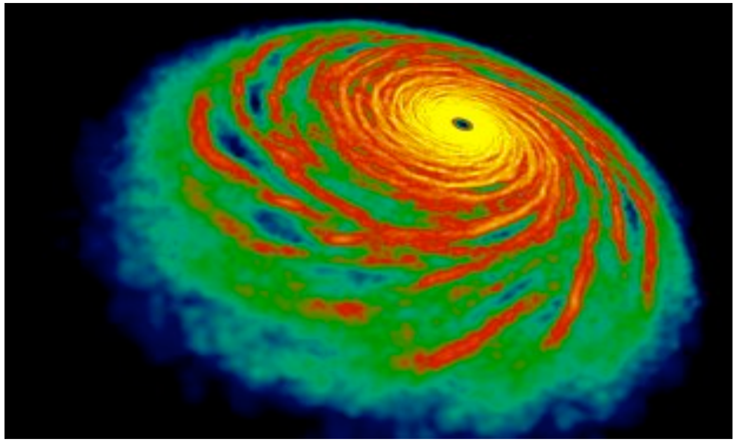
University of Leicester

Modelling AGN Feeding and Feedback
A First Principles Approach



Chris Power, University of Leicester

in collaboration with

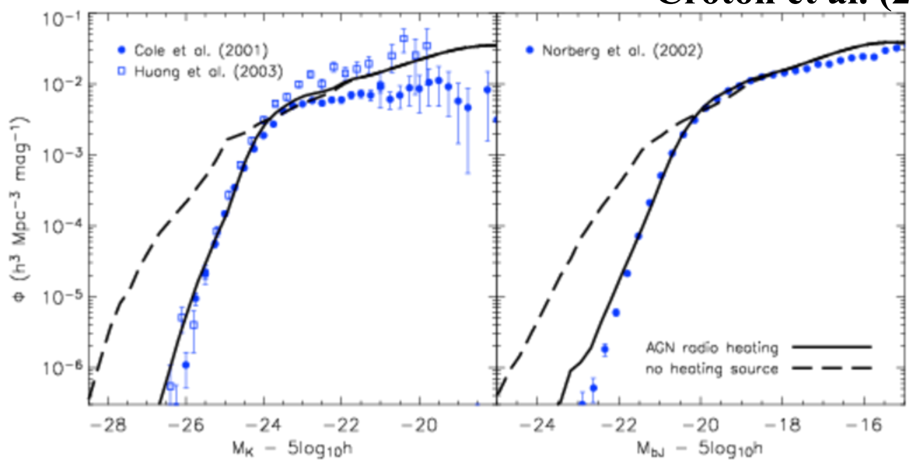
Alexander Hobbs, Andrew King, Sergei Nayakshin, Kastytis Zubovas

What I'm about to say...

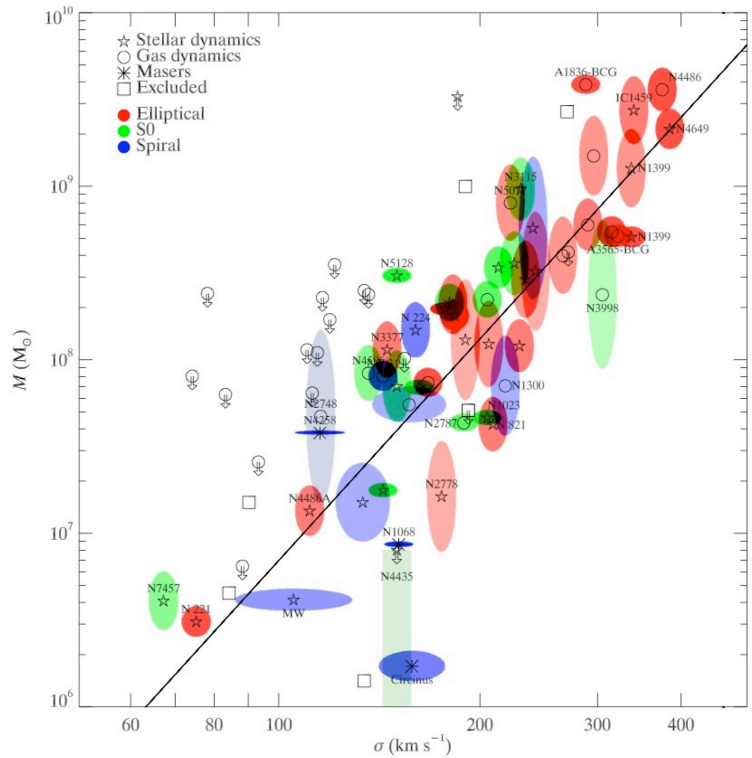
- AGN feedback must be momentum driven, at least initially...
  - Natural explanation for observed M_{BH}-σ relation.
  - Relation reflects the “limiting case”
- AGN feeding is much more challenging problem...
  - Bondi-Hoyle estimates are of limited validity.
  - Angular momentum of accretion flow is important.
- Competition between black hole growth and star formation...
  - Nuclear star clusters rather than BHs in low-mass galaxies.
  - Stellar feedback as important as AGN feedback.

Why is AGN feedback important?

