Formation Processes of IMBHs

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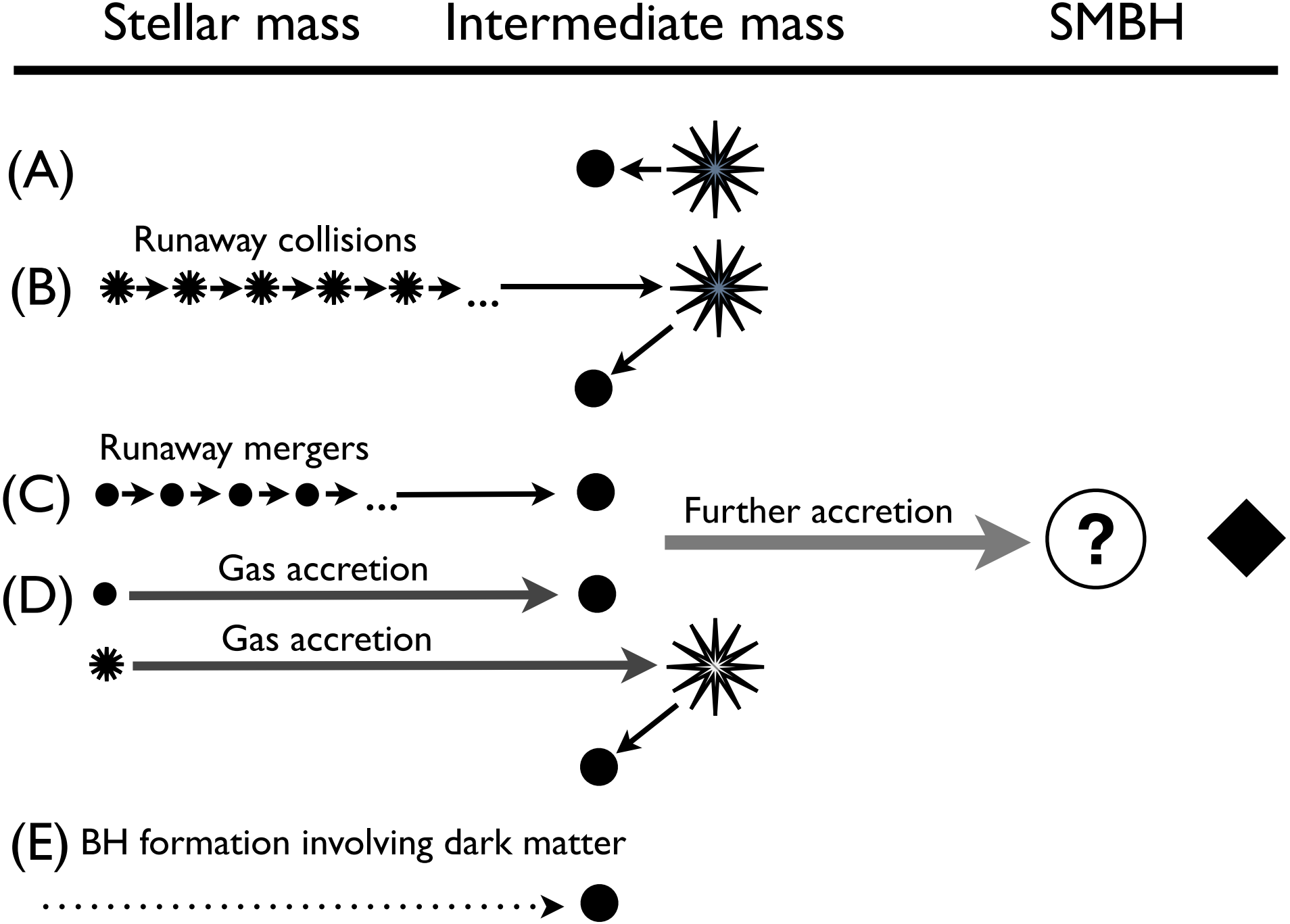
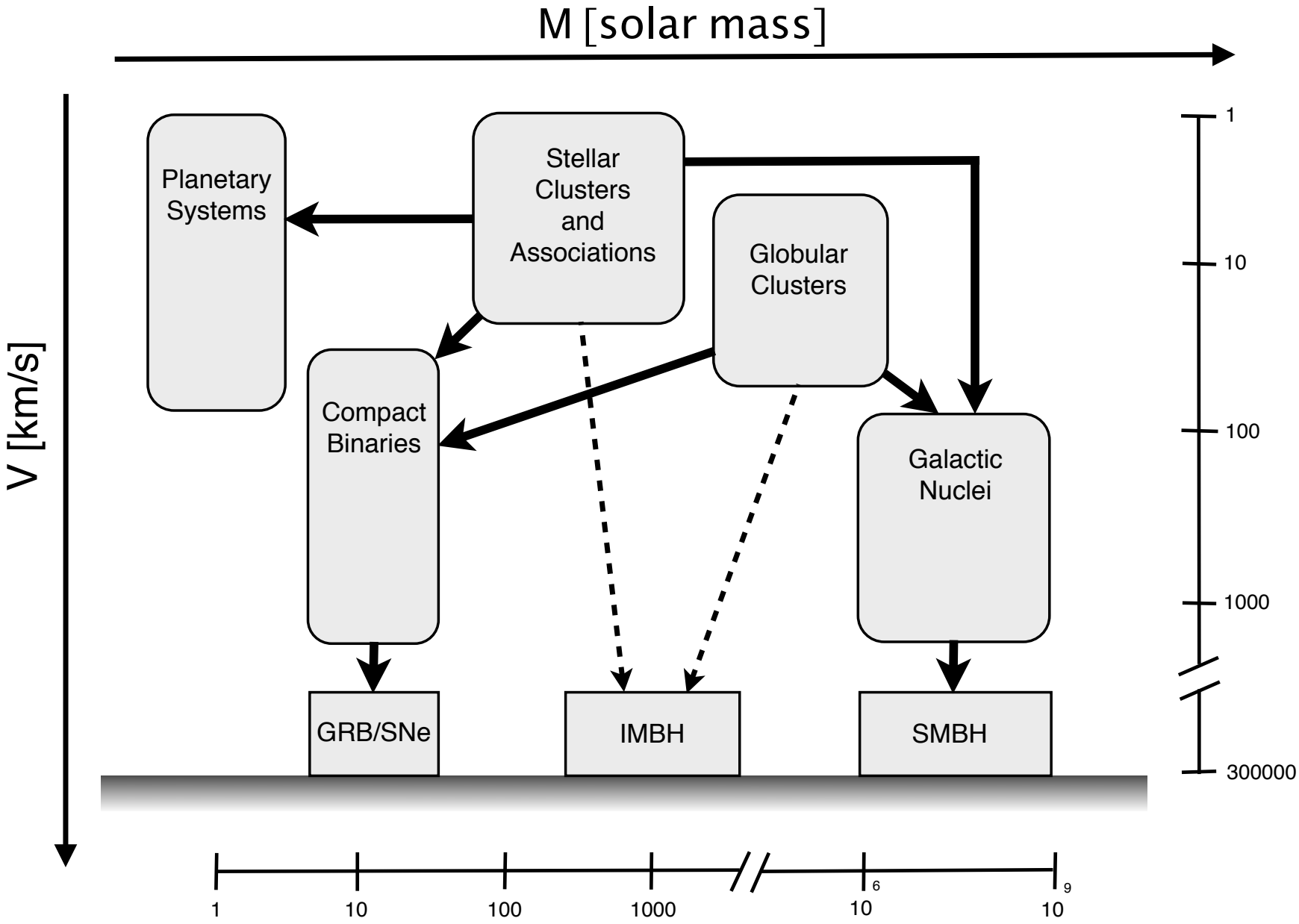

