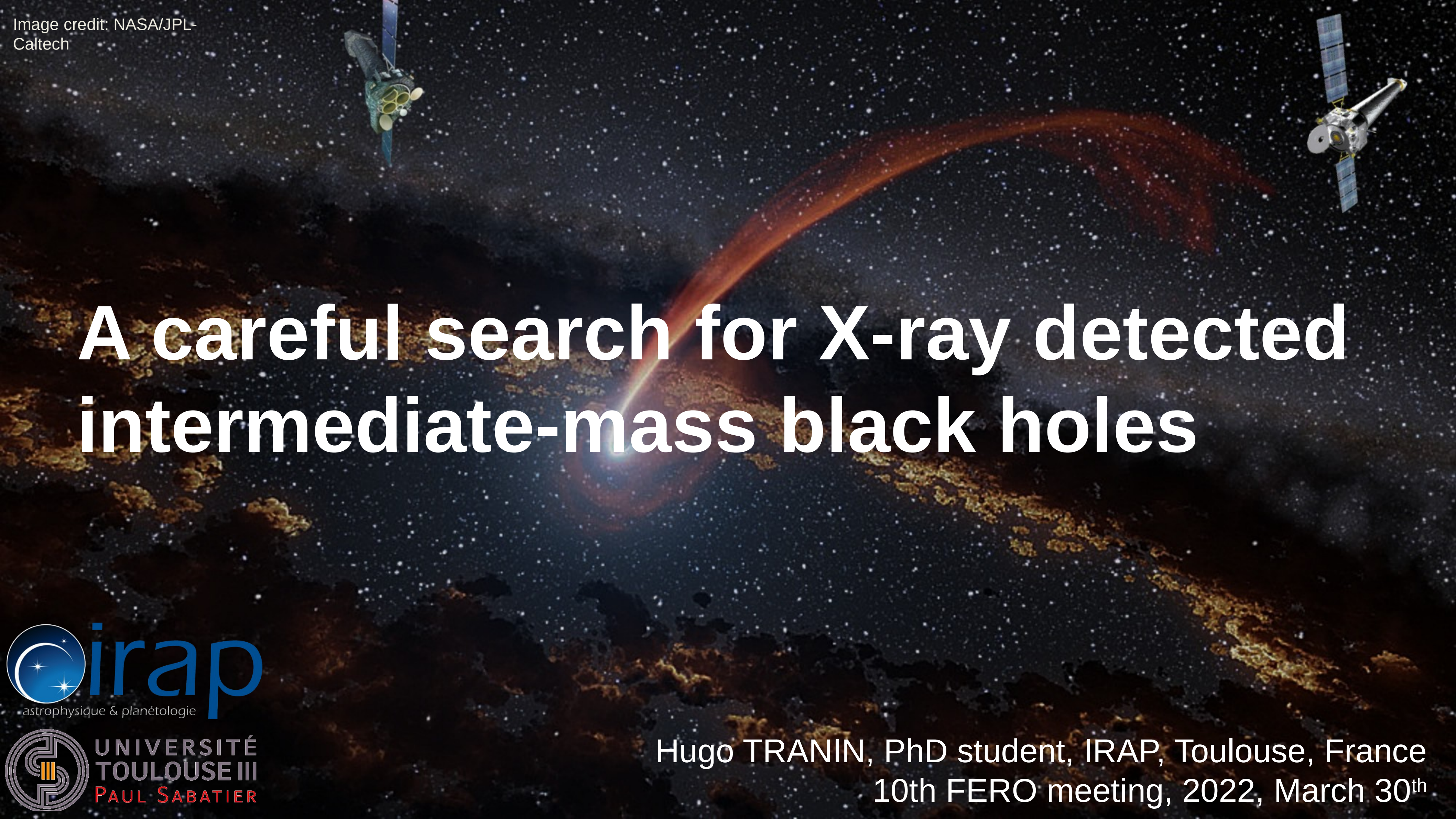

Image credit: NASA/JPL-Caltech

A careful search for X-ray detected intermediate-mass black holes

irap
astrophysique & planétologie

UNIVERSITÉ TOULOUSE III PAUL SABATIER

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10th FERO meeting, 2022, March 30th

Outline

1) Context : how to search for IMBH in X-rays

2) Classification of X-ray sources

3) Results on ULX, HLX, TDE

4) Expectations for dwarf galaxies

Applications of an X-ray source classification

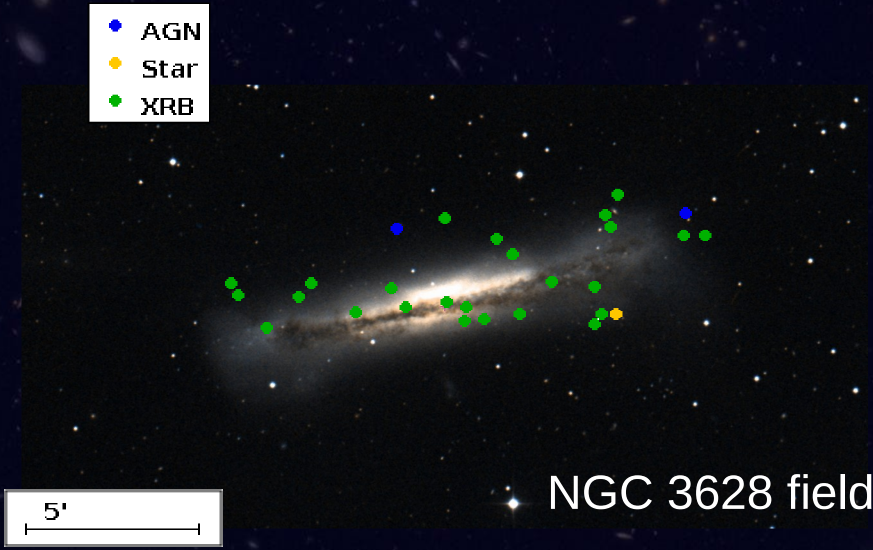
X-ray catalogues: about 10^6 sources, mostly *serendipitous*
⇒ automatic classification

Population studies, e.g. type II AGN, flaring stars, ULX...

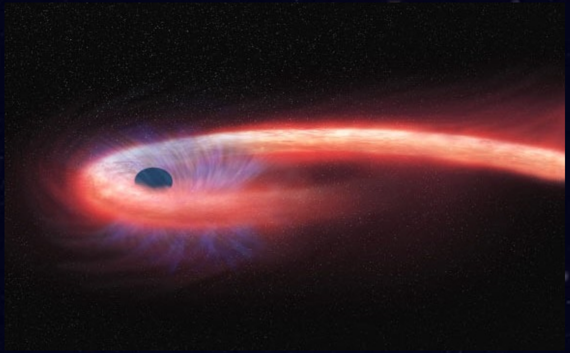
Find exotic objects (TDE, CLAGN...)

