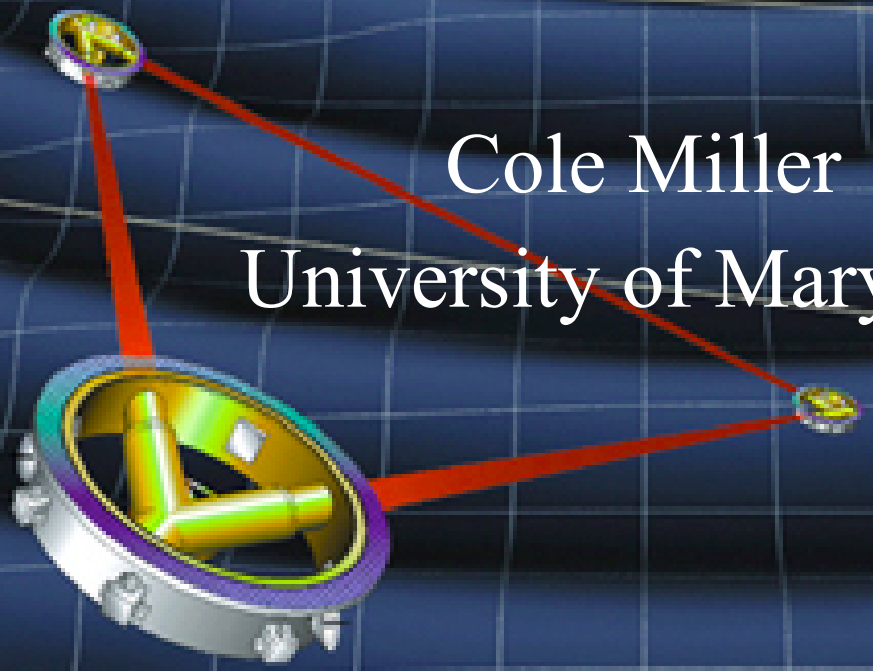
Massive Black Holes

Cole Miller
University of Maryland



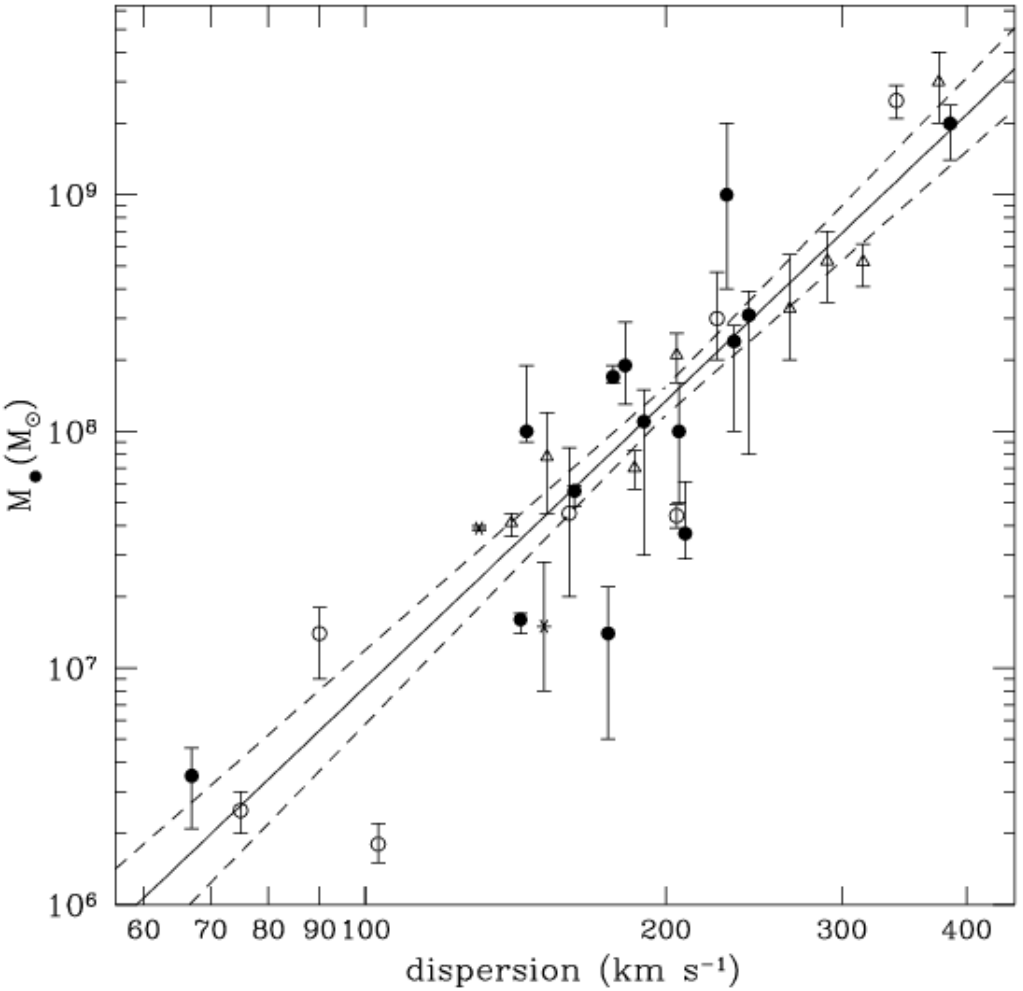
Outline

- Roles of massive black holes in the universe
- Current observations of MBH
- Possible role of E/IMRIs
- Astrophysical inputs and uncertainties
- Key questions

For mergers of two massive black holes,
see talk by Colpi.

The Galaxy-BH Link

- SMBH mass vs. bulge velocity dispersion. $M_8=(\sigma/200\text{km/s})^4$
- Link regulated by feedback?
- Merging galaxies, accreting BH might blow out gas as well.

