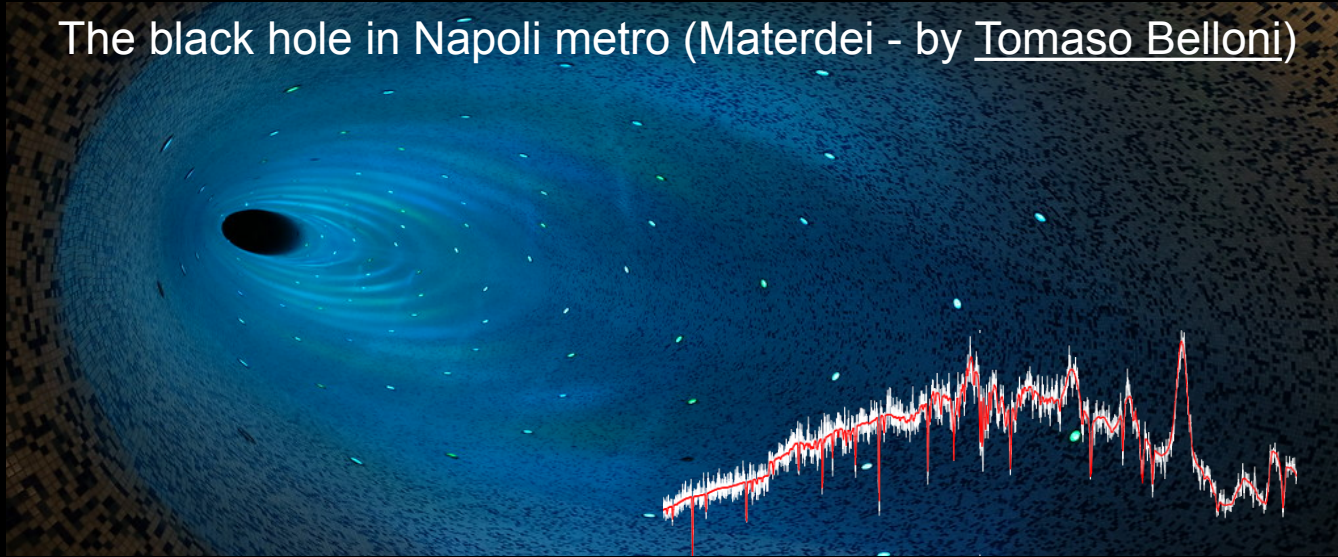


The enchanted kingdom of ultraluminous X-ray sources

The black hole in Napoli metro (Materdei - by Tomaso Belloni)



Ciro Pinto



IASF

Istituto di Astrofisica Spaziale
e Fisica cosmica

Palermo

F. Barra, S. Caserta, N. Kumari, S. Banerjee,
P. Kosec, DJ Walton, and many more



Finanziato
dall'Unione europea
NextGenerationEU



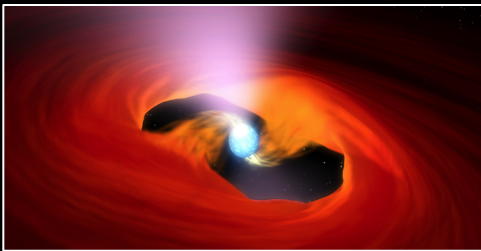
Ministero
dell'Università
e della Ricerca



Italiadomani
PIANO NAZIONALE
DI RIPRESA E RESILIENZA



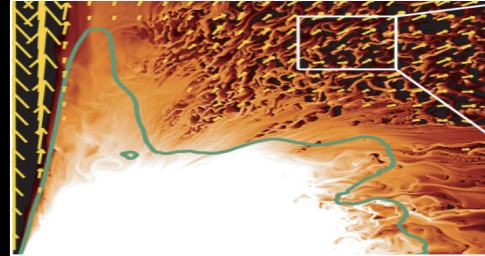
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FOR ASTROPHYSICS



1



2



- **Accretion**

→ X-ray broadband spectral-timing

- **Outflows**

→ X-ray high-resolution spectroscopy

- **Environ**

→ Multi-Wavelength data (briefly)

- **Lookahead**

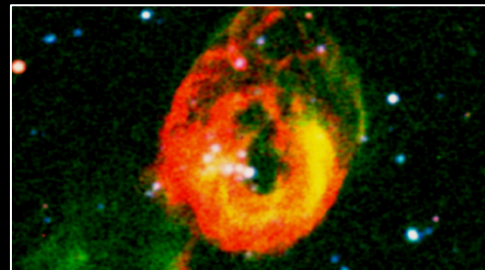
→ Future X-ray missions (briefly)



4

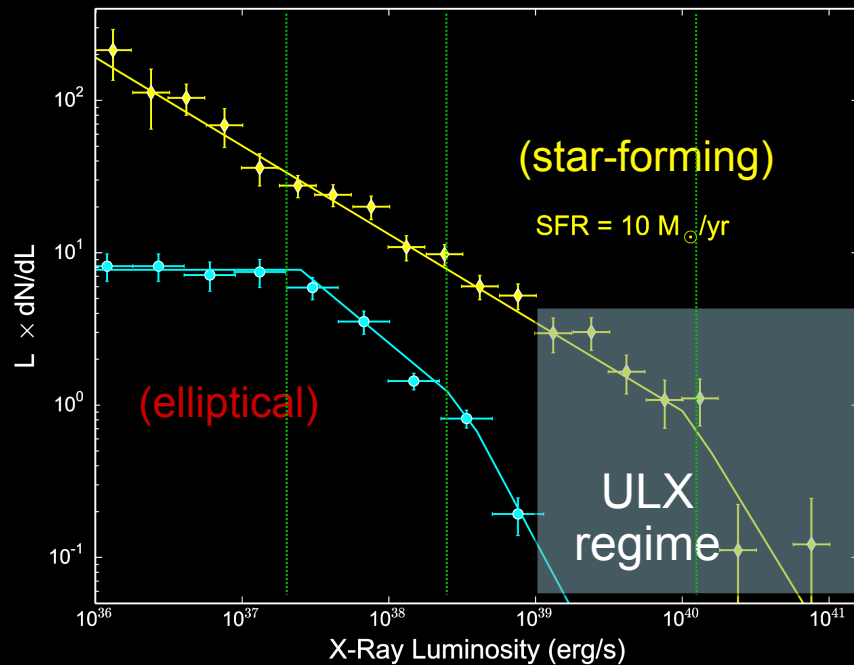
Happy to discuss!

3



Ultra-Luminous X-ray sources (ULXs)

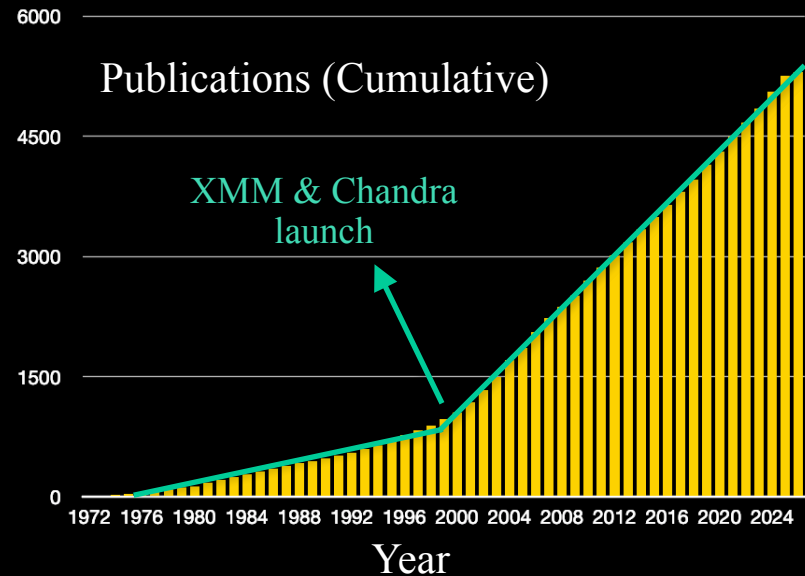
Brighter than a $10 M_{\odot}$ black hole accreting @ Eddington limit
 $L_X > 10^{39} \text{ erg s}^{-1}$ and off-nuclear



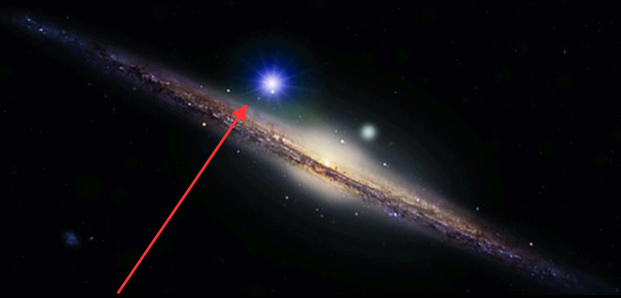
High Mass or High $\dot{M}$?

$Z \downarrow$ $M_{\text{BH}} \uparrow$ $\%_{\text{BH}} \uparrow$ $N_{\text{ULX}} \uparrow$

→ see also talks by
Wolter & Luangtip



The quest for intermediate-mass black holes ($10^{2-5} M_{\odot}$)



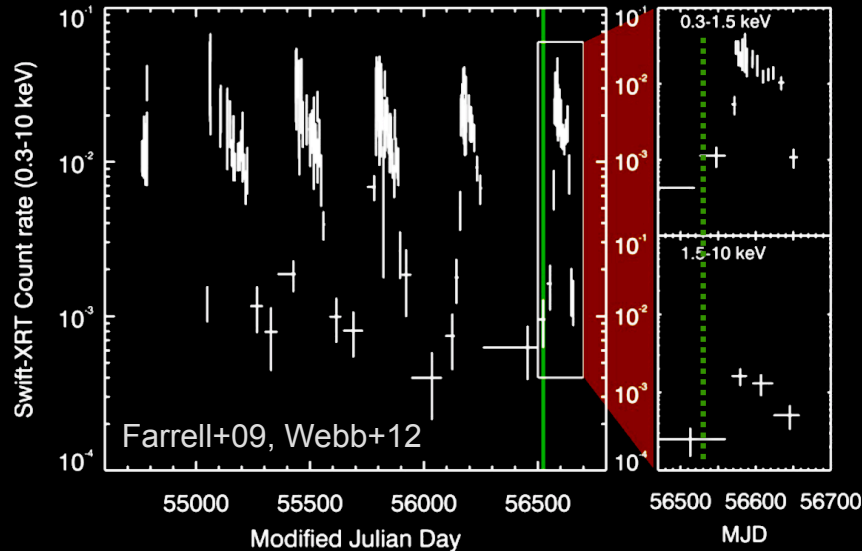
HLX-1 in ESO 243-39

Disk-like temperatures of $\sim 0.1\text{-}0.2$ keV

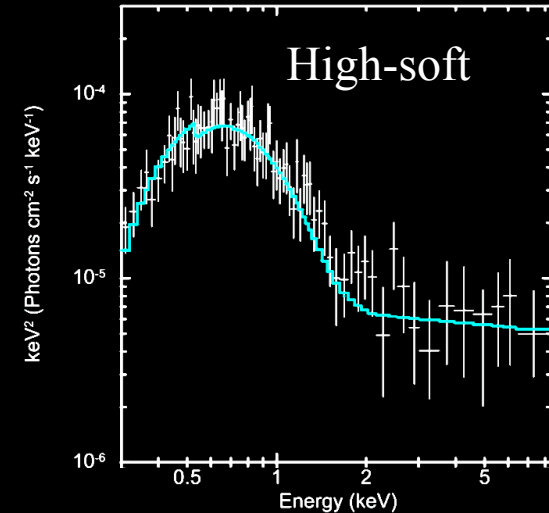
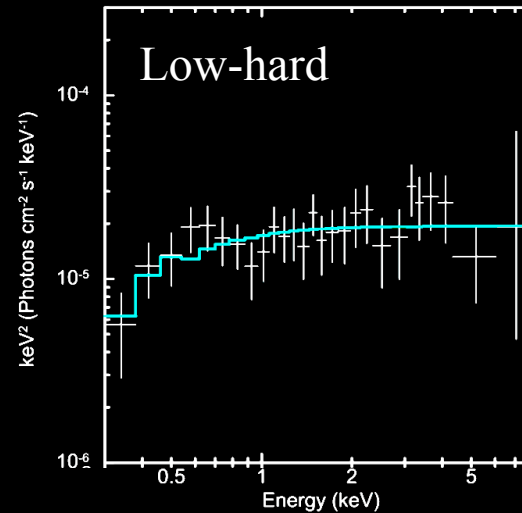
→ Would imply masses $\sim 10^4\text{-}5 M_{\odot}$

→ Very low $\dot{M}$ and hard spectra

... very rare in ULXs



A tidal peeling event in a stripped dwarf galaxy



Spectra + light curves $\Rightarrow$ a few $10^4 M_{\odot}$ (e.g. Soria+17)

Very massive with low $\dot{M}$ vs Stellar-mass with high $\dot{M}$?

X-ray astronomy 2009 Bologna

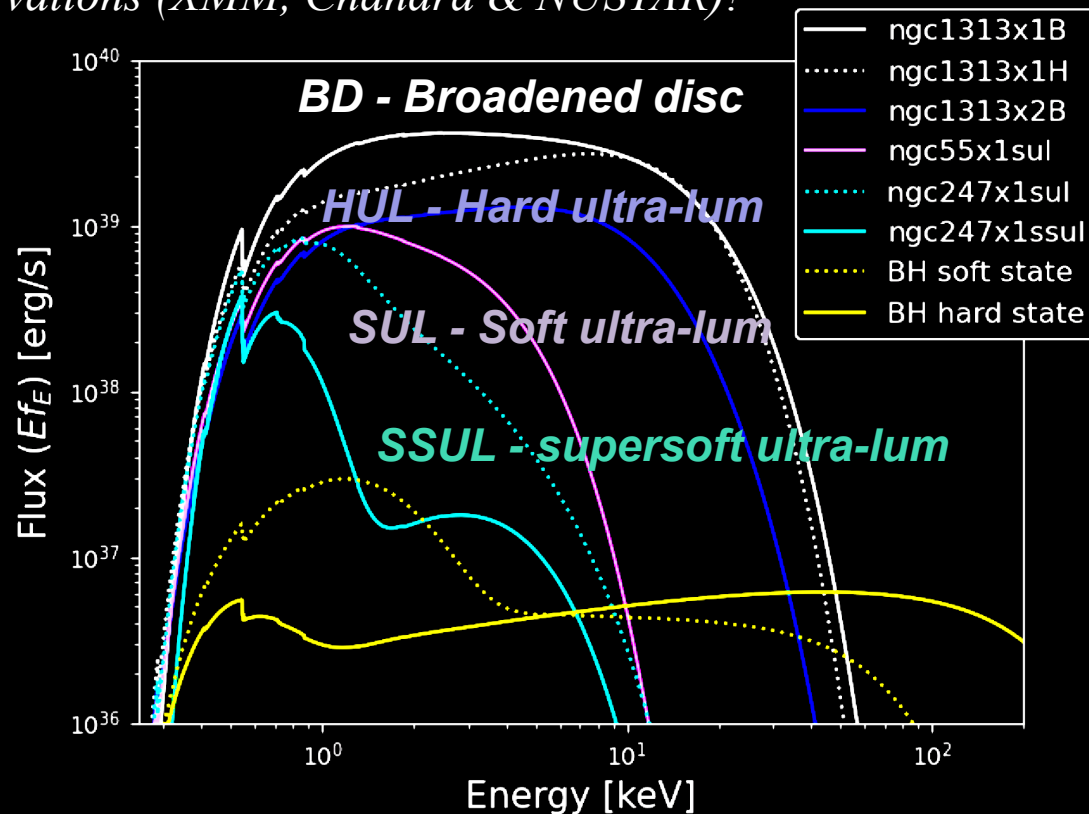
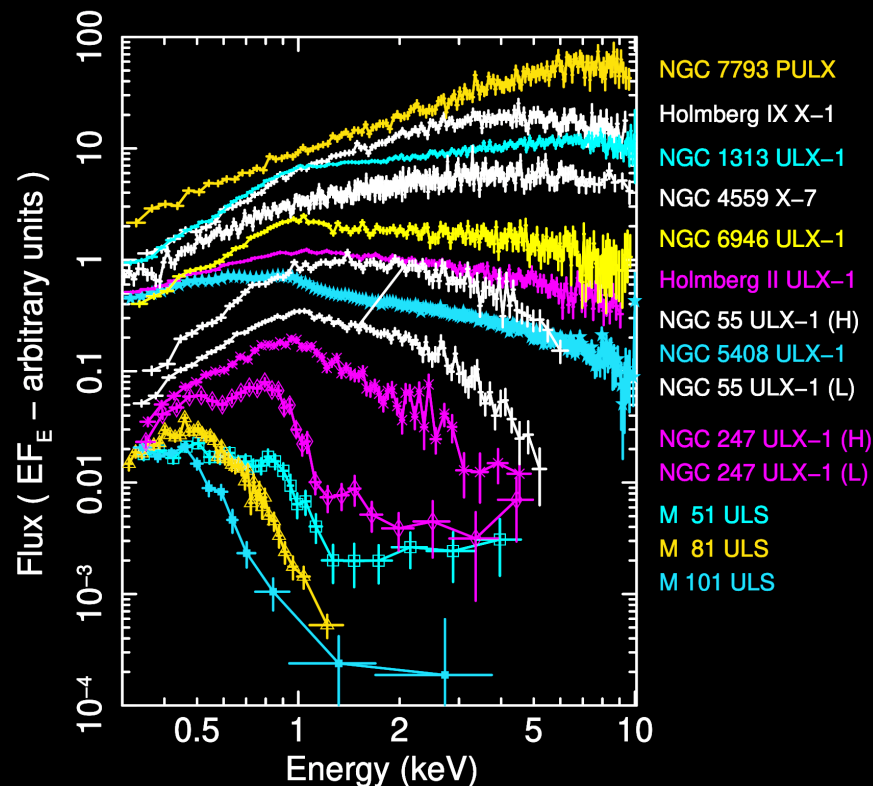


Belloni+2010 (actually 2009)

Longer & extended campaigns with sensitive instruments such as XMM-Newton & Chandra are needed [...] both new observation of fainter systems & repeated observations of bright ones ...

ULX vs Galactic XRB states

Thanks (indeed) to repeated & deep X-ray observations (XMM, Chandra & NUSTAR)!

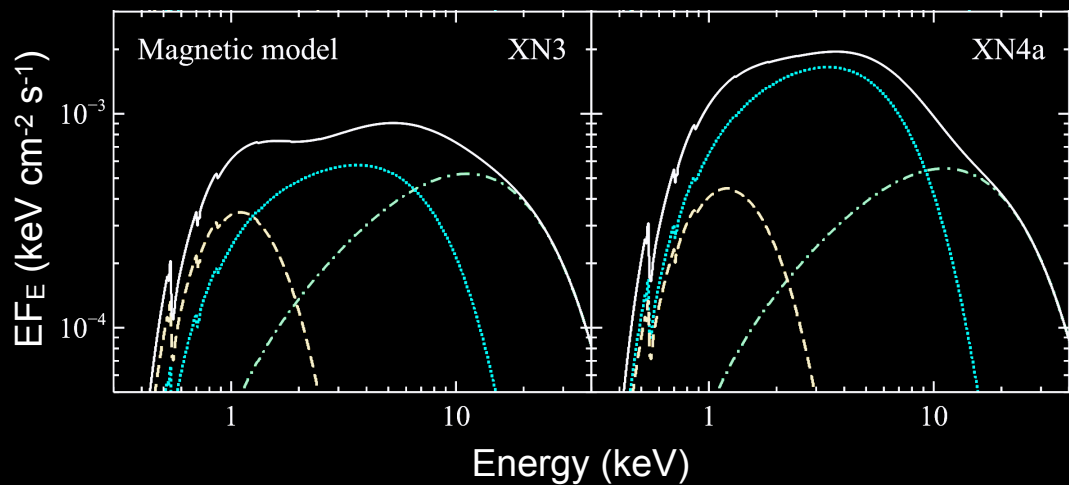
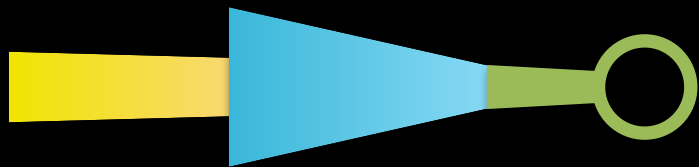


Pinto & Walton (review, 2023)
See also Sutton+2013 (*the ultraluminous state*)

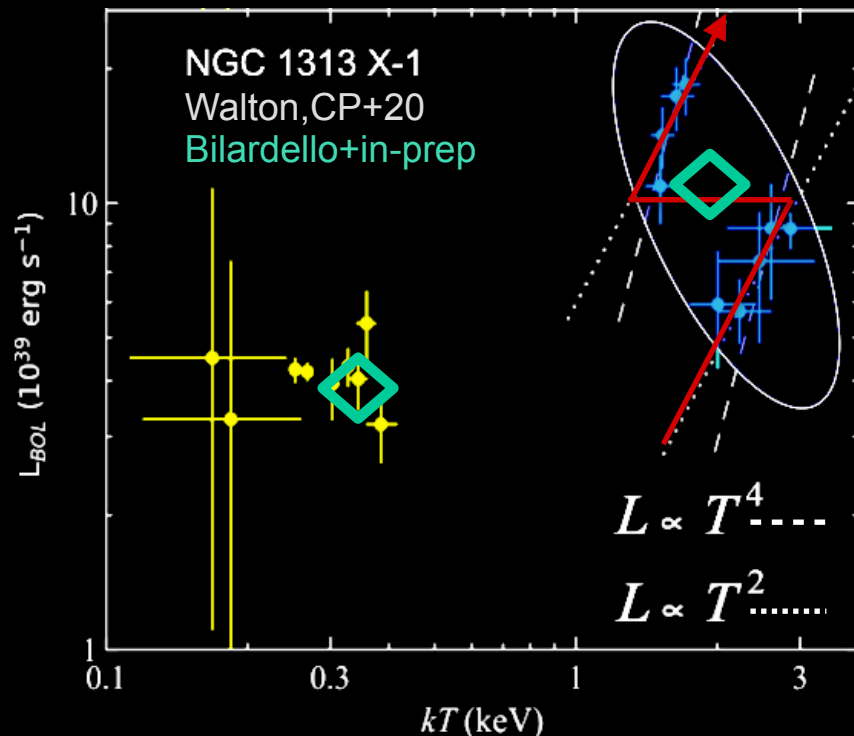
Much softer than Galactic XRB spectra ...

ULX spectral components

1. Cool (0.1-0.5 keV) blackbody
2. Hot (1-5 keV) broader disc BB
3. Hard (> 7 keV) powerlaw tail

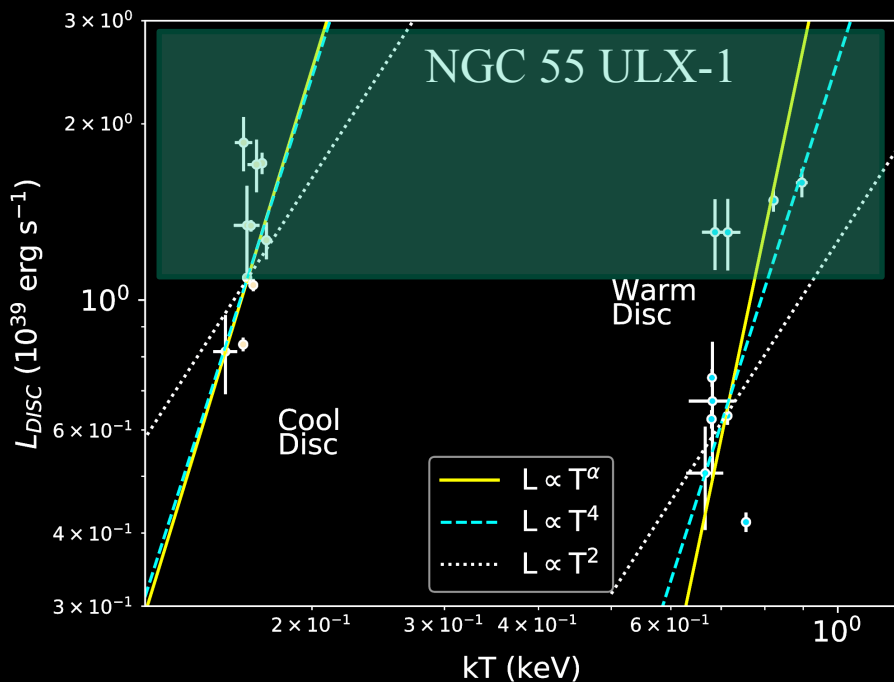


Luminosity – Temperature deviates from
Shakura – Sunyaev thin disc: $L \neq T_{in}^4$



A weird variability

1. Cool (0.1-0.5 keV) blackbody
2. Hot (1-5 keV) broader disc BB
3. Hard (> 7 keV) powerlaw tail



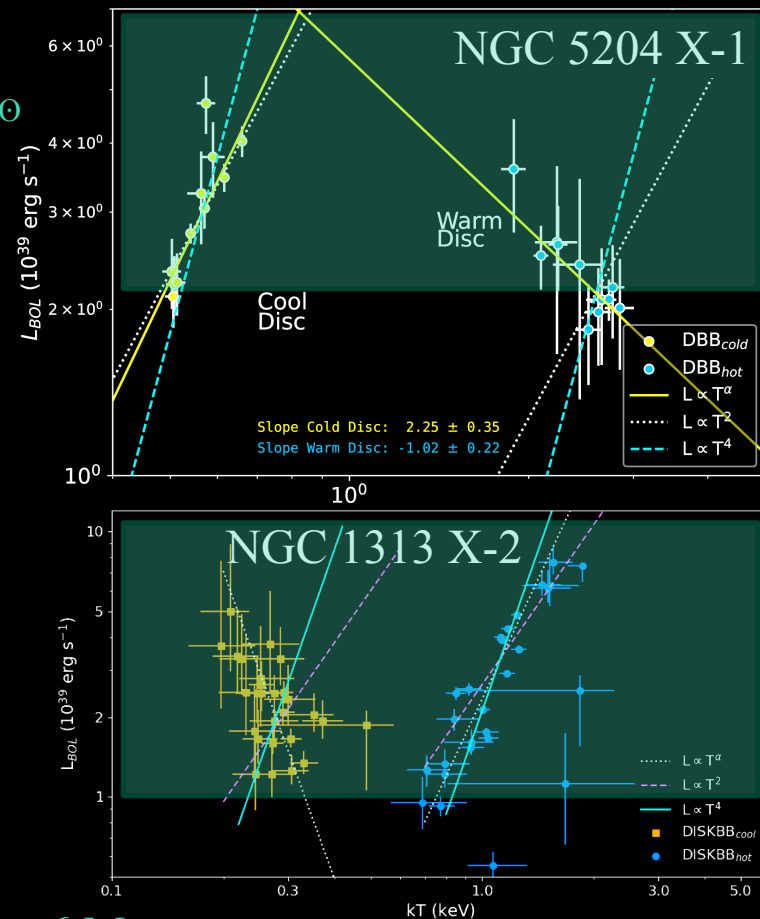
Barra,CP+2022-2025

$M \approx 11 M_\odot$

$M \approx 6 M_\odot$

If $\dot{M} \approx \dot{M}_{\text{cr}}$
 $\sim 9/4 \dot{M}_{\text{Edd}}$

Luminosity – Temperature deviates from
 Shakura – Sunyaev thin disc: $L \neq T_{\text{in}}^4$



