OAC Osservatorio Astronomico di Cagliari

REGIONE AUTÒNOMA DE SARDIGNA
REGIONE AUTONOMA DELLA SARDEGNA

# Ultraluminous X-ray Sources: three exciting years

**Matteo Bachetti**
INAF - Osservatorio Astronomico di Cagliari
**Madrid, 2015/06/10**

NO AGN

Single sources

**Definition:**

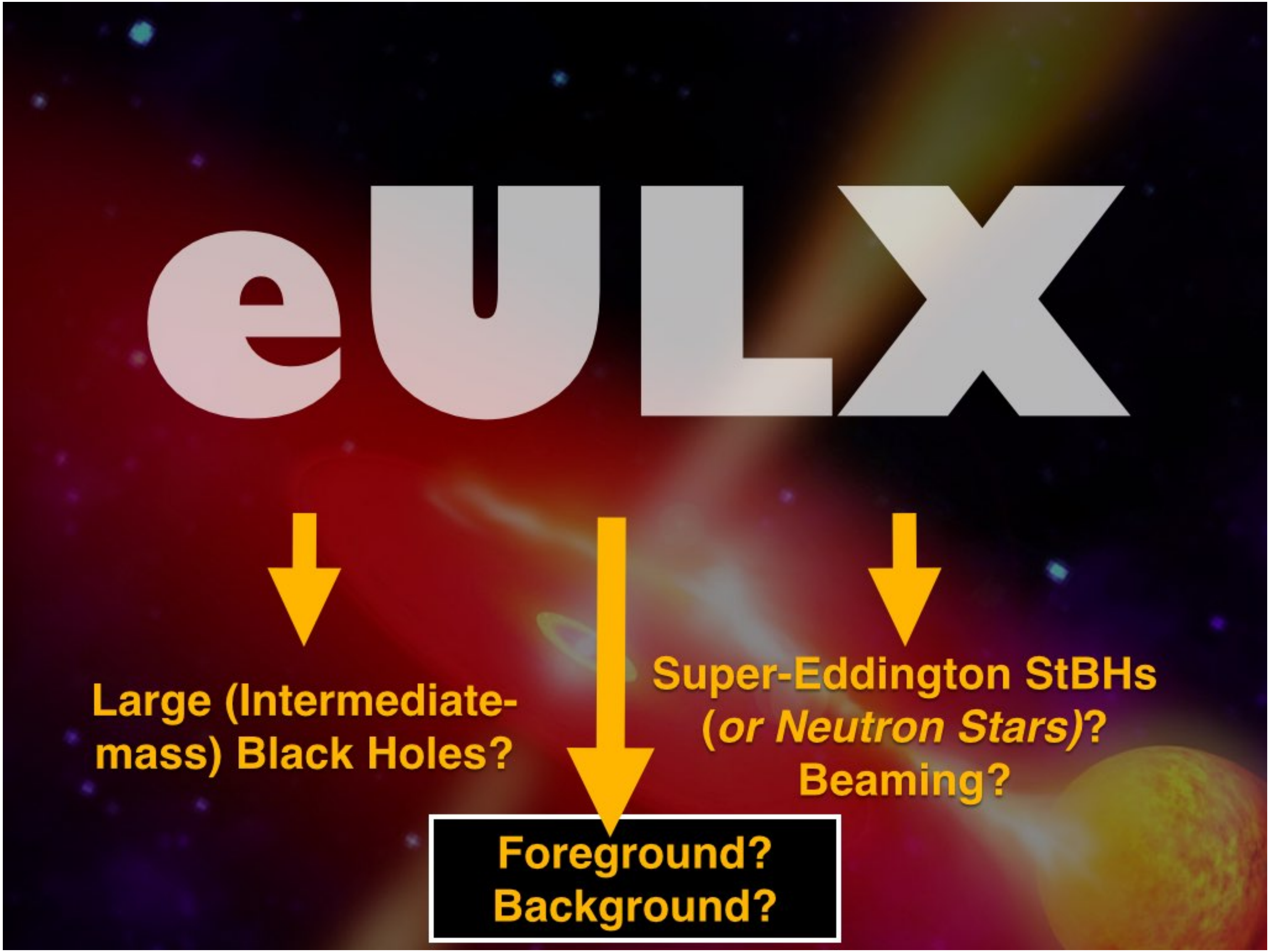
Ultraluminous X-ray sources are off-nuclear, point-like X-ray sources exceeding the (isotropic) Eddington limit for a stellar-mass Black Hole (StBH)

$$L_{Edd} \approx 1.38 \cdot 10^{38} \frac{M}{M_\odot} \mathrm{erg/s}$$

$$\approx 1.38 \cdot 10^{39} \frac{M}{10 M_\odot} \mathrm{erg/s}$$

*Extreme* ULXs (eULXs): $L_{Edd} > 10^{40}$ erg/s

*Hyper*luminous X-ray sources: $L_{Edd} > 10^{42}$ erg/s


eULX
Large (Intermediate-mass) Black Holes?
Foreground?
Background?
Super-Eddington StBHs
(*or Neutron Stars*)?
Beaming?

Monthly Notices
of the
ROYAL ASTRONOMICAL SOCIETY

MNRAS **450**, 787–793 (2015) doi:10.1093/mnras/stv505

# The hyperluminous X-ray source candidate in IC 4320: another HLX bites the dust

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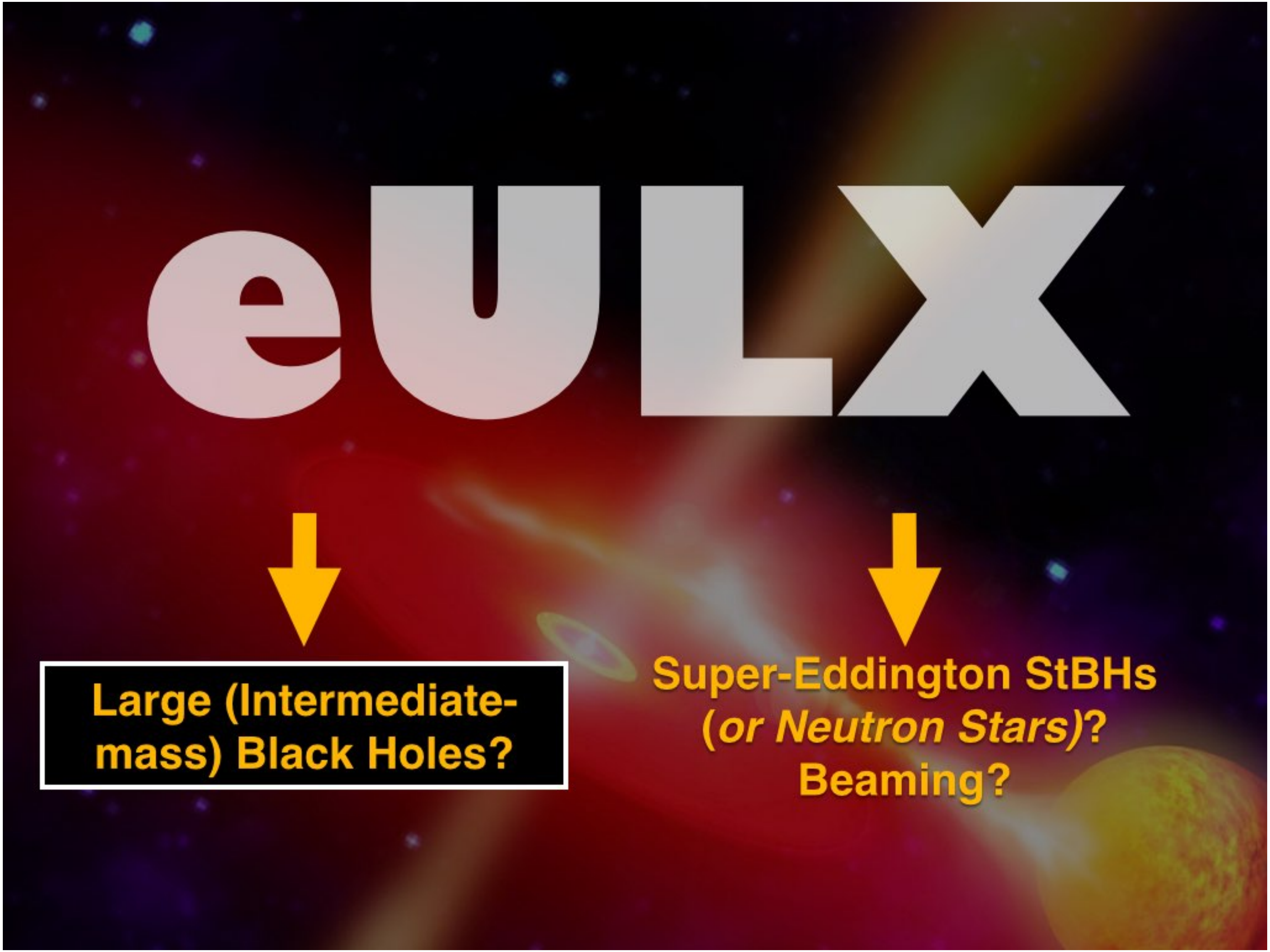
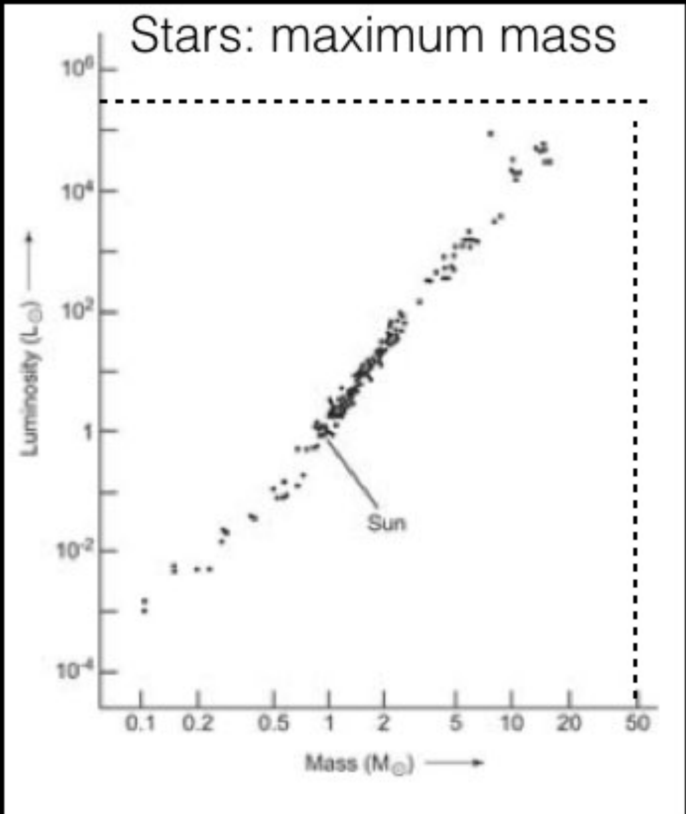
**ABSTRACT**

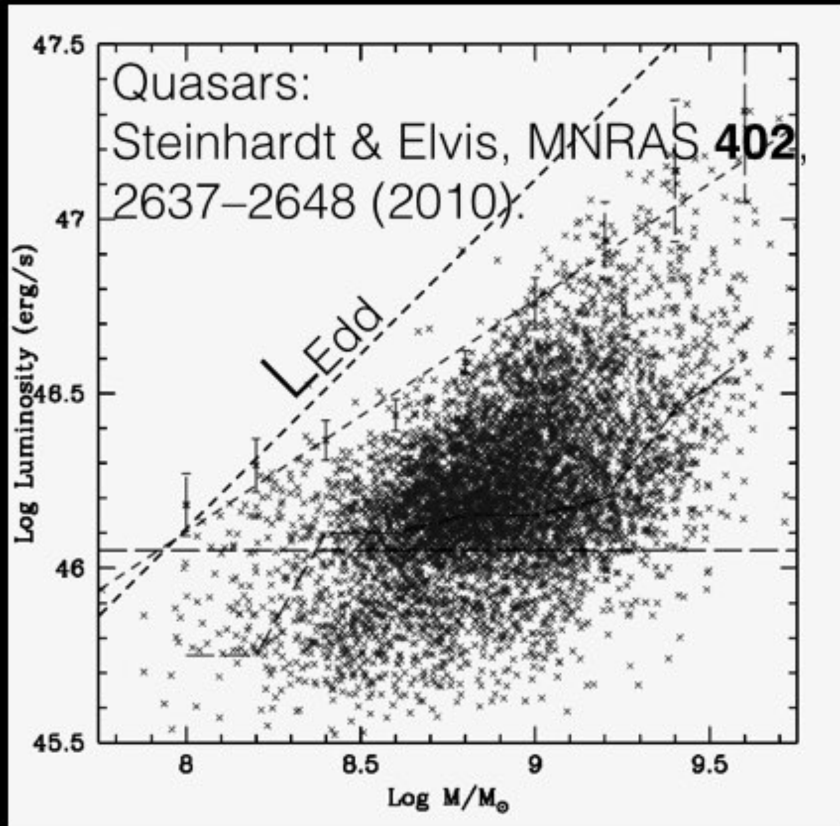
The known members of the class of hyperluminous X-ray sources (HLXs) are few in number, yet they are of great interest as they are regarded as the likeliest intermediate-mass black hole (IMBH) candidates amongst the wider population of ultraluminous X-ray sources (ULXs). Here we report optical photometry and spectroscopy of an HLX candidate associated with the galaxy IC 4320, that reveal it is a background AGN. We discuss the implications of the exclusion of this object from the small number of well-studied HLXs, that appears to accentuate the difference in characteristics between the good IMBH candidate ESO 243-49 HLX-1 and the small handful of other HLXs.

**Key words:** accretion, accretion discs – black hole physics – X-rays: binaries – X-rays: galaxies.


eULX
Large (Intermediate-mass) Black Holes?
Super-Eddington StBHs
(*or Neutron Stars*)?
Beaming?

# The Eddington limit works…

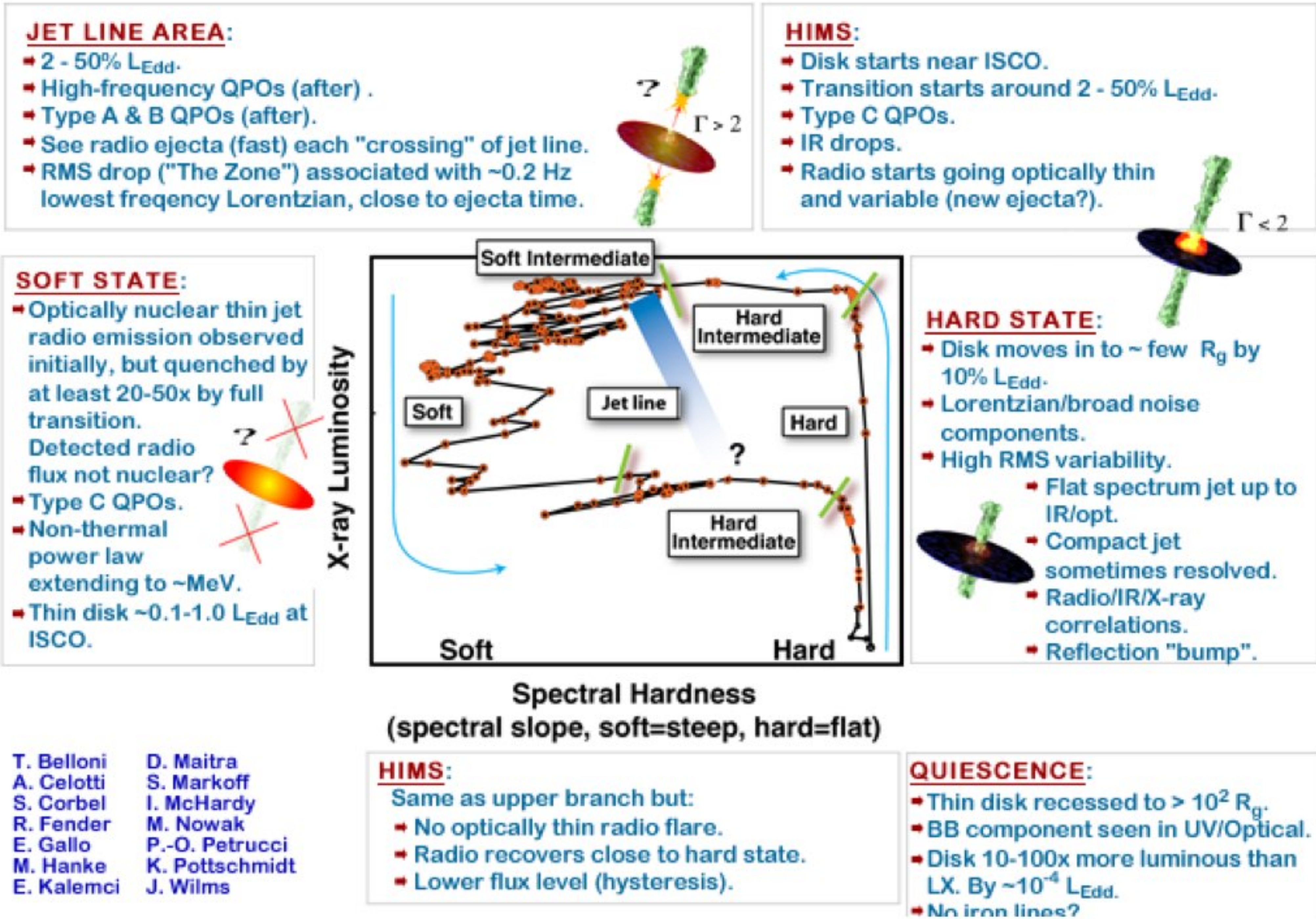


# Intermediate mass BHs?

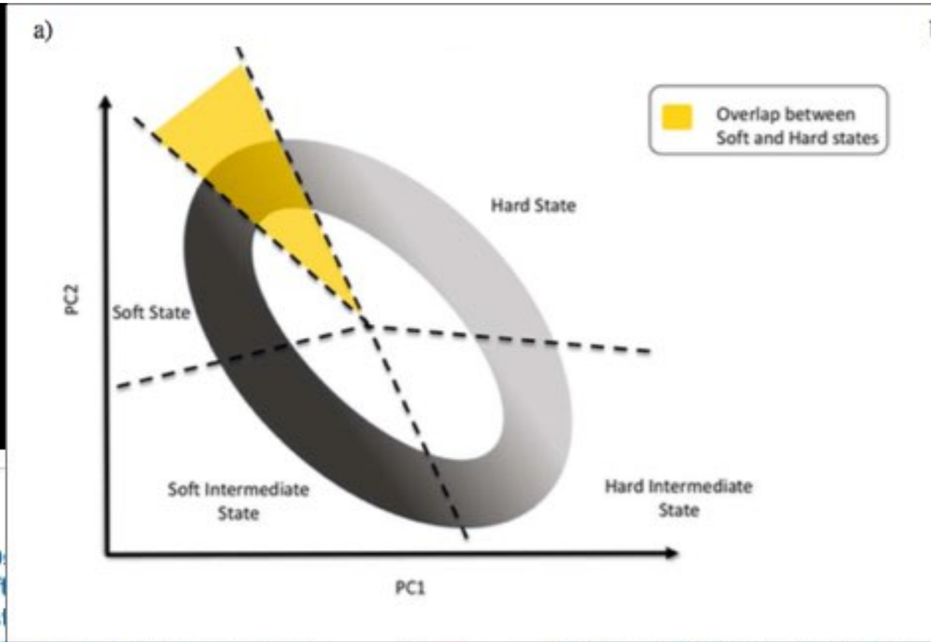

Credits: NASA/JPL

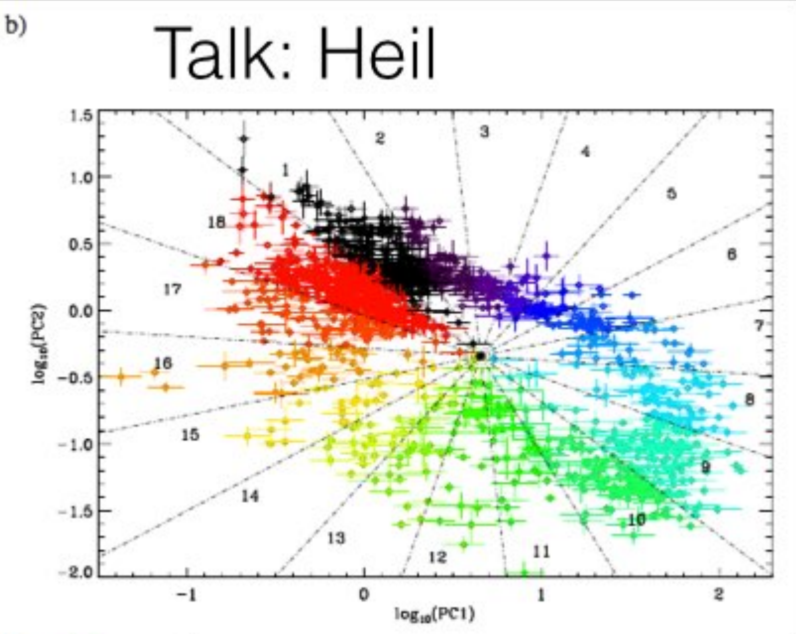
Population III large StBH, seeds for SMBHs: Madau & Rees, *ApJ* **551**, L27–L30 (2001).




