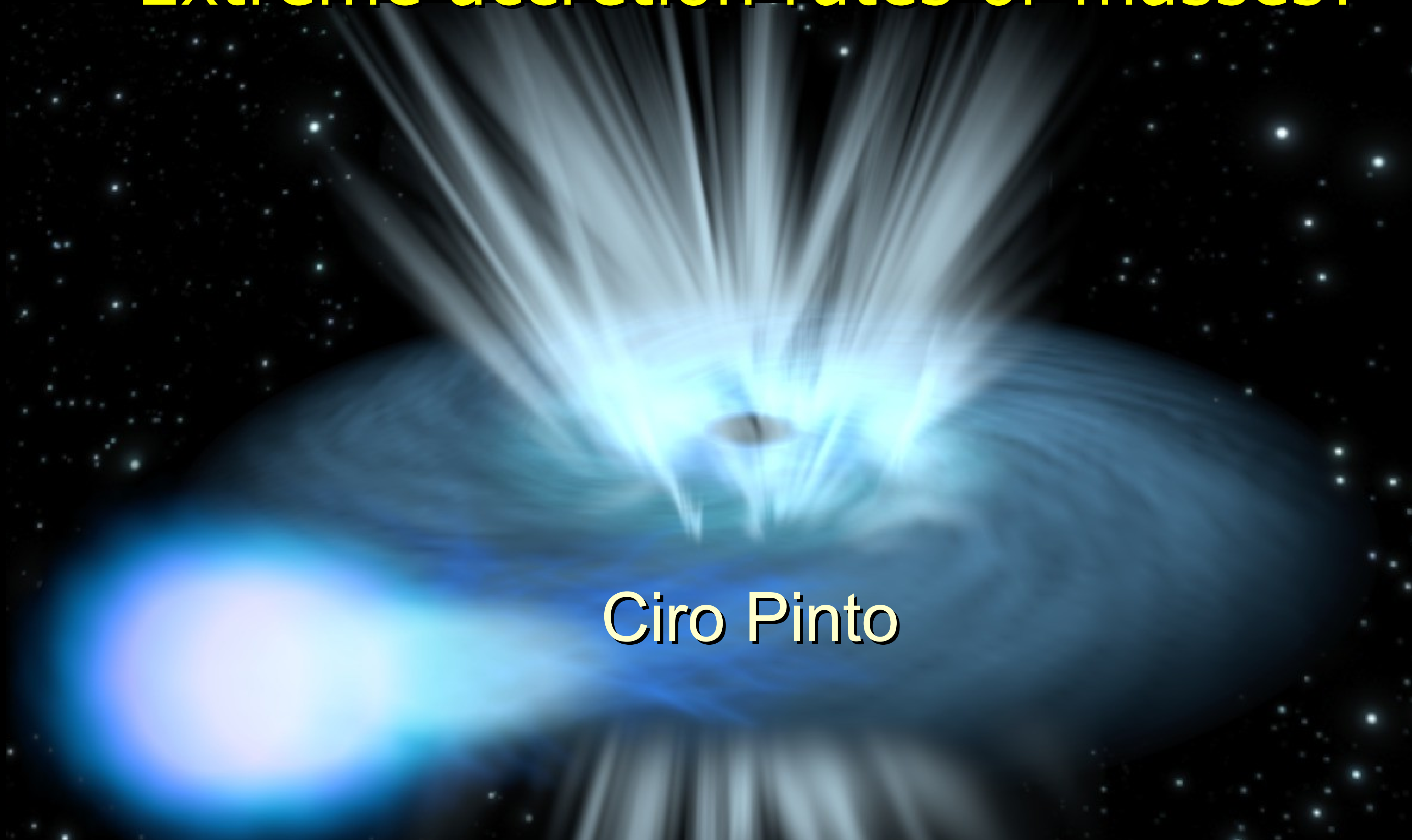
Ultra-Luminous X-ray sources: Extreme accretion rates or masses?



Ciro Pinto

UNIVERSITY OF CAMBRIDGE

ioa

erc European Research Council
Established by the European Commission

Cambridge X-Ray Astronomy

Ultra-Luminous X-ray sources: Extreme accretion rates or masses?

μινώταυρος

VS

θησέας

Massive and slow or small and fast?

Outline

- Cosmological context and requirements
- ULXs versus Galactic X-ray binaries
- ULXs as intermediate mass black holes
- ULXs as super-Eddington accretors

  → The role of fast winds

  → The big picture
- The Future

1. The importance of ULXs

Cosmological context

- AGN detected at high (>6) redshifts (Fan+03, Mortlock+11)

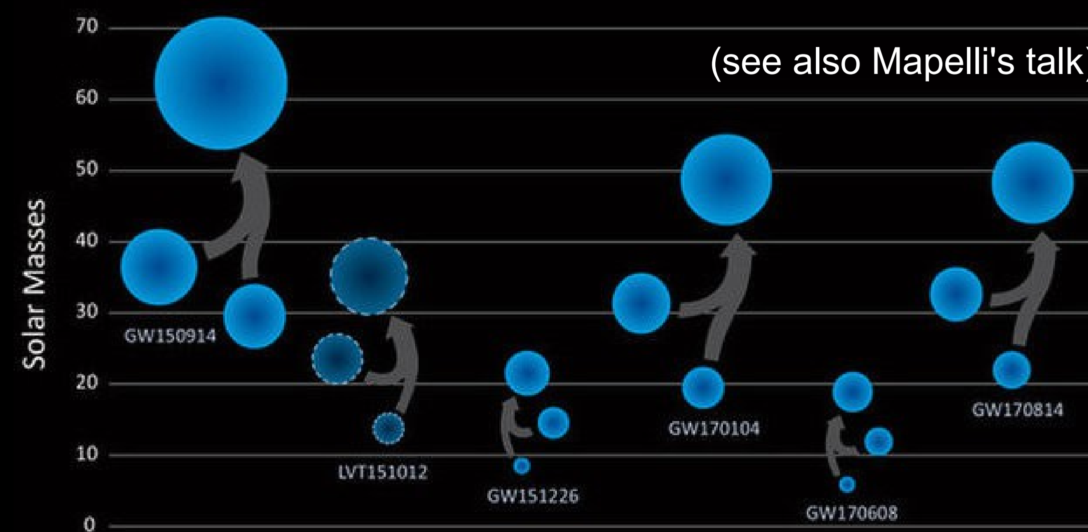
  → IMBHs as seeds of SMBHs (Volonteri+03)

  → Super-Eddington accretion (Begelman & Volonteri 16)

- Gravitational waves discovery LIGO + Virgo (Abbott + 16 a,b, 17)

  → massive BH (+ NS) binaries (see also Mapelli's talk)

- HMXRB roles in early Universe

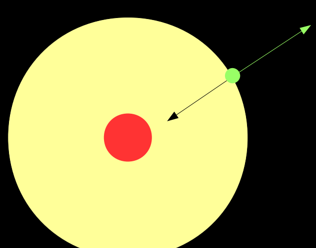


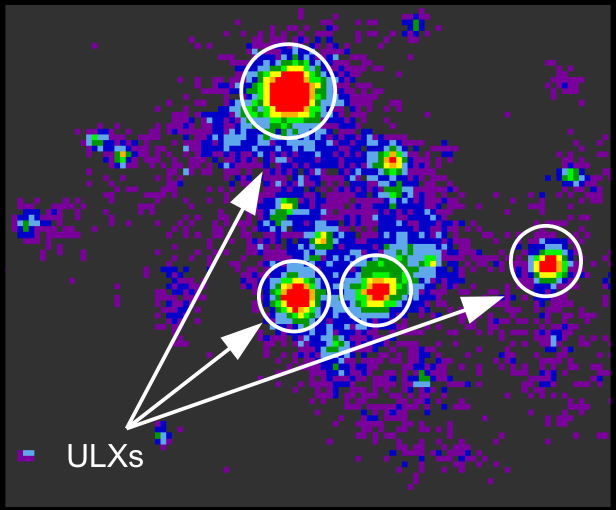
Ultraluminous X-ray sources (ULXs)

Brighter than a 10 M_{Sun} black hole accreting at the Eddington limit (10^{39-41} erg/s).

Fainter than active galactic nuclei, off-nucleus & brighter than any known stady stellar process.

Eddington Limit:
maximum luminosity at the balance between radiation force and gravitational force



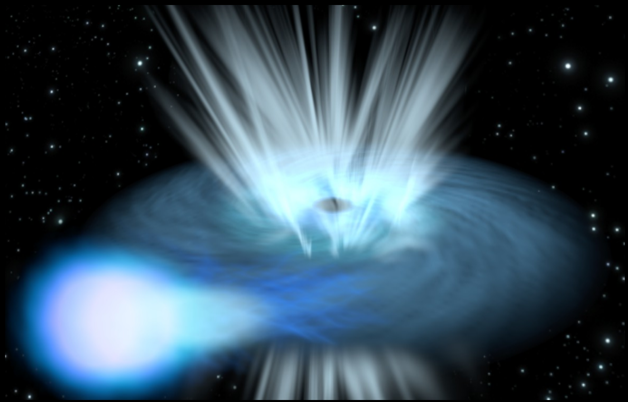


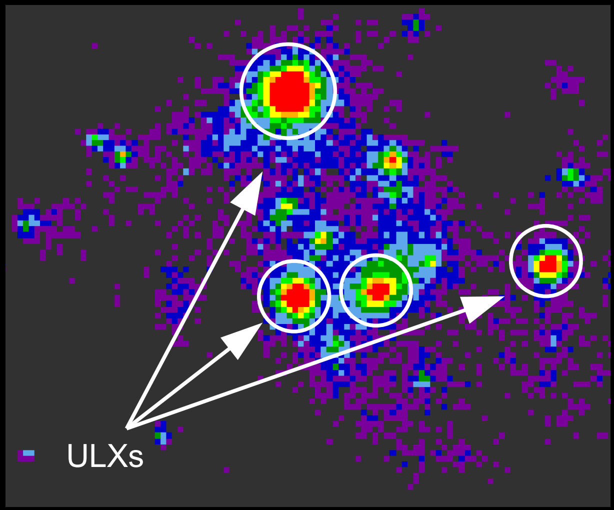
NGC 6946 "Fireworks Galaxy"

What powers ULXs?

Either a massive black hole

or huge accretion onto a stellar BH/NS





NGC 6946 "Fireworks Galaxy"

2. Are ULXs extreme XRB?

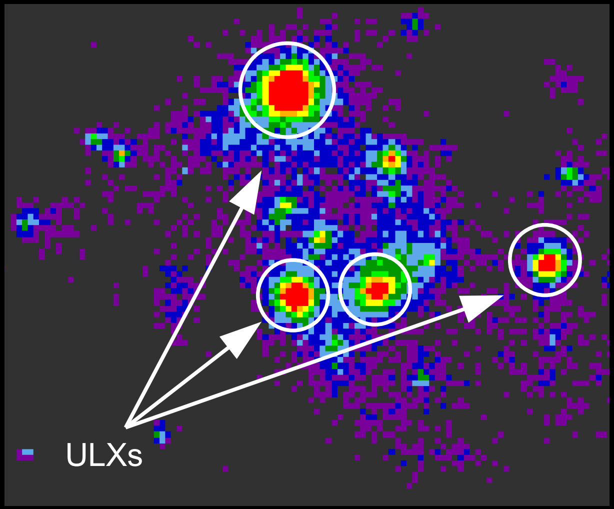
ULXs : the early days

Early discovered with Einstein Observatory in 1980

More common in star-forming / low-metallicity galaxies

10% of ULX turned out to be background quasars

Typically 1-2 per galaxy



NGC 6946 "Fireworks Galaxy"

Roberts (2000 *cat*, 2007 *rev*)

Colbert & Ptak (2002 *cat*)

Liu & Bregman (2005 *cat*)

Feng & Soria (2011 *rev*)

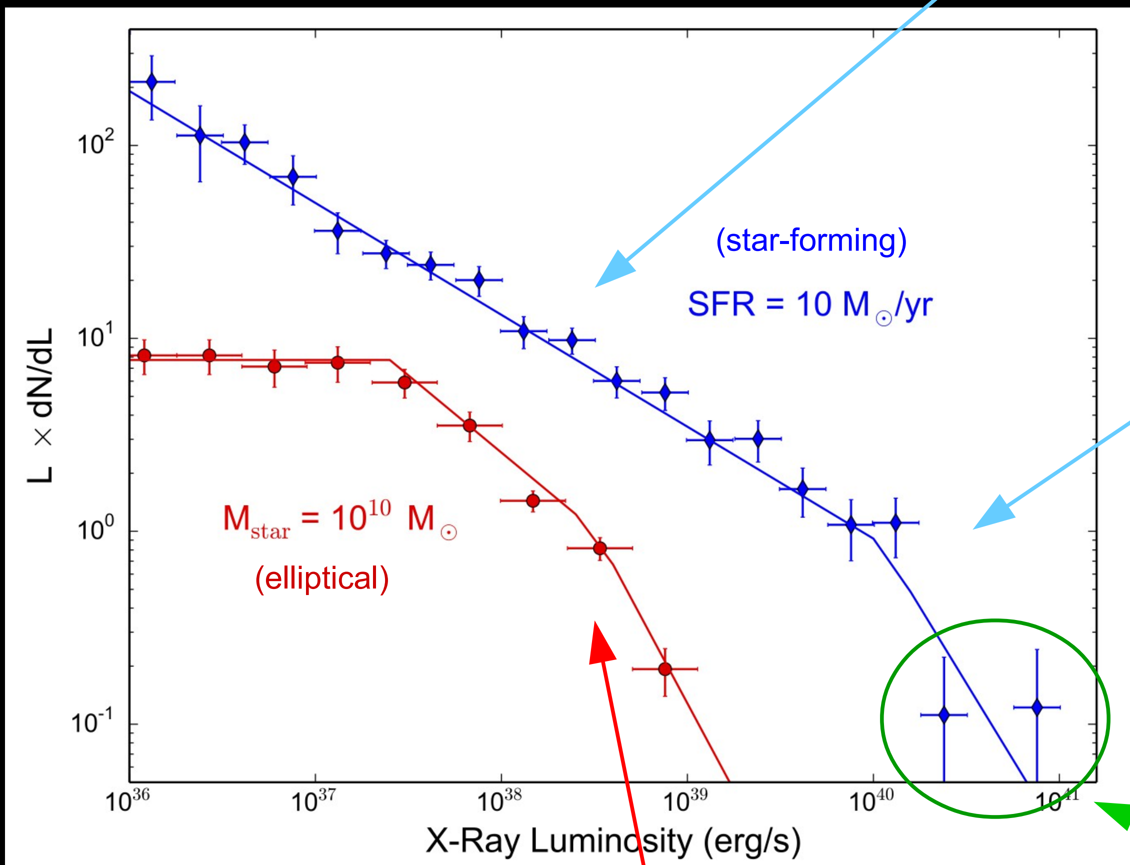
Walton, Roberts, Mateos & Heard (2011 *cat*)

Kaaret, Feng & Roberts (2017 *rev*)

ULXs : X-ray luminosity function

Break missing for Eddington NS?

