Getting Really Close to the Massive Black Holes at the of Centers of Nearby Galaxies

NOAO Interferometry November 13, 2006

Tod R. Lauer

High resolution Observations of galaxy centers

- Masses of central black holes. Velocity ellipsoids.
- Central stellar population. Star formation around black holes. Interaction of stars with black hole.
- Binary black holes. Observation of merged black hole systems. Investigation of the "final parsec" problem. Merger rates.
- 100m baselines or 0.01 - 0.1 pc resolution in nearby galaxies is required.
- Observations require detection of faint stars and decade time baselines.


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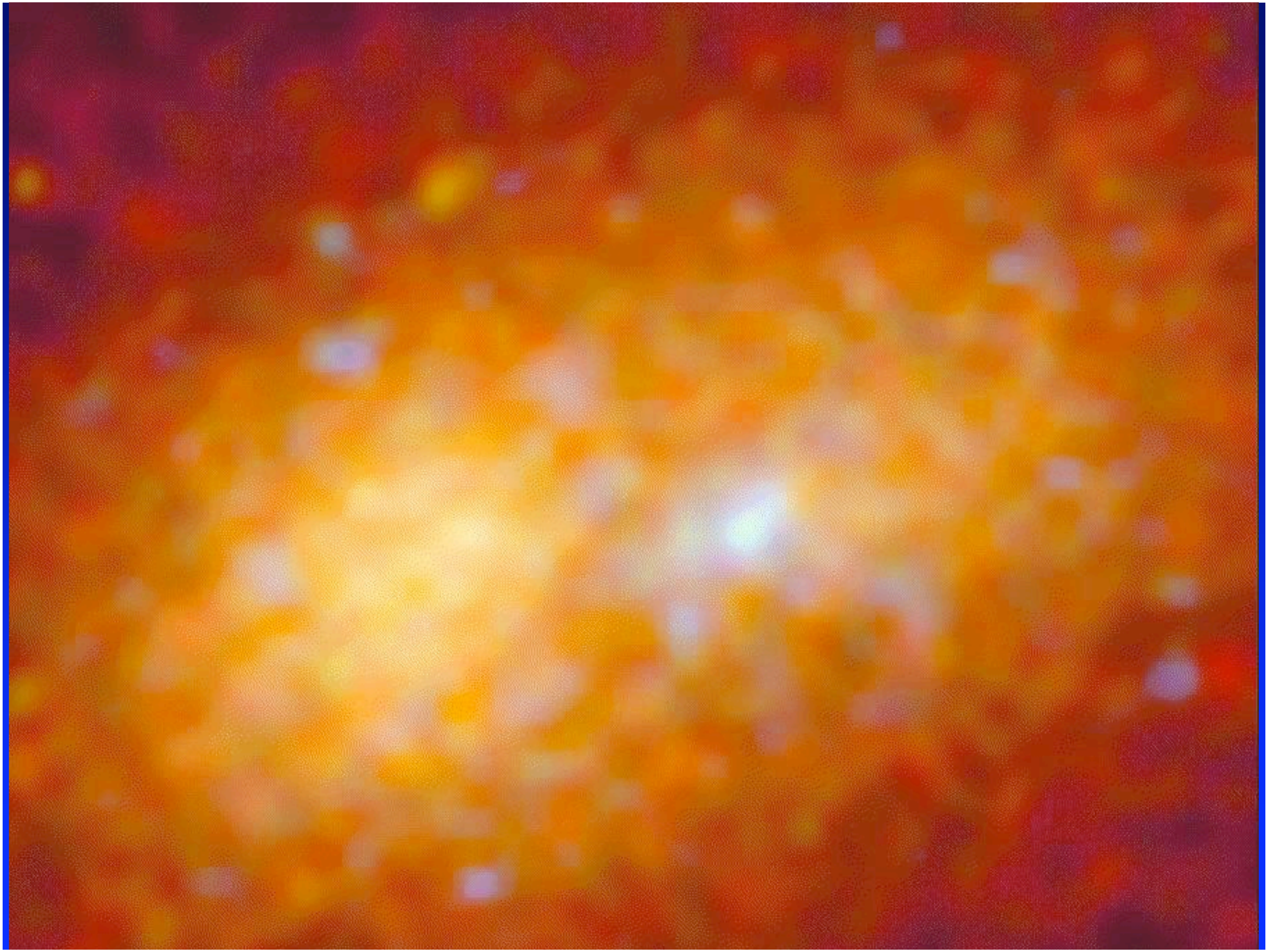
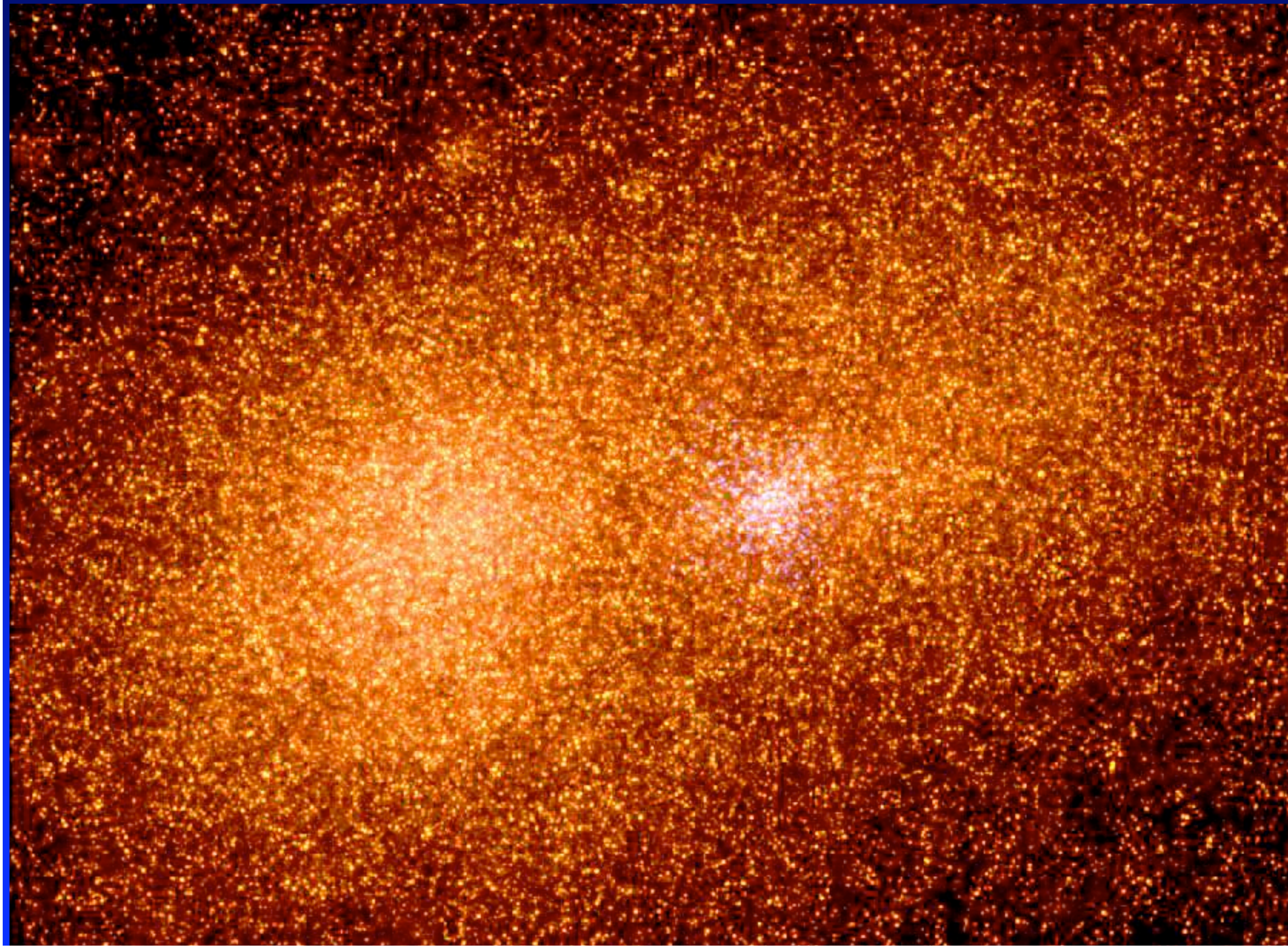
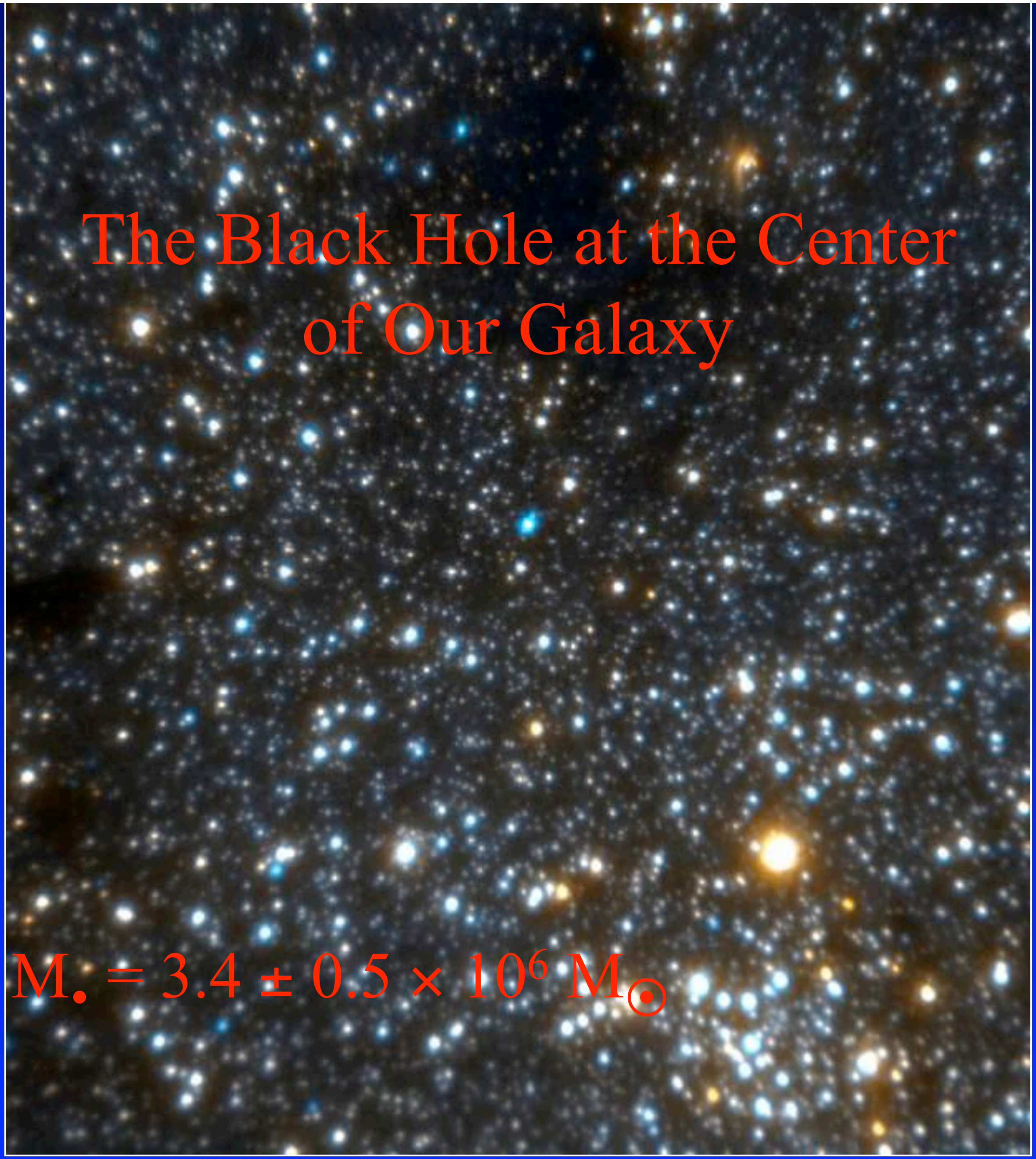