-> Talks by Malzac, Fender, Vaughan, Heil…

Talk: Heil

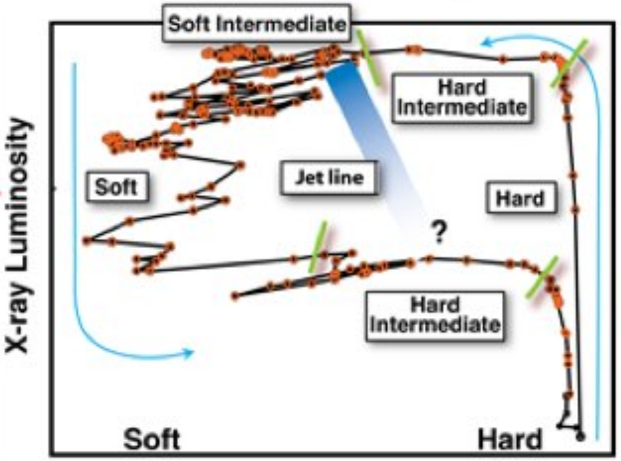


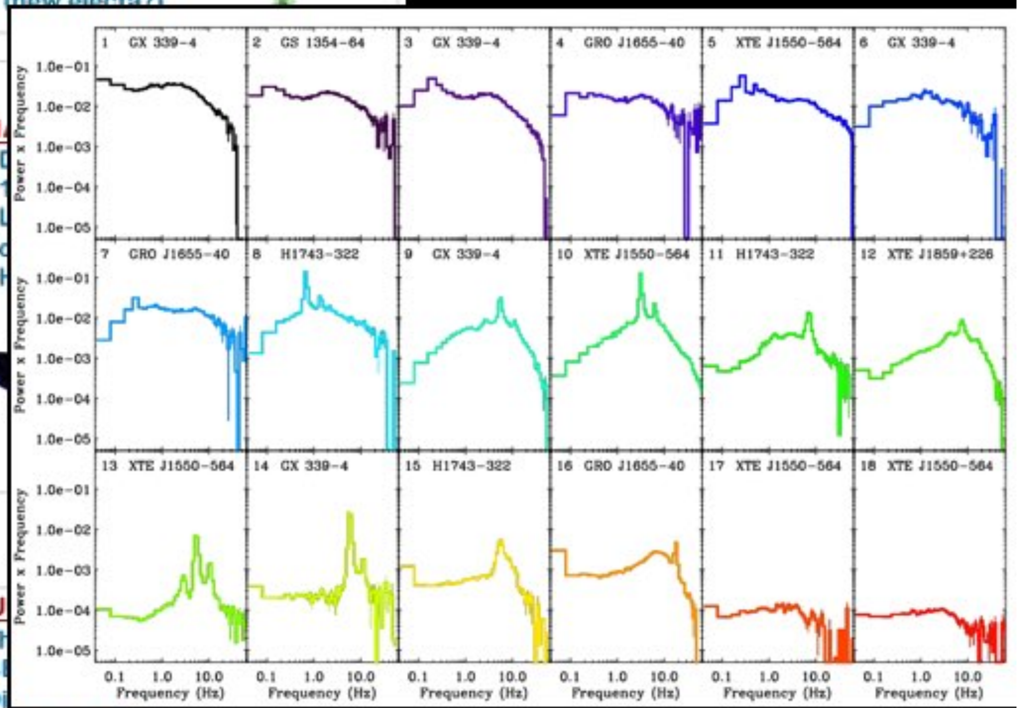

**JET LINE AREA:**
- 2 - 50% $L_{Edd}$.
- High-frequency QPO
- Type A & B QPOs (aft
- See radio ejecta (fast
- RMS drop ("The Zone") associated with ~0.2 Hz lowest freqency Lorentzian, close to ejecta time.

Radio starts going optically thin and variable (new ejecta?)

**SOFT STATE:**
- Optically nuclear thin jet radio emission observed initially, but quenched by at least 20-50x by full transition. Detected radio flux not nuclear?
- Type C QPOs.
- Non-thermal power law extending to ~MeV.
- Thin disk ~0.1-1.0 $L_{Edd}$ at ISCO.




Spectral Hardness
(spectral slope, soft=steep, hard=flat)




T. Belloni, A. Celotti, S. Corbel, R. Fender, E. Gallo, M. Hanke, E. Kalemci, D. Maitra, S. Markoff, I. McHardy, M. Nowak, P.-O. Petrucci, K. Pottschmidt, J. Wilms

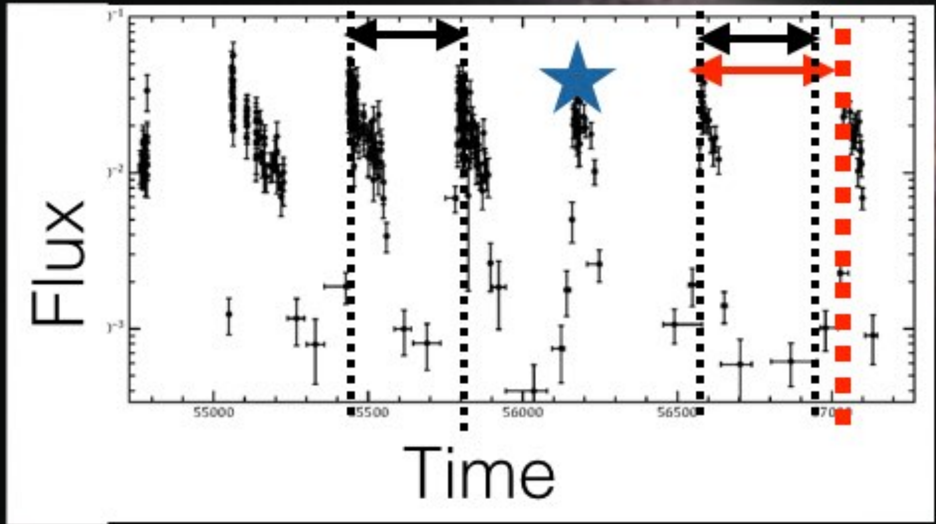
**HIMS:**
Same as upper branch but:
- No optically thin radio flare.
- Radio recovers close to hard state.
- Lower flux level (hysteresis).

QU...
LX. By ~$10^{-4}$ $L_{Edd}$.

Probing the X-Ray Binari

-> Talks by Malzac, Fender, Vaughan, Heil…

# ESO 243-49 HLX-1




Farrell et al. *Nat.* **460**, 73–75 (2009).
Lasota et al. *ApJ* **735,** 89 (2011).
Servillat et al. *ApJ* **743,** 6 (2011).
Godet et al. *ApJ* **793**, 105 (2014).

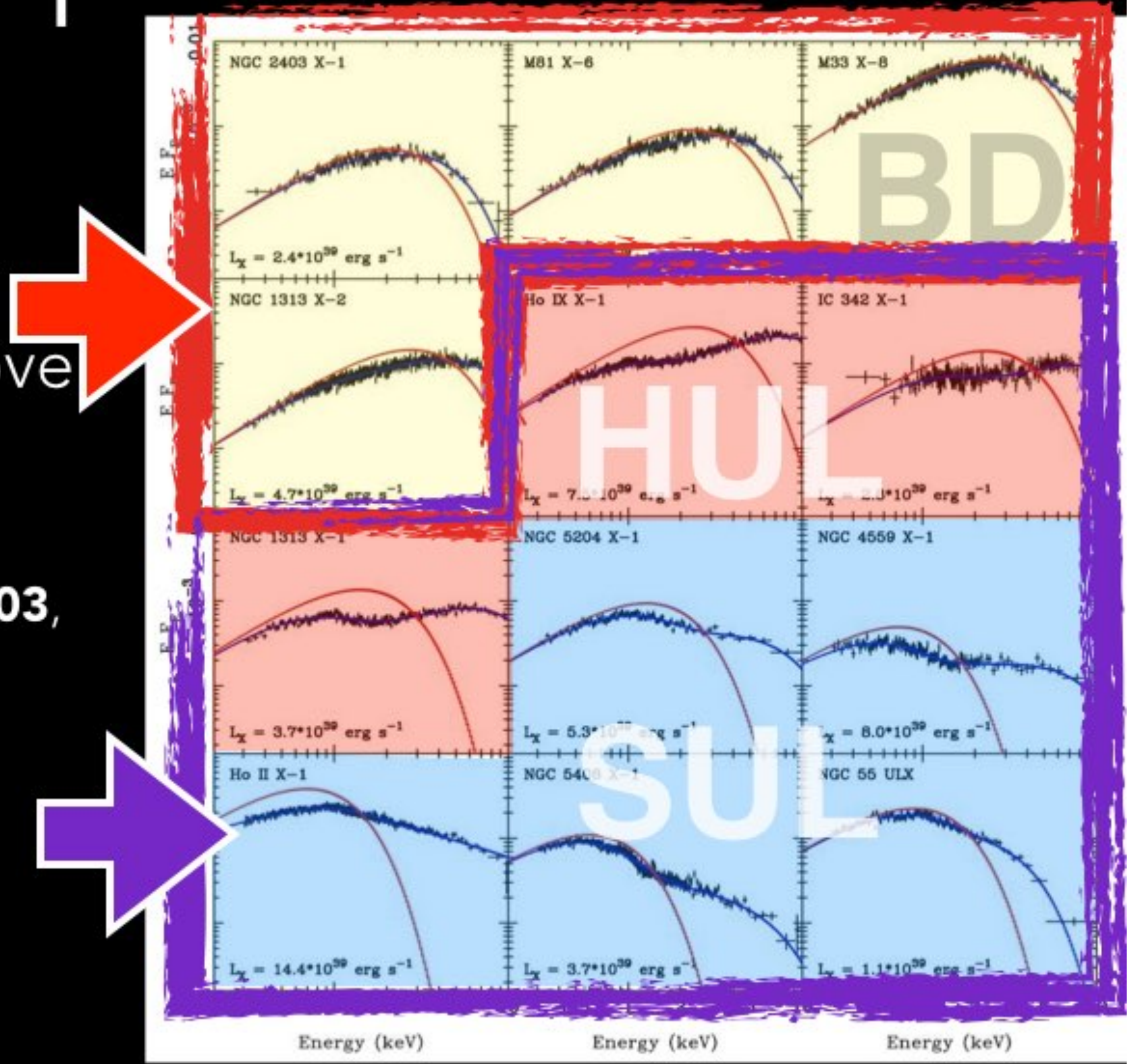
- $L > 10^{42}$ erg/s
- Spectral states comparable to standard BHs
- Best IMBH candidate (alternative interpretation: King & Lasota, *MNRAS Let.* **444,** L30–L33 (2014).)

Posters: Webb (B11) and Detoeuf (A6)
for another IMBH candidate, see Earnshaw's talk

# ULX spectra…

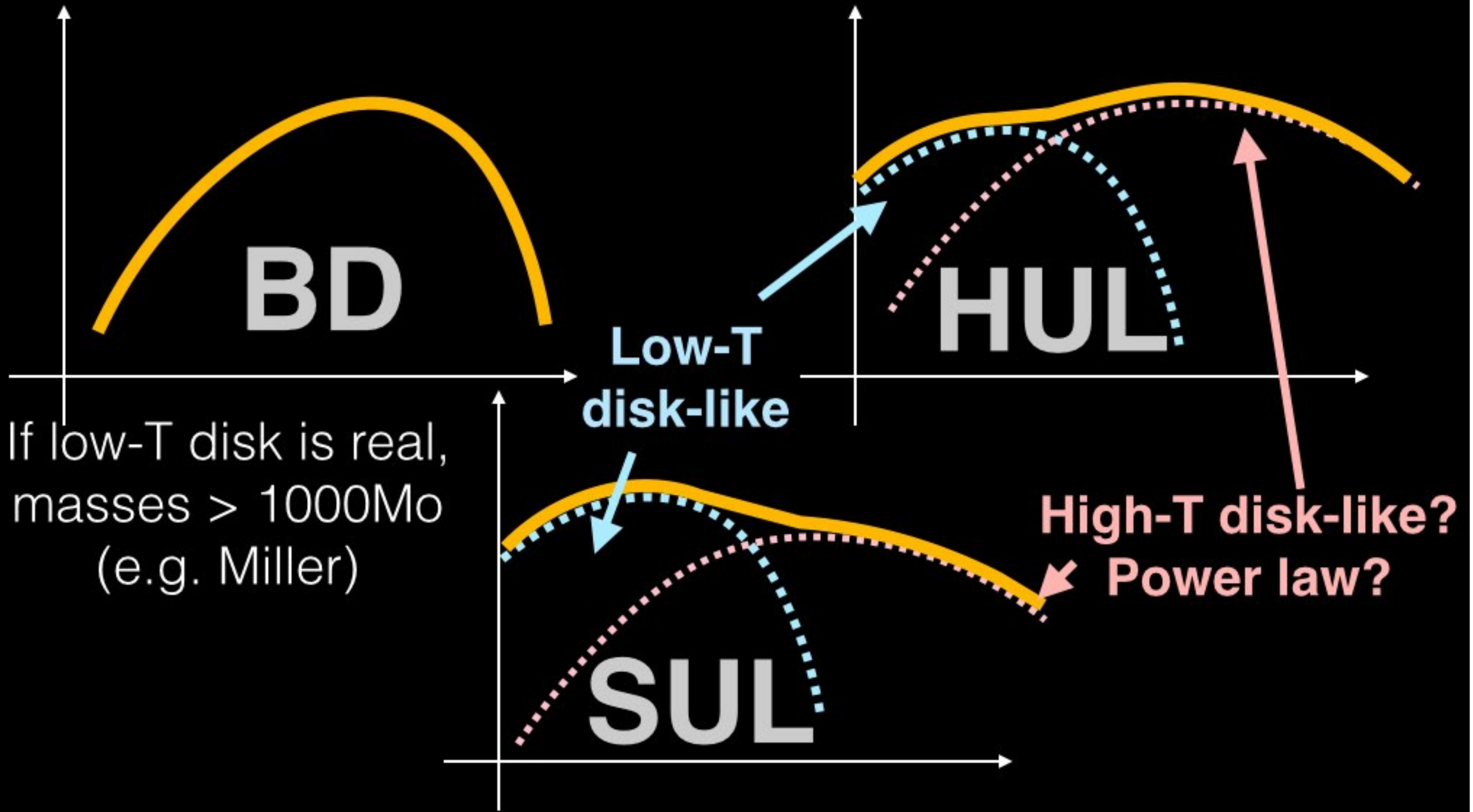
- Low-luminosity ULXs: BHs with luminosities around or slightly above Eddington
  (e.g. Middleton *et al. Nat.* **493,** 187–190 (2013); Liu et al. *Nat.* **503**, 500–503 (2013).)

- "Extreme" ULXs — $L_X > 10^{40}$ erg/s




Gladstone, Roberts & Done, *MNRAS* **397**, 1836–1851 (2009).

# ULX spectra…



BD
HUL
SUL
Low-T
disk-like
High-T disk-like?
Power law?
If low-T disk is real,
masses > 1000Mo
(e.g. Miller)

# Vintage slide:

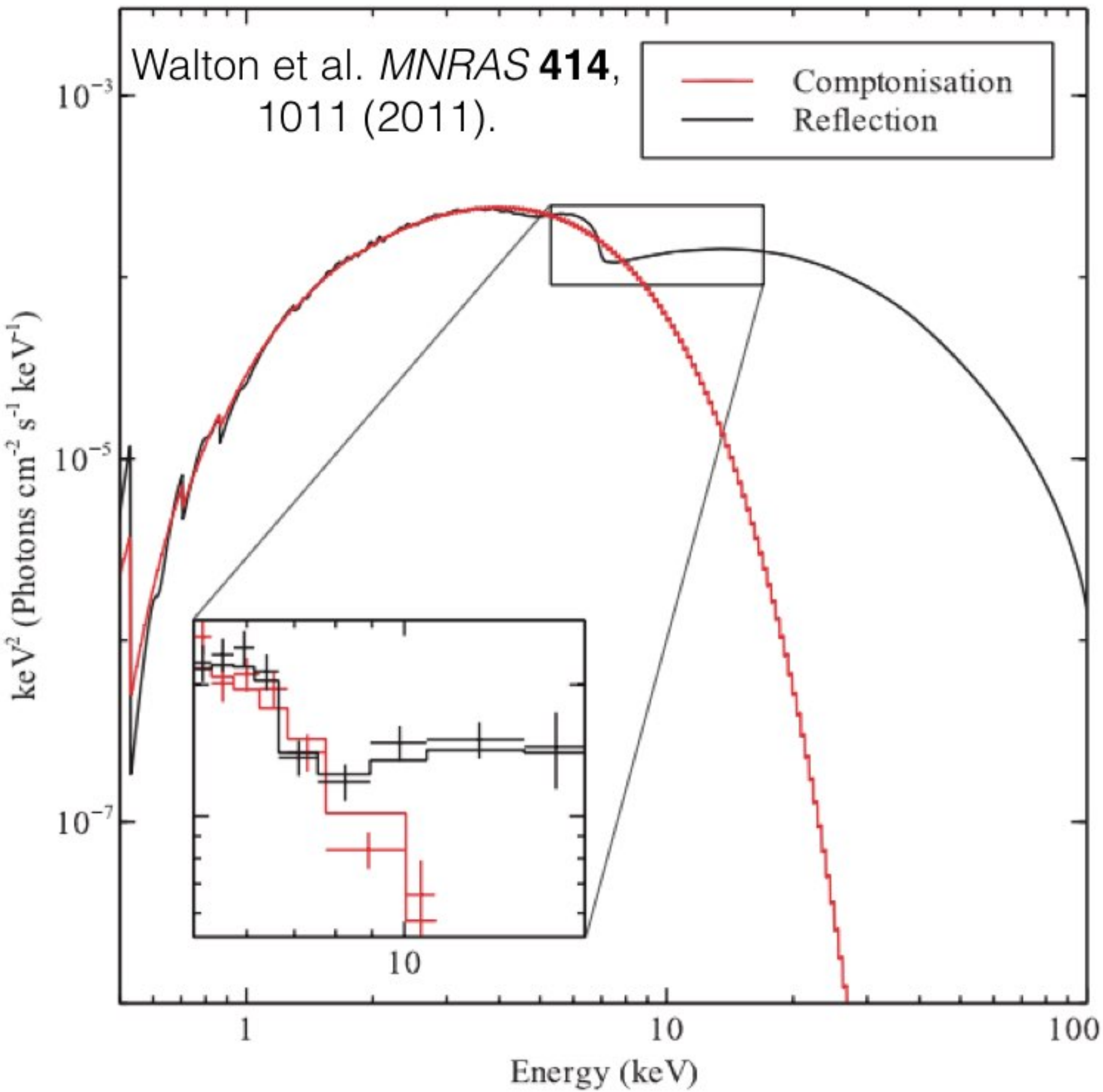
# ULXs < 10 keV

- Mostly Persistent!
- A soft excess(?)
- A hard turnover(?)

- Standard disk cut at the ISCO? (IMBH! e.g. Miller+04)
- Blurred emission lines? (e.g. Caballero-Garcia+10)
- A partially covered disk? (e.g. Gladstone+09)
- A soft deficit? (e.g. Gonçalves+06)

- A cutoff? (e.g. Stobbart+06)
- A local turnover due to a broadened iron complex? (e.g. Caballero-Garcia +10)
- A second disk component? (e.g. Miller+13)
- A conspiracy? An illusion?


Caballero-Garcia & Fabian MNRAS 402, 2559 (2010).
Gladstone, Roberts & Done MNRAS 397, 1836 (2009).
King, MNRAS Let. 385, L113 (2008).
Miller, Fabian & Miller ApJ 607, 931–938 (2004).
Stobbart, Roberts & Wilms, MNRAS 368, 397 (2006).
Gonçalves & Soria MNRAS 371, 673 (2006).

