Intermediate mass black holes

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How do supermassive black holes (SMBH) form ?

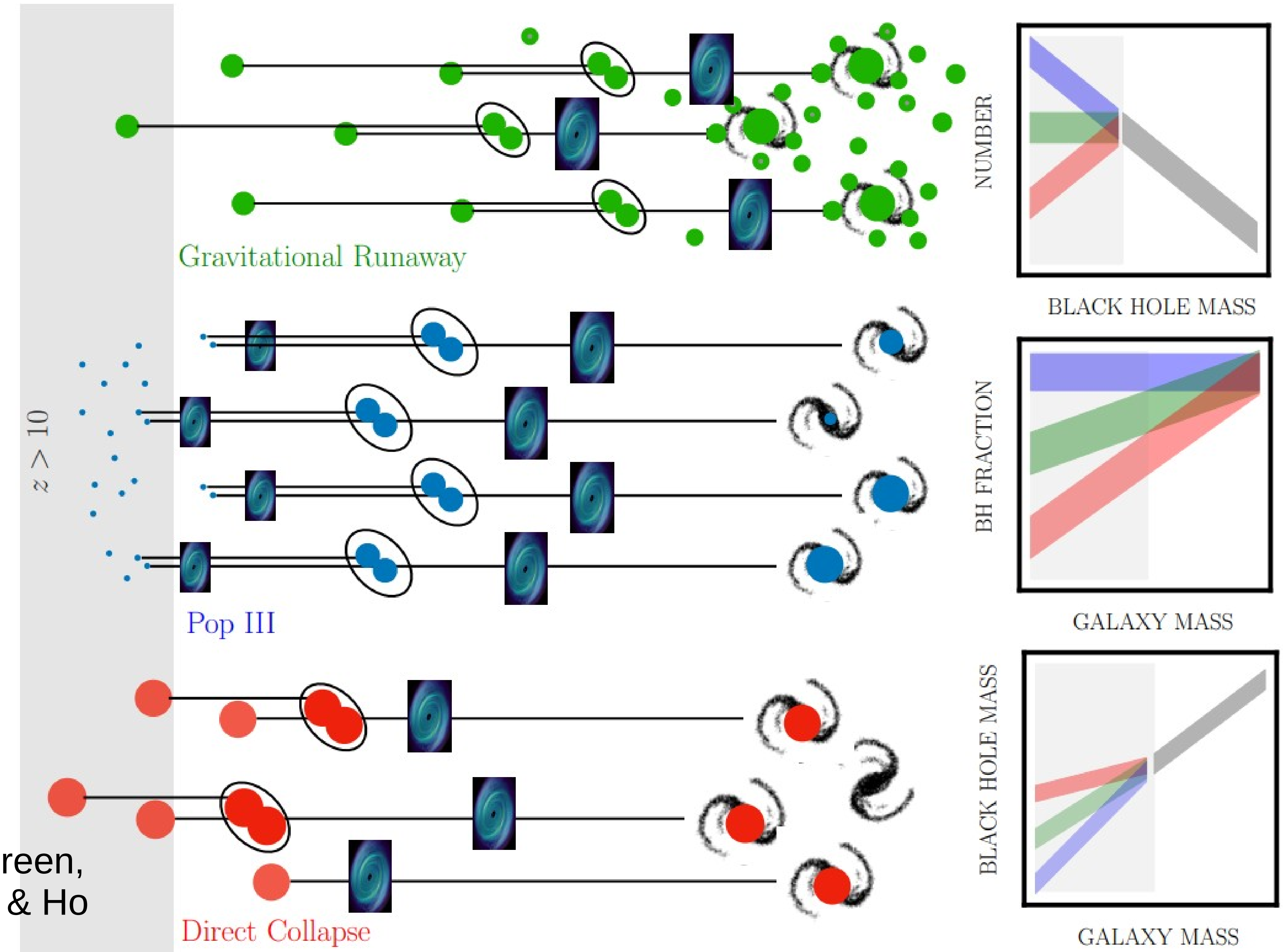
Stellar mass black holes (~3-100 $M_\odot$) form at the end of the lives of massive stars or from the coalescence of neutron stars

But supermassive black holes 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 8×10^8 $M_\odot$ at z=7.54 Bañados et al. 2018)

Require more massive « seeds » and/or super-Eddington accretion to form supermassive black holes (e.g. Volonteri, 2012; Volonteri, Silk & Dubus, 2015)

Evolution from seeds to supermassive black holes



From Green, Strader & Ho (2020)

How do supermassive black holes form ?

Without significant accretion/ recoil through encounters, some « seeds » will remain today

Finding these seeds/intermediate mass black holes (IMBH) and determining their mass will prove their existence and indicate where they reside

This data can be used for simulations to understand the early Universe

Few IMBH known today

Future observations will access high redshift IMBH allowing us to discern between seeding mechanisms

Where should we look for intermediate mass black holes?

In the centres of low mass galaxies

In the outskirts of galaxies/galaxy clusters

In stellar clusters

(In Ultra Luminous X-ray Sources, ULXs)

But intermediate mass black holes (IMBH) are often accreting very little and therefore are very faint and difficult to detect

Detect when they go through a period of high accretion

Identify faint/low mass galaxies which may house IMBH

Search for signatures of low level accretion (compact jets)

A few words about ULXs

ULXs are off-nuclear sources with luminosities exceeding the Eddington luminosity for a 10 $M_\odot$ black hole

8 ULXs shown to be pulsating (Bachetti et al. 2014, Fürst et al. 2016, Quintin et al. 2021, etc), implying that the compact object is a neutron star

Many papers published proposing that the majority of ULXs may contain neutron stars, not black holes (e.g. King & Lasota 2016)

Observing ULXs may be the key to understanding super-Eddington accretion, possible important for growth of SMBH

Generally agreed that only ULXs with 'extreme' luminosities ($>10^{41}$ erg s^{-1}) could house an intermediate mass black hole

4XMM-DR11

3 Feb. 2000–17 Dec. 2020

Released : 18th August 2021

895415 detections, 602543 unique sources - detected up to 80 times

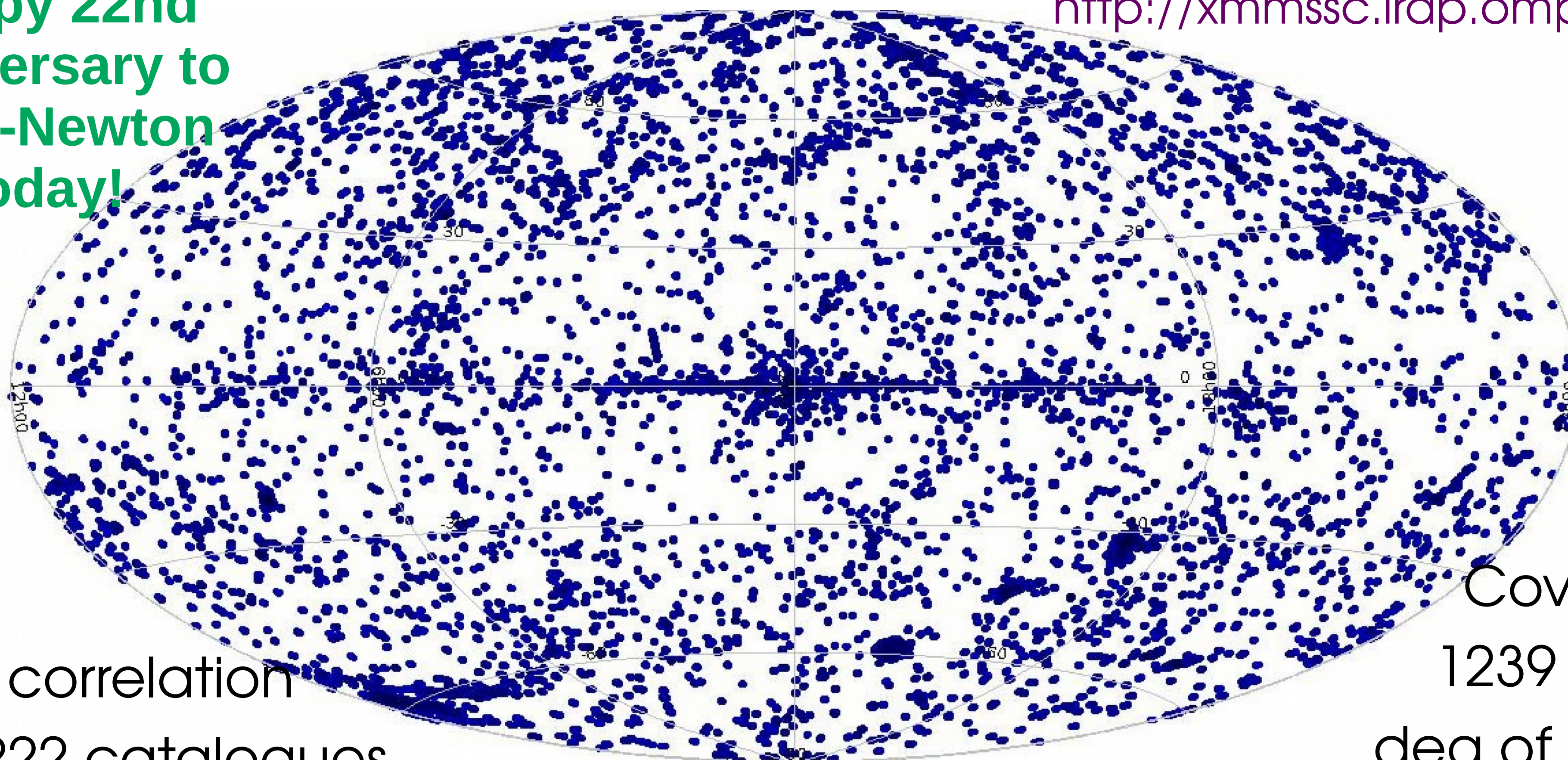
288282 (36%) sources with spectra and lightcurves

Webb, et al. (2020)

