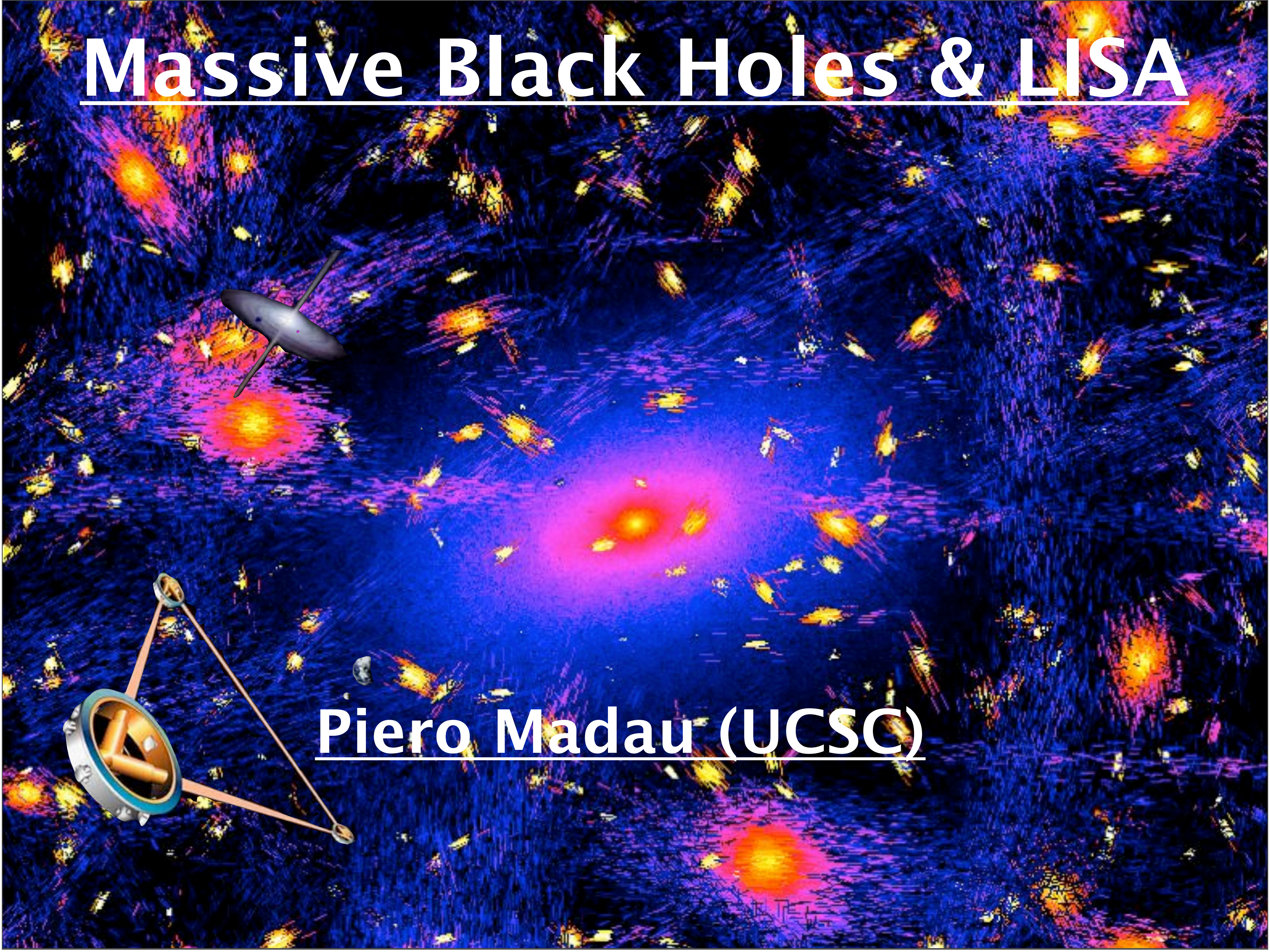
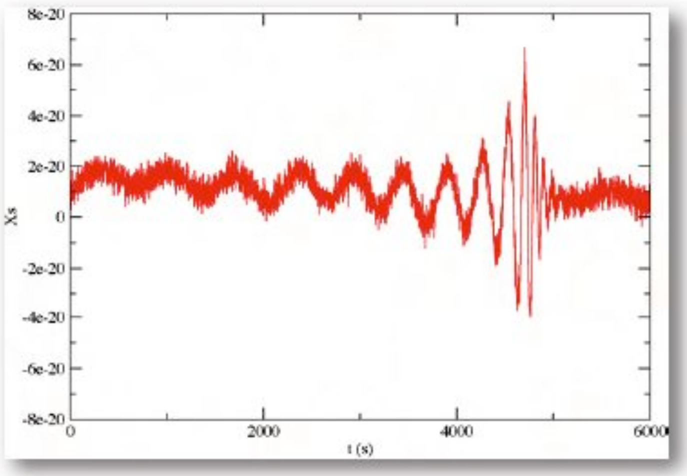
Massive Black Holes & LISA



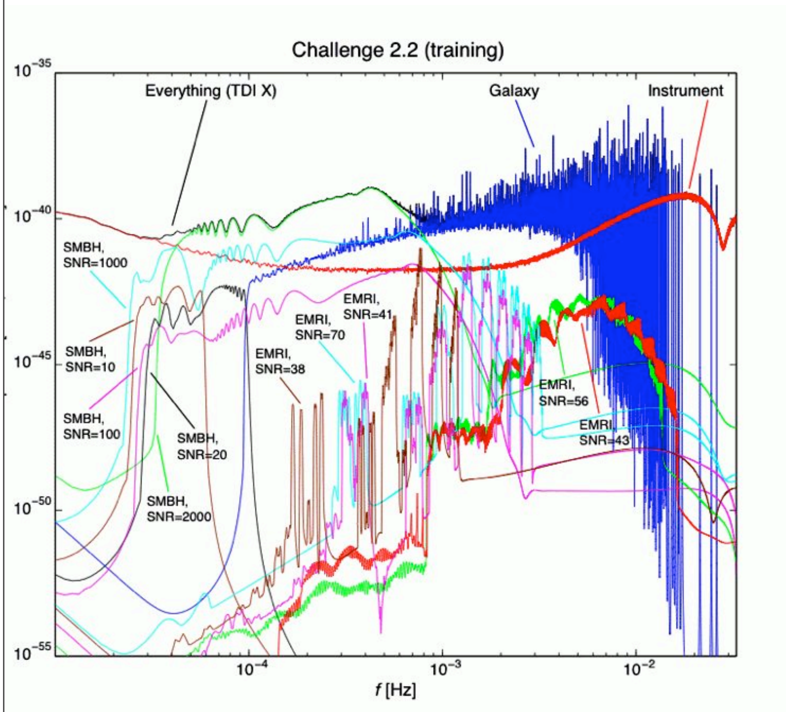
Piero Madau (UCSC)

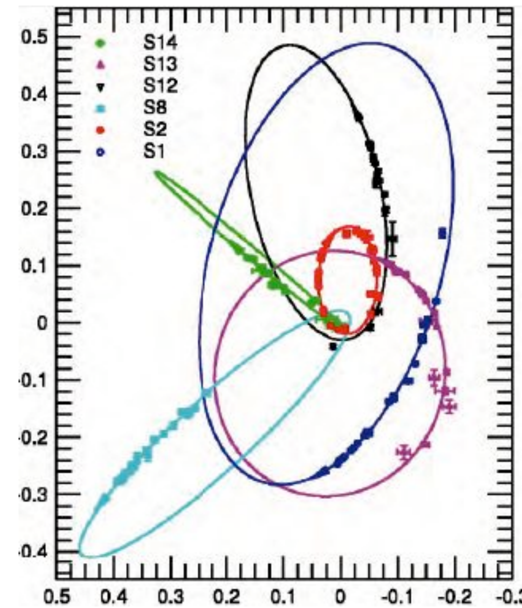
LISA as an "Observatory for Galaxy Formation"

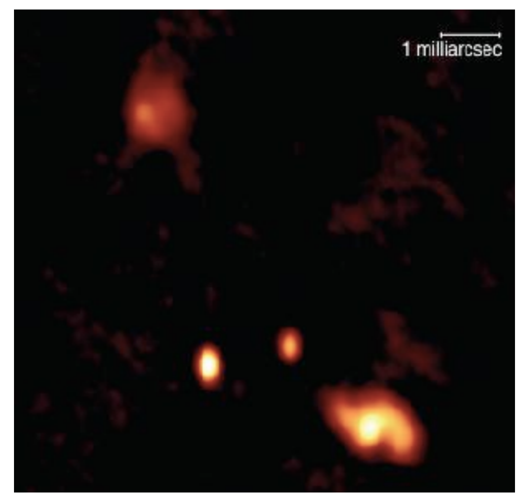


Impact of LISA on our understanding of:

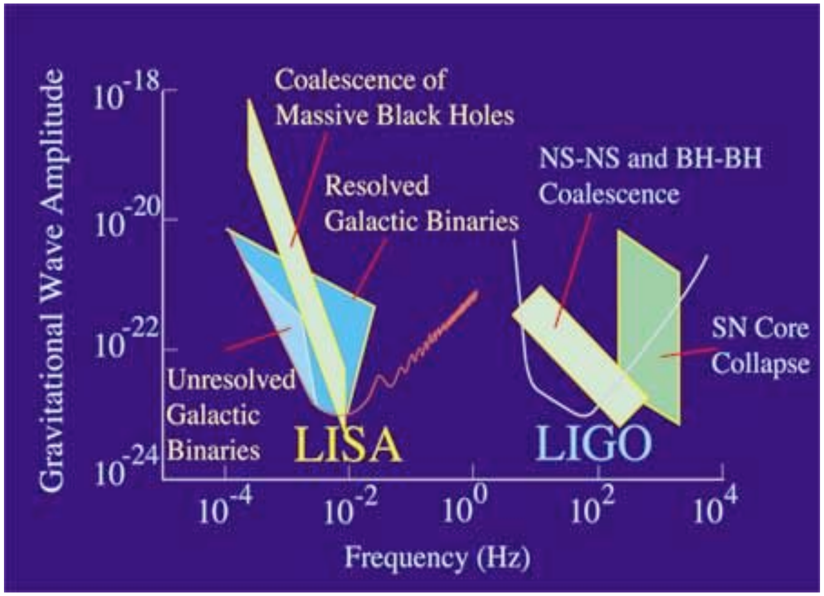
- **Epoch of First Light in the Universe**
- **Building blocks of galaxies**
- **Merger history of galaxies and associated MBHs**
- **Mechanisms that build SMBHs out of small initial "seeds"**

