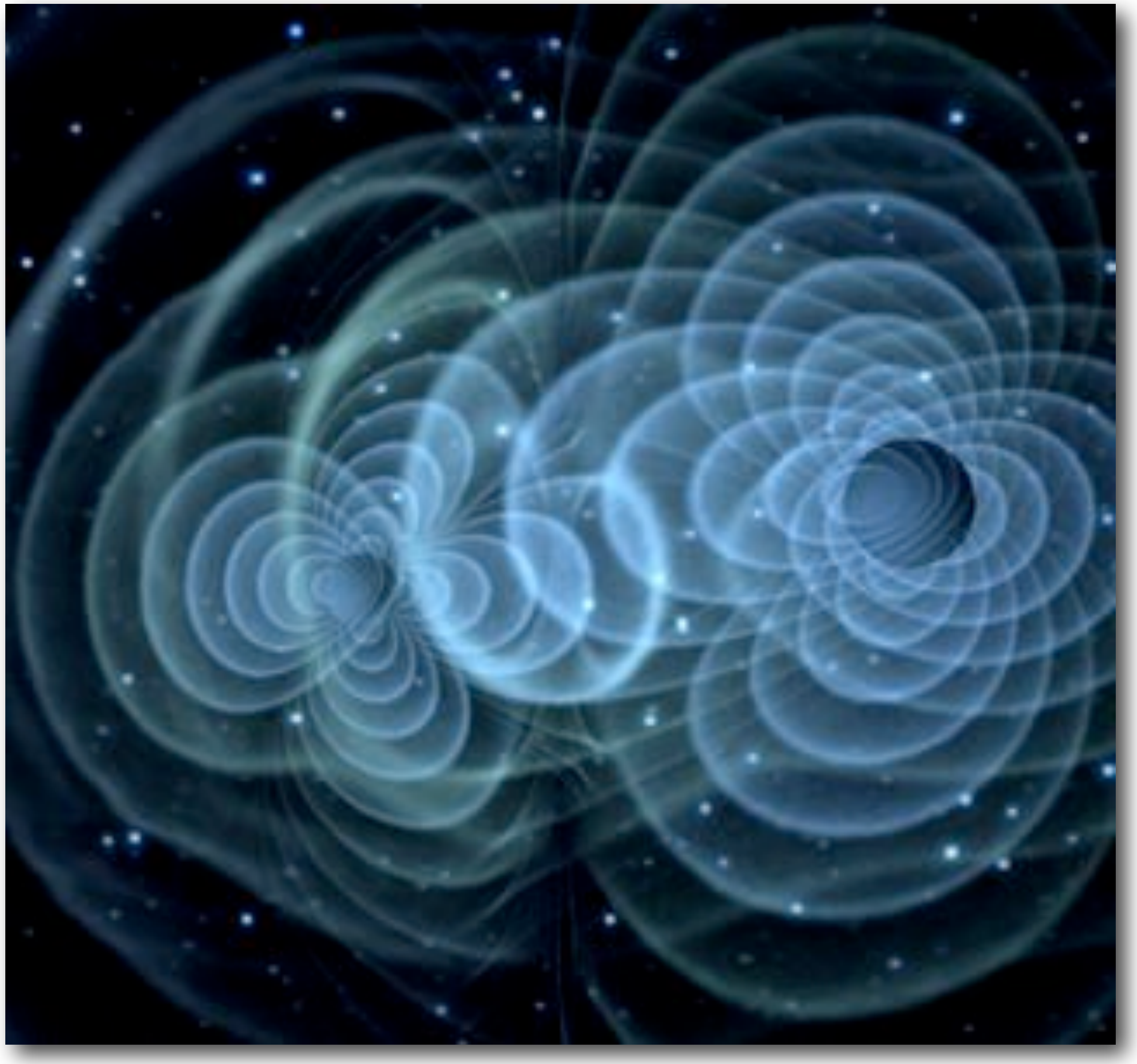
Recoiling Massive Black Holes as Offset AGN



Javiera Guedes[1]

Single and Double Black Holes in Galaxies

August 24, 2011

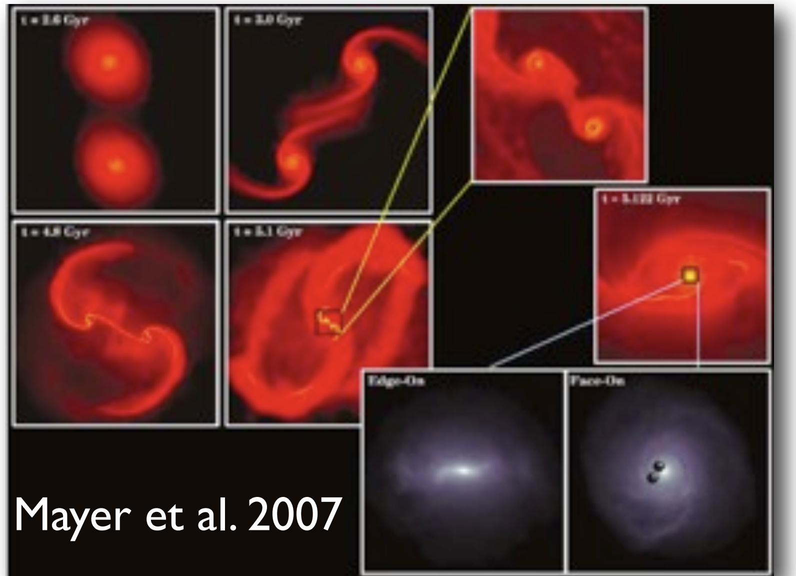
with Piero Madau[2], Simone Callegari[3], Lucio Mayer[1,3], Jürg Diemand[3], Marcel Zemp[4] ,Michael Kuhlen[5]

(1) ETH Zurich, (2) UCSC, (3) Uni Zurich, (4) UMichigan, (5) Berkeley,

Path to Coalescence

Phase I: a=1pc		Phase II: $a=10^{-2}$ pc	Phase III: a=0

major mergers

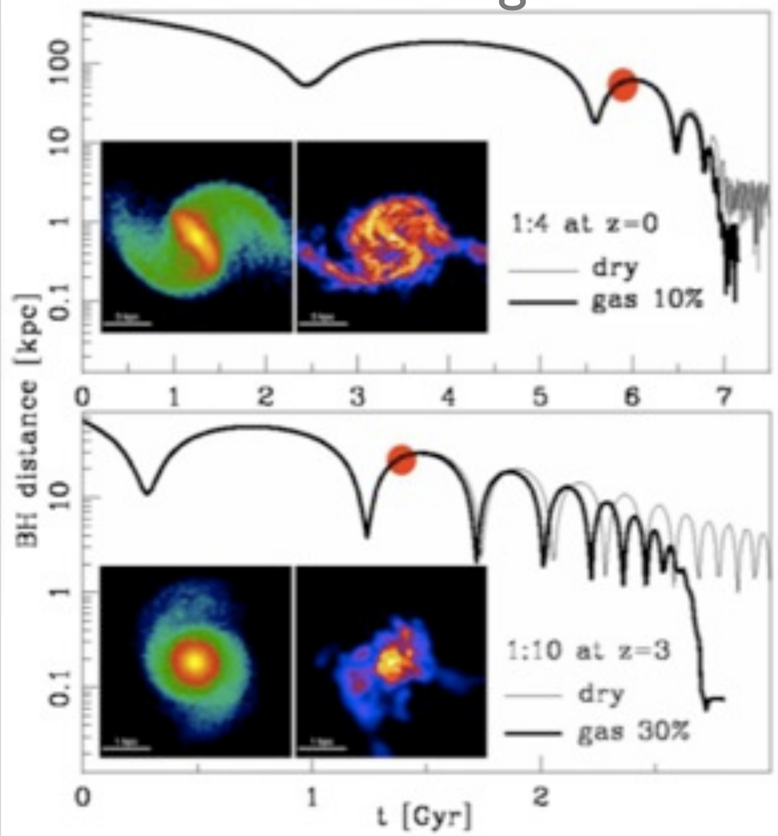


1.5 million gas particles :: 3000 $M_\odot$ :: force softening 2pc

- Efficient in major mergers
- Efficient for high gas fractions: decay timescales of $10^{6\text{-}7}$ yr in galaxies with gas fractions of at least $f_{gas}=0.1$ (e.g. Escala et al. 2004, Mayer et al. 2007, Callegari et al. 2009)
- Depends on the thermodynamics of the gas

$$a_h = \frac{Gm_2}{4\sigma^2} = 1\,pc \left(\frac{m_2}{2\times10^7\, M_{sun}} \right) \sigma_{150}^{-2}$$

minor mergers



Callegari et al. 2009
Unequal Mergers, q=0.25, 0.1

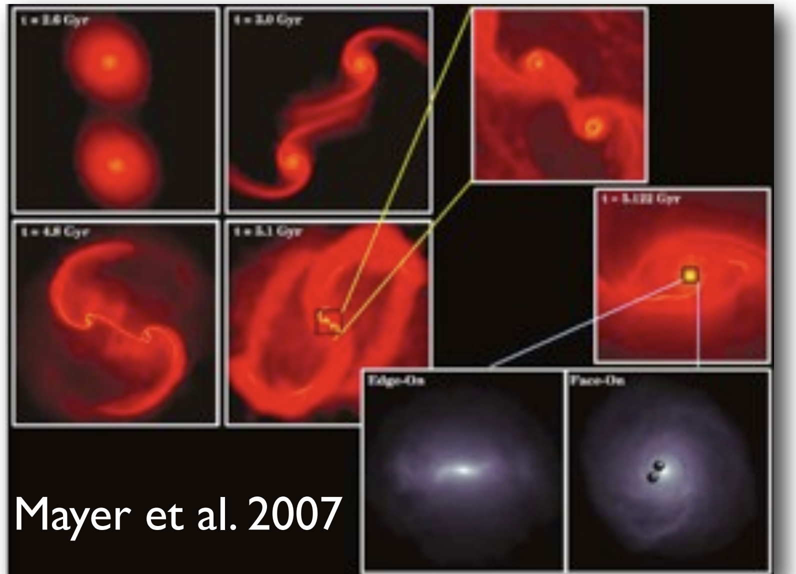
Dry mergers do not form close pairs

q	SF	f_g	z	BH final distance[a]
0.25	No	0	0	2–4 kpc
0.25	Yes	0.1	0	200 pc
0.1	No	0	3	1–6 kpc
0.1 (Hi-Res)	No	0	3	1–5 kpc
0.1	Yes	0.1	3	400 pc
0.1	Yes	0.3	3	70 pc

Path to Coalescence

Phase I: a=1pc

major mergers



Mayer et al. 2007

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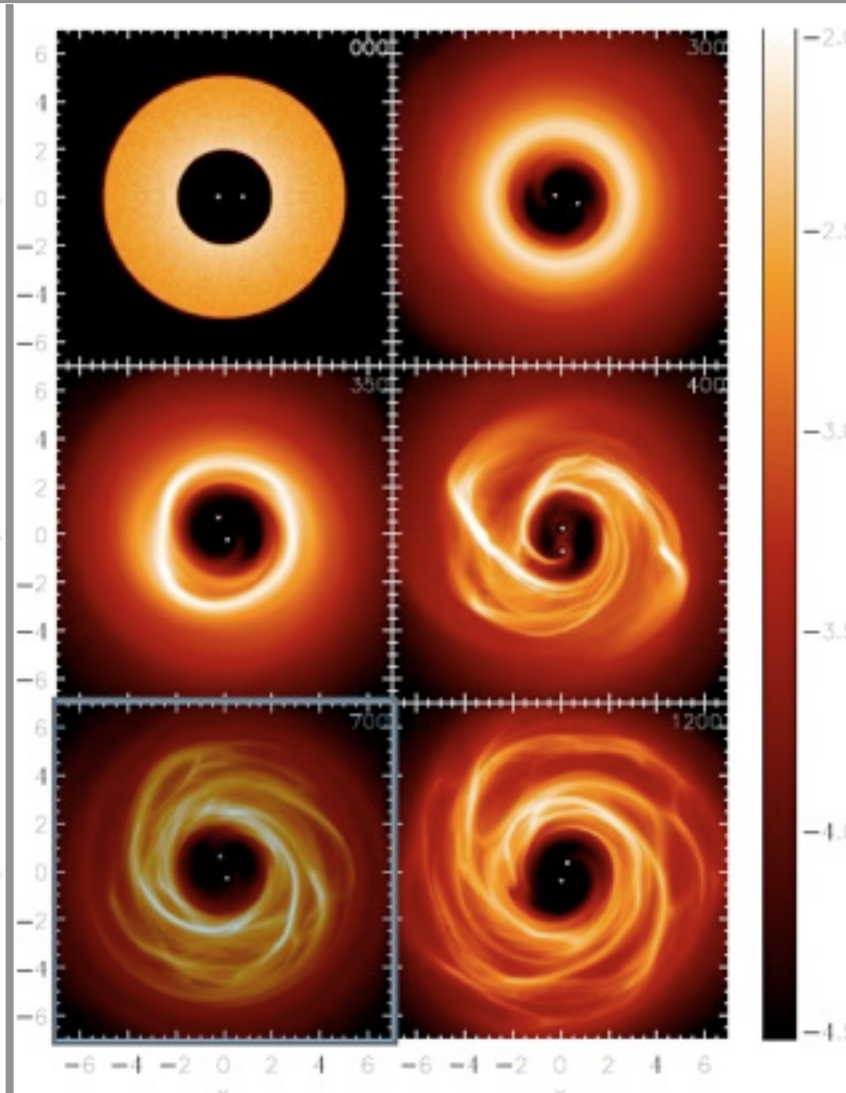
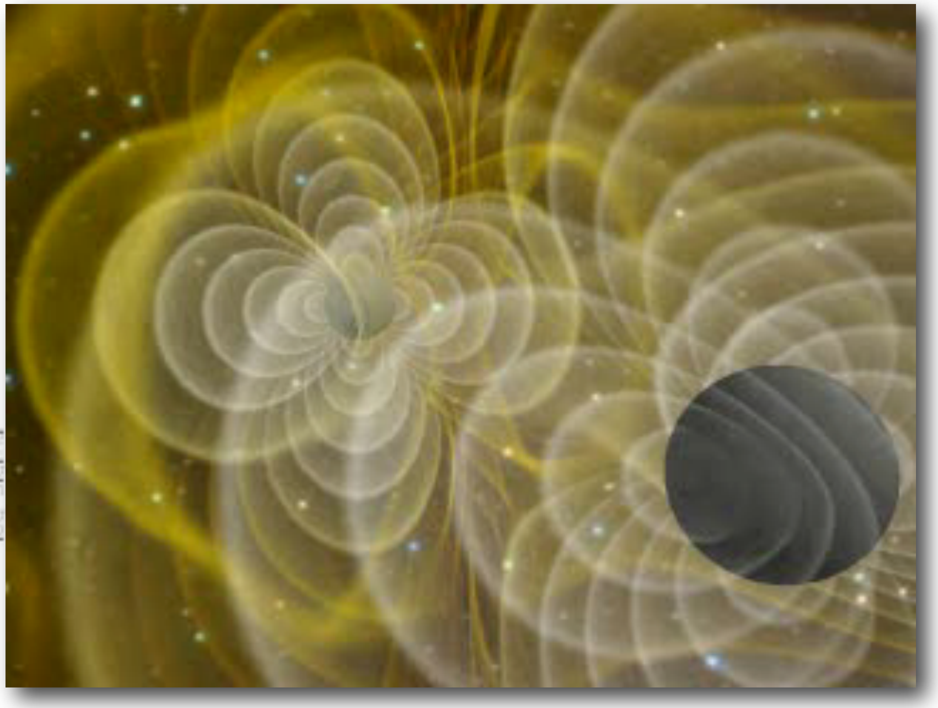
Phase II: a=10^{-2} pc



Cuadra et al 2009

- Torques applied by the disk on the binary cause angular momentum losses to the gas, which shrinks the binary to sub-pc scales (e.g. Cuadra et al. 2009).
- Also purely stellar dynamical processes in triaxial potentials (e.g. Merritt et al. 2005, Preto et al. 2011)

Phase III: a=0



Baker et al. 2008

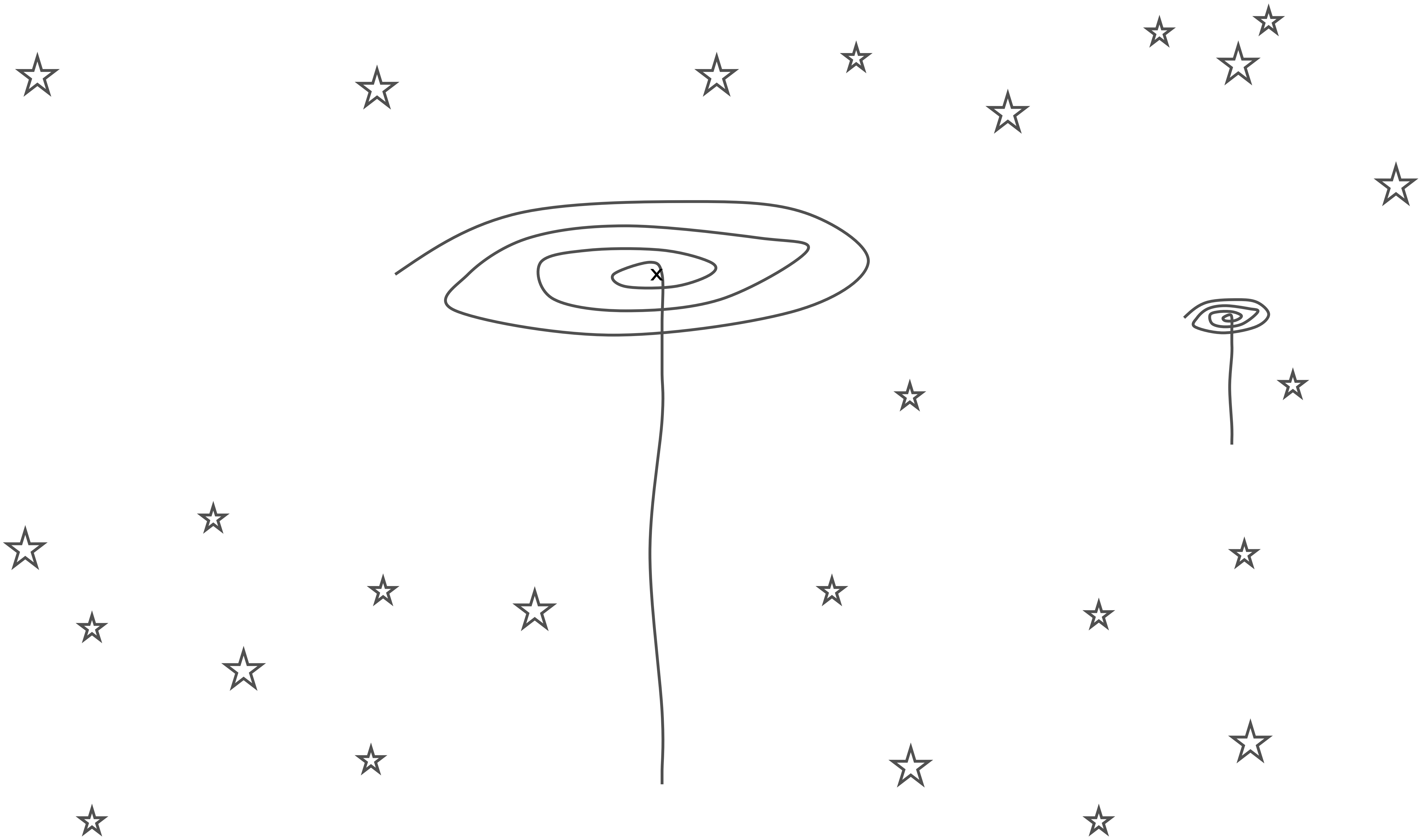
At sufficiently small separations, gravitational wave radiation is responsible for further orbital energy loss

Merritt 1999, Miloslavjevic & Merritt 2001

$$a_{GW} \approx 0.0014\ pc\left(\frac{Mm_1m_2}{10^{18.3}M_{sun}^3}\right)^{1/4}$$