Separate galactic / extragalactic sources e.g. for photo-z computation

Identify relevant alerts for transient astronomy, e.g. multimessenger events



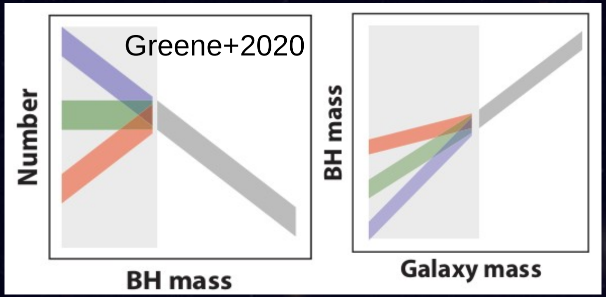
NGC 3628 field



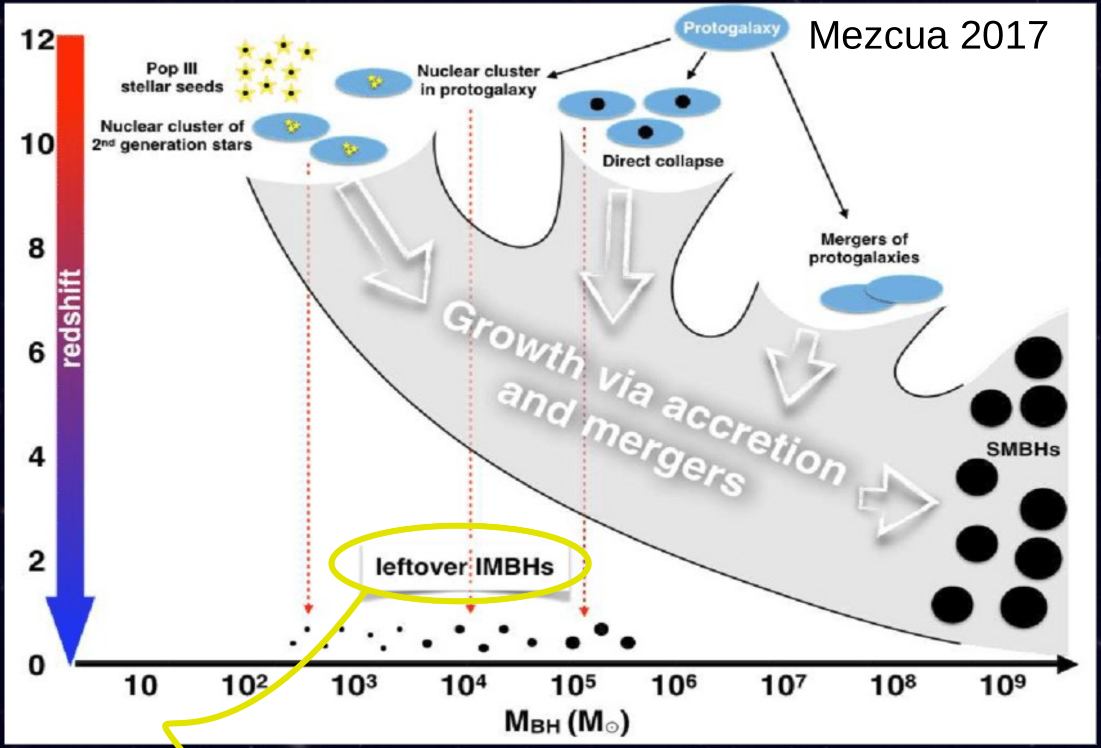
Intermediate-mass black holes (IMBH)

- $10^2 < M < 10^5\ M_\odot$
- Uncertain formation

Remnants of pop III ?
Runaway merger in GC ?
Direct collapse ?



- Uncertain evolution into SMBH



Hard to find !
- Wait for efficient accretion (TDE)
- Find hidden BH in dwarf
- but also...

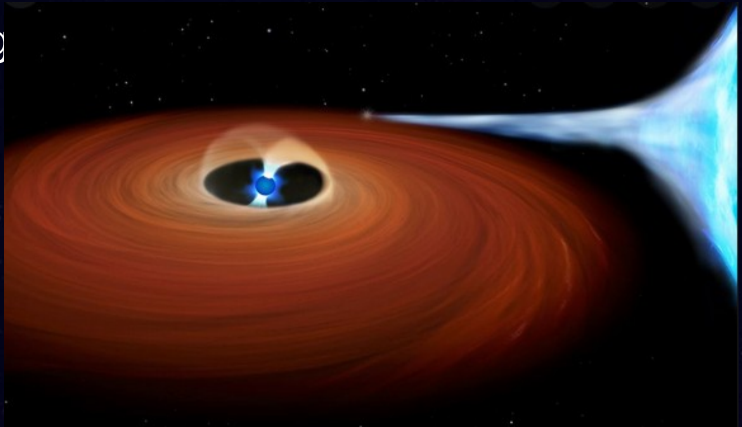
(Some) Ultraluminous X-ray sources contain IMBH

ULX : $L_X > 10^{39}$ erg/s, outside the nucleus

$\Rightarrow L_X > L_{Edd}$ of a $8M_{sun}$ black hole

HLX-1, $M \sim 10^4\ M_\odot$, Farrell+2009

- Extrapolation of XRB (in « ultraluminous state »)
- Some are neutron star accretors, other are super-Eddington BH
- We expect IMBH in the most luminous (HLX, $L_X > 10^{41}$ erg
- 20% are background / foreground contaminants
- **Use source classification** to remove them



Sketch of a NS ULX, credit:NAOJ

Previous X-ray classification studies

- Few are probabilistic

⇒ Use a Bayesian method

- Almost all are on small samples (but see Pineau+2009)

⇒ Use the full X-ray catalogues

- Trade-off efficiency - interpretability

⇒ Develop visualisation tools to improve

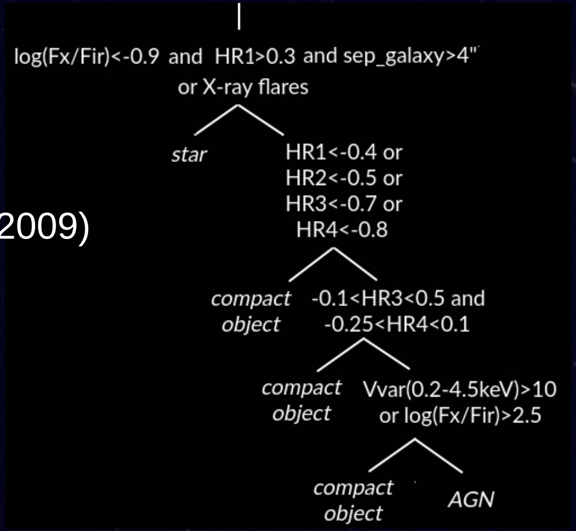
- Suboptimal catalogue enhancement

⇒ Supplement it with VO tools, careful correlations

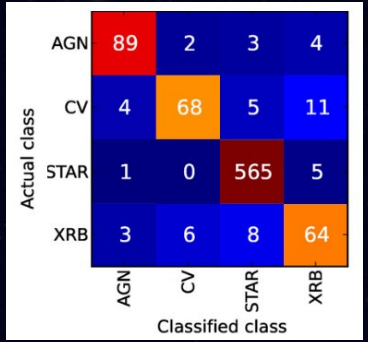
- Samples of known XRB, CV, TDE… are small

⇒ Use updated databases to enlarge them

Lin+2012 (4330 bright sources)



Farrell+2015 (3696 variable sources)



Arnason+2020
(943 M31 sources)

		Actual Class				
		AGN	SNR	fgStar	XRB	Total
Predicted Class	AGN	5	0	2	2	9
	SNR	0	3	1	0	4
	fgStar	3	2	5	0	10
	XRB	6	1	4	15	26
	Total	14	6	12	17	49

Step 1: take large catalogues and enhance them

X-ray	4XMM-DR11	600k
	Chandra CSC2	315k
	Swift 2SXPS	200k
Optical	Gaia EDR3	1.8G
	PanSTARRS	1.9G
Infrared	2MASS	471M
	AllWISE	747M
Identification	AGN in the MIR (Secrest+2015)	1.3M
	Stars : HIPPARCOS	1.2M
	XRB : miscellaneous...	~1500 X-ray sources
	CV : miscellaneous...	~500 X-ray sources
Galaxies	GLADE (Dalya+2016)	1.9M

High sky density

⇒ multiple counterparts

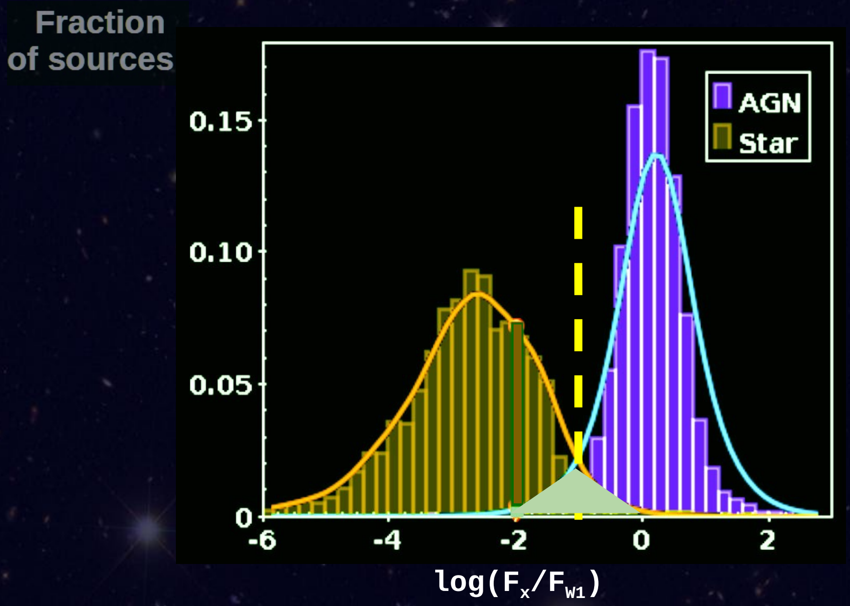
⇒ bayesian treatment (*nway*, Salvato+2017)