$M < 6 M_\odot$

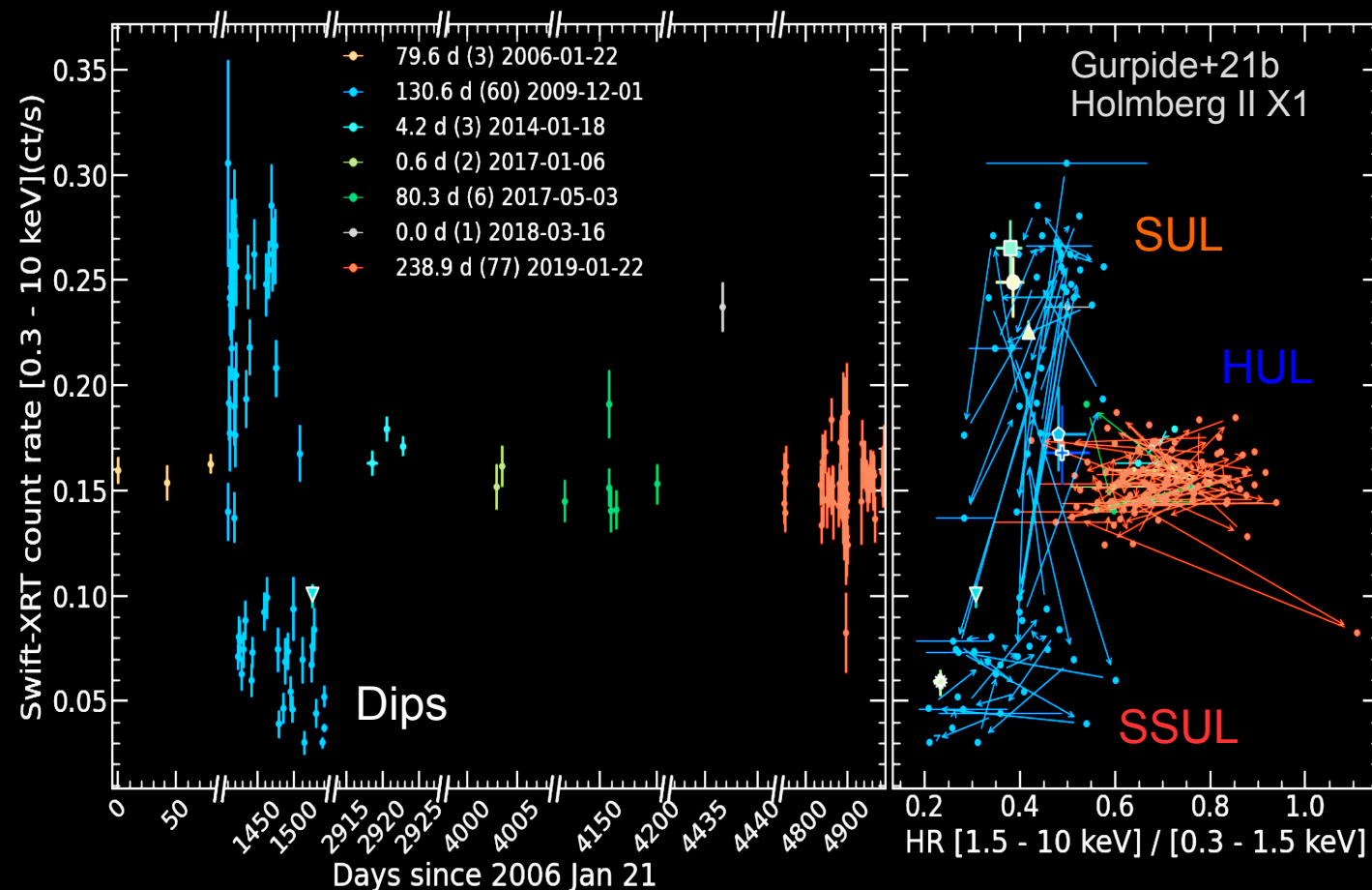
Robba,CP+2021

Spectral transitions: long timescales ($\sim$ days)

HUL $\leftrightarrow$ SUL $\leftrightarrow$ SSUL

More variable when brighter

HUL to SUL on $\sim$ days

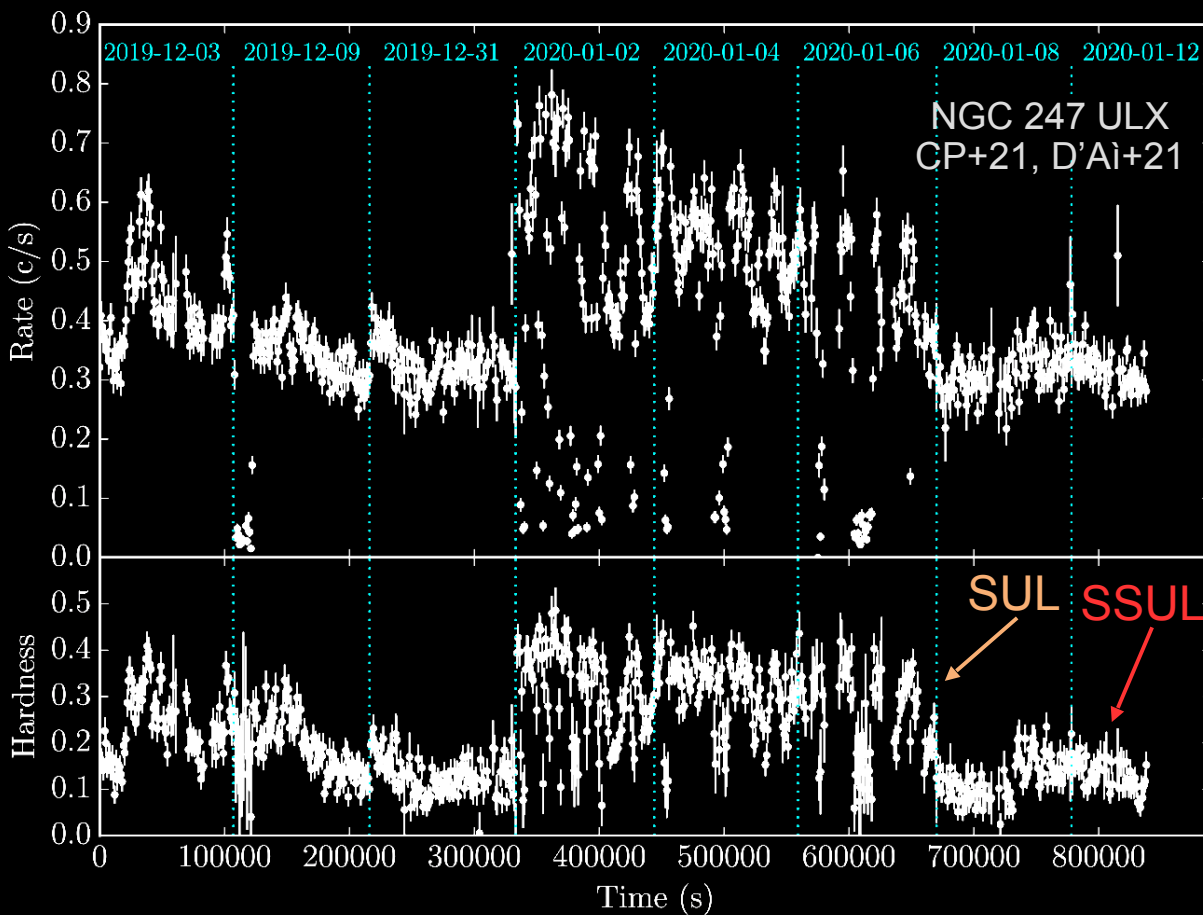


Spectral transitions: short timescales ($\sim$ hours)

HUL $\leftrightarrow$ SUL $\leftrightarrow$ SSUL

More variable when brighter

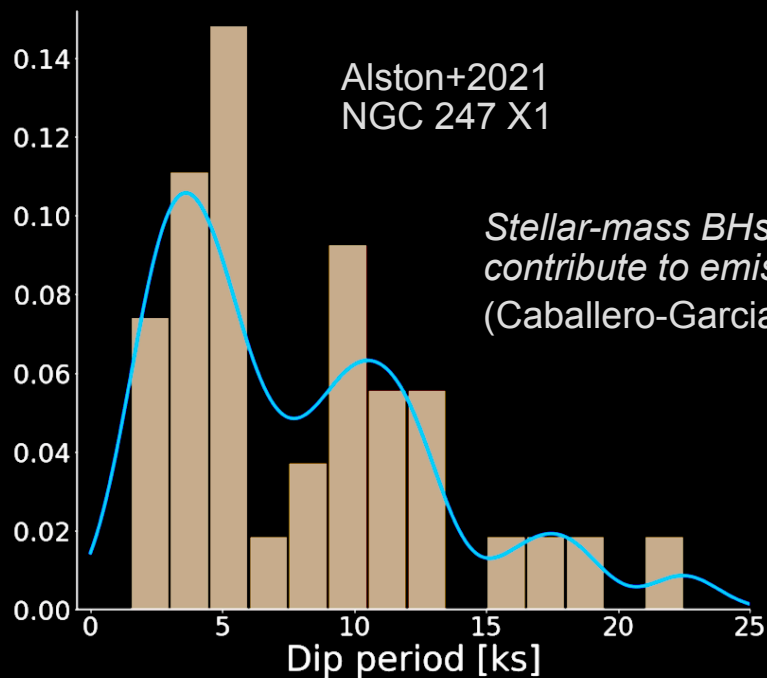
SUL to SSUL on $\sim 0.1 - 15$ ks



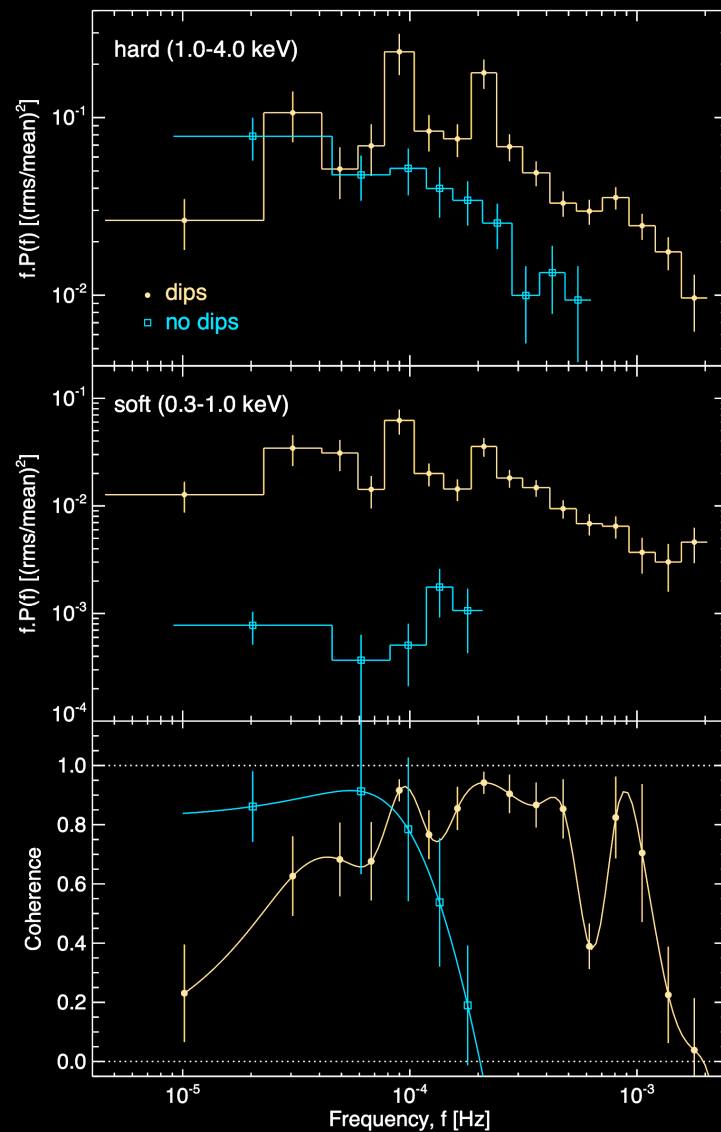
Quasi-periodic oscillations

Soft Dips are associated with timescales of 2 – 15 ks

→ $R \sim 10^{4-5} R_G \sim 50-500 R_{\text{phot}}$ → Clumps in the LOS?



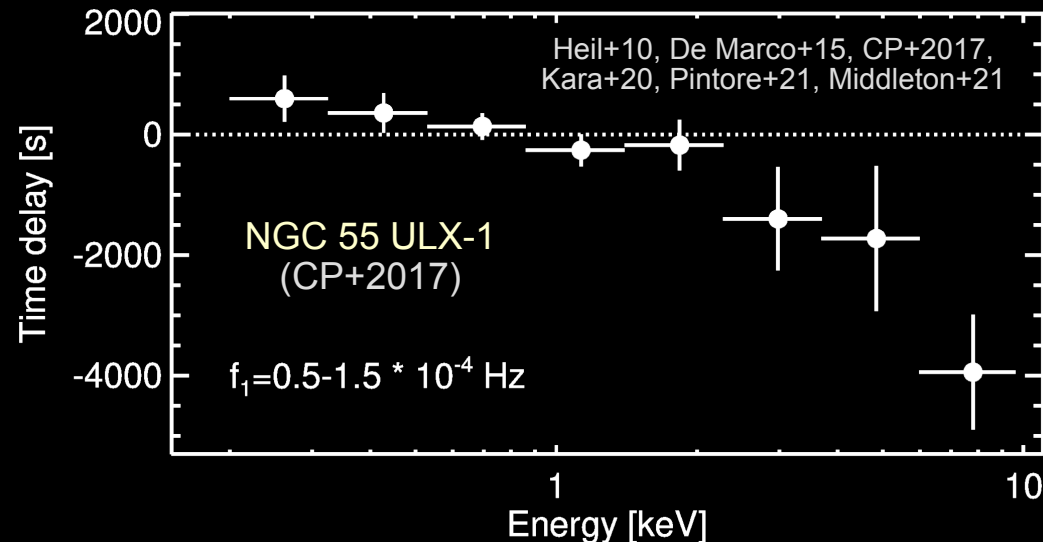
Stellar-mass BHs with winds that contribute to emission and RMS?
(Caballero-Garcia, Belloni+2013)



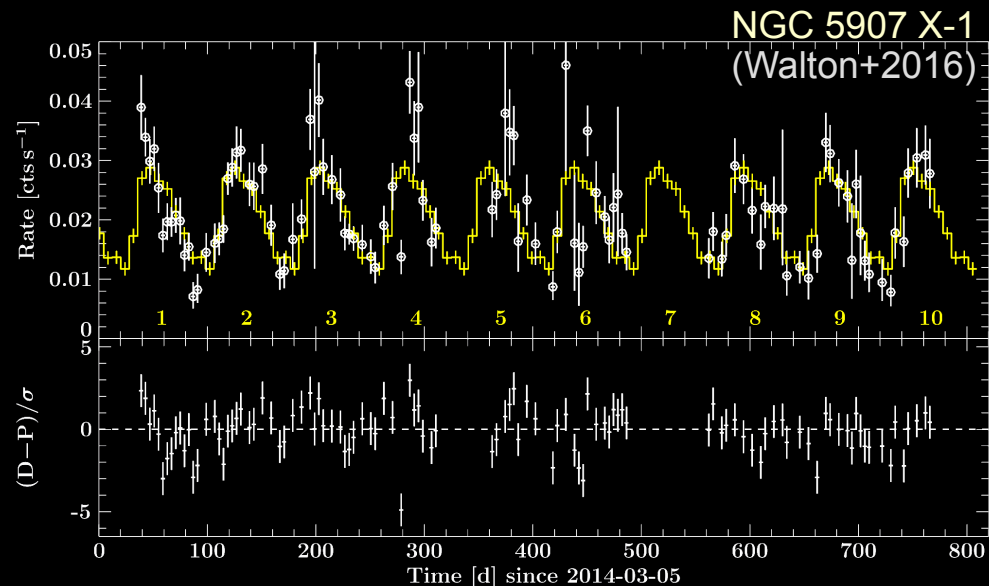
Short-term vs Long-term variability

- QPOs (mHz-Hz) as early IMBH indicators ⚠
- Huge soft-energy time lags (up to > 1 ks)
- multiple scattering in outer thick disc / wind?

→ more on lags: talks by W. Leone

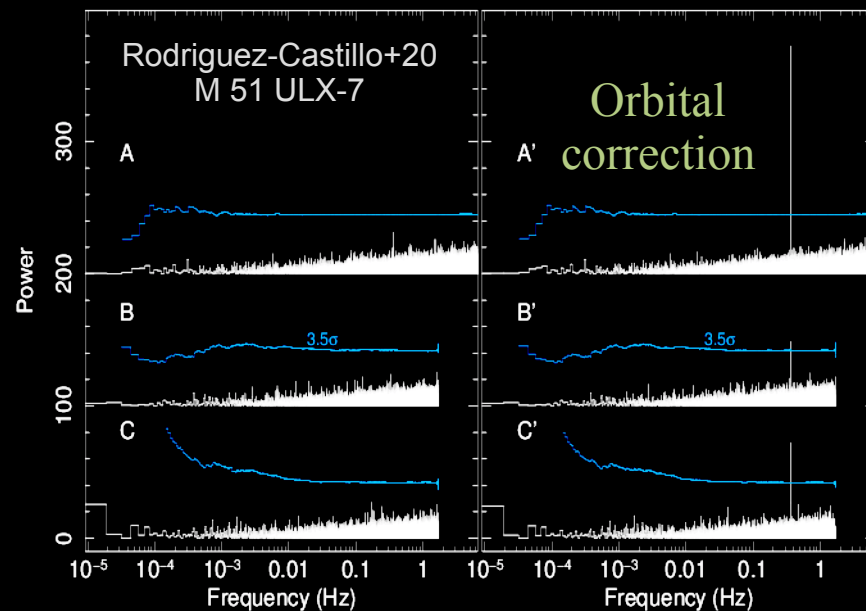
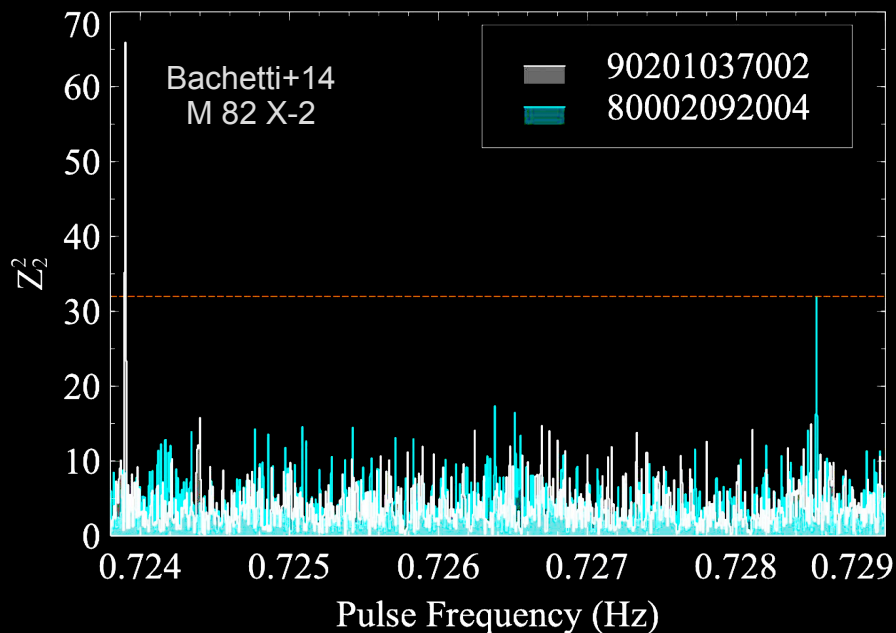
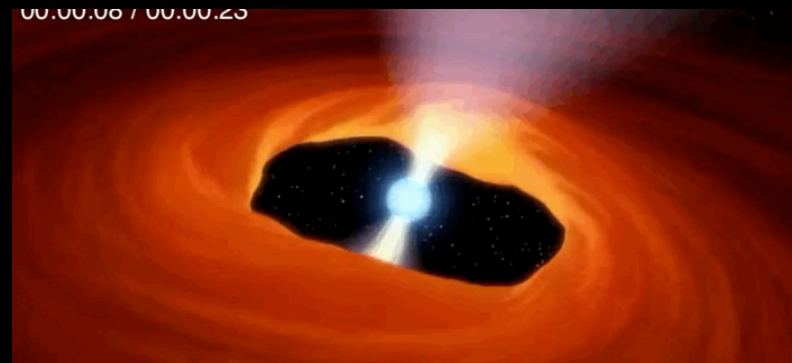


- Long-term quasi-periodicities
- (Weeks to months)
- variable $\dot{M}$, propeller? precession?



Pulsations on $\delta t \sim$ seconds $\rightarrow$ neutron stars!

- NGC 5907 pULX-1 $\sim 10^{41}$ erg/s $\sim$ 500 $\times$ L_{Edd}
- Magnetic fields $\rightarrow 10^{10-14}$ G (dipole vs multipole)
- Pulsations in 20-25% of ULXs *high quality data!*



12 NS-ULX candidates (including transients)

Also show QPOs! (Imbrogno+24, Caballero & Belloni+13, Bu & Belloni+17)

King + 2023

ULX	P_{pulse} (s)	Spin up rate (ss^{-1}) (baseline)	Pulse fraction (E range)	P_{orb}	$P_{\text{s-orb}}$ (d)	L_{max} ($\times 10^{39} \text{ erg s}^{-1}$)	M_2 ($M_{\odot}$)
M82 X-2 ^{a,b,c}	1.4	1×10^{-11} (2.5 years)	5%–13% (3–30 keV) 8%–23% (10–30 keV)	2.5	~60	20	≥ 5.2
NGC 5907 ULX-1 ^{d,e}	1.1	-8×10^{-10} (11 years)	12% (0.2–2.5 keV) 20% (7–30 keV)	5.3	78	200	?
NGC 7793 P13 ^{f,g,h}	0.4	4×10^{-11} (4 years)	18%–22% (0.1–12 keV)	64	64	~10	18–23 (B9I)
NGC 300 ULX-1 ^{i,j}	31.6	-6×10^{-7} (3.6 days)	~60% (0.2–10 keV) ~70% (3–20 keV)	>290	?	5	8–10 (RSB?)
SMC X-3 ^{k,l,m,n}	7.8	$\sim 4 \times 10^{-9}$ (110 days)	30%–100% (3–70 keV)	~45	?	~3	>3.7 (Be?)
M51 ULX-7 ^{o,p}	2.8	-1×10^{-9} (13 years)	<5%–20% (0.1–12 keV)	2	38	~10	>8
NGC 1313 X-2 ^q	1.5	1.2×10^{-12} (98 days)	~5% (0.3–10 keV)	<4	?	20	?
NGC 2403 ULX ^r	18	3.4×10^{-10} (?)	?	60–100	?	1.2	Be?
Swift J0243.6+6124 ^s	9.86	2.2×10^{-10} (?)	?	28.3	?	≥ 1.5	Be?
RXJ0209.6-7427 ^t	9.3	1.165×10^{-10} (?)	?	> 50	?	1–2	Be
M51 ULX-8 ^u	?	?	?	8–400	?	2	40(?)
NGC 1313 PULX ^v	765.6	?	38% (0.3–7 keV)	?	?	1.6	Be?

high!

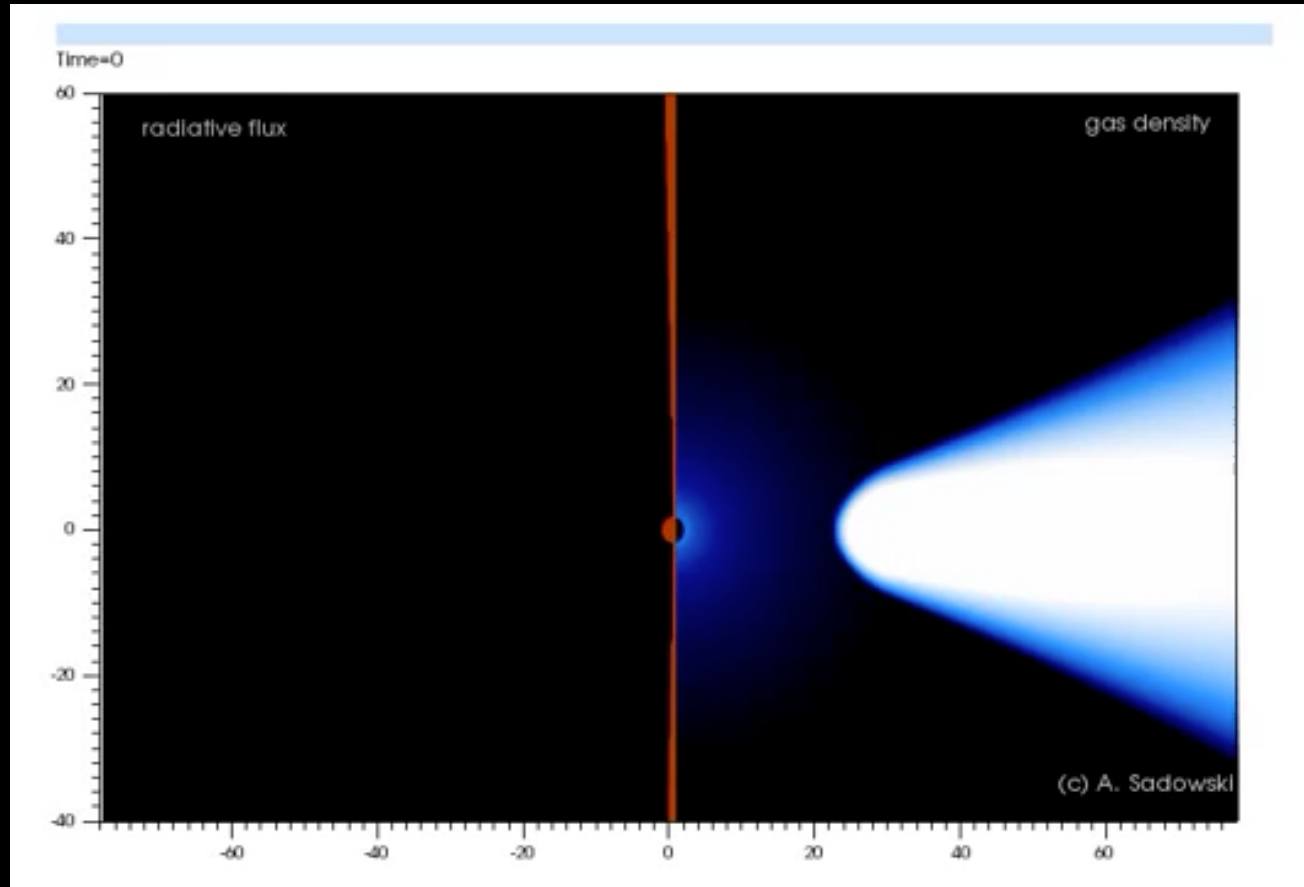
→ more on pulsations by A. Knight, M. Bachetti & S. Mereghetti

Further candidates to be confirmed:

NGC 7793 ULX-4 (Quintin + 2021), NGC 2403 XMM 4 (Luangtip & Roberts 2024), M 81 X-6 (Amato+23), Atapin+23 ...

