Black Hole Feedback

A theoretical perspective

what this talk is about

- Why does the Universe need black holes?
  – The galaxy stellar mass function
  – (the lack of) X-ray emission from groups and clusters
- Why do theorists like black holes?
- Black hole feedback in semi-analytic models
  – Two "modes" for BH feedback?
- Black hole feedback in hydro-dynamic simulations
  – The EAGLE project : the answer to everything?

"Micro-physics" vs "Macro-physics"

- Hydrodynamic simulation
  - You know the equations, so solve them
    - SPH
    - AMR
  - Add cooling, star formation, supernovae, black holes (accretion + feedback)

$$\rho_i = \sum m_j W(r_{ij}, h)$$

$$P_i = K_i \rho_i^{\gamma}$$

$$\left.\frac{dv_i}{dt}\right|_{hydro} = -\sum m_j \left[\frac{P_i}{\rho_i^2} \nabla W_{ij}(h_i) + \frac{P_j}{\rho_j^2} \nabla W_{ij}(h_j) \right]$$

$$\left.\frac{dv_i}{dt}\right|_{visc} = -\sum m_j \Pi_{ij} v_{ij} \quad \text{where } \Pi_{ij} \text{ is a viscosity}$$

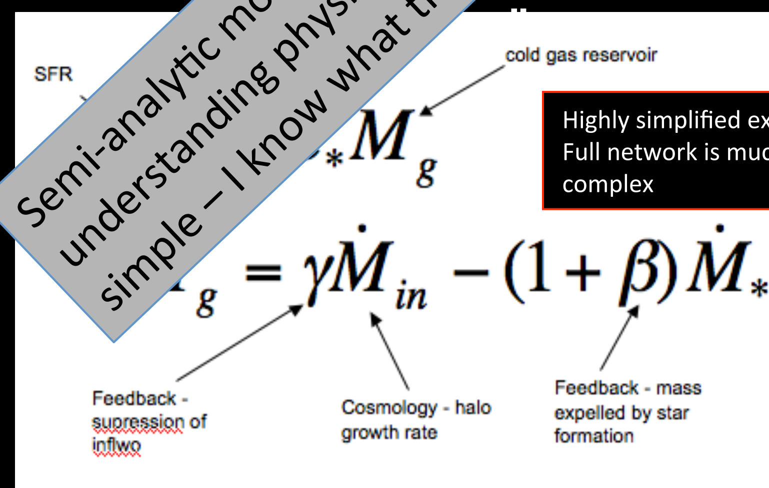
$$P_{visc} \approx \tfrac{1}{2} \rho^2 \Pi_{ij}$$

$$\frac{dK_i}{dt} = \frac{1}{2} \frac{\gamma - 1}{\rho_i^{\gamma-1}} \sum m_j \Pi_{ij} (v_{ij} \cdot \nabla W_{ij})$$

oo

Part I

- "Semi-analytic" mod
  - Follow the spir ... al papers…
  - Reduce t ... a coupl ... linear diff ... tions



Highly simplified example.. Full network is much more complex

Semi-analytic models are great for understanding physics.. Galaxy formation is simple – I know what the equations are!

White & Frenk 1991; Kaufmann et al. 1994; Cole et al 1996,2000; back-of-the-envelope model: Dave et al 2012

"Micro-physics" vs "Macro-physics"

Part II

- Hydrodynamic simul...
  – You know the e... solve them
    - SPH
    - AM...
  – Ad... ...on, ...s ...ck)

Galaxies is represented by 1000s of particles, we are solving fundamental physics equations. Uncertainties arise because of finite resolution – but the "sub-grid" models (in EAGLE) have solid mathematical motivation (Schaye etal 2014).

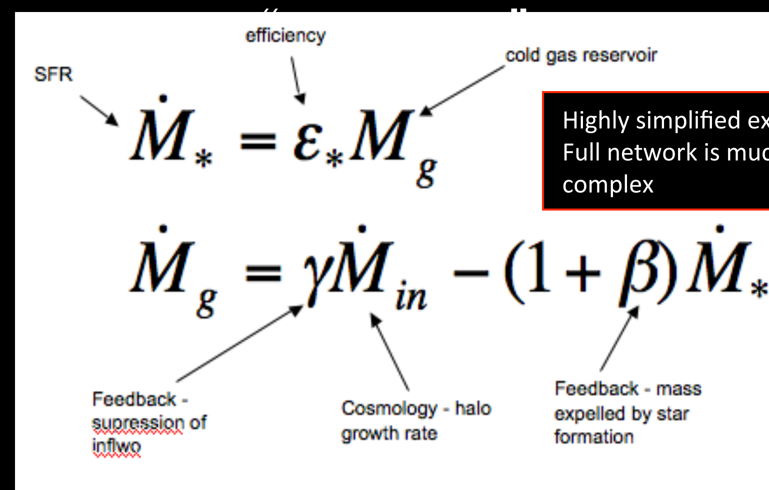
$$\left[\frac{P_i}{\rho_i^2}\nabla W_{ij}(h_i)+\frac{P_j}{\rho_j^2}\nabla W_{ij}(h_j)\right]$$

$\sum m_j \Pi_{ij} v_{ij}$ where Π_{ij} is a viscosity

$$P_{visc} \approx \tfrac{1}{2}\rho^2\Pi_{ij}$$

$$\frac{dK_i}{dt} = \frac{1}{2}\frac{\gamma-1}{\rho_i^{\gamma-1}}\sum m_j \Pi_{ij}(v_{ij}\cdot\nabla W_{ij})$$

- "Semi-analytic" model
  – Follow the spirit of the original papers...
  – Reduce the problem to a coupled set of non-linear differential equations



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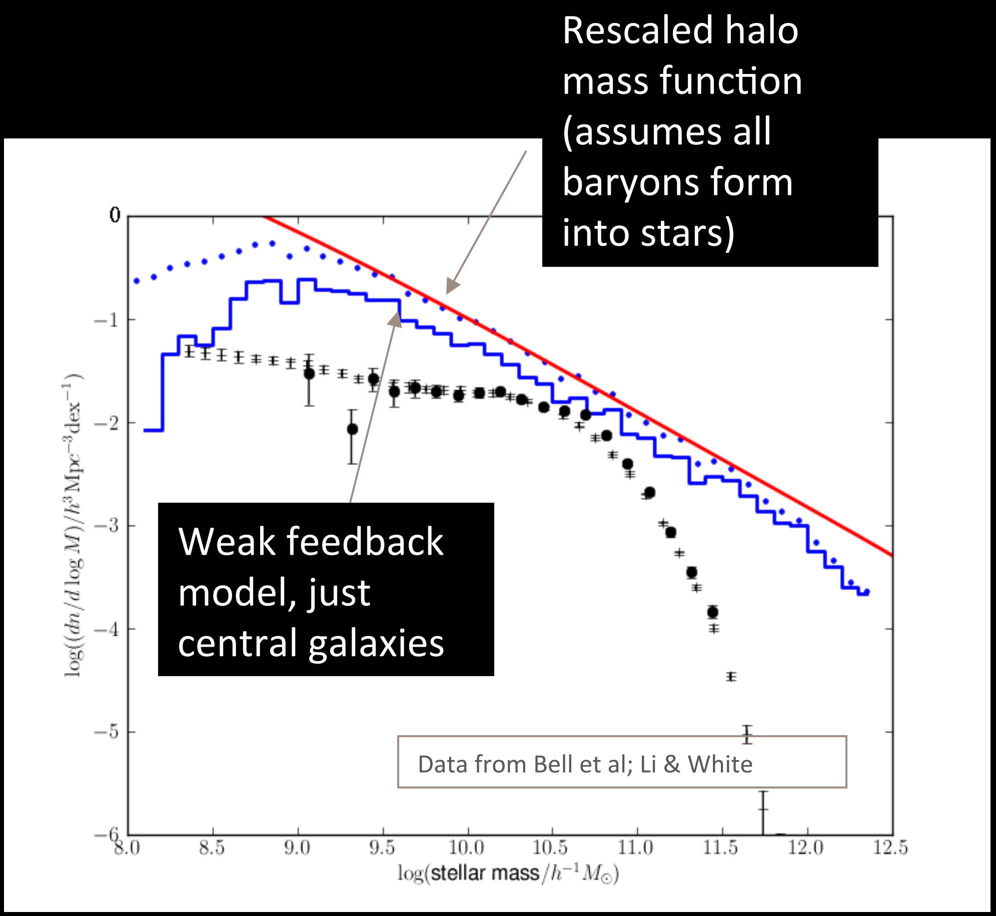
Why the Universe needs black holes…