Stellar mass
Intermediate mass
SMBH
(A)
Runaway collisions
(B)
...
Runaway mergers
(C)
...
Further accretion
?
(D)
Gas accretion
Gas accretion
(E) BH formation involving dark matter

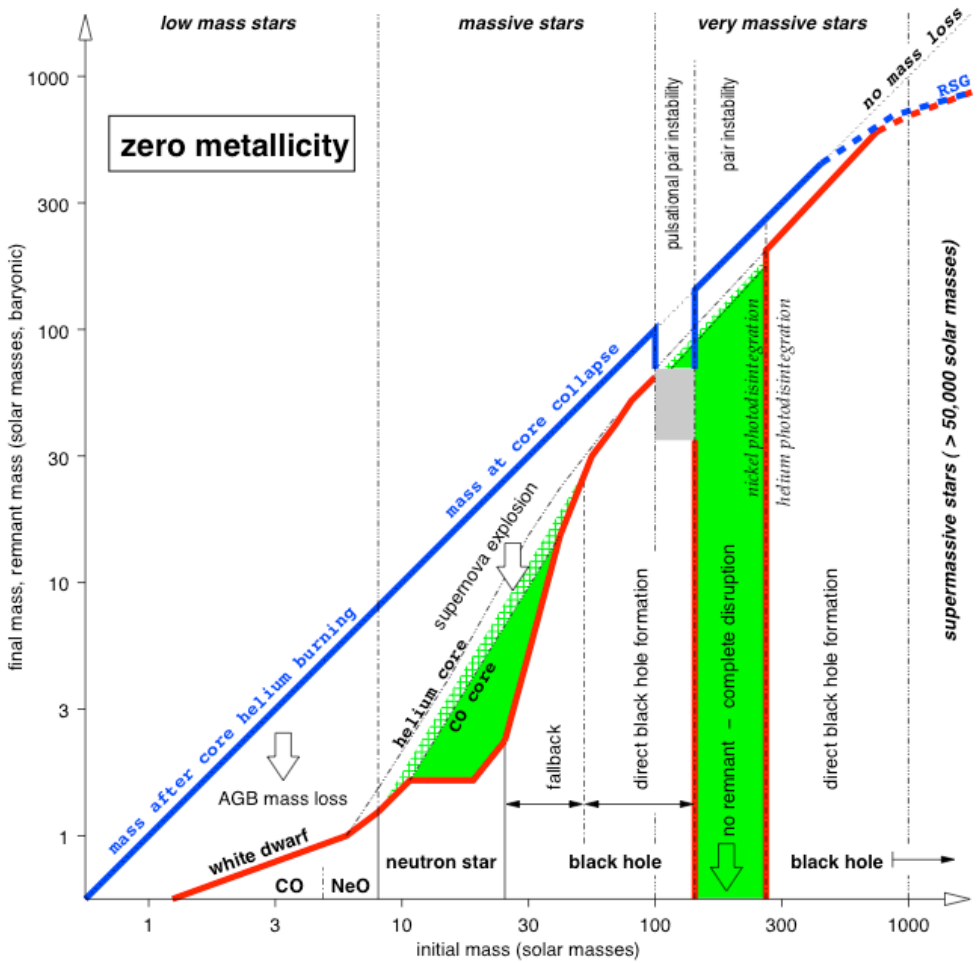
Stellar clusters play an important role

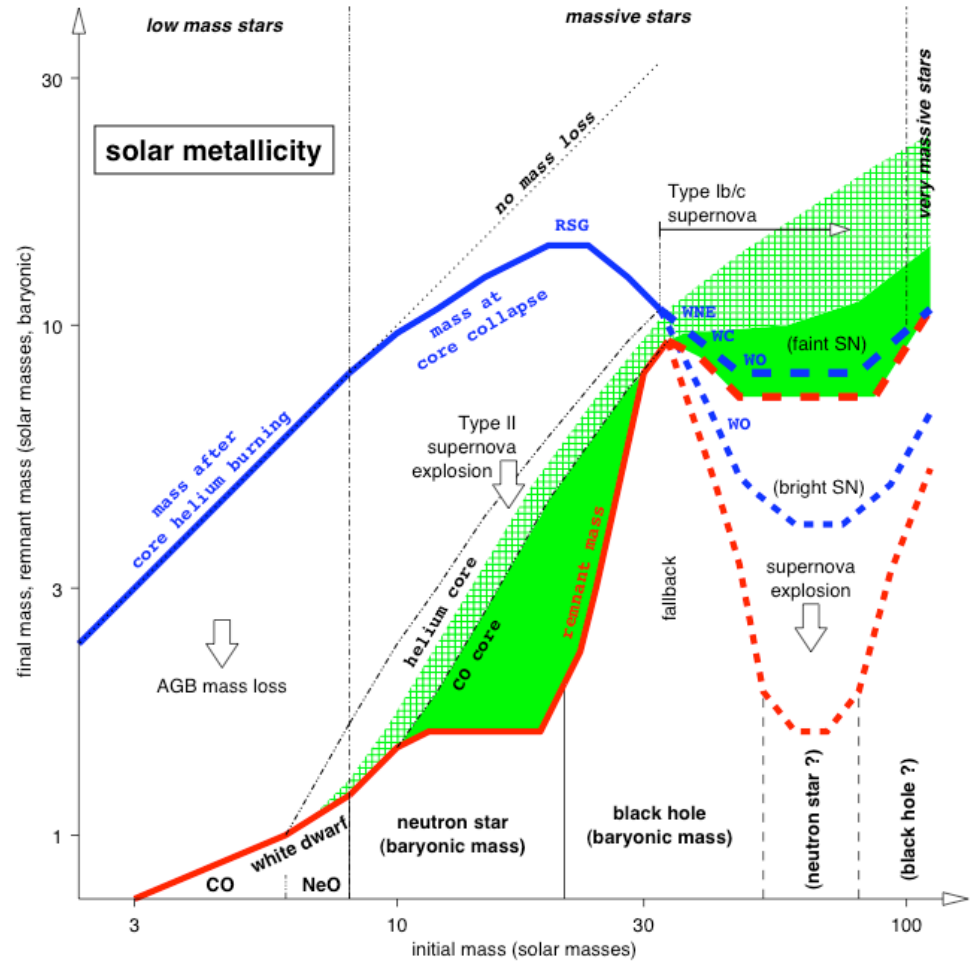


Consider eight channels

1. Direct formation from very massive stars
2. Runaway collisions forming massive stars
3. Bag-of-cores variation on channel (2)
4. Merger of stellar-mass BHs within clusters
5. Accretion from GMCs and AGN accretion discs
6. Gas infall (into nuclear stellar cluster)
7. Accretion of gas onto BH in a stellar cluster
