IMBHs manifested as low-luminosity AGN

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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)

- This study: ADASS-2015 tutorial in Sydney by IZ & IC
Introduction

- IMBHs \((100 \, M_\odot < M_{\text{BH}} < 10^5 \, M_\odot)\) 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 $L_\text{X} > 10^{41}$ 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

NGC 4395, POX 52, NGC 404
RGG 118, NGC 4861, UGC 06728

NGC104 Kiziltan17

![Graph showing the relation between black hole mass and stellar velocity dispersion](image-url)
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
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](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)
- $M_{\text{BH}} < 2 \times 10^5 M_\odot$ (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 $L_X - L_{[\text{OIII}]}$ 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 $M_{\text{BH}} < 2 \times 10^5 M_\odot$, 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 $M_\odot$

<table>
<thead>
<tr>
<th>$M_{\text{BH}}$ comparison</th>
<th>Original</th>
<th>This study</th>
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<tbody>
<tr>
<td>RGG118</td>
<td>50 000 $M_\odot$</td>
<td>70 000 ± 20 000 $M_\odot$</td>
</tr>
<tr>
<td>Dong07</td>
<td>70 000 $M_\odot$</td>
<td>116 000 ± 10 000 $M_\odot$</td>
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$M_{\text{BH}} = 1.146e+05 \pm 2.366e+04$, $\chi^2 = 0.735$, $\chi^2_{\text{NOBLR}} = 0.938$
Results

our $M_{BH}$ vs Dong12

$L_X$ vs $L_{[OIII]}$ correlation

$M_{BH}=1.146e+05 \pm 2.366e+04$, $\chi^2 = 0.735$, $\chi^2_{NOLR} = 0.938$
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 $M_{BH} - \sigma_*$ 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