Black holes in galaxy mergers

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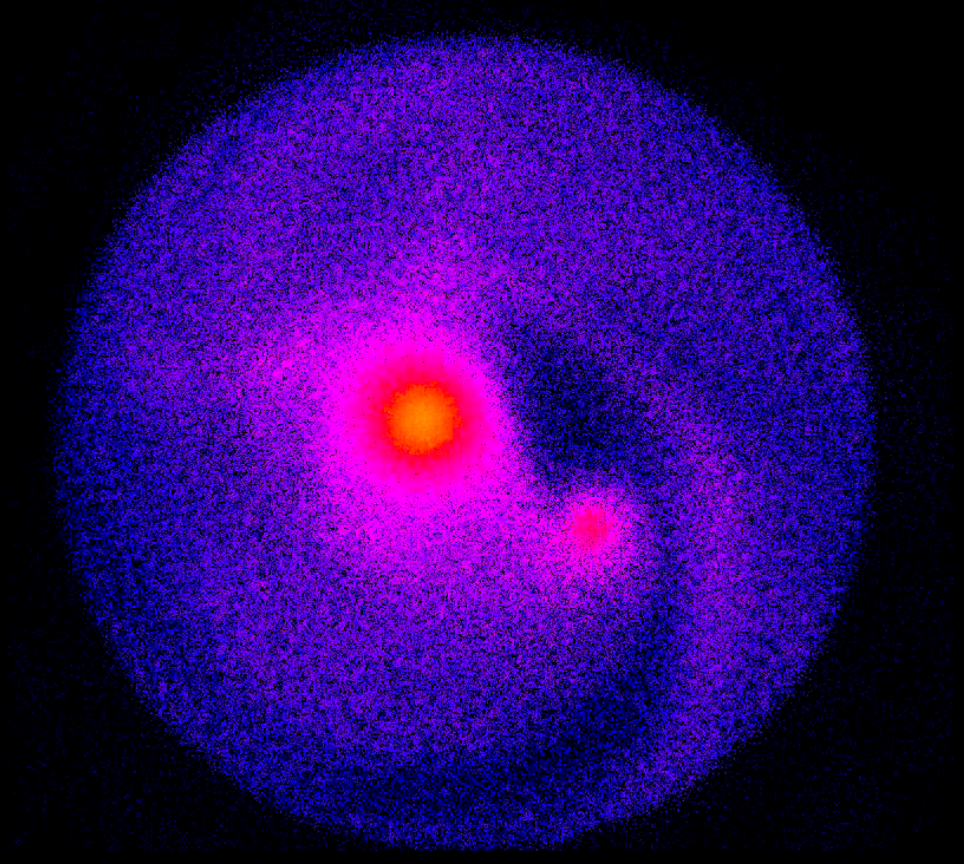
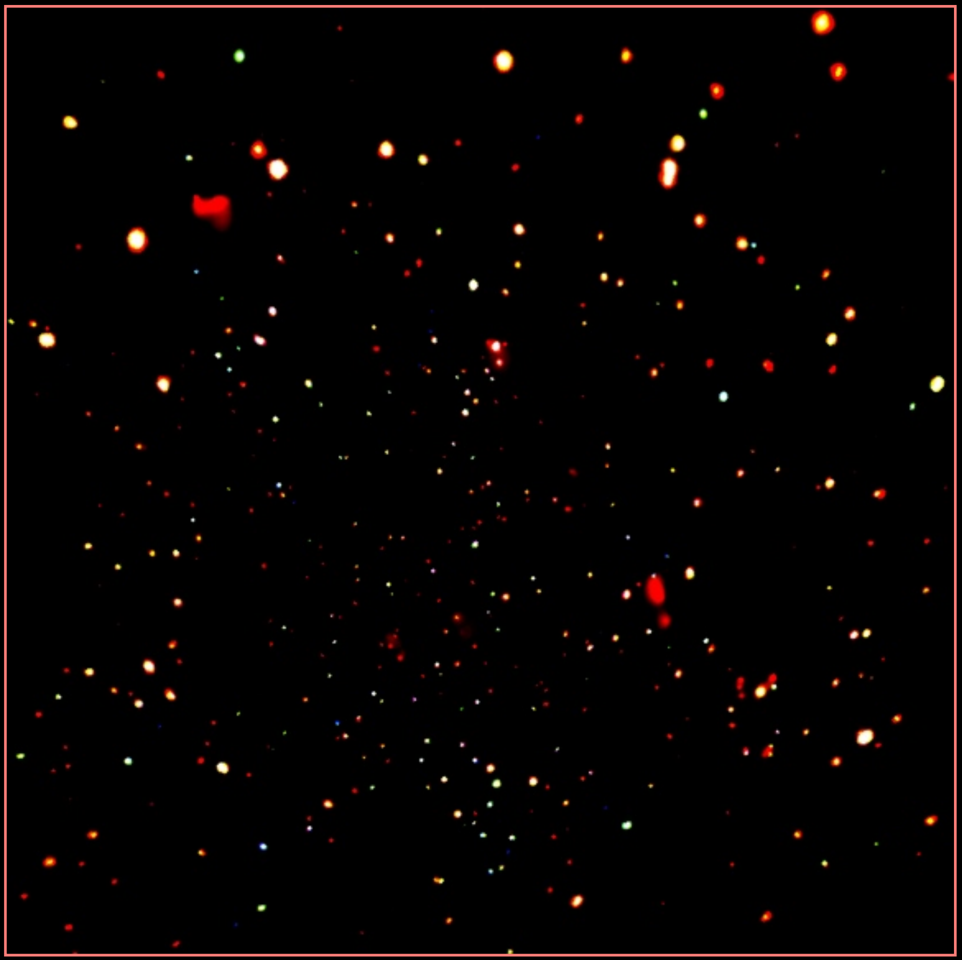


Shiny black holes out there....