8. Build up of BHs involving dark matter

1. Direct formation from very massive stars





Introduce concept of useless black holes (UBH)

Recall Tom Abel talk on Sunday

(Heger et al. 2003)

2. Runaway collisions forming massive stars

Cross section is given by

$$\sigma = \pi R_{min}^2 \left[1 + \frac{2G(M_1 + M_2)}{R_{min} V_\infty^2}\right]$$

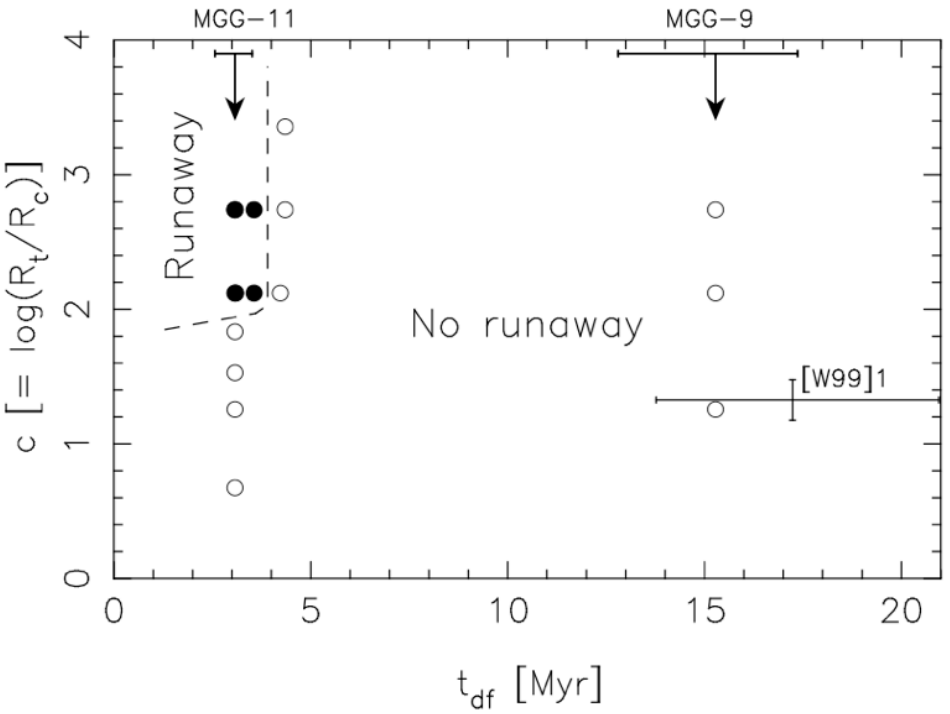
Timescale for a given star to undergo an encounter is

$$\tau_{enc} \sim 10^{11} yr \left(\frac{10^5/pc^3}{n}\right) \cdot \left(\frac{M_\odot}{M}\right) \cdot \left(\frac{R_\odot}{R_{min}}\right) \cdot \left(\frac{V_\infty}{10 km/s}\right)$$

