AGN feedback

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Extragalactic Relativistic Jets: Cause and **Effect** at ICTS
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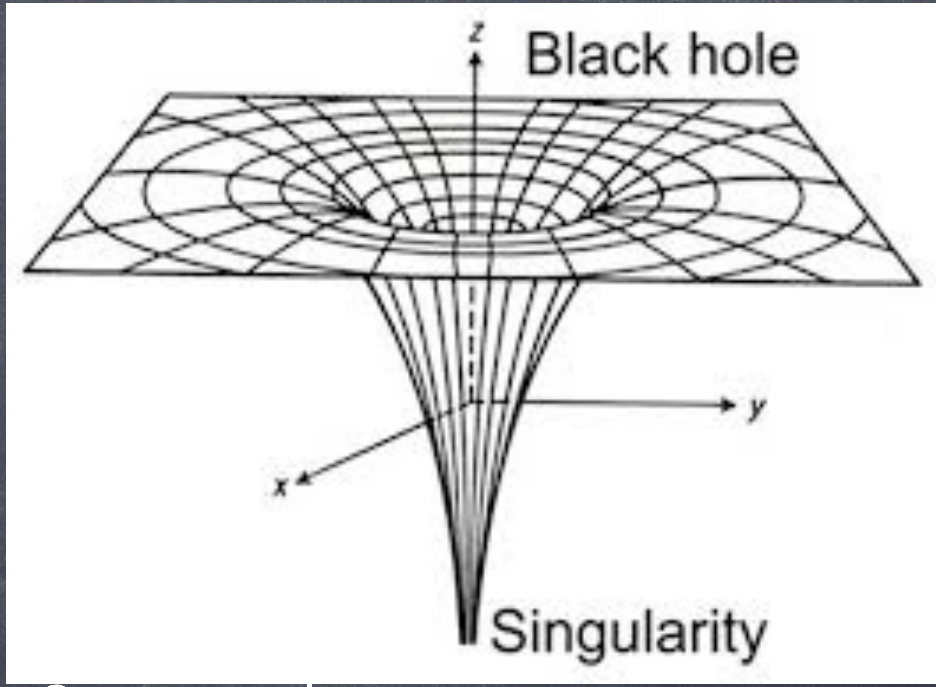
Outline

- SMBHs at galactic centers
- accretion
- jets driven by SMBHs
- influence of jets on global galaxy formation
- TI model for cold gas condensation
- putting it all together in a big picture

What's a BH?

an object so dense that even light cannot escape



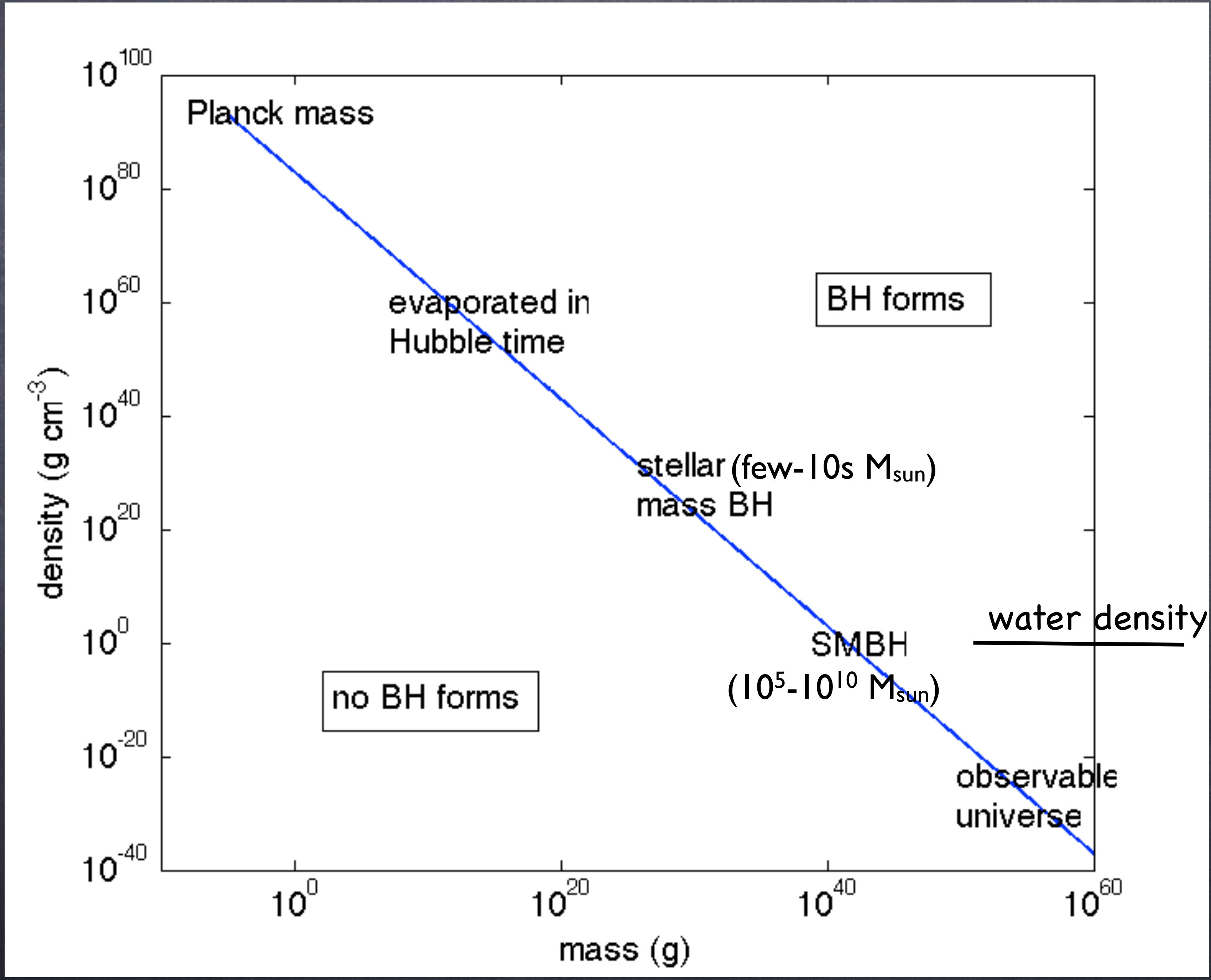
or, $R<2GM/c^2$ (Schwarzschild radius)

or, $\rho > c^6/(32G^3M^2)$

completely specified by mass, spin

If the semi-diameter of a sphere of the same density as the Sun were to exceed that of the Sun in the proportion of 500 to 1, a body falling from an infinite height towards it would have acquired at its surface greater velocity than that of light, and consequently supposing light to be attracted by the same force in proportion to its vis inertiae, with other bodies, all light emitted from such a body would be made to return towards it by its own proper gravity.
—John Michell, 1783

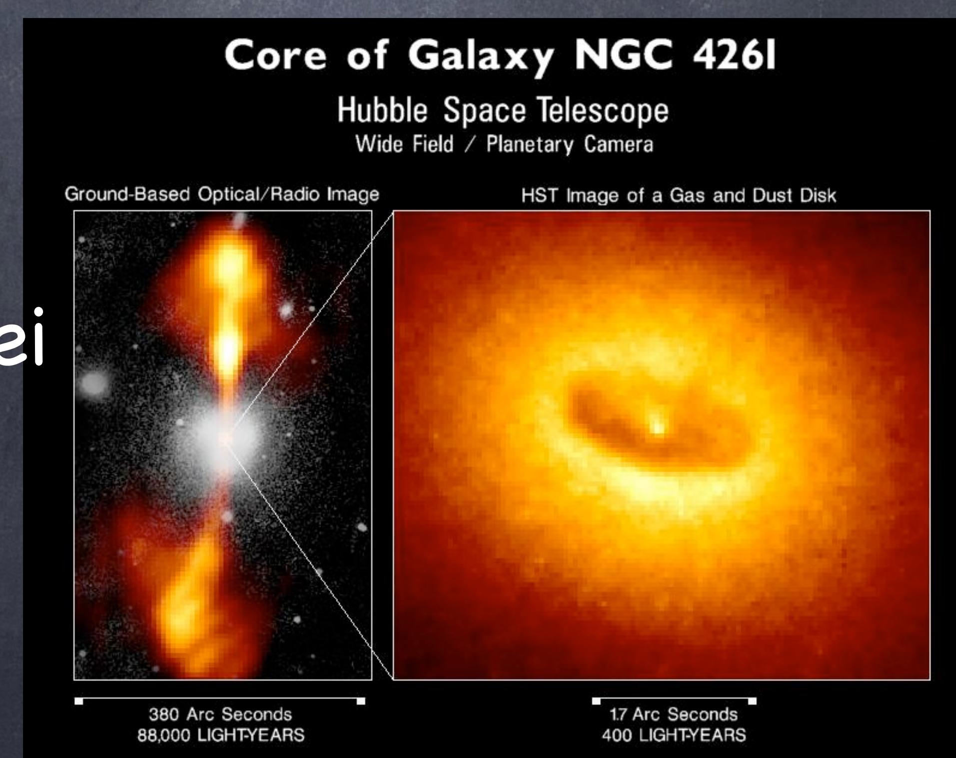
Different types



Astrophysical BHs

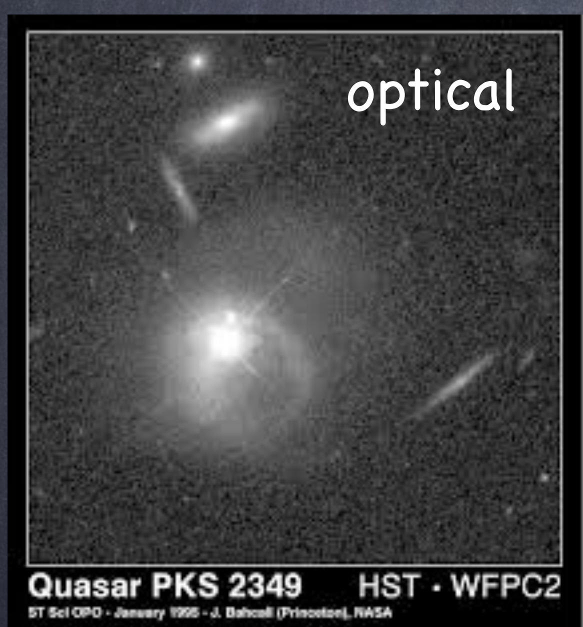
Stellar BHs: a result of death of some massive stars (10s of Msun)
observed as X-ray binaries - XRBs

Supermassive BHs (SMBH):
at centers of most galaxies
observed as quasars, Active Galactic Nuclei (AGN)