Hubble Deep Field

all galaxies



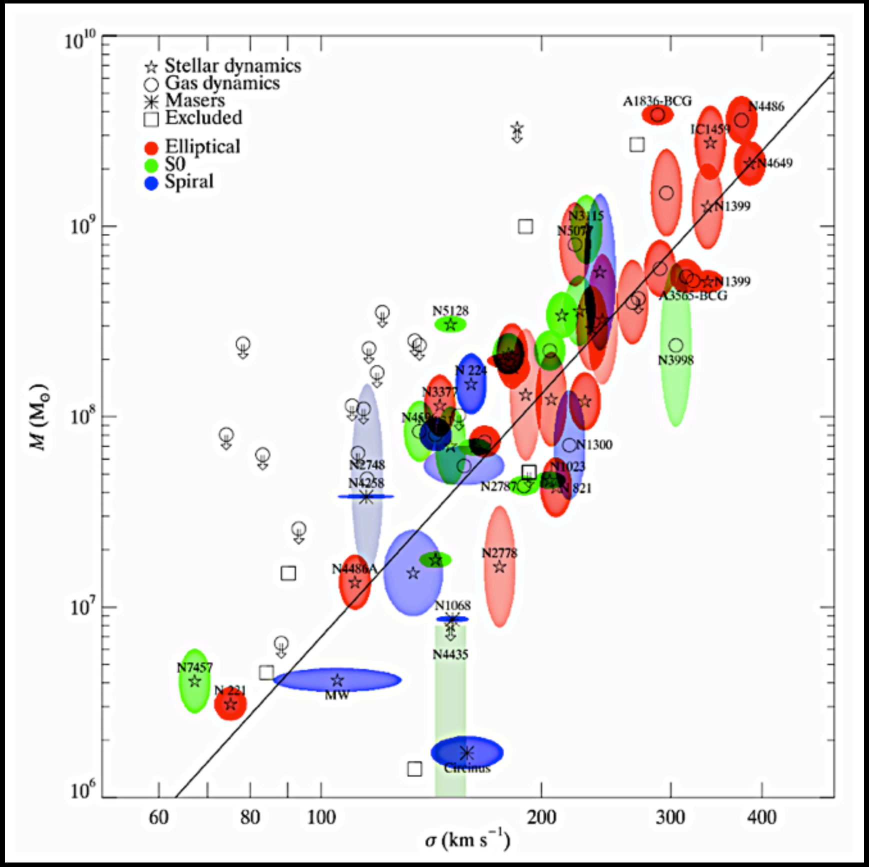
Chandra Deep Field

active galaxies

black holes

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

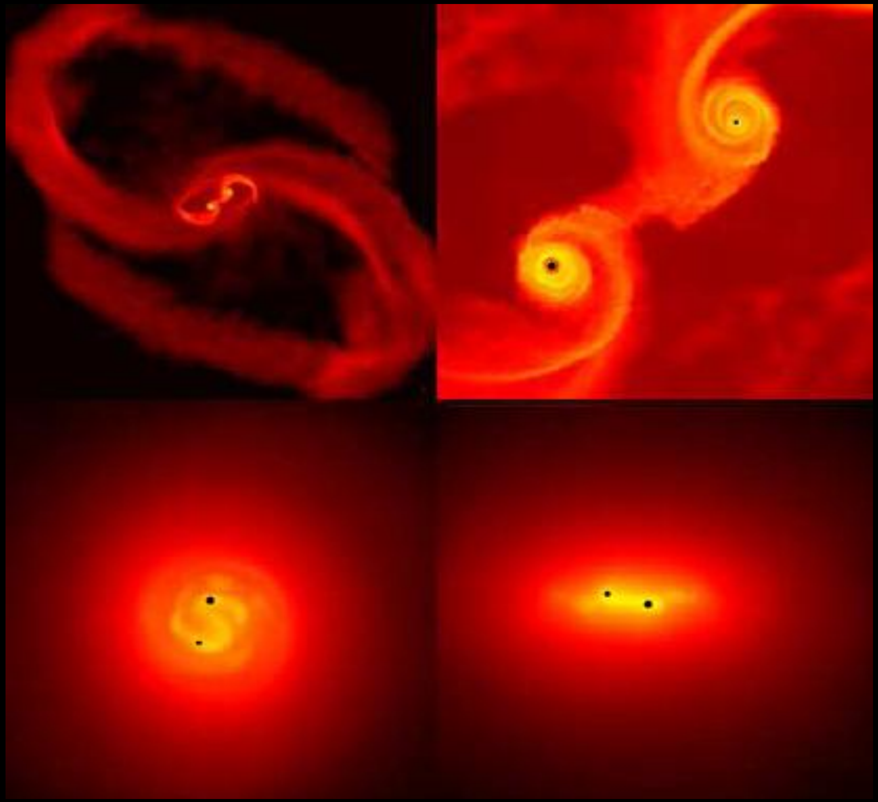


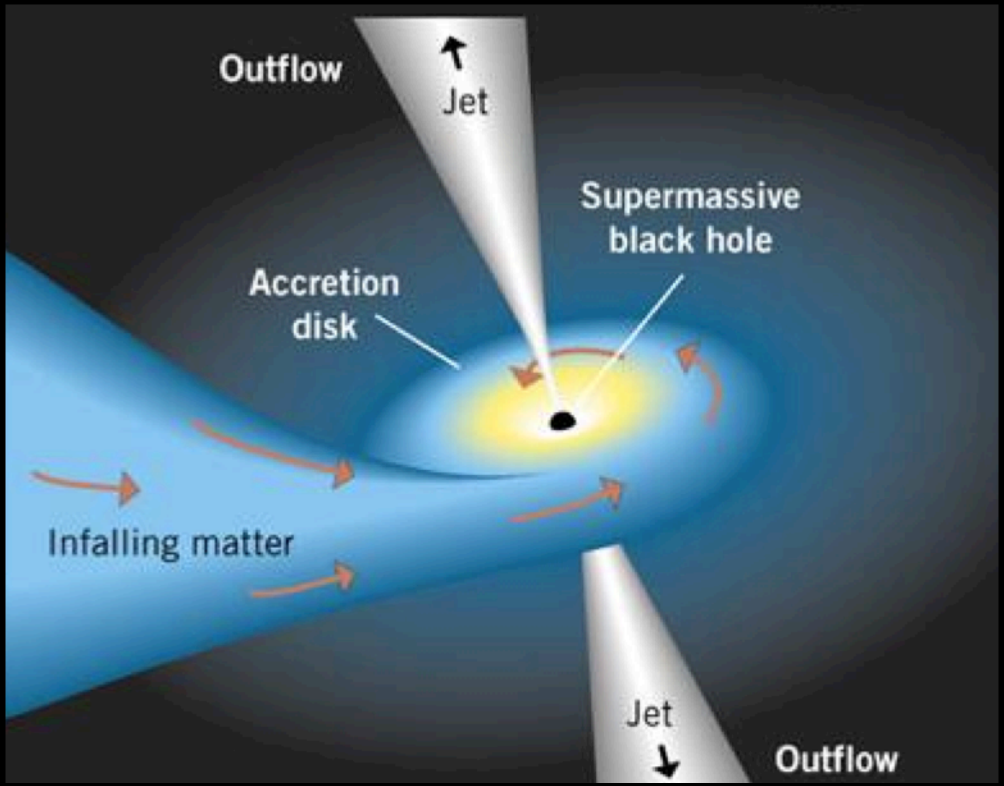
from Gultekin et al. 2009

Growing MBHs

How do MBHs grow to become supermassive?

BH-BH mergers and gas accretion

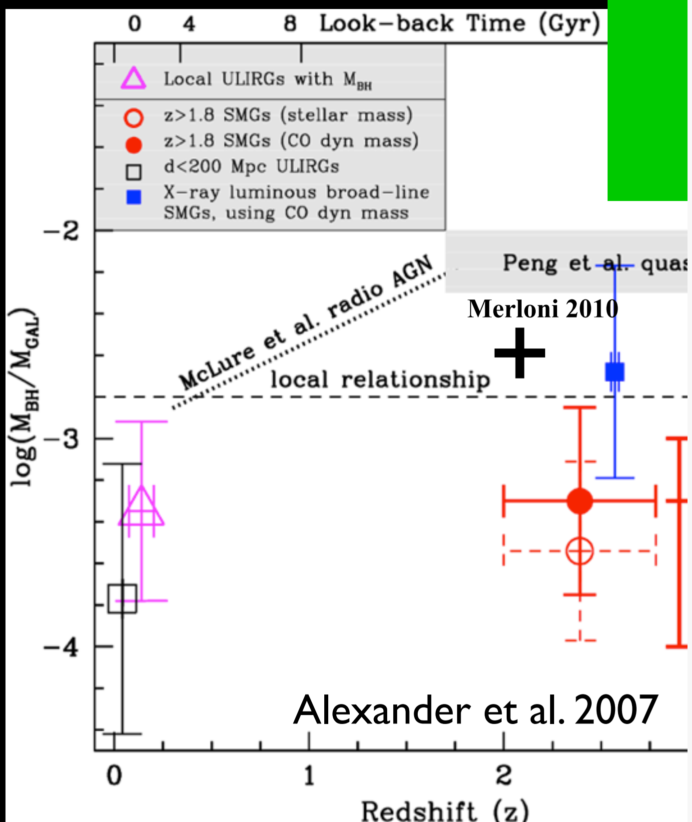


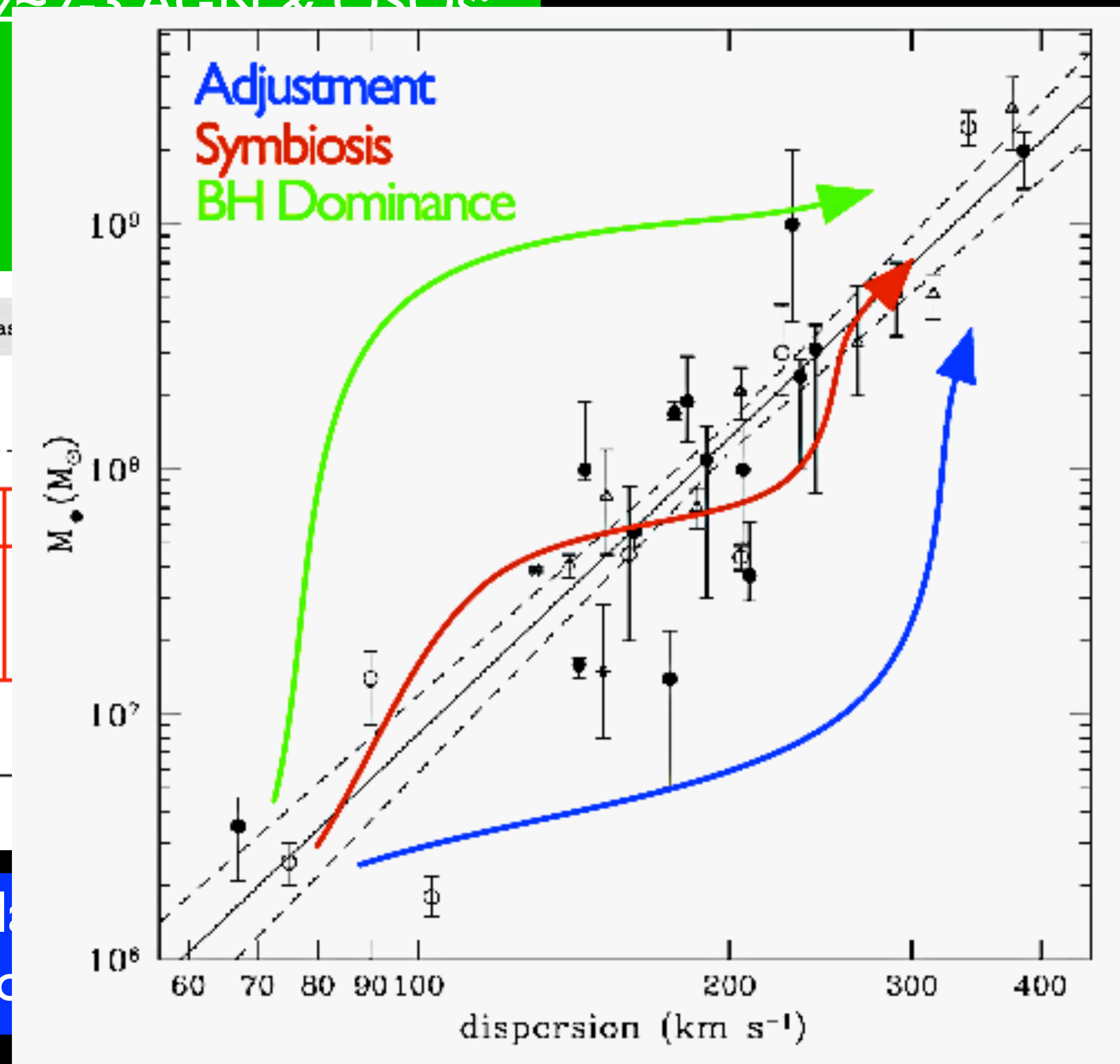


Need to probe *both* processes to understand MBH growth and co-evolution with host

JWST/ALMA/Fermi/Chandra/ATHENA etc can observe ***active*** MBHs and their *hosts* up to high-z

z~2-3 AGN & QSOs:

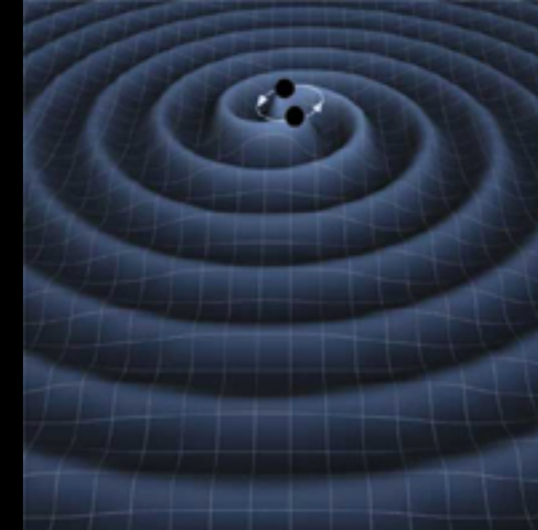


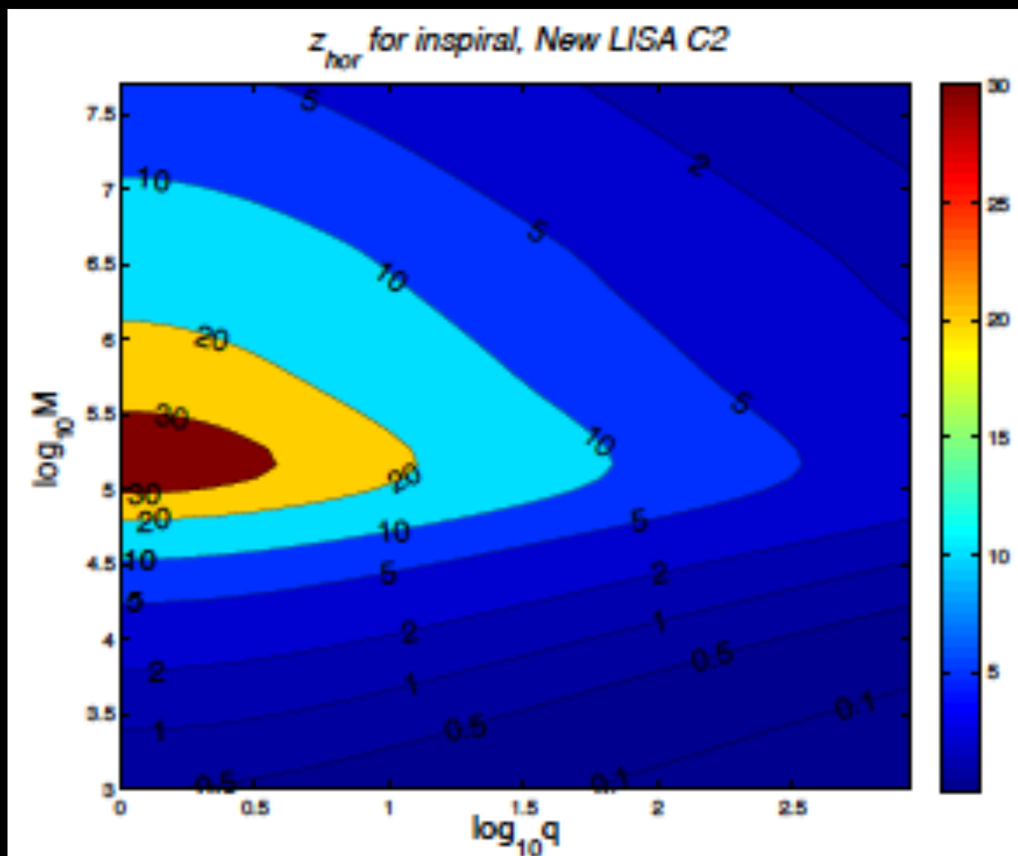


SCUBA gal

MBH lags the stellar gro

The new-LISA ESA mission can ‘observe’ ***merging* MBHs** up to high-z via gravitational waves





Maximum redshift that allows secure detection (SNR>10) of a given MBH-MBH binary merger (courtesy of E. Berti)

A multi“messenger” effort:

GWs: demography of “black” MBHs as a function of cosmic epoch

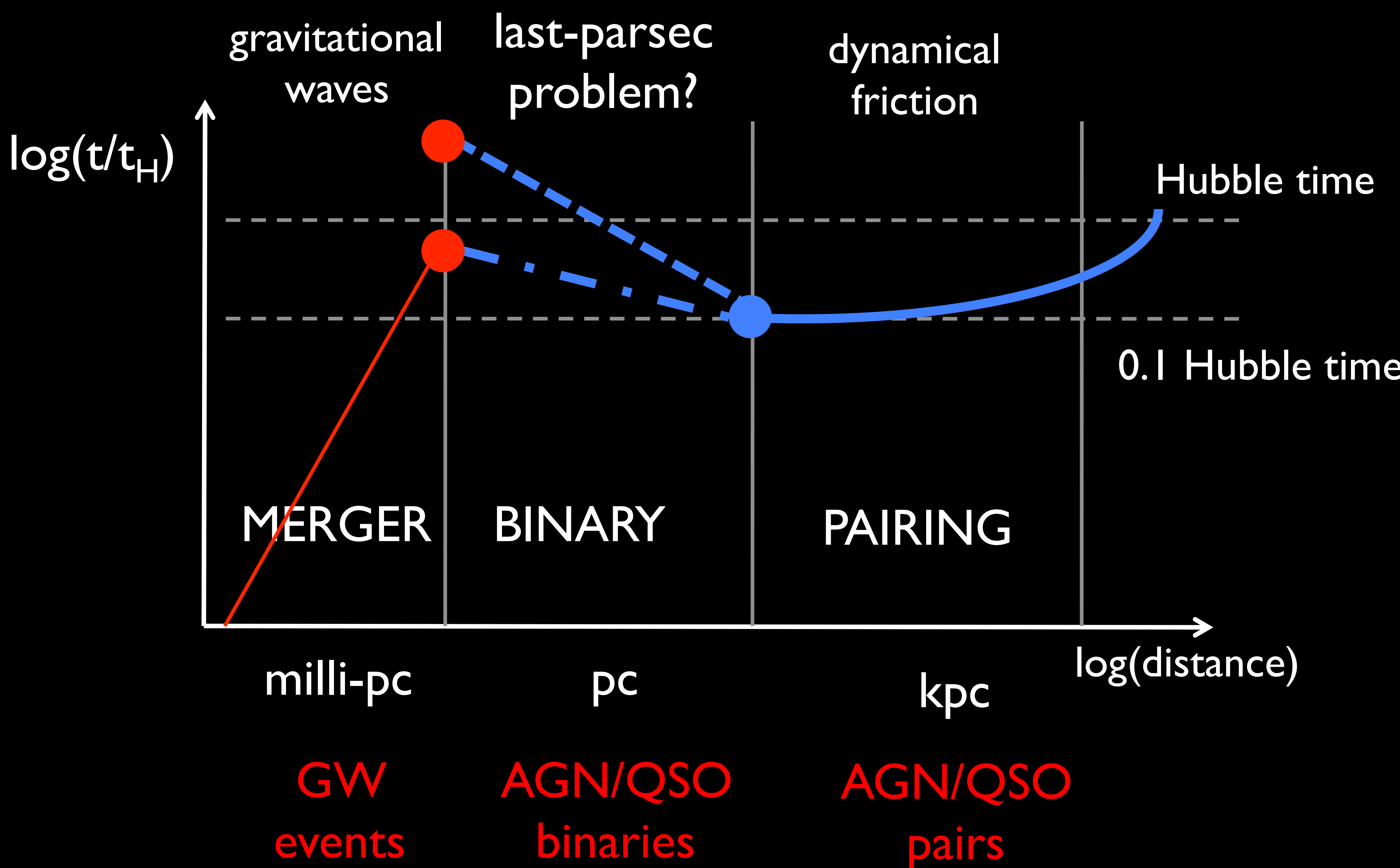
Measure: masses, spins

EM radiation: demography of “active” MBHs as a function of cosmic epoch

Measure: luminosity, jets, host properties, spins

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 and gravity waves


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

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: which galaxies host MBHs

Semi-analytical models

➔ cosmic evolution ➔ statistical samples

GW events

AGN/QSO binaries

AGN/QSO pairs

MBHs: small scale dynamics

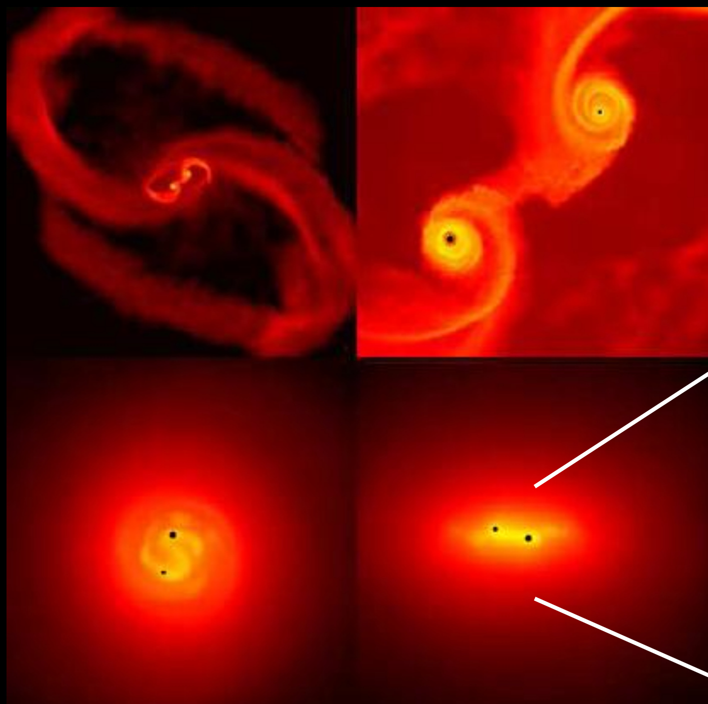
Final parsec problem – dynamical friction from a stellar background not enough to move past pc separations (Milosavljevic & Merritt 2000)

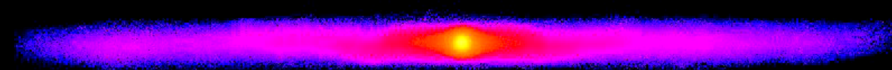
Gas important to push orbital decay below the parsec level (e.g., Mayer et al. 2007, Dotti et al. 2009)

Binary AGN/QSOS and GW events to test our theoretical understanding

MBHs in merger remnants

Dotti et al. 2009





Re-simulate the final product of a galaxy merger – a circumnuclear disc – at high resolution

MBHs in merger remnants

Dotti et al. 2009

Central MBH:
$M_{BH} = 4 \times 10^6\, M_\odot$

Gas disc (Mestel):
$M_{Disc} = 10^8\, M_\odot$

$R_{Disc} = 100$ pc

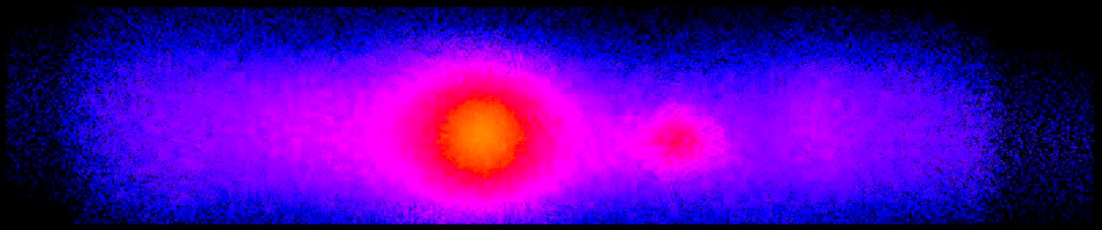
Stellar bulge (Plummer):

