THE ROLE OF BLACK HOLES IN GALAXY FORMATION

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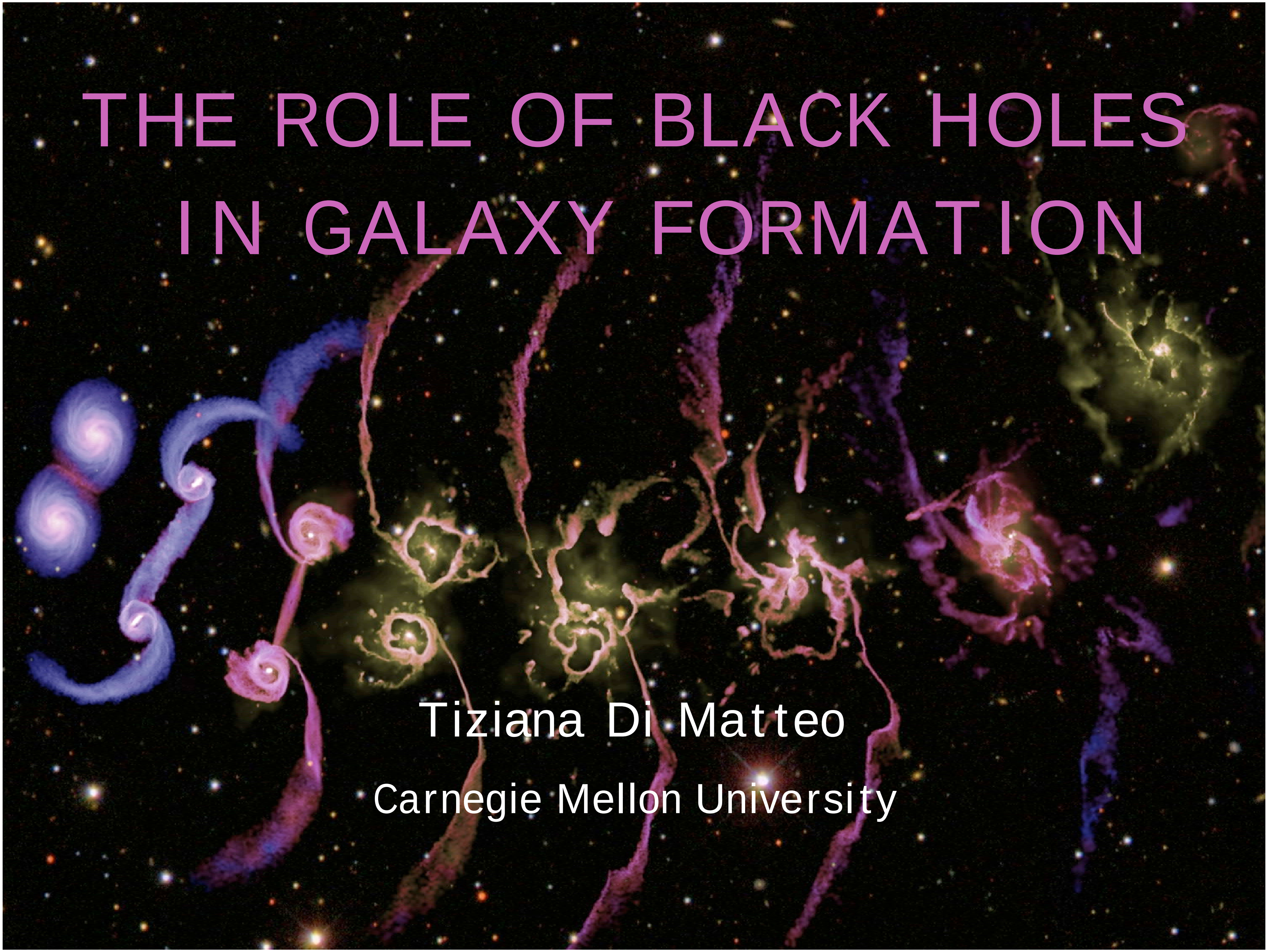


OUTLINE:

- A ‘rough’ black hole timeline

- The black hole – galaxy connection :
  what have we learnt from recent observations?

- Supermassive black holes and galaxies in computer simulations

Collaborators: Volker Springel (MPA), Lars Hernquist (Harvard)

“The unreasonable effectiveness of mathematics in the physical sciences”

Eugene Wigner

BLACK HOLES:

EXACT SOLUTION TO EINSTEIN FIELD EQUATIONS

$$G_{\mu\nu} = 8\pi T_{\mu\nu}$$

$$G_{\mu\nu} = 0$$

Karl Schwarzschild (1916)

Sitz. Ber. Kgl. Preuss. Akad. d. Wiss. Berlin 1916, 189–196 (1916)

Über das Gravitationsfeld eines Massenpunktes nach der Einsteinschen Theorie.

Von K. Schwarzschild.

(Vorgelegt am 13. Januar 1916 [s. oben S. 42].)

§ 1. Hr. Einstein hat in seiner Arbeit über die Perihelbewegung des Merkur (s. Sitzungsberichte vom 18. November 1915) folgendes Problem gestellt:

Ein Punkt bewege sich gemäß der Forderung

$$\delta \int ds = 0, \qquad (1)$$

wobei

$$ds = \sqrt{\sum g_{\mu\nu} dx_\mu dx_\nu} \qquad \mu, \nu = 1, 2, 3, 4$$

ist, $g_{\mu\nu}$ Funktionen der Variabeln x bedeuten und bei der Variation am Anfang und Ende des Integrationswegs die Variablen x festzuhalten sind. Der Punkt bewege sich also, kurz gesagt, auf einer geodätischen Linie in der durch das Linienelement ds charakterisierten Mannigfaltigkeit.

Die Ausführung der Variation ergibt die Bewegungsgleichungen des Punktes

$$\frac{d^2 x_\alpha}{ds^2} = \sum_{\mu,\nu} \Gamma^\alpha_{\mu\nu} \frac{dx_\mu}{ds} \frac{dx_\nu}{ds}, \qquad \alpha, \beta = 1, 2, 3, 4$$

wobei

$$\Gamma^\alpha_{\mu\nu} = -\frac{1}{2} \sum_\beta g^{\alpha\beta} \left(\frac{\partial g_{\mu\beta}}{\partial x_\nu} + \frac{\partial g_{\nu\beta}}{\partial x_\mu} - \frac{\partial g_{\mu\nu}}{\partial x_\beta} \right)$$

ist und $g^{\alpha\beta}$ die zu $g_{\alpha\beta}$ koordinierte und normierte Subdeterminante in der Determinante $|g_{\mu\nu}|$ bedeutet.

Der Vergleich mit (2) gibt die Komponenten des Gravitation

$$\Gamma^1_{11} = -\frac{1}{2} \frac{1}{f_1} \frac{\partial f_1}{\partial x_1}, \quad \Gamma^1_{22} = +\frac{1}{2} \frac{1}{f_1} \frac{\partial f_2}{\partial x_1} \frac{1}{1 - x_2^2},$$

$$\Gamma^1_{33} = +\frac{1}{2} \frac{1}{f_1} \frac{\partial f_2}{\partial x_1} (1 - x_2^2),$$

$$\Gamma^1_{44} = -\frac{1}{2} \frac{1}{f_1} \frac{\partial f_4}{\partial x_1},$$

$$\Gamma^2_{21} = -\frac{1}{2} \frac{1}{f_2} \frac{\partial f_2}{\partial x_1}, \quad \Gamma^2_{22} = -\frac{x_2}{1 - x_2^2}, \quad \Gamma^2_{33} = -x_2(1 - x_2^2),$$

$$\Gamma^3_{31} = -\frac{1}{2} \frac{1}{f_2} \frac{\partial f_2}{\partial x_1}, \quad \Gamma^3_{32} = +\frac{x_2}{1 - x_2^2},$$

$$\Gamma^4_{41} = -\frac{1}{2} \frac{1}{f_4} \frac{\partial f_4}{\partial x_1}$$

(die übrigen null).

Bei der Rotationssymmetrie um den Nullpunkt genügt e Feldgleichungen nur für den Äquator ($x_2 = 0$) zu bilden, so daß da nur einmal differenziert wird, in den vorstehenden Ausdr überall von vorneweg $1 - x_2^2$ gleich 1 setzen darf. Damit liefert die Ausrechnung der Feldgleichungen

$$\text{a)} \quad \frac{\partial}{\partial x_1} \left(\frac{1}{f_1} \frac{\partial f_1}{\partial x_1} \right) = \frac{1}{2} \left(\frac{1}{f_1} \frac{\partial f_1}{\partial x_1} \right)^2 + \left(\frac{1}{f_2} \frac{\partial f_2}{\partial x_1} \right)^2 + \frac{1}{2} \left(\frac{1}{f_4} \frac{\partial f_4}{\partial x_1} \right)^2,$$

$$\text{b)} \quad \frac{\partial}{\partial x_1} \left(\frac{1}{f_1} \frac{\partial f_2}{\partial x_1} \right) = 2 + \frac{1}{f_1 f_2} \left(\frac{\partial f_2}{\partial x_1} \right)^2,$$

$$\text{c)} \quad \frac{\partial}{\partial x_1} \left(\frac{1}{f_1} \frac{\partial f_4}{\partial x_1} \right) = \frac{1}{f_1 f_4} \left(\frac{\partial f_4}{\partial x_1} \right)^2.$$

Sitz. Ber. Kgl. Preuss. Akad. d. Wiss. Berlin 1916, 189–196 (1916)

man durch direkte Ausführung der Variation die Diff der geodätischen Linie bildet und aus diesen die liest. Die Differentialgleichungen der geodätischen L element (9) ergeben sich durch die Variation unmit

$$0 = f_1 \frac{d^2 x_1}{ds^2} + \frac{1}{2} \frac{\partial f_4}{\partial x_1} \left(\frac{dx_4}{ds} \right)^2 + \frac{1}{2} \frac{\partial f_1}{\partial x_1} \left(\frac{dx_1}{ds} \right)^2 - \frac{1}{2} \frac{\partial f_2}{\partial x_1} \Big[\frac{\quad}{1-}$$

$$0 = \frac{f_2}{1 - x_2^2} \frac{d^2 x_2}{ds^2} + \frac{\partial f_2}{\partial x_1} \frac{1}{1 - x_2^2} \frac{dx_1}{ds} \frac{dx_2}{ds} + \frac{f_2 x_2}{(1 - x_2^2)^2} \Big(\frac{dx_2}{ds}$$

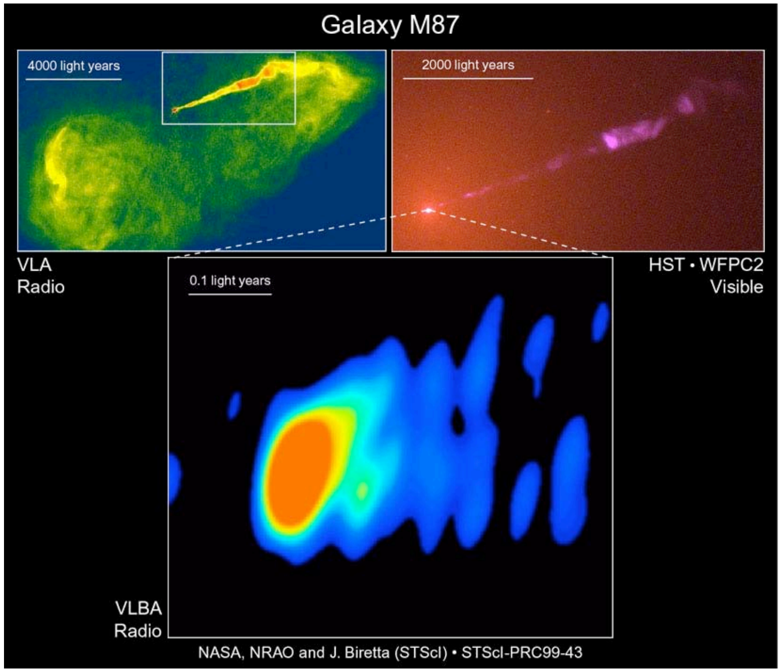
$$0 = f_2 (1 - x_2^2) \frac{d^2 x_3}{ds^2} + \frac{\partial f_2}{\partial x_1} (1 - x_2^2) \frac{dx_1}{ds} \frac{dx_3}{ds} - 2 f_2 x_2 \frac{dx_2}{ds}$$

