Supermassive Black Holes

Outline

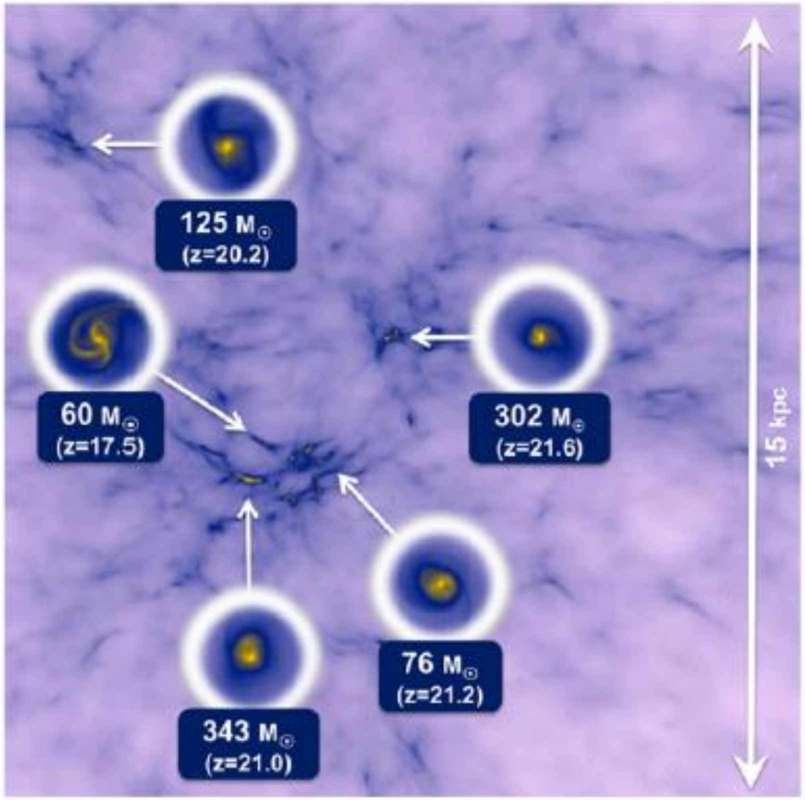
- Formation of SMBHs
- SMBH mass function
- SMBH-galaxy correlations (observation)
- Theoretical explanations of SMBH-galaxy correlations

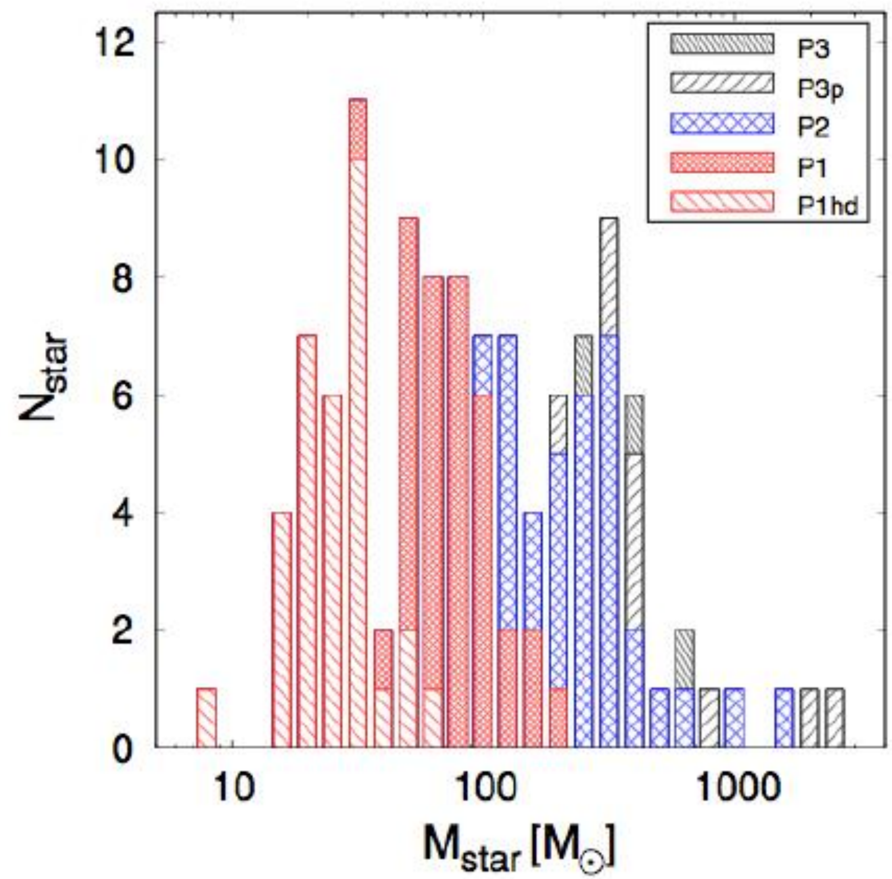
Formation of Supermassive BHs

Supermassive black holes at high redshift

- The highest-redshift black hole observed is at z=7.085 with 2×10^9 solar masses (Mortlock et al. 2011).
- A supermassive black hole with 12 billion solar masses has been observed at z=6.3 (Wu et al. 2015).
- Total accreted mass at z~6 $<1000\ M_{solar}\ Mpc^{-3}$ (Treister et al. 2013).

Progenitors as massive primordial stars?





Hirano et al. (2014): Potentially stars more than 1000 solar masses.

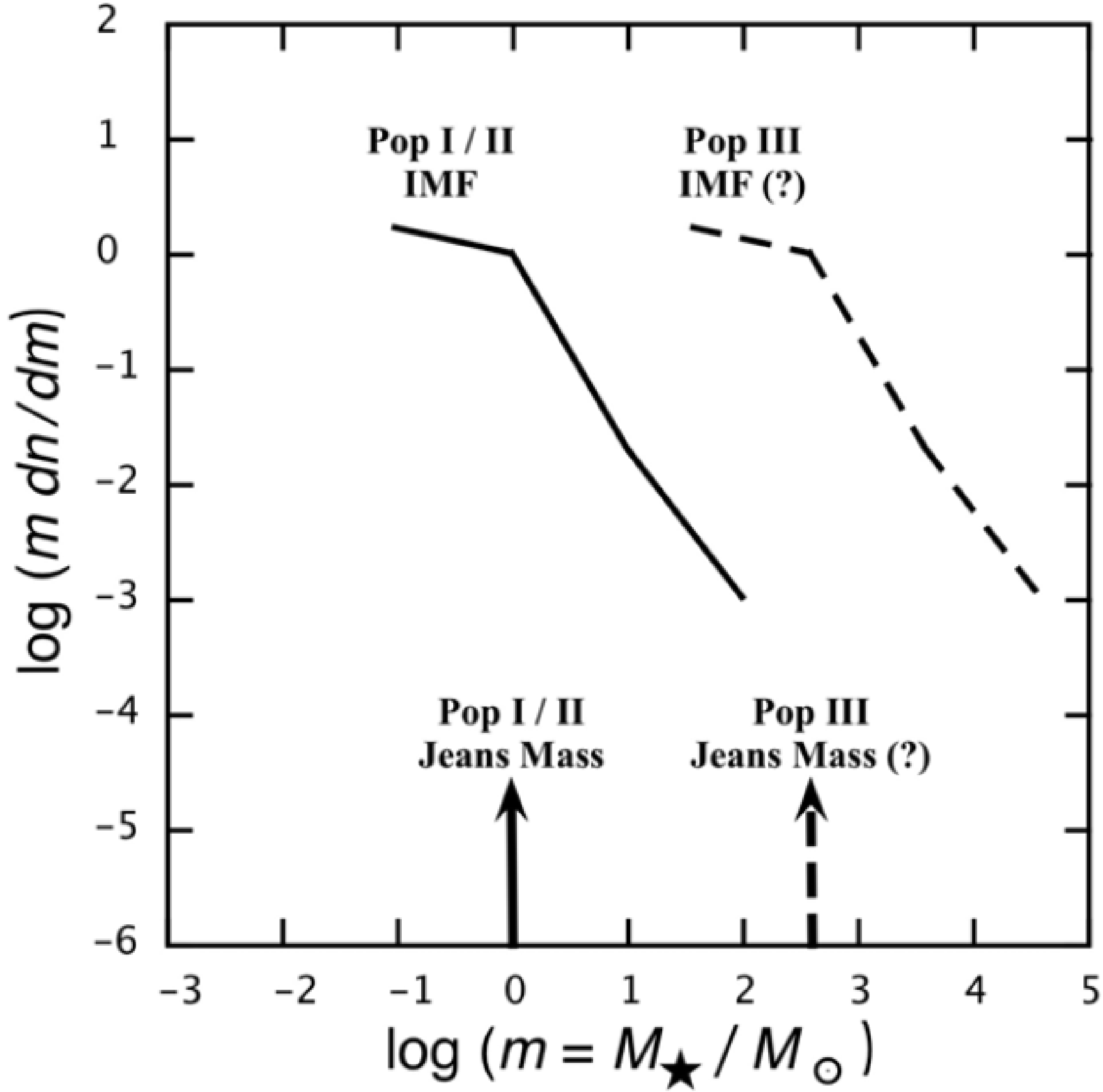


Fig. 10.6: The IMF for Pop I and II stars (solid curve), given in eq. (10.1), and a suggested one for Pop III stars in the early universe, based on the temperature and Jeans mass in equation (10.4) (dashed line). Whatever the actual Pop III IMF, it should have a feature at the predominant Jeans mass at that time, allowing much more massive stars (and, therefore, black holes) to form.

Jean’s mass

- Sound crossing time = gravitational free-fall time

$$t_{sound} = \frac{R}{c_s} \simeq (5 \times 10^5 \text{ yr}) \left(\frac{R}{0.1 \text{ pc}}\right) \left(\frac{c_s}{0.2 \text{ km s}^{-1}}\right)^{-1}$$

$$t_{\text{ff}} = \frac{1}{\sqrt{G\rho}} \simeq (2 \text{ Myr}) \left(\frac{n}{10^3 \text{ cm}^{-3}}\right)^{-1/2}$$

Jean's mass

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$$t_{\rm ff} = \frac{1}{\sqrt{G\rho}} \simeq (2 \text{ Myr}) \left(\frac{n}{10^3 \text{ cm}^{-3}}\right)^{-1/2}$$

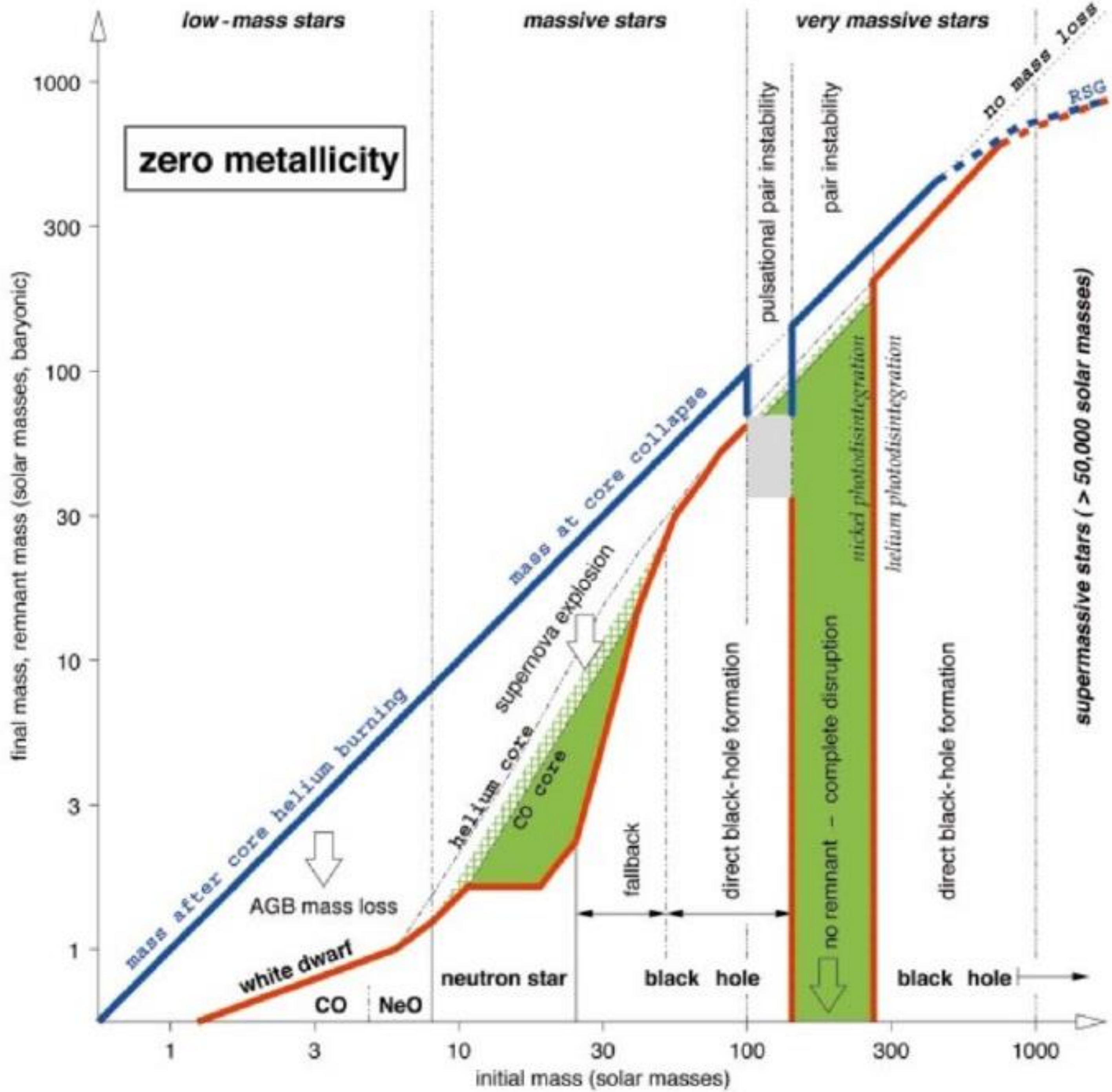
$$R_J \simeq \frac{1}{2} \frac{G M_J \mu}{\mathfrak{R} T}$$

$$\rho_a \approx \rho(R_J) = \frac{2}{\pi} \left(\frac{\mathfrak{R} T}{G\mu}\right)^3 \frac{1}{M_J^2}$$

$$M_J \simeq \left(\frac{2}{\pi \, n \, \mu \, m_p}\right)^{1/2} \left(\frac{\mathfrak{R} T}{G\mu}\right)^{3/2} \sim 0.97 \, \mathrm{M}_\odot$$