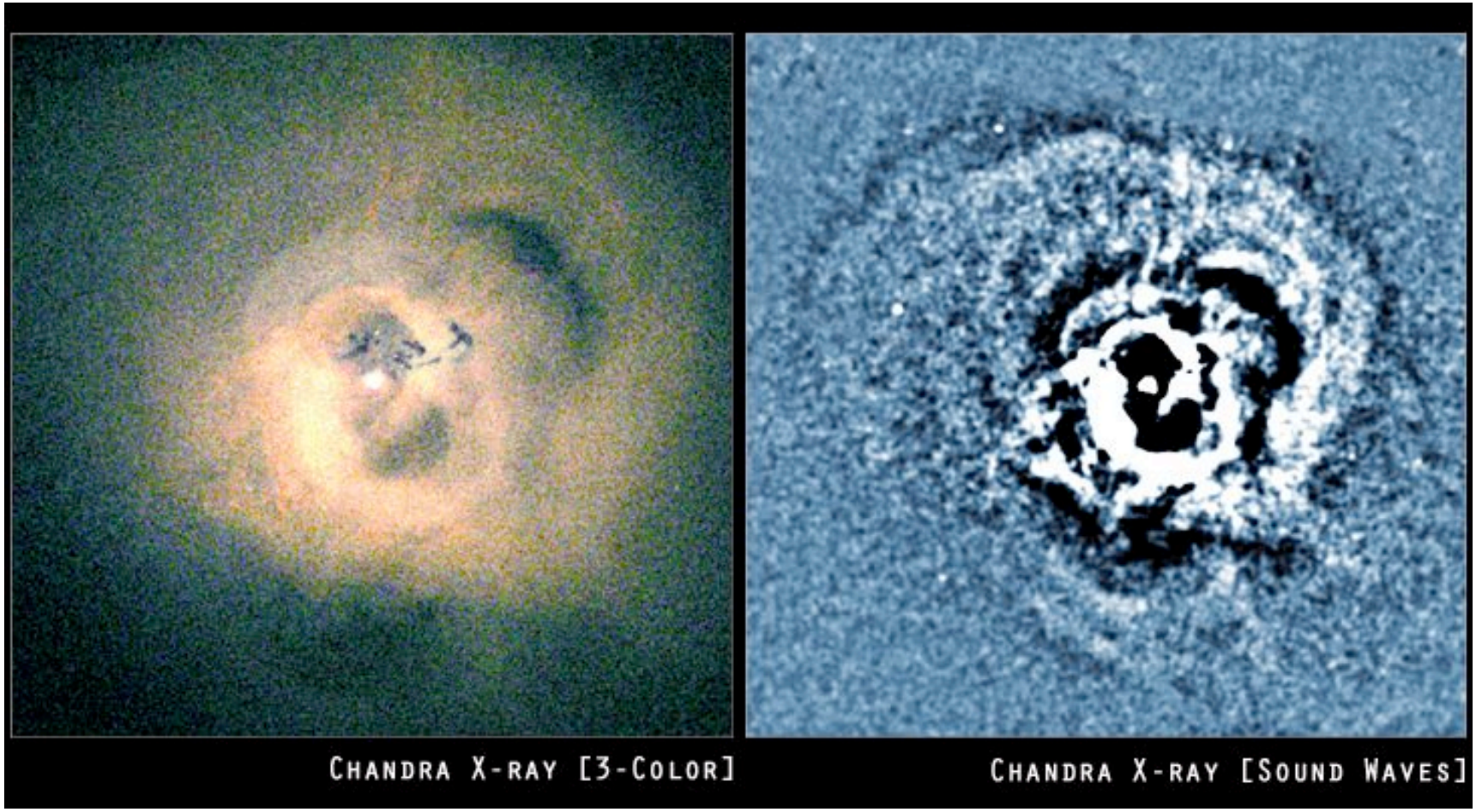


Tremaine et al. 2002

di Matteo et al.: Simulation of galaxy collision, gas blown out in fifth step. Explanation for ellipticals?

