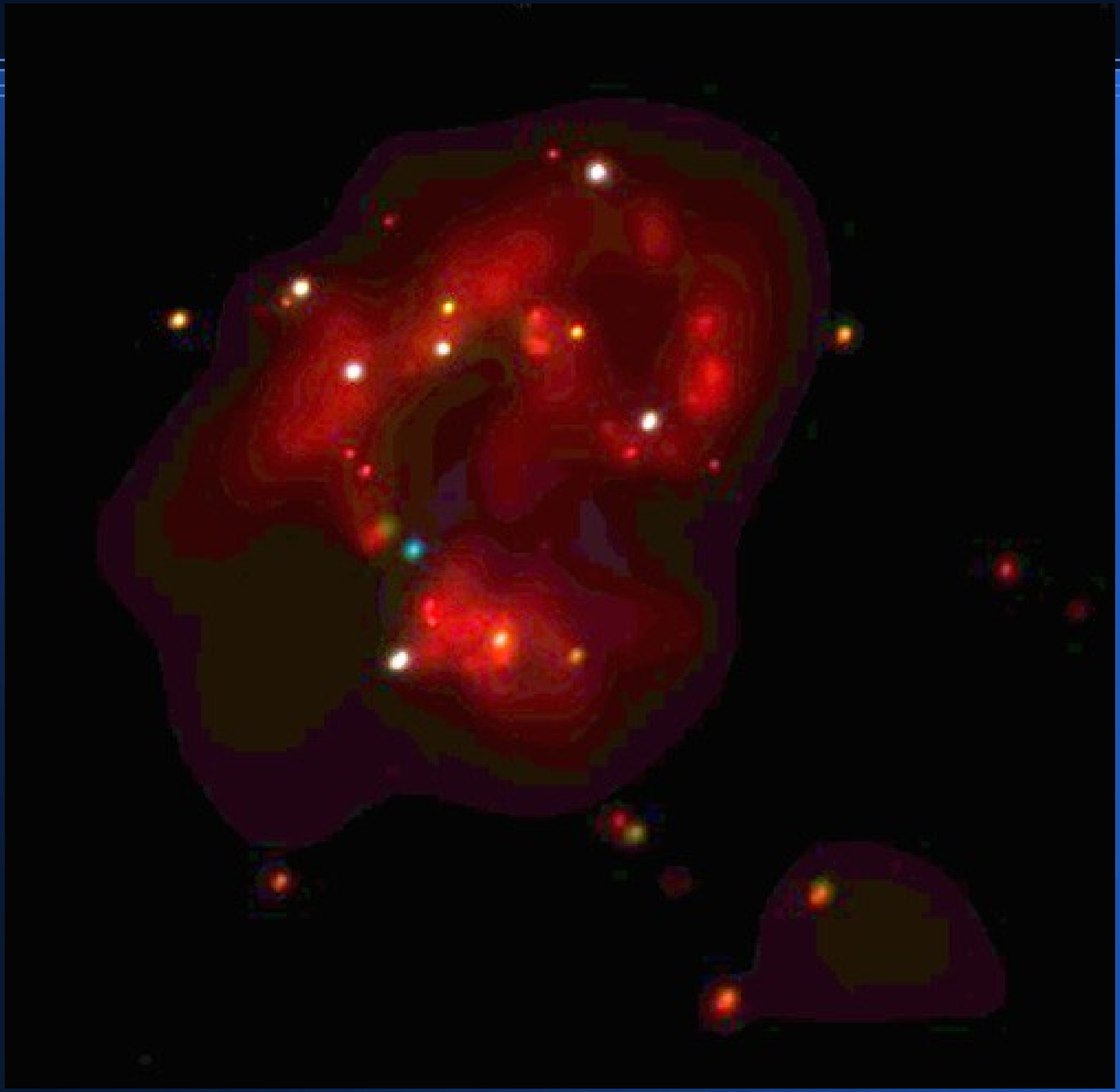
On the search of the elusive Intermediate Mass Black Holes

M. D. Caballero-Garcia (ASU-CAS), M. Bursa (ASU-CAS), M. Dovčiak (ASU-CAS), *S. Fabrika (SAO-RAS), A. J. Castro-Tirado (IAA-CSIC), V. Karas (ASU-CAS), on behalf of a larger collaboration*

Ultra-Luminous X-ray sources



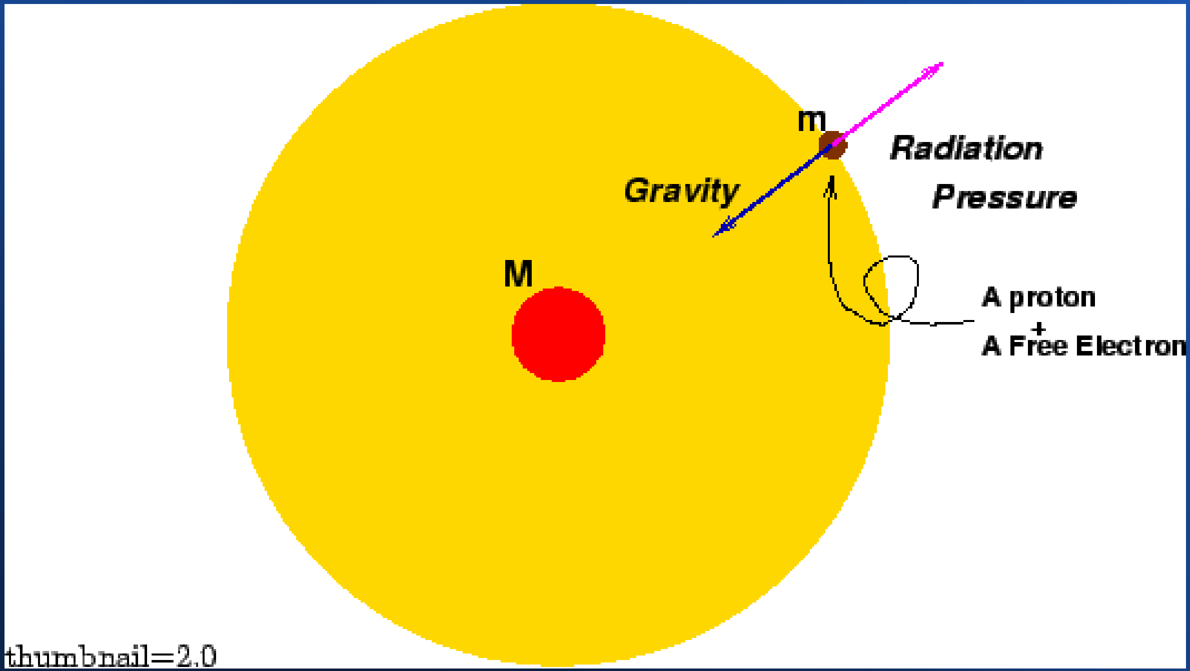
Chandra X-ray image of the Antennae galaxies (from Fabbiano et al. 2004)

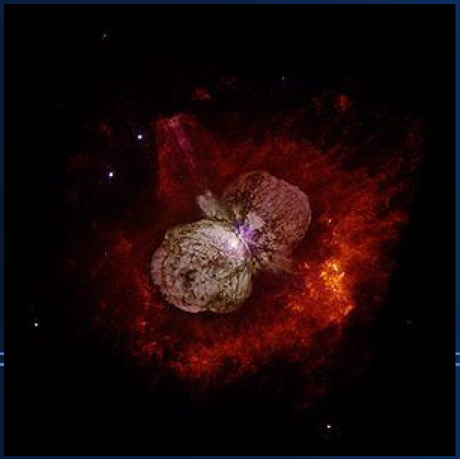
The Ultra-Luminous X-ray sources

- Ultra-Luminous X-ray (ULX) sources are point-like, off-nuclear sources observed in other galaxies, with ***total observed*** luminosities greater than the Eddington luminosity **for a stellar-mass black hole** ($L_X \sim 10^{38}$ erg/s).