$n \sim 3 \times 10^4 \, \mathrm{cm}^{-3}, T \sim 10 \, \mathrm{K}$

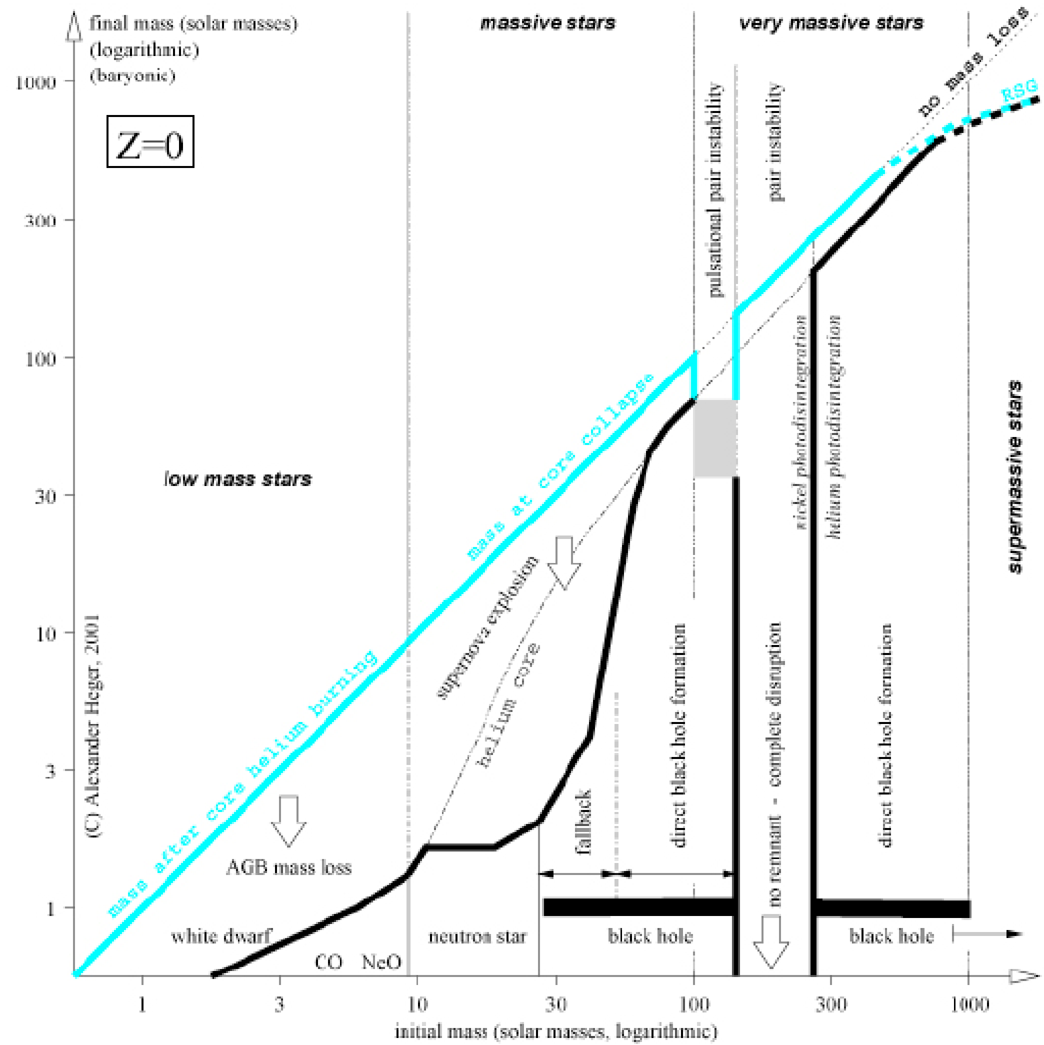
$$M_J \approx 380 \, \mathrm{M}_\odot \left(\frac{n}{3 \times 10^3}\right)^{-1/2} \left(\frac{T}{250 \, \mathrm{K}}\right)^{3/2}$$



low-mass stars
massive stars
very massive stars
zero metallicity
no mass loss
RSG
1000
300
100
30
10
3
1
final mass, remnant mass (solar masses, baryonic)
mass after core helium burning
mass at core collapse
pulsational pair instability
pair instability
nickel photodisintegration
helium photodisintegration
supermassive stars (> 50,000 solar masses)
supernova explosion
helium core
CO core
fallback
direct black-hole formation
no remnant – complete disruption
direct black-hole formation
AGB mass loss
white dwarf
CO
NeO
neutron star
black hole
black hole
initial mass (solar masses)

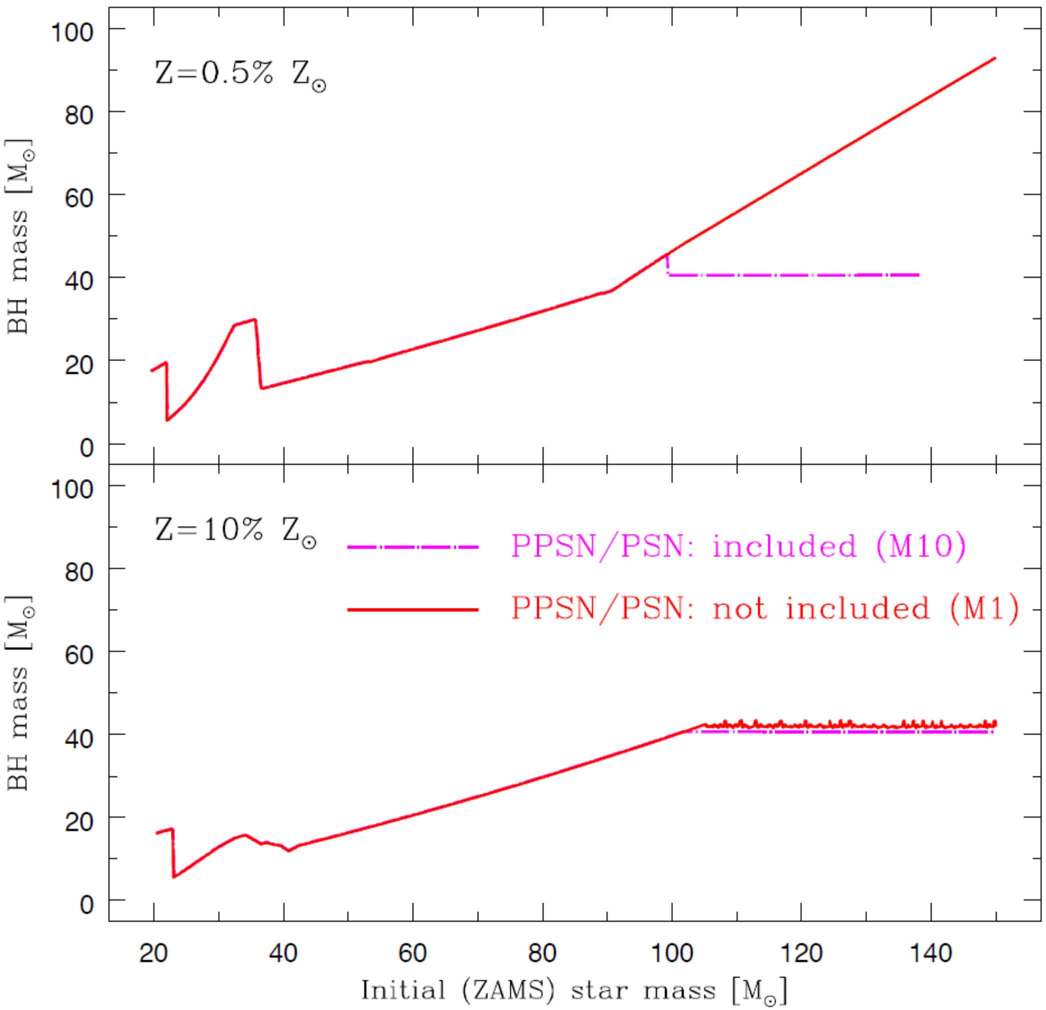
Black holes from the first stars

- Stellar black holes could form between 30-100 or 300 to 1000 solar masses.
- Recent simulations show fragmentation and reduced masses (Clark et al. 2011, Greif et al. 2012, Latif et al. 2013).



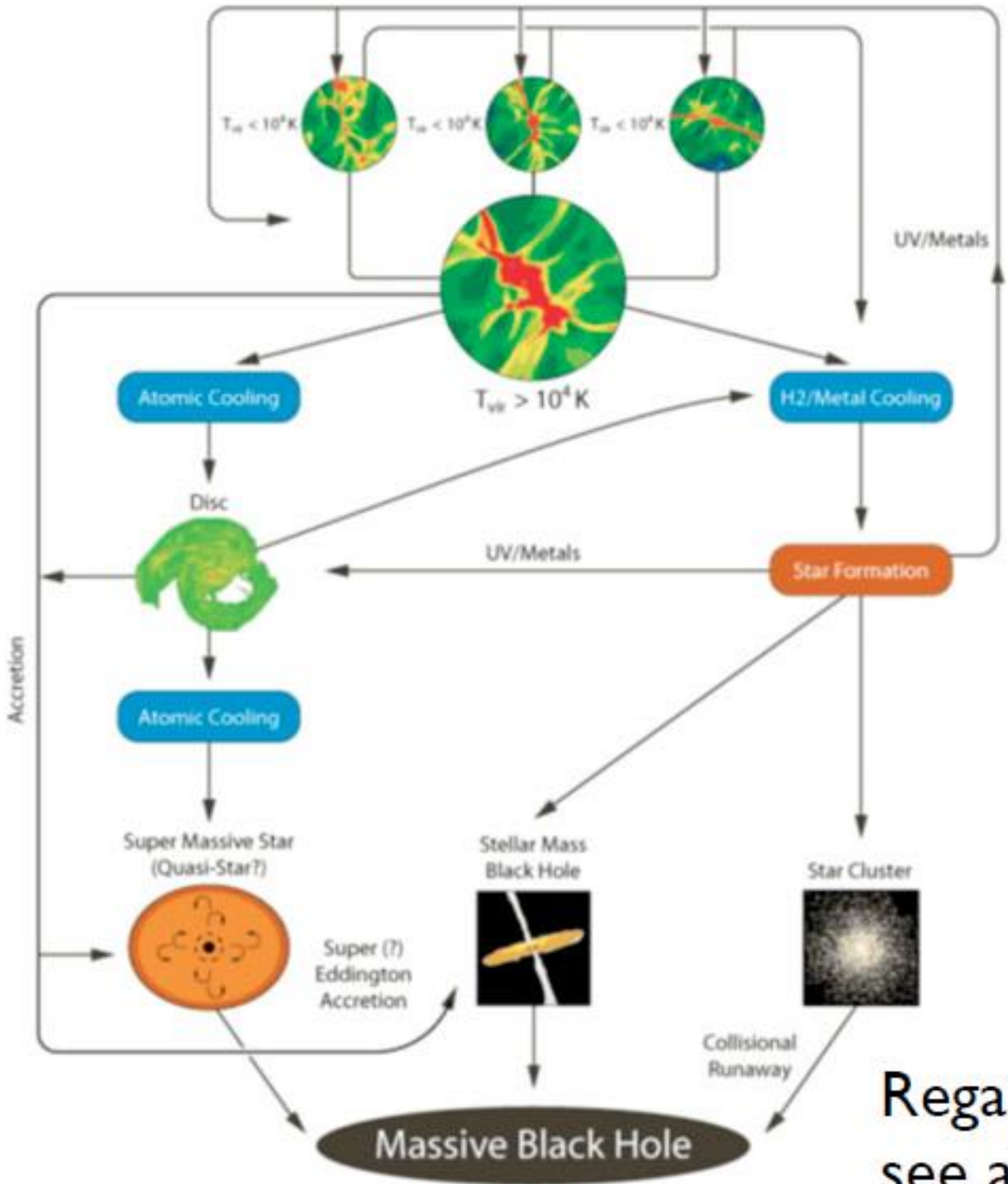
Heger et al. (2002)

