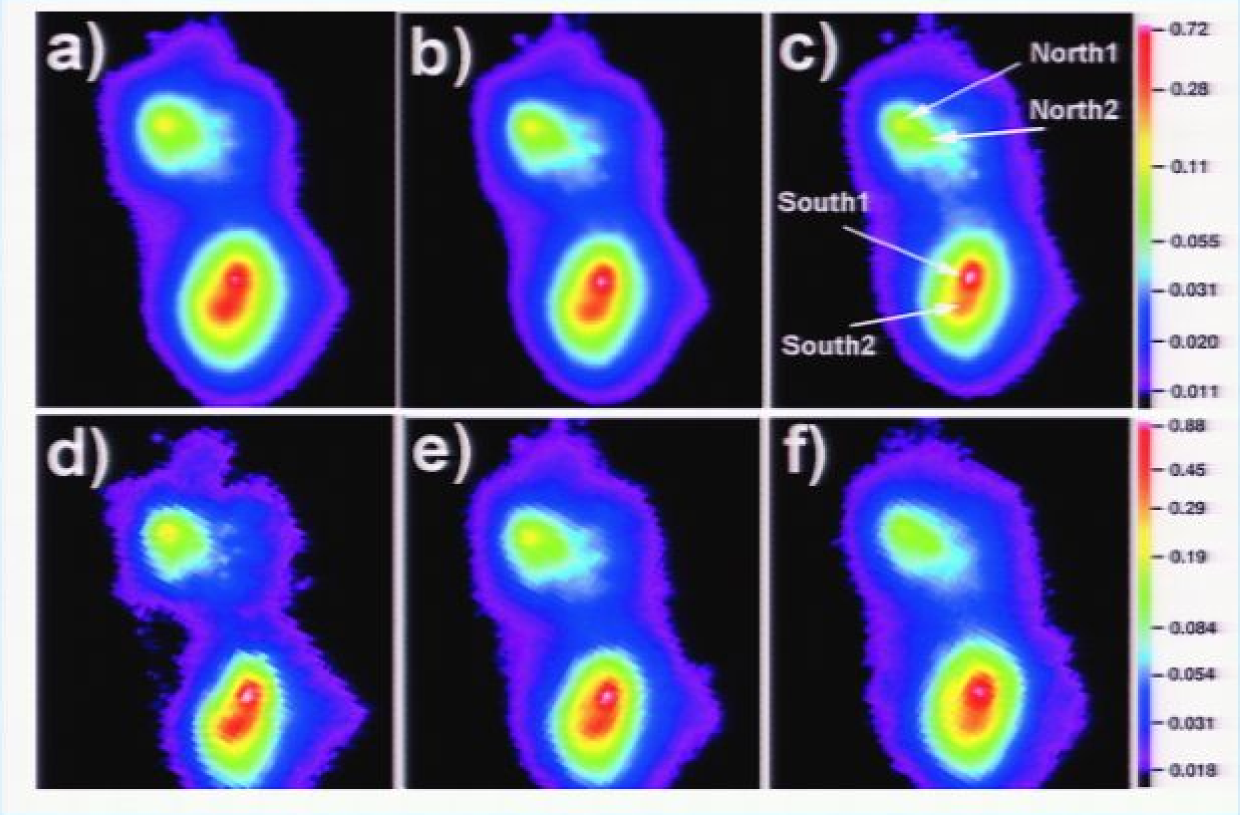
Title: The formation of massive BH seeds at high redshift

Date: Jan 22, 2009 04:00 PM

URL: http://pirsa.org/09010022

Abstract: TBA

The formation and evolution of black hole seeds



Priya Natarajan

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Talk outline

- Motivation
- Constructing accretion histories
- Observational constraints from high and low z
- I. A new channel for producing BH seeds
- II. Evidence for upper mass limits for BHs
- III. New signature in BBH mergers
- Open questions and future prospects

ollaborators: Philip Armitage, Giuseppe Lodato, Ezequiel Treister, Marta
olonteri

Approach to building accretion histories

- Globally averaged constraint (Soltan 1982)

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

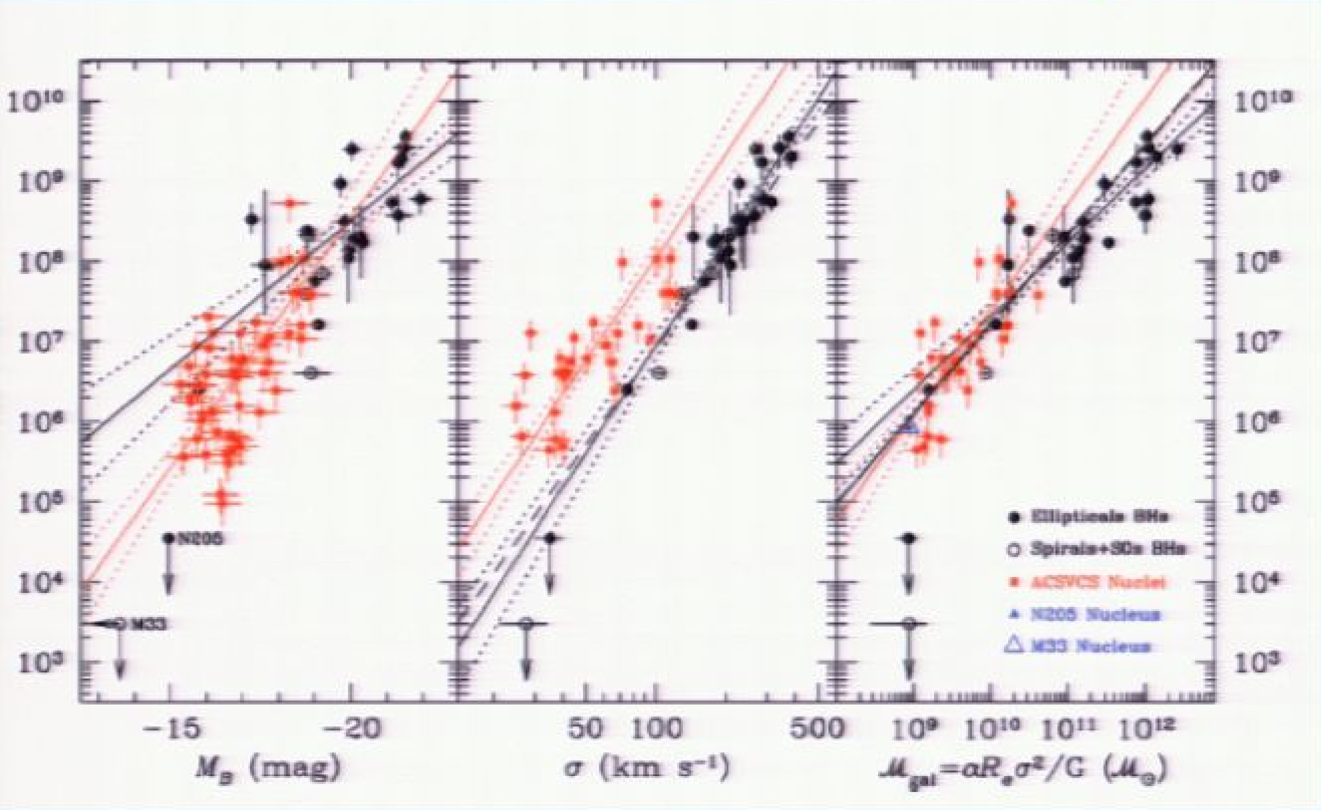
$$E = \iint E(L,t)\,dL\,dt = \frac{4\pi}{c}\int dz\,(1+z)\int dS\,S\,n(S,z),$$

$$\rho_{\rm BH} = \frac{1}{c^2 \varepsilon}\int_0^{13.1} {\rm d}t \int_0^{\infty} {\rm d}\ln L\, L\,\Phi(L,t).$$

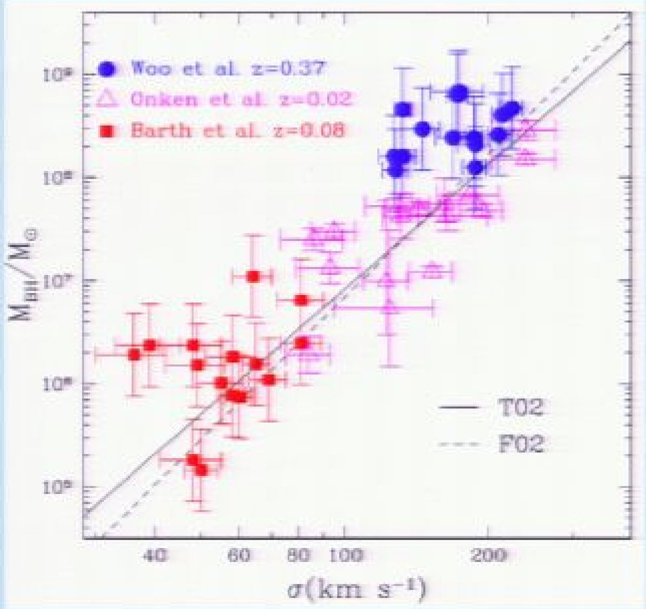
- Continuity argument for mass accumulation as a function of time (Small & Blandford 1992)

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

Observational estimates of masses of central massive objects



BH mass determined from the size of the BLR and vel disp. of the H_{beta} line



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

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

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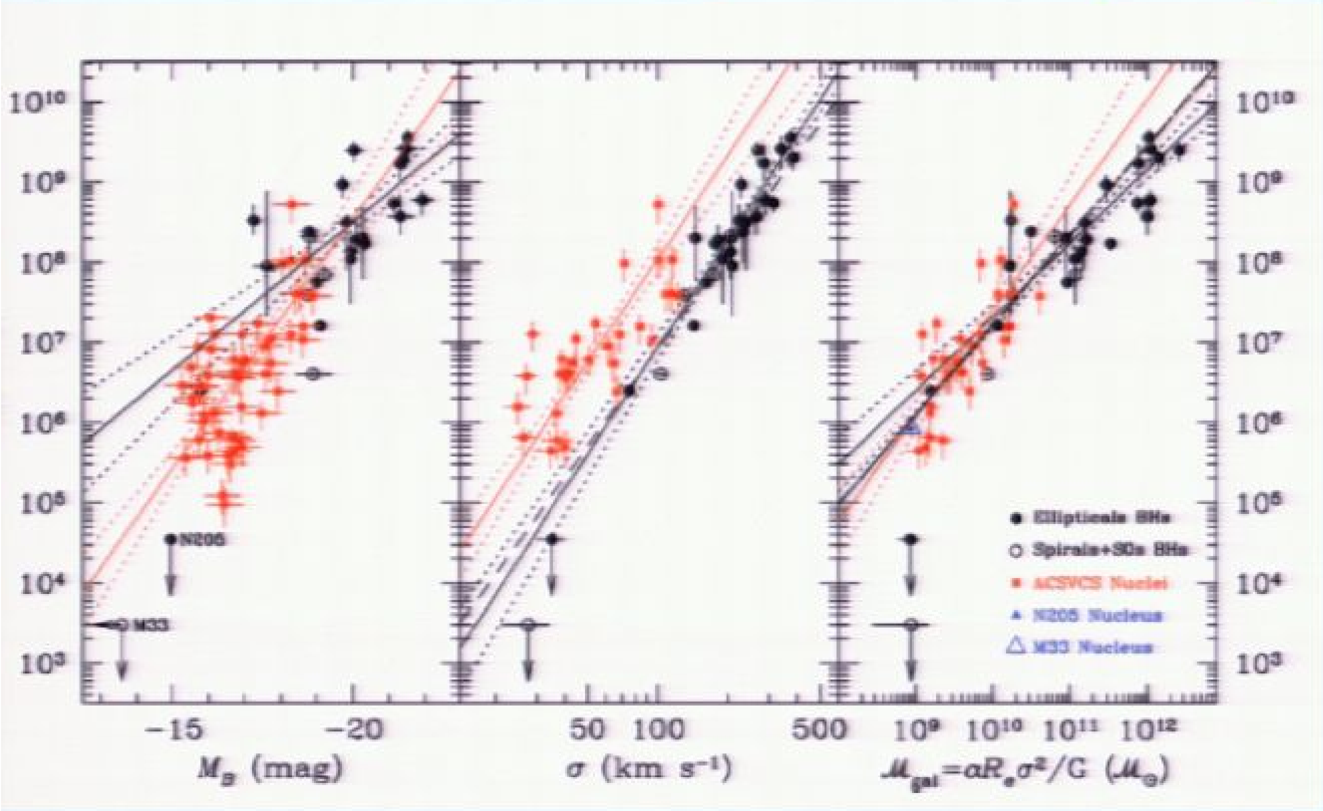

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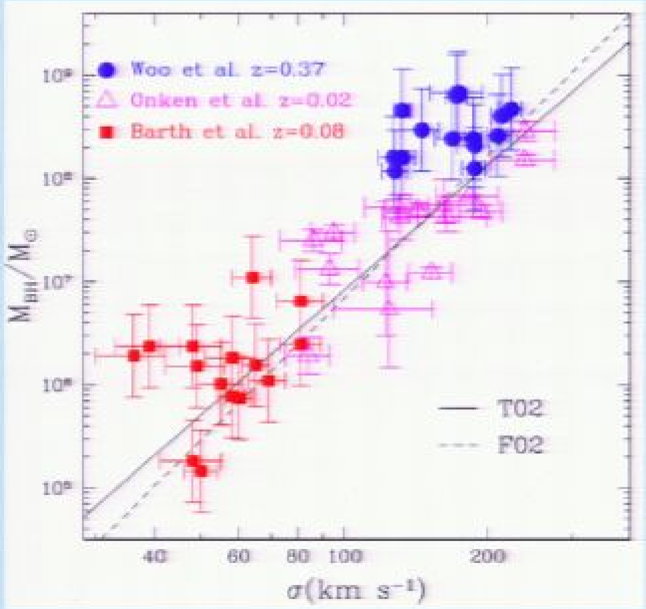

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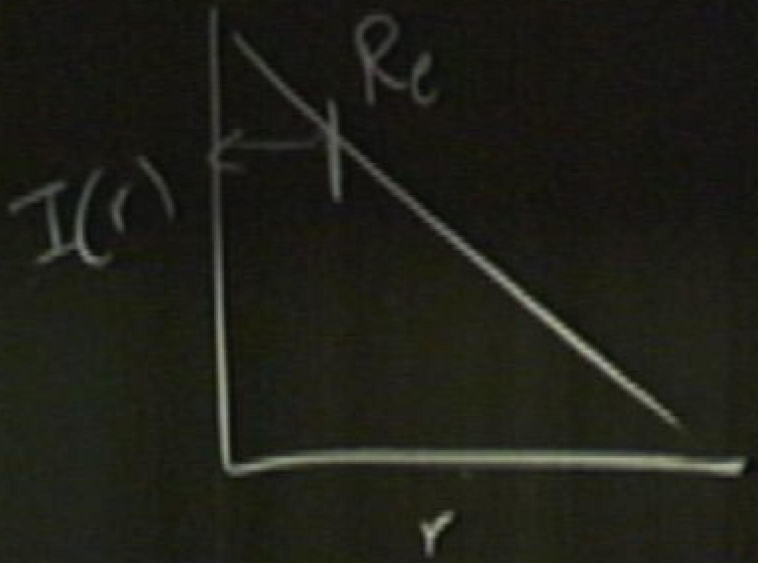
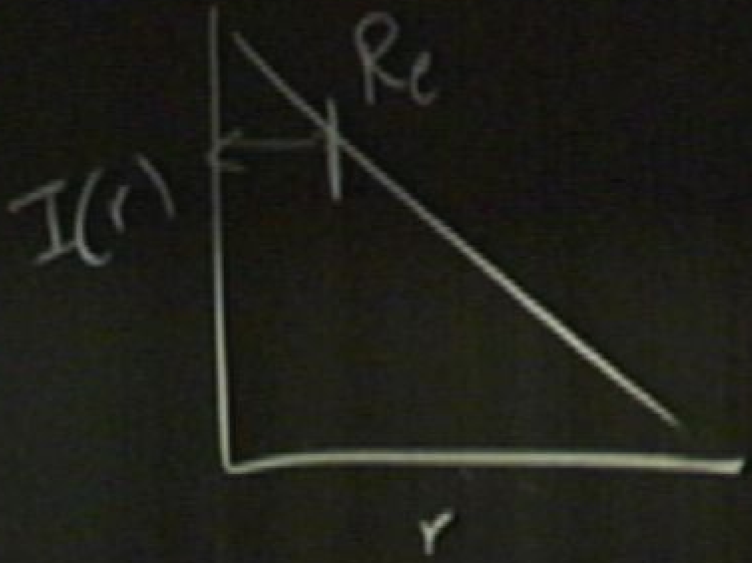
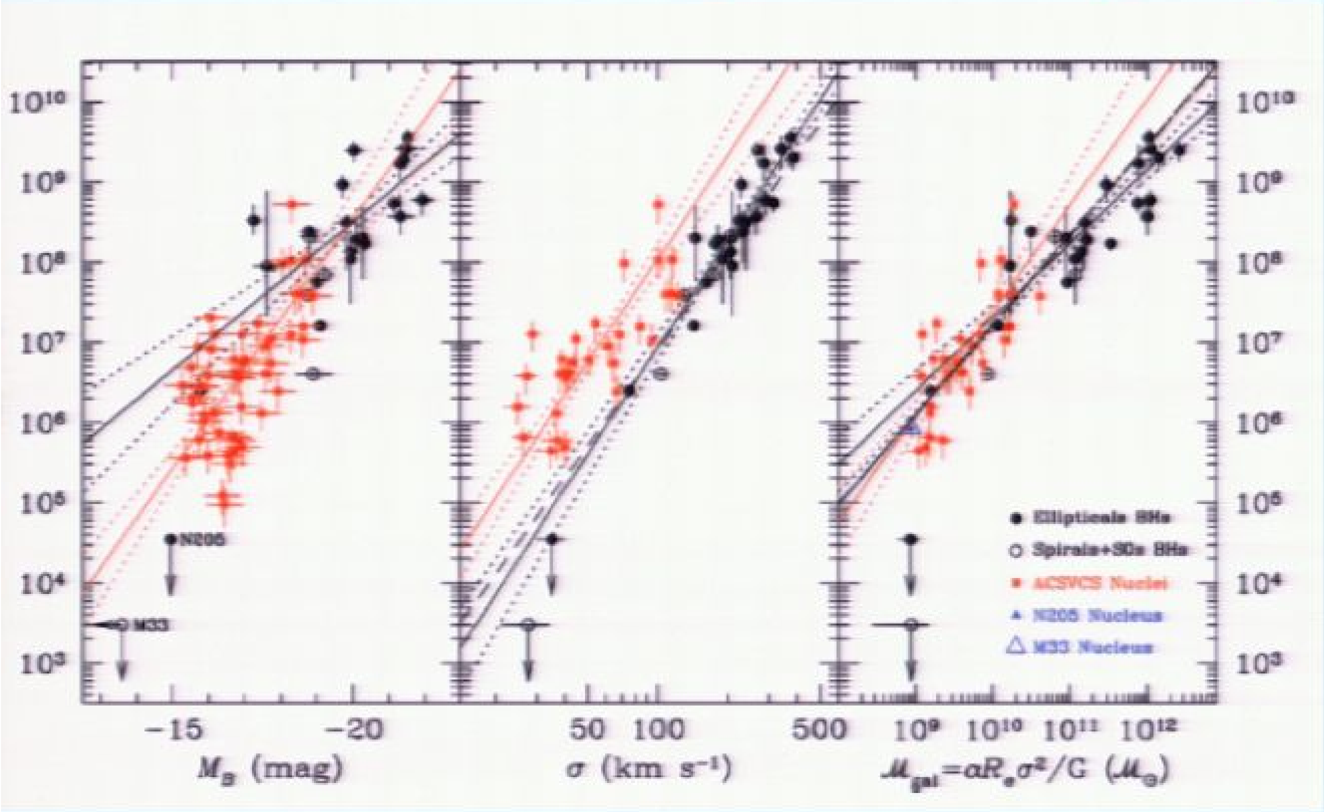

R_c
$I(r)$
r



$$e^{-(R/R_e)^{1/4}}$$

Observational estimates of masses of central massive objects



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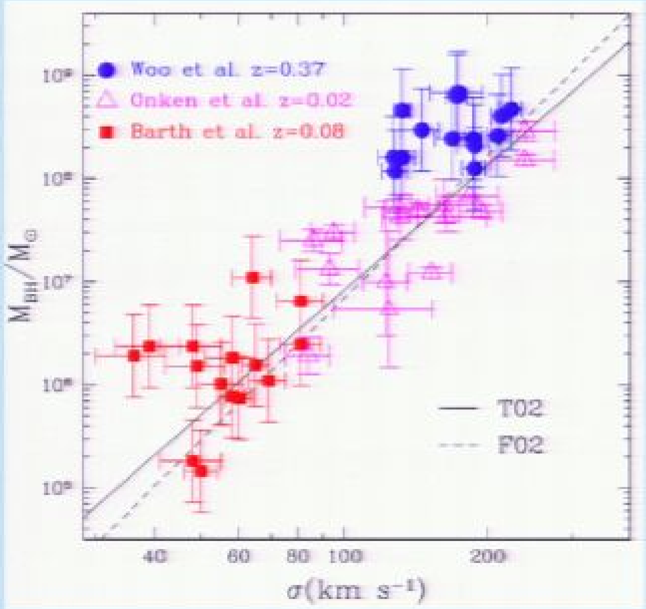

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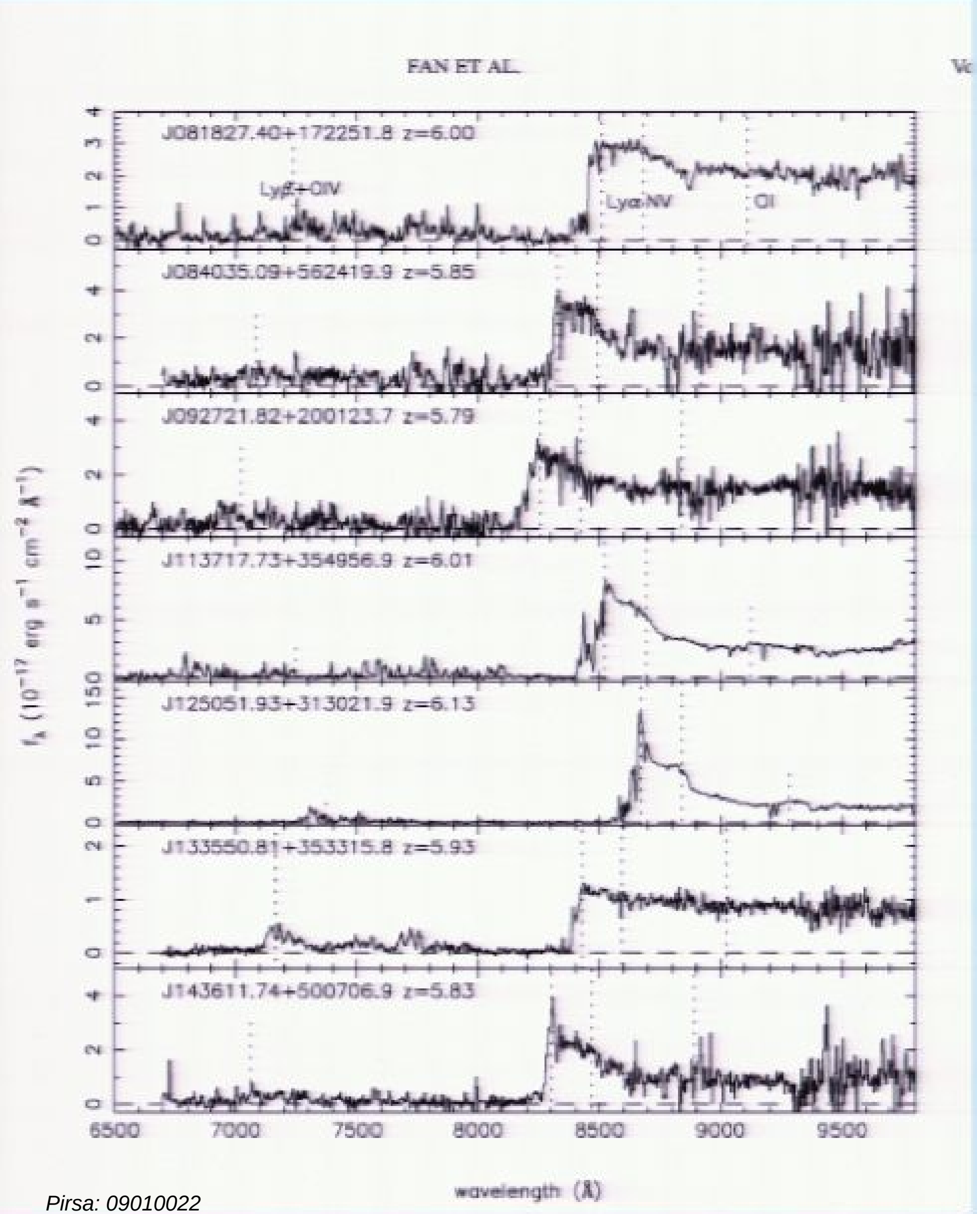
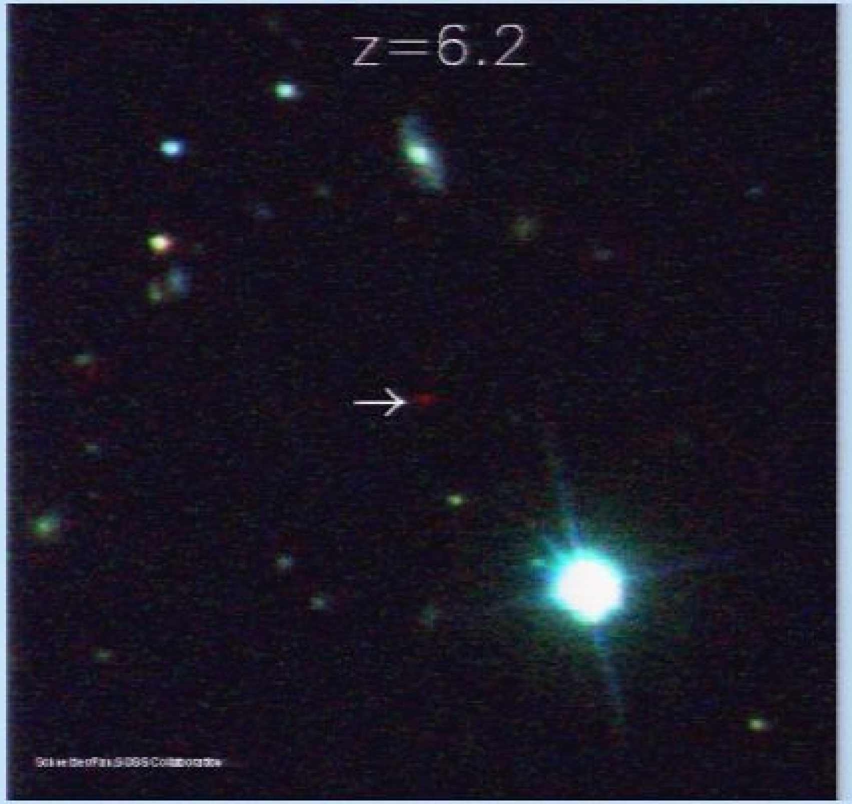
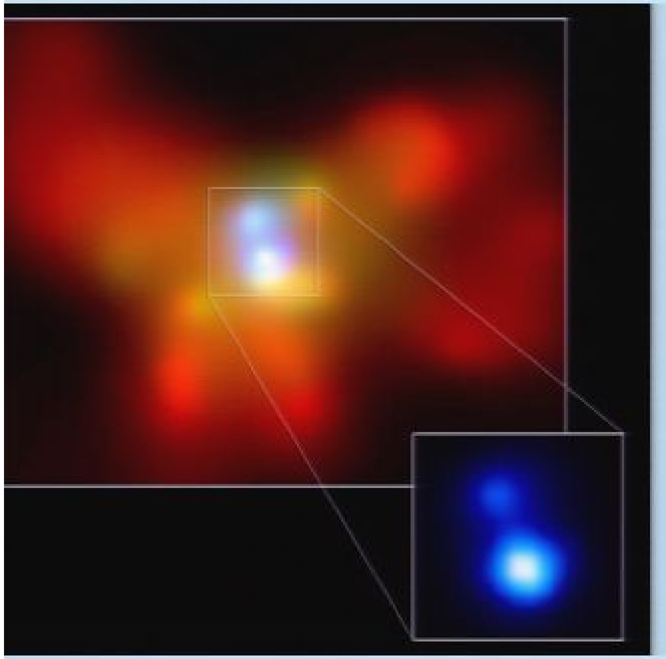
Abundance and LF of quasars at high and low z





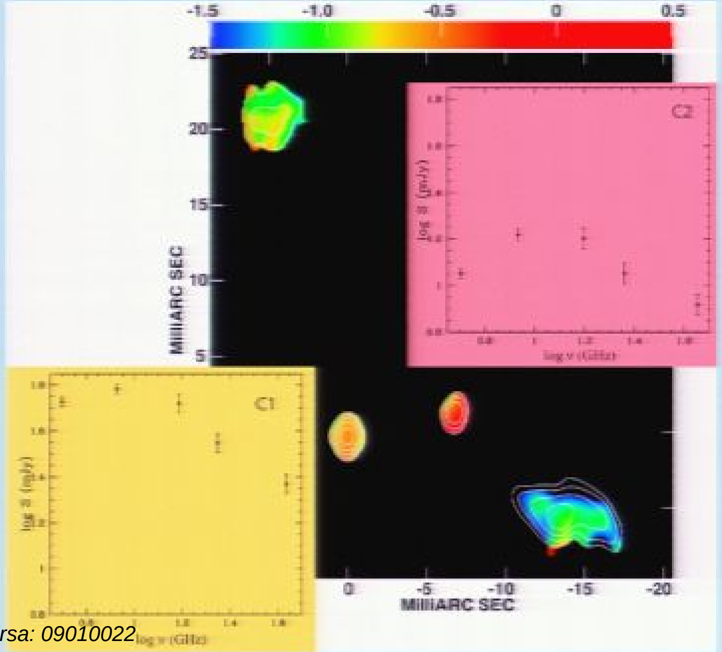
Most recent census from SDSS and 2dF Fan+ 2001; Croom+ 2004



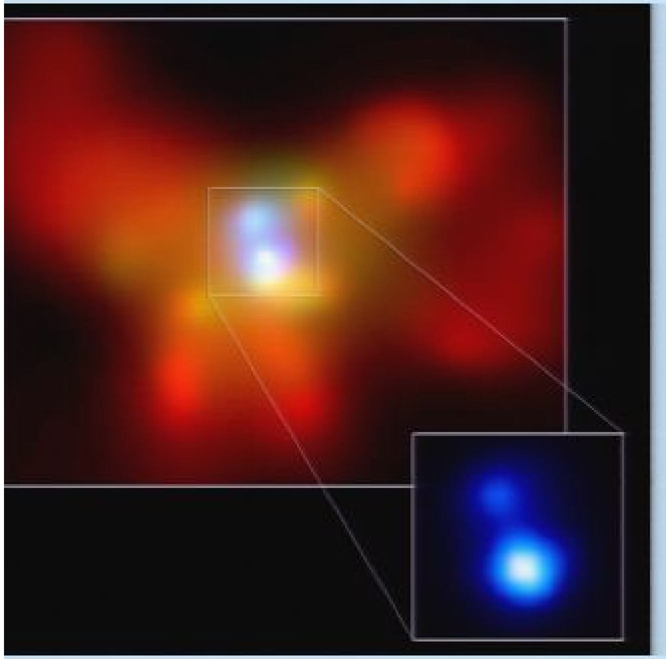
Observationally

Handful of identified pre-merger
binary black holes

NGC 6240: d ~ kpc
Komossa+ 2003; 2007; 2008



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



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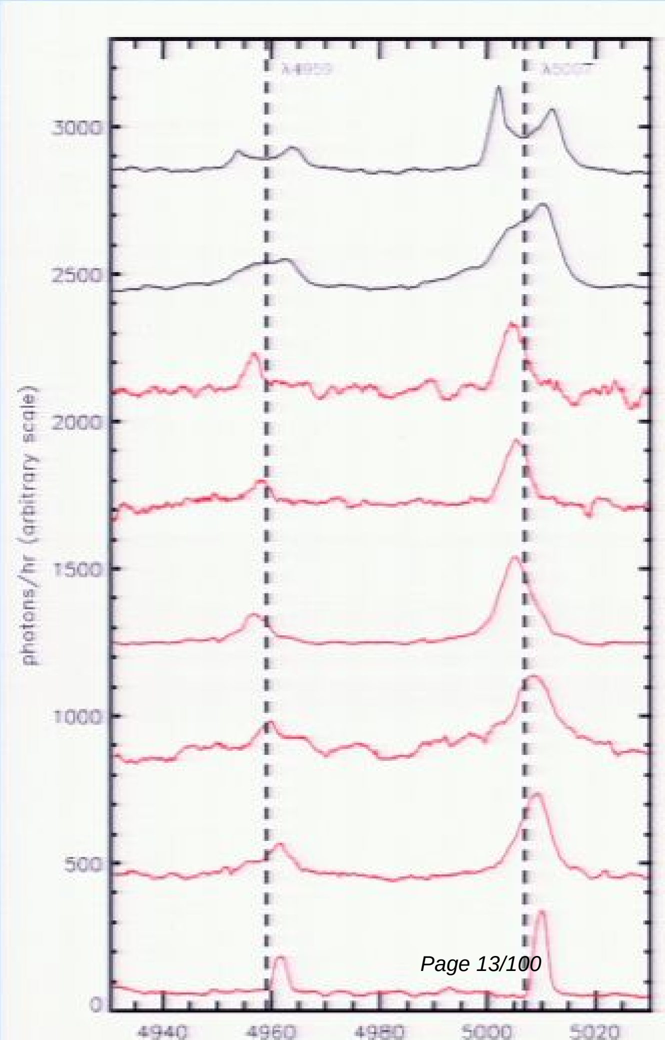
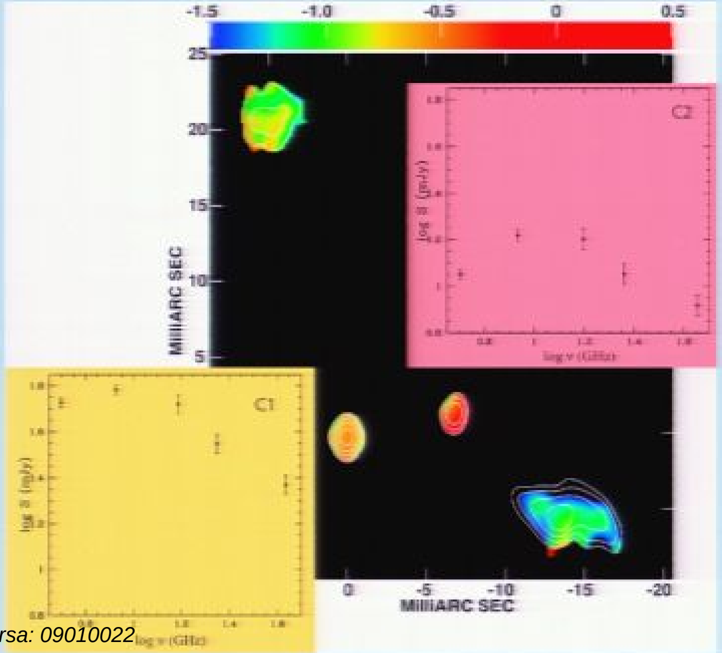
Comerford+ 2008?





