Intermediate-mass black holes and their host galaxies

Chilingarian et al. 2018, ApJ 863 1

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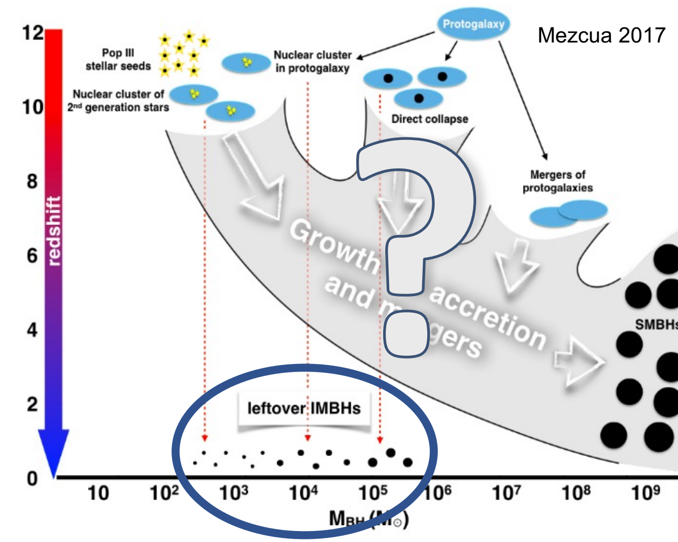
CENTER FOR ASTROPHYSICS
HARVARD & SMITHSONIAN

SAI Relativistic Astrophysics Seminar – Apr 5, 2022

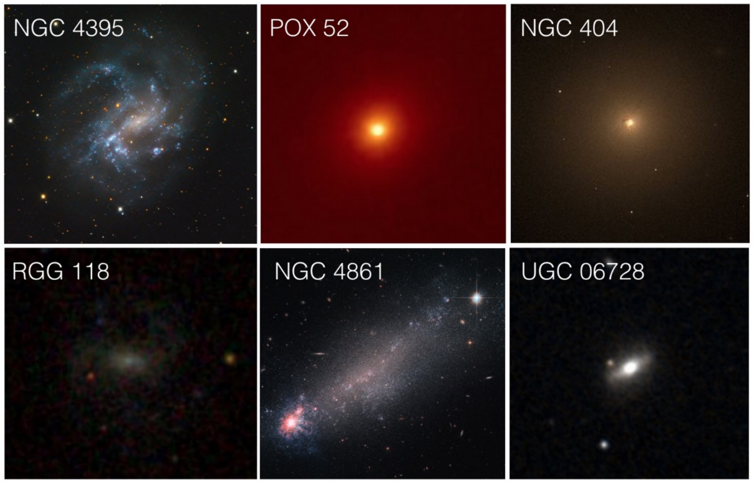
Introduction

- IMBHs (100 $M_\odot$ < M_{BH} < 10^5 $M_\odot$) are important for cosmology:
  - early SMBH assembly: low-mass (~100 $M_\odot$) or heavy (>10^5 $M_\odot$) “seed” black holes?
  - reionization
  - gravitational waves
  - constraints on galaxy formation theories
- Little doubt they exist (but…):
  - 1st LIGO GW detection (62 $M_\odot$); then >100 $M_\odot$
  - ESO 243-49 HLX-1 (but King14)
  - RGG118 (but only 4 X-ray photons); J1605+17
  - 47 Tuc (Kiziltan17 but Brock14, Zocchi17)
- IMBHs searches:
  - AGN
  - Ultra/Hyper-Luminous X-ray sources: bright off-nuclear X-ray sources
  - Globular clusters
- The ultimate questions: **what are the SMBH seeds and how did they grow into SMBHs**?



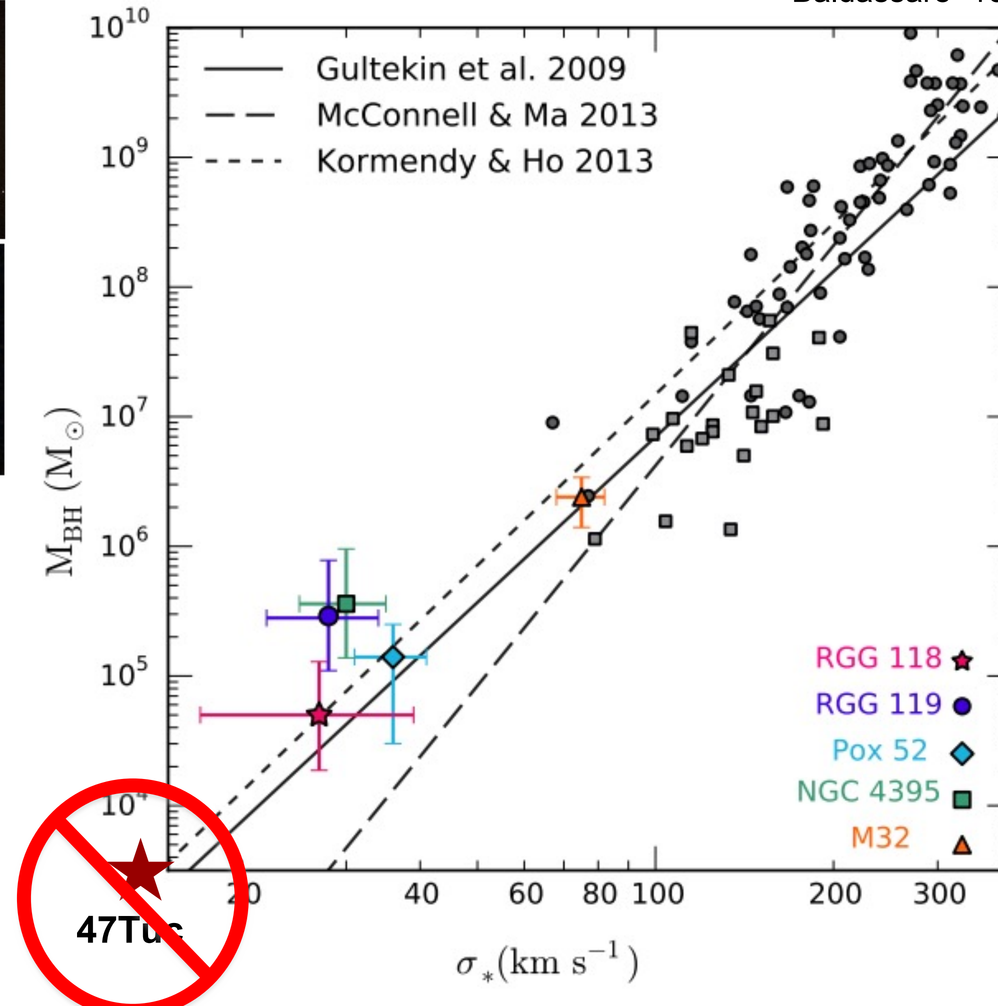
Mezcua 2017

Nuclear (I)MBH: what was known by 2017

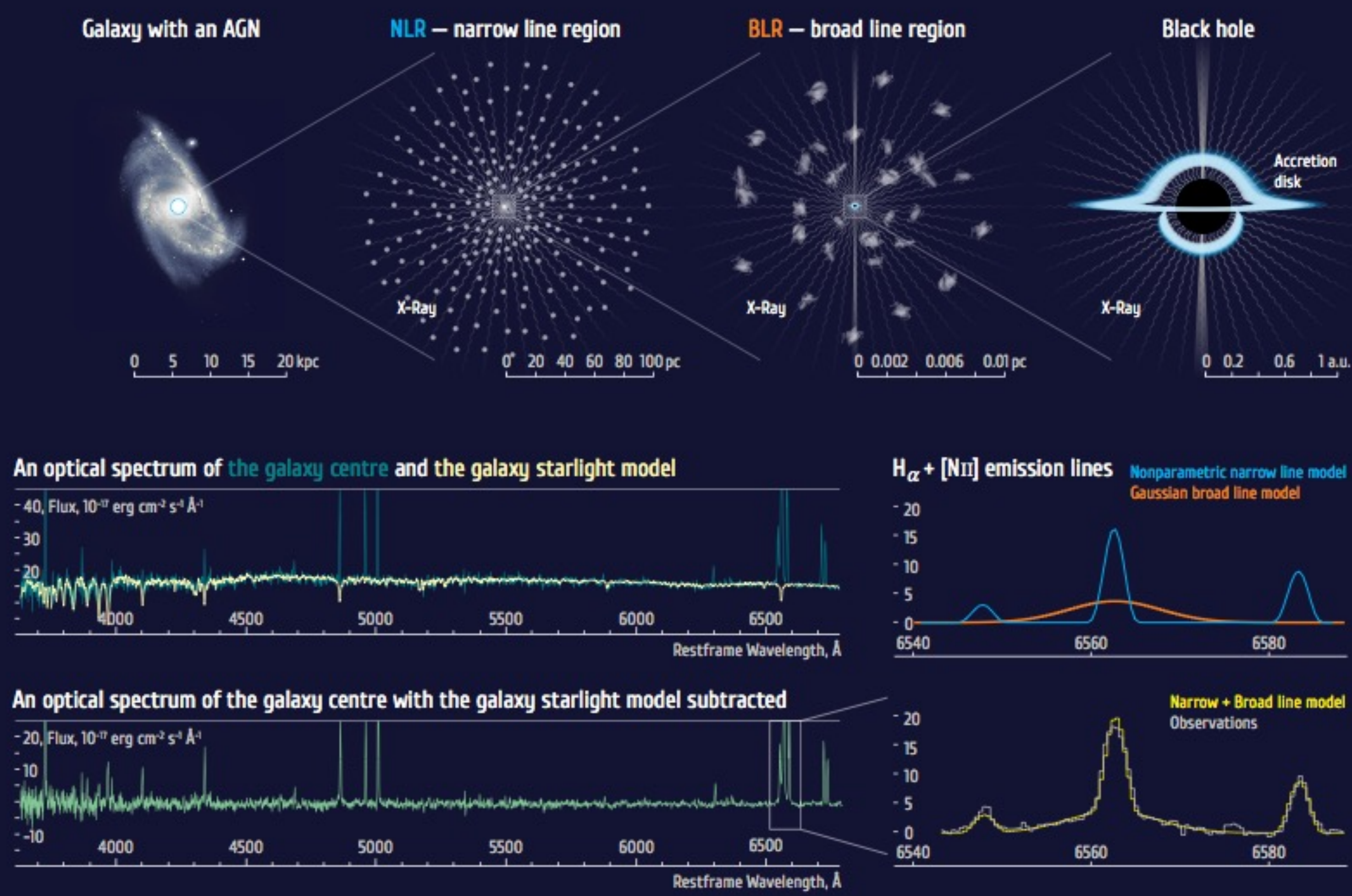


NGC104 [Kiziltan17]