$M_{Bulge} = 7 \times 10^8\, M_\odot$

$a = 55$ pc

Secondary MBH:
$M_{BH} = 4 \times 10^6\, M_\odot$
$e \approx 0.7$
co- or counter- rotating

spatial resolution=0.1 pc



MBHs in merger remnants

Dotti et al. 2009

Adiabatic evolution:

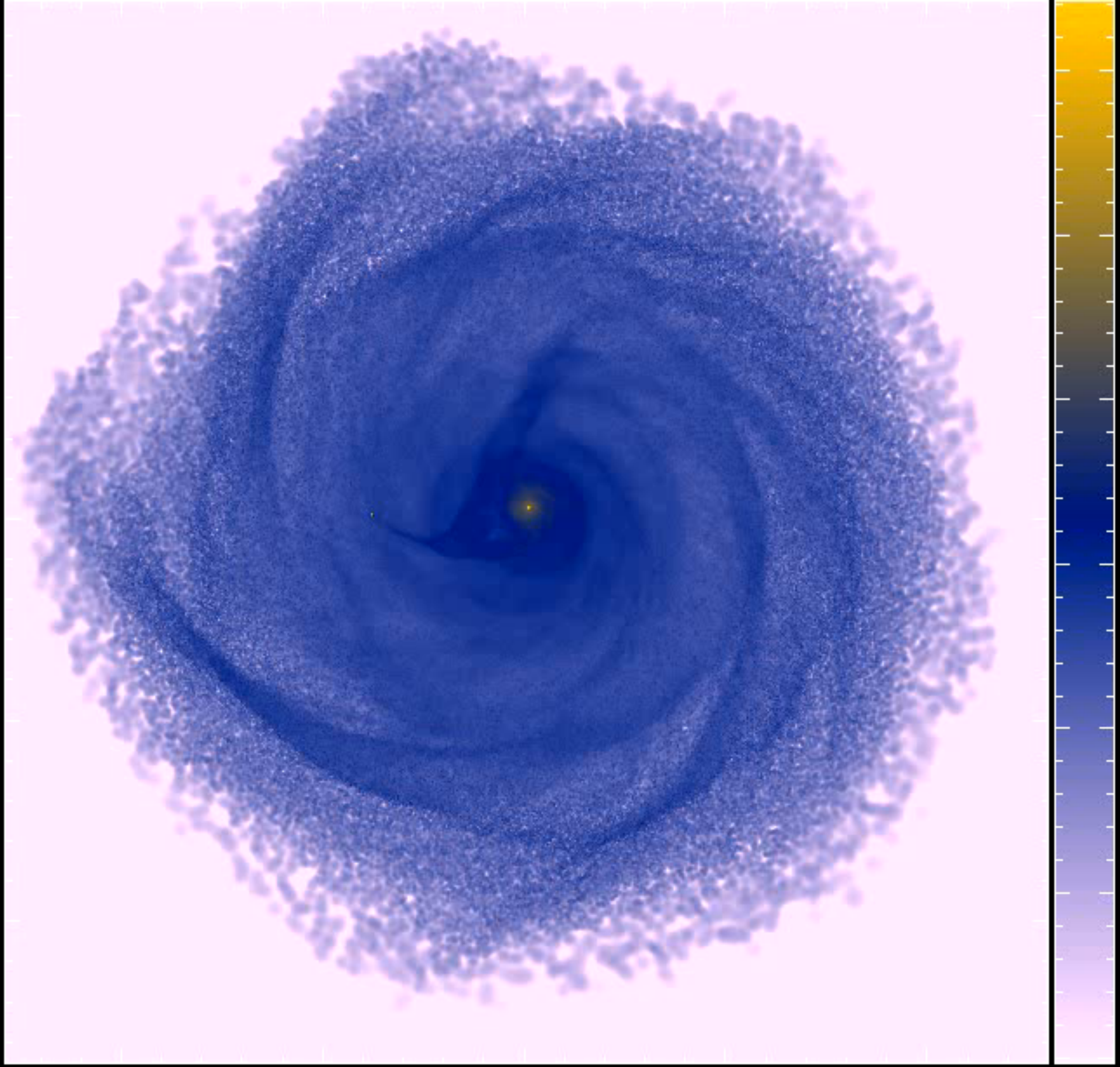
'COLD' disk: $\gamma=7/5$

'HOT' disk: $\gamma=5/3$

Accretion:

- accrete only bound particles, within Bondi radius
- need to resolve the MBHs Bondi radii (h=0.1 pc)

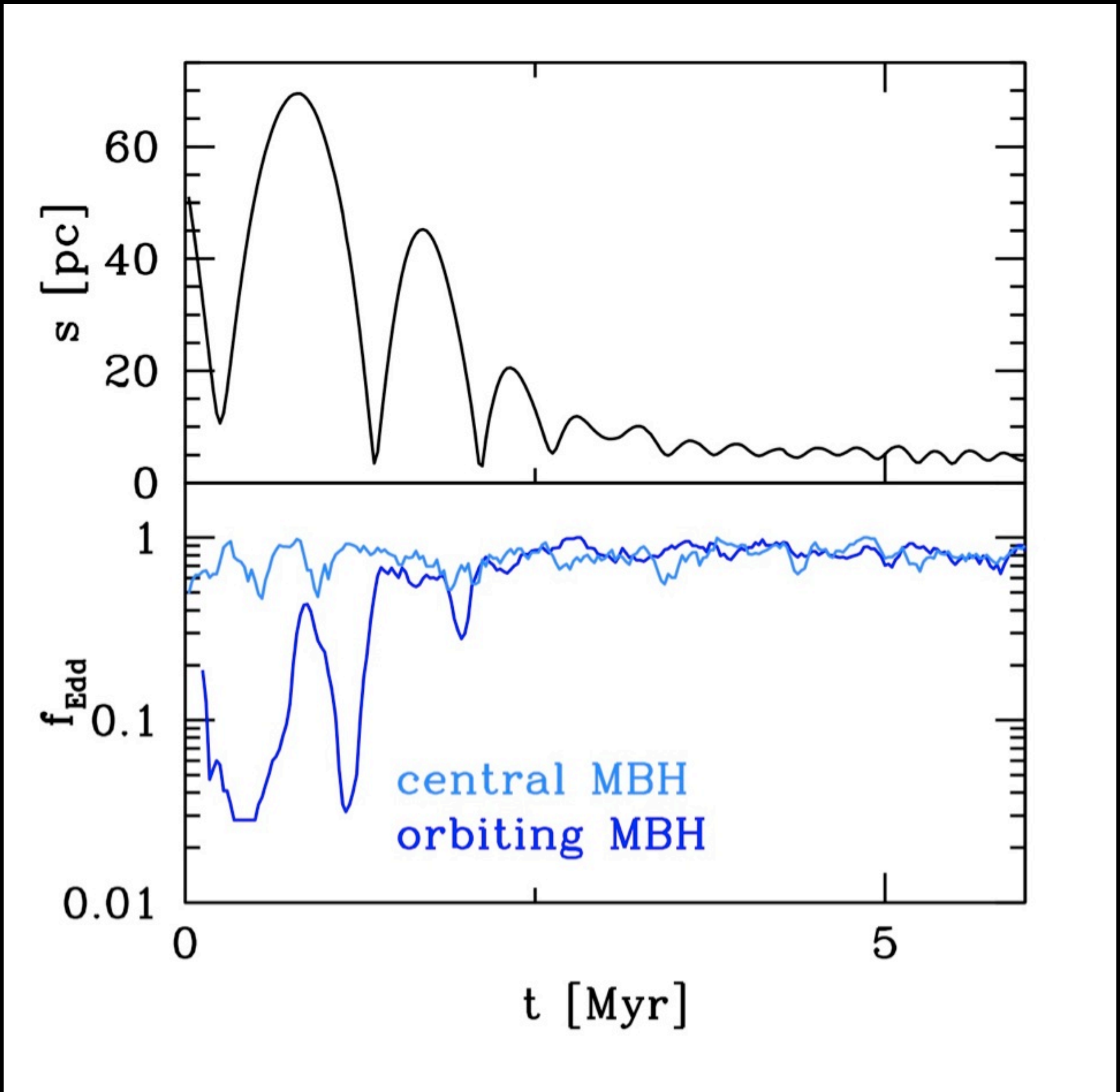
$$\dot{M}_{BH} = \frac{4\pi G^2 M_{BH}^2 \rho}{\left(c_s^2 + v_{rel}^2\right)^{3/2}}$$



