# Supermassive black hole hierarchical evolution

NASA/CXC animation

# Outline

1. SMBHs in the local universe: where from?
2. SMBHs Mass Growth: Accretion vs Merging
   - AGN at low redshift
3. Dynamical Evolution of MBHs:
   - Formation and coalescence of MBH binaries
   - Gravitational rocket
4. Consequences on MBHs spin
5. Gravitational waves

# $M_{BH}$- σ relation: co- evolution of SMBHs and galaxies

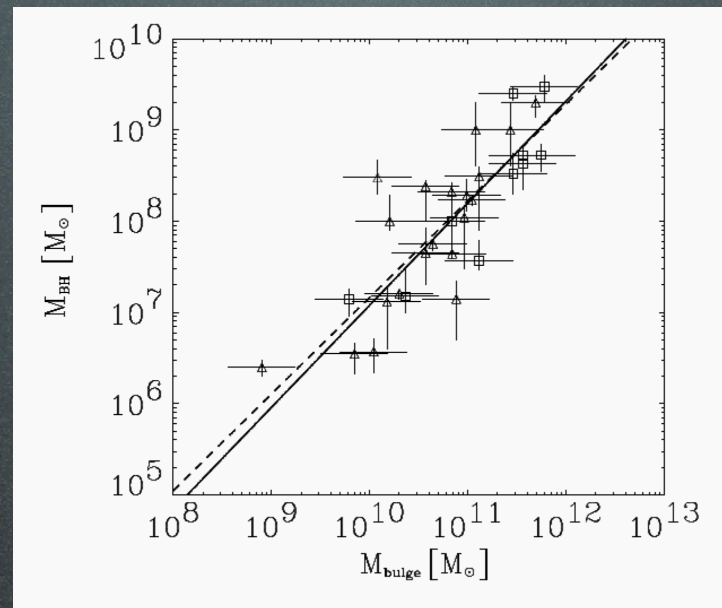
***SMBHs***

↕

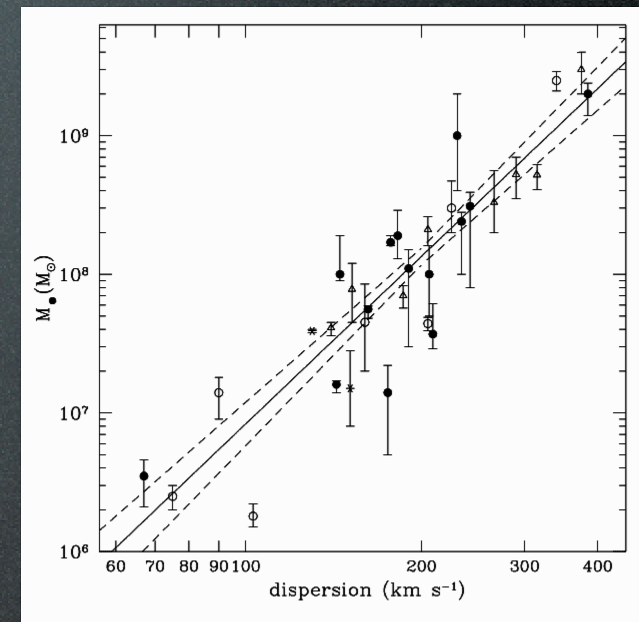
***stellar bulges***

↕

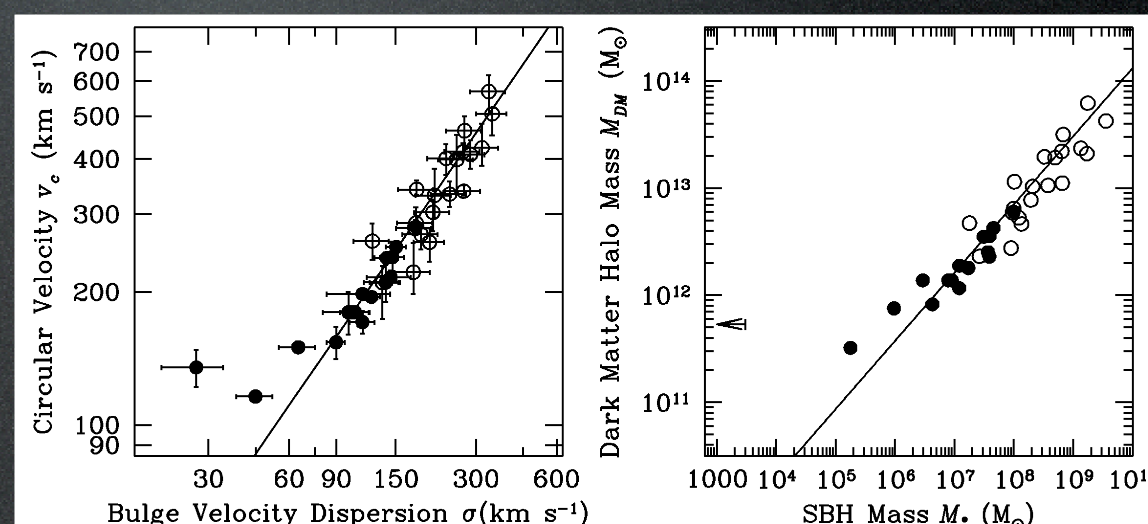
***host DM halos (???)***




from Marconi & Hunt 2004



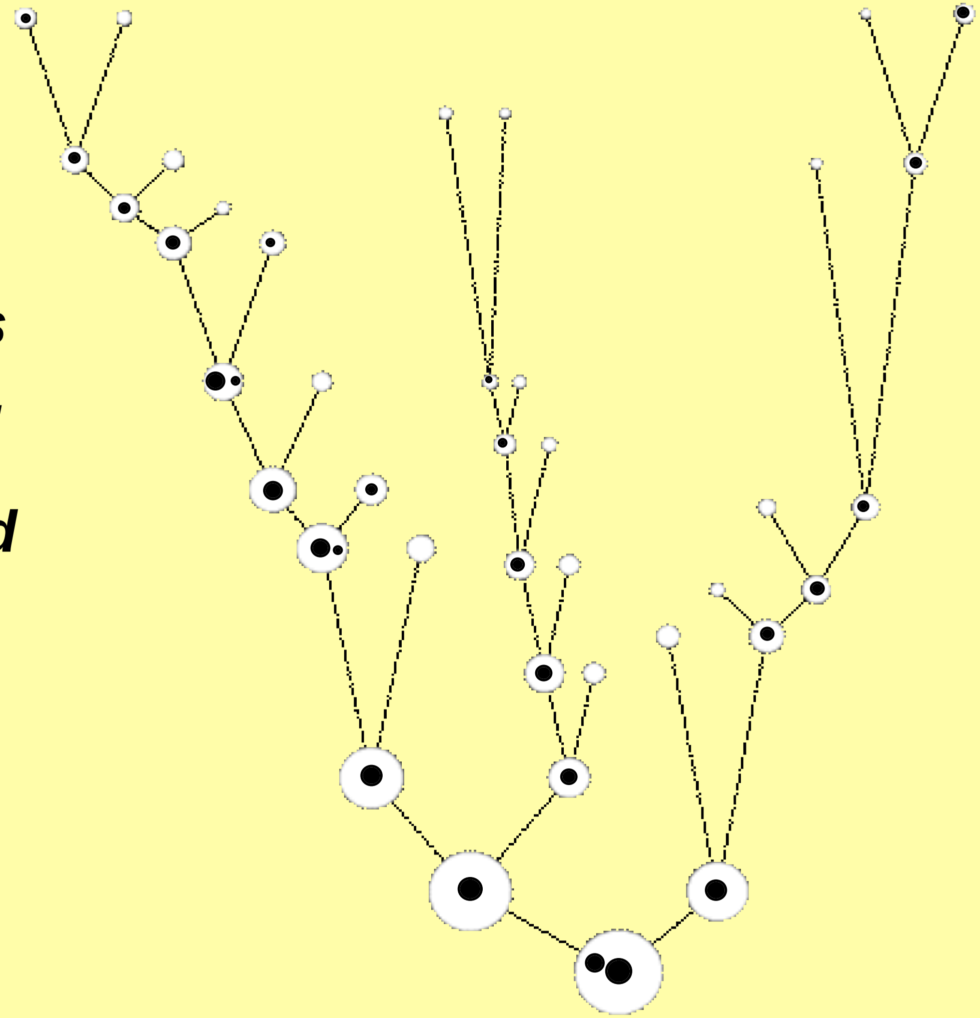

from Tremaine 2002




from Ferrarese 2002

# THE MODEL

***SMBHS are grown from seed pregalactic BHs. These seeds are incorporated in larger and larger halos, accreting gas and dynamically interacting after mergers.***



Volonteri, Haardt & Madau 2003

***Note: in most of what follows I'll consider seeds which are the endproduct of the first stars. Results at low-z are unchanged***

# Chapter 2

The seeds at z>20 are tiny, ~100-$10^4$ $M_{sun}$

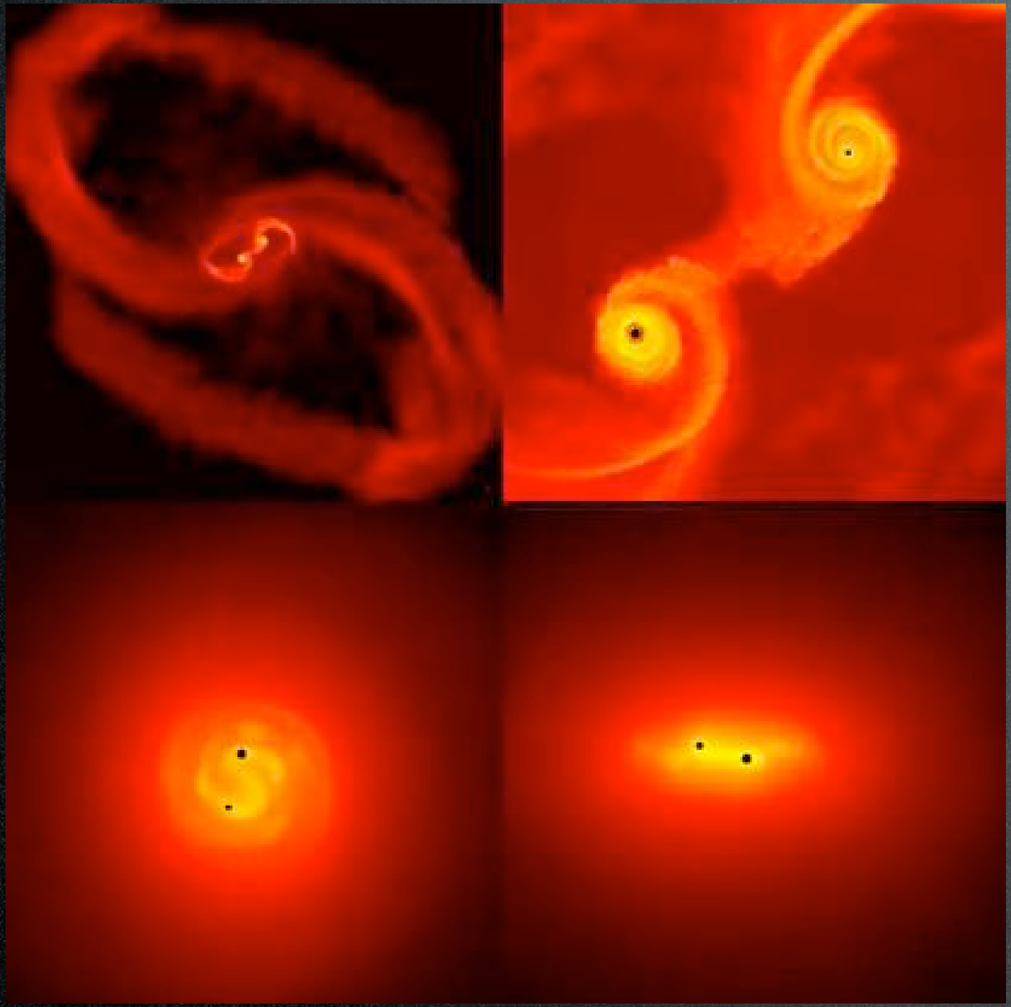
How do they grow to become supermassive?
Gas accretion vs BH-BH mergers

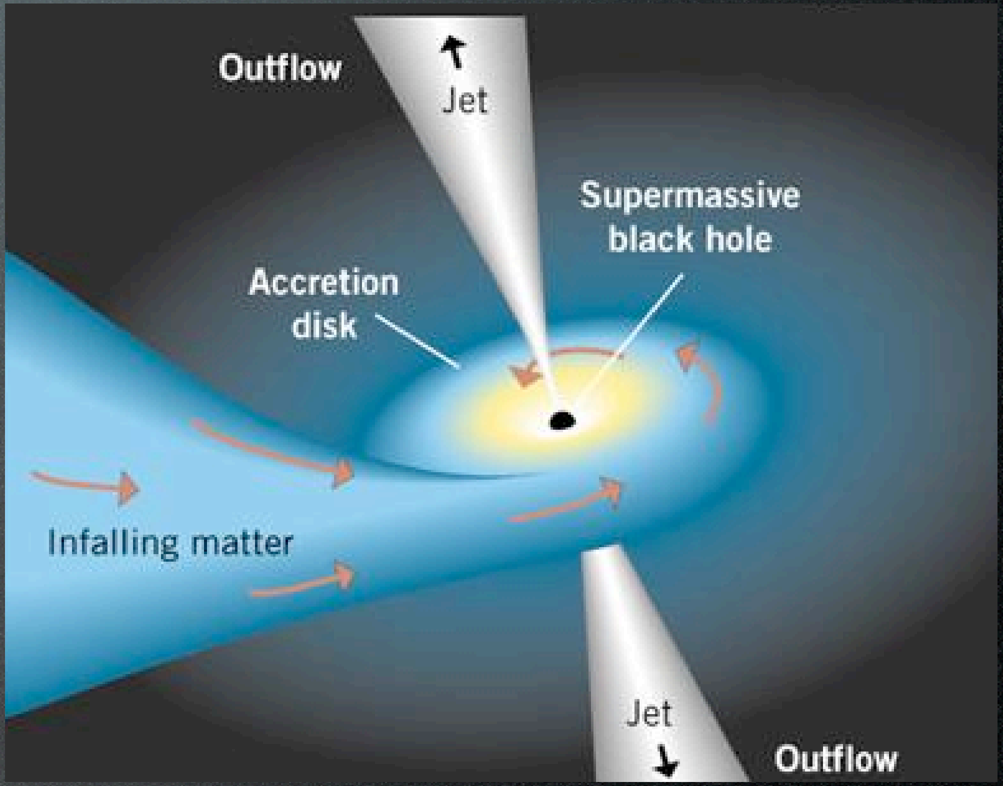
Can we meet the constraints at low-ish redshift?
Matching the LF of quasars

## *How does the SMBHs mass grow along the cosmic history?*

➞ ***Mergers***

➞ ***Accretion***





## *How does the SMBHs mass grow along the cosmic history?*

➡ ***Mergers***

➡ ***Accretion***

**Soltan's argument**

$\rho^{B}_{qso(0)}=2\text{x}10^{5}[0.1(1-\varepsilon)/\varepsilon]M_{sun}\ Mpc^{-3}$

$\rho^{X}_{qso(0)}=2\div4\text{x}10^{5}[0.1(1-\varepsilon)/\varepsilon]M_{sun}\ Mpc^{-3}$

$\rho_{SMBH}=2.5\div4.5\text{x}10^{5}M_{sun}\ Mpc^{-3}$

*Yu & Tremaine 2002, Elvis et al 2002, Merloni et al 2004*

➞ $\varepsilon \geq 0.06$ *@ z<5 : Kerr BHs?*

➞ *the final mass of the SMBHs is dominated by accretion, with mergers playing a secondary role*
$M_{BH,acc} >> M_{BH,merg}$

