Hard X-ray Cataclysmic Variables

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Outline

- Introduction:
  - CV types, magnetic fields and evolutionary links
  - Hard X-ray surveys: role in Galactic X-ray Source populations?

- X-ray follow-ups:
  - New members with XMM-Newton
  - Temporal and spectral properties

- Conclusions and future perspectives
  - What do we still need ?

CV sub-types

~ 1300 CVs known to date

Non-Magnetic CVs

Dwarf novae & Novalike

~80 % of all CVs

$B_{WD} << 10^5 – 10^6$ G

Magnetic CVs

Intermediate Polars & Polars

~20 % of all CVs

$B_{WD} \sim 1 \rightarrow 230$MG

Isolated Magnetic WDs

~10 % of all WDs

$B_{WD} \sim 3$kG -> 1000MG

High incidence of magnetism

Magnetic Cataclysmic Variables

Polars

Porb ≅ Prot (hrs)

$B_{WD} > 10$ MG

Polarized in optical/nIR

Intermediate Polars (IPs)

Prot (mins) < Porb (hrs)

$B_{WD} < 10$MG (?)

Unpolarized or weakly polarized

Bright in soft X-rays

(ROSAT era)

~ 110 system

Bright in hard X-rays

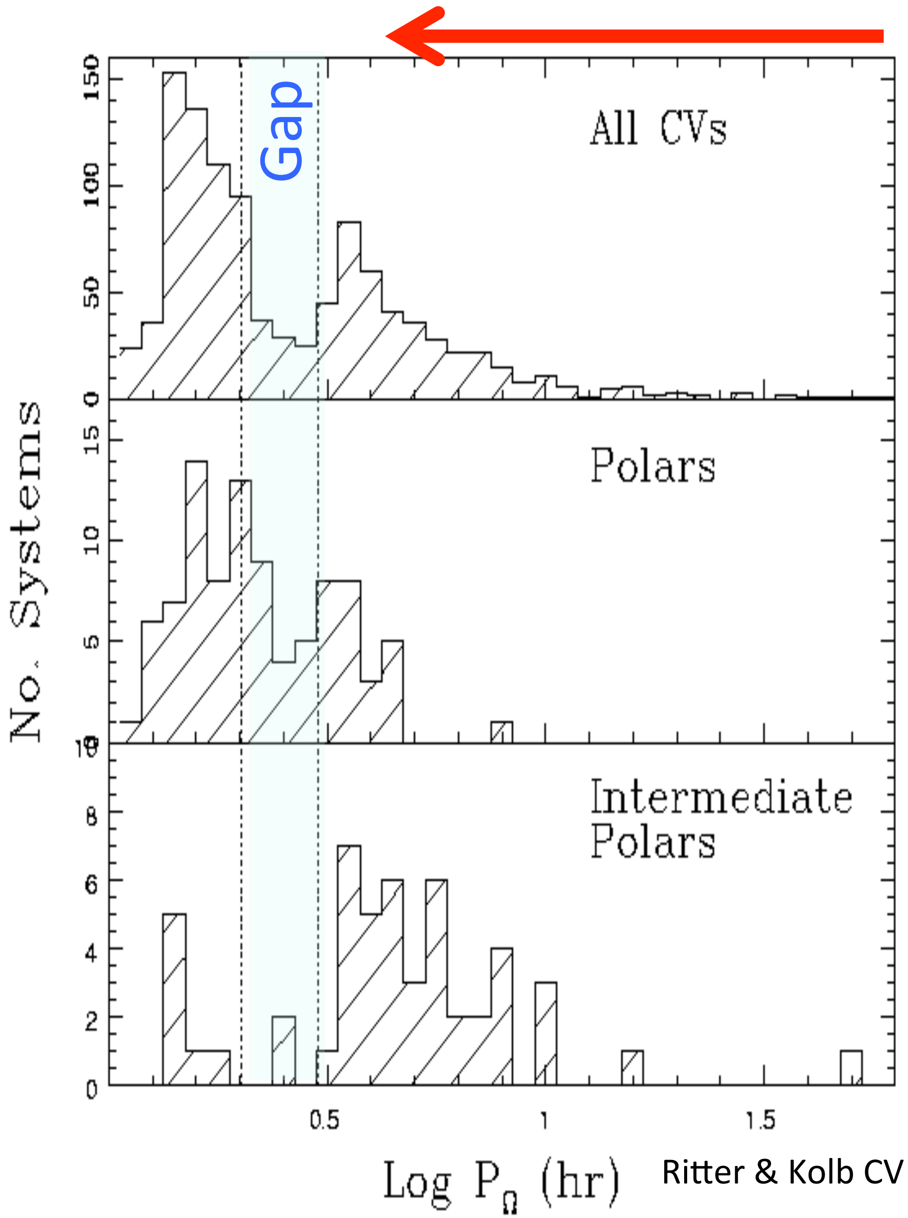
(INTEGRAL/SWIFT era)

~ 66 systems

Is there a relation between two types ?

- Different B-fields?
- Same B but evolutionary link?

Orbital Period Distribution



Ritter & Kolb CV Cat. 7.20v 2013

Binaries evolve towards short Porb

Angular Momentum Losses via:

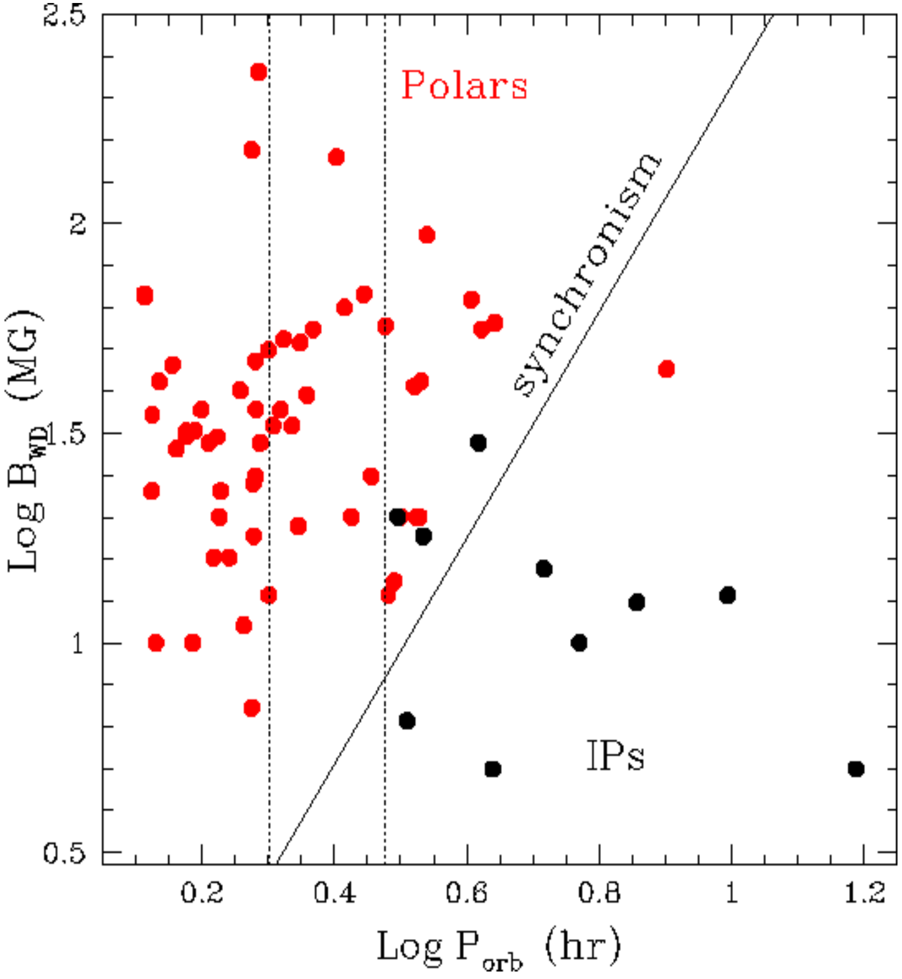
- Magnetic Braking above CV 2-3h “gap”
- Gravitational Braking below “gap”

➢ Most IPs are above gap

➢ Most Polars are below gap

IPs may evolve into Polars if similar B-fields

Orbital Period vs B-field



Ferrario, de Martino, Gaensicke 2015

Synchronism

when torque of magnetostatic interaction of μ_{WD} and μ_{Sec} balances accretion:

$$G_{sync} = G_{accret}$$

$$\mu_{WD}\ \mu_{Sec}/a^3 \approx (dM/dt)\ R_{lobe,WD}{}^2/Porb$$

$$B \cong 8.2\ (dM/dt_{-10})^{1/2}\ (Porb/4h)^{7/6}\ MG$$

Polarised IPs likely progenitors of low-B Polars

Galactic faint X-ray source populations

- Galactic Center: Chandra 1Ms survey

(Muno et al.2004; Ruiter et al. 2006; Hong et al. 2012;2014):

- Thousands faint sources resolved:
- Hard Spectra: Power law $\Gamma < 1 – 1.5$ (or KT ~ 25keV) & Fe line (6.7keV) in a few
- $L_x \sim 10^{30} - 10^{33}$ erg/s (1-8kpc)
- Variability: Periodic (≈ 1.3 – 3.4hr)

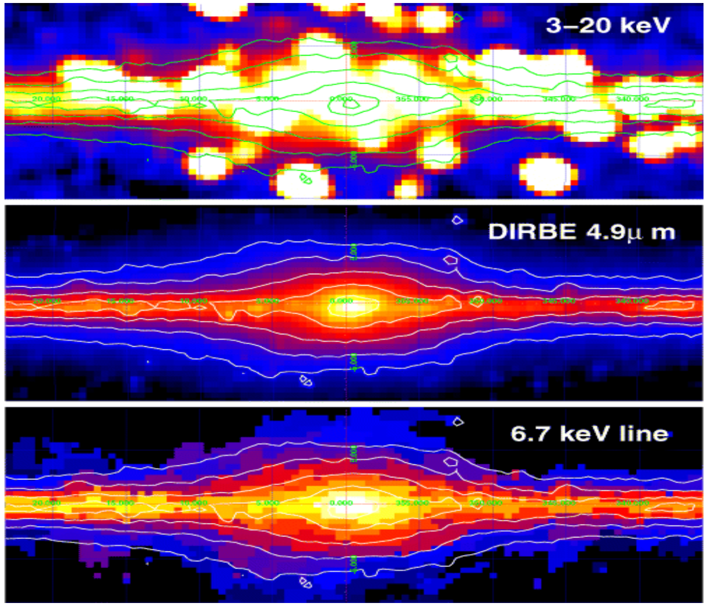
- Galactic Ridge X-ray Emission (GRXE):

RXTE, Chandra, INTEGRAL, Suzaku, NuSTAR, XMM-Newton

(Revnivtsev et al. 2006,2009; Sazonov 2006; Yuasa et al. 2012 Warwick et al. 2014; Perez et al 2015; Haley et al. 2016)

- ~80% of diffuse X-ray emission @ 6.7keV resolved in discrete sources
- $L_x \sim 10^{32} – 10^{35}$ erg/s → CVs most magnetic
- $L_x < 10^{32}$ erg/s → coronally active binaries, non-mCVs?