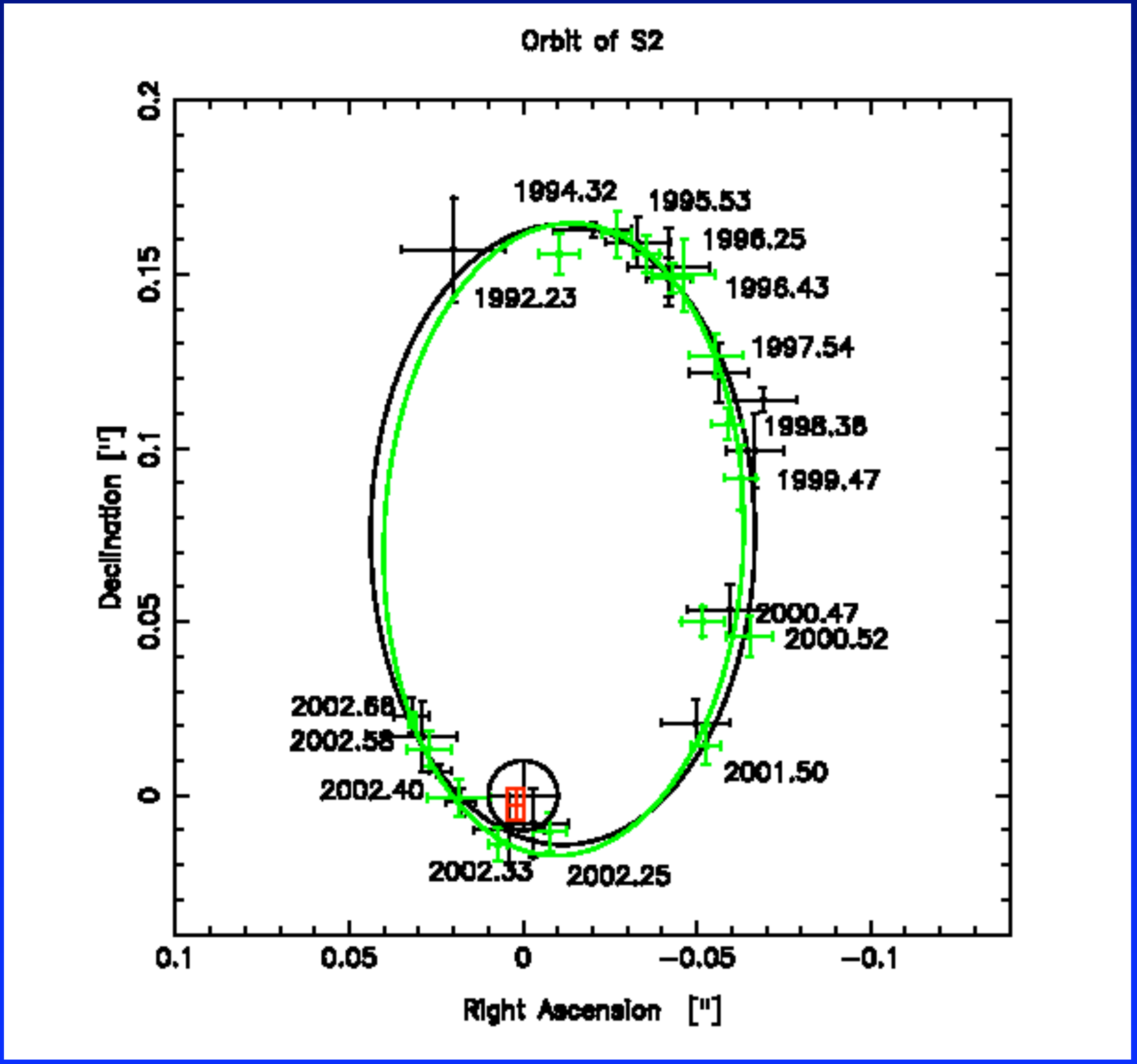


The Black Hole at the Center of Our Galaxy



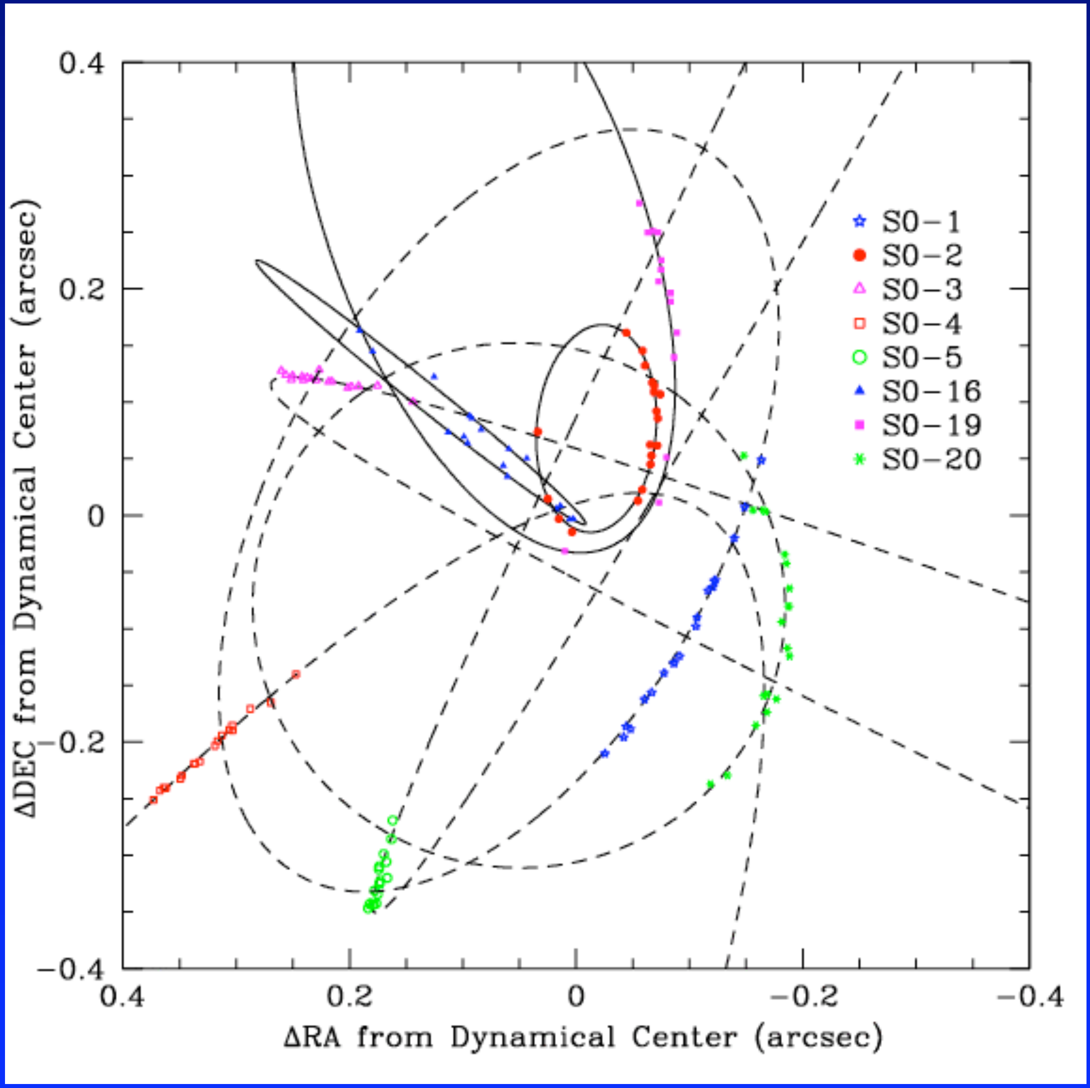
$M_{\bullet} = 3.4 \pm 0.5 \times 10^{6}\, M_{\odot}$

Orbit of a Star Bound to the MW BH



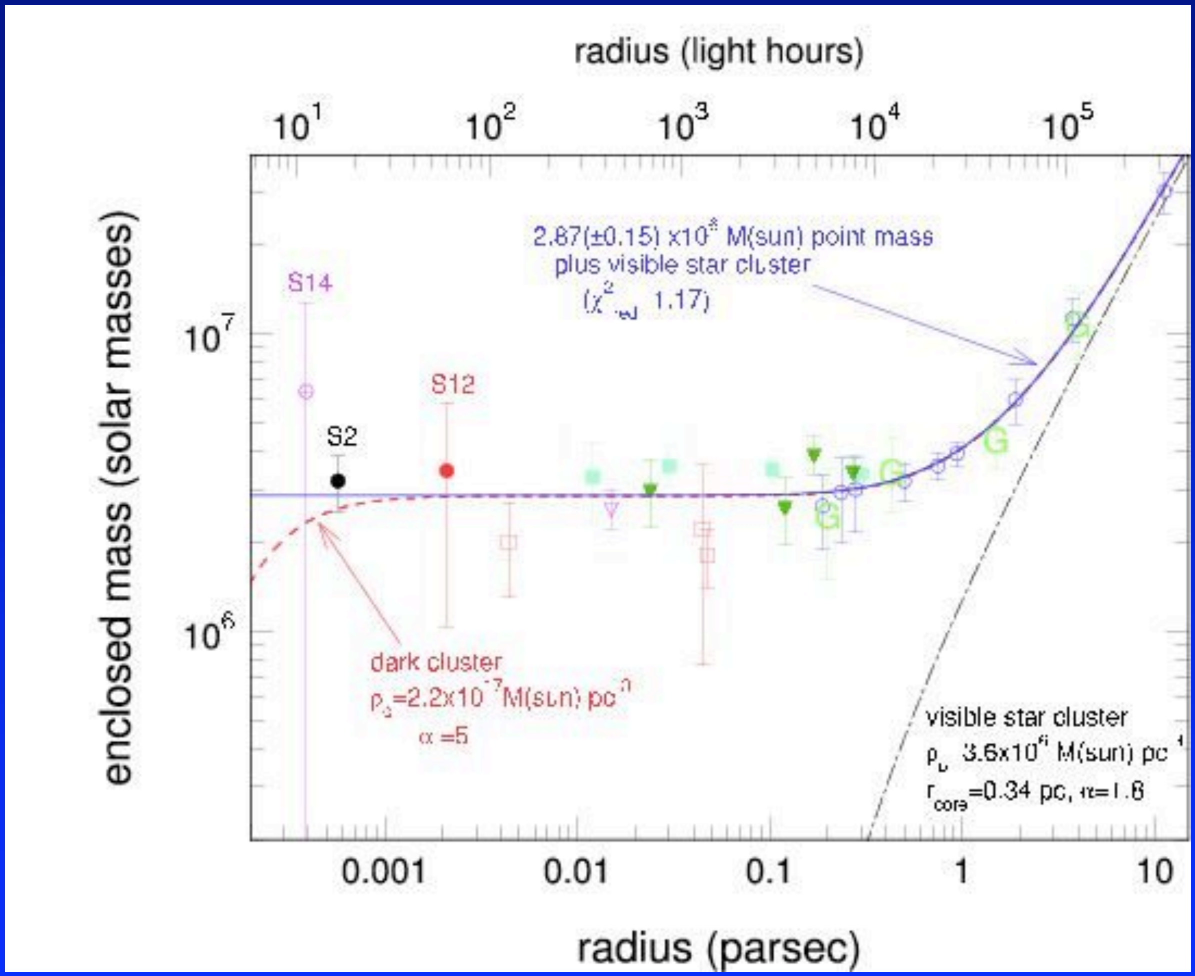
Schodel, Genzel, et al. (2003)

