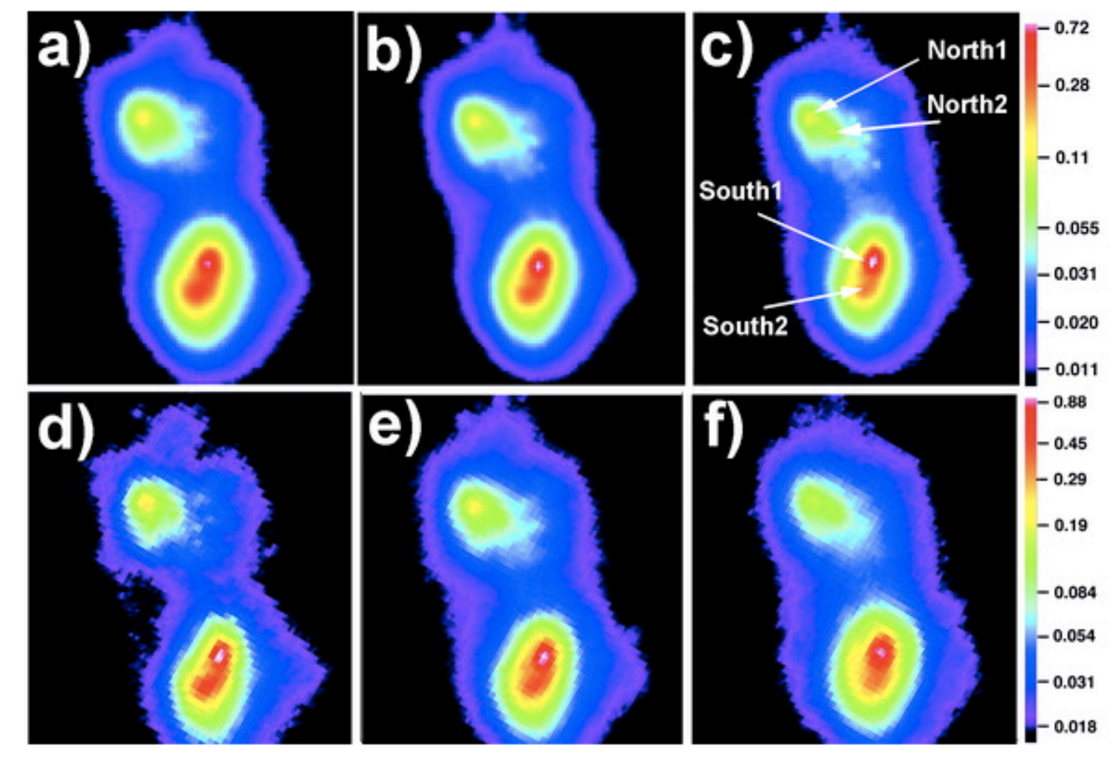
The formation and growth of black holes in the Universe



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Talk outline

- What do we know for certain about the accretion history of BHs?
- Observational evidence for BHs
- How do BHs form?
- How do they grow?
- Evidence for mergers?
- Observational signatures of mergers
- Future prospects

Collaborators: Philip Armitage, Giuseppe Lodato, Ezequiel Treister, Marta Volonteri

BH accretion: what we do know

- The critical luminosity when radiation pressure balances gravity is the Eddington limit
- Depends on mass of accreting object and opacity of the surrounding gas

$$f_{rad} = f_{grav} ; \frac{\kappa L}{4\pi c r^2} = \frac{GM}{r^2} ; L_{Edd} = \frac{4\pi c G M}{\kappa_T} = 1.25 \times 10^{45} \left(\frac{M}{10^7 M_{sun}} \right) \text{erg s}^{-1}$$

Gas flowing toward black holes produces radiation as the gravitational potential energy is released

$$L_{accretion} = \varepsilon \dot{M} c^2$$

accretion luminosity

radiative efficiency of the accretion process = the *fraction* of the rest mass energy of the gas that is radiated

gas inflow rate (the accretion rate): units g s^{-1}

For a BH accreting gas through a disk, the radiative efficiency ~ 0.1

Characteristic growth timescale

- Bright quasars must have M > 10^8 Msun
- Eddington limit caps growth rate of mass

$$\boxed{\frac{dM}{dt} = \frac{L_{acc}}{\eta c^2} < \frac{4\pi G M m_p}{\eta c \sigma_T}}$$

$$\boxed{M \leq M_0 e^{\frac{t}{\tau}}}$$

$$\boxed{\tau = \frac{\eta c \sigma_T}{4\pi G m_p} \approx 5 \times 10^7 \, yr}$$

Salpeter timescale

Energy output from accreting BHs

- Accretion=> Gravitational Energy=> EM radiation

If all energy is thermalized, Black body with temperature

$$T_b = \{\frac{L_{acc}}{4\pi R^2 \sigma}\}^{\frac{1}{4}}$$

For SMBHs:

$$M \approx 10^8 M_{sun}; R = \frac{2GM}{c^2} \approx 3 \times 10^{13} cm$$

$$T_b \approx 10^7 (\frac{M_{sun}}{M})^{\frac{1}{4}} K \approx 10^5 K$$

Expect accreting BHs to be UV, X-ray and possibly gamma-ray emitters

Approach to building accretion histories

- Globally averaged constraint (Soltan 1982)

census of the total energy emitted by a population of accreting BHs

$$E = \iint E(L,t)\,dL\,dt = \frac{4\pi}{c}\int (1+z)\,dz \int n(S,z)\,S\,dS$$

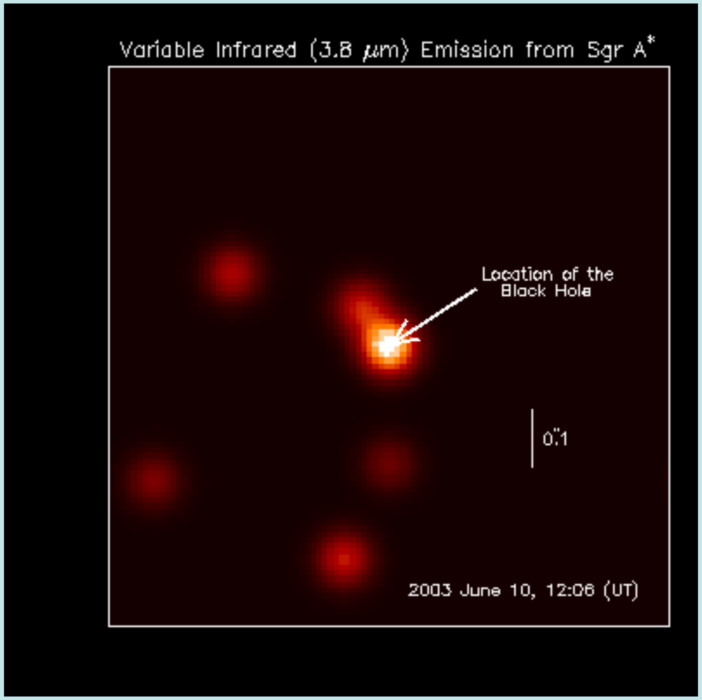
$$\rho_{BH} = \int_0^{t_{age}} dt \int_0^{\infty} d(\ln L)\,L\,\phi(L,t)$$

- Continuity argument for mass accumulation as a function of time (Small & Blandford 1992; Haehnelt, PN, Rees 1998, Haiman & Loeb 1999……Volonteri et al. 2005; Merloni & Heinz 2008)

attempt to relate the observed evolution of quasars to physical models of AGN

Astrophysical environment of BHs

Empirically, two modes of accretion in galactic nuclei, X-ray binaries



UCLA Galactic Center group

- radiatively inefficient accretion

e.g. Galactic Center

$$\dot{m} \equiv \dot{M}/\dot{M}_{Edd} \sim 10^{-7}$$

(Shcherbakov et al. 2010)

Ubiquitous: fed by stellar winds, "hot" $T_{ion} \sim T_{vir}$ quasi-spherical flow

- thin disk accretion: radiatively efficient (e ~ 0.1) AGN mode

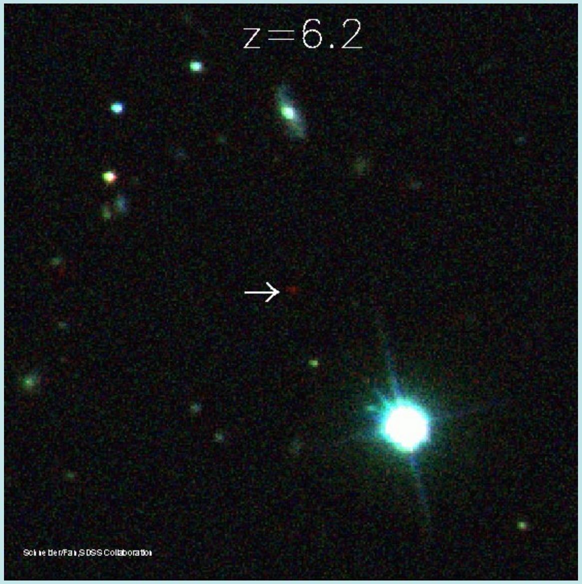
Feeding mechanism unclear, rare in the local Universe

Typical merger environment *only* if thin disks **cause** or are otherwise preferentially correlated with BH coalescences

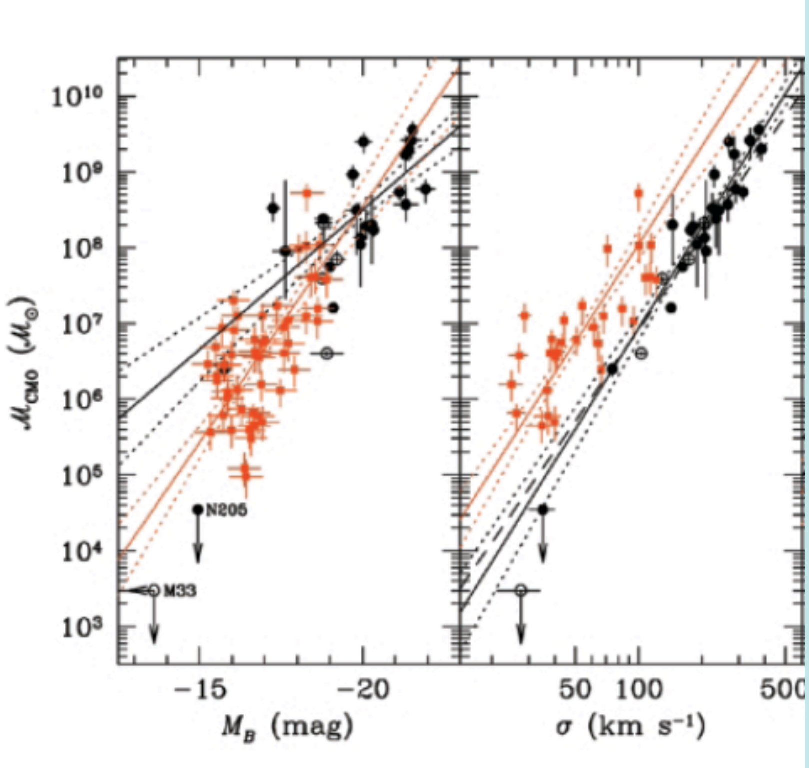
Observations from high and low redshift

Abundance & LF of High redshift quasars

Age of the
Universe 2 Gyr!



Most recent census from
SDSS and 2dF Fan+ 2007;
Croom+ 2004



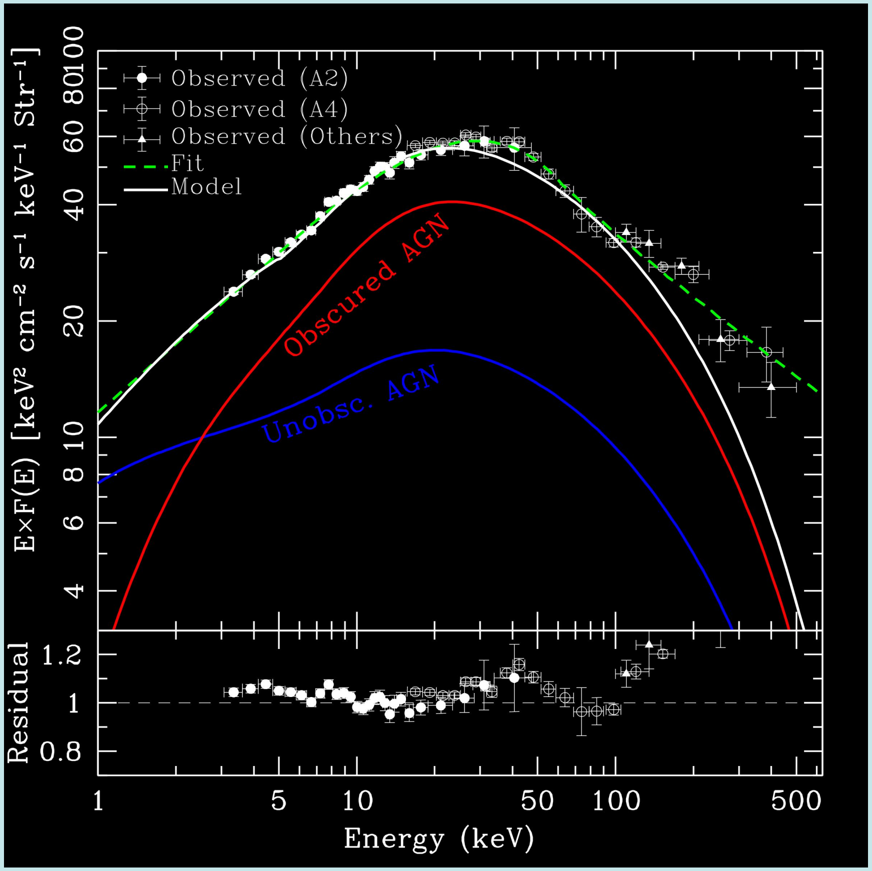
Observational estimates of masses of central massive objects

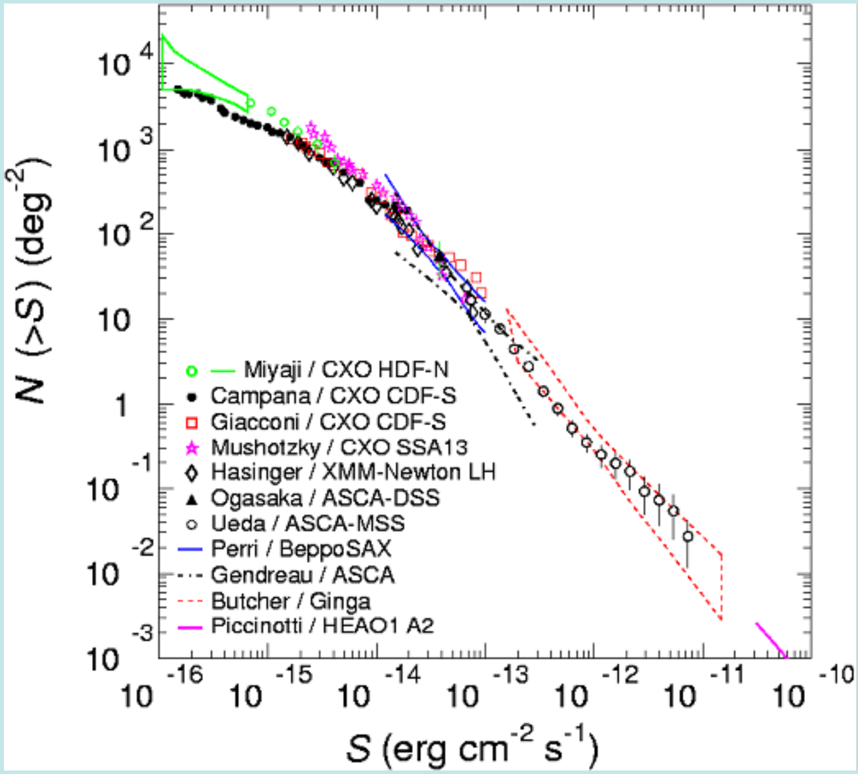
observed correlation between bulge luminosity and BH mass => BH mass and vel. Disp

Ferrarese+ 2006; Ferrarese & Merritt 2002; Tremaine+ 2002; Kaspi+ 2005

The X-Ray Background (XRB) spectrum and number counts

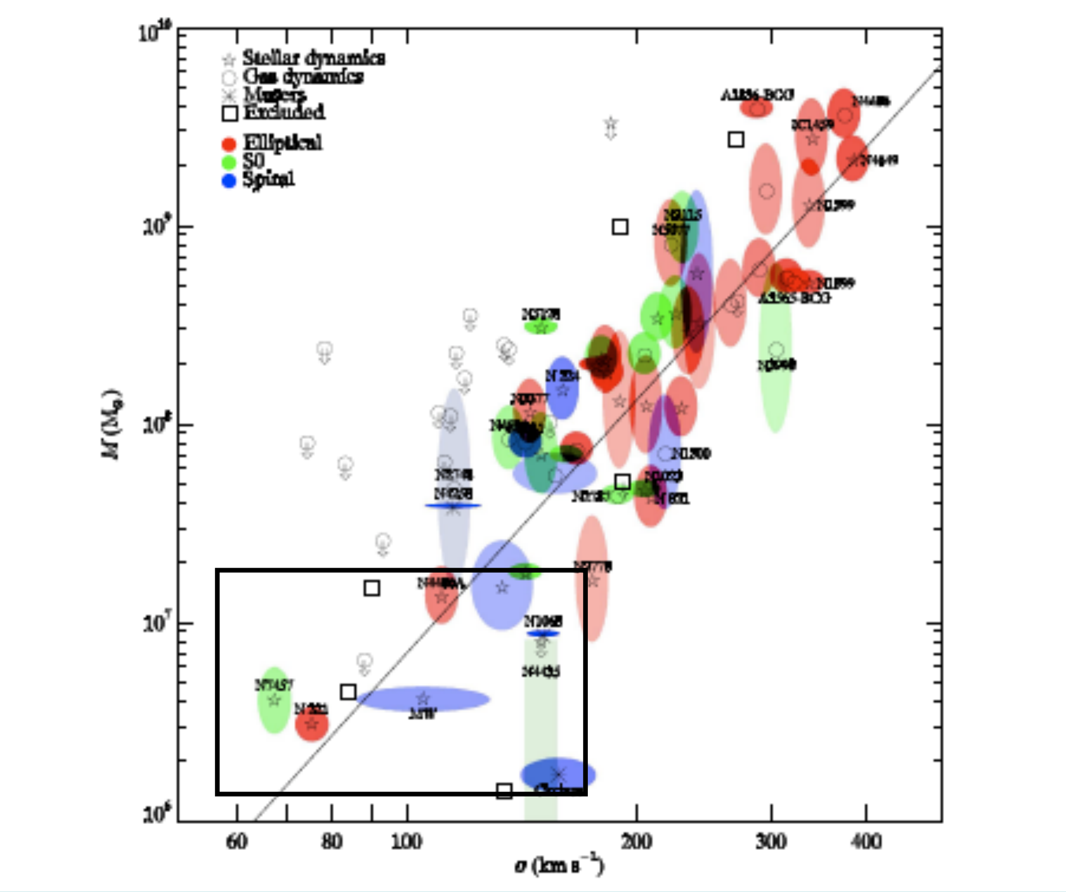
- The XRB is the integrated emission from all AGNs in the Universe, the energy density peaks at ~ 30 keV
- The shape of the XRB indicates that most of the AGNs are obscured, harder energies needed to detect the contribution of these obscured sources





