Formation and cosmic evolution of supermassive black holes

Debora Sijacki

Summer school: “Black Holes at all scales”
Ioannina, Greece, Sept 16-19, 2013

Lecture 1:

- formation of black hole seeds
- low mass versus massive seed scenarios
- growth of the black holes in the early Universe
- powering of high redshift quasars
- relative importance of gas accretion and black hole mergers with cosmic time

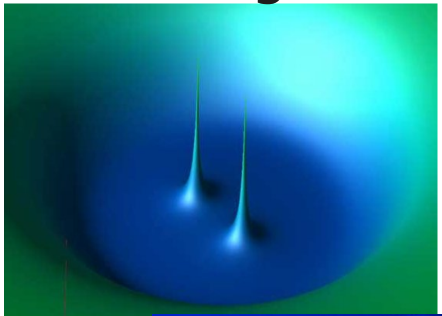
Lecture 2:

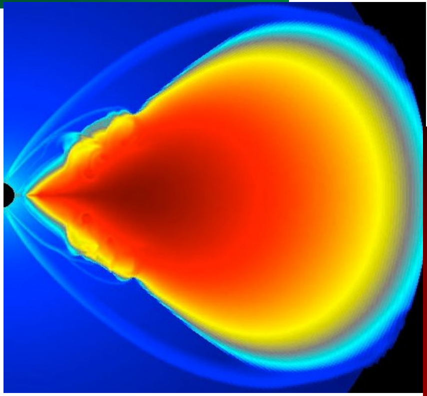
- physical conditions of accreting gas: from large scale inflows to accretion disks
- black hole binary mechanisms
- black hole spins
- gravitational recoils
- AGN feedback processes and their impact on the host galaxies across the Hubble sequence

Physical conditions of accreting gas: from large scale inflows to accretion disks

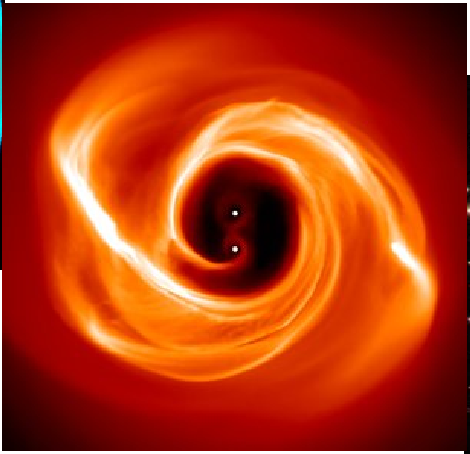
- vast dynamical range
- uncertainties in physical mechanisms that occur on widely different scales

BH mergers

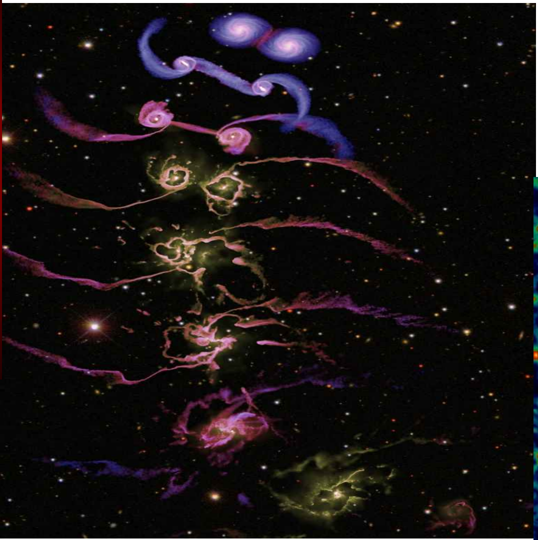




BH accretion disk

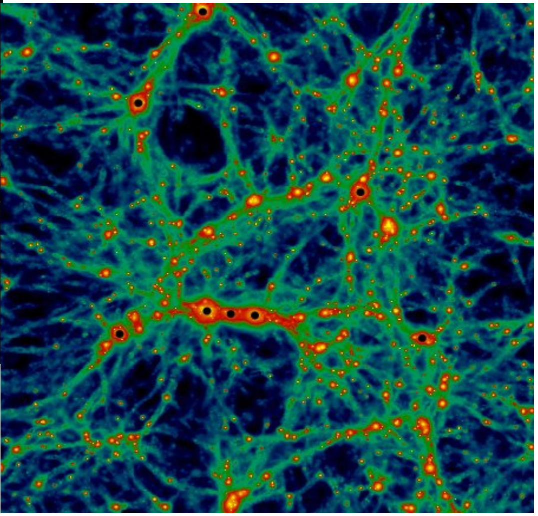


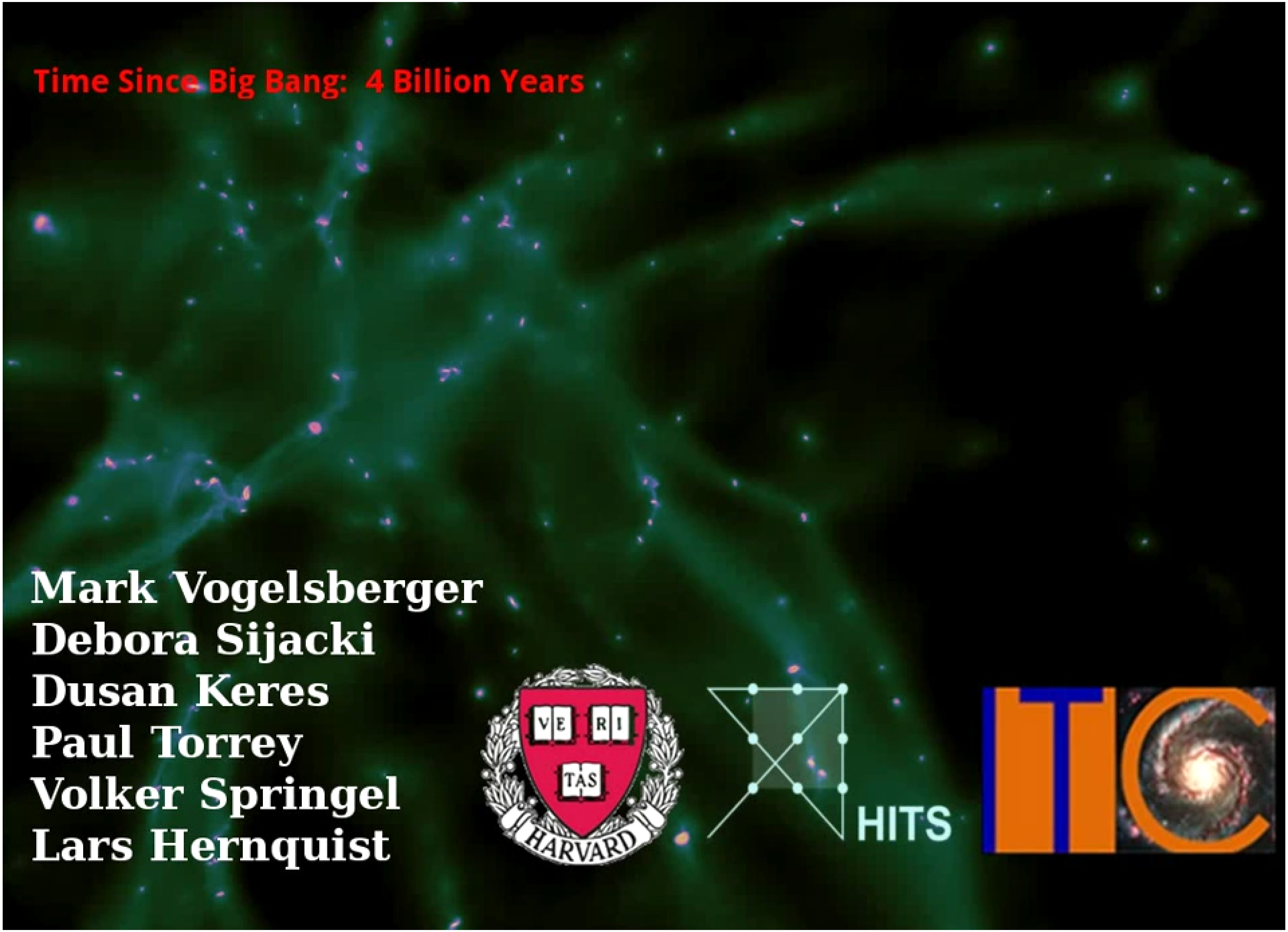
circumbinary disk



galaxy merging

cosmological structure formation





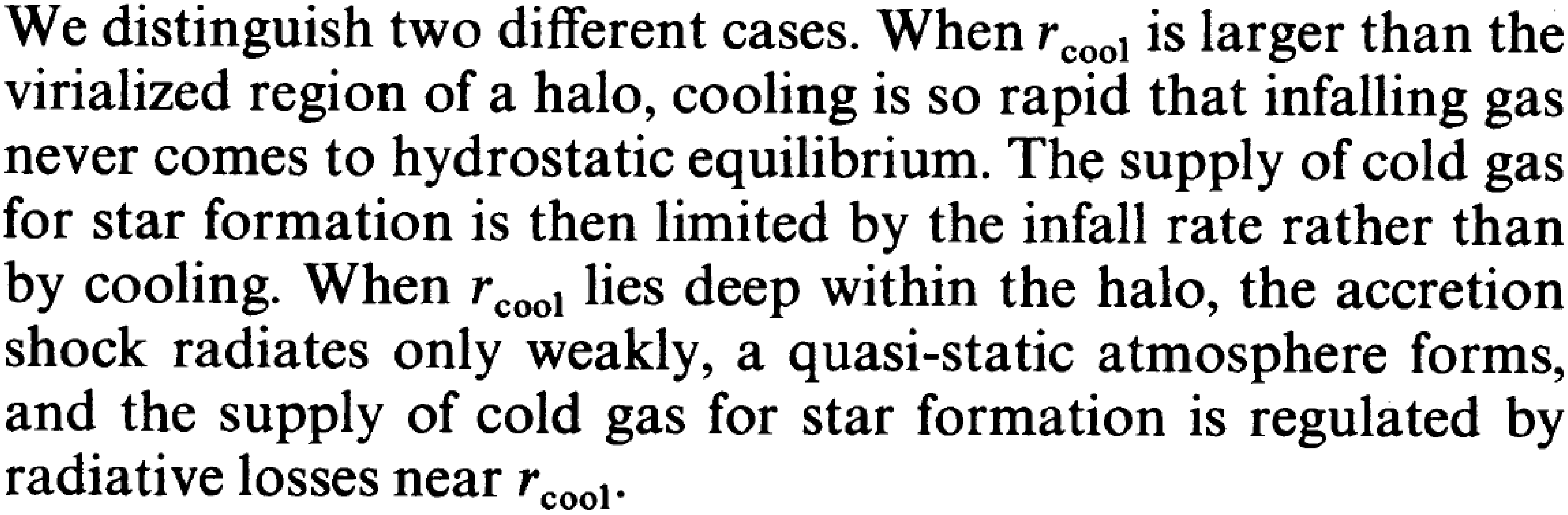
Time Since Big Bang: 4 Billion Years

Mark Vogelsberger
Debora Sijacki
Dusan Keres
Paul Torrey
Volker Springel
Lars Hernquist

HITS

Physical conditions of accreting gas: from large scale inflows to accretion disks

- Analytical works from the end of 70s, 80s and early 90s have developed fundamental ideas which still guide our understanding of galaxy formation

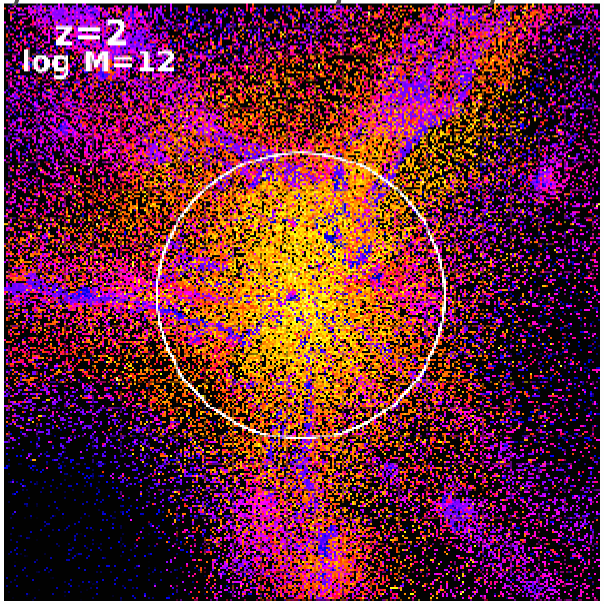


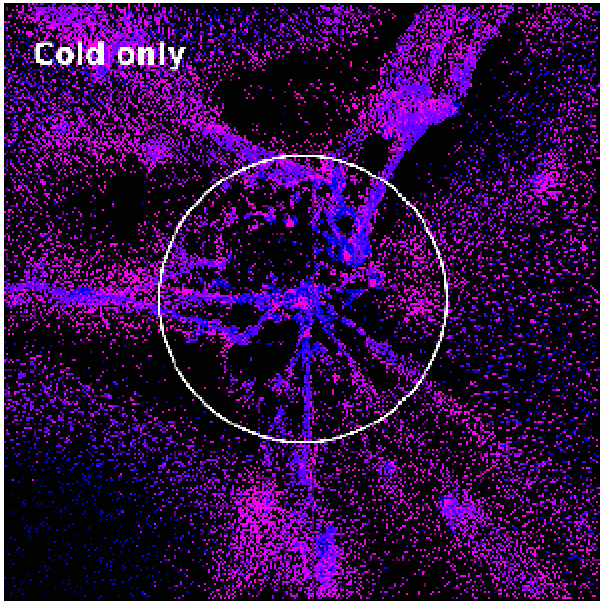
We distinguish two different cases. When $r_{\rm cool}$ is larger than the virialized region of a halo, cooling is so rapid that infalling gas never comes to hydrostatic equilibrium. The supply of cold gas for star formation is then limited by the infall rate rather than by cooling. When $r_{\rm cool}$ lies deep within the halo, the accretion shock radiates only weakly, a quasi-static atmosphere forms, and the supply of cold gas for star formation is regulated by radiative losses near $r_{\rm cool}$.

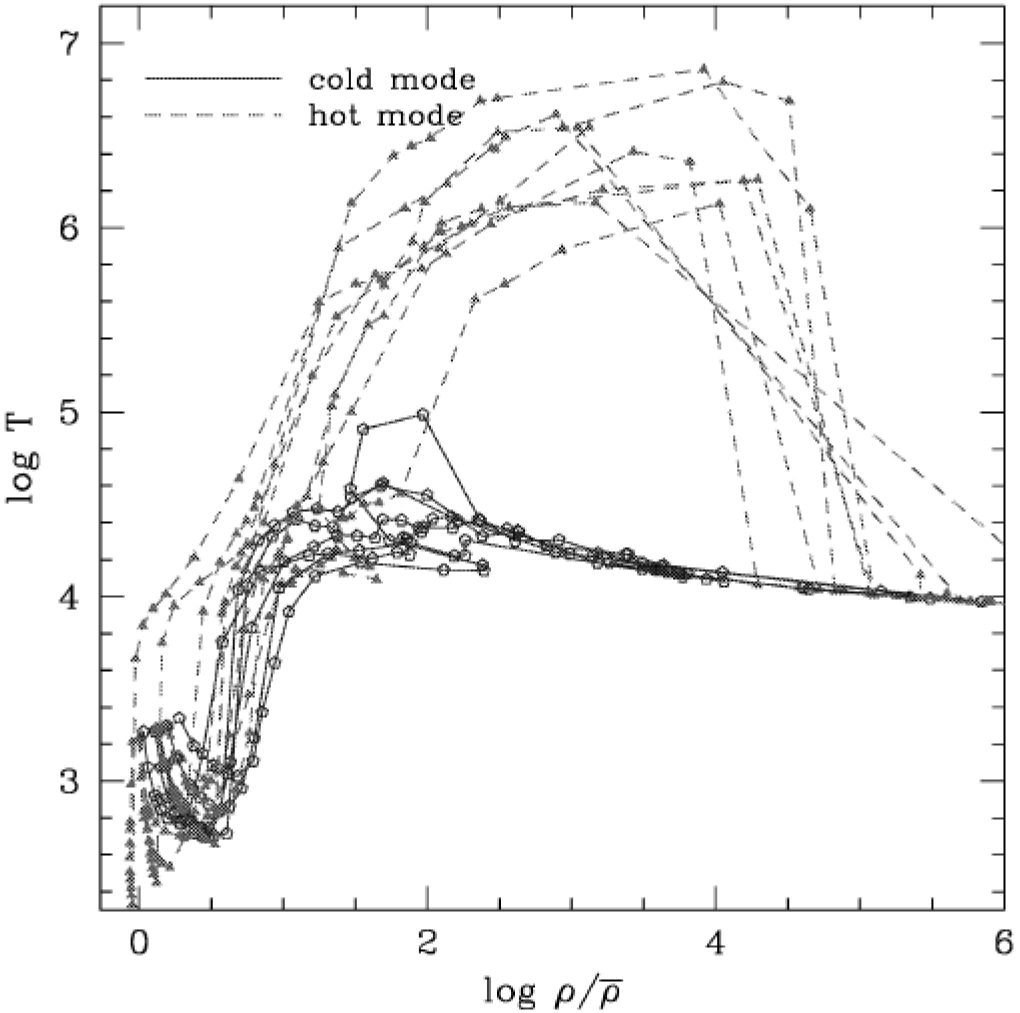
E.g. Binney 1977
Rees & Ostriker 1977
Silk 1977
White & Rees 1978
White & Frenk 1991

Physical conditions of accreting gas: from large scale inflows to accretion disks

Numerous works invoking simplified and fully cosmological hydro simulations employed to revisit the issue (e.g. Katz 2003, Birnboim & Dekel 2003, Keres 2005/2009, Ocvirk 2008, Brooks 2009...)