Present Observations of Stellar Orbits



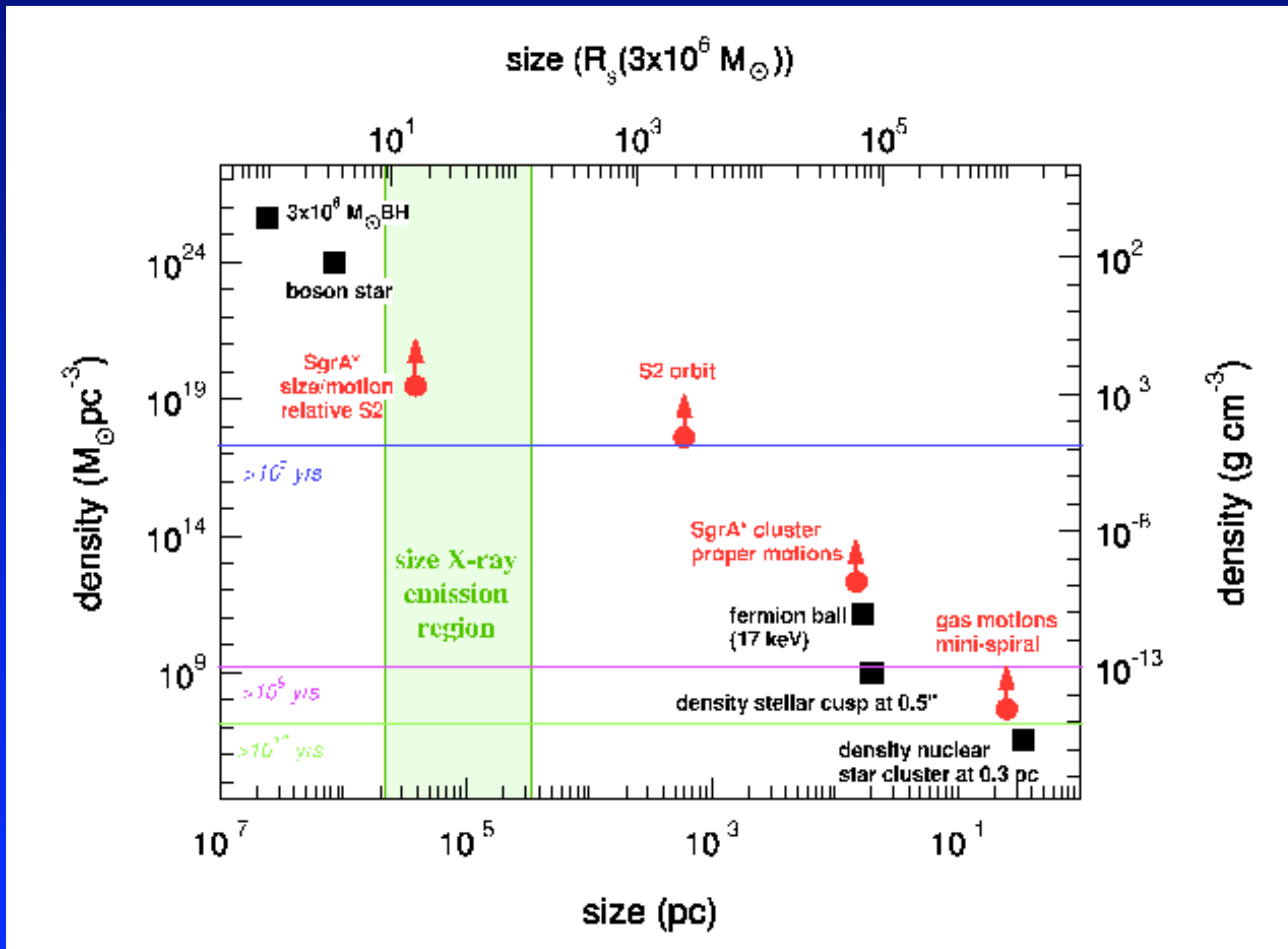
Ghez et al. (2003)

MW Central Enclosed Mass with Radius



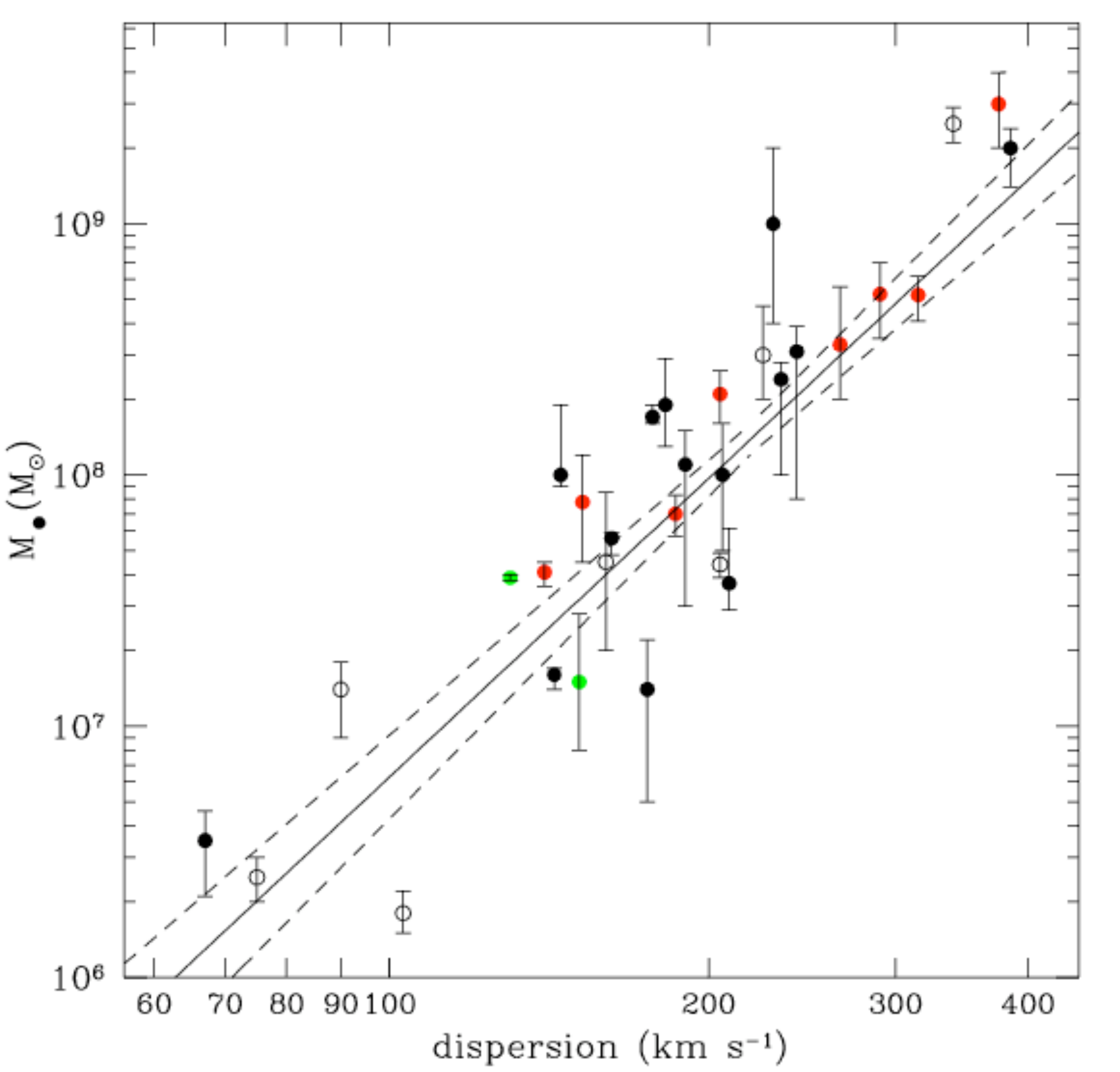
Schodel, Genzel, et al. (2003)

Massive Dark Object Candidates



Schodel, Genzel, et al. (2003)

