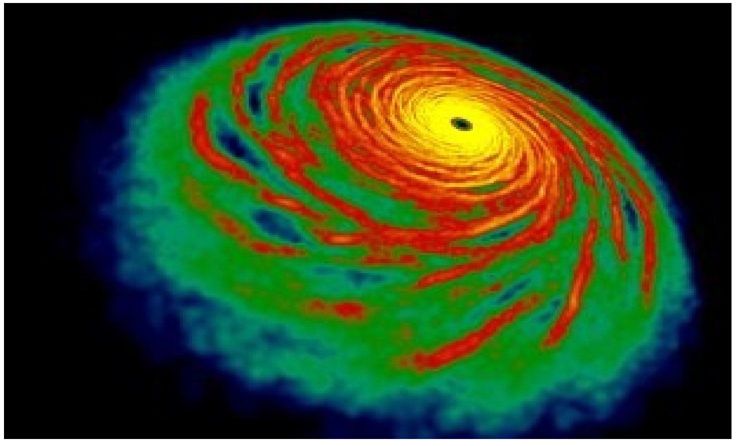
University of Leicester

AGN Feeding and Feedback
Ideas and Simulations



Chris Power, University of Leicester

in collaboration with

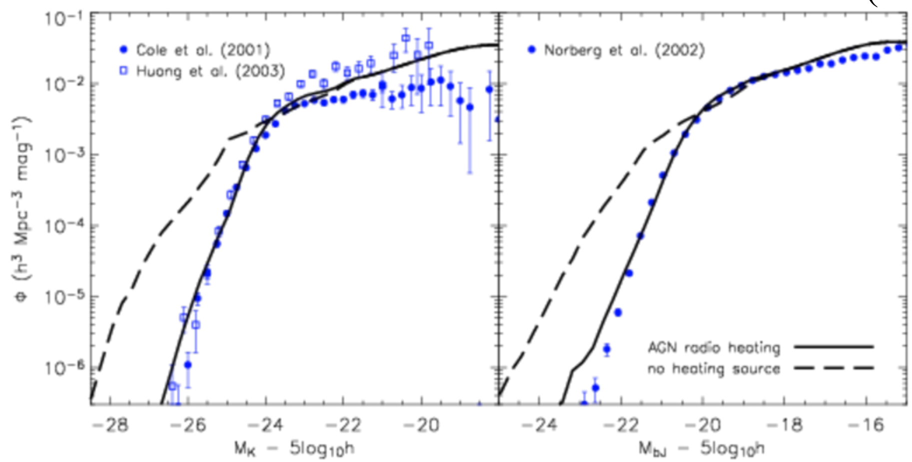
Alex Hobbs, Andrew King, Sergei Nayakshin, Kastytis Zubovas

What I'm about to say...

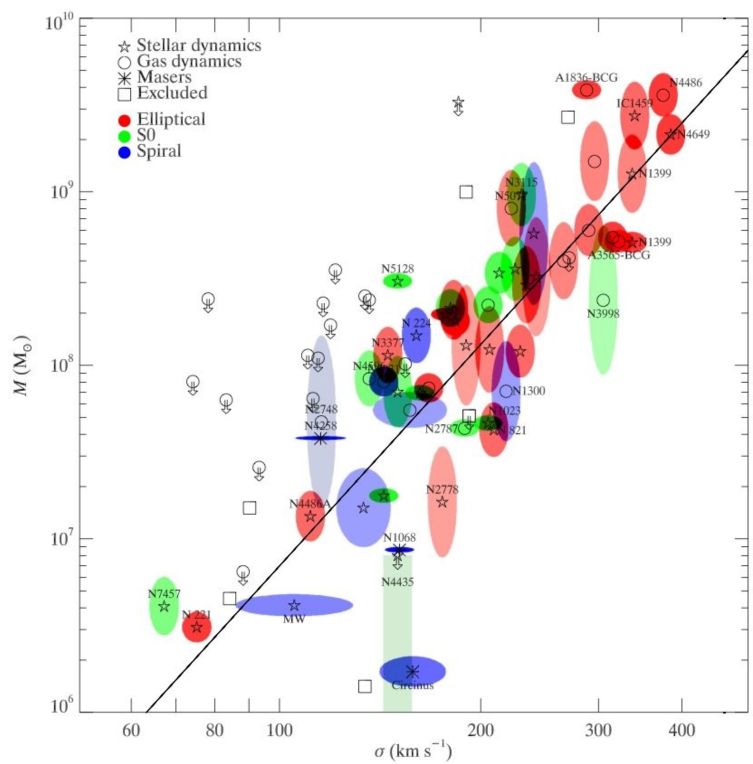
- If we are to understand how galaxies form, then we need to understand how feedback works.
    - Challenging, but AGN feedback can provide important clues.
- AGN feedback must be momentum-conserving, at least initially.
    - Could explain the observed M_{BH}-σ relation...
- Problem of AGN feeding equally challenging...
    - Need to account for angular momentum of accretion flow...
- Competition between black hole growth and star formation...
    - BHs lose out in low-mass galaxies.
- Stellar feedback can be more important than AGN feedback...
    - Origin of the M_{BH}-$M_{spheroid}$ relation?

Why is AGN feedback important?

Croton et al. (2006)



Gultekin 2009



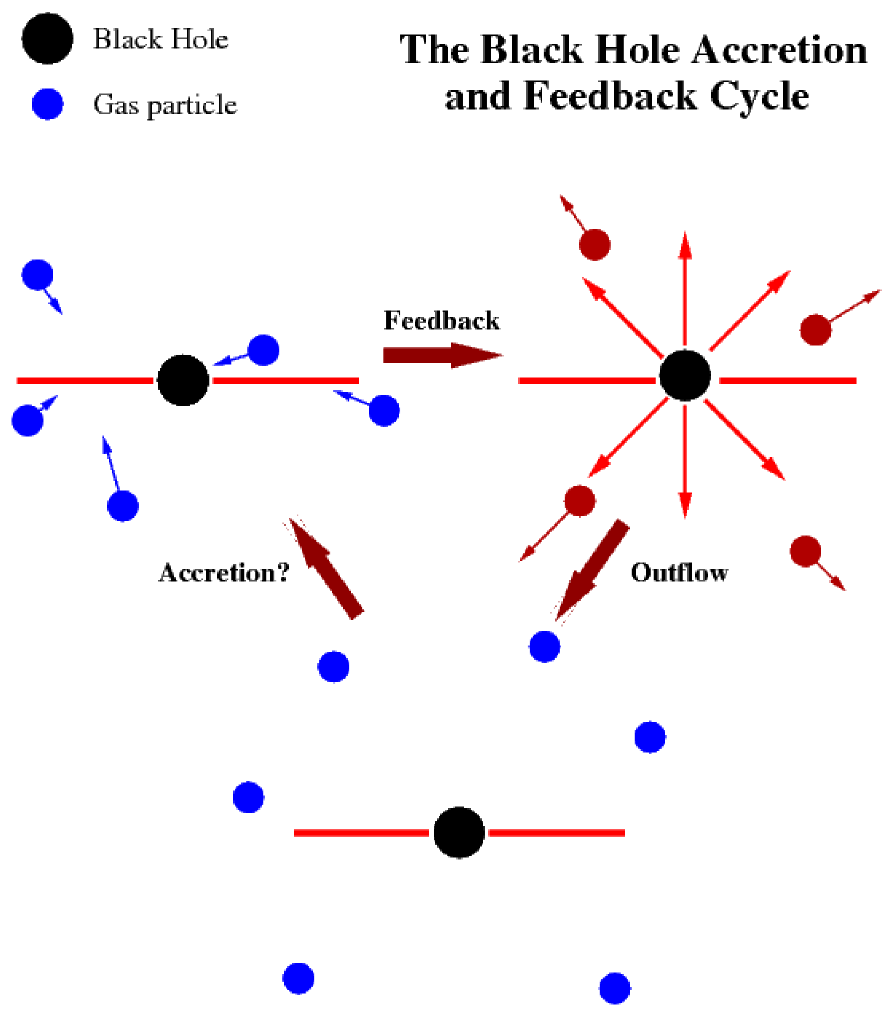
- Understanding feedback is crucial if we are to understand galaxy formation and evolution.
- Expect AGN feedback to be important in massive galaxies.
- Accretion onto BHs most efficient way to extract rest mass energy from matter.
- Helps to “fix” the luminosity function (e.g. Croton et al. 2006, Bower et al. 2006)
- Provides a natural explanation for the observed M-σ relation (e.g King 2005, Murray et al. 2005).

How does AGN feeding/feedback work?