→ either the emission *is not isotropic* ***or the black hole has a higher mass*** ***($M_{BH} \geq 20\ M_\odot$)***.

The Eddington limit





Eta Carinae (Eddington limit exceeded)

- Probably the maximum luminosity of a star.

$$\sigma_p \frac{L}{4\pi c r^2} \leq \frac{GMm_p}{r^2}$$

$$L \leq \frac{4\pi G m_p c}{\sigma_T} M \equiv L_{EDD}$$

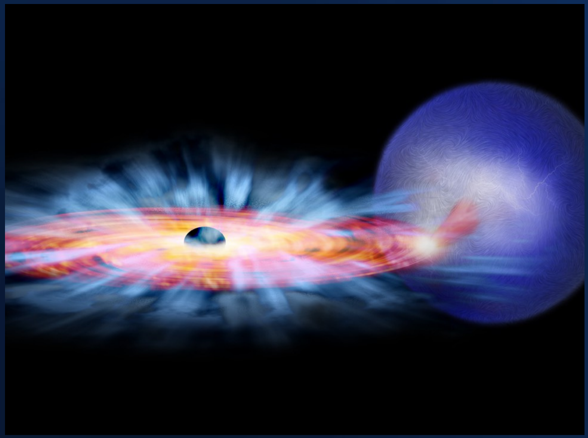
$$L_{EDD} = 1.2\times 10^{38} \left(\frac{M}{M_{\odot}}\right)$$

- It depends on the mass of the star.
- When the source emits isotropically. If not, this limit can be *exceeded*.

The Ultra-Luminous X-ray sources

- This opens a real possibility to the *existence of the InterMediate-Mass Black Holes* (IMBHs; $M_{BH} \geq 10^2$-10^4 $M_\odot$; Colbert & Mushotzky, 1999).

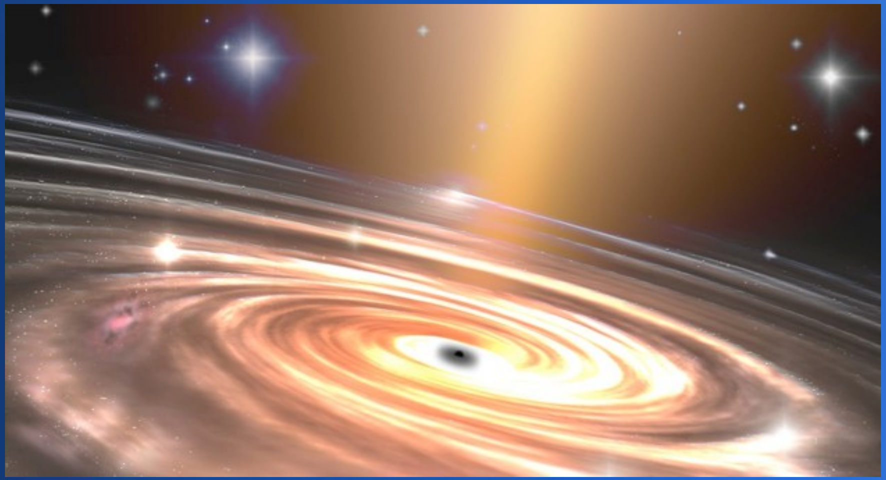
- The existence of these ULXs-IMBHs is controversial only few cases recently confirmed (ESO 243-49 HLX1, Farrell et al. 2011; see Sutton et al. 2012 for a few more candidates). See Mezcua+17 for many IMBH candidates with $M_{BH} \geq 10^3$-10^4 $M_\odot$



Stellar-mass Black Hole (BH); ***$M_{BH} \leq 10$ $M_\odot$***

IMBHs (Madau & Rees, 2001)

?



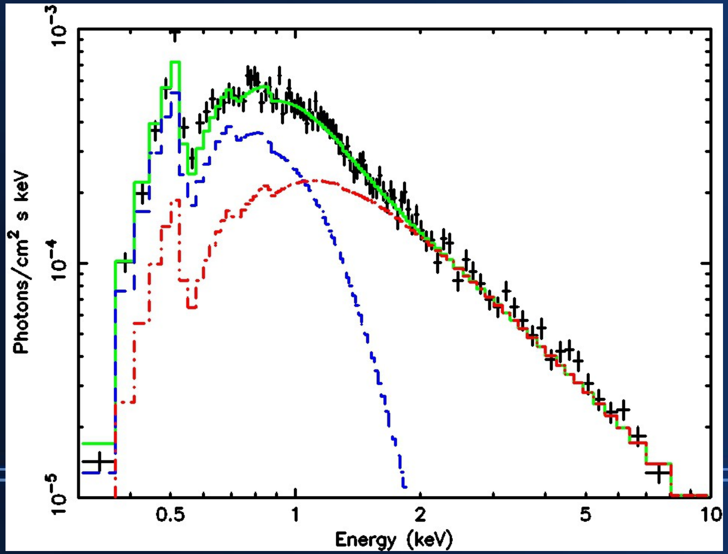
Supermassive Black Hole (AGN); ***$M_{BH} \geq 10^6$ $M_\odot$***

The Ultra-Luminous X-ray sources – the Standard (thin) Disc Theory

- **X-ray spectroscopy is useful. From the *Standard (Thin) Disc Theory* (applicable to sub-Eddington flows) the inner disk temperature scales with the mass of the BH as (Makishima et al. 2000)**