But this doesn't work: pulsational pair instabilty



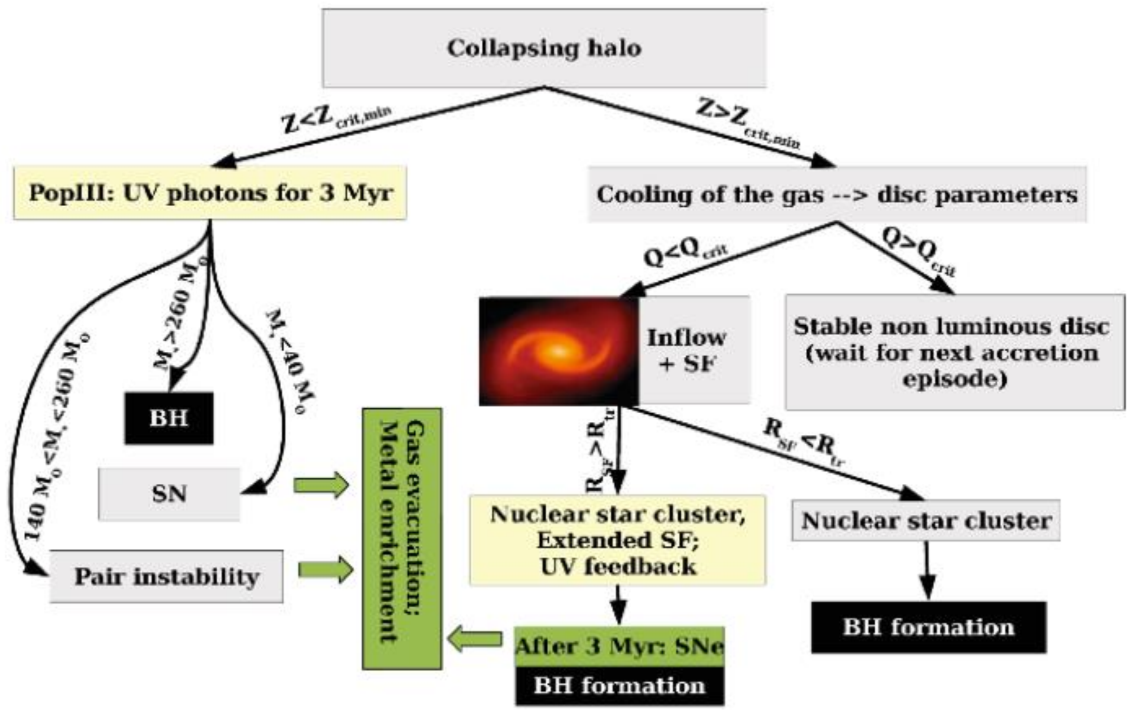
Belczynski et al. 2016, arxiv:1607.13116

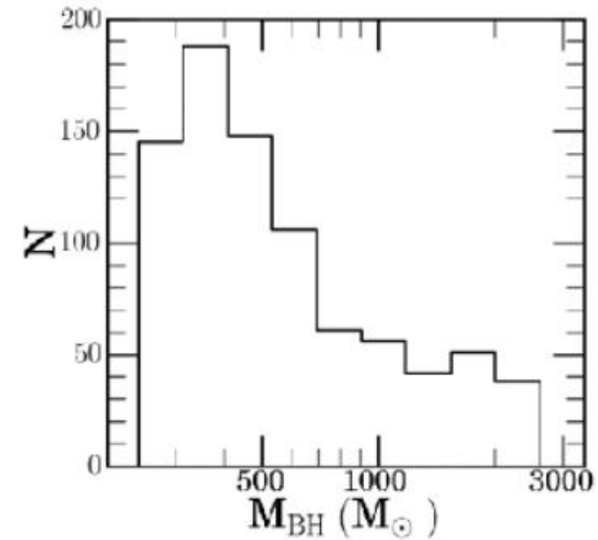
Pathways to black hole formation



Regan et al. (2009),
see also M. Rees (1978)

Black holes from stellar clusters





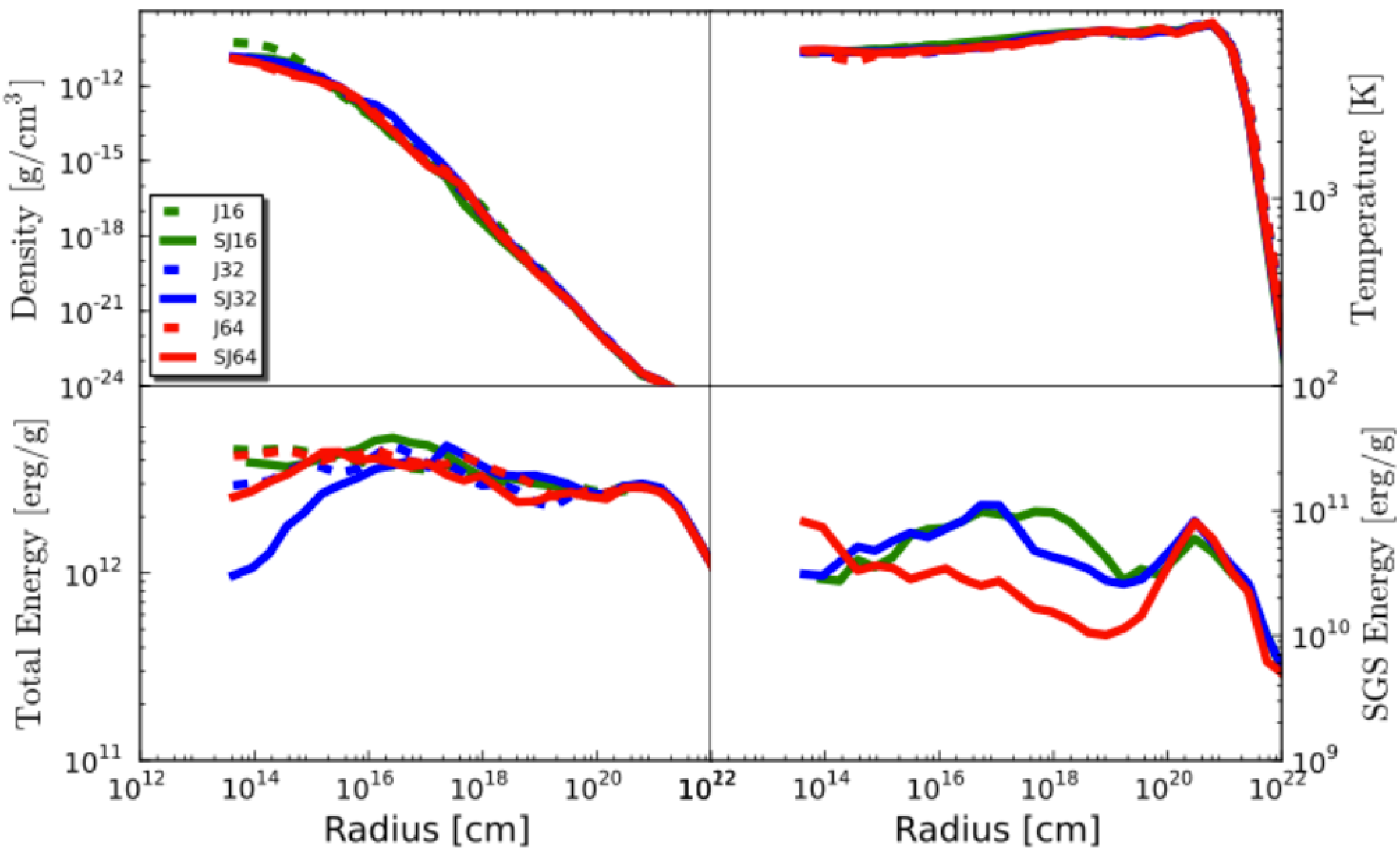
~1000 M_{solar} mass black holes from stellar clusters

Devecchi et al. (2012)

Simulations of black hole formation

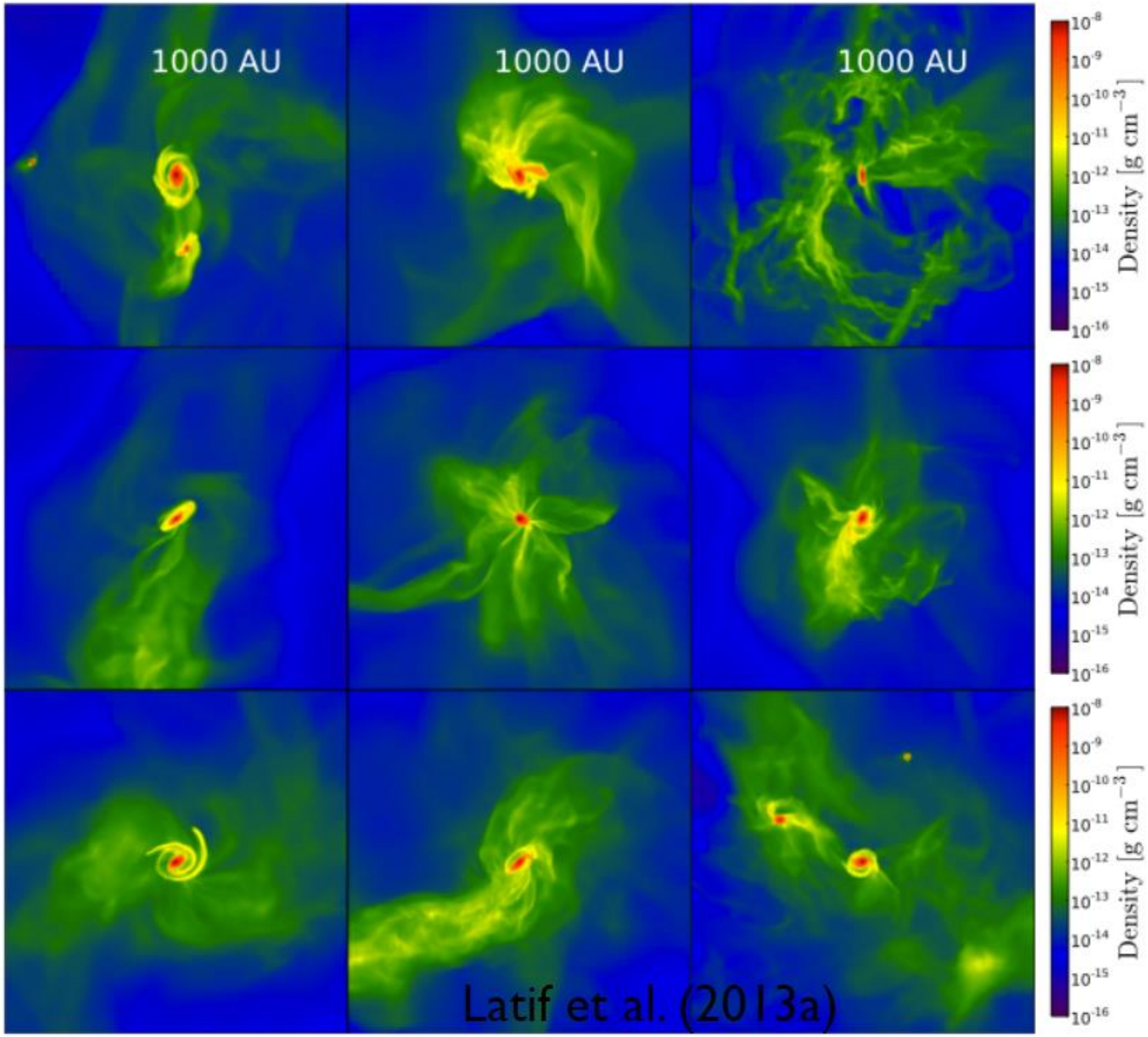
- Cosmological simulations with the adaptive mesh refinement code Enzo.
- Physics modules: dark matter, hydrodynamics, SGS turbulence and primordial chemistry.
- Focus on gravitational collapse in 10^7 solar mass halos.
- The evolution becomes adiabatic at densities $>10^{-10}$ g cm^{-3} to mimic the formation of protostellar cores.
- We will initially consider a strong radiation background to dissociate molecular hydrogen.

Halo structure after the initial collapse

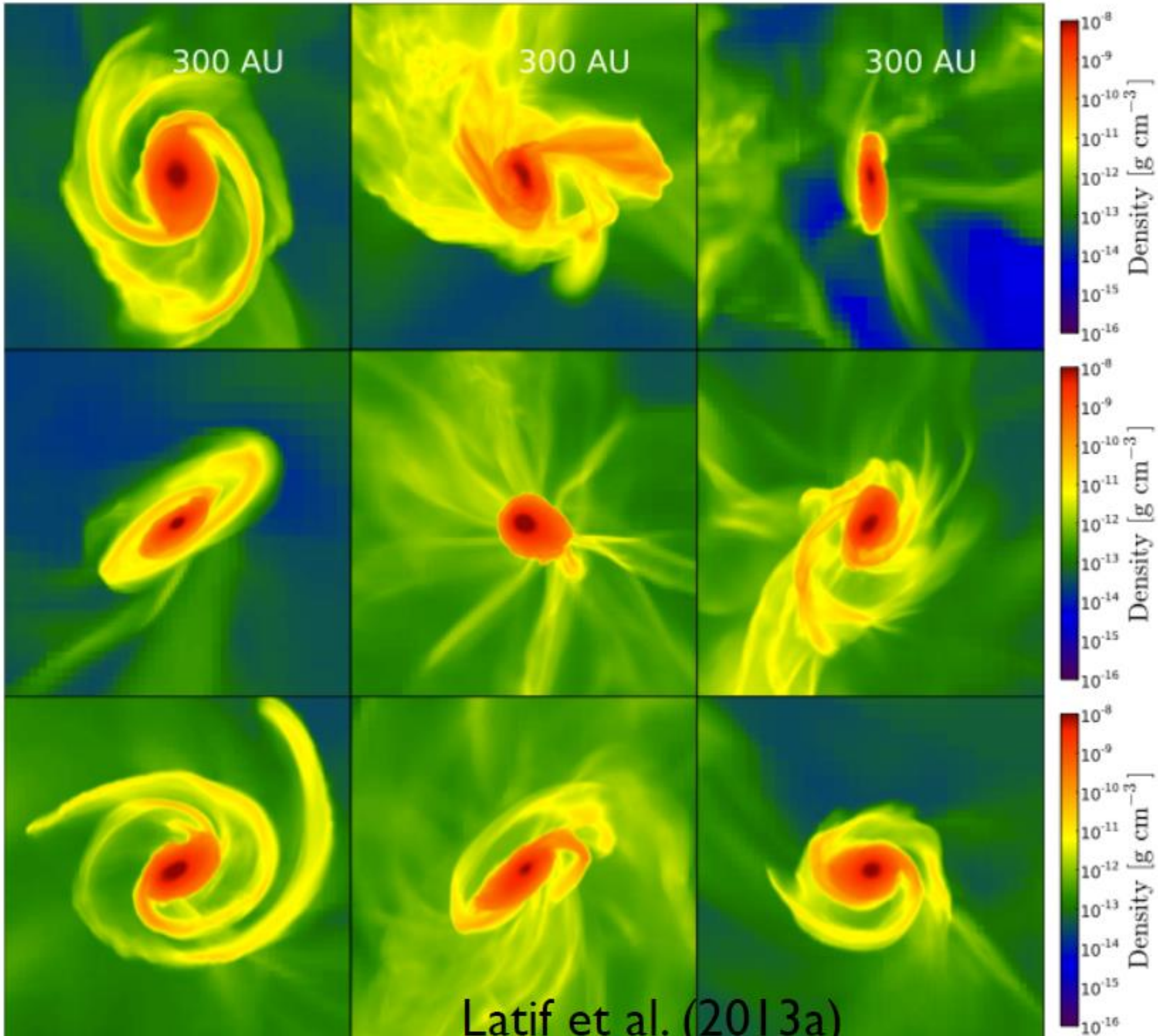


Latif, Schleicher, Schmidt & Niemeyer (2013a)