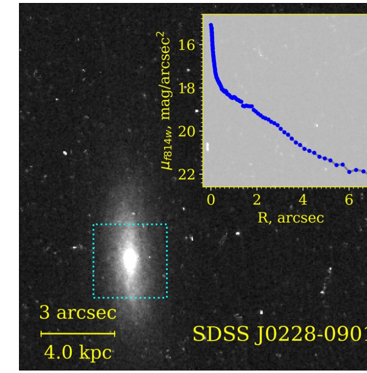
Baldassare+16



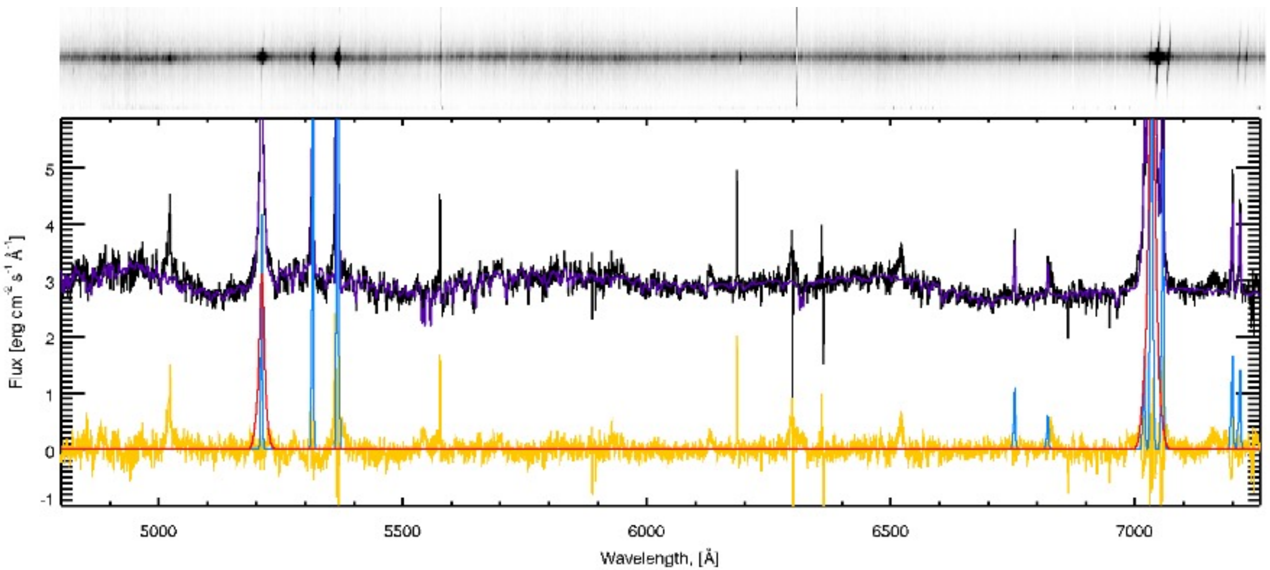
AGN phenomenon and our IMBH search technique

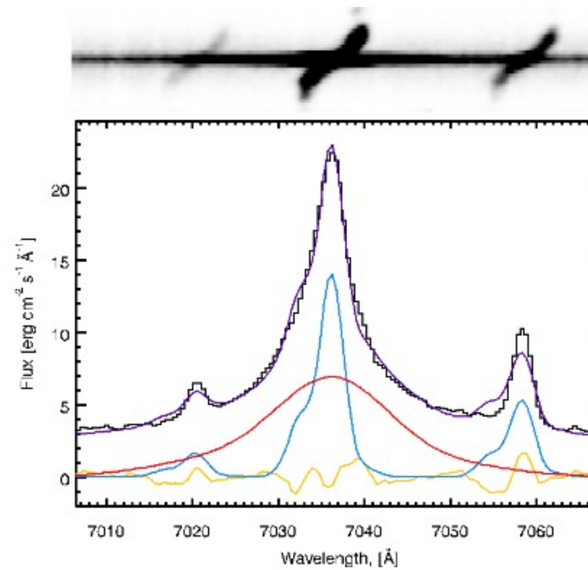


Our IMBH search: BLR/NLR decomposition



- The approach is conceptually similar to Greene & Ho: estimating BLR parameters, but we use a more general and stable technique for the BLR/NLR decomposition
    - Non-parametric NLR via linear inverse problem with regularisation
    - Parametric (Gauss-Hermite or Lorentzian) BLR



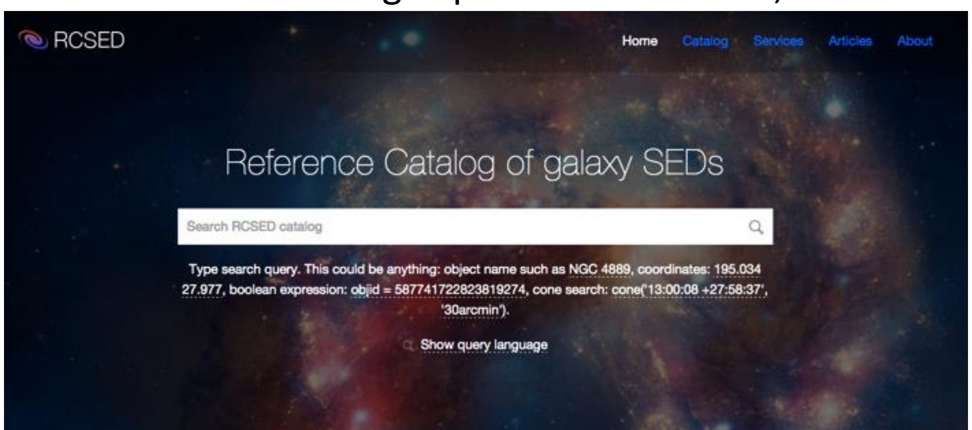


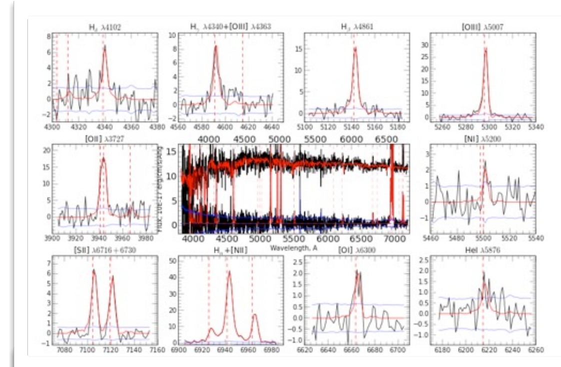
Our IMBH search: the workflow

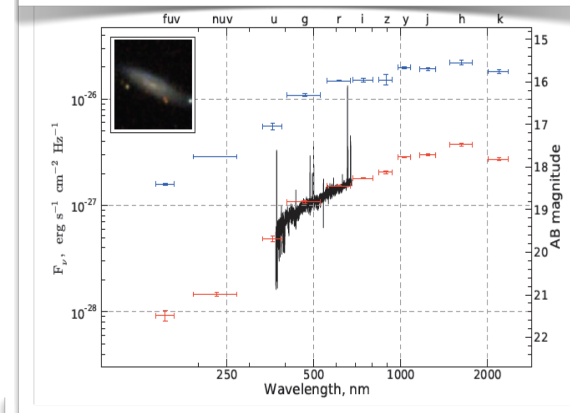
- Massively parallel automated workflow analysing 1 million SDSS DR7 spectra without pre-selection adding crucial information from large multiwavelength catalogs (RCSED, *WISE*, FIRST, *XMM-Newton*, *Chandra*, *Swift*, *ROSAT*)
- Final workflow product: `imbh.fits`, 1M rows, 200+ columns
- Filter for reliable objects with BLR signatures

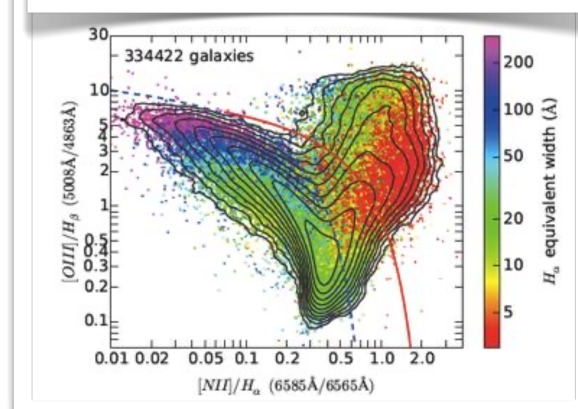
http://**RCSED**.sai.msu.ru

- Reference Catalog of galaxy SEDs: 800,000 galaxies
- Great discovery potential (e.g. [2015Sci...348..418C](2015Sci...348..418C))
- Easy-to-use and feature rich website:
  - Google like queries
  - Interactive diagrams
  - Tutorials
- Has everything you need about galaxies in one place:
  - UV-to-NIR SEDs (k-corrected, of course)
  - Stellar masses
  - Stellar Ages and Metallicities
  - Morphologies
  - Emission lines: gas-phase metallicities; SFRs



