Probing Black Hole Astrophysics through Gravitational Lensing

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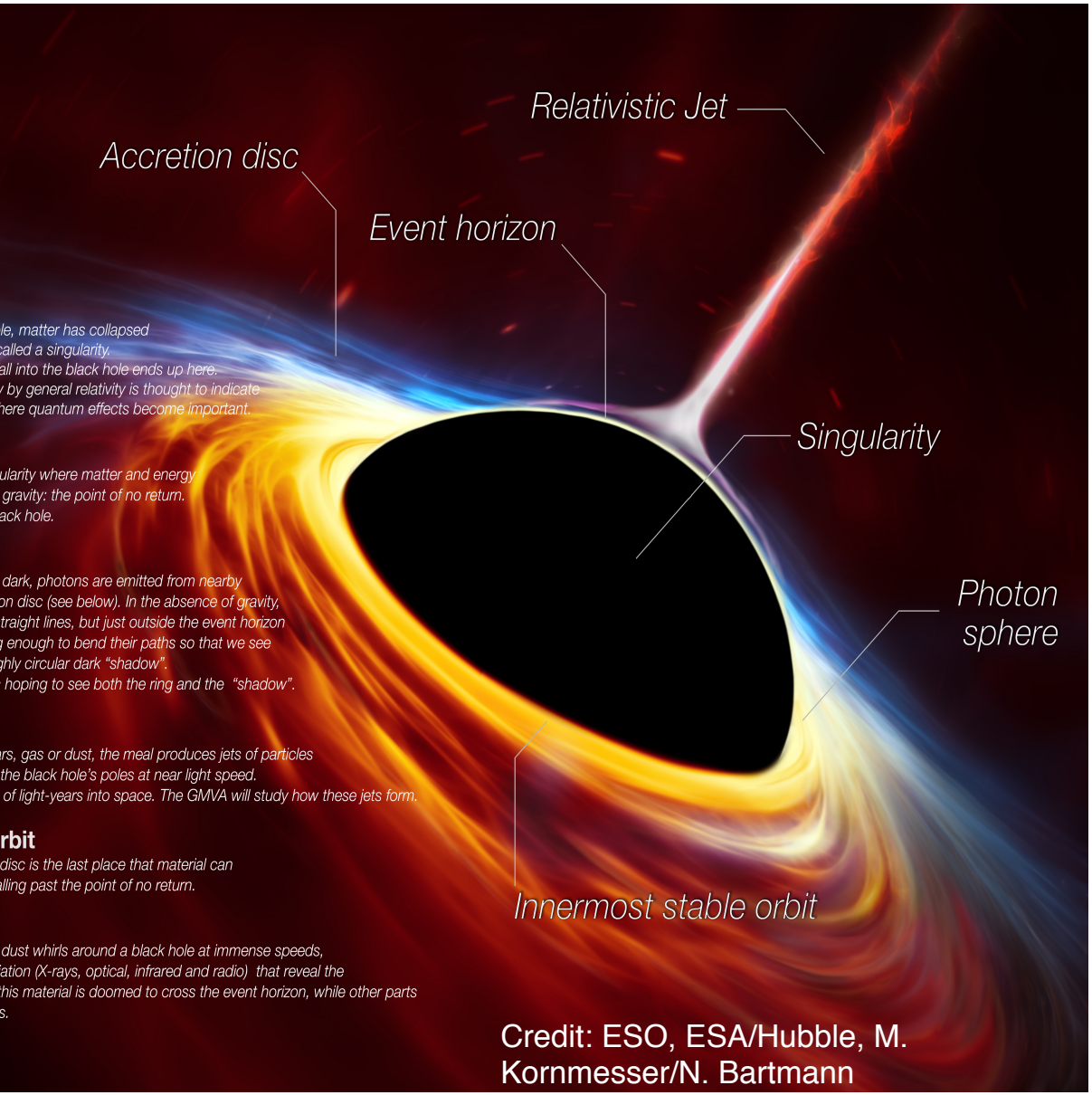
JAMES LOWENTHAL (SMITH COLLEGE)

re simple, energetic, and yet mysteriou

of a black hole



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

- **Supermassive BHs**
  $M_\odot$), seen as active
  galactic nuclei (AG
- **Stellar-mass BHs (**
  $M_\odot$), seen as X-ray
  binaries (XBs)
- **Presence of interme**
  mass BHs (10^2–10^5 M
  has also been specu

gin: Luminous quasars or AGNs at high-z

↓

SMBHs already exist in the early universe

↓

What are their seeds? How do they grow?

N
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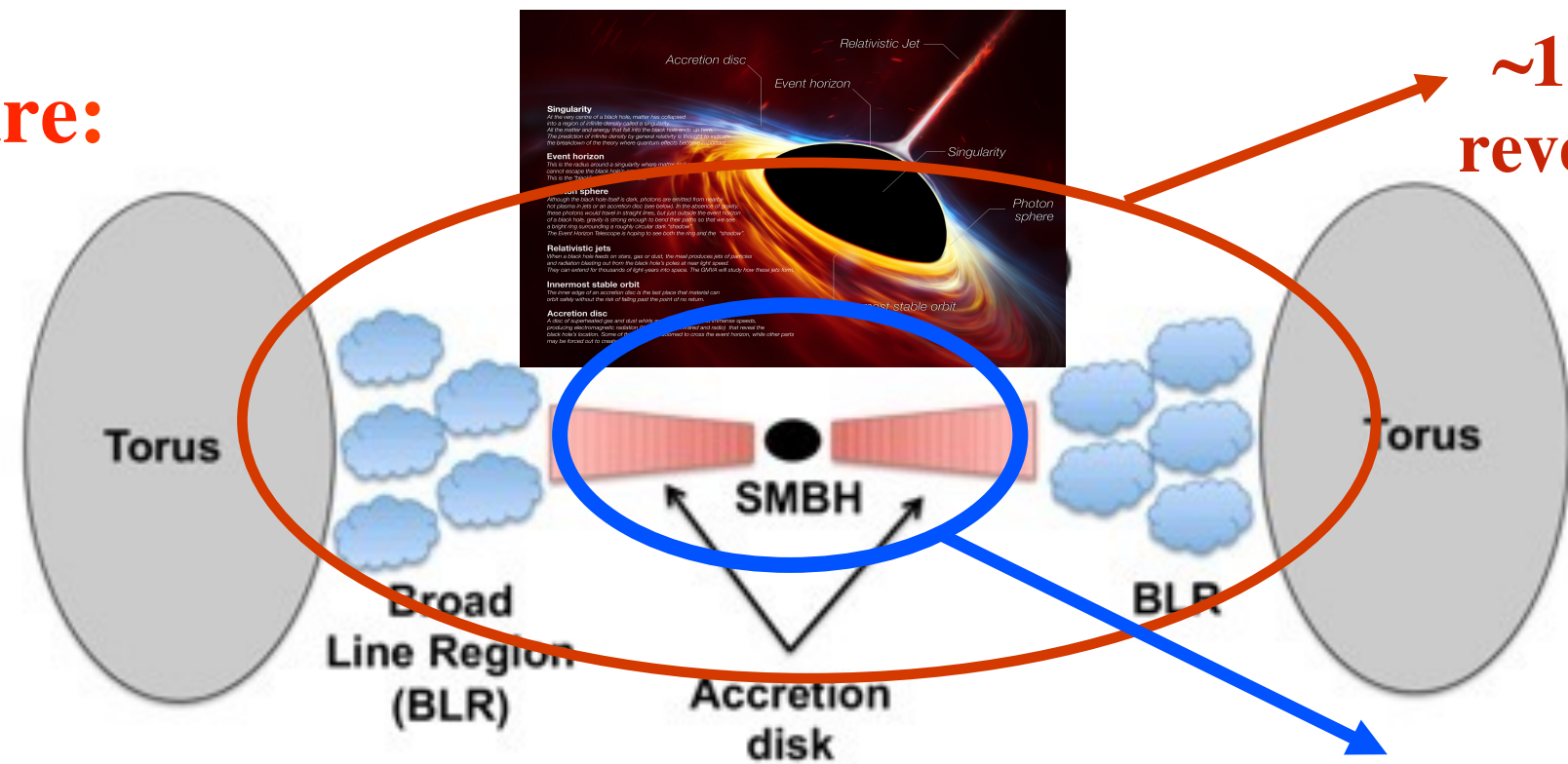
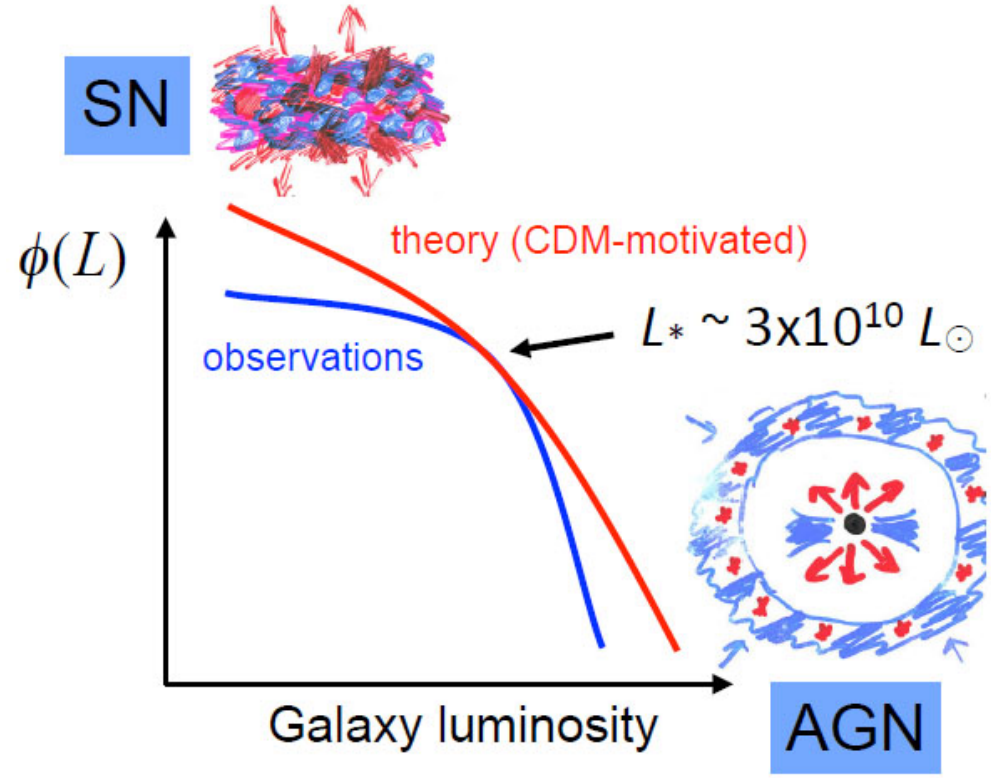


~1 pc, probed via reverberation map

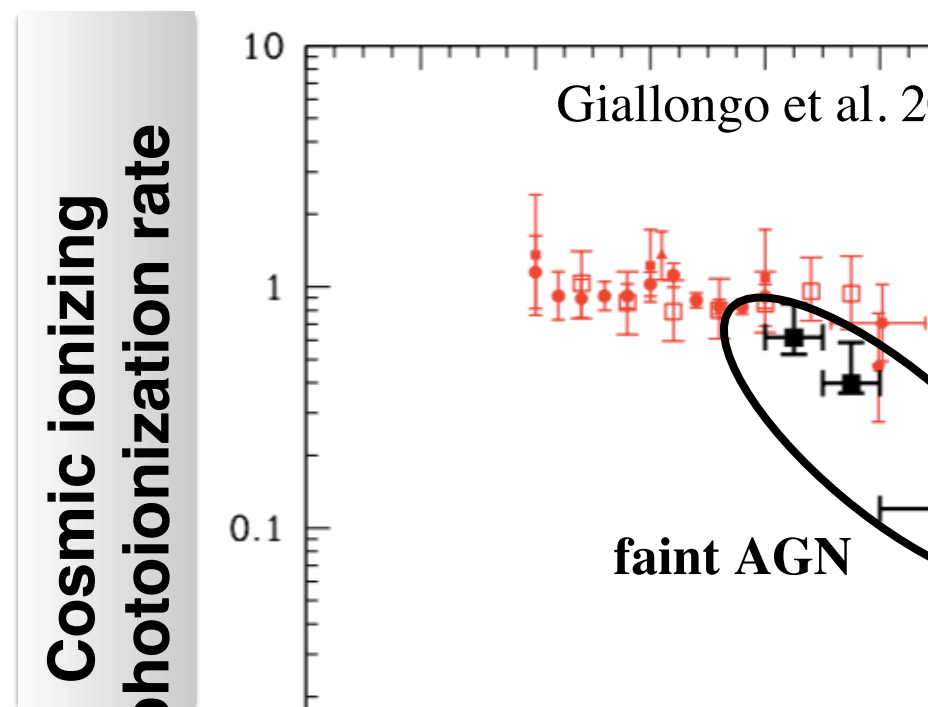
Corona < 0.01 pc

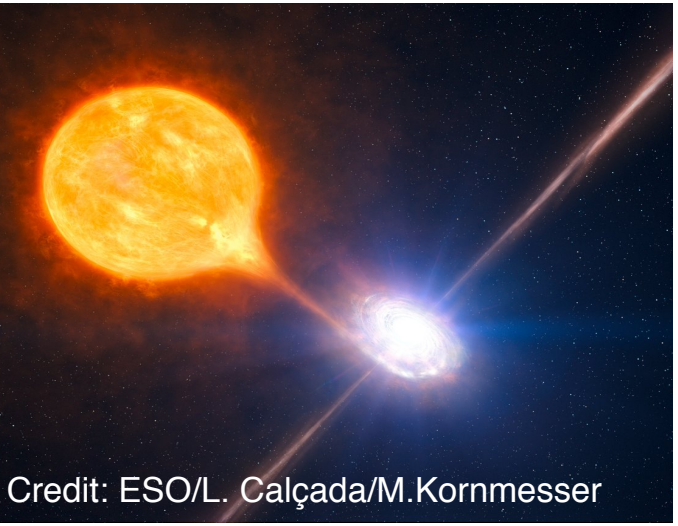
laxy formation/evolution
g. AGN feedback)



Credit: Joseph Silk

-ionization of the Universe:
int) AGN and/or stellar-mass
Is could be important



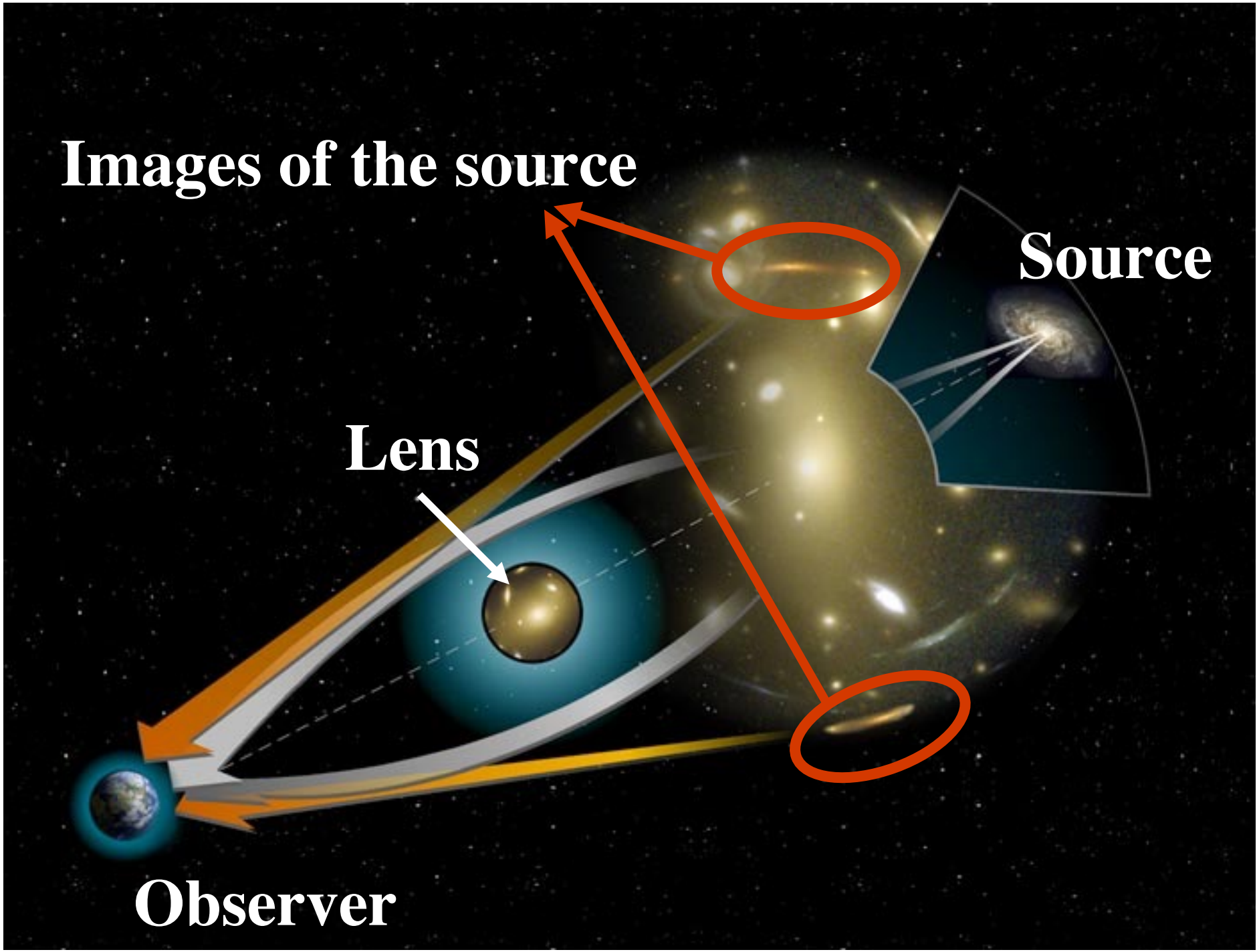


Stellar mass BHs were only known i
accreting XBs, until the detection of
the gravitation waves from merging
BH binaries.

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

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

Why gravitational lensing?

