Probing Black Hole Astrophysics through Gravitational Lensing

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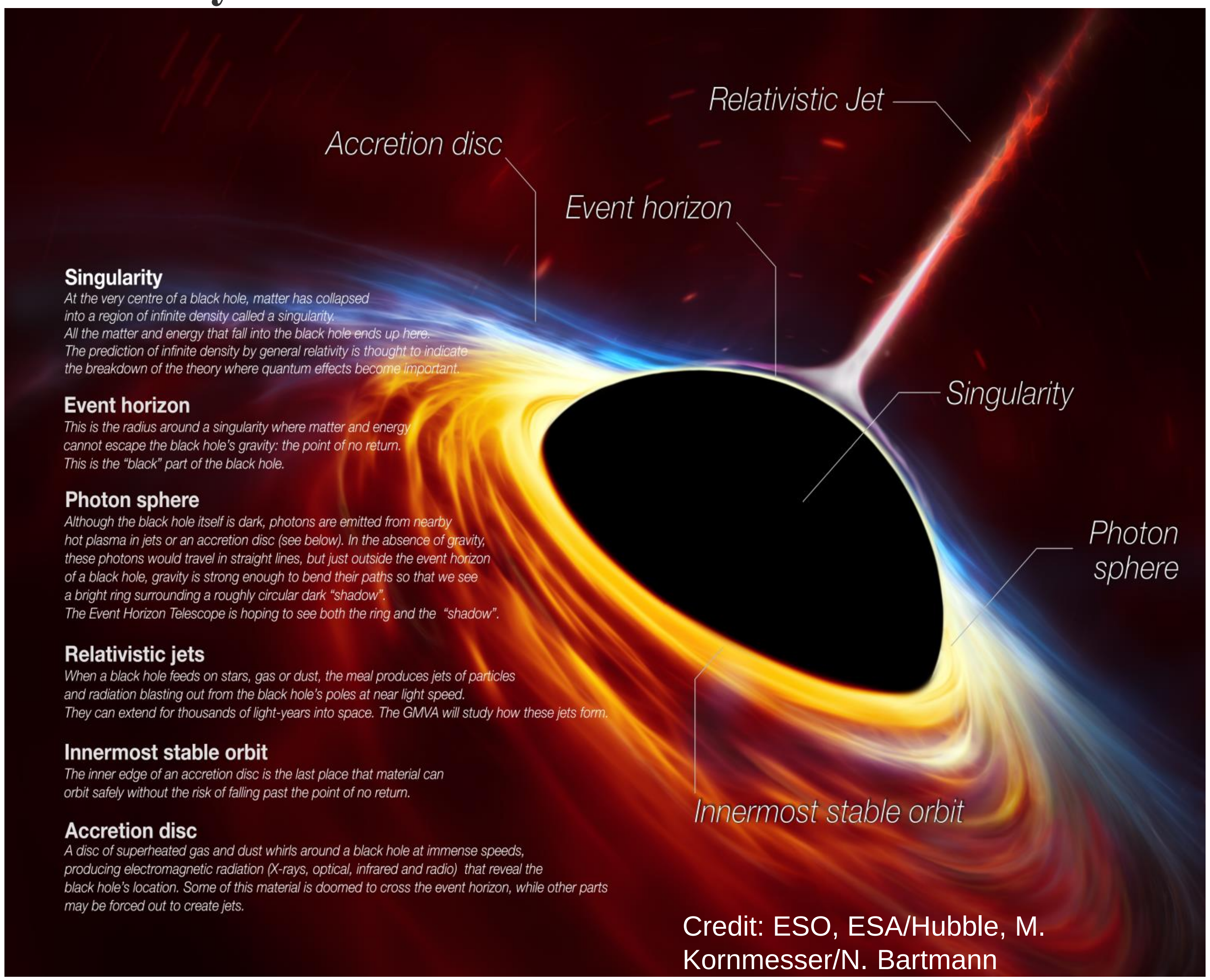
Black holes (BHs) are simple, energetic, and yet mysterious!

Anatomy of a black hole



- **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.**

Mystery of supermassive BHs

Origin:

Luminous quasars or AGNs at high-z

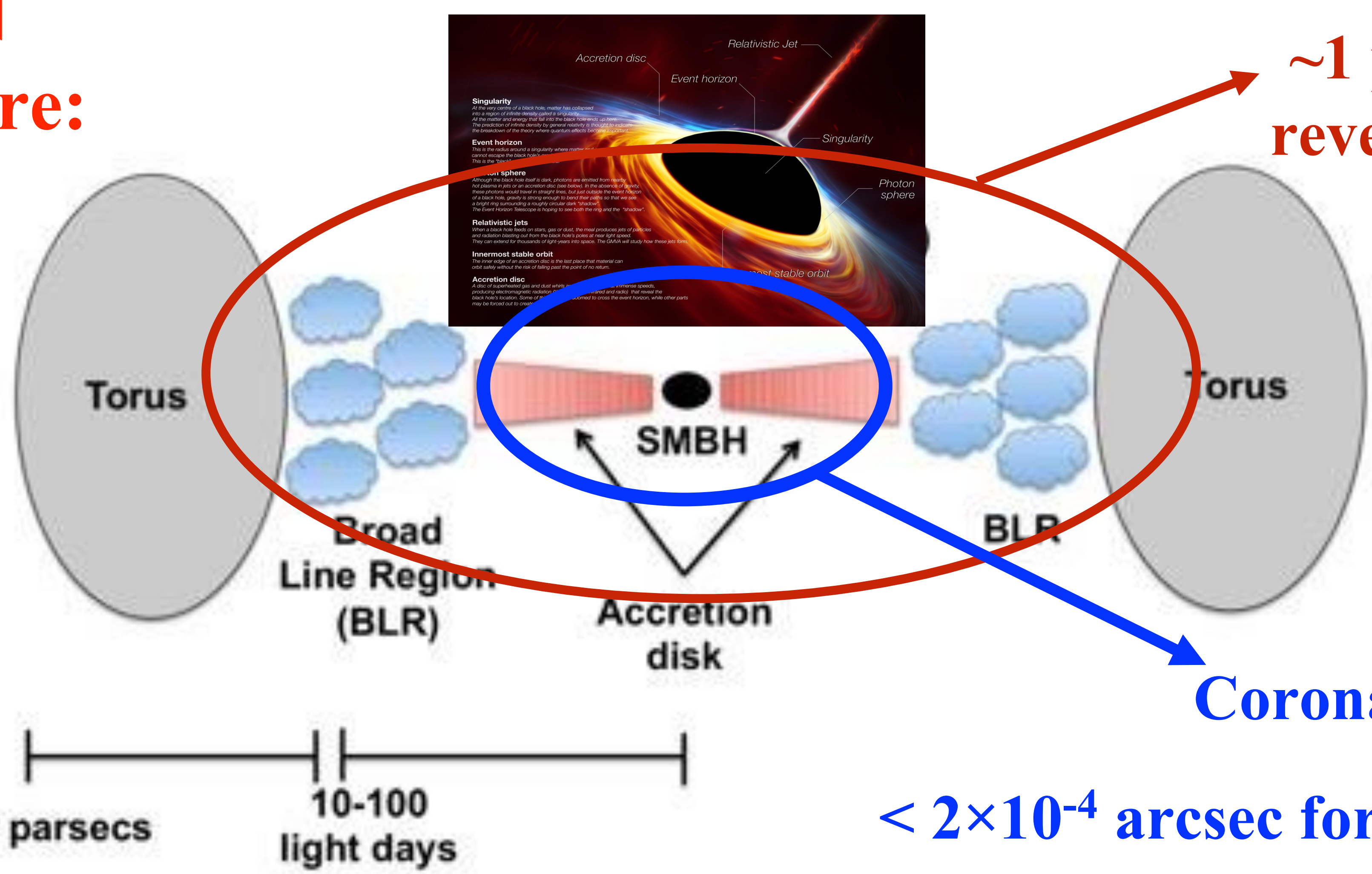
↓

SMBHs already exist in the early universe

↓

What are their seeds? How do they grow?