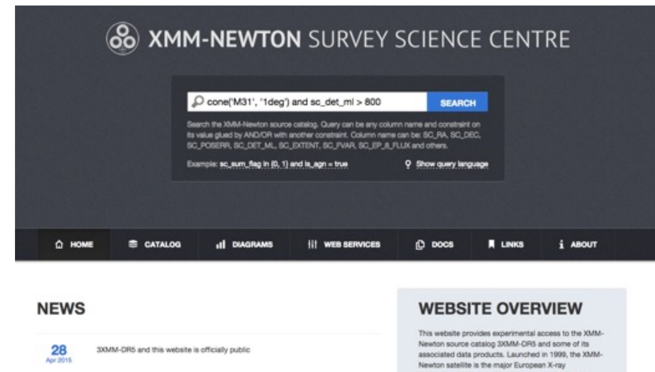


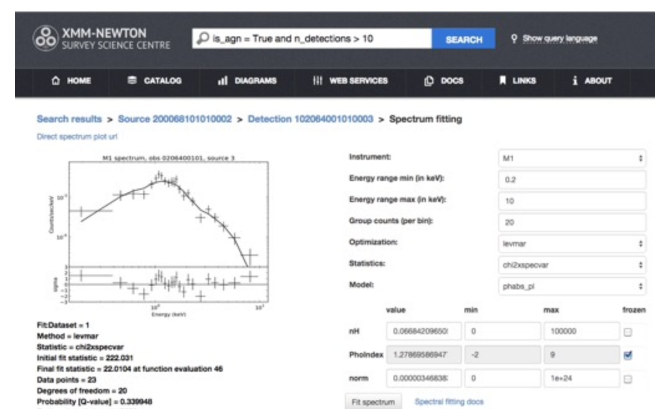


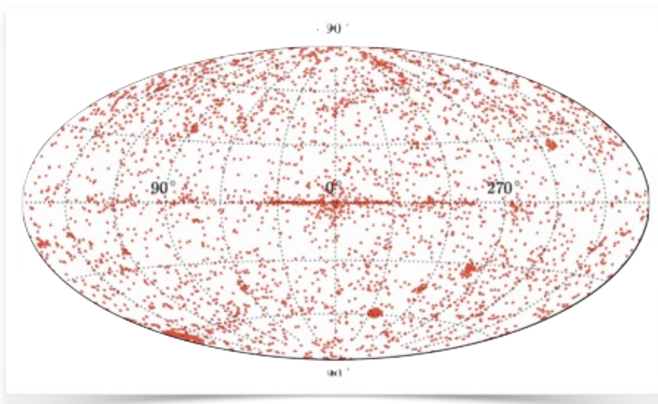


XMM-Newton source catalog

- Largest X-ray source catalog ever created: *XMM-Newton* observations from 2000 to 2016
- Latest release: 3XMM-DR7, released on Jun 1, 2017
- 727,790 detections of 499,266 unique sources, ~2.5% of the sky
- Convenient supporting website: http://xmm-catalog.irap.omp.eu
- Deep expertise in our team: I. Zolotukhin among principal authors

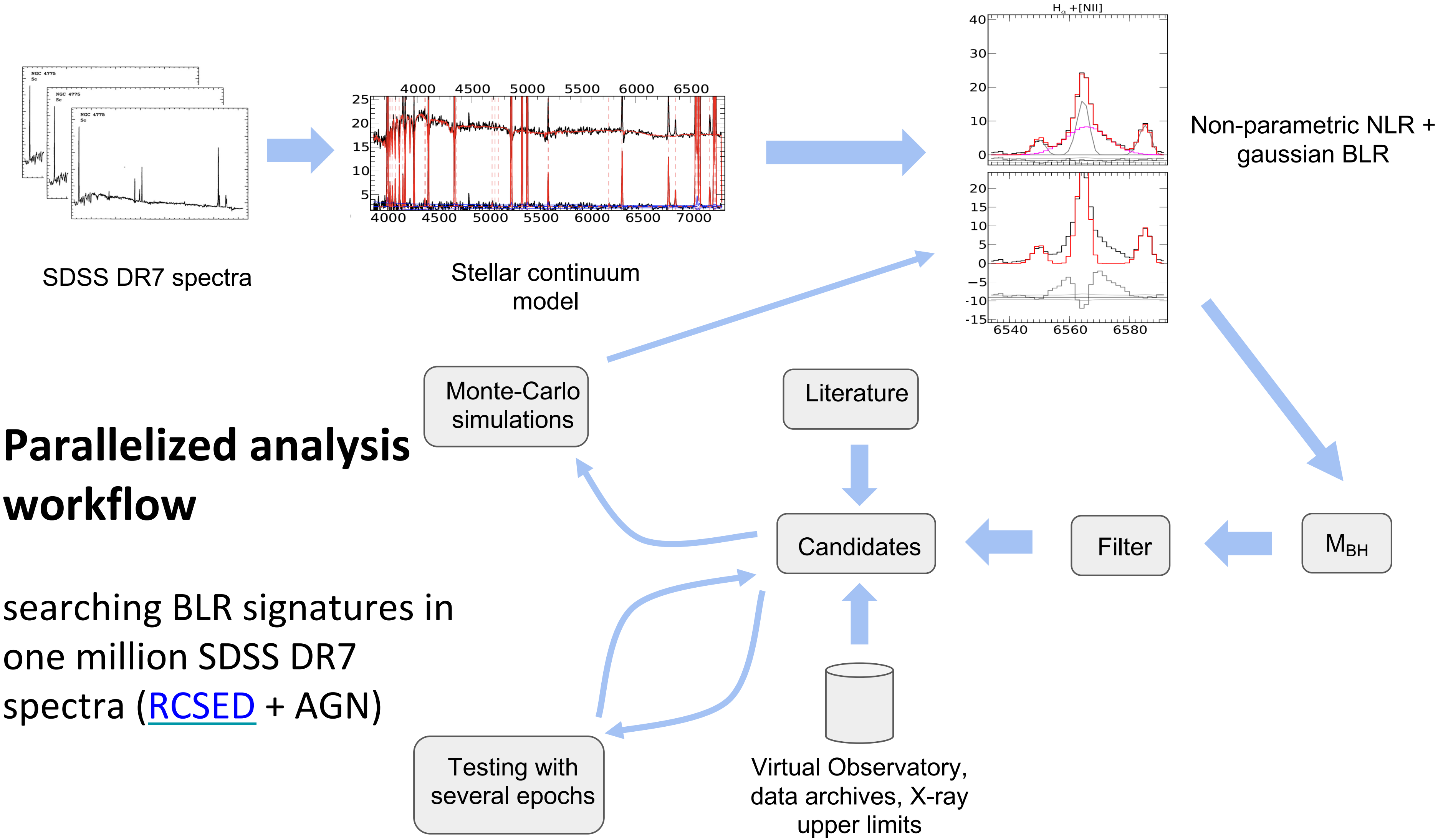






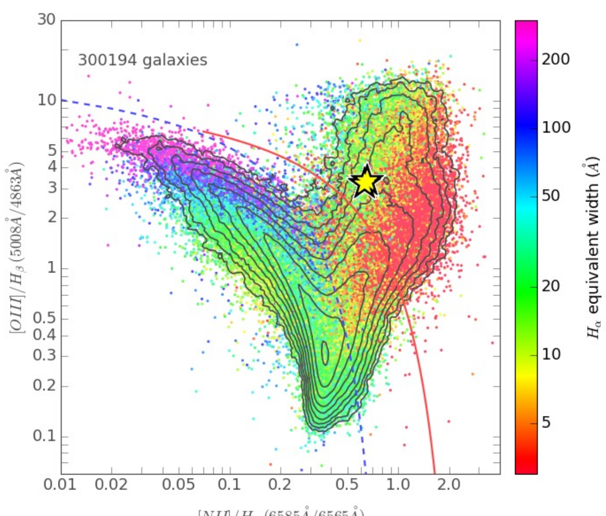
Parallelized analysis workflow

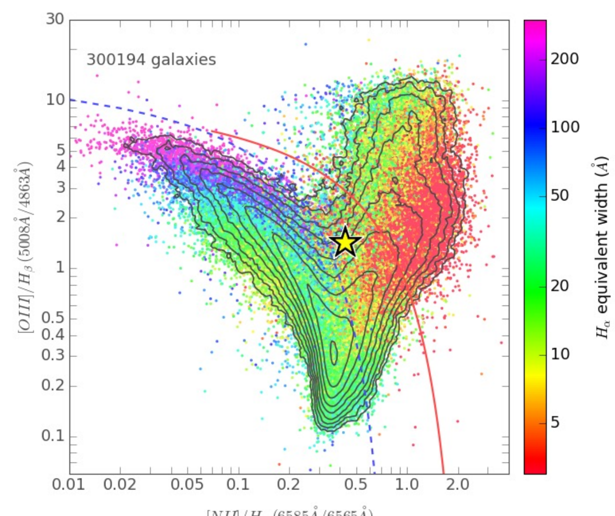
searching BLR signatures in one million SDSS DR7 spectra (RCSED + AGN)



Caveats: SN, shocks, TDEs, algorithm

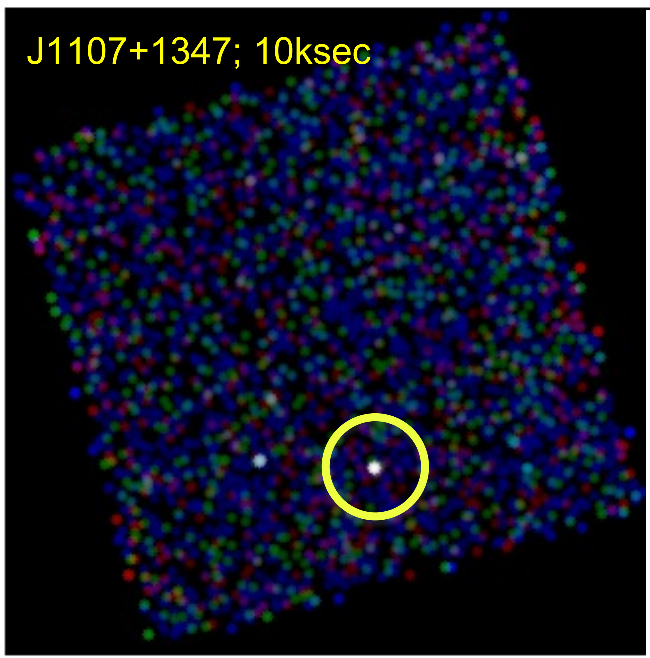
- Does virial mass estimate make sense? What about the coefficients?
- BPT: select AGN or composites (SF BLRs do not persist in multi-epoch spectroscopy, e.g. Baldassare16)
- Candidates with X-ray: more L_X than expected from LMXB/HMXB
- Candidates with X-ray upper limit: not a single X-ray drop-out detected given expected L_X from L_X–$L_{[OIII]}$ correlation
- Multi-epoch spectroscopy with SDSS and Magellan/MagE: no evidence for significant line variability for a random sample of sources
- No matches with "resolved SN" spectra from e.g. Graur13 (~100 SNe in SDSS)
- In case of low signal-to-noise spectra, the fitting procedure becomes unstable