The mass-dispersion relation

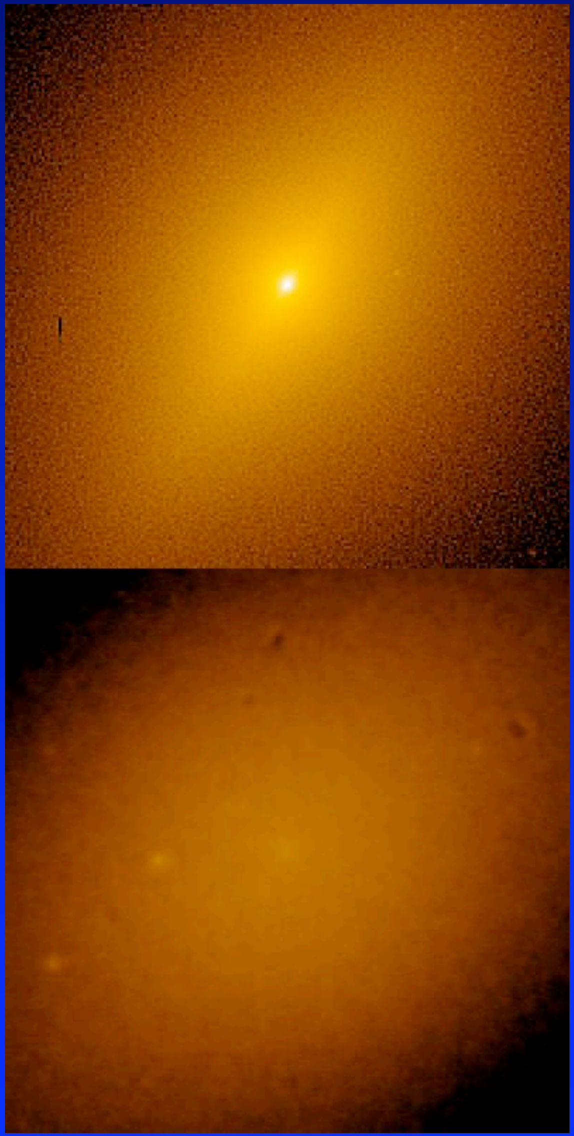


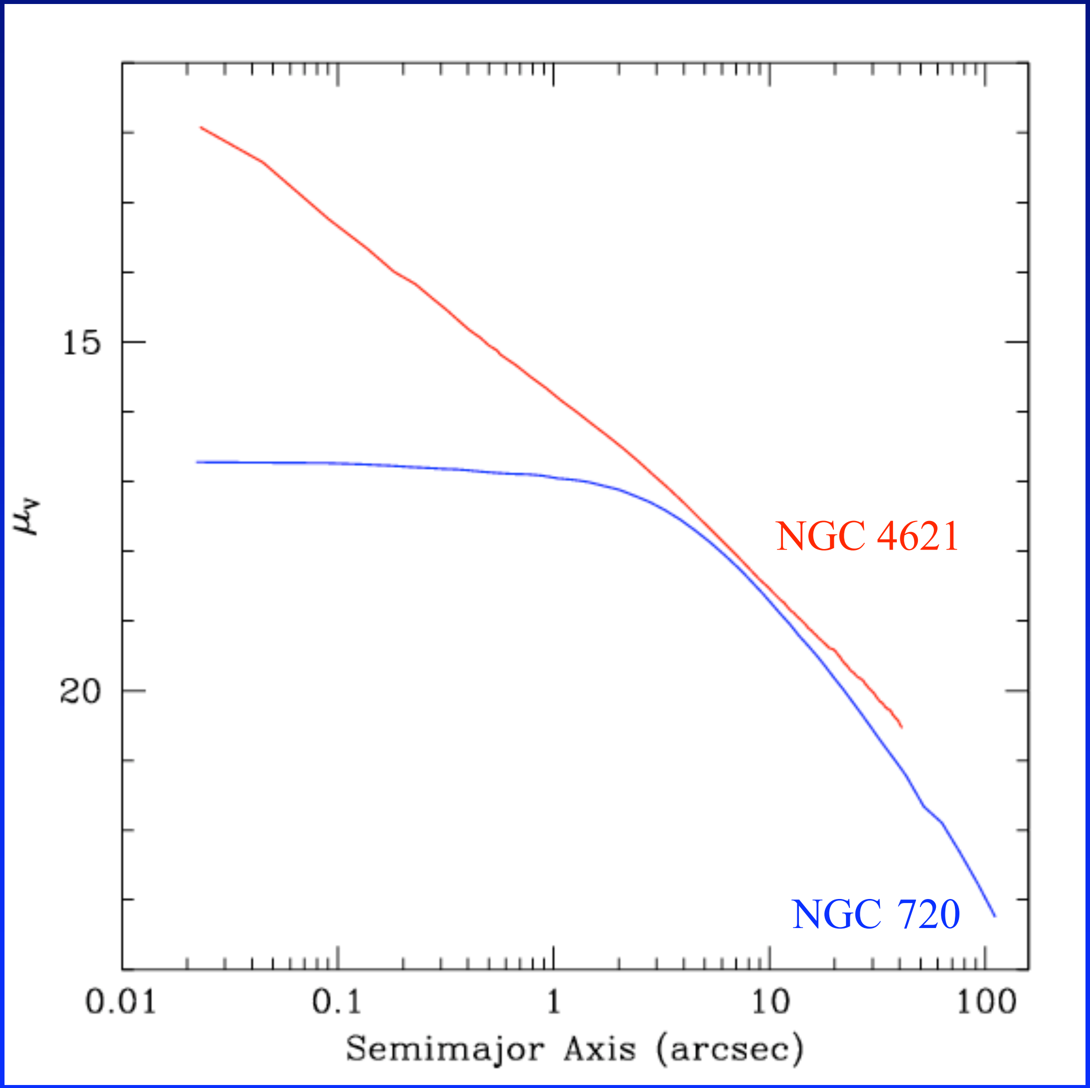
Tremaine et al. (2002)

- maser kinematics
- gas kinematics
- stellar kinematics (Nukers)
- ° stellar kinematics (others)

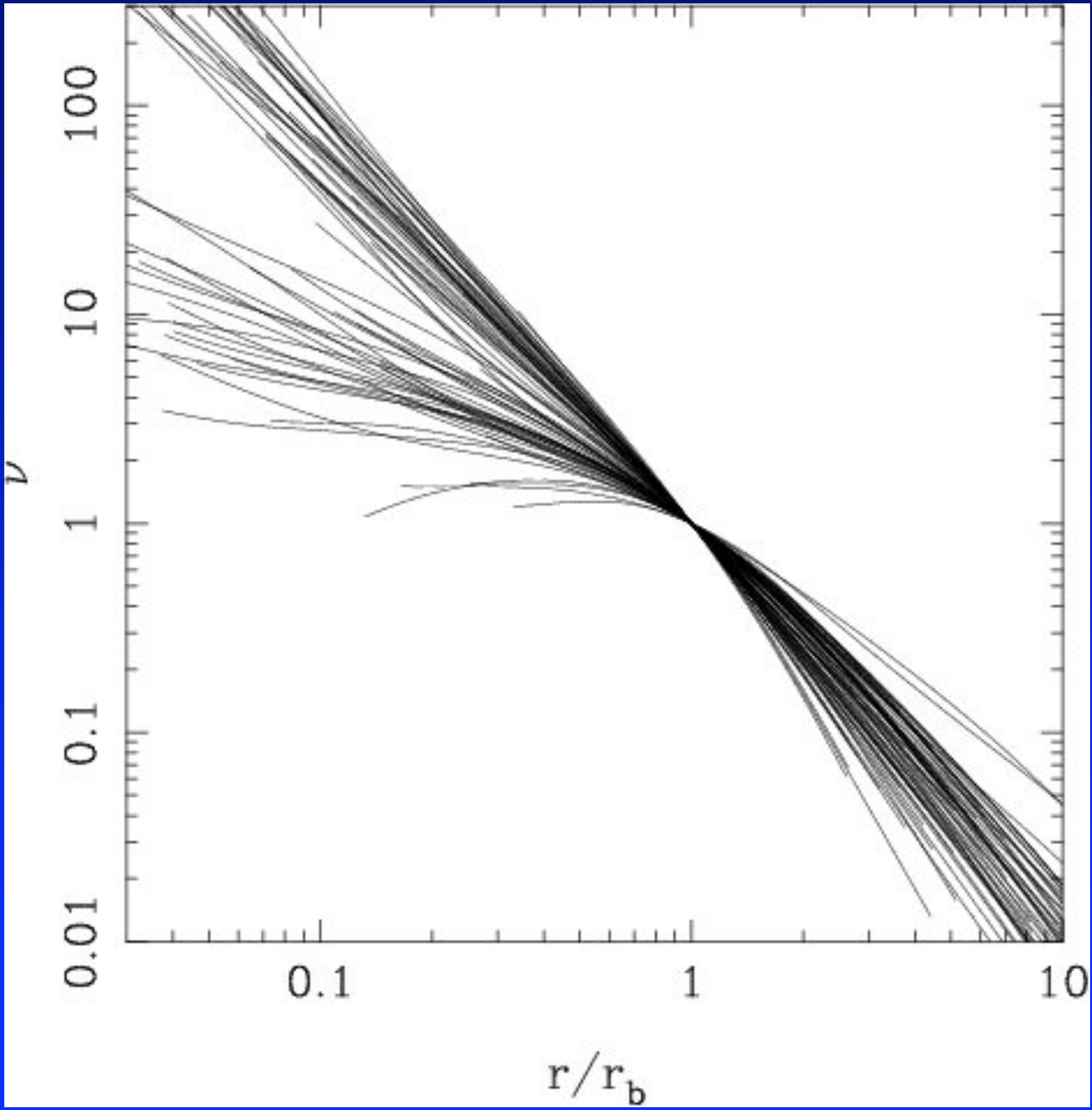
- $M \sim \sigma^\beta$, $\beta = 4.0 \pm 0.3$
- intrinsic dispersion in M of <0.3 dex (for comparison, Faber-Jackson relation $L \sim \sigma^4$ has dispersion 0.4 dex)
- *Gebhardt et al. (2000), Ferrarese & Merritt (2000)*

Core and Power-Law Galaxies





Core & Power-law density profiles are bimodal



Lauer et nuk. (2006)

Cores are a signature of black holes

- Cores are generated by the in-spiral of a binary black hole created in a merger. Energy exchange removes stars.
- Cores are preserved against later mergers with centrally-dense galaxies by their nuclear black holes.
- Double nuclei may be eccentric stellar disks stabilized by nuclear black holes.
- *Hollow Galaxies* may be a special variant of core formation with black holes:
  - *Core – Core mergers and core evacuation*
  - *Relatives of double nuclei*

Denoting core size by "M deficit"="M ejected"

Milosavljevic & Merritt 2001

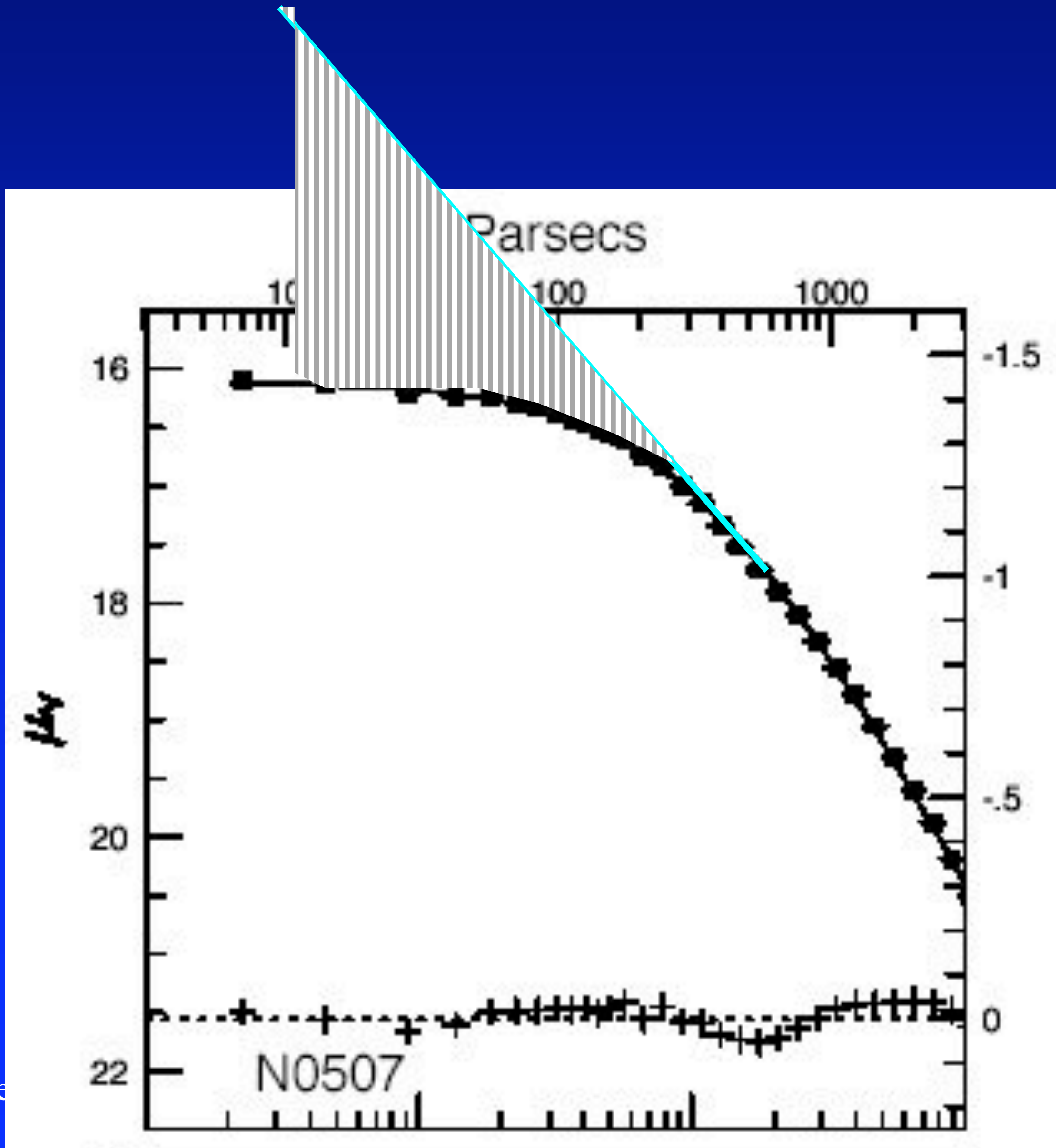
$$M_{ej} = \frac{2(2-\Gamma)}{(3-\Gamma)G}\,\sigma^2 r_b$$