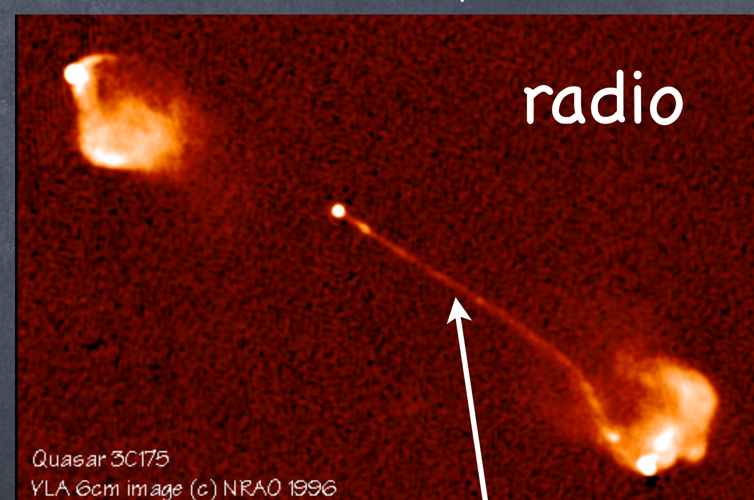
Manifestations of SMBHs

seen via emission from matter in extreme gravity of BHs

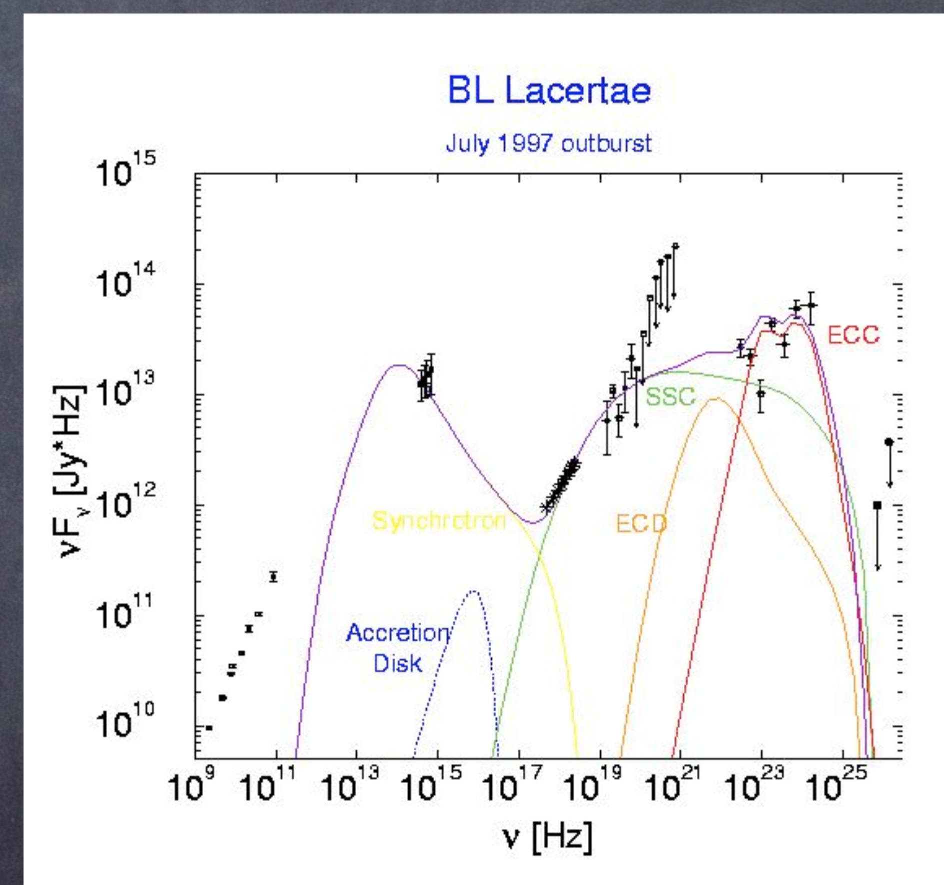


outshines host galaxy
10^{45} erg/s ($10^{11} L_{sun}$)
concentrated in 100 AU

~200 kpc

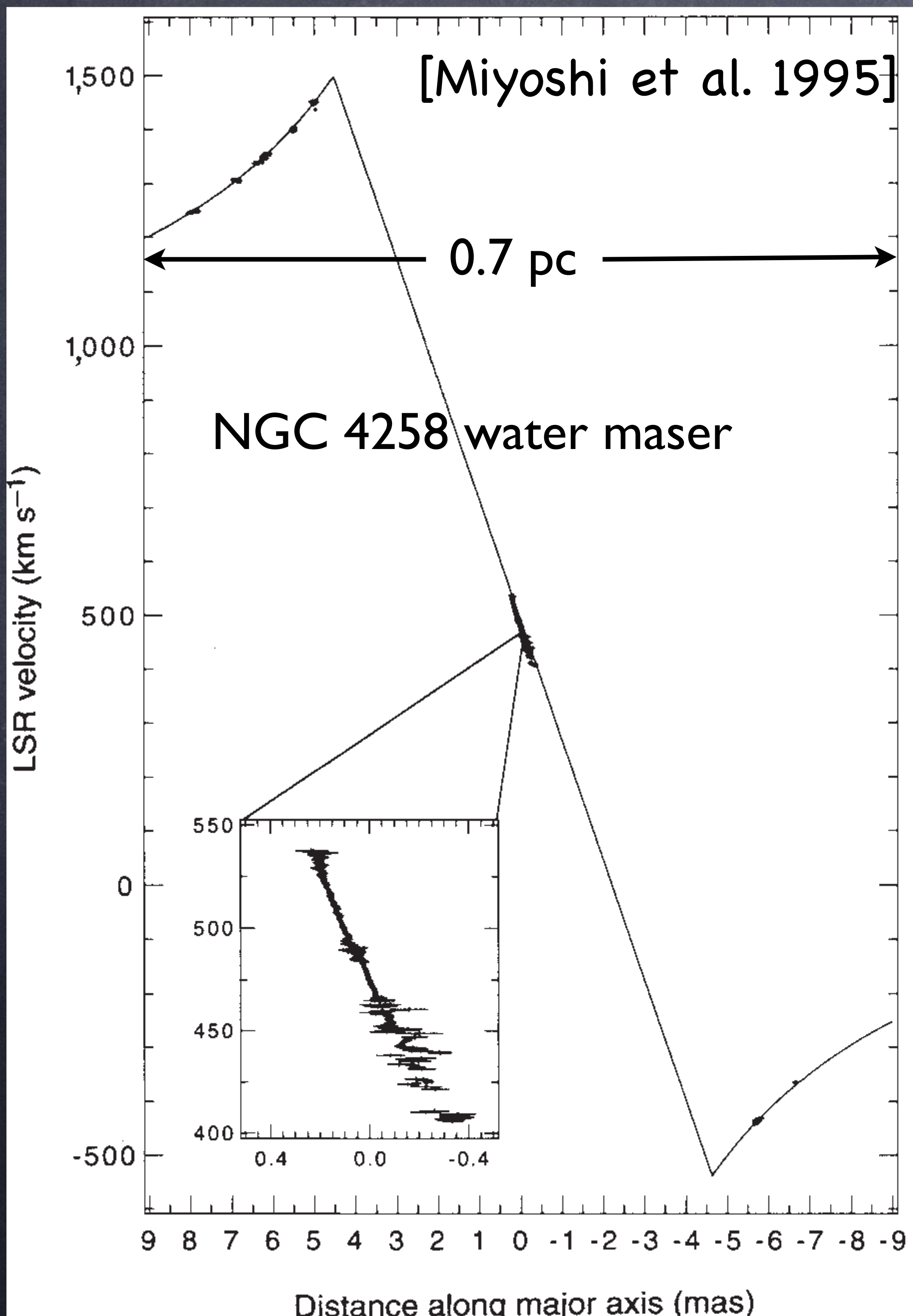


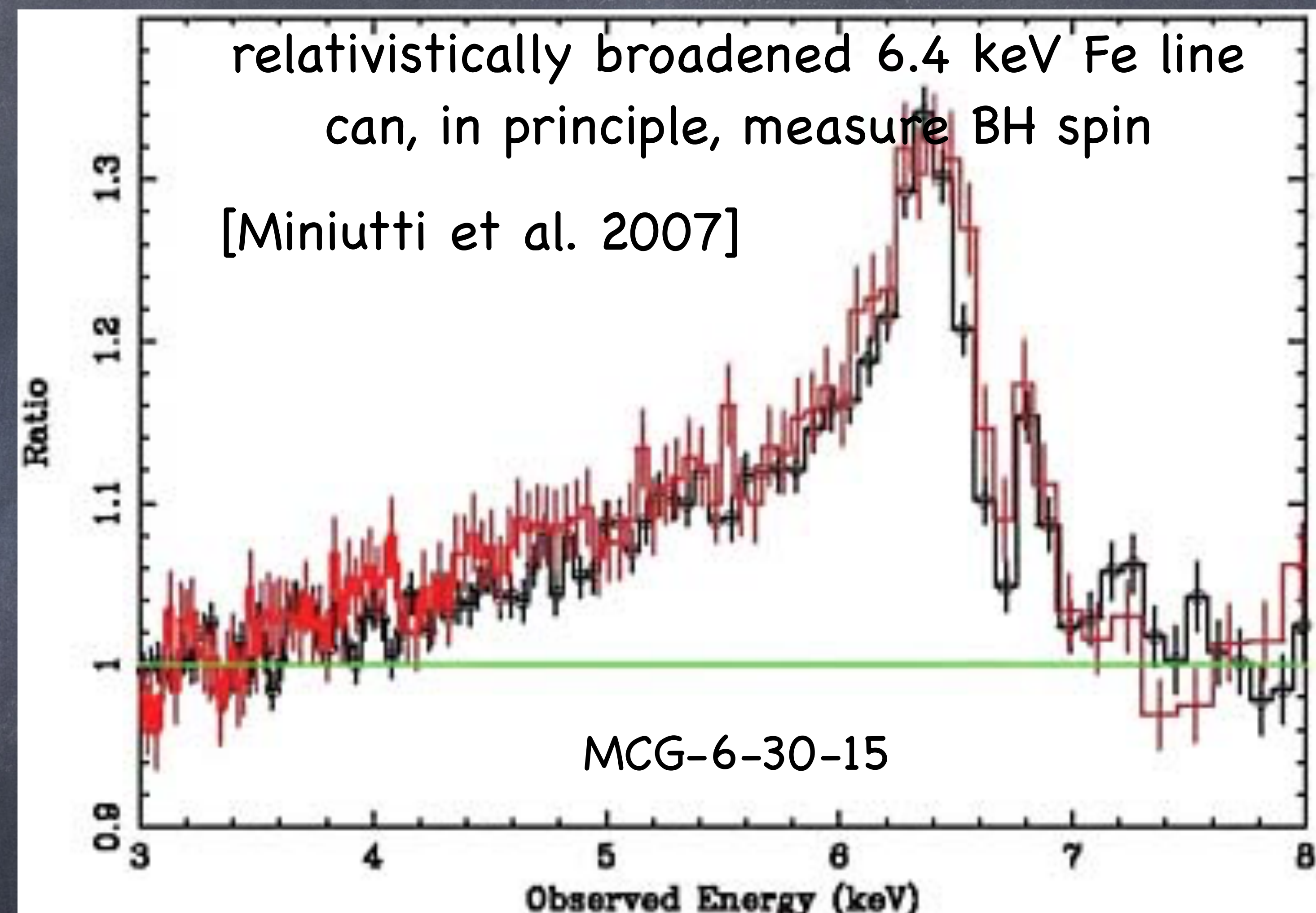
relativistic beaming
influences large scales!



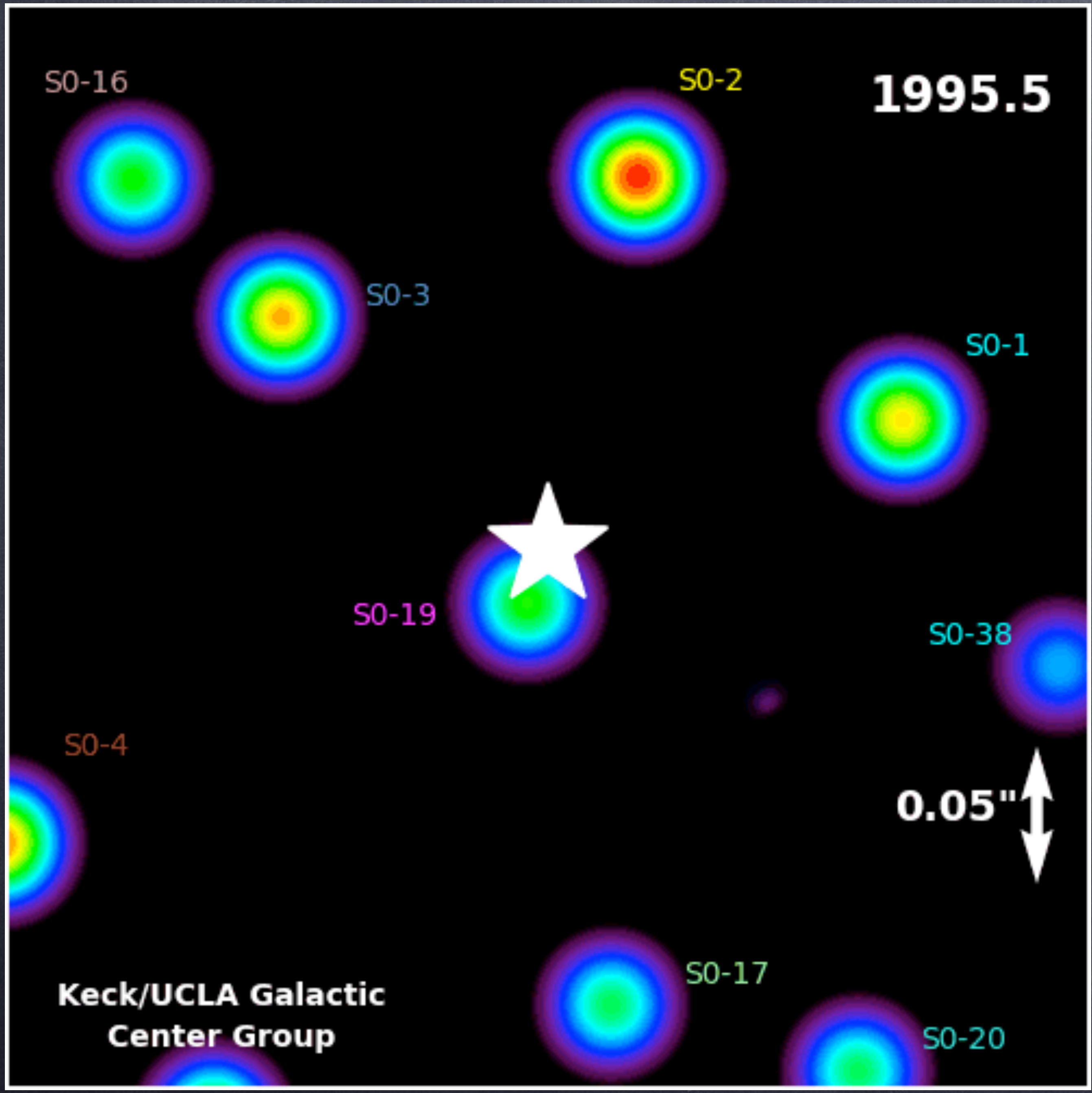
broadband emitters unlike stars
nonthermal radiation

SMBHs at galactic centers





Sgr A* in MW center



Keplerian orbits projected on the sky
invisible mass at the common focus

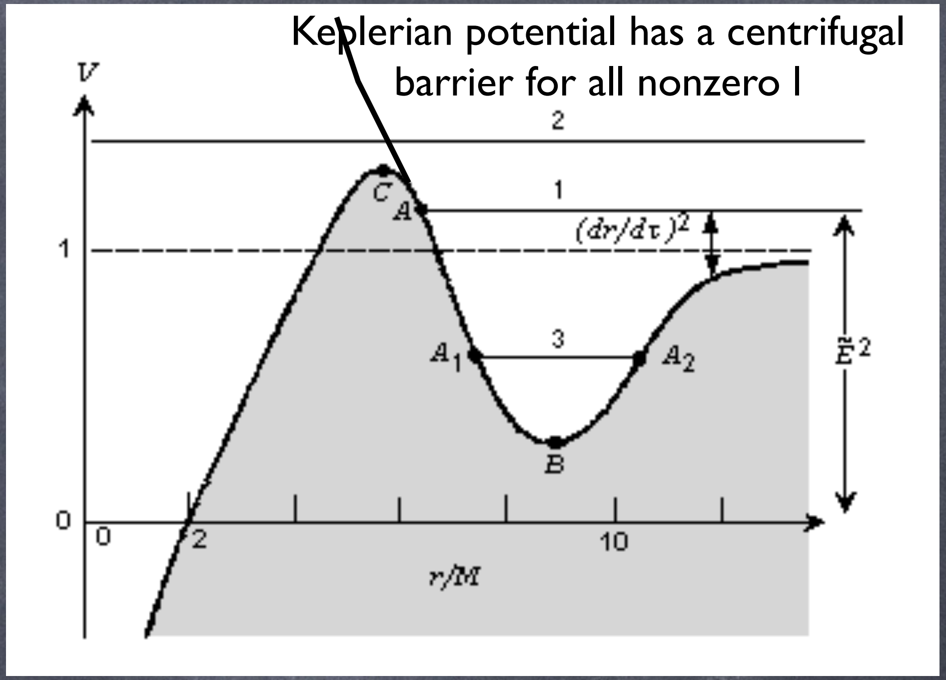
achieved by adaptive optics
4×10^6 Msun SMBH

best evidence for SMBH

star S2 closest at 120 AU ~ 1500 R_{sh}
moving at 0.17c!