Galaxy Formation- a quick overview

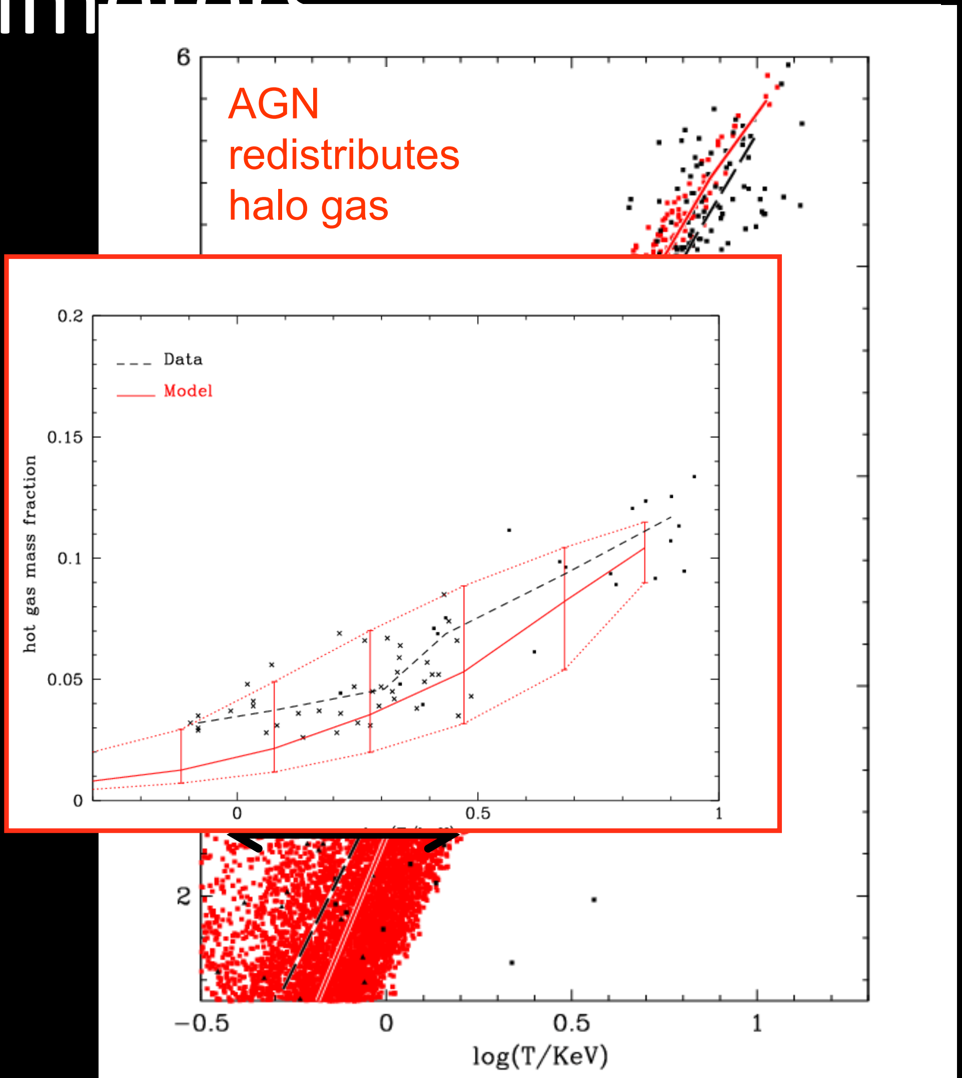
- The dark matter halo mass function has little to do with the galaxy stellar mass function
  - Low mass galaxies are much less abundant that low mass haloes.
    - Gas is efficiently blown out of low mass galaxies
    - …by supernovae
  - Exponential cut-off in the galaxy mass fn is not present in the halo mass function.
    - Requires some extra suppression mechanism in haloes with long cooling times
    - …by black holes (?)



Benson et al 2003

Groups and Clusters as Cosmic calorimeters

- The "flipside" of galaxy formation
- Investigating the X-ray emission from galaxy groups shows that most of their baryons are missing.
- Another reason to love black hole feedback

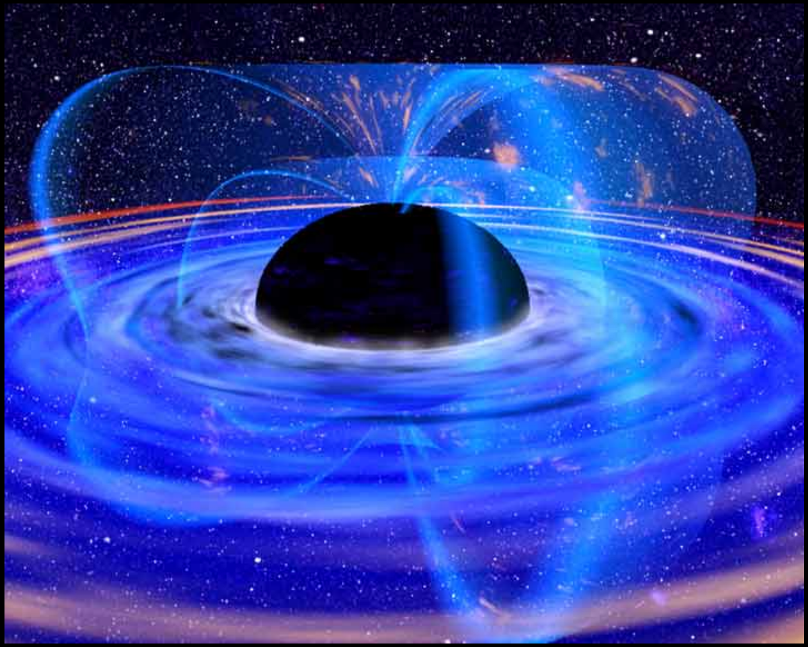


Bower etal 2008

Why theorists like black holes…

Black holes – the ultimate energy source

- Black holes are extremely efficient energy sources
- ~ 10% of rest mass converted to energy
- The huge energy of black hole formation
  - 10^9 black hole releases more than the total thermal energy of a galaxy group
  - But is this radiated away? Or effectively coupled to the surrounding gas?
- Physics is poorly understood???
  - AGN feedback = "anything goes now"



Comparison of energies:

Thermal energy of a 10^{13} M_o halo
… 10^{61} erg

Accretion energy of a 10^{9} M_o black hole
… 2×10^{62} erg

Black hole feedback in “semi-analytic” models

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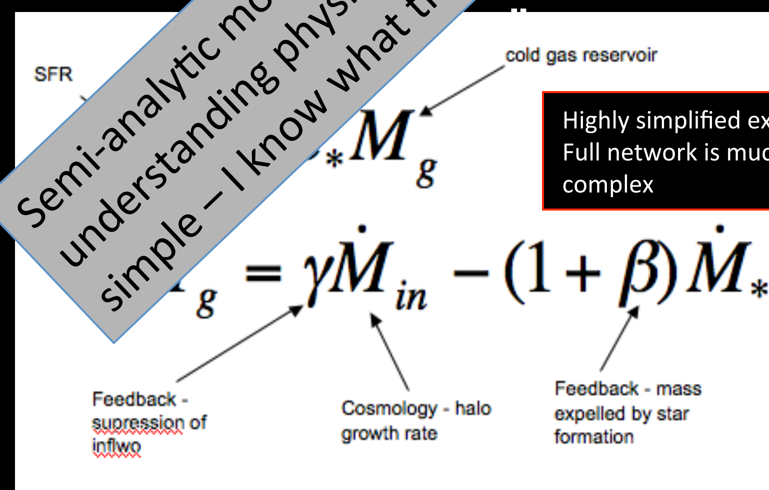

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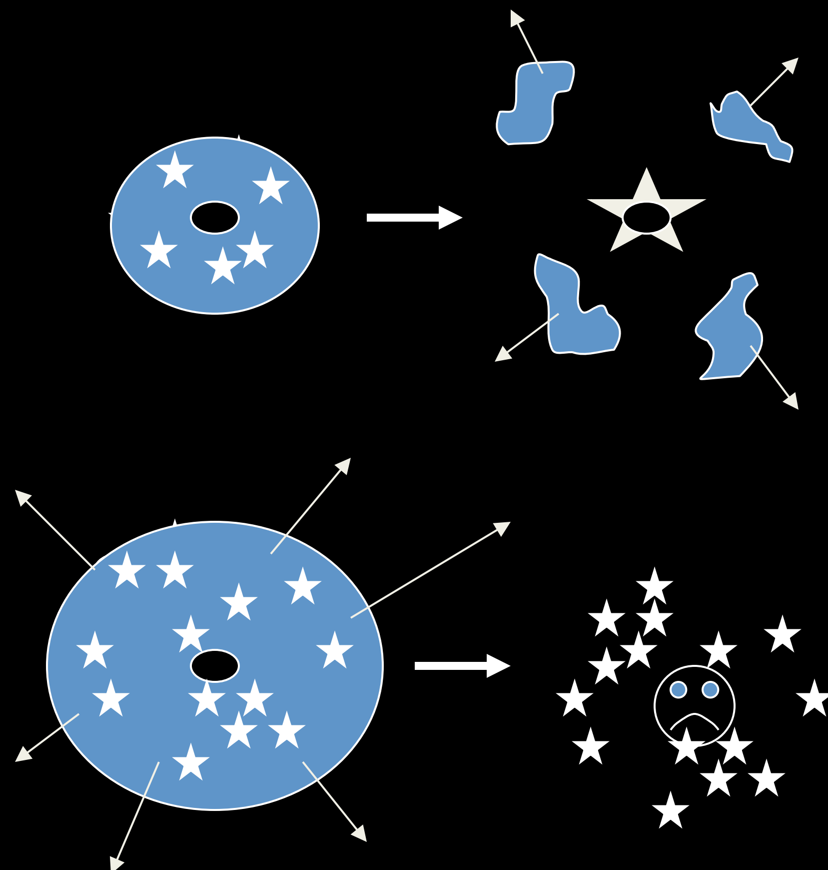
The black-hole - galaxy bulge correlation

- Does black hole formation truncate the formation of the bulge?
- Does bulge formation stimulate fuelling of the black hole?
- Is it simply the central limit theorem?