Comastri+ 1995; Ueda+ 2003; Treister & Urry 2005; Merloni+ 2004; PN & Treister 2008

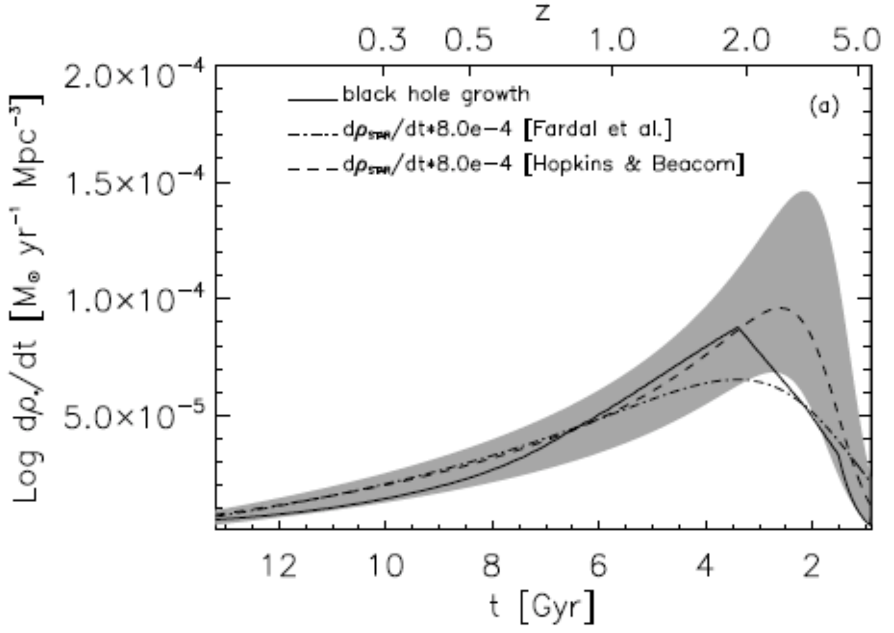
The M_{bh}-sigma relation



Gultekin+ 2010; Greene & Ho 2009

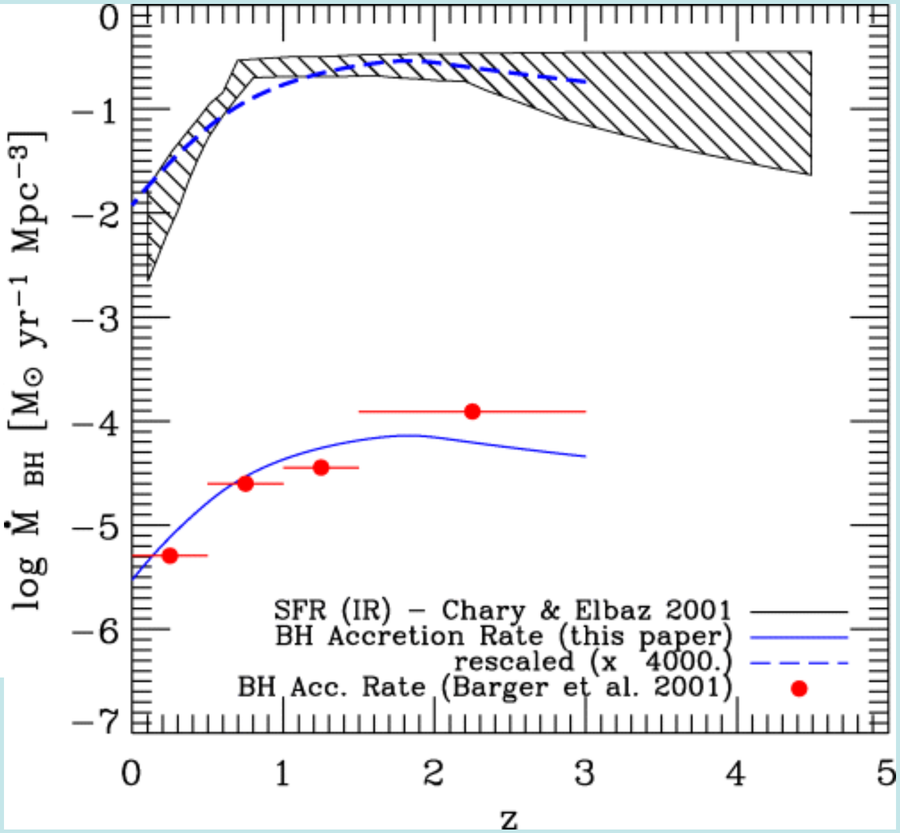
Co-evolution of galaxy and super massive black holes in galactic centres

BH mass vs stellar mass



e.g., Marconi & Hunt 2003; Shankar, Weinberg & Miralda-Escude 2007

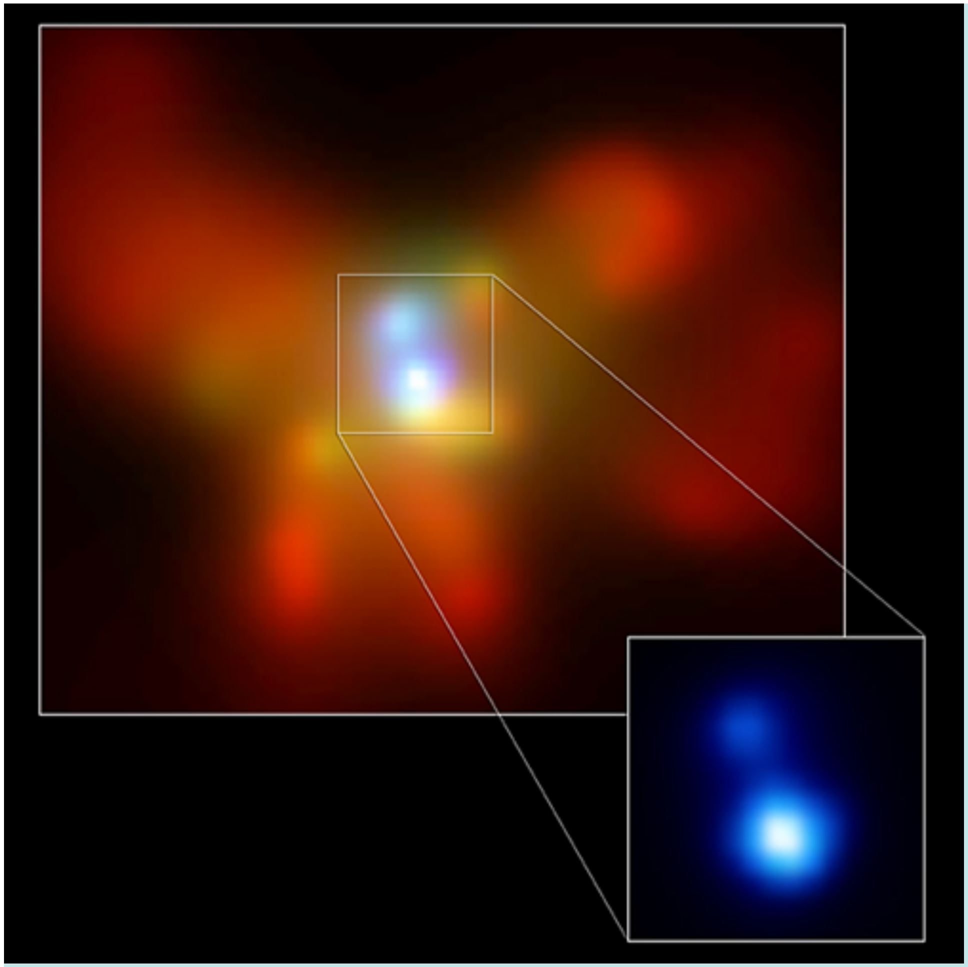
Star forming history vs accretion history



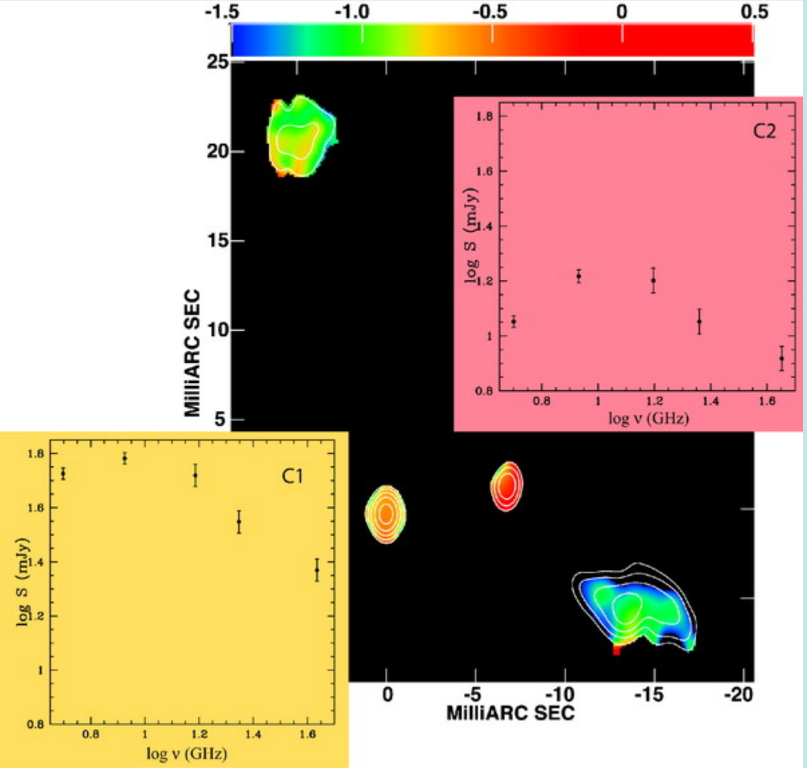
Marconi+ 2004

Observationally

Handful of identified pre-merger binary black holes

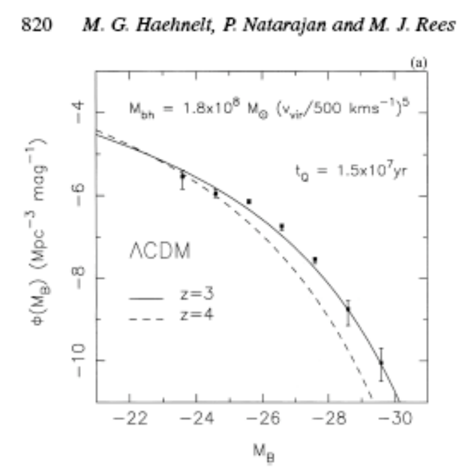


NGC 6240: d ~ kpc
Komossa+ 2003



0402+379: d = 7pc (Rodriguez+ 2006)

Predictions in the context of CDM

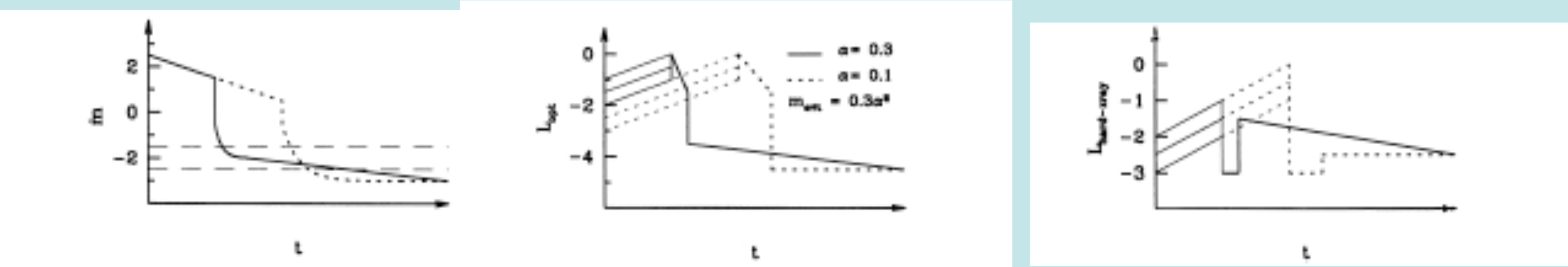


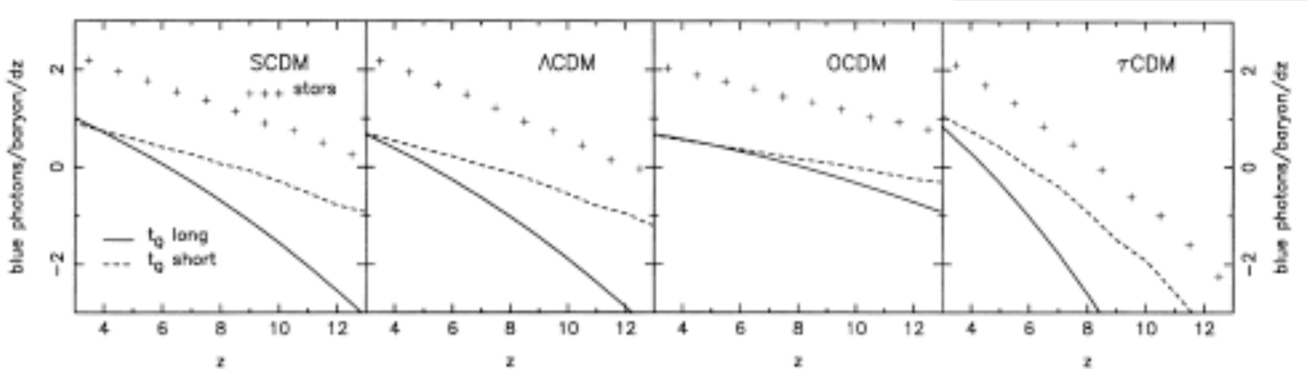
820 *M. G. Haehnelt, P. Natarajan and M. J. Rees*

Relation between black hole mass and host halo mass

$$M_{bh} \approx 10^8 f(j_d,\lambda_{halo},m_d)\left(\frac{v_{halo}}{400\,km/\sec}\right)^5 M_\Theta$$

Accretion history & SFR





blue photons per baryon from quasars and SF

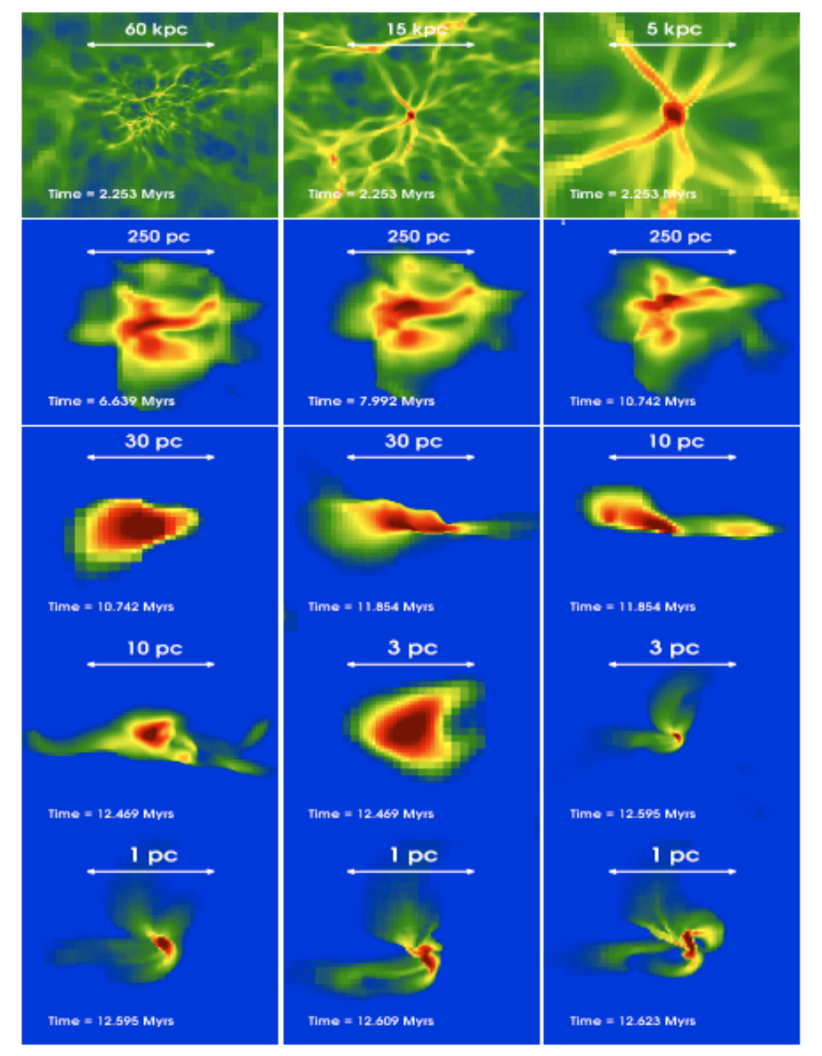
Including a model for galaxy mergers

- Black holes grow during major mergers
- A fixed fraction of the available cold gas driven to the center and accreted at arbitrarily high rates (no seeds)
- Amount of cold gas is set by cooling and stellar feedback
- Growth during the optically bright quasar and the obscured phase
- Simple light curve with luminosity independent/dependent lifetime

Growth dominated by accretion + at late times by merging of BHs

Haehnelt, PN & Rees 1998; Haiman & Loeb 1999; PN 2003; Yu & Tremaine 2002; Kauffmann & Haehnelt 2000,2003; Wyithe & Loeb 2004; Granato+ 2004; Shanker+ 2005; PN 2006; Kauffmann & Haehnelt 2000, 2003

Massive BH seed formation



Regan & Haehnelt 2008

Pathways to making BH seeds

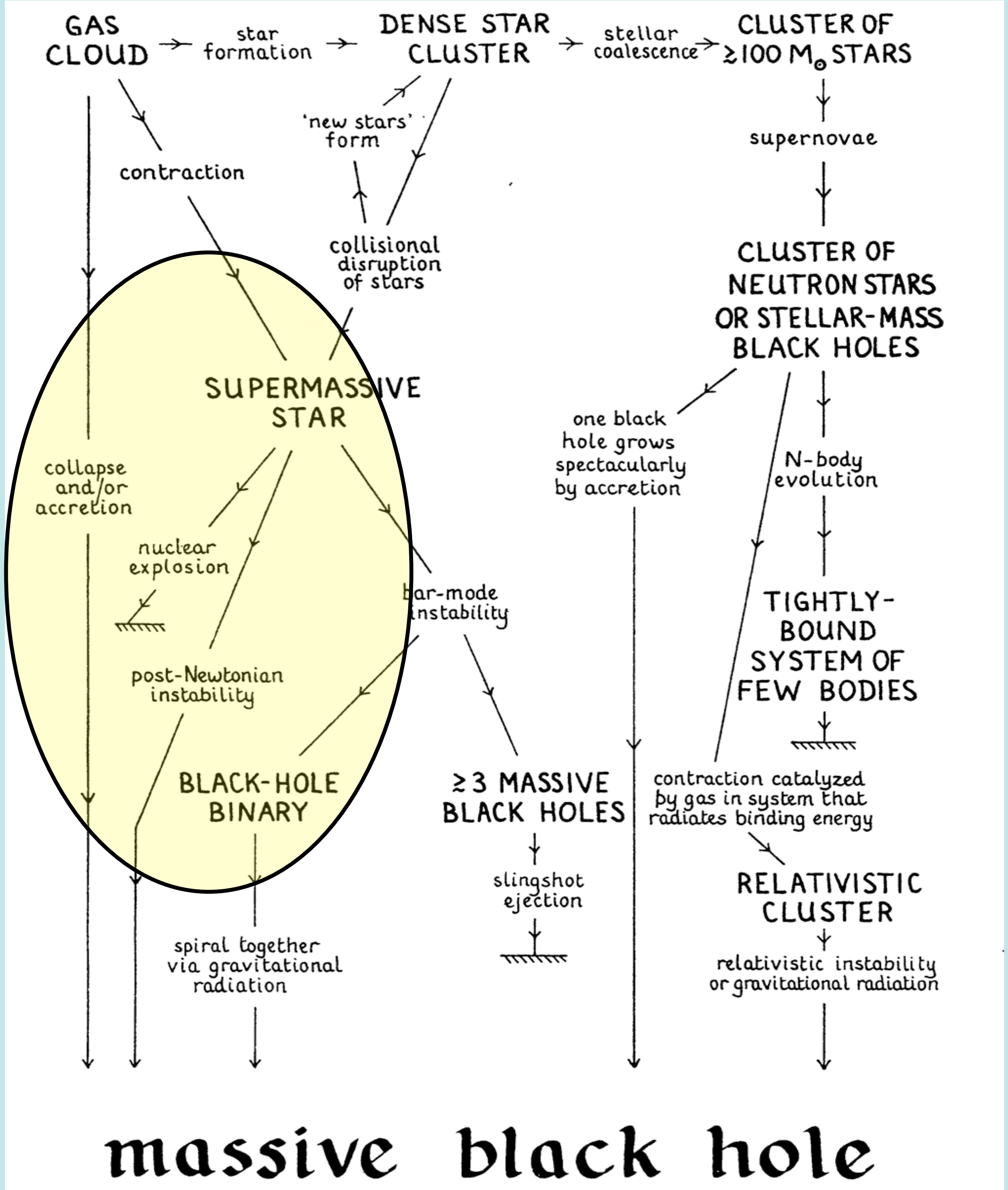


Figure 1 Schematic diagram [reproduced from Rees (106)] showing possible routes for runaway evolution in active galactic nuclei.

