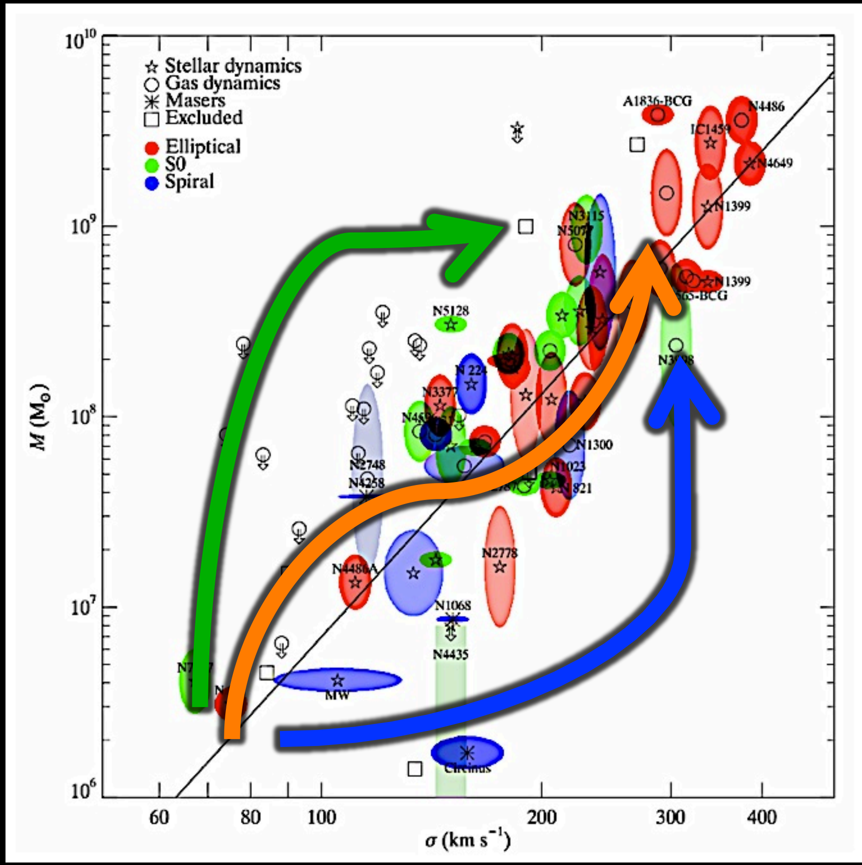
Massive black holes in galaxy mergers:
accretion and dynamics

Marta Volonteri
Institut d'Astrophysique de Paris

S. Van Wassenhove,
M. Dotti,
J. Bellovary

MBHs in local galaxies

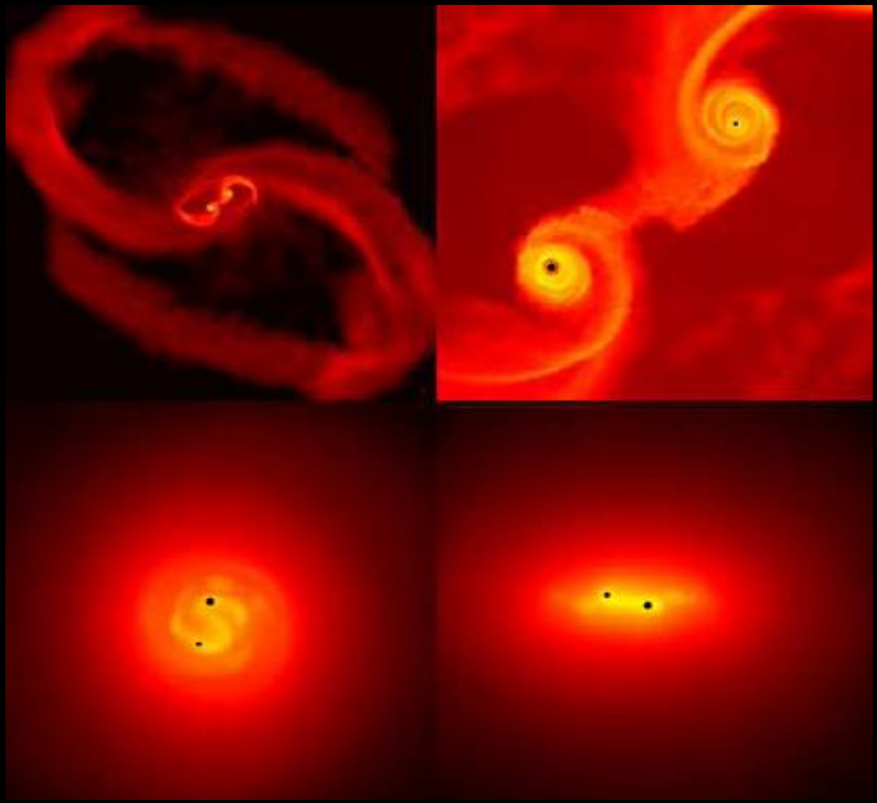
- Black holes are found in the centers of most nearby galaxies
- Scaling relations between BHs and host galaxies provide evidence for co-evolution (M_{BH}- σ, M_{BH}-L, M_{BH}-M_{bulge})
- BHs should naturally grow along with galaxies through accretion and mergers and influence the galaxy through feedback

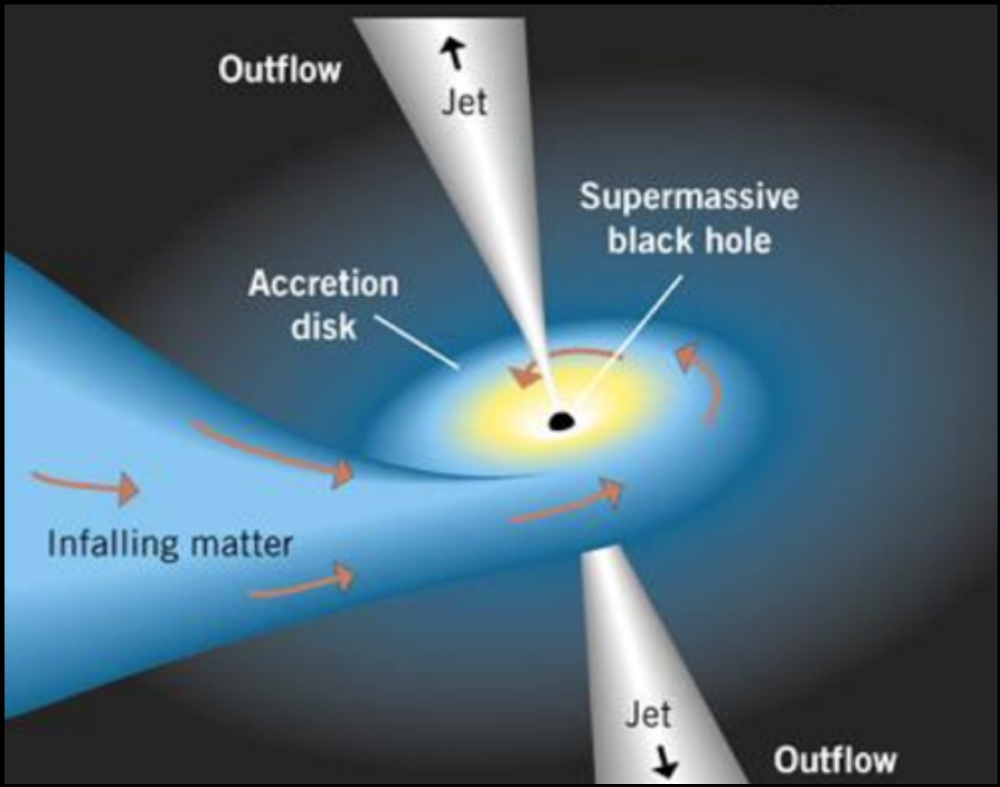


from Gultekin et al. 2009

Growing MBHs

How do MBHs grow to become supermassive?
BH-BH mergers and gas accretion





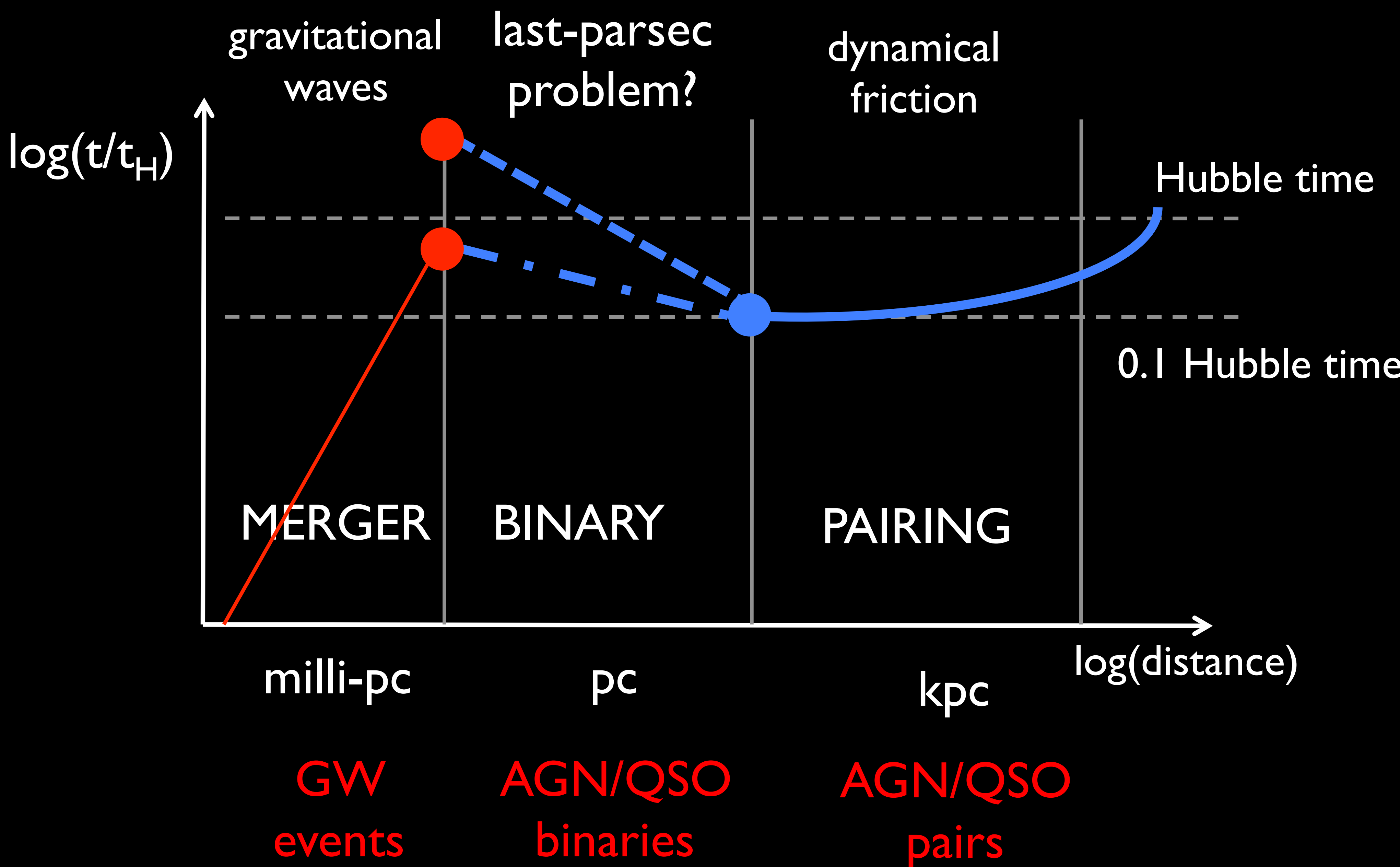
Need to probe *both* processes to understand MBH growth and co-evolution with host