Does this matter?



What observations can distinguish these?

The black-hole - galaxy bulge correlation

- What triggers the growth of the black hole?
  - Mergers?

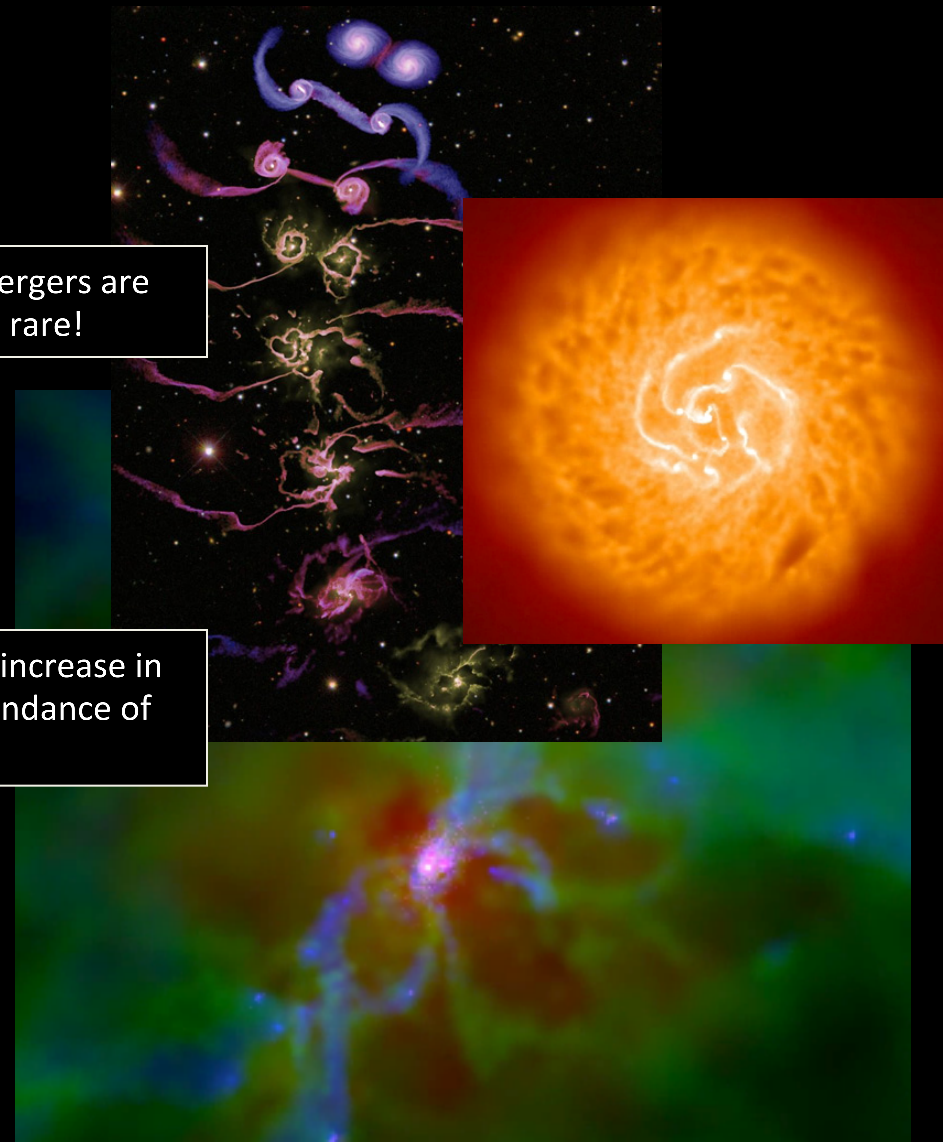
WINNER!

  - Disk instabilities?
  - "cold flows"

But mergers are rather rare!

Fits in with increase in the gas abundance of galaxies

Eh?



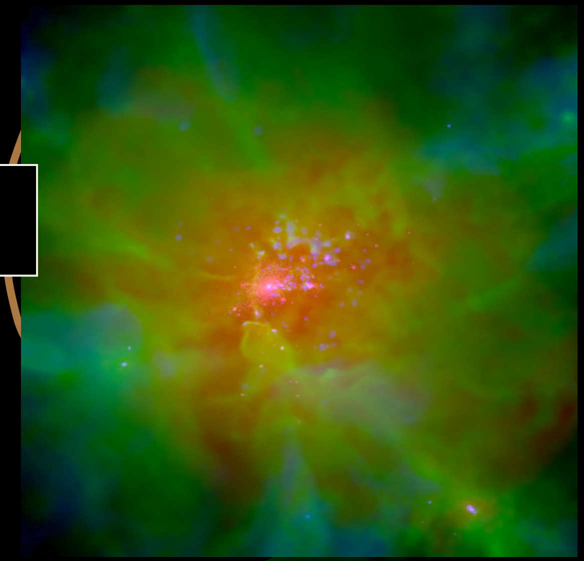
Springel Di Matteo et al; RGB 06; White & Frenk 91 /Keres 2003

The break in the stellar mass function

- What sets the cut-off scale?
  - Rapid cooling or hydrostatic halo cooling?
  - The mode of black hole fuelling: accretion disk or Bondi?

Nothing to do with black holes!

SS vs ADAF disk accretion?



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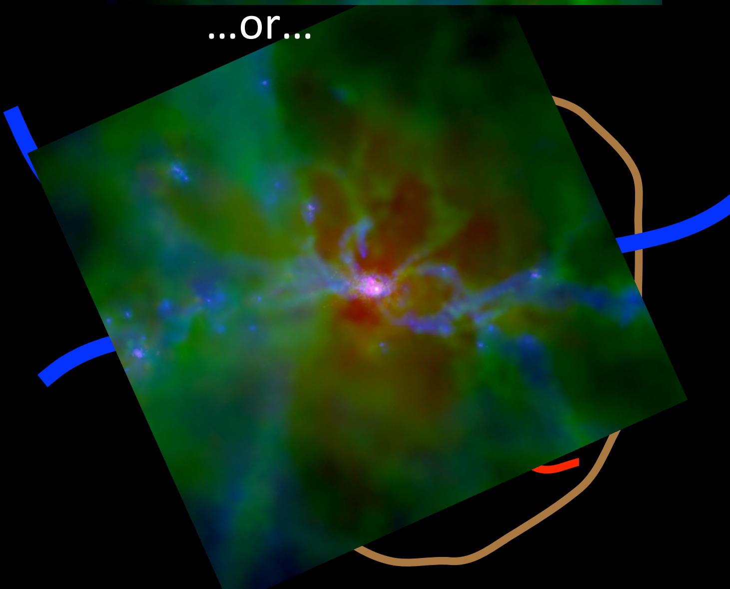

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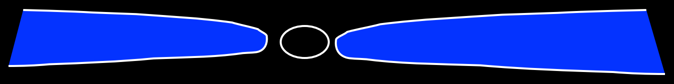

