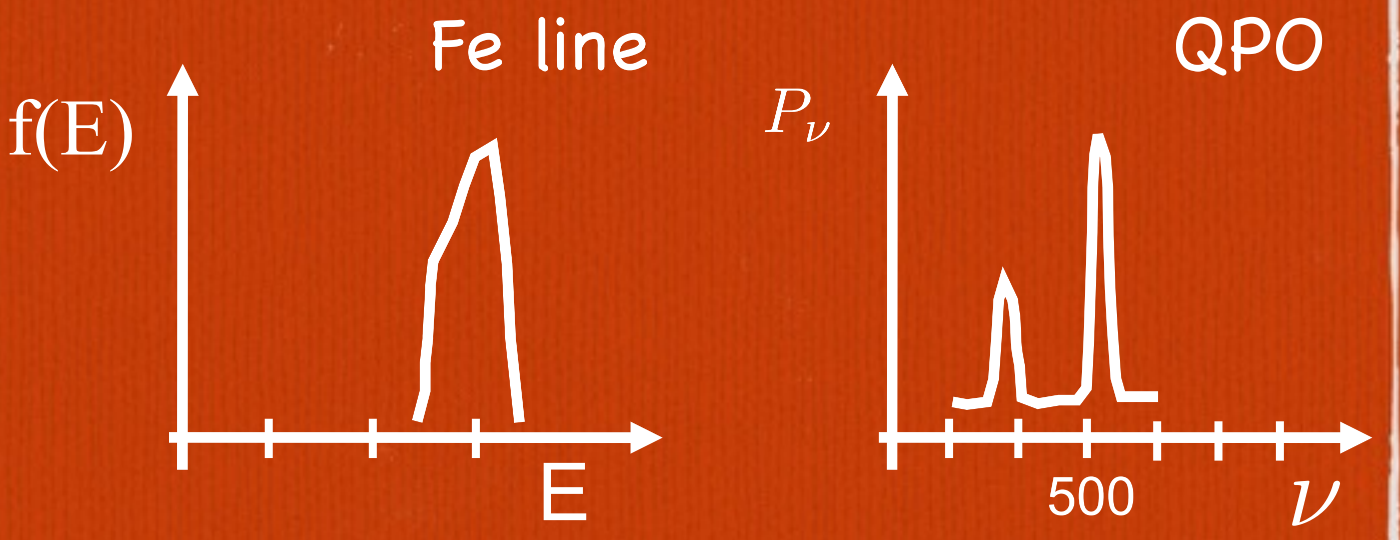
NS LXMB: kHz QPOs



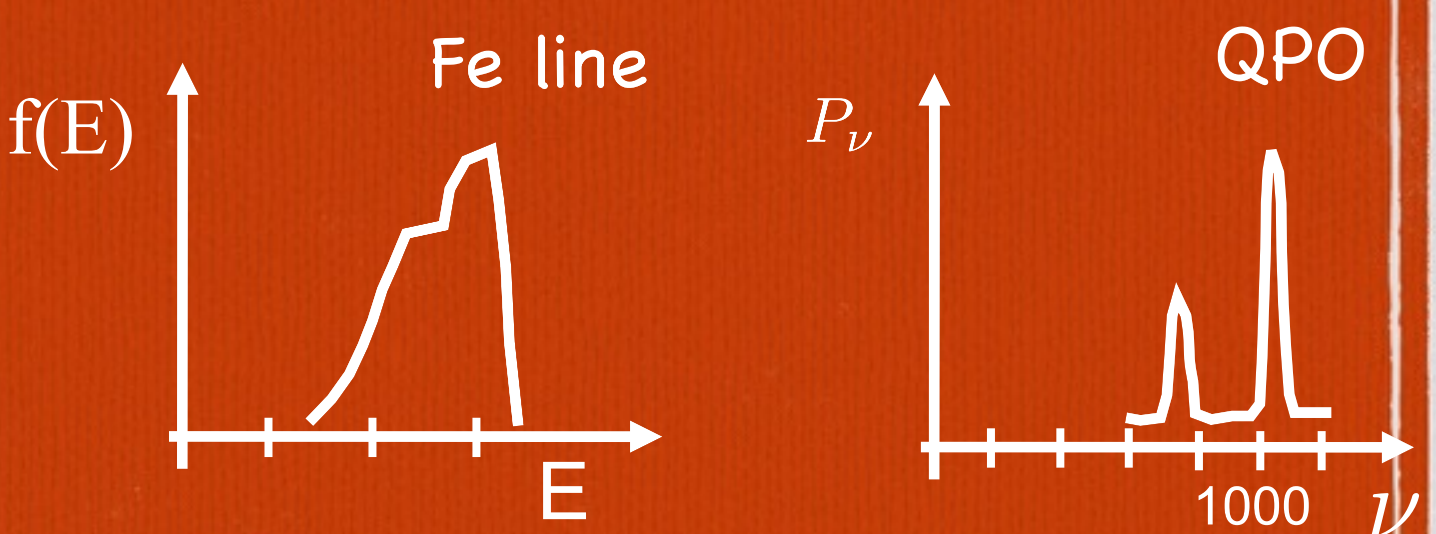
NS LXMB: kHz QPOs



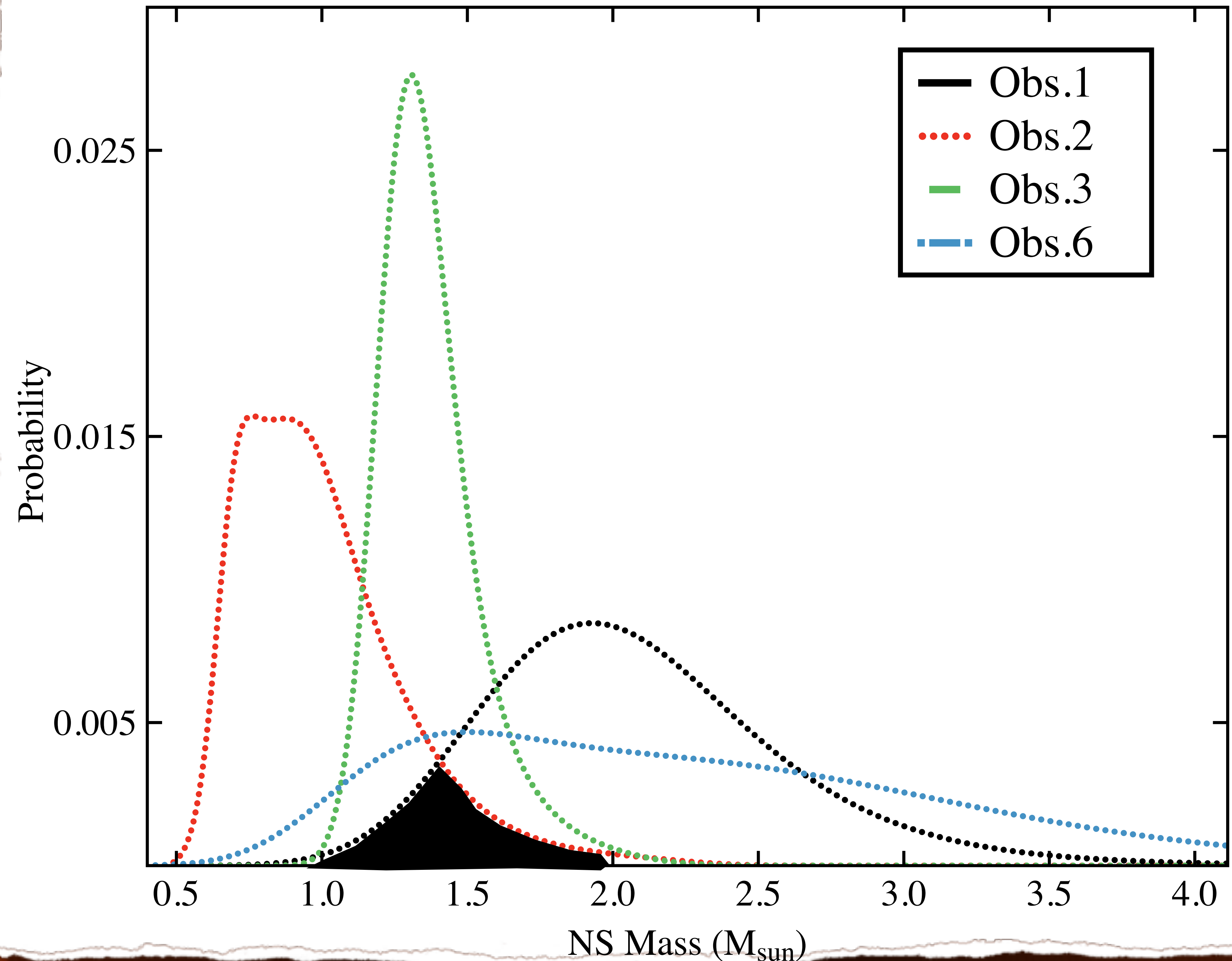
Hard state



Soft state

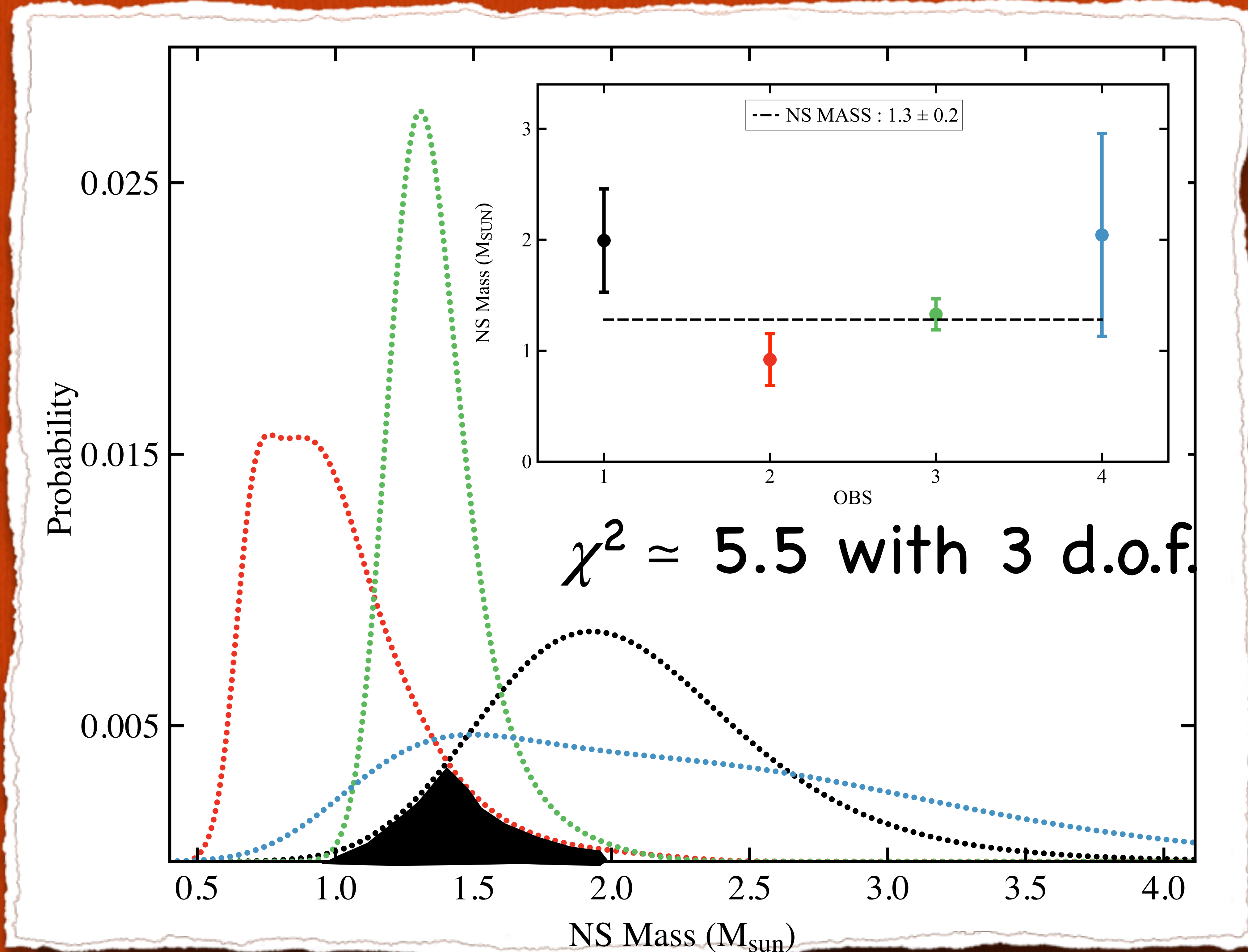


NS LXMB: kHz QPOs



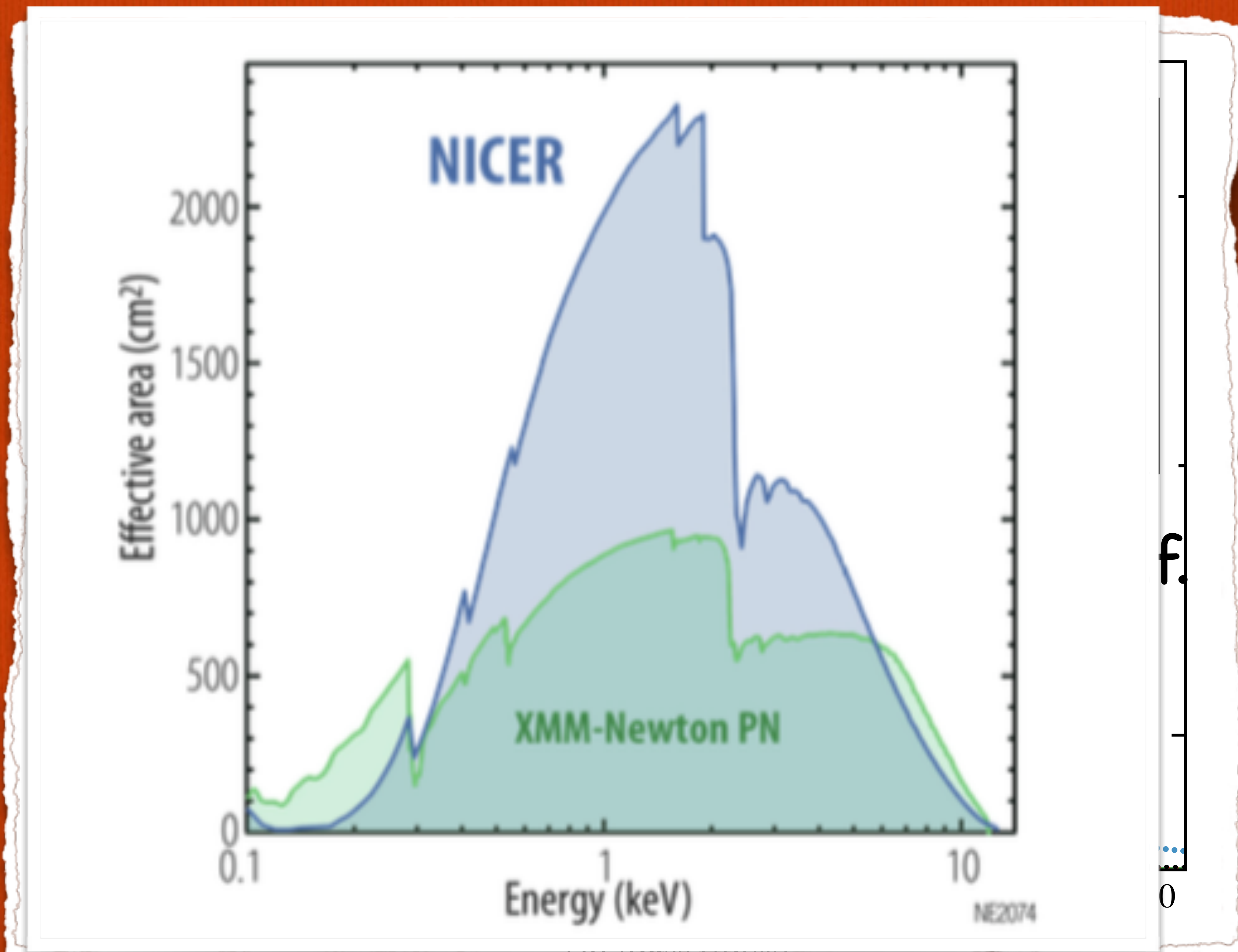
Sanna et al. 2014

NS LXMB: kHz QPOs



Sanna et al. 2014

NS LXMB: kHz QPOs

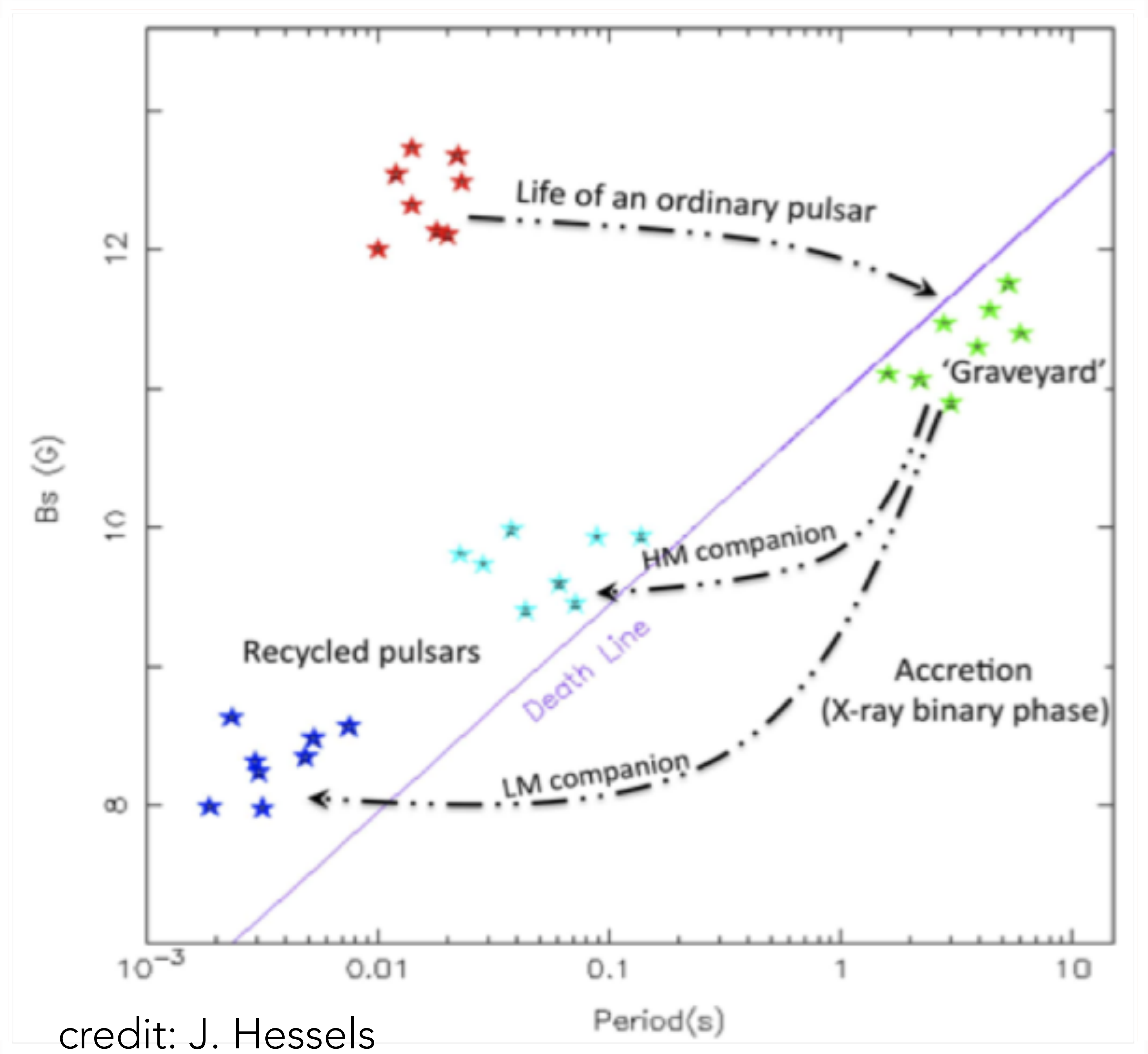


Sanna et al. 2014

Accreting Millisecond X-ray pulsars

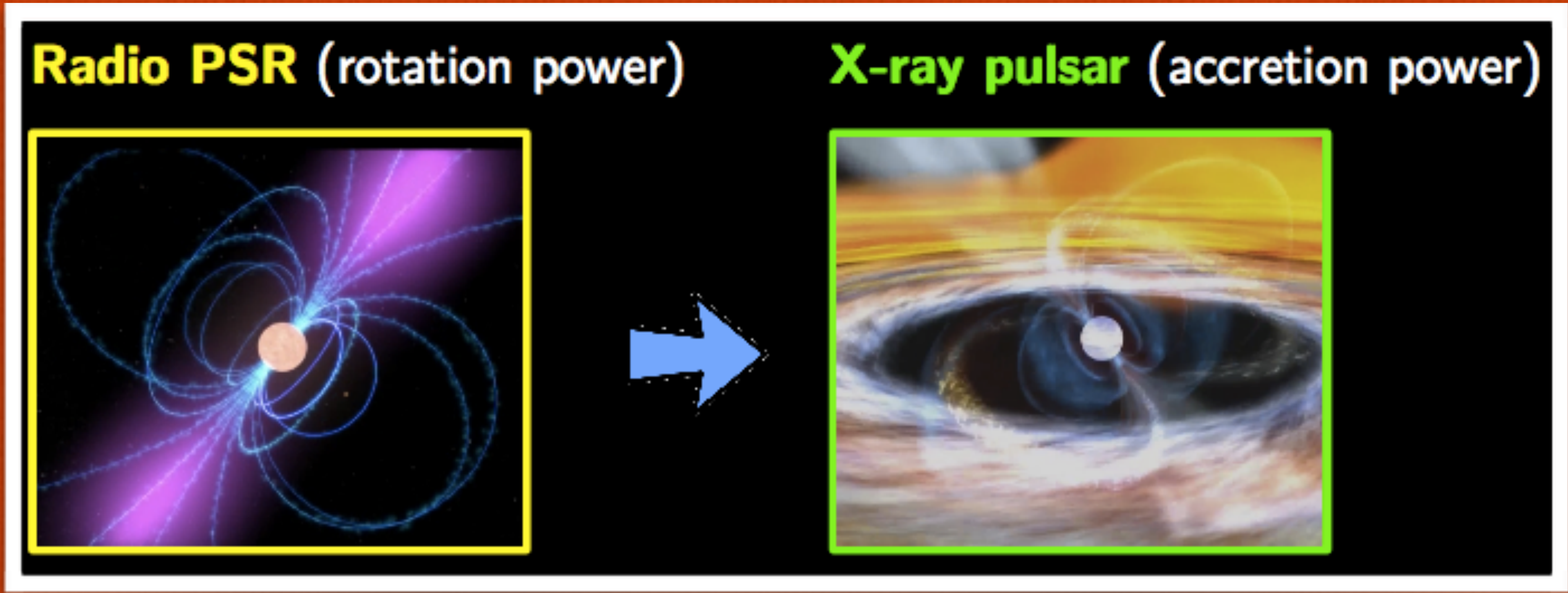
Name	P_spin (ms)	P_orb (h)	Ref
SAX J1808.4-3658	2.5	2.0	Wijnands & van der Klis 1998
XTE J0929-314	5.4	0.73	Galloway et al. 2002