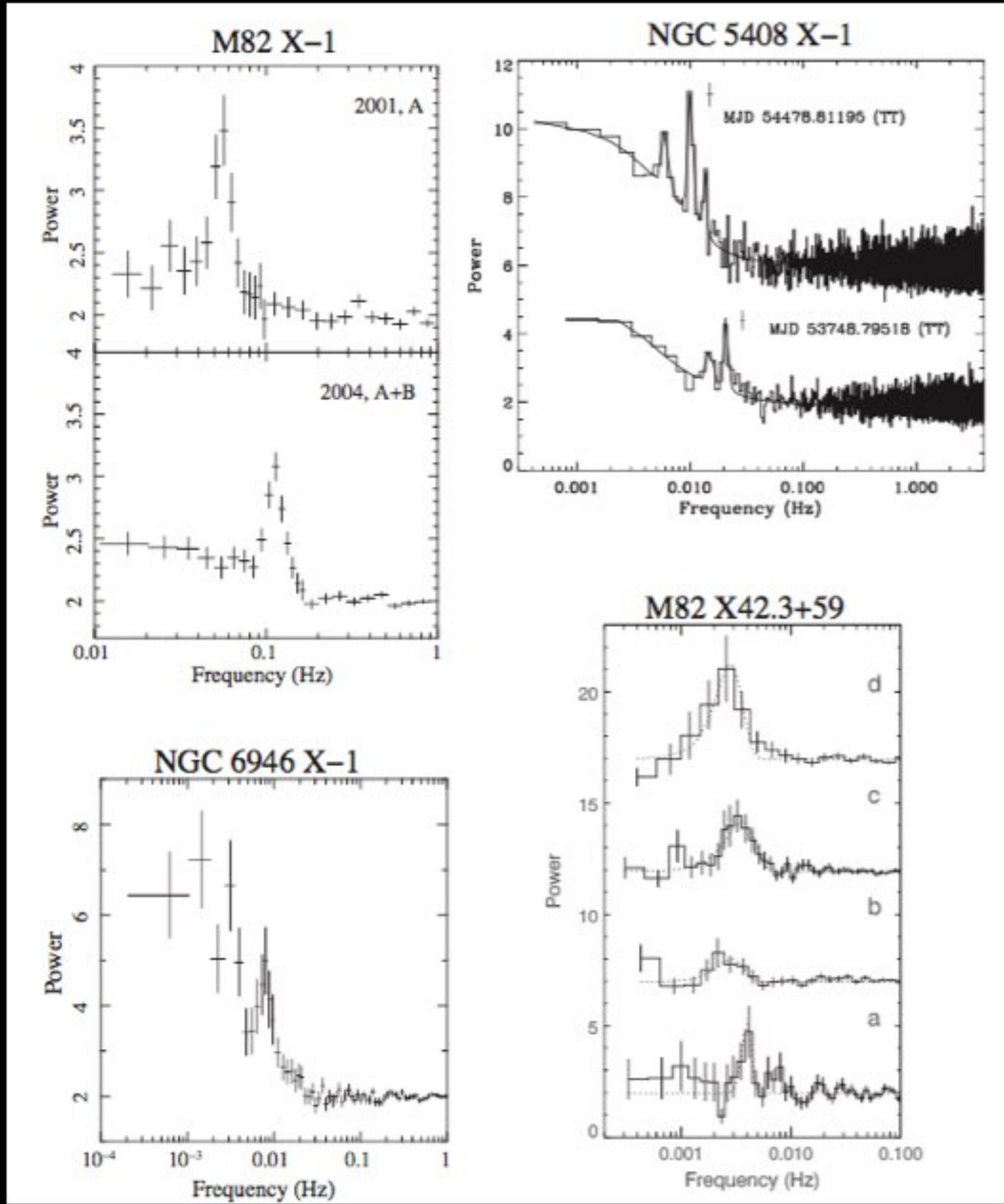


Walton et al. *MNRAS* **414**, 1011 (2011).
Comptonisation
Reflection
keV² (Photons cm⁻² s⁻¹ keV⁻¹)
10⁻³
10⁻⁵
10⁻⁷
1
10
100
Energy (keV)

# ULX variability

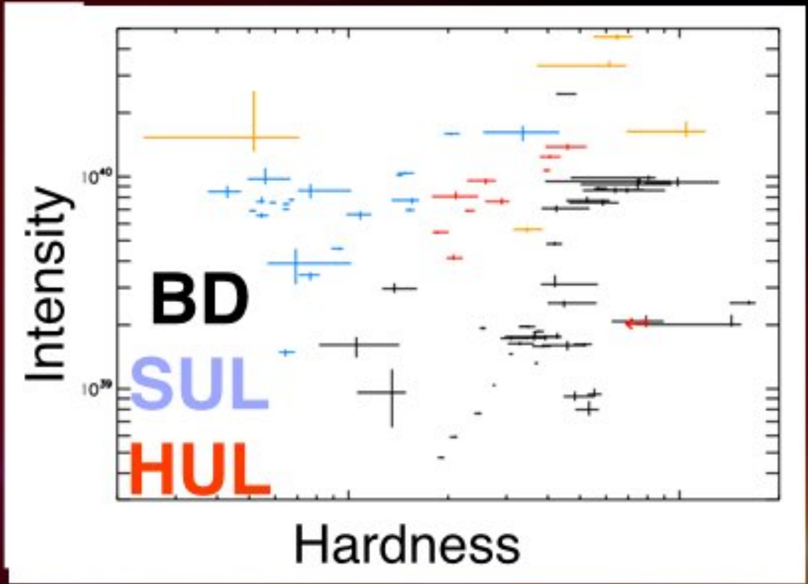
- QPOs and aperiodic variability
- rms-flux correlation and 'soft lags' in NGC 5408 X-1
  Heil & Vaughan, *MNRAS Let.* **405,** L86–L89 (2010).
  De Marco, B. *et al.*, *MNRAS* **436,** 3782–3791 (2013).

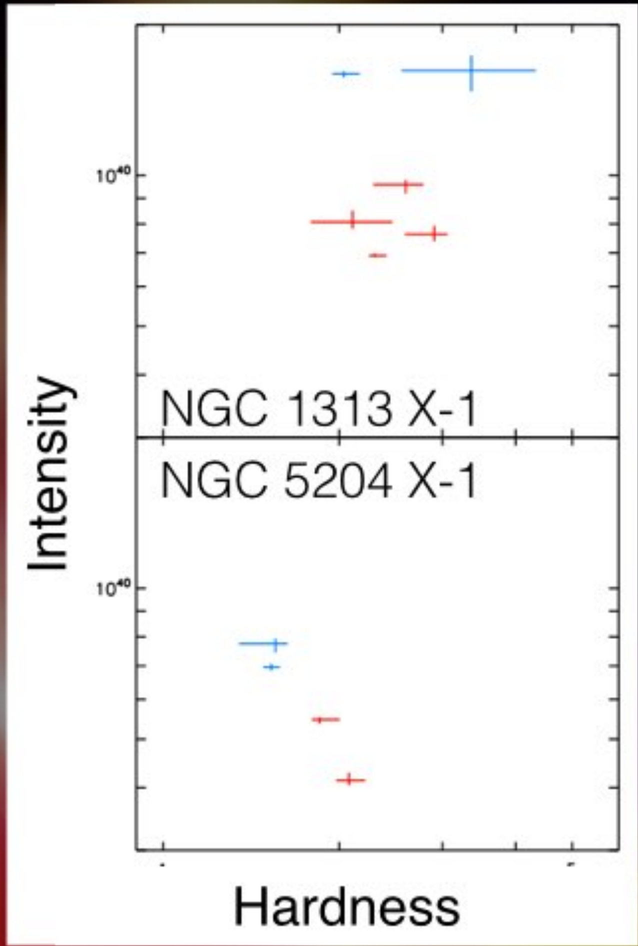
-> Caballero-Garcia poster

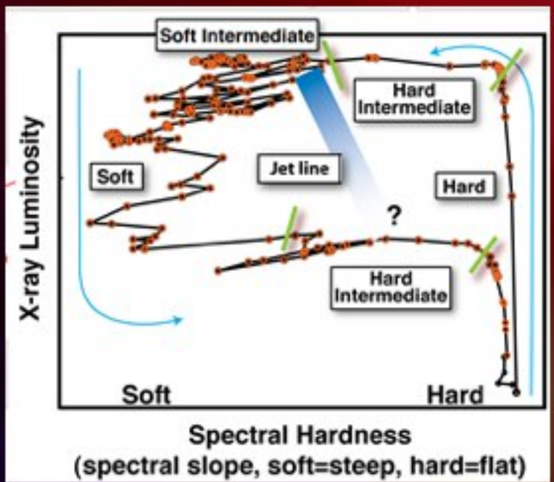



From Feng & Soria, *New Astronomy Reviews* **55,** 166 (2011). Authors: Strohmayer+, Rao+, Feng+

# ULX phenomenology



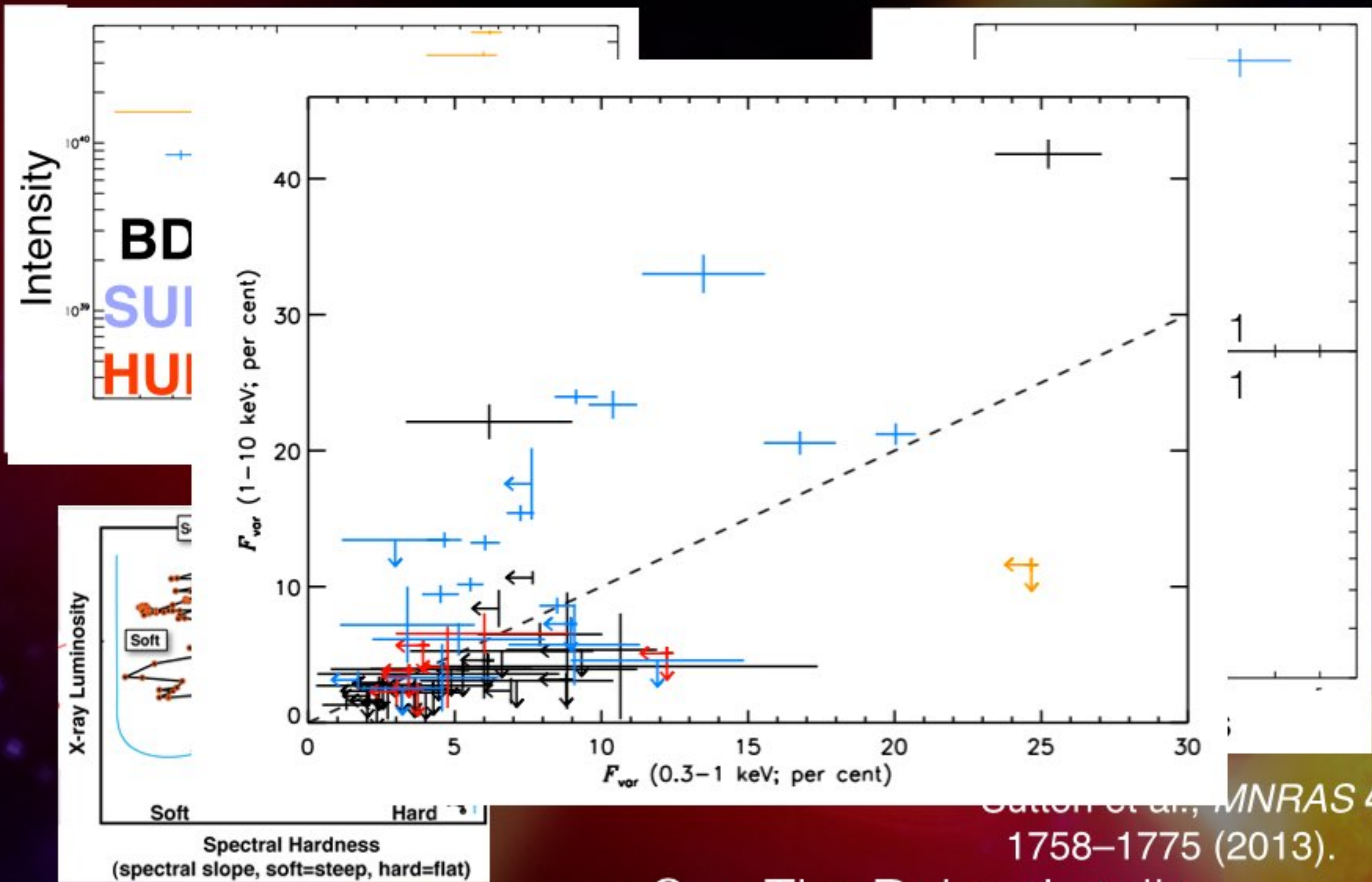




Sutton et al., *MNRAS* **435,** 1758–1775 (2013).

-> See Tim Robert's talk

# ULX phenomenology




Sutton et al., *MNRAS* **435,** 1758–1775 (2013).

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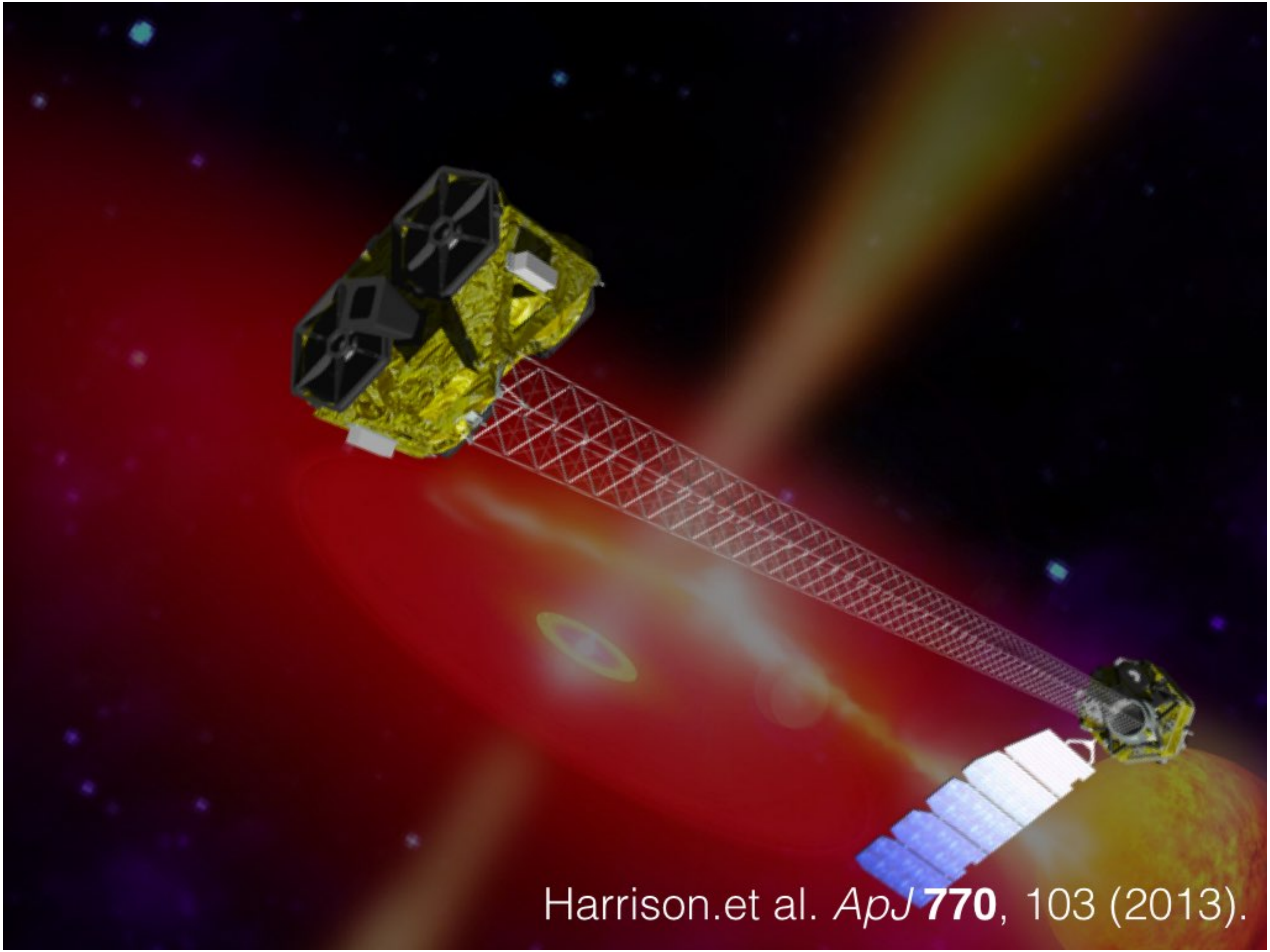
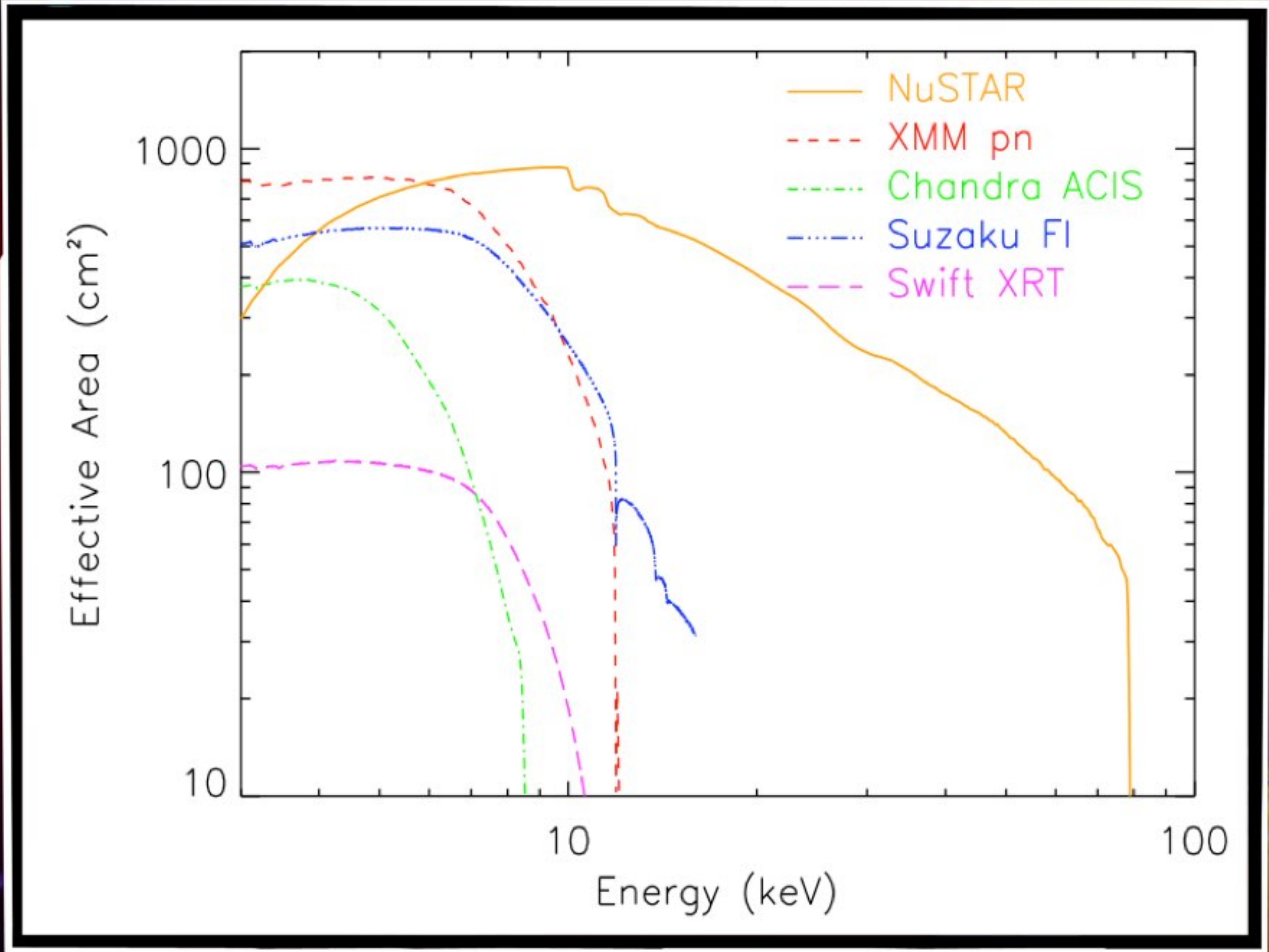

Harrison.et al. *ApJ* **770**, 103 (2013).