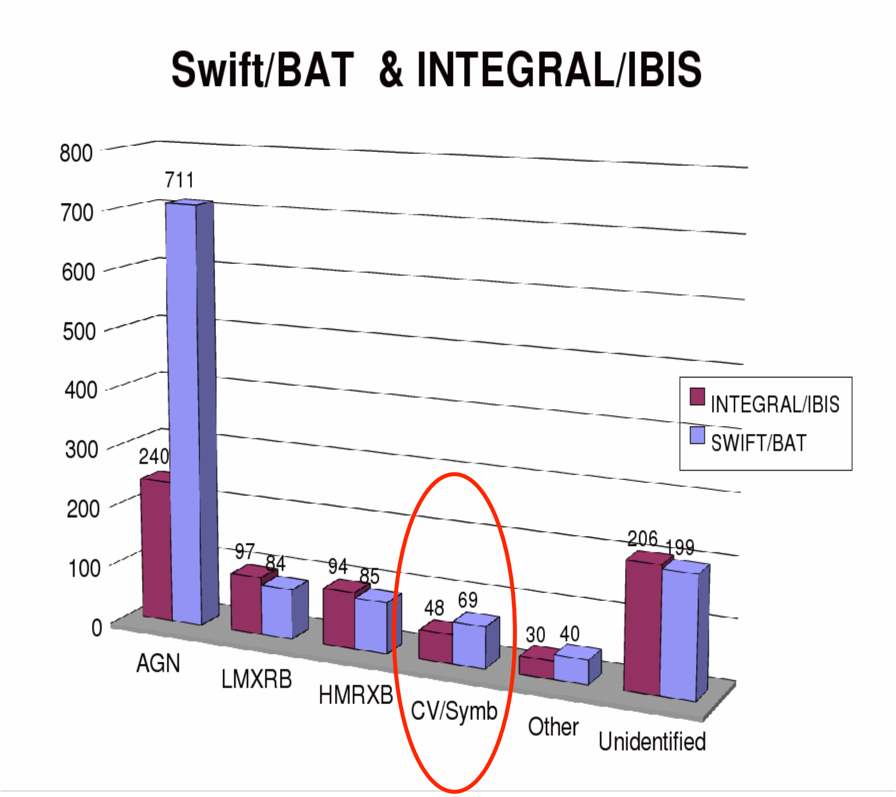
Revnivtsev et al. 2006



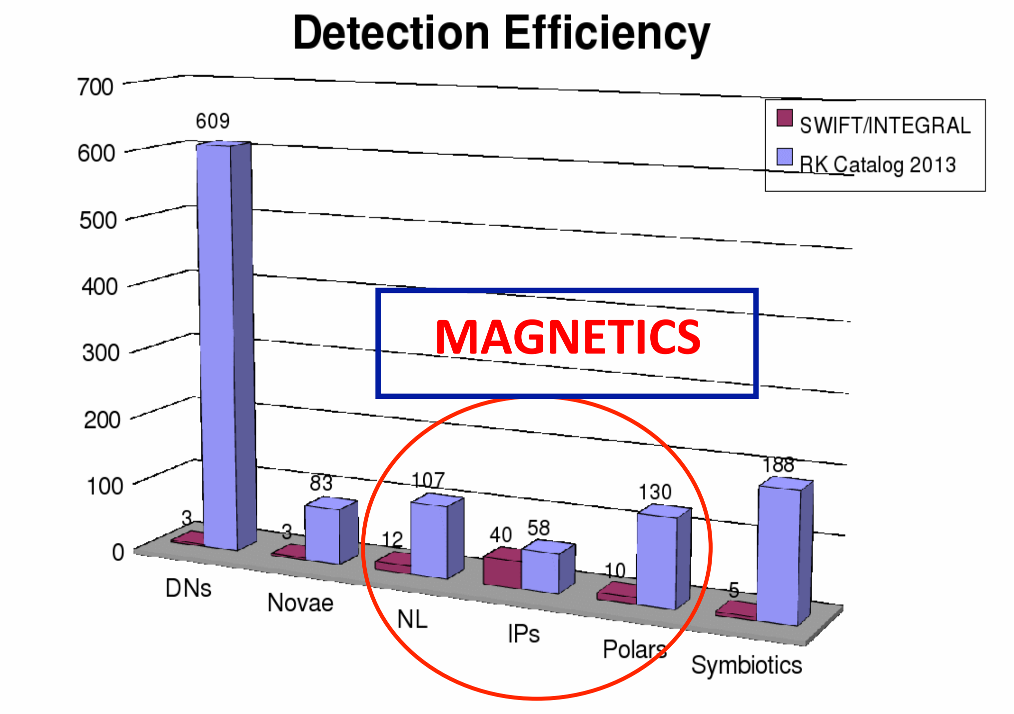
MCVs purported as dominant hard low-Lx population

The Hard X-ray Surveys

- INTEGRAL/IBIS and SWIFT/BAT changed our view of X-ray sky
- 20% of Galactic X-ray sources are CVs
- Efficient only for some CV types

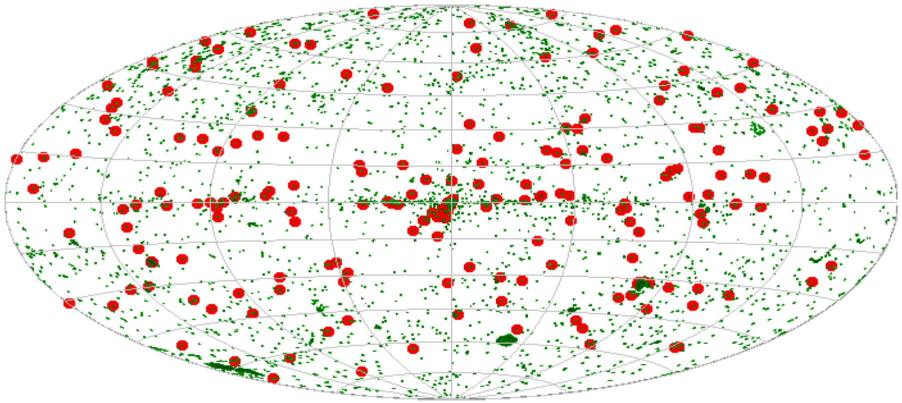


Bird et al. 2010; Krivonos et al. 12
Cusumano et al. 2010; Baumgartner et al. 2013



Ritter & Kolb Cat. 7.20v 2013

Accreting WD Binaries in XMM-Newton Serendipity Survey

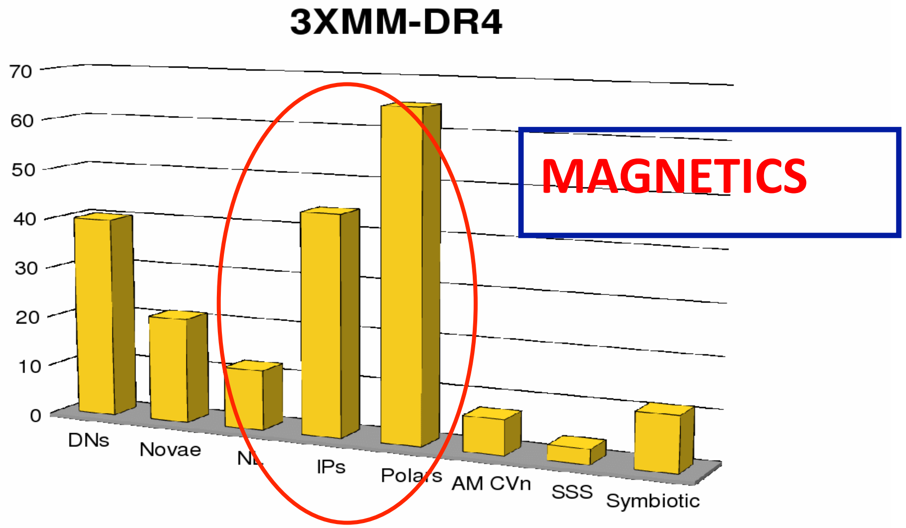


1999 - … : XMM-Newton/EPIC 30’ FoV 6” FWHM

Range: 0.2-12keV F_{lim}: ~ 2.4 x10^{-14}cgs

3XMM-DR4 Catalogue: 372728 sources

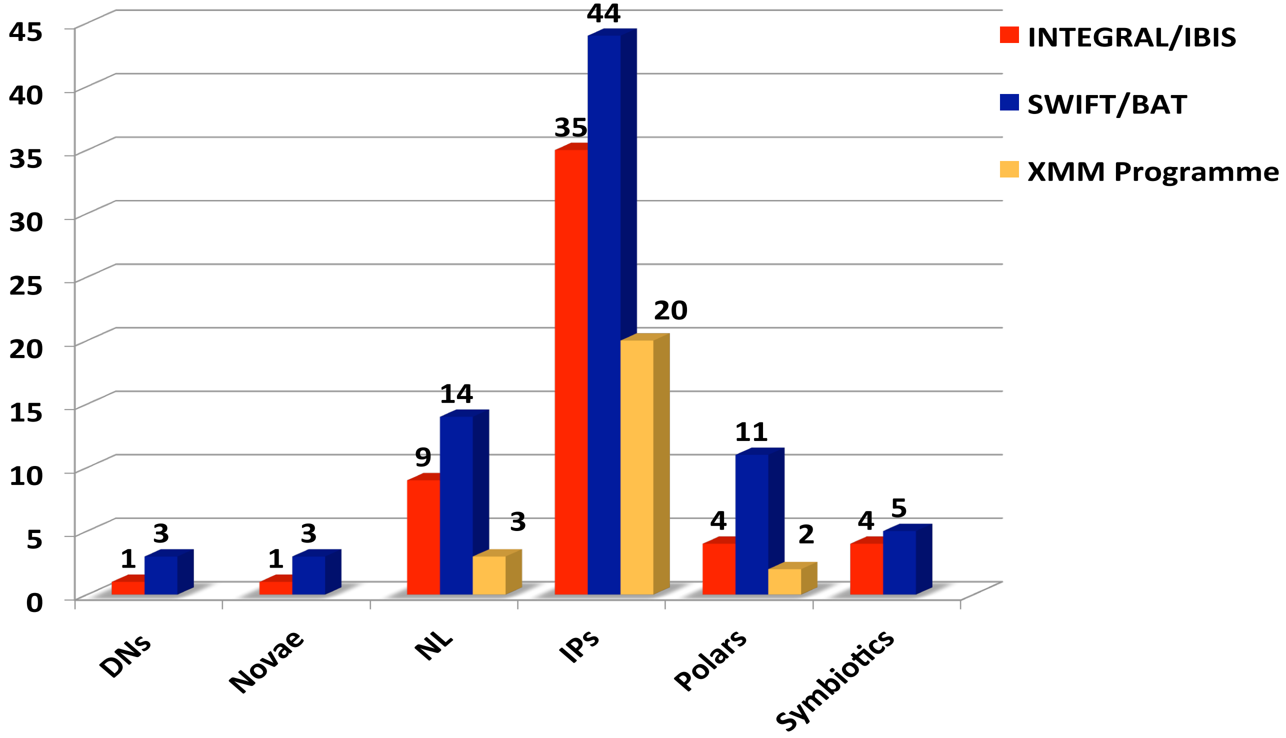
203 Accreting WD Binaries



MAGNETICS

What type of hard CVs

- Novalike CVs include magnetics – many disputed to be mCVs
- IPs doubled in number with INTEGRAL/SWIFT detections!
- Still unidentified hard X-ray mCV candidates from optical spectroscopy



XMM-Newton Programme

26 CV Candidates: 20 IPs confirmed + 1 LMXB + 3 NL + 2Polar

- X-ray Power Spectra of mCVs :

  - Accretion mode diagnostic : $\omega \approx \Omega$ → Stream-fed Polars

    ω → Disc-fed IP

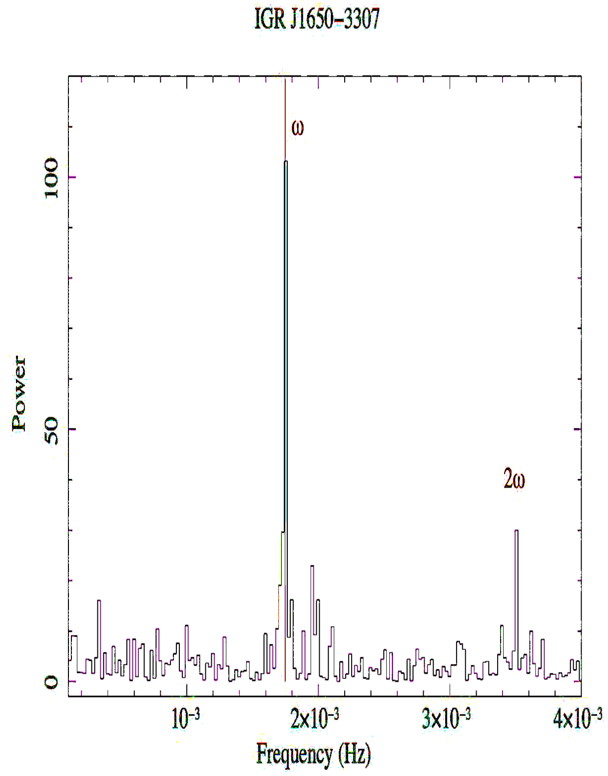
    $\omega - \Omega$ → Stream-fed IP

    ω and ω-Ω → Disc-overflow (Hybrid)