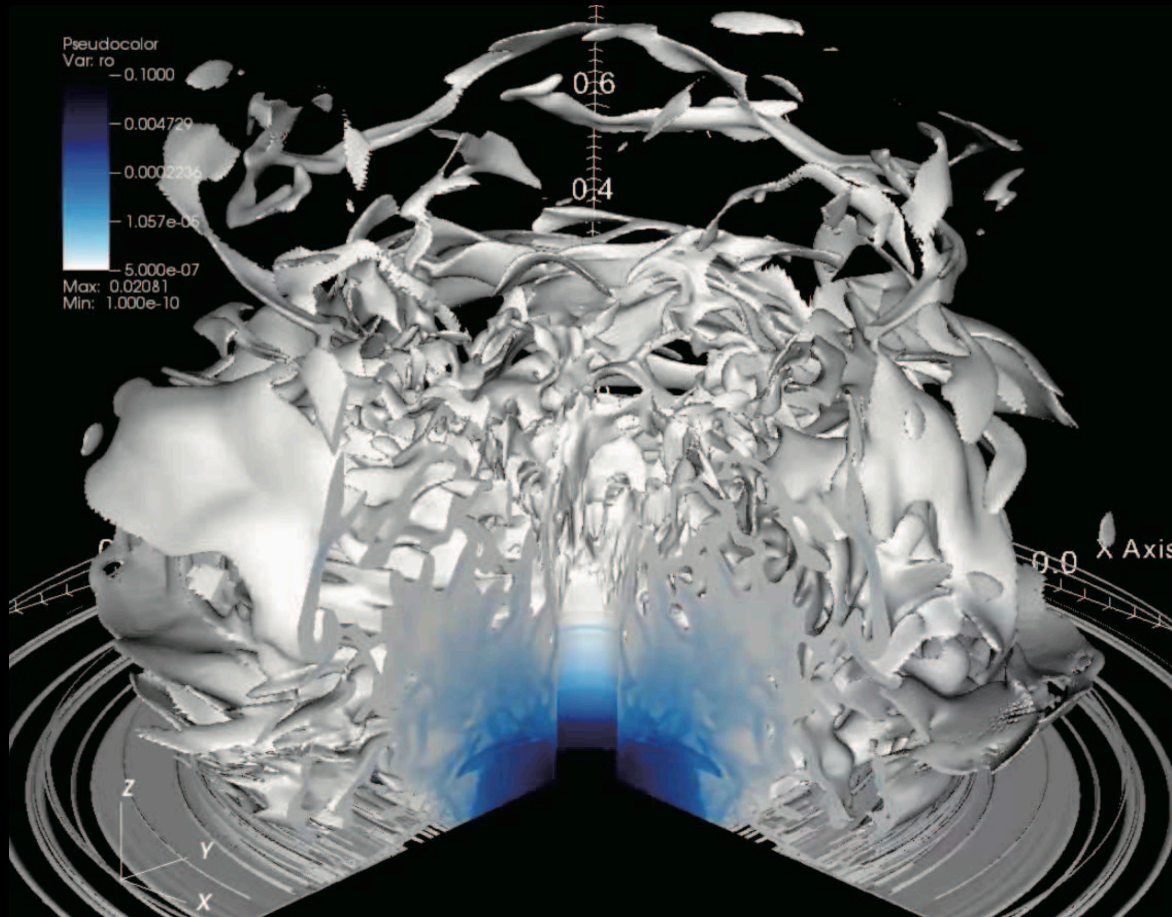
Super-Eddington accretion disc & winds

The radiation pressure inflates the disc and launches a wind : **funnel geometry**



Super-Eddington accretion disc & winds

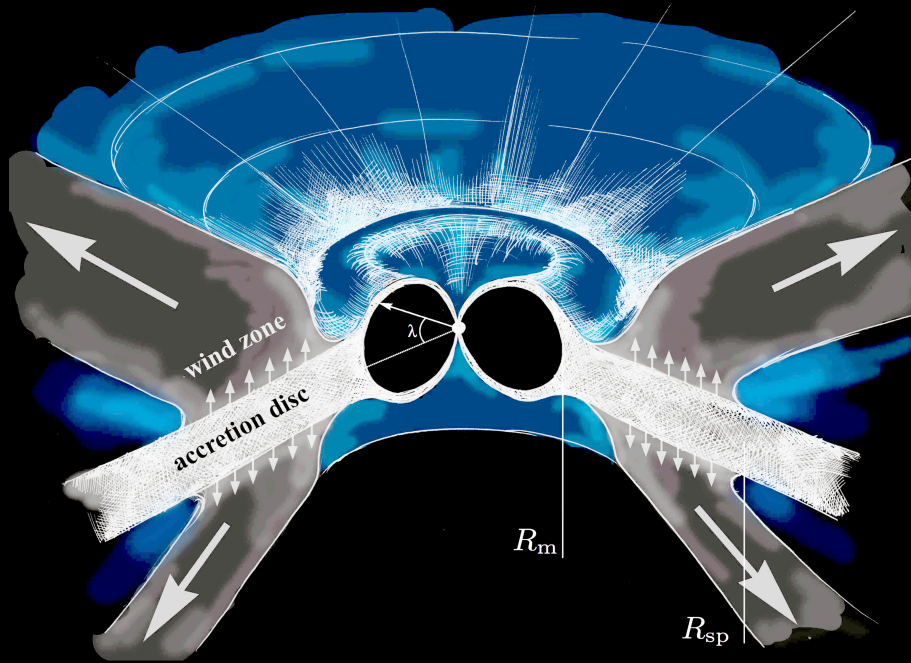
The radiation pressure inflates the disc and launches a wind : **funnel geometry**



See also
Poutanen+2007

Kobayashi+18
(K. Ohsuga)

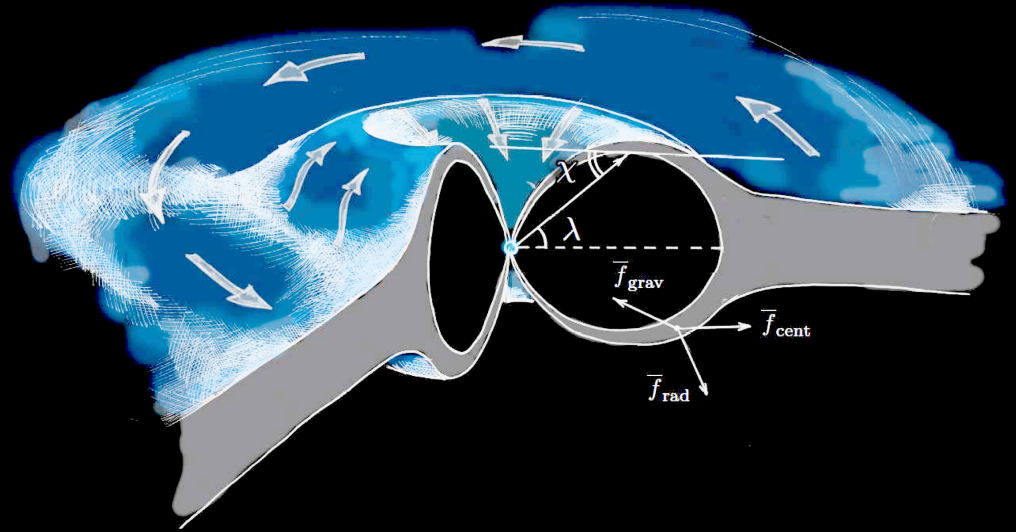
Intermediate vs Strong (dipolar) magnetic fields



$B \approx 10^{13} \text{ G}$

Strong winds

Mushtukov+17-19

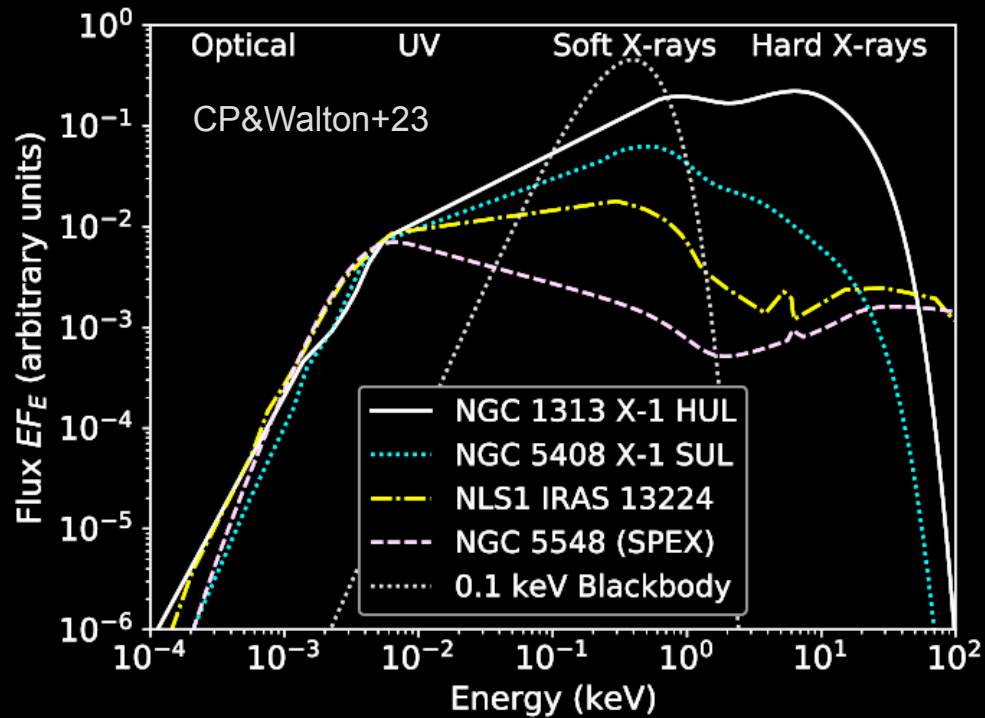


$B \geq 10^{14} \text{ G}$

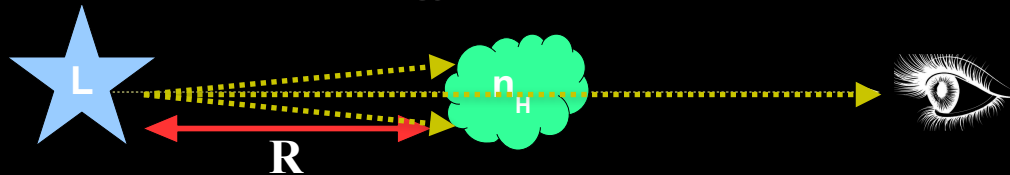
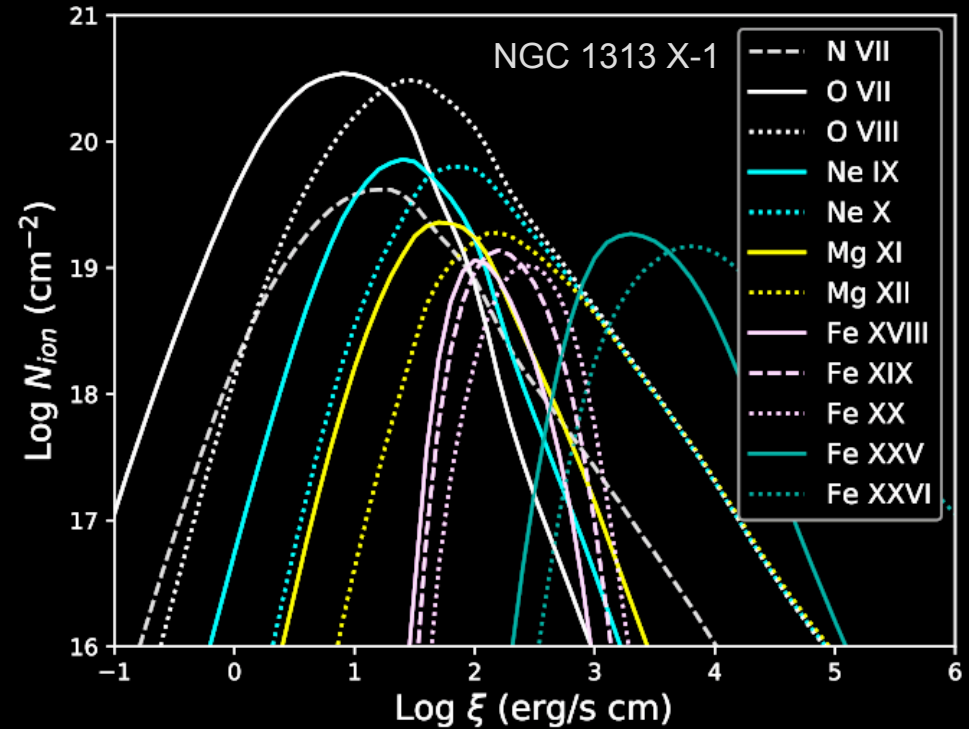
Weak winds

What lines should we expect to find?

Spectral energy distribution



Ionic columns vs ionisation parameter

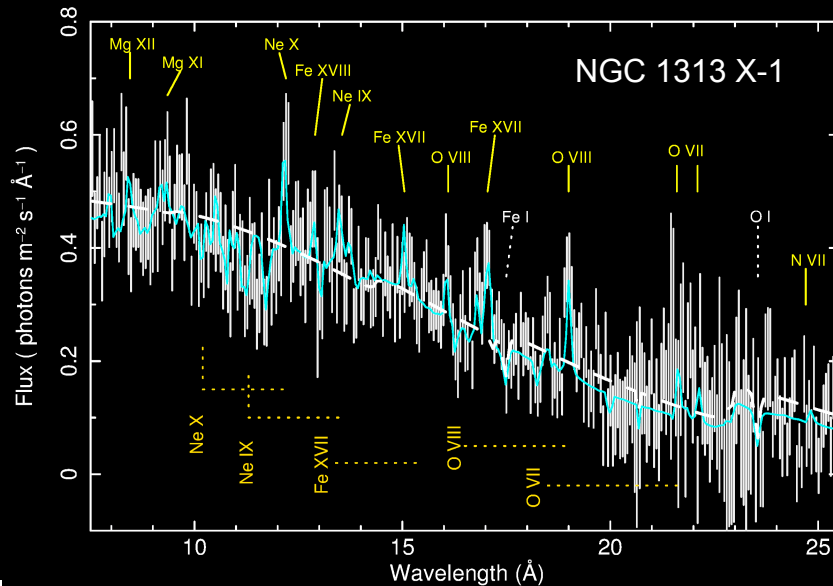


$$\xi = \frac{L_{ion}}{n_H R^2}$$

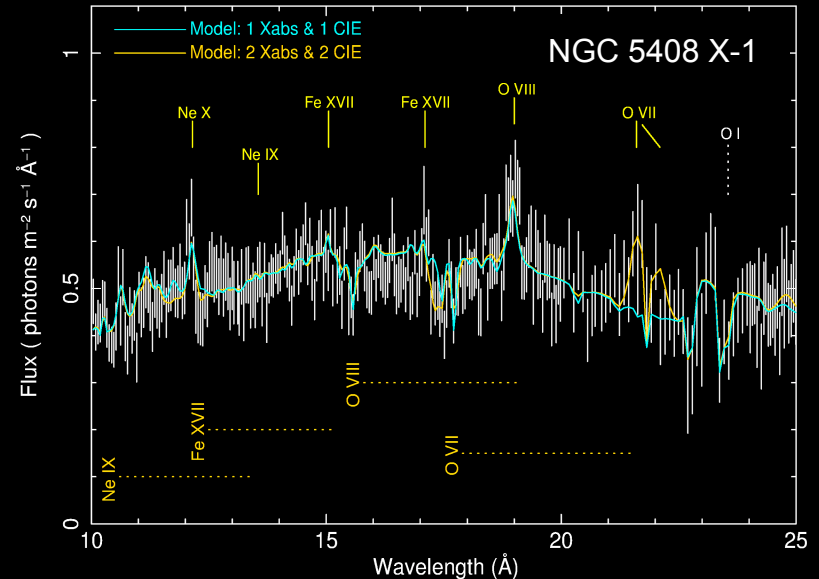
Atomic lines identify mildly-relativistic winds



- **Emission lines** close to laboratory wavelengths → **Thermal** winds / disc lines (Middleton+22)
- **Absorption lines** blueshifted by $\sim 0.2c$ → **Radiatively-driven** winds (Ohsuga+07)



350ks

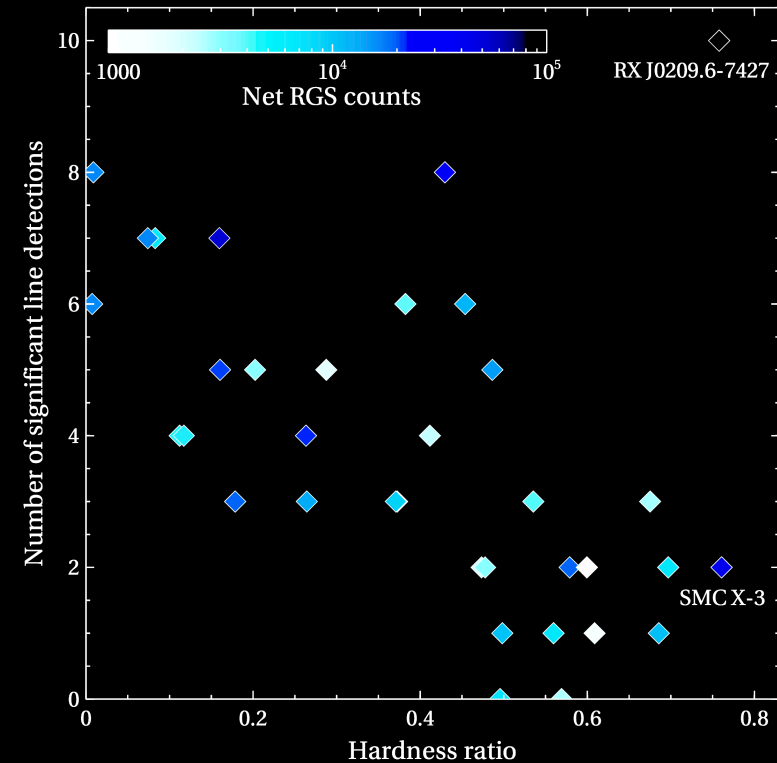
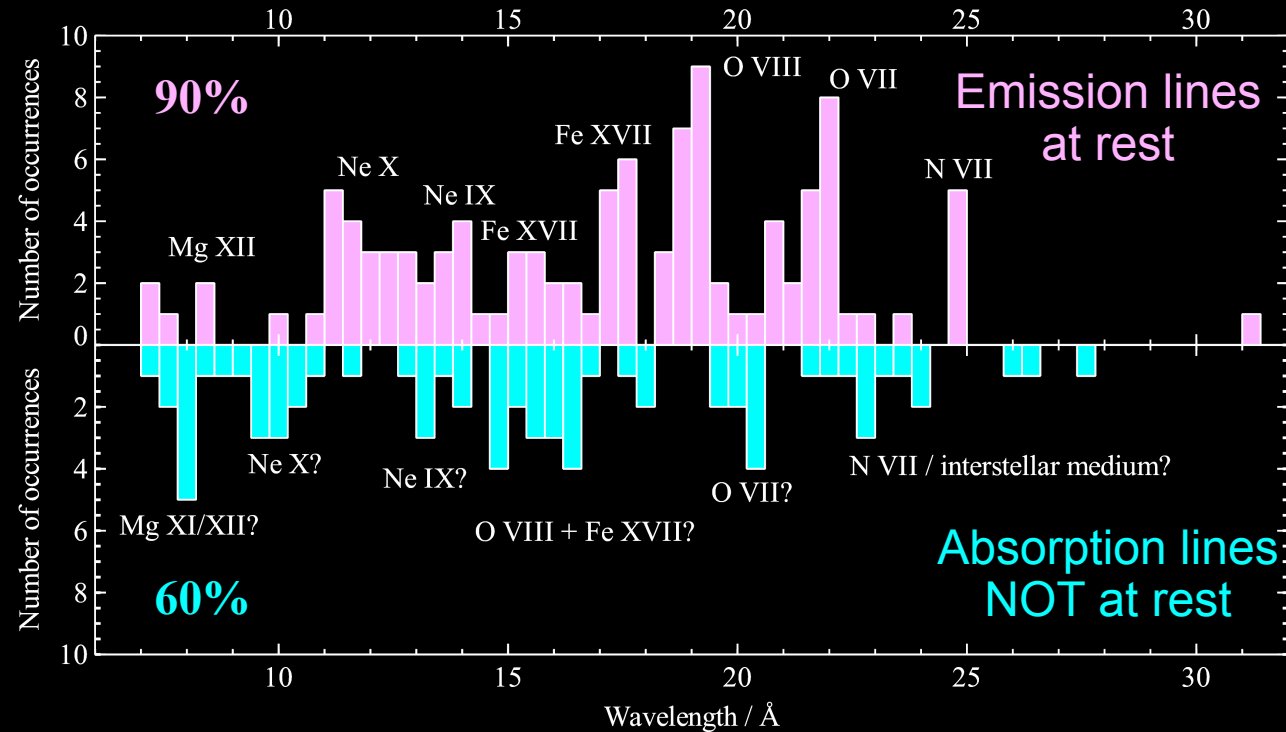


550ks

CP+2016-17, Walton+2016
Kosec+2018-21, Koliopanos+2018, Wang+2019



A census of identified spectral lines in ULXs



19 ULXs Kosec, CP+21

→ Bonus slides on methods:
Line scan VS Cross correlation

Equatorial winds!

O VII triplets

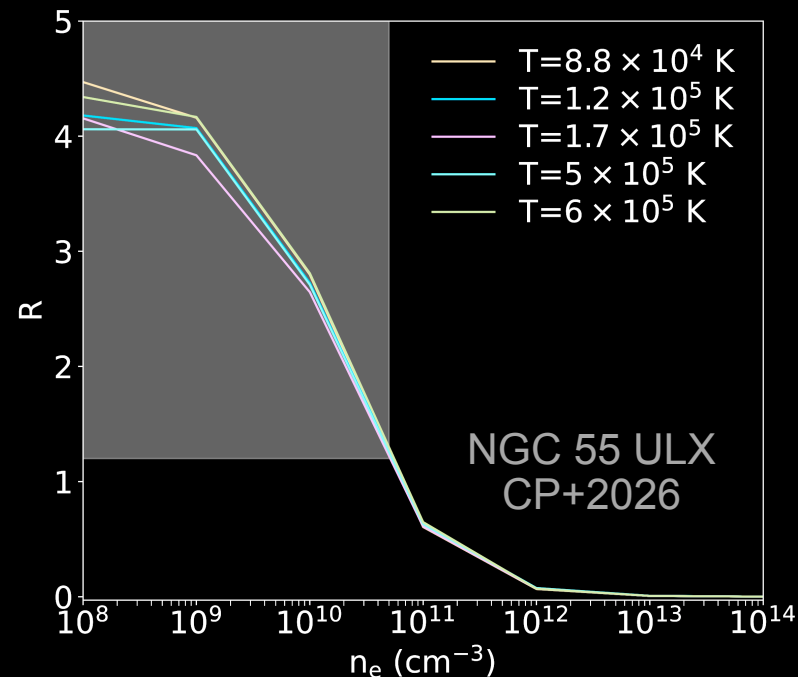
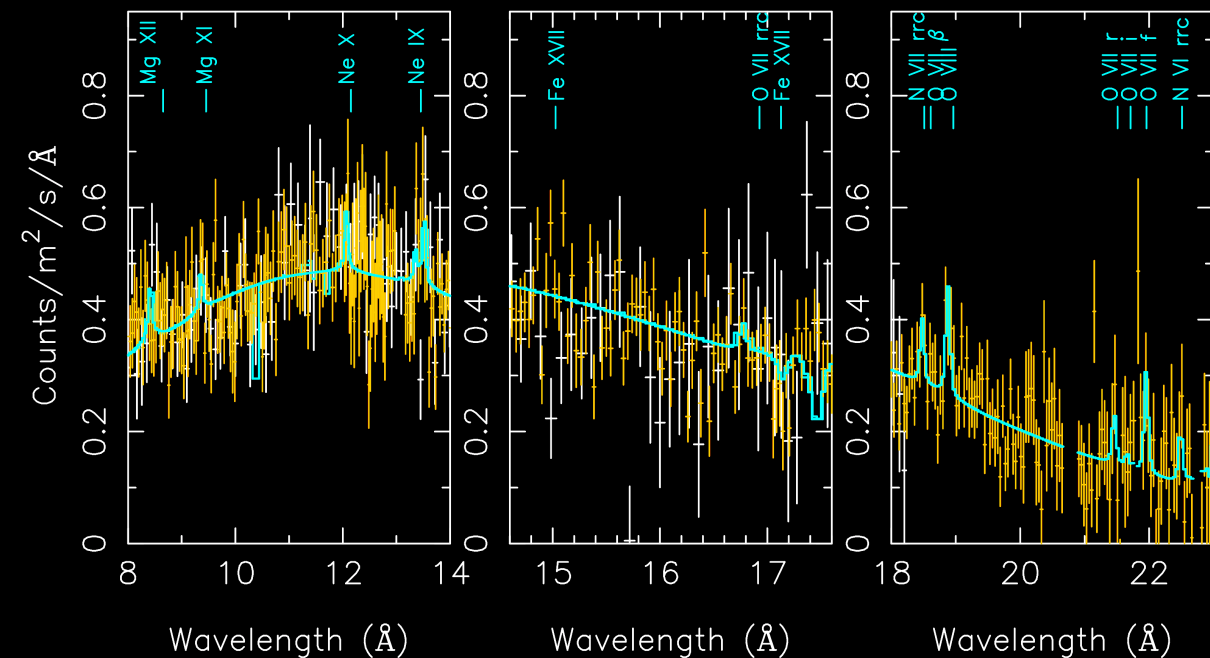
Density $\sim 10^{10-12} \text{ cm}^{-3}$, Temperature $\lesssim 10^5 \text{ K}$

→ Agree with He-like triplets of Galactic XRBs

→ Emitting region around 0.1-1 U.A.