Γ = slope of ***space density*** profile

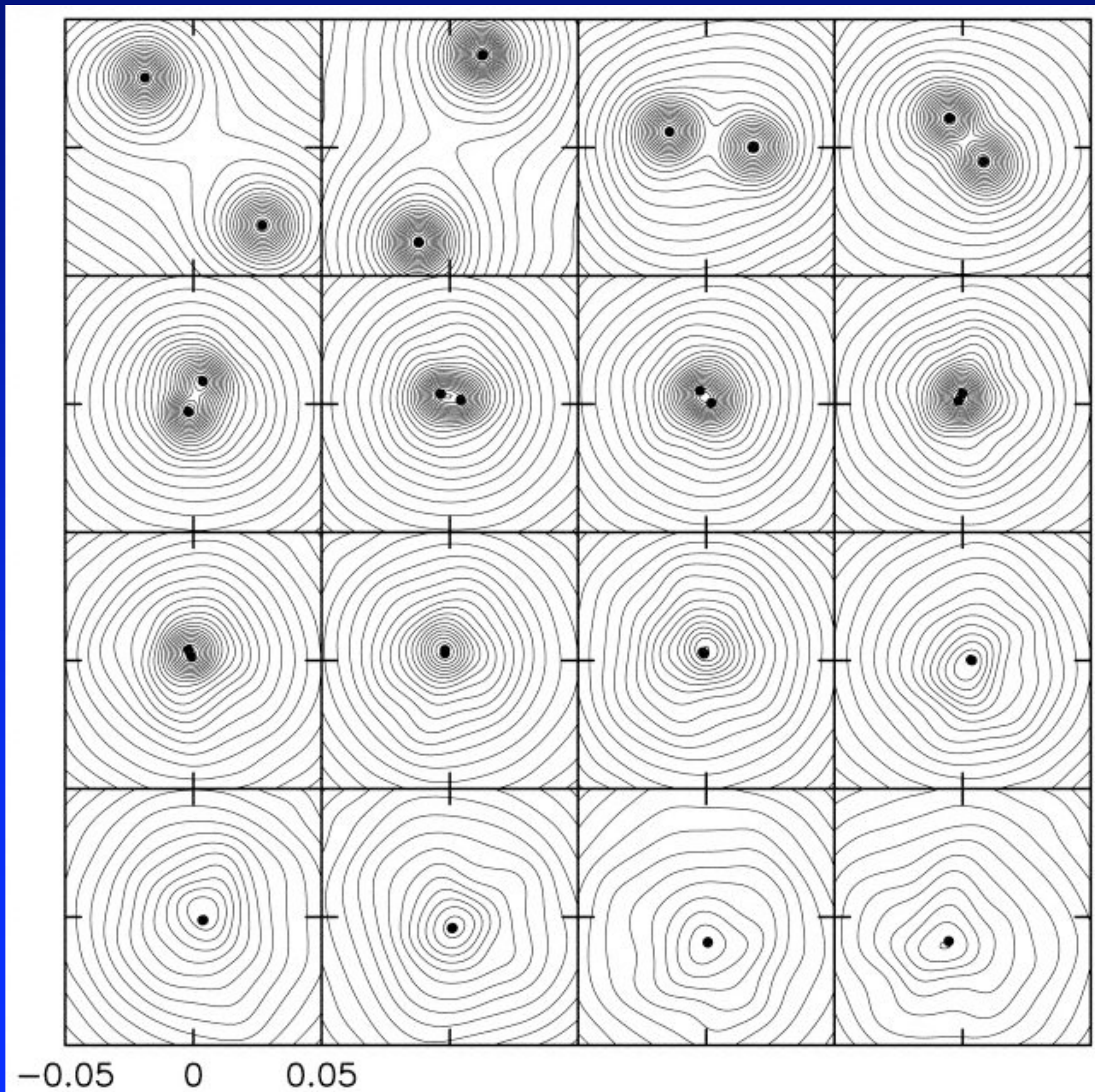
Follow two paths for ejected mass: 1) σ-based, and 2) L-based:

$$M_{ej} \sim \sigma^2 r_\gamma$$

$$M_{ej} \sim l_\gamma r_\gamma^{\,2}$$



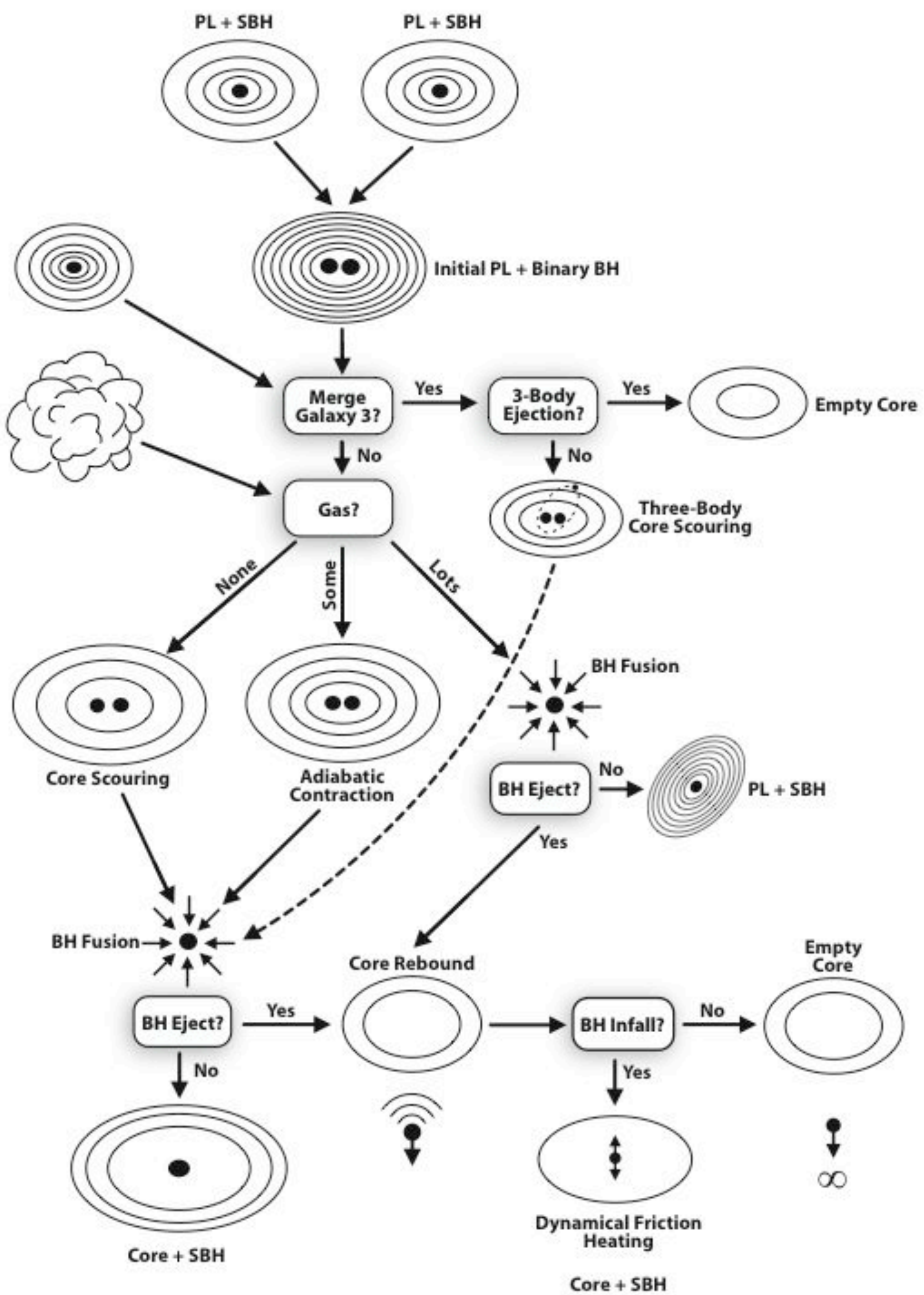
Simulated Mergers of Power-law Galaxies with MBH



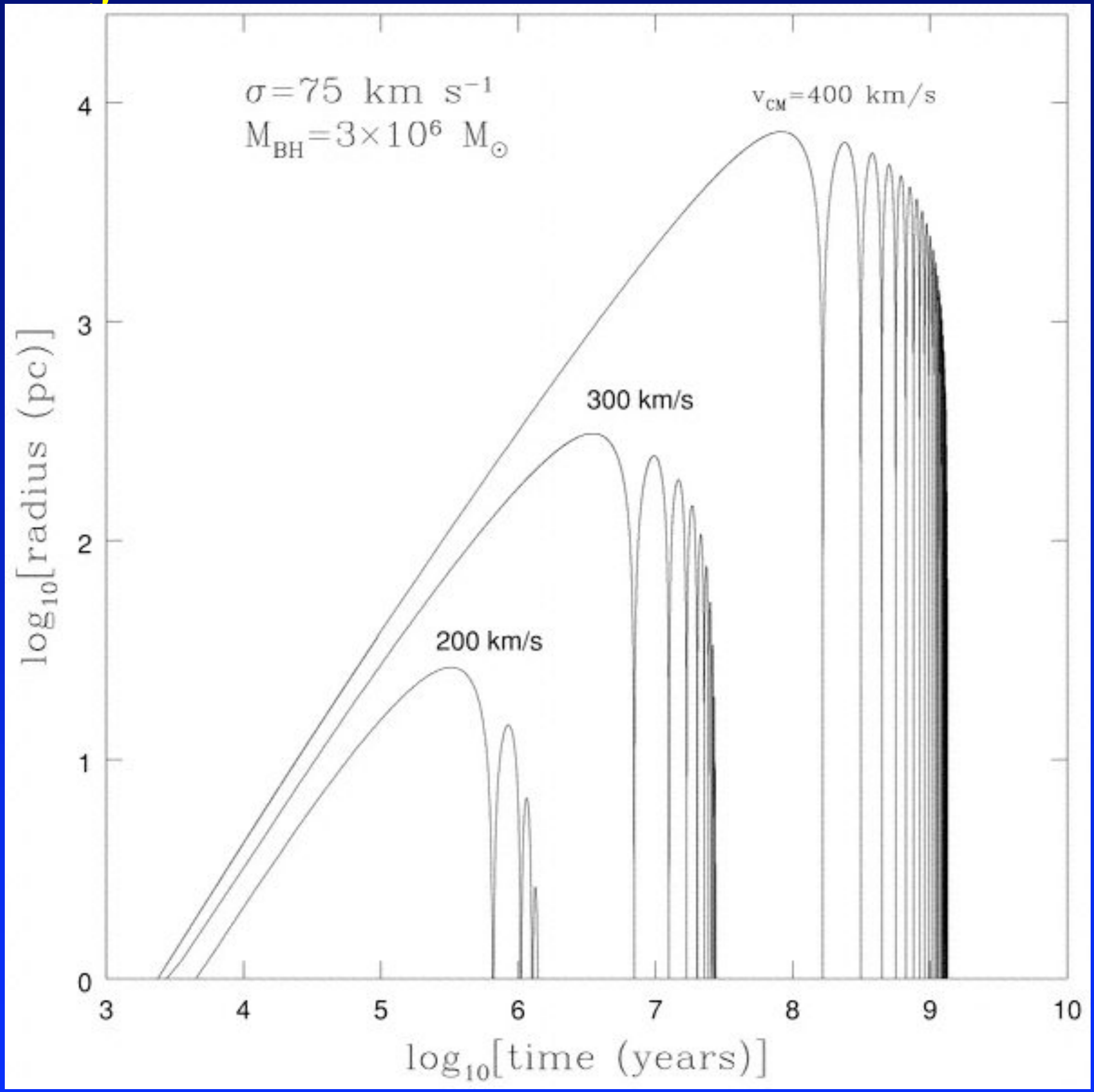
Milosavljevic & Merritt (2001)