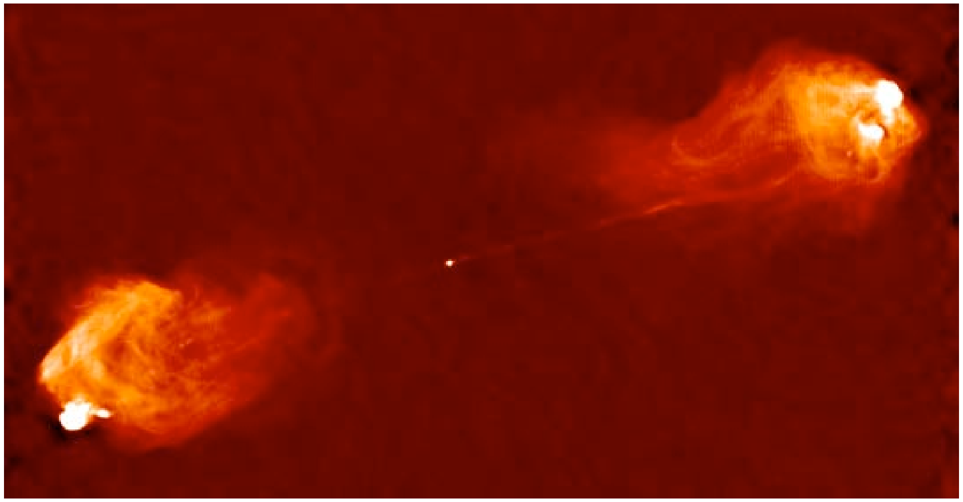
$$0 = f_4 \frac{d^2 x_4}{ds^2} + \frac{\partial f_4}{\partial x_1} \frac{dx_1}{ds} \frac{dx_4}{ds}.$$

$$(d\tau)^2 = \left(1 - \frac{2m}{r}\right)(dt)^2 - \left(\frac{r}{r - 2m}\right)(dr)^2 - r^2 (d\theta)^2 - r^2 \sin(\theta)^2 (d\phi)^2$$

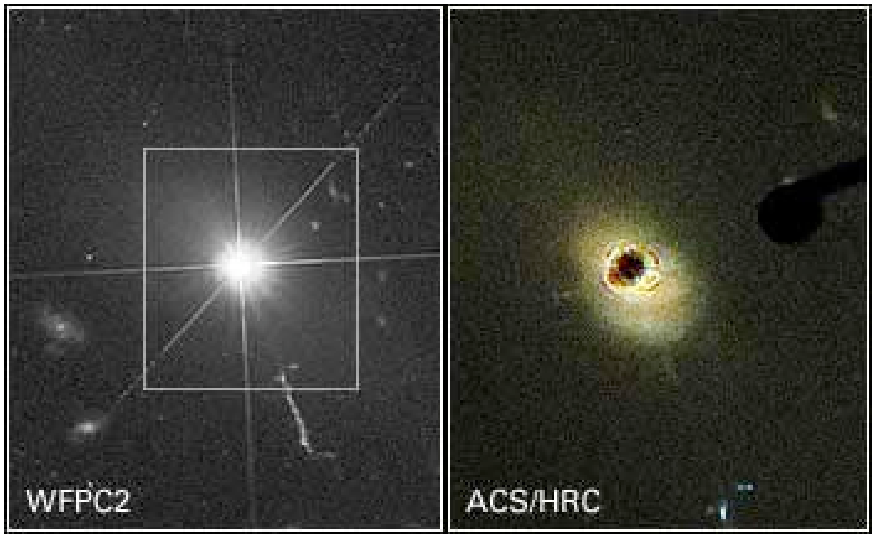
SUPERMASSIVE BLACK HOLES:

THE DISCOVERY OF QUASARS (Quasi-Stellar Objects) IN GALAXIES





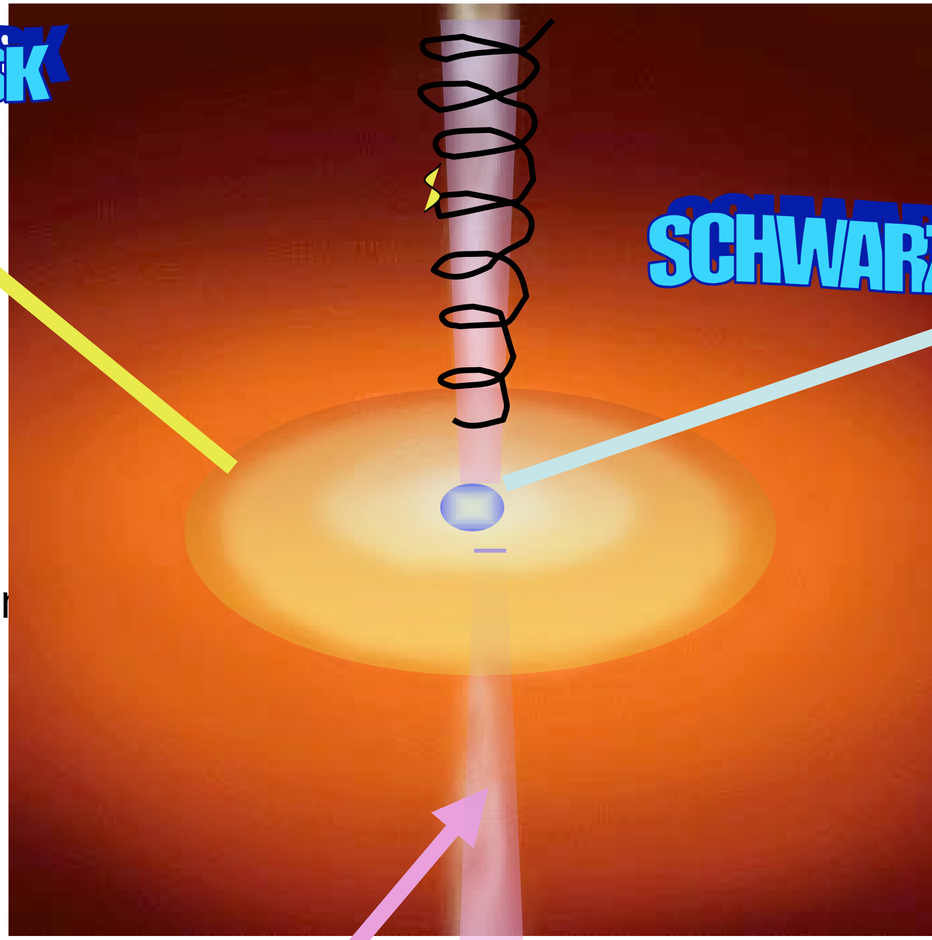
Maarten Schmidt (1960) et al.



BLACK HOLE "ANATOMY"

ACCRETION DISK

matter around the BH forms an accretion disk. Gas particles interact as they move around. They heat up, lose energy and ang. mom emit radiation.



SCHWARZCHILD RADIUS

As matter comes within a certain radius from a black hole it is trapped: gravity is so strong not even light can escape

$$R_S = \frac{2GM_{BH}}{c^2}$$

~ 3 M/Msun [km]

JETS

Highly relativistic jets stream out Perpendicular to the disk: charged particles Accelerated along strong B fields

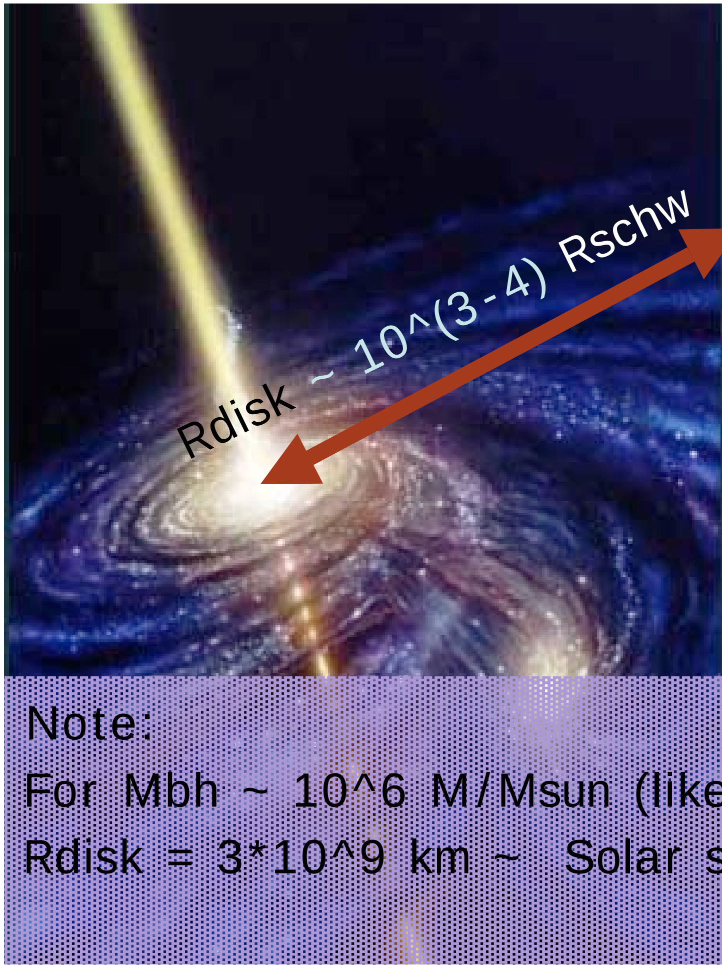
Matter falls onto black holes

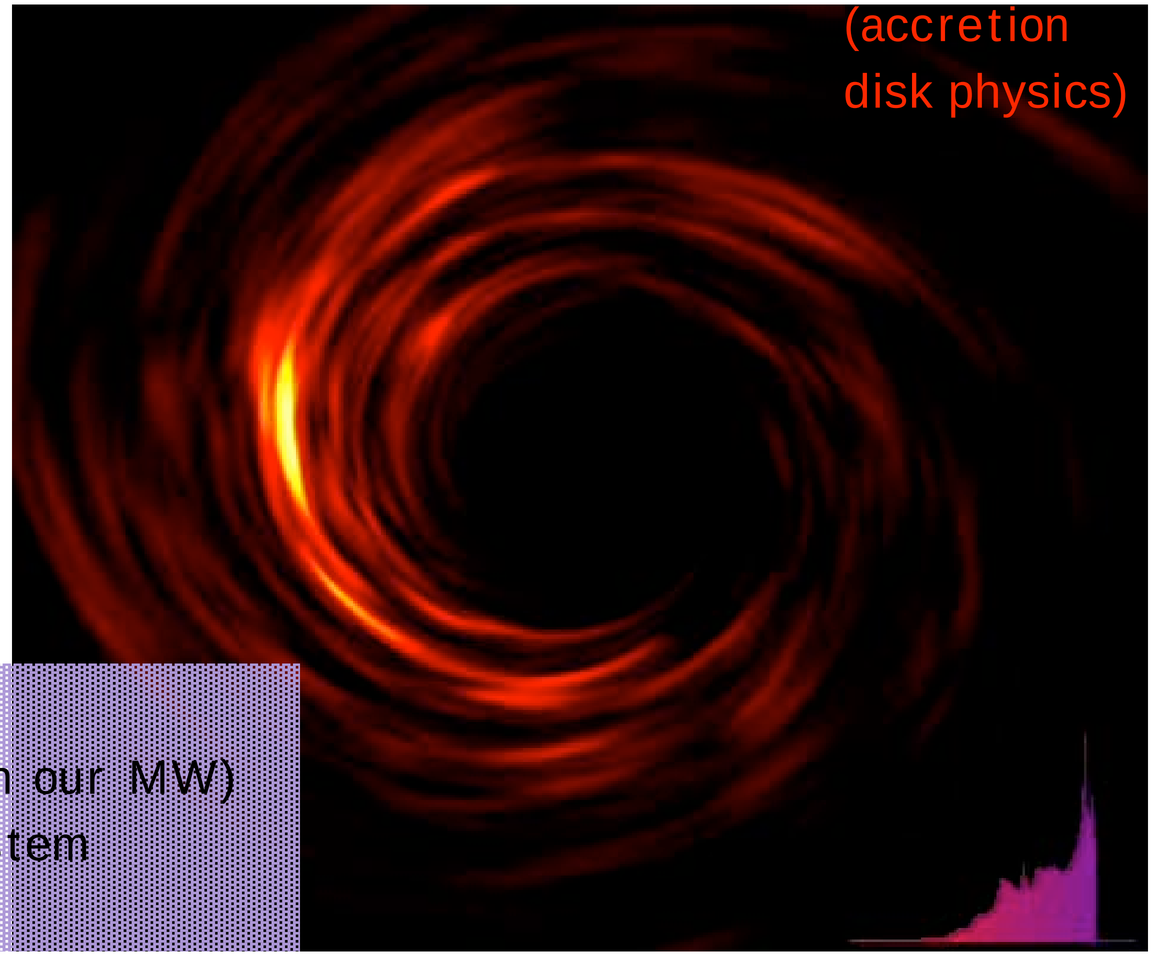
BH luminosity= energy released by matter falling onto BH

$$L = \eta \dot{M} c^2$$

mass supply rate

Efficiency (accretion disk physics)