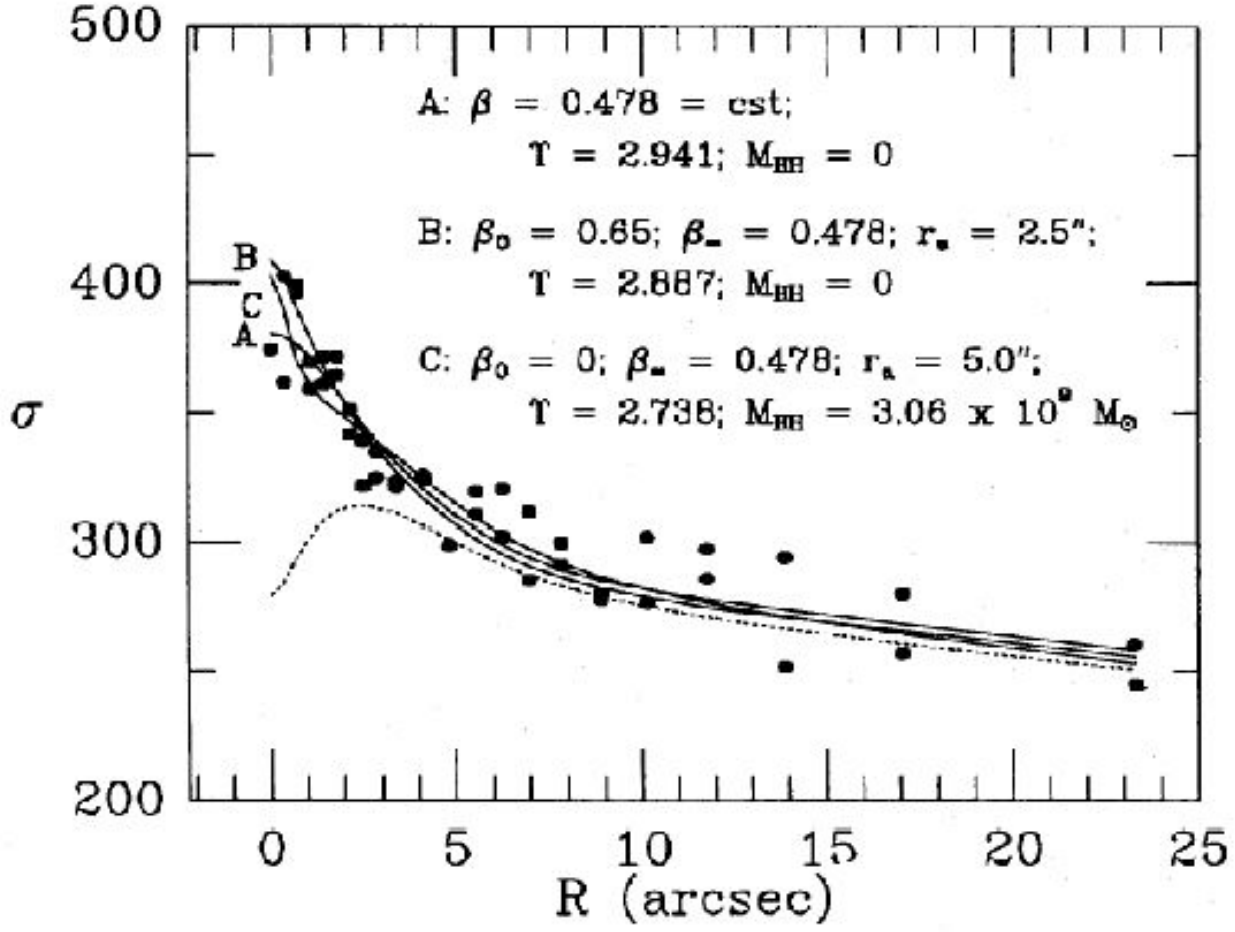
Heating of Galaxy Clusters

- Gas in clusters does not cool down indefinitely.
- Kinetic energy from SMBH jets is good candidate.



Measuring MBH Mass

- Ideal: see clear Keplerian increase in speed.
- Must be careful about dynamical models.



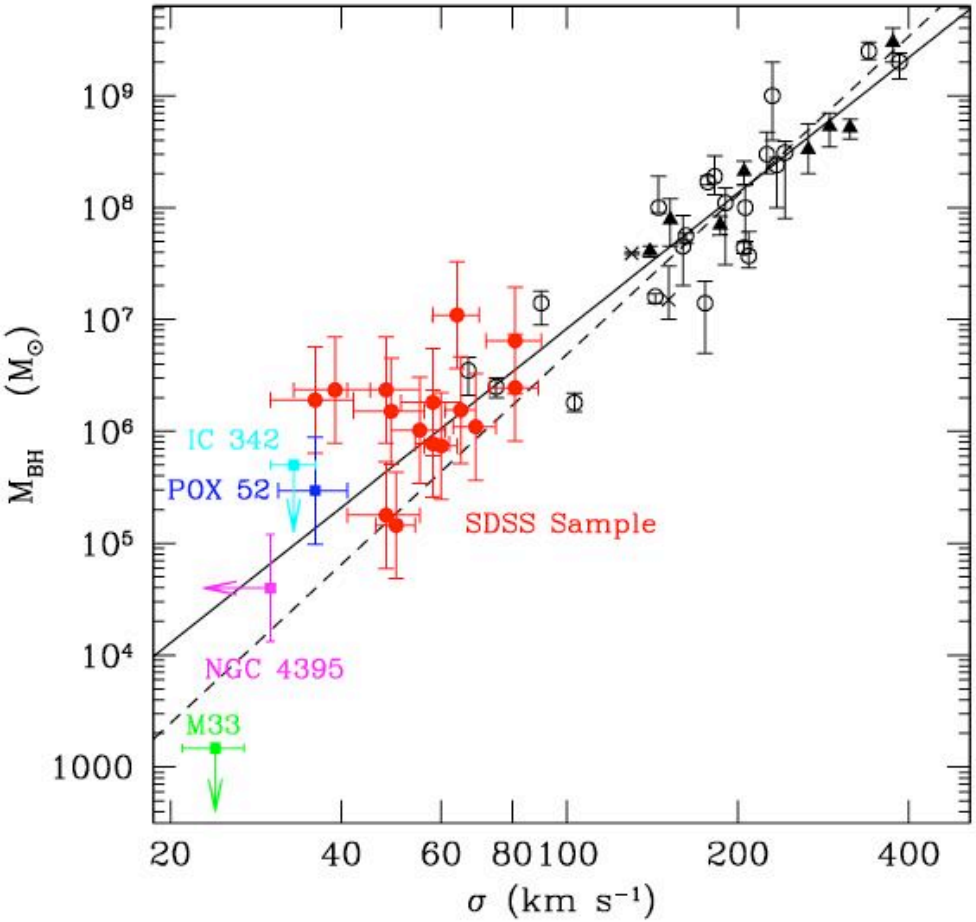
M87: van der Marel

The Radius of Influence

- Another problem: need to resolve $R_{infl}=GM/\sigma^2$ to be sure of effect.
- For $M=10^6\ M_{sun}$, $\sigma=60$ km/s, $R_{infl}>1$" only for distance < 250 kpc!
- Also, $\sigma=60$ km/s tough to resolve in spectra.
- For black holes in prime LISA range, do not have direct kinematical confirmation.

