Probing Black Hole Astrophysics through Gravitational Lensing

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Black holes (BHs) are simple, energetic, and yet mysterious!

- **Supermassive BHs** ($>10^5 M_\odot$), seen as active galactic nuclei (AGN)
- **Stellar-mass BHs** ($<10^2 M_\odot$), seen as X-ray binaries (XBs)
- Presence of intermediate-mass BHs ($10^2 - 10^5 M_\odot$) has also been speculated

Credit: ESO, ESA/Hubble, M. Kornmesser/N. Bartmann
Origin:

Luminous quasars or AGNs at high-z

SMBHs already exist in the early universe

What are their seeds? How do they grow?

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Detail:

AGN structure: ~1 pc, probed via e.g. reverberation mapping

Corona: < 0.01 pc

Corona < 0.01 pc
Effects on the cosmic structure formation (e.g. AGN feedback)

Galaxy formation/evolution

Re-ionization of the Universe: (faint) AGN and/or stellar-mass BHs could be important

Credit: Joseph Silk

Giallongo et al. 2015
Stellar mass BHs were only known in accreting XBs, until the detection of the gravitation waves from merging BH binaries.

When and where do such BHs form? How does the formation depend on metallicity and/or star formation rate?
Why gravitational lensing?

Images of the source

Lensing always conserves surface brightness
It is sensitive to the mass (e.g., a BH)!

Einstein Radius:

$$\theta_E = \left[\frac{4GM}{c^2}(1/D_L-1/D_s)\right]^{0.5}$$

For a point lens and source, the lensing equation is

$$\theta = \beta + \theta_E^2/\theta$$

The image of a source in the lens plane is split into two images when at

$$\theta = 0.5\left[u \pm (u^2+4)^{0.5}\right] \theta_E$$

with magnifications

$$m = 0.5\left[\frac{u^2+2}{u(u^2+4)^{0.5}} \pm 1\right]$$

Lens mass (M), lens distance (D_L), source distance (D_S)
Nzs: Observing high-z AGN is essential to determining how SMBHs grow and affect their environment. Existing work is mostly on luminous AGN; faint AGN populations at high-z are probed by very deep X-ray exposures (> 1 Ms, e.g. Chandra Deep Fields).

XBs: Detection of XBAs at high-z will enable us to check how their formation depend on galaxy environment: e.g., metallicity and/or star formation rate (SFR). Stacking of distant galaxies have been used, which suffers the uncertainty in the underlying faint AGN contribution.

Strongly lensed galaxies

Magnified flux  Amplification $\rightarrow$ “zoom-in”

Probe fainter individual AGN.

Collective emission of XBs.
Existing X-ray Observations

Chandra observations of 3C220.1 – a galaxy cluster at $z \sim 0.61$.

Total exposure: 170 ks

The lensed galaxy (arc) is at $z \sim 1.5$ (Worrall et al. 2001).

The lensing cluster is known to be a major merger, which complicates the X-ray morphology.
• Very marginal detection of diffuse X-ray emission in 2-8 keV, or 5-20 keV in the rest frame of the lensed galaxy.

• There are existing/upcoming Chandra observations of similar lensing systems selected from SDSS (PI: Matt Bayliss); a few of them have also been selected as JWST early release science targets.

• But these systems generally have too low star formation rates and Chandra exposures to improve the detection significantly.

Dedicated new observations are needed!
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- **The most highly magnified starburst galaxy**

  - Our proposed 308 ks exposure (PI: Bayliss) will reach an unprecedented sensitivity to detect X-ray emission from PSZG311, a galaxy (arc) magnified for a factor ~120.

  - The natural “zoom-in” effect transforms the Chandra resolution (~0.5") into a physical scale of ~400 pc at z = 2.37.

More proposed 308 ks exposure (PI: Bayliss) will reach an unprecedented sensitivity to detect X-ray emission from PSZG311, a galaxy (arc) magnified for a factor ~120.

The natural “zoom-in” effect transforms the Chandra resolution (~0.5") into a physical scale of ~400 pc at z = 2.37.
What kind of lensed galaxies are suitable?

X-ray surface brightness contrast at $R_E$.

Different lines of the same color correspond to different $R_e$.

The surface brightness of the lensing object assumes

$$S(R) = S_0 [1 + \left( \frac{R}{R_e} \right)^2]^{-3\beta+0.5}$$

$$L_X = L_0 \left( \frac{M}{M_0} \right)^\alpha$$

The surface brightness of the lensed galaxy assumes the $L_X/SFR$ with or without $(1+z)$-evolution (upper and lower limits).