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 and gravity waves

Counter-rotating MBH



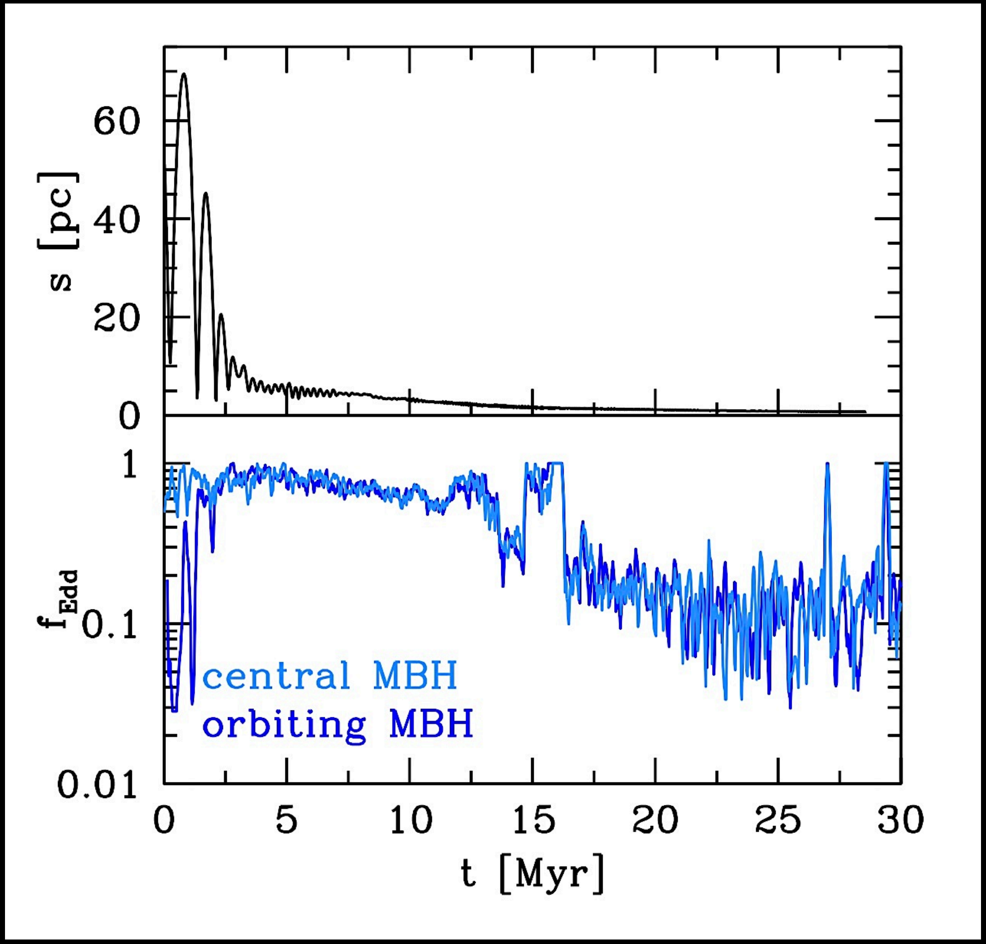
Accretion rate depends on the relative velocity between MBH and gas

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

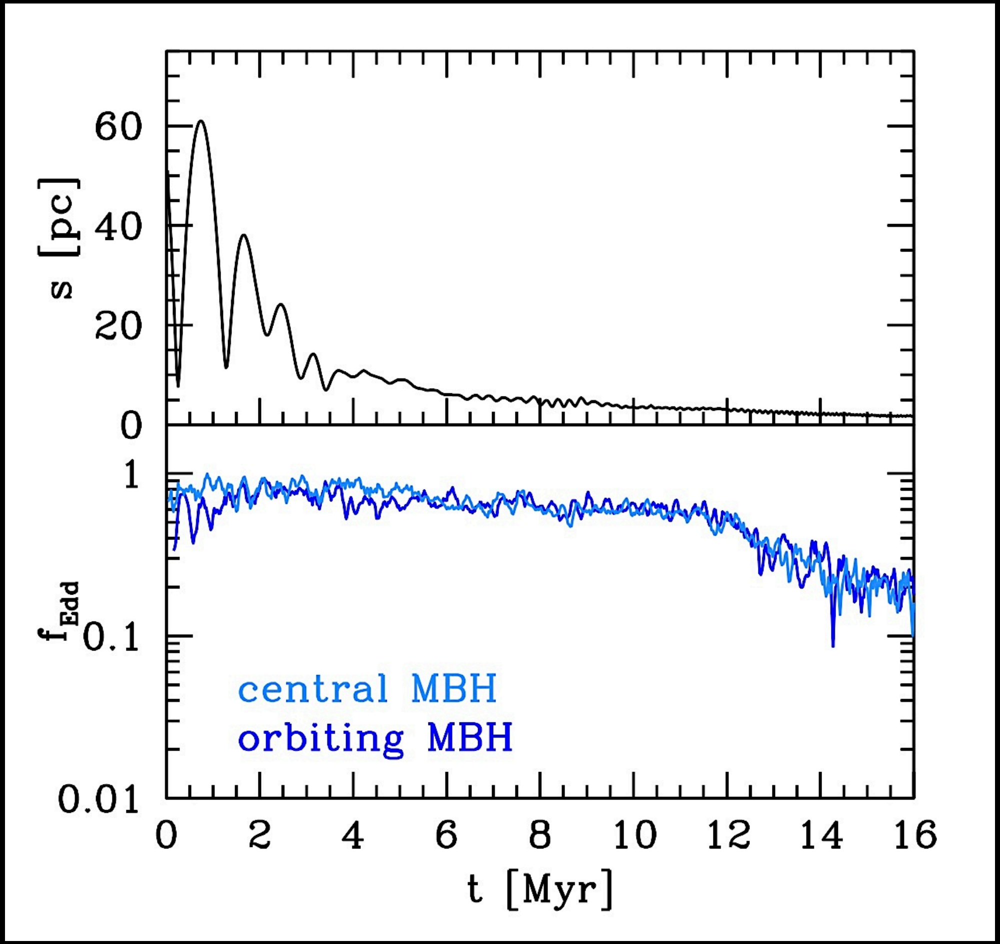
Modulation in the accretion rate of the orbiting MBH

Accretion rate jumps when the MBH starts co-rotating – angular momentum flip

Long term evolution: self-termination



Counter-rotating MBH

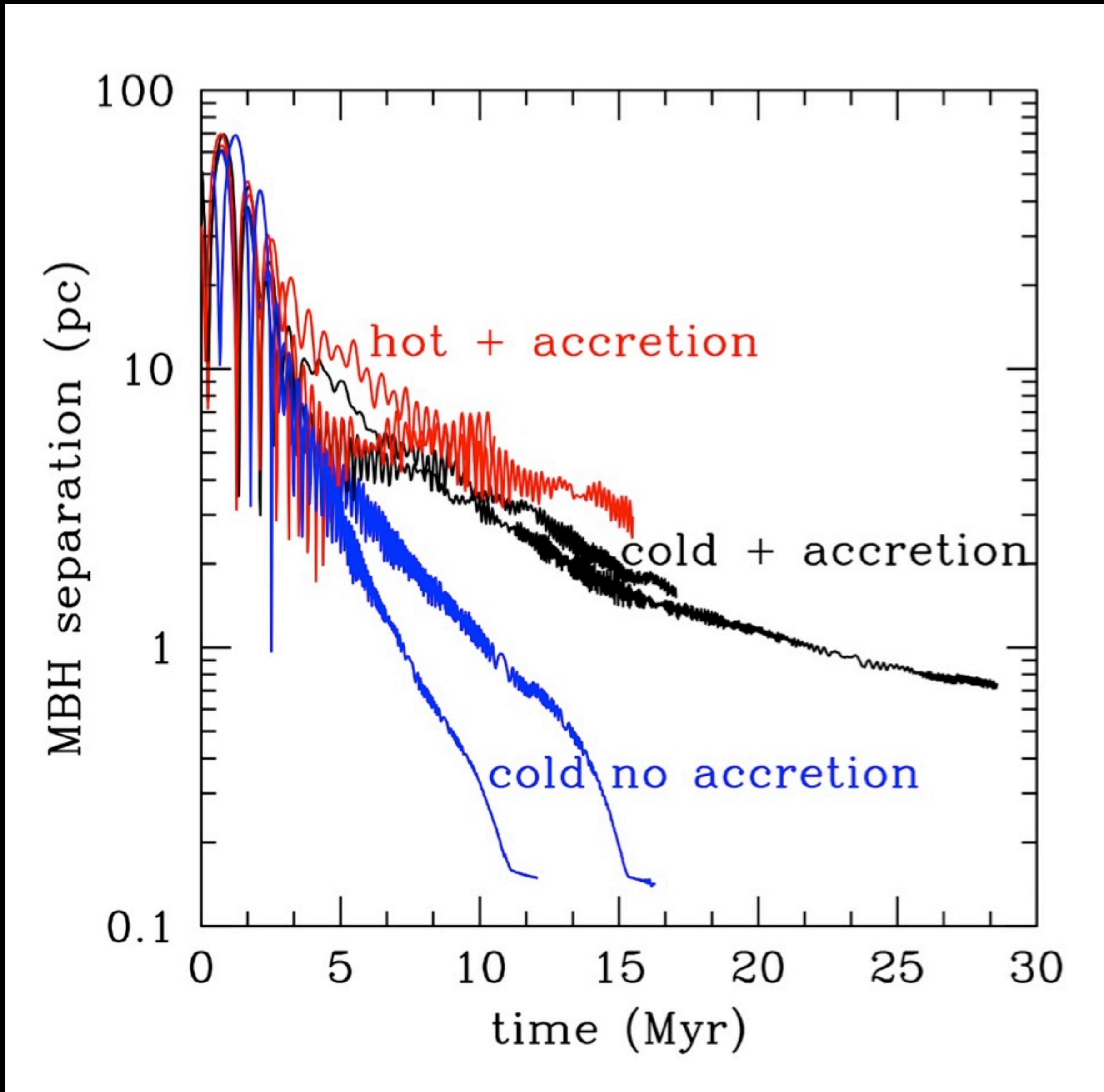


Co-rotating MBH

What we want to know

- When and where MBHs grow most efficiently
  - Need to model *jointly* dynamics, thermodynamics and accretion
- Whether MBHs merge as efficiently as their host galaxies