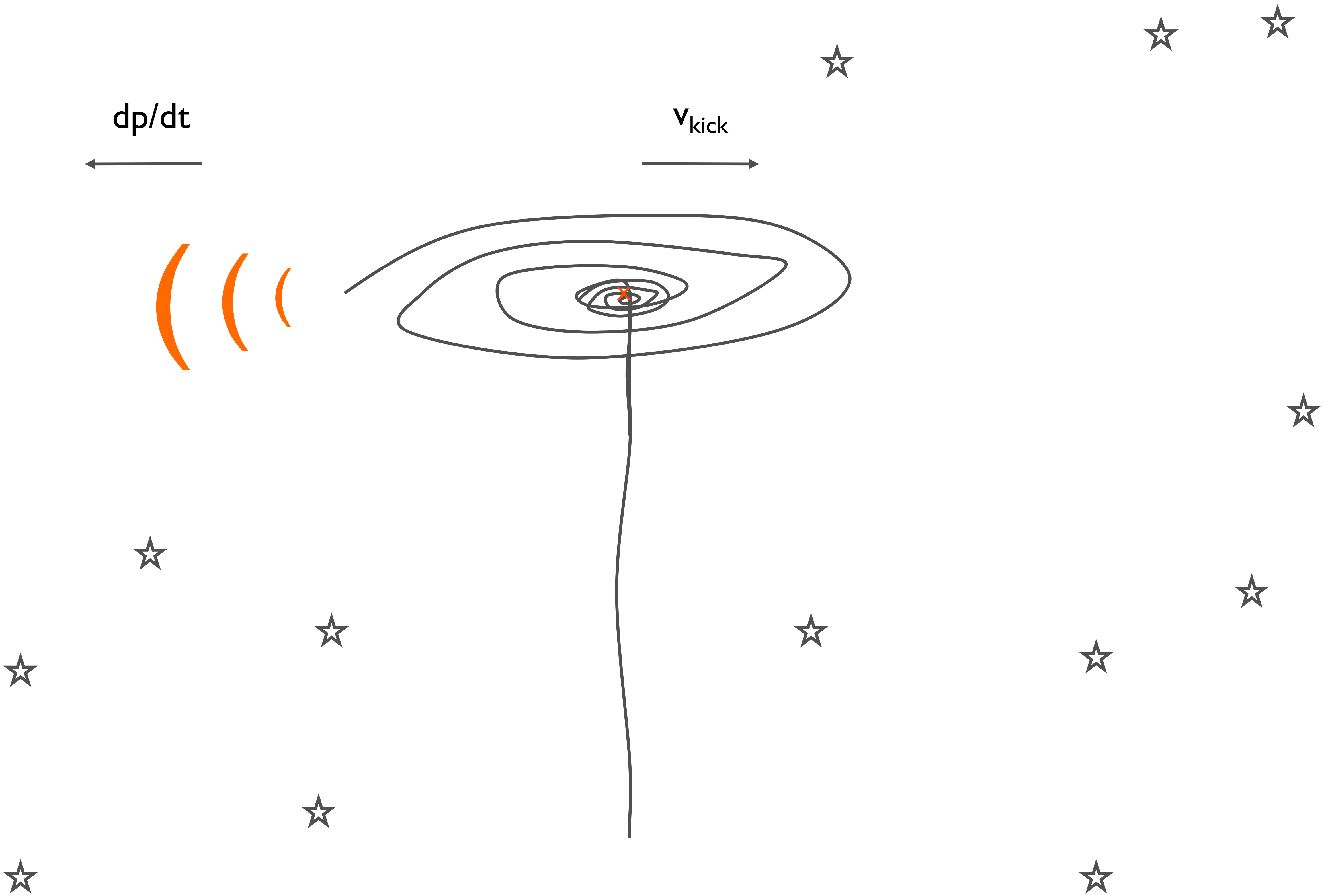
Phase IV: recoil?

The Origin of MBH Recoil



Cartoon movie: http://dl.dropbox.com/u/1043915/Website/movies/recoil_cartoon.mov

The Origin of MBH Recoil



Cartoon movie: http://dl.dropbox.com/u/1043915/Website/movies/recoil_cartoon.mov

The Origin of MBH Recoil

Favata, Hughes & Holtz, 2004

Rate at which momentum is radiated:

$$\frac{dP^k_{\mathrm{GW}}}{dt} = \frac{r^2}{16\pi}\int d\Omega \left\langle \dot{h}_+^2 + \dot{h}_\times^2 \right\rangle n^k$$

$h_{+,x}$ are the "plus" and "cross" GW polarizations

n^k is the radial vector from the source

+ x

First order expansion:

$$\frac{dP^k_{\mathrm{GW}}}{dt} = \frac{2}{63}\left\langle \frac{d^4\mathcal{I}^{ijk}}{dt^4}\frac{d^3\mathcal{I}^{ij}}{dt^3}\right\rangle + \frac{16}{45}\left\langle \epsilon^{kpq}\frac{d^3\mathcal{I}^{pj}}{dt^3}\frac{d^3\mathcal{S}^{qj}}{dt^3}\right\rangle$$

I^{ij}, S^{ij}, I^{ijk} are (the symmetric, trace-free mass) quadrupole*, current quadrupole, and mass octupole moments

Recoil:

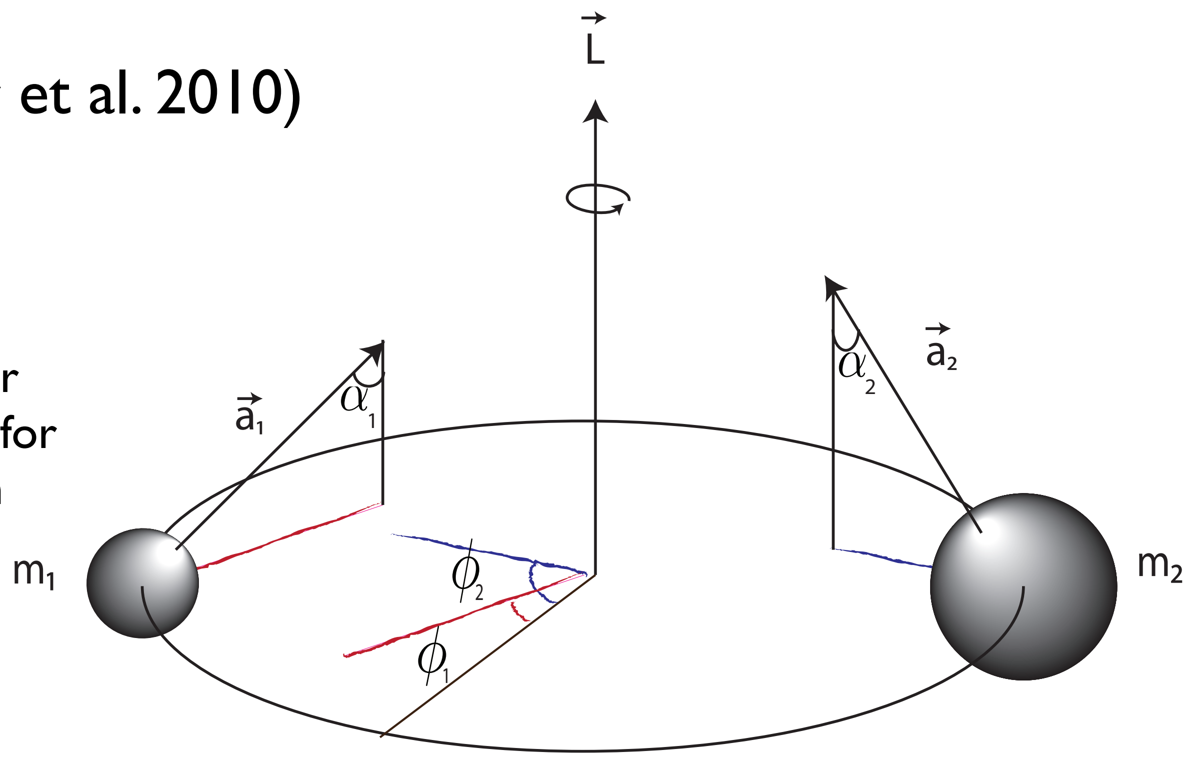
$$dP^k_{\mathrm{com}}/dt = -dP^k_{GW}/dt$$

Gravitational Wave Recoil arises from the cross terms in the mass multipole expansion

*Einstein 1918 made a factor of 2 error in the calculation of the mass quadrupole, i.e. the Energy carried by GW was a factor of 2 too small (Thorne 1980)

Recoil Velocity

Latest GR simulations of black hole recoil (Van Meter et al. 2010) show that the best-fit recoil velocity is given by



$$
\begin{aligned}
\vec{V}_{\text{kick}} &= v_{\perp,m}\,\vec{e}_x + v_{\perp,s}(\cos\xi\,\vec{e}_x + \sin\xi\,\vec{e}_y) + v_{\parallel}\,\vec{e}_z,\\
v_{\perp,m} &= A\eta^2\sqrt{1-4\eta}\,(1+B\eta),\\
v_{\perp,s} &= H\frac{\eta^2}{(1+q)}\,(a_2\cos\alpha_2 - q\,a_1\cos\alpha_1),\\
v_{\parallel} &= \frac{K_2\eta^2+K_3\eta^3}{1+q}[q\,a_1\sin\alpha_1\cos(\phi_1-\Phi_1)\\
&\quad -a_2\sin\alpha_2\cos(\phi_2-\Phi_2)]\\
&\quad +\frac{K_S(q-1)\eta^2}{(1+q)^3}[q^2\,a_1\sin\alpha_1\cos(\phi_1-\Phi_1)\\
&\quad +a_2\sin\alpha_2\cos(\phi_2-\Phi_2)],
\end{aligned}
$$

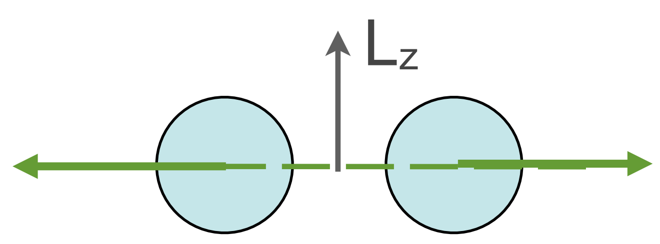
linear terms for spin

The parallel term vanishes when both black holes are aligned with L

where $\eta = q/(q+1)$ and $q = m1/m2 < 1$. A,B,H,K, ξ, and Φ_i are constants.

Maximum recoil: ~4000 km/s

Campanelli et al. 2007

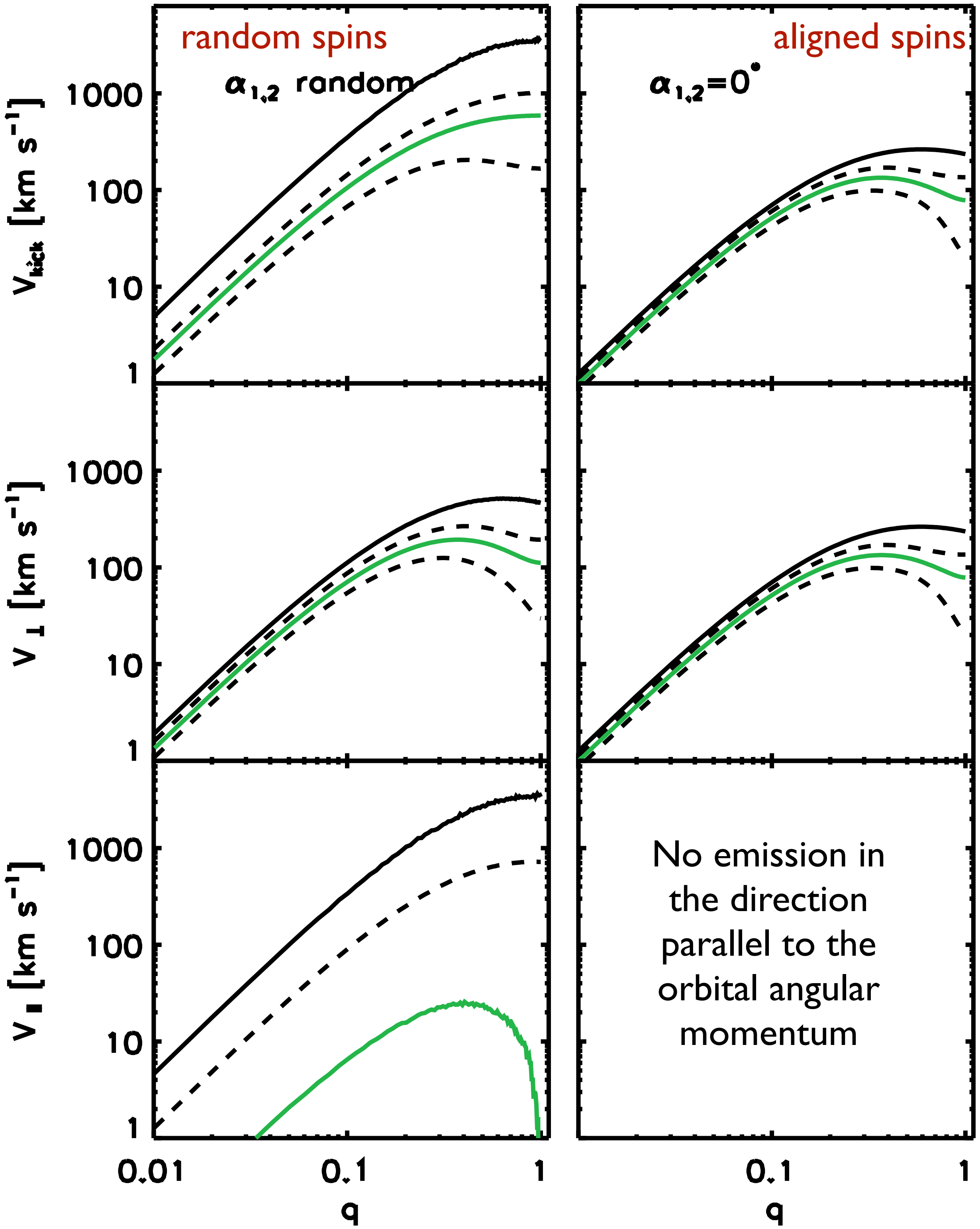


- The maximum recoil velocity is about 4000 km/s and occurs when the spins are exactly anti-aligned and q=1.

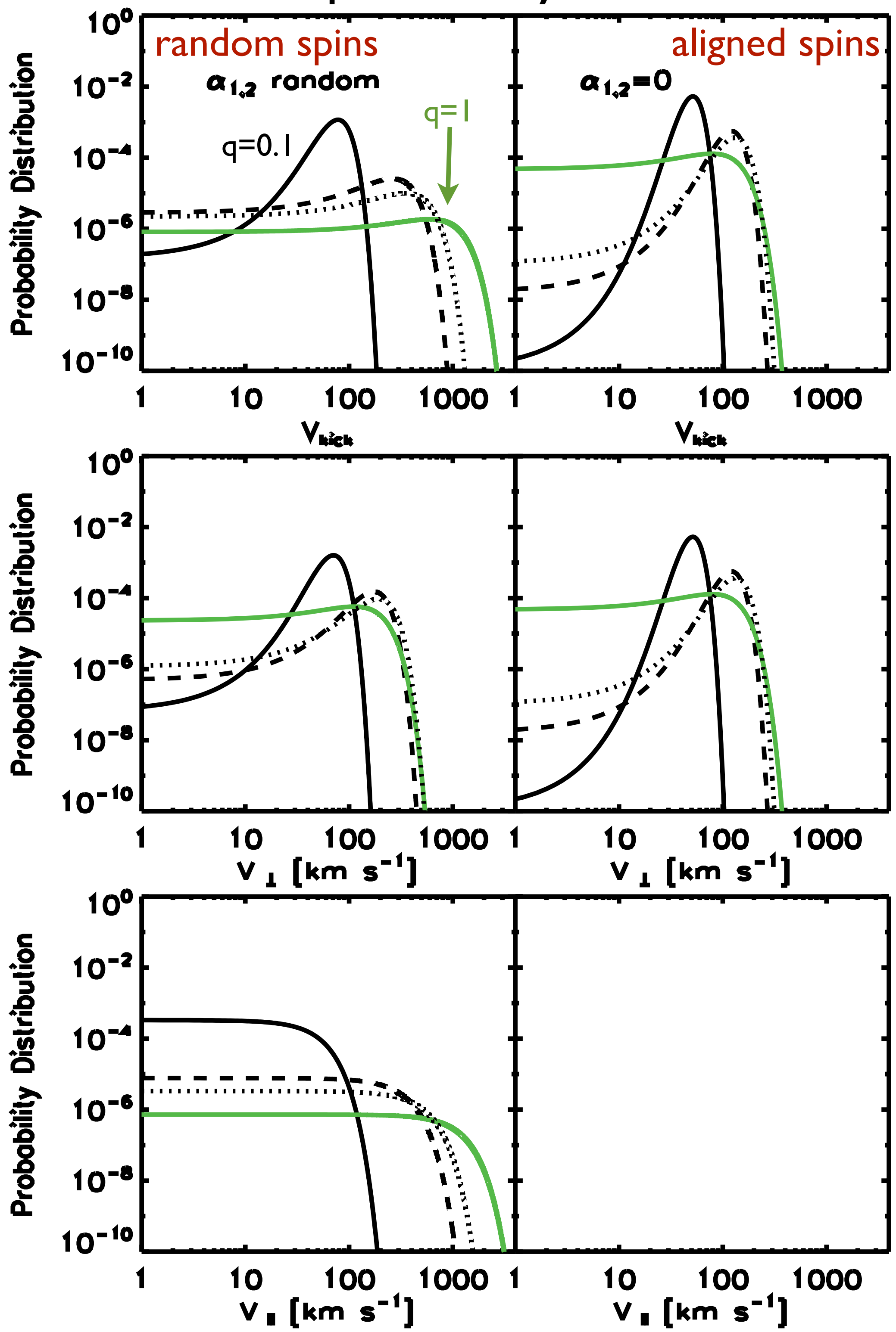
Recoil Velocity

Guedes+2011a

velocity distribution



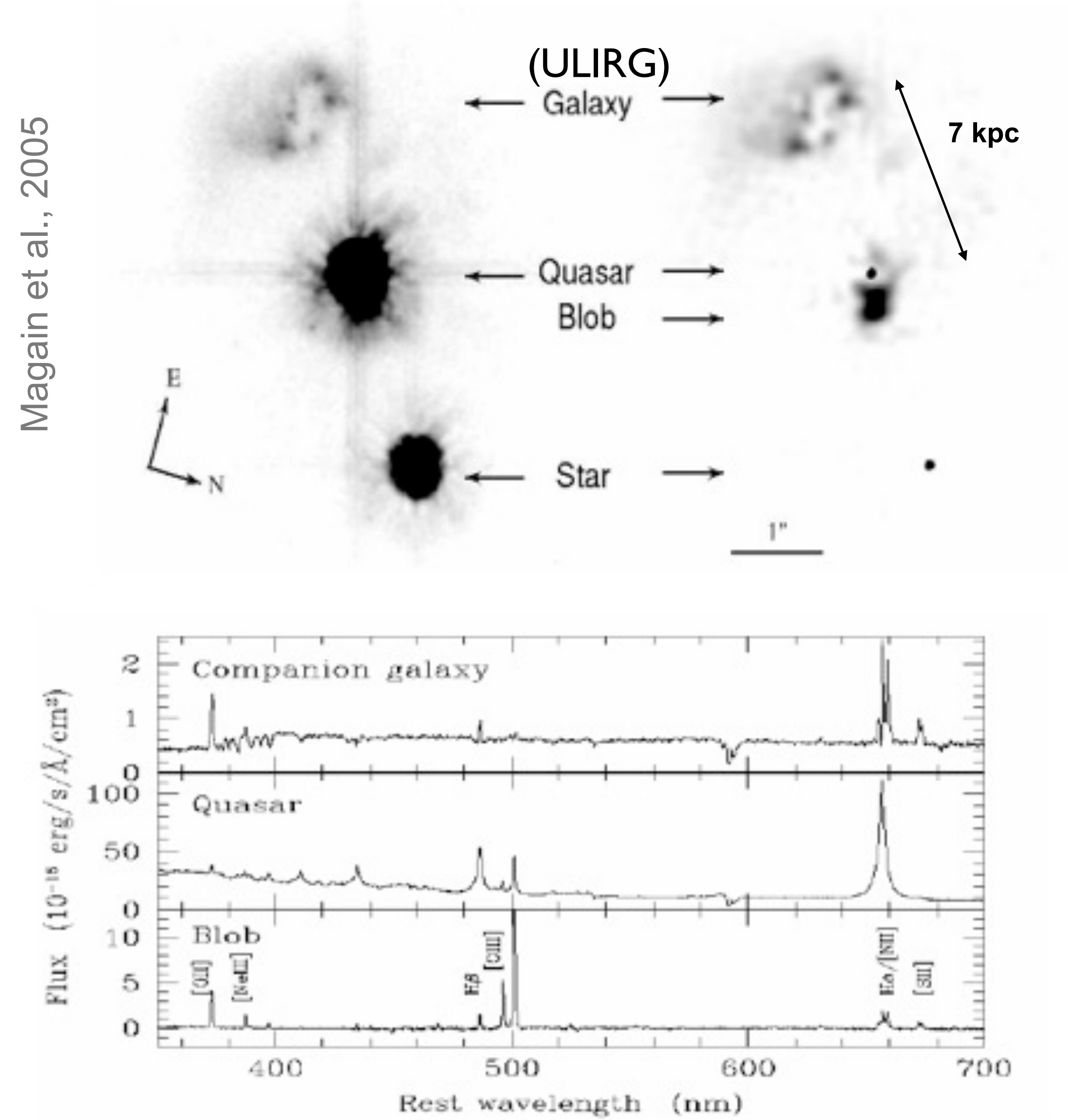
probability distribution



Naked QSOs?

