# Extreme and intermediate-mass black hole inspirals

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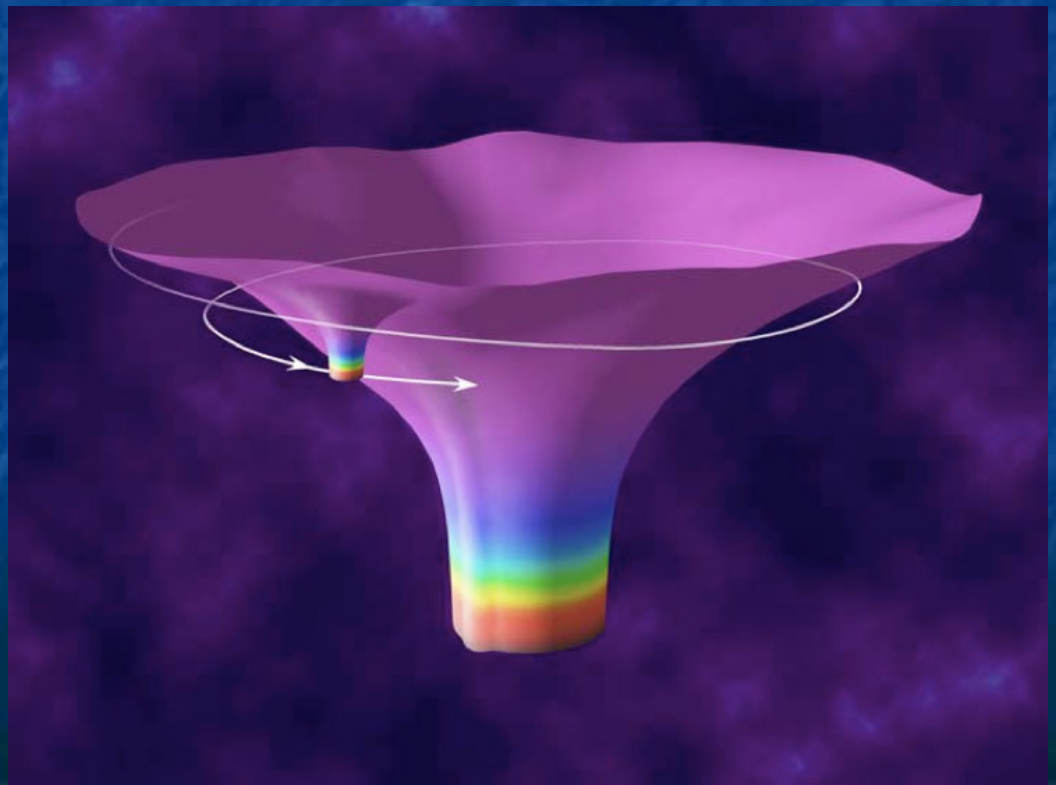


# Outline

- Dynamical issues in galactic nuclei:
  Two-body relaxation and mass segregation
  Triaxiality and net rotation of core
  Resonant relaxation
- Intermediate-mass black holes
- Insights into rates from tidal disruptions?

# Major Questions

- What are the primary paths towards EMRIs and IMRIs, and can we distinguish between those paths?
- How well can the growing number of TDE observations constrain the dynamics and rates of EMRIs/IMRIs?

# Some Useful Scales

Assuming a primary mass $M=10^6\ M_{sun}$:

- Critical pericenter for ecc. 10 $M_{sun}$ EMRI: ~0.1 AU, or ~10M
- Typical apocenter for EMRI from two-body: ~0.05 pc ~$10^4$ AU ~$10^6$M
- Critical pericenter to disrupt solar-type star: ~0.5 AU, or ~50 M
- Inspiral time for circular orbit, m<<M: $T_{insp} \sim 5 \times 10^9\ \mathrm{yr}\ (m/10\ M_{sun})^{-1}(a/20\ \mathrm{AU})^4$

# 2-Body Relaxation, Segregation

- 2-body relaxation:
  $t_{rlx} \sim \sigma^3/(\rho m)$
  $t_{rlx} < t_{Hub}$ for $M <$ few x $10^6$ $M_{sun}$
- Massive things sink
- Ang mom relaxes faster for high e
- Core collapse in $< t_{rlx}$ for broad mass distribution
- But energy source (binaries, MBH) stalls collapse