$$R(n_e) = \frac{f}{i}$$

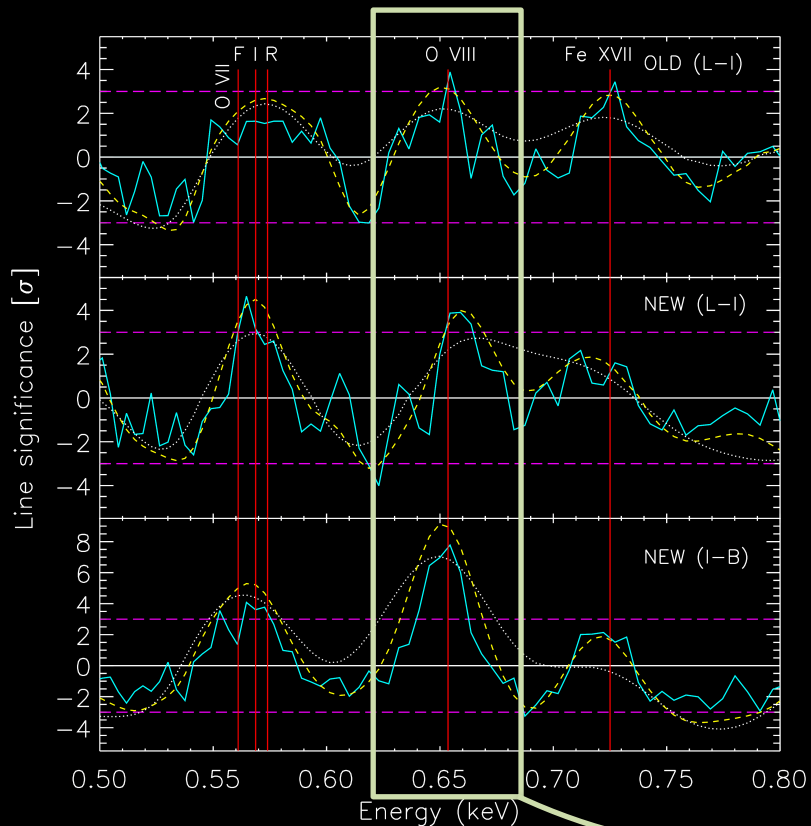
$$G(T_e) = \frac{f+i}{r}$$



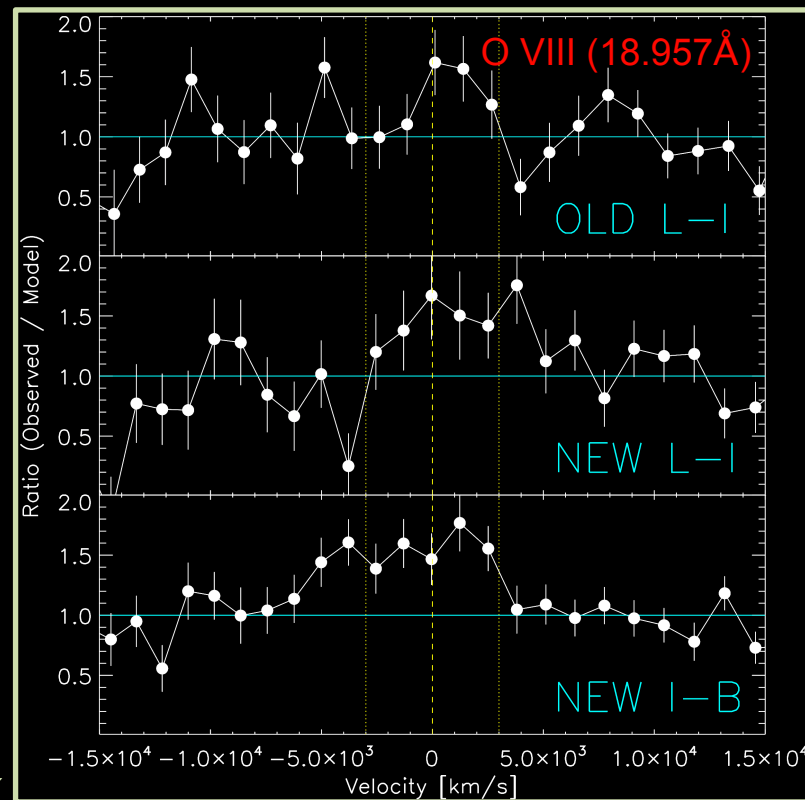
O VIII line shape & variability in NGC 1313 X-1

Lines **stronger**, **bluer** & **broader** at higher flux ~ 5000 km/s $\rightarrow$ higher $\dot{M}$

Also in AGN!
Xu, CP+ 2023



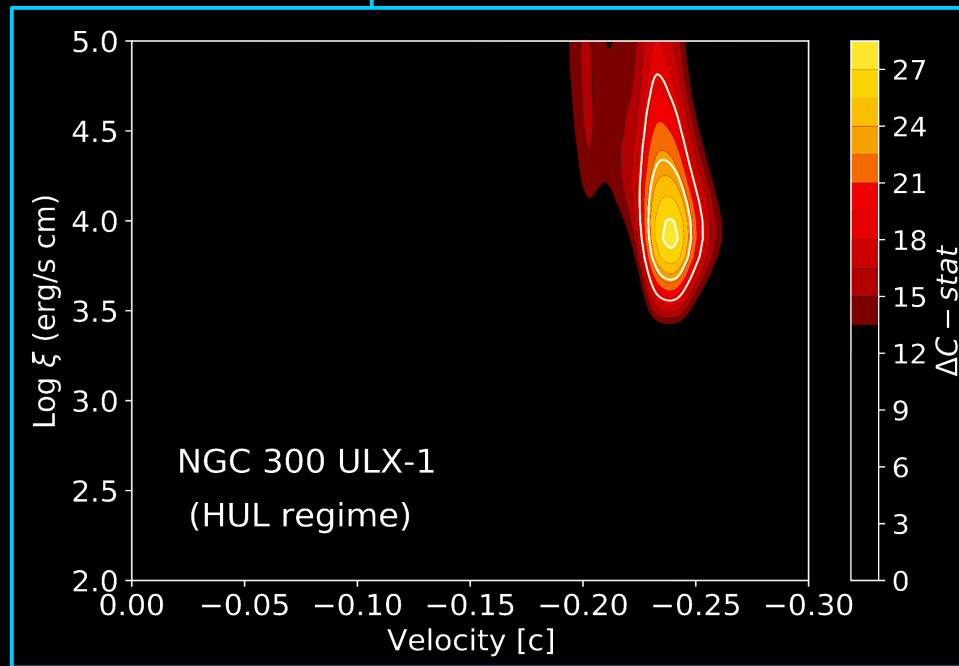
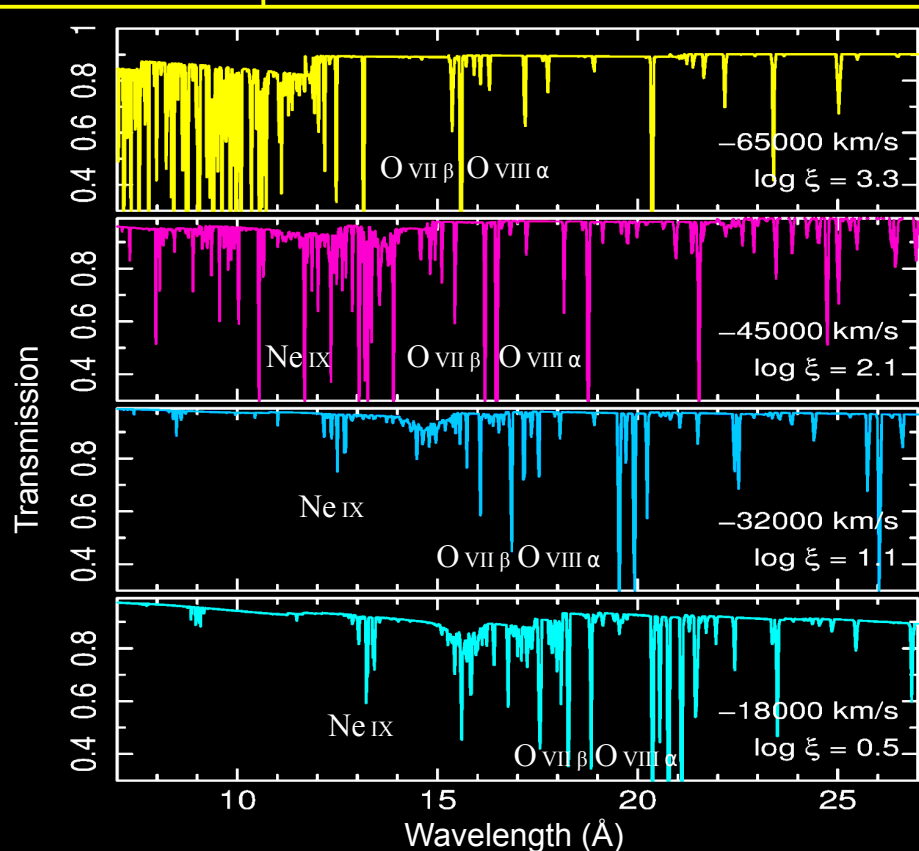
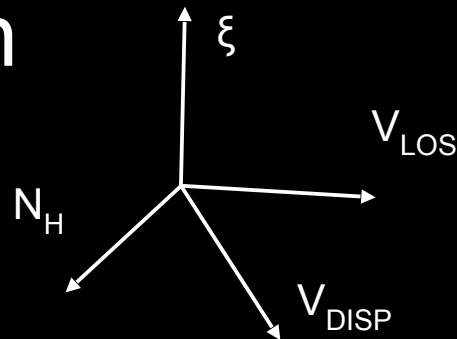
CP+2020



Multi-dimensional scan: absorption

Grid examples / multi-dimension scan

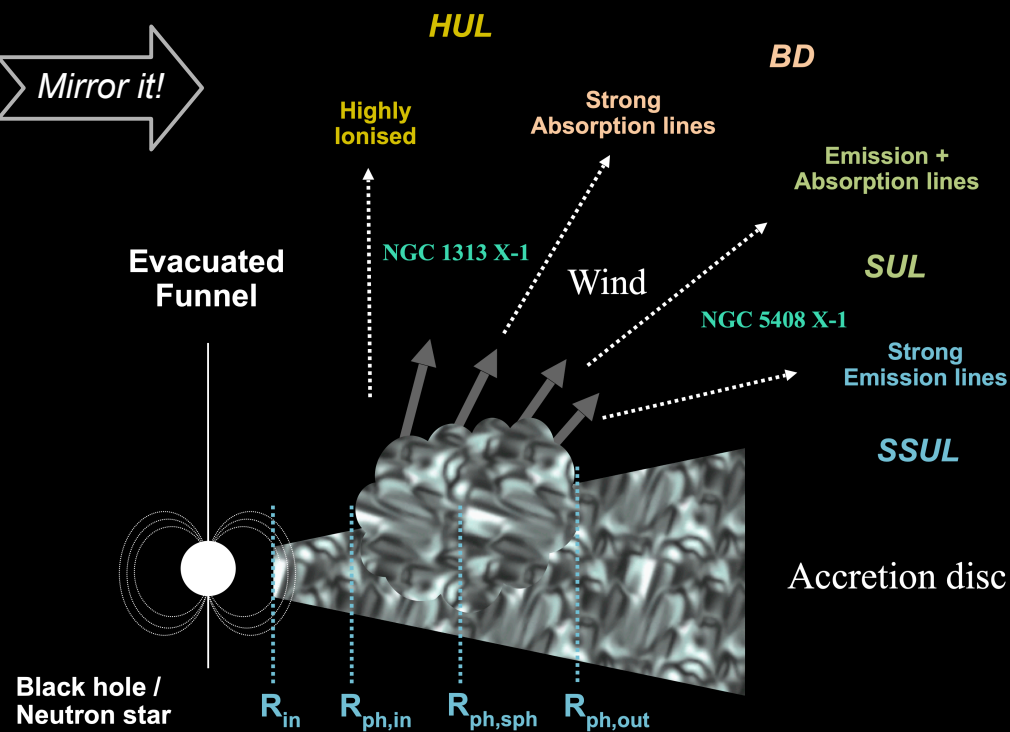
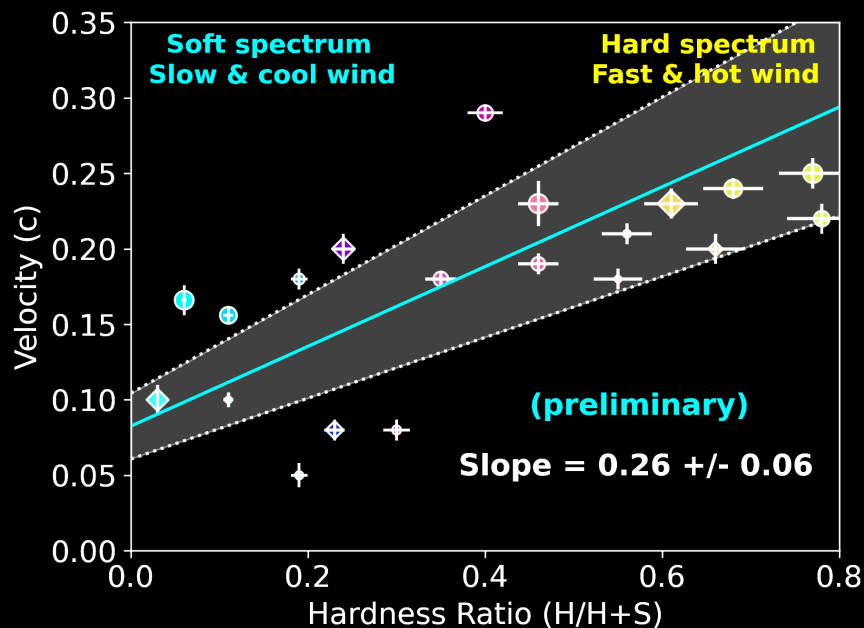
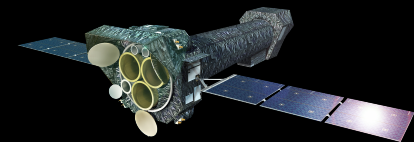
→ Bonus slides:
Significance via MC!



CP + 2016-21, Kosec + 2018-21

Wind properties to probe inclination & $\dot{M}$

- **Harder** spectra exhibit **faster** and **hotter** outflows
- Different launching radii?

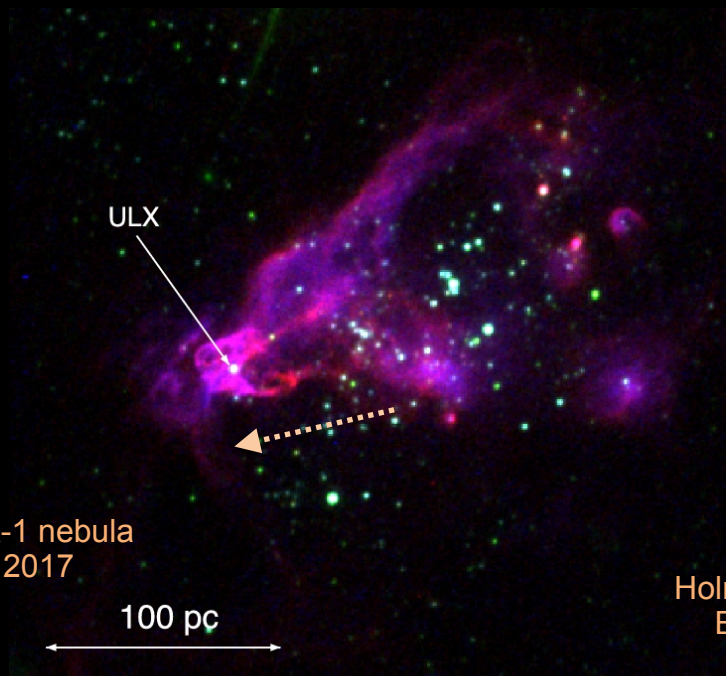


Wind properties & the donor

$$L_{\text{PION}} = 10^{38} \text{ erg/s}$$

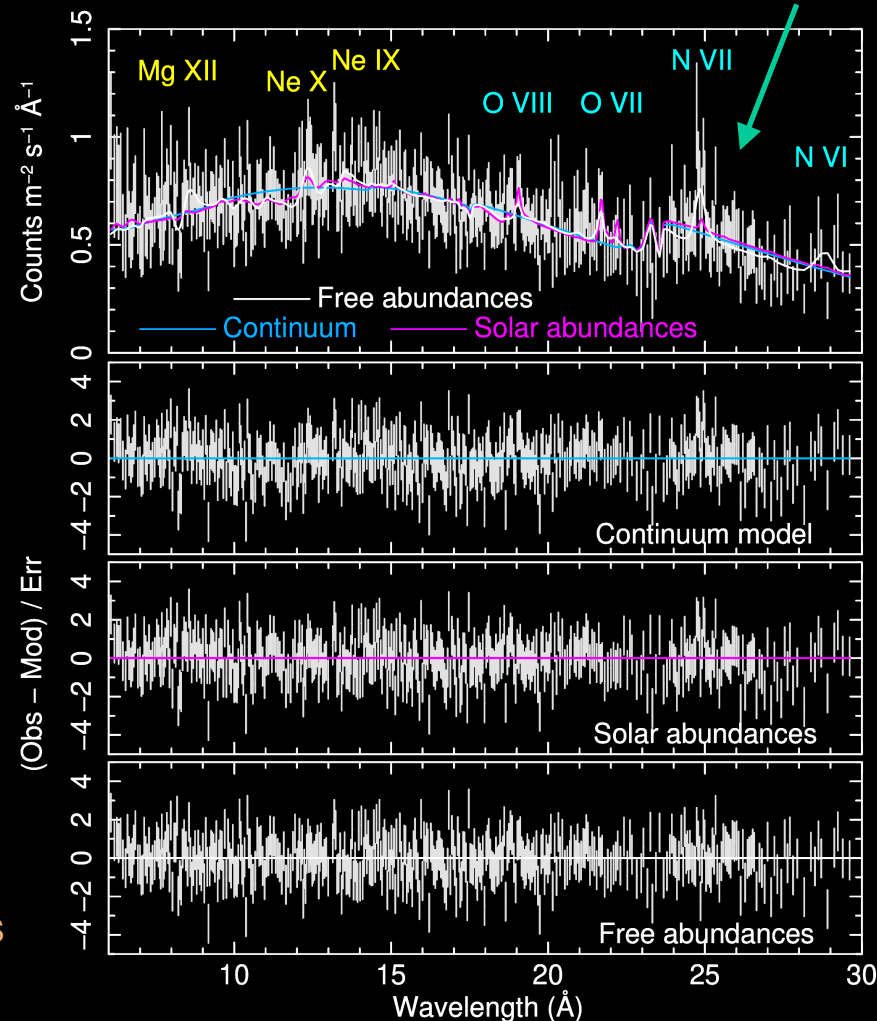
$$v_{\sigma} \approx 2500 \text{ km/s}$$

- Particularly **strong N VII** emission lines
- Enhanced nitrogen (and neon) abundance
- Blue/Red (S)G star as a companion?



Holmberg II X-1 nebula
Egorov + 2017

Holmberg II X-1 RGS
Barra, CP+2023



Can the winds *power* ULX bubbles?

Kinetic power :

$$L_{\text{wind}} = \frac{1}{2} \dot{M}_{\text{out}} v^2$$

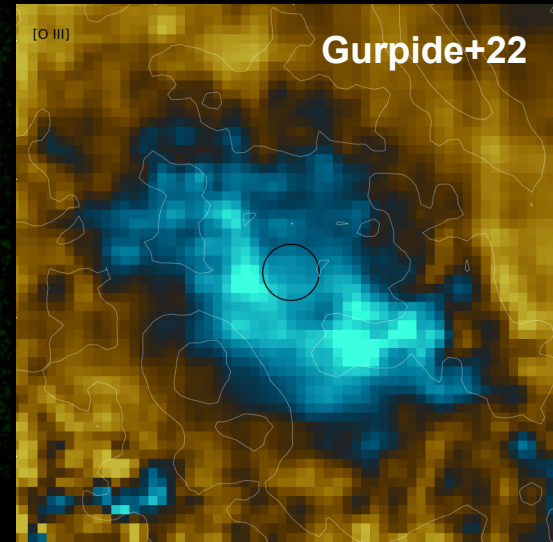
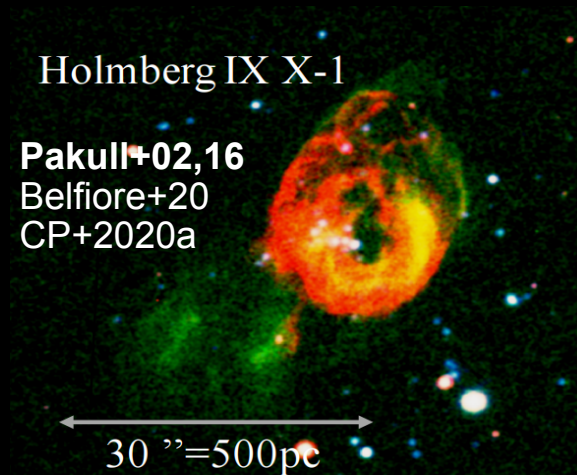
$$= 2 \pi m_p \mu \cdot \Omega C \cdot L_{\text{ion}} \frac{v^3}{\xi}$$

$$\approx 10^{39-40} \text{ erg s}^{-1}$$



Up to ~ **50%** of the total budget!

$$(\dot{M}_{\text{out}} = 4 \pi R^2 \rho v^2 \Omega C, \xi = L_{\text{ion}} / n_H R^2, \rho = n_H m_p \mu)$$



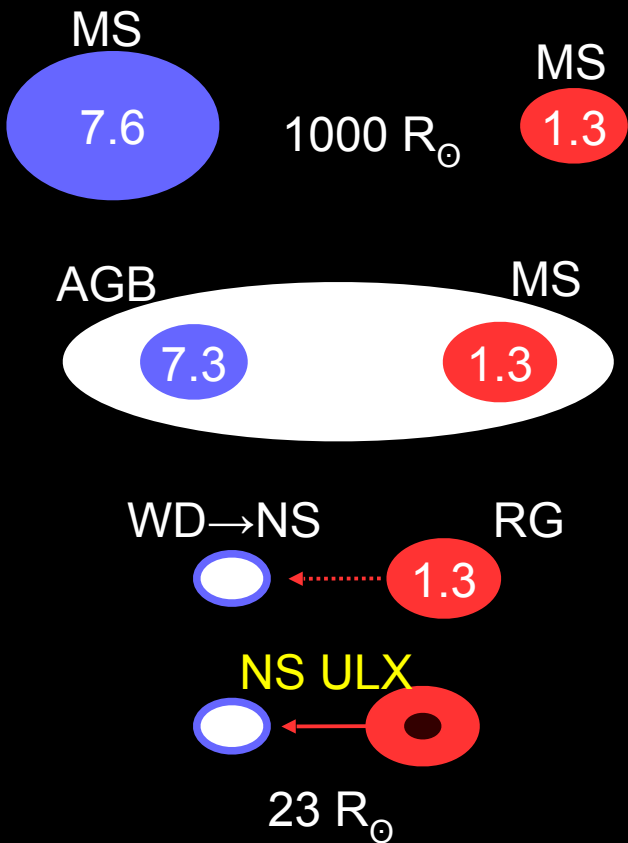
Required mechanical power :

$$L_{\text{Mechanical}} \geq 10^{39} \text{ erg/s}$$

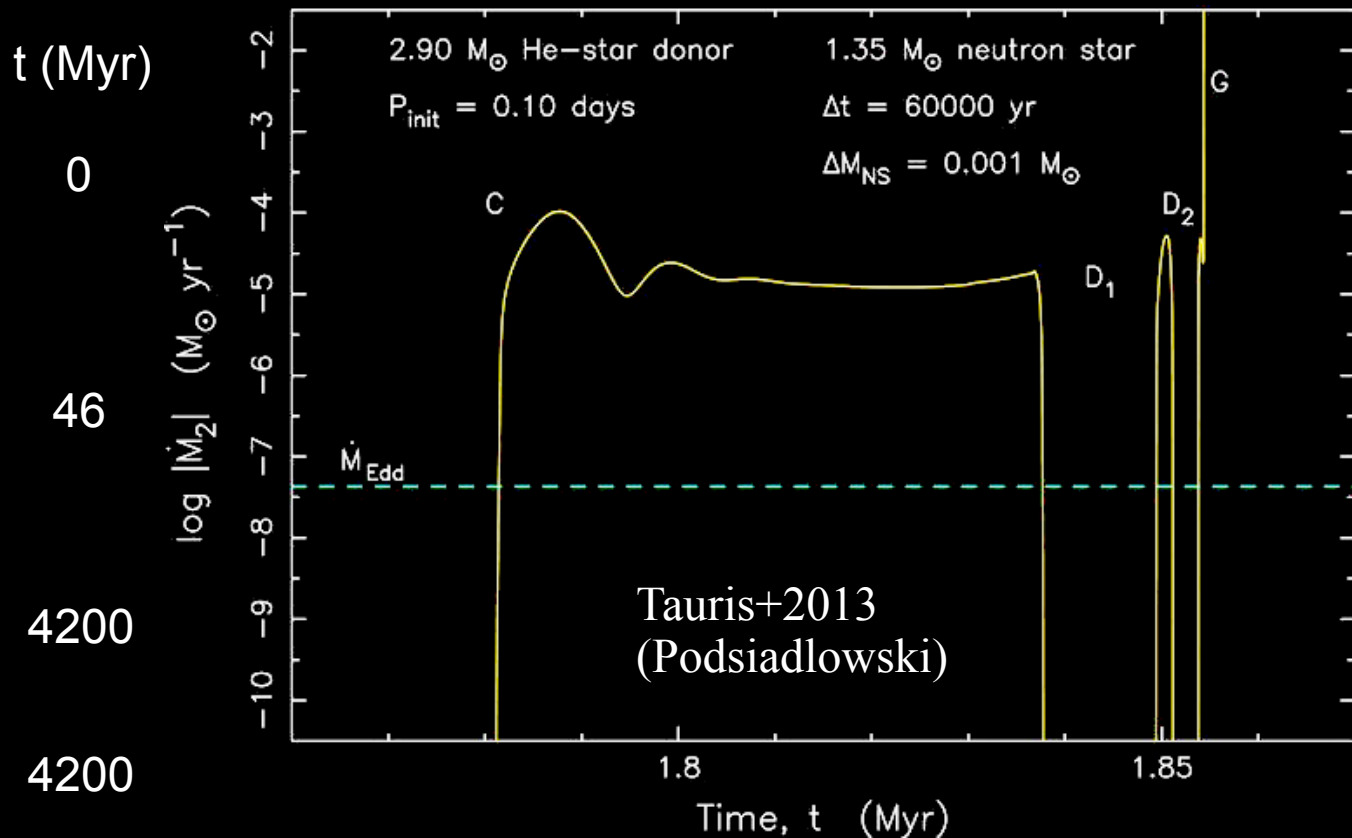
→ More on bubbles / radio
by C. Salvaggio & Y. Zhang

Pakull+02,16
Belfiore+20
CP+2020a

Binary system & super-Eddington accretion



Wiktorowicz+2017, Mondal+2020



→ More on high $\dot{M}$ in NS-ULX by M. Bachetti

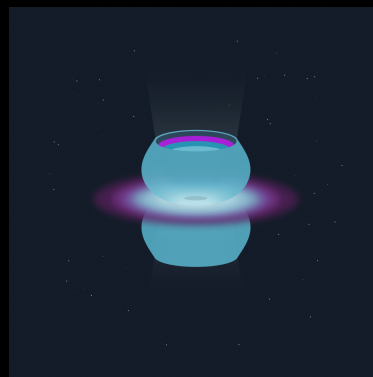
Optical counterparts: RSG / BSG
Heida+2015, Lopez+2017

Current limitations & Future advances

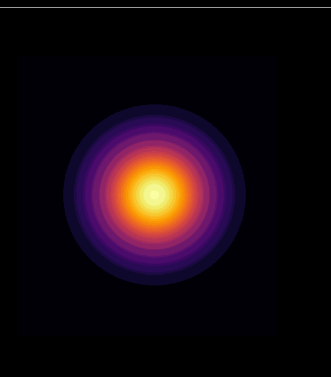
On what timescales & how do the properties of disc, wind & pulsations (inter-)change?