112084 extended sources

http://xmmssc.irap.omp.eu

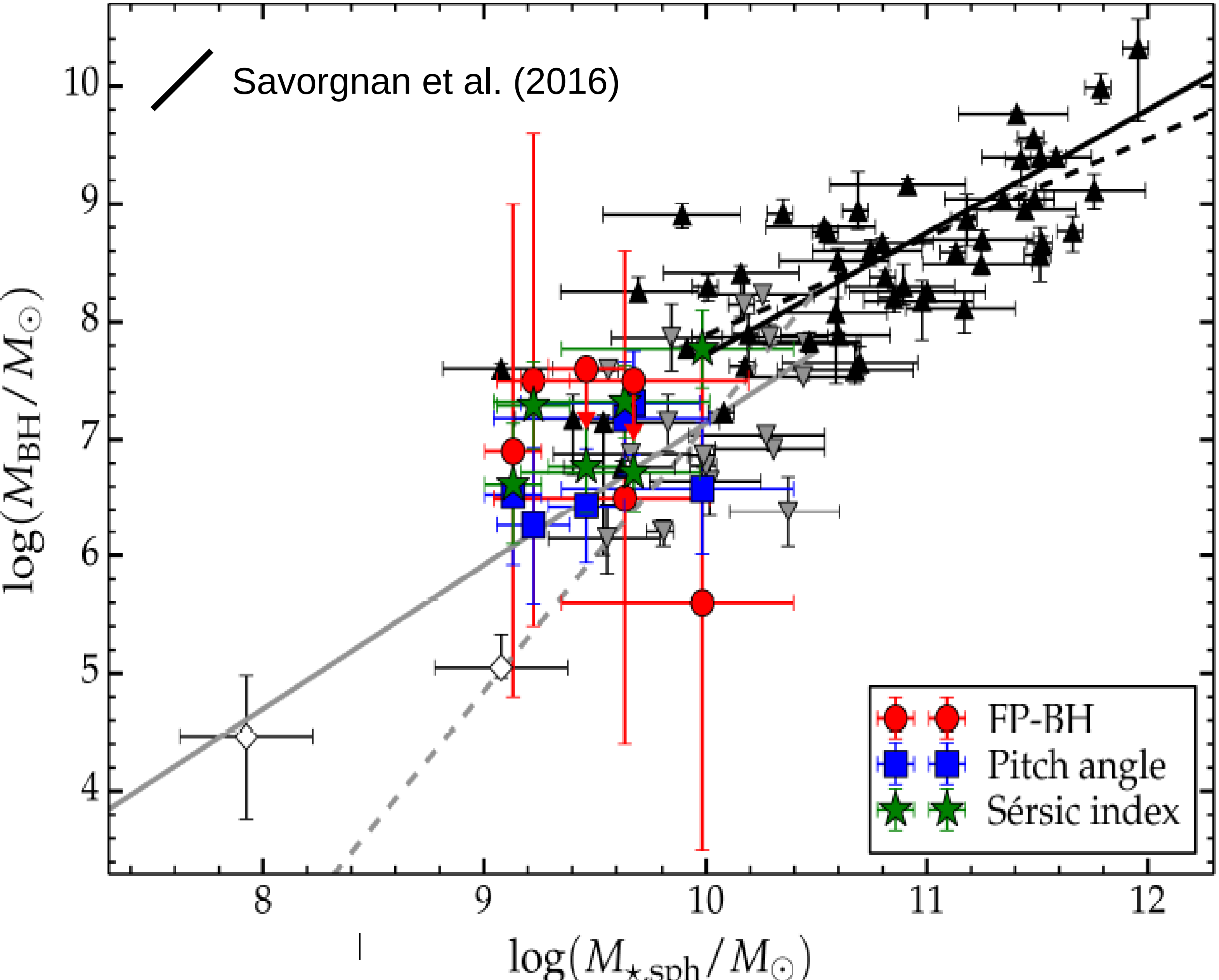
Happy 22nd anniversary to XMM-Newton today!



Cross correlation with 222 catalogues

Covers 1239 sq. deg of sky

IMBH in dwarf galaxies



Koliopanos et al. (2017)

Recent M_{BH}-$M_{spheroid}$ (abs. mag. at 3.6 μm)

M_{BH}-n_{sph} (major axis Sérsic index of spheroid) rel.

M_{BH}-PA (spiral pitch angle) rel.

Radio, X-ray & mass relation of low state BHs

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 $M > 10^8 M_\odot$

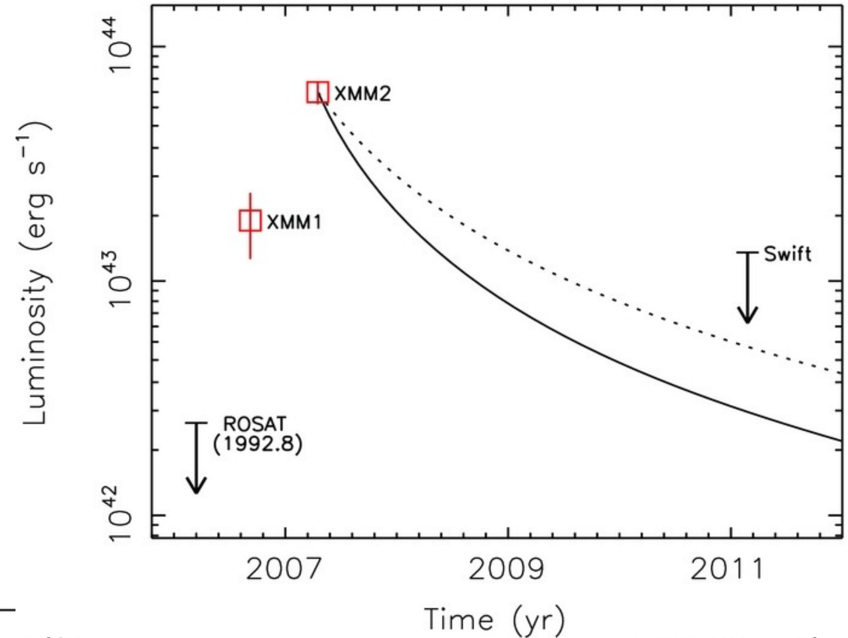
Observe TDE from lower mass BHs + accretion (super-)Eddington

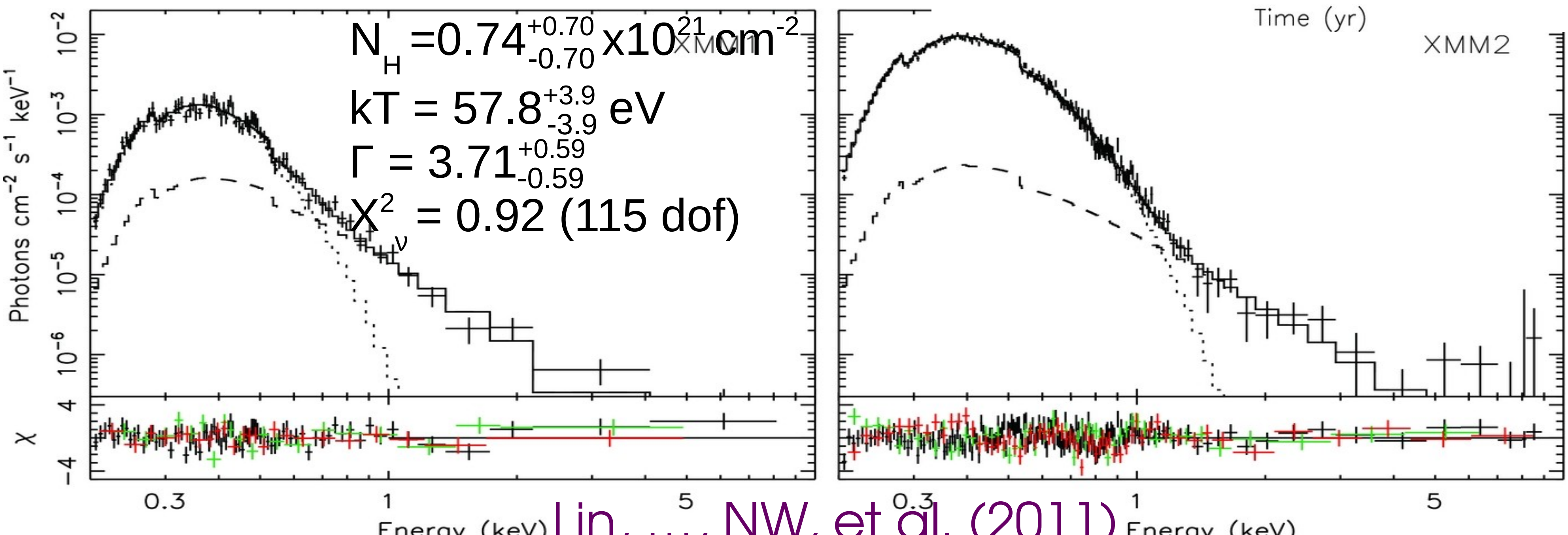
Could help understand the growth of supermassive black holes (SMBH)

$1.7 \pm^{2.85}_{1.27} \times 10^{-4}$ TDE per galaxy per yr (Hung et al., 2018)

XMM-Newton tidal disruption events

- Coincident with centre of IC 4765-f01-1504 at z=0.0353
- Galaxy inactive
- Modelling the disc with kerrbb $\Rightarrow M_{BH} \sim 6 \times 10^4 - 4 \times 10^6 M_\odot$

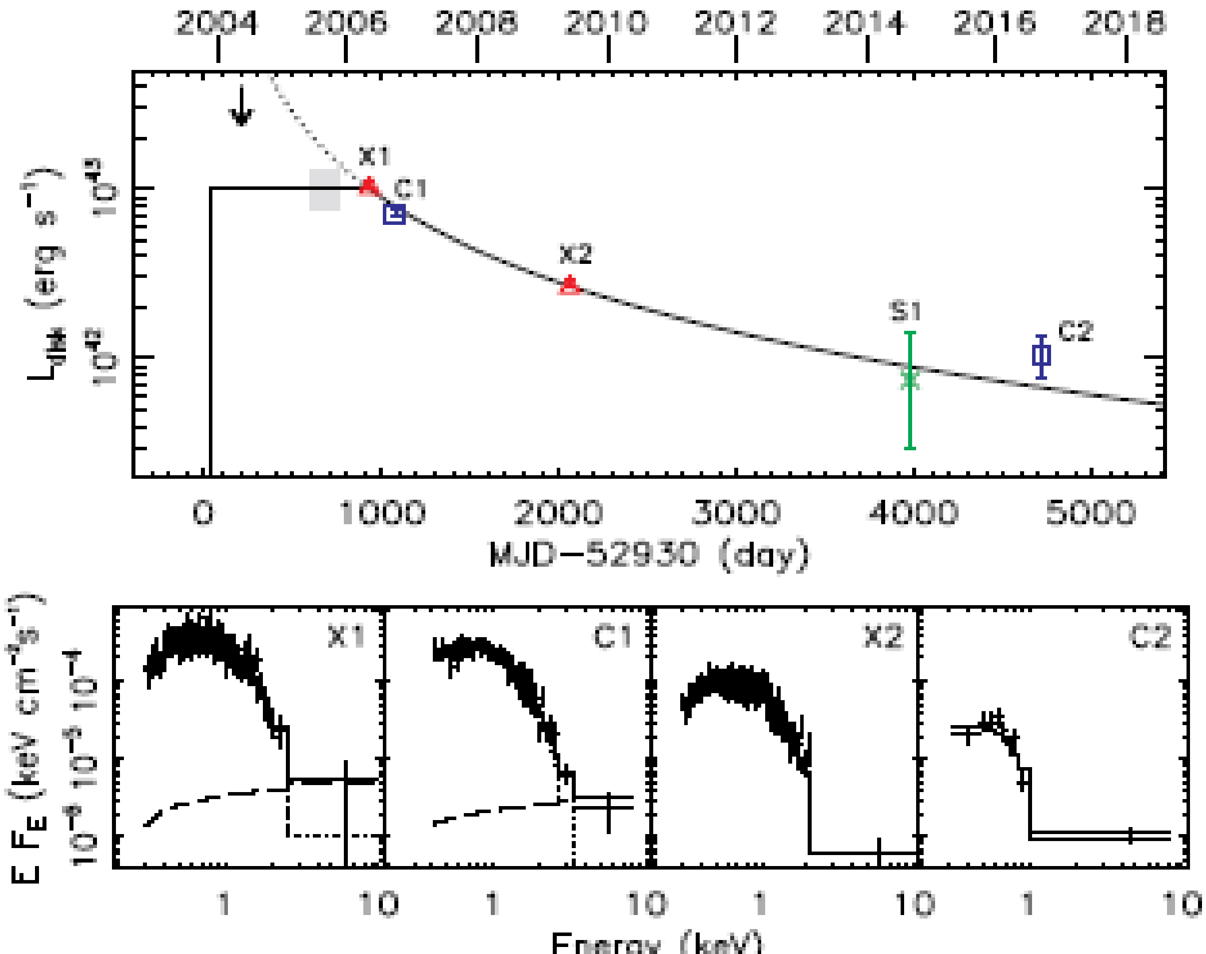




$N_H = 0.74^{+0.70}_{-0.70} \times 10^{21}$ cm^{-2}
$kT = 57.8^{+3.9}_{-3.9}$ eV
$\Gamma = 3.71^{+0.59}_{-0.59}$
$X^2_\nu = 0.92$ (115 dof)

