Monsters on the Move: A search for supermassive black holes undergoing gravitational recoil

Yashashree Jadhav

Dr. Andrew Robinson

ysj1195@rit.edu

PhD candidate

Outline

- Background
  - SMBH binary formation and merger
  - Gravitational Recoil
  - Post recoil oscillations
- Searching for displaced SMBH
  - Sample definition
  - Analysis
  - Results
- Future Work

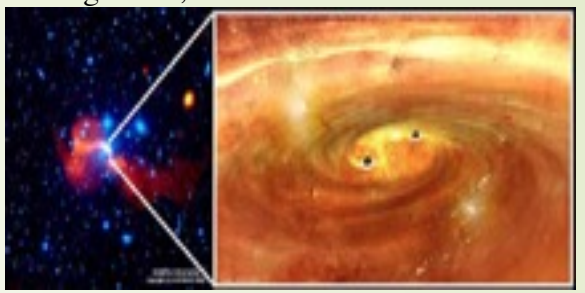
Central supermassive blackhole

+

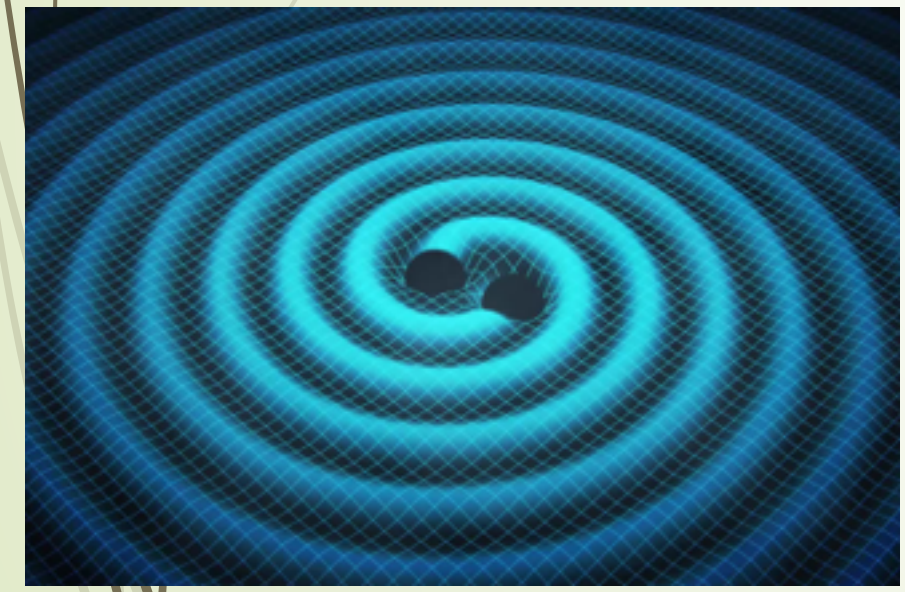
Galactic mergers

=

Begelman, Blandford & Rees 1990



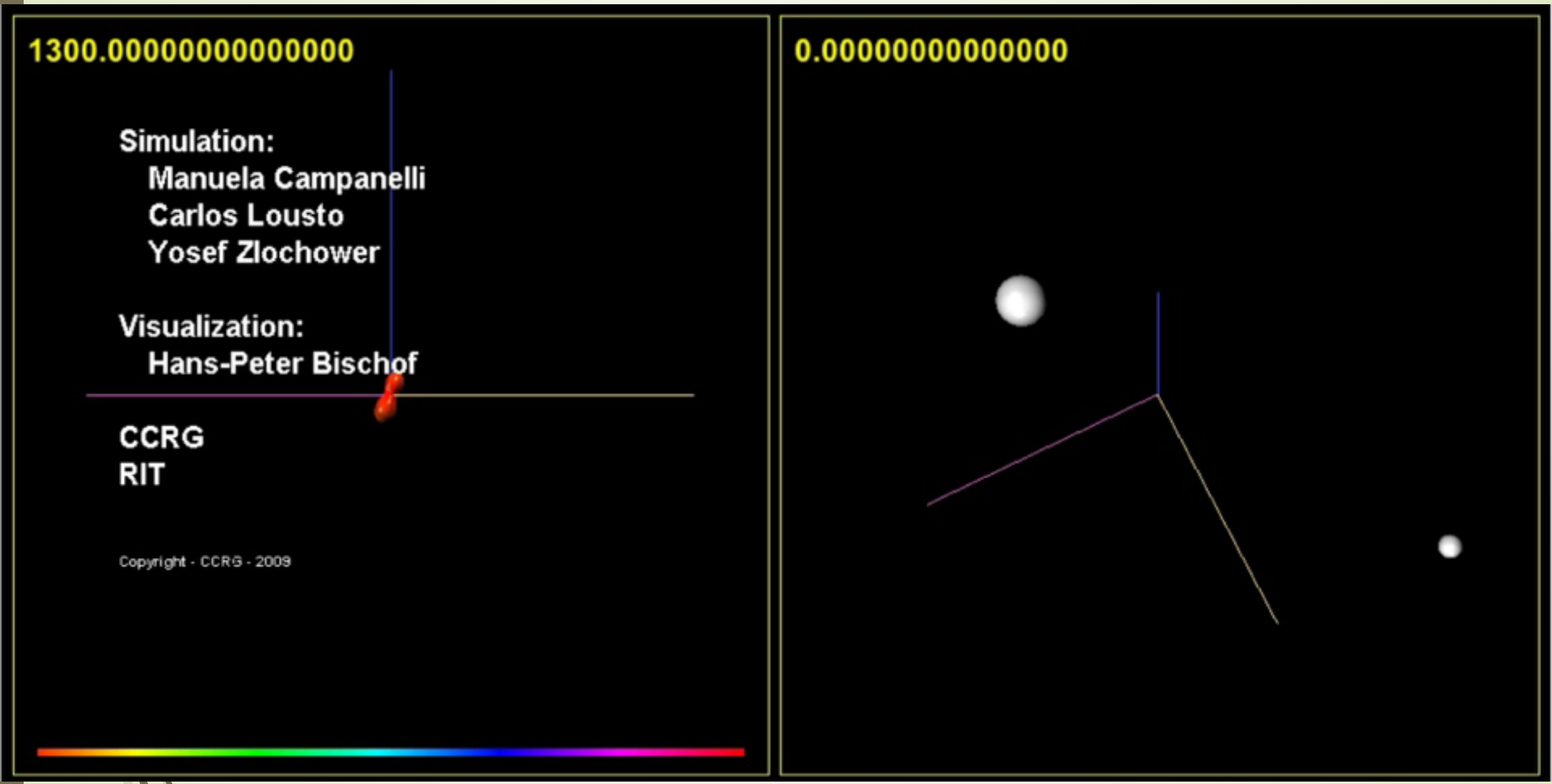
Binary SMBH forms in merged galaxies

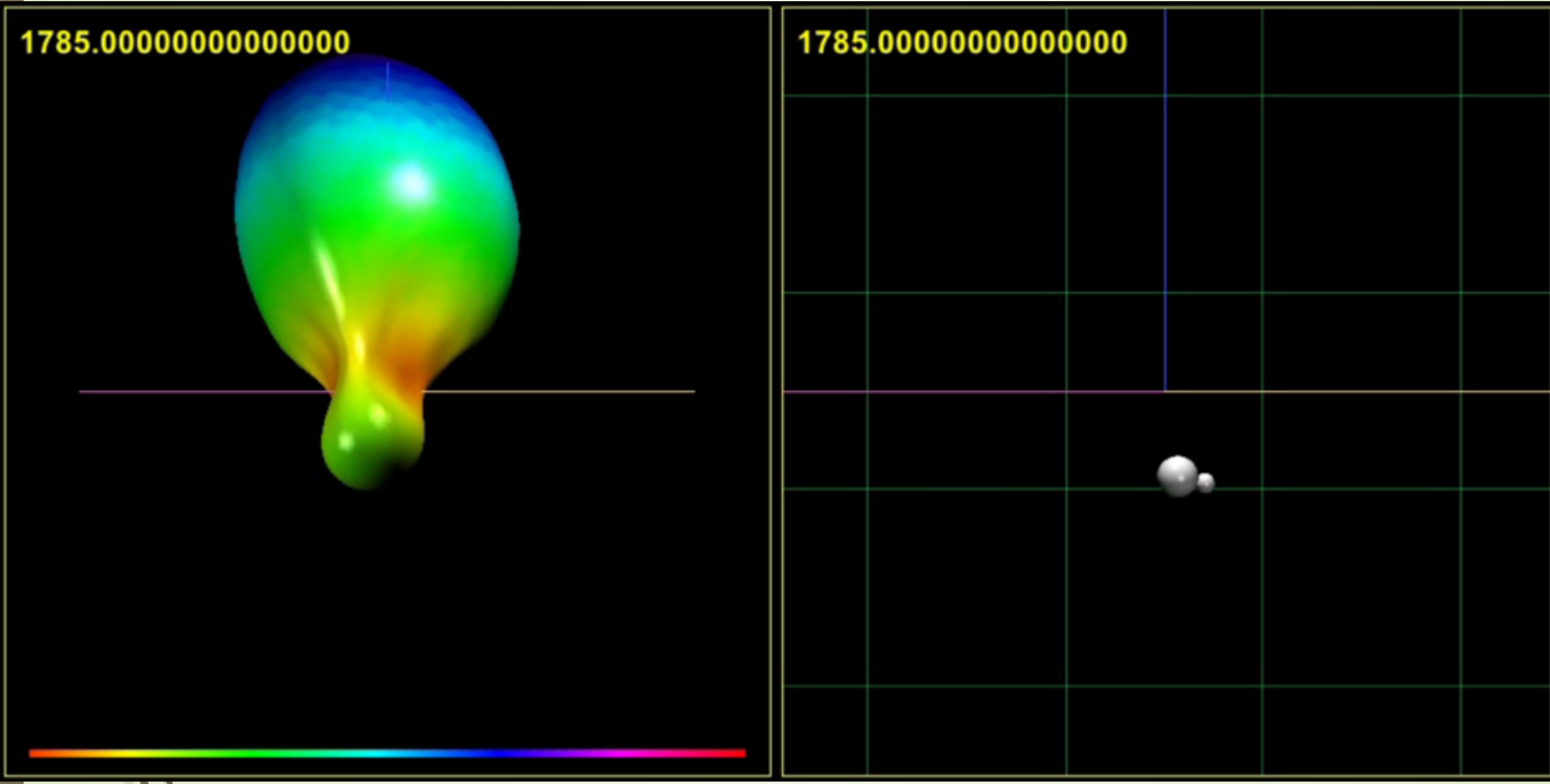


Binary SMBH → gravitational waves driven merger

Can we/have we detected kicked/ recoiling SMBH?