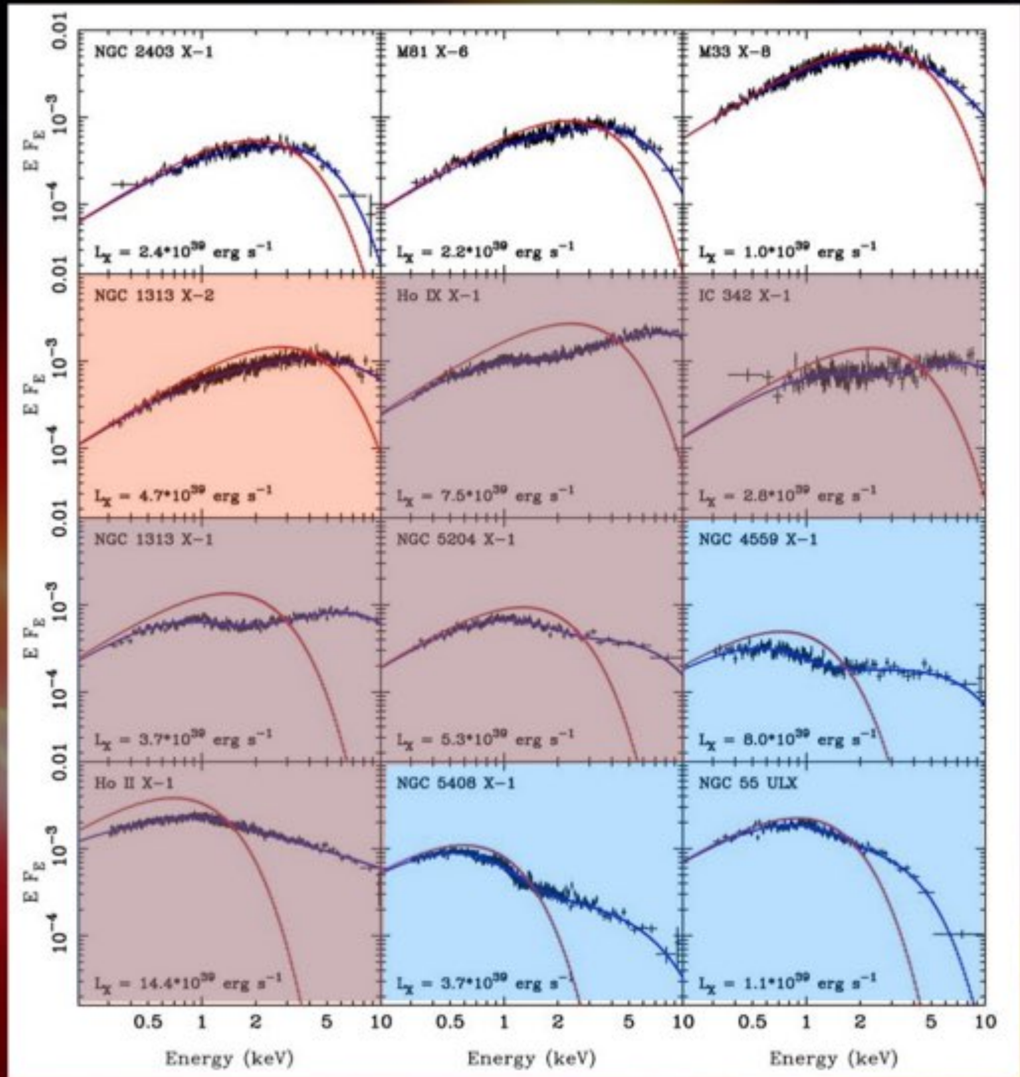



-> talk by Walton

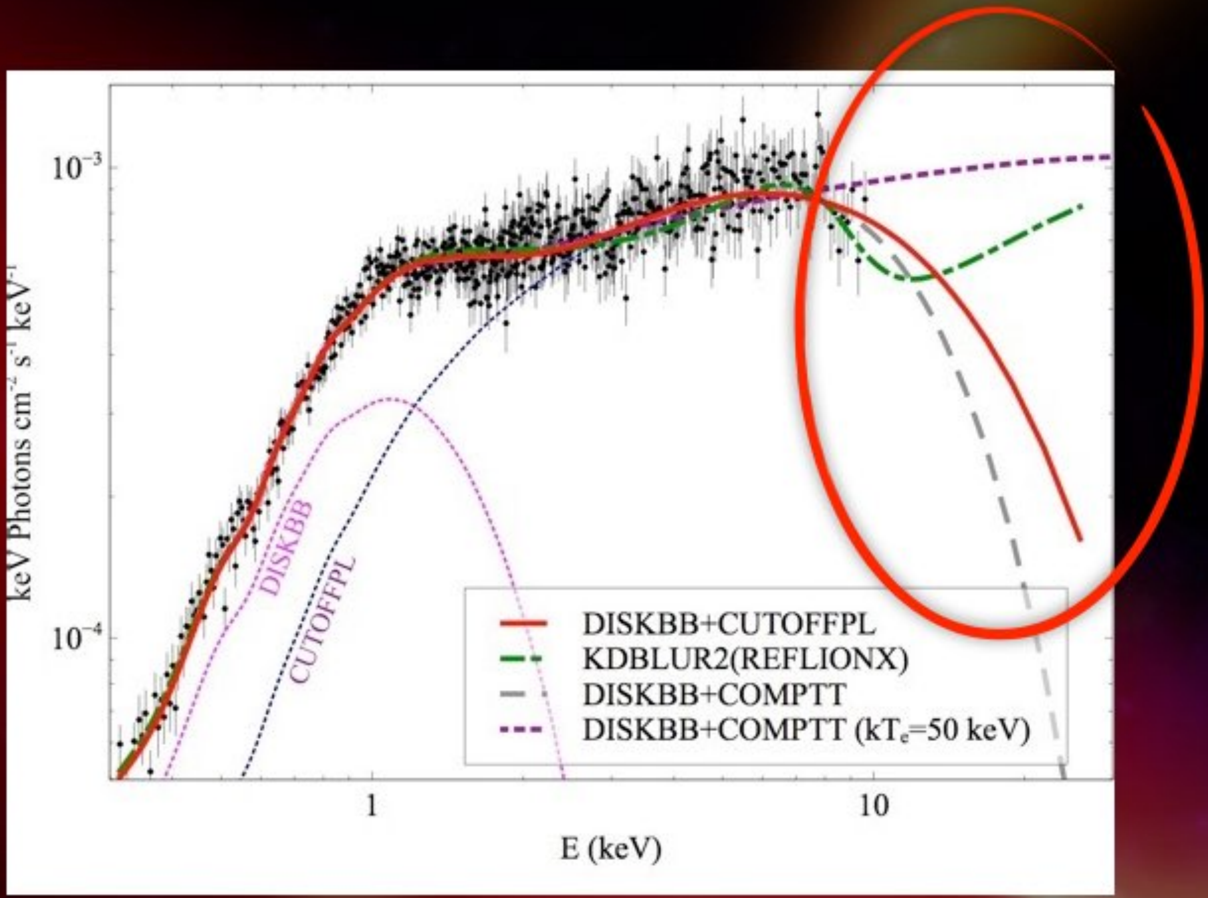
Harrison.et al. *ApJ* **770**, 103 (2013).

# ULXs in the original program

- **eULXs**
- Chosen for **distance** and **hardness**

# NGC 1313 X-1 with NuSTAR




MB et al., *ApJ* **778**, 163 (2013).

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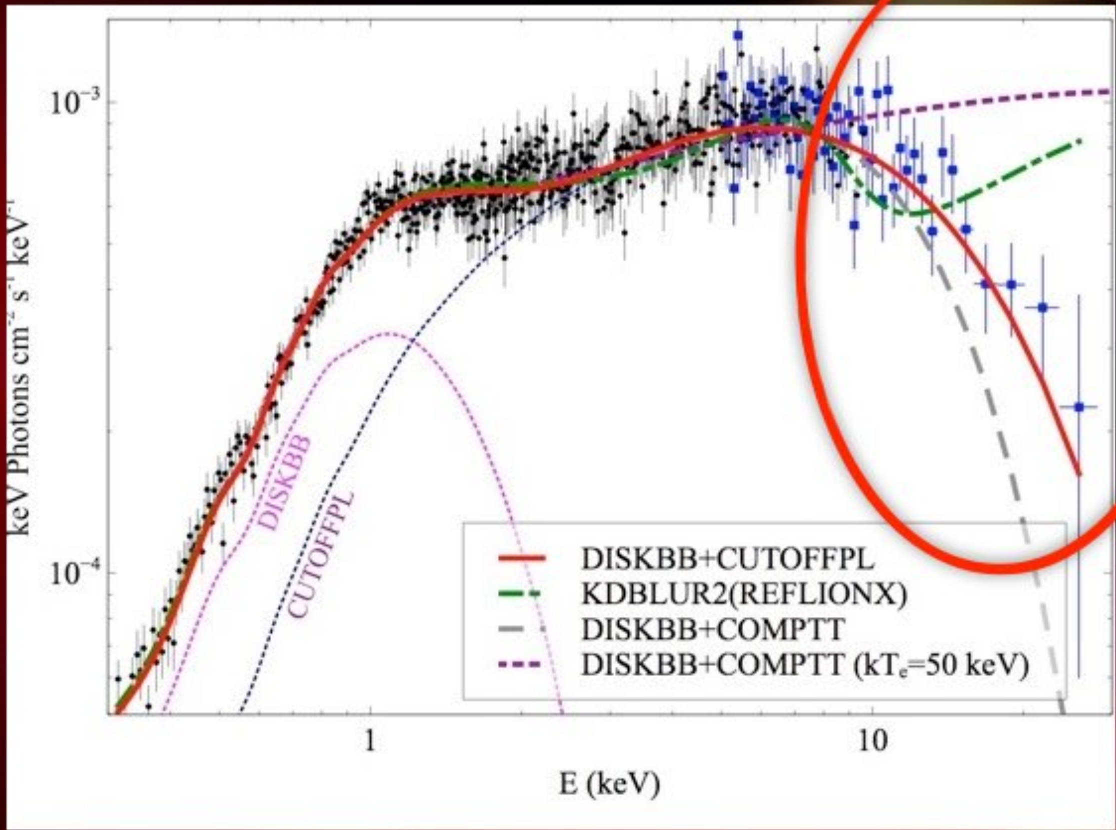


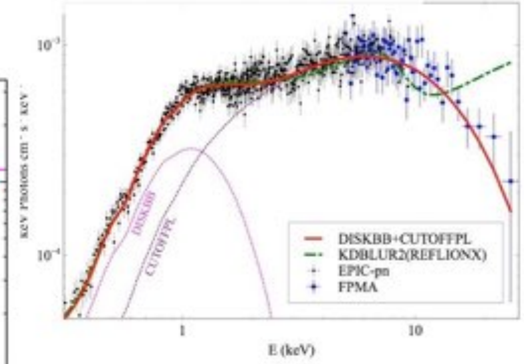

MB et al., *ApJ* **778**, 163 (2013).

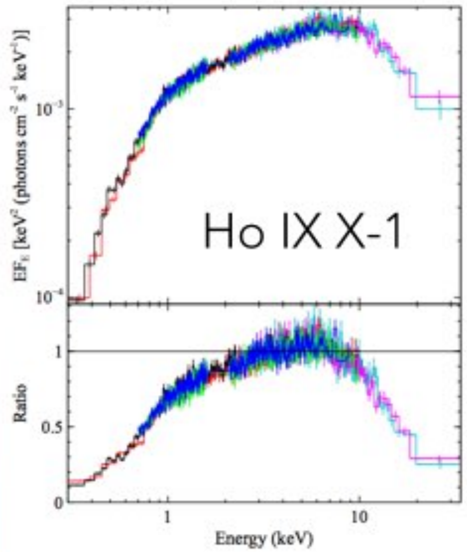
# CUTOFFS, CUTOFFS EVERYWHERE

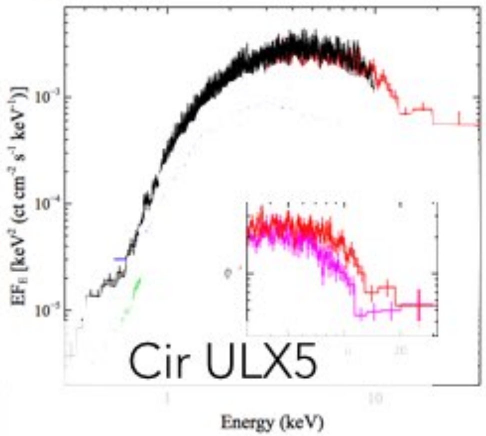
Well, cutoffs. That's it, right?

MB et al. *ApJ* **778**, 163 (2013).
Walton et al. *ApJ* **779**, 148 (2013).
Miller, MB et al. *ApJL* **785**, L7 (2014).
Walton et al. *ApJ* **793**, 21 (2014).
Rana et al. *ApJ* **799**, 121 (2015).
Walton et al. *ApJ* **799**, 122 (2015).
Mukherjee et al. arXiv:1502.1764 (2015).

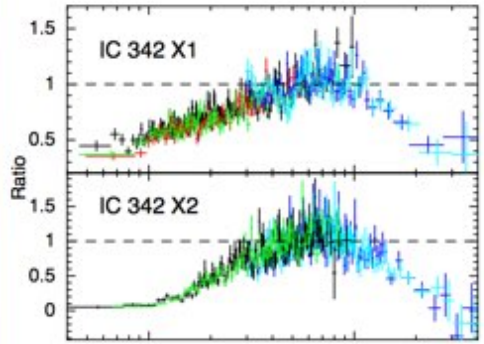
N1313 X-1



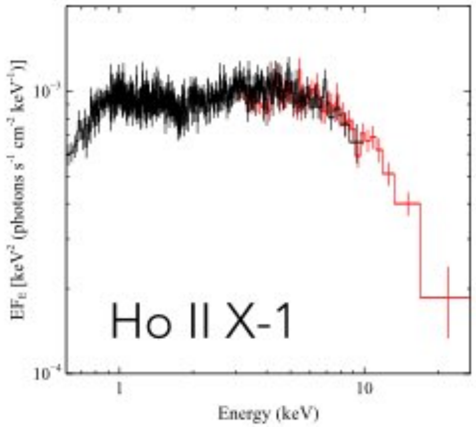




IC 342 X-1




IC 342 X-2



# EXCESSES, EXCESSES EVERYWHERE(?)

**Low energy:** a **disk-like <1 keV component** in most sources.

**High energy:** cutoff in excess of single-kT Comptonization

MB et al. *ApJ* **778**, 163 (2013).
Walton et al. *ApJ* **779**, 148 (2013).
Miller, MB et al. *ApJL* **785**, L7 (2014).
Walton et al. *ApJ* **793**, 21 (2014).
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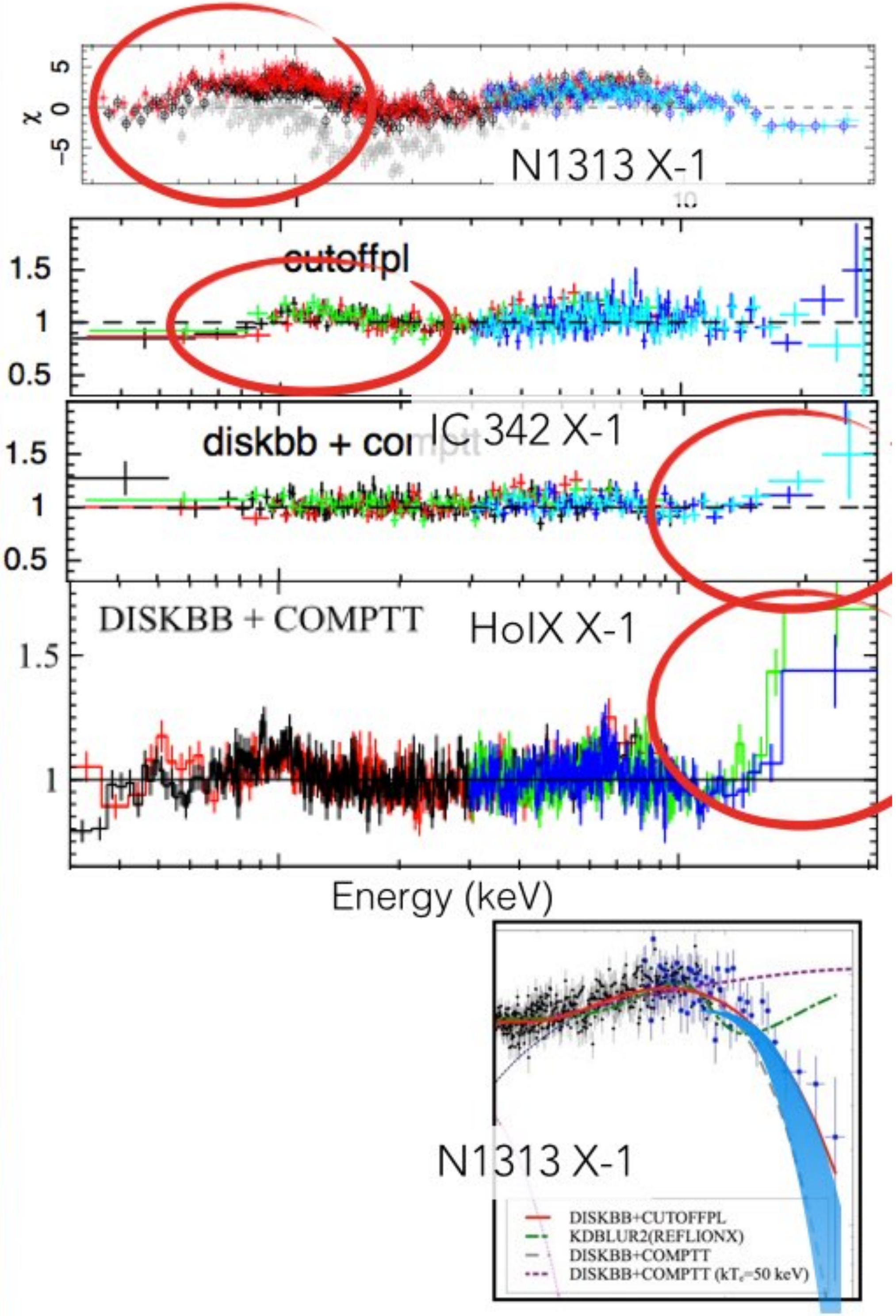

# VARIABILITY, VARIABILITY EVERYWHERE(~)

- Several sources showed a **fast (~weeks) evolution** of spectral shapes.
- **Short-term variability** appears mostly in the **soft intermediate** and **broadened disk** states (as previously known).


MB et al. *ApJ* **778**, 163 (2013).
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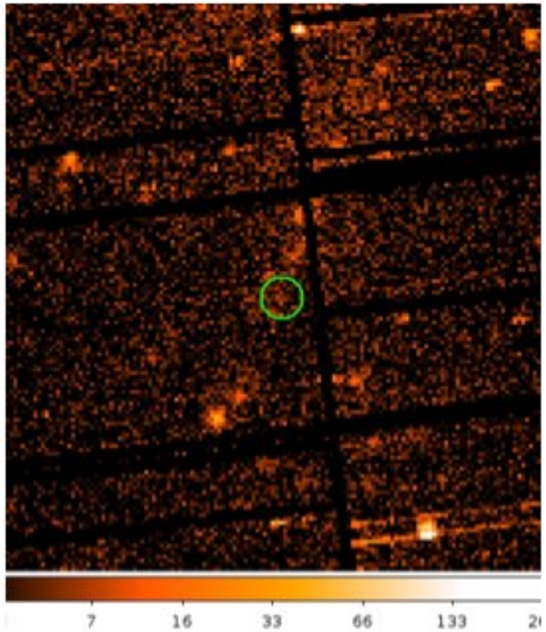
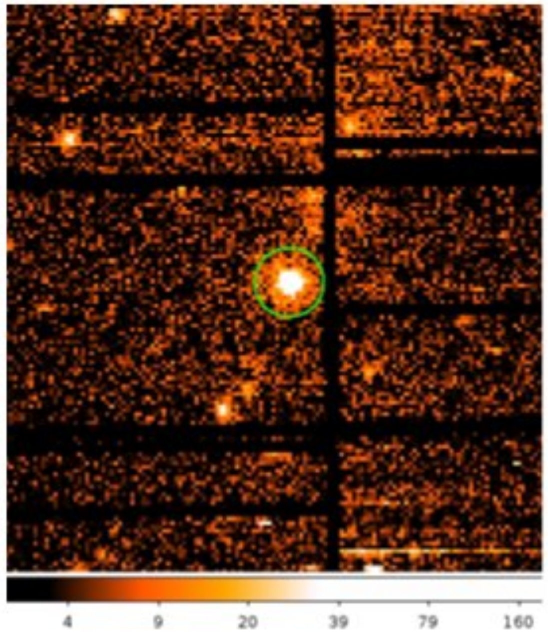