$$kT_{in} \sim M^{-1/4}$$

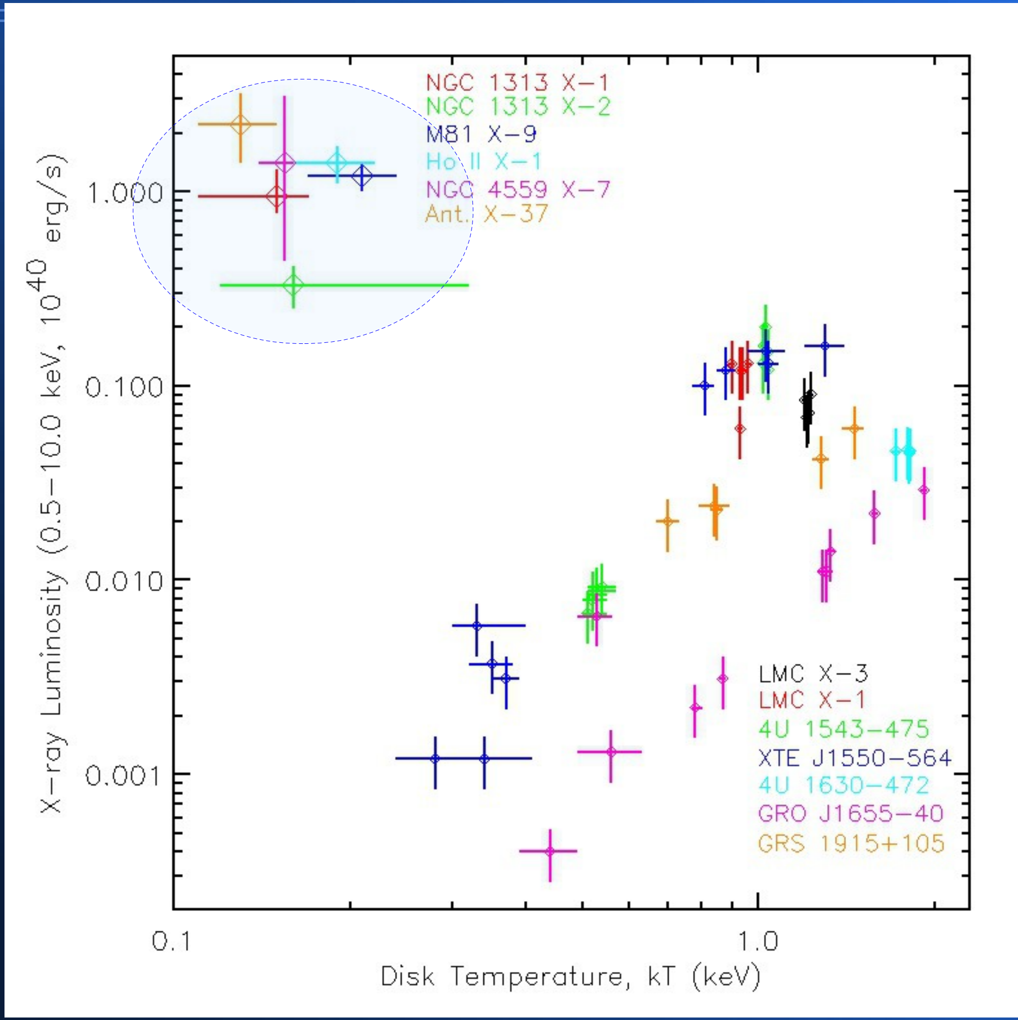
→ Inner disc t*emperatures found imply IMBHs for some ULXs (Miller et al. 2004).*



The XMM-Newton/EPIC-pn X-ray spectrum of NGC 1313 X-1 is shown (Miller, Fabian, & Miller 2004).

The need of slim-disc models

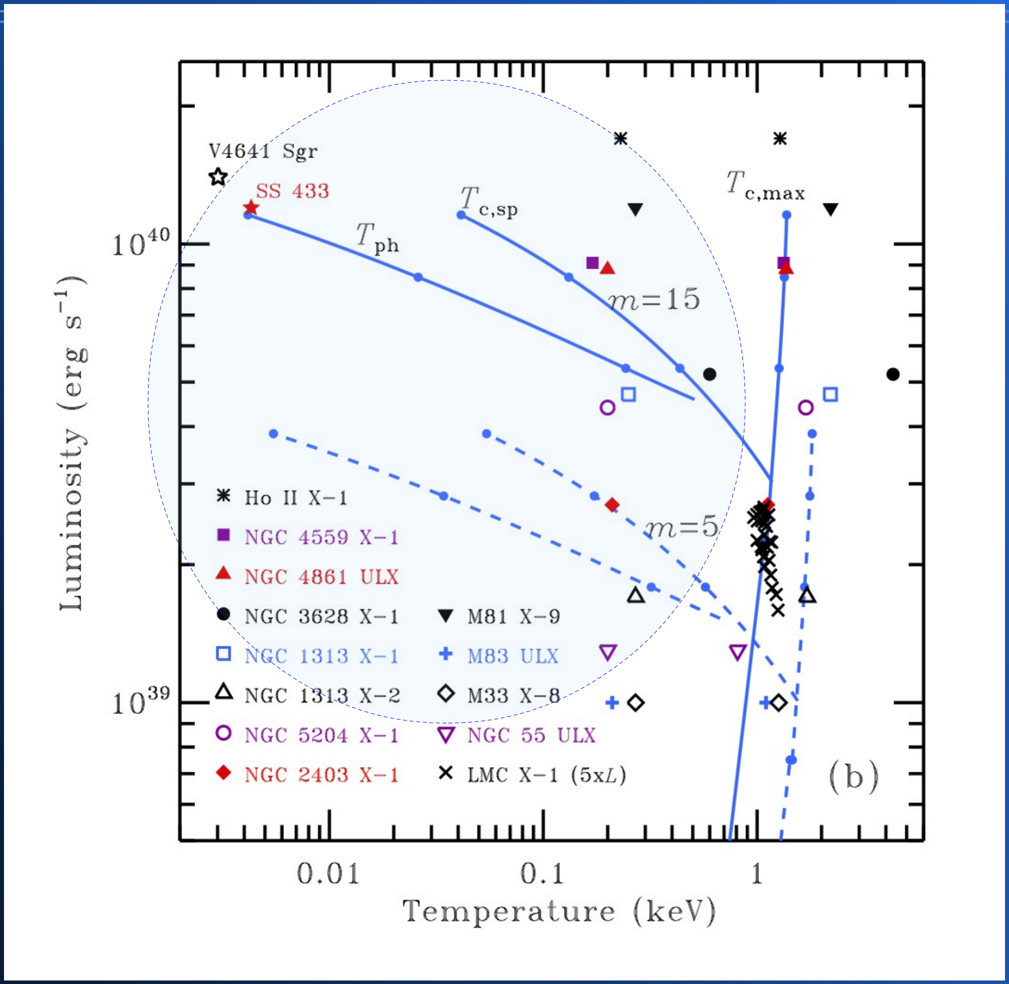
INNER DISC TEMPERATURE IS APPROX. “CONSTANT” (0.1-0.2 keV)



X-ray luminosity versus inner disc temperature inferred from X-ray spectral fits for a sample of ULXs and of BHBs. Figure taken from Miller, Fabian & Miller (2004).

The need of slim-disc models

IS THE ACCRETION DISC REALLY "STANDARD" IN ULXs ?