Rees 1978

First black holes in pre-galactic halos z ~20-30

$M_{BH} \sim 100 - 500\ M_{sun}$

Pop III remnants

Simulations suggest that the first stars were massive 100 - 500 M_{sun} (Bromm+ 2002 ; Abel+ 2002; Abel+ 2000; Alvarez+ 2008)

Metal free Pop III stars with $M > 260\ M_{sun}$ leave remnant BHs with $M_{seed} > 100\ M_{sun}$ (Fryer, Woosley & Heger)

$M_{BH} \sim 10^3 - 10^6\ M_{sun}$

Viscous transport - efficient angular momentum transfer,

formation of central concentration (Eisenstein & Loeb 1995; Koushiappas+ 2004)

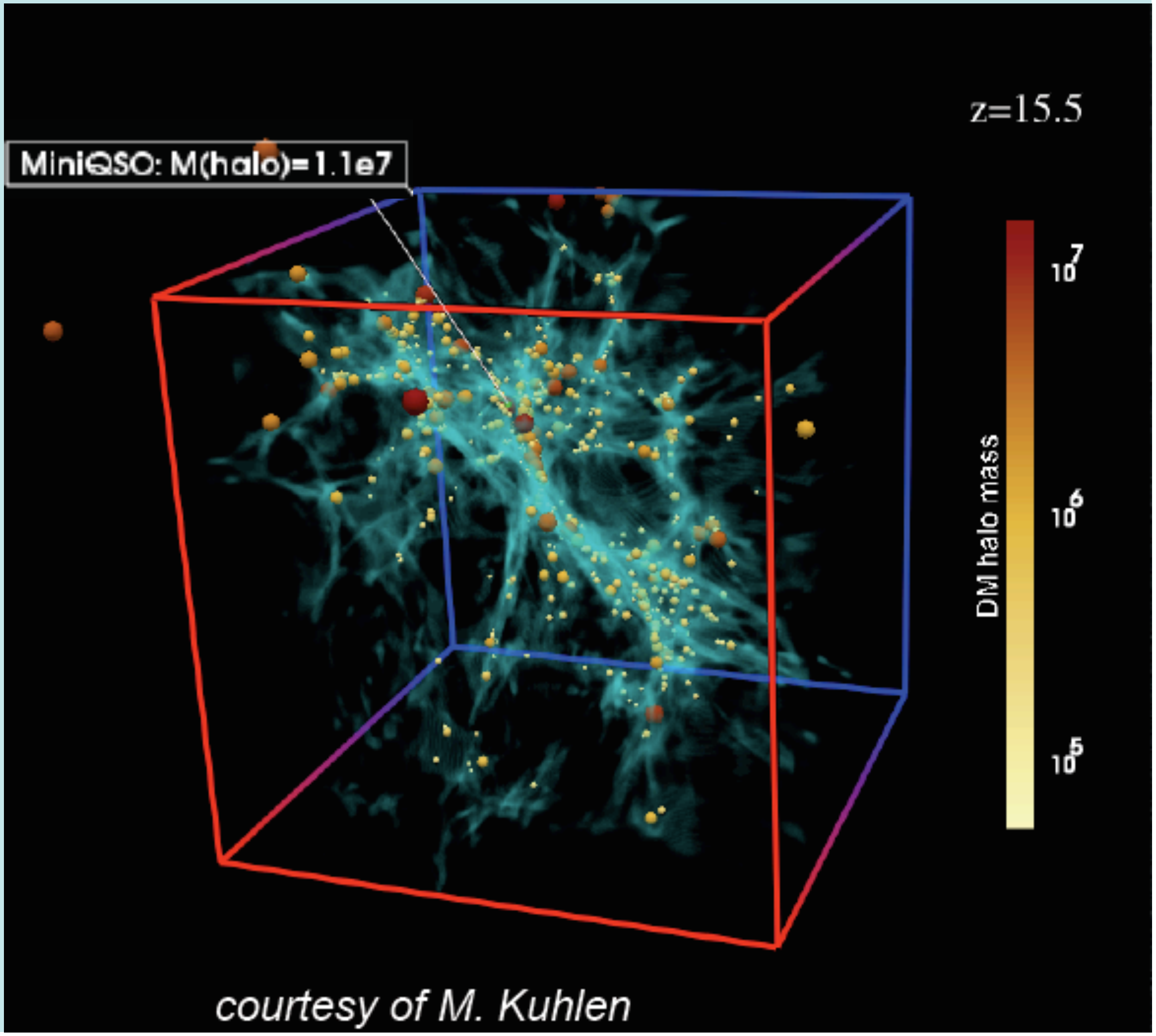
+ proper dynamical treatment of disk stability (Lodato & PN 2006, 2007)

Supermassive star (Haehnelt & Rees 1993)

Bar unstable self-gravitating gas + large quasi-star (Begelman, Volonteri & Rees 2006)

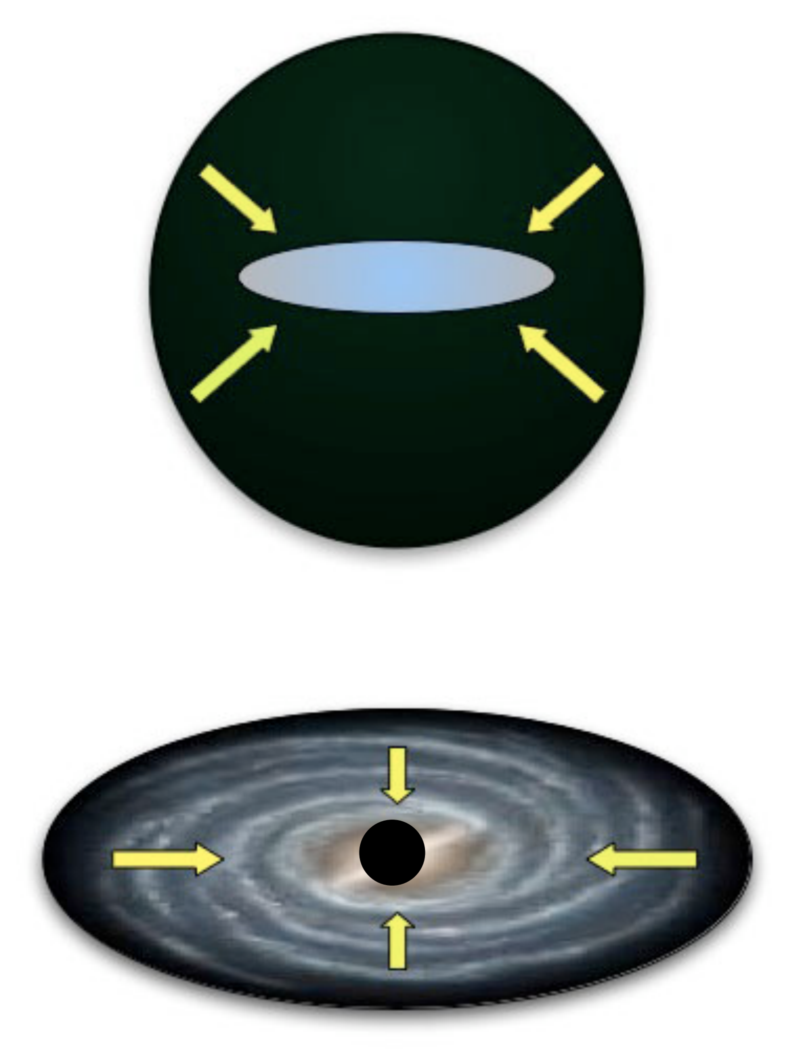
First black holes

- Unclear if PopIII remnants will do as seeds (Alvarez+ 2008!)
- Other ways of making more massive BH seeds need to be considered



courtesy of M. Kuhlen

BH seed formation at high z



Baryons inside DM halo collapse and form a rotating pre-galactic disc

Disc becomes gravitationally unstable and accretes to the center

Lodato & PN 2006, 2007

Sequence of events

DM halo mass M, T_{vir}, no metals, gas mass $f_b M$
hot disc ~4000 K, cold disc ~ 400 K

$T_{vir} > T_{gas}$ gas collapses and forms rotationally
supported disc, disc subject to grav.
instabilities, onset when Toomre Q_{crit} ~ 1 - 3

Disc evolution tussle between accretion and fragmentation

Bars lead to redistribution of J, feed matter to center
continues till central mass stabilizes the disc

Accumulated central mass depends on spin, halo mass, T_{gas}/T_{vir}, max.
spin for which the disc is grav. Unstable, provides upper limit to M_{BH}

For large M, the internal torques needed to redistribute J too large to be sustained, causes disc to fragment when $T_{vir} > T_{max}$

Happens for critical value of $\alpha \sim 0.06$ in Keplerian discs

Fragmentation is rapid, timescale local dynamical time stops when enough mass is converted into stars to make disc stable, no J losses, no mass funnelled to center

Key property is T_{gas}, atomic or molecular H cooling
2 extreme cases: fragmentation quenches accretion
and fragmentation not taken into account

$$\frac{dn}{dM_{bh}}(M_{bh};z) = \int_{M(T_{min})}^{M(T_{max})} \frac{dn}{dM}(M;z)p[\lambda(M_{bh},M)] \left| \frac{d\lambda}{dM_{BH}} \right| dM$$

n(M) of DM halos Sheth & Tormen 1999; Gammie+ 2001; Rice & Lodato 2005

Fragmentation criteria

3 interesting regimes:

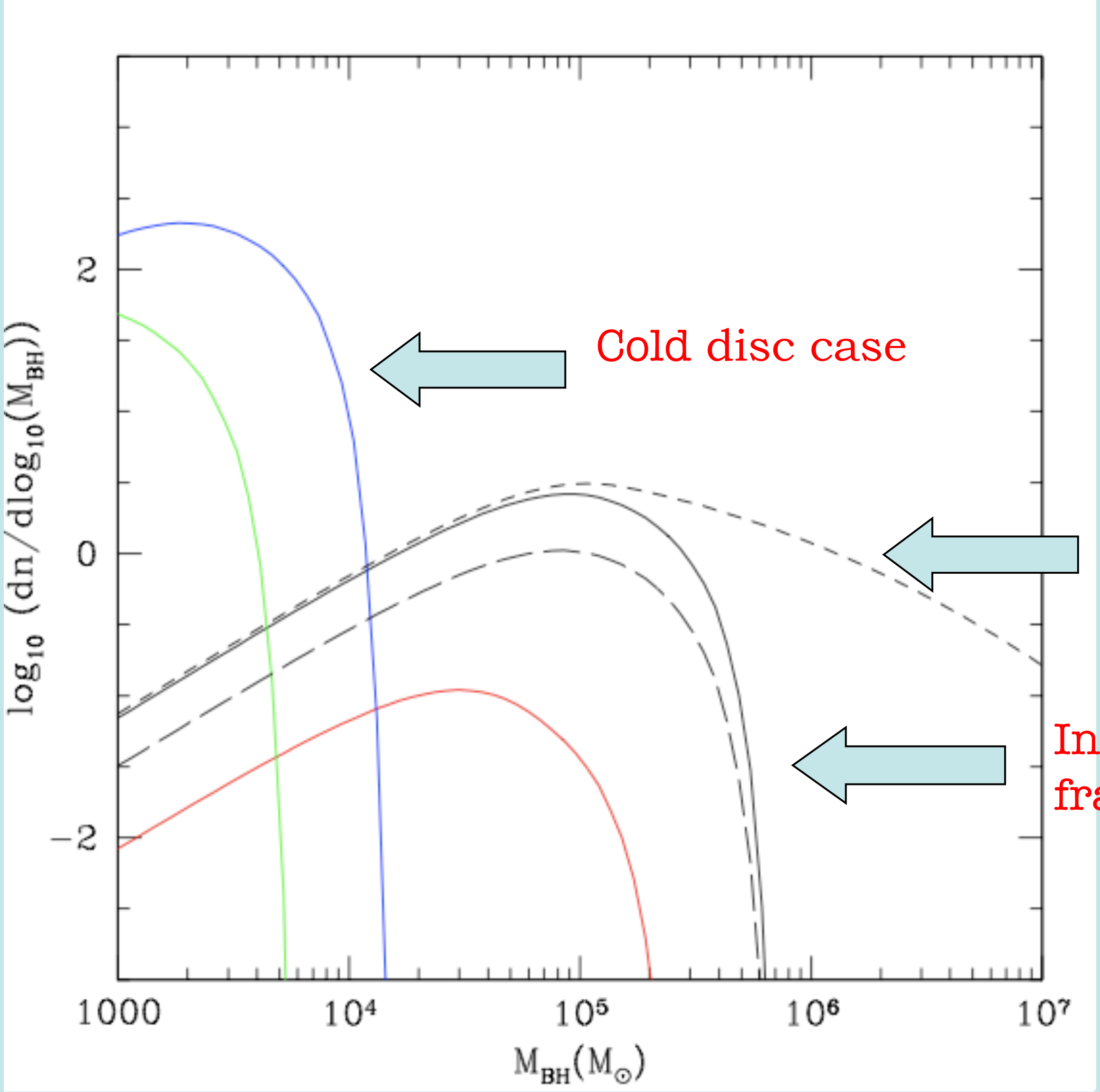
$T_{vir}/T_{gas} > 3$ will fragment and form stars and no central mass concentrations

$2 < T_{vir}/T_{gas} < 3$ will fragment and form stars and central mass concentrations

$T_{vir}/T_{gas} < 2$ will not fragment to form stars, will accrete gas into central mass concentrations that will form BHs

Oh+ 2003; Lodato & PN 2006

Mass function of seed BHs at z = 15



Cold disc case

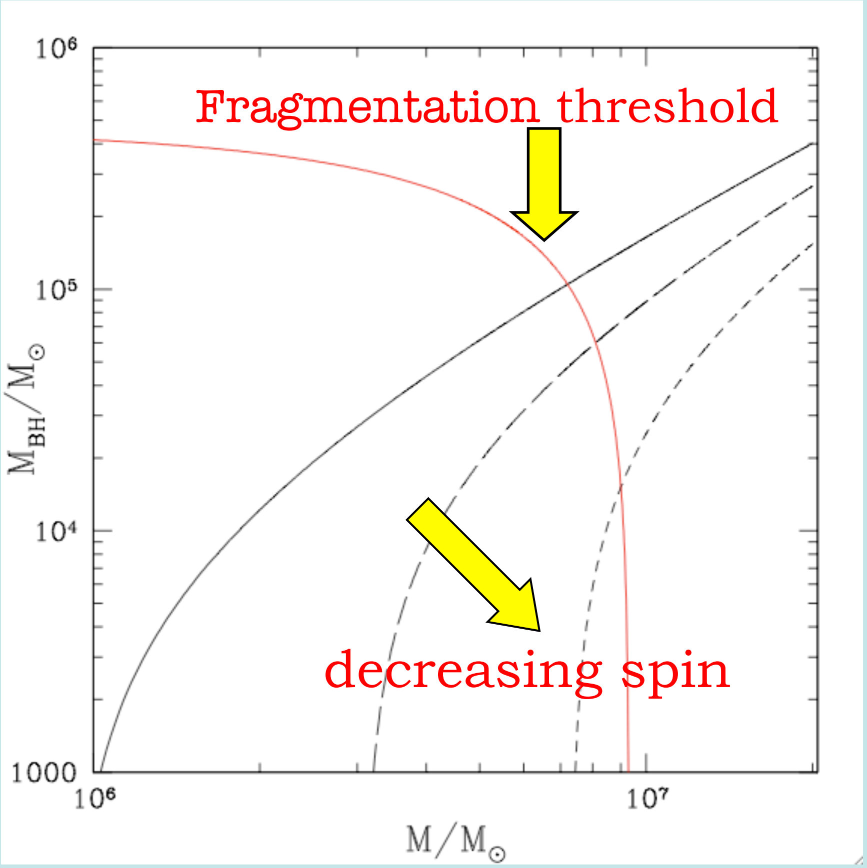
Without fragmentation

Including fragmentation

Koushiappas+ 2004; Lodato & PN 2006a, 2006b

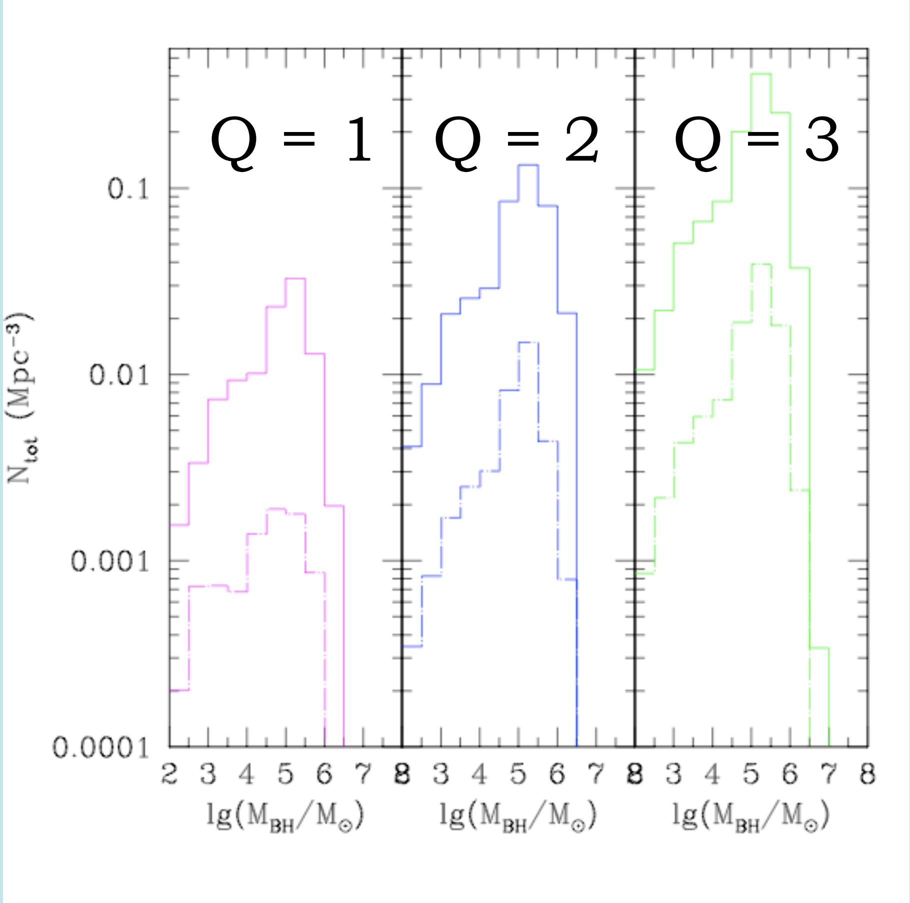
Key features of the model

- Different relationship between M_{BH} and spin parameter
- High spin halos do not host BHs at early times as disc is not massive enough, stable to grav. instabilities
- Massive, low spin halos host the most massive seeds