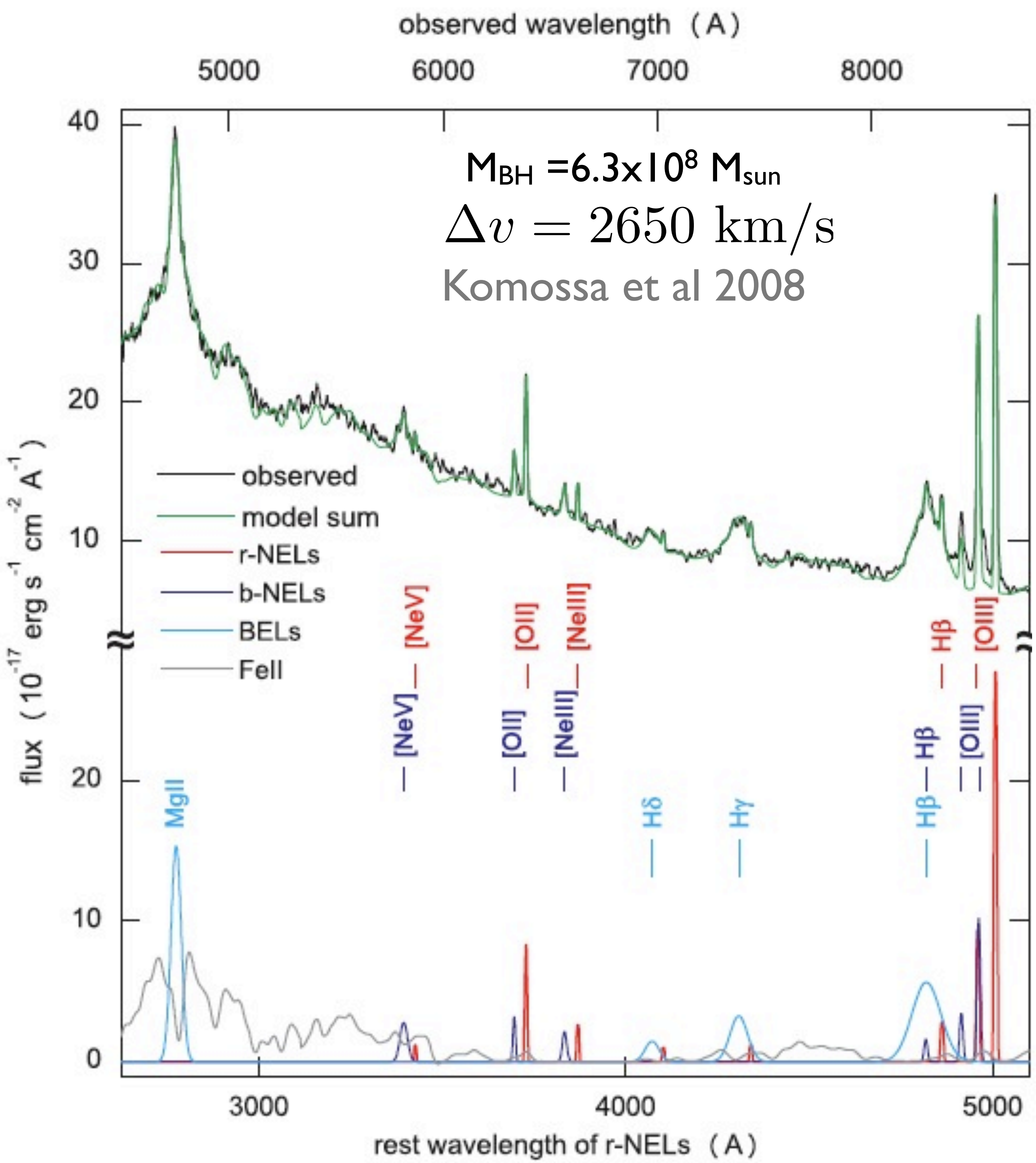
HE0450-2958 z = 0.285 HST/ACS image

$M_{BH} = 8 \times 10^8 \, M_{sun}$ $M_v = -21.2$

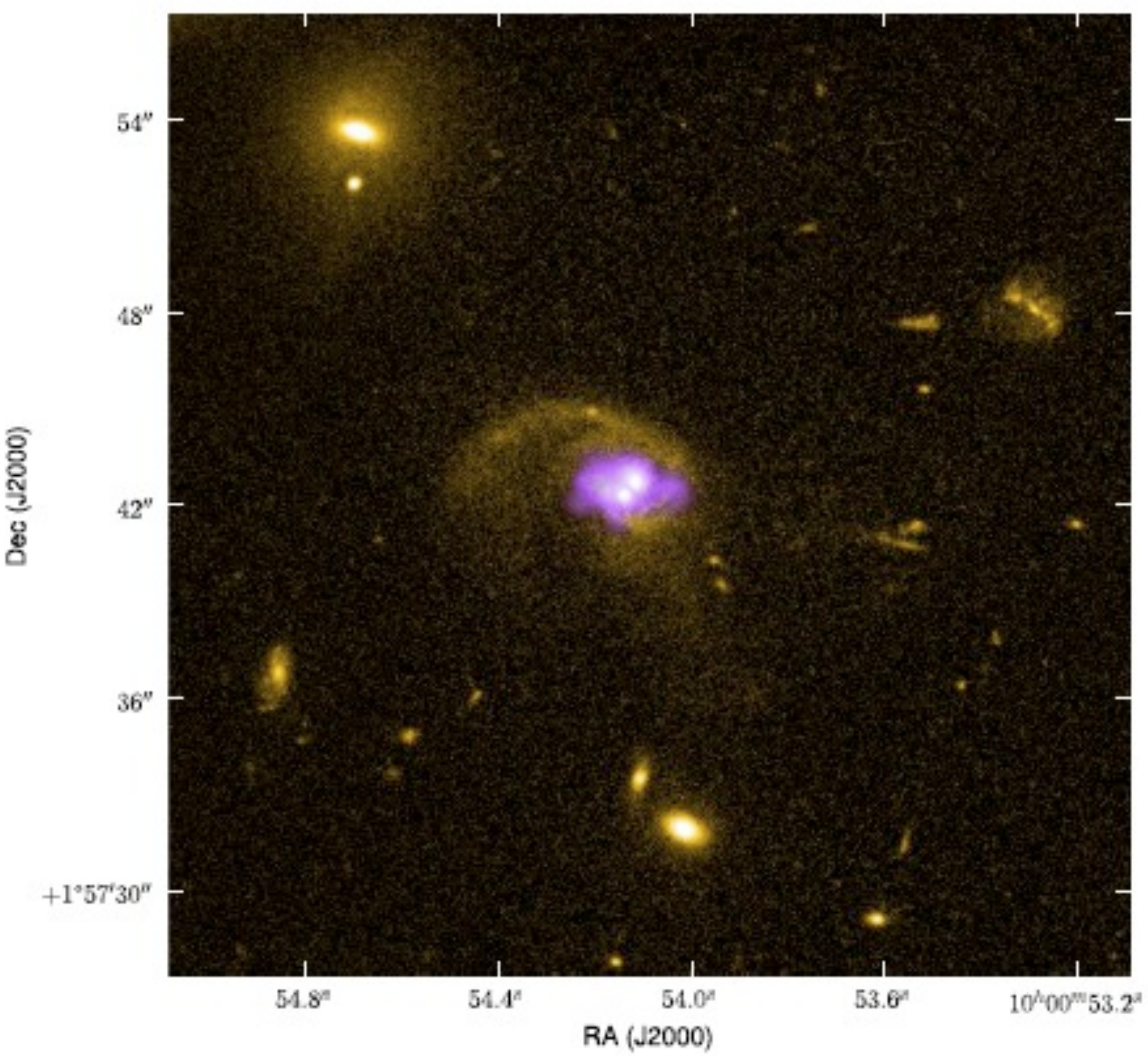


"If interpreted as an image of the host galaxy, we would have the surprising result that the quasar does not reside inside its host, but just next to it."

Recoil candidates in SDSS and COSMOS



Civano et al. 2010



J100043.15+020637.2
z=0.36, recent merger

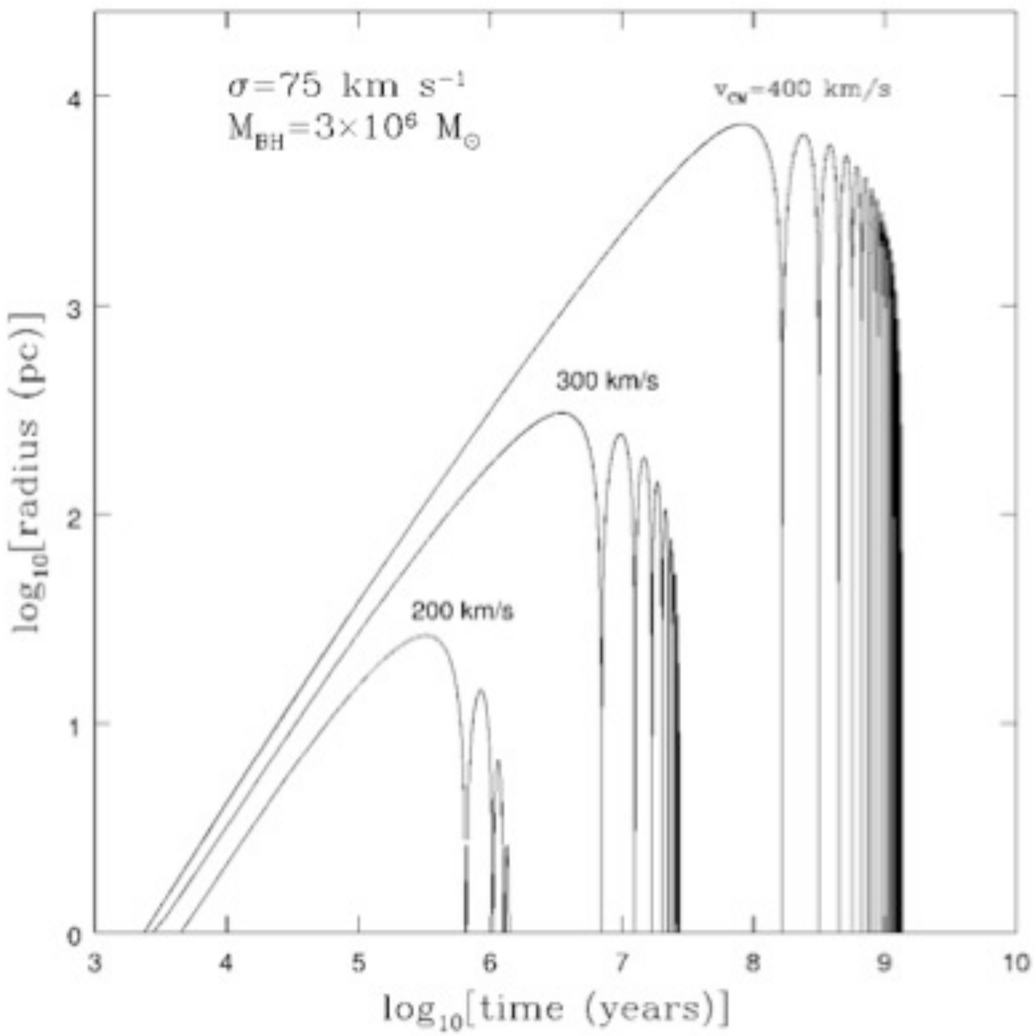
How Observable Are Recoiling MBHs?

We investigate their detectability through two sets of high-resolution simulations:

1. Dark Matter Only
What is the effect of the triaxiality of the dark matter potential on the wandering time of the MBH and the apocenter of its orbit?
Guedes et al. 2008

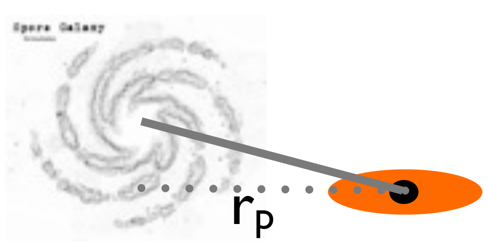
2. Gas-Rich Galaxy Mergers
How important is gas drag in damping the orbital energy of the MBHS? What is the duty cycle of the wandering AGN and how does that affect the is detection probability?
e.g. Guedes et al. 2011a, Blecha et al. 2011, Sijacki et al. 2011

Madau & Quataert 2004



Kinematically offset AGN

Spatially offset AGN



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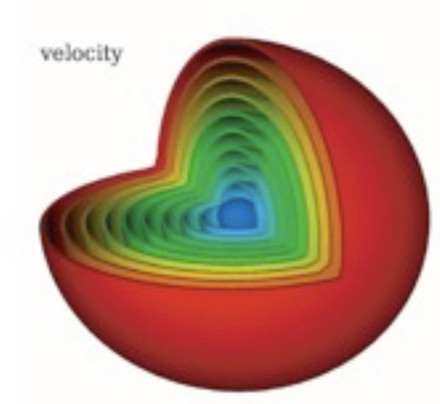


1. Dark Matter Only

What is the effect of the triaxiality of the dark matter potential on the wandering time of the MBH and the apocenter of its orbit?

Diemand et al. 2006

Via Lactea + MBH
High resolution dark-matter only simulation
234 million particles + 1
Force Resolution: 90 pc
Massive Black Hole Mass: 3.6×10^{6} M_{sun}
code: PKDGRAV (Stadel 2001)
Simulations begin after last major merger

The Model:

$$\frac{d\mathbf{v}}{dt} = -\nabla\Phi + \mathbf{f}_{\rm DF}$$

$$\Phi = \cancel{\Phi_{\rm gas}} + \cancel{\Phi_{\rm stars}} + \boxed{\Phi_{\rm dark}}$$

$$\mathbf{f}_{\rm DF} = -\frac{4\pi G^2 M_\bullet \ln\Lambda\rho}{v^3} I_v \mathbf{v}$$

In a triaxial dark matter halo:

$$\Phi = \frac{GM_{200}}{f(c)} \frac{\ln(1 + r_e/R_s)}{r_e}$$

$$\mathbf{f}_{\rm DF} = -\Gamma_a V_a \hat{e_a} - \Gamma_b V_b \hat{e_b} - \Gamma_c V_c \hat{e_c}$$

$$\Gamma_i = \frac{2\sqrt{2\pi G^2 \rho \ln\Lambda M_\bullet}}{\sigma_1} \times B_i(\mathrm{V}, \sigma)$$

$$B_i = \int_0^\infty \frac{\exp(-\sum_{i=1}^{3} \frac{V_i^2/2\sigma_i^2}{\epsilon_i^2+u})}{\sqrt{(\epsilon_1^2+u)(\epsilon_2^2+u)(\epsilon_3^2+u)}} \frac{1}{\epsilon_i^2+u} du,$$

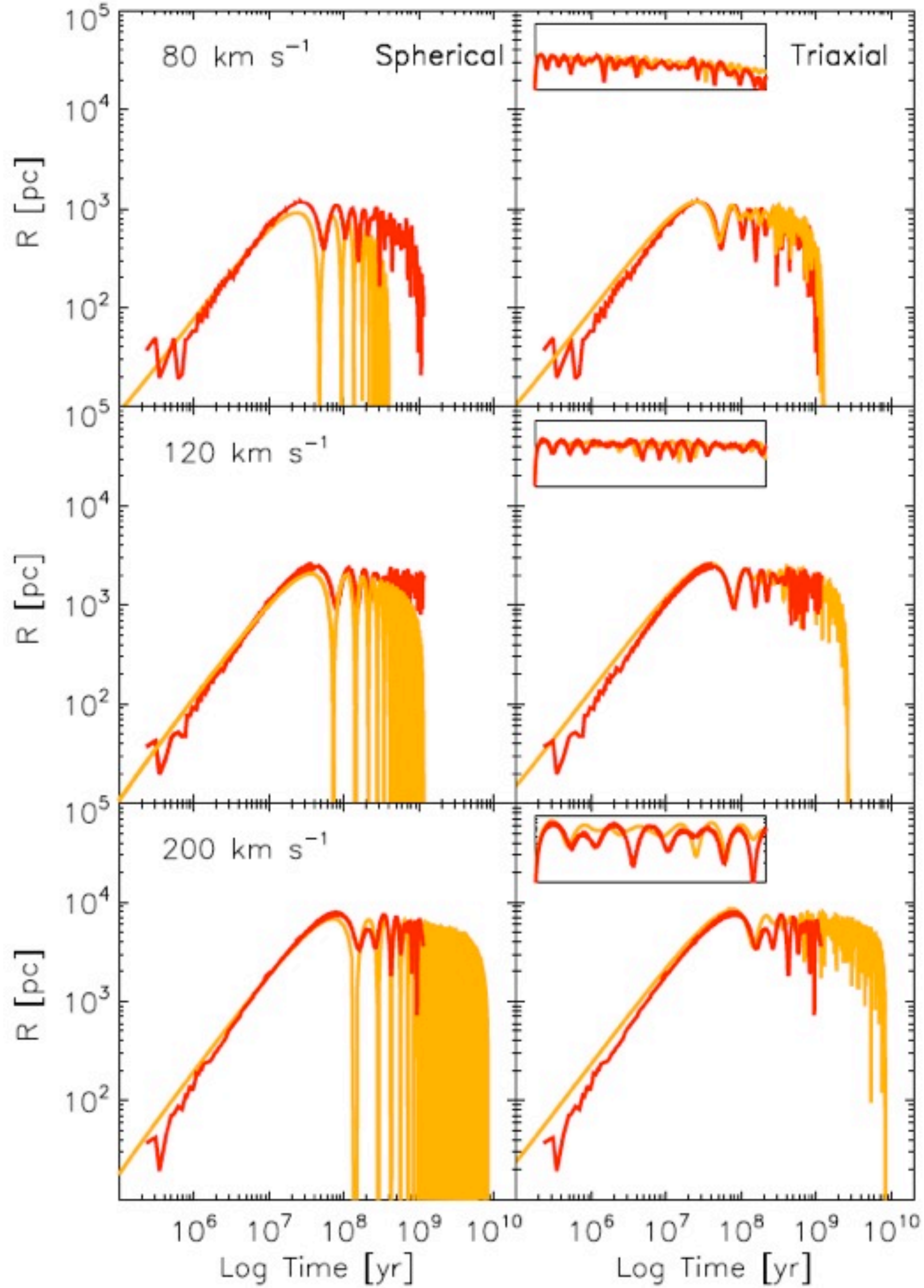
Triaxial Models Yield Longer Wandering Times

- Our semi-analytical of a recoiling MBH in a triaxial dark matter halo successfully characterizes the results of the N-body simulations.

- The spherical case always under estimates the return time of the MBH, especially for small kicks.