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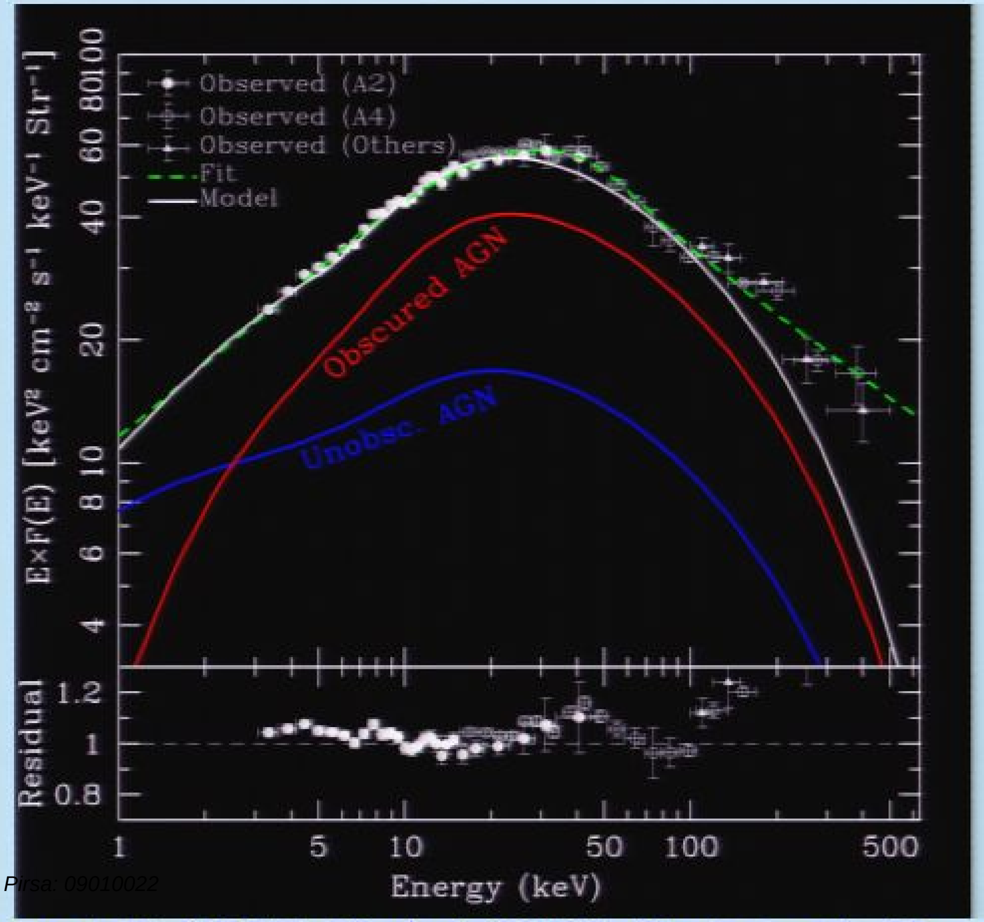
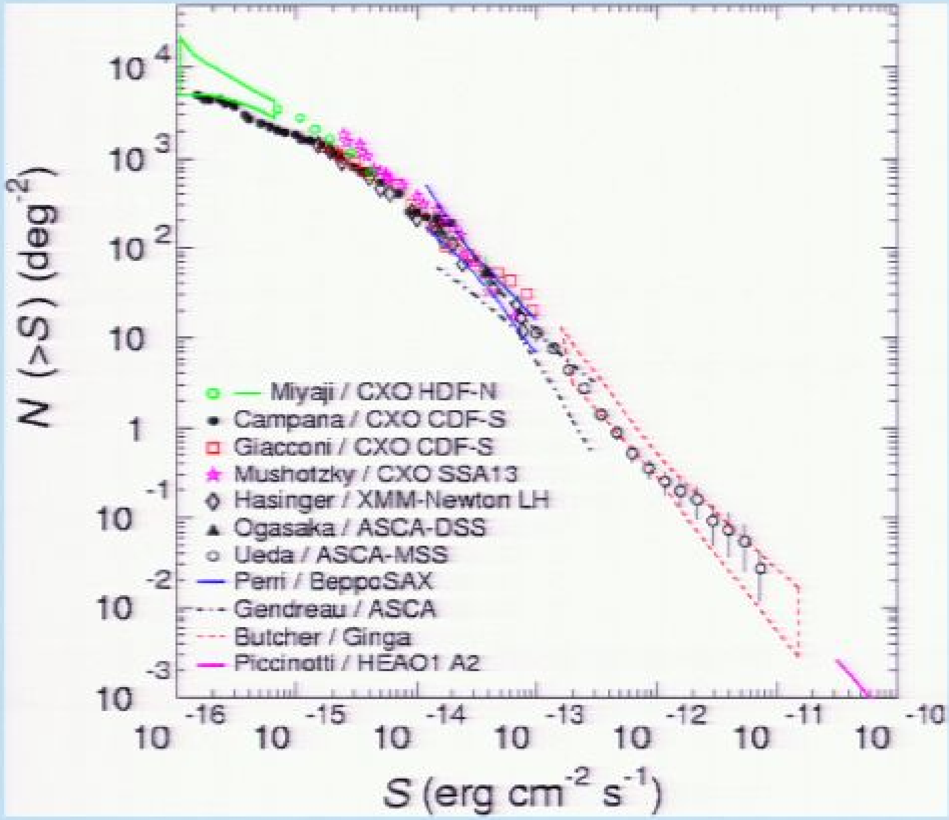
The X-Ray Background (XRB) and number counts

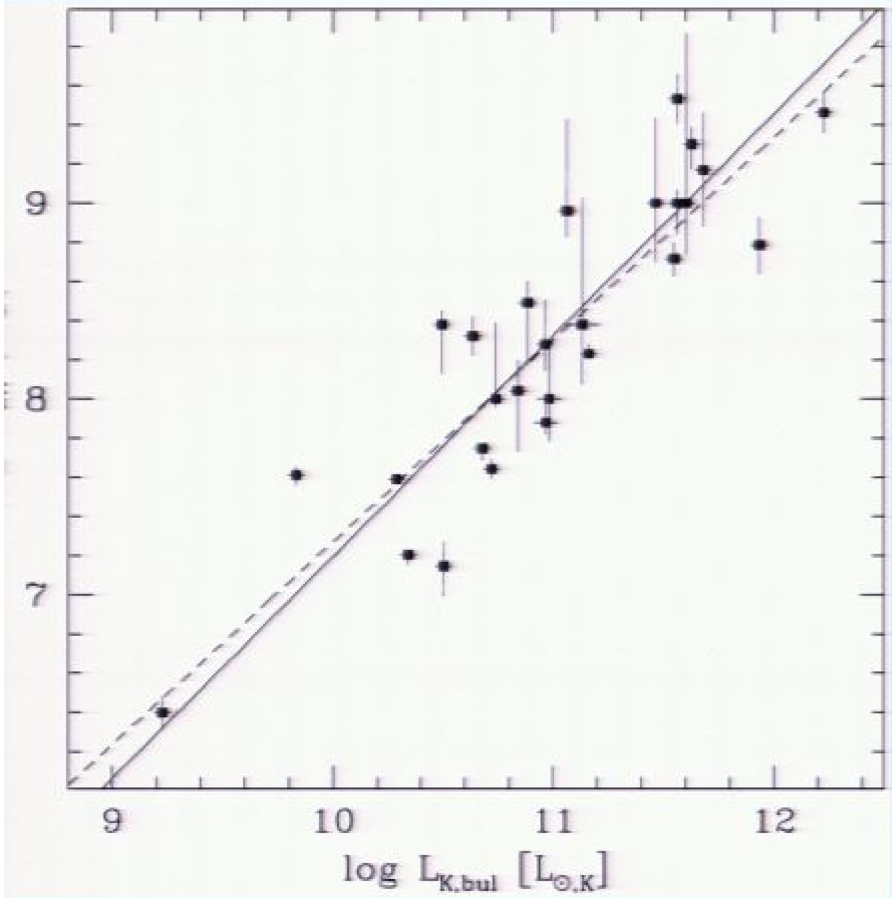
- The XRB is the integrated emission from all AGNs in the Universe, the energy density peaks at ~ 30 keV
- The shape of the XRB indicates that most of the AGNs are obscured, harder energies needed to detect the contribution of these obscured sources



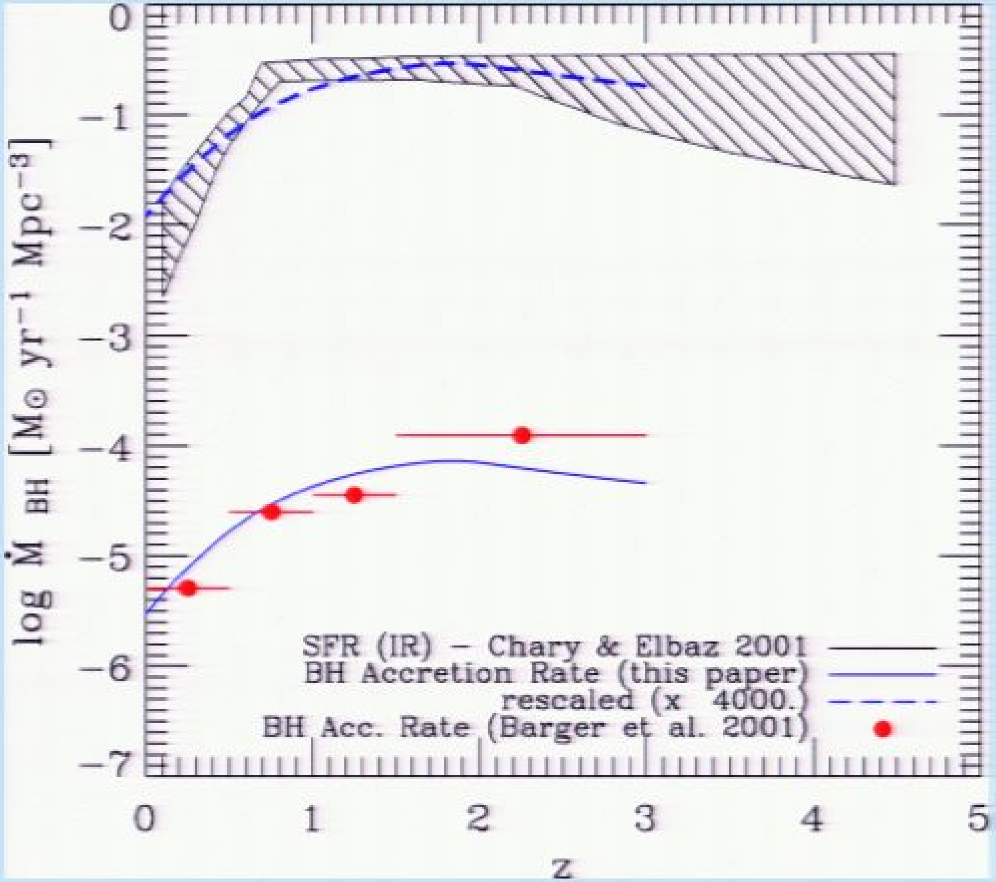


omastri+ 1995; Ueda+ 2003; Treister & Urry 2005; Merloni+ 2004; PN & Treister 2008

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



Star forming history vs accretion history

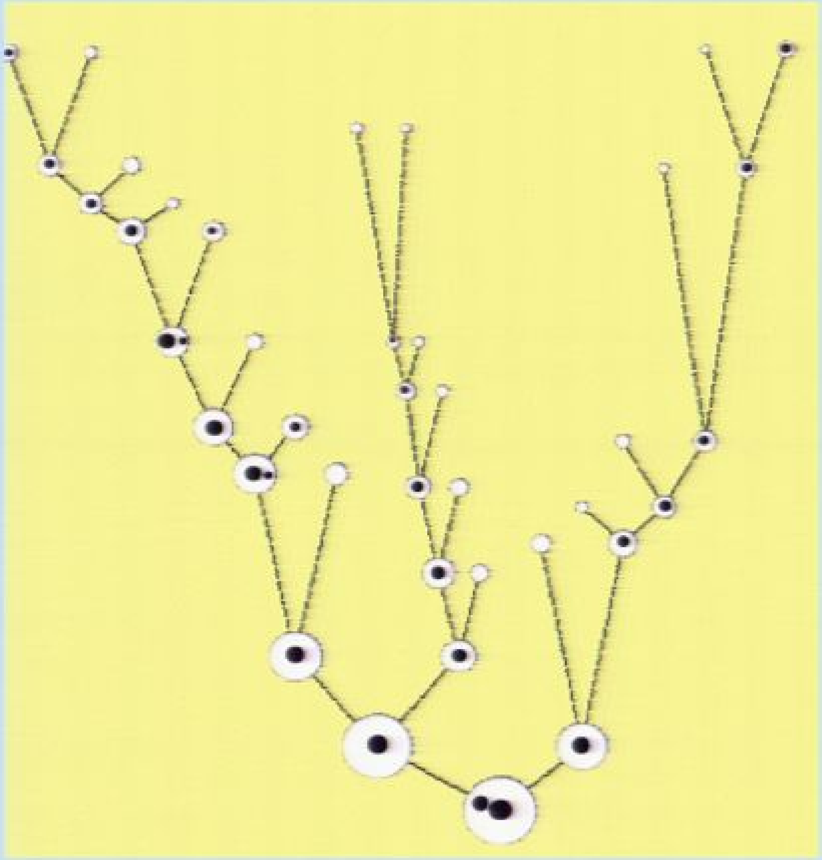


e.g., Marconi & Hunt 2003;

Marconi+ 2004

Current evolutionary model

- Start with initial mass function of seeds
- Generate Monte Carlo merger tree, consistent with LCDM
- MBH seed formation ceases at z ~ 12
- Propogate different BH seed models for z = 0 signatures
- Assume halos merge, galaxies merge and their BHs merge
- Every merger induces accretion of gas
- At z < 15, merger-driven accretion, gas mass accreted scales with v_c^5
- L dependent life-time ala Hopkins+ 2006
- Compare with observed local BH mass function, empirical correlations
- Predict high z LFs in the optical, X-ray



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

Pathways to making BH seeds

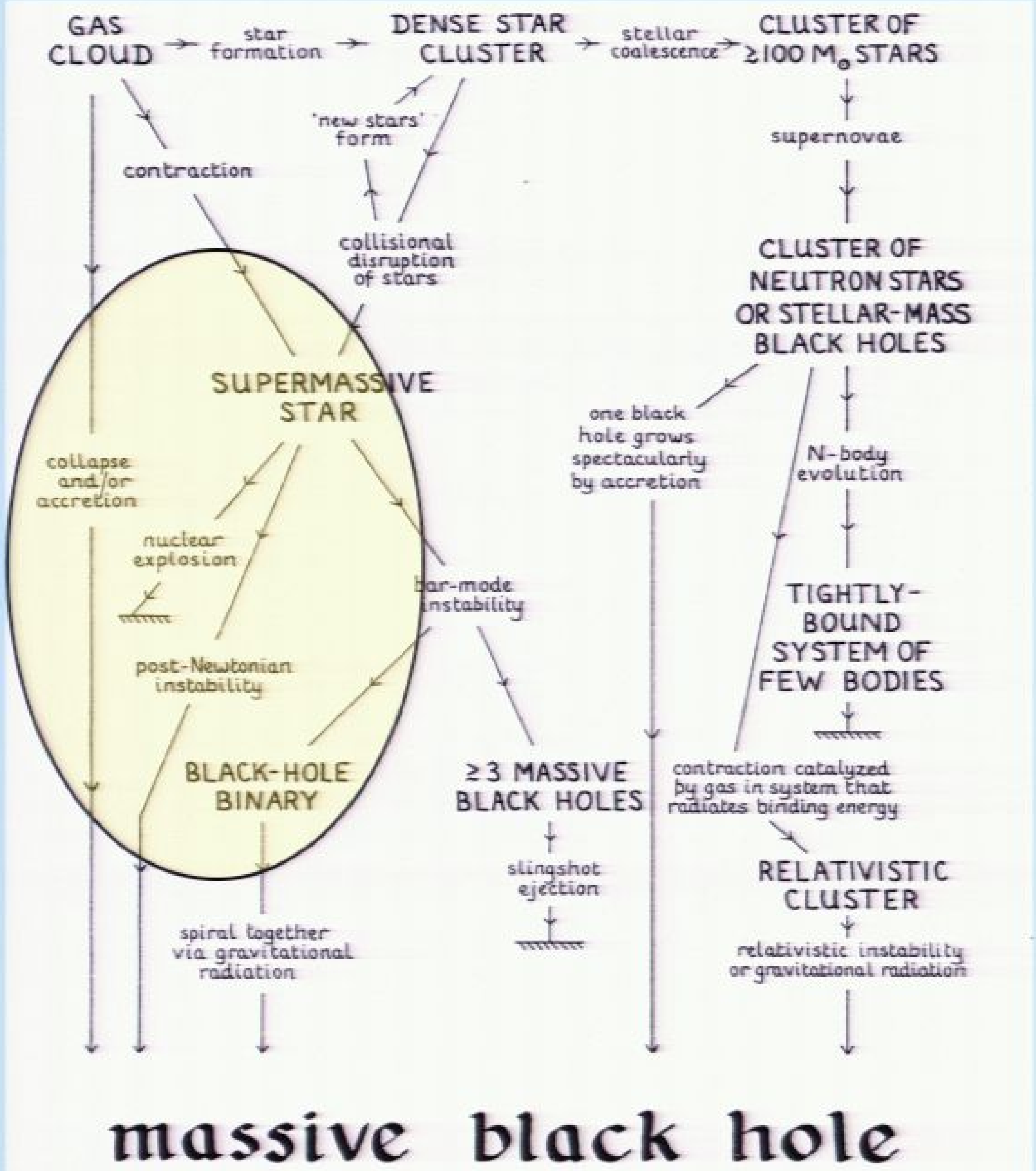


Figure 1 Schematic diagram [reproduced from Rees (106)] showing possible routes for

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)

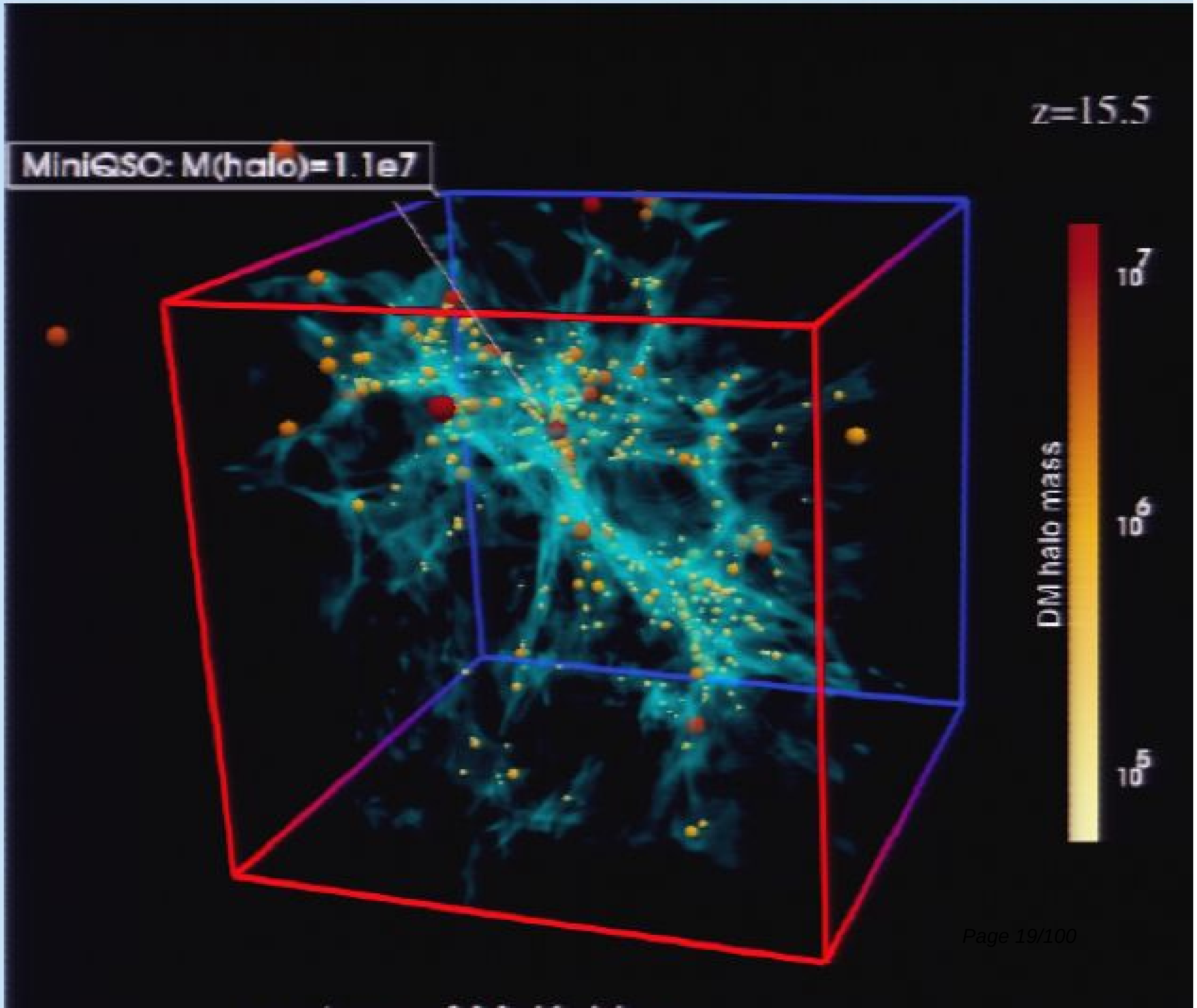
+ proper dynamical treatment of disk stability (Lodato & PN 2006, 2007)

Supermassive star (Haehnelt & Rees 1993)

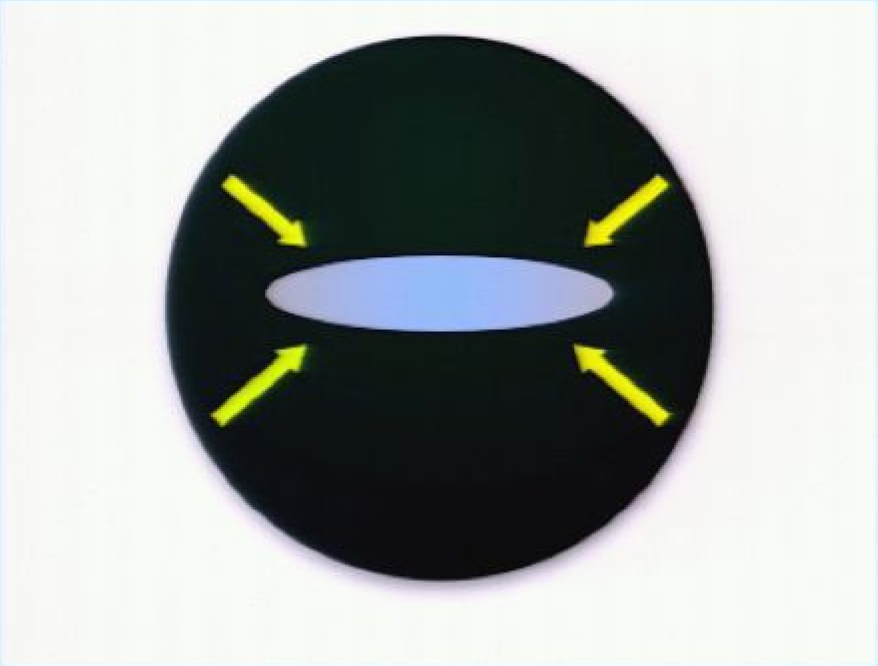
Bar unstable self-gravitating gas + large quasi-star (Begelman, Volonteri & Rees 2006)

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



SMBH formation at high z



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

Lodato & PN 2006, 2007

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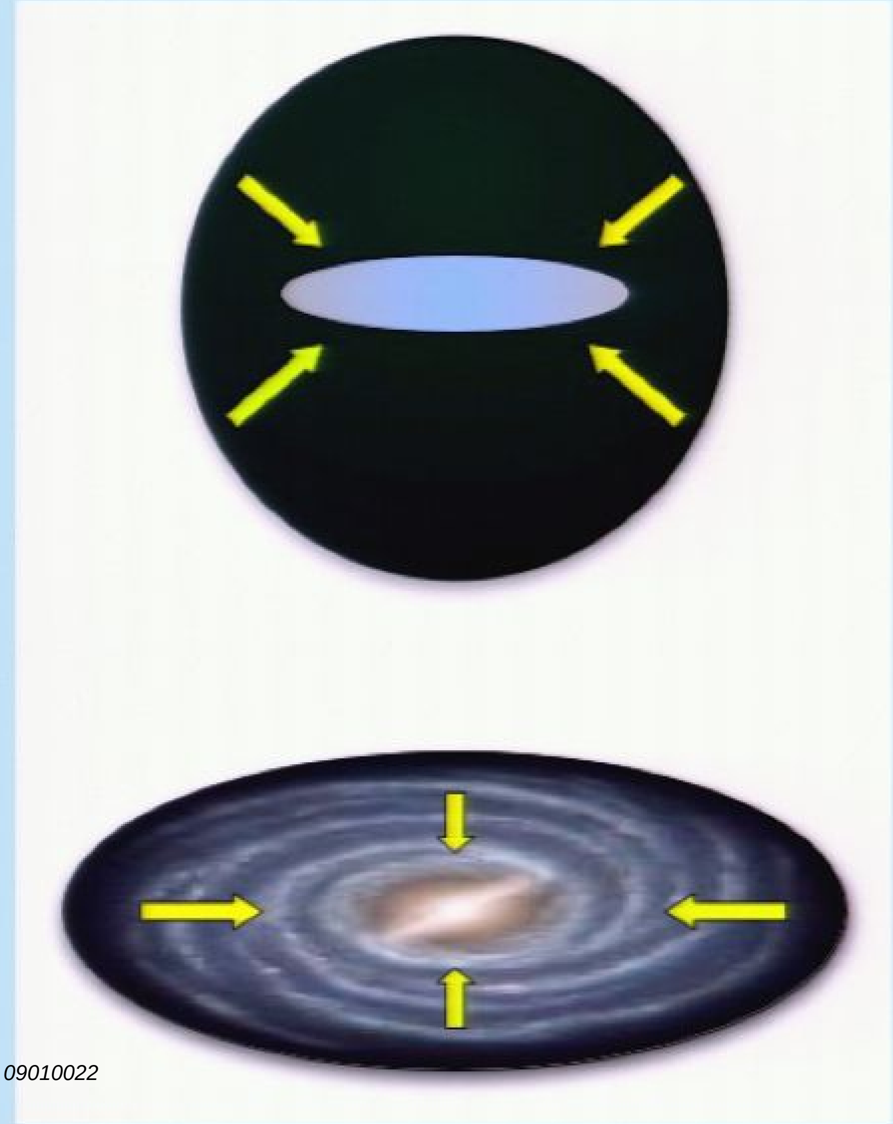


Baryons inside DM halo collapse and form a rotating pre-galactic disc

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 $Q_{crit} \sim 1 - 3$

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

$$\frac{\mathrm{d}n}{\mathrm{d}M_{\mathrm{BH}}}(M_{\mathrm{BH}};z) = \int_{M(T_{\mathrm{min}})}^{M(T_{\mathrm{max}})} \frac{\mathrm{d}n}{\mathrm{d}M}(M;z) \quad p[\lambda(M_{\mathrm{BH}},M)] \left|\frac{\mathrm{d}\lambda}{\mathrm{d}M_{\mathrm{BH}}}\right| \mathrm{d}M,$$

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

Fragmentation criteria

3 interesting regimes:

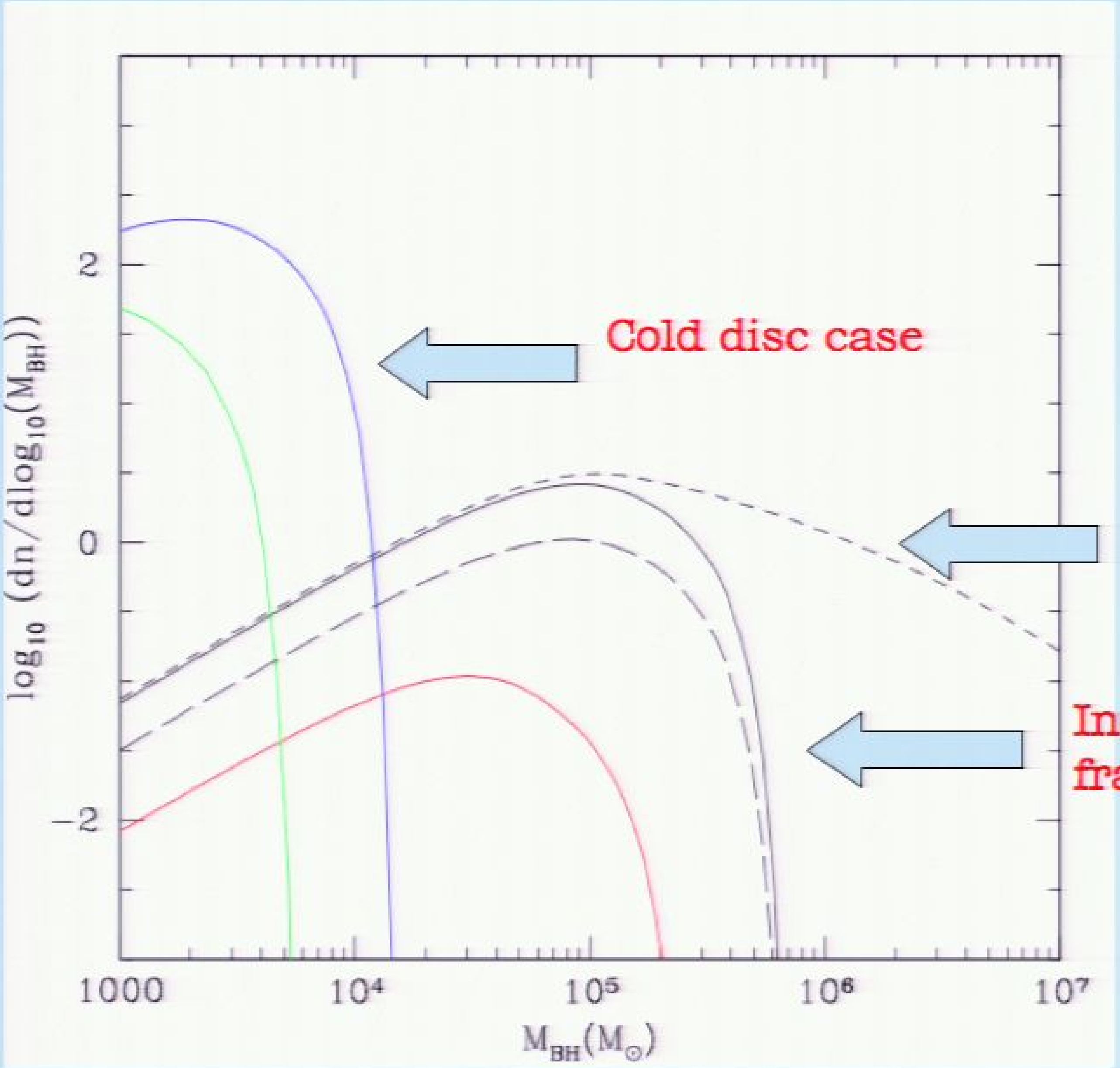
$T_{vir}/T_{gas} > 3$ will fragment and form stars and no central mass concentrations