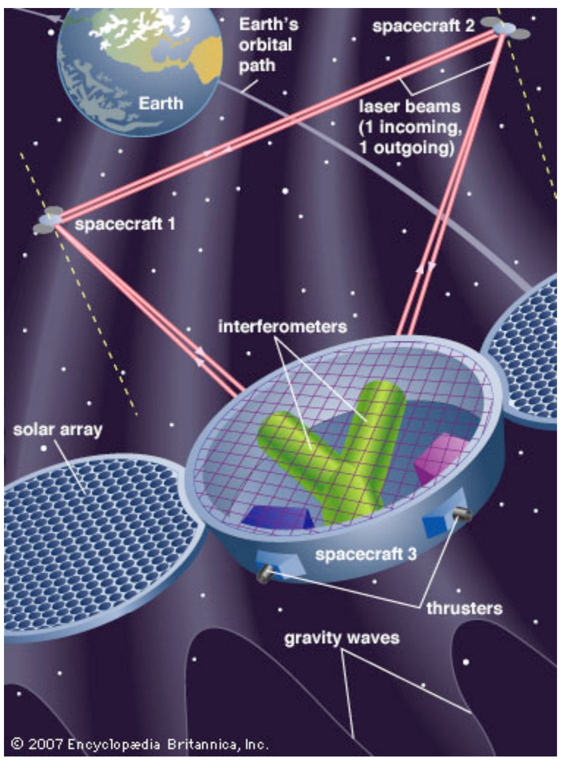


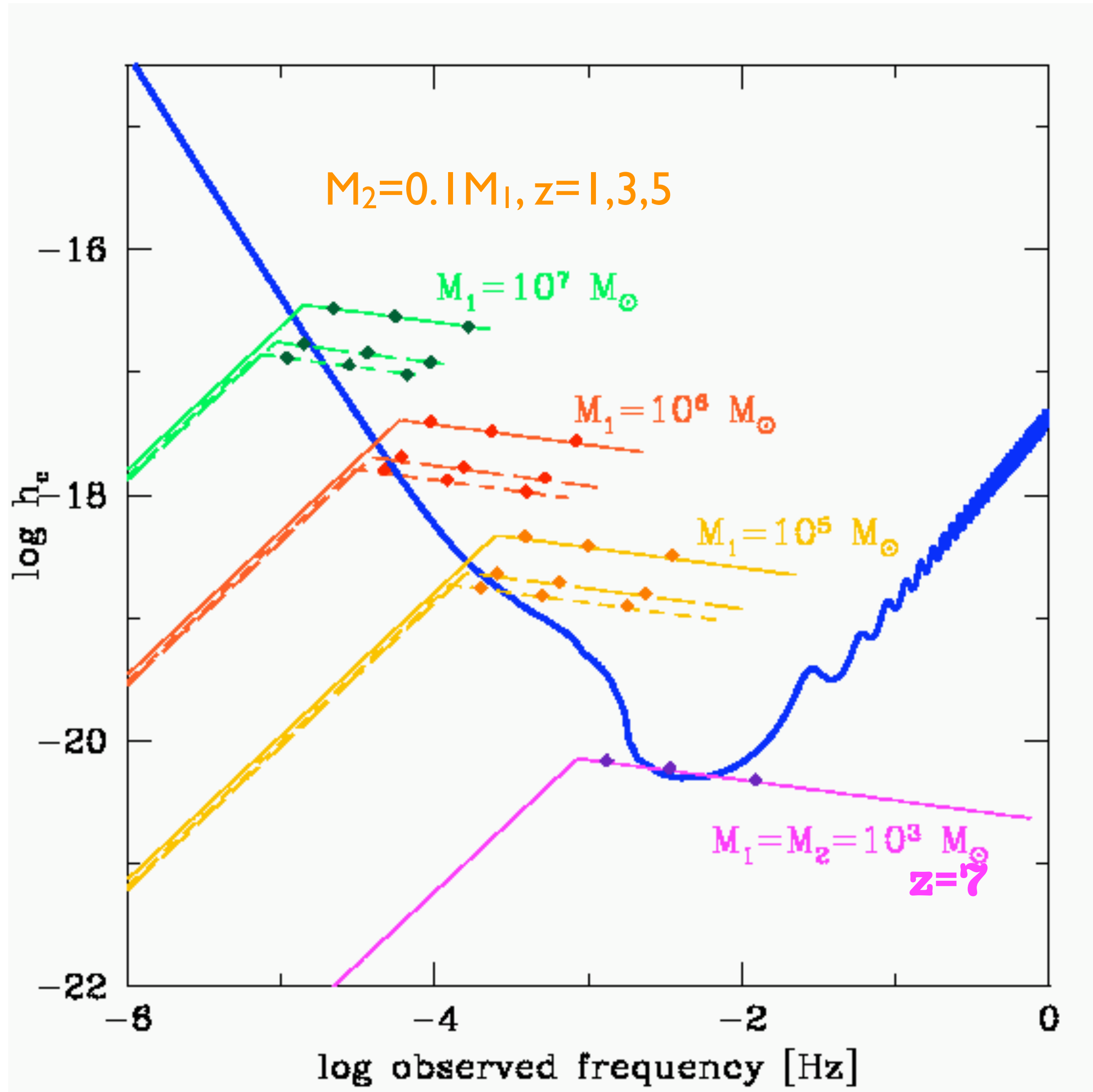




Laser Interferometer Space Antenna







Near-ubiquity of MBHs in the local Universe

Giant Ellipticals/S0s

Yes

Spirals

Yes but BH mass scales with bulge σ*

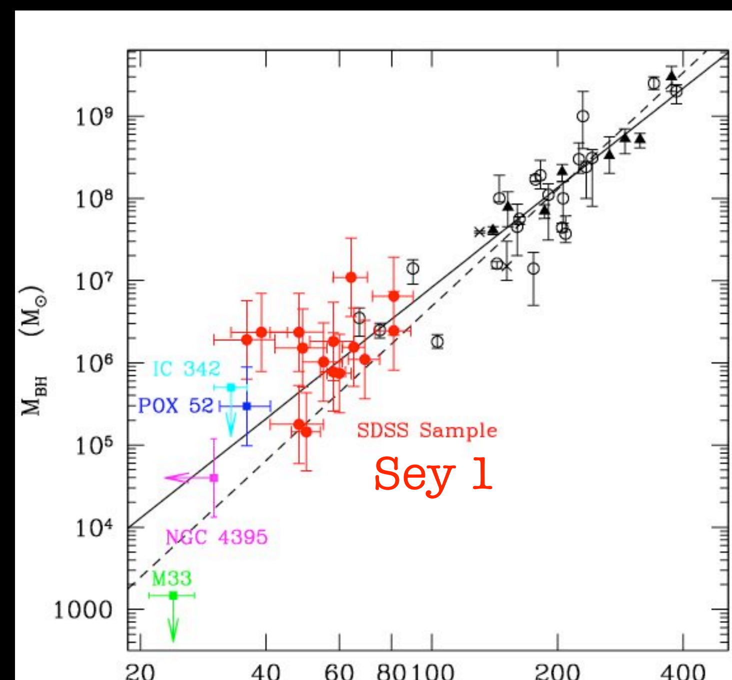
Dwarfs

Some

Globular Clusters

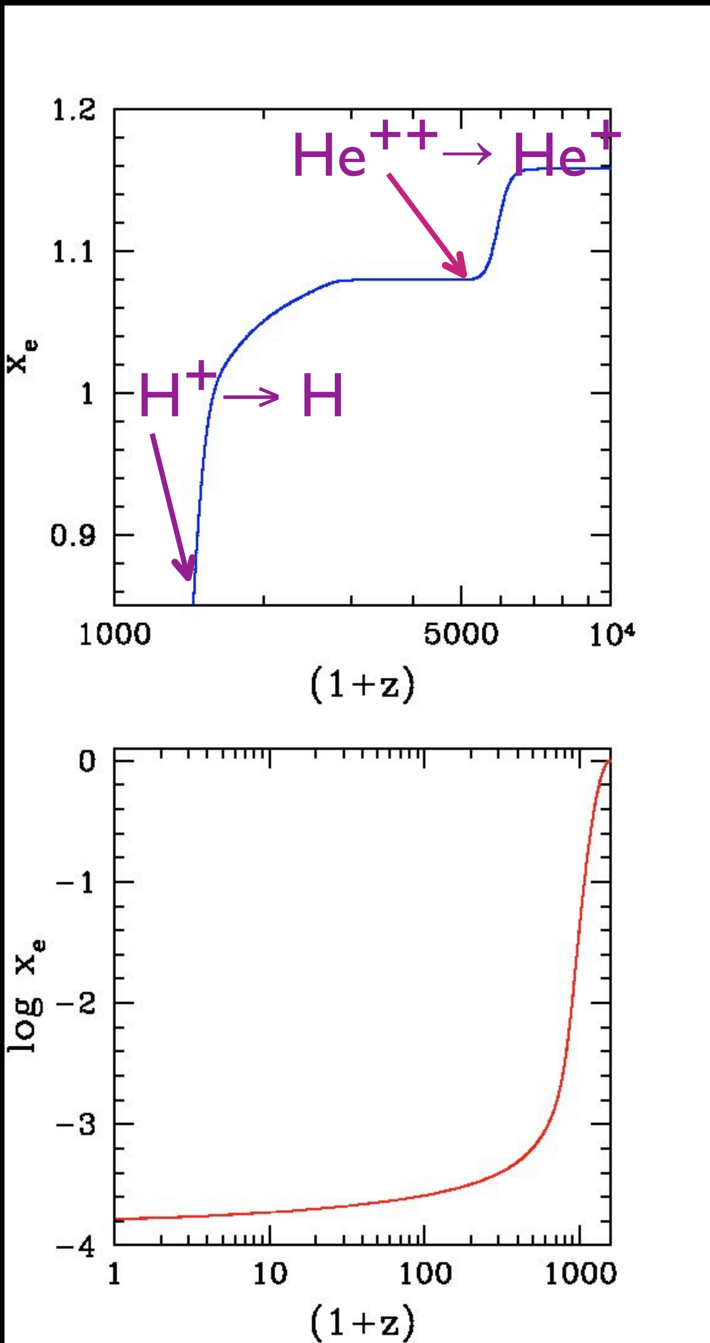
Maybe

MBHs: generic by-product of galaxy formation with $M_{BH} \approx 0.2\% \, M_{host}$. MBHs become less common at low M_{host}



Barth+ 05

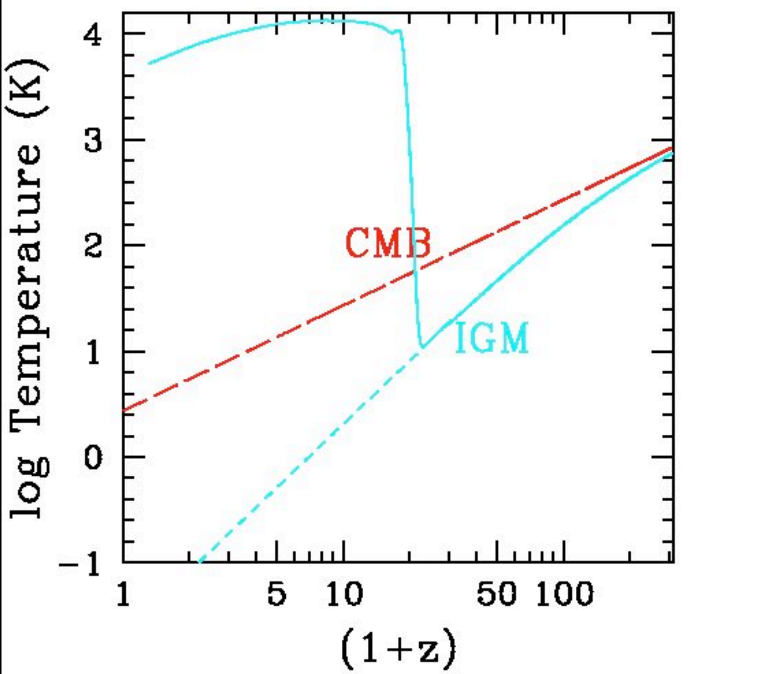
The post-recombination Universe

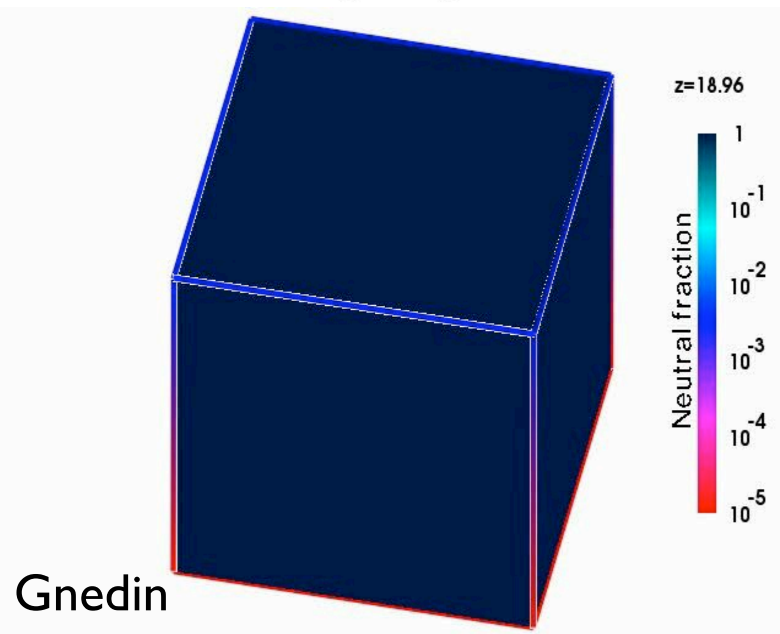


@ z=1090, t=370,000 yr after big bang, Universe becomes optically thin to Thomson scattering

at this epoch the electron fraction x_e drops below 13% and CMB cools below 3000 K

we understand the microphysics at these very early stages well: recombination freezes out with $x_e \approx 2 \times 10^{-4}$





residual e^- keeps $T_{IGM}=T_{CMB}$ until $z_{th}\approx150$ (age=10 Myr)

$T_{IGM}(z<z_{th})\propto(1+z)^2$

Universe becomes semi-opaque again after reionization. WMAP scattering opacity $\tau_e=0.09$ ⇨ $z_{rei}=11\pm1.4$ (age=400 Myr)

⇨ significant star-formation activity at very early times!!

unique prediction of CDM: first stars formed @ z>15 in shallow potential wells ($M>10^6\ M_\odot$, gas coolant=H_2)

⇨ it is this first stellar systems, accompanied perhaps by early accreting MBHs in their nuclei, that reheated and reionized the cosmos.