MBH & Core Structure

- Core scouring
- 3-BH scouring
- Adiabatic BH growth
- Gas induced binary-BH fusion.
- BH recoil ejection and core rebound.
- BH return and dynamical friction heating.

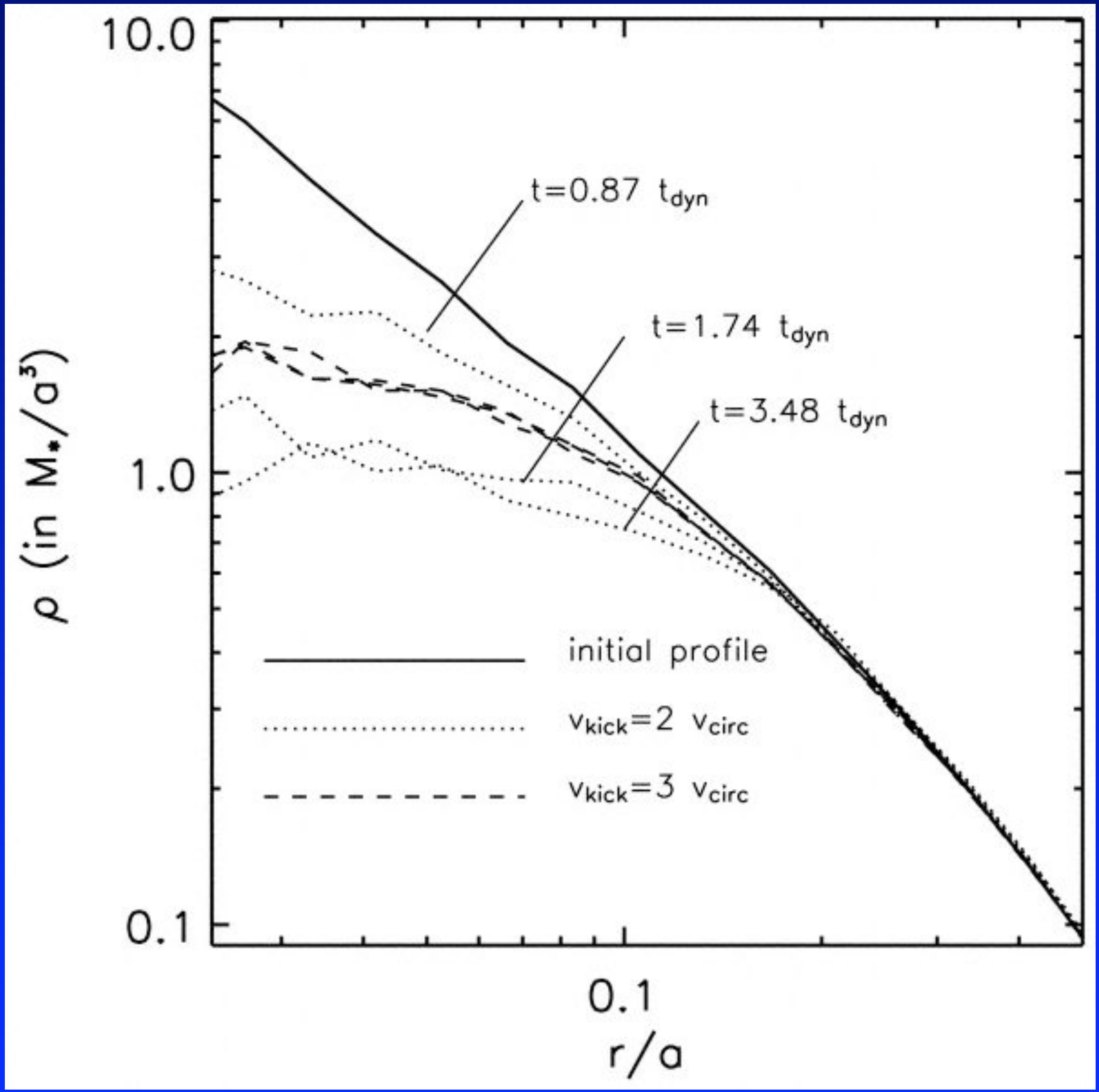


BH Ejection from Gravitational Recoil

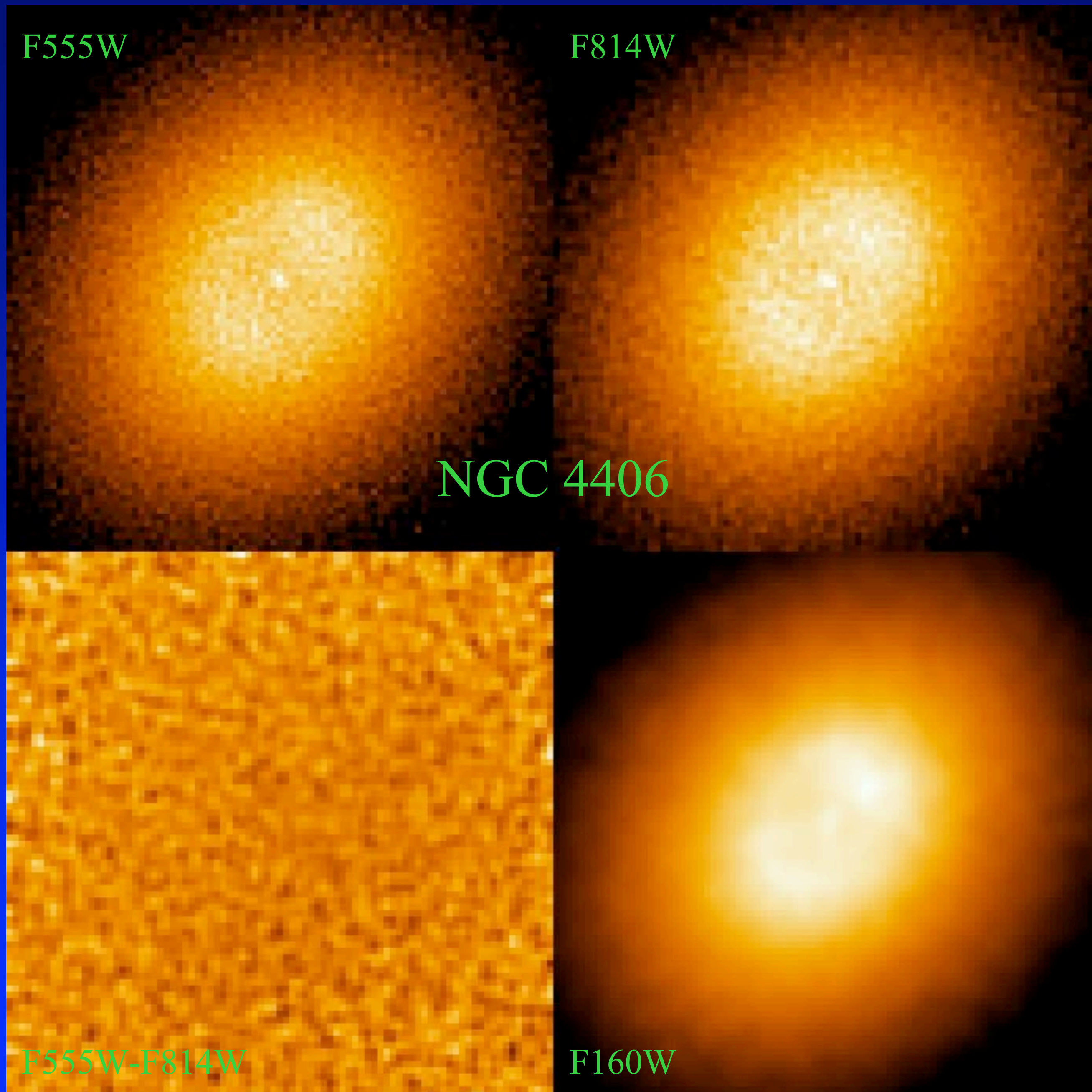


Boylan-Kolchan, Ma, & Quataert (2004)