The central region after four free-fall times

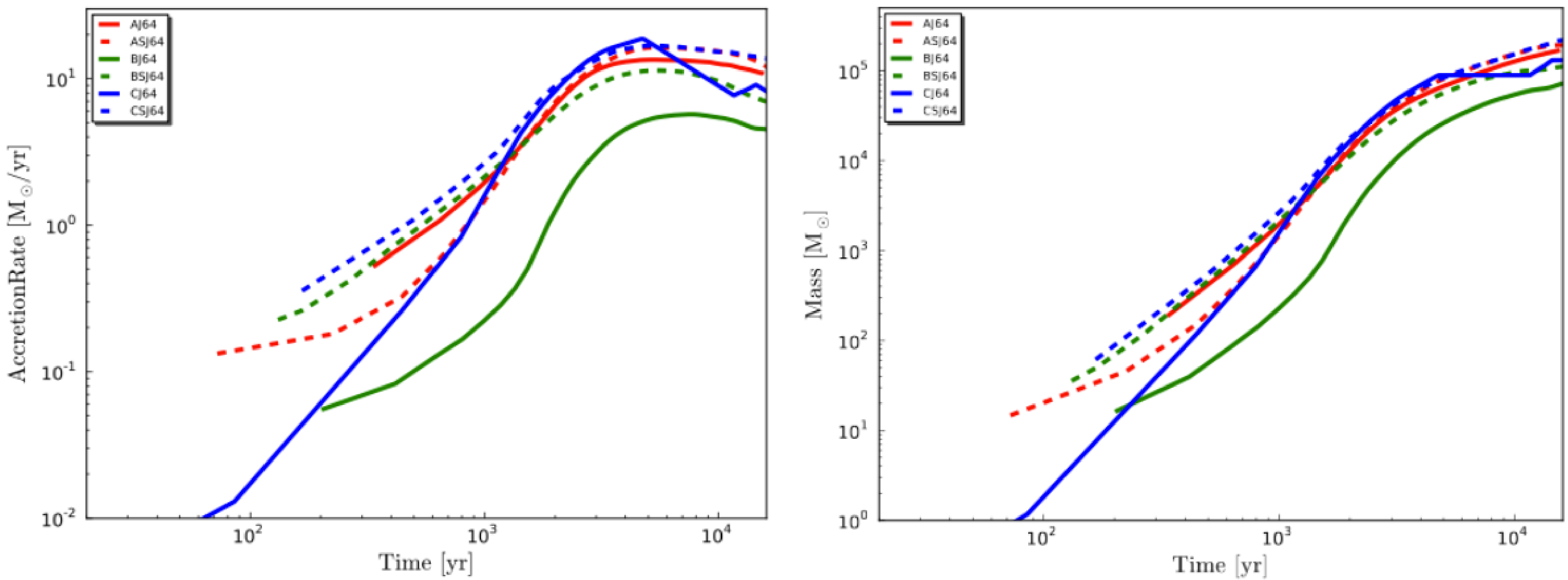


Formation of self-gravitating disks



Latif et al. (2013a)

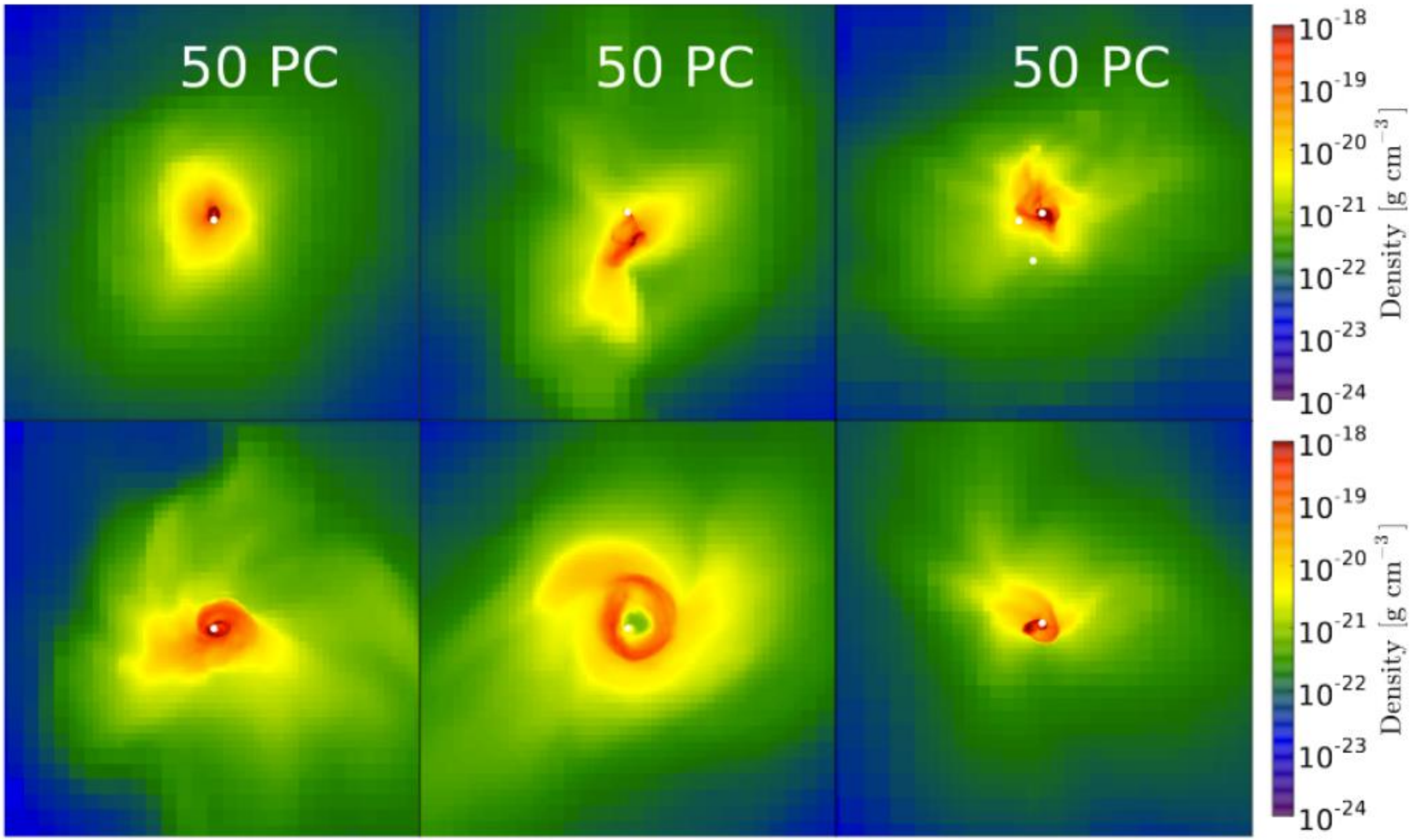
The longer-term evolution



Characteristic time evolution of the accretion in four different halos

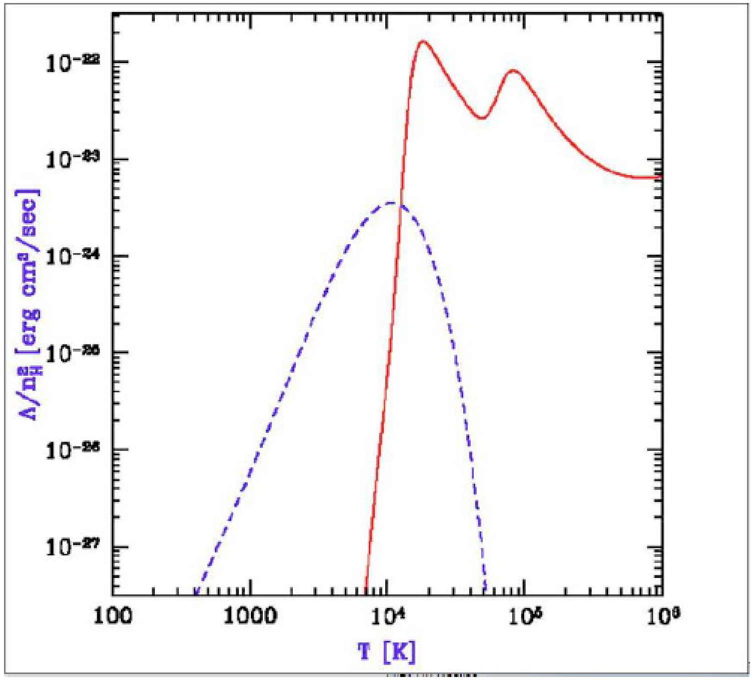
Latif, Schleicher, Schmidt & Niemeyer (2013b)

Density distribution after 20000 years



Latif, Schleicher, Schmidt & Niemeyer (2013b)

Important caveats



- The simulations so far assume a very strong UV background to dissociate molecular hydrogen.
- The required value is however very high, the process thus extremely rare (e.g. Dijkstra et al. 2014, Latif et al. 2015).
- Realistic scenarios of black hole cooling should therefore consider H_2 cooling in self-gravitating disks.
- The long-term evolution of such disks is currently just marginally understood -> further investigation.

Summary

- Massive black holes with 10^5 solar masses can form if molecular hydrogen is fully dissociated.
- Large-scale simulations indicate the formation of 10^3-10^4 solar mass objects for moderate amounts of H2.
- Large uncertainties in the determination of J_{crit}
  -> importance of 3D simulations!
- On scales of 10-100 AU, viscous heating can stabilize the disk and support the formation of very massive objects.
- The impact of metals and dust needs to be further explored in the future.

Other avenues for forming an SMBH

- Star cluster → Gravothermal instability → runaway collapse

1. Equilibrium structure

$$\frac{dp}{dr} = -\rho \frac{Gm(r)}{r^2}$$

$$p = n\,kT \;=\; \rho\,\sigma_{\rm V}^2$$

$$\rho = \frac{\sigma_{\rm V}^2}{2\pi\,G}\,\frac{1}{r^2}$$

Other avenues for forming an SMBH

- Star cluster → Gravothermal instability → runaway collapse

1. Equilibrium structure

$$\frac{dp}{dr} = -\rho \frac{Gm(r)}{r^2}$$

$$p = n\,kT \;=\; \rho\,\sigma_V^2$$

$$\rho = \frac{\sigma_V^2}{2\pi G} \frac{1}{(r^2 + r_c^2)}$$

Introduce core

Other avenues for forming an SMBH

- Star cluster → Gravothermal instability → runaway collapse

1. Equilibrium structure

$$\frac{dp}{dr} = -\rho \frac{Gm(r)}{r^2}$$

$$p = n\,kT \;=\; \rho\,\sigma_{\rm V}^2$$

$$\rho = \rho_t \, \exp\left[-\frac{G\,M_{\rm clst}}{r_t\,\sigma_{\rm V}^2} \left(1 \,-\, \frac{r_t}{r} \right) \right]$$