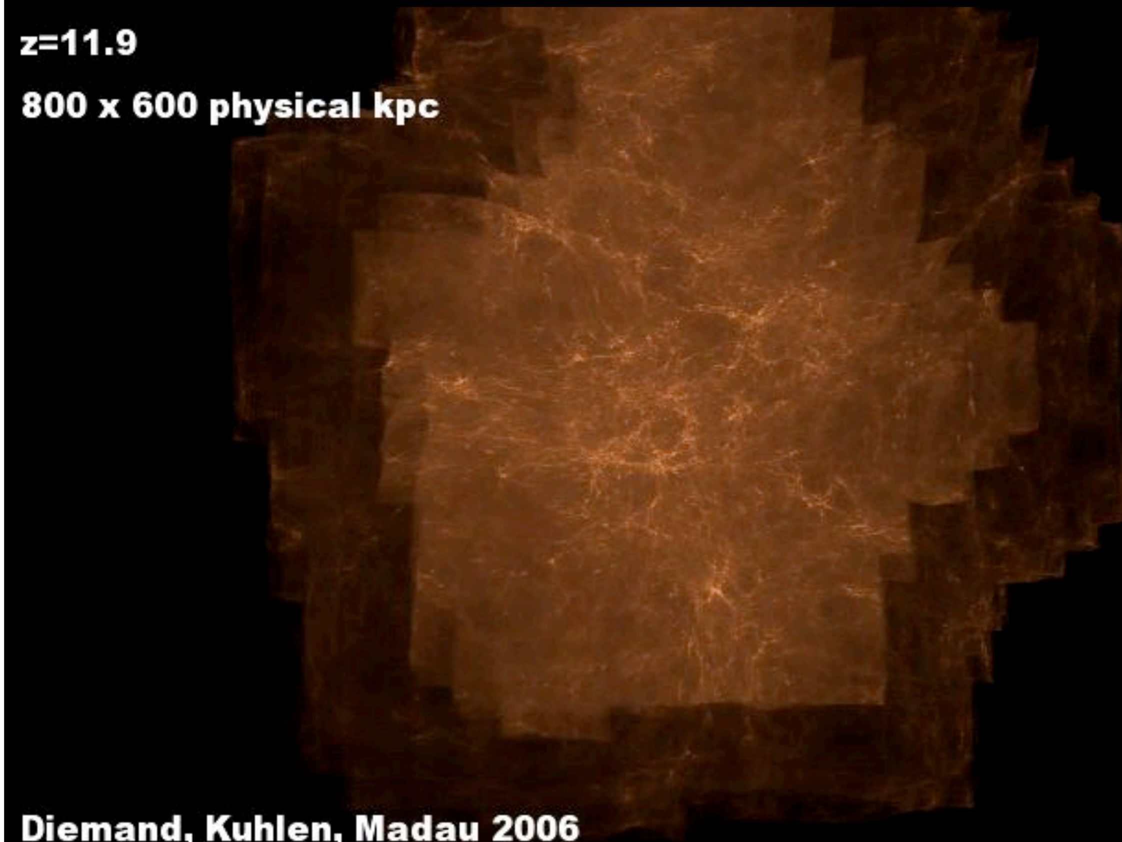
Hierarchical structure formation

Also unique prediction of CDM: galaxies form hierarchically, with low-mass "halos" collapsing earlier and merging to form larger and larger systems over time.

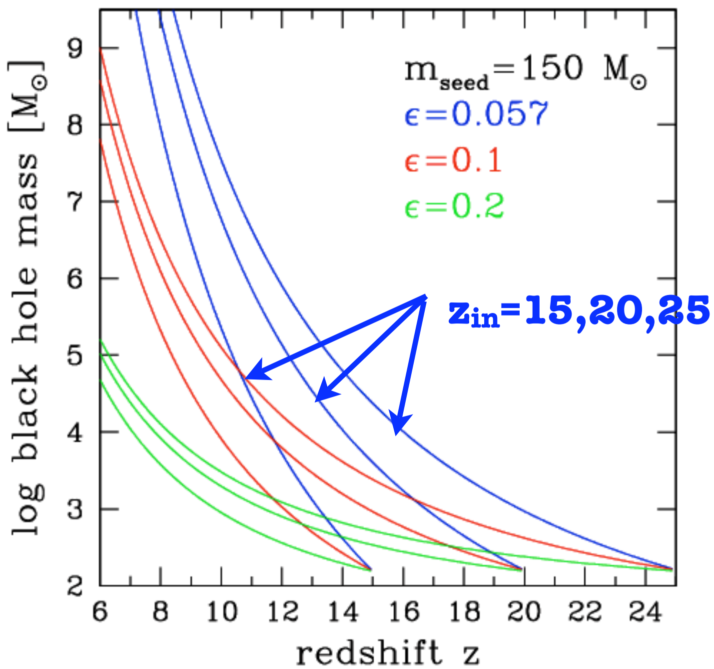
Q: Did the first MBHs form in subgalactic units far up in this merger tree?

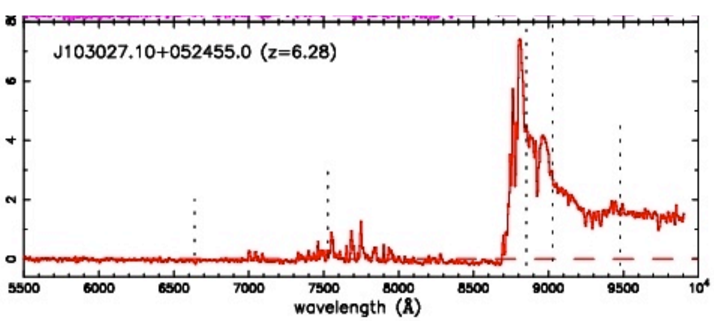
And how massive were the initial "seeds"?

Are there thousands of 10^3–10^4 IMBHs "wandering" in the halo of the Milky Way today?



Growth by gas accretion: the stellar evolution or "petite" route





$$L_{\rm Edd} = \frac{4\pi G c m_p}{\sigma_T} M_{\rm BH} = \epsilon \dot{M}_{\rm acc} c^2$$

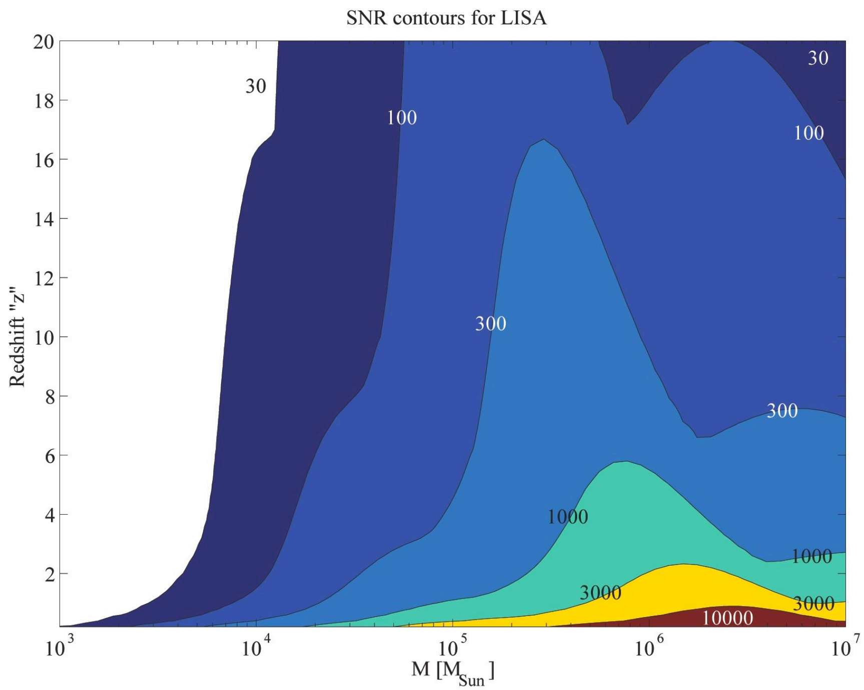
ε=radiation efficiency

$$M_{\rm BH} = m_{\rm seed} e^{t/t_{\rm Edd}}$$

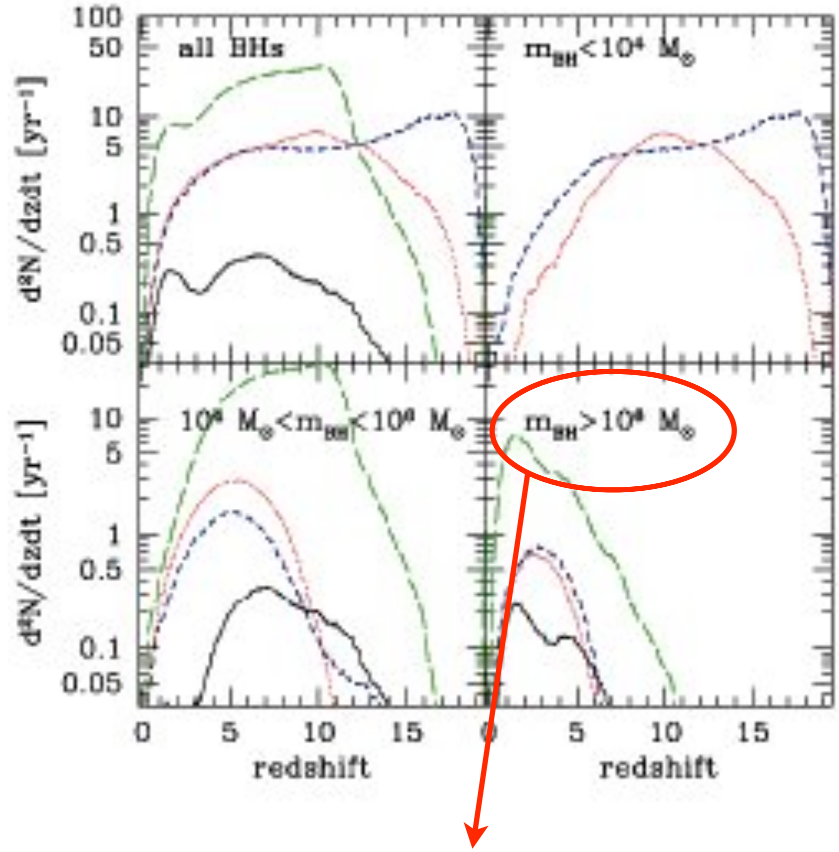
$$t_{\rm Edd} \equiv 450\,{\rm Myr}\,\frac{\epsilon}{1-\epsilon}$$