Break → 20x masses or rates?



Mineo, Gilfanov & Sunyaev (2012)

ULX↑ SFR↑

Mapelli et al. (2010)

NS ~ 10-50x BH,

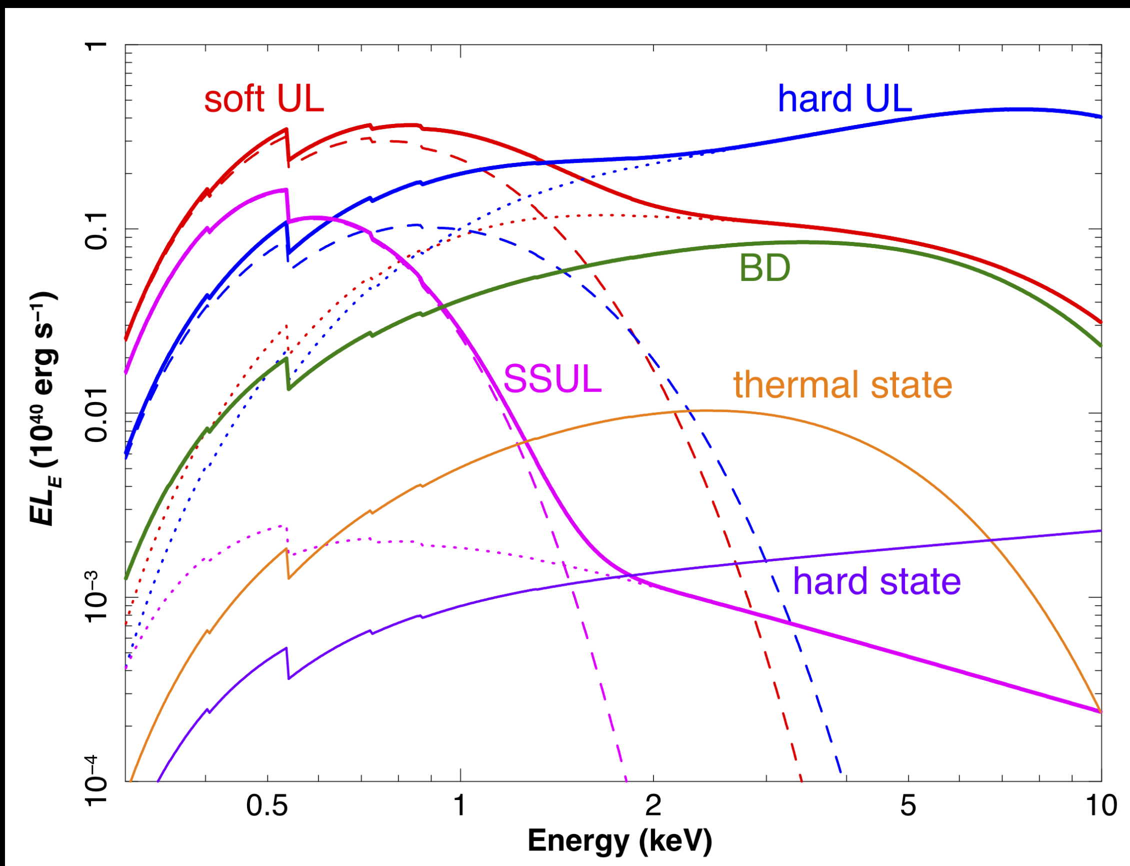
M_{BH}↑ Z↓

Belczynsky et al. (2009,10)

HLX: a new class?

Break → beamed NS?

ULXs : X-ray spectra (vs XRB)



Soft & Hard Ultra-Luminous state:

T_{BB} ~ 0.2 , T_{CORONA} ~ 2 keV , 10^{40} erg/s

Broadened disk (BD) state:

T_{BB} ~ 1-2.5 keV , p ~ 0.6 , $2 \cdot 10^{39}$ erg/s

Supersoft ultralumin. (SSUL) state:

T_{BB} ~ 0.1 keV , Γ ~ 3 , $3 \cdot 10^{39}$ erg/s

Thermal & hard XRB BH states

T_{BB} ~ 1 keV , $2 \cdot 10^{38}$ erg/s

Γ ~ 1.7 , $0.5 \cdot 10^{38}$ erg/s

Kaaret, Feng & Roberts (2017)
Sutton et al. (2015)

Absence of reflection features e.g. Fe K ...

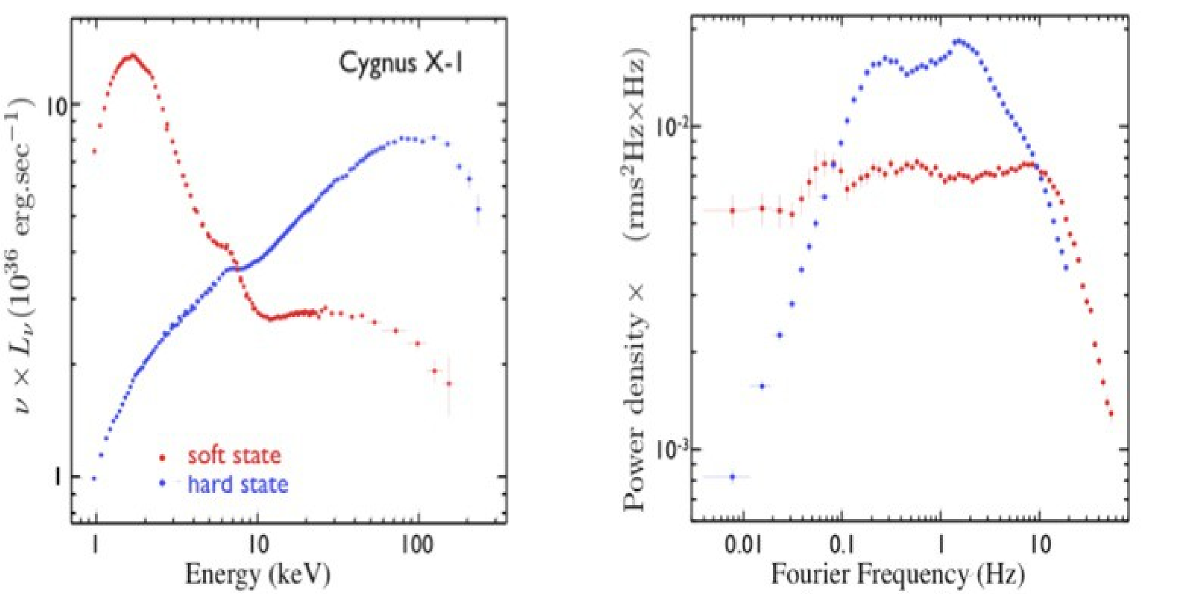
... and of course some ULXs switch state!

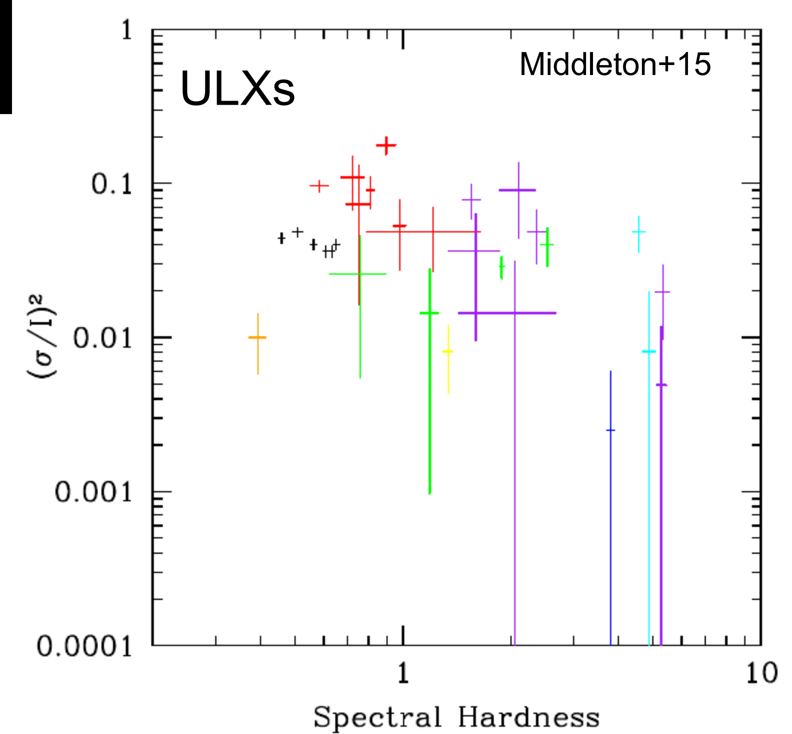
ULXs : X-ray timing (vs XRB)

XRB: up to 10^7 flux changes, quiescence, outburst, hysteresis, pulsations & bursts (NS), LF / HF QPOs, radio jets, time lags

ULX: flux changes < 10 (10^2 a few), most persistent over decade, QPOs (?), reverse large time lags (?), non-linear varibility

X-ray binary Power spectra





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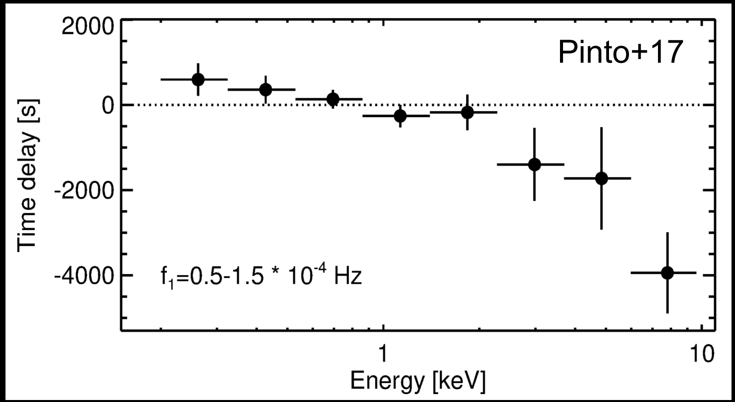
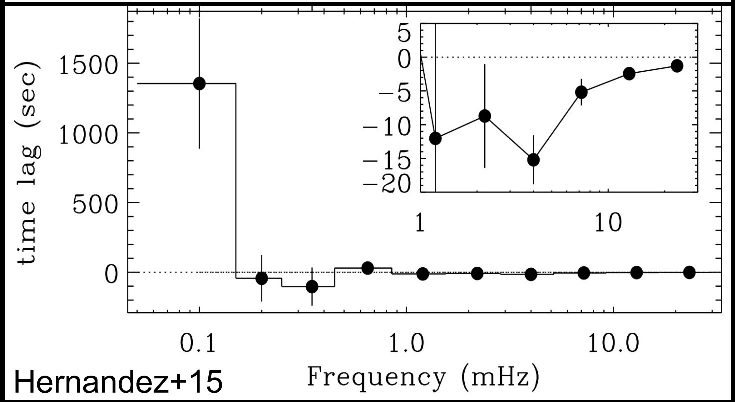
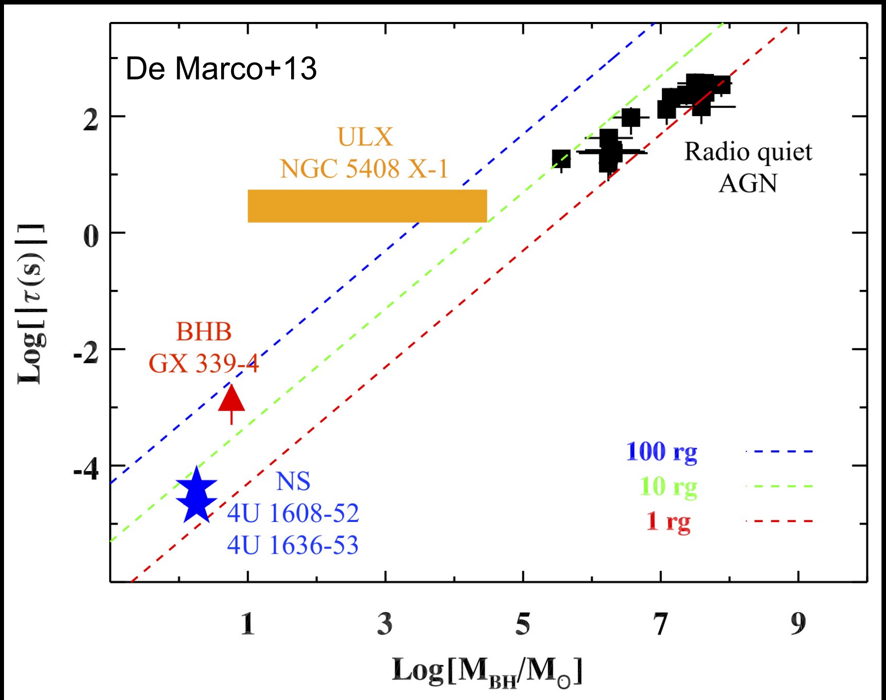