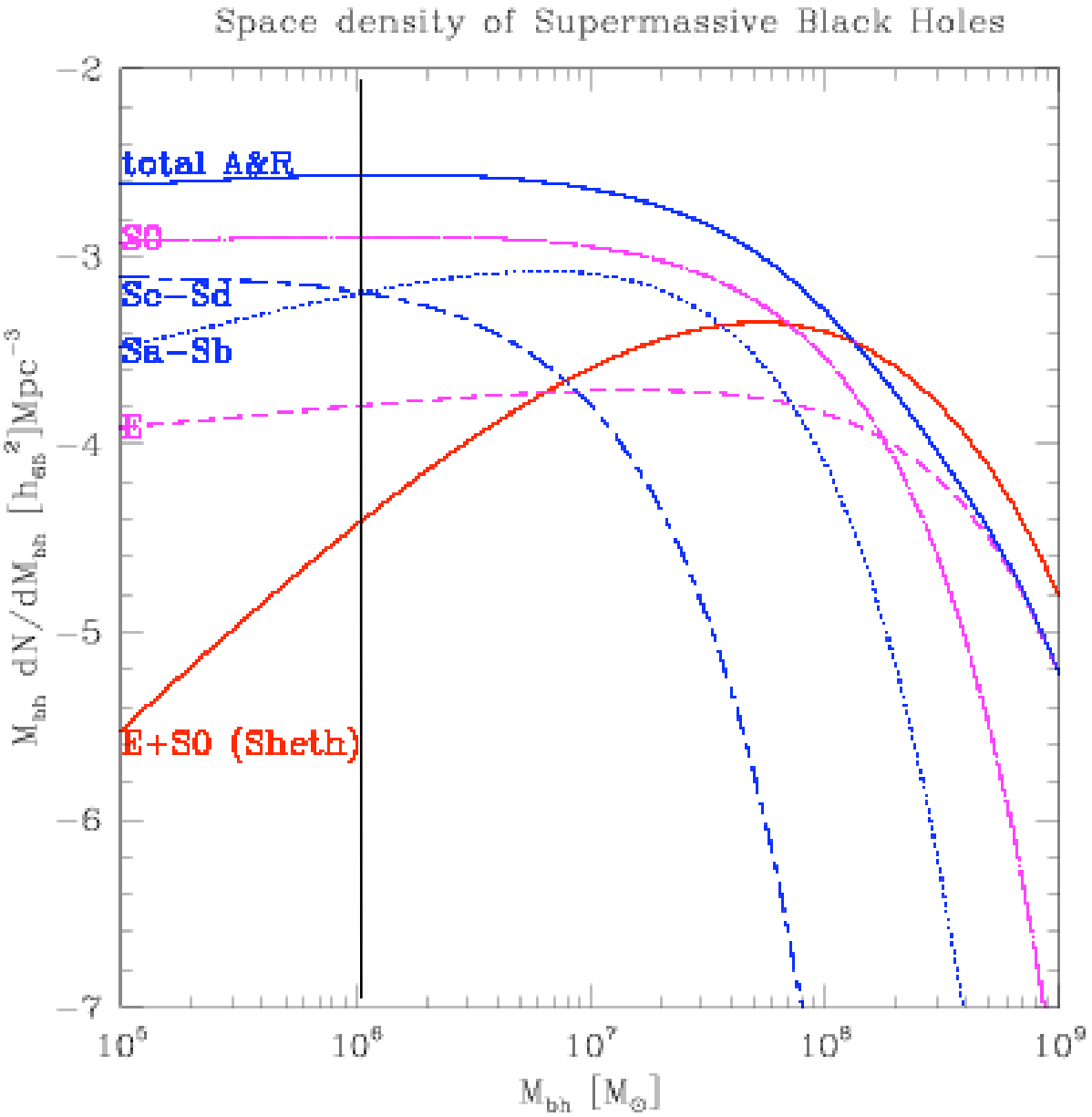
Other Mass Measurements

- Reverberation mapping: time-spectra correlations.
- Line and continuum correlations; systematics?



Barth, Greene, & Ho 2005

Uncertainties in Space Density



LIST EMRI wg: Barack et al. 2003. Projections to low mass based on different assumptions

Role of E/IMRIs

- LISA observations will:
  Provide reliable masses.
  Provide reliable spins.
  Be unique probe of nuclear dynamics.
  Map spacetime and test GR (maybe)
- We have discussed masses; let us now turn to spins and dynamics.

Spins

- For SMBH>$10^{7\text{-}8}$ M_{sun}: accretion, high a/M

  Soltan argument: light versus ρ_{BH}.

  Implies most mass from accretion.

  Also implies rad. efficient: $L/(dM/dt)>0.2c^2$.

  But: most SMBH mass around 10^8 M_{sun}.

  Not an argument at all stages.

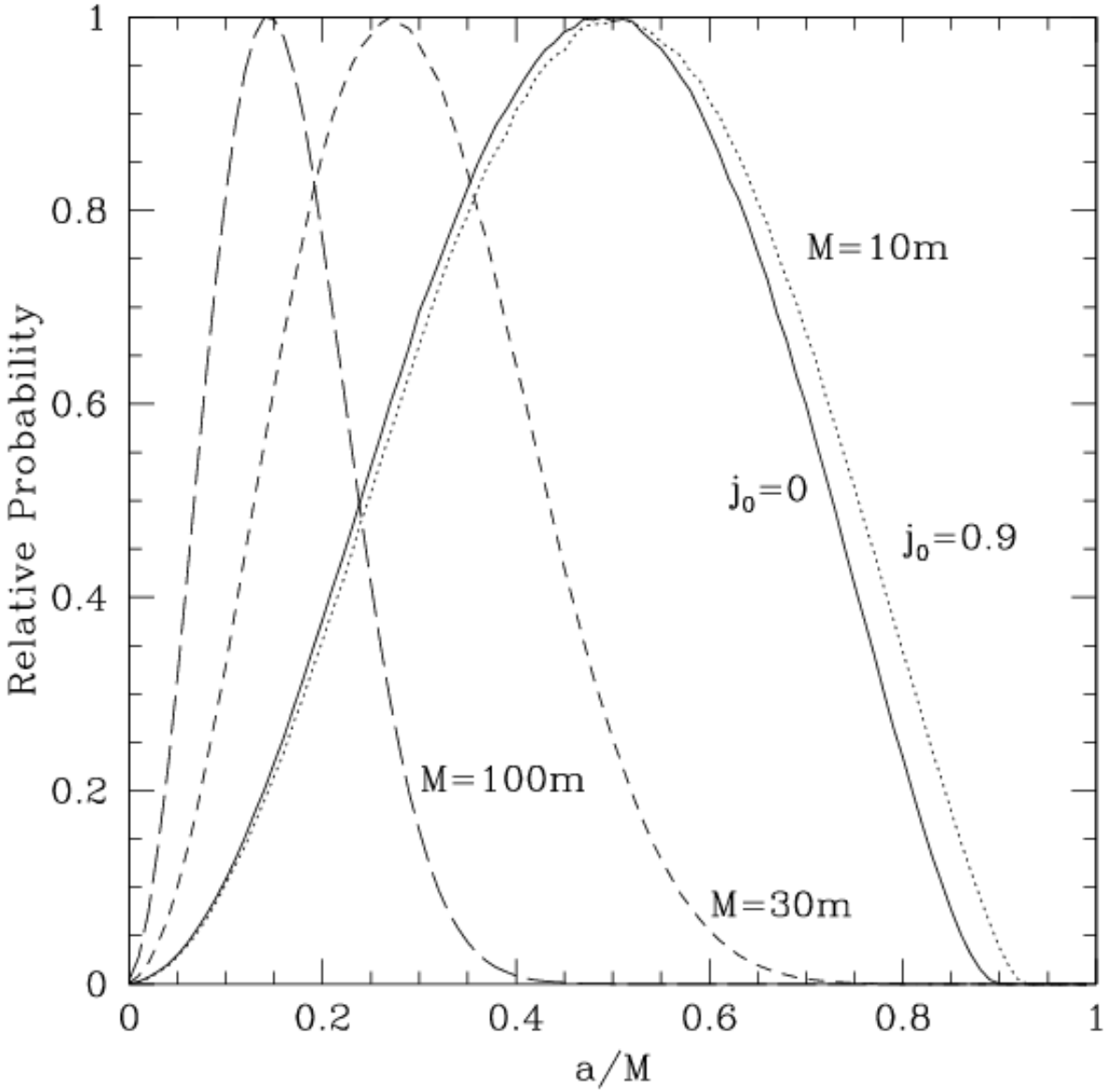
  Also: SMBH-SMBH merger decreases mass!