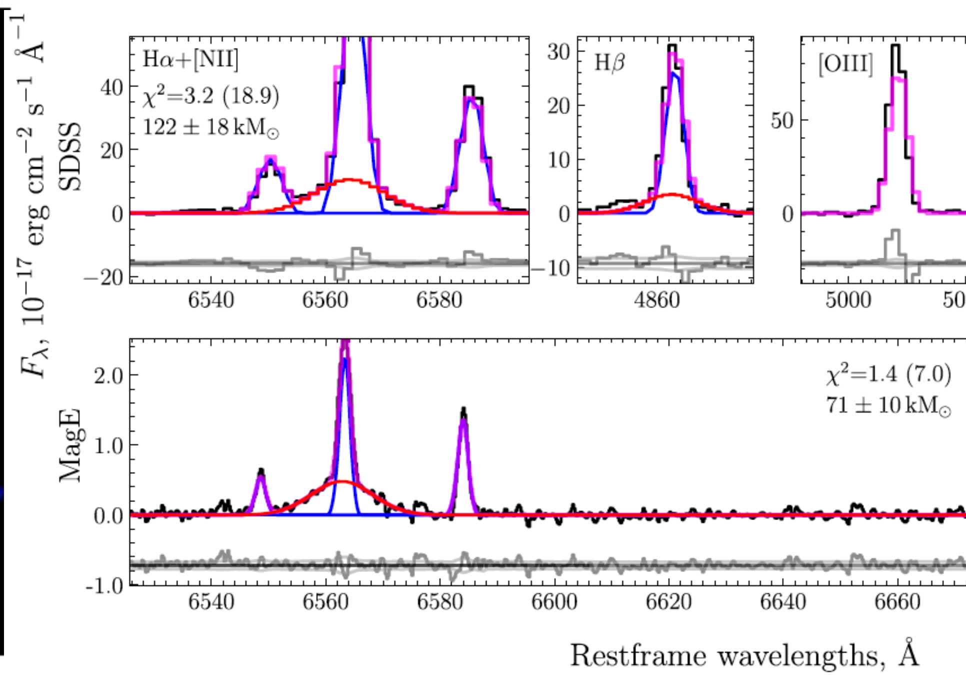


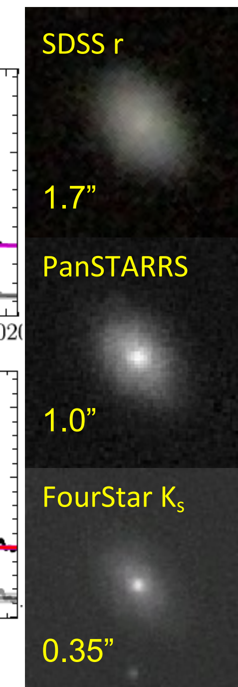


1st follow-up campaign during summer 2017

- 2 objects: *Chandra* DDT (1 confirmed)
- 2 objects: *XMM-Newton* DDT (1 confirmed)
- 11 objects: optical spectroscopy with MagE (6.5-m Magellan)
- 7 objects: NIR imaging with FourStar (6.5-m Magellan)

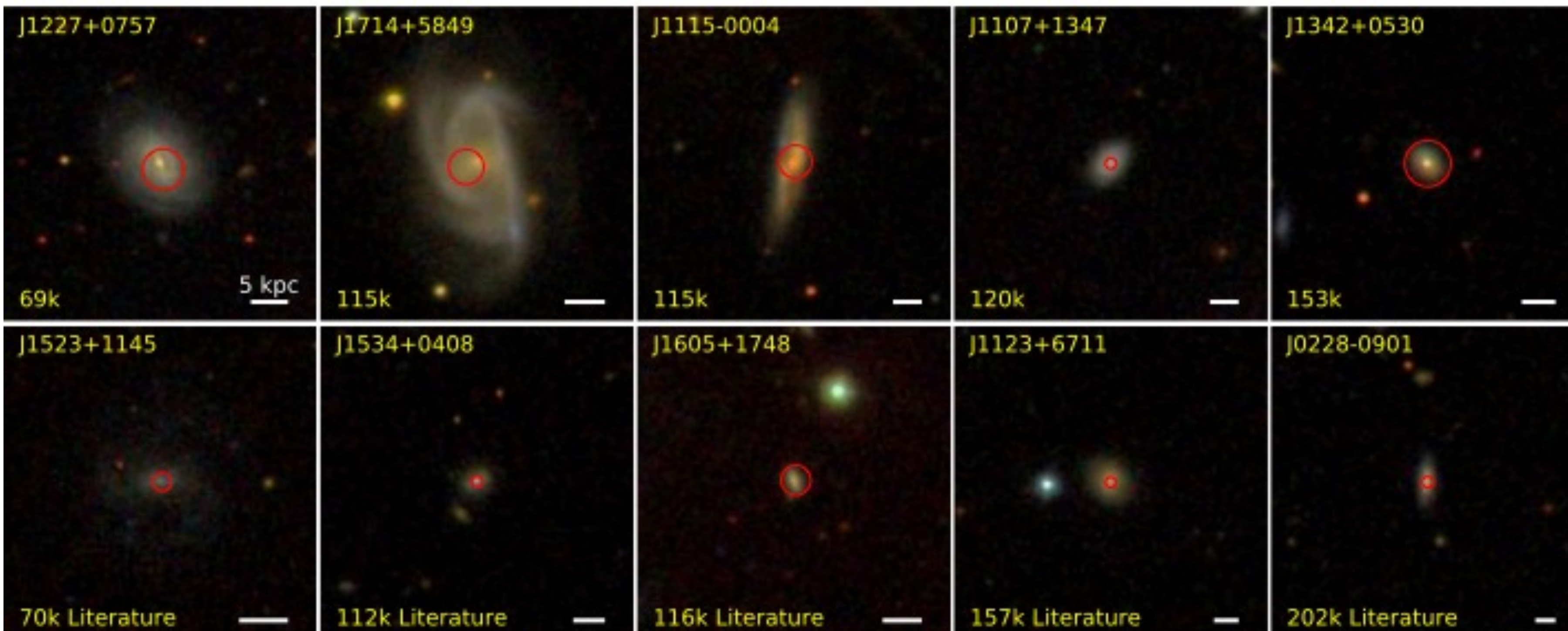






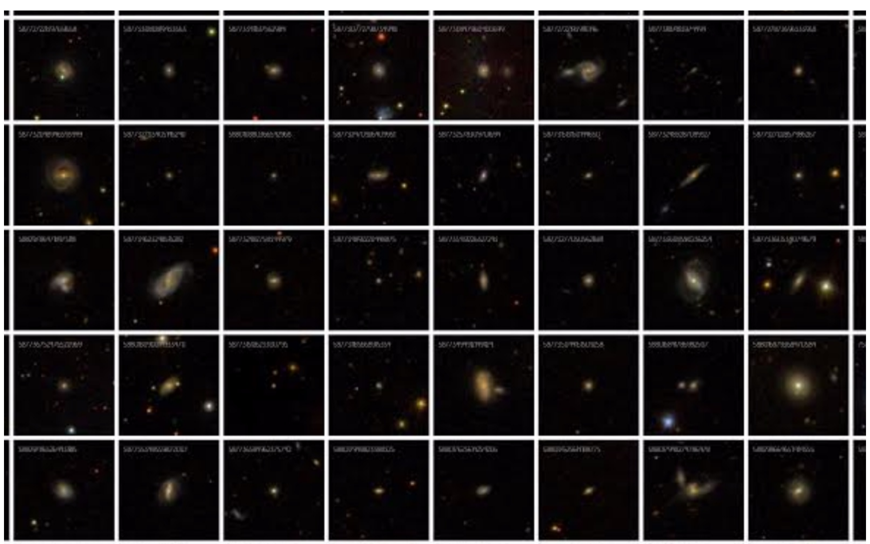
Results

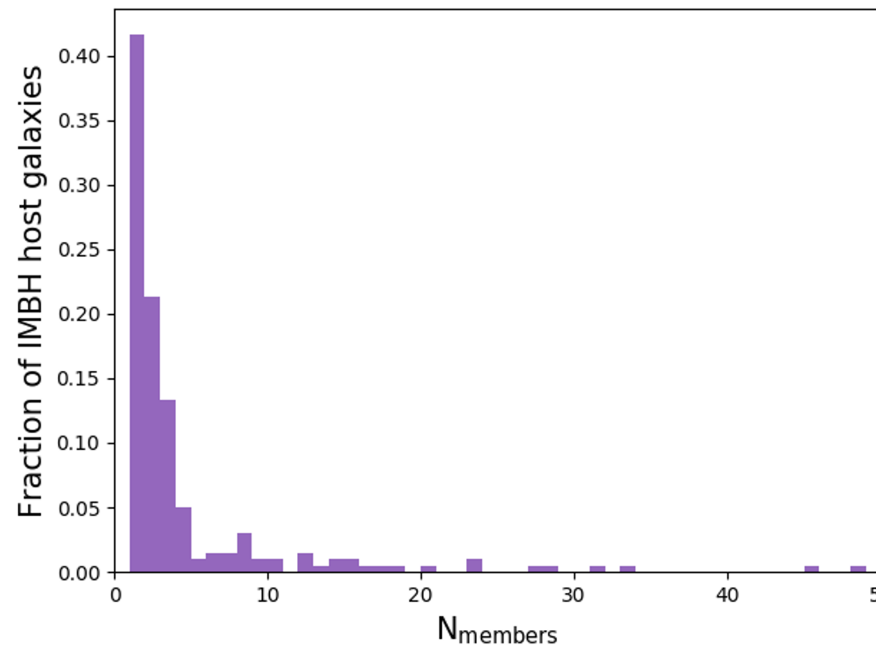
- 305 IMBH candidates with $M_{BH} < 2 \times 10^5\ M_\odot$, 10 of which with X-ray counterparts (5 literature, 4 new from archives, 1 new Chandra obs), 70% cleanliness
- Demographics: low-luminosity galaxies and small bulges



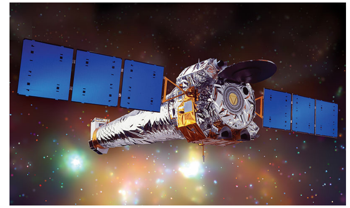
Results

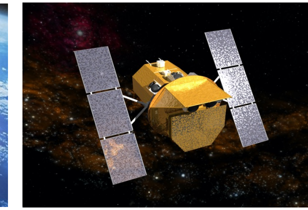
- 305 IMBH candidates with $M_{BH} < 2 \times 10^5\ M_\odot$, 10 of which with X-ray counterparts (5 literature, 4 new from archives, 1 new Chandra obs), 70% cleanliness; 15 additional candidates were confirmed in X-ray later
- Demographics: low-luminosity galaxies and small bulges; 79% of IMBH hosts reside in groups with <5 confirmed members (including isolated)