particle orbits for BHs

$$\frac{1}{2}\left(\frac{dr}{dt}\right)^2 + \frac{l^2}{2r^2} - \frac{GM_*}{r - r_g} = E$$



effective potential for a non-rotating BH

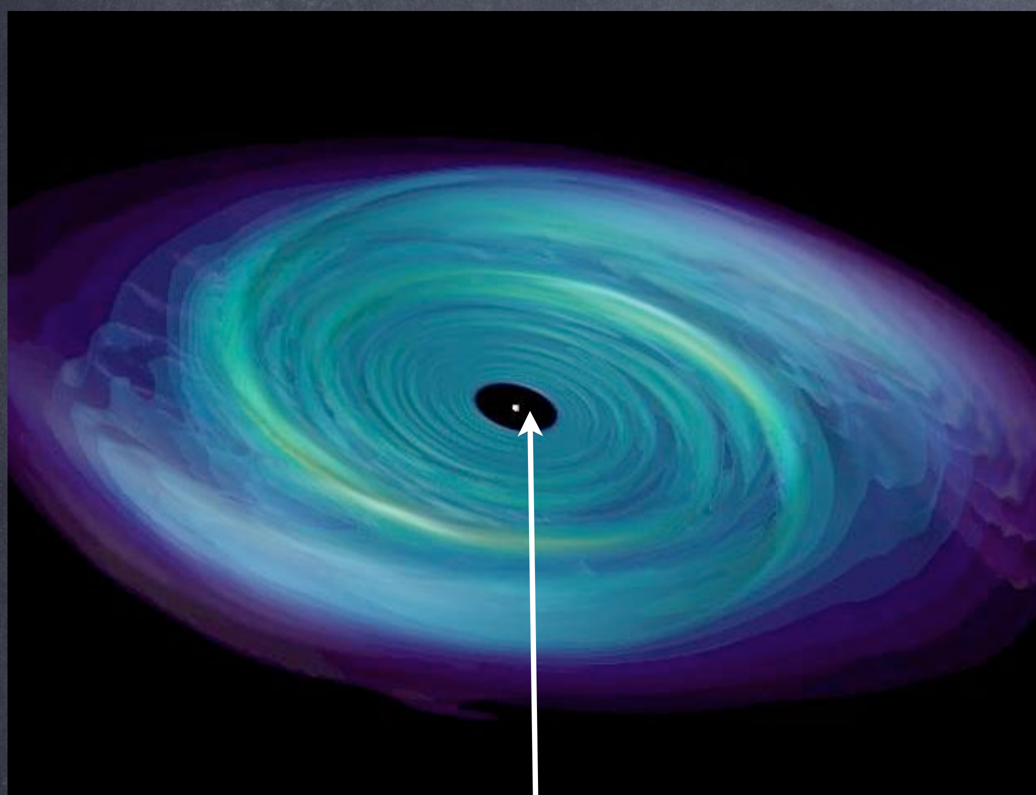
last stable orbit (ISCO) at 3 R_{Sh}

l should exceed l_{crit} to form a stable orbit

particles must lose energy & ang. mom. (< l_{crit}) to get accreted

BH can acquire spin due to accretion

Accretion power



$E \sim -GM/2r$; $GM/2r$ lost as radiation/outflows

ISCO: in GR stable orbits only exist outside ISCO!

~1/6 of rest mass energy can be extracted till ISCO ($3R_{Sh}$)

ISCO at GM/c^2 for maximally rotating BH
~0.4 of rest mass energy can be extracted

compare with 0.007 extracted from nuclear burning!

$L \sim 4\pi\, \sigma R^2 T^4 \sim GM\dot{M}/2R$

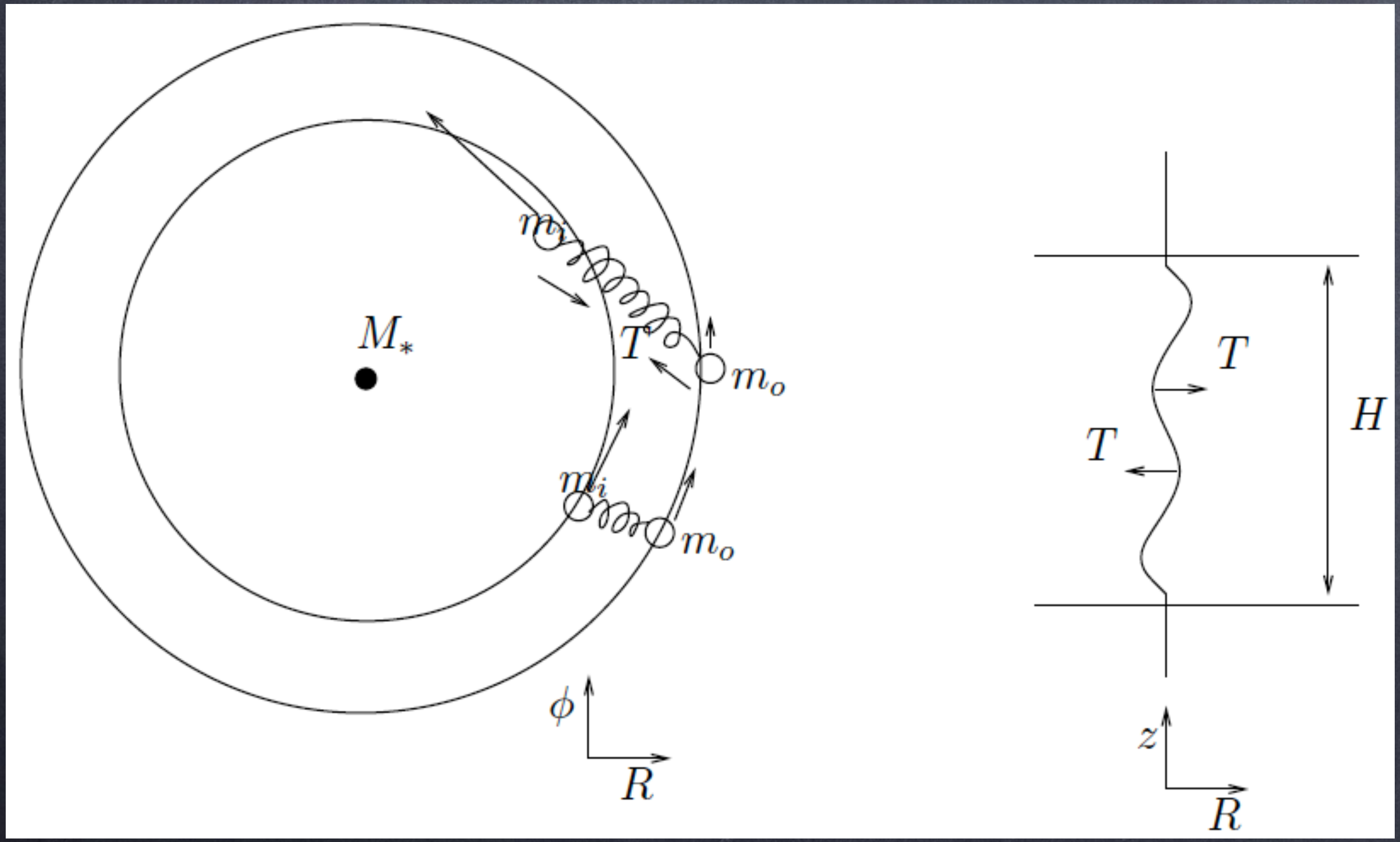
no radiation from within ISCO
no surface unlike WDs & NSs

substantial emission from surface

Angular momentum transport

how does matter lose angular momentum and fall in?
essentially hydrodynamic/MHD nonlinear transport problem

[Balbus & Hawley 1991]



Keplerian disks are Rayleigh stable

specific angular momentum increases w. radius $(GMR)^{1/2}$

$$w^2 = \frac{k_z^2}{k^2}\kappa^2$$

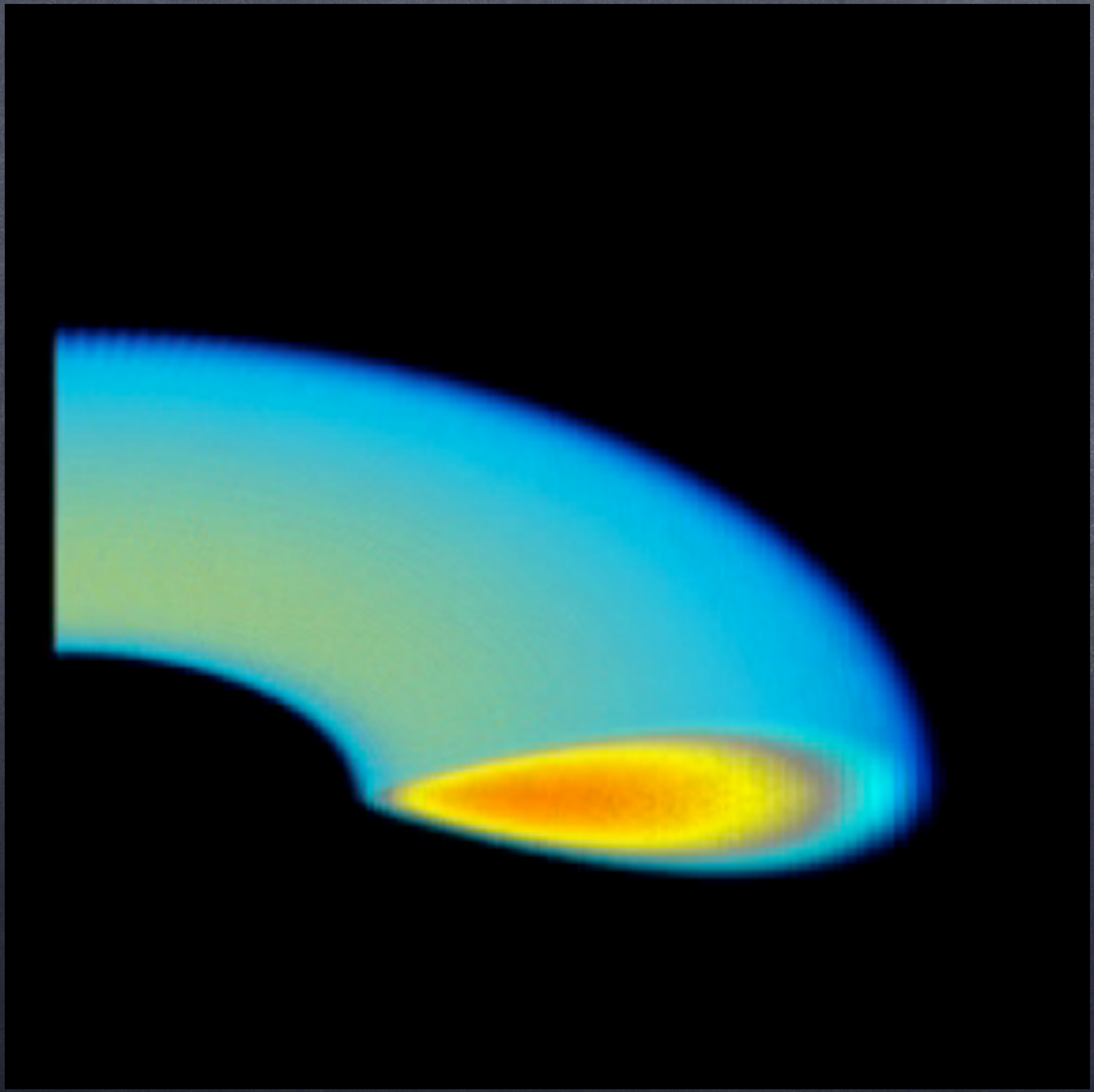
$$\kappa^2 = \frac{2\Omega}{R}\frac{dl^2}{dR}$$

local axisymmetric MHD instability: MRI

works for ionized flows

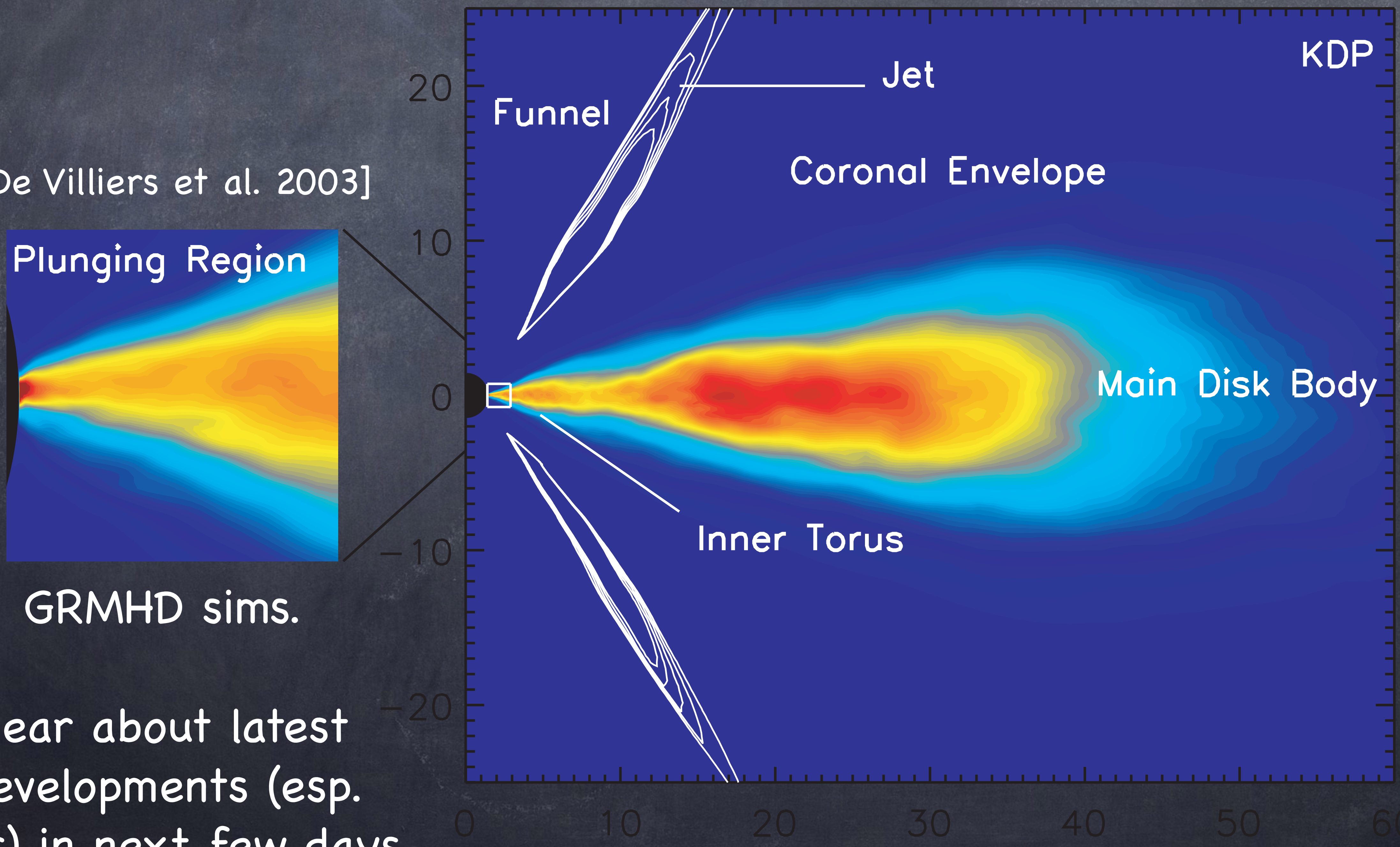
a solved problem, at least for BHs

[credit: John Hawley]