MBHs and galaxy mergers

- LCDM: galaxy mergers are an integral part of structure evolution
- MBHs co-evolve with their host galaxies
- MBHs must take part in galaxy mergers
  - *merger-driven accretion*
  - *MBH merger rates*

MBHs in galaxy mergers: what we want to know

- When and where MBHs grow most efficiently
- Whether MBHs merge as efficiently as their host galaxies
- How we can interpret observations of MBH activity – AGN


gravitational waves
last-parsec problem?
dynamical friction
log(t/t_H)
Hubble time
0.1 Hubble time
MERGER
BINARY
PAIRING
log(distance)
milli-pc
pc
kpc
GW events
AGN/QSO binaries
AGN/QSO pairs

log(distance)

milli-pc	pc	kpc
GW events	AGN/QSO binaries	AGN/QSO pairs

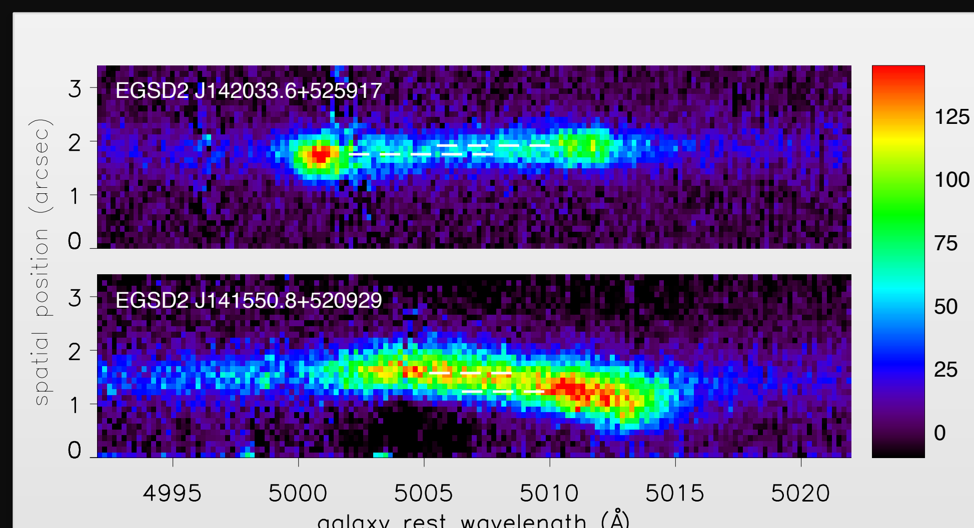
MERGER	BINARY	PAIRING	CONTEXT
	Dotti, MV et al.	van Wassenhove, MV et al.	Bellovary, MV et al.
Numerical Relativiy + analytical	Zoomed-in simulations of merger remnants: nuclear discs	Suite of galaxy merger simulations	Cosmological simulations + semi-analytical models: which galaxies host MBHs

Rarity of Dual AGN

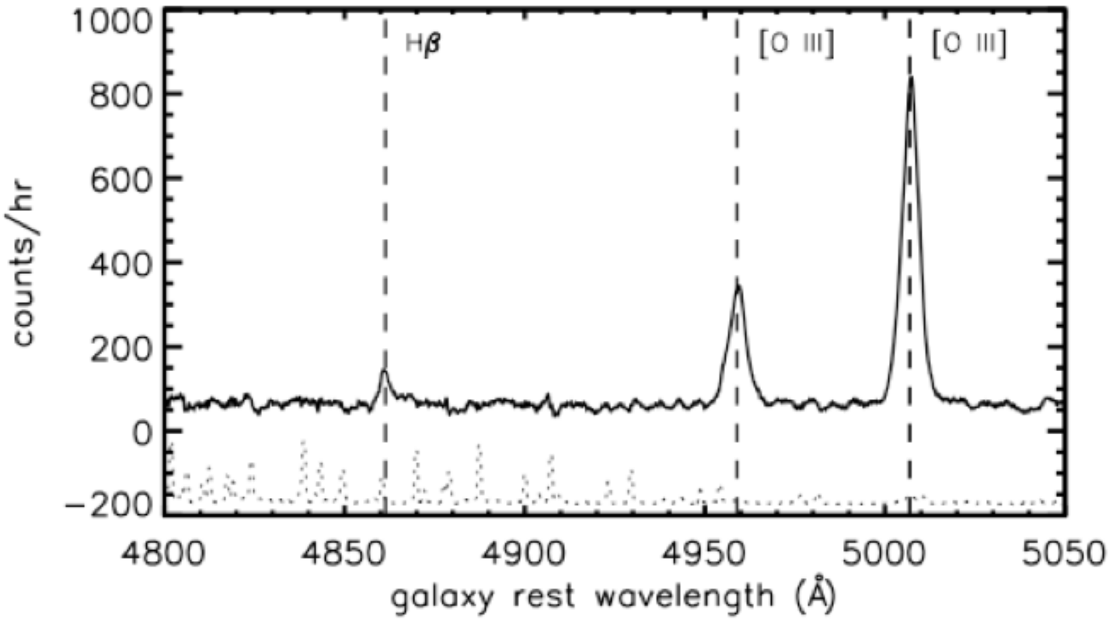
If most galaxies host MBHs and galaxy mergers trigger accretion, duals should be common.

Optical surveys:

- Spectroscopy: search for galaxy spectra with pairs of AGN emission lines

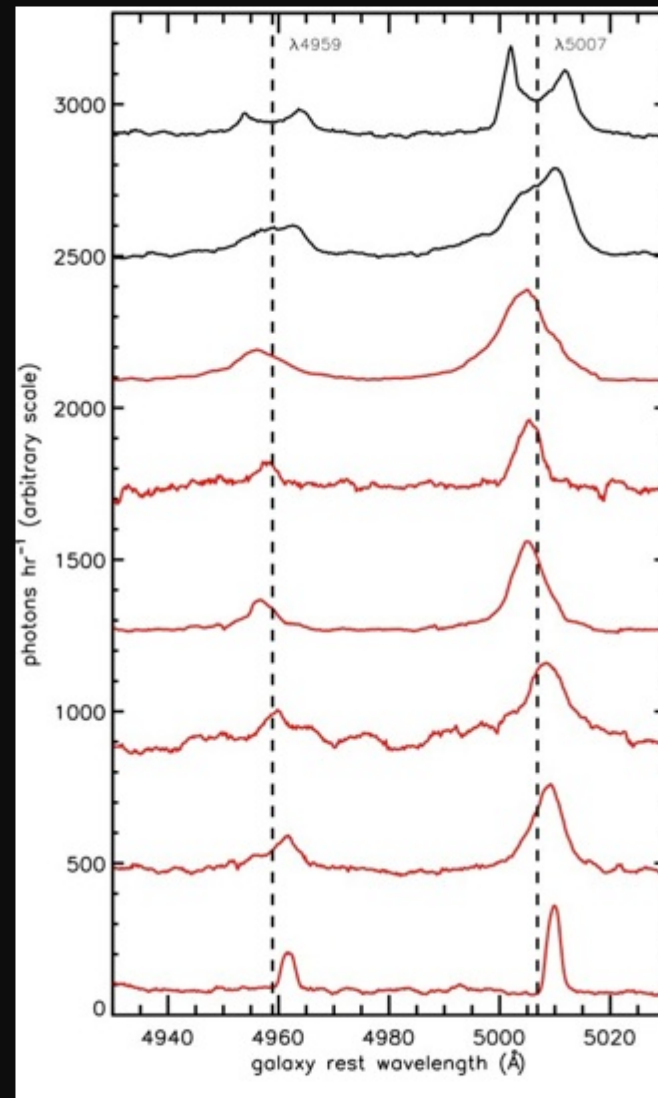


Comerford et al. 2009

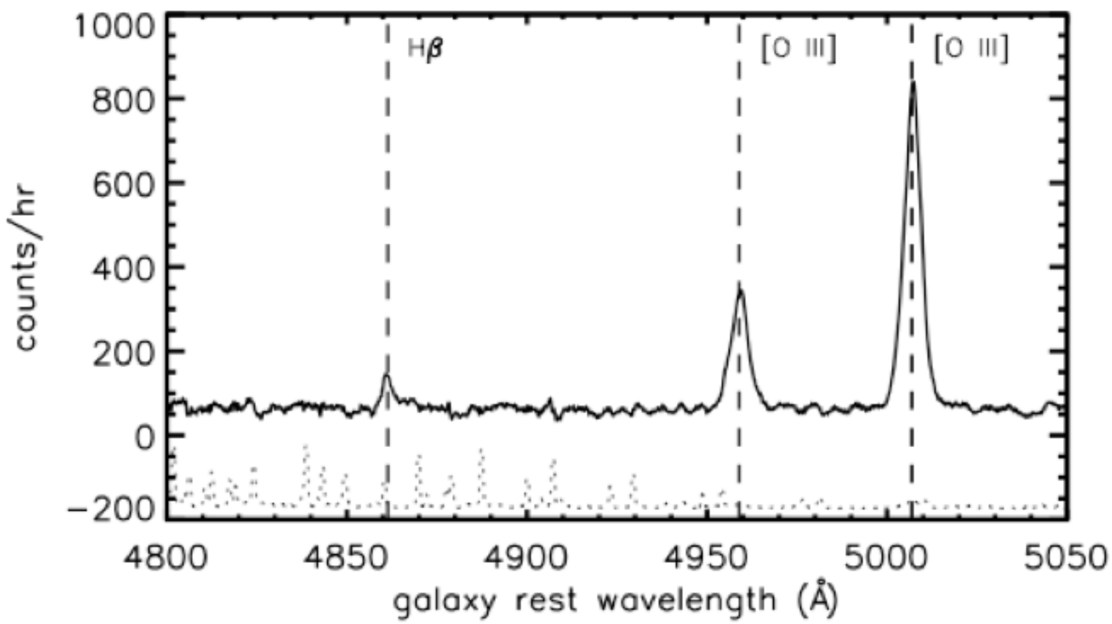


AGN is at rest with respect to the host galaxy

If a MBH is moving and accreting, the **OFFSET AGN** emission lines will be blue- or red- shifted with respect to the host galaxy rest frame



Comerford et al. 2009

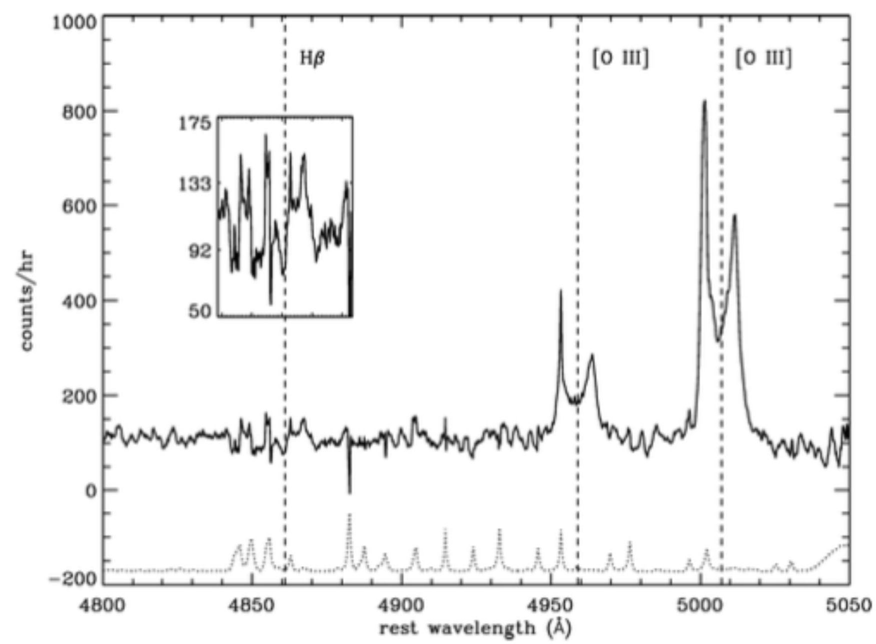


AGN is at rest with respect to the host galaxy

If a MBH is moving and accreting, the AGN emission lines will be blue- or red- shifted with respect to the host galaxy rest frame