Lin, …, NW, et al. (2011)

Low mass tidal disruption events



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

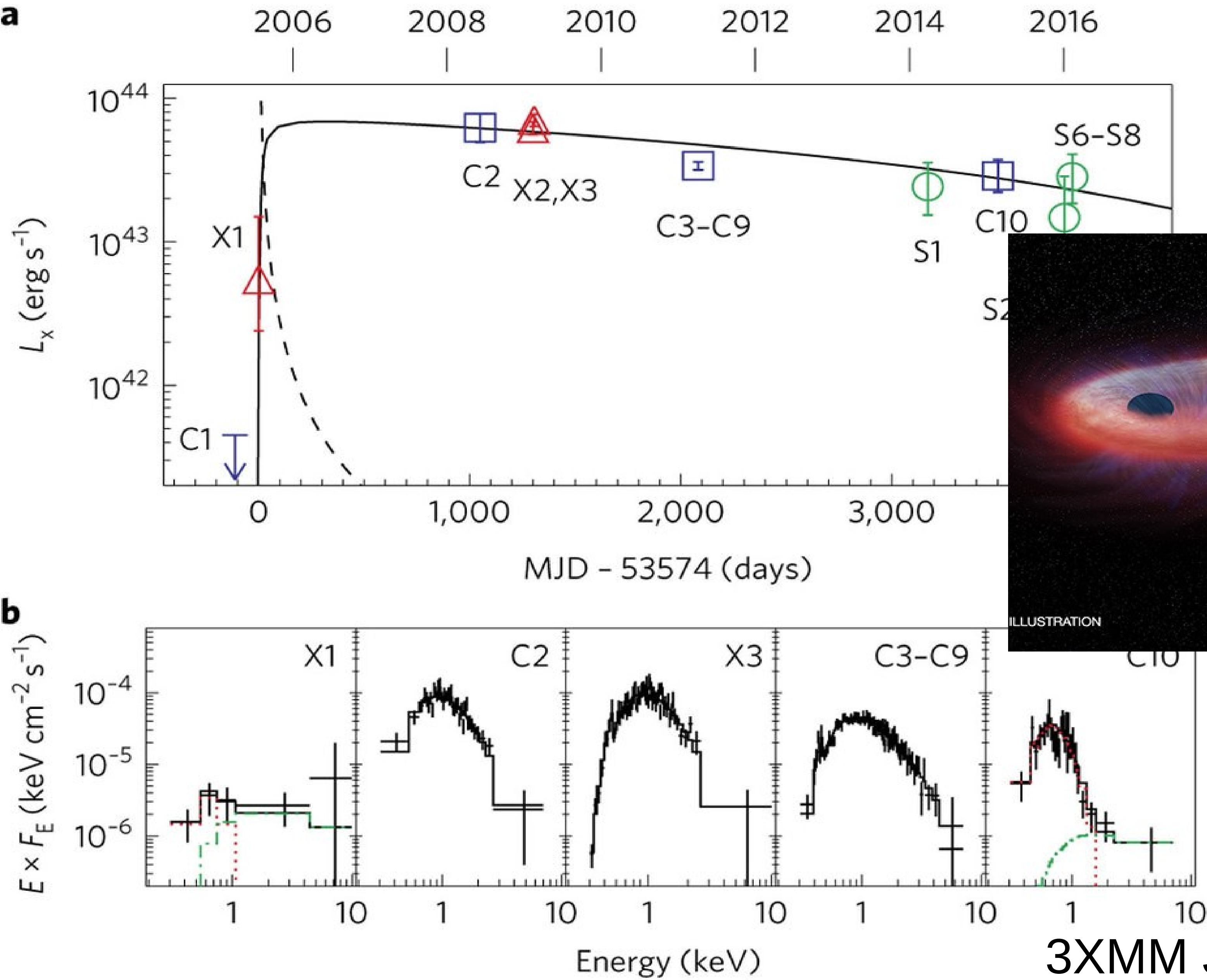
Modelling with *optxagnf* :

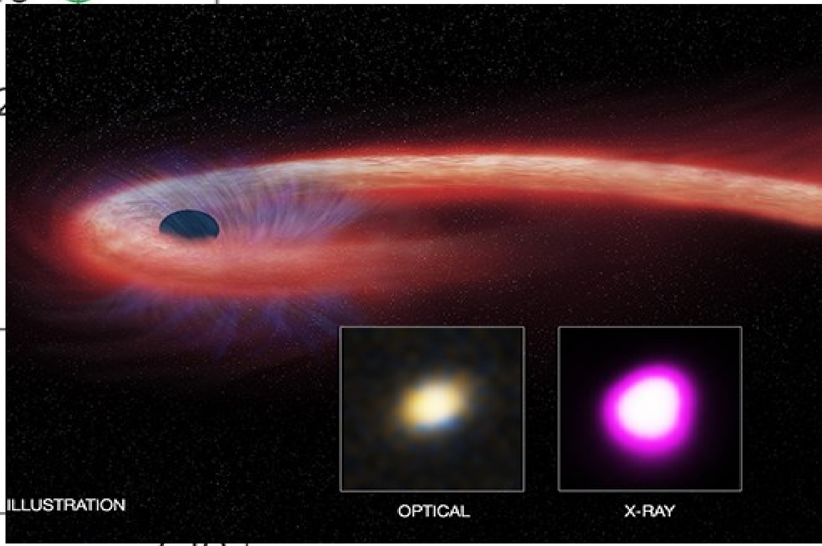
$0.92 < a_*$ (spin) < 1.0 (D_L =247 Mpc)

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

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

Extreme tidal disruption event





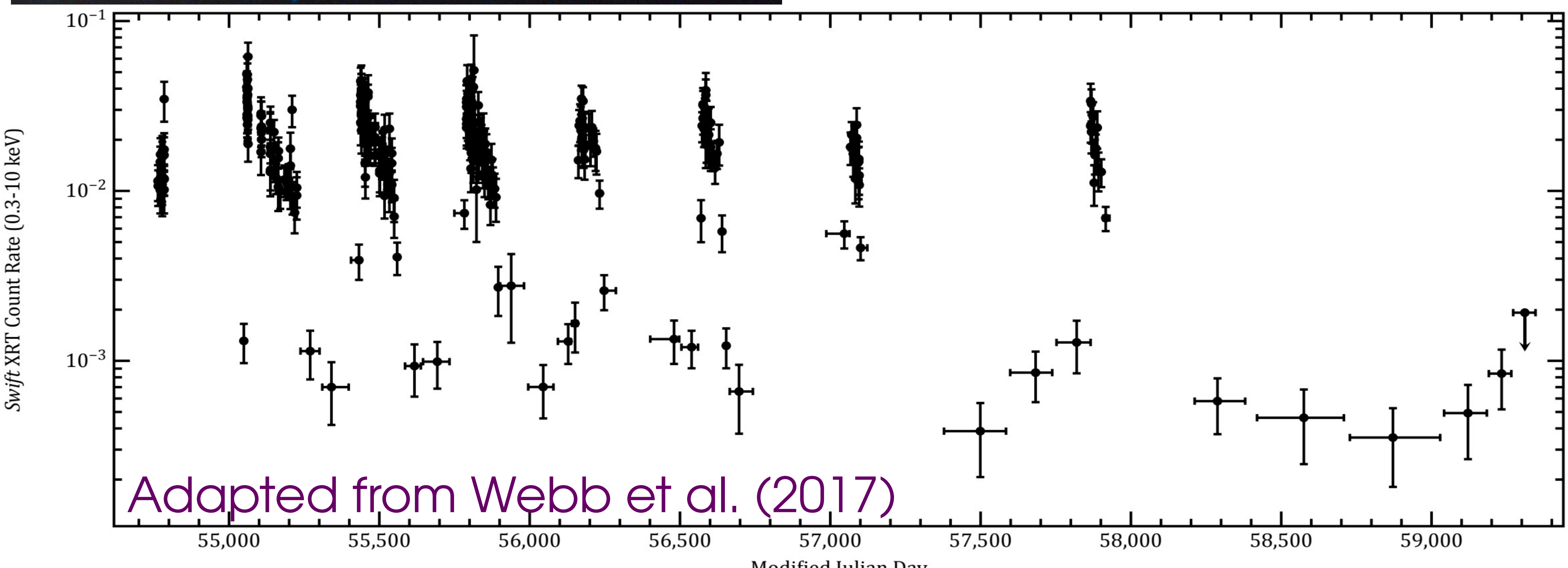
Lin, …, NW, et al.
Nature Astronomy
(2017)

3XMM J150052.0+015452

A very bright ULX (HLX-1)

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)

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

Finding IMBH in other wavelengths/multi-messengers

- Intensive automated catalogue exploitation (e.g. Chilingarian et al. 2018, 305 IMBH from fitting broad SDSS spectral lines (vel. disp.))
- eRosita – to detect (many) new TDEs
- Half of TDEs detected in optical – Rubin observatory (~5000 yr^{-1} Bricman & Gomboc 2019)
- SKA – low state IMBH (in our galaxy) (Maccarone et al. 2005,

  Mezcua et al. 2013)

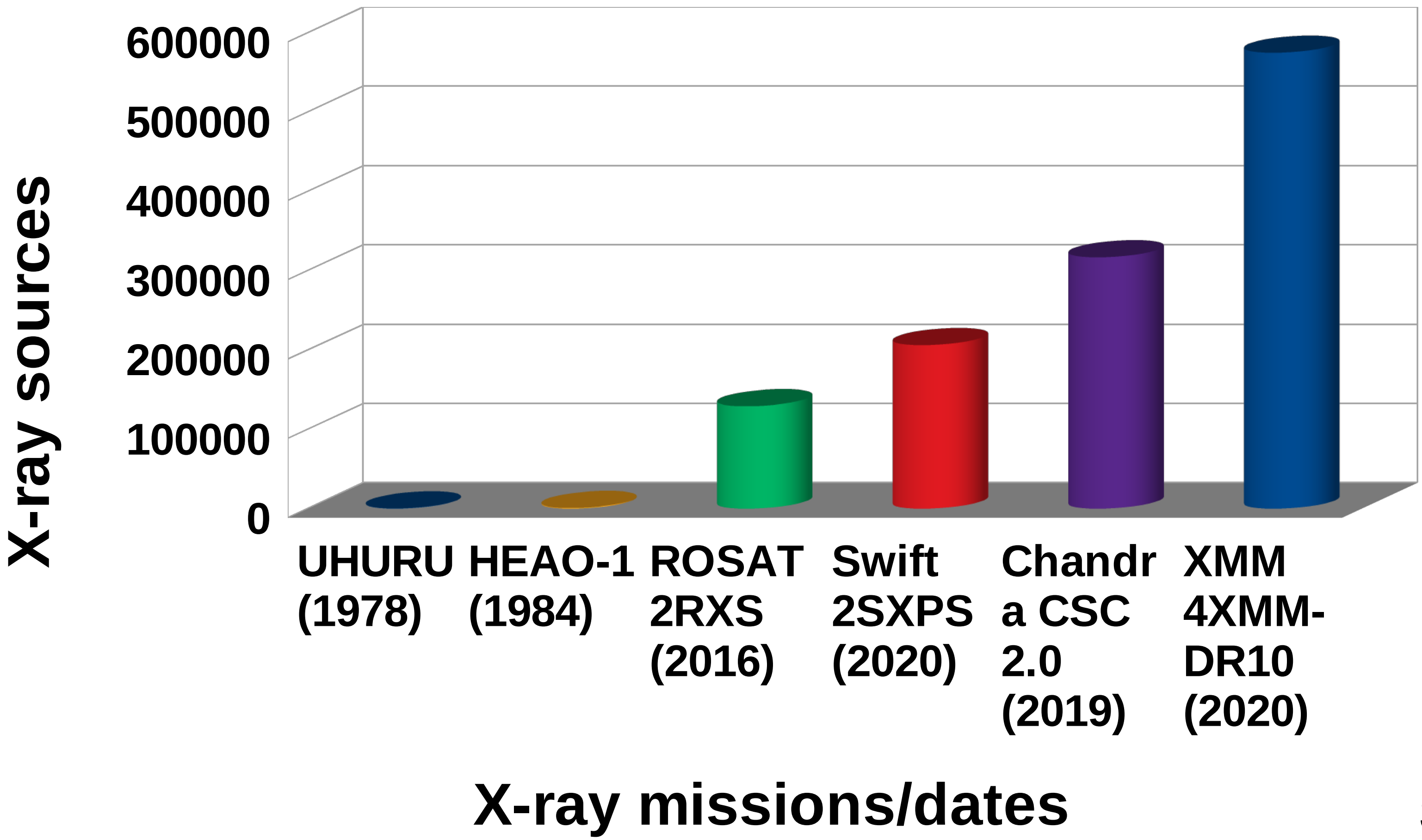
  – jet ejecta (à la HLX-1or Arp 299, Mattila et al. 2018)
- New transients including TDEs and ULXs with SVOM (& Theseus)
- Athena – detect faint IMBH and TDEs – synergy Athena/LISA
- Gravitational wave observations with LISA