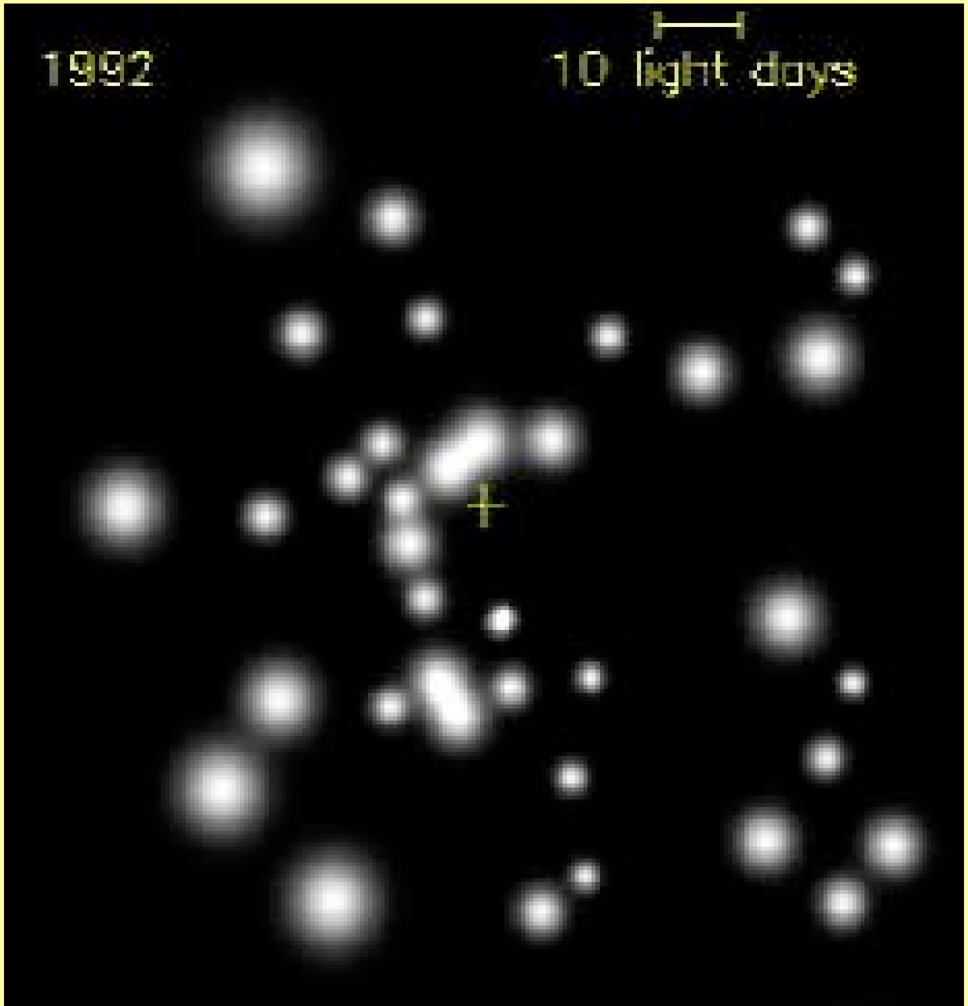




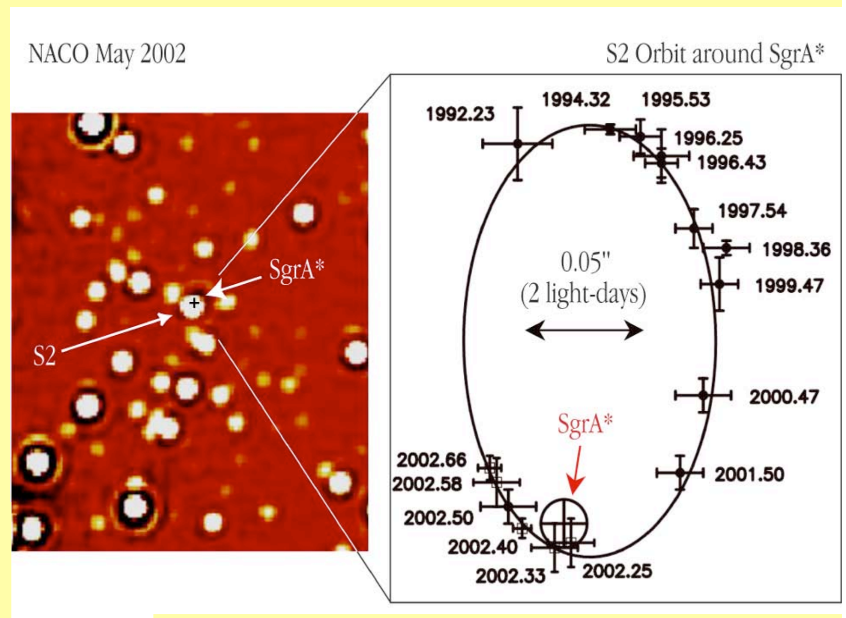
Note:
For Mbh ~ 10^6 M/Msun (like in our MW)
Rdisk = 3*10^9 km ~ Solar system