AGN structure:



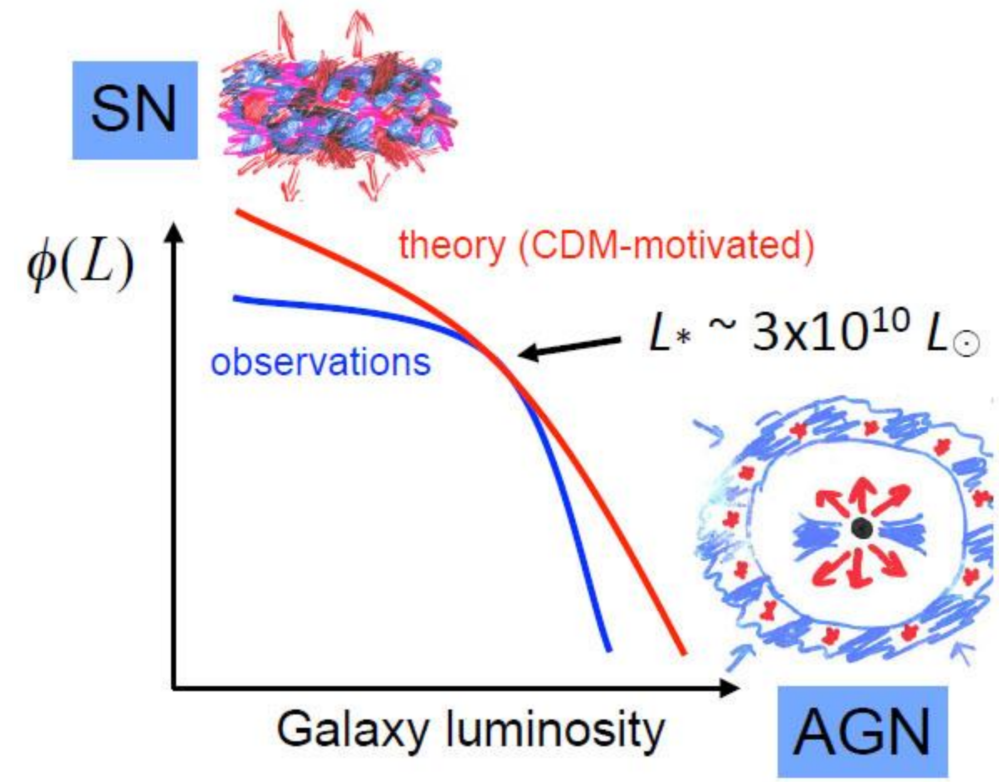
~1 pc, probed via e.g. reverberation mapping

Corona < 0.01 pc

< 2×10^{-4} arcsec for an AGN at ~ 10 Mpc

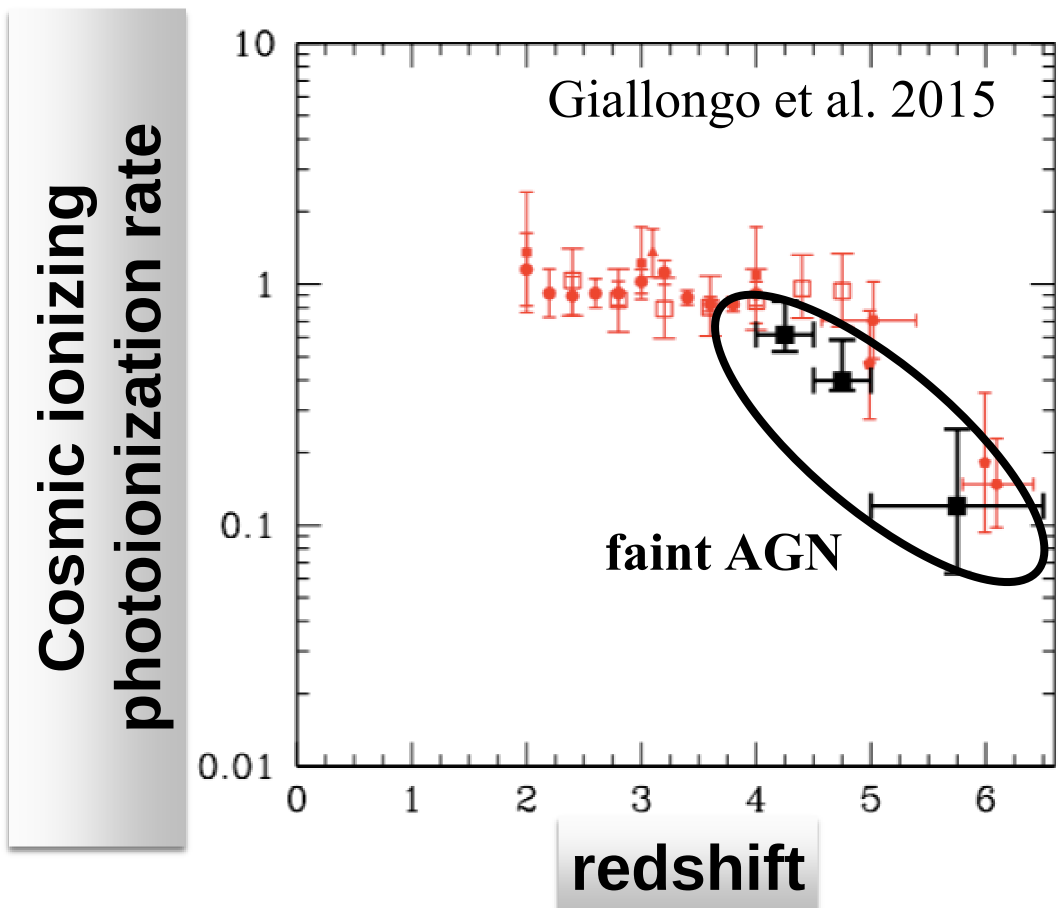
Effects on the cosmic structure formation

Galaxy formation/evolution (e.g. AGN feedback)