- Matter accretes onto BH and fraction (~10%) of rest mass energy radiated away.
- Couples to gas in in vicinity of black hole and changes its thermo-dynamical state.
- Regulates accretion rate and radiated luminosity.

BUT...

- We don't really understood how this works,
- Challenging problem – must model processes on Mpc → sub-pc scales.



Modelling AGN Feeding & Feedback

From Di Matteo et al. 2005

• Galaxy formation simulations follow the coevolution of SMBHs and their host galaxies from high redshifts to the present day in a cosmological setting (e.g. Di Matteo et al. 2008)

• Simple models for AGN feeding and feedback – Bondi-Hoyle “capture” and thermal feedback (e.g. Springel et al. 2005, Booth & Schaye 2009)

• Simulations reproduce, for example, the M_{BH}-σ relation (e.g. Di Matteo et al. 2008)

BUT...

• Do these models really tell us anything useful?

AGN Feedback

Analytical Models of AGN Feedback I

• Silk & Rees (1998) considered impact of quasar outflows at high redshifts on star formation in their host galaxies.

• Quasars heat gas in their immediate surrounding; excess thermal pressure drives an outflow, sweeping up a shell of gas as it expands.

• Once velocity of shell exceeds escape velocity, it's driven out of the potential and growth of SMBH powering AGN is shut down; this happens for

$$M_{bh} > \frac{\alpha\kappa}{G^2 c}\sigma^5 = 8\times10^8\gamma(\sigma/500\,\mathrm{km\,s^{-1}})^5\,\mathrm{M}_\odot$$

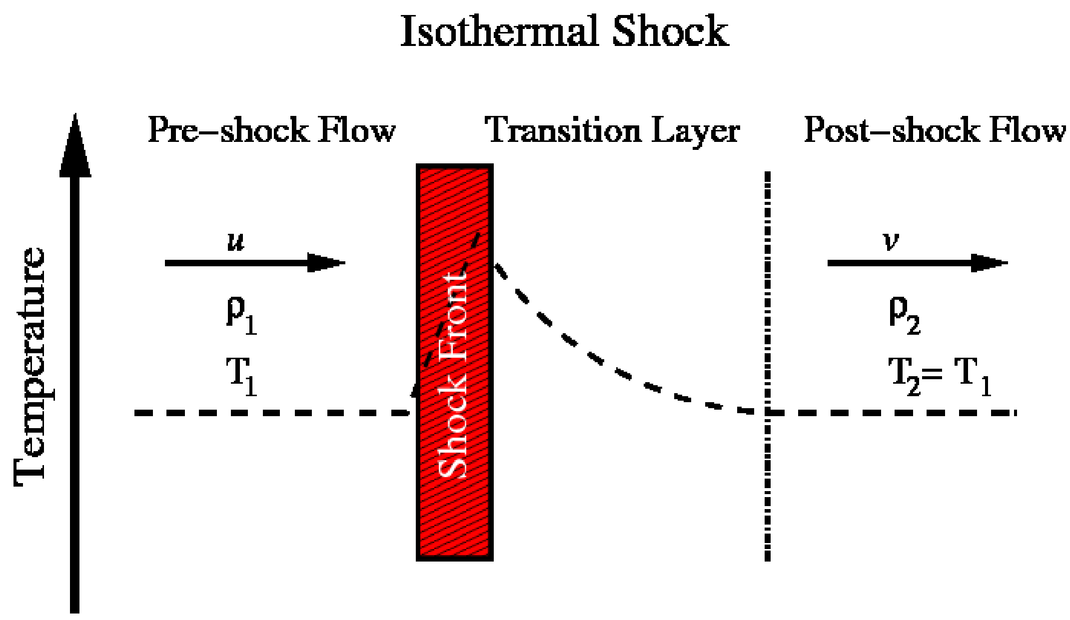
where $\gamma \approx 1$ – see their equation 1.

• Template for galaxy formation simulations (until recently).

• **Problem 1. :** Energy-conserving outflows are too efficient – scaling as σ^5.

• **Problem 2. :** Cooling is efficient close to the galaxy – expect outflow to be momentum-conserving instead.

Momentum- vs Energy-Conserving Outflows



- If cooling time is short, shocked gas radiate its energy away and shock is isothermal → only ram pressure drives gentle expansion of shell.
- If not, shock is adiabatic → thermal pressure of shocked gas dwarfs ram pressure of outflow and accelerates expansion of the shell.
- Note that a momentum-conserving outflow can become energy-conserving.

Analytical Models of AGN Feedback II

• King (2003, 2005) and Murray et al. (2005) have shown that momentum-conserving outflows from AGN can recover a M_{BH}-σ relation consistent with data.

• If AGN luminosity is Eddington limited, then the momentum flux of outflow is

$$\dot{P}_{\rm SMBH} \approx \frac{L_{\rm Edd}}{c} = \frac{4\pi G M_{\rm BH}}{\kappa}$$

• Equation of motion of a swept up shell of gas can be written as

$$\frac{d}{dt}(R\dot{R}) = \frac{L_{\rm Edd}}{c} - \frac{G M_{\rm enc} M}{R^2} = -2\sigma^2 \left[\frac{M_{\rm BH}}{M_\sigma} - 1\right]$$

where

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

(1) King, 2003, ApJL, 596, 27; (2) King, 2005, ApJL, 635, 121

Analytical Models of AGN Feedback III

• King assumes that SMBH is supplied with mass at super-Eddington rates; material surrounding SMBH is Compton thick (i.e. electron scattering) and so absorbs the momentum of the radiated luminosity of the AGN, with $\tau \sim 1$.

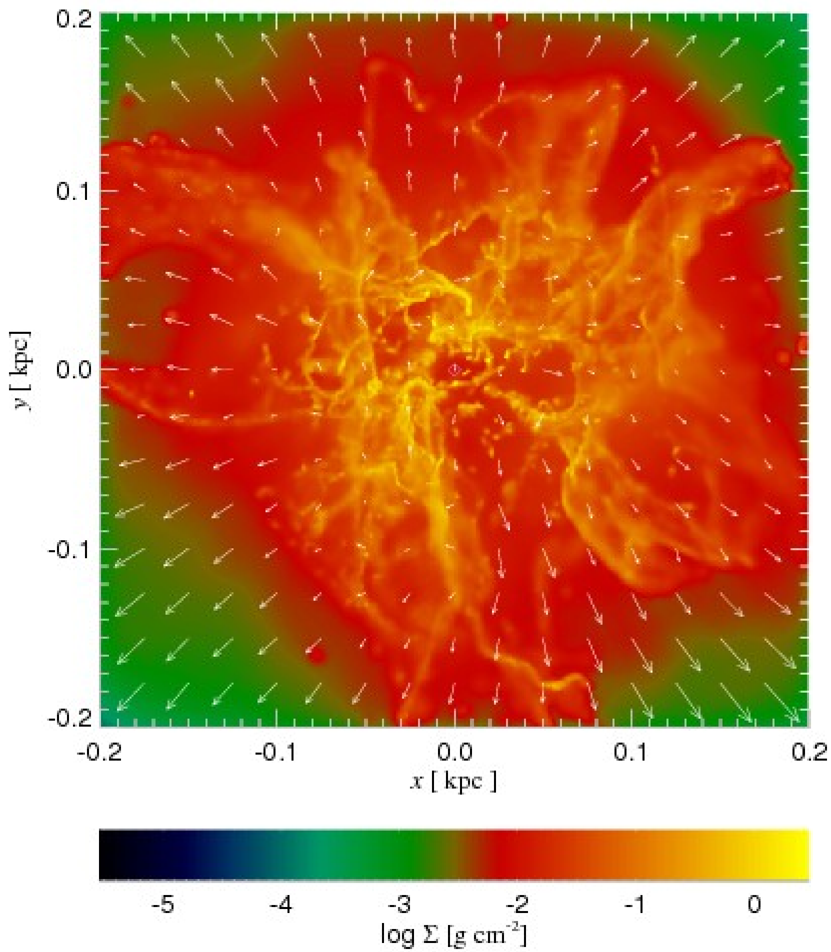
• Below M_σ mass, shell of swept up gas is driven outwards initially but has insufficient momentum to escape – and falls back onto the SMBH.

• At M_σ mass, shell stalls until SMBH grows sufficiently to start accelerating it outwards ($v_{shell} \approx v_{esc}$); at a certain radius (<1 kpc for a typical galaxy) outflow becomes energy-conserving, shell accelerates rapidly outwards ($v_{shell} >> v_{esc}$).

• **Implication 1 :** The M_σ mass is a limiting mass, reflecting the depth of the potential well in which the SMBH sits; M_{BH}-σ points can lie below the relation, but not too much above it.