Time lags



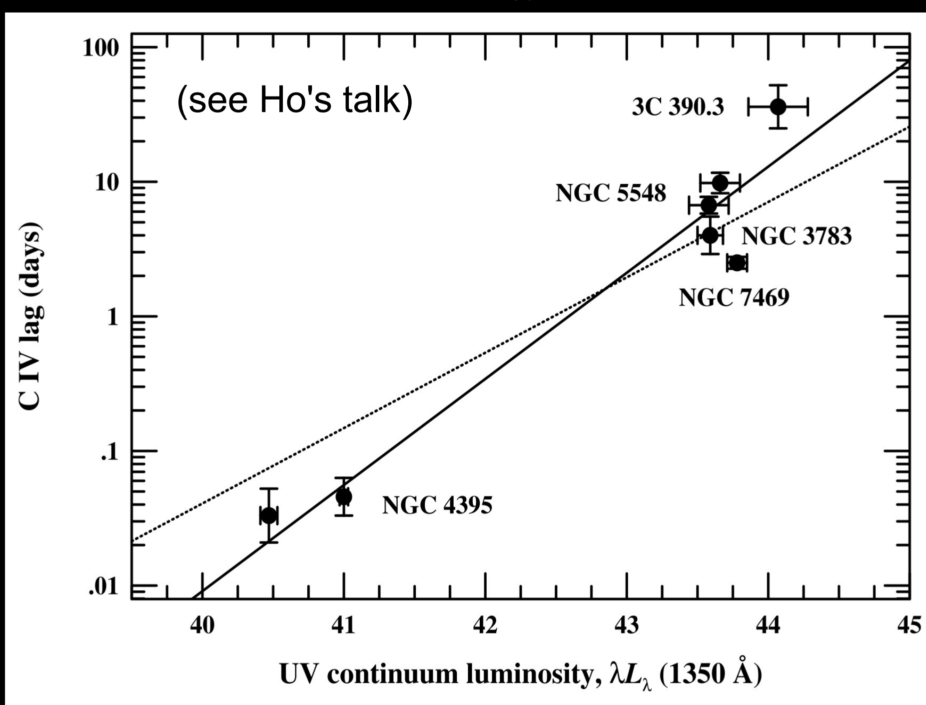
3. ULXs as IMBH candidates

IMBH (10^{2-5} M_{sun}) candidates

1000 M_{sun} (thin disks) would follow $T_{in} \sim M^{-0.25}$ (or $L_{disk} \sim T_{in}^4$)

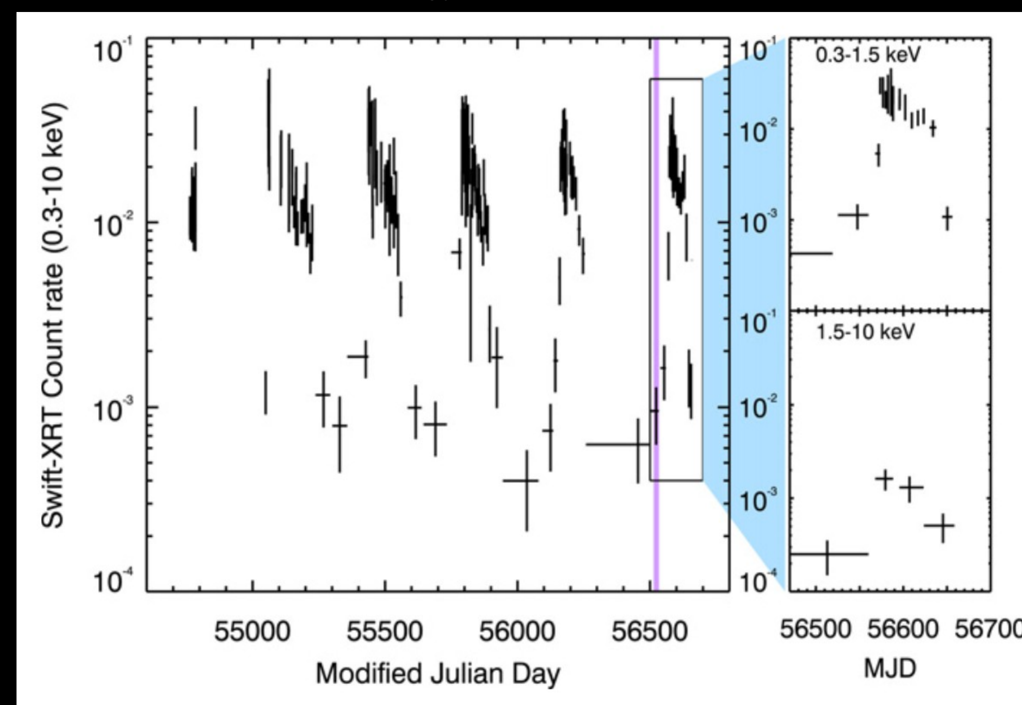
Low-Luminosity Active Galactic Nuclei

NGC 4395 (~10^5 M_{sun} Peterson+05)



High / soft - low/hard state ULX transitions

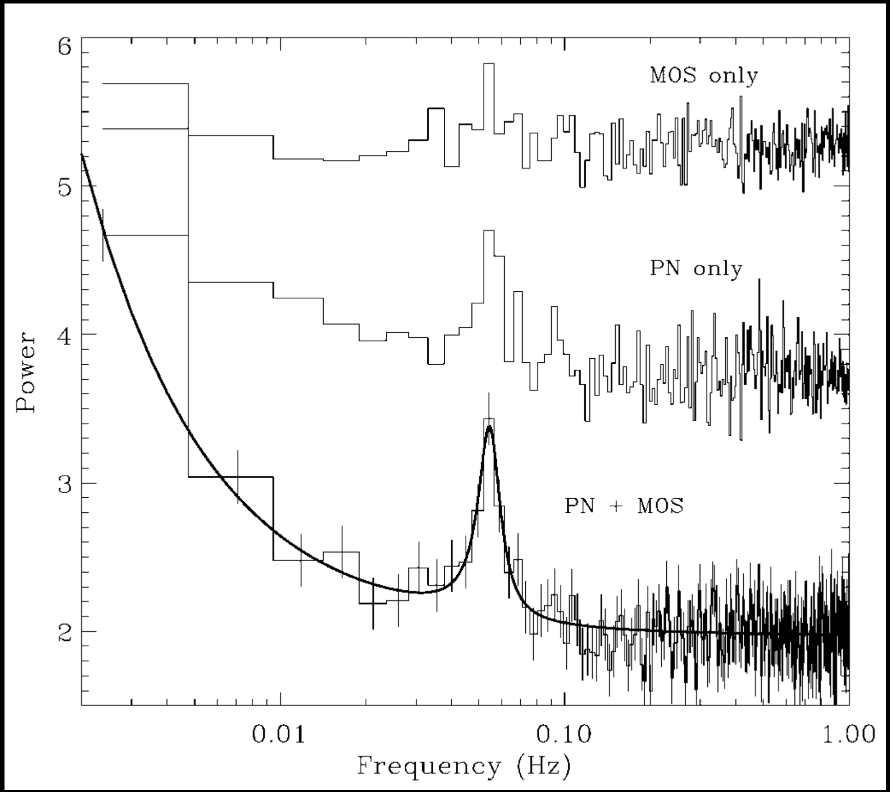
HLX-1 (10^{4-5} M_{sun} Farrell+09, Godet+14)



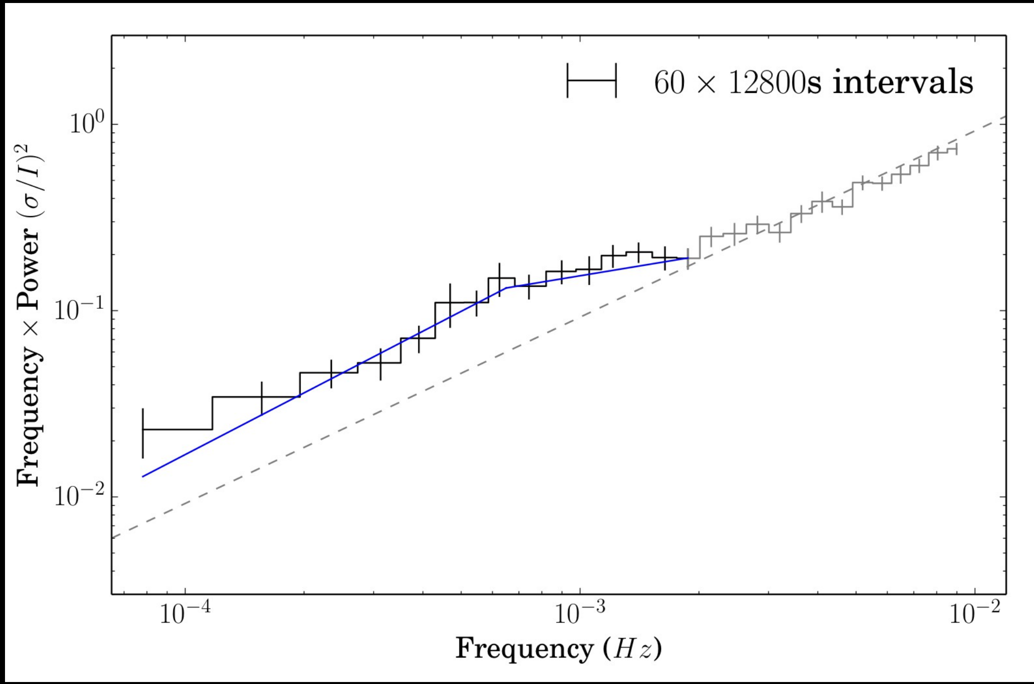
IMBH (10^{2-5} M_{sun}) candidates

1000 M_{sun} (thin disks) would follow $T_{in} \sim M^{-0.25}$ (or $L_{disk} \sim T_{in}^{4}$)

M 82 QPO (~10^{2-4} M_{sun} S&M+03)



M 51 X-7 (10^{3-4} M_{sun} Earnshaw+16)