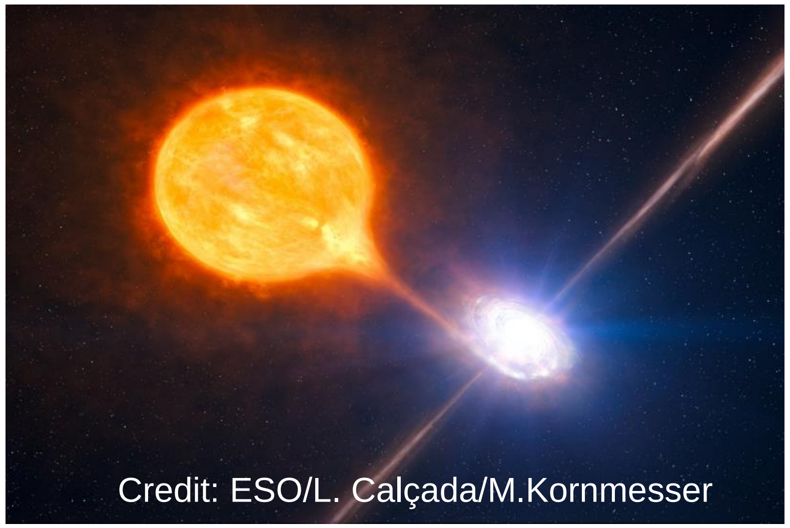


Credit: Joseph Silk

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



Mystery of stellar-mass BHs

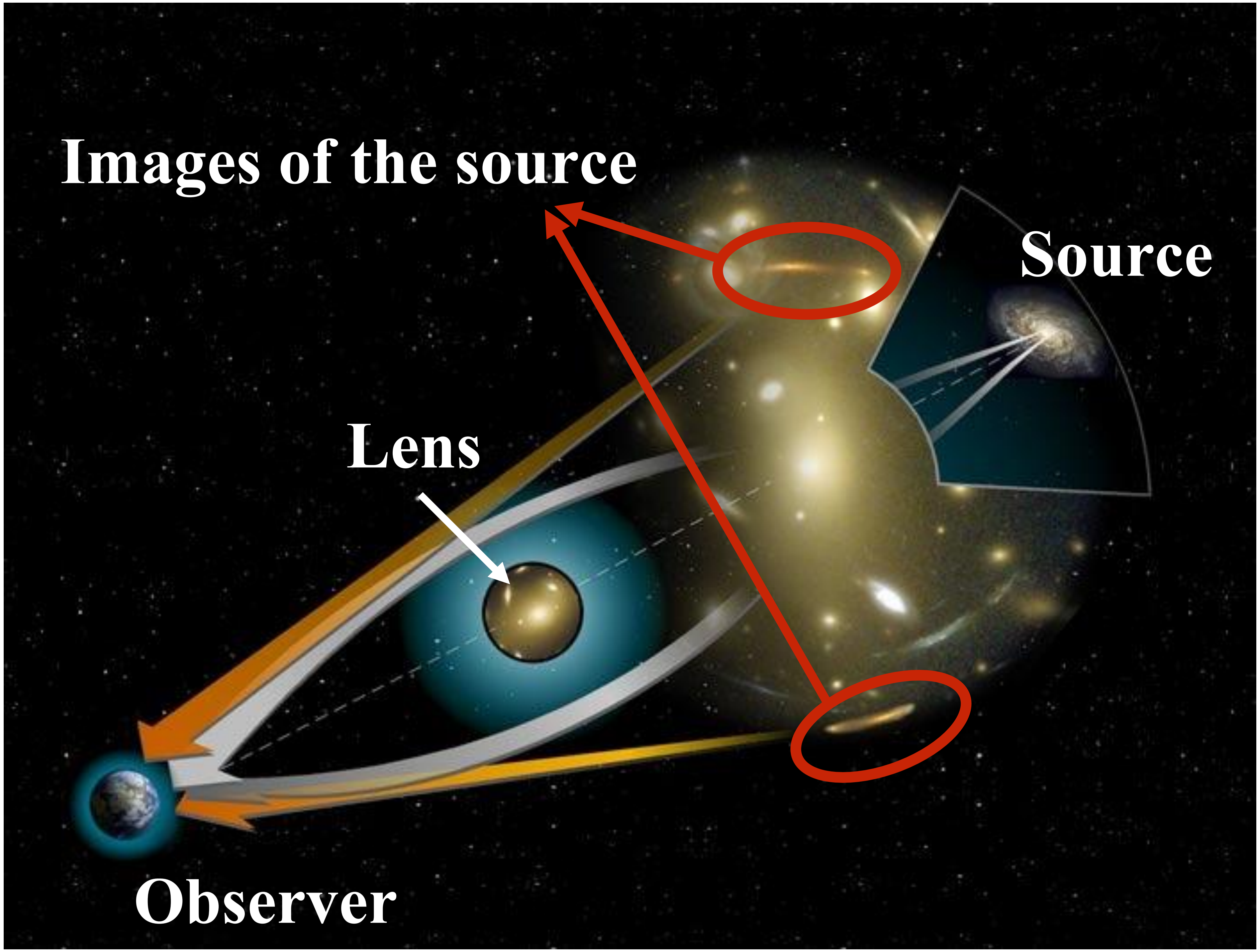


Stellar mass BHs were only known in accreting XBs, until the detection of the gravitation waves from merging BH binaries.

Name	$M_1/M_\odot$	$M_2/M_\odot$	TYPE
GW150914	35.4	29.8	BHB
GW151226	14.2	7.5	BHB
GW170104	31.2	19.4	BHB
GW170608	12.0	7.0	BHB
GW170814	30.5	25.3	BHB
GW170817	1.5	1.2	NSB

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

Why gravitational lensing?



Lensing always conserves surface brightness
→ both amplification and magnification

Why Gravitational Lensing?

It is sensitive to the mass (e.g., Einstein Radius:

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

For a point lens and source, the lensing equation is

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

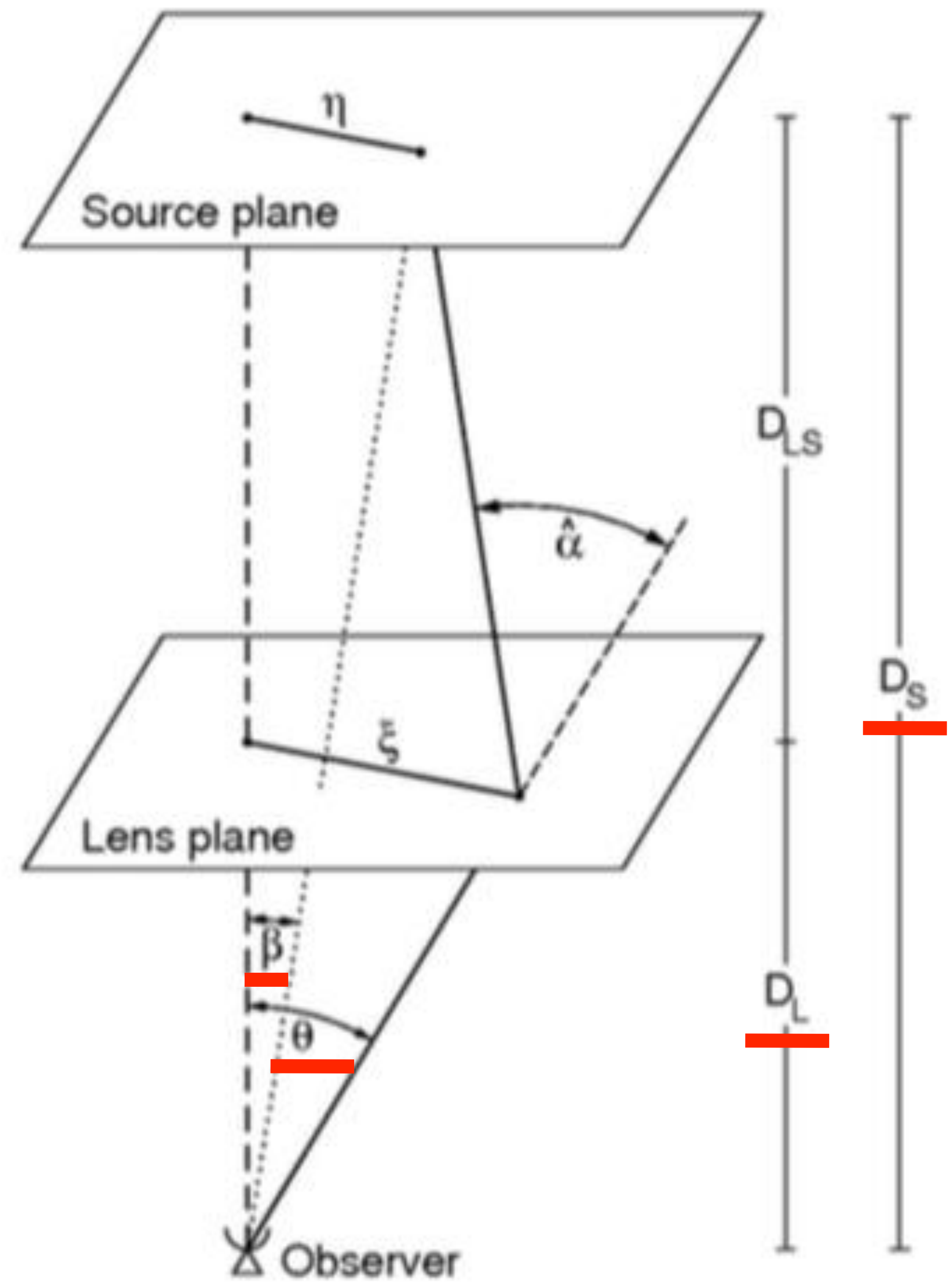
The image of a source in the lens plane is split into two images seen at

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

and with magnifications

$A_\pm = 0.5[(u^2+2)/(u(u^2+4)^{0.5}) \pm 1]$

where $u = \beta/\theta_E$



Lens mass (M), lens distance (D_L), source distance (D_S)

Approach 1: BHs in high redshift (z > 2) galaxies

AGNs: 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).

XRBs: Detection of XBs 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 underlining faint AGN contribution.

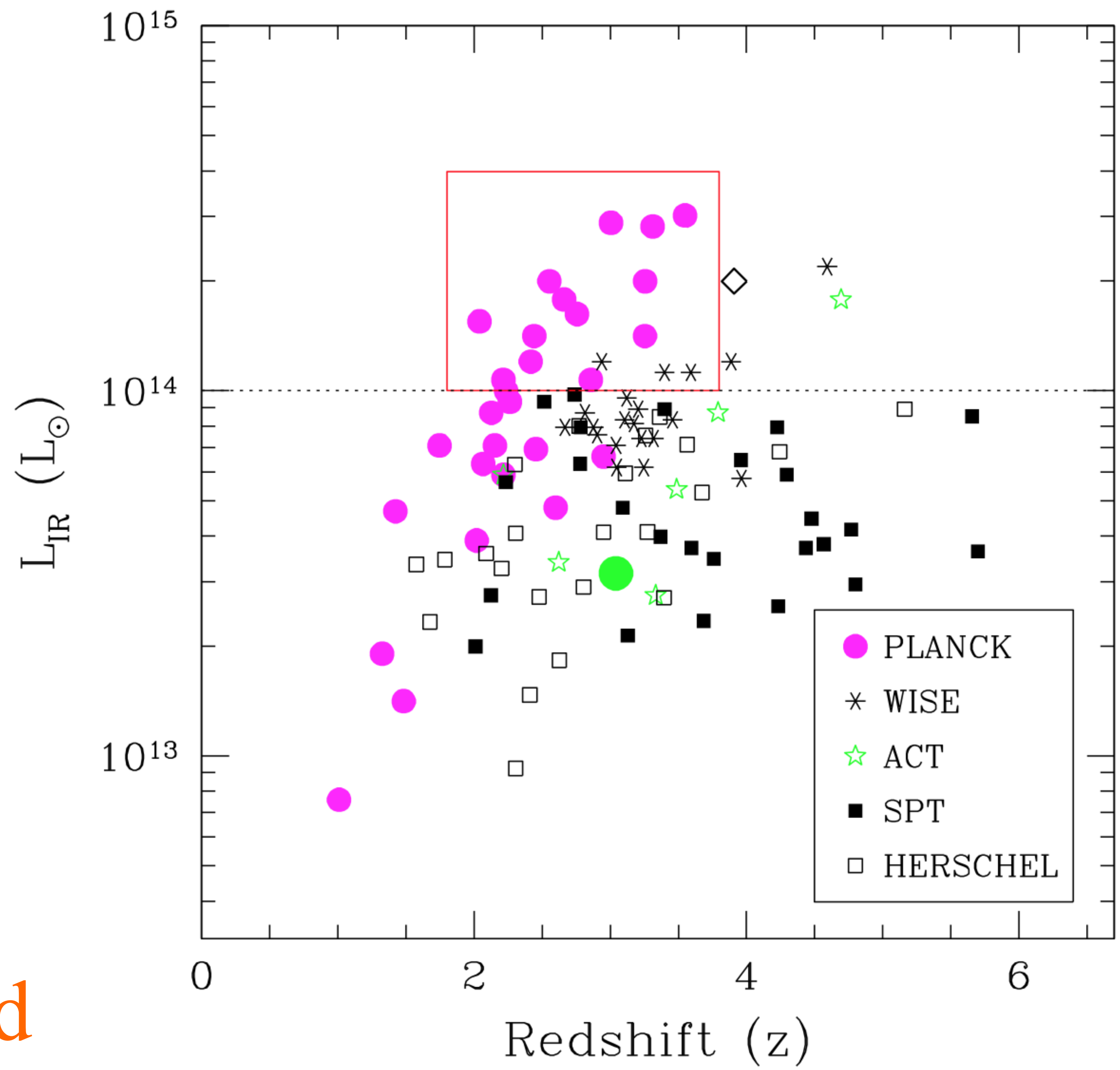
Strongly lensed galaxies

Magnified flux	Amplification → "zoom-in"
↓	↓
Probe fainter individual AGN	Collective emission of XBs

Extreme starburst galaxies

- With apparent IR luminosities range from ~ 0.1 - 3 x 10^{14} $L_\odot$, these galaxies present the upper envelope of the L_{IR}-z distribution.
- The brightest ones indicate SFR ~ 10,000 – 28,000 $M_\odot$ /year, which are too extreme to be physical!