•**Implication 2 :** Luminous AGN with high Eddington ratios are laggards – SMBHs with masses below their M_σ mass.

Numerical Models of AGN Feedback



From Power & Nayakshin, in prep

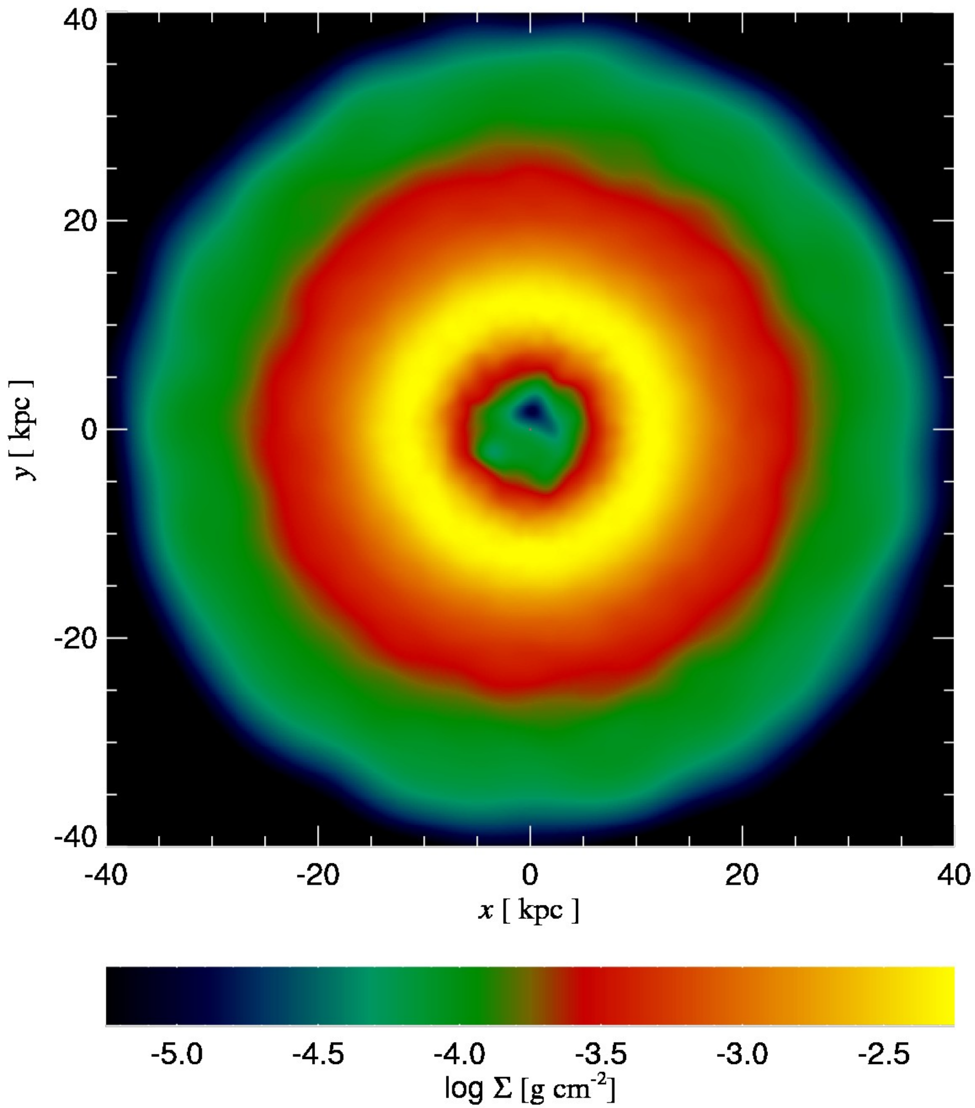
• Analytical models provide useful insights -- but they are idealised and require simplifying assumptions to be made – need numerical simulations!

• Apply RHD module embedded in Volker Springel's GADGET code (Nayakshin, Cha & Hobbs 2009) which we use to model an AGN “wind” (Nayakshin & Power 2010).

• Run simple idealised models first before applying to e.g. galaxy merger simulations (in progress!!!).

(1) Nayakshin, Cha & Hobbs, 2009, MNRAS, 397, 1314; (2) Nayakshin & Power, 2010, MNRAS, 402, 789

Numerical Model of BH Outflows



- Look at spherically symmetric shells of gas falling onto a central BH in an isothermal potential.
- Assume that BH is growing and radiating at its Eddington limit – doubles in mass every ~30 Myrs.
- Shell falls from rest at 40 kpc, freefall time ~250 Myrs.
- BH grows sufficiently quickly to reverse infall of shell and drive it out of potential.
- Simulations and analytical model in excellent agreement!

From Nayakshin & Power 2010

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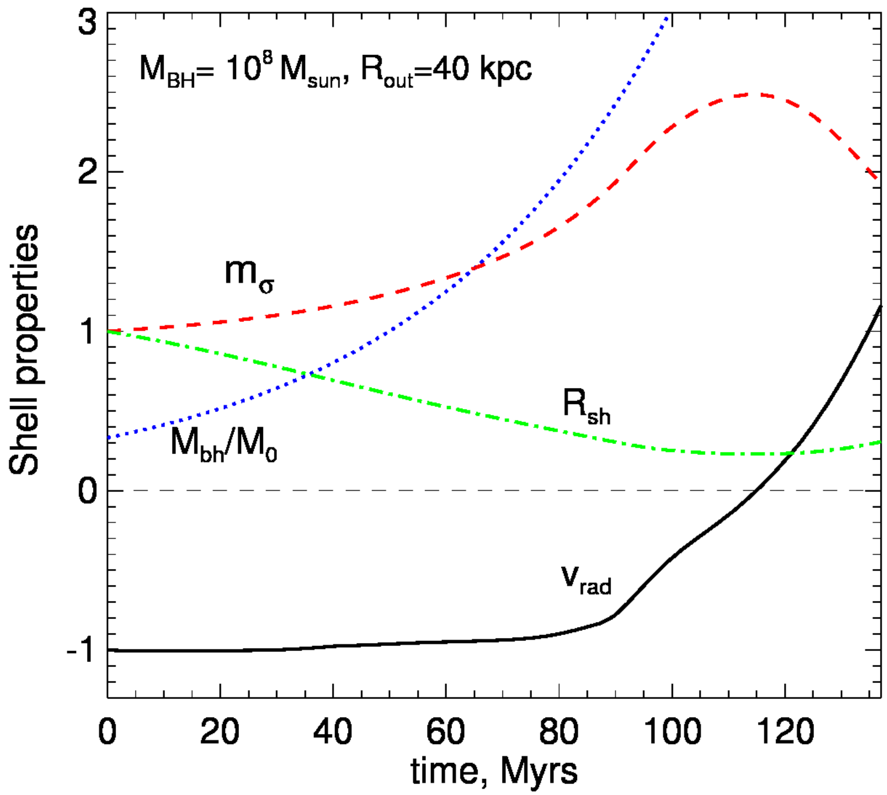