- Extended return times would be favorable for the detection of off-nuclear QSO.

red: N-body simulation
orange: analytical model



Guedes et al 2008
Guedes et al. 2009

How Observable Are Recoiling MBHs?

2. Gas-Rich Galaxy Mergers
How important is gas drag in damping the orbital energy of the MBHS? What is the duty cycle of the wandering AGN and how does that affect the is detection probability?

The Simulations:

The highest resolution merger simulations we could find.

1:1 merger

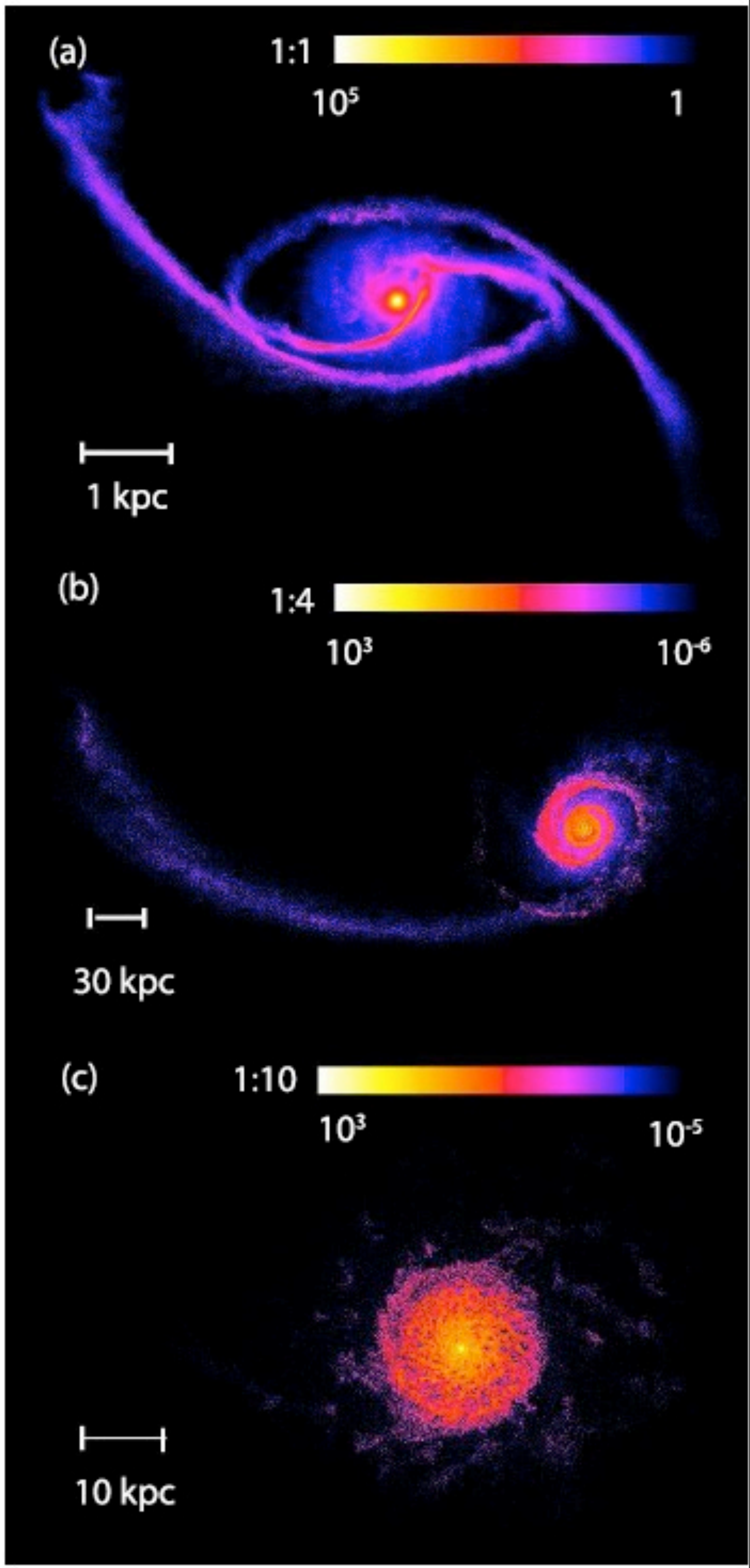
1.5 million gas particles :: 3000 $M_\odot$ :: force softening 2 pc
Mayer et al. 2007

1:4 merger

10^5 gas particles :: 3000 $M_\odot$ :: force softening 60 pc in satellite
Callegari et al. 2009

1:10 merger

10^5 gas particles :: 100 $M_\odot$ :: force softening 20 pc in satellite
Callegari et al. 2009



Guedes et al. 2011a

How Observable Are Recoiling MBHs?

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How important is gas drag in damping the orbital energy of the MBHS? What is the duty cycle of the wandering AGN and how does that affect the is detection probability?

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$$\mathbf{f}_{\rm DF} = -\frac{4\pi G^2 M_\bullet \ln\Lambda\rho}{v^3} I_v \mathbf{v}$$

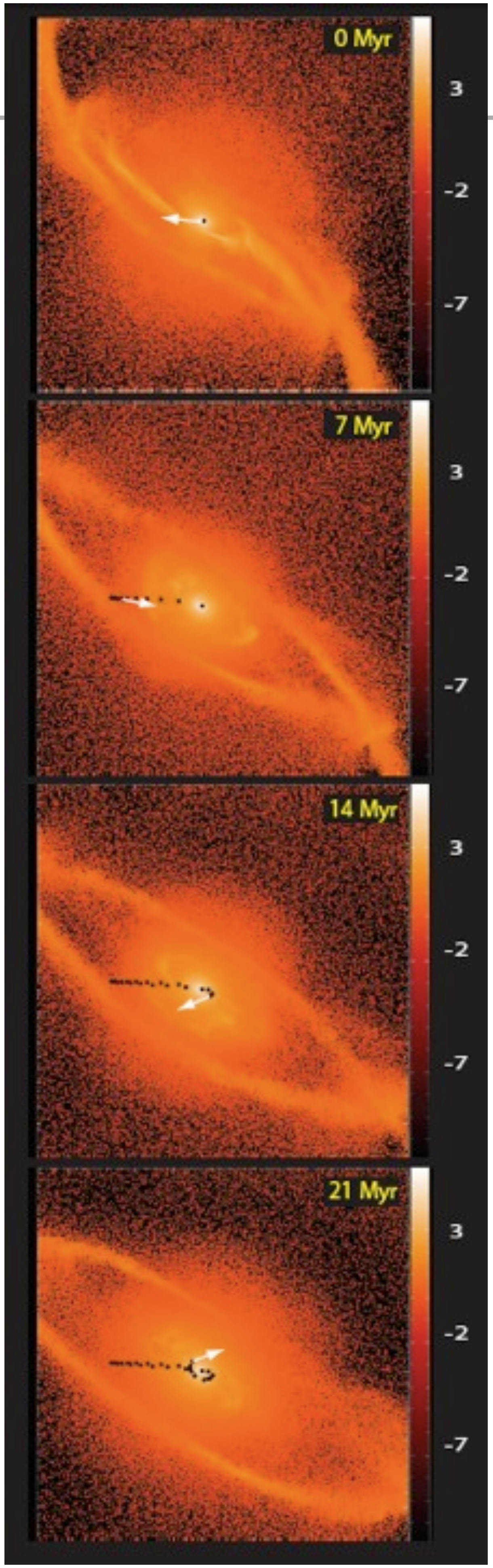
The ejected MBH carries a punctured disk of outer radius

$R_{out} \approx GM / v_{ej}^2$

Inside R_{out} the orbital velocity of the gas is higher than v_{ej} and the gas elements maintain the adiabatic invariants of their orbit around the MBH (Loeb 2007)

$$M_{\rm disk} \approx 1.9 \times 10^6 \alpha_{-1}^{-0.8} \eta^{-0.6} M_7^{2.2} v_8^{-2.8} M_\odot.$$

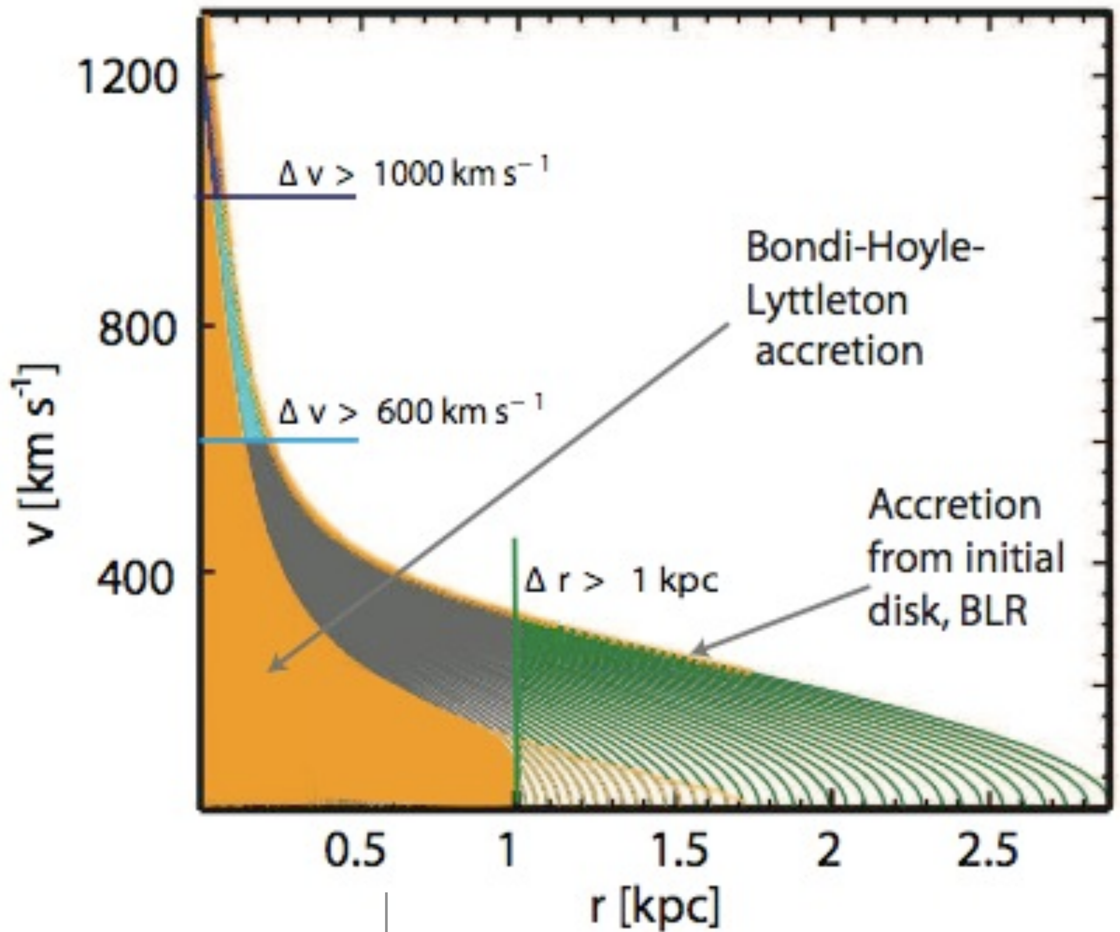
$$t_{\rm disk} \approx 8.4 \times 10^6 \alpha_{-1}^{-0.8} \eta^{0.4} M_7^{1.2} v_8^{-2.8} \text{ yr}.$$



Guedes et al. 2011a

MBH Orbits in Gas-Rich Mergers

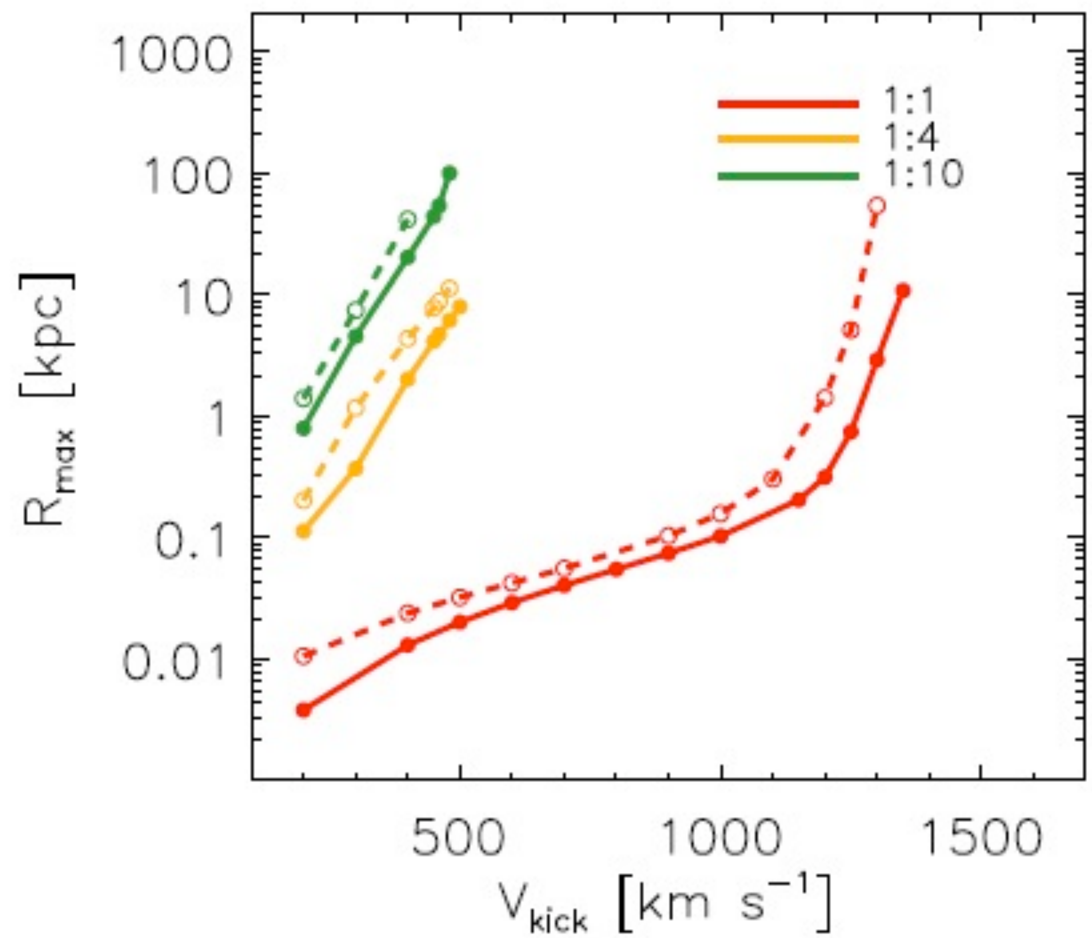
Guedes et al. 2011a



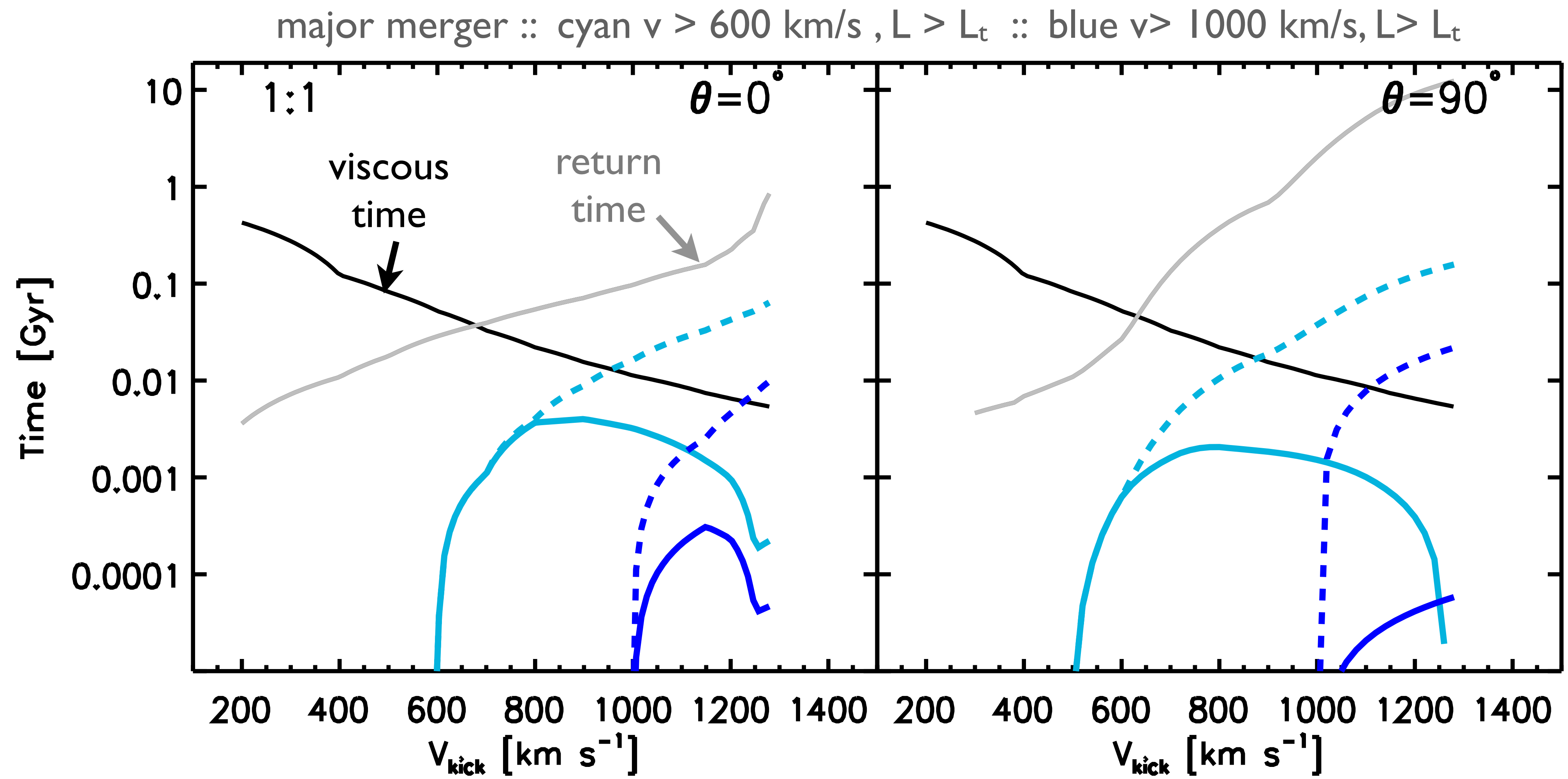
A dissection of the orbit of a recoiling MBH of mass 5.2x10^6 M$_\odot$. Regions of the orbit that overlap with regions in which the MBH can accrete, are considered detectable.

$$\dot{M}_{\rm BHL} = \frac{4\pi G^2 M_\bullet^2 \rho}{(c_s^2 + v^2)^{3/2}},$$

First apocenter of recoiling MBH orbits in our gas mergers. Shallower potential wells allow for larger displacements. The dense nuclear disk at the center of the major merger prevents the MBHs from reaching larger distances.