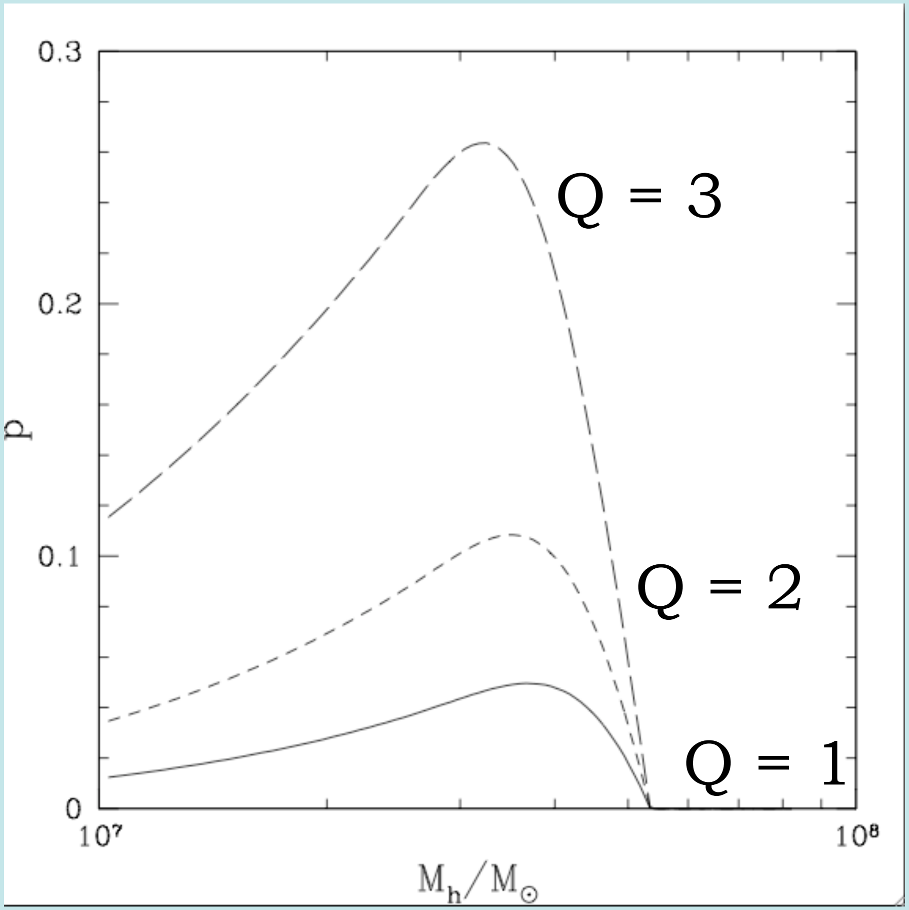


T_{gas}~ 4000 K, m_d=j_d= 0.05, Q = 2

Model features

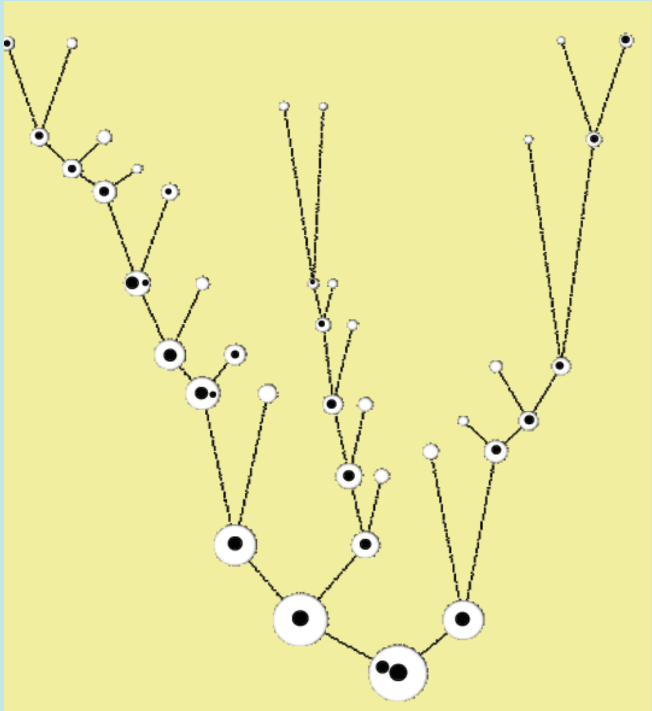


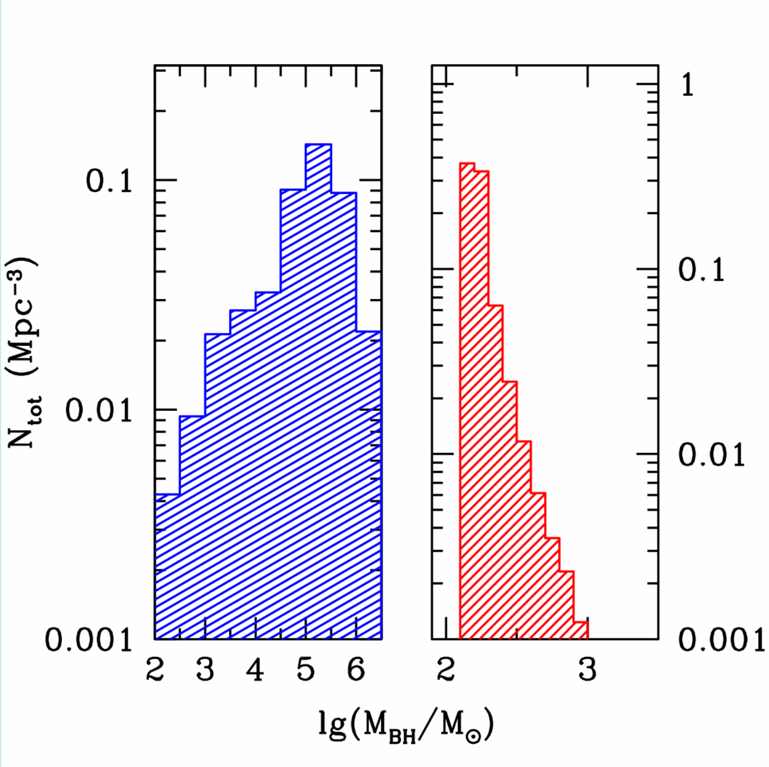
The mass function of seeds for
3 different BH formation efficiency
models



Probability of hosting a BH
seed of any mass

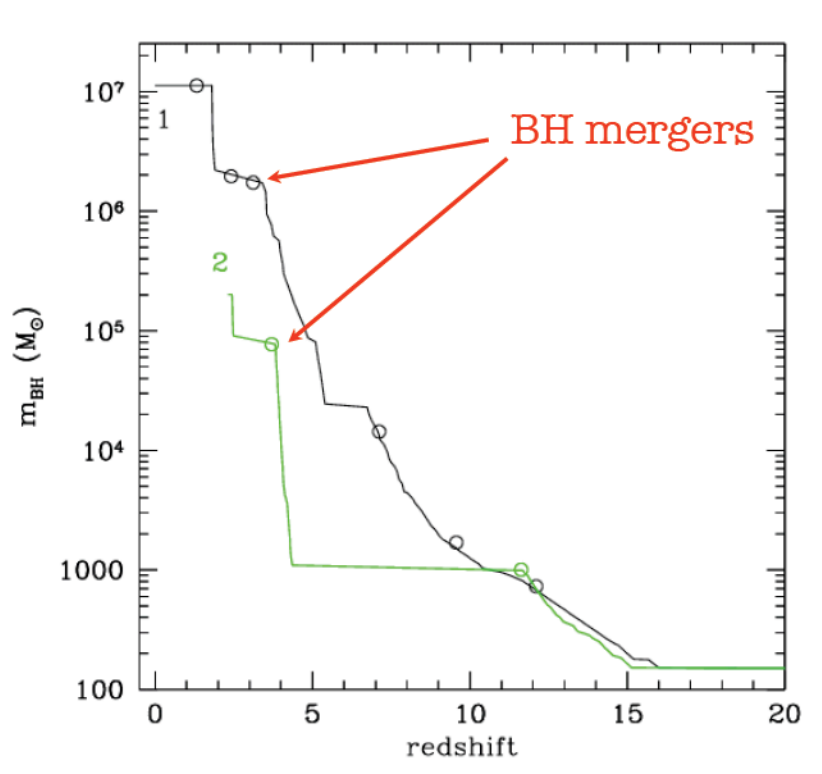
Merger induced accretion + CDM merger tree + seeds





- Plant with initial mass function of seeds
- Generate Monte Carlo merger tree in LCDM
- MBH seed formation ceases at z ~ 12
- Propogate different BH seed models
- Every major merger (mass ratii 1:10 or greater) induces accretion of gas
- 2 models: (I) gas mass accreted scales with v_c^5 and (II) BH mass simply doubles

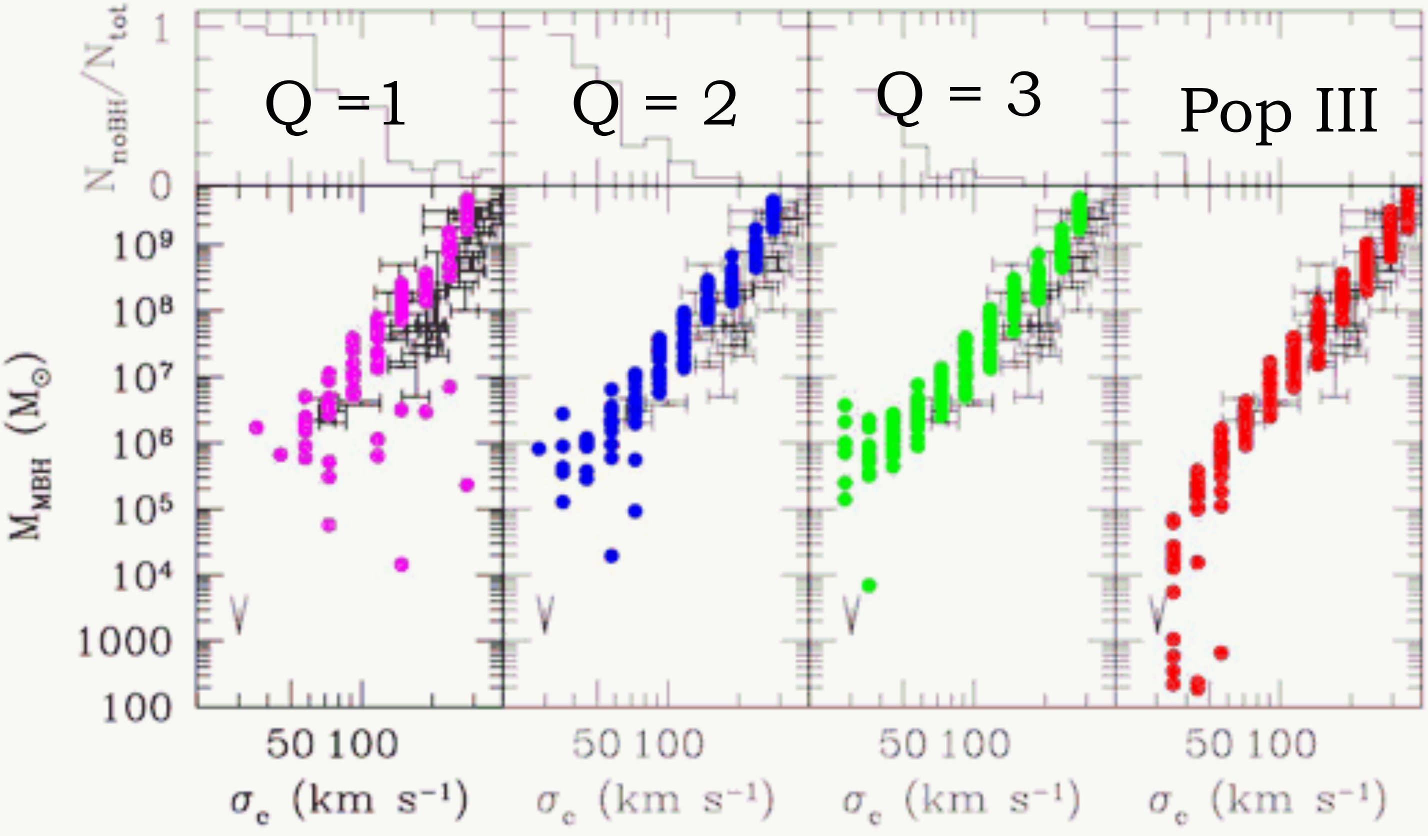
Hernquist+ 2007; Kauffmann & Haehnelt 2000; Croton+ 2006; Bower+ 2006; Kimm+ 2008; Volonteri, Haardt & Madau 2003; Miloslavjevic & Merritt 2001; Armitage & PN 2004; Hopkins+ 2007; 2008; 2009



- MBH mergers are rare events, as they require the merger of two galaxies each with a central BH
- Not only all MBHs experience a major merger during their lifetime, only ~ 40 - 50 %
- Dynamical and gravitational interactions can displace MBHs
- Mergers detectable with signatures EM and GW signatures, predict event rates for LISA

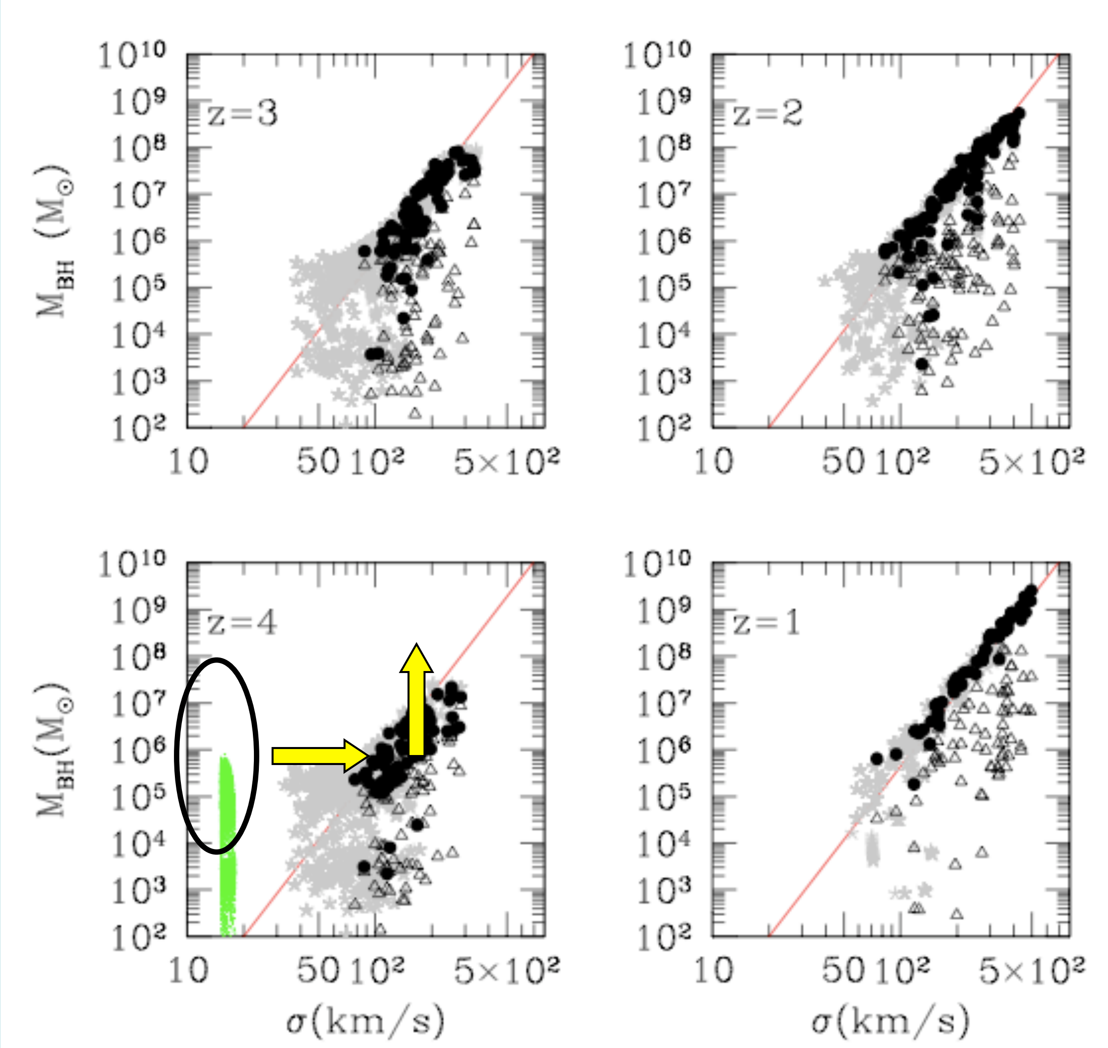
Sesana+ 2004; Dotti+ 2006; PN& Volonteri 2008