If both MBHs moving and accreting, the **DUAL AGN** emission lines will show two peaks one blue- one red- shifted with respect to the host galaxy rest frame

Double-peaked [O III] emission lines separated by 630 km/s



Gerke et al. 2009

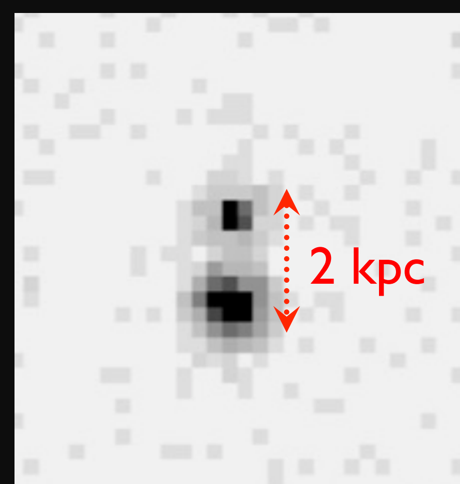
Rarity of Dual AGN

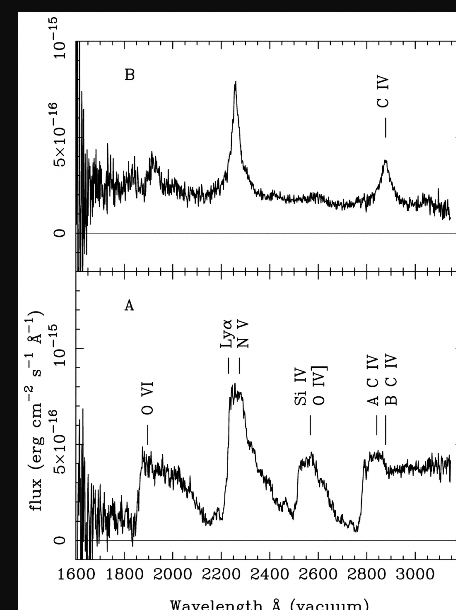
If most galaxies host MBHs and galaxy mergers trigger accretion, duals should be common.

Optical surveys:

- Spectroscopy: search for galaxy spectra with pairs of AGN emission lines
- Imaging: search for AGN pairs that are not lenses

Dual AGN fraction generally at most a few %



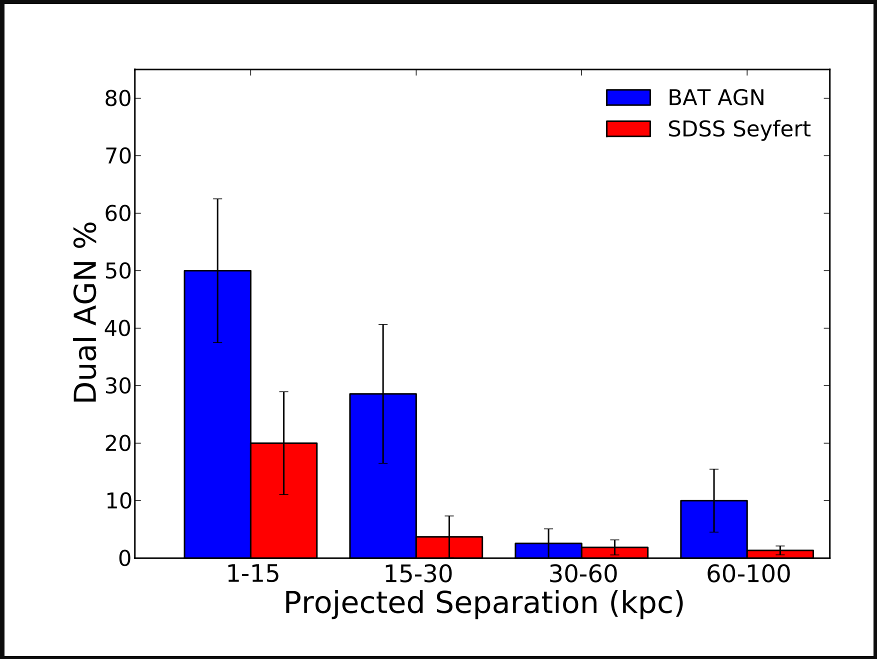


LBQS 0103-2753
(Junkkarinen et al. 2001)

Rarity of Dual AGN

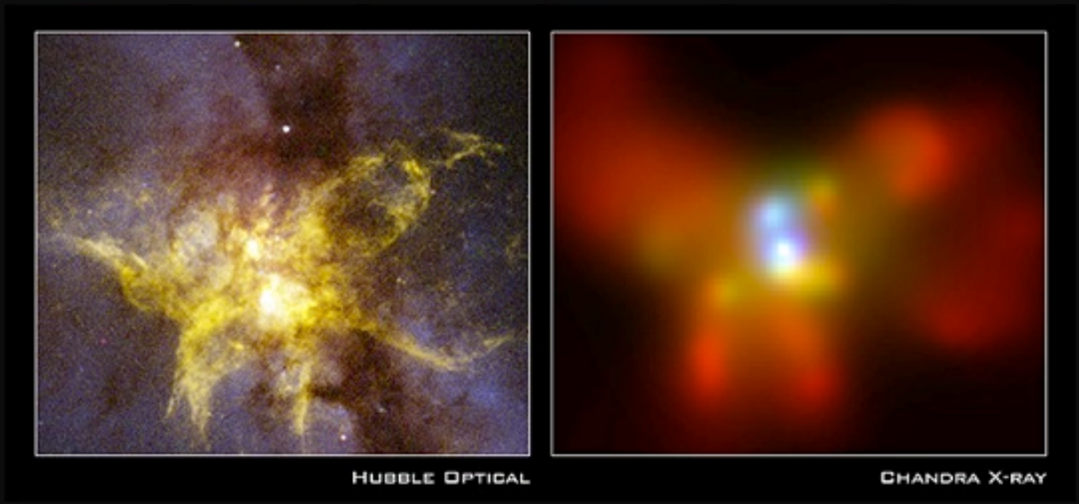
X-ray:

- Serendipitous discovery, eg, NGC 6240; Arp 299; NGC3393
- Search for AGN in companion galaxies of hard X-ray AGN (Swift)
- Dual fraction increases for galaxies with small separations



Koss et al. 2012

Results indicate a higher dual fraction than optical surveys



NGC 6240, Komossa et al. 2002

Simulating Galaxy Mergers

- Consider a realistic parameter space, not just 1:1 mergers - 1:2; 1:4 and 1:10 mergers
- Discs and spheroids
- Focus on observational counterparts to MBH activity

Simulating Galaxy Mergers

- Galaxies are constructed out of nested profiles of dark matter, stars, and gas
- Spiral gas disks have gas fractions of 30%
- One MBH placed in each galaxy according to scaling relations
- z=3 => peak of merger rate

Gasoline

- Simulations use GASOLINE, an N-body SPH code

- Includes star formation, supernova feedback, radiative cooling, BH accretion and feedback

Bondi-Hoyle-Lyttleton accretion

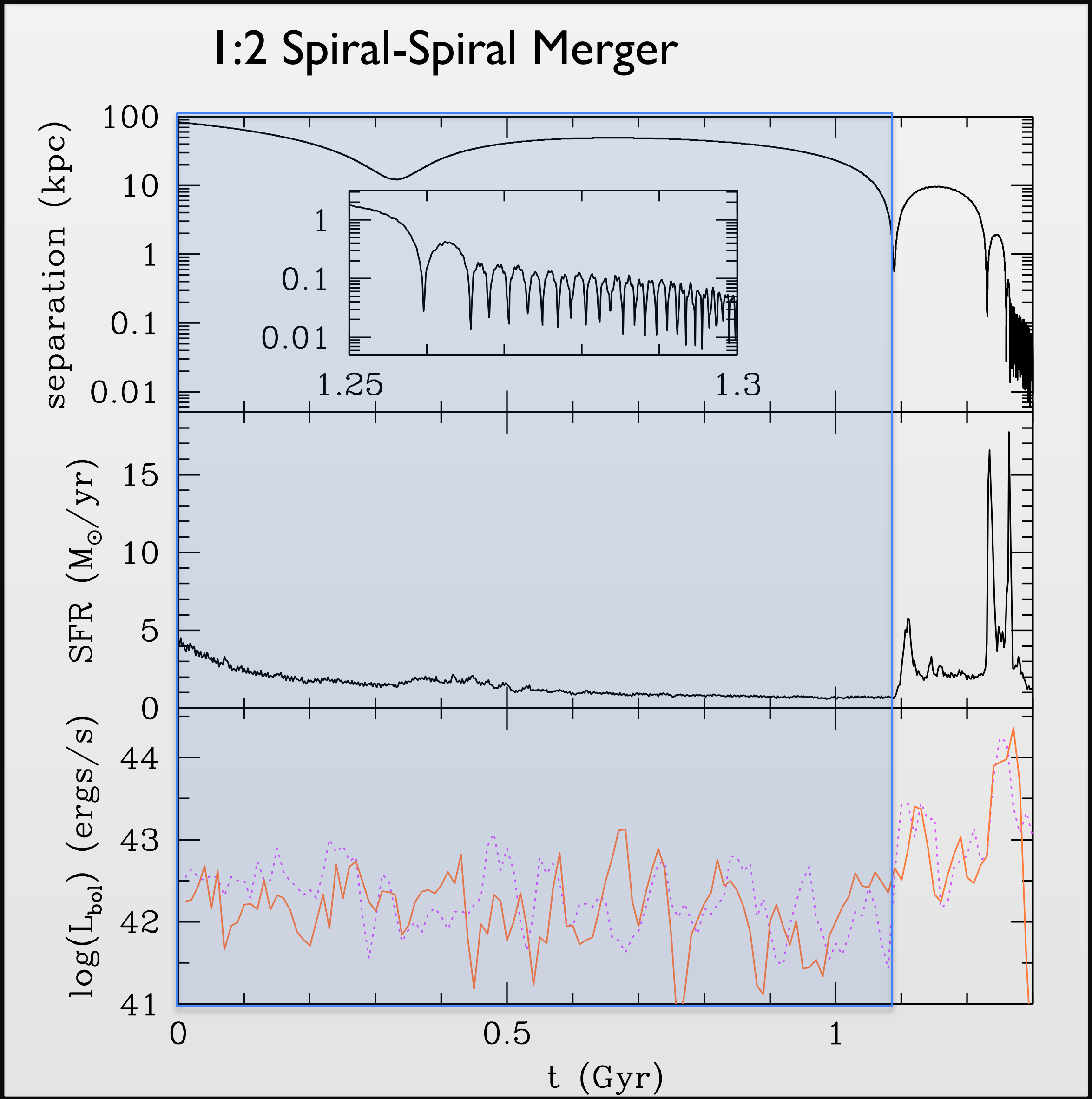
$$\dot{M}_{BH} = 4\pi G \frac{M_{BH}^2 \rho_g}{\left(V^2 + c_s^2\right)^{3/2}}$$

