Black Holes in Astrophysics

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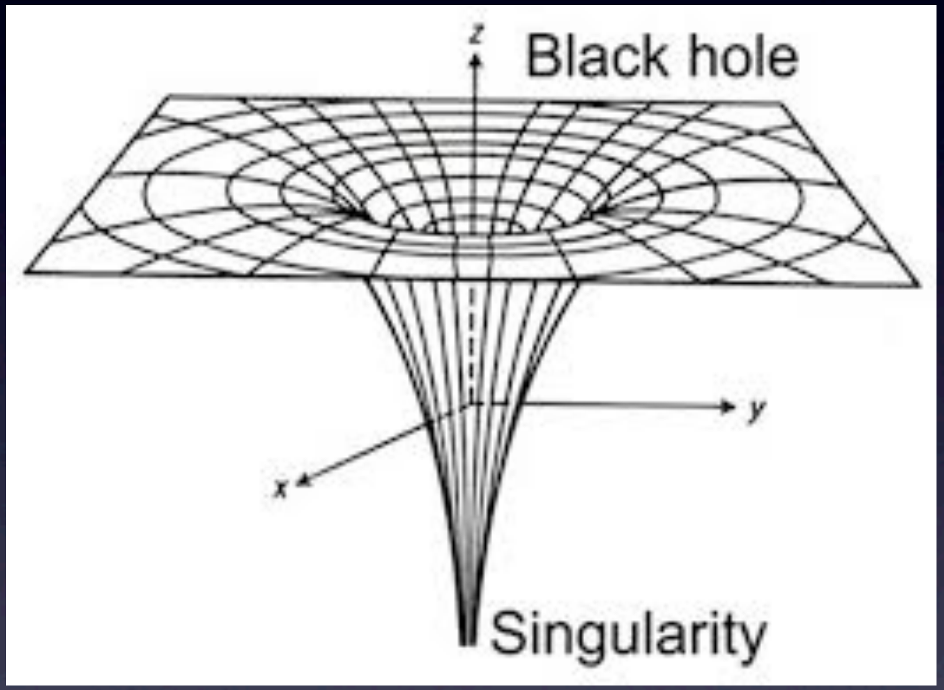
What's a BH?

an object so dense that even light cannot escape



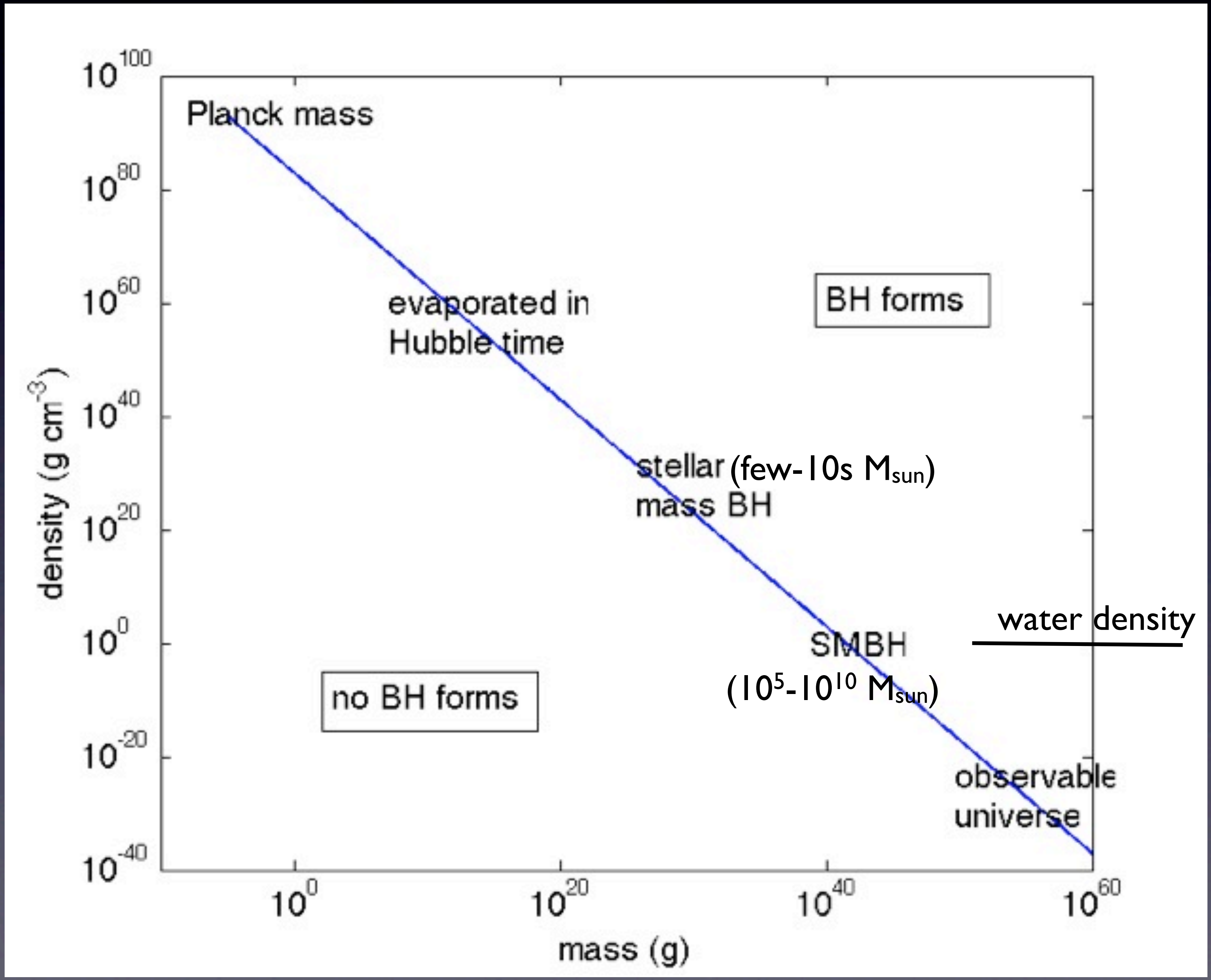
or, $R<2GM/c^2$ (Schwarzschild radius)

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

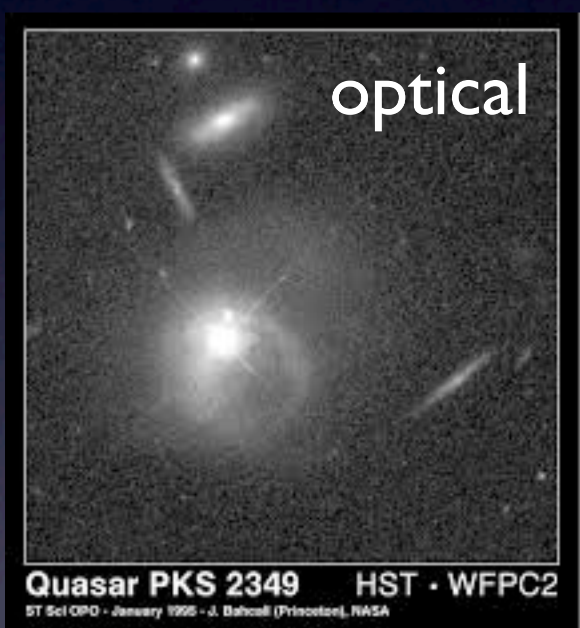
Different types



How can we ‘see’ BHs?

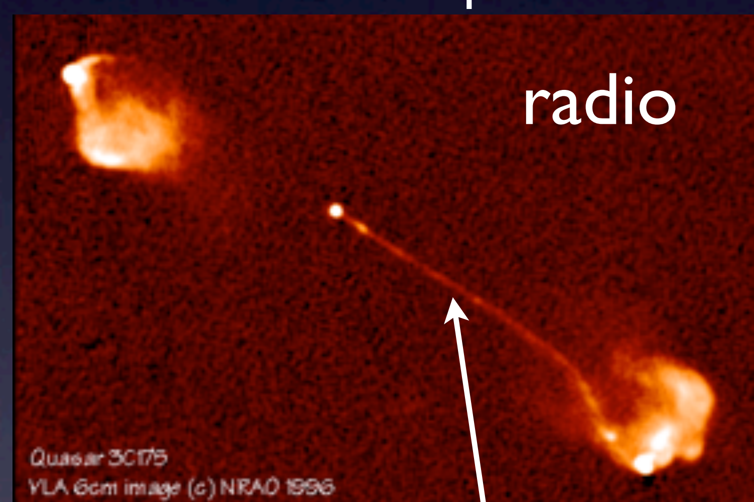
direct thermal (Hawking) radiation extremely faint: 10^{-22} $(M/M_{sun})^{-2}$ erg/s

-via emission of matter in extreme gravity of BHs

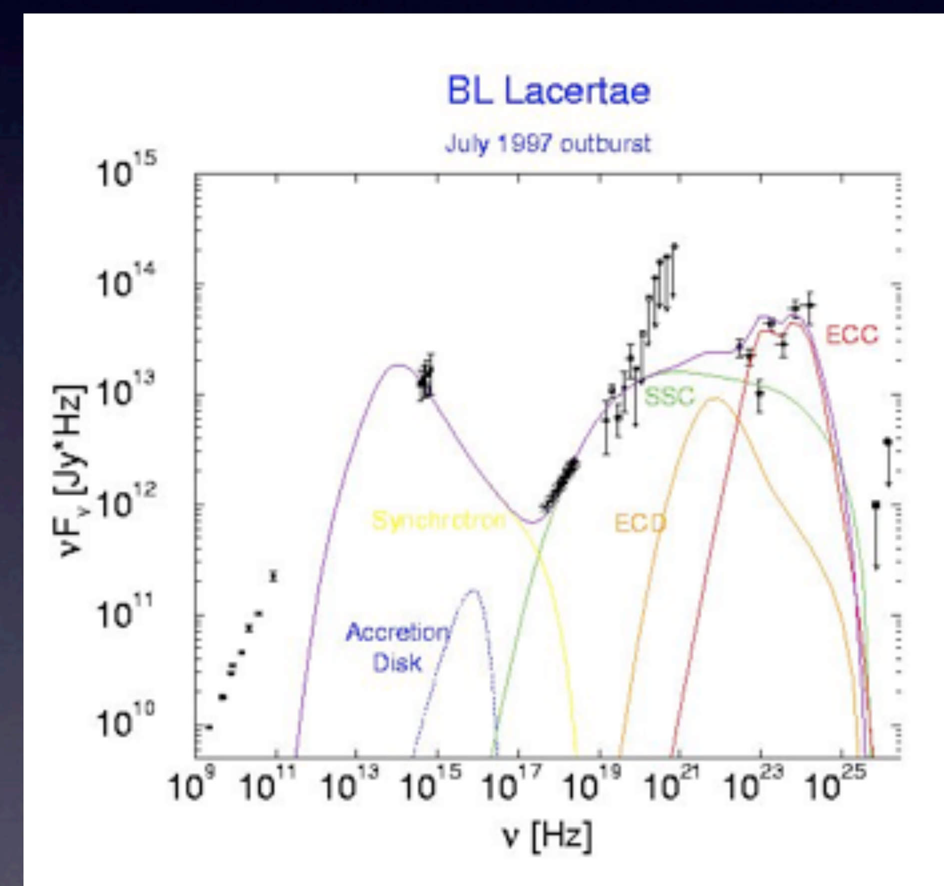


outshines host galaxy
10^{45} erg/s ($10^{11} L_{sun}$)
concentrated in 100 AU

~200 kpc



relativistic beaming
influences large scales!

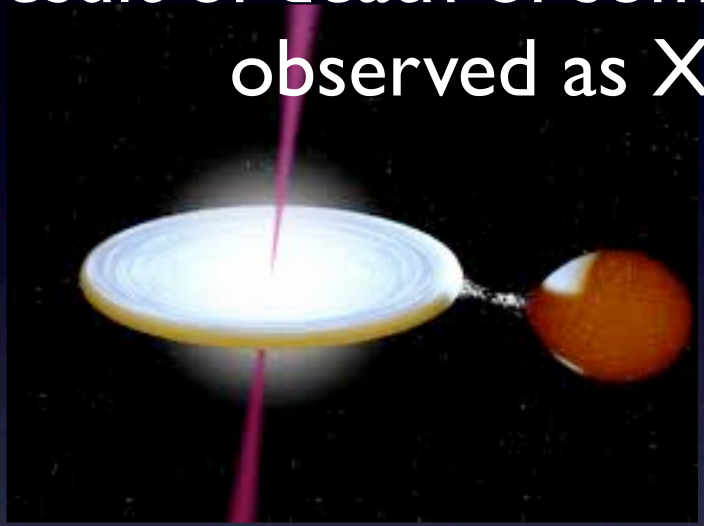


broadband emitters unlike stars
nonthermal radiation

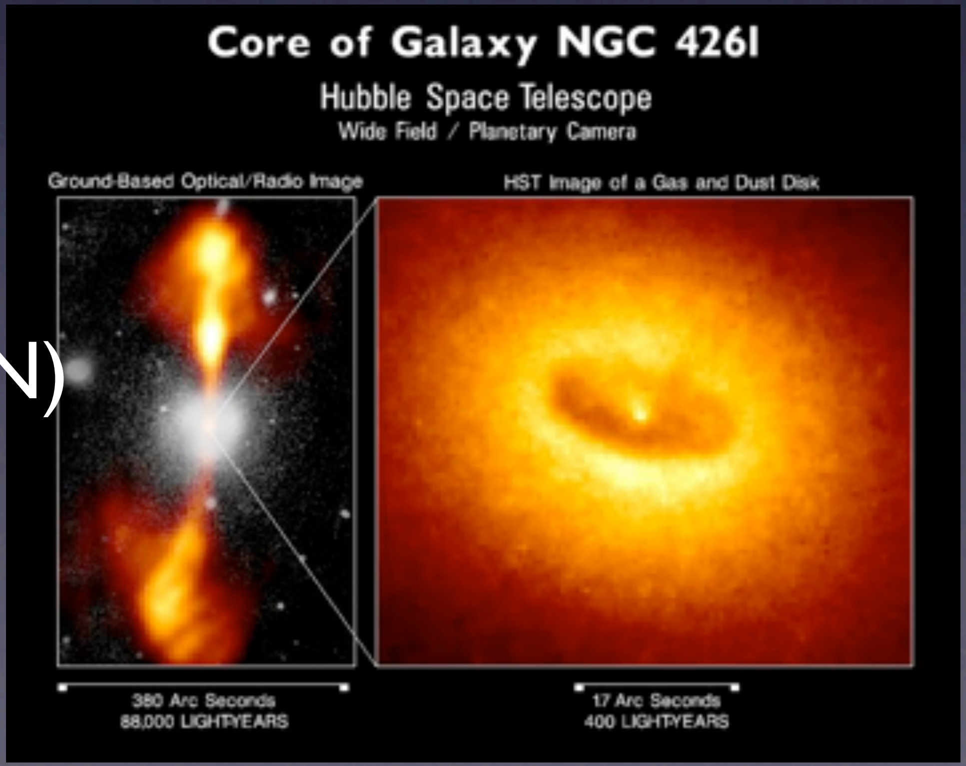
Astrophysical BHs

Stellar BHs: a result of death of some massive stars (10s of Msun)

observed as X-ray binaries - XRBs



Supermassive BHs (SMBH):



