IMBHs manifested as low-luminosity AGN

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on behalf of:
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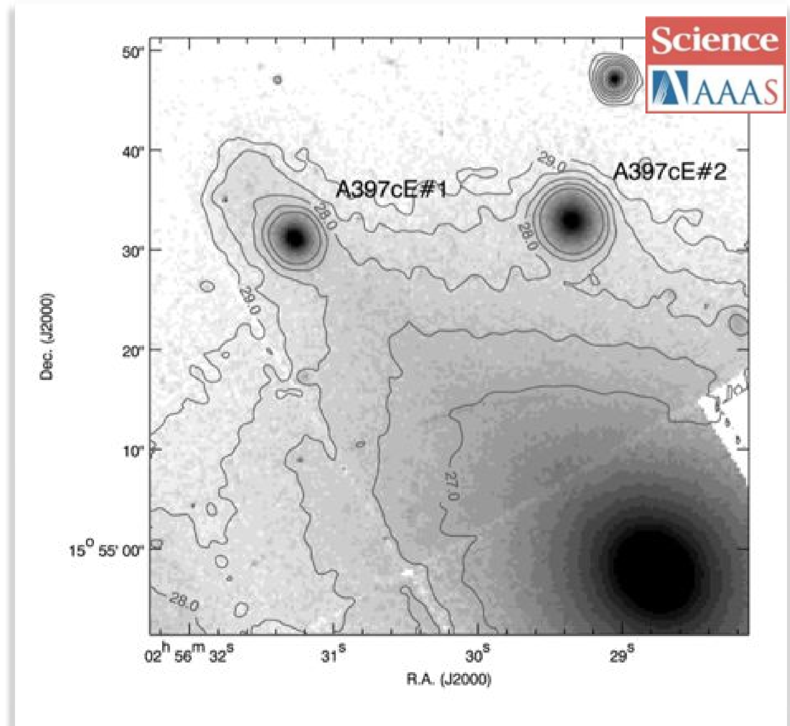
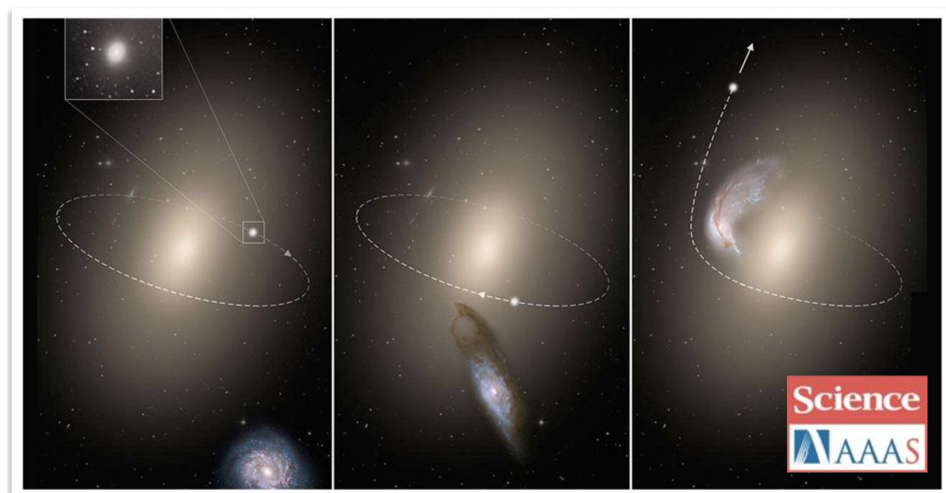
Elusive AGN — Jun 12, 2017

Our team

- Distributed team:
  - Harvard-Smithsonian CfA
  - Moscow U
  - IRAP, Toulouse
- Focus (methodology):
  - data mining
  - Virtual Observatory
  - data intensive astronomy
- Known for:
  - Discovery of a cE population (Science, 2009)
  - Discovery of runaway galaxies (Science, 2015)
  - Discovery of the 1st pulsar in M31 (ApJ, 2017)
  - RCSED (ApJS, 2017)
- This study: ADASS-2015 tutorial in Sydney by IZ & IC





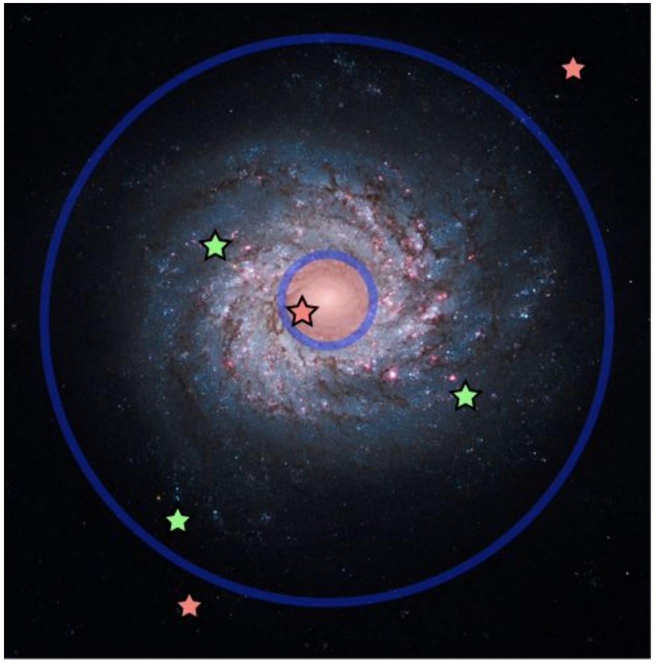
Introduction

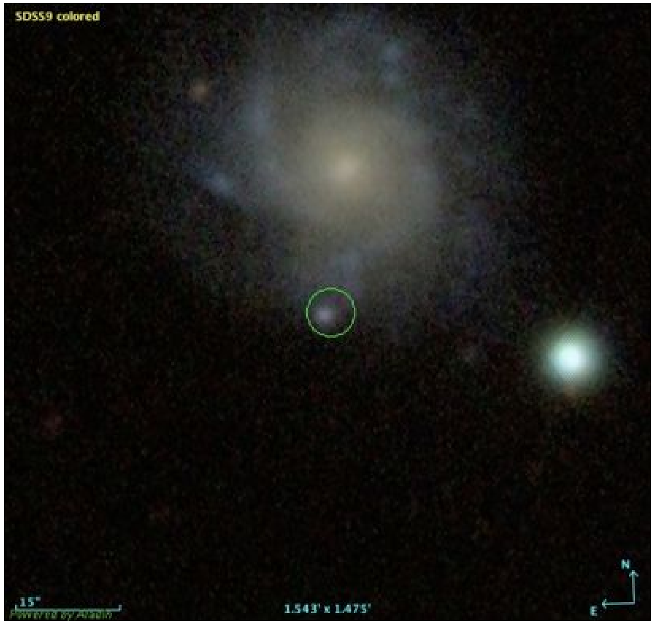
- IMBHs ($100\ M_\odot < M_{BH} < 10^5\ M_\odot$) are important:
  - early SMBH assembly
  - reionization
  - GW
  - constraints on hierarchical Universe
- Little doubt they exist:
  - LIGO GW detection
  - ESO 243-49 HLX-1
  - RGG118
- IMBHs searches:
  - AGN
  - Ultra/Hyper-Luminous X-ray sources: bright off-nuclear X-ray sources
  - Globular clusters (e.g. Kiziltan17)