Introduce truncation outside of the tidal radius

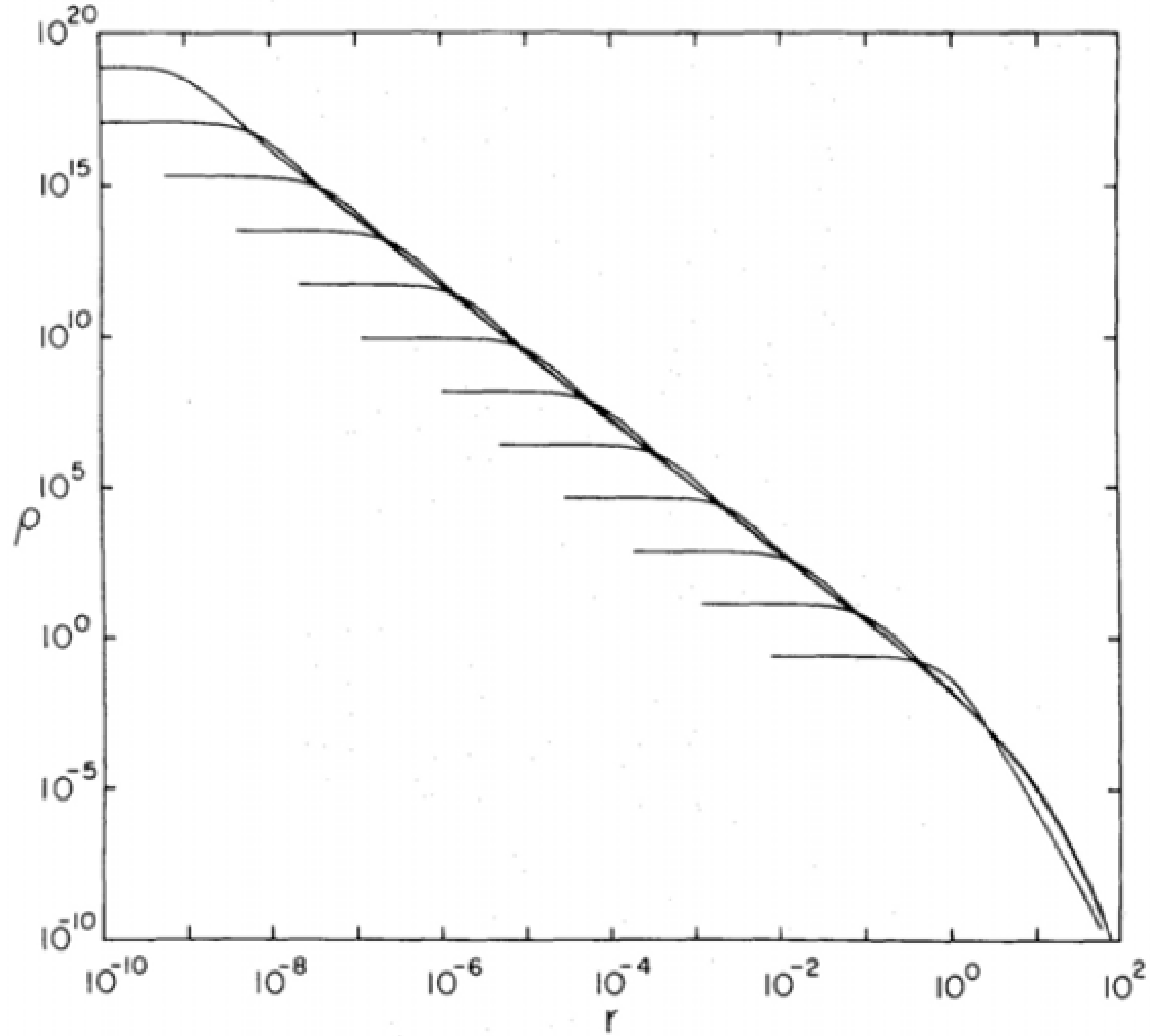


Fig. 10.8: Evolution of a King model core radius during core collapse, from simulations by Haldan Cohn when he was at Harvard Center for Astrophysics [394]. Note that an approximate $\rho \propto r^{-2}$ profile is preserved throughout the event. While this collapse can proceed to an extremely high central density, the mass enclosed in the core is proportional to r_c, which goes to zero as the core shrinks. As a result, core collapse in a cluster of equal-mass stars is not thought to form a central black hole of any significant mass. Reproduced from Fig. 1 in [394], by permission of the AAS.

Lynden-Bell & Wood (1968)

- Core collapse!
- On longer timescale isothermal structure is unstable
- instability forming a central core in 16 t_{rlx}

$$\tau_{\rm rlx} = \left(\frac{r_c^3}{G\,M_{\rm clst}} \right)^{1/2} \frac{M_{\rm clst}}{\langle m_\star \rangle\; 8 \ln \Lambda}$$

$$= 120\,{\rm Myr}\, \left(\frac{r_c}{\rm pc} \right)^{3/2} \left(\frac{M_{\rm clst}}{10^5\,{\rm M_\odot}} \right)^{1/2} \left(\frac{\langle m_\star \rangle}{0.5\,{\rm M_\odot}} \right)^{-1} \left(\frac{\ln \Lambda}{10} \right)^{-1}$$

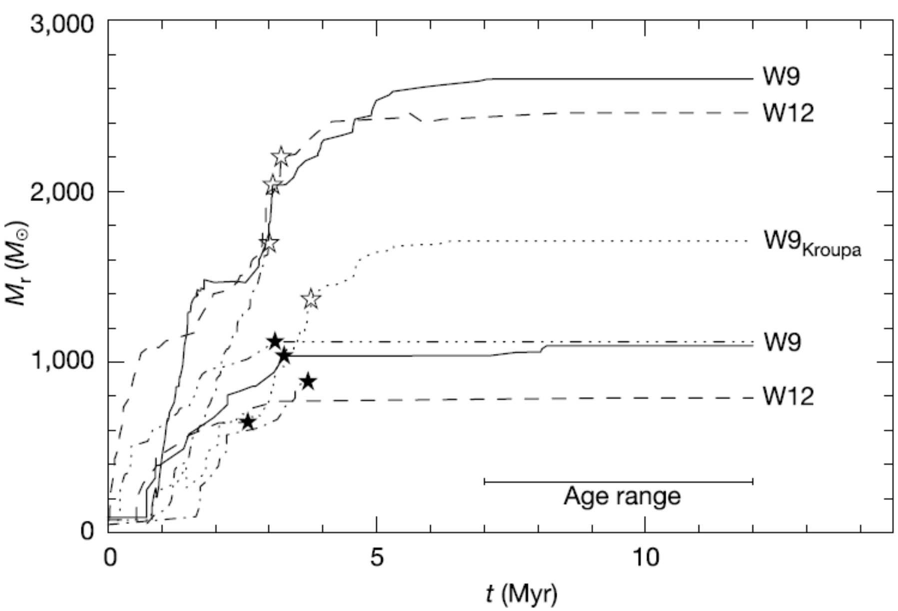
Lynden-Bell & Wood (1968)

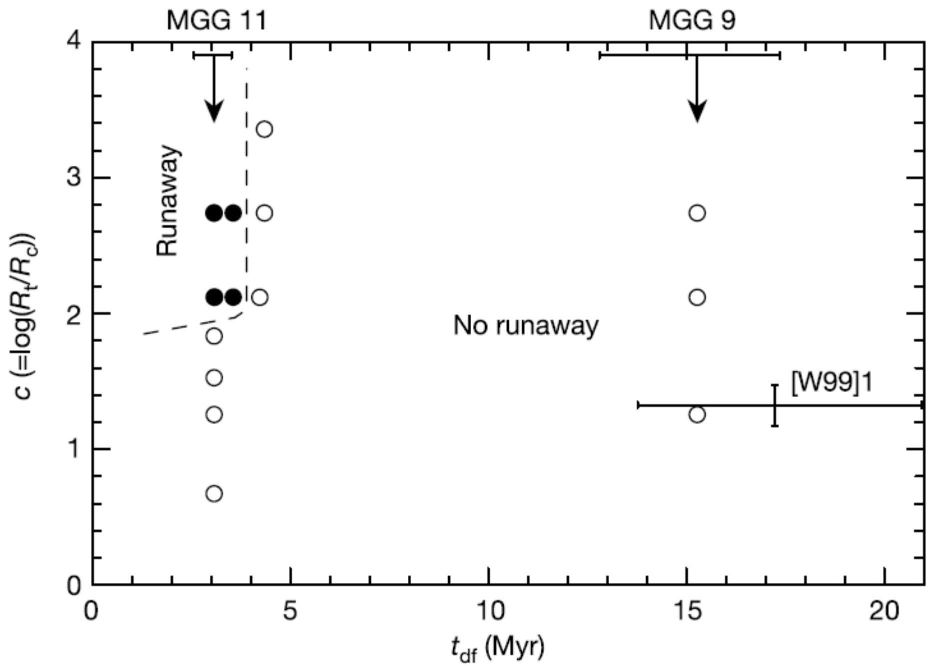
- Core collapse!
- On longer timescale isothermal structure is unstable
- instability forming a central core in 16 t_{rlx}
- Heavier objects relax faster

$$\tau_{\rm seg} \approx \frac{\langle m_\star \rangle}{m_\star} \tau_{\rm rlx}$$
$$= 6\,{\rm Myr} \left(\frac{r_{\rm c}}{\rm pc}\right)^{3/2} \left(\frac{M_{\rm clst}}{10^5\,{\rm M}_\odot}\right)^{1/2} \left(\frac{m_\star}{10\,{\rm M}_\odot}\right)^{-1} \left(\frac{\ln \Lambda}{10}\right)^{-1}$$

Runaway collapse

(Portegies Zwart & McMillan 2004)
Direct N-body simulation





$$t_{\rm df} \approx \frac{\langle m \rangle}{100 M_\odot} \frac{0.138 N}{\ln(0.11 M / 100 M_\odot)} \left(\frac{R^3}{GM} \right)^{1/2}$$

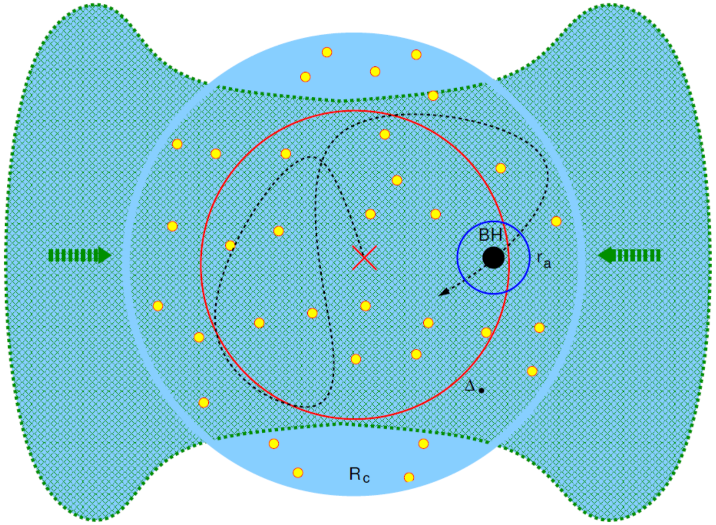
Other avenues

- Runaway collisions in quasar accretion disks

(McKernan et al. 2013)

- Hypereddington Bondi accretion

(Alexander & Natarayan 2014)



Supermassive black hole mass function

Soltan's argument (1982)

"estimating the mass of the ash"

- Predict the number of quiescent supermassive black holes in our local universe based on quasars

- Measure number of quasars vs. redshift and luminosity of quasars

→ Integrated energy density of radiation = 8.5×10^{66} erg/Gpc^3

If 10% of the accreted gas mass was converted to radiation

- Total BH mass accumulated in quasars = 5×10^4 M_{sun}/Mpc^3
- Mean BH mass per galaxy = 10^7 M_{sun}

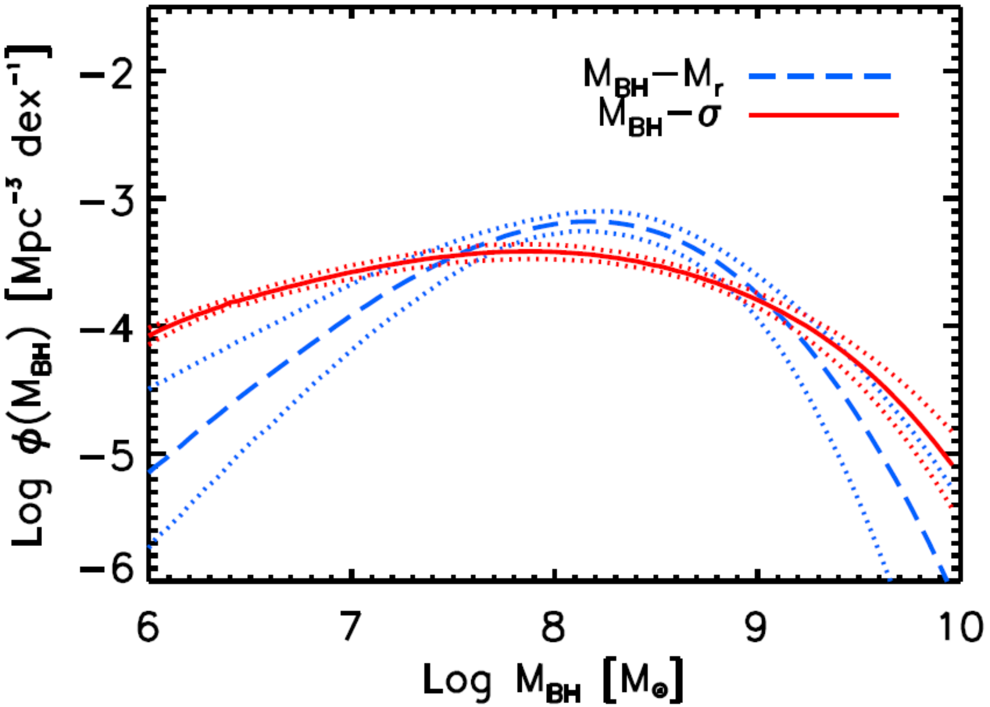
  → all galaxies have a supermassive BH at their centers!

Prediction: quiescent supermassive black holes may be found in all nearby galaxies!