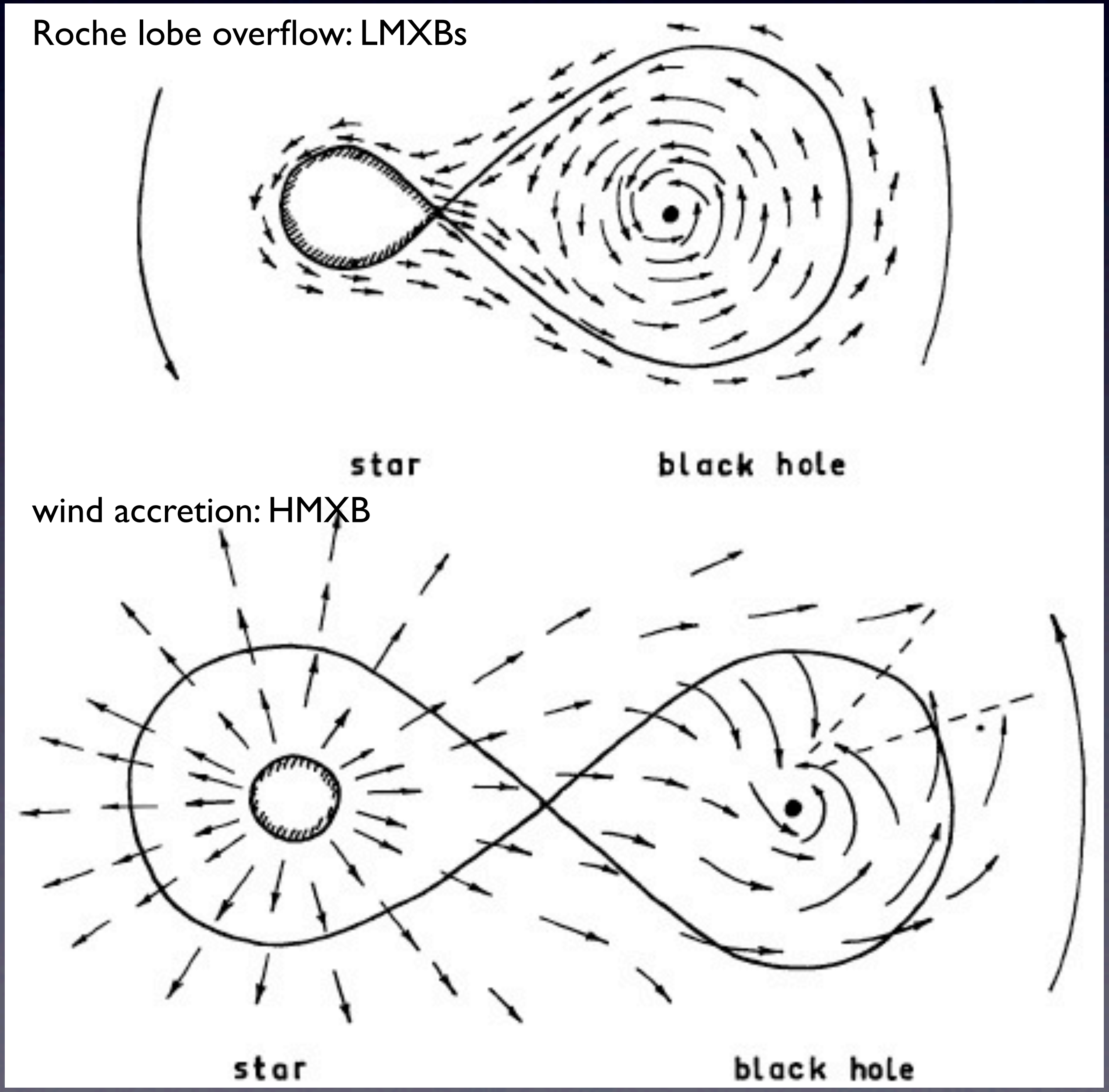
at centers of most galaxies

observed as quasars, Active Galactic Nuclei (AGN)

Accretion around BHs

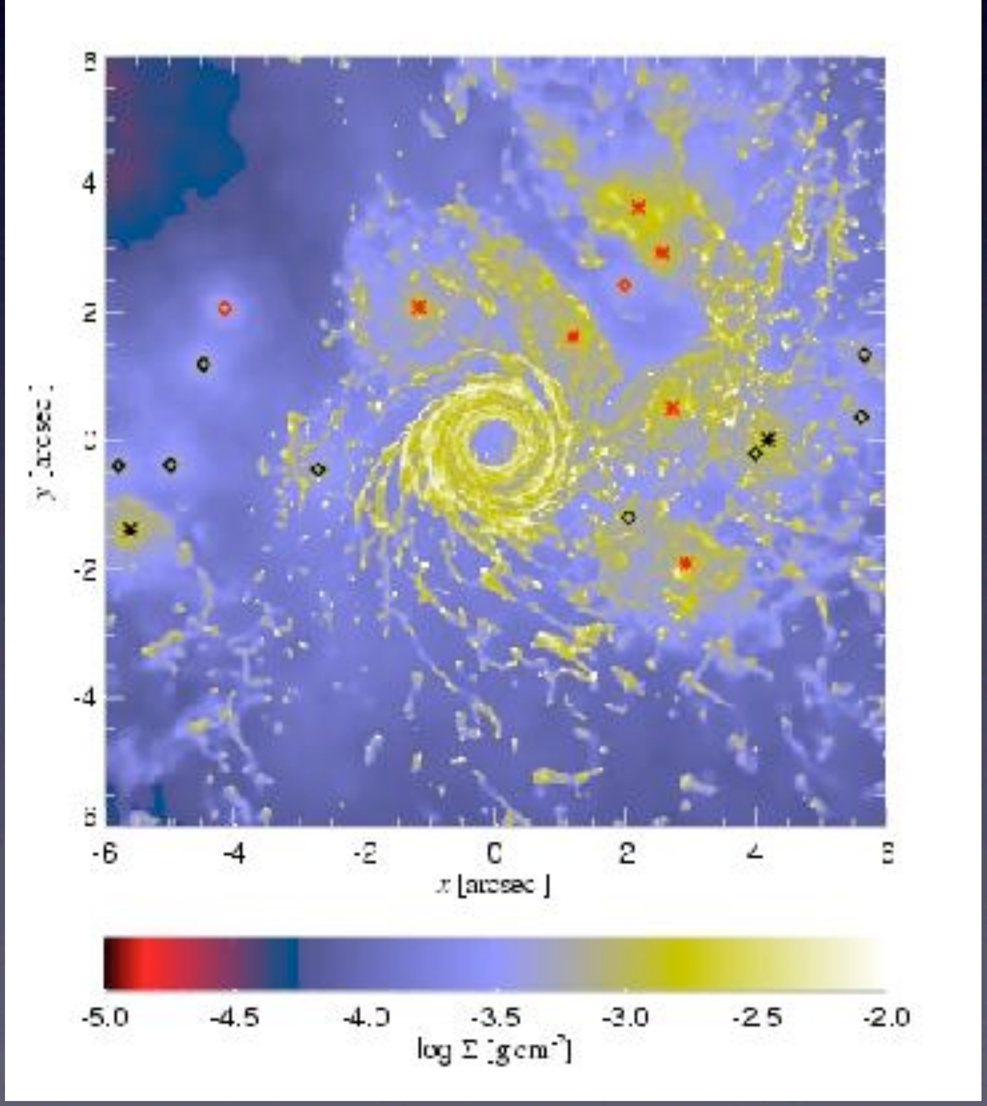
stellar BHs accrete from an evolved companion

[Shakura & Sunyaev 1973]

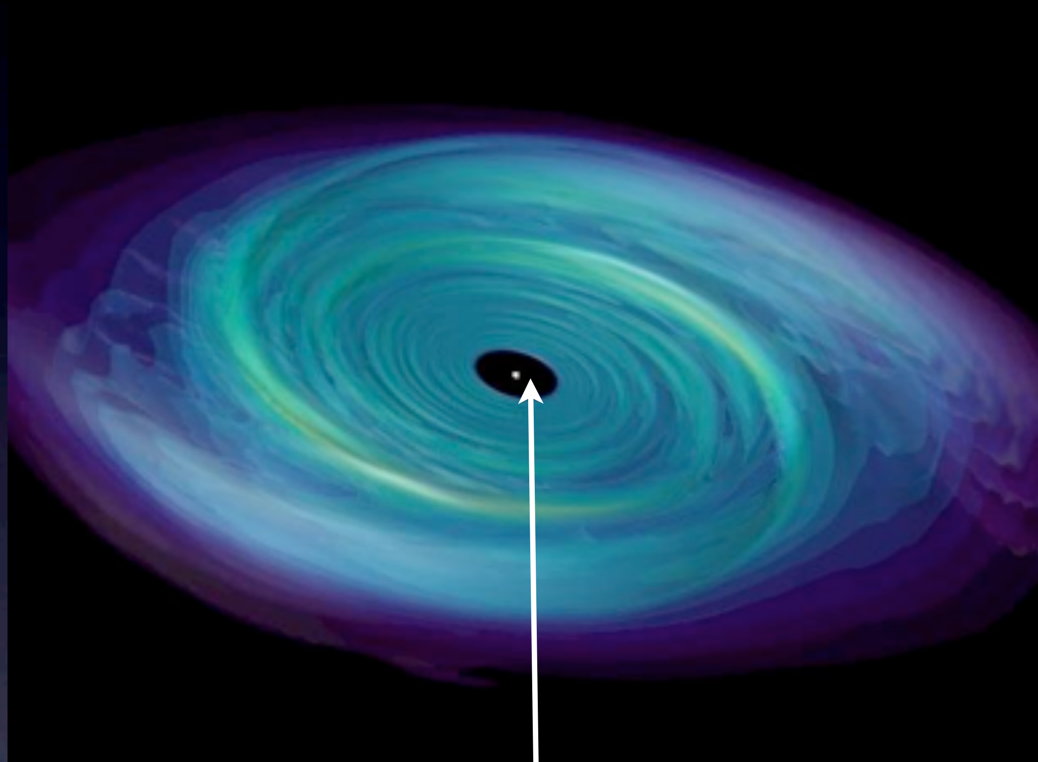


SMBHs accrete from surrounding medium

[Cuadra et al. 2005]



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!

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

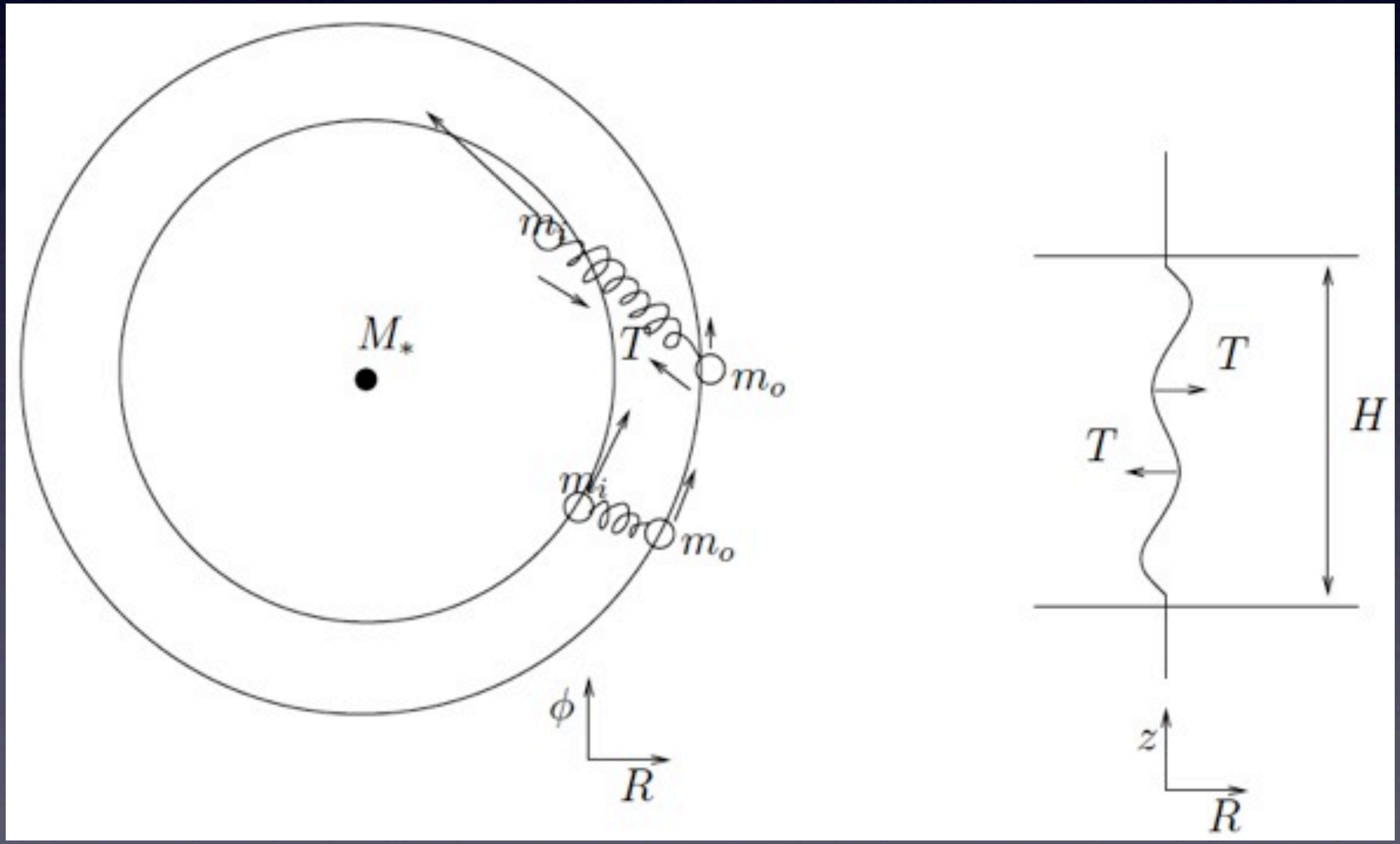
no radiation from within ISCO
no surface unlike WDs & NSs

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 $(GMR)^{1/2}$

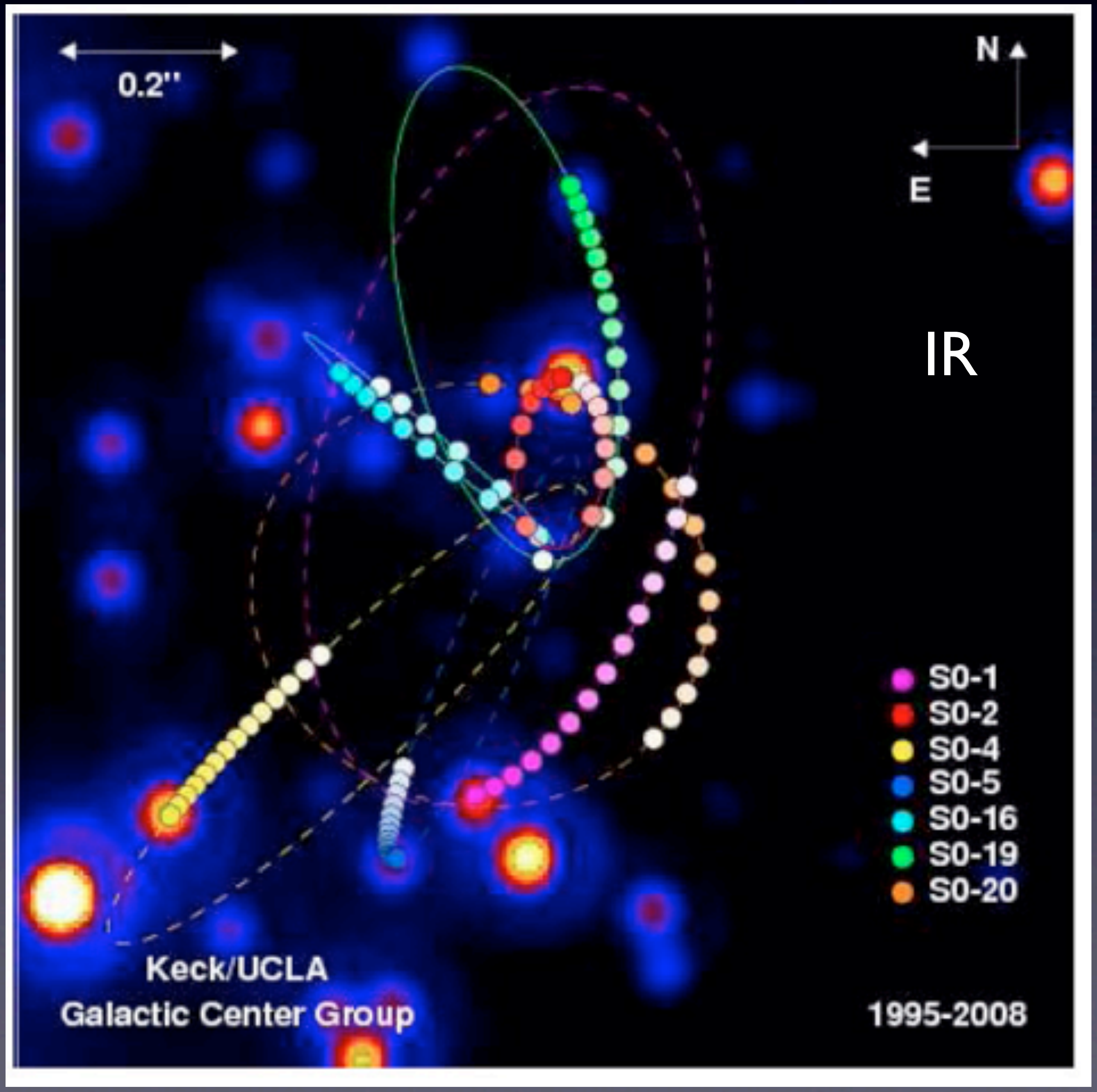
$$w^2 = \frac{k_z^2}{k^2}\kappa^2 \qquad \kappa^2 = \frac{2\Omega}{R}\frac{dl^2}{dR}$$

local axisymmetric MHD instability: MRI

works for ionized flows

Sgr A*: SMBH in MW

simple Keplerian orbits projected on the sky!