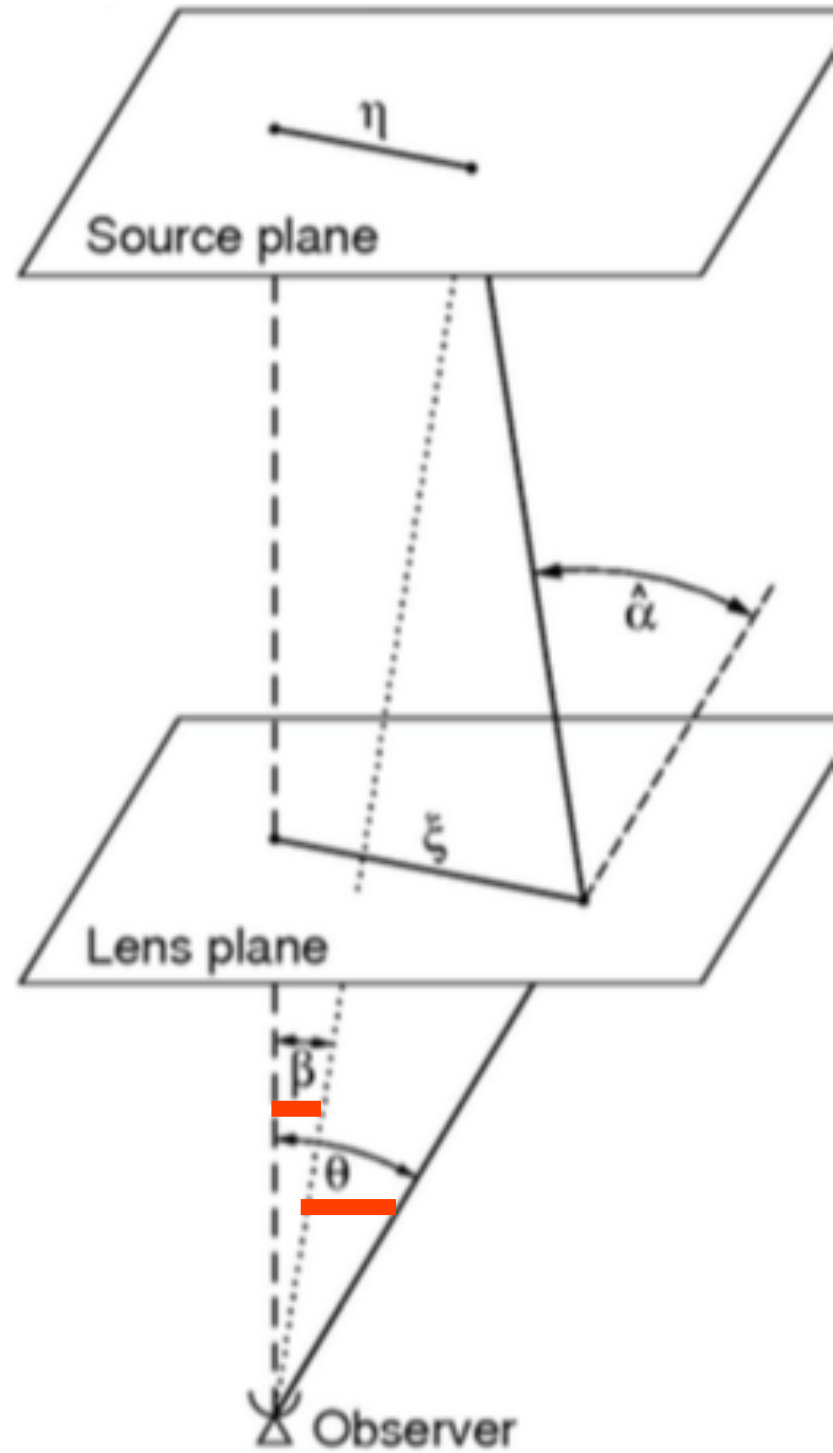


Lensing always conserves surface brightness

s sensitive to the mass (e.g.,
nstein Radius:
$= [4GM/c^2(1/D_L-1/D_s)]^{0.5}$

r a point lens and source, the
sing equation is
$=\beta+\theta_E^2/\theta$

e image of a source in the lens
ne is split into two images
n at
$= 0.5[u \pm (u^2+4)^{0.5}]\theta_E$
d with magnifications
$= 0.5[(u^2+2)/(u(u^2+4)^{0.5}) \pm 1]$



Lens mass (M), lens distan

Ns: Observing high-z AGN is essential to determining how SMB
w and affect their environment. Existing work is mostly on lumin
N; faint AGN populations at high-z are probed by very deep X-
osures (> 1 Ms, e.g. Chandra Deep Fields).

Bs: Detection of XBs at high-z will enable us to check how t
mation depend on galaxy environment: e.g., metallicity and/or
mation rate (SFR). Stacking of distant galaxies have been used, wh
fers the uncertainty in the underlining faint AGN contribution.

Strongly lensed galaxies

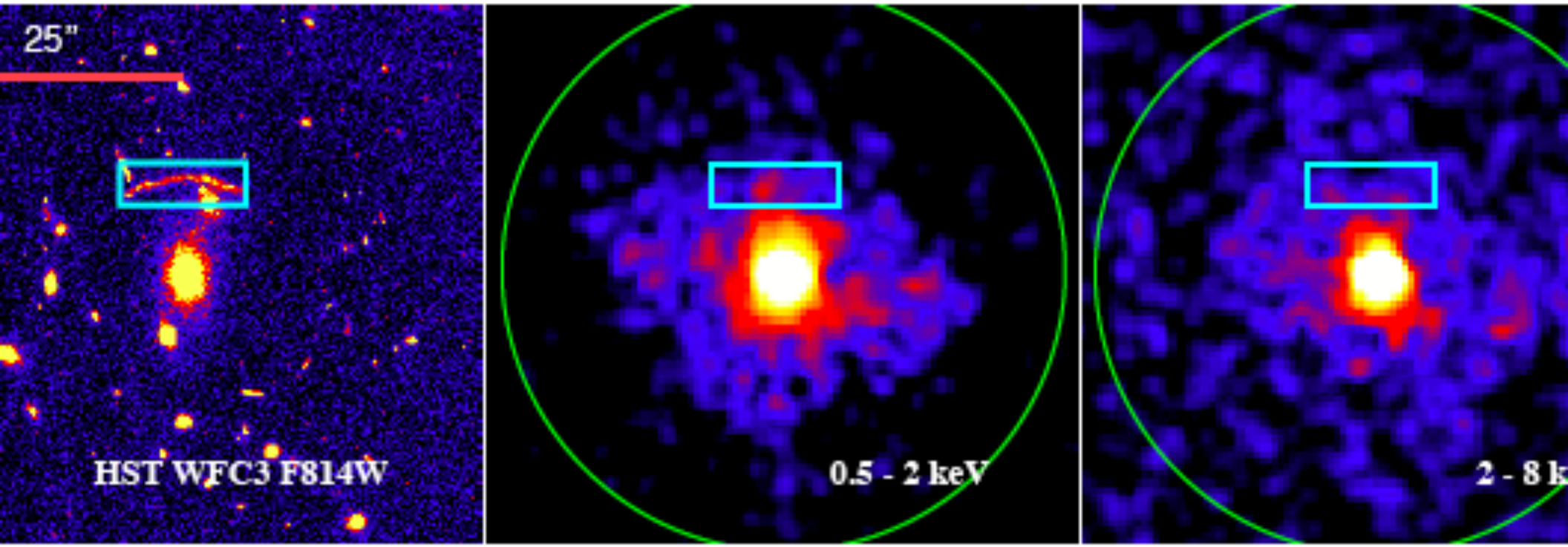
Magnified flux

Amplification → "zoom-

obe fainter individual AGN

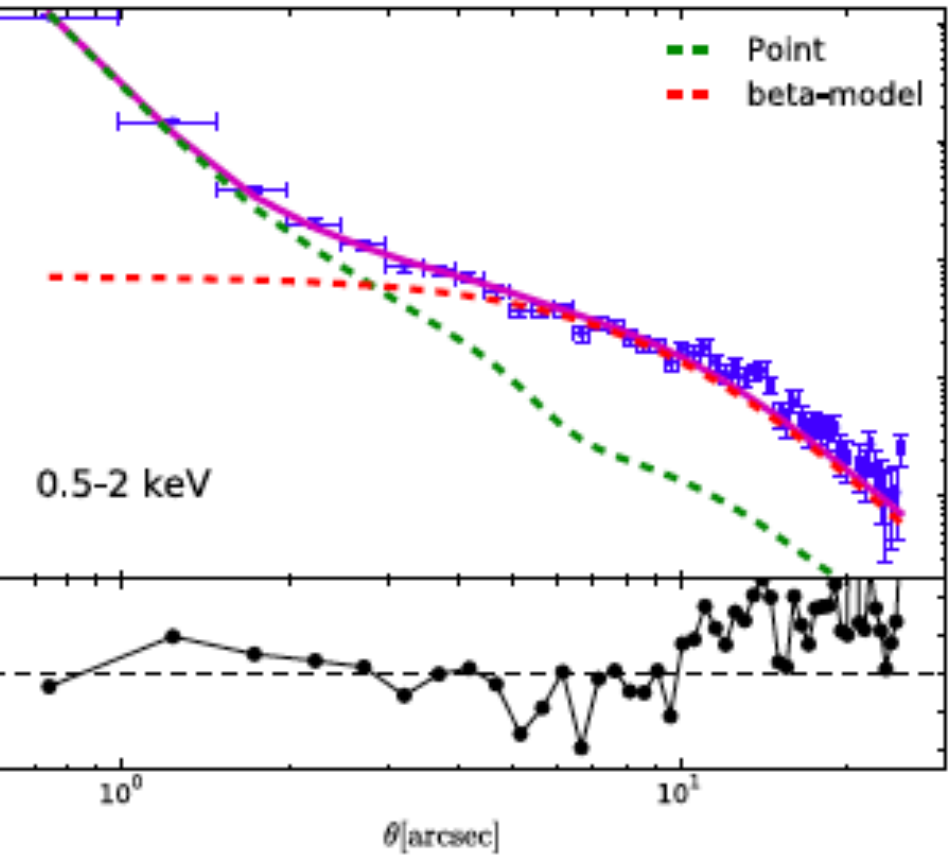
Collective emission of X

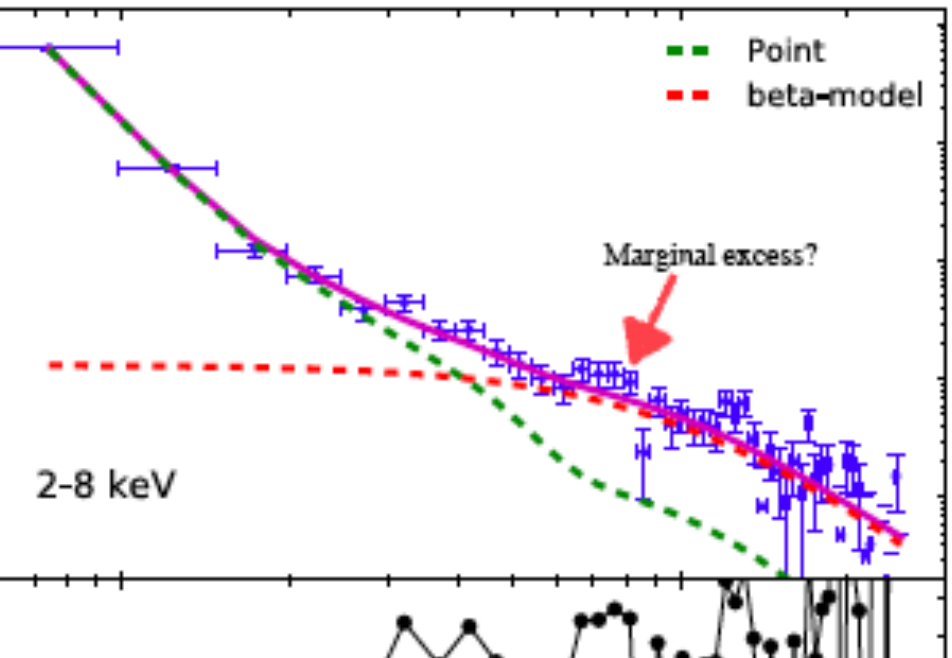
Existing X-ray Observations



Chandra observations of 3C220.1 – a galaxy cluster at z ~ 0.61
Total exposure: 170 ks
The lensed galaxy (arc) is at z ~ 1.5 (Worrall et al. 2001).
The lensing cluster is known to be a major merger, which complicates the X-ray morphology.

Existing X-ray Observations

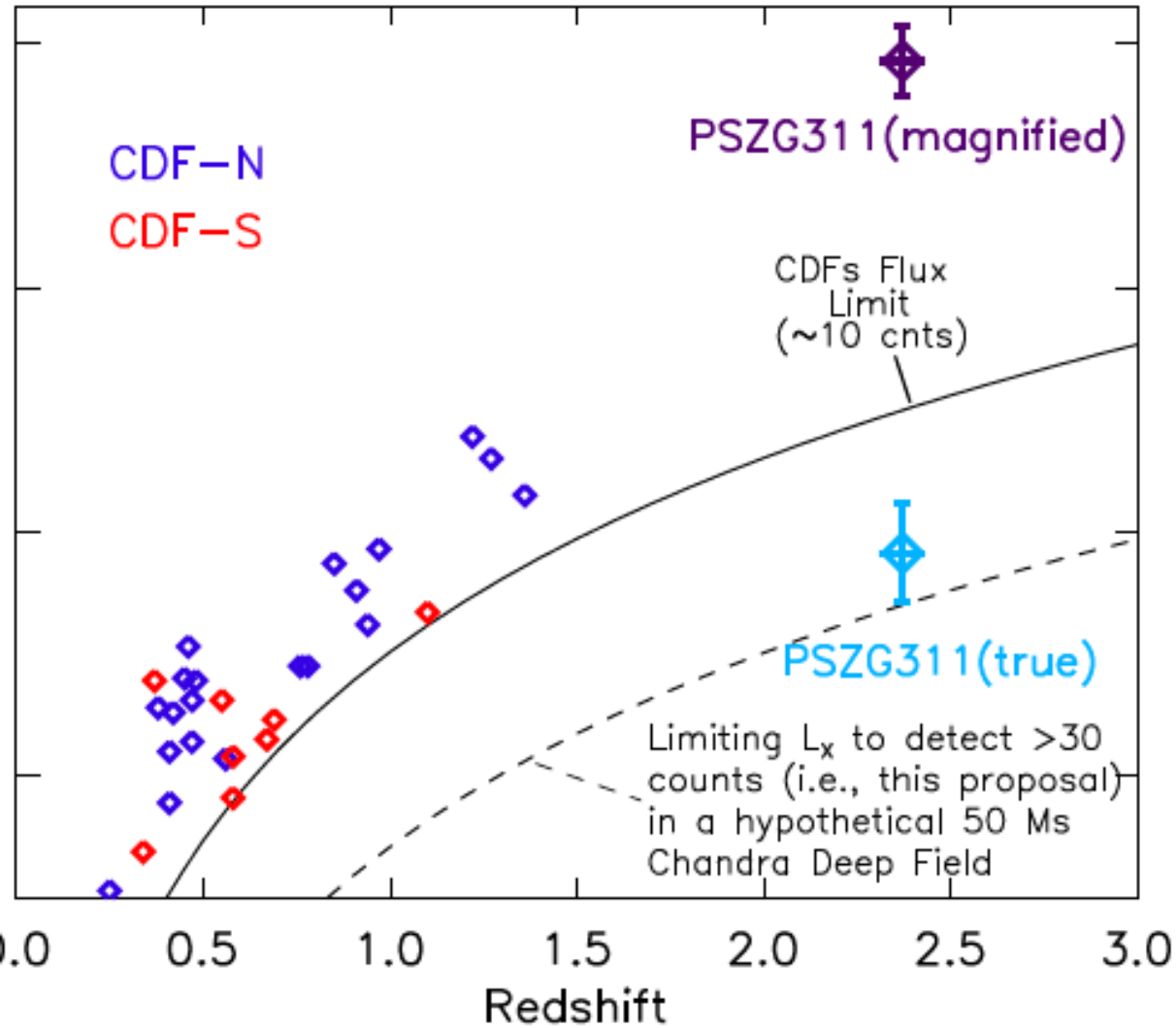


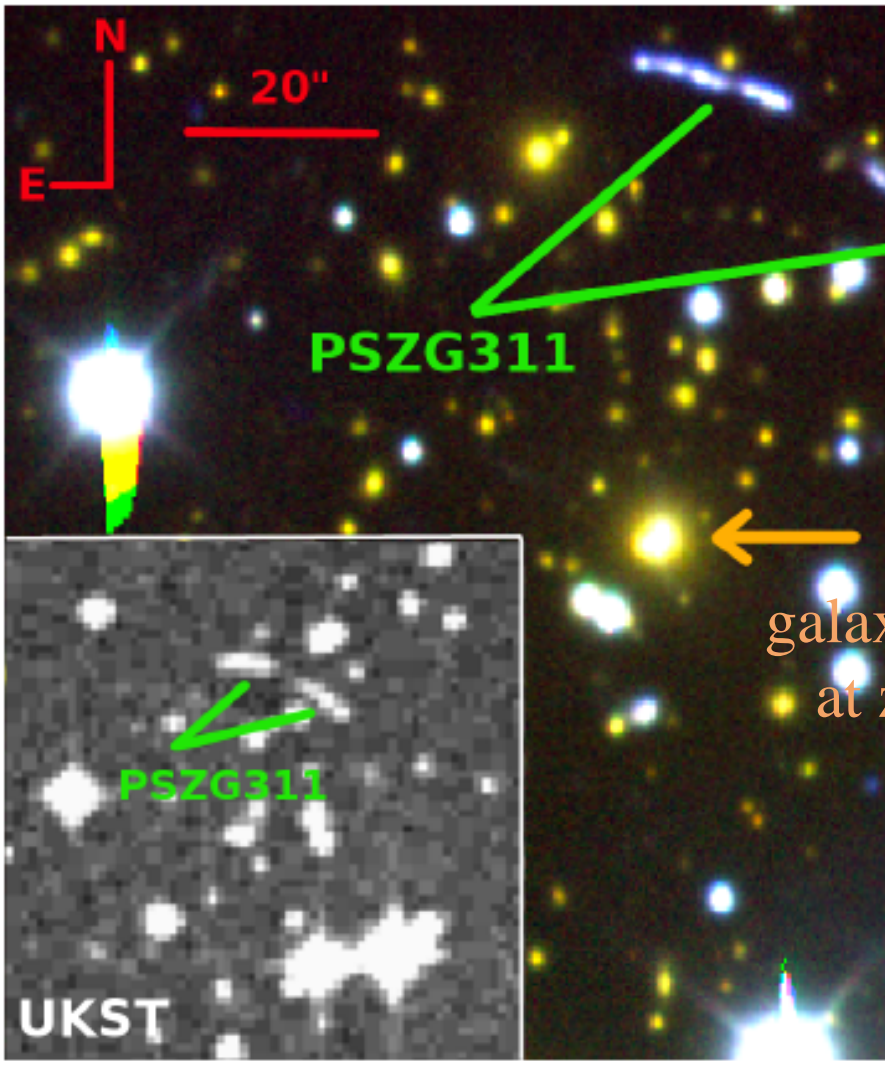


- Very marginal detection of dif
X-ray emission in 2-8 keV, or
keV in the rest frame of the le
galaxy.
- There are existing/upcoming
Chandra observations of simil
lensing systems selected from
SDSS (PI: Matt Bayliss); a few
them have also been selected a
JWST early release science ta
- But these systems generally ha
too low star formation rates an
Chandra exposures to improve
detection significantly.