- Un-pulsating: neutron stars or black holes?
- Cyclotron RSFs a few & doubtful: why?
- Time lags are very large: wind scatterings?
- L-T^α trends differ in ULXs: NS vs BH vs angle?
- Spectral transitions → $\dot{M}_{\text{in}}$, $\dot{M}_{\text{wind}}$ or angle?
- Winds are transients → $\dot{M}_{\text{in}}$ or angle?
- Winds nature → radiative or magnetic?

Viewing angle

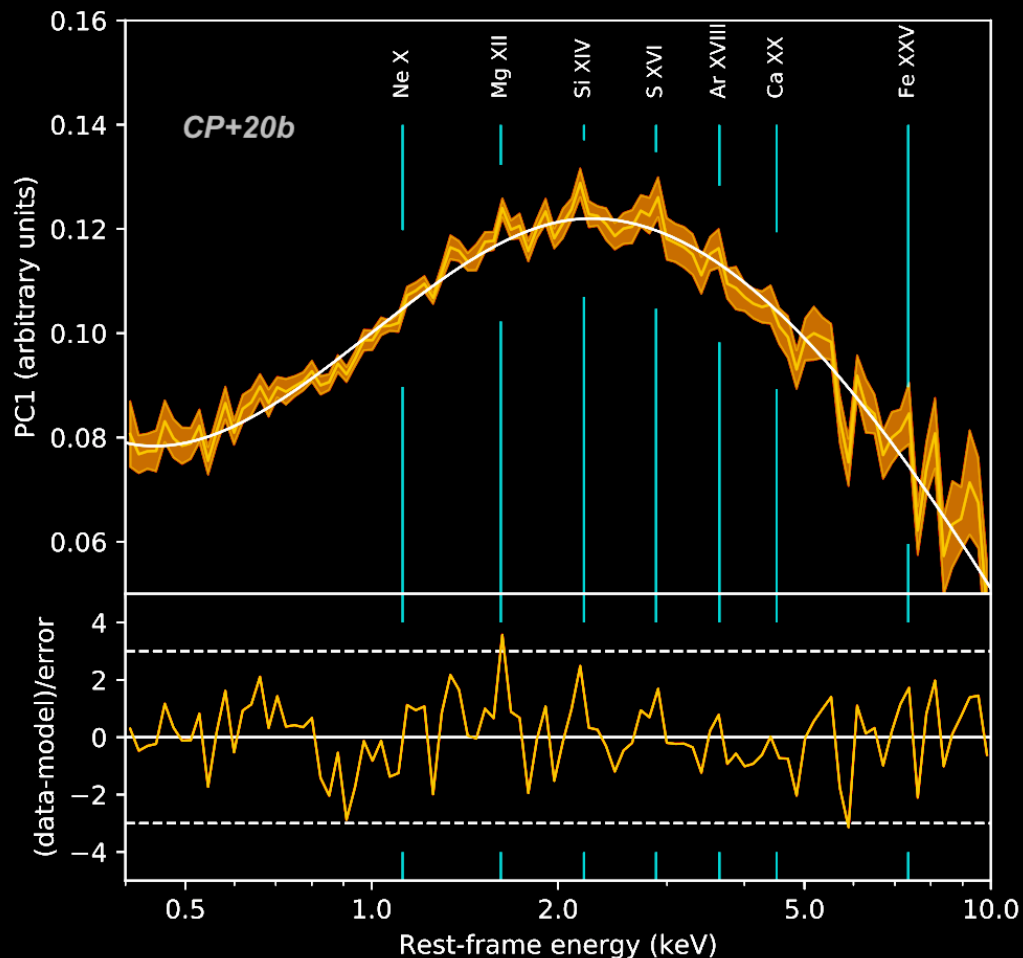


Variable $\dot{M}_{\text{in}} / \text{wind}$



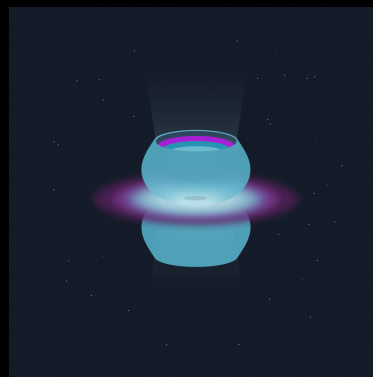
*Stellar winds also affect variability in XRBs (E.V. Lai+2022)
as well as UFOs in AGN (Xu+2024b)*

Current limitations & Future advances

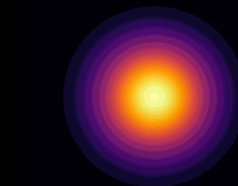


On what timescales & how do the properties of disc, wind & pulsations (inter-)change?

Viewing angle



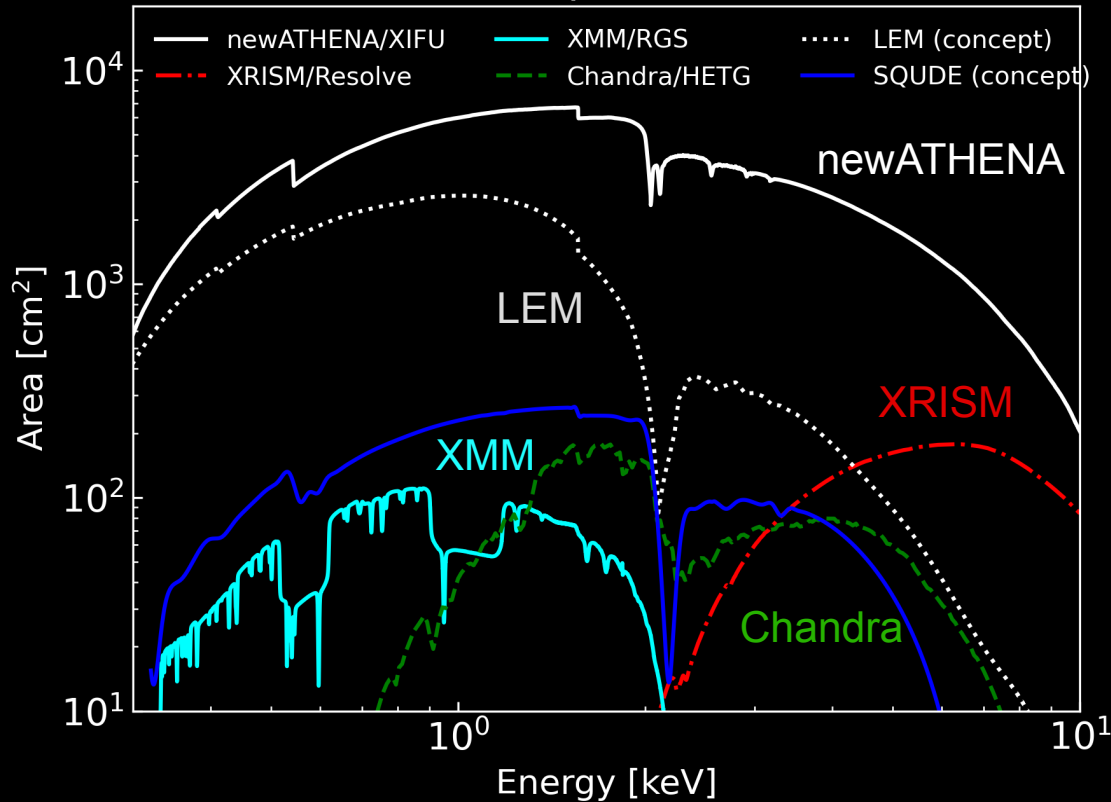
Variable $\dot{M}_{\text{in}} / \text{wind}$



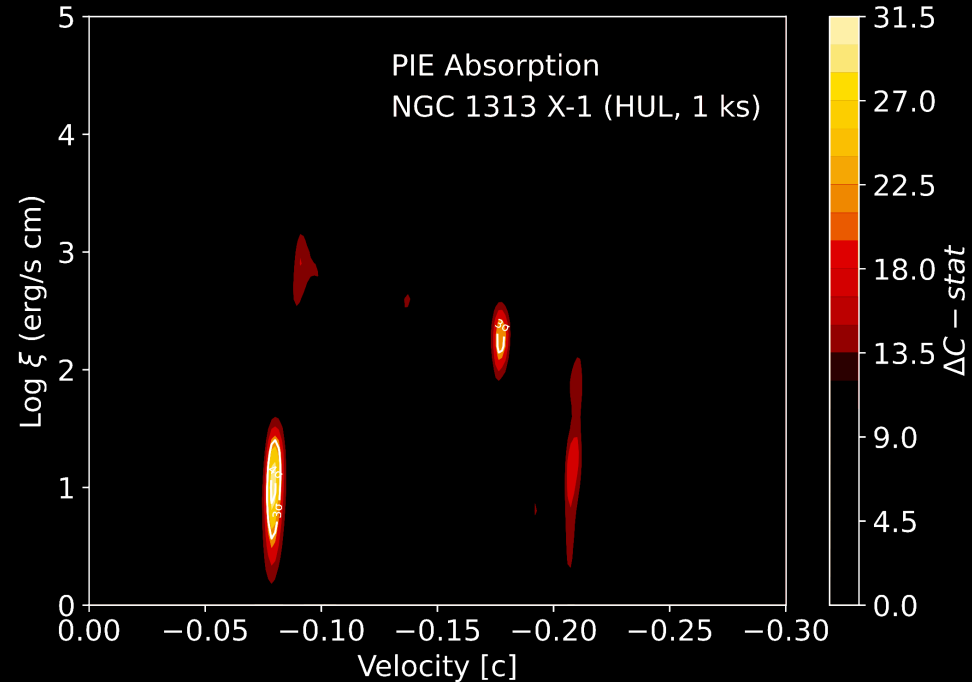
Stellar winds also affect variability in XRBs (E.V. Lai+2022)
as well as UFOs in AGN (Xu+2024b)

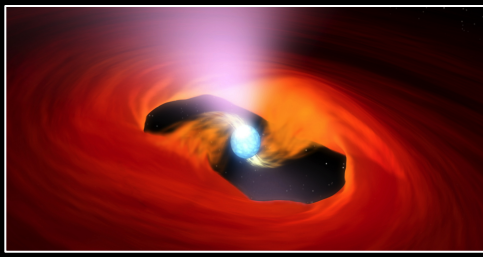
NewAthena / X-IFU

High-res X-ray spectroscopy

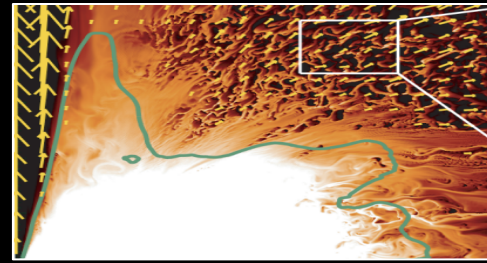


- Outflow properties characterised in **<1 ks** matching the **timescales** of lags & variability





Take away message

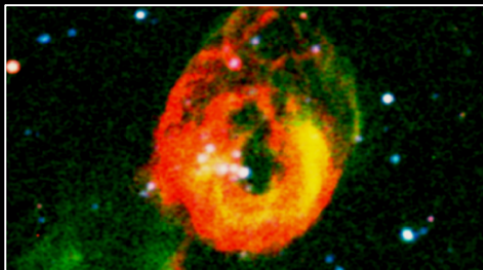


*Interested in extreme accretion & feedback? **ULXs** are the way to go!*

→ Useful local alternatives for understanding **early (SM)BHs growth**

Outflows likely power the bubbles *but the net growth rate may exceed **Eddington***

NewAthena will transform this research field!



Bonus slides

X-ray Broadband

Eddington Luminosity & Accretion Rate

(For a spherical geometry)

Gravitational
Force

$$F_{grav} = G \frac{M m}{R^2}$$

Radiation
Force

$$F_{rad} = \frac{L}{c} \frac{k m}{4 \pi R^2}$$

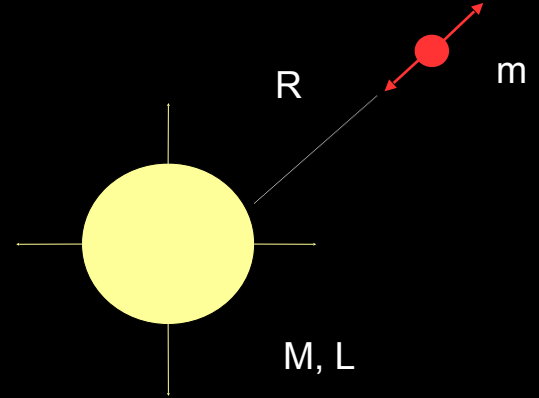
Radiation =
Gravity

$$L = \frac{4 \pi G M c}{k} = \frac{4 \pi G M c m_p}{\sigma_T}$$

$$= 1.3 \cdot 10^{38} \left(\frac{M}{M_{sun}} \right) \text{erg/s}$$

Accretion Rate

$$\dot{M} = \frac{L}{\epsilon c^2} \xrightarrow[\epsilon = 10\%, M = 10 M_{sun}]{} 2 \times 10^{-7} M_{sun} \text{yr}^{-1}$$



2 branches in the hardness-intensity diagram

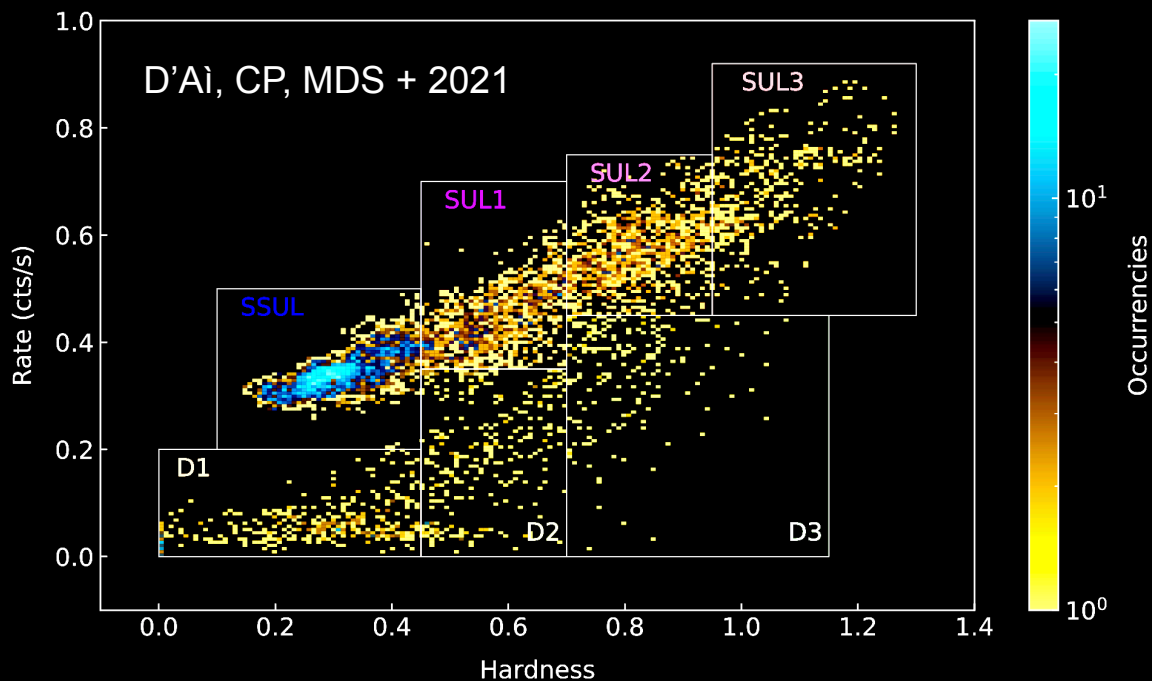
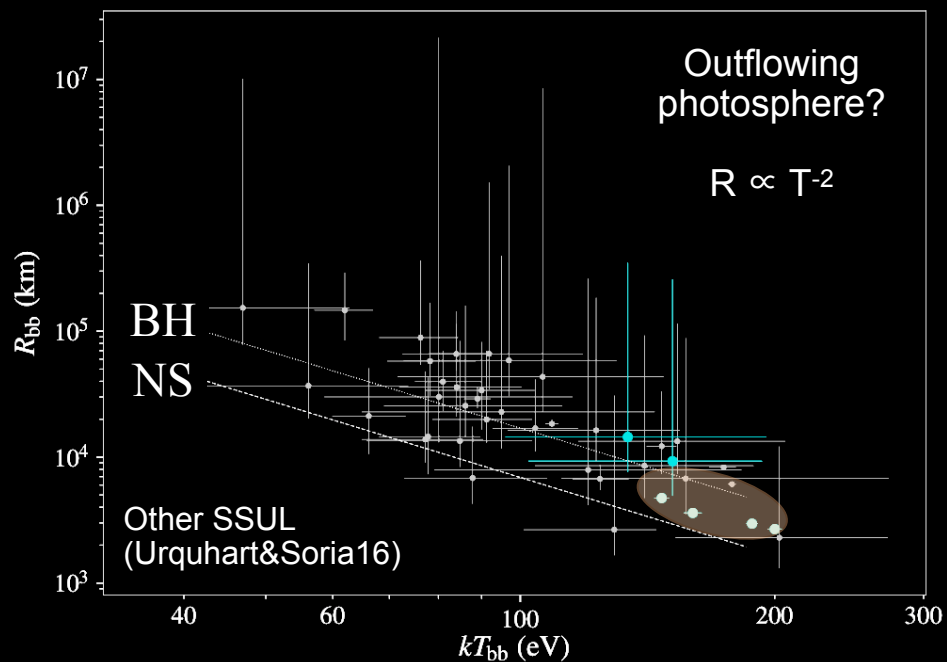
SUL $\leftrightarrow$ SSUL transitions

Main branch shows $R \propto T^{-2}$

$\rightarrow$ *outflowing photosphere?*

$L_{\text{dip}} \sim 2 \cdot 10^{38} \text{ erg/s} \leftrightarrow L_{\text{max}} \sim 5 \cdot 10^{39} \text{ erg/s}$

Dip branch: if propeller $\rightarrow B \sim 2 \cdot 10^{11} \text{ G}$



2 branches in the hardness-intensity diagram

Soft $\leftrightarrow$ Supersoft transitions

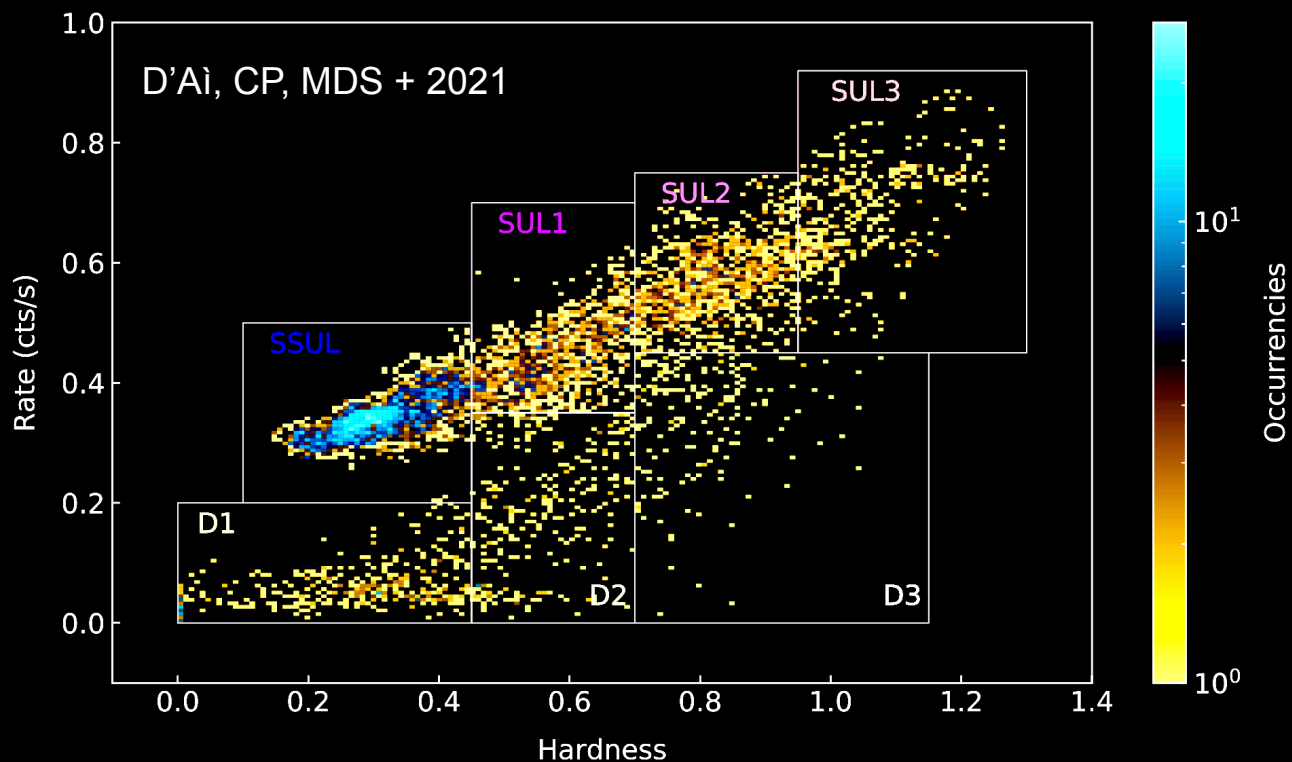
1) **Main branch** shows $R \propto T^{-2}$

→ *outflowing photosphere?*

2) **Dip branch** $L_{\max} \sim 5 \cdot 10^{39}$ erg/s

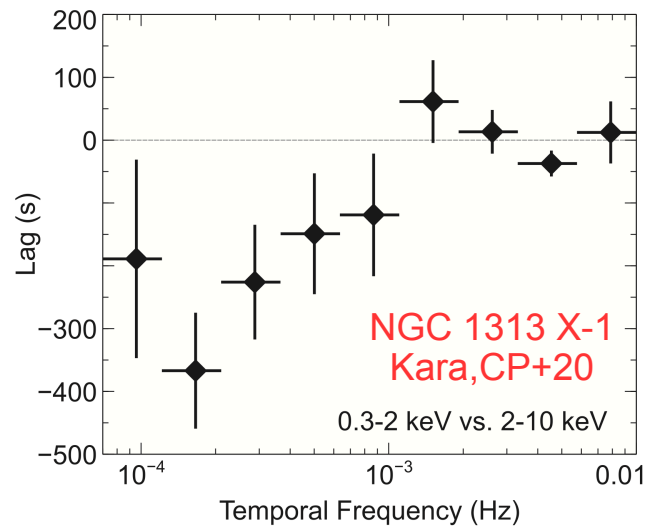
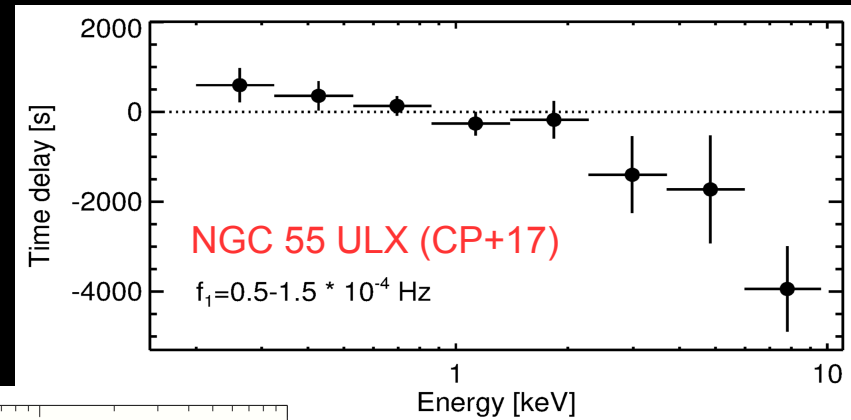
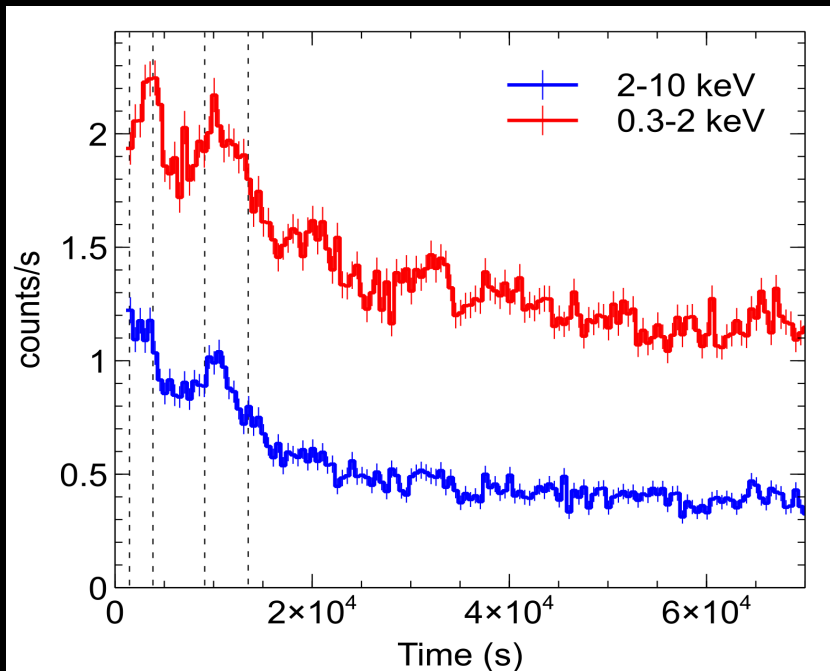
down to $L_{\text{dip}} \sim 2 \cdot 10^{38}$ erg/s