IR

$M_{BH} \sim 4x10^6$ M_{sun}

rather faint!

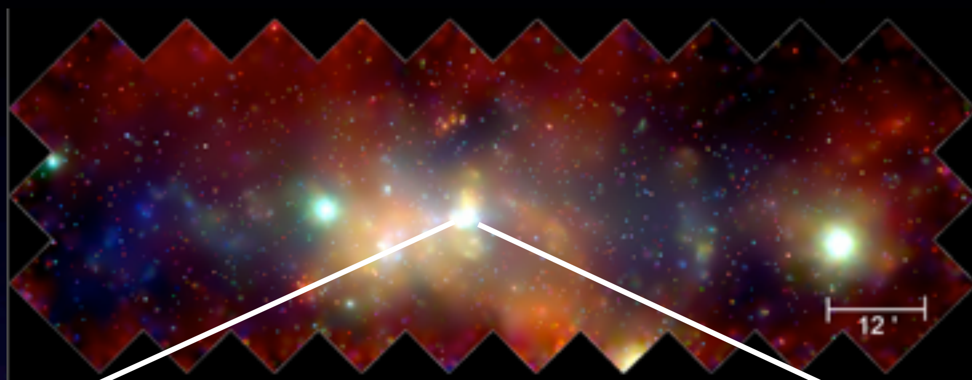
$L_{bol} \sim 100$ L_{sun}

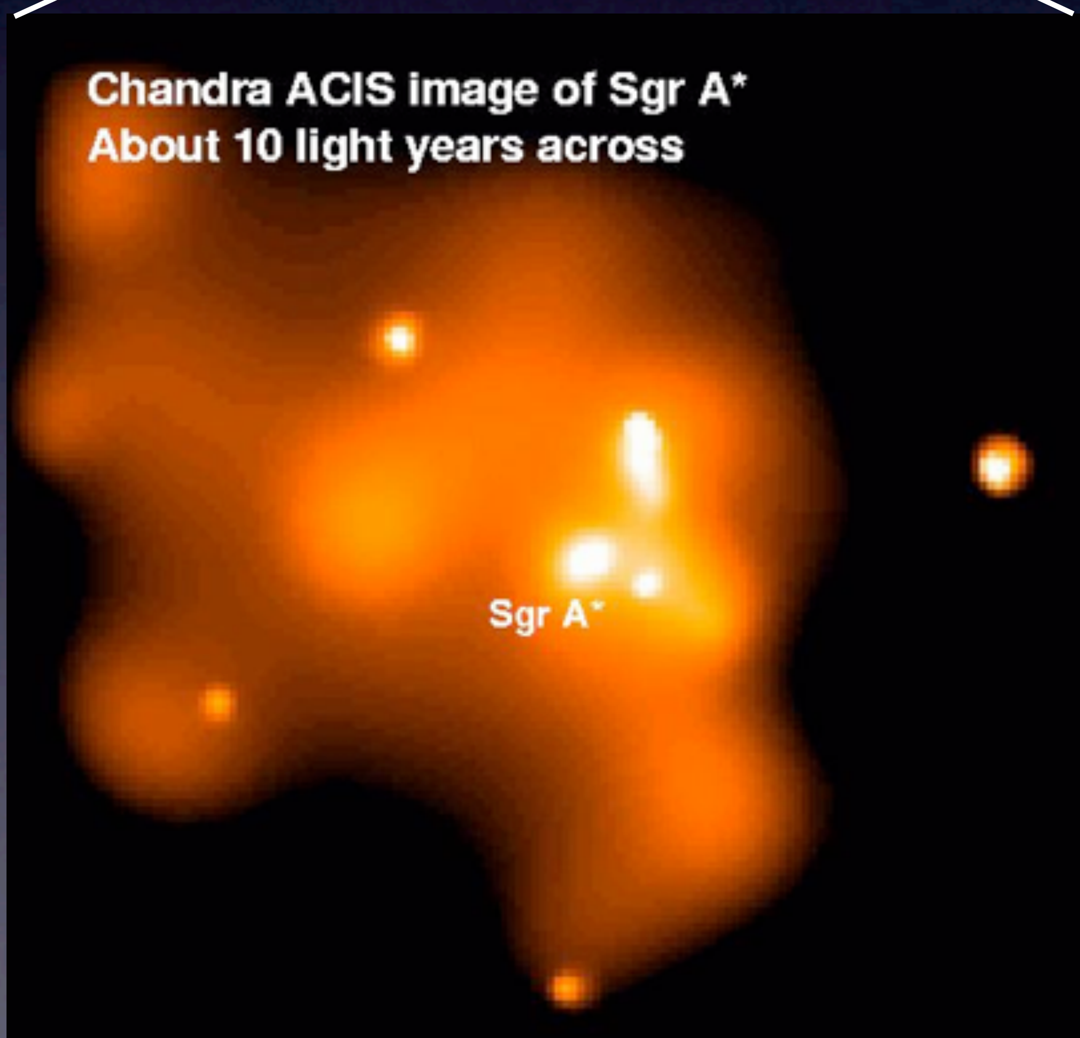
compare w. AGN: 10^{11} Lsun

technical breakthrough (AO) needed for resolving in crowded field

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

Sgr A*: SMBH in MW

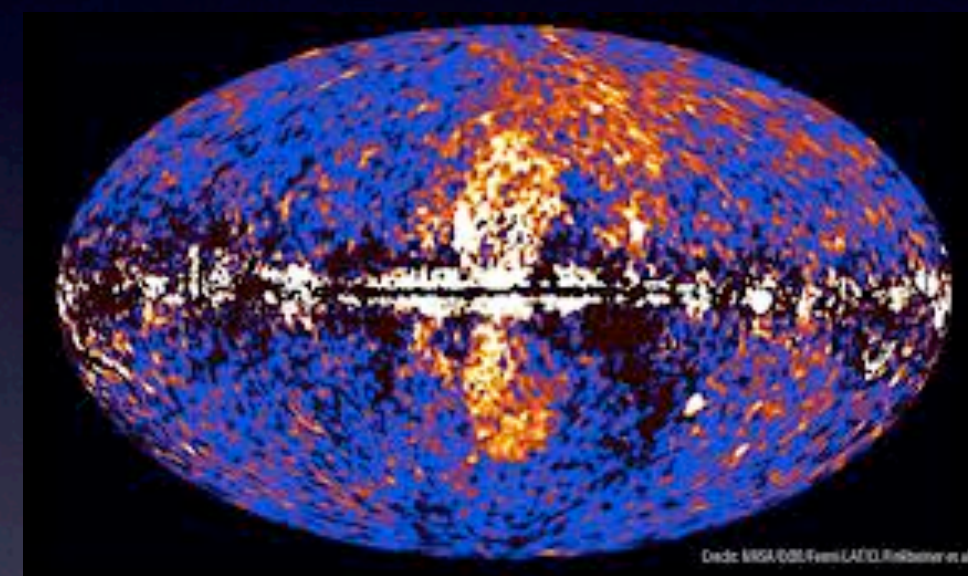




accretion variable on different timescales

X-ray flare, NuSTAR

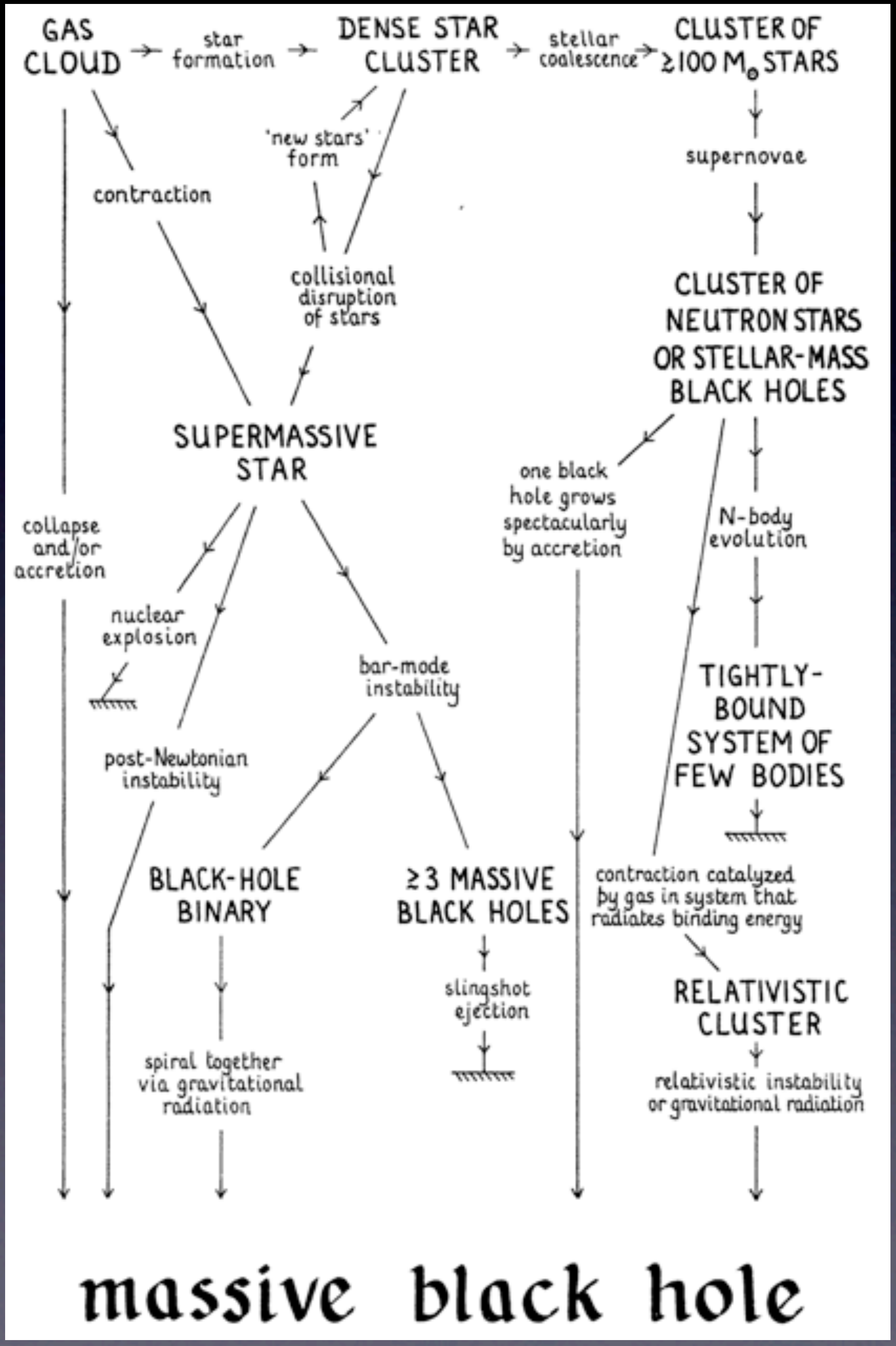
FERMI bubbles



higher activity over ~10 Myr ago?
prototype of AGN feedback over large scales
an AGN event?

X-ray echoes show ~10^4 times
larger L_X 100 years ago

Supermassive BHs



[Rees1984]

formation still not understood
various routes!

fast gas accretion required

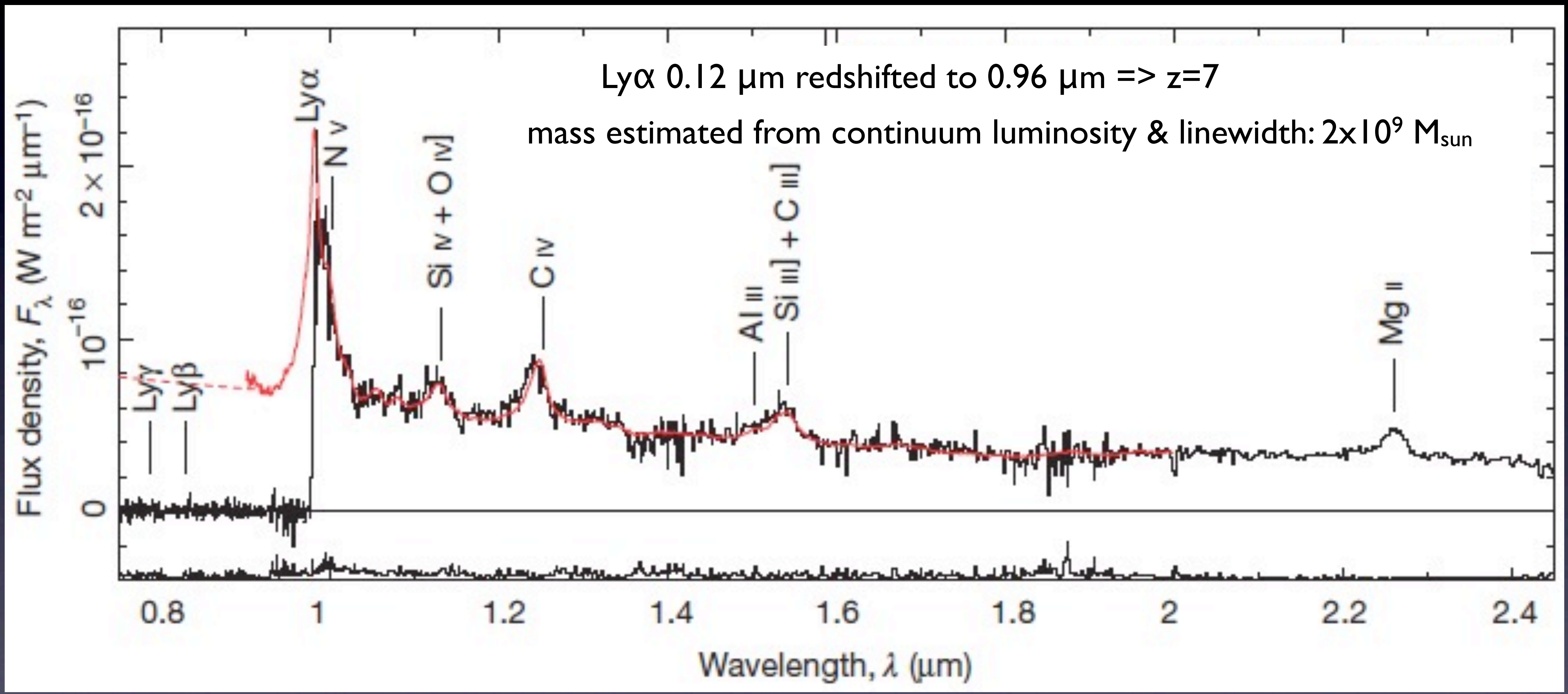
need massive seeds to explain
high redshift quasars (SMBHs)

~10^9 M_{sun} BHs already at z~7 (.77 Gyr after BB)!

