Athena and LISA synergies

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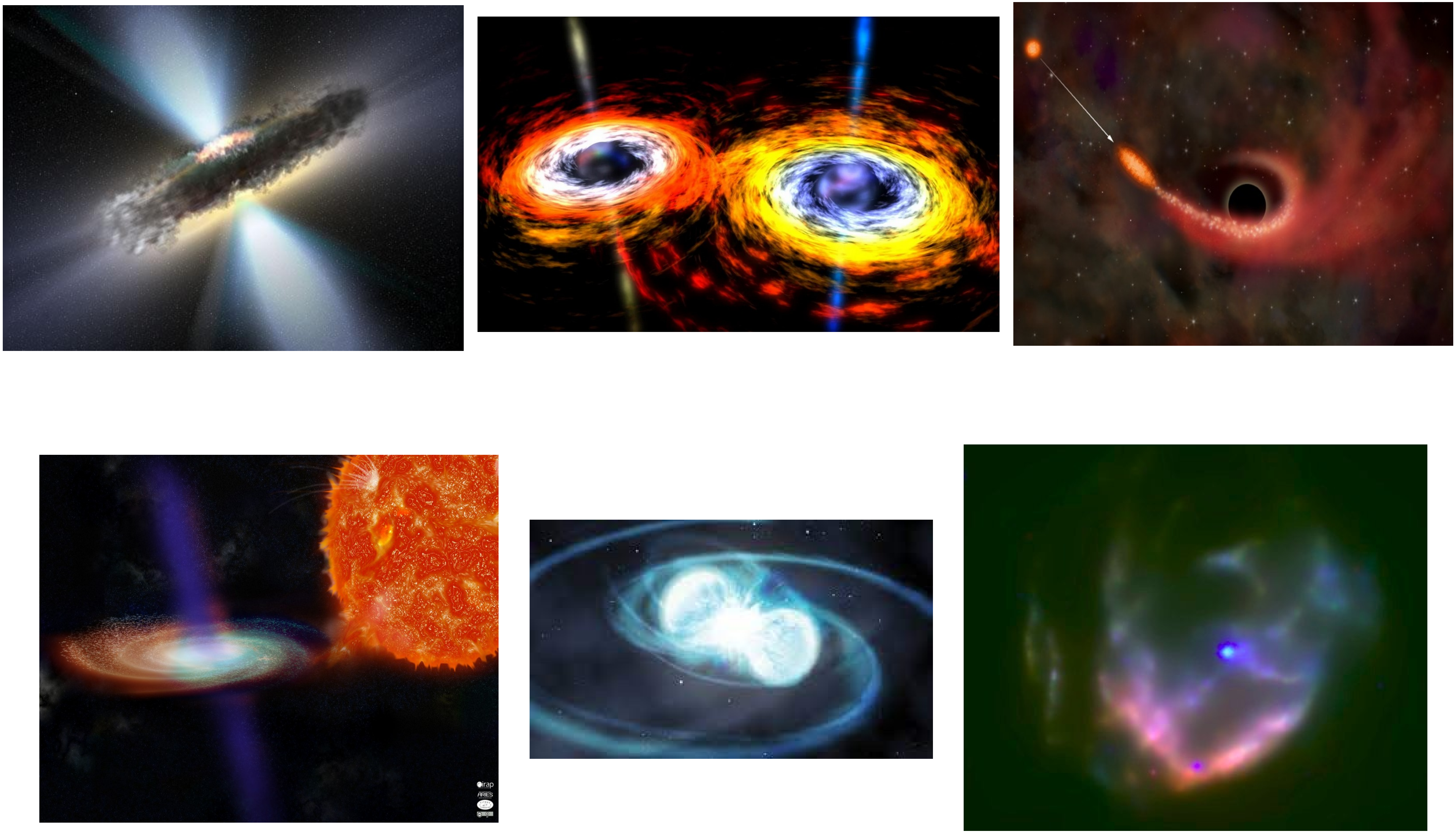
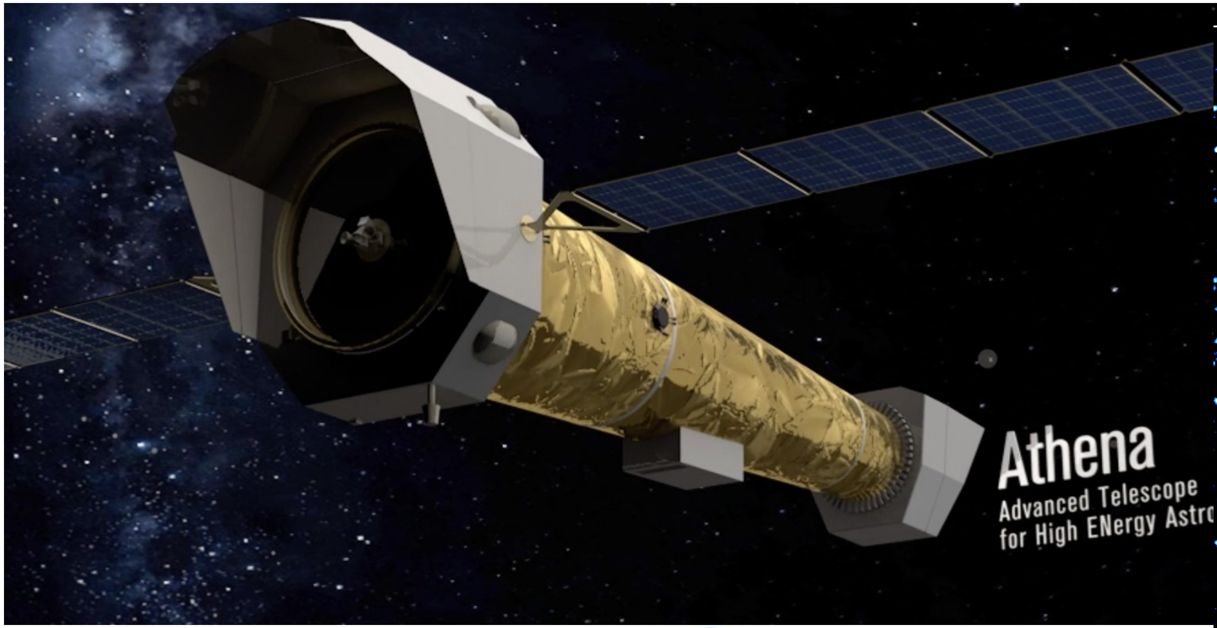
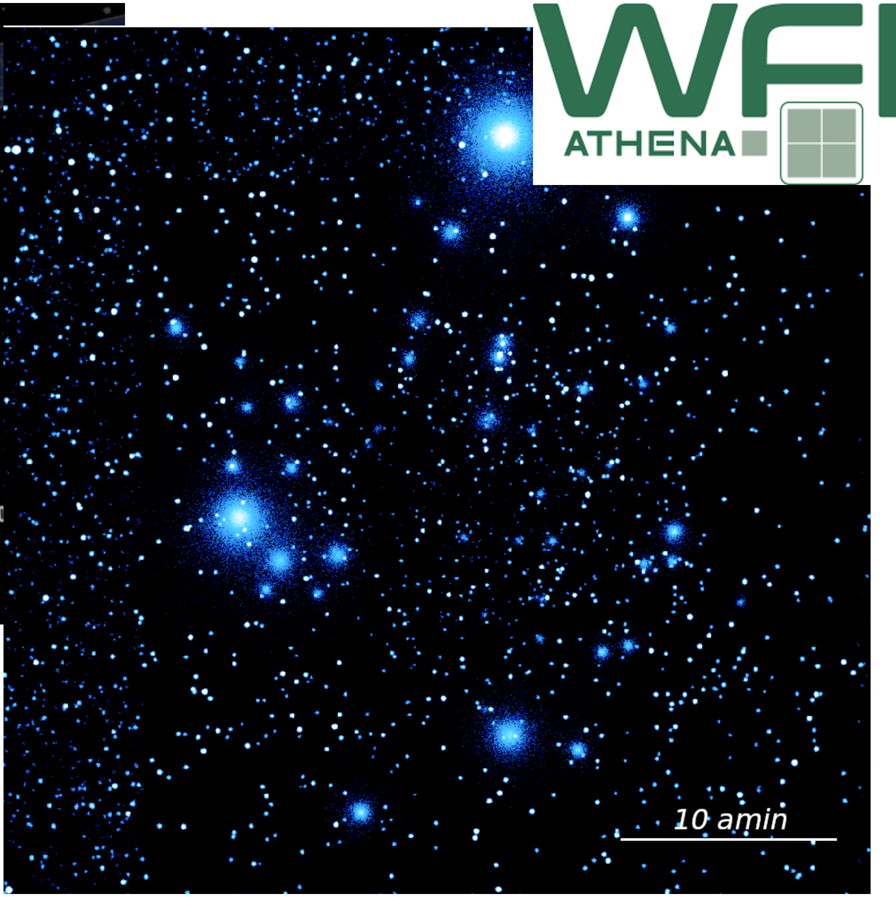
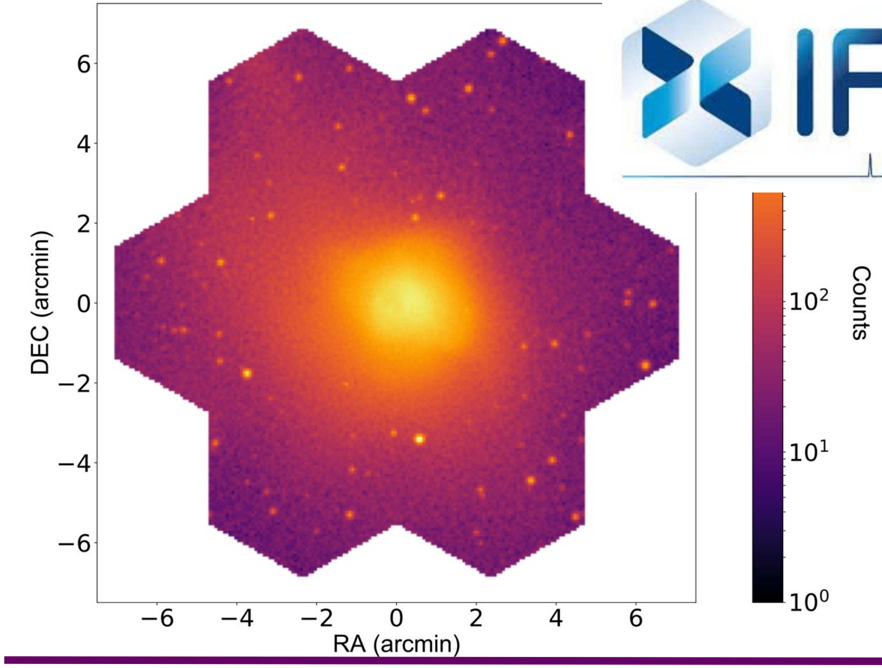
Some objects that are observed in X-ray