XTE J1751-305	2.3	0.7	Markwardt et al. 2002
XTE J1814-338	3.2	4.0	Markwardt et al. 2003
XTE J1807-294	5.3	0.67	Markwardt et al. 2003
IGR J00291+5934	1.7	2.5	Galloway et al. 2005
HETE J1900.1-2455	2.7	1.4	Kaaret et al. 2005
SWIFT J1756.9-2508	5.5	0.9	Markwardt et al. 2007
Aql X-1	1.8	19	Casella et al. 2007
SAX J1748.9-2021	2.3	8.8	Altamirano et al. 2007
NGC 6440 X-2	4.8	0.96	Altamirano et al. 2010
IGR J17511-3057	4.1	3.5	Markwardt et al. 2009
SWIFT J1749.4-2807	1.9	8.8	Altamirano et al. 2010
IGR J1749.8-2921	2.5	3.84	Papitto et al. 2011
IGR J18245-2452	3.9	11.03	Papitto et al. 2013
XSS J12270	1.7	6.9	Bassa et al. 2014
PSR J1023+0038	1.7	4.75	Archibald et al. 2015
MAXI J0911-655	2.9	0.74	Sanna et al. 2017
IGR J17062-6143	6.1	>0.28	Strohmayer & Keek 2017
IGR J16597-3704	9.5	0.77	Sanna et al. 2017

AMXPs: Recycling Scenario

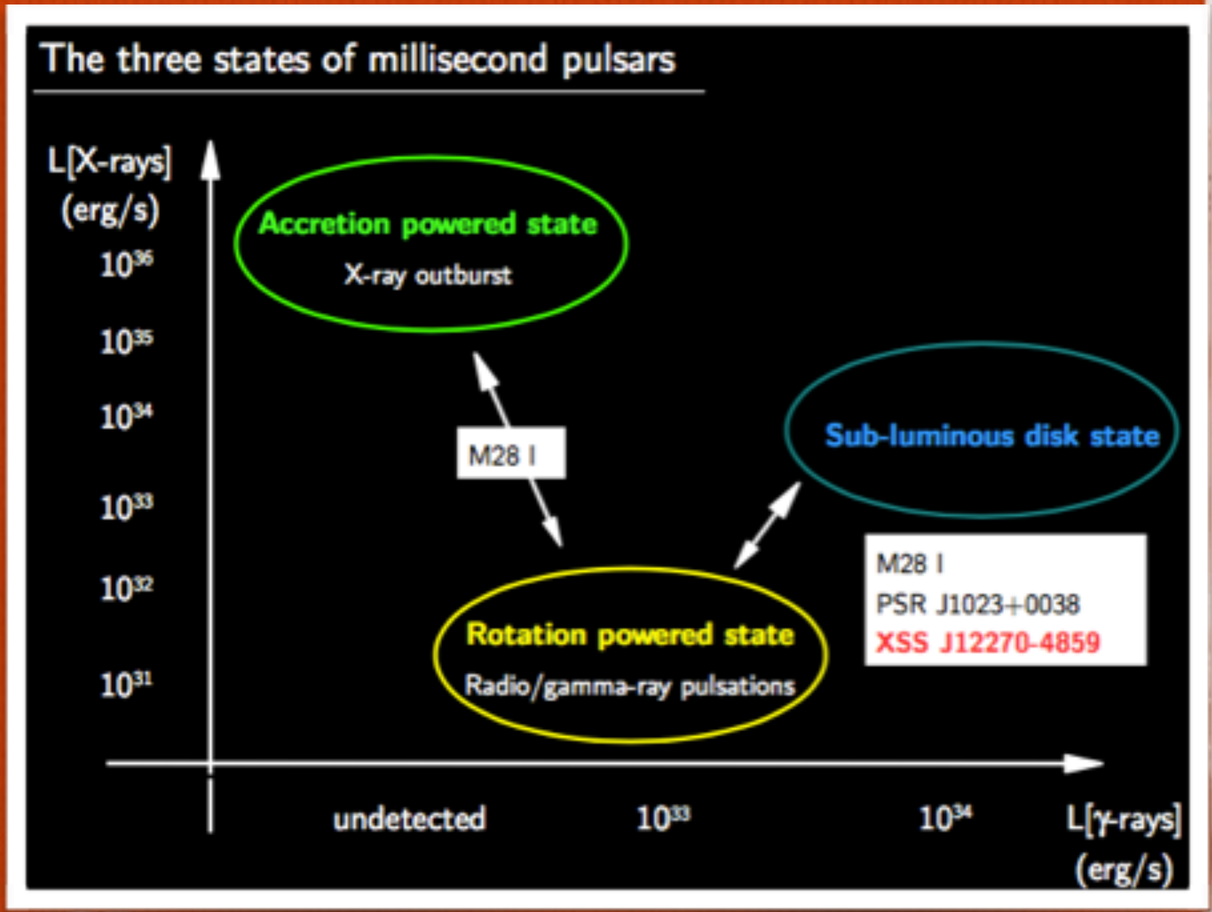


credit: J. Hessels

Transitional MSP



- PSR J1023+0038
- IGR J18245-2452
- XSS J12270-4859

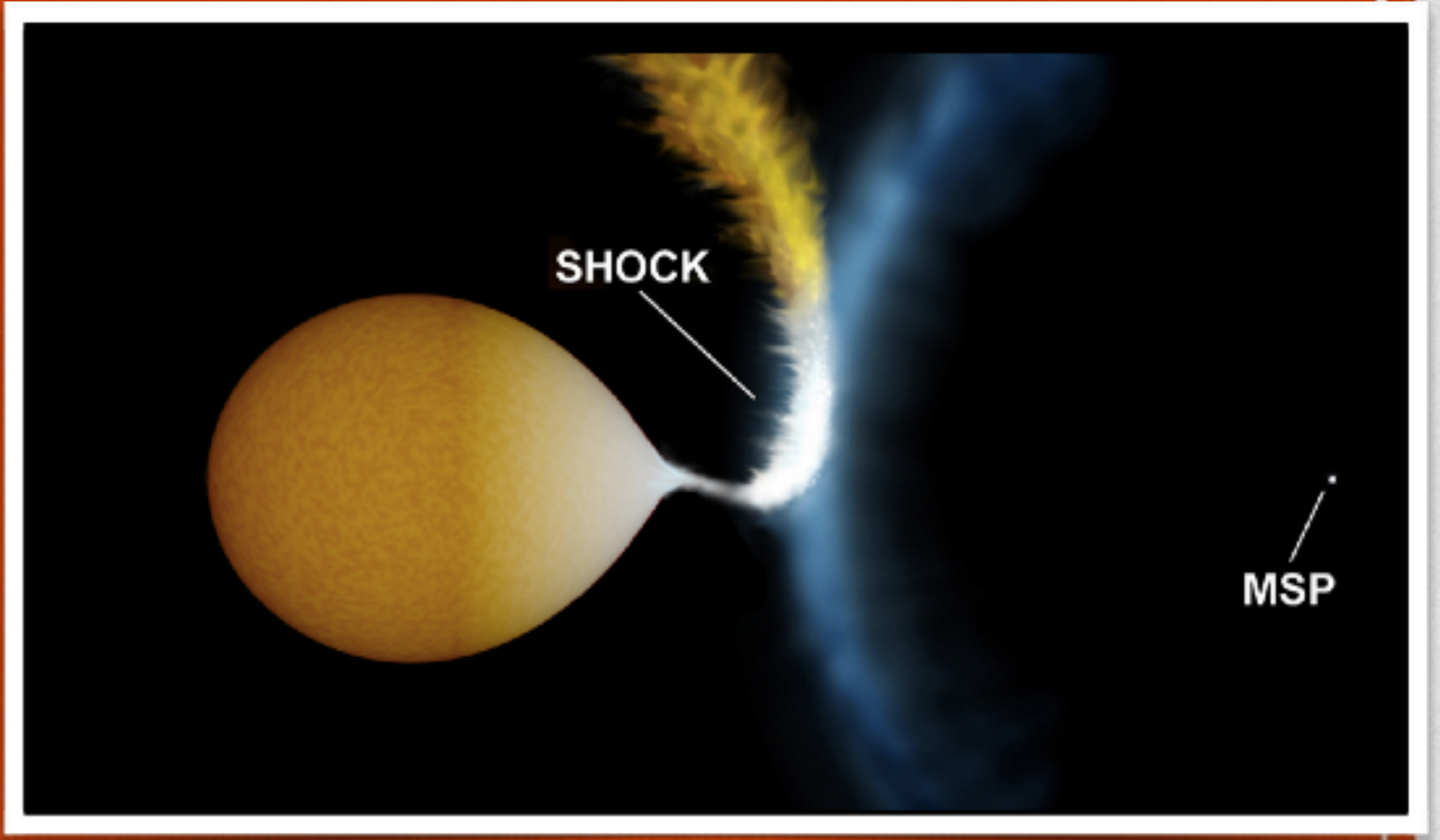


Did Transitionals reach the end of their LMXB phase?

Question: Can the LMXB phase finish at all??

For close systems (i.e. relatively short Porb), even if the companion star is detached, sooner or later GR will bring it in contact, resuming mass transfer and accretion.