$M=M_0 exp(t/0.04Gyr)$; Eddington limited accretion

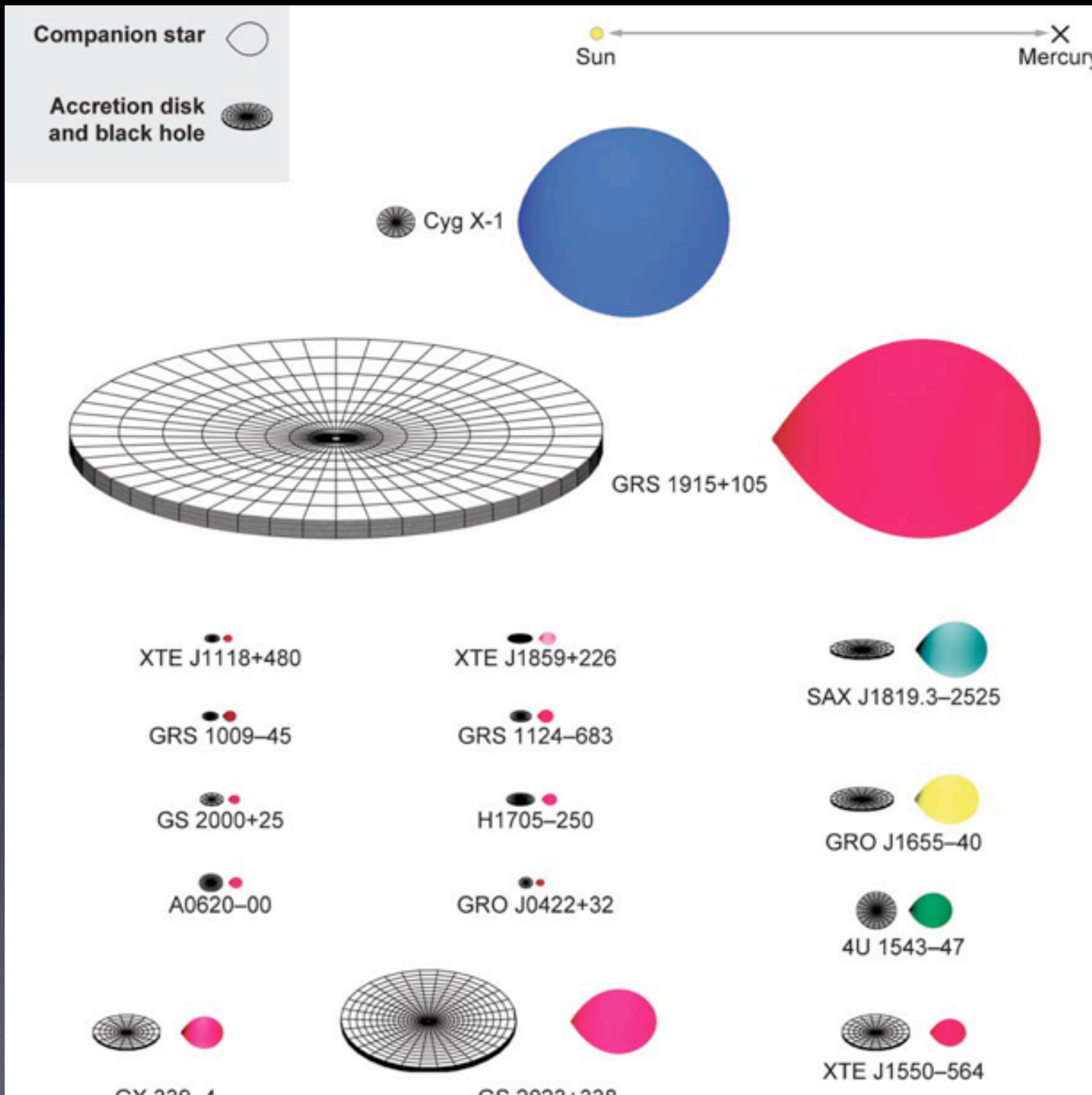
Example at z=7

[Mortlock et al. 2011]



Galactic BHXRBs

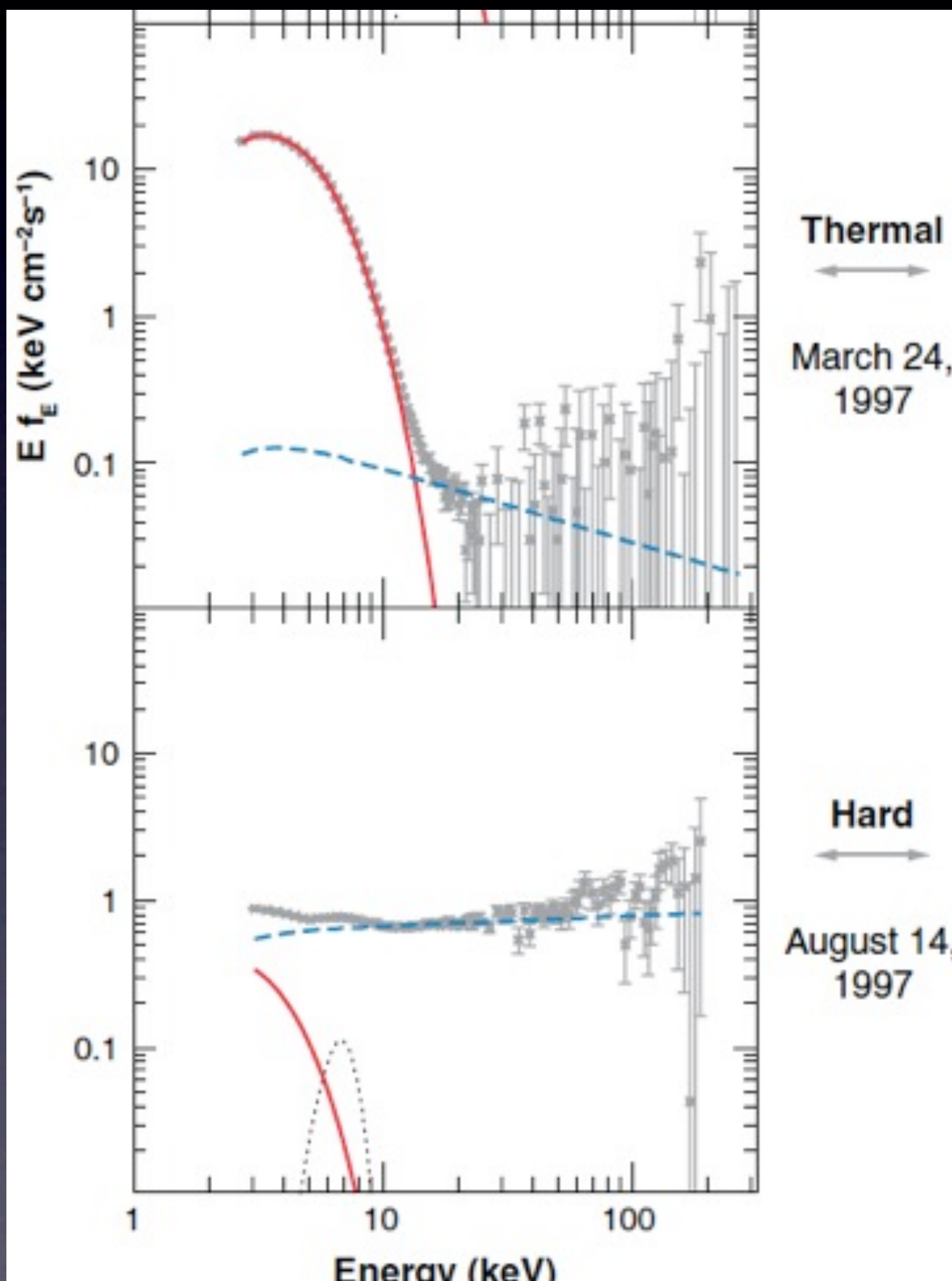
[Remillard & McClintock 2006]



mass>3Msun
from binary observations
can't have anything but a BH

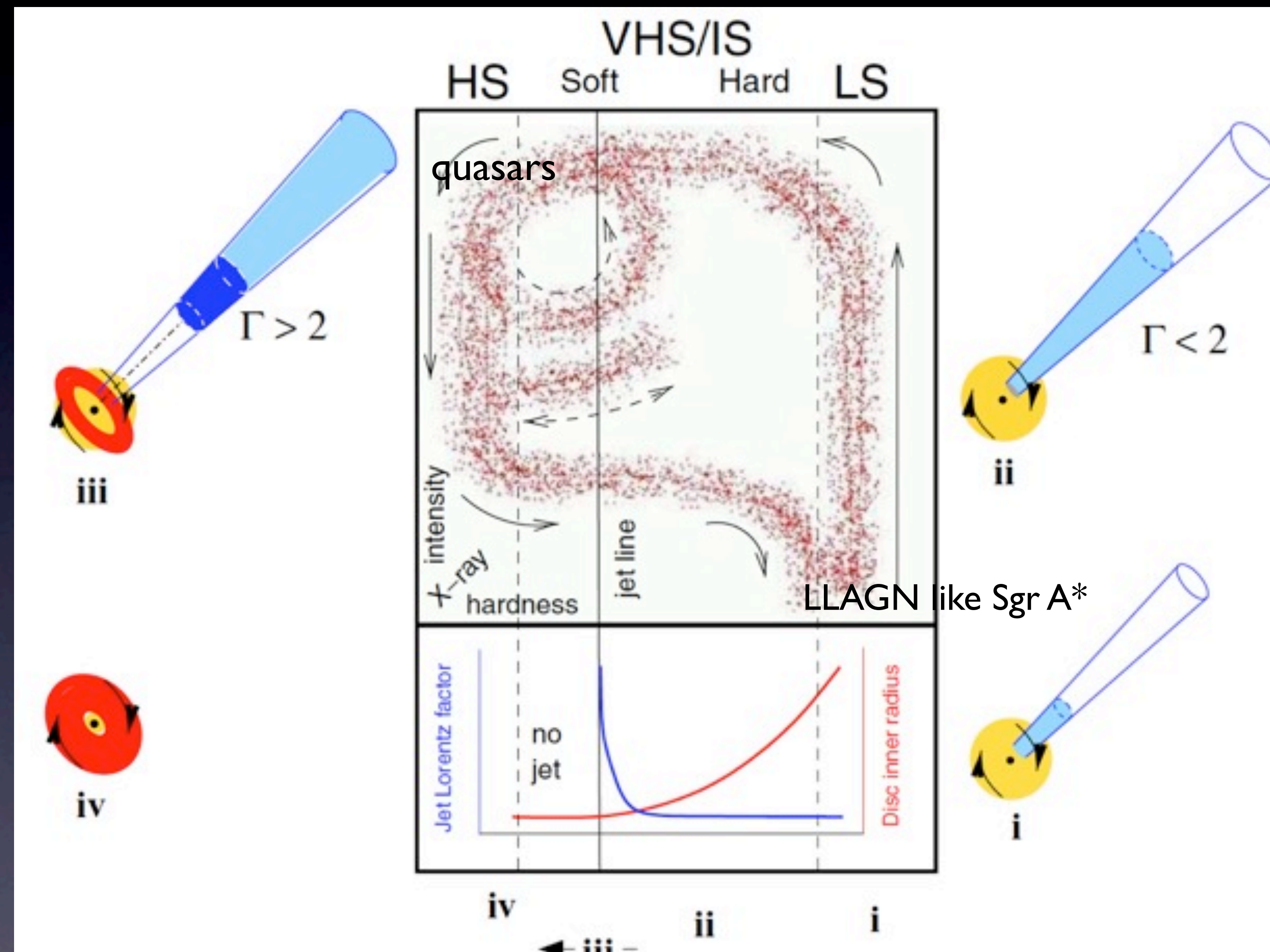
UNRESOLVED systems!

Spectral states & q-plot



rich phenomenology

[Fender et al. 2004]

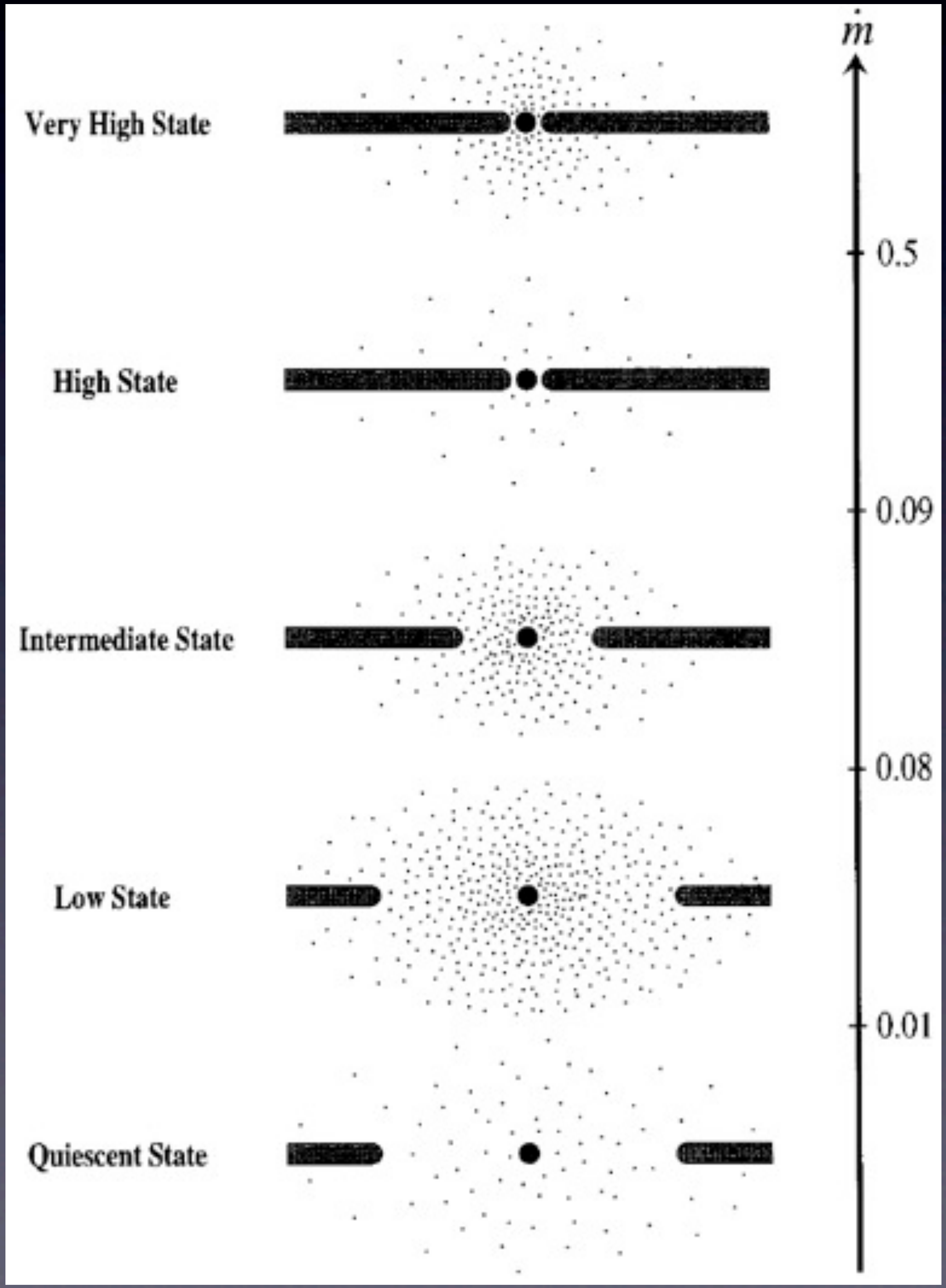


successful model should reproduce this qualitatively

prototypes for understanding AGN because timescales are humanly accessible; $t \propto M_{BH}$ ~ months

Physical picture

[Esin et al. 1997]



quasars
w. BB component require
efficient cooling & dense,
optically thick, geom. thin disk
absence of radio jets

accretion flow thermodynamics
(heating,cooling) essential

radio jets
hard spectrum

subdominant BB;
hot/coronal plasma
needed for hard spectrum

Sgr A* is way down!