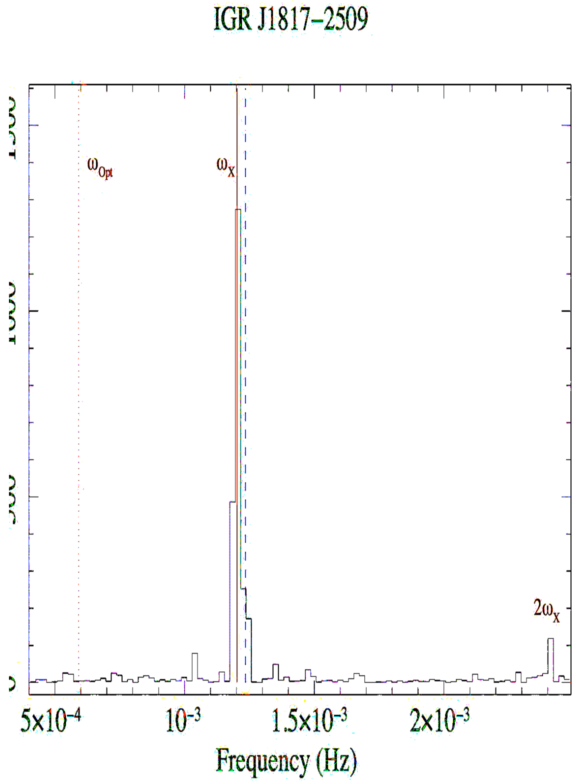
- Energy dependent X-Ray/UV/Optical pulses:
  - Geometry and B-field complexity
  - Sites of Primary & Reprocessed radiation
  - Absorption effects

- X-Ray spectra:
  - Accretion region: Pre-Shock, Post-Shock, bulge at disc rim
  - WD irradiation and WD mass

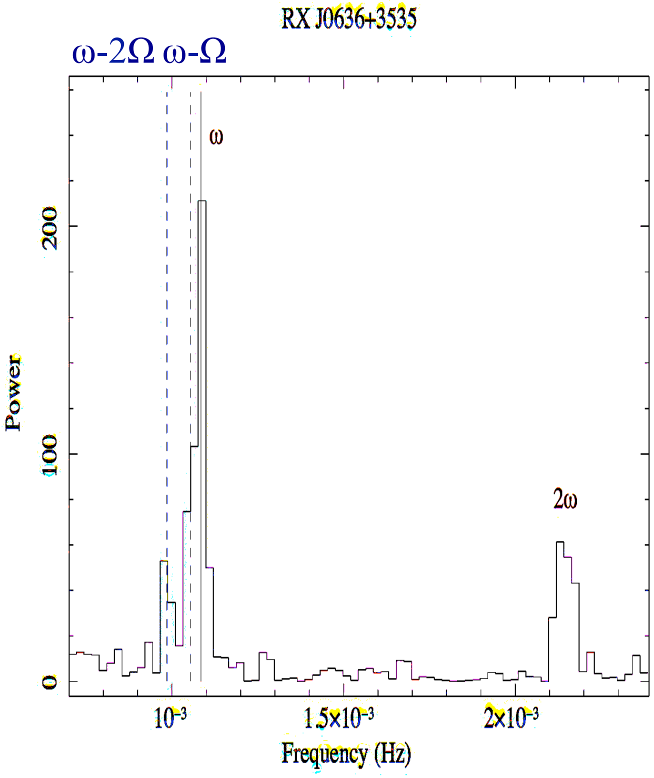
X-ray power spectra of IPs


IGR J1650−3307

Main and secondary pole


IGR J1817−2509

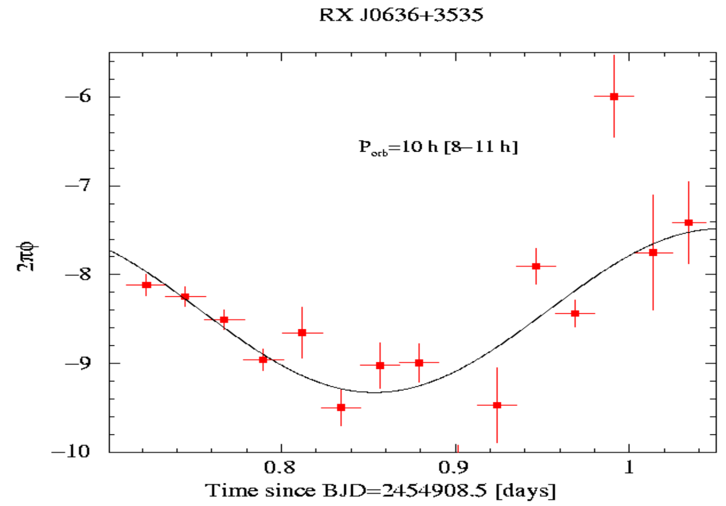
Two equal poles

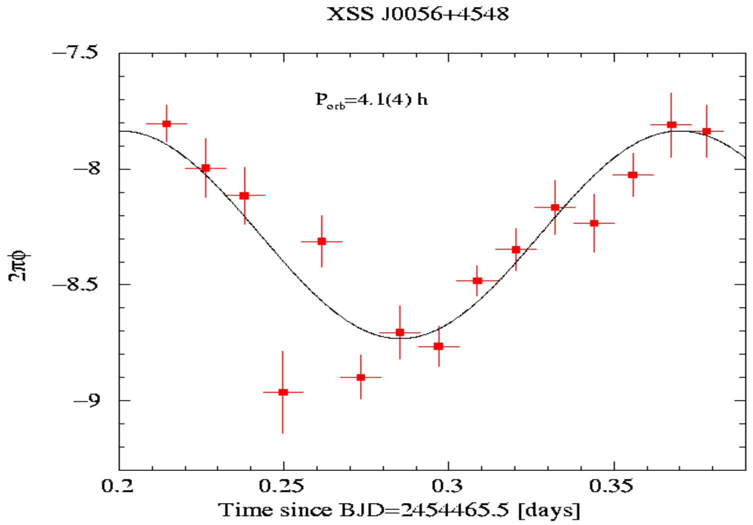

RX J0636+3535

Two poles hybrid

(Bernardini et al. 2012)

Orbital period search in IPs



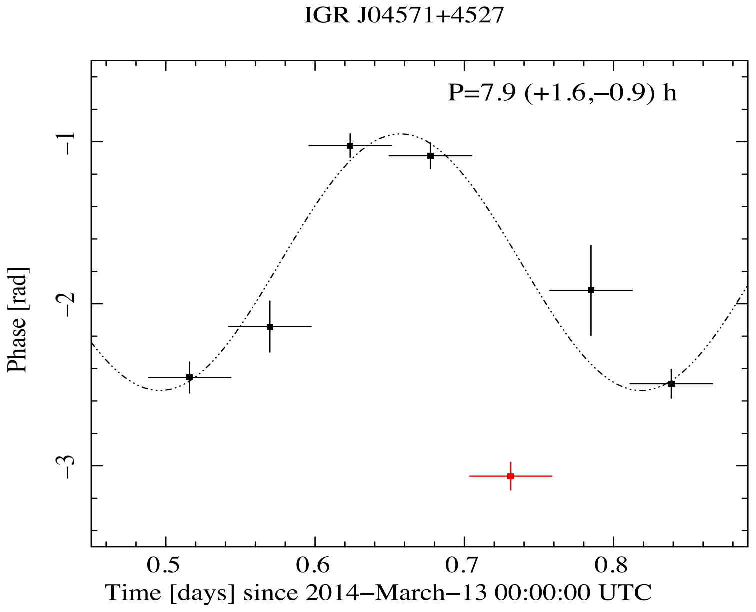


Bernardini et al. 2012

Orbital dependence of spin pulse phases

↓

Porb can be estimated

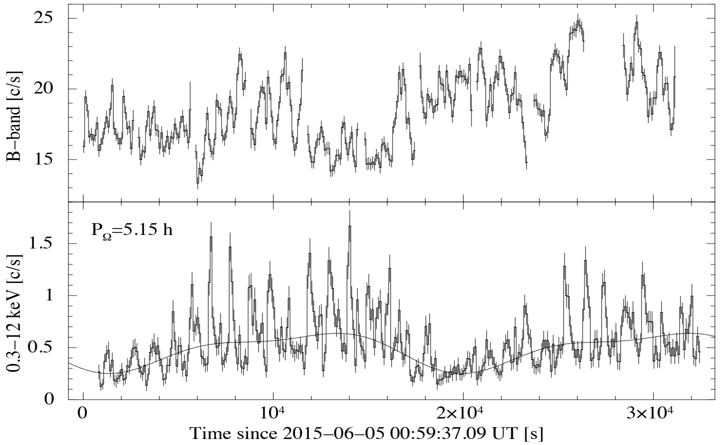


Bernardini et al. 2015

X-ray orbital variability in IPs

P_{Ω} = 5.2h
P_{ω}=1033.5s
$P_{\omega-\Omega}$=1093.4s

SwiftJ0927.7-6945



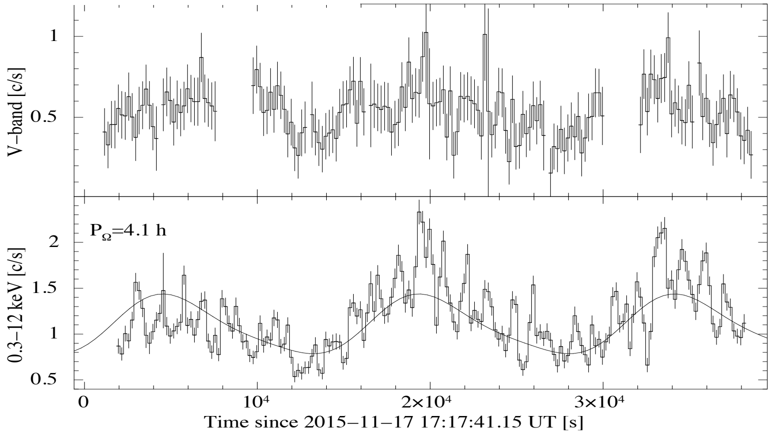
- X-ray orbital modulation in many sources
- Modulation is energy dependent
- X-ray beat with $A_{\omega-\Omega}/A_{\omega} \geq 1$