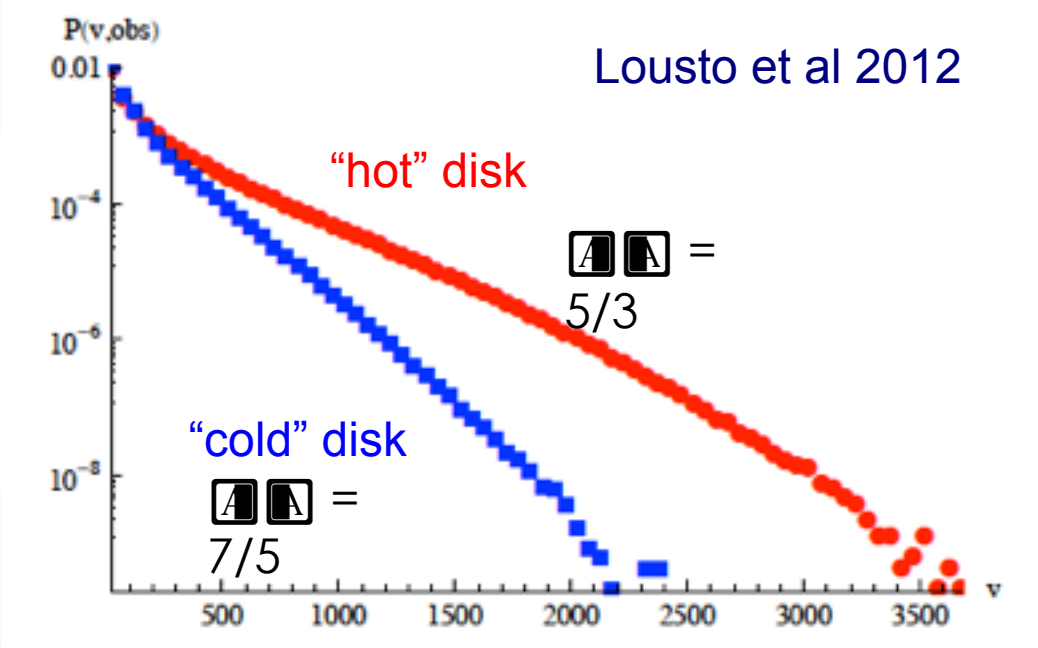
Not to scale


1300.00000000000000
Simulation:
Manuela Campanelli
Carlos Lousto
Yosef Zlochower
Visualization:
Hans-Peter Bischof
CCRG
RIT
Copyright - CCRG - 2009
0.00000000000000


1785.00000000000000
1785.00000000000000

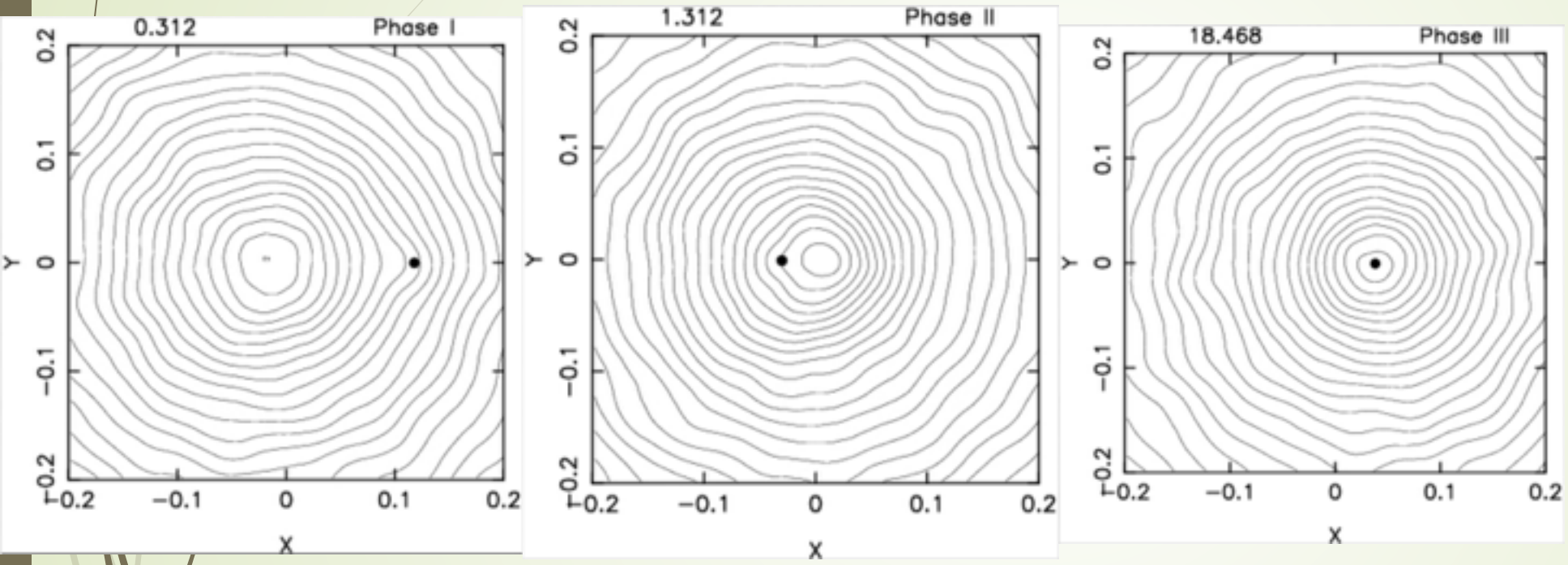
Kick velocity distributions

- Initial parameters affecting kick velocity:
  - Orbital and spin configurations of BH
  - Binary SMBH mass ratio
- Partially aligned spins → 'Hangup Spin Configurations'
  - Kick velocities up to ~5000 km/s



Probability distribution of recoil velocities (km/s) along the line of sight for spin magnitude & direction distributions predicted by accretion simulations. □□ is the index for the equation of state