The black hole in the MILKY Way center

VLT, Genzel et al. (MPE)
Keck, Ghez

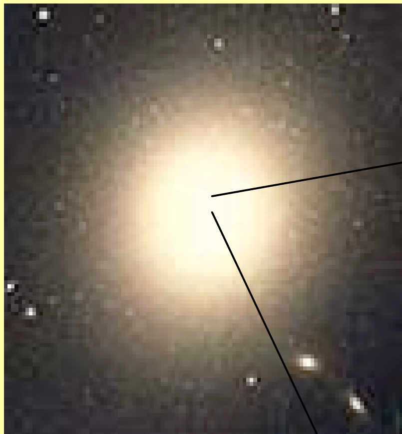


IR : 1.6 – 3.2 μm

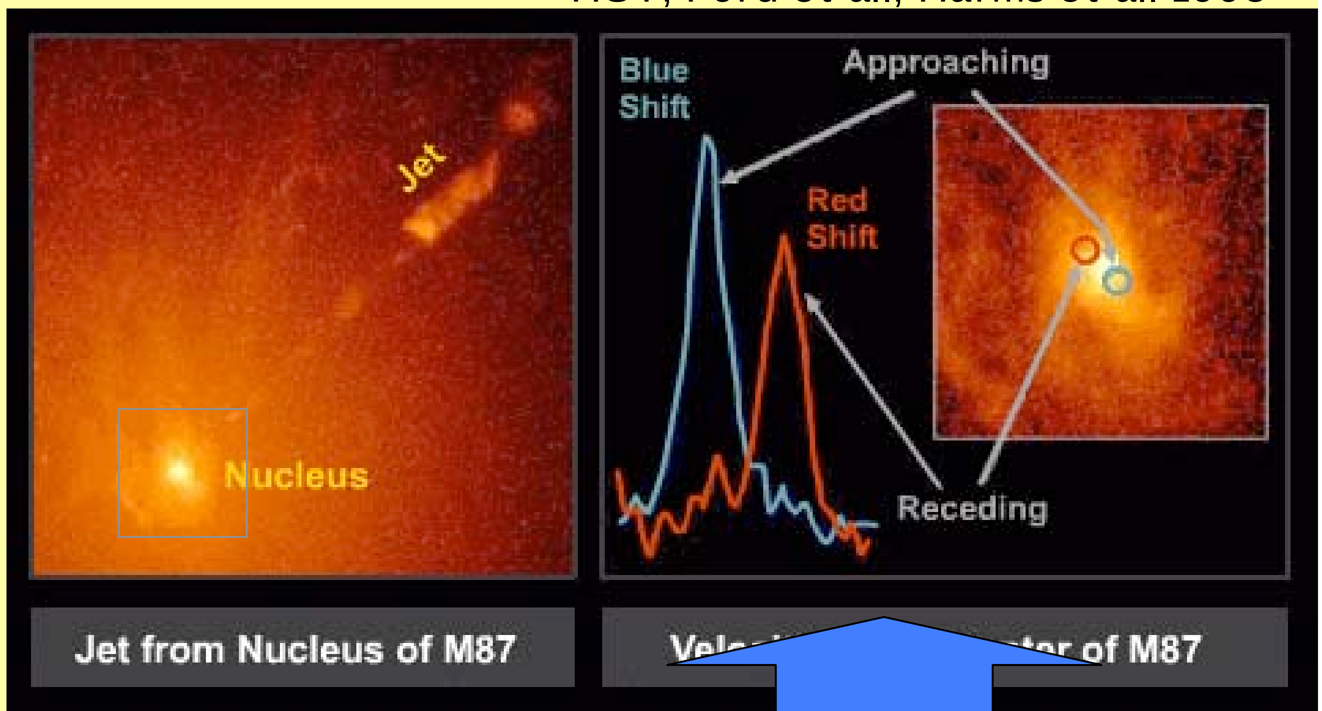


$$M_{BH} = 2.6 \times 10^{6}\, MSun$$

Black holes in the center of galaxies: M87

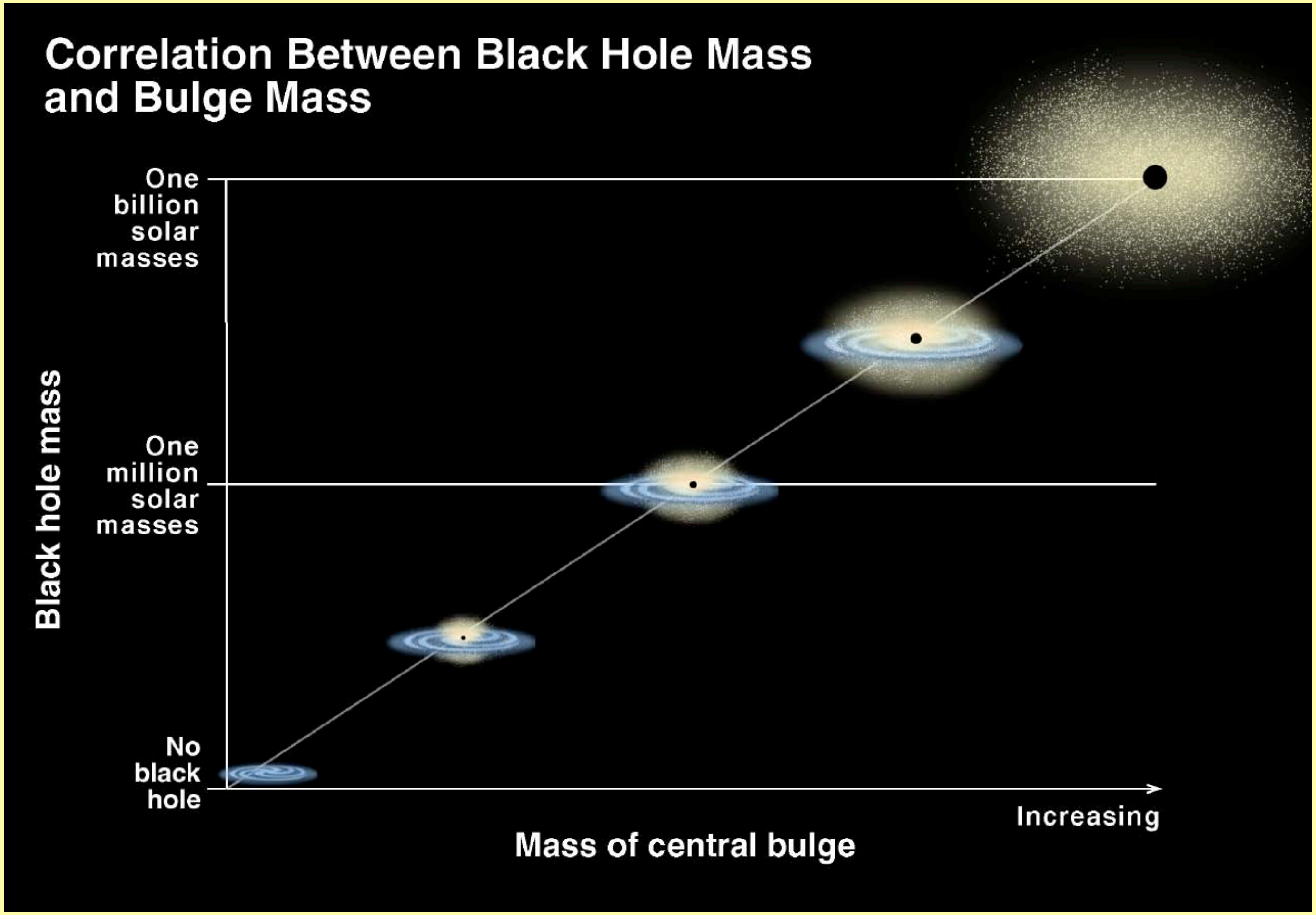


HST, Ford et al., Harms et al. 1995



$$M_{BH} = 3 \times 10^{9} M_{\odot}$$

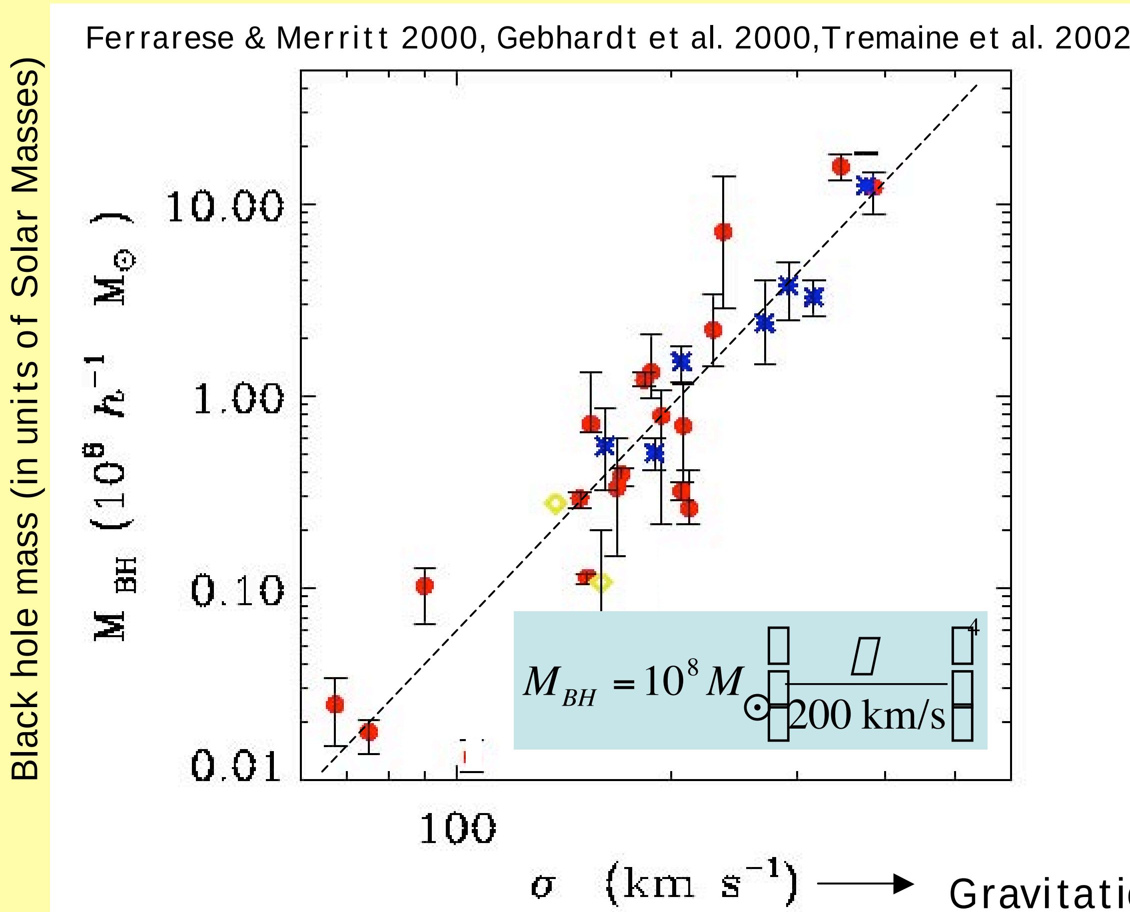
THE BLACK HOLE – GALAXY CONNECTION



Magorrian et al. 1998; Kormendy & Richstone 1995

THE BLACK HOLE – GALAXY CONNECTION

The M - σ relation for supermassive black holes



Gravitational potential of spheroid

Stellar Velocity Dispersion

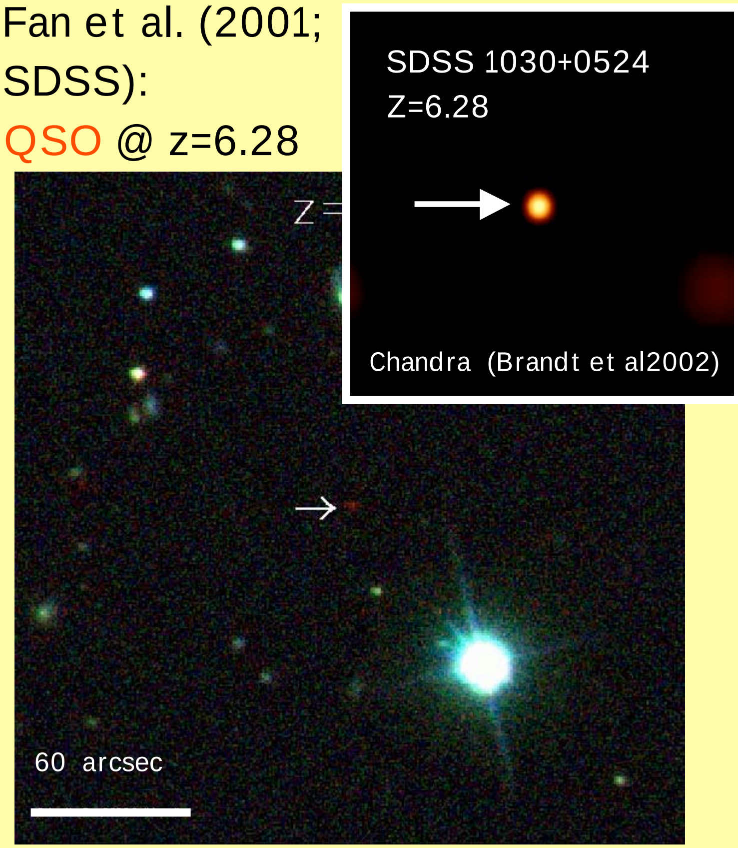
Black hole mass related to large scale properties of galaxies

fundamental link between assembly of black holes and galaxy formation

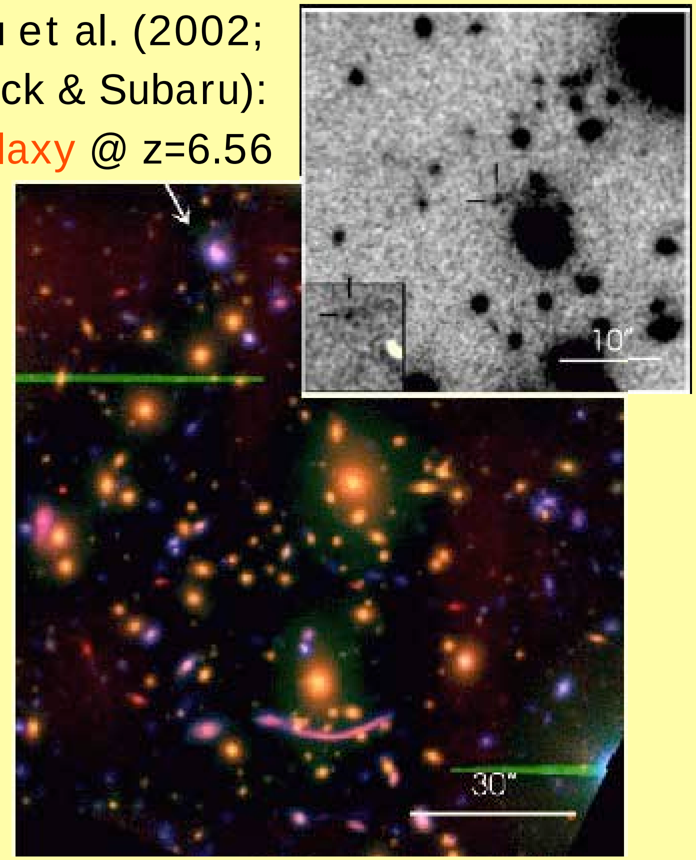
THE BLACK HOLE – GALAXY CONNECTION

Galaxies & Quasars already show up during first 10^9 years

Fan et al. (2001; SDSS):
QSO @ z=6.28



Hu et al. (2002; Keck & Subaru):
galaxy @ z=6.56



$\longrightarrow$ $M_{BH}=4\text{x}10^9\ M_\odot$

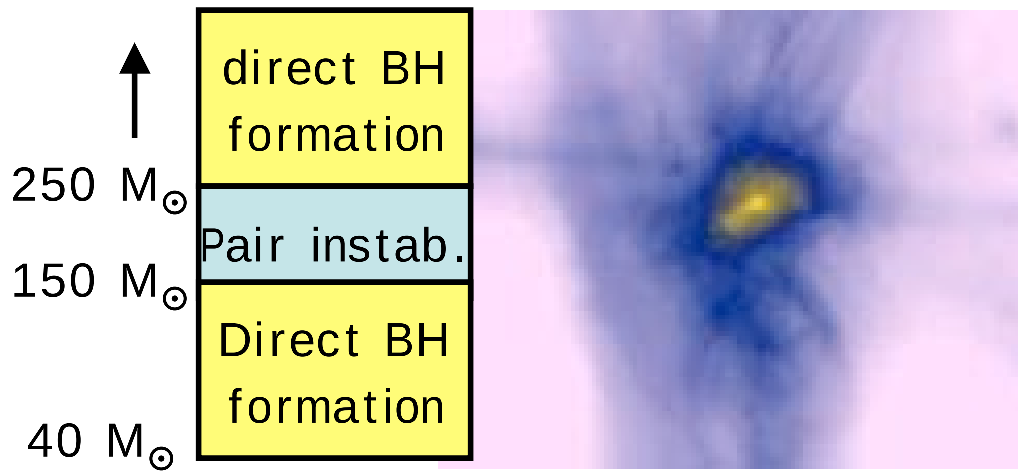
SUPERMASSIVE BH FORMATION

ORIGIN UNCERTAIN !!!

Stellar mass black holes end product of massive star evolution
form from collapse of star $M > 3\ M_\odot$

SMBH PROBABLY GROW FROM SEED POPULATION:

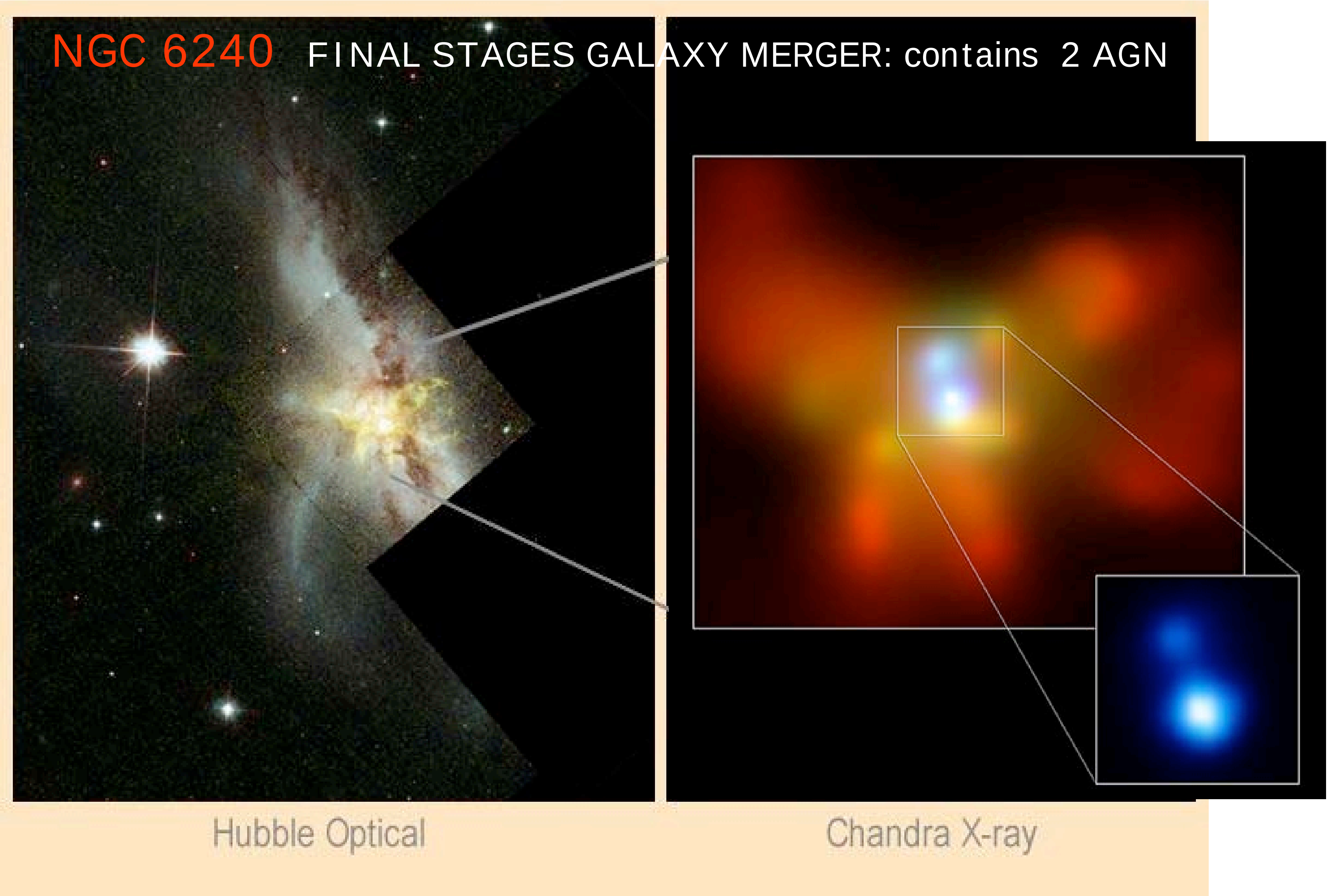
FIRST proto-galaxies form in
rare density peaks of
primordial density fluctuations
at $z > 20$.
Here the first generation
of star that forms