Summary

- Finding and studying IMBH is essential for understanding the origin and evolution of SMBH
- ULXs are super-Eddington accretors – useful for studying super-Eddington accretion
- Only the very brightest ULXs may be accreting IMBH
- Tidal disruption events enable us to search out (faint) IMBH
- New good IMBH candidates discovered
- HLX-1 contains a ~2 x 10^4 $M_\odot$ black hole, but the origin is unknown
- Systematic near-real time X-ray searches would reveal more IMBH
- Future observations will reveal significant populations of IMBH

Backup slides

4XMM-DR10



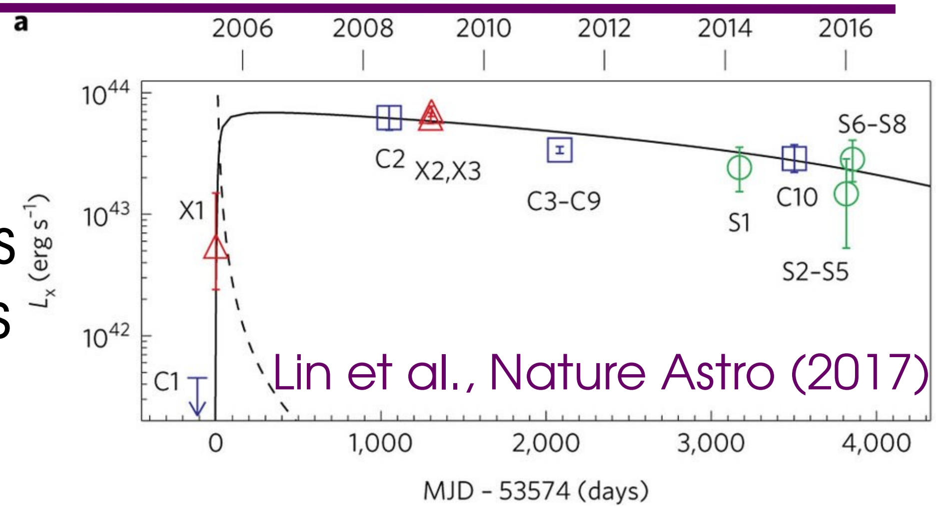
The catalogue is excellent for :

- 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)

XMM2ATHENA

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

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

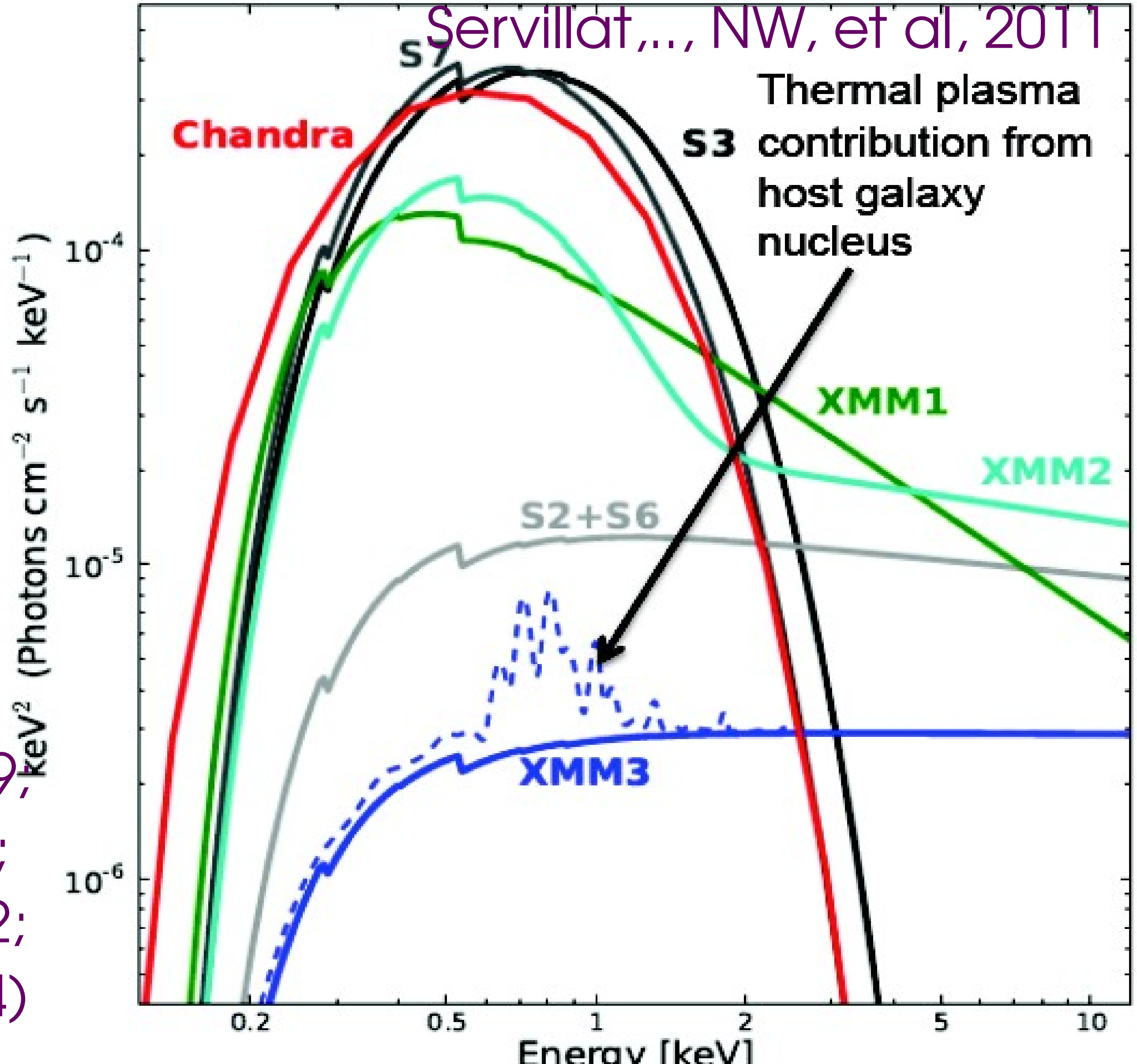
A very bright ULX (HLX-1)

Fitting thermally dominated spectra with relativistic models (BHSPEC, KERRBB, Kawaguchi, 2003) constrains mass : $10^{3\text{-}5}\,M_\odot$

Accretion sub/ near Eddington

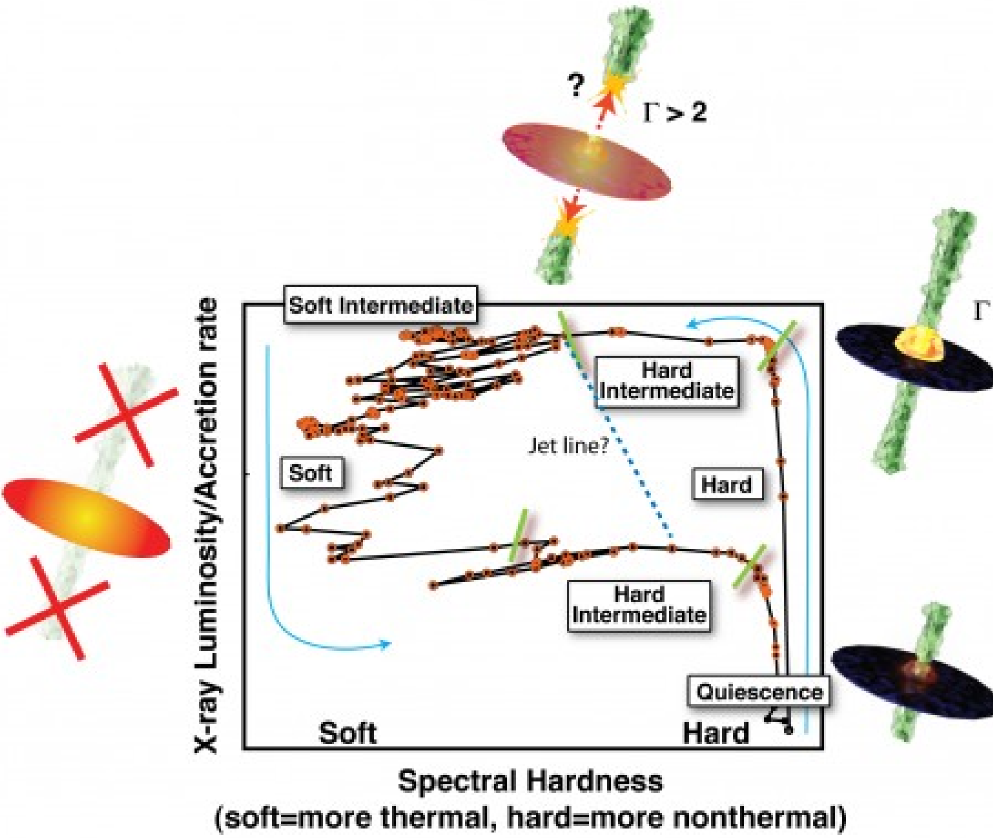
(Godet,…,NW, et al, 2009; Davis,…, NW, et al., 2011; Godet,…,NW, et al., 2012; Straub,…, NW, et al. 2014)