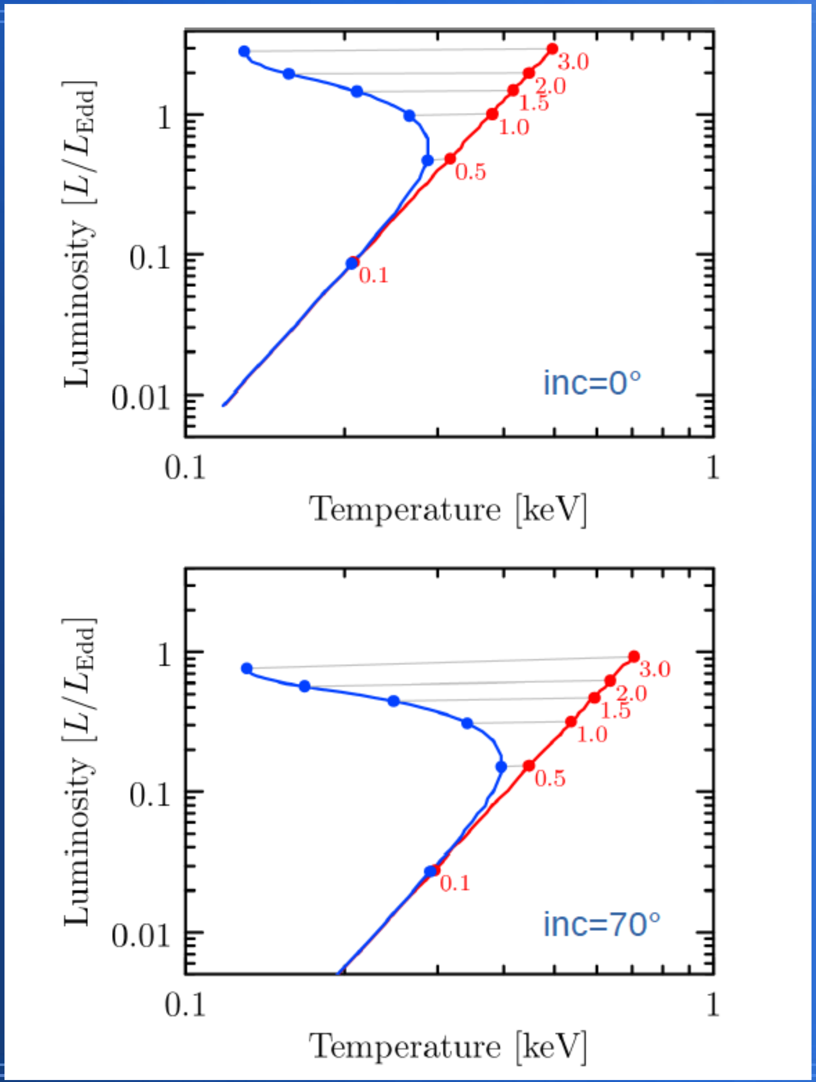


X-ray luminosity versus inner disc temperature inferred from X-ray spectral fits for a sample of ULXs and of BHBs. Figure taken from Poutanen et al. (2007).

The need of slim-disc models

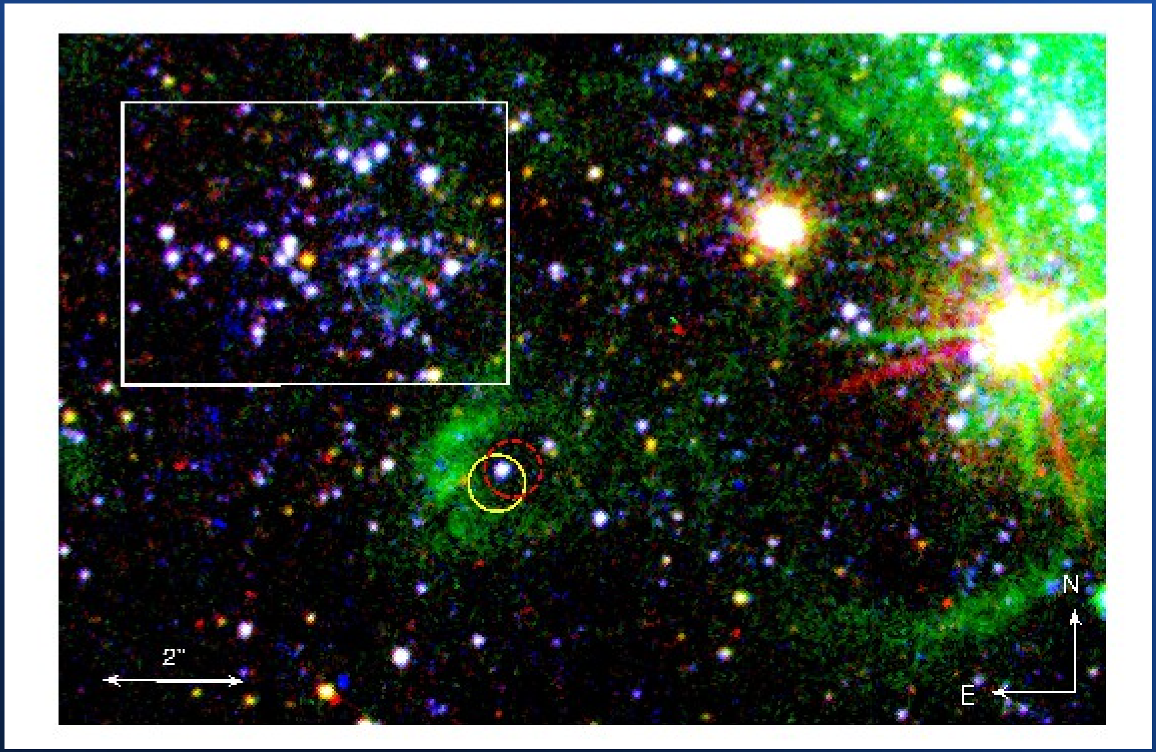
L-T plot in near-Eddington case

- Standard (thin) disc follows $L \sim T^4$ relation.
- Advection and obscuration effects cause *significant deviations from that relation in super-Eddington regime*.
- The effect is strong inclination dependent.
- Observed luminosity *can stay around Eddington* if mass accretion rate is high.



X-ray luminosity versus inner disc temperature for the standard (red) and the slim accretion disc (blue). Figure taken from Bursa (2016).