Dedicated new observatio

Dedicated new observations are needed:
: the most highly magnified starburst galax

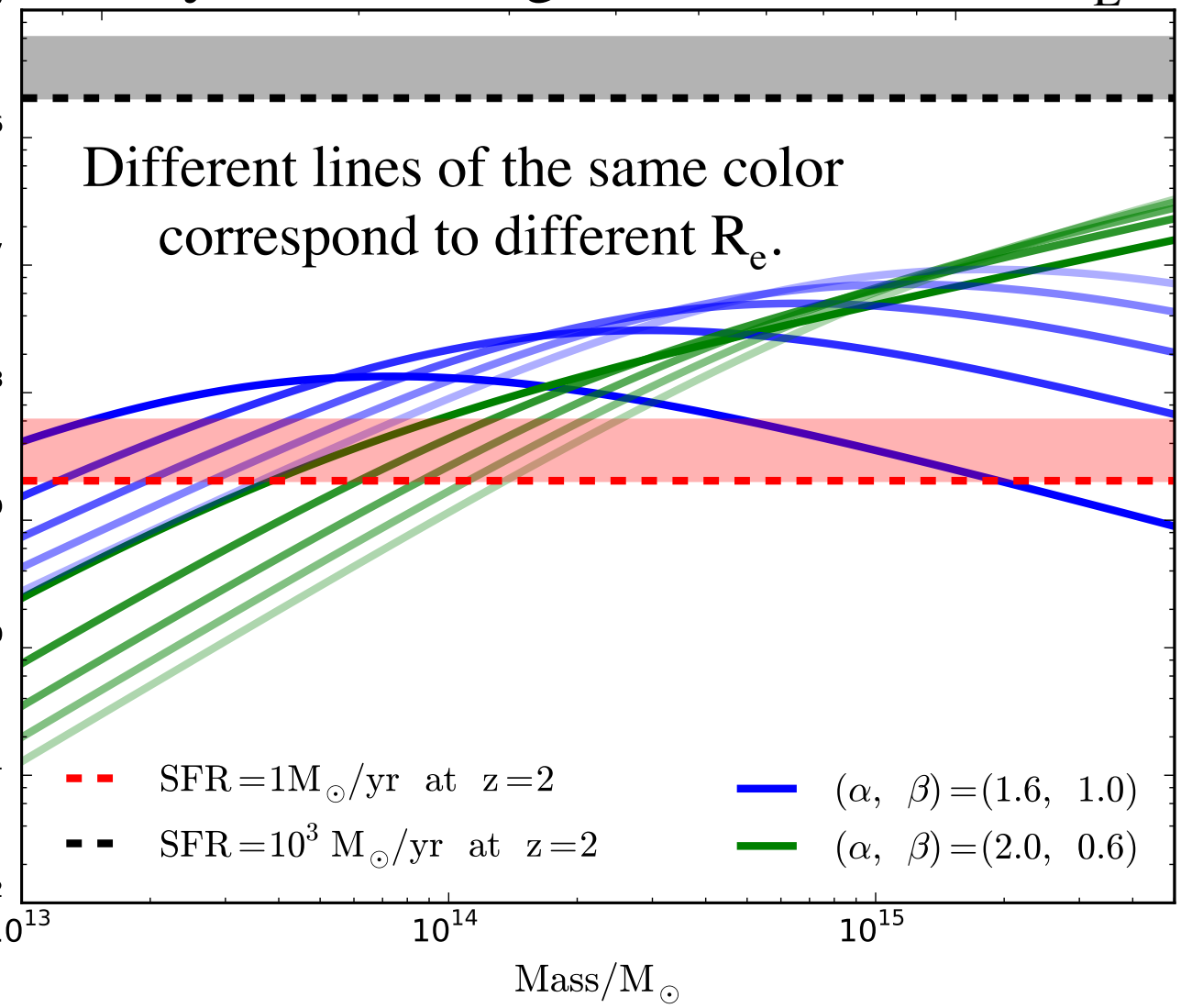




r proposed 308 ks exposure (PI: Bayliss) will reach an unprec
nsitivity to detect X-ray emission from PSZG311, a galaxy (arc
gnified for a factor ~120.

What kind of lensed galaxies are suitable

X-ray surface brightness contrast at R_E.



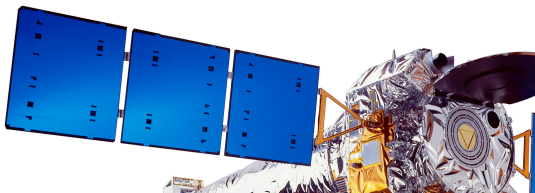
The surface brightness
the lensing object
assumes

$$S(R) = S_0[1 + (\frac{R}{R_e})^2]^{-3\beta+0.}$$

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

The surface brightness
the lensed galaxy assu
the Lx/SFR with or
without (1+z)-evolutio
(upper and lower limit

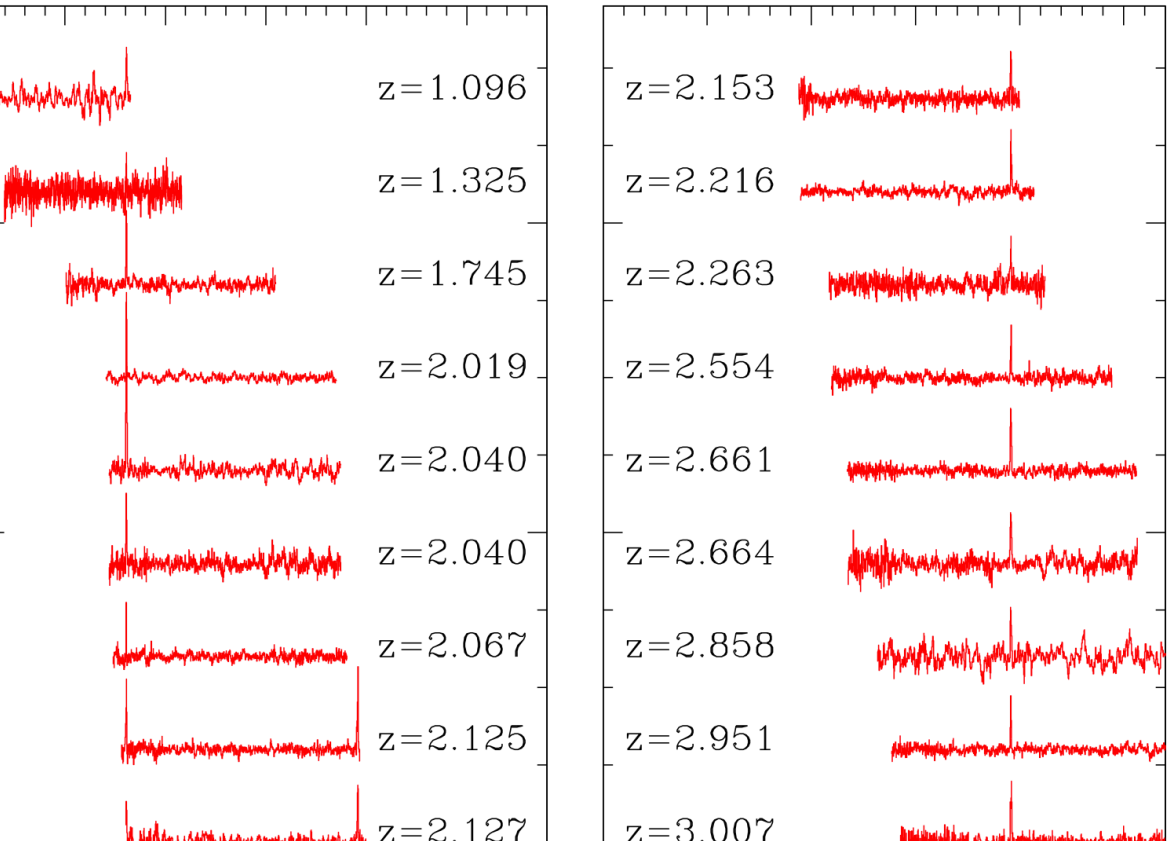
need Chandra observations of relatively
mass foreground lensing objects with



Brightest submm galaxies as the best targe

These SMGs appear to undergo extreme starbursts at z ~ 2

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



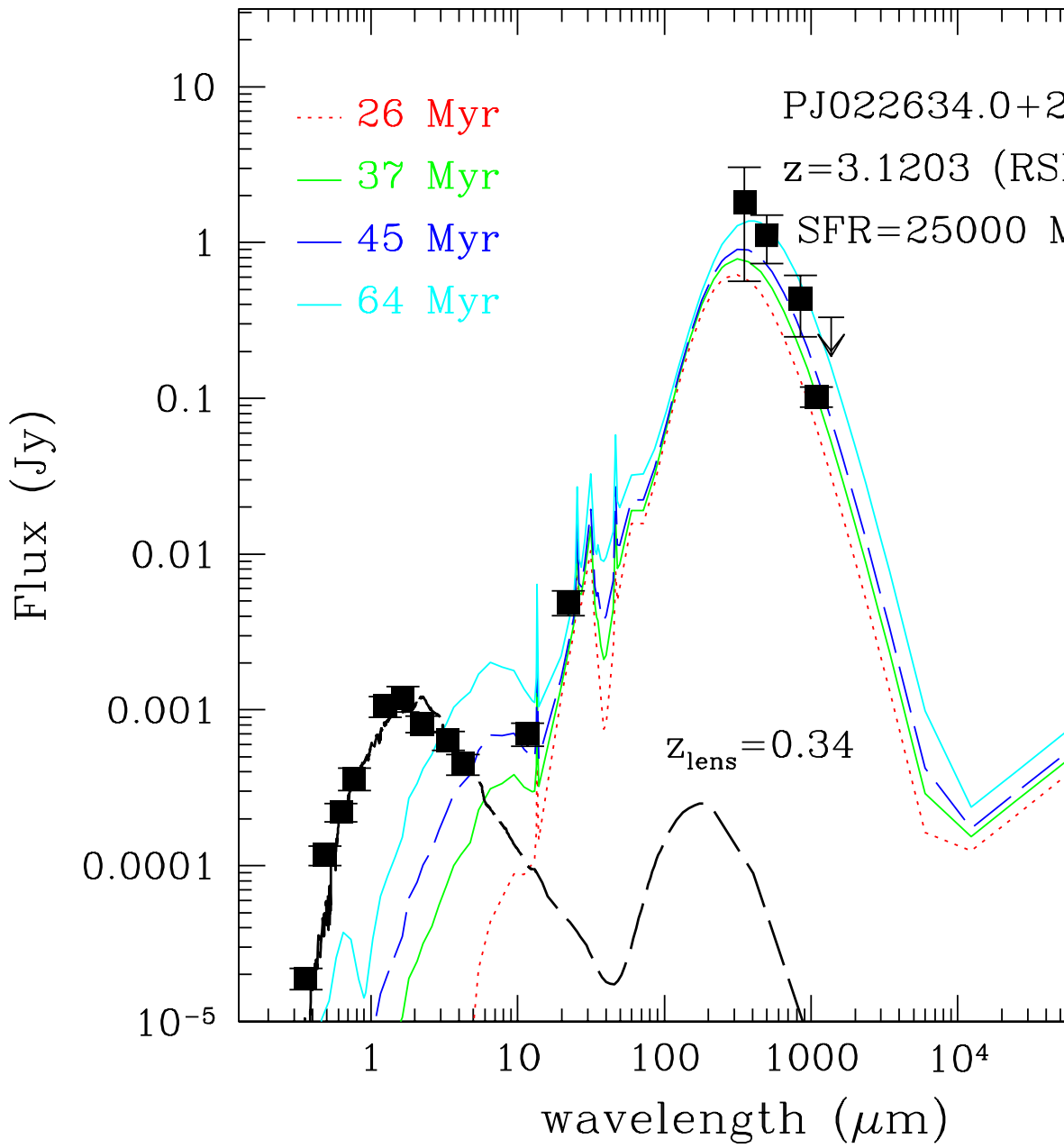
The Large Millimeter Telescope, jo
constructed by Mexico and UMass
50m diameter millimeter-wave teles
at the summit of Volcano Sierra Ne
an elevation of 4600m.

Measuring L_{IR}, SFRs, etc.

anck, Herschel, AzTEC,
. photometry fit with
rburst template SEDs

egrated IR luminosity
easured from best-fit
mplate, then converted to
R (e.g. Kennicutt 1998)

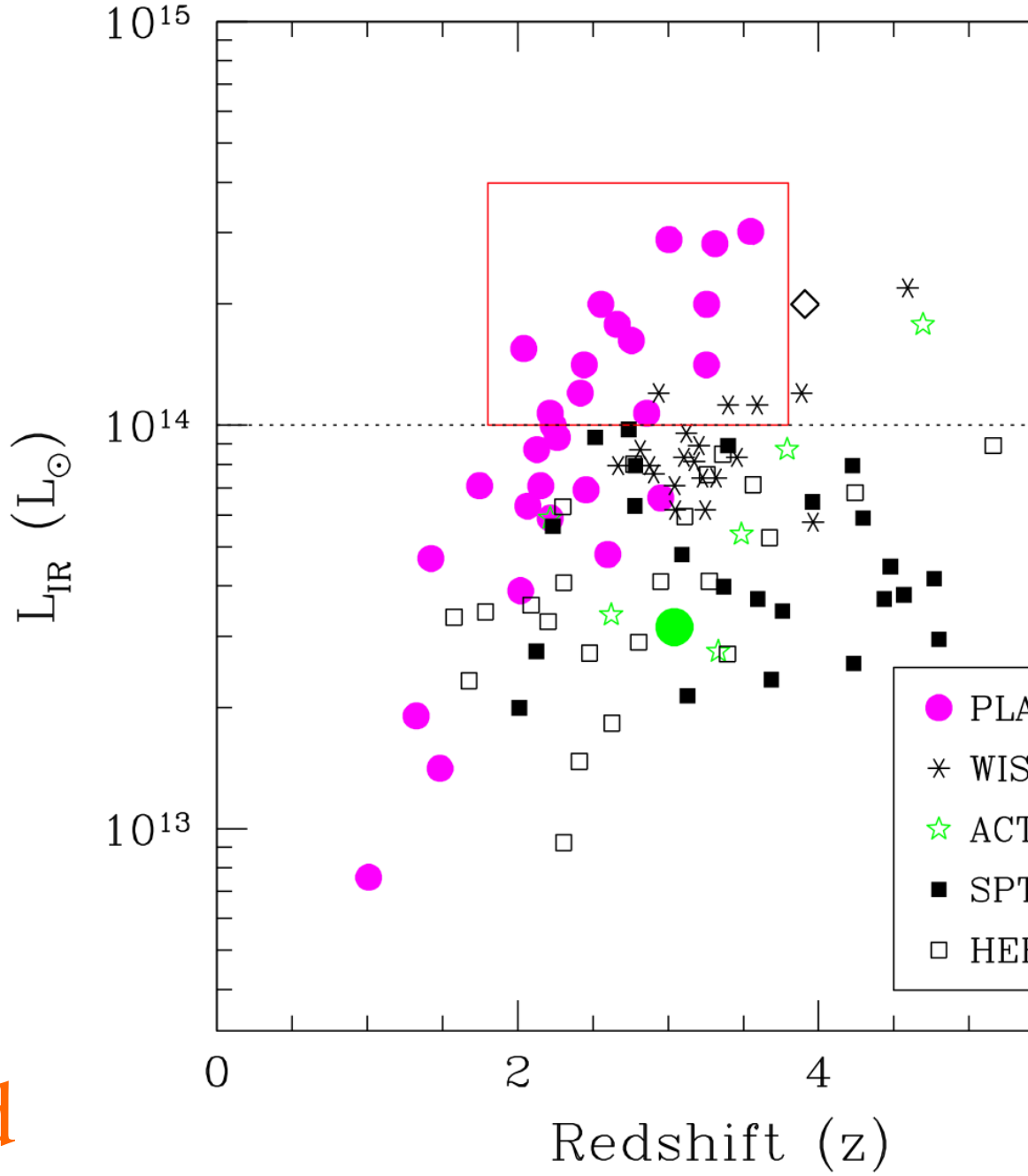
me of the galaxies show
cess in radio emission,
licating the presence of
lio-active AGNs.



Extreme starburst galaxies

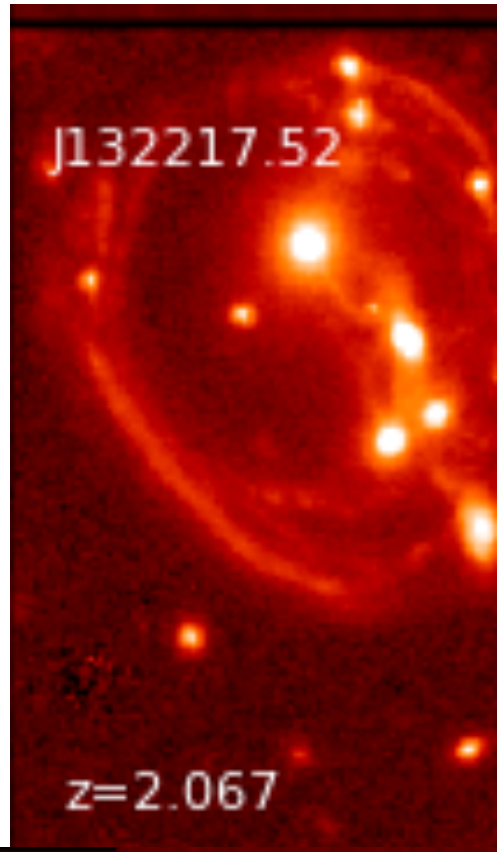
ith apparent IR
minosities range from ~
1 - 3 x 10^{14} $L_{\odot}$, these
laxies present the upper
velope of the L_{IR}-z
stribution.
e brightest ones indicate
FR ~ 10,000 – 28,000
$_{\odot}$ /year, which are too
treme to be physical!

they largely magnified
gravitational lensing?



