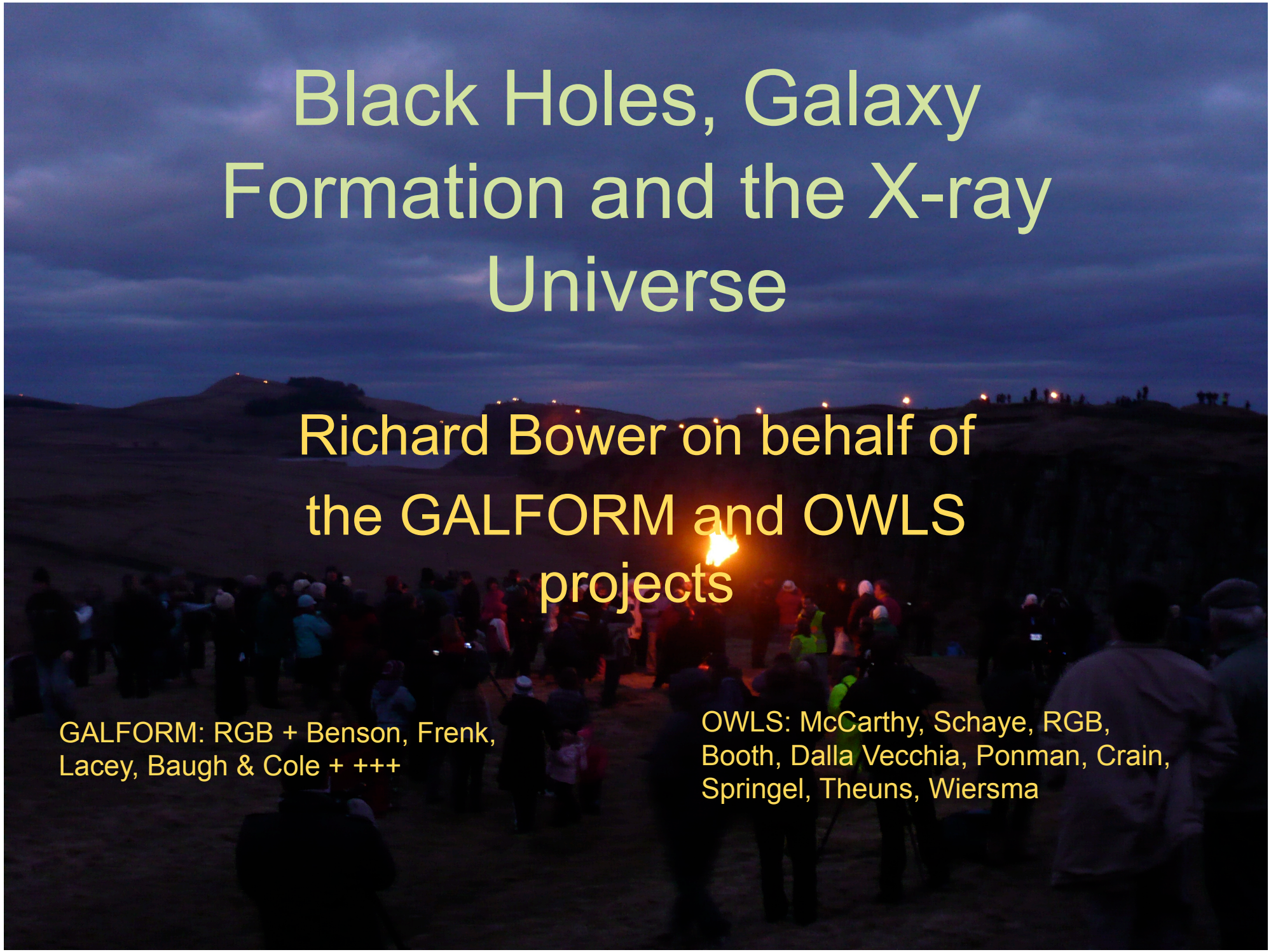


Black Holes, Galaxy Formation and the X-ray Universe

Richard Bower on behalf of the GALFORM and OWLS projects

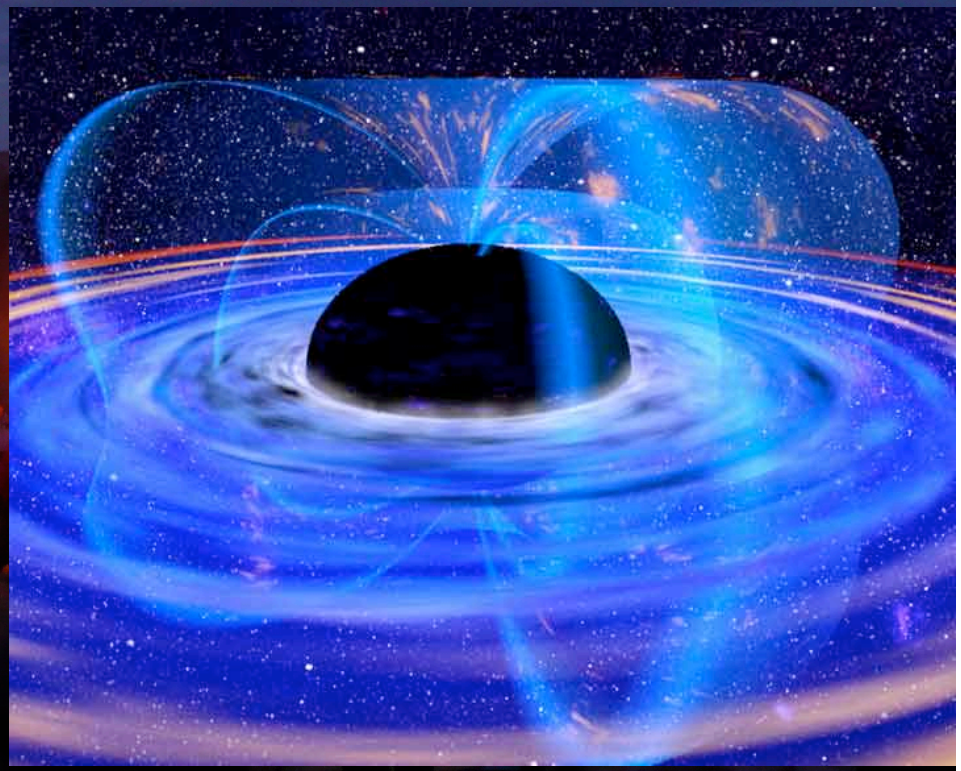
GALFORM: RGB + Benson, Frenk, Lacey, Baugh & Cole + +++

OWLS: McCarthy, Schaye, RGB, Booth, Dalla Vecchia, Ponman, Crain, Springel, Theuns, Wiersma


Part I
What do black holes have to do with galaxy formation?