N5907 X-1



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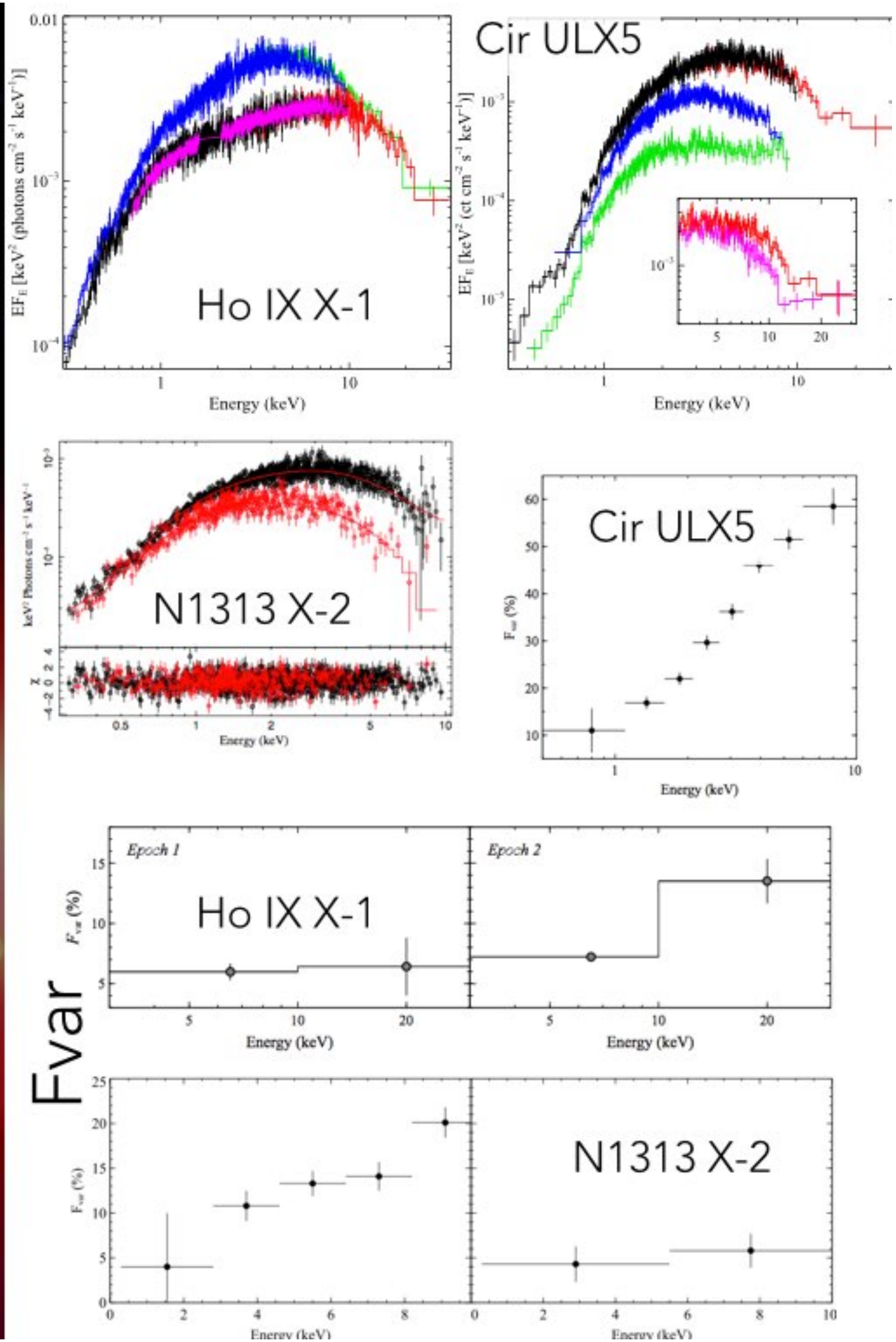
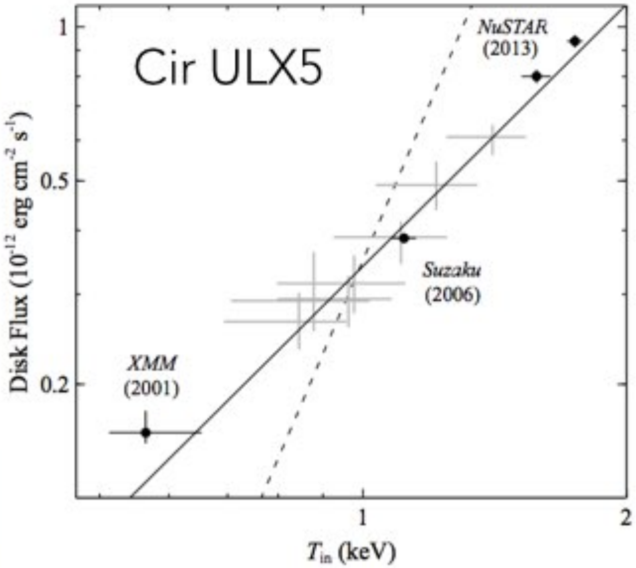
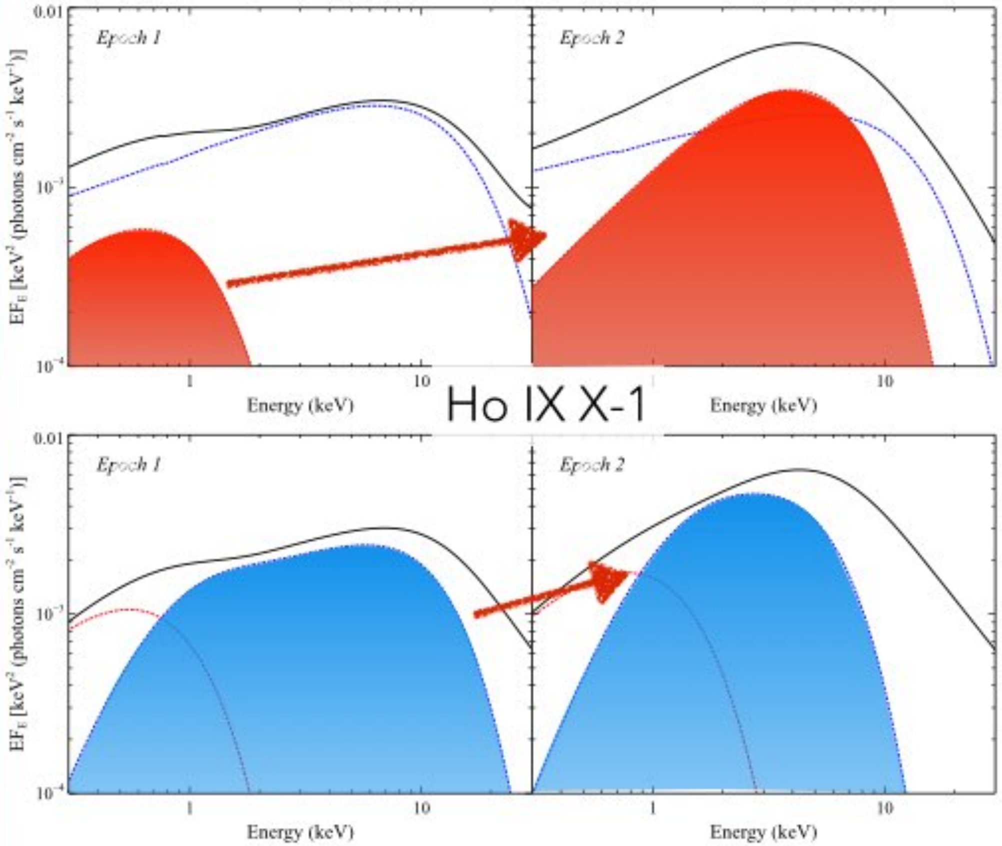


# VARIABILITY, VARIABILITY EVERYWHERE(~)

- Temperature-luminosity relation deviates from SS disk in Cir ULX-5:
- $L \propto T^{\alpha}, \alpha \sim 1.7$ (exp.: 4)
- Spectral evolution highly non-standard.





MB et al. *ApJ* **778**, 163 (2013).
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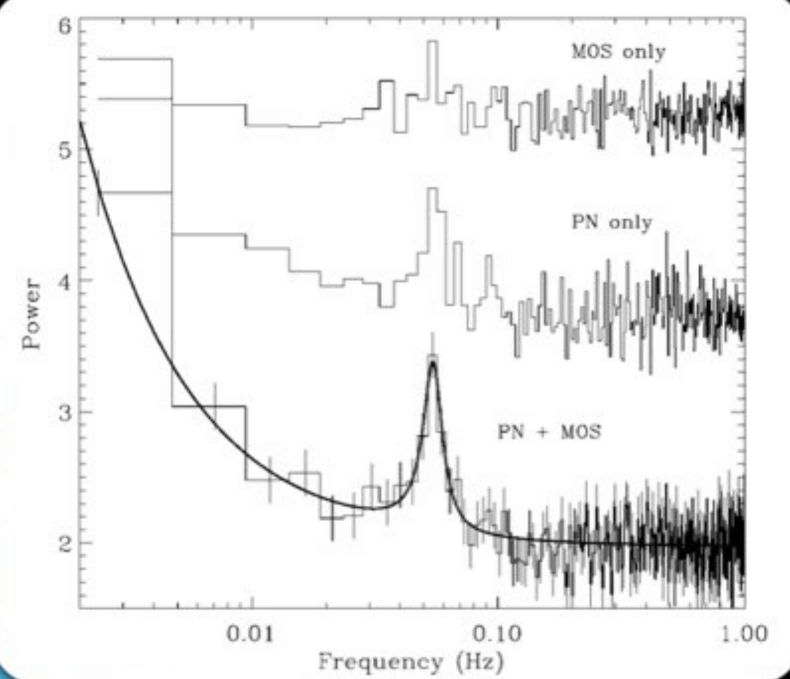
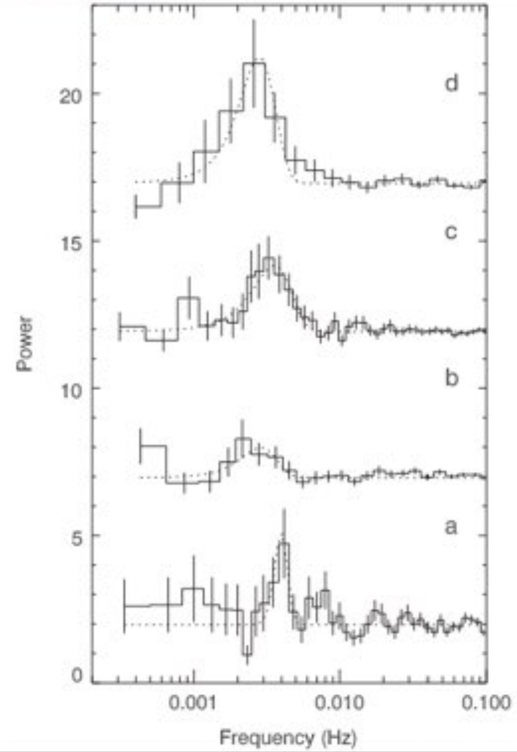
# M82

Two ULXs in M82, both "extreme" (one borderline HLX…), showing QPOs:

- **M82 X-1/X41.4+60:** $L_X \sim 10^{41}$
  $f_{QPO}$: **50—190 mHz** (SM03, K+06)
- **M82 X-2/X42.3+59:** $L_X \sim 10^{40}$
  $f_{QPO}$: **3—4 mHz** (FK10)
- Both used to infer masses of the BHs in the **IMBH range** (FK07, FK10)

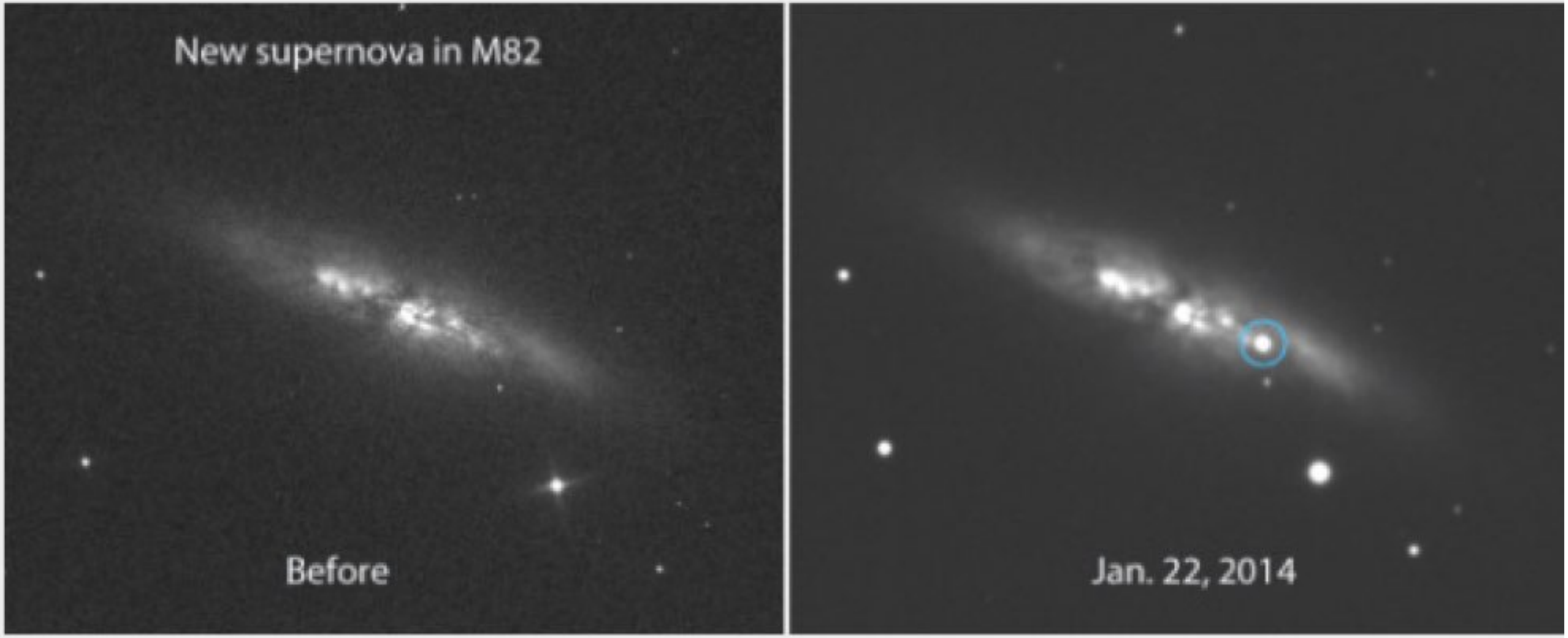



SM03: Strohmayer, T. E. & Mushotzky, R. F., ApJ 586, L61–L64 (2003).
K+06: Kaaret, P., Simet, M. G. & Lang, C. C., ApJ 646, 174–183 (2006).
FK07: Feng, H. & Kaaret, P., ApJ 668, 941–948 (2007).
FK10: Feng, H., Rao, F. & Kaaret, P., ApJL 710, L137–L141 (2010).

# Bright New Supernova Blows Up in Nearby M82, the Cigar Galaxy

*by* BOB KING *on* JANUARY 22, 2014




Before and after photos of the galaxy M82 showing the appearance of a brand new 11.7 magnitude supernova. The object is located in the galaxy's plane 54" west and 21" south of its

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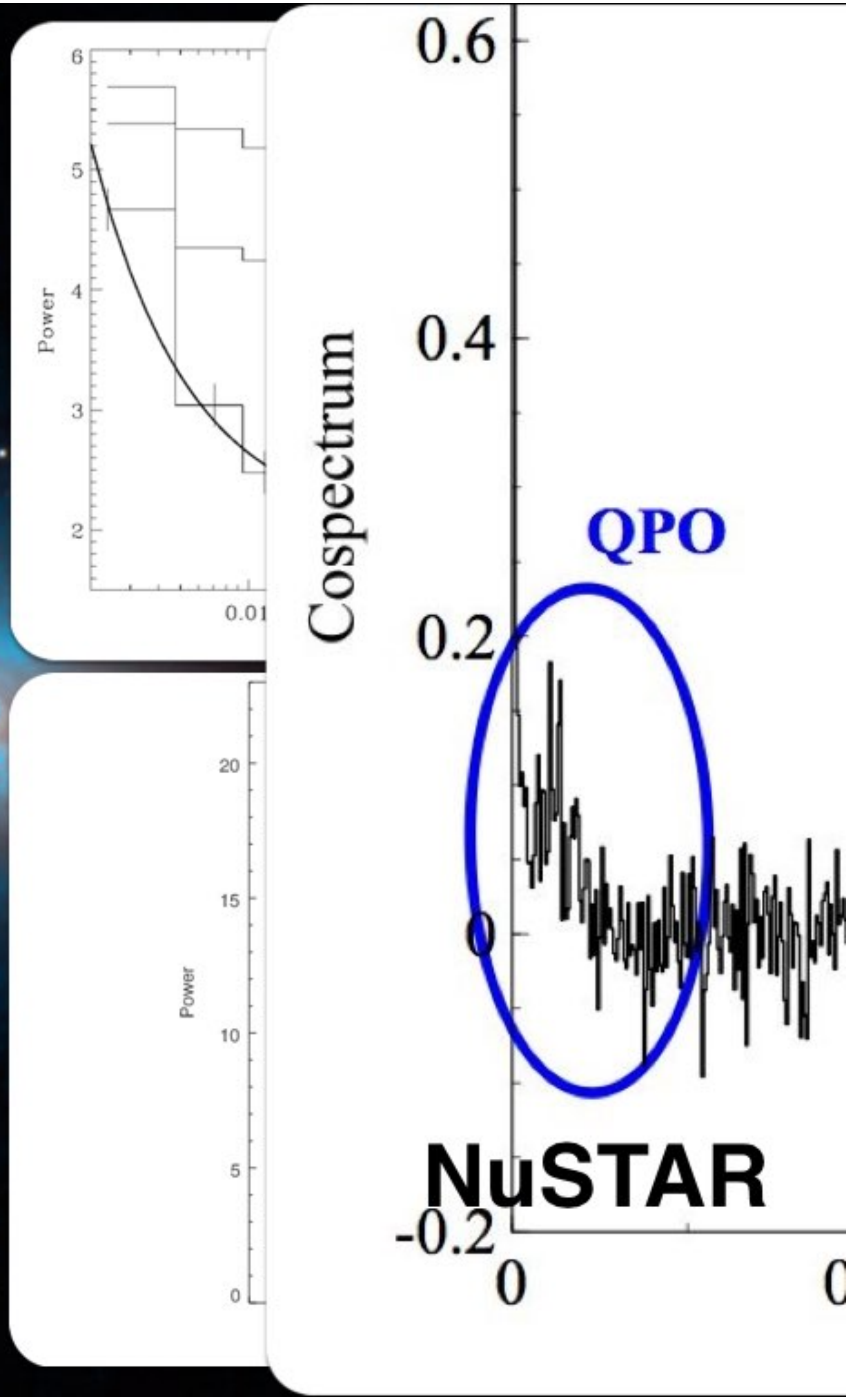
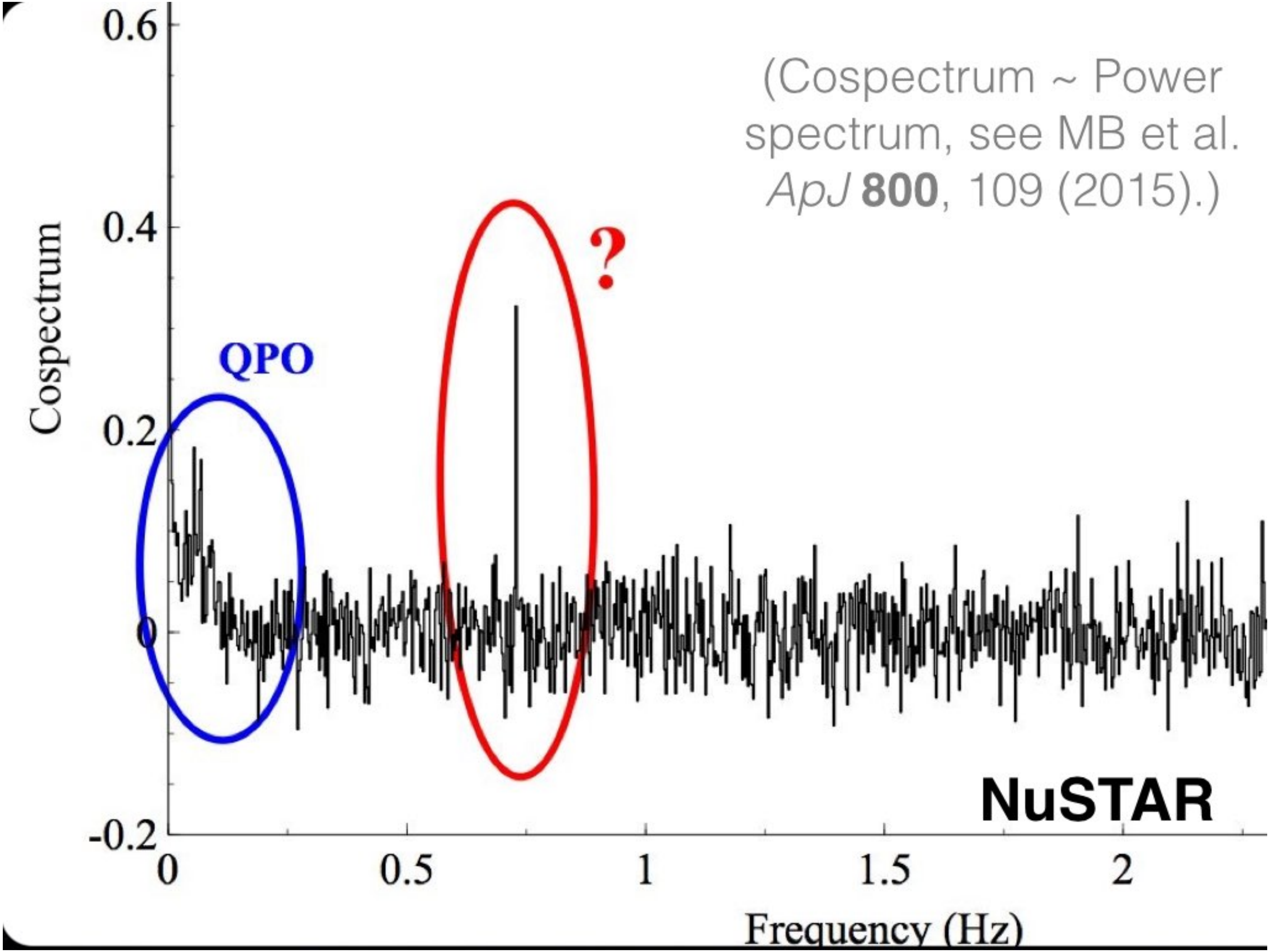
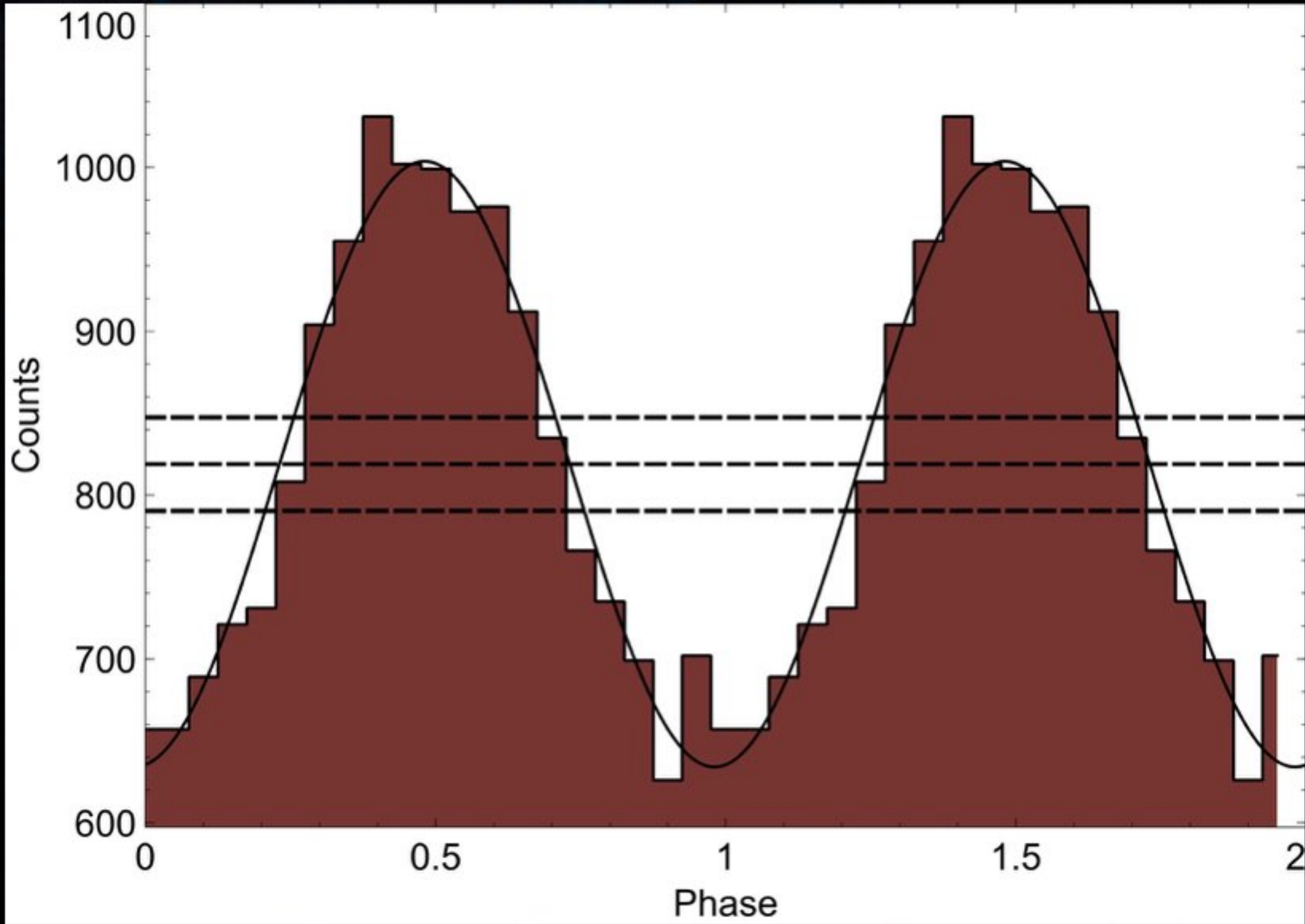