$2 < T_{vir}/T_{gas} < 3$ 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

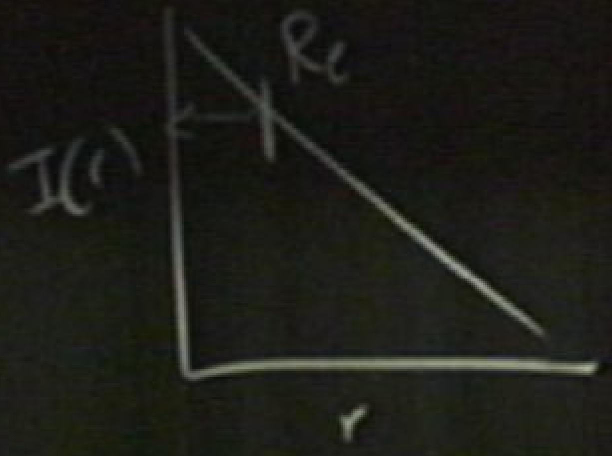


Cold disc case

Without fragmentation

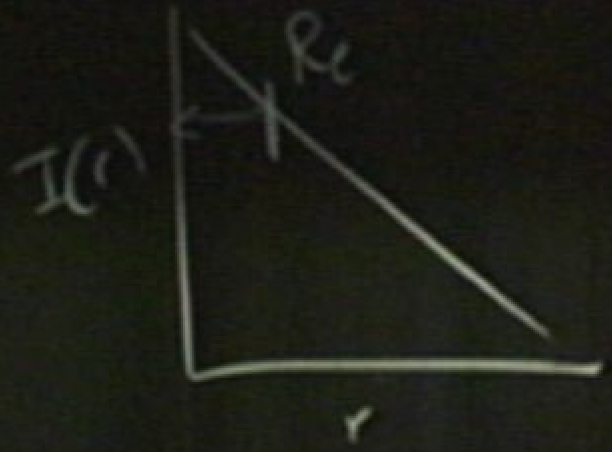
Including fragmentation

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



$e^{-(R/R_e)^{1/4}}$

$M_{DM} \sim 10^{6} M_{\odot}$ $z \sim 15-20$



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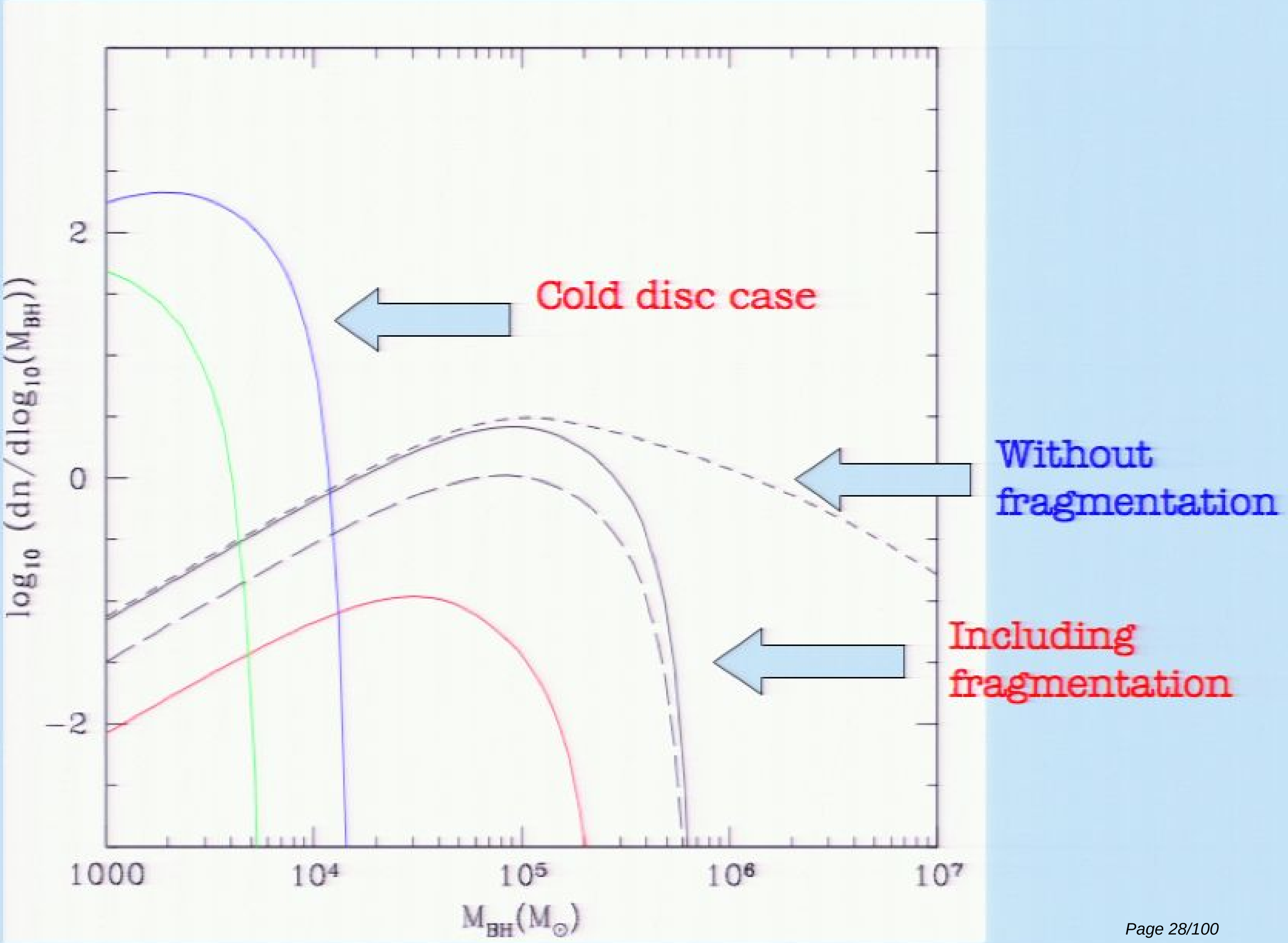

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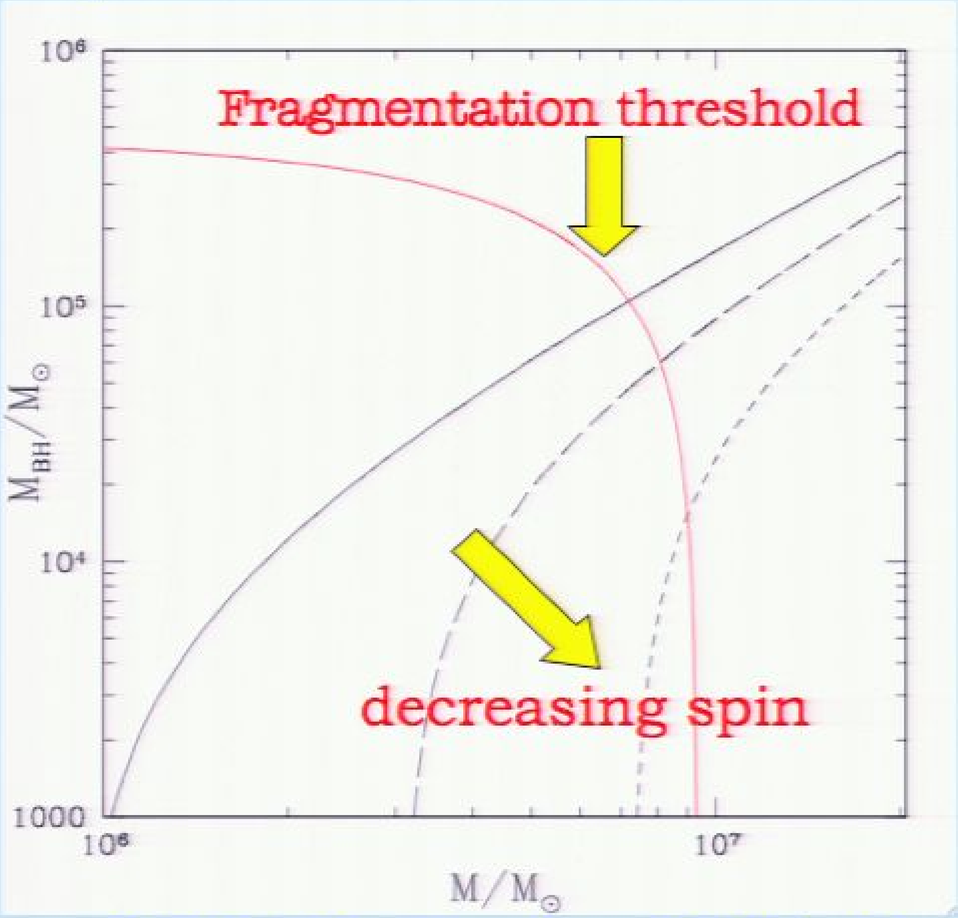
Without fragmentation

Including fragmentation

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

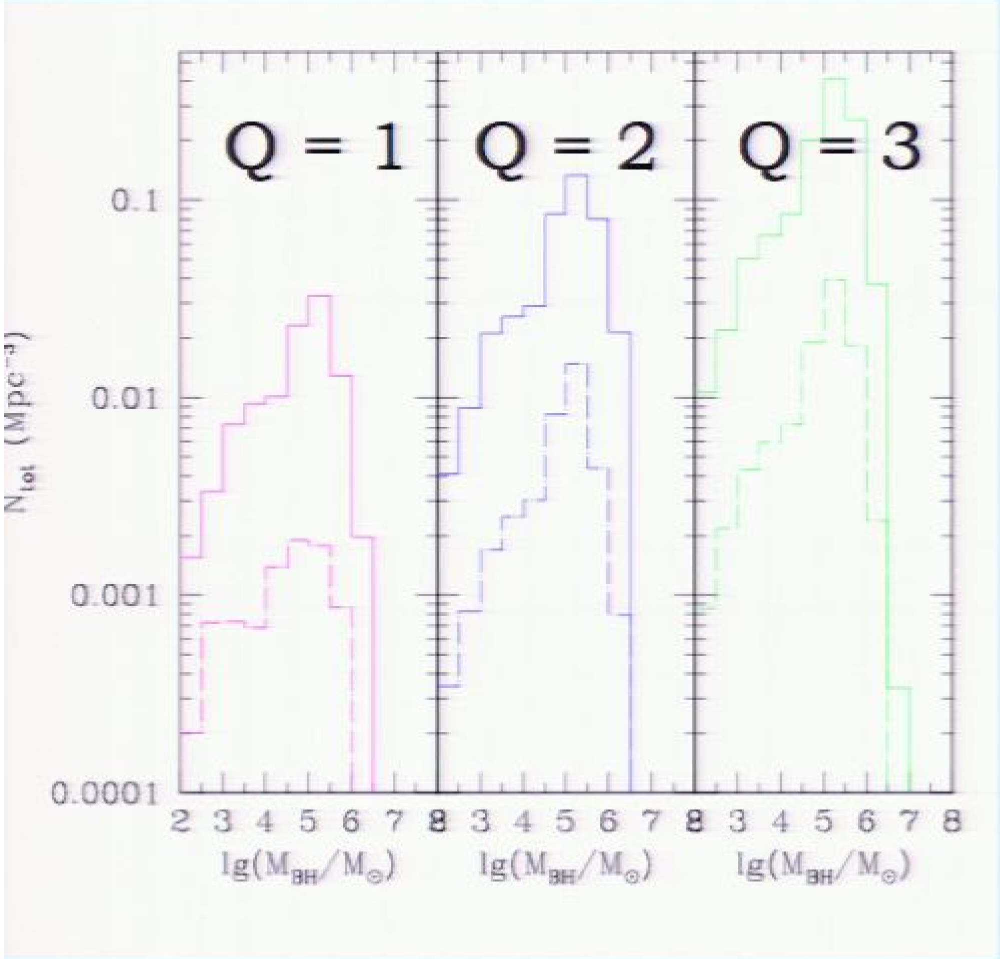
Key features of our model

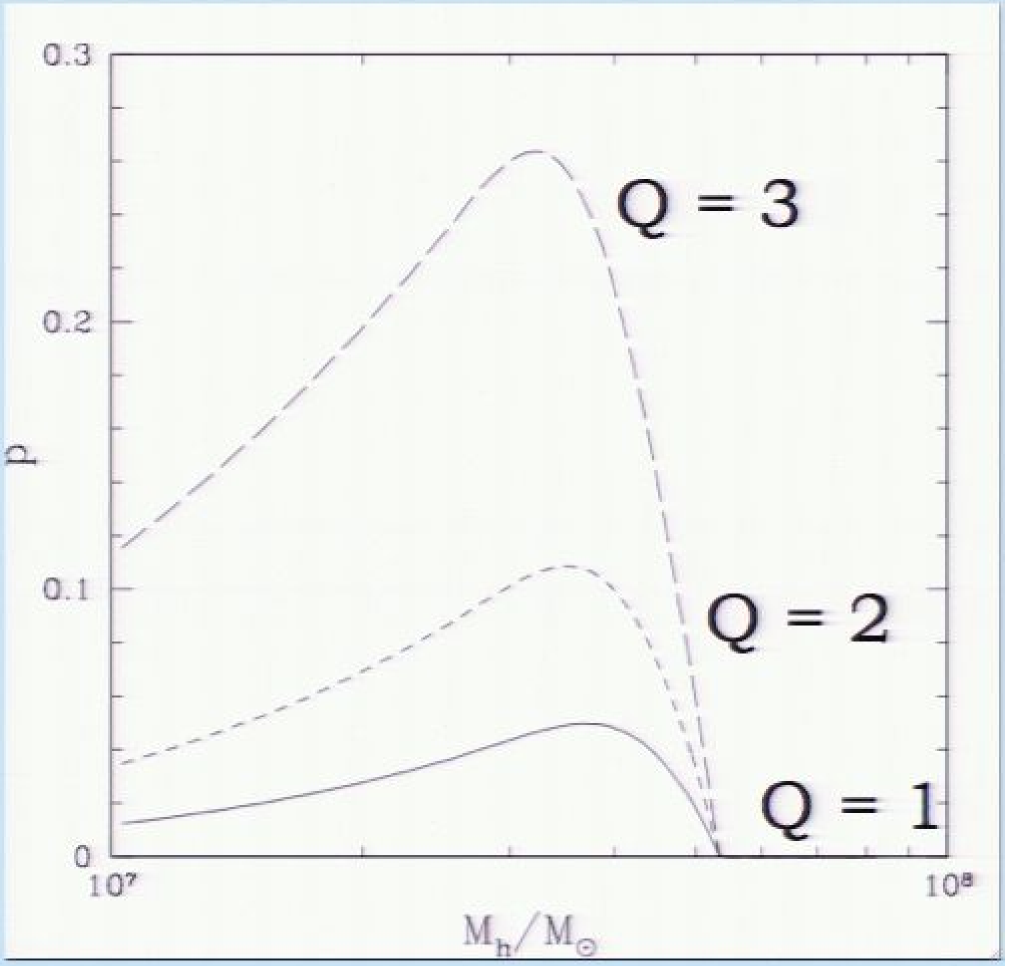
- Different relationship between M_{BH} and spin parameter
- High spin halos do not host BHs at early times as disc is not massive enough, stable to grav. instabilities
- Massive, low spin halos host the most massive seeds



$T \sim 4000$ K, $m = j = 0.05$, $Q = 2$

Model features

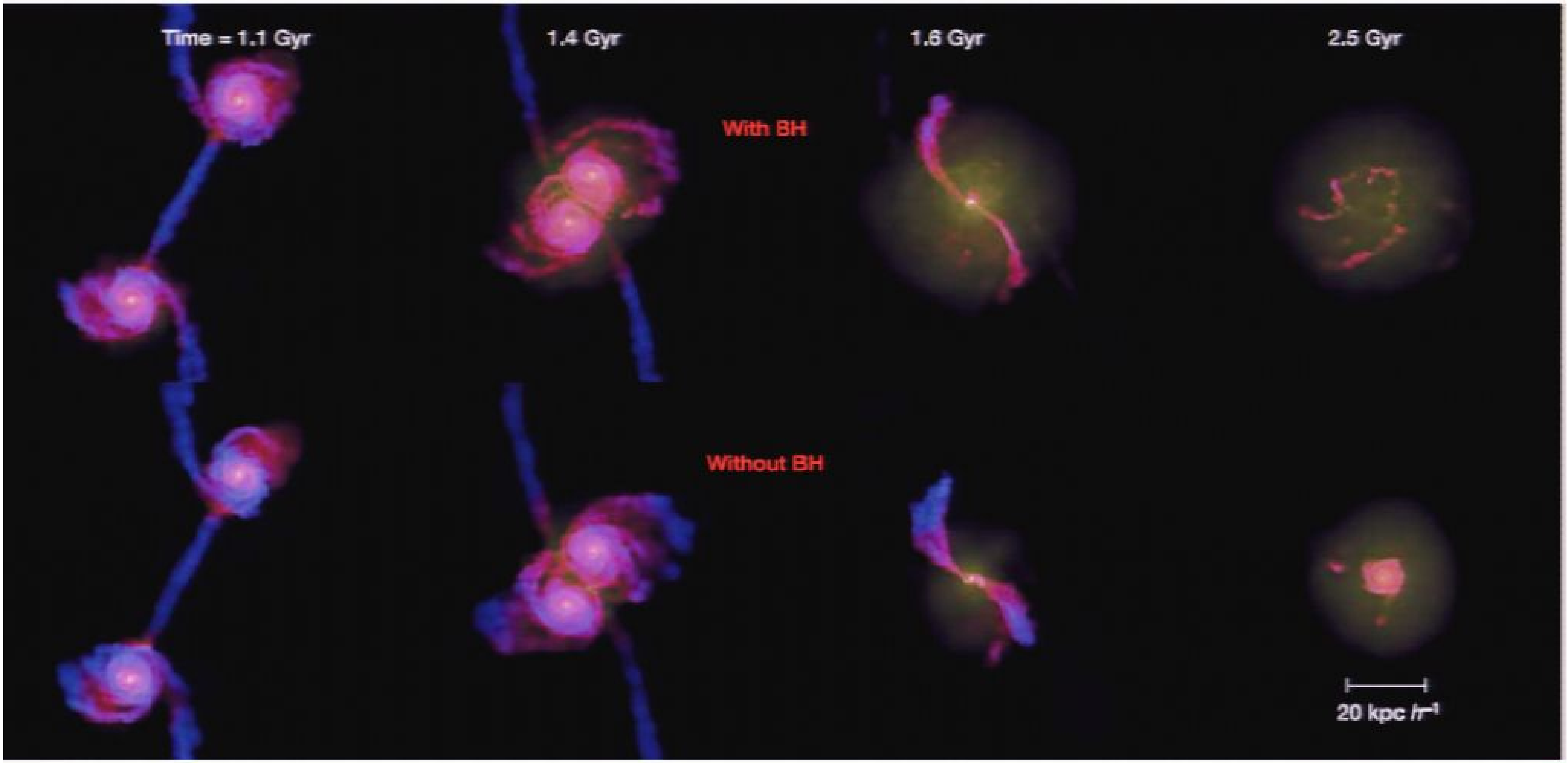




The mass function of seeds for 3 different BH formation efficiency models

Probability of hosting a BH seed of any mass

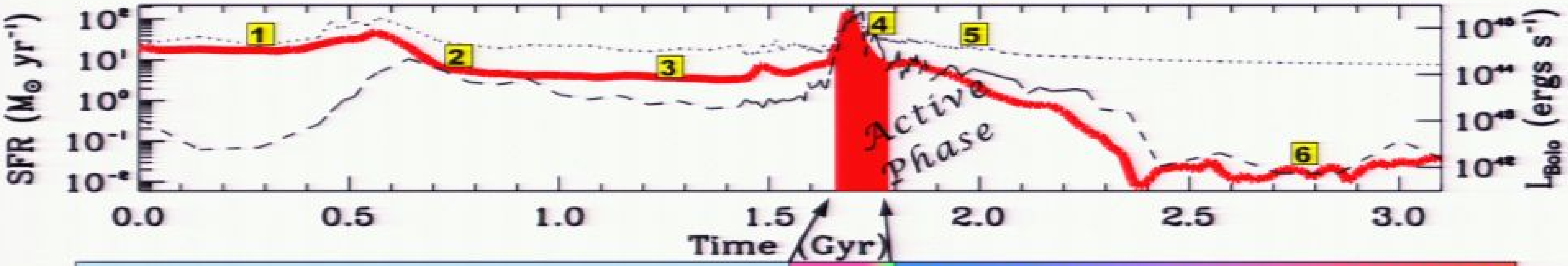
Merger induced accretion: modeling the dynamics



Hydrodynamic simulations of BH mergers including BH growth feedback, sub-grid model of SF including multi-phase ISM + Bondi accretion onto BH + thermal energy from stars and AGN returned to the ISM

Di Matteo, Springel & Hernquist 2005; Hopkins + 2005, 200

Proposed Chronology of a Galaxy Merger



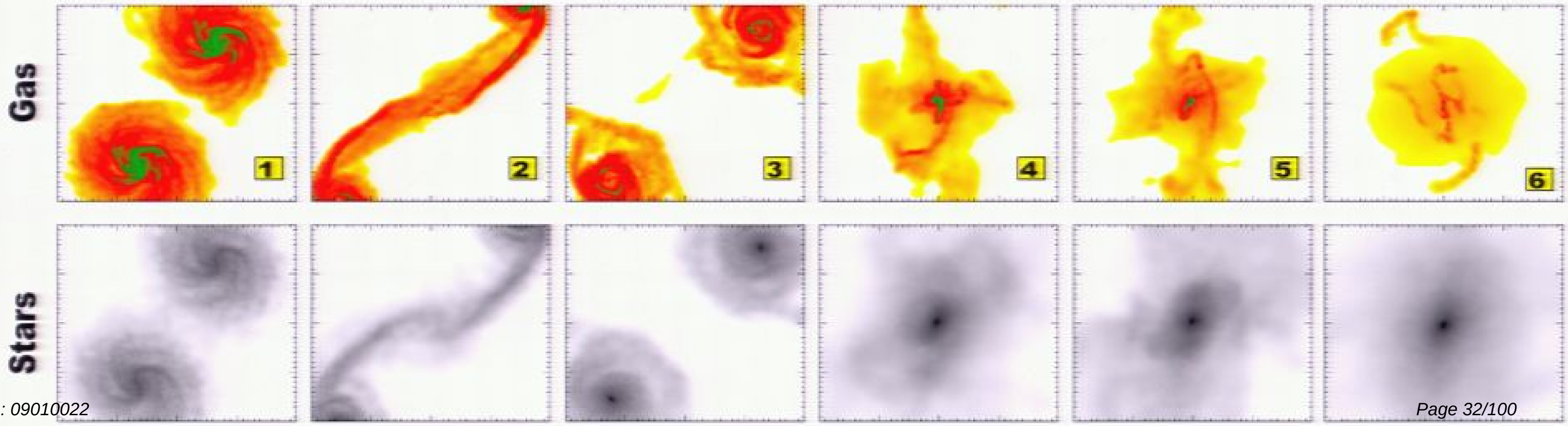
Inspiral Stage
- multiple nuclei, tidal tails, bridges
- the majority of stars are formed

Starburst-driven winds

(U)LIRG

QSO

Merger Remnant ⟶ Elliptical
- kinematics: tidal tails, shells, plumes & loops, kinematic subsystems
- colors redden
- formation of a hot gaseous halo
- declining AGN activity
- satisfies $M_{BH} - \sigma$ & FP



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

Self regulation of SF and BH growth

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

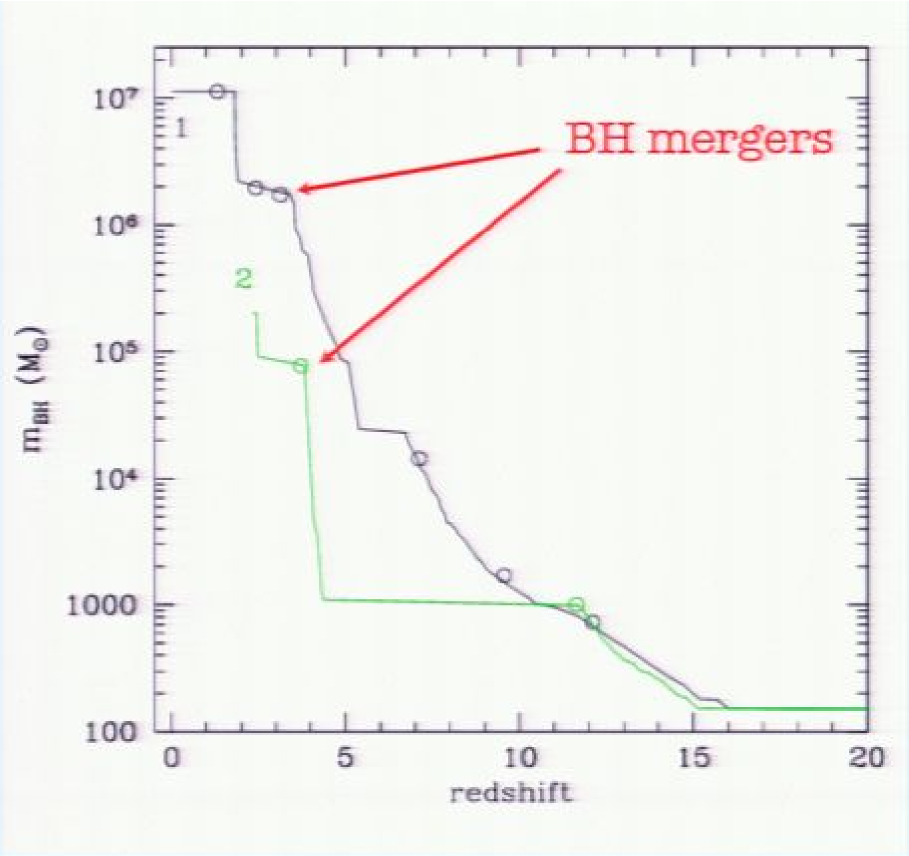
$$M_{bh} > \alpha \frac{\sigma^5 \kappa}{G^2 c} = 8 \times 10^8 \gamma (\sigma / 500\,\mathrm{km\,s^{-1}})^5\,\mathrm{M}_\odot.$$

$$M_{\rm bh} \sim 10^8 \mathrm{M}_\odot\,(f_{\rm kin}/0.001)^{-1}\, j_{\rm d}^{-5} \left(\frac{\lambda}{0.05}\right)^{-5} \left(\frac{m_{\rm d}}{0.1}\right)^5 \times \left(\frac{v_{\rm halo}}{400\,\mathrm{km\,s^{-1}}}\right)^5 \mathrm{M}_\odot,$$

Momentum-driven winds

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

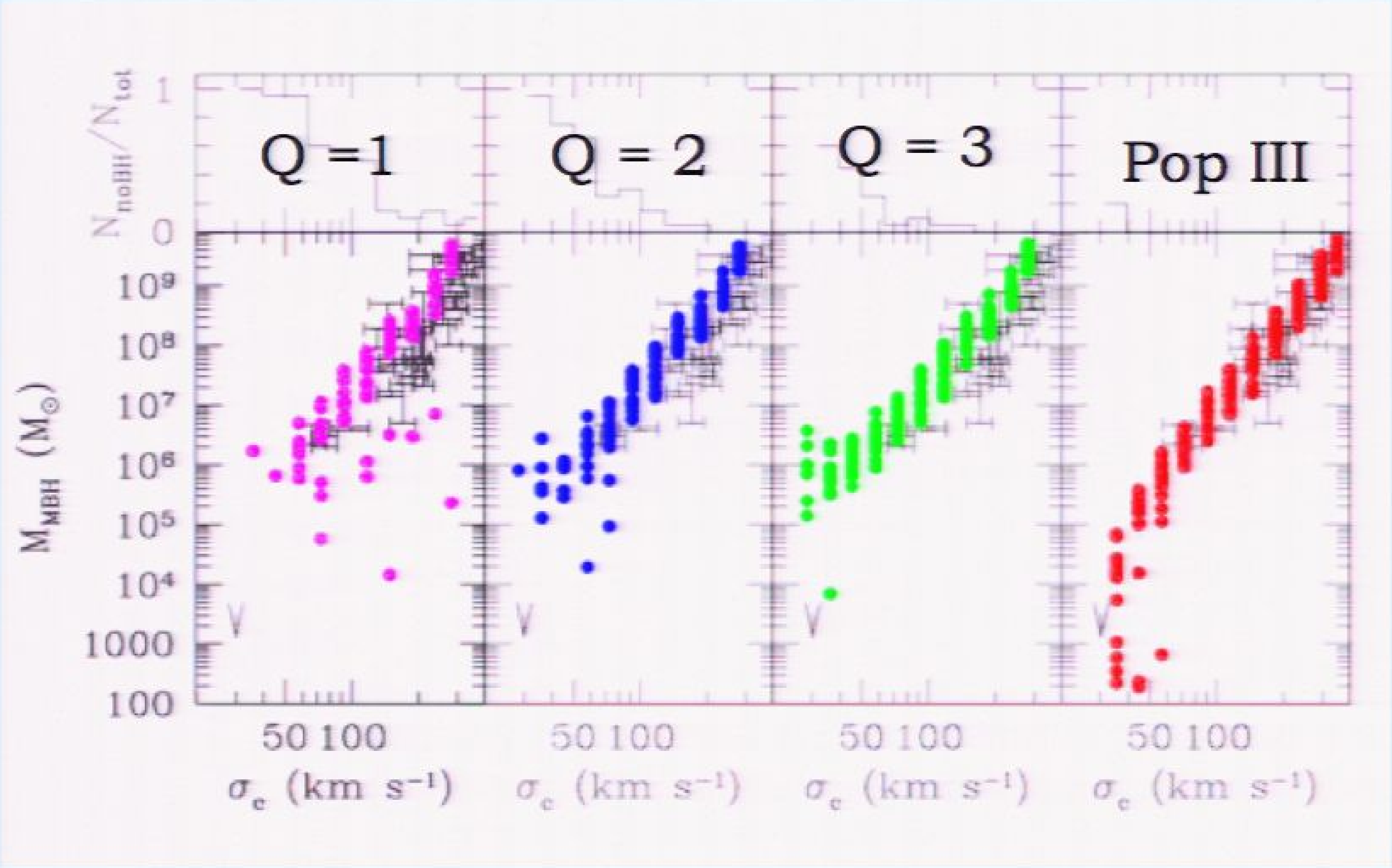
aehnelt, PN & Rees 1998; Silk & Rees 1998; Wyithe & Loeb 2003; King 2004;
hompson, Murray & Quataert 2004; PN 2008



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

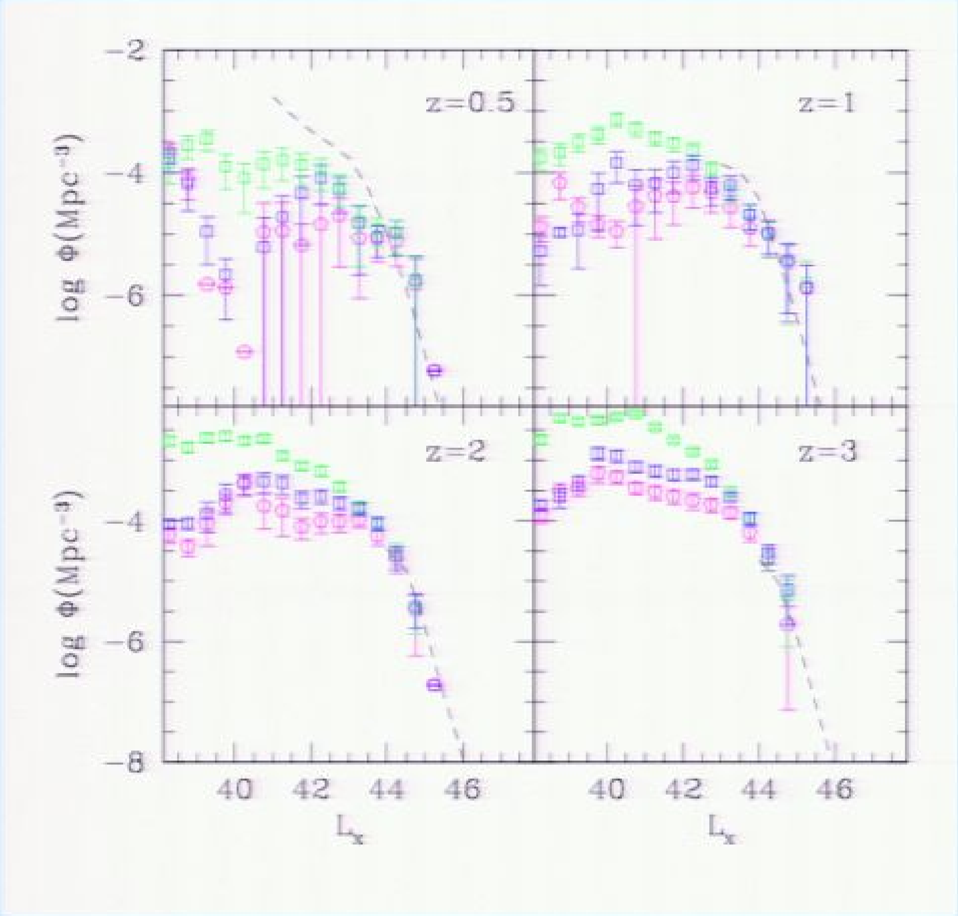
Sesana+ 2004; Dotti+ 2006; PN& Volonteri 2008

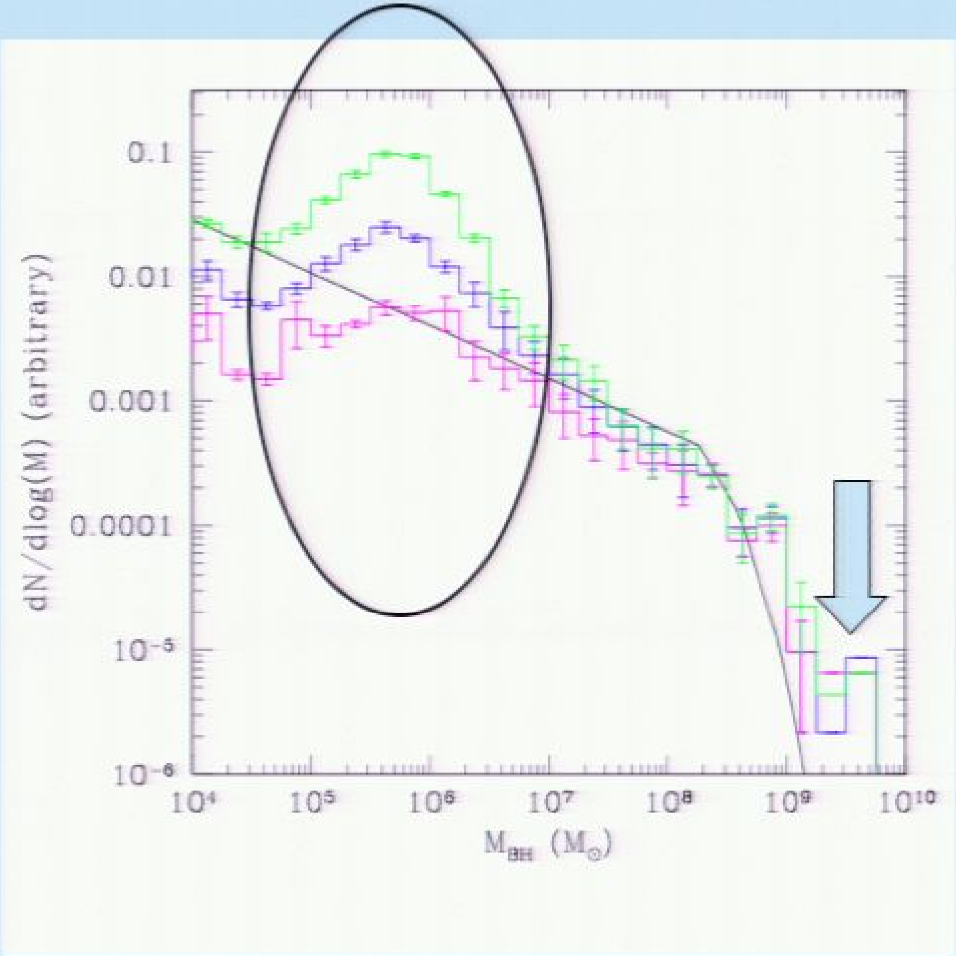
Key prediction at the low mass end



Volonteri, Lodato & PN 2007

Model predictions for the quasar LF & local SMBH mass density





Faint end of the XLF

Better census from Fermi/GLAST

Local BH mass density
Need new techniques to push to measure lower BH masses

PN, Volonteri & Lodato 2008

$e^{(R/R_e)^{1/4}}$

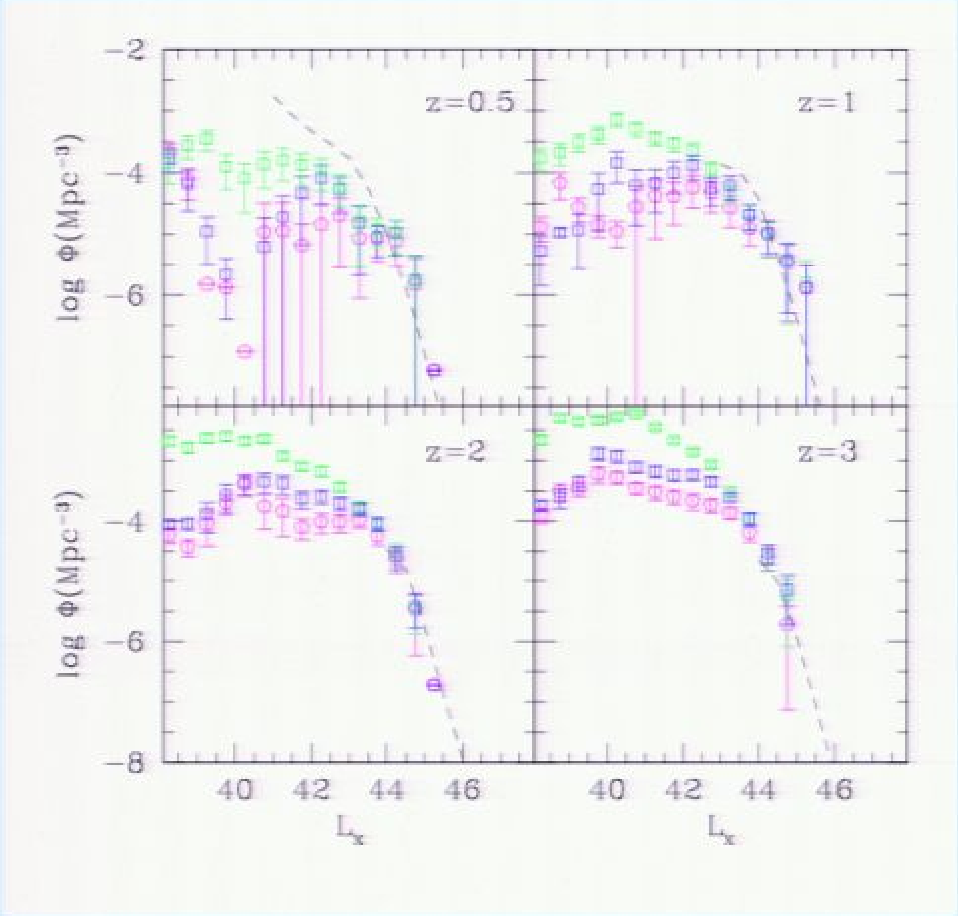
$M_{DM} \sim 10^6 M_\odot$ $z \sim 15-20$

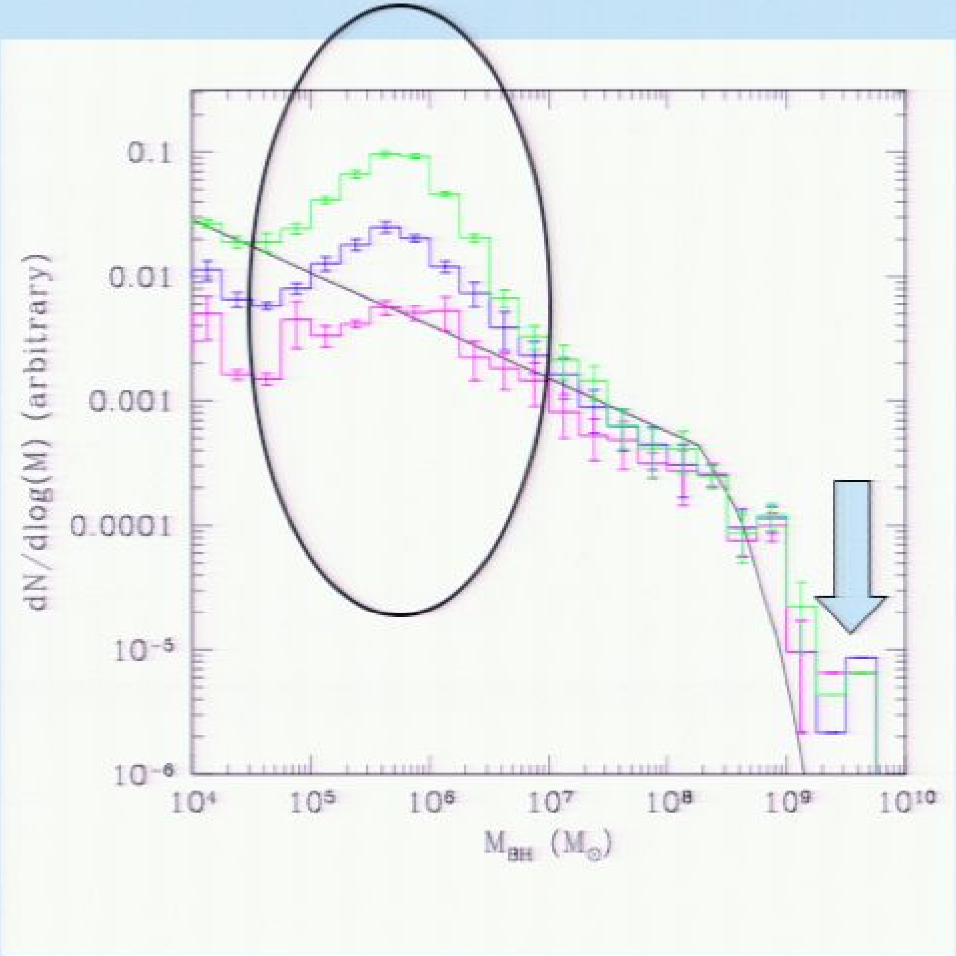
$> 3.5\sigma$ peaks.