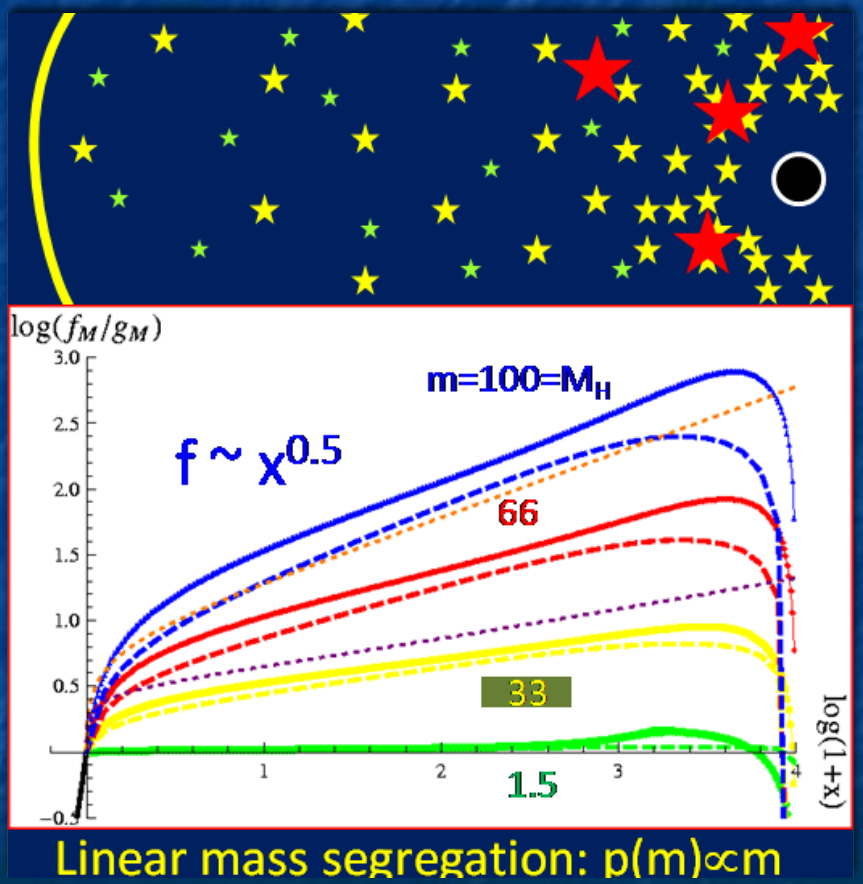
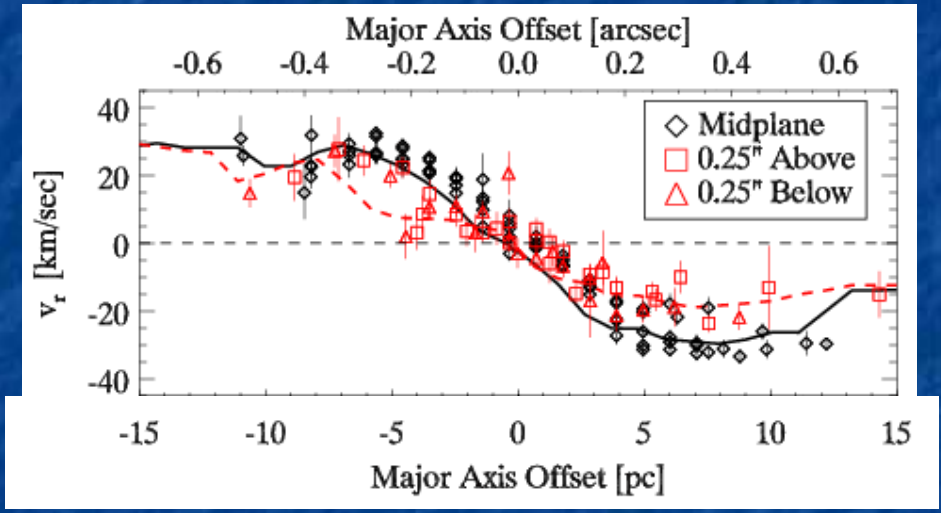



Figure by Uri Keshet

# Net Rotation?

- 2-bod relaxation and mass segregation are enhanced when relative speeds of stars are decreased $t_{rlx} \sim v_{rel}^3$
- If there is net rotation in the inner ~1 pc, relaxation times are therefore decreased
- Some simulations suggest this could make a huge difference to rates, properties

NGC 4244 rotation




Adapted from Seth et al. 2008

$v_{rot} \sim \sigma$ at 10 pc

Q: how common is it that $v_{rot} \sim \sigma$ in inner pc?