MBH orbital decay



The orbital evolution depends on the **thermodynamical** properties of the gas

The orbital evolution depends on **accretion**

if MBHs swallow gas, the density decreases

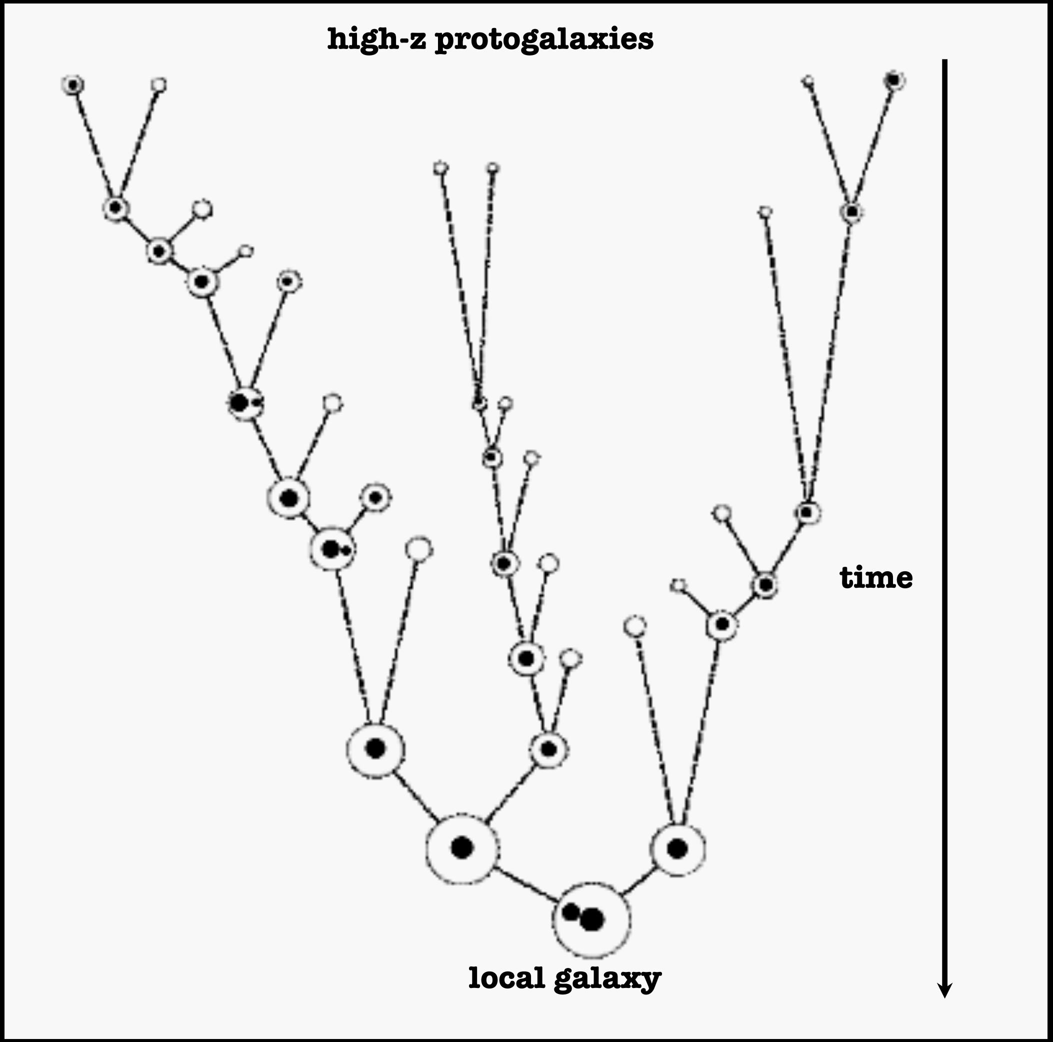
What we want to know

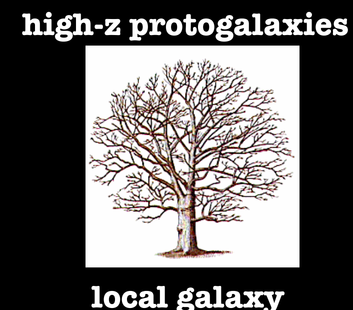
- When and where do MBHs grow most efficiently
  - Need to model *jointly* dynamics, thermodynamics and accretion
- Whether MBHs merge as efficiently as their host galaxies
  - The orbital decay depends on thermodynamics and it's intertwined with accretion and AGN activity
- How we can interpret observations of MBH activity – gravitational waves and AGN

Cosmic evolution of MBHs

MBHs grow from seed high-z BHs. These seeds are incorporated into larger and larger halos, accreting gas and dynamically interacting after mergers.

MV, Haardt & Madau 2003





Connect well known cosmological background to black hole evolution inside cosmic structures.

Cosmic evolution of MBHs

Cosmology:
Monte-Carlo realizations of the merger history of dark matter halos in a ΛCDM cosmology

MBH mergers:
- dynamical evolution of MBHs
- spin evolution
- GW recoil

Accretion and quasars:
- triggered by galaxy mergers
- self-regulated with host (feedback)
- on or below Eddington limit
- spin evolution

e.g., MV, Haardt & Madau 2003, MV, Lodato & Natarajan 2008, MV & Begelman 2010

Gravitational waves from MBH mergers

with the LISAPE taskforce, Arun et al. 2008

4 models that differ by either BH seeds or accretion

- **S** models have more, but smaller, black hole seeds than **L** models
- **E** models have slower accretion than **C** models

All models MUST match the luminosity function of quasars at z~0.5-3 and the mass density in MBHs today => realistic models => realistic merger rates

Gravitational waves from MBH mergers

with the LISAPE taskforce, Arun et al. 2008

4 models that differ by either BH seeds or accretion

- **S** models have more, but smaller, black hole seeds than **L** models
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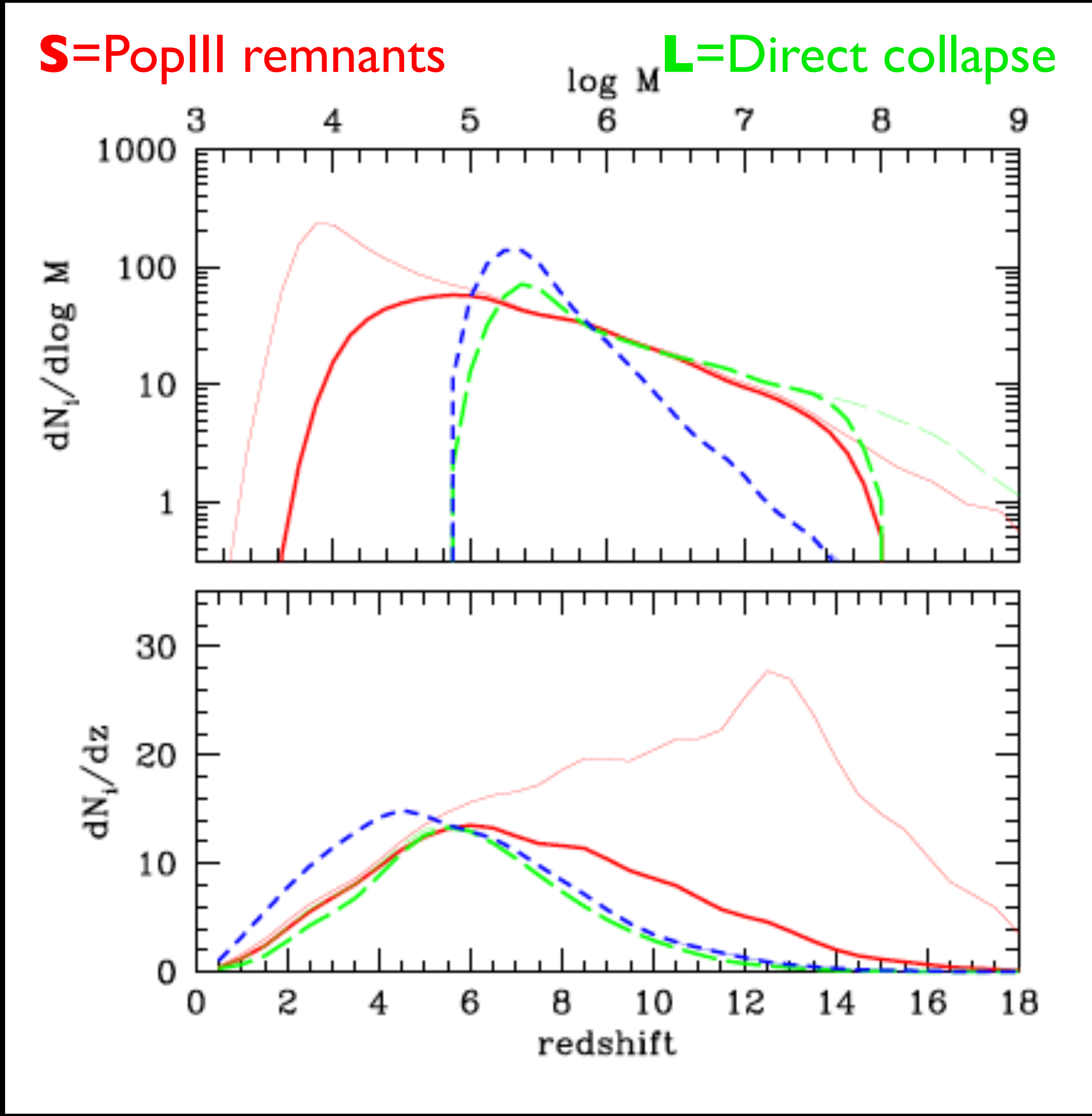
Model	N	$N_{\rm det}$	$N_{10\% D_L}$	$N_{10\,{\rm deg}^2}$	$N_{10\,{\rm deg}^2,\,10\% D_L}$	$N_{1\,{\rm deg}^2}$	$N_{1\,{\rm deg}^2,\,1\% D_L}$
SE	80	33 (25)	21 (8.0)	8.2 (1.5)	7.9 (1.1)	2.2 (0.6)	1.7 (0.1)
SC	75	34 (27)	17 (4.4)	6.1 (0.4)	5.5 (0.4)	1.3 (0.1)	1.3 (0.1)
LE	24	23 (22)	21 (7.7)	10 (0.8)	10 (0.7)	2.2 (0.1)	1.2 (0.05)
LC	22	21 (19)	14 (4.3)	6.5 (0.5)	5.4 (0.5)	1.8 (0.04)	1.0 (0.1)

New-LISA: work in progress with taskforce to evaluate various de-scope options for the new mission

Science case by May 17… stay tuned!