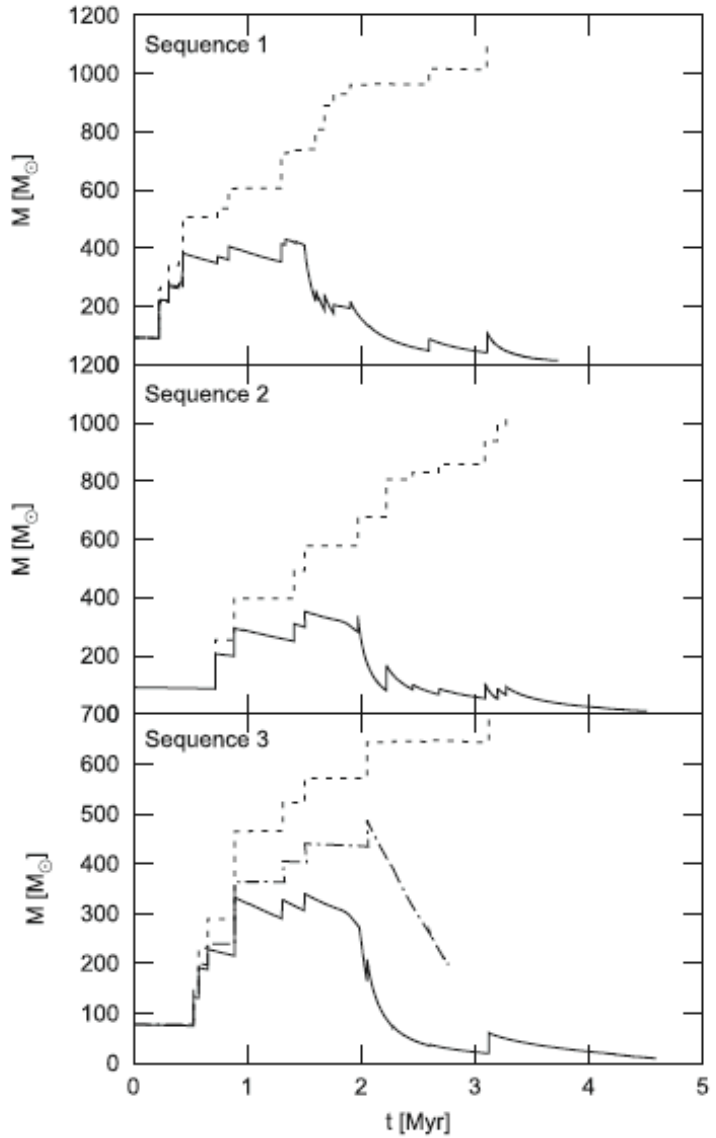
BIG IDEA: in order to have a runaway merger, we need

$\tau_{enc} \ll \tau_{evol}$ *What are the required cluster properties?*

Cluster properties giving runaway mergers



(Portegies Zwart et al. 2004;
Freitag, Gürkan & Rasio 2006)



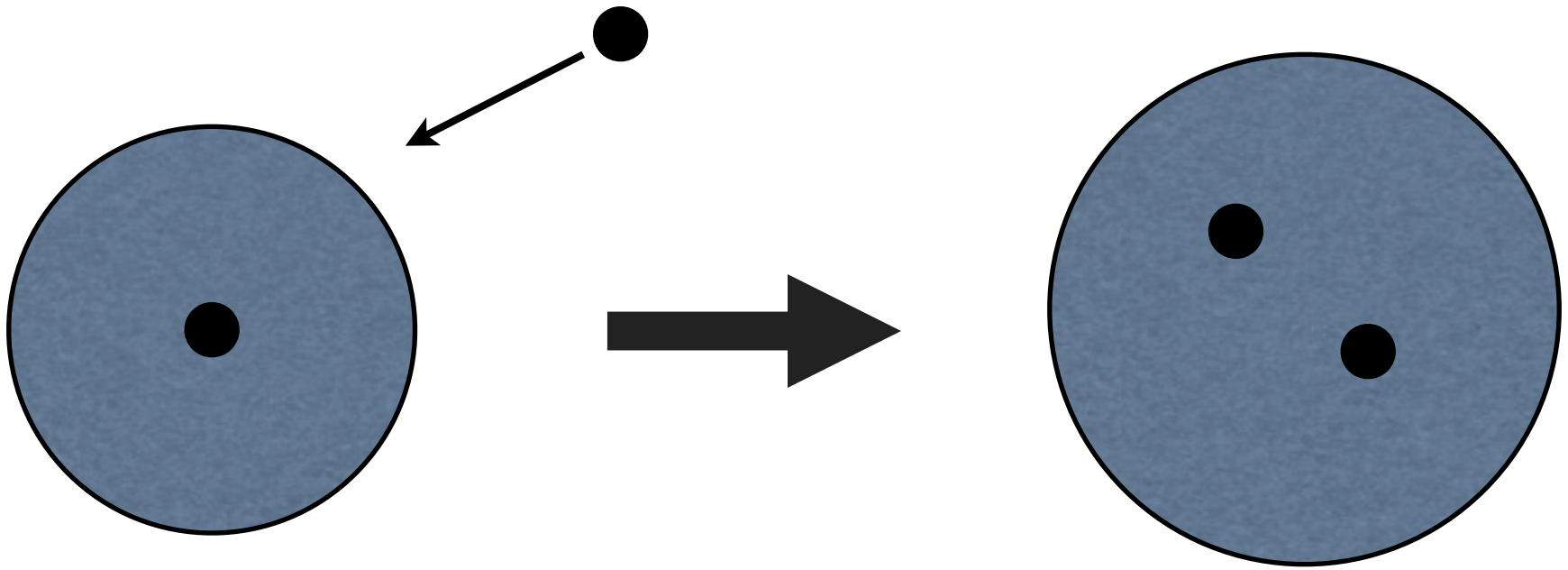
(Glebbeek et al. 2009)

But massive stars emit *hefty winds* which lead to significant mass loss for solar metallicity.