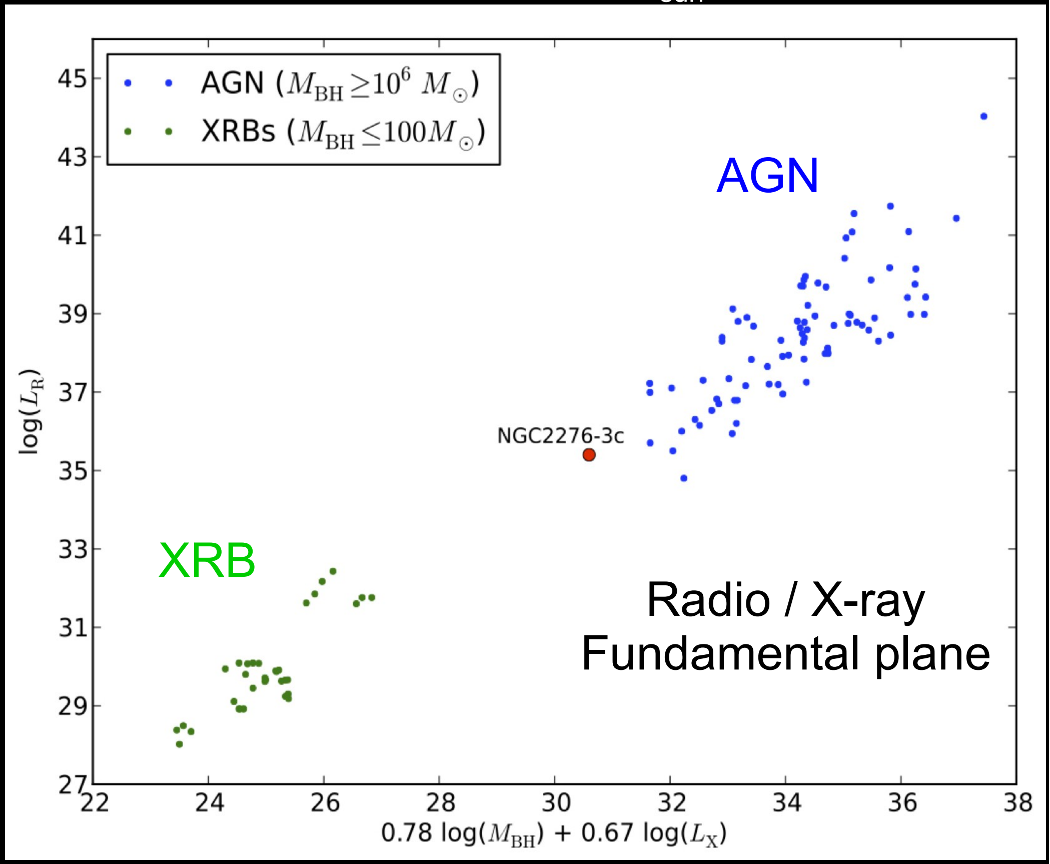


IMBH (10^{2-5} M_{sun}) candidates

1000 M_{sun} (thin disks) would follow $T_{in} \sim M^{-0.25}$ (or $L_{disk} \sim T_{in}^{4}$)

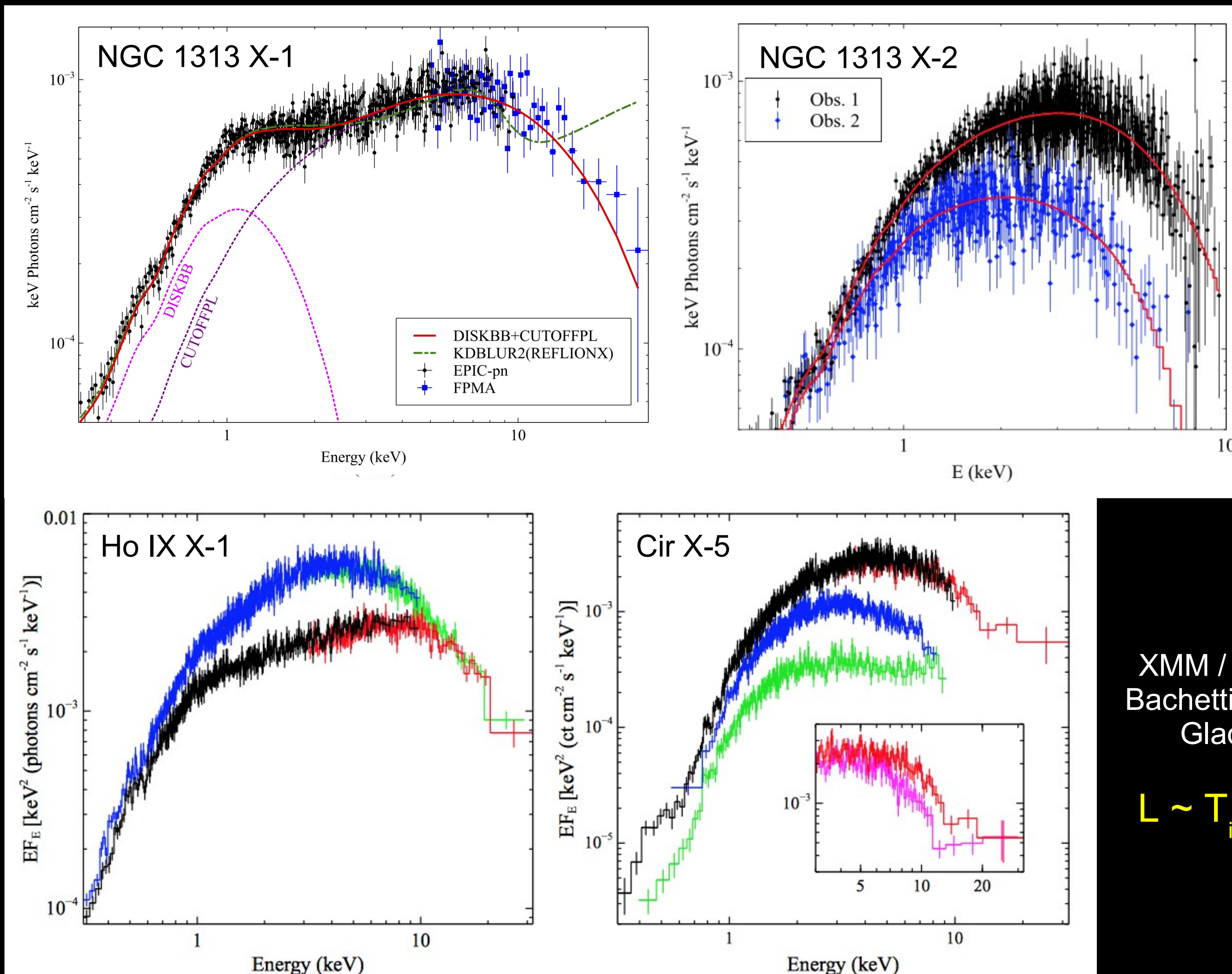
Few more objects in Sutton+12
(just based on the spectral shape)

NGC 2276 3c ($5 \cdot 10^4$ M_{sun} Mezcua+13,15)



4. ULXs as SE candidates

Issues with sub-Eddington models

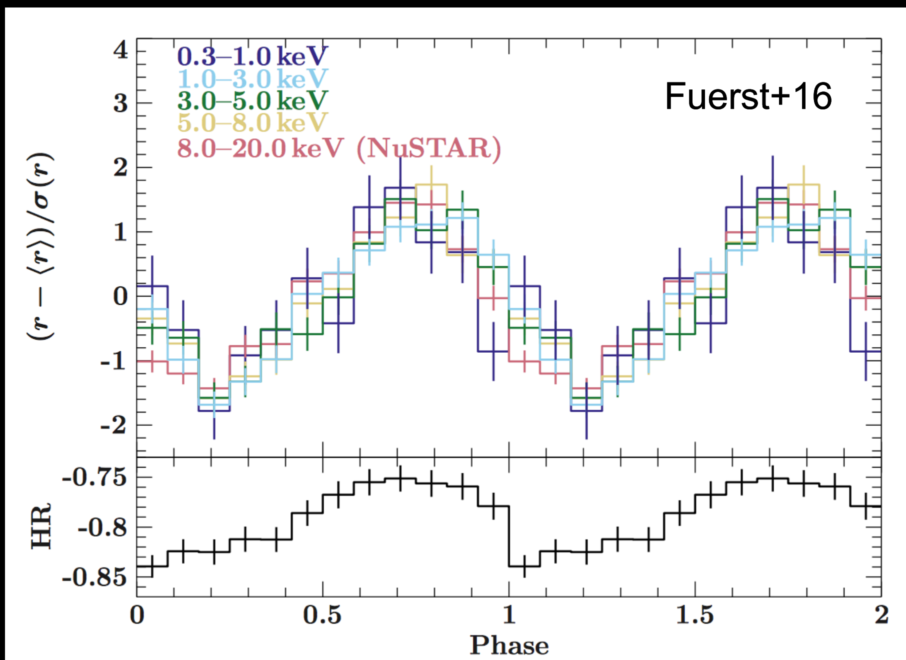


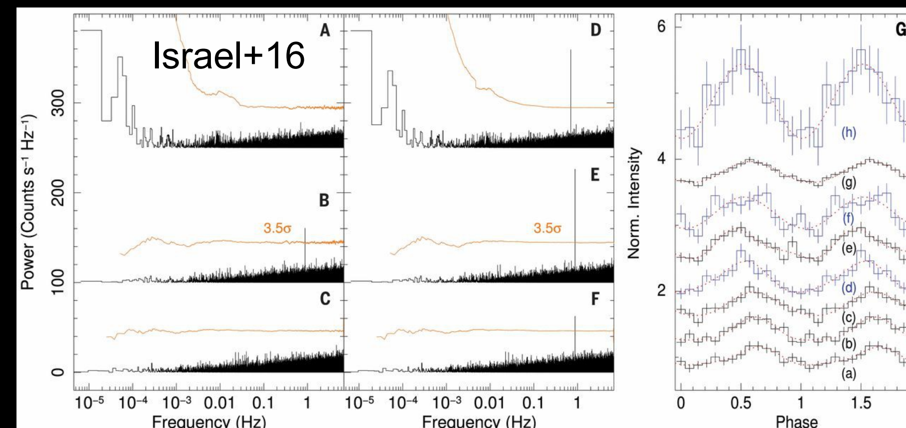
XMM / NuSTAR ULX spectra
Bachetti et al. (2014), see also
Gladstone et al. (2009)

$L \sim T_{in}^{2}$ or lower index

... at least 4 ULXs are neutron stars !!!

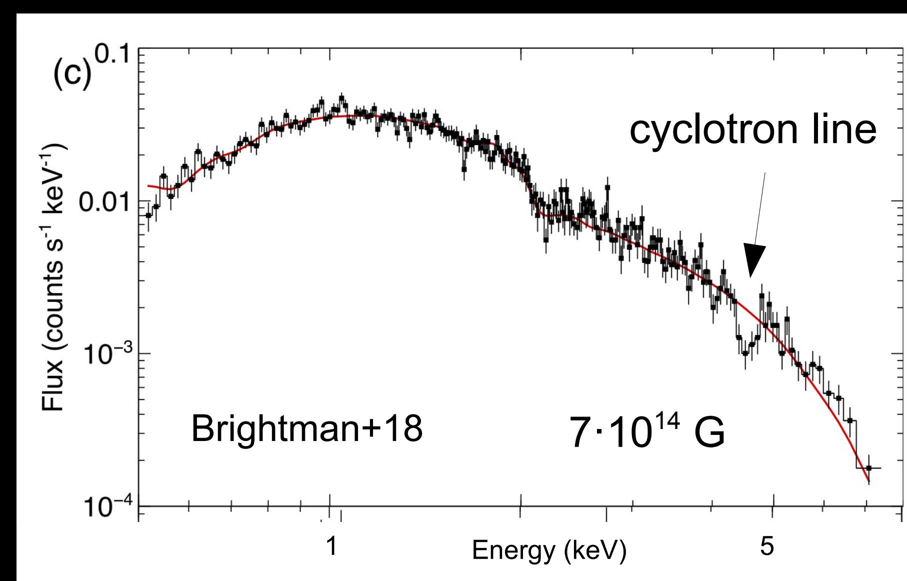
The 4 musketeers (ctz. DM, Bachetti+2014, Israel+16ab, Fuerst+16, Carpano+18)





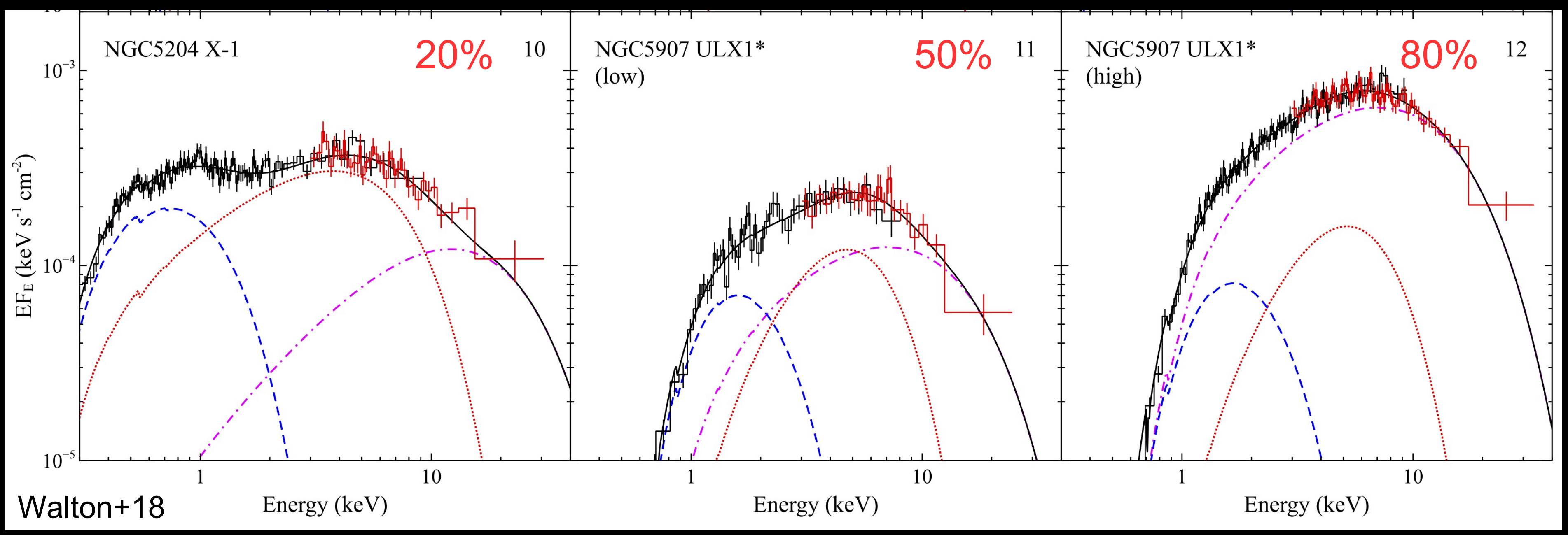
> 100x Eddington (up to 10^{41} erg/s)

Damned!



Detecting pulsations is actually difficult

- 20 - 80 % of the X-ray flux is likely within the accretion column
- But typically needs > 50% to detect pulsations