ε_{fb} = 0.001 of accreted energy deposited in nearby gas

- Gravitational softening lengths are 10-20 parsecs to resolve MBH pairing

Galaxy Merger: Early Stages

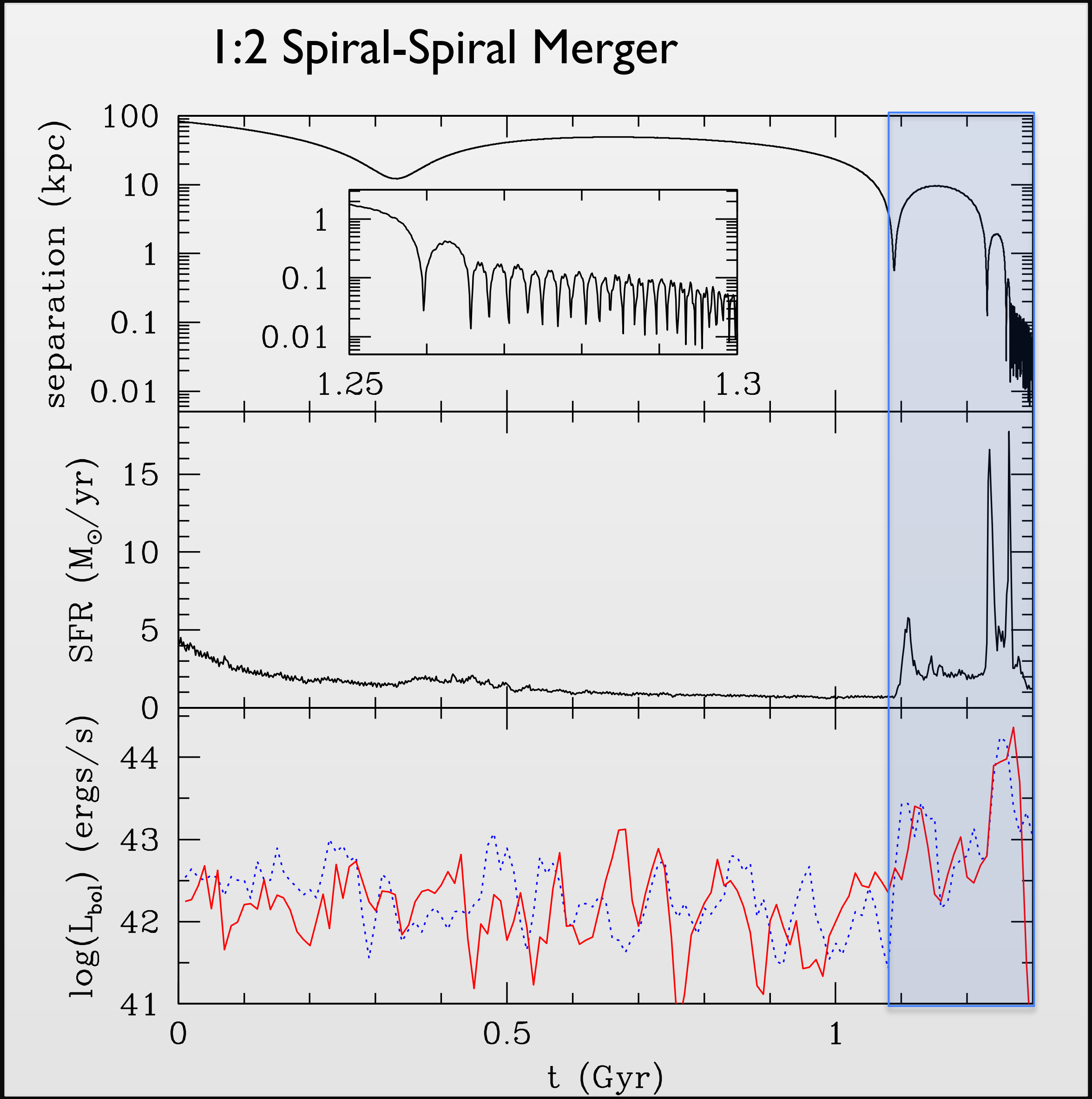
- Both galaxies and BHs grow quiescently
- AGN luminosities remain low, generally $<10^{43}$ erg/s
- AGN activity is not triggered by galaxy dynamics, any dual activity is random



Van Wassenhove et al. 2012

Galaxy Merger: Late Stages

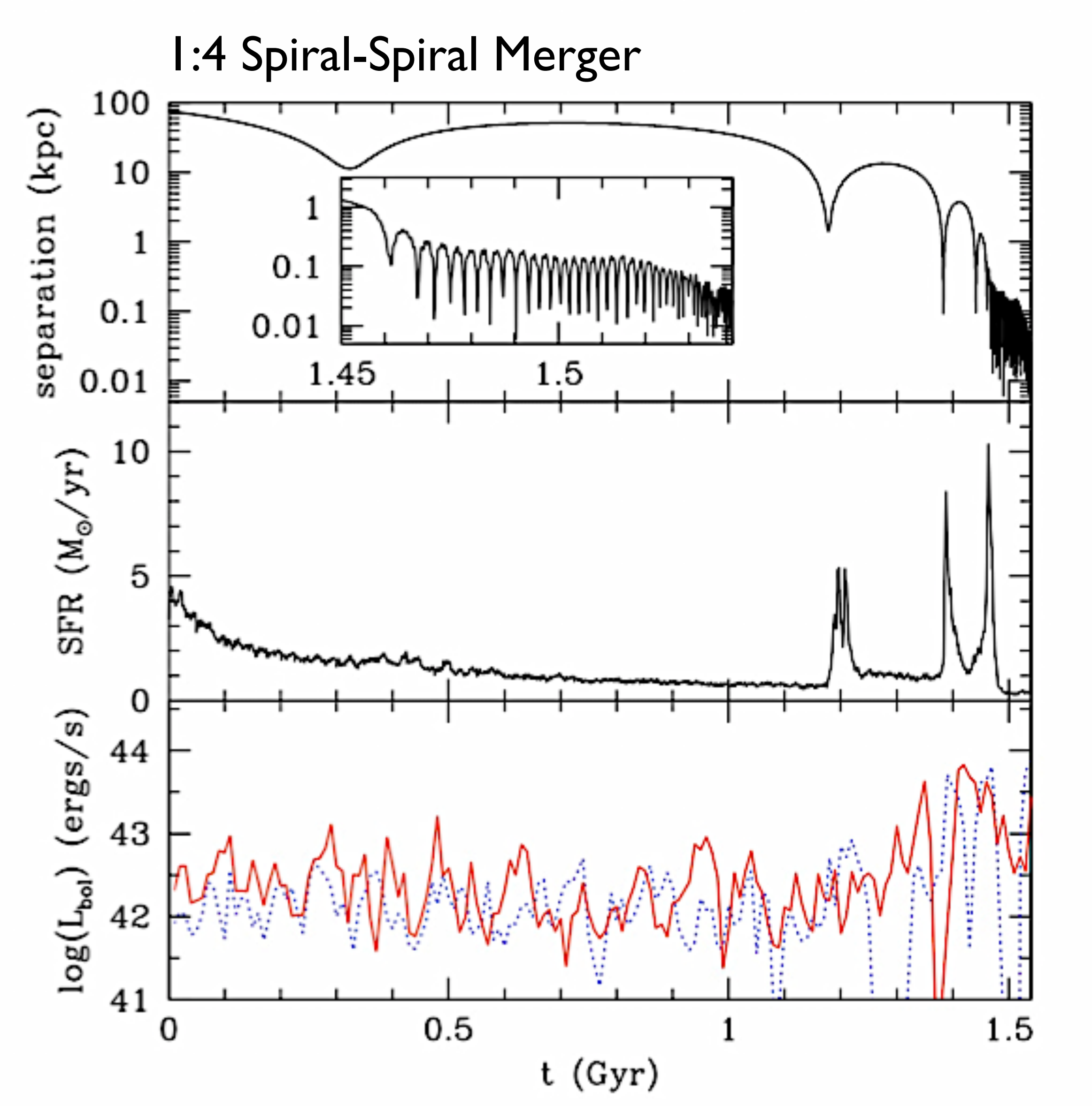
- Tidal forces trigger strong gas inflows in both galaxies
- Star formation rates and AGN activity peak together following pericenter passages
- BHs reach 10^{44} erg/s and have better correlated accretion, producing dual AGN



Van Wassenhove et al. 2012

Galaxy Merger: nuclear coup

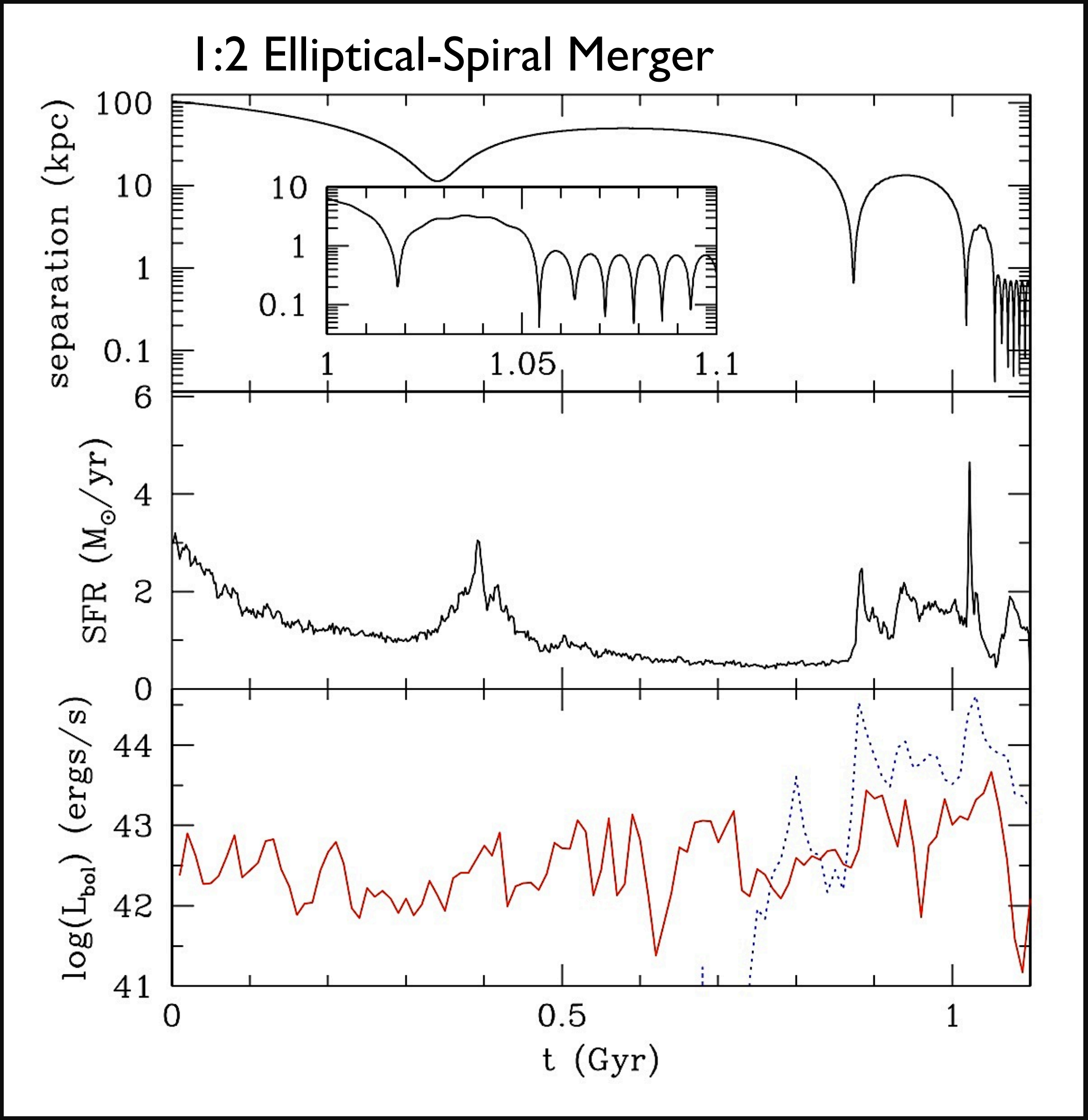
- Weaker SFR in primary, stronger central SF in the companion
- Secondary builds up dense cusp whereas primary does not - primary nucleus disrupted
- Accretion mostly uncorrelated