Key prediction at the low mass end



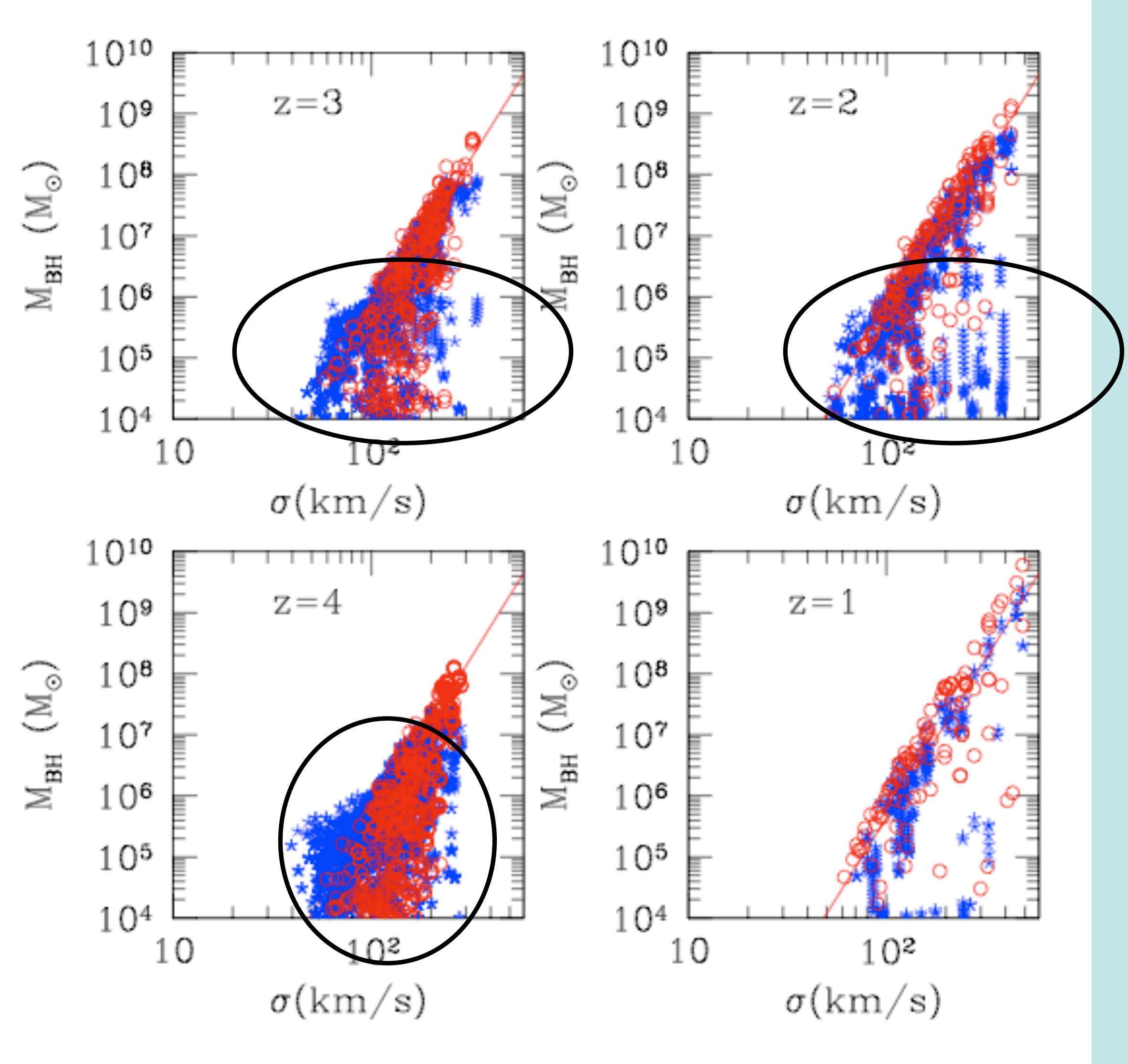
Volonteri, Lodato & PN 2007

Merger history of a present day $10^{13}\,M_{sun}$ halo (merging BHs)



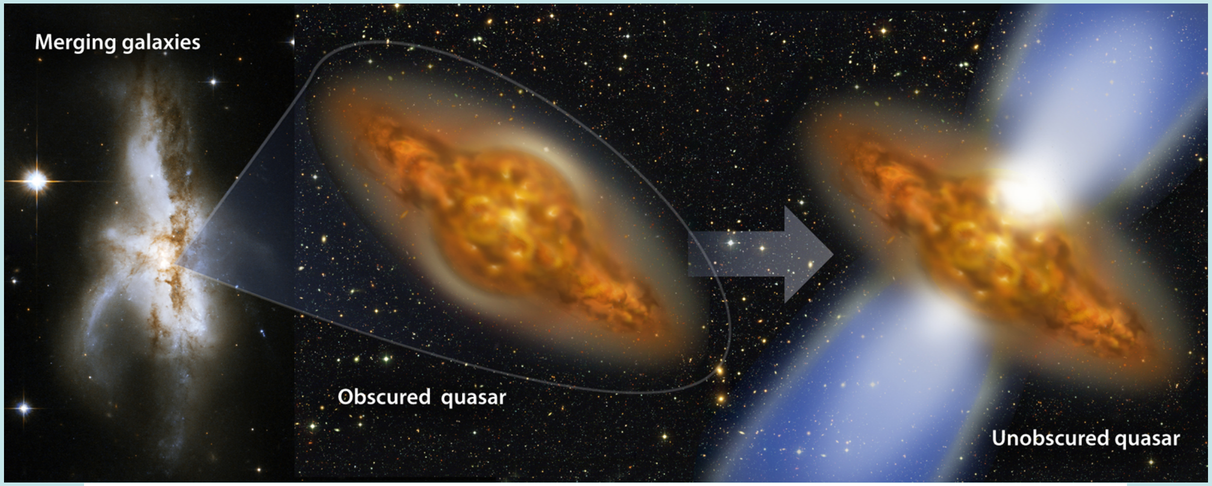
initially over-massive, massive seeds in 3.5-4 sigma peaks

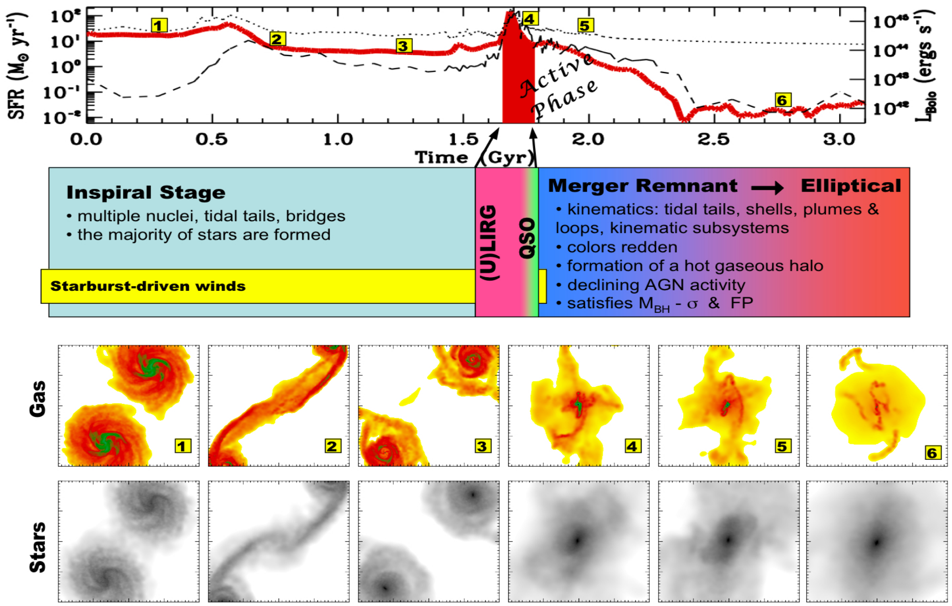
Merger history of a present day 10^{13} M_{sun} halo (accreting BHs)



blue - massive seeds; red - Pop III remnants

Stages in the growth of a SMBH following a merger

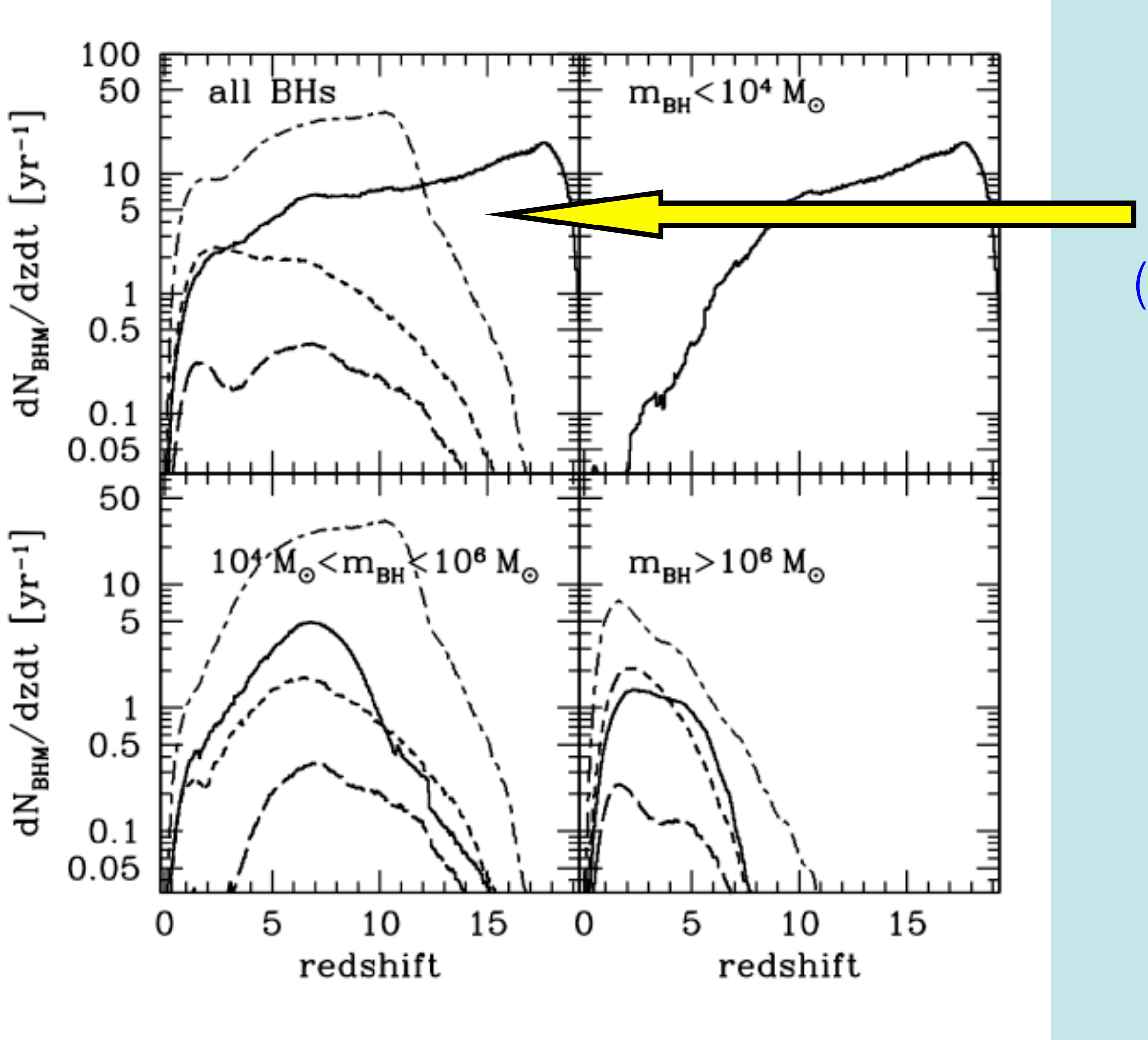




Di Matteo+ 2005; Cox+ 2006; Hopkins+ 2005, 2006; Robertson+ 2005

Treister, PN + 2010 (Science)

Number of MBHB mergers/yr



Massive seed
Models
(dot dash, solid)

Sesana+ 2007;Volonteri & PN 2010

Self regulation of SF and BH growth

Quasar driven wind sweeps up gas shell and expels it,
inhibiting SF and limiting BH mass

$$M_{bh} > \alpha \frac{\sigma^5 \kappa}{G^2 c} = 8 \times 10^8 \gamma \left(\frac{\sigma}{500 km/s}\right)^5 M_\Theta$$

$$\boxed{M_{bh} \approx 10^8 \left(\frac{f_{kin}}{0.001}\right)^{-1} j_d^{-5} \left(\frac{\lambda}{0.05}\right)^{-5} \left(\frac{m_d}{0.1}\right)^5 \left(\frac{v_{halo}}{400 km/s}\right)^5 M_\Theta}$$

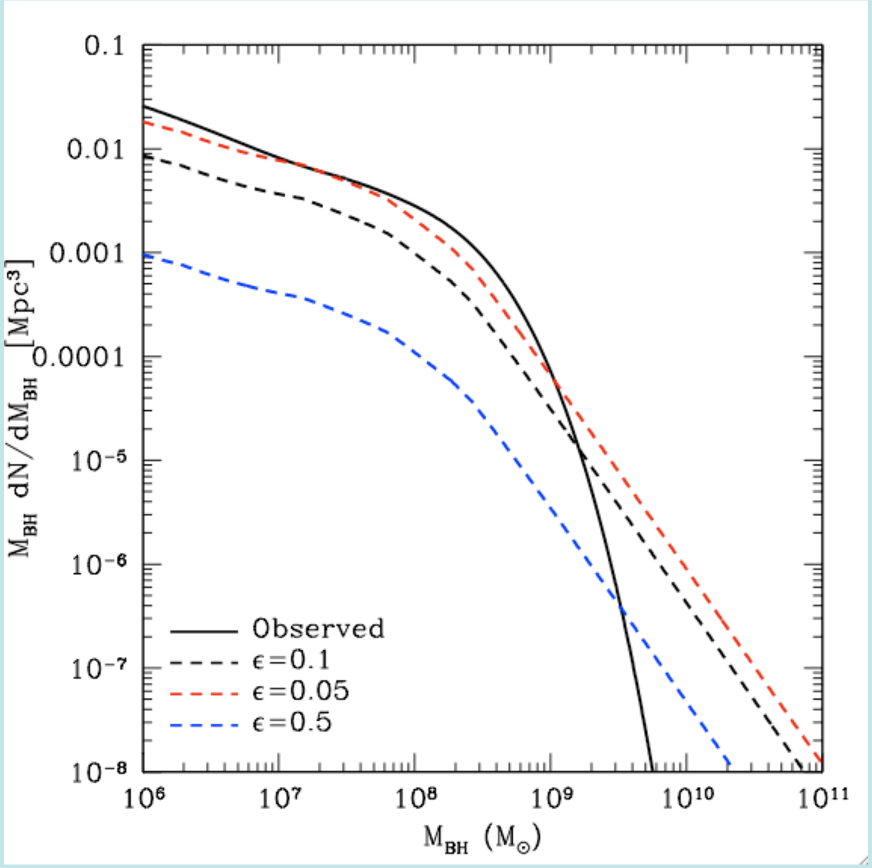
Momentum-driven winds

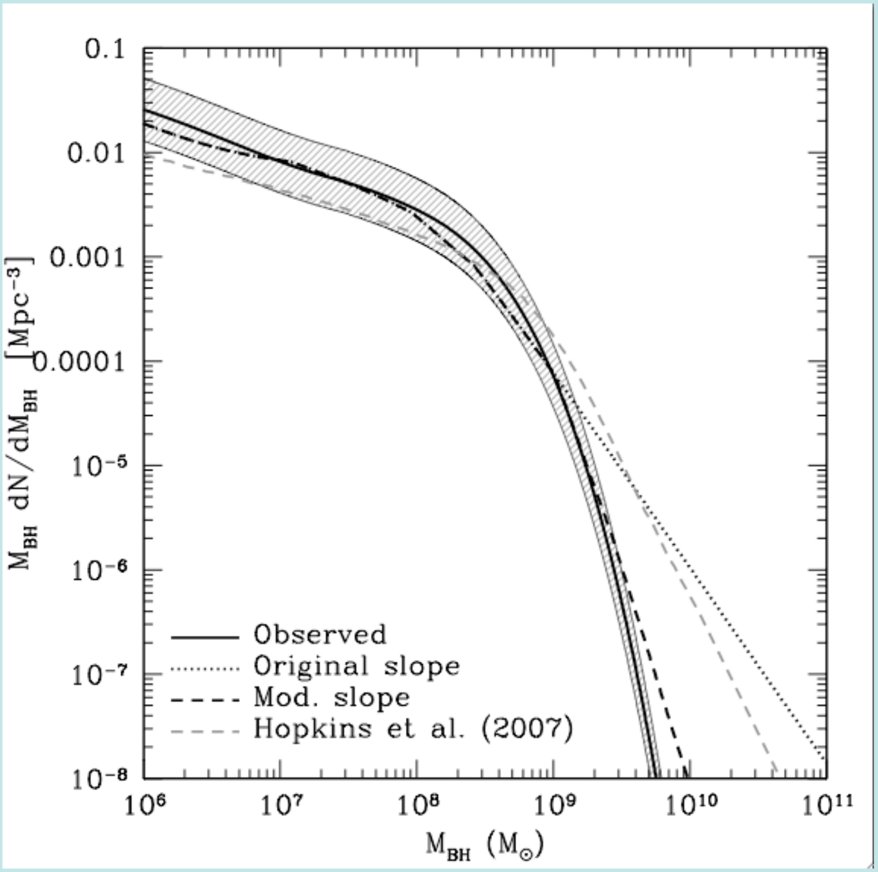
$$L_{crit} = \frac{4 f_g c}{G} \sigma^4$$

$$M_{\bullet,crit} / M_{sun} = 0.12 \eta_{Edd}^{-1} \left(\frac{f_g}{0.1}\right) \left(\frac{\sigma}{km/s}\right)^4$$

Haehnelt, PN & Rees 1998; Silk & Rees 1998; Wyithe & Loeb 2003; King 2004; Thompson, Murray & Quataert 2004; PN 2008

An upper limit to BH masses?

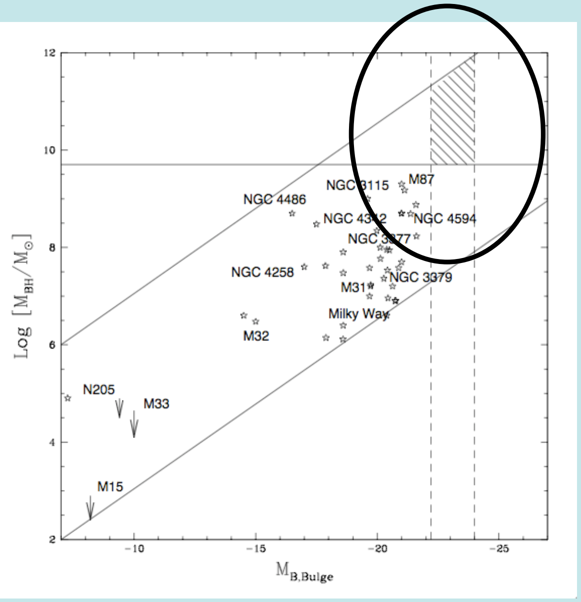


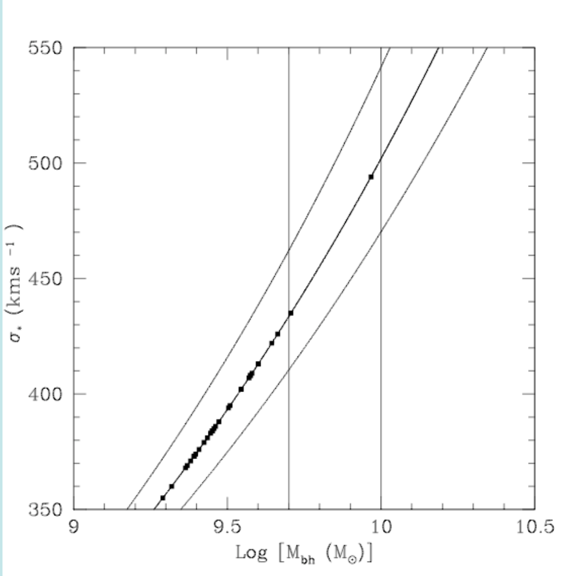


$M_{\text{upper-limit}}$ (BH) ~ few times X 10^{10} Msun for cD galaxies

PN & Treister 2008

Predict existence of UMBHs





Expected in the centers of cDs

SDSS results of nearby cDs and bright ellipticals

Lauer+ 2005; 2006; Bernardi+ 2006

Signatures of mergers of BHs

STELLAR DYNAMICS vs. GAS-DRIVEN

1. Does the gas in a circumbinary disk remove the angular momentum? Observationally, AGN appear to host disks of a few X 0.1 pc
2. Are there electromagnetic counterparts: precursors / afterglow?
3. Does the gravitational wave signature preserve information about cause of merger?