- For SMBH<10^6 M_{sun}, not clear; accretion or mergers could play role.

Original Spin?

Spins of BH can help reveal history: Accretion implies high spin, but mergers at random angles decrease spin

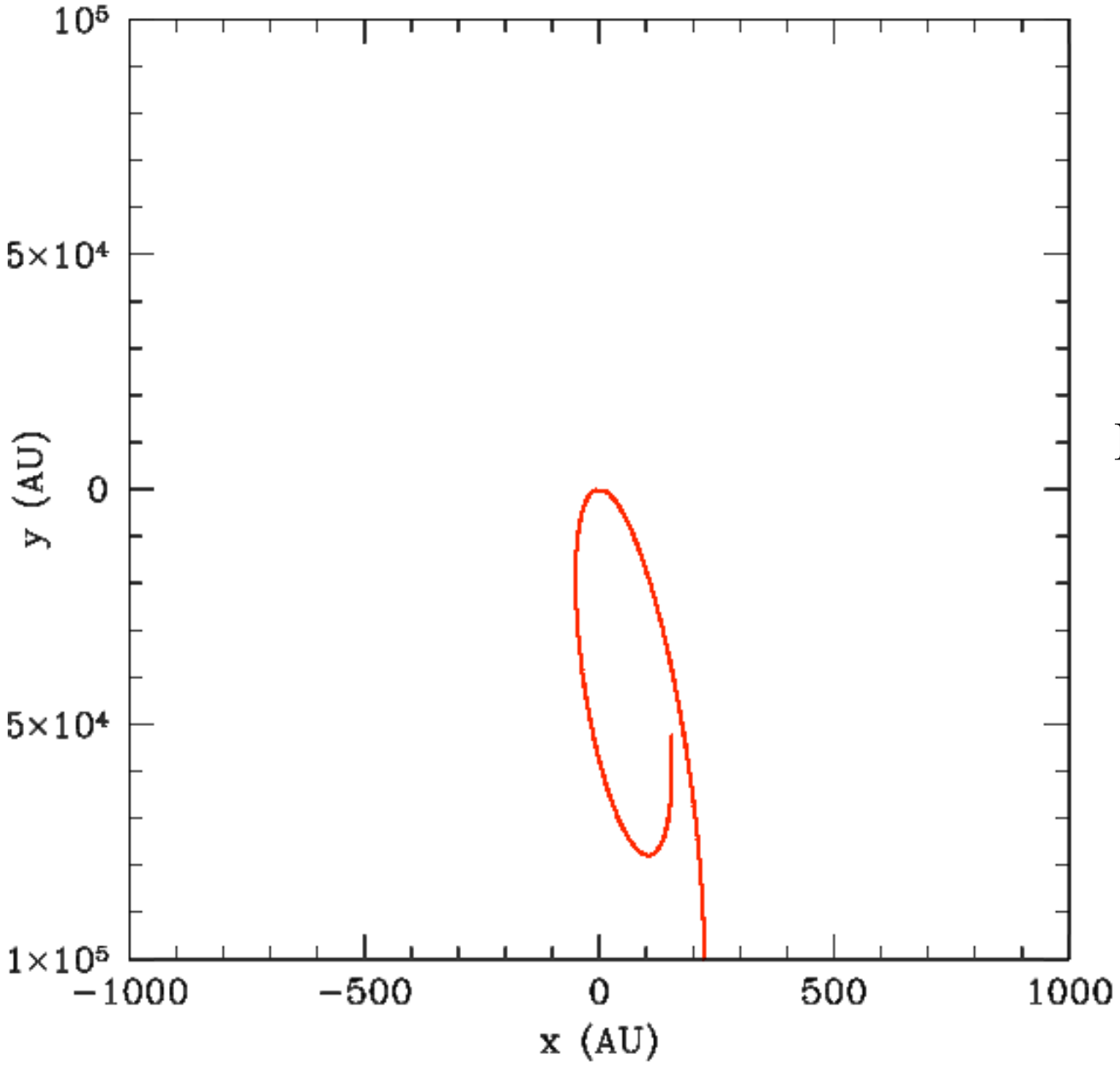
Miller 2002



Extreme Mass Ratio Inspirals

- Stellar-mass BH with SMBH.
- Standard picture:
  BHs orbit in center of galaxy.
  2-body effects perturb orbits gradually.
  Small enough pericenter => capture.
  Very high eccentricity.
- Rates still uncertain by factor ~100.
  See Freitag, Regimbau, …