Croton et al. (2006)



Gultekin 2009



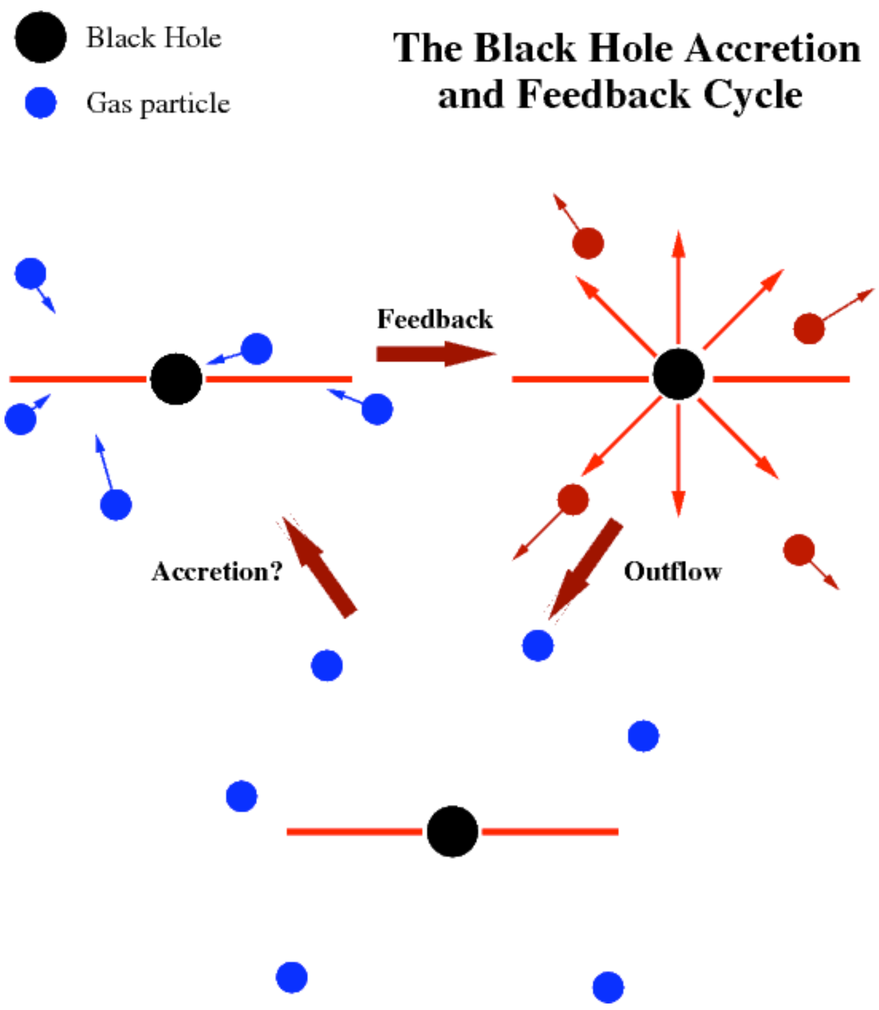
- Feedback plays a crucial role in galaxy formation and evolution.
- Accretion most efficient way to liberate rest mass energy...
- … so expect AGN to be important sources of feedback.
- Expected AGN feedback to regulate the formation of massive galaxies (e.g. Bower et al. 2006, Croton et al. 2006).
- Provides a natural explanation for the observed M-σ relation (e.g. Fabian 1999, King 2003, 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 use sub-grid models for AGN feeding and feedback.
- Variations on a theme – Bondi-Hoyle "capture" and thermal feedback (e.g. Springel et al. 2005, Booth & Schaye 2009; but see e.g. De Buhr et al. 2010)
- Reproduce, e.g, the M_{BH}-σ relation (e.g. Di Matteo et al. 2008)

BUT...

- Are sub-grid models satisfactory?
- AGN feedback is a more subtle and sophisticated process than it is generally given credit for.

Back to Basics : AGN Feedback

- Simple model : an AGN outflow sweeps up shell of ambient gas in the galaxy and drives it outwards, possibly expelling it from the potential
- Silk & Rees (1998) : energy-conserving outflow

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

- … but too efficient and unphysical – cooling will be efficient on small scales, robbing outflow of its energy.

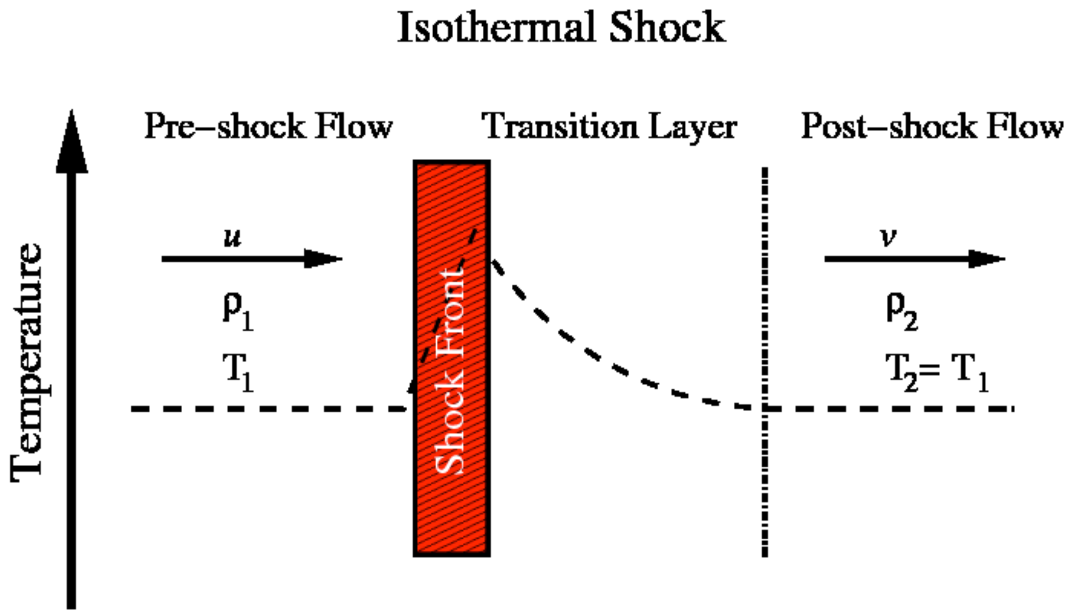
- King (2003, 2005) : momentum-conserving outflow.
- If AGN radiates at its Eddington rate, then momentum flux is