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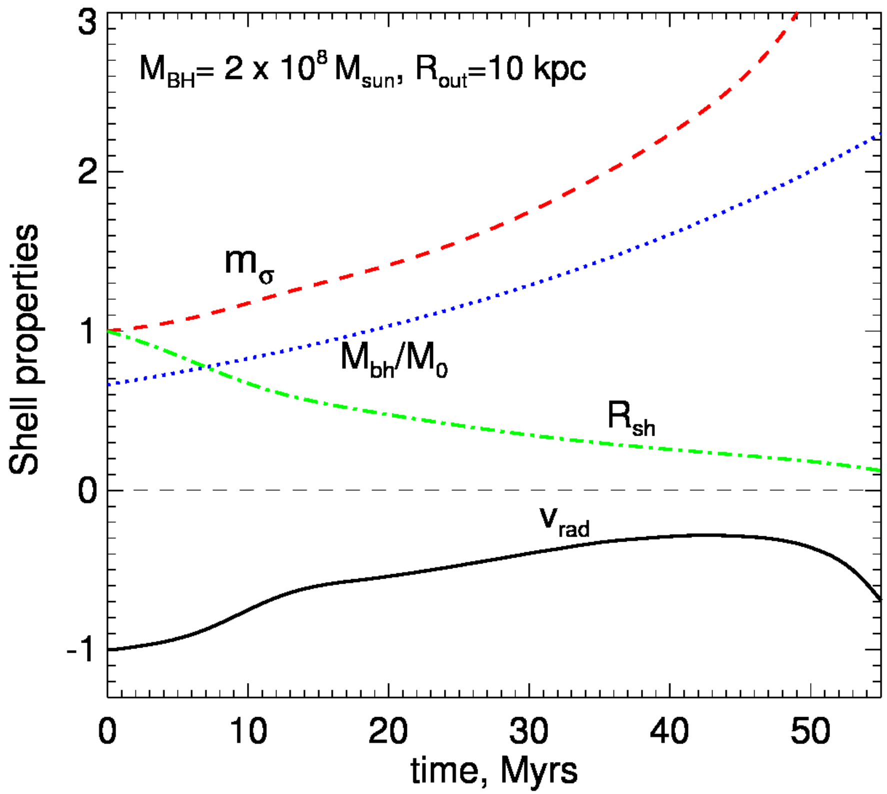
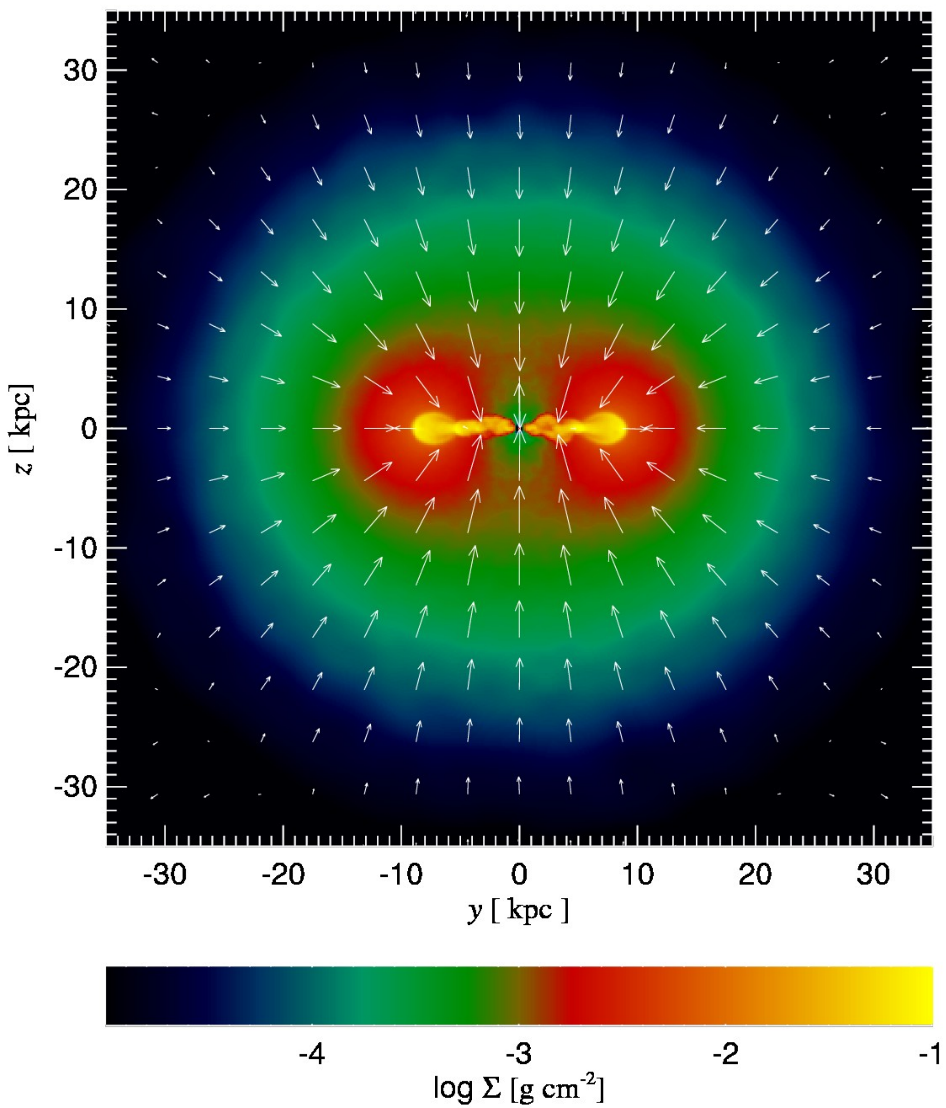
When Feedback Fails... I



- Shell falls from rest at 10 kpc, freefall time ~60 Myrs.
- More massive initial BH mass, but it cannot grow quickly enough to prevent shell falling to centre.
- If star formation timescale short, star formation favoured over BH growth.
- Stellar wind feedback drives gas away.
- "Competitive feedback" – see below.

From Nayakshin & Power 2009

When Feedback Fails... II



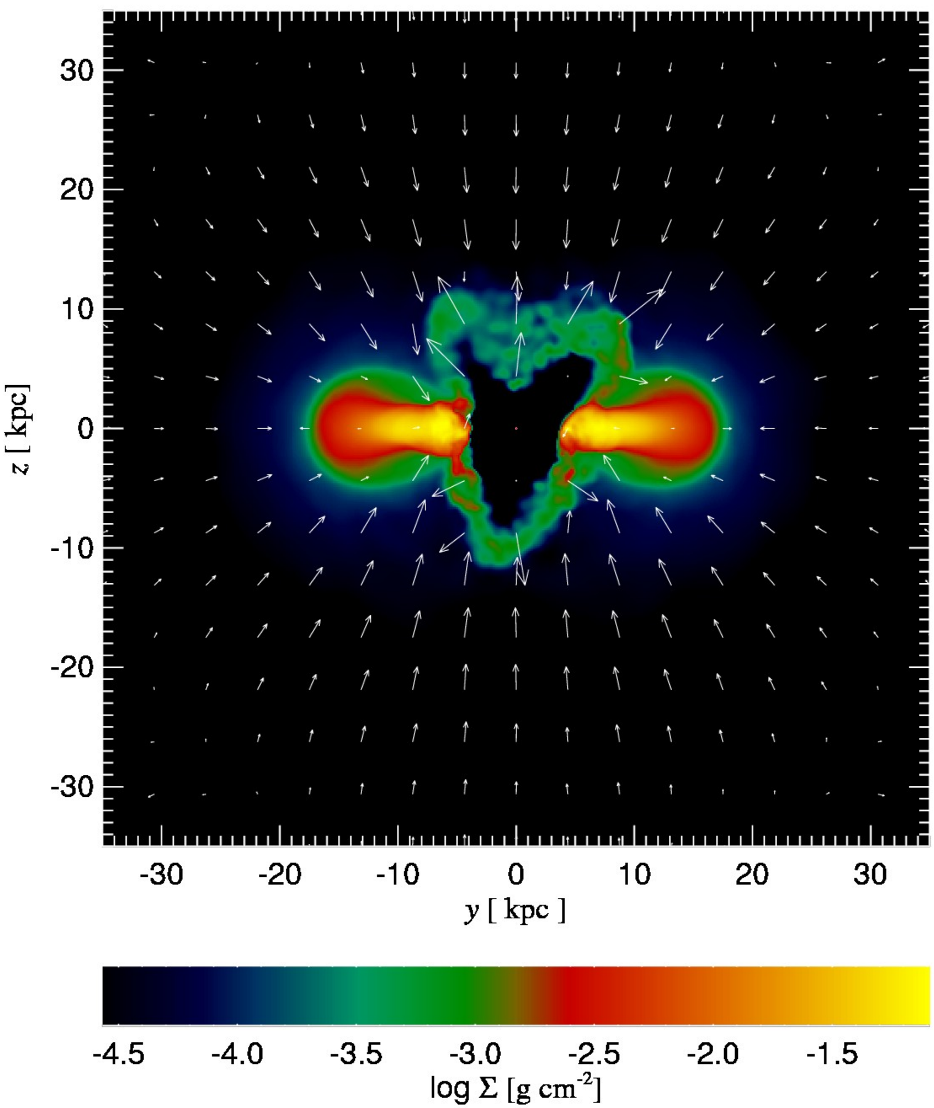
From Nayakshin & Power 2009

- As before, but shell rotates about z-axis.
- No feedback – settles into a disc.
- Feedback – gas expelled along z-axis, but high column density gas in disc difficult to get rid of.
- Problem – no obvious way to shut down its growth, no obvious limiting mass.

BUT...

- Feedback independent of accretion rate – unrealistic.

When Feedback Fails... II



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BUT...

- Feedback independent of accretion rate – unrealistic.

AGN Feeding

Modelling AGN Feeding

- Want to tie AGN feedback to AGN feeding – range of scales is a problem!

- How do we relate accretion rate onto SMBH on sub-parsec scales to properties of accretion flow at 100 pc? 1 kpc? 10 kpc? (e.g Thompson et al. 2005, Hopkins & Quataert 2009)

- Need to distill complex physical picture into a simple estimator...