SMBH mass function

- Measure distribution of some galaxy parameter y
- Use observed correlation

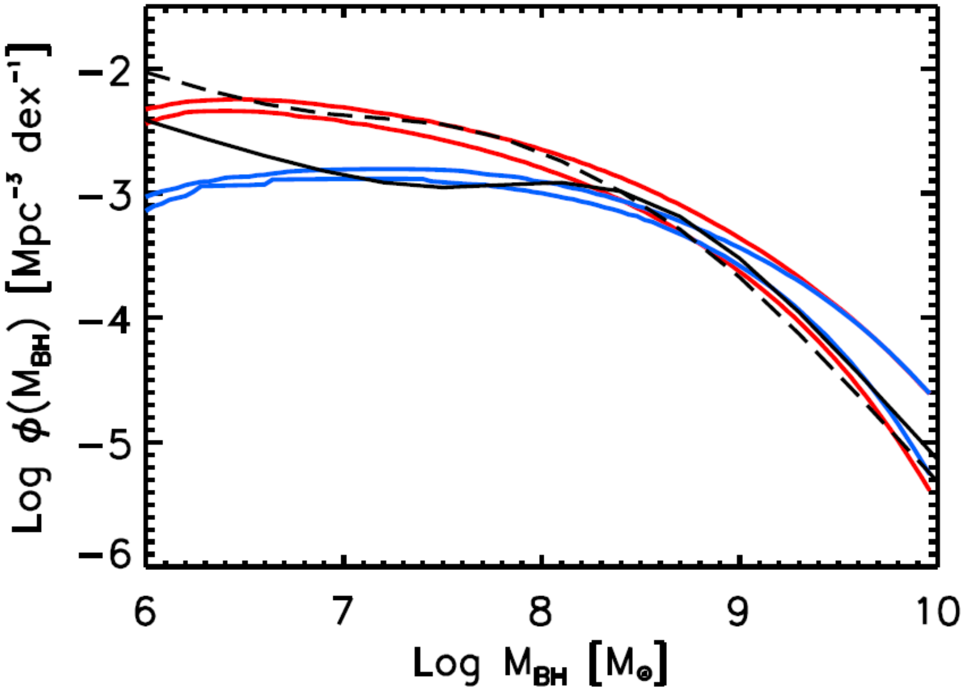
$$\Phi(M_{\rm BH}) = \int \Phi(y) \frac{1}{\sqrt{2\pi\eta^2}} \exp\left[-\frac{(M_{\rm BH} - [a + by])^2}{2\eta^2}\right] dy$$



SMBH mass function

- Measure distribution of some galaxy parameter y
- Use observed correlation for elliptical galaxies

$$\Phi(M_{\rm BH}) = \int \Phi(y) \frac{1}{\sqrt{2\pi\eta^2}} \exp\left[-\frac{(M_{\rm BH} - [a + by])^2}{2\eta^2}\right] dy$$



Questions on SMBH evolution

- How does the SMBH mass function grow with redshift?
  - observations show that massive SMBHs are created early (?!)
  - SMBHs may grow by gas accretion during galaxy mergers

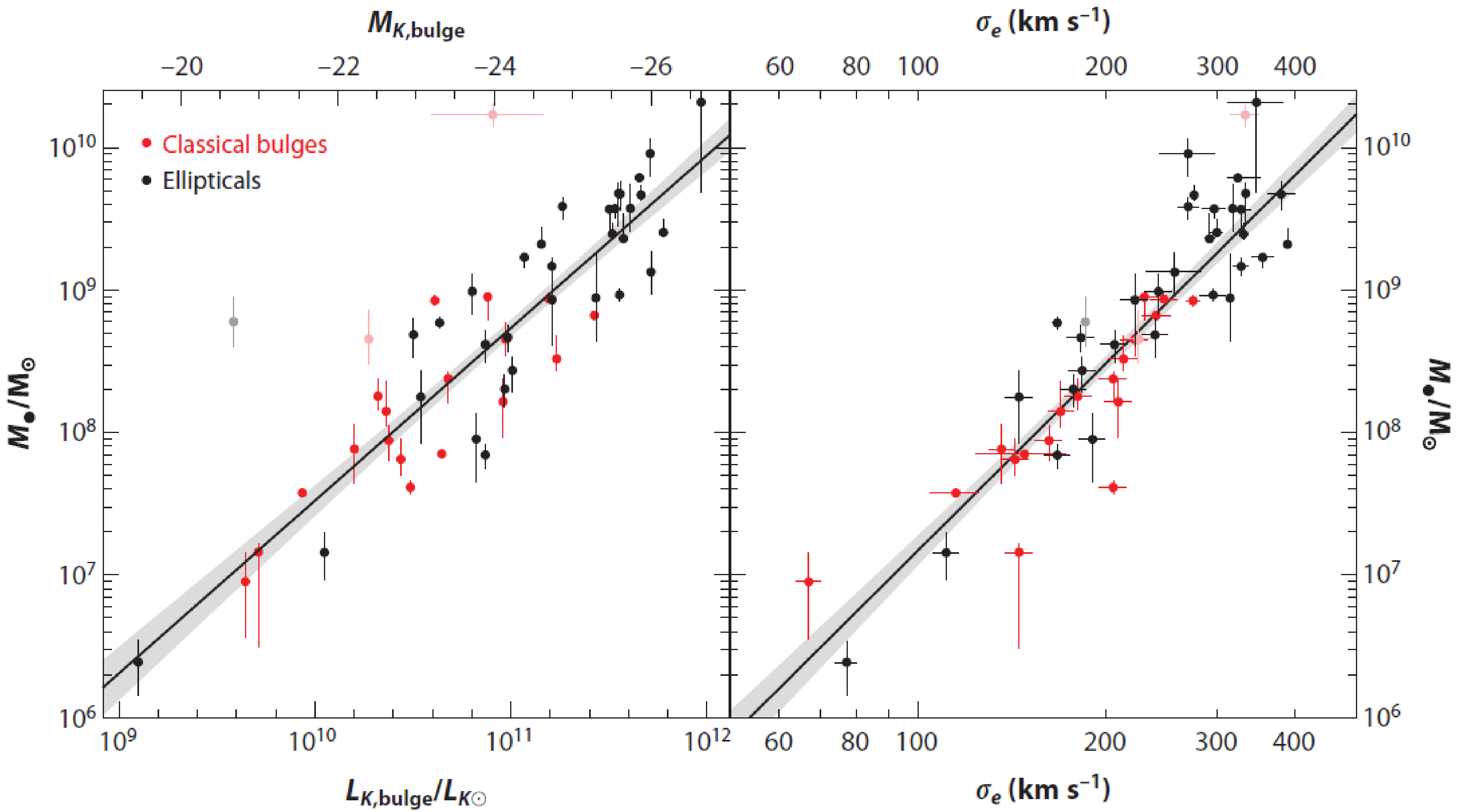
- If black holes merge, they may get kicked out due to gravitational wave emission
  - Kick velocity 50—180 km/s if mass ratio > 1/3
  - Are black holes kicked out from dwarf galaxies?

SMBH function uncertain at low masses (<10^6 Msun)

LISA will measure the growth of SMBHs with cosmic time

Black hole – Galaxy Correlations

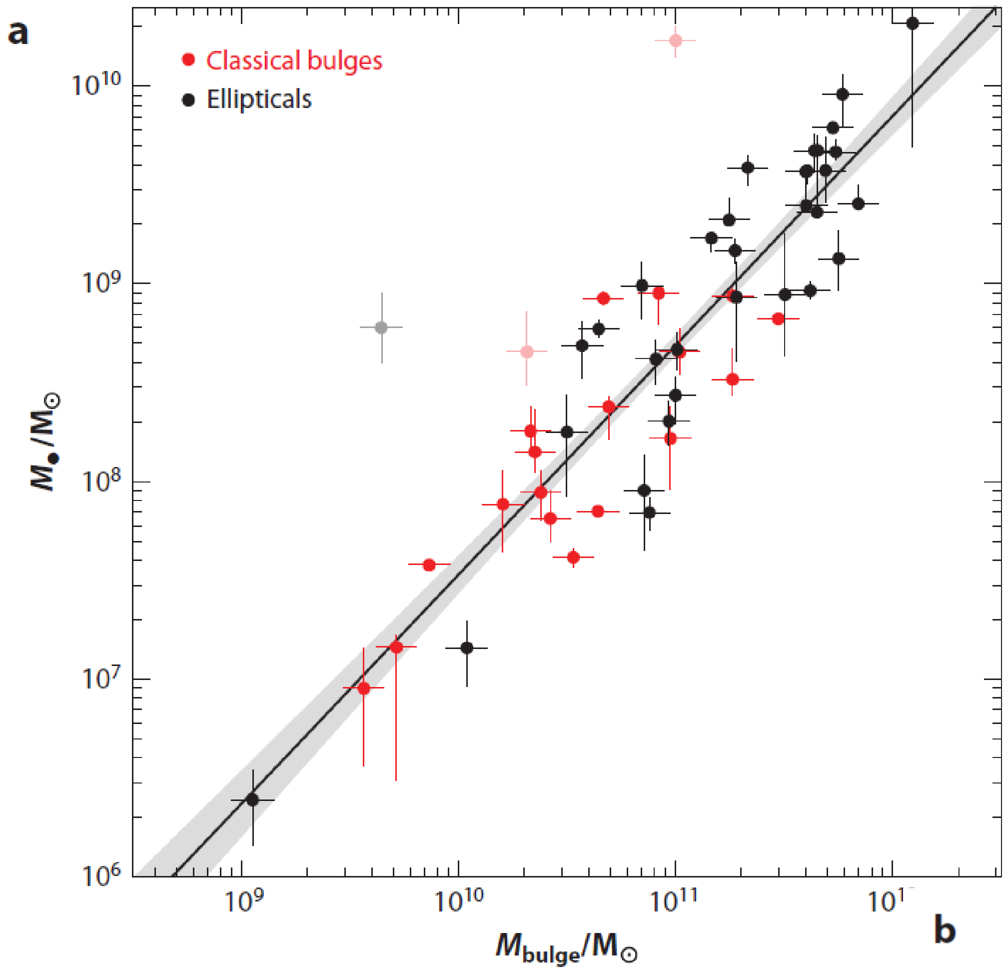
M-L_{bulge} M-σ



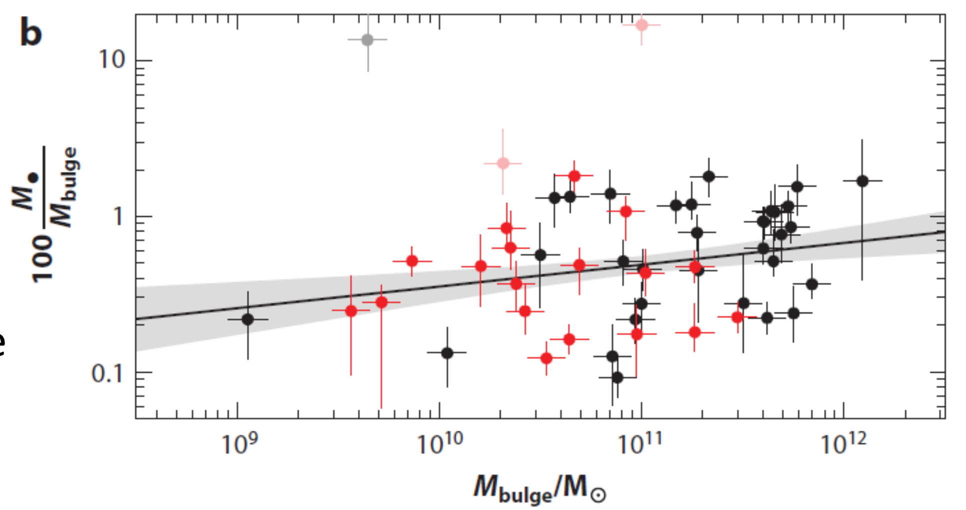
$$\frac{M_\bullet}{10^9\,\mathrm{M}_\odot} = \left(0.544^{+0.067}_{-0.059}\right)\left(\frac{L_{K,\mathrm{bulge}}}{10^{11}\,L_{K\odot}}\right)^{1.22\pm0.08}$$

$$\frac{M_\bullet}{10^9\,\mathrm{M}_\odot} = \left(0.310^{+0.037}_{-0.033}\right)\left(\frac{\sigma}{200\,\mathrm{km\,s^{-1}}}\right)^{4.38\pm0.29}$$

M-M_{bulge}

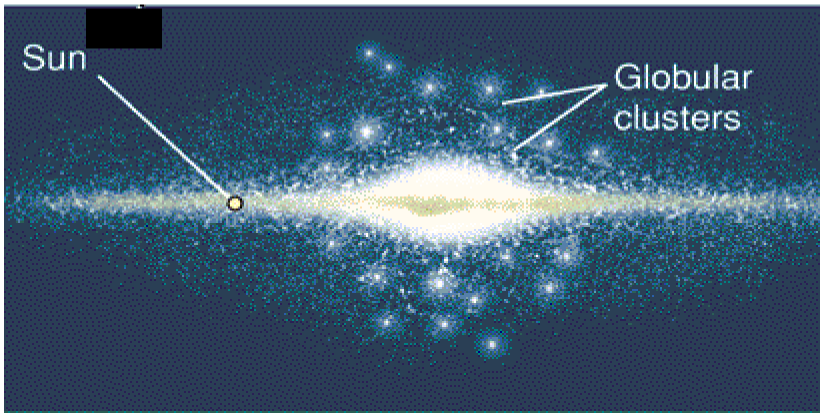


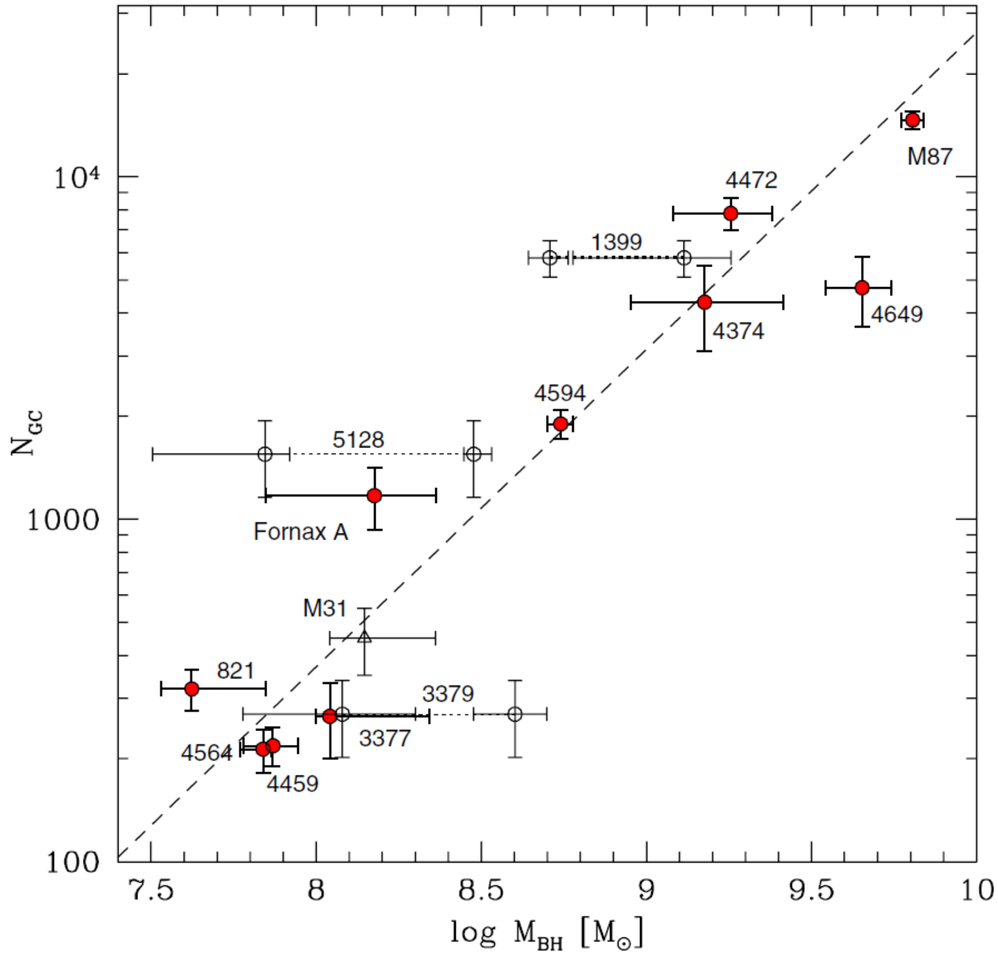
$$\frac{M_\bullet}{10^9\,M_\odot} = (0.49^{+0.06}_{-0.05})\left(\frac{M_{bulge}}{10^{11}\,M_\odot}\right)^{1.17\pm0.08}$$



Supermassive black hole mass = 0.5% of bulge

M-N$_{\text{globular clusters}}$





$$\log \frac{M_\bullet}{M_\odot} = (8.14 \pm 0.04) + (1.08 \pm 0.04) \log \frac{N_{GC}}{500};$$

Supermassive black hole mass correlates with the number of globular clusters in elliptical galaxies. Scatter (0.2dex) is smaller than for M-sigma (0.3dex).