Keres et al. 2005/2009

Physical conditions of accreting gas: from large scale inflows to accretion disks

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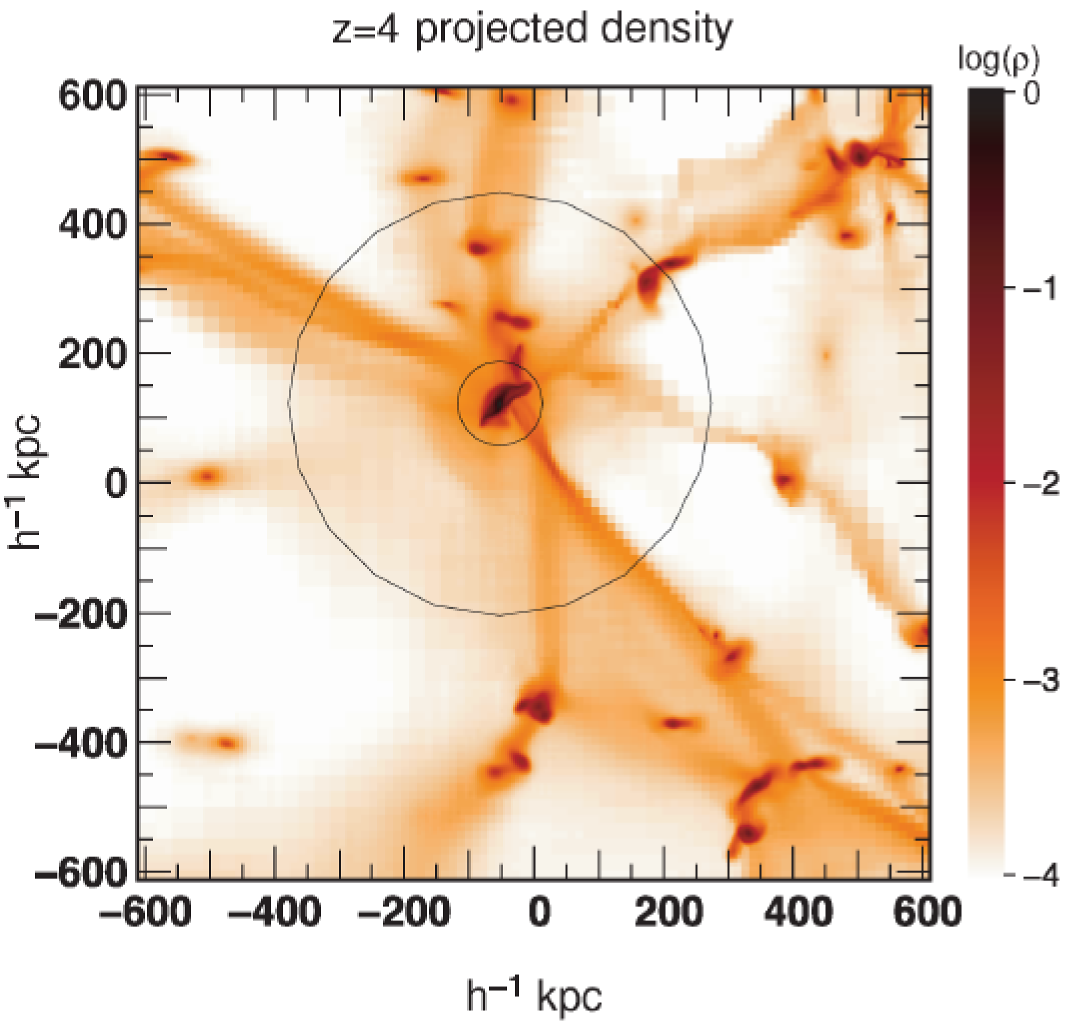
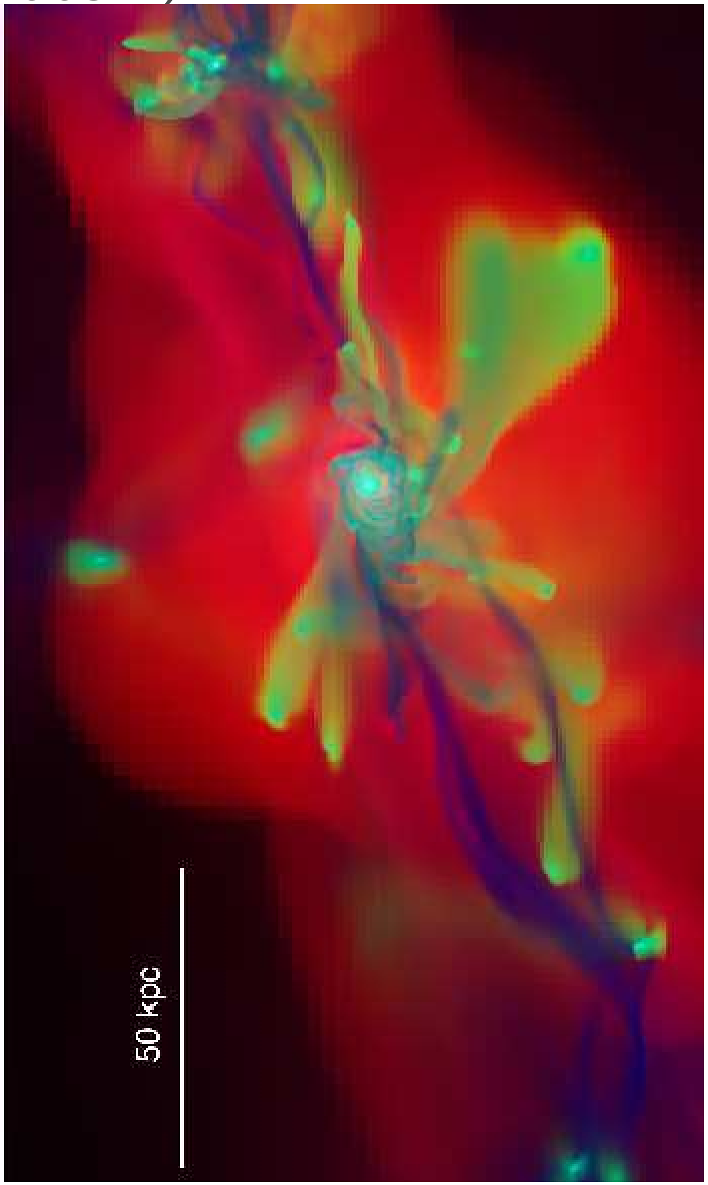




Ocvirk 2008 (MareNostrum, RAMSES)
Agertz 2009 (High-z galaxy, RAMSES)

Physical conditions of accreting gas: from large scale inflows to accretion disks

- Large uncertainties still persist in our understanding how cosmic gas from large scales is incorporated into the galaxies and what happens with its entropy and angular momentum content

- Weather gas is shock heated at the virial radius or not, if gas cooling is efficient it will eventually collapse towards the centre

- In many situations gas will likely retain some angular momentum which acts as an “accretion barrier” with respect to the scenario where gas plunges on purely/predominantly radial orbits (e.g. Bondi accretion)

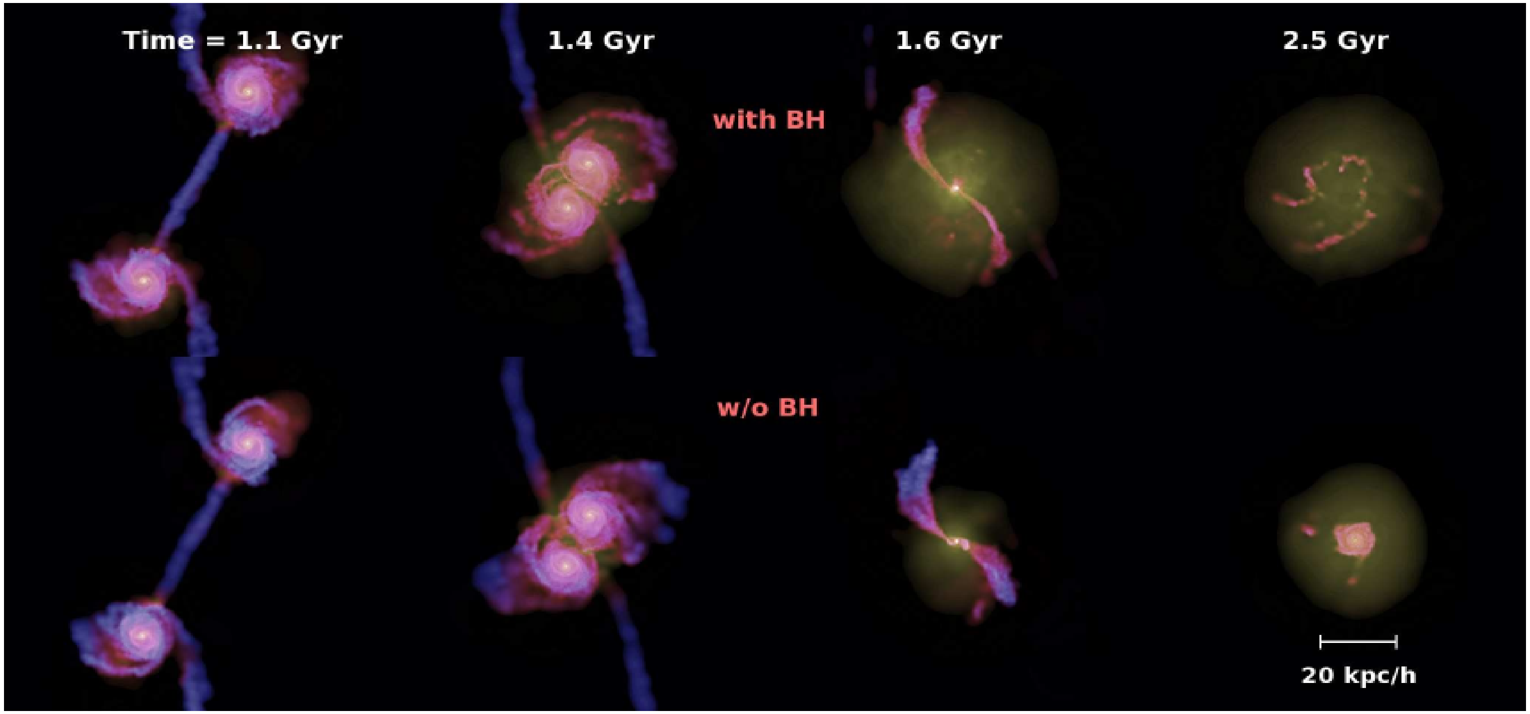
- When gas angular momentum is negligible c.f. circularization radius << radius of accretor?
→ high redshift quasars (rapid gas cooling regime)?
→ black hole accretion from a hot intracluster medium?

- Accretion disks are generally ubiquitous and a mechanism that efficiently transports angular momentum is needed for rapid black hole growth to occur

Physical conditions of accreting gas: from large scale inflows to accretion disks

- Angular momentum transport mechanisms:
→ major (and minor) galaxy mergers
→ internal disk instabilities, e.g. “bars-within-bars”
→ hydrodynamical turbulence (self-gravity, supernovae)
→ MHD turbulence,...

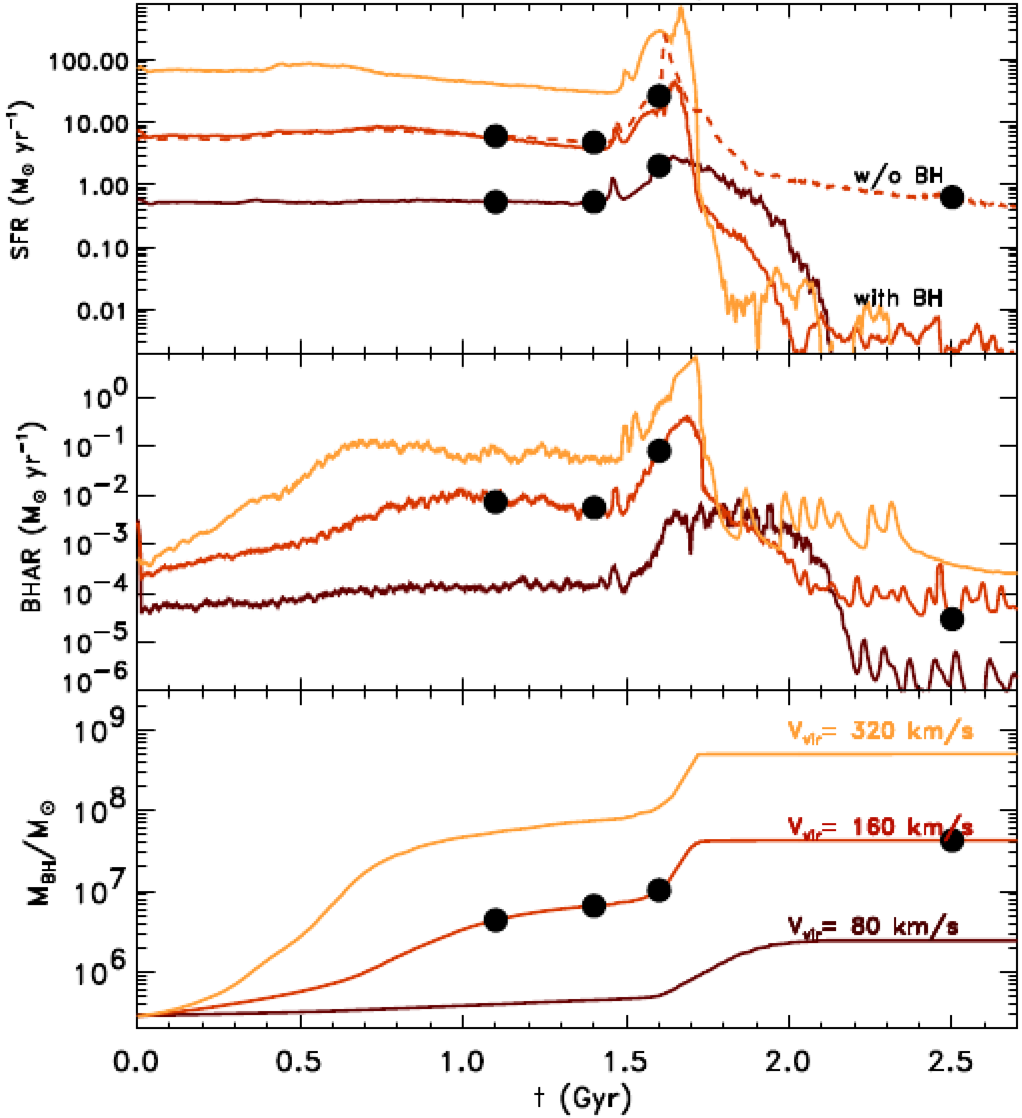
- Major galaxy mergers: gravitational tidal forces during galaxy collisions can efficiently extract angular momentum from gas in the ISM of disk and drive it towards the centre



Di Matteo et al. 2005

Physical conditions of accreting gas: from large scale inflows to accretion disks

- Central gas increase resulting from mergers may give rise to powerful nuclear starburst (Toomre & Toomre, 1972, Toomre, 1977, Barnes&Hernquist, 1992, Mihos & Hernquist, 1994) and may feed the central black hole (e.g. Di Matteo et al. 2005, Springel et al. 2005, Hopkins et al. 2006,...)



Black symbols (time sequence):

1. first passage
2. galaxies distorted by mutual tidal interaction
3. final coalescence
4. quasi-static, spheroidal merger remnant

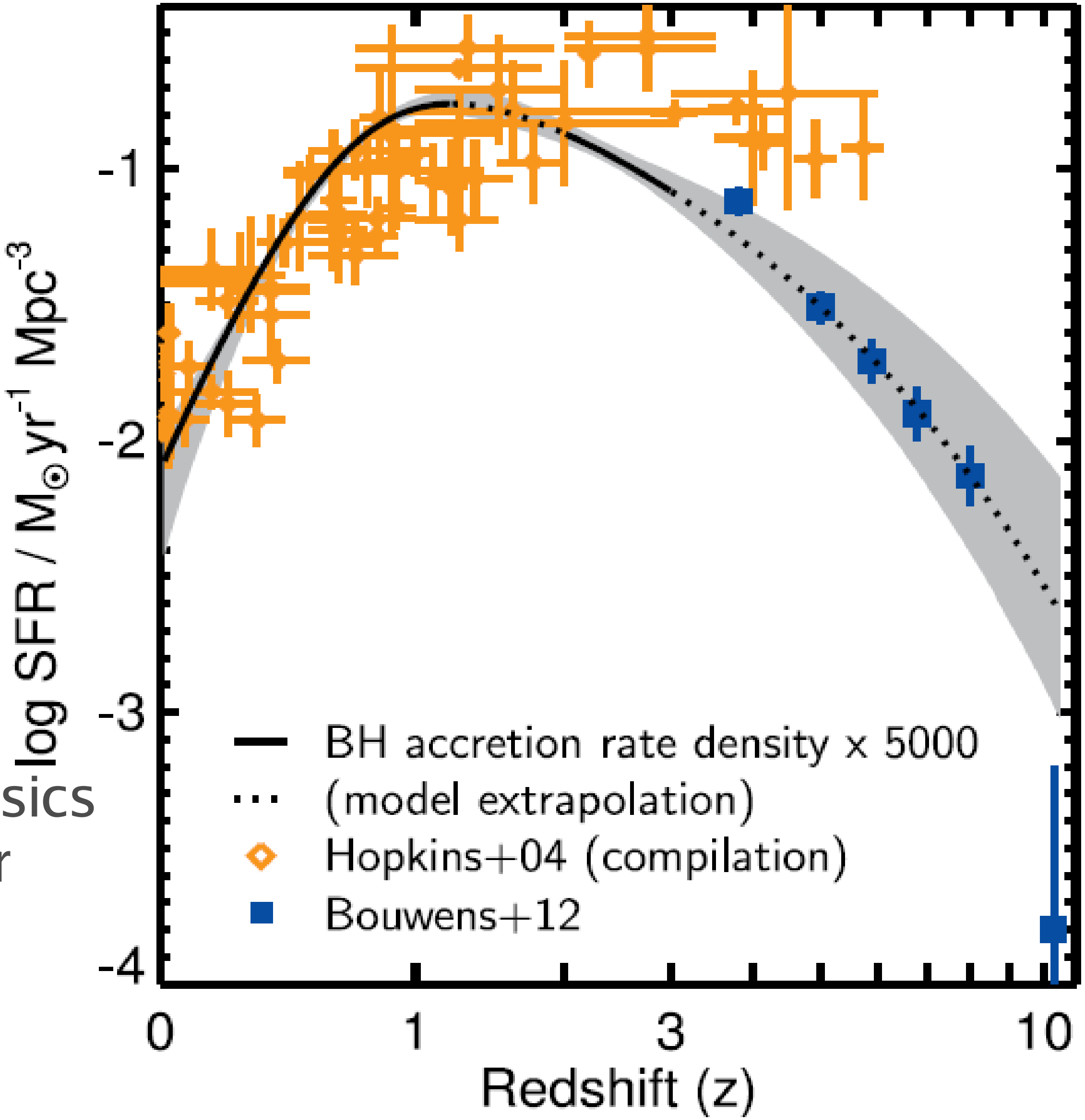
Di Matteo et al. 2005

Physical conditions of accreting gas: from large scale inflows to accretion disks