Highly complete galaxy catalogue >1M galaxies at D<500Mpc

⇒ Enable data-mining + add meaningful observables

F_X/F_{OPT} F_X/F_{IR} L_X F_{MAX}/F_{MIN} …

Step 2: use criteria



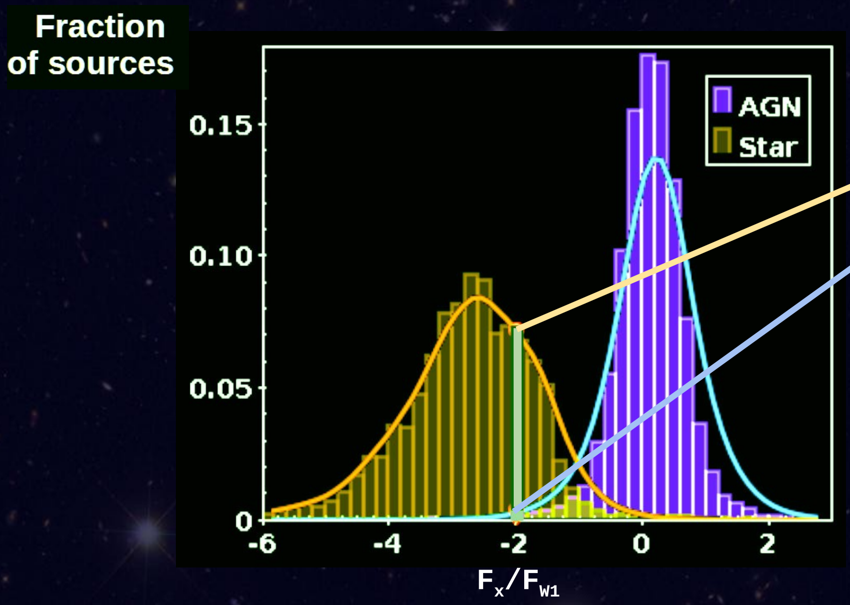
Possible criterion:

$\log(F_X/F_{W1}) < -1 \Rightarrow$ star

else $\Rightarrow$ AGN

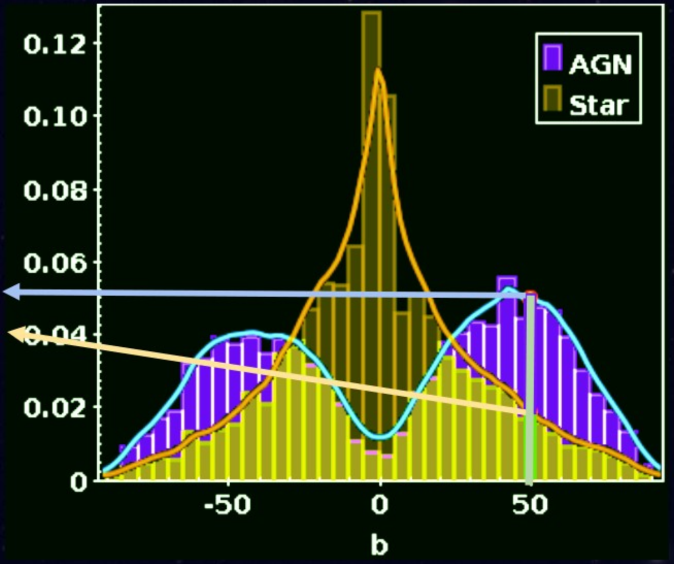
… but overlap

Step 2: use ~~criteria~~ probabilities



If F_x/F_{W1} = 0.01
$\mathscr{L}_{b,\ Star}$ = 93%
$\mathscr{L}_{b,\ AGN}$ = 7%

If b = 50°
$\mathscr{L}_{b,\ AGN}$ = 67%
$\mathscr{L}_{b,\ Star}$ = 33%



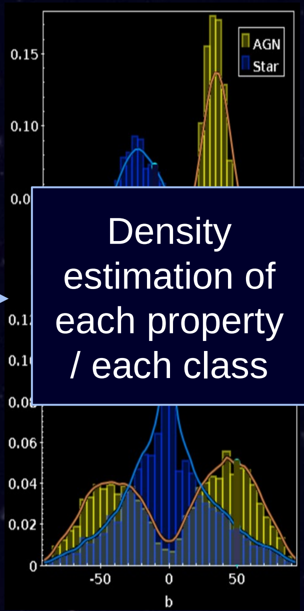
$$\mathbb{P}(\mathrm{AGN}|D) = \frac{\mathcal{P}(\mathrm{AGN})\mathcal{L}(\mathrm{AGN}|D)}{\mathcal{P}(\mathrm{AGN})\mathcal{L}(\mathrm{AGN}|D) + \mathcal{P}(Star)\mathcal{L}(Star|D)}$$ = 31% here

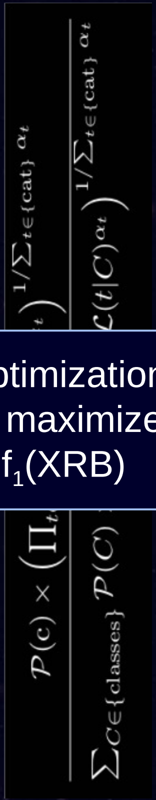
(with priors $\mathcal{P}$(AGN)=0.75, $\mathcal{P}$(Star)=0.25)

Combine the 17 features ⇒ **Naive Bayes classification**

Final structure

Catalogue enhancement → Training sample → Density estimation of each property / each class → Optimization to maximize f_1(XRB) → Application on test sample → Results





CLAssification of X-ray sources using Bayesian Optimized Inference

CLAXBOI public code, Tranin et al. A&A 2022

Results

Application to the whole catalogue

on 4XMM training sample

	AGN	Star	XRB	CV
→ AGN	18373	25	46	149
→ Star	15	6197	10	12
→ XRB	80	12	479	10
→ CV	4	0	8	81
recall (%)	99.5	99.4	88.2	32.1
precision (%)	98.9	97.2	93.7	84.6
f_1-score	0.992	0.983	0.909	0.465

Tranin et al. A&A 2022

on 2SXPS

Truth →	AGN	Star	XRB	CV	Total cl.
→AGN	19515	82	25	191	19813
→Star	44	4628	3	27	4702
→XRB	140	18	326	17	501
→CV	9	9	2	124	144
Total	19708	4737	356	359	Average
recall (%)	99.0	97.7	91.6	34.5	80.7
precision (%)	97.0	98.6	90.7	85.5	92.3

Random Forest on 2SXPS

Truth →	AGN	Star	XRB	CV	Total cl.
→AGN	5889	7	20	39	5955
→Star	6	1404	1	3	1414
→XRB	9	5	83	5	102
→CV	7	1	1	68	77
Total	5911	1417	105	115	Average
recall (%)	99.6	99.1	79.0	59.1	84.2
precision (%)	96.8	99.2	95.2	87.9	95.2

⇒ **better results on XRB + better interpretability**

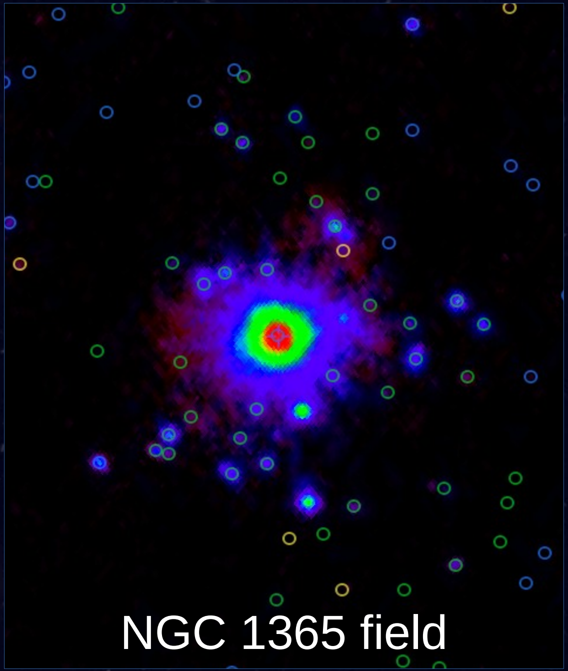
Results

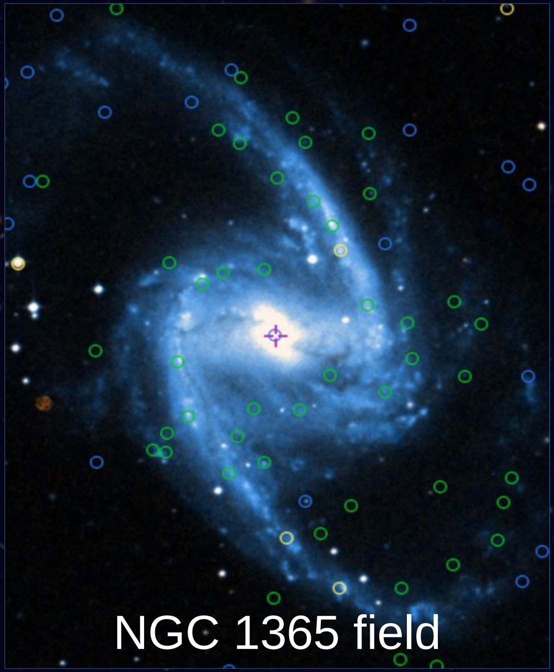
Application to nearby galaxies

on 4XMM x GLADE (Dalya+2016)