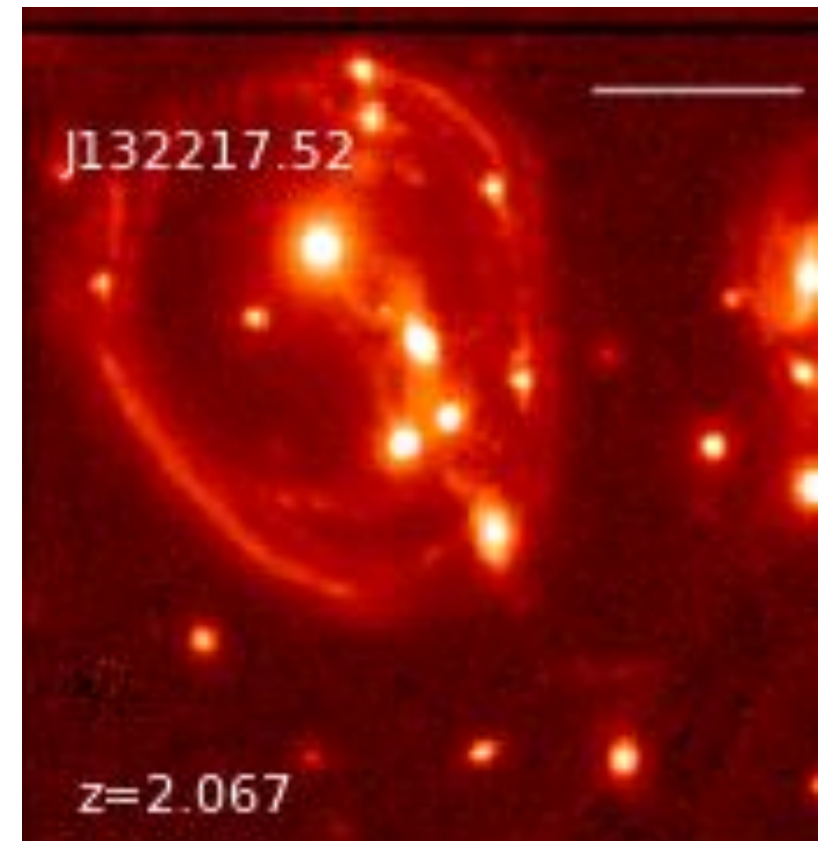
Are they largely magnified via gravitational lensing?

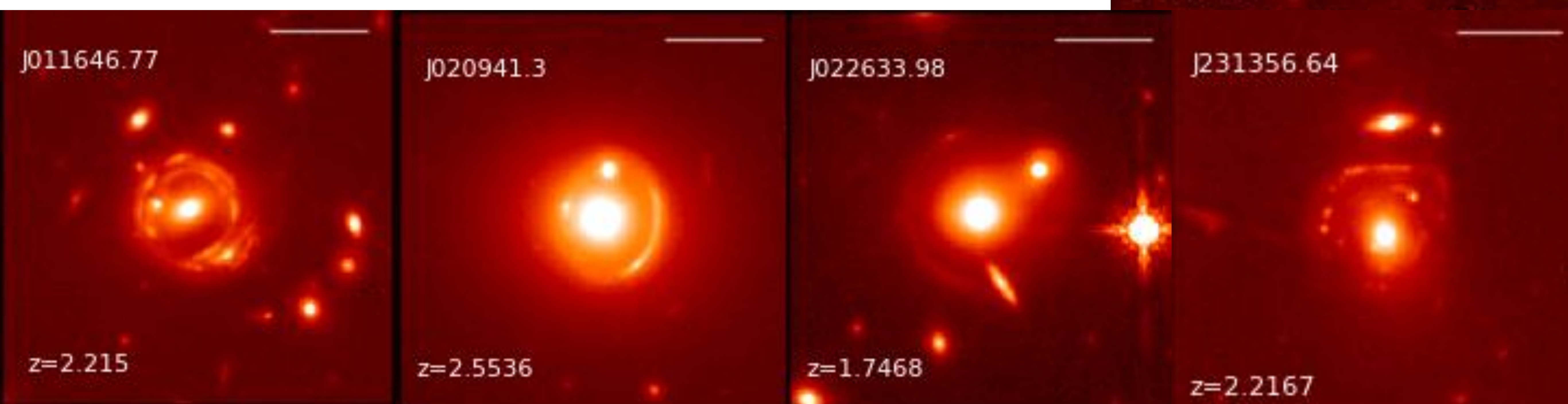


HST confirmation of the strong gravitational lensing

Using WFC3/F160W (1.6 μm) filter

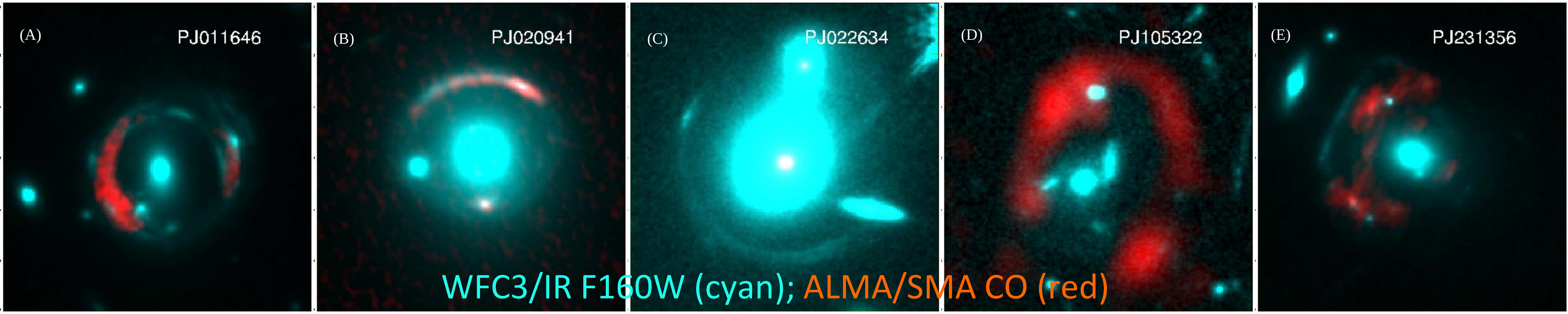
- Most are lensed by single galaxies, showing Einstein "rings"
- Others are by small groups and still more by massive clusters





Chandra observations are needed!