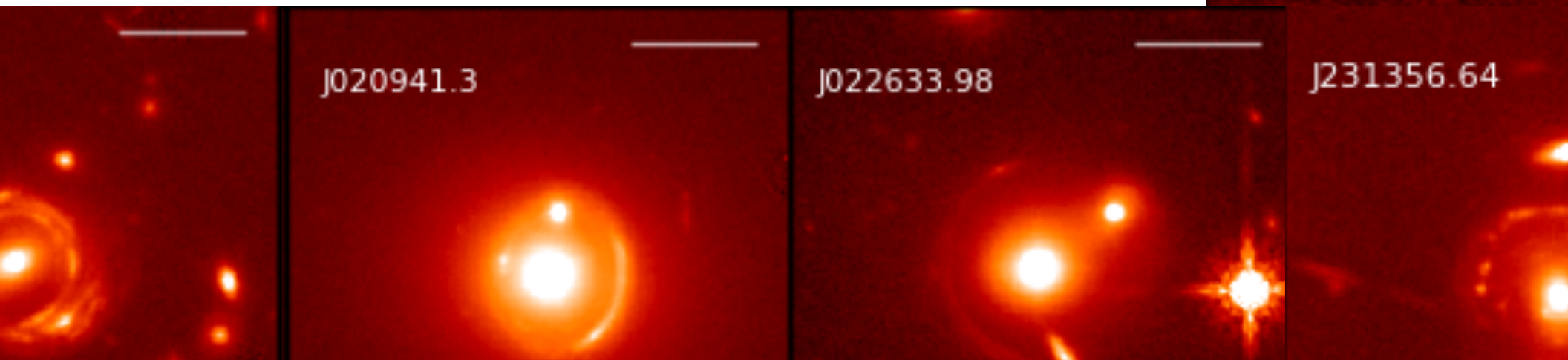
the strong gravitational lensing

g WFC3/F160W (1.6 μm) filter

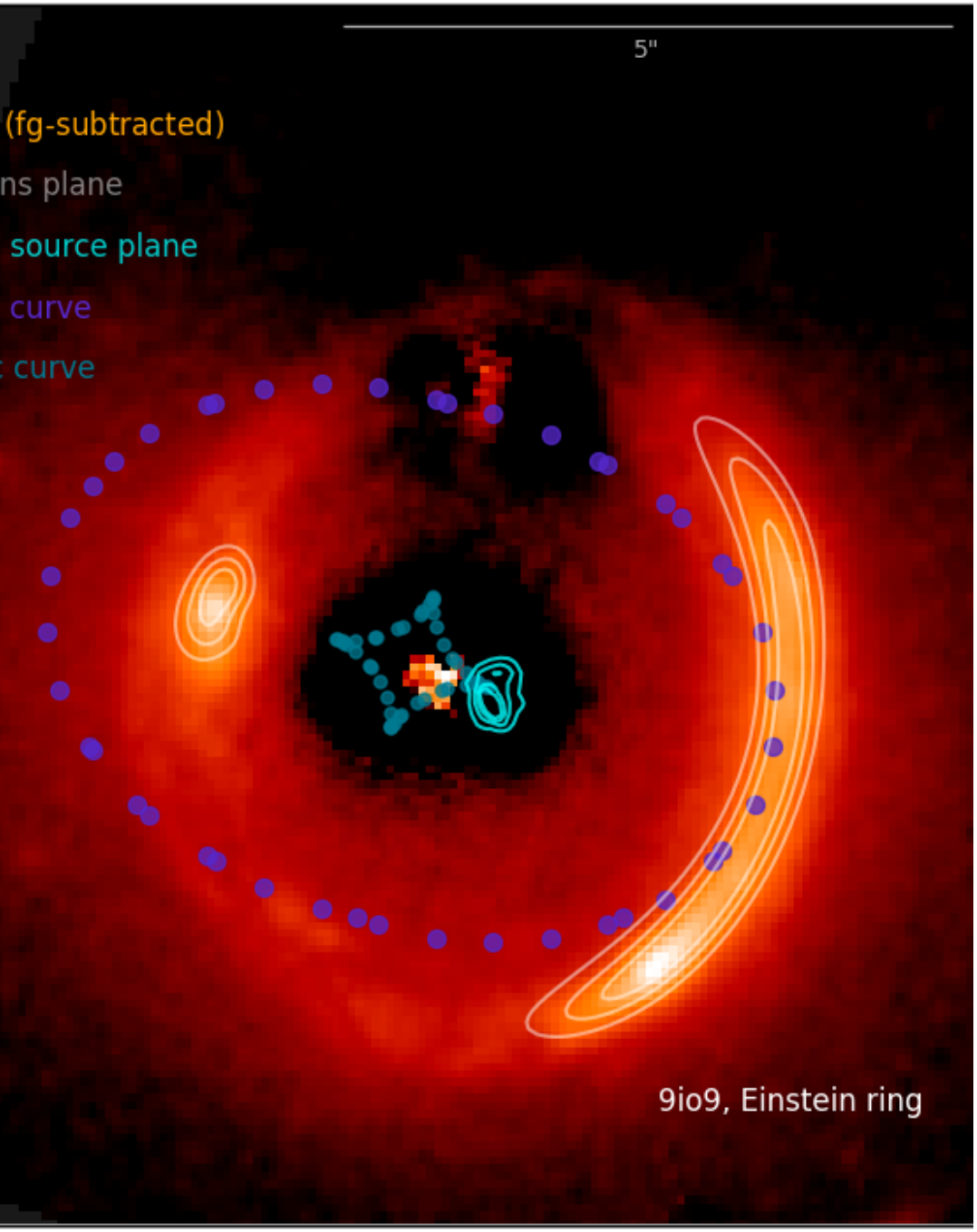


Iost are lensed by single galaxies,
lowing Einstein "rings"

thers are by small groups and still
ore by massive clusters

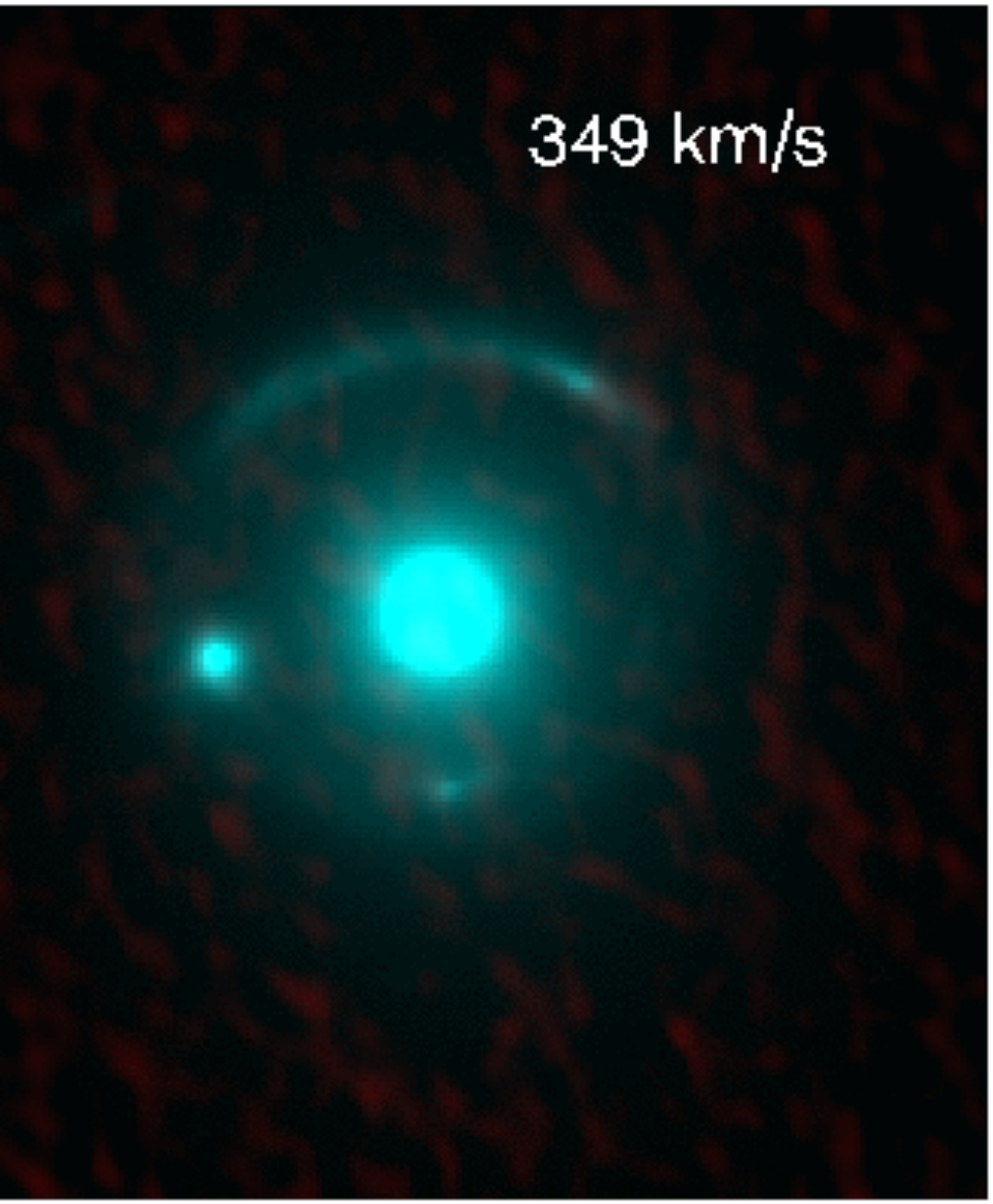


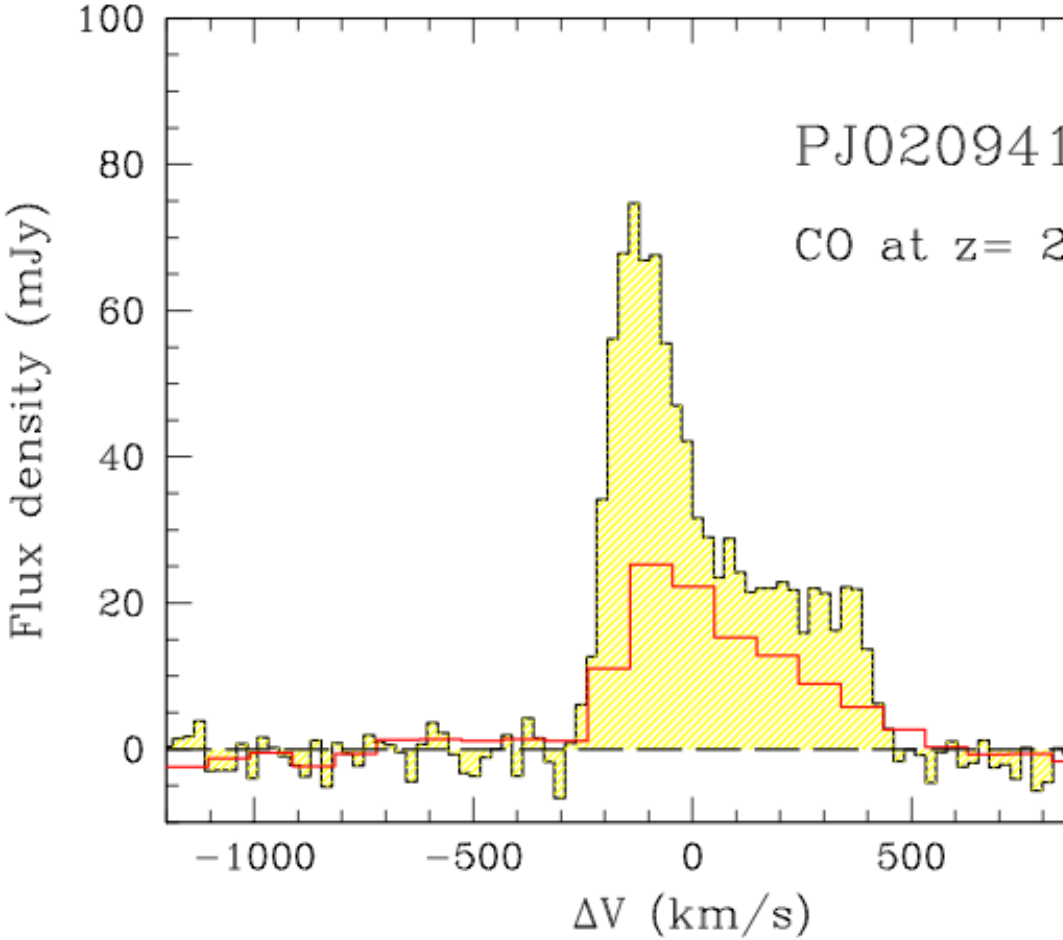
Preliminary gravitational lens modeling



- The typical magnificati
is ~10.
- So these SMGs remain
be among the brightest
galaxies, even intrinsic
- There are no local anal
to such galaaxies. Thus
detailed investigation o
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
  resolution and velocity at ~10 k
- Strong outflows are indicated.

Chandra observations of the extreme SMGs

of the brightest SMGs (z=2.2-3.6), which are primarily
xy-galaxy lenses, are proposed for the upcoming cycle.
he "zoom-in" of the gravitational lensing will allow for
etecting both AGN and non-AGN (high-mass XB)
missions with minimal cross-contamination, important f
etermining intrinsic spectral shapes (including absorptio
nd connections to the extreme star formation.
hese observations in the 0.5-8 keV range will be sensiti
the rest-frame $2 - 36$ keV emission and hence to very
ighly obscured AGNs.

Chandra observations of the extreme SMG

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

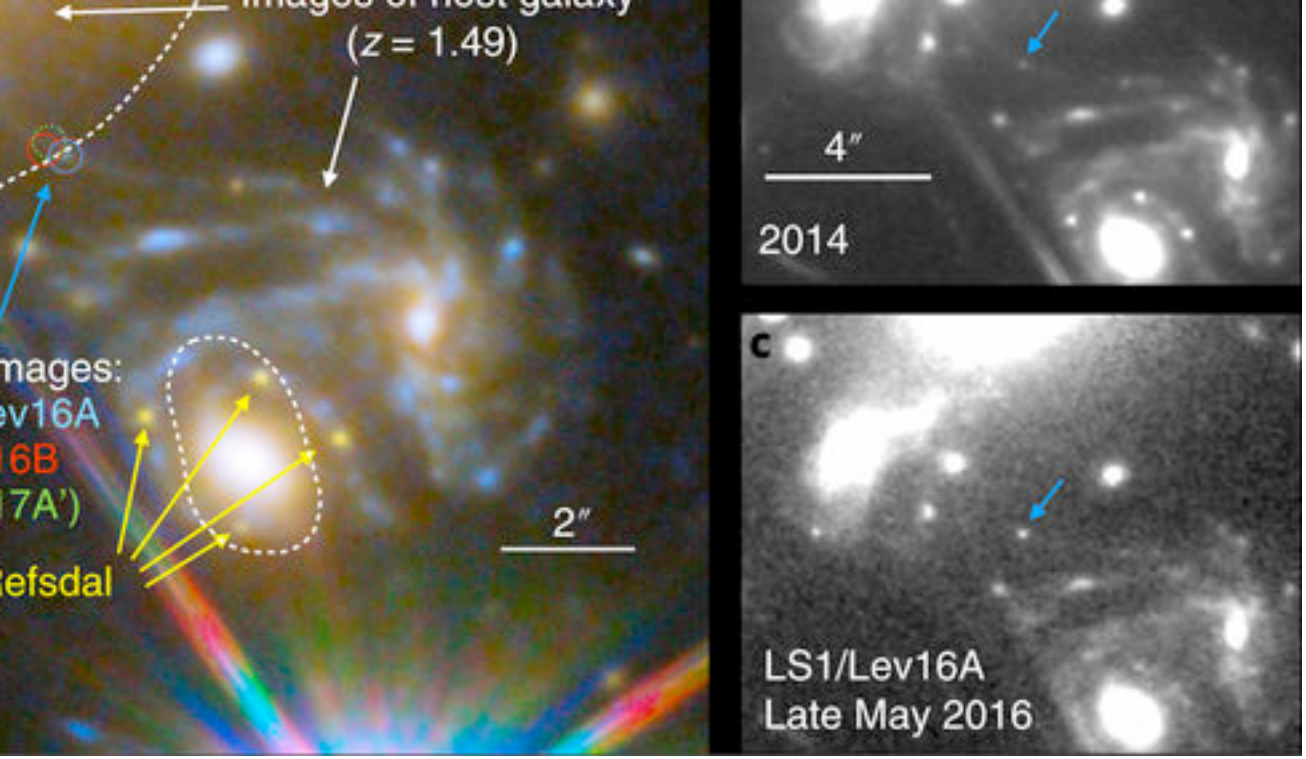
e are lucky, we may detect individual XBs in these gala

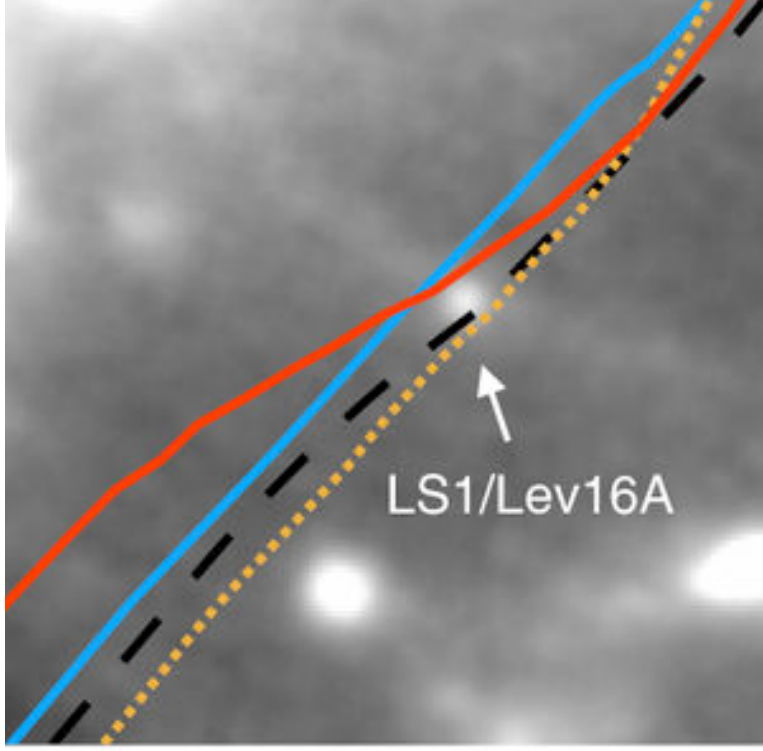
TICLES
oi.org/10.1038/s41550-018-0430-3
nature astrono