a solved problem, at least for BHs

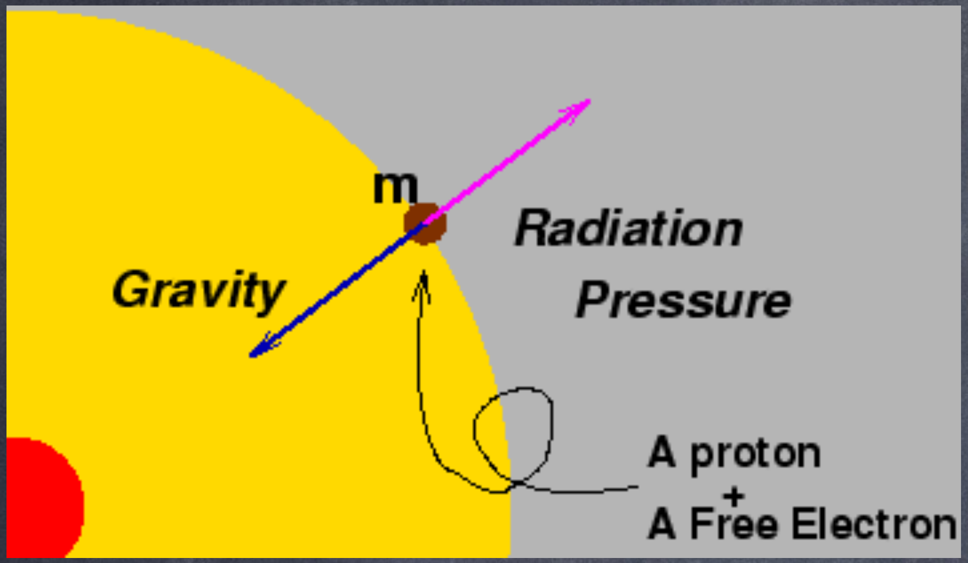
[De Villiers et al. 2003]



GRMHD sims.

hear about latest developments (esp. jets) in next few days

Eddington limit & accretion state



$\sigma_T L_{Edd}/(4\pi r^2 c) = GMm_p/r^2 \Rightarrow L_{Edd}=10^{38}\,(M/M_{sun})$ erg/s

$L_{Edd}=0.1\,\dot{M}_{Edd}c^2$; $\dot{M}_{Edd}=10^{-8}\,(M/M_{sun})\,M_{sun}/yr$

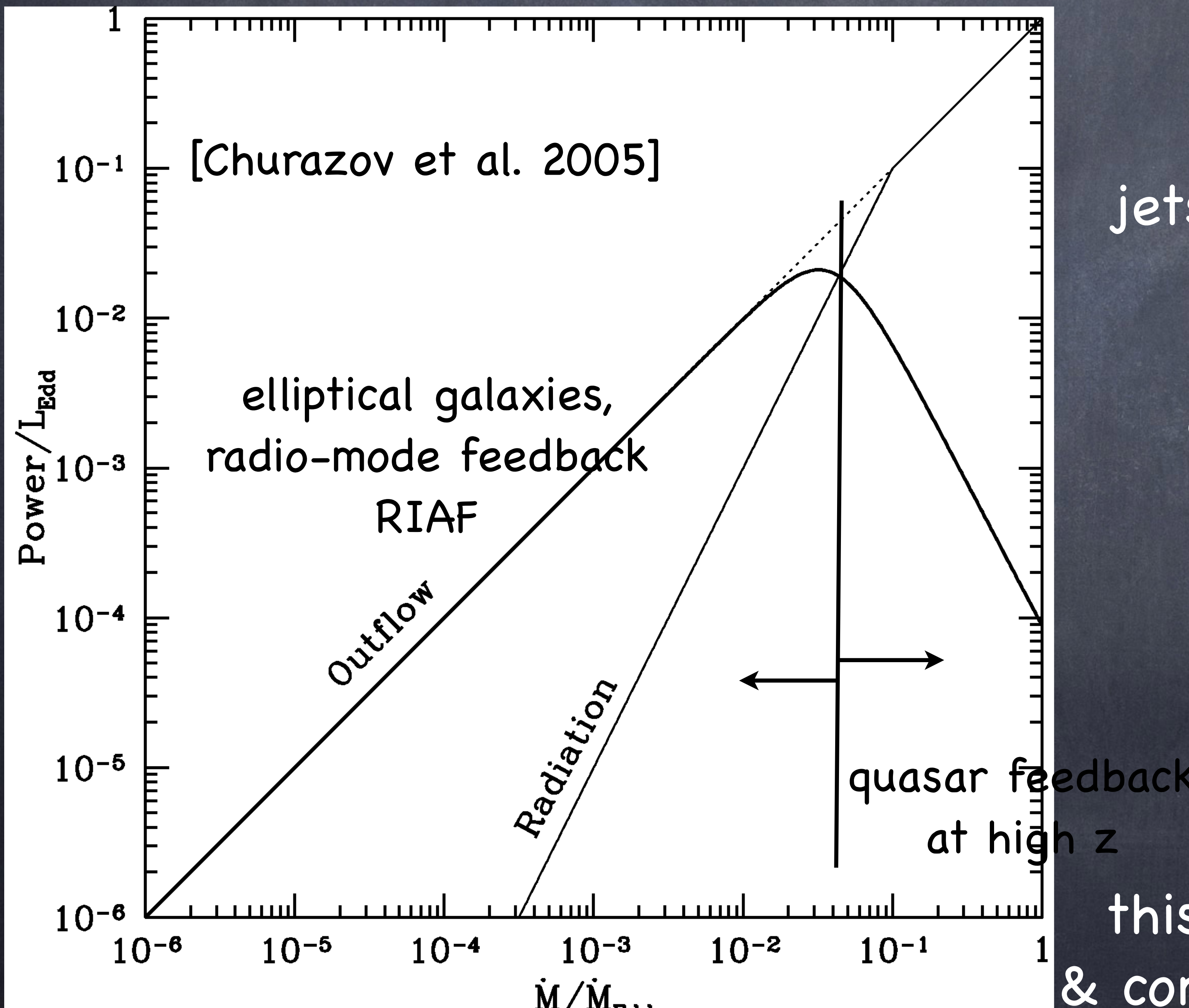
Eddington limit: luminosity for which radiation force equals gravity
spherical accretion can't exceed this limit

accretion is radiatively inefficient if matter accretes before it can cool
$t_{cool} \sim nkT/n^2\Lambda$, $t_{visc} \sim r^2/\nu \sim r^2/(\alpha c_s H)$

t_{cool}/t_{visc} expressible in more versatile $\dot{M}/\dot{M}_{Edd}$

$t_{cool}/t_{visc}=1$ is equivalent to $\dot{M}/\dot{M}_{Edd} \sim 0.1\,\alpha^2$

Energy: radiation vs jets/outflows



energy comes out mostly as jets/outflows for low accretion rate: radio galaxies

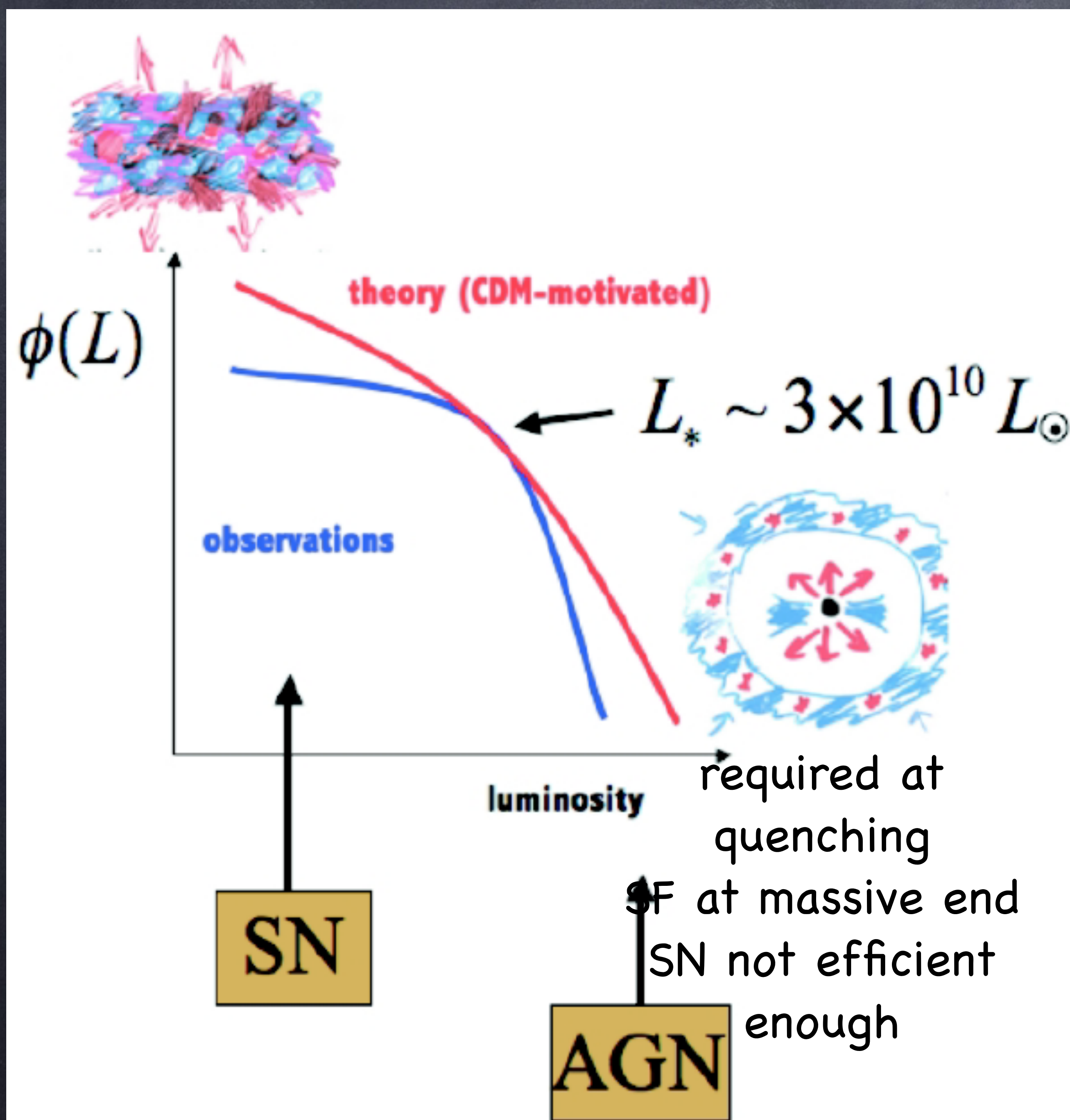
& as radiation for higher rate: quasars

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

this energy can couple to the ISM & control star formation & BH growth

BHs & galaxy formation

[Silk 2011]