Armitage & PN 2002, 2005; PN & Armitage 2006; PN 2007
Milosavljevic & Phinney 2005
Macfadyen & Milosavljevic 2006
Escala et al. 2004, 2005; Kocsis+ 2007; Dotti+2007; Sesana+ 2006

Will there be electromagnetic counterparts?

Motivation: identification of LISA sources; astrophysics

Merger driven by stellar dynamics:

perhaps (resonant capture of low mass
stars + tidal disruption possible channel)

Merger driven by gas dynamics:

- delayed X-ray rebrightening
- impulsive disk response to change in potential (probably unobservable)
- bright, variable precursors
- Pre-merger variability

Electromagnetic Counterparts from Mergers in Thin Disks

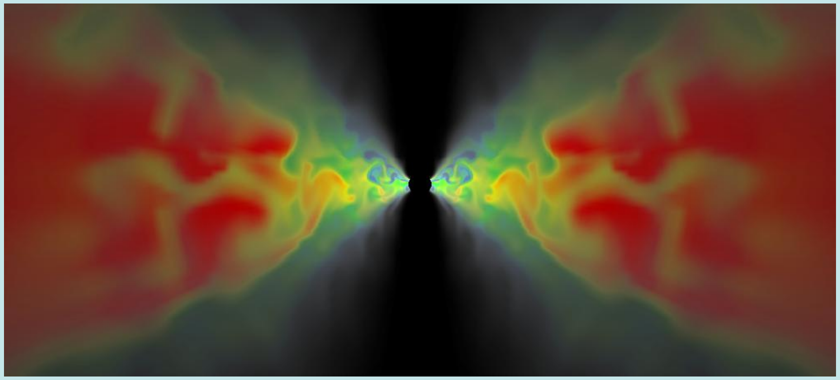
Prospects for detecting counterparts depends on:

- <u>emission physics</u> – radiation *per unit mass* of gas due to:
  1. Binary / merger dynamics
  2. Mass loss
  3. Kick
  4. Viscous evolution post-merger

- <u>astrophysical environment</u> of mergers – typical density, temperature, geometry of gas "near" merger:

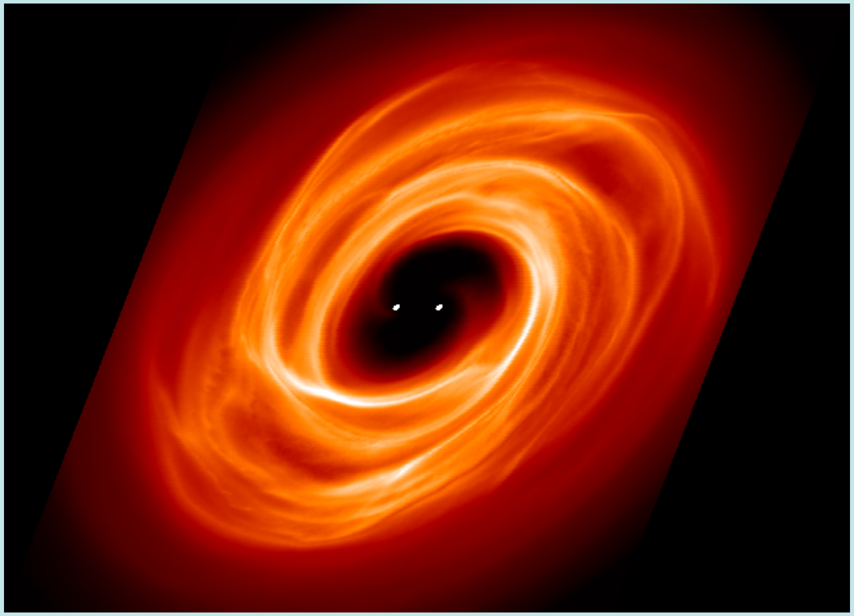
  1. GM / c^2 ($t \sim$ seconds)
  2. $\sim 10^5\ GM / c^2$ ($t_{dyn} \sim$ yr for $10^6\ M_{sun}$; $r \sim 10^{-2}$ pc)

Counterparts from thin and thick accretion flows



Thick disks

- inevitably present
- gas close to horizon (no tidal truncation)
- low density



Cuadra et al. 2009

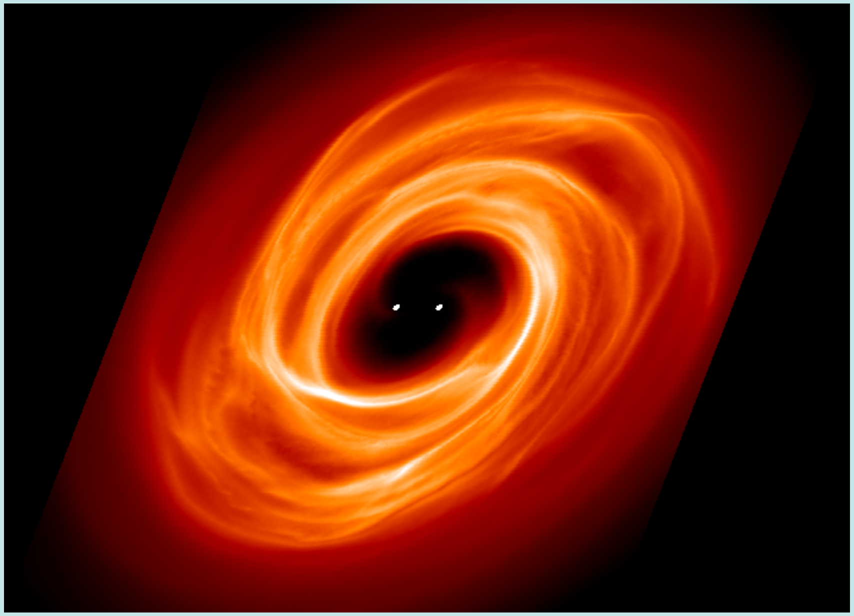
Thin disks

- *may* be common?
- circumbinary gas disk truncated by tides a ~ 100 GM / c^2 *(e.g. Tanaka & Menou 2010)*
- high density
- unclear if circumprimary/secondary disks also exist at merger *(Lodato et al. 2009; Chang et al. 2010)*

Disk evolution before, during and post-merger

Qualitatively well-understood

- binary shrinks by combination of GW losses, torques from circumbinary disk
- gas in disk flows in "viscously", opposed by binary torque

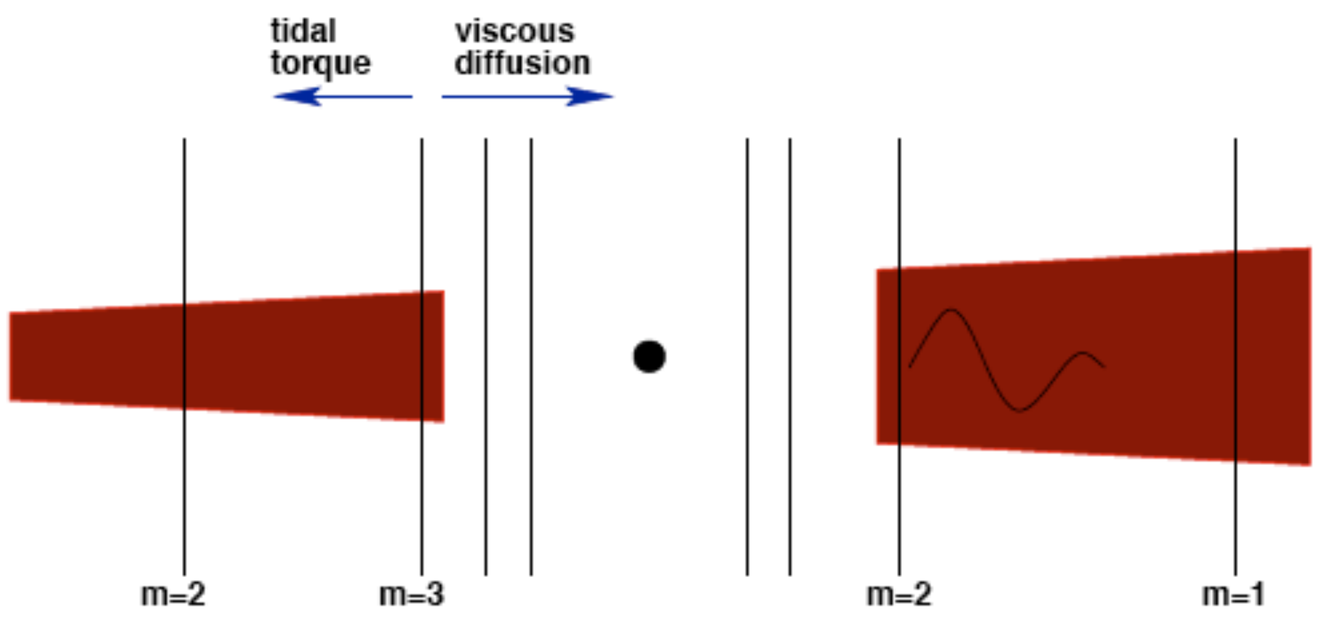


3 distinct time scales (Armitage & PN 2002; 2005)

$t_{GW}(a,e,M_1,M_2)$ – merger time due to gravitational waves
t_{gas} – merger time due to circumbinary torques
t_{visc} – inflow time for gas at inner edge of disk

$$t_{gas} \neq t_{visc} \text{ since } M_{disk} << M$$

Opening up of a gap in the accretion disk and migration



A gap can open when the time scale for opening a gap of width Δr due to tidal torques becomes shorter than the time scale on which viscous diffusion can refill the gap.

Expectations for gas driven mergers

Transition between: gas driven merger at large radius followed by gravitational radiation inspiral at small radius

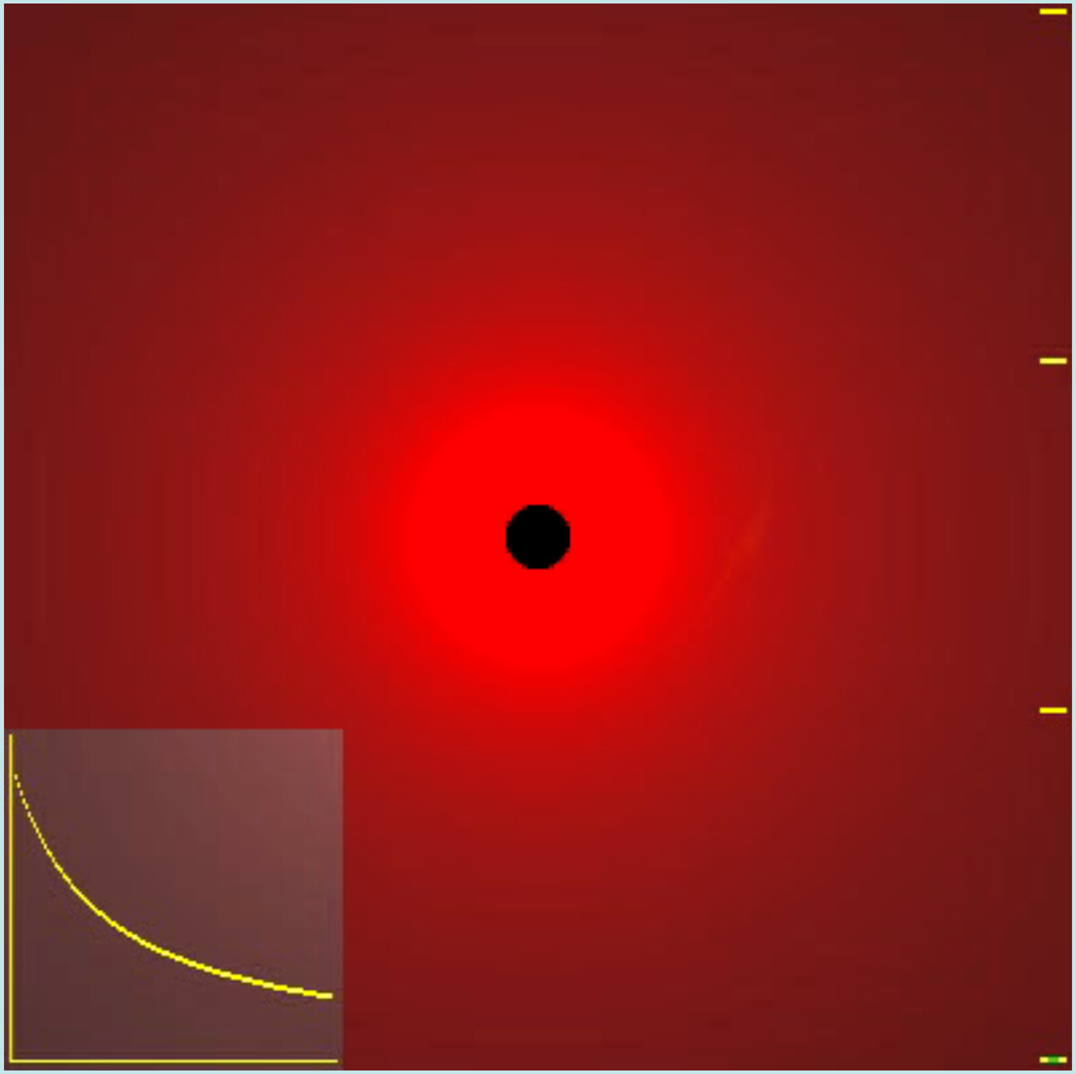
$$\dot{a}_{visc} \approx -\frac{3}{2}\left(\frac{h}{r}\right)^2 \alpha v_K \qquad \dot{a} = -\frac{64 G^3 M_1 M_2 (M_1 + M_2)}{5 c^5 a^3}$$

$$a_{crit} = \left(\frac{128}{5}\right)^{\frac{2}{5}} \left(\frac{h}{r}\right)^{\frac{-4}{5}} \alpha^{\frac{-2}{5}} q^{\frac{2}{5}} \left(\frac{GM_1}{c^2}\right)$$

Transition radius depends on disk parameters and the mass ratio q

Probable consequences: disk interaction induces significant eccentricity to binary probably for q > 0.05 (Papaloizou, Nelson & Masset 2001); possibly for lower q (Goldreich & Sari 2002)

Spin of the primary ® warped disk interior to the binary orbit, timescale for realignment uncertain (PN & Pringle 1998)

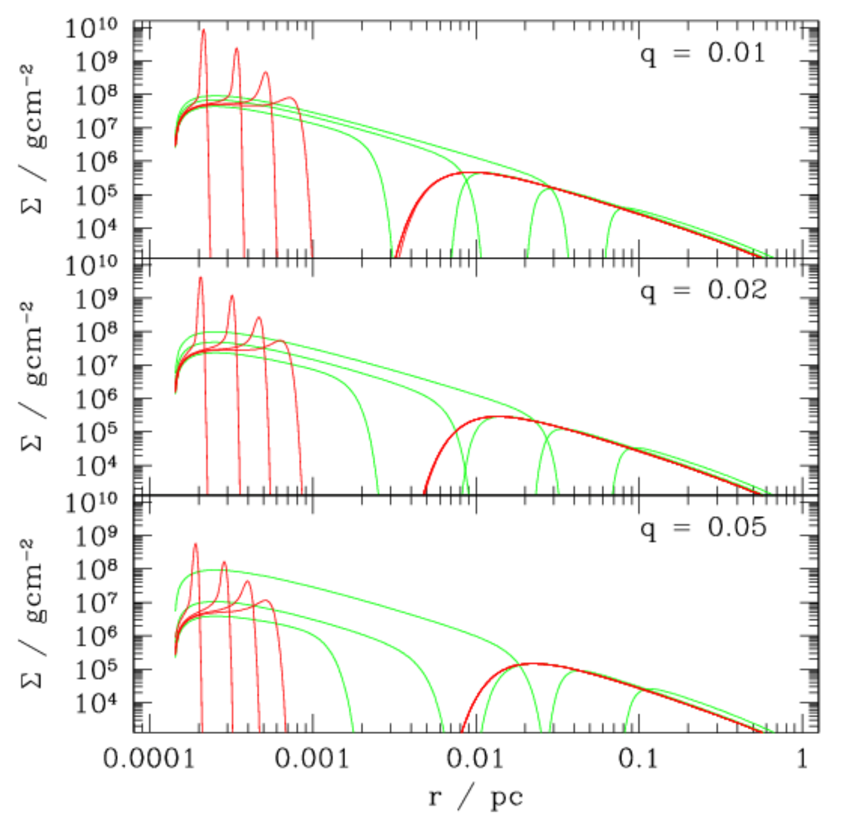


Disk evolution before, during and post-merger

Well-before merger ($t_{GW} >> t_{visc}$) gas disk follows the merger in:

- modulated accretion *(Haiman et al. 2009)*
- if $t_{GW} > t_{gas}$, gas drives merger, e rises *(Armitage & Natarajan 2005)*

Once $t_{GW} < t_{visc}$, binary detaches from disk ($a \sim 10^2\ GM / c^2$)

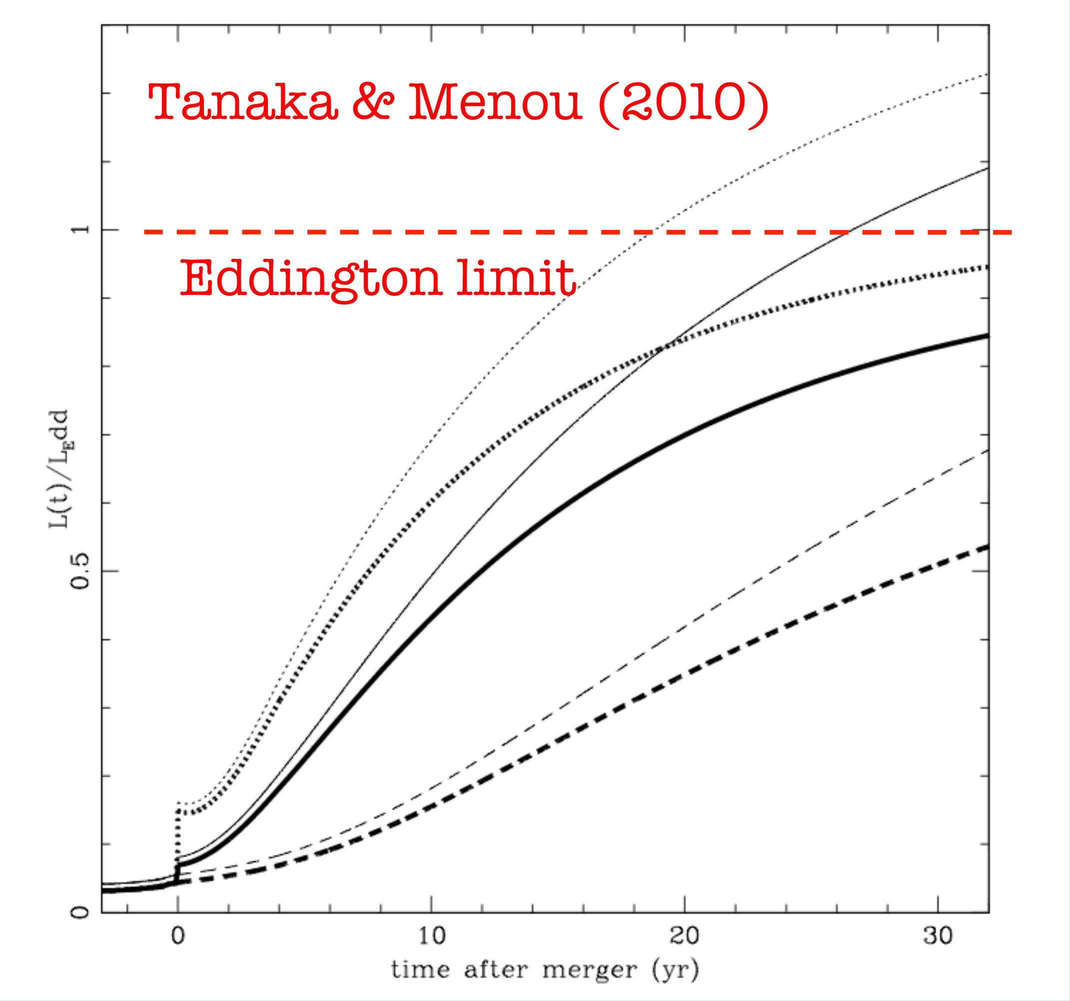


- possible **precursor** if dense gas around black holes is not accreted prior to merger
- **prompt signature** (mass loss, kick, inviscid accretion)
- **afterglow** from viscous refilling of cavity

Armitage & PN 2002

Afterglow from viscous refilling of cavity

Observe an AGN turn on in the X-ray as the missing inner disk is replenished (+ changes in jet properties etc?)