# Triaxiality

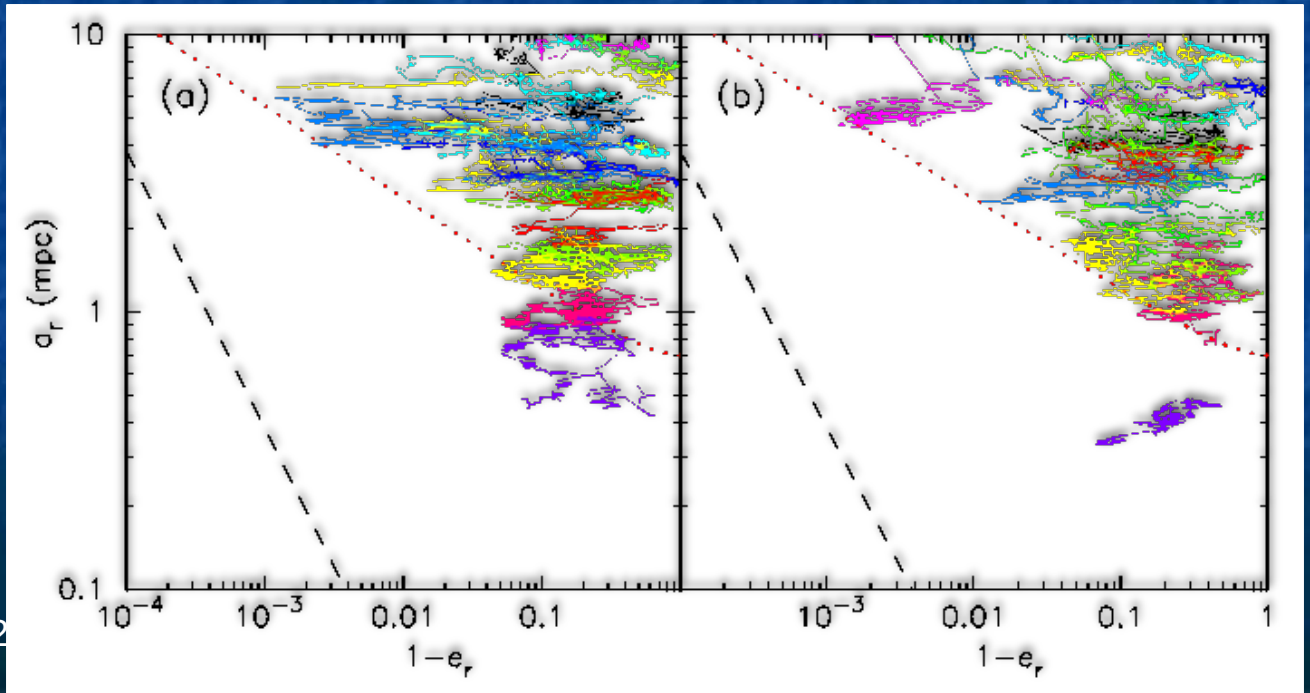
- Galaxy collisions can cause cores to be triaxial
- Then no symmetry preserves angular momentum of individual orbits
- Not as true close to SMBH
- Increased feeding rates to center, boosting EMRIs? Most important for binaries because they come from farther out

M87


Q: how triaxial are inner 10s of pc?

# Resonant Relaxation

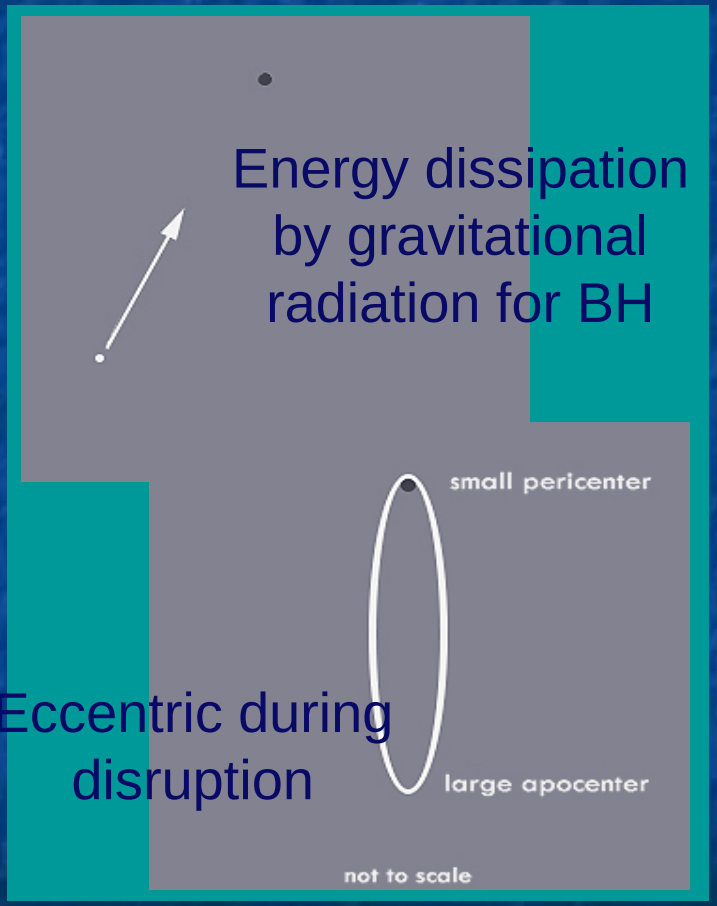
In near-Keplerian potentials, orbits are ~fixed in space, so can exert long-term torques (Rauch and Tremaine 1996). But when GR precession is important, “Schwarzschild barrier” (Merritt et al. 2011) often reflects orbits back. But not for TDEs