Single-body capture: distant view



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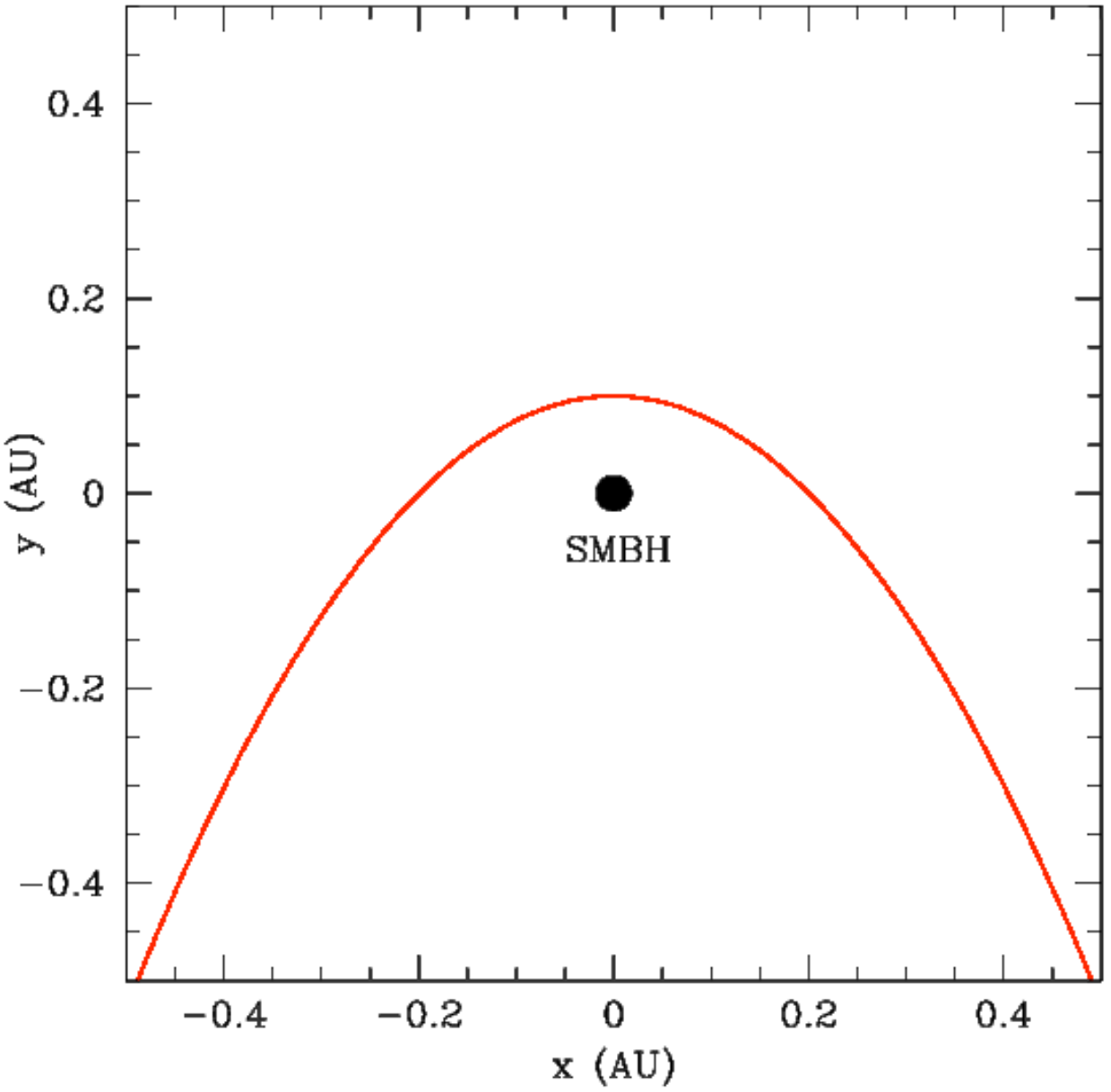
Single-body capture: close-up



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Questions in Standard Picture

- LISA-detectable events need long inspiral; what is probability of plunge? (Bender, Hopman, Alexander)
- Triaxiality, centrophilic orbits? (Holley-Bockelmann)
- Secular resonances, PN dynamics? (Kupi, Amaro-Seoane, Spurzem, Freitag, Davies, Gultekin, Preto, …)