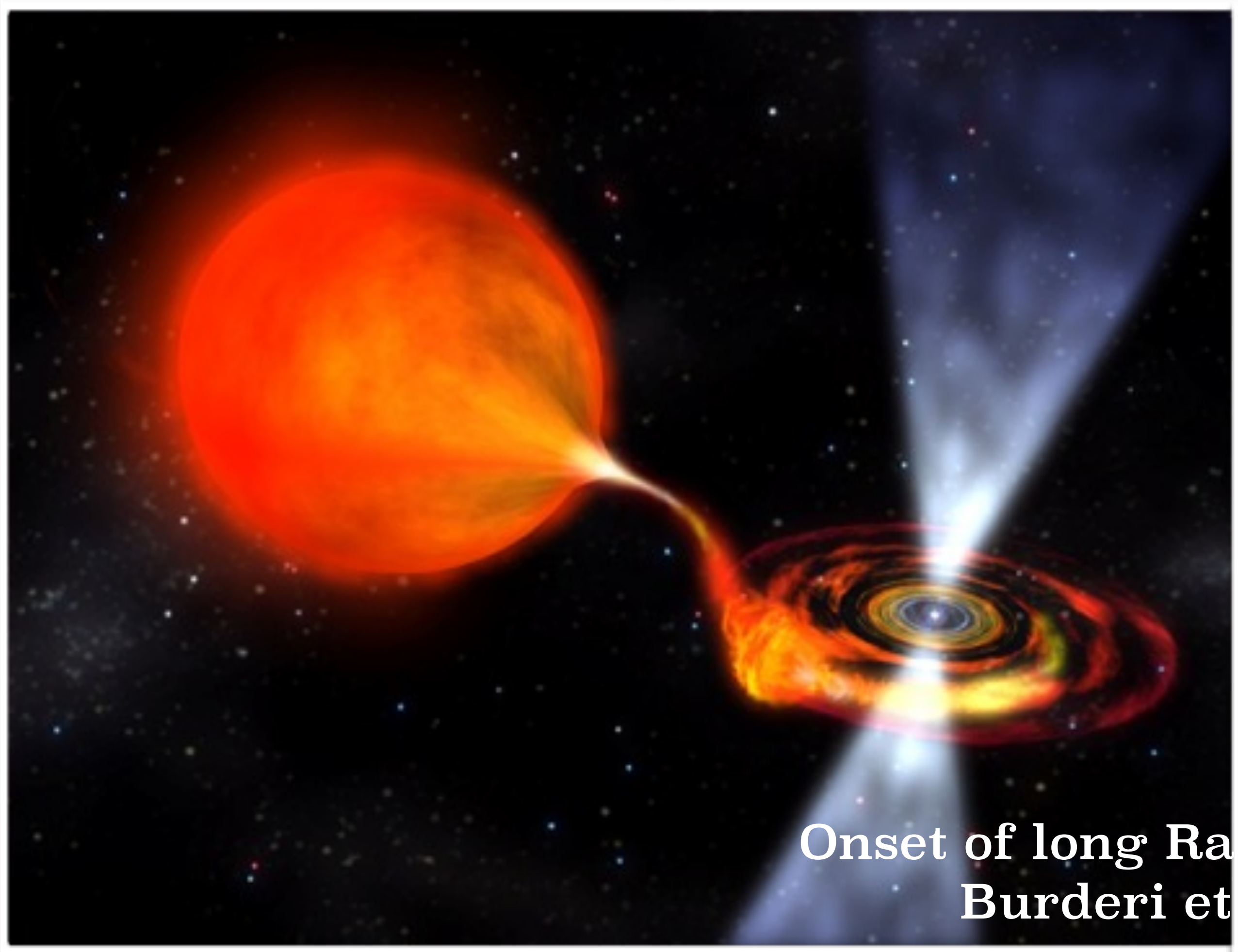
What if there is a process able to stop the accretion phase and start a Millisecond Radio Pulsar (detached) phase: i.e. the **radiation pressure from the Millisecond Pulsar**. (see also Chen et al. 2013).

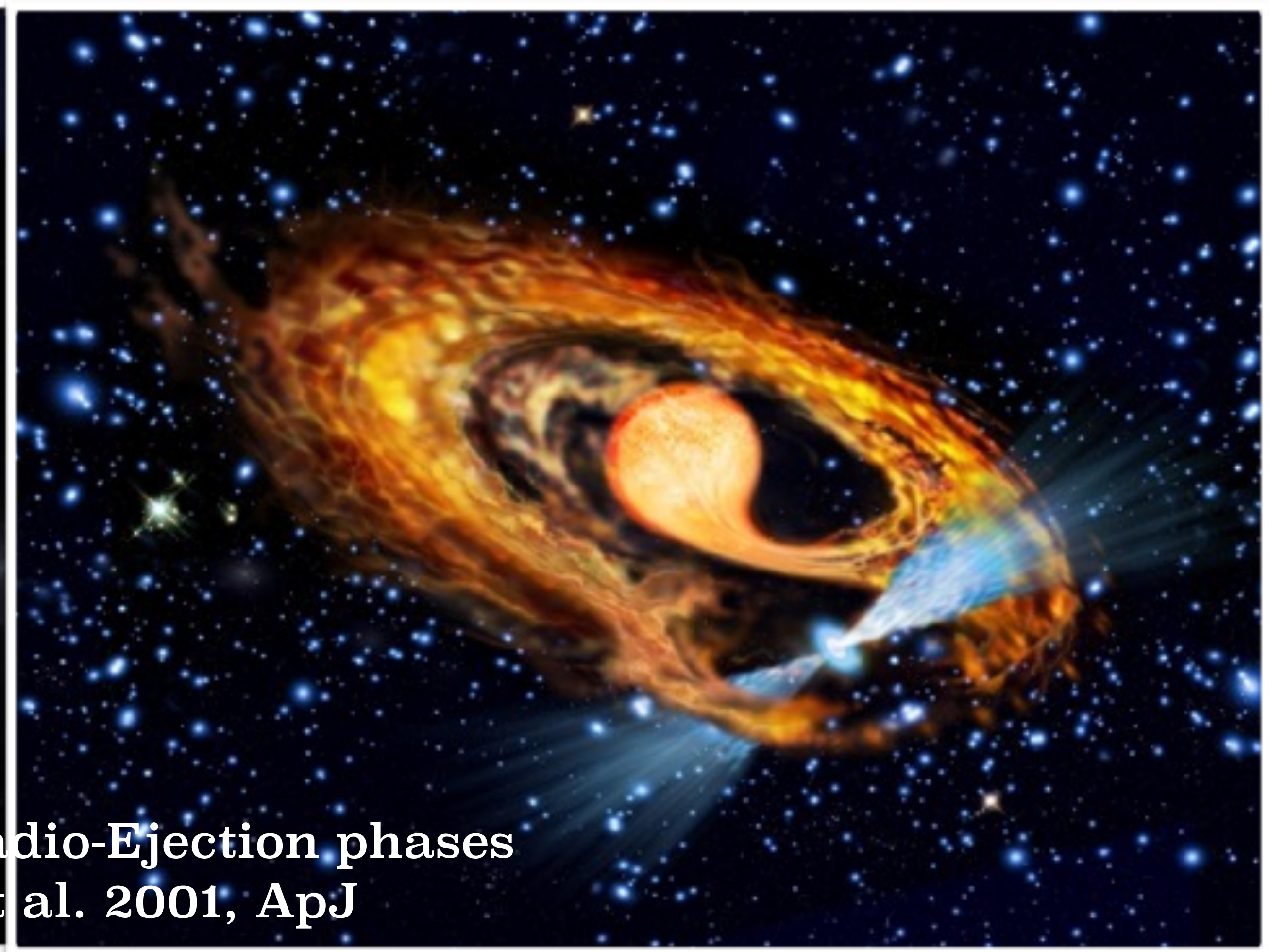


The Radio-Ejection hypothesis

Outburst:
accretion phase

Quiescence:
radio ejection



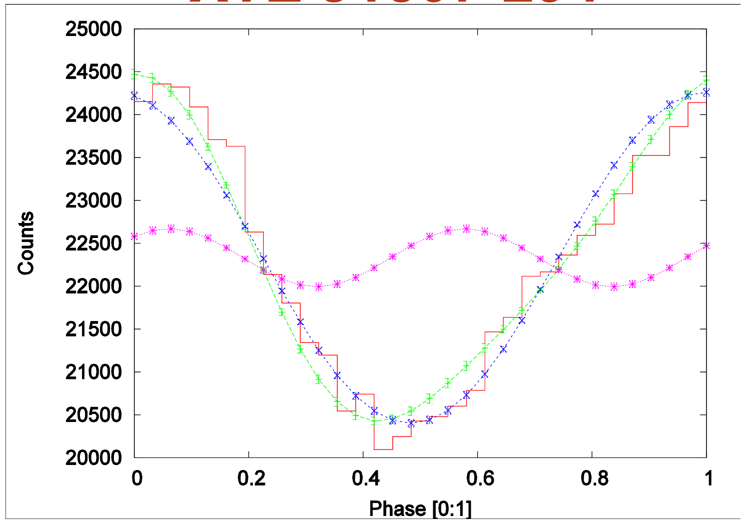


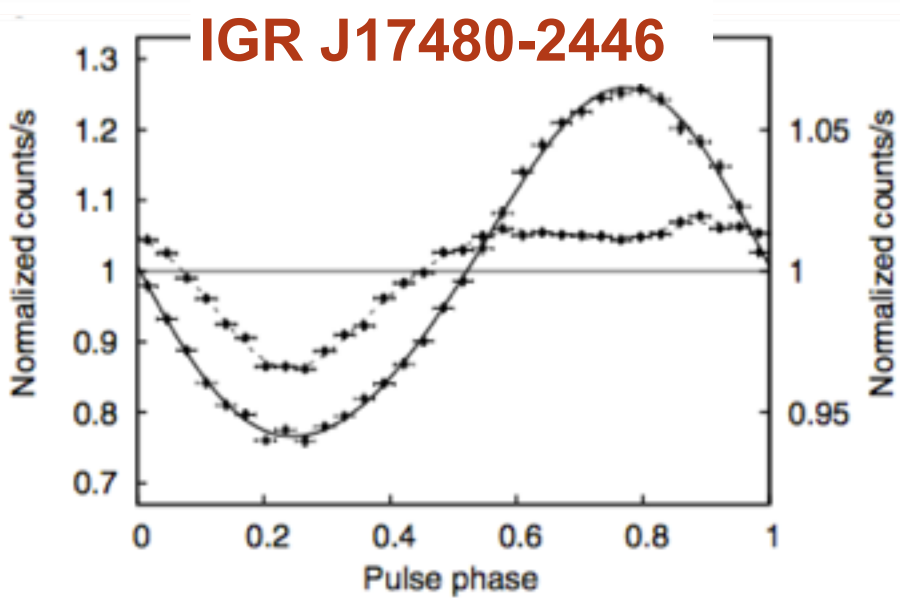
Onset of long Radio-Ejection phases
Burderi et al. 2001, ApJ

(Burderi et al. 2001, Di Salvo et al. 2008)