↓

Disc-overflow accretion configuration
where absorbing material at the disc rim

P_{Ω} = 4.1h
P_{ω}=1265.6s
$P_{\omega-\Omega}$=1373.8s

SwiftJ2113.5+5422



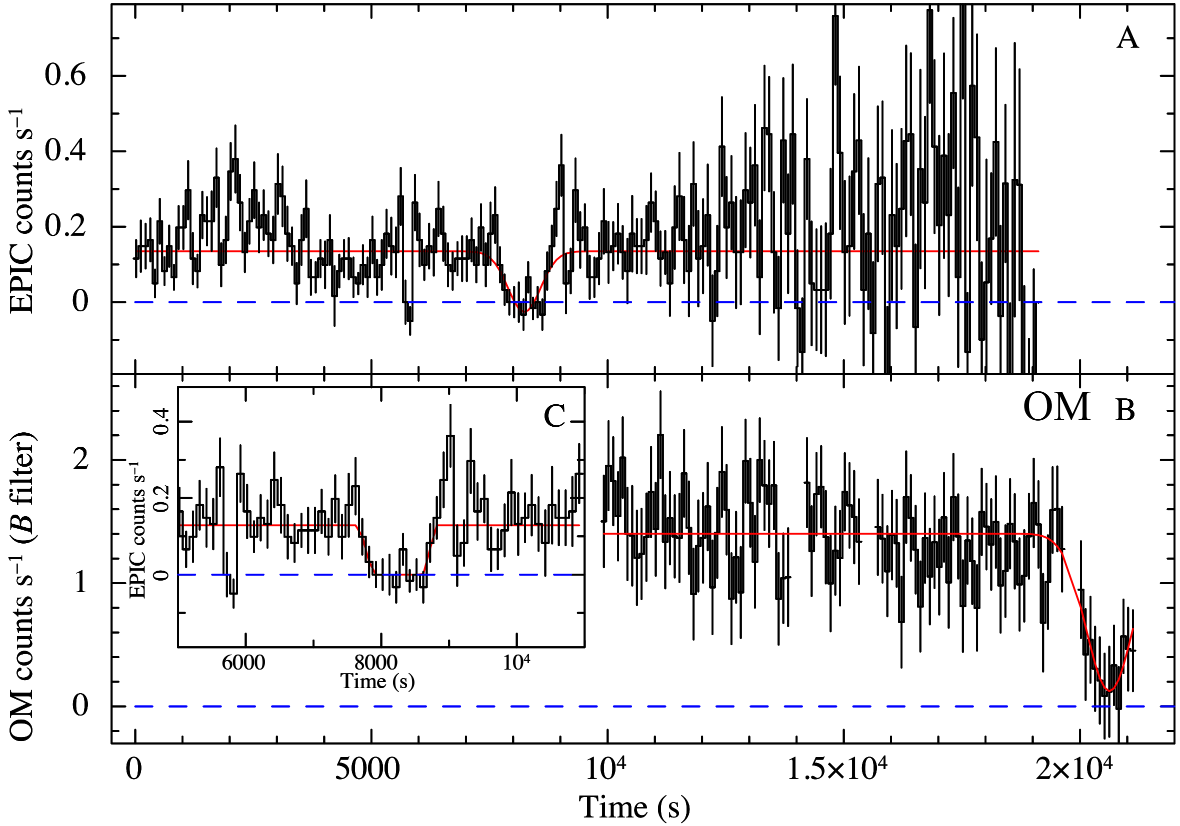
Many other IPs also show X-rays @ Porb
(Parker et al. 2005, Bernardini et al. 2012)

Bernardini et al. 2017

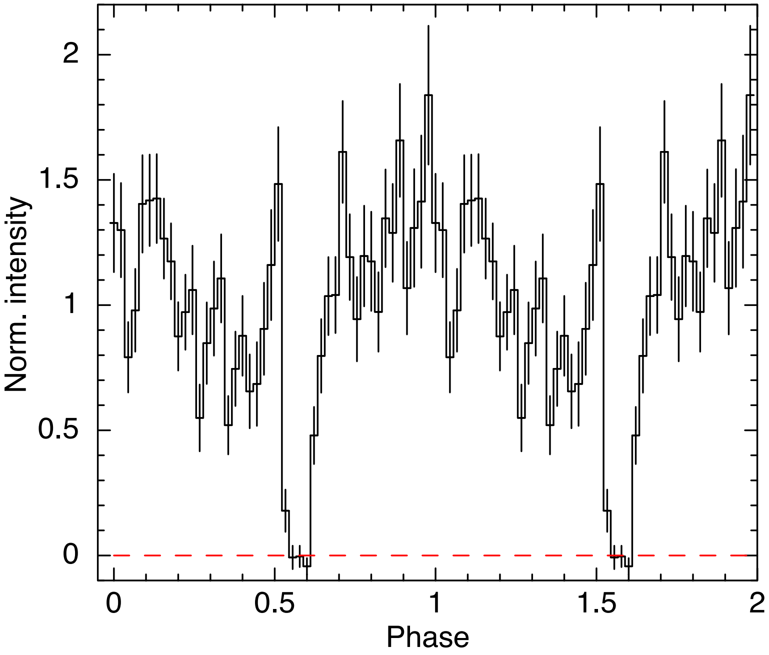
X-ray orbital variability in IPs

Eclipsing IPs – quite rare (7 so far)

$P_{\Omega} = 3.4h$
$P_{\omega} = 491s$


Swift J201424.9+1529

XMM-Newton



Swift/XRT

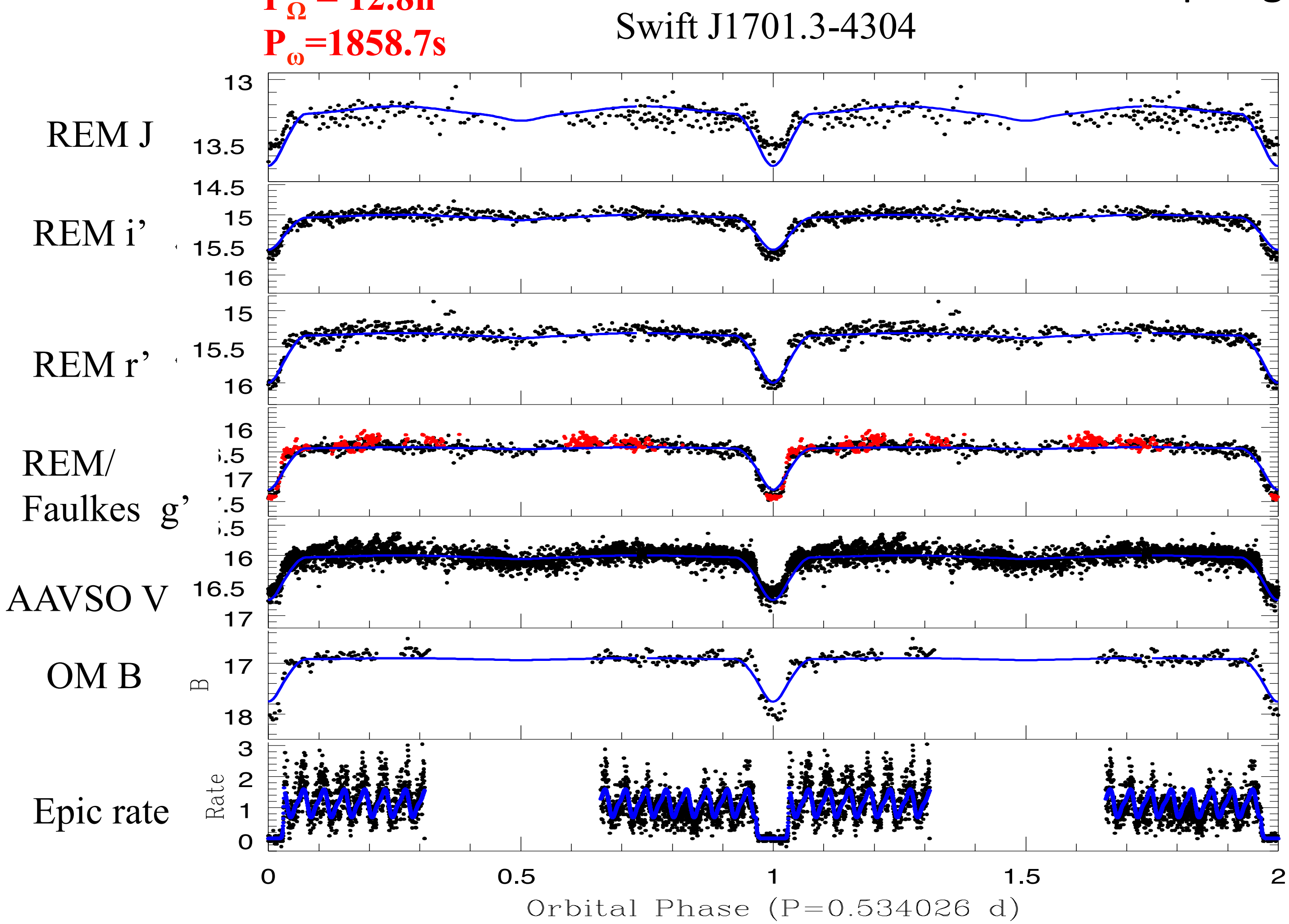
Esposito et al. 2015

X-ray orbital variability in IPs

Eclipsing IPs – quite rare (7 so far)

P_{Ω} = 12.8h

P_{ω}=1858.7s



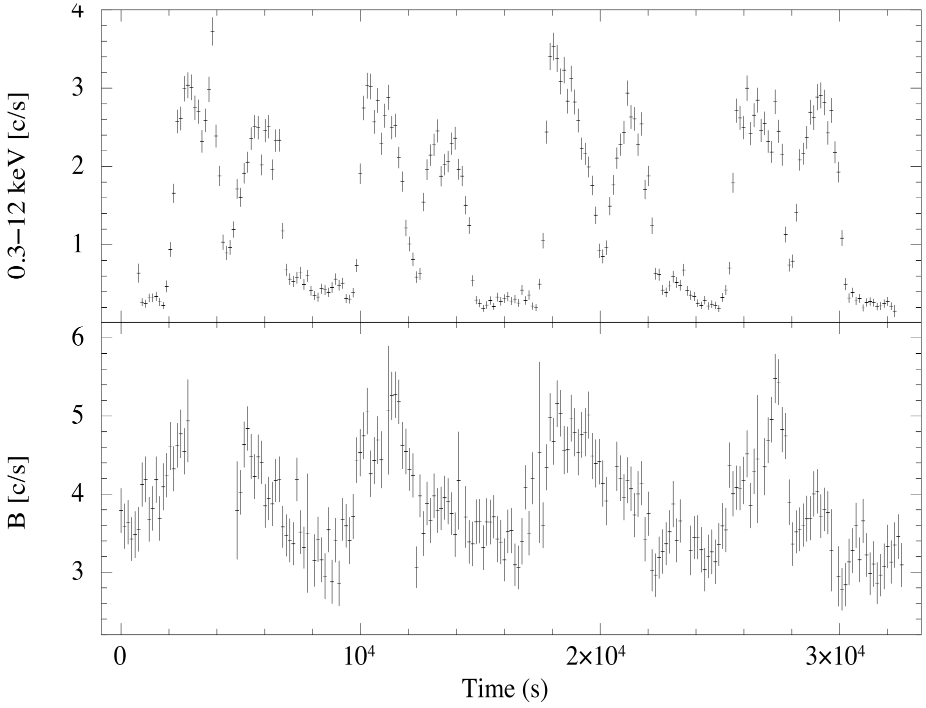
The first longest Porb eclipsing IP

Bernardini et al. 2017

X-ray light curves of new hard Polars

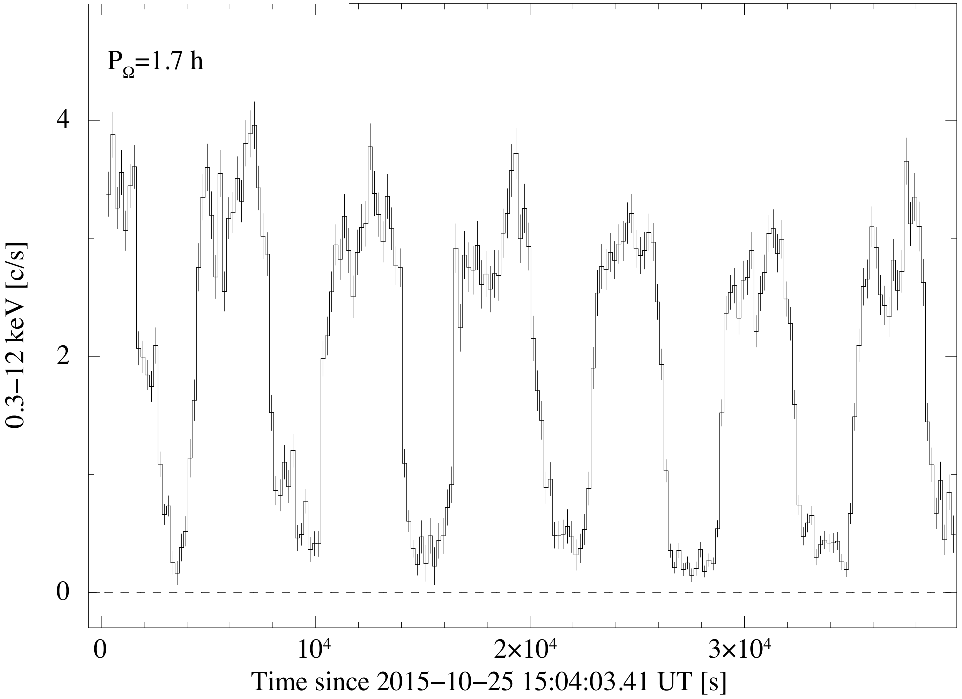
$P_\omega = P_\Omega$

$P_\Omega = 2.16h$ SWIFTJ2218.4-1925



(Bernardini et al. 2014)