Athena



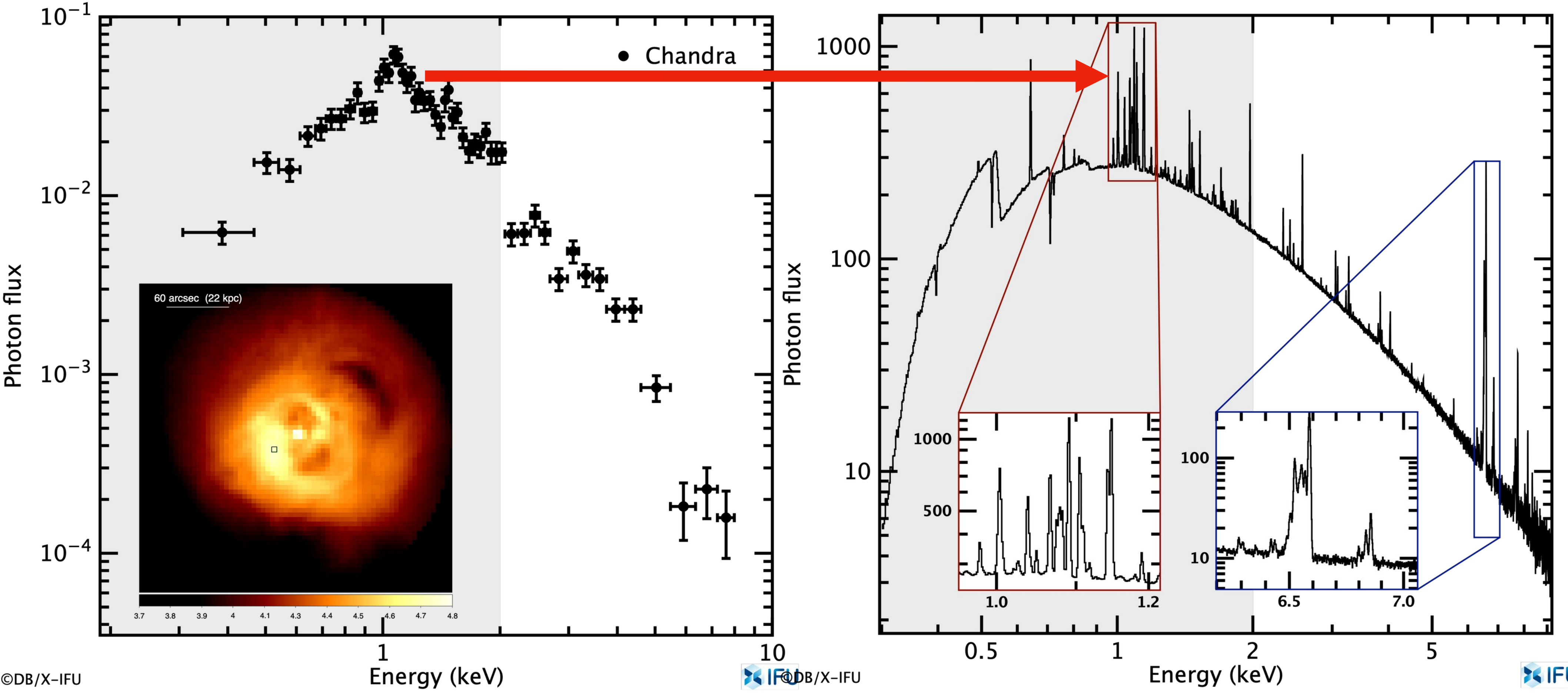




- Scope of Athena currently undergoing revision
- Expected for late 2030s
- 15x more sensitive than XMM
- High resolution capabilities

Athena

Credit: J. Sanders, C. Pinto, A. Fabian & X-IFU team



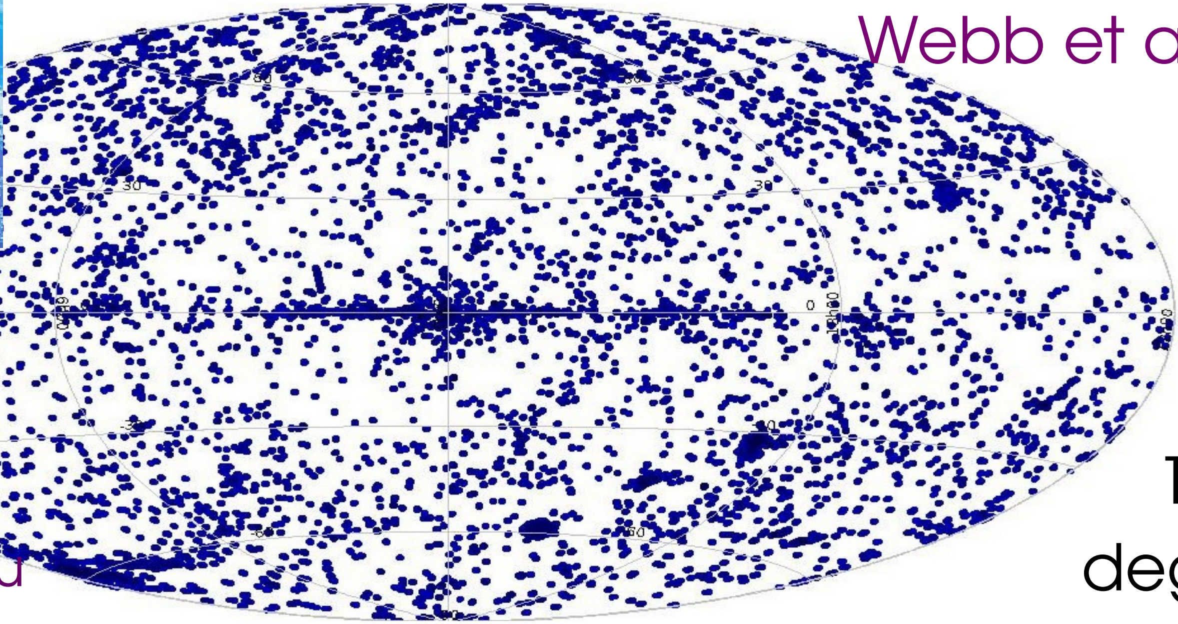
Perseus spectrum with Chandra

Perseus spectrum with X-IFU

In the meantime….. XMM-Newton

3 Feb. 2000–31 Dec. 2021 Released : 28th July 2022

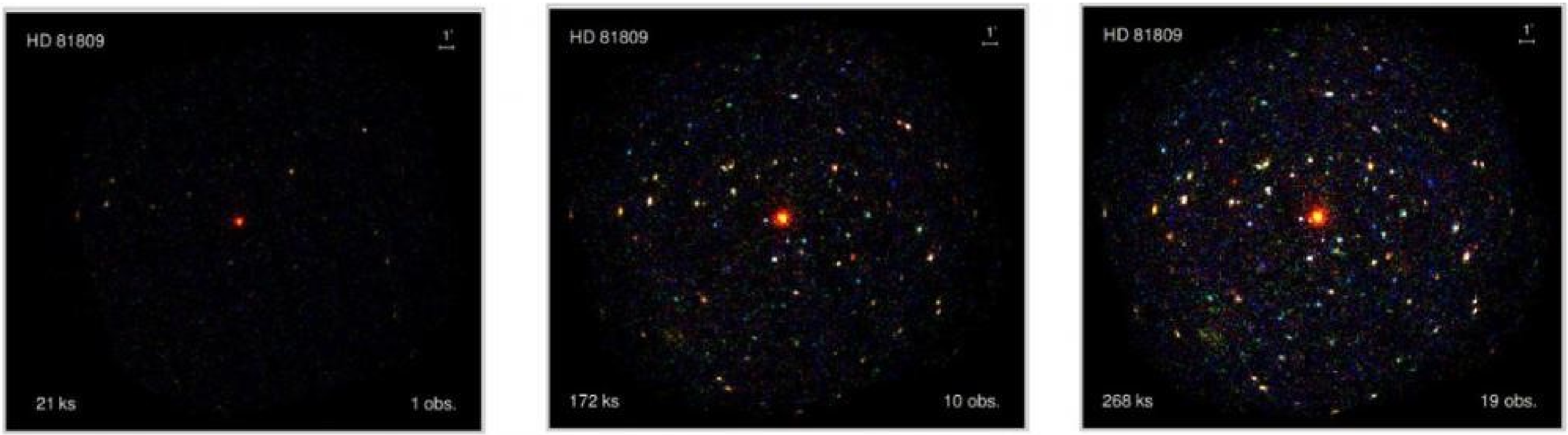
939270 detections, 630347 unique sources - detected up to 84 times



Webb et al. (2020)

Covers 1283 sq. deg of sky

http://xmmssc.irap.omp.eu



How do supermassive black holes (SMBH) form ?