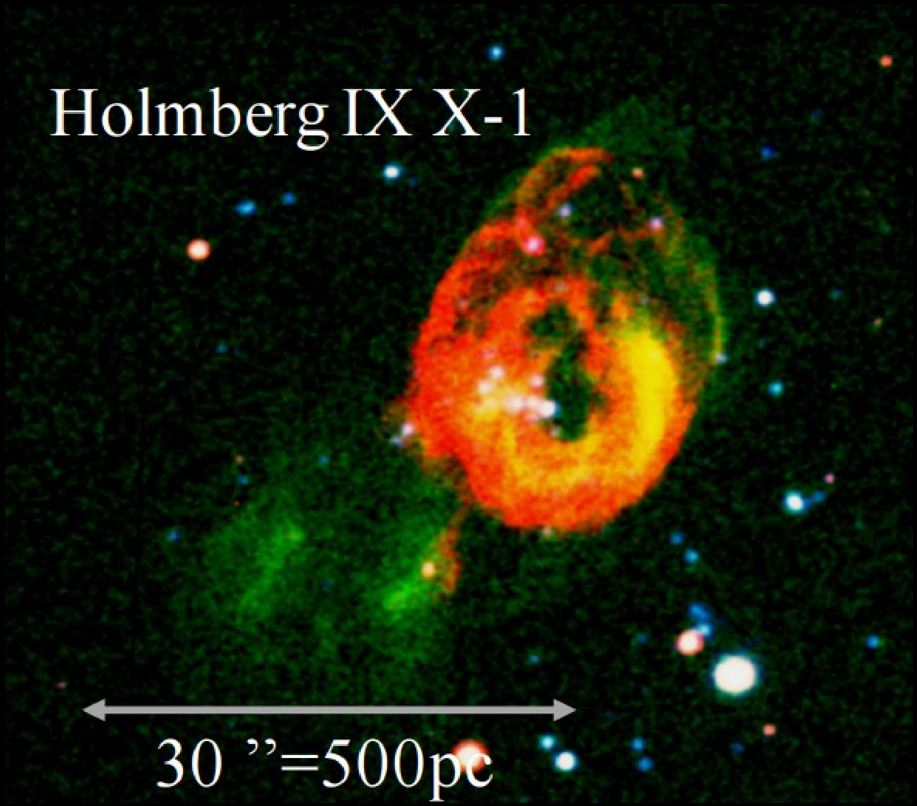


Further discoveries supporting Super-Eddington

- Super bubbles

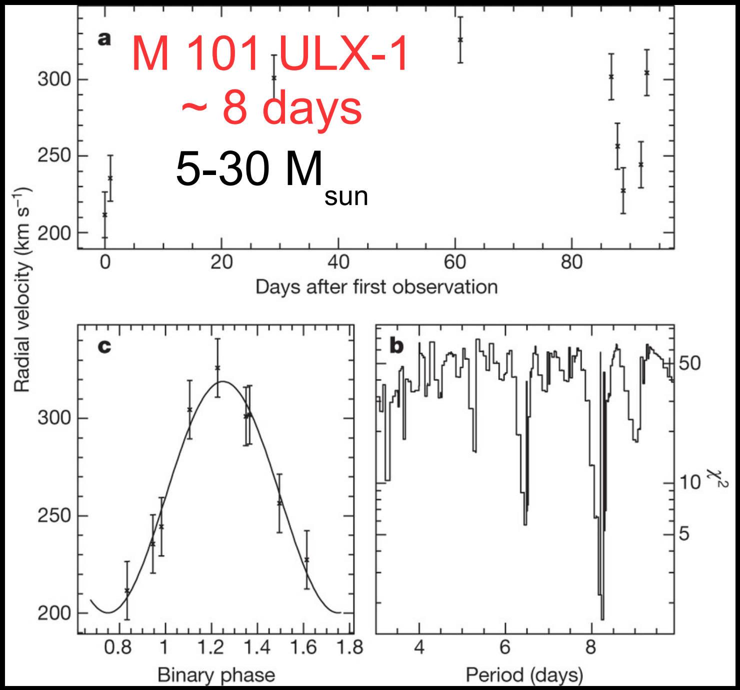
(e.g. Pakull+02, Grise+12, Cseh+14)

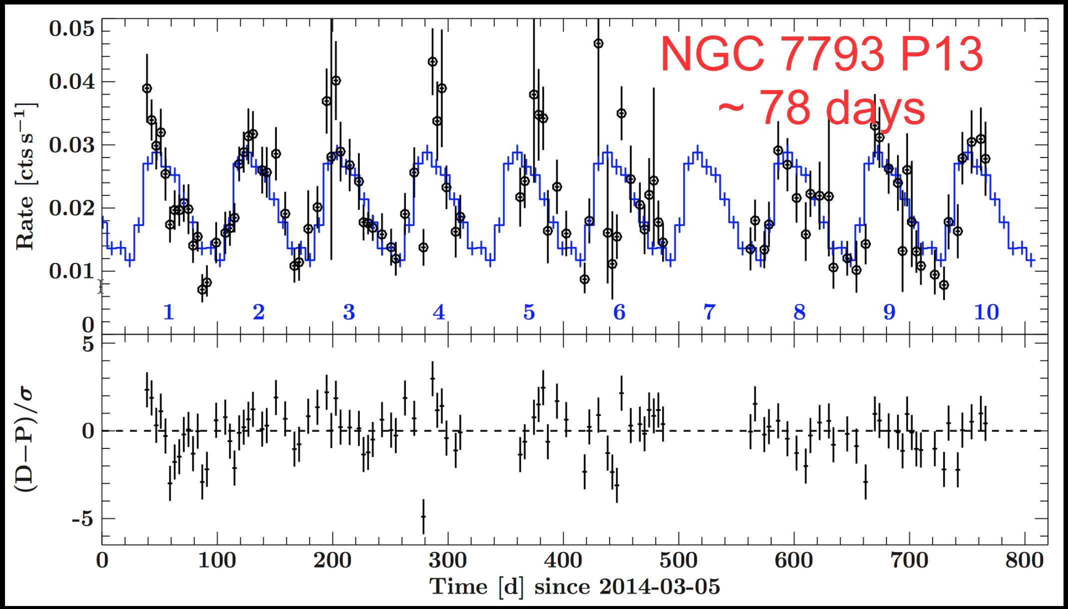
Bubble ionisation matches
the ULX radiation field
and wind power



Further discoveries supporting Super-Eddington

- Super bubbles (e.g. Pakull+02, Grise+12, Cseh+14)
- High-mass companion and (Super-) orbital periods
  (Tao+11, Gladstone+13, Liu+13, Motch+14, Heida+15, Walton+2016, U&S+16)





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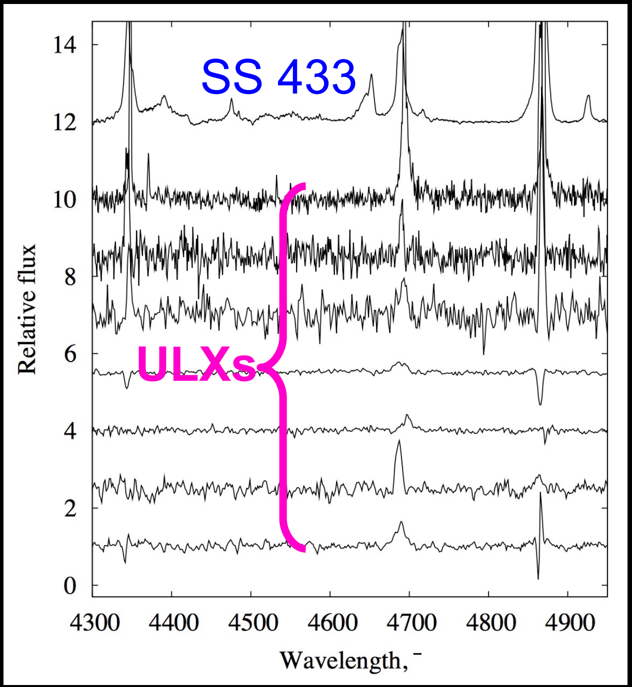
- High-mass companion and (Super-) orbital periods
  (Tao+11, Gladstone+13, Liu+13, Motch+14, Heida+15, Walton+2016, U&S+16)
- Optical spectra (e.g. Fabrika+17, Motch+11)

WNL type (late nitrogen Wolf-Rayet stars)
or LBV (luminous blue variables)
in their hot state



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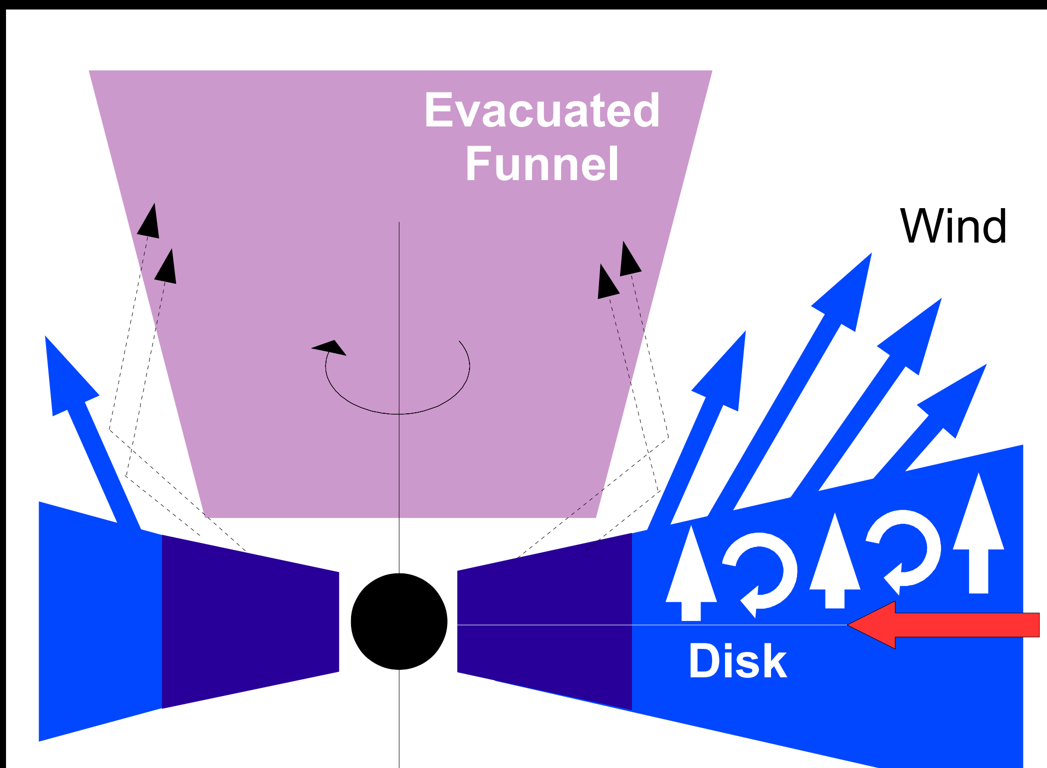
- Super bubbles (e.g. Pakull+02, Grise+12, Cseh+14)
- High-mass companion and (Super-) orbital periods (Tao+11, Gladstone+13, Liu+13, Motch+14, Heida+15, Walton+2016, U&S+16)
- Optical spectra (e.g. Fabrika+17, Motch+11)
- Winds (?)

Super-Eddington?
Okay, but how does
it work?

Super-Eddington accretion disks



$$L \approx \frac{1.3 \cdot 10^{38}}{b} \left(\frac{M_{BH}}{M_{sun}} \right) \left(1 + \frac{3}{5} \ln \dot{m} \right)$$

Radiation + advection dominated thick disks

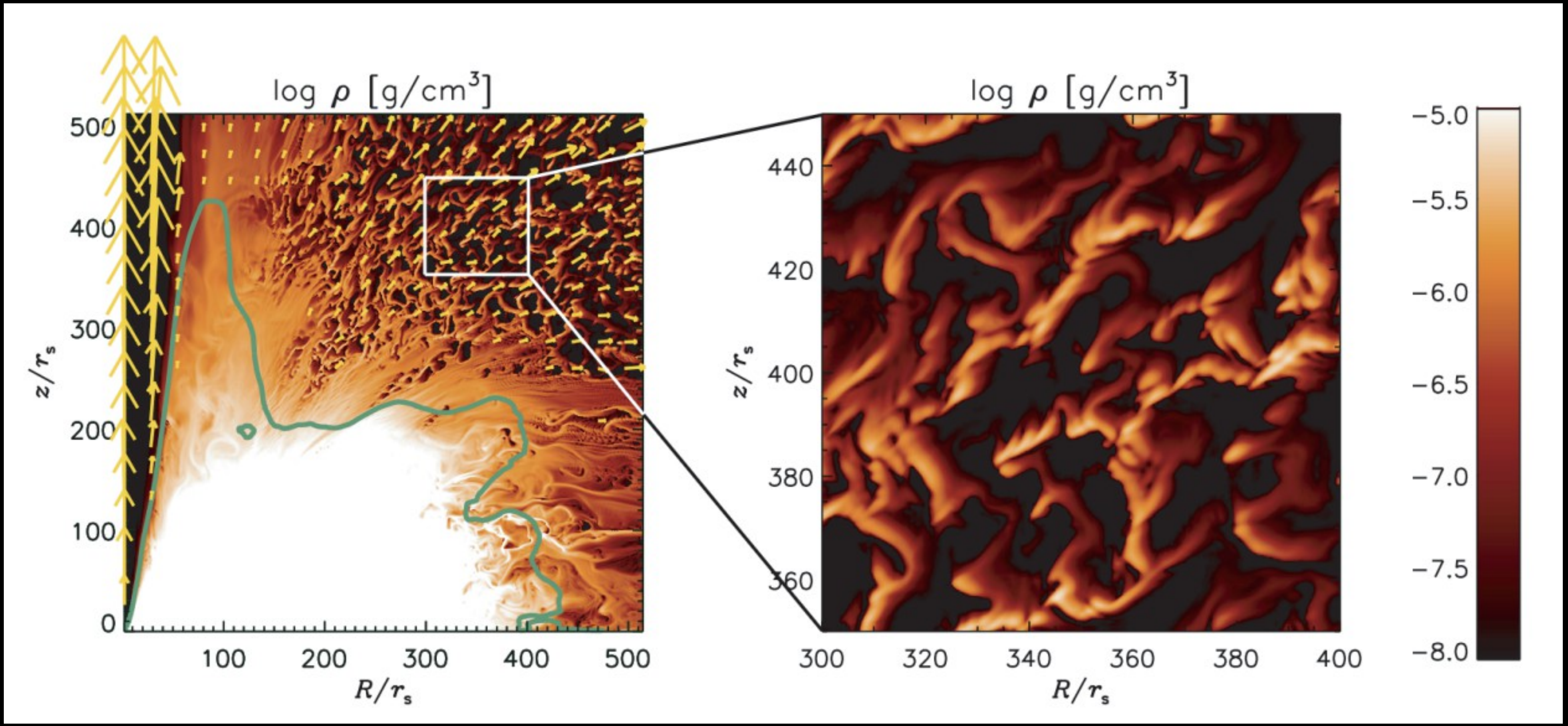
+ powerful winds

Gladstone+09
Shakura & Sunyaev 73
King+01, Poutanen+07
Middleton+11-15

AGN? Yes! → NLS1 galaxies (Jin+12)
Or ask Chris Done ...