	AGN	Soft source	XRB
→ AGN	1578	29	22
→ Soft source	15	54	19
→ XRB	65	23	358
recall (%)	95.2	50.9	89.7
precision (%)	95.8	68.9	80.4
f_1-score	0.955	0.585	0.848

Goal:
Identify XRB and ULX in nearby galaxies

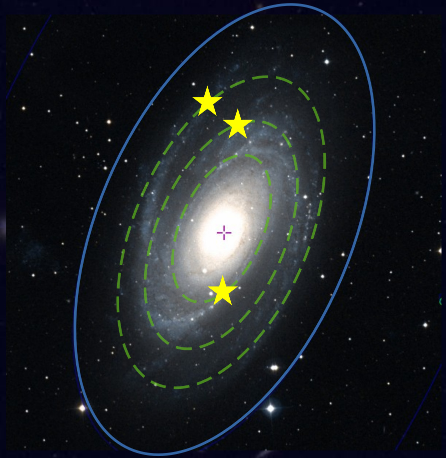




Tranin et al. to be sub

Results: ULX, HLX, TDE

Identifying XRB and ULX in nearby galaxies



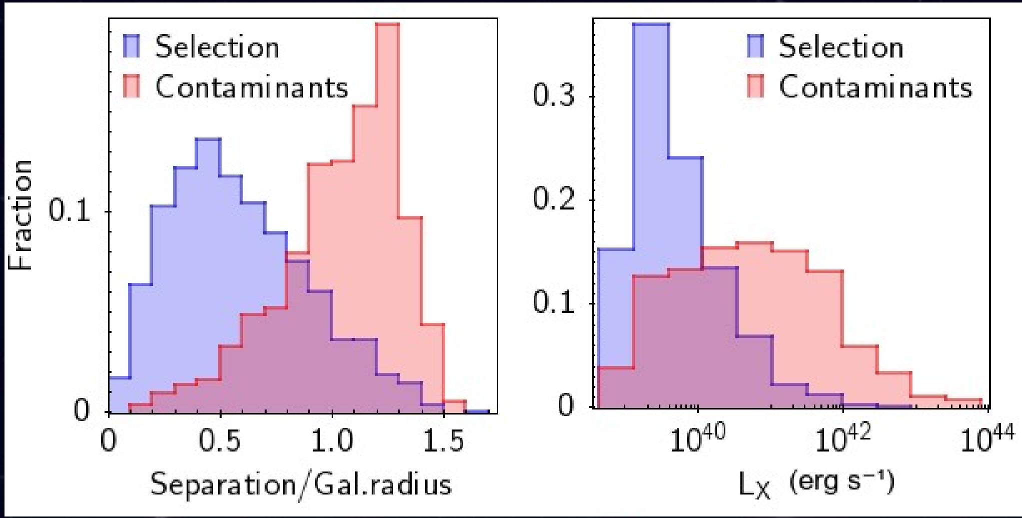
Output of the classification:

$P_{XRB} = 1 - P_{soft} - P_{AGN}$ ⇒ select sources with $P_{XRB} > f_{cont}$

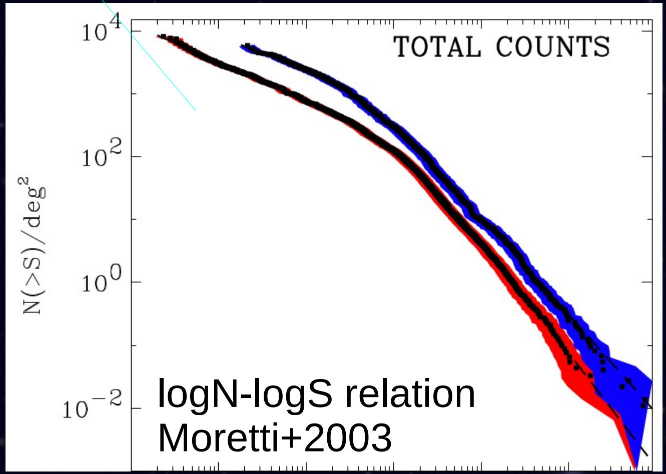
f_{cont}

Example of contaminant : 4XMM J125306.0-091315

Example of candidate : 4XMM J191127.7-570331



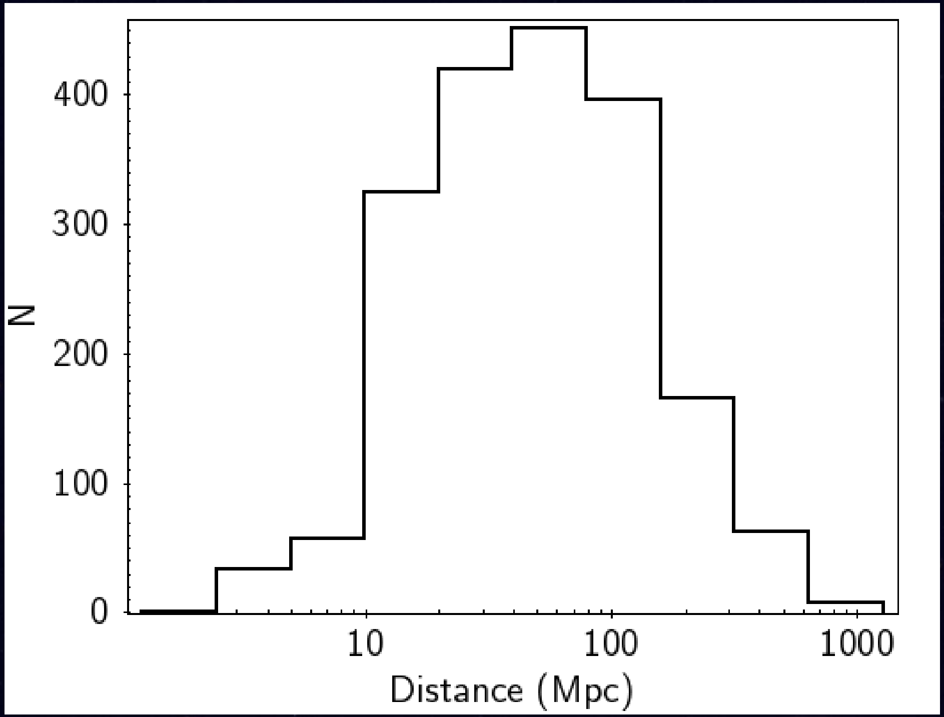
Tranin et al. (to be sub)