Kinematically Offset AGN



- The MBH is mostly visible in cases where the MBH has just been ejected (a few Myr) or during pericenter passages.
- Very difficult to remove the MBH from the center (also Sijacki et al. 2011, Blecha et al. 2011).
- In minor mergers the timescales during which the MBH is observable as a kinematic offsets are much shorter, since in this case $V_{kick} > V_{esc}$

Spatially Offset AGN

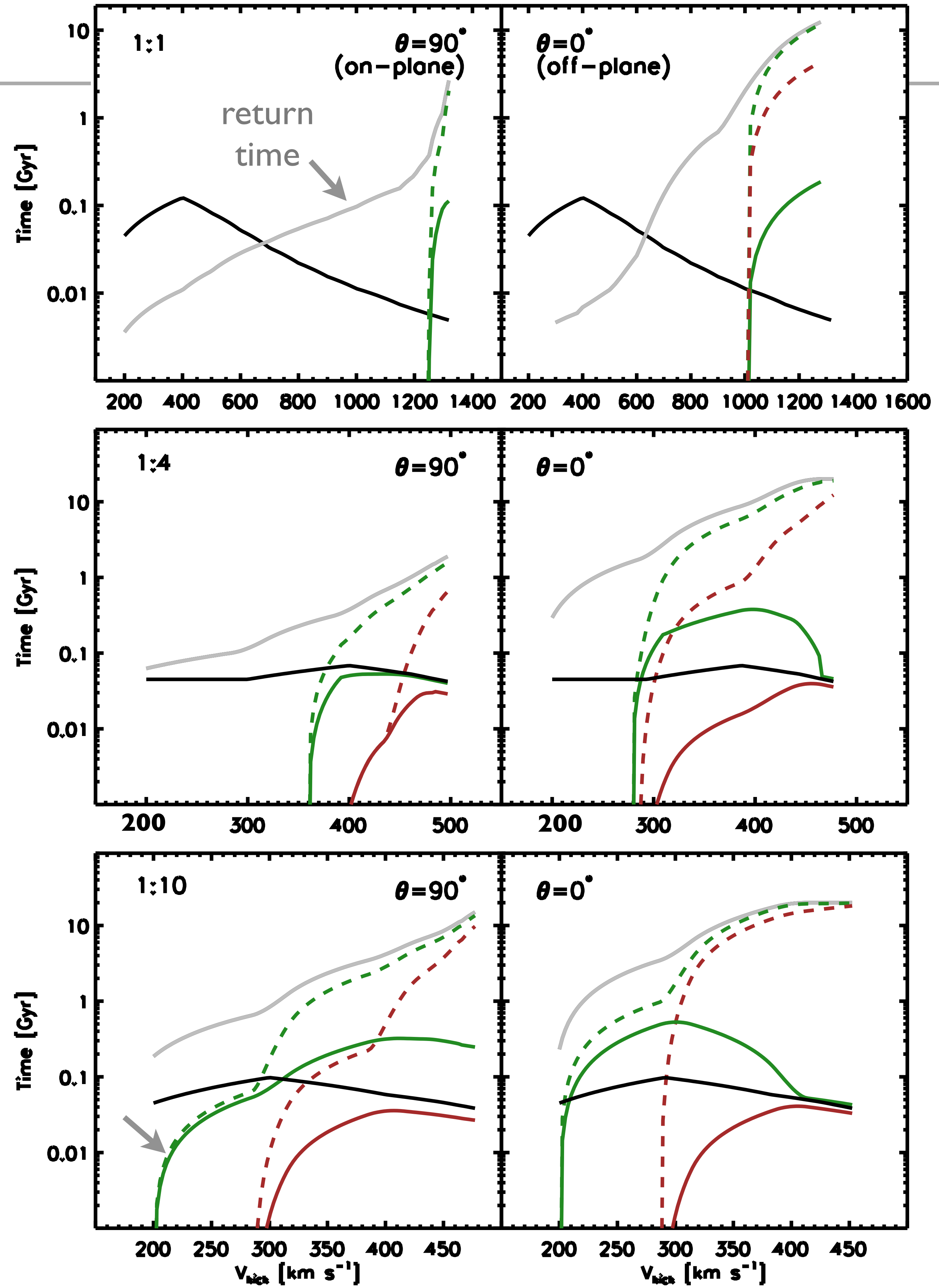
Timescales in which the MBH in our major mergers are detectable as spatially offset AGN.

- Assumes that the MBH can accrete through the Bondi-Hoyle-Lyttleton mechanism when initial disk is exhausted

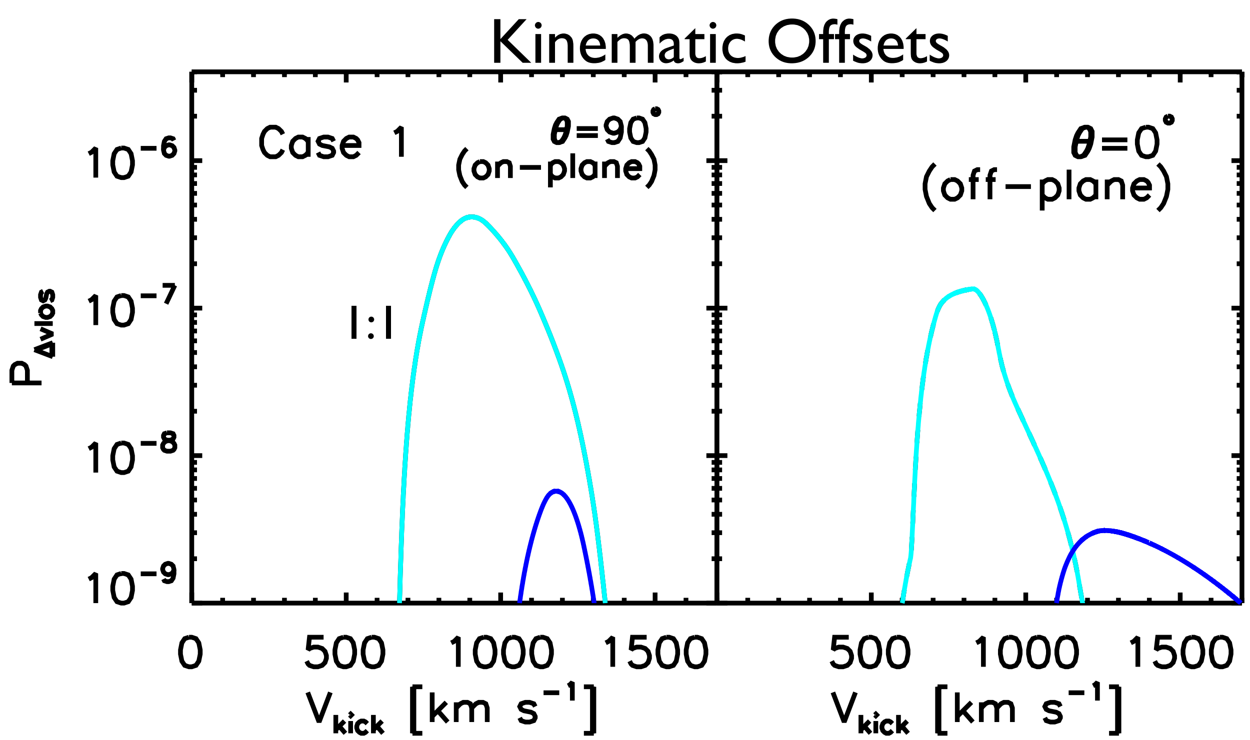
-The MBH is mostly visible near apocenter, as long as it can refuel.

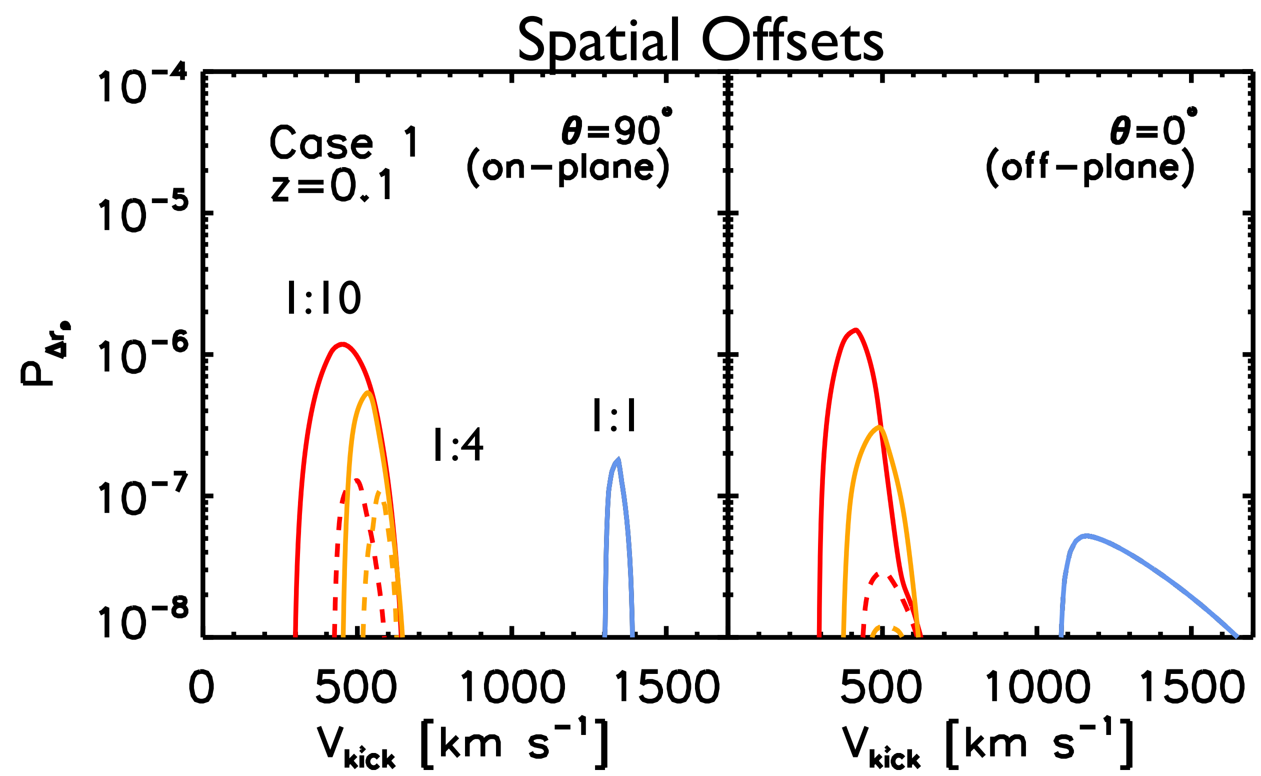
- Low inclination recoil velocities yield generally longer timescales for detectability.

- In the 1:10 merger, the lower central densities allow the MBH to be seen shining at 10 kpc for a few Myr.



Detection Probability





Case 1 (Optimistic)

a) Randomly oriented spins

b) Random orientation of the orbital plane with respect to the galactic disk

c) Assume that MBHs grow during the merger.

Case 2 (Pessimistic)

a) The spins of the MBHs are aligned with the angular momentum vector prior to the merger of the MBH binary, i.e maximum recoil velocities of 200 km/s (Bogdanovic et al. 2007), although see Lousto et al. 2011.

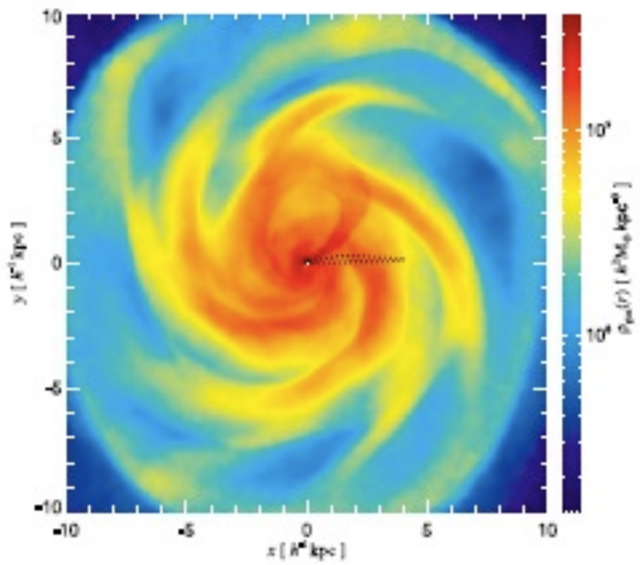
b) The orbital plane of the binary is aligned with the gaseous disk.

This assumption, together with (a), implies that no recoils can occur in the direction parallel to the angular momentum of the disk.

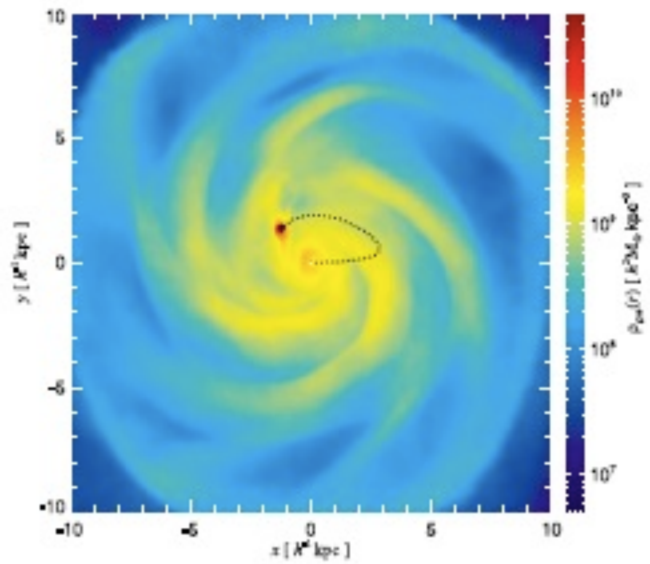
c) No black hole growth is assumed to occur during the galaxy merger.

Accretion and Feedback

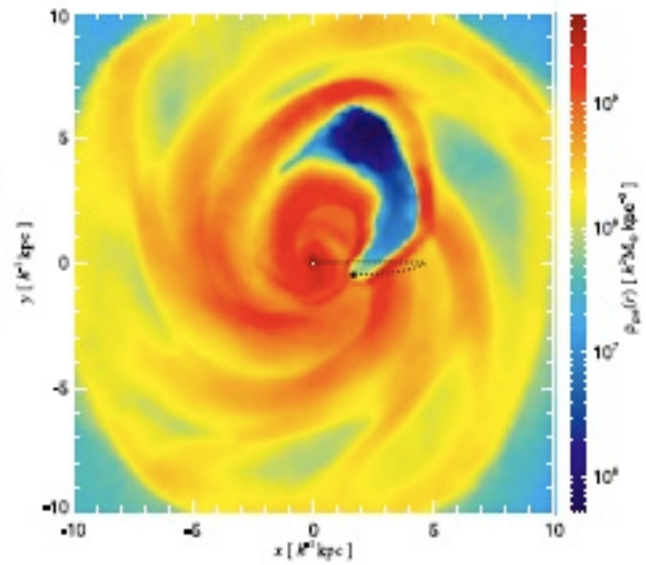
Sijacki et al. 2011



No accretion



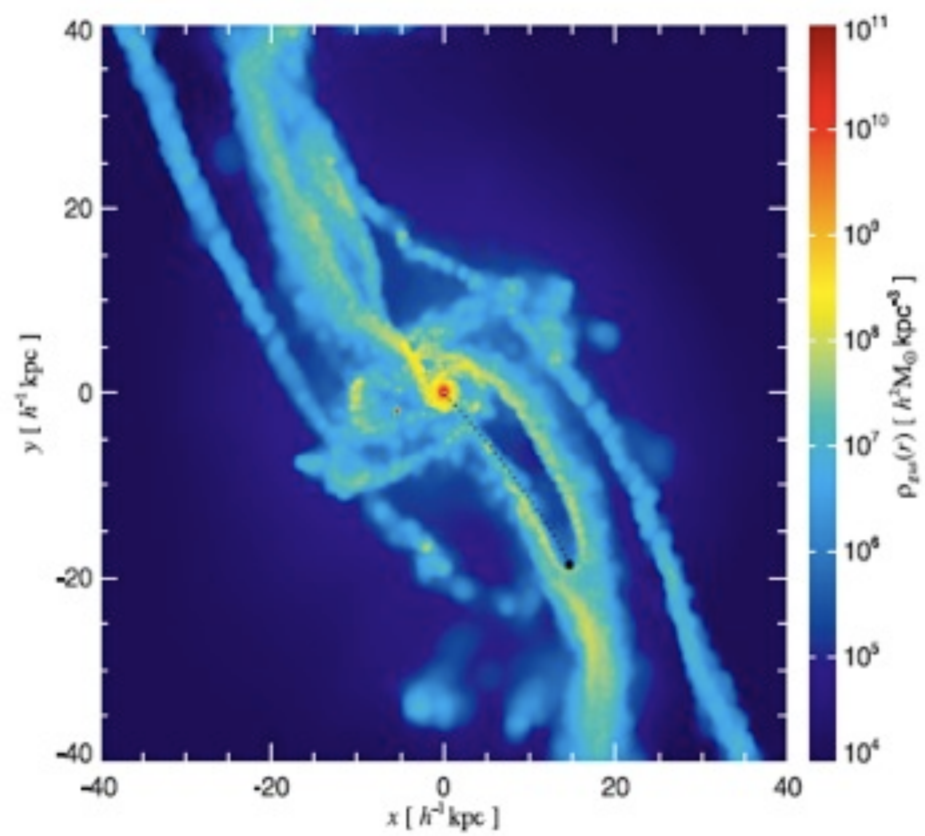
Accretion but no feedback



Accretion and feedback

Accretion and feedback play a role in regulating the star formation around the MBH and in the details of its orbit.

- Prior to the merger, MBHs accrete a nearly the Eddington rate.
- Post recoil the accretion rate drops
- More stars form at the center due to lack of AGN feedback
- Less gas for feeding when the MBH returns to the center
- Lower densities in the vicinity of the MBH extend the return timescale



What are the chances?

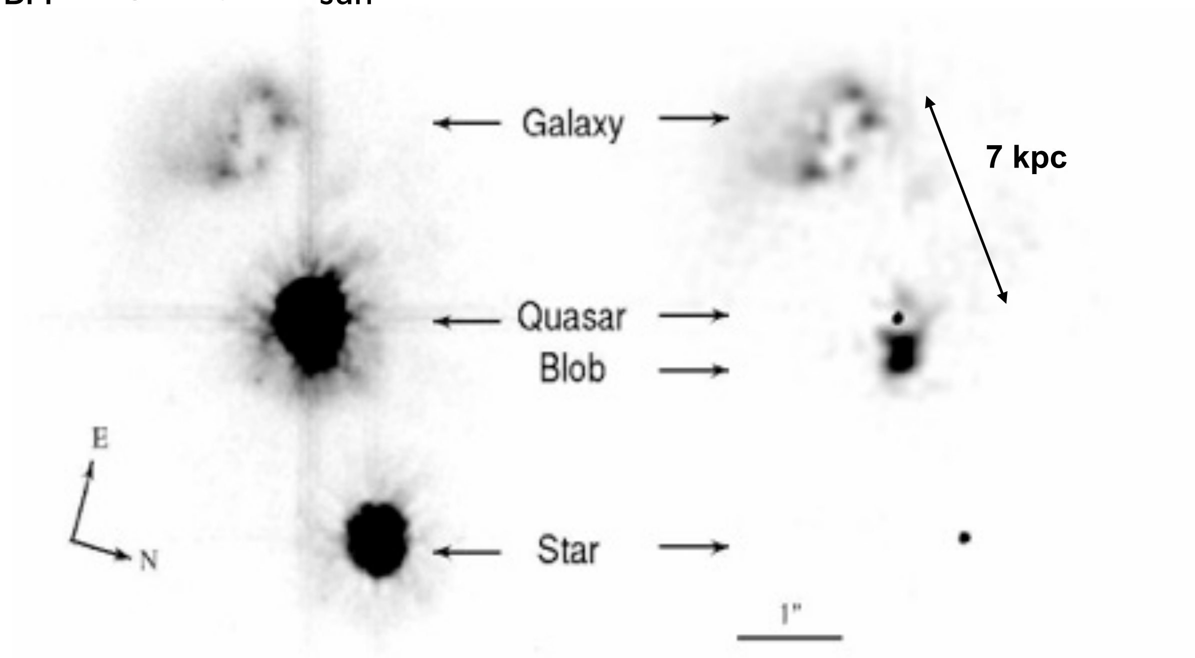
Slim

Slim Evidence for Off-Center MBHs

HE0450-2958 z = 0.285 HST/ACS image

M_{BH} = 8x10^8 M_{sun} M_v = -21.2

Magain et al., 2005



Problems at all wavelengths

Optical: (Merritt et al. 2006)

The QSO shows narrow emission-line region. Object has spectral features of Seyfert I, and $M_{BH} \simeq 9\mathrm{x}10^7\, M_{sun}$, consistent with M_v = -21.2

X-ray: (Xin-Lin, Fang, Lu & Wang 2007)