Van Wassenhove et al. 2012

Galaxy Merger: stripping

- Elliptical initially completely gas poor
- Gas stripped from secondary at pericenter passages fuels MBH in primary
- Secondary is eventually disrupted

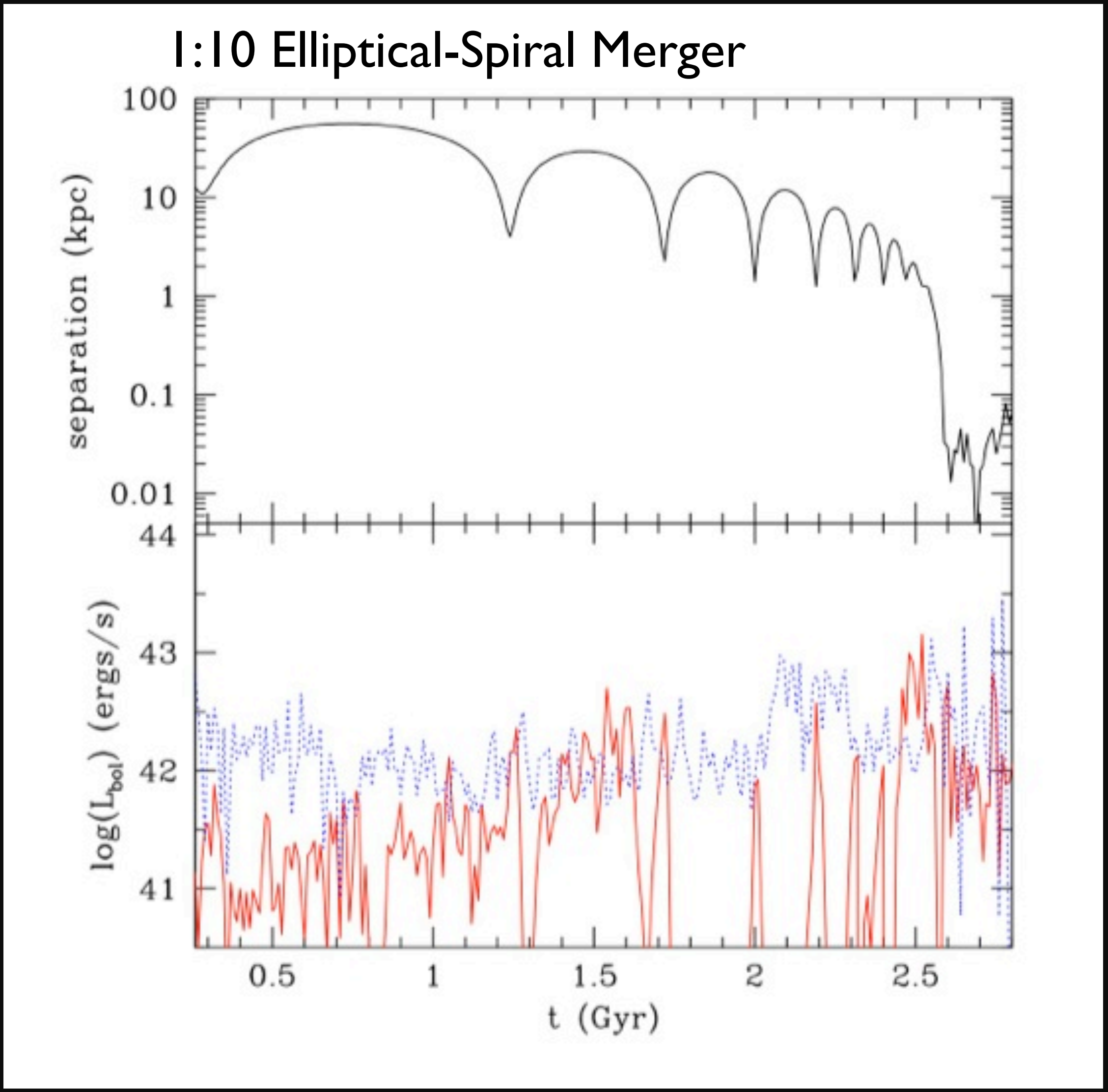


Van Wassenhove et al. 2012

Galaxy Merger: minor

- As mass ratio decreases merger timescale lengthens

- Secondary is eventually disrupted



Van Wassenhove et al. 2012

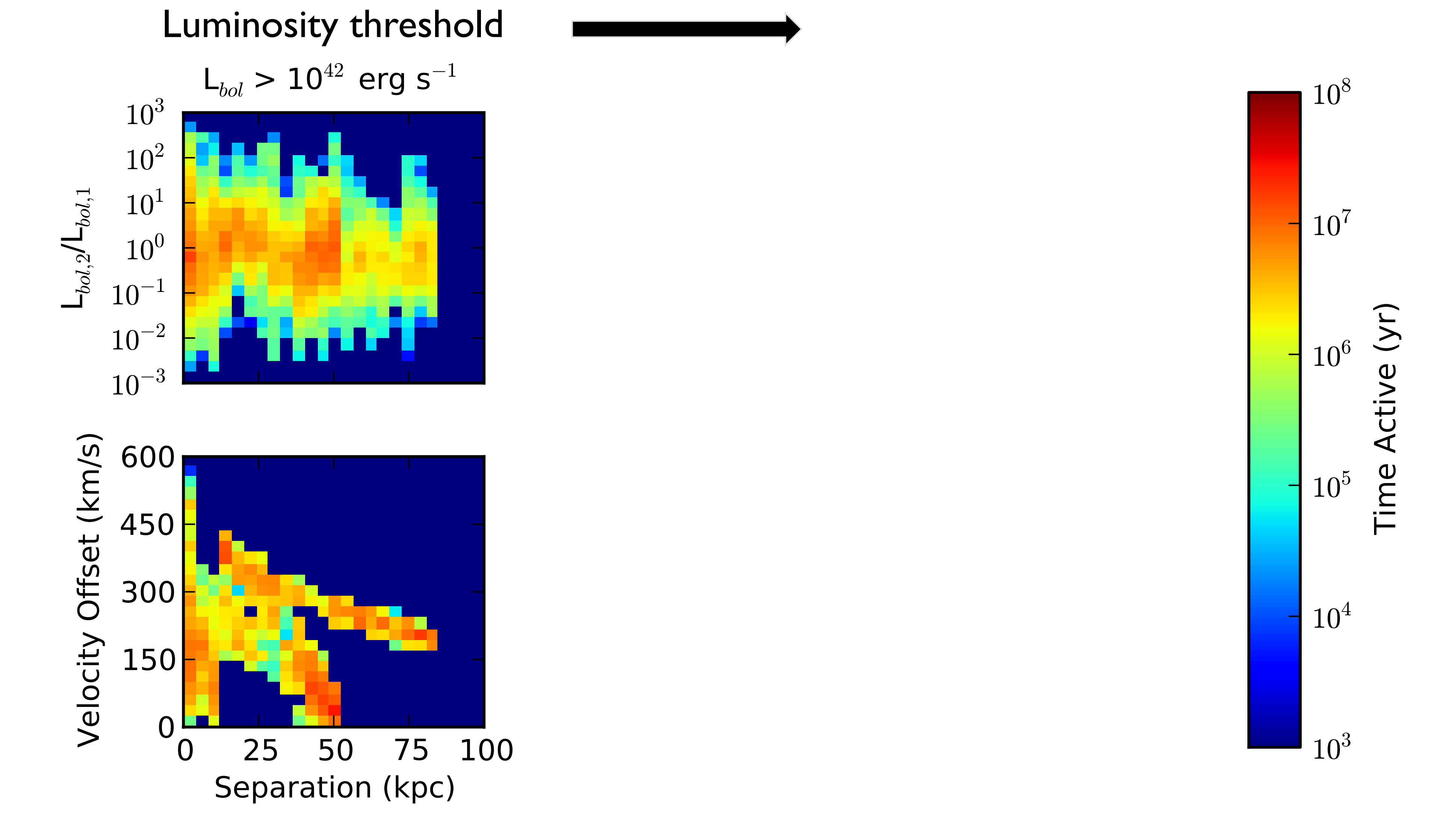
Detectability

- Flux/luminosity threshold

- Imaging: separation between AGN > resolution element of telescope
  - few kpc for, e.g., Chandra, HST
  - tens of kpc for, e.g., SDSS

- Spectroscopy: velocity offset > spectral resolution of spectrograph
  - ~150 km/s for DEEP2, SDSS