$P_\Omega = 1.70h$ SWIFT J0706.8+0325



(Bernardini et al. 2017)

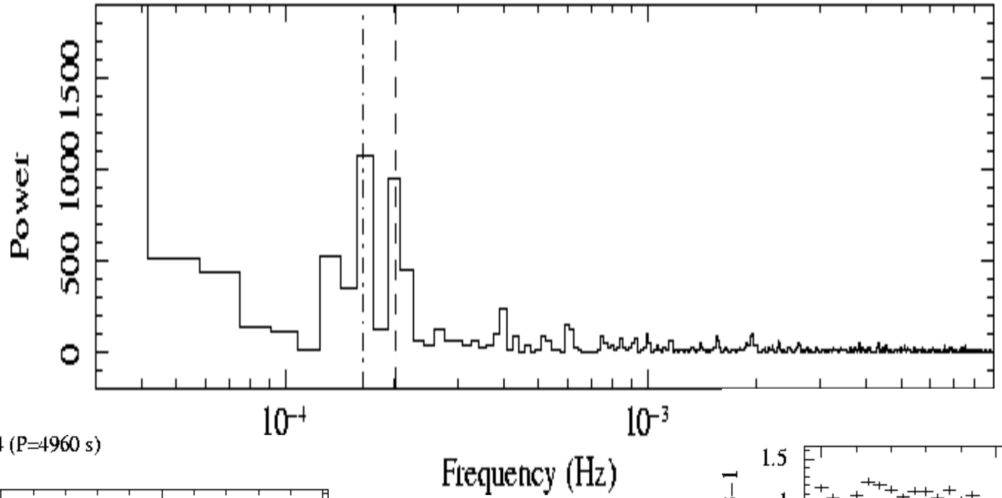
IGRJ1955+0044
A “Paloma analogue” below the gap

Porb =1.69h Pspin=1.38h

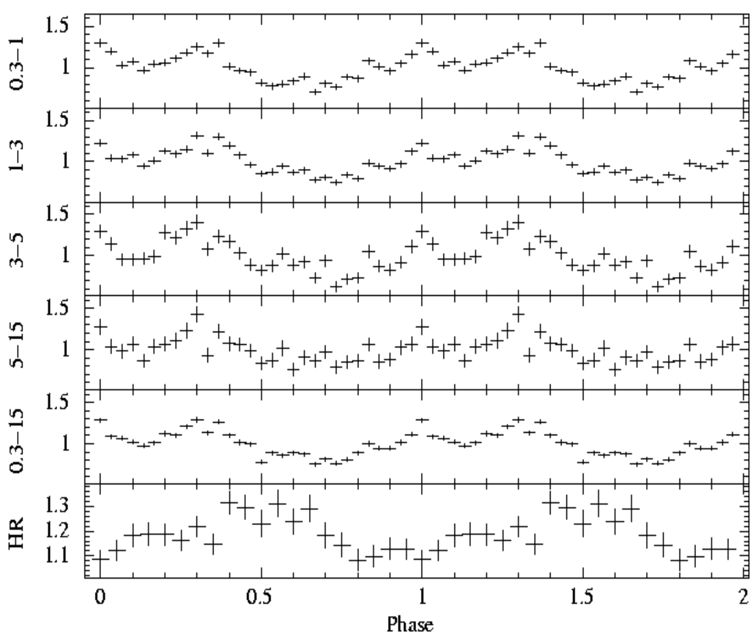
Pspin/Porb ~ 0.8

Paloma (Schwarz 2006)
Pspin =2.35h
Porb = 2.62h
Pspin/Porb ~ 0.90

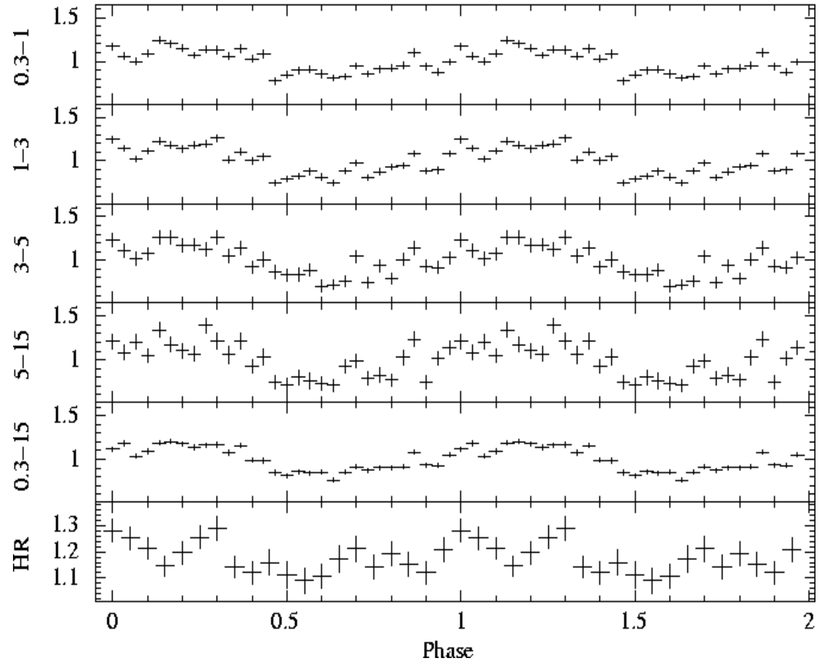
Bernardini et al. 2013



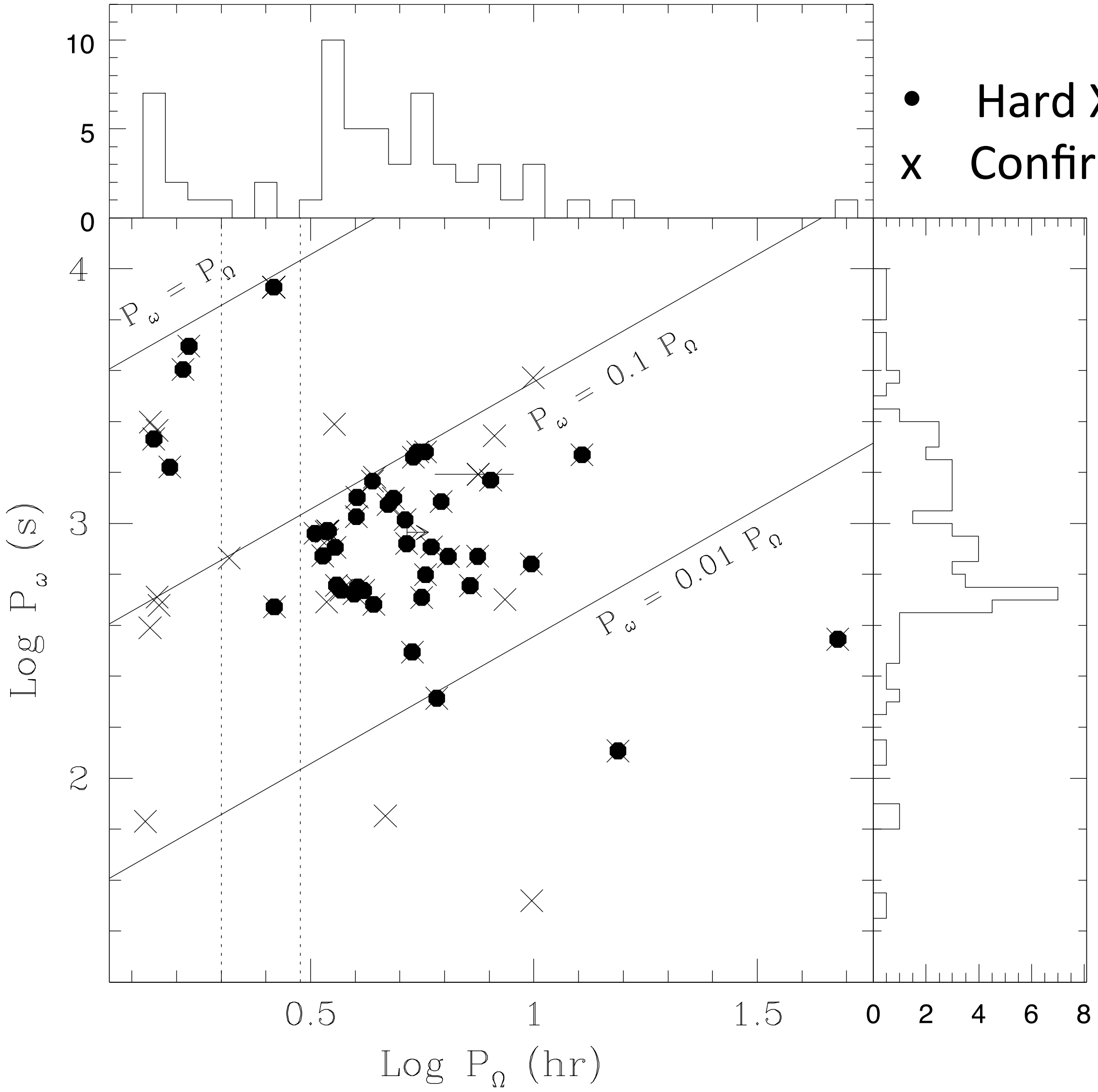
P_{ω} =1.38h



P_{Ω} = 1.69h



The confirmed IP sample

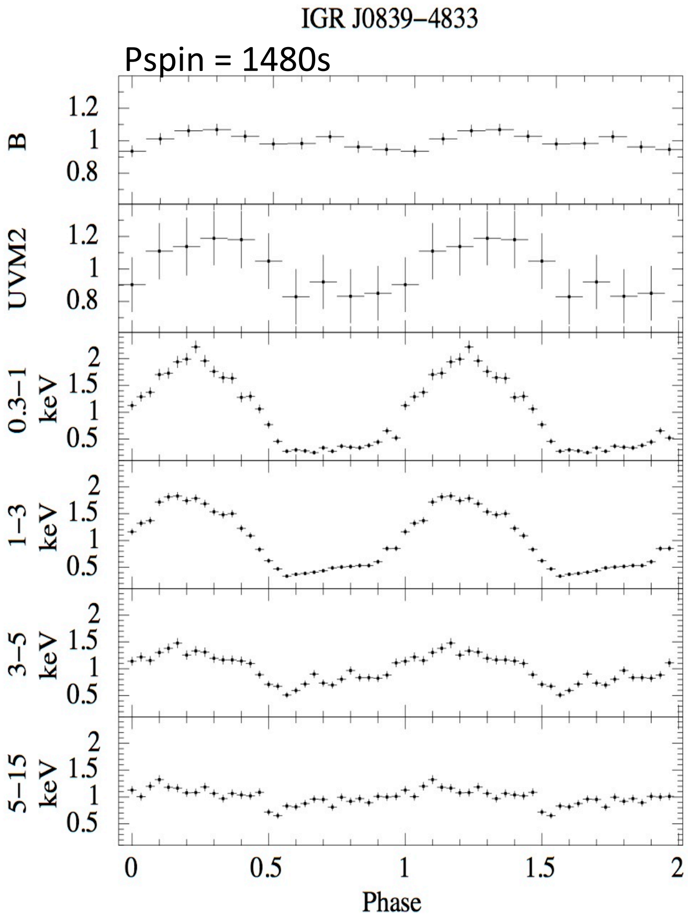


- ● Hard X-ray IPs
- x Confirmed IPs

- P_{ω}: hundreds – thousands sec
- Most at $P_{\Omega} > 3$hr
- Clustering at $P_{\omega}/P_{\Omega} \approx 0.05$- 0.1
- Weakly desynchronized at $P_{\Omega} <$ 2-3hr
- 46/66 detected by INTEGRAL/SWIFT