Estimate for the SMBH mass $M \simeq 3\mathrm{x}10^7\, M_{sun}$

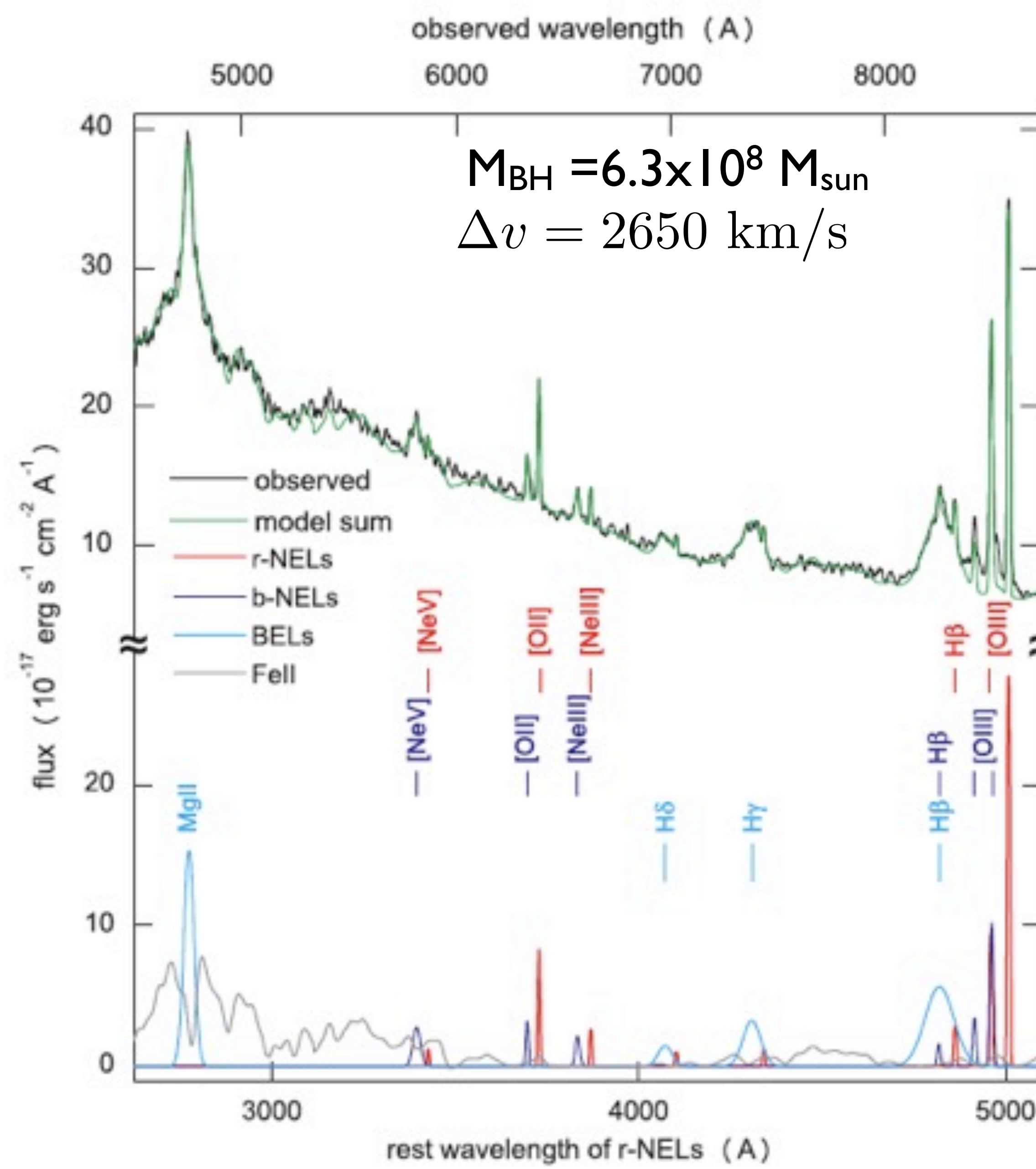
Again, galaxy consistent with M_v = -21.2

Radio: (Klamer et al. 2007)

QSO was dressed by star formation activity that amounts to 70% of the QSO radio activity.

Infrared: (Kim, Ho, Peng & Im 2006)

The companion galaxy is not a ULIRG, so probably not a merger remnant.



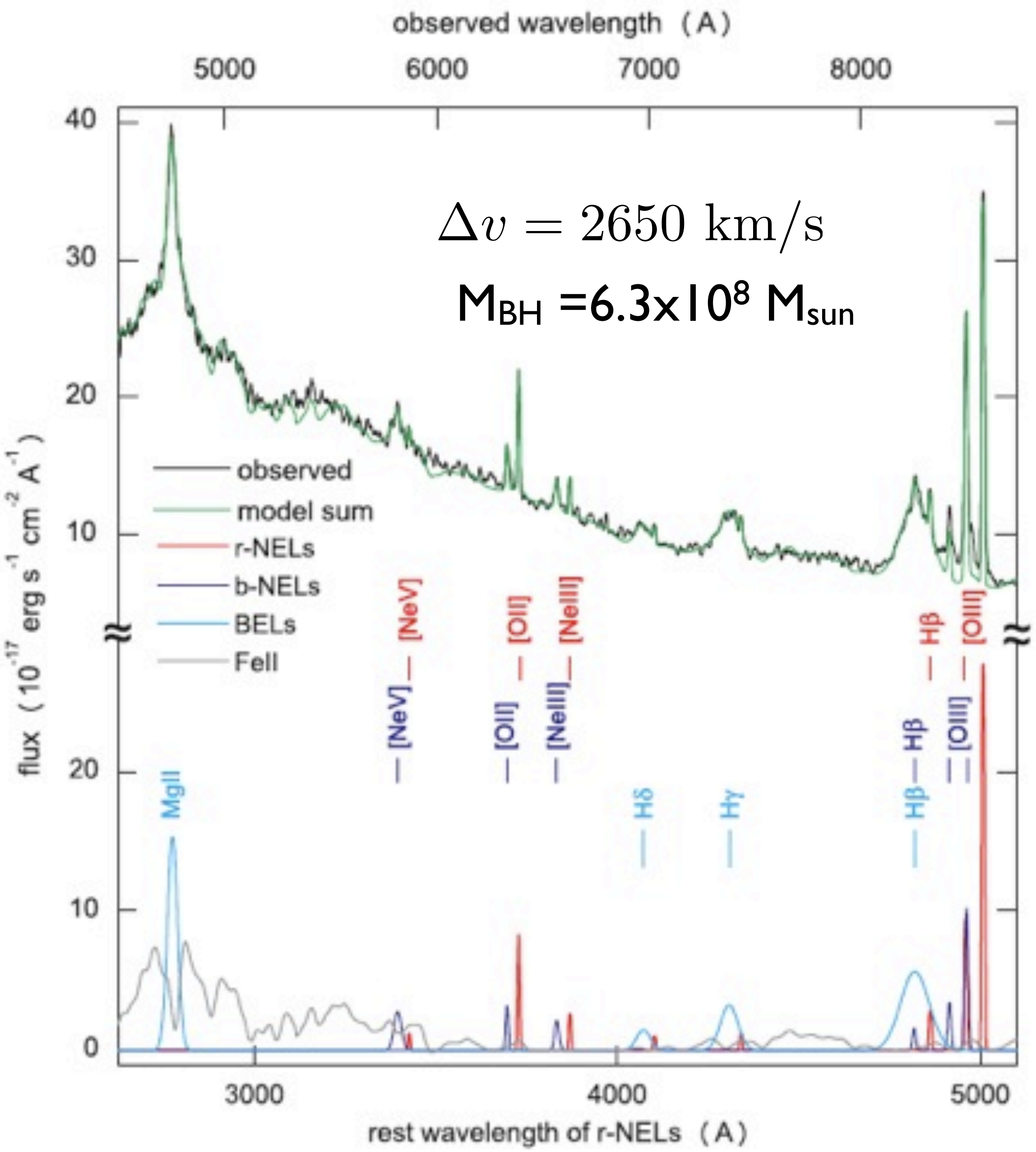
Interacting Galaxy Pair:

Shields et al. 2009, Heckman et al. 2009

Binary MBH:

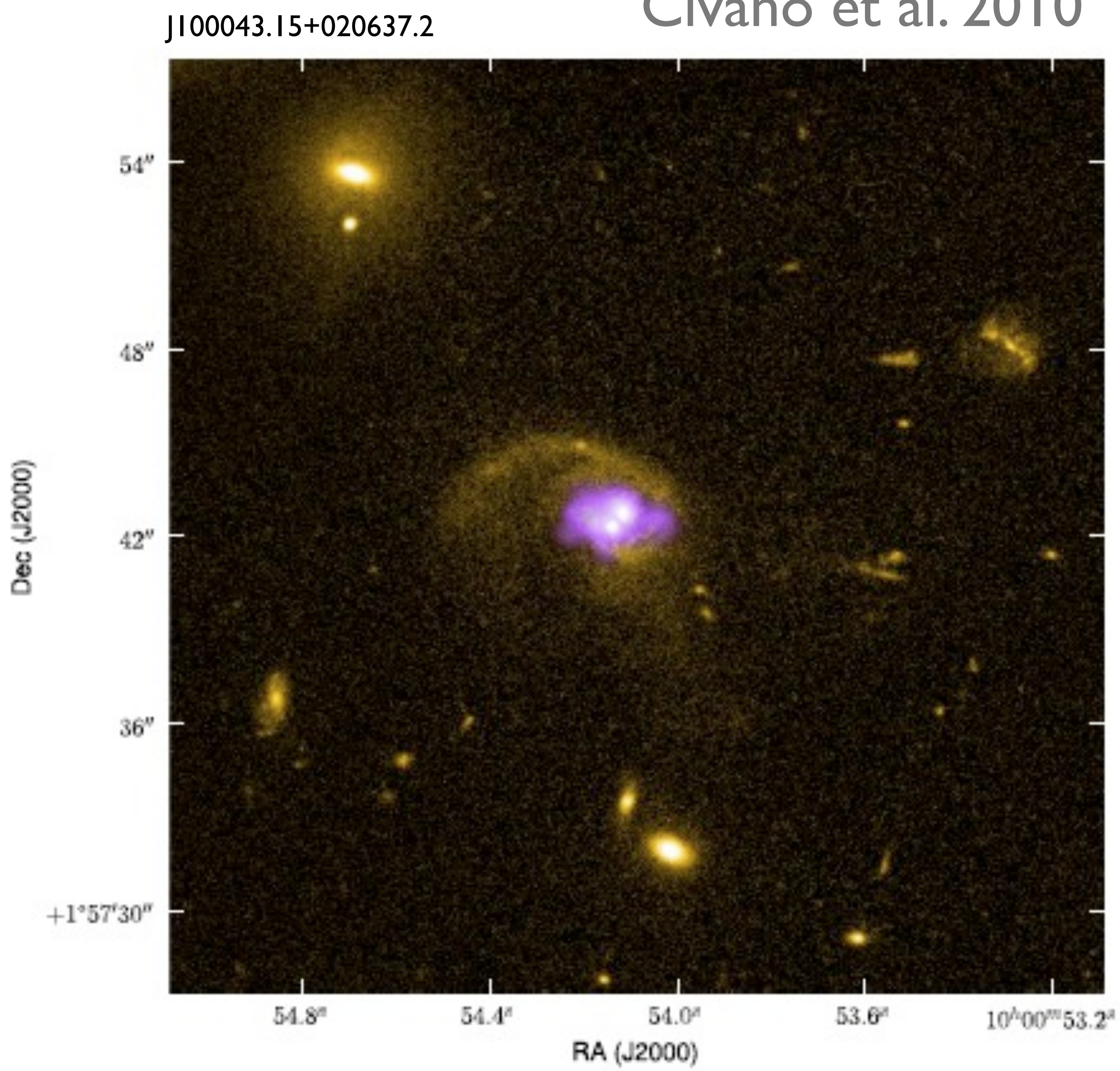
Dotti et al. 2008, Bogdanovic et al. 2009

Slim Evidence for Off-Center MBHs



Interacting Galaxy Pair:
Shields et al. 2009, Heckman et al. 2009
Binary MBH:
Dotti et al. 2008, Bogdanovic et al. 2009

Civano et al. 2010

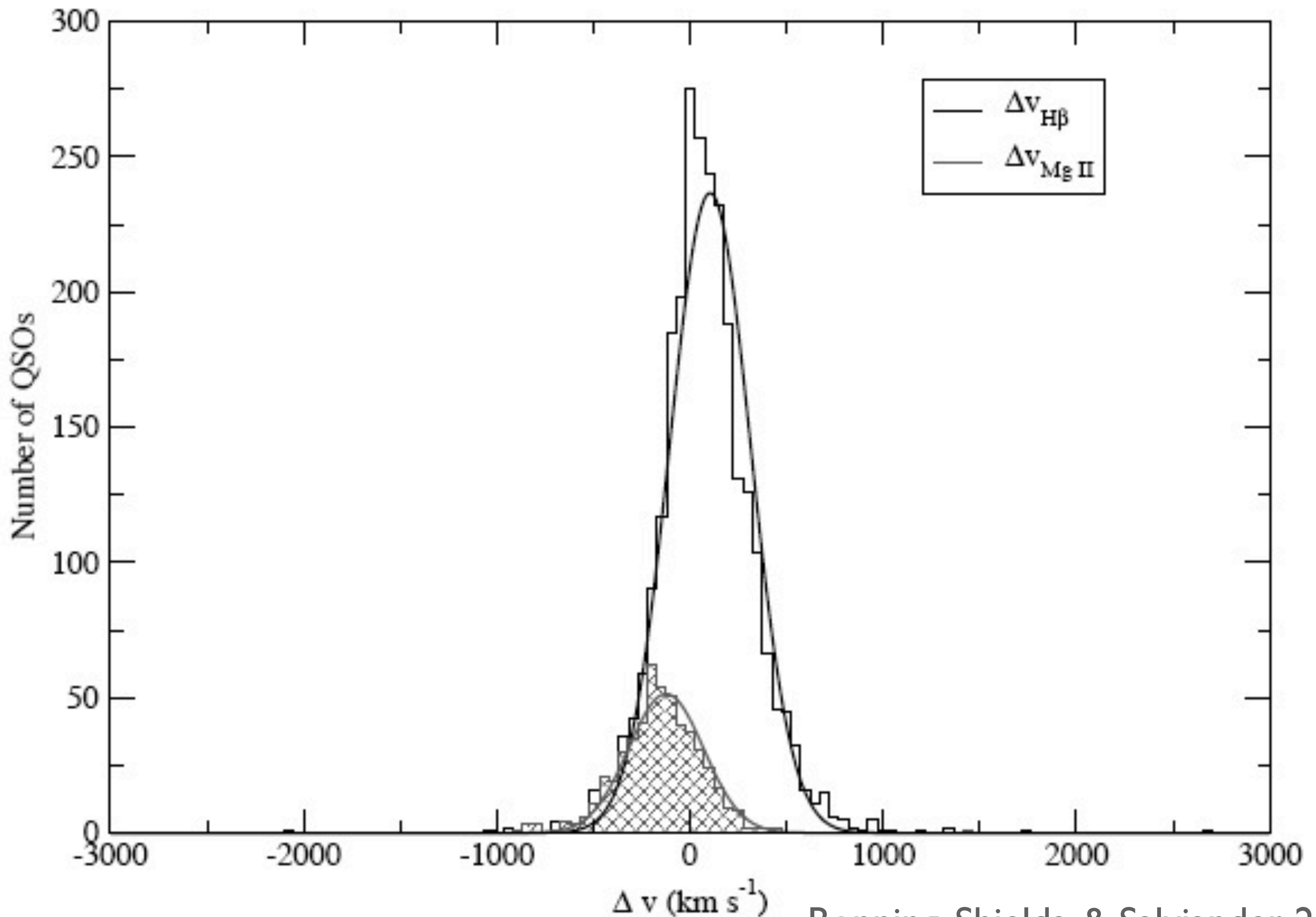


z=0.36, recent merger

Dual AGN (Comerford et al. 2009)
or Recoiling MBH with v~1200 km/s
(Civano et al. 2010)?

The SDSS QSO Sample

40 QSOs in the range 0.1 < z < 0.81 have displacements of > 600 km/s



Bonning, Shields, & Salviander 2007

"We find no convincing evidence for recoiling black holes carrying accretion disks. We place an upper limit on the incidence of recoiling black holes in QSOs of 4% for kicks greater than 500 km/s and 0.35% for kicks greater than 1000 km/s line-of-sight velocity."

Recoil events are more frequent at high z when these observations become more difficult.

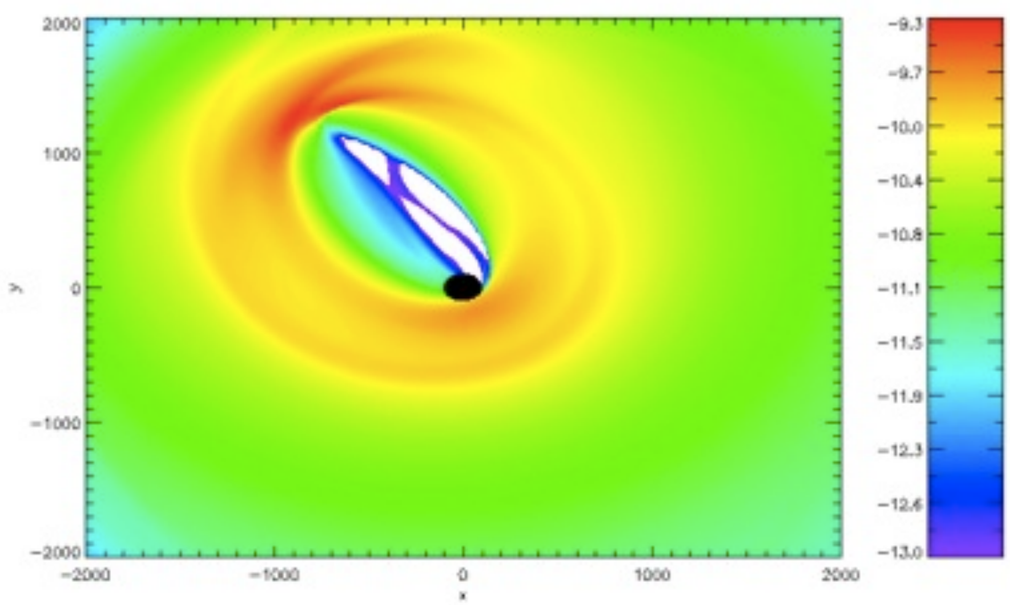
Consequences of MBH Recoil

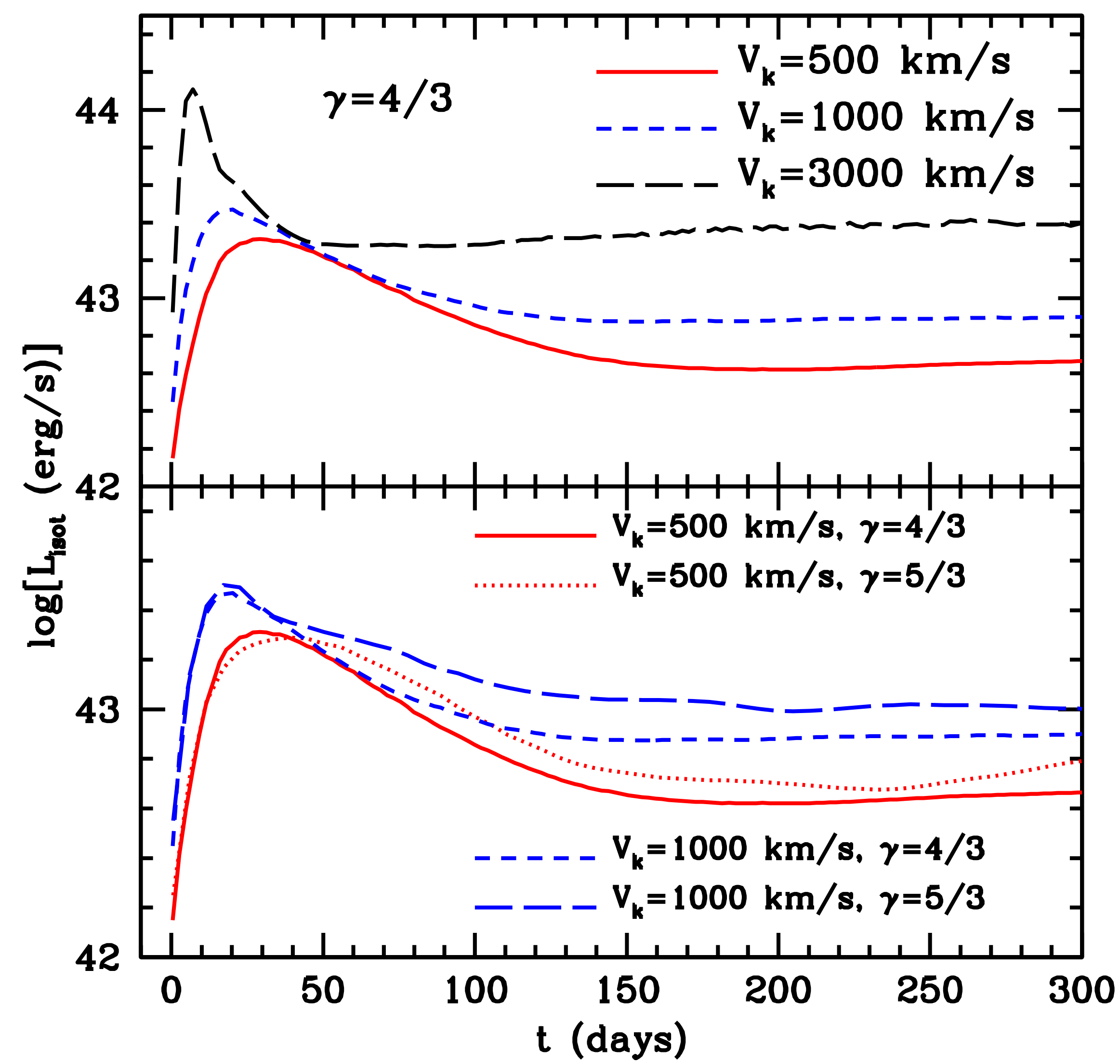
Electromagnetic Counterparts ~~to LISA detections~~

The coalescence of MBHs can have also E&M counterparts:

- Through the increase of stellar tidal disruptions (Stone & Loeb 2011)
- Interaction of the MBH with surrounding material (e.g. Milosavljević & Phinney 2005, Schnittman 2010, Zanotti et al. 2010). For strong Mach numbers, the MBH can produce shocks on the surrounding gas.