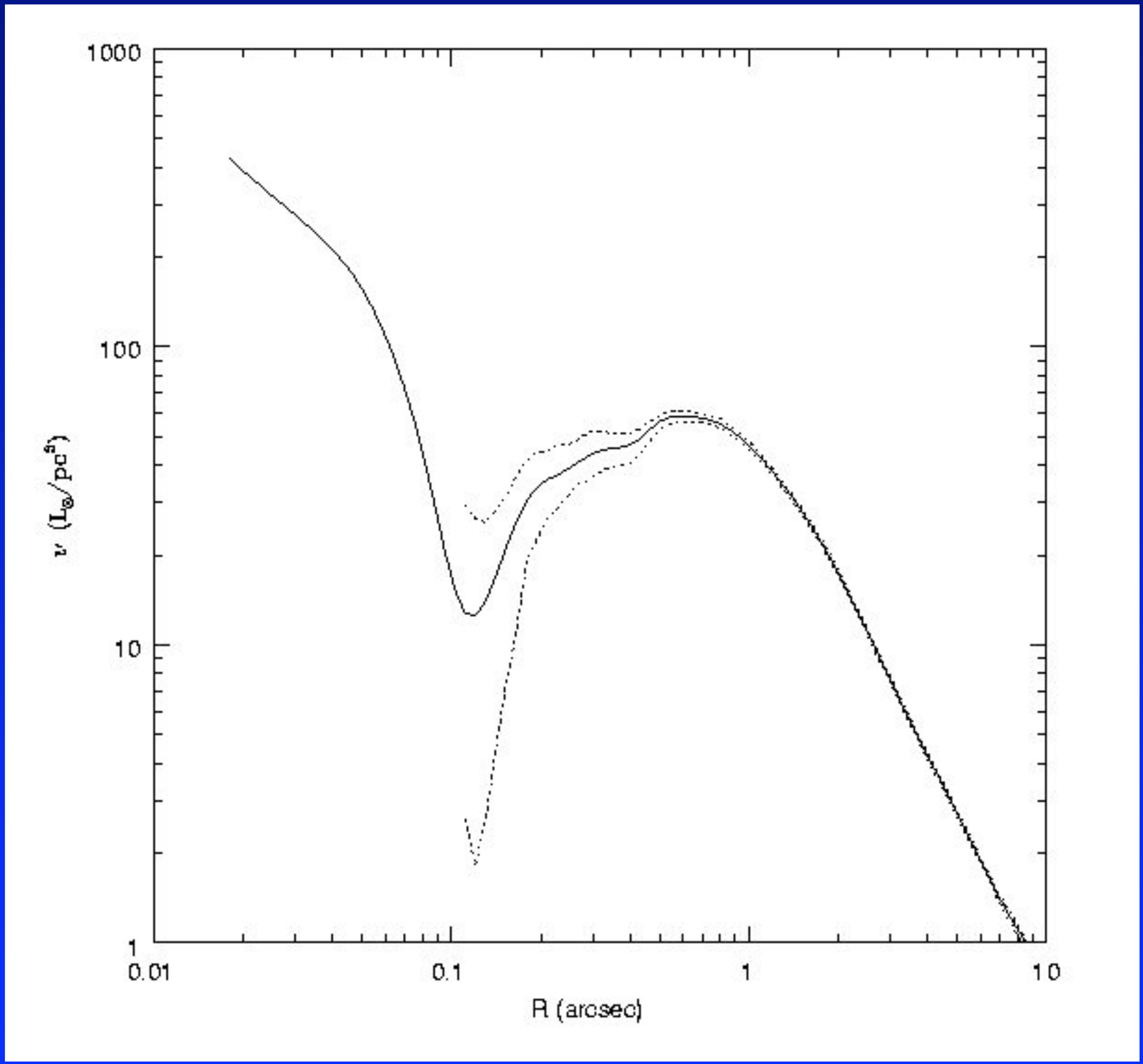
Core Forms From Ejection + Infall of BH



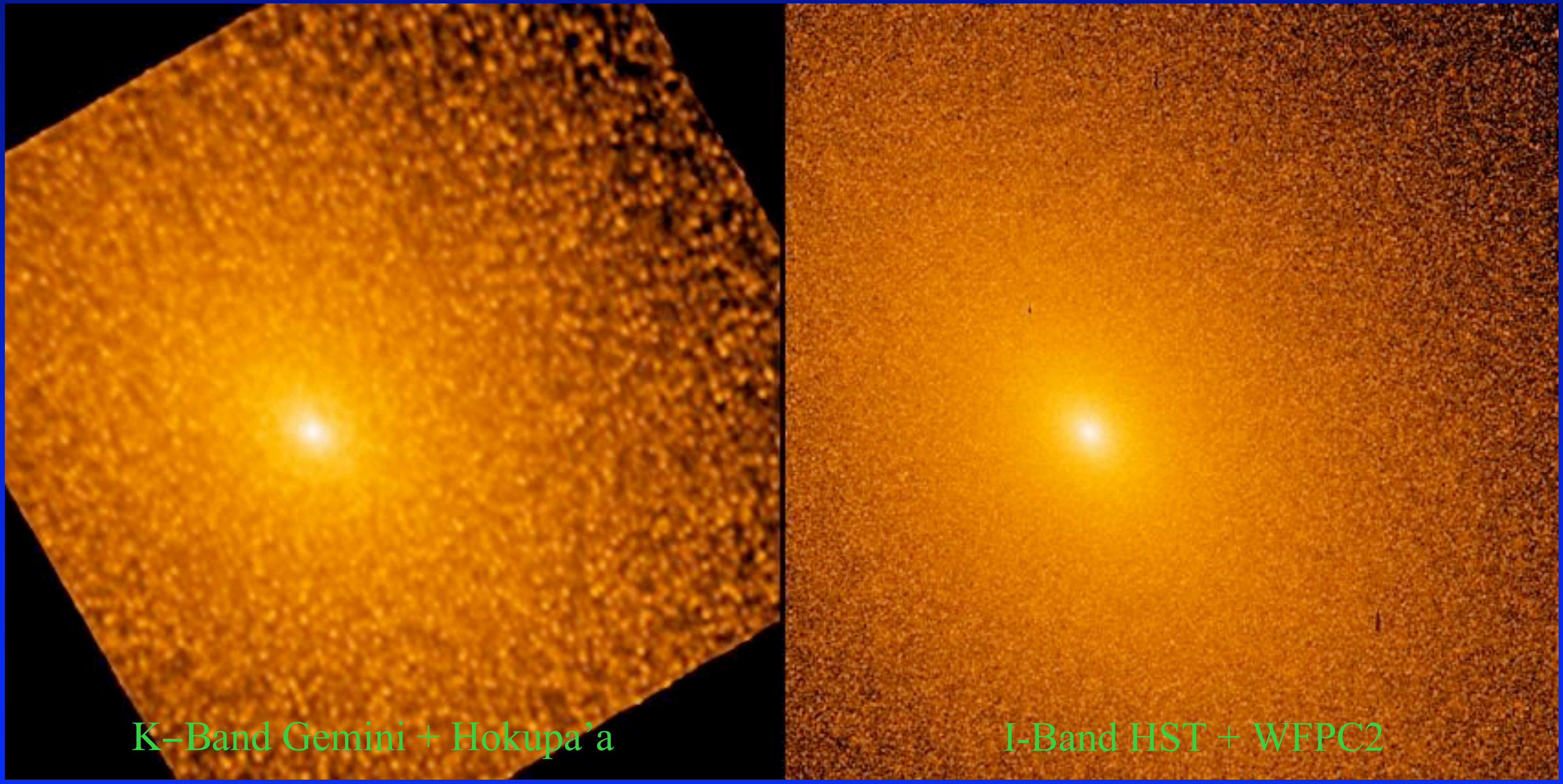
Madau & Quataert (2004)