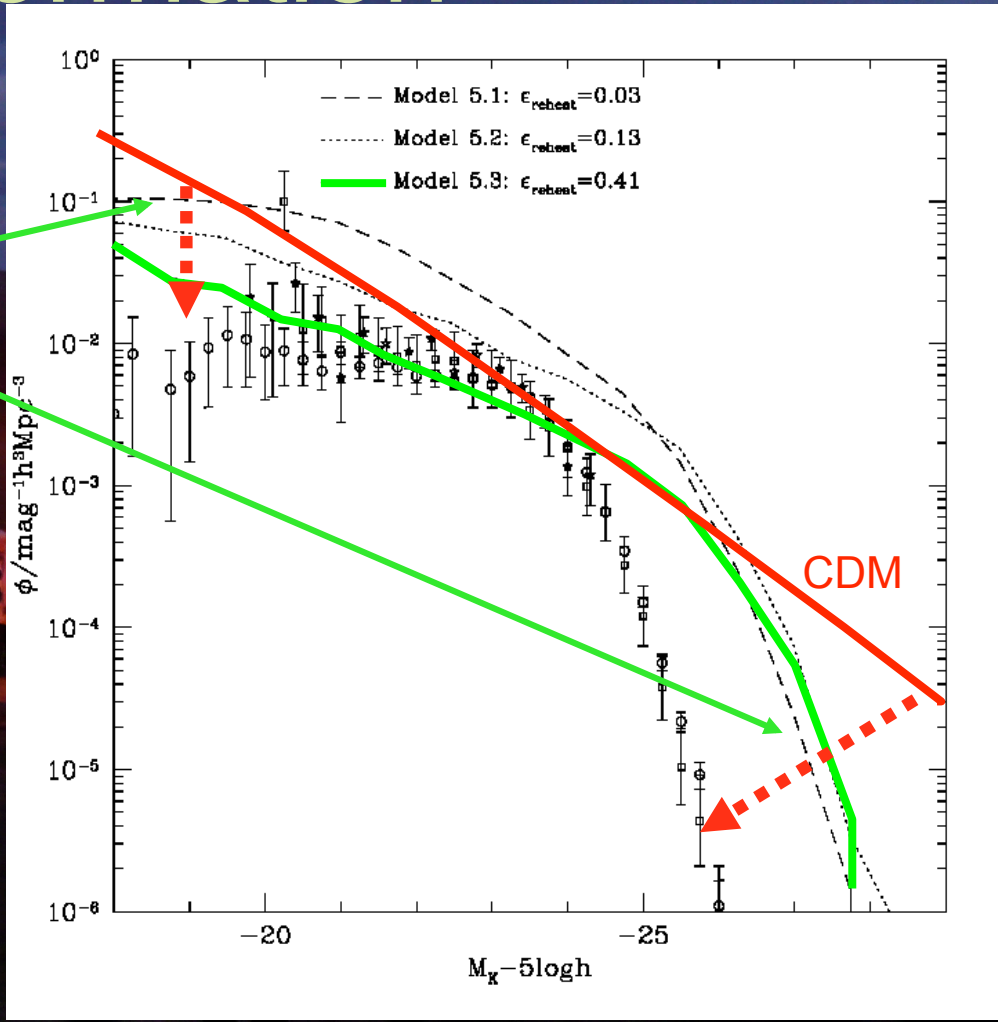
What do black holes have to do with galaxy formation?

- Black holes are interesting objects in their own right…
  - Test of strong gravity
  - Most luminous objects in the sky
- But what do they have to do with galaxy formation?



Making the connection with galaxy formation

- The three problems of galaxy formation
  - Faint galaxies far less abundant than the CDM mass function .
  - Sharp cut off at the bright end of the galaxy mass function
  - Lack of prolific star formation in central galaxies in clusters
  - Only 10% of the baryons condense into stars and cold gas
- Super-Novae may be the answer for faint galaxies?
- … but what creates the break at the bright end?



The energetics of black hole formation

- Forming a BH releases plenty of energy
- But…
  - Is this all radiated away?
  - The BH is very small how can it affect the whole galaxy?
  - Is the process too stocastic?

Comparison of energies:

Thermal energy of a 10^{13} M_o halo

… 10^{61} erg

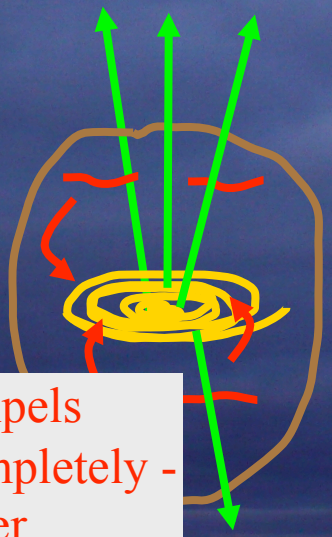
Accretion energy of a 10^{9} M_o black hole

… 2×10^{62} erg

It seems unlikely that AGN are unimportant!

The Two Modes of AGN Feedback

- The “Superwind” mode
  - Rapid accretion by the BH drives a powerful outflow of gas from the DM halo. The baryons leaves the halo and cannot cool.
- The “Radio” mode
  - Slow accretion on to BH powers radio jet. This heats surrounding gas preventing it from cooling.



Feedback expels material completely - it is no longer available for cooling.

Feedback energy heats the gas halo, cancelling radiative cooling

Benson et al 2003; Croton et al 2006; Bower et al 2006

The Two Modes of AGN Feedback

IMPORTANT! the wind needs to be really powerful - so that the material escapes the galaxies halo - is this observed???