Instrinsic vs observable distributions



thin=
instrinsic

thick=
observable

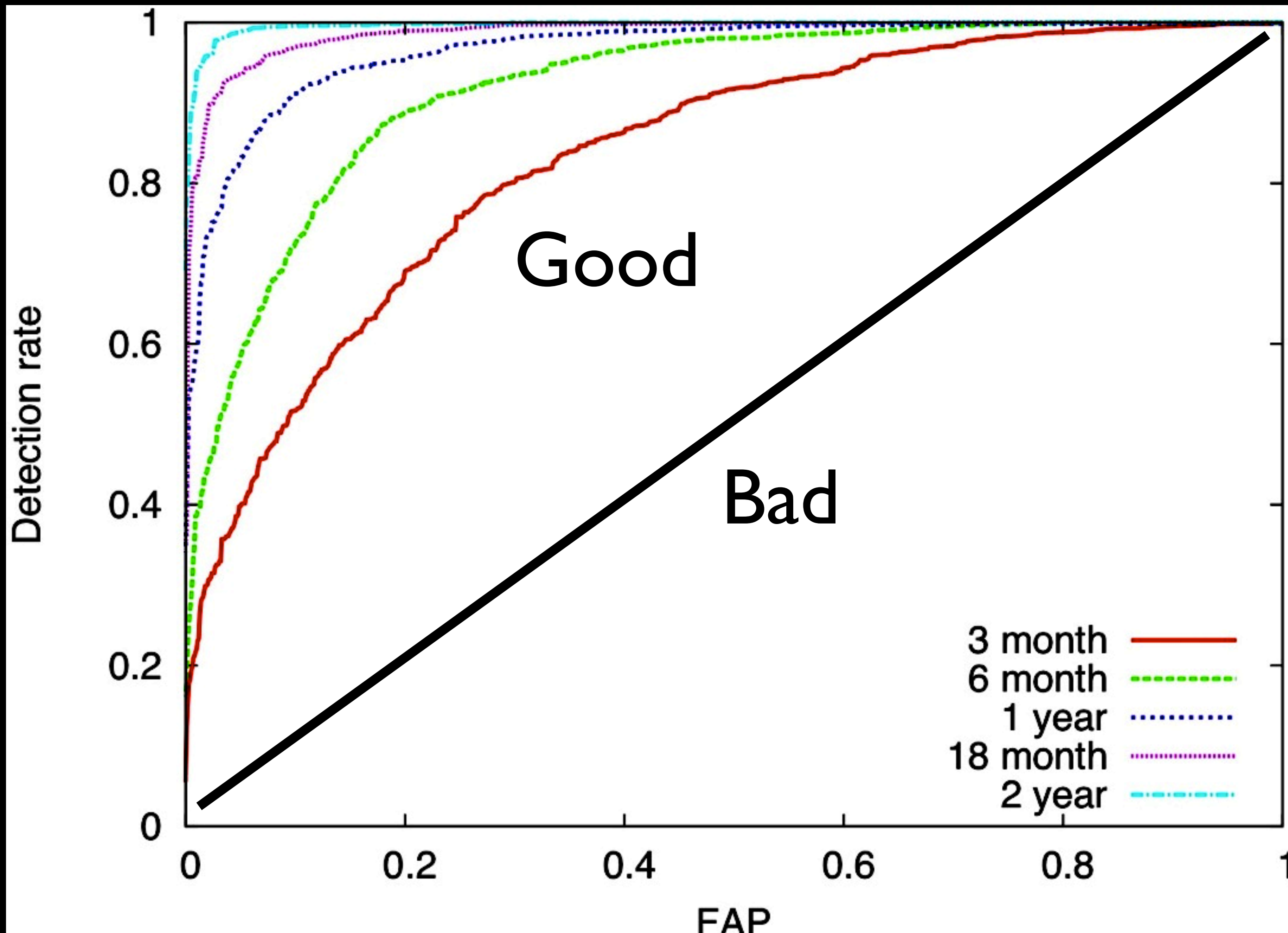
Sesana, Gair,
Berti, MV 2011

Reconstructing the massive black hole cosmic history

- Create a dataset of MBH mergers from a given model (GW detection with SNR>8 or >20).

- Likelihood ratio tells us which model a given dataset prefers.

- For a given likelihood ratio threshold that characterizes a “detection”, realizations from model A determine *detection rate* and realizations from model B determine *false alarm probability.*



With a two-year observation we have more than a 90% probability that the parent model of an observed sample will be safely identified at >95% confidence level

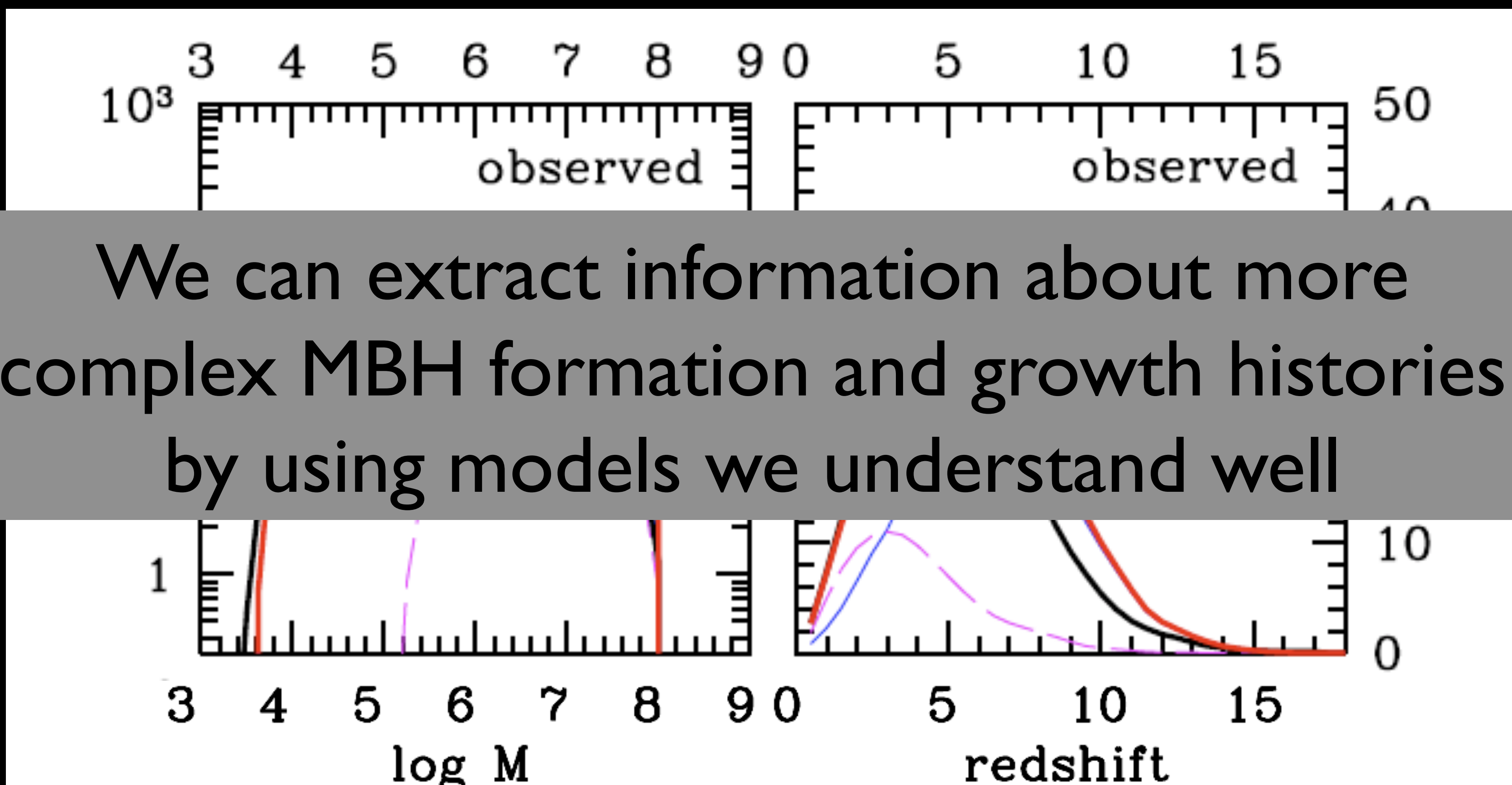
Models vs reality

The true MBH population might not be perfectly described by our models, or may come from a completely unexplored physical mechanism.

How can we analyze LISA's datastream to extract useful astrophysical information?

- Create a new *artificial* model, independent of the 4 cases described above, but consistent with current constraints on the MBH population

- Search the artificial model's datastream with pure models' distributions (masses, mass ratios and redshifts)



We can extract information about more complex MBH formation and growth histories by using models we understand well

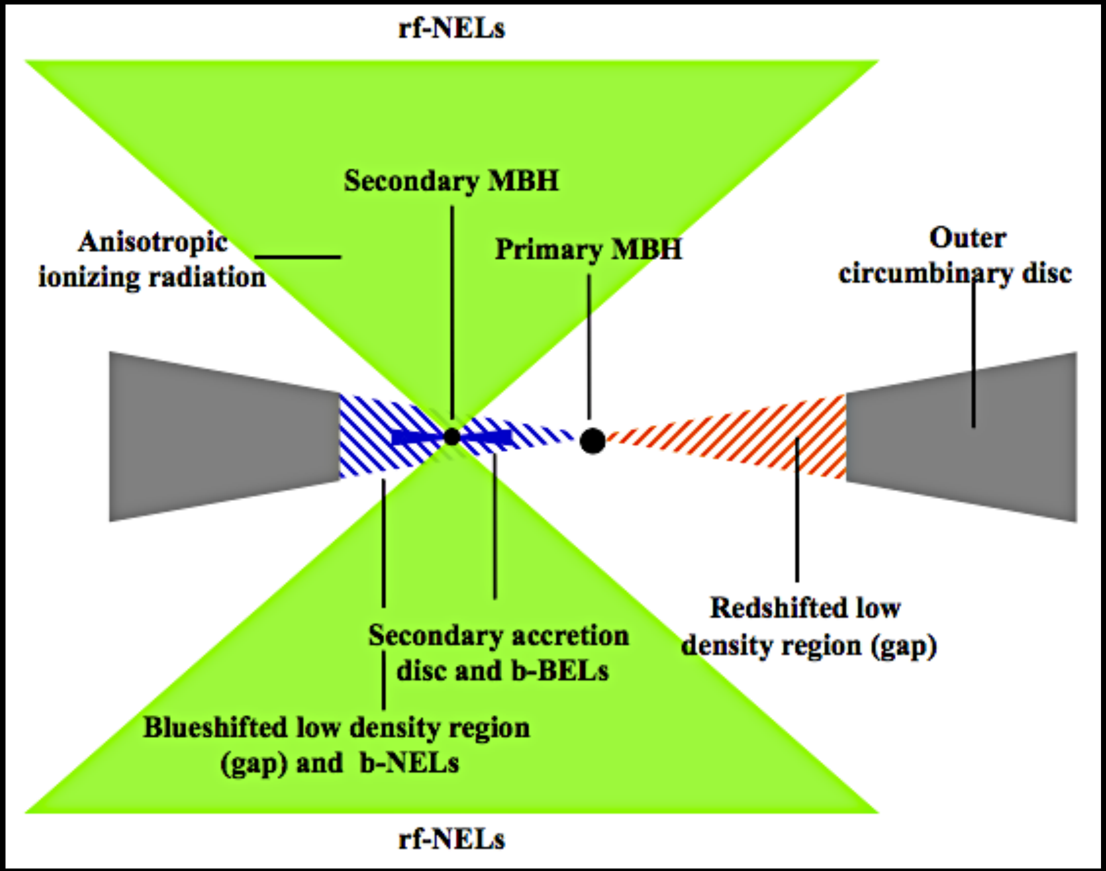
Theory vs observations

JMM's challenge:

You predict all these tens of mergers per year that LISA will detect.