Super-Eddington radiation-driven winds

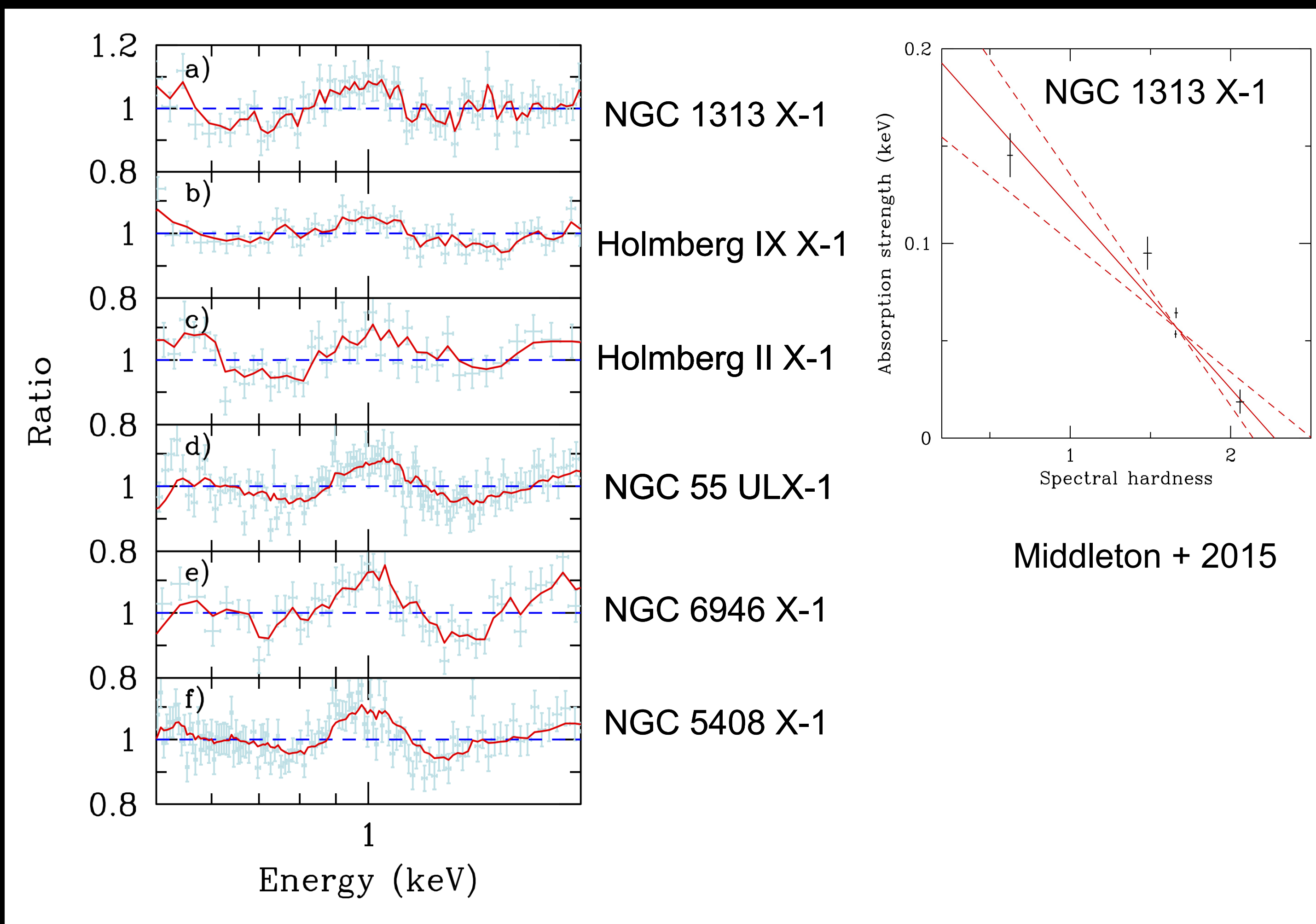
GR-MRHD simulations by Takeuchi + 13



V ~ 0.1c , 10º-50º , clumpy > 250 r_S , clumps ~ 10 r_S , c_V ~ 0.3

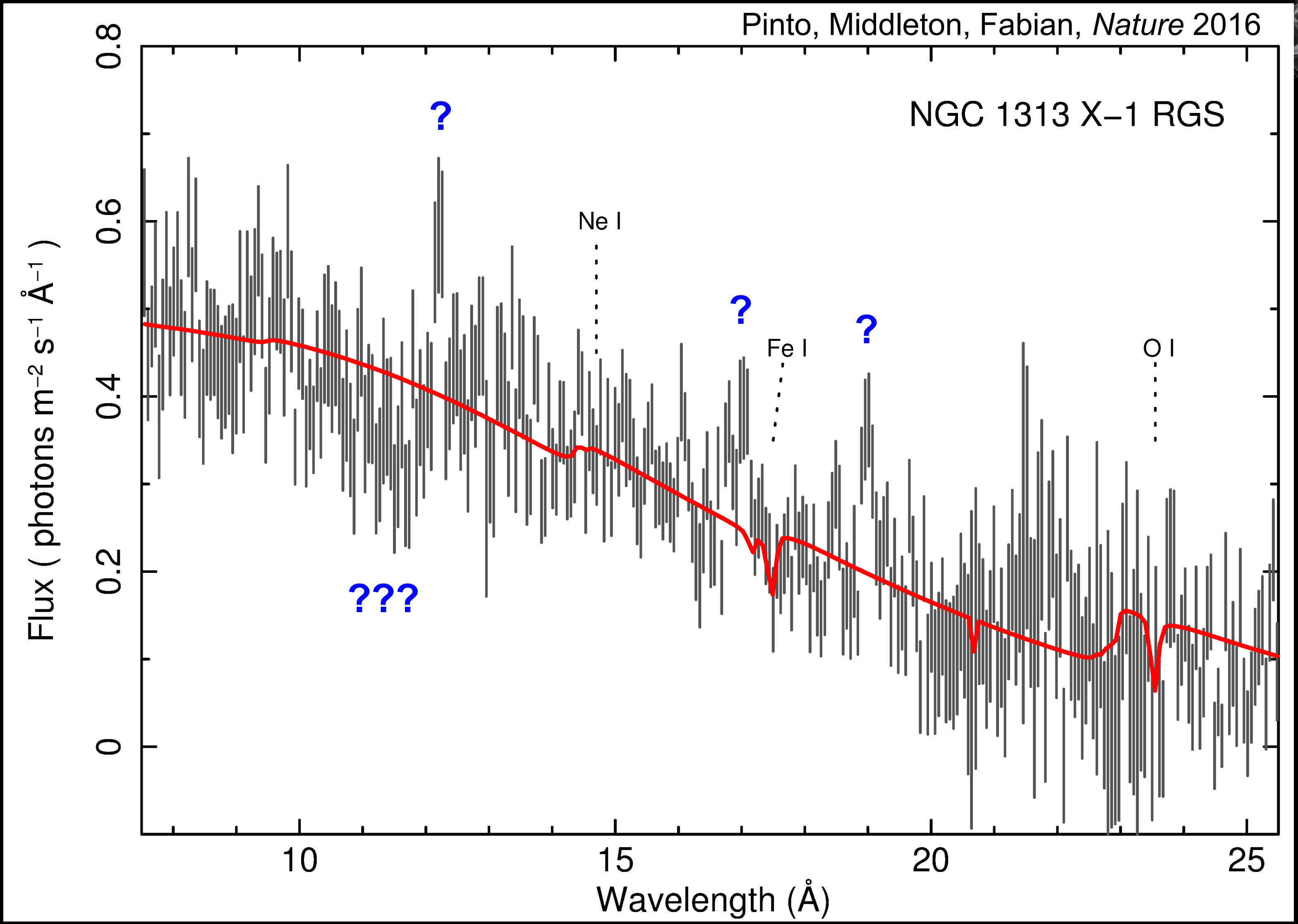
Early signals

Variable soft X-ray residuals in CCD spectra

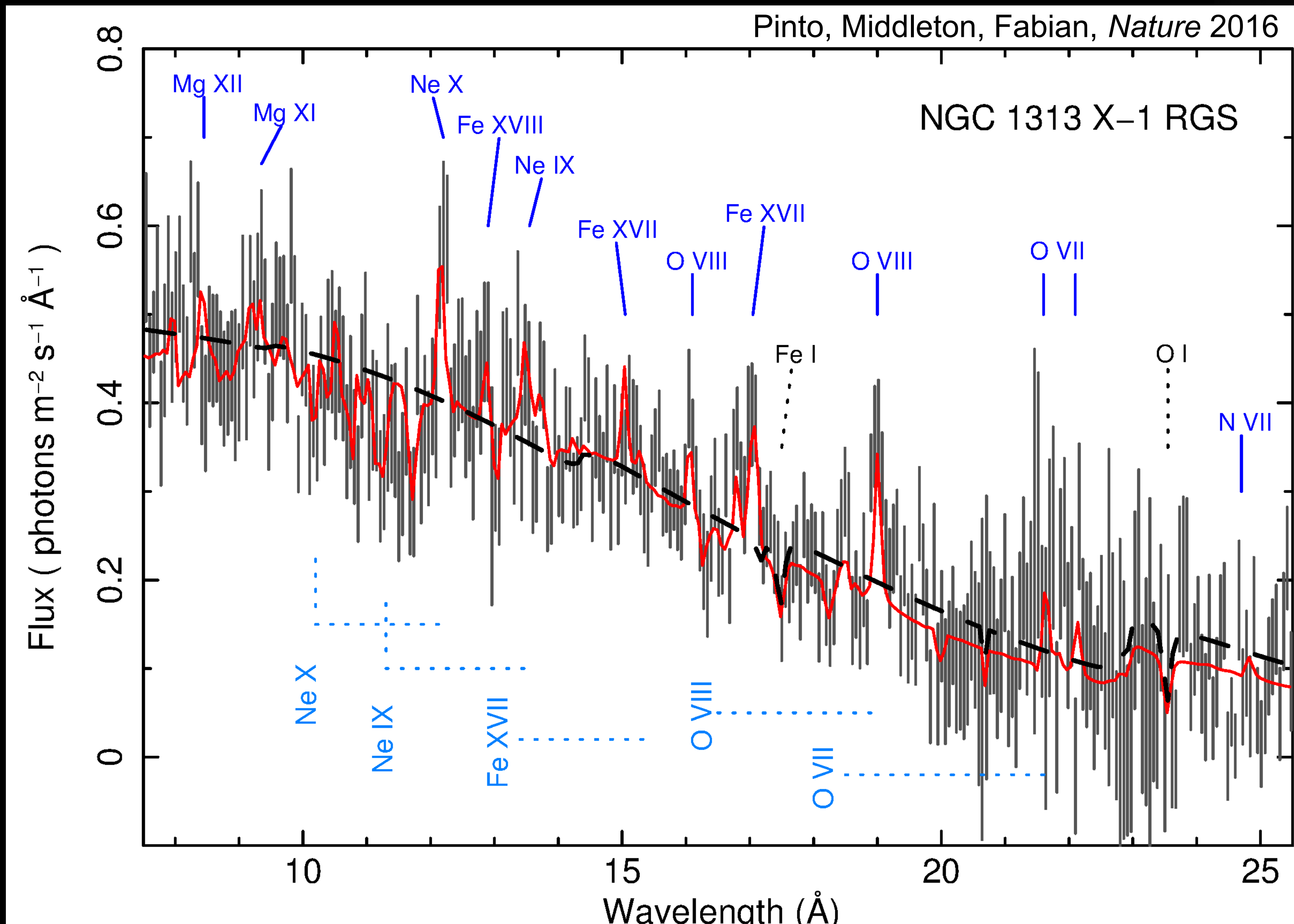


Soria+04 .... NGC 5408 X-1
Goad+06 .... Holmberg II X-1
Roberts+06 .... NGC 5204 X-1 (Chandra)
Stobbart+06 ...... Holmberg IX-II X-1
M 33 X-8, M 83 ULX
NGC 55 ULX
NGC 2403-3628-4395 X-1
NGC 1313 X-1,2
NGC 4559-4861-5204 X-1
Soria+07 .... NGC 1365 X-1, X-2
Gladstone09 ..... Same as Stobbart +
\+ IC 342 X-1, M 81 X-6
Bachetti+13 .... NGC 1313 X-1,2
Middleton+14 ..... NGC 6946-5408 X-1
Sutton+15 .... NGC 5408 X-1 (Chandra)