Servillat,.., NW, et al, 2011

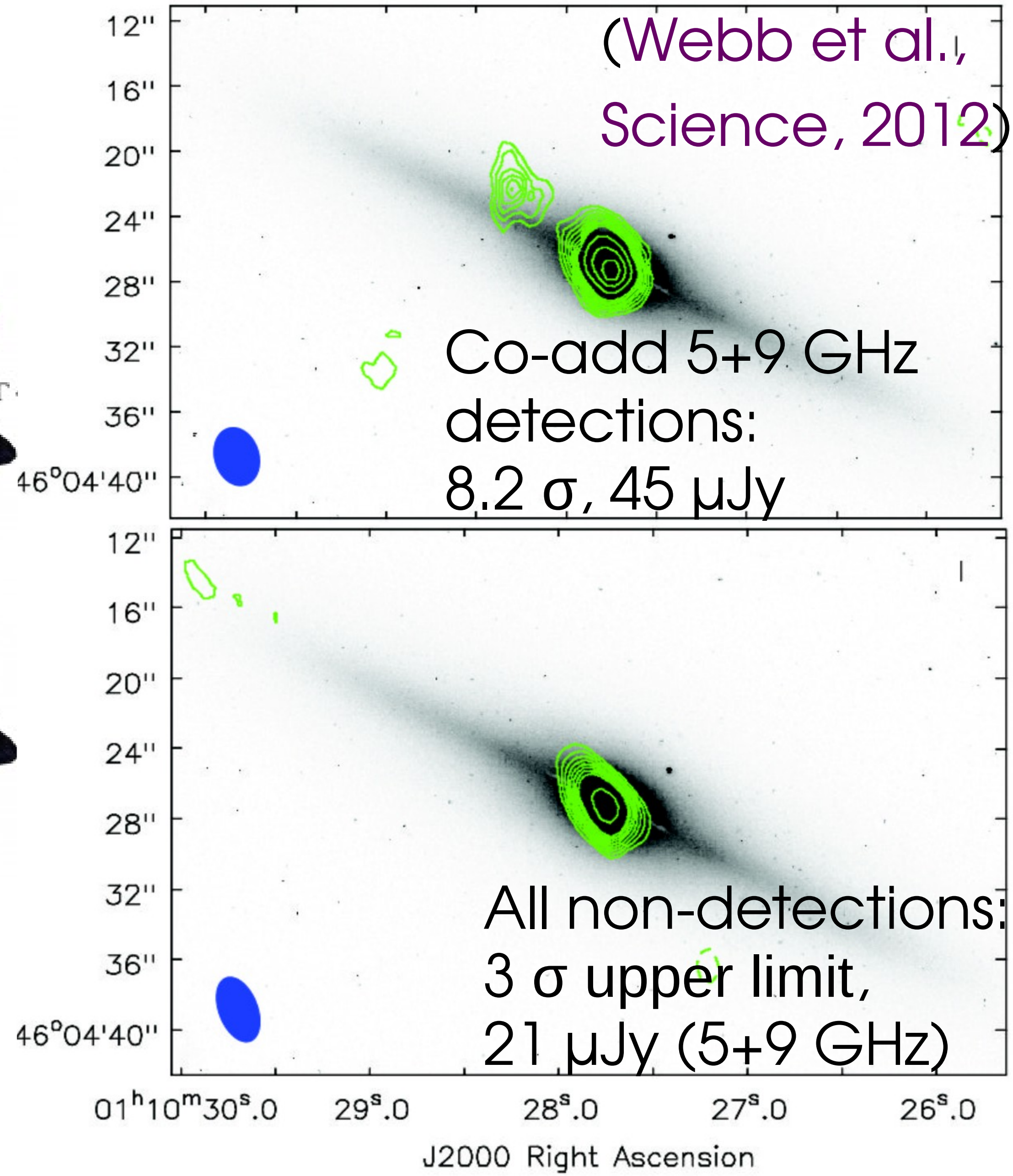


Spectral evolution incompatible with beaming

Radio jets (HLX-1)



Courtesy S. Markoff



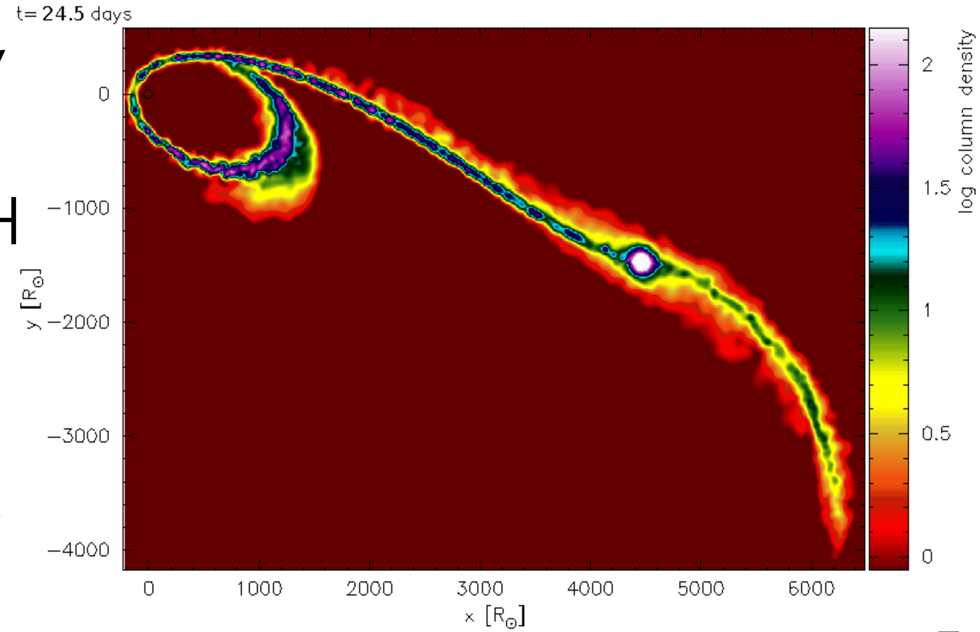
(Webb et al., Science, 2012)

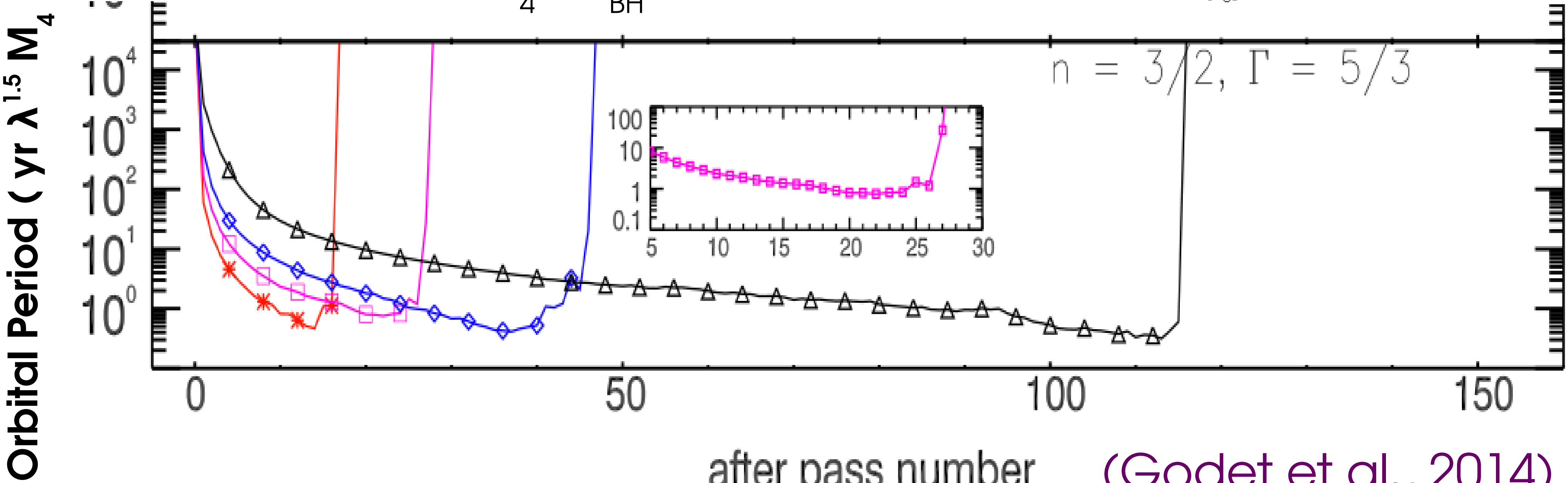
Co-add 5+9 GHz detections:
8.2 σ, 45 μJy

All non-detections:
3 σ upper limit,
21 μJy (5+9 GHz)

HLX-1

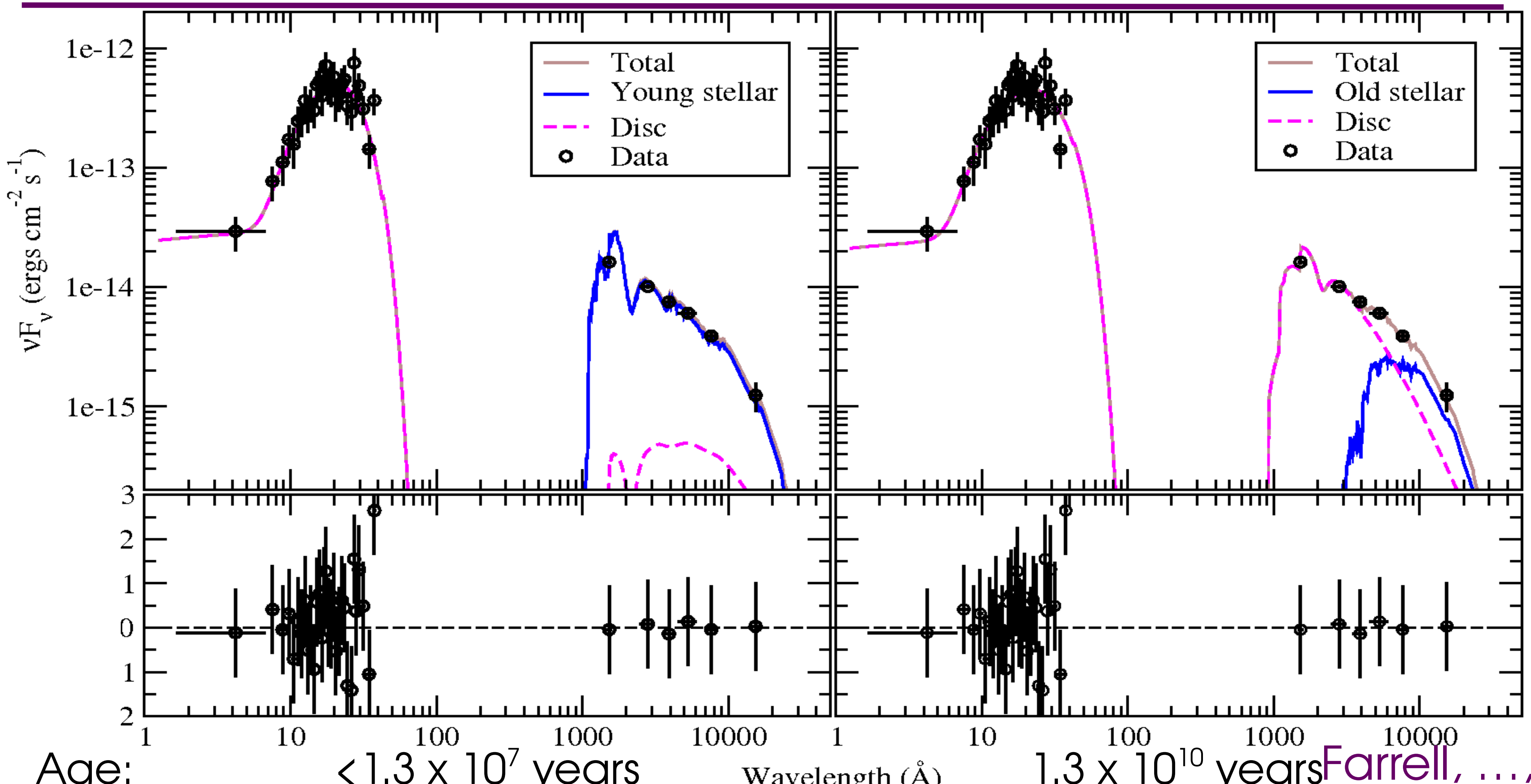
Orbital evolution of a companion, polytrope n=1.5, Γ=5/3 and initial periapsis separation from the IMBH (relative to the tidal radius) of 2.3 (red), 2.4 (magenta), 2.5 (blue), 2.7 (black), $\lambda = R/0.01R_\odot$ and $M_4 = M_{BH}/10^4\ M_\odot$





(Godet et al., 2014)