MASSIVE BLACK HOLES

INEVITABLE END PRODUCT OF FIRST EPISODE of galactic star formation

BH GROWTH and Fuelling of AGN :



S.Komossa et al. 03 (MPE)

Smooth Particle Hydrodymic simulations of galaxy formation

DARK MATTER

GAS

STARS

N-body METHOD: mass discretised in particles
modeled as collisionless fluid governed
by Boltzmann Eq. -
grav potential solved with Poisson Eq.

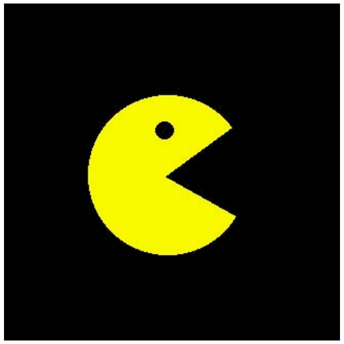
SPH Method: fluid represented by particles
smoothed by local kernel averaging
Hydro eqns solved in its Galilean-invariant
Lagrangian Formulation.

SUB-RESOLUTION
multiphase MODEL
for the ISM

- Radiative cooling of gas within halos (dissipation)
- Star formation and feedback processes

Code: GADGET2 (Springel ‘05)

BHs in Numerical Simulations of Galaxy formation



- BH: “sink” particle in galaxies of small mass

- ACCRETION: BH swallows the gas from the surrounding galaxy and grows

$$\dot{M}_B = \square 4 \square \frac{(GM_{BH})^2}{(c_s{}^2 + V_{rel}^2)^{3/2}} \square$$

- FEEDBACK: energy extracted from the black hole injected in the surrounding gas

$$\dot{E} = 0.1 f \dot{M} c^2 \qquad f \square 0.5\%$$

We construct compound disk galaxies that are in dynamical equilibrium

Springel, Di Matteo & Hernquist, '05

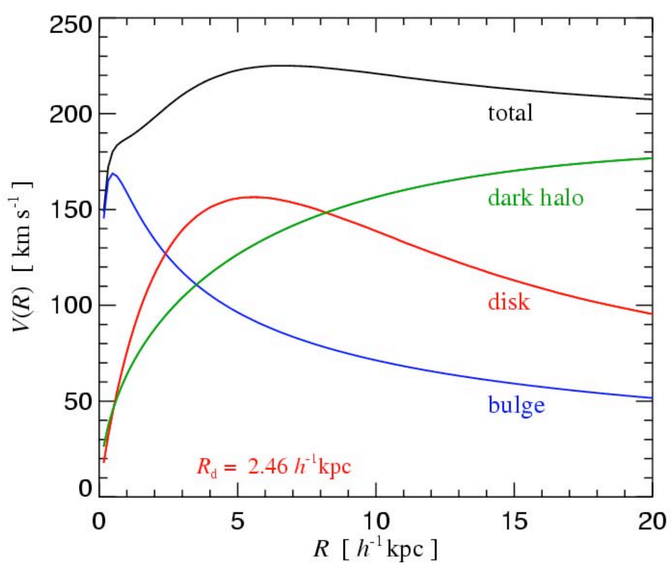
STRUCTURAL PROPERTIES OF MODEL GALAXIES

Components:

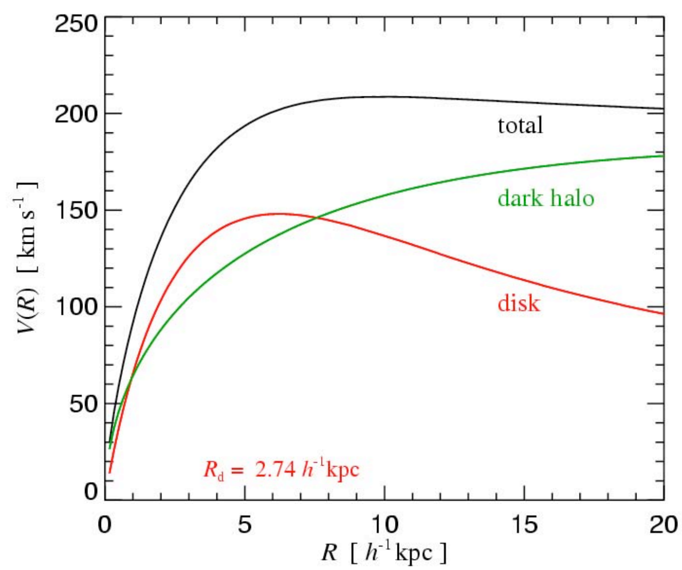
- Dark halo (Hernquist profile matched to NFW halo)
- Stellar disk (expontial)
- Stellar bulge
- Gaseous disk (expontial)
- Central supermassive black hole (small seed mass)

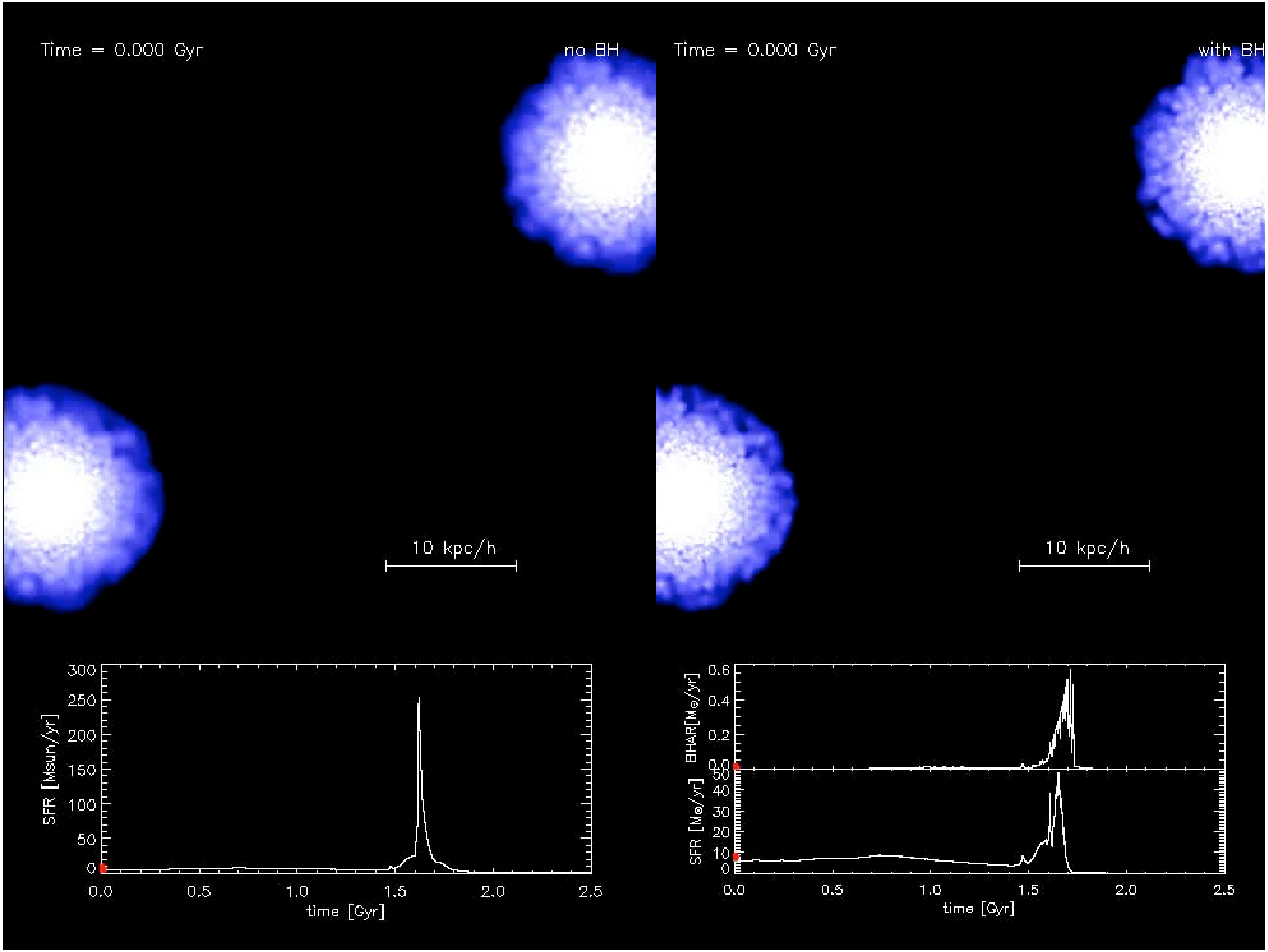
- We compute the exact gravitational potential for the axisymmetric mass distribution and solve the Jeans equations
- Gas pressure effects are included
- The gaseous scale-height is allowed to vary with radius