F555W
F814W
NGC 4406
F555W-F814W
F160W

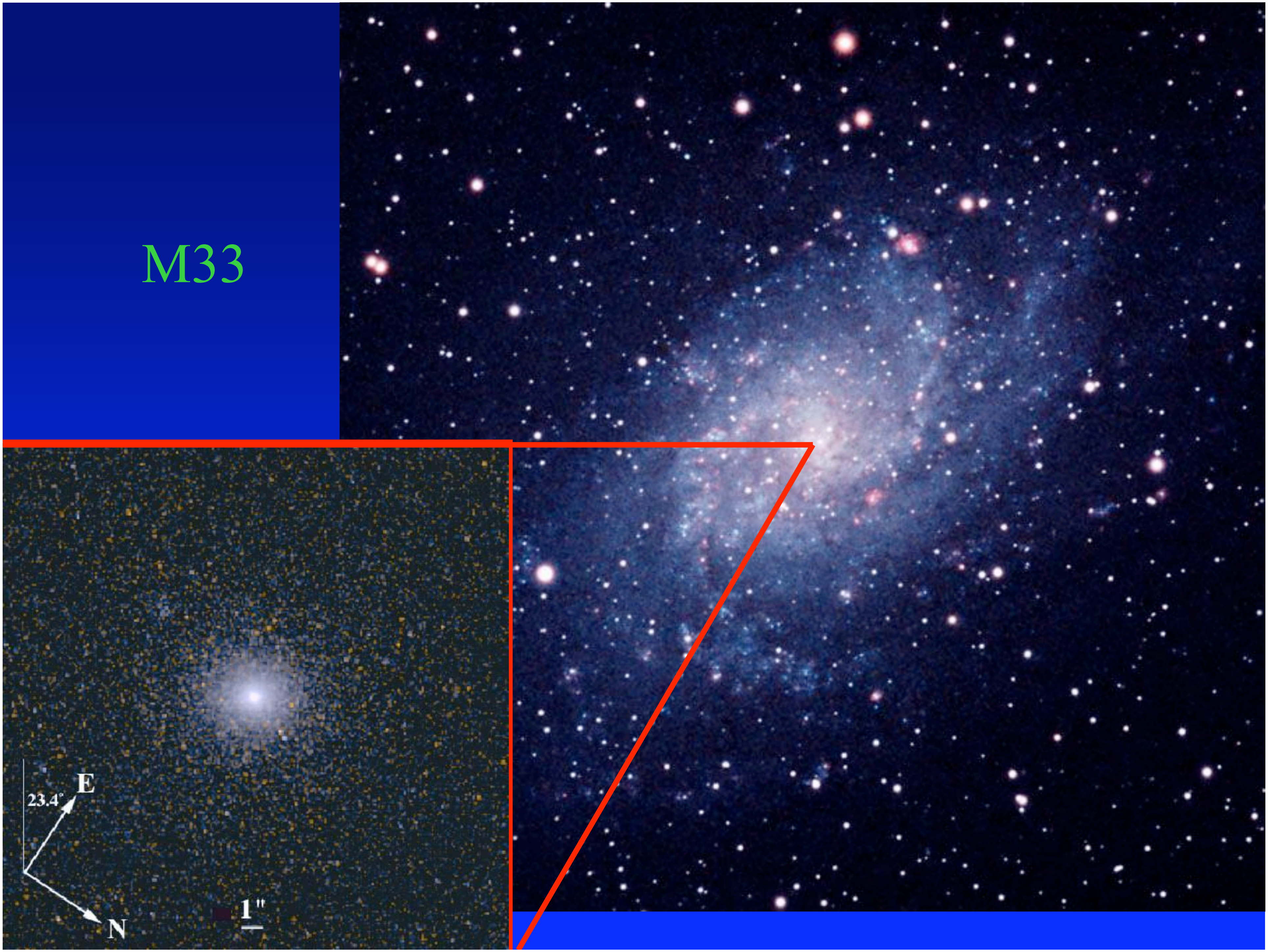
NGC 4406 Luminosity Density



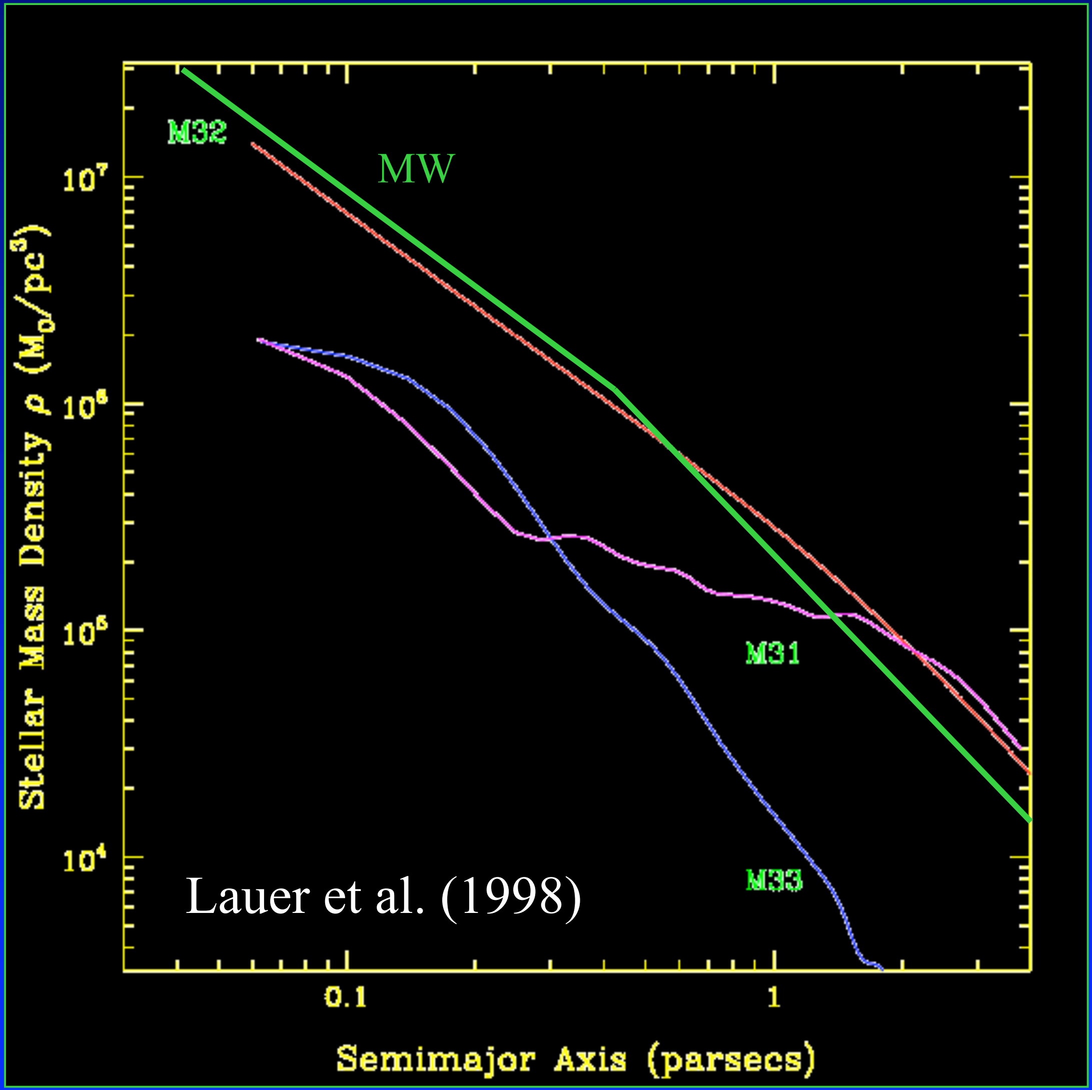
M32



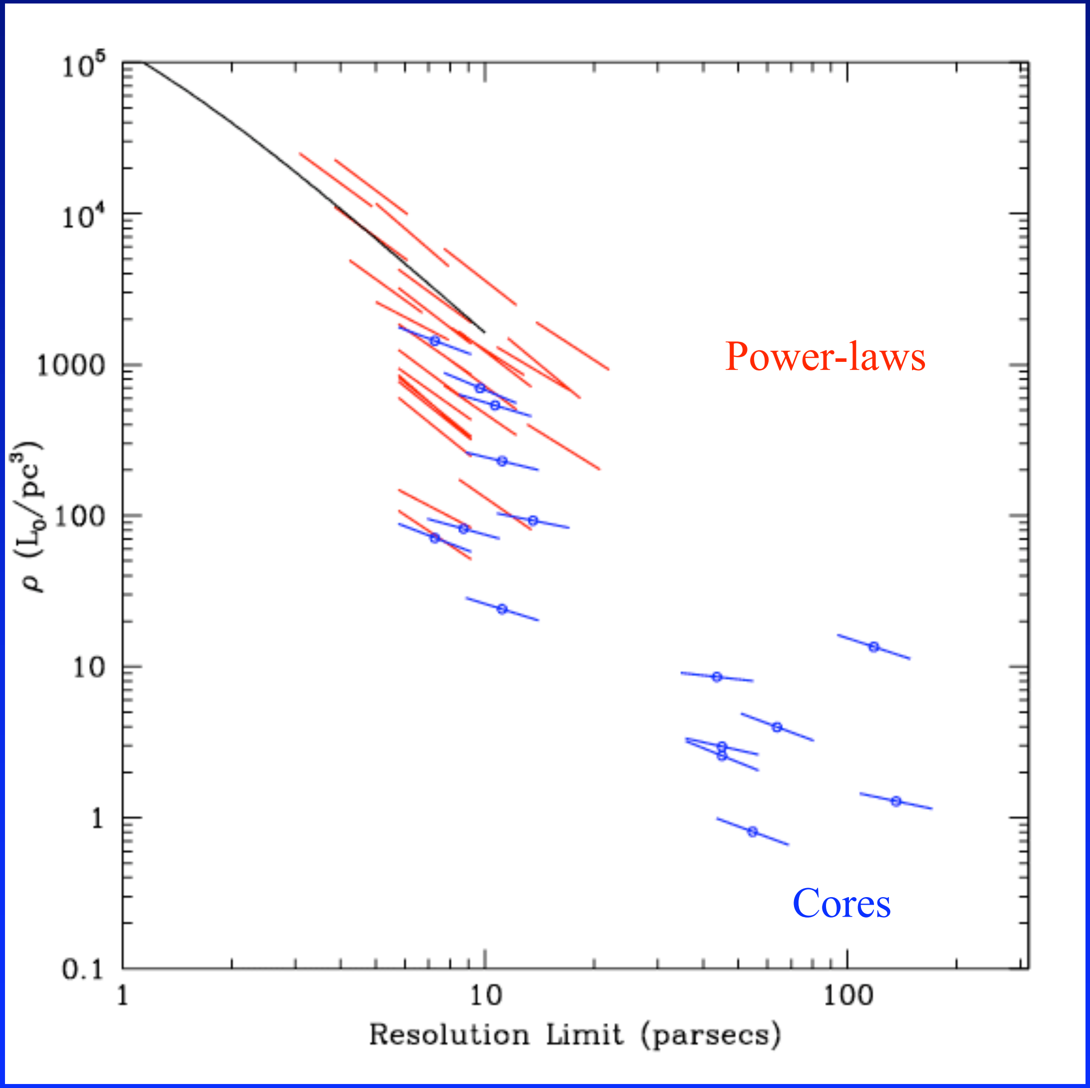
M33



M32±1 Stellar Mass Density Profiles



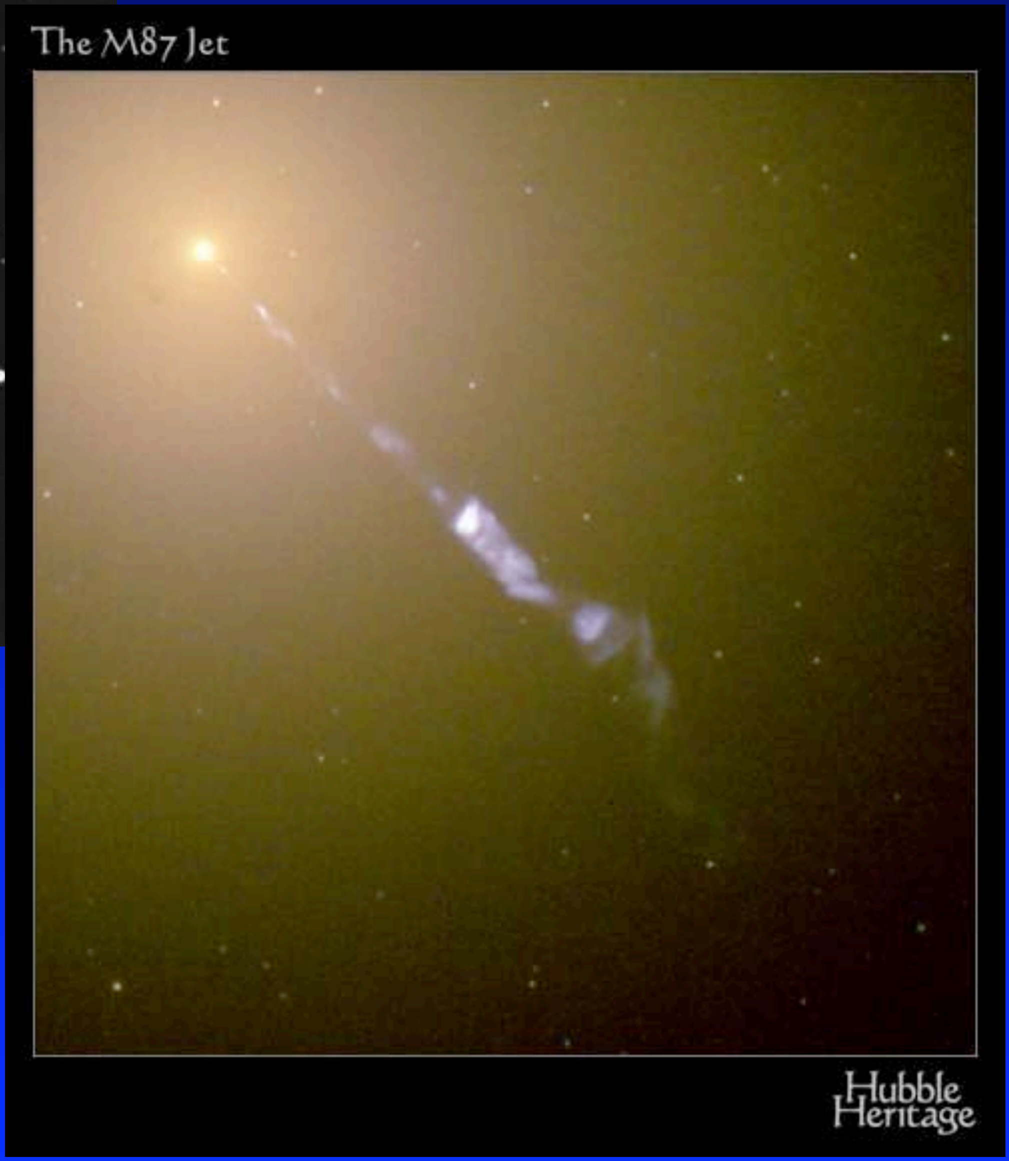
Central luminosity densities vary by $>10^4$



Lauer et nuk. (1995)

Central Stellar Interaction Timescales

	ρ $M_\odot/pc^3$	σ km / s	Θ	Relaxation yr.	Collision yr.
M31	1×10^6	720	0.2	…	6×10^{10}
M32	7×10^6	240	1.6	3×10^9	2×10^{10}
M33	2×10^6	21	230	3×10^6	3×10^9



M87

$M_{\bullet} = 2.4 \pm 0.7 \times 10^{9}\ M_{\odot}$

M87 and M31 Test Cases

M87 typical time for significant proper motion

$$T = 8.6yr\left(R/0.1pc\right)^{3/2}\left(M_\bullet/3\times10^9 M\right)^{-1/2}$$

M31 typical time for significant proper motion

$$T = 1.5yr\left(R/0.01pc\right)^{3/2}\left(M_\bullet/1\times10^8 M\right)^{-1/2}$$

Minimum resolution required - 1mas. Stellar sources $M_V > 20$ for M31, $M_V > 27$ for M87 $\Rightarrow$ 100m baselines. Well-resolved in M31, just resolved in M87. AGN source will help.

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