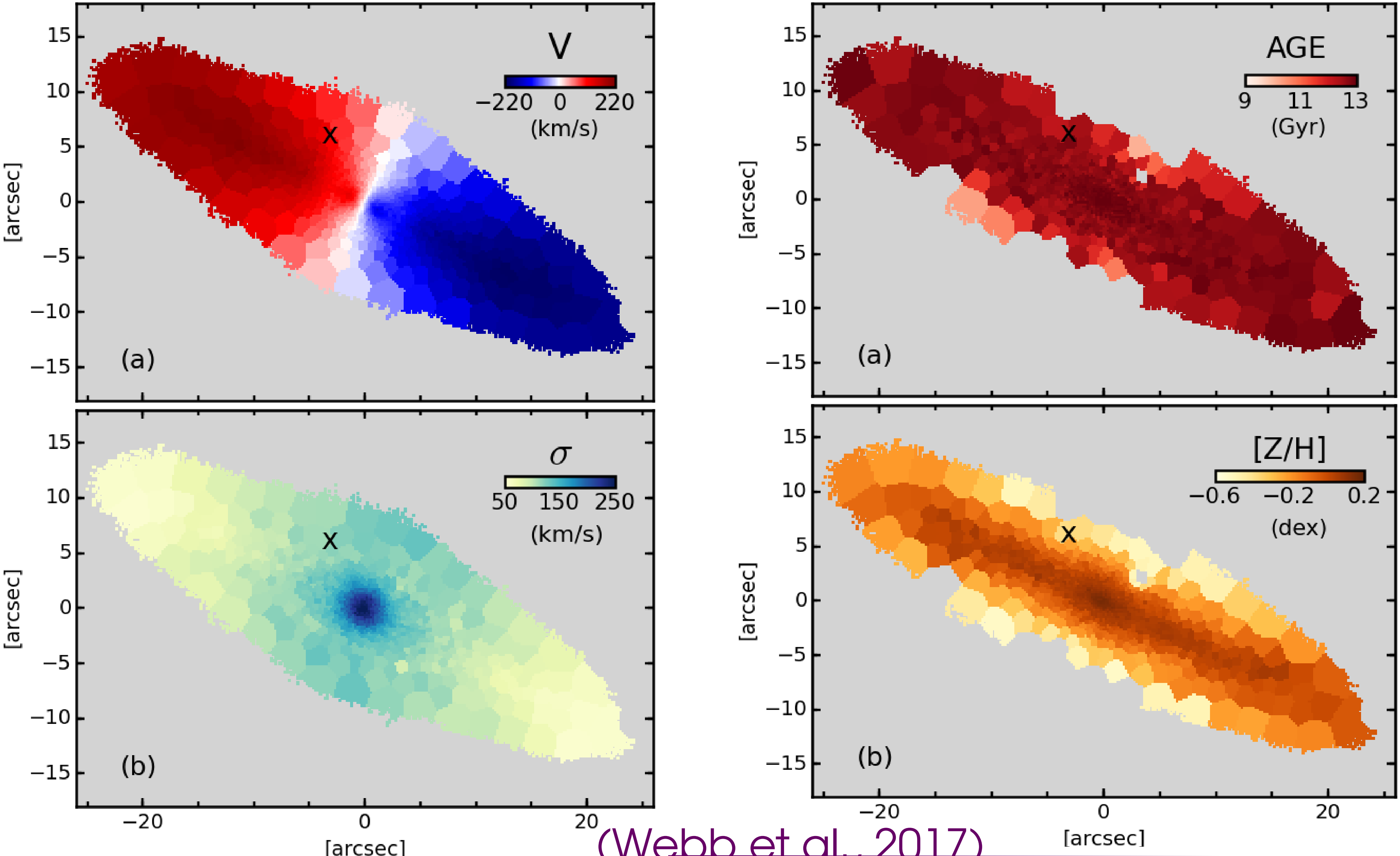
The origin of HLX-1



Age:	<1.3 x 10^7 years	1.3 x 10^{10} years
Mass:	4 x 10^6 $M_\odot$	6 x 10^6 $M_\odot$
Disc irradiation :	8 x 10^{-7}	0.098
X^2 (d.o.f.) :	23.38 (27)	24.28 (27)

Farrell, …, Webb, et al. (2012)

Searching for the origin of HLX-1



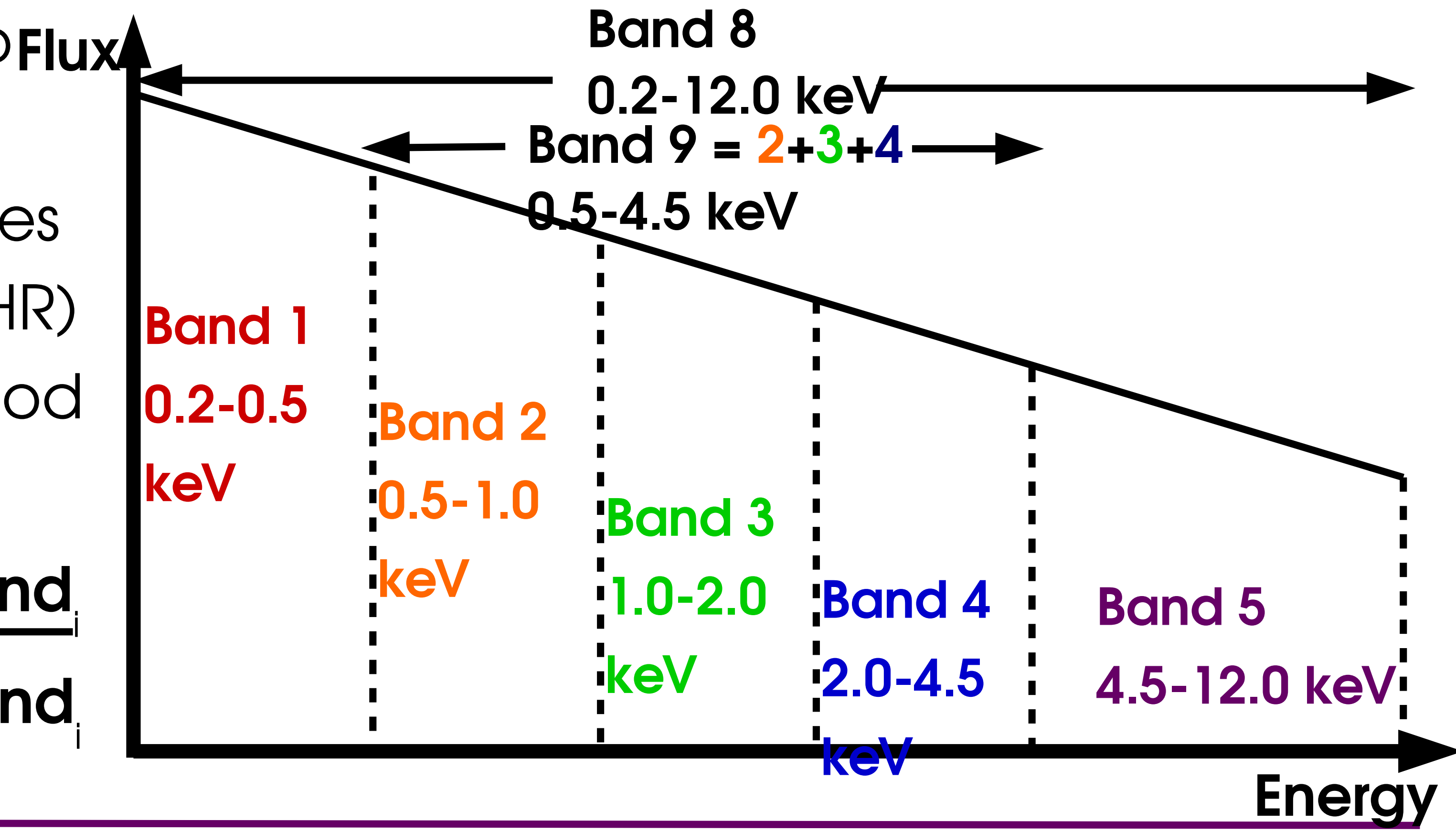
(Webb et al., 2017)

3XMM-DR8 – data proposed

332 columns of information including :

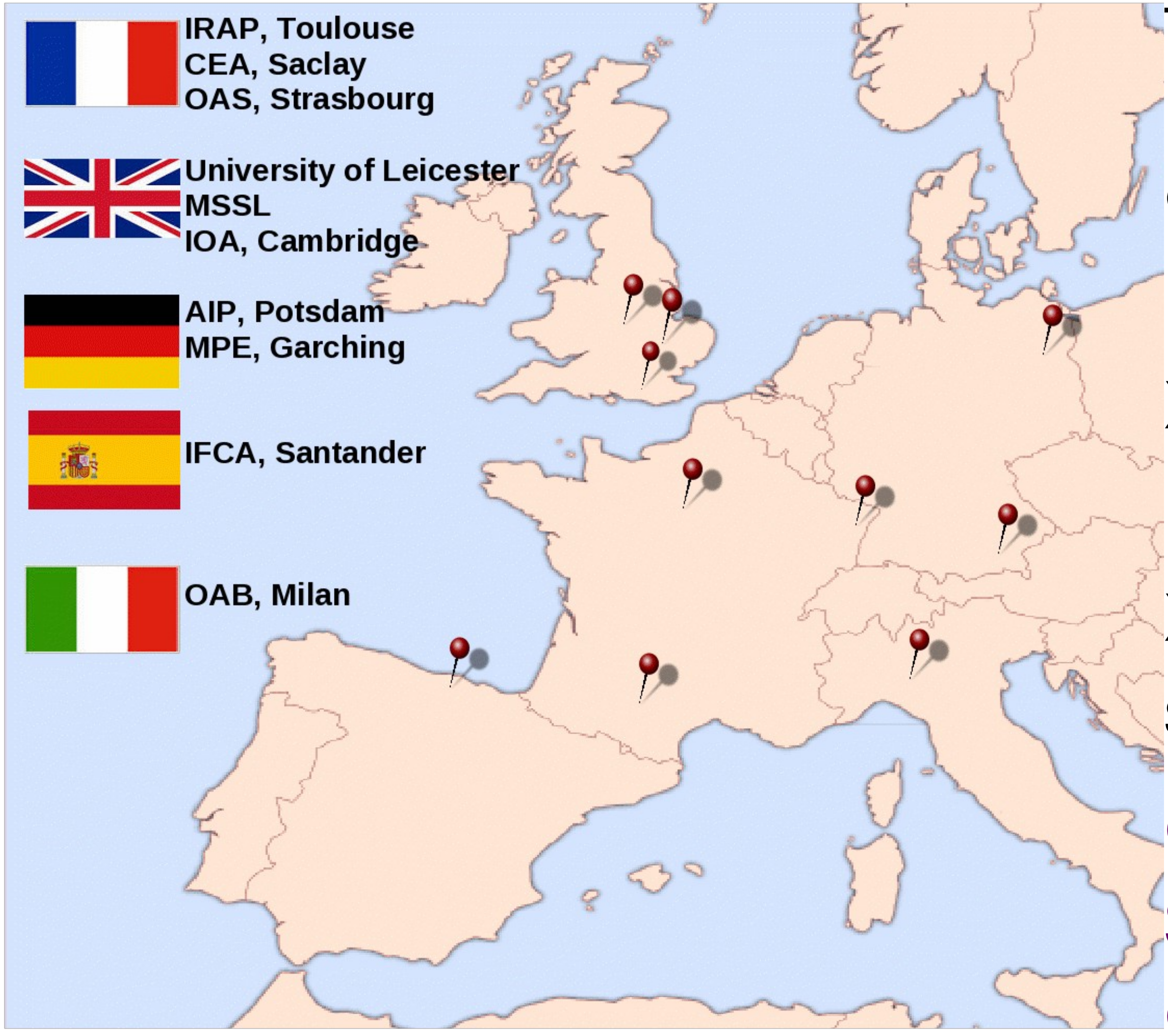
- Identifiers/coordinates
- Observation date/time and observing mode
- Exposure /background info
- Extent
- Counts/fluxes/rates
- Hardness ratios (HR)
- Maximum likelihood
- Quality flags
- Variability