→ propeller? → $B \sim 2 \cdot 10^{11}$ G



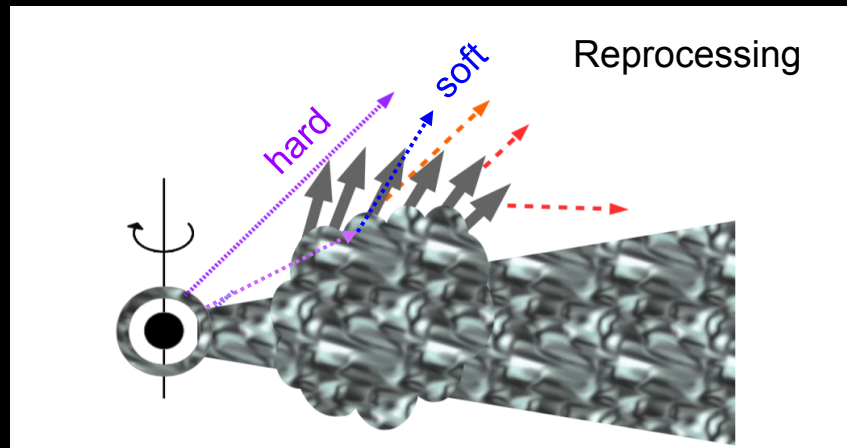
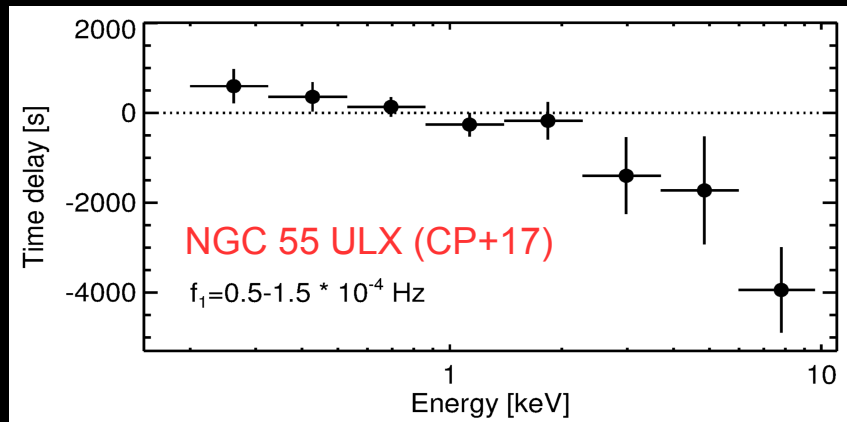
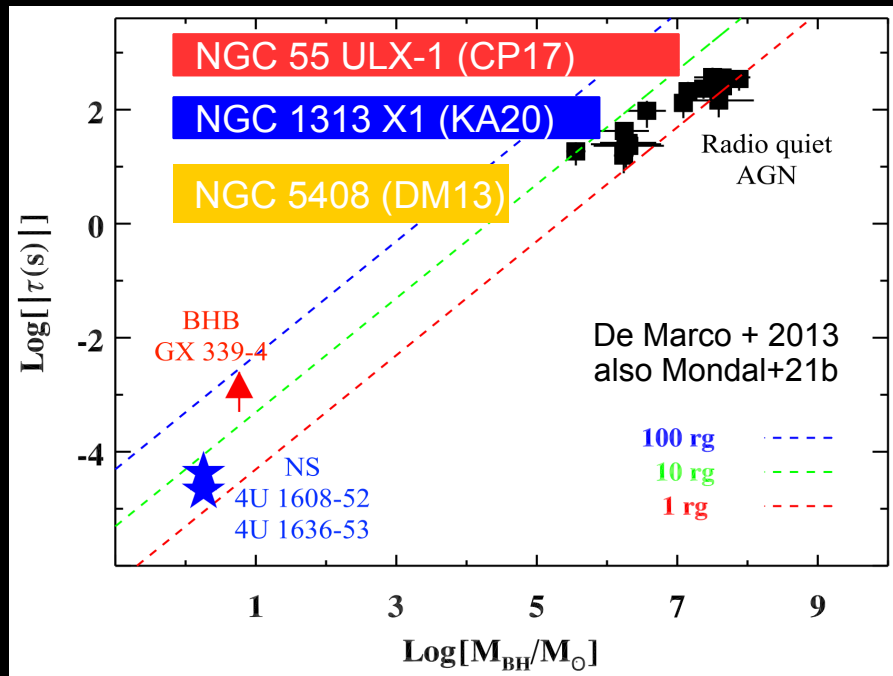
ULX – Time delays between energy bands

The soft X-ray band (0.3 – 2 keV)
lags the hard band (2 – 10 keV)



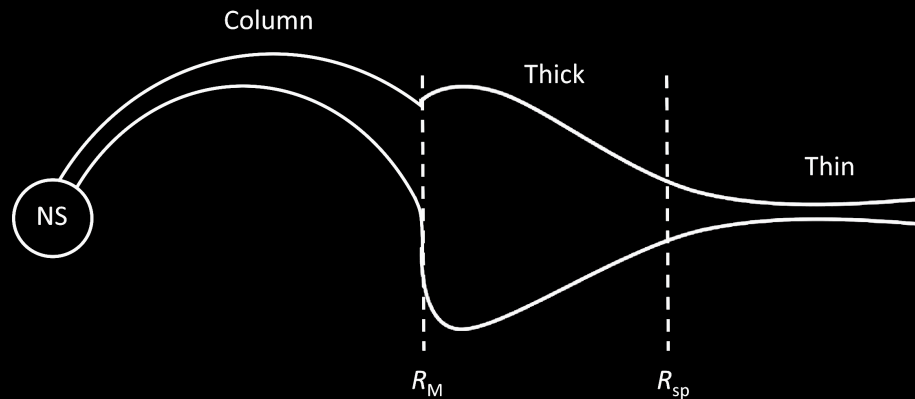
ULX – Time delays between energy bands

Reverberation or **wind reprocessing**?



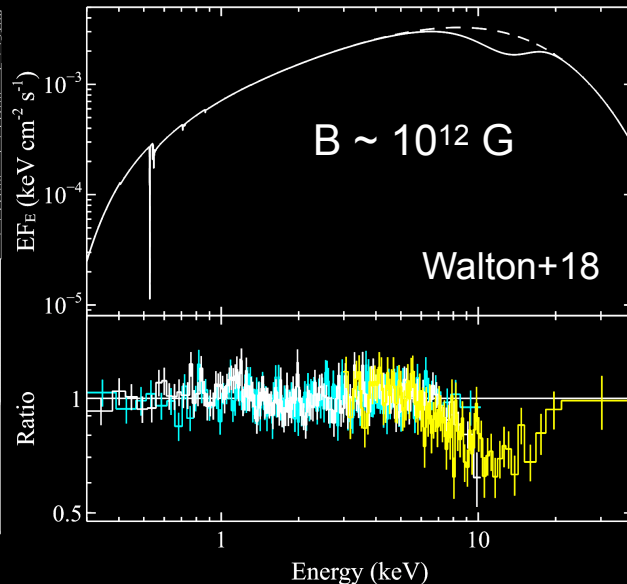
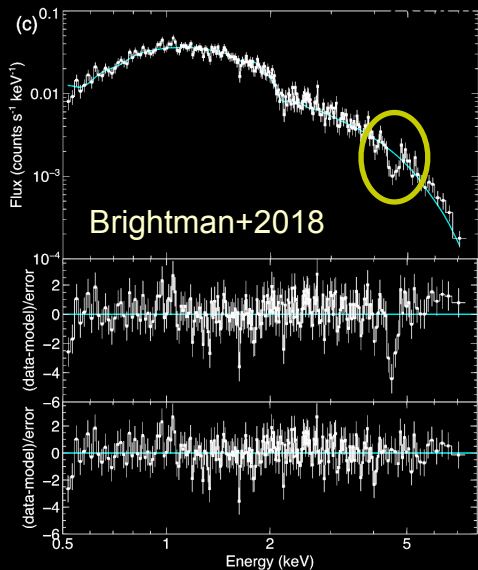
Cyclotron Resonance Scattering Features?

Strong magnetic field

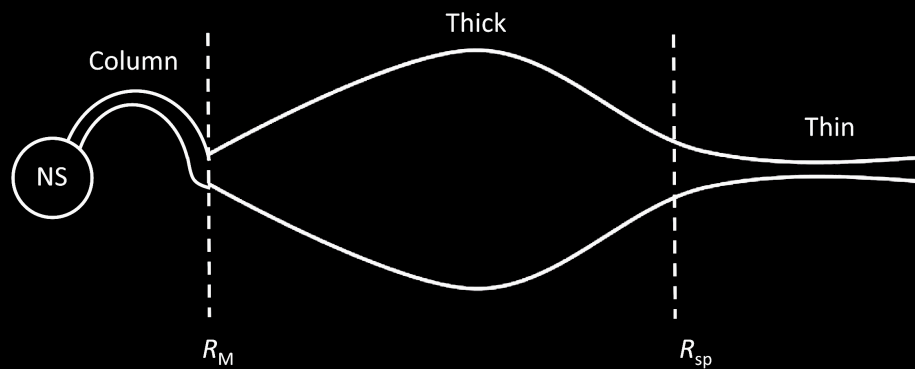


M 51 ULX-8

NGC 300 pULX-1



Weak magnetic field



$$\text{Electrons} \rightarrow \Delta E_{CRSF} = 11.6 (B/10^{12} G) (1 + z_{grav})^{-1}$$

$$\text{Protons} \rightarrow \Delta E_{CRSF} = 6.3 (B/10^{15} G) (1 + z_{grav})^{-1}$$

X-ray high-resolution

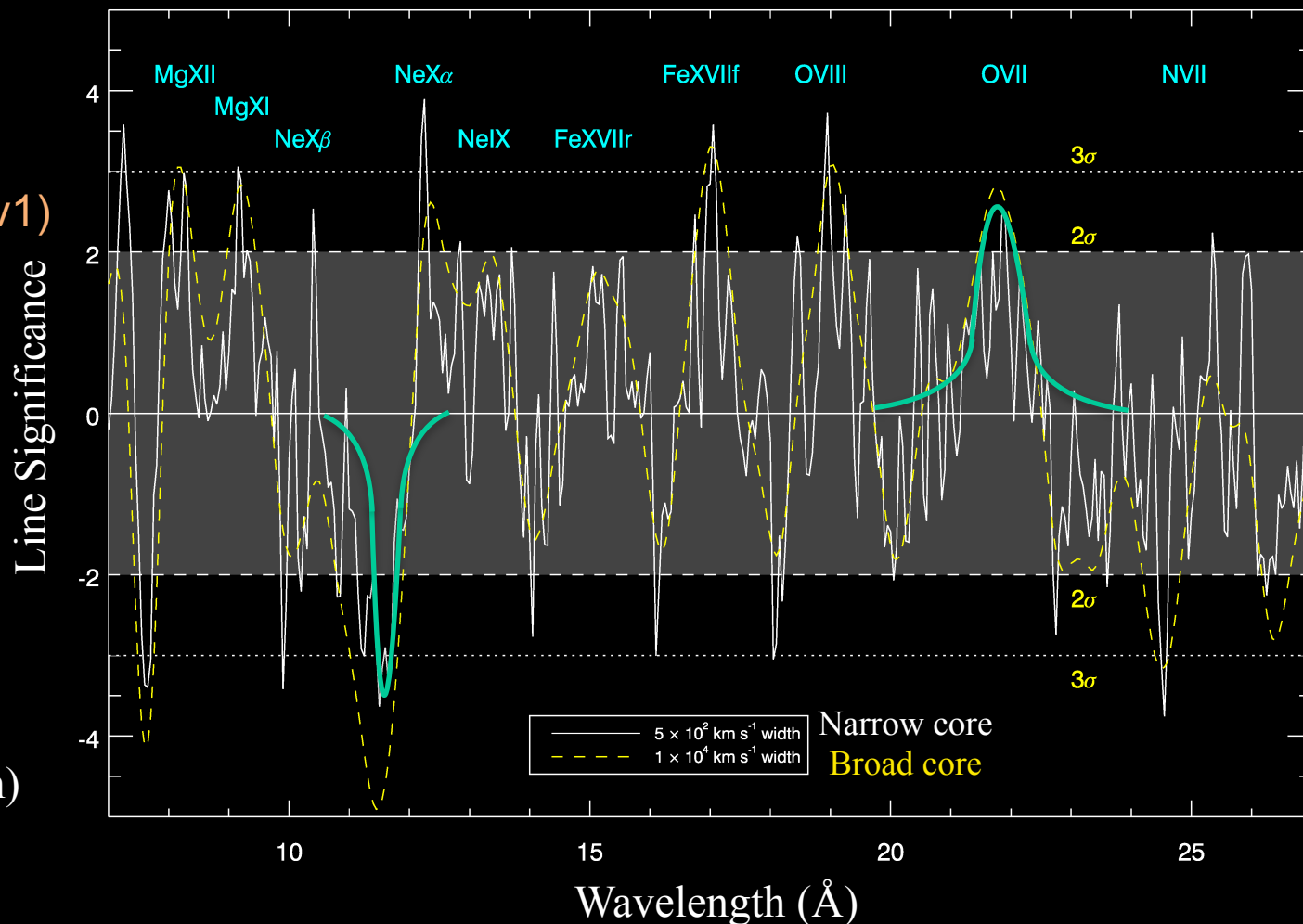
One line to detect them all!

NGC 1313 X-1 RGS

Gaussian line scan

(Traditional method / v1)

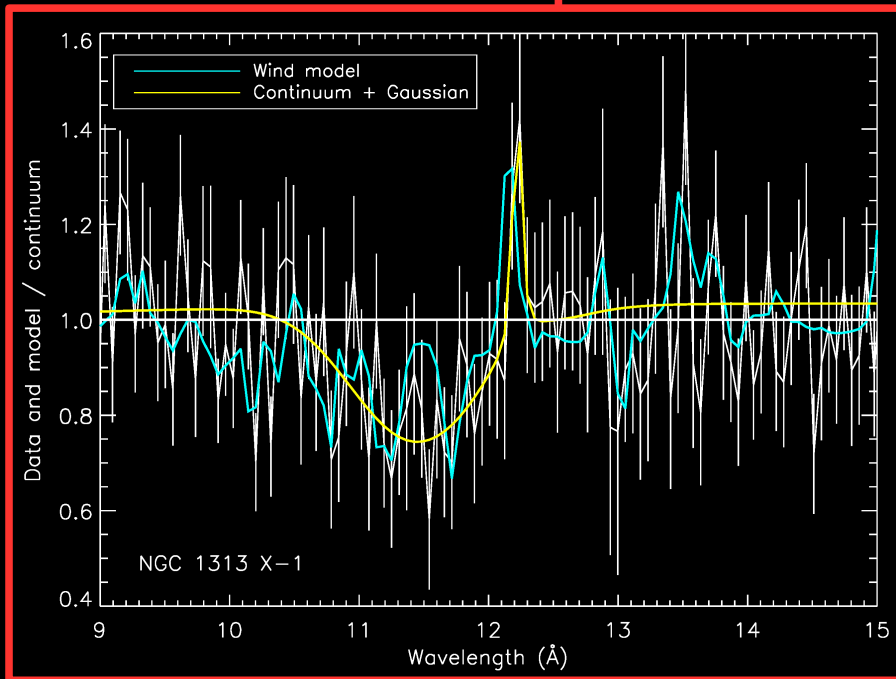
1. $\sqrt{\Delta X^2} * \text{sign}(\text{Norm.})$
or
2. $\text{Norm} / \text{error}(\text{gaussian})$



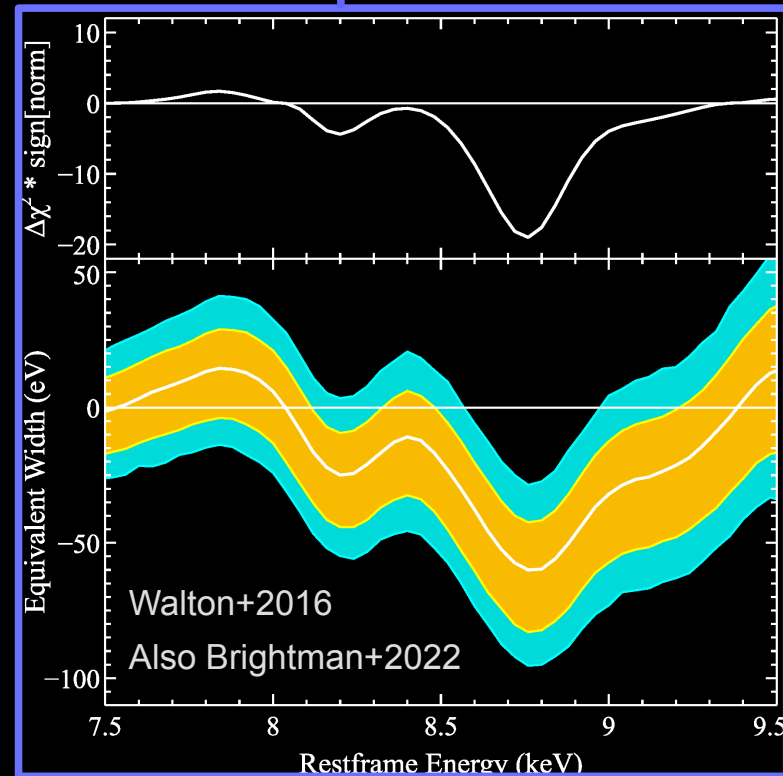
NGC 1313 X-1 Fe K counterpart

Fe L

Fe K

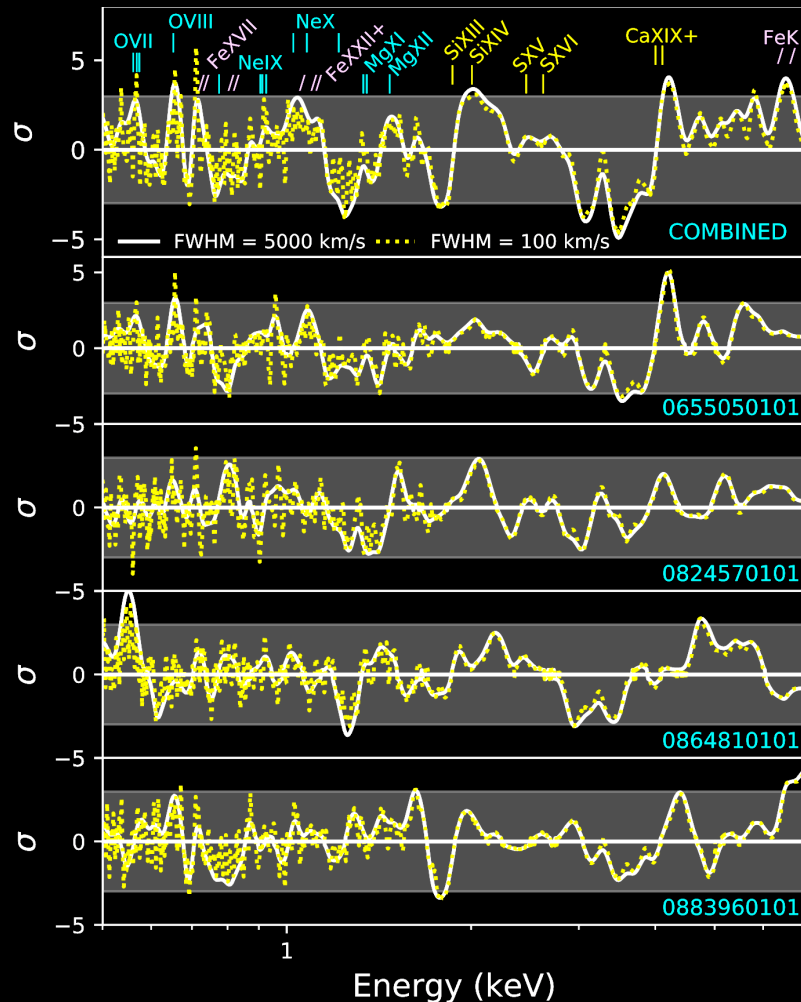
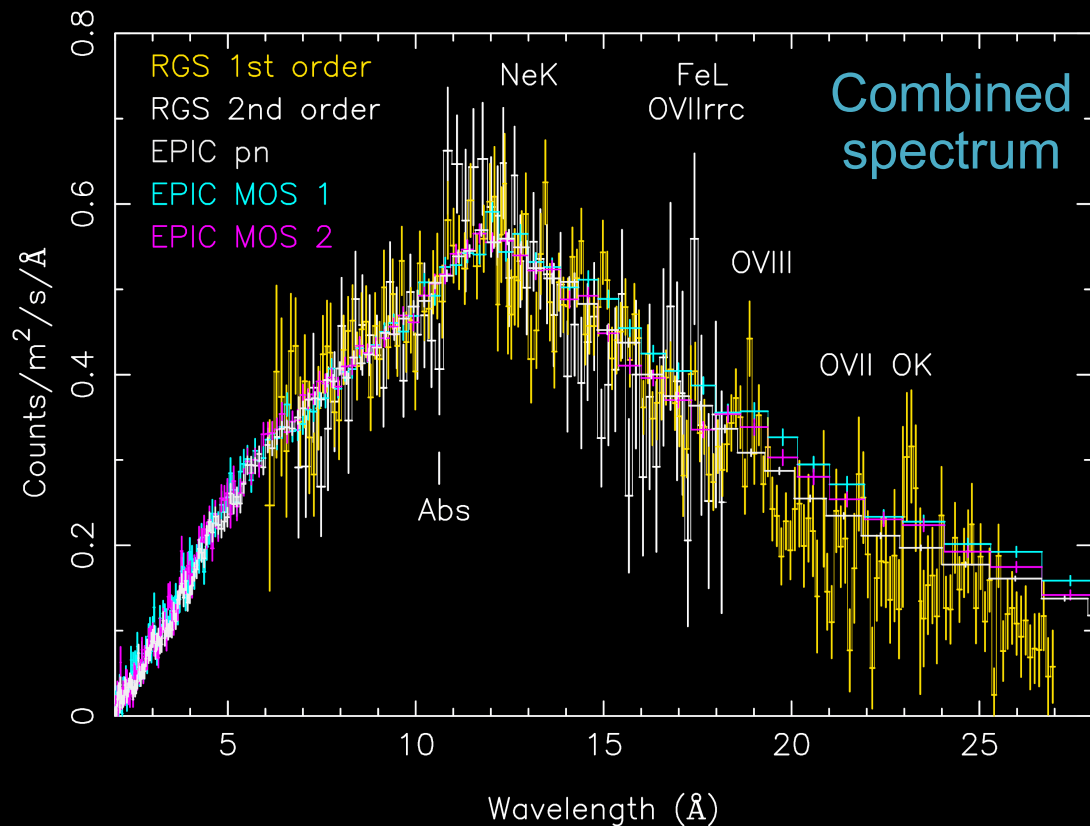


CP+2016

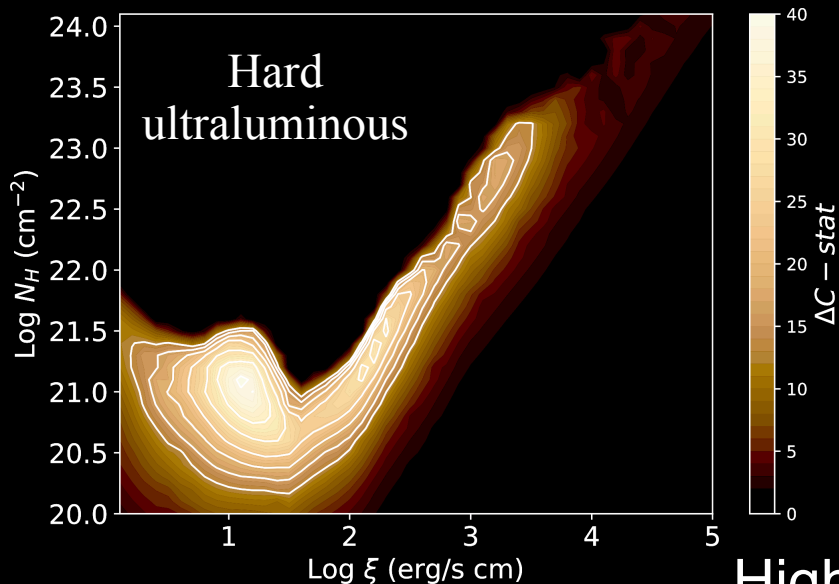
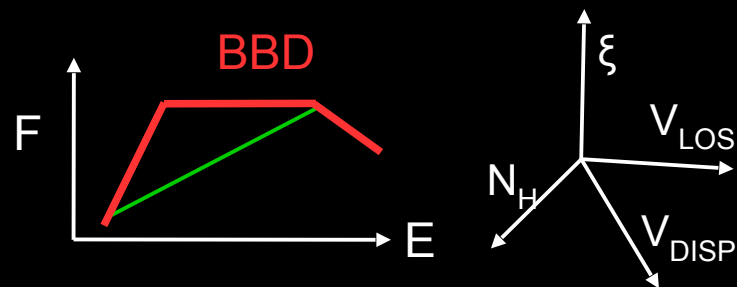
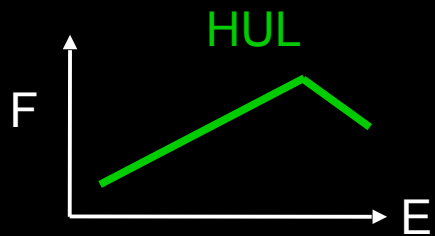


NGC 55 1 keV edge & other features

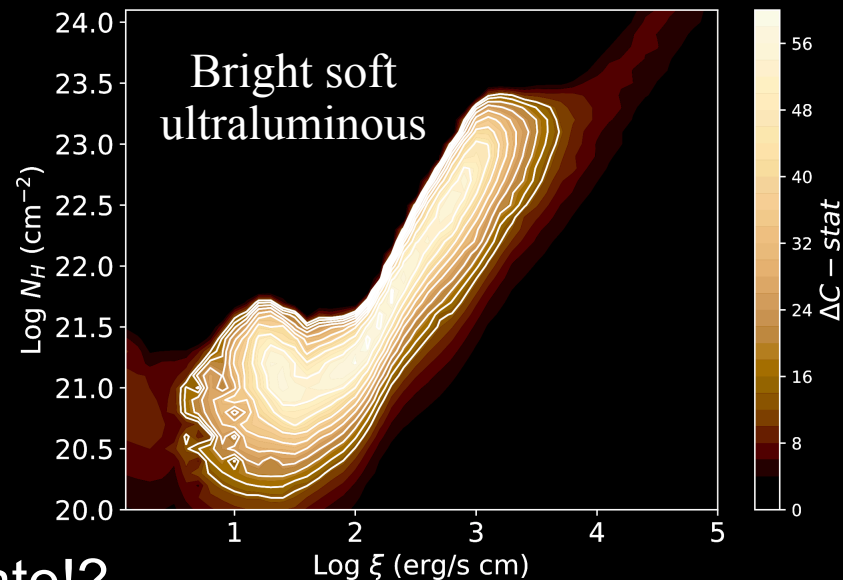
RGS resolves the 1 keV edge ubiquitous in CCDs



Wind vs. Continuum: emission lines

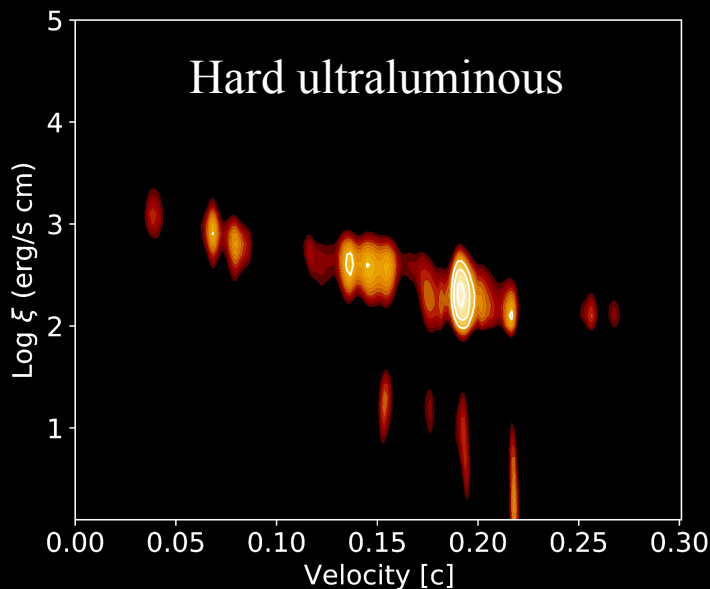
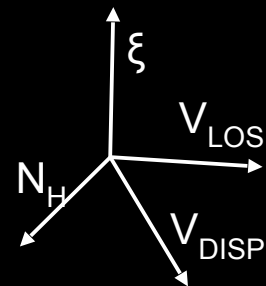
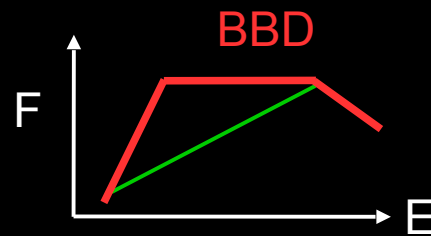
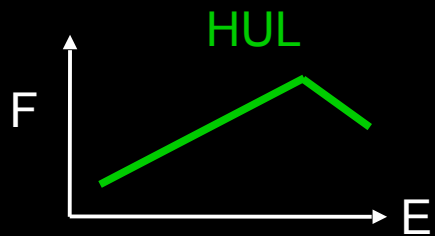


Emitting
Component
At rest



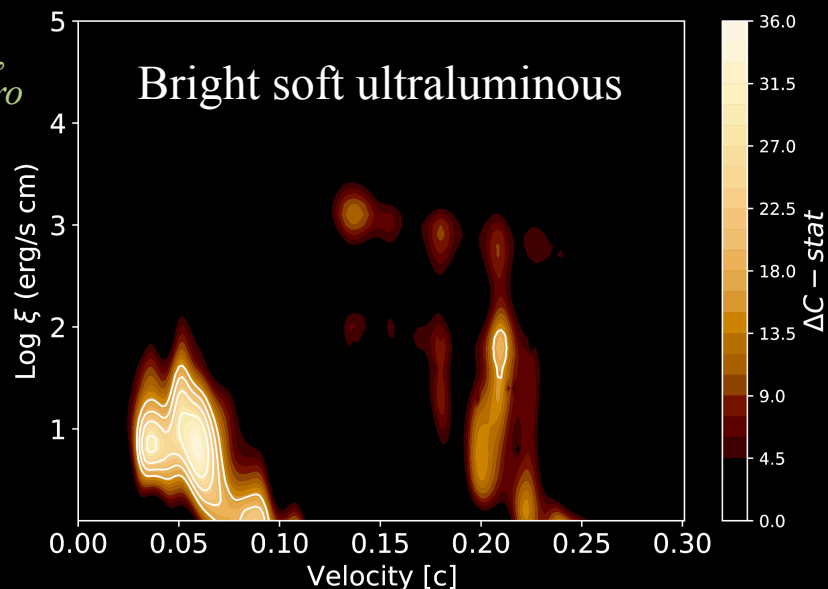
Higher accretion rate!?