structure in the universe grows via mergers

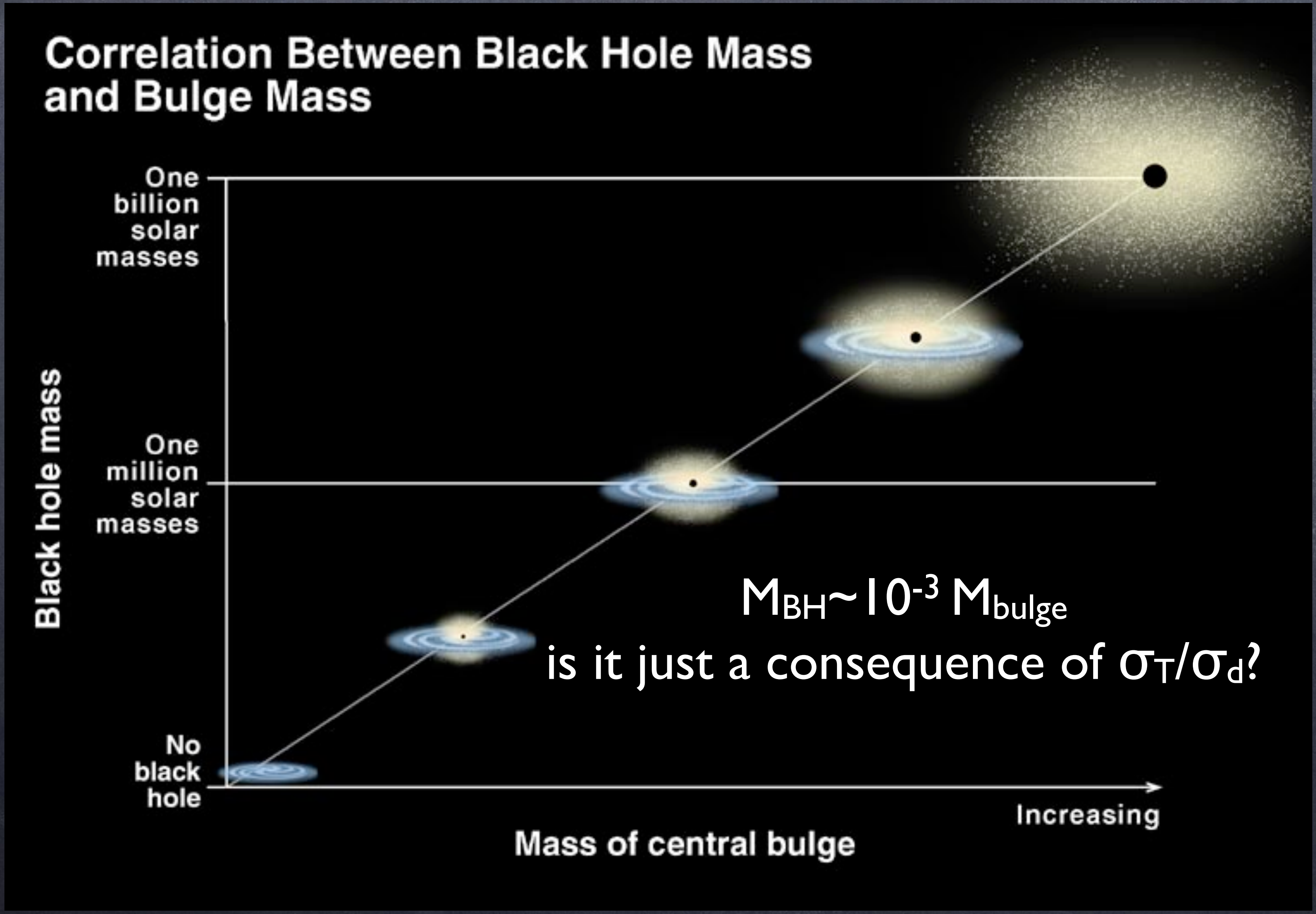
gravity acting on DM leads to LSS

DM only interacts gravitationally

BUT
baryons undergo complex processes
heating and cooling

BH-bulge correlations

bulge >> BH sphere of influence & yet is correlated w. BH => BH affects star-formation in bulge



$M_{BH} \sim 10^{-3} M_{bulge}$

is it just a consequence of σ_T/σ_d?

Quasar mode: energy & momentum arguments

[Silk & Rees 1998]

gravitational potential energy ~ energy released due to BH accretion

$$f_g GM^2/R \sim \eta M_{BH} c^2$$
$$\sigma^2 \sim GM/R$$
$$GM/R^3 \sim 100 H^2$$
$$M_{BH} \sim 10^6 M_\odot (\sigma/200\ \mathrm{km/s})^5$$

[King 2003, Faucher-Giguere & Quataert 2012]

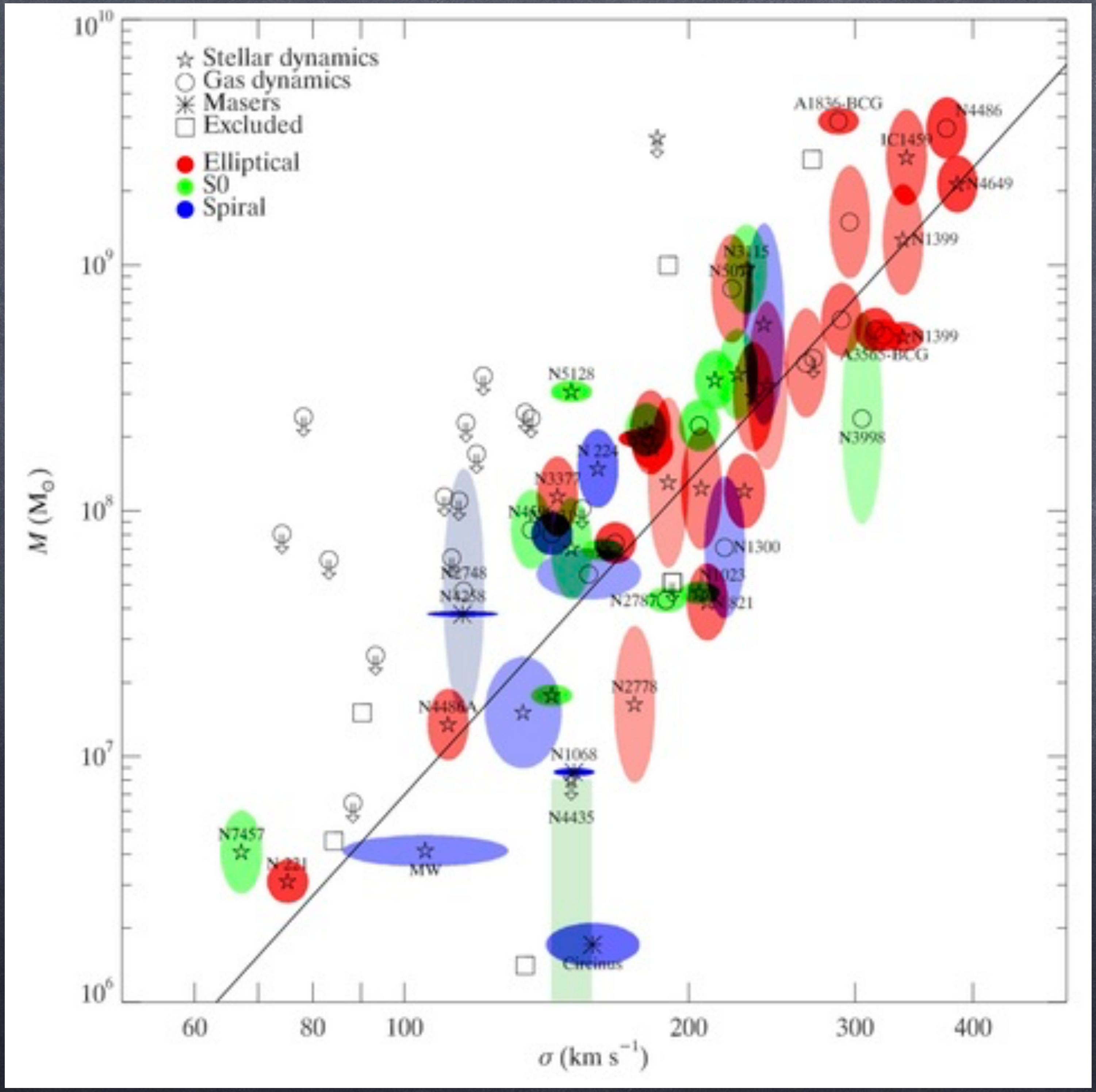
$$L_{\mathrm{Edd}}/c = 4\pi G M_{BH} m_p/\sigma_T = f_g GM^2/R^2 = f_g \sigma^4/G$$
$$M_{BH} \sim 5 \times 10^7 M_\odot (\sigma/200\ \mathrm{km/s})^4$$

e^-s can cool efficiently due to Compton cooling & energy lost => momentum of photons pushes against gravity

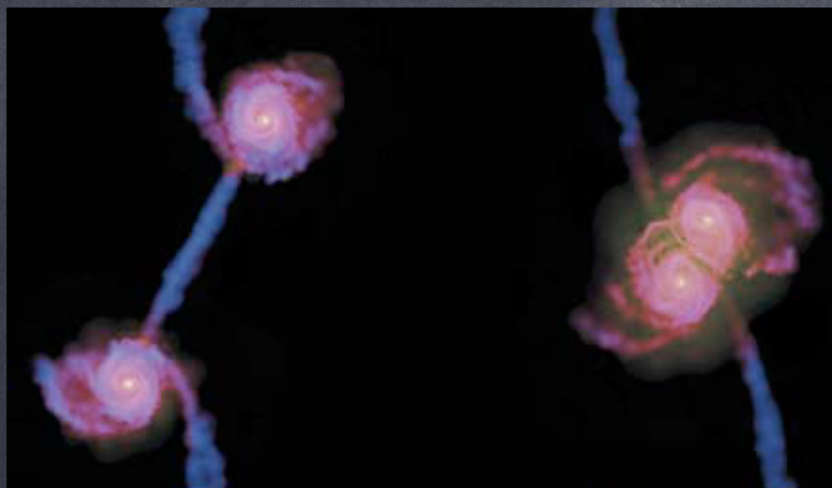
BUT, e^-s and protons may not be coupled => still energy conserving

Observations: M–σ

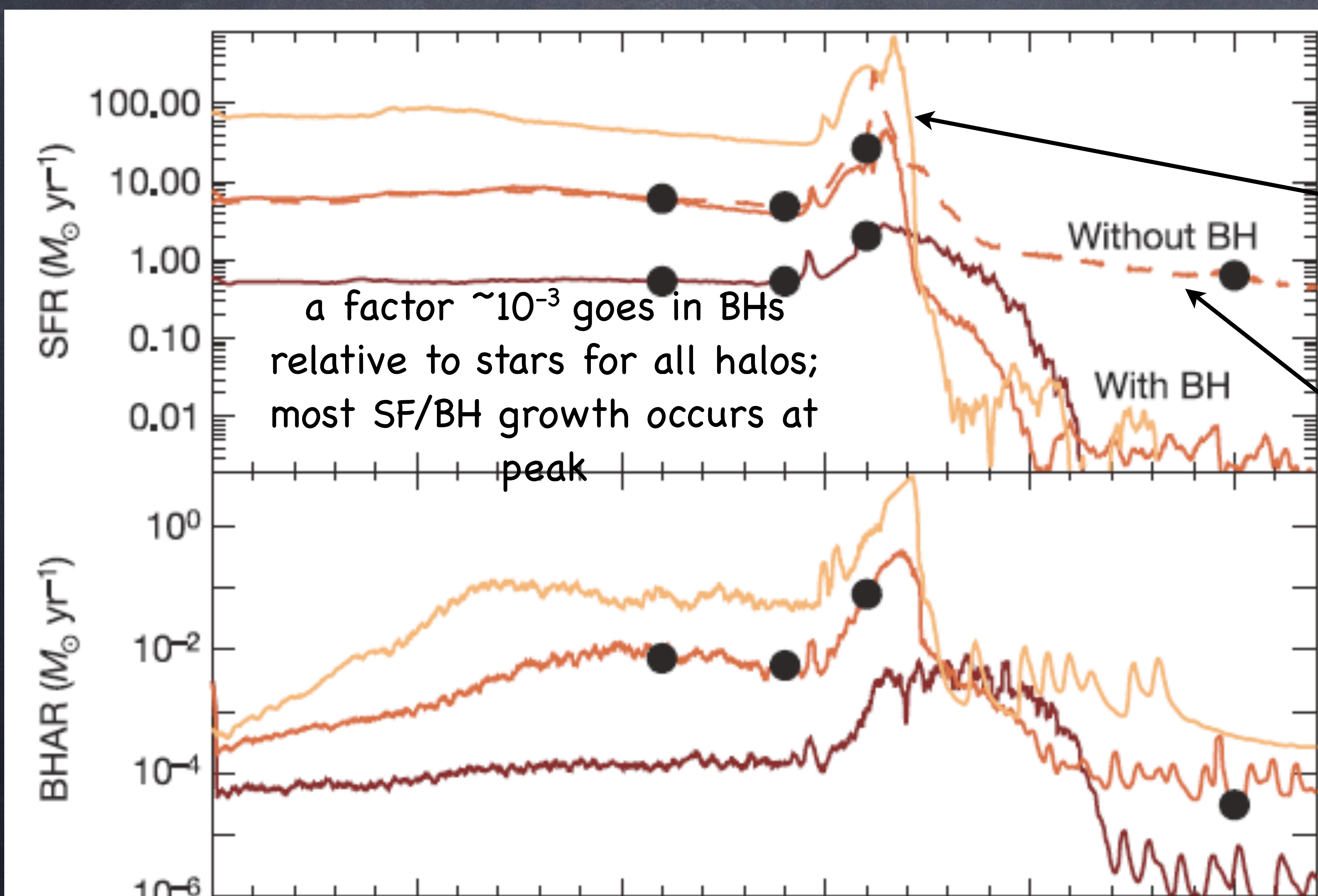
[Gultekin 2009]



BHs affects galaxy formation at large scales!