- Gas-rich major galaxy mergers are more important at high redshifts, where both SFR and BHAR are peaking

- Even though SFR and BHAR peak at somewhat different redshift their similar decline at lower z may indicate that the physical mechanisms driving star formation in galaxies and black hole growth are interlinked

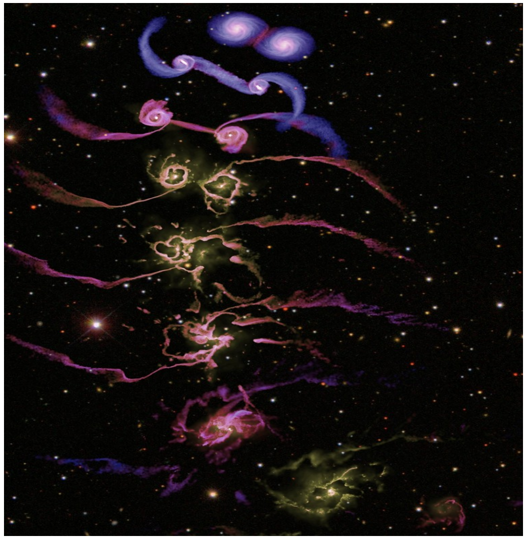
- However, there is still large gap between resolvable cosmological inflows and BH accretion disk! Need to understand better the physics of the ISM: gas fragmentation, star formation, role of magnetic fields

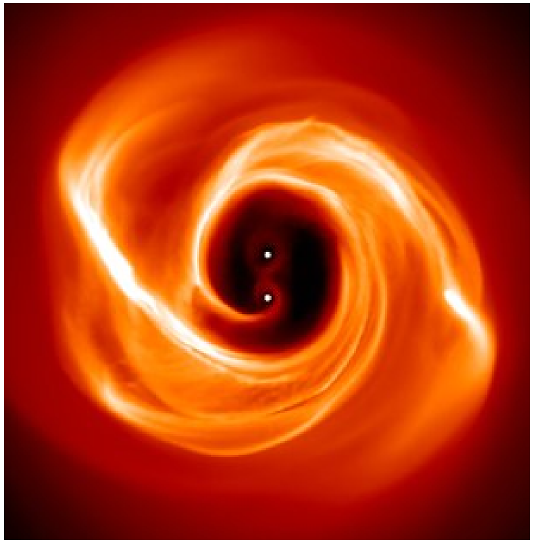


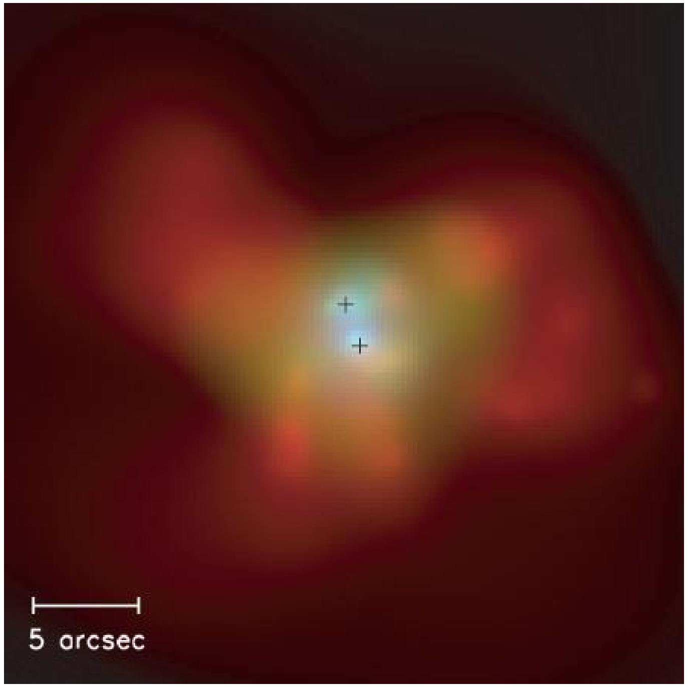
Kormendy & Ho, 2013, Aird et al. 2010

Black hole binary shrinking mechanisms

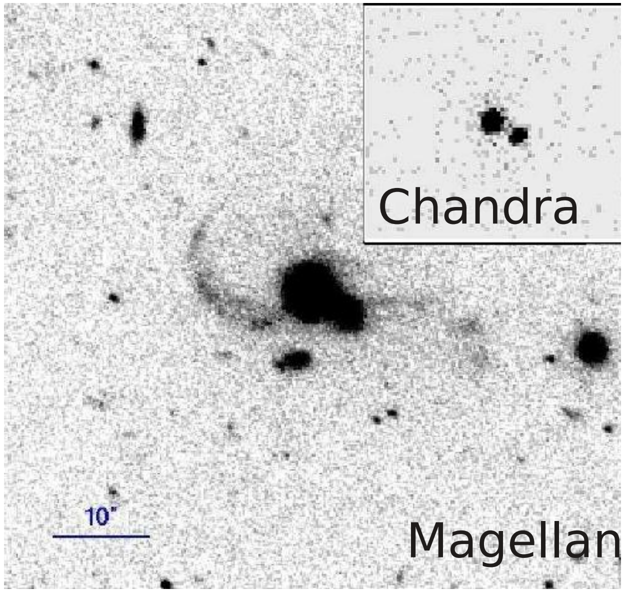
hierarchical mergers of galaxies with SMBHs



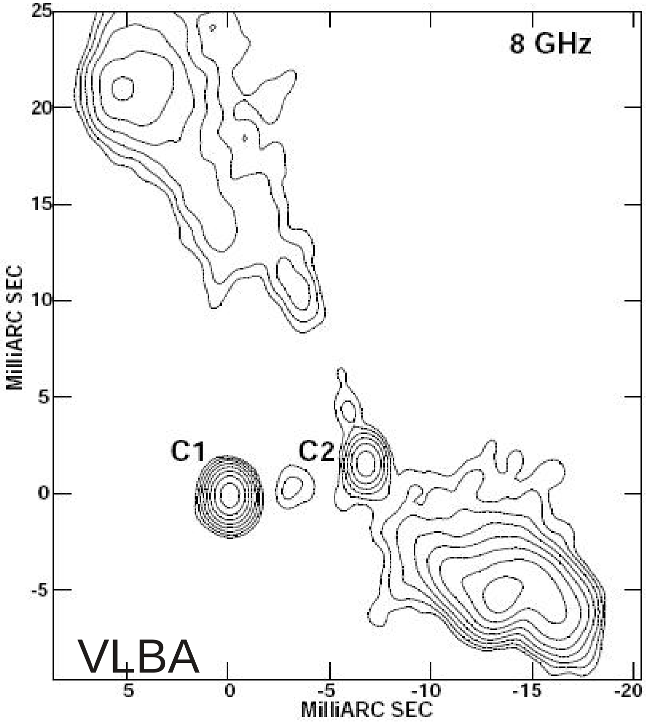




Komossa 2003: X-ray image
ULIRG NGC6240 ~1.4kpc



Green 2010: Optical + X-ray
gas-rich merger ~21kpc



Rodriguez 2006: Radio
Elliptical ~7pc

Black hole binary shrinking mechanisms

1. As the galaxies merge the supermassive black holes sink toward the centre of the new galaxy via dynamical friction where they form a binary

2. The binary continues to decay via gravitational slingshot interactions in which stars on orbits intersecting the binary are ejected at velocities comparable to the binary's orbital velocity, while the binary's binding energy increases

3. If the binary's separation decreases to the point where the emission of gravitational waves becomes efficient at carrying away the remaining angular momentum, black hole binary will coalesce rapidly

During the transition from 2 to 3 if the binary ejects all the stars on intersecting orbits, binary hardening will stall before the GW can take over
→ FINAL PARSEC PROBLEM

Solutions:
- interaction with gas
- refilling of the loss cone via star-star encounters
- triaxial distortions

Black hole binary shrinking mechanisms

Interaction with stars:

- Each ejected star carries away energy and angular momentum, causing the semi-major axis, eccentricity, orientation and center-of-mass velocity of the binary to change and the local density of stars to drop

- Let a be the semi-major axis of the BH binary. The angular momentum of a star with a pericenter $\sim \mathcal{R}\times a$ where R is of order of unity is (e.g. Merritt2005):

$$L_{lc} = \mathcal{R}a\sqrt{2\left[E - \Phi(\mathcal{R}a)\right]} \approx \sqrt{2Gm_{12}\mathcal{R}a}.$$

- The “loss cone” is the region in phase space defined by $L < L_{lc}$

- A binary BH depletes its loss cone very quickly since stars within the loss cone need inly a few close encounters with the binary to be ejected

- Two body scattering of stars can re-supply the loss cone, e.g. a passing star can cause a small angular momentum perturbation which can deflect a star into the loss cone
- However, detailed calculation of collisional refilling rates in real galaxies (Yu 2002), indicates that this is not an efficient mechanism for coalescence

Black hole binary shrinking mechanisms

Interaction with stars:

- In galaxies that continue to experience mergers (and/or accretion events), time-dependent loss cone refilling might be much more effective

- In non-axisymmetric potentials, such as a triaxial or bar-like, much greater number of stars may be on "centrophilic" orbits (boxy or chaotic), which can be much closer to the BH binary. Recent, N-body simulations of triaxial nuclei seem to confirm this picture (Merritt et al. 2011)

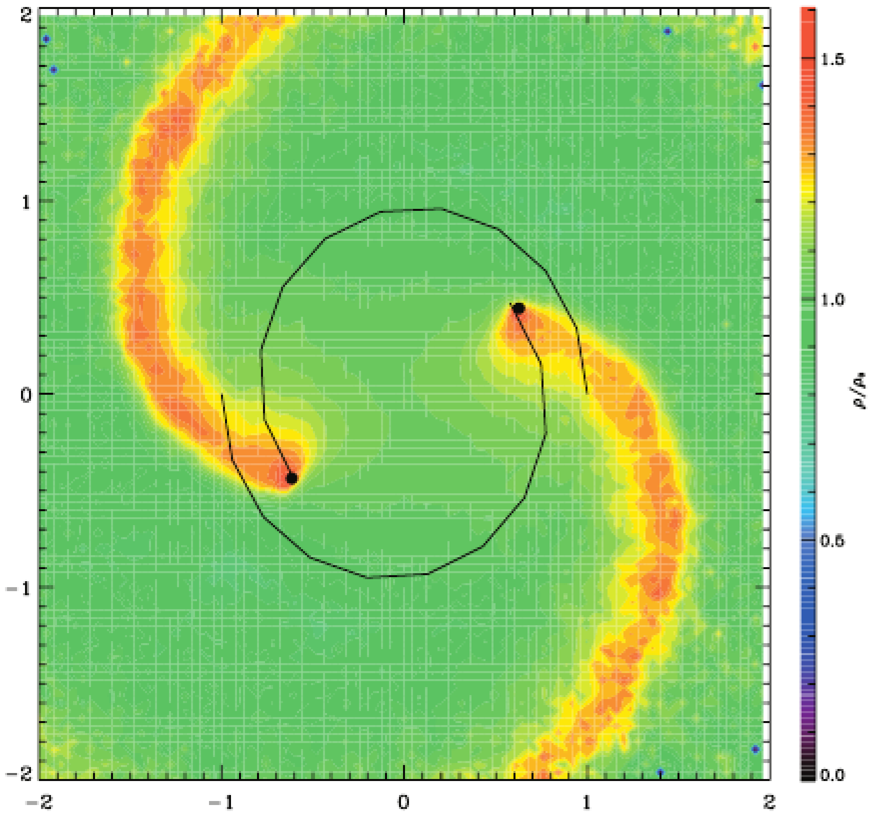
- There is a close parallel between the final parsec problem and the problem of quasar fueling: both require that ~ 10^8Msun be supplied to the inner parsec of a galaxy in a time shorter than the Hubble time. As for the QSOs, gas flows driven by torques from stellar bars could aim binary hardening: renewed formation of stars, gas torques on the binary, gas accretion,...

Black hole binary shrinking mechanisms

Interaction with gas:

- Interaction of a BH binary with a hot gaseous cloud leads to efficient binary hardening if the mass of the hot gas is comparable to the BH binary mass (Escala et al. 2004)

- Interaction with a cold gaseous disk very complex: might lead to binary hardening but depends sensitively on the gas thermodynamics, binary mass,... (e.g. Cuadra et al. 2009)



Black hole spins

- While astrophysical black holes are characterized both by their mass and spin in large scale cosmological simulations (as well as semi-analytic treatments) black hole spins are largely neglected
- Black hole spins affect the radiative efficiencies of black holes → thus changing the amount of material that can be accreted by the black hole (and also affecting the feedback strength)
- For standard accretion disks radiative efficiency at the innermost stable co-rotating circular orbit (Bardeen et al. 1972) varies from 0.057-0.42 for a non-spinning (a = 0) to a maximally spinning black hole (a = 1)

$$e_{\rm max} = 1 - \frac{\tilde{r} - 2 + a/\sqrt{\tilde{r}}}{\sqrt{\tilde{r}^2 - 3\tilde{r} + 2a\sqrt{\tilde{r}}}} ,$$

where

$$\tilde{r} = 3 + A_2 - \sqrt{(3 - A_1)(3 + A_1 + 2A_2)} ,$$

$$A_1 = 1 + (1 - a^2)^{1/3}\left[(1 + a)^{1/3} + (1 - a)^{1/3}\right]$$

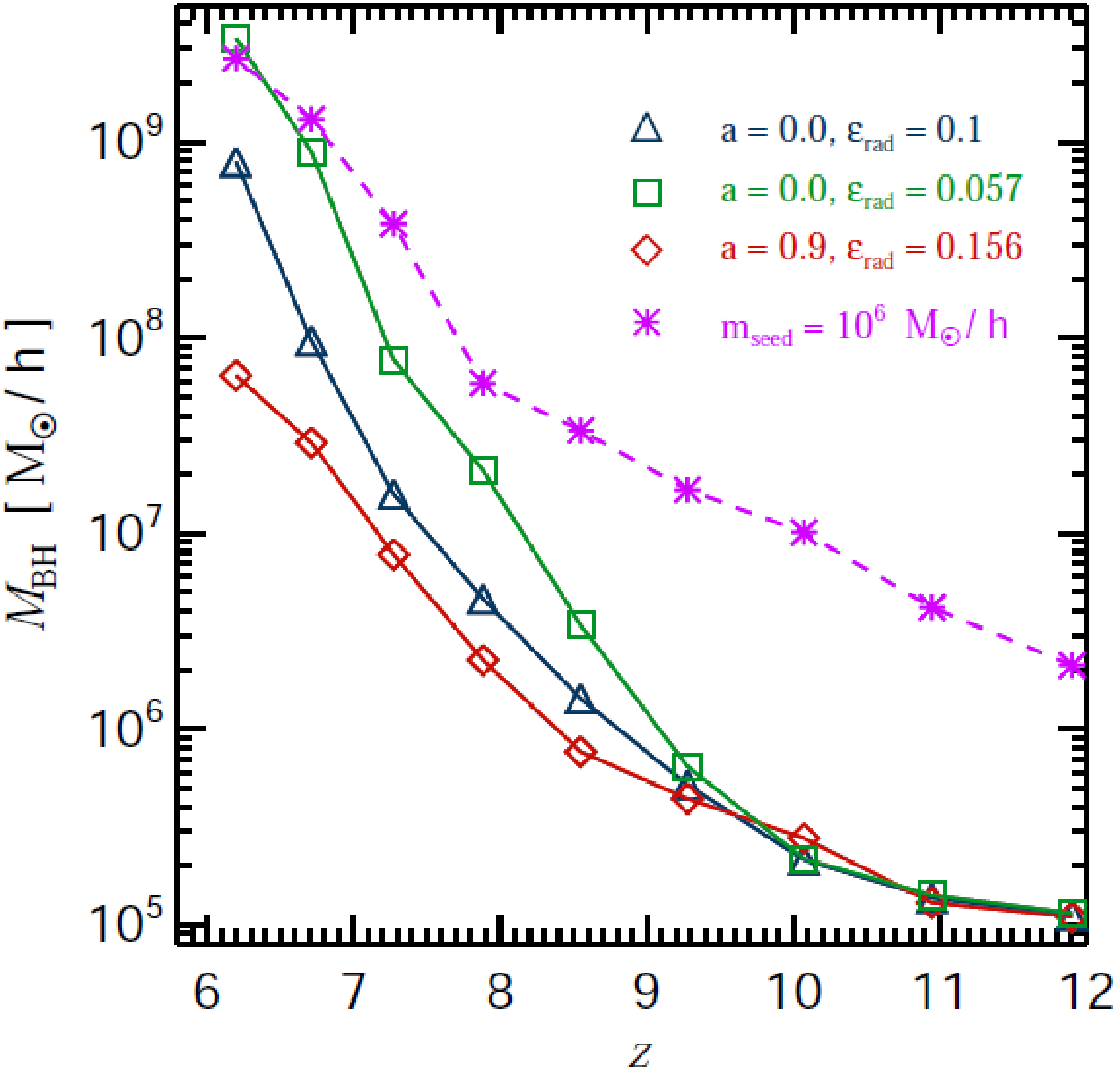
and

$$A_2 = \sqrt{3a^2 + A_1^2} .$$

Black hole spins

- Black hole spins can have a large impact on the early growth history of black holes (Shapiro et al. 2005, Volonteri & Rees, 2006, Sijacki et al. 2009)

- While Soltan's argument (Yu & Tremaine, 2002) constrains the average radiative efficiency of QSOs to be ~ 0.1 – 0.2 certain fraction of black holes (e.g. at high z, at high masses, etc.) could be rapidly spinning

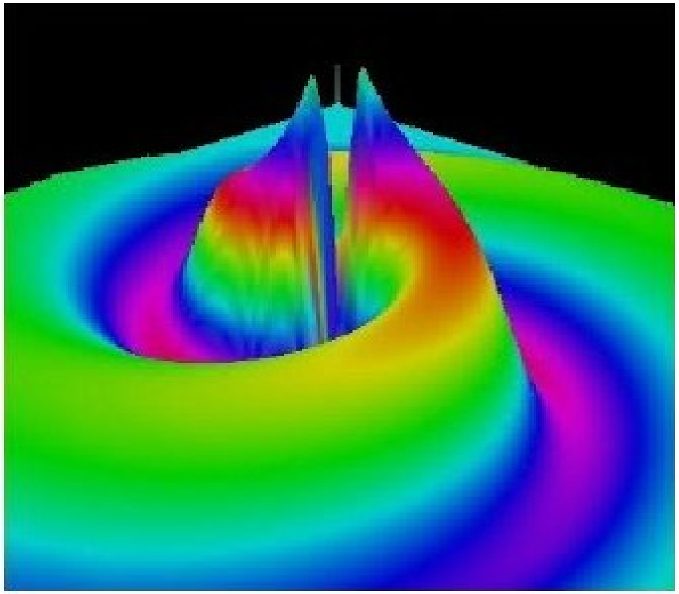


Sijacki et al. 2009

Black hole spins

- It is unlikely that a spin of a black hole (and thus its radiative efficiency) will stay constant with cosmic time

- Spins change with:
→ gas accretion
this is still poorly understood; both spin-ups (coherent accretion, Volonteri & Rees, 2005) and spin-downs (chaotic accretion, King & Pringle, 2006) are possible
→ mergers with other black holes
recent breakthrough in numerical relativity permits to compute spins of binary black hole merger remnants for a variety of configurations (e.g. Rezzola et al. 2008)



H.-P. Bischof/Rochester Inst. of Tech.