Wind vs. Continuum: absorption lines



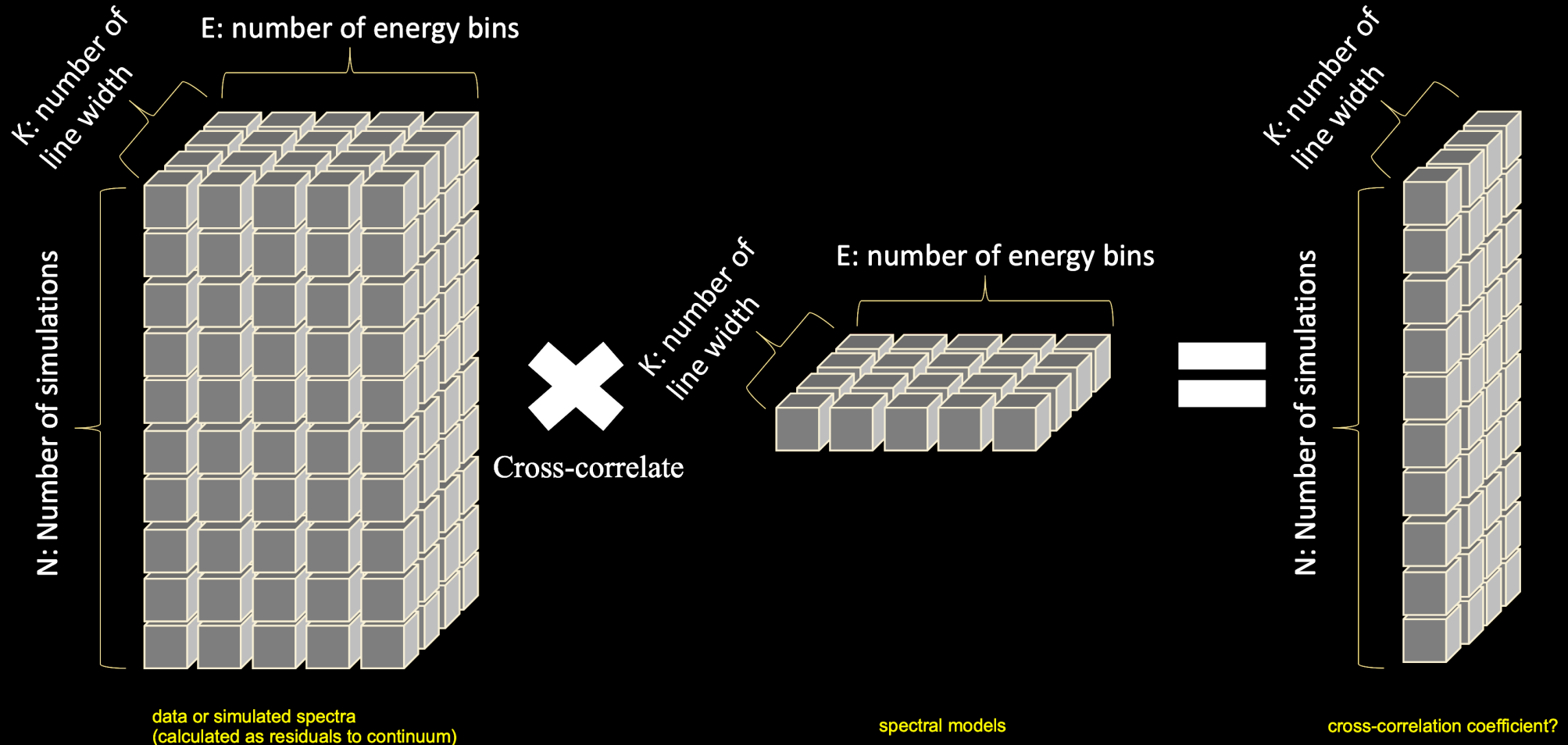
→ Also in AGN!!!
 Parker, CP + 2017 *Nature*,
 Alston, CP+ 2020 *NatAstro*
 CP+20, Xu+ 2021-2024

Absorbing
 Component
Outflowing



CP + 20b

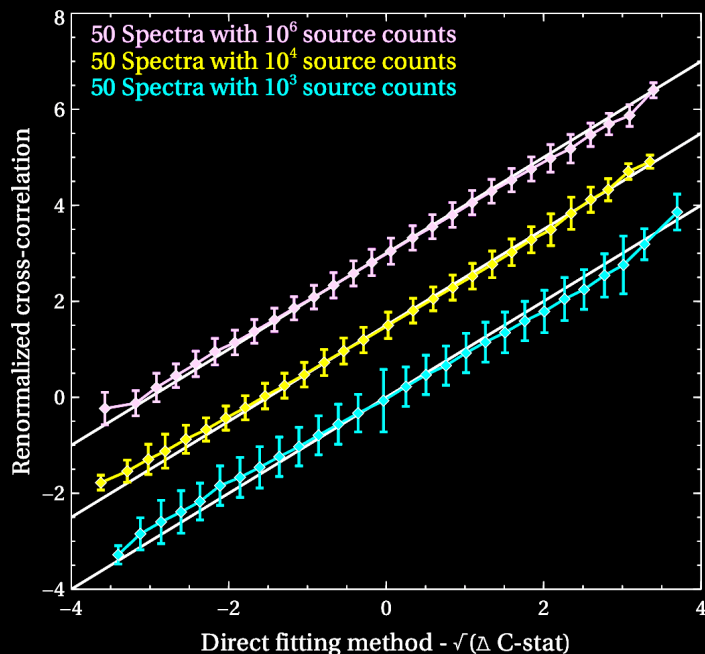
Cross-correlation method



Cross-correlation of spectral residuals

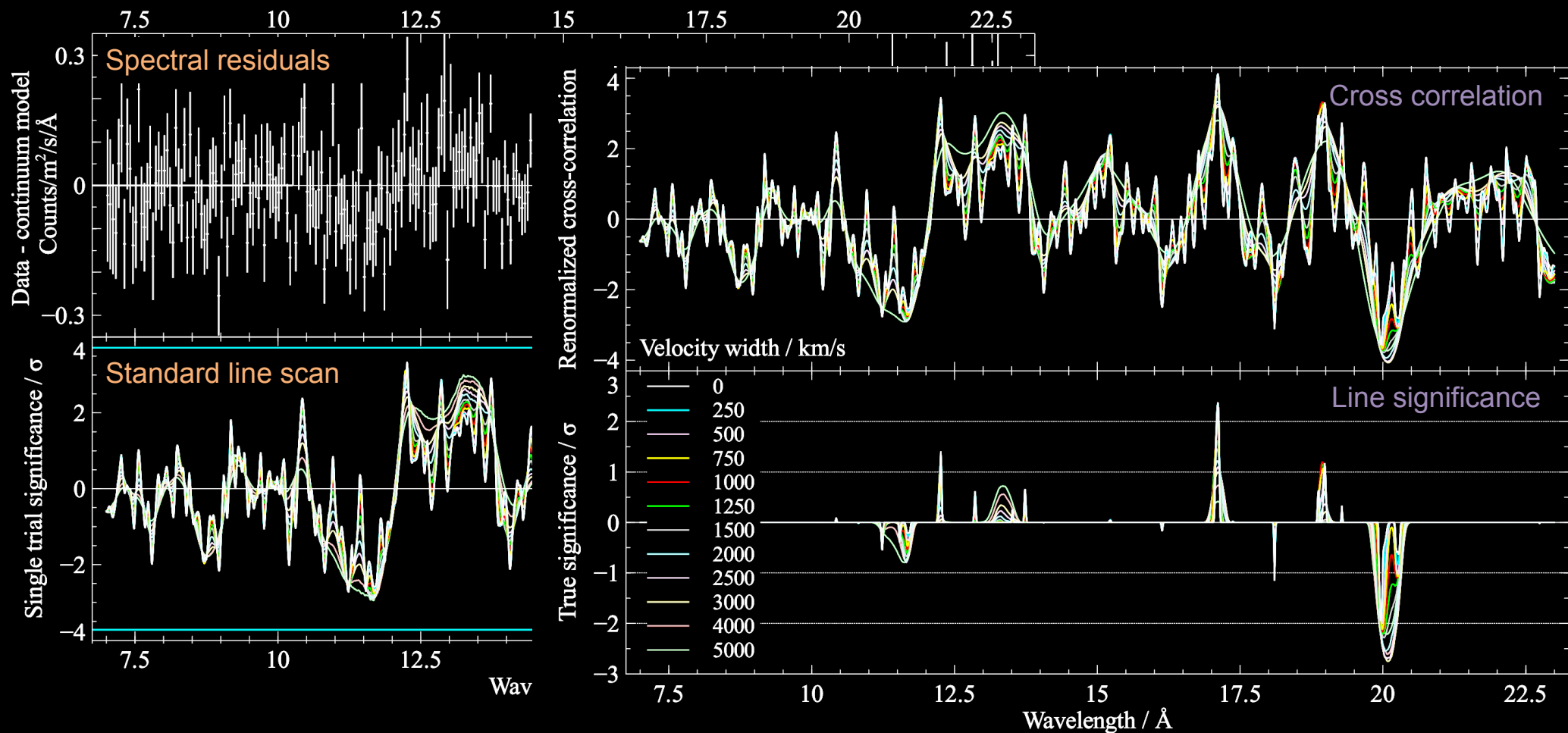
$$C = \sum_{i=1}^N x_i y_i$$

$$RC = \frac{C}{R_{\lambda,w}} \quad R_{\lambda,w} = \sqrt{\frac{1}{N} \sum C_i^2}$$



- Fit data (continuum), dump residuals in a file
- Simulate N spectra and dump residuals
- Generate grids of plasma models
- Cross-correlation residuals & models
- Renormalise the cross-correlation
- Compute false-alarm probability (p-value)

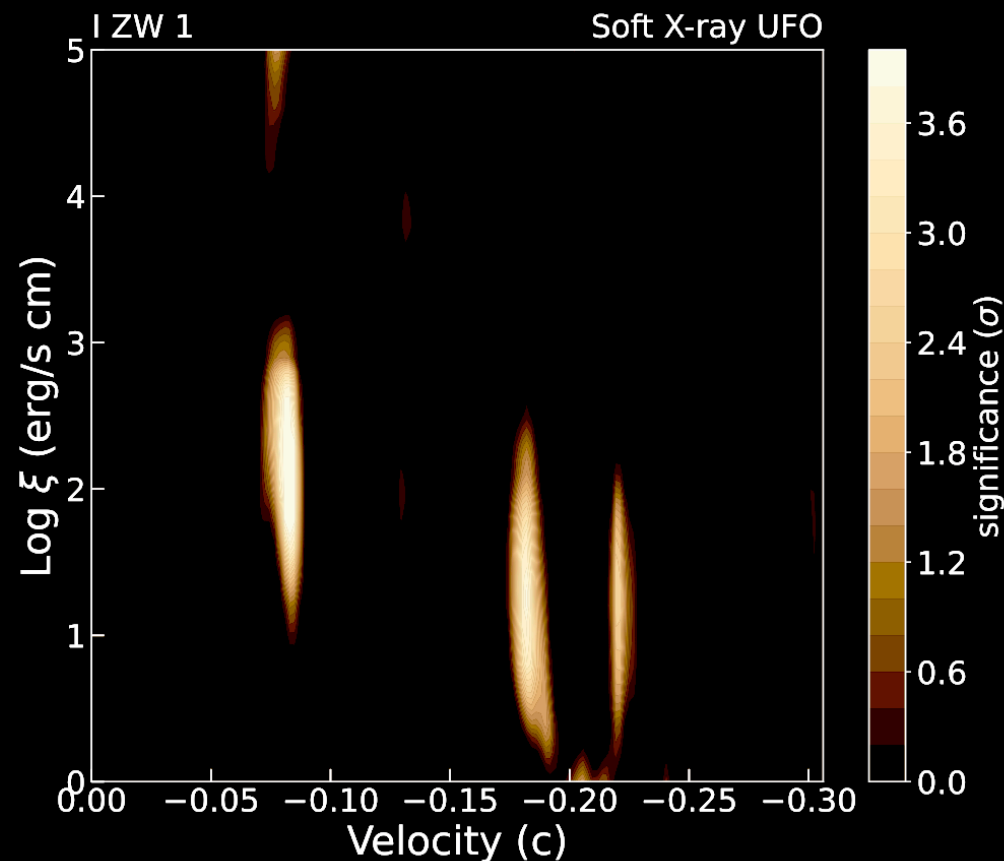
Cross-correlation of spectral residuals: gaussian



Cross-correlation of spectral residuals: xabs

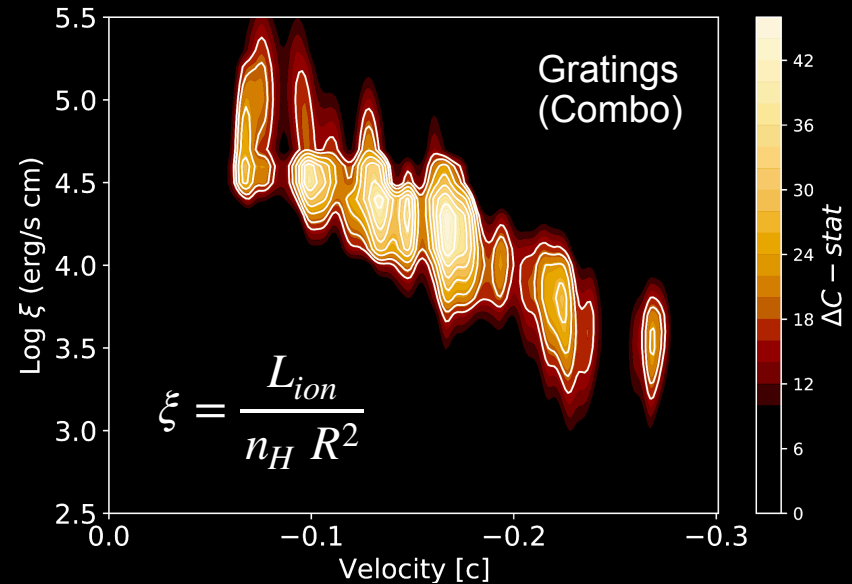
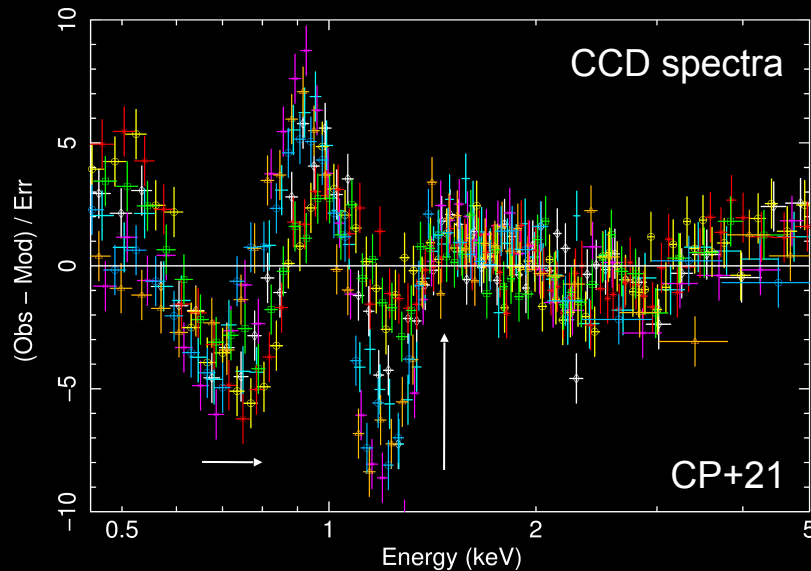
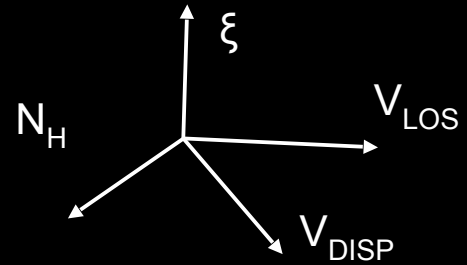
10,000 times faster!

Conservative but multiple lines
→ the most powerful!



Variable wind in supersoft NGC 247 ULX-1

- Higher blueshifts (**faster** wind?) when brightening
- and stronger low-energy (**cooler** wind?) lines



Bonus slides: significance of the wind detection via Monte Carlo simulations

NGC 55 ULX-1

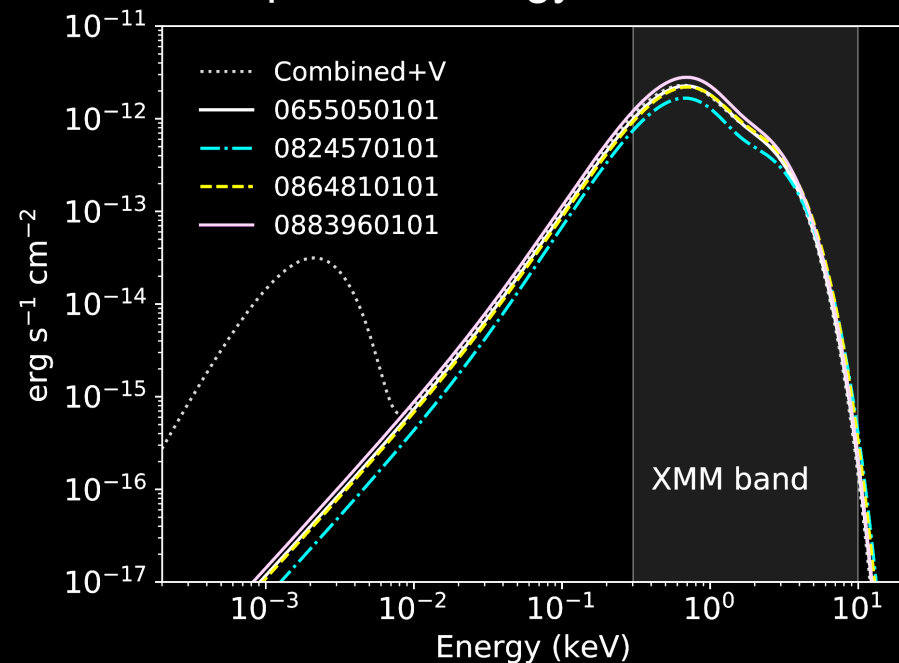
- Plasma components are typically in PIE balance
- But most likely clumpy and of different origin

$$\Xi = \frac{\boxed{F/c}}{\boxed{n_H k T}} \propto \frac{\xi}{T}$$

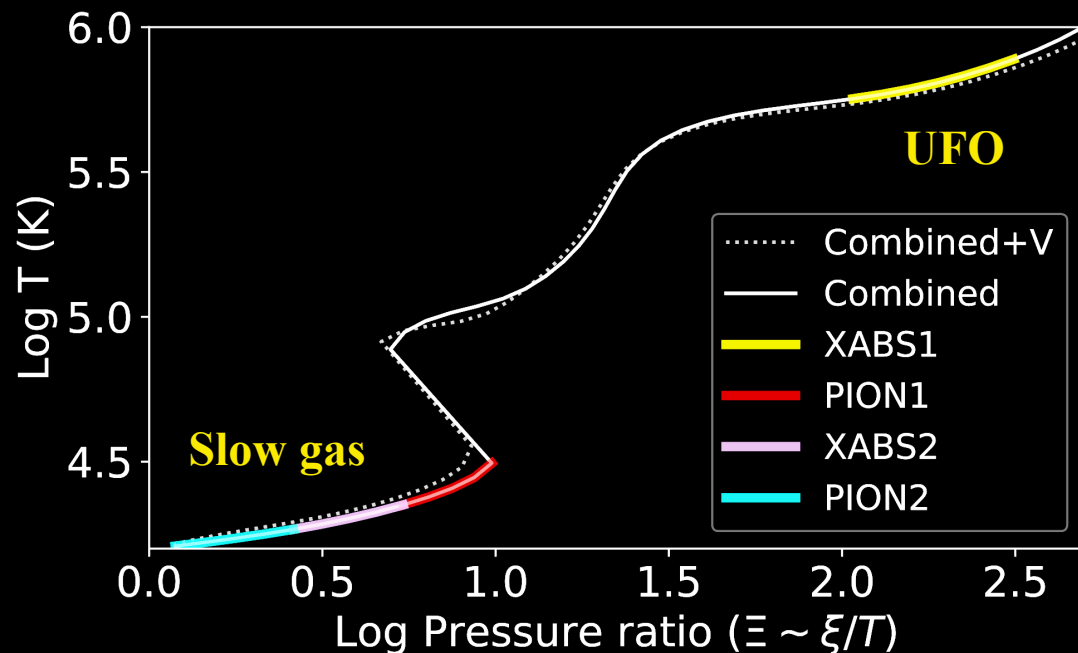
Rad. pressure

Th. pressure

Spectral Energy Distribution



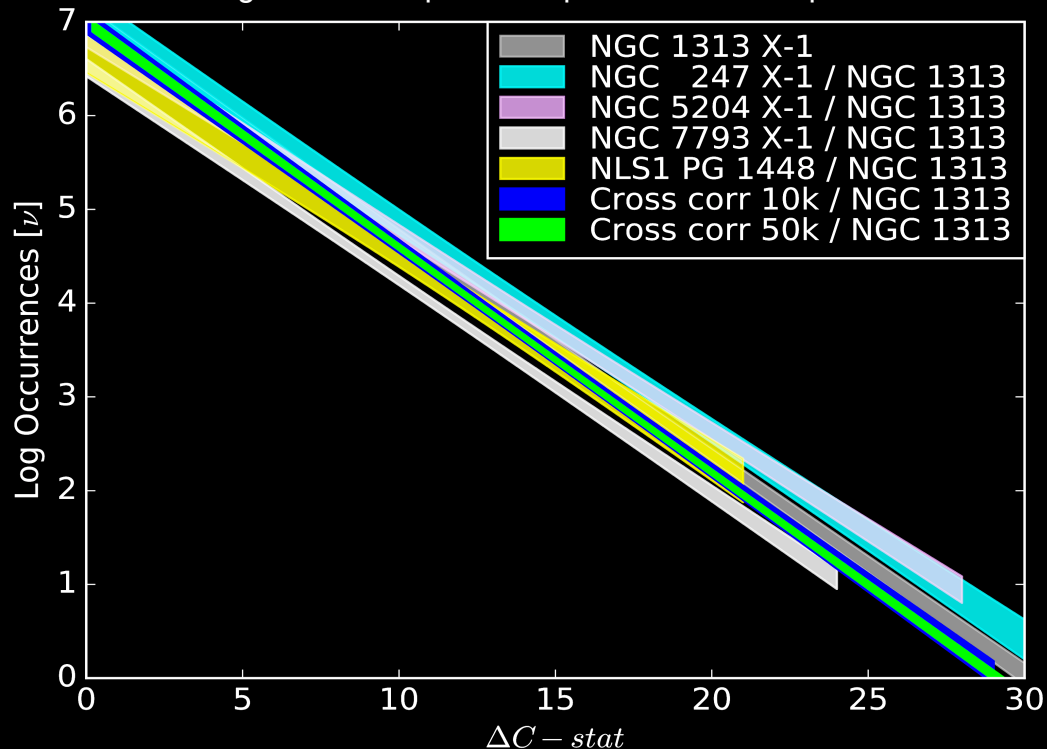
Photoionised plasma stability curve



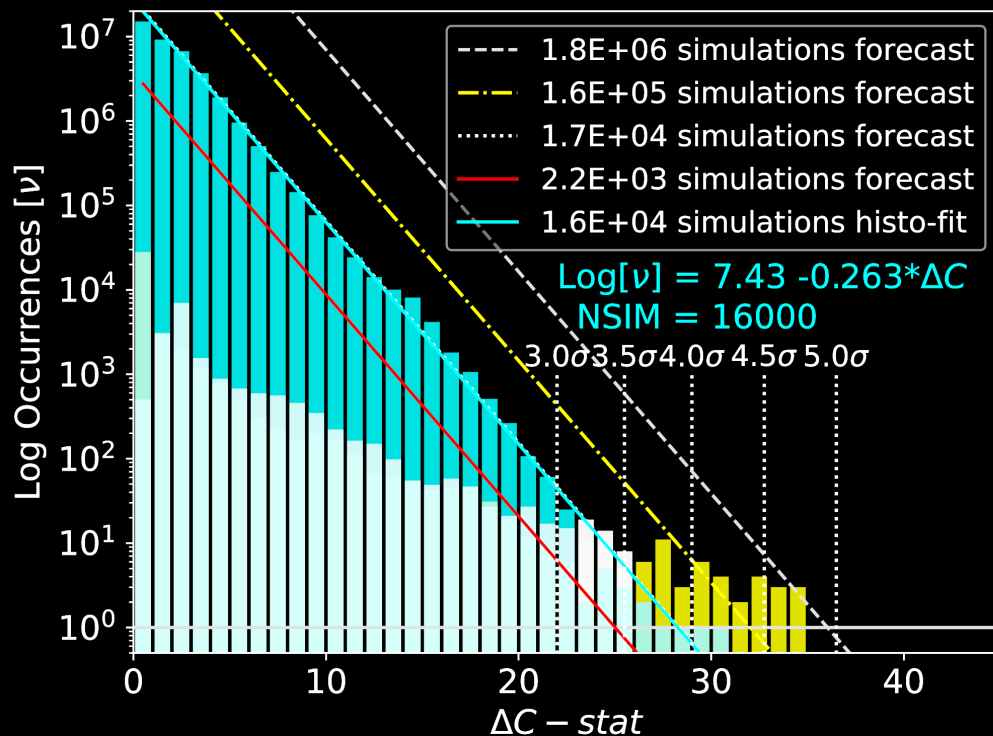
Wind detection significance

A featureless spectrum (continuum model only) is simulated N-times and scanned the same way!