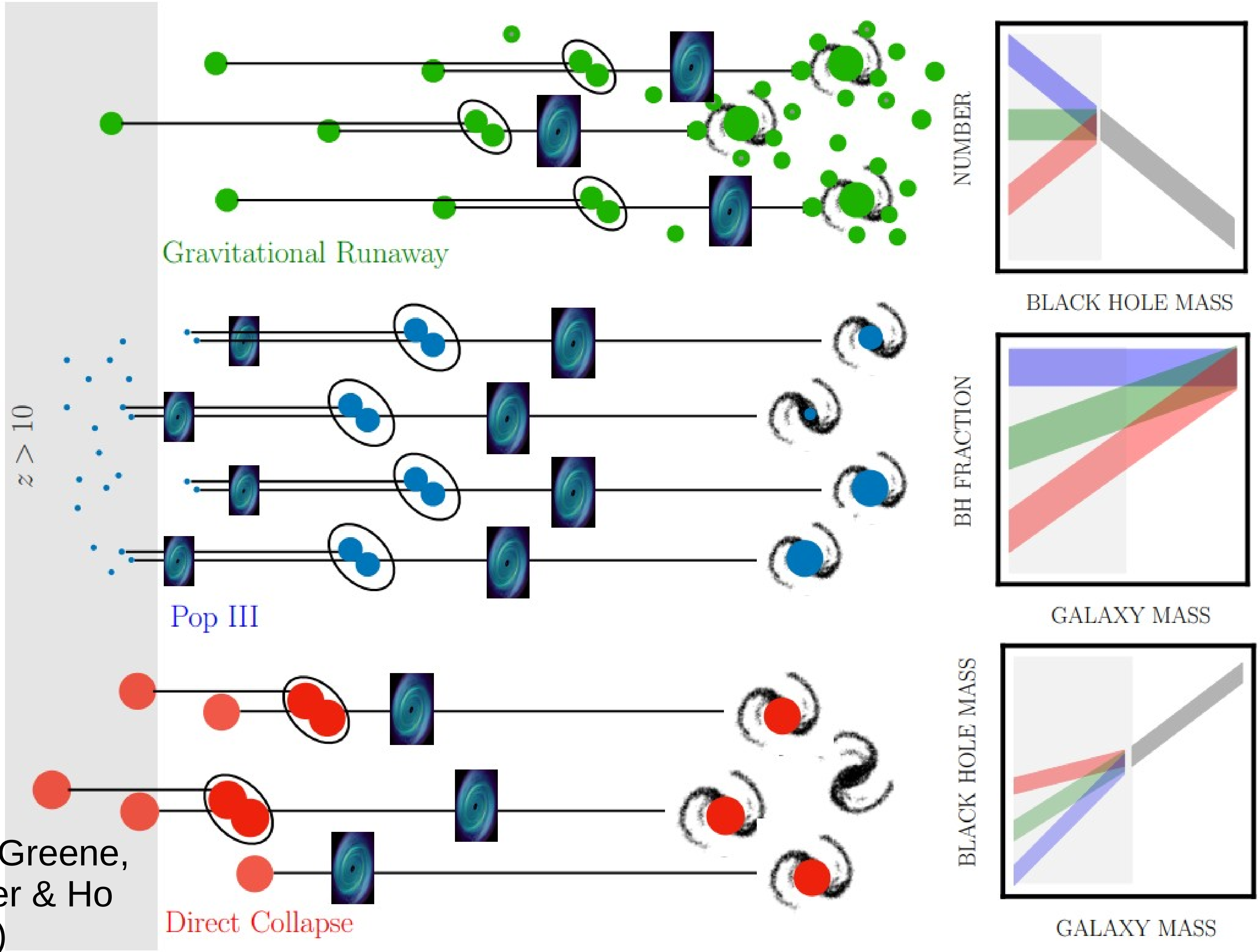
Stellar mass black holes (~3-100 $M_\odot$) form at the end of the lives of massive stars or from the coalescence of neutron stars

But supermassive black holes (~10^{6-10} $M_\odot$) can not form in the same way

Accretion onto a stellar mass black hole, even at the maximal rate (Eddington limit), difficult to explain a population of black holes of ~10^9 $M_\odot$ at z>7 (e.g. z~7.1e.g. Mortlock et al. 2011, or 8x10^8 $M_\odot$ at z=7.54 Bañados et al. 2018)

Requires high merger rates and/or more massive « seeds » (~10^{2-5} $M_\odot$) and/or super-Eddington accretion to form supermassive black holes (SMBH, e.g. Volonteri, 2012; Volonteri, Silk & Dubus, 2015)

Evolution from seeds to supermassive black holes



From Greene, Strader & Ho (2020)

LISA + X-ray data will help to answer these questions

Natalie Webb

6ème Assemblée Générale du GdR Ondes Gravitationnelles, Toulouse, Oct 2022

Observations to constrain the evolution of SMBH

LISA :

- Pinpoint mergers with time – determine merger rate / redshift
- Locate low mass seeds (intermediate mass black holes)

X-ray / Athena / electromagnetic data

- Identify new binary massive black holes (MBH)
- Locate low mass seeds through tidal disruption events
- Study super-Eddington accretion
- Measure radial velocities in binary MBH
- Study gas dynamics, prior to merger
- Locate the event for multi-wavelength follow-up
- Study merger environment to understand galaxy hosts

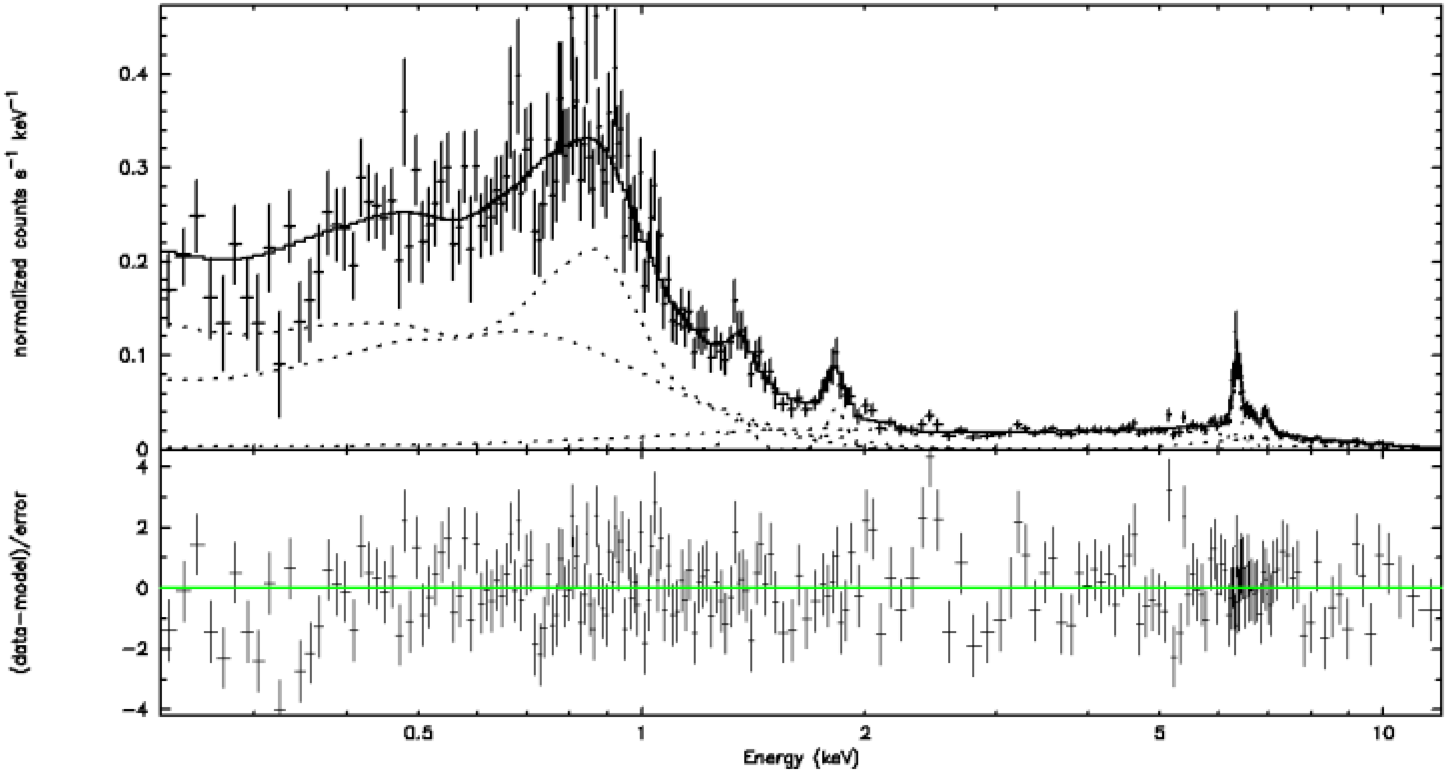
Key : before LISA launch after LISA/Athena launch