With Bulge

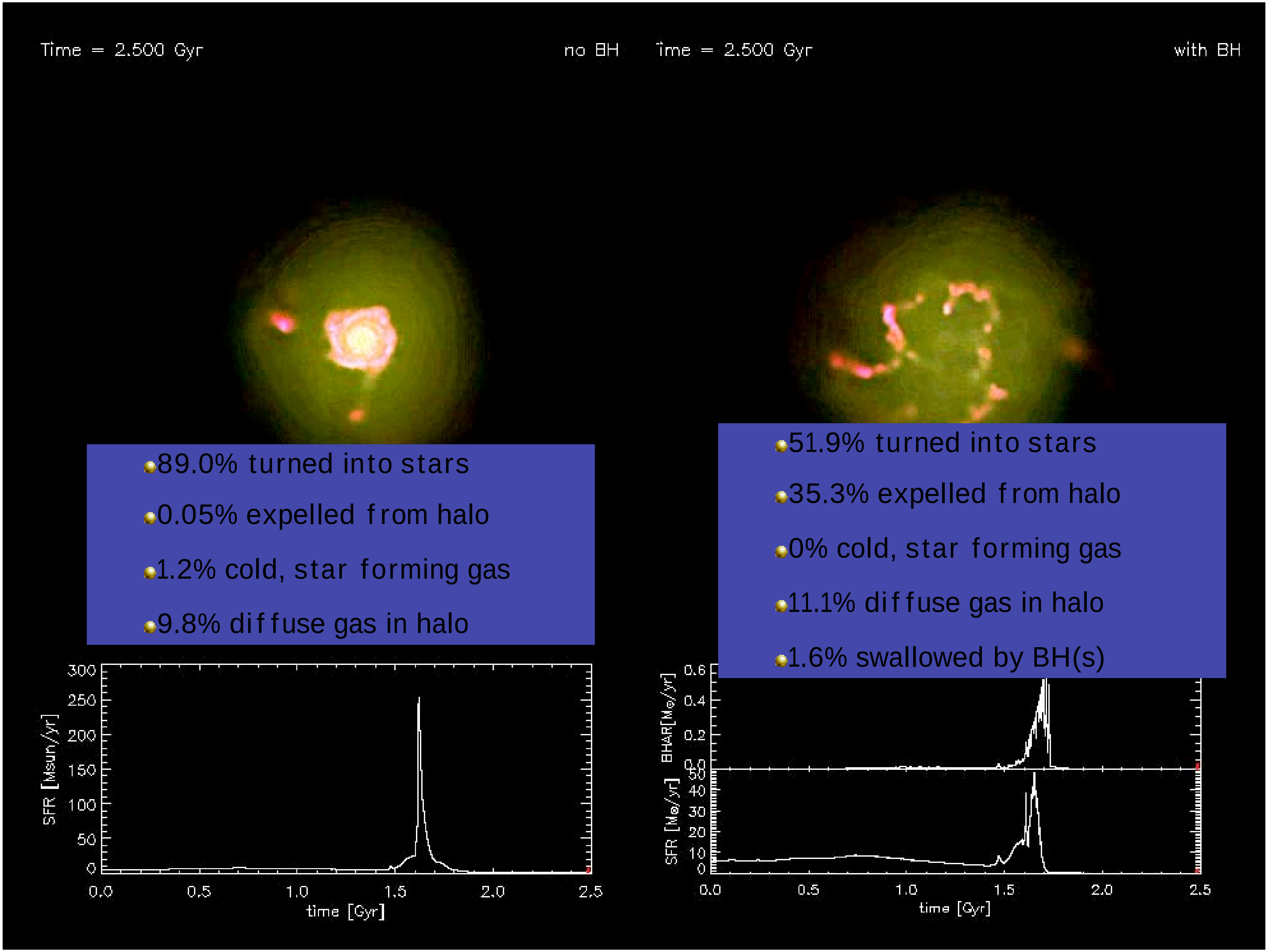


Without Bulge

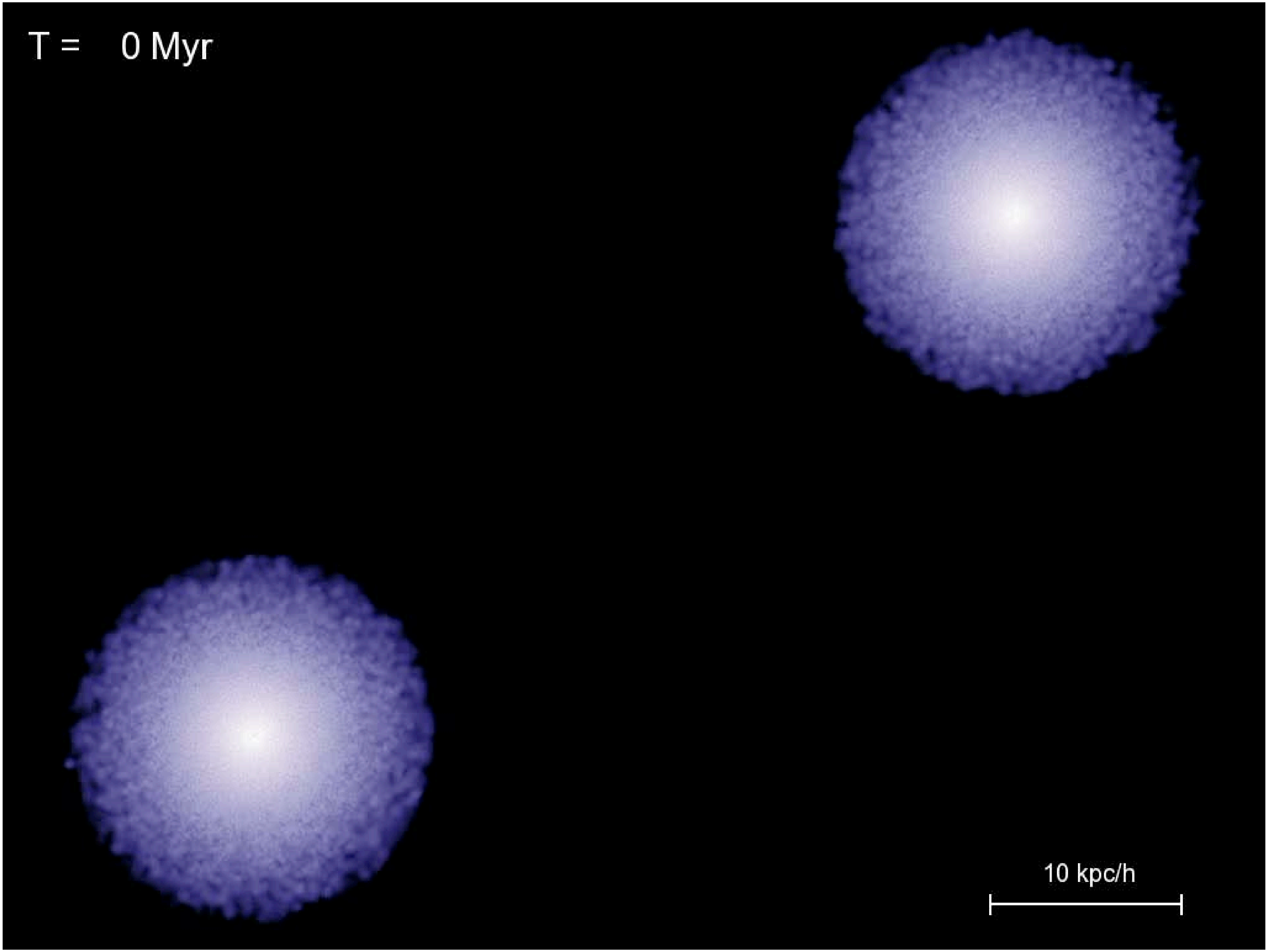


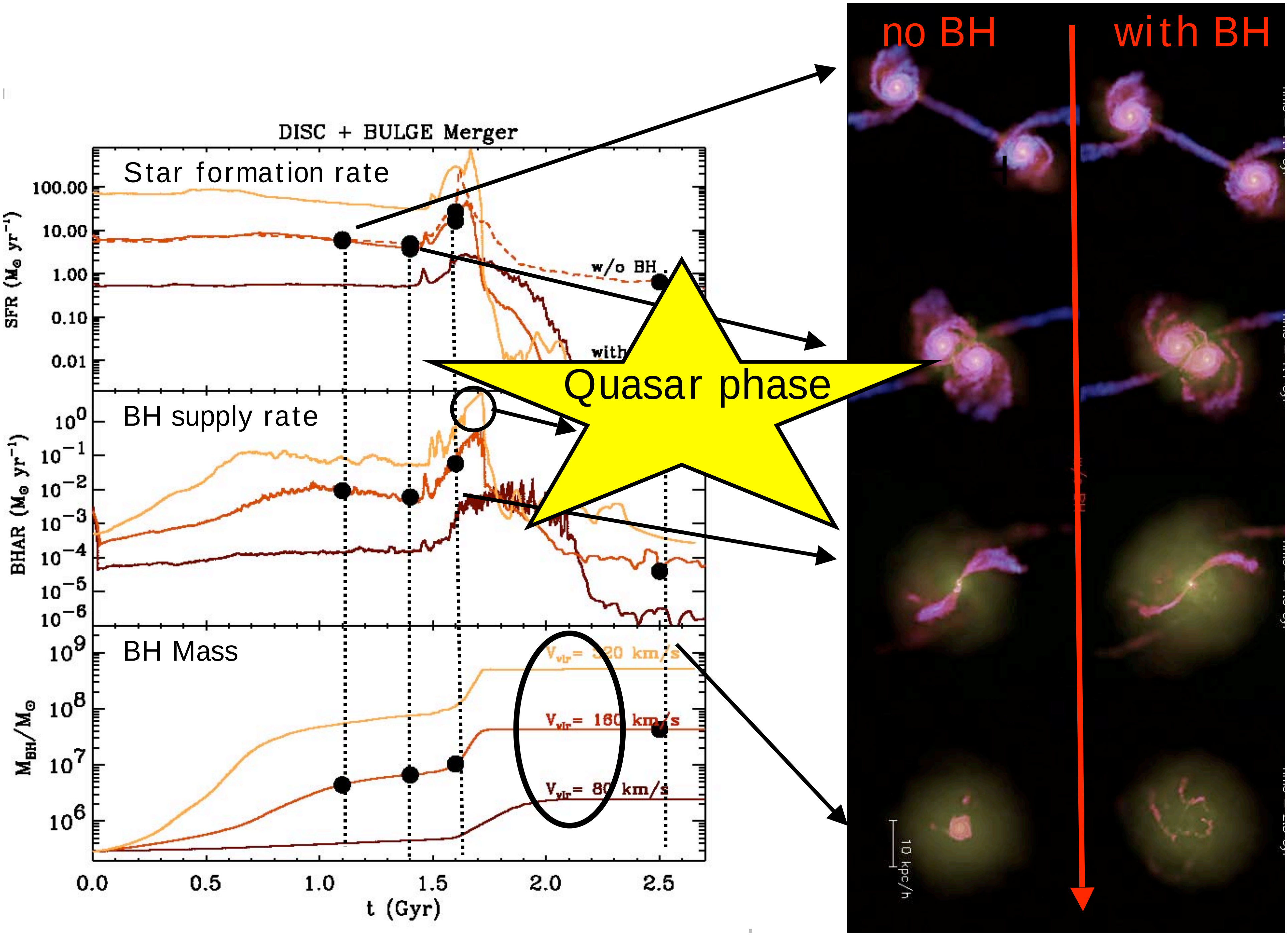


Time = 0.000 Gyr
no BH
10 kpc/h
SFR [Msun/yr]
time [Gyr]
Time = 0.000 Gyr
with BH
10 kpc/h
BHAR[M⊙/yr]
SFR [M⊙/yr]
time [Gyr]



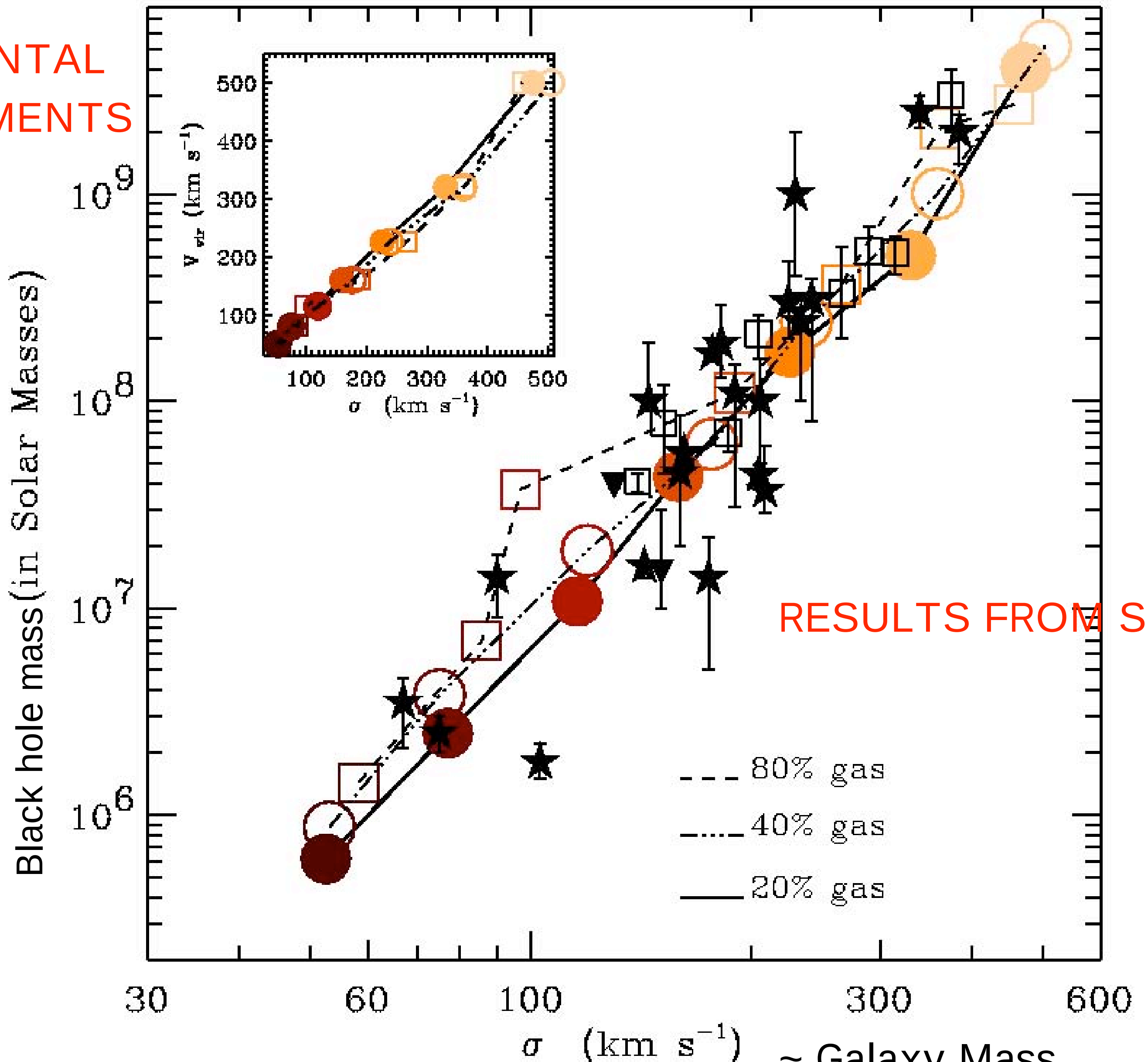
Time = 2.500 Gyr
no BH
Time = 2.500 Gyr
with BH
89.0% turned into stars
0.05% expelled from halo
1.2% cold, star forming gas
9.8% diffuse gas in halo
51.9% turned into stars
35.3% expelled from halo
0% cold, star forming gas
11.1% diffuse gas in halo
1.6% swallowed by BH(s)
SFR [Msun/yr]
300
250
200
150
100
50
0
0.0
0.5
1.0
1.5
2.0
2.5
time [Gyr]
BHAR[M⊙/yr]
0.6
0.4
0.2
0.0
SFR [M⊙/yr]
50
40
30
20
10
0
0.0
0.5
1.0
1.5
2.0
2.5
time [Gyr]