Post-recoil Trajectory



Gualandris & Merritt 2008

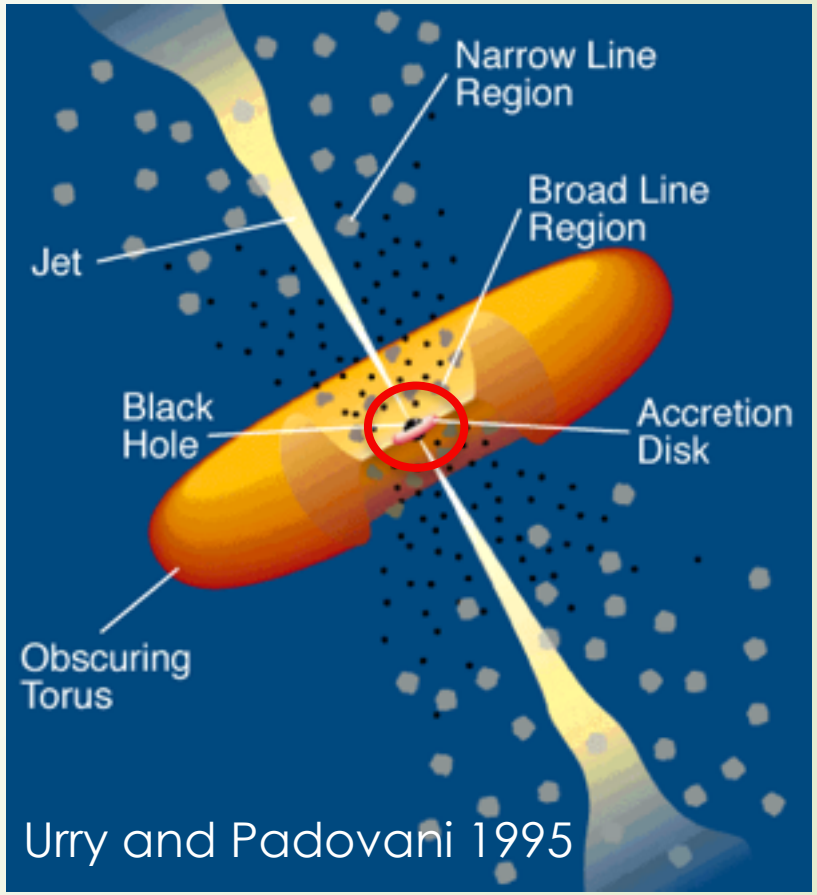
- Phase I: Harmonic oscillations
  - t ~ 10^7 years
- Phase II: Amplitude 10 – 100 pc
  - t ~ 10^9 years
  - SMBH appears displaced from center of the galaxy
- Phase III: Brownian motion
  - SMBH → thermal equilibrium with surrounding stars

Active Galactic Nuclei

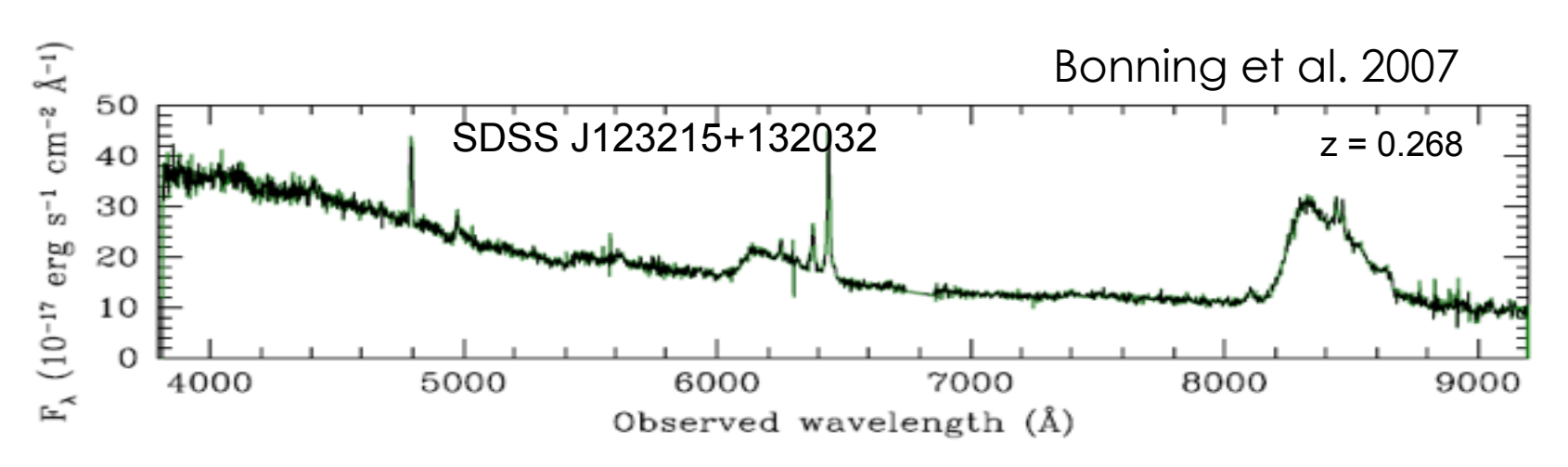
- Kicked black hole is seen as a displaced AGN
  - Broad line region and accretion disk remain attached where $V_{Keplerian} > V_{recoil}$

$$r_G = (0.43\ \text{pc})\left(v_{recoil}/10^3\ \text{km s}^{-1}\right)^{-2}\left(M_\bullet/10^8\, M_\odot\right)$$

  - Radius up to which materials remain attached to the kicked black hole
  - Narrow line region and torus are left behind (depending on kick velocity)



Observational evidence



- Two types of offsets
  - Velocity offset – offset between Broad Line Region and Narrow Line Region
    - Only velocity offsets due to larger kicks will stand out but these are rarer
  - Spatial offsets – between the AGN and the galaxy center
    - Need either large offsets or events in nearby galaxies to be detectable

Motivation

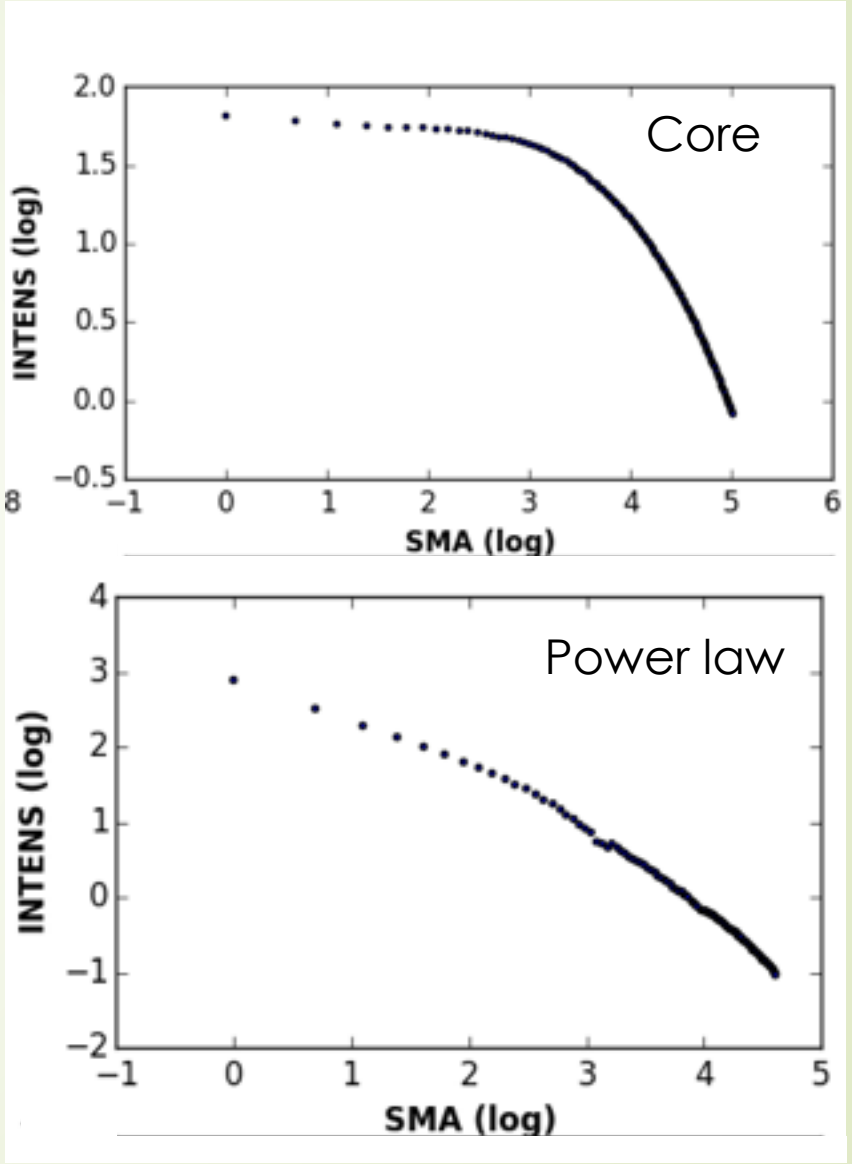
- Time scale of galaxy mergers comparable with timescale of recoil oscillations → 1 Gyr
- After merger the SMBH continues to accrete
  - Identified as AGN
- Expect to see such recoiling SMBH even in nearby elliptical galaxies which have undergone recent mergers