Current work to identify new binary MBH in X-rays

- Studied 3 binary SMBH with <1 kpc separation
- NGC 7727 @ 27.4 Mpc, $M_1 \sim 1.54 \times 10^8\ M_\odot$ & $M_2 \sim 6.33 \times 10^6\ M_\odot$
- OJ 287 @1.3 Gpc, sep. 0.056 pc, $M_1 \sim 1.8 \times 10^{10}\ M_\odot$ & $M_2 \sim 1.5 \times 10^8\ M_\odot$
- PKS 2131-021 @ 1.5 Gpc, sep. 0.01-0.001 pc
- Identified spectral characteristics
- Searched for similar objects in 4XMM-DR11
- Found objects used for input + other candidates, inc. NGC 7582
- NGC 7582 is a galaxy in pair @~20 Mpc
- Following up other candidates
- Method promising and can be used with other X-ray catalogues

XMM-Newton data of NGC 7582

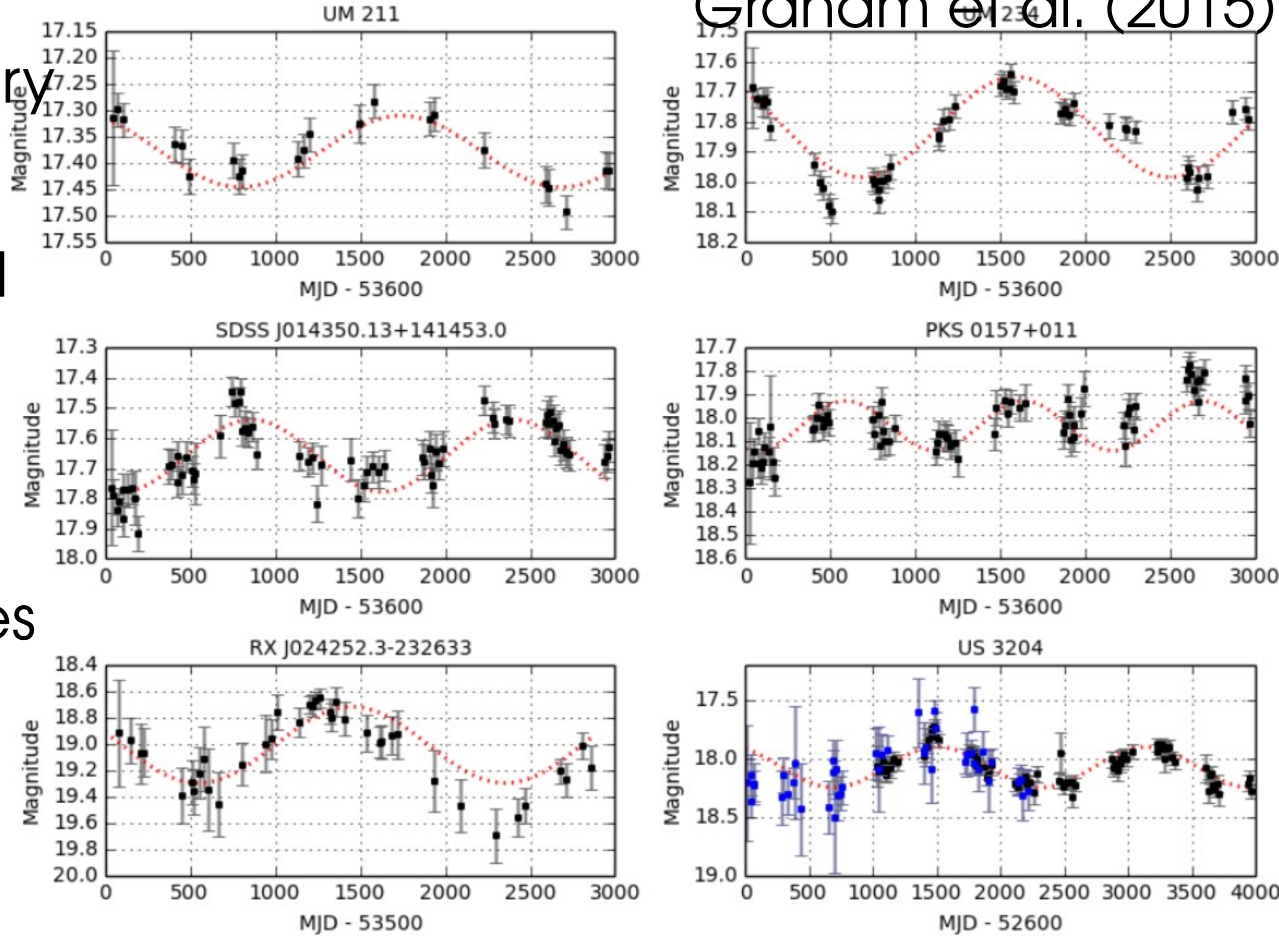
- X-ray colour image shows red and blue side
- Radial velocity study lends weight to rotation detected
- XRISM spectroscopy could help confirm rotation
- Athena/X-IFU would be the ideal instrument to study rotation, ….



New binary MBH from long-term lightcurves

- Binary SMBH long-term lightcurves can show (sinusoidal) modulation
- Graham et al. (2015) analysed Catalina real-time survey data of 243500 quasars
- Found 111 candidate binary SMBH (<0.1 pc sep.)
- Searched for well-sampled long-term OM lightcurves
- 441 sources showed ~Keplerian modulation
- Majority stars, some binaries
- 6 potential binary SMBH
- To search other optical/UV catalogues

Graham et al. (2015)

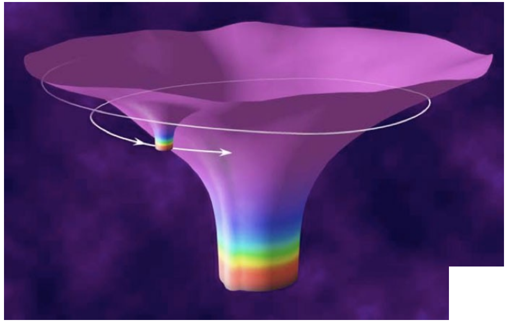


- X-ray period~3.7 yr found in OJ 287 (Foustoul et al., in prep) & ~12 yr period (Lehto & Valtonen, 1996)

Other physics from the merger (see Colpi et al. 2019)

- Correlate X-ray modulation with GW chirp. If modulation is dominated by Doppler and/or relativistic boosting, can test speed of gravity on cosmological scales compared to photon propagation (Abbott et al. 2017a; Haiman 2017)
- Identify host galaxy through X-ray/optical follow-up so distance-redshift relationship can be measured to ~1 % to probe late time background expansion of Universe (Tamanini et al. 2016)

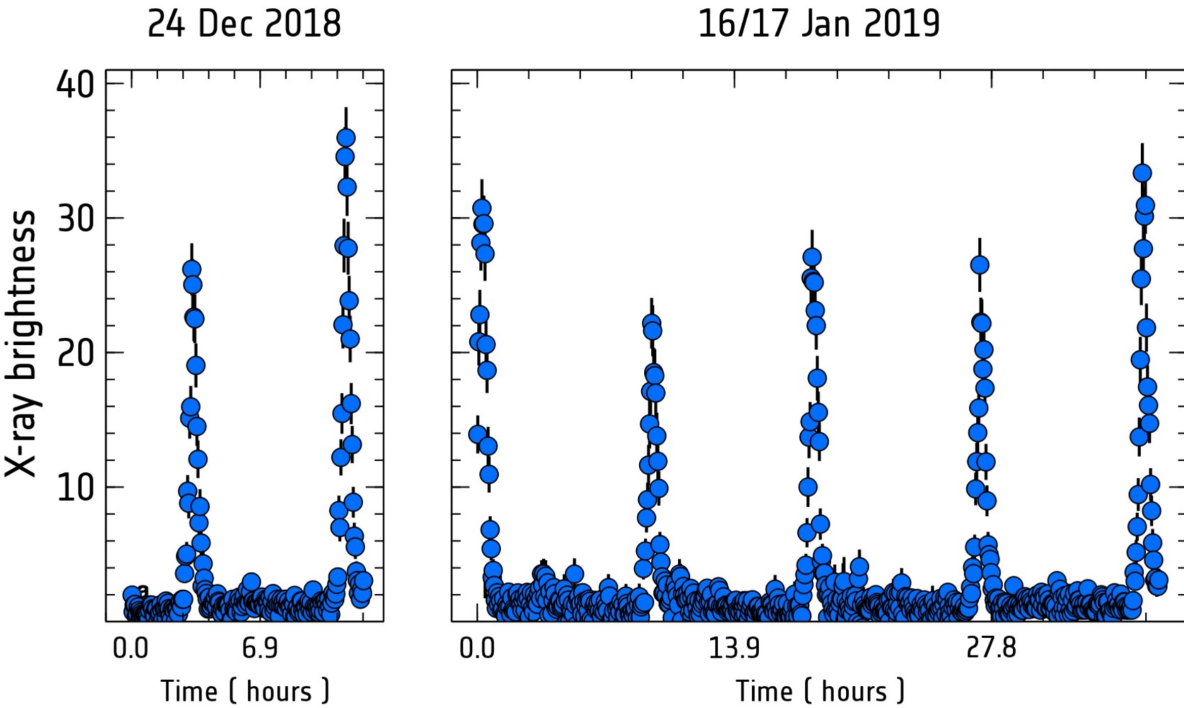
Extreme Mass Ratio Inspirals (EMRIs)