$\ln(M_{BH}/m_{seed})$= $\ln(3\times10^9/150)$=17 e-foldings

rotating seeds may have grown to 10^4–10^5 $M_\odot$ by redshift z=6–15

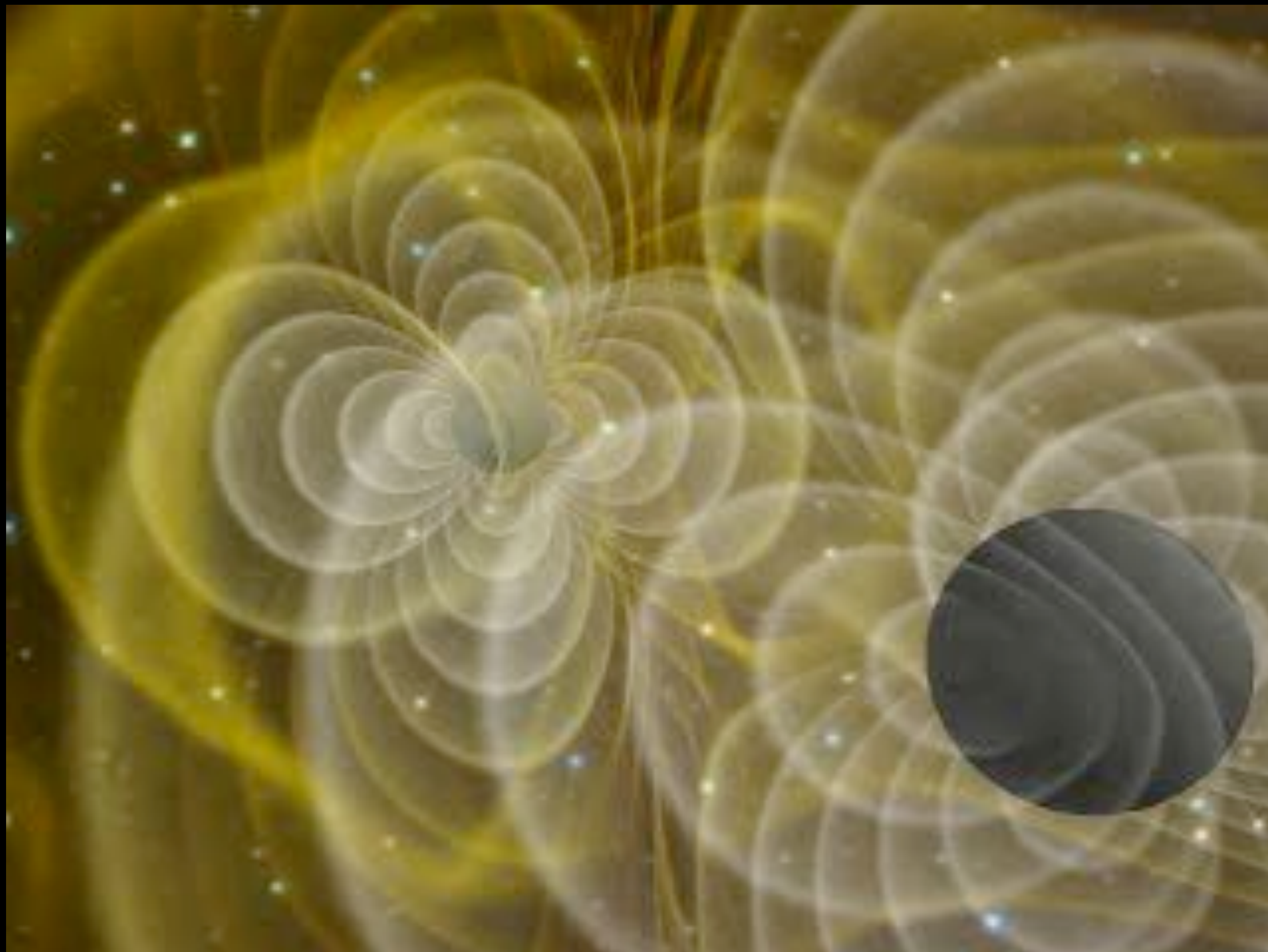


MBH merger rates are very uncertain!



M_1	M_2	D_L Uncertainty	Spin Uncertainty	SNR
1.00E+04	3.00E+02	31.90%	0.012	10.80
	1.00E+03	34.10%	0.029	18.50
	3.00E+03	43.20%	0.070	30.90
	1.00E+04	41.10%	0.115	47.90
3.00E+04	3.00E+02	28.50%	0.005	14.90
	1.00E+03	26.80%	0.008	26.40
	3.00E+03	25.00%	0.016	45.30
	1.00E+04	24.20%	0.041	79.50
1.00E+05	3.00E+02	31.70%	0.005	14.60
	1.00E+03	23.30%	0.006	27.80
	3.00E+03	20.20%	0.008	46.00
	1.00E+04	19.30%	0.020	75.00
3.00E+05	3.00E+03	22.50%	0.016	10.20

Hughes 2007

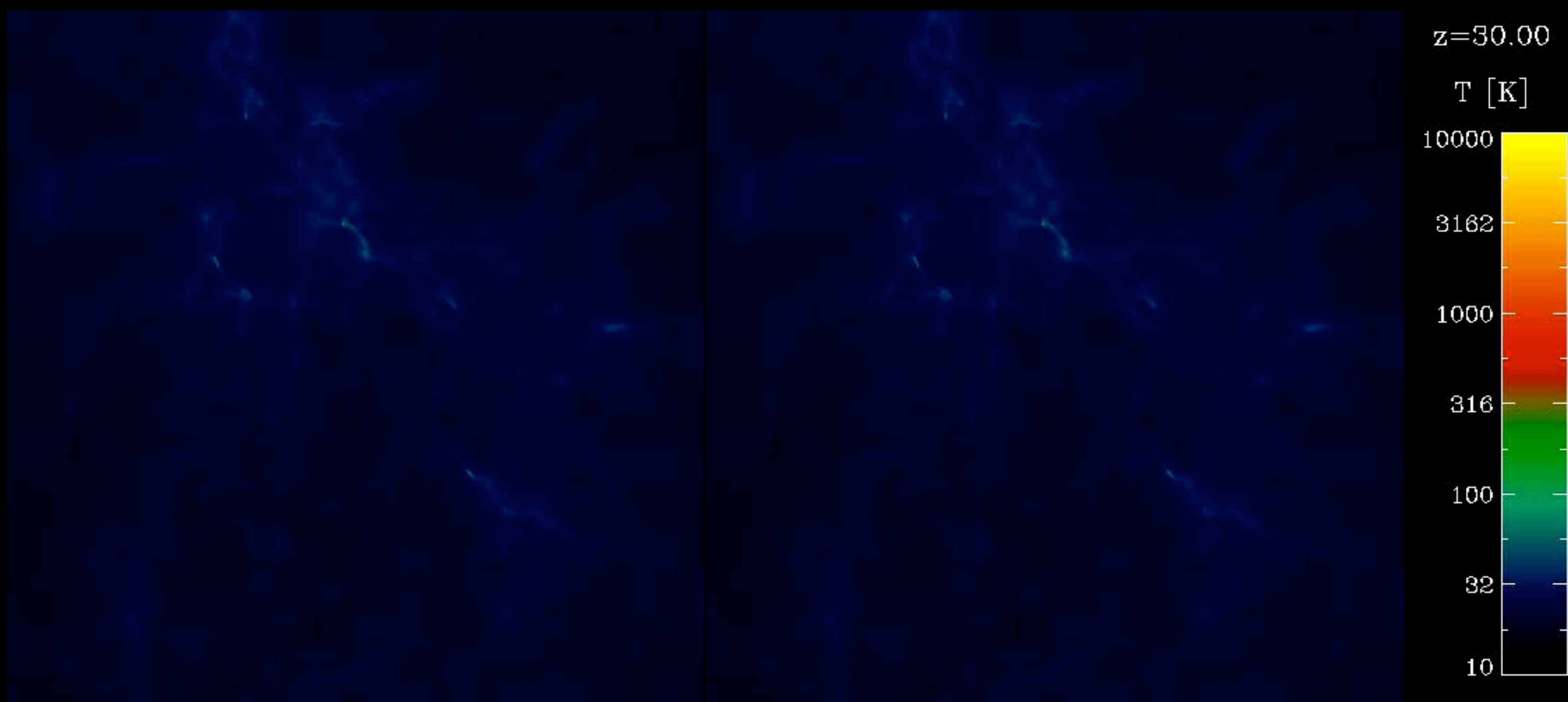


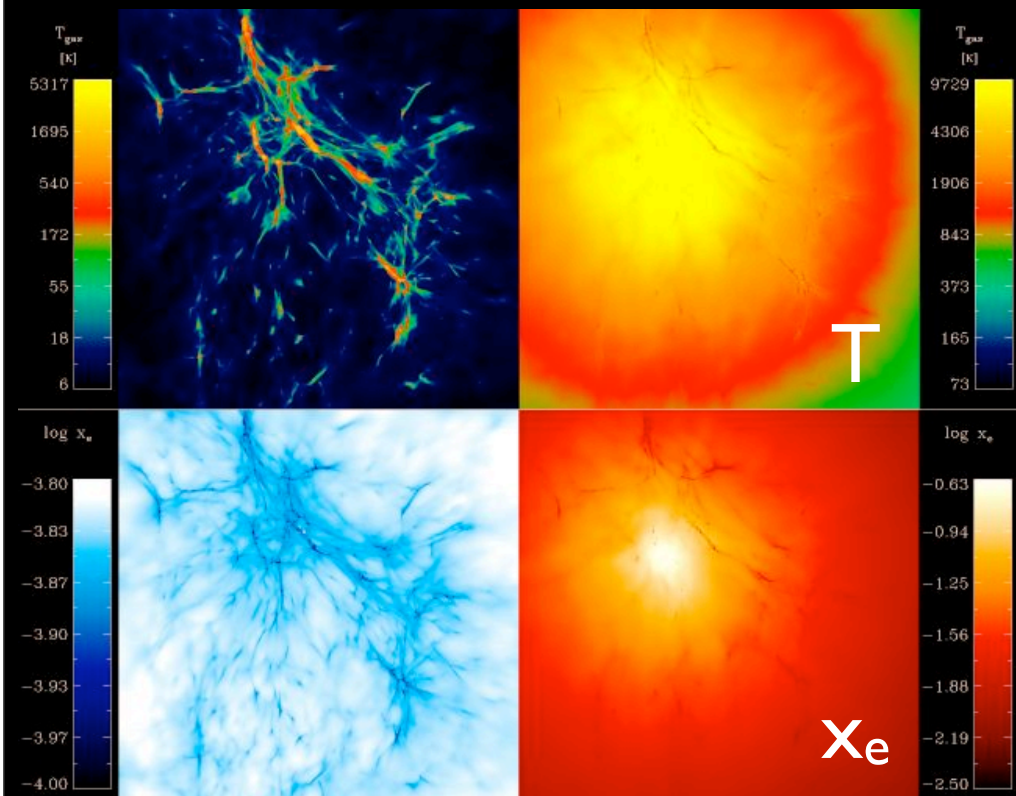
http://web.mit.edu/sahughes/www/sounds.html