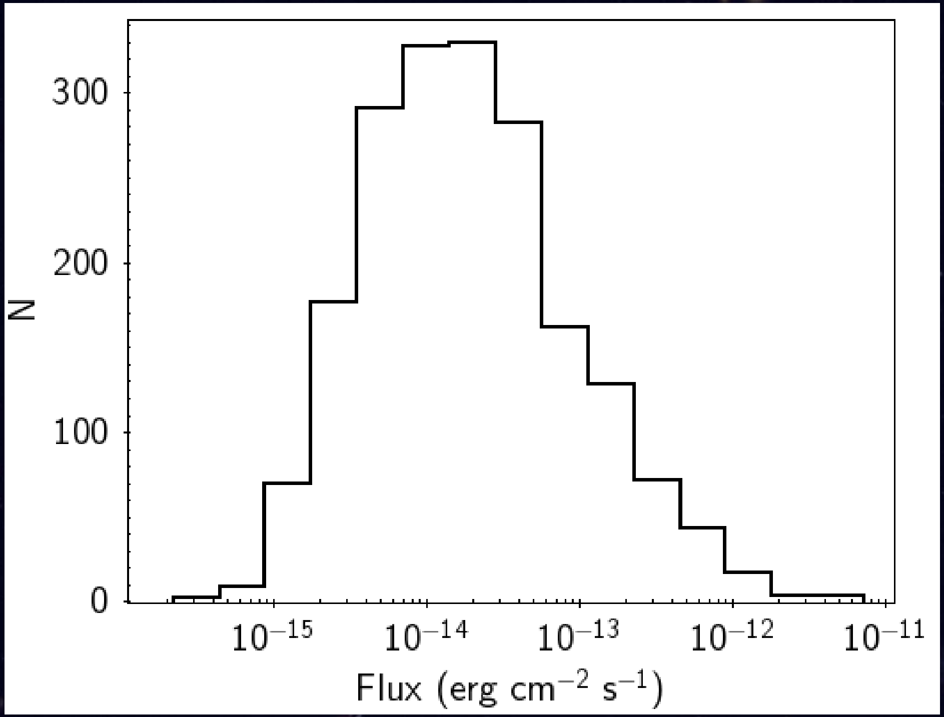


⇒ clean sample: **3600 XRB**
1900 ULX

ULX sample

⇒ clean sample: **1900 ULX**



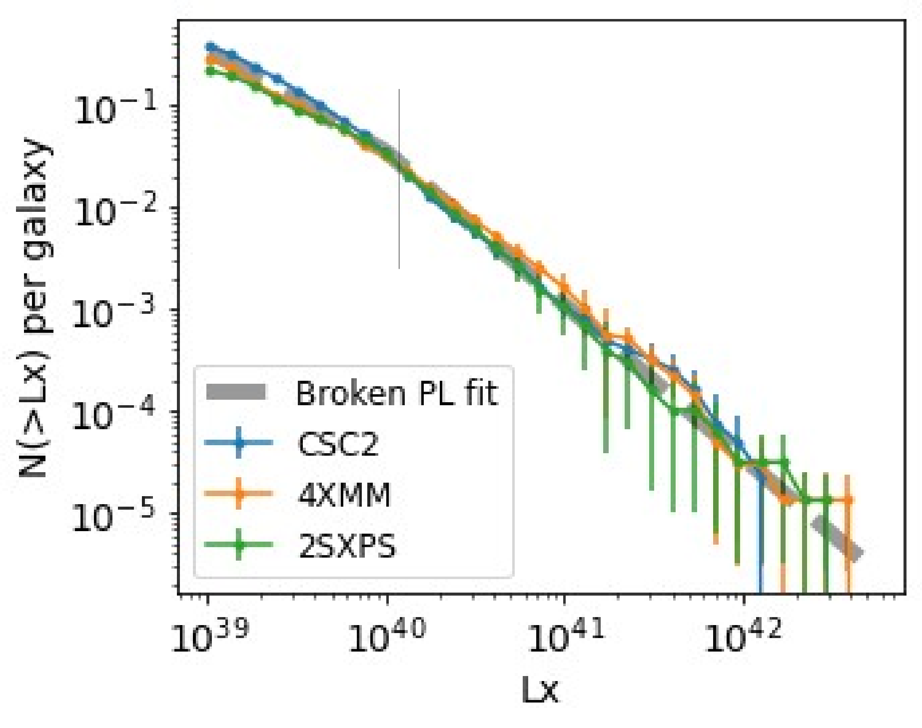


Tranin et al. (to be sub)

X-ray luminosity function

Significant break at 10^{40} erg s^{-1}

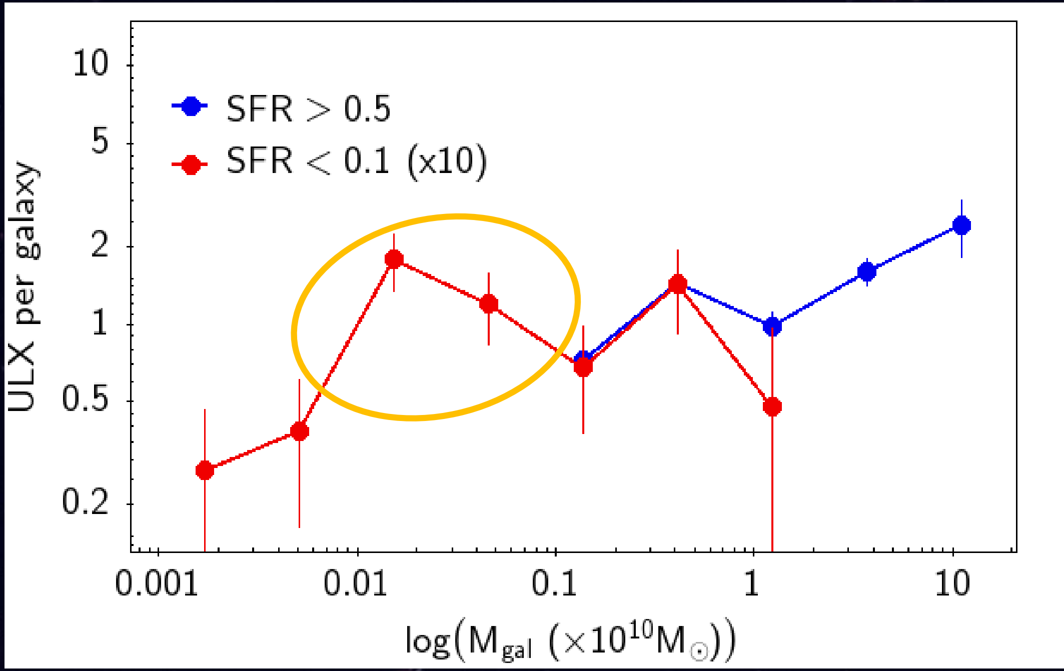
- Already in Swartz+2004, Mineo+2012 but at low significance. Ruled out in Wang+2016
- Kaaret+2017 review:
  "Sources with luminosities above the break could represent a new class of objects"
- Not in population synthesis models (but see Lehmer+2020)
- Some ULX models cut at ~10^{40} erg s^{-1} (e.g. Krticka+2022)



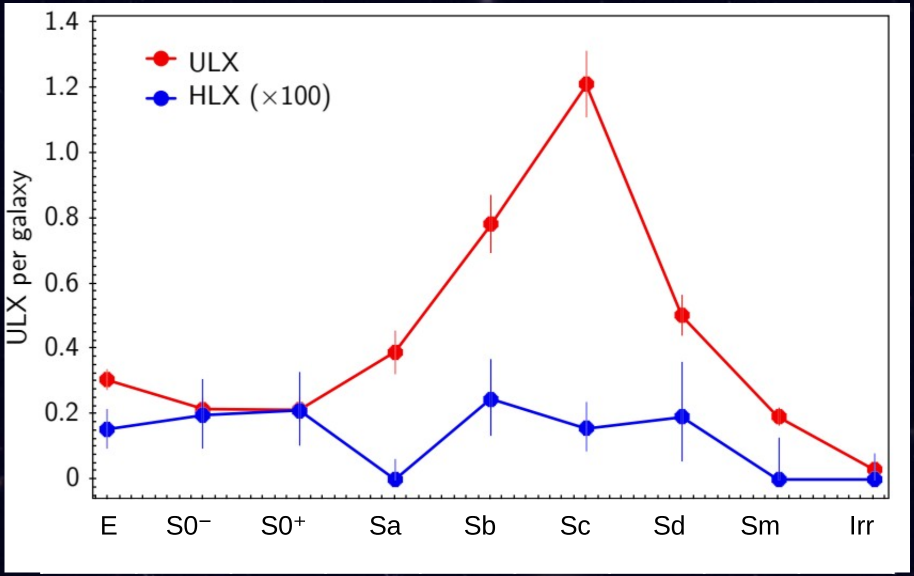
ULX in dwarf galaxies – more IMBH ?

ULX are in excess in dwarf galaxies

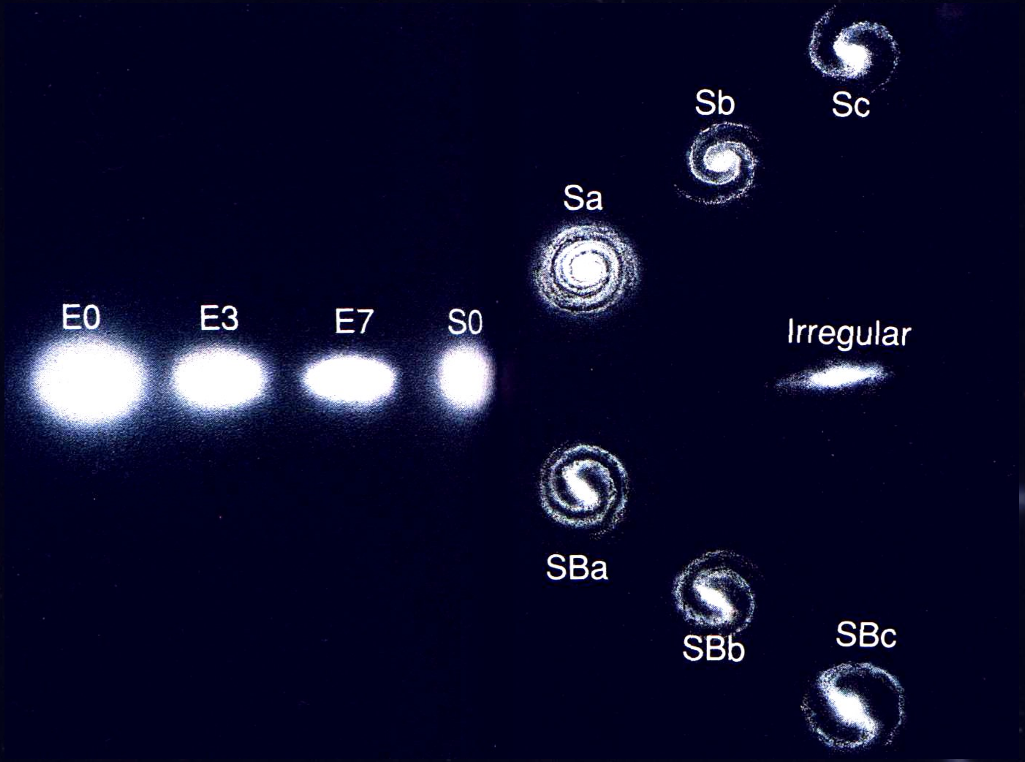
- Environment where IMBH are expected (e.g. Chilingarian+2018)
- They can wander in the galaxy (Bellovary+2019, Reines+2020)