X-ray/ Athena

- EMRIs possibly detected ??
- Find other examples (e.g. Quintin, Webb et al., to sub)
- Probe effect of acc. disc
- Search for (IMBH-SMBH) radial velocity signatures
- Study EMRI environment

Miniutti et al. (2019)



- **LISA** :
- Pinpoint EMRIs
- Measure general-relativistic and Lense–Thirring precession
- Constrain compact object parameters

Key : before LISA launch after LISA/Athena launch

Double white dwarf binaries

Up to12000 double white dwarfs could be detected with LISA (Lamberts et al. 2019)

Athena

- Insight into start of mass transfer, to understand rates of SN Ia
- Routinely measure gravitational red-shifted Fe Ka line to give constraint on the white dwarf mass (Nandra et al., 2013).
- Measure temp., mass & chemical composition of novae + super-soft sources to understand SN Ia progenitors (Motch et al., 2013).

LISA :

- Find double white dwarfs to better understand stellar evolution
- Study rôle of grav. wave emission and accretion in evolution

Key : before LISA launch after LISA/Athena launch

Stellar mass black hole/neutron star binaries

- Observed by LISA ~a few years before coalescence ($z \lesssim 0.5$, Sesana 2016)
- If some accretion, they could be detected with Athena (Lamberts et al. 2018)
- Locate binary to be followed during coalescence (Colpi et al. 2019)

Summary

- How supermassive black holes form and grow still open questions
- LISA observations will identify seeds and probe MBH mergers
- Athena can locate the mergers for follow-up
- Athena will enable detailed studies of accretion & environment
- Complementary LISA/Athena observations of mergers can constrain physics and cosmology
- Electromagnetic observations will find pre-mergers in massive catalogues using spectral constraints and long-term modulation
- LISA/Athena observations will give insight into double white dwarfs and thus type Ia supernovae (essential for measuring cosmological distances)
- Stellar mass compact object binaries can be located before merger and followed in real time

Backup slides

Backup slides

Tidal disruption events

Detecting TDEs allows us to find massive black holes normally too faint to detect

Tidal radius inside black hole (BH) event horizon for $M > 10^8 M_\odot$

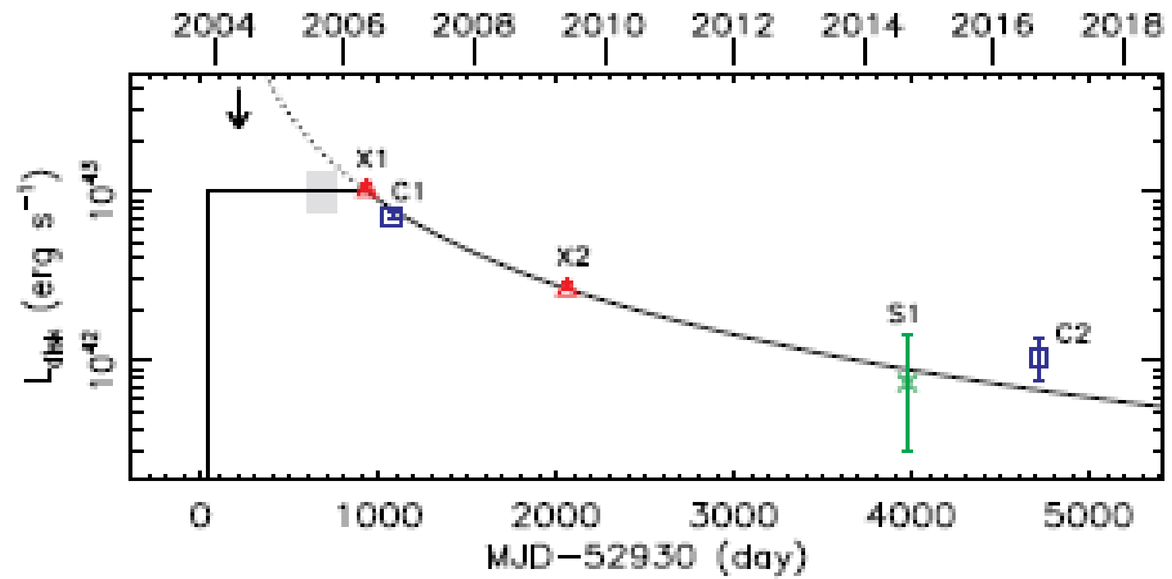
Observe TDE from lower mass BHs + accretion (super-)Eddington

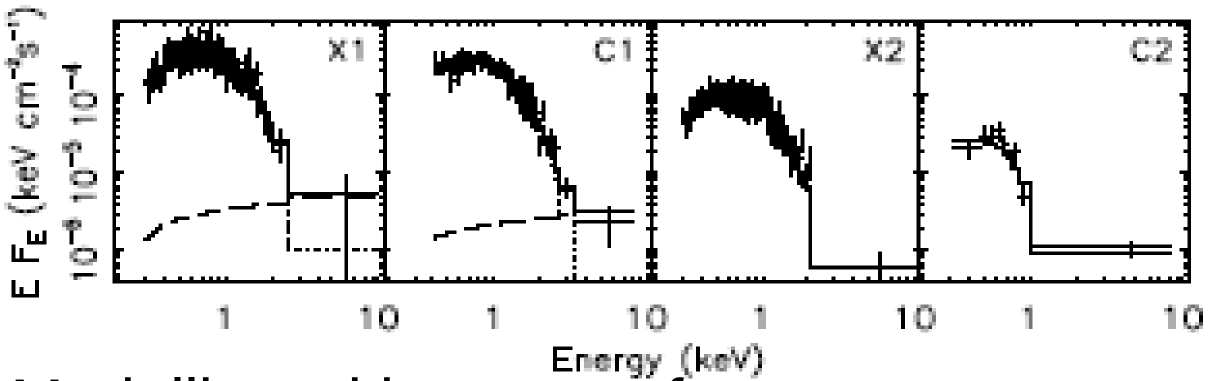
Could help understand the growth of supermassive black holes (SMBH)

$1.7\pm^{2.85}_{1.27}\times10^{-4}$ TDE per galaxy per yr (Hung et al., 2018)

Low mass tidal disruption events

Lin, …, NW, et al. Nature Astronomy (2018)





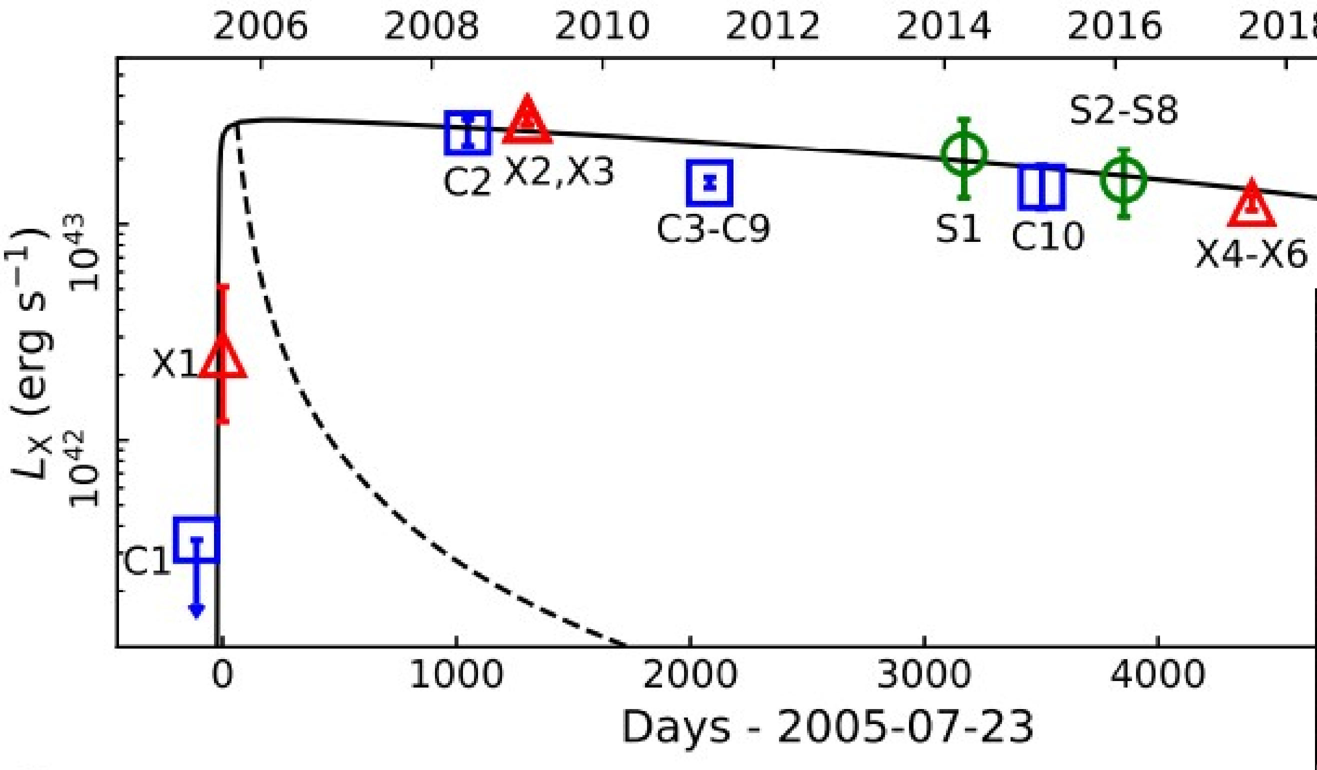
Modelling with *optxagnf* :