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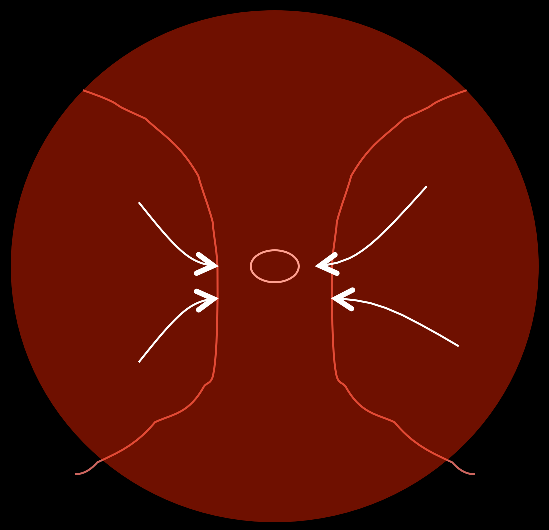
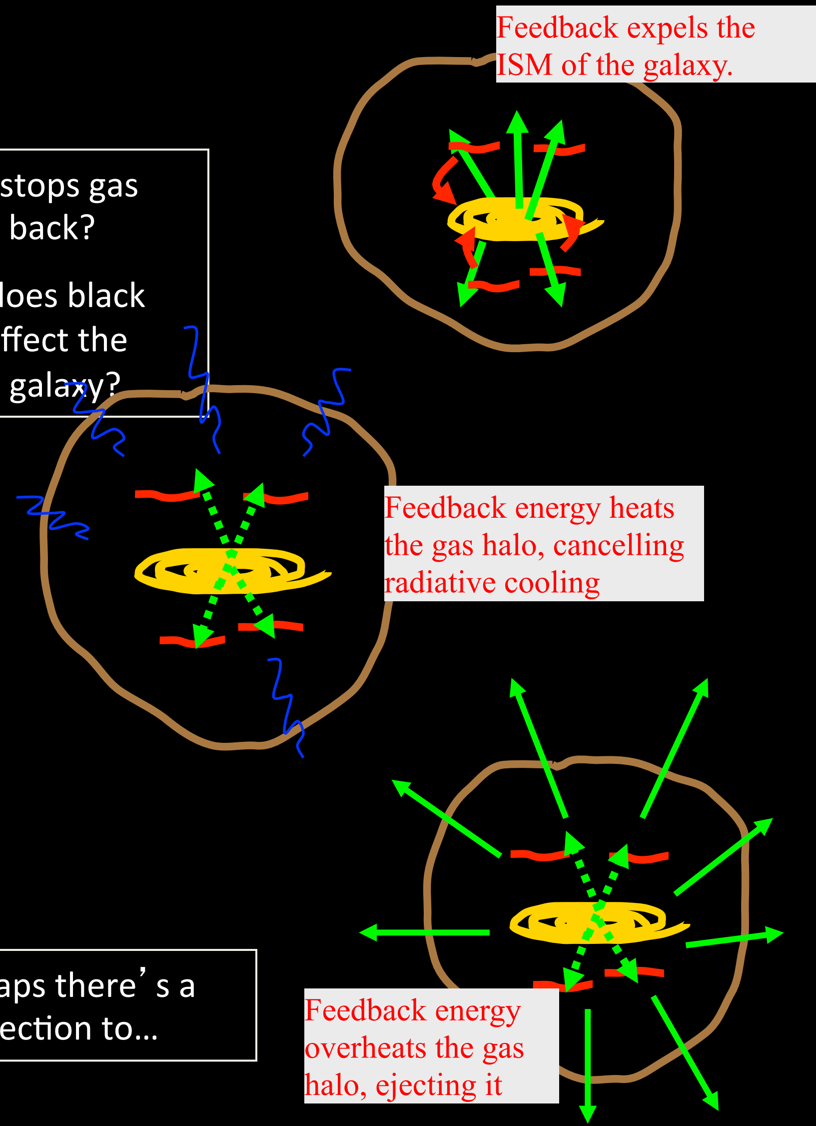


The break in the stellar mass function

- How does the black hole feedback create the break?
  - Expelling the ISM from the galaxy?
  - Heating the surrounding gas?
  - Expelling the surrounding IGrM from the halo?

What stops gas falling back?

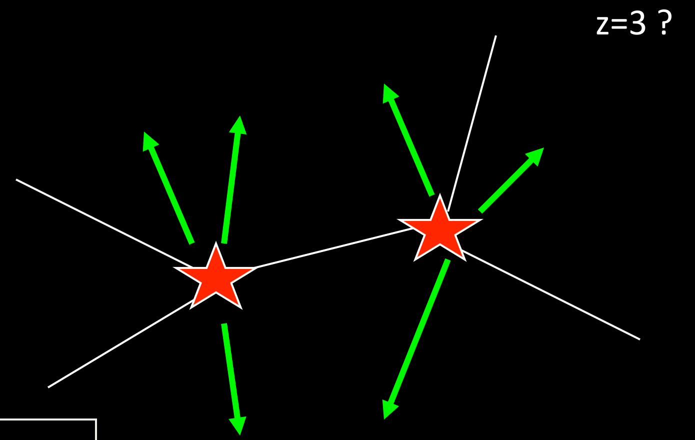
Why does black hole affect the whole galaxy?



Perhaps there’s a connection to…

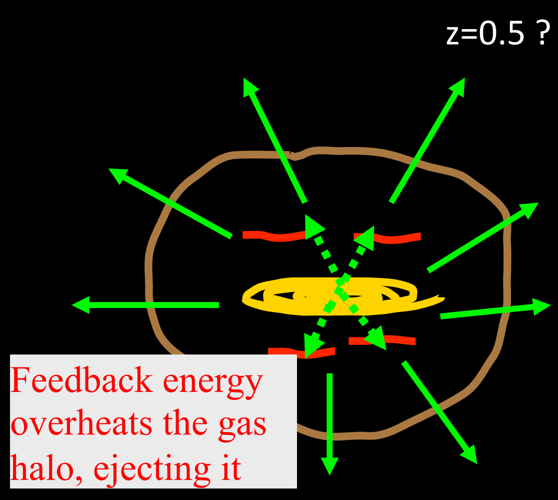
The X-ray scaling relations of galaxy groups

- What causes the low L_x of galaxy groups?
  - Gas converted to stars
  - Gas expelled at early times
  - Gas heated as the halo grows



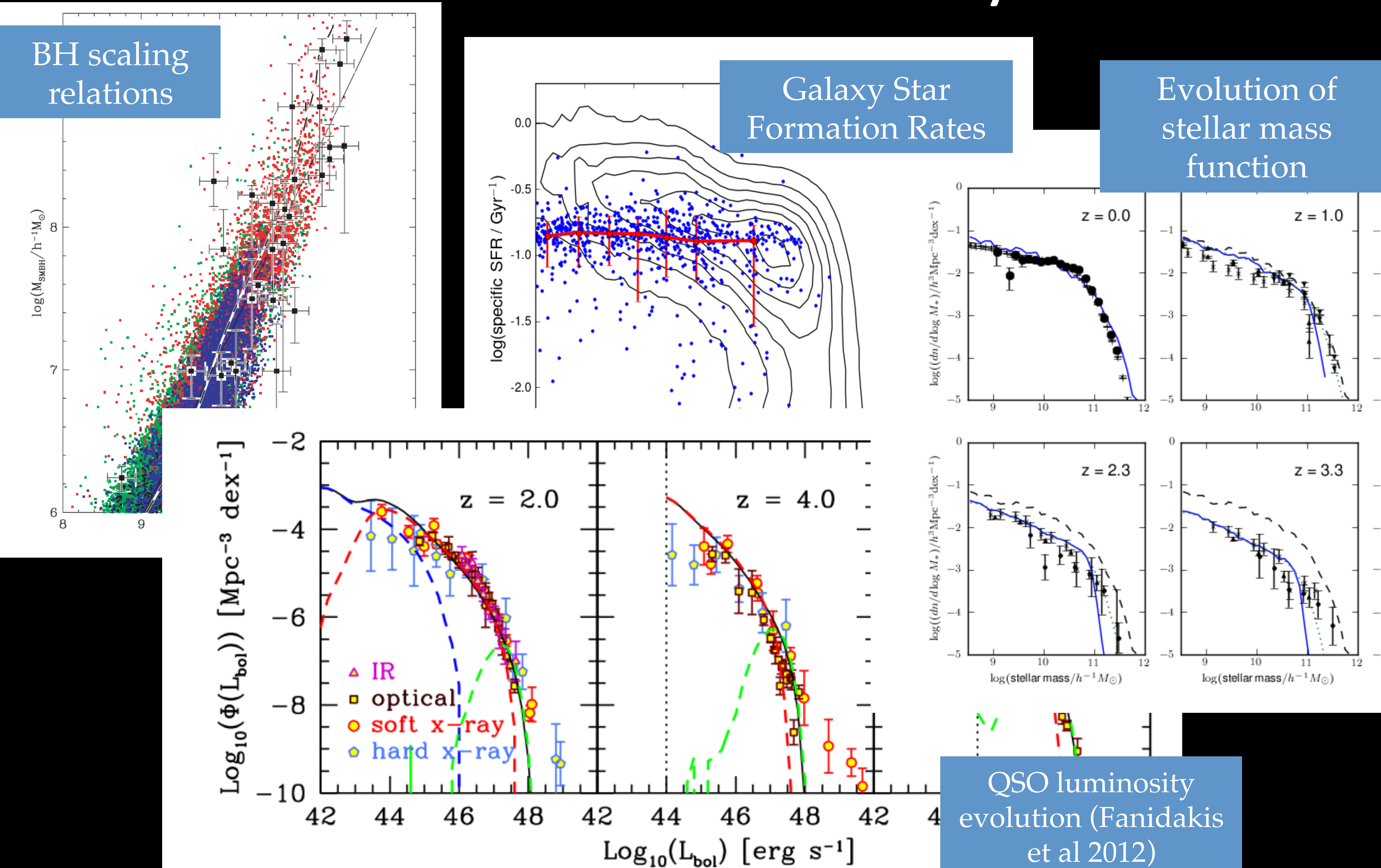
By Quasars?

...or...



By radio galaxies?