- Most popular approach has been to use Bondi-Hoyle "capture" (e.g. Springel et al. 2005, Booth & Schaye 2009)

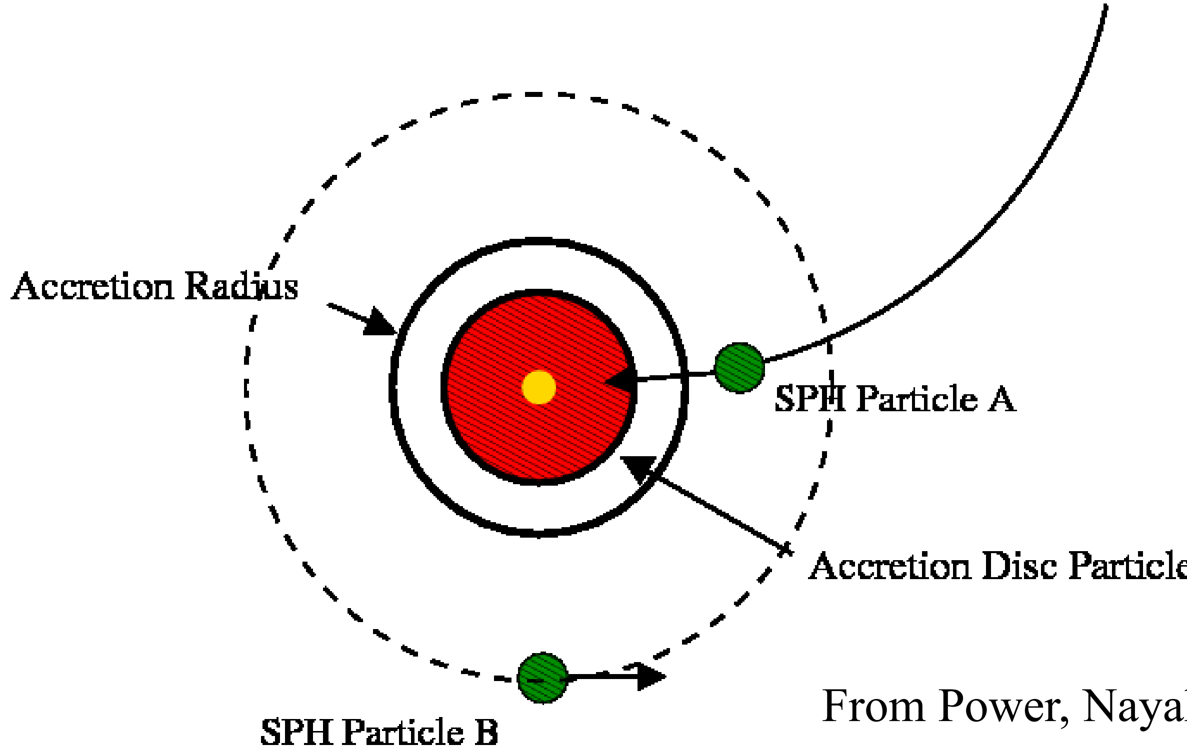
$$\dot{M}_{\rm BH} = \frac{4\pi\,\alpha\,G^2 M_{\rm BH}^2\,\rho}{(c_s^2 + v^2)^{3/2}}$$

but this is very unsatisfactory...

- **<u>Problem 1 :</u>** BH is embedded in the potential of a galaxy and its dark matter halo; boundary conditions non-trivial (Hobbs, Power et al., in prep)

- **<u>Problem 2 :</u>** Angular momentum is an efficient barrier to accretion – Bondi-Hoyle cannot account for this.

Accretion Disc Particle Approach

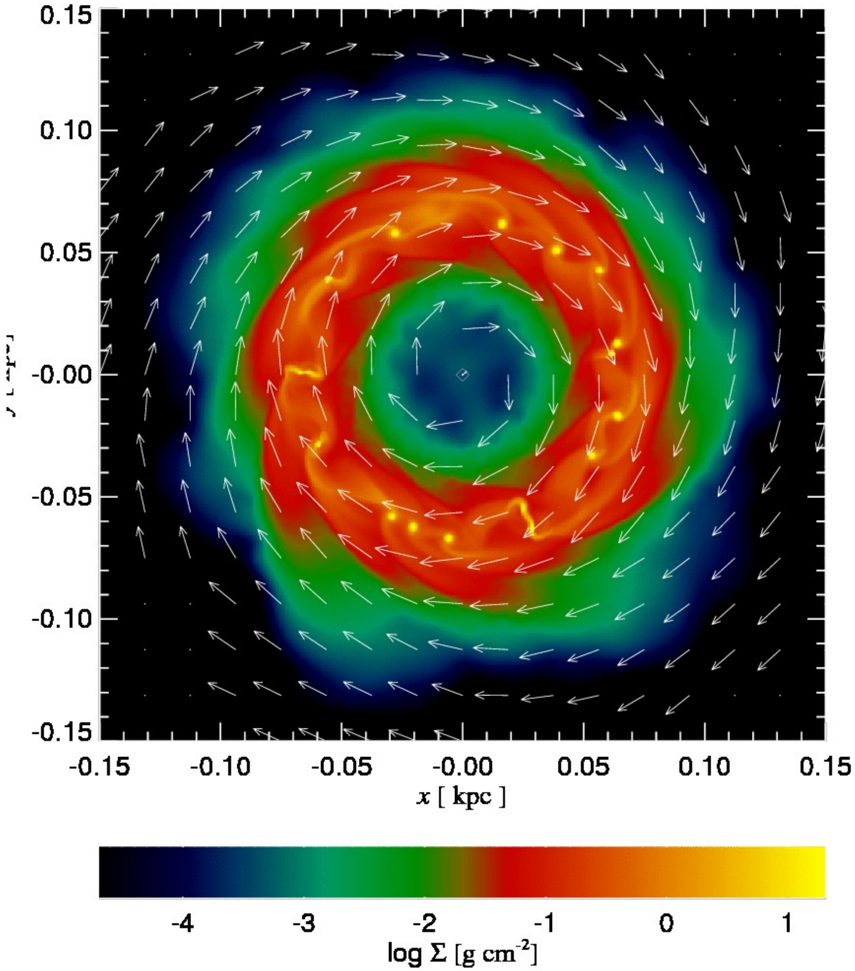


From Power, Nayakshin & King 2010

- Extension of sink particle method of Bate et al. (1995) – particle only accreted if angular momentum is sufficiently small.
- Adds to mass of accretion disc, BH fed on viscous timescale.
- Feedback proportional to accretion rate – Eddington limited.

Power, Nayakshin & King, 2010, astro-ph:arxiv:1003.0605

Angular Momentum is Important



From Power, Nayakshin & King 2010

- Compare ADP and Bondi-Hoyle capture estimates.
- Simple example : rotating shell of gas in isothermal potential with a SMBH embedded in the centre.
- Gas should settle into a thin rotationally supported disc in absence of any feedback.
- Choose $M_{BH} \sim 10^6 M_{\odot}$.
- Feedback modelled as momentum-conserving outflow (Nayakshin & Power 2010).

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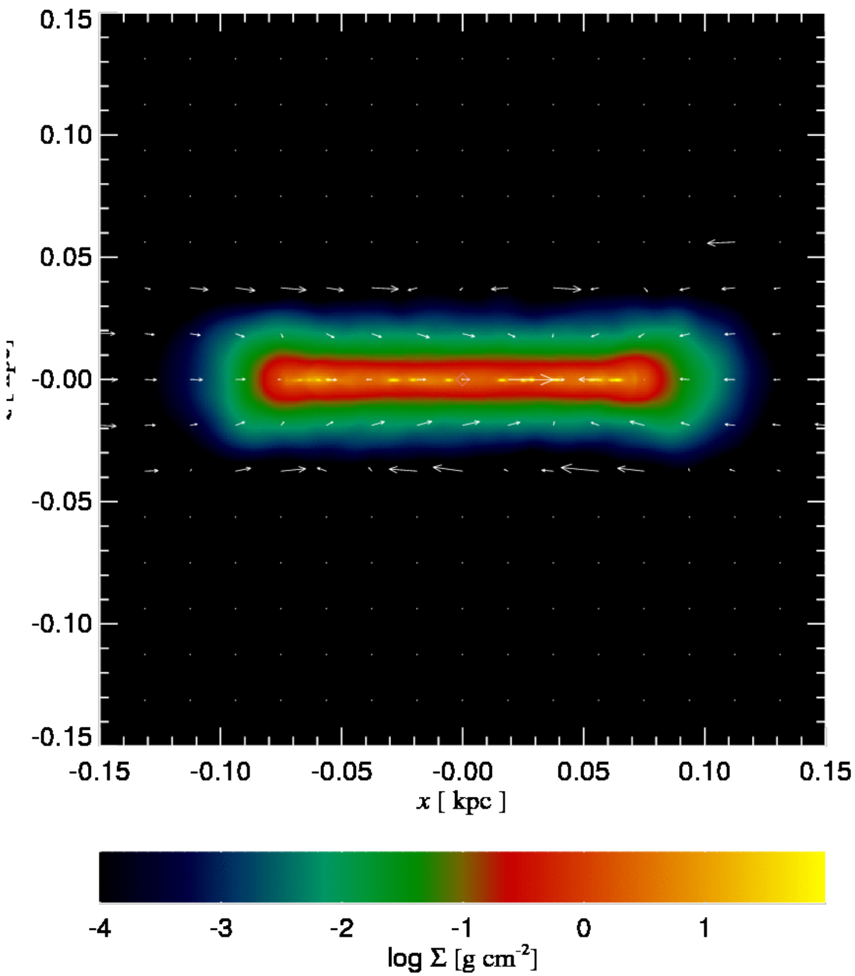