0.92 < a_* (spin) < 1.0 (D_L=247 Mpc)

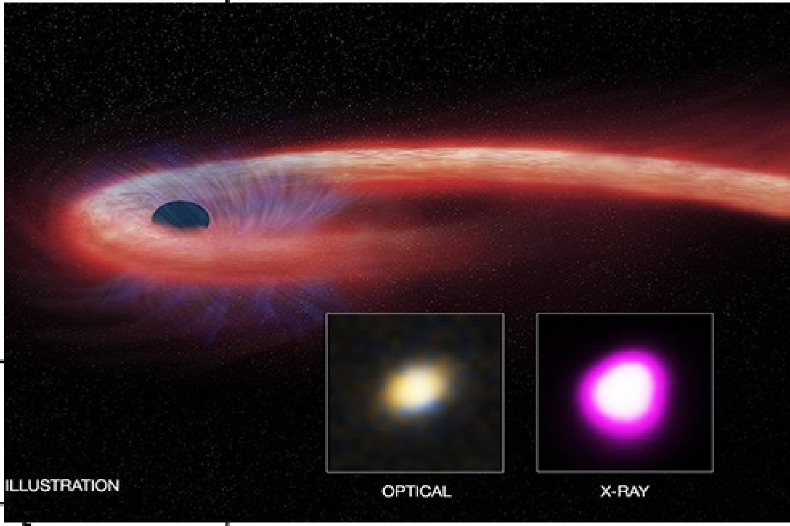
5.3 x 10^4 $M_\odot$ < mass < 1.2 x 10^5 $M_\odot$

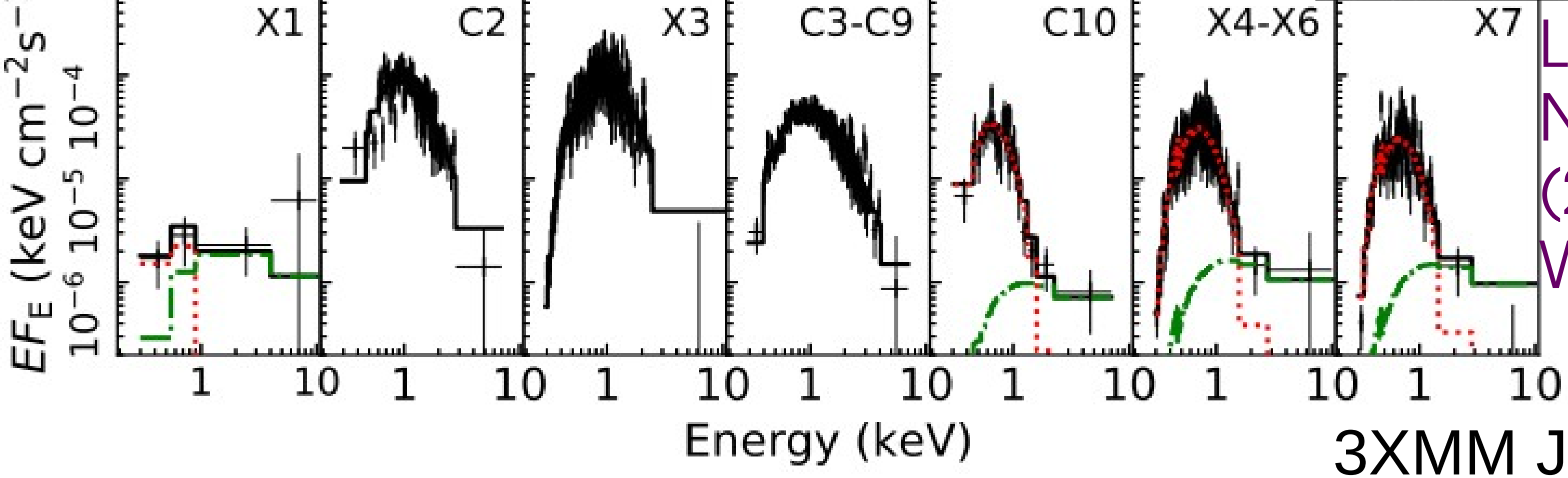
7.1 x 10^4 $M_\odot$ (Chen & Shen 2018)

Extreme tidal disruption event



$0.75M_\odot$ star
Disrupted by a
(2.2-7.6)x10^5 $M_\odot$
BH

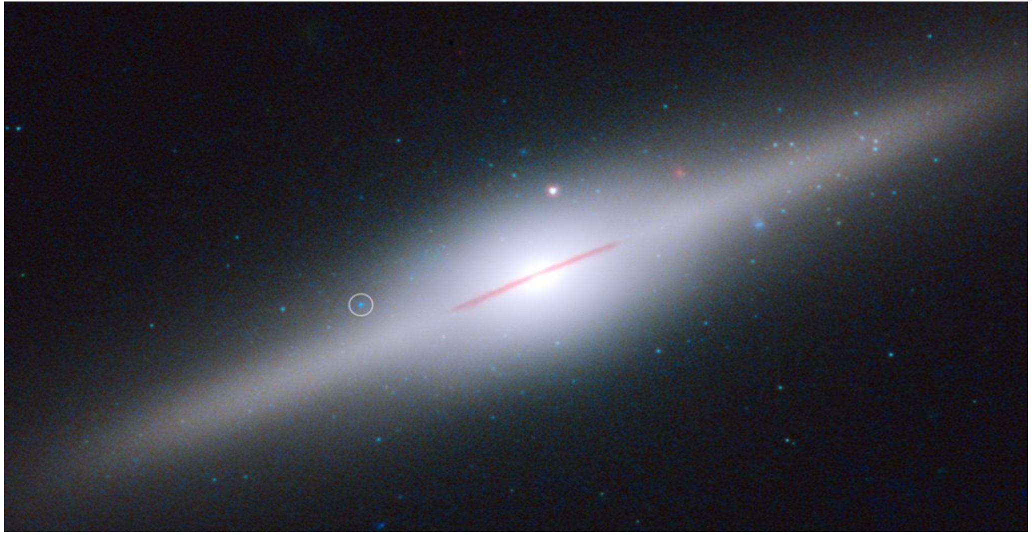




Lin, …, NW, et al. Nature Astronomy (2017), Lin, Godet, Webb et al. (2022)