Numerical Sims.

$$\frac{d\rho}{dt} + \rho \nabla \cdot \mathbf{v} = 0,$$

Euler's eqs. w. viscosity
& ff cooling

$$\rho \frac{d\mathbf{v}}{dt} = -\nabla P - \rho \nabla \phi + \nabla \cdot \boldsymbol{\sigma},$$

$$\rho \frac{d(e/\rho)}{dt} = -P \nabla \cdot \mathbf{v} + \boldsymbol{\sigma}^2/\mu - n_e n_i \Lambda(T).$$

$$\phi = -\frac{GM}{r - R_g}$$

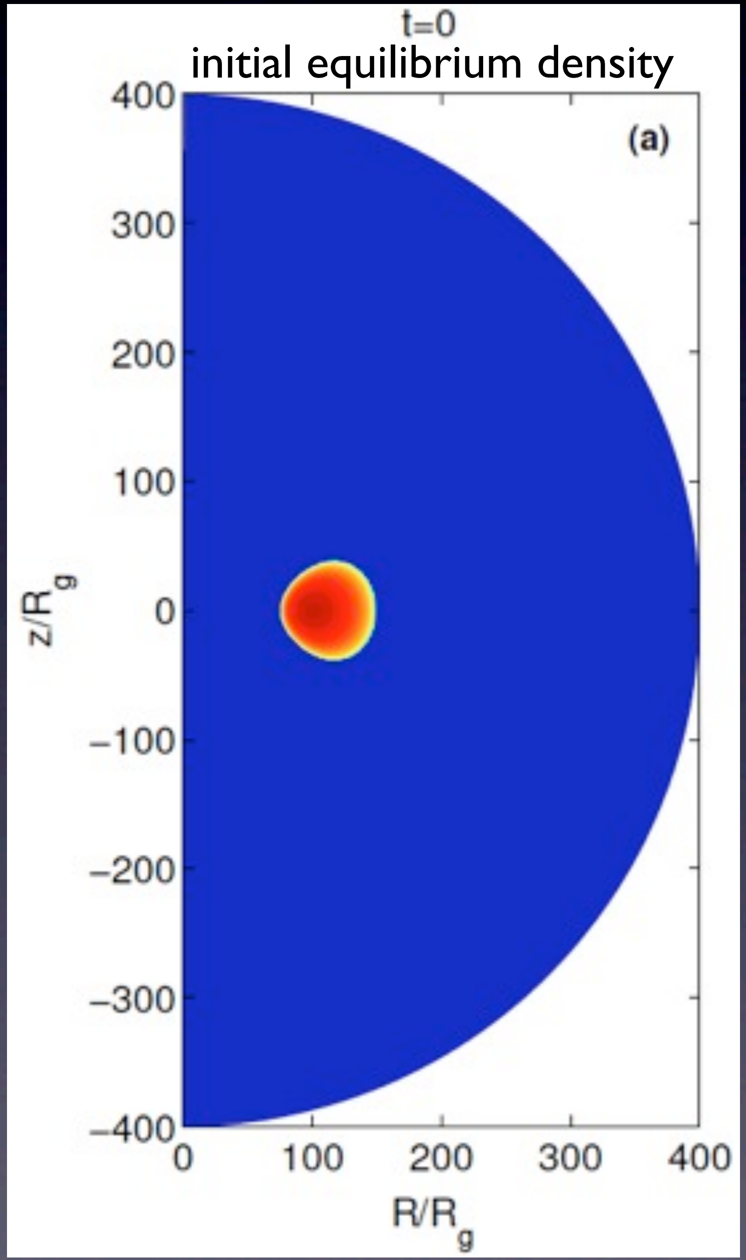
pseudo-Newtonian
potential

$$\sigma_{r\phi} = \sigma_{\phi r} = \mu r \frac{\partial}{\partial r}\left(\frac{v_\phi}{r}\right)$$

viscous stress responsible
for accretion in hydro

caveats: actual transport is MHD; idealized
cooling; 2D; no radiation transport

2D sims. *[Das & Sharma 2013]*



vary torus density to change Mdot
eqs. scale simply with M, Mdot

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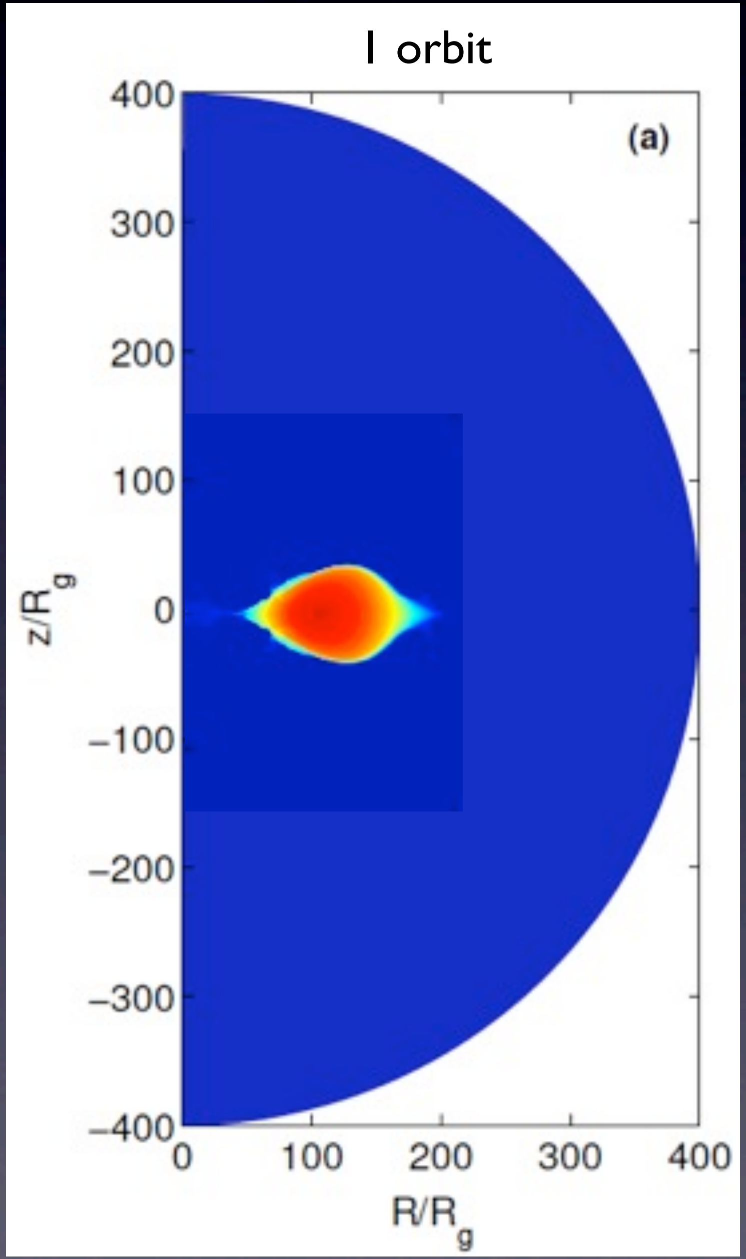

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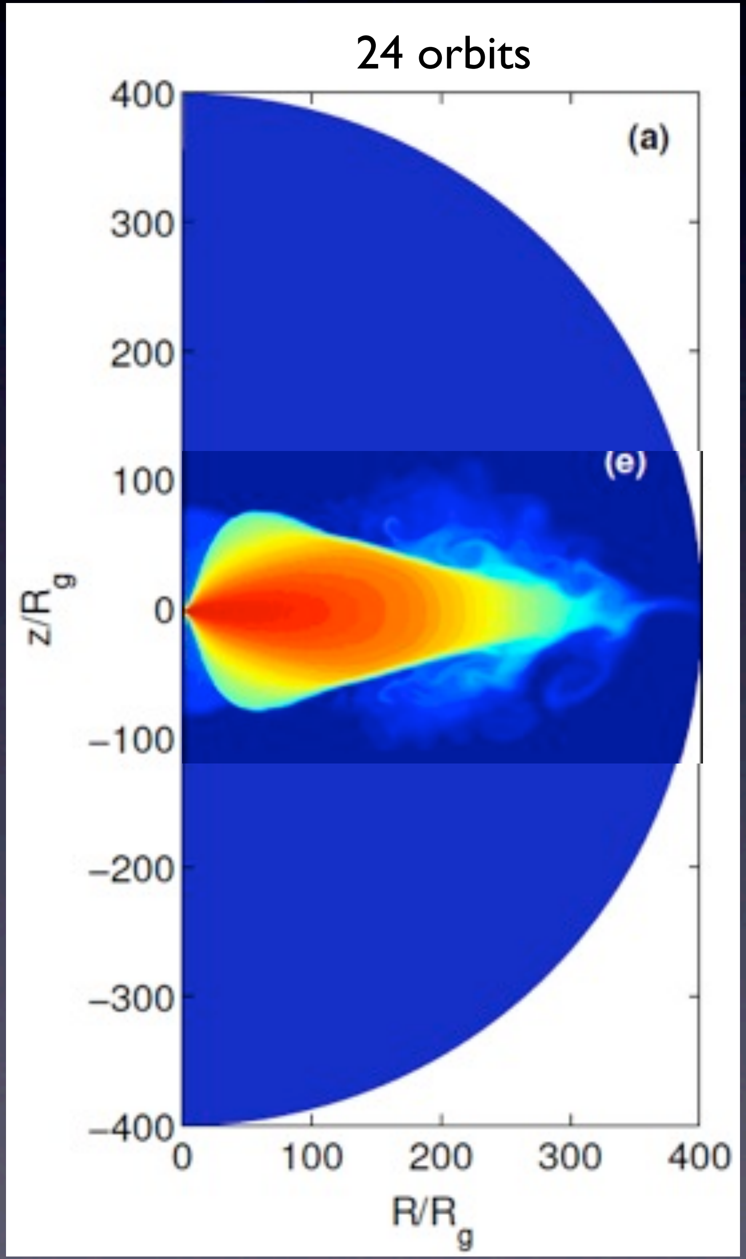

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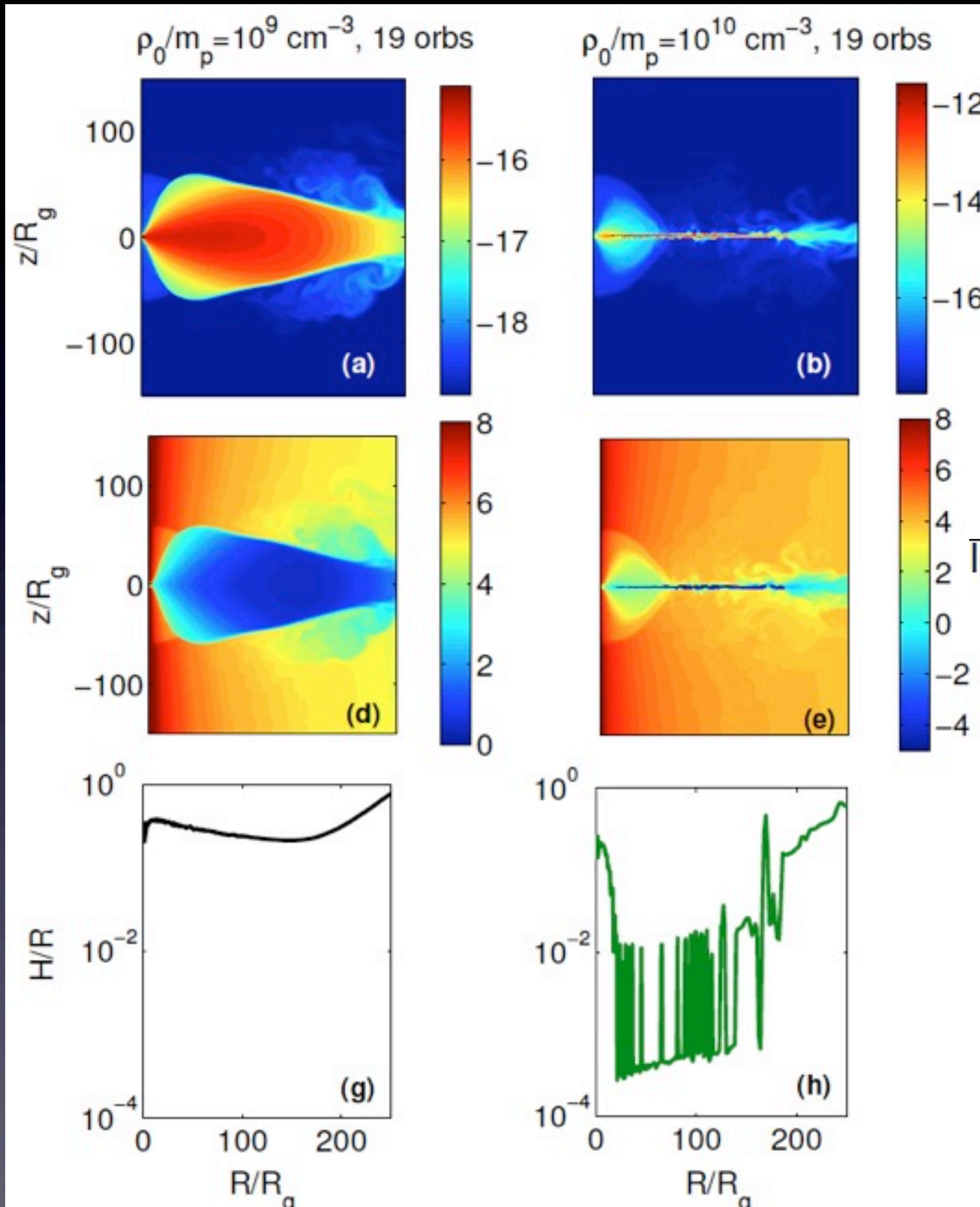


evolution unaffected by cooling if $t_{cool} > t_{visc}$; i.e., if matter accretes before cooling

$t_{cool} \sim nkT/n^2\Lambda(T)$; $t_{visc} \sim r^2/\upsilon$

$\upsilon=\alpha c_s H$; ‘eddy viscosity’

$t_{cool} \propto T^{1/2}/n \propto r^{0-1}$; $t_{visc} \propto 1/(\alpha\Omega) \propto r^{3/2}$

cooling dominates at large radii
=> inner hot flow + outer thin disk

$\dot{M}/\dot{M}_{Edd}$

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

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

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

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

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

$10^9\ M_{sun}$ becomes quasar for $M_{dot}>0.01\ M_{sun}/yr$ and a
10 Msun BH in soft state for Mdot>$10^{-9}\ M_{sun}/yr$

broadly consistent with observations!