Suggested by *Milosavljević & Phinney (2005)*

Time scale long:

$$\tau \sim 9\left(\frac{M}{10^6 M_{sun}}\right)^{1.3} \text{yr}$$

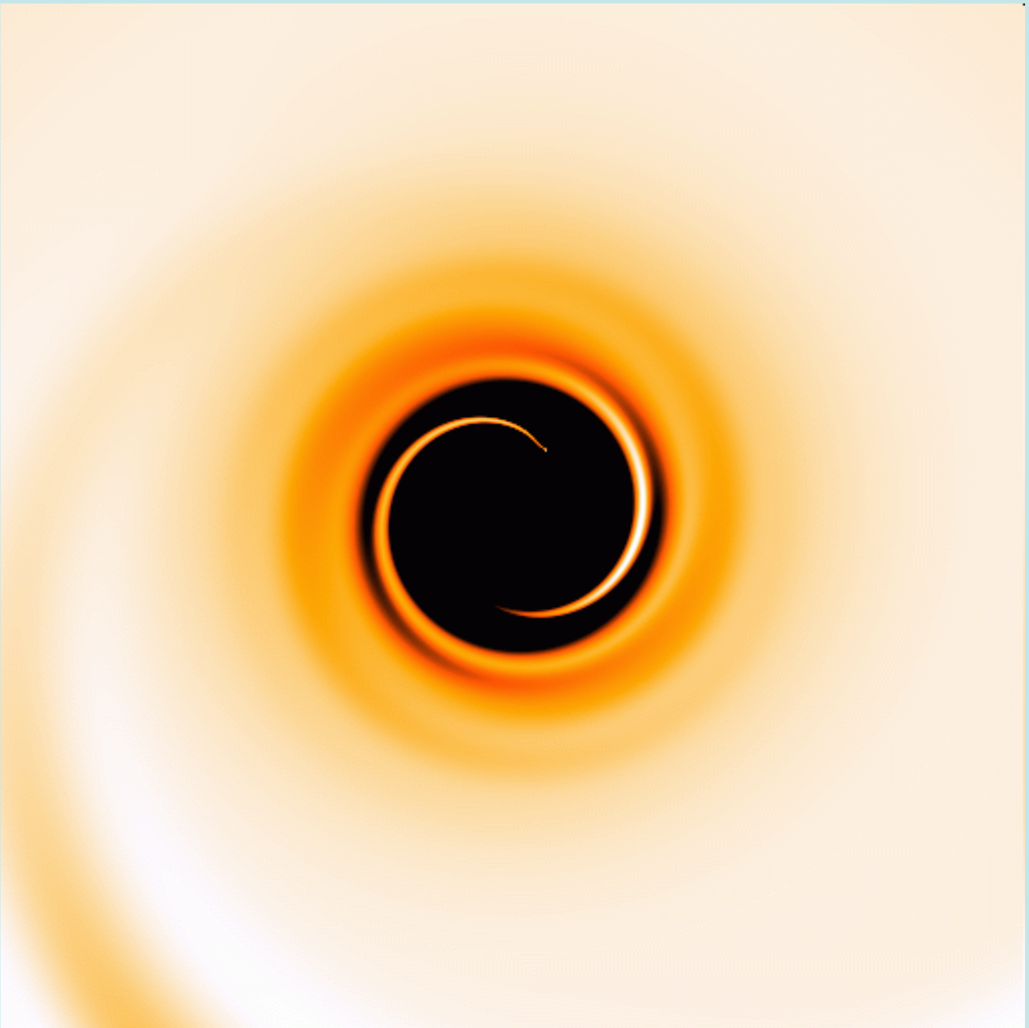
…but significant rebrightening on shorter time scales

Very interesting for accretion physics, but for z > 1 needs “post-*Chandra*” X-ray mission whose existence unclear…

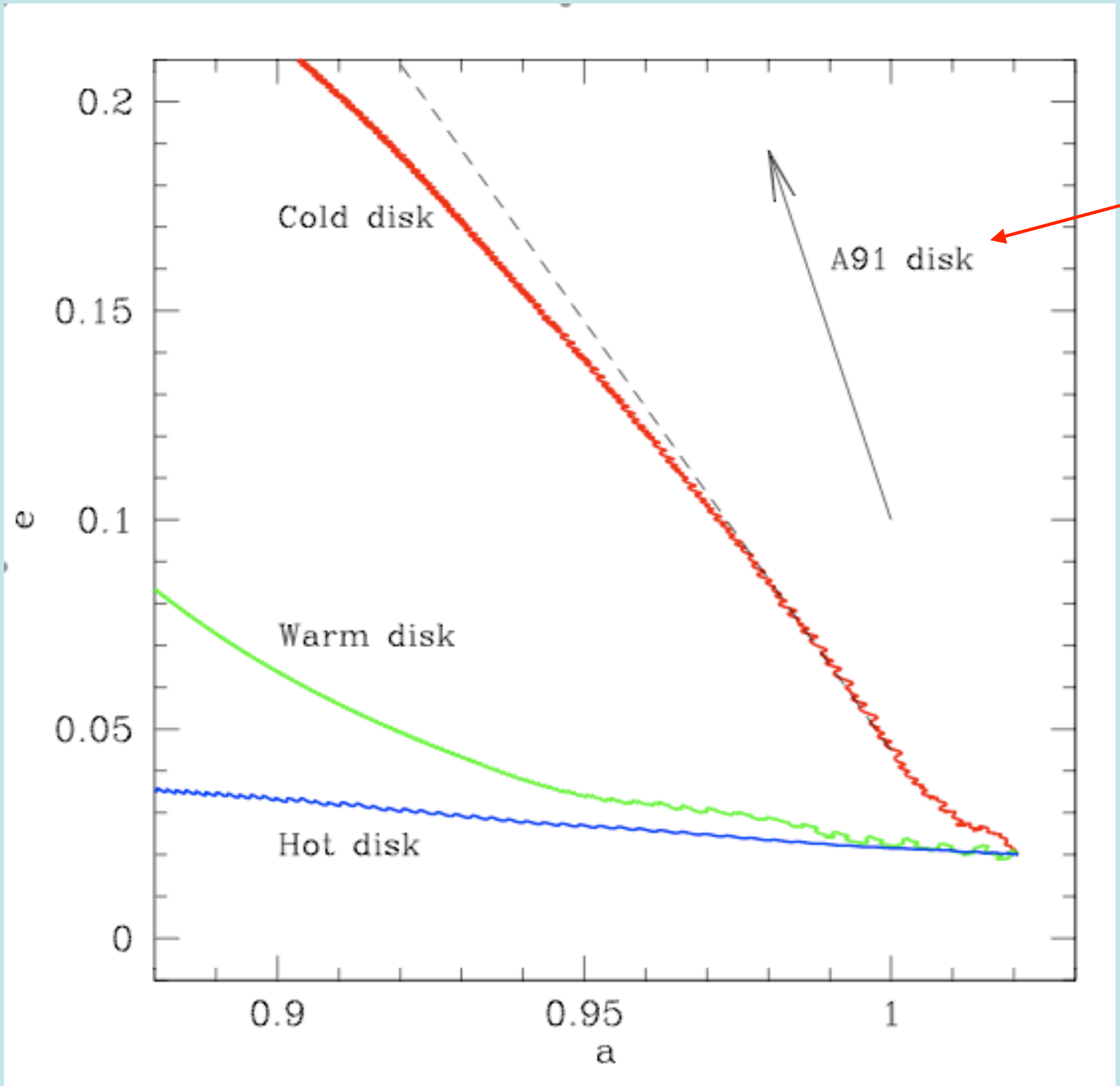
Evidence of merger cause in gravitational waves?

If gas disk drives merger, expect that interaction excites eccentricity of both binary and gas disk

Understood as a consequence of tides clearing gas from nearby resonances that damp eccentricity - e grows easily for $q > q_{crit}(h/r)$



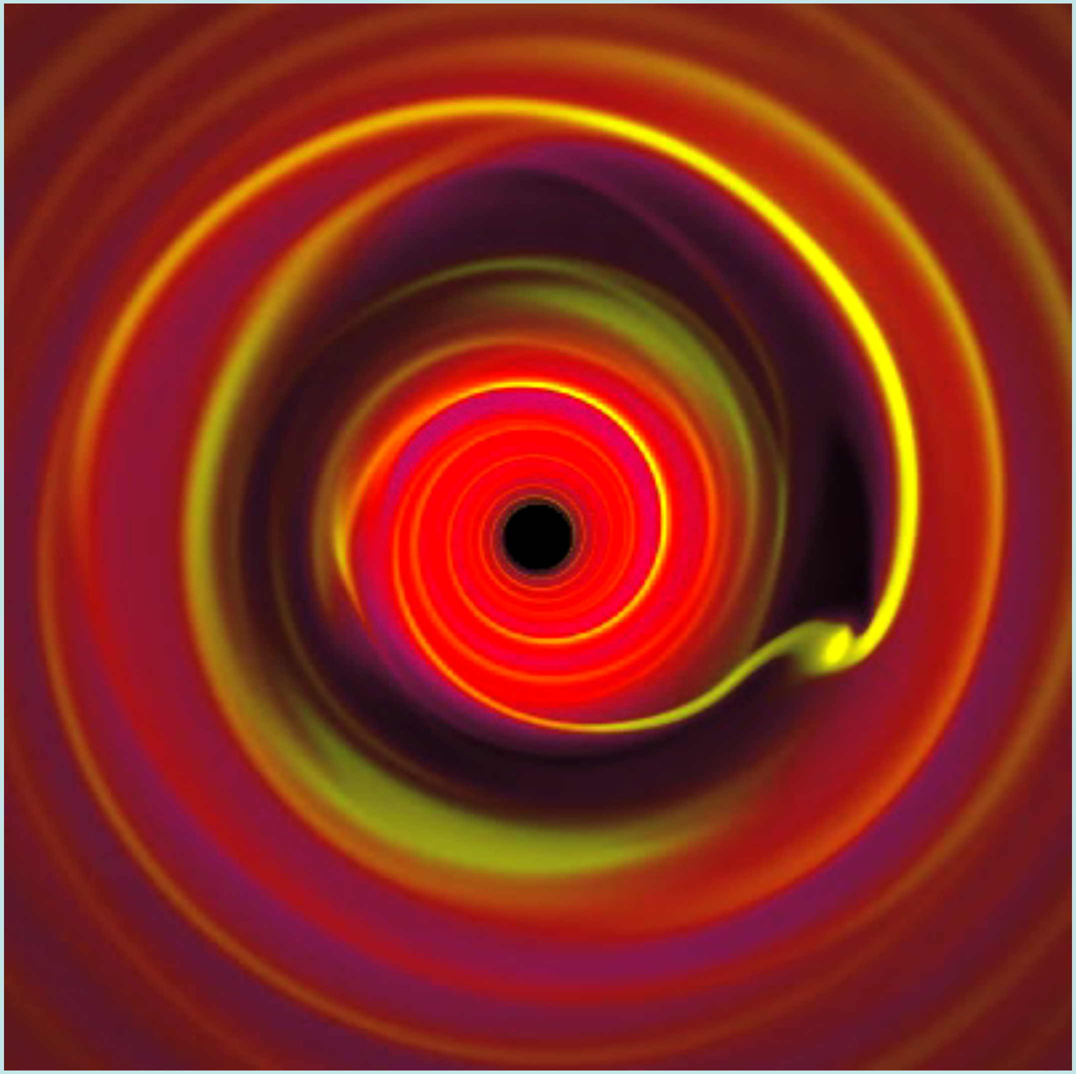
Evolution of the eccentricity



effect seen in SPH simulations of circumbinary disks by Artymowicz et al. (1991)

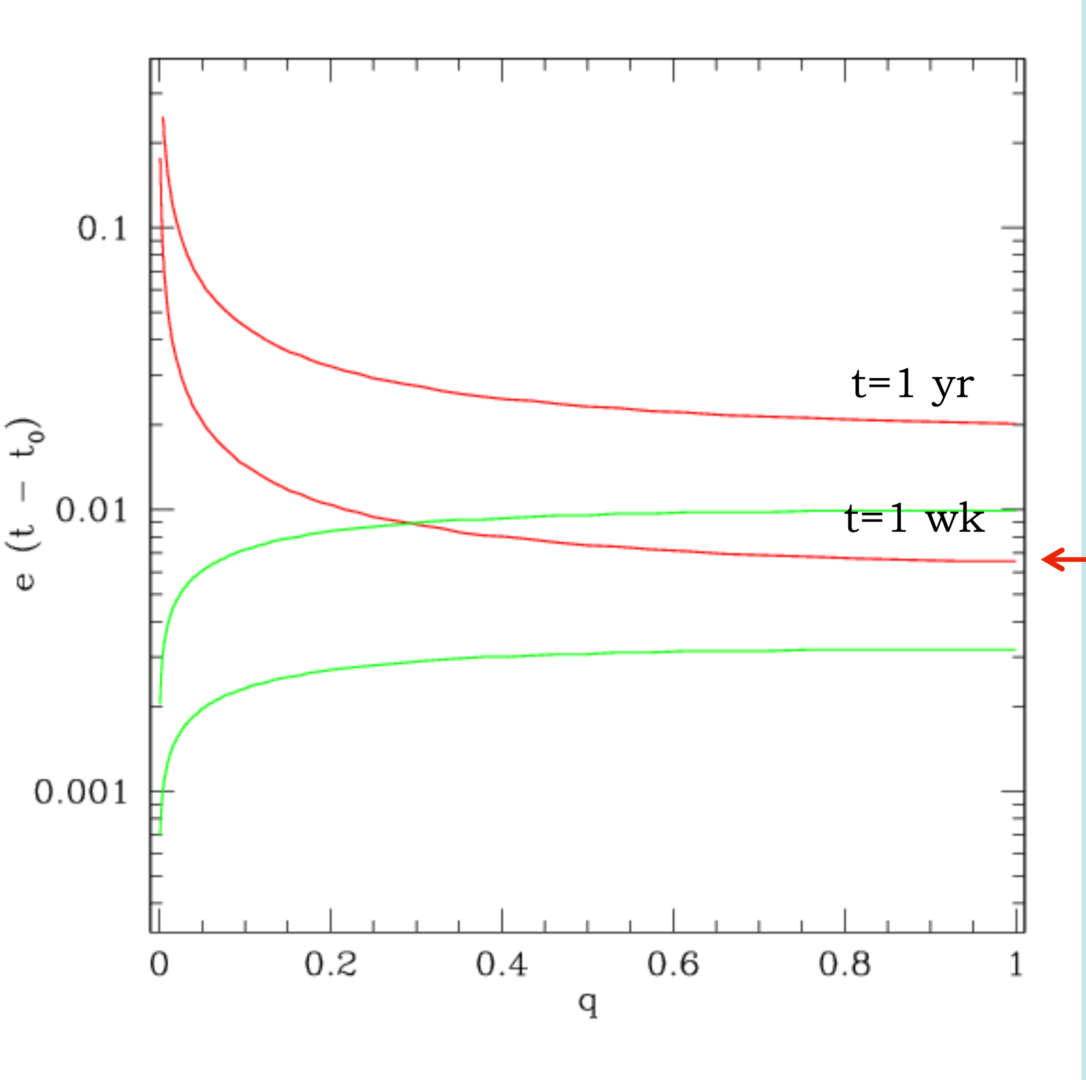
Highest initial e growth for coolest, thinnest disk

Starting with a modestly eccentric orbit



same general behavior as before..