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



XMM-Newton Survey Science Centre (SSC)

The XMM-Newton Survey Science Centre was selected by ESA to ensure that the scientific community can exploit XMM-Newton data



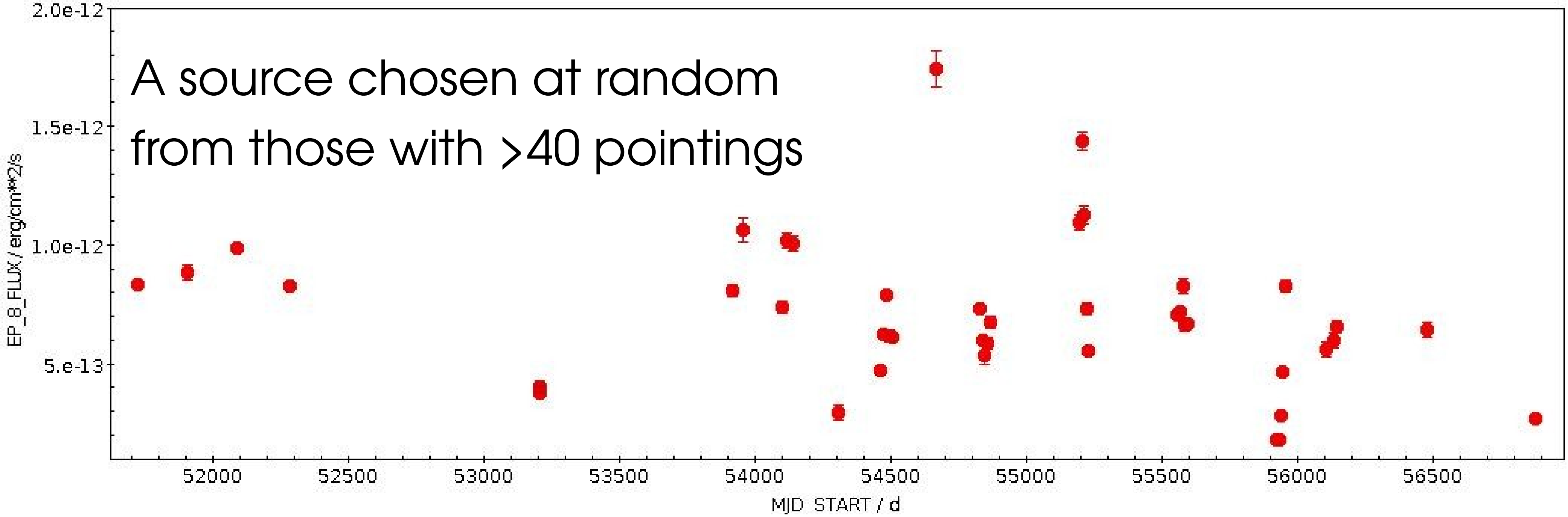
Responsibilities :

Development of science analysis software (SAS)

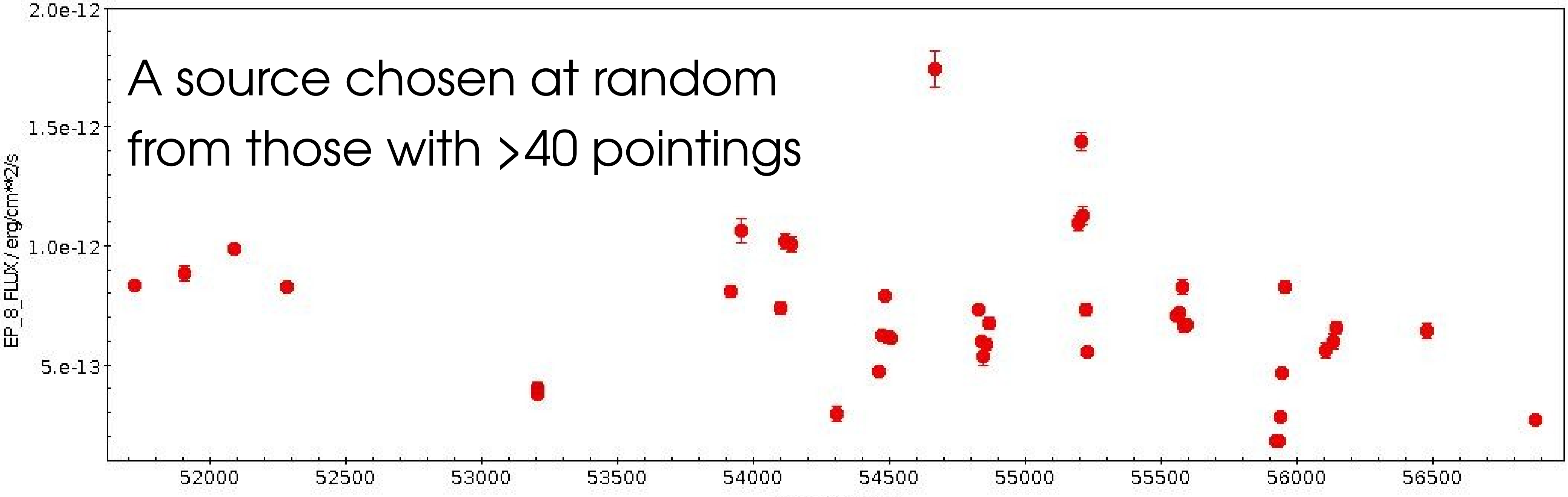
Pipeline processing of all XMM-Newton observations.

Follow-up/identification of the XMM-Newton serendipitous sky - the XID Programme

Compilation of the Serendipitous Source Catalogue.


A source chosen at random
from those with >40 pointings
2.0e-12
1.5e-12
1.0e-12
5.e-13
EP_8_FLUX / erg/cm**2/s
52000
52500
53000
53500
54000
54500
55000
55500
56000
56500
MJD START / d

3XMM-DR8



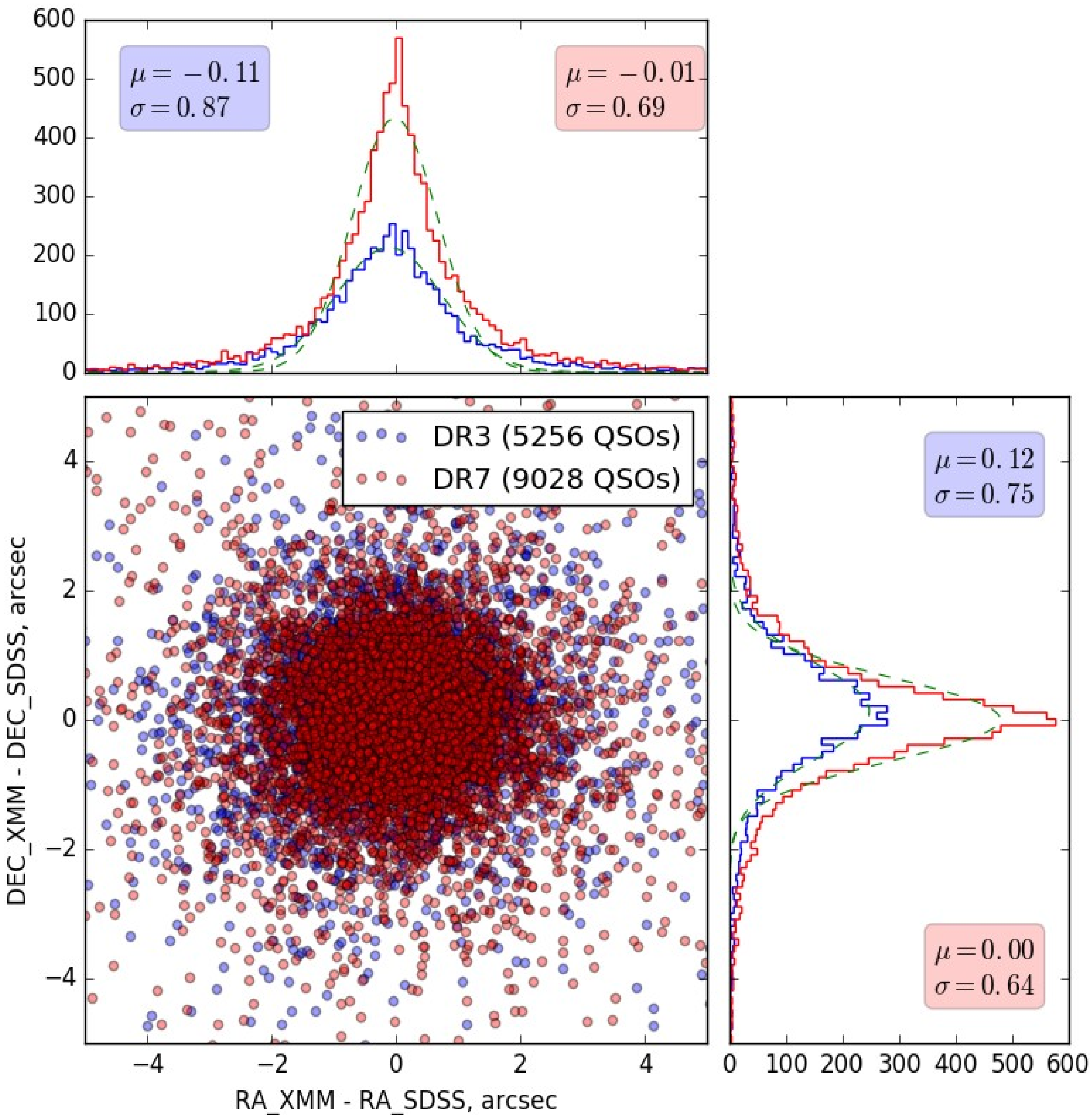
New XMM-Newton stacked catalogue for July (Traulsen et al. 2018)

- Improved signal to noise for stacked sources
- 71951 sources with up to 66 pointings per field, 7543 new sources
- a long-term light curve in all standard XMM-bands

Highly variable sources may be :

- gravitational wave events
- γ-ray bursts
- cataclysmic variables
- tidal disruption events
- supernovae
- .....
- X-ray binary outbursts
- magnetars

3XMM-DR7 – data quality



Astrometry

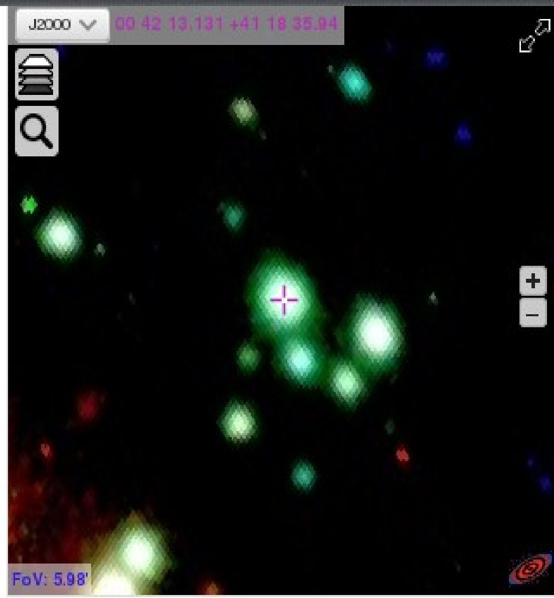
- Cross-match with latest version of SDSS quasars catalogue
- Comparison between 2XMM-DR3 and 3XMM-DR7