Bernardini et al. 2017

Energy dependent pulses



Pspin = 1480s

Bernardini et al. 2012

- ➢ Energy dependent Spin pulses:

- Amplitude decreases with energy

→ Photoelectric absorption from cool material

- Shapes change with energy

→ Additional emission components

→ Multi-component spectra

Broad-band Spectra:
combining XMM-Newton + Swift/BAT or Integral/IBIS

Spectra are thermal and complex:

- Multi-T plasma : $T_{low} \approx 0.16$keV …… $T_{high} \approx 30$-50 keV — Post-shock
- Cool absorbers : total ($N_H \sim 10^{20} - 10^{21}$ cm^{-2}) — Interstellar
  partial ($C_F \sim 40$-60%; $N_H \sim 10^{22} - 10^{23}$ cm^{-2}) — Pre-shock
  additional partial ($C_F \sim 40$-70%; $N_H \sim 10^{23}$ cm^{-2}) — Outer disc rim (Bulge)
- Gaussian @ 6.4keV: EW ~ 100-250 eV — Reflection Pre-shock/WD

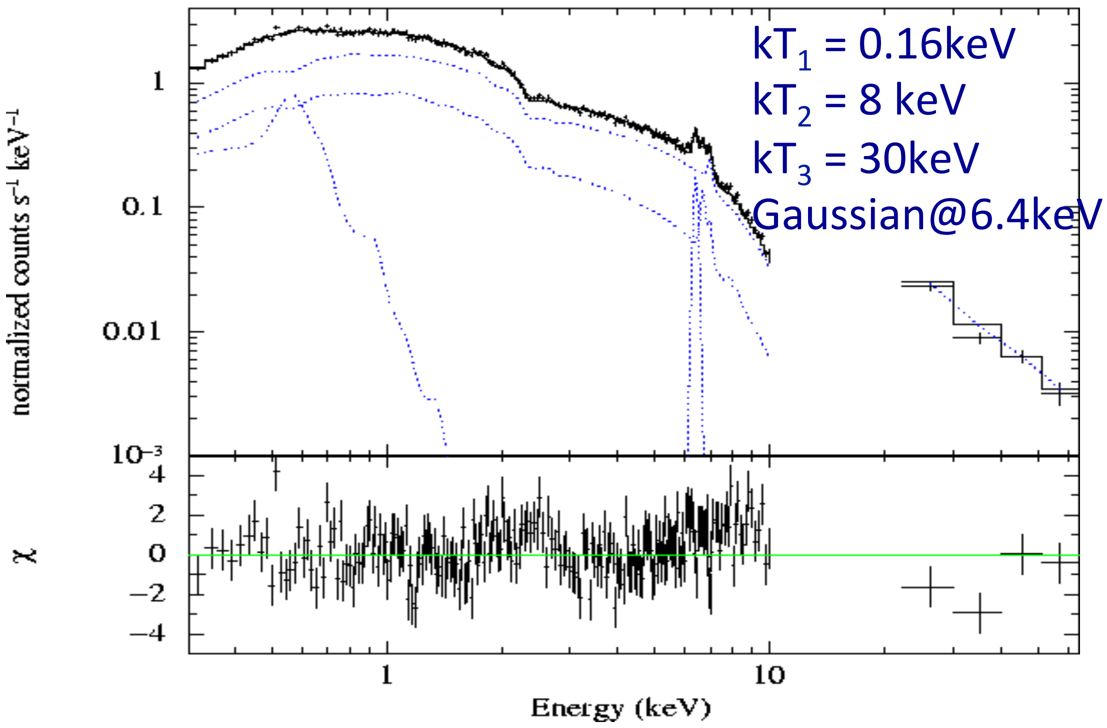
- Phase-resolved spectra:

1) changes in Partial covering absorbers

2) Changes in EW of 6.4keV line in some cases

Bernardini et al. 2012

IGR J1719–4100



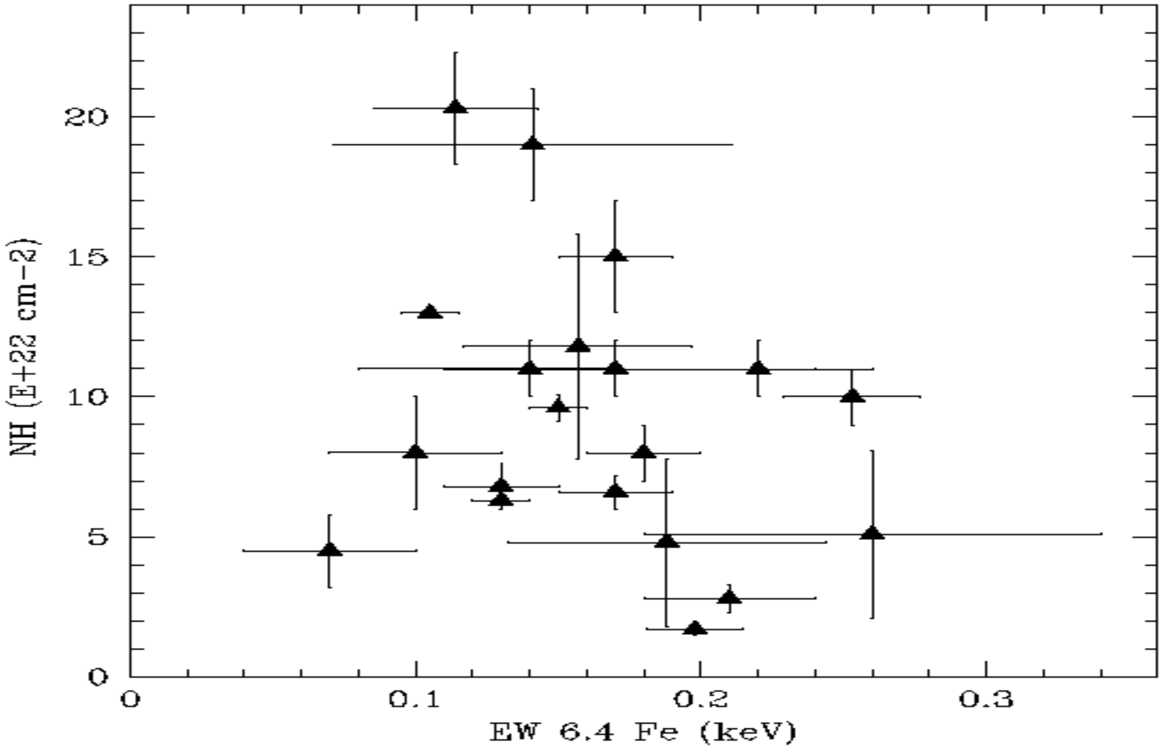
$kT_1 = 0.16$keV
$kT_2 = 8$ keV
$kT_3 = 30$keV
Gaussian@6.4keV

Broad-band Spectra

Gaussian @6.4keV: EW ~ 100-250 eV

→ Reflection from cold neutral matter should be important but reflection component not required in most cases.

Origin: WD photosphere, pre-shock material (or both)



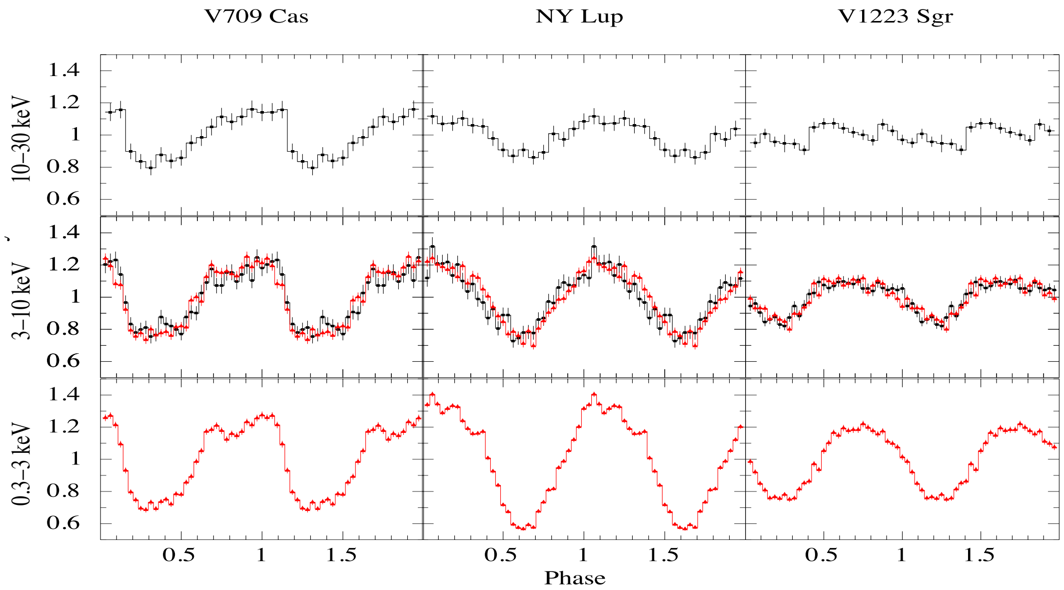
- No correlation of EWs with N_H high density absorber

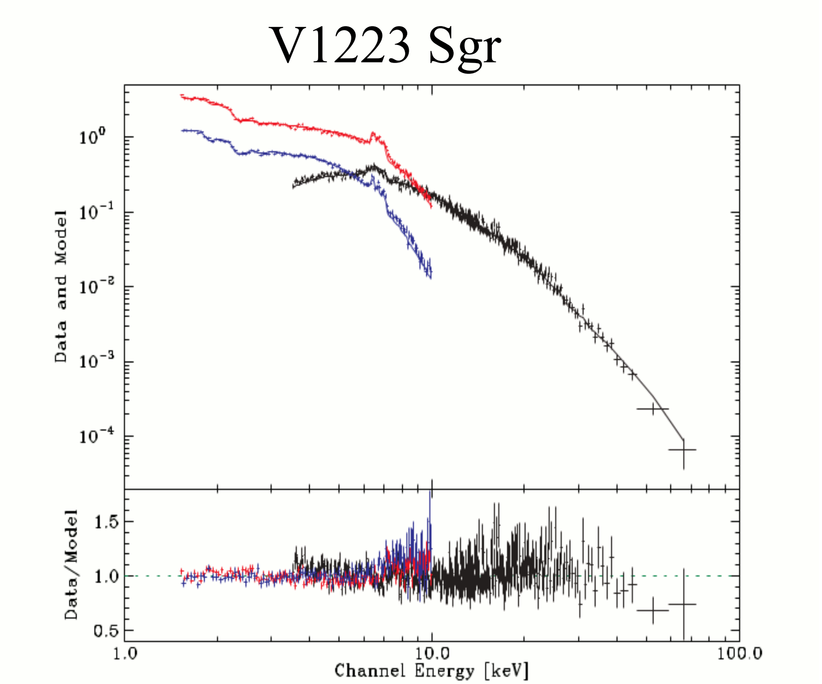
- 5 cases max EW @ spin min WD photosphere favoured

First evidence of reflection

Mukai et al. 2015

Joint XMM-Newton / Nustar observations of 3 bright IPs





phabs∗pwab(reflect∗mkcflow+Gaussian)

Rel_ref ~0.45	*≥ 1.0*	*~ 0.7*
H_shock ~ 0.2Rwd	*< 0.05 Rwd*	*~ 0.05 Rwd*
EW(6.4keV)= 105eV	*EW(6.4keV)=132 eV*	*EW(6.4keV)=90eV*