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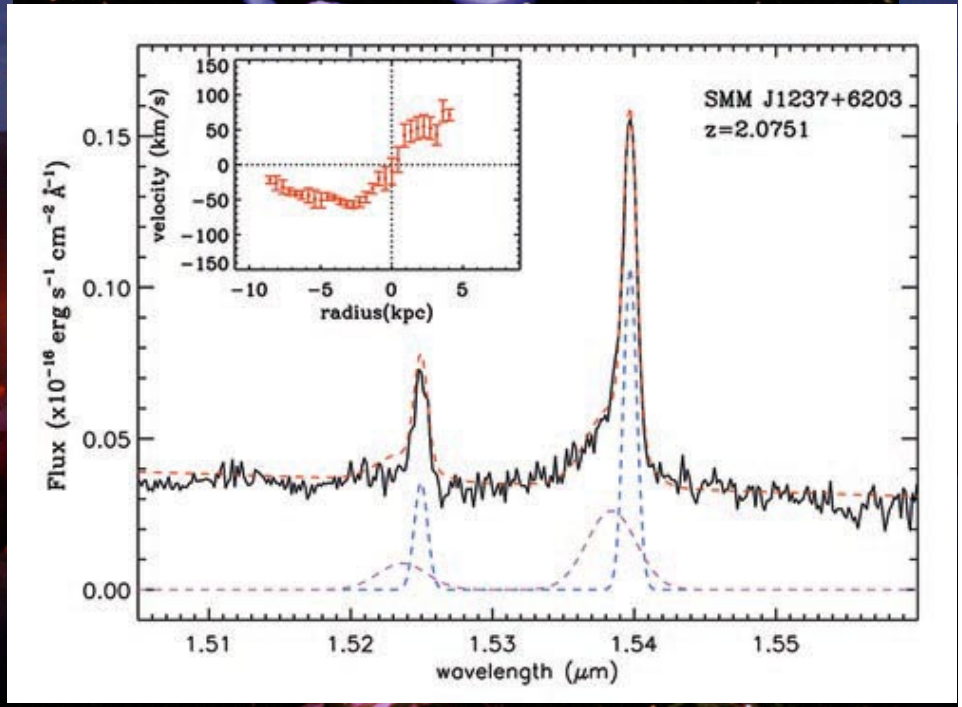