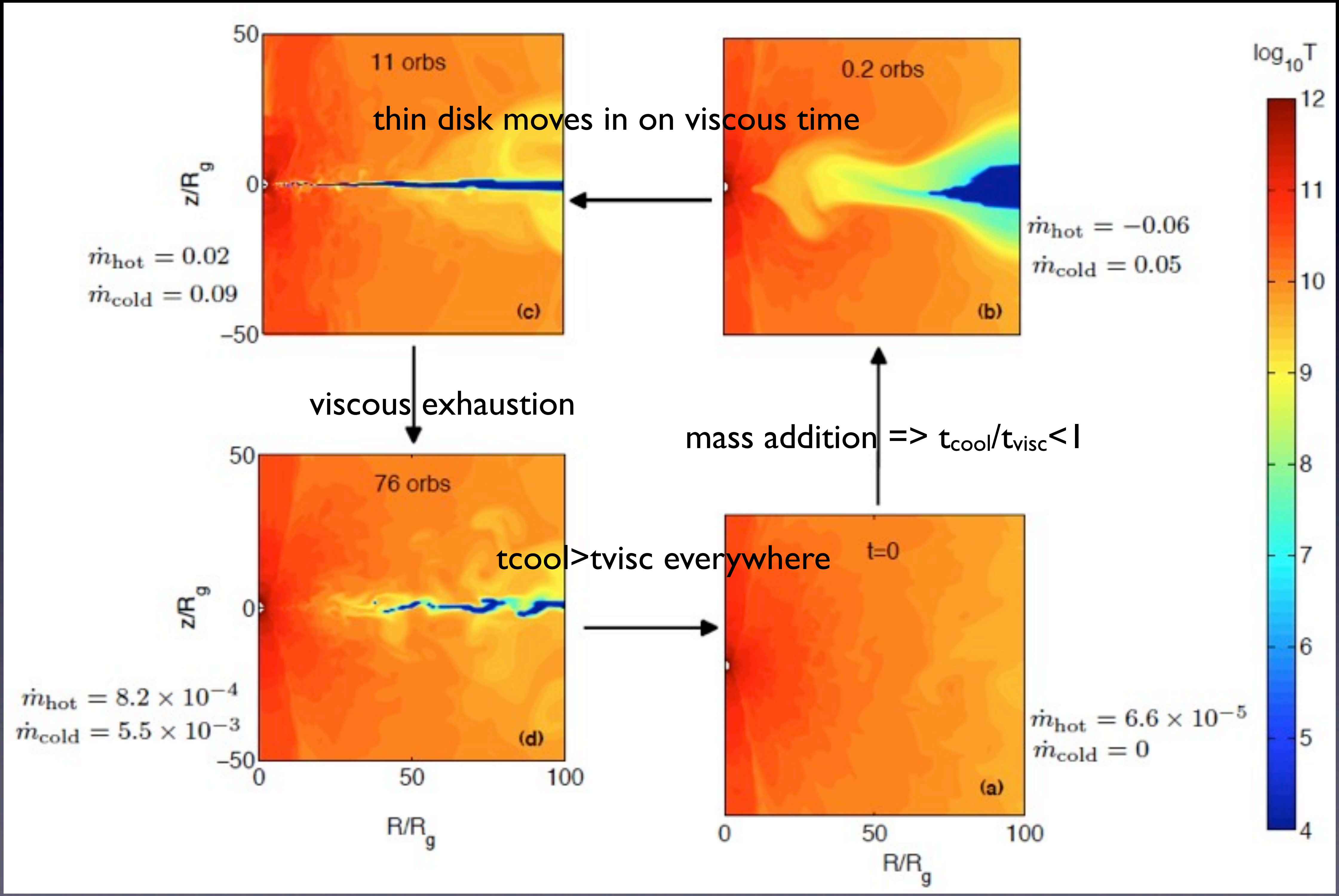
BH transients

quite natural

what causes M_{dot} variation?

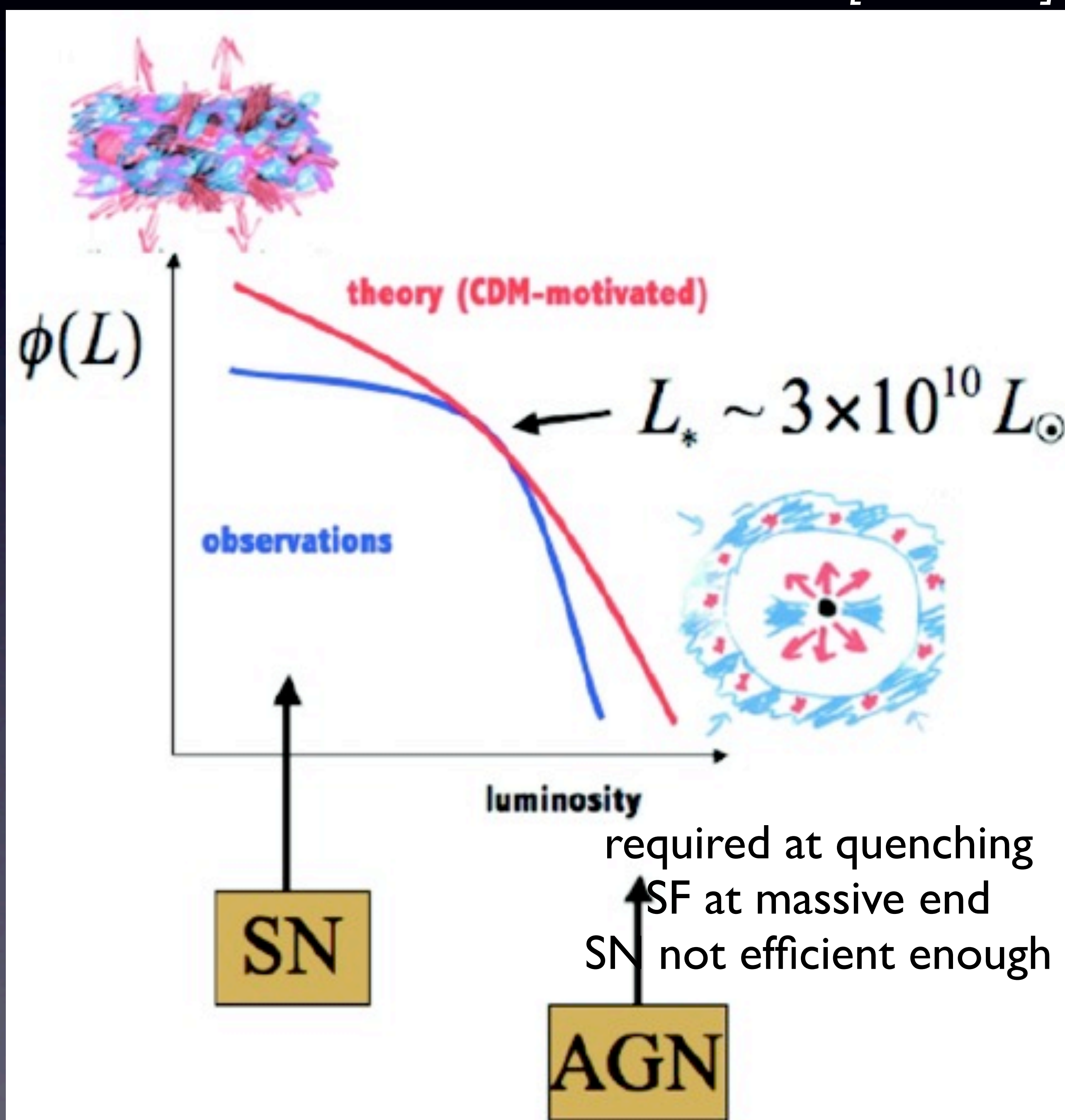
variable wind, H ionization instability, turbulence

timescales depend on r_{circ}



BHs & galaxy formation

[Silk 2011]



structure in the universe grows via mergers

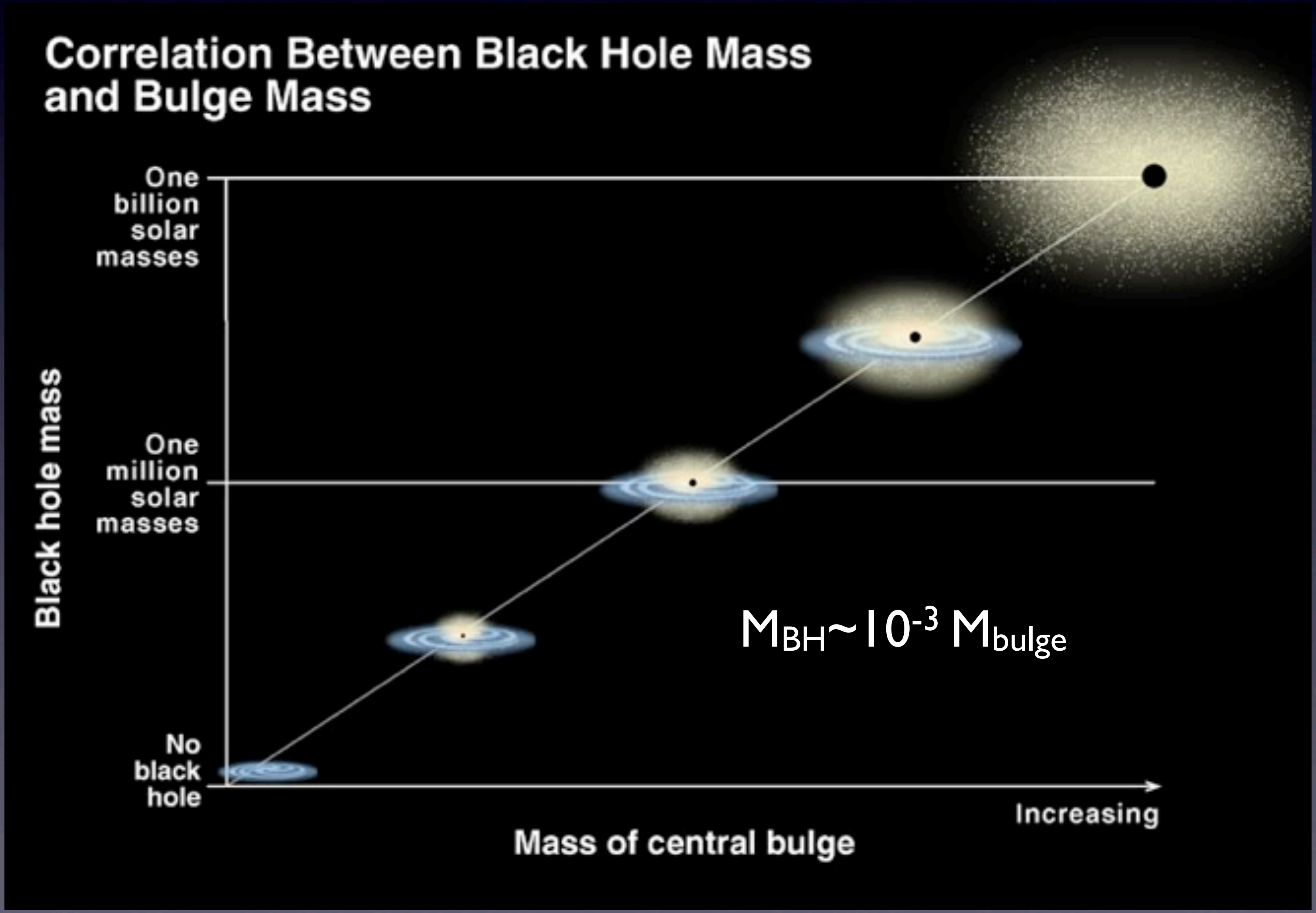
gravity acting on DM leads to LSS

DM only interacts gravitationally

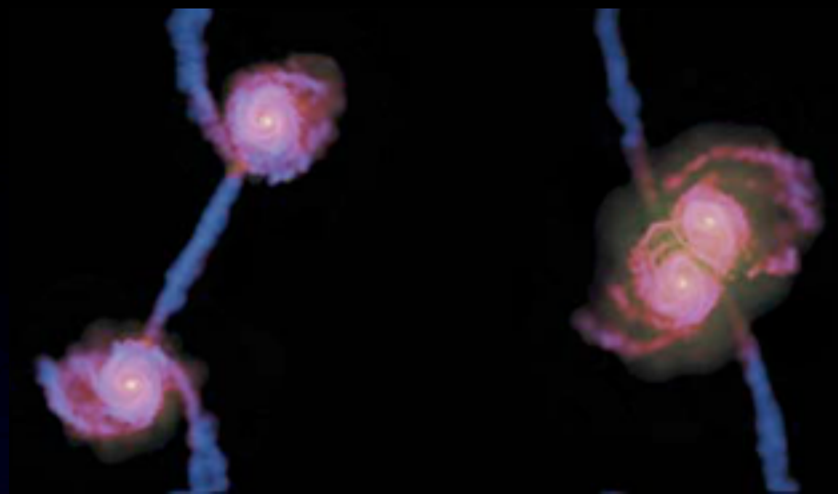
BUT
baryons undergo complex processes
heating and cooling

BH-bulge correlations

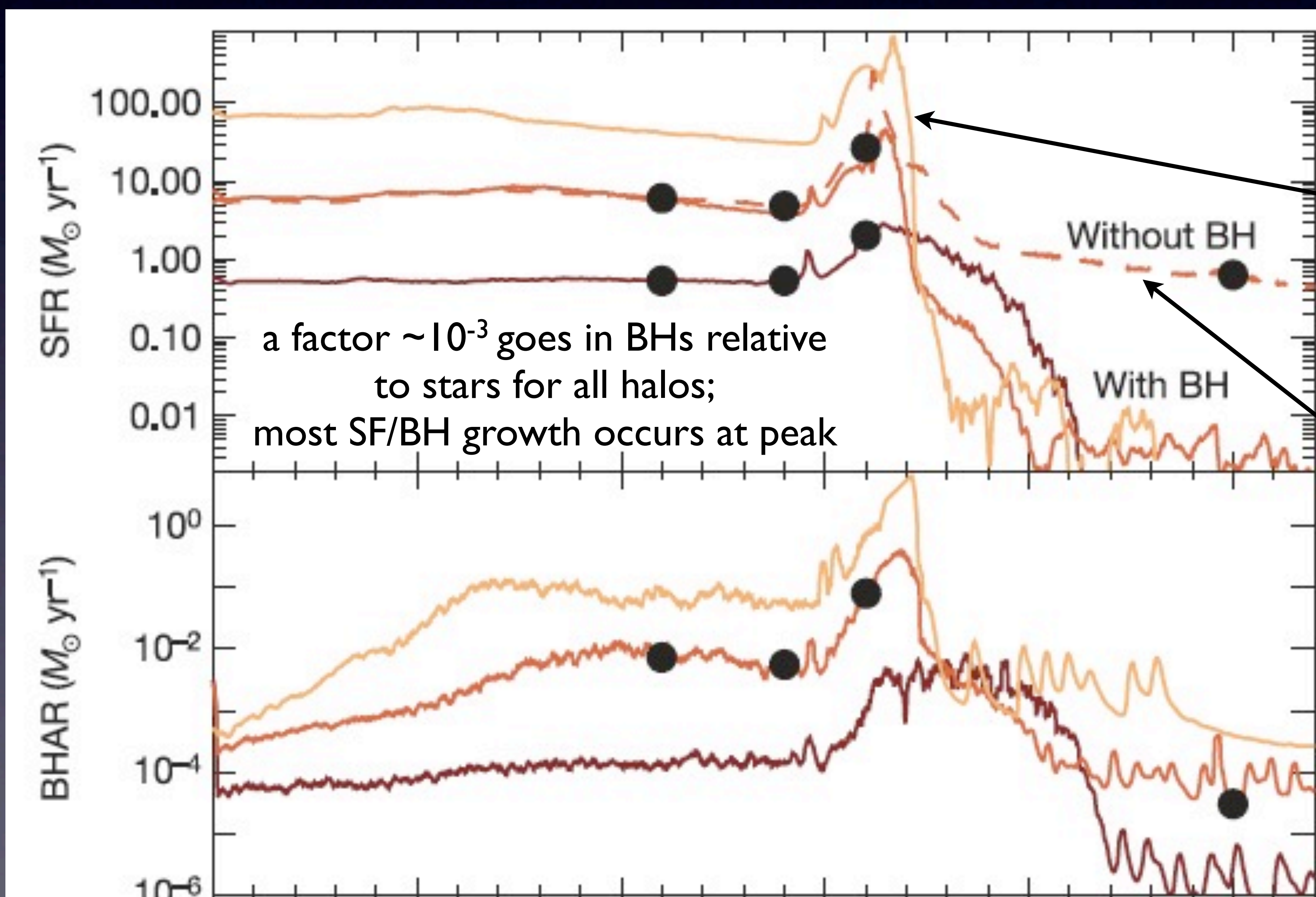
bulge >> BH sphere of influence & yet is correlated w. BH
=> BH affects star-formation in bulge



BHs affects galaxy formation at large scales!