Merritt et al. 2011

# TDE/EMRI 1: High Eccentricity Inspiral

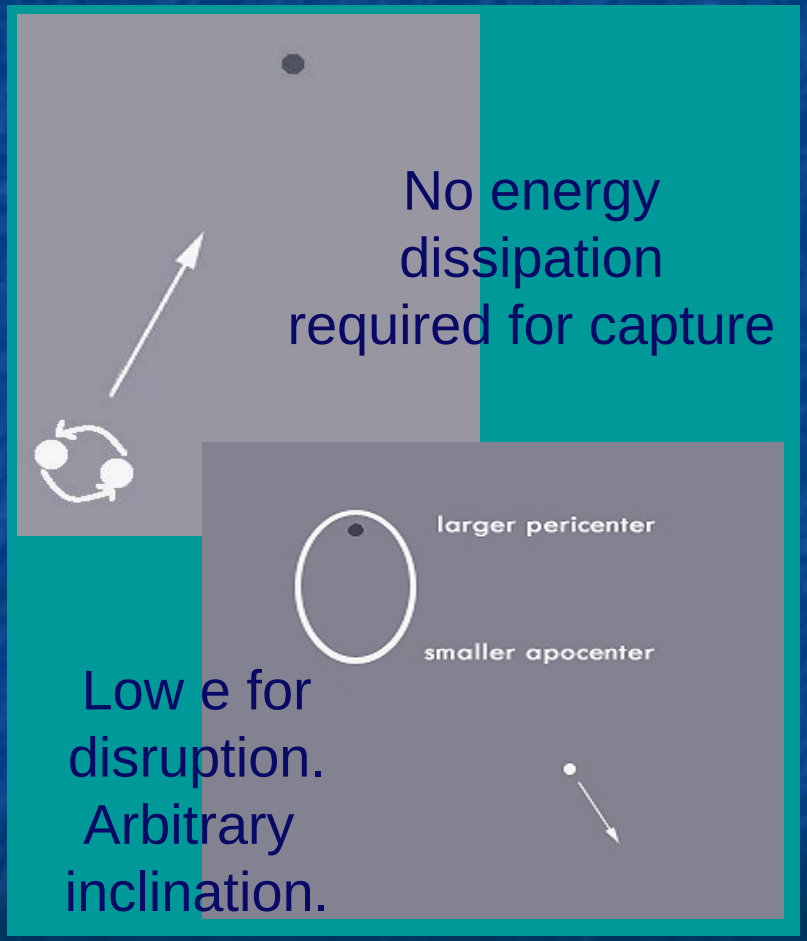
- High apocenter orbit
- 2-body rel -> plunge
- Small pericenter means loss of energy for EMRI, or direct disruption
- Inspiral over $10^{4-5}$ orb
- Eccentric disruption/EMRI
  Arbitrary inclination
- Triaxiality unlikely to boost




Courtesy V. Lauburg

# TDE/EMRI 2: Binary Tidal Separation

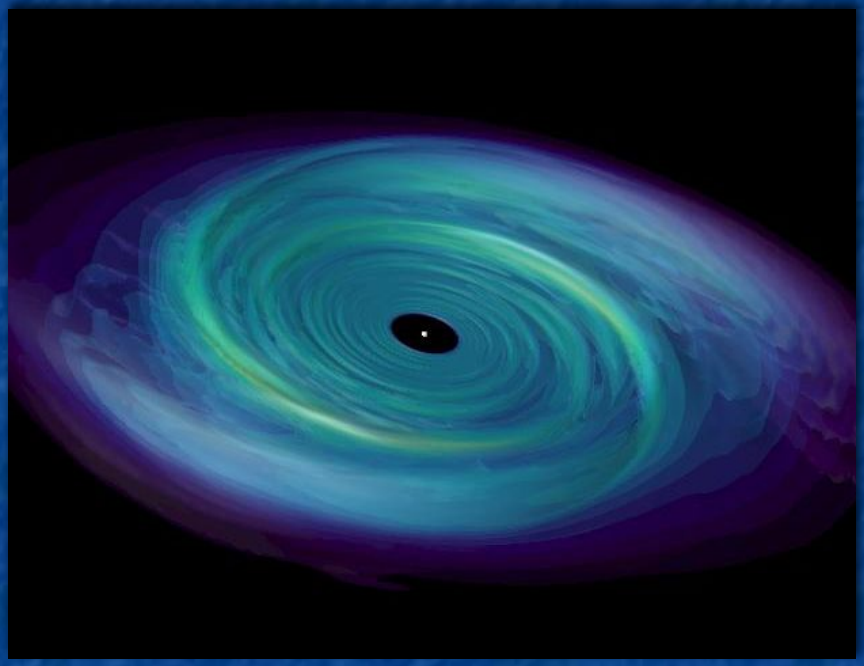
- What if BH/star in binary?
  Hills 1988: HVS
- Binary separates
  No energy loss needed
- High pericenter, low apocenter
- Dynamical evol., EMRI or TDE?
  Miller+ 2005, Amaro-Seoane+ 2012, Bromley+ 2012
  Schwarzschild barrier?
- Low-e, arb. i disruption/EMRI?
- Triaxiality might boost




Courtesy of V. Lauburg

# TDE/EMRI Scenario 3: Settling in Accretion Disk

- Miralda-Escude & Kollmeier 2005, Levin 2007
- Star plunging through or forming in disk settles in disk
- Zero eccentricity
- Zero inclination
- Disruption?  Amaro-Seoane et al. 2013