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

which implies

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

Momentum- vs Energy-Conserving Outflows



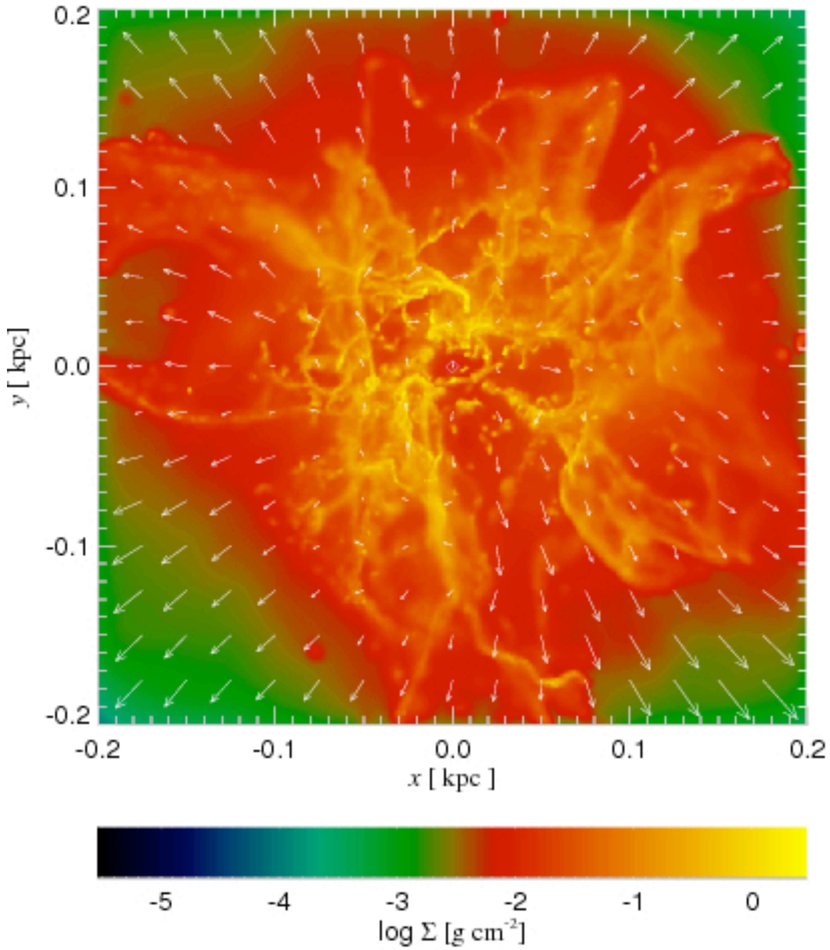
- Why is this distinction important?
- If cooling time is short, shocked gas radiates its energy away and shock is isothermal → ram pressure drives gentle expansion of shell.
- If not, shock is adiabatic → thermal pressure of shocked gas dwarfs ram pressure of outflow and accelerates expansion of the shell.
- A momentum-conserving outflow can become energy-conserving.

Momentum-Conserving AGN Feedback

- 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 ($v_{shell} >> v_{esc}$).

1. **Most luminous AGN are laggards – growing towards M_σ**
2. **M_σ is a limiting mass, reflecting depth of potential well; M_{BH}-σ points can lie below the relation, but not too much above it.**

Numerical Models of AGN Feedback

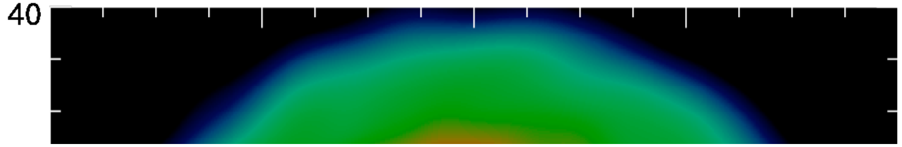


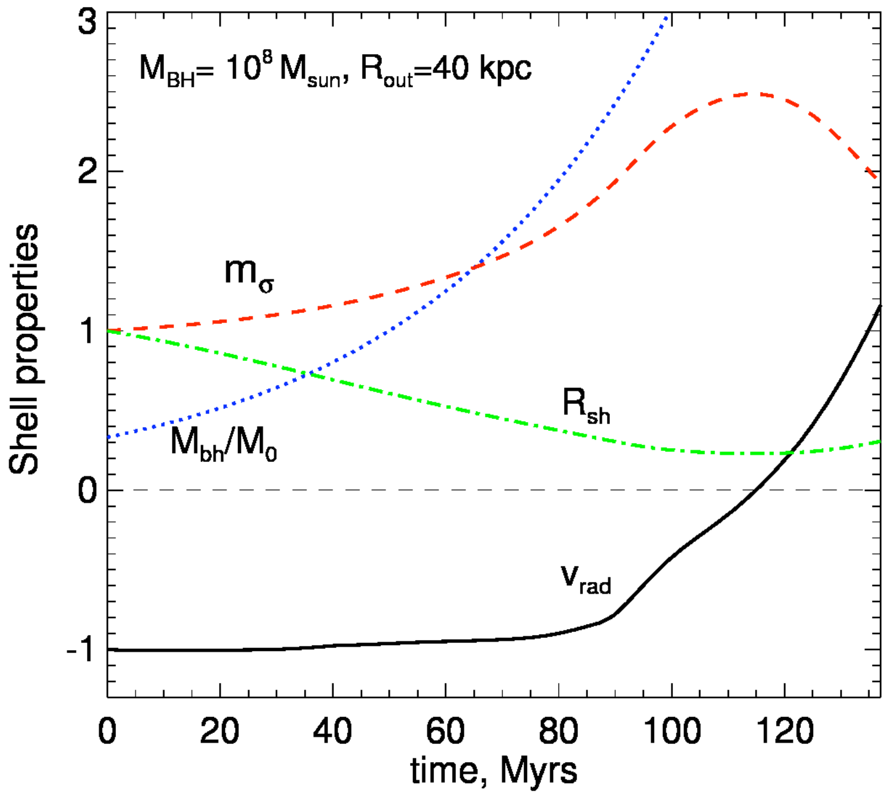
From Power & Nayakshin, in prep

- Monte Carlo Radiation Hydrodynamics in GADGET.
- Use in single-scattering limit to model AGN wind.
- Develop simple theoretical framework using toy models, then apply to more complicated situations.