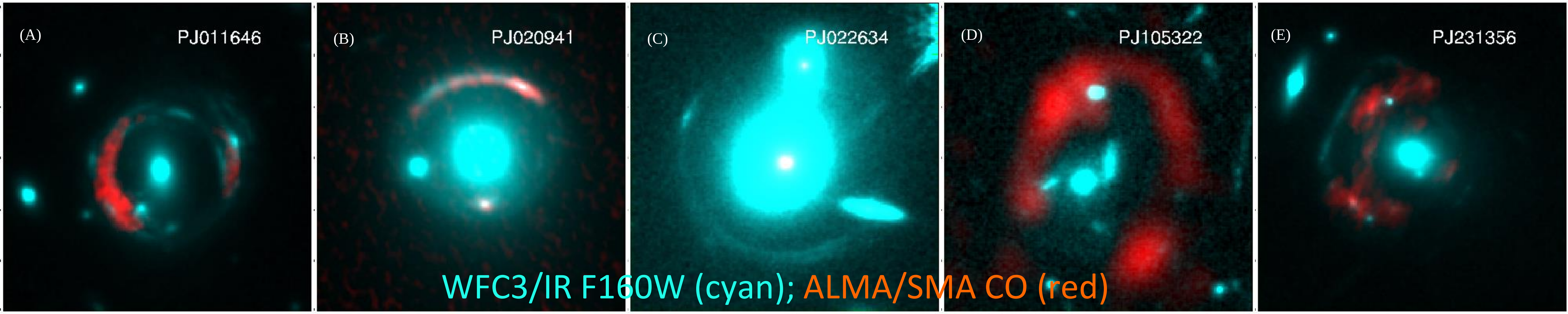
- The "zoom-in" of the gravitational lensing will allow for detecting both AGN and non-AGN (high-mass XB) emissions with minimal cross-contamination, important for determining intrinsic spectral shapes (including absorptions) and connections to the extreme star formation.
- These observations in the 0.5-8 keV range will be sensitive to the rest-frame $2-36$ keV emission and hence to very highly obscured AGNs.



Chandra observations of the extreme SMGs

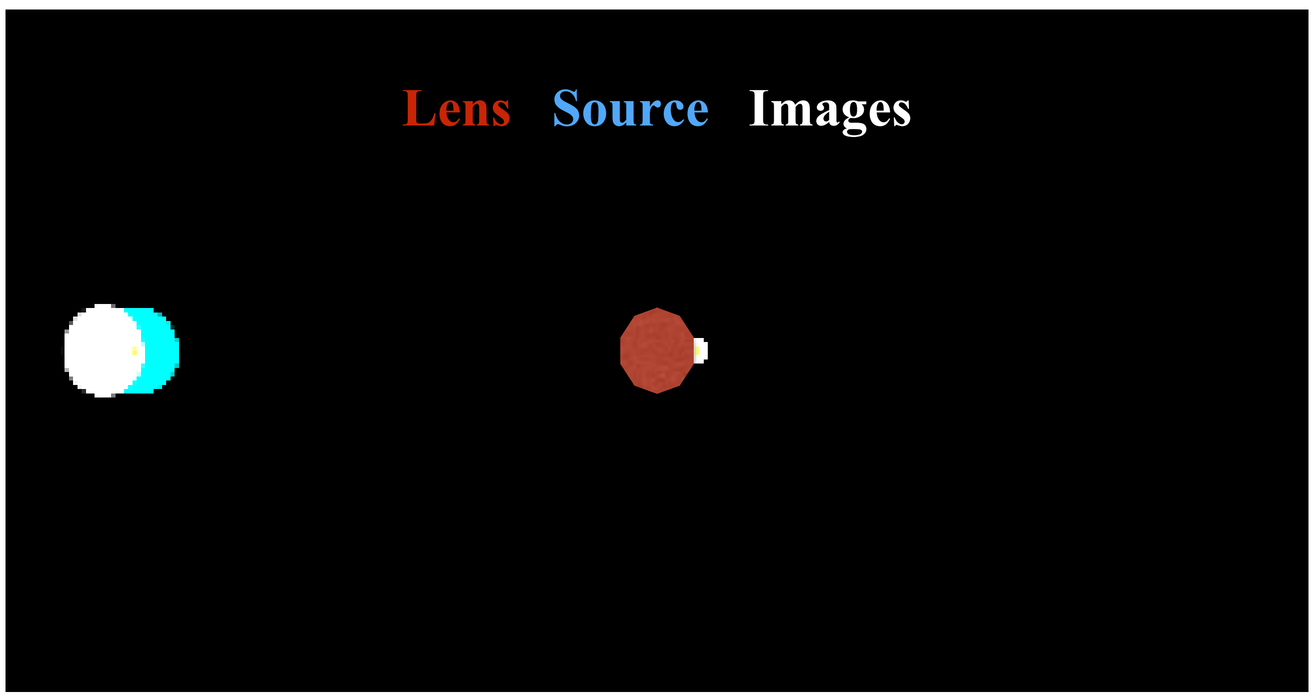
- AGN will be detected down to the luminosities below the non-AGN emission of individual SMGs.
- The measurement of the non-AGN Lx/SFR ratio will help to find AGN in other SMGs.
- The radio, compared with the locally-calibrated value (Mineo et al. 2014), will provide an important constraint on the formation and mass distribution of stellar BHs in the SMGs.

If we are lucky, we may detect individual XBs in these galaxies!



Gravitational Microlensing

Special cases of gravitational lensing where the multiple images produced by foreground lens are too close (due to the limitation small θ_E) to be separated and resolved of instrumentation.



- **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

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.

Microlensing: photometric effect

Widely used in searching for MACHO and exoplanets.

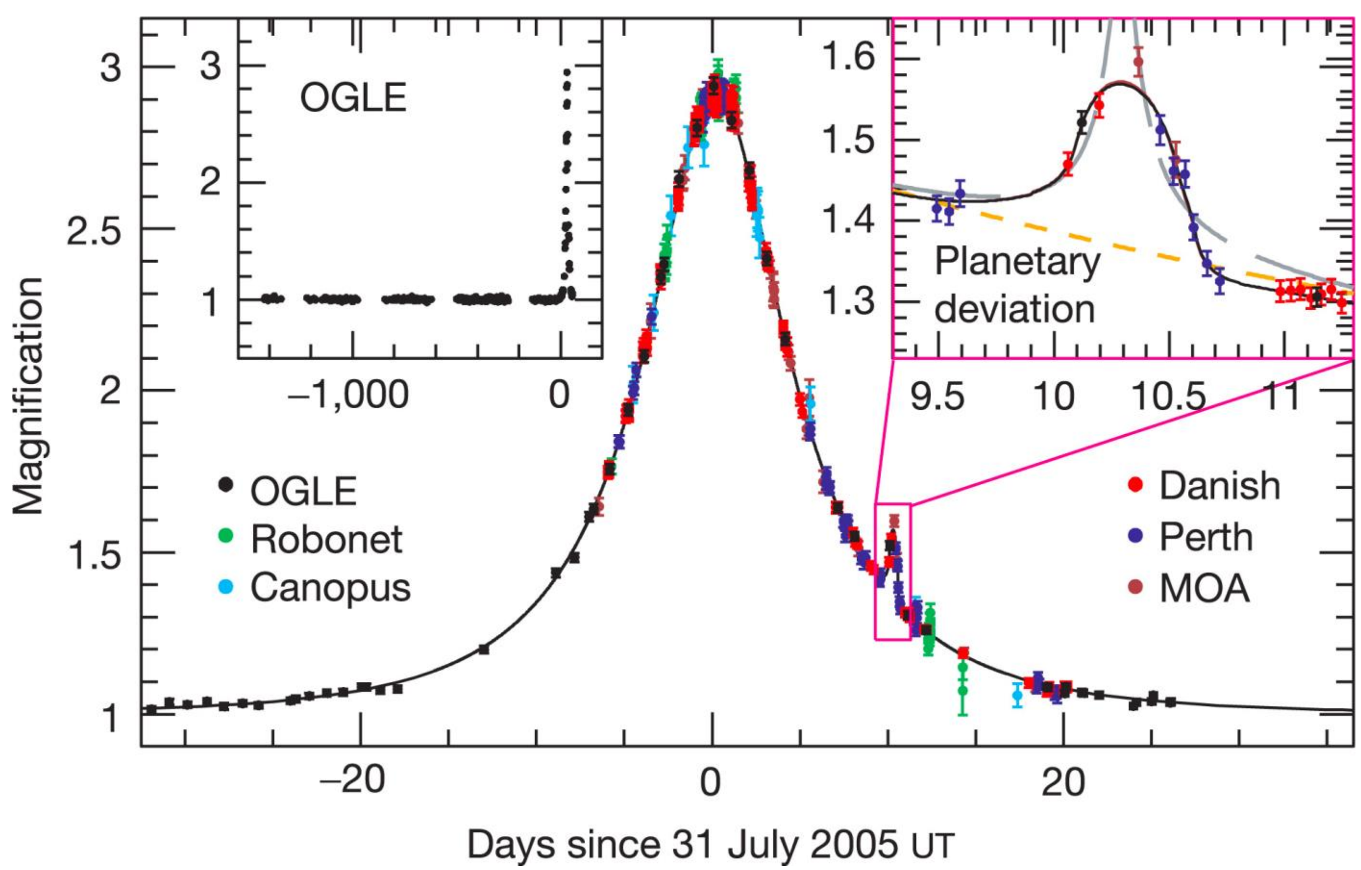
Symmetric light curve for a point source,