HLX search

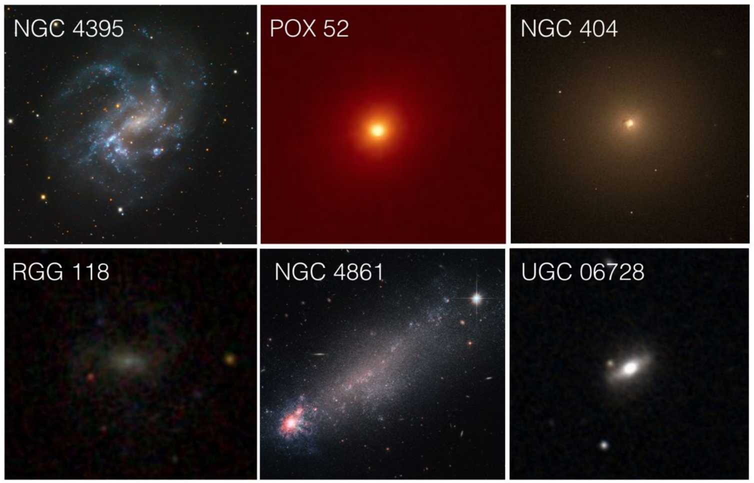
- Zolotukhin16:
  - 98 HLX candidates with $L_X > 10^{41}$ erg/s from off-nuclear cross-match of SDSS spectral sample and *XMM-Newton* catalog
  - Background contamination < 80%
  - HLX population does exist

- Ongoing spectral follow-up campaign on Keck/Palomar (with D. Stern and M. Heida)



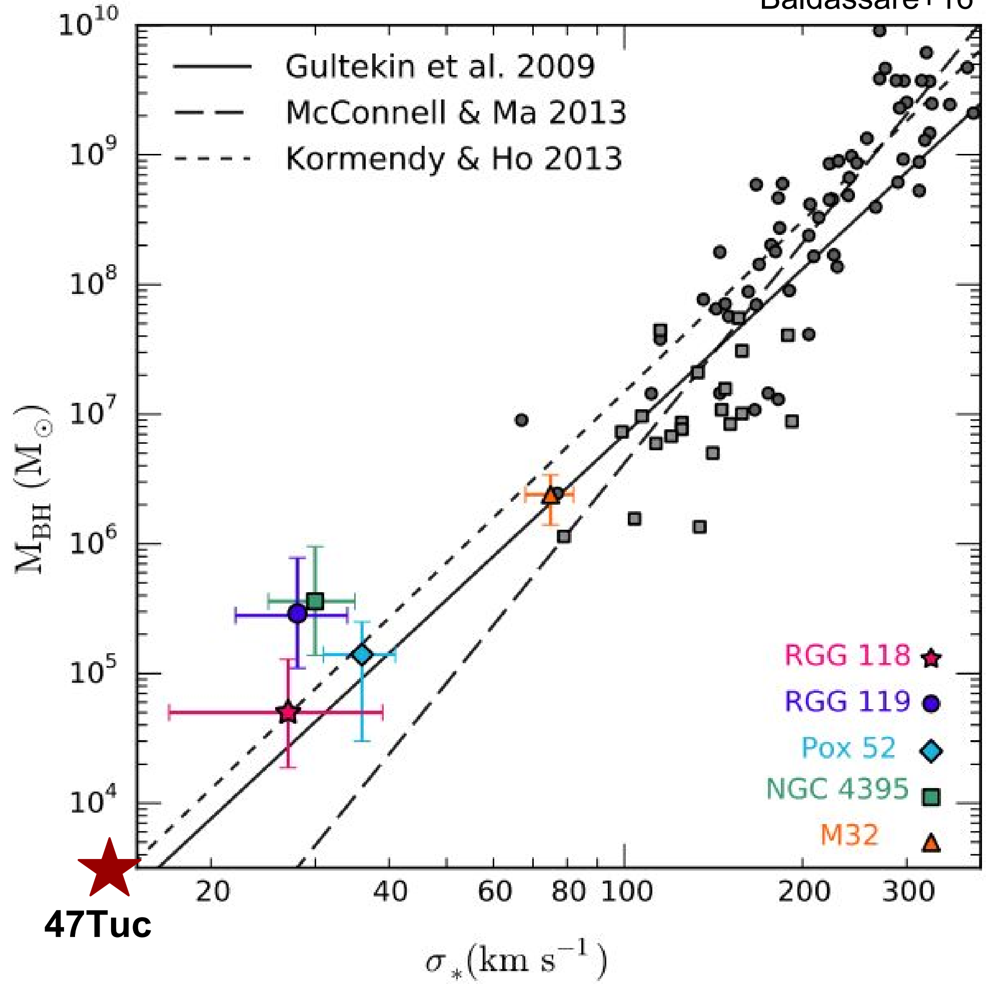


Nuclear (I)MBH: what is known so far



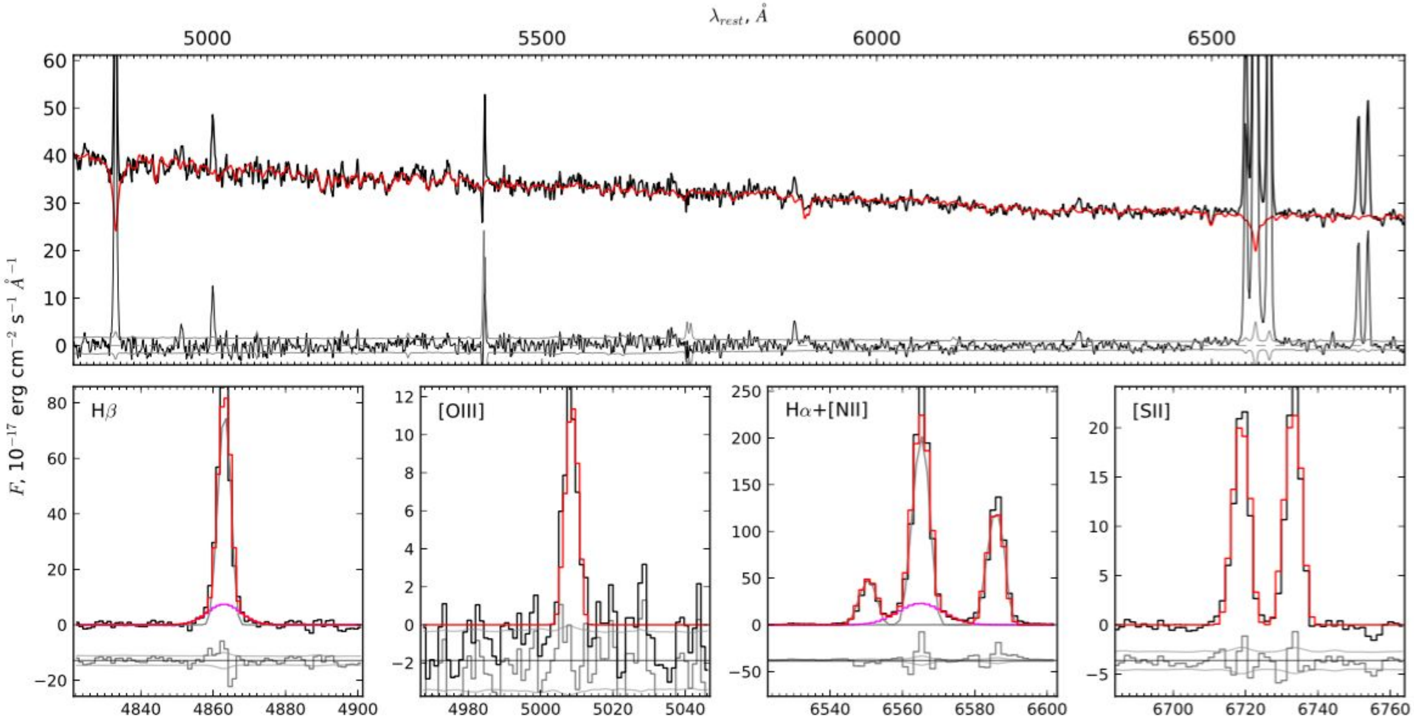
NGC104 [Kiziltan17]