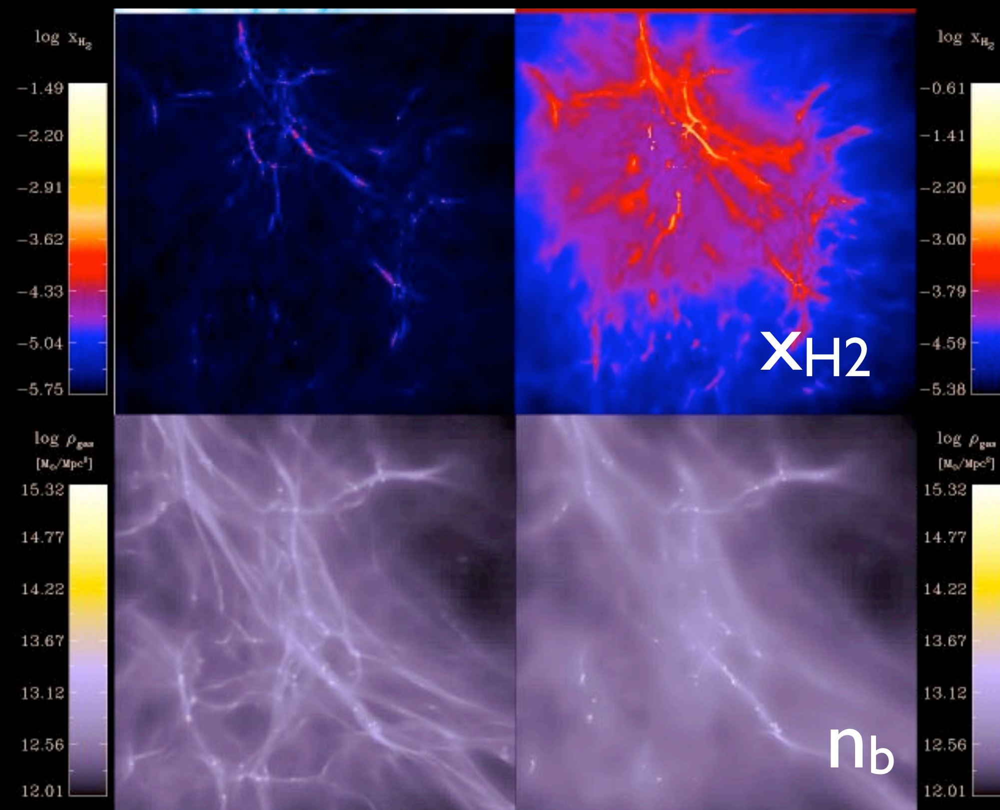
The epoch of First Light

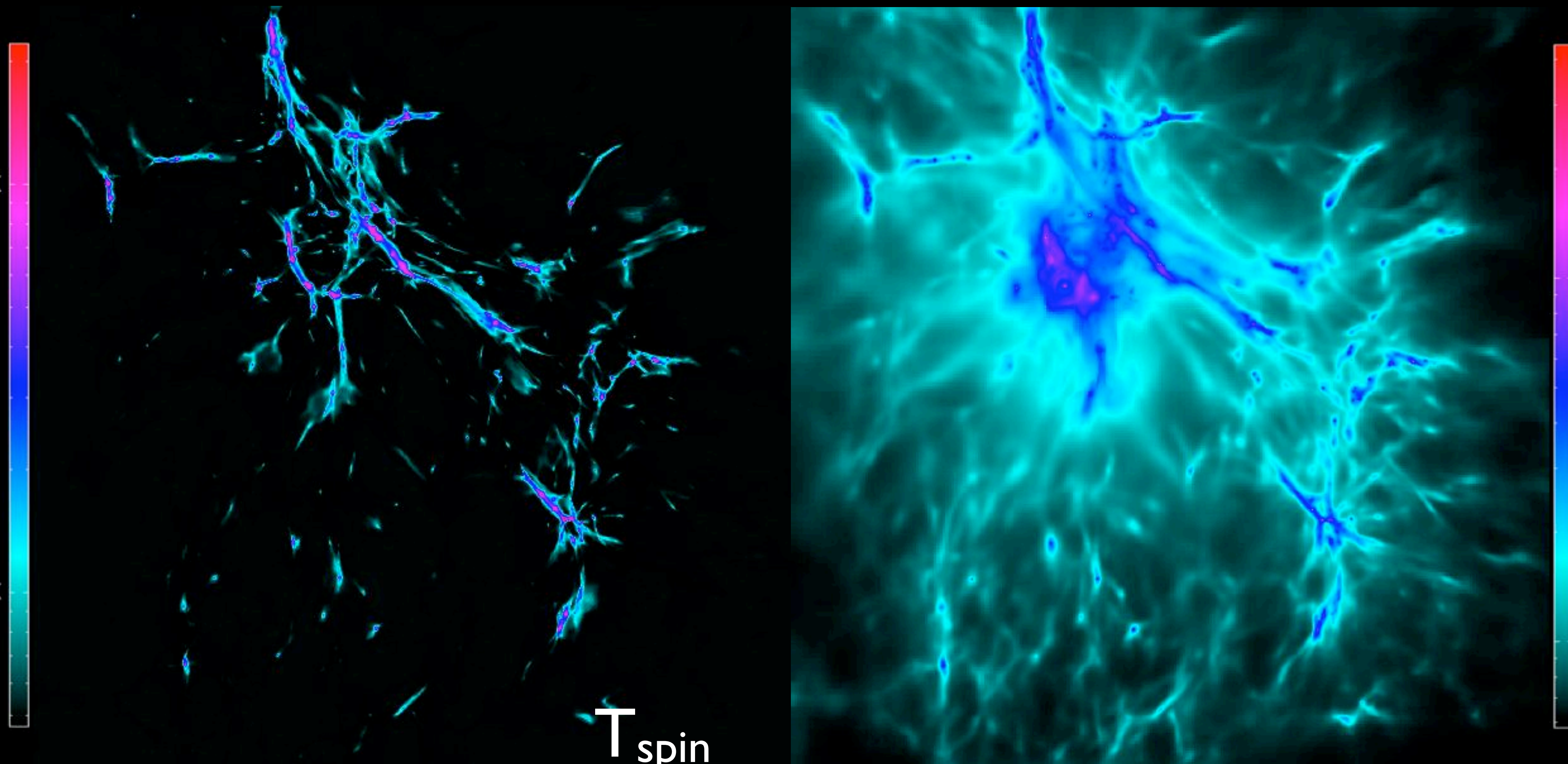
Mini-quasars powered by seed MBHs can structure the all-pervading IGM and regulate star formation in their host galaxies

$z=21$ turn on 150 $M_{\odot}$ MBH accreting at Eddington rate and shining for a Salpeter timescale at 200eV-10KeV




T
[K]
5317
1695
540
172
55
18
6
9729
4306
1906
843
373
165
73
log x
-3.80
-3.83
-3.87
-3.90
-3.93
-3.97
-4.00
-0.63
-0.94
-1.25
-1.56
-1.88
-2.19
-2.50
T
xe


log x
-1.49
-2.20
-2.91
-3.62
-4.33
-5.04
-5.75
-0.61
-1.41
-2.20
-3.00
-3.79
-4.59
-5.38
log ρ
15.32
14.77
14.22
13.67
13.12
12.56
12.01
xH2
nb


1000K
100K
T_{spin}
1000K
100K

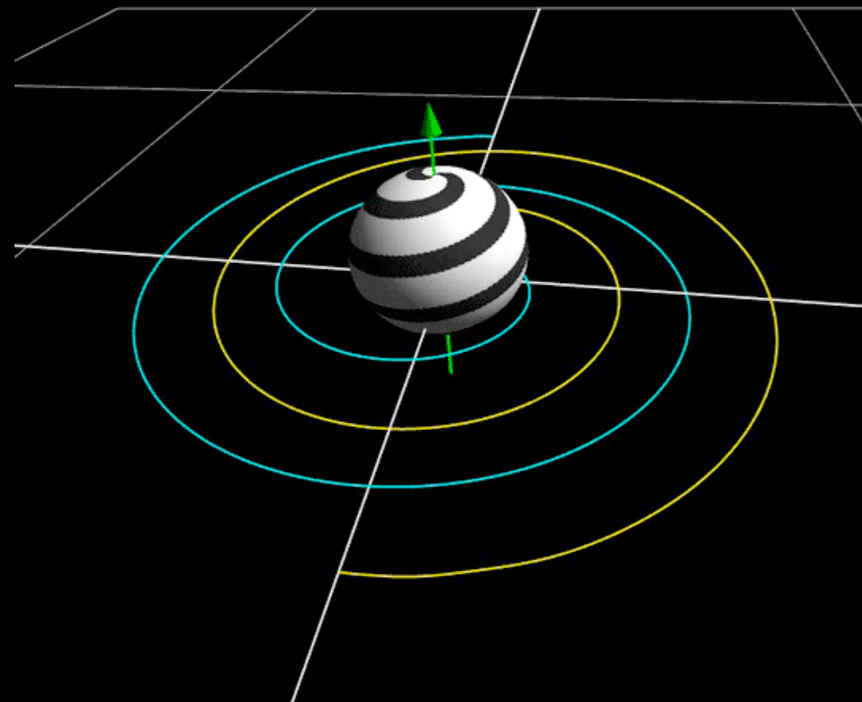
LISA as a probe of accretion history

In addition to their masses, astrophysical MBHs are characterized by their spin

$$S = aGM_{\rm BH}^2/c, \qquad 0 \le a \le 1.$$

The spin of a MBH is expected to have a crucial effect on its observational manifestation:

1) it determines the efficiency of converting accreted mass into radiation and has implications for the direction of jets in active nuclei;



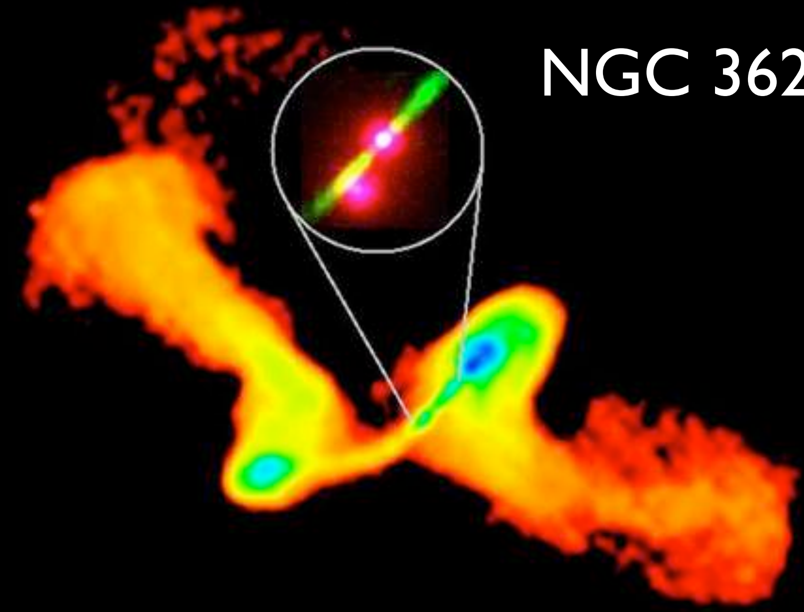
black hole spin a_*	thin disk radiation efficiency (corrected for capture by hole) $\epsilon = L_{\rm disk}/(\dot{M}c^2)$
0[a]	0.057
0.7[b]	0.133
0.9[c]	0.151
0.998[d]	0.308
1[e]	0.400

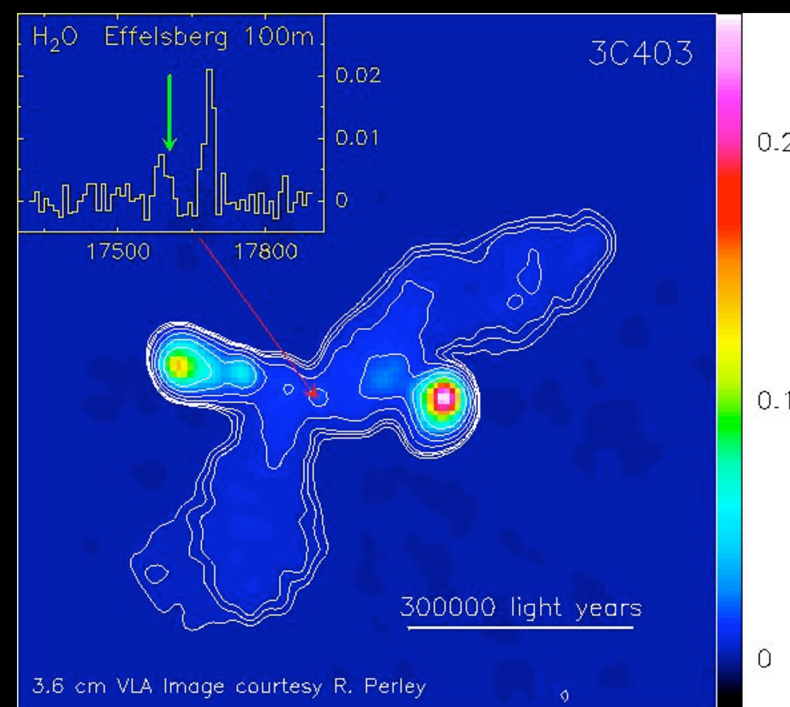
[a] result of isotropic accretion of small bodies.
[b] result of collapse or equal mass merger.
[c] approx equilibrium spin in magnetised disk accretion.
[d] equilibrium spin in unmagnetised disk accretion.
[e] maximal rotation before naked singularity appears.

2) the electromagnetic braking of a rapidly spinning black hole may extract rotational energy (Blandford & Znajek 1977), convert it into directed Poynting flux and power some radio galaxies and GRBs;

3) the orientation of the spin is thought to determine the innermost flow pattern of gas accreting onto Kerr holes (Bardeen & Petterson 1975);

4) the coalescence of two spinning black holes in a radio galaxy may cause a sudden reorientation of the jet direction, perhaps leading to the X-type radio sources (Merritt & Ekers 2002).