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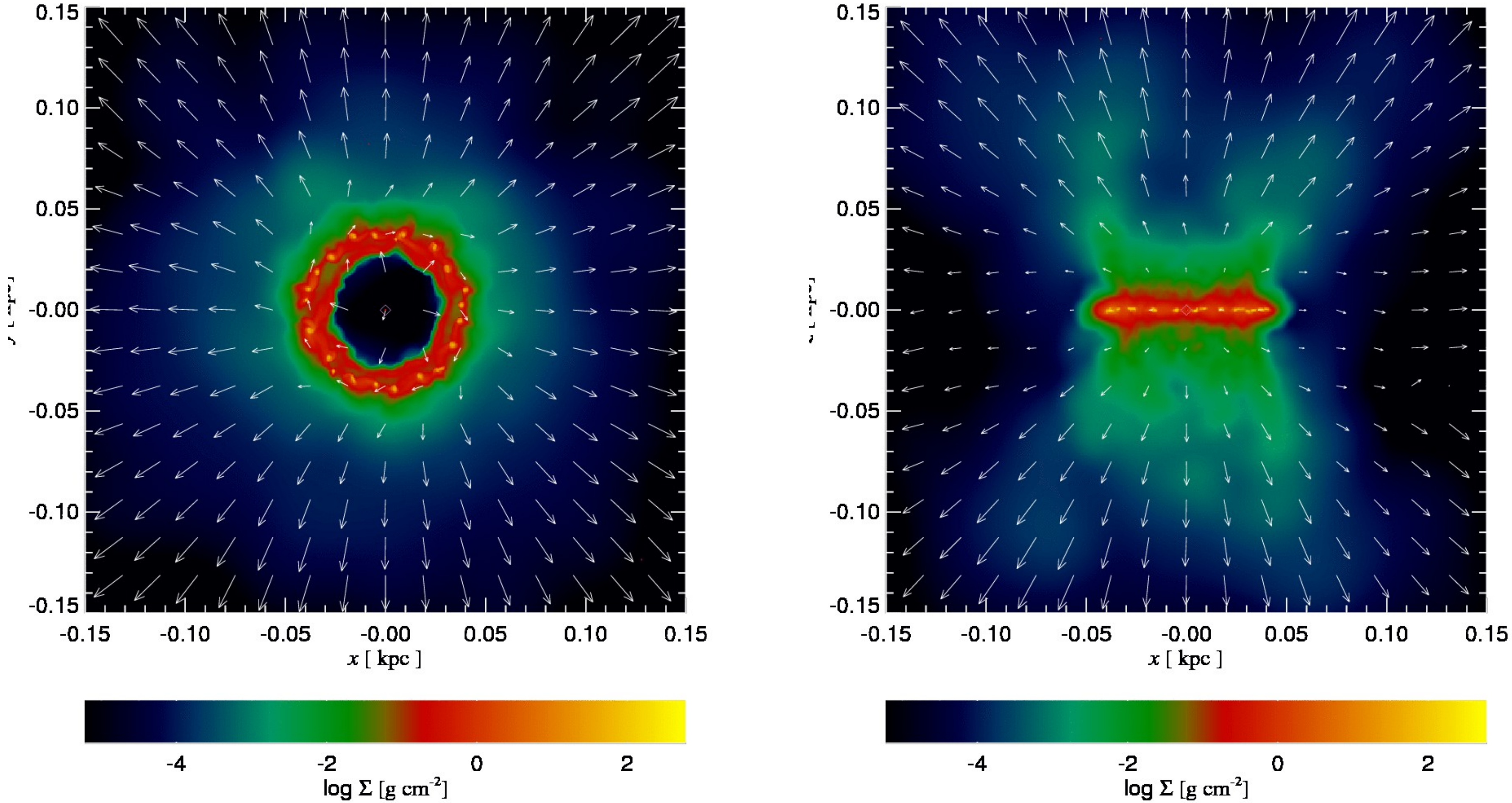
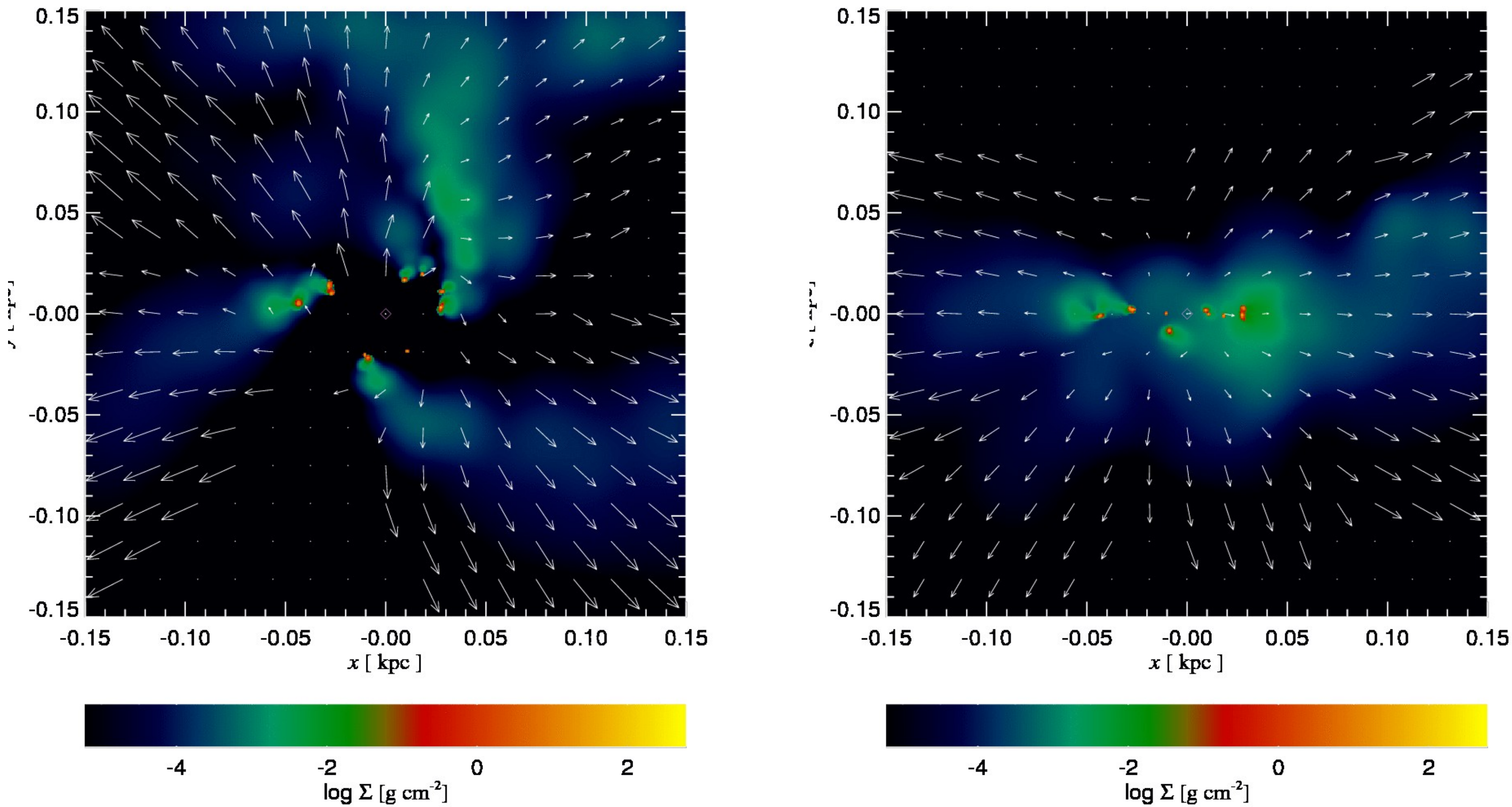
Early Times : Bondi-Hoyle