http://apod.nasa.gov/apod/image/0503/accretion_mpowen_c1.jpg

# Signatures of Scenarios

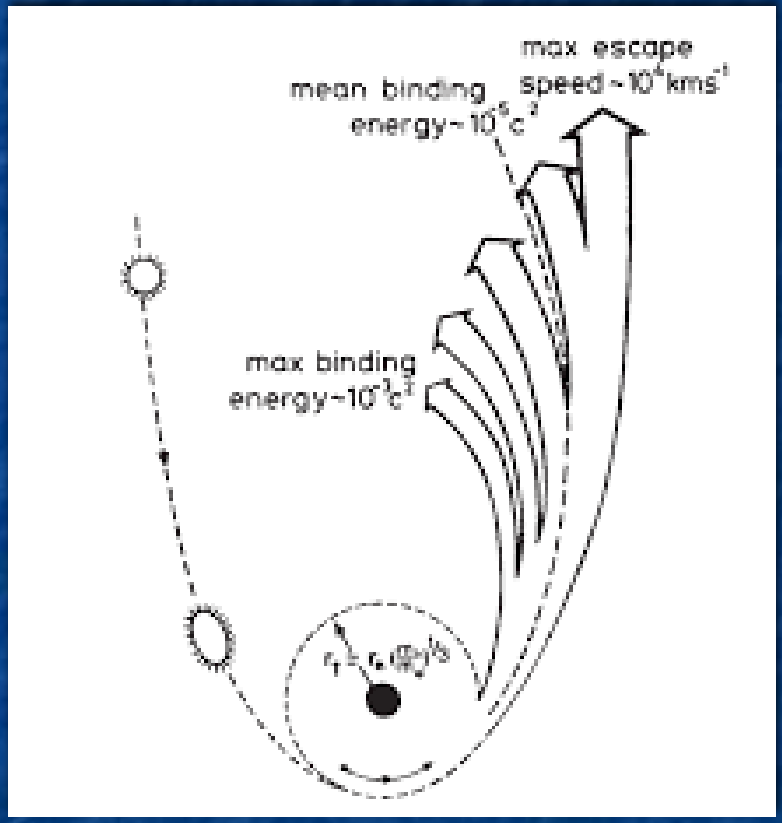
- Inclination and eccentricity
- Scenario 1 (2-body relaxation): arbitrary inclination, large initial eccentricity
- Scenario 2 (tidal separation): arbitrary inclination, low initial eccentricity
- Scenario 3 (EMRI from disk): equatorial, essentially circular

# EMRI Rates

- Many rate calculations have been performed
- But we have new information at our disposal: over the last ~decade, many new observations have been made of tidal disruption events (TDEs)
- What can TDEs tell us about EMRIs?

# TDEs

- Star ripped apart by supermassive BH
- Maximum pericenter: $r_p <\sim (M_{BH}/m_*)^{1/3} R_*$
- ~0.5 AU for solar-type star around $10^6$ $M_{sun}$ BH
  As before: ~50M, vs ~10M for 10 $M_{sun}$ EMRI



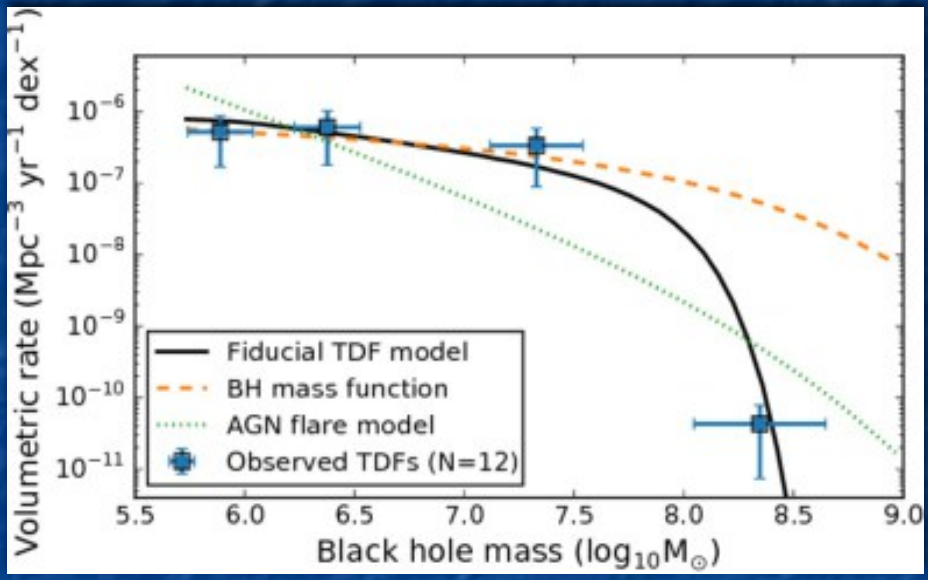

Rees 1988

# Dynamics of TDEs

- In principle, same mechanisms as EMRIs
- In practice, the ~dozen detected TDEs fit the two-body relaxation channel (high eccentricity)
- Not susceptible to Schwarzschild barrier
  But Amaro-Seoane 2018 argues that the barrier has little role in EMRIs, either, and as before, rates might be supply-limited

# Rate of TDEs

- Observationally, rate in $10^6$-$10^7$ $M_{sun}$ range is few x $10^{-7}$ $Mpc^{-3}$ $yr^{-1}$
- In ~1 Gpc LISA range, would be hundreds per year
- EMRI rate?