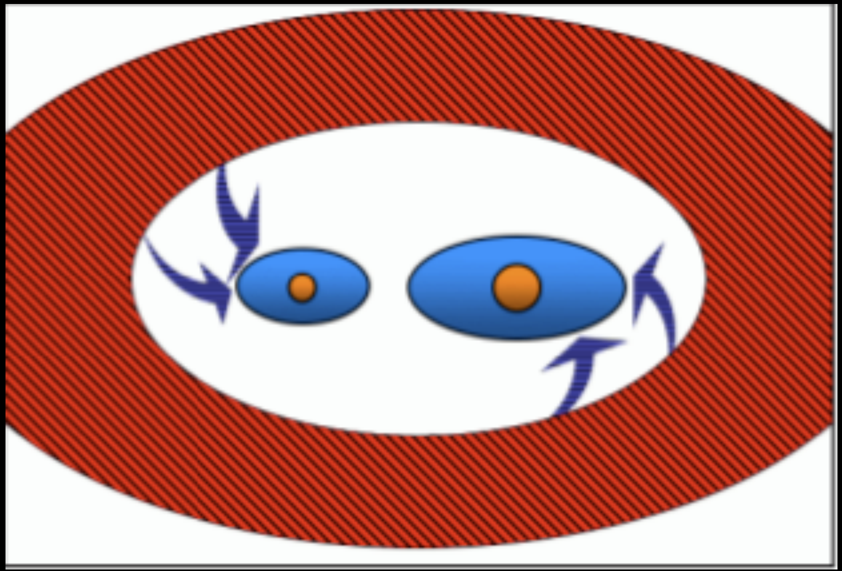
How come there are so few binary QSOs out there?!?

Hunting for sub-parsec binaries



Spectroscopic detection: broad lines (moving with the MBHs) displaced from narrow lines (at the galaxy's restframe)

SDSS J092712.65+294344.0
(Bogdanovic et al. 09, Dotti,.., MV et al. 09)
SDSS J153636.22+044127.0
(Boroson & Lauer 09, Chornok et al. 09)
4C+22.25 (De Carli et al. 2010)
SDSS J105041.35+345631.3
(Shields et al. 2009)

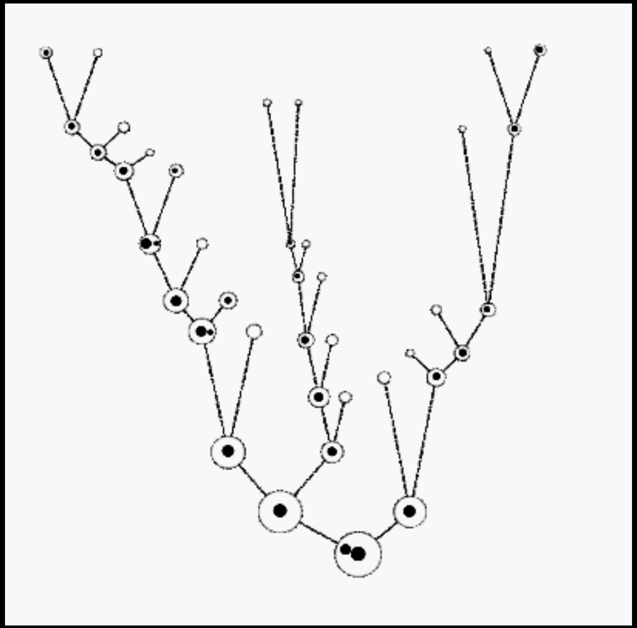


Sub-parsec binary QSOs

MV, Miller & Dotti 2009

You predict all these tens of mergers per year that LISA will detect.
How come there are so few sub-parsec binary QSOs in the SDSS?!?

- same MBH cosmic evolution models used for GW estimations
- add modeling of binary QSOs
- apply SDSS selection criteria



Sub-parsec binary QSOs

MV, Miller & Dotti 2009

- MBH merger rate from hierarchical evolving MBH population

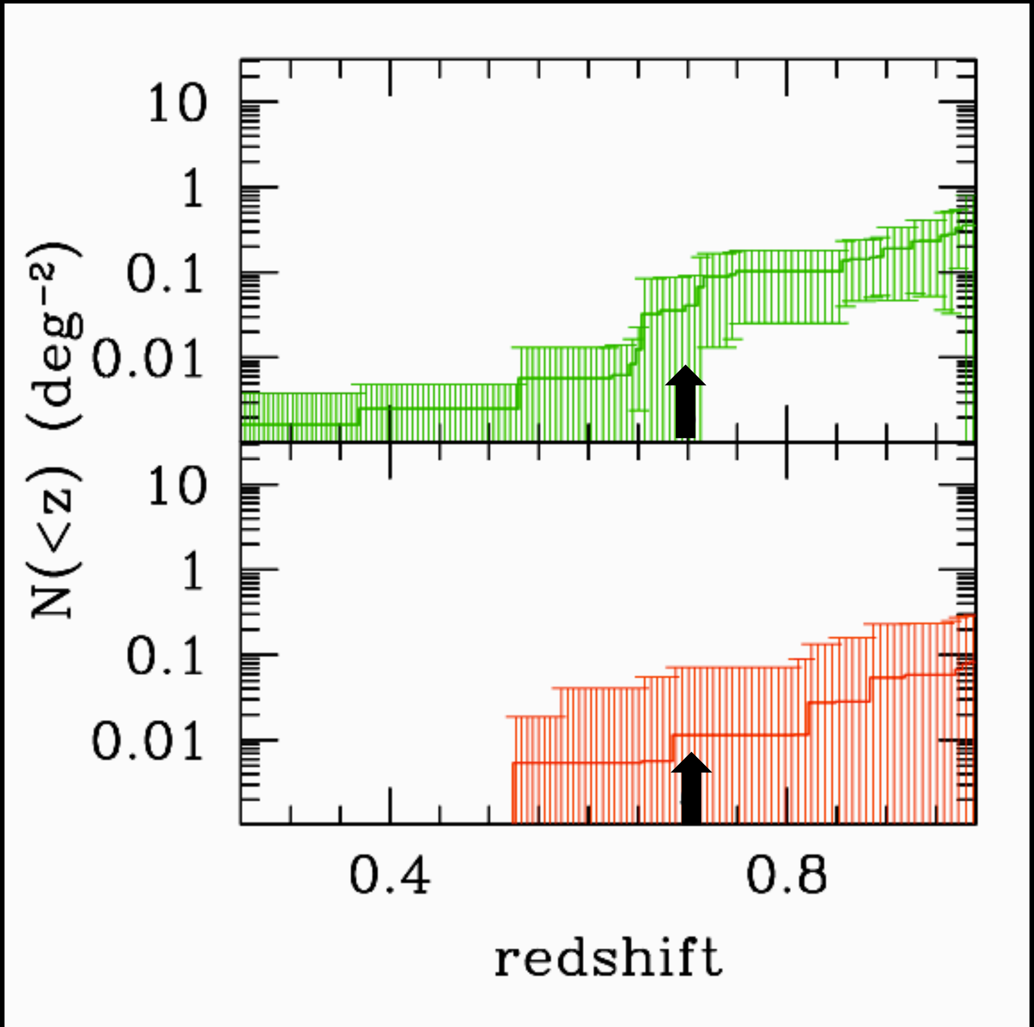
- select only MBHs with v_{orb}>2000 km/s (to match SDSS observational selection)

- assign luminosity
  - all MBHs are active at some level (Merloni 2009)
  - quasars are triggered by galaxy mergers

- assign lifetime

$$t_{\rm life} = 6{\rm Myr} \left(\frac{M_{\rm bin}}{10^7\,{\rm M}_\odot}\right)^{3/4} \left(\frac{4\,q}{1+q^2}\right)^{3/8} \left(\frac{10^\lambda}{0.1}\right)^{-5/8}$$

(Haiman et al. 2009; see also Armitage & Natarajan 2002, 2005
MacFadyen & Milosavljevic 2008, Cuadra et al. 2009)



All MBHs are active at some level

Merger-driven quasar activity

Most MBH binaries are expected to occur at

- higher redshift
- lower masses

than sampled by the SDSS quasar catalog

MV et al 2003; Sesana, MV & Haardt 2007

BINARY

Dotti, MV et al.

Nuclear scales (sub-pc scale)

– Bridge from friction-driven to gravitational radiation-driven decay
– Spin evolution ⇔ Jet formation

PAIRING

van Wassenhove, MV et al.

Galaxy scales (kpc-pc scale)

– Which galaxy mergers lead to MBH binaries?
– Merger-driven quasar/AGN activity

CONTEXT

Bellovary, MV et al.

Cosmic scales (Gpc-kpc scale)

– How and when MBHs form
– How many galaxies host MBHs

Semi-analytical models → cosmic evolution → statistical samples → observables

GW events

AGN/QSO binaries

AGN/QSO pairs

MBH occupation fraction, LF of QSOs/AGN

A 3-layer approach: zooming in on MBH physics

1. Cosmological scales (Gpc-kpc scale)
   - How and when MBHs form
   - How many galaxies host MBHs

2. Galaxy scales (kpc-pc scale)
   - Which galaxy mergers lead to MBH binaries?
   - Merger-driven quasar/AGN activity

3. Nuclear scales (sub-pc scale)
   - Bridge from friction-driven to gravitational radiation-driven decay
   - Spin evolution ⇔ Jet formation