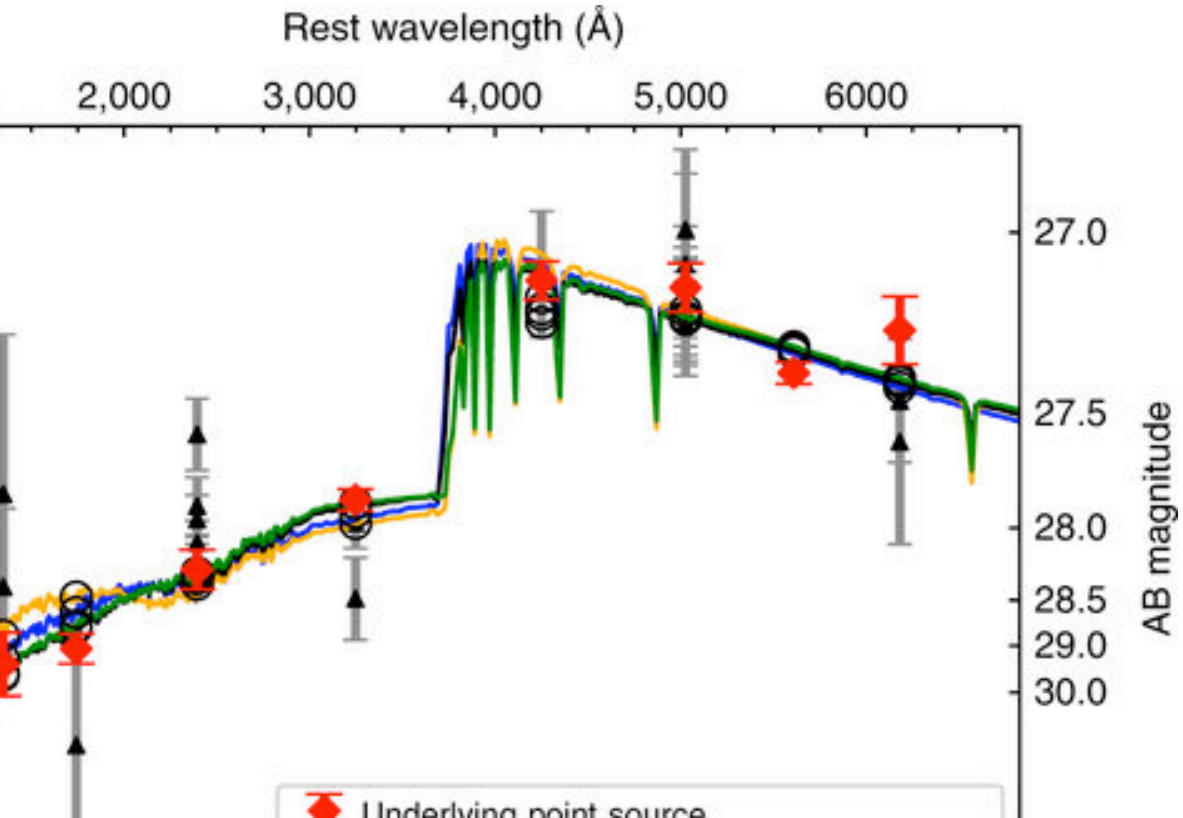
reme magnification of an individual star at shift 1.5 by a galaxy-cluster lens

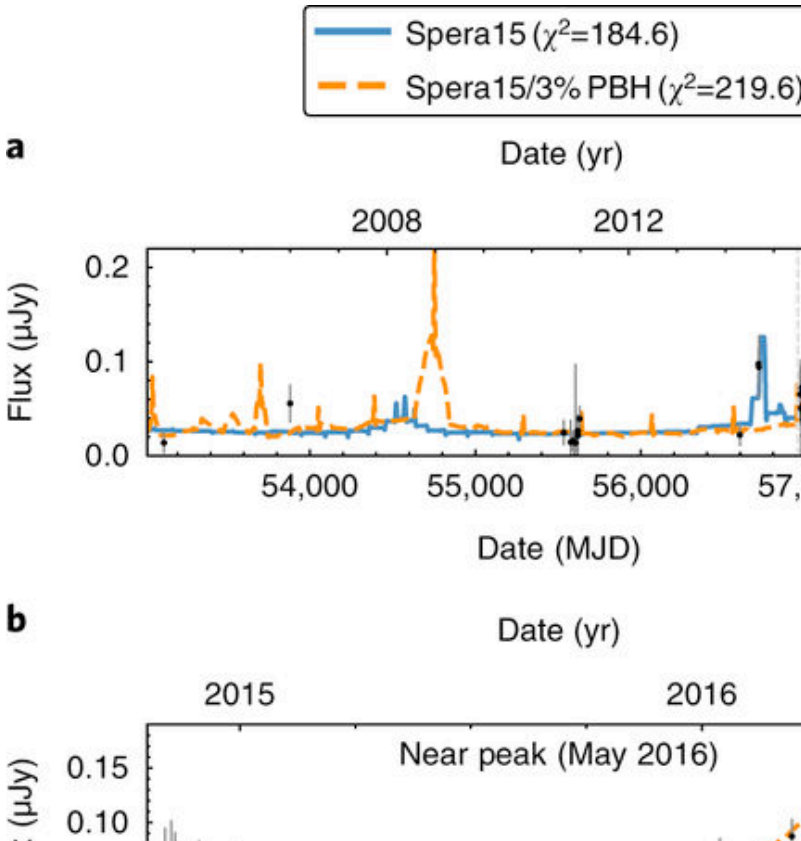
L. Kelly[1,2*], Jose M. Diego[3], Steven Rodney[4], Nick Kaiser[5], Tom Broadhurst[6,7], Ad
so Treu[9], Pablo G. Pérez-González[10], Takahiro Morishita[9,11,12], Mathilde Jauzac[13,14,15],
n Selsing[16], Masamune Oguri[17,18,19], Laurent Pueyo[20], Timothy W. Ross[1], Alexei V. Filippe
Smith[22], Jens Hjorth[16], S. Bradley Cenko[23,24], Xin Wang[9], D. Andrew Howell[25,26],
Richard[27], Brenda L. Frye[22], Saurabh W. Jha[28], Ryan J. Foley[29], Colin Norman[30], Marusa B
g Zheng[1], Gabriel Brammer[20], Alberto Molino Benito[32], Antonio Cava[33], Lise Christe
E. de Mink[34], Or Graur[35,36], Claudio Grillo[16,37], Ryota Kawamata[38], Jean-Paul Kneib[39],
s Matheson[40], Curtis McCully[25,26], Mario Nonino[41], Ismael Pérez-Fournon[42,43], Adam G. R
osati[44], Kasper Borello Schmidt[45], Keren Sharon[46] and Benjamin J. Weiner[22]

uster gravitational lenses can magnify background galaxies by a total factor of up to ~50. Here we report a
dual star at redshift $z = 1.49$ (dubbed MACS J1149 Lensed Star 1) magnified by more than $\times 2{,}000$. A separ
briefly 0.26″ from Lensed Star 1, is probably a counterimage of the first star demagnified for multiple y
$\gtrsim 3$ solar masses in the cluster. For reasonable assumptions about the lensing system, microlensing fluct

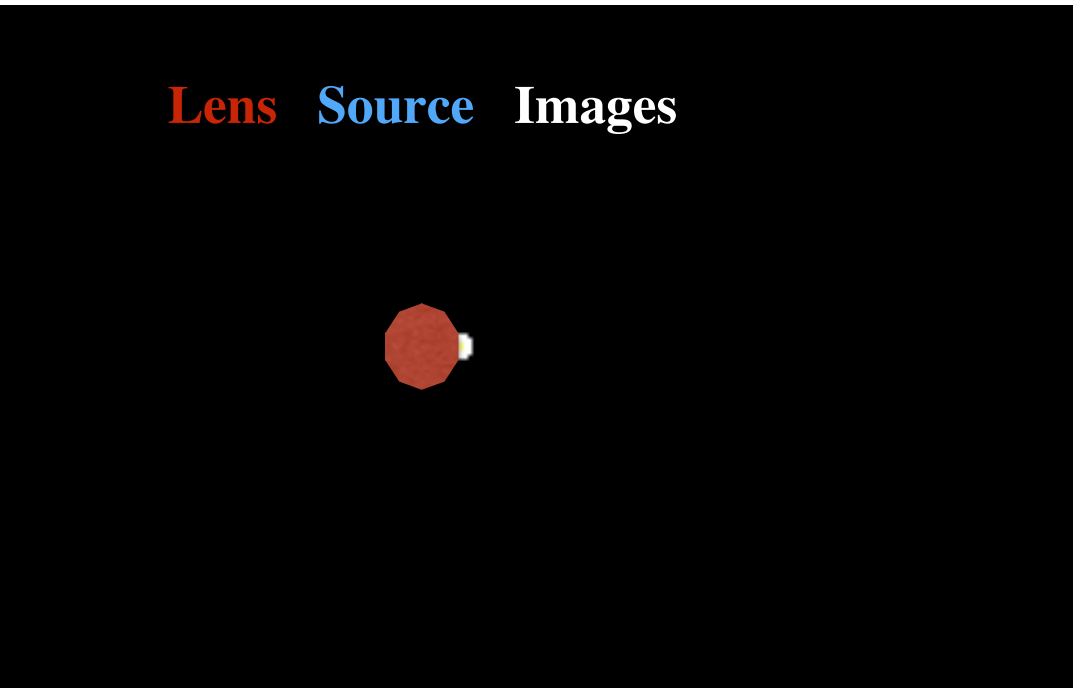

(z = 1.49)
mages:
ev16A
16B
17A')
efsdal
2″
4″
2014
c
LS1/Lev16A
Late May 2016


LS1/Lev16A


Rest wavelength (Å)
2,000
3,000
4,000
5,000
6000
27.0
27.5
28.0
28.5
29.0
30.0
AB magnitude
Underlying point source


Spera15 (χ²=184.6)
Spera15/3% PBH (χ²=219.6)
a
Date (yr)
2008
2012
Flux (μJy)
0.2
0.1
0.0
54,000
55,000
56,000
Date (MJD)
b
Date (yr)
2015
2016
Near peak (May 2016)
0.15
0.10

al cases of gravitational lensing where the mul
es produced by foreground lens are too close (due to
tion small θ_E) to be separated and resolved
mentation.



- **Source**: where the light c
from
- **Lens**: which deflects the
by an amount related t
quantity of mass/energy
- **Images**: what the observer

ke with strong lensing, no single observation can esta
microlensing is occurring. Instead, the changing so

/idely used in searching for MACHO and exoplanets.

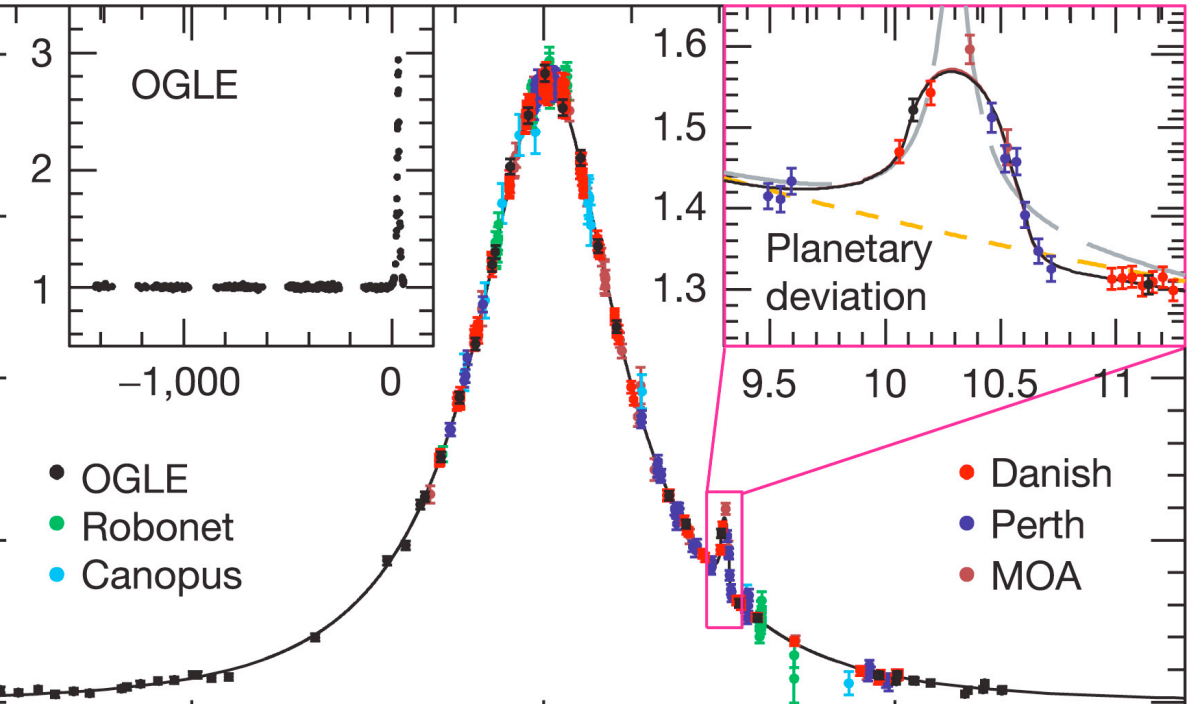
ymmetric light curve for a point source,

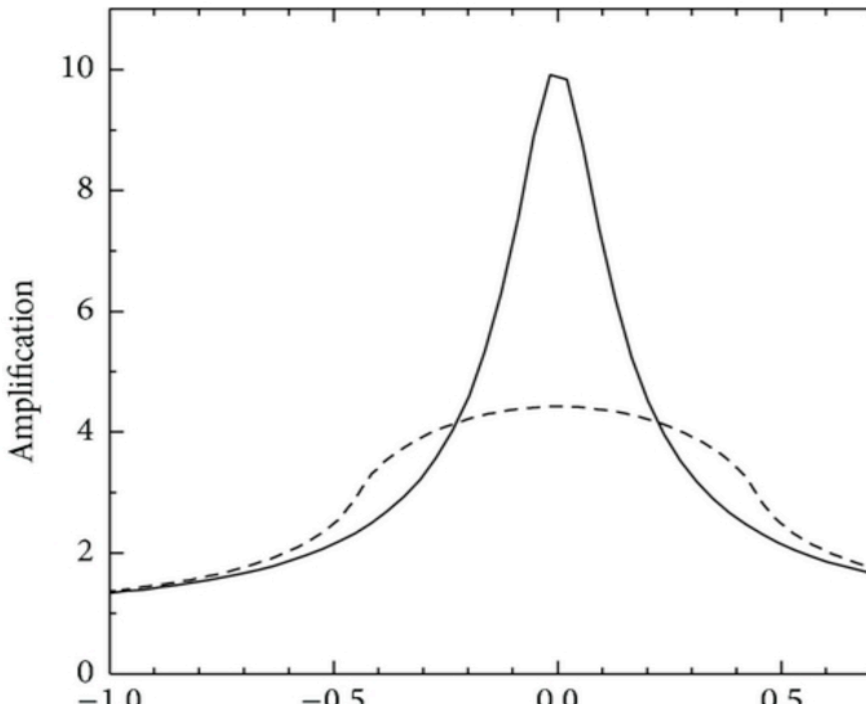
$= A_+ + A_- = (u^2+2)/[u(u^2+4)^{0.5}]$

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

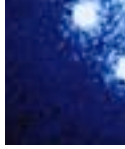
vent timescale depends on lens-source relative motion (v_{rel}):

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





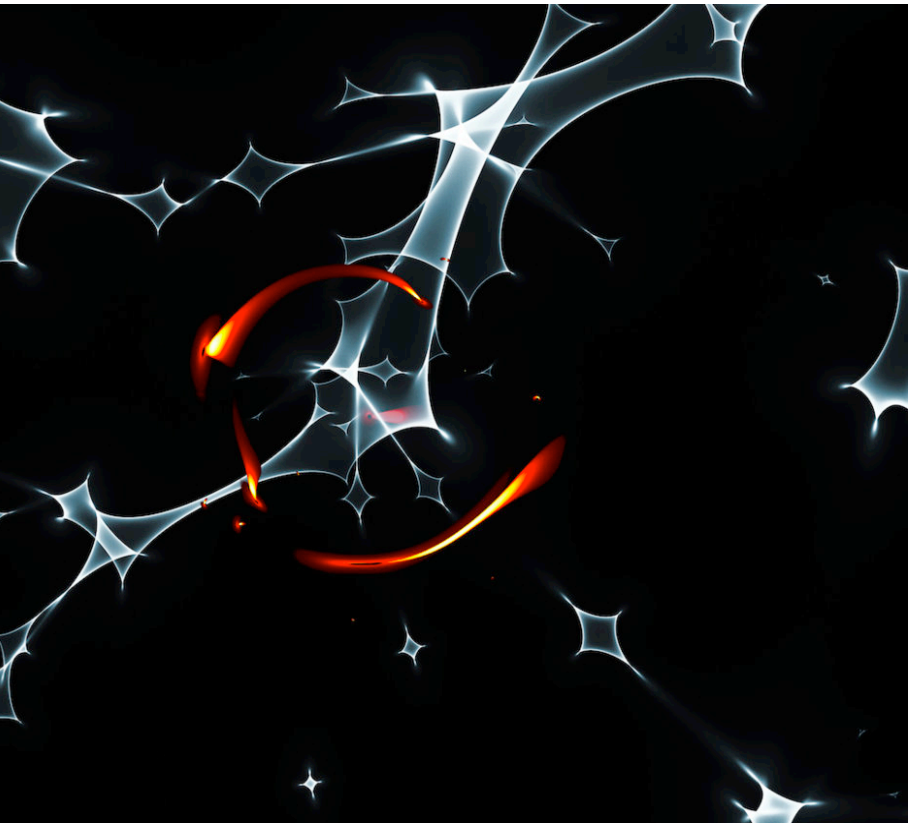
pproach 2: detecting microlensed AGN



sic Properties of the flux variability:

he larger the AGN corona, the lower the variability mplitude.

he more distant the lens, the longer the duration.



e.g., Mosquera+(2013)

- Microlensing by a distant lensing galaxy is optically t
- Stars collectively form so-c caustics, the crossing of wh leads to flux variation.
- *Statistical* analysis of flux variation among multiple images of strongly lensed A has been used to constrain t

Near-field Microlensing of AGN

Objective: Better constrain the size and geometry o
AGN coronae by detecting individual microlensin
vents.