$M_{BH} \propto \sigma$

$\boxed{f(\sigma, z)}$

Model predictions for the quasar LF & local SMBH mass density





Faint end of the XLF

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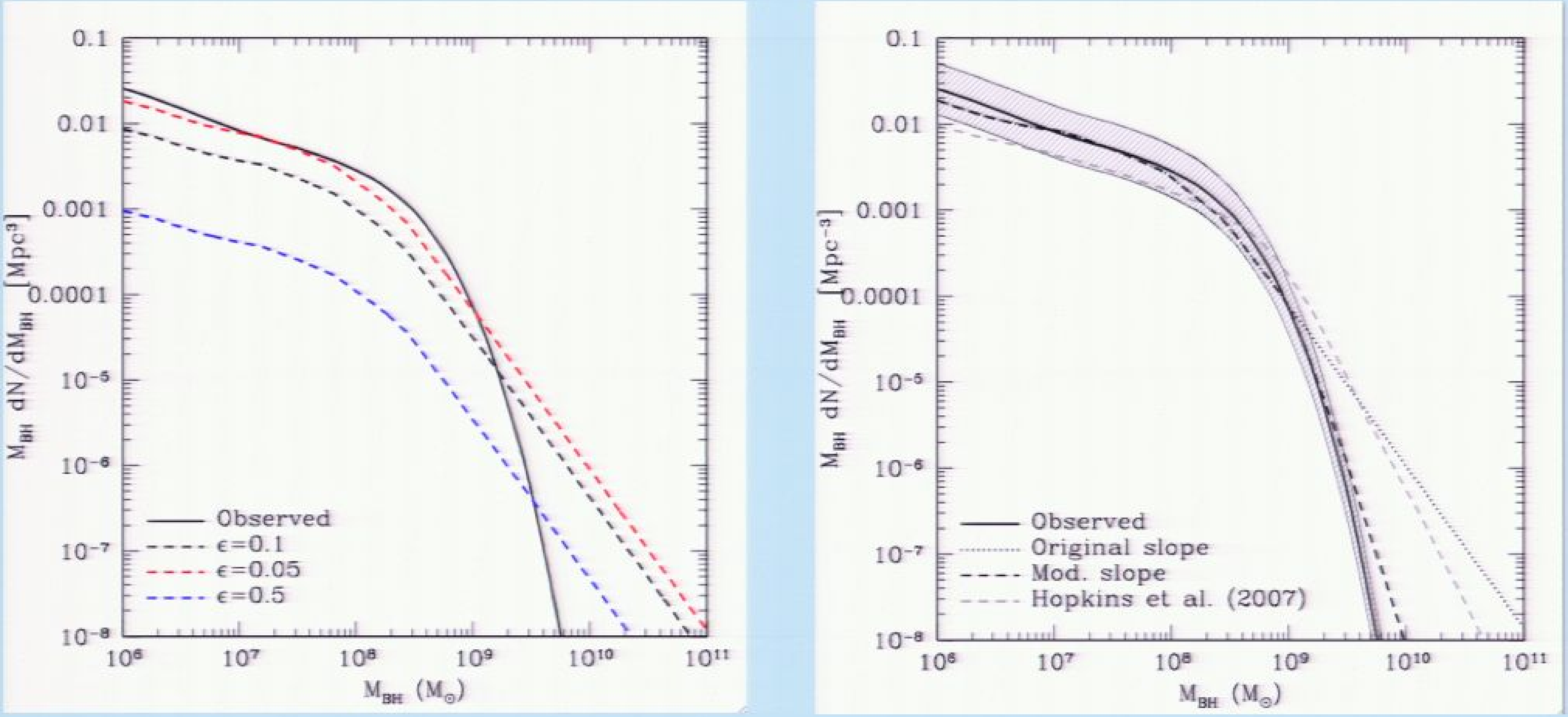
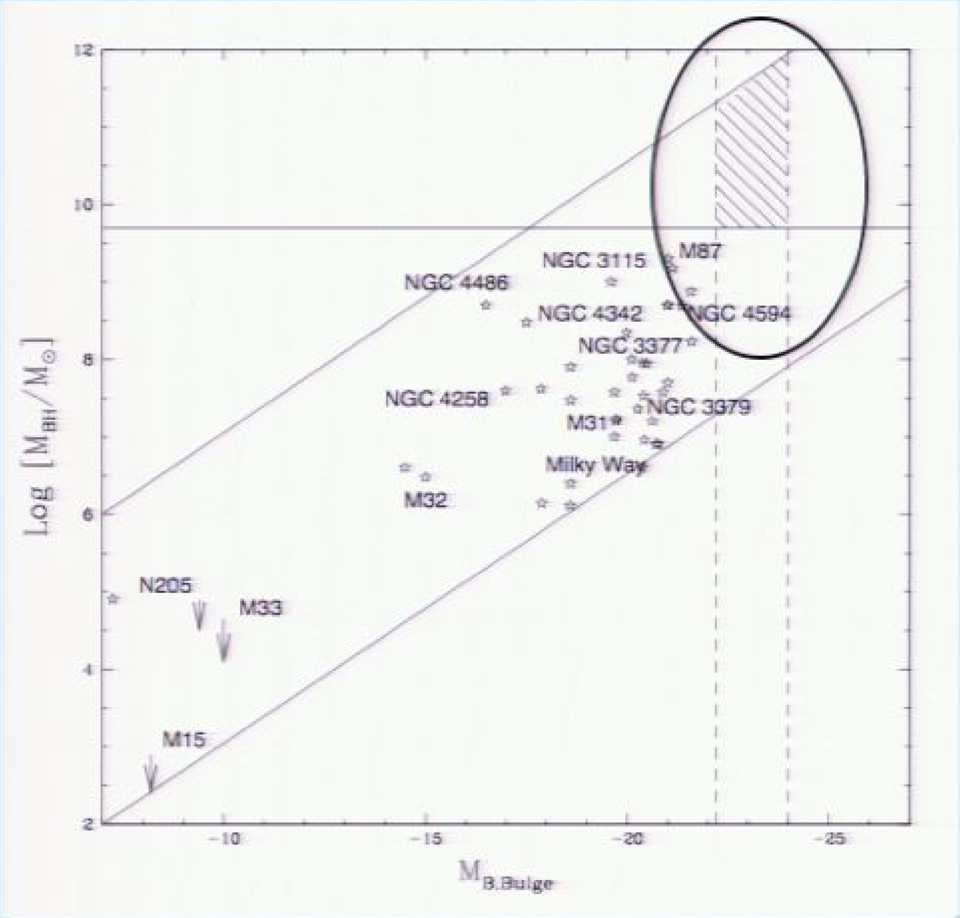
PN, Volonteri & Lodato 2008

Require self-regulation to suppress the observed local BH mass function at high masses

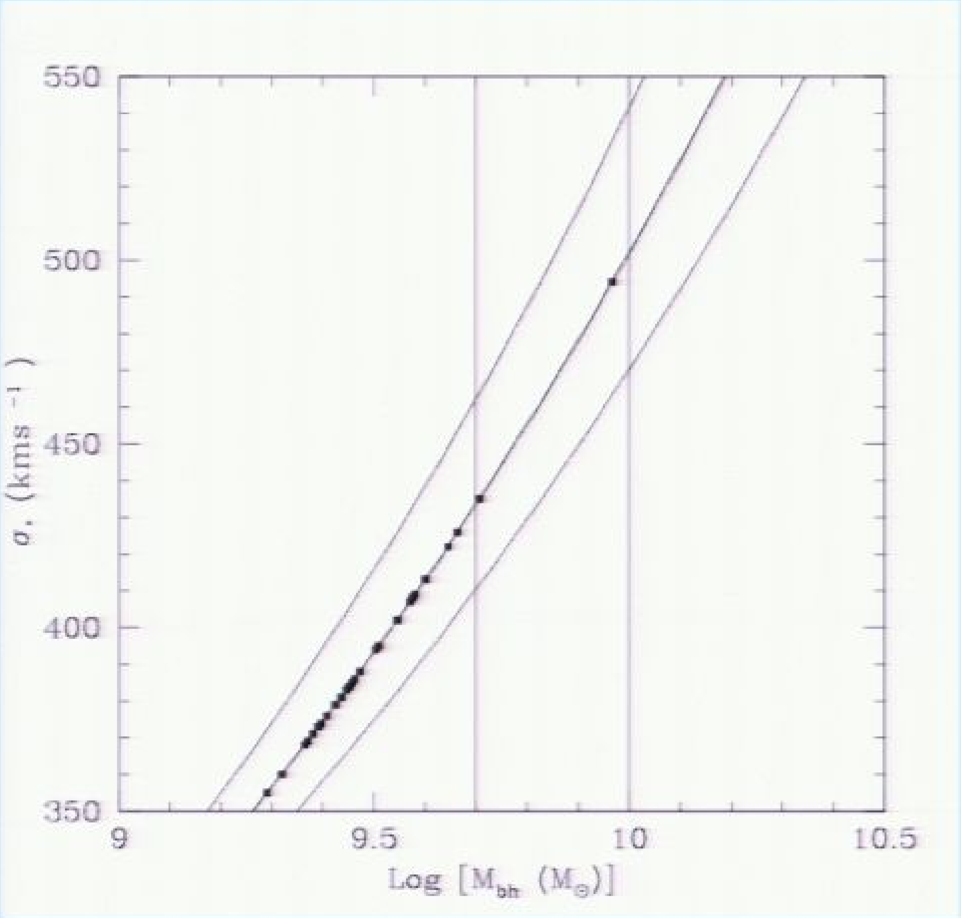


PN & Treister 2008

Predict existence of UMBHs



Expected in the centers of cDs



SDSS results of nearby cDs and bright ellipticals

Lauer+ 2005; 2006; Bernardi+ 2006

Where are the local UMBHs?

II. The dying gasps of merging supermassive black hole binaries

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

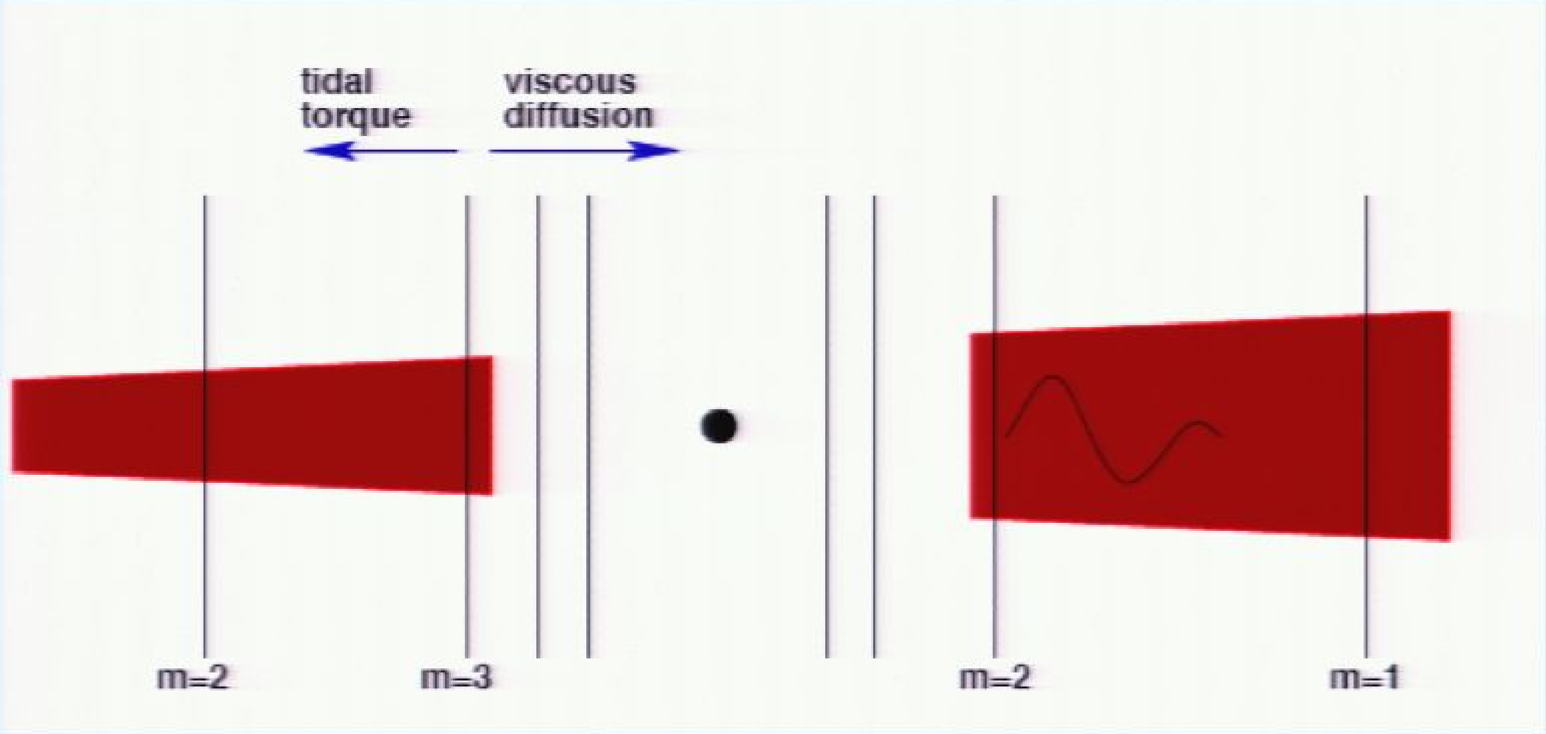
Merger driven by stellar dynamics:

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

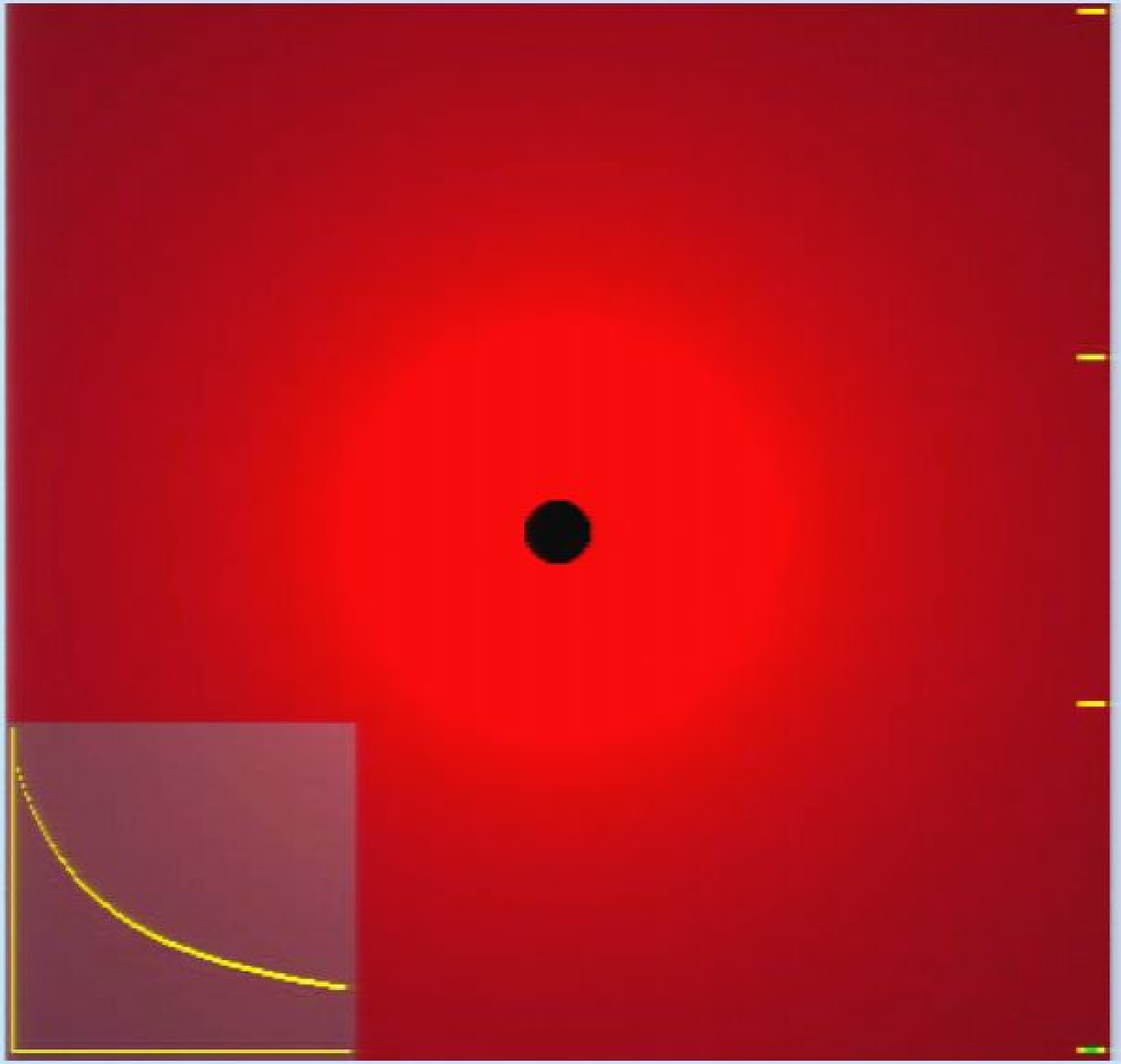
Merger driven by gas dynamics:

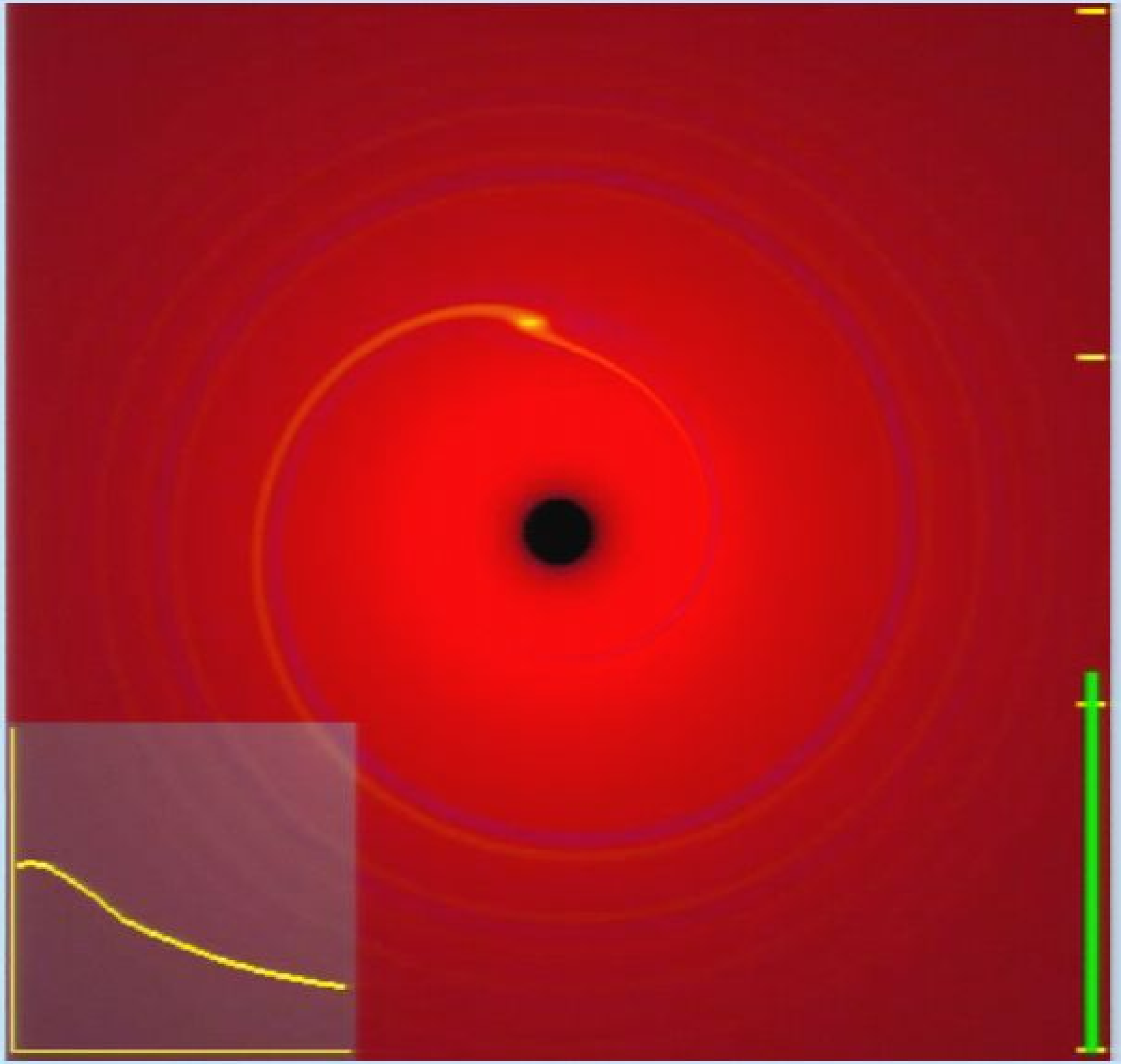
- delayed X-ray rebrightening
- impulsive disk response to change in potential (probably unobservable)
- bright, variable precursors
- Pre-merger variability

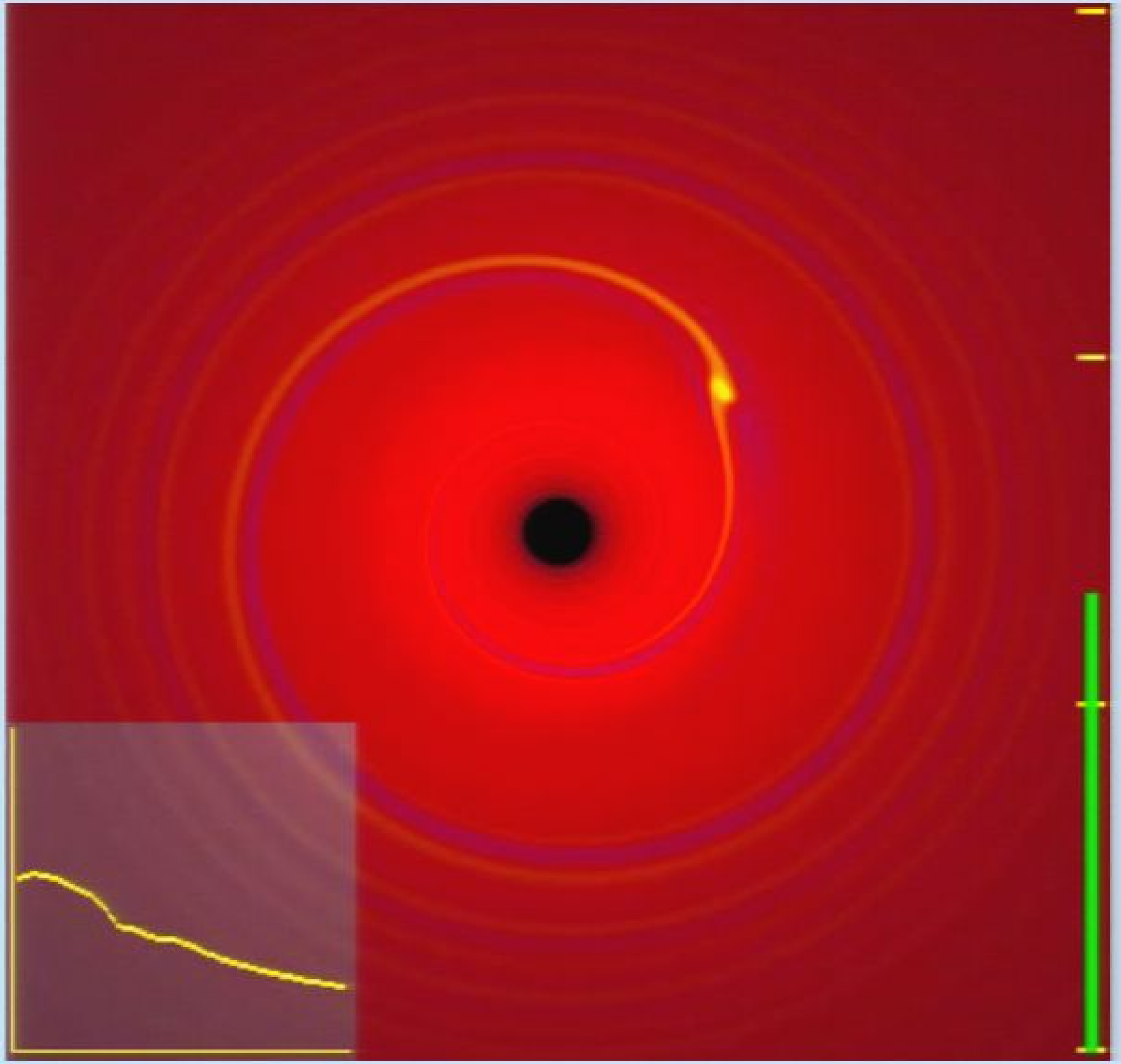
Opening up of a gap in the accretion disk and migration

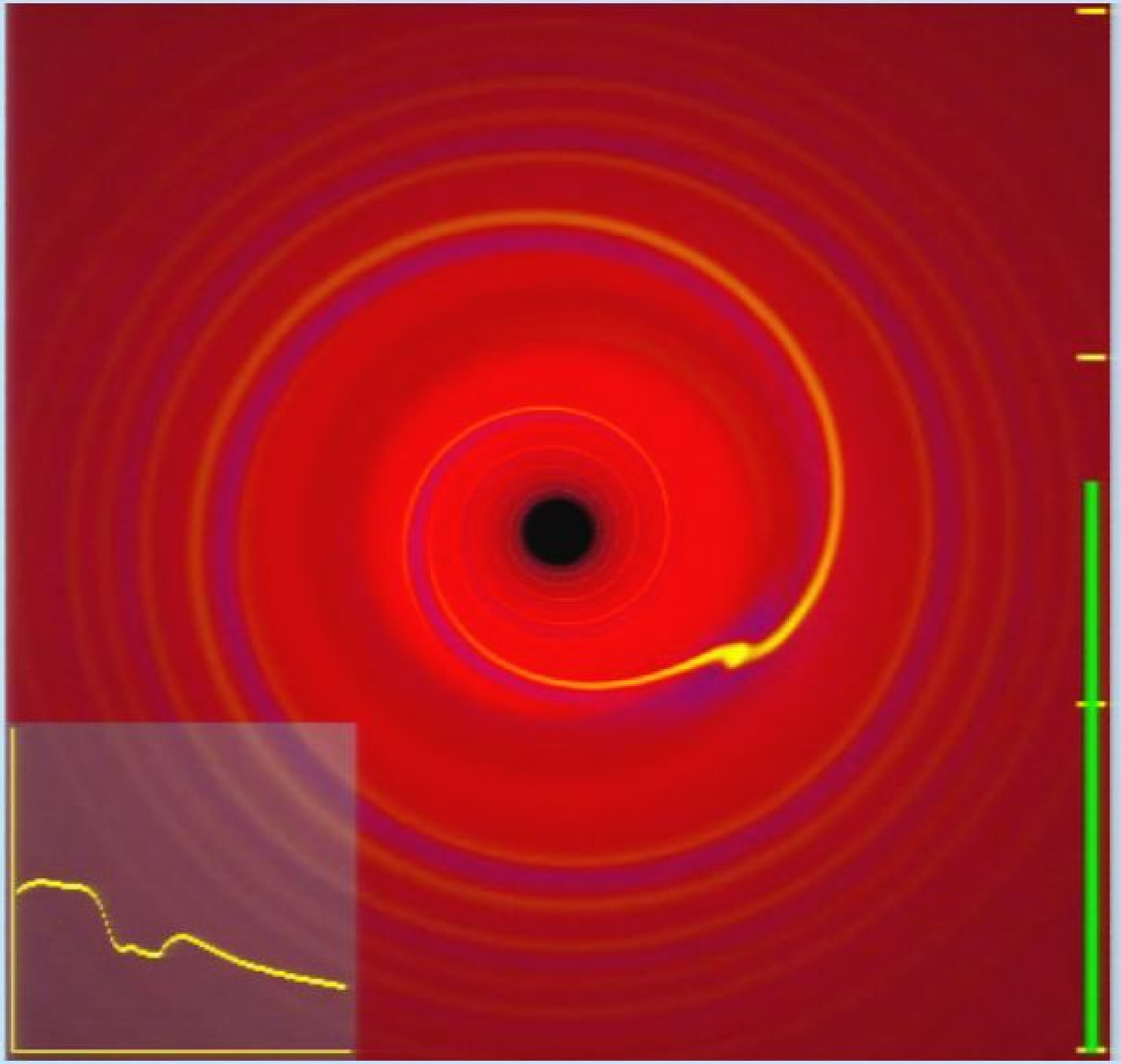


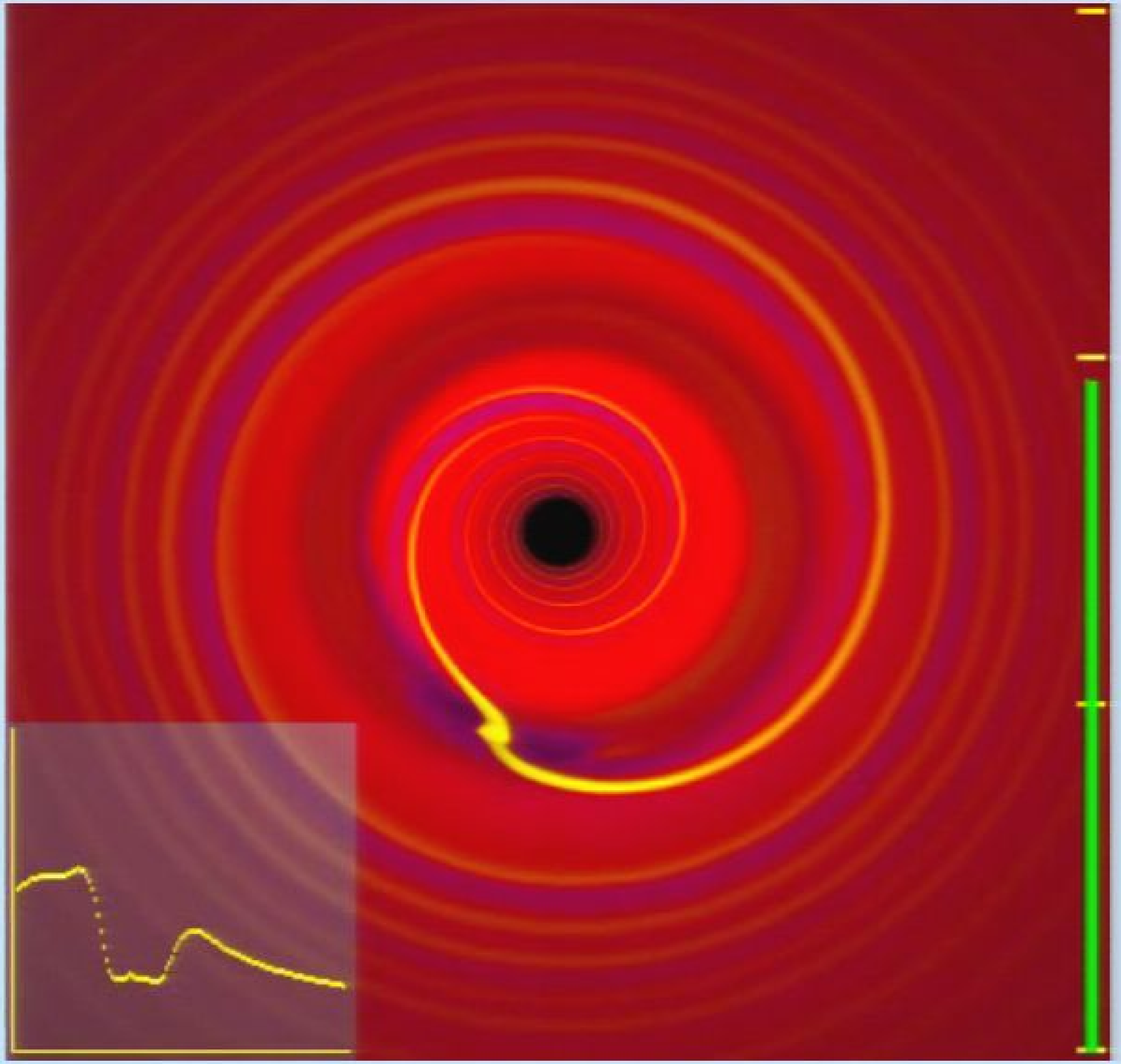
A gap can open when the time scale for opening a gap of width Δr due to tidal torques becomes shorter than the time scale on which viscous diffusion can refill the gap.