[Di Matteo et al. 2005]



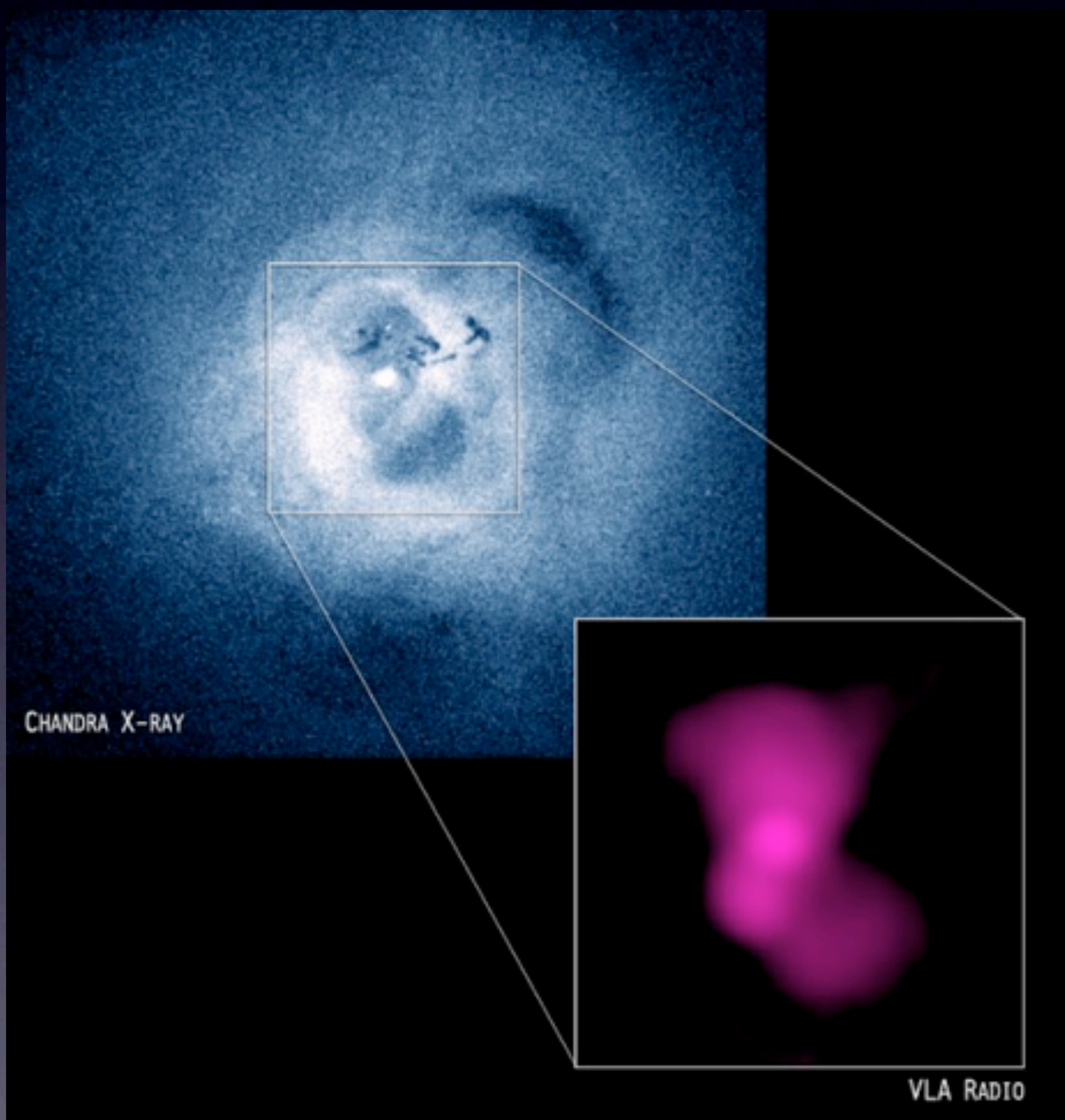
quasar feedback quenches SF & BH growth, producing massive ellipticals here growth is triggered by merger

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

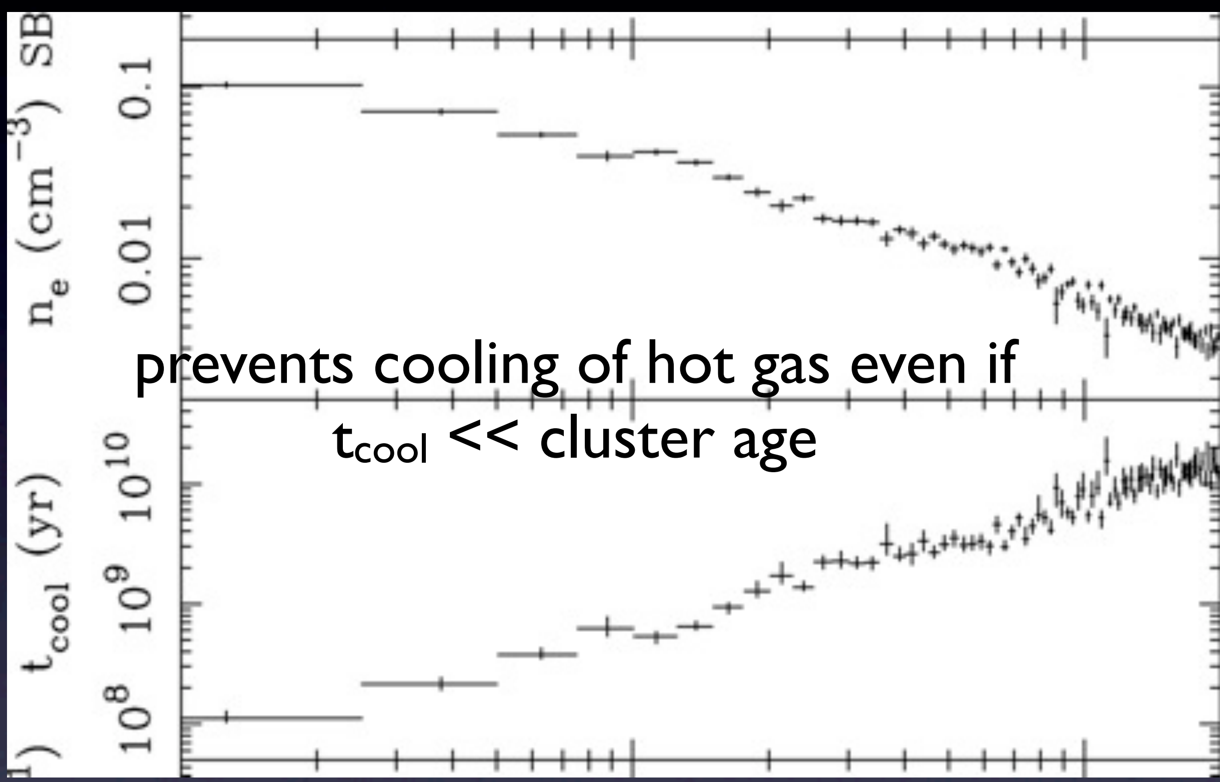
time from 0 to 2.5 Gyr

Kinetic FB

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



[Johnstone et al. 2002]



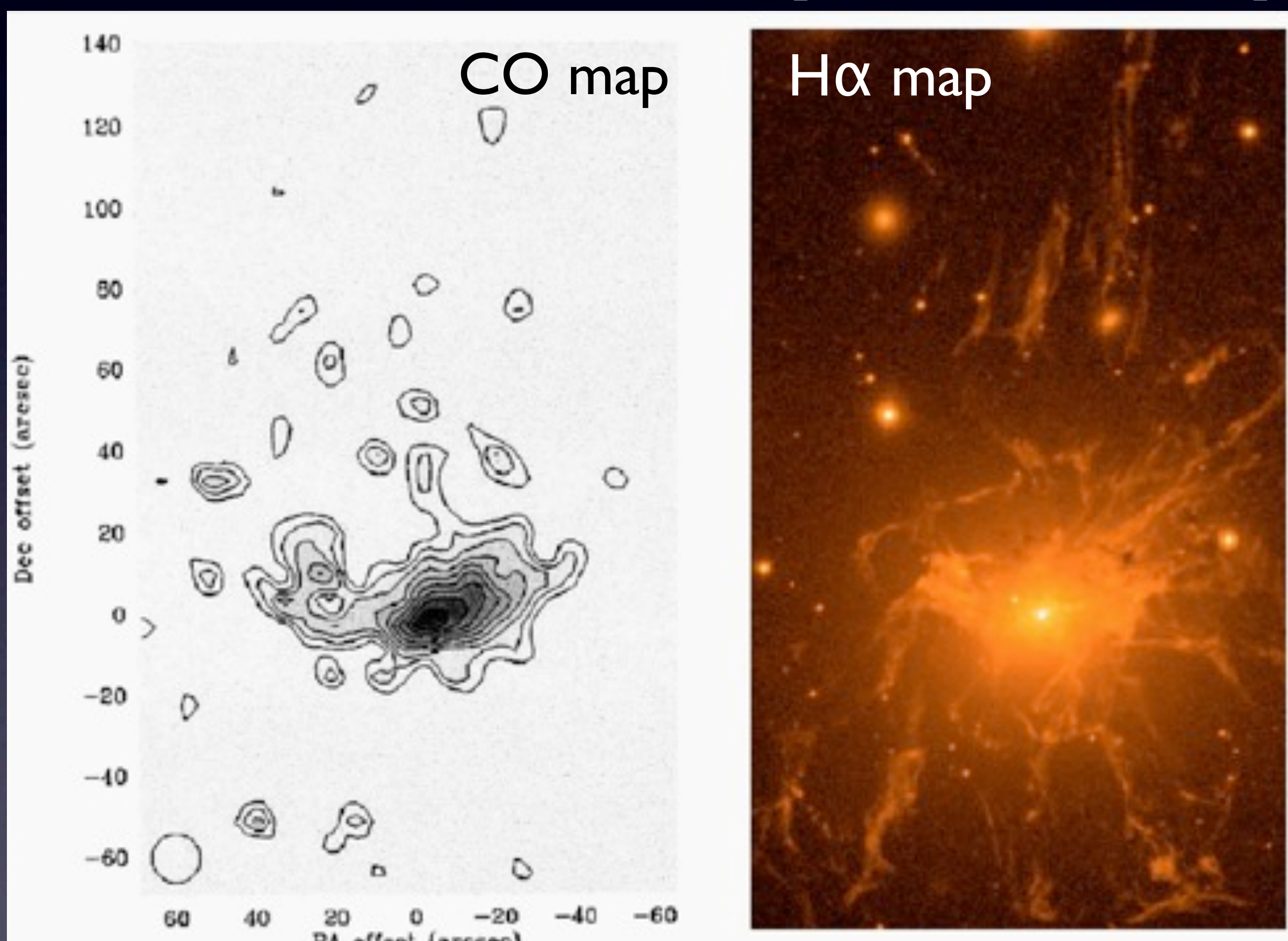
prevents cooling of hot gas even if
$t_{cool} \ll$ cluster age

1kpc 200kpc

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

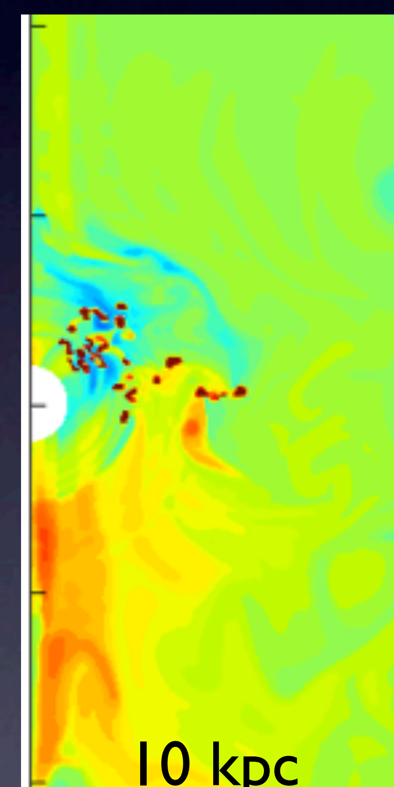
TI & multiphase gas

[Salome et al 2006]

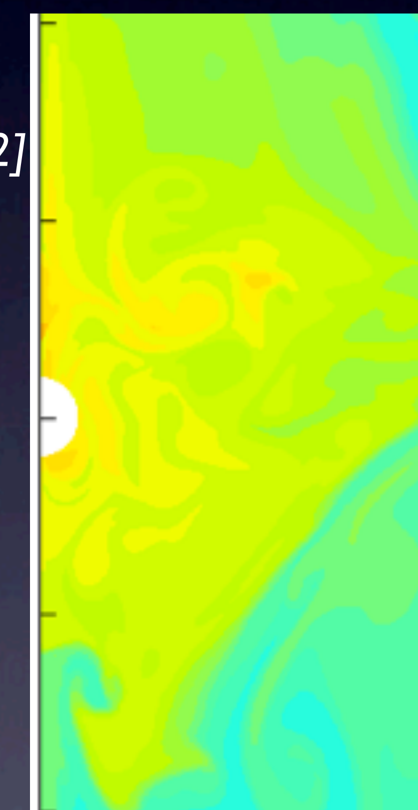


Perseus

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

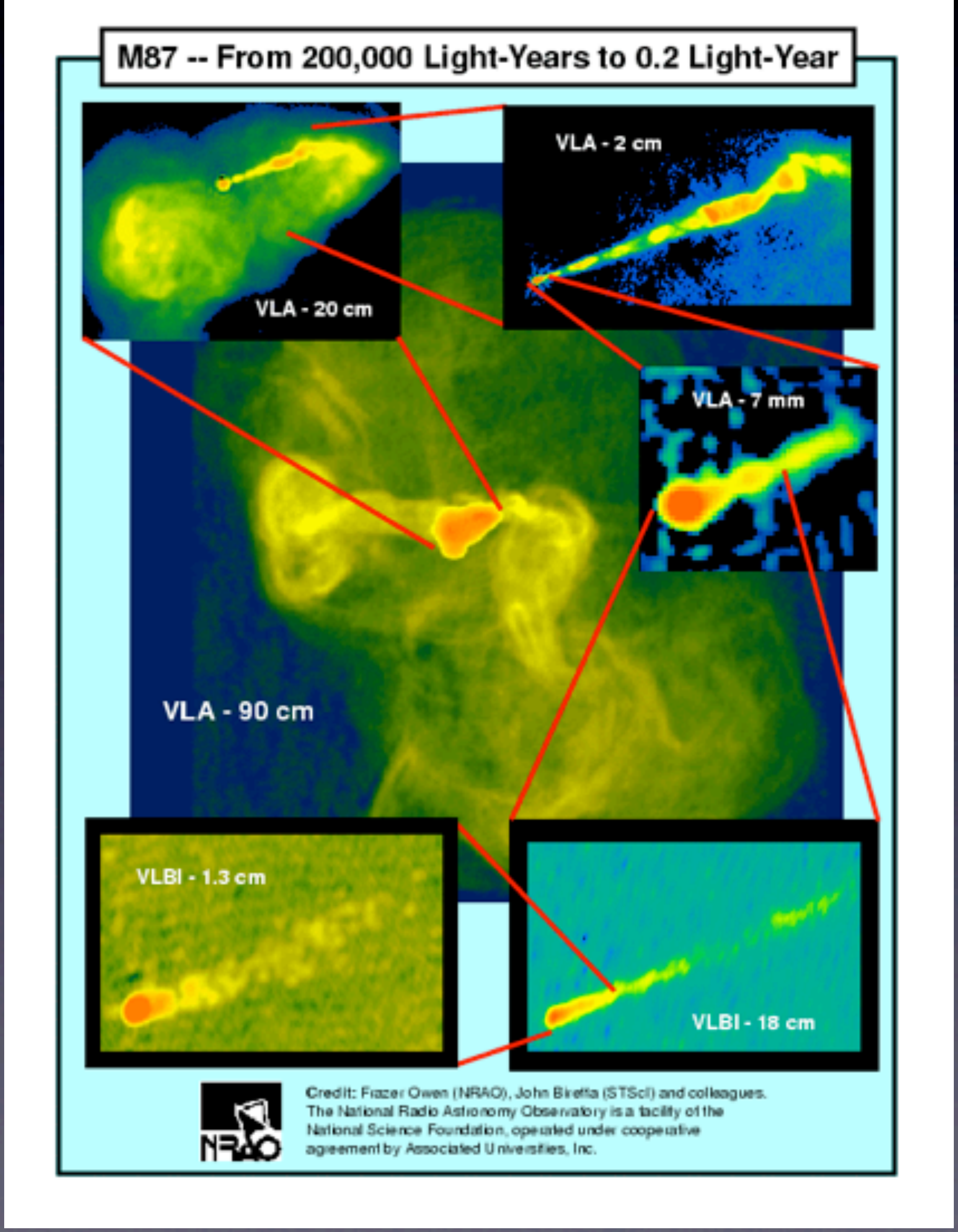


[Sharma et al. 2012]