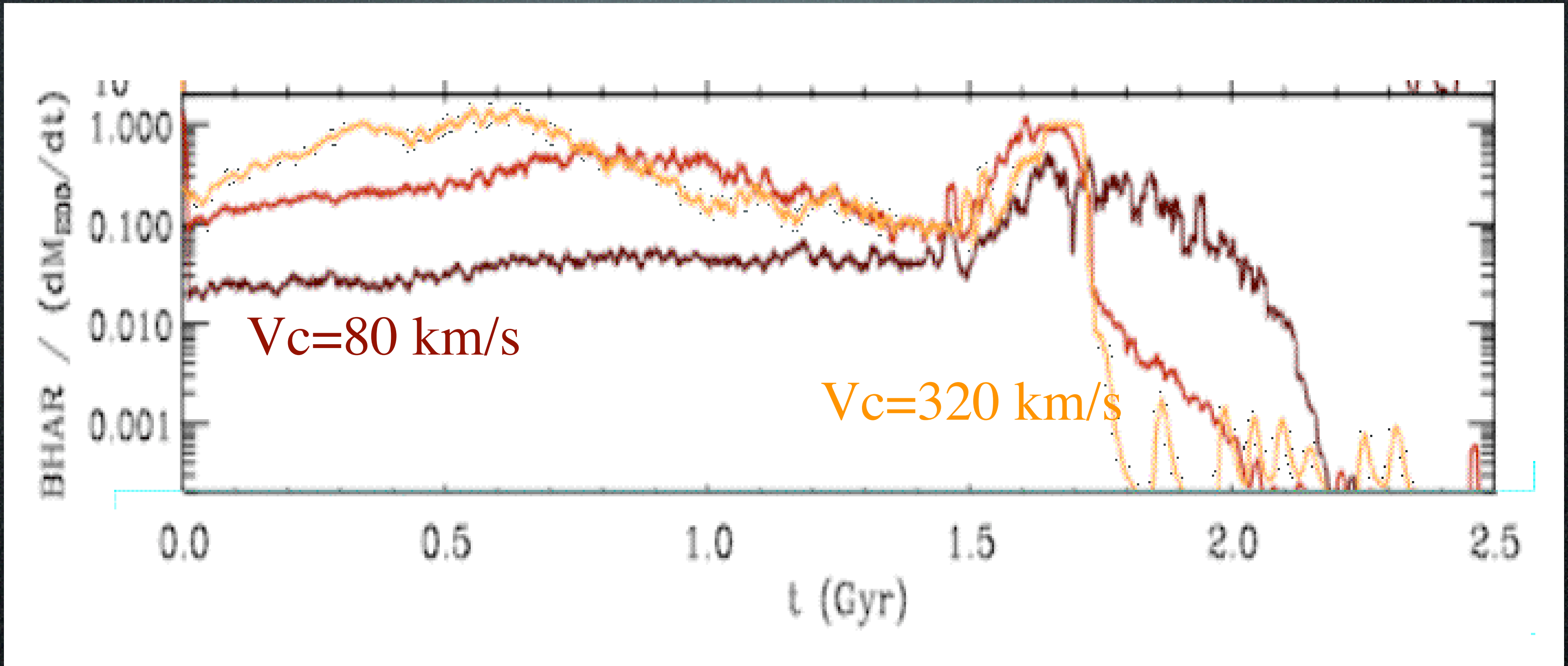
To recover the local $M_{BH}$- $\sigma$ & the quasar LF @ z <6:

✓ only during major mergers { space density of quasars; SMBHs-bulges connection

✓ the accreted mass is a fixed fraction of the $M_{BH}$- $\sigma$ relation { BH growth limited by feedback

cfr. Di Matteo et al.

✓ Eddington accretion rate { a sensible assumption?

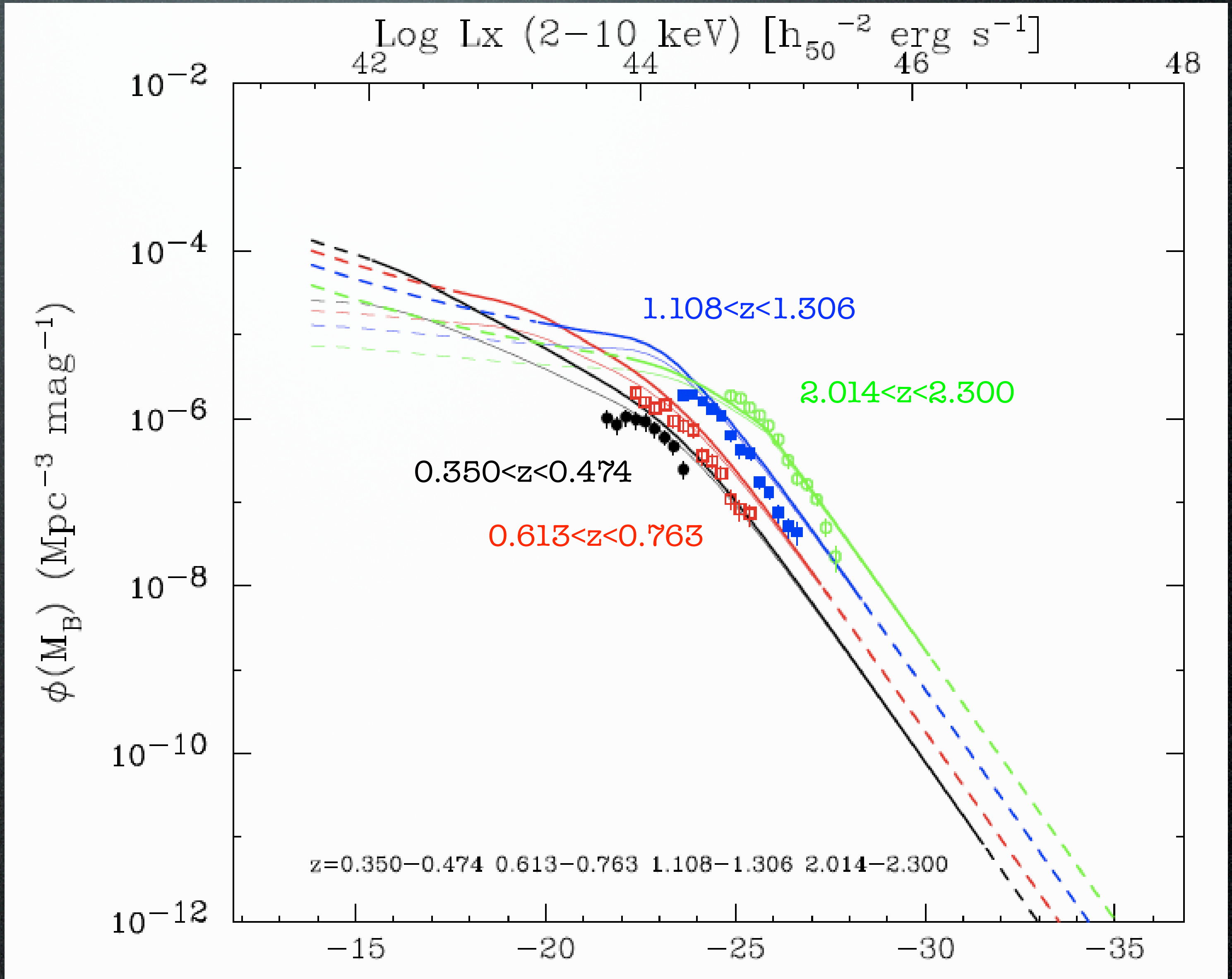



*courtesy of T. di Matteo*

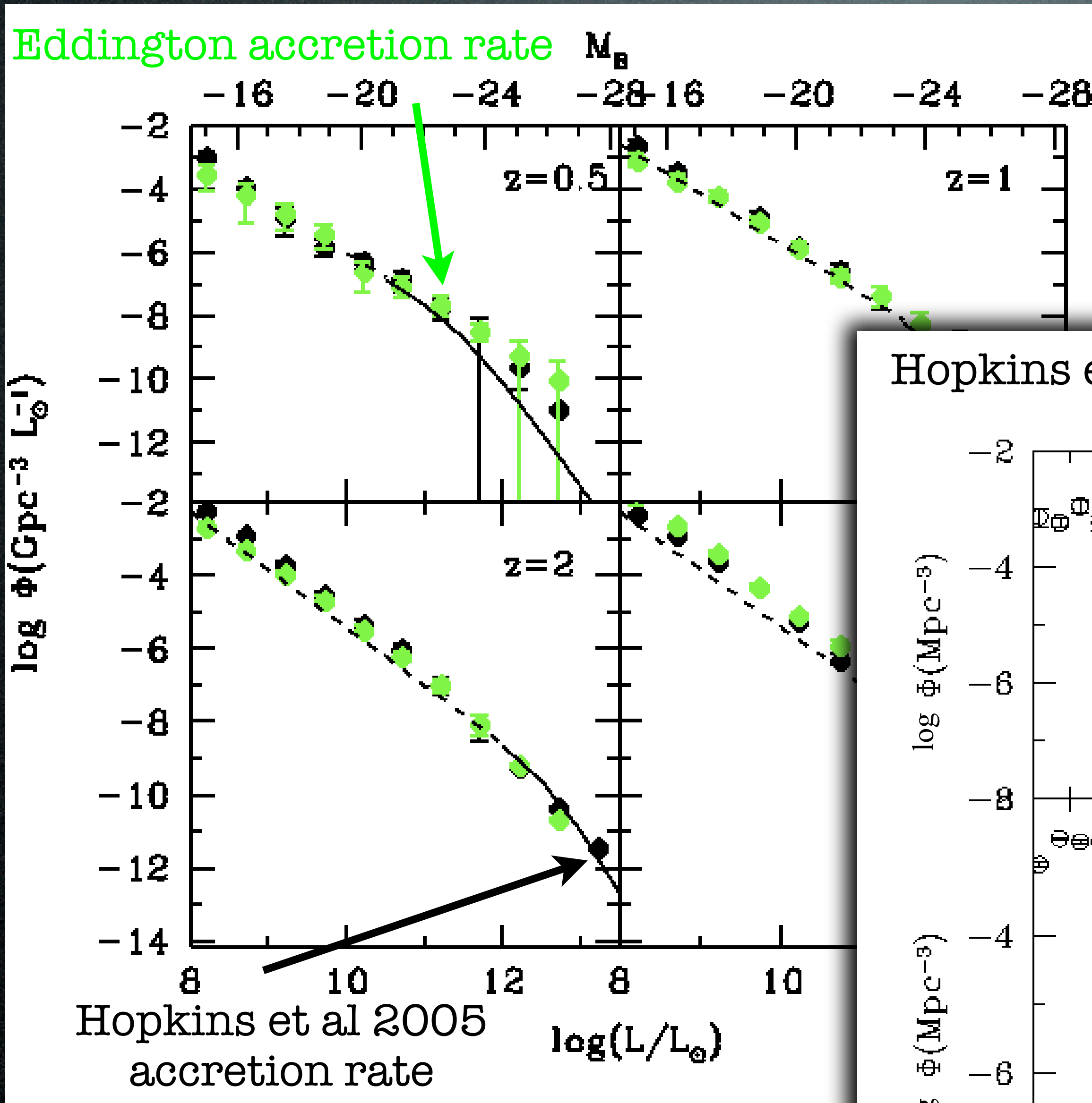
*Can the LF alone discriminate between models with a varying or constant Eddington ratio?*

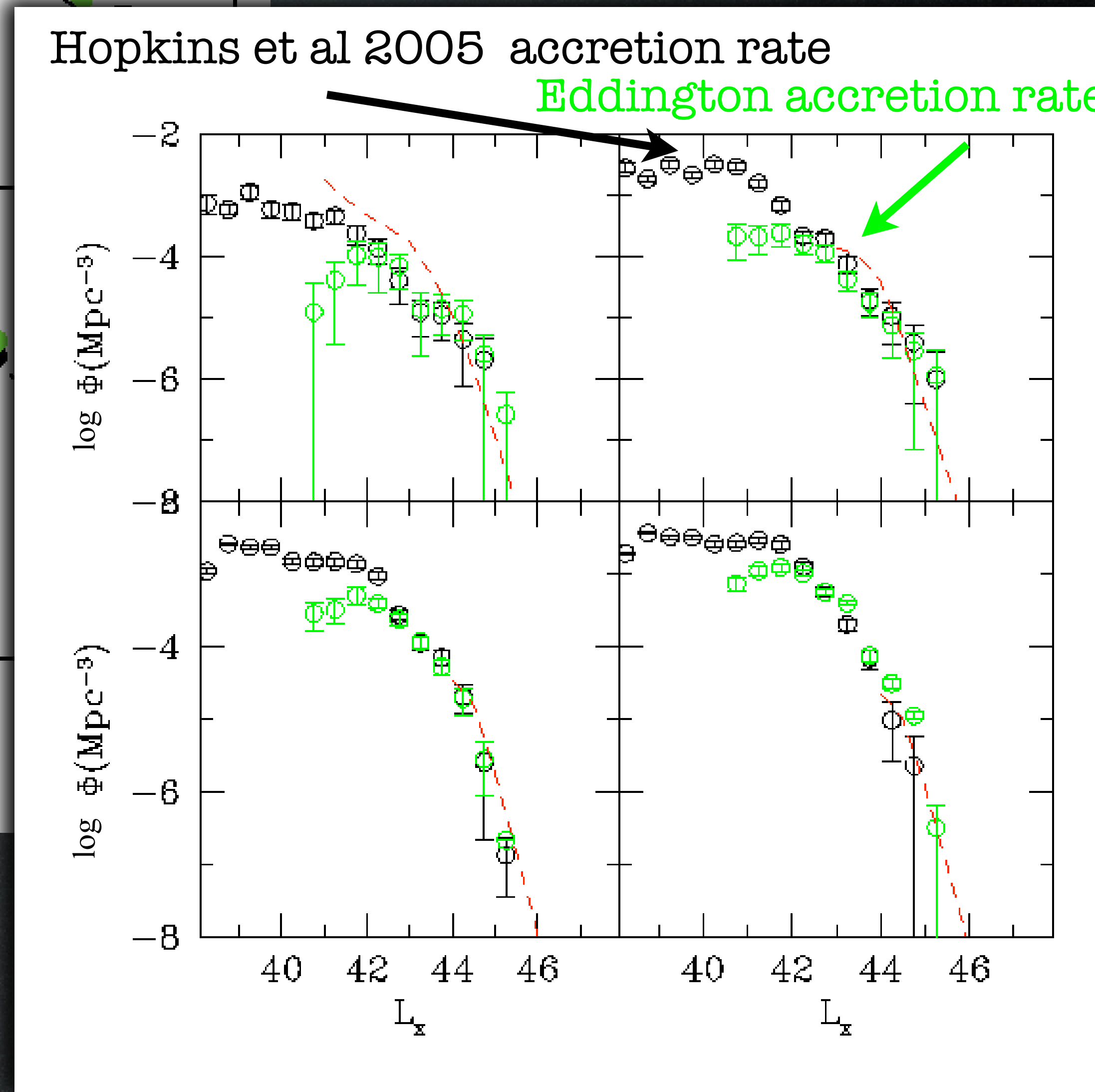
# *Testing the model at "low" redshift*

*Optical LFs underestimate the AGN population **BOTH** at the **FAINT** and **BRIGHT** end*




from Ueda et al. 2003




Volonteri, Salvaterra & Haardt in prep.