Some successes for semi-analytic models



Bower et al. (2006; 2008; 2012) (see also Croton et al. 2006; De Lucia & Blaizot 2007; Somerville et al. 09)

Black holes in hydrodynamic simulations

Part II

- Hydrodynamic simul…
  - You know the e… solve them
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…o

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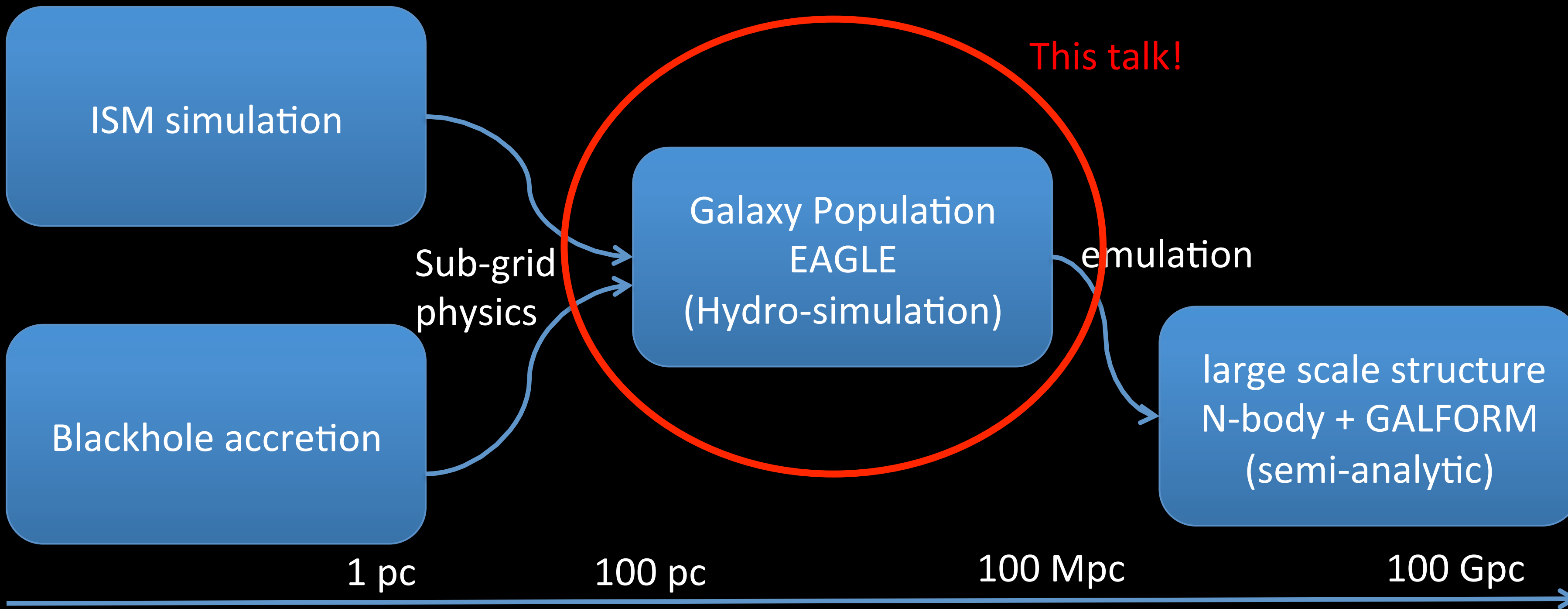
A hierarchy of galaxy formation simulations



The big uncertainties in galaxy formation simulations

- Star formation
- The pc-scale structure of the ISM
- Supernova driven winds
- Black hole accretion and feedback

Simulating the Universe
The EAGLE simulation project

Richard Bower

Durham: Michelle Furlong, Carlos Frenk, Matthieu Schaller, James Trayford, Yelti Rosas-Guevara, Tom Theuns, Yan Qu, John Helly, Adrian Jenkins.

Leiden: Rob Crain, Joop Schaye.

ROW: Claudio Dalla Vecchia, Ian McCarthy, Craig Booth…

+ Virgo Consortium

Schaye et al 2014 ; icc.dur.ac.uk/Eagle

DiRAC

VIRGO

ICC Institute for Computational Cosmology

PRACE

Sub-grid schemes in EAGLE

(what's different about EAGLE?)

Each *particle* only knows about neighboring gas particles. Feedback etc is a local function of gas on ~700 pc scales

1 particle =10^6 (10^5) Mo;
MW galaxy -> 30,000 particles
There are 3000 galaxies like this in EAGLE