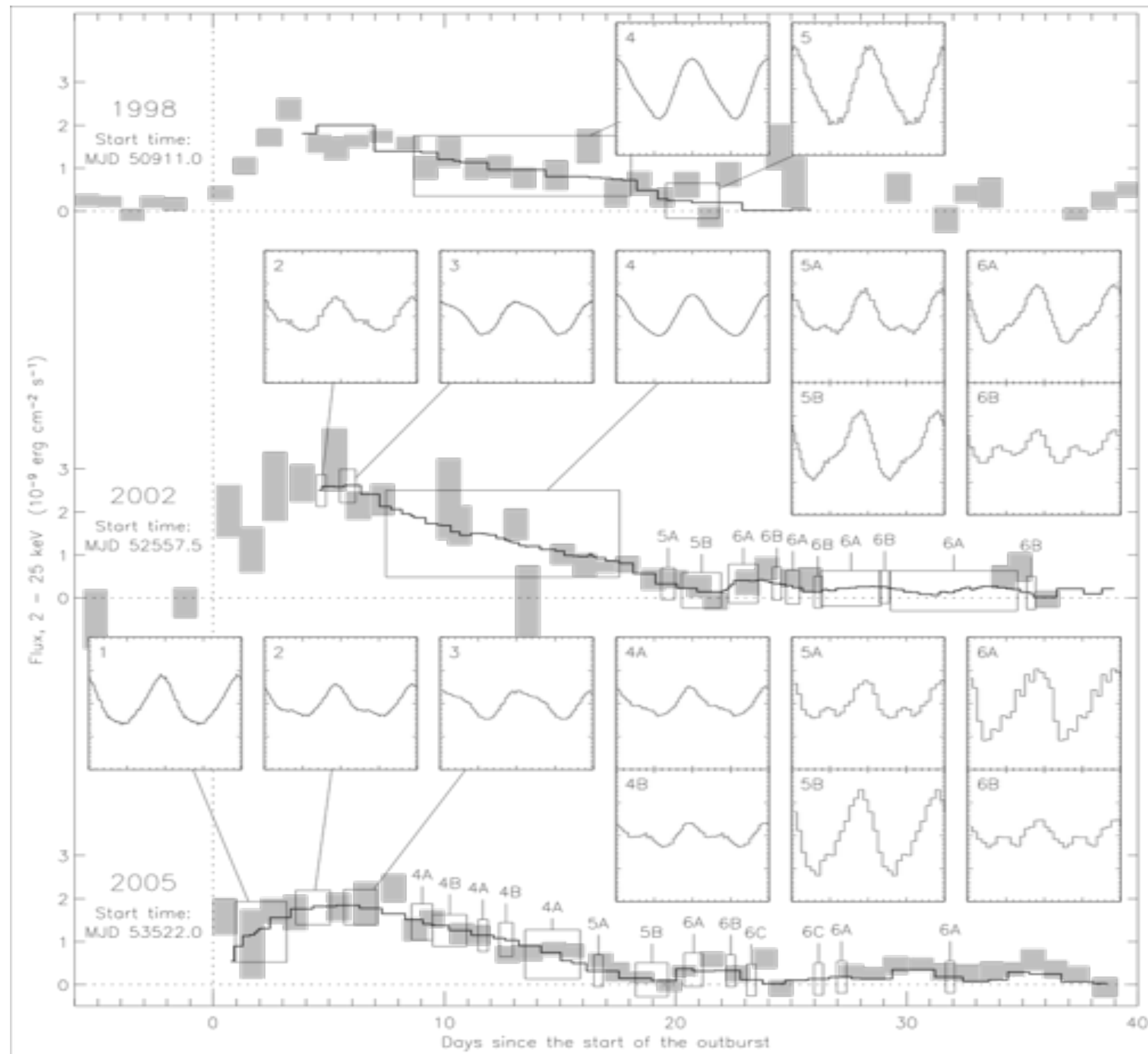
NS LXMB: pulse profile

XTE J1807-294

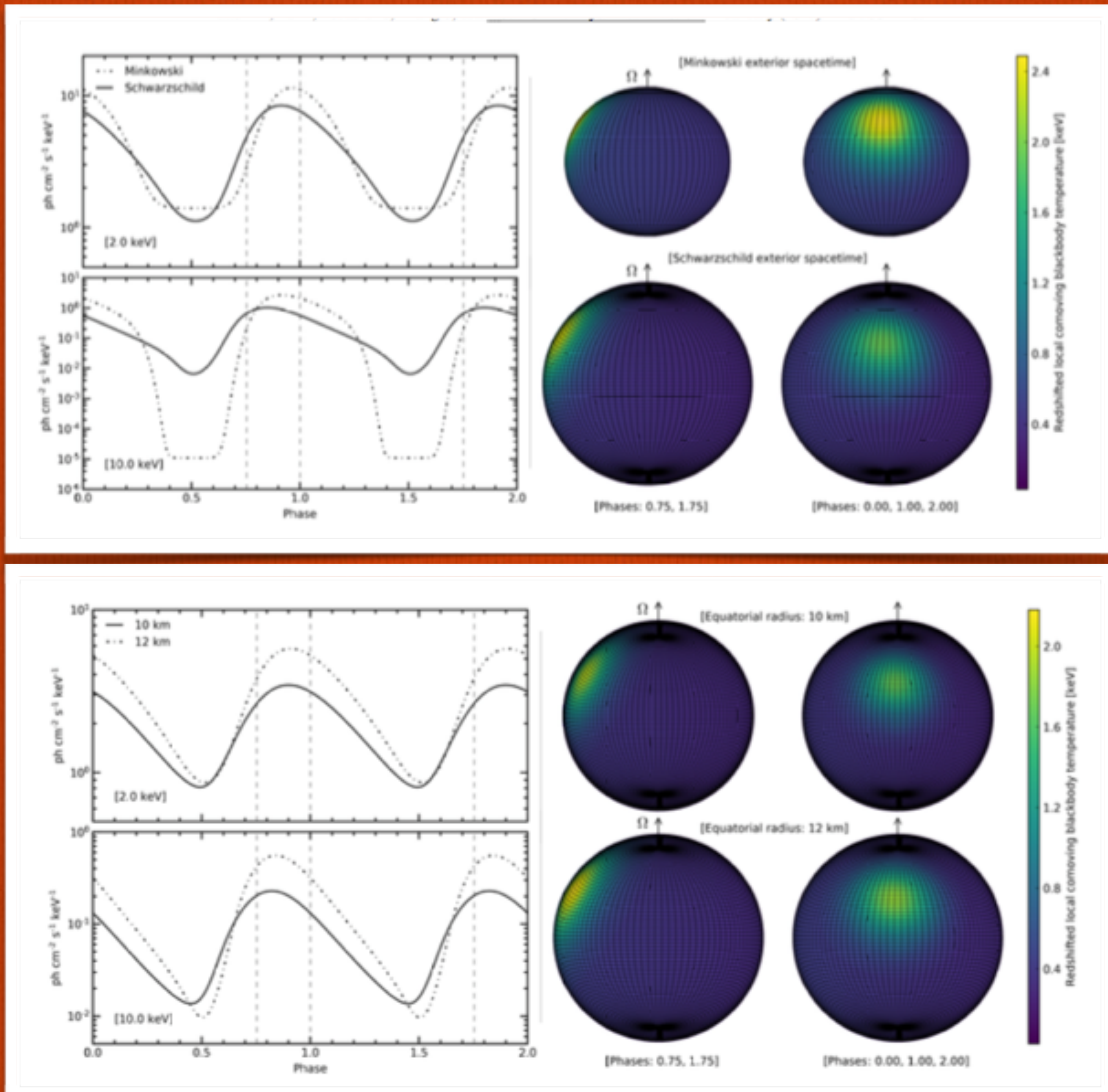




SAX J1808.4-3658



NS LXMB: pulse profile

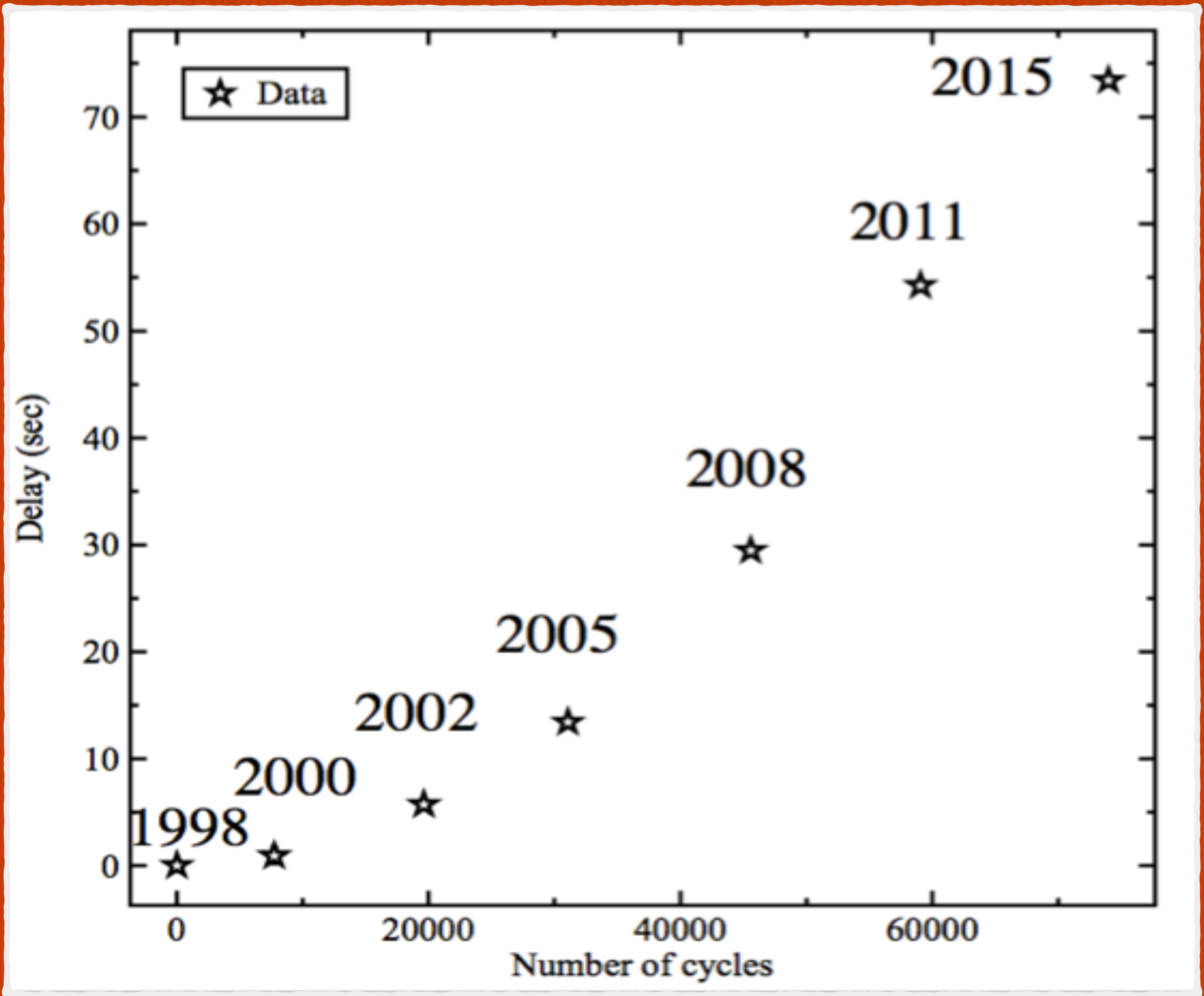


Watts et al. 2017

- Light bending
- Gravitational redshift
- Relativistic beaming

Thanks for the attention!