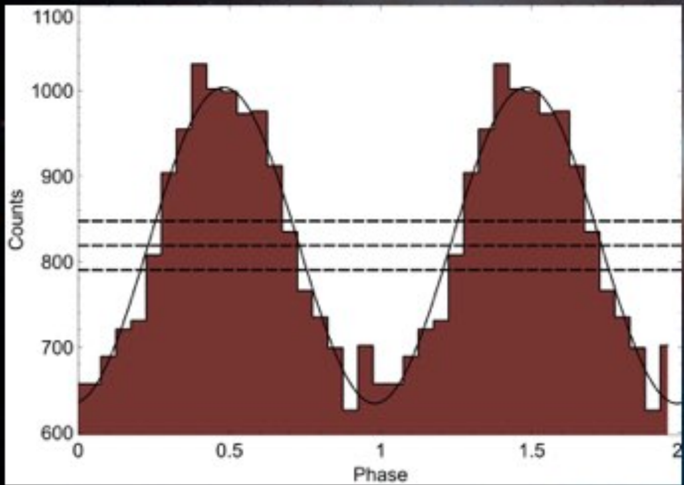


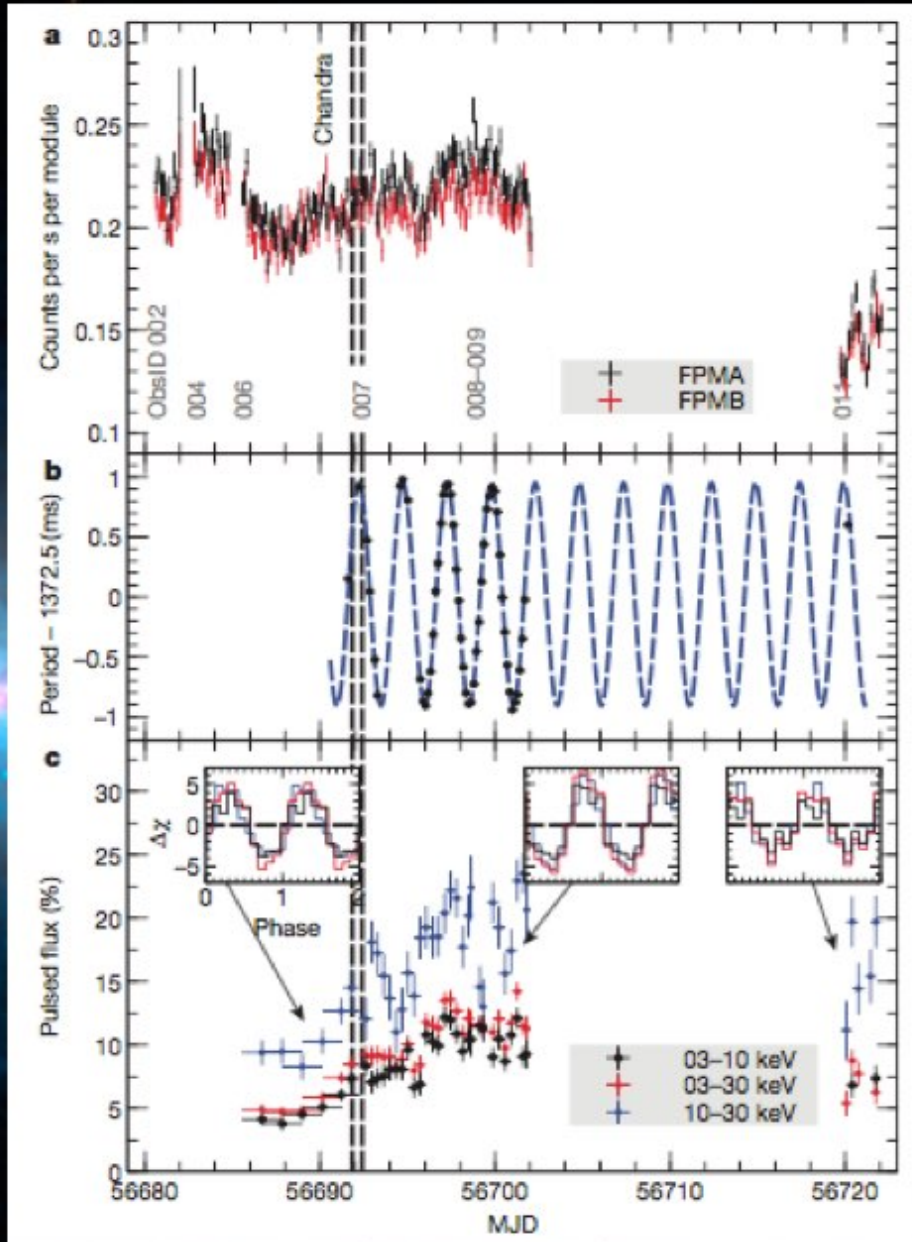
(Cospectrum ~ Power spectrum, see MB et al. ApJ 800, 109 (2015).)
?
QPO
NuSTAR
Cospectrum
0.6
0.4
0.2
0
-0.2
0
0.5
1
1.5
2
Frequency (Hz)

# M82

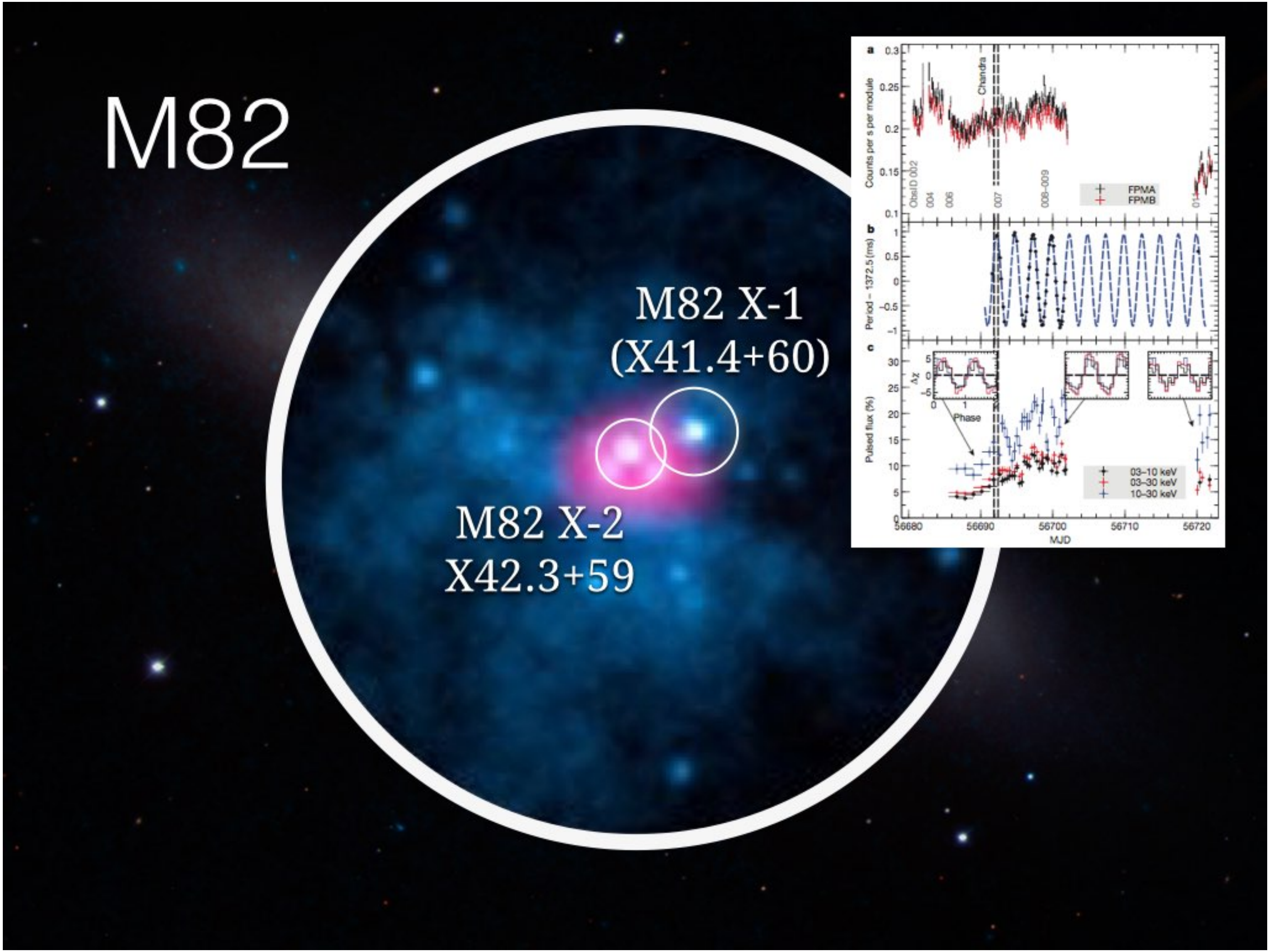


# M82

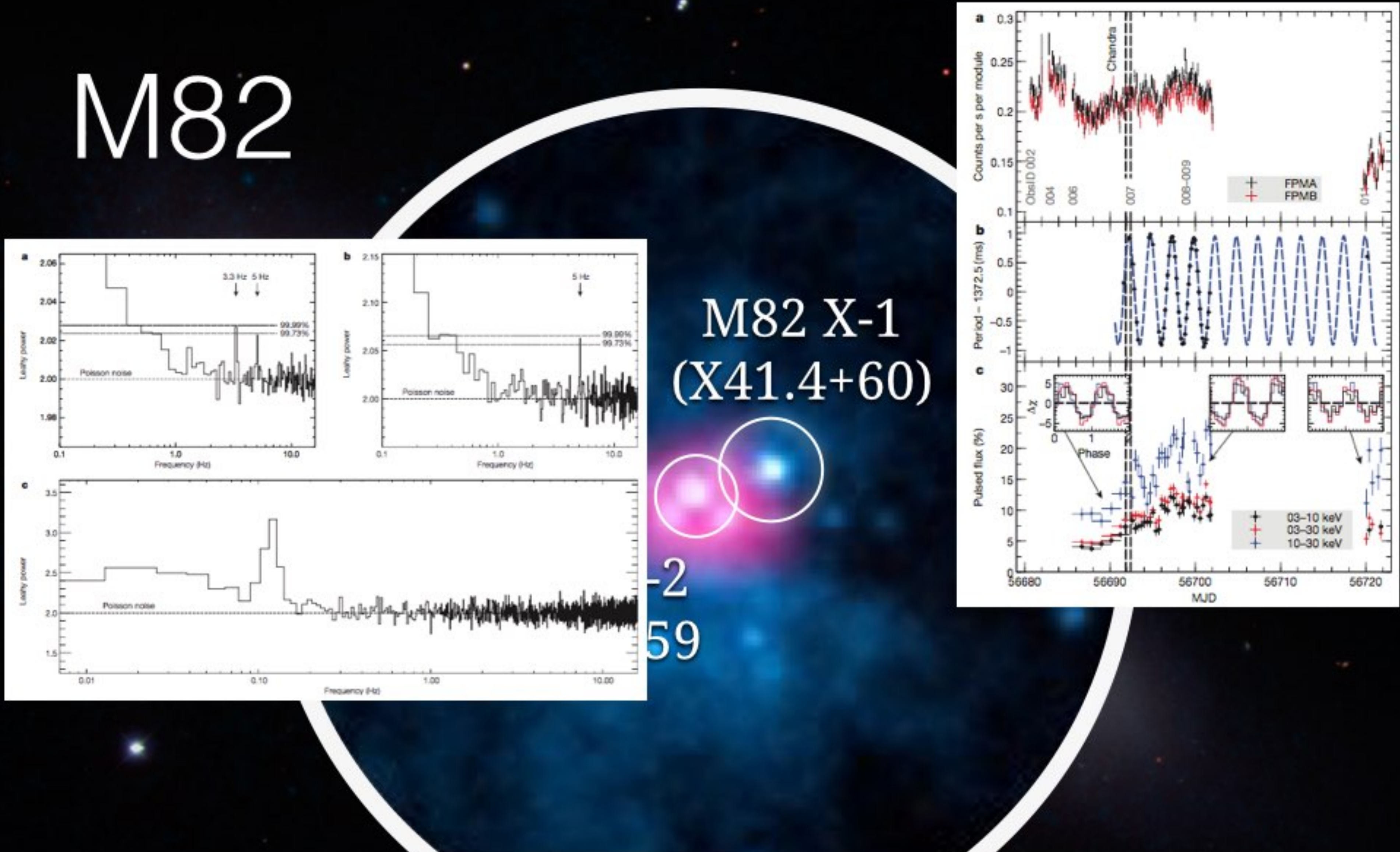



MB et al. *Nature* **514**, 202–204 (2014).


M82
M82 X-1
(X41.4+60)
M82 X-2
X42.3+59
Counts per s per module
Chandra
FPMA
FPMB
Period – 1372.5 (ms)
Pulsed flux (%)
Phase
03–10 keV
03–30 keV
10–30 keV
MJD

# M82




M82 X-2: A **pulsar**! MB et al. *Nature* **514**, 202–204 (2014).
M82 X-1: An **IMBH** (based on QPOs)! Pasham, Strohmayer & Mushotzky, *Nature* **513,** 74–76 (2014).

# Models of M82 X-2

- a low-magnetic field (~$10^9$ G) neutron star in an unusual high-mass X-ray binary (HMXB), -> new channel for millisecond pulsar and/or BH formation? [K14];
- a highly magnetized pulsar [e.g. L14, E14, DO14];
- a pulsar with standard magnetic field ~ $10^{12}$ G [C14, T15]
- a bright, young neutron star [à la MP13] (disfavored by variability)
- a spinning *intermediate mass black hole* (?!) [TK15]


C14: Christodolou et al., arXiv:1411.5434

E14: Ekşi et al. *MNRAS Let.* **448**, L40–L42 (2015).

DO14: Dall'Osso et al., *ApJ* **798**, 25 (2015).

F14: Fragos et al. *ApJL* **802**, L5 (2015).

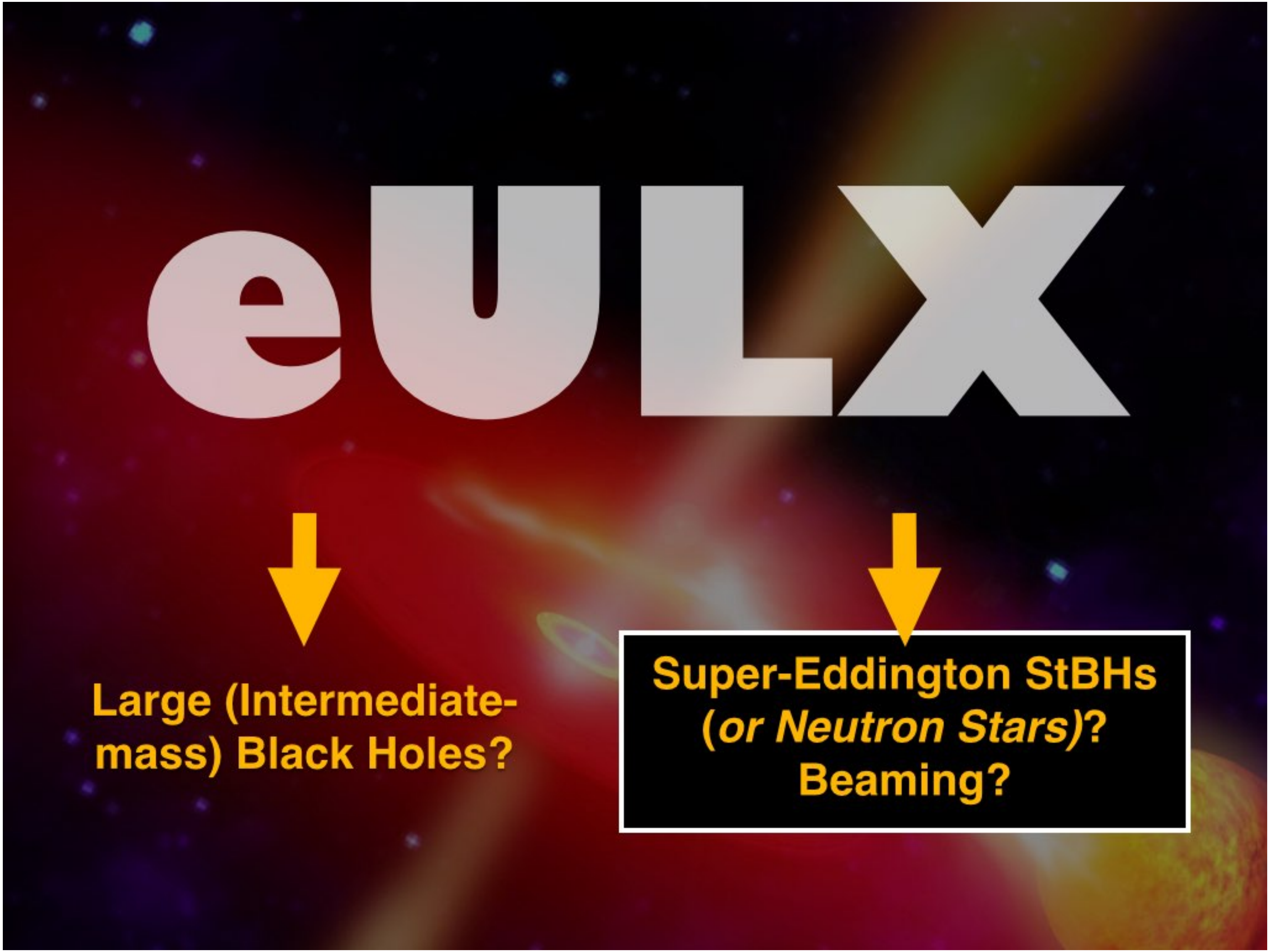
K14: Kluzniak & Lasota, MNRAS Let. 448, L43–L47 (2015).

L14: Lyutikov, arXiv:1410.8745 (2014). -> POSTER

MP13: Medvedev & Poutanen, MNRAS 431, 2690–2702 (2013).

TK15 Ter-Kazarian, ArXiv:1506.1222 (2015).