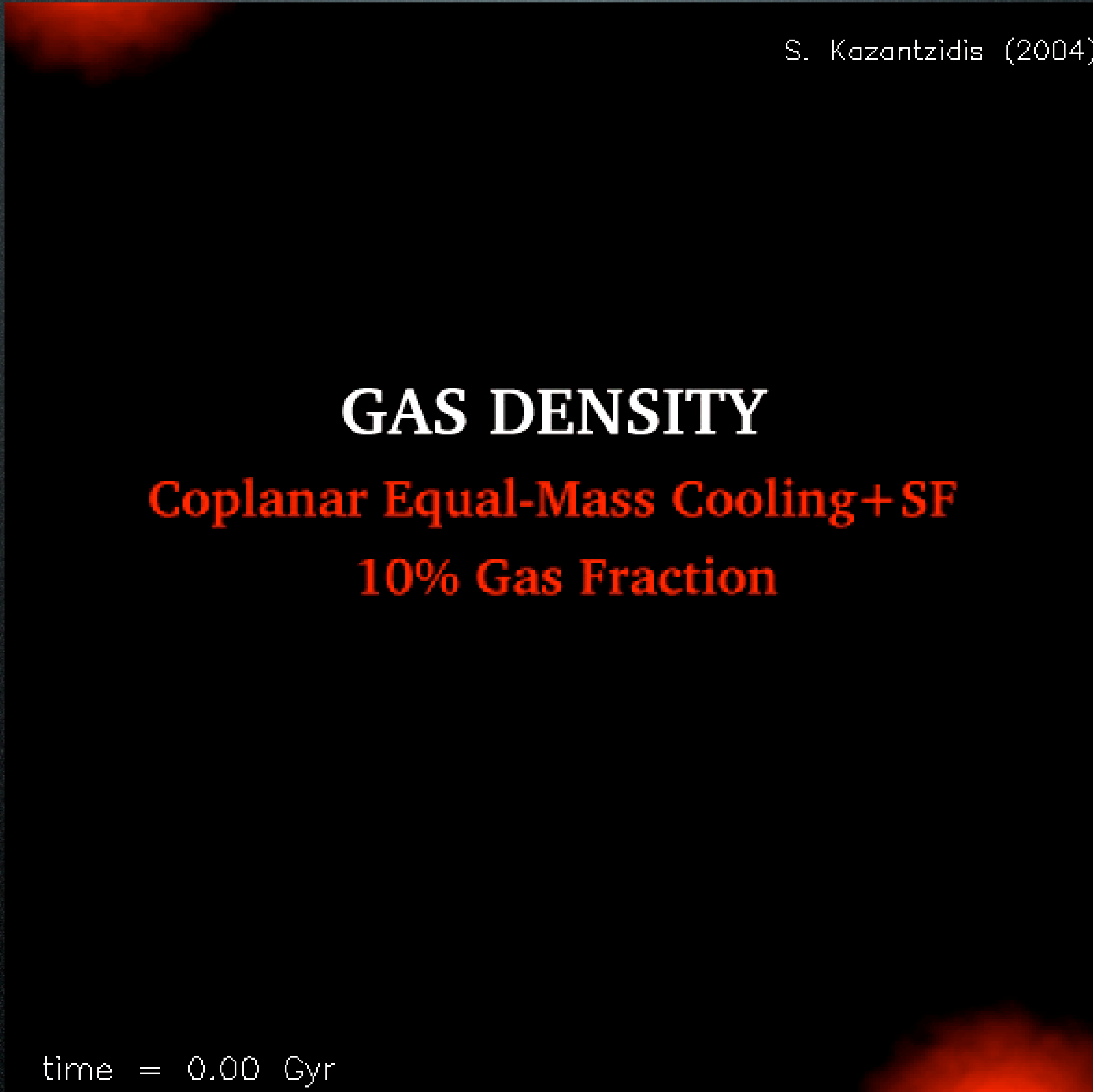
# Chapter 3

MBHs **weddings**...

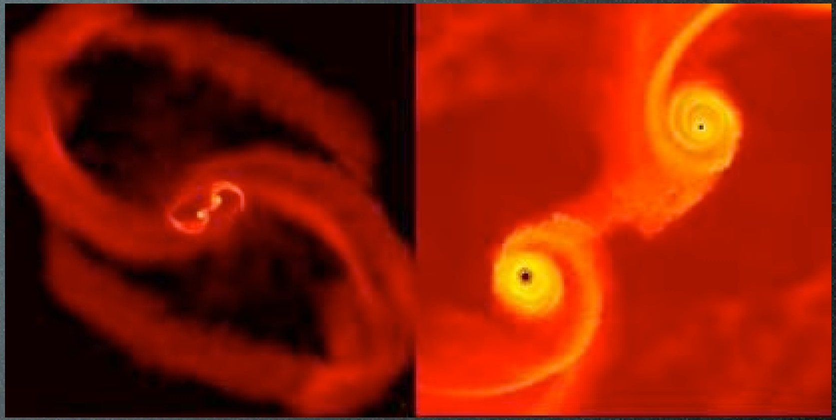
MBH mergers: can we cut a long story short? Most dynamical processes for MBH mergers imply long timescales. We observe very few systems... **nature must be much more efficient than our calculations**...

... and **honeymoons**

how MBHs take long trips, sometimes never to return


S. Kazantzidis (2004)
GAS DENSITY
Coplanar Equal-Mass Cooling+SF
10% Gas Fraction
time = 0.00 Gyr

# Dynamical evolution of BH pairs



**1.** dynamical friction

✓ *efficient only for major mergers against mass stripping*

*minor mergers: orbital decay > Hubble time*

$$t_{\rm df} \propto \frac{r_{\rm circ}^2 V_c}{M_s} \propto \frac{1+P}{P} \frac{1}{H\sqrt{\Delta_{\rm vir}}}$$

## 2. hardening of the binary (Quinlan 1996, Merritt 1999, Miloslavljevic & Merritt 2001)

*the binding energy of the BHs is larger than the thermal energy of the stars*

$$a_h = \frac{Gm_2}{4\sigma^2} = 1\,\mathrm{pc} \quad \left(\frac{m_2}{2\times 10^7\ \mathrm{M}_\odot}\right)\sigma_{150}^{-2}$$

✗ *3 bodies scattering between the binary and the surrounding stars: the SMBHs create a stellar density core ejecting the background stars*

→ *explain shallow cores in bright ellipticals*

$$\frac{d\mathcal{M}_{\rm ej}}{d\ln(1/a)} = J(m_1+m_2)$$

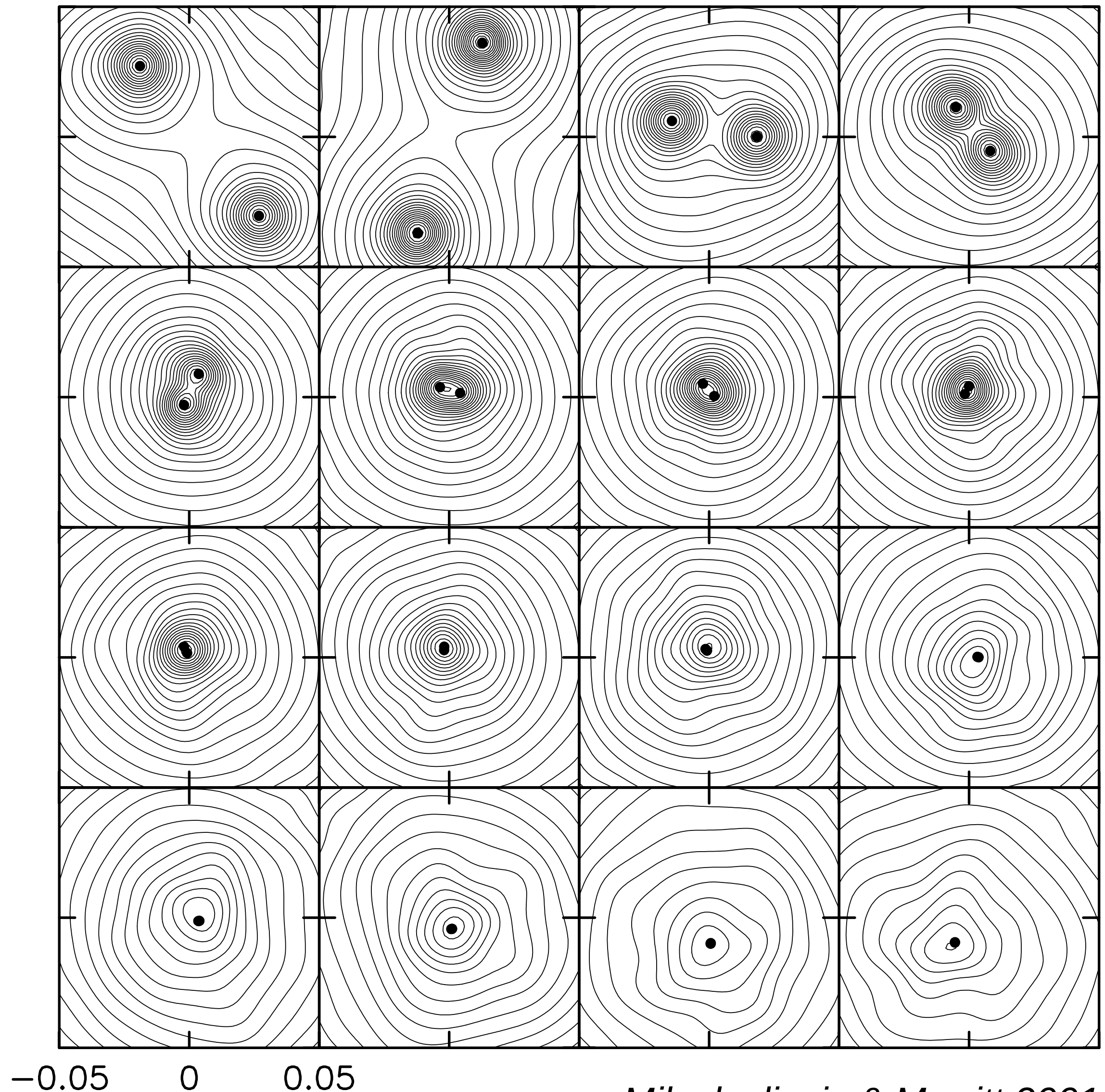
*As the binary shrinks, ejecting a mass in stars comparable to its own mass, the star density decreases and the merging timescale increases*

$$\rho_c(t) = \frac{8\sigma^6}{9\pi G^3 \mathcal{M}_{\rm ej}^2(t)}$$

$$t_h = \frac{\sigma}{G\rho_\star a H}$$

As the binary shrinks ejecting stars the central density drops

Numerical simulations do not have the required resolution (relaxation, wandering...) yet?

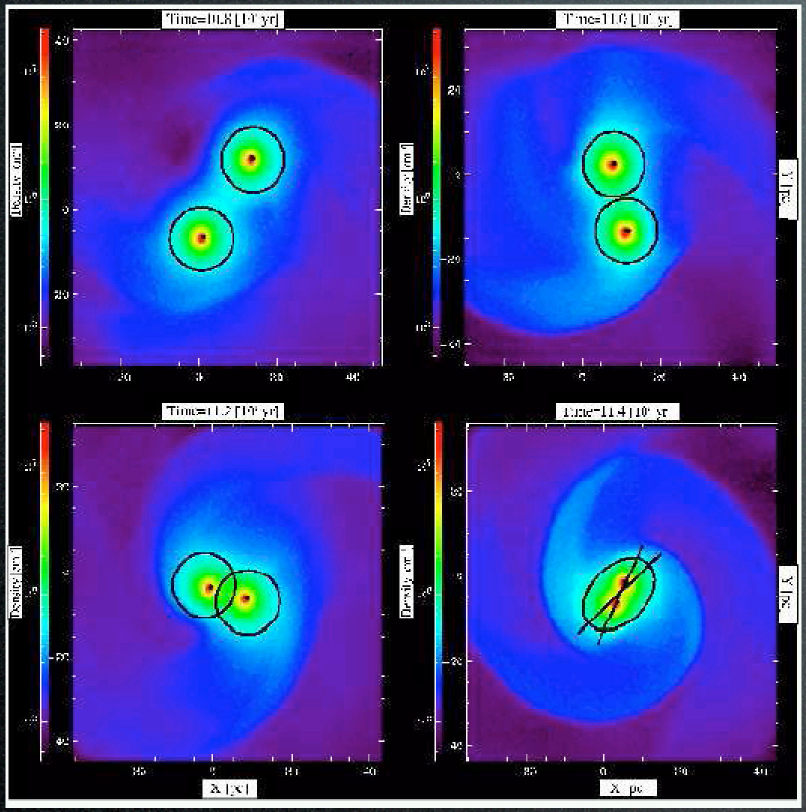


Miloslavljevic & Merritt 2001

The BH sphere of influence is typically smaller than the core radii: additional processes to enlarge the core (e.g. hierarchical evolution, heating by reprocessed BHs orbital decay)

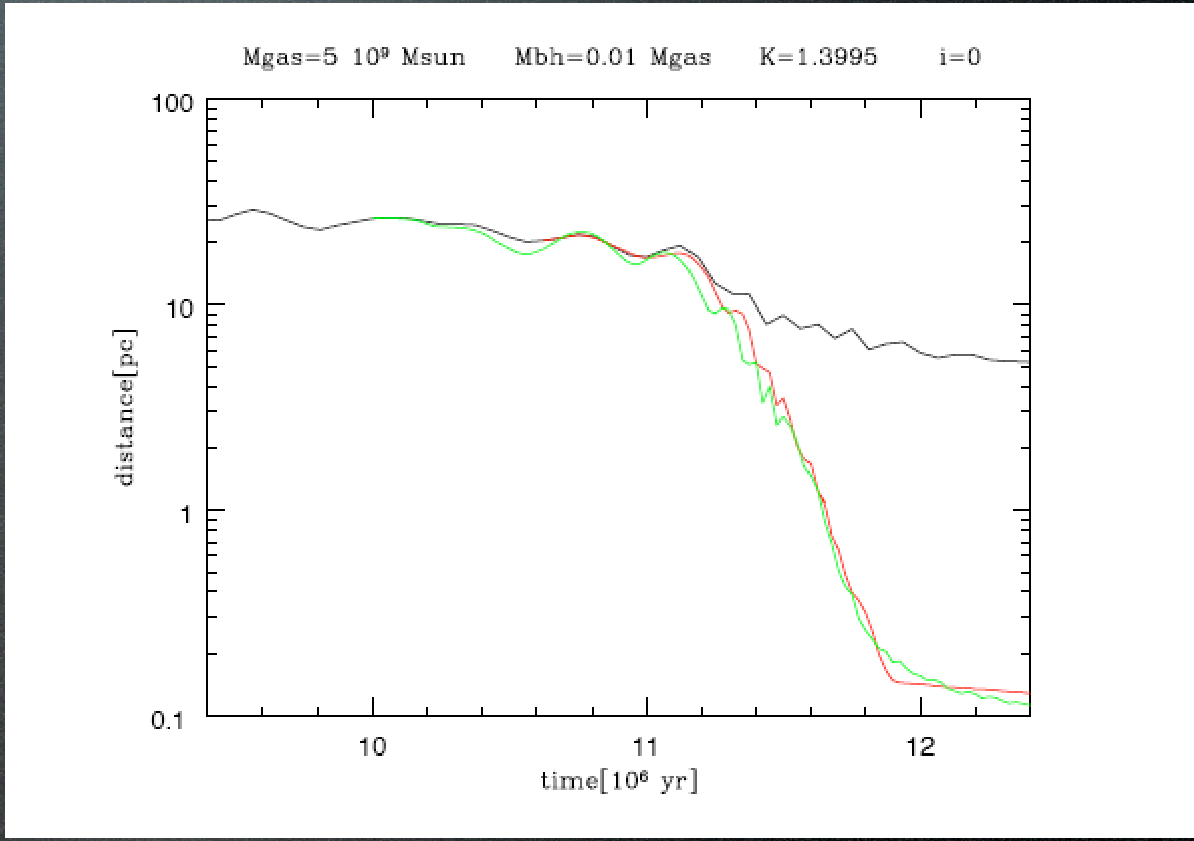
## 2. hardening of the binary (Quinlan 1996, Merritt 1999, Miloslavljevic & Merritt 2001)