Baldassare+16



Our IMBH search: BLR/NLR decomposition

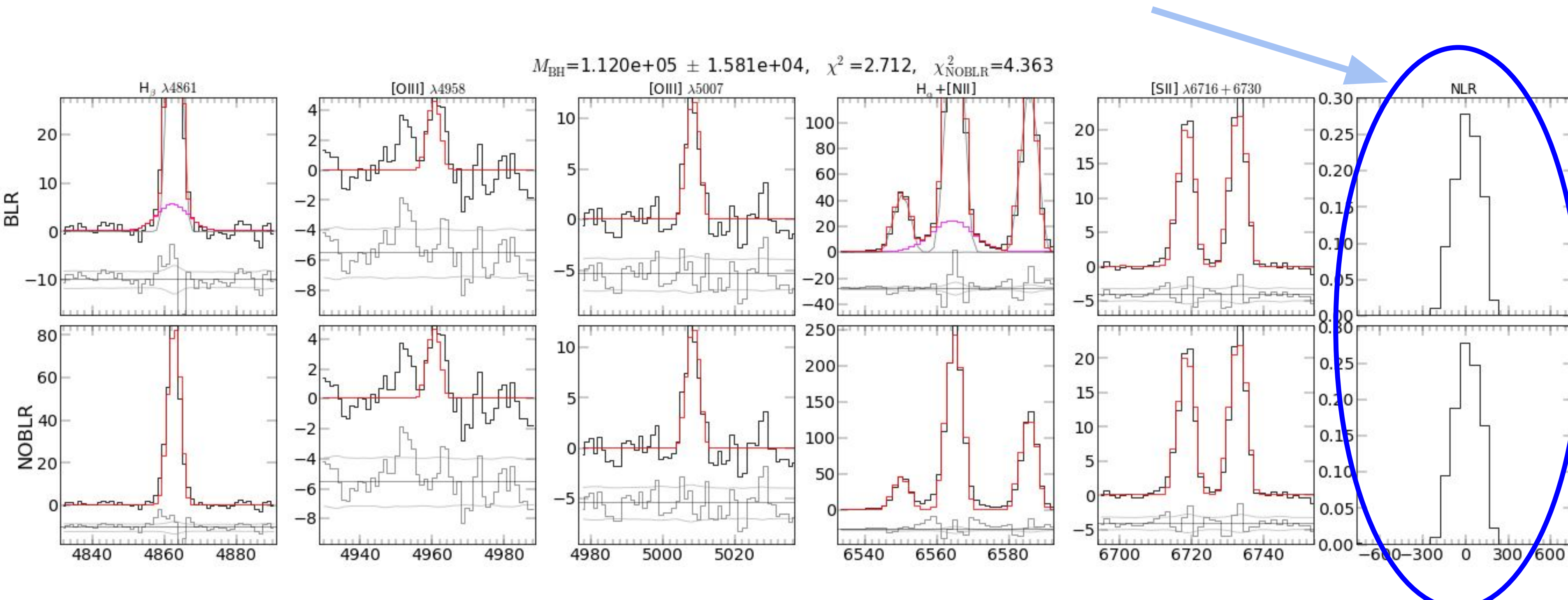
- The approach is conceptually similar to Greene & Ho: estimating BLR parameters, but we use a more general and stable technique for the BLR/NLR decomposition



Our IMBH search: BLR/NLR decomposition

- The approach 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 (Gaussian) BLR

NLR profile recovered non-parametrically

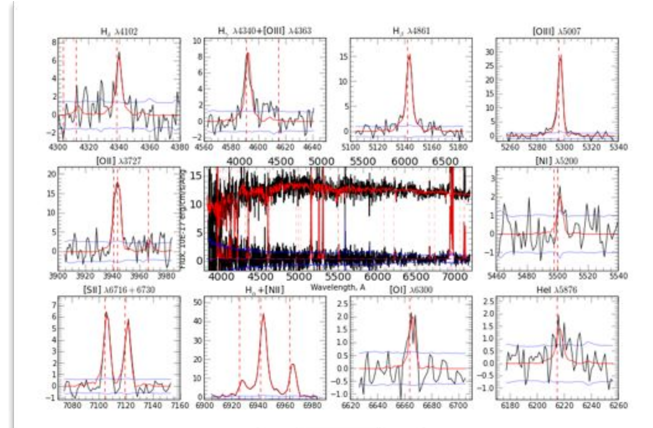


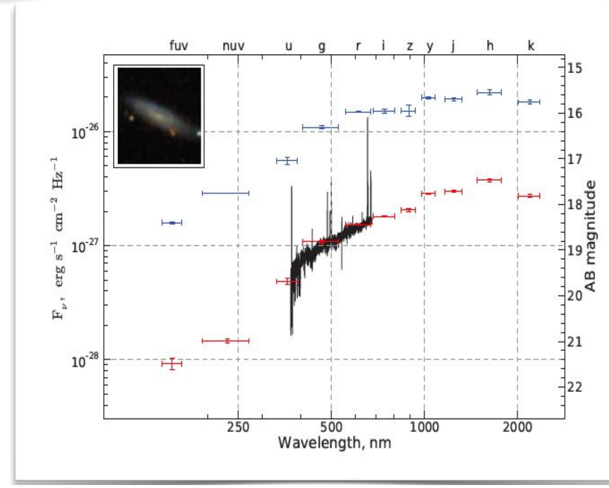
Our IMBH search: the workflow

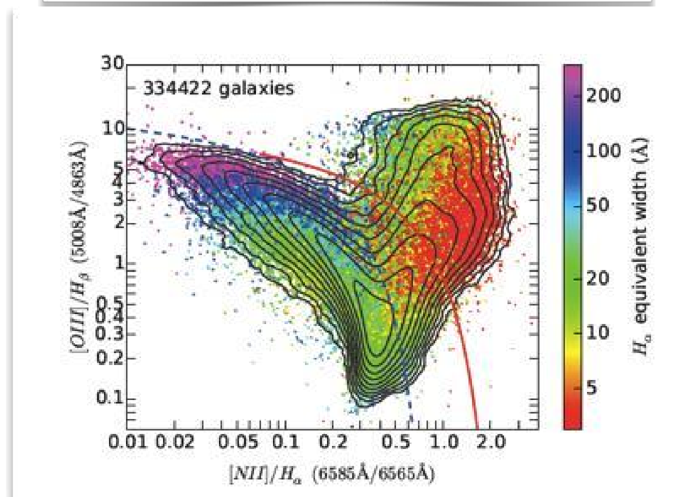
- Massively parallel automated workflow analysing 1 million SDSS DR7 spectra without pre-selection adding crucial information from large multiwavelength catalogs (RCSED, *WISE*, FIRST, *XMM-Newton*, *Chandra*, *Swift*, *ROSAT*)
- Final workflow product: `imbh.fits`, 1M rows, 200+ columns
- Filter for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