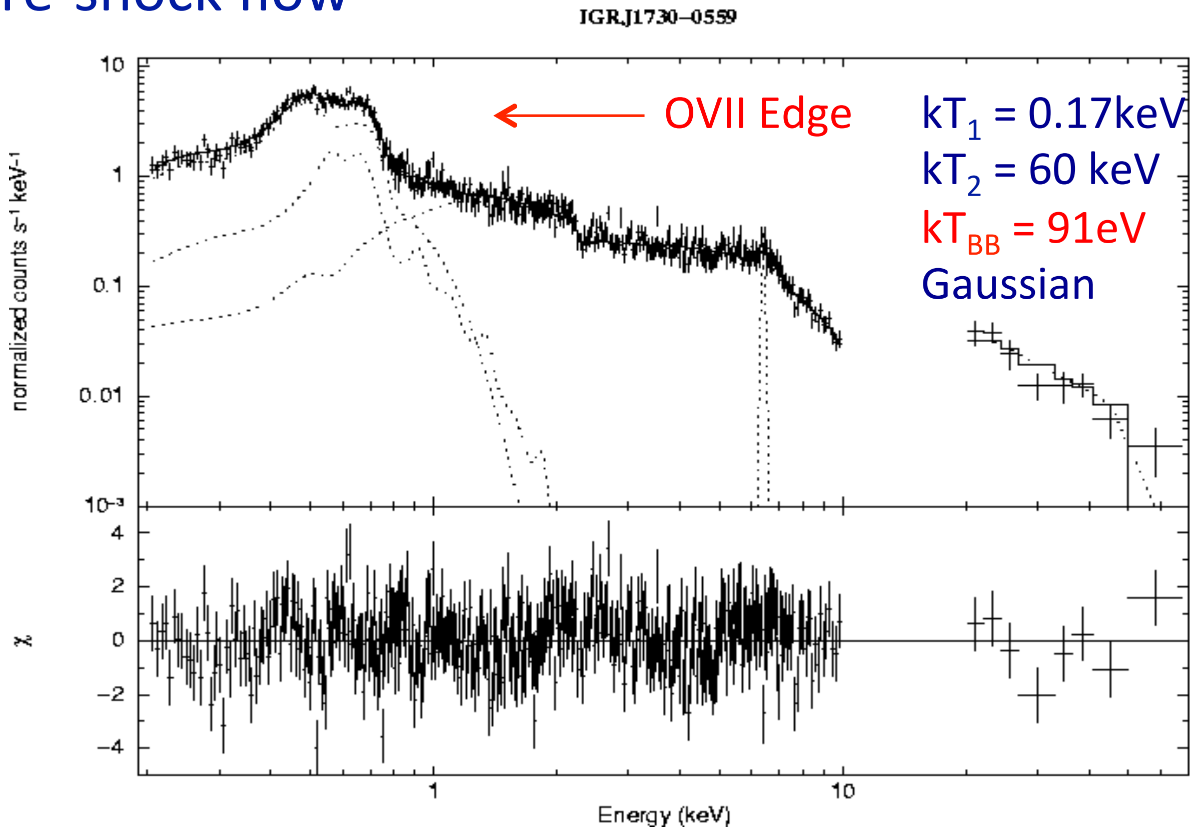
- Finite shock height -> low Reflection amplitude & strong hard X-ray modulation
- Small shock height -> large reflection amplitude & weak hard X-ray modulation but viewing geometry to be accounted

Broad-band Spectra: combining XMM-Newton + Swift/BAT or Integral/IBIS

In a few cases (3 so far) also:

- Absorption edge: ~ 0.74keV OVII K-shell

→ Warm absorber in the pre-shock flow



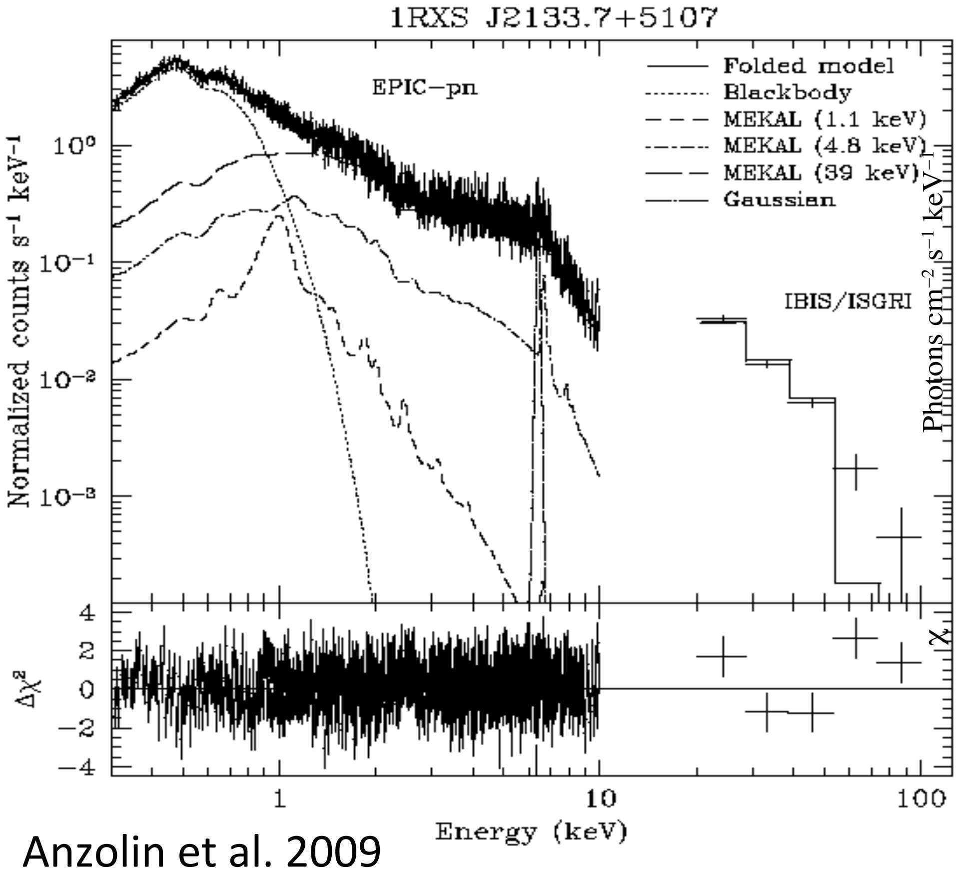
OVII Edge

kT_1 = 0.17keV
kT_2 = 60 keV
kT_{BB} = 91eV
Gaussian

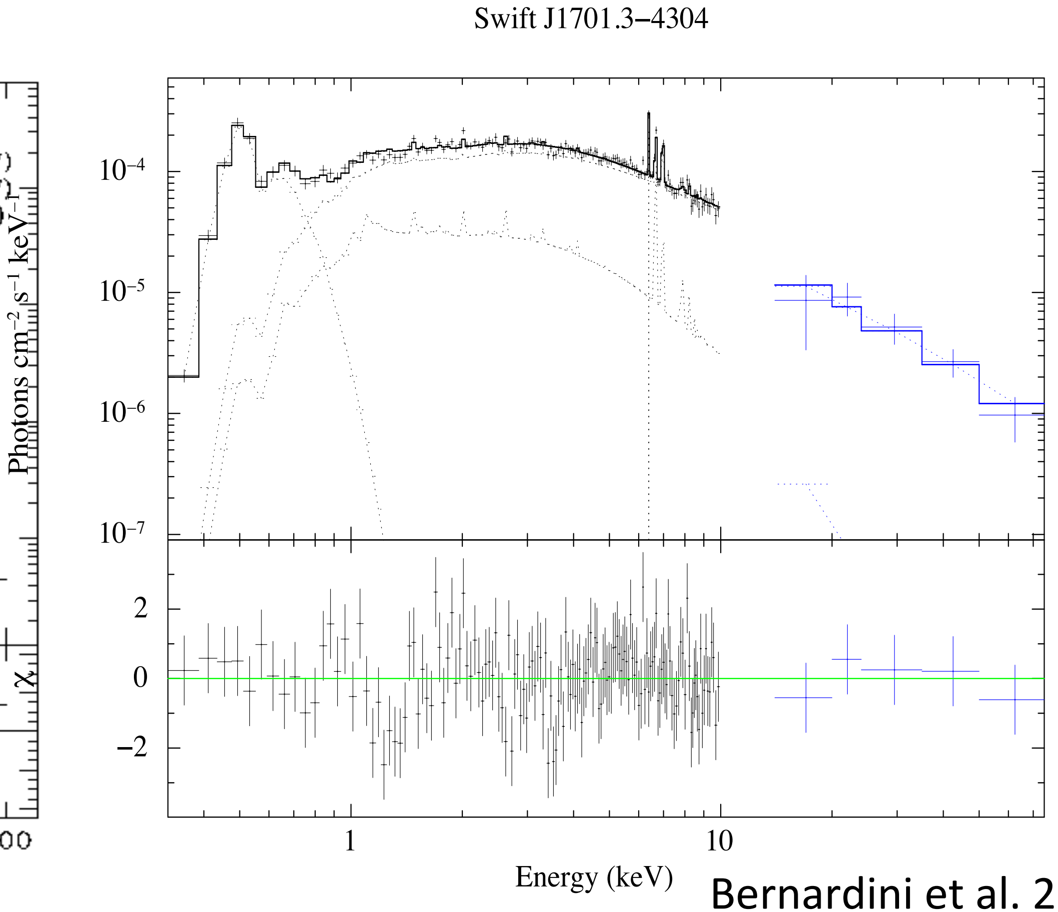
de Martino et al. 2008

Broad-band Spectra: combining XMM-Newton + Swift/BAT or Integral/IBIS

And in many cases also: Blackbody: kT ≈ 30-90 eV
→ Reprocessing at WD surface



Anzolin et al. 2009



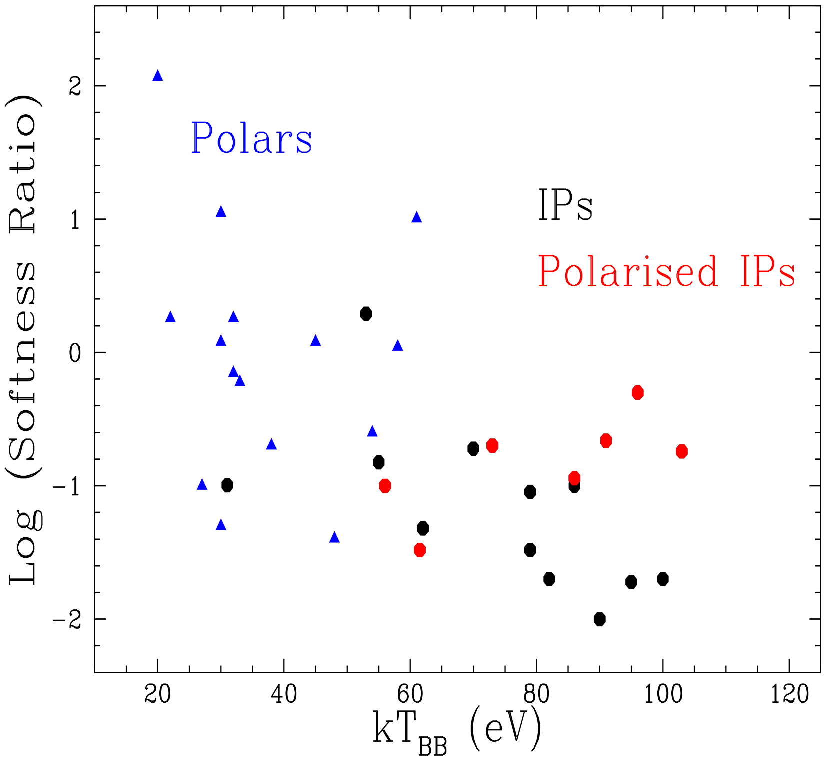
Bernardini et al. 2017

XMM-Newton reveals a new soft X-ray view of MCVs

Increasing number of IPs (19/66) with a soft BB component

→ Reprocessing at WD as most Polars

But with differences:



- L_{soft}/L_{hard}(Polars) > L_{soft}/L_{hard}(IPs)

Cyclotron cooling important at high B :

$L_{BB} \approx L_{cyc} + L_{hard}$ with $L_{cyc} > L_{hard}$

but for AM Her reprocessing emerges in the UV

→ soft BB due to blobby accretion

- Wide range kT_{bb} -uncomfortable high!