T = 0 Myr
10 kpc/h


DISC + BULGE Merger
Star formation rate
SFR ($M_\odot$ yr^{-1})
100.00
10.00
1.00
0.10
0.01
w/o BH
with
BH supply rate
BHAR ($M_\odot$ yr^{-1})
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
BH Mass
$M_{BH}/M_\odot$
10^9
10^8
10^7
10^6
V_{vir}= 320 km/s
V_{vir}= 160 km/s
V_{vir}= 80 km/s
0.0
0.5
1.0
1.5
2.0
2.5
t (Gyr)
Quasar phase
no BH
with BH
10 kpc/h

BLACK HOLE MASS AND GALAXY PROPERTIES:

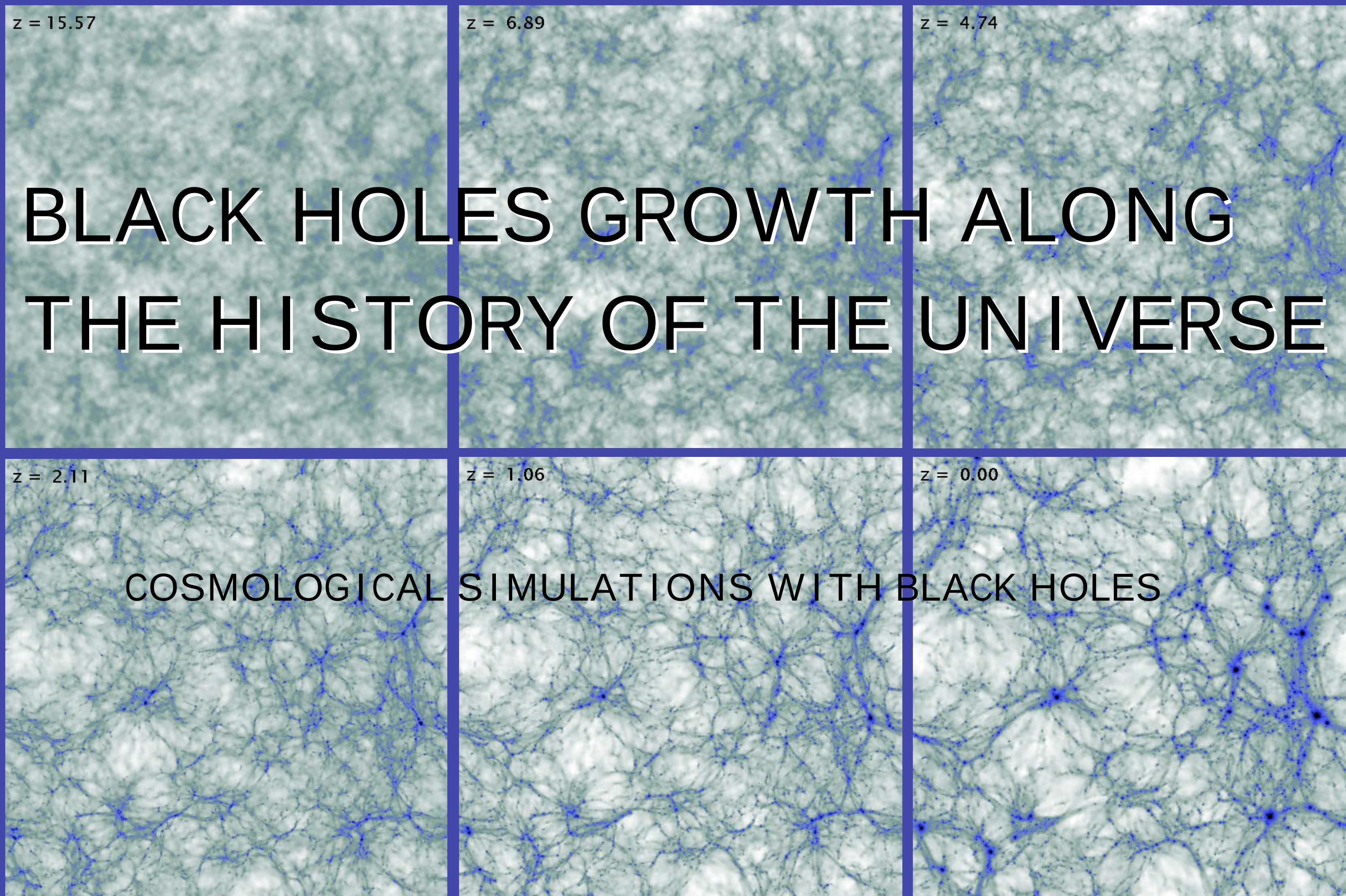
EXPERIMENTAL MEASUREMENTS



RESULTS FROM SIMULATIONS

~ Galaxy Mass

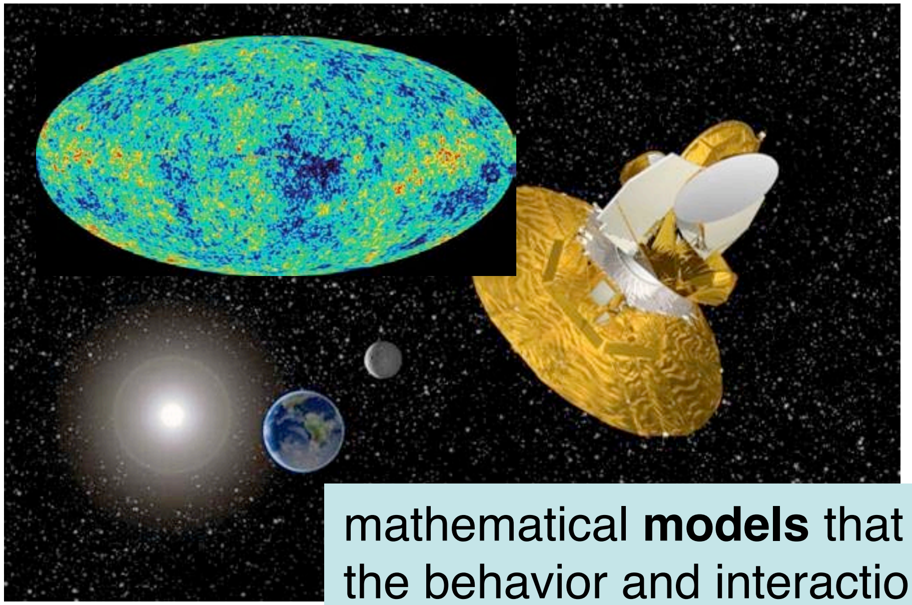
BLACK HOLES GROWTH ALONG THE HISTORY OF THE UNIVERSE

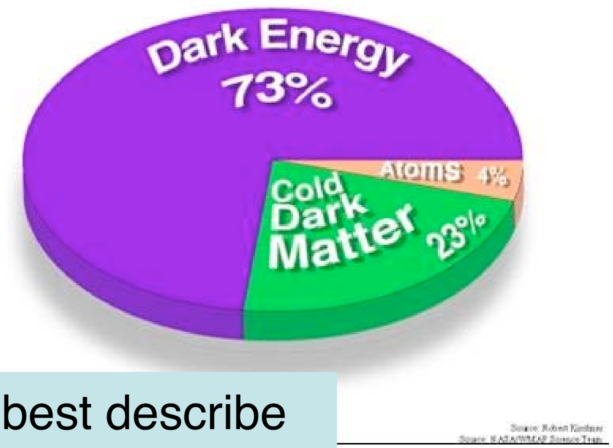


COSMOLOGICAL SIMULATIONS WITH BLACK HOLES

What does it take to put the Universe in a box?

- Recipe





mathematical **models** that best describe the behavior and interactions of the major physical components involved at different times and scales of cosmic evolution