✗ interaction with gas/accretion disc: much more efficient than stellar scatterings (Armitage & Natarayan, Escala et al)



*Gas is much more efficient than stellar scattering (Escala et al. 2004, Dotti et al 2006)*

*High-z galaxies: plenty of gas, few stars*

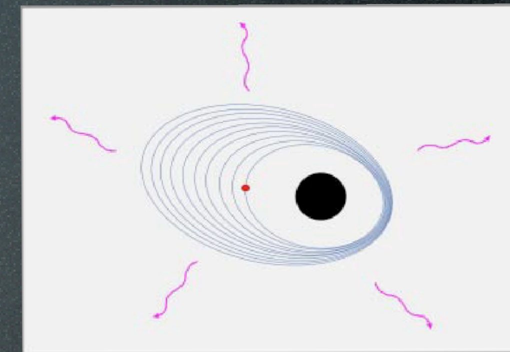


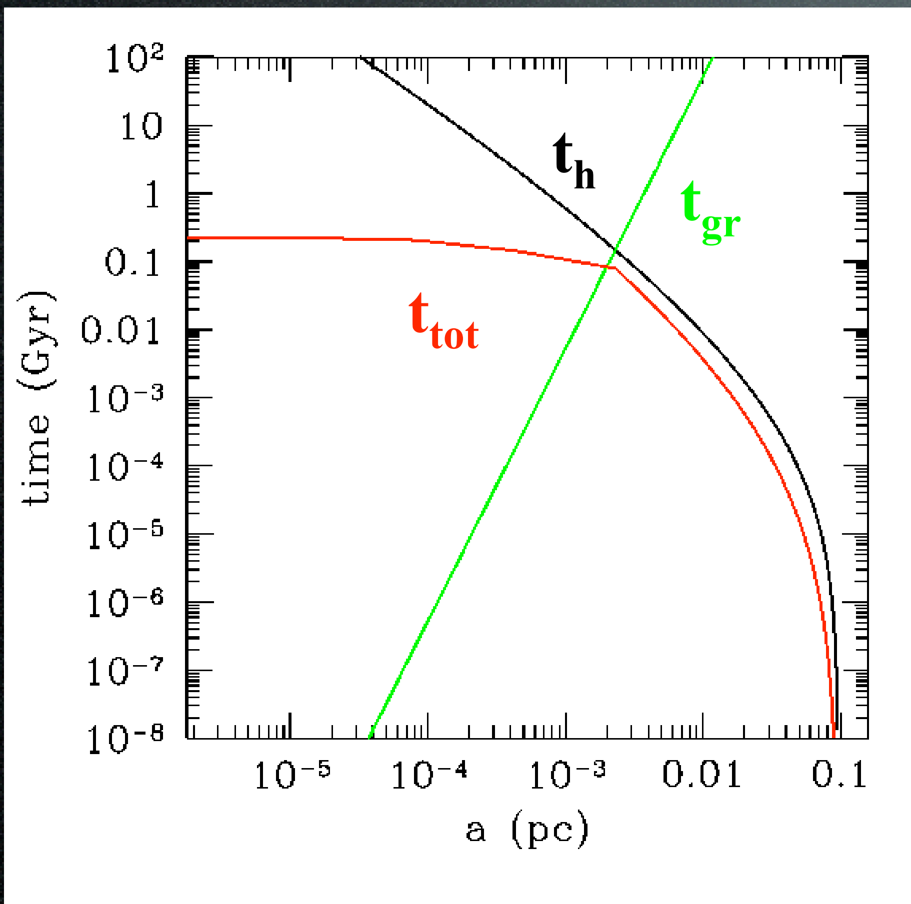

*Also, if an accretion disc is present, the satellite BH is dragged in by viscosity on short-ish timescales*
*(e.g. Armitage & Narayan, Ivanov et al. )*

*$t_{gr}(0.1pc)$~200 Gyr*

## **3.** emission of gravitational waves *(Peters 1964)*

*Takes over at subparsec scales...*






$$t_h = \frac{\sigma}{G\rho_i a H} \qquad \rho_c(t) = \frac{8\sigma^6}{9\pi G^3 \mathcal{M}_{\rm ej}^2(t)}$$

$$\frac{d\mathcal{M}_{\rm ej}}{d\ln(1/a)} = J(m_1 + m_2)$$

$$t_{\rm gr} = \frac{5c^5 a^4}{256 G^3 m_1 m_2 (m_1 + m_2)}$$

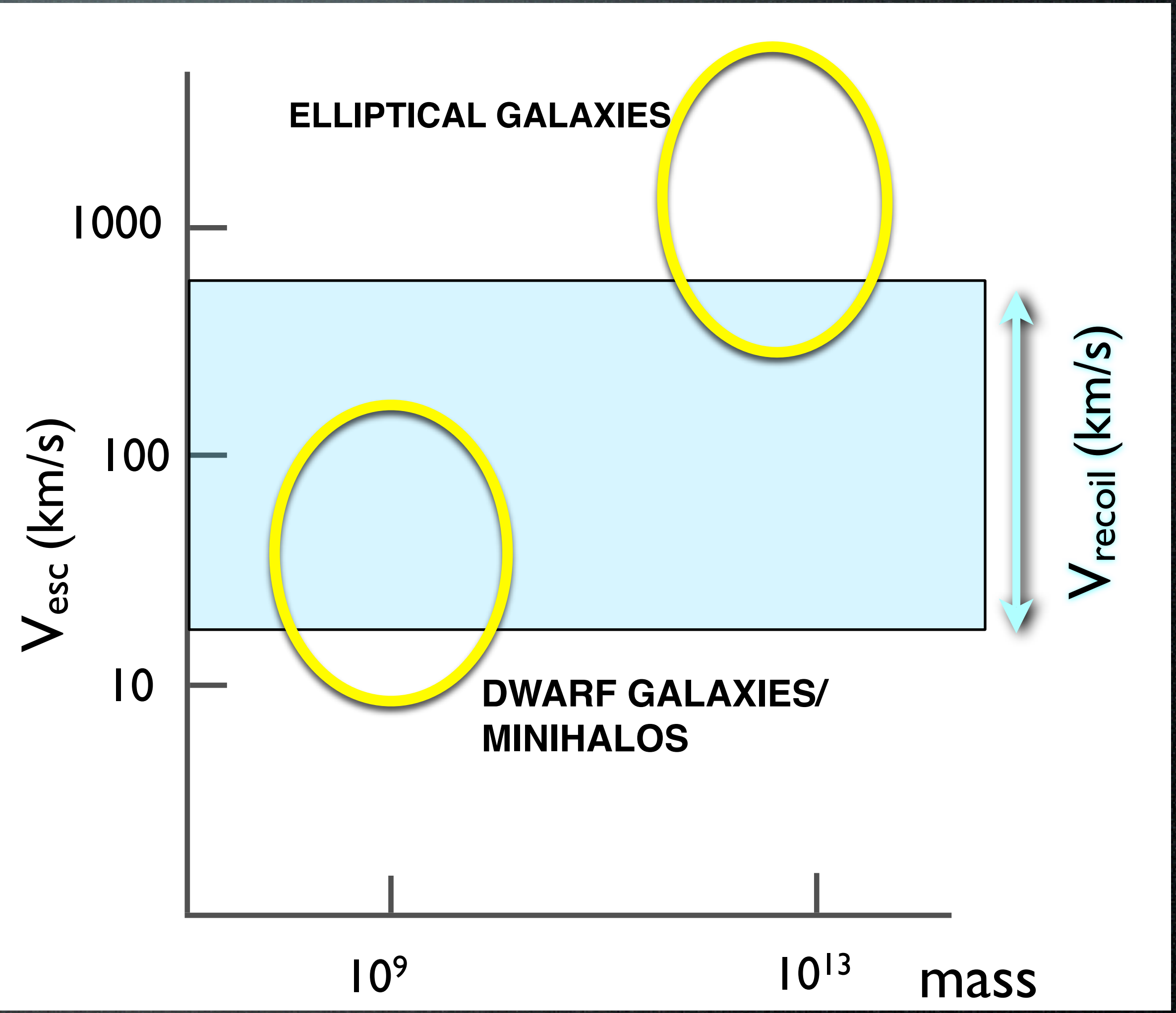
# Gravitational Rocket

***binary center of mass recoil during coalescence due to asymmetric emission of GW***

*(e.g. Fitchett 1983, Favata et al 2004, Blanchet et al 2005, Baket et al 2006)*

**BH mergers: positive or negative contribution?**

***Are merging BHs ejected from galaxies?***



# *If mergers do happen **efficiently**, how much is the **gravitational rocket** effect a **threat** for the SMBH evolution?*

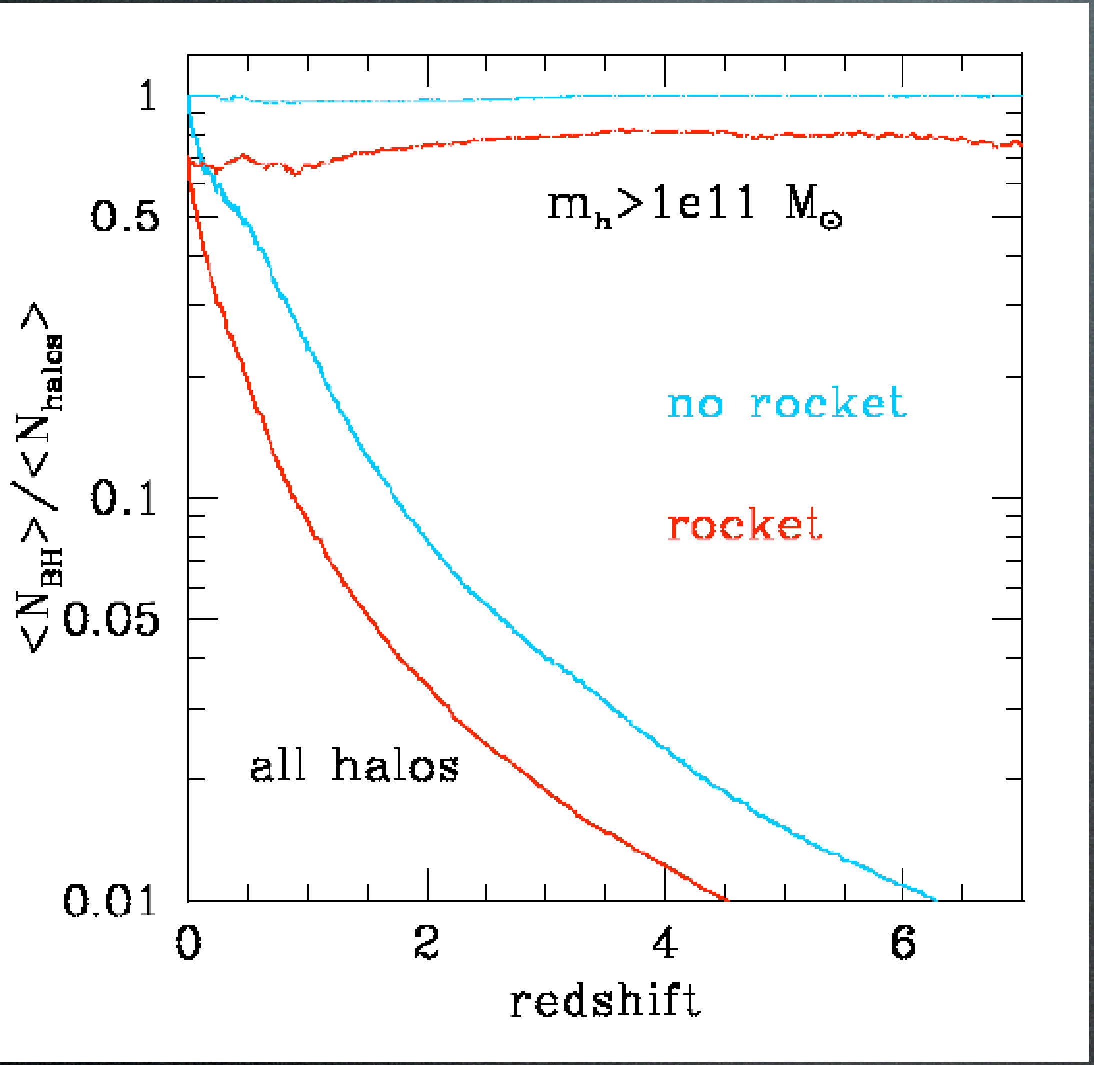
1. *not ALL BHs experience a merger in their lifetime, only ~40-50%*

2. *about 50% of the merging BHs are ejected out of their host halo, but 80% at z>10!*

3. *SMBHs gain their mass primarily by accretion at "low-ish" redshift (z<5)*

Volonteri & Rees 2006

# MBH Occupation Fraction




*for halos with mass larger than 3e12 $M_{sun}$, the occupation fraction is unity, though*

# Chapter 4

We can model the **mass growth of MBHs** as traced by **evolution** of the **quasar LF**

The comparison between the total qso **energy density** and the **SMBH mass density** suggest a radiative efficiency $\varepsilon \geq 0.1$

Are BHs rapidly spinning?

What is the **typical BH spin** predicted by the hierarchical evolution?