Sample selection

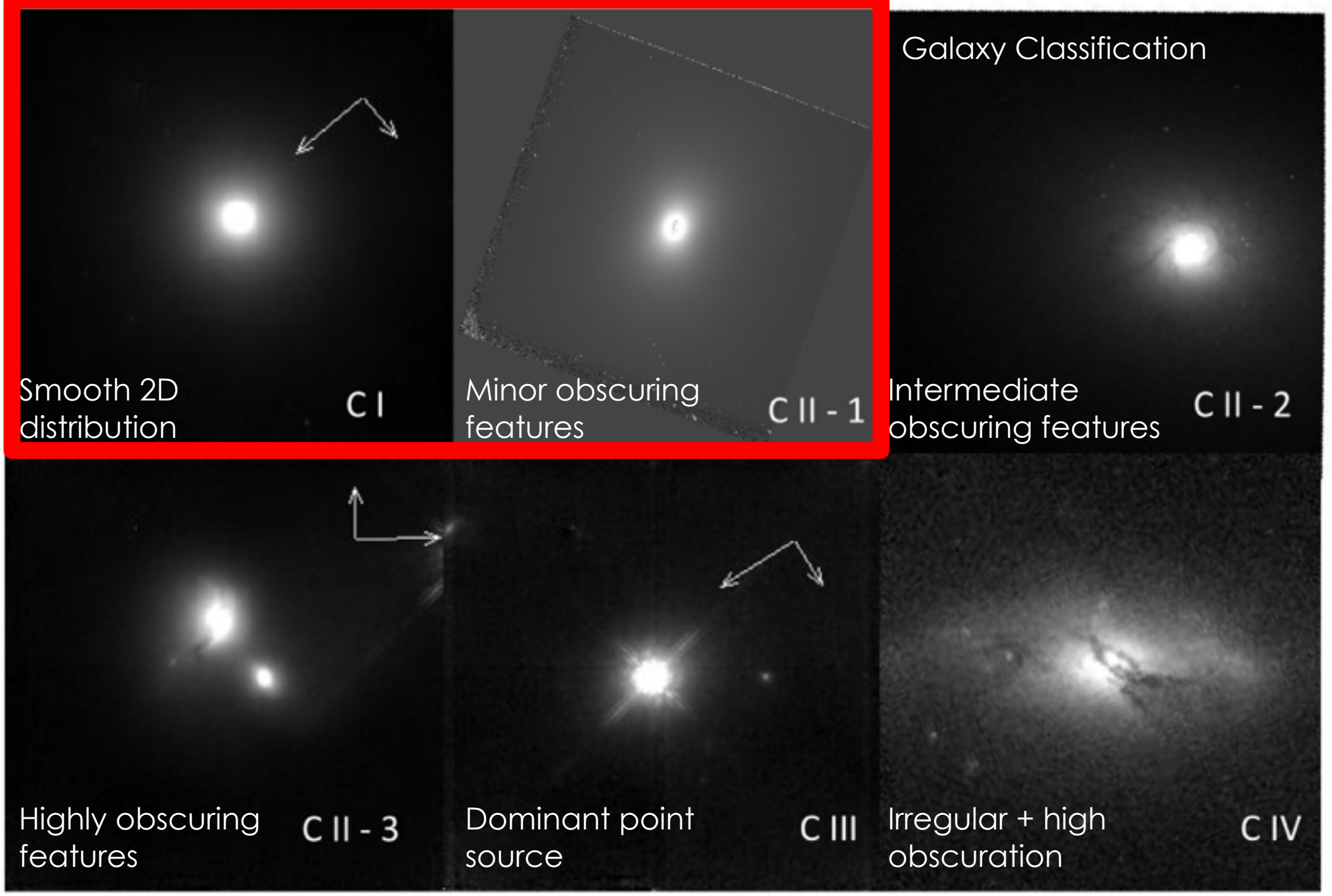
- Expect small displacements : 10-100pc
- z <0.3
- Elliptical galaxies with an identified (unobscured) AGN point source

- Previous by Lena et al 2012
  - 14 nearby core elliptical galaxies
- Expanded sample (from previous studies on radio identified AGN) add references to the studies
  - Z <0.3
  - 51 core
  - 45 power law

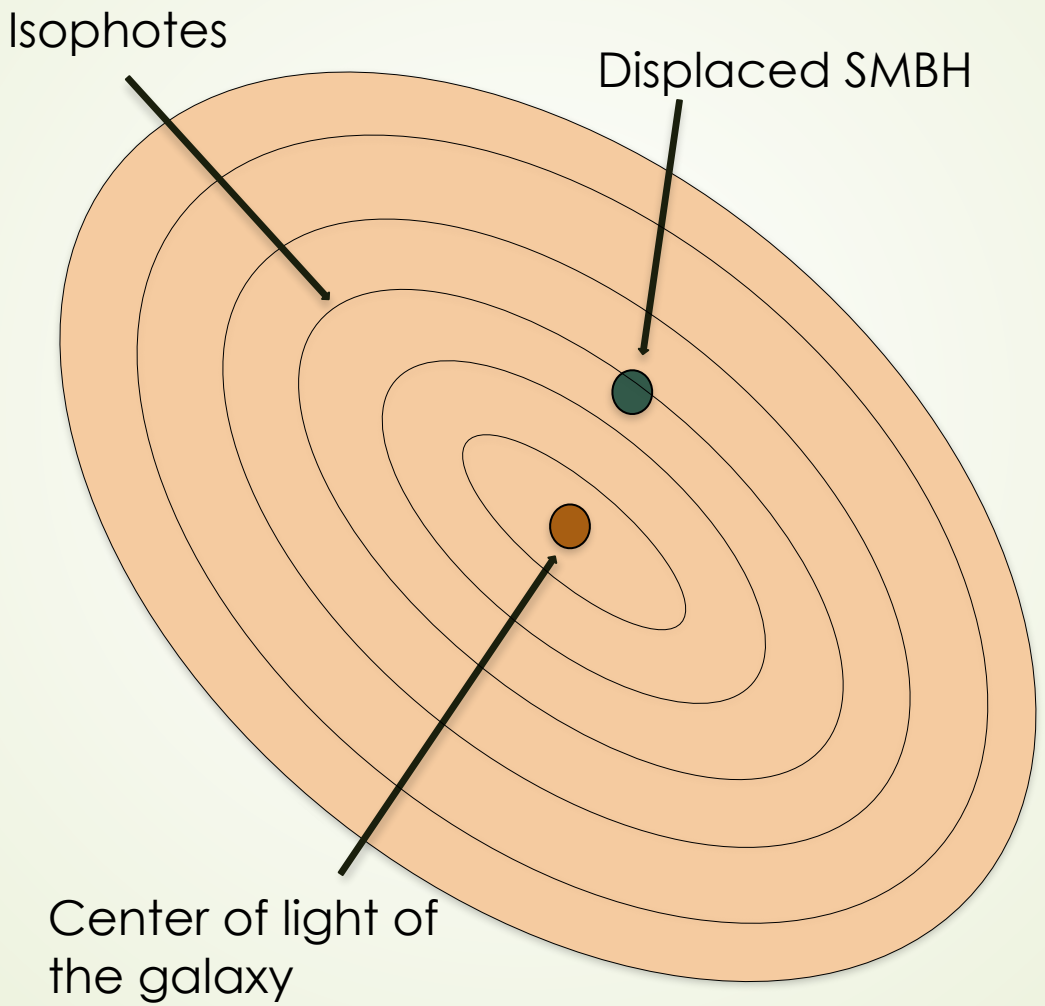
- Most images are taken from archival Hubble Space Telescope data
  - New IR images were obtained for 5 objects without any IR images in the archive



Galaxy Classification

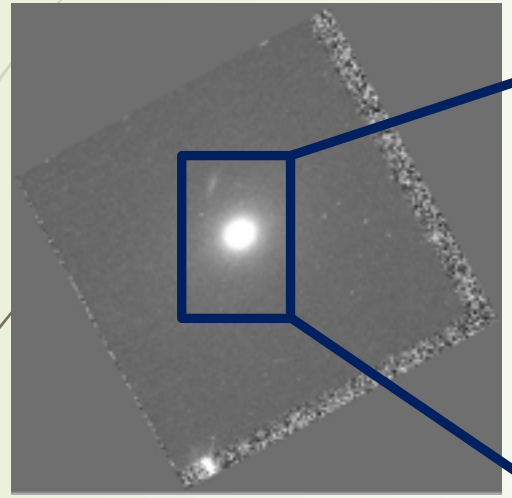


Analysis : HST image analysis

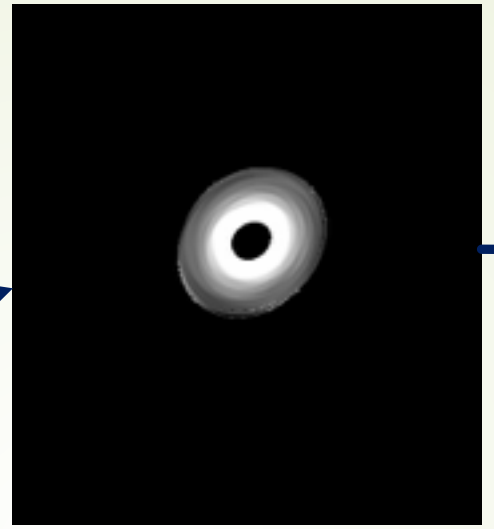


Not to scale

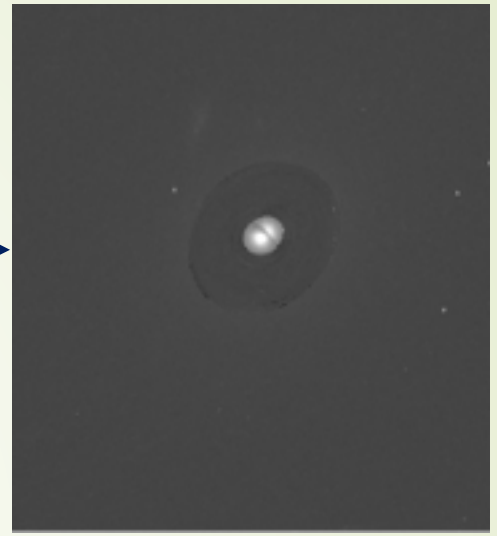
Part 1
2-D isophotal analysis to find photocenter