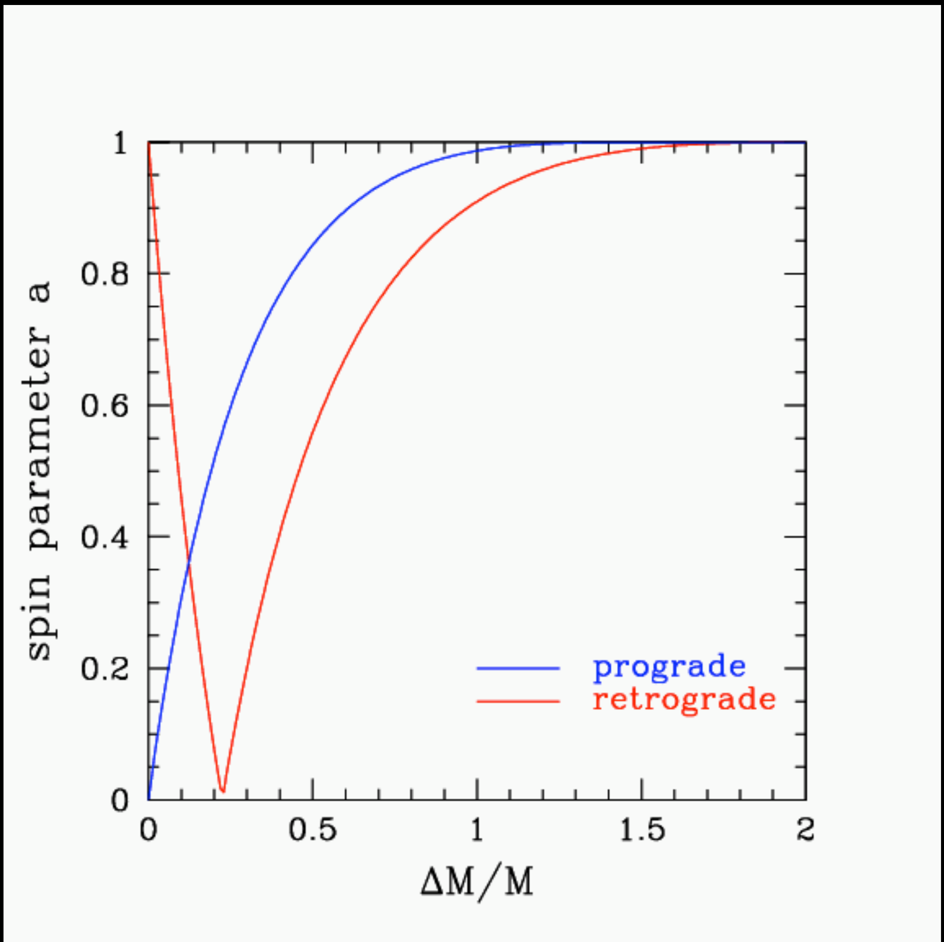


What is the spin of accreting MBHs?

$$M_{\rm BH} \to M_{\rm BH} + dm$$

(in equatorial plane)

$$\frac{da}{d\ln m} = \frac{L_{\rm ISCO}}{M_{\rm BH} E_{\rm ISCO}} - 2a.$$



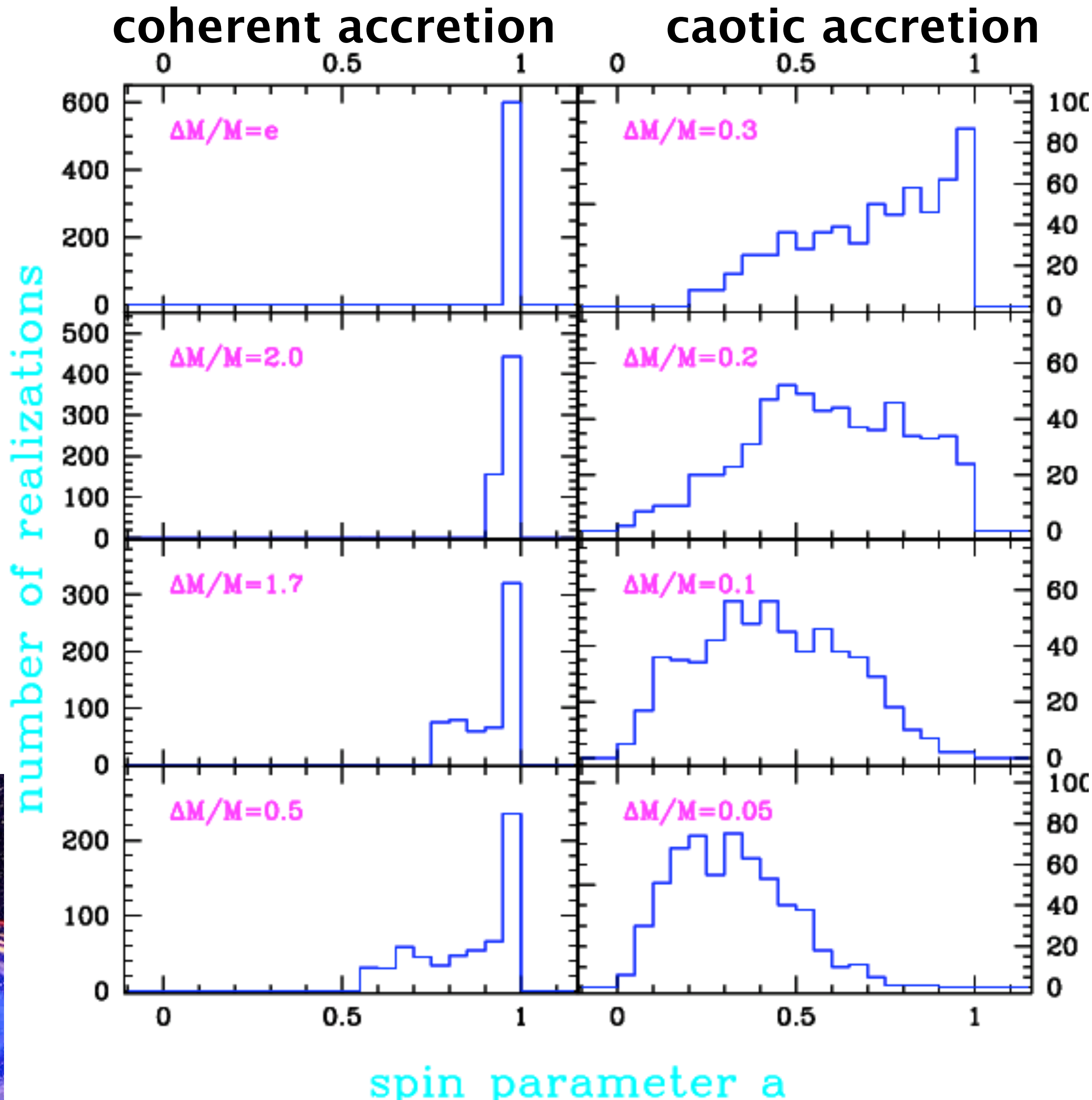
hole that is initially nonrotating (r_{isco}=6M_{BH}) gets spun up to a=1 after a modest amount of accretion, ΔM/M=1.4

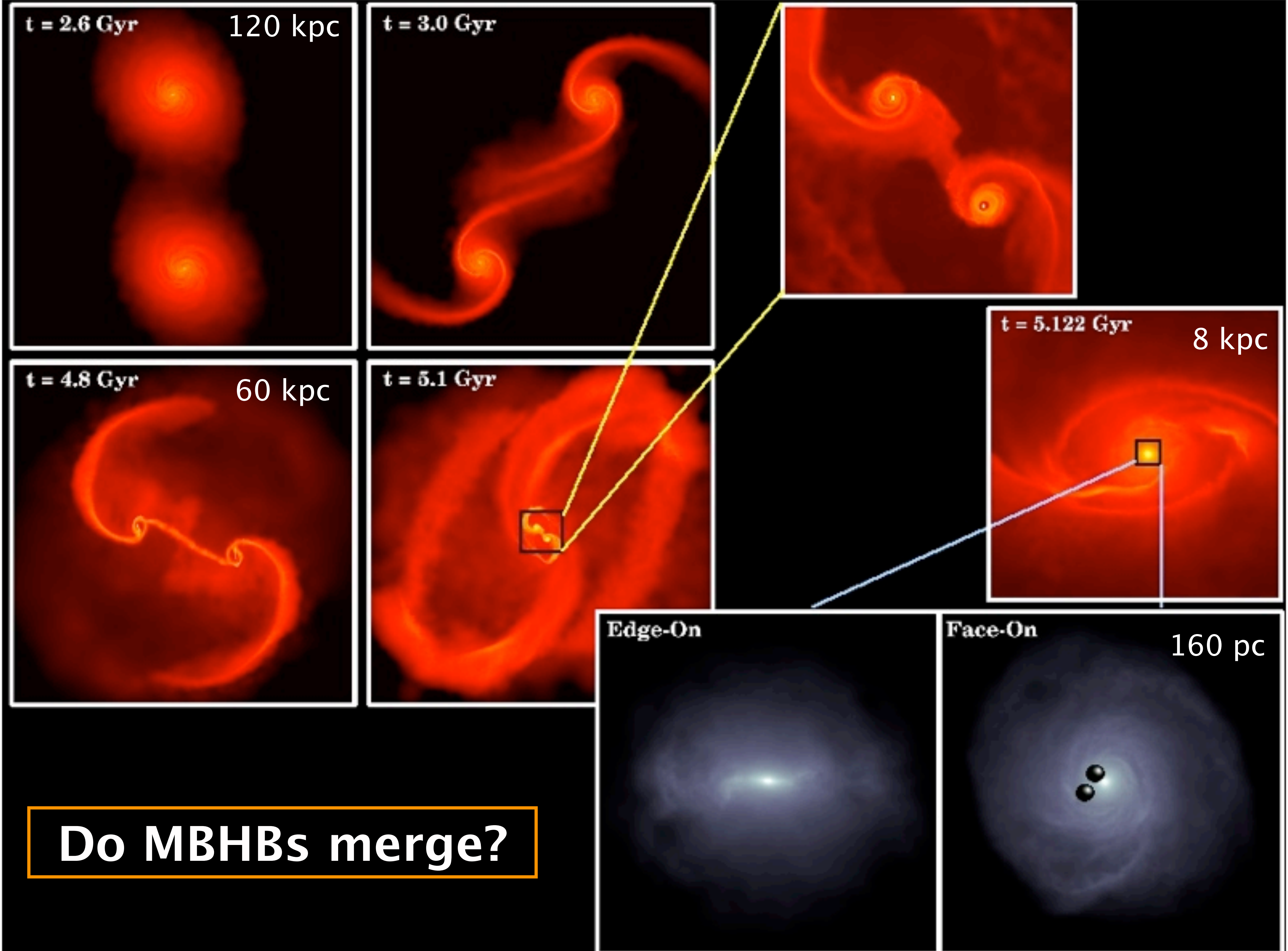
a=1 hole spun down by retrograde accretion (r_{ISCO} =9 M_{BH}) to a=0 after ΔM/M=0.225

a=1 hole does a 180° flip after ΔM/M=2

Monte Carlo realizations of hole spin distribution when matter ΔM added at random orientations

Spin distribution of MBHs provides information on large scale "coherence" of accretion flow





Do MBHBs merge?

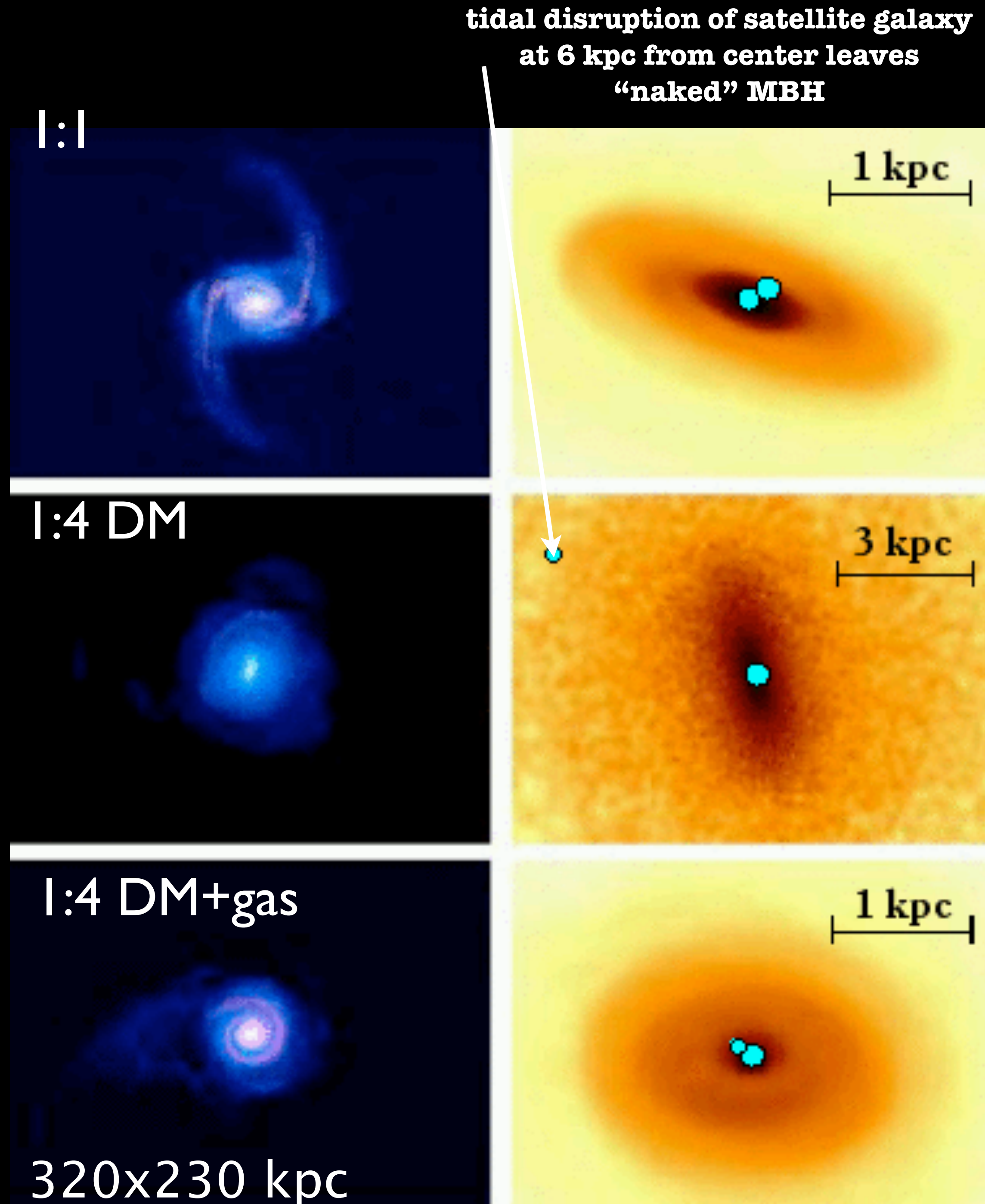
4 main phases in dynamical evolution of merging galaxy +MBH systems:

1: MBHs sink toward center by dynamical friction acting on the host “satellite” halo

2: formation of a BH binary as holes lose angular momentum due to dynamical friction or gas drag in stellar/gaseous background

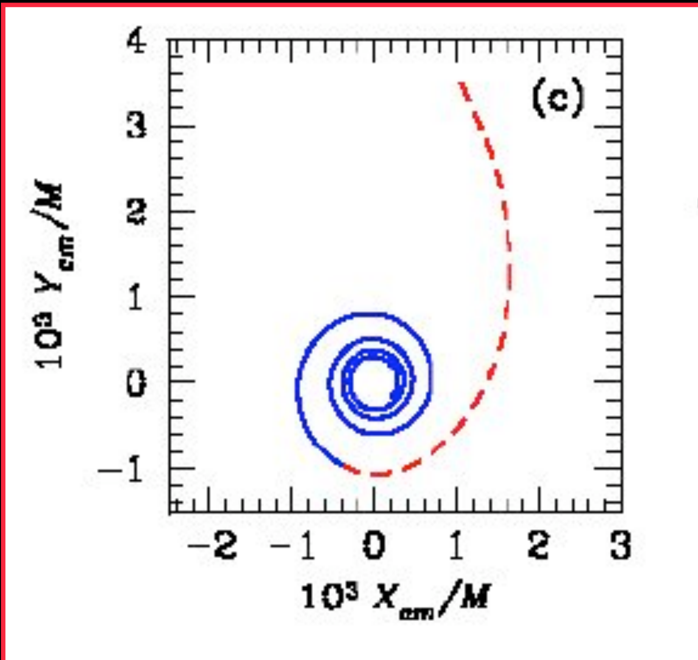
3: slow decay of BH binary by three-body encounters with stars (gravitational “slingshot”) on low-angular momentum orbits <u>(or gas drag)</u>

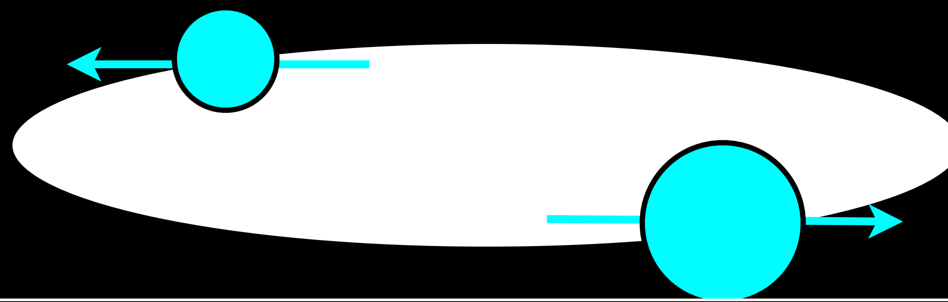
4: final coalescence when binary separation is so small that GW losses dominate



"gravitational rocket": getting a kick from strong field effects lack of symmetry of the binary system: non-zero net linear momentum carried away by gravitational waves

motion of the center of mass of the BH system





maximum possible recoil for comparable-masses ($q \sim 1$), maximally-spinning ($a_{1,2} \sim 1$) holes, spins in orbital plane, counteraligned: $V_{kick} \sim 3{,}750$ km/s!

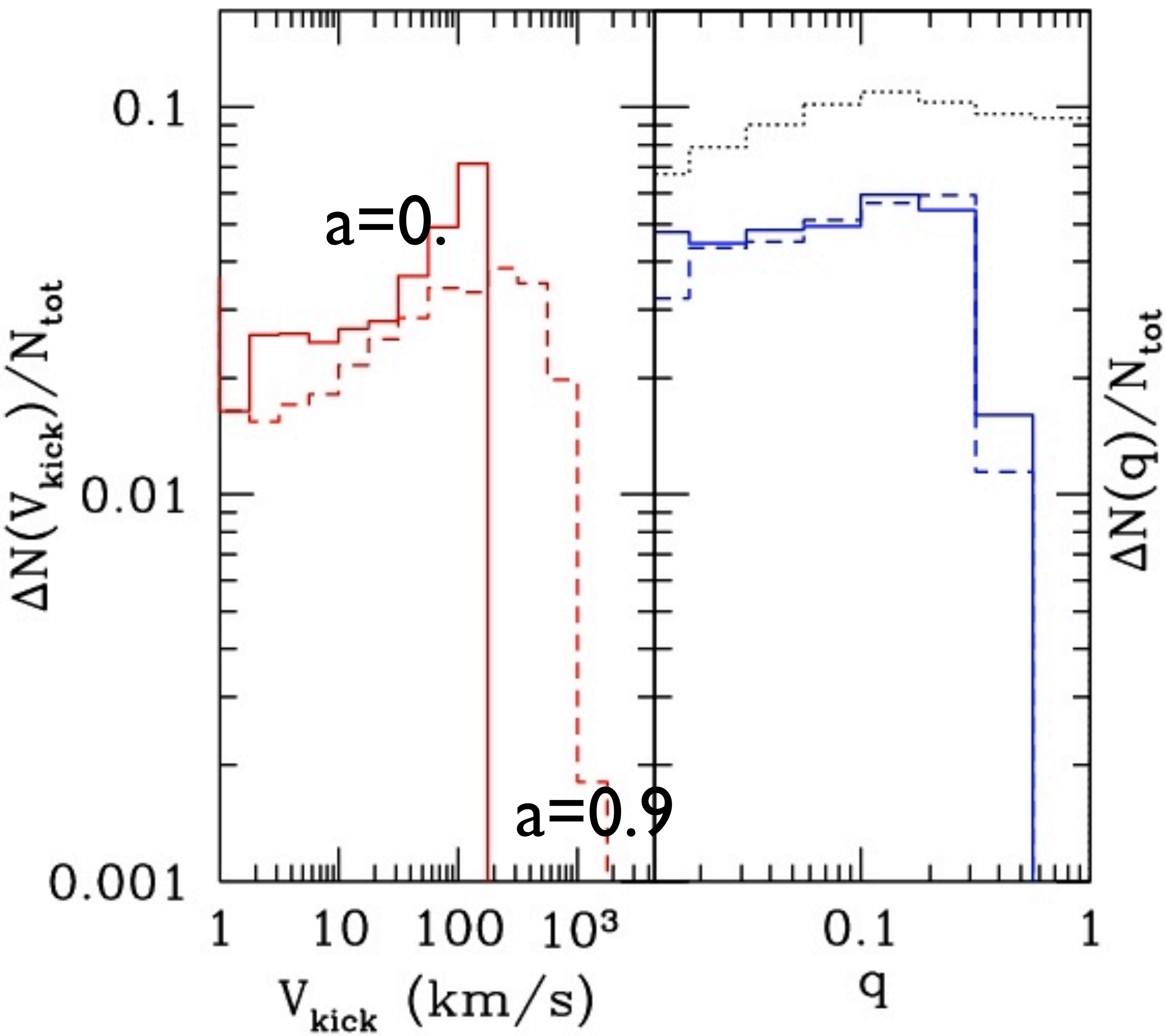
$$\vec{V}_{\rm kick} = v_m\, \vec{e}_x + v_\perp (\cos\xi\, \vec{e}_x + \sin\xi\, \vec{e}_y) + v_\| \,\vec{e}_z\,, \quad (1)$$

$$v_m = A\eta^2\sqrt{1-4\eta}\,(1+B\eta), \quad (2)$$

$$v_\perp = H\eta^2(1+q)^{-1}\left(a_2^\| - q a_1^\|\right), \quad (3)$$

$$v_\| = K\eta^3(1+q)^{-1}\cos(\Theta-\Theta_0)\left(a_2^\perp - q a_1^\perp\right), \quad (4)$$

Expected distribution of kick velocities



z<3, $M_1+M_2>1e5\ M_\odot$

The best candidate to date for a recoiling hole (Komossa et al 2008) shows an exceptional optical emission-line spectrum with broad emission lines that are blueshifted by 2650 km/s relative to the narrow-line gas left behind!

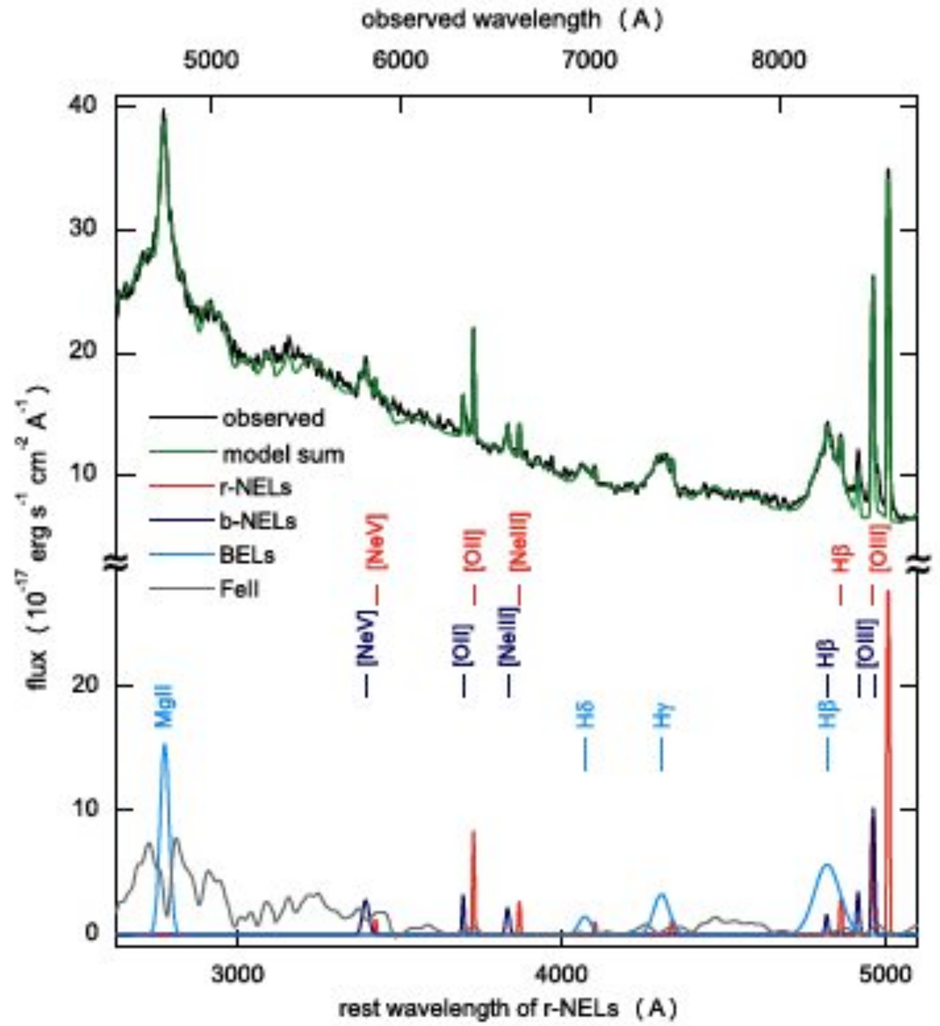


FIG. 1.—SDSS spectrum of SDSS J0927+2943, showing two sets of emission lines separated by a velocity of $v \approx 2650$ km s^{-1}. *Red*: Red set of narrow emission lines (r-NELs). *Blue and light blue*: Blue set of emission lines (b-NELs and BELs, respectively). *Gray*: Fe II spectrum.