1:2 Spiral-Spiral Merger

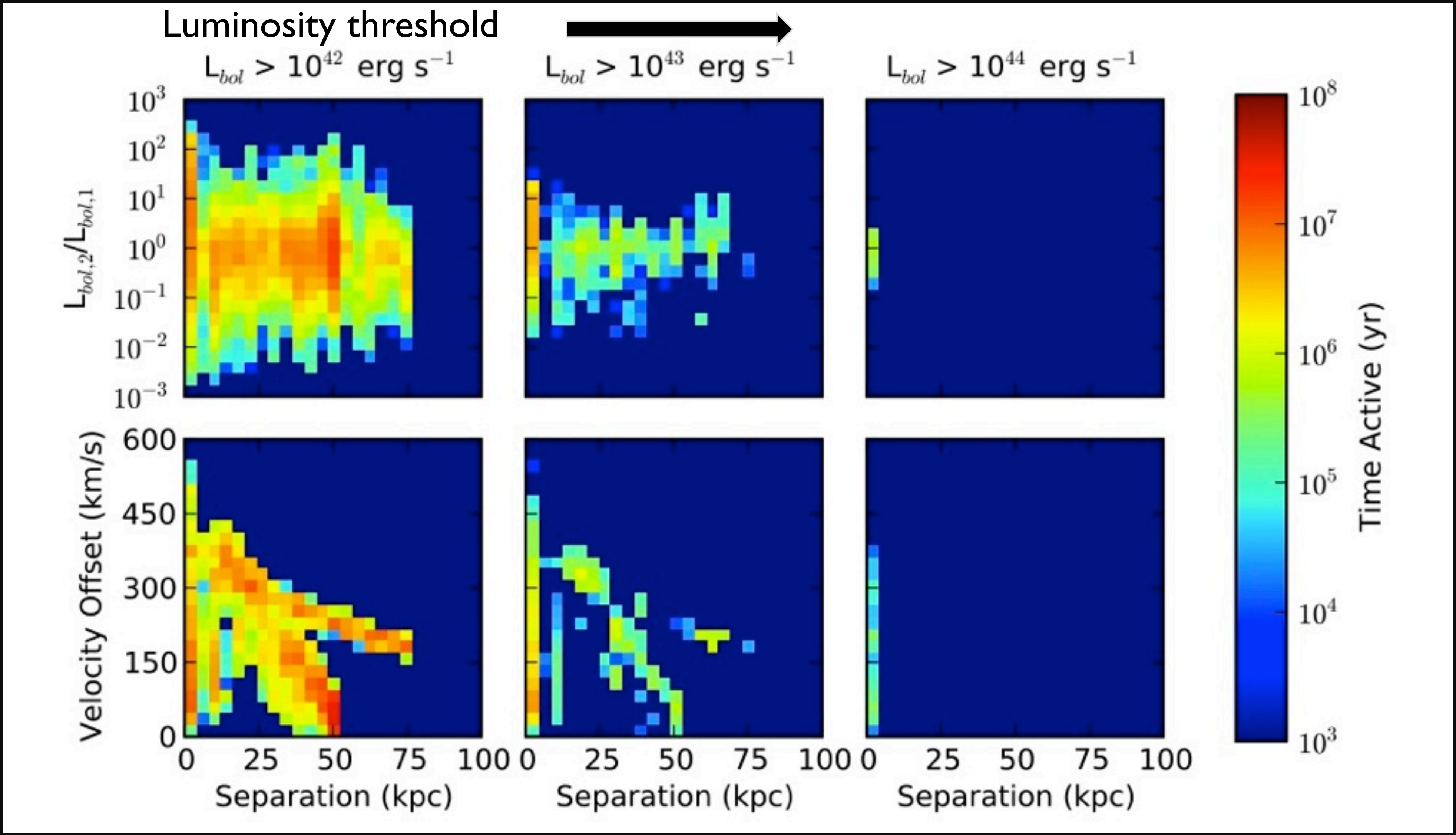


Low threshold: active most of the simulation; lots of dual AGN

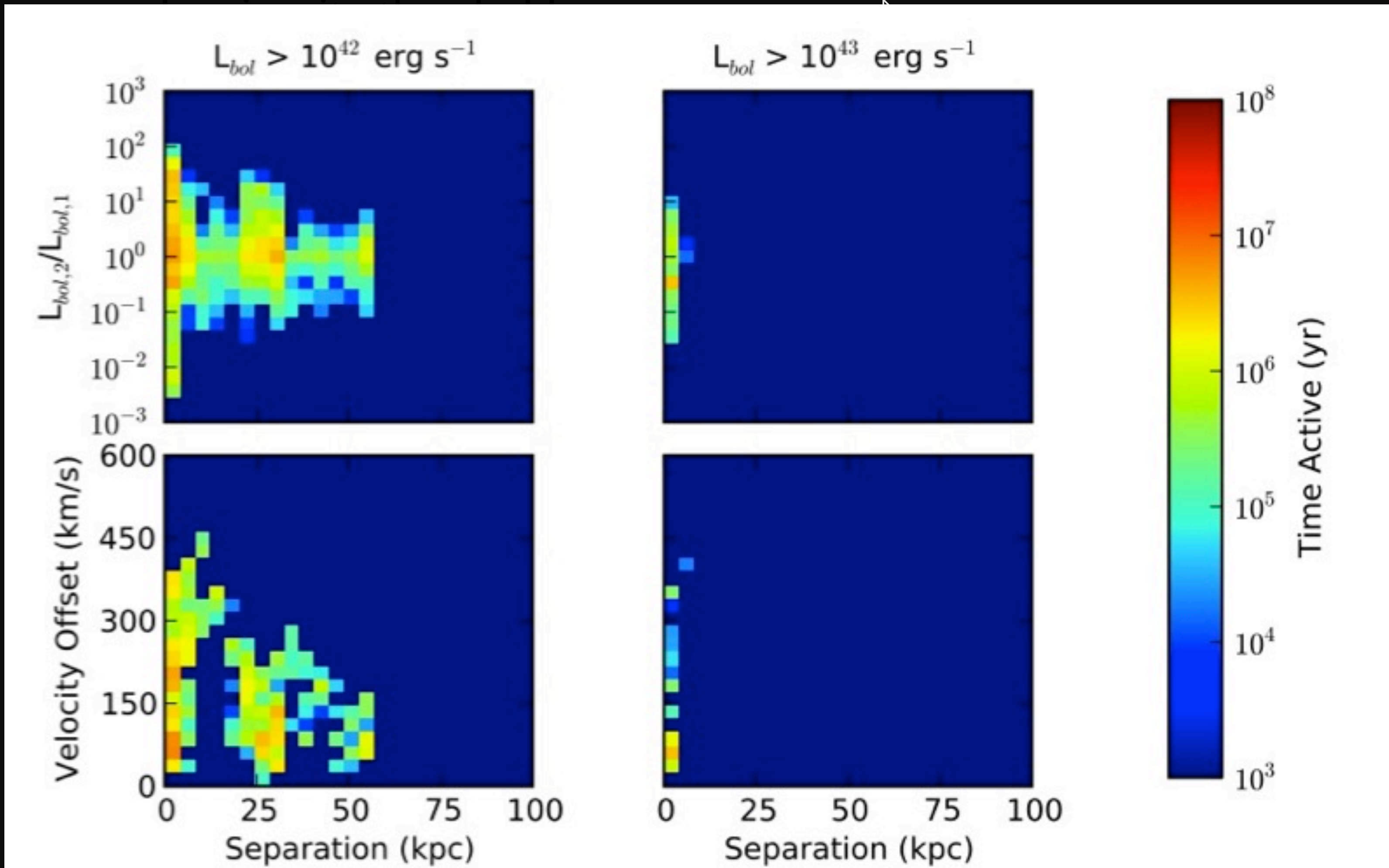
Intermediate threshold: apocenter – where MBHs spend most of their time, or pericenter – where most active

High threshold: probes times when AGN accretion is triggered by merger dynamics

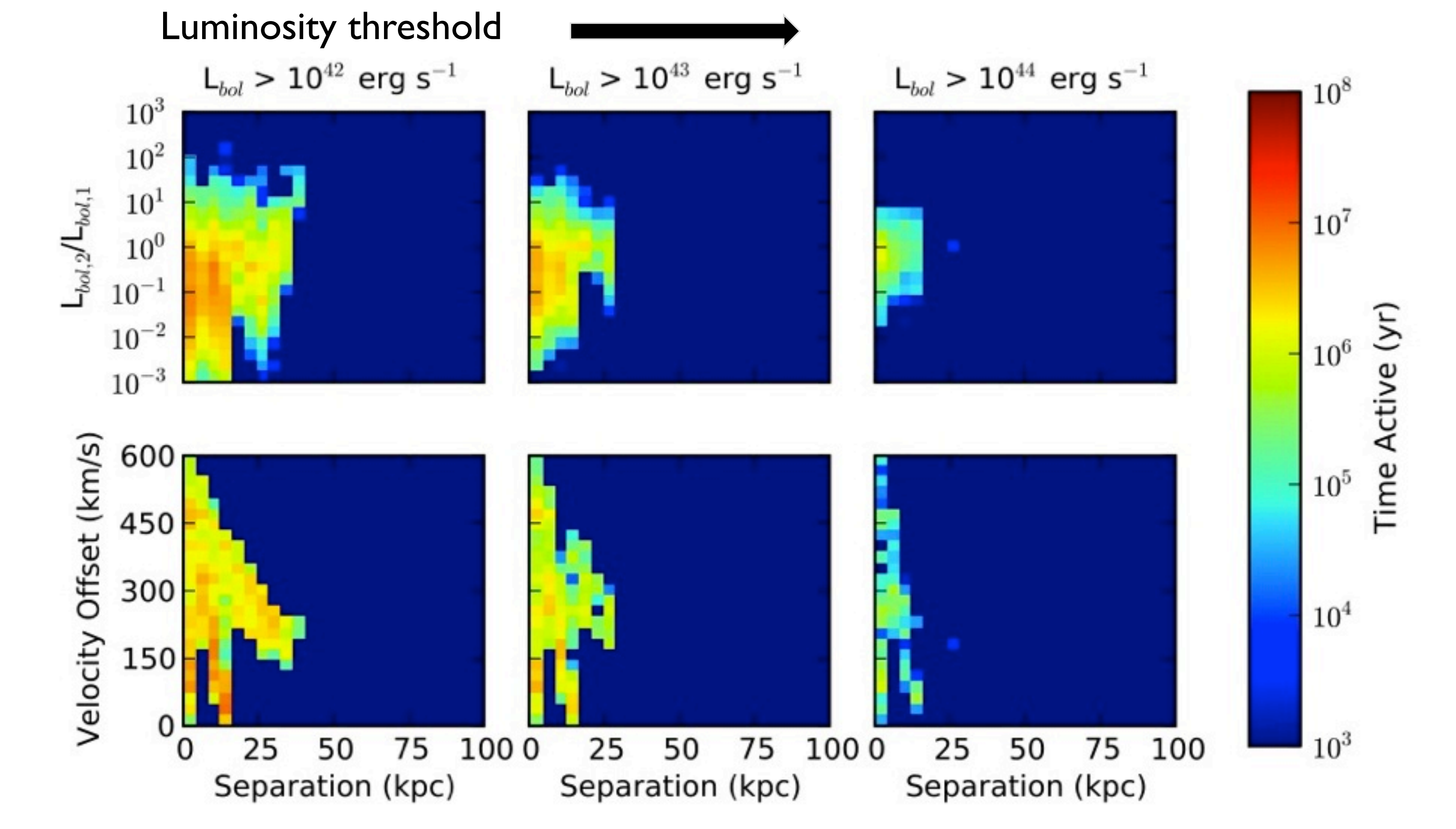
1:4 Spiral-Spiral Merger



1:10 Spiral-Spiral Merger



1:2 Elliptical-Spiral Merger



Timescales – 1:2 Coplanar Spiral-Spiral

Bolometric luminosity	BH_1	BH_2	Both AGN - Dual
10^{42} erg/s	1047 Myr	876 Myr	703 Myr
10^{43} erg/s	286 Myr	207 Myr	69 Myr
10^{44} erg/s	36 Myr	35 Myr	12 Myr

A realistic threshold cuts out most of the dual emission

Bolometric luminosity	[2-10] kev luminosity	B-band luminosity
10^{42} erg/s	10^{41} erg/s	4×10^{40} erg/s
10^{43} erg/s	10^{42} erg/s	7×10^{41} erg/s
10^{44} erg/s	6×10^{42} erg/s	10^{43} erg/s

Much of the dual activity is difficult to detect

Timescales – 1:2 Coplanar Spiral-Spiral

Bolometric luminosity	BH_1	BH_2	Both AGN - Dual
10^{42} erg/s	1047 Myr	876 Myr	703 Myr
10^{43} erg/s	286 Myr	207 Myr	69 Myr
10^{44} erg/s	36 Myr	35 Myr	12 Myr

A realistic threshold cuts out most of the dual emission

	Dual Timescale	Dual Fraction
No cutoff	12 Myr	19.2%
d > 1 kpc	10 Myr	16.5%
d > 10 kpc	0.06 Myr	0.1%
v > 150 km/s	3 Myr	4.8%

Observational limitations reduce dual emission further to ≤ a few %, in rough agreement with optical survey results