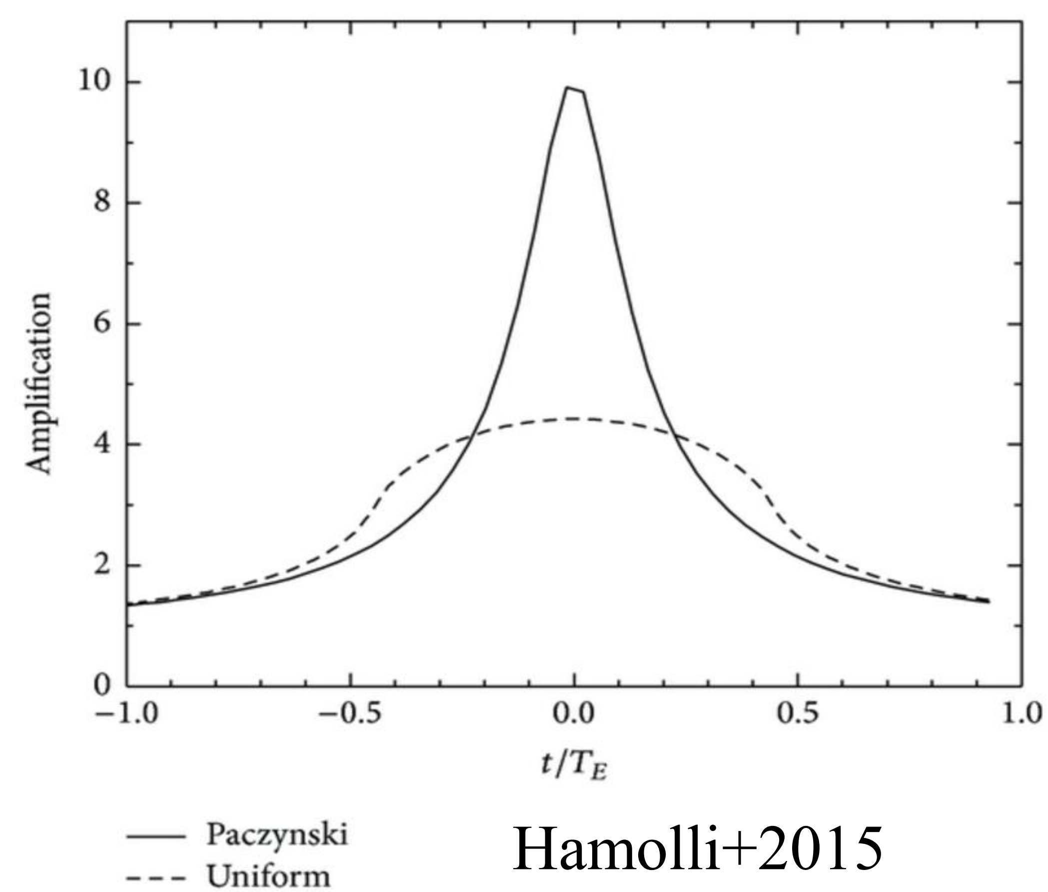
$A = A_{+} + A_{-} = (u^2+2)/[u(u^2+4)^{0.5}]$

$$\theta_E = 10^{-3}\left(\frac{M}{M_\odot}\right)\left(\frac{D_L}{8\mathrm{kpc}}\right)^{-1/2}\left(1-\frac{D_L}{D_S}\right)^{1/2}\mathrm{arcsec}$$

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

$$t_E = D_L\theta_E/v_{rel} \approx 2\mathrm{yr}\cdot\left(\frac{M}{M_\odot}\right)^{1/2}\cdot\left(\frac{D_L}{800\mathrm{kpc}}\right)^{1/2}\cdot\left(\frac{v_\perp}{200\mathrm{km/s}}\right)^{-1}$$