Environment of HLX



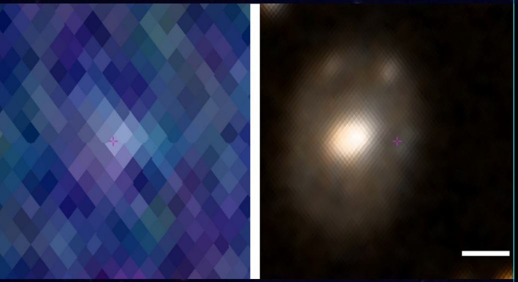
Unlike ULX, HLX reside both in spiral and elliptical galaxies



(clean sample: 45 HLX)

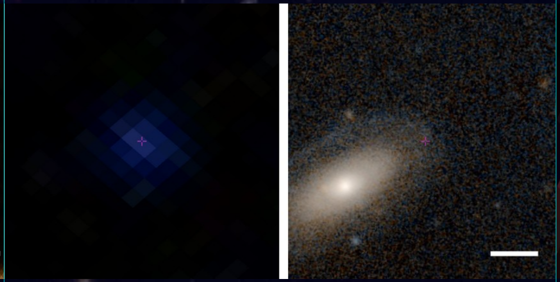
Diversity of HLX

Unstudied HLX from our sample



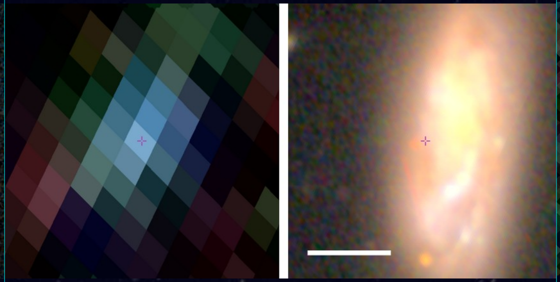
In ring galaxy, where source confusion is likely

⇒ spurious ?



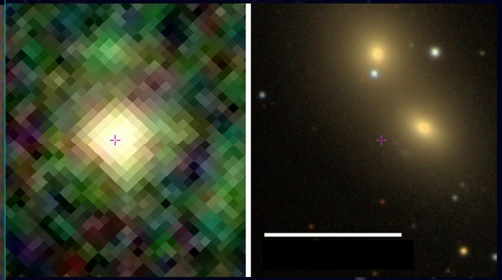
Absorbed, close to edge

⇒ DG before merger ?
background AGN ?



In starforming galaxy, softer

⇒ extreme ULX ?
DG after merger ?



Soft/high, transient, in early-type galaxies

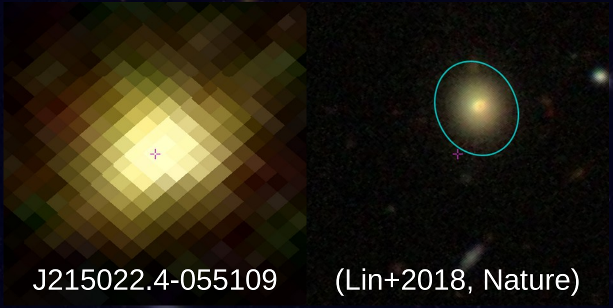
⇒ TDE ?

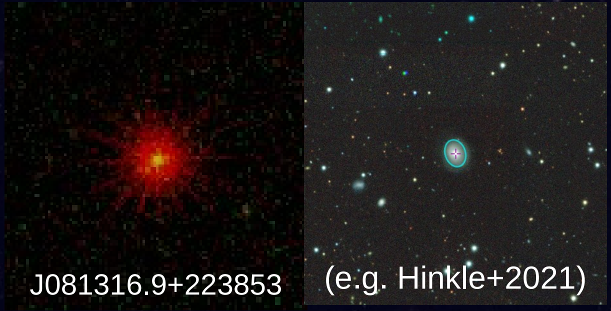
⇒ careful study + manual inspection
Tranin et al. (to be sub)

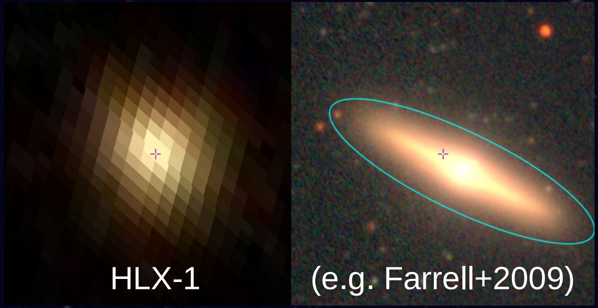
Tidal disruption event candidates

- Validation of our classification (outliers)
- XMM sample:

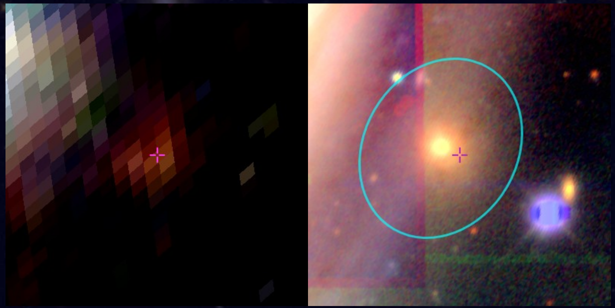
Known candidates

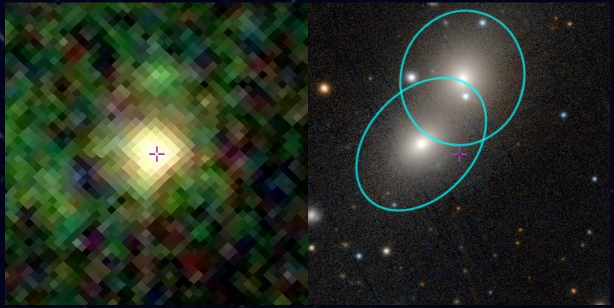






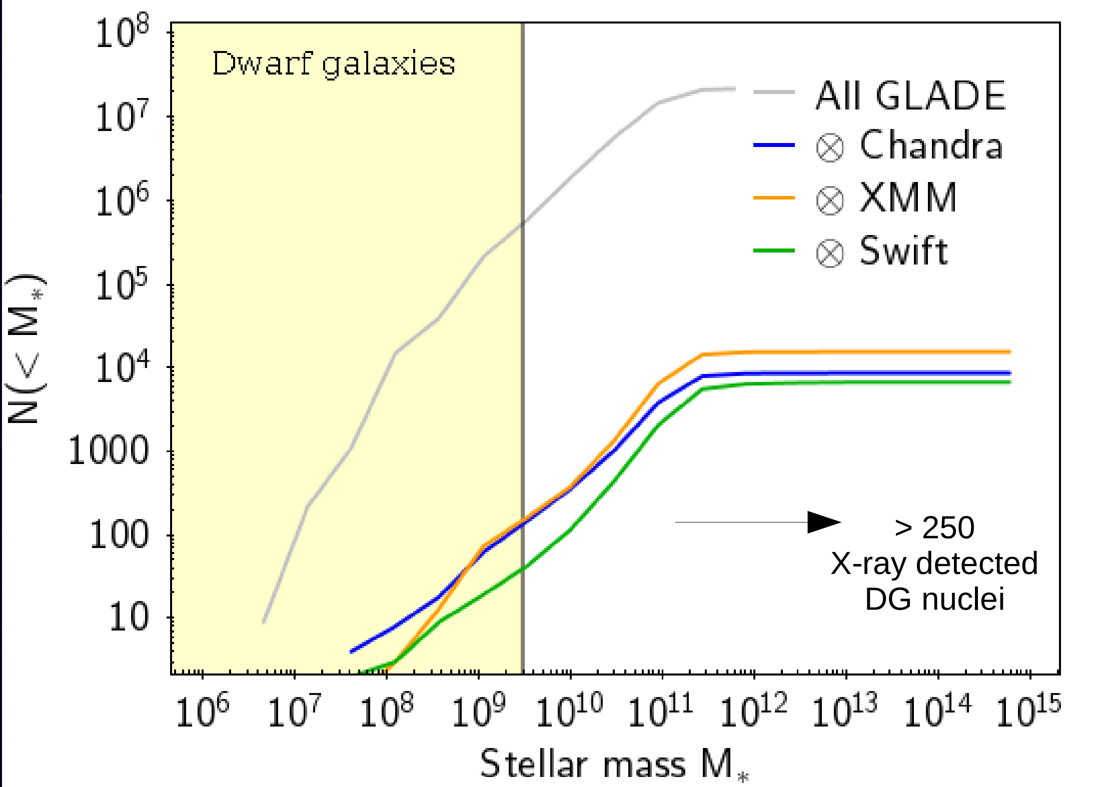
New candidates





Prospect: IMBH in dwarf galaxies

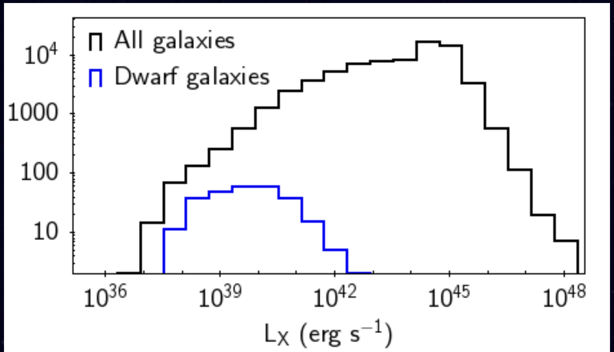
Dwarf galaxies from GLADE



Intermediate-mass black holes in dwarf galaxies out to redshift ∼2.4 in the *Chandra* COSMOS-Legacy Survey

Mezcua+2018

- Occupation fraction is capital to constrain SMBH formation scenarios
- Wandering black holes are seen in DG (Bellovary+2019, Reines+2020)
- Thanks to GLADE (its completeness):
  - ➔ > 250 X-ray sources in nuclei
  - ➔ > 350 offnuclear sources
- Further work is needed to validate these IMBH candidates



Take-home messages

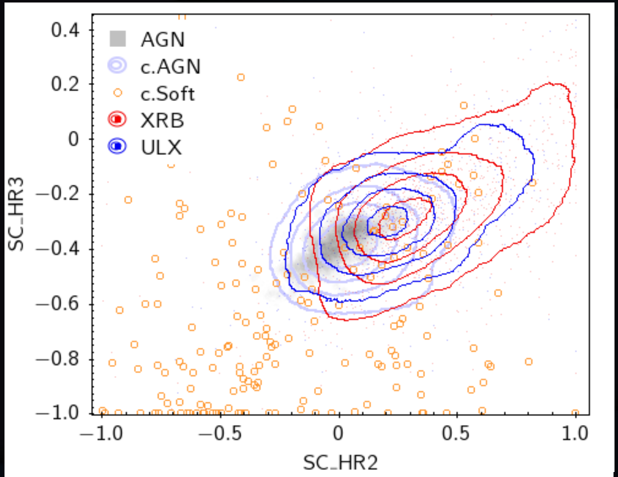
- CLAXBOI is an efficient probabilistic source classification, easy to interpret and adapted to a **wide range of applications**
- It enabled to retrieve a clean sample of **3600 XRB and 1900 ULX**
- An excess of ULX in dwarf galaxies, and a large fraction of HLX, suggest the **presence of IMBH accretors**
- A lot remains to be done to understand ULX as a population, notably given the **high-luminosity break in the XLF**

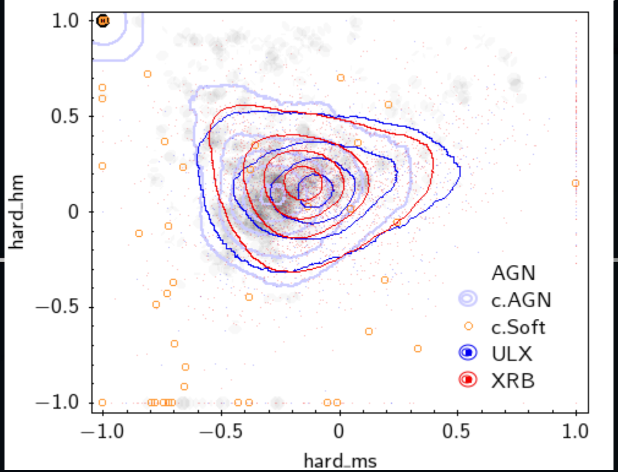
Outlook

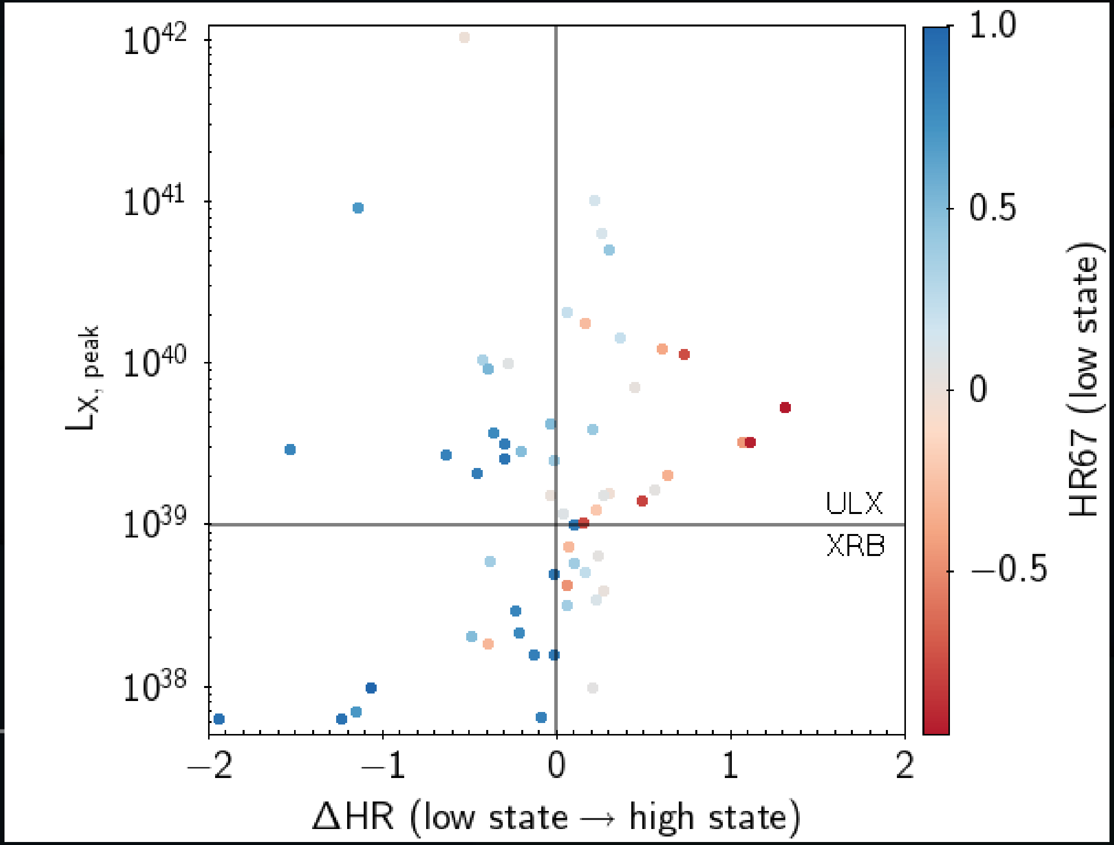
- Potential of CLAXBOI: population studies
  - ULX & HLX (to be sub),
  - AGN candidates in dwarf galaxies,
  - Study AGN subpopulations…
- Search and study outliers in known populations
- Application to eROSITA sources