3. Making a bag-of-cores via runaway collisions

KEY IDEA: if collisional timescale if less than thermal timescale, then collisions occur whilst previous collision product is still *puffed up*.

(Dale & Davies 2006)



QUESTION: how does such a bag-of-cores evolve? ♦♦

4. Merger of stellar-mass BHs within clusters

Clusters are factories for producing exotic objects produced via dynamical encounters, including binaries containing two stellar-mass BHs.

$$\tau_{enc} \sim 10^{11} yr \left(\frac{10^5/pc^3}{n}\right) \cdot \left(\frac{M_\odot}{M}\right) \cdot \left(\frac{R_\odot}{R_{min}}\right) \cdot \left(\frac{V_\infty}{10 km/s}\right)$$

These binaries can then harden, spiral together by emission of gravitational radiation and merge.

$$t_{\rm GW} = 3.151 \times 10^{17}\ {\rm yr}\ g(e) \left(\frac{a}{\rm AU}\right)^4 \left(\frac{M_\odot}{m_1}\right) \left(\frac{M_\odot}{m_2}\right) \left(\frac{M_\odot}{m_1+m_2}\right)$$

$$g(e) = \left(1-e^2\right)^{7/2} \left(1 + \frac{73}{24}e^2 + \frac{37}{96}e^4\right)$$

(Peters 1964)

Merging BHs receive kicks due to asymmetry of GR emission.

$$V_{\rm kick} = 1.20 \times 10^4 \eta^2 \sqrt{1-4\eta}\,(1-0.93\eta)\ \ {\rm km/s}$$

$$\eta = \frac{q}{(1+q^2)}$$

(Gonzalez et al. 2007)

So merged BHs typically ejected from clusters as:

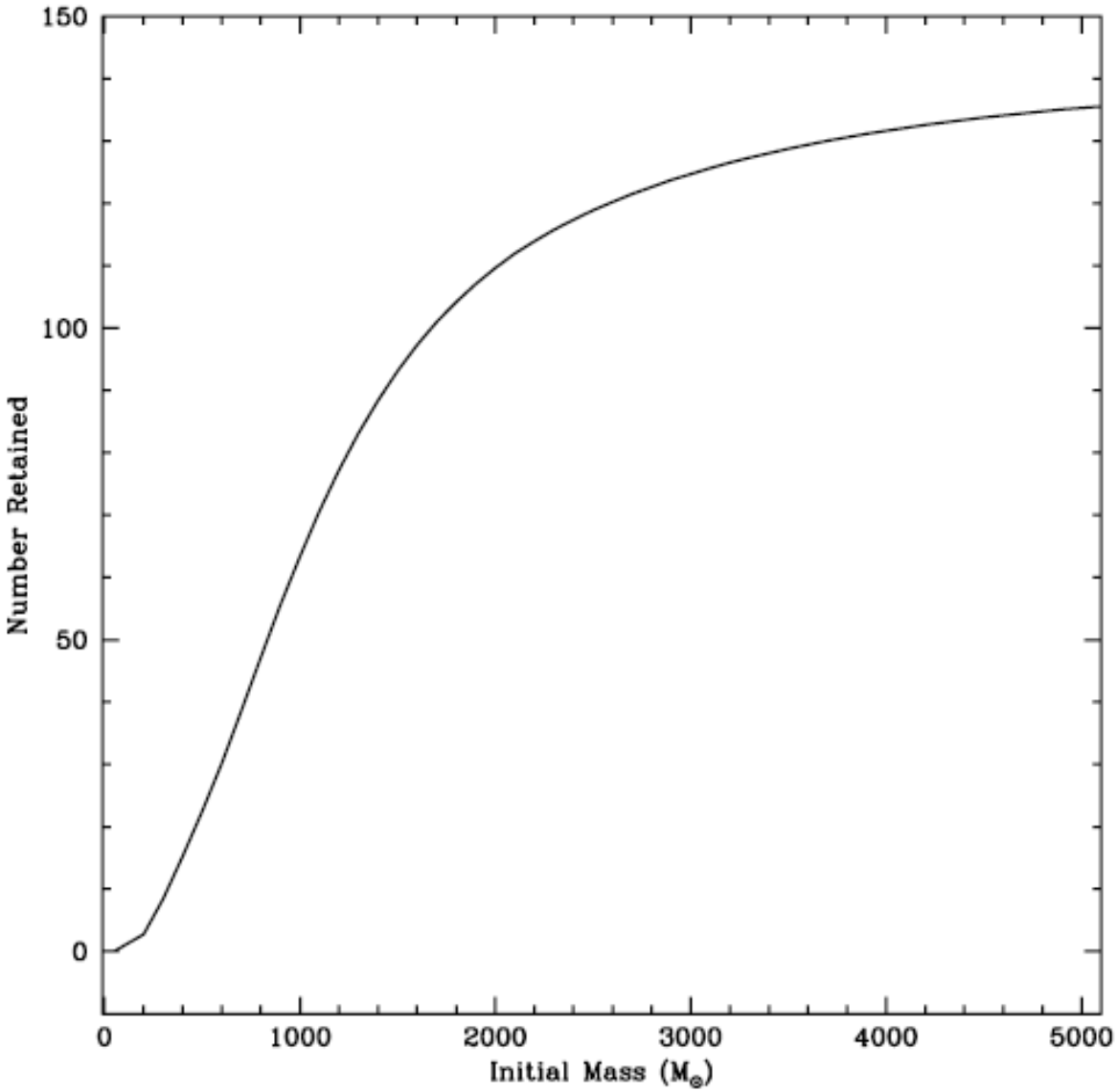
$$V_{\rm kick} \gg V_{\rm esc}$$ *i.e. merge once then out*

Modelling of BHs in globular clusters shows that BH binaries can be ejected by both mergers and scattering.