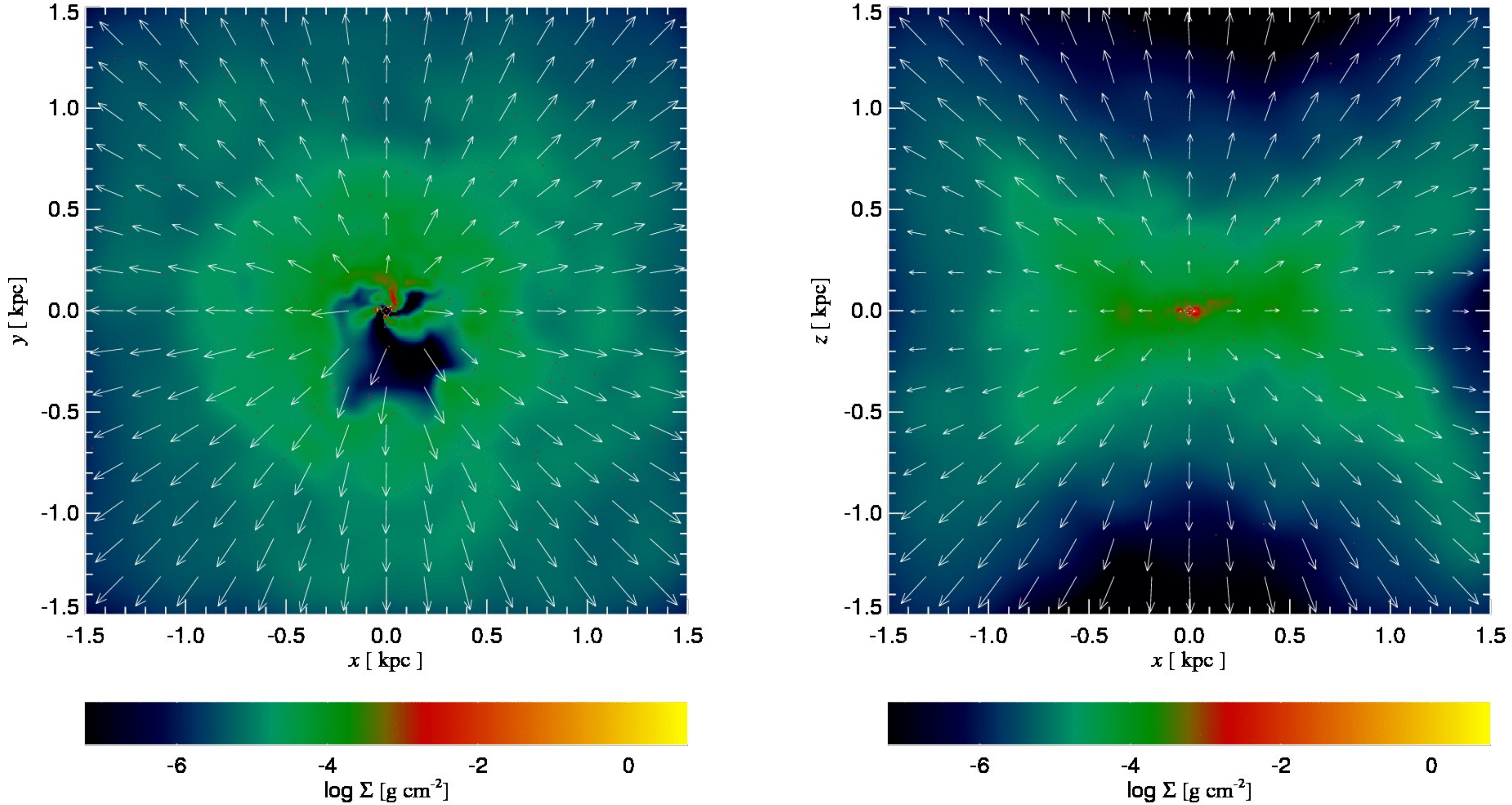
From Power, Nayakshin & King 2010

Late Times : Bondi-Hoyle



From Power, Nayakshin & King 2010

Late Times & Large Scales : Bondi-Hoyle



From Power, Nayakshin & King 2010

Stellar Feedback

Competitive Feedback

- Black holes grow on a Salpeter timescale,

$$t_{\rm Sal} = 45\,{\rm Myr}\,\left(\frac{\eta}{0.1}\right)$$

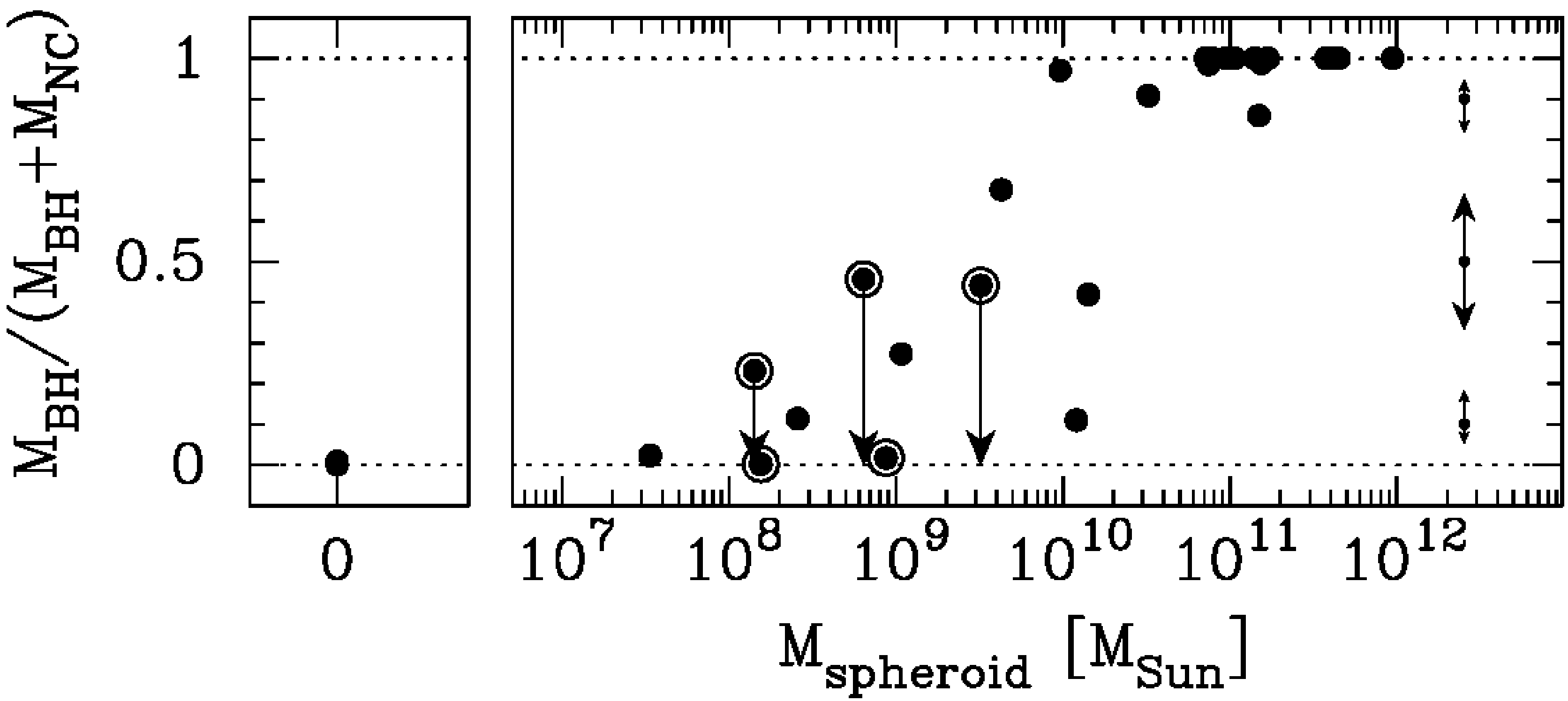
- Star form on roughly a dynamical timescale,

$$t_{\rm dyn} = 17\,{\rm Myr}\left(\frac{\sigma}{150{\rm kms}^{-1}}\right)^{2.06}$$

- The Salpeter timescale is a constant whereas the dynamical timescale is not; so in lower-σ galaxies the dynamical timescale can be much shorter than the Salpeter timescale and star formation is favoured over black hole growth.
- Feedback from young massive stars is much the same as feedack from a black hole, albeit with a lower efficiency – gas is blown away.
- Expect black holes in lower-σ galaxies to be undernourished.