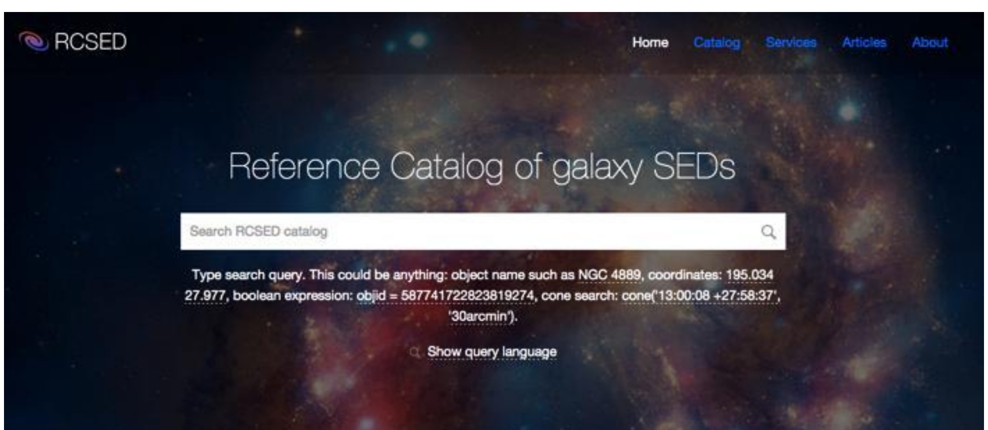
http://RCSED.sai.msu.ru

- Reference Catalog of galaxy SEDs: 800,000 galaxies
- Great discovery potential (e.g. 2015Sci...348..418C)
- 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