We need Chandra observations of relatively low mass foreground lensing objects with strongly lensed galaxies of large SFRs.
Brightest submillimeter galaxies as the best targets

These SMGs appear to undergo extreme starbursts at $z \sim 2$

Initially elected from the all-sky Planck 350 µm source catalog with extensive follow-up observations with LMT, HST, JVLA, ALMA, Gemini…

The Large Millimeter Telescope, jointly constructed by Mexico and UMass, is a 50m diameter millimeter-wave telescope at the summit of Volcano Sierra Negra at an elevation of 4600m.
Measuring $L_{IR}$, SFRs, etc.

Planck, Herschel, AzTEC, etc. photometry fit with starburst template SEDs

Integrated IR luminosity measured from best-fit template, then converted to SFR (e.g. Kennicutt 1998)

Some of the galaxies show excess in radio emission, indicating the presence of radio-active AGNs.
Extreme starburst galaxies

With apparent IR luminosities range from $\sim 1 - 3 \times 10^{14} \, L_\odot$, these galaxies present the upper envelope of the $L_{\text{IR}}$-z distribution.

The brightest ones indicate SFR $\sim 10,000 - 28,000 \, M_\odot$/year, which are too extreme to be physical!

Are they largely magnified via gravitational lensing?
the strong gravitational lensing

Using WFC3/F160W (1.6 μm) filter

Most are lensed by single galaxies, showing Einstein “rings”

Others are by small groups and still more by massive clusters
Preliminary gravitational lens modelling

- The typical magnification is $\sim 10$.
- So these SMGs remain to be among the brightest galaxies, even intrinsically.
- There are no local analogs to such galaxies. Thus a detailed investigation of them is the only way to probe the underlying physical processes.
ALMA observations: 3-D properties of the molecular gas

- Resolve the spatial structure at ~0.5" resolution and velocity at ~10 km/s.
- Strong outflows are indicated.
of the brightest SMGs (z=2.2-3.6), which are primarily galaxy-galaxy lenses, are proposed for the upcoming cycle. The “zoom-in” of the gravitational lensing will allow for detecting both AGN and non-AGN (high-mass XB) emissions with minimal cross-contamination, important for determining intrinsic spectral shapes (including absorptions) and connections to the extreme star formation. These observations in the 0.5-8 keV range will be sensitive to the rest-frame $2 - 36$ keV emission and hence to very highly obscured AGNs.
AGN will be detected down to the luminosities below the non-AGN emission of individual SMGs.

The measurement of the non-AGN Lx/SFR ratio will help to find AGN in other SMGs.

The radio, compared with the locally-calibrated value (Mineo et al. 2014), will provide an important constraint on the formation and mass distribution of stellar BHs in the SMGs.

If we are lucky, we may detect individual XBPs in these galaxies.
Extreme magnification of an individual star at redshift 1.5 by a galaxy-cluster lens

Cluster gravitational lenses can magnify background galaxies by a total factor of up to ~50. Here we report a bright individual star at redshift \( z = 1.49 \) (dubbed MACS J1149 Lensed Star 1) magnified by more than \( \times 2,000 \). A separate source, \( \alpha = 0.26^\circ \) from Lensed Star 1, is probably a counterimage of the first star demagnified for multiple years by \( \geq 3 \) solar masses in the cluster. For reasonable assumptions about the lensing system, microlensing fluctuation...
Special cases of gravitational lensing where the multiple images produced by foreground lens are too close (due to the limitation small $\theta_E$) to be separated and resolved of instrumentation.

Unlike with strong lensing, no single observation can establish that microlensing is occurring. Instead, the changing source brightness and/or position must be monitored over time.

- **Source**: where the light comes from
- **Lens**: which deflects the light by an amount related to its quantity of mass/energy
- **Images**: what the observer sees
Microlensing: photometric effect

Widely used in searching for MACHO and exoplanets.

Symmetric light curve for a point source,

\[ A = A_+ + A_- = \frac{u^2 + 2}{u(u^2 + 4)^{0.5}} \]

Event timescale depends on lens-source relative motion (\( v_{\text{rel}} \)):

\[ t_E = \frac{D_L \theta_E}{v_{\text{rel}}} \approx 2 \text{yr} \cdot \left( \frac{M}{M_\odot} \right)^{1/2} \cdot \left( \frac{D_L}{800 \text{kpc}} \right)^{1/2} \cdot \left( \frac{v_\perp}{200 \text{km/s}} \right)^{-1} \]
Approach 2: detecting microlensed AGN

Basic Properties of the flux variability:

- The larger the AGN corona, the lower the variability amplitude.
- The more distant the lens, the longer the duration.
- Microlensing by a distant lensing galaxy is optically thick.
- Stars collectively form so-called caustics, the crossing of which leads to flux variation.
- Statistical analysis of flux variation among multiple images of strongly lensed AGN has been used to constrain the corona size. 

e.g., Mosquera+(2013)
Near-field Microlensing of AGN

Objective: Better constrain the size and geometry of AGN coronae by detecting individual microlensing events.