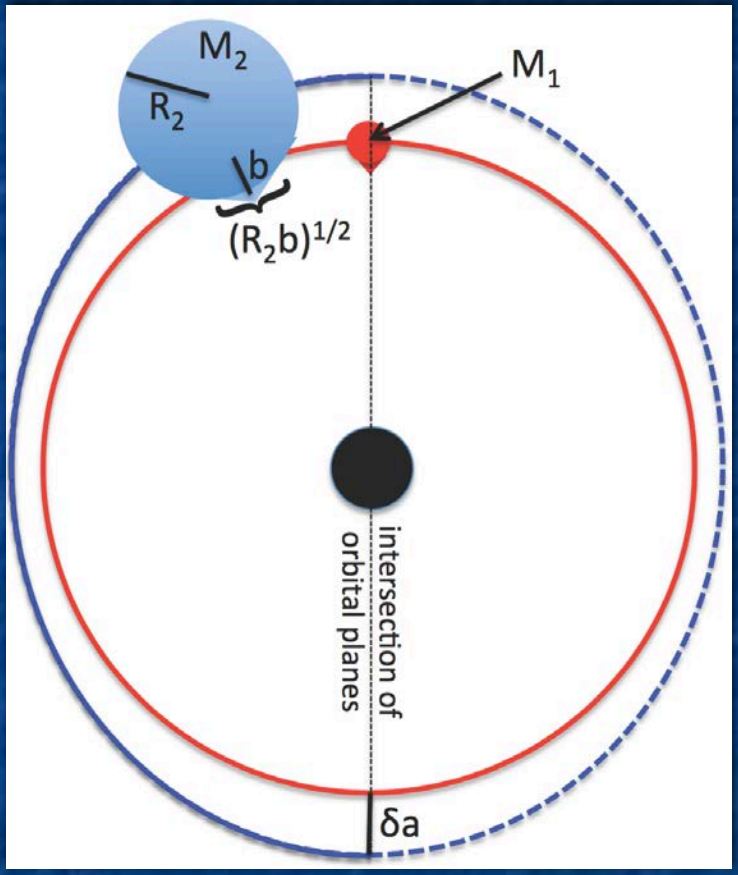

Stone et al. 2018

# Implications for EMRI rate

- Theory, and recent observations, suggest a TDE rate of ~$10^{-4}$ $gal^{-1}$ $yr^{-1}$
- ~$10^{-3}$ of stars are black holes
- MWEG number density: ~$10^{-2}$ $Mpc^{-3}$
- Multiplied together, get ~$10^{-9}$ $Mpc^{-3}$ $yr^{-1}$
- Thus several per year out to 1 Gpc
- Mass segregation, dwarf galaxies will increase rate; factor of 10 or more?

# TDE for other channels?

- What about binary tidal separation?
- Nothing for sure yet, but Metzger+Stone suggest that nearly circular TDEs could stall (mass transfer) and lead to grazing collisions (EMRI impostors!)




Metzger and Stone 2017

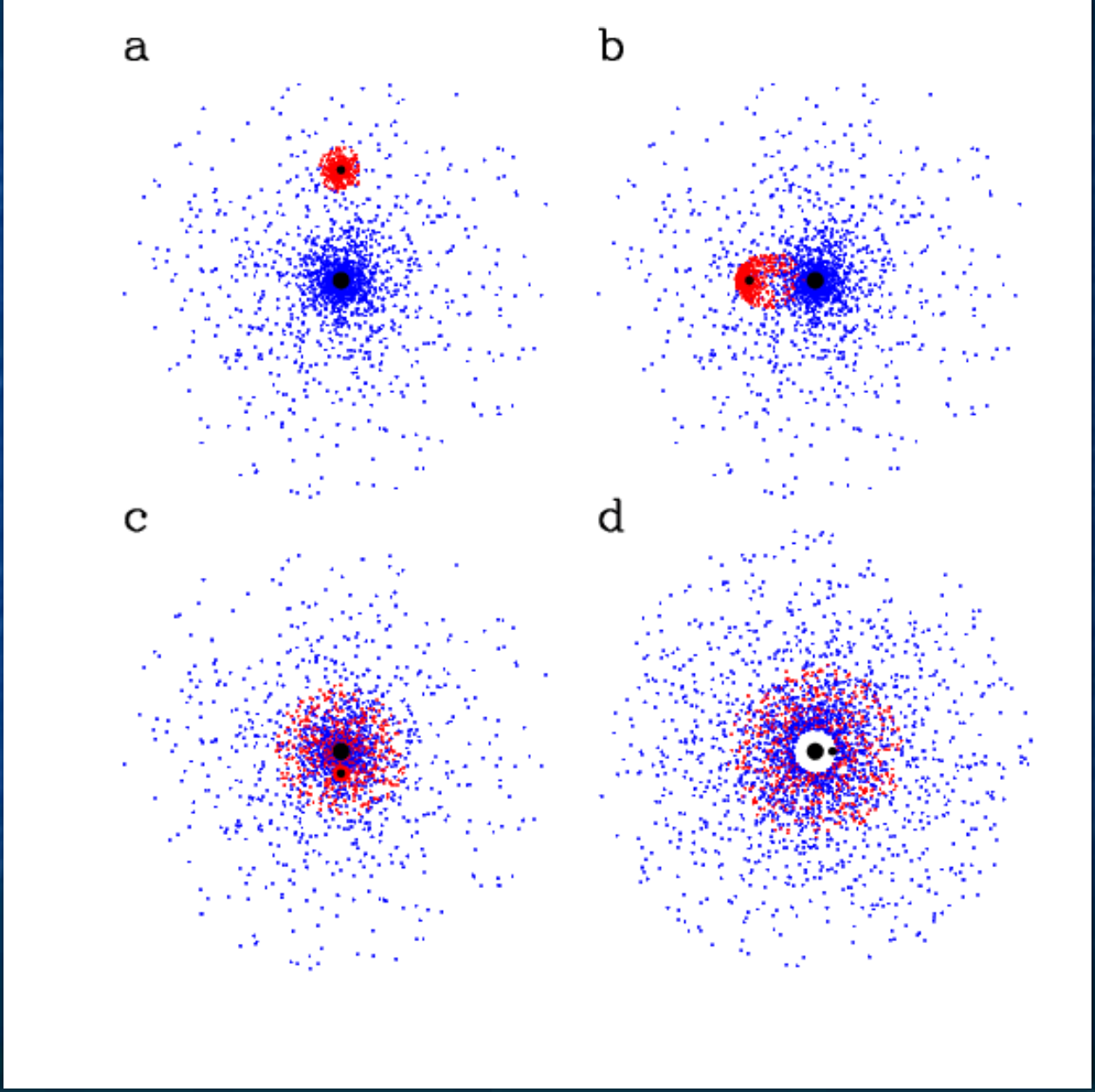
# TDE for other channels?