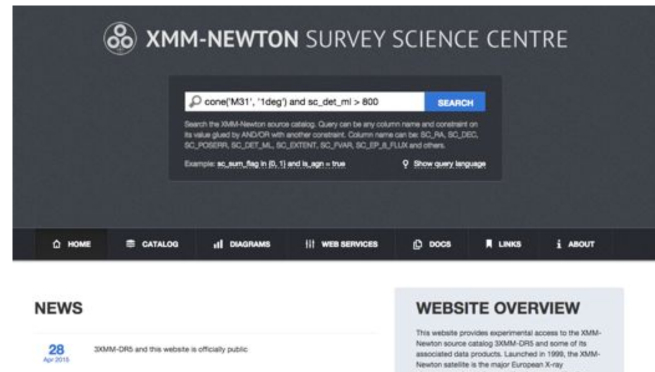


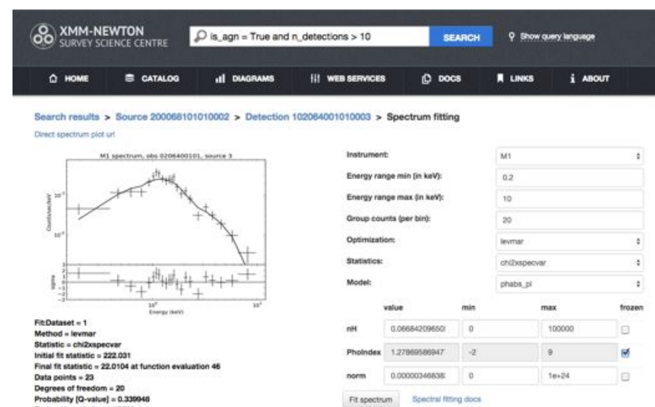


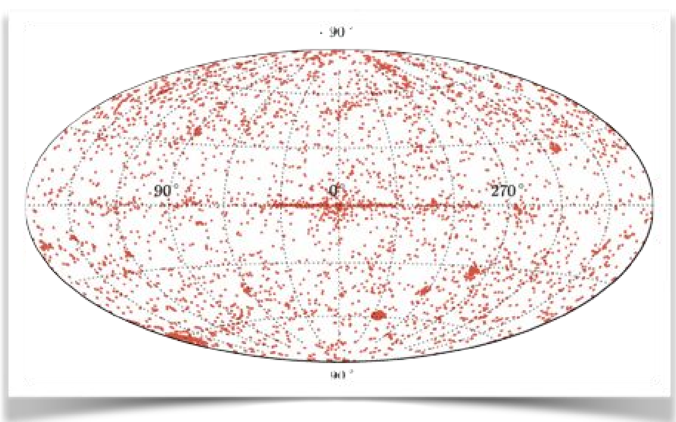


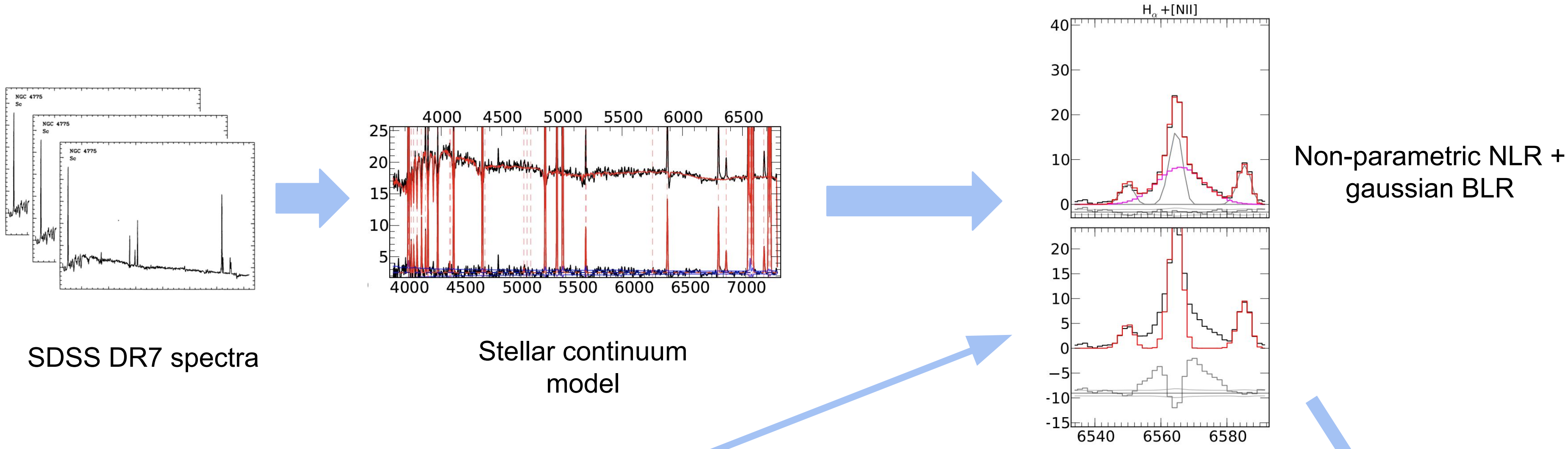
XMM-Newton source catalog

- 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



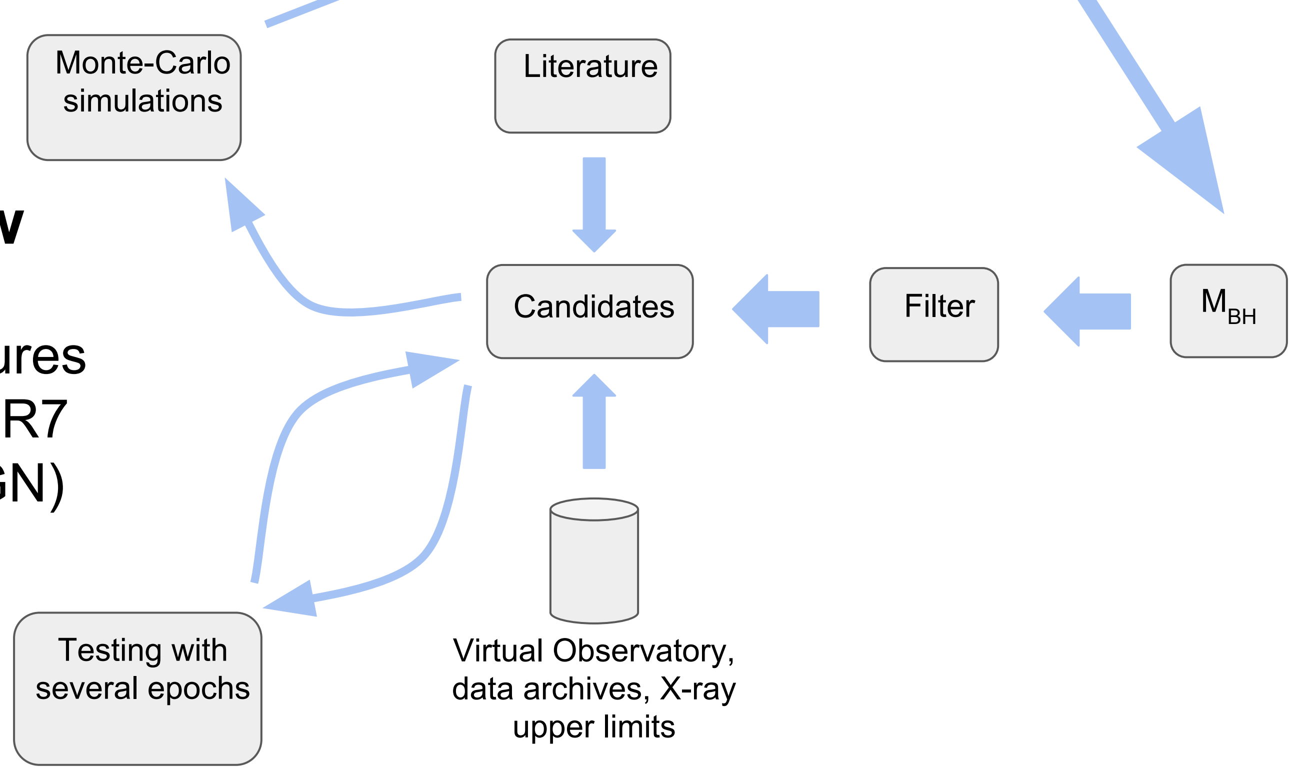






Parallelized analysis workflow

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



IMBH search: our selection criteria

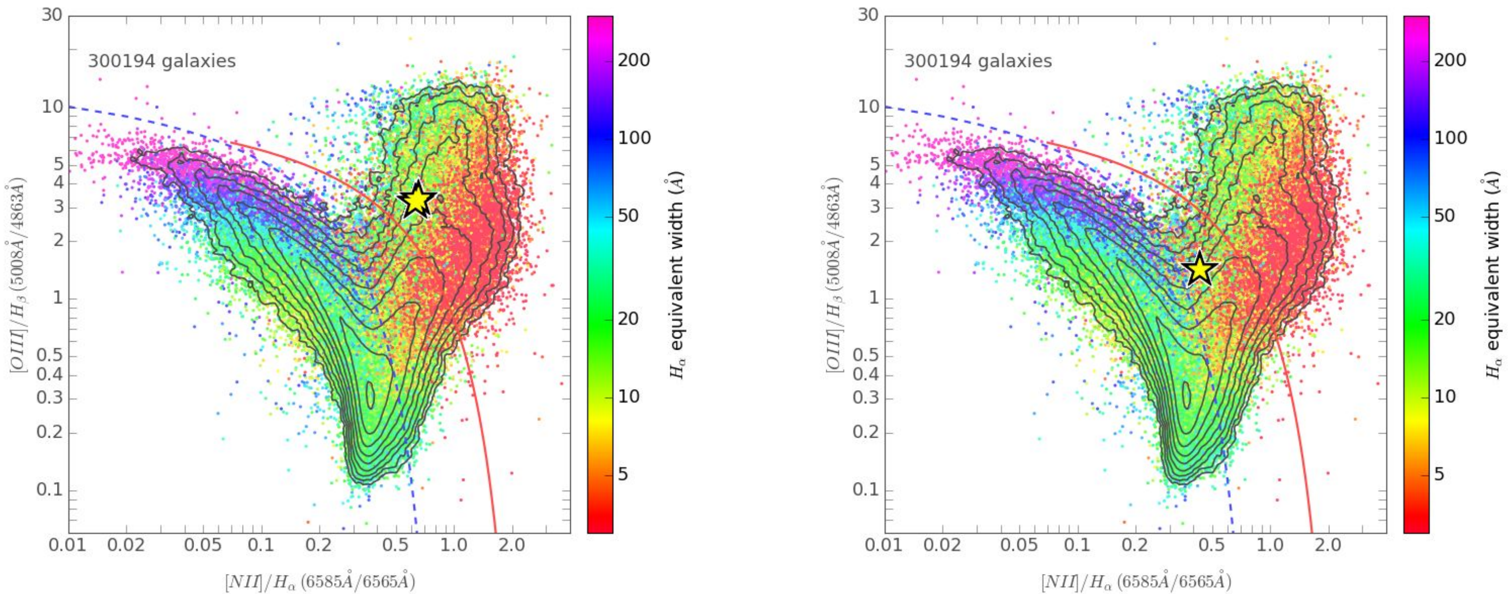
- AGN or composite in the BPT diagram with S/N > 3 for all its 4 lines (no SF)
- $M_{BH} < 2 \times 10^5 M_\odot$ (assuming the BLR mass uncertainty 0.3 dex) and S/N > 3 (using the Reines13 calibration)
- Narrow lines are narrow, broad lines are broad
- Fit with BLR describes data significantly better than fit without it