- Physics

Gravity

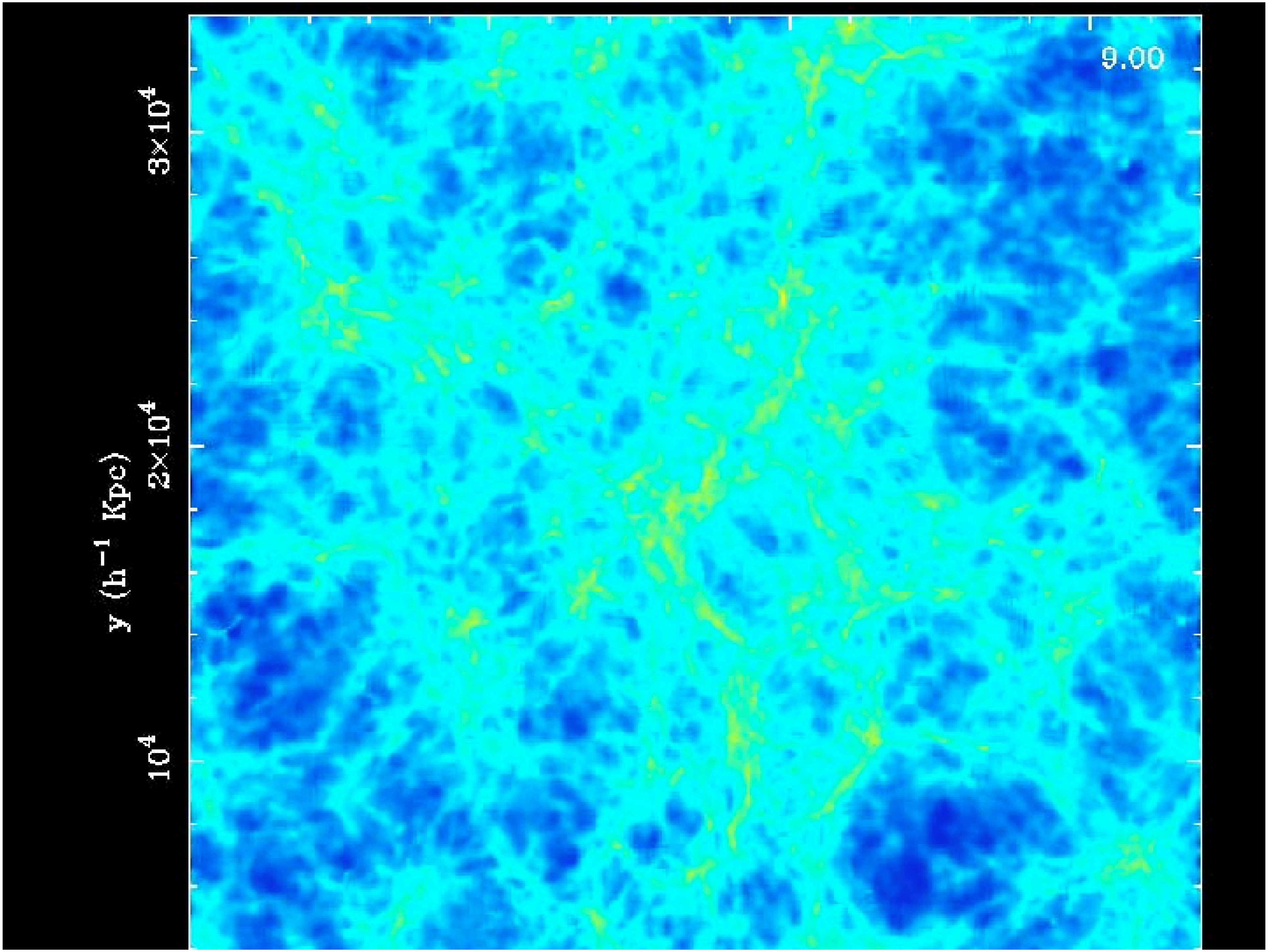
Dark matter collisionless dynamics

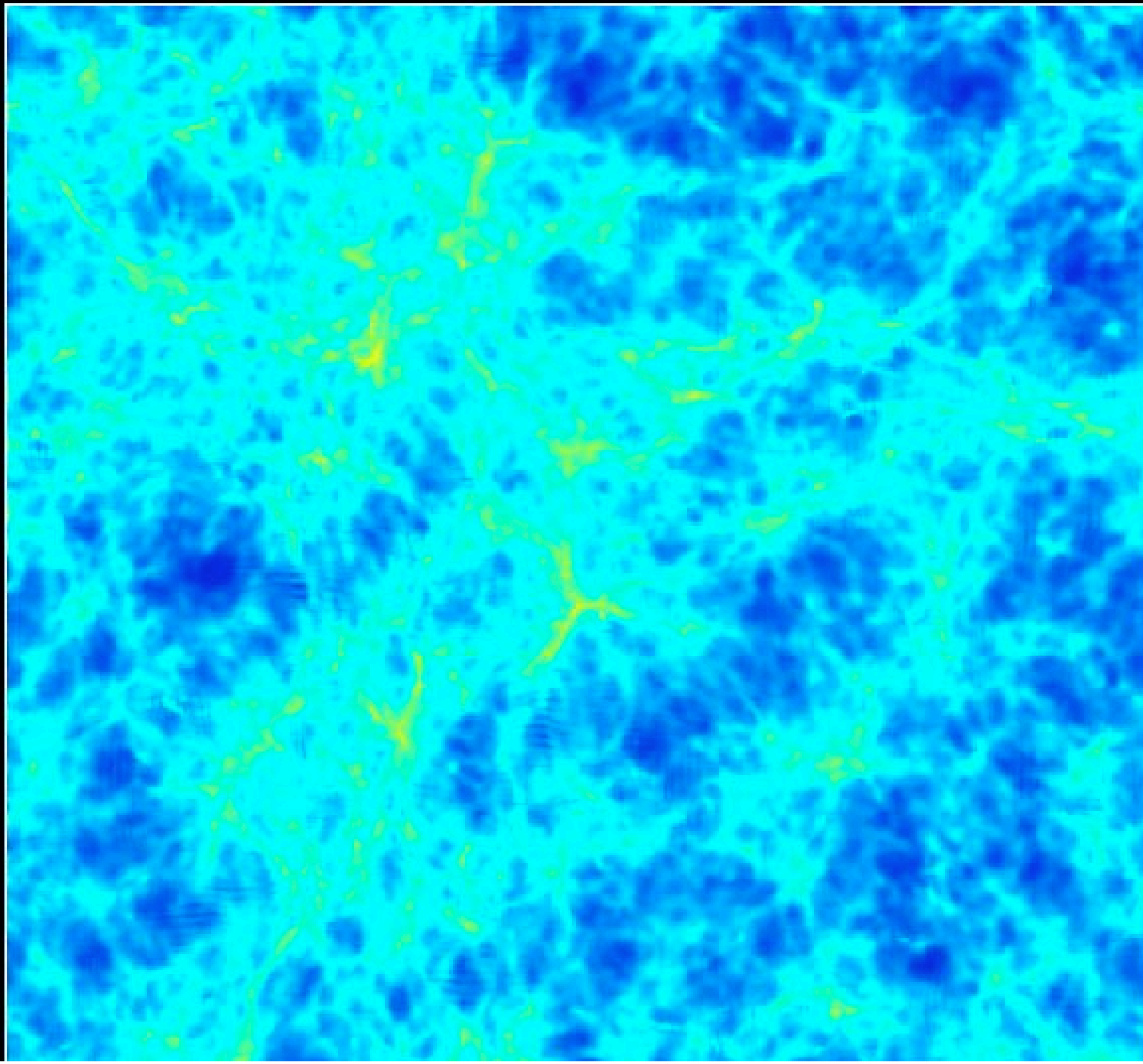
Gas Dynamics

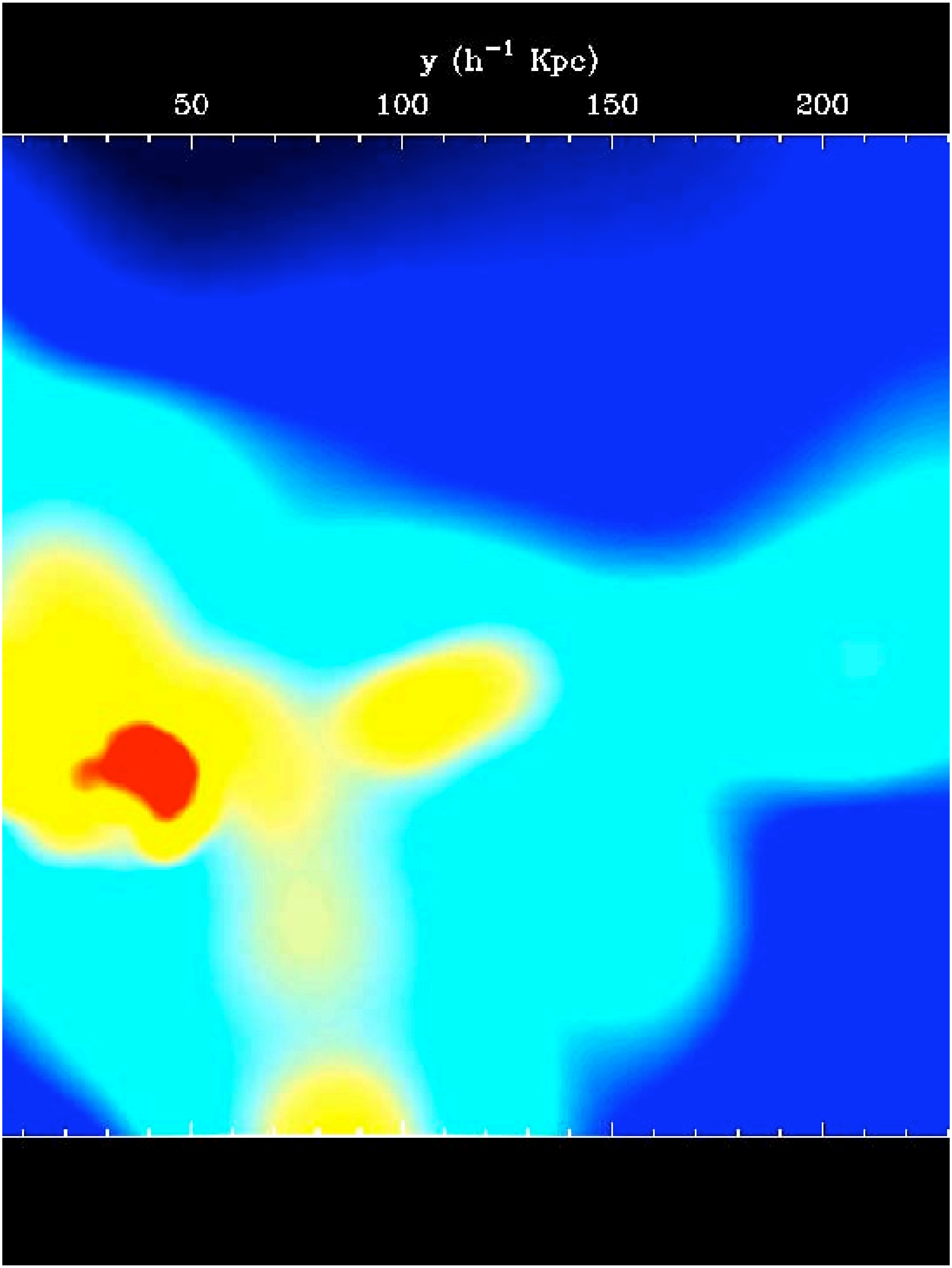
Star Formation Galaxy Formation

Black holes

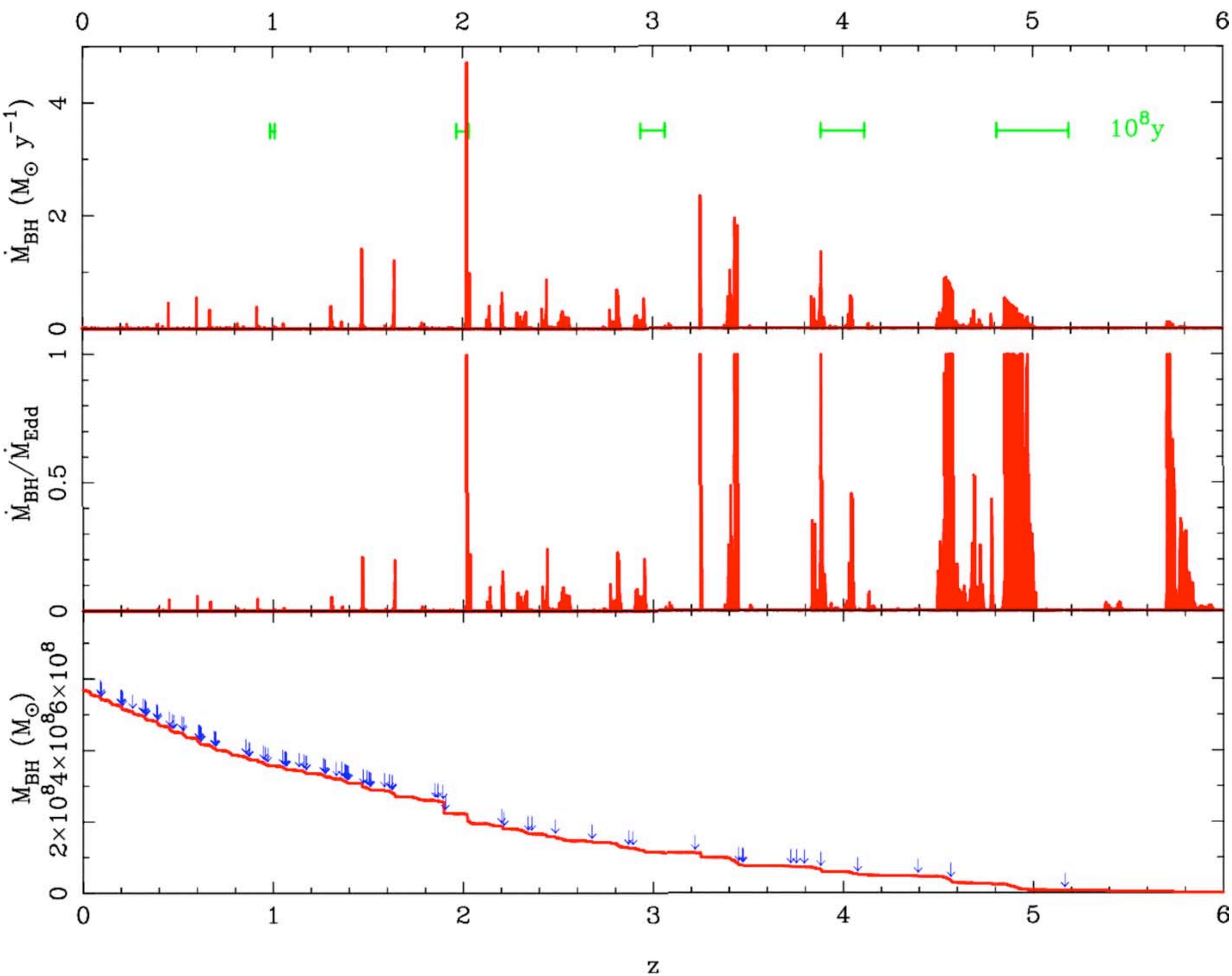
- A BIG computer!


9.00
y (h^{-1} Kpc)
3×10^4
2×10^4
10^4





y (h^{-1} Kpc)
50
100
150
200



0 1 2 3 4 5 6
$\dot{M}_{BH}$ ($M_\odot$ y^{-1})
10^8y
$\dot{M}_{BH}/\dot{M}_{Edd}$
M_{BH} ($M_\odot$)
2×10^8 4×10^8 6×10^8
z

COEVOLUTION OF BLACK HOLES AND GALAXIES

- Self-Consistent treatment of BLACK HOLES IN NUMERICAL SIMULATIONS OF GALAXY FORMATION