IRAP catalogue server

xmm-catalog.irap.omp.eu/source/201125704010012 80% Search

XMM-NEWTON SURVEY SCIENCE CENTRE

cone('00 41 41.4','+41 19 17','0.2deg') SEARCH Show query language



sc_ep_1_flux	2.83214e-15 ± 8.93324e-17	sc_ep_2_flux	4.15314e-14 ± 3.17139e-16
mjd_first	51720.4884491	sc_ep_3_flux	1.94199e-13 ± 7.02137e-16
mjd_last	56479.4418866	sc_ep_4_flux	2.50582e-13 ± 1.3788e-15
sc_chi2prob	0.00323261	sc_ep_5_flux	8.57917e-14 ± 2.47017e-15
sc_ra	10.5547131248	sc_ep_8_flux	5.55128e-13 ± 3.0474e-15
sc_dec	41.3099819881	sc_ep_8_fmax	1.74306e-12 ± 7.50653e-14
sc_poserr	0.0484553	sc_ep_8_fmin	1.77926e-13 ± 1.00496e-14
sc_det_ml	47769.8	sc_ep_9_flux	4.01314e-13 ± 1.18207e-15
sc_ext_ml	0.0	sc_extent	0.0
sc_fvar	0.252154 ± 0.0542623	sc_hr1	0.86285 ± 0.00386822
sc_hr2	0.629318 ± 0.00244231	sc_hr3	-0.341634 ± 0.00264739
sc_hr4	-0.808007 ± 0.00395566	sc_sum_flag	1
sc_var_flag	False	confused	False

This source in external databases: XCatDB, Chandra CSC 20" VOTable, Swift 1SXPS 20", RCSED, Simbad 2', Vizier 20", NED 2'

Detections (observations of this source at different epochs)

detid	revolut	obs_id	src_num	poserr	ep_8_flux	utc_start	exptime	ep_offax	spectrum
101125704010012	0100	0112570401	12	0.329335	8.36703e-13	2000-06-25 11:43:22.000	31232	5.27103	True (Fit spectrum)
101125706010013	0193	0112570601	13	0.327963	8.83526e-13	2000-12-28 00:51:02.000	9849	5.96841	True (Fit spectrum)
101092701010011	0285	0109270101	11	0.223599	9.89186e-13	2001-06-29 06:59:13.000	52508	5.30718	True (Fit spectrum)
101125701010013	0381	0112570101	13	0.33079	8.2724e-13	2002-01-06 18:44:42.000	61198	6.07995	True (Fit spectrum)
102022302010031	0843	0202230201	31	0.266496	4.0448e-13	2004-07-16 16:40:09.000	18335	4.27041	True (Fit spectrum)
102022303010030	0843	0202230301	30	0.276143	4.00074e-13	2004-07-17 12:30:57.000	23196	4.26273	True (Fit spectrum)

HLX-1

ID	Observatory	Date	Spectral model	χ^2/dof	Luminosity
R1	Rosat	1990 Jul 11-1991 Aug 13*	-	-	<11
R2	Rosat	1992 Jun 20-1993 Jul 10	-	-	<0.9
X1	XMM-Newton	2004 Sep 23	Γ=3.4$\pm$0.3	113.4/108	$11\pm^{0.1}_{4.0}$

HLX-1

ID	Observatory	Date	Spectral model	χ^2/dof	Luminosity
R1	Rosat	1990 Jul 11-1991 Aug 13*	-	-	<11
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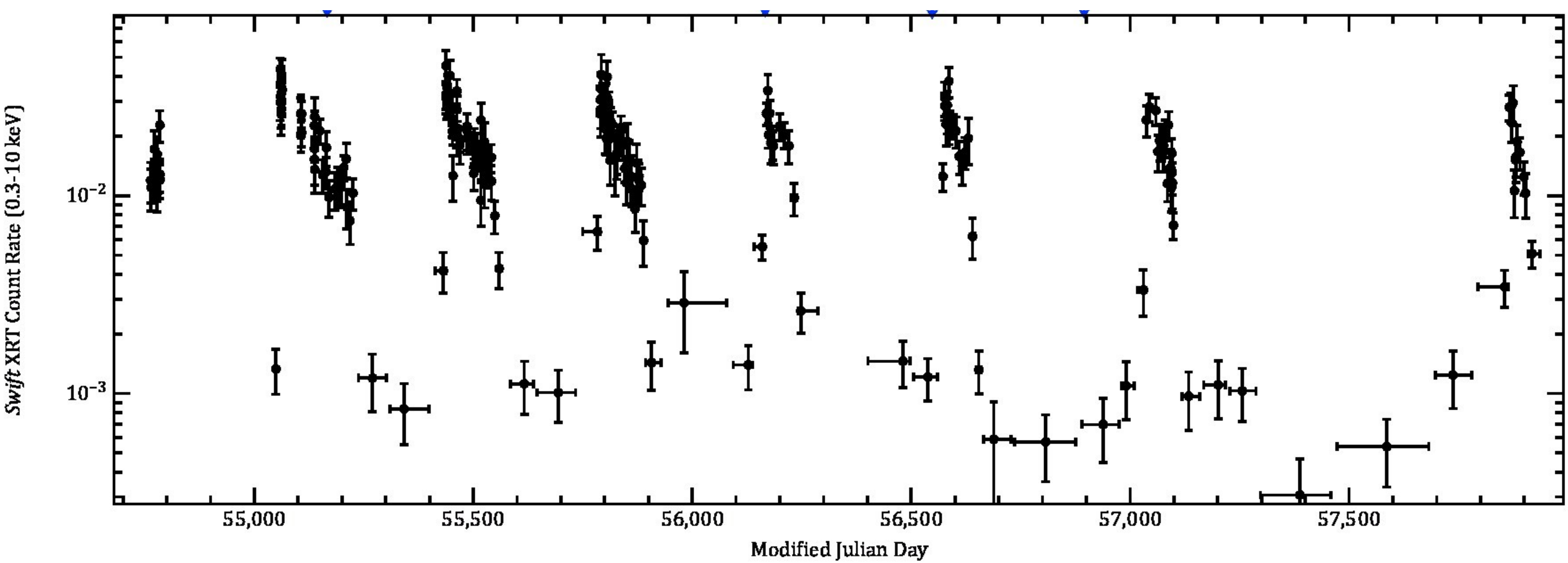
X1	XMM-Newton	2004 Sep 23	Γ=3.4±0.3	113.4/108	$11\pm^{0.1}_{4.0}$



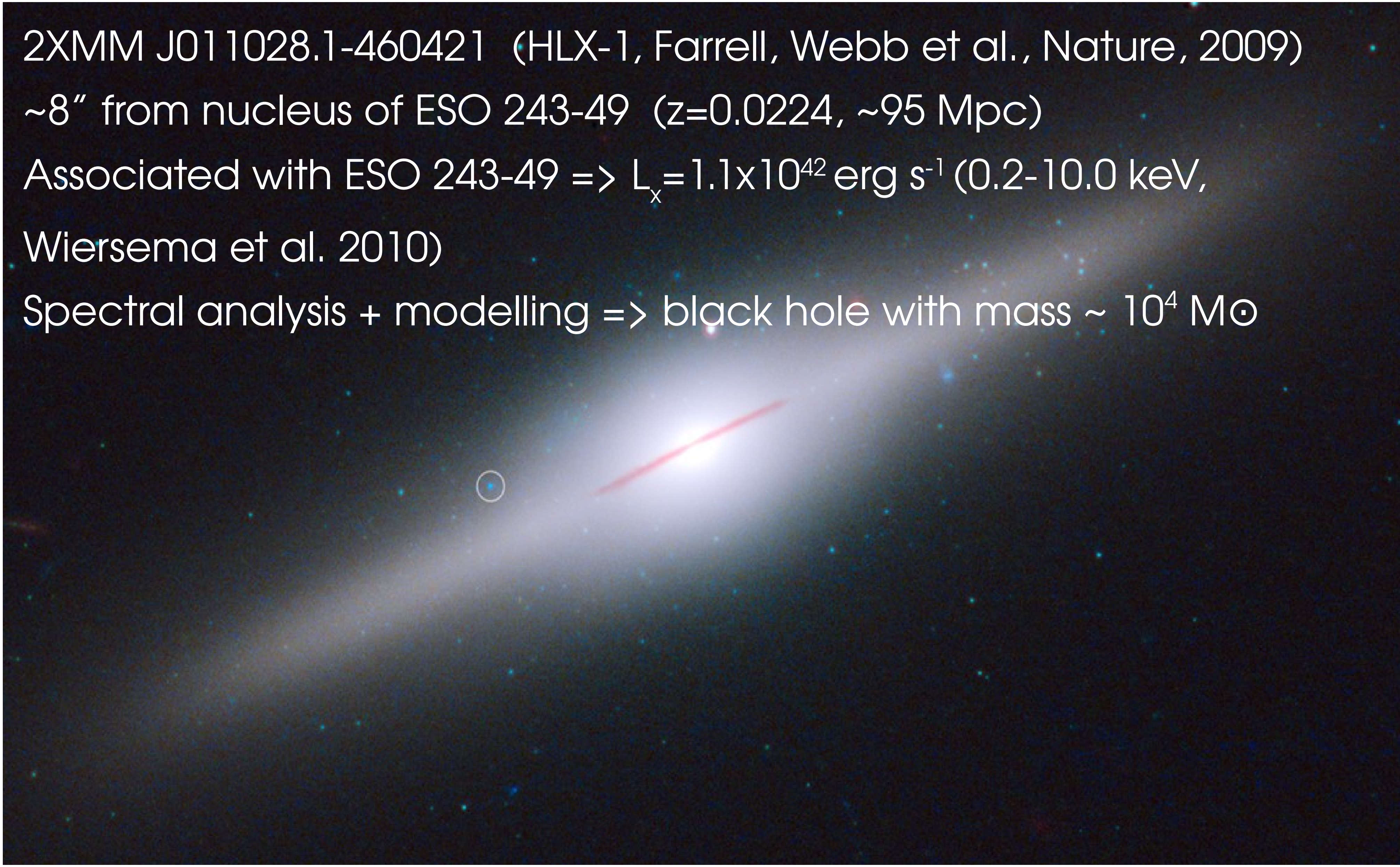
HLX-1

2XMM J011028.1-460421 (HLX-1, Farrell, Webb et al., Nature, 2009)

~8" from nucleus of ESO 243-49 (z=0.0224, ~95 Mpc)

Associated with ESO 243-49 => $L_x=1.1\times10^{42}$ erg s^{-1} (0.2-10.0 keV, Wiersema et al. 2010)

Spectral analysis + modelling => black hole with mass ~ 10^4 $M_\odot$



New catalogues

The stacked catalogue will be released in 2018

- Uses standardised source-detection for overlapping observations
- Provides a convenient handling of multiple pointings

- 71951 sources with up to 66 pointings per source

- Improved signal to noise for stacked sources

- A population of low significance detections in 3XMM-DR7 spurious

- 7543 new sources in the stacked catalogue

4XMM anticipated for 2019 - full re-reduction of all data (~10500 obs.) with improved software and improved calibration

to include : variability between observations in catalogue
added variability analysis
improved source flagging
sky exposure for population studies, etc

SUSS 3.0

Field of view coincides with 3XMM FOV

6,880,116 detections

4,751,899 unique sources

867,022 have multiple entries

Visible (U, B and V) and UV (UVW1, UVM2 and UVW2)

Detections down to AB magnitude:		FWHM ('')
UVW2~	23.0	1.98
UVM2~	24.1	1.8
UVW1~	24.8	2.0
U ~	25.2	1.55
B ~	24.0	1.39
V ~	23.4	1.38

(Page et al. 2012)