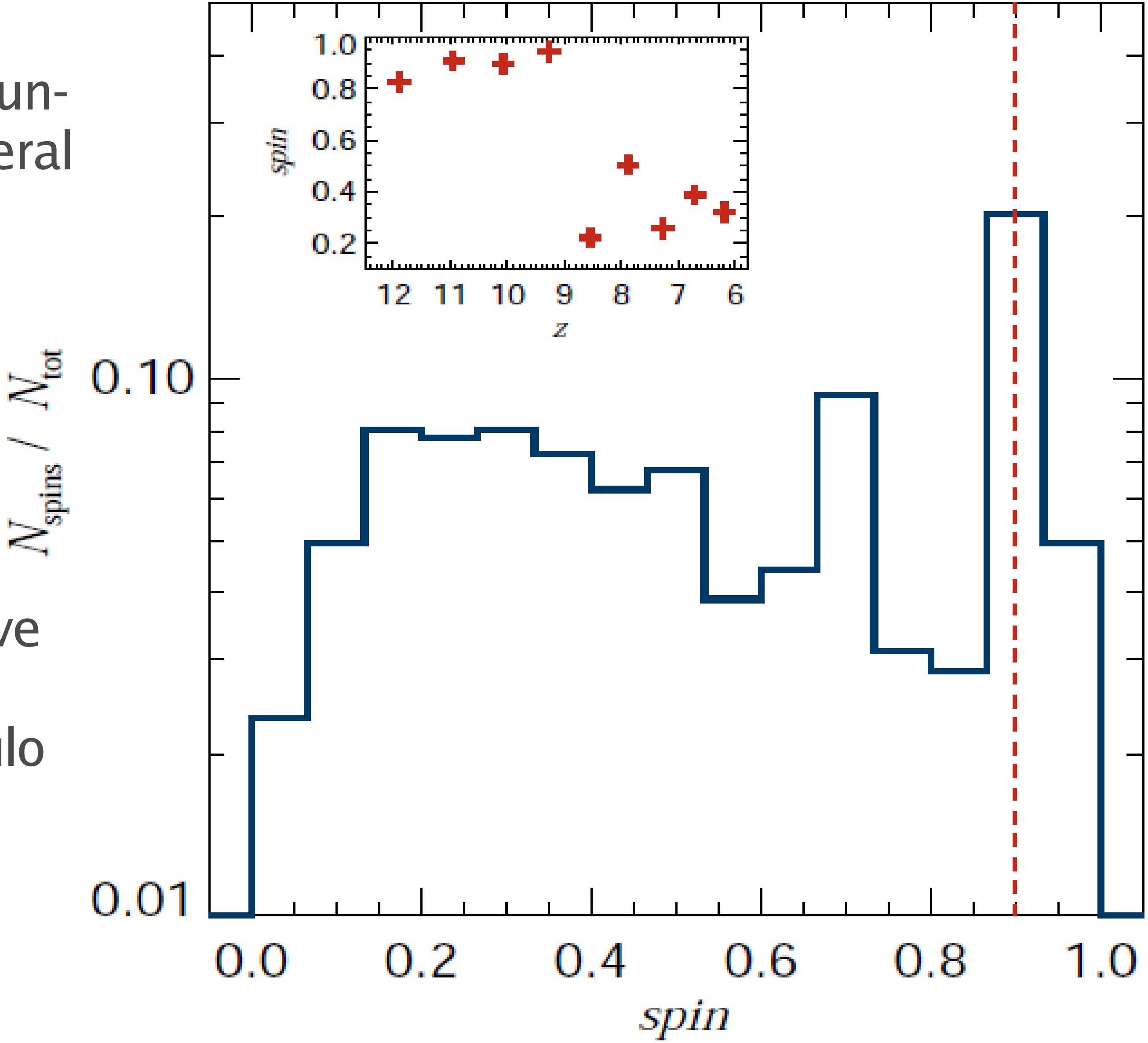
Black hole spins

- Black hole spin evolution with cosmic time due to mergers alone (spins parallel with the orbital angular momentum and initial spin = 0.9)

- Majority of black hole is spun-down after experiences several mergers (only 5% spun-up)

- For spin-ups special spin configurations & mass ratio conditions need to be met (Hughes & Blandford, 2003)

- Thus, possibly high radiative efficiencies are not an issue for bright z ~ 6 QSOs (modulo gas accretion)



Sijacki et al. 2009

Gravitational recoils

- Asymmetry in a merging black hole binary, such as different mass, spin and spin orientation, leads to anisotropic emission of GW at the merger, which imparts a kick to the remnant

- Numerical relativity simulations have characterized the magnitude of the recoil for a variety of initial configurations in binary systems (Gonzalez 2007, Campanelli 2007, Backer 2007/2008, Rezzolla 2007/2008)

- In the case of spinless black holes a difference in mass of the two merging black holes can lead to the recoil velocities of up to ~ 175 km/s (Fitchett, 1983, Gonzalez 2007)

- For spinning black hole recoil velocities are much larger:

→ if the spins are parallel to the orbital angular momentum maximum kick velocity is ~ 460km/s (spins anti-aligned, maximal and mass ratio = 1)

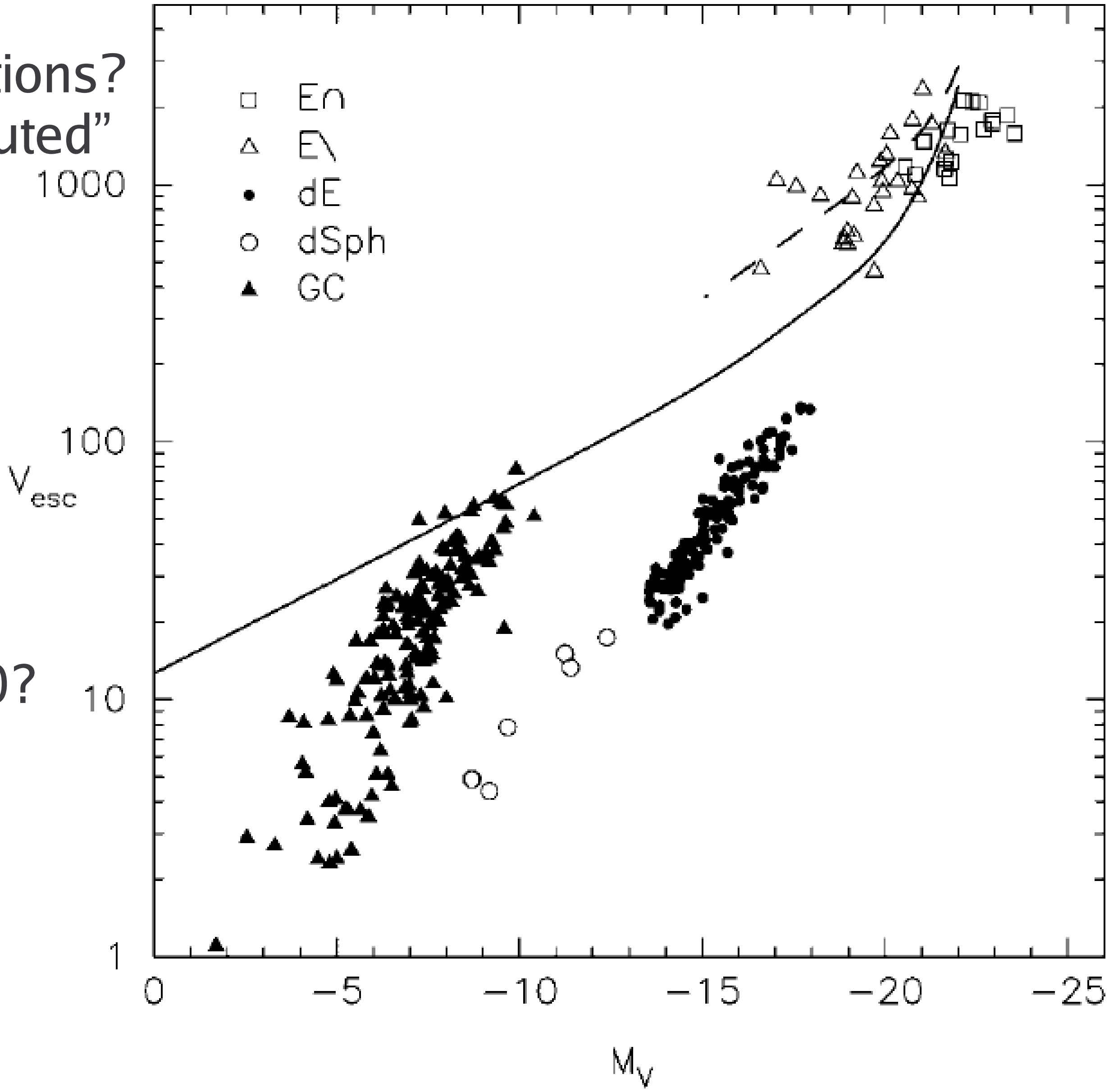
→ if spins are not parallel to the orbital angular momentum recoils even up to 4000km/s are possible (spins anti-aligned and in the orbital plane)

Gravitational recoils

- Astrophysical consequence: recoils can expel black holes from their host galaxies, especially if they have low mass (shallow potential wells)

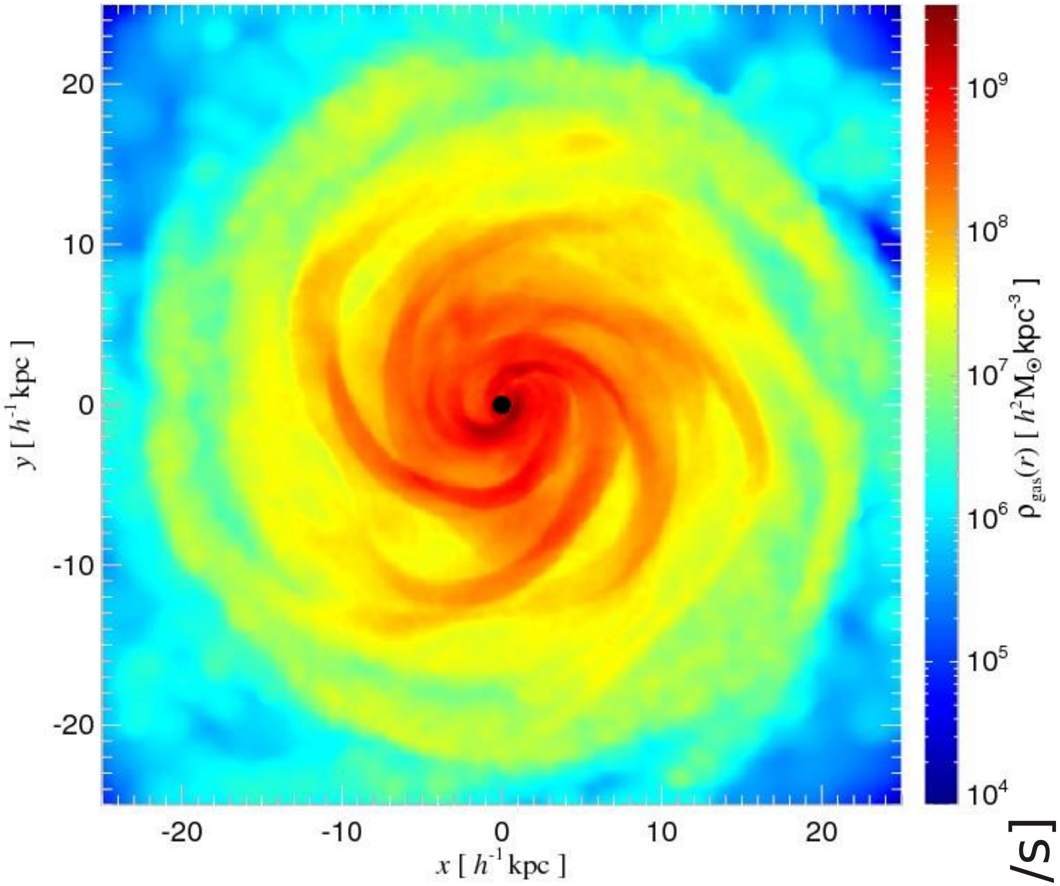
- Implications:
Extra scatter in BH-galaxy relations?
Can offset BHs provide “distributed” heating in galaxy cores?
Shut-off BH growth?
Stall the growth of bright QSOs at z~6?

- So far, no firm observational evidence for a recoiled black hole SDSSJ092712.65+294344.0?