Follow-up campaign

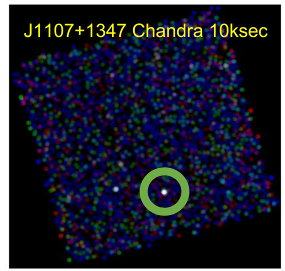


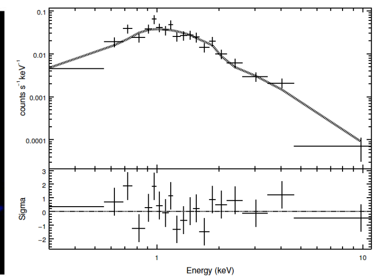


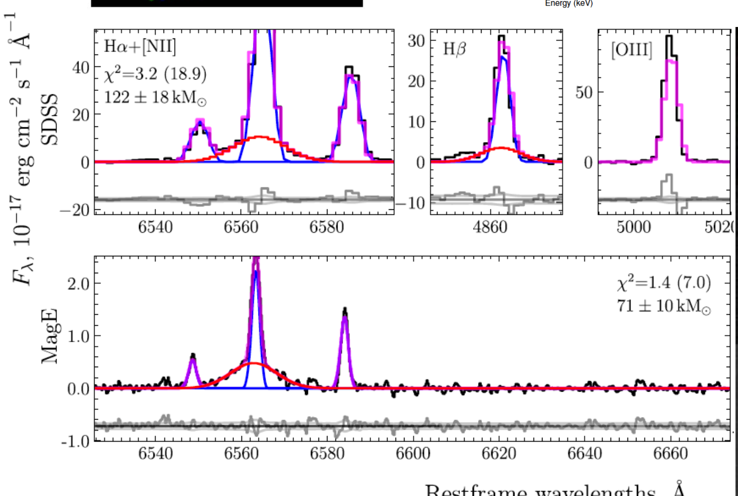
- Expanding the X-ray sample
  - New XMM-Newton observations
  - New Chandra and Swift observations
  - Chandra/XMM/Swift archives
- Populating M_{BH}–σ_* (optical spectra)
  - Magellan MagE (R=7000)
  - Keck ESI (R=8000)
  - SALT RSS (R=4000)
    - BLR Balmer gradient to eliminate dust effects on M_{BH}
    - Improved virial M_{BH} thanks to higher resolution and depth
- Populating M_{BH}–$M_{*,bulge}$ (images)
  - Magellan FourStar (NIR)
  - HST/CFHT/Subaru archives (optical)

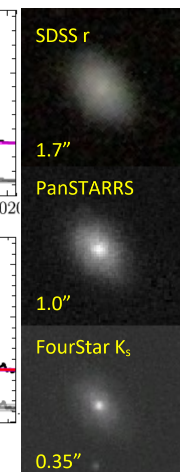
Confirmed in X-ray as of now:

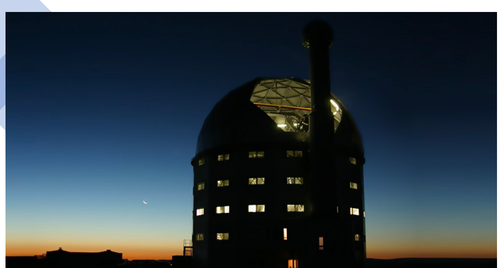
- **24 IMBHs ($M_{BH}<2*10^5\ M_\odot$)**
- **180+ low-mass BHs ($M_{BH}<10^6\ M_\odot$)**





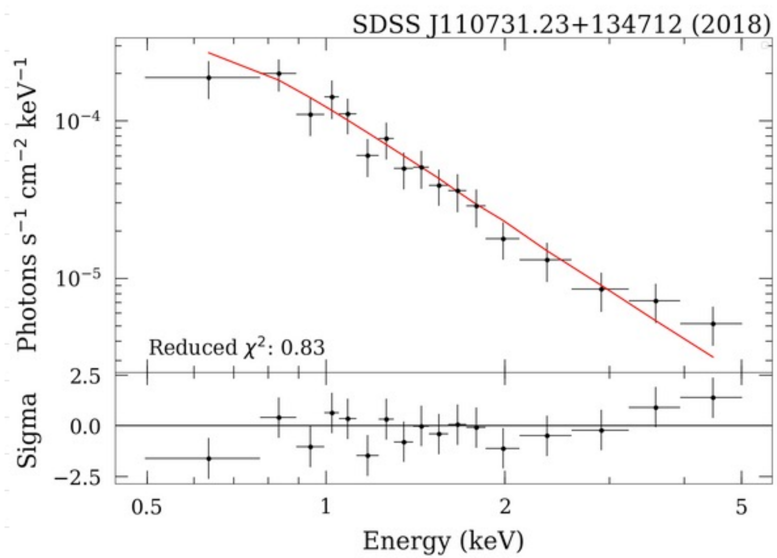


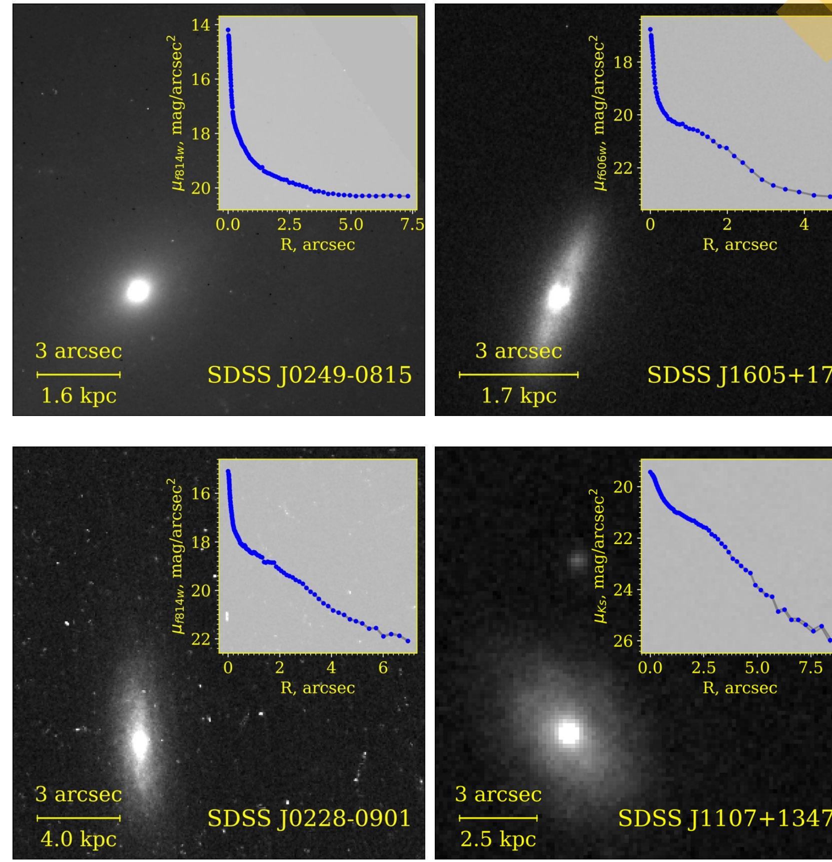




Eddington-limited IMBH growth

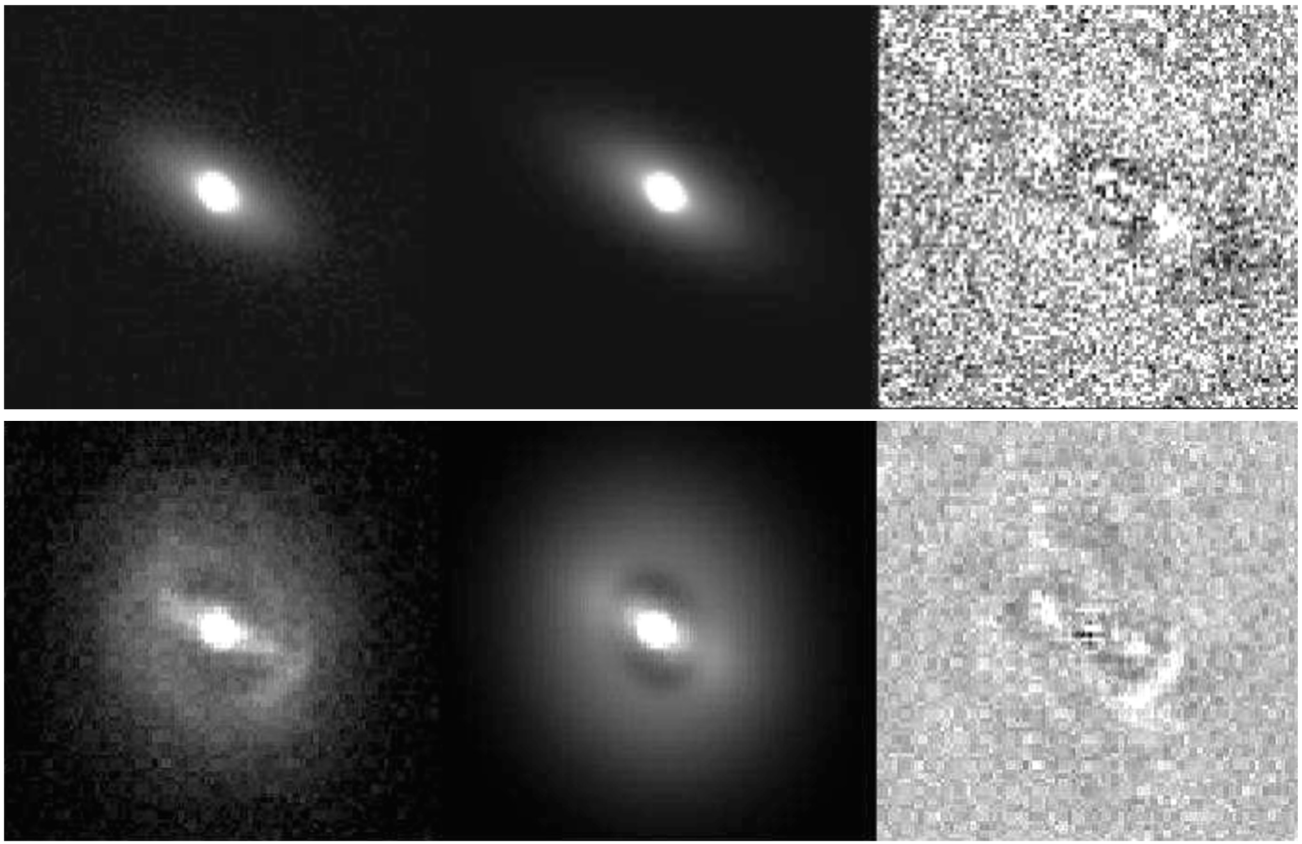
- 7 out of 24 IMBHs have soft X-ray luminosity of at least 3% of L_{Edd} that translates the L_{bol}>0.4L_{Edd}; and soft X-ray spectra (Γ>2.5) atypical for "normal" AGN
  - J1107+1347: L_X(0.2-10 keV) = 2.7×10^{42} erg/s = 0.2-0.3 L_{edd}; Γ=2.5; no variability on 1d-1m-1y timescales
- They are growing fast and can increase their mass tenfold in 120–300 Myr if the accretion rate persists
- They show signs of ratiative outflows in the [OIII] line however, the feedback is probably too weak to affect star formation in their hosts: more data is needed (JWST)