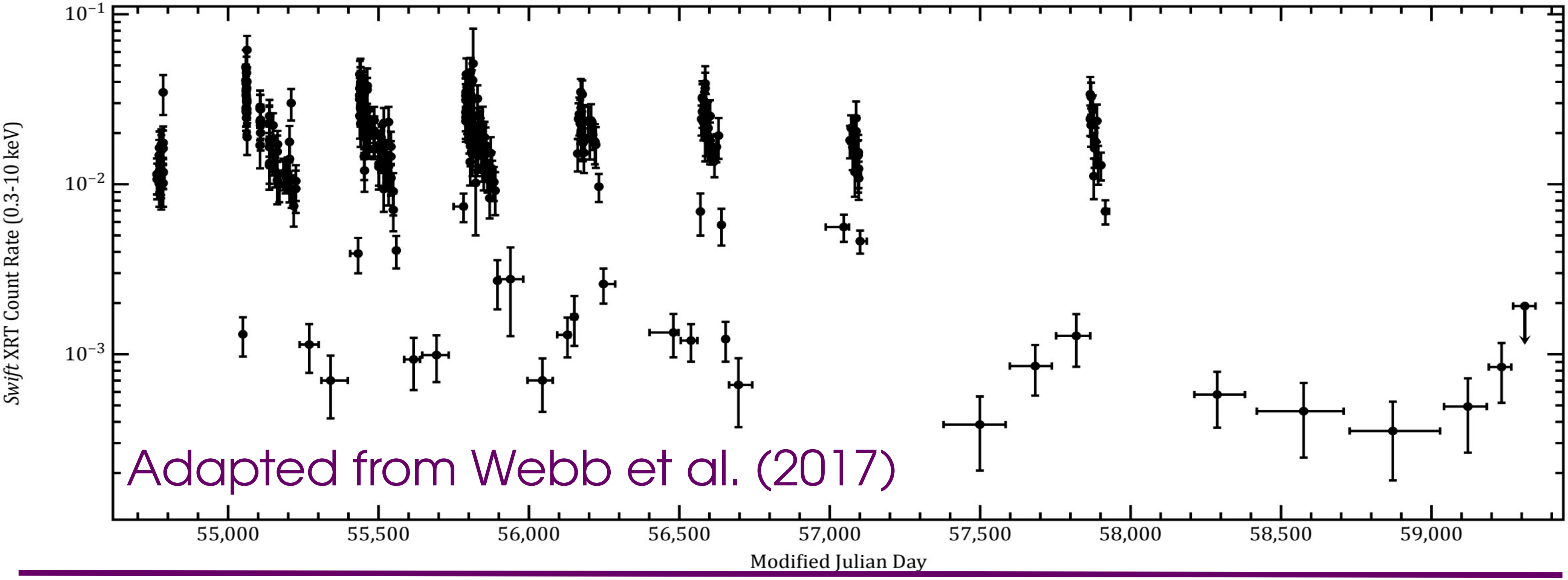
3XMM J150052.0+015452

A failed tidal disruption



HLX-1 associated with ESO 243-49 at 95 Mpc (Farrell, NW et al. 2009, Nature; Wiersema, Farrell, NW et al. 2010)

$L_{x(max)}$ =1.2 x 10^{42} erg s^{-1} (Godet, Barret, NW et al. 2009)



Adapted from Webb et al. (2017)

Understanding HLX-1

Black hole mass ~20000 $M_\odot$ with compact companion (Godet et al. 14)

Failed tidal disruption event (TDE) can explain HLX-1data

Possibly due to merger causing cluster star to change trajectory

Likely to be fairly common as only observed for ~30 years

Other systems likely to exist

More TDEs detected in galaxies that have undergone merger (Arcavi et al. 2014)

Are there other TDEs in XMM-Newton data ?

98 TDEs @ https://tde.space about half are detected in X-ray

Found 10 in the XMM catalogue (Lin et al – many papers)

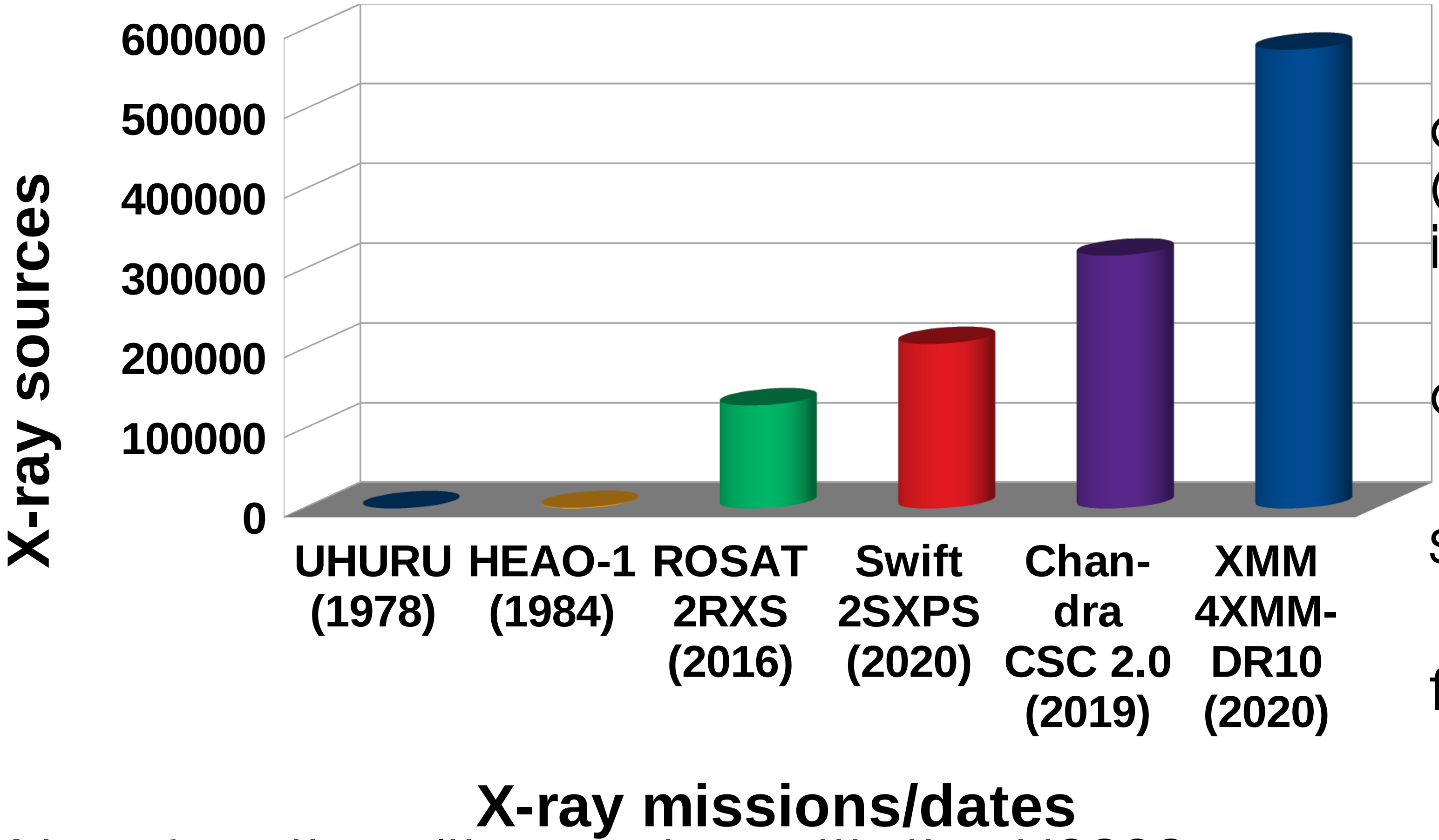
Hundreds more expected to be hidden in XMM catalogue (Webb, 2019), but need to identify them

Require rapid follow-up observations to constrain TDE nature

Work in progress to do this (Quintin et al., in prep + PNHE talk)

TDEs (and other transients such as gravitational wave events, γ-ray bursts, cataclysmic variables, tidal disruption events, supernovae, X-ray binary outbursts, magnetars, etc) could then be followed up in near real time

4XMM-DR10



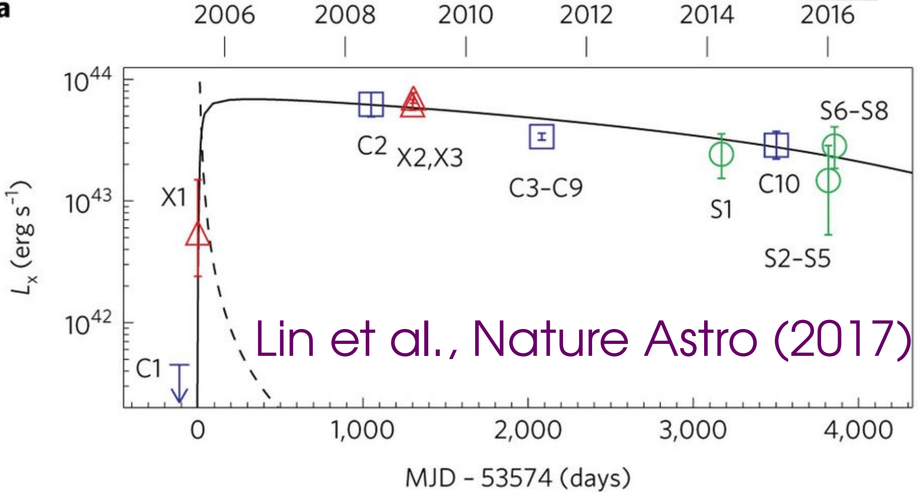
The catalogue is excellent for :

- Quick access to data products (fluxes, spectra, images, etc)
- Finding new objects
- Population studies
- Cross correlation for multi-λ studies

New functionality coming with the H2020 XMM2ATHENA programme (2021-2024)

Open questions concerning tidal disruption events

Why is outburst duration so variable?
- maybe linked to accreted star mass
- or inefficient circularisation of debris stream, so high fallback