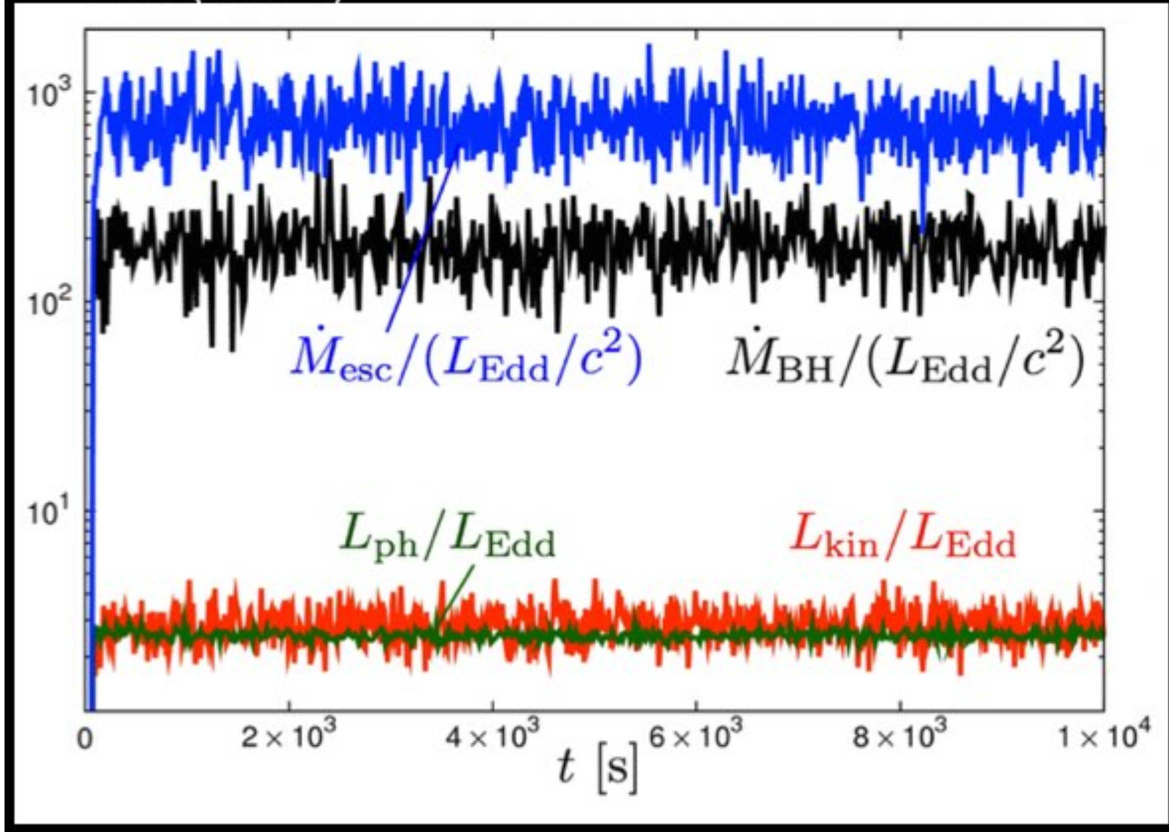
T15: Tong, *RAA* **15**, 517–524 (2015).

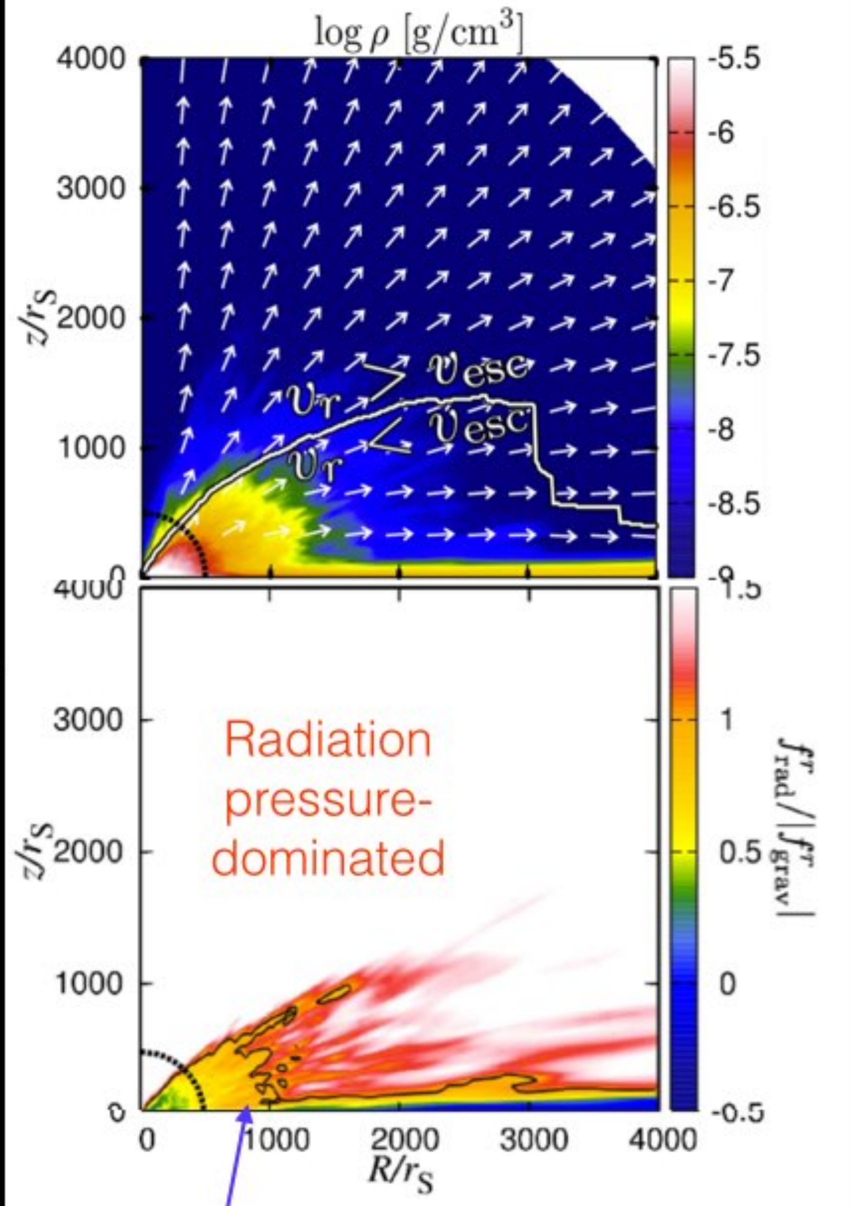

eULX
Large (Intermediate-mass) Black Holes?
Super-Eddington StBHs (*or Neutron Stars*)? Beaming?

# What about super-Eddington?

# And you thought super-Eddington *luminosity* was the problem…

RHD simulations: Hashizume et al. *PASJ* 144 (2014)

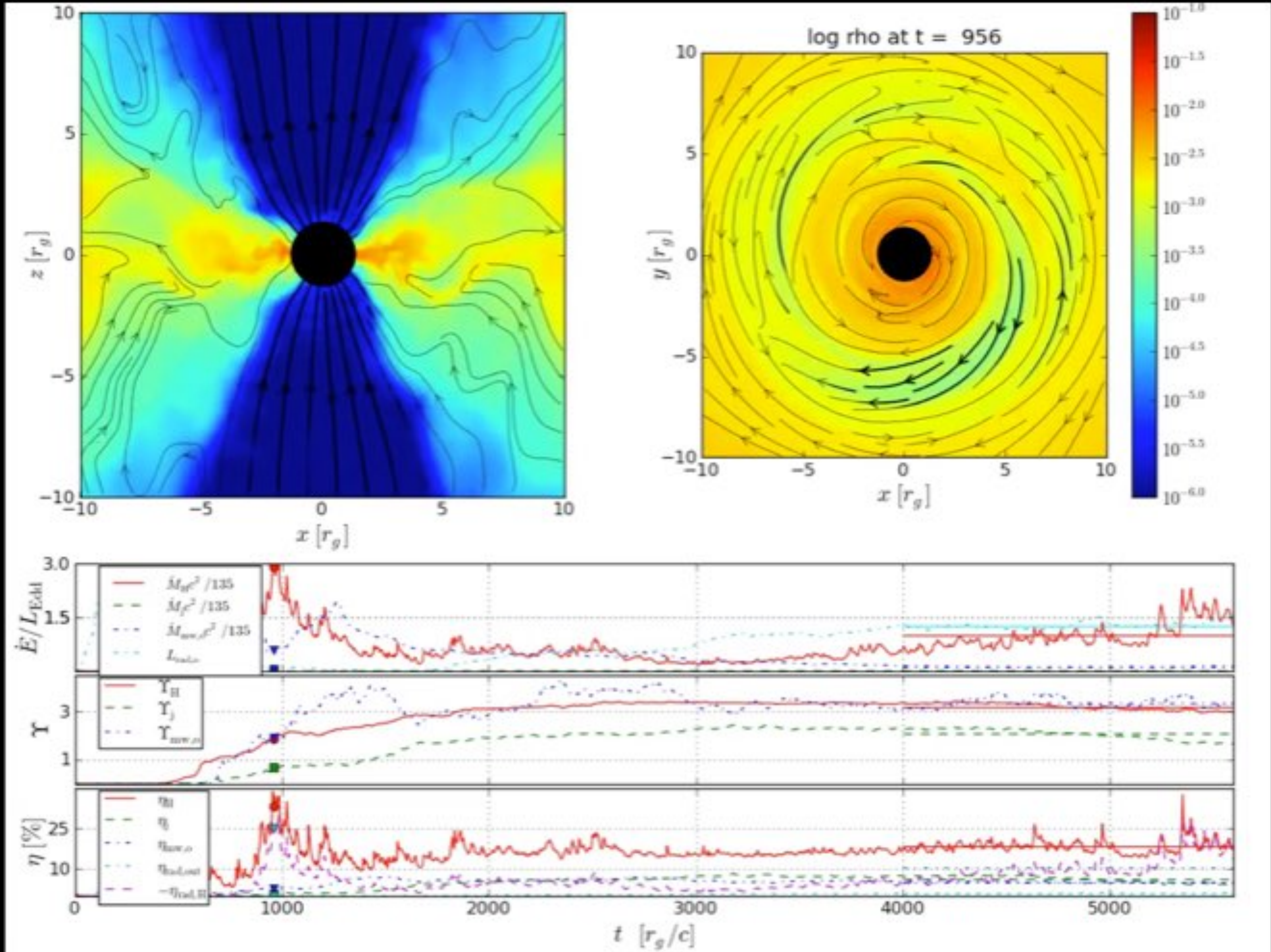



**Eddington luminosity -> 100+ times Eddington mass accretion rate!**

# And you thought super-Eddington *luminosity* was the problem…

Different simulation setups, consistent results.




RMHD: McKinney et al. *MNRAS* **441,** 3177–3208 (2014).

# Spectra from simulations

Kawashima et al. *ApJ* **752**, 18 (2012).
Strong dependence of isotropic luminosity on **viewing angle**

**Spectral shapes similar but still not perfect. Promising**

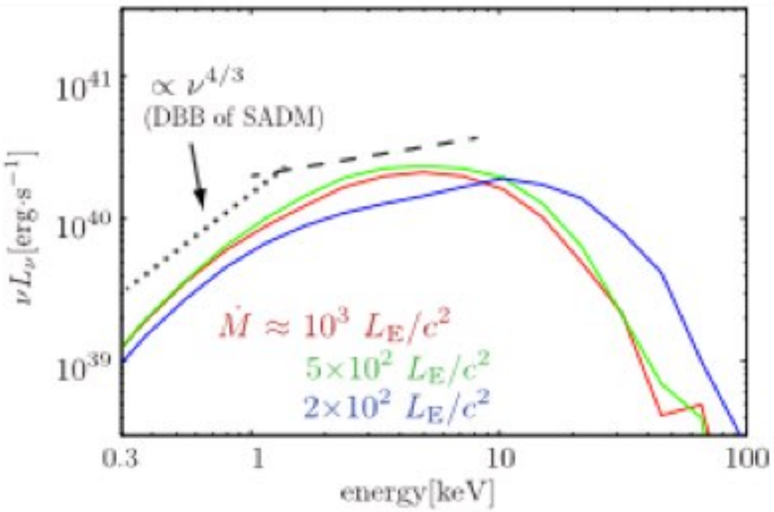



**Figure 2.** SEDs for models with mass accretion rates $\dot{M} \approx 1000$ (red), 500 (green), and $200L_E/c^2$ (blue). The dotted line shows the disk blackbody spectrum of a standard thin accretion disk model, while the dashed one shows the typical photon index of the spectra of ULXs.

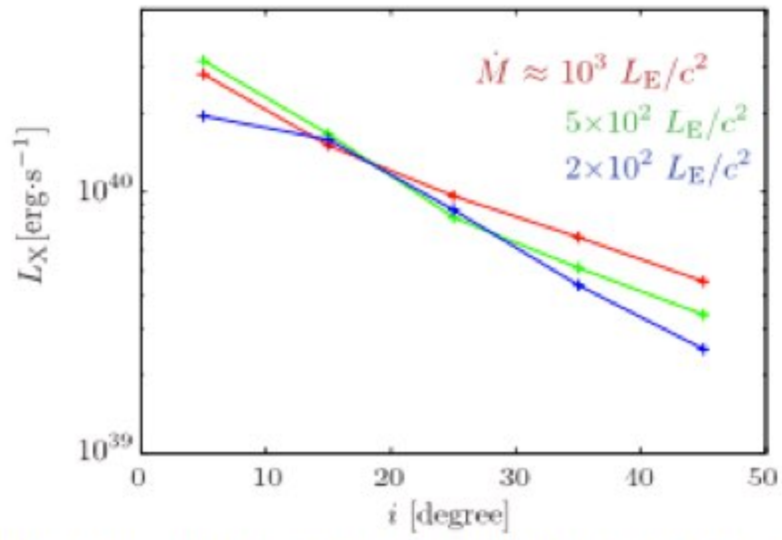
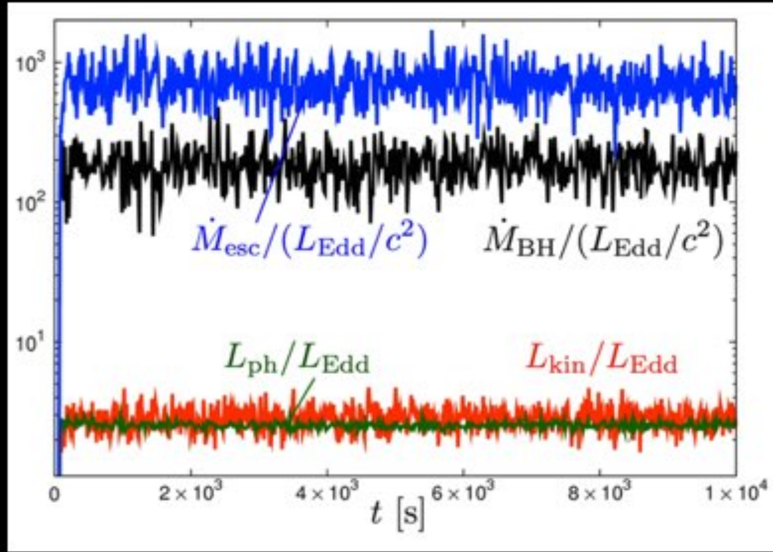
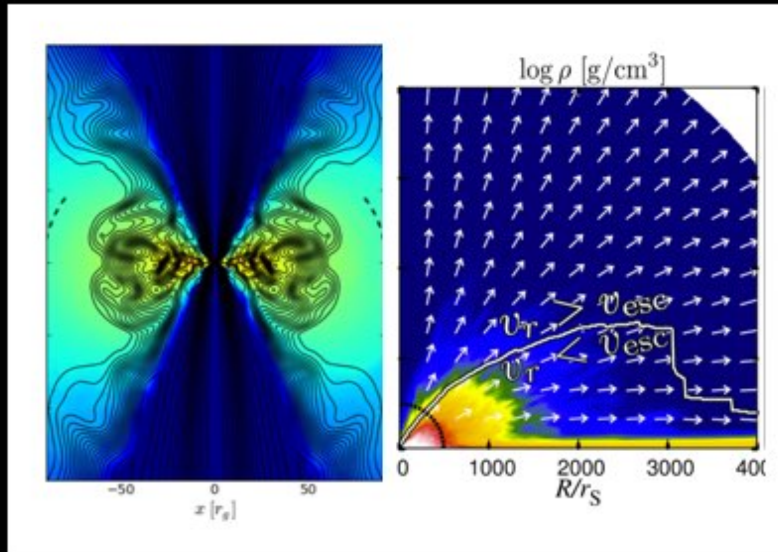



**Figure 3.** Dependence of isotropic X-ray luminosity (0.3–10 keV) on viewing angle $i$. The red, green, and blue lines display the isotropic luminosity for $\dot{M} \approx$ 1000, 500, and $200L_E/c^2$, respectively.

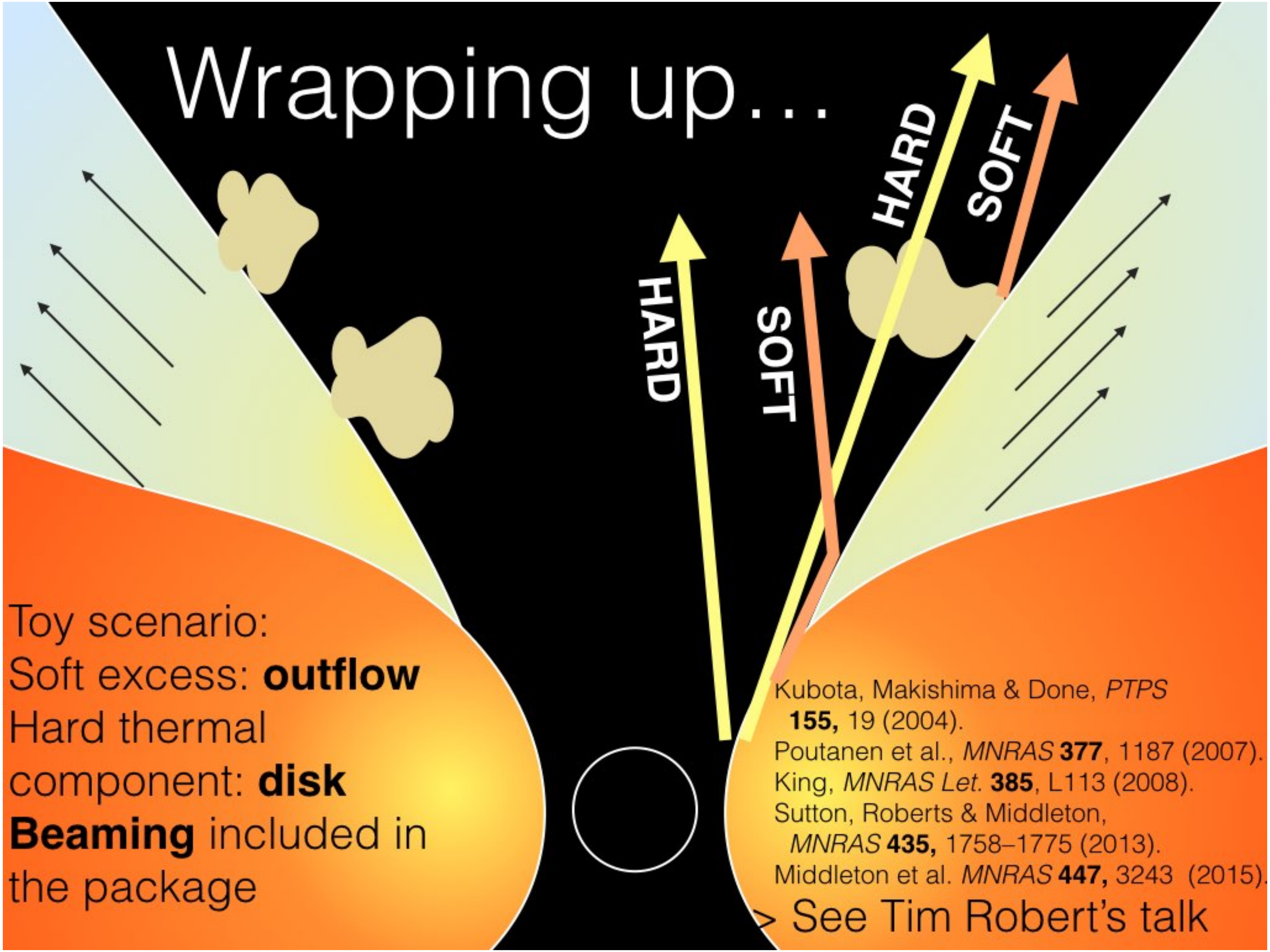
# Indications from simulations

- **Very** high accretion rates are possible
- Ubiquitous outflows/jets
- The mass accretion rate is *higher* than inferred from the isotropic luminosity, *even accounting for beaming!*



# Wrapping up…

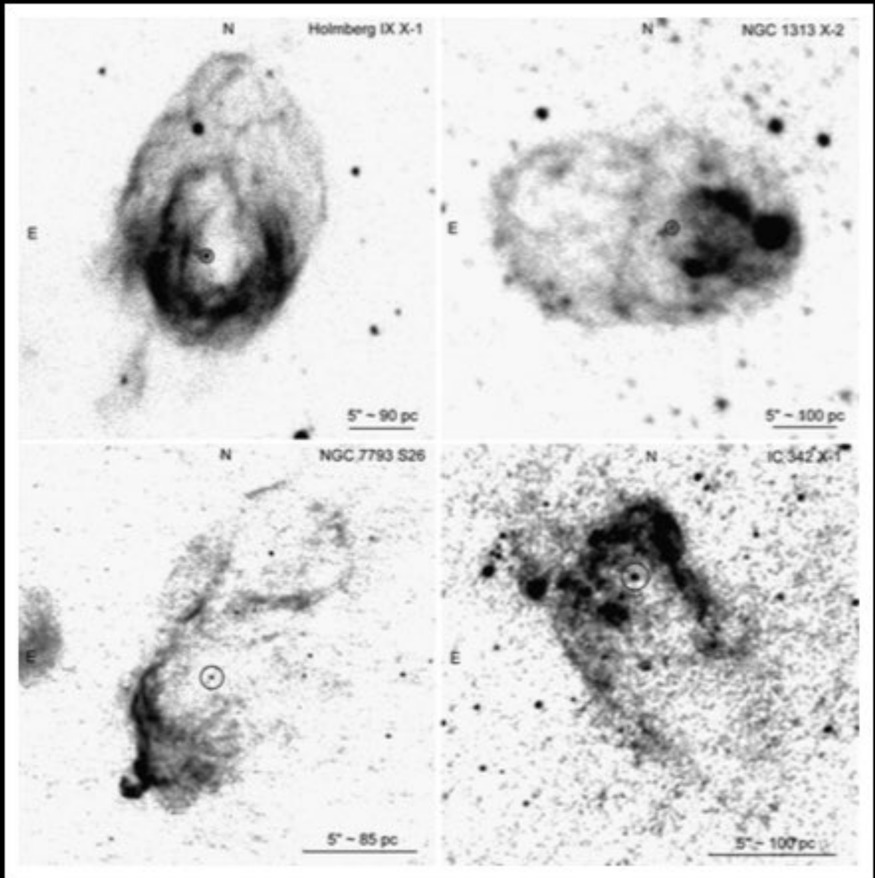



Toy scenario:
Soft excess: **outflow**
Hard thermal component: **disk**
**Beaming** included in the package

Kubota, Makishima & Done, *PTPS* **155,** 19 (2004).
Poutanen et al., *MNRAS* **377**, 1187 (2007).
King, *MNRAS Let.* **385**, L113 (2008).
Sutton, Roberts & Middleton, *MNRAS* **435,** 1758–1775 (2013).
Middleton et al. *MNRAS* **447,** 3243 (2015).