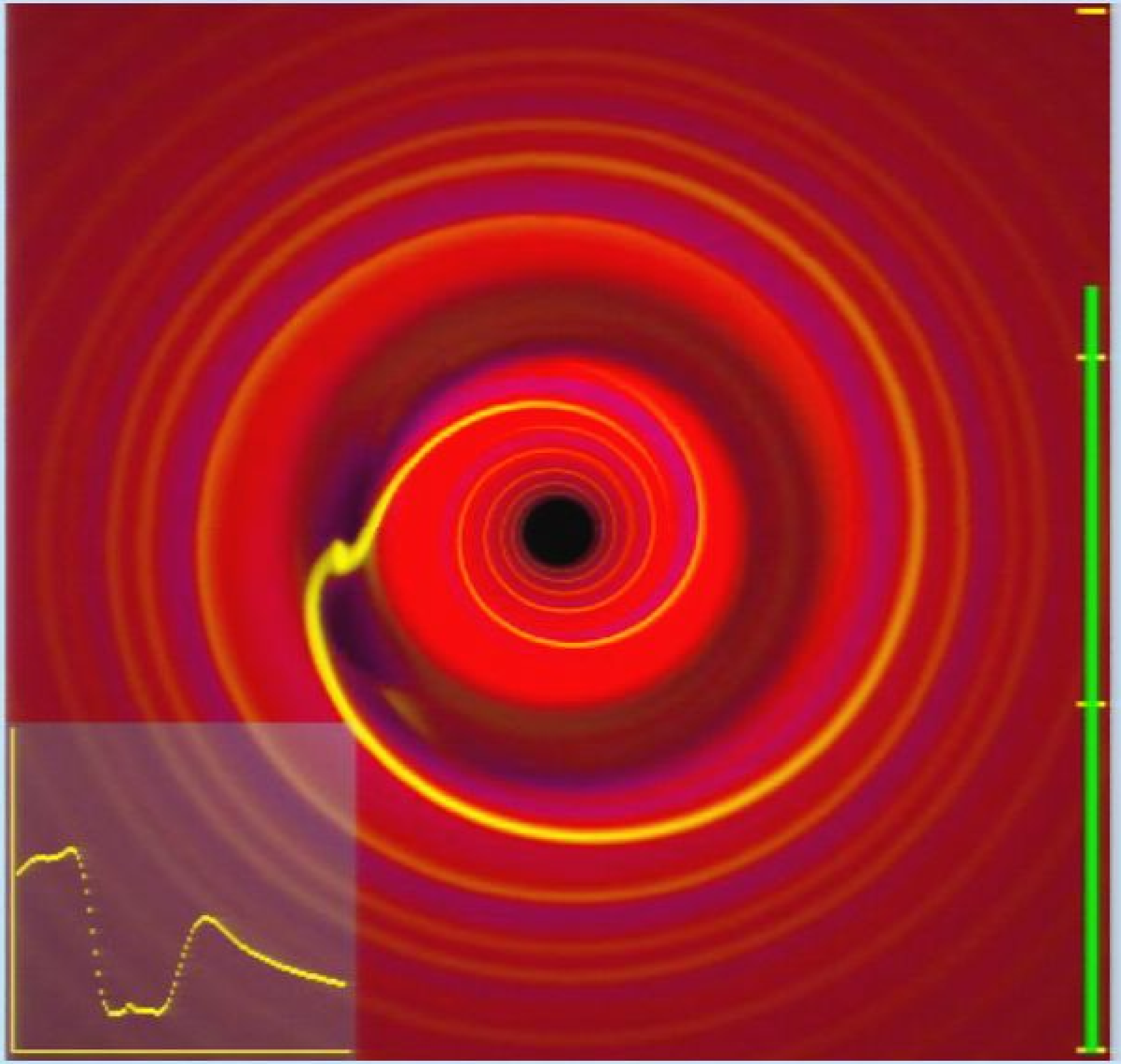


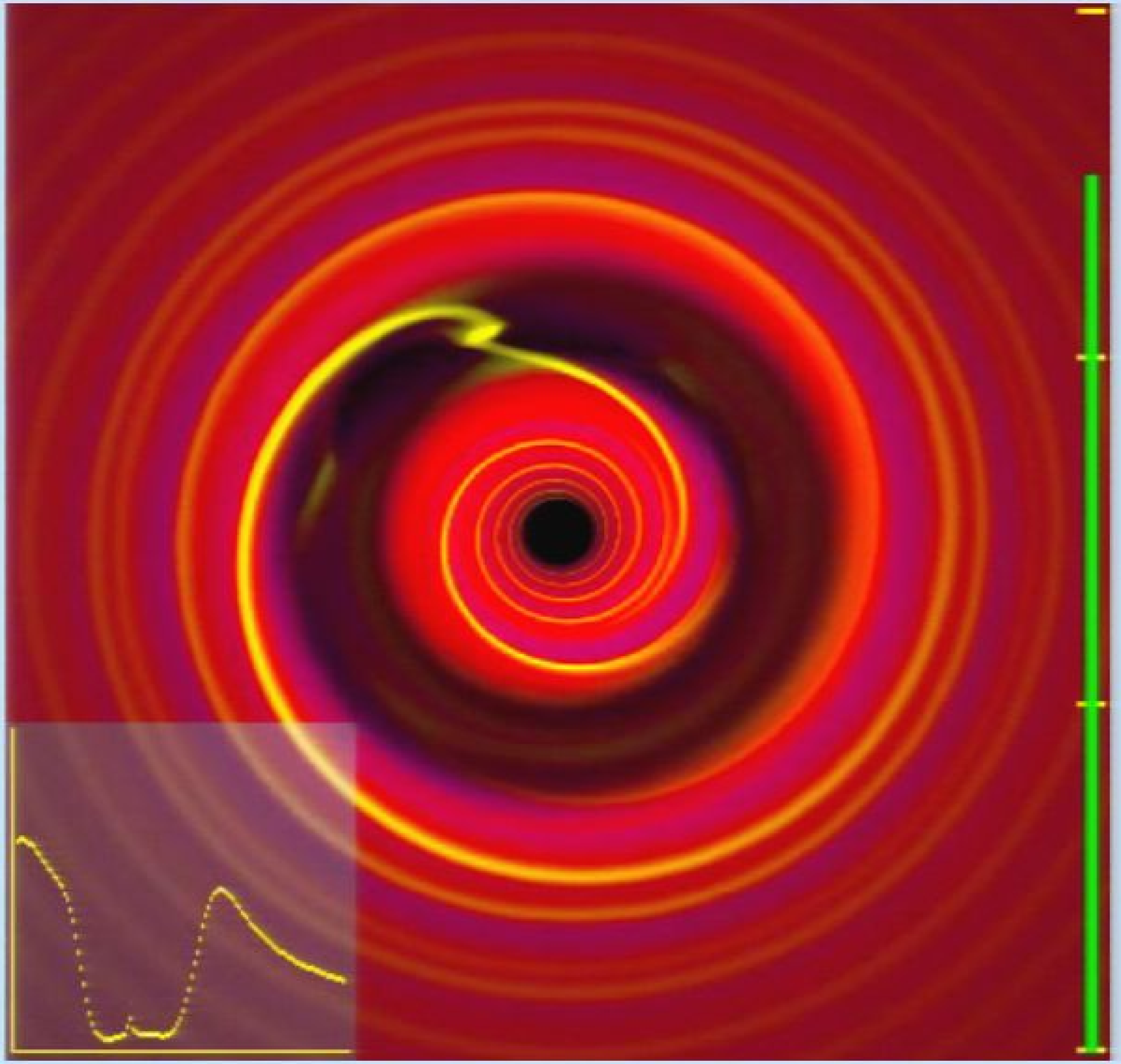


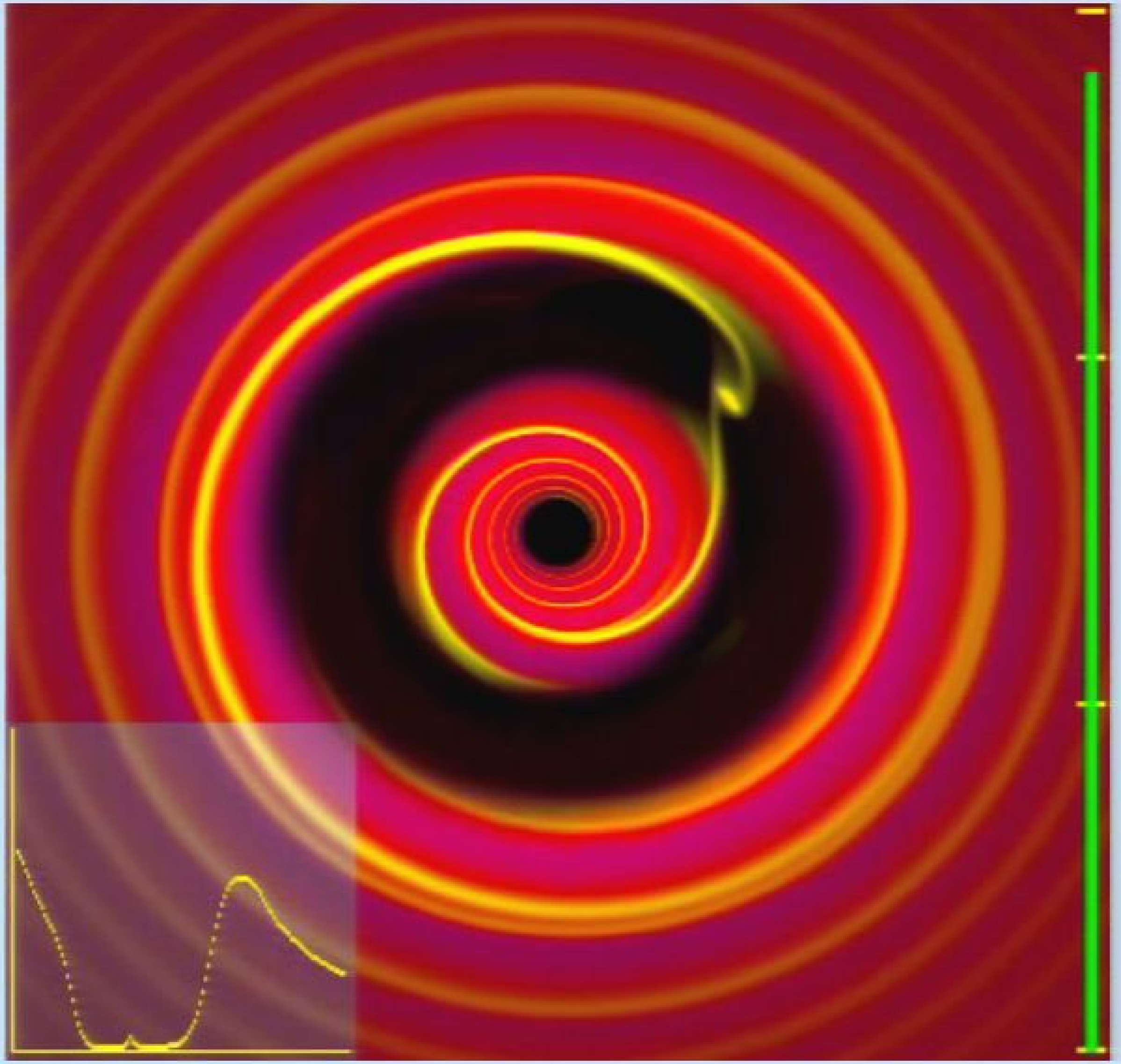


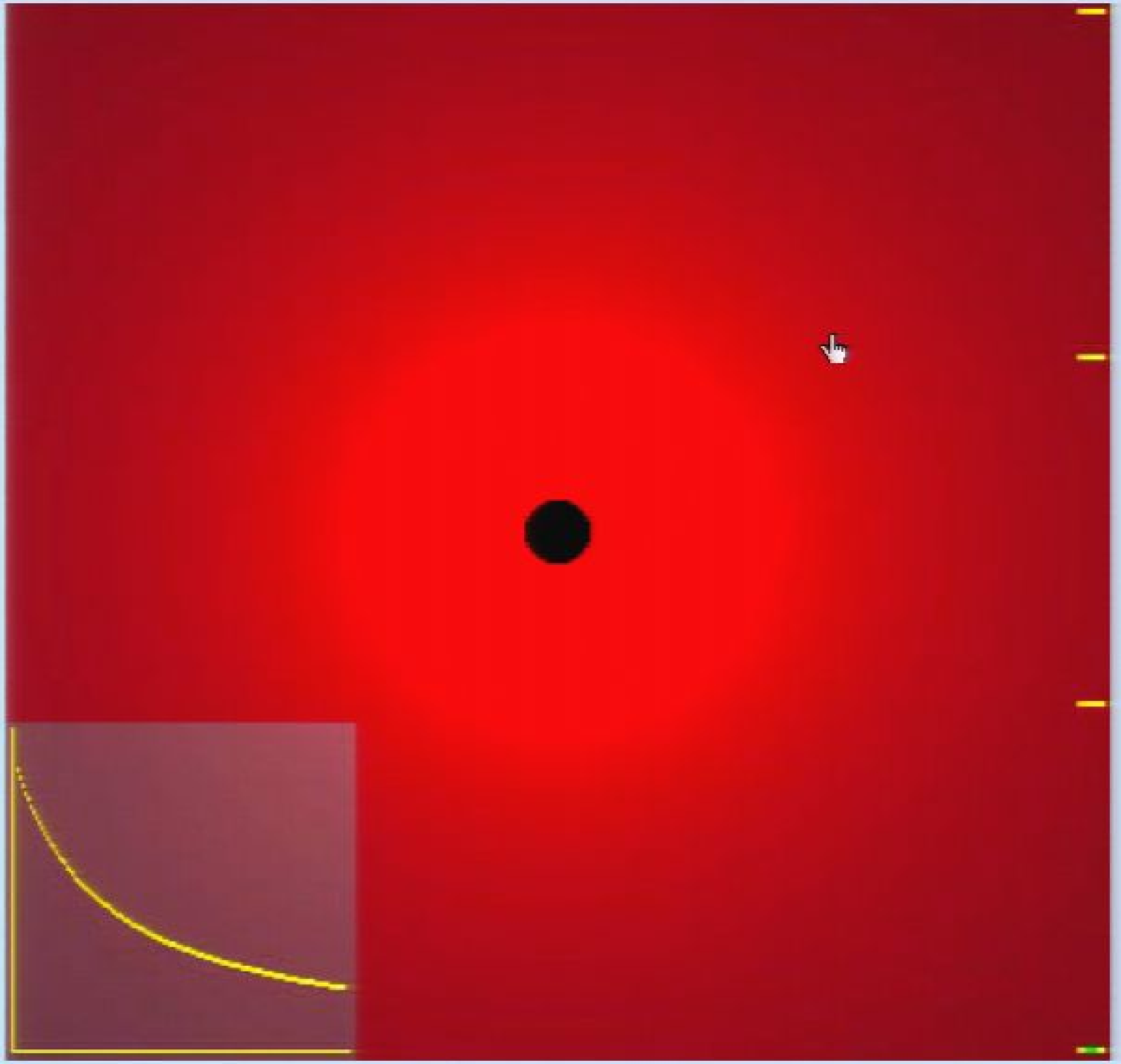


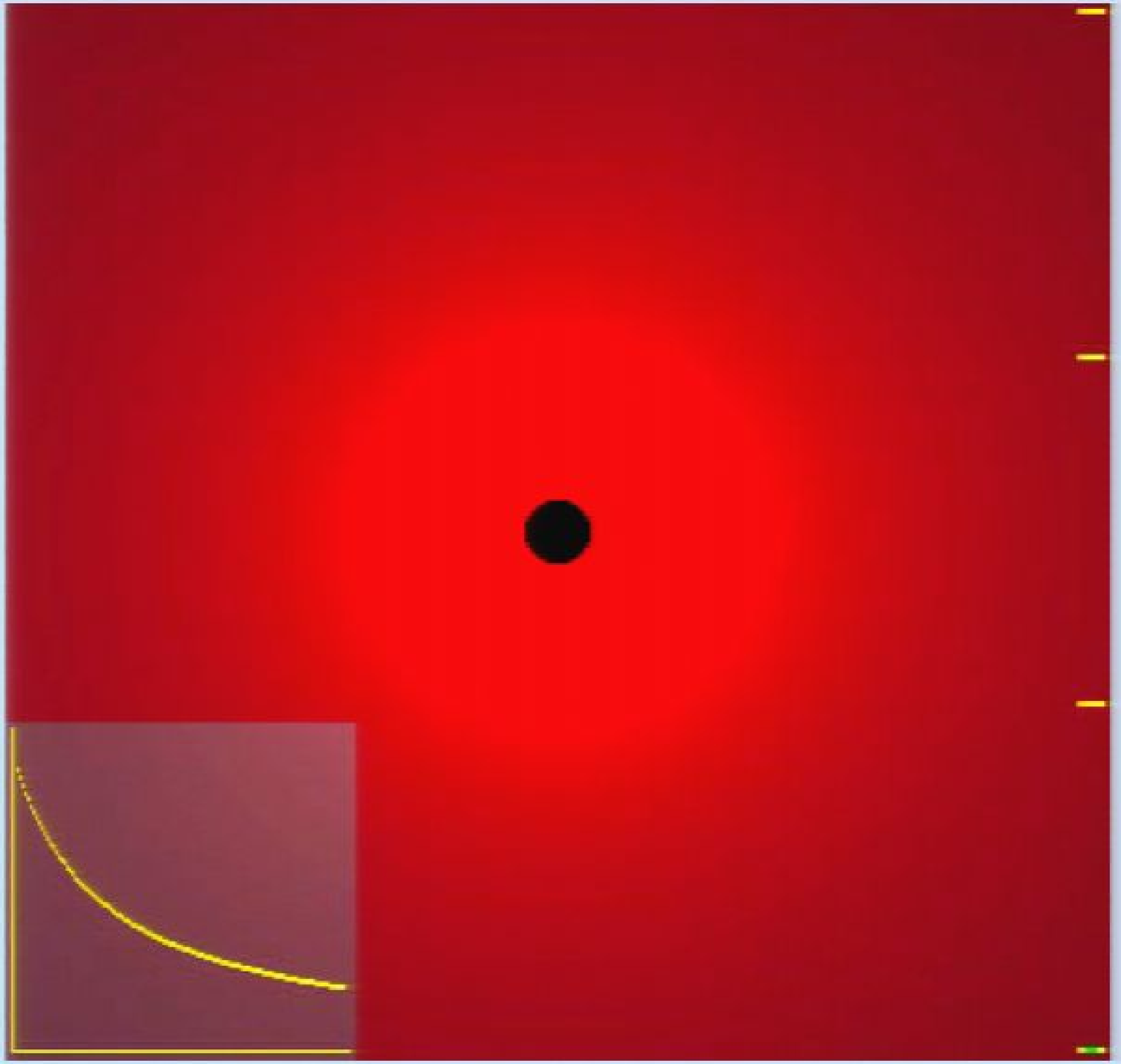












Expectations for gas driven mergers

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

$$\dot{a}_{\mathrm{visc}} \simeq -\frac{3}{2}\left(\frac{h}{r}\right)^{2} \alpha v_{\mathrm{K}},$$

$$\dot{a}_{\mathrm{GW}} = -\frac{64 G^{3} M_{1} M_{2} (M_{1} + M_{2})}{5 c^{5} a^{3}},$$

$$a_{\mathrm{crit}} = \left(\frac{128}{5}\right)^{2/5} \left(\frac{h}{r}\right)^{-4/5} \alpha^{-2/5} q^{2/5} \left(\frac{G M_{1}}{c^{2}}\right)$$

Transition radius depends on disk parameters and the mass ratio q

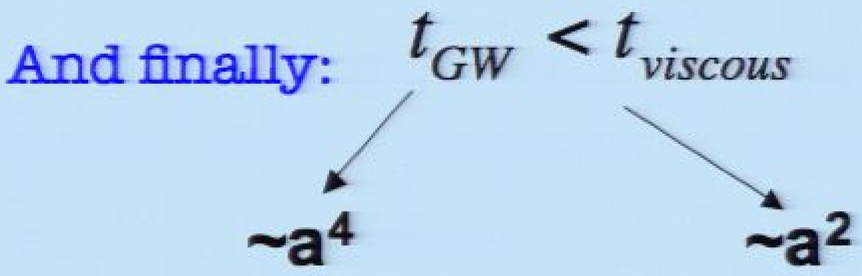
Probable consequences: disk interaction ® significant eccentricity to binary probably for q > 0.05 (Papaloizou, Nelson & Masset 2001); possibly for lower q (Goldreich & Sari 2002)

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

Stages of gas-driven mergers

Eventually: $t_{GW} < t_{decay}$

Gas ceases to be dynamically significant, but disk inner edge still moves in fast enough to keep up with binary

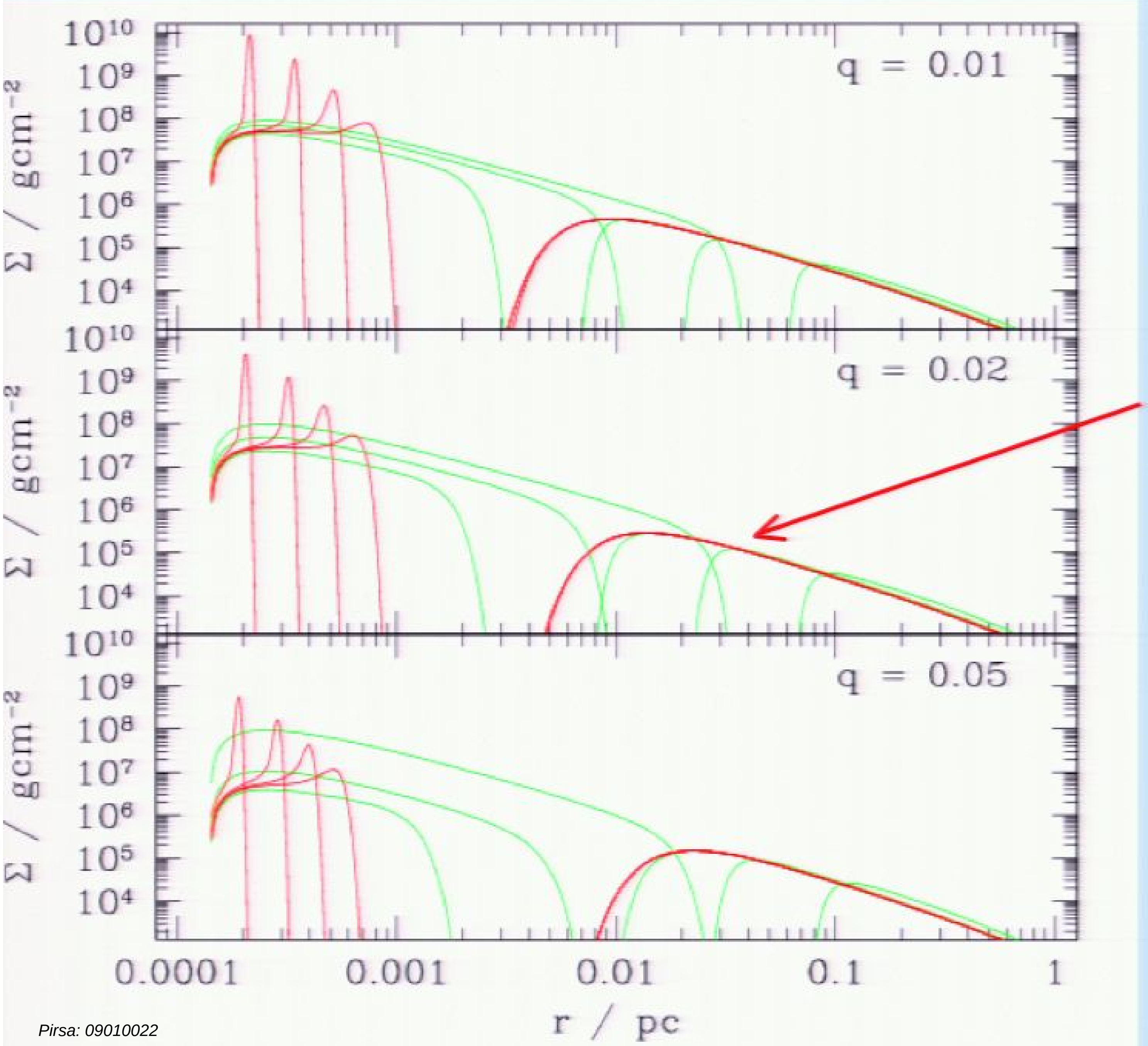


And finally: $t_{GW} < t_{viscous}$

$\sim a^4$

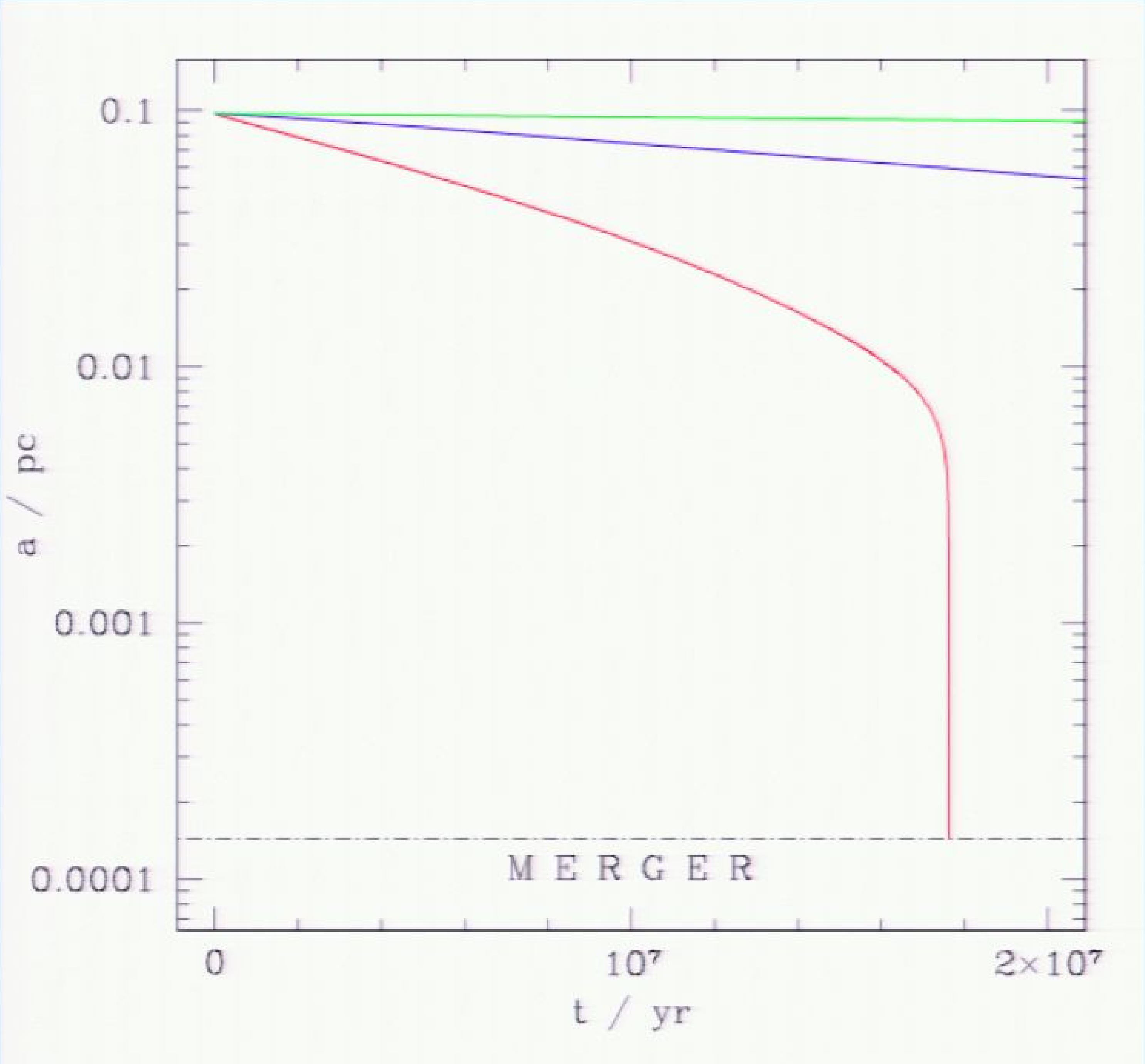
$\sim a^2$

Gas can't keep up, binary merges while gas disk remains frozen



frozen circumbinary gas disk as binary merges

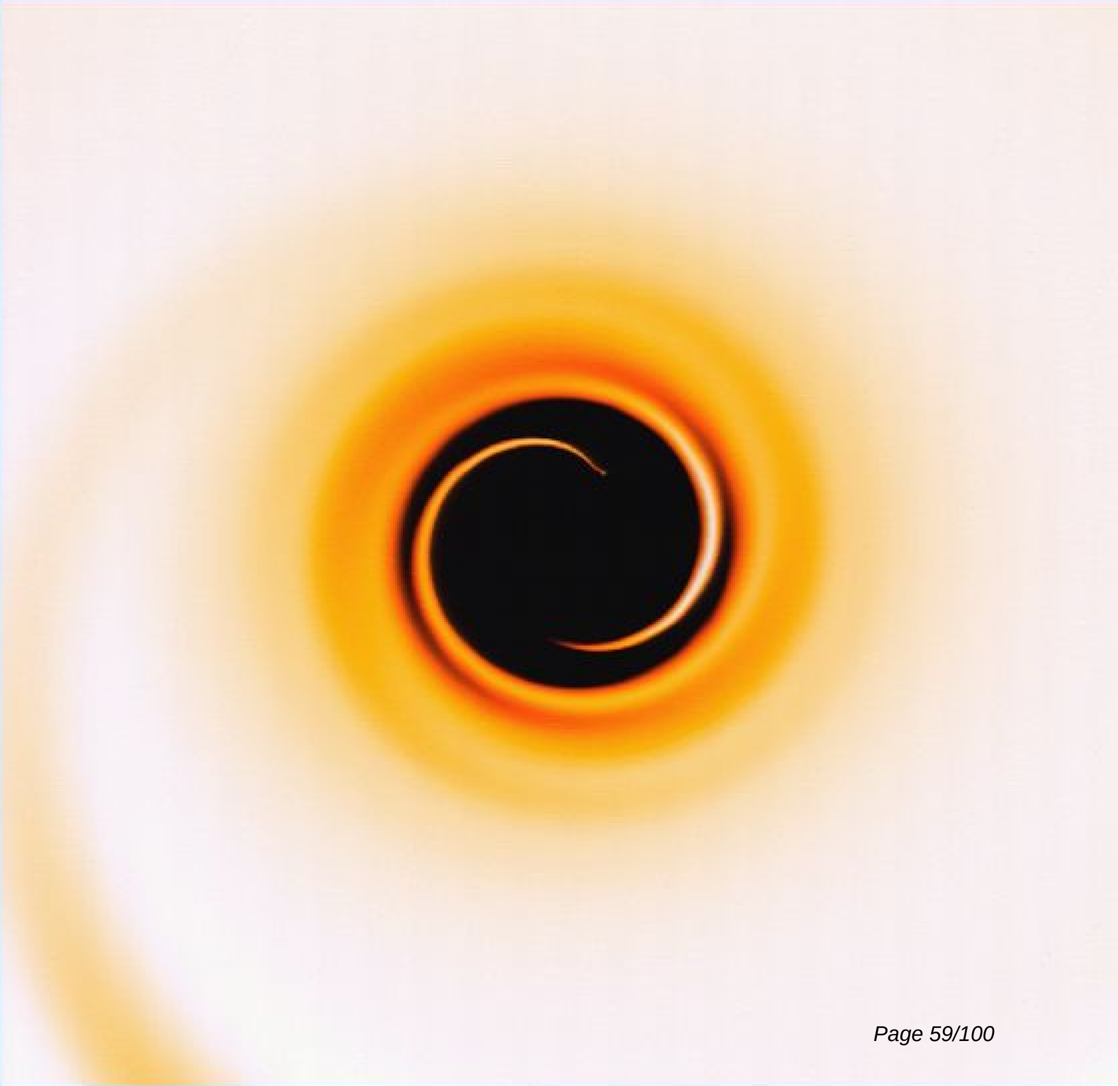
Armitage & PN 2002


0.1
0.01
0.001
0.0001
a / pc
MERGER
0
10^7
2×10^7
t / yr

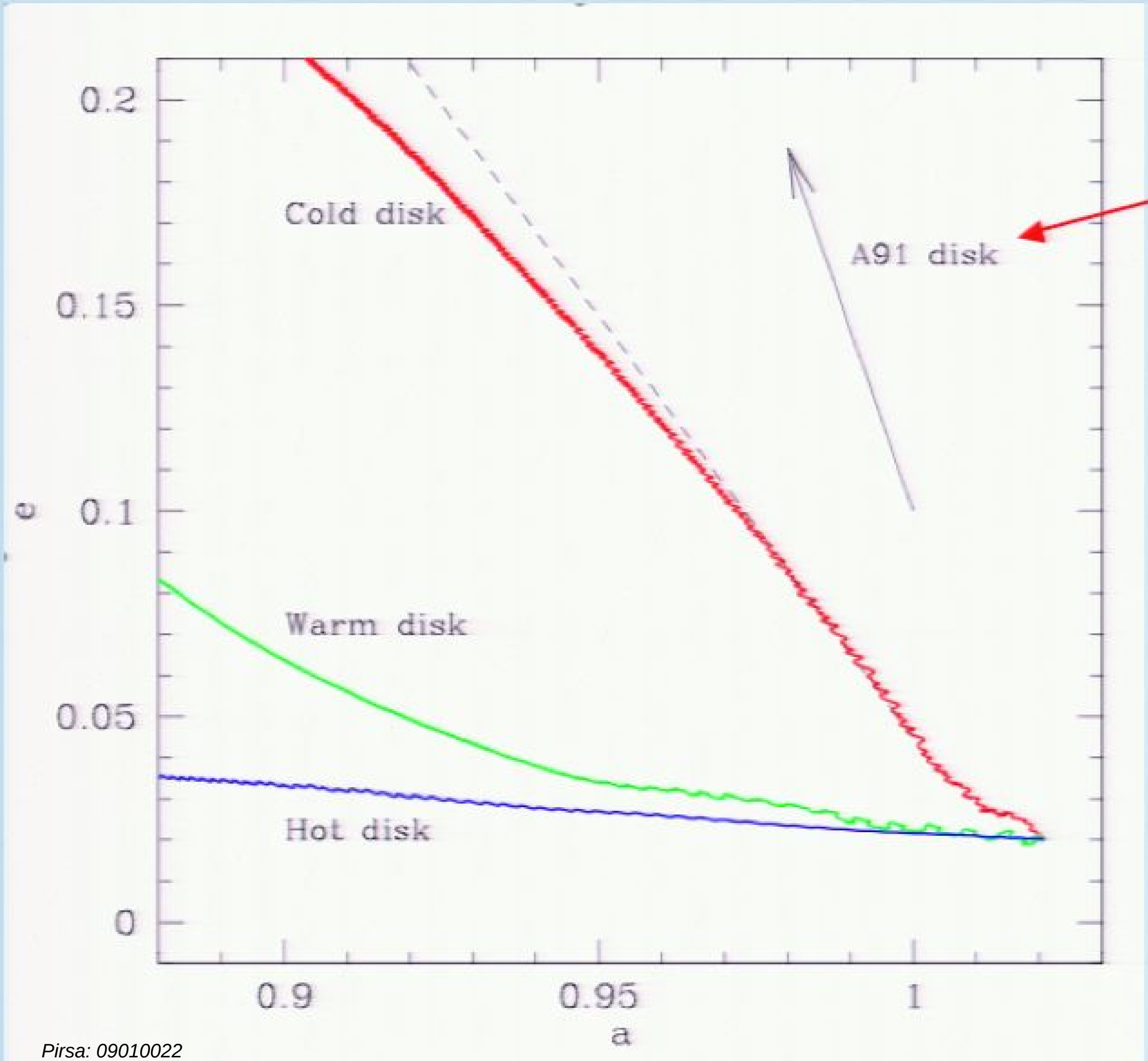
Evidence of merger cause in gravitational waves?