- What about capture/production in AGN accretion disks?
- Suggestions by McKernan et al.
- Maybe!  Would this lead to extra-massive stars?  To intermediate-mass black holes?
- What specific signatures would there be for TDEs from this channel?

# IMBHs and IMRIs

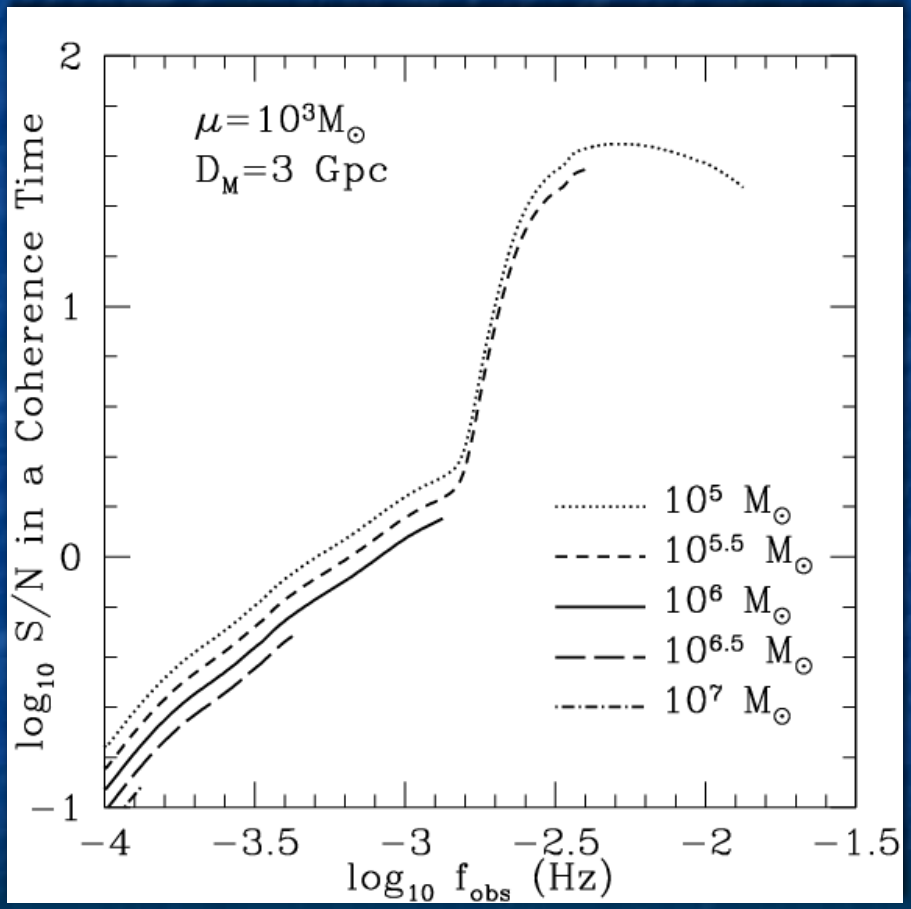
- What about intermediate-mass black holes? $10^2$-$10^5$ $M_{sun}$
- Would be much stronger signals than EMRIs
- If the mass ratio with the SMBH is in the 0.01-0.1 range, then their study will require new analytic techniques