Star formation

$$\tau_* \propto P^{n_{KS}}$$

Cooling and photo-ionisation

ISM turbulence

$$P_{ISM} \propto \rho^{\gamma}$$

Subgrid physics with fully coupled hydrodynamics

AGN feedback

$$p_{heat} = \frac{0.01\dot{m}c^2}{kT_{heat}}$$

Supernova feedback

$$p_{heat} = \frac{E_{SN}}{kT_{heat}} f(Z,\rho)$$

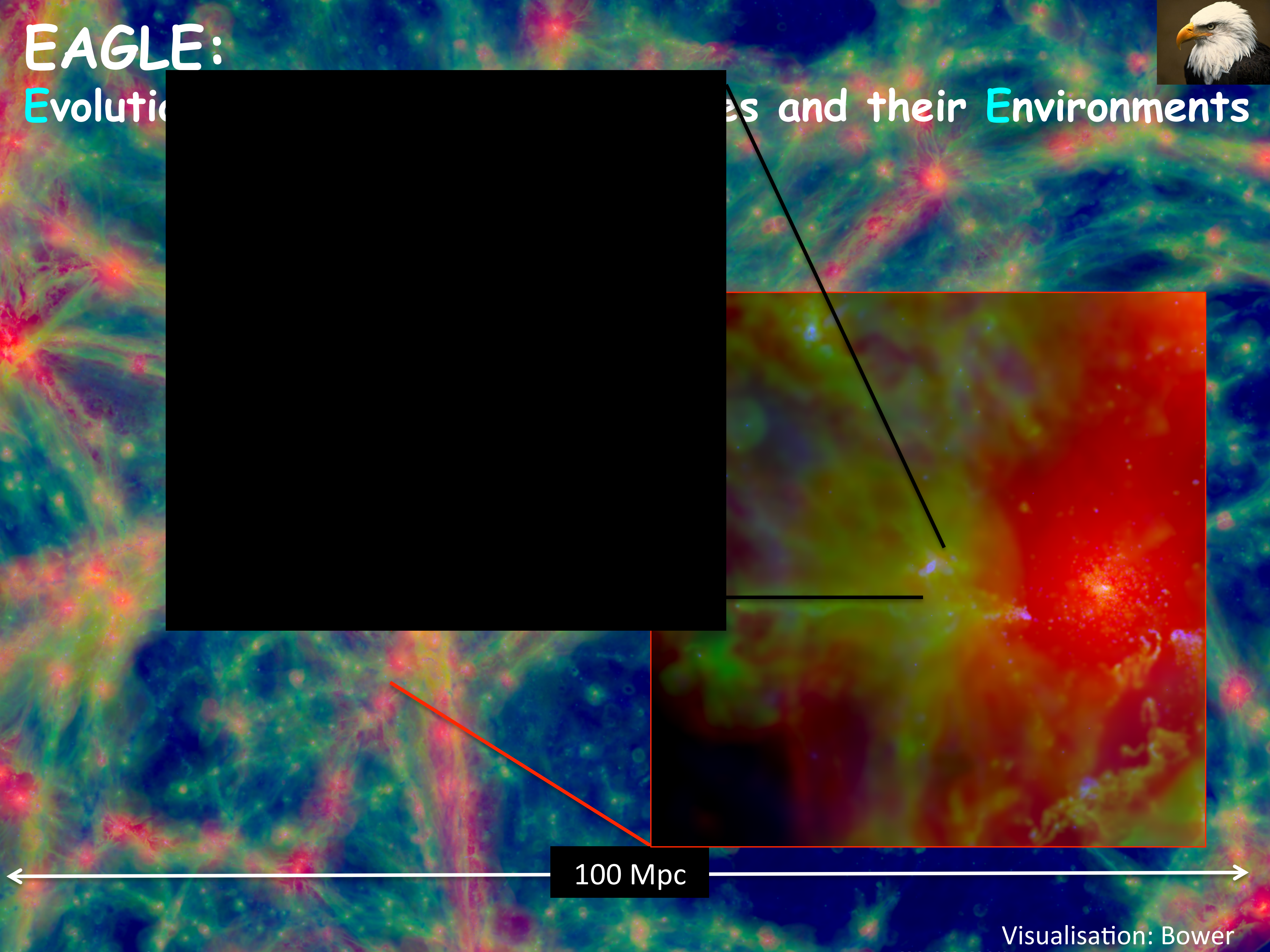
AGN accretion

$$\dot{m}_{BH} = \max\left(f(\rho, v_\phi), \dot{m}_{Edd}\right)$$

Metal enrichment and stellar mass loss

Dalla Vecchia & Schaye 2009, 2012; Roasas-Guevara et al 2014; Schaye et al 2014

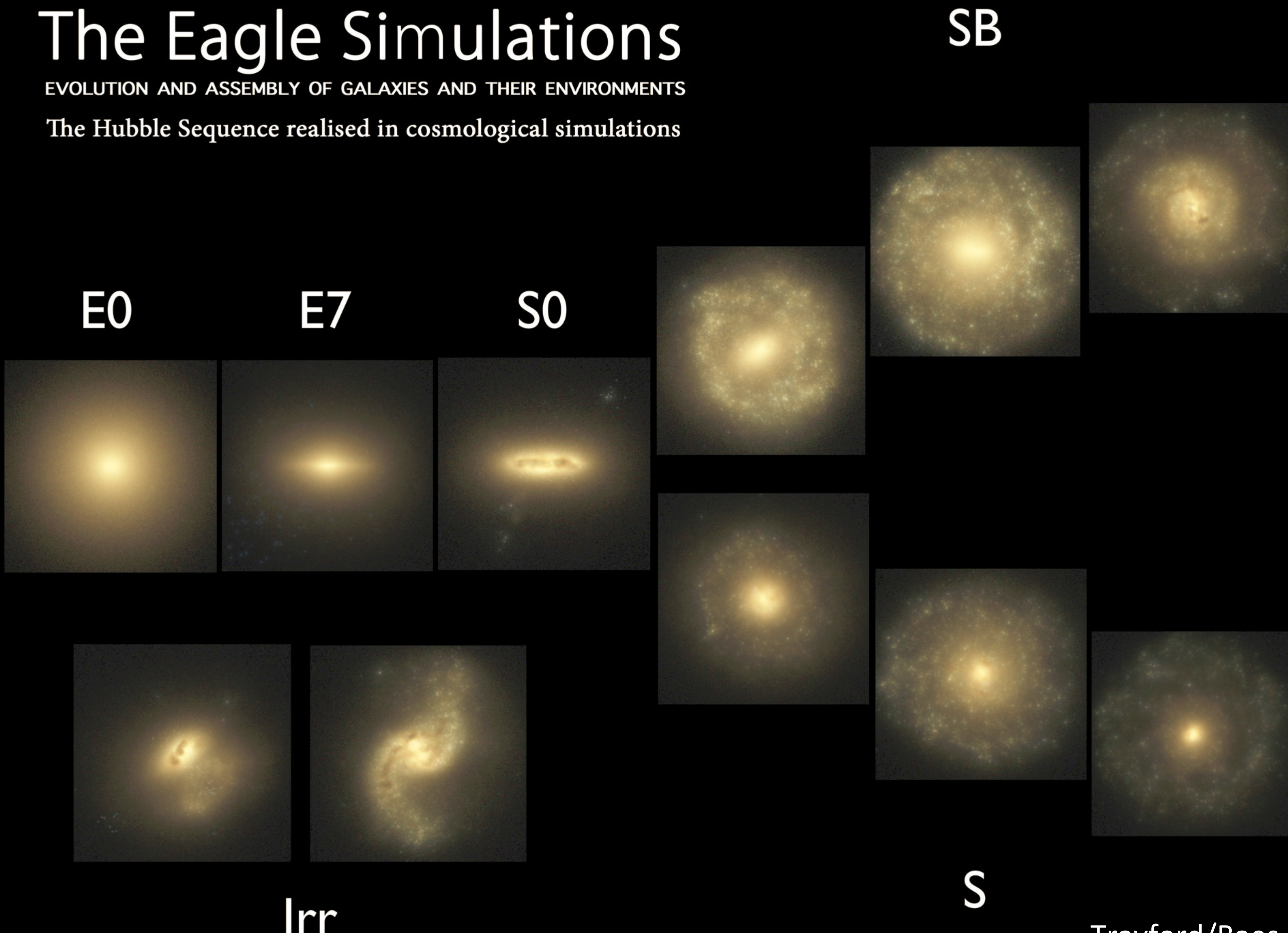
EAGLE:
Evoluti[redacted]es and their Environments



The Eagle Simulations

EVOLUTION AND ASSEMBLY OF GALAXIES AND THEIR ENVIRONMENTS

The Hubble Sequence realised in cosmological simulations



Trayford/Baes

Accounting for Angular Momentum in black hole accretion

- Standard model assumes that accretion rate is given by a modified Bondi Formula

$$\dot{m}_{BH} = \alpha \frac{4\pi G^2 M_{BH}^2 \rho}{\left(v_{rel}^2 + c_s^2\right)^{(3/2)}}$$

$$\alpha = \left(\frac{n}{n^*}\right)^{\beta}$$

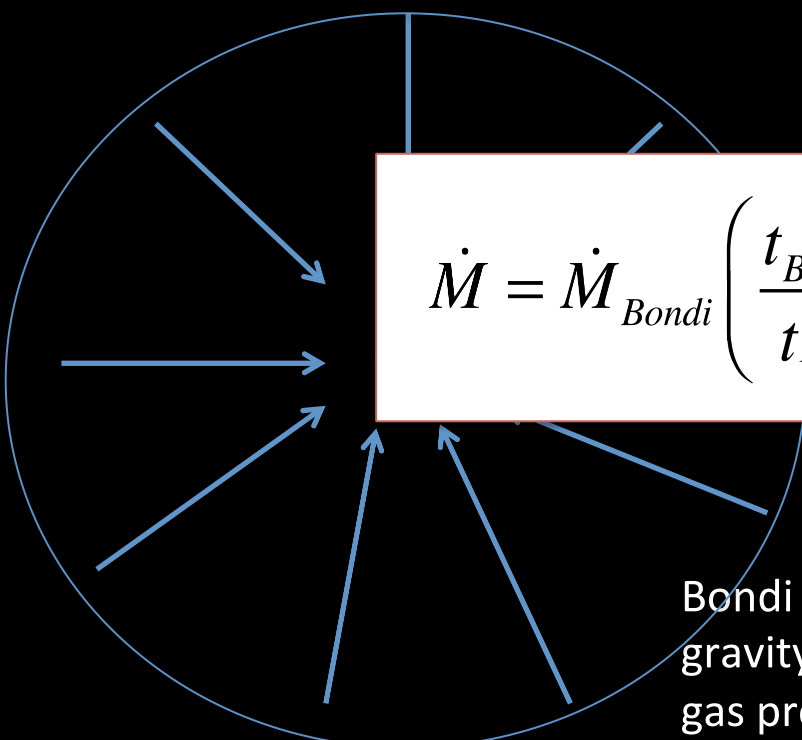
Springel et al 2005; Booth & Schaye 2009

- But this takes no account of angular momentum.

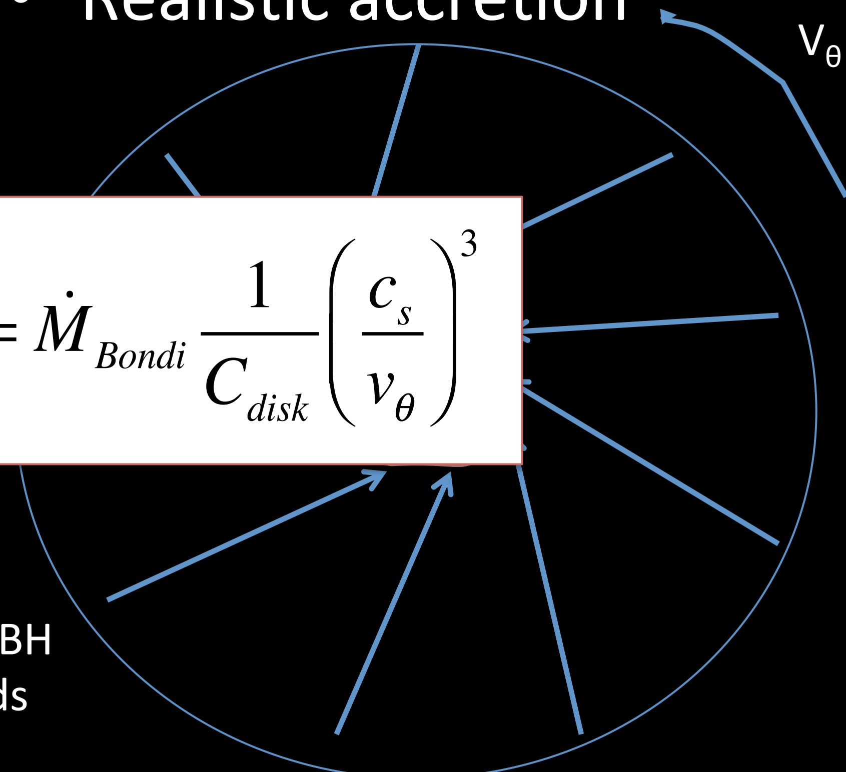
Rosas-Guevara et al 2014, For alternative approaches, see Hopkins & Quataert 2011; Power et al., 2011;