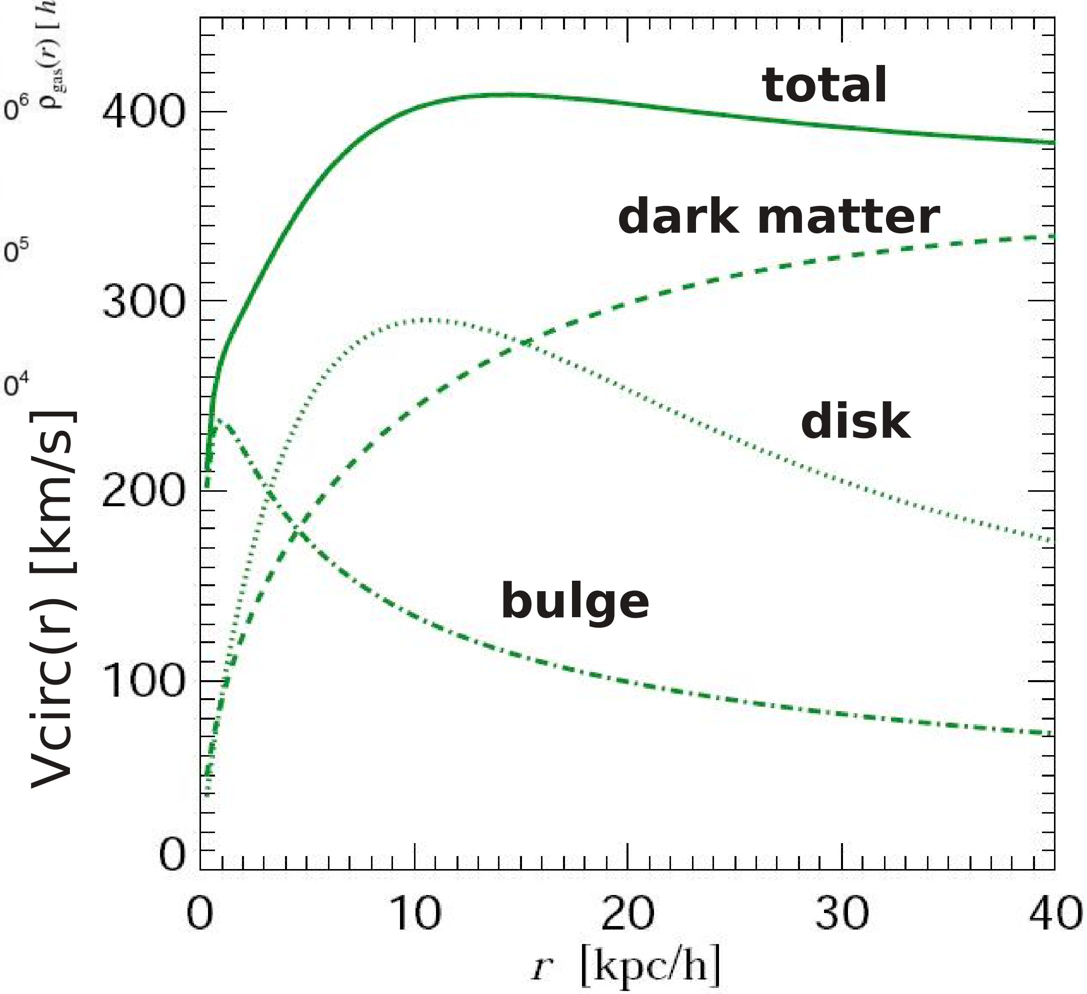


Merritt et al. 2004

Gravitational recoils



STABLE MASSIVE GAS RICH GALAXY



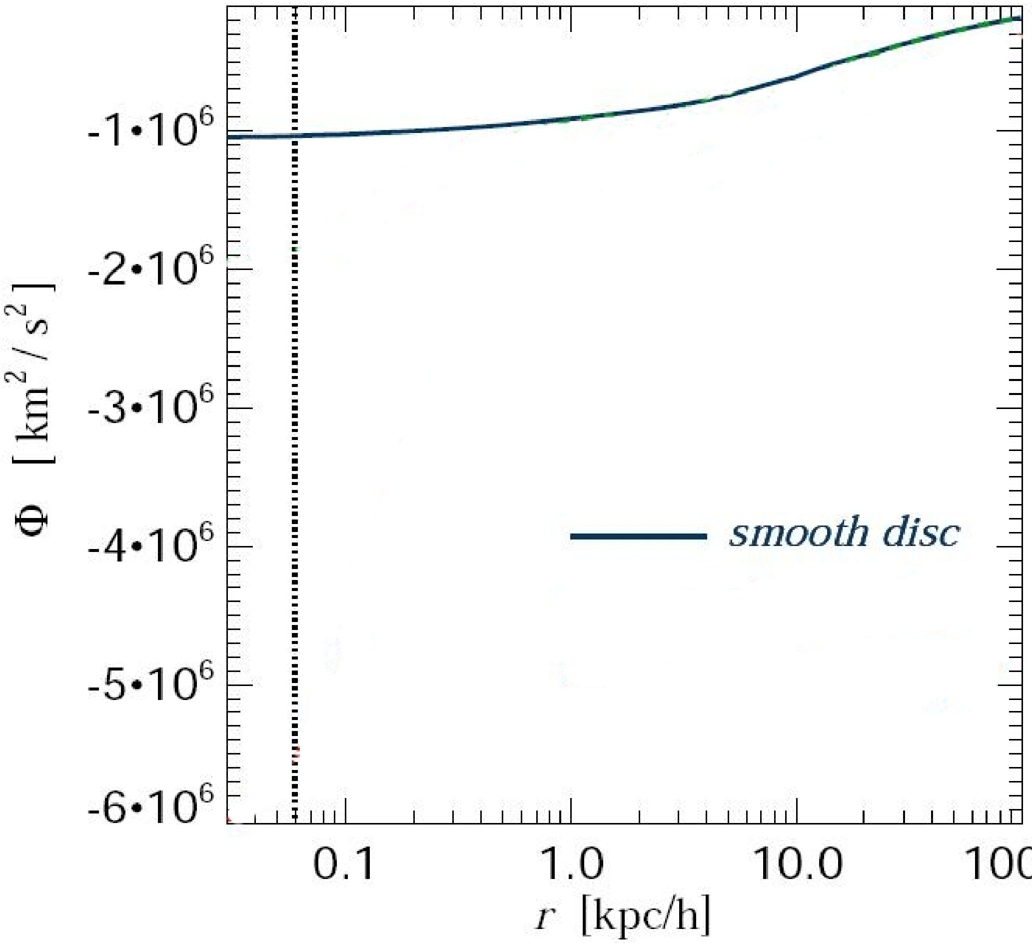
M_{200} = 6.3 x 10^{12} M⊙/h
v_{200} = 300km/s
M_{disk} = 0.041, m_{bulge} = 0.008
f_{gas} = 0.6, l_{disk} = 4.8kpc/h
M_{BH} = 5 x10^{7-8} M⊙/h

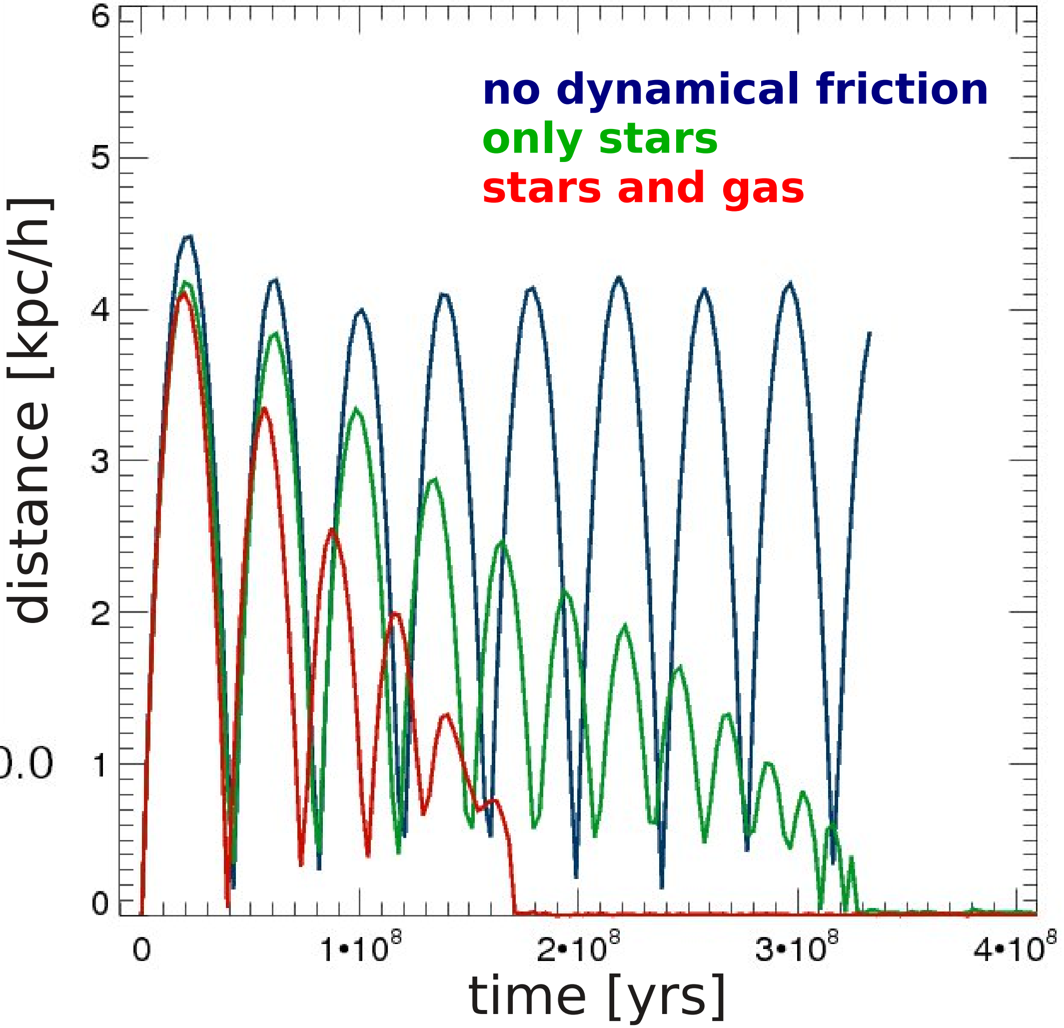
Sijacki et al. 2010

Gravitational recoils

$$v_{\rm esc}(0) = \sqrt{2\,\Phi(r=0)} \sim 1450 {\rm km/s}$$ → TO LEAVE THE CENTER:

$v_{\rm kick} > 0.3\, v_{\rm esc}(0)$



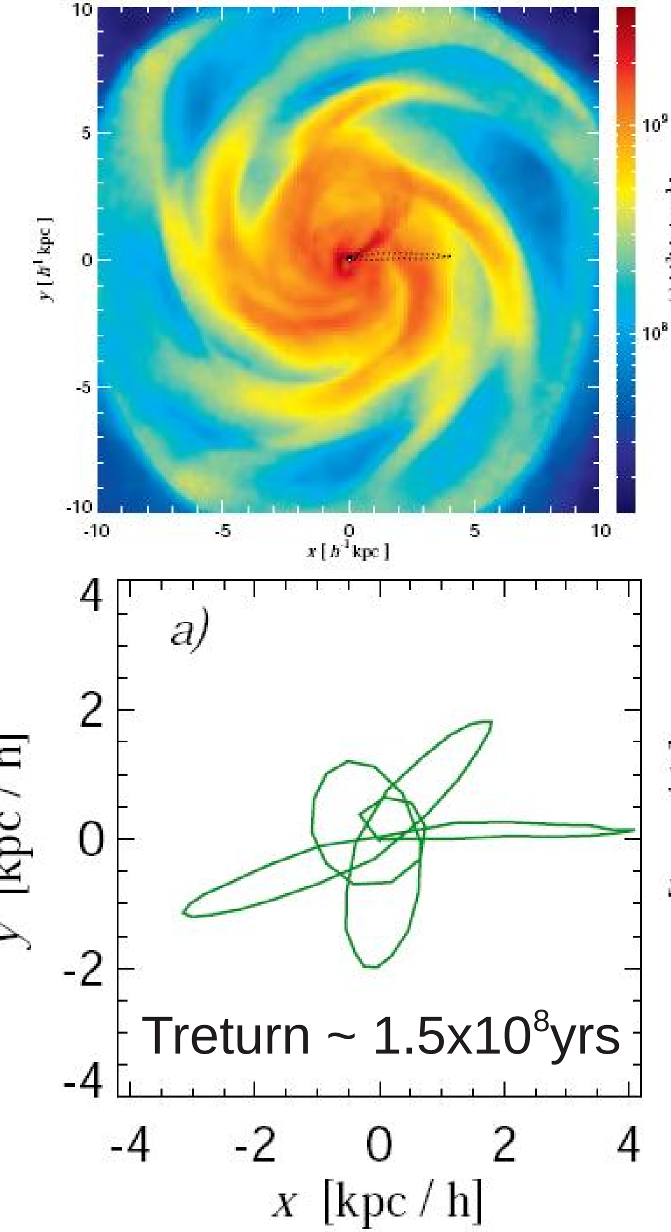


gas dynamical friction reduces BH return time-scale

Sijacki et al. 2010

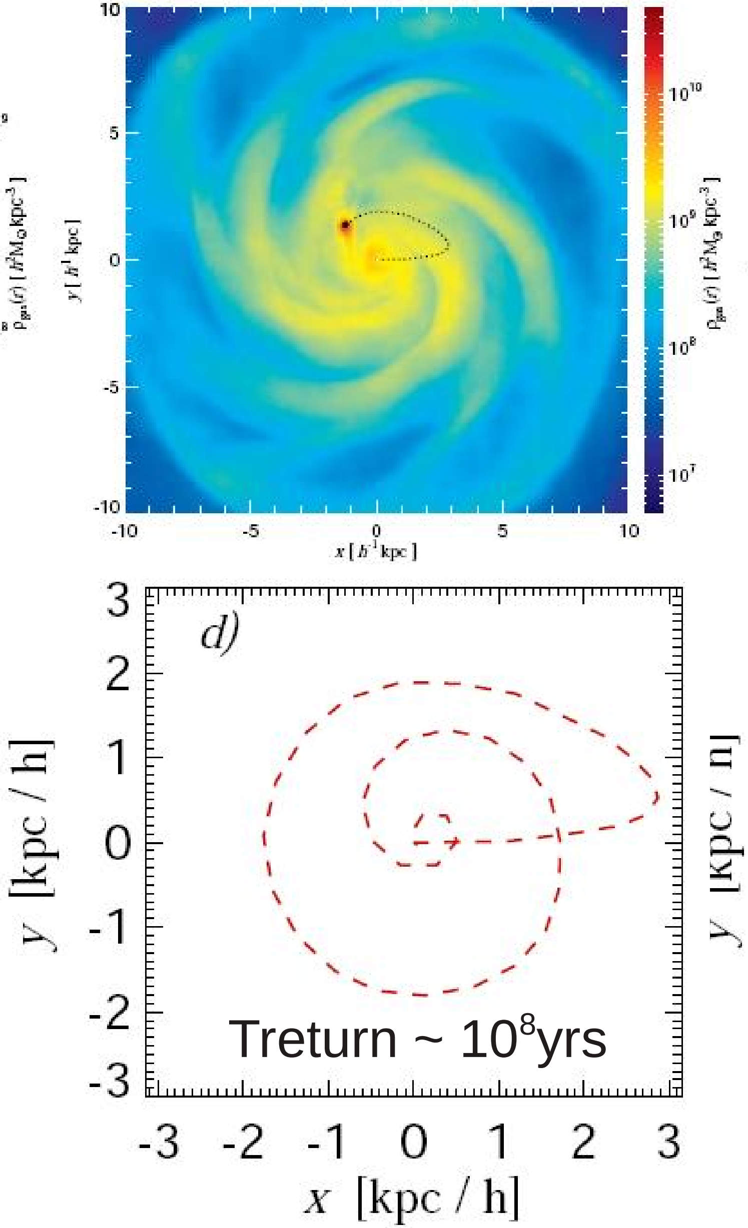
Gravitational recoils: dependence on accretion and feedback