***What is the typical radiative efficiency value?***
***Are BHs rapidly spinning?***

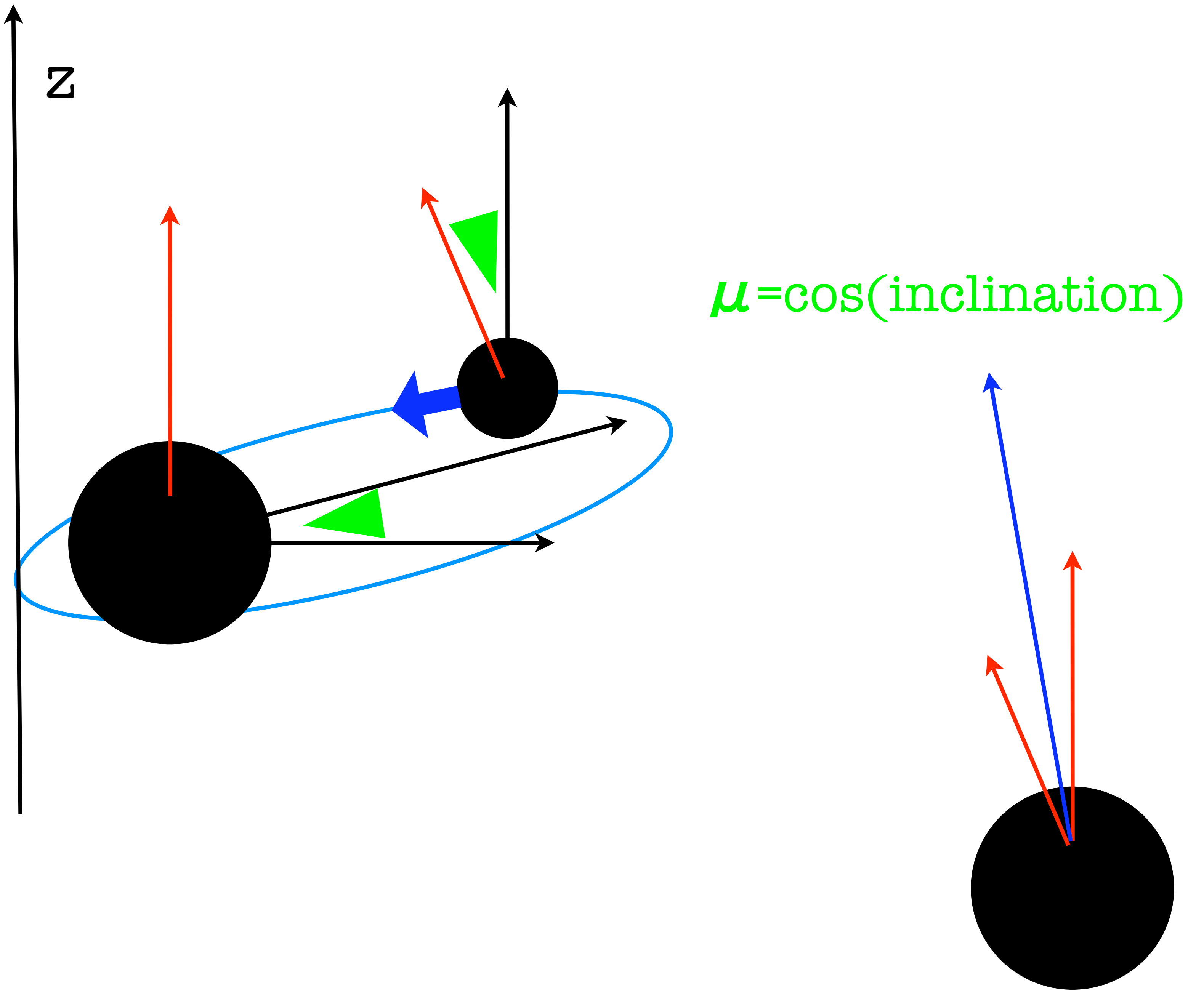
## ***BHs spin is modified by BH mergers and the coupling with the accretion disc***

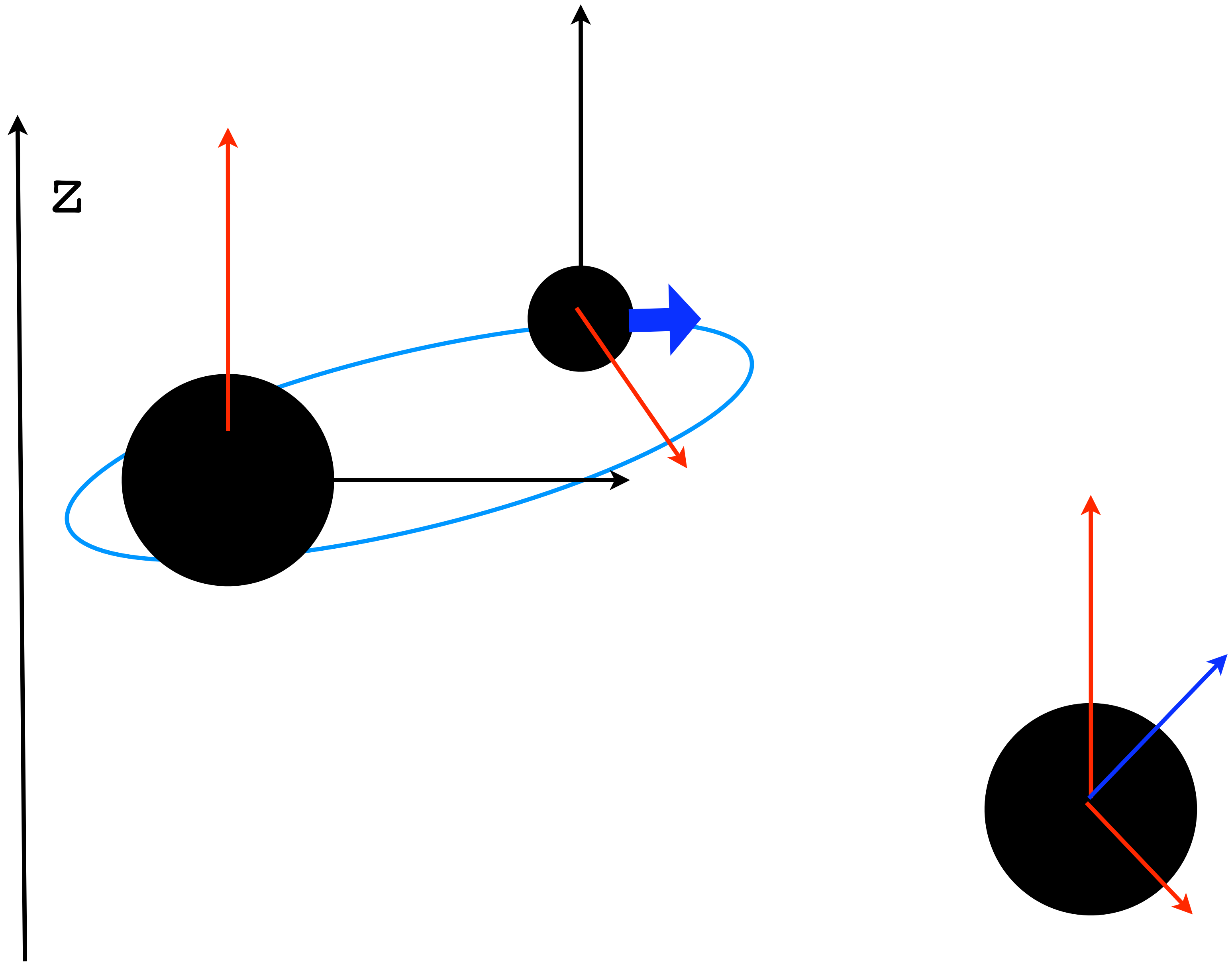
- ✓ *mergers can spin BHs either up or down*
- ✓ *alignment with a thin disc spins up*

## ***... but BH mergers are rare events!***

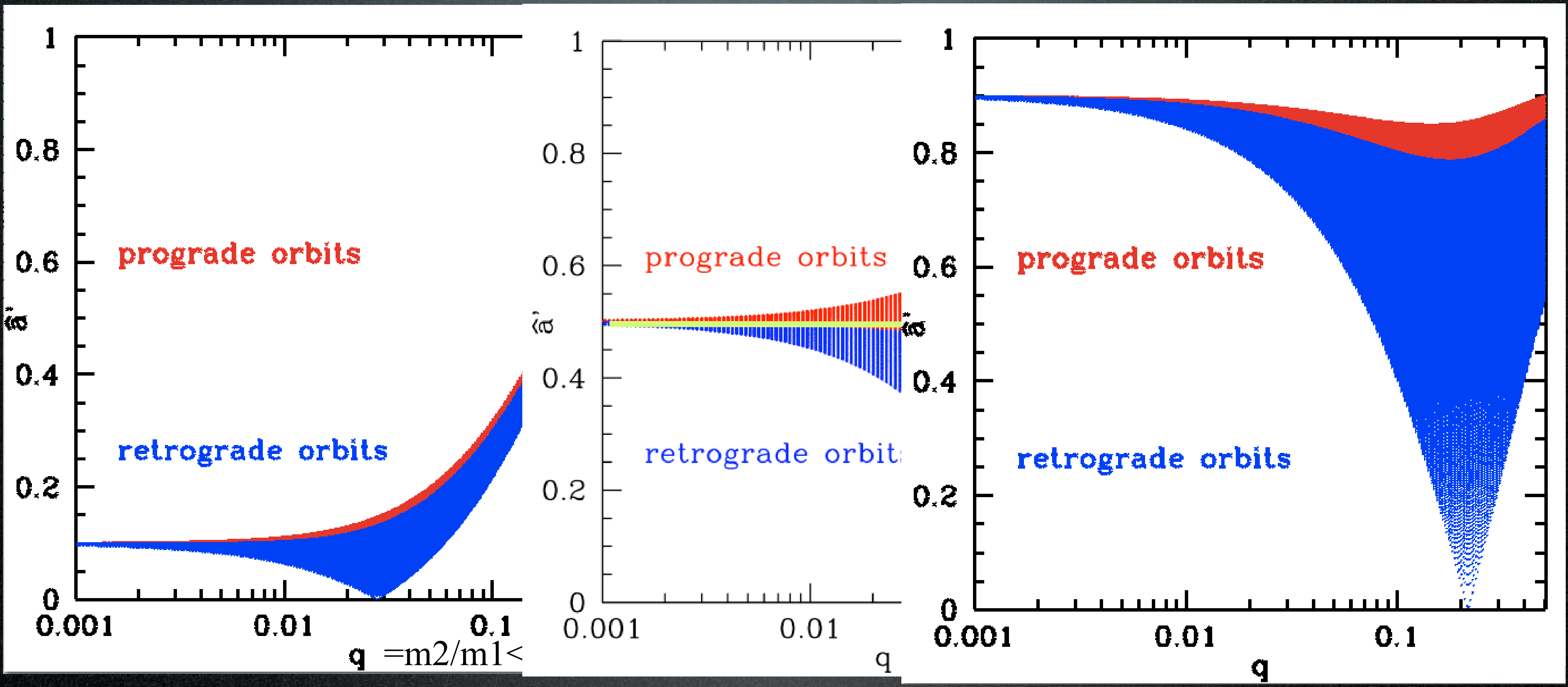
Volonteri, Madau, Quataert & Rees 2005

# Evolution of BH Spin: MERGERS




z

# Evolution of BH Spin: MERGERS



# Equatorial prograde/retrograde orbits

$$\hat{r}_{\rm LSO} = 3 + Z_2 \mp \sqrt{(3 - Z_1)(3 + Z_1 + 2Z_2)}$$

$$\hat{L}_{\rm LSO} = \pm \frac{2}{3\sqrt{3}}[1 + 2(3\hat{r}_{\rm LSO} - 2)^{1/2}] \qquad \hat{E}_{\rm LSO} = \left(1 - \frac{2}{3\hat{r}_{\rm LSO}}\right)^{1/2}$$

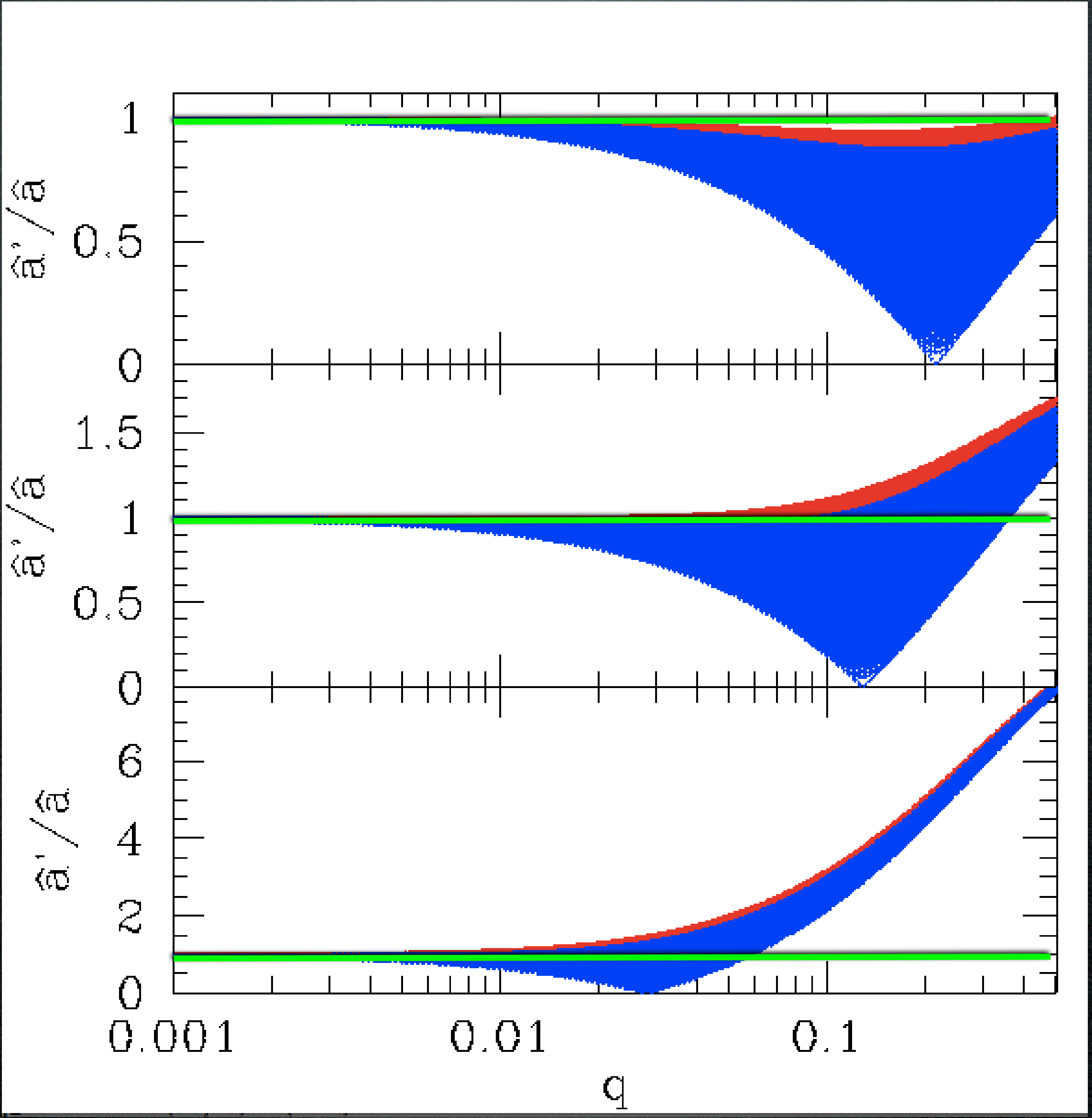
Orbits with random inclination: ***μ***=cos(inclination)

$$\hat{L}_{\rm LSO} = \hat{L}_{\rm LSO}(mu, \hat{a}_1) \qquad \hat{E}_{\rm LSO} = \hat{E}_{\rm LSO}(mu, \hat{a}_1)$$

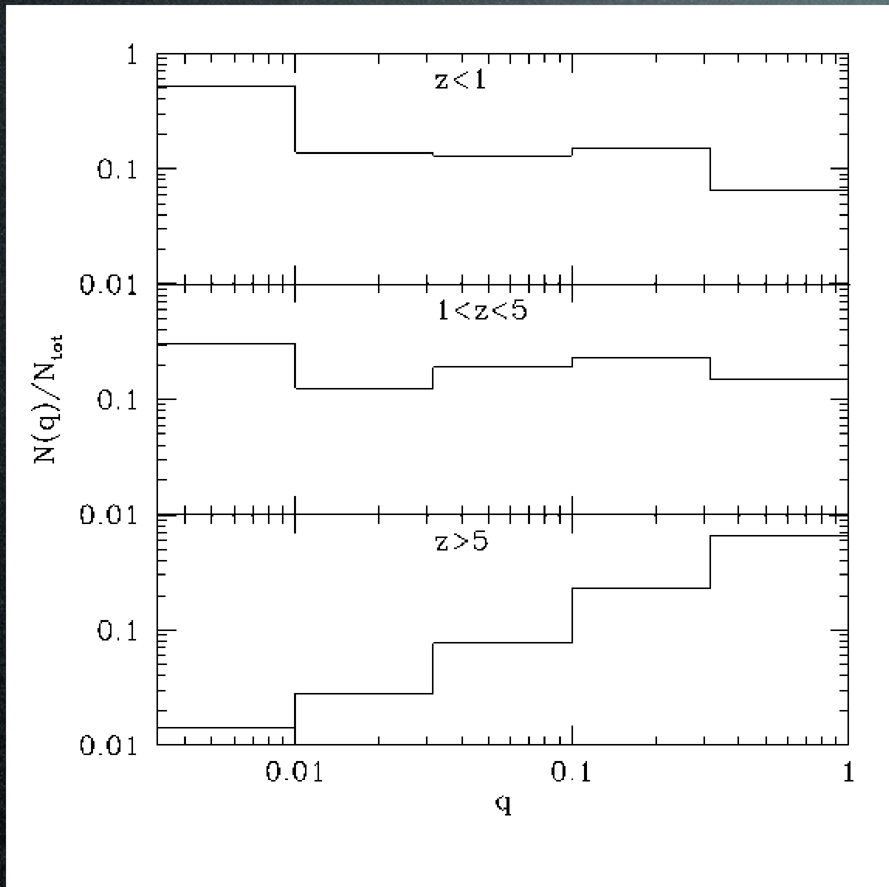
After the merger:

$$S'_z = m_1^2[\hat{a}_1 + q\mu|\hat{L}(\hat{a}_1, \mu)|] \qquad S'_\perp = q m_1^2 |\hat{L}(\hat{a}_1, \mu)|\sqrt{1 - \mu^2}$$

$$\hat{a}' \simeq \frac{\sqrt{S'^2_z + S'^2_\perp}}{(1+q)^2 m_1^2} \qquad \hat{a}'^2 \simeq \frac{\hat{a}_1^2 + q|L|(q|L| + 2\hat{a}_1\mu)}{(1+q)^4}$$