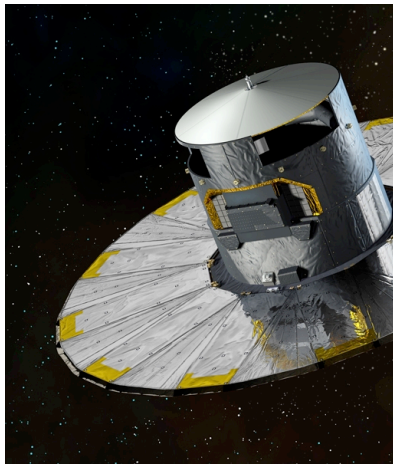
Approach:

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
easure the corona structure of the lensed AGN

near-field microlensing experiment of AGN

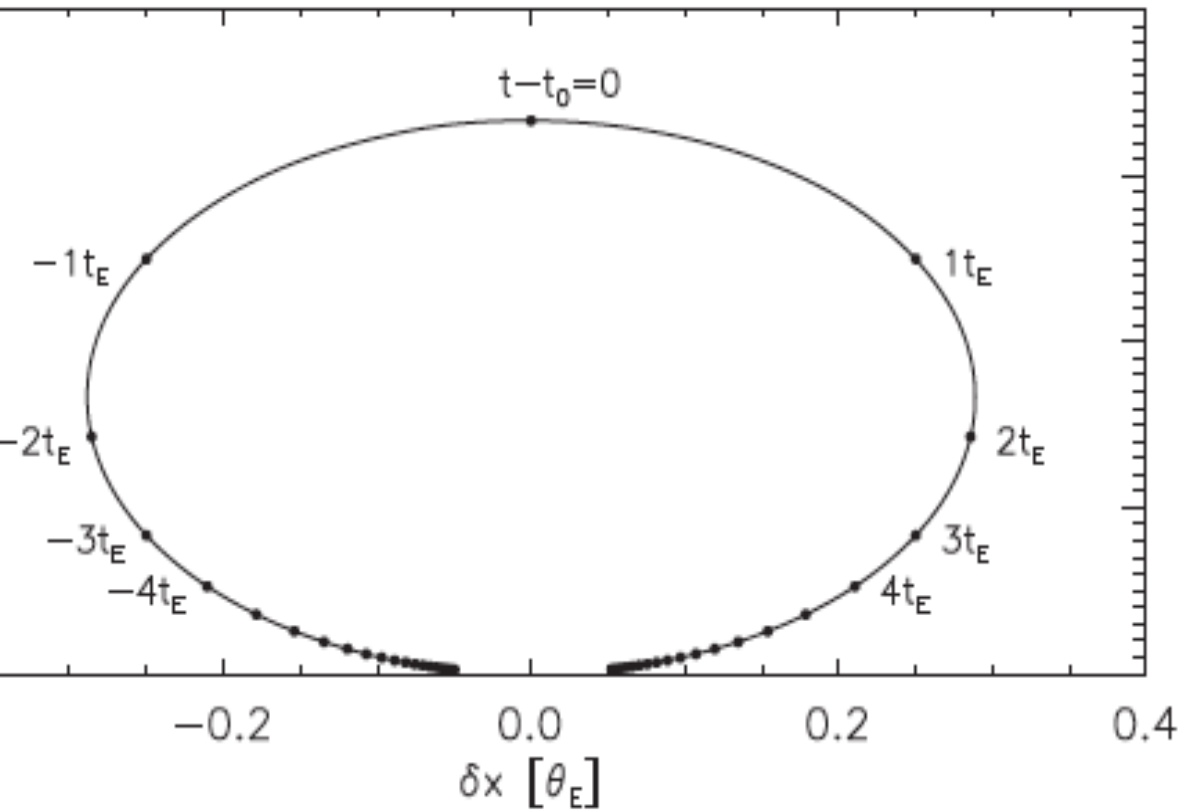
oss-matching *The Half Million Quasars* catalog (Flesch
5) with Gaia DR1 (~2 million stars with proper motion
ormation; Lindegren et al. 2016)



d a candidate pair, which will become near
gnment in ~ 7 yrs, when dense monitoring of
AGN and star can be easily scheduled.
he mean time, their relative astrometry and
per motion still be better measured.

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

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



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

Assuming the astrometric cen
precision of an instrument Δ.

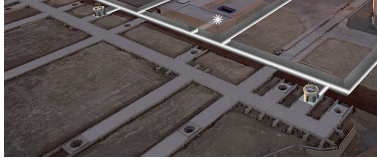
We assume that if $\Delta > \delta\theta_{max}$ (~
$0.35\theta_E$), the cross section of
astrometric microlensing is σ_A

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

For local stellar objects, whe
100 μas, this factor is often >

The effective cross sec

the Galactic center



thin the central 1 pc: both models and observations
ggest the existence of a number of (~ 10^4 - 10^5) such BH

.g. inward radial mass
gregation (Morris 1993;
reitag et al. 2006)

Genzel et al. 2003 hundreds o
O/B stars
Muno et al. 2005 excess XRE

o date, no DIRECT detection of stellar mass BHs in
e Galactic center.

e commissioning VLT near-IR
erferometer GRAVITY
illessen et al. 2010) will provide
e position measurement to be

Stellar Mass BHs in the Galactic center

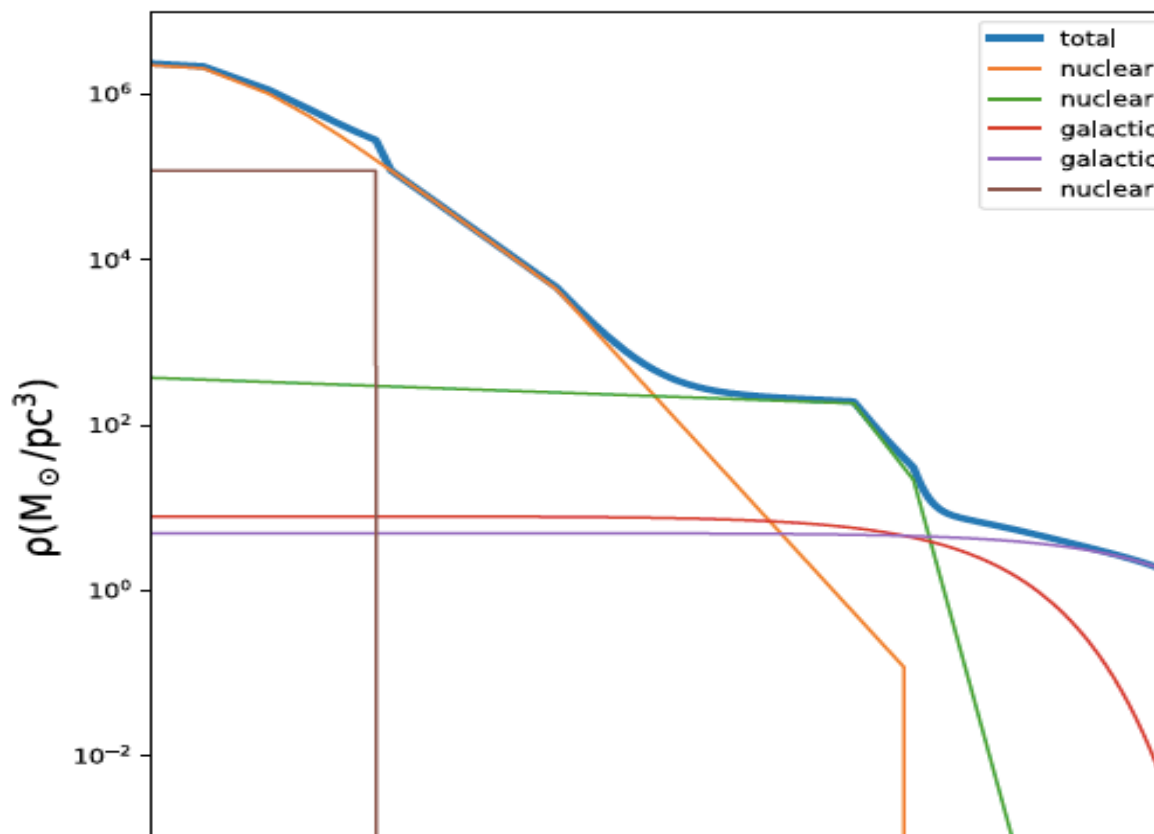
rometric microlensing events:

ptical depth $$\tau = \int_0^{D_S} n(D_L)\cdot\sigma(D_L)dD_L = \frac{4G\pi}{c^2}\int_0^{D_S}\rho(D_L)(D_L - \frac{D_L^2}{D_S})(u_2^2 - u_1^2)$$

event rate $$\Gamma = \frac{8G}{c^2}\frac{v_{rel}}{\Delta}\int_0^{D_S}\rho(D_L)(1 - \frac{D_L}{D_S})dD_L$$

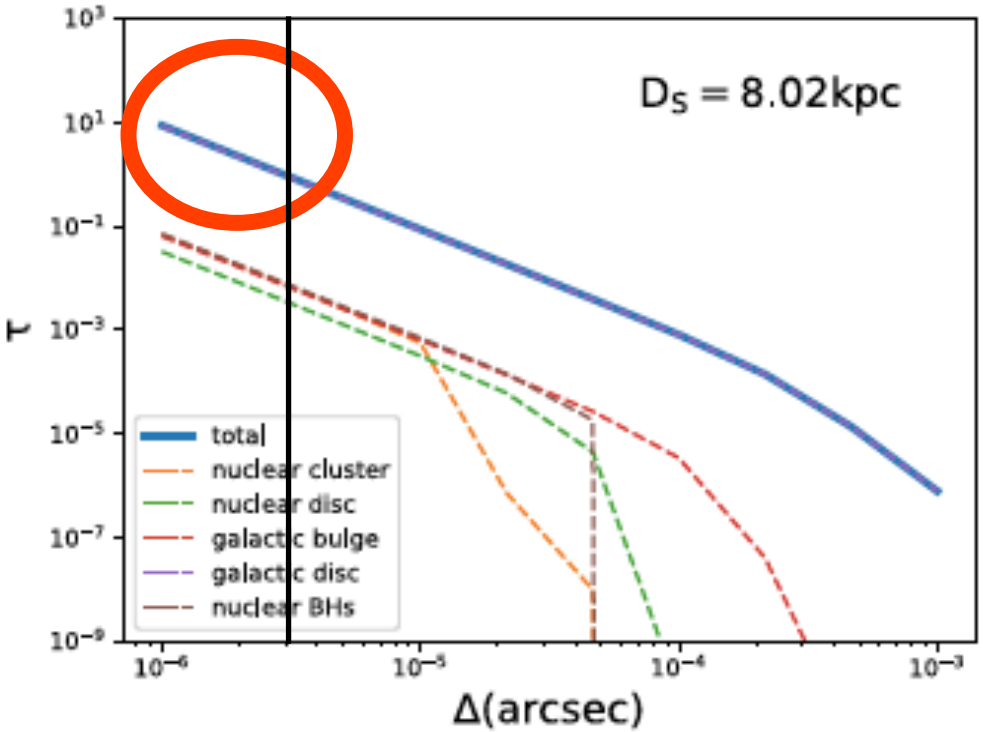
llar mass distribution along the line of sight

dopting the Muno et al. 2006) stellar mass istribution for stars. ssuming 5 * 10^4 stellar nass BHs (10 Msun) niformly distribute within central 1 pc

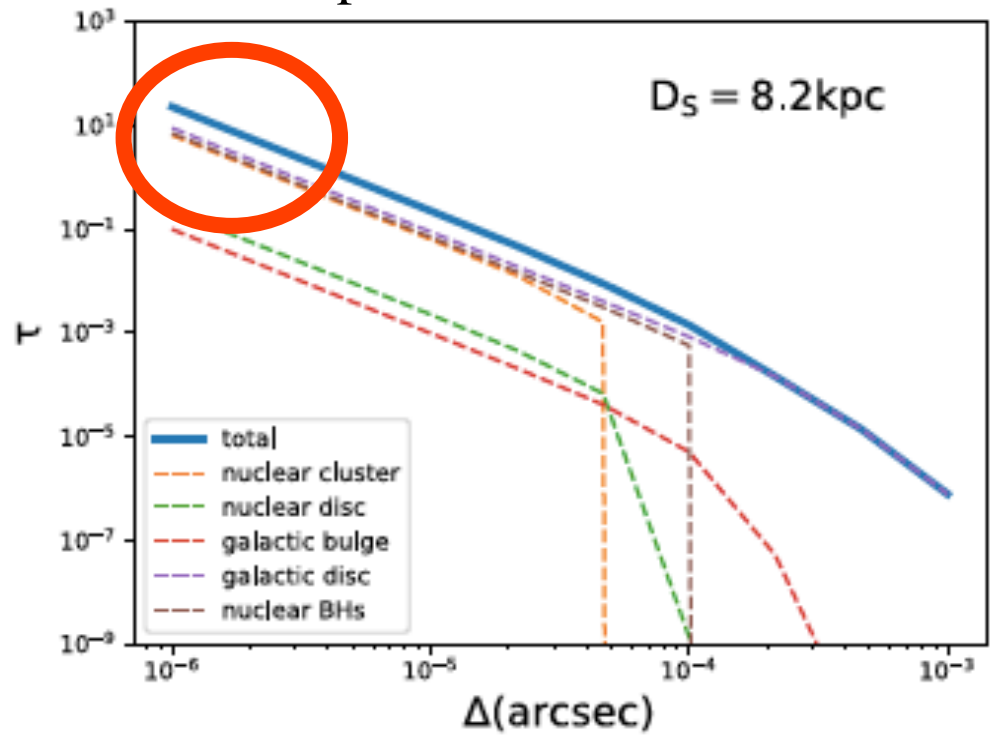


Optical depth of astrometric microlensing

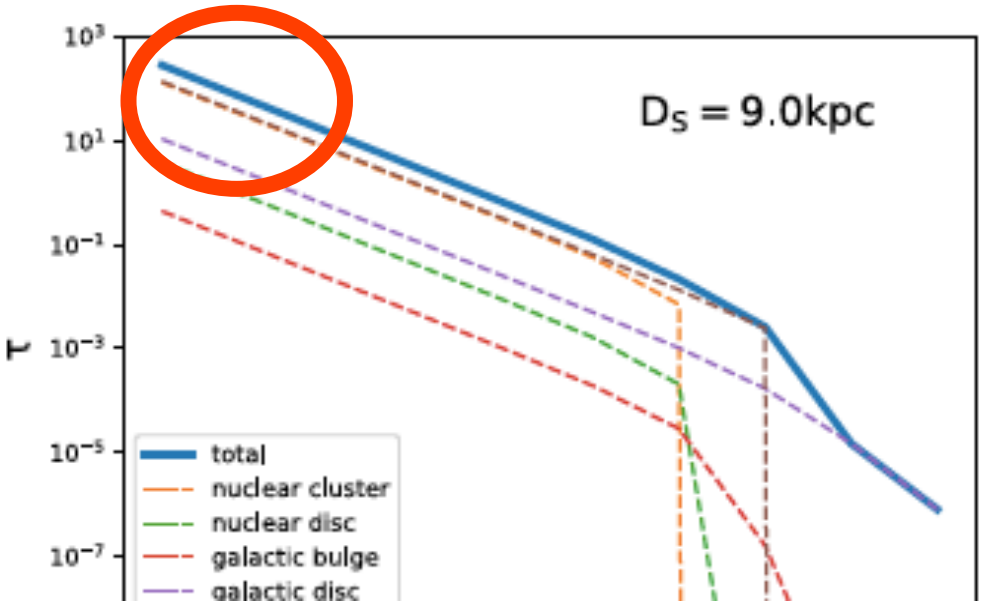
Δ: the astrometric centroid precision of an instrument

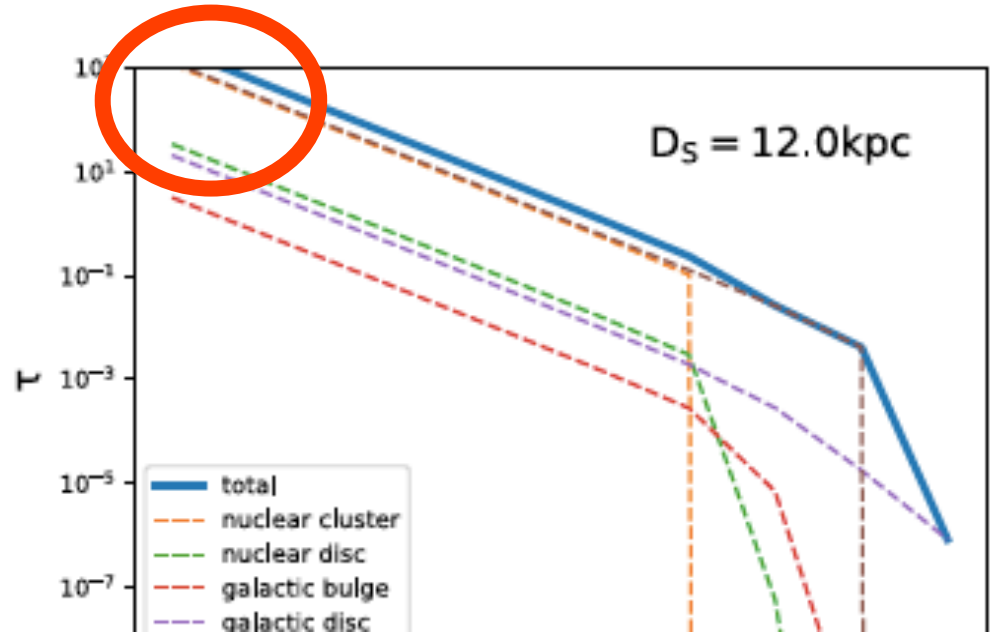


a



b





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 even rate of ~ 10^{-3} - 10^{-2} yr^{-1};

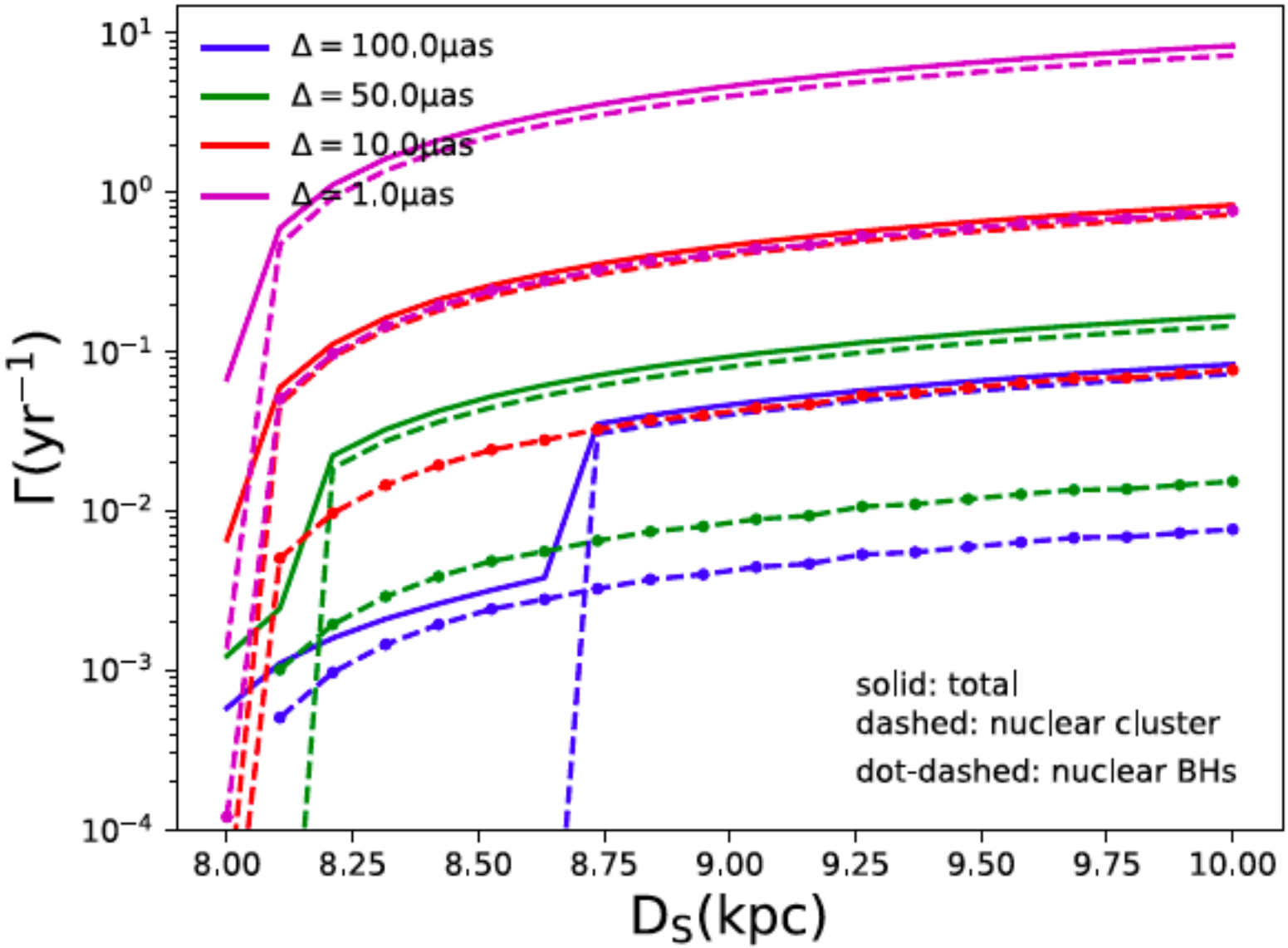
With 100 - 1000 stars with high astrometric accuracy (< 10 μas), one expects to find a few events by nuclear BHs alone each year.