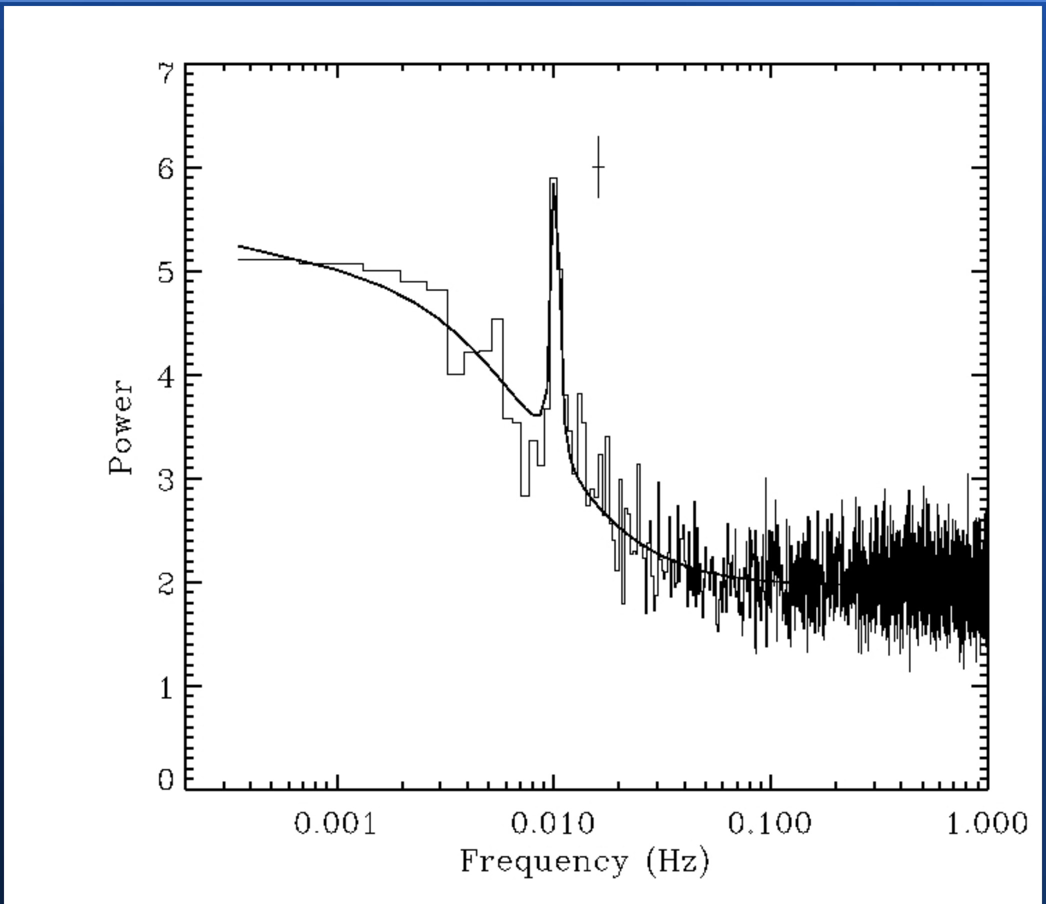
NGC 5408 X-1



HST image (blue - F225W, green - F502N, red - F845M) of ULX NGC 5408 X-1 (circled), the surrounding field and a nearby stellar association (box) (from Grise et al. 2012)

- Nearby (D=4.8 Mpc)
- Peak (*RXTE*, 0.3-10 keV, 2008-2009) X-ray luminosity of $L_X=2\times10^{40}$ erg/s (Strohmayer, 2009).
- Strohmayer & Mushoztky (2009) estimated a BH mass of $M=10^3$-10^4 $M_\odot$
- 6-Long 100 ks observations with XMM-Newton performed in 5 years (2006-2011).
- *X-ray timing and spectral analysis* reported in Strohmayer et al. (2007), Strohmayer & Mushotzky (2009), Dheeraj & Strohmayer (2012), Caballero-Garcia et al. (2013).

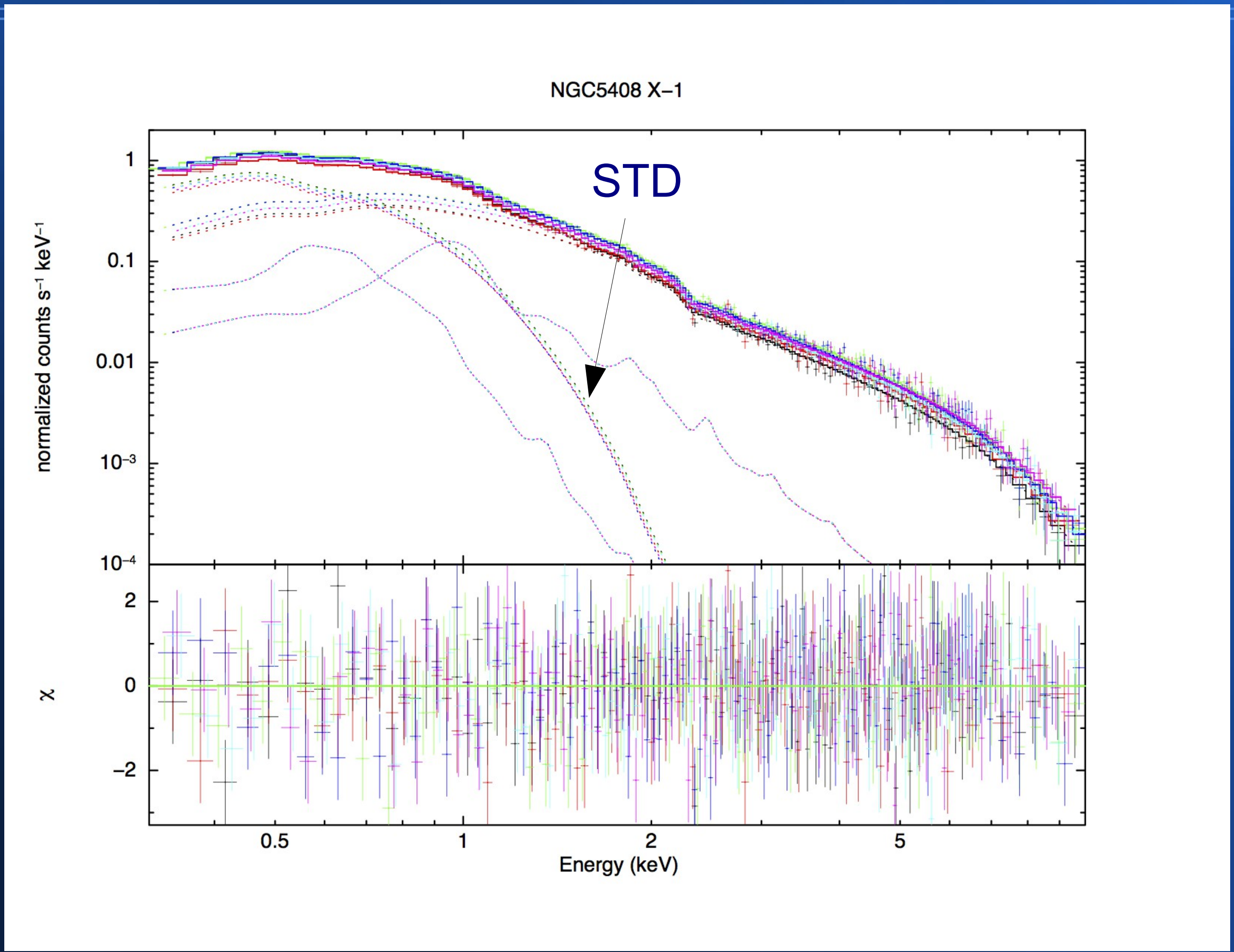
NGC 5408 X-1 – X-ray timing



Average PDS of NGC5408 X-1 (from Strohmayer & Mushotzky, 2009)

- BH masses scale with the break frequency of their Power Density Spectrum (PDS; McHardy et al. 2006; Kording et al. 2007). This relation holds over six orders of magnitude in mass, i.e., from Black Hole Binaries (BHBs) to Super-Massive Black Holes (SMBHs).
- PDS and the energy spectrum of NGC 5408 X-1 are *very similar to that of BHBs in the Steep Power-law (SPL) state. BUT the* characteristic timescales within the PDS are lower by a factor of ≈100 and X-ray luminosity is higher by a factor of a few ×10, when compared to BHBs → $M_{BH} \geq 10^3$-10^4 $M_\odot$.