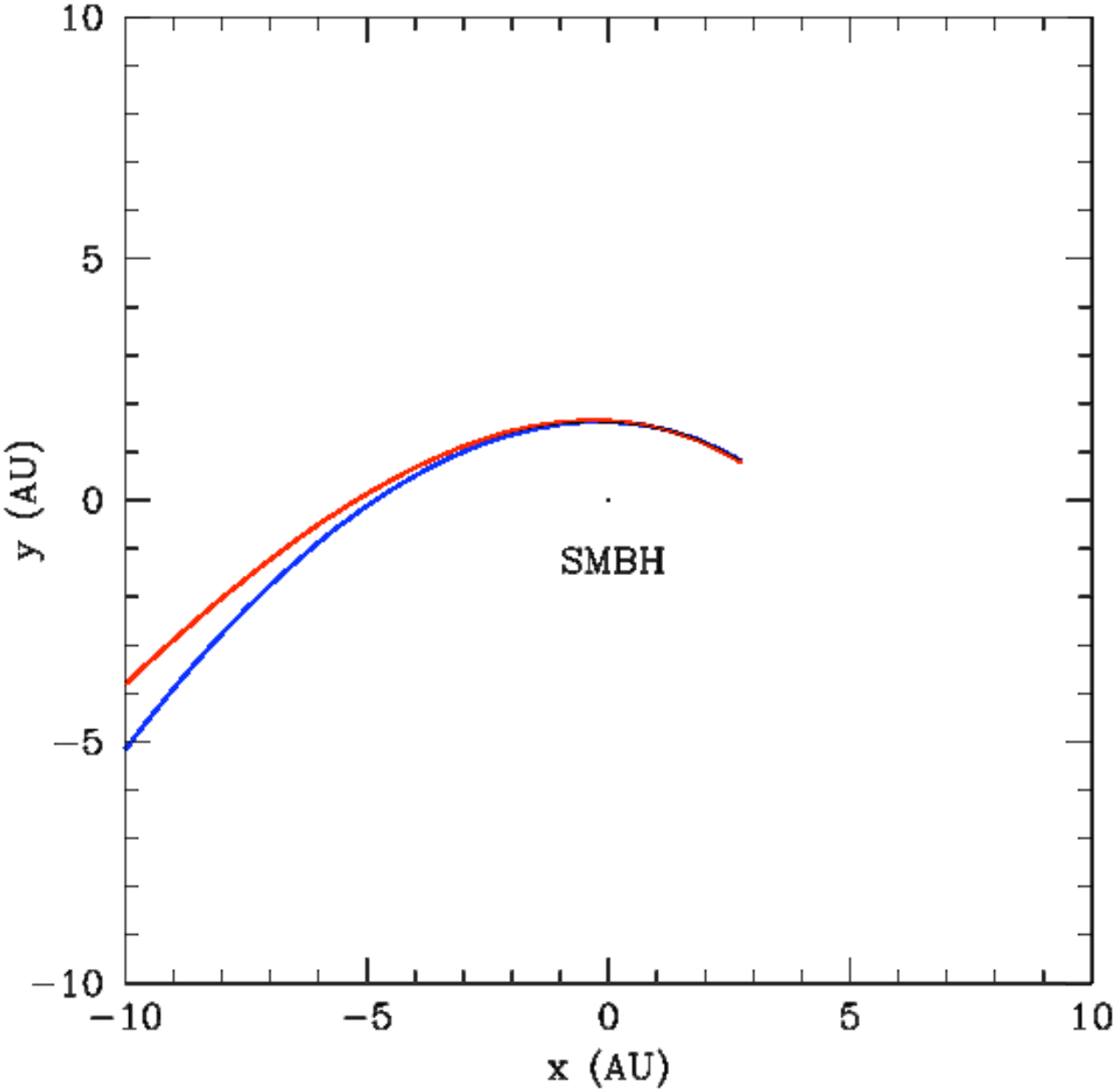
Alternative: Stars in Disk

- Levin 2006; Schnittman et al. 2006
- Star formation in self-gravitating disk.
  Star capture? Miralda-Escude
- Evolve to BH, dragged into SMBH.
- Potentially tens of detections per year.
  Dynamics not modified much by disk.
- Eccentricities expected to be low, orbit in spin plane of SMBH.

Alternative: Binary Tidal Separation

- If BH in binary, pericenter distance can be much greater, hence cross section higher. Miller, Freitag, Hamilton, Lauburg (2005) Separation by IMBH in clusters? Pfahl (2005)
- Circularized orbits, but random plane.
- No perturbation to plunge.
- Key: calculation of binary fraction and properties.

Binary separation: close-up



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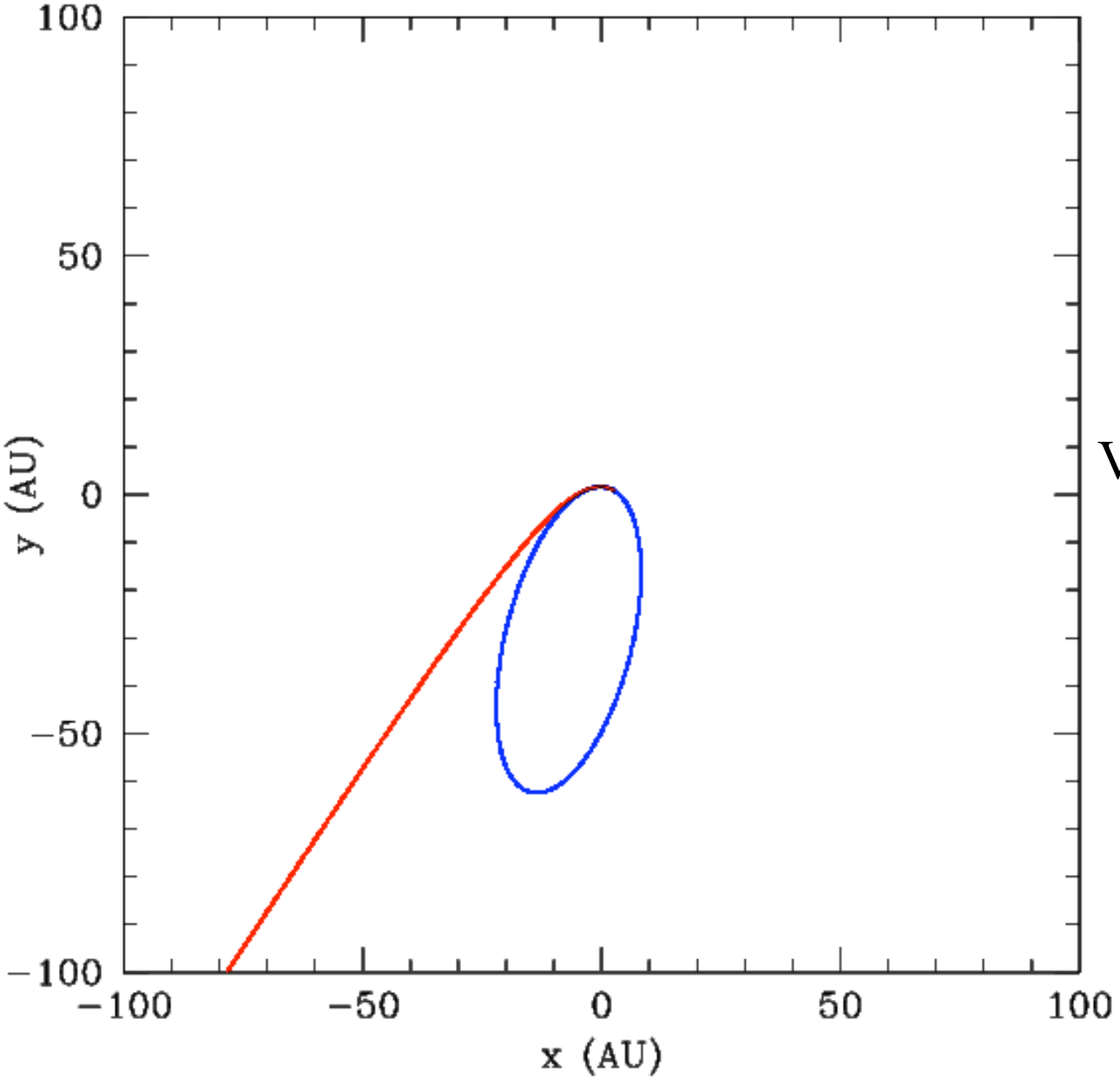
Binary separation: distant view