Recovers 2 known prominent IMBH candidates: Dong07 (=RGG127), RGG118 (and e.g. RGG119 but it is more massive) in a good agreement with literature mass estimates

```
(
!(
  abs((1+z) * 4861.0 - 5577.0) < 4 ||
  abs((1+z) * 5007.0 - 5577.0) < 4 ||
  abs((1+z) * 4861.0 - 5893) < 6 ||
  abs((1+z) * 5007.0 - 5893) < 6 ||
  abs((1+z) * 4861.0 - 6300) < 4 ||
  abs((1+z) * 5007.0 - 6300) < 4 ||
  abs((1+z) * 4861.0 - 6364) < 4 ||
  abs((1+z) * 5007.0 - 6364) < 5)
) &&
MBH_TOPCAT < 2.0e5 &&
MBH_TOPCAT / MBH_TOPCAT_ERR > 3 &&
GOOD_BPT &&
(BPT_AGN || BPT_TRANS) &&
abs(BLR_POS) < 3. * NLR_STDDEV &&
(NLR_FLUX_HBETA - NLR_FLUX_HBETA_ERR * sqrt(DECOMP_CHI2DOF)) / (NLR_FLUX_HALPHA + NLR_FLUX_HALPHA_ERR * sqrt(DECOMP_CHI2DOF)) < 0.5 &&
(BLR_FLUX_HBETA - BLR_FLUX_HBETA_ERR * sqrt(DECOMP_CHI2DOF)) / (BLR_FLUX_HALPHA + BLR_FLUX_HALPHA_ERR * sqrt(DECOMP_CHI2DOF)) < 0.5 &&
sqrt(BLR_SIG * BLR_SIG - NLR_STDDEV * NLR_STDDEV) > 2.0 * NLR_STDDEV &&
DECOMP_CHI2_NOBLR - DECOMP_CHI2 > 20 &&
DECOMP_CHI2_NOBLR_40 - DECOMP_CHI2_40 > 75
```

Caveats: SN, shocks, TDEs, algorithm

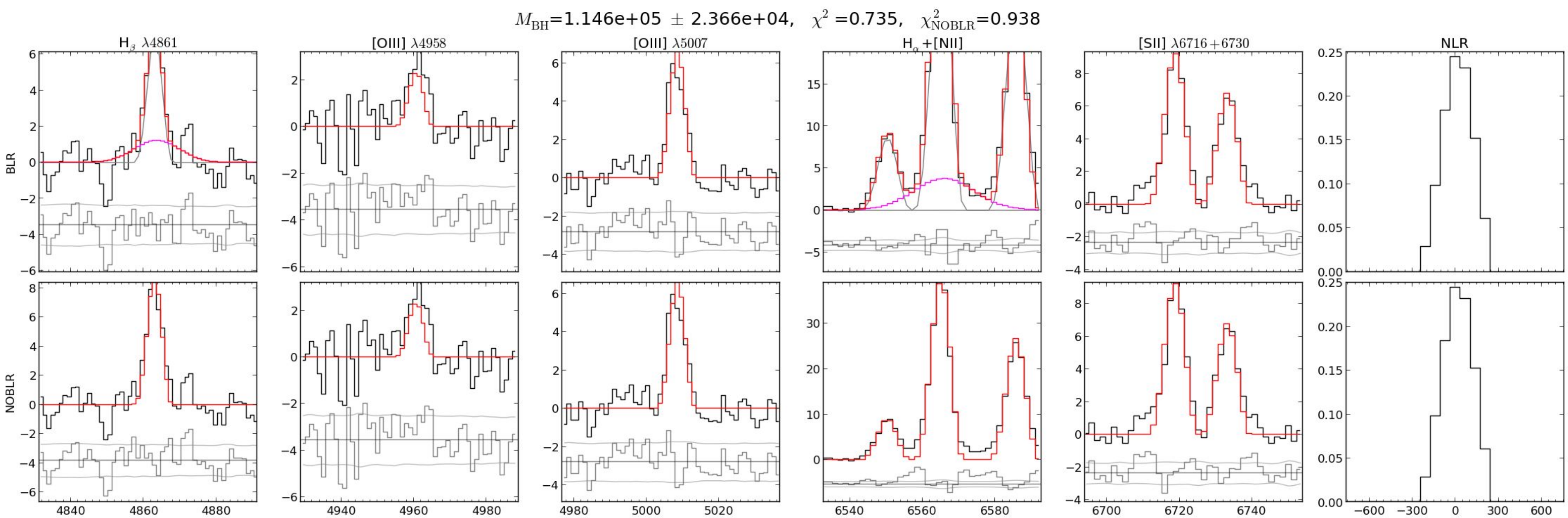
- Does virial mass estimate make sense? What about the coefficients?
- BPT: select AGN or composites (SF BLRs do not persist in multi-epoch spectroscopy, e.g. Baldassare16)
- Candidates with X-ray: more L_X than expected from LMXB/HMXB
- Candidates with X-ray upper limit: not a single X-ray drop-out 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



Results

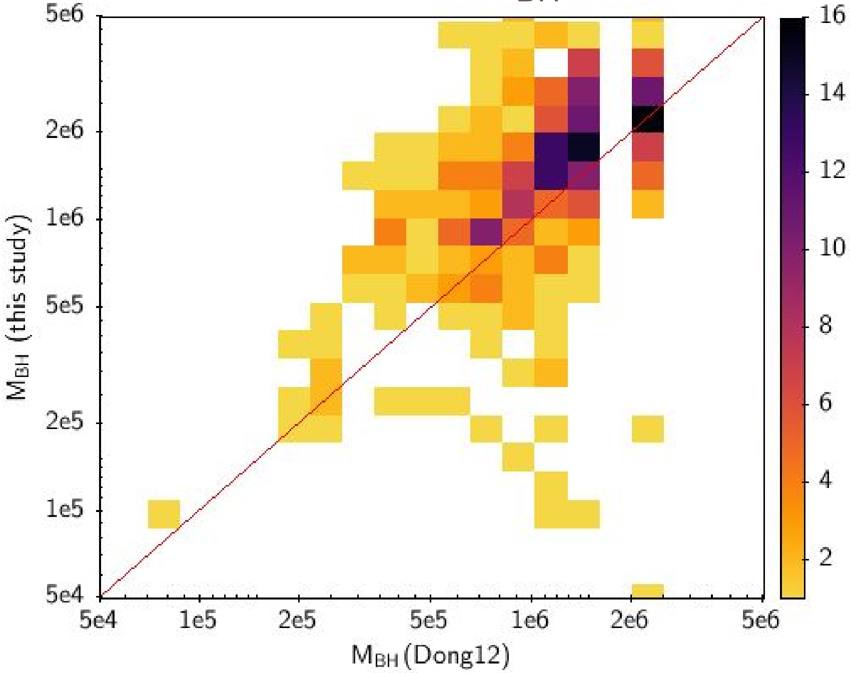
- 304 IMBH candidates (10 known from the literature) with $M_{BH} < 2 \times 10^5\ M_\odot$, 13 of which with X-ray counterparts (41k, 62k, 102k $M_\odot$)
- Demographics: low-luminosity (dwarf-ish) galaxies and small bulges
- Monte-Carlo simulations suggest that we can go as low as 30k $M_\odot$