Zanotti et al. 2010





Ejection in Early Halos

Recoil events are very relevant at high redshift!

$$V_{\rm esc} = 220\ {\rm kms}^{-1}\ g(c)^{1/2}(M_{\rm vir}/10^{10}M_{\odot})^{0.27}$$

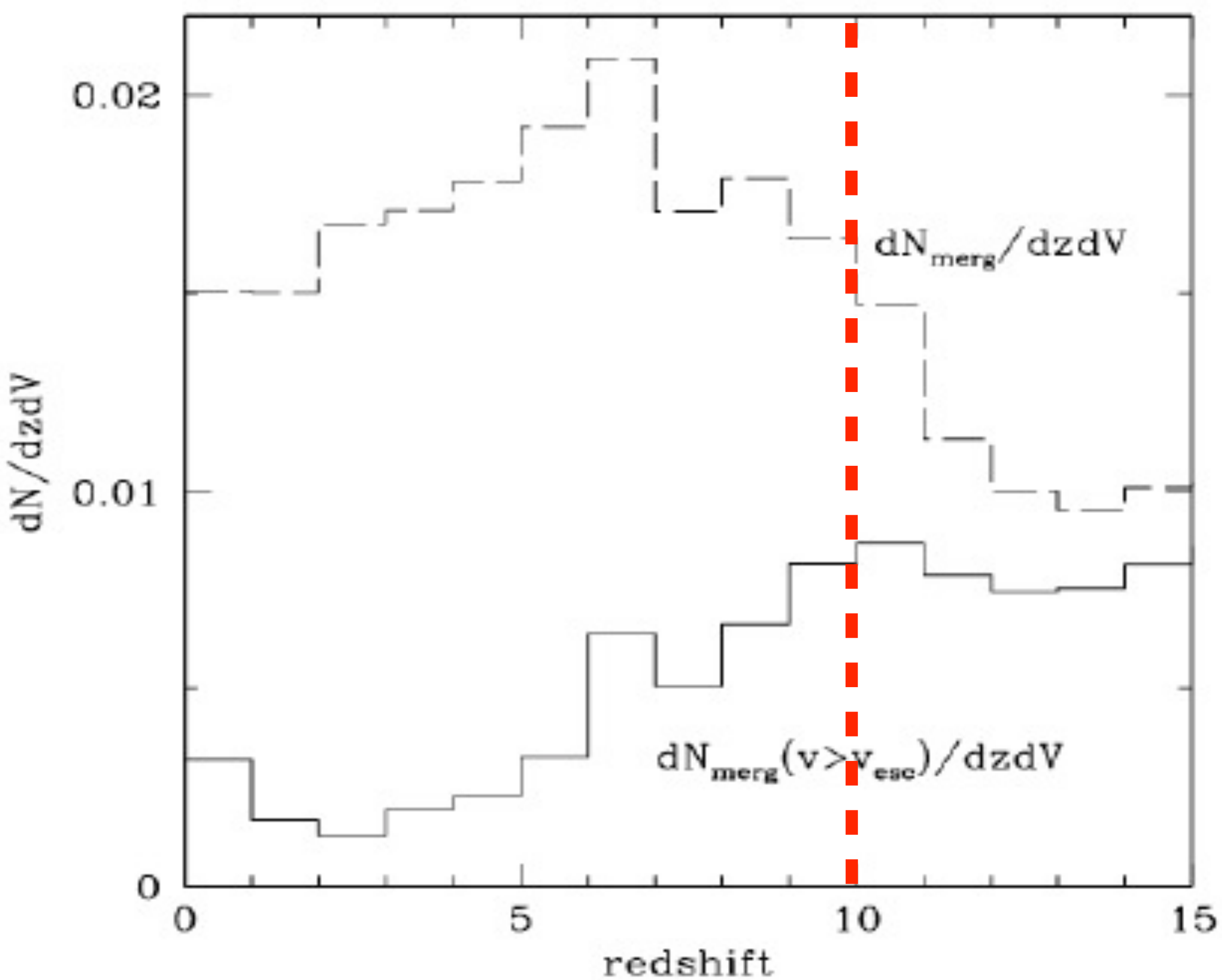
A kick velocity of 250 km/s is comparable to the escape velocity of a 10^{10} Msun dark halo at high z.

Escape velocity today would be much larger.

More than 80% of MBHs can be kicked out of their haloes at z > 10
Volonteri & Rees 2006

Small halos have higher probability of ejection but suffer less merger events. Recoil can decrease the occupation fraction in small galaxies by 60% and up to 20% in larger galaxies.

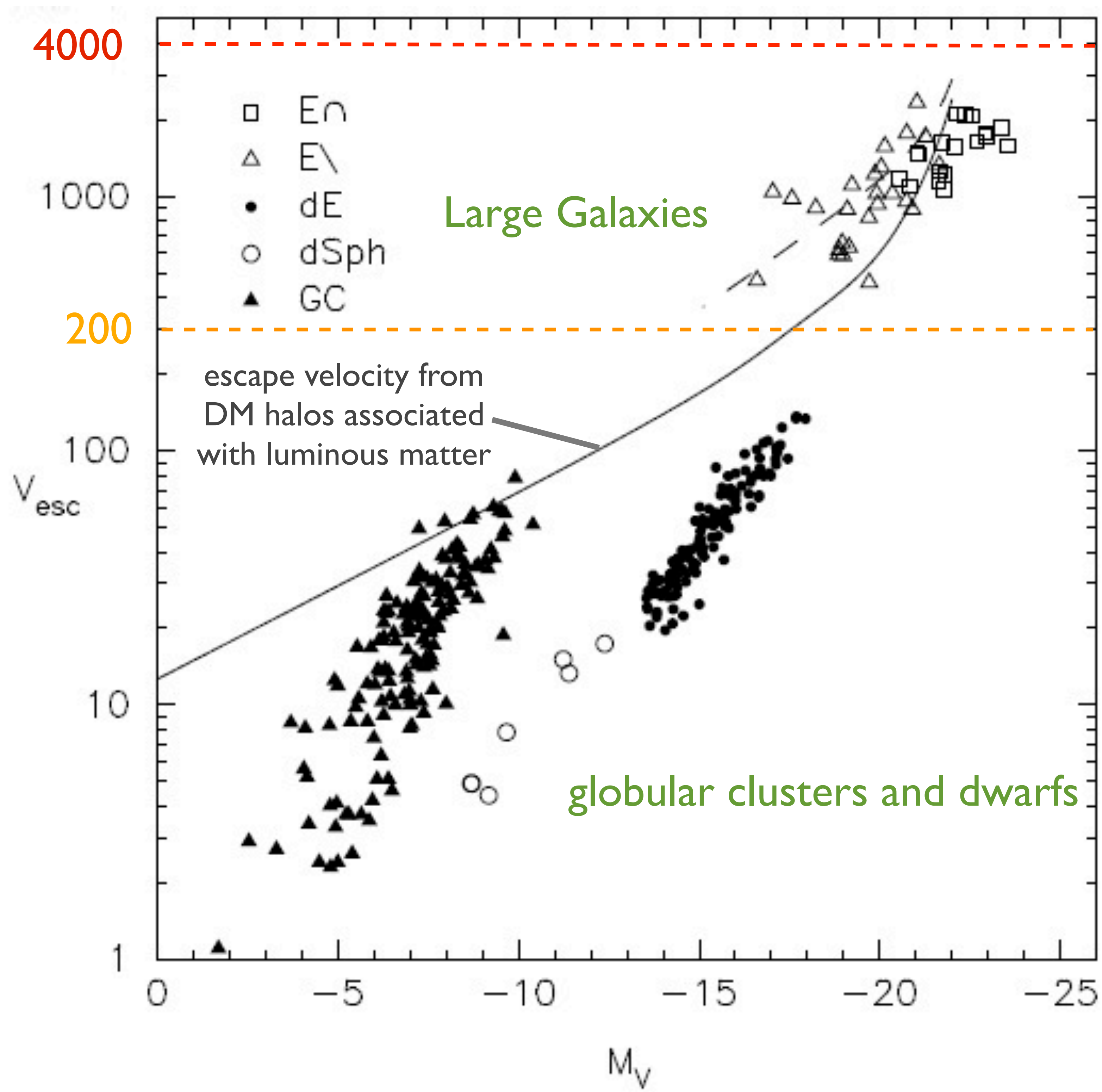
Volonteri, Gultekin, & Dotti 2010



Volonteri & Rees 2006

MBH Retention Today

- Initial kick velocities of ~200 km/s would unbind BHs from Globular Clusters and dSph galaxies whether or not they are embedded in DM halos.
- Consistent with the lack of observational evidence for central BHs in faint galaxies.
- Maximum kick (3750 km/s) can eject BHs from the largest galaxies even when dark matter is accounted for.

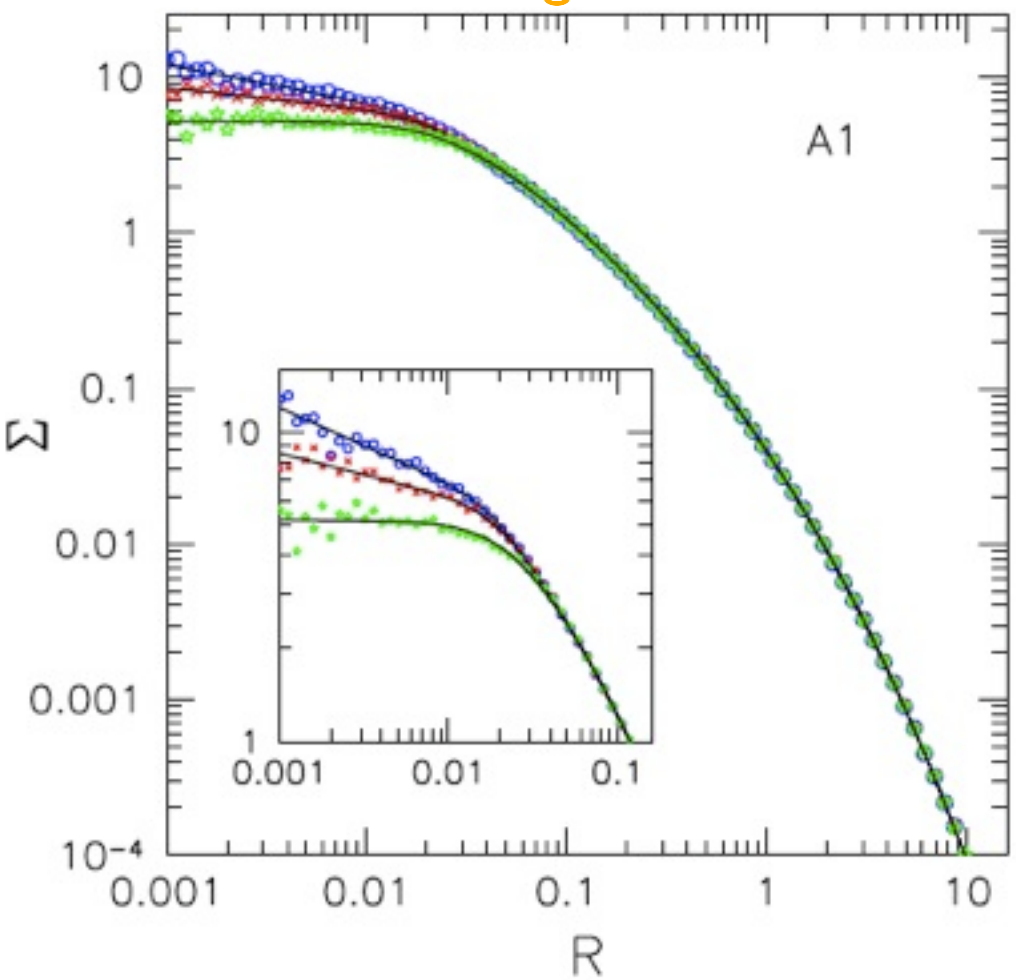


Merritt et al. 2004

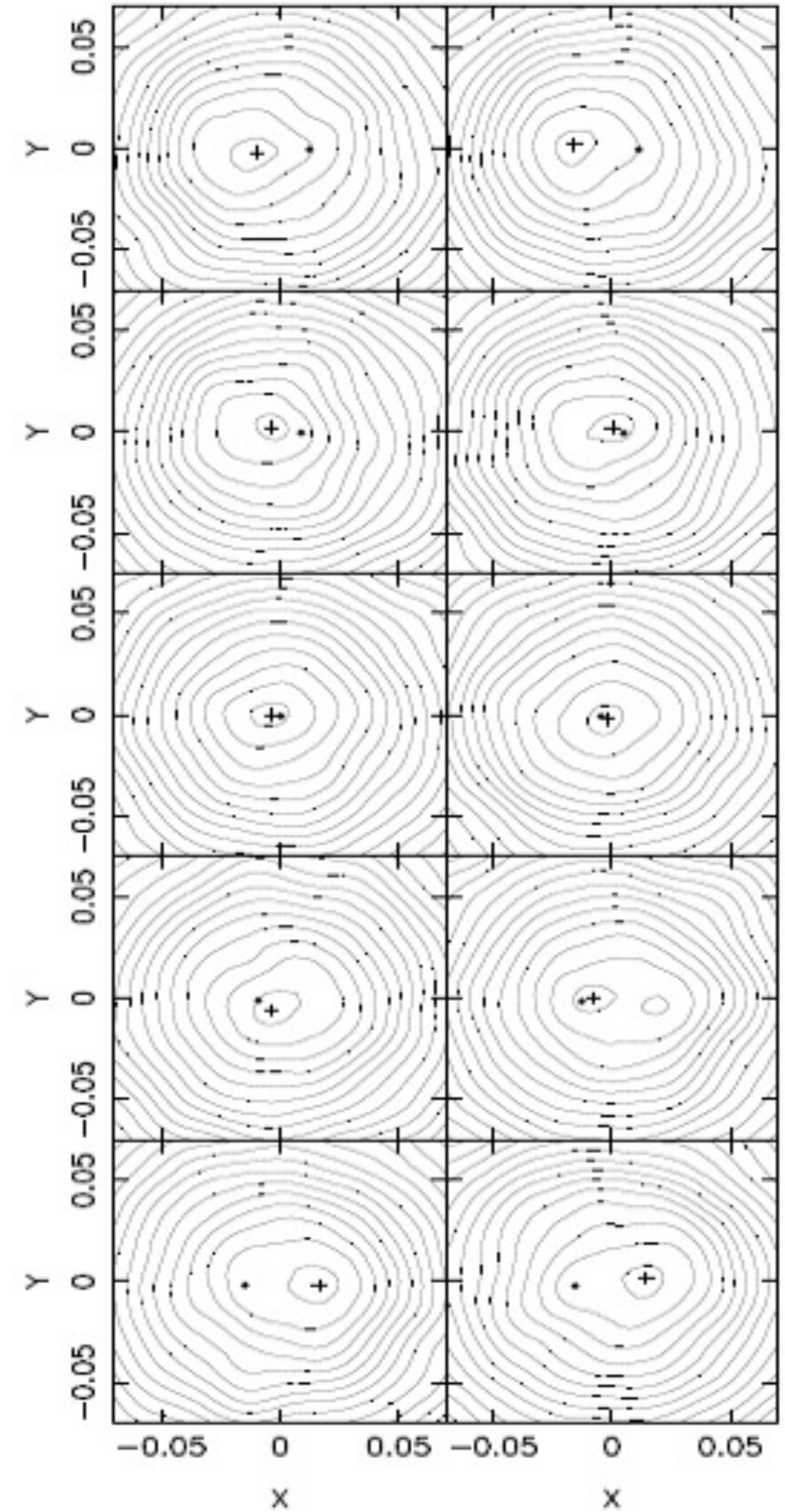
Core Formation

- Direct summation simulations of a recoiling MBH and its effect on the surrounding stelar medium.
- **Spherically symmetric potential, collisionless.**
- Approaches Chandrasekhar dynamical friction formula for $2 < \ln\Lambda < 3$