NGC5408 X-1 X – X-ray spectroscopy



XMM-Newton fitted-spectra from the 6 observations (from Caballero-Garcia et al., 2013)

- Little spectral evolution (slight spectral hardening), in spite of the observations spread in 5 yr.
- Fit with several phenomenological models (*diskbb* or *diskpn* for the soft X-rays and *powerlaw* or *compTT* for the high-energies; 2 *apec* for the diffuse emission).
- Steep spectra ($\Gamma \approx 3$) and cold (and constant) inner disc temperature ($kT_{in} \approx 0.17$ keV) → $M = 2\times10^{3}\,M_{\odot}$; $\eta = 10^{-1}$

Does it mean that we have found one of the IMBHs proposed to exist as cosmological seeds of current galaxies by *Madau & Rees (2001)* ?

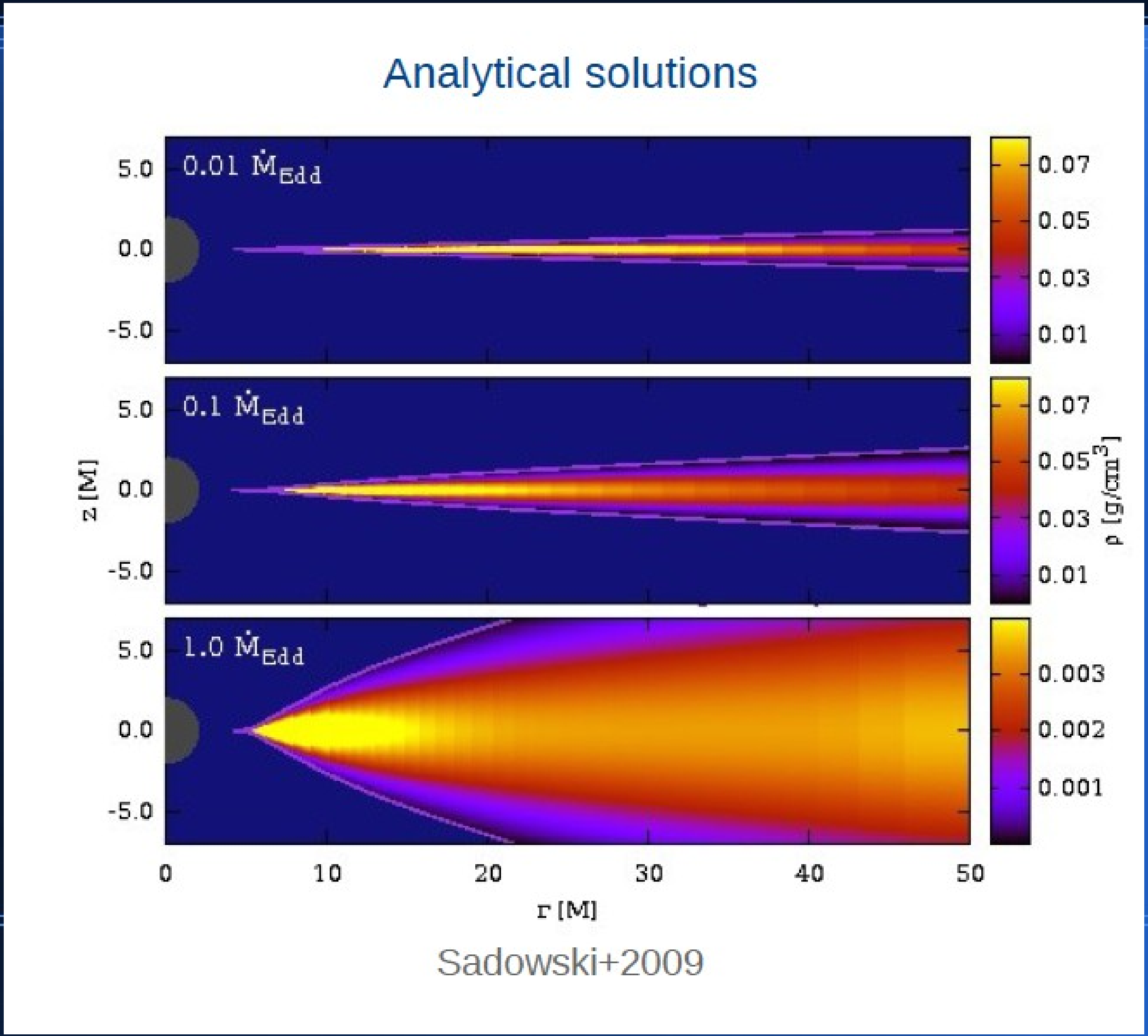
Very likely not

The SLIMULX model

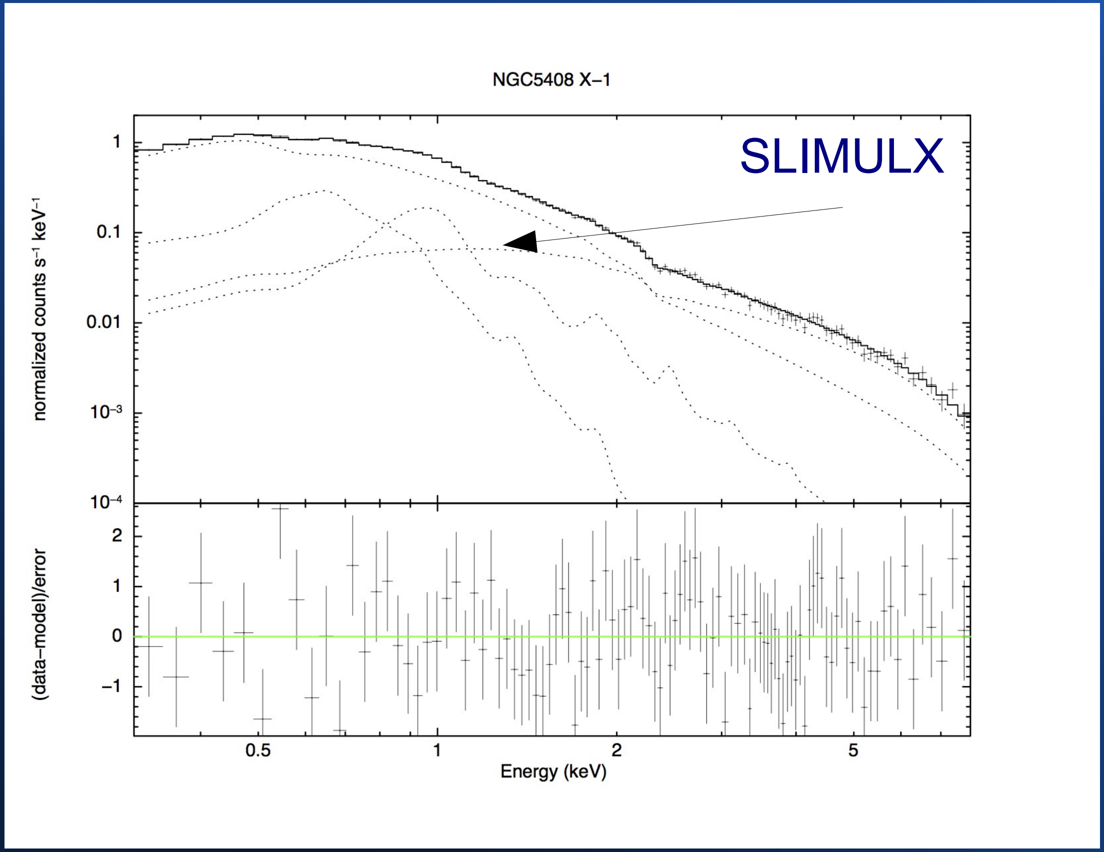
[*It is a thermal disc model (effects from the corona not taken into account)*]

- Thin disc model is inaccurate for $L>0.3\ L_{EDD}$.
- Such models tend to give incorrect values for BH masses and for accretion rate (luminosity).
- Standard (thin) discs follow $L \sim T^4$ relation.
- Advection and obscuration effects cause significant deviations from that relation in super-Eddington regime.
- The effect is strongly inclination dependent.
- Observed luminosity can stay around Eddington even if mass accretion rate >> 1 → *Reduces inferred BH mass* !!!!!
- General Relativistic effects are fully consistently taken into account.