Original image: 3C076.1
z = 0.032489
WFPC2/F555W/PC1



Model of galaxy using *Ellipse* (*Iraf)* to fit isophotes



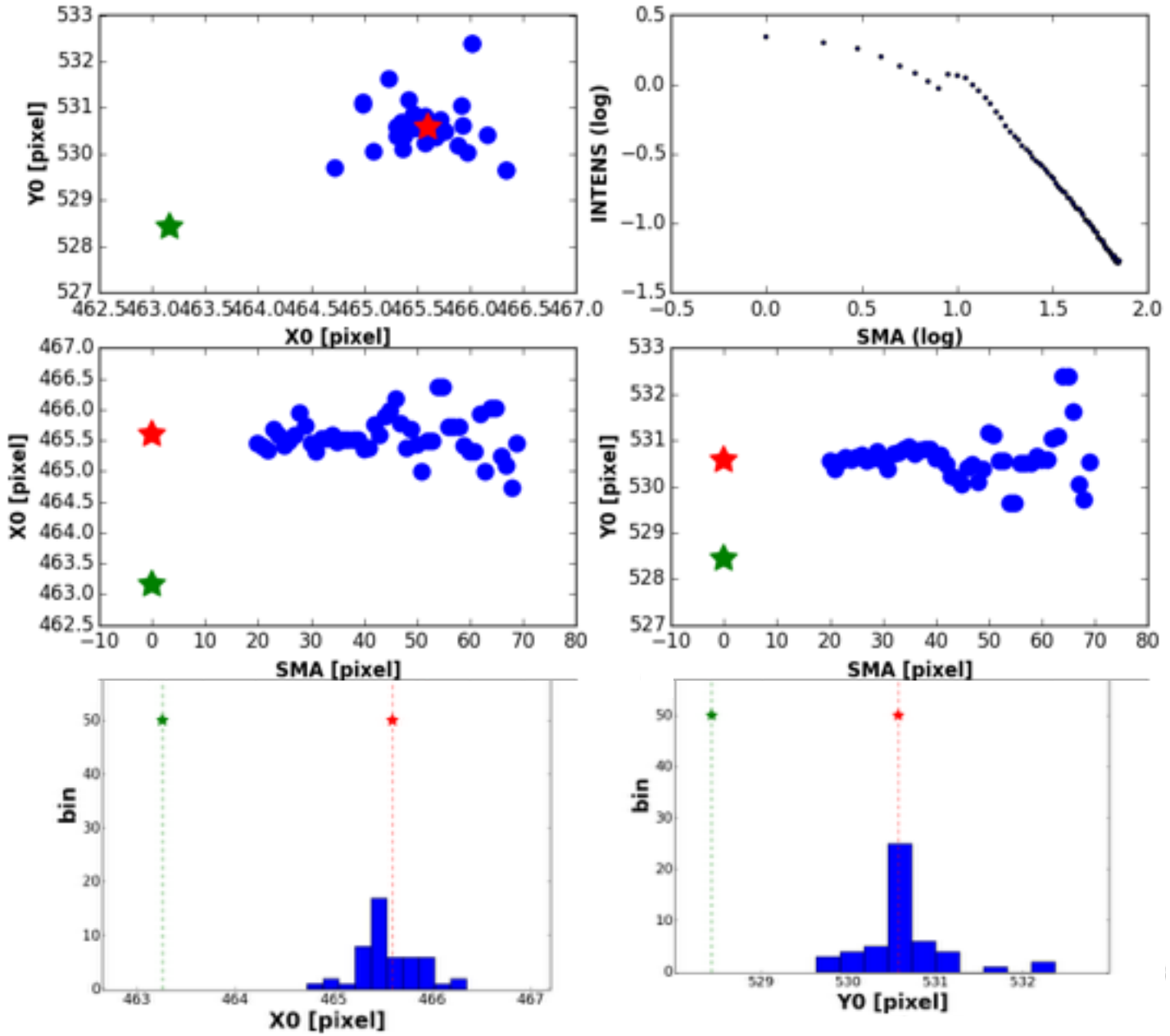
Residual image

Part 2
Unsharp masking to find AGN point source

Median smoothed image

Median subtracted residual image to show position of SMBH

Results
Core Galaxy
3c076.1



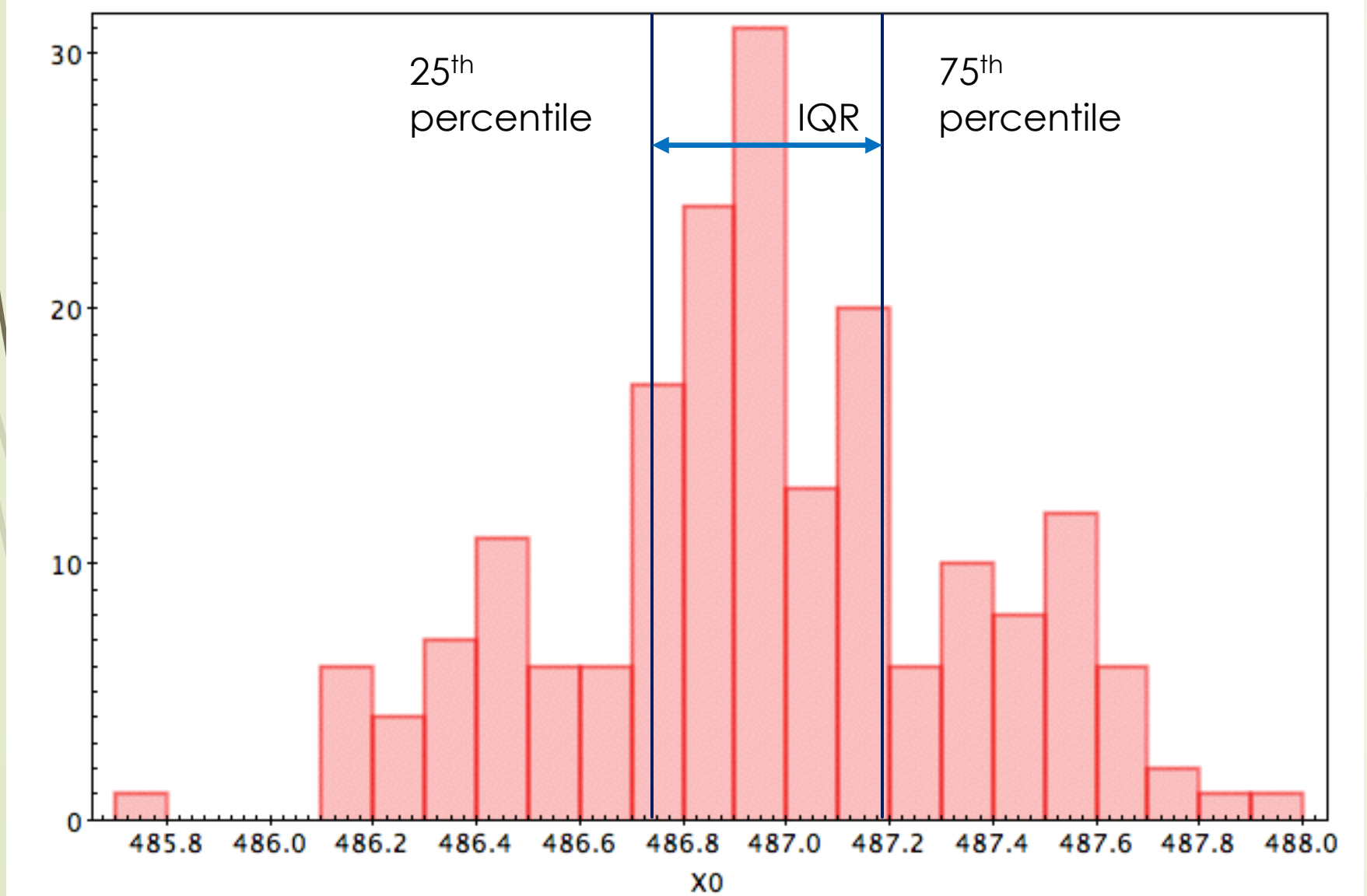
Legend

Isophote centers
Error ~ 0.3 pixel