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 $q > q_{crit}(h/r)$



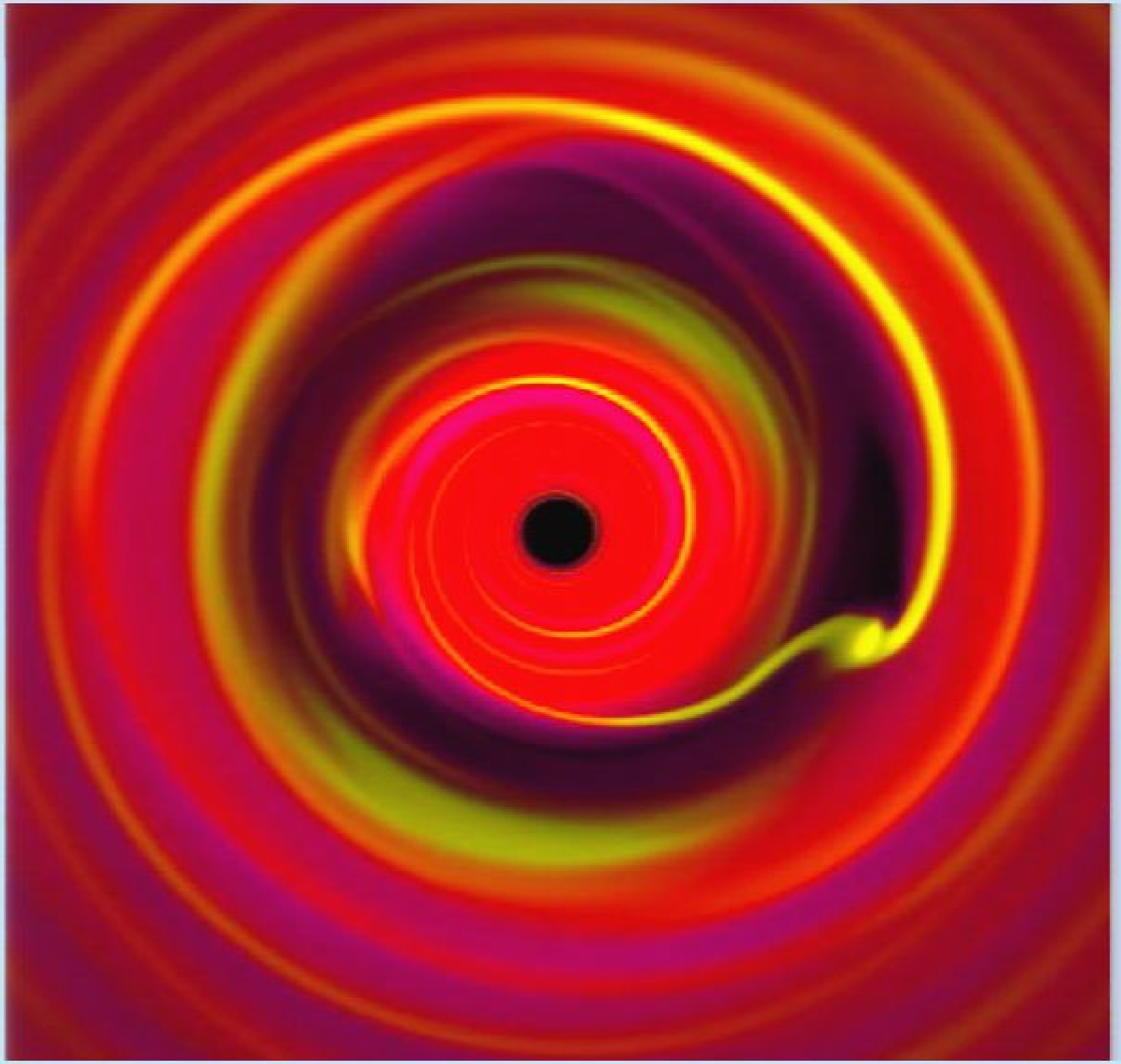
Evolution of the eccentricity



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..

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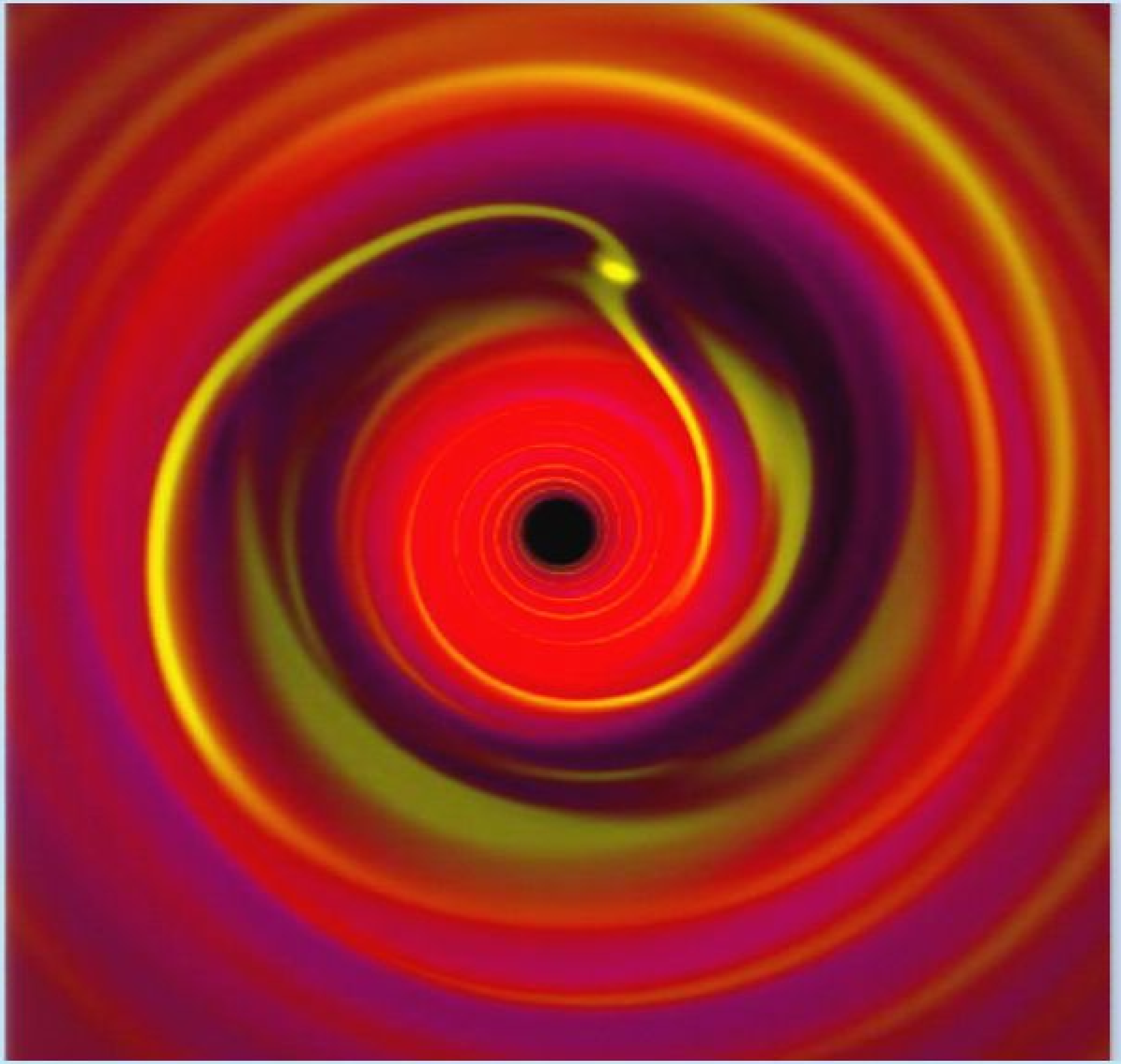

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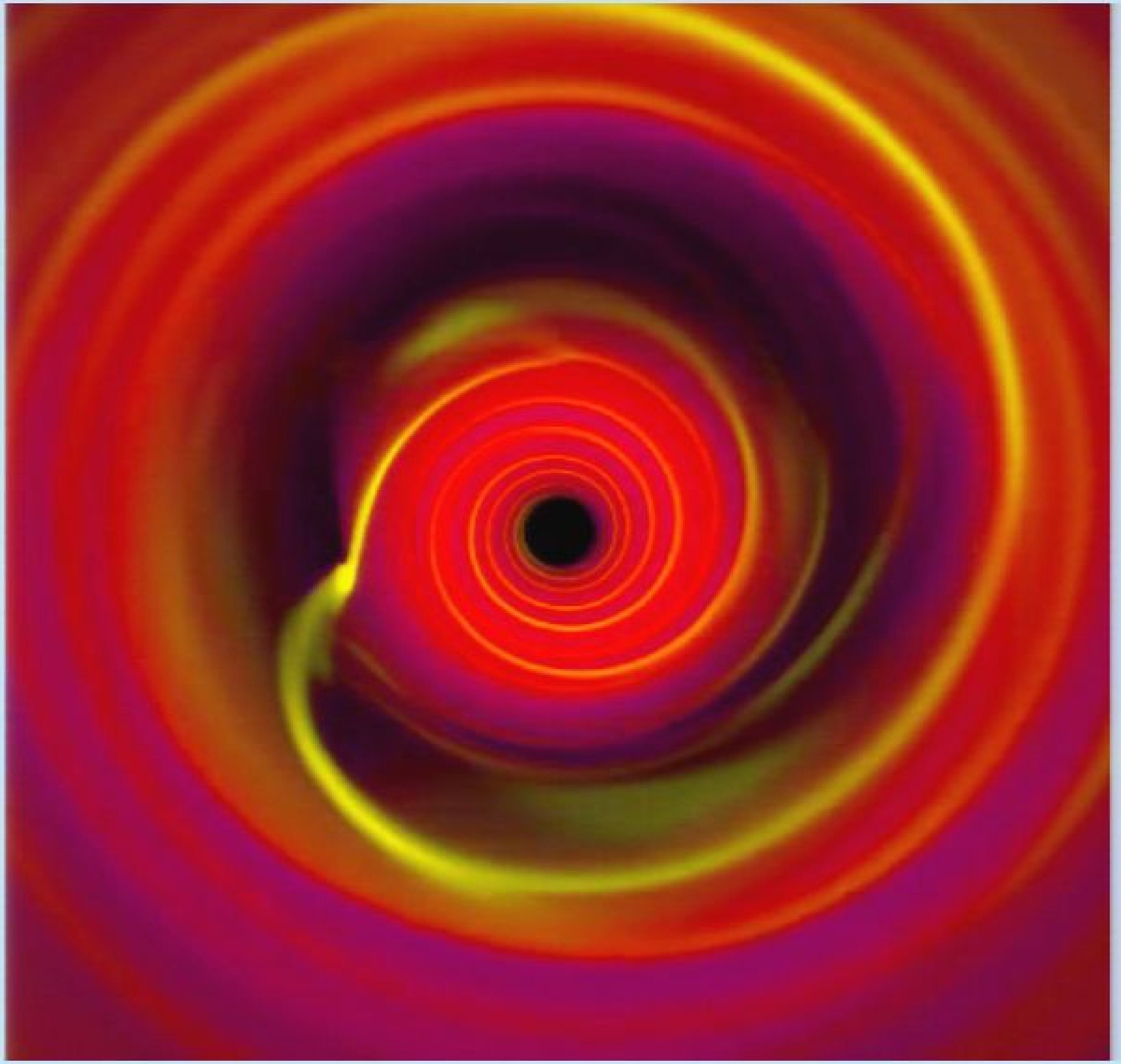

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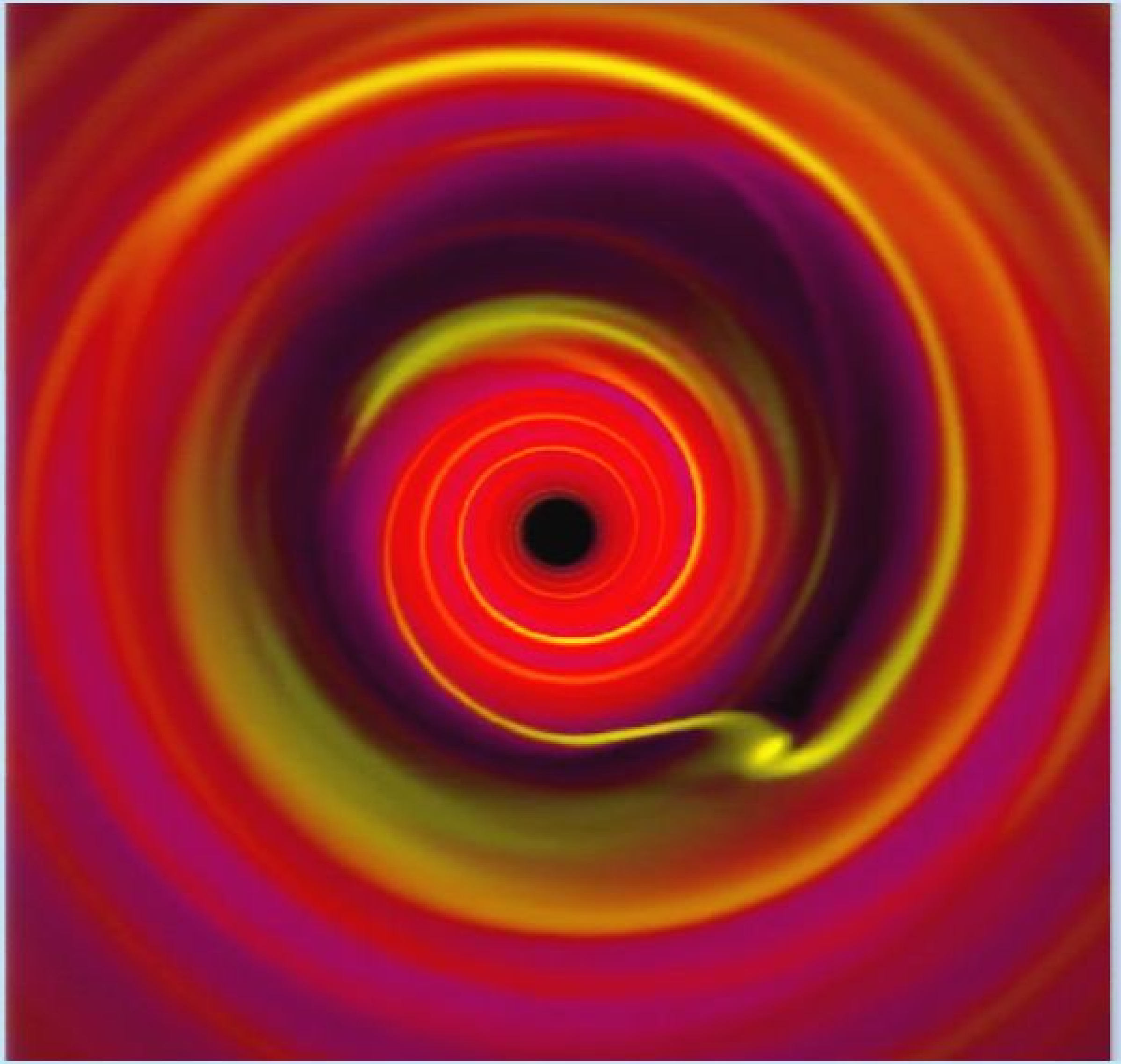

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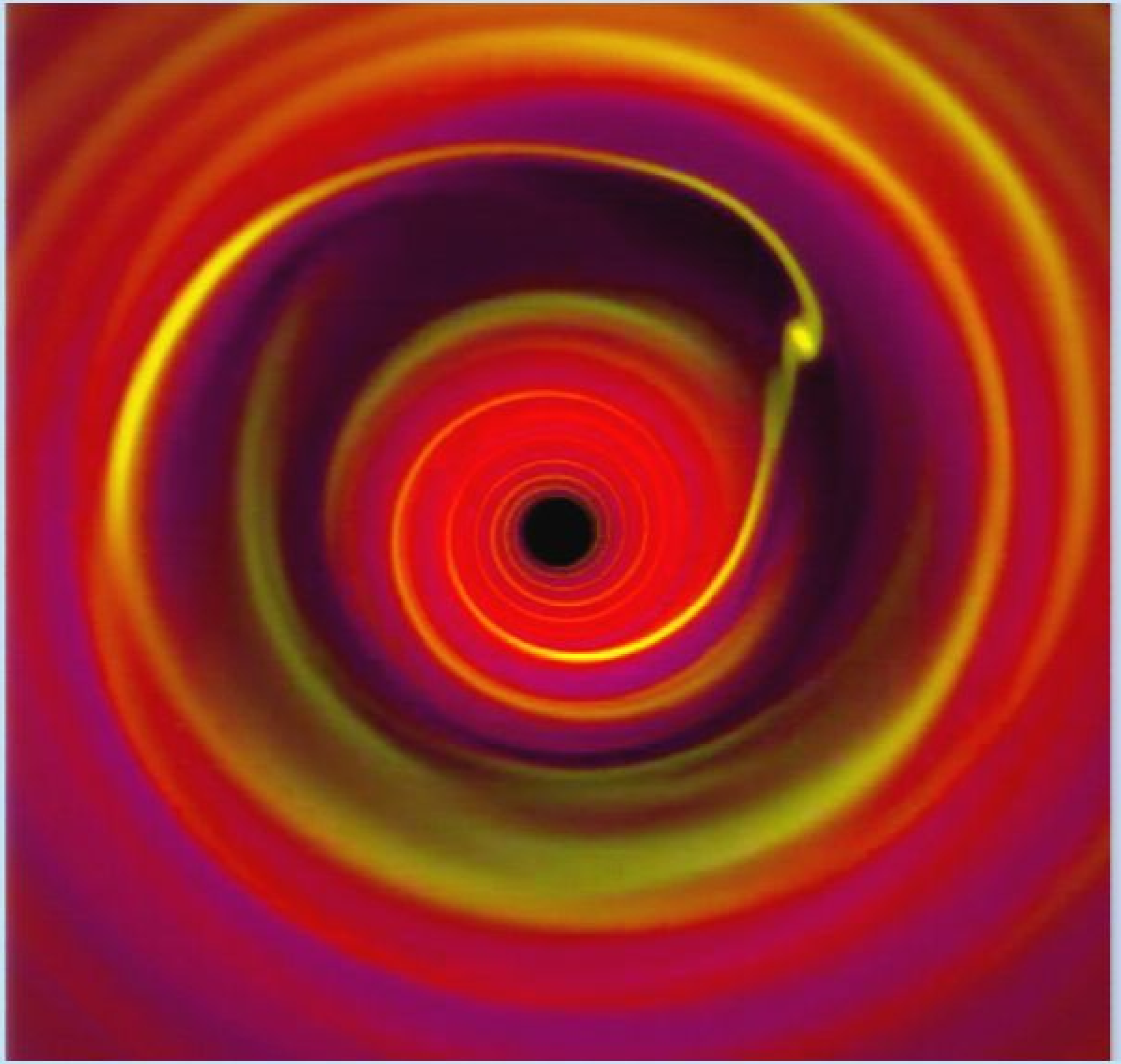

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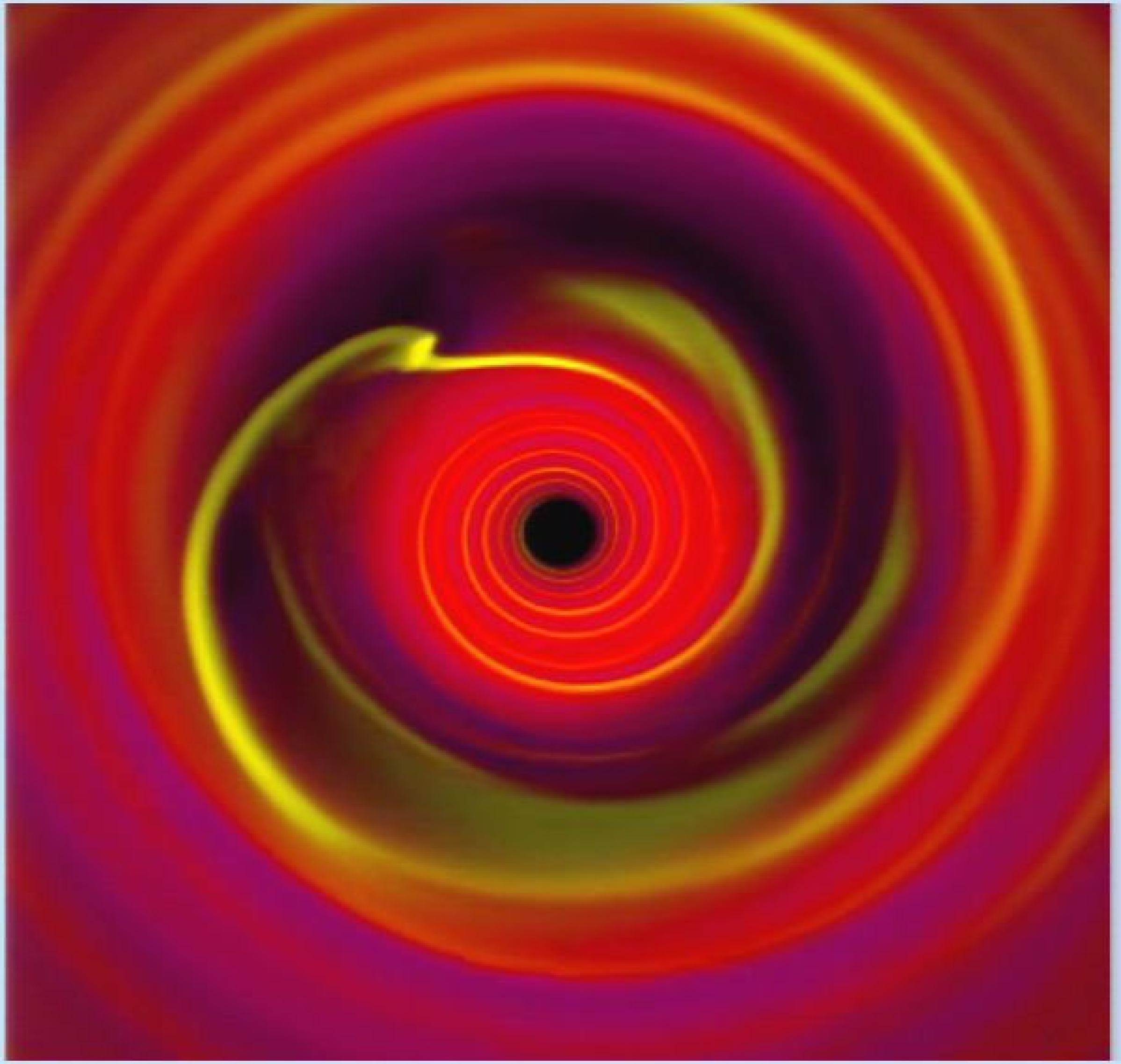

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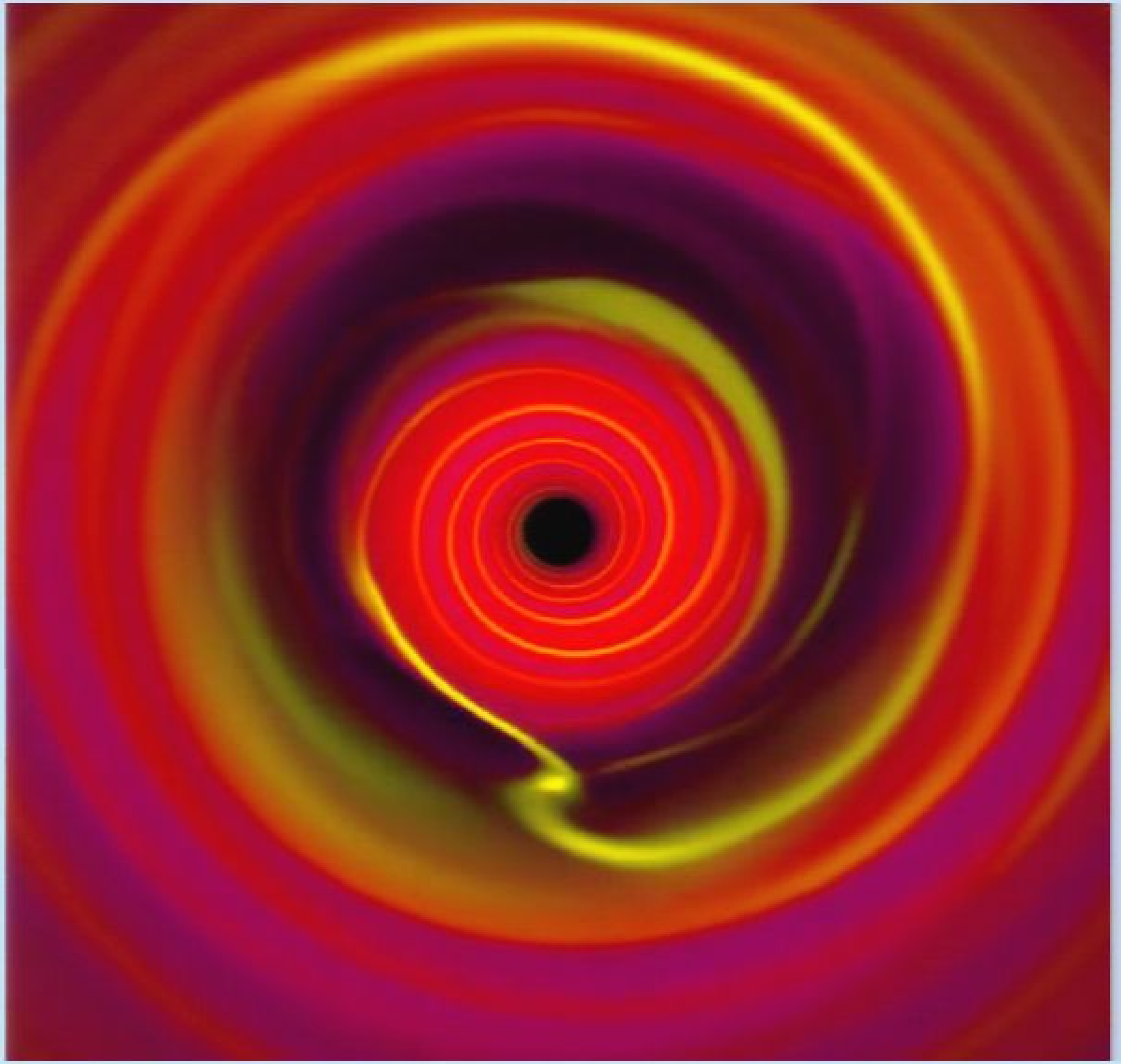

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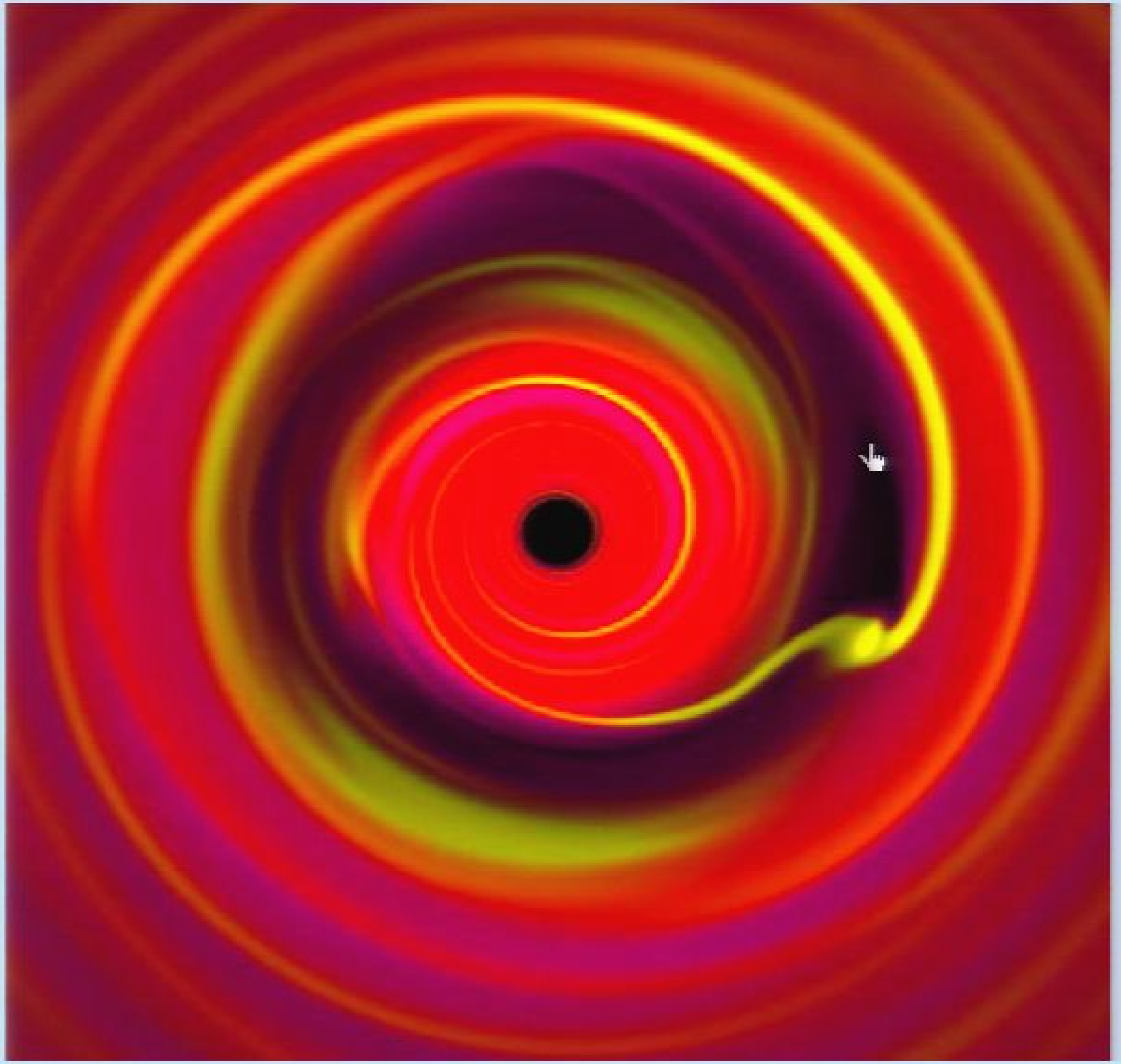
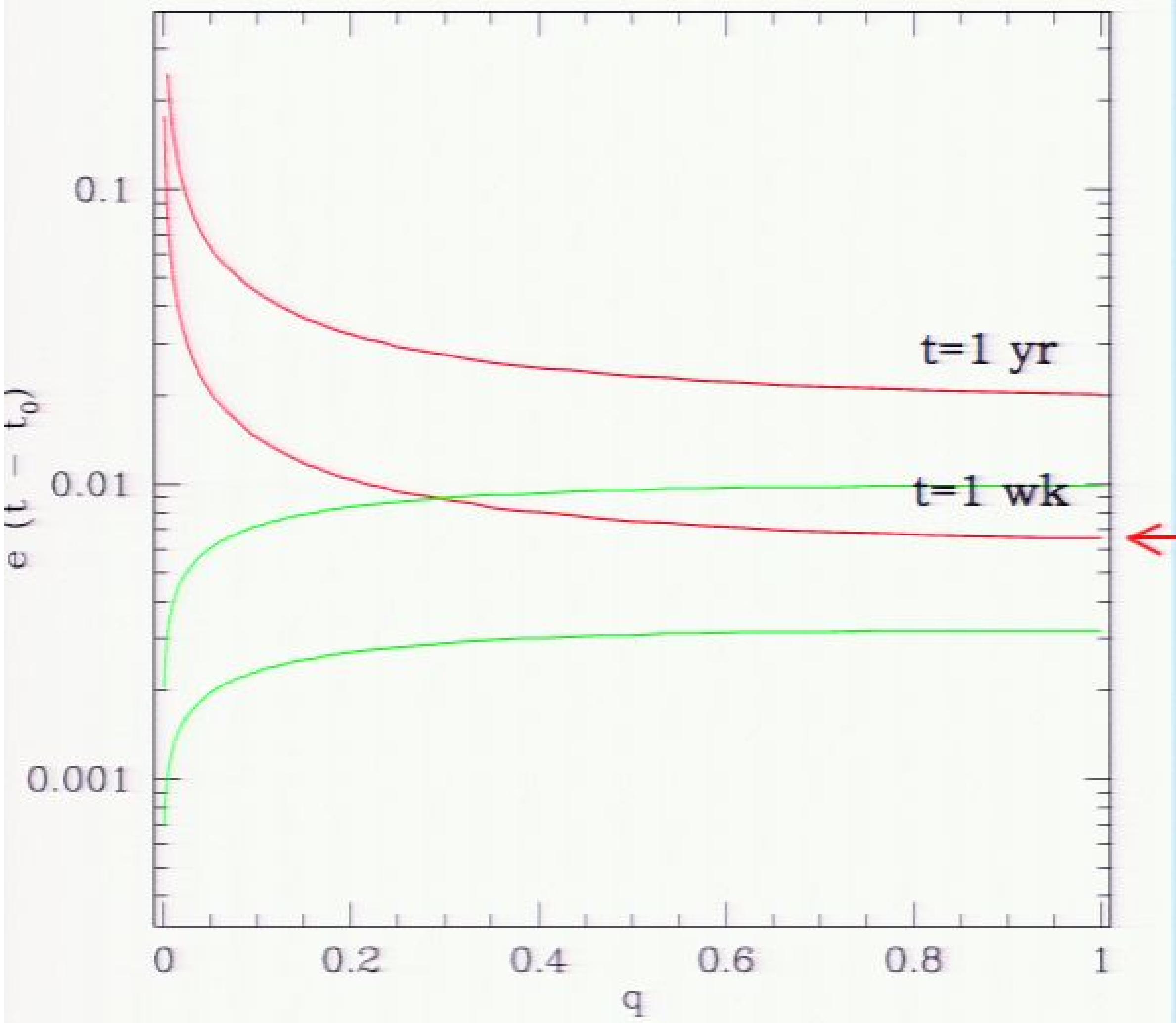
Starting with a modestly eccentric orbit