[Di Matteo et al. 2005]



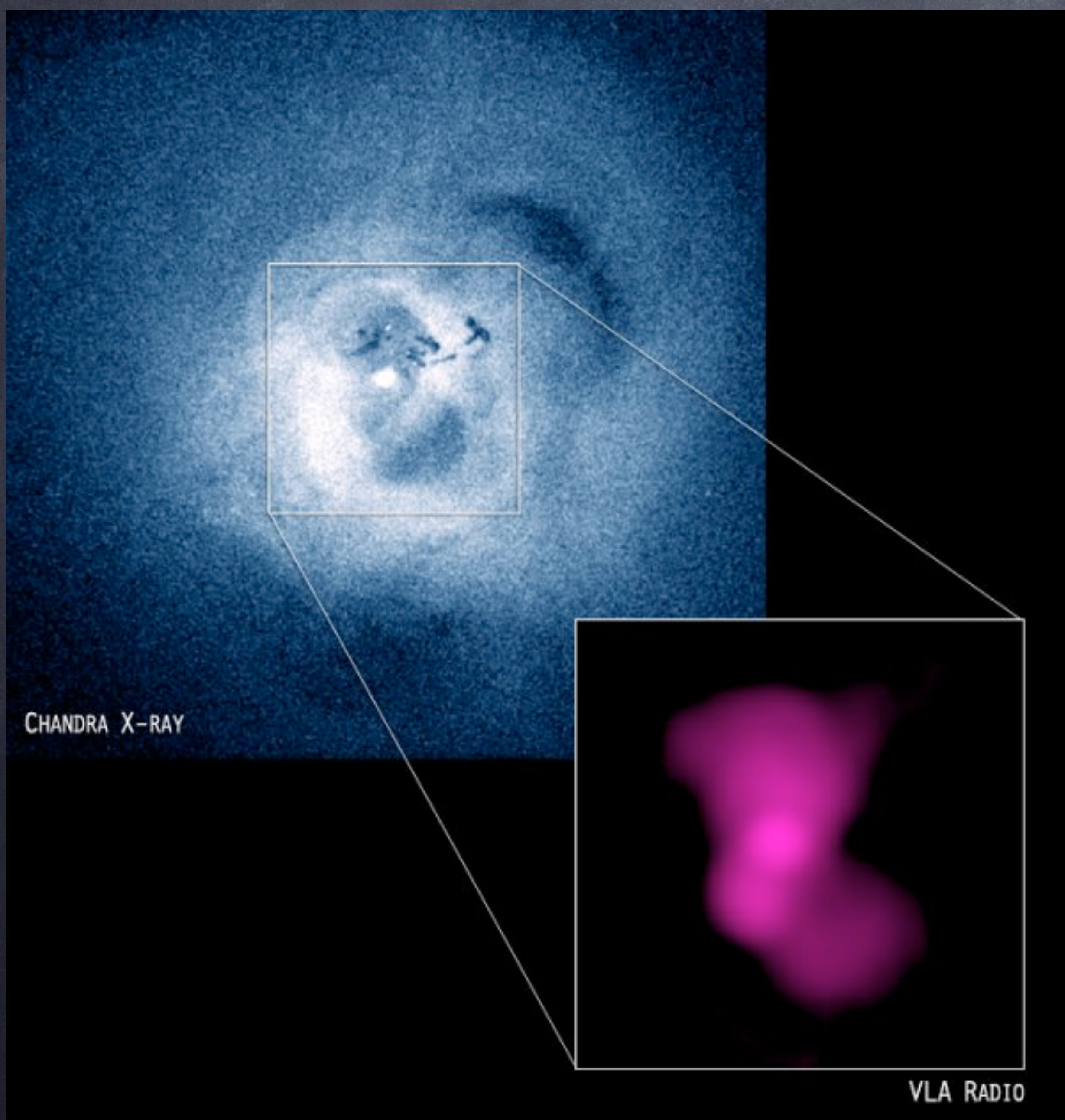
quasar feedback quenches SF & BH growth, producing massive ellipticals here growth is triggered by merger

maintenance/radio mode FB: still reqd. to prevent hot gas from cooling & preventing SF

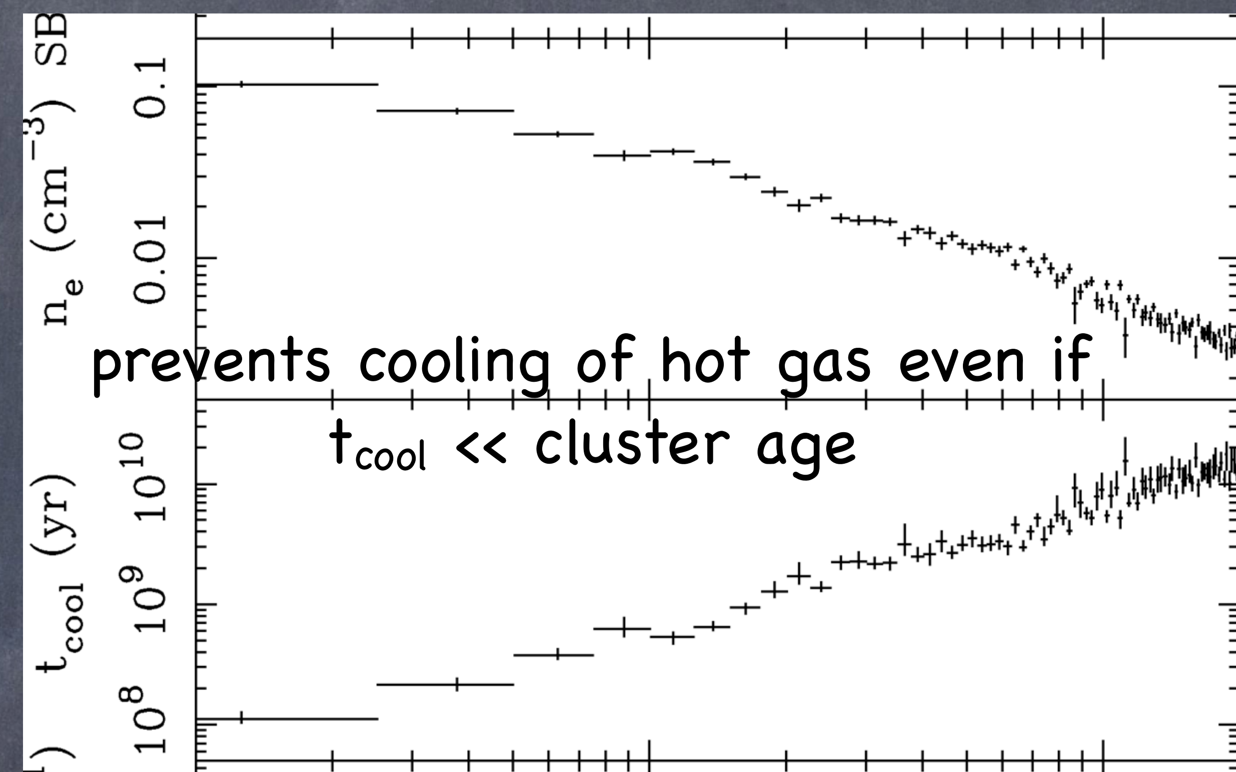
time from 0 to 2.5 Gyr

Kinetic/Radio/Maintenance FB

best observed in galaxy clusters,
home to biggest BHs and galaxies



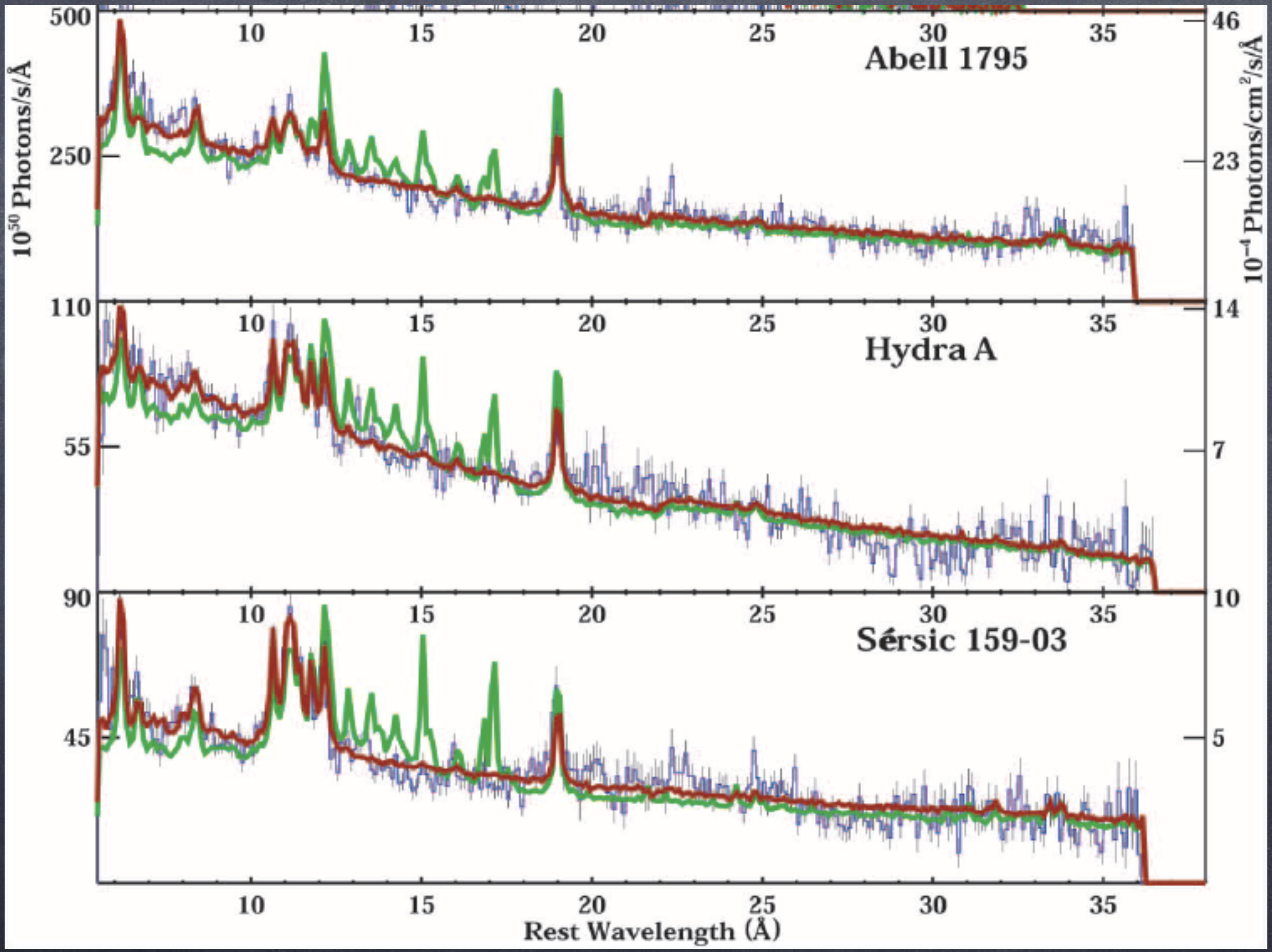
[Johnstone et al. 2002]



jet/cavity power ~ core-luminosity
=> cooling losses balanced by AGN heating
& thermal eqbn.

Cooling absent!

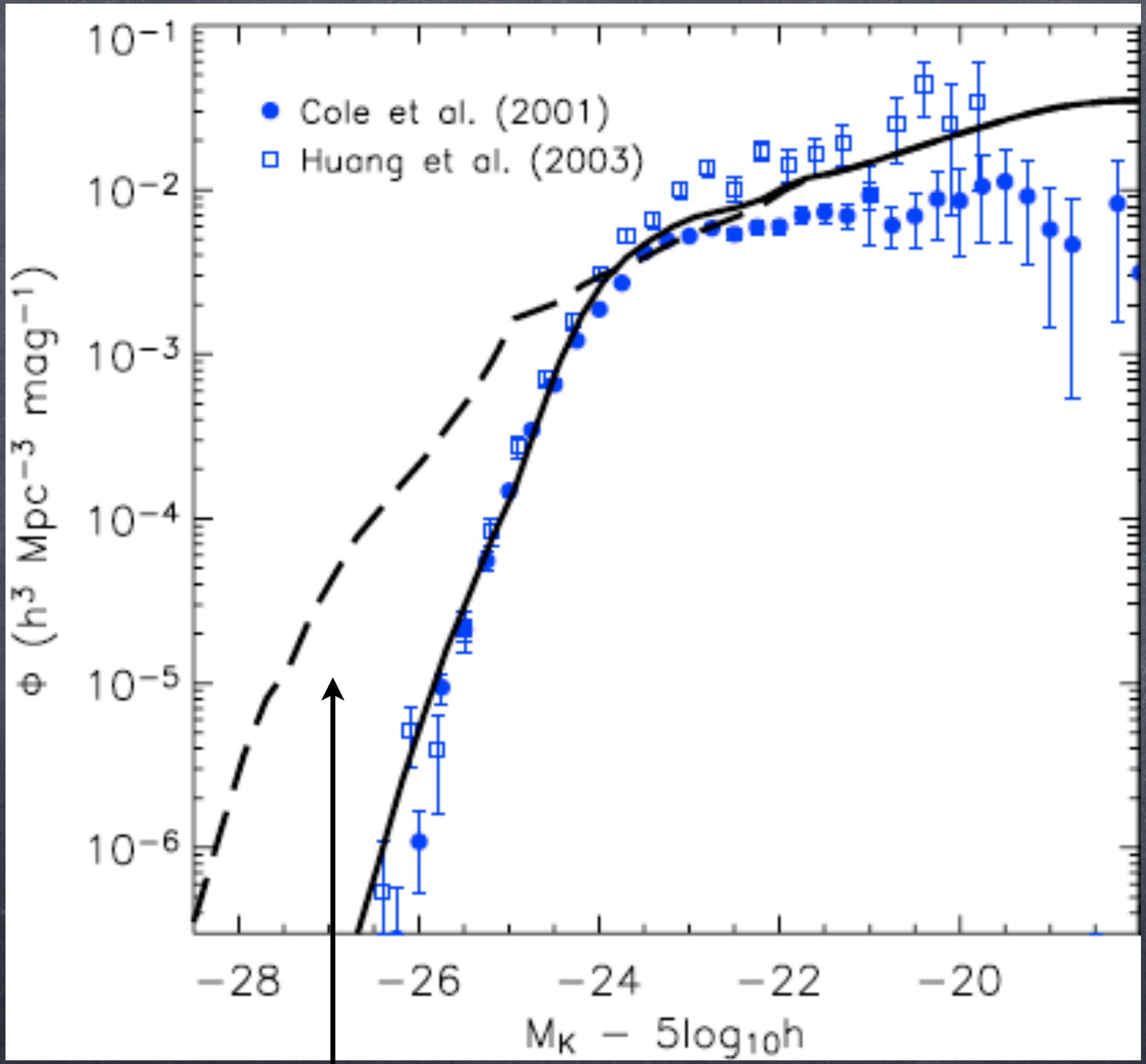
[Peterson et al. 2003]



soft X-ray lines missing!

SF absent!