Including angular momentum

- Bondi accretion



- Realistic accretion



$$\dot{M} = \dot{M}_{Bondi}\left(\frac{t_{Bondi}}{t_{visc}}\right) = \dot{M}_{Bondi}\frac{1}{C_{disk}}\left(\frac{c_s}{v_\theta}\right)^3$$

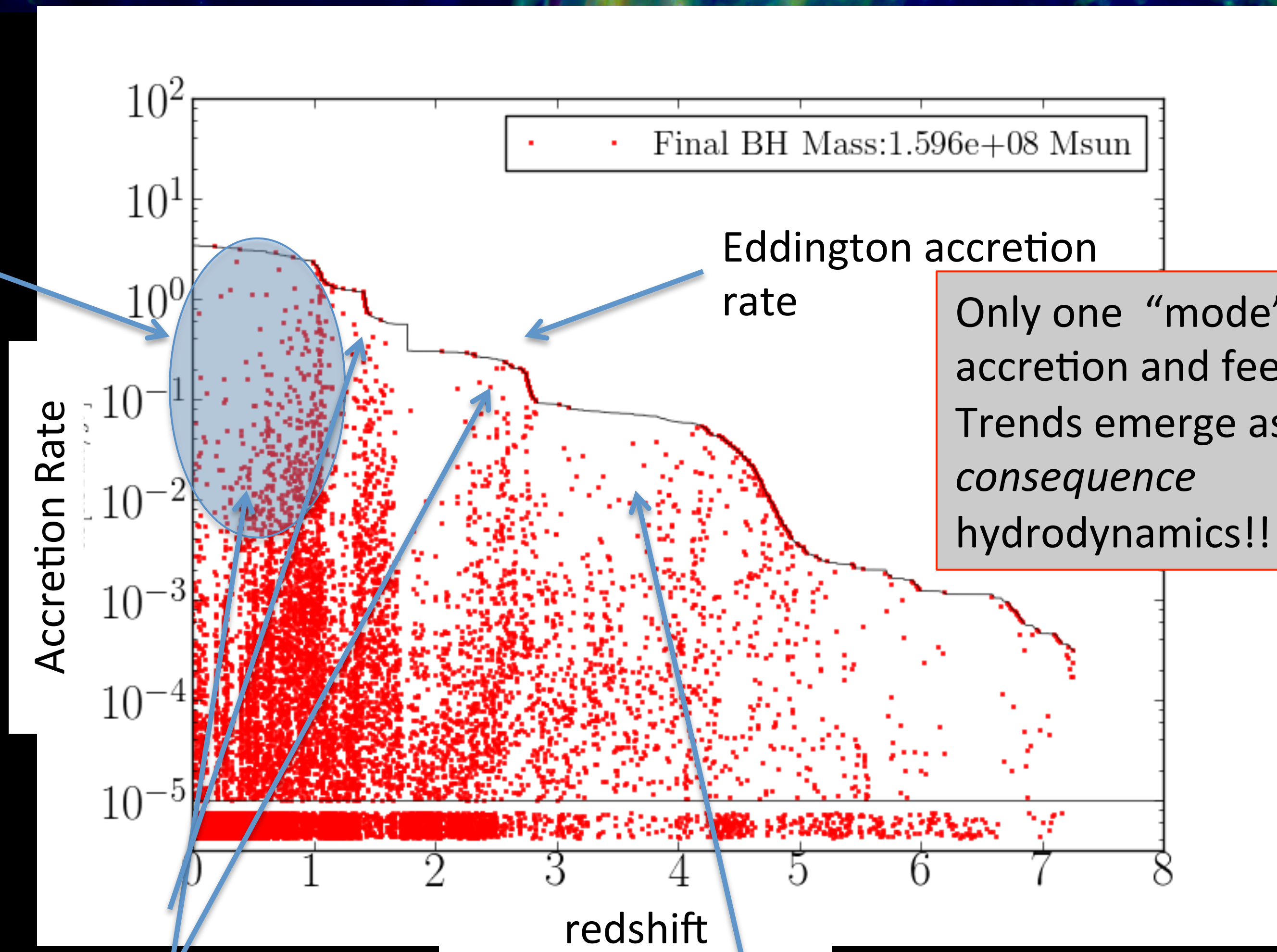
Material crossing the Bondi radius free-falls into the black hole

Accreting matterial forms a disk at r_{cric}. It then flows into the black hole on the viscous timescale of the disk

The life of one black hole…

Frequent moderate accretion events

- But not often reaching Eddington
- Ideal accretion rates for generating radio jets



Only one "mode" of accretion and feedback. Trends emerge as a *consequence* hydrodynamics!!

Eddington-limited (quasar-like) accretion events

Long periods without significant accretion

BH feedback in action

- Sit back and watch BH feedback at work

The impact of BH activity on star forming gas

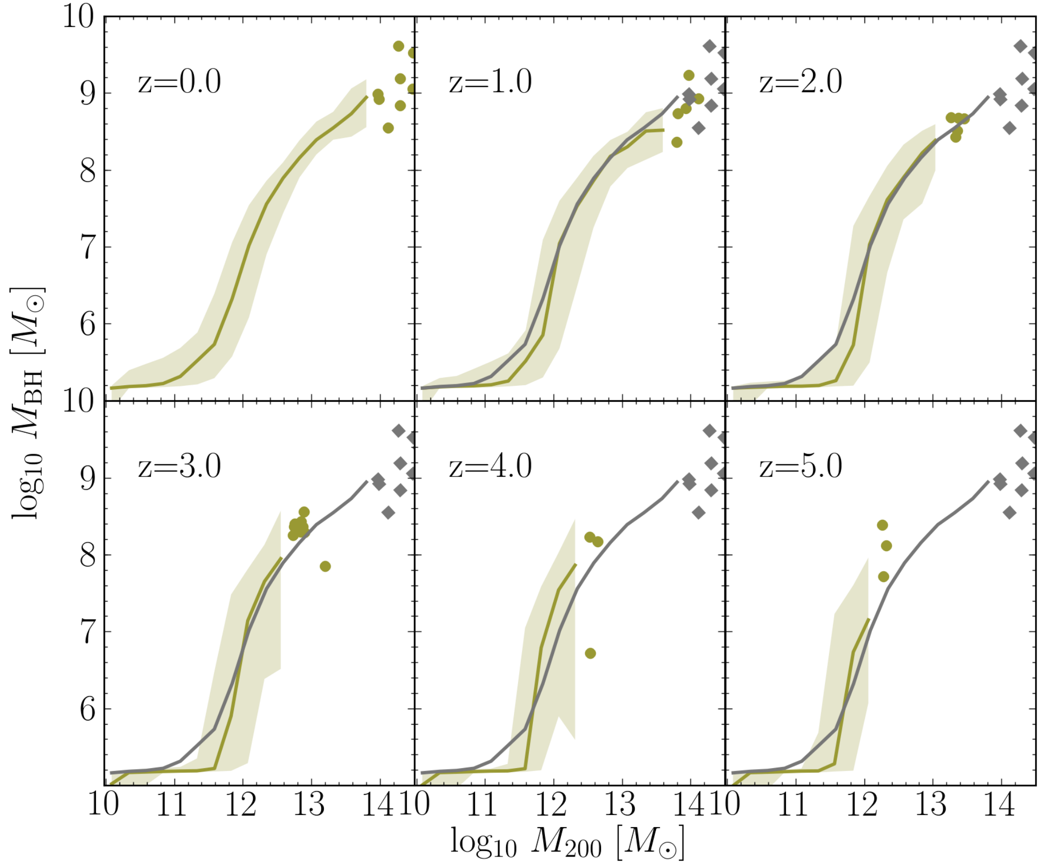
What’s going on?

That all looks like the really universe!

…but no “modes” of BH accretion were used - it all happens because of the way BH interact with their environment

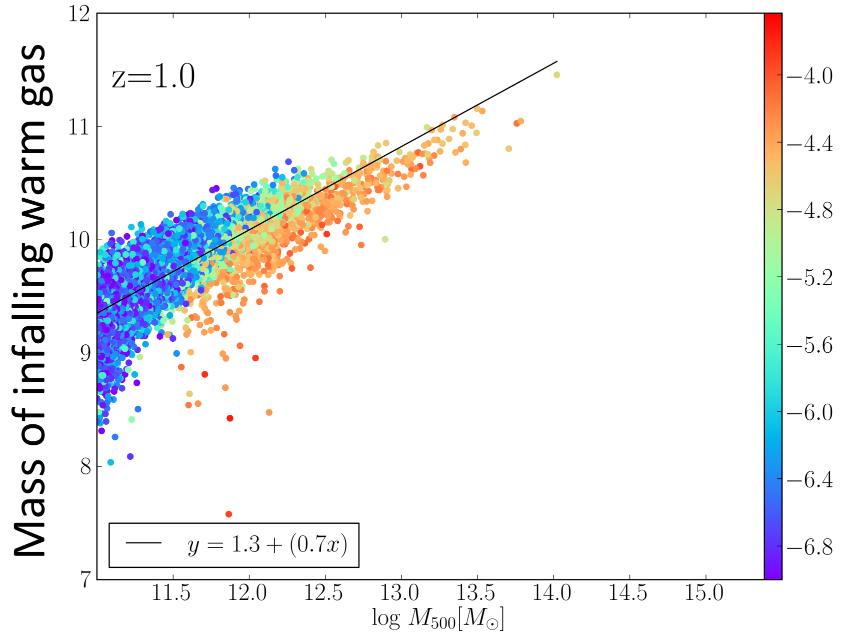
BH "switch on" at a particular halo mass