Springel, di Matteo et al. 2005

Nesvadba et al. 2006, Alexander et al 2010

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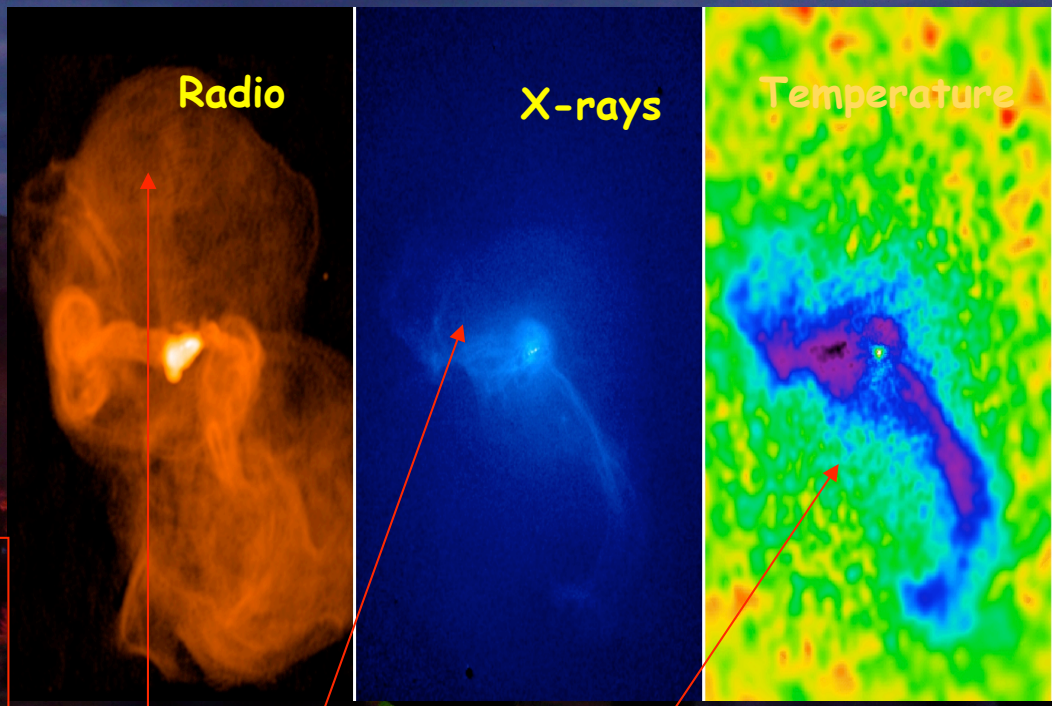
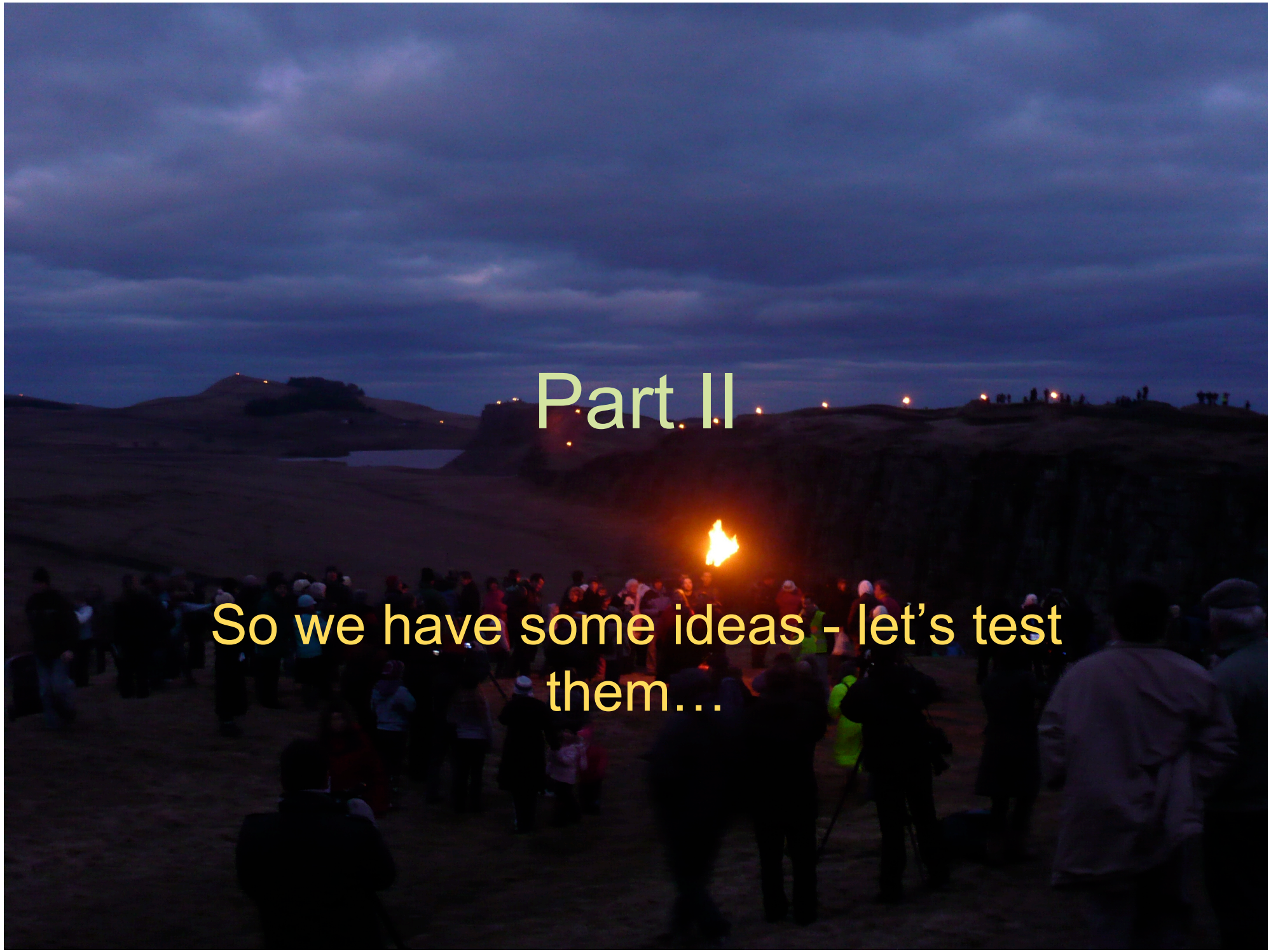
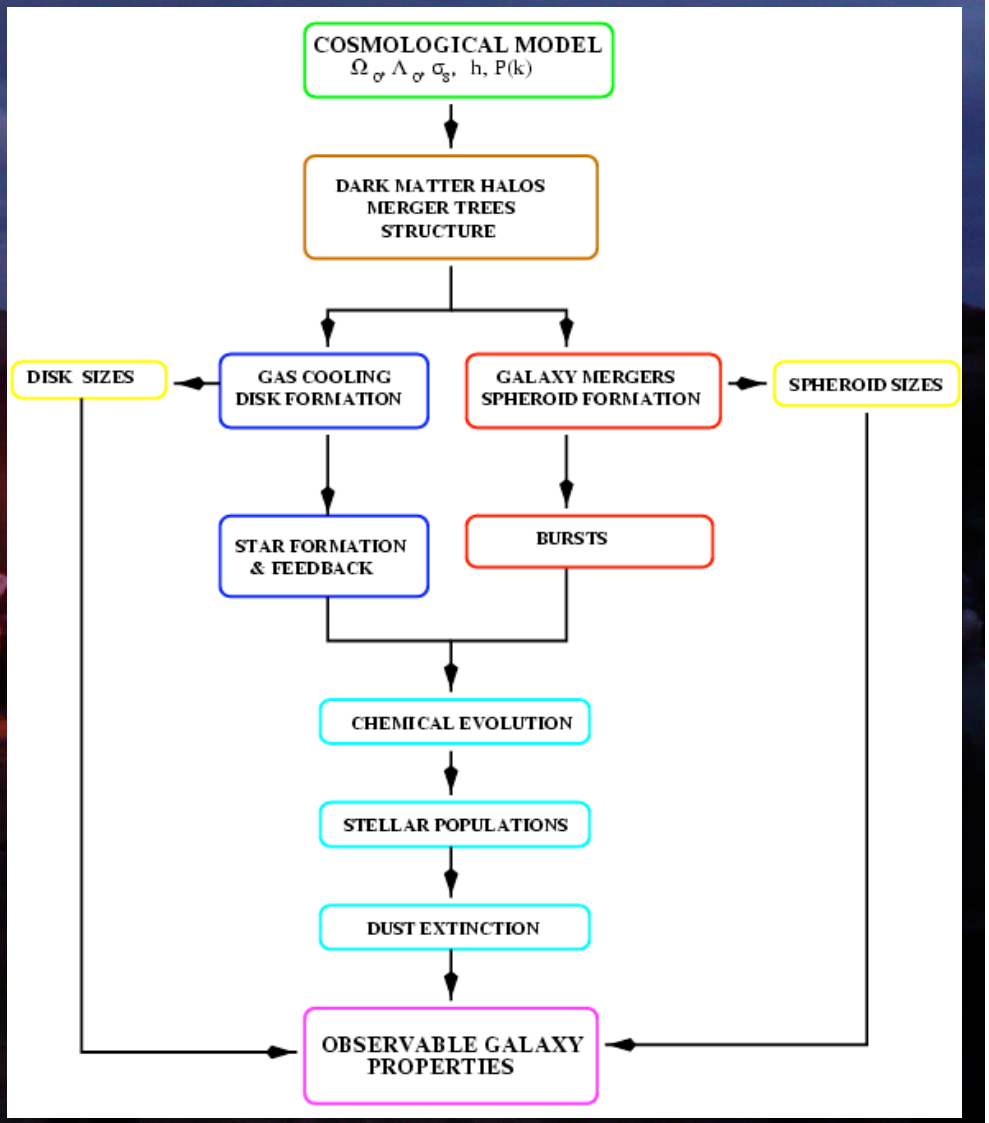


M87: Forman et al 2006;
Perseus: Fabian et al 2000, 2006


Part II
So we have some ideas - let’s test them…

Semi-Analytic models

- A way to experiment with galaxy formation.
  - Add and subtract bits of physics
  - Control the way that BH affect galaxies
  - Fast - so we can explore parameter space
- But “recipes” need to be justified by numerical experiments.



The “radio mode” feedback loop

“radio” mode

$P_{max} = \varepsilon L_{edd}$

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