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

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

Armitage & PN (2005)

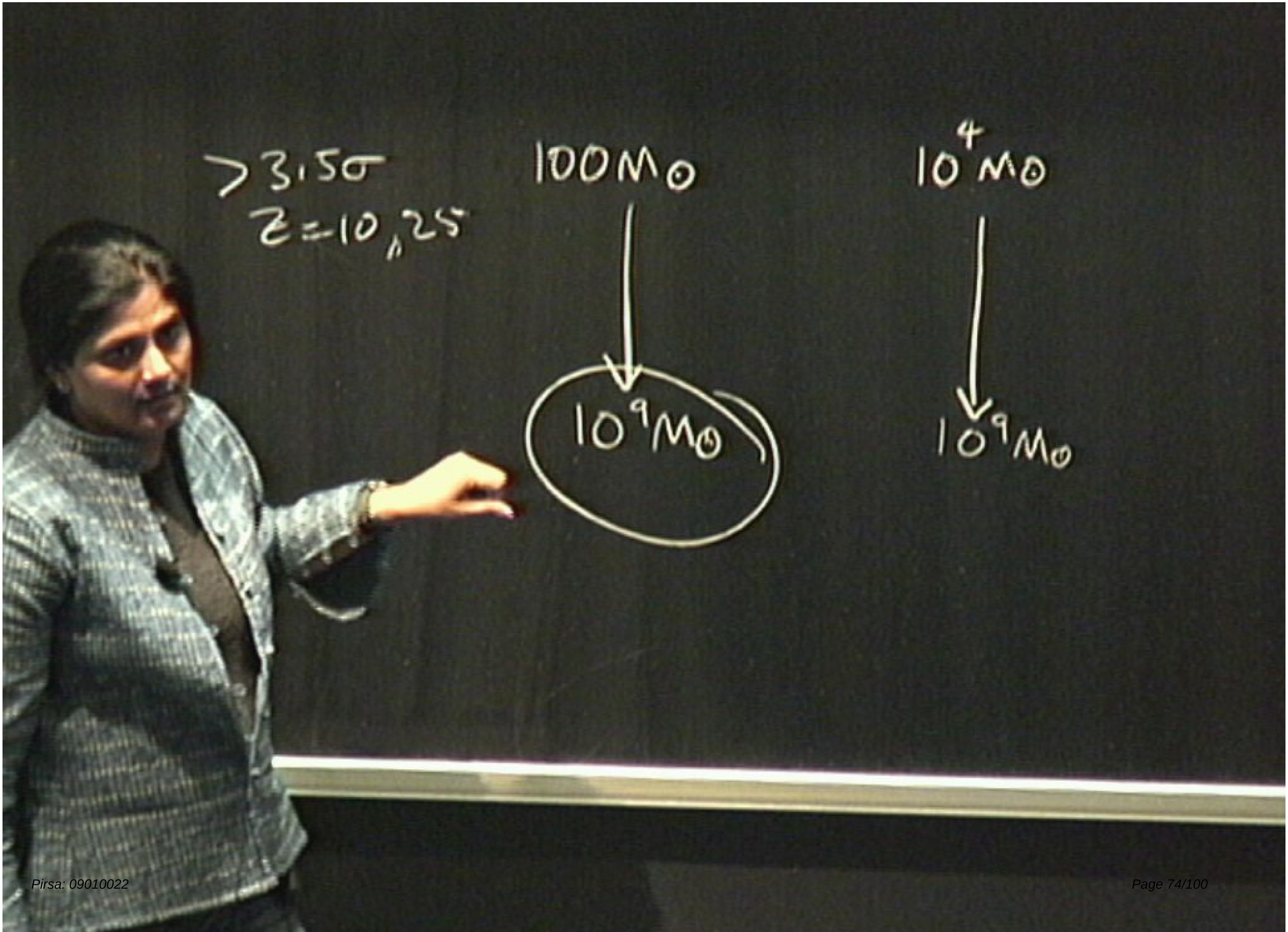
Counter-parts signaling BBH mergers

- Electromagnetic counterparts: precursors and afterglows
- Otherwise LISA will fail 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

Conclusions

- Massive BH seeds from the direct collapse of pre-galactic gas discs
- Models that take into account time evolution of these discs and fragmentation
- Mass function of these BHs depend on host DM halo properties
- Predictions for the z = 0 BH mass function - both at the high and low mass end
- Can account for the observed z ~ 6 SDSS quasars
- Low surface brightness, bulgeless galaxies with large discs least likely sites for high z BH formation
- The efficiency of BH seed formation has a direct influence in BH occupation fraction at z = 0
- A population of low mass galaxies do not host nuclear BHs at z = 0
- Predict the existence of UMBHs at the high mass end at every epoch

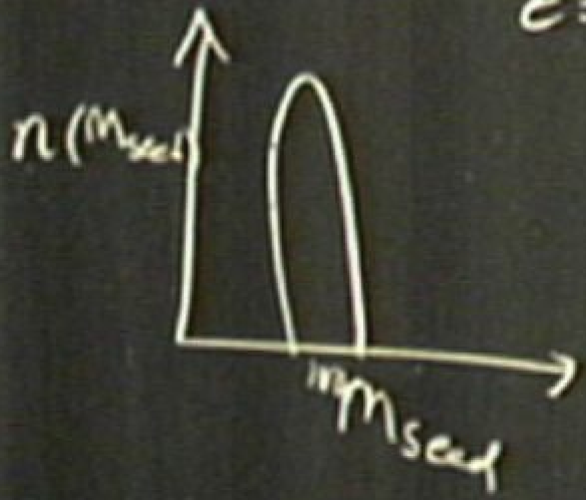
$$\begin{array}{c} 100\,M_\odot \\ \Big\downarrow \\ 10^9\,M_\odot \end{array} \qquad\qquad \begin{array}{c} 10^4\,M_\odot \\ \Big\downarrow \\ 10^9\,M_\odot \end{array}$$



$> 3.5\sigma$

$z = 10, 25$

$$\begin{tikzcd} 100 M_\odot \arrow[d] & 10^4 M_\odot \arrow[d] \\ 10^9 M_\odot & 10^9 M_\odot \end{tikzcd}$$



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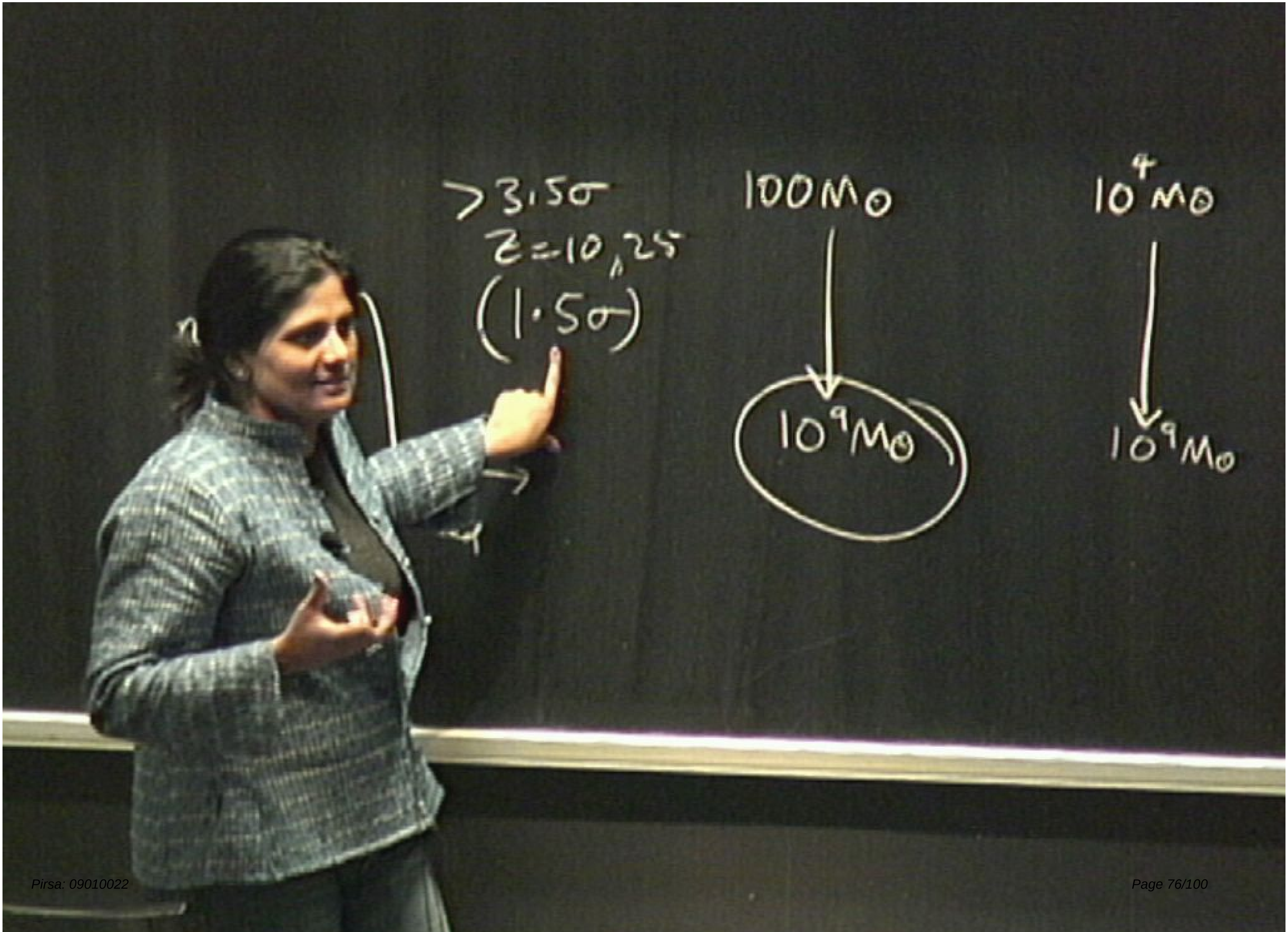

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(1.5σ)

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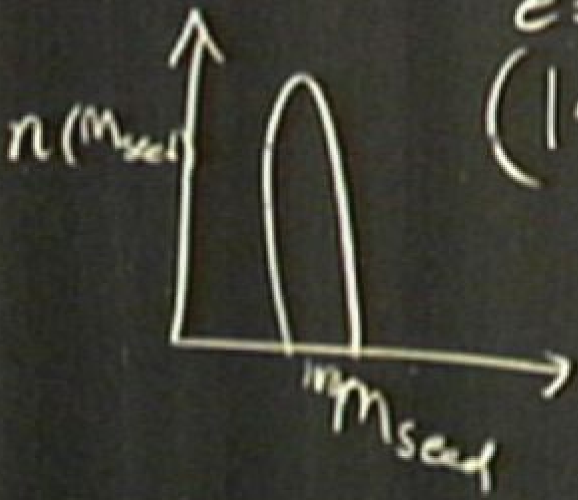

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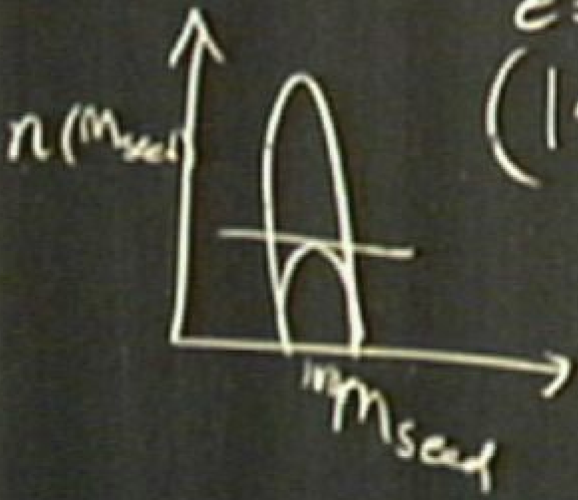

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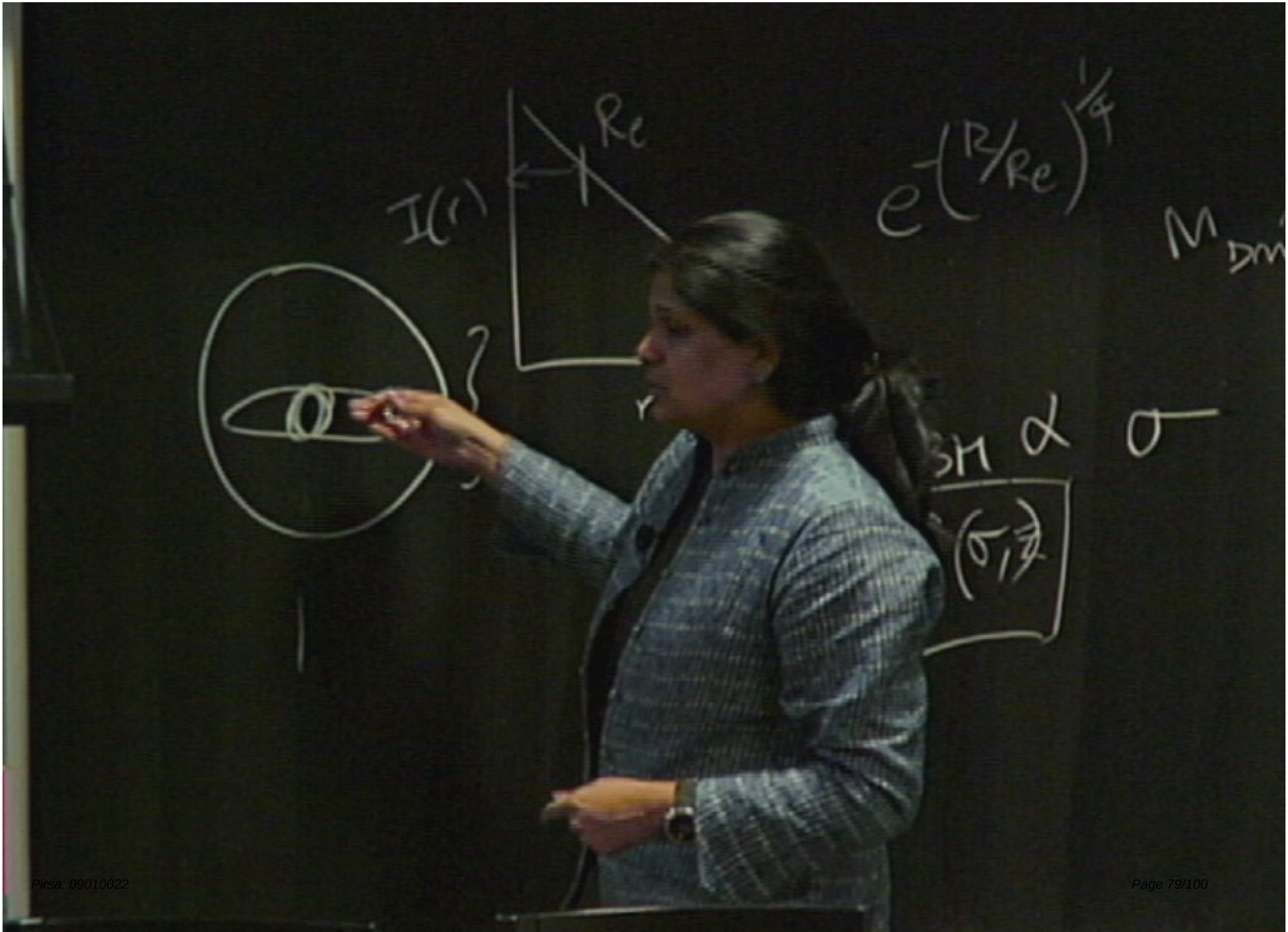
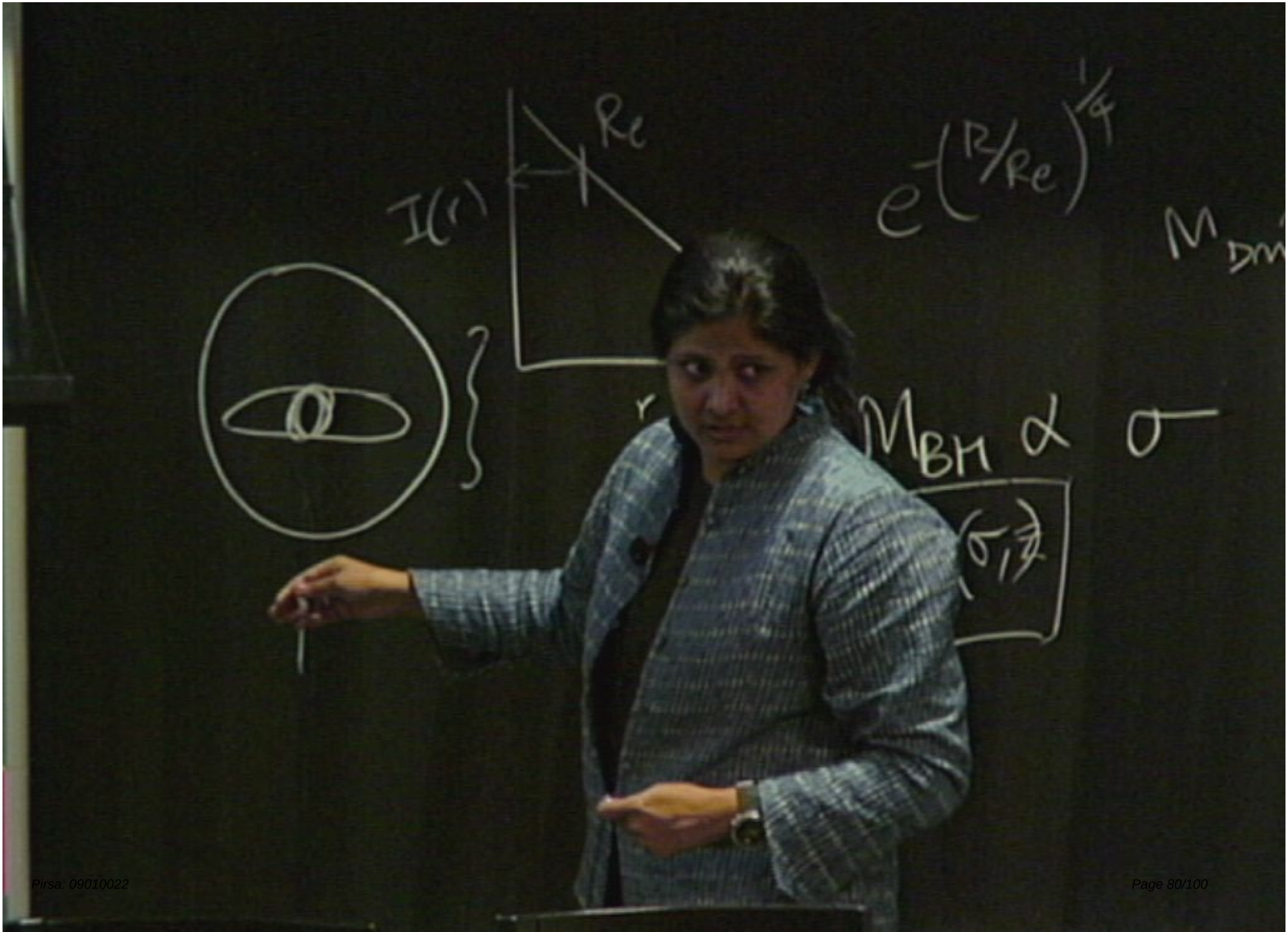
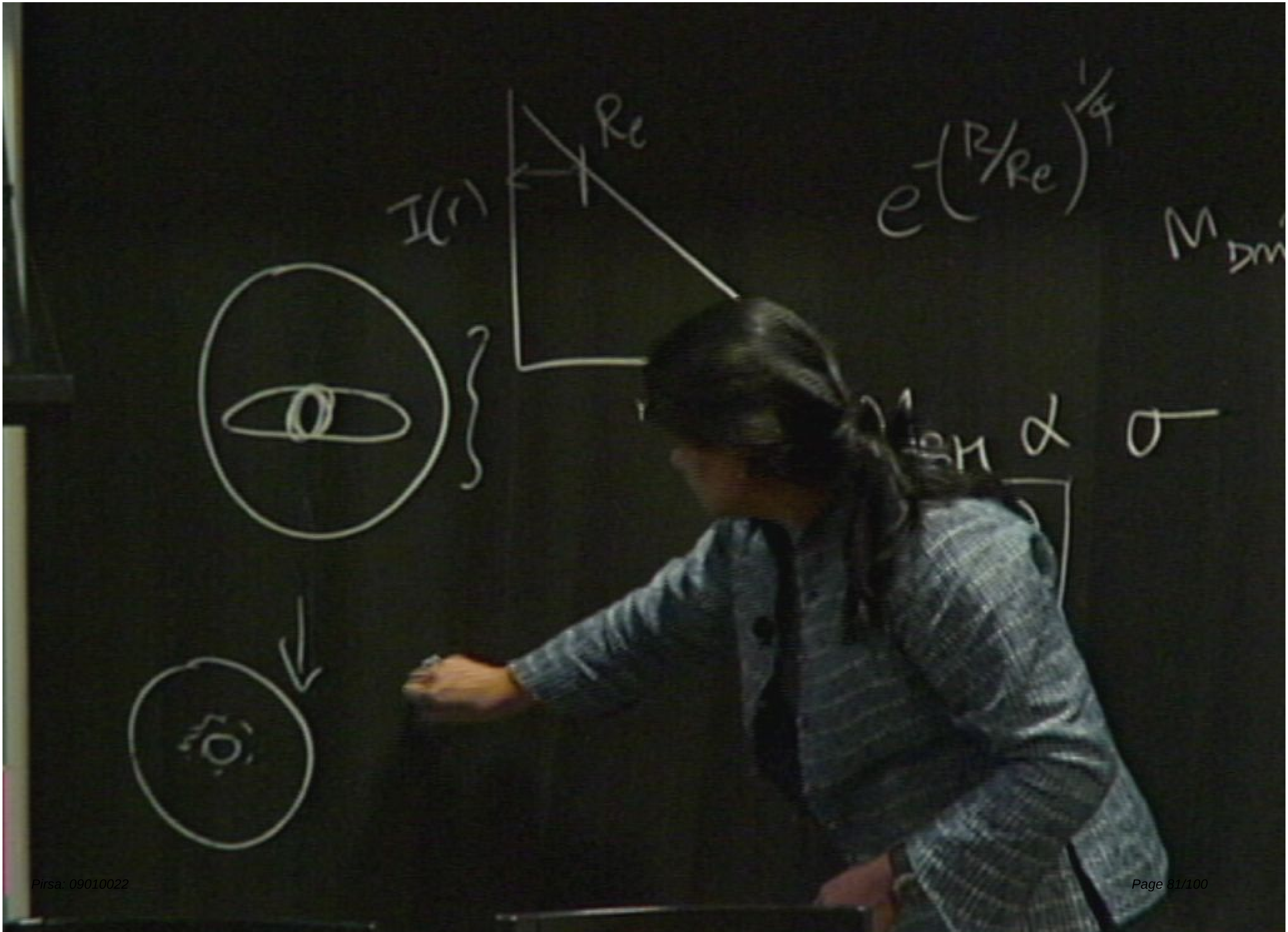

I(r)
Re
r
e^-(R/Re)^1/4
M_DM
BH ∝ σ


I(r)
Re
r
e^-(R/Re)^1/4
M_DM
M_BH ∝ σ
(σ, ...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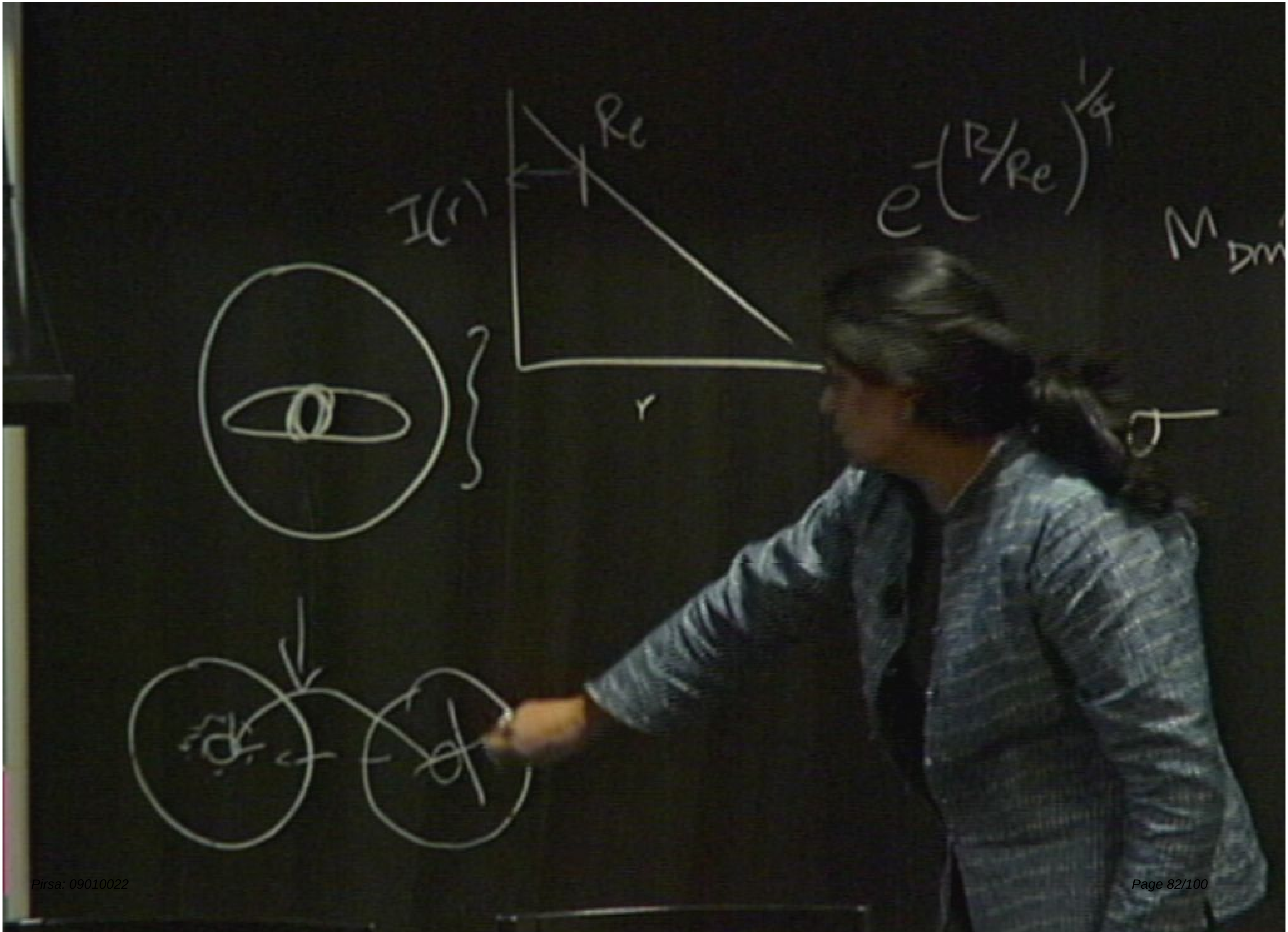
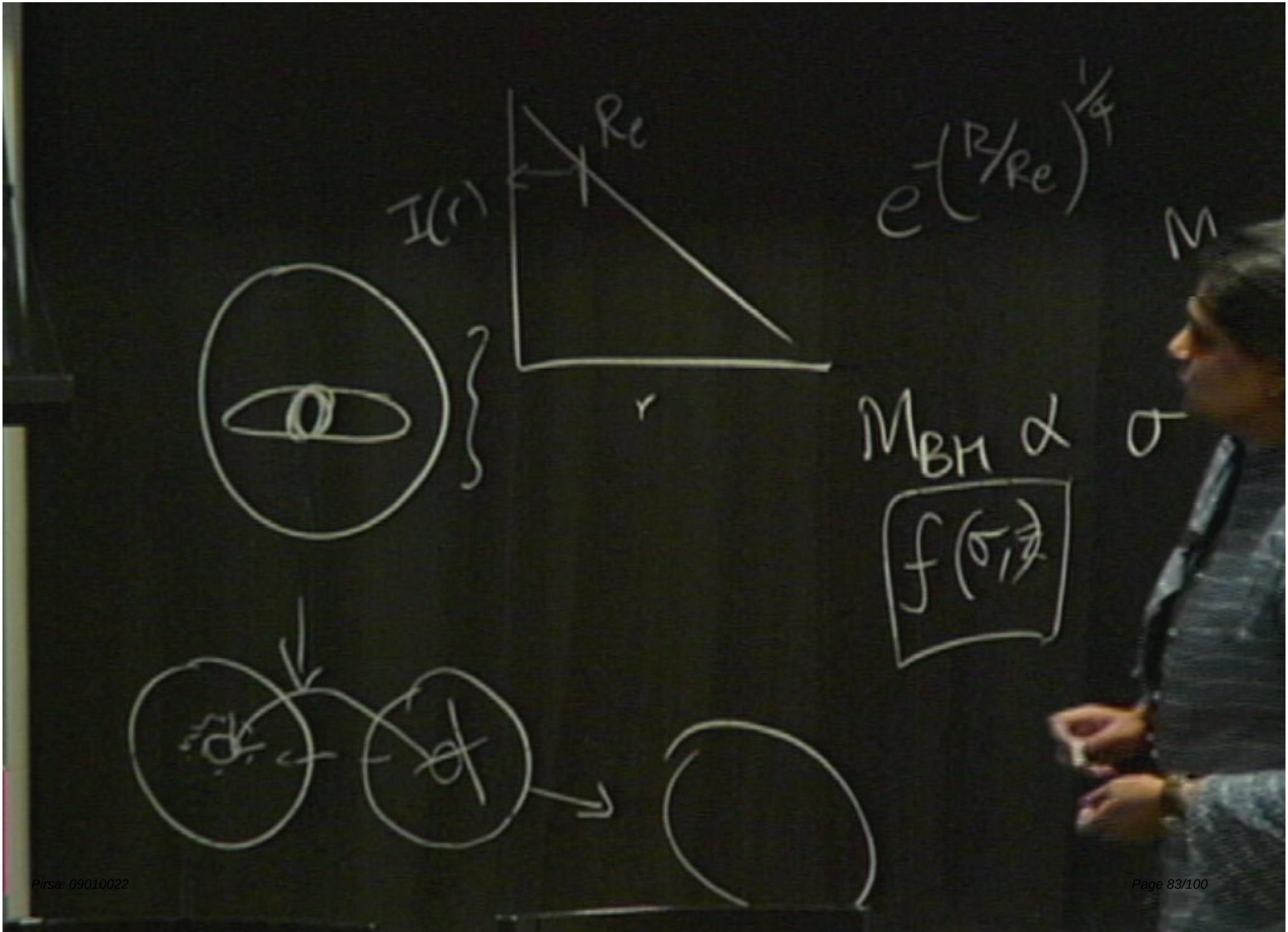
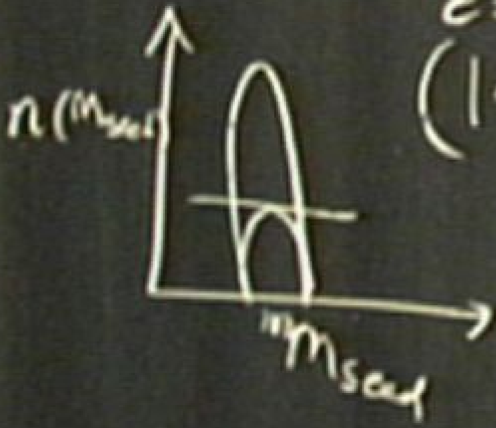
Re
e^-(R/Re)^1/4
M_DM
M ∝ σ