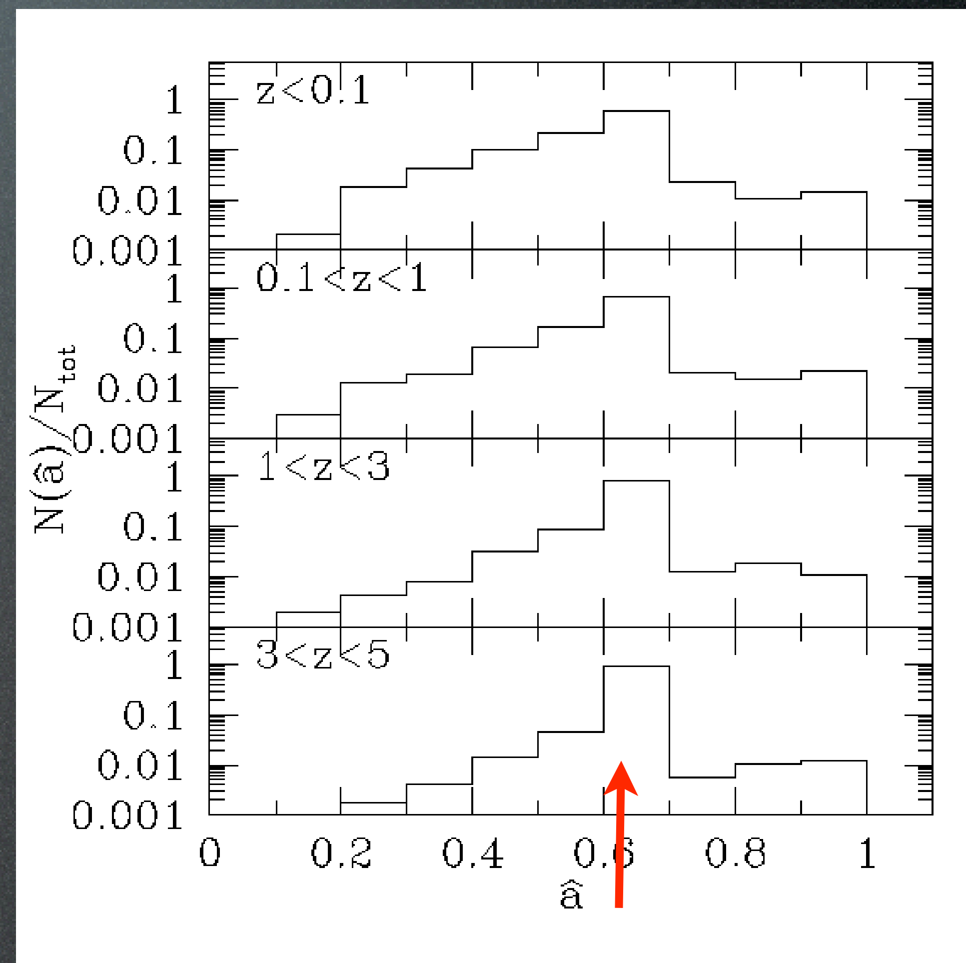


1
0.5
0
1.5
1
0.5
0
6
4
2
0
0.001
0.01
0.1
q
â' / â
â' / â
â' / â

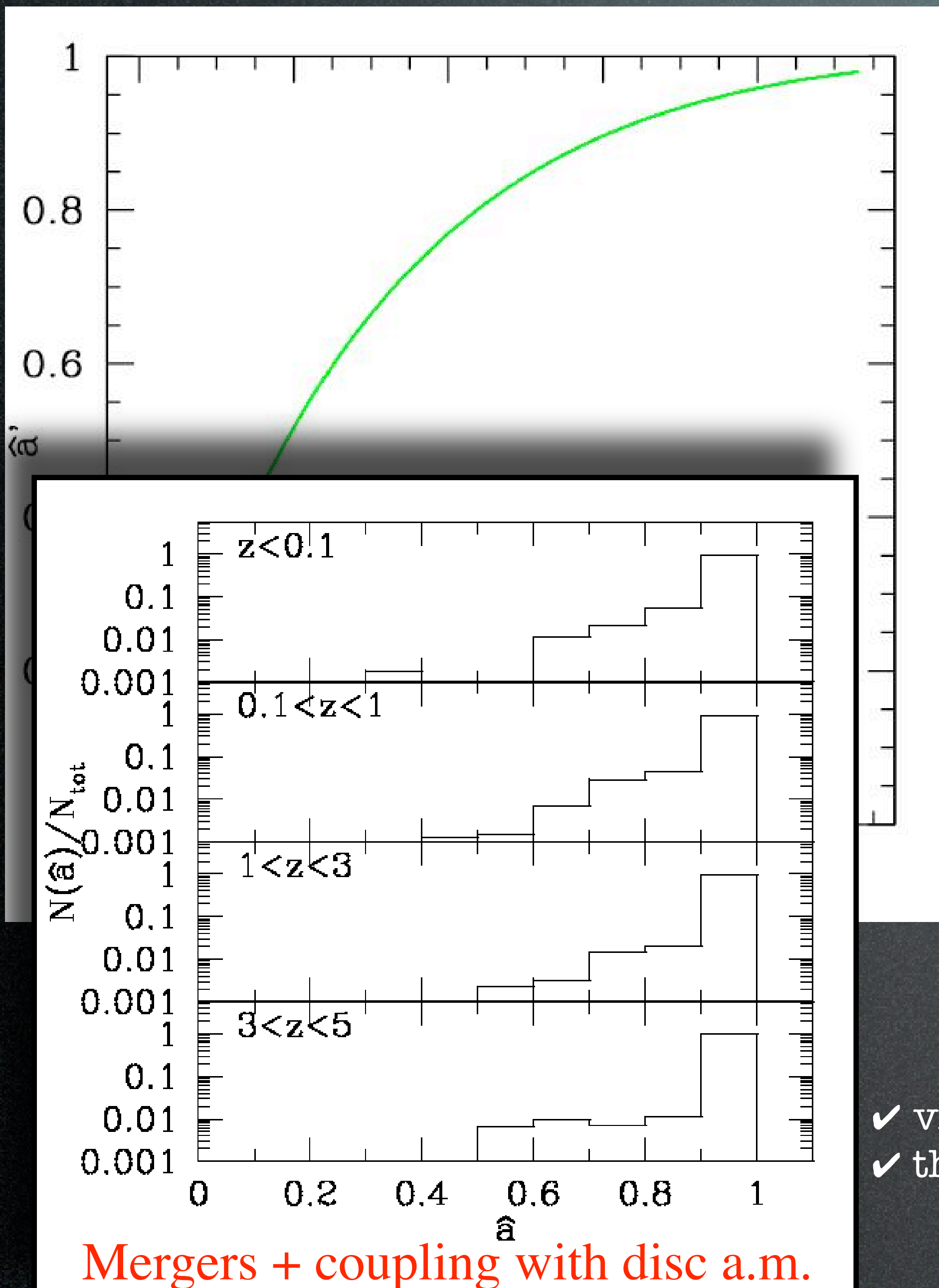


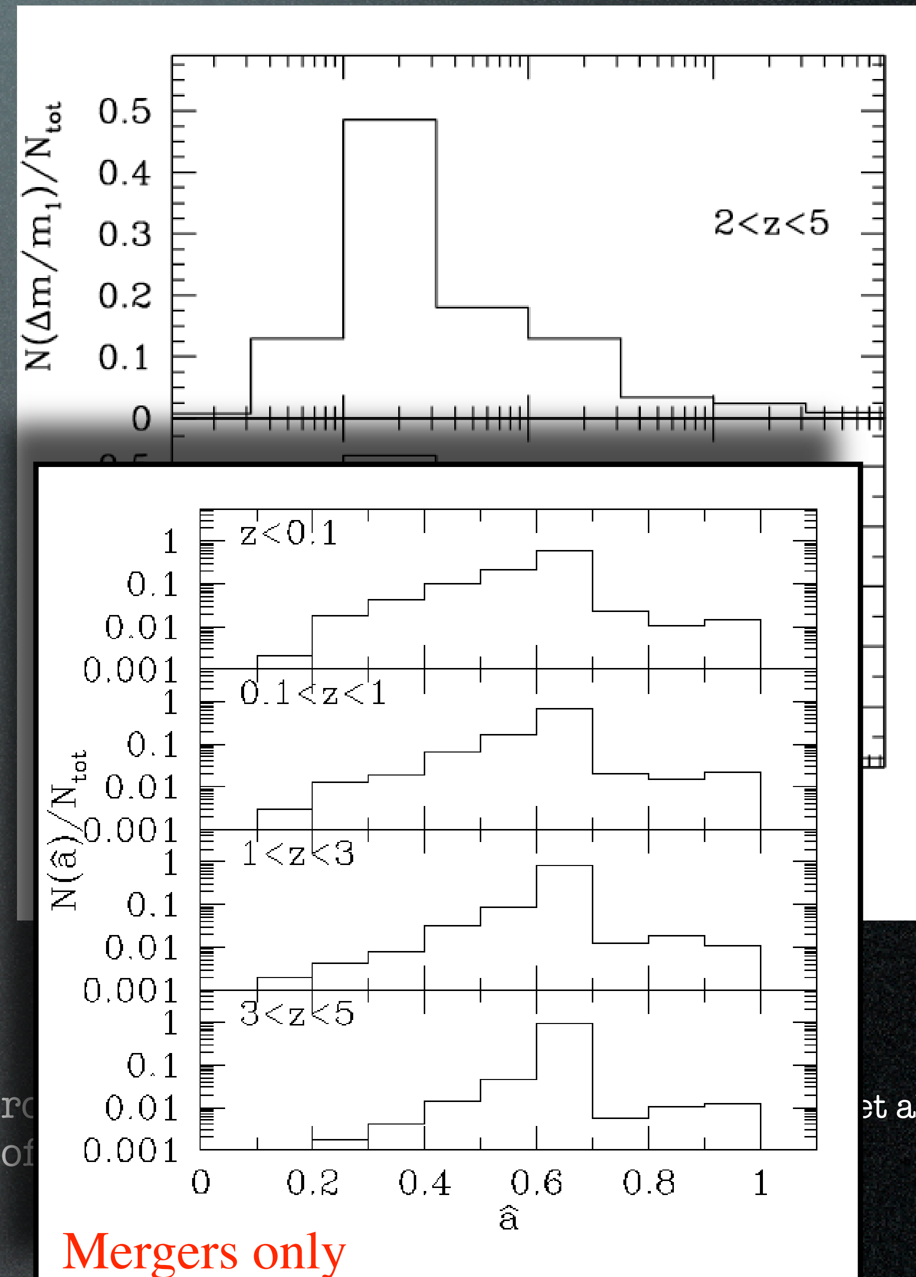

Distribution of black hole mass ratios from the whole cosm. evolution q=m2/m1<=1

Distribution of black hole spins if only mergers influence them



# Evolution of BH Spins




✔ via bro

✔ the sof

et al 2005)

# Chapter 6

How can we probe SMBH seeds? GW

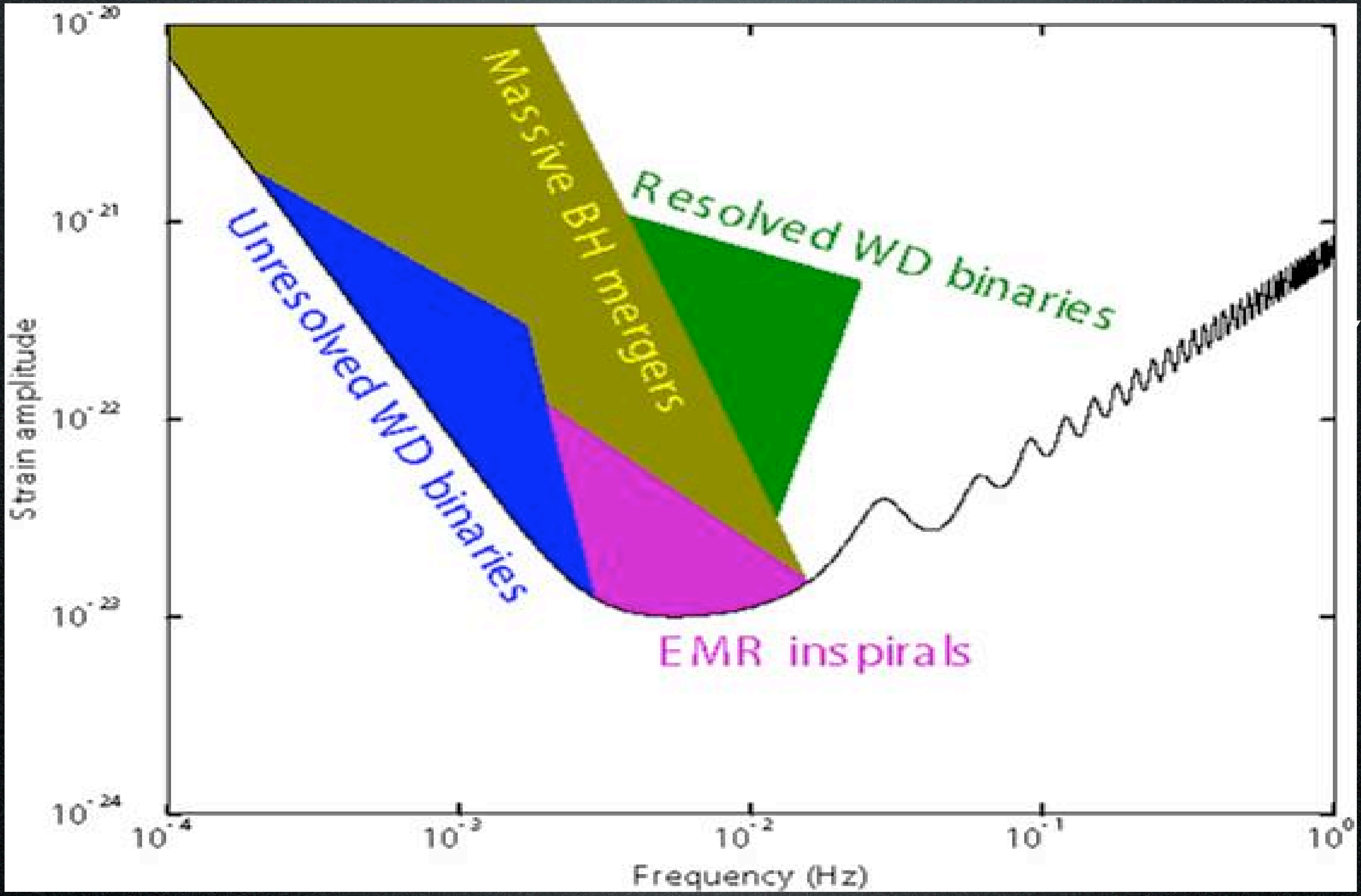
How can we probe SMBH spins? GW

How can we win a Nobel prize? GW ;)

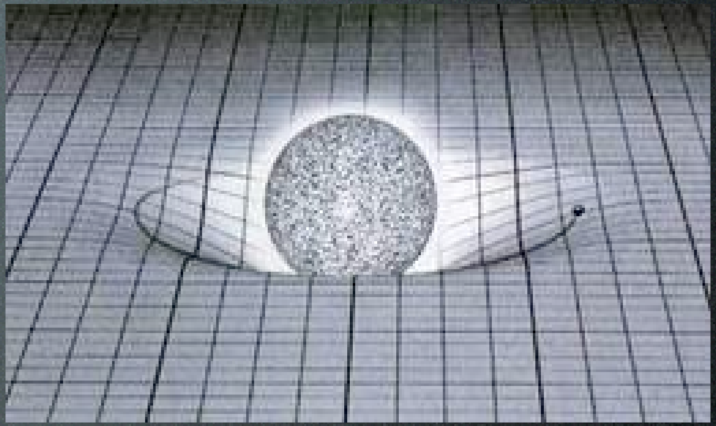
... well if NASA behaves...