BH ACCRETION ✘
BH FEEDBACK ✘



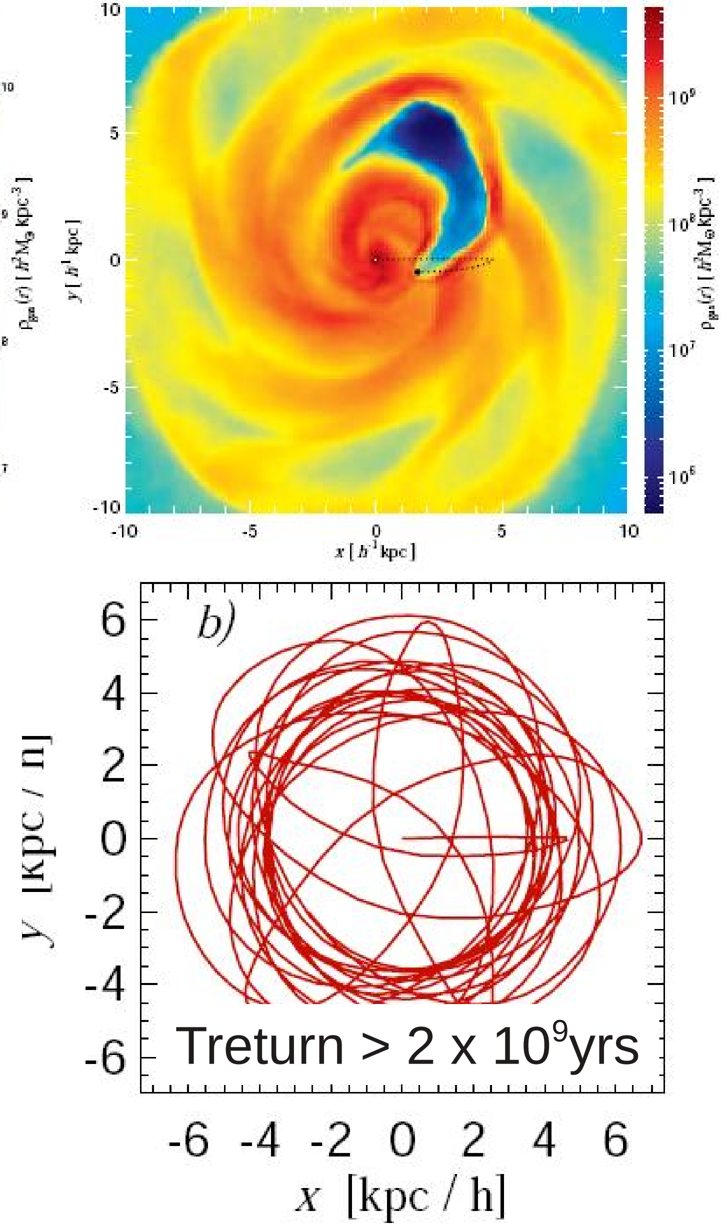
Treturn ~ 1.5x10^8yrs

BH ACCRETION ✔
BH FEEDBACK ✘



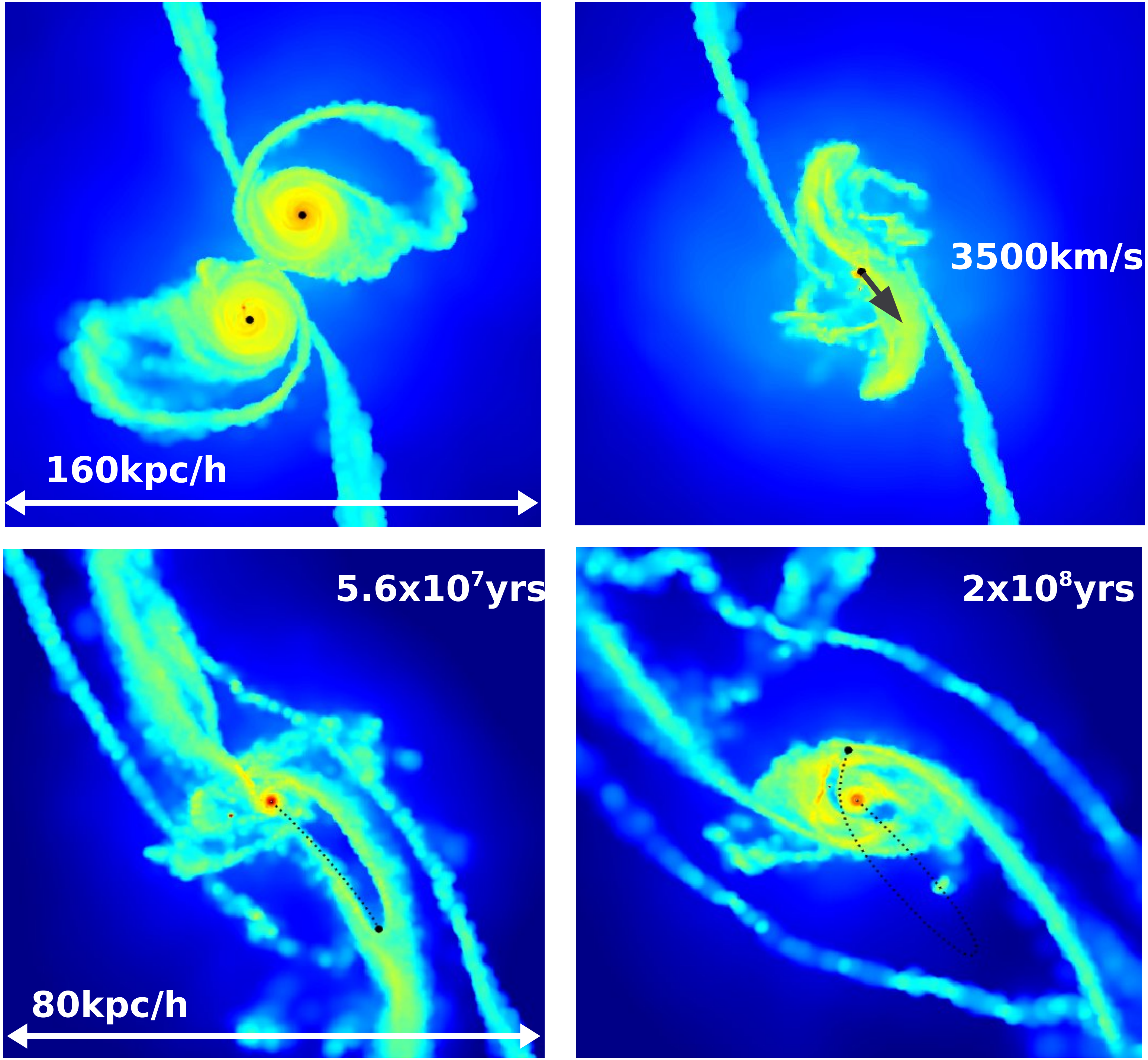
Treturn ~ 10^8yrs

BH ACCRETION ✔
BH FEEDBACK ✔



Treturn > 2 x 10^9yrs

Gravitational recoils: galaxy mergers

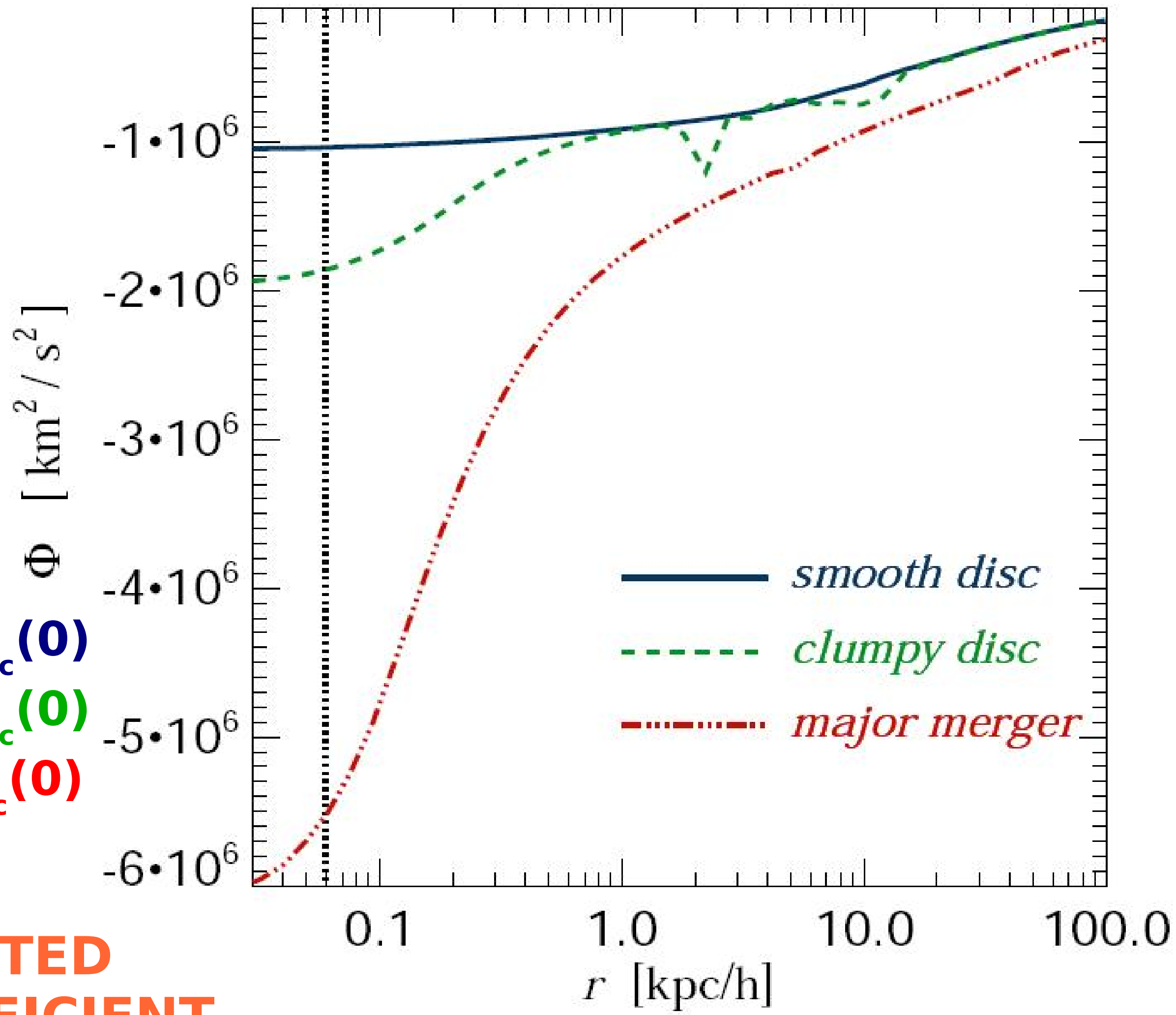


Gravitational recoils: galaxy mergers

- Shape of the gravitational potential in the central region affects strongly which black holes can leave the centre
- This will depend on a variety of baryonic processes (e.g. efficiency of cooling,...)

BH LEAVES THE CENTER:

$v_{esc}(0) = 1450km/s$ $v_{kick} > 0.3\ v_{esc}(0)$
$v_{esc}(0) = 1980km/s$ $v_{kick} > 0.5\ v_{esc}(0)$
$v_{esc}(0) = 3510km/s$ $v_{kick} > 0.8\ v_{esc}(0)$

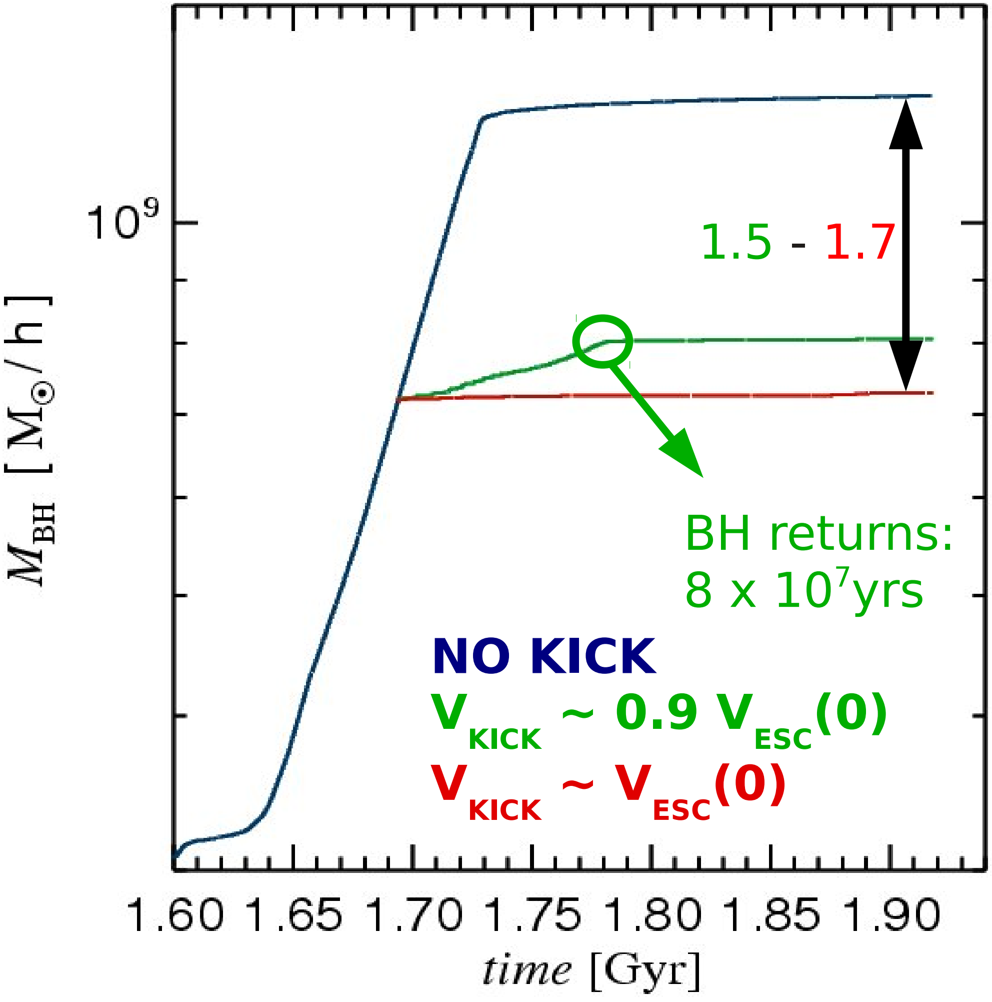


NOT EVEN MAXIMUM PREDICTED RECOIL VELOCITIES ARE SUFFICIENT TO COMPLETELY EJECT THE BH FROM THIS MERGING SYSTEM

Sijacki et al. 2010

Gravitational recoils: galaxy mergers

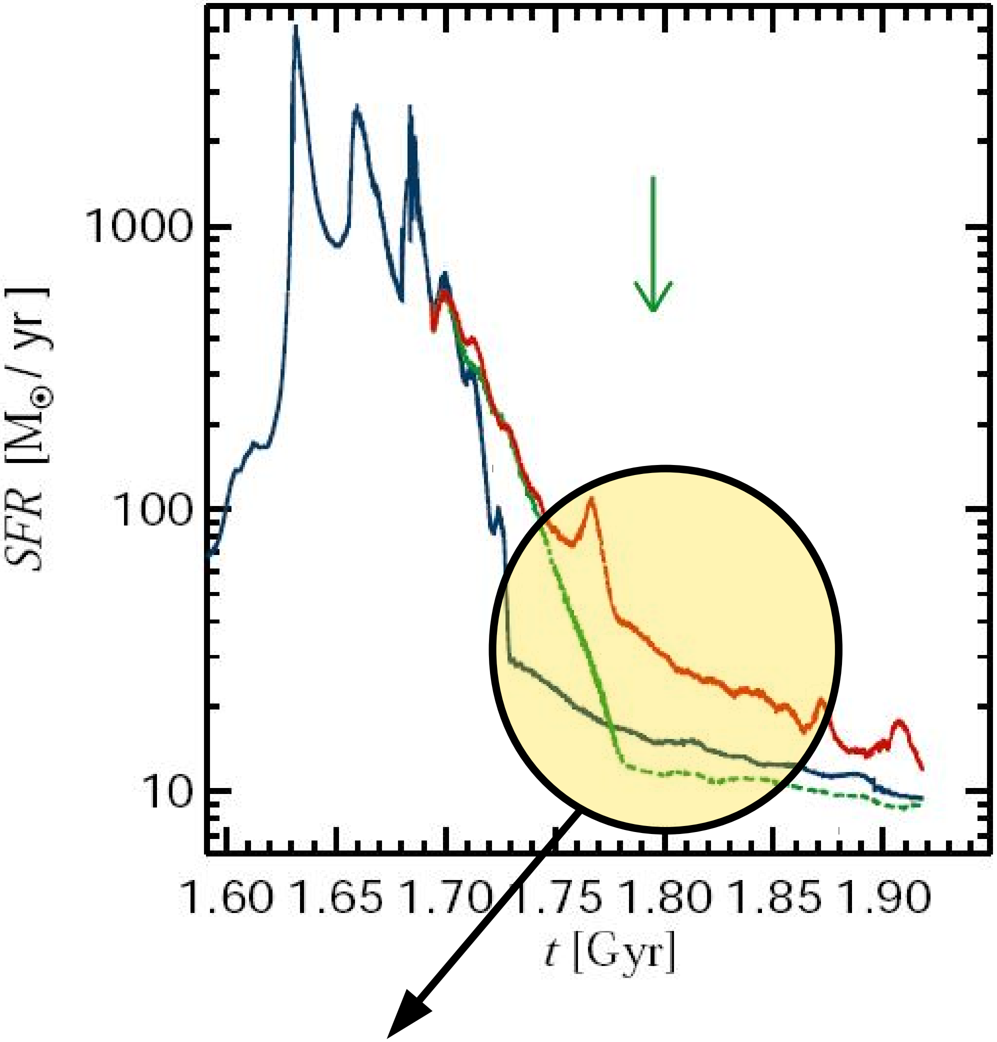
BH MASS REDUCED BY A FACTOR OF ~1.5-2:
IMPLICATIONS FOR BH - HOST GALAXY SCALING RELATIONS



1.5 - 1.7

BH returns:
8×10^7yrs

NO KICK
$V_{\rm KICK}$ ~ 0.9 $V_{\rm ESC}$(0)
$V_{\rm KICK}$ ~ $V_{\rm ESC}$(0)



PROLONGED STAR FORMATION RATE

Gravitational recoils: galaxy mergers

Wandering BHs exhibit complex interplay with the surrounding gas: return time-scale can be prolonged or shortened depending on detailed properties of BH accretion/feedback, gas fraction and thermodynamic state

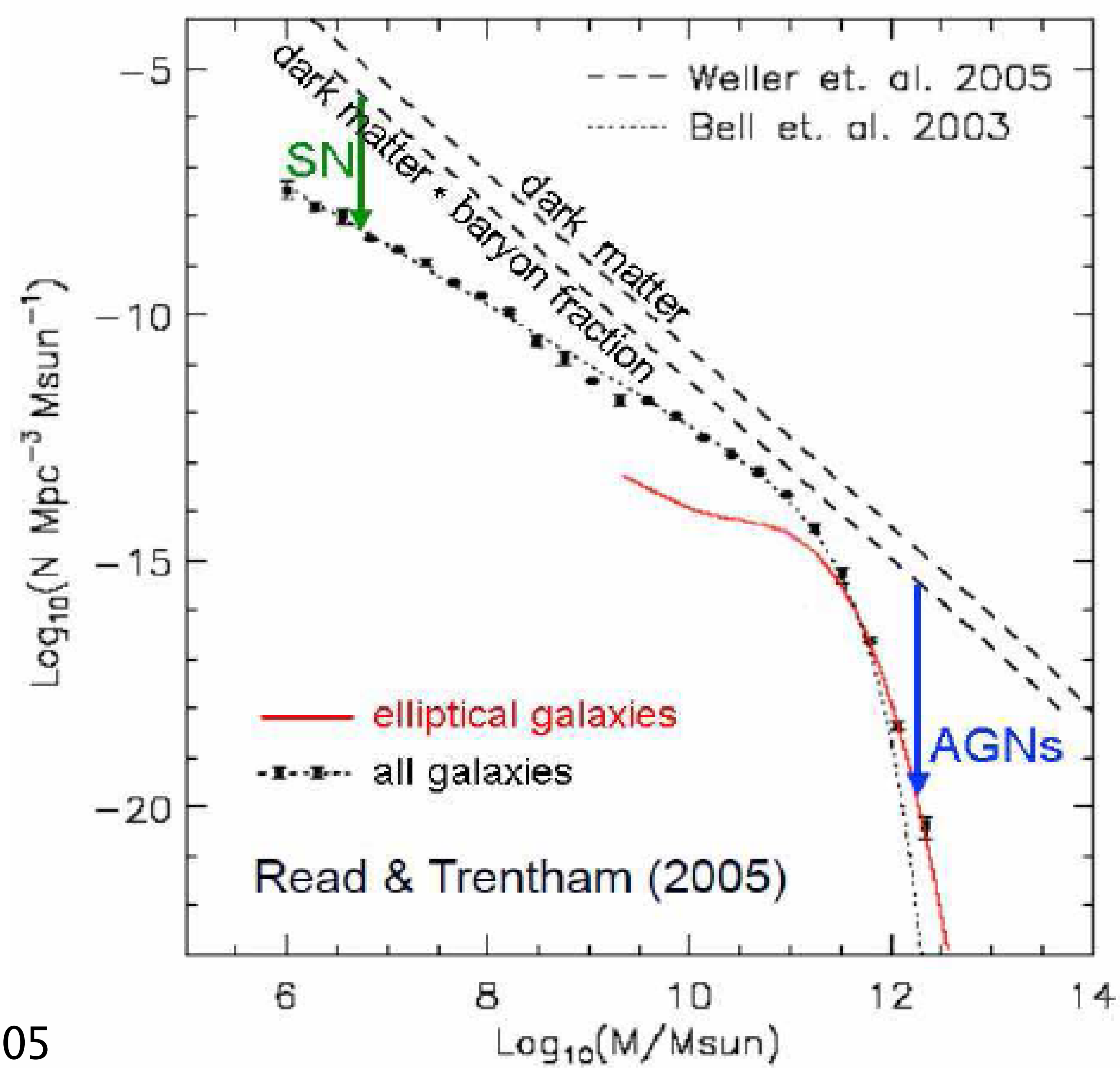
Gas dynamical friction can play an important role!