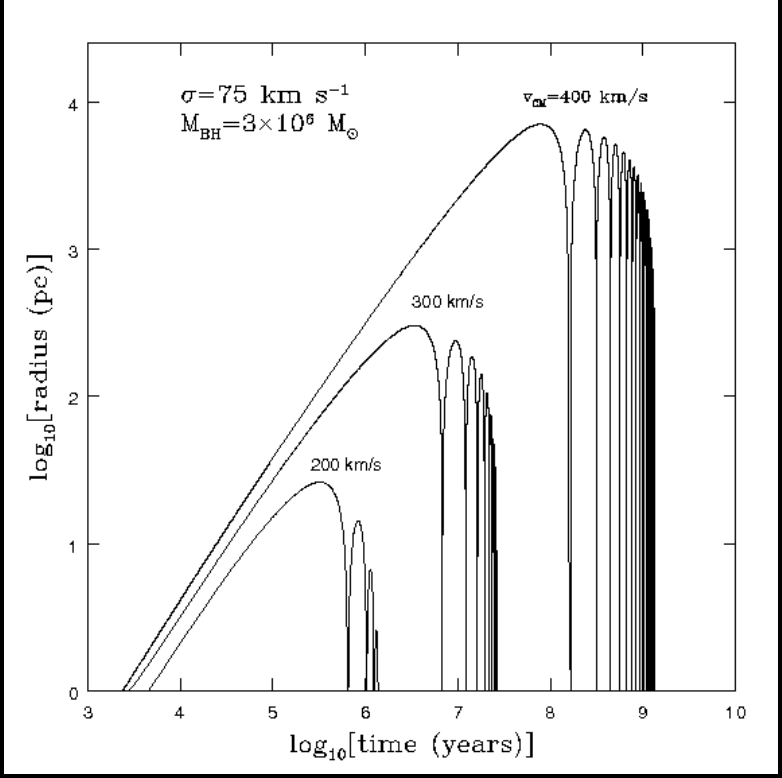
⇨ gravitational recoil may:

1) deplete MBHs from dwarf galaxies and give origin to a population of intergalactic holes (NB absence of MBHs in shallow potential wells today may not necessarily imply inefficient MBH formation: even galaxies that do not currently harbor BHs may have done so in the past);

2) produce off-nuclear AGNs (Madau & Quataert 2004)

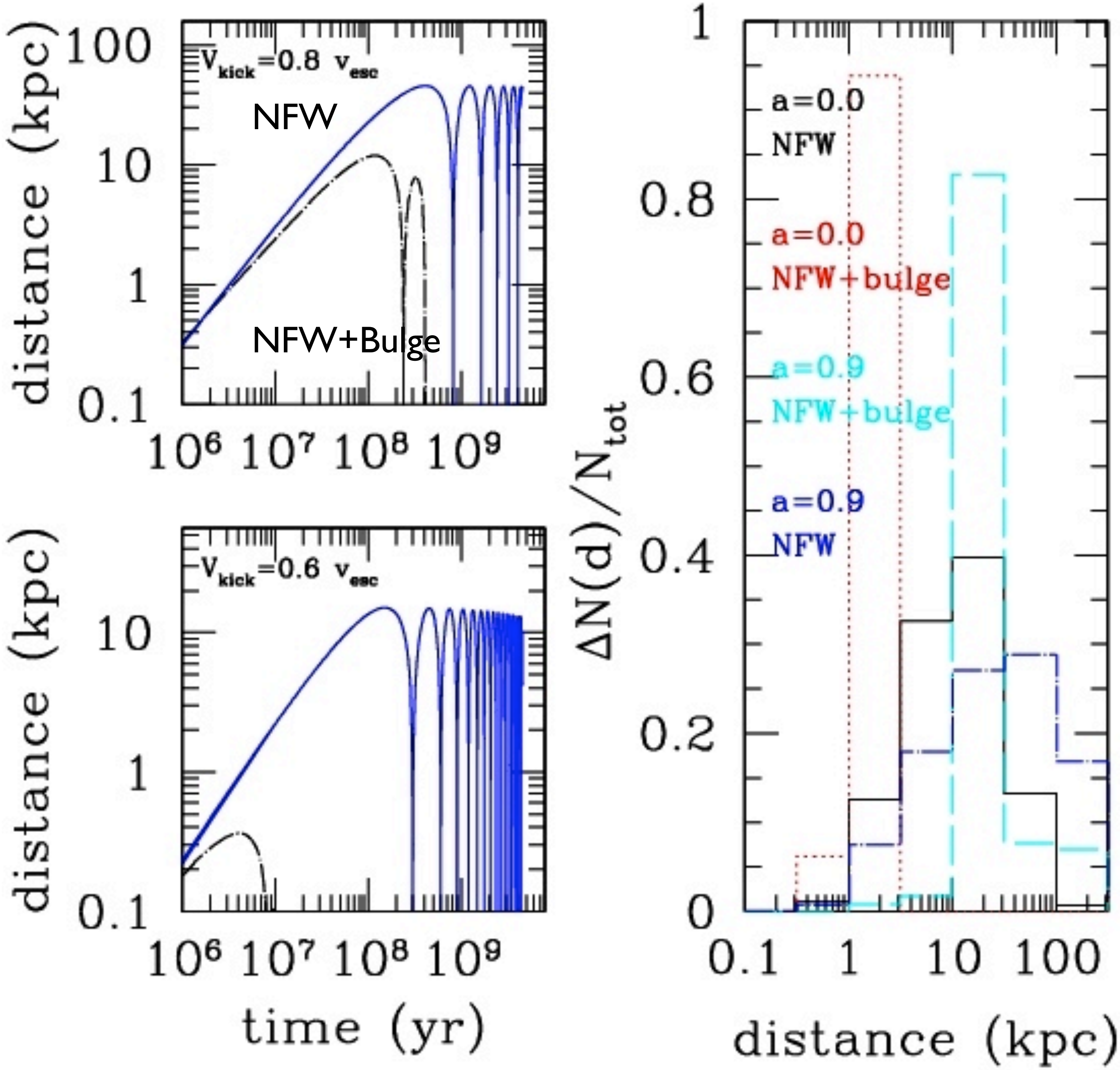
Dwarfs

Some

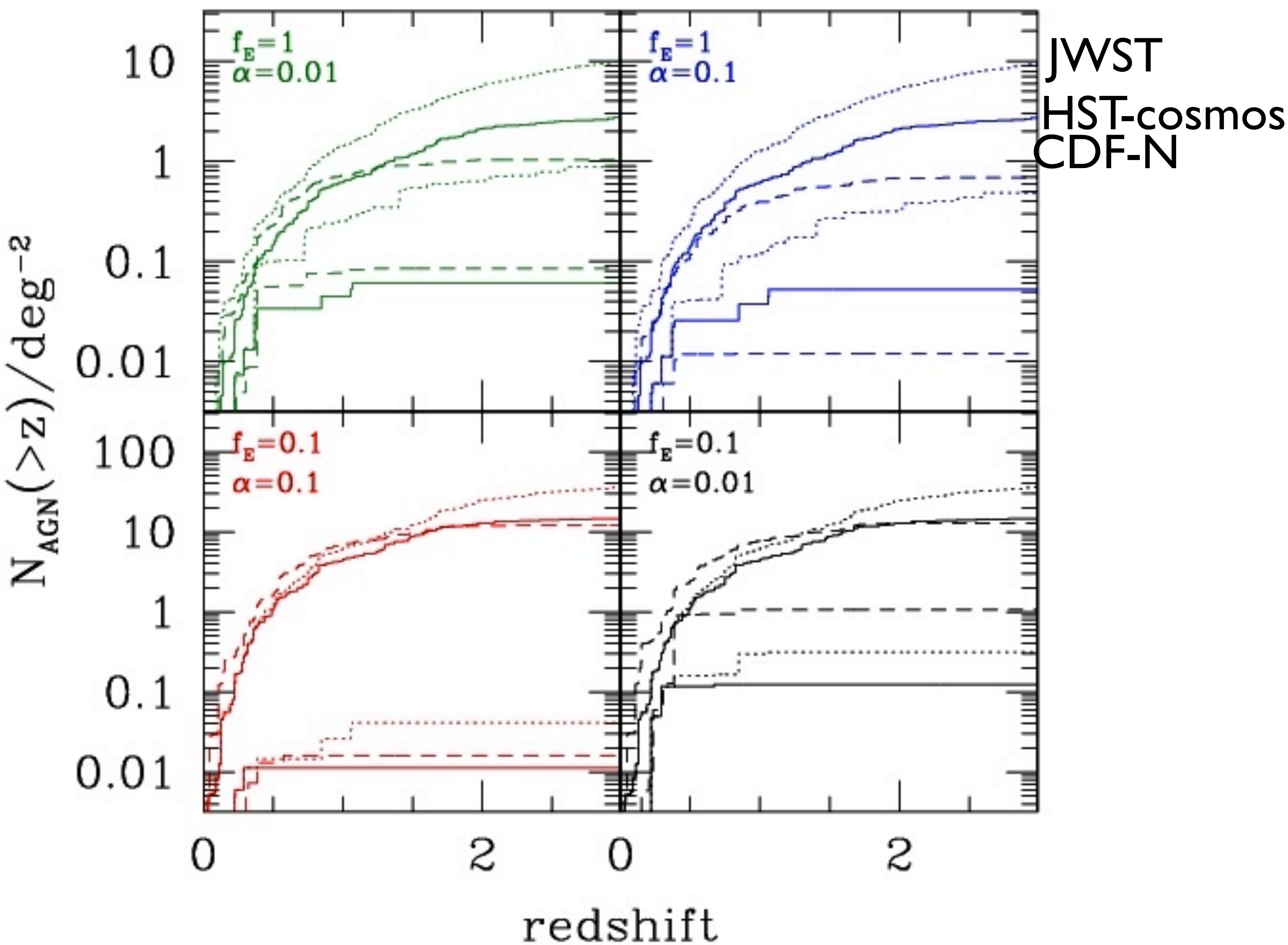


Response of a 3e6 M_{sun} MBH to a recoil velocity V_{CM} in an isothermal potential with dispersion σ=75 km/s (assuming radial orbits)

dynamical friction time $t_{DF} \propto r^2$
"residence" time $t \propto r/V$ ⇨ orbit decay by friction occurs mostly during each passage through the nucleus.



V_{kick}=0.8 v_{esc}
NFW
NFW+Bulge
distance (kpc)
100
10
1
0.1
10^6 10^7 10^8 10^9
V_{kick}=0.6 v_{esc}
distance (kpc)
10
1
0.1
10^6 10^7 10^8 10^9
time (yr)
$\Delta N(d)/N_{tot}$
1
0.8
0.6
0.4
0.2
0
a=0.0
NFW
a=0.0
NFW+bulge
a=0.9
NFW+bulge
a=0.9
NFW
0.1 1 10 100
distance (kpc)



$$M_{\rm disk} \approx (1.9 \times 10^6\, M_\odot)\ \alpha_{-1}^{-0.8} (\epsilon_{-1}/f_E)^{-0.6} M_7^{2.2} V_3^{-2.8}$$

$$M_{\rm disk} < M_{\rm BH} \qquad V_{\rm kick} \geq 550 {\rm kms}^{-1}\ \alpha_{-1}^{-0.28} (\epsilon_{-1}/f_E)^{-0.21} M_7^{0.43}$$

THE END

Summary

The last decade has witnessed great advances in our understanding of the formation and co-evolution of galaxies and their MBHs -- from the SDSS discovery of QSOs at $z=6$ (age$=0.07\ t_H$) to the $M_{BH}-\sigma$ relation to the discovery of a binary MBH in the nucleus of NGC6240 to advances in numerical relativity and the first hydrodynamic simulations of galaxy merging that follow the formation of a bound MBHB down to 1 pc.

The underlying goal of all these efforts is to understand the growth of cosmic structures, the internal properties of galaxies, their self-regulating nuclear activity, the thermodynamics of the IGM, and ultimately map the star formation and MBH growth histories from the end of the “dark ages" to the present epoch.

In spite of some significant achievements, many fundamental questions related to the assembly of the first galaxies+MBH systems, the formation and evolution of MBH binaries and their coalescence rate, the spin distribution of MBHs, the effect of the energy released by active nuclei on their surroundings and the IGM, the impact of the “gravitational rocket” remain, at best, only partially answered.

It will probably take a combination of the JWST, LISA, the TMT, Con X-Xeus etc to fully understand the epoch of first light and the impact of MBHs on the formation of cosmic structure..