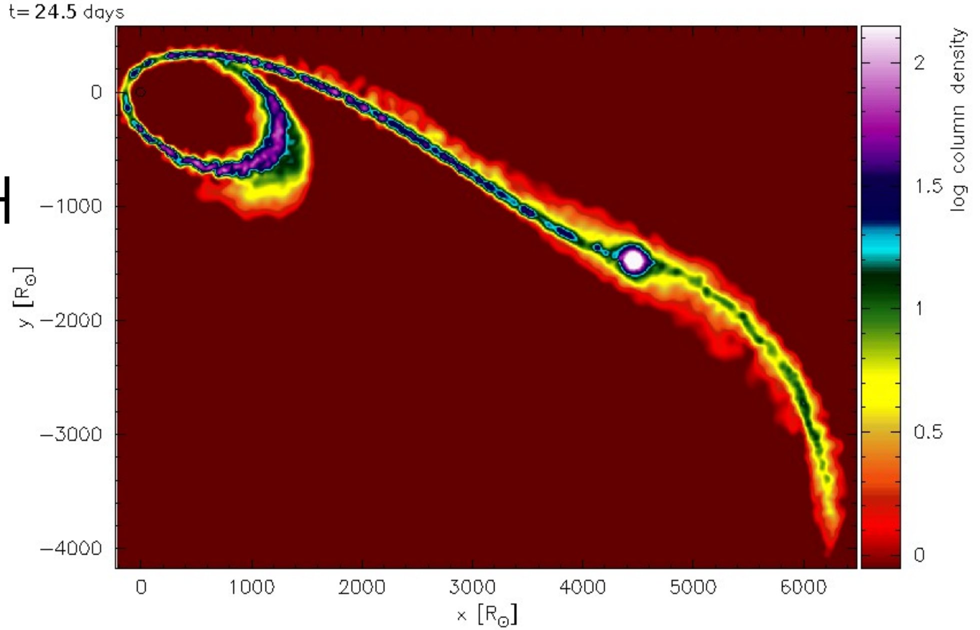
Lin et al., Nature Astro (2017)

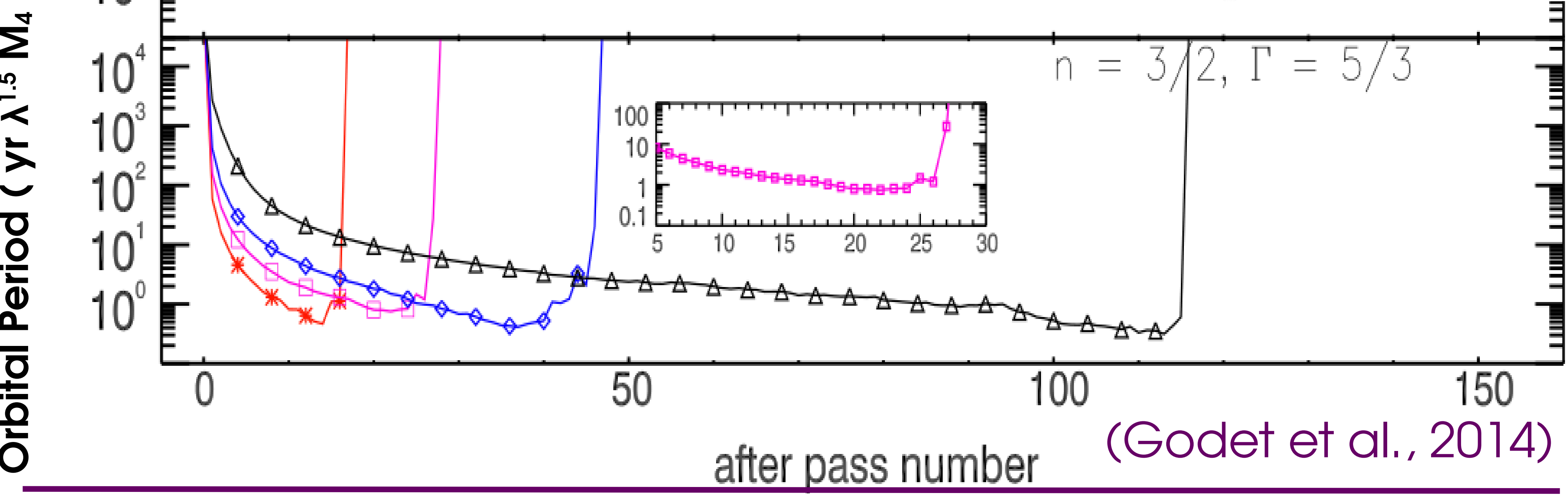
Why do some TDEs have hard spectra instead of thermal spectra?
- possibly due to jets (e.g. Auchettl et al. 2017)
- or e.g. shocks in accretion flows (Hryniewicz & Walter 2016)

Why are some TDEs detected at some wavelengths and not others?
- possibly from reprocessing of X-ray emission from the disk
- or from shocks between the debris streams as they collide
- or a combination of both
- or due to viewing angle, obscuration by dust, or something else

HLX-1

Orbital evolution of a companion, polytrope n=1.5, Γ=5/3 and initial periapsis separation from the IMBH (relative to the tidal radius) of 2.3 (red), 2.4 (magenta), 2.5 (blue), 2.7 (black), $\lambda = R/0.01R_\odot$ and $M_4 = M_{BH}/10^4 M_\odot$



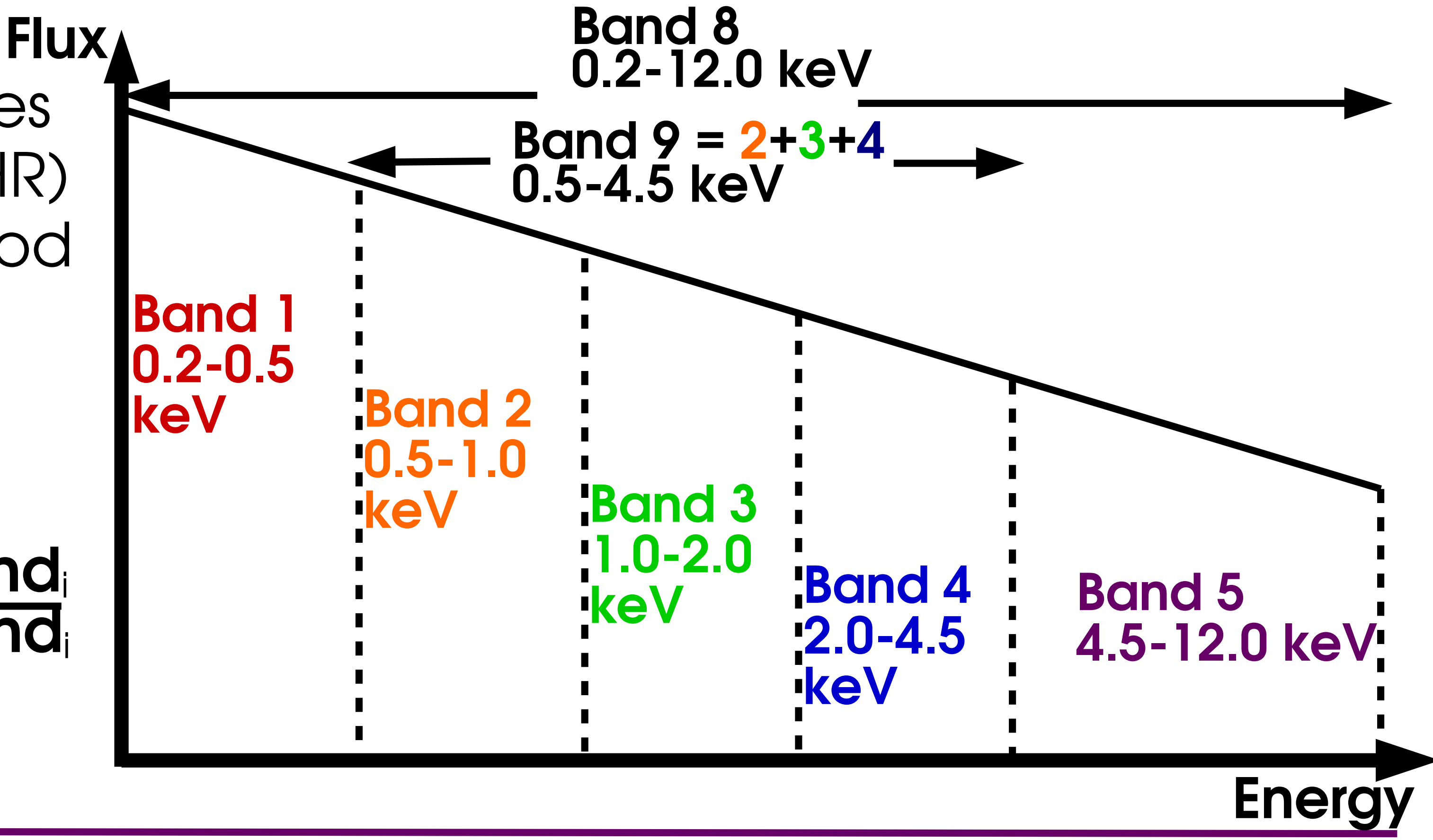


(Godet et al., 2014)

3XMM-DR8 – data proposed

332 columns of information including :
- Identifiers/coordinates
- Observation date/time and observing mode
- Exposure /background info
- Extent
- Counts/fluxes/rates
- Hardness ratios (HR)
- Maximum likelihood
- Quality flags
- Variability

$$HR_i = \frac{Band_{i+1} - Band_i}{Band_{i+1} + Band_i}$$



Flux

Band 8
0.2-12.0 keV

Band 9 = 2+3+4
0.5-4.5 keV

Band 1
0.2-0.5 keV

Band 2
0.5-1.0 keV

Band 3
1.0-2.0 keV

Band 4
2.0-4.5 keV

Band 5
4.5-12.0 keV

Energy