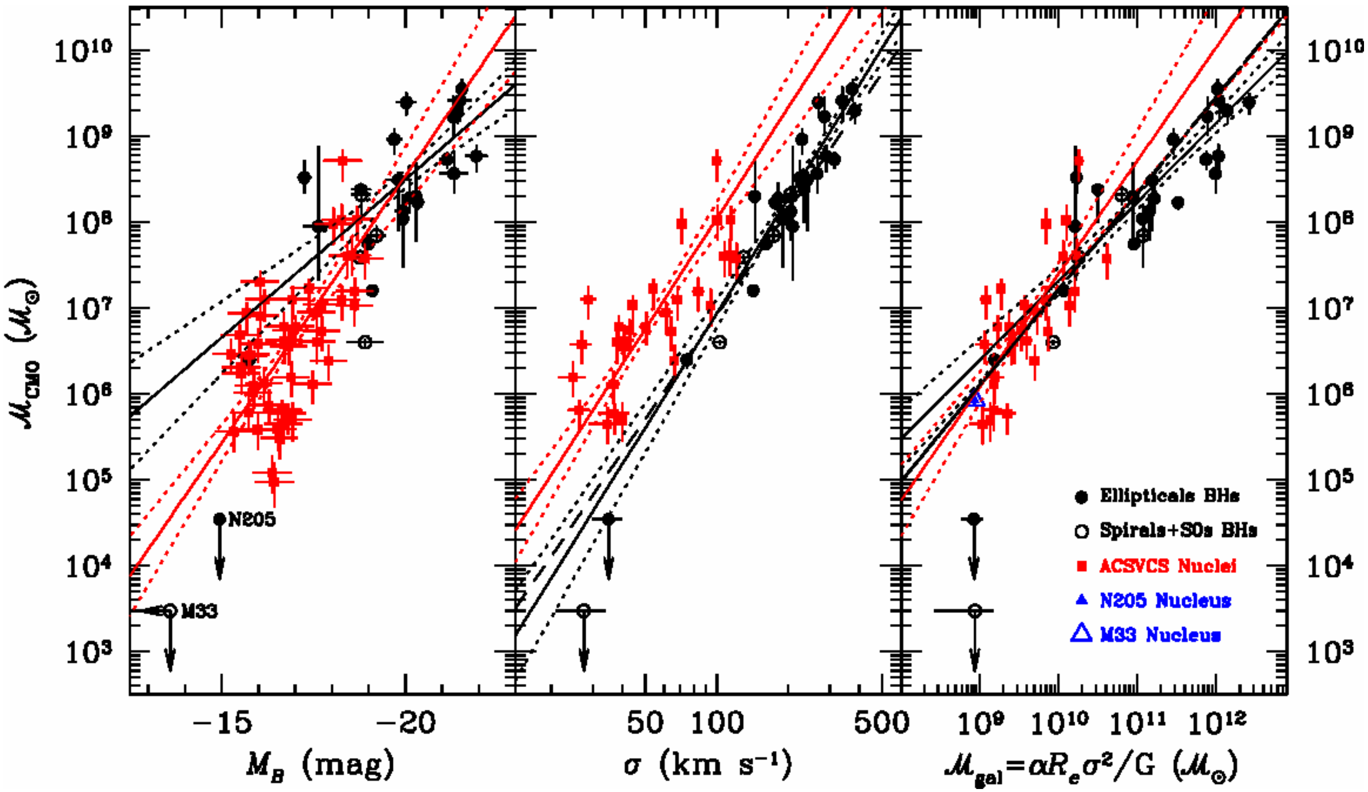
Nayakshin, Wilkinson & King 2009, MNRAS, 398, 54

Competitive Feedback in Action?



From Graham & Spitler 2009

Feedback & the M_{NC}-σ Relation



Ferrarese et al. 2006

- Young massive stars produce feedback at roughly their Eddington rate.
- Implies that a M_{NC}-σ relation should exist...

$$M_{\rm NC} = \frac{f_g \kappa}{\lambda \pi G^2} \sigma^4$$

McLaughlin, King & Nayakshin, 2006, ApJL, 650, 37

Feedback & the M_{BH}-M_{bulge} Relation

- What determines M_{bulge}? Why should $M_{BH} \sim 0.001\ M_{bulge}$?

- Look at stellar feedback from the bulge; while M_{BH} is below its characteristic M_σ value, the SMBH has little influence on its host galaxy.

- Stellar feedback limits the mass of stars that can form in situ;

$$M_{\rm bulge} < M_{\rm max} \simeq \eta M_0 \frac{\sigma}{\epsilon_* c}$$

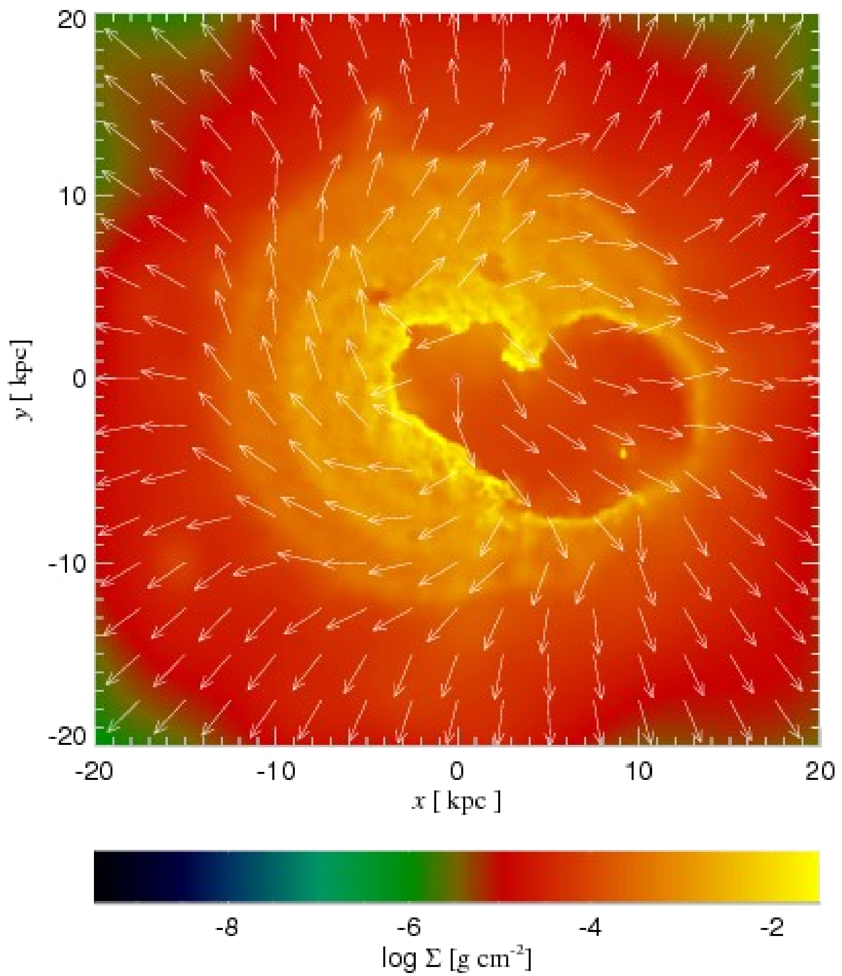
- Once the SMBH reaches its M_σ value, it can expel any remaining gas from the bulge; this gives

$$\frac{M_{\rm BH}}{M_{\rm bulge}} \sim 7.5 \times 10^{-4} \eta^{-1}$$

- Requires a feedback efficiency $\eta \sim 0.3 - 0.5$ to observational estimate ($\sim 1.6 \times 10^{-3}$) – which implies that the bulge mass cannot be limited by stellar feedback alone.

Power, Zubovas, Nayakshin & King 2010, Submitted to MNRAS

Future Work



Power, Hobbs & Read, in prep

• Simulations of competitive feedback in action; model growth of MBH, star formation and stellar feedback simultaneously.

• Galaxy merger simulations & SMBH feeding (a la Hopkins & Quataert 2009).

• Cosmological galaxy formation simulations.

What I've said...

• Developing physically motivated models for BH feeding and feedback based on a “first principles” approach.

• Momentum-driven feedback predicts a limiting BH mass in agreement with observed M-σ relation.

•Angular momentum of gas provides a natural barrier to accretion...

  - Motivation for our “accretion disc particle” method.
  - Only lowest-angular momentum can feed BH.
  - Offset in M-σ relation in systems with high angular momenta?

• Expect competition between black hole growth and star formation...

  - BHs lose out in low-mass galaxies → nuclear star clusters.
  - Expect a M-σ relation for star clusters.

• Stellar feedback important for bulge mass, but needs help from SMBH.