AMXPs: Orbital Evolution



SAX J1808.4-3658

Reference: outburst 1998

For each outburst we calculated:

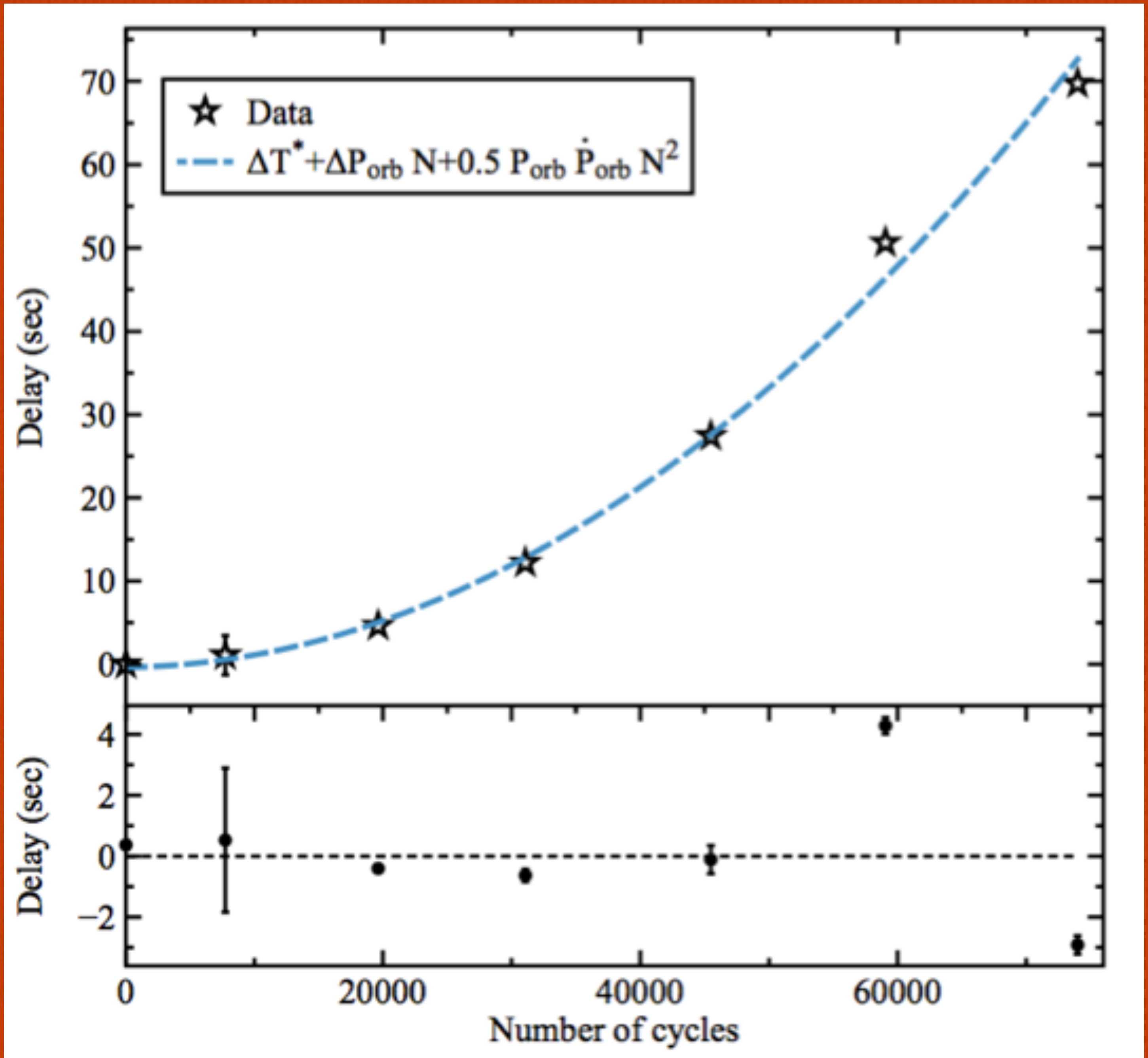
$$T_{NOD_{PRE}} = T_{NOD_{98}} + \\ + N P_{ORB_{98}}$$

$$\Delta T_{NOD} = T_{NOD} - T_{NOD_{PRED}}$$

(Sanna et al. 2017)

AMXPs: Orbital Evolution

$$f(N) = \Delta T_{NOD} + \Delta P_{ORB} N + \frac{1}{2} P_{ORB} \dot{P}_{ORB} N^2$$



$\dot{P}_{ORB} =$
$3.6(4) \times 10^{-12}$s/s

Differently from the 2011 orbital timing, no significant cubic term ($\ddot{P}_{ORB}$) is required.

Residuals appear like fluctuations around a global parabolic trend.

Theory of Dynamical (Orbital) evolution

1. J_{TOT} conservation
2. Kepler's third law
3. Contact condition $\dot{R}_{L2}/R_{L2} = \dot{R}_2/R_2$
4. Companion well described by $R_2 \propto M_2^n$
5. $\dot{J}/J$ driven by GR

$$\dot{P}_{ORB} = -1.4 \times 10^{-12}\, m^{5/3}\, q(1+q)^{-1/3}\, P_{2h}^{-5/3} \left[\frac{n - 1/3}{n - 1/3 + 2g}\right] \mathrm{s/s}$$

where

$$g(\beta, q, \alpha) = 1 - \beta q - (1-\beta)(\alpha + q/3)/(1+q)$$

$$q = m_2/m_1 \qquad \dot{M}_1 = -\beta \dot{M}_2 \qquad \alpha = l_{ej}/\Omega_{ORB}\, r_2^2$$

(Di Salvo et al. 2008)

Predictions vs Observations

2. Fully non-conservative mass transfer

$\beta = 0$ ⇨ $g = 1 - (\alpha + q/3)/(1+q)$

assuming

$$m_1 = 1.4 M_\odot$$
$$m_2 = 0.05 M_\odot$$

$n \simeq -1/3$

fully convective/ degenerate companion star

we find that

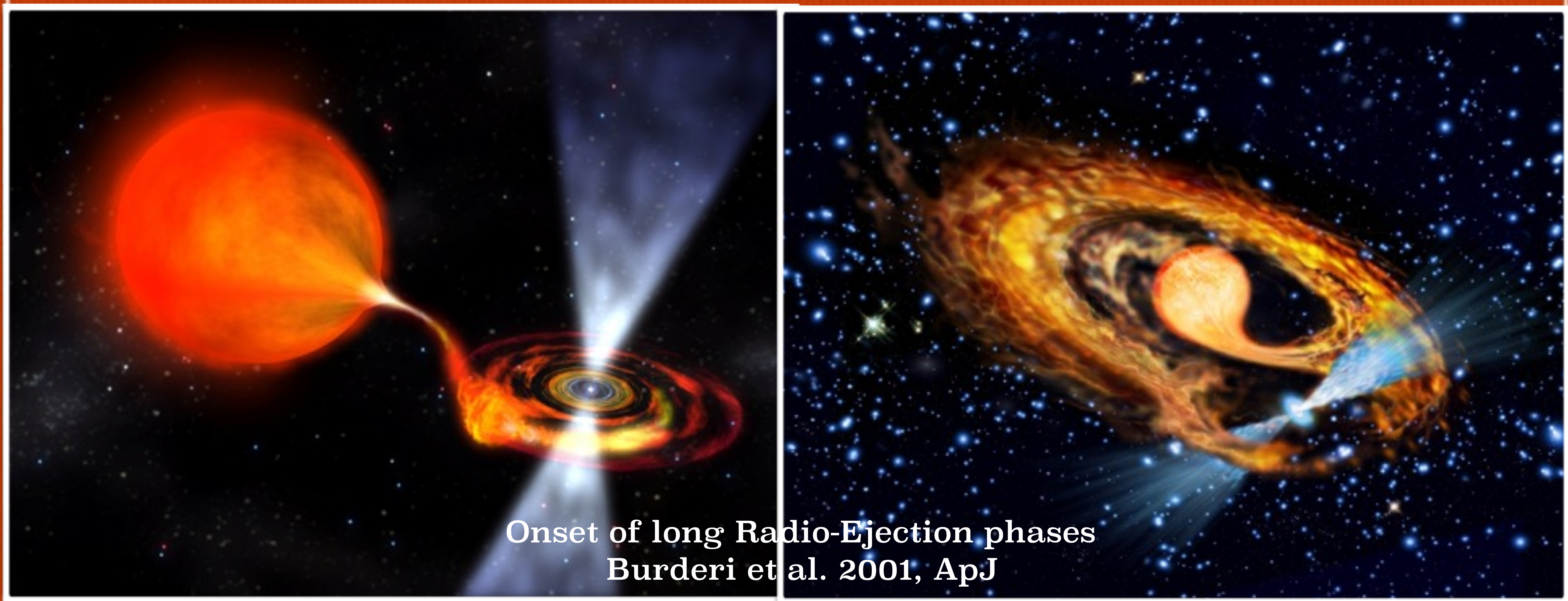
$$\dot{P}_{ORB} \simeq \dot{P}_{ORB_{OBS}} \text{ for } \alpha \sim 0.7$$

matter ejected from the inner Lagrangian point.