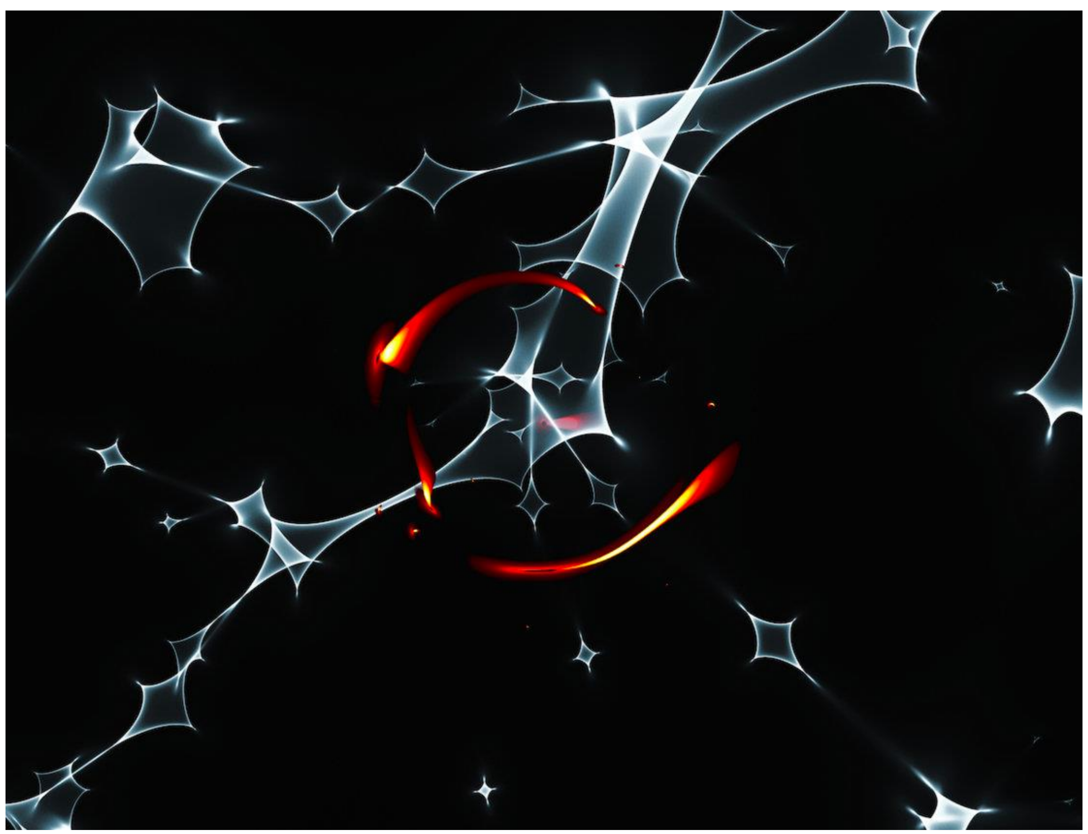


Hamolli+2015

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.



e.g., Mosquera+(2013)

- 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.

Near-field Microlensing of AGN

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

Approach:

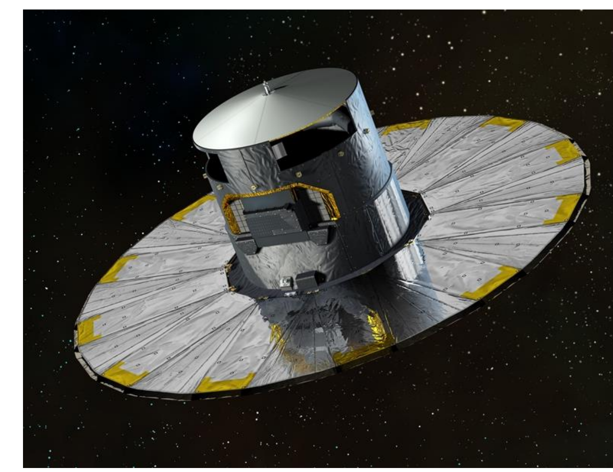
- Have the lensing star nearby enough so that its mass and distance can be measured;
- Short event duration (~ day-year) allowing for good sampling of both flux and position variations.

With these measurements, we can then directly measure the corona structure of the lensed AGN.

The time is right to do a near-field microlensing experiment of AGN

Cross-matching *The Half Million Quasars* catalog (Flesch 2015) with Gaia DR1 (~2 million stars with proper motion information; Lindegren et al. 2016)

↓



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

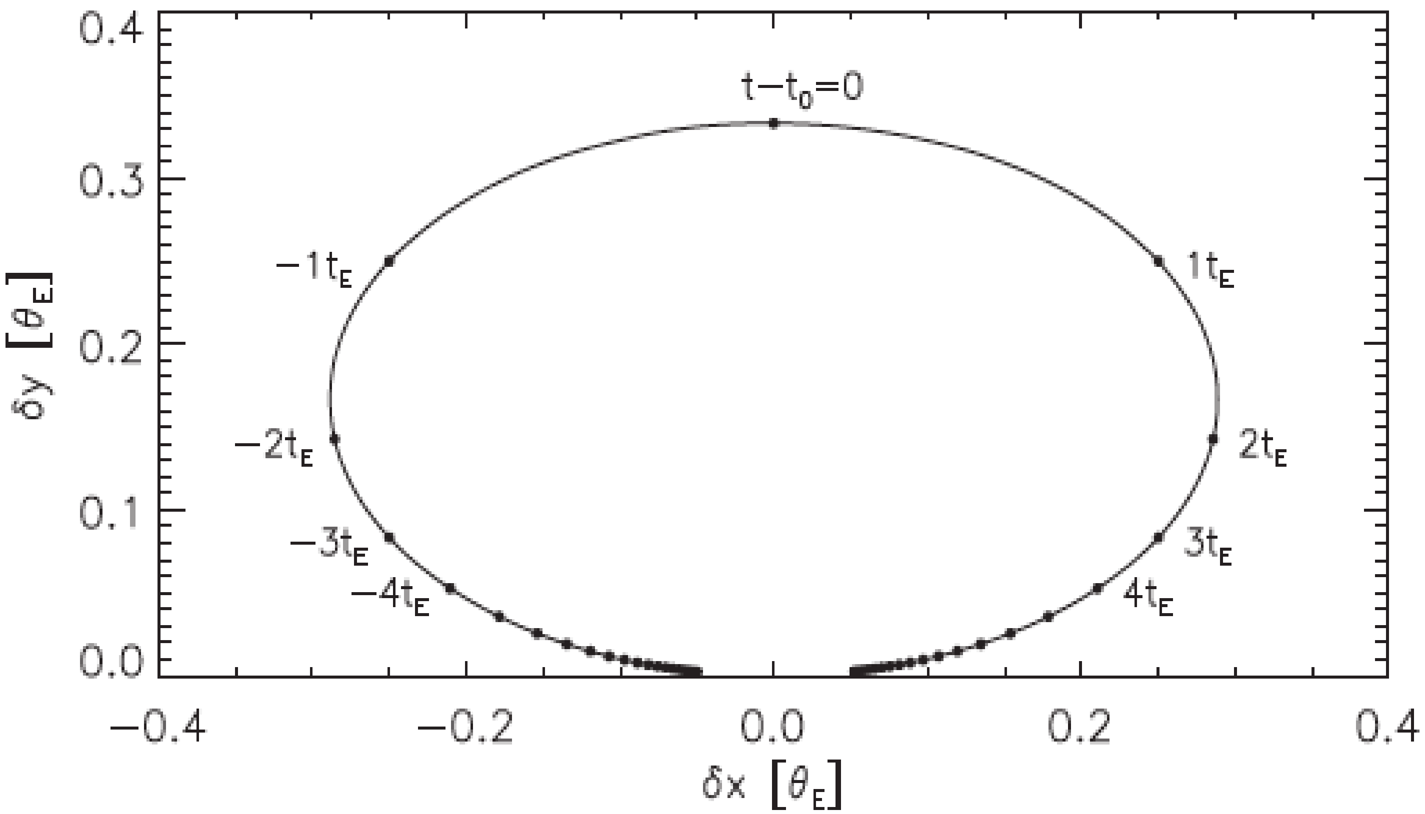
Gaia DR2 (~1.3×10^9 stars) is now available!

↓

Better measurements (~ μas) and more pairs.

Gravitational microlensing: astrometric effect

Centroid shift: $\delta\theta = \frac{A_+\theta_+ + A_-\theta_-}{A_+ + A_-} = \frac{u}{u^2+2}\theta_E$



The ellipse only depends on the minimum u (Kains+2017).

Assuming the astrometric centroid precision of an instrument Δ.

We assume that if $\Delta > \delta\theta_{max}$ ($\sim 0.35\theta_E$), 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 μas, this factor is often >> 1

The effective cross section $\sigma_A \gg \sigma_p \sim \pi\theta_E^2$

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.