[Croton et al. 2006]

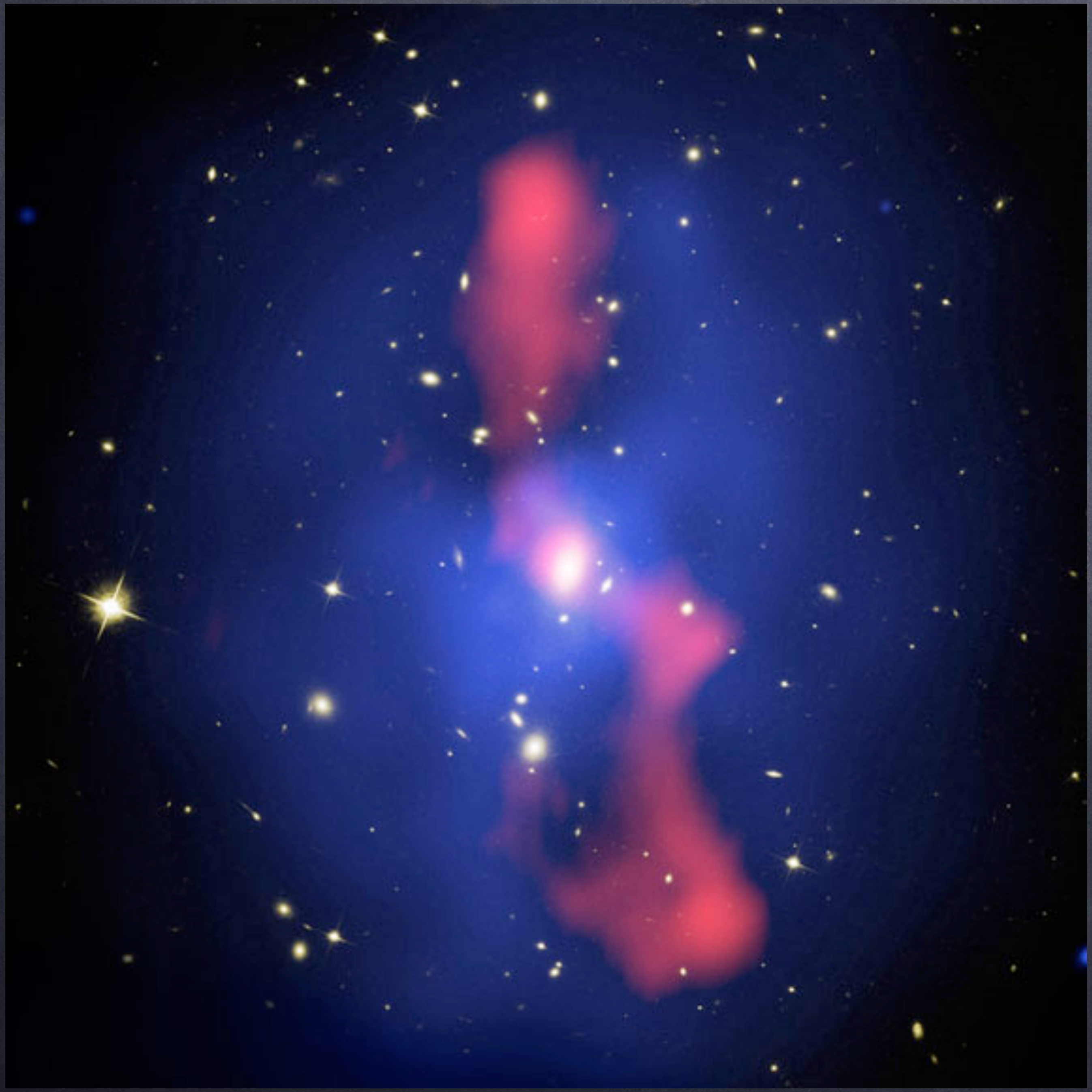


increasing mass

massive galaxies not seen

AGN Heating?

[McNamara & Nulsen 2007]



cooling ICM can power AGN
negative feedback loop
prevents catastrophic cooling

jet/cavity power ~ X-ray luminosity
& lack of cooling

=> rough thermal balance

Jet Power

[Churazov et al. 2002] as bubble/cavity expands it does PdV work on the ICM

a fraction of it converts to irreversible heating

$$E_0 = \gamma/(\gamma - 1)PV$$

initial bubble energy

energy stored+pdV work

$$\Delta E = -\int V\rho \frac{\mathrm{d}\phi}{\mathrm{d}r}\mathrm{d}r = E_0 - \frac{\gamma}{\gamma - 1}PV$$

$$= E_0 \left[1 - \left(\frac{P}{P_0}\right)^{1-1/\gamma}\right],$$

energy dissipated=work done by buoyancy force

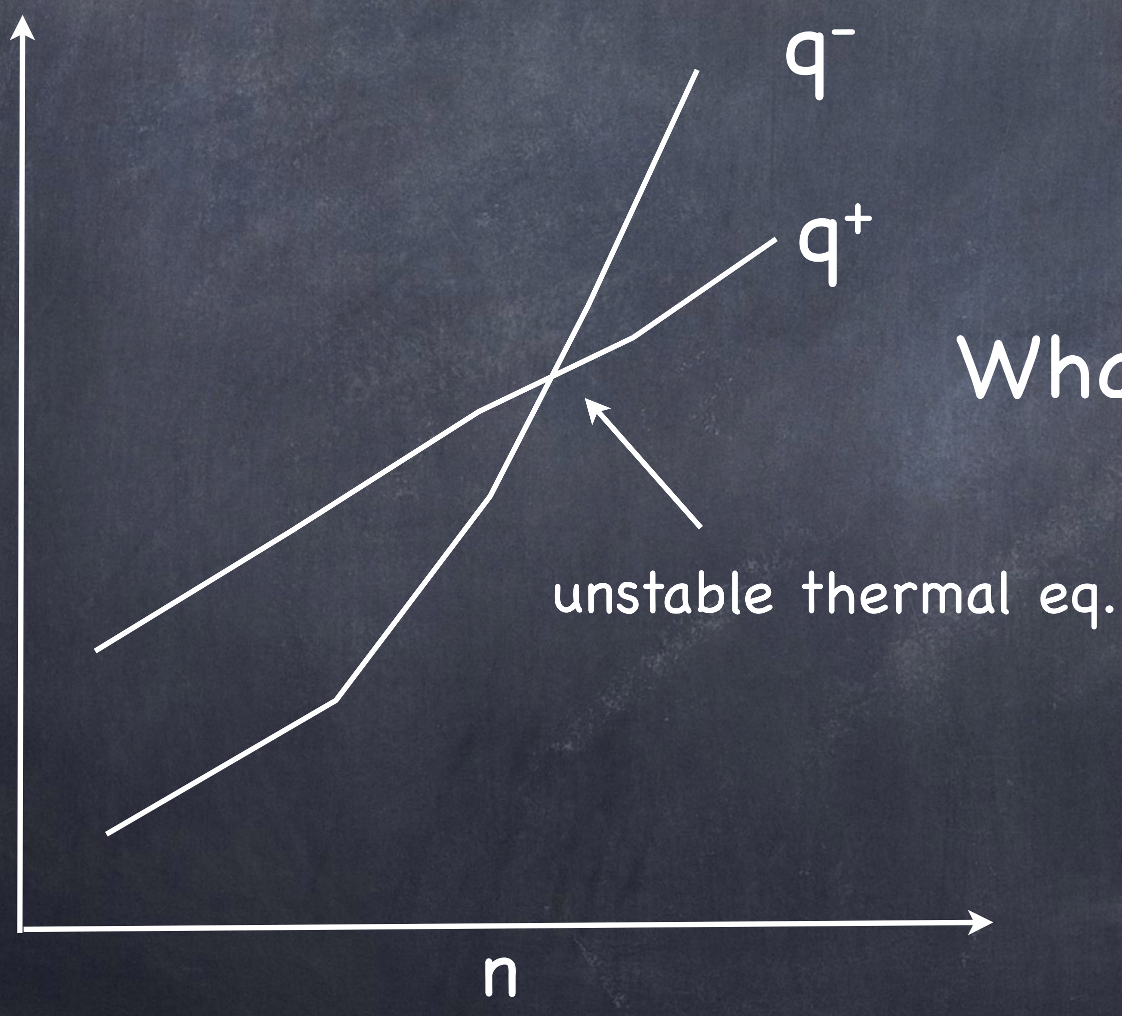
$$\Delta W = \frac{\gamma}{\gamma - 1}(p_0 V_0 - p_1 V_1) = H_0 - H_1$$

$$P = \Delta W/\tau$$

timescale given by rise time~dynamical time~sound-crossing time

Thermal Stability

AGN heating can balance cooling globally



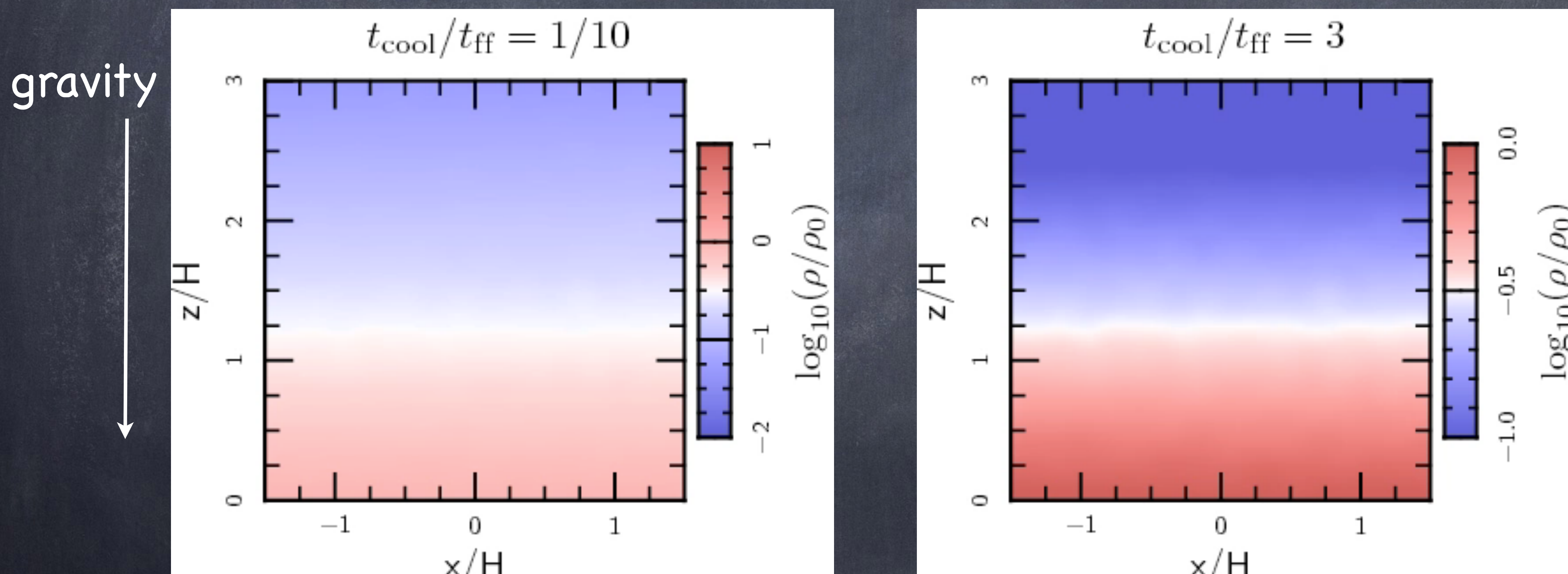
What about local thermal stability?

What abt Gravity?

-ansatz: heating = <cooling> at each ht.

-we know this is true globally

[McCourt et al. 2012]

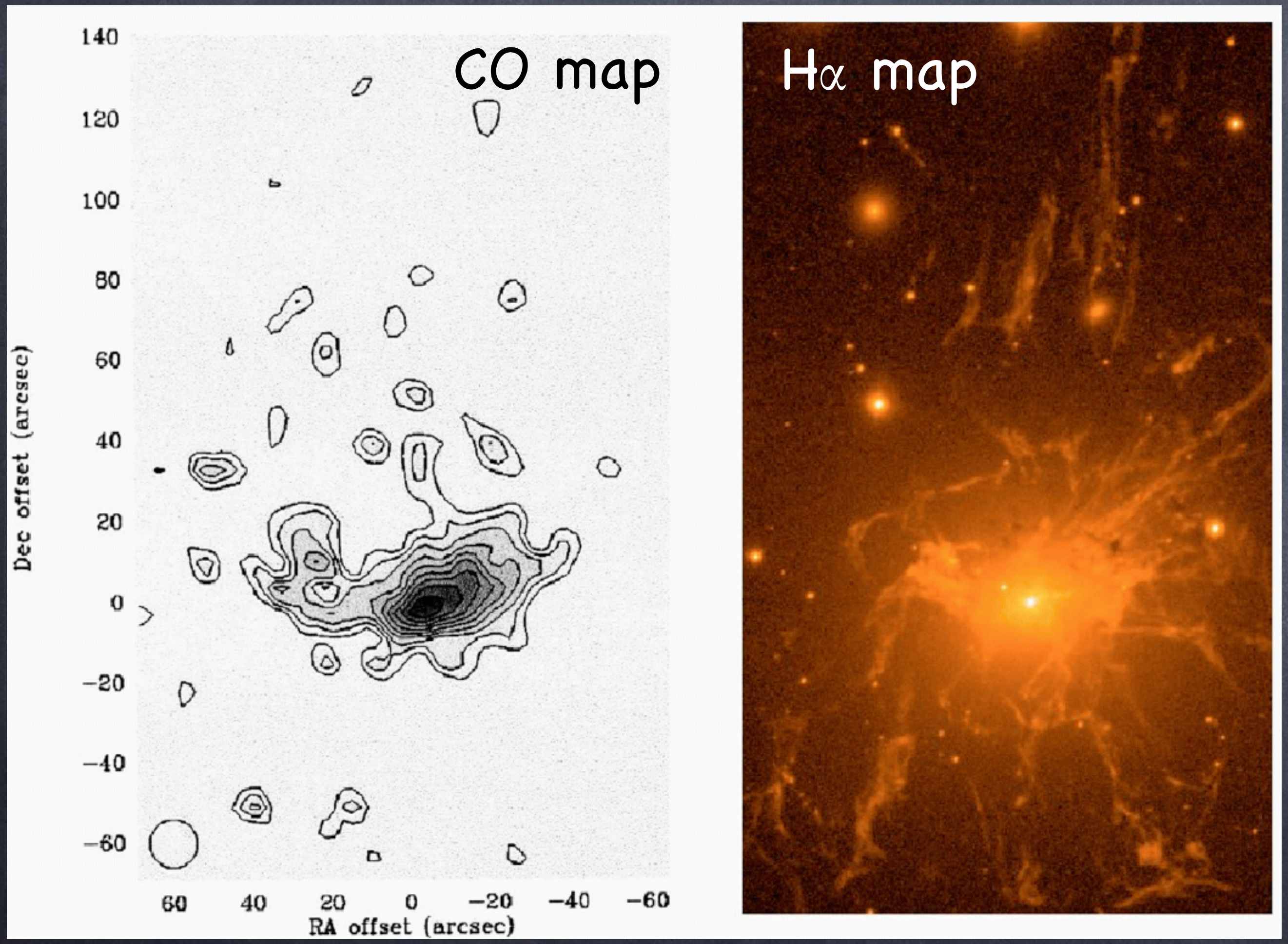


multiphase only when $t_{TI}/t_{ff} < 1$ (crucial parameter)