# GWs from MBH binaries

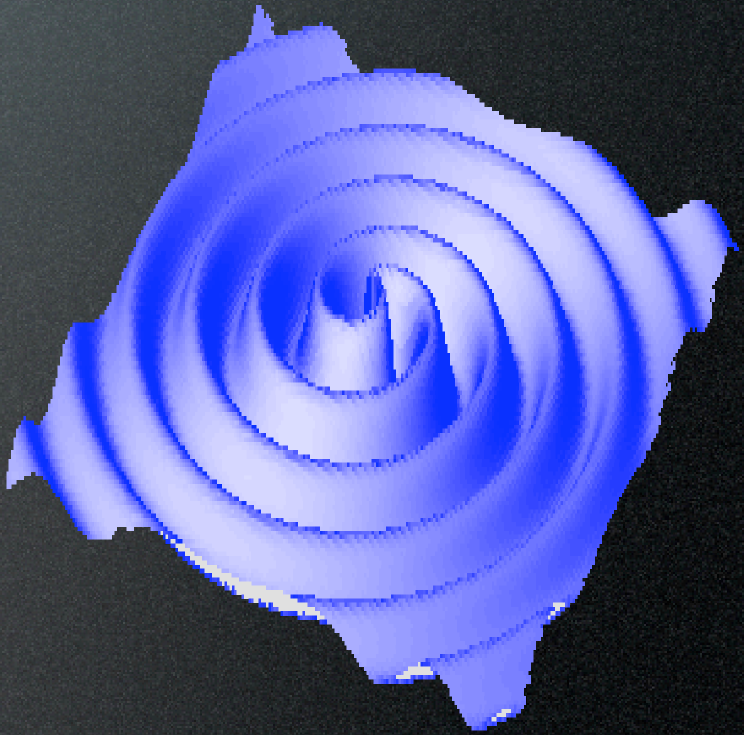
*Fluctuations in spacetime curvature, generated by rapidly accelerating masses: an exciting new window on the Universe to complement electromagnetic observations.*



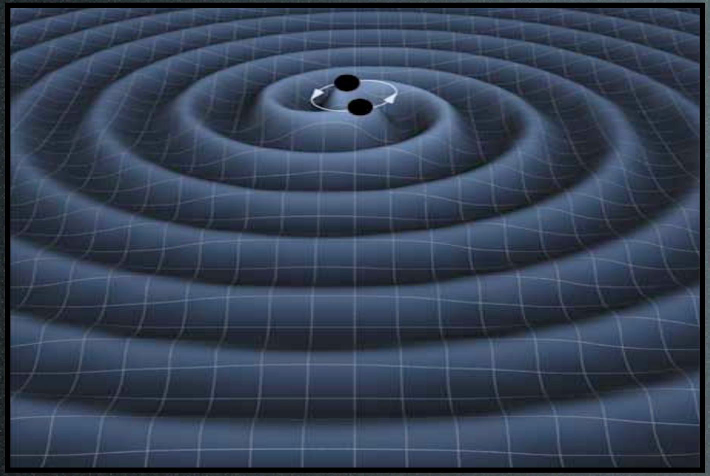
Gravity is spacetime curvature.

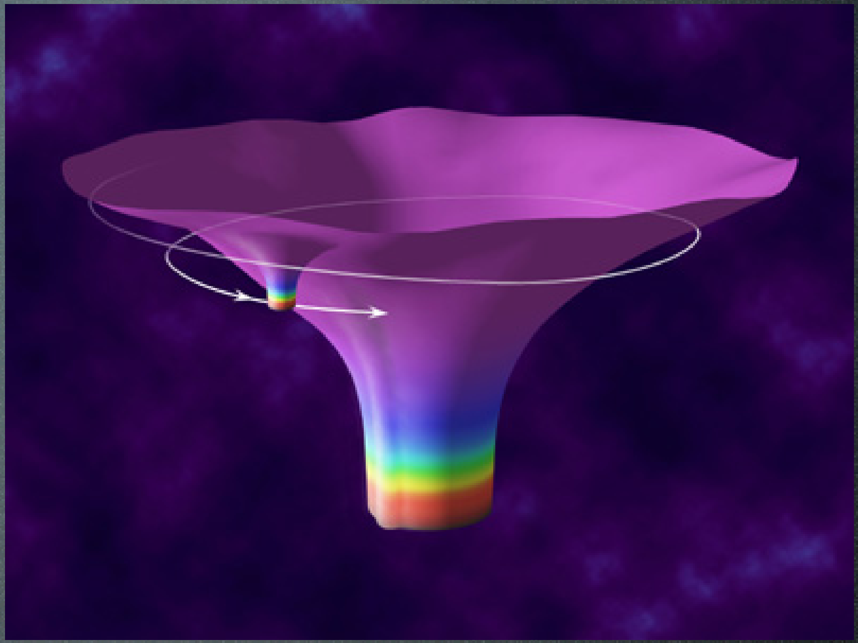


Any mass/energy bends spacetime near it.



Rapidly moving masses generate fluctuations in spacetime curvature: gravitational waves!





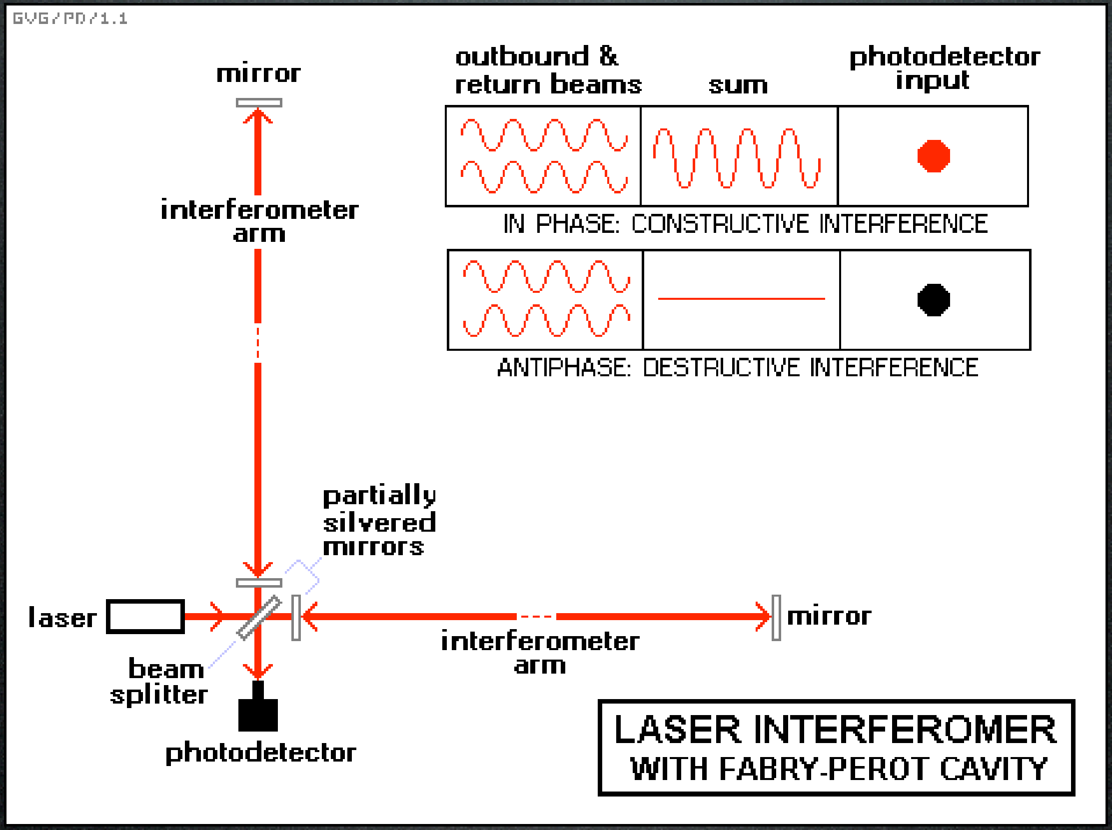
$$f = \frac{2f_{kepler}}{1+z} = \frac{1}{\pi(1+z)} \left( \frac{G(M_1 + M_2)}{r^3} \right)^{1/2}$$

$$r > R_{Sch} = \frac{2G(M_1 + M_2)}{c^2}$$

$$f < \frac{4 \times 10^{-3}}{1+z} \text{Hz} \left( \frac{10^6 M_\odot}{M_1 + M_2} \right)$$

Several **ground based interferometers** are now operating or are being built

Exploit quadrupole nature of GWs – space is distorted in opposite sense in two perpendicular directions – use a Michelson interferometer



Several **ground based interferometers** are now operating or are being built

$L \propto \lambda \propto 1/f$

$h = \Delta L / L \sim 10^{-20}$ $\Delta L = 10^{-15}$ cm !!!

LIGO – US project. Two 4km and one 2km detector

GEO – British/German project. One 600m detector

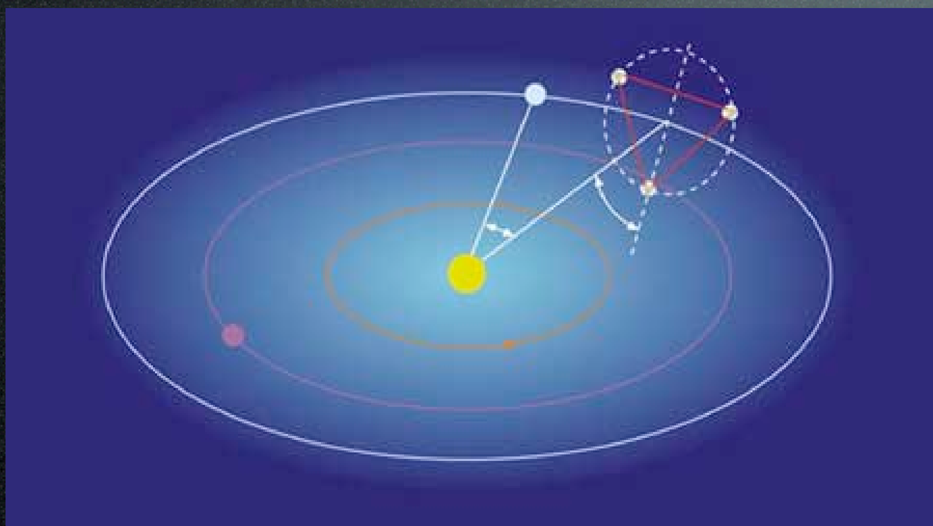
VIRGO – Italian/French project. One 3km detector

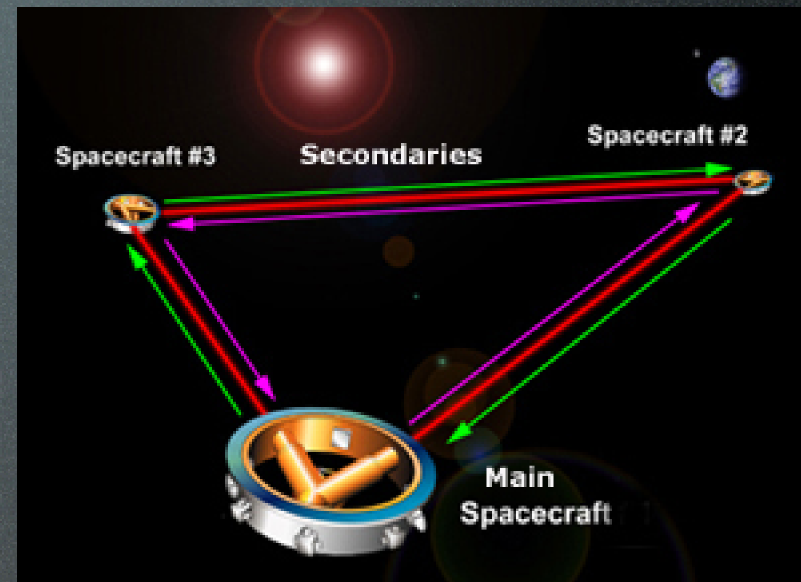
TAMA – Japanese project. One 300m detector

AIGO – Australian project. One 80m detector

# space based interferometer: **LISA**

Joint NASA/ESA mission - launch date is 20??