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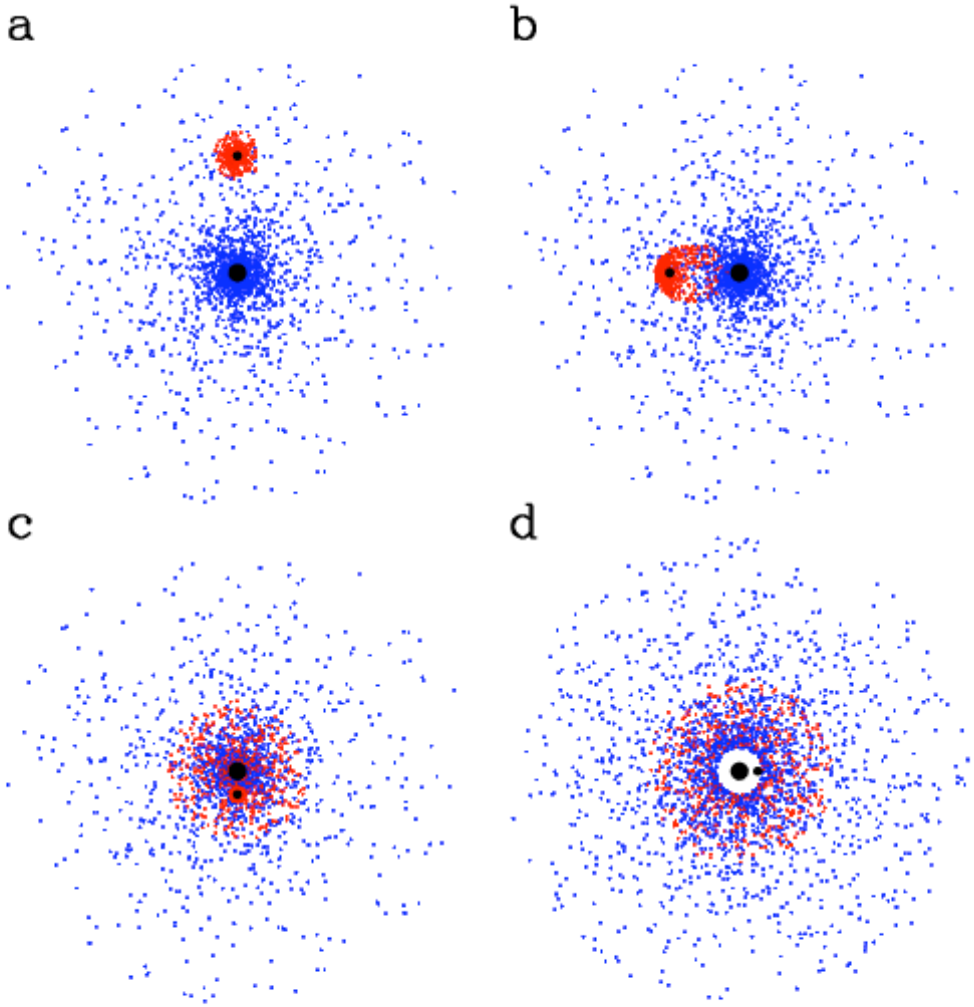
IMBH-SMBH Mergers

- If cluster with IMBH sinks to center, IMBH likely to merge with SMBH later.
- Signal strong enough to detect easily, but still is large mass ratio (IMRI). Berti
- Rate? Properties of orbits?
  Miller 2005
  Matsubayashi et al. 2005
  Portegies Zwart et al. 2006

IMBH-SMBH Merger Sequence



Eccentricities

- What eccentricities do we expect?
- Massive BH systems interact in sea of stars
- Circularization from GW versus eccentricity wander due to stellar interactions.
- If total binary mass M, reduced mass μ, binary must interact with mass $\sim\mu$ to change *e* or *a* significantly.
- What is ratio of GW time to effective interaction time?

Circularization vs. Interactions

$$t_{GW}/t_{int} \sim 100\,[\mu/10\ M_{sun}]^{-2} \times (M/10^6\ M_{sun})^{2/3} \times (\rho/10^6\ M_{sun}\ pc^{-3}) \times (\sigma/60\ km\ s^{-1})^{-1} \times (f_{max}/10^{-4}\ Hz)^{-10/3} \times (1-e)^{-5/2}$$

Here t_{GW} is the GW circularization time; t_{int} is the time for stellar interactions to change e significantly; ρ is the mass density of stars; σ is the velocity dispersion; and f_{max} is the GW frequency at pericenter.

Results for Eccentricities

- EMRIs (10 M_{sun} - 10^6 M_{sun}) will not circularize if they were very eccentric.
- IMRIs (10^3 M_{sun} - 10^6 M_{sun}) will circularize.
- Special circumstance: secular resonance can produce high eccentricities…
  Miller & Hamilton 2002, Blaes et al. 2002
- …but for stellar-mass BH, e_{ground} still low.
  Wen 2003

Key Questions

- Astrophysics: can new observations and simulations reduce the many uncertainties?
- Data analysis: how well can masses, spins be determined in presence of many events? Also: model-free IMRI analysis?
- Numerical GR: what are kicks, waveforms as function of mass ratio, spin, orientation?