Physical origin of correlations

SMBH affects galaxy bulge **(King & Pounds 2015)**

outflow energy $\sim 0.1 M_{BH} c^2$ is $\sim 10^{61}$ erg
for $10^8 M_\odot$ black hole
binding energy of bulge of mass $10^{11} M_\odot$
and $\sigma = 200$ km s^{-1} is 10^{58} erg

more than enough energy to unbind bulge – only a fraction used

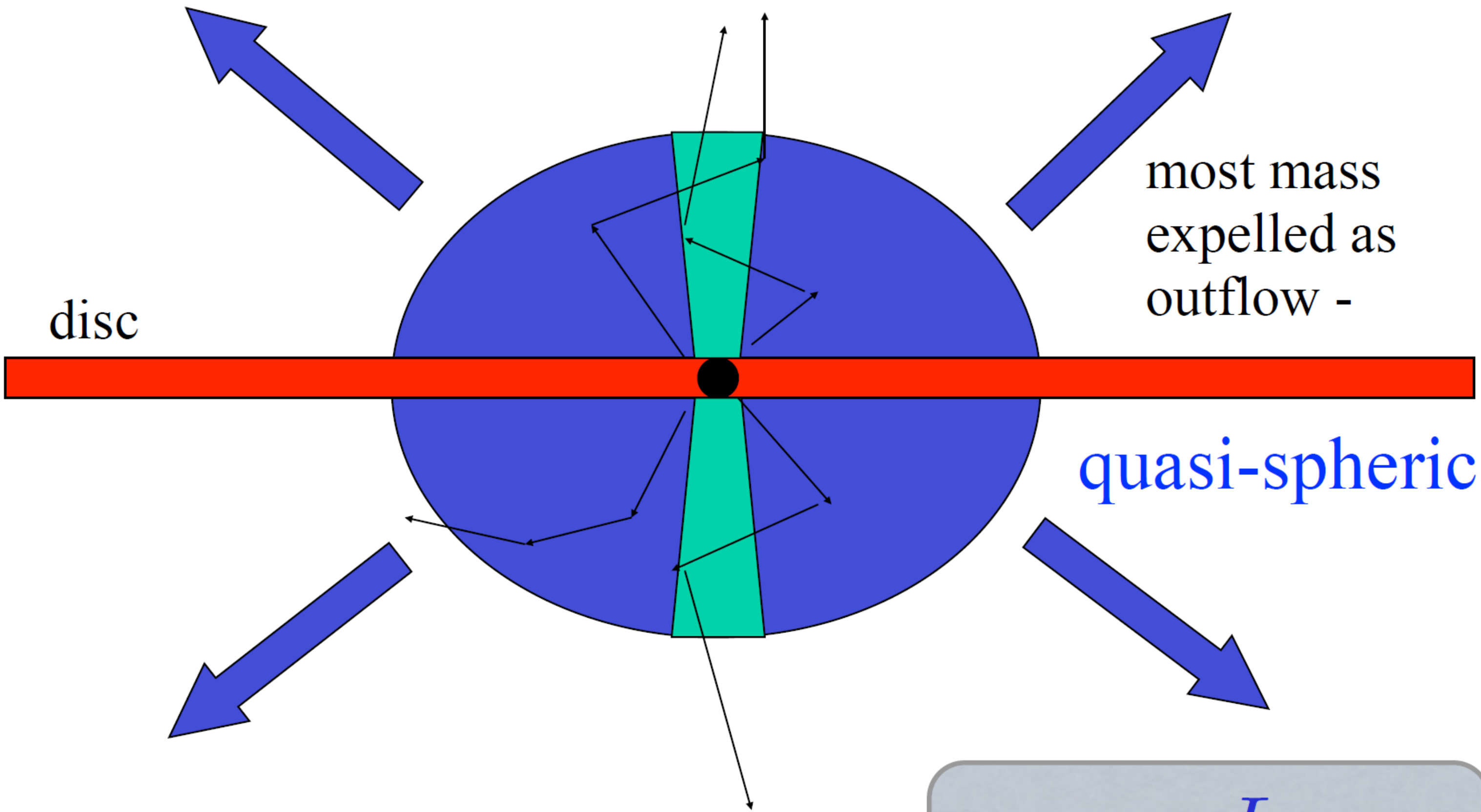
galaxy must notice presence of hole

- a bomb waiting to go off!

curtesy of Andrew King

Outflow

most photons eventually escape along cones near axis



most mass expelled as outflow -

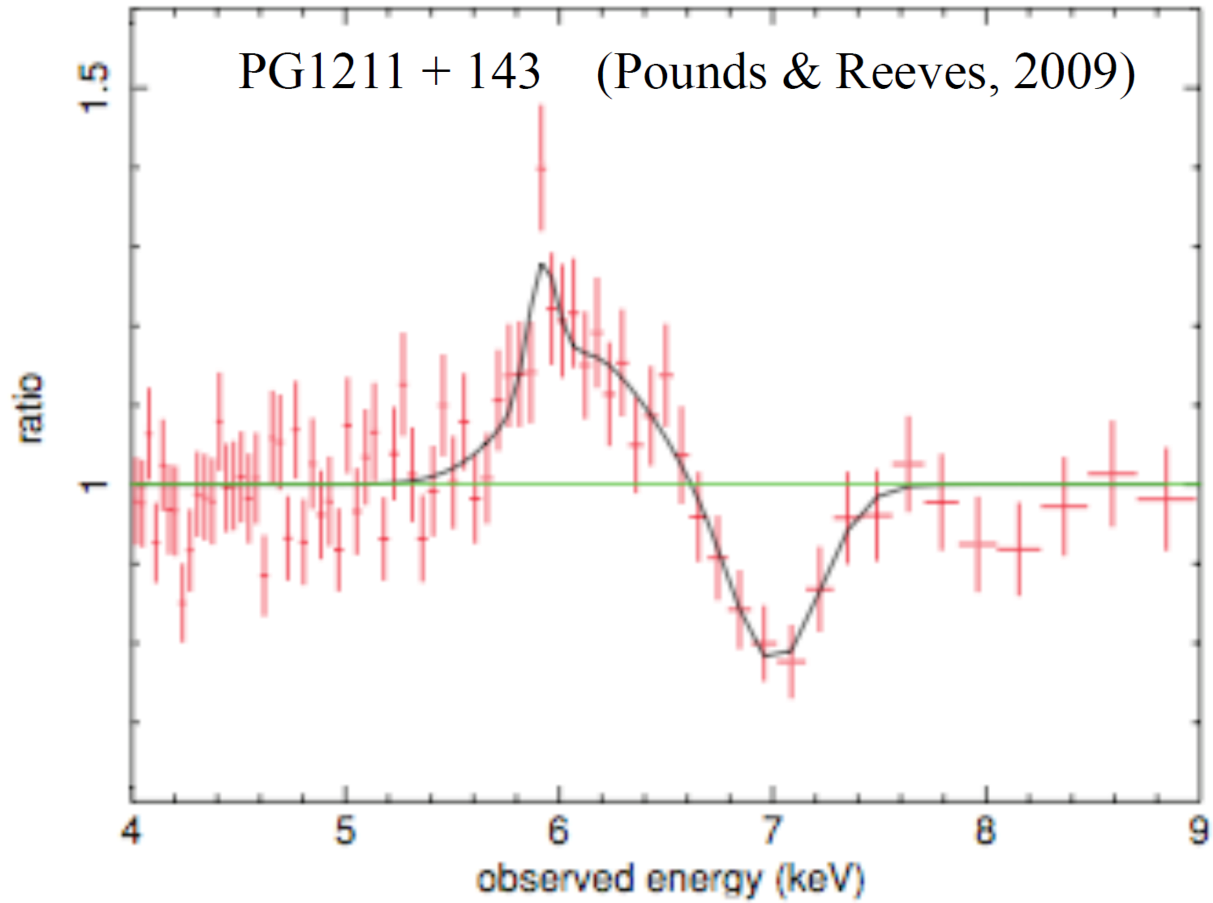
quasi-spherical

on average photons give up all momentum to outflow after ~ 1 scattering

$$\dot{M}v = \frac{L_{\rm Edd}}{c}$$

curtesy of Andrew King

Outflow



P Cygni profile of iron K- alpha: *outflow* with $v \simeq 0.1c$

curtesy of Andrew King

wind shock

wind must collide with bulge gas, and shock – what happens?

either

(a) shocked gas cools: `momentum–driven flow'
negligible thermal pressure

or

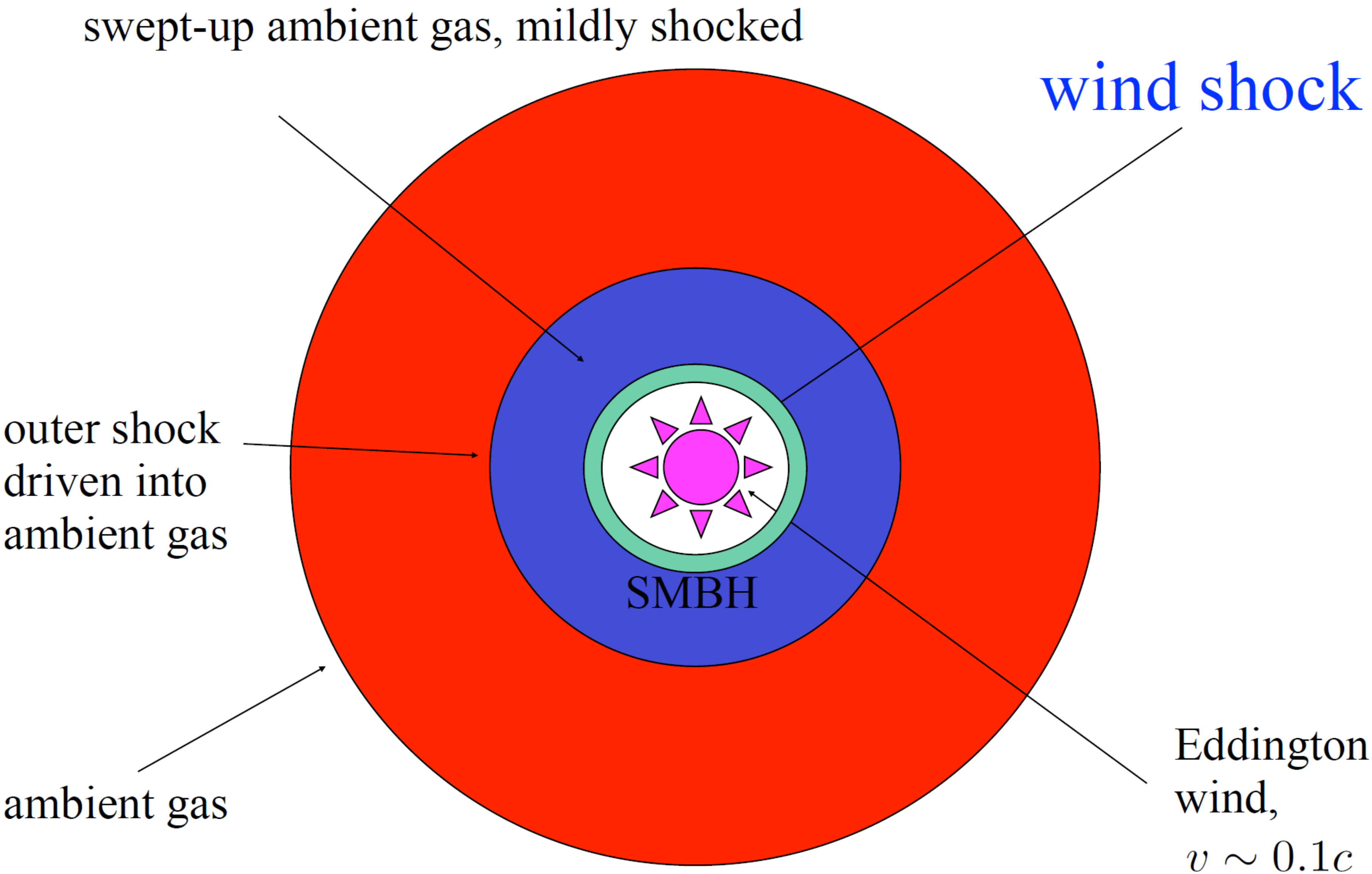
(b) shocked gas does not cool: `energy–driven flow'
thermal pressure > ram pressure