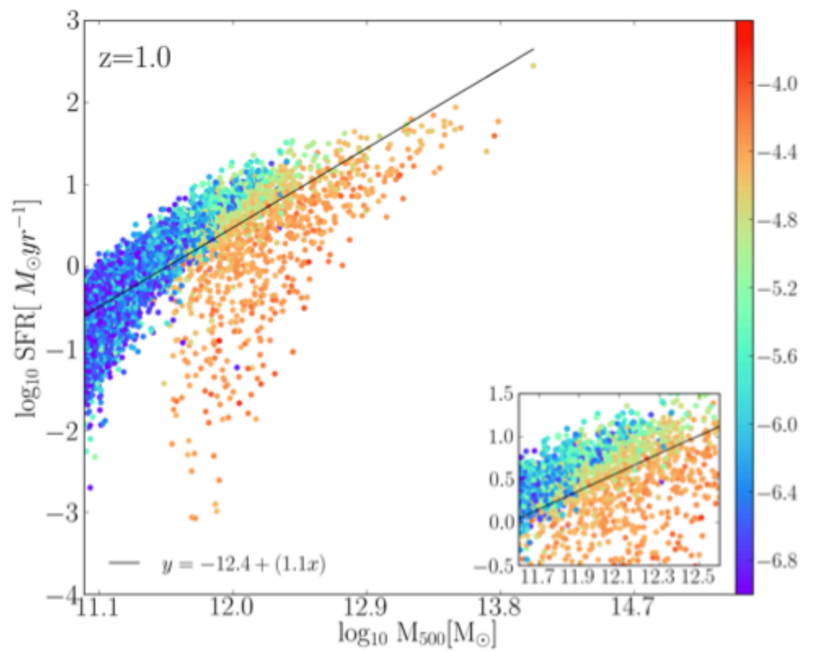
- BH mass – halo mass has a very steep rise.
- A function of stellar mass, or of halo mass?
  - Even steeper transition
- A transition in every sense!
  - Inflow/outflow is regulated by
  - Star formation in haloes < 10^12
  - BH in haloes > 10^12
- Why?
  - …
- So transition is NOT because feedback is ineffective in low mass haloes.



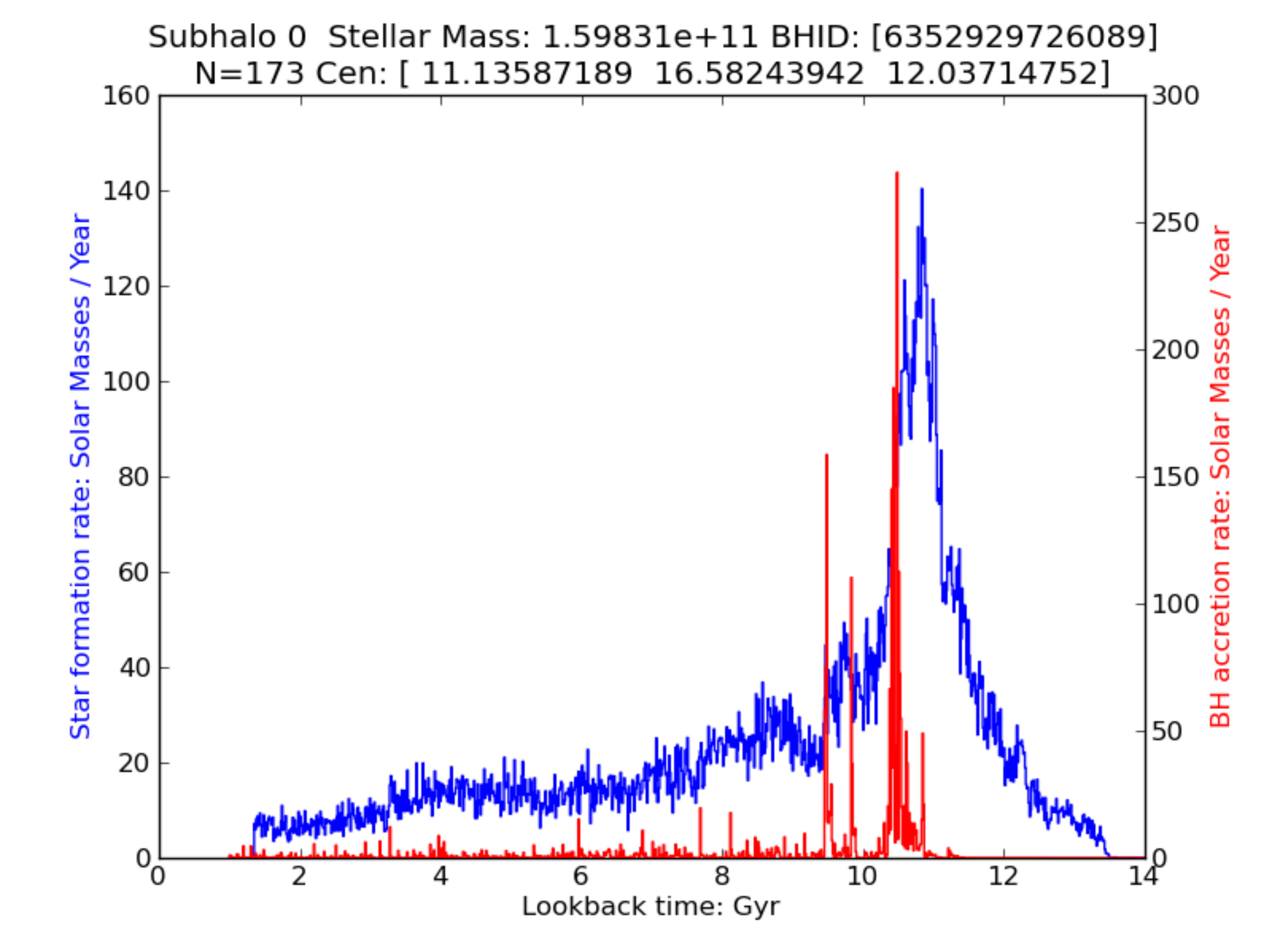
Impact of BH feedback

- BH starts to grow rapidly when Mhalo=10^12
- What does that do?
- It suppresses star formation
- And ejects gas from halo (or makes the gas hot)
- Disrupts infalling filaments

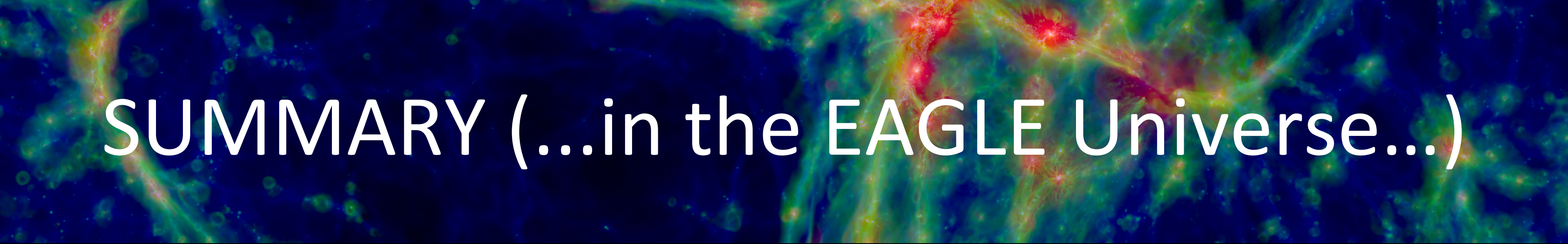




One example object…



Answers to the questions



SUMMARY (...in the EAGLE Universe...)

- What evidence is there for a symbiotic relationship between star formation and AGN activity?
  - Its paracytic. The galaxy feeds the black hole and the black hole grows, then kills it host.

- What mechanisms are important in driving luminous AGN
  - Mergers (although they are rather rare). Triggers loss of AM and thus major BH growth
- What mechanisms are important in driving low-luminosity AGN
  - Smaller mergers and instabilities

- What impact does radio-quiet (high eddington) accretion have on star formation?
  - Little direct impact.
  - Major impact if the halo mass is susceptible

- What impact does radio-loud (low eddington) accretion have on star formation?
  - In big BH low eddition ratios are still a formidable energy input rate!
  - Keeps the hot gas halo from collapsing

- Next steps:
  - Compare with observational data (see Michele Furlong's talk)

Schaye et al 2014 ; icc.dur.ac.uk/Eagle

BH feedback in action

- Sit back and watch BH feedback at work