For centrally concentrated, clumpy galaxies or gas-rich merger remnants central potential might be deep enough to reduce substantially the fraction of ejected BHs

Gravitational recoils might introduce scatter in BH-host galaxy scaling relations: however, exact magnitude will depend on the BH binary hardening time-scale and on the efficiency of central star formation

AGN feedback processes and their impact on the host galaxies across the Hubble sequence

- Baryonic mass function very different than the dark matter mass function



Read & Trentham, 2005

AGN feedback processes and their impact on the host galaxies across the Hubble sequence

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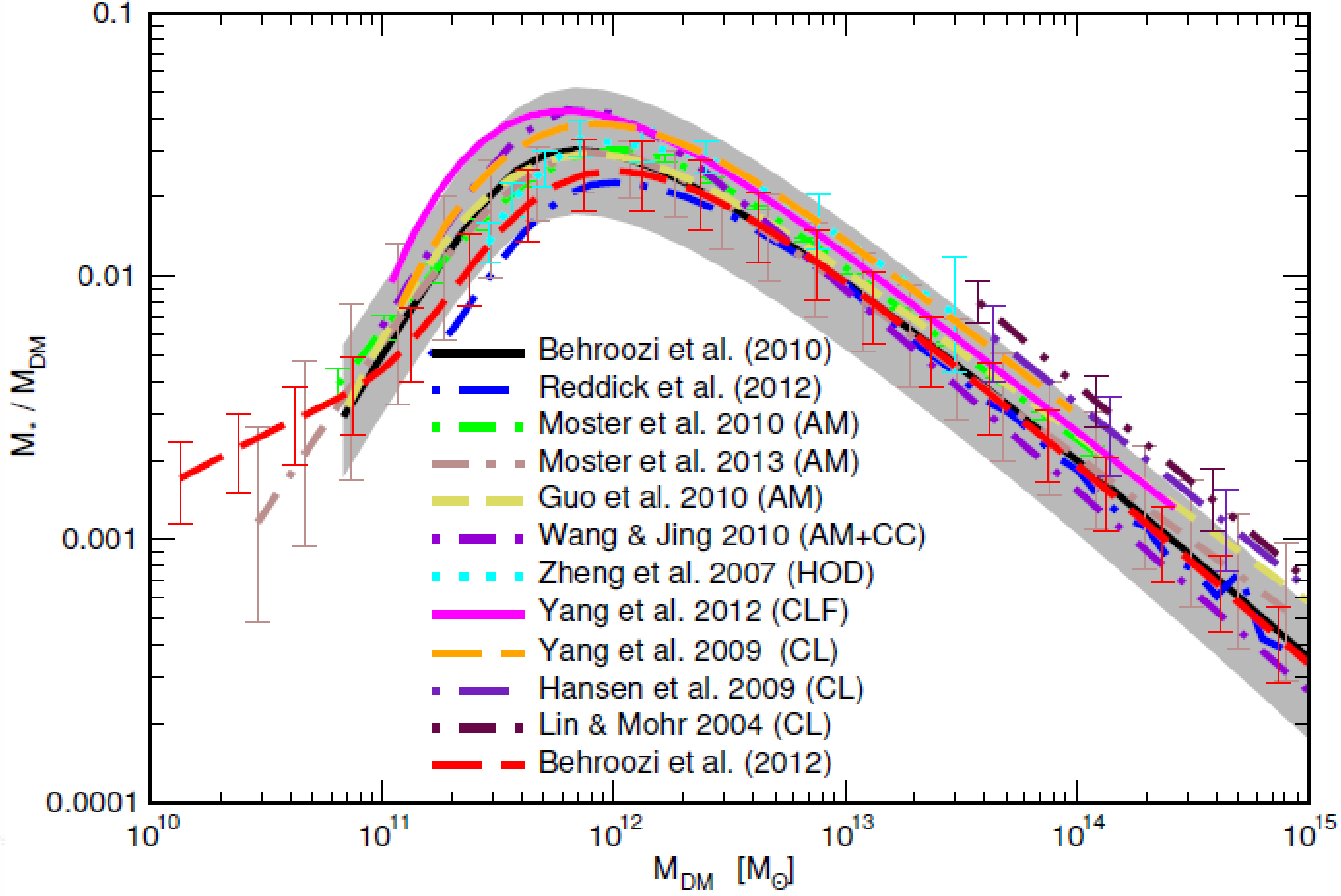
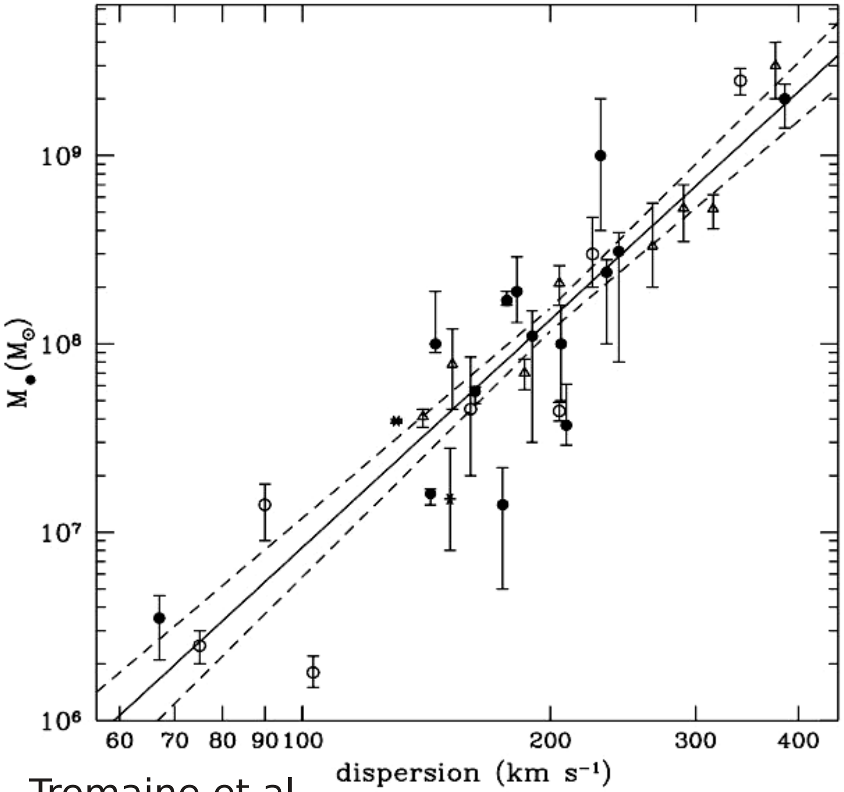


Behroozi et al. 2013

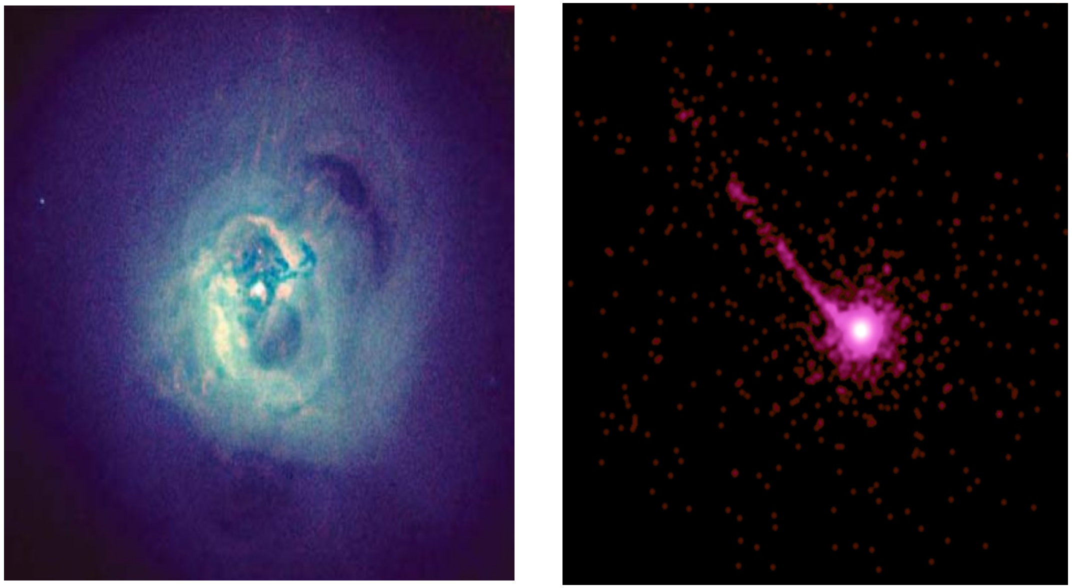
AGN feedback processes and their impact on the host galaxies across the Hubble sequence

- It is believed that virtually all galaxies with a spheroidal component host in their centre a massive BH
- BH masses and stellar properties of their host galaxies are tightly linked, e.g. M_{BH}-σ and M_{BH}-M_{bulge} relations (e.g. Ferrarese2000, Tremaine2002; Kormendy1995, Magorrian1998, Marconi2003, Haering2004,...)



Tremaine et al. 2002

- How do BHs influence their hosts?
- In which form does AGN feedback appear at different z and in different hosts?
- can we characterize the growth and feedback processes of a hole population of BHs in a cosmological context?



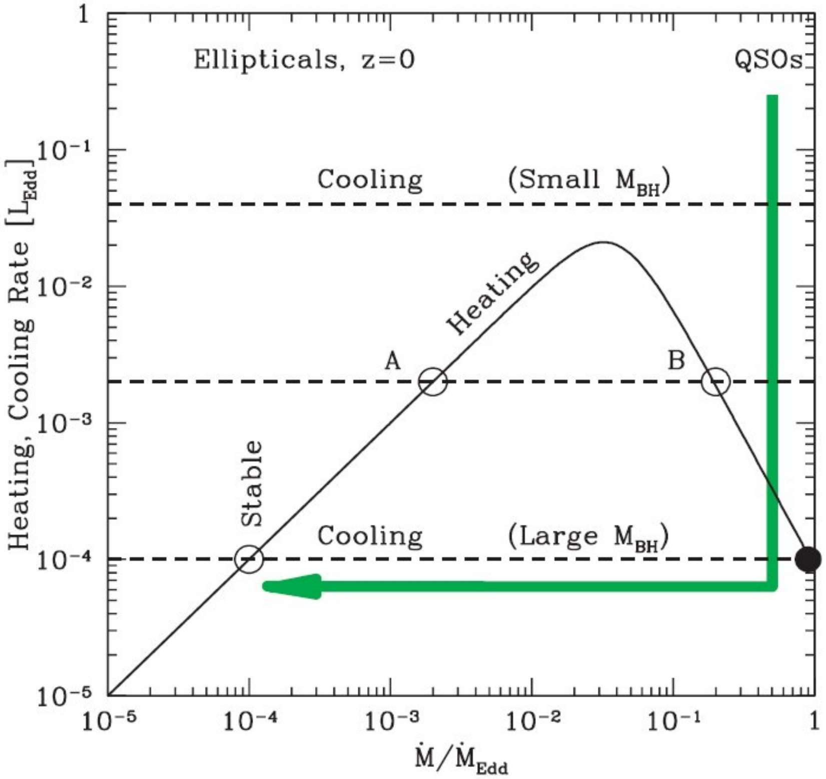
Fabian et al. 2006

AGN feedback processes and their impact on the host galaxies across the Hubble sequence

- In the newly emerging scenario AGN feedback might be composed of two modes:

1. At high z, due to the major mergers, large amount of gas can be accreted by the central BH => powerful QSO

2. SMBH at low redshifts, have very low L_{bol} – but they show evidence of outflows (jets, bubbles), with $L_{mech} > L_{bol}$.



Churazov et al., 2005
-see also, Croton et al, Bower et al, Merloni et al. Sijacki et al.

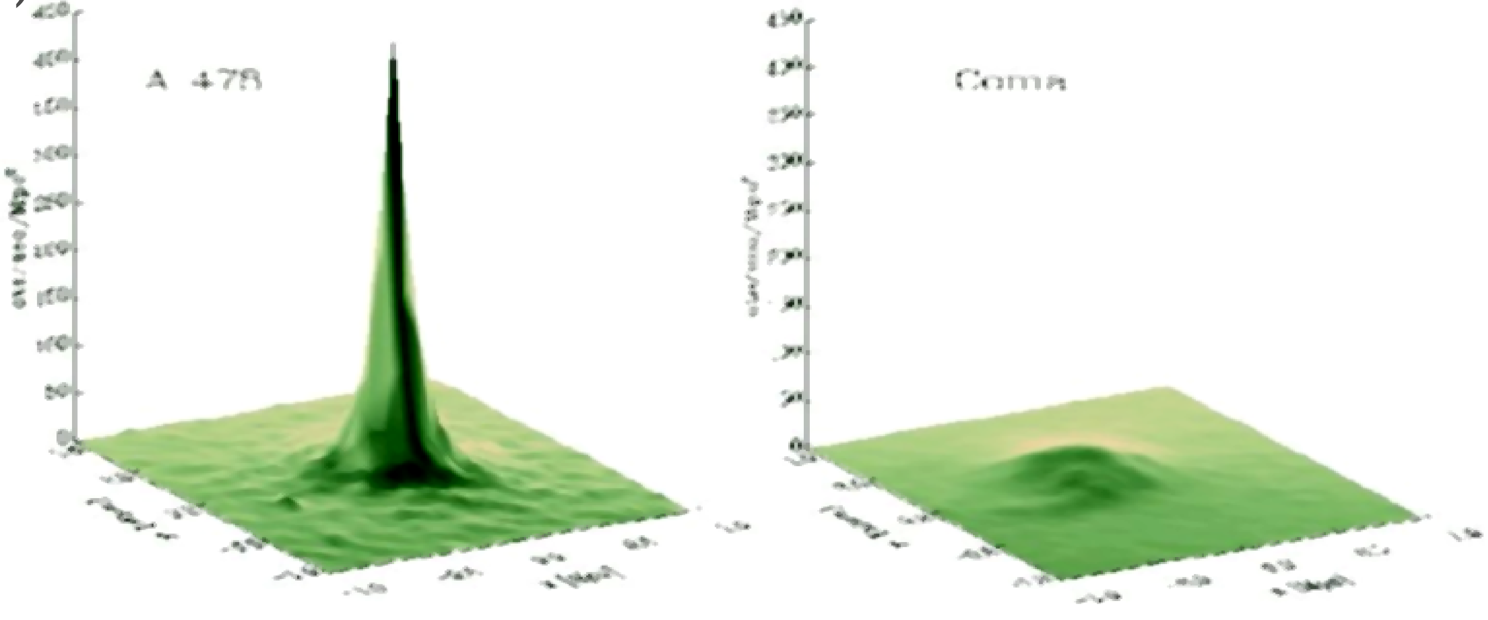
- Some bright QSO show evidence of outflows with velocities > 0.1c and mass loss rates of several tens of solar masses per year (Pounds & Page, 2006, Tombesi et al. 2012)

- At high redshifts QSO can exibit even much more powerful outflows reaching a few 1000 of solar masses per year (Maiolino et al. 2012)

AGN feedback processes and their impact on the host galaxies across the Hubble sequence

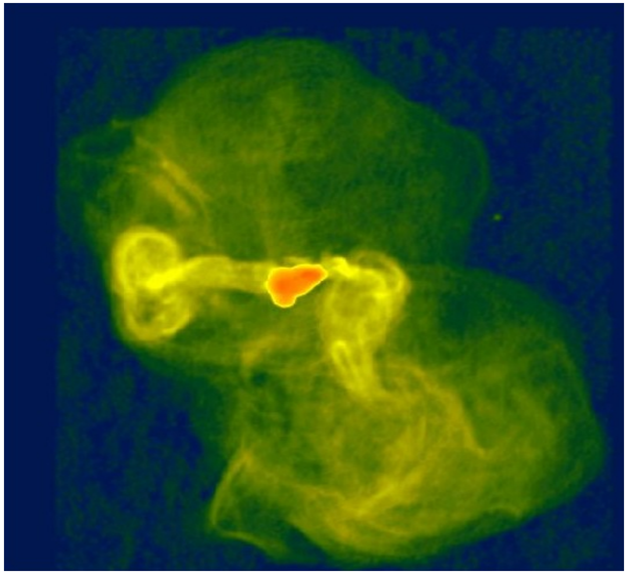
- One of the most puzzling observational facts of galaxy clusters is perhaps the so-called the cooling flow problem. The inferred cooling time in the central regions of many galaxy clusters is less than 1.e10yrs and if there is no heating source mass depositions rates of 100-1000M⊙/yr are derived (Fabian, 1977, 1994; White, 1997; Allen, 2000).

- But, recent X-ray and optical observations have failed to detect sufficient amount of cold gas to support this picture, suggesting that the mass deposition rates should be at least 10 times smaller (McNamara, 2000; Balogh, 2001; Kaastra, 2001; Fabian, 2001; Peterson, 2001; Boehringer, 2002;...).

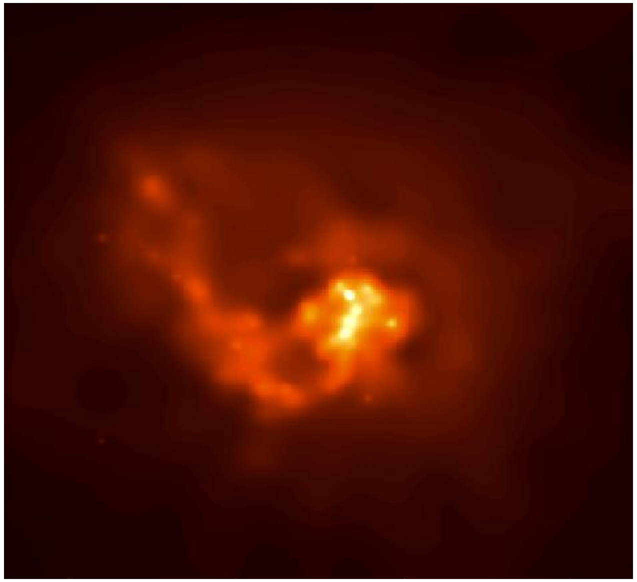


AGN feedback processes and their impact on the host galaxies across the Hubble sequence

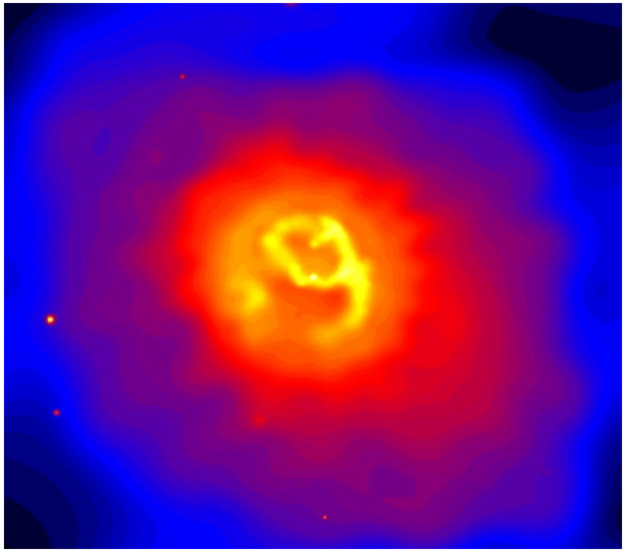
- Observationally, many clusters of galaxies show evidence for X-ray cavities filled with radio plasma, which are thought to be inflated by relativistic jets generated by the central BH (e.g. Owen, 2000; McNamara 2000, 2005; Blanton, 2001; Fabian 2002, 2006; Mazzotta, 2002; Birzan, 2004).