$kT_{BB} \; \alpha \; (dM/dt) \; f^{-1/4}$

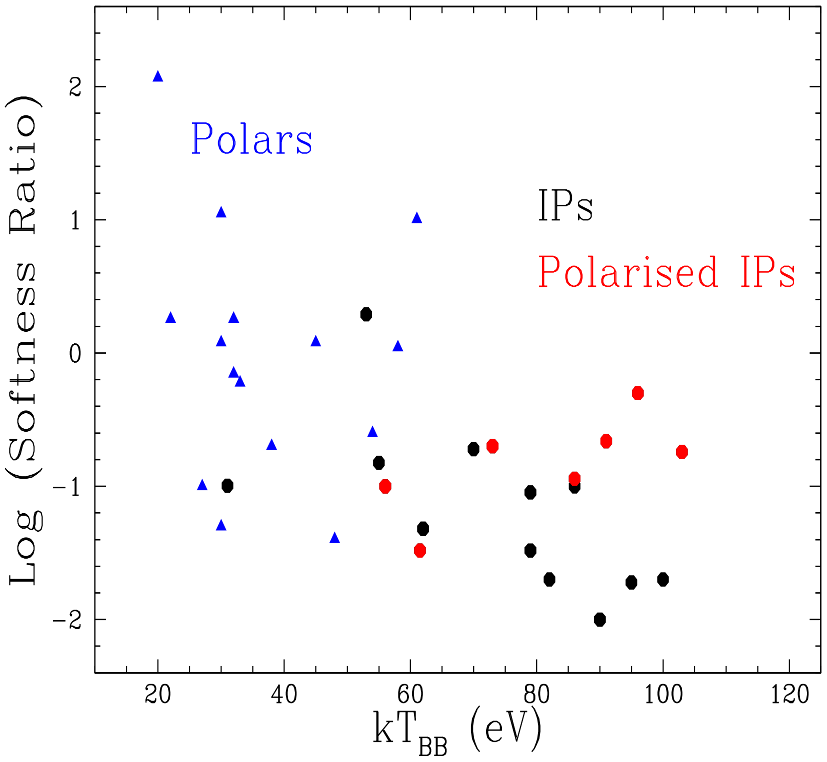
- $f_{IPs} \sim 10^{-6} - 10^{-5} \ll f_{Polars} \sim 10^{-4} - 10^{-3}$

Anzolin et al. 2008, Bernardini et al. 2017

- 7 out of 19 soft IPs found polarised

XMM-Newton reveals a new soft X-ray view of MCVs

Only 13% of Polars observed with XMM-Newton show soft X-ray excess
Many new Polars without a soft BB component



Anzolin et al. 2008, Bernardini et al. 2017

Soft BB component is not a defining characteristic of Polars anymore

(Ramsay & Cropper 2004, Ramsay et al. 2009, Bernardini et al. 2014; Worpel et al. 2016; Bernardini et al. 2017)

Hard X-ray view of MCVs

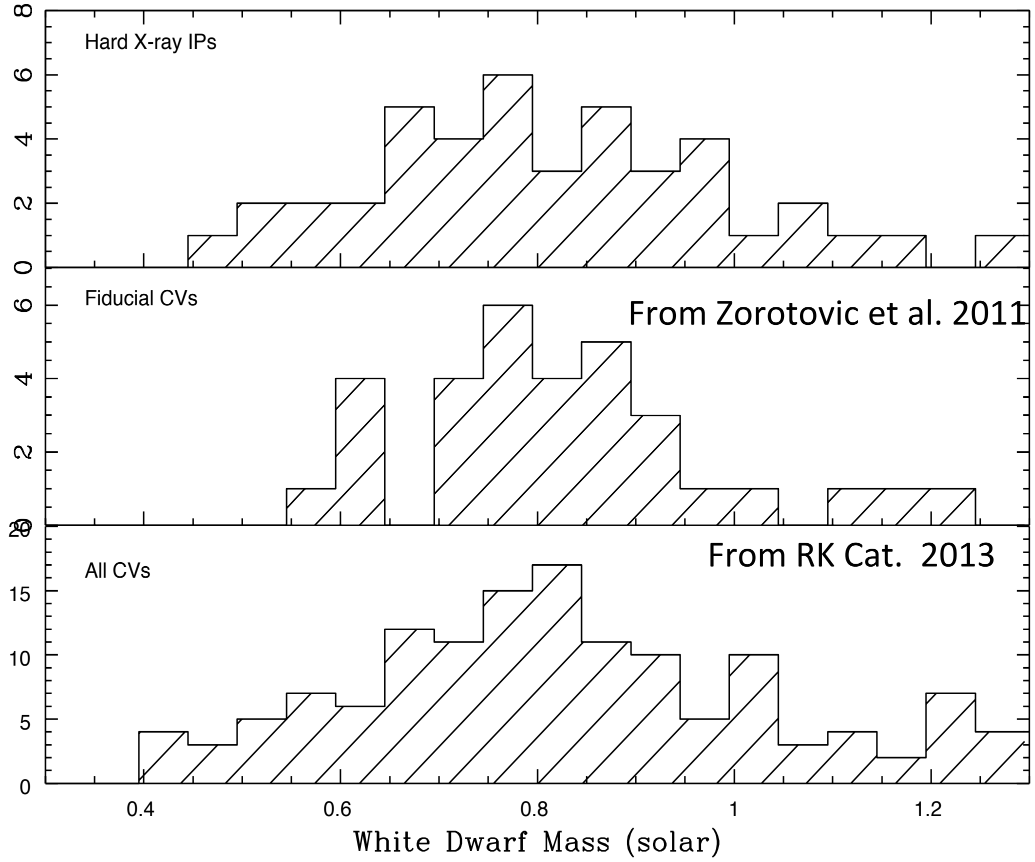
IPs dominate hard X-ray detected CVs in INTEGRAL and Swift surveys

Do they host massive WDs?

$$kT_{shock} = 3/8\, G\, M_{WD}/R_{WD}\, \mu\, m_H$$

$$<M_{IPs}> = 0.81 \pm 0.18\, M_\odot$$
$$<M_{Fid}> = 0.82 \pm 0.15\, M_\odot$$
$$<M_{CVs}> = 0.82 \pm 0.24\, M_\odot$$

Using Anzolin+08,09, Brunschweiger09 Tomsick 16, Bernardini+12,+13,15,17



From Zorotovic et al. 2011

From RK Cat. 2013

WD IP masses not so different from other WD CVs

What Cooling mechanism?

Radiative losses by Cyclotron & Bremsstrahlung for B>1MG

$\text{Frad} \approx \rho^{a}\,\text{Te}^{\,b}$

One-fluid plasma in low B and high flow rates

(Fisher & Beuermann 2001; Beuermann 2003)

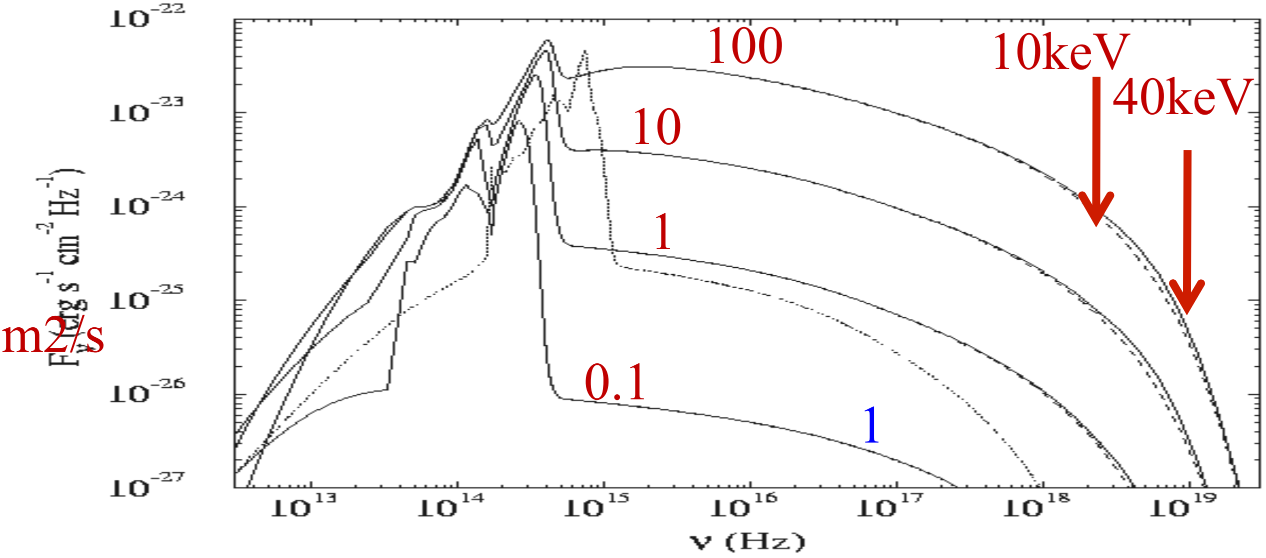
Bremsstrahlung is primary & Cyclotron is secondary

Systems with moderately low field and high dm/dt can be hard X-ray sources

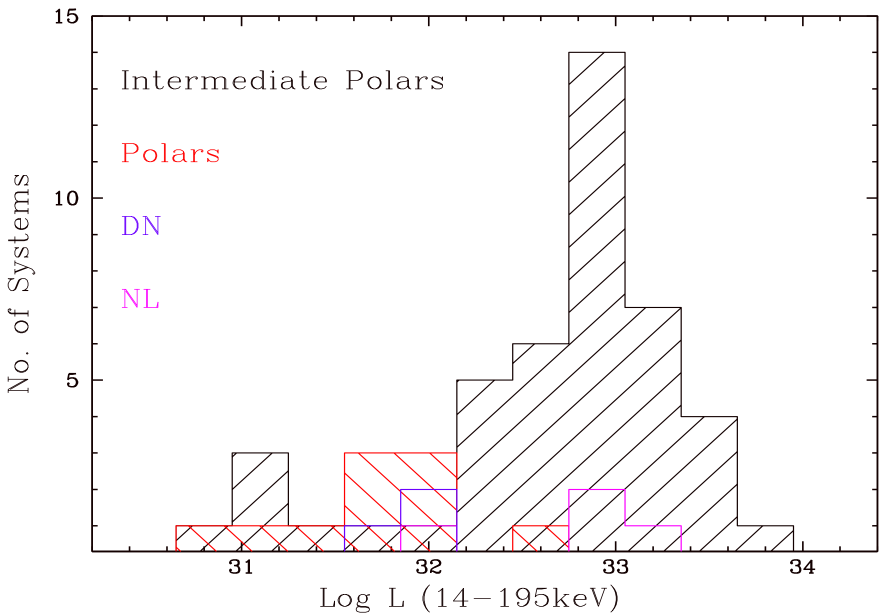
B=30 MG; dm/dt=100,10,1,0.1 g/cm2/s

B=100MG dm/dt=1 g/cm2/s

From Fisher & Beuerman 2001



Hard X-ray Luminosities



Subject to distance uncertainties
- need of Gaia !

- IPs: <Lx> ~ 8×10^{32} erg/s (up to ~1kpc)
- 6 IPs at Lx ~ 0.5-5×10^{31} erg/s with 4 below the 2-3h gap
- Polars: Lx ≤ 2×10^{32} erg/s (up to 240 pc)
- Too few non magnetics
- Low Lx: Polars, short Porb IPs or even DNs ?

(see Reis et al. 2013; Pretorius& Mukai 2014)

What we still need:

Near Future:

- Census of hard X-ray CVs :
  - Ongoing XMM-Newton identification programme
  - Searches of new systems in 3XMM (Extras project)

- Polarimetric survey of mCVs and IPs in particular

Bit Far Future:

XIPE/iXPE to probe accretion geometry through X-ray polarization

- e-ROSITA will find thousands of hard X-ray CVs requiring follow-ups
- eXTP will study faint mCVs over a broad-band range
- ATHENA will trace post-shock plasma (Oxygen, Fe, Si, Mg, S) ;
  warm and cool absorbers;
  WD mass via Grav. Redshift of 6.4keV fluorescent line

Conclusions

- Hard X-ray CVs dominated by mCVs of IP type

- Increase by more 50% IP members thanks to INTEGRAL/SWIFT

- IPs found to share similar BB component as the Polars

- Hard mCVs have:
  - wide range of B-fields but not higher than 30-40MG
  - WDs are not so massive
  - Hard mCVs because of moderate B & high dm/dt

- Faint X-ray sources to be identified