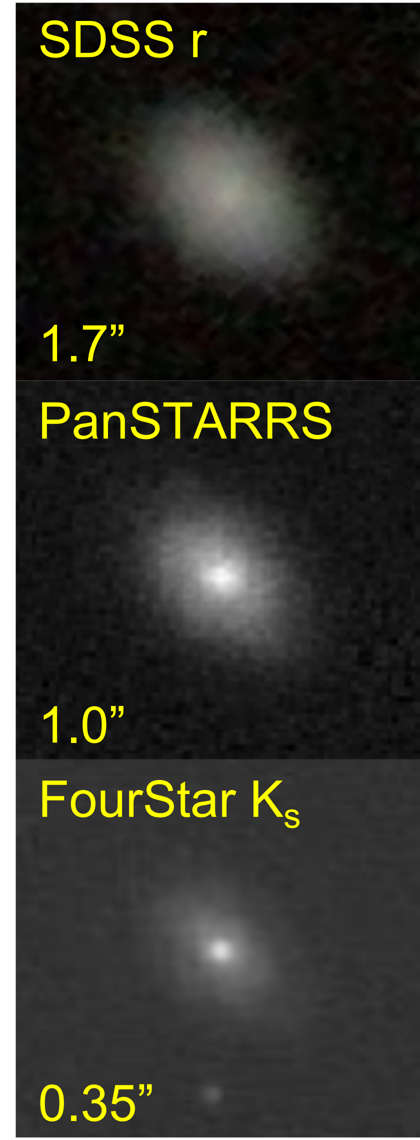




$M_{BH} - M_{*,bulge}$ scaling relation

- Mergers are likely the main factor forming it
- Mass estimates: photometric decomposition (*galfit*) + stellar mass-to-light ratio from spectra





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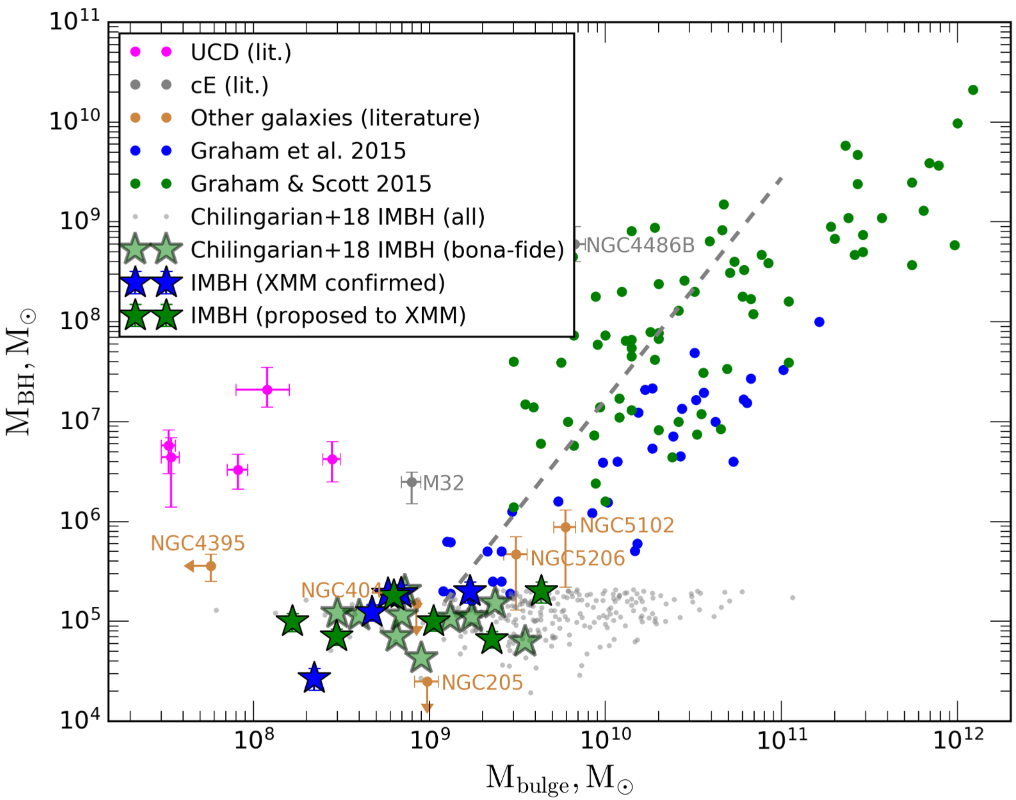
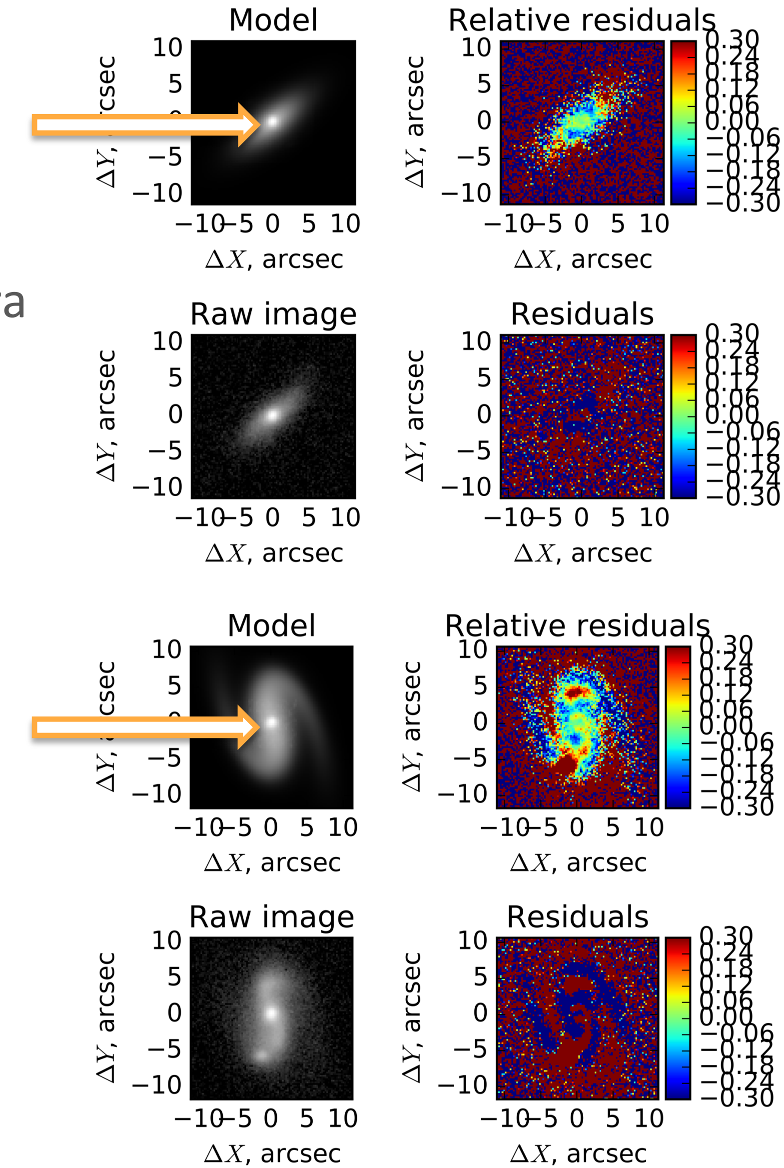
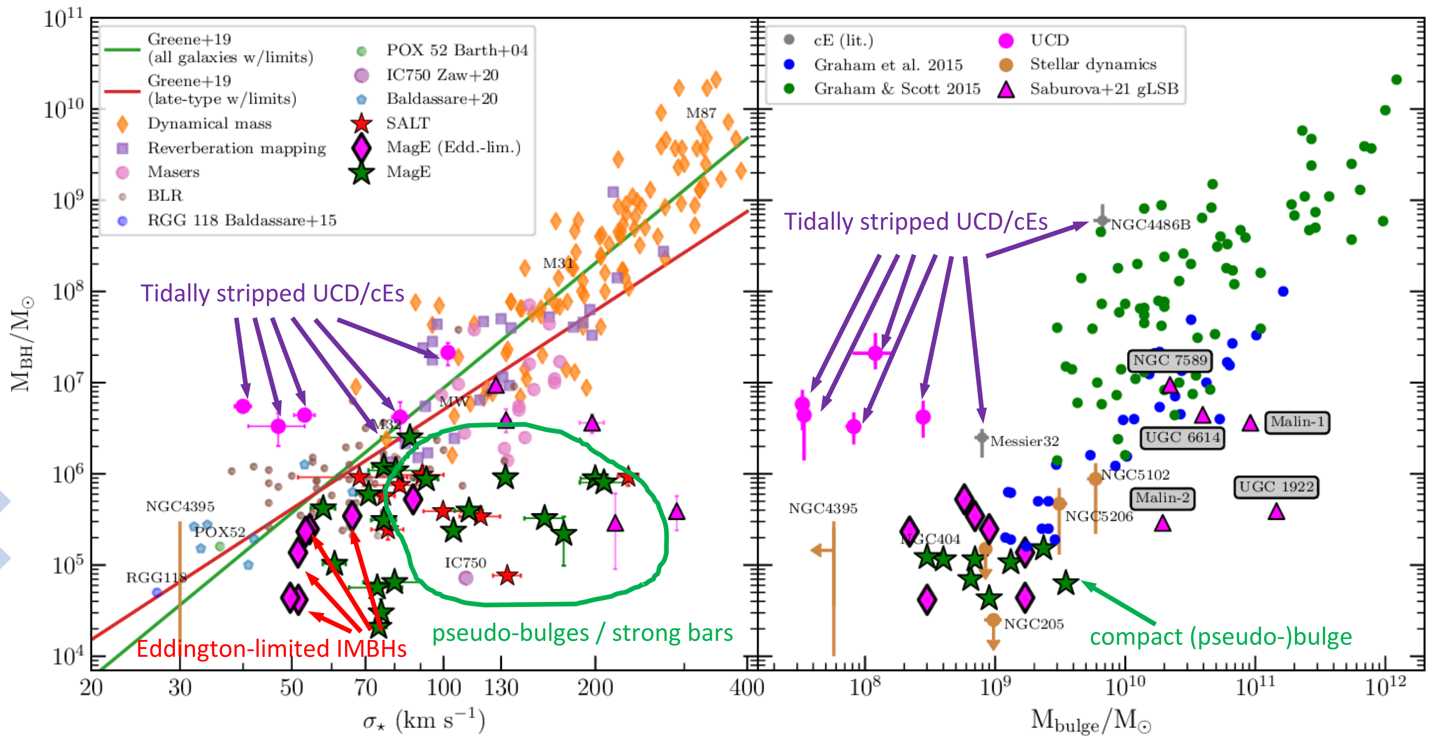