Flux weighted avg

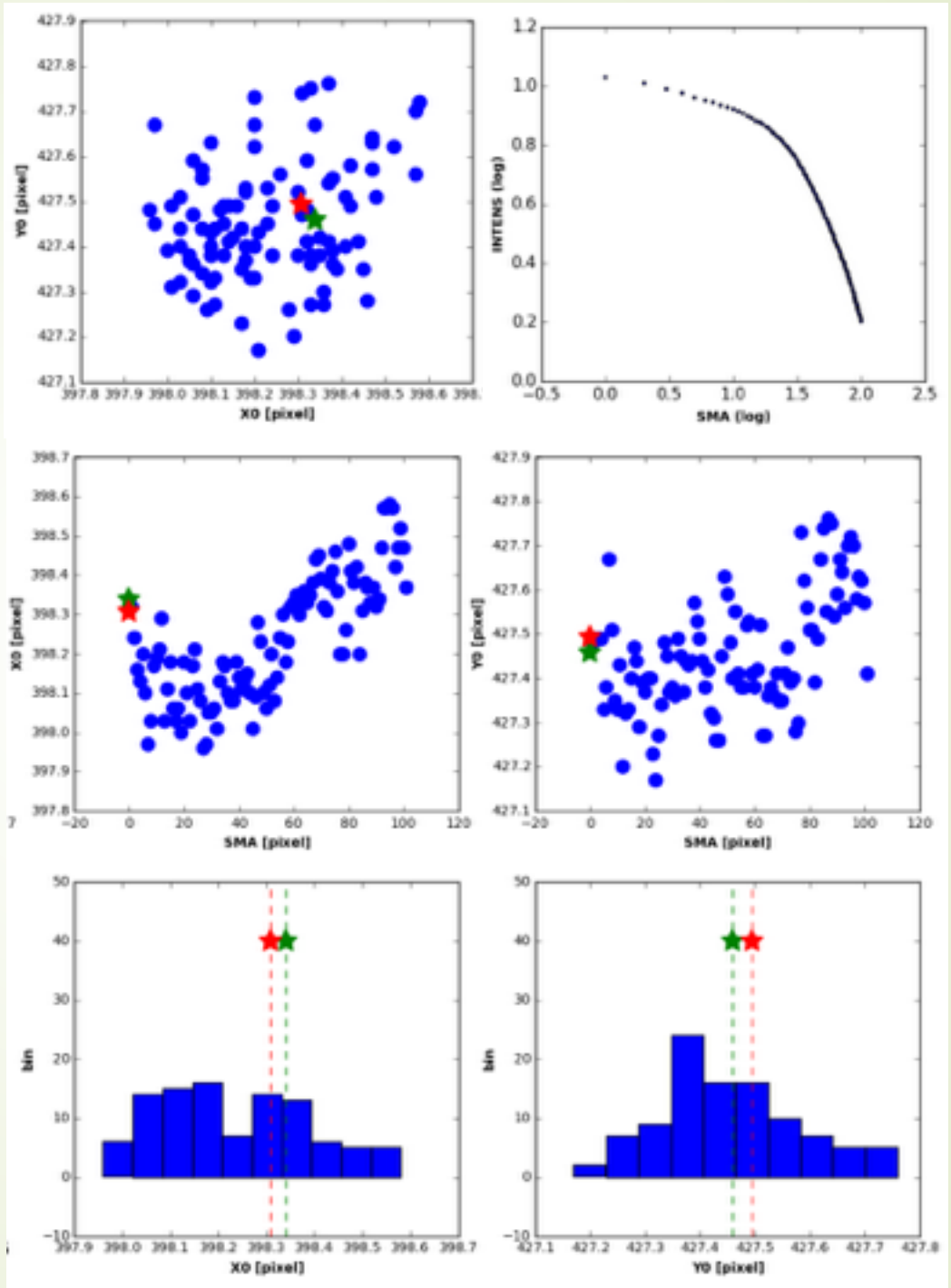
AGN position

Inter Quartile Range

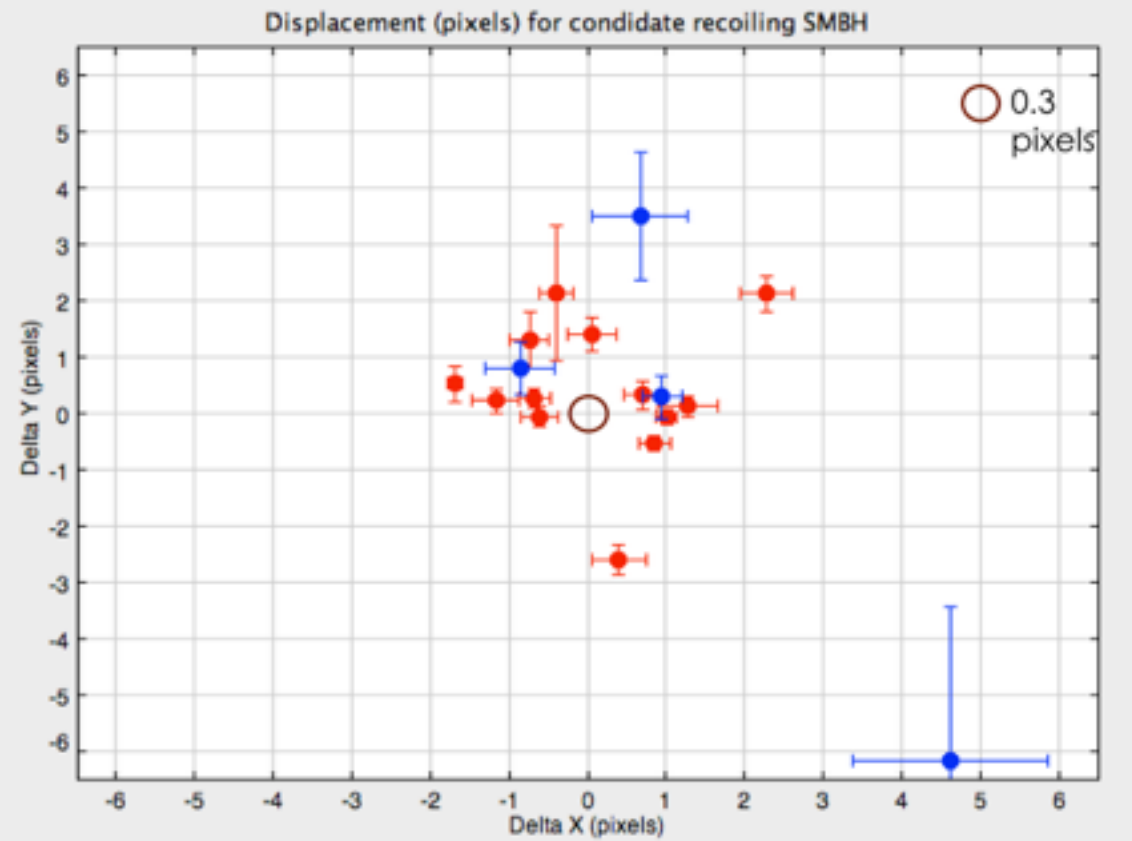


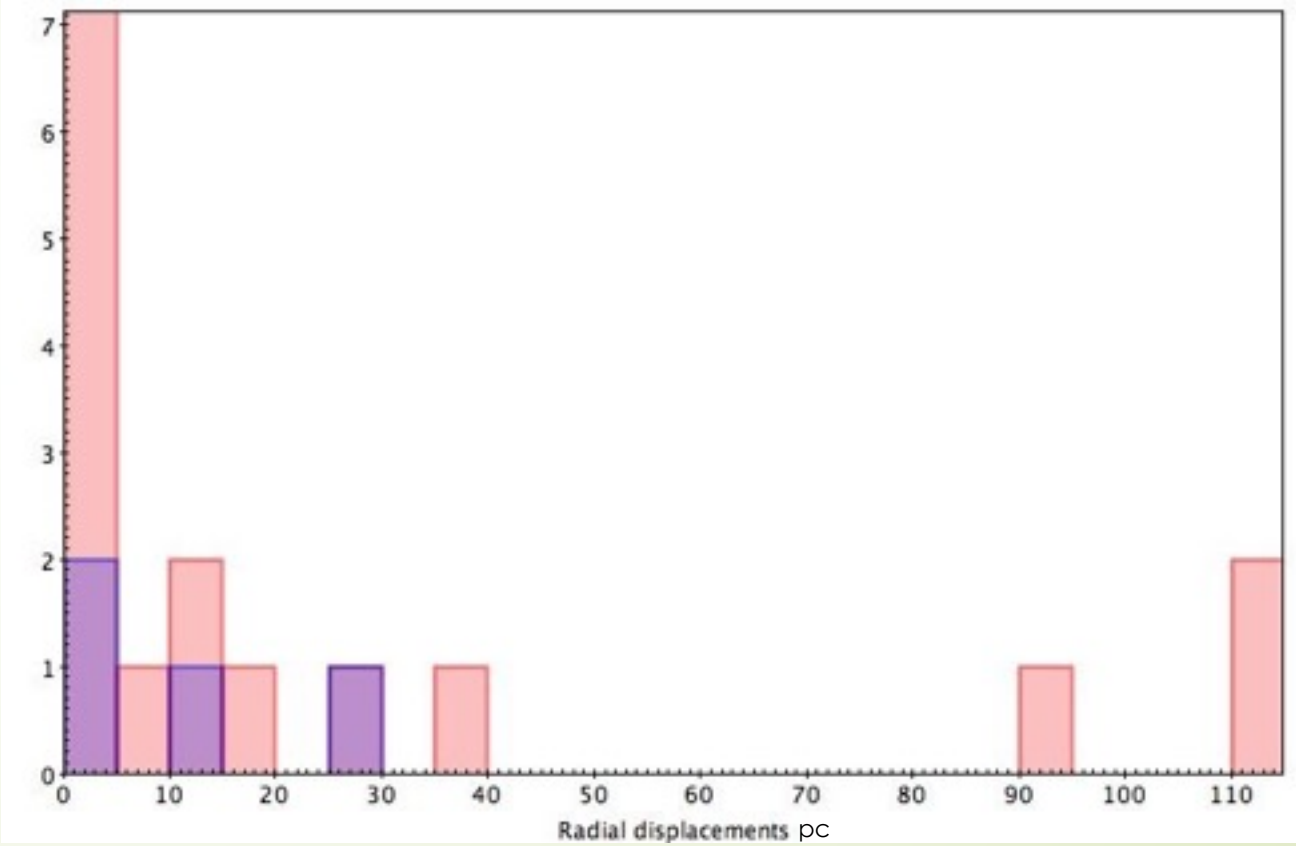
- Null
  $\Delta x, \Delta y < 0.8$ IQR
- Low
  $0.8\text{IQR} \leq \Delta x, \Delta y < 1.6\text{IQR}$
- Intermediate
  $1.6\ \text{IQR} \leq \Delta x, \Delta y < 2.4\ \text{IQR}$
- High
  $2.4\ \text{IQR} \leq \Delta x, \Delta y$