The Radio-Ejection hypothesis

Outburst:
accretion phase

Quiescence:
radio ejection



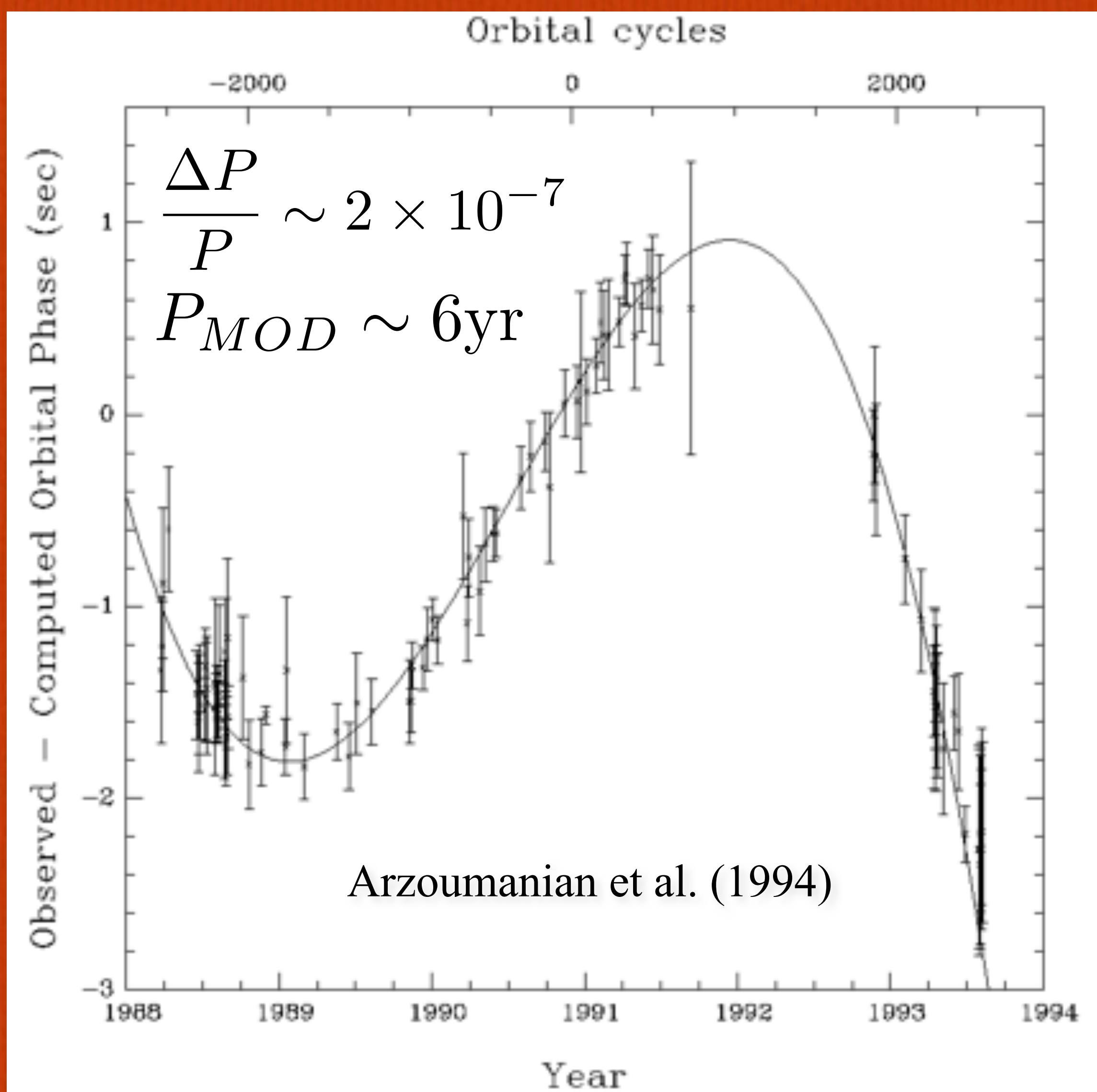
(Burderi et al. 2001, Di Salvo et al. 2008)

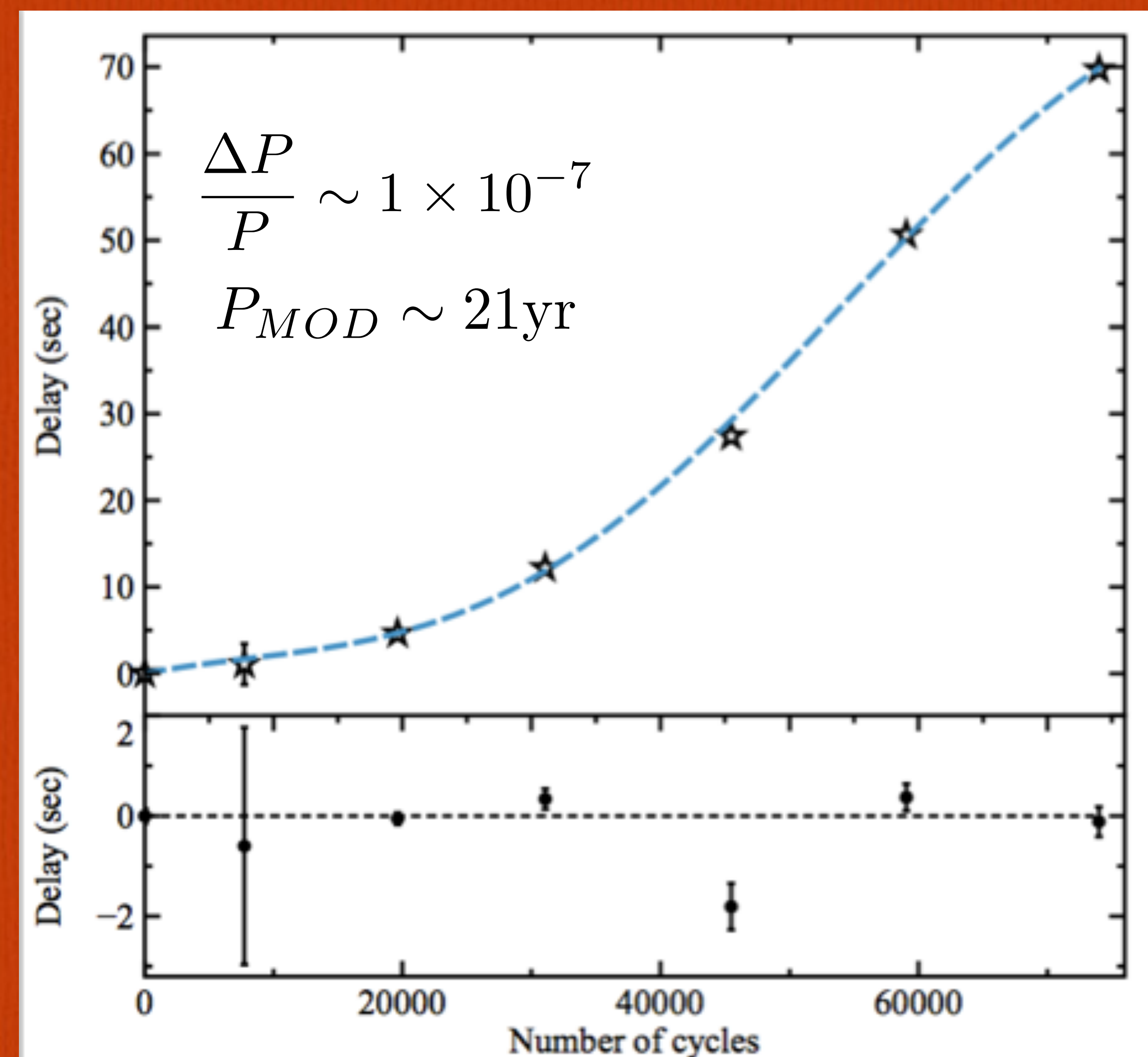
Thanks for the attention!

Alternative mechanism:

Applegate & Shaham model for periodic orbital modulations Gravitational Quadrupole Changes (GQC)

Hartman et al. (2008) and Patruno et al. (2011) proposed that magnetic activity in the companion is responsible for the orbital variability of SAXJ1808 – as discussed by Applegate & Shaham (1994) and Arzoumanian et al. (1994) to explain the orbital varability observed in PSR B1957+20