# IMBH-SMBH mergers?



# IMBH-SMBH mergers?

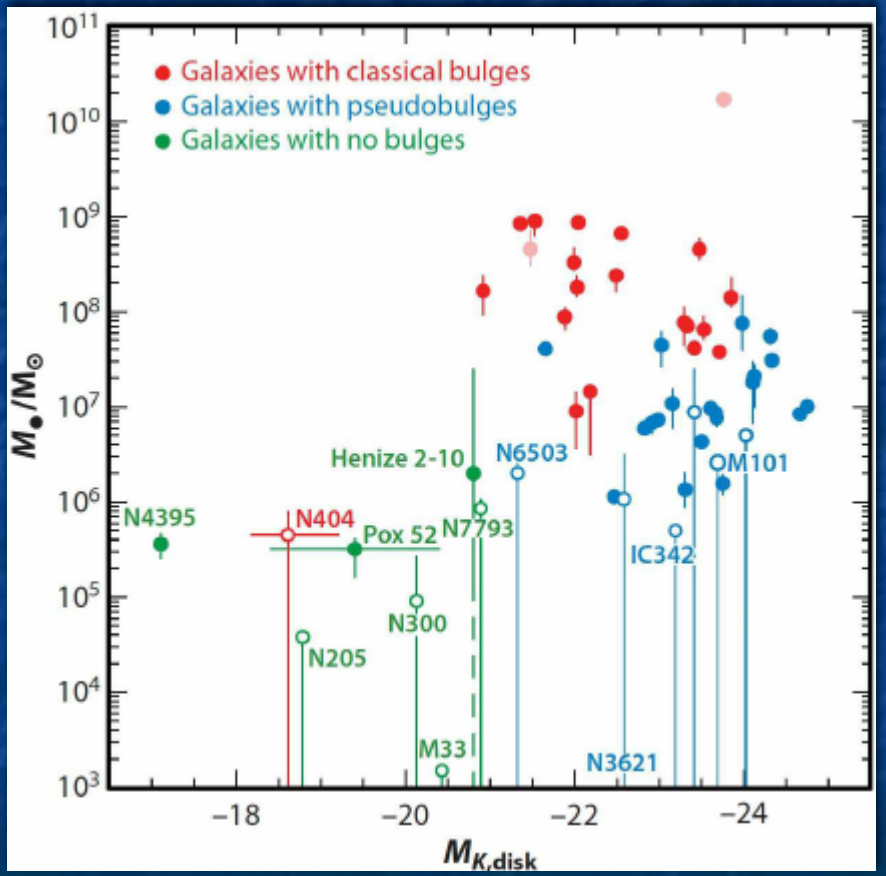
- If IMBH with masses $M \sim 10^3 M_{sun}$ exist, they would produce very strong EMRIs
- Could detect on coherence timescale
- Would allow precise tests of GR
- What is the evidence?




Miller 2005

# Evidence for IMBHs

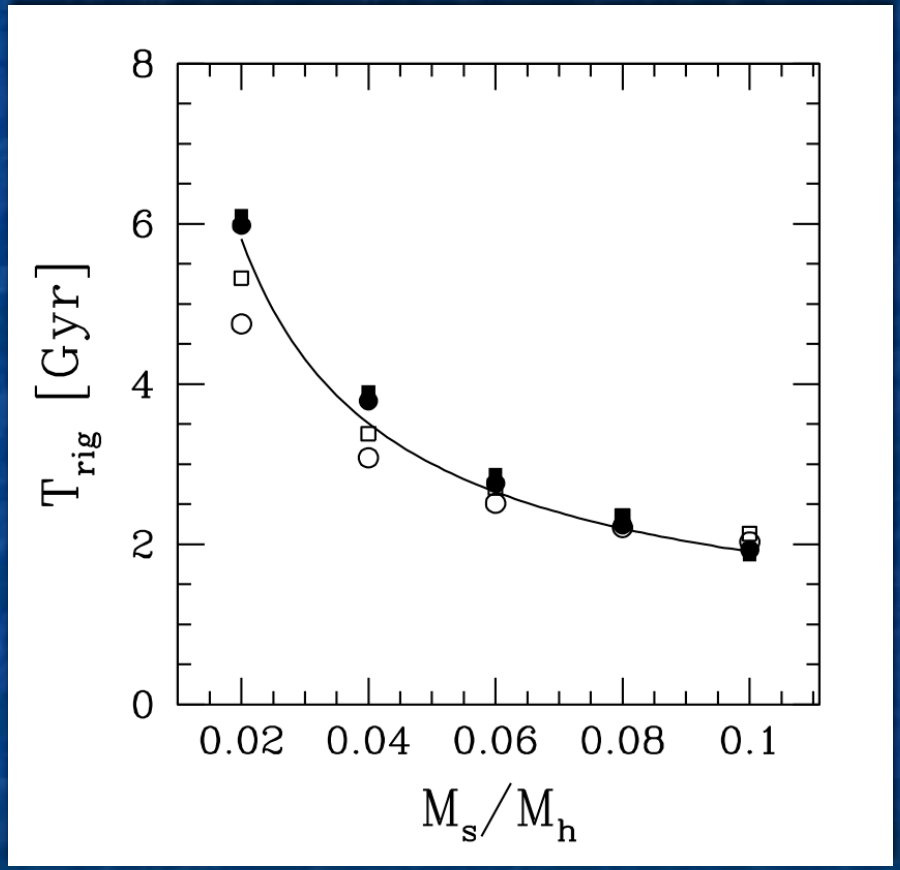
- As an astro guy, I think of IMBHs as coming from a new formation scenario
- But you don't care!
- Fine if in dwarf gals.
- Good evidence!
- So we're set, right?




Kormendy 2015

# Dynamical Friction

- Not so easy...
- IMBHs in satellite galaxies need to get to the center to merge with SMBH
- But those galaxies get stripped
- Mass drops, DF time becomes huge!




Taffoni et al. 2003

# Other ways to make IMBHs?

- Population III stars?
- Dynamics in young or old stellar clusters? E.g., long-term core collapse
- These could happen nearer galactic centers
- But there is no positive evidence for any of these. Limits are weak but strengthening

# Summary

- Roles of resonant relaxation, rotation, triaxiality, and binary dynamics are still not settled
- TDEs are especially crucial probes
- Good prospects for obs/theory partnerships!