(e.g. Miller & Hamilton 2002; Moody & Sigurdsson 2009; see also Morscher et al. 2014)

See also Meagan Morscher talk on Monday afternoon

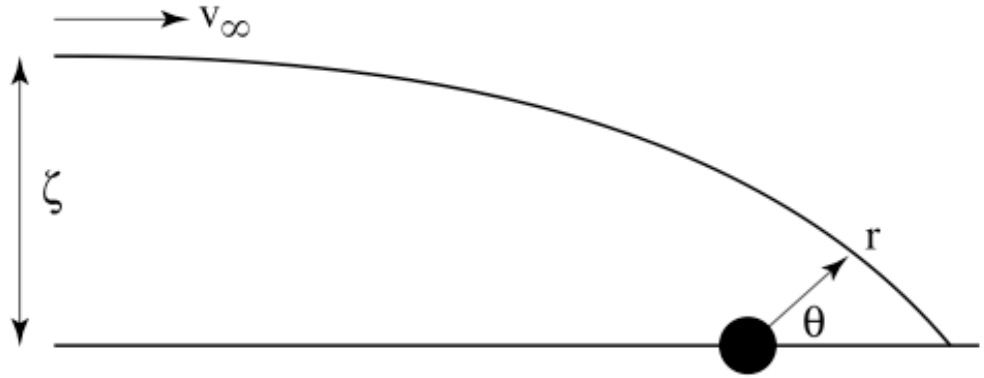
Number of Milky Way globulars retaining IMBHs



So there could be a population of halo (IM)BHs

(Holley-Bockelman et al. 2008)

5. Accretion from GMCs and accretion discs



(Edgar 2004)

$$\dot{M}_{\rm BH} = \frac{4\pi G^2 M^2 \rho}{(c_{\rm s}^2 + v_\infty^2)^{3/2}}$$

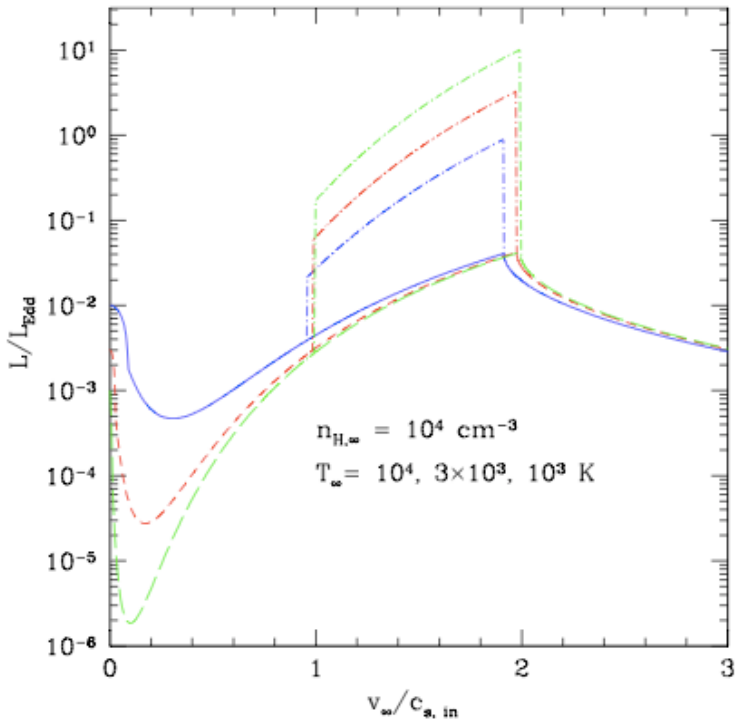
(Hoyle & Lyttleton 1939; Bondi & Hoyle 1944)

Can reach high accretion rates by going slowly through cold, dense gas, but note Eddington limit (and more...).

(e.g. Krolik 2004; Miller & Colbert 2004)