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

Numerical Model of BH Outflows



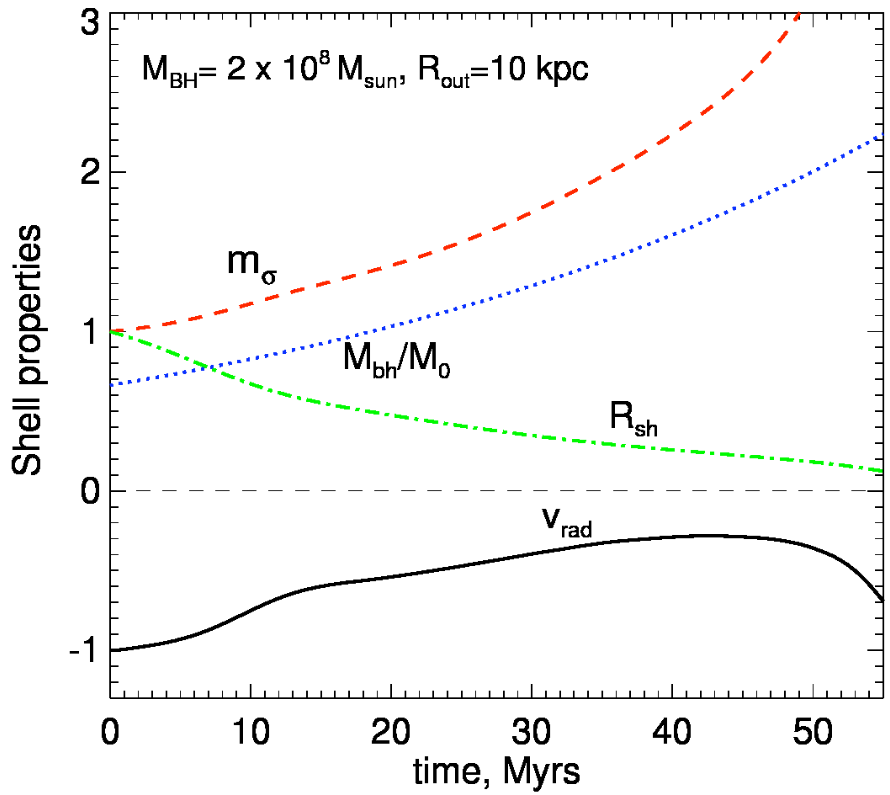


log Σ [g cm^{-2}]

- Look at spherically symmetric shells of gas falling onto a central BH in an isothermal potential.
- BH is growing and radiating at its Eddington limit.
- 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…
- … but how do we feed the BH?