Approach:
- Have the lensing star nearby enough so that its mass and distance can be measured;
- Short event duration (~ day-year) allowing for good sampling of both flux and position variations.

With these measurements, we can then directly measure the corona structure of the lensed AGN.
near-field microlensing experiment of AGN

Find a candidate pair, which will become near alignment in ~ 7 yrs, when dense monitoring of AGN and star can be easily scheduled. In the mean time, their relative astrometry and proper motion still will be better measured.

Gaia DR2 (~10^9 stars) is scheduled for this month!

Cross-matching The Half Million Quasars catalog (Flesch 2015) with Gaia DR1 (~2 million stars with proper motion information; Lindegren et al. 2016)
Centroid shift: \[ \delta \theta = \frac{A_+ \theta_+ + A_- \theta_-}{A_+ + A_-} = \frac{u}{u^2 + 2 \theta_E} \]

Assuming the astrometric centroid precision of an instrument \( \Delta \).

We assume that if \( \Delta > \delta \theta_{\text{max}} \) (~0.35\( \theta_E \)), the cross section of astrometric microlensing is \( \sigma_A = 0 \), else, \( \sigma_A = \sigma_p \left( \frac{\theta_E}{\Delta} \right)^2 \sqrt{1 - 8 \left( \frac{\Delta}{\theta_E} \right)^2} \).

For local stellar objects, when \( \Delta < 100 \mu \text{as} \), this factor is often >> 1.

The effective cross section \( \sigma^* \gg \sigma_p \sim \pi \theta_{E}^{-2} \).
Approach 3: Stellar Mass BHs in the Galactic center

Within the central 1 pc: both models and observations suggest the existence of a number of ($\sim 10^4 - 10^5$) such BHs, e.g., inward radial mass segregation (Morris 1993; Freitag et al. 2006; Genzel et al. 2003 hundreds of O/B stars; Muno et al. 2005 excess XRBs).

To date, no DIRECT detection of stellar mass BHs in the Galactic center.

The commissioning VLT near-IR interferometer GRAVITY (Gillessen et al. 2010) will provide the position measurement to be better than ~10 microarcsec.
Stellar Mass BHs in the Galactic center

Gravimetric microlensing events:

optical depth \[ \tau = \int_0^{D_S} n(D_L) \cdot \sigma(D_L) dD_L = \frac{4G\pi}{c^2} \int_0^{D_S} \rho(D_L) \left( D_L - \frac{D_L^2}{D_S} \right) (u_2^2 - u_1^2) dD_L \]

event rate \[ \Gamma = \frac{8Gv_{rel}}{c^2} \frac{1}{\Delta} \int_0^{D_S} \rho(D_L) (1 - \frac{D_L}{D_S}) dD_L \]

Stellar mass distribution along the line of sight

Adopting the Muno et al. (2006) stellar mass distribution for stars.

Assuming \( 5 \times 10^4 \) stellar mass BHs (10 Msun) uniformly distribute within central 1 pc
Optical depth of astrometric microlensing

$\Delta$: the astrometric centroid precision of an instrument
Expected detection rate of the astrometric microlensing events in the Galactic center

The Galactic center is going to be monitored by GRAVITY;
The data can be used to find stars behind the Galactic center;
Each will have an astrometric microlensing event rate of $\sim 10^{-3} - 10^{-2} \text{ yr}^{-1}$;
With 100 - 1000 stars with high astrometric accuracy ($< 10 \mu\text{as}$), one expects to find a few events by nuclear BHs alone each year.
Summary

We have been investigating the possibility to probe black hole astrophysics via gravitational lensing. The following approaches appear feasible:

1. Test formation theories of stellar and supermassive BHs from detecting faint AGN and non-AGN X-ray emissions from strongly lensed high-z galaxies.
2. Measure the structure of AGN accretion coronae via the light-curves of microlensing events caused by individual foreground stars.
3. Constrain the stellar-mass BH population in our Galactic center by observing astrometric microlensing of background stars.
Astrometric microlensing event rates for sources
Results:

We may map larger sky area with relatively low sensitivity, e.g. all sky survey, to find such microlensing events.

eROSITA will potentially be powerful enough to study the background AGN via microlensing because of its all-sky coverage ( ~ 20 times deeper than previous ROSAT all-sky survey, offers us high quality maps of large areas, e.g. the entire Milky Way bulge).