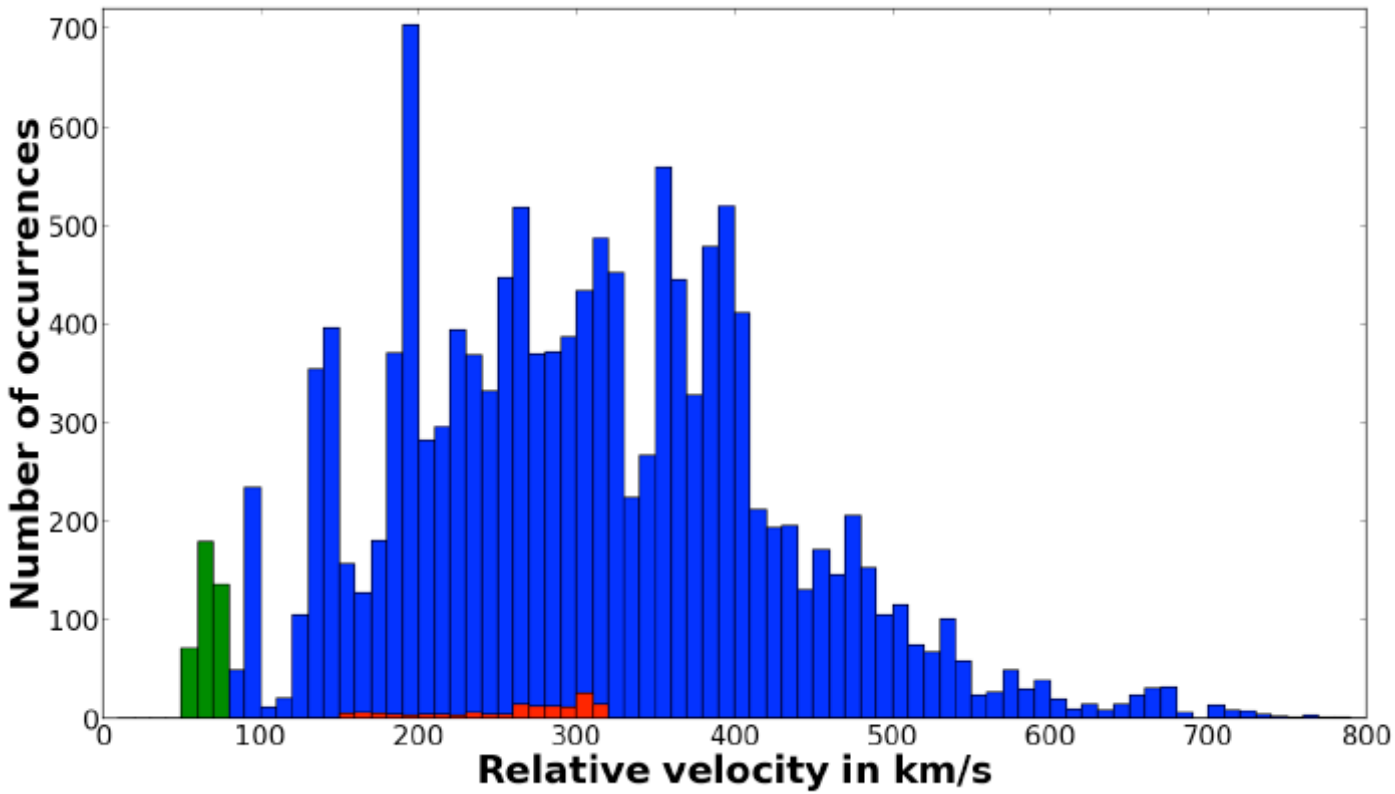
Can use computer modelling to measure accretion rate.

(e.g. Park & Ricotti 2011, 2012, 2013)



(Park & Ricotti 2013)

XRBs from IMBH accretion in GMCs



Halo objects move too quickly

Known globular cluster orbits

NGC 6838

NGC 6553

(Krueger & Davies, in prep.)

But disc IMBHs produced within young rich clusters might be visible (but not so many of them: it depends on one's runaway optimism).

Accretion within AGN discs

Probably a better place to build up mass of BHs.

Stellar masses can grow by accretion.

(e.g. Syer et al. 1991; Artymowicz et al. 1993)

Can also produce supermassive stars.

(Goodman & Tan 2004)

Timescale to grow by accretion is given by

$$t_{\rm acc} \sim \left(\frac{H}{R}\right)^4 \frac{M_{\rm smbh}}{\Sigma_{\rm disc} R^2} \frac{M_{\rm smbh}}{m_\star} \frac{1}{\Omega}$$

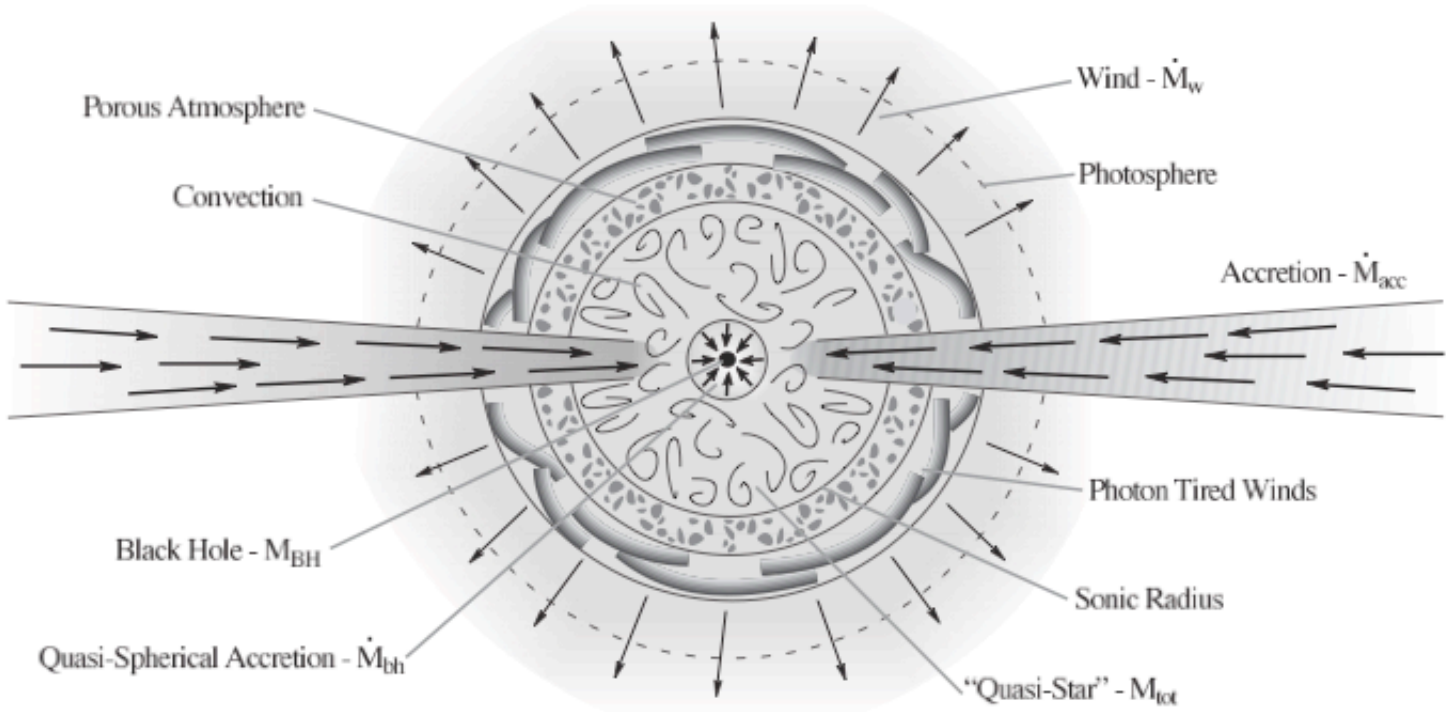
(Syer et al.1991)