Eccentricity will damp once disk dynamically unimportant, small eccentricity may survive until immediate pre-merger



Transition occurs close to gas / radiation pressure boundary in disk

10^6 Solar masses, merger - 1 week

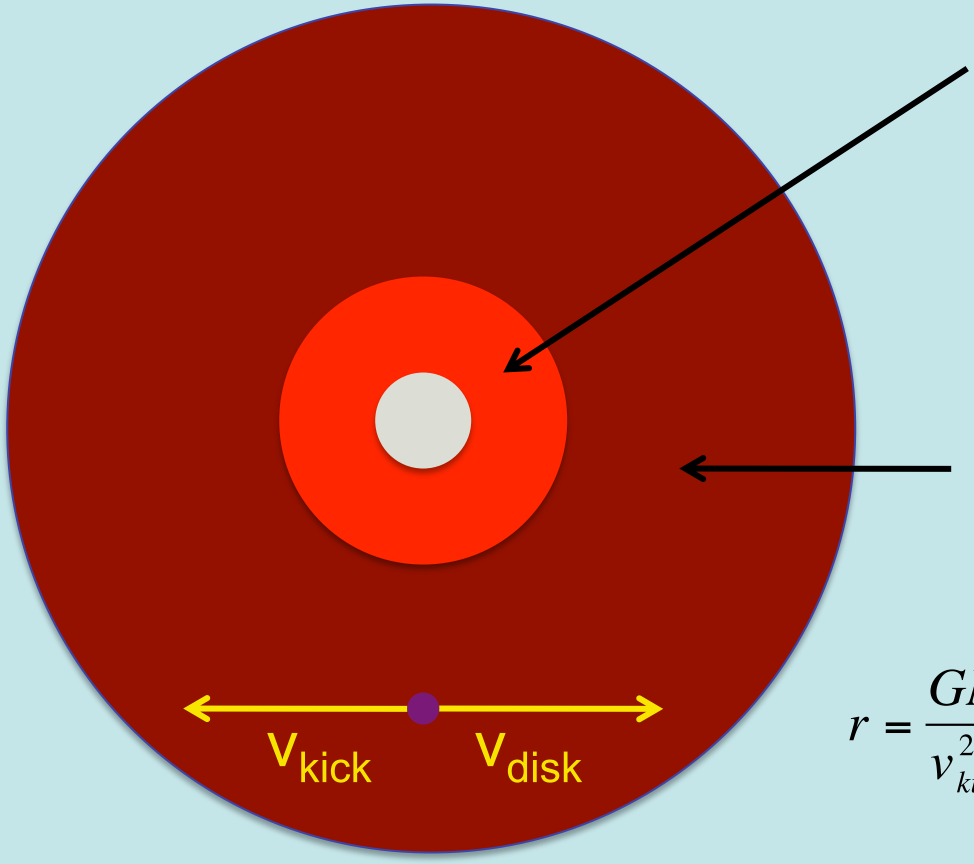
Stronger effect for extreme mass ratios

alpha = 0.01, e_init = 0.25 (gas driven stage), $M_1+M_2= 10^6$

Armitage & PN (2005)

Prompt disk emission from relativistic effects

Mass loss and kick perturb **v**(r,f) in disk, generate (Newtonian) waves that yield afterglow where they steepen into shocks



mass loss dominates, specific energy

$$\Delta\varepsilon = \frac{1}{2}\frac{GM}{r}\left(\frac{\delta M}{M}\right)^2$$

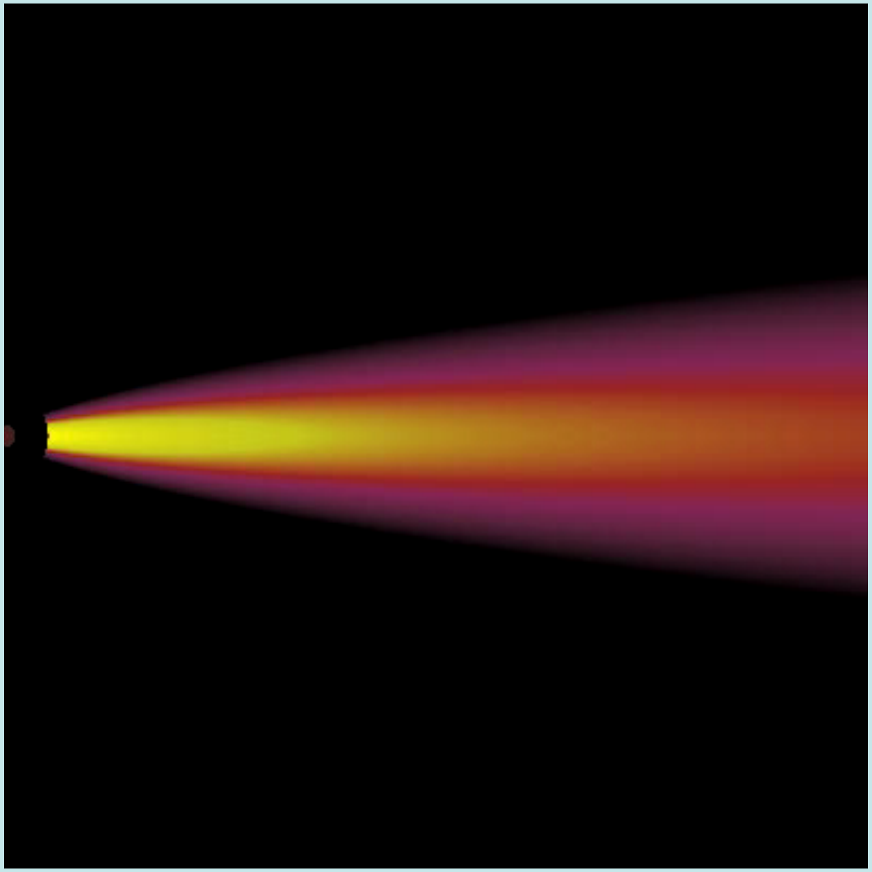
kick dominates, $\Delta\varepsilon = v_{kick}^2 / 2$

$$r = \frac{GM}{v_{kick}^2}$$

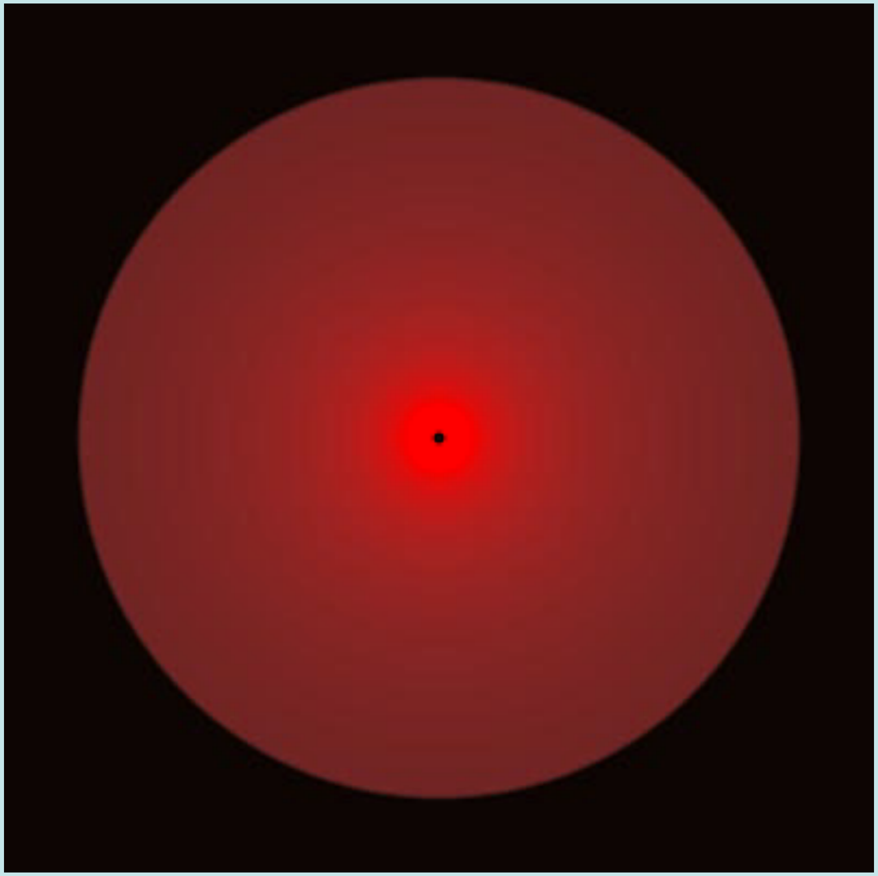
in-plane yields l=0 gas, inviscid accretion yields energy on free-fall time

Relative importance depends on S(r), time scale (accretion often dominates, but on long time scale for massive hole / small kick)

Disk response to kick *(Rossi et al. 2010)*

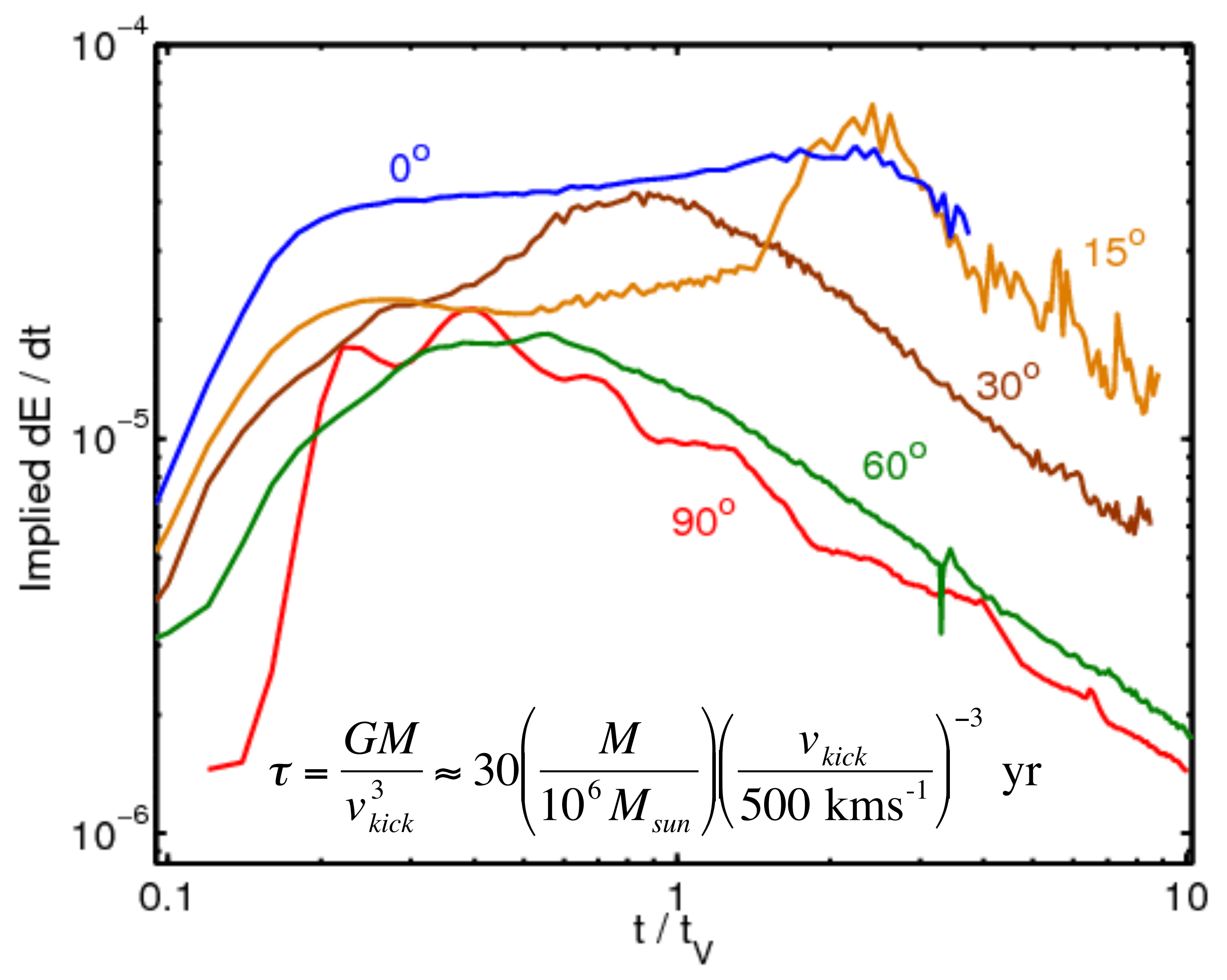


Perpendicular kick, non-linear regime (waves dissipative, numerically converged)



In-plane kick, bulk of integrated luminosity from induced accretion

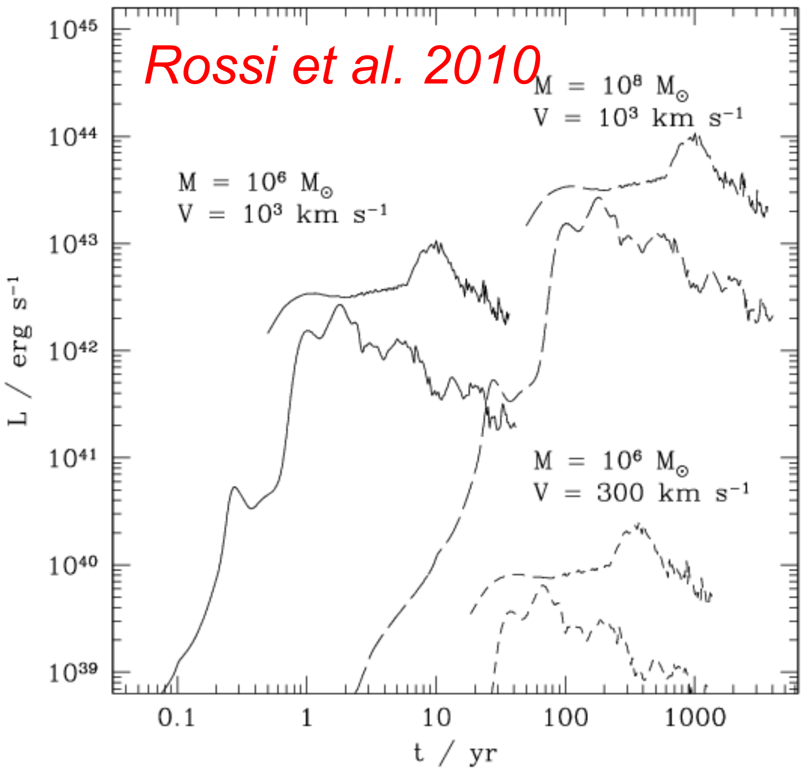
Inclination dependent disk response to kick

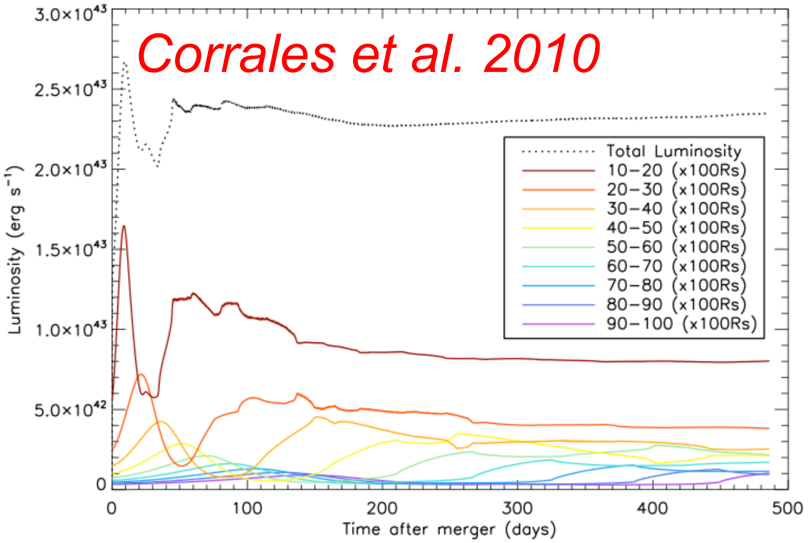


$$\tau = \frac{GM}{v_{kick}^3} \approx 30\left(\frac{M}{10^6 M_{sun}}\right)\left(\frac{v_{kick}}{500\ \mathrm{kms}^{-1}}\right)^{-3}\ \mathrm{yr}$$

Rossi et al 2010

Lightcurves from kicked disks





Bolometric luminosities of ~10% of Eddington possible provided kick velocity is high (500-1000 km / s), with time scales of ~yr *(Rossi et al. 2010; Corrales et al. 2010)*

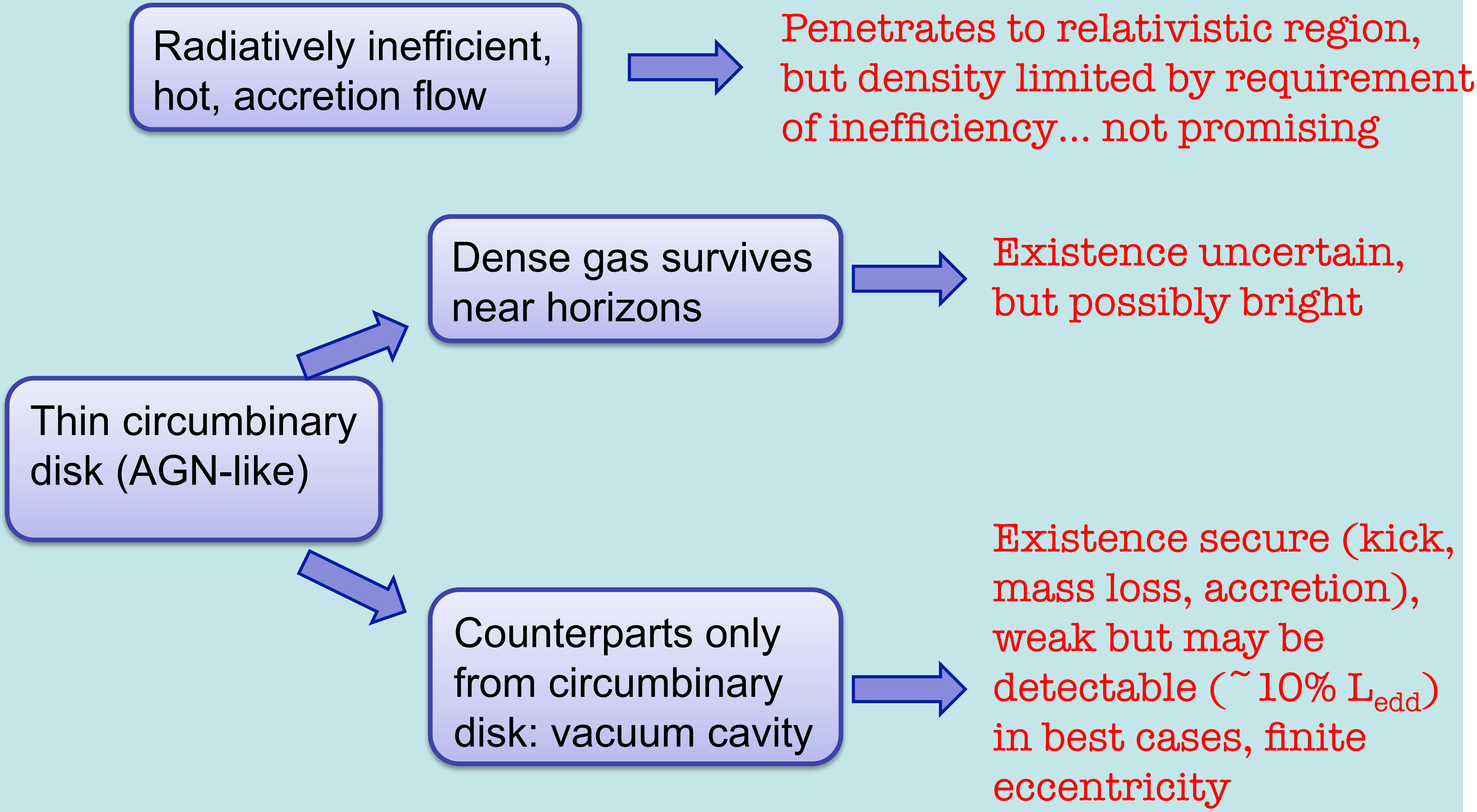
Consistent with prior estimates given varying assumptions as to disk properties *(Lippai et al. 2008; Schnittman & Krolik 2008)*

Counter-parts signaling BBH mergers

- Electromagnetic counterparts: precursors and afterglows
- Needed for LISA to identify host galaxies of SMBH mergers
- On longer timescales impulsive changes to the final BH spin following merger (Hughes & Blandford)
- Changes in directions of jets launched (Merritt & Ekers)
- Final eccentricity before merger (Armitage & PN) if disks catalyze low mass ratio binary mergers
- Potentially detectable perturburations to the disk from BH recoils and kicks

Summary of potential observables from mergers

Do not know typical gas density in mergers well enough to realistically predict likelihood of counterparts… very wide range of scales matter!



Radiatively inefficient, hot, accretion flow

Penetrates to relativistic region, but density limited by requirement of inefficiency… not promising

Dense gas survives near horizons

Existence uncertain, but possibly bright

Thin circumbinary disk (AGN-like)

Counterparts only from circumbinary disk: vacuum cavity

Existence secure (kick, mass loss, accretion), weak but may be detectable (~10% L_{edd}) in best cases, finite eccentricity

Future prospects

Instruments like LSST, LISA will revolutionize these studies with huge amounts of data

Will provide us with larger samples probing the faint end of the QSO LF at high and low redshifts
Finding ~ few thousand blazars will add to our inventory of accreting sources

Will provide us with a more complete census of AGN and BBH in various stages of merging

Will provide large samples to study the nature of correlations between star formation and BH growth

Will provide deeper insights into accretion physics as well fundamental properties of supermassive black holes