mass deficit in galactic cores



core oscillations

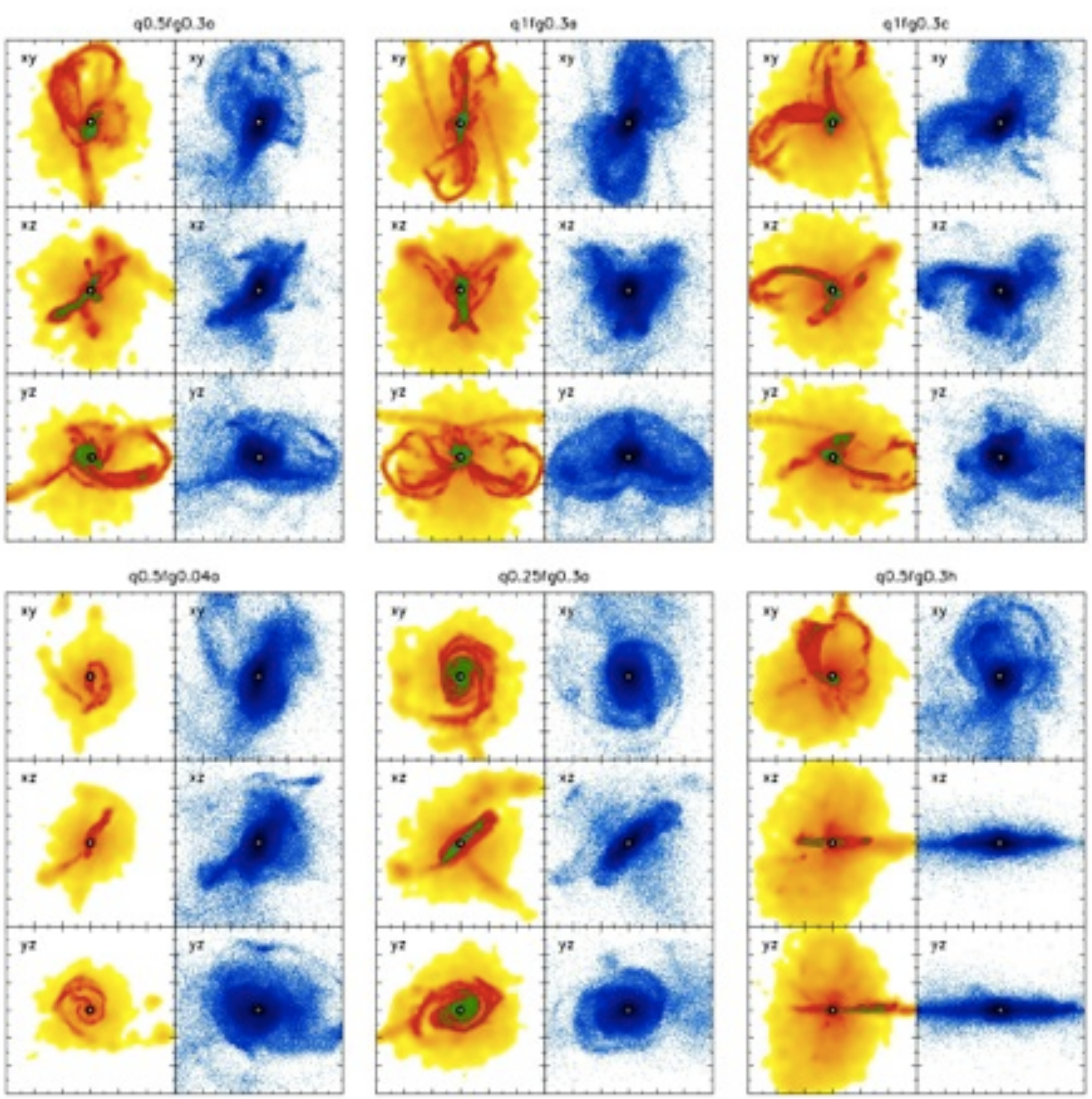


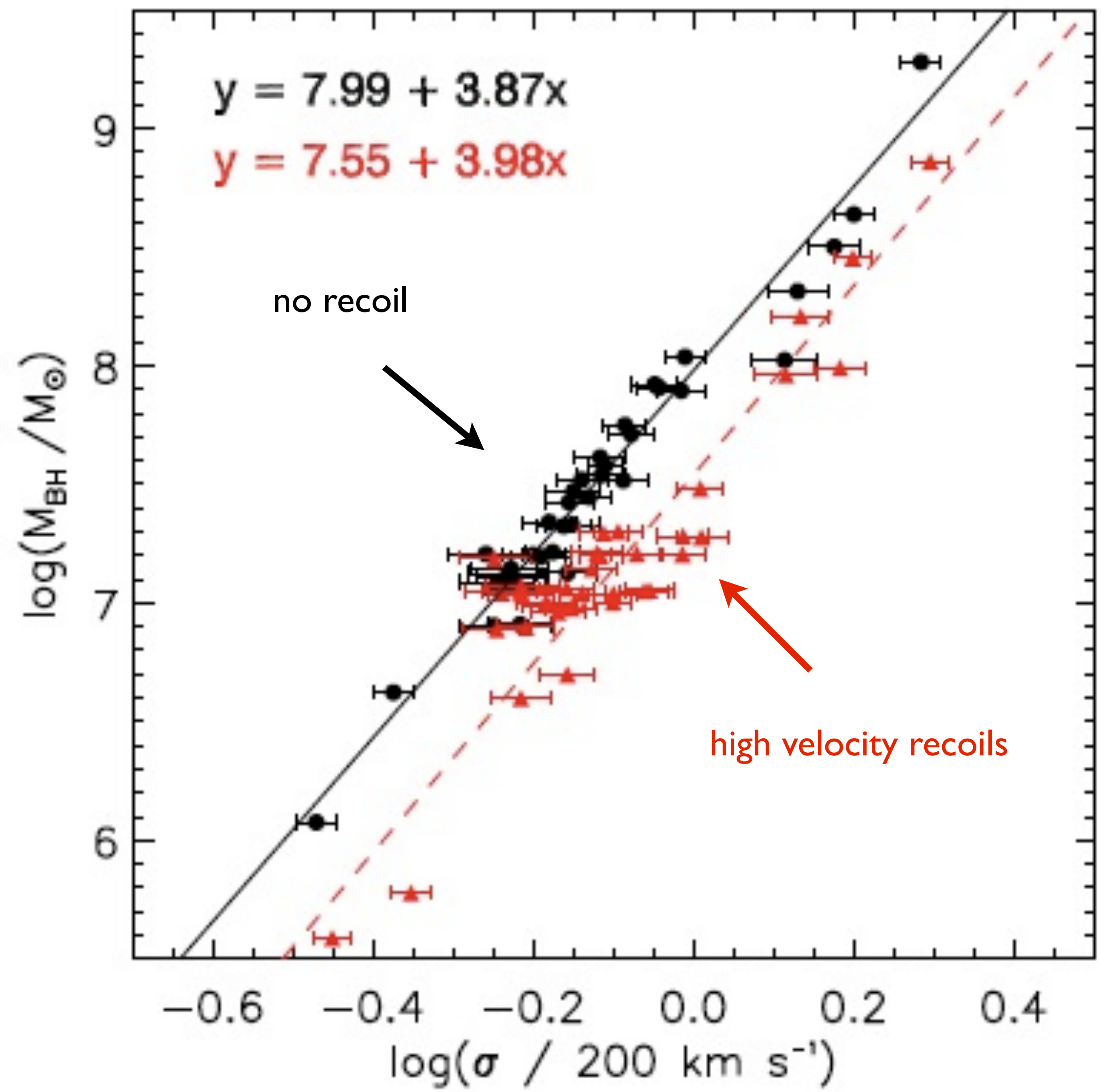
Gualandris & Merritt 2008

Effect of Recoil on the M-Sigma Relation

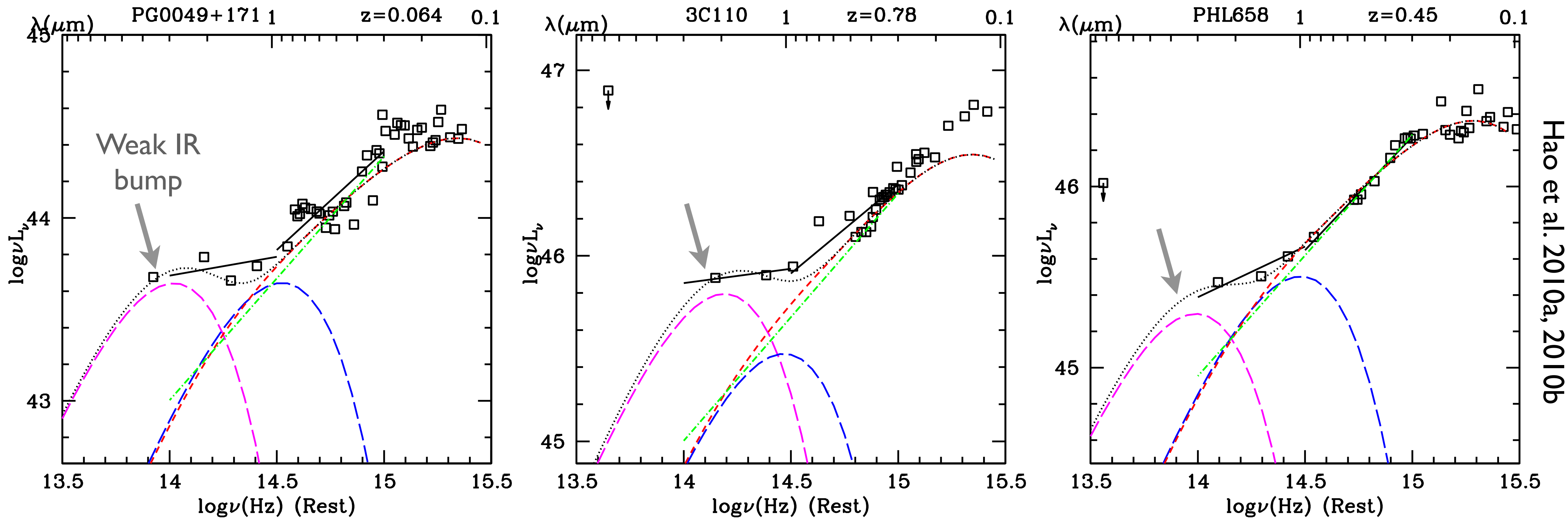
About 200 simulations using different MBH mass ratios, velocity kicks, accretion.

Blecha et al. 2010





Hot-dust-free AGN/QSOs?



- Nearly 10% of spectroscopically confirmed type I AGNs samples and XMM-COSMOS (Elvis et al. 2010 in prep) show a relatively weak infrared bump, associated with dust emission.
- The number of these objects has been shown to increase with redshift, from 6% at $z<2$ to 20% at $2<z<3.5$.
- Since these AGN are in the redshift range $0 < z < 4$, these hot-dust-free AGN are not recently born AGN which have not time to form a dusty torus (Jiang et al. 2010).
- Based on their spectral resolution 2Å, a z=2 source could have a relative velocity of 50-70 km/s.

Summary

✳The merging of massive black holes at the centers of galaxies can lead to a population of kinematically / spatially offset AGN.

✳Galaxies that do not harbor a MBH today may have done so in the past.

✳Differentially triaxial dark matter halos lead to longer wandering time scales.

✳Kinematic offsets are more likely to be observed in major mergers where high recoil speeds can retain the MBHs. The MBH will be seen as a kinematic offset for a few years after recoil and during pericenter passages.

✳Spatial offsets are more likely to be observed in minor mergers, where the shallower host potential allow for larger MBH displacements. In this case the MBH can accrete from the surroundings (depending on the inclination angle of the kick and gas supply) and shine at $r > 1$ kpc for several Myr.

✳The detectability of recoiling MBHs is challenging, particularly at high redshift where most mergers are expected to occur.

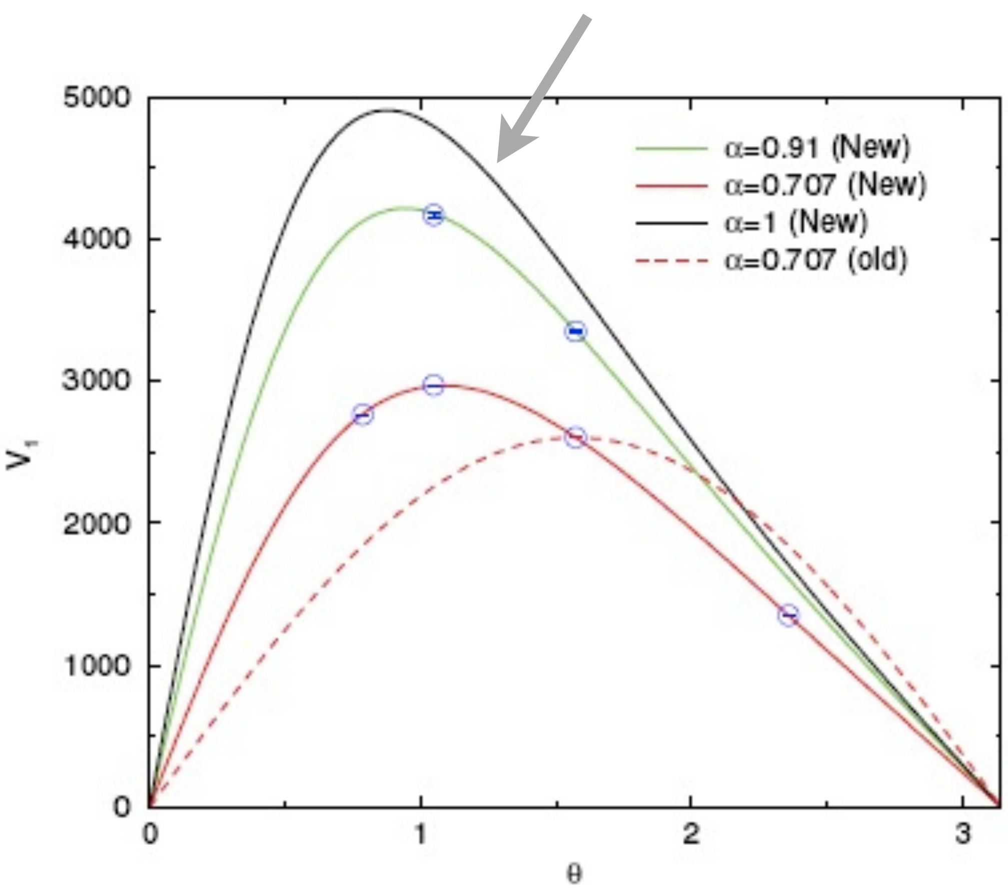
✳Recoiling MBHs could give rise to the observed population of hot-dust-poor AGN/ QSOs.

Open Questions

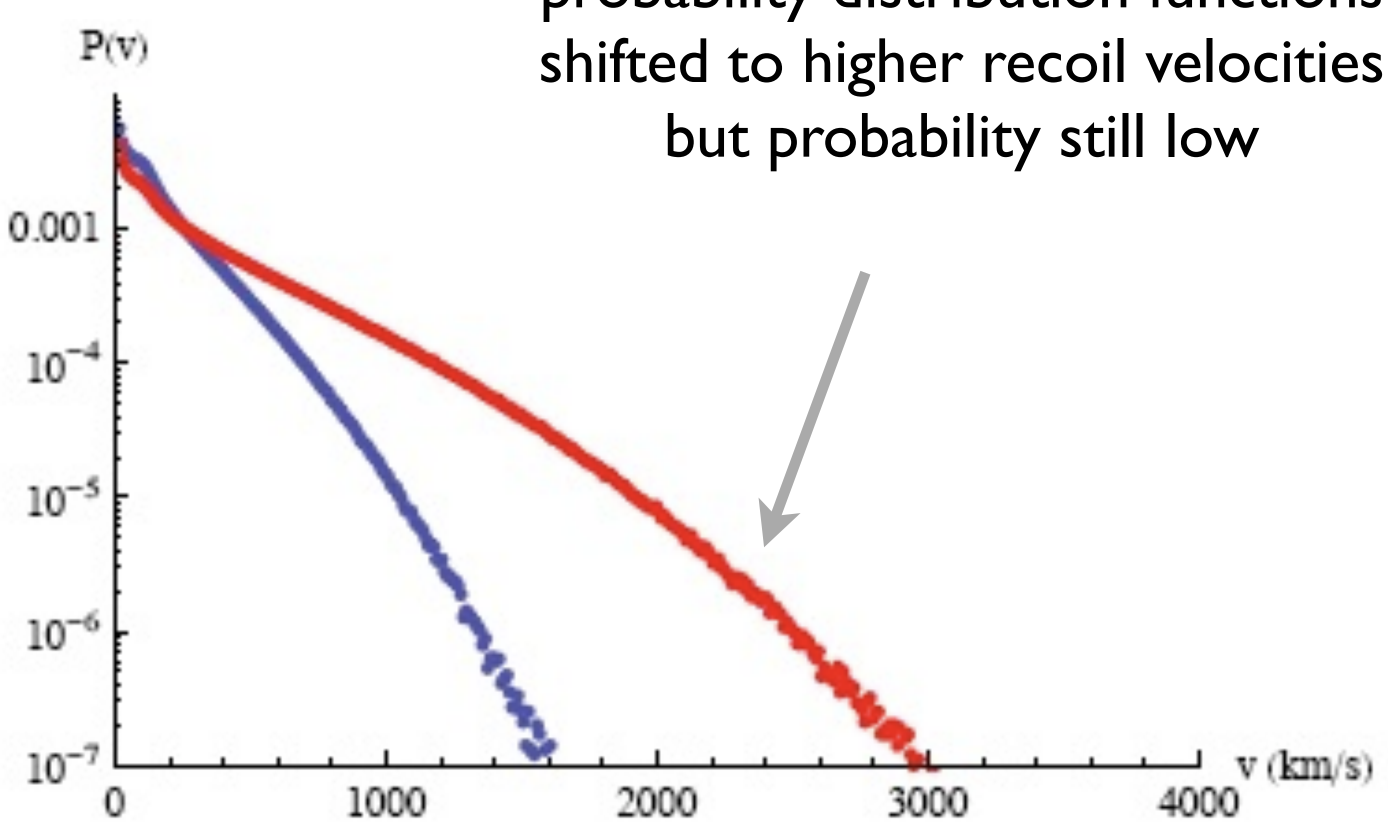
1. Are recoiling massive black holes observable?
2. Is there a test that would confirm offset AGN to be recoiling massive black holes?
3. Do massive black holes really merge: Have we solved the final parsec problem?

New calculations that include non linear terms in the spin

peak occurs at 5000 km/s in the case of ***nearly aligned*** spins



probability distribution functions shifted to higher recoil velocities but probability still low



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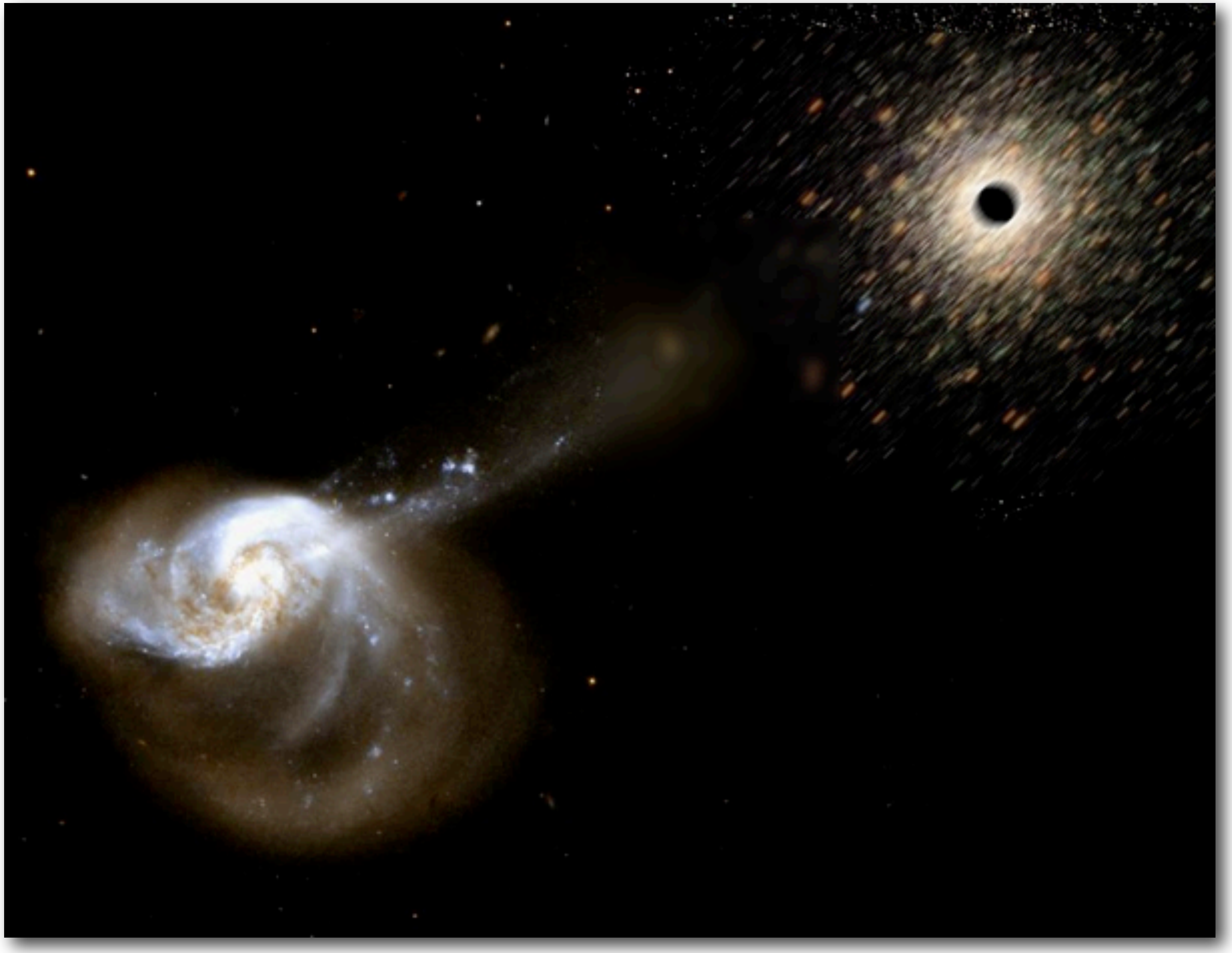

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The importance of thermodynamics in MBH mergers