From Nayakshin & Power 2010

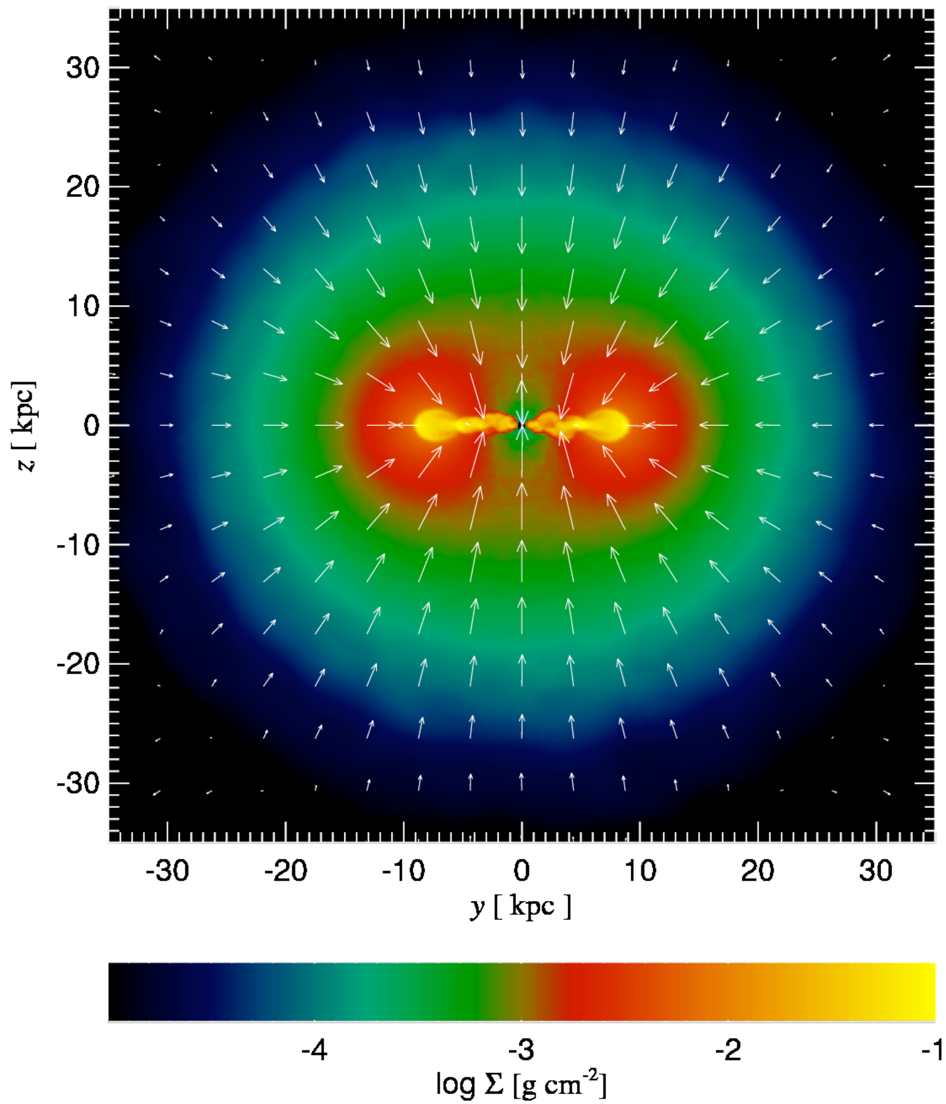
When Feedback Fails... I



- 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 2010

When Feedback Fails... II



From Nayakshin & Power 2010

- 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.

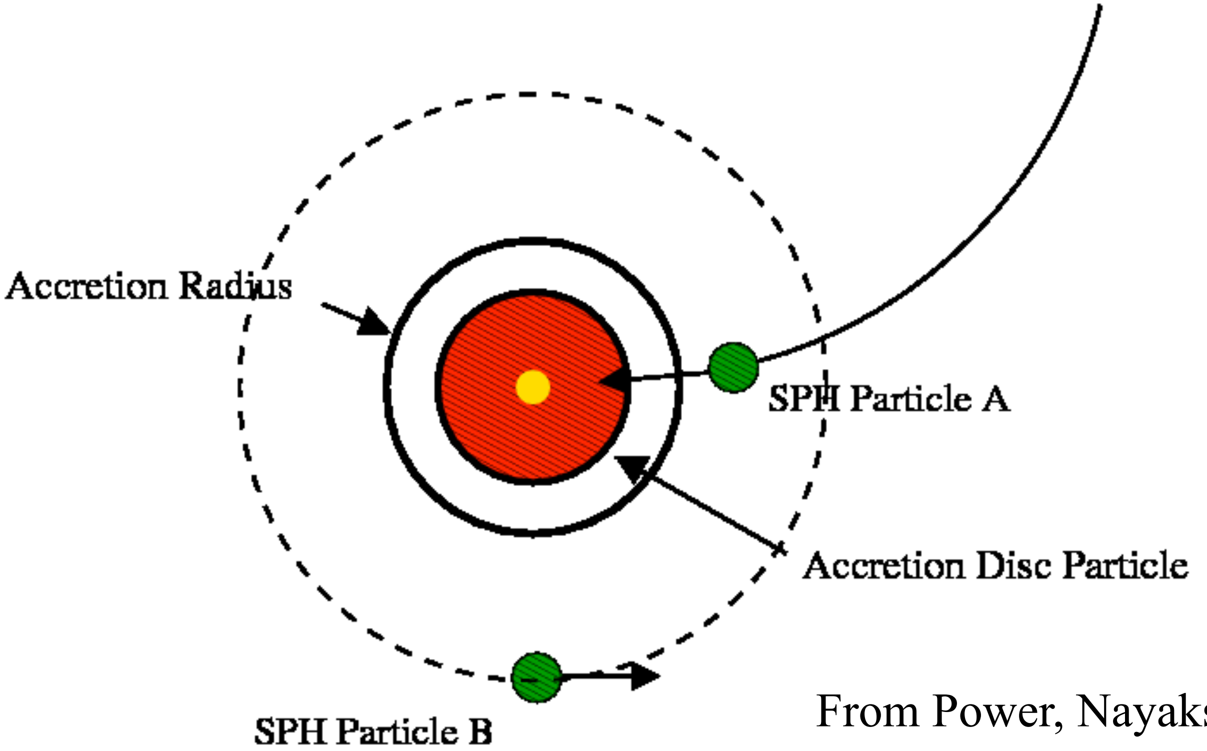
Modelling AGN Feeding

- 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)
- 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)