Smoking guns

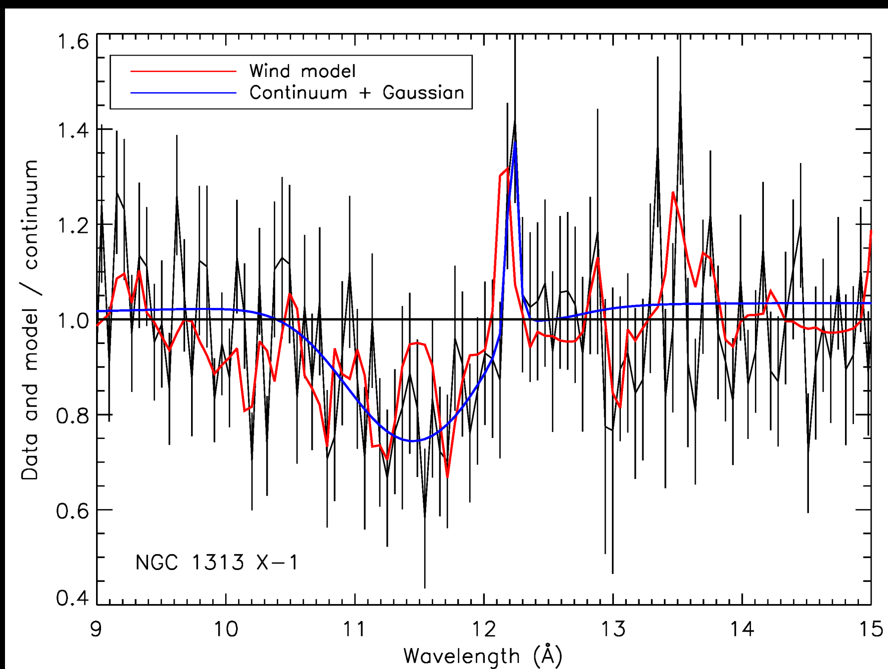


Smoking guns



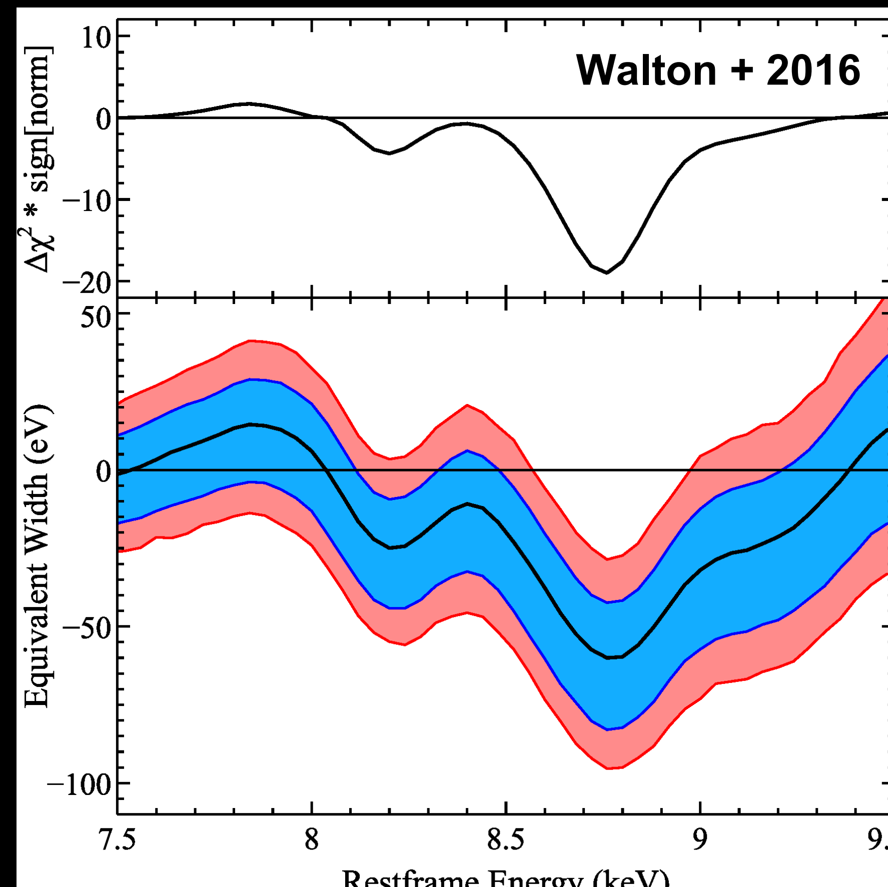
- Photoionised absorber with ~0.2c outflow velocity
- Collisionally-ionised emission at rest

NGC 1313 X-1 Fe K counterpart



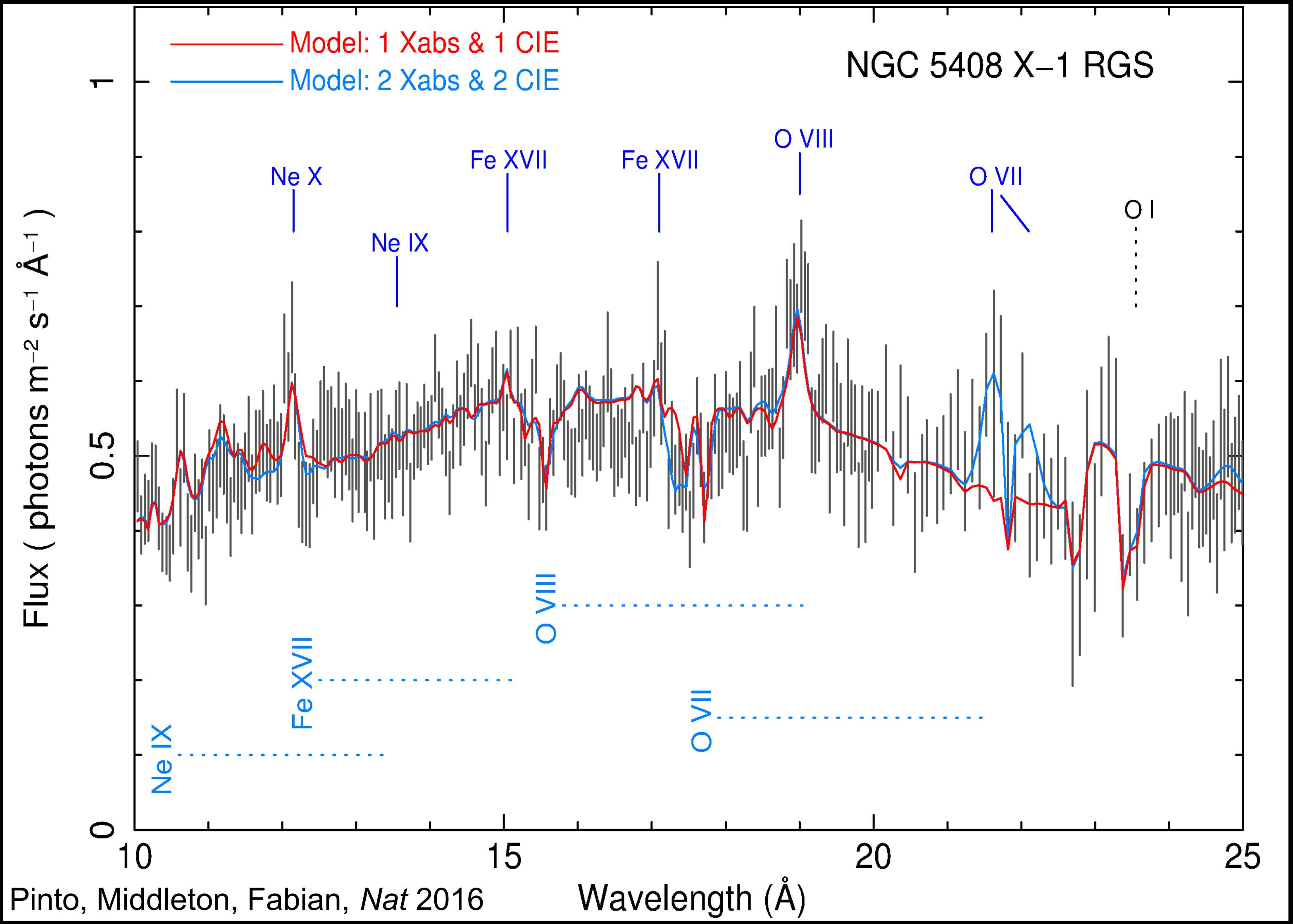
Adapted from Pinto+2016

XMM / RGS gratings



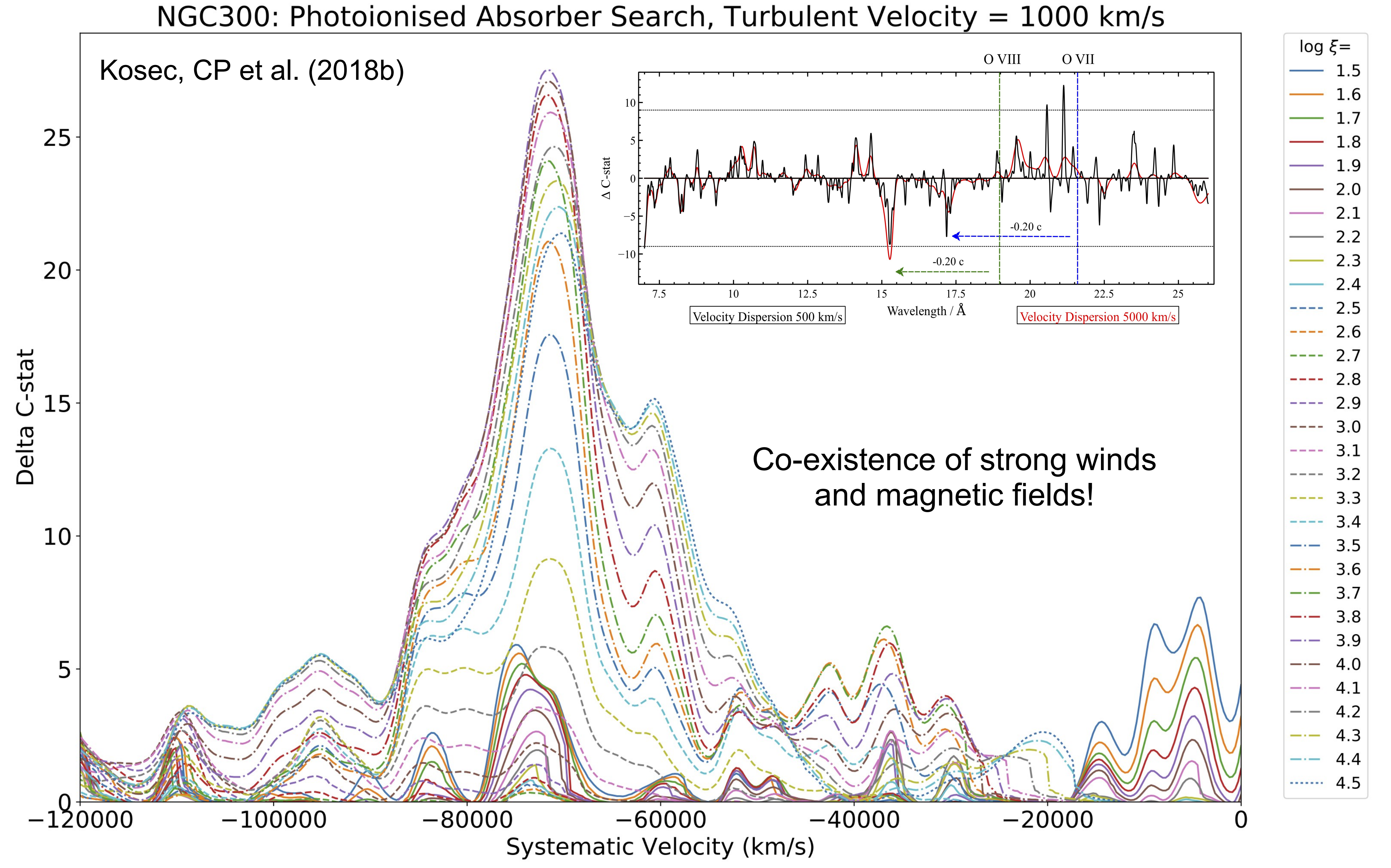
XMM CCD + NuSTAR

NGC 5408 X-1



- Photoionised absorber with ~0.2c outflow velocity
- Collisionally-ionised emission at rest

NGC 300 ULX pulsar



Co-existence of strong winds and magnetic fields!

How much energy is lost in launching the winds?
Do they require high Eddington fraction?
Are these winds actually powerful?

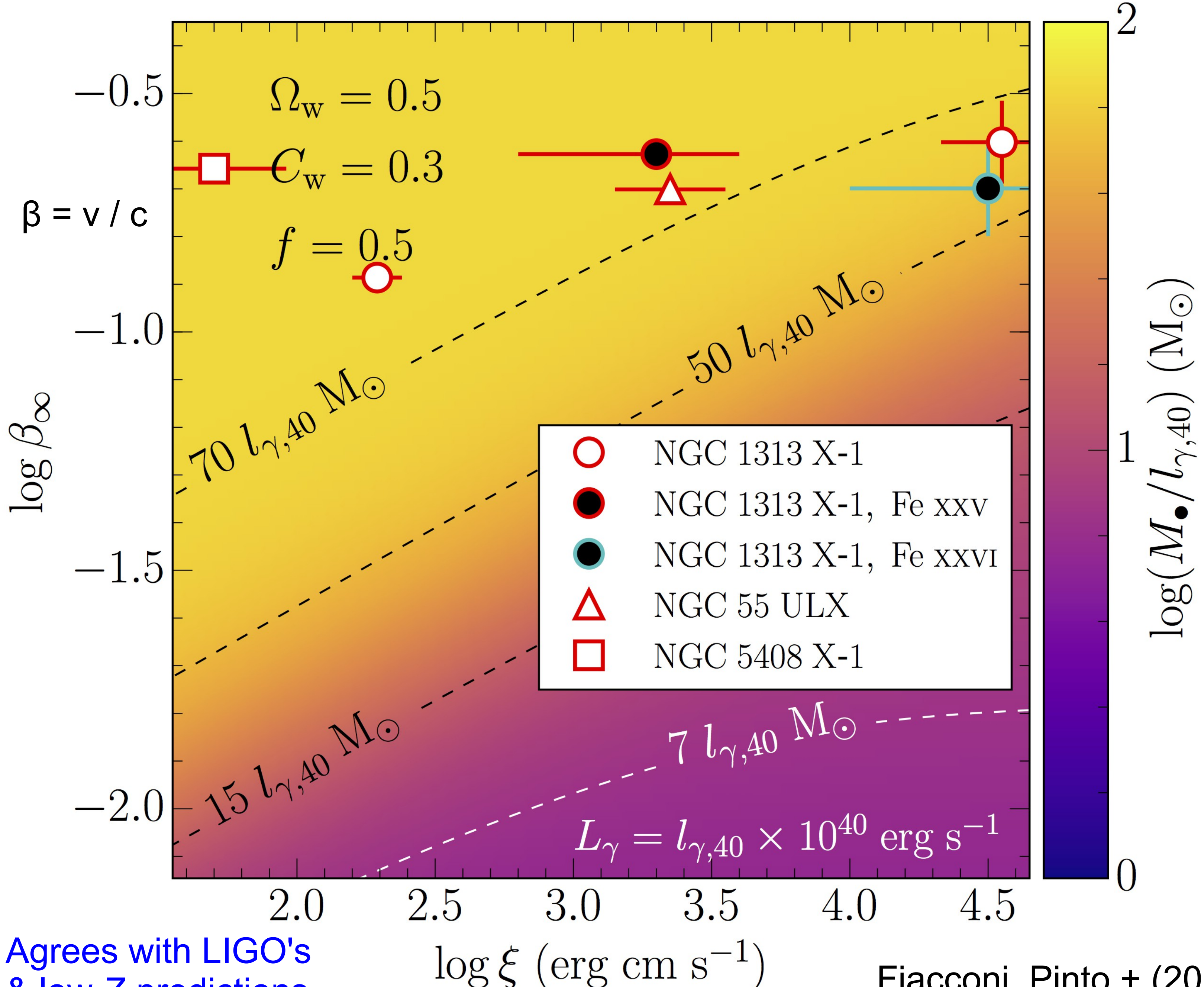
Key parameter : L_{wind} / L_{bol} (AGN normally ~0.05)