TI & multiphase gas

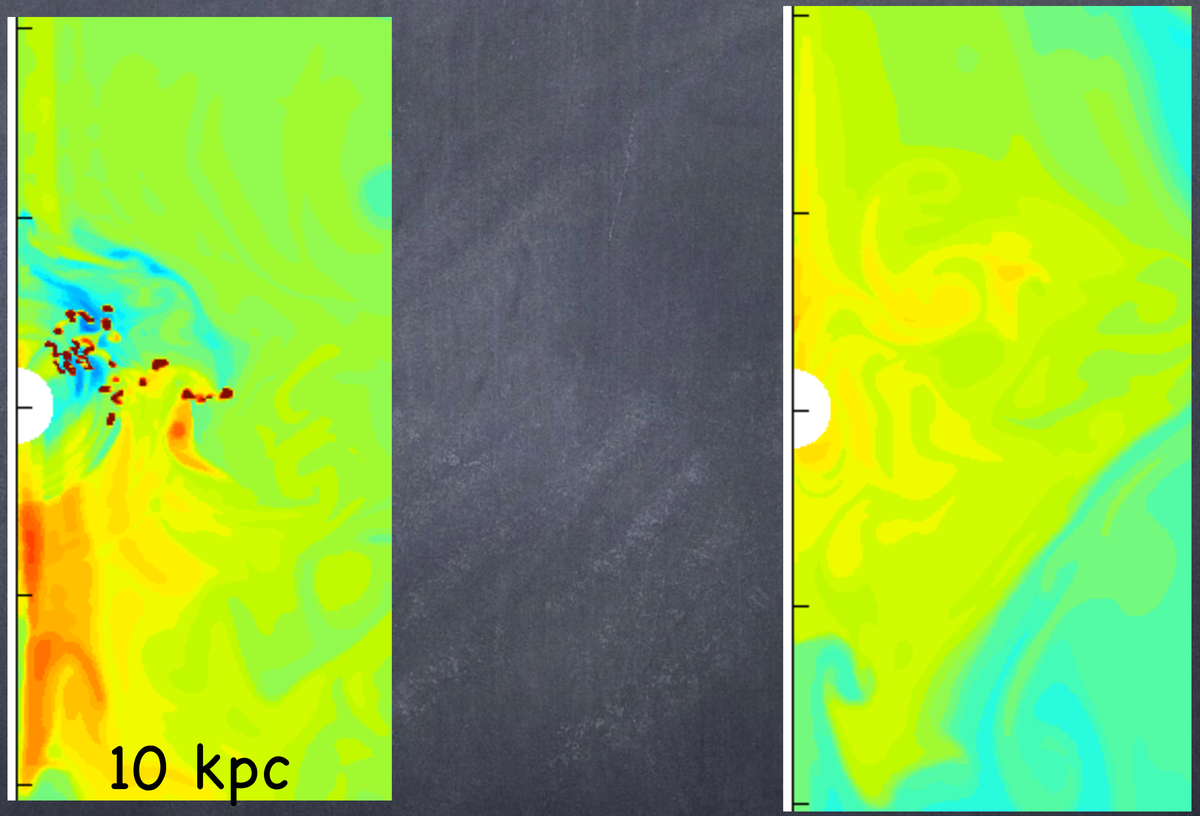
cold filaments condense when $t_{cool}/t_{ff} < 10$

[Salome et al 2006]



Perseus

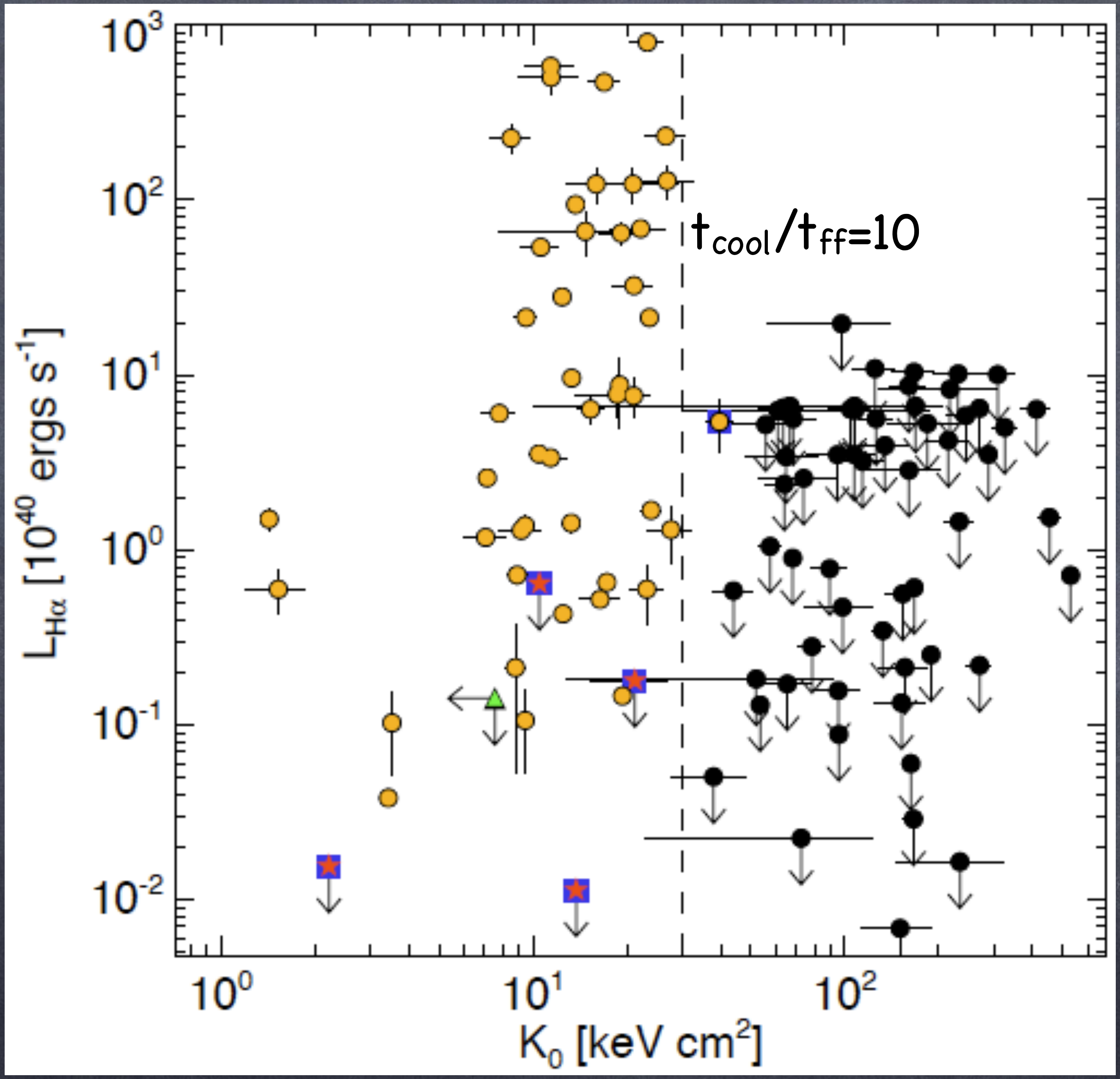
[Sharma et al. 2012]



condensation of cold gas fundamentally changes accretion onto SMBH; stochastic accretion instead of smooth accretion from hot phase

Self-Adjustment of ICM

[Cavagnolo et al. 2008]



CC/NCC division corresponds to our t_{cool}/t_{ff} criterion!

AGN jet feedback

core cooling

↓

large accretion onto SMBH

↓

negative FB, heating wins over cooling, energy pumped back in ICM

↓

after few cooling times rough thermal balance in core

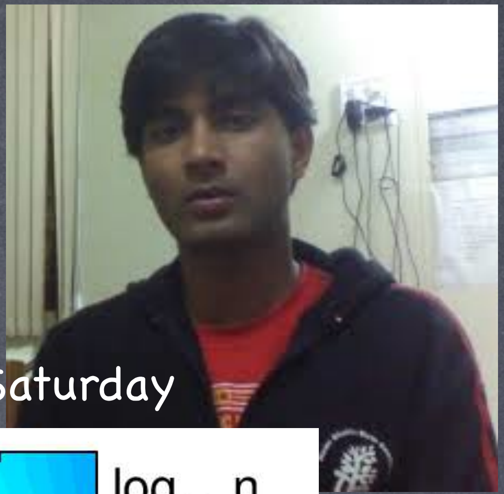
↓

cold, multiphase gas condenses if $t_{cool}/t_{ff} \lesssim 10$; Bondi/hot accretion invalid

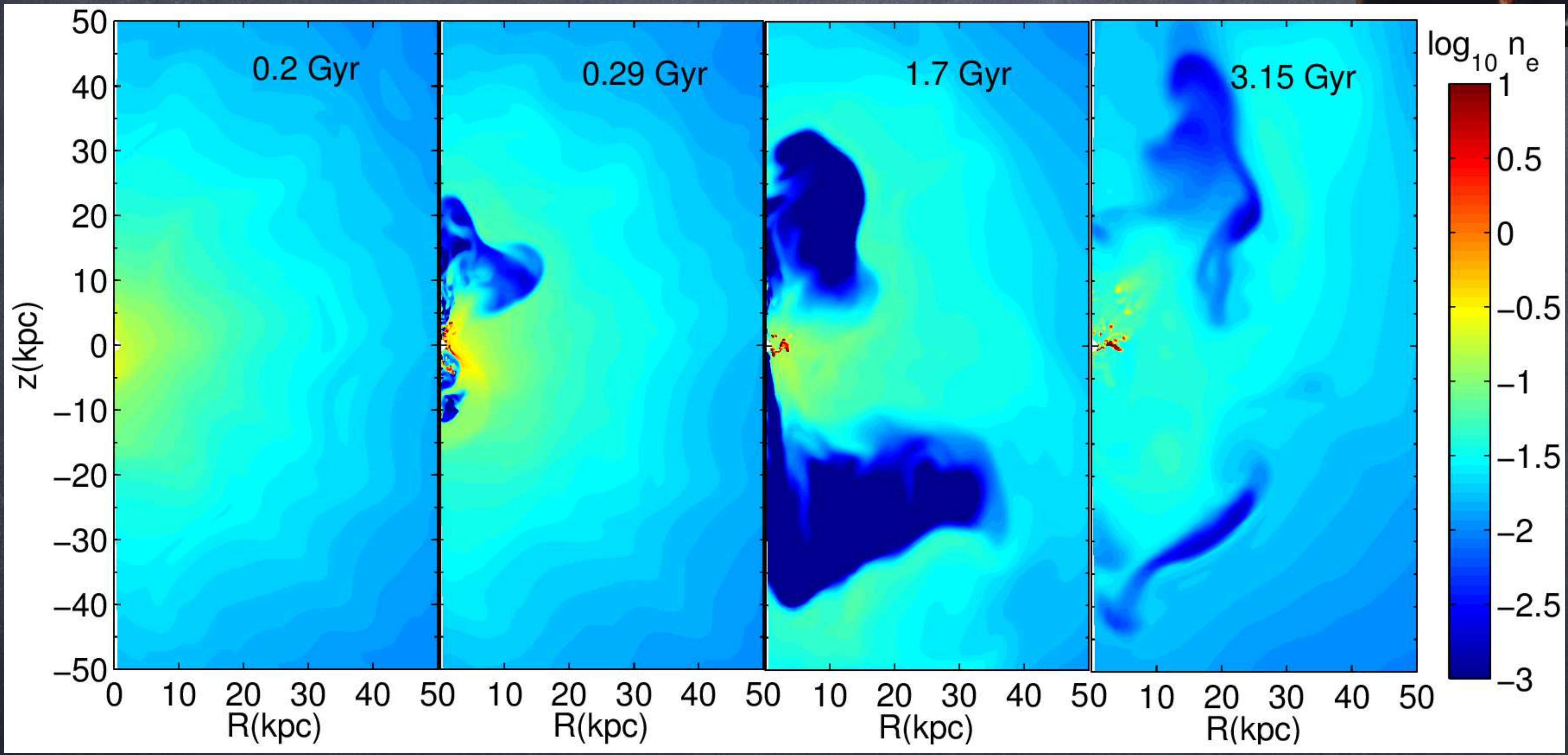
↓

cooling & AGN jet heating cycles in cool-core clusters

Simulated jets



[Prasad et al. 2015], more in Deovrat's talk on Saturday



Low density, high temperature (but in rough pressure balance) regions correspond to jets

Calculated jet power ~ core X-ray luminosity

Conclusions

- importance of BHs in galaxy formation
- setup/quasar vs maintenance/radio modes
- galaxy clusters: laboratory for radio mode
- jet-regulated thermal eqbn. & local thermal instability
- erratic cold accretion & cooling/heating cycles

Thank You!