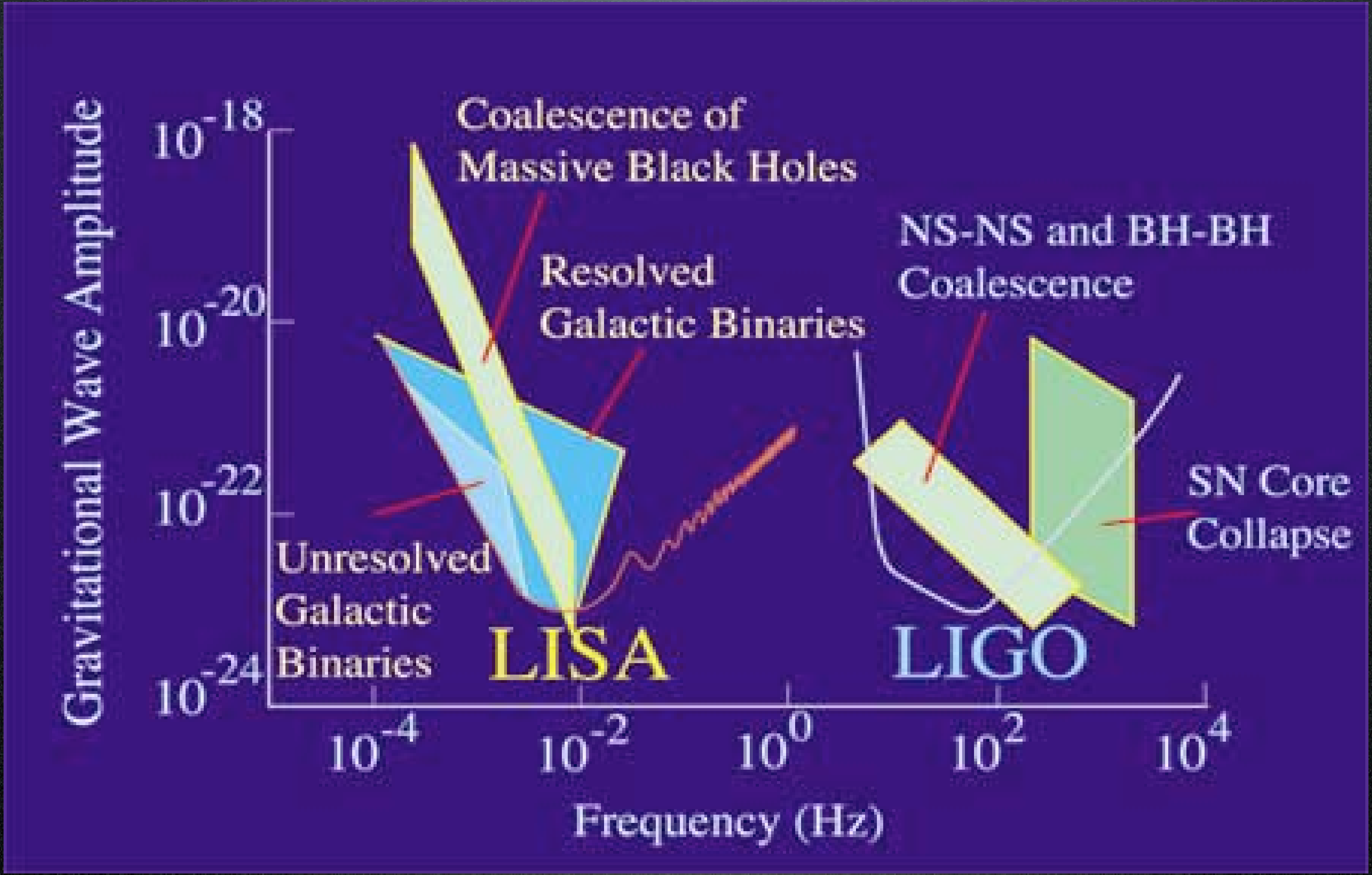



Longer baseline (5 million km) gives sensitivity to lower frequency gravitational waves

$L \propto \lambda \propto 1/f$

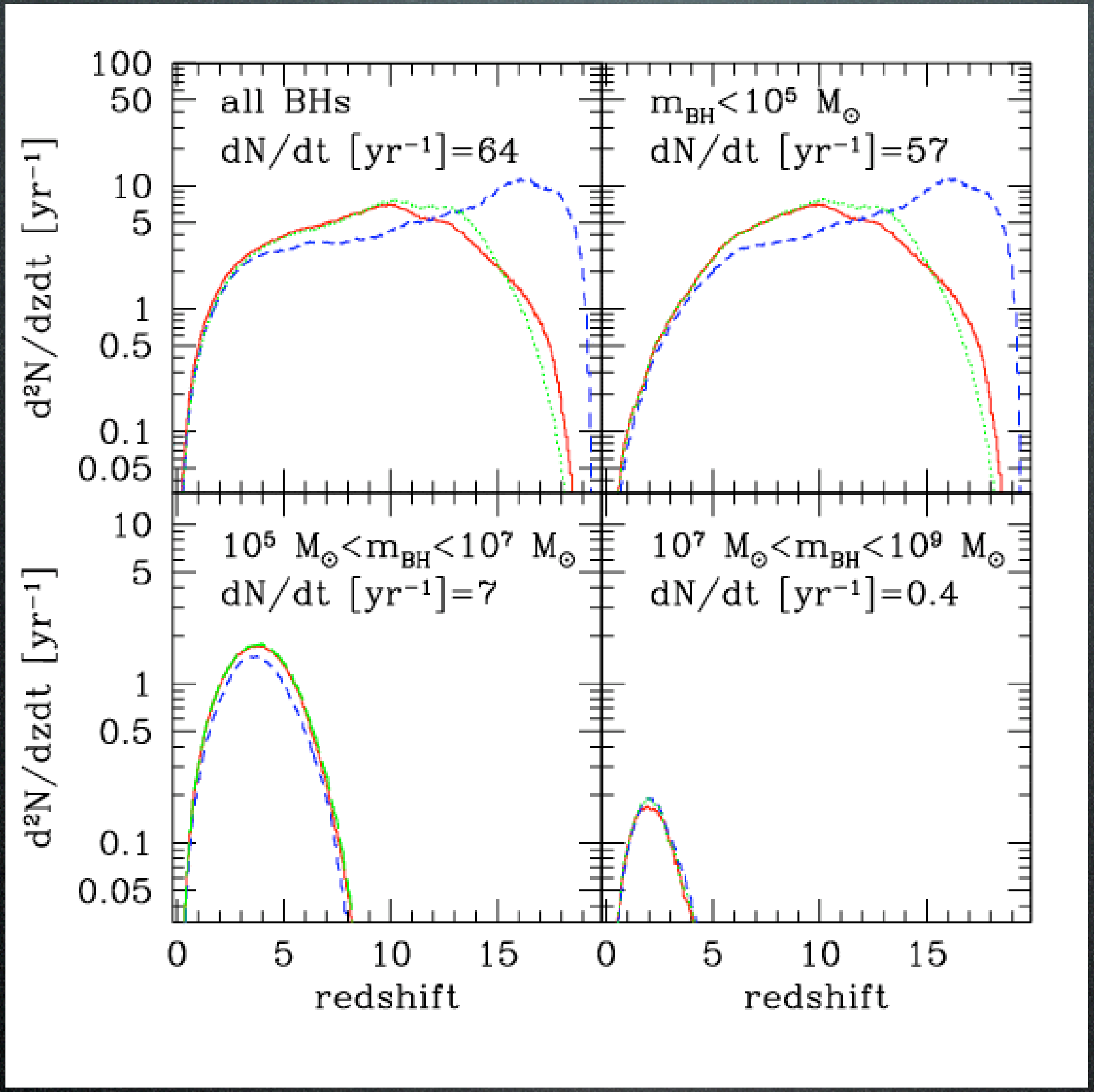
$h=\Delta L/L \sim 10^{-20}$ $\Delta L=10^{-8}$ cm for 5 million km!!!

LISA will be a true GW telescope



Gravitational Wave Amplitude
$10^{-18}$
$10^{-20}$
$10^{-22}$
$10^{-24}$
Coalescence of
Massive Black Holes
Resolved
Galactic Binaries
Unresolved
Galactic
Binaries
LISA
NS-NS and BH-BH
Coalescence
SN Core
Collapse
LIGO
$10^{-4}$
$10^{-2}$
$10^{0}$
$10^{2}$
$10^{4}$
Frequency (Hz)

# SMBH binary merger rate



# Emission spectrum of a MBH binary

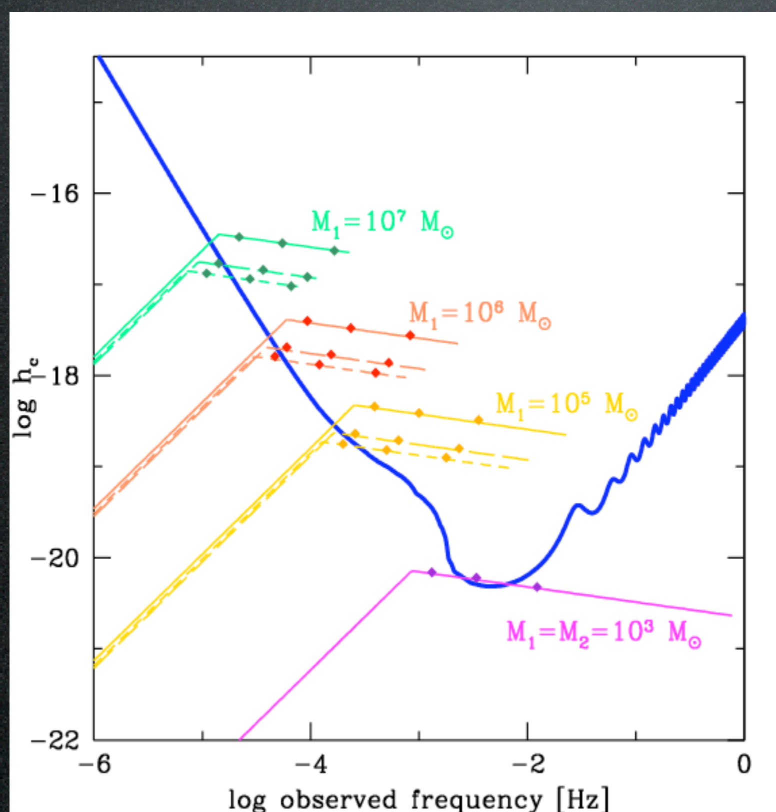
$$h_c^2(f) \propto \left(\frac{dE_{gw}}{df}\, f\right)\, f^{-2}$$

$$\frac{dE_{gw}}{df}\, f = \frac{dE_{gw}}{dt}\, \frac{dt}{dr}\, \frac{dr}{df}\, f.$$

$$\frac{dr}{df}\, f = -\frac{2}{3}\left[\frac{G\,(M_1+M_2)}{\pi^2}\right]^{1/3} f^{-2/3}$$

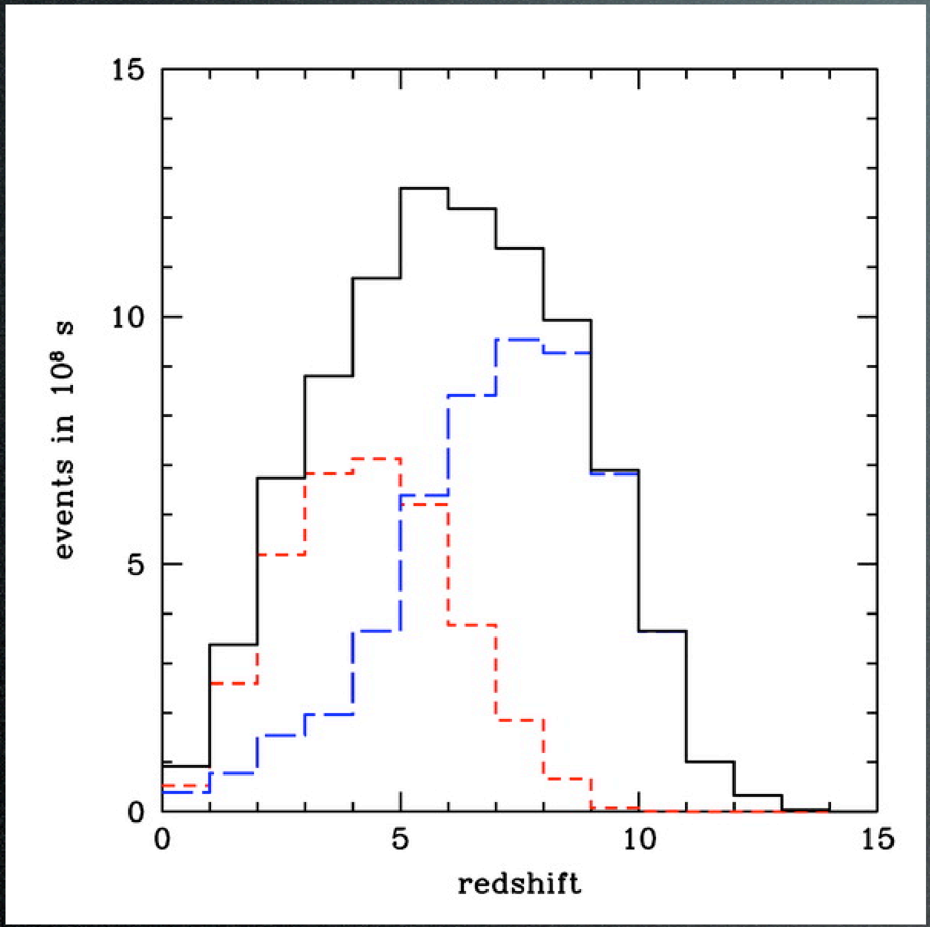
$$L_{gw} = \frac{32\, G^{7/3}\, \pi^{10/3}}{5\, c^5} (\mathcal{M}\, f)^{10/3}$$

$h_c \propto f^{-1/6}$




MBHs M<$10^5$ Msun can be detected up to z=15-20.
Can really distinguish seed models

# Resolvable events in 3 years




Typical masses ~$10^3$-$10^6$ $M_{sun}$

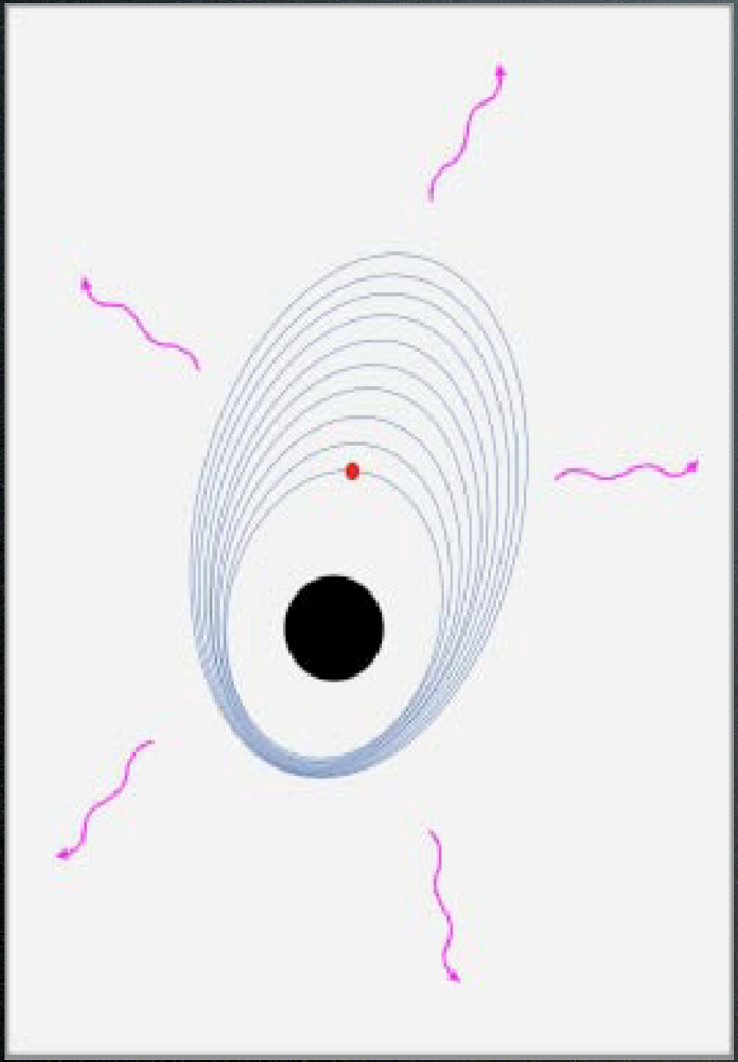
Typical mass ratio ~0.1

Sesana et al. 2004, 2005

Inspirals: longlasting wide binaries, small frequency change

Bursts: binaries coalescing during the observation period

# Extreme mass ratio inspirals



Inspiral of a compact object (WD, NS, BH) into a supermassive black hole in the centre of a galaxy.

LISA can see $10M_{sun}$ + $10^6M_{sun}$ inspiral out to z~2 → can probe SMBH spin evolution if event rate is high enough!!

For a typical event with SNR~30, determine parameters with errors
(Barack & Cutler, Creighton et al.)

$\Delta M \sim 2x10^{-4}$
$\Delta(S/M^2) \sim 10^{-4}$
$\Delta(\ln m) \sim 10^{-4}$
$\Delta(\ln D) \sim 0.05$

# Summary

## SMBHs can be built up from seeds dating back to the end of the cosmological dark ages

- *seed BHs from the first stars, in the highest peaks of density fluctuations at z~20-30*
- *mass accretion onto BHs triggered by major mergers efficiently spins-up black holes*
- *BHs interactions can displace BHs BUT they don't hinder the assembly of low-z SMBHs*
- *z=6 SDSS quasars require a large and quick mass build up: the early evolution can proceed differently - and more rapidly - in the most massive metal free halos: supercritical accretion*
- *If accretion is limited to the Eddington value dynamical effects must be mild*