Histogram of the spectral improvements: comparison



Histogram of the spectral improvements: NGC 55 single obs

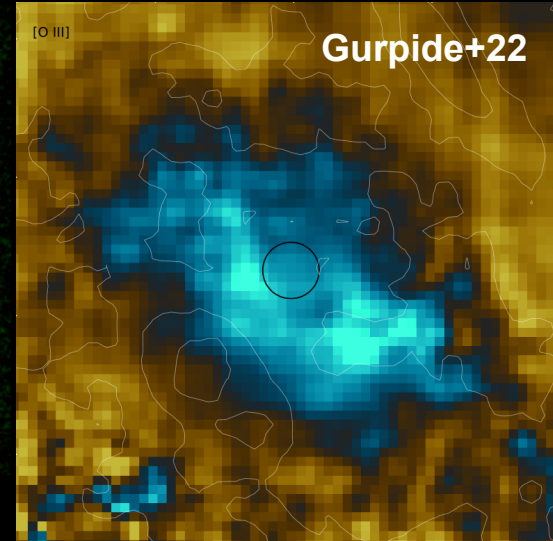
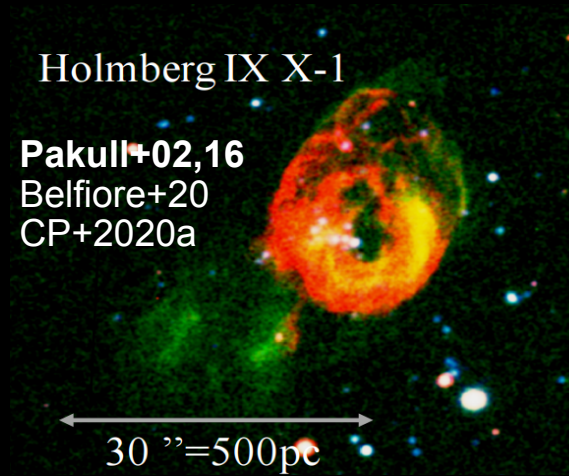


Environ

Can the winds *inflate* ULX bubbles?

Kinetic power :

$$\begin{aligned}
 L_{\text{wind}} &= \frac{1}{2} \dot{M}_{\text{out}} v^2 \\
 &= 2 \pi m_p \mu \cdot \Omega C \cdot L_{\text{ion}} \frac{v^3}{\xi} \\
 &\approx 10^{39-40} \text{ erg s}^{-1}
 \end{aligned}$$



$$R_{\text{Bubble}} = 0.76 \left(\frac{\dot{M}_w v_w^2}{2 \rho_{\text{ISM}}} \right)^{1/5} t_{\text{Bubble}}^{3/5} \approx 100 \text{ s pc}$$

$$(t_{\text{Bubble}} \approx 10^{5-6} \text{ yr})$$

Required bubble dimension :

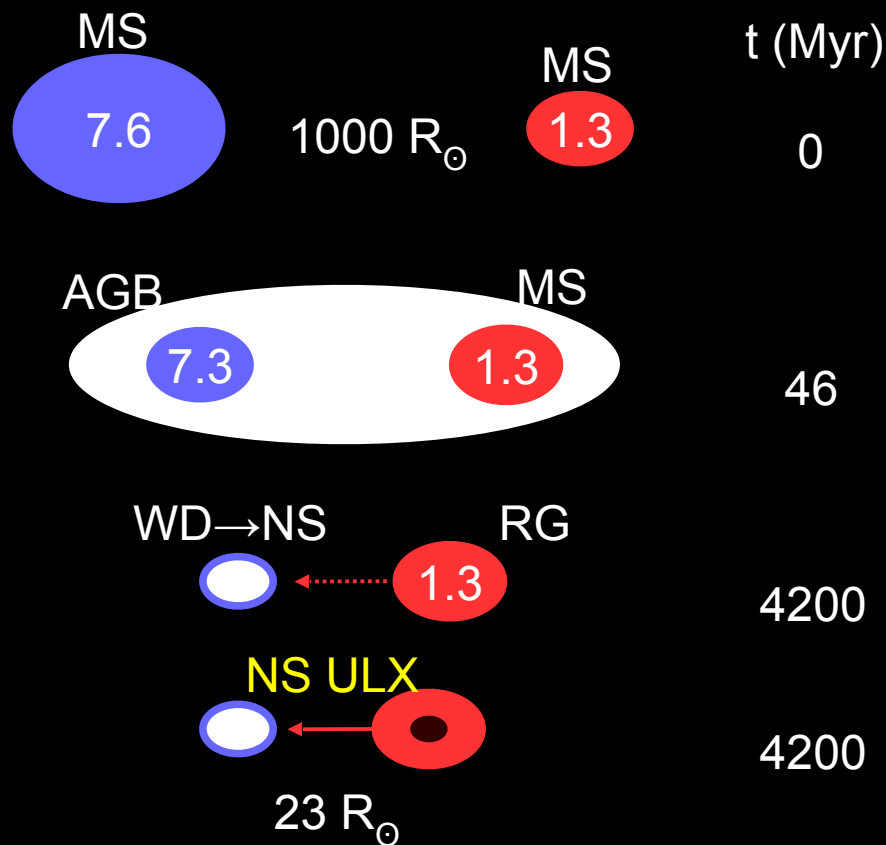
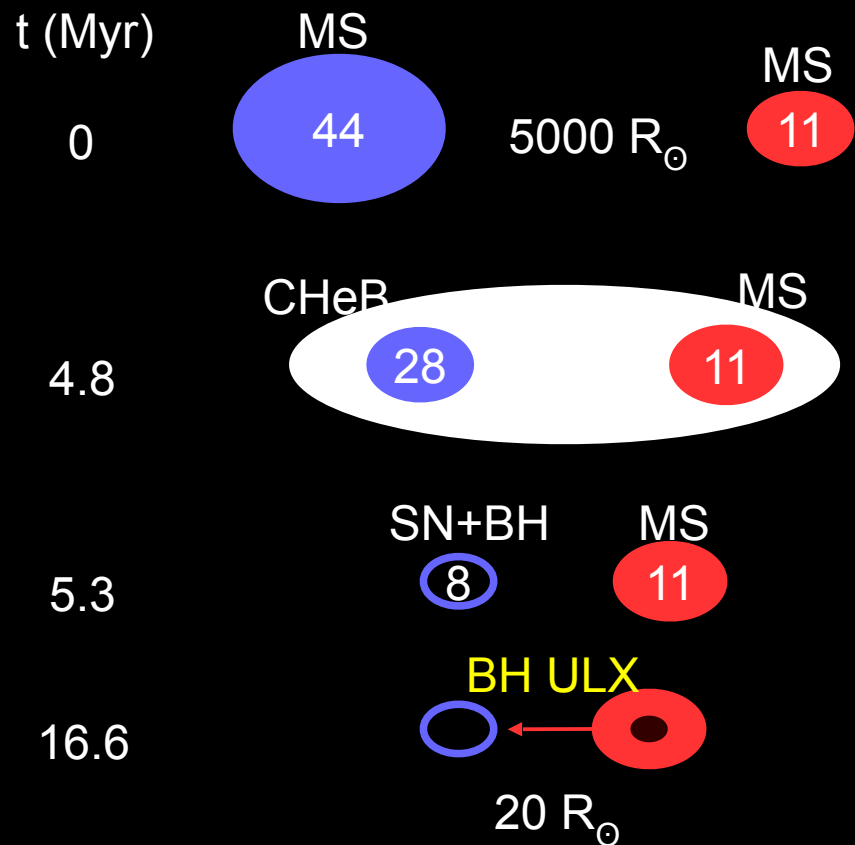
$$R_{\text{Bubble}} \geq 100 \text{ pc}$$

Pakull+02,16
Belfiore+20
CP+2020a

ULX – binary system formation channels

Optical counterparts: BSG / RSG
Heida+, Lopez+

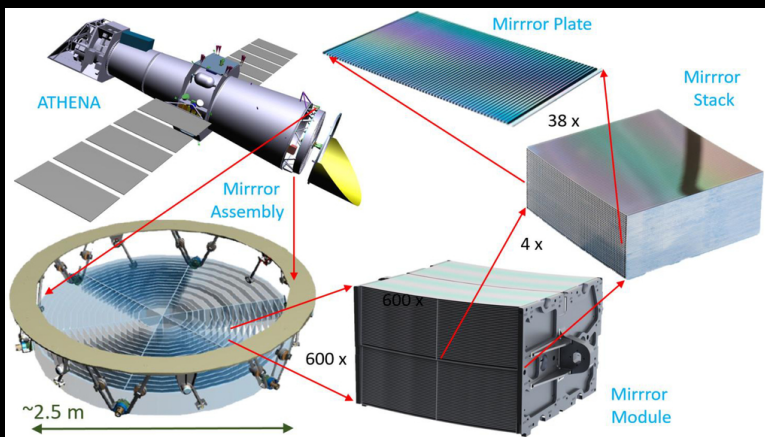
Wiktorowicz+17
Mapelli+10



Future Missions

NewAthena

The (new) Advanced Telescope for High ENergy Astrophysics



Mirror

Silicon Pore Optics
HEW better the 9''
(XRISM ~ 90'')

$$\text{Area} = 1\text{m}^2$$

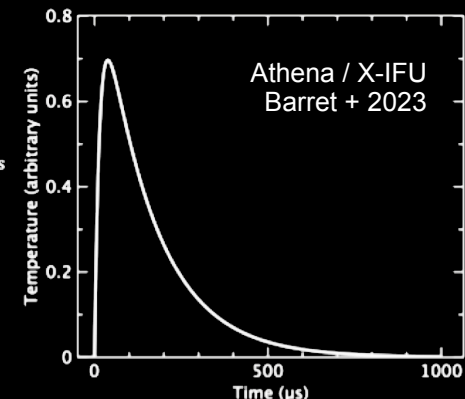
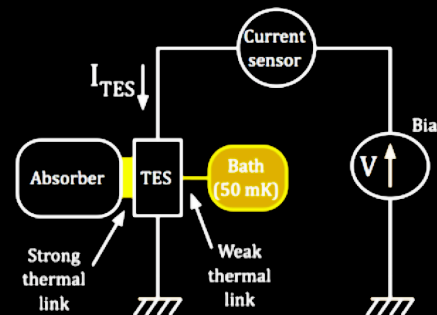
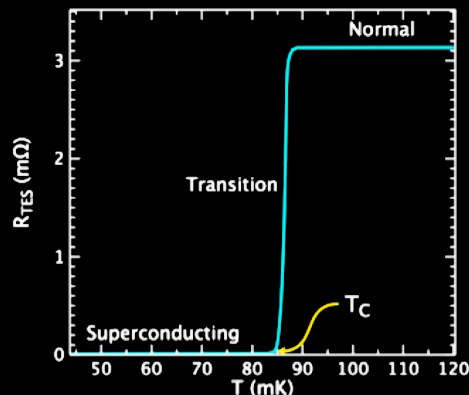
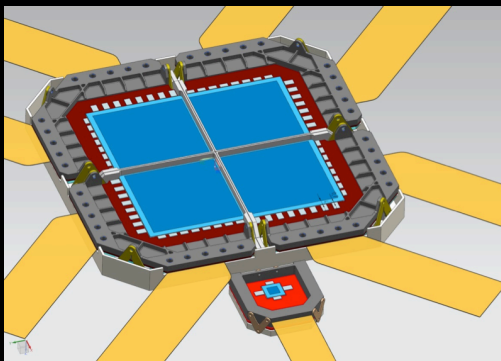


X-ray Integral Field Unit (X-IFU)

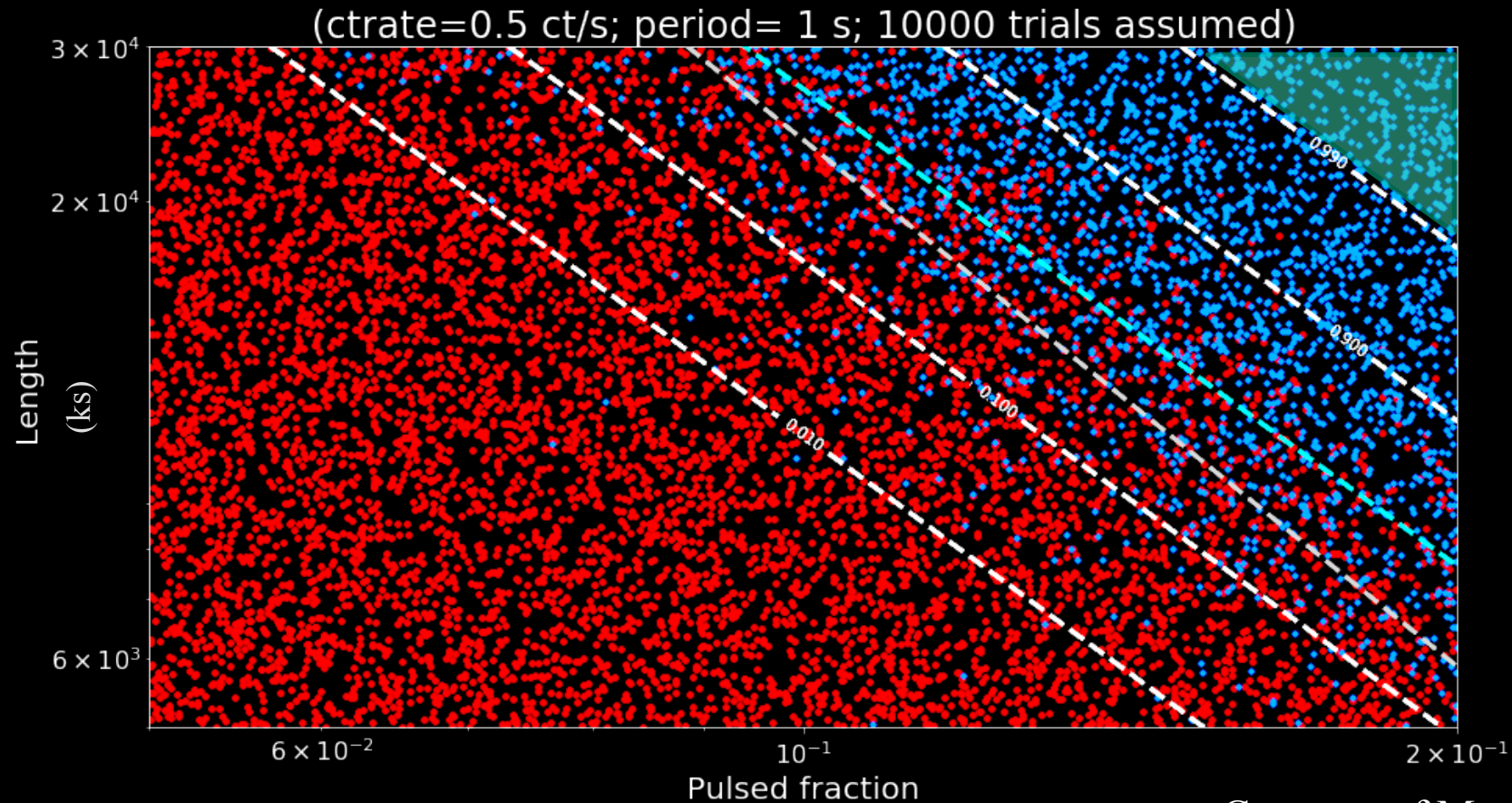
1 TES = $50\text{ }\mu\text{m}^2$ Mo/Au bilayer voltage at a
superconducting-to-normal transition
temperature $\sim 90\text{ mK}$ ($<4\text{eV}$ resolution)

Wide Field Image (WFI)

CCD, 40', $<5\text{ms}$, low BKG



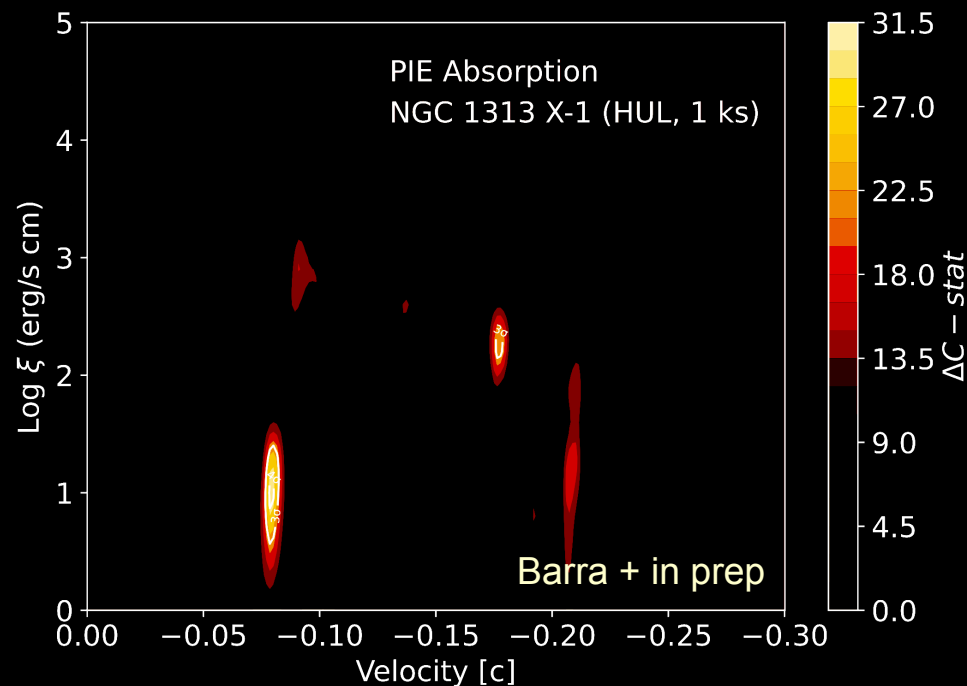
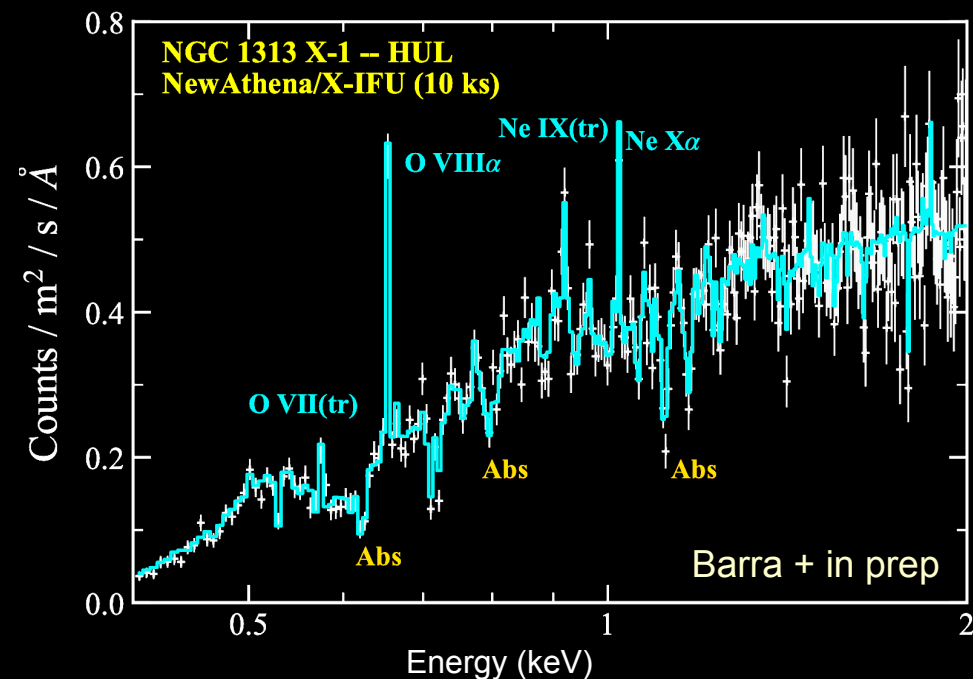
Athena simulation of pulsation detection



Courtesy of Matteo Bachetti

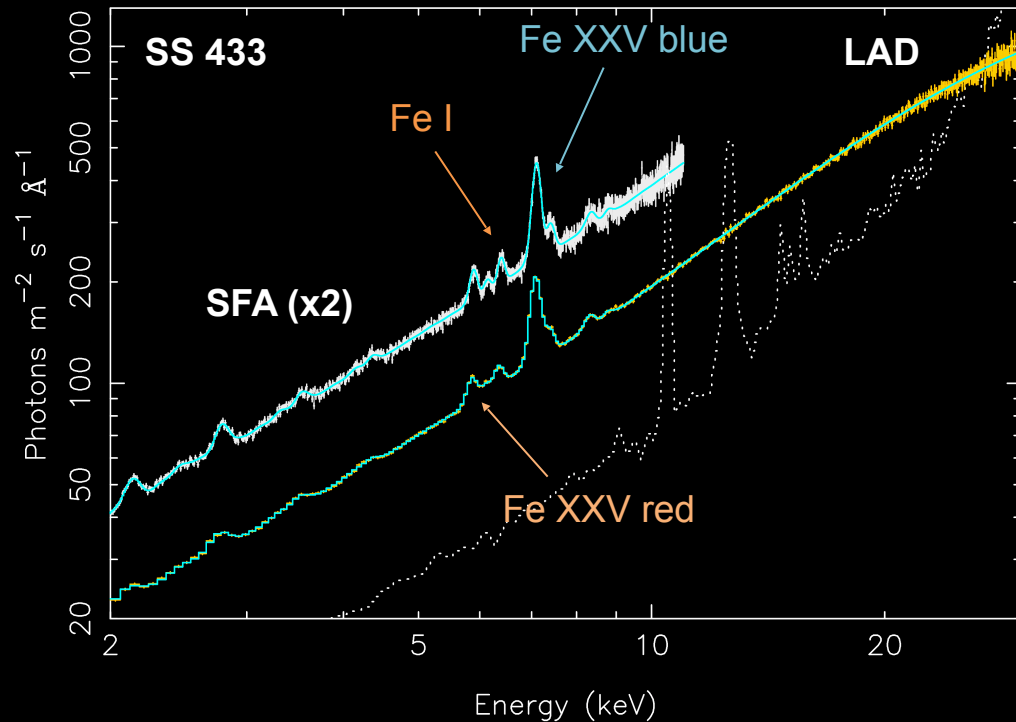
NewAthena / X-IFU simulations

- Individual lines detected at $>5\sigma$ in observations <10 ks
- Outflow properties characterised in ≤ 1 ks matching the timescales of lags & variability

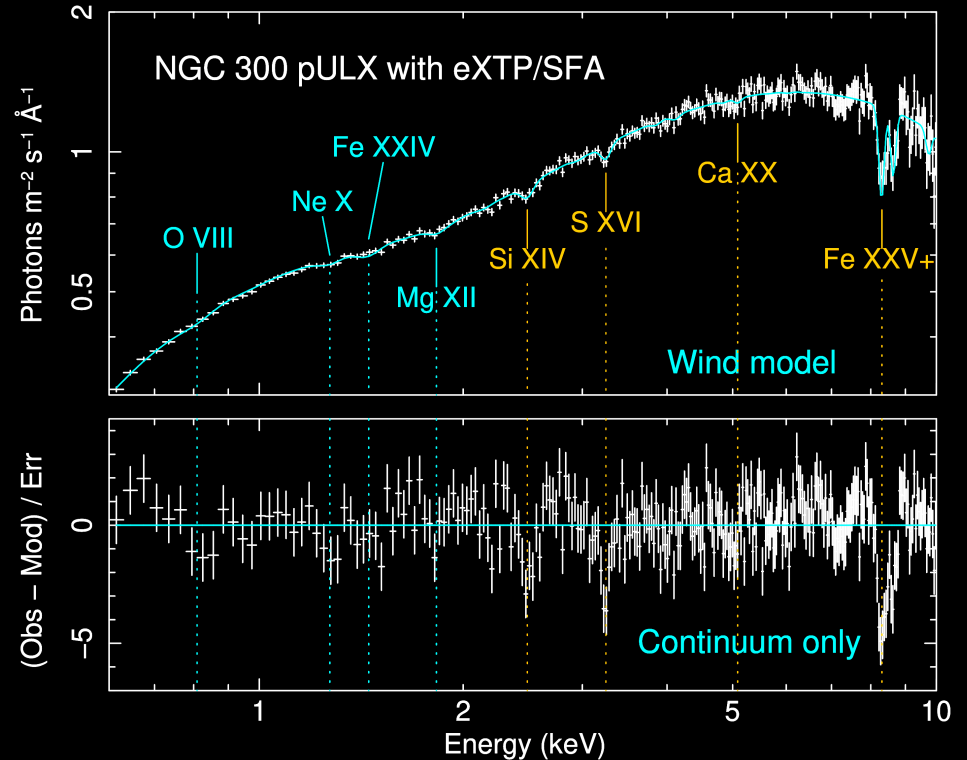


Enhanced X-ray Timing & Polarimetry Mission

Detecting jets in SS 433 (& bright ULXs)



Detecting winds in hard ULXs & pulsars



SQUDE calorimetry concept mission

- Individual lines detected at $>5\sigma$ in observations <100 ks
- Outflow properties characterised in **~ 10 ks** matching intermediate variability timescales