		BHs Alone		Duals	Observational Limitations		
Simulation	Threshold	BH_1	BH_2	Dual AGN	$d > 1$ kpc (imaging)	$d > 10$ kpc (imaging)	$\Delta v > 150$ km s^{-1} (spectroscopy)
1:2 Spiral-Spiral	$L_{bol} > L_{42}$	77.8	64.9	57.6	53.4	43.9	35.7
	$L_{bol} > L_{43}$	21.2	15.3	16.3	13.5	5.61	8.23
	$L_{bol} > L_{44}$	2.68	2.61	19.2	16.5	0.10	4.76
	$f_{Edd} > 0.005$	59.9	63.0	49.3	45.9	36.8	31.1
	$f_{Edd} > 0.05$	11.1	14.2	13.8	11.8	3.99	6.51
	$f_{Edd} > 0.5$	1.47	2.26	18.5	17.2	0.07	3.44
1:4 Spiral-Spiral	$L_{bol} > L_{42}$	74.9	53.9	47.7	44.2	38.3	27.1
	$L_{bol} > L_{43}$	21.3	11.7	11.0	7.57	3.75	6.09
	$L_{bol} > L_{44}$	1.80	2.47	2.90	1.25	0	1.36
	$f_{Edd} > 0.005$	56.7	66.9	47.8	45.1	39.5	28.7
	$f_{Edd} > 0.05$	10.8	17.3	8.95	7.03	4.01	5.18
	$f_{Edd} > 0.5$	0.70	2.94	1.28	0.67	0	0.56

Fraction of total simulation time that each BH accretes at the given threshold

In 1:2 case dual fraction increases at the highest observability thresholds – simultaneous triggered accretion

Strongest triggering occurs at small separations and velocity offsets - difficult to observe

In 1:4 case ... lowering the dual fraction

Dual AGN Summary

- Dual fraction generally under a few % for observable conditions, in agreement with observations
- AGN activity increases as the galaxy separation decreases, also in agreement with observations
- Hard X-ray surveys circumvent obscuration, may find higher dual fraction because they probe stronger AGN
- No obscuration or dilution from star formation included in observability test

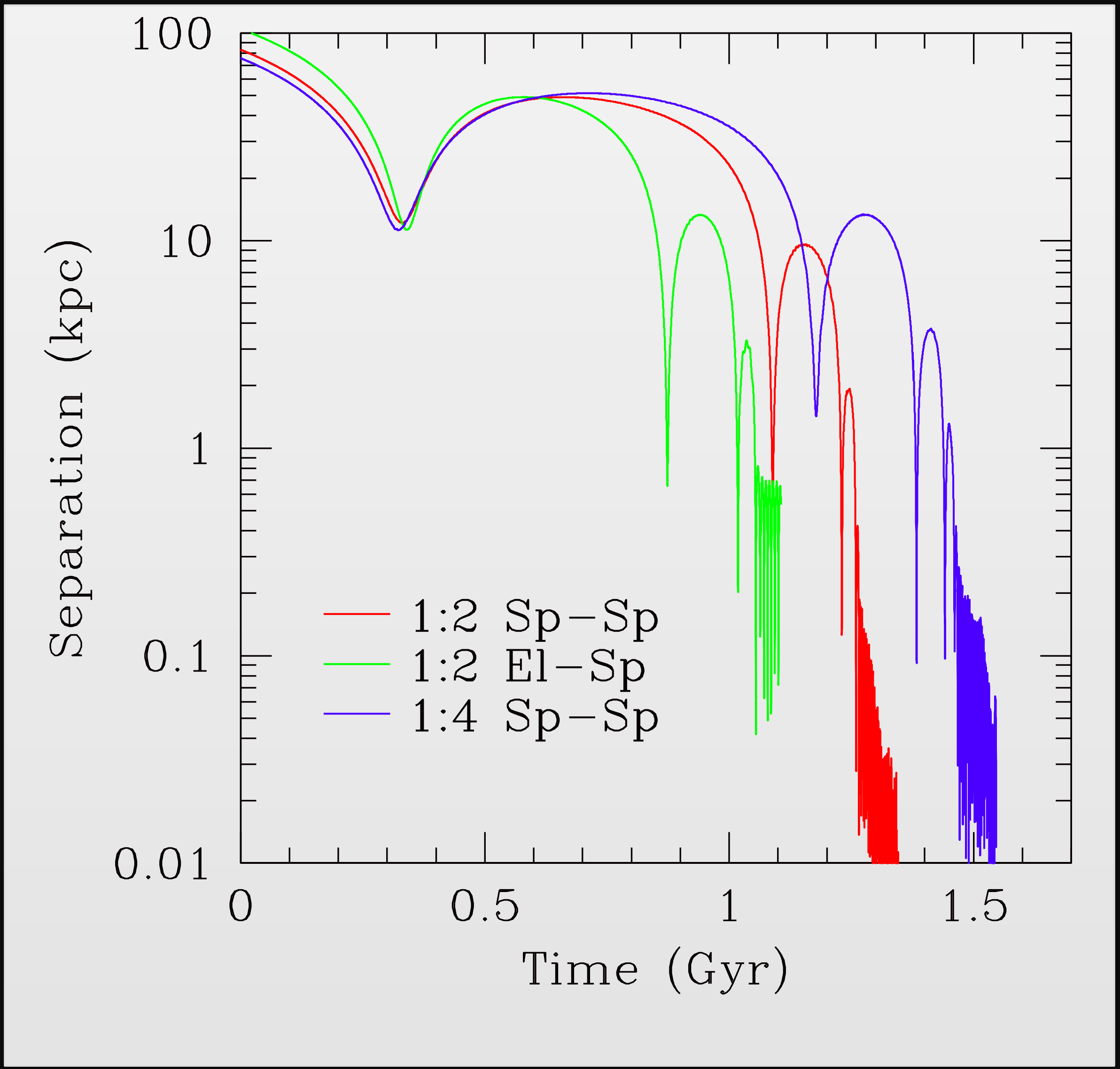
The key to successful pairing

Form a dense stellar cusp that will resist stripping and deliver the MBH to the center of the merger remnant

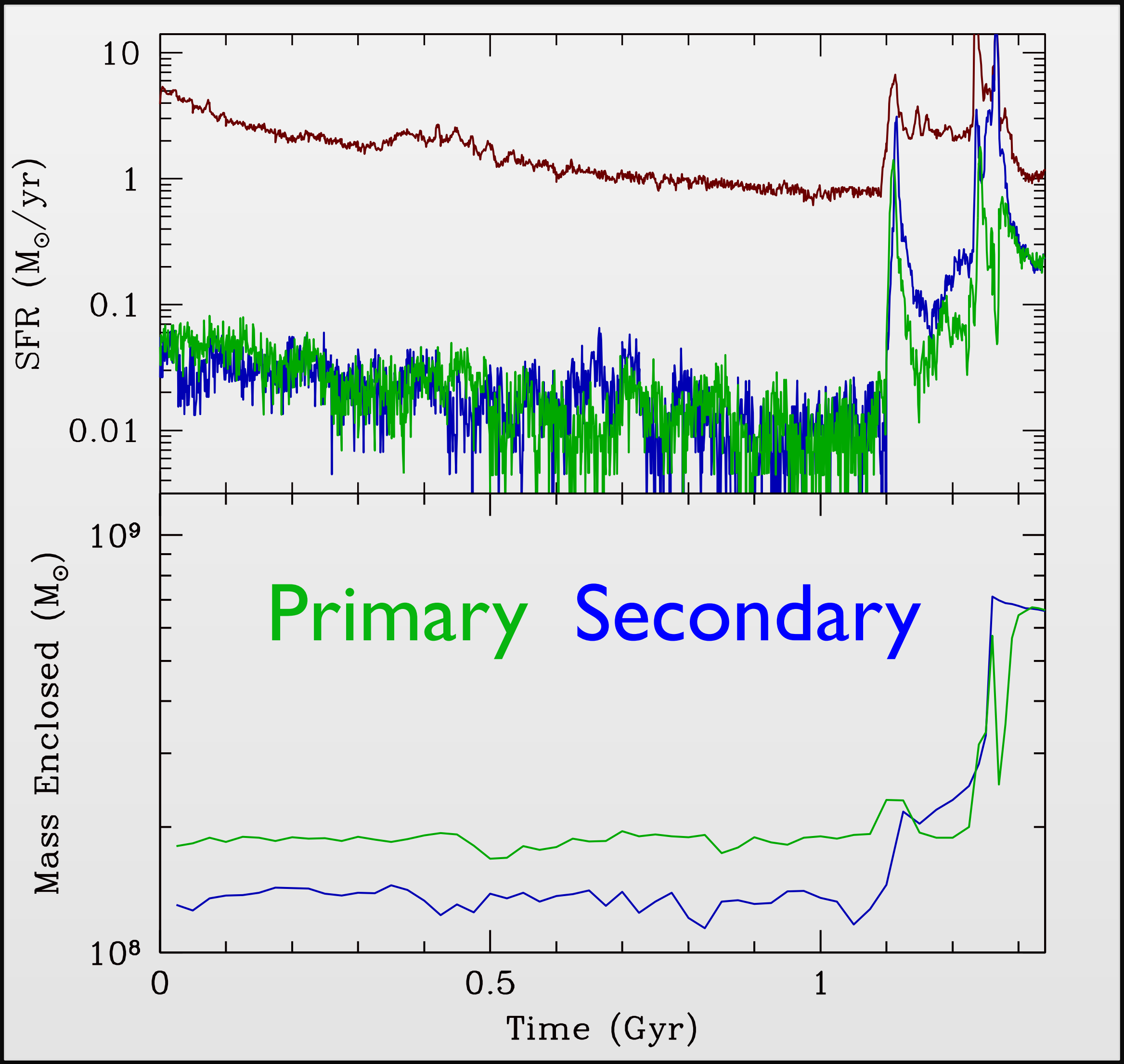
A gas rich secondary galaxy is important!

Pairing Results

- Spiral-spiral simulations end with BHs at separations of tens of parsecs – binary will form soon
- More concentrated elliptical disrupts secondary at hundreds of parsecs – binary should form within a few hundred Myr