Dense monitoring is required to have a better sampling of light curves, which should be possible for selected regions (e.g. the bulge) with eROSITA after its all-sky survey phase.
Centroid shift: $\delta \theta = \frac{A_+ \theta_+ + A_- \theta_-}{A_+ + A_-} = \frac{u}{u^2 + 2 \theta_E}$

Assuming the astrometric centroid precision of an instrument $\Delta$, we assume that if $\Delta > \delta \theta_{\text{max}}$, cross section of astrometric microlensing is $\sigma_A = 0$,

else, $\sigma_A = \sigma_p \left( \frac{\theta_E}{\Delta} \right)^2 \sqrt{1 - 8 \left( \frac{\Delta}{\theta_E} \right)^2}$

For local stellar objects, when $\Delta < 100 \mu\text{as}$, this factor is often >> 1.
AGN MICROLENSED BY LOCAL GALAXIES

Method: We derive and estimate the detectable event rate of background sources with flux > $S$.

The average event rate per (1 deg)$^2$ is estimated as:

$$10^{-6} \text{yr}^{-1} \left( \frac{M_L}{10^{10} M_\odot} \right) \left( \frac{t_E}{2 \text{yr}} \right)^{-1} \left( \frac{I}{80} \right)$$

where $M_L$ is the mass of lens objects.

In principal, the event rate can be very high if we can mapping a large sky area (i.e. large $M_L$) with high sensitivity (i.e. large $N(>S)$). In reality, however, it is limited by instrumental capabilities (e.g. mapping speed, effective area etc.).

We estimate $N(>S)$ of Moretti et al. (2003), as derived from six different data performed by ROSAT, Chandra and XMM-Newton.
**AGN MICROLENSED BY LOCAL GALAXIES**

**Results:**

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<tr>
<th></th>
<th>Current</th>
<th>Future</th>
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<tbody>
<tr>
<td></td>
<td>$\Gamma$ (LogS = -15)</td>
<td>$\Gamma$ (LogS = -16)</td>
</tr>
<tr>
<td>M31 Bulge</td>
<td>$0.02 \text{ yr}^{-1}$</td>
<td>$0.07 \text{ yr}^{-1}$</td>
</tr>
<tr>
<td>MW Nuclear Cluster (&lt;15pc)</td>
<td>$0.05 \text{ yr}^{-1}$</td>
<td>$0.17 \text{ yr}^{-1}$</td>
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<tr>
<td>MW Nuclear Disk (&lt;150pc)</td>
<td>$0.8 \text{ yr}^{-1}$</td>
<td>$2.9 \text{ yr}^{-1}$</td>
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<tr>
<td>MW bulge</td>
<td>$6.0 \text{ yr}^{-1}$</td>
<td>$21.0 \text{ yr}^{-1}$</td>
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**XMM-Newton, Chandra FOV: $\sim (30')^2$**

With existing data, the estimated observable microlensing event rate for the M31 bulge and nuclear region of the Milky Way is too low for this study.

The next generation of X-ray telescopes, e.g., Athena and Lynx, will have higher sensitivity, higher resolution, and/or larger FOV.
Fig. 1. A gravitational microlensing magnification map generated by the parallel ray-tracing code. We have assumed a random star field with mean lens mass $\langle M_\bullet \rangle = 0.3 M_\odot$, surface mass densities $\kappa_c = 0.4$, $\kappa_\gamma = 0.2$, and external shear $\gamma = (0.2, 0)$. The image is of high resolution $6400 \times 6400$ and size about $12 \theta_E \times 12 \theta_E$ where $\theta_E$ is the Einstein ring angle of a lens of mass $\langle M_\bullet \rangle$. The host computer node, Xeon Phi 7216A, was used to generate the map.
Near-field Microlensing of AGN

Objective: Constraining the size and geometry of accretion disk coronae by obtaining the X-ray lightcurves of microlensed AGN.

Appropriate event duration (~ day-year) for lightcurve sampling --> the lenses need to be local.

Near alignment between an AGN and a star can make the emitting structure resolved in such a lightcurve.

Cross-matching *The Half Million Quasars* catalog (Flesch 2015) with Gaia DR1 (Lindgren et al. 2016)

Finding of a candidate pair, which will become near alignment in ~ 7 yrs, although their relative astrometry and proper motion still need to be better measured.

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