Example null result



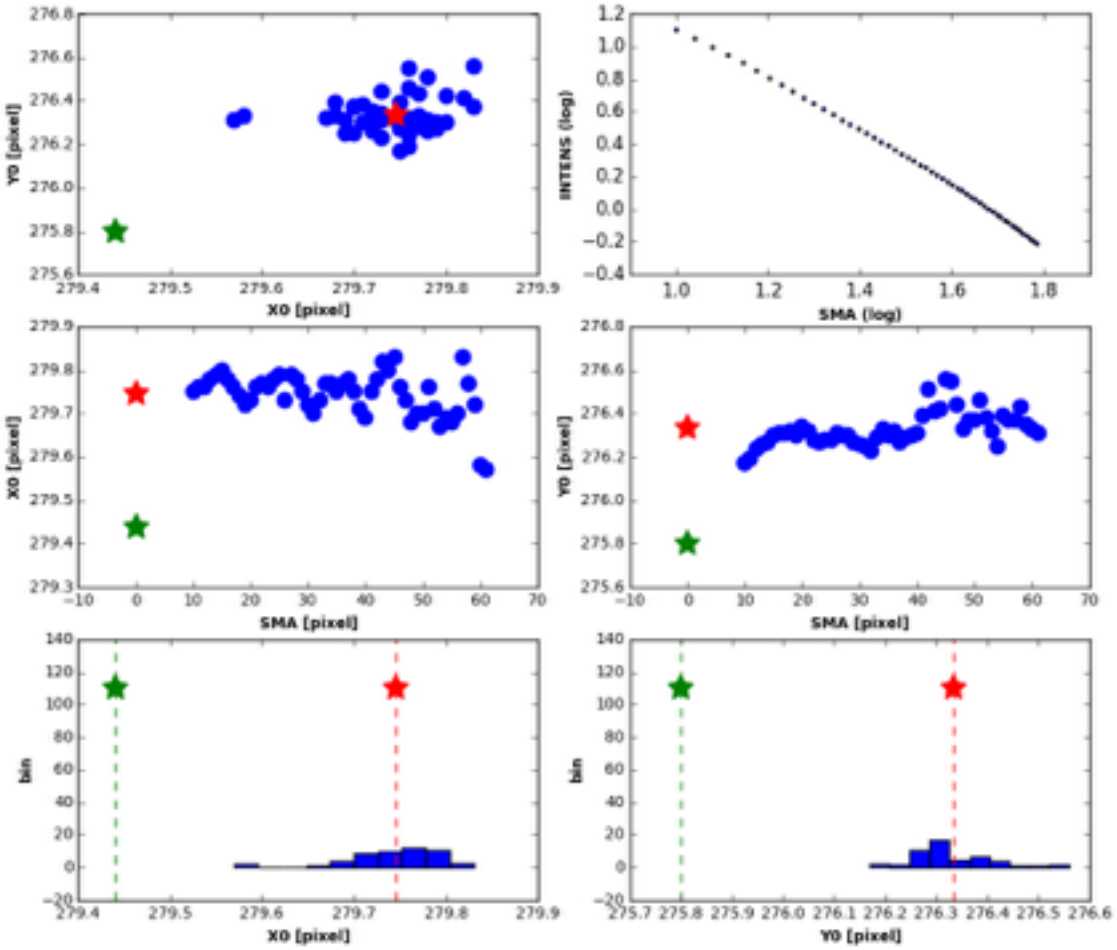
Results of WFPC2 analysis



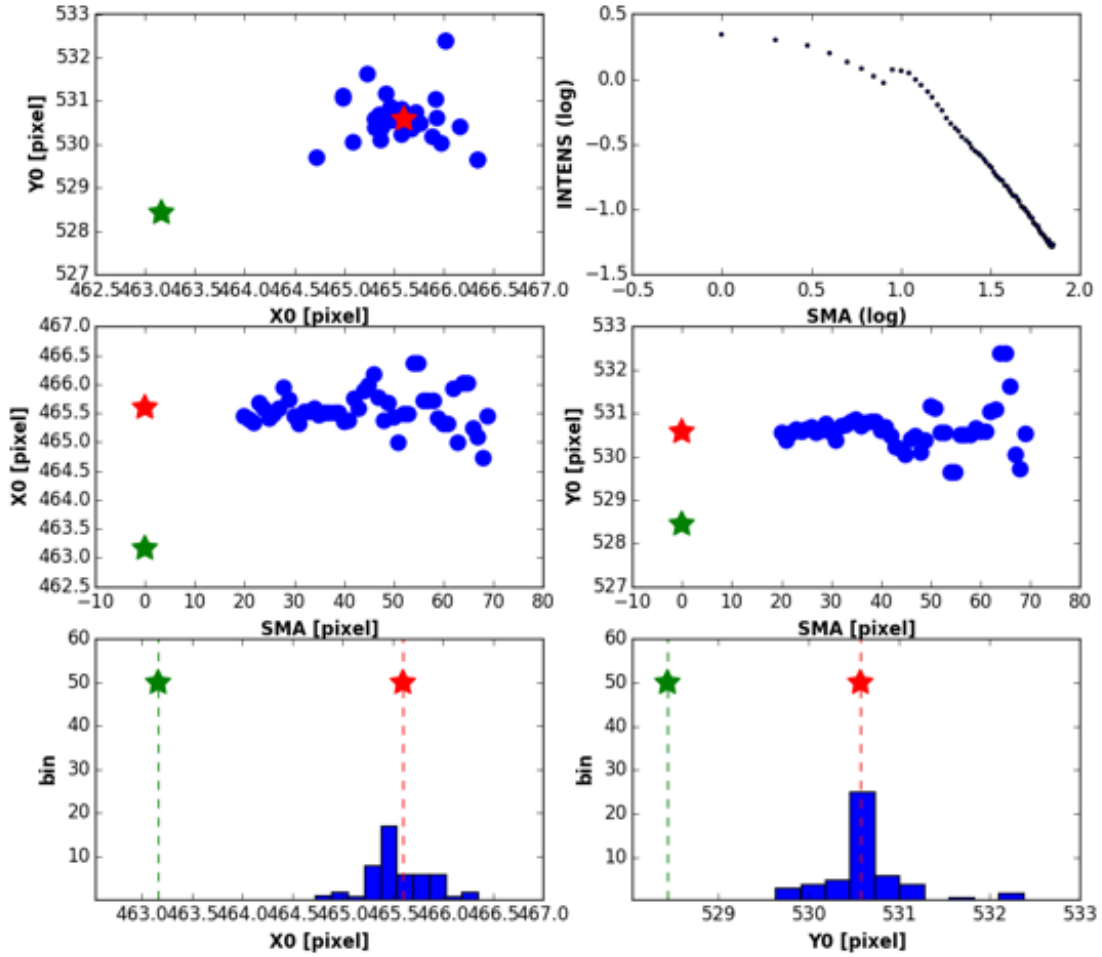


Multi-filter analysis - 3c076.1

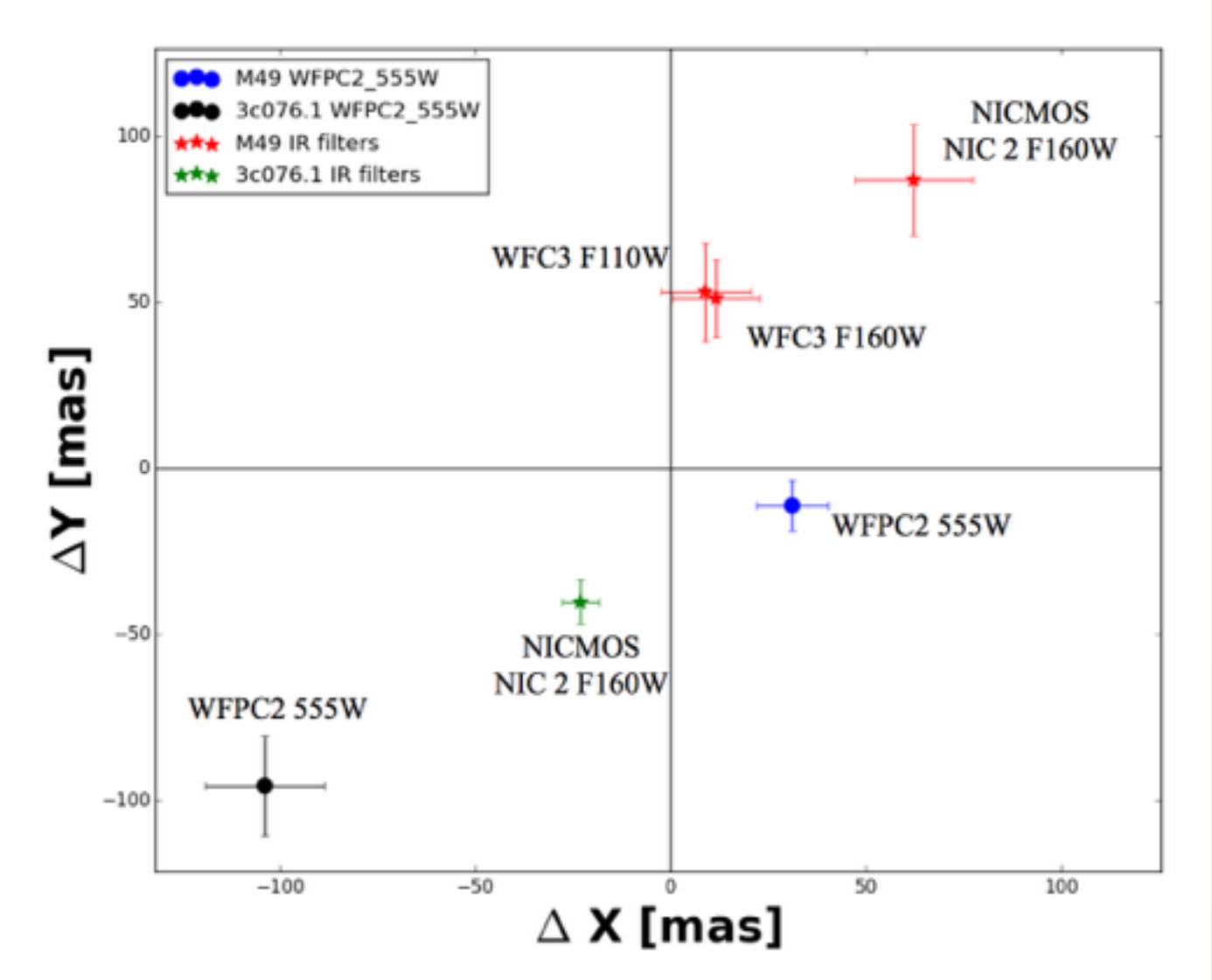
NICMOS2 F160W



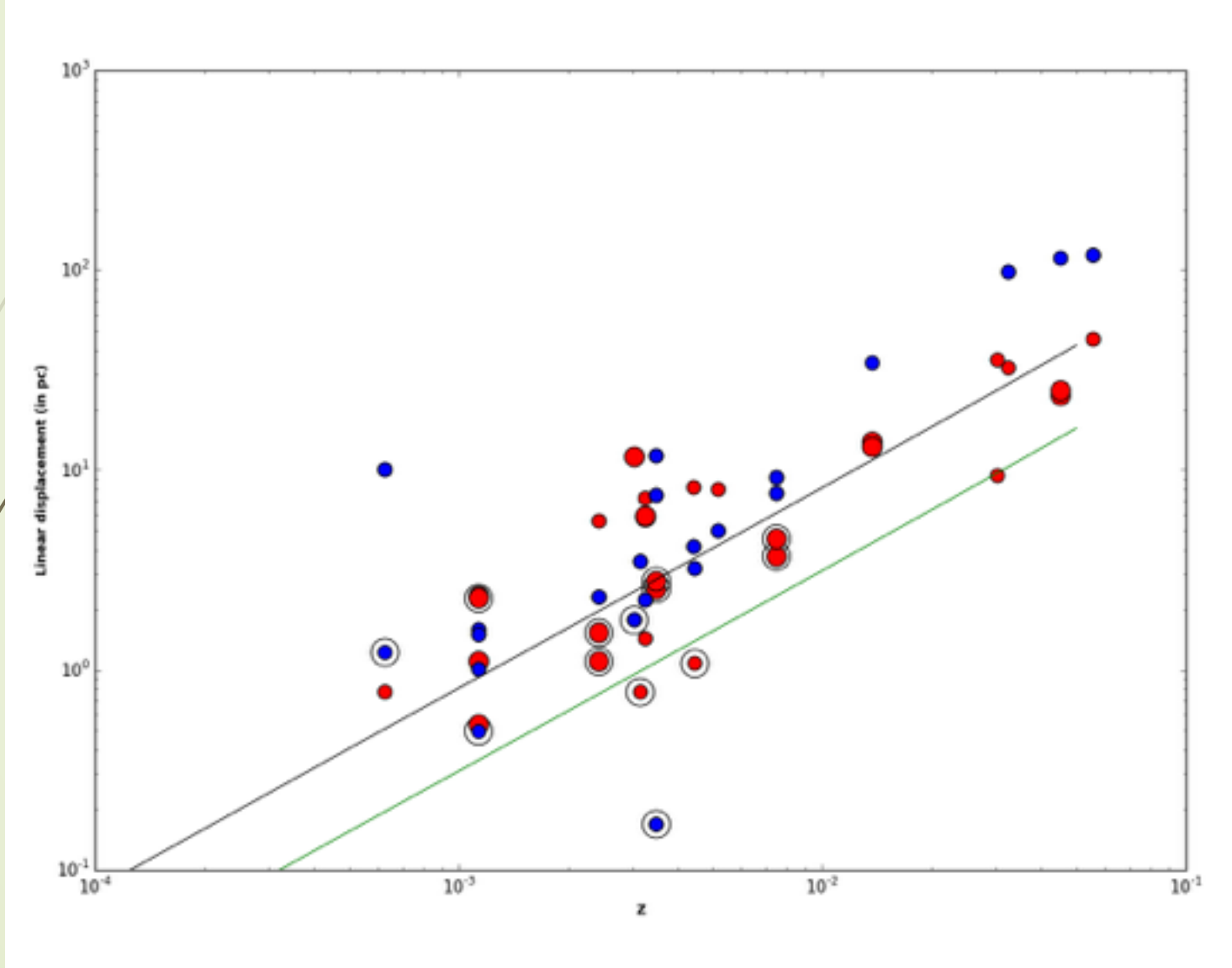
WFPC2 F555W



Multi-filter analysis



Results (cont.)



Size of circle

1 pixel = 0.05"
WFPC2/PC, NICMOS 1&2, ACS

1 pixel = 0.13"
WFC3/IR, NICMOS 3

Low confidence results

IR data

Optical data

lines corresponding to equivalent distance for 0.3 HST pixels

Displacement Mechanisms

- Asymmetric Jets
  - Asymmetry in jet power over several Myr → sufficient acceleration to the SMBH
  - Tight correlation between displacement vector and jet axis
- Stalled Binary Black Holes
  - Center of mass lies near the center of the galaxy and secondary is accreting
- Massive Perturbers
  - Stellar mass black holes, giant molecular clouds and globular clusters
  - No correlation between displacement vector and jet axis
- Gravitational recoil

Results

- 18 candidates with significant displacements
  - Up to ~150mas
  - 2 – 112 pc radial displacements
  - 17 with High $\Delta x/IQR$ or $\Delta y/IQR$ (for WFPC2 analysis) (similar for other filters)
  - 14 core elliptical galaxies
  - 4 power-law elliptical galaxies
- Expanded sample of 96 galaxies produce
  - 20% candidates with significant displacements
  - Displacements found preferentially in **core** galaxies
- Implications
  - Better statistics on the rate of SMBH binary mergers → galaxy mergers → galaxy evolution
  - Source of strong gravitational waves

Future Work

- Investigate correlation between jet axis and displacement vector
- Use Monte Carlo simulations to estimate probabilities of finding displacements
  - Include recoil velocity distributions
  - To verify if incidence and magnitude of displacements are consistent with current galaxy merger rates
- Provide empirical data points for LISA!