The SLIMULX model



NGC 5408 X-1 spectrum fitted with SLIMULX



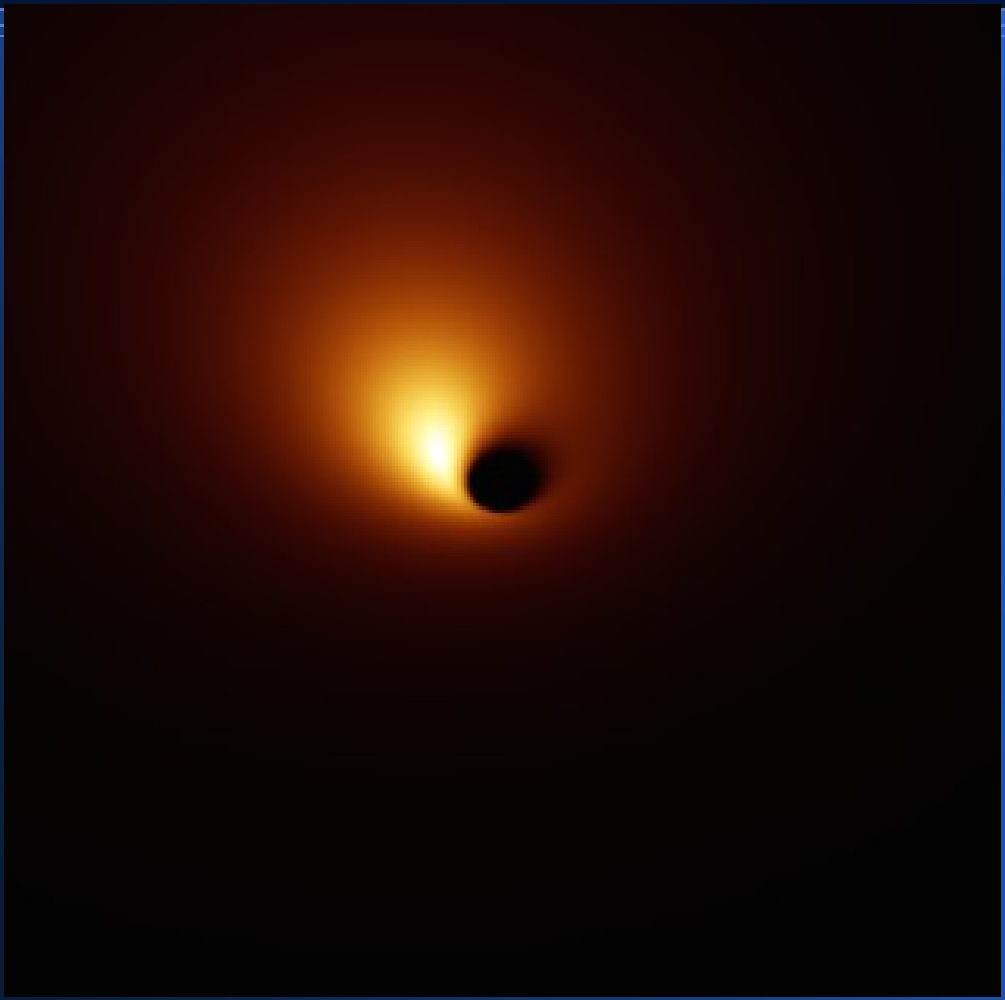
XMM-Newton fitted-spectrum using SLIMULX (from Caballero-Garcia et al., 2017)

We fitted the spectrum of NGC 5408 X–1 with the model *TBabs (apec + apec + slimulx + powerlaw)* in XSPEC.

Obtained parameters

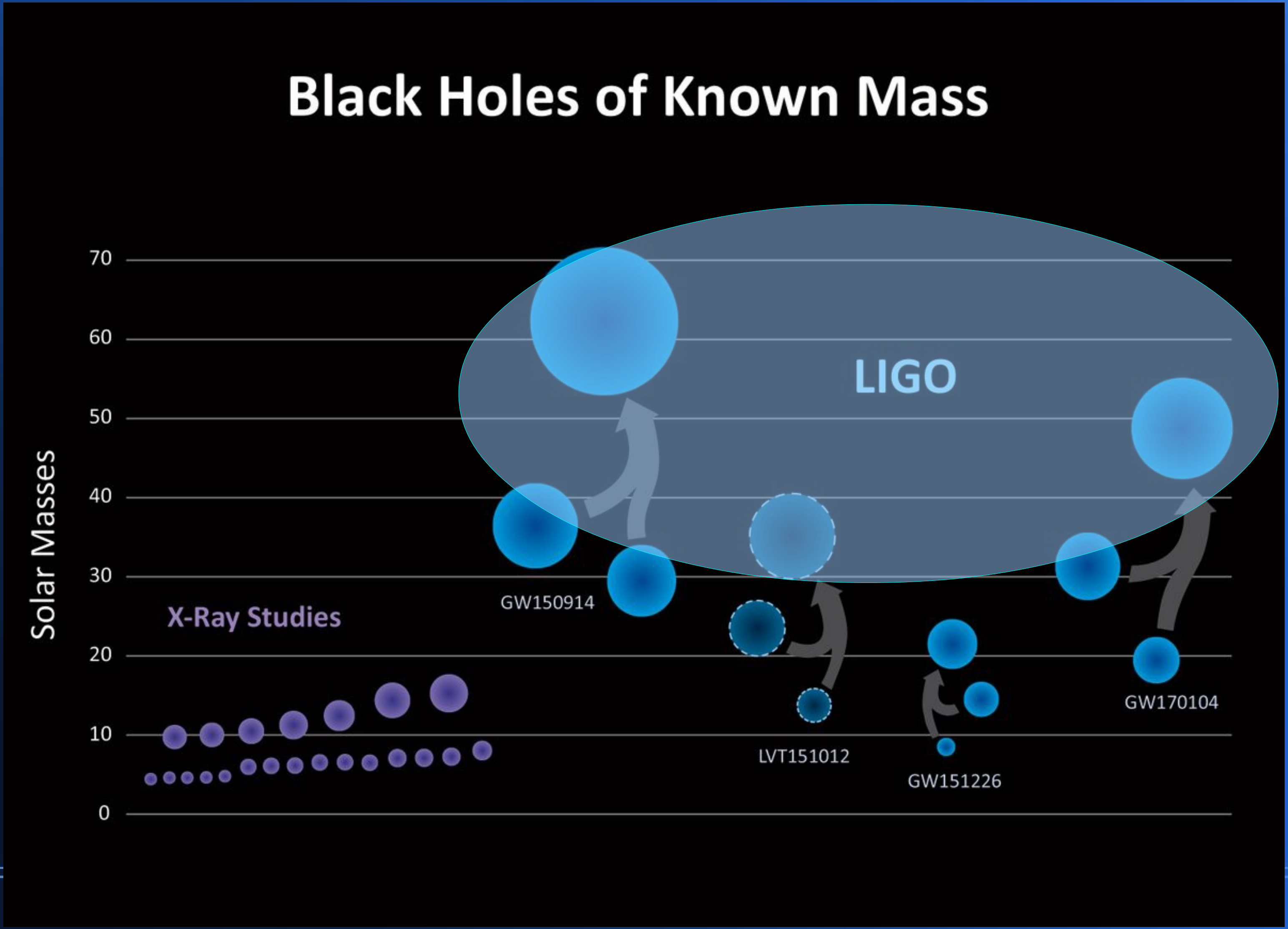
- **M_{BH}= 5.7 ± 0.2 $M_\odot$**
- a = 0.99
- L = 3.2 ± 0.3 L_{EDD}
- i ≤ 30 deg.
- h (disc thickness)= 1