> See Tim Robert's talk

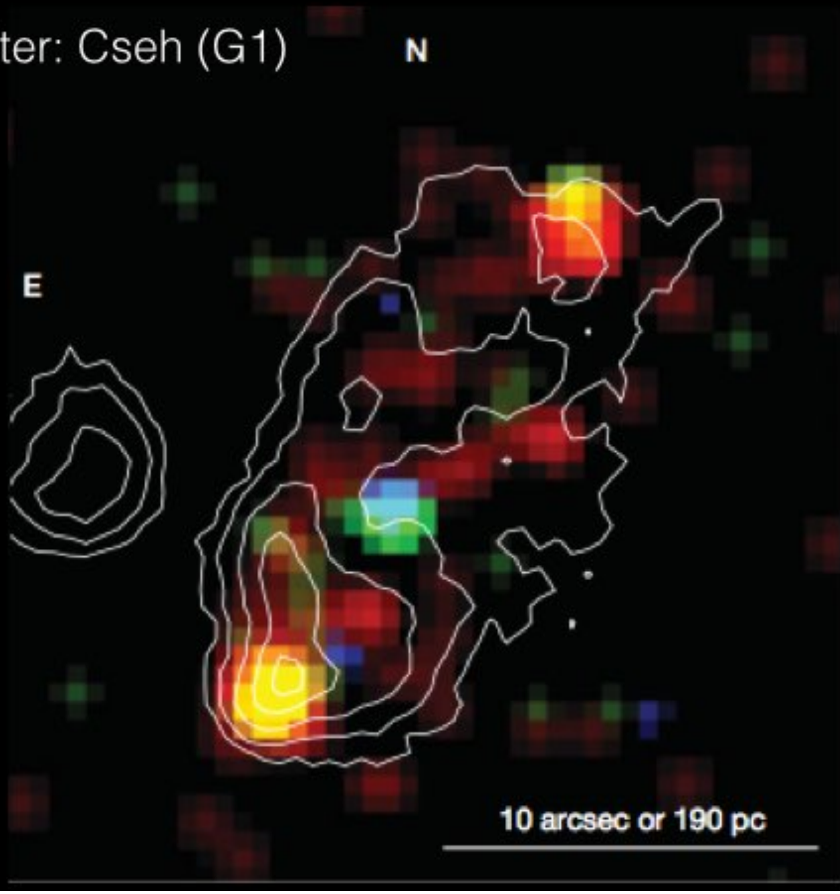
# Indications of outflows and jets? Check!




Hα bubbles
(credit: F. Grisé, in Feng & Soria *NAR* **55**, 166–183 (2011).)

Pakull,& Mirioni, *Winds* **15**, 197 (2003).
Mezcua, et al. *MNRAS* **436,** 3128–3134 (2013).
Cseh, D. et al. *MNRAS Let.* **439**, L1–L5 (2014).
Pakull, Soria & Motch, *Nat.* **466**, 209–212 (2010).

Poster: Cseh (G1)



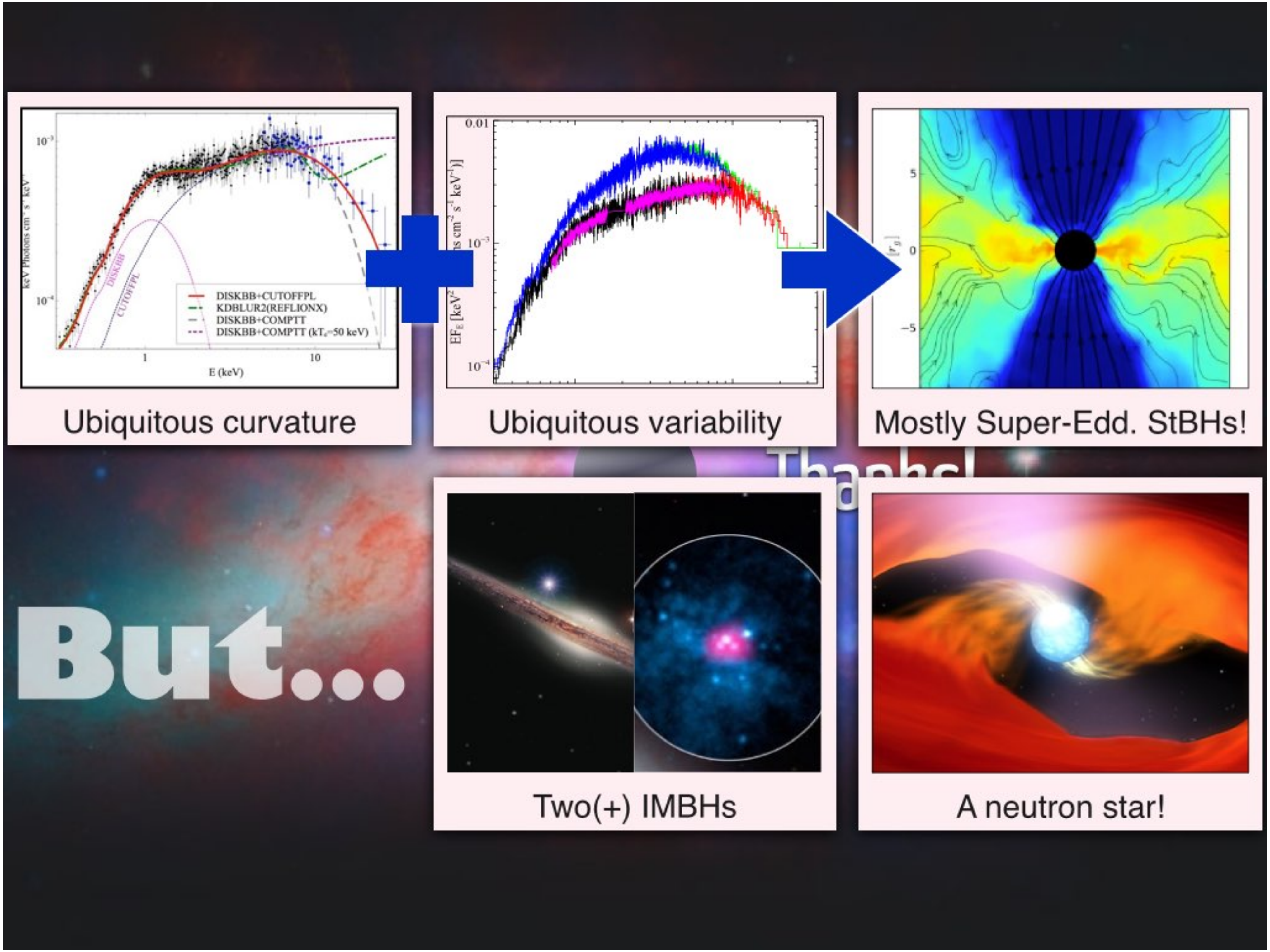
# Open questions

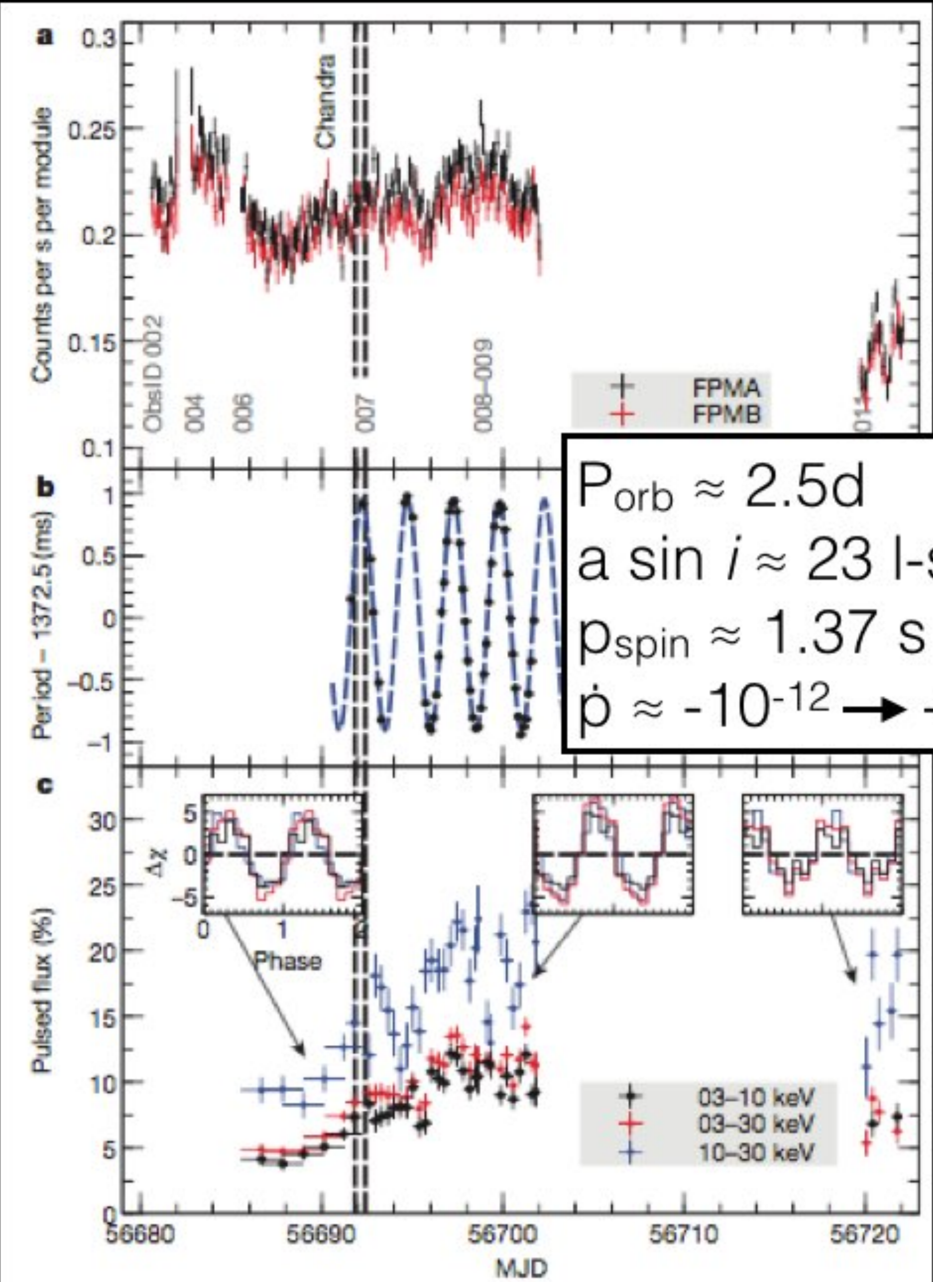
- X-ray emission and absorption from Outflows?
- What's the real accretion rate?
- How do we model spectra?
- How many pulsars?
- How many IMBHs?
- …. see next talks!

THE MORE YOU KNOW
THE MORE YOU REALIZE YOU DON'T KNOW

-> But see talk by Roberts!


That's all Folks!


DISKBB+CUTOFFPL
KDBLUR2(REFLIONX)
DISKBB+COMPTT
DISKBB+COMPTT (kTe=50 keV)
E (keV)
Ubiquitous curvature
Ubiquitous variability
Mostly Super-Edd. StBHs!
But…
Two(+) IMBHs
A neutron star!

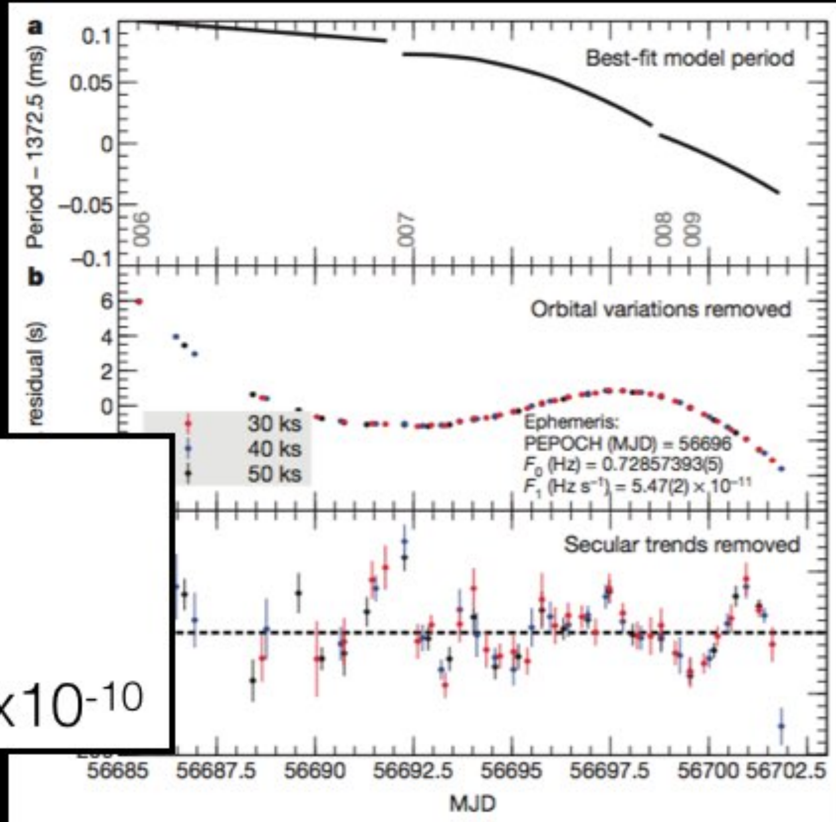


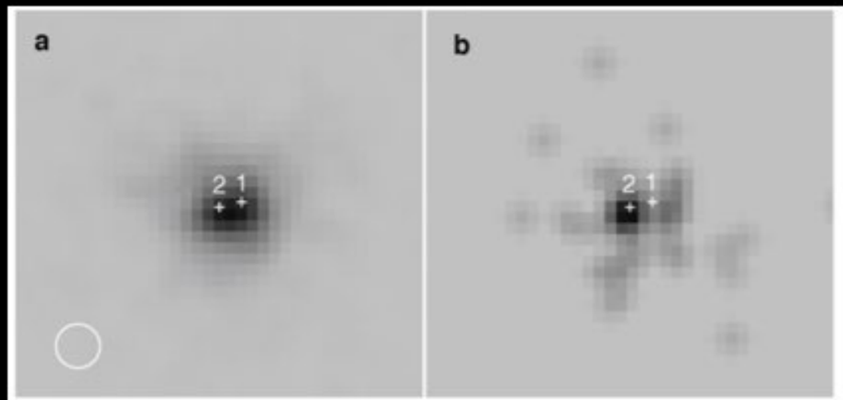

$P_{orb} \approx 2.5\text{d}$

$a \sin i \approx 23$ l-s

$p_{spin} \approx 1.37$ s

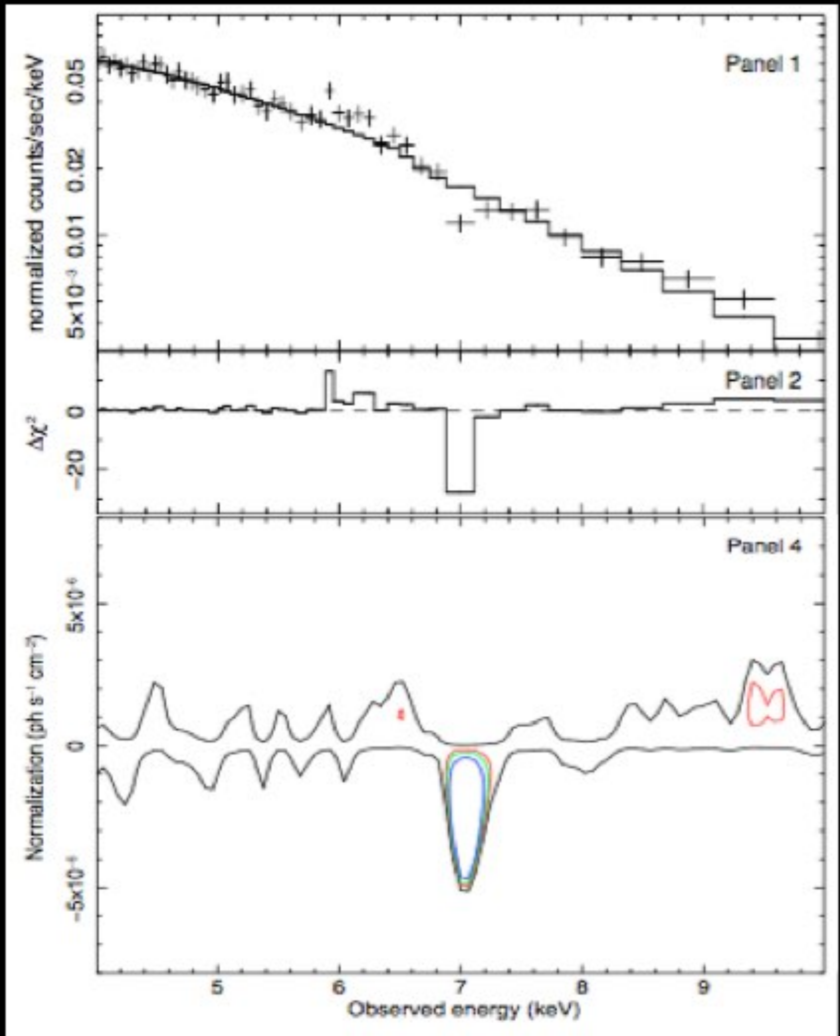
$\dot{p} \approx -10^{-12} \rightarrow -2\text{x}10^{-10}$



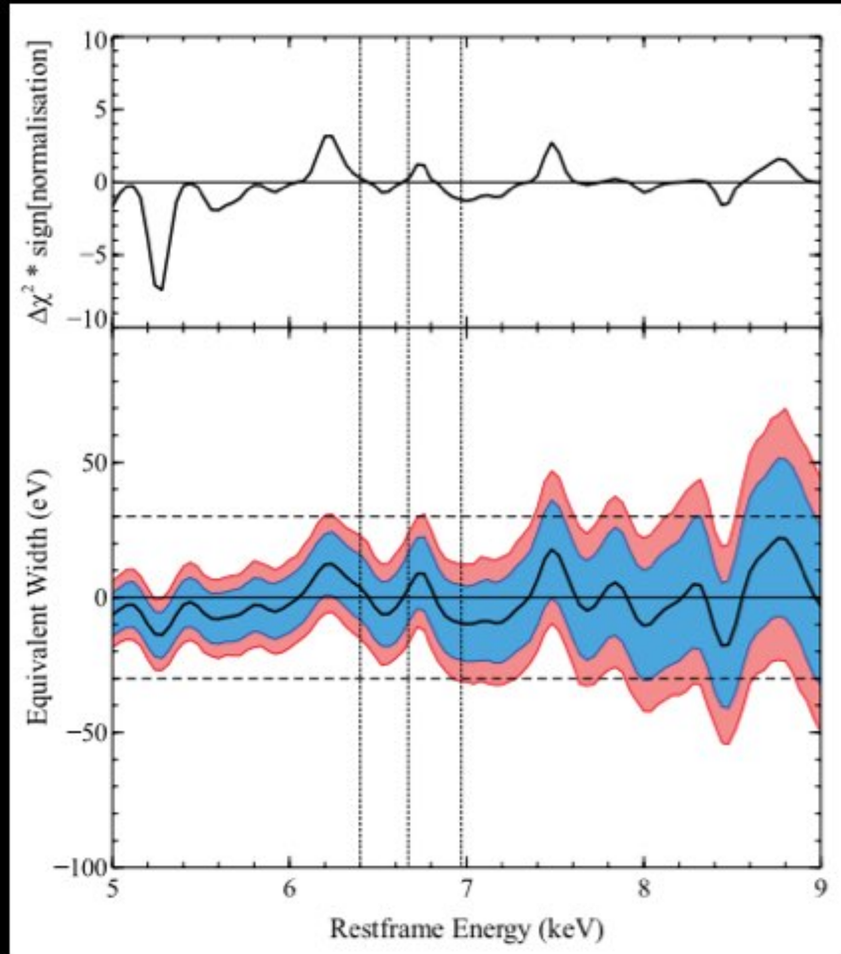
# Outflows

## what we expect




Tombesi et al. *A&A* **521**, 57 (2010)

## what we see




Walton et al. *MNRAS* **426**, 473 (2012)