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 $M_\odot$

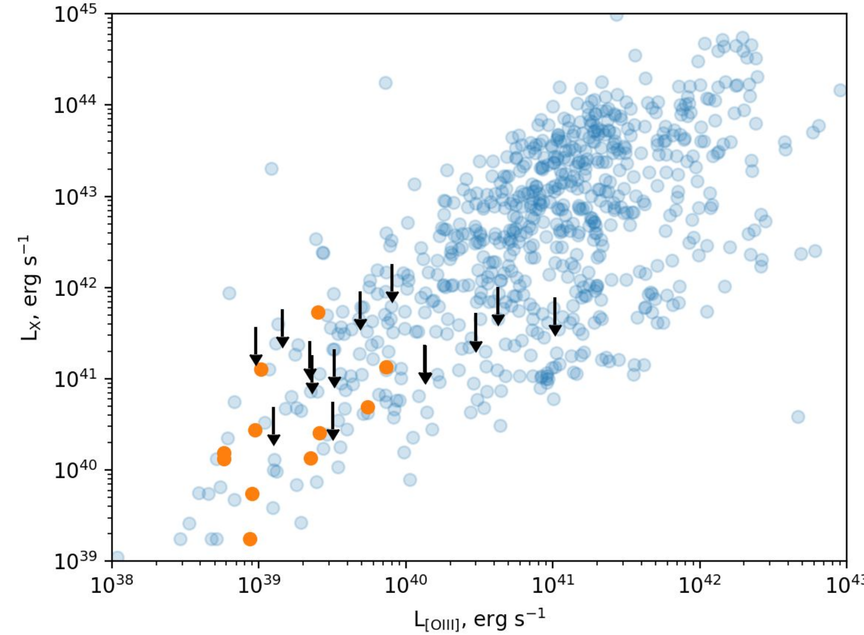


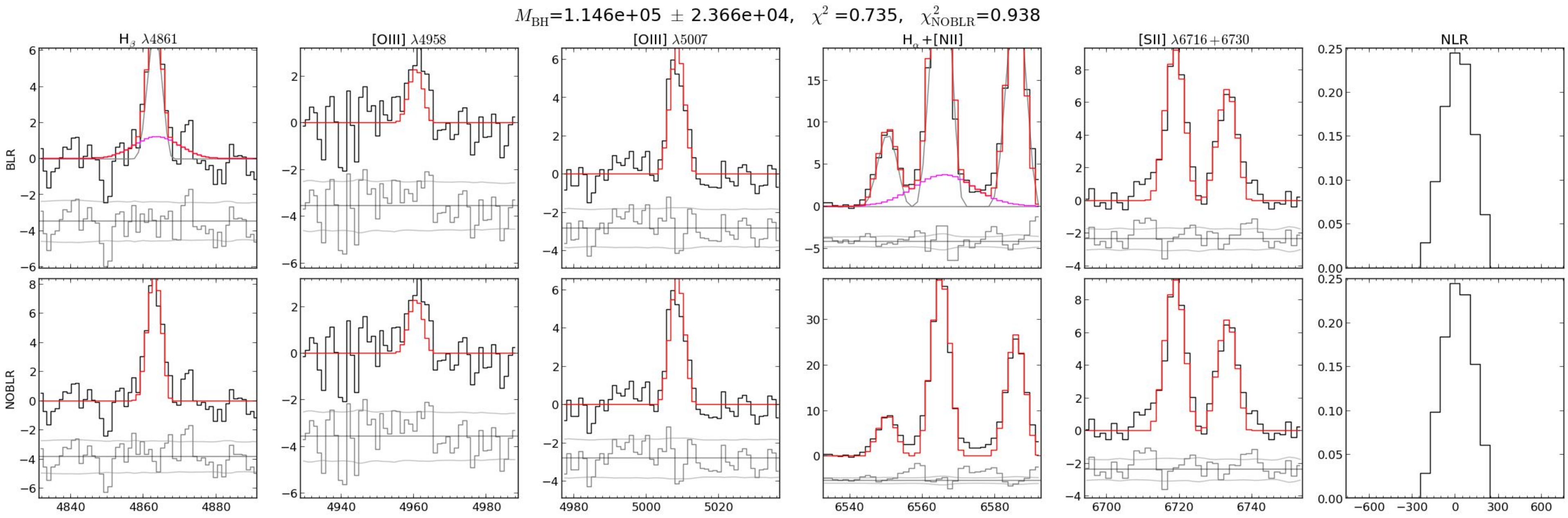
Results

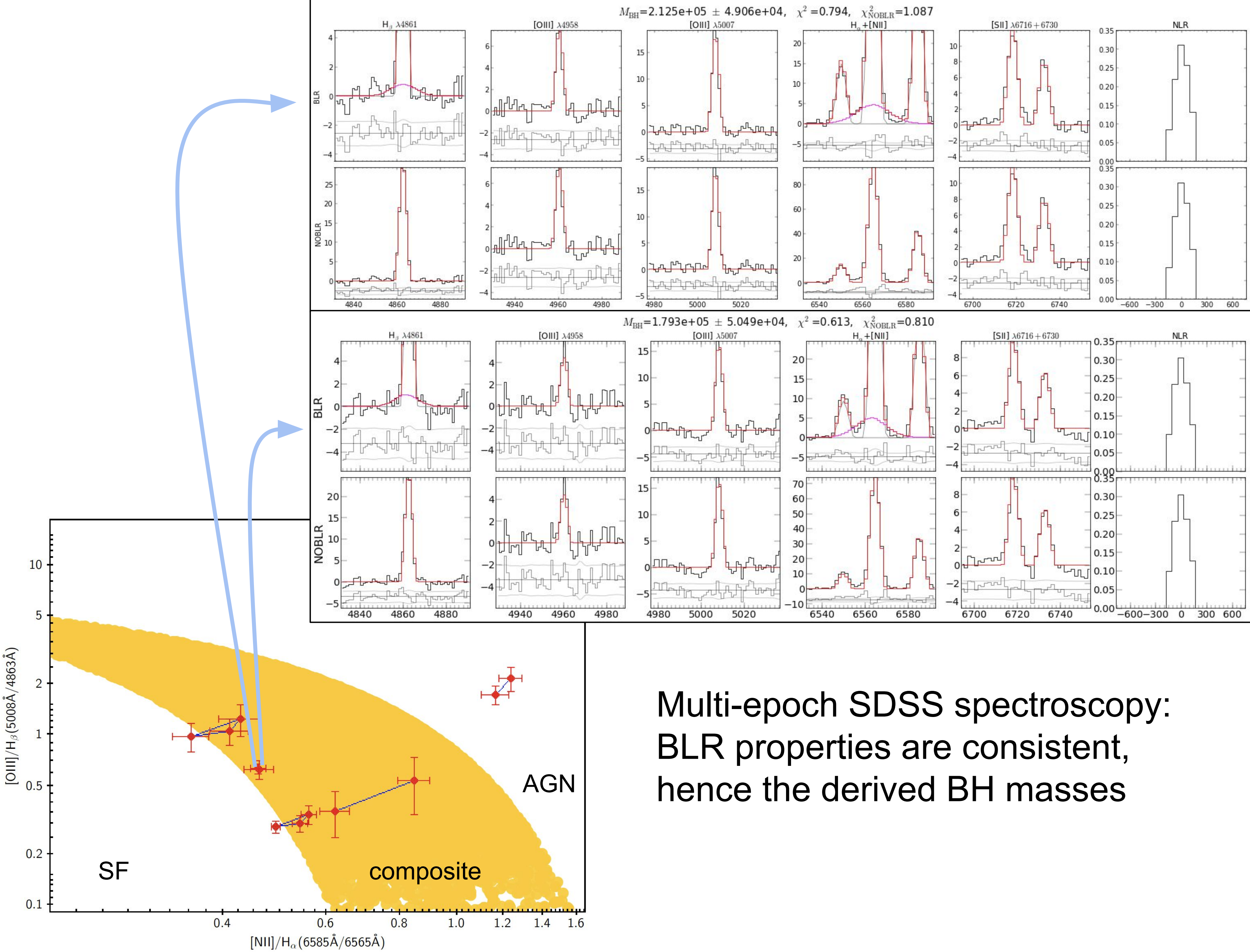
our M_{BH} vs Dong12



L_X vs $L_{[OIII]}$ correlation







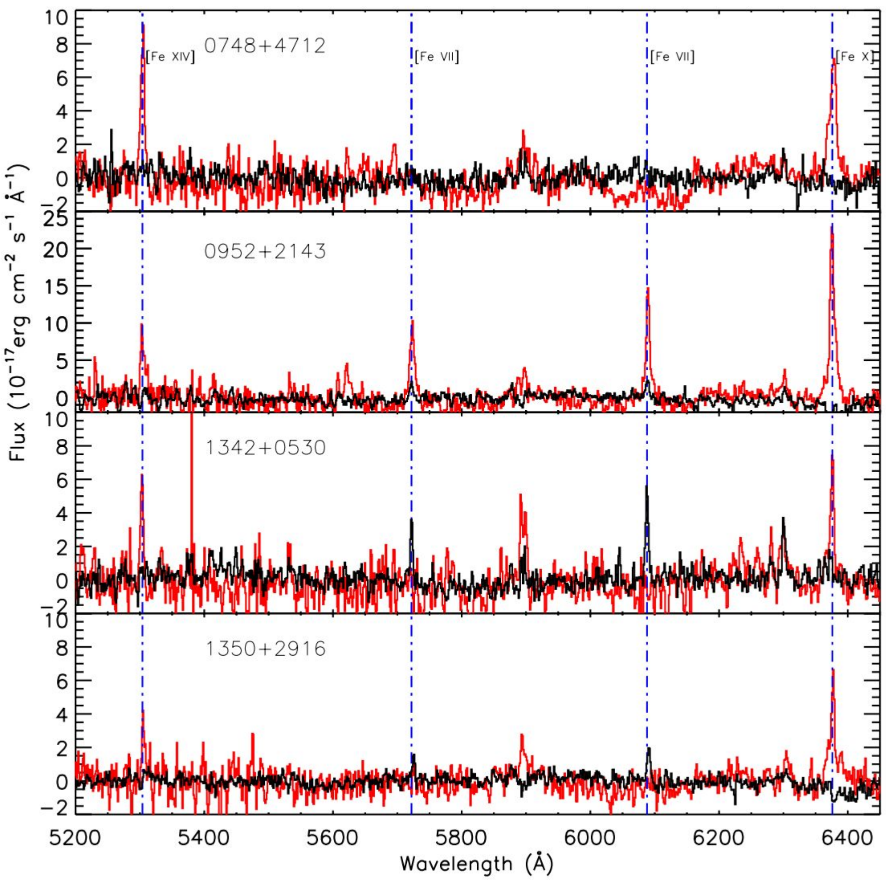
Multi-epoch SDSS spectroscopy: BLR properties are consistent, hence the derived BH masses

Tidal Disruption Events

- The high-ionization narrow lines that vary on timescales of years are unique features of the light echo of TDEs

Hence watch for:

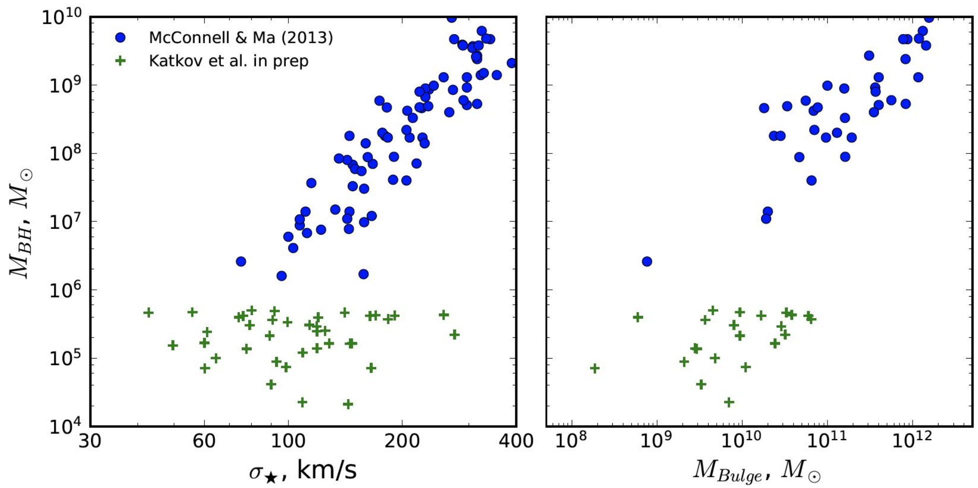
- Strong coronal lines, e.g. [Fe VII]
- Variability (multi-epoch)

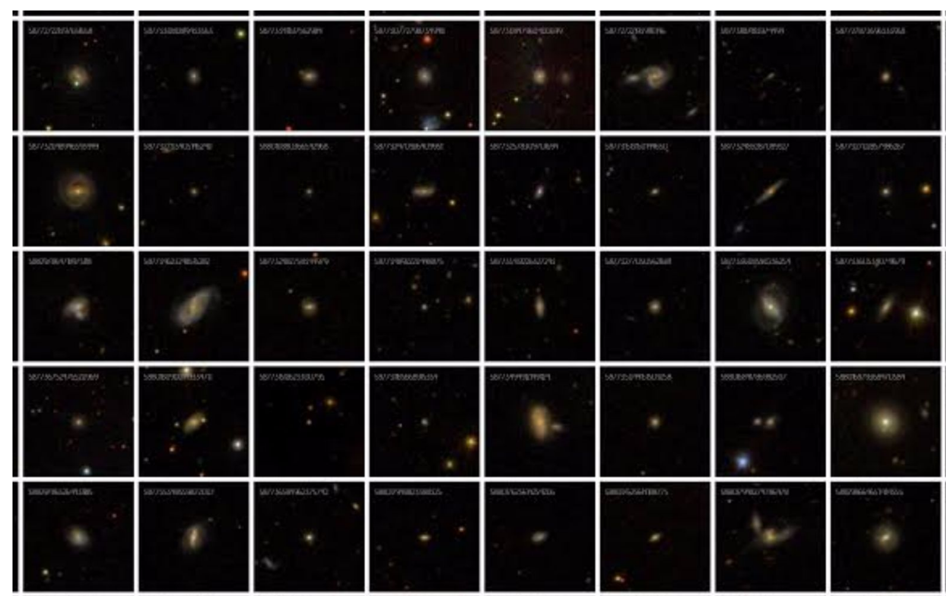


MMT vs SDSS (Yang13)

Work in progress

- Photometric decomposition for the M_{BH}—M_{bulge} relation (`galfit`-based pipeline for CFHT and Subaru data)
- Follow-up spectroscopy for the M_{BH}—$\sigma_{\star}$ relation and multi-epoch BLR component confirmation (Magellan - MMT)
- X-ray confirmation of AGN: Chandra/XMM
- Future: follow-up several IMBH hosts with the JWST NIRspec IFU and obtain:
  - spatially resolved star formation histories
  - maps of stellar and gas kinematics
  - maps of NIR emission line ratios in the narrow-line AGN region
  - improved IMBH mass estimates using AGN broad line region in H-alpha and Paschen-alpha





Conclusions

- Available evidence and tests:
  - multi-epoch spectroscopy with SDSS
  - mid-res spectroscopy with MagE
  - immediate X-ray confirmation for some objects
  - lack of non-detection with X-ray upper limits
  - Monte-Carlo simulations
- The population of IMBHs in AGN with $M < 10^5 M_{\odot}$ exists

Thank you