Backup slides

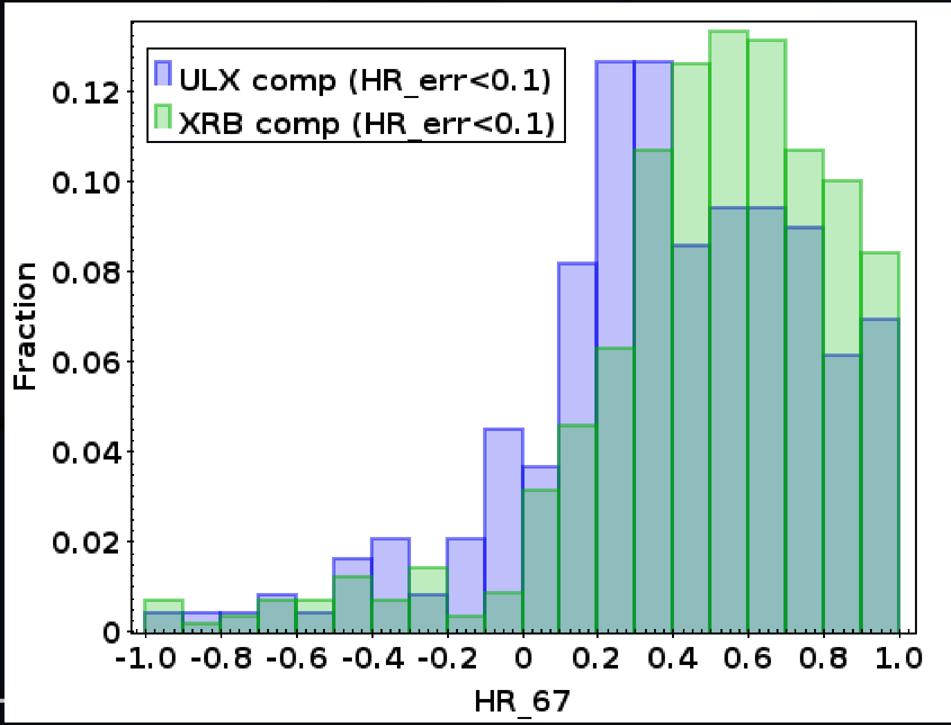
Hardness of ULX / XRB

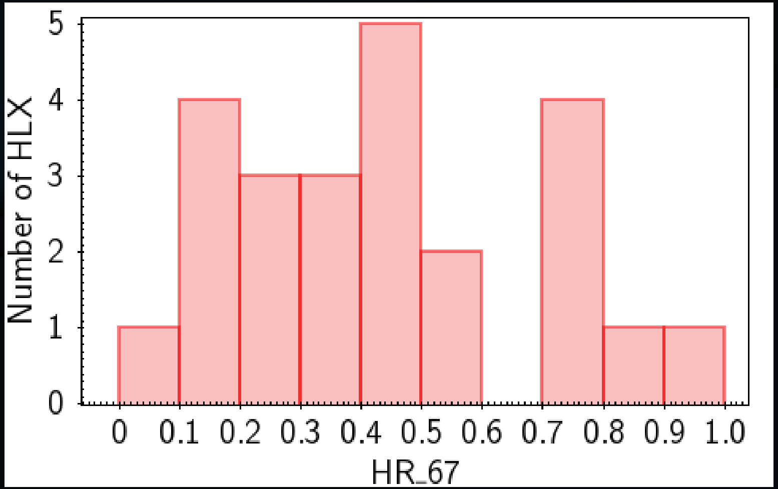






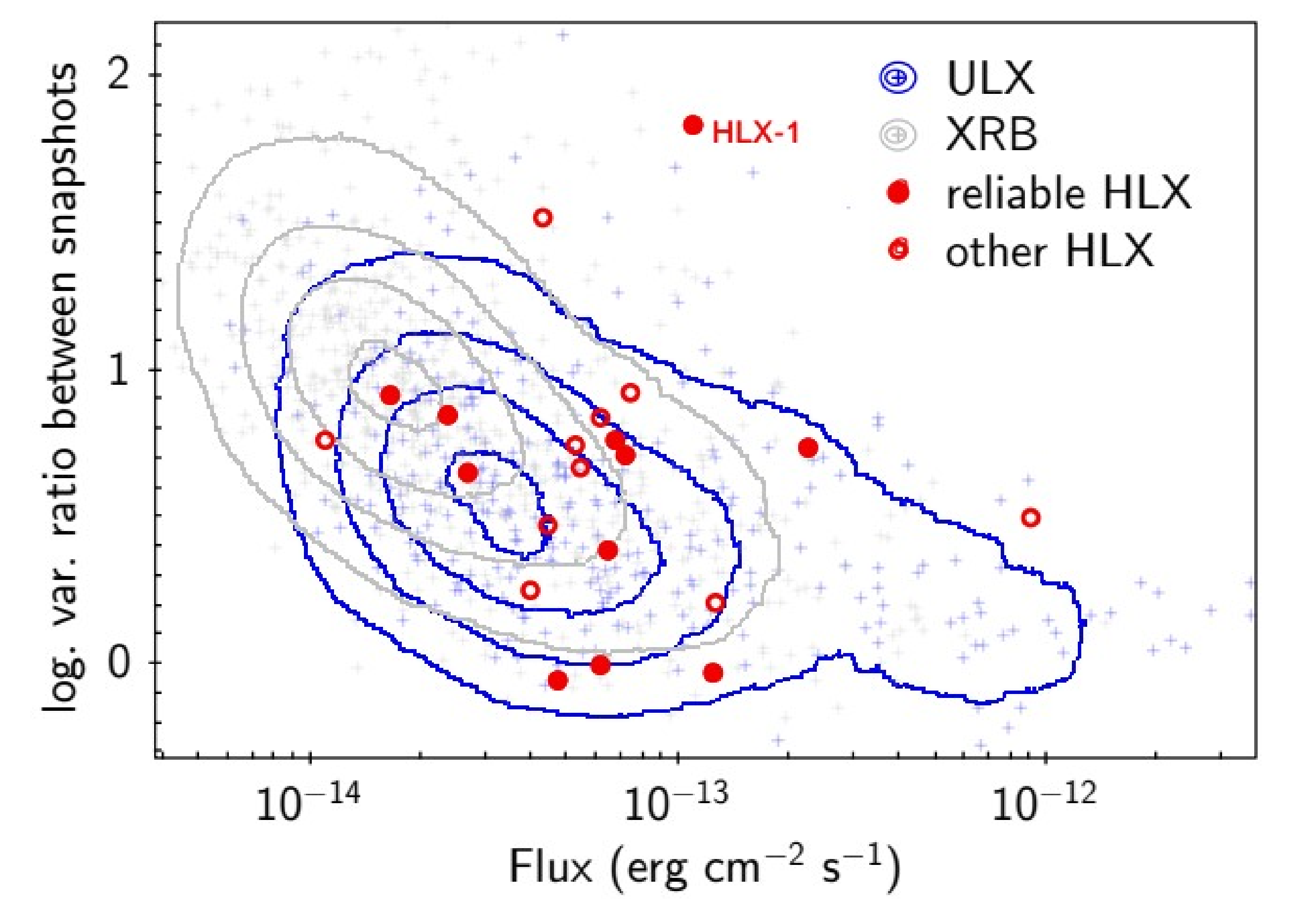
Hardness of ULX / XRB / HLX





84 % probability of intrinsic bimodality

Variability of ULX / XRB / HLX

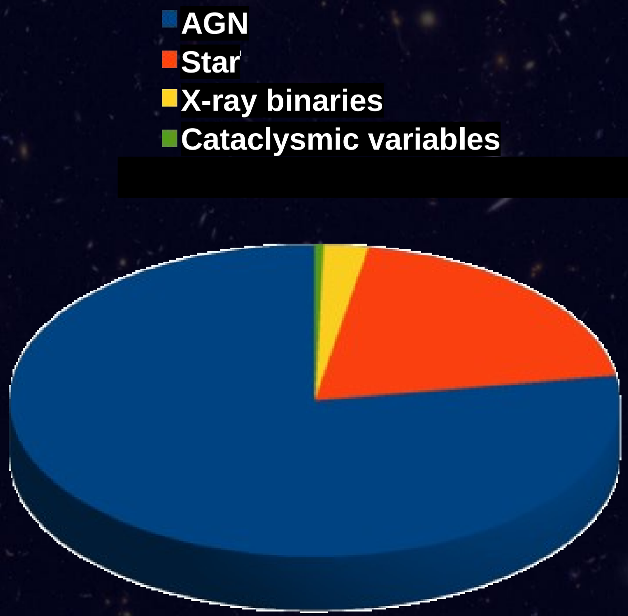


Results on the whole sample

Test sample

- >200 sources analyzed manually (Swift+XMM)
- >90% accuracy on the sources classified as AGN and stars
- About 40-60 % accuracy on … as XRB
  60 % accuracy on … as CV

→ Challenge 1: false positives are often types under-represented in our training sample.
→ Challenge 2: small training sample for XRB and CV



⇒ ~250,000 new AGN candidates

Tranin et al. A&A 2022

Features

Name	Category
Galactic latitude	Location
Gaia proper motion	Location
Relative distance to the host center	Location
X-ray over optical (b,r) flux ratio	Counterparts
X-ray over infrared (W1,W2) flux ratio	Counterparts
X-ray max to min flux ratio	Variability
X-ray lower max to higher min flux ratio	Variability
X-ray hardness ratio HR1, HR2, HR3...	Hardness
Power law index fitted to X-ray spectrum	Hardness
X-ray luminosity	Hardness

For 2SXPS :

Coefficient α_{location}	8.8
Coefficient α_{hardness}	7.3
Coefficient $\alpha_{\text{multiwavelength}}$	2.1
Coefficient $\alpha_{\text{variability}}$	3.9