The SLIMULX model



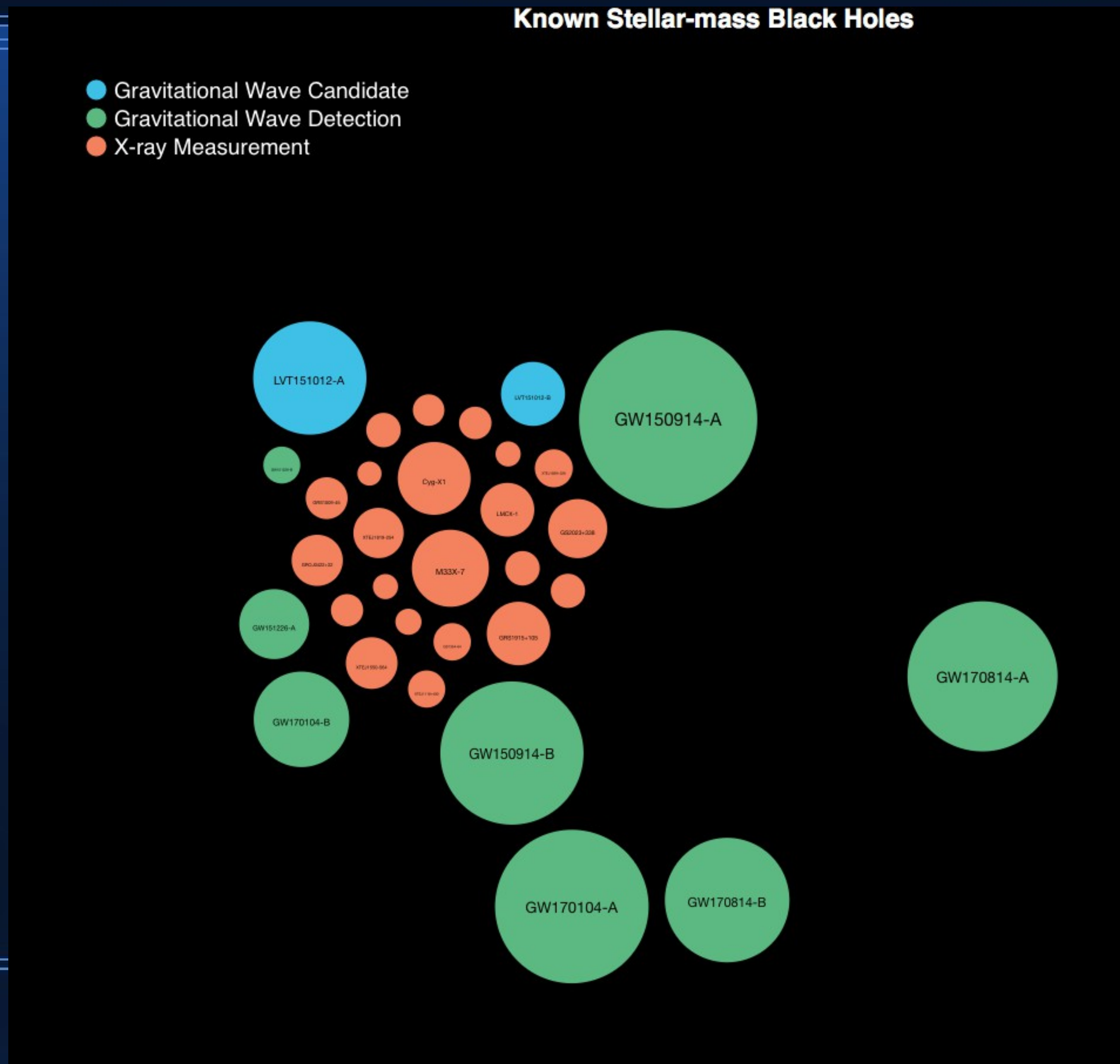
Accretion disc as seen from an observer located at inf nity (credits: M. Bursa)

Gravitational Waves: a new window to the Universe



"Elusive" IMBHs ($M_{BH} \geq$ 30-10^2 $M_\odot$)

Gravitational Waves: a new window to the Universe



Gravitational Waves: a new window to the Universe

- BHs do not necessarily have EM counterpart (i.e. they are “black”).
- Only BHs interacting with another star and/or clouds of gas can have EM counterpart.
- **The EM counterpart of BHs with masses of $M_{BH} \geq 30\text{-}10^2\ M_\odot$ has never been detected so far.**
- These invisible/ “elusive” BHs ($M_{BH} \geq 30\text{-}10^2\ M_\odot$) are now systematically being observed by GW-detectors (LIGO, VIRGO,...).
- The discovery of BHs in the mass-range of $M_{BH} \geq 30\text{-}10^2\ M_\odot$ is unexpected (they are “black” and they have been detected in this mass-range with GWs).
- They might constitute a significant part of the enigmatic “dark matter”.

Summary and Conclusions

- Standard (thin) disc model is inaccurate for $L_{disc} > 0.3\ L_{EDD}$.
- Such models tend to give incorrect values for BH masses and for accretion rate (luminosity).
- Standard (thin) accretion disc theory is not enough → need to move on to *slim-discs*.
- For the case of NGC 5408 X-1 ***a maximally rotating, of 5 $M_\odot$ BH*** is inferred.
- No need of IMBH for NGC 5408 X-1 (prototype of the ULX classification).
- **Many ULXs previously understood as IMBHs are instead super-Eddington accreting stellar-mass compact objects (NS/BH).**
- Gravitational waves are finding the "elusive" IMBHs.
- BH binaries in dense plasmas may produce EM counterparts → Look for them ! → Robotic and automatic systems are absolutely mandatory !

Acknowledgements

Financial support provided by the European "Seventh Frame-work Programme (FP7/2007-2013) under grant agreement # 312789".

Period of the project's realization 1.1.2013 – 31.12.2017

STRONGGRAVITY

EU FP7-SPACE research project 312789 2013 - 2017