(Arzoumanian et al. 1994) **(Sanna et al. 2017)**

Applegate & Shaham: basic concept

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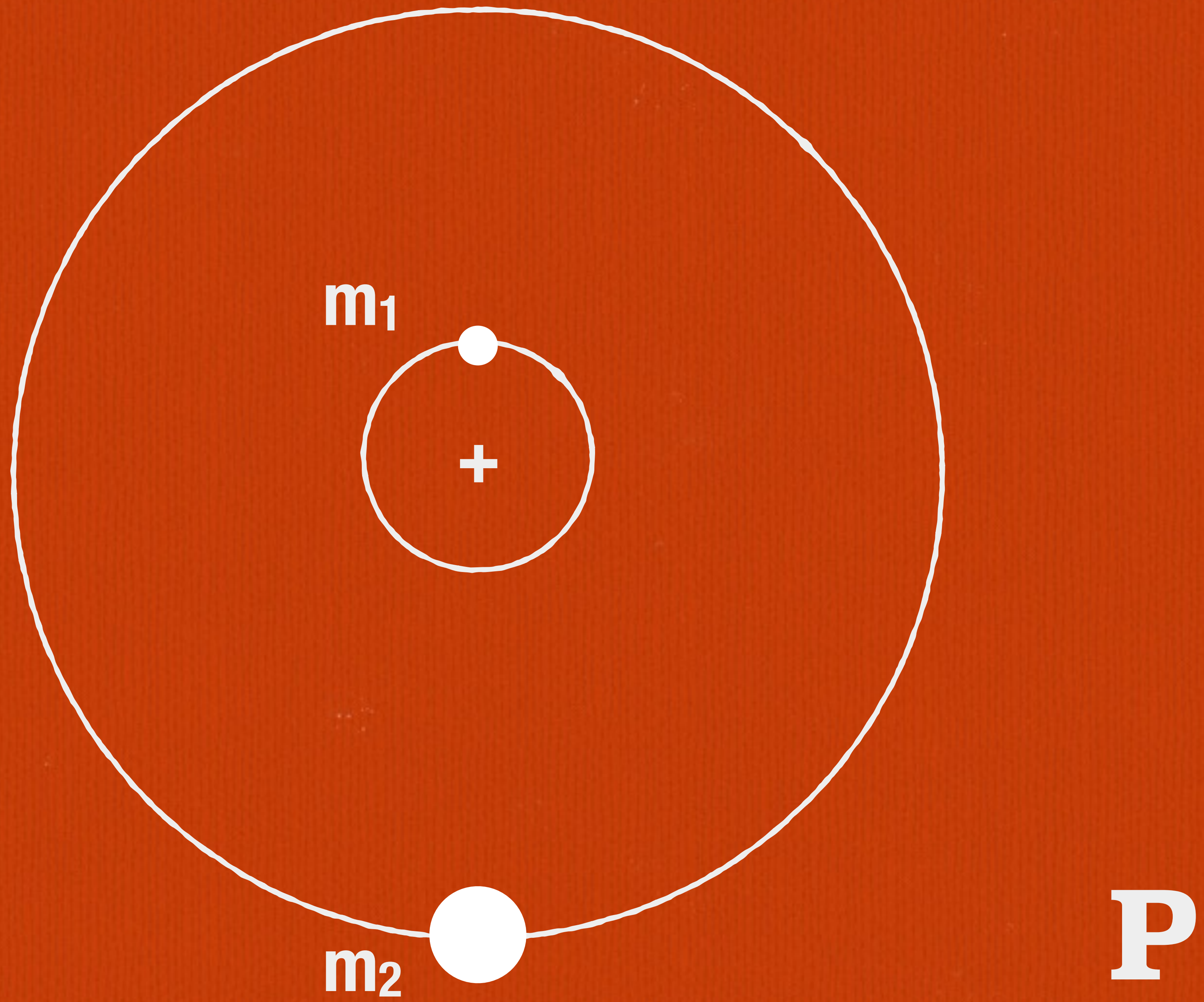
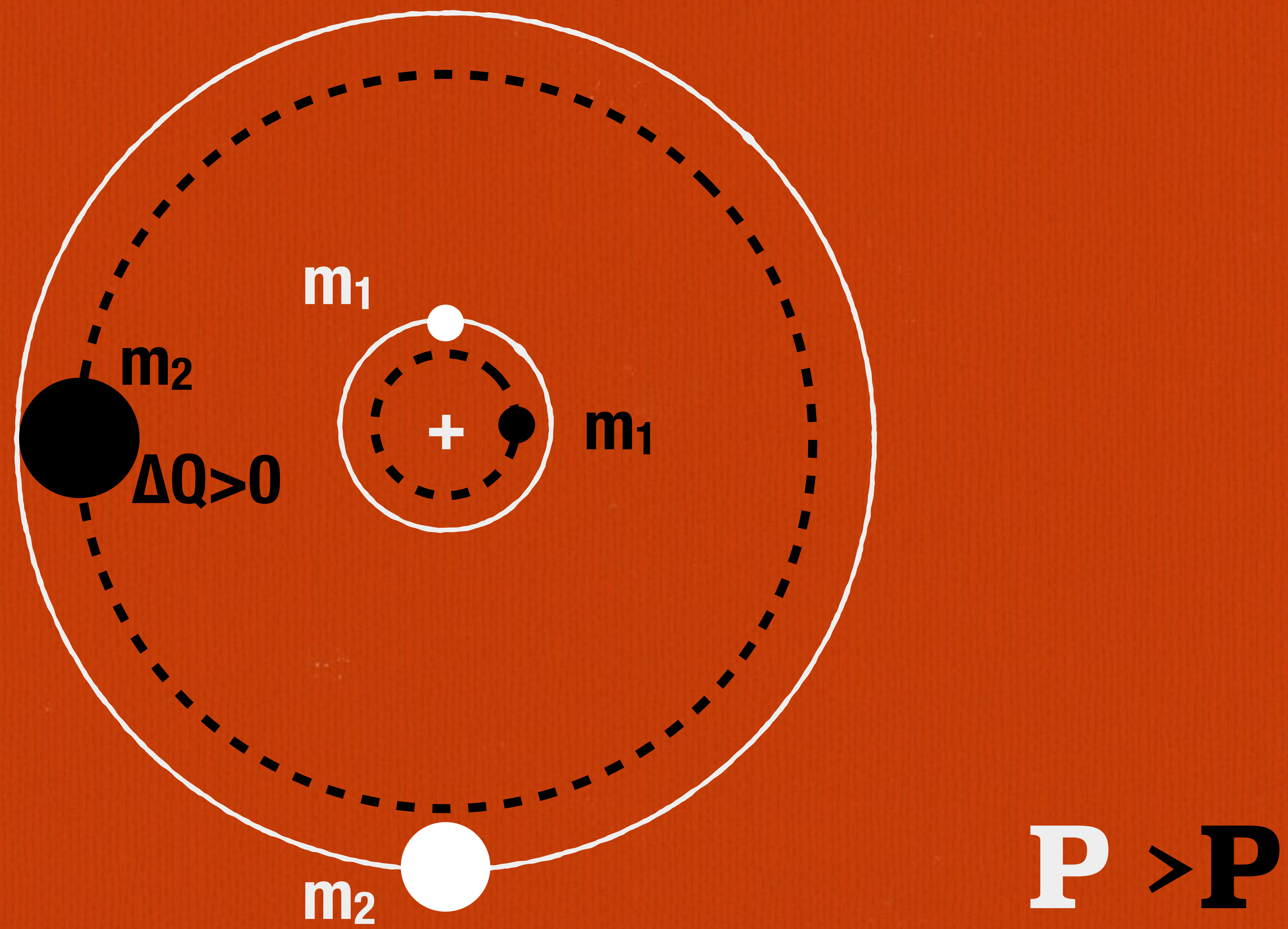
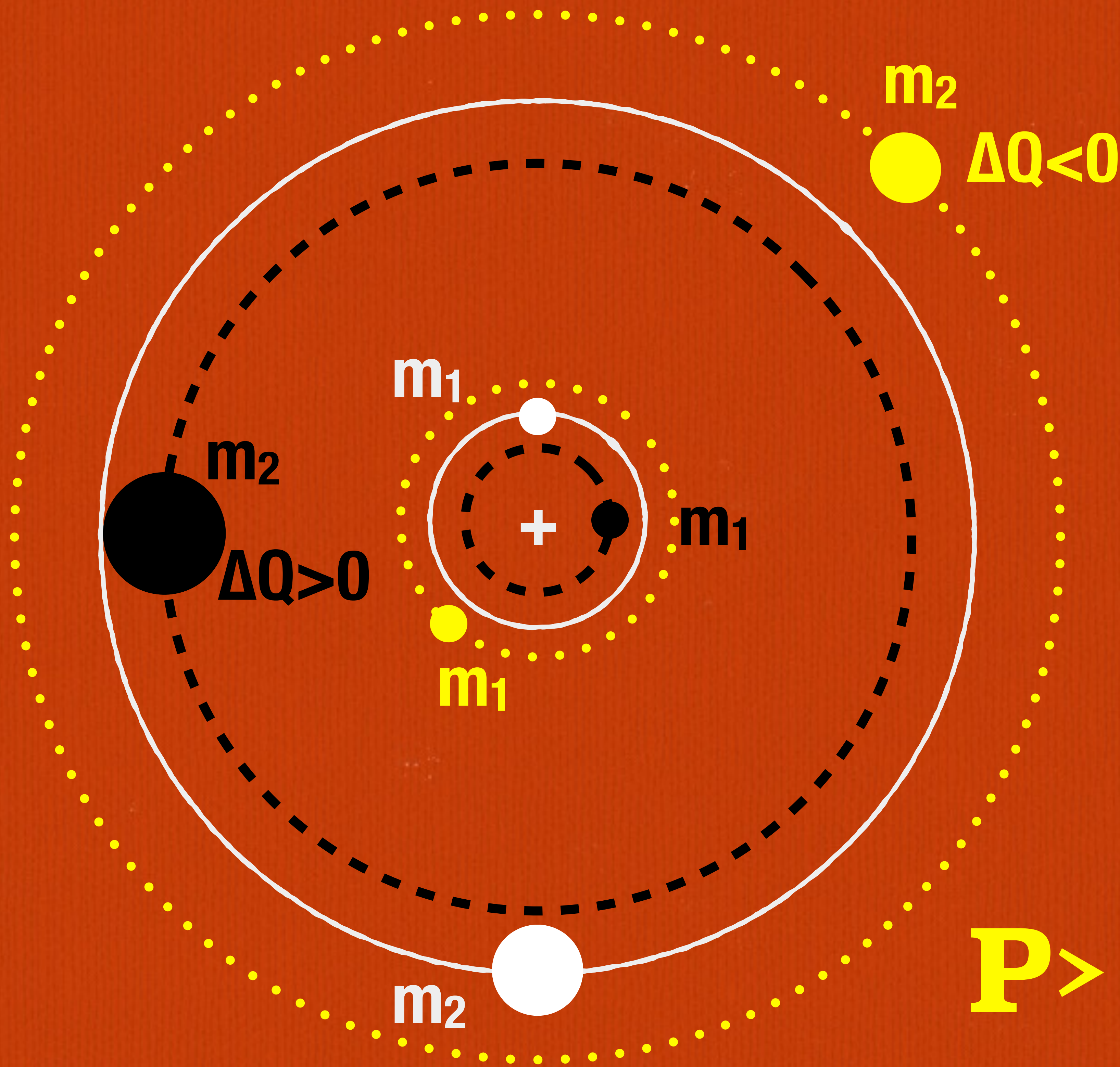


Applegate & Shaham: basic concept



Applegate & Shaham: basic concept

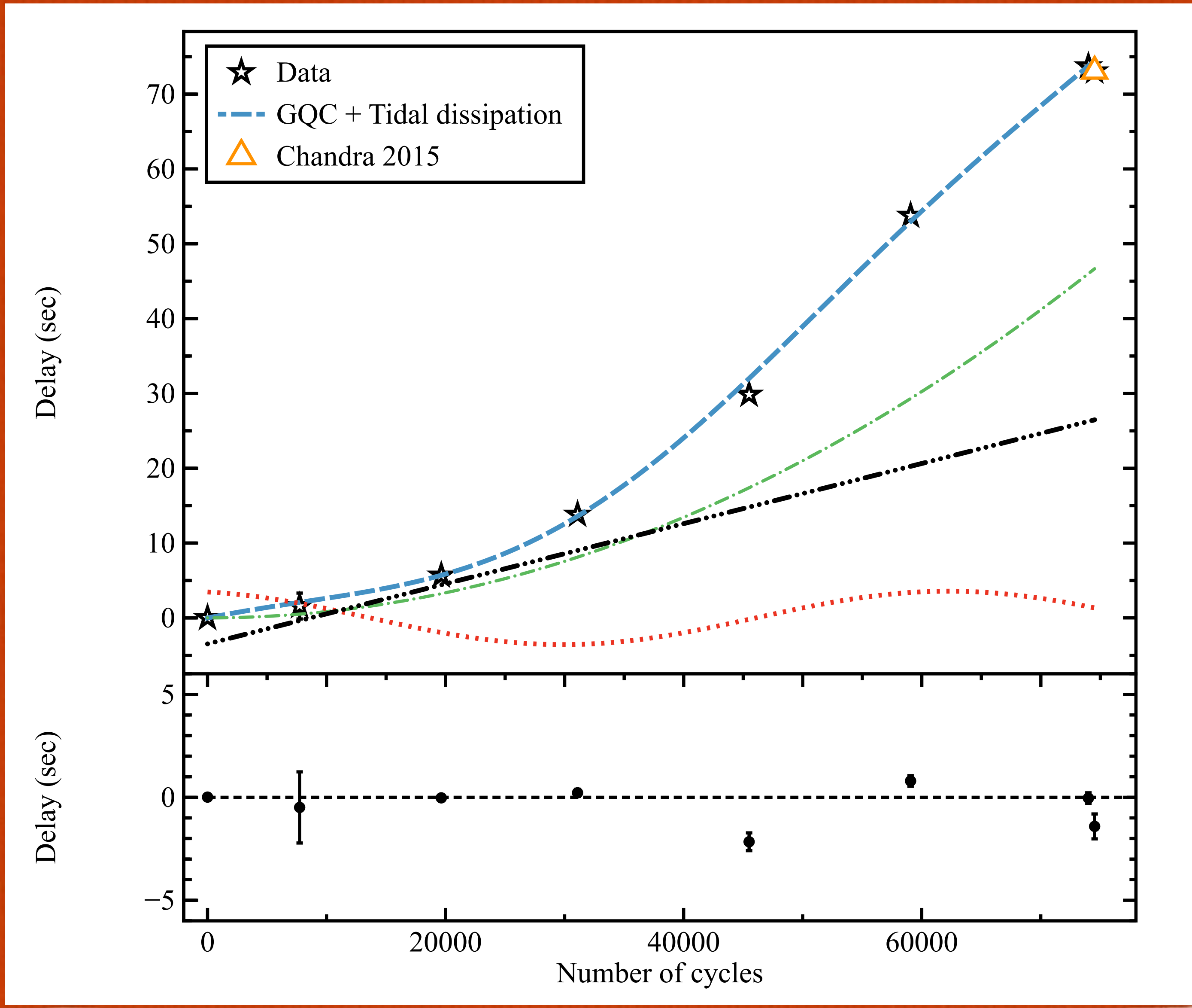


P> P >P

Applegate & Shaham: sources of energy

- **Tidal dissipation:**

to take into account the ejected matter we included a parabolic trend to fit the differential correction ΔT_{NOD}



$$A = 4(0.7)\,\mathrm{s}$$

$$P_{mod} = 14.9(2.7)\,\mathrm{yr}$$

$$\dot{P}_{orb} = 2.3 \times 10^{-12}\,\mathrm{s/s}$$

$$\dot{m} = 8.8 \times 10^{-10}\,\mathrm{M_{\odot}}/yr$$

Thanks for the attention!