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

- **<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

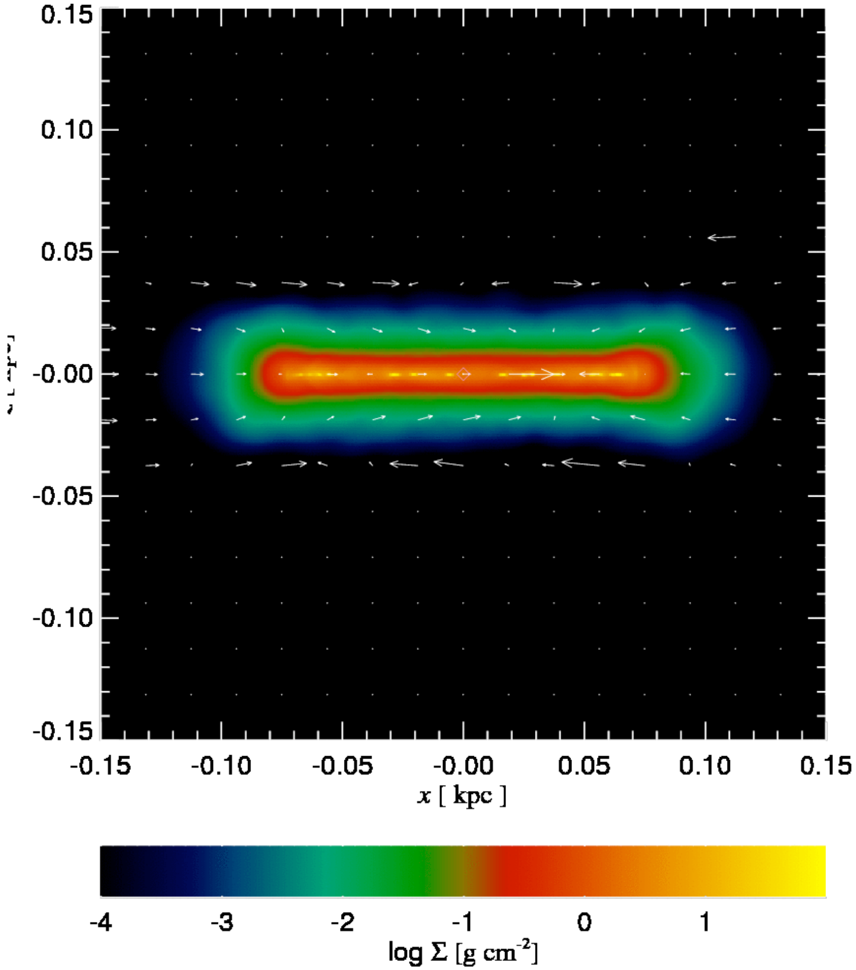


From Power, Nayakshin & King 2010

- 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

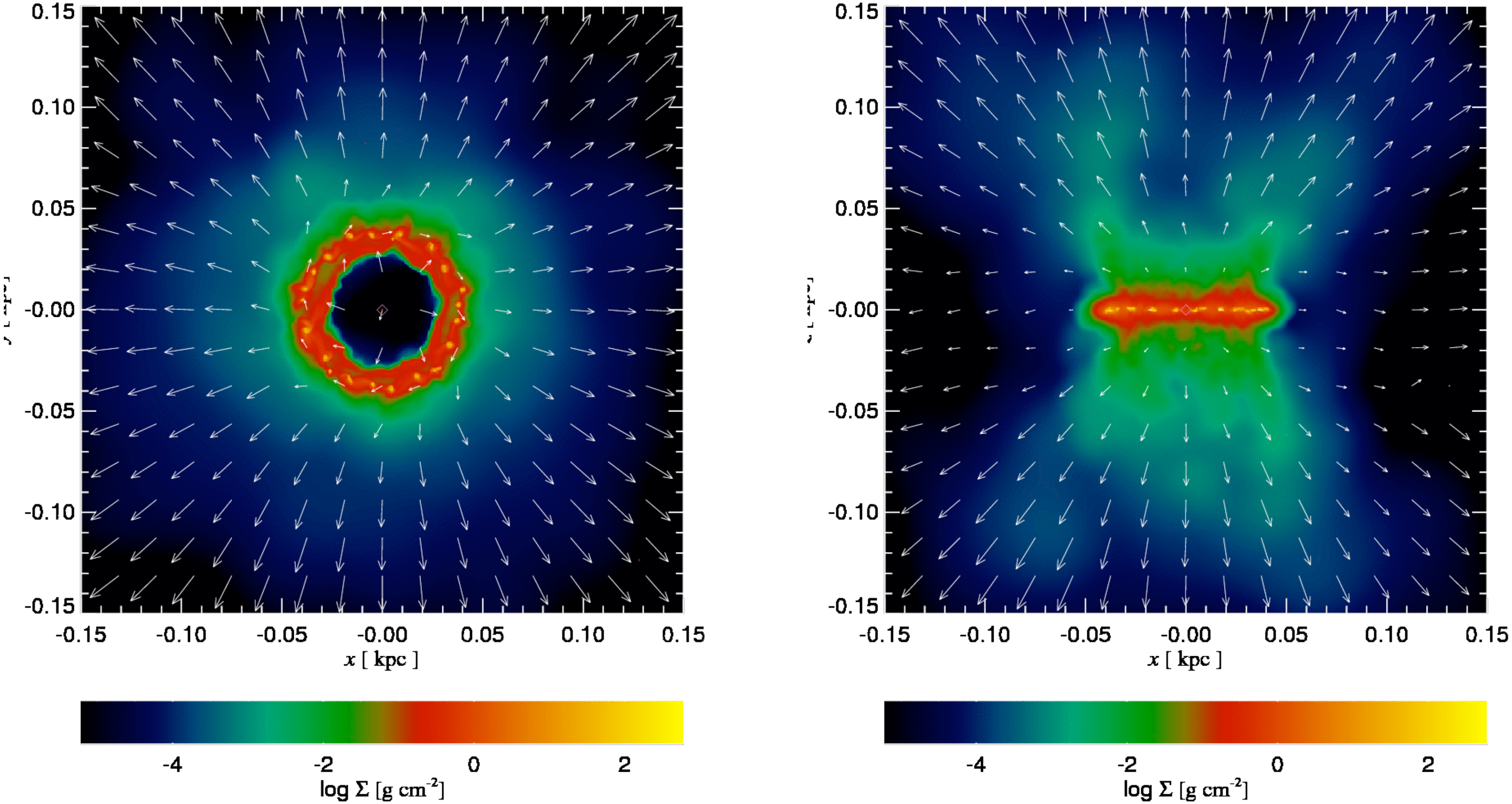
Angular Momentum is Important



From Power, Nayakshin & King 2010

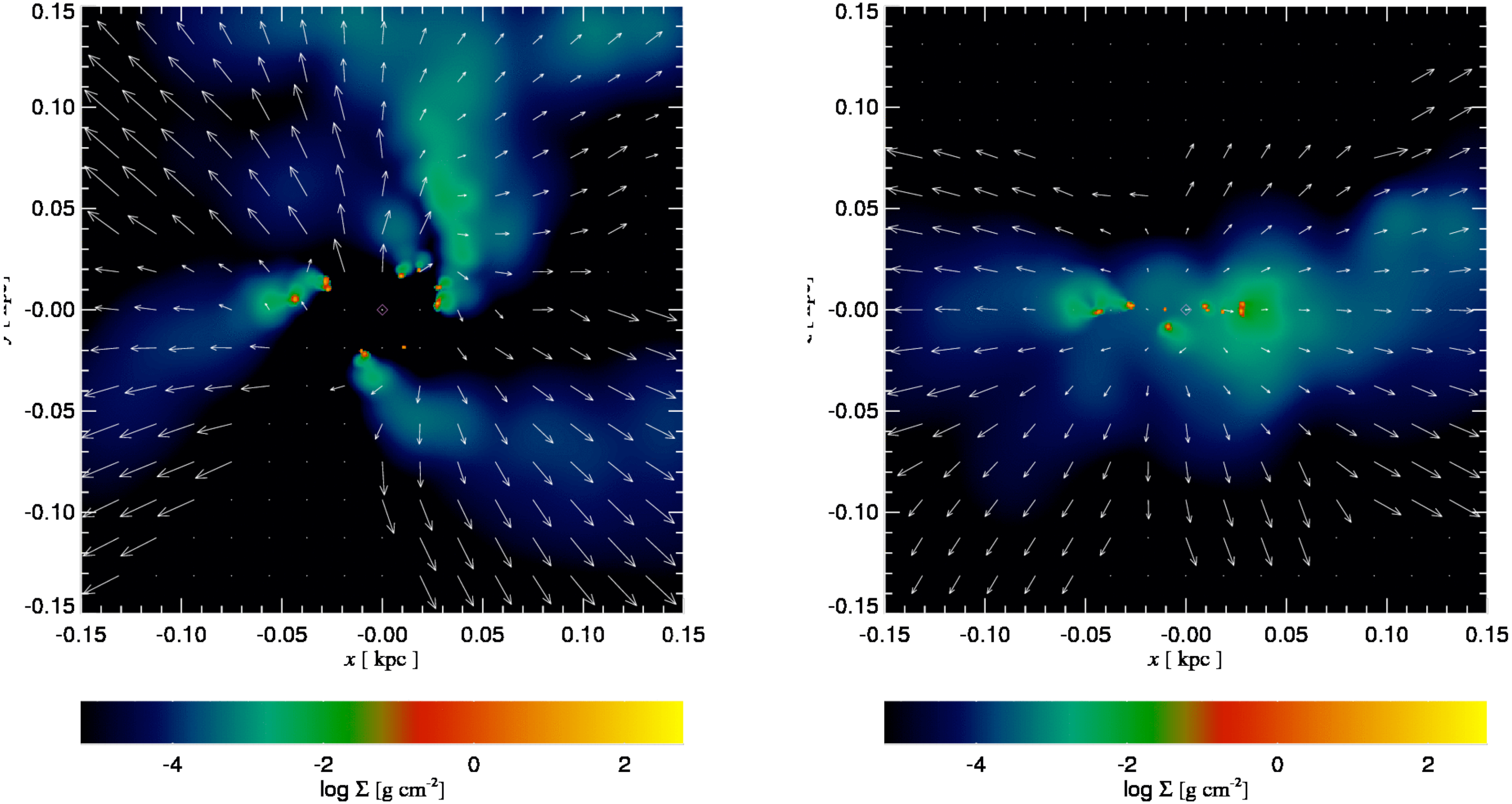
- Compare ADP and Bondi-Hoyle capture estimates.
- Simple example : rotating shell of gas in isothermal potential with a SMBH embedded in the centre.
- Gas should settle into a thin rotationally supported disc in absence of any feedback.
- Choose $M_{BH} \sim 10^6 M_\odot$.
- Feedback modelled as momentum-conserving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