$$\approx (L_X / L_{bol}) \cdot (v_{out}^3 / \xi) \cdot \Omega C_V$$

$$\approx 10 - 1000 \, \Omega C_V \geq 1$$

~ 50% of the total budget

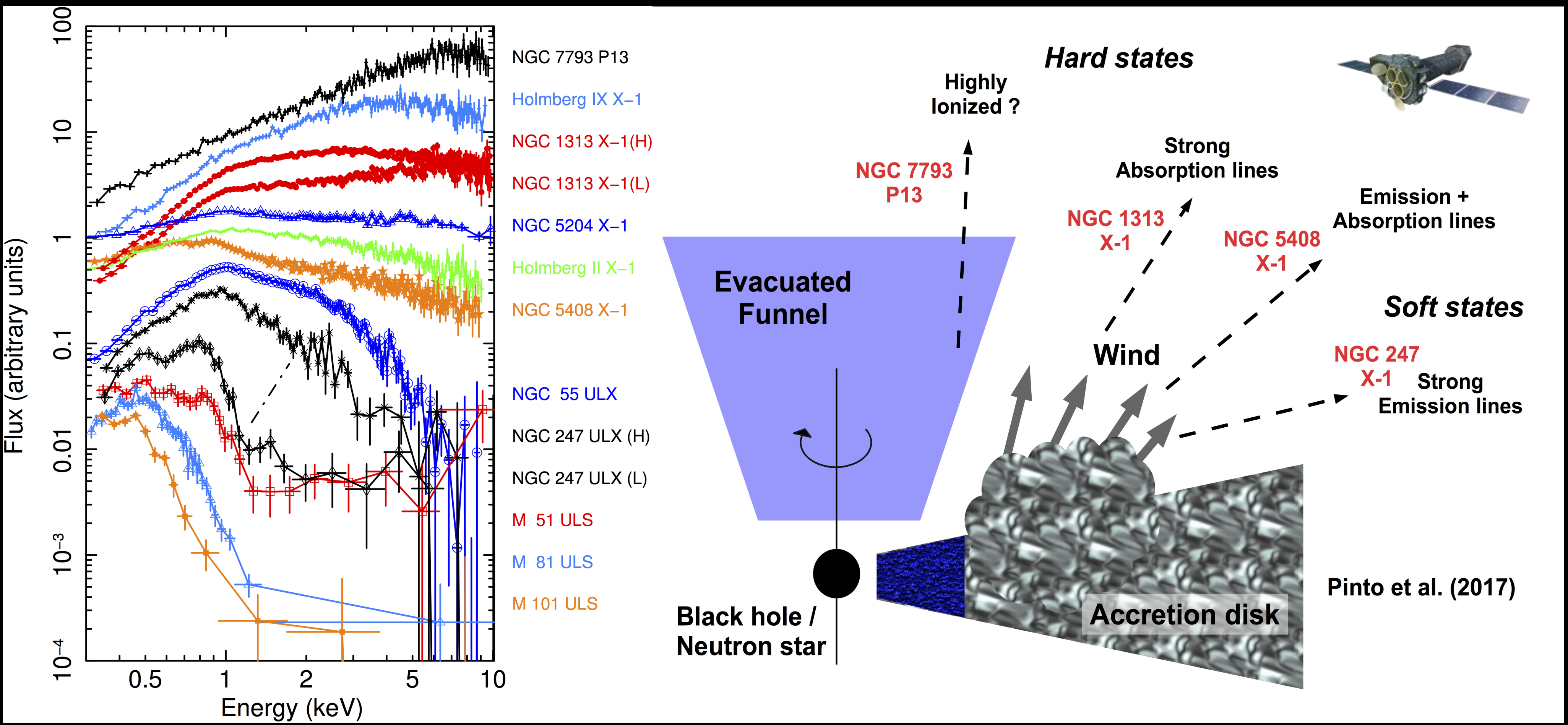
Weighing black holes



Agrees with LIGO's & low-Z predictions

Fiacconi, Pinto + (2017)

Towards a Unified Scenario



Take away message

Some ULXs exhibit pulsations and powerful, relativistic, winds likely driven by radiation pressure in super-Eddington accretion discs

Inclination and accretion rate are key parameters

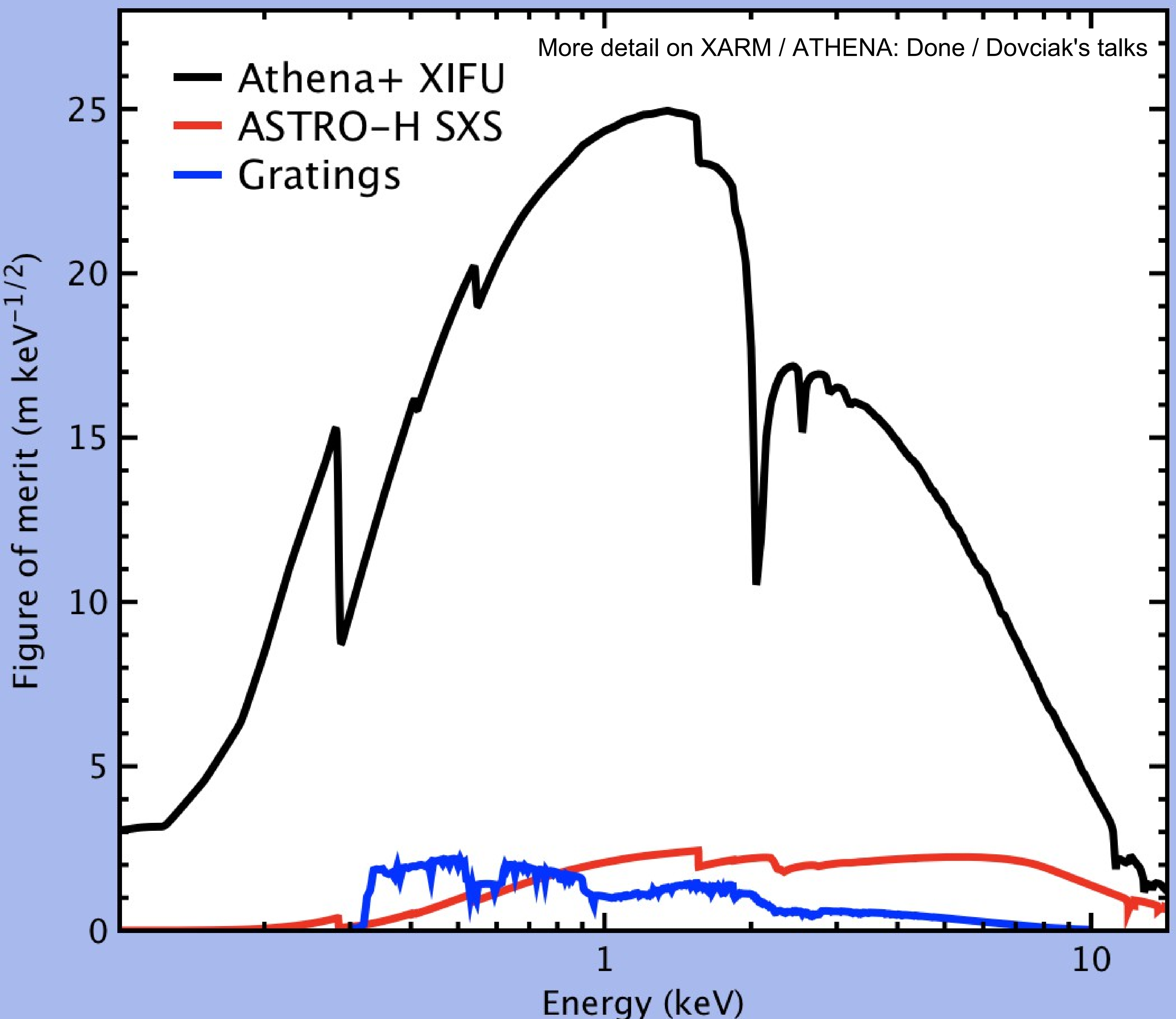
ULSs are likely ULXs seen at high inclination

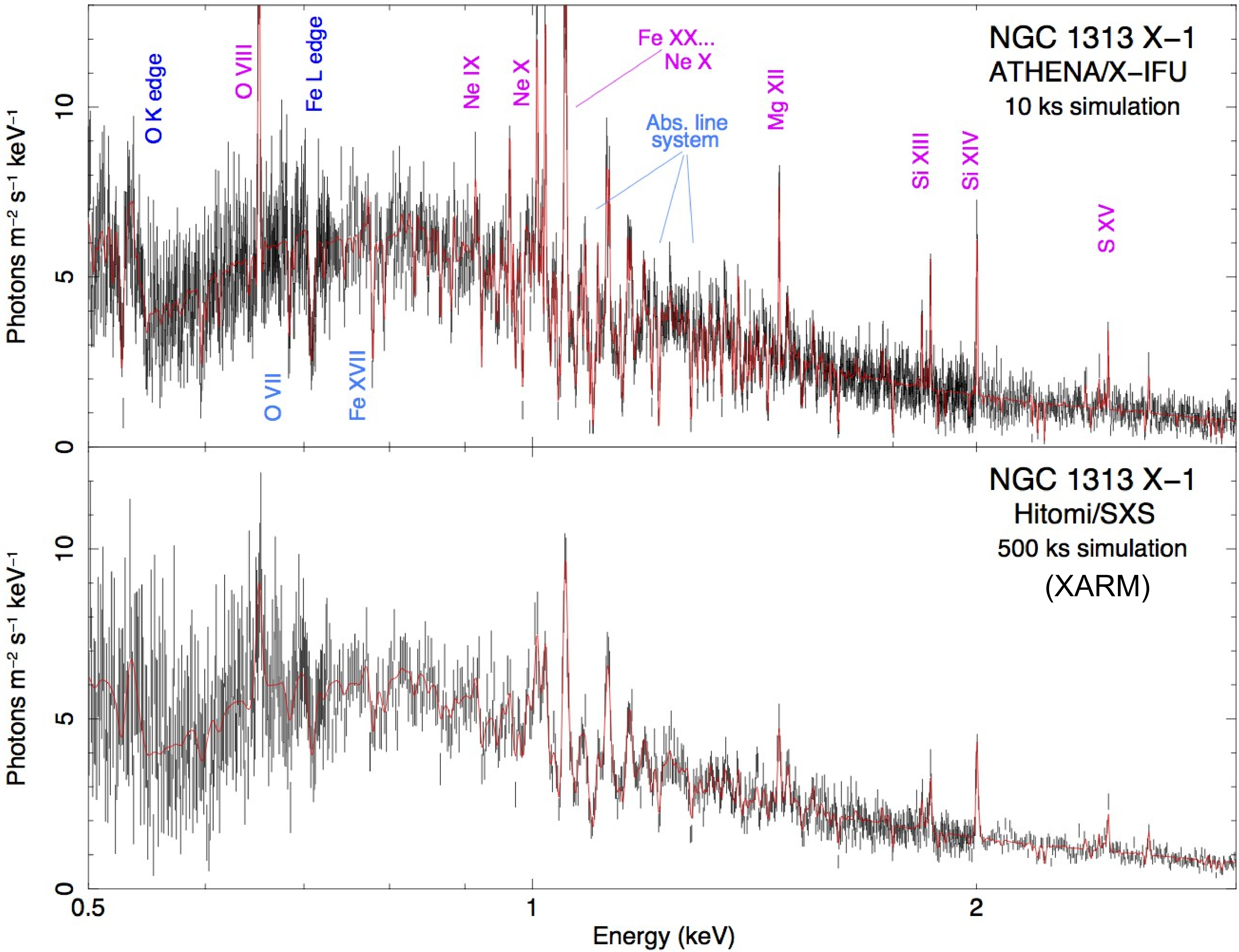
A few ULXs are IMBH candidates

Next steps

- Relation between jets and winds (like in XRB) ?
- Wind stability through ionisation balance ?
- Pulse-dependent behaviour of the wind ?
- New campaigns available, work in progress ...

  ... does the wind produce ULX state transitions ?
- A larger sample is needed (IMBH and SE candidates)
- Future *awesome* missions ...


More detail on XARM / ATHENA: Done / Dovciak's talks
Athena+ XIFU
ASTRO-H SXS
Gratings
Figure of merit (m keV$^{-1/2}$)
25
20
15
10
5
0
1
10
Energy (keV)



NGC 1313 X−1
ATHENA/X−IFU
10 ks simulation
O K edge
O VIII
Fe L edge
Ne IX
Ne X
Fe XX...
Ne X
Abs. line system
Mg XII
Si XIII
Si XIV
S XV
O VII
Fe XVII
NGC 1313 X−1
Hitomi/SXS
500 ks simulation
(XARM)
Photons m⁻² s⁻¹ keV⁻¹
Energy (keV)
0
5
10
0.5
1
2

Of course, Theseus gets Minotaur in the end.

Enjoy your time in Crete, it's a beautiful island !!!