(IM)BH masses can grow by accretion.

(e.g. McKernan et al. 2012, 2014)

See also Bence Kocsis talk on Thursday

6. BH formation from gas infall (into NSCs)



6a. Quasistars (e.g. Dotan, Rossi & Shaviv 2011)

KEY IDEA for 6b: Addition of gas into nuclear stellar cluster leads to significant contraction in core and increase in cluster velocity dispersion. Binaries can no longer support cluster which undergoes core collapse.

How an I(S)MBH may form:

Tight binaries merge but are retained to go on to merge with other objects thus building up a massive IMBH

IMBH will reach a mass of around 10^5 solar masses from stellar-mass BHs, NSs, and WDs within cluster.

Eddington-limited growth onto moderately spinning black hole would see growth to ~10^9 solar masses by z ~7.

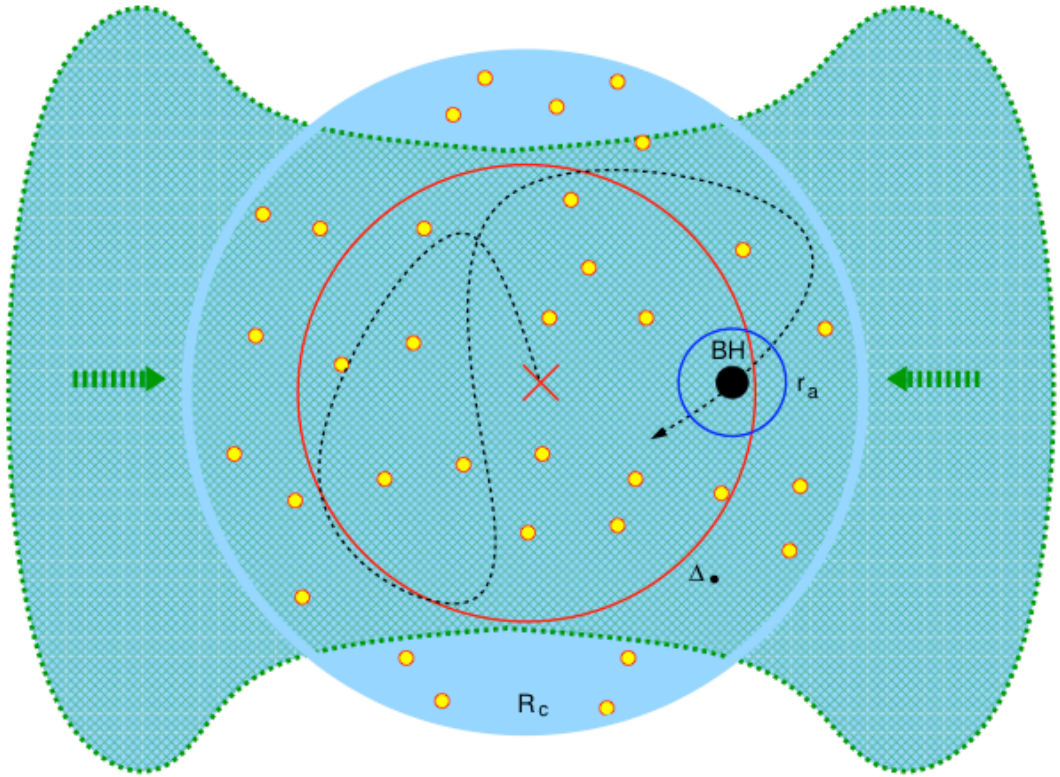
(Davies, Miller & Bellovary 2011)

Currently working with Lucio Mayer et al. on gas inflow and formation of stellar clusters.

7. Accretion of gas inside a stellar cluster

KEY IDEA: low-mass BH fed by infalling gas inside a stellar cluster. High opacity in gas traps accretion radiation. Random motions prevent formation of accretion disc around BH.

(Alexander & Natarajan 2014)



See also Tal Alexander talk from Sunday

Note: this requires a minimum gas density for photon advection to occur.

8. Build up of BHs involving dark matter

INTRIGUING IDEA: if a small fraction of dark matter is very strongly-interacting, one can get gravothermal core collapse and form seed black holes in the centre of a halo at very high redshifts which then give time to form 10^9 solar-mass BHs by z ~7.

(Pollack, Spergel & Steinhardt 2015)

Questions to ponder

1. How metal poor is metal poor?
2. Bag-of-cores evolution?
3. BH mass as function of stellar mass?
4. Size of stellar-mass BH natal kicks?
5. Structure of accretion flows: Eddington+/-?
6. Gas inflow histories into clusters/nuclei?
7. Other consequences/limits on sticky DM?
8. How often does IM(BH) lead to SM(BH)?