Compton cooling by quasar radiation field very effective out to large bulge radii (cf Ciotti & Ostriker, 1997, 2001)

expansion into bulge gas is driven by momentum $\frac{L_{\rm Edd}}{c}$

- most energy lost - bomb is disarmed

curtesy of Andrew King



curtesy of Andrew King

motion of swept-up shell

total mass (dark, stars, gas) inside radius R of unperturbed bulge is

$$M_{\rm tot}(R) = \frac{2\sigma^2 R}{G}$$

but swept-up gas mass $M(R) = \frac{2 f_g \sigma^2 R}{G}$

forces on shell are gravity of mass within R , and wind ram pressure:
since gas fraction f_g is small, gravitating mass inside R
is $\simeq M_{\rm tot}(R)$: equation of motion of shell is

$$\frac{\rm d}{{\rm d}t}[M(R)\dot{R}] + \frac{GM(R)[M + M_{\rm tot}(R)]}{R^2} = 4\pi R^2 \rho v^2 = \dot{M}_{\rm out} v = \frac{L_{\rm Edd}}{c}$$

where M is the black hole mass

curtesy of Andrew King

using $M(R), M_{\rm tot}(R)$ this reduces to

$$\frac{\mathrm{d}}{\mathrm{d}t}(R\dot{R}) + \frac{GM}{R} = -2\sigma^2\left[1 - \frac{M}{M_\sigma}\right]$$

where $$M_\sigma = \frac{f_g \kappa}{\pi G^2}\sigma^4$$

integrate equation of motion by multiplying through by $R\dot{R}$: then

$$R^2\dot{R}^2 = -2GMR - 2\sigma^2\left[1 - \frac{M}{M_\sigma}\right]R^2 + \text{constant}$$

if $M < M_\sigma$, no solution at large R (rhs < 0)

Eddington thrust too small to lift swept-up shell

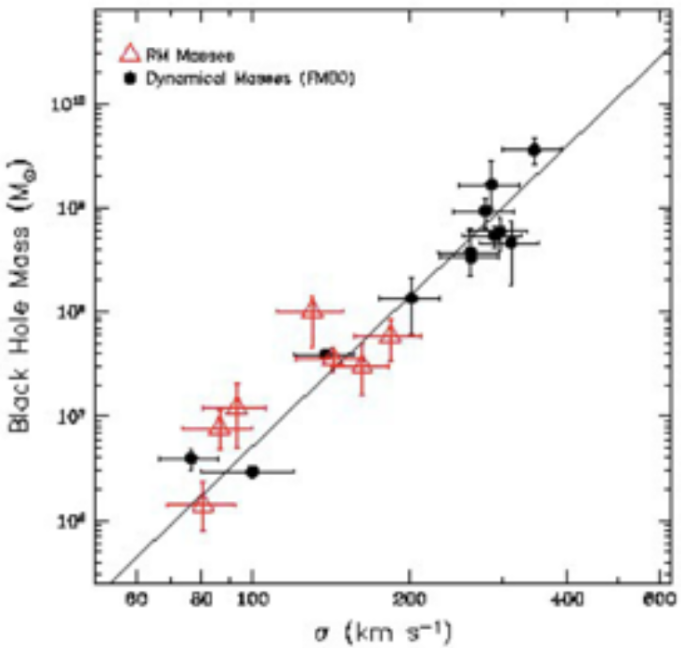
but if $M > M_\sigma$, $\dot{R}^2 \rightarrow 2\sigma^2$, and shell can be expelled completely

curtesy of Andrew King

critical value

$$M_\sigma = \frac{f_g \kappa}{\pi G^2}\sigma^4 \simeq 2 \times 10^8 M_\odot \sigma_{200}^4$$

remarkably close to observed $M - \sigma$ relation despite effectively no free parameter $(f_g \sim 0.1)$ (King, 2003; 2005)



SMBH mass grows until
Eddington thrust expels gas feeding it

curtesy of Andrew King

Summary of SMBH galaxy connection
(King & Pounds 2015)

- Is the supermassive black hole significant
  - Yes!

  Total energy in radiation >> total mechanical energy of the bulge

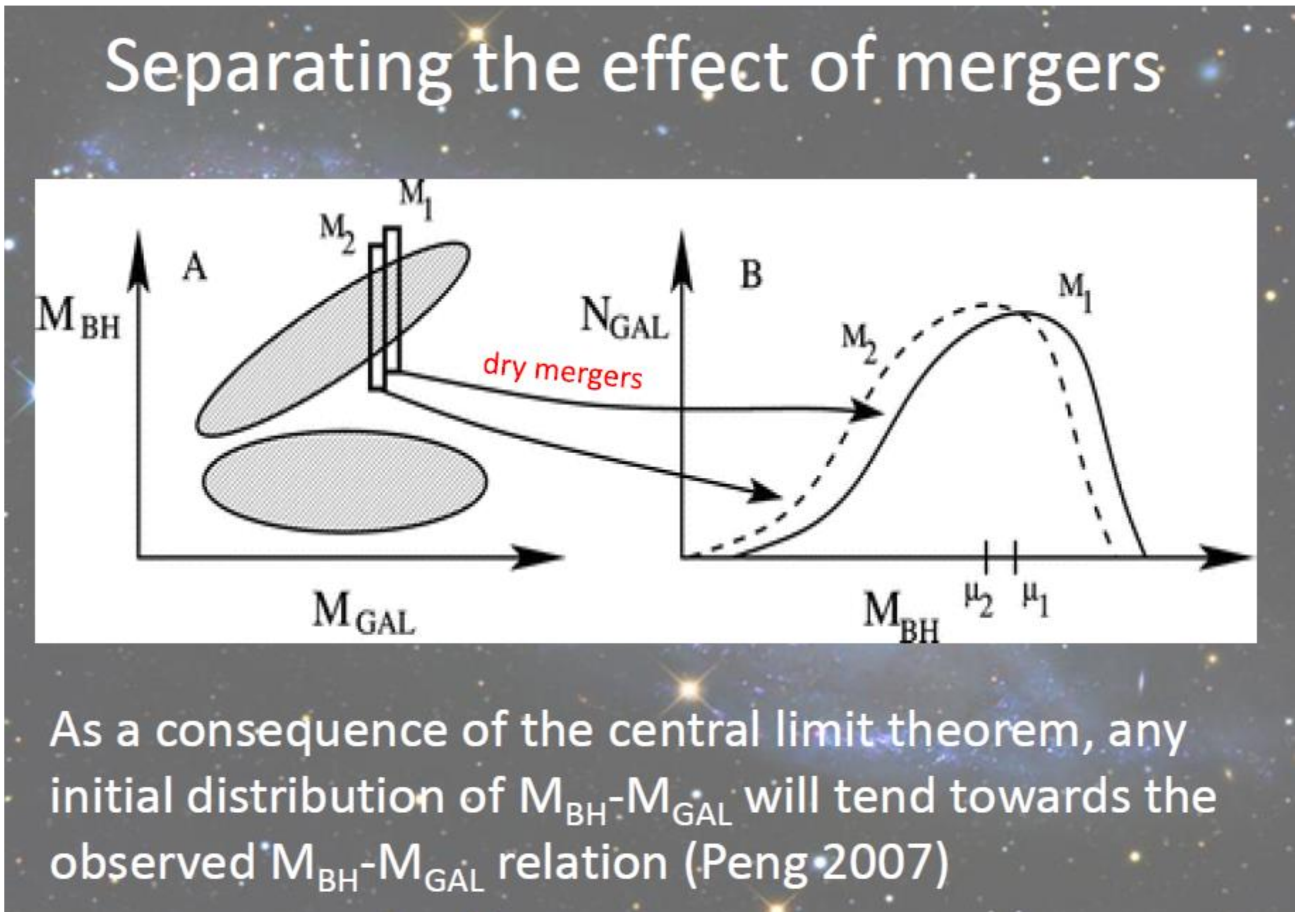
How does the supermassive black hole couple to the galaxy?

- Disk of gas around black hole
- Accretion due to viscosity (MRI, gravitational turbulence?)
- Viscous heating → bright source of radiation
- Radiation drives a wind → relativistic outflow
- wind collides with interstellar gas
- shock heating and Compton cooling → narrow region hot
- most of the gas is cold and pushed out by momentum transfer,

  works until M-sigma is reached

Other explanations of M-σ

- galaxy collisions



Other explanations of M-σ

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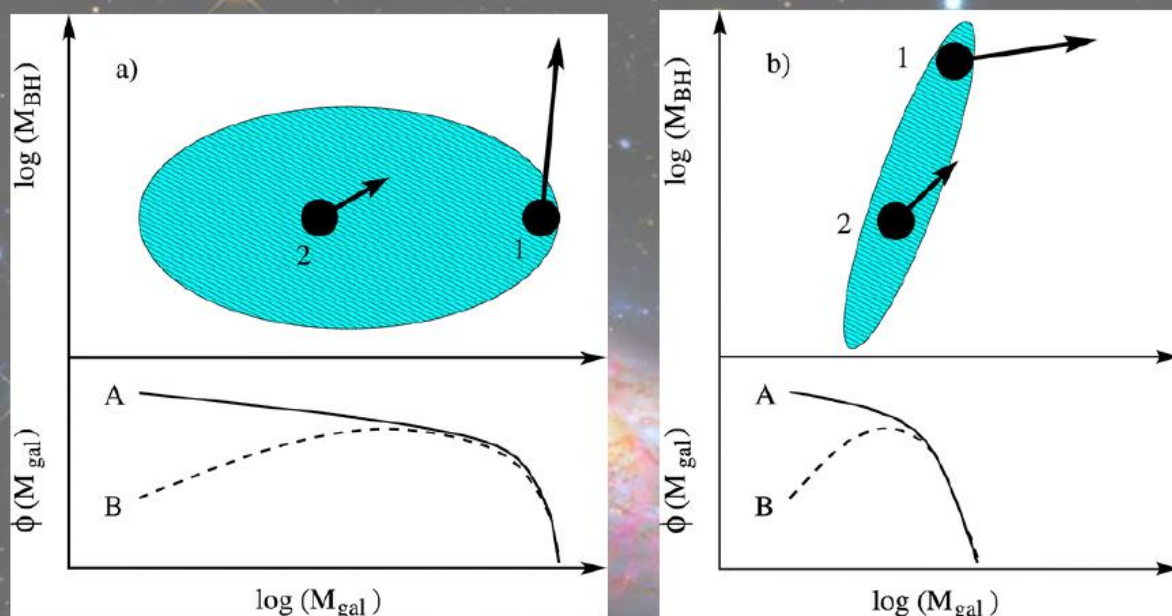


Peng (2007)

In the case of an initially uncorrelated M_{BH}-M_{gal} relation, the present day M_{BH}-M_{gal} relation will emerge due to dry mergers

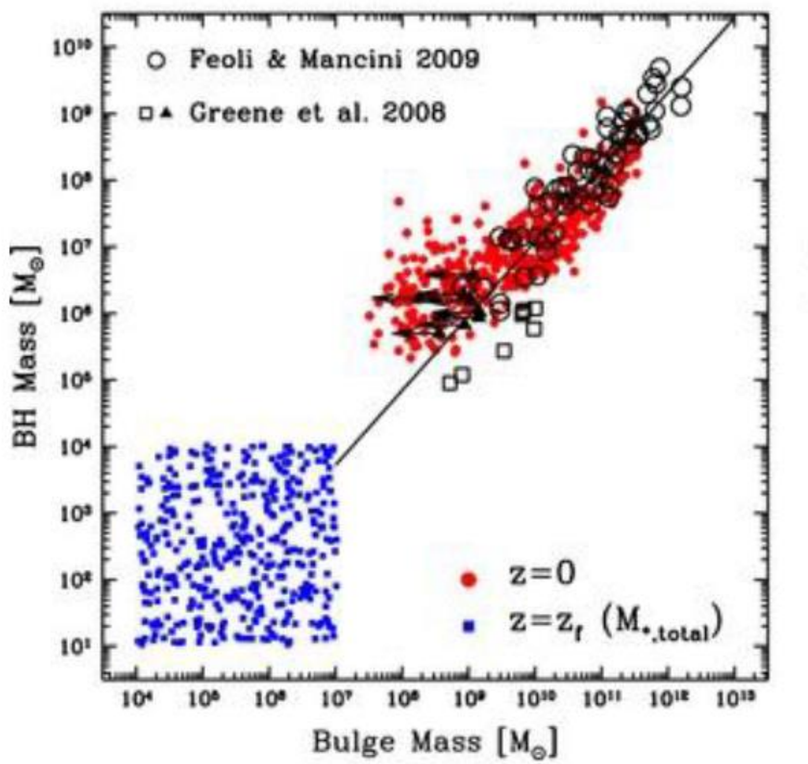
In the case of an initially correlated M_{BH}-M_{gal} relation, mergers will maintain the relation

Other explanations of M-σ

- Galaxy collisions

Jahnke & Macciò (2011)

"All basic properties of the BH-bulge mass scaling relation in the local universe are produced naturally by the merger driven assembly of bulge and BH mass, and without any coupling of star formation an BH mass growth per individual galaxy. "



Explanation of M-M_{bulge}

- Star formation feedback

Power et al. (2011)

- Argue that star formation in galaxy bulges is self-regulating and that stellar feedback sets the relation $M_{bulge} \propto \sigma^4$
- Similarly, they argue that AGN momentum feedback produces the relation $M_{BH} \propto \sigma^4$