M_{BH}–σ_* and M_{BH}–$M_{*,bulge}$ relations

correlation vs causation

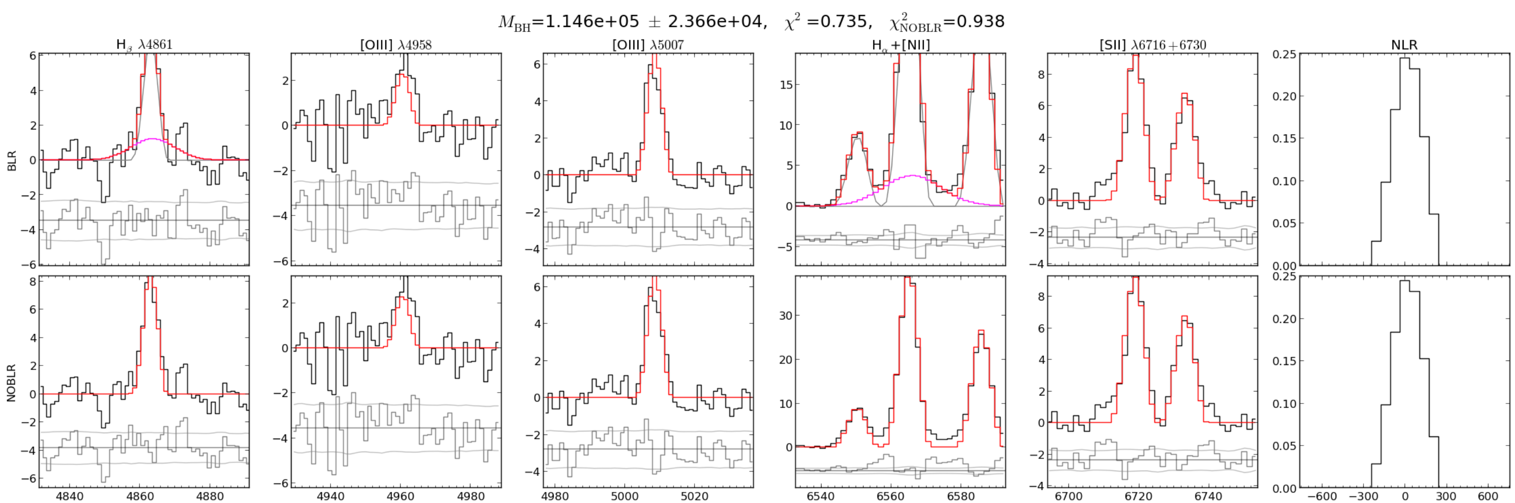
- Many low-mass BHs deviate from correlations toward higher σ_*/$M_{*,bulge}$
  - The strongest outliers are giant low-surface brightness galaxies, the largest known disk galaxies in the Universe living in voids
- Quite a few IMBHs live in barred starforming non-dwarf galaxies, some without evident bulges
- As expected, cEs/UCDs are off M_{BH}–$M_{*,bulge}$



Results: summary

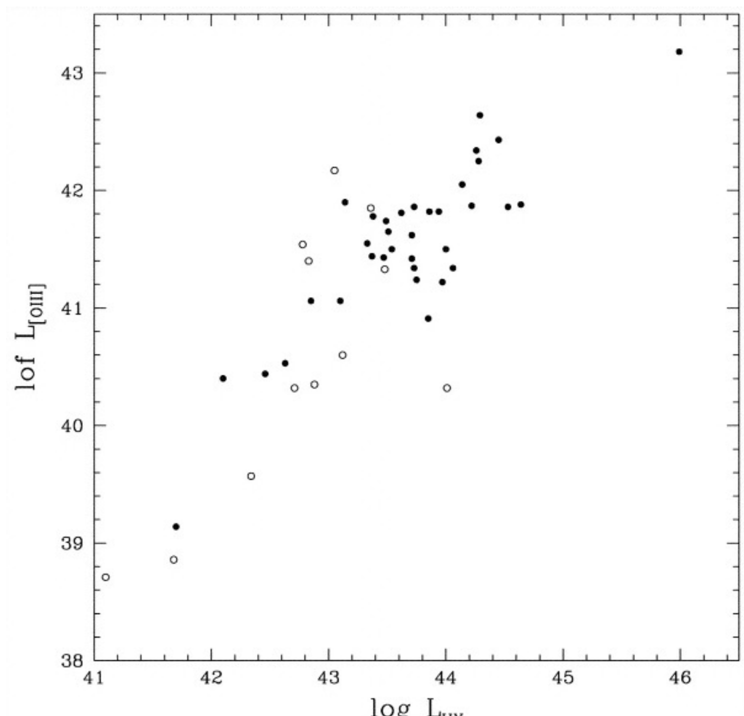
- 305 IMBH candidates with $M_{BH} < 2 \times 10^5\ M_\odot$, 25 with X-ray counterparts; 1600+ more massive $M_{BH} < 2 \times 10^6\ M_\odot$ candidates (160 with X-ray)
- Demographics: low-luminosity (dwarf-ish) galaxies and small bulges
- Monte-Carlo simulations suggest that we can go as low as 30k $M_\odot$

M_{BH} comparison	**Original**	**This study**
RGG118	50 000 $M_\odot$	70 000 ± 20 000 $M_\odot$
Dong07	70 000 $M_\odot$	116 000 ± 10 000 $M_\odot$



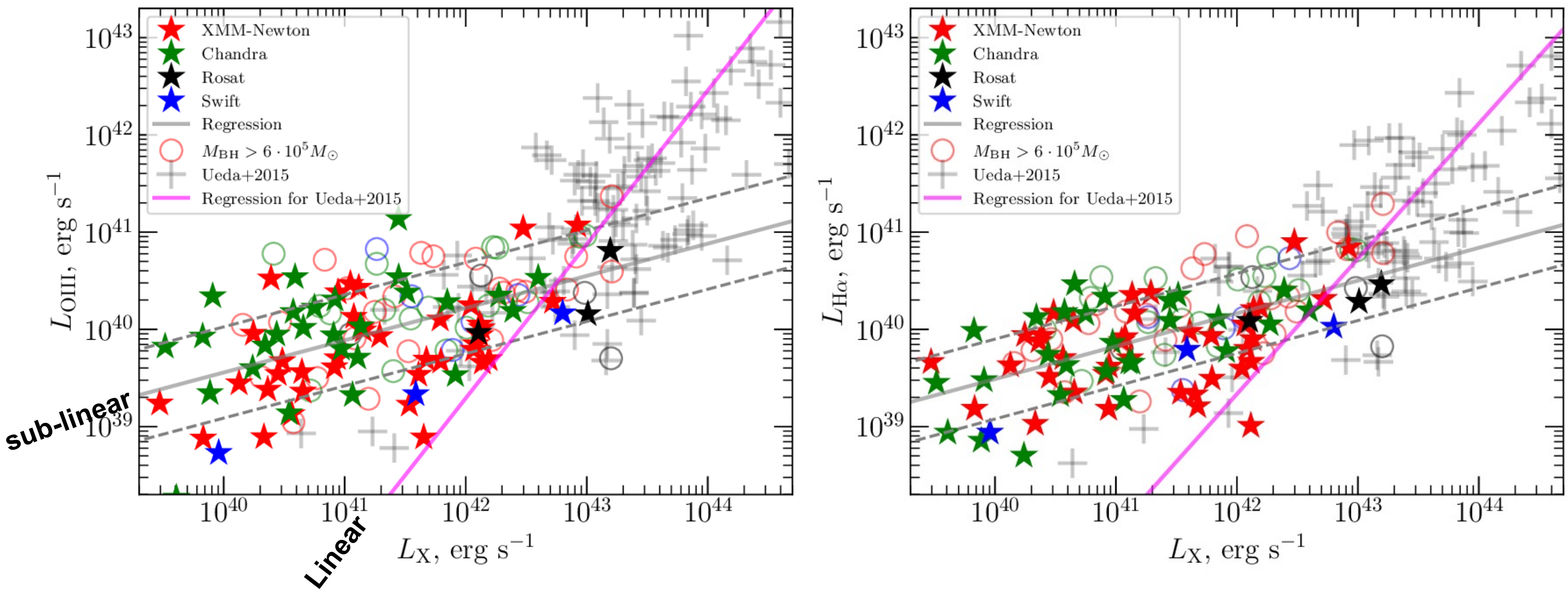
The $L_{[OIII]} - L_X$ relation for low-mass black holes

- First time noticed by Heckman et al. (2005) for hard X-ray (3-20 keV), it connects optical and X-ray properties of AGN
  - Linear correlation $L_{OIII} = 0.7\% * L_X$ with large spread (0.8 dex)
  - It is thought to illustrate the ionization of gas in the NLR by the AGN accretion disk corona