Early Times : Bondi-Hoyle



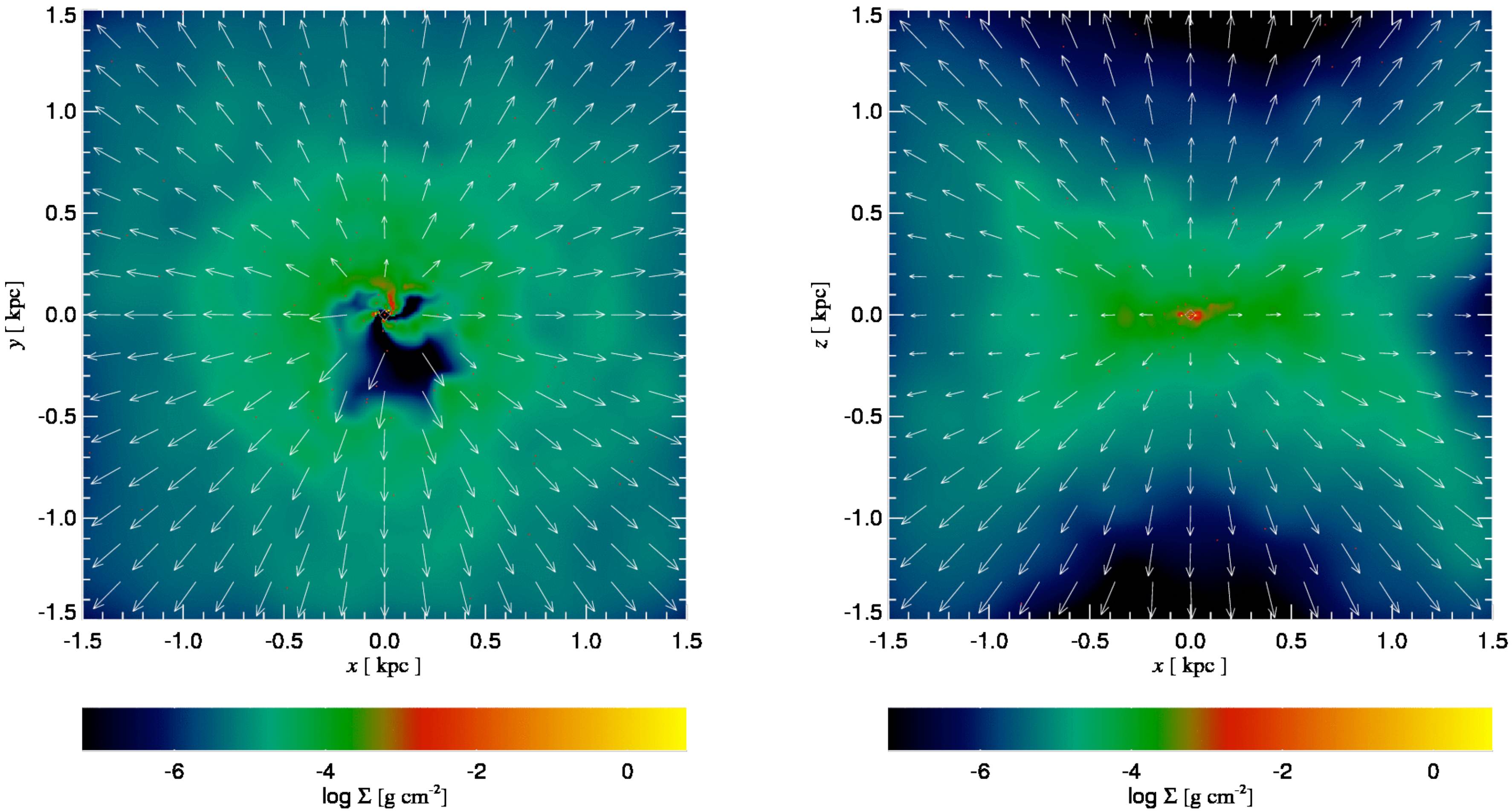
From Power, Nayakshin & King 2010

Late Times : Bondi-Hoyle



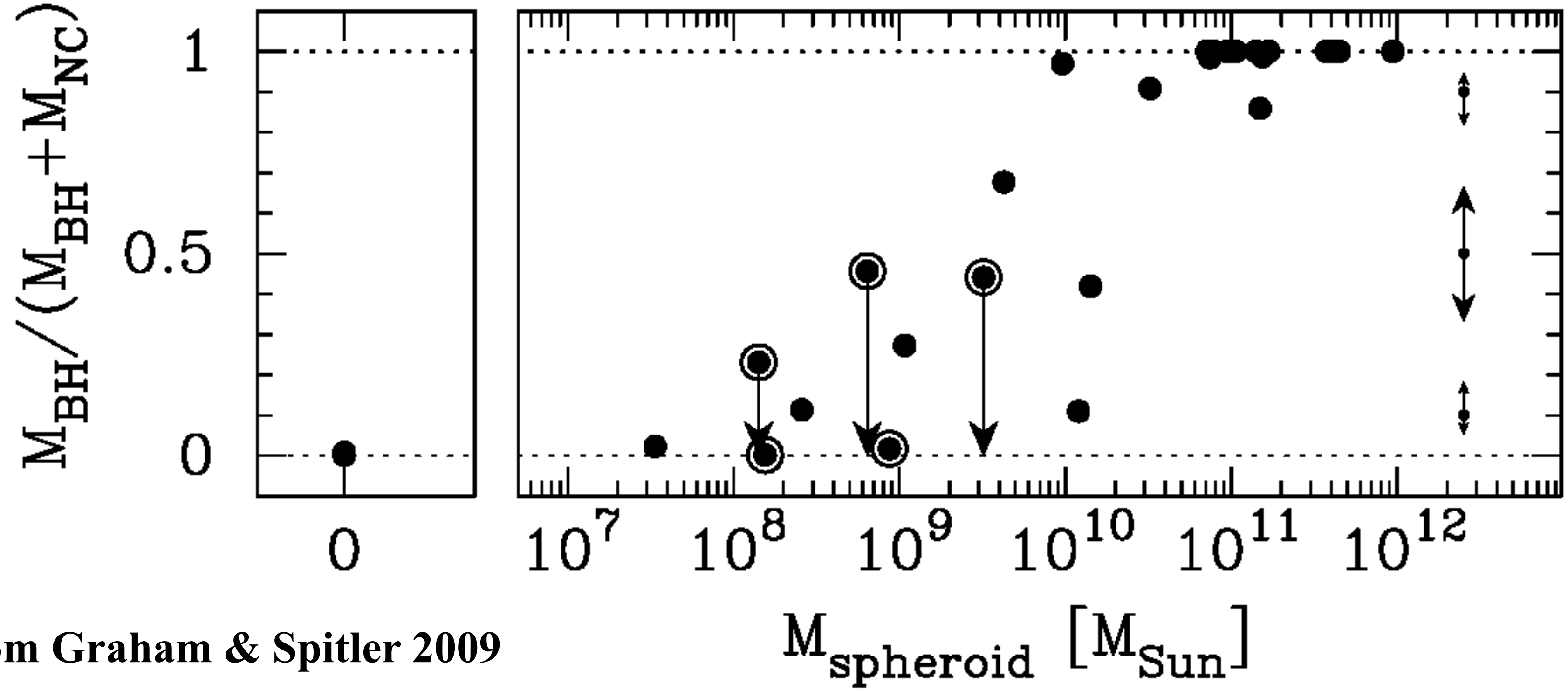
From Power, Nayakshin & King 2010

Late Times & Large Scales : Bondi-Hoyle



From Power, Nayakshin & King 2010

Competitive Feedback



From Graham & Spitler 2009

- BHs grow on a fixed Salpeter timescale, but stars form on roughly a dynamical timescale.
- Expect BHs in lower-σ galaxies to be undernourished.

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

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  - Stellar feedback as important as AGN feedback.

- **Go and look at Alexander Hobbs' poster (Board #4)!**

The Fate of the Galaxy

David Cole, Alexander Hobbs, Chris Nixon, Chris Power, Justin Read