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

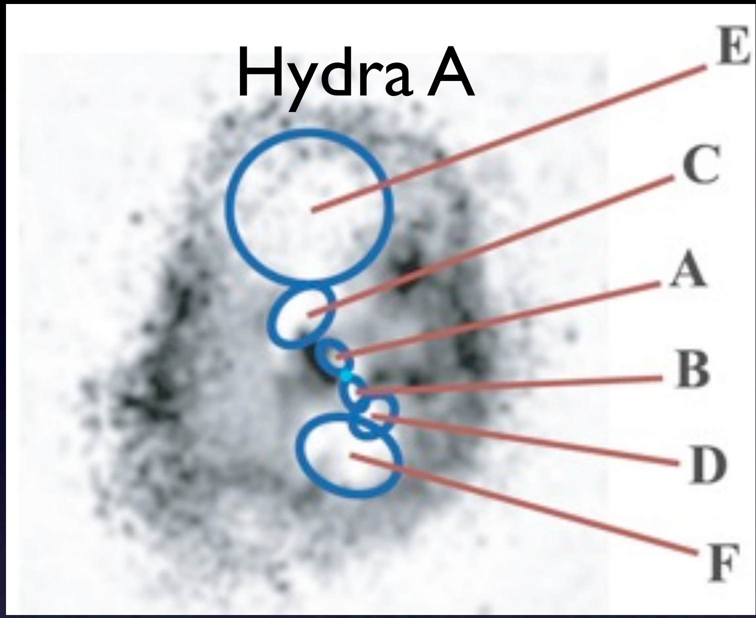
Rapidly reorienting jets

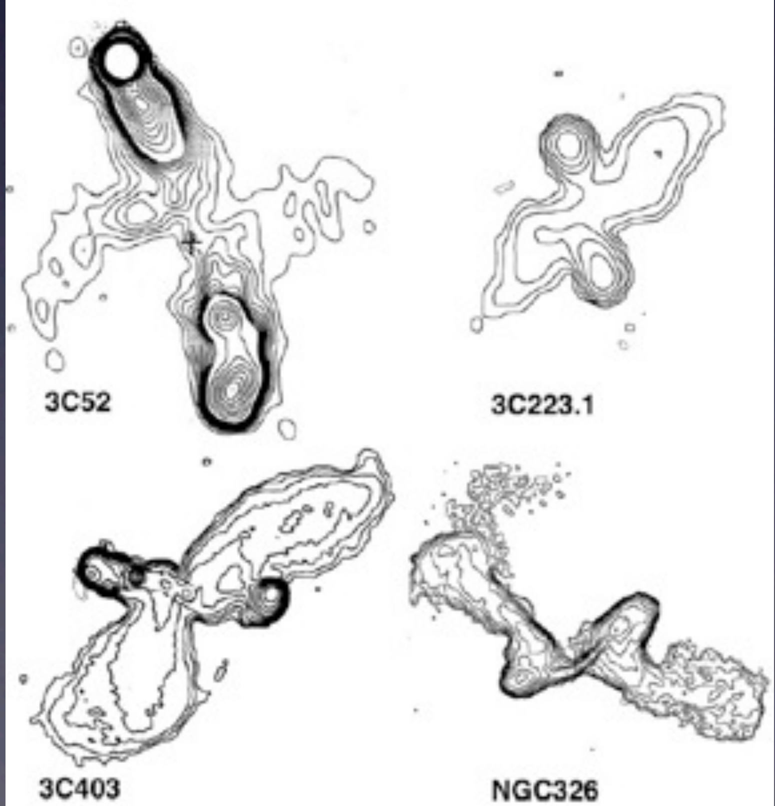


way to istropically spread AGN htg.

can be understood with stochastic cold accretion

how are jets re-oriented so quickly?

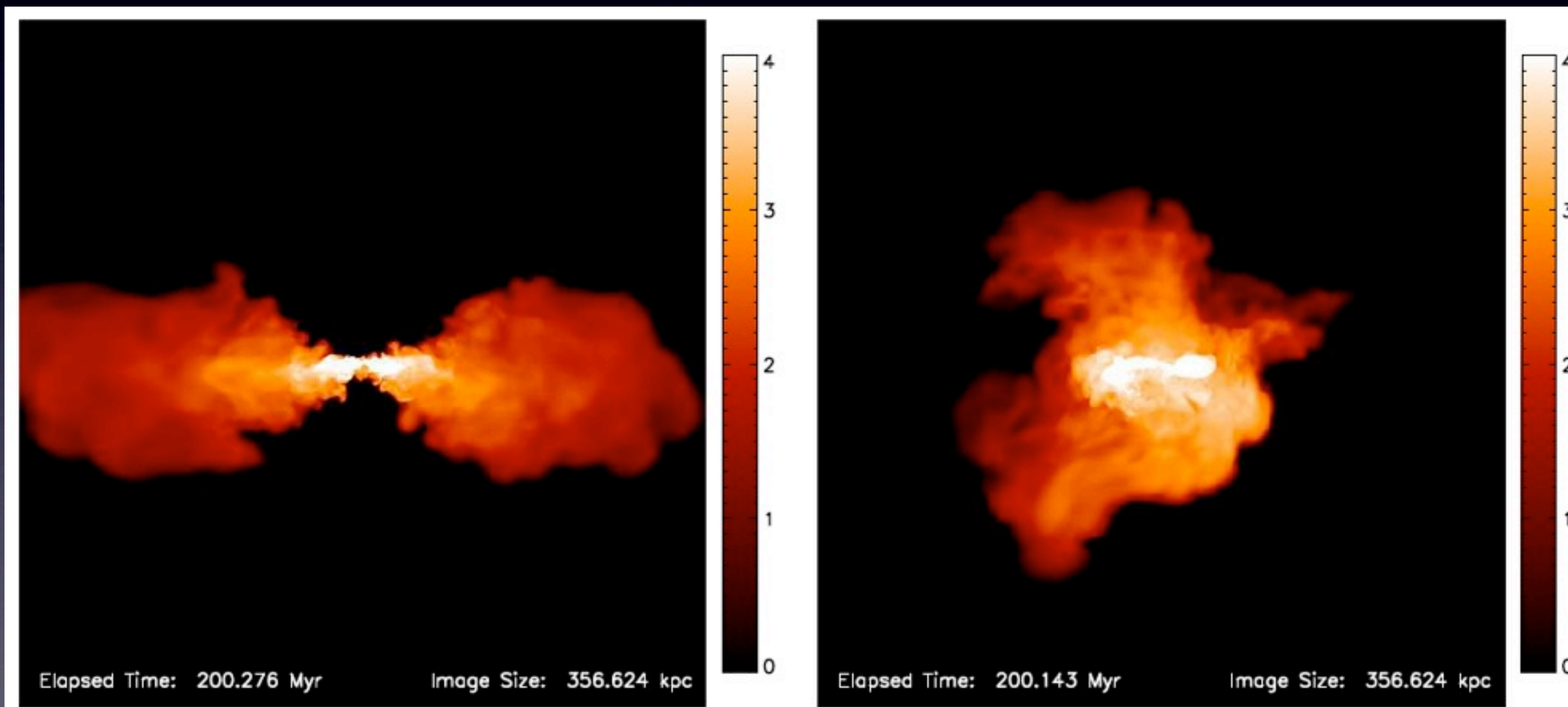




X-shaped radio galaxies

ICM weather?

idealized hydrostatic ICM *[Morsony et al. 2010]* turbulent ICM

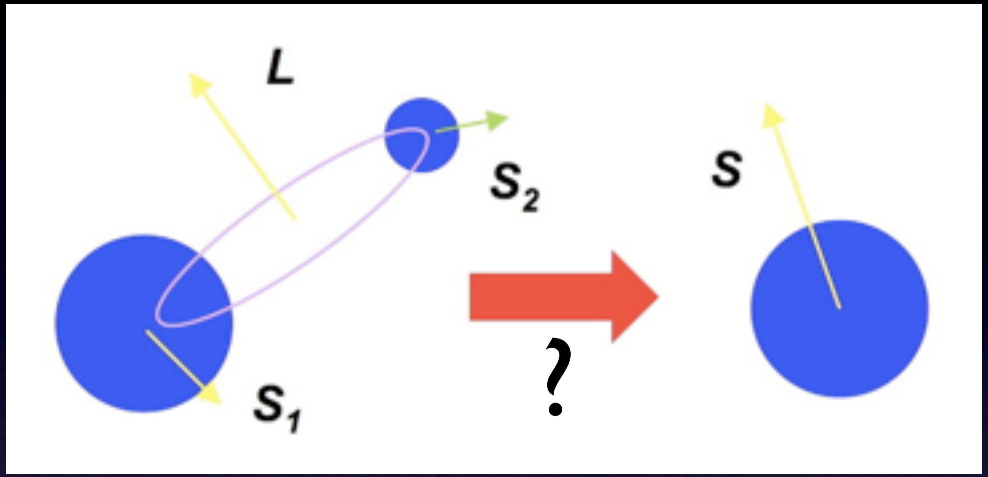


requires unrealistically large velocities!

Changing BH spin

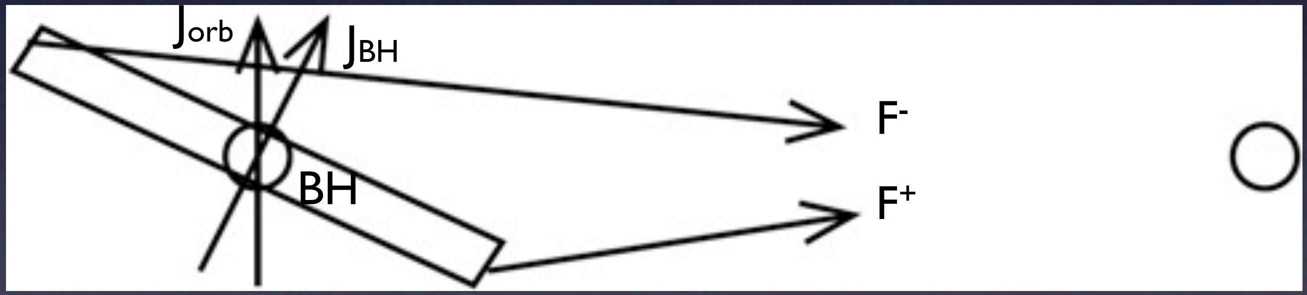
[Merritt & Ekers 2002]

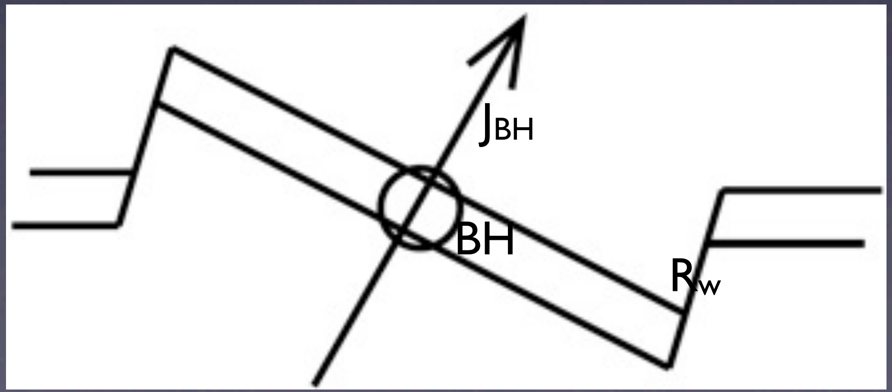
spin flips due to BH mergers
problem: SMBH mergers are uncommon



GWs!

binary BH (spin-orbit) precession, precession of inner accretion disk
problem: requires a binary SMBH; rarely see jets from both BHs





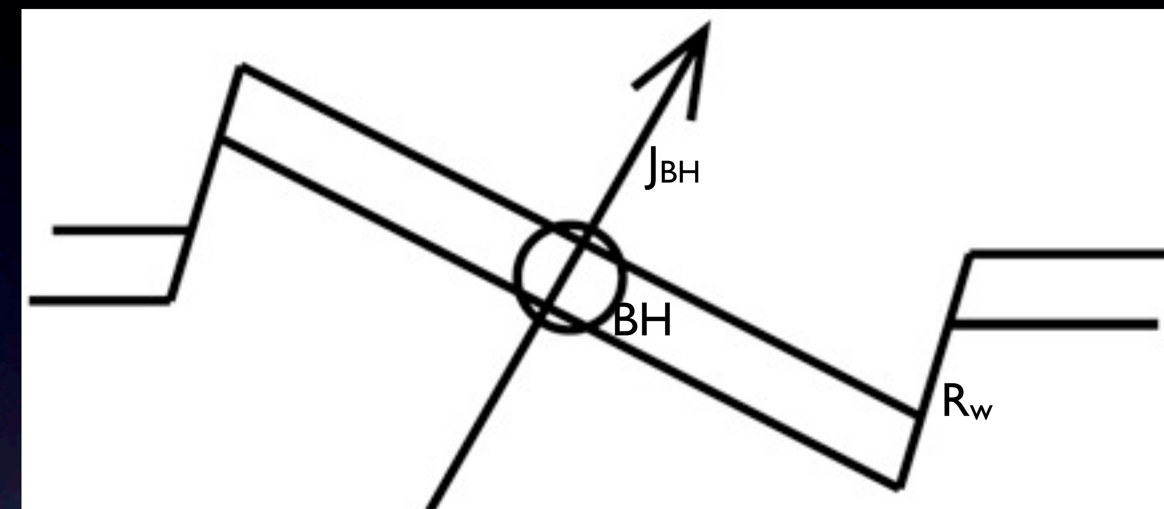
accretion disk slewing via Lense-Thirring /Bardeen-Petterson effect due to uncorrelated accretion of cold gas.

problem: should shine as a quasar
doesn't work for high spin

Slewing disk via BP

LT effect: GR effect which induces rotation

[Babul, Sharma, Reynolds 2013]



$$\vec{\tau}_{LT} \sim a(R_g/R)^3(\hat{J}_{BH} \times \vec{L})/(R_g/c)$$

$$\vec{\tau}_{visc} \sim \frac{\nu}{R}\frac{d}{dR}\left(R^3\frac{d\vec{\Omega}}{dR}\right)$$

$$\frac{R_w}{R_g} \sim \left(\frac{a}{(H/R)^2}\right)^{2/3}$$

$$t_{align} \sim t_{prec} \sim \frac{J_{BH}}{\dot{M}\Omega_w R_w^2}$$

viscosity aligns!

thin disk needed, else $t_{align} \sim t_{dbl}$ >> Myrs

S&S thin disk when $M_{dot} \gtrsim 0.01\ M_{dot,Edd}$ ($25 M_{sun}$/yr for $10^9\ M_{sun}$ BH)

self-gravity & fragmentation (if $M_d/M_{BH} \gtrsim H/R$) limits M_{dot}

short quasar phase in CC systems

accretion “events” via thin disk => slowly spinning SMBHs! & low efficiency

Conclusions

- solid evidence for stellar & SM BHs
- BHs simple, accretion flows complex
- rich phenomenology & connections
- t_{cool}/t_{visc} ($\dot{M}/\dot{M}_{Edd}$) & q-plot
- AGN feedback: quasar/radio modes
- reorienting AGN jets via short-lived quasar phase
- from theoretical curiosity BHs have become mainstay of astronomy!

Thank you