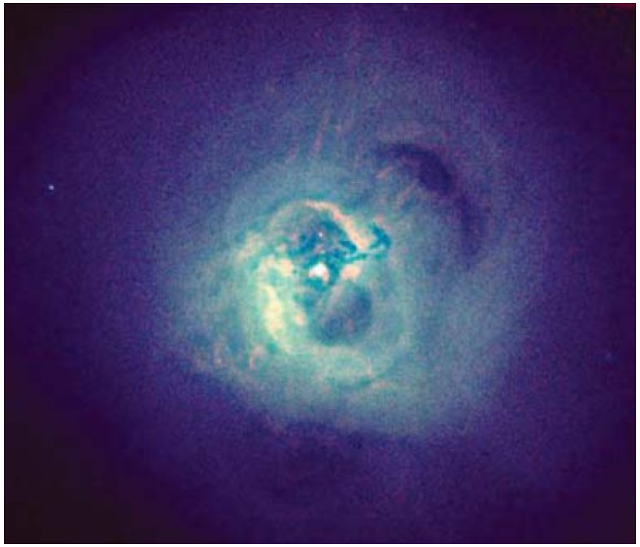
Owen, 2000: VLA radio image at 90cm of M87 (67kpc)



Sanders&Fabian 2002: Chandra 31ks image of Centaurus (50kpc)



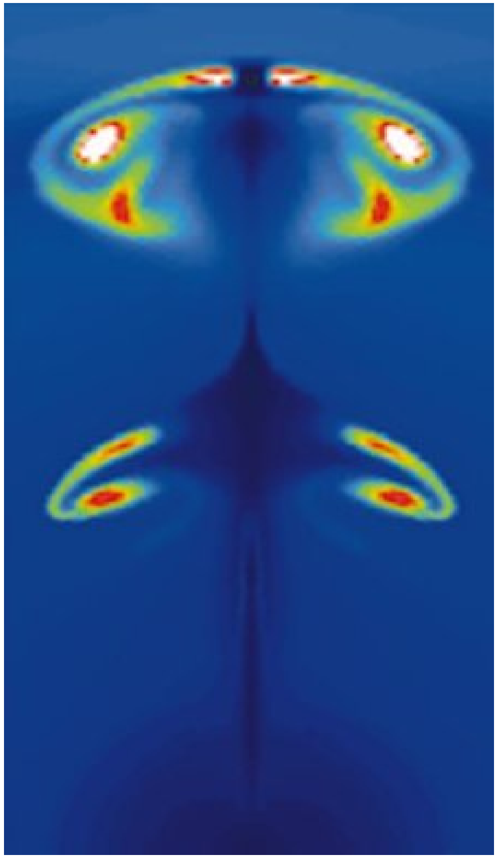
Blanton,2001: Chandra 37ks image of Abell 2052 (140kpc)



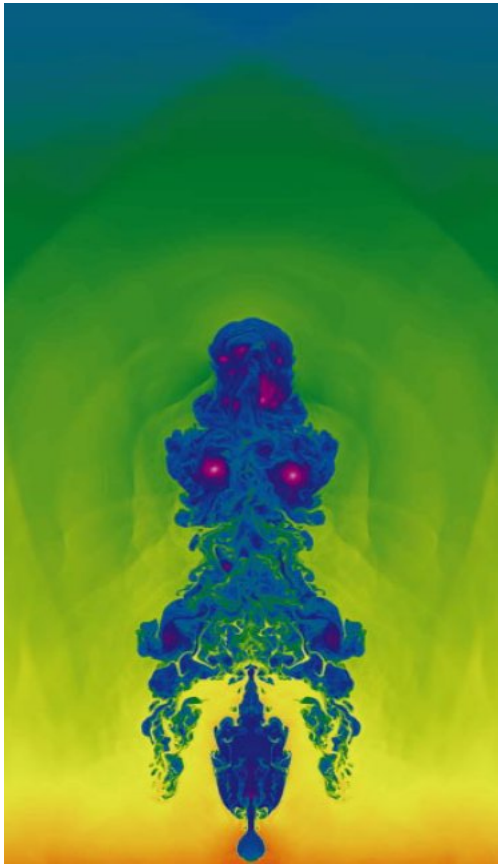
Fabian, 2006: Chandra 1Ms image of Perseus (220kpc)

AGN feedback processes and their impact on the host galaxies across the Hubble sequence

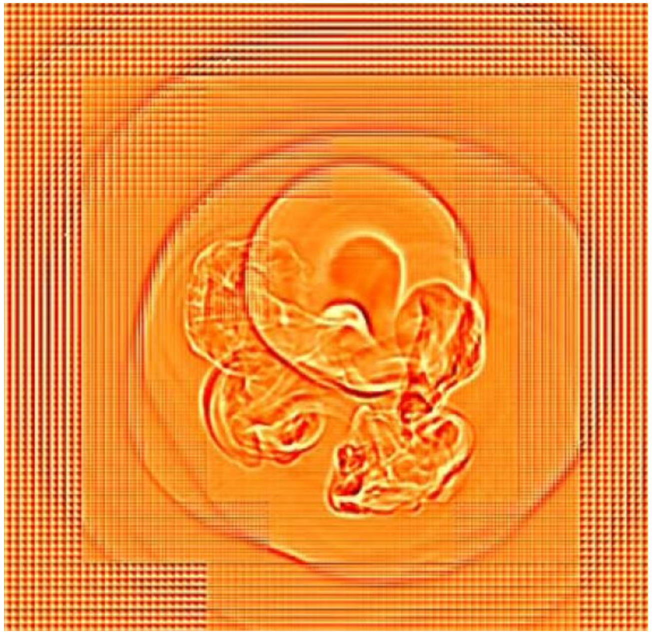
- Theoretically it has been shown by different authors (e.g. Churazov, 2001; Quilis, 2001; Ruszkowski, 2002; Brueggen 2002, 2003; Dalla Vecchia 2004, Sijacki, 2006,2007) that these bubbles may rise buoyantly, and lift up some of the central cool gas, and that they may heat the ICM mechanically and maybe viscously => good qualitative agreement with observations and the importance of bubble feedback!



Churazov, 2001

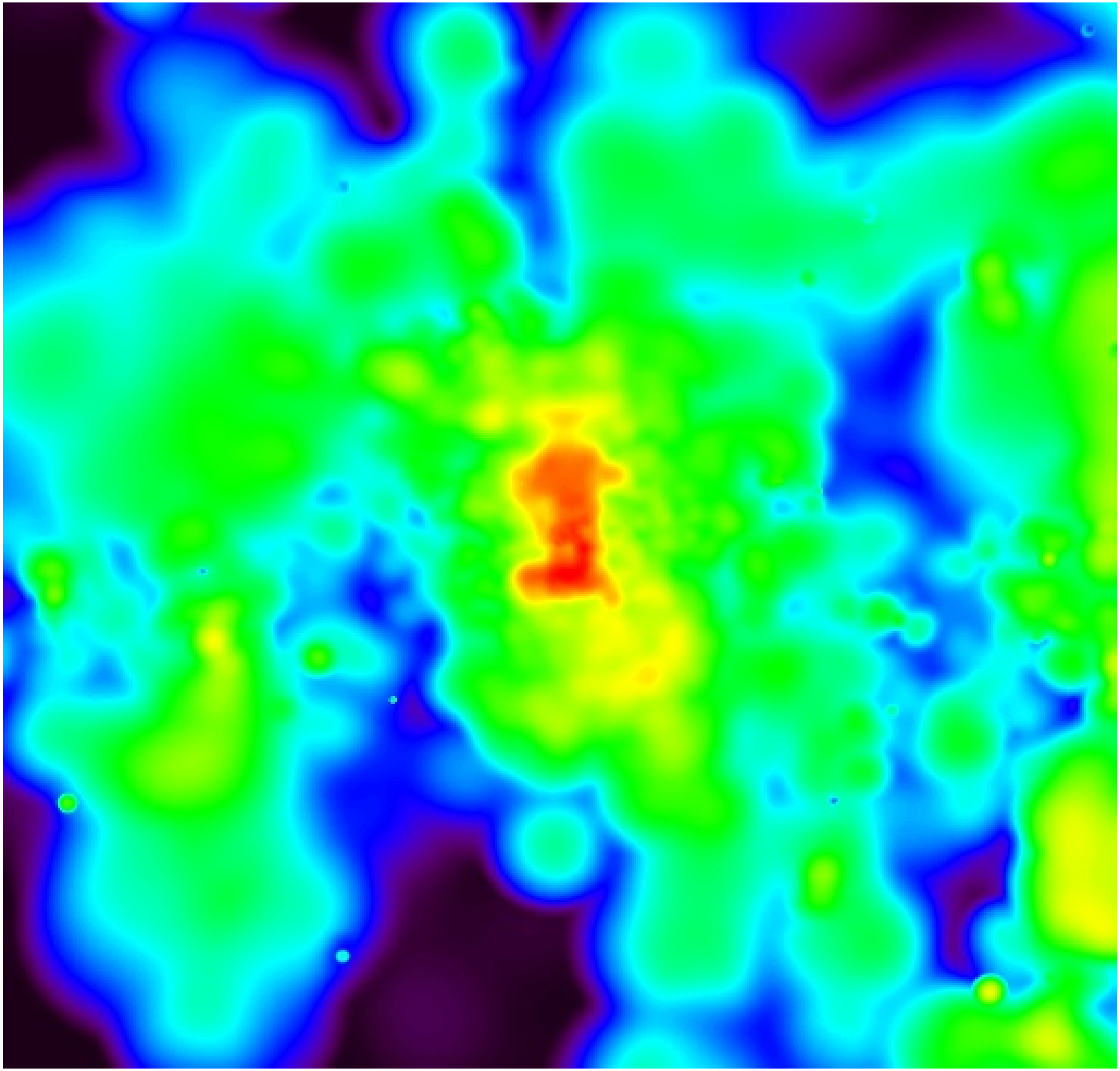


Brueggen, 2002



Dalla Vecchia, 2004

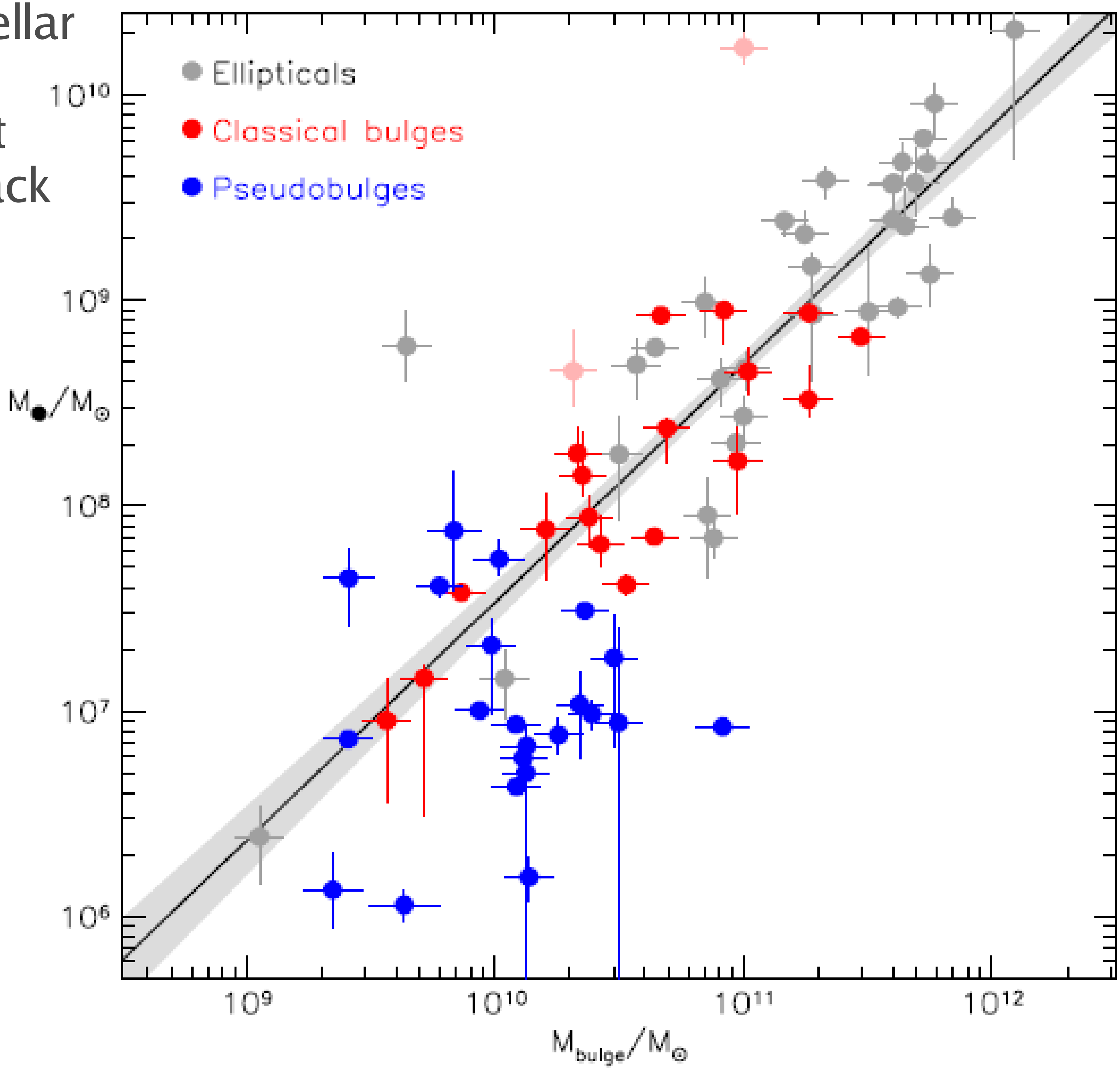
AGN feedback processes and their impact on the host galaxies across the Hubble sequence



Sijacki, 2009

AGN feedback processes and their impact on the host galaxies across the Hubble sequence

Black hole mass – stellar bulge mass relation: pseudo bulges do not correlate well with black holes

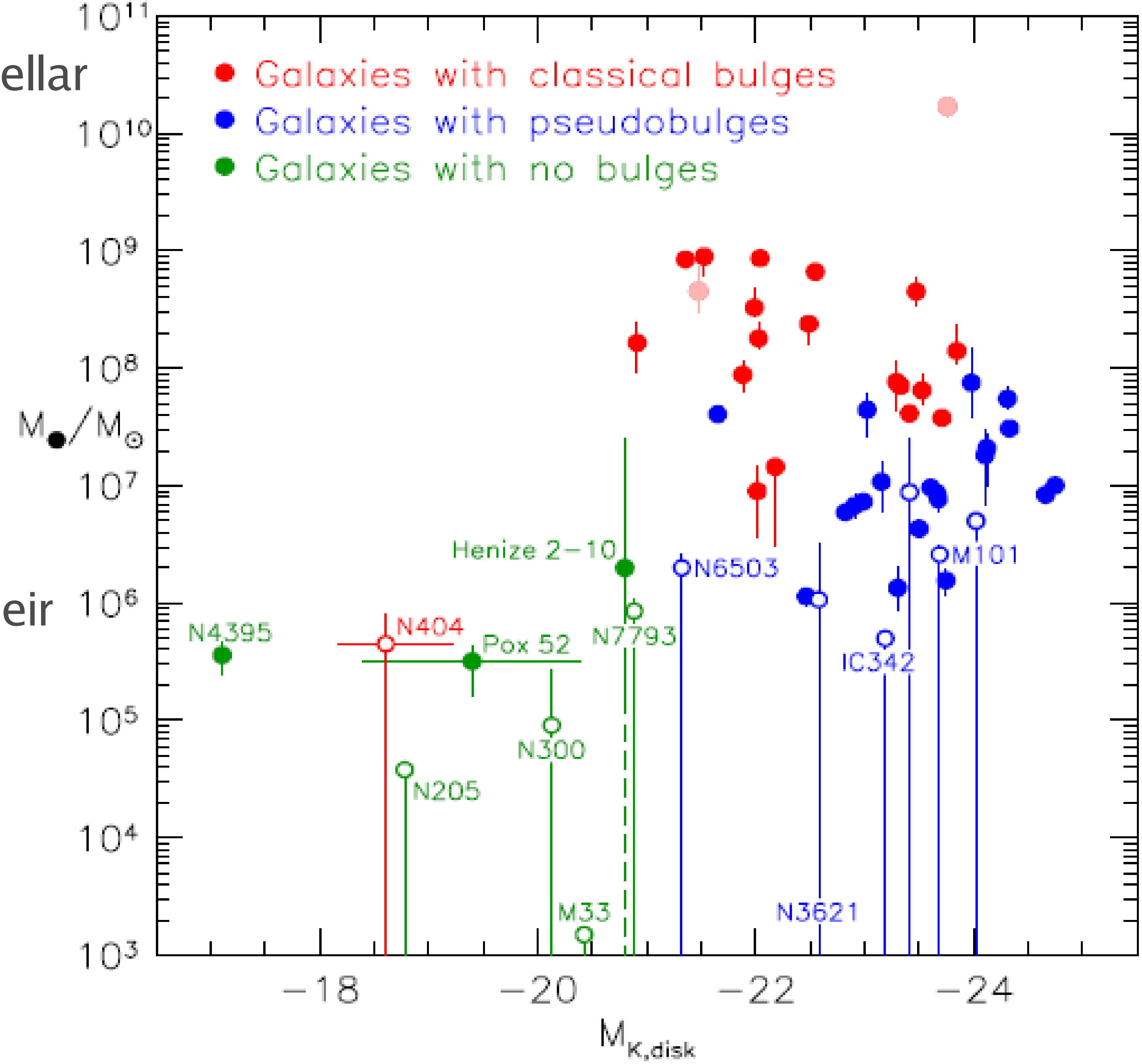


Kormendy & Ho, 2013

AGN feedback processes and their impact on the host galaxies across the Hubble sequence

Black hole mass – stellar disk mass relation: black holes do not “know” about the properties of their host disks

- Next frontier of theoretical modeling will connect galaxy morphologies with their central black hole properties



Kormendy & Ho, 2013