I(r)
Re
r
$e^{-(R/R_e)^{1/4}}$
M_{DM}
σ


$I(r)$
R_e
r
$e^{-(R/R_e)^{1/4}}$
M
$M_{BH} \propto \sigma$
$\boxed{f(\sigma, z)}$



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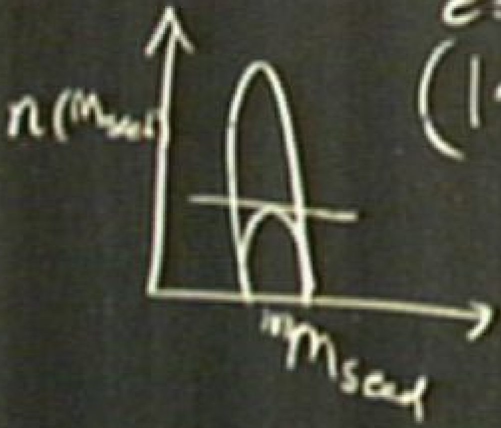
(1.5σ)

$$\begin{tikzcd} & \boxed{100 M_\odot} \arrow[d] & 10^4 M_\odot \arrow[d] \\ \underline{2\,\text{Gyr}} & \boxed{\underline{10^9 M_\odot}} & 10^9 M_\odot \end{tikzcd}$$



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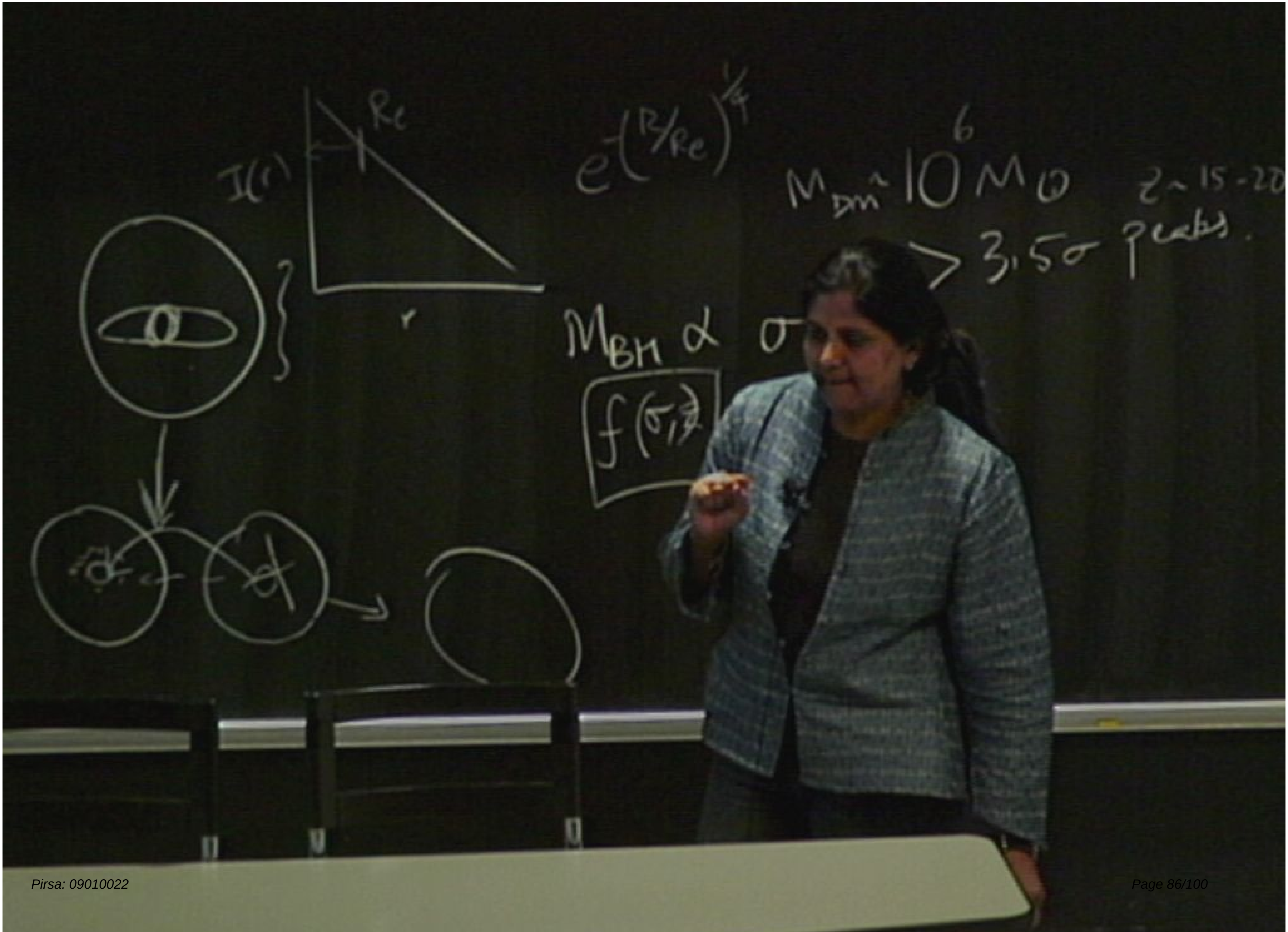
I(r)
Re
r
e(R/Re)1/4
MDM ~ 10^6 M⊙
z ~ 15-20
> 3.5σ peaks.
MBH ∝ σ
f(σ, z)

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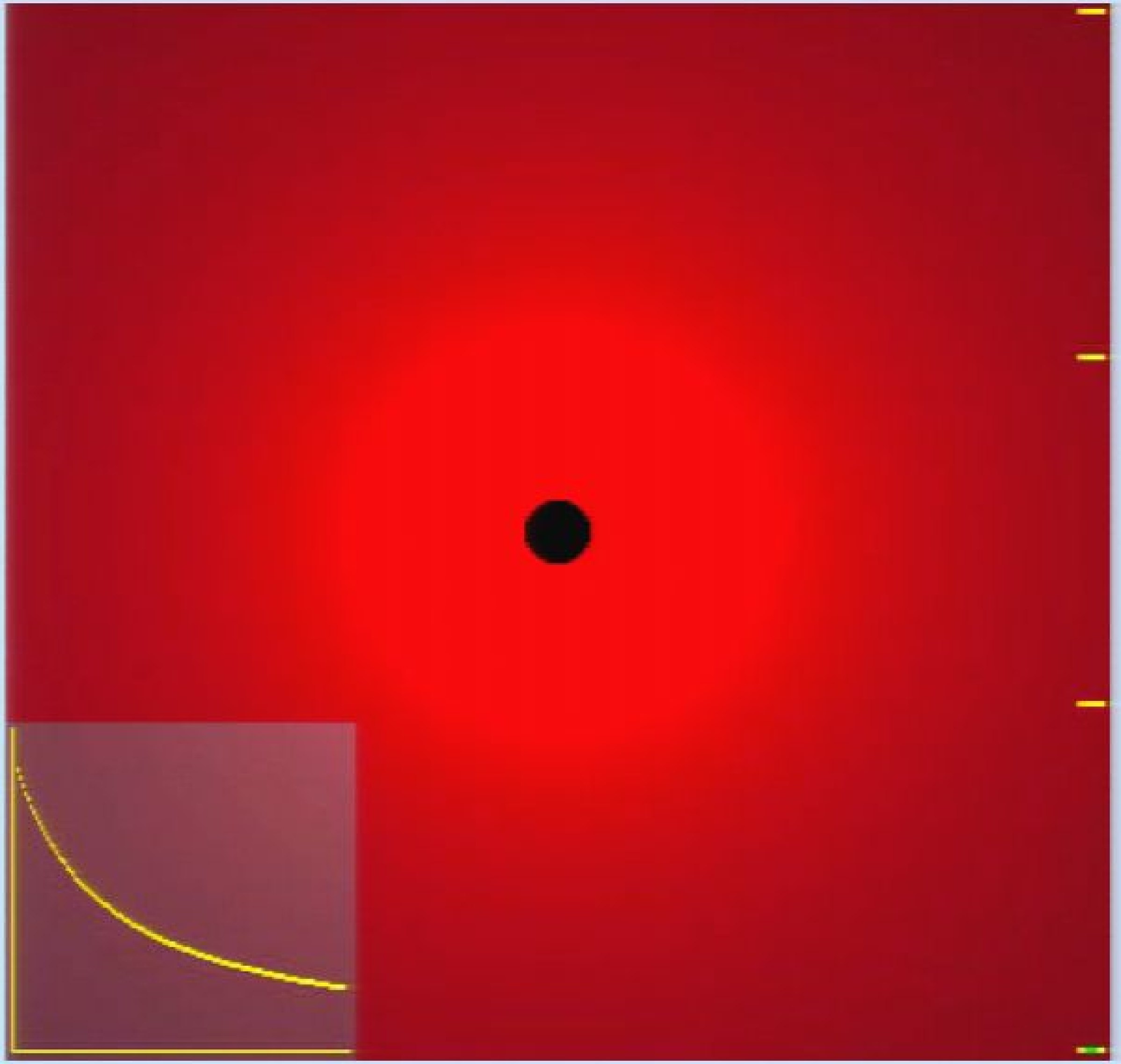

Will there be electromagnetic counterparts?

Motivation: identification of LISA sources; astrophysics

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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
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Armitage & PN 2002, 2005; PN & Armitage 2006; PN 2007
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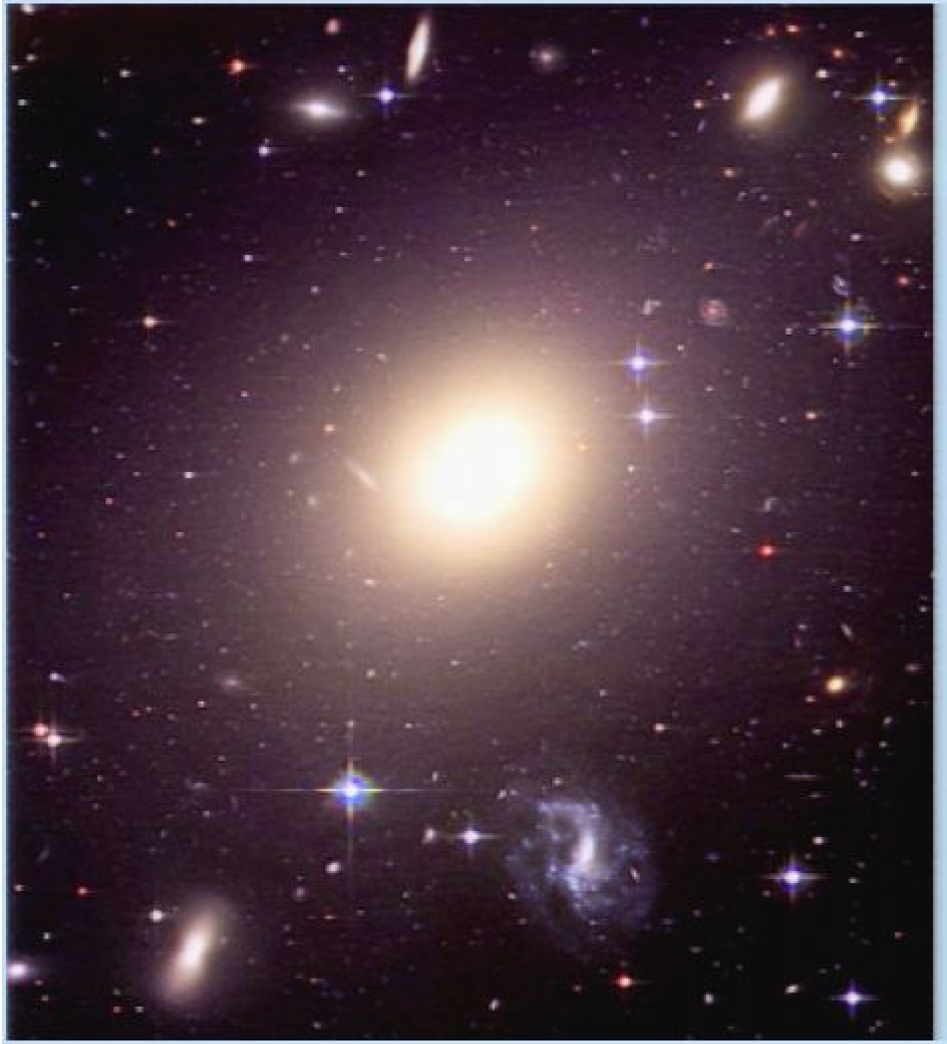
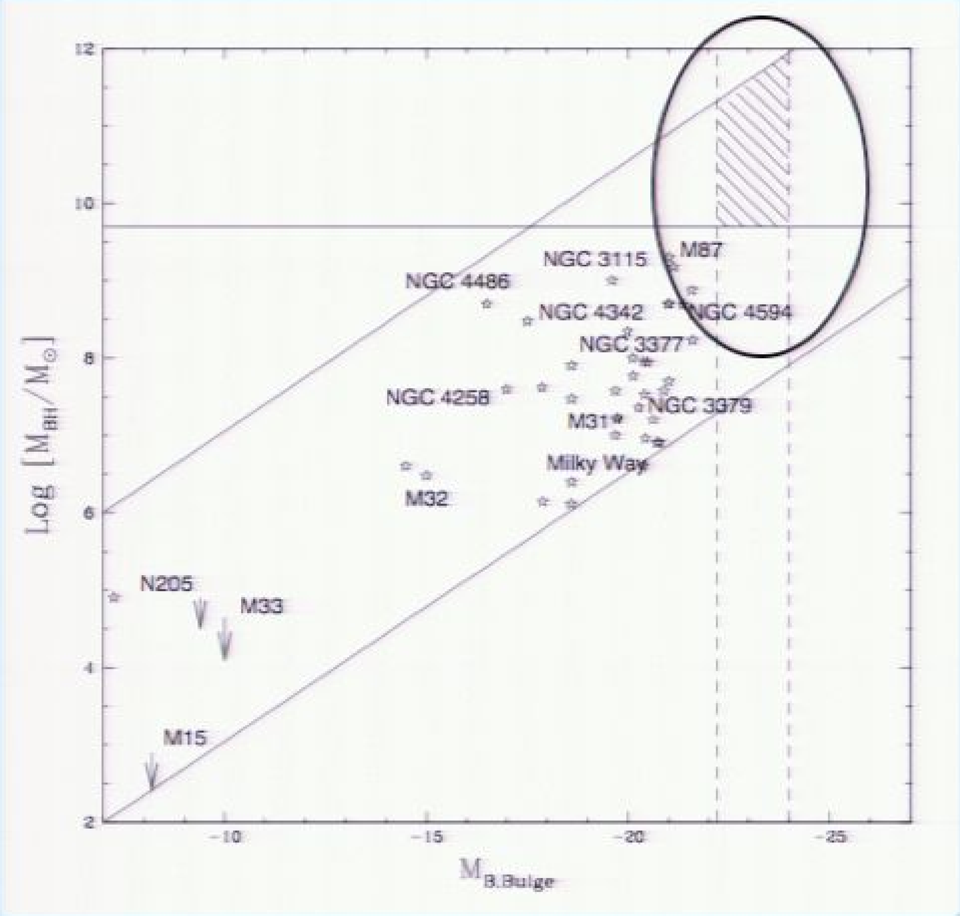
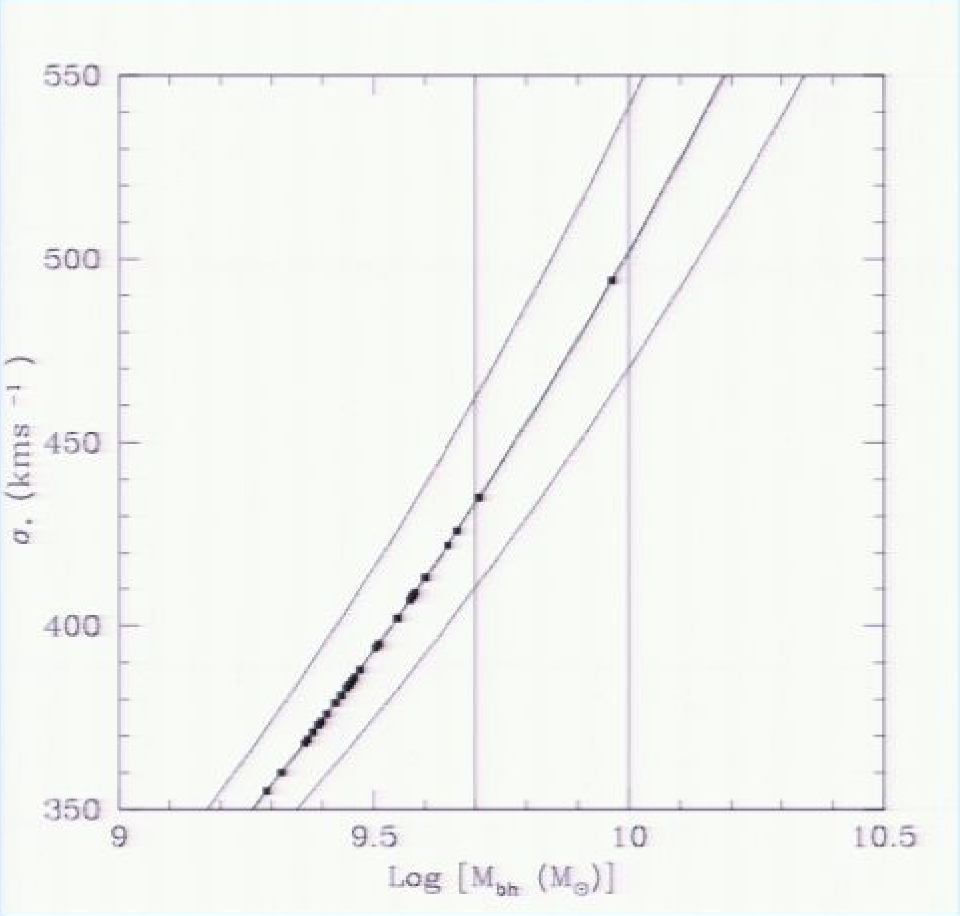


Predict existence of UMBHs



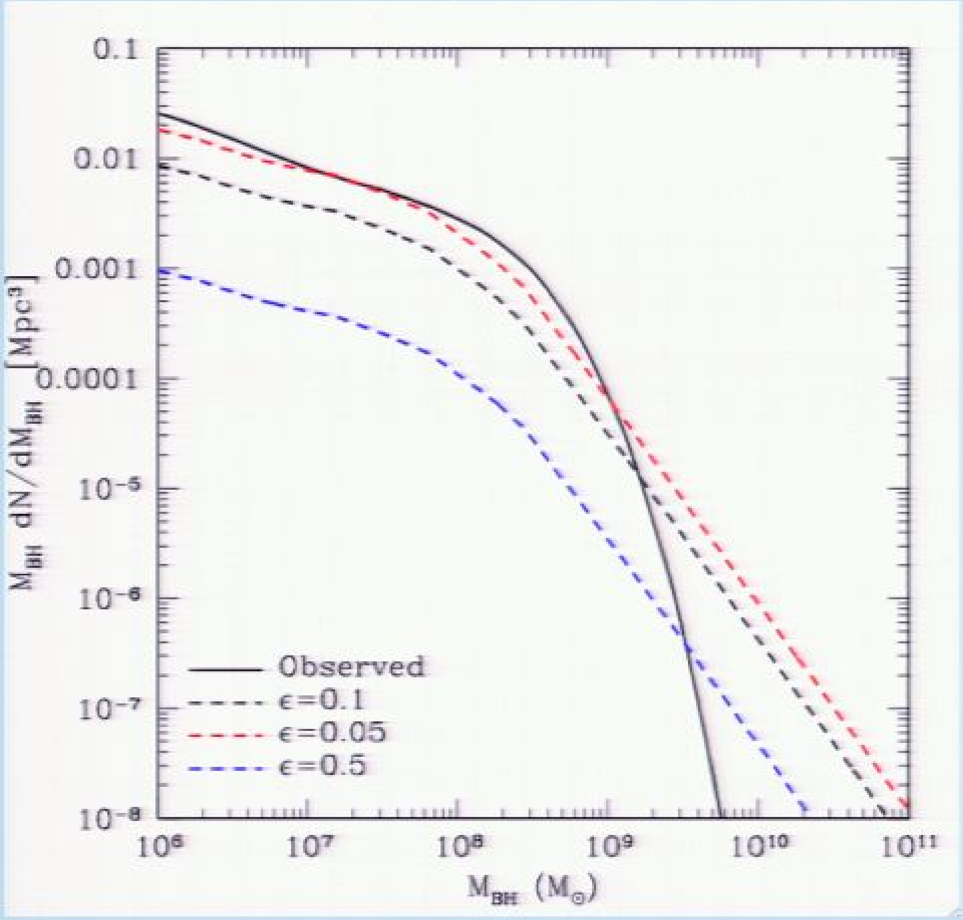
Expected in the centers of cDs

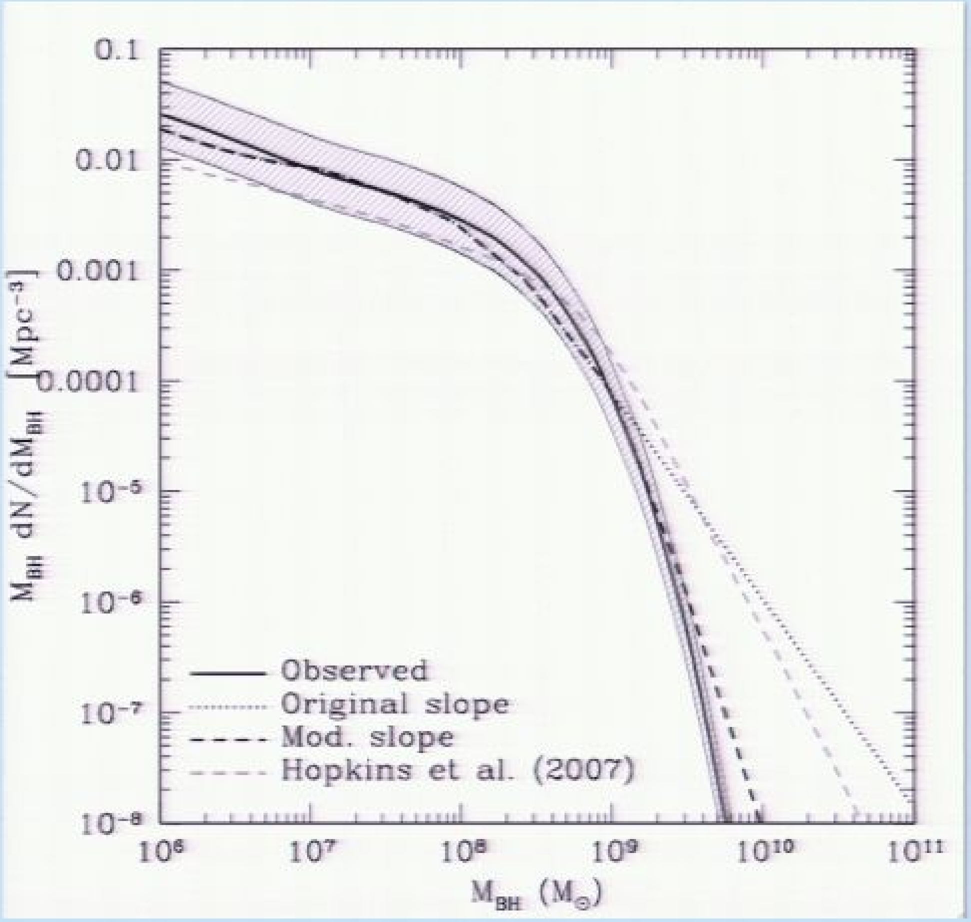


SDSS results of nearby cDs and bright ellipticals

Lauer+ 2005; 2006; Bernardi+ 2006

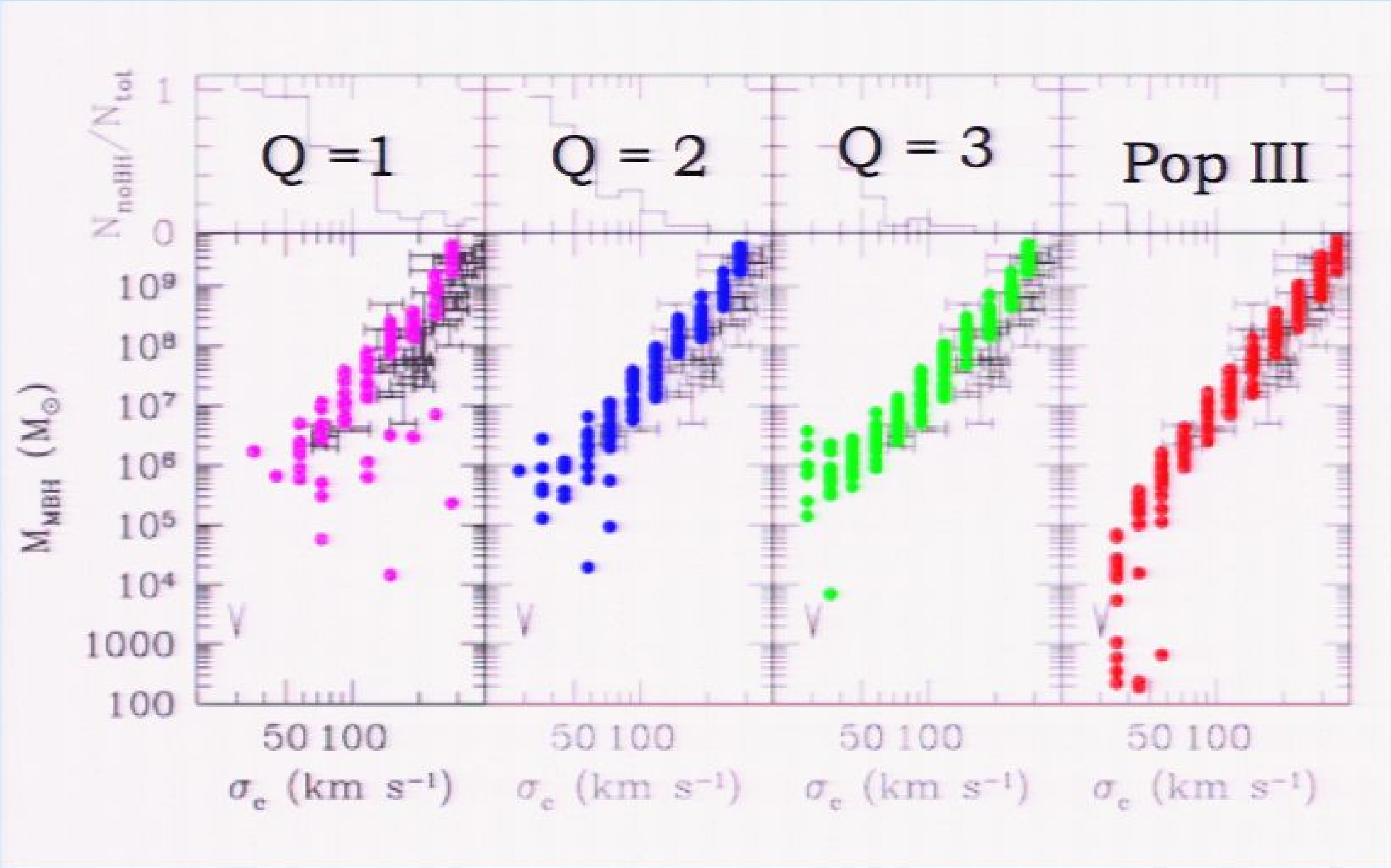
Require self-regulation to suppress the observed local BH mass function at high masses



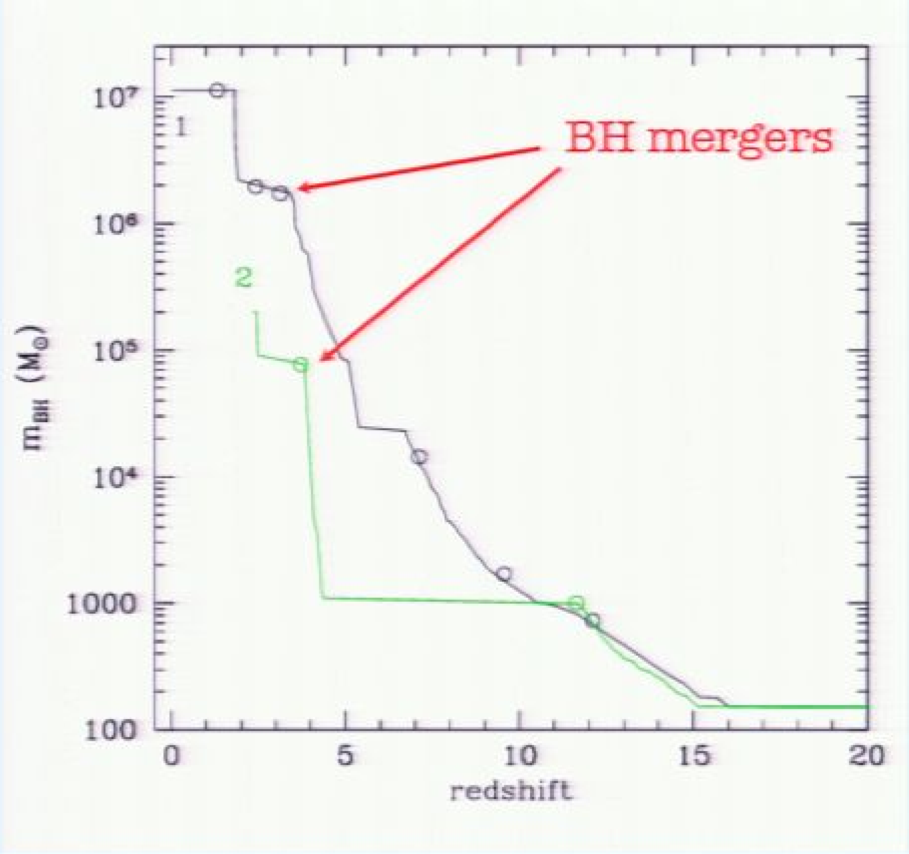


PN & Treister 2008

Key prediction at the low mass end



Volonteri, Lodato & PN 2007



- MBH mergers are rare events, as they require the merger of two galaxies each with a central BH
- Not only all MBHs experience a merger during their lifetime, only ~ 40 - 50 %
- Mergers unimportant for low-z mass build-up of BHs
- 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

Self regulation of SF and BH growth

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

$$M_{bh} > \alpha \frac{\sigma^5 \kappa}{G^2 c} = 8 \times 10^8 \gamma (\sigma / 500\,\mathrm{km\,s^{-1}})^5\,\mathrm{M}_\odot.$$

$$M_{\rm bh} \sim 10^8 \mathrm{M}_\odot\,(f_{\rm kin}/0.001)^{-1}\,j_{\rm d}^{-5}\left(\frac{\lambda}{0.05}\right)^{-5}\left(\frac{m_{\rm d}}{0.1}\right)^5 \times \left(\frac{v_{\rm halo}}{400\,\mathrm{km\,s^{-1}}}\right)^5 \mathrm{M}_\odot,$$

Momentum-driven winds

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

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

aehnelt, PN & Rees 1998; Silk & Rees 1998; Wyithe & Loeb 2003; King 2004;

II. The dying gasps of merging supermassive black hole binaries

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+

Will there be electromagnetic counterparts?

Motivation: identification of LISA sources; astrophysics

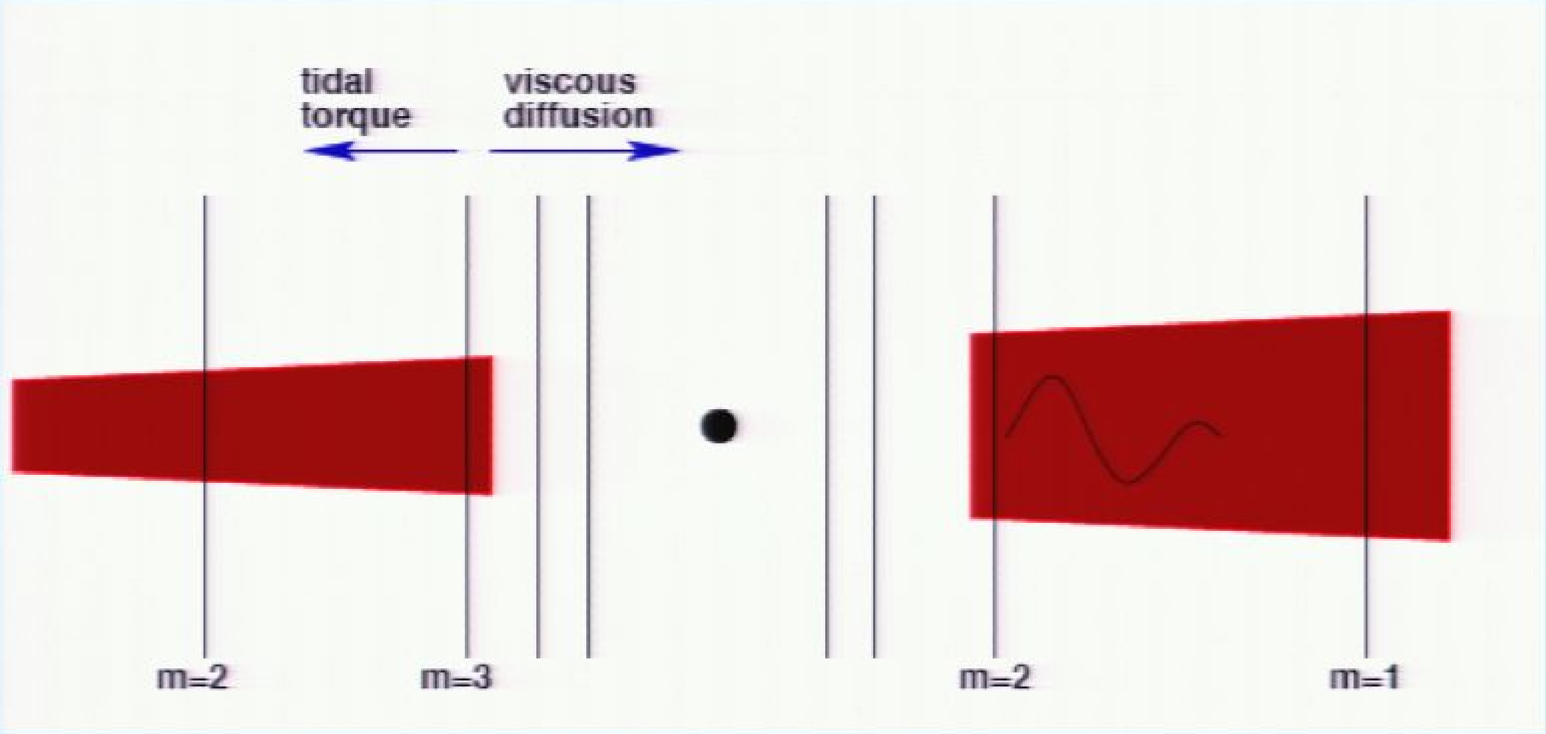
Merger driven by stellar dynamics:

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

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.