Summary

We have been investigating the possibility to probe blac
hole astrophysics via gravitational lensing. The followin
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 microlensin of background stars.

Astrometric microlensing event rates for sources



AGN MICROLENSED BY LOCAL GALAXIES

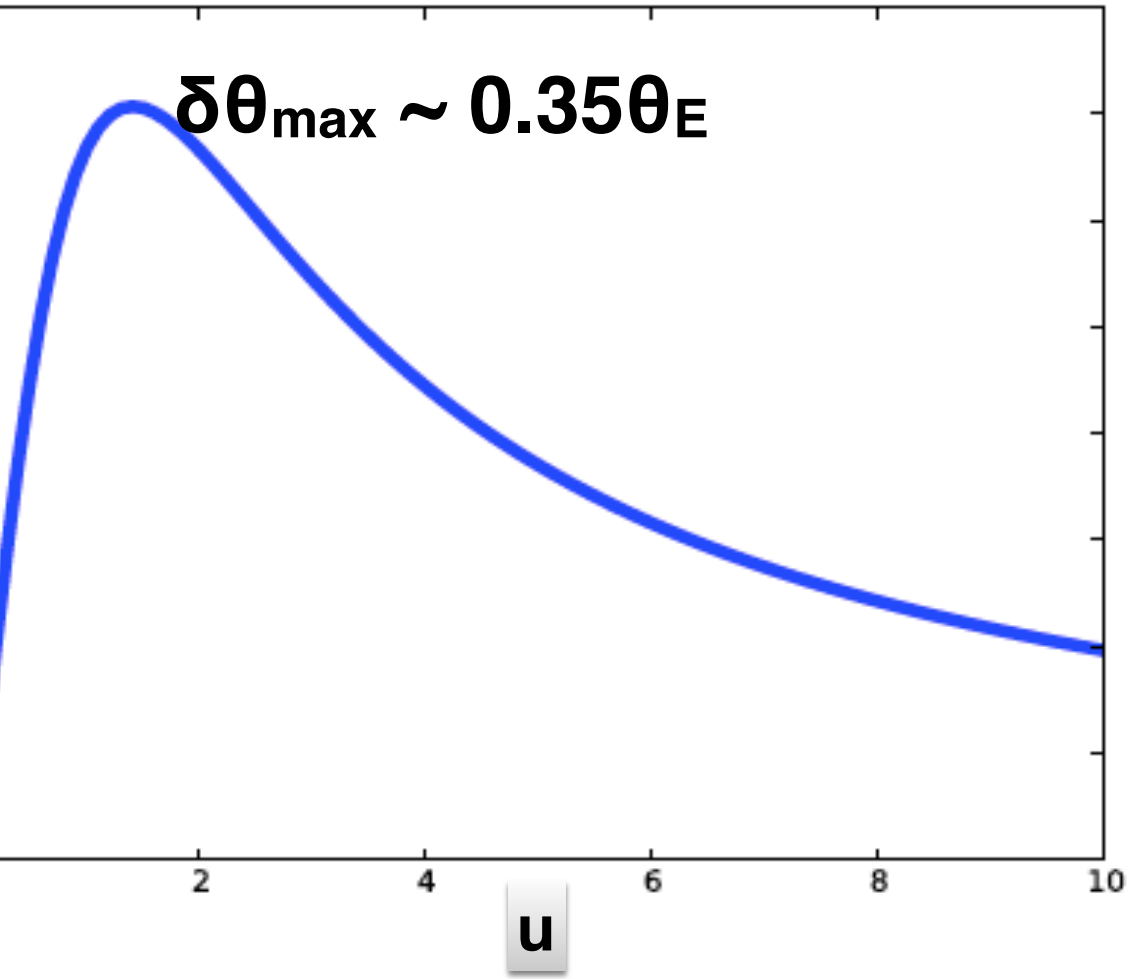
lts:

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

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

Dense monitoring is required to have a etter sampling of light curves, which hould be possible for selected regions

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



Assuming the astrometric cent
precision of an instrument Δ,

We assume that if $\Delta > \delta\theta_{max}$, c
section of astrometric microlen
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
100 μas, this factor is often >

AGN MICROLENSED BY LOCAL GALAXIES

od: We derive and estimate the detec

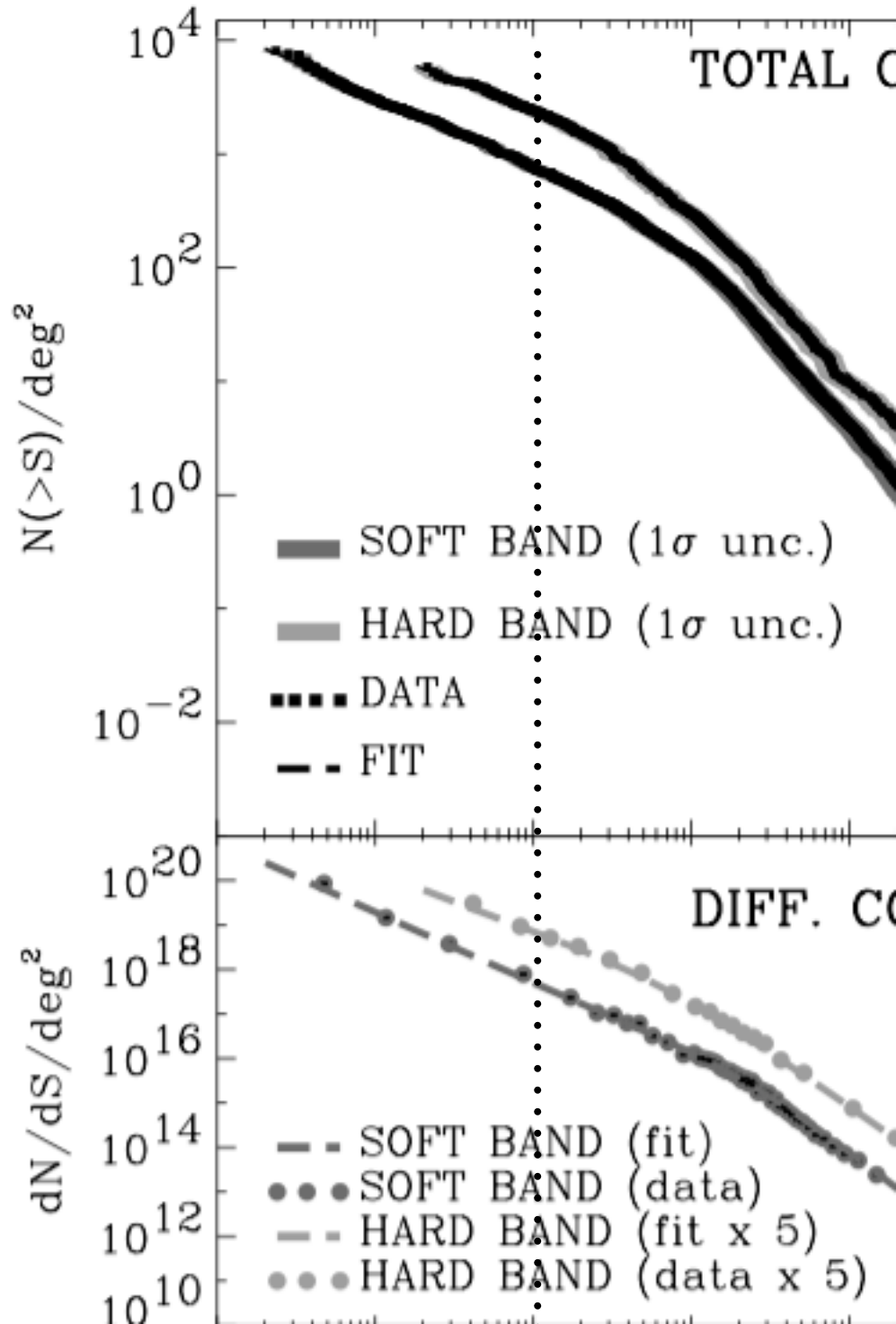
$$10^{-6}\mathrm{yr}^{-1}\left(\frac{M_L}{10^{10}M_\odot}\right)\left(\frac{t_E}{2\mathrm{yr}}\right)^{-1}\left(\frac{I}{80(}\right.$$

mass of lens objects

the avera
of backg

mate N(>S) of Moretti et al.
as derived from six different
data performed by ROSAT,
a and XMM-Newton.

cipal, the event rate can be very
we can mapping a large sky area
ge M_L) with high sensitivity
ge N(> S)). In reality, however,
ited by instrumental capabilities



AGN MICROLENSED BY LOCAL GALAXIES

lts:

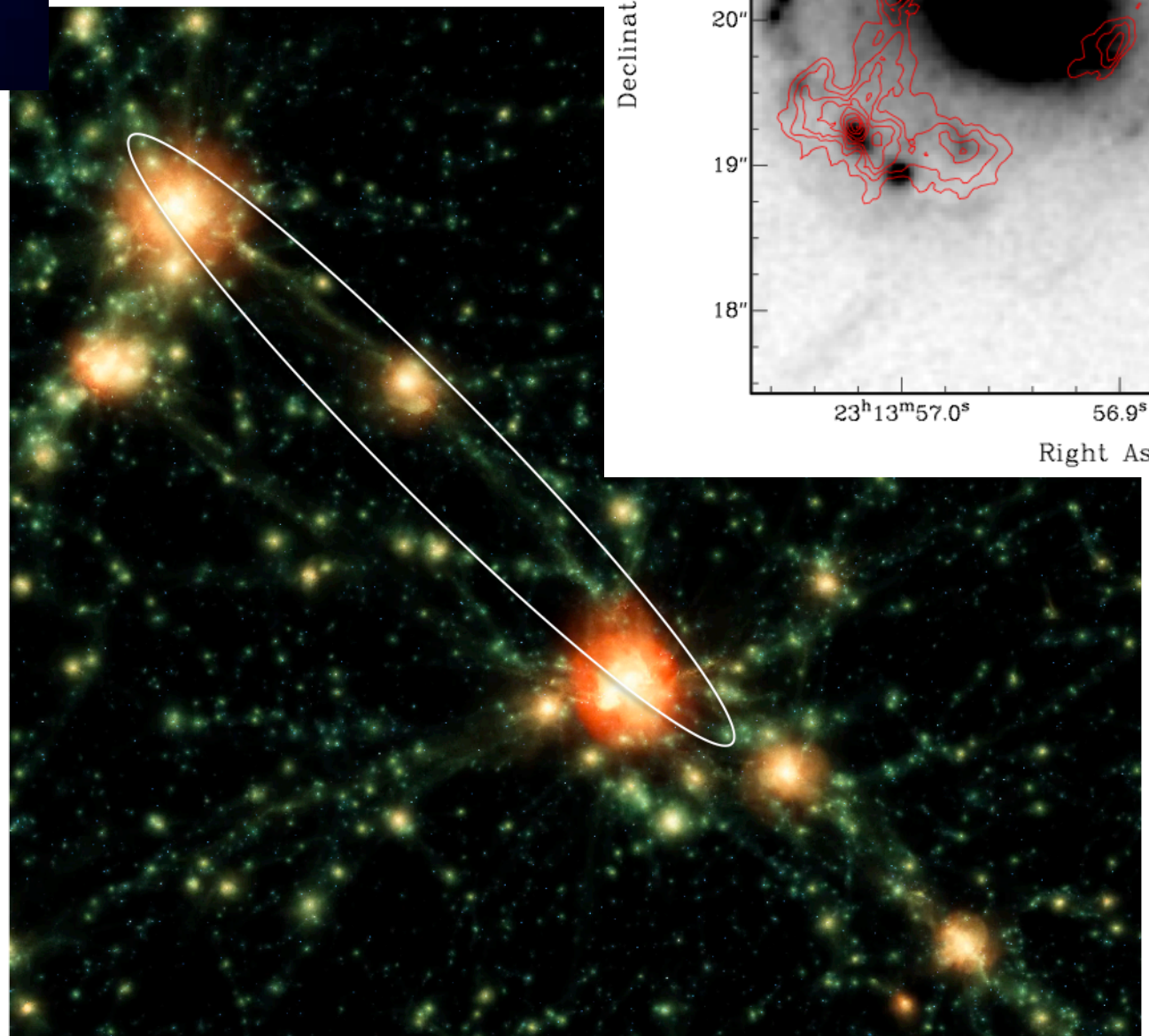
Current | Future

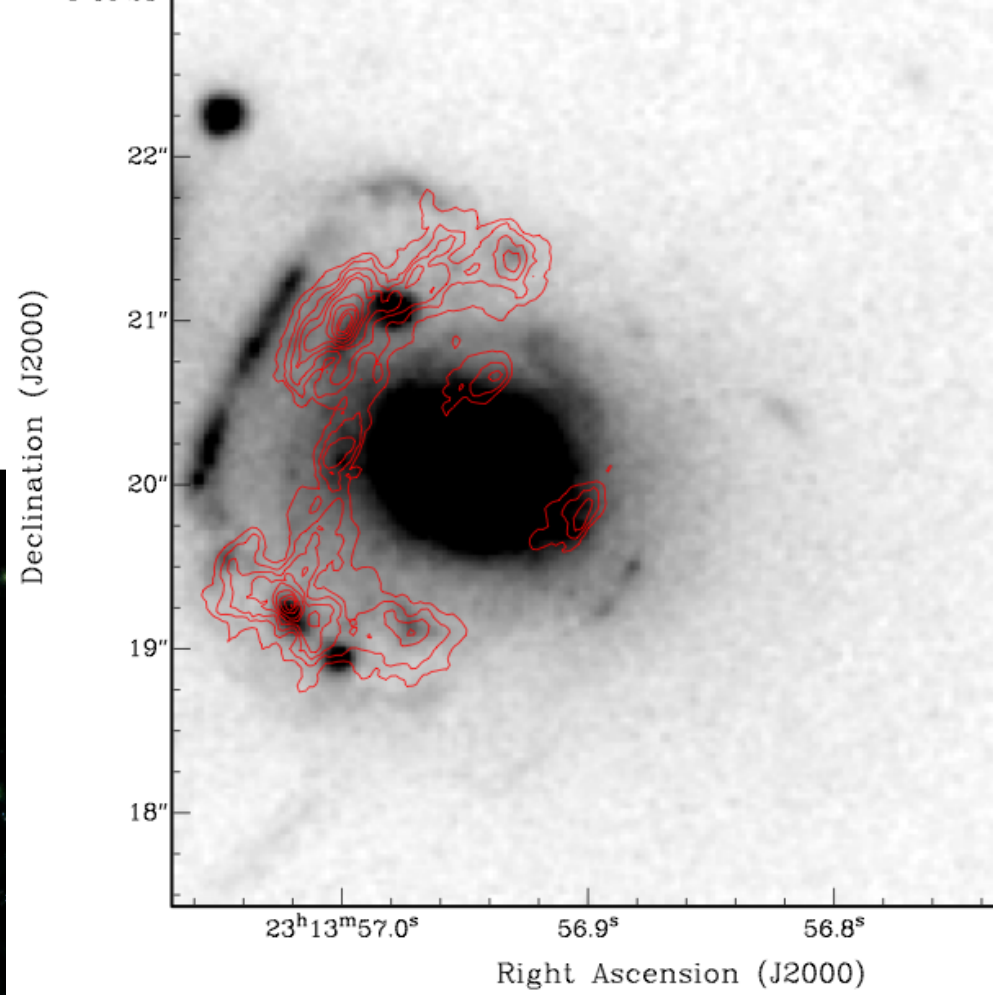
	Area	Γ (LogS = -15)	Γ (LogS = -16)	Γ (LogS = -17)
M31 Bulge	~ (4'.3)^2	0.02 yr^{-1}	0.07 yr^{-1}	0.25 yr^{-1}
MW Nuclear Cluster (<15pc)	~ (6'.4)^2	0.05 yr^{-1}	0.17 yr^{-1}	0.63 yr^{-1}
MW Nuclear Disk (<150pc)	~ (1°)^2	0.8 yr^{-1}	2.9 yr^{-1}	10.2 yr^{-1}
MW bulge	~ (7°)^2	6.0 yr^{-1}	21.0 yr^{-1}	75.0 yr^{-1}