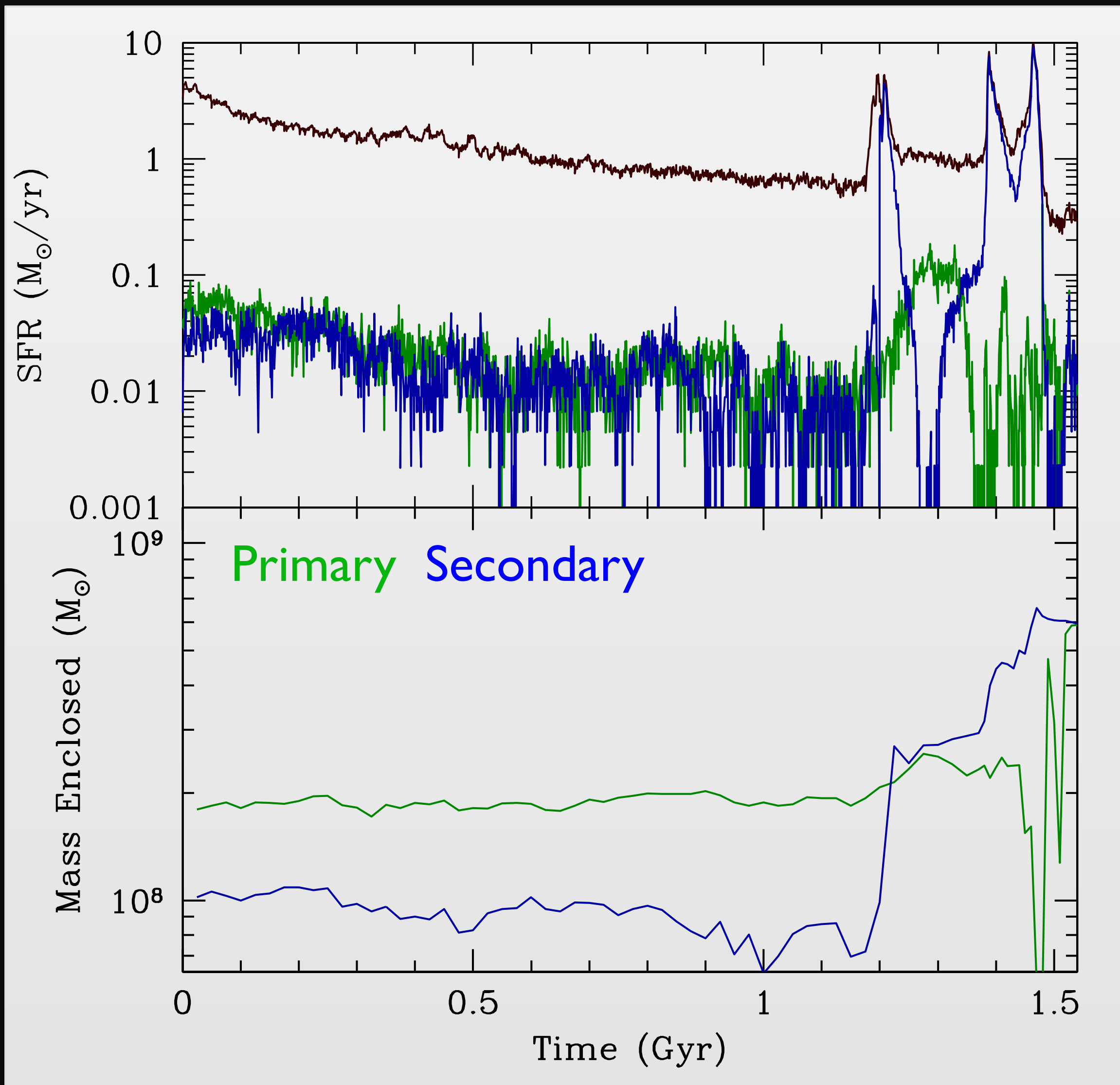
1:2 Nucleus Disruption



SFR and mass enclosed in central 100 pc near each BH

- Strong central SF in both galaxies triggered after pericenter passages
- Both galaxies build up a similar amount of mass on small scales, but companion has slightly more
- At the fourth pericenter passage, the primary nucleus is disrupted and the primary SMBH is left orbiting around the secondary nucleus and BH

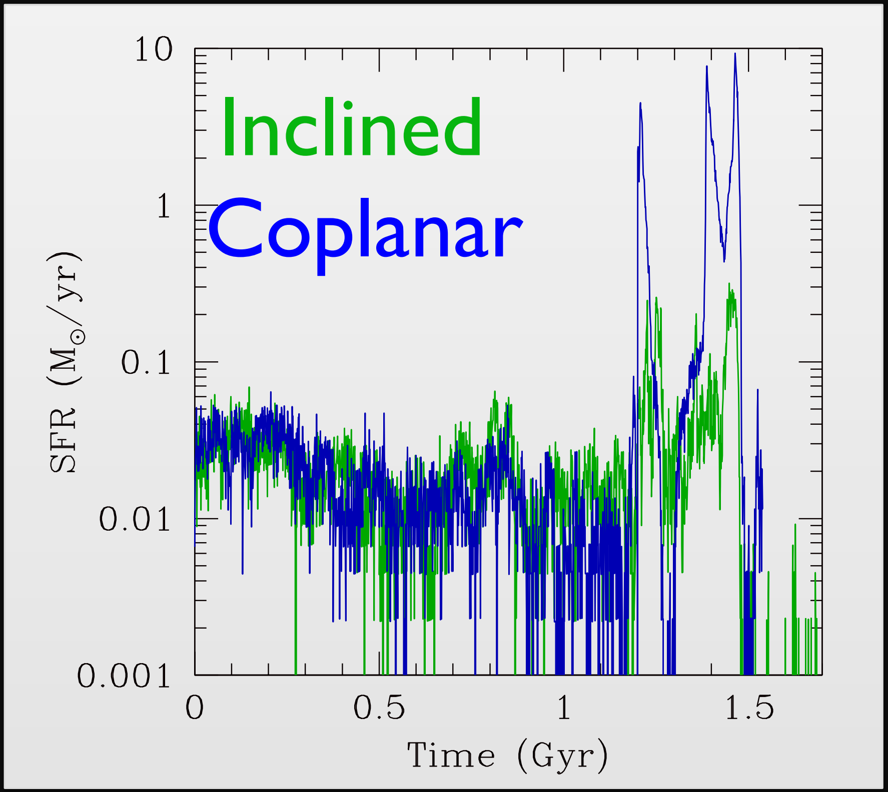
1:4 Nucleus Disruption



SFR and mass enclosed in central 100 pc near each BH

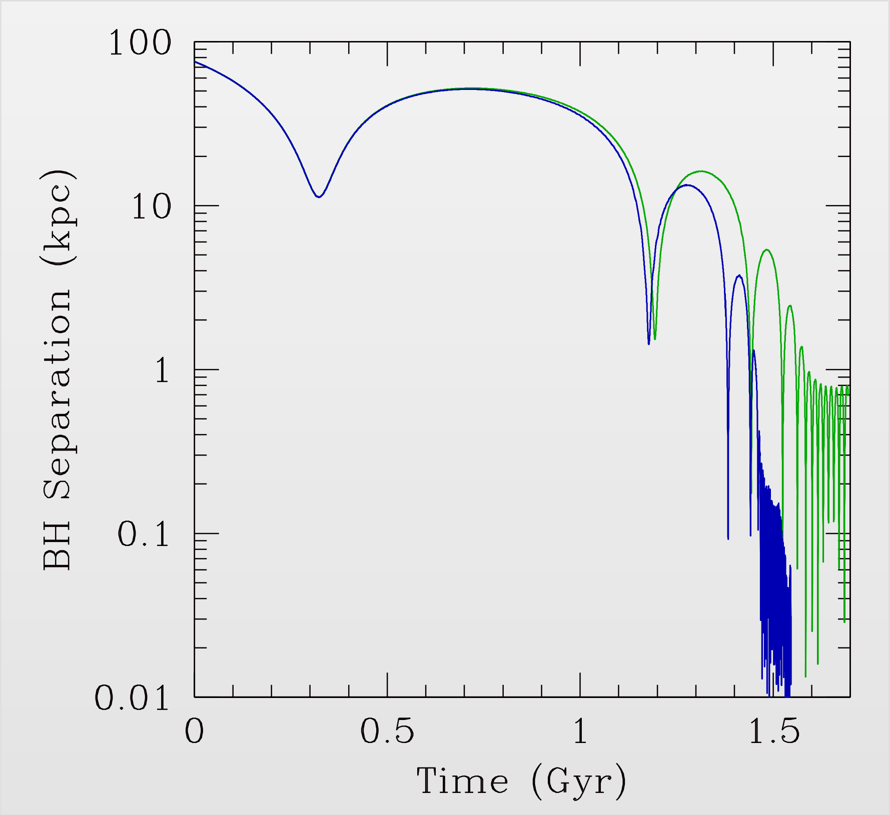
- Weaker SFR in primary, less perturbed by smaller companion
- Stronger central SF in the companion – almost all of the global SF occurs there
- Companion builds up dense cusp whereas primary does not
- Primary nucleus again disrupted, but `easier' than in the 1:2 merger

Inclined 1:4 merger: Insufficient Star Formation



Less central SF in the secondary leads to disruption at ~kpc separations rather than efficient pairing

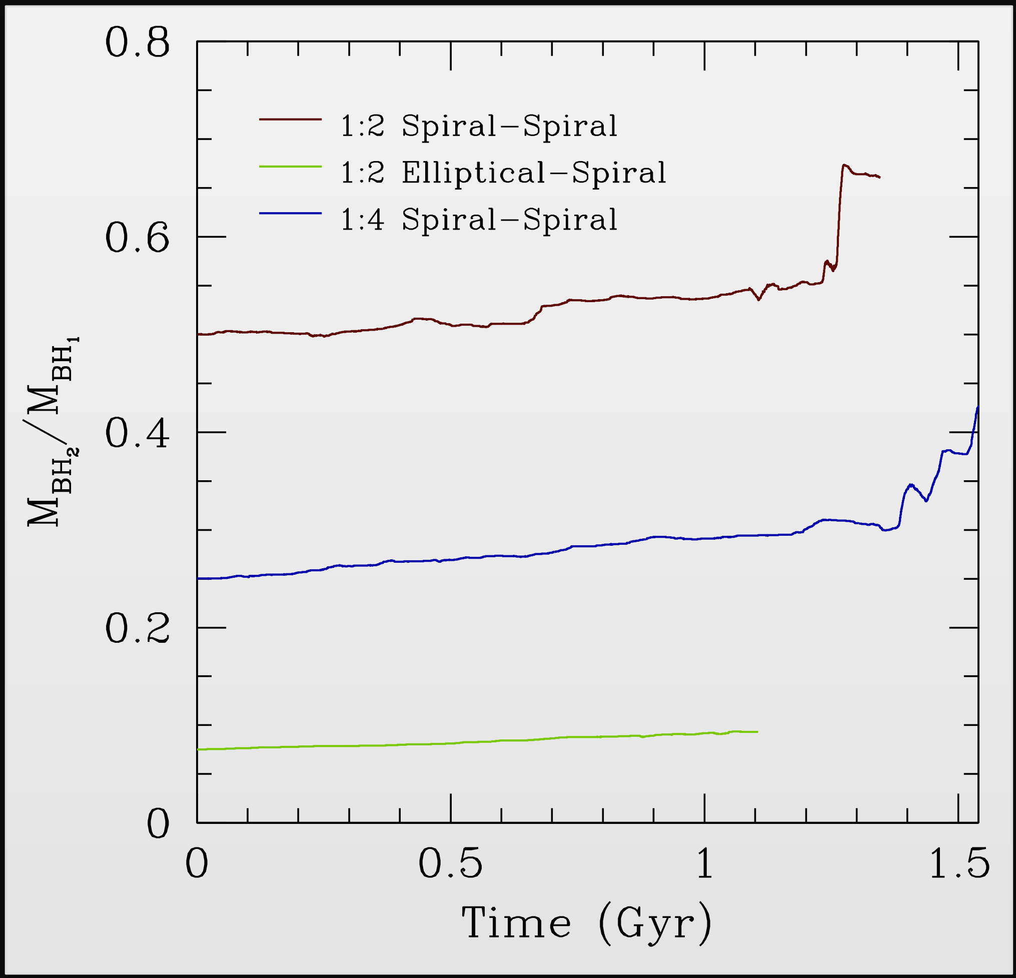
Weaker gas inflows and early disruption lead to significantly less dual AGN activity than in the coplanar merger



Relative Accretion

- Strong gas inflows in the secondary galaxy drive stronger accretion onto the secondary BH

- BH mass ratio increases significantly throughout the merger in coplanar mergers
  - 1:2 Sp-Sp: 32%
  - 1:2 El-Sp: 24%
  - 1:4 Sp-Sp: 70%



Summary

- Star formation and BH activity peak late in galaxy mergers – much of the dual AGN activity occurs at small separations and velocity offsets, making it difficult to detect (Van Wassenhove, MV et al. 2012)

- Central star formation is key to efficient pairing in unequal mass mergers (Callegari et al. 2009)

- In some situations, the secondary nucleus may disrupt the primary, resulting in a ‘nuclear coup’