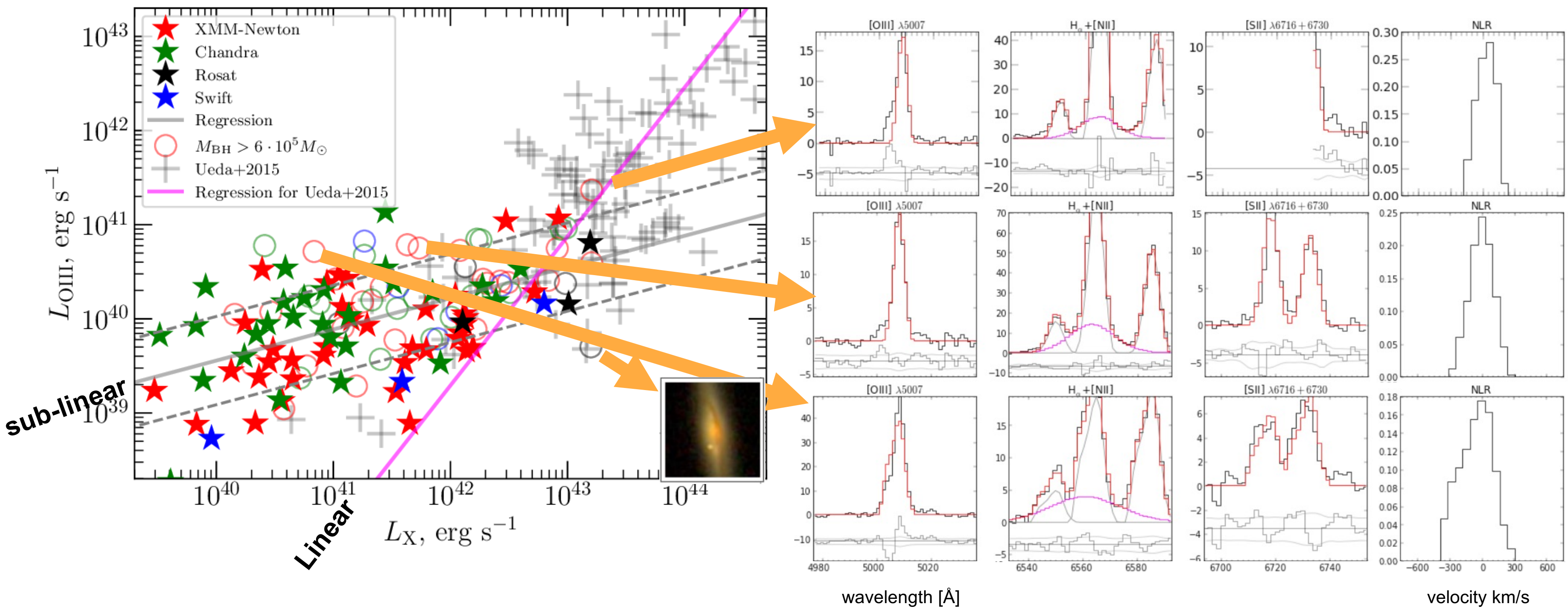
The $L_{[OIII]} - L_X$ and $L_{bH\alpha} - L_X$ relation for light-weight SMBHs

- We found that for M_{BH}<600 k$M_{\odot}$ the relation is different
  - sub-linear: $L_{OIII} \sim L_X^{0.33}$ and much tighter (0.3 dex); similar story for the $L_{bH\alpha} - L_X$ relation
  - puffs up and steepens when including more massive BHs
  - not connected to SFR or total stellar mass; **broad Hα originate from the SMBH vicinity**



The $L_{[OIII]} - L_X$ and $L_{bH\alpha} - L_X$ relation for light-weight SMBHs

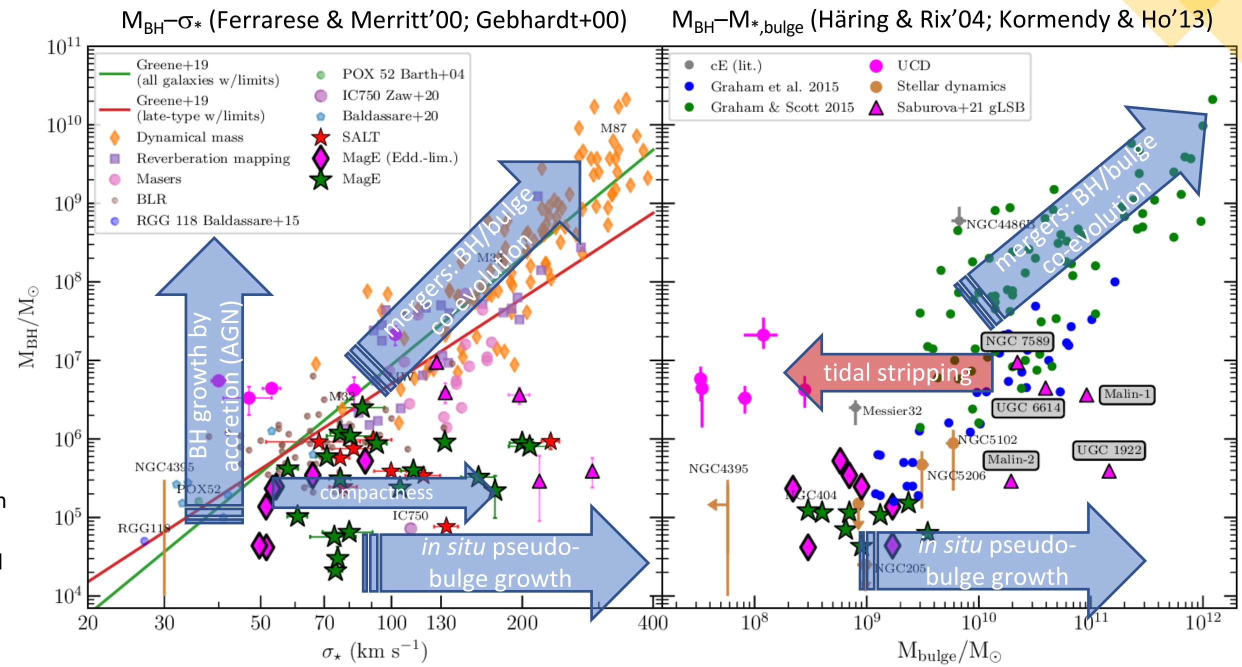
- Objects deviating “up” (higher [OIII]) exhibit outflows
  - asymmetric and broad forbidden line profiles with a “blue wing”
- Objects deviating “down” are dusty star-forming galaxies



SMBH growth in the IMBH regime

What can we learn from new data?

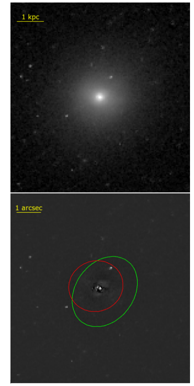
- Co-evolution is important for massive bulges, which assembled their mass via mergers
- gLSB galaxies grow their massive bulges secularly in sparse environment and, hence, become strong outliers below the BH-host scaling relations
- Compact stellar systems are outliers (above)
- Many IMBHs and light-weight SMBHs are offset to the bottom/right:
  - Dwarf early-type galaxies are subject to morphological transformation by environment, which heats them up and increases velocity dispersion
  - We can sometimes miss a low-mass bulge in a dE and consider the whole galaxy as a bulge: this will also offset it to the right
  - If these hypothesis is right, then there should be an environmental dependence of the position of a galaxy on the diagrams in the low-mass regime
- Eddington-limited BHs are almost exactly on the relation: perhaps this is because 6/7 live in relatively poor environment

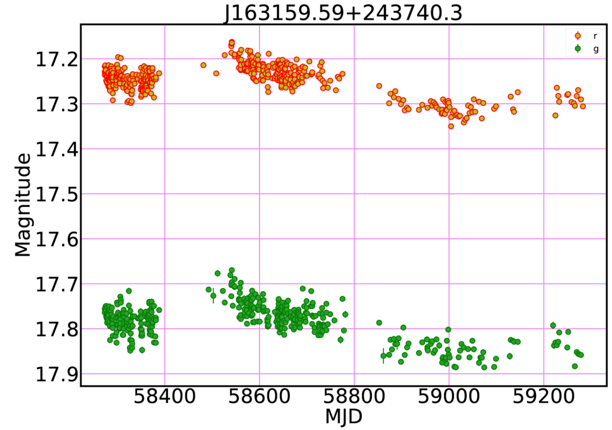


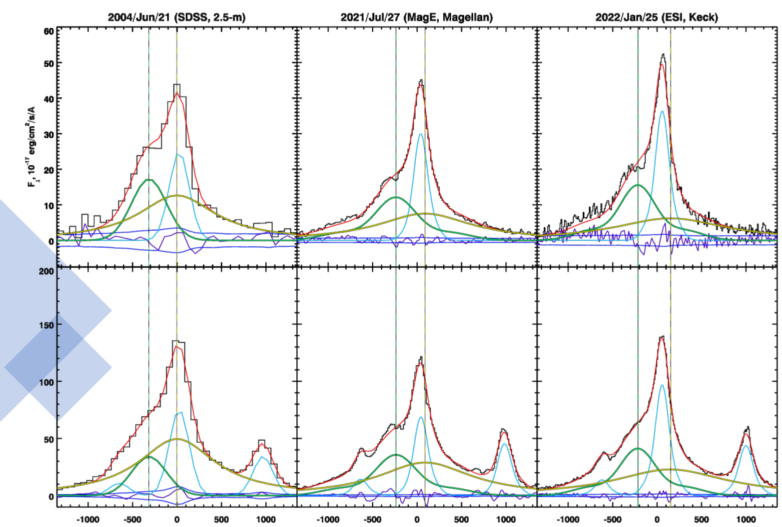
J1631+24: a 13:1 mass ratio binary IMBH candidate

One object in the 1M sample caught our attention

- Asymmetric broad Balmer lines with a blue “hump”
- Low-mass elliptical host galaxy; HST data analysis reveal disturbed morphology: a recent dry minor merger?
- Strong variability revealed from a light curve generated by Zwicky Transient Facility
- Secure X-ray identification with Chandra and XMM







Follow-up observations with Magellan and Keck (HST is coming)

- “Hump” is persistent for 17 years, can be decomposed into two broad-line profiles in Hα, Hβ, Hγ, Hδ: it is not an outflow-related variability of a broad line profile
- Velocity separation between the components stay the same, about 300 km/s, intensities change over time
- HeI/II and Paschen lines also display the same two-component structure although helium lines are broader (as expected): this is not an effect of dust extinction in the torus

Viable explanation: a 0.05pc-separated binary IMBH

- Virial masses of $6*10^4$ and $8*10^6$ M_{Sun}; orbital period ~1000 yr

Summary

- We conclude that a population of IMBHs in AGN with $M_{BH} < 10^5\ M_{\odot}$ exists and this fact disfavors massive SMBH seeds
- IMBHs in the nearby Universe do not seem to co-evolve with their host galaxies: they grow by accretion, while their hosts grow secularly (even though the gas supplies may be connected)
- If the same happens at high redshifts, then the (super-)Eddington accretion is the dominant SMBH growth mechanism at low masses, and we expect to see high-z IMBHs in X-ray with the next generation facilities Athena and Lynx
- There are still a lot of things to explore at the low-mass end of the SMBH properties, e.g. X-ray vs optical, feedback, environment

Thank you