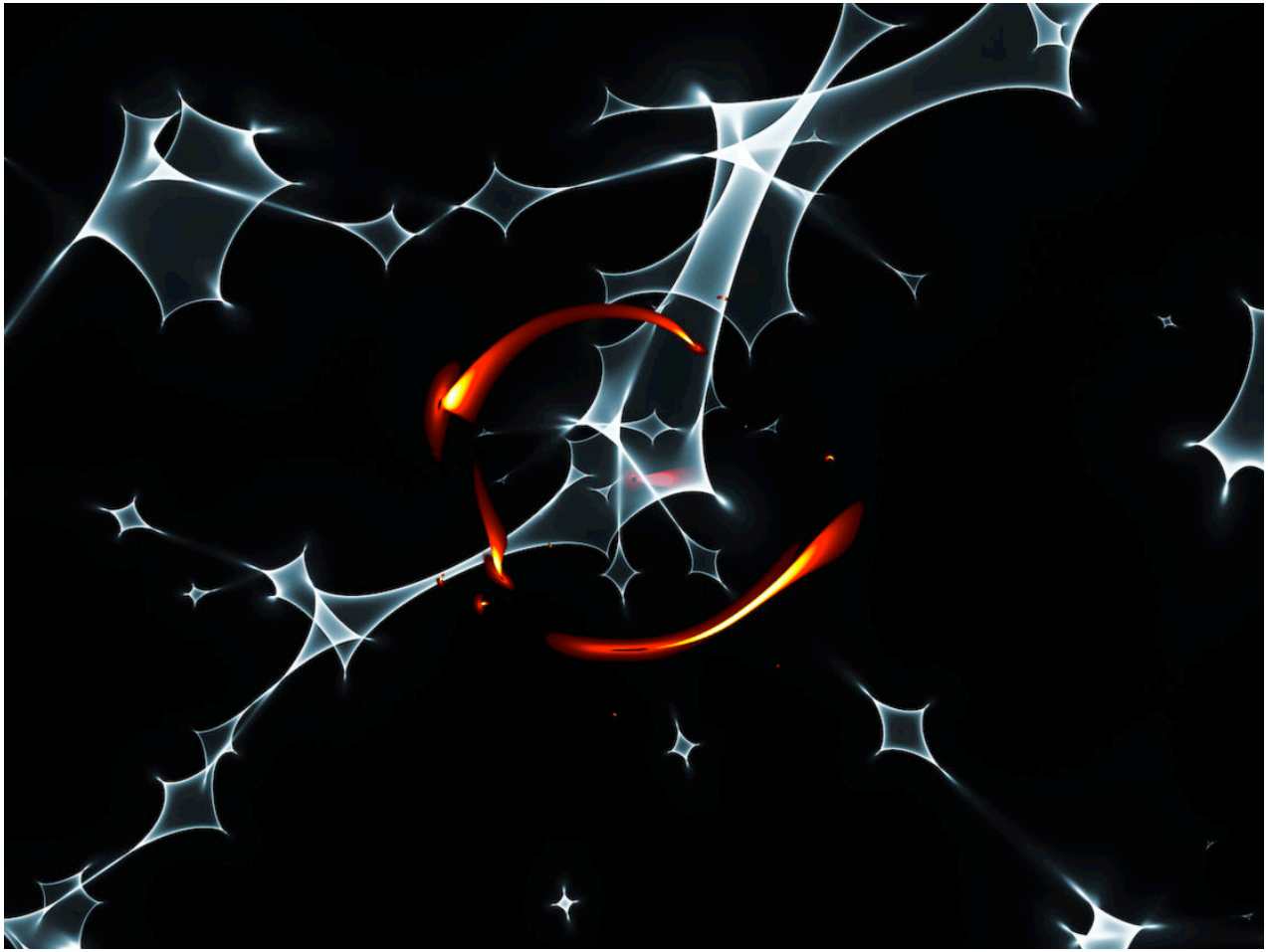
M-Newton, Chandra FOV: ~ (30')^2

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

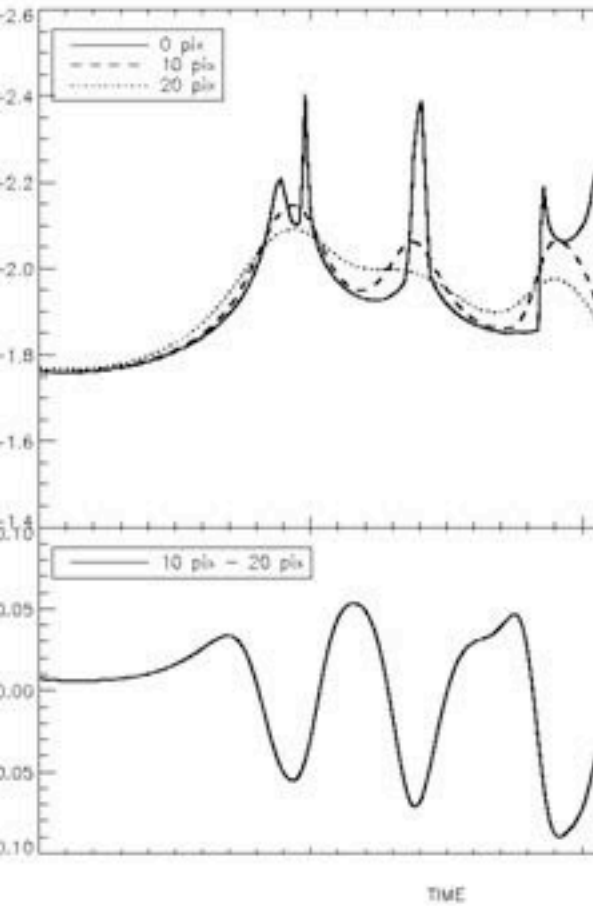
t generation of X–ray telescopes, e.g. Athena and Lynx, will have high

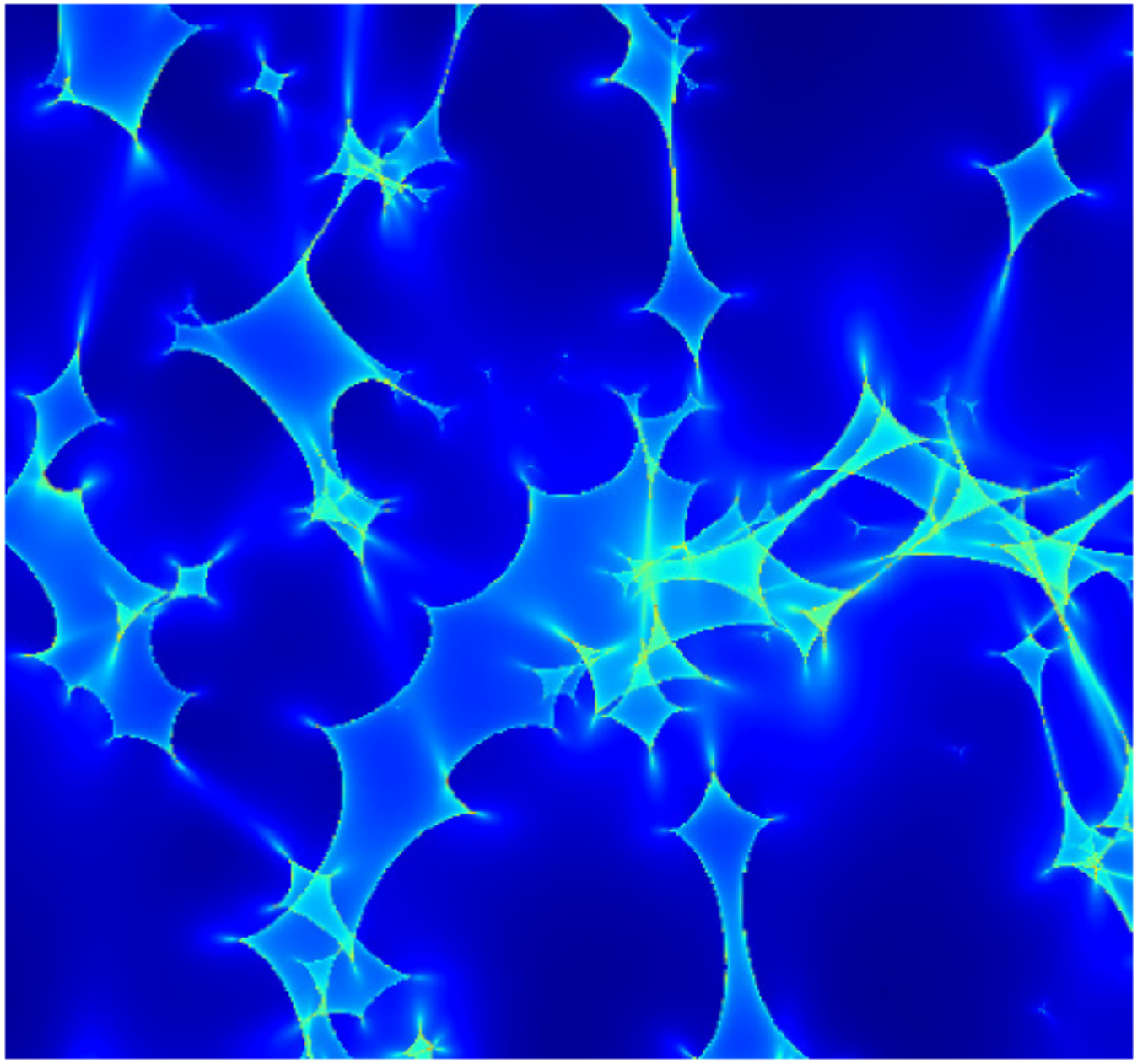



22″
21″
20″
19″
18″
Declination (J2000)
23h13m57.0s
56.9s
56.8s
Right Ascension (J2000)

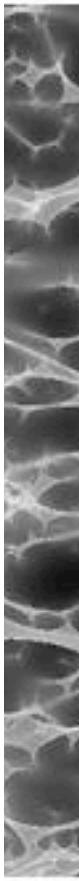


ight and color curve for the given track





d)



$\left(2.54 \times 10^{17}\sqrt{0\right.$

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 $\langle M_* \rangle = 0.3M_\odot$, surface mass densities $\kappa_c = 0.4$, $\kappa_* = 0.2$, and external shear $\gamma = (0.2, 0)$. The image is of high resolution 6400×6400 and size about $12\theta_E \times 12\theta_E$ where θ_E is the Einstein ring angle of a lens of mass $\langle M_* \rangle$. The host computer node, Xeon Phi

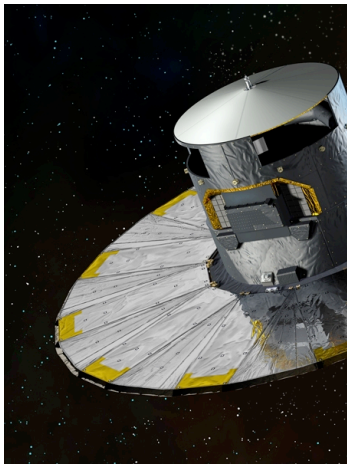
Near-field Microlensing of AGN

jective: Constraining the size and geometry of accretion d
onae by obtaining the X-ray lightcurves of microlensed AGN.

propriate event duration
lay-year) for lightcurve
pling --> the lenses need
e local.

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

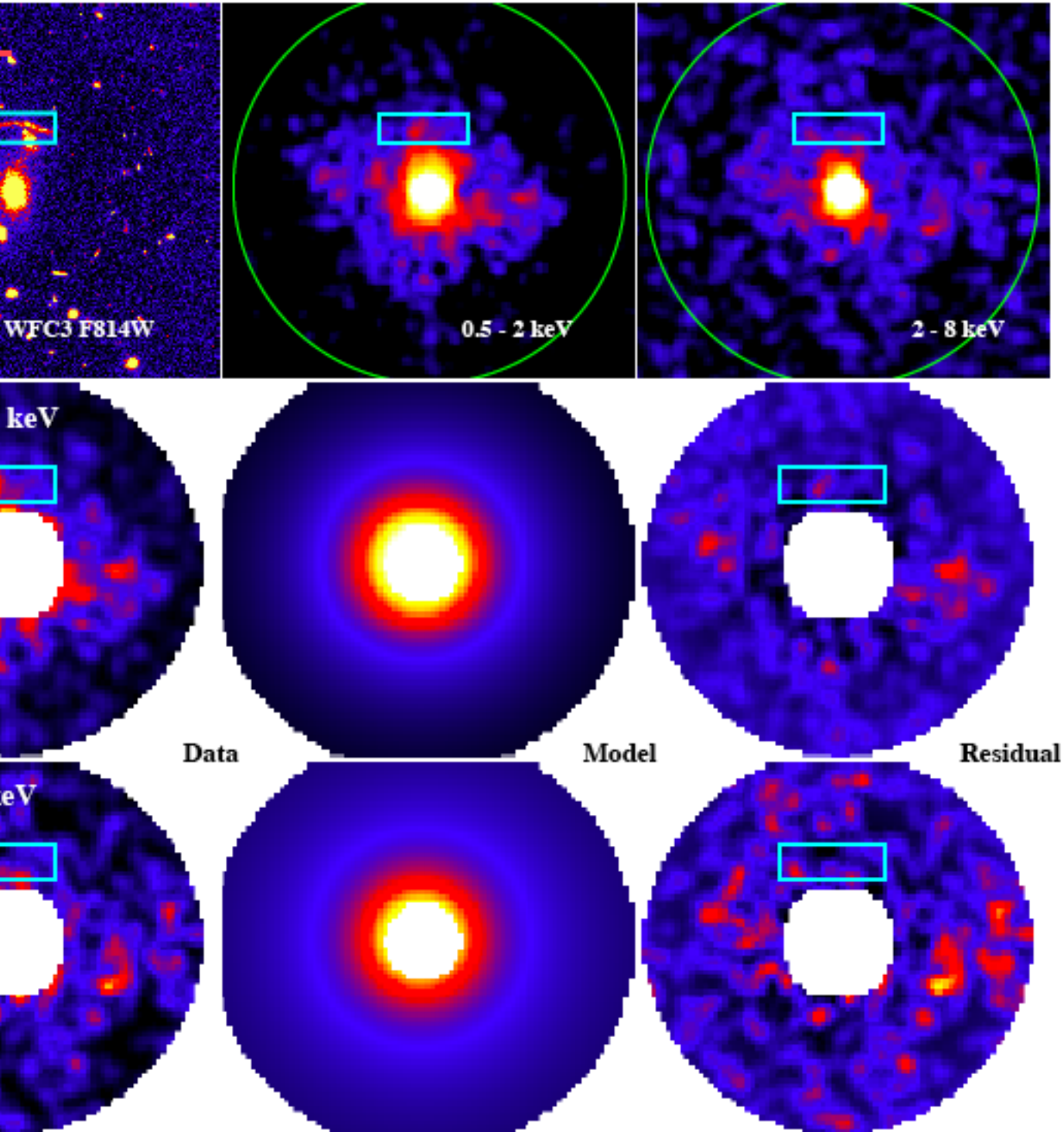
oss-matching *The Half Million Quasars* catalog (Flesch 2015)
n Gaia DR1 (Lindegren et al. 2016)



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

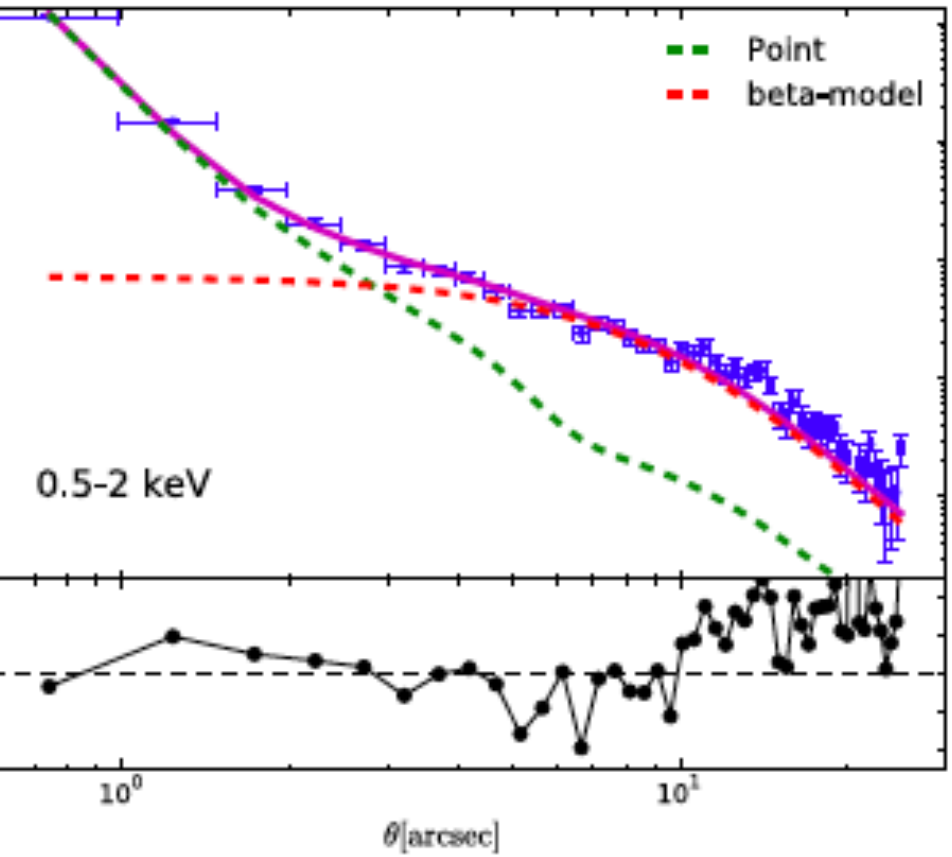
Gaia DR2 is scheduled for this month!

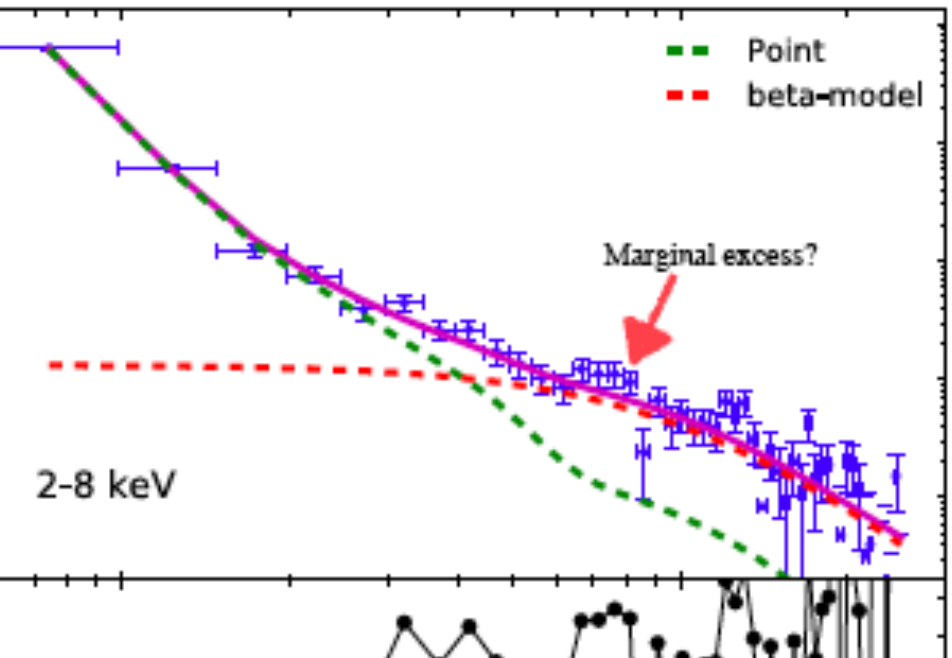
Existing X-ray Observations



- Chandra observati
3C220.1 – a galax
cluster at z ~ 0.61
- Total exposure: 1
- The lensed galaxy
is at z ~ 1.5 (Worr
al. 2001).
- The lensing cluste
known to be a maj
merger, which
complicates the X
morphology.

Existing X-ray Observations





- Very marginal detection of dif
X-ray emission in 2-8 keV, or
keV in the rest frame of the le
galaxy.
- There are existing/upcoming
Chandra observations of simil
lensing systems selected from
SDSS (PI: Matt Bayliss); a few
them have also been selected a
JWST early release science ta
- But these systems generally ha
too low star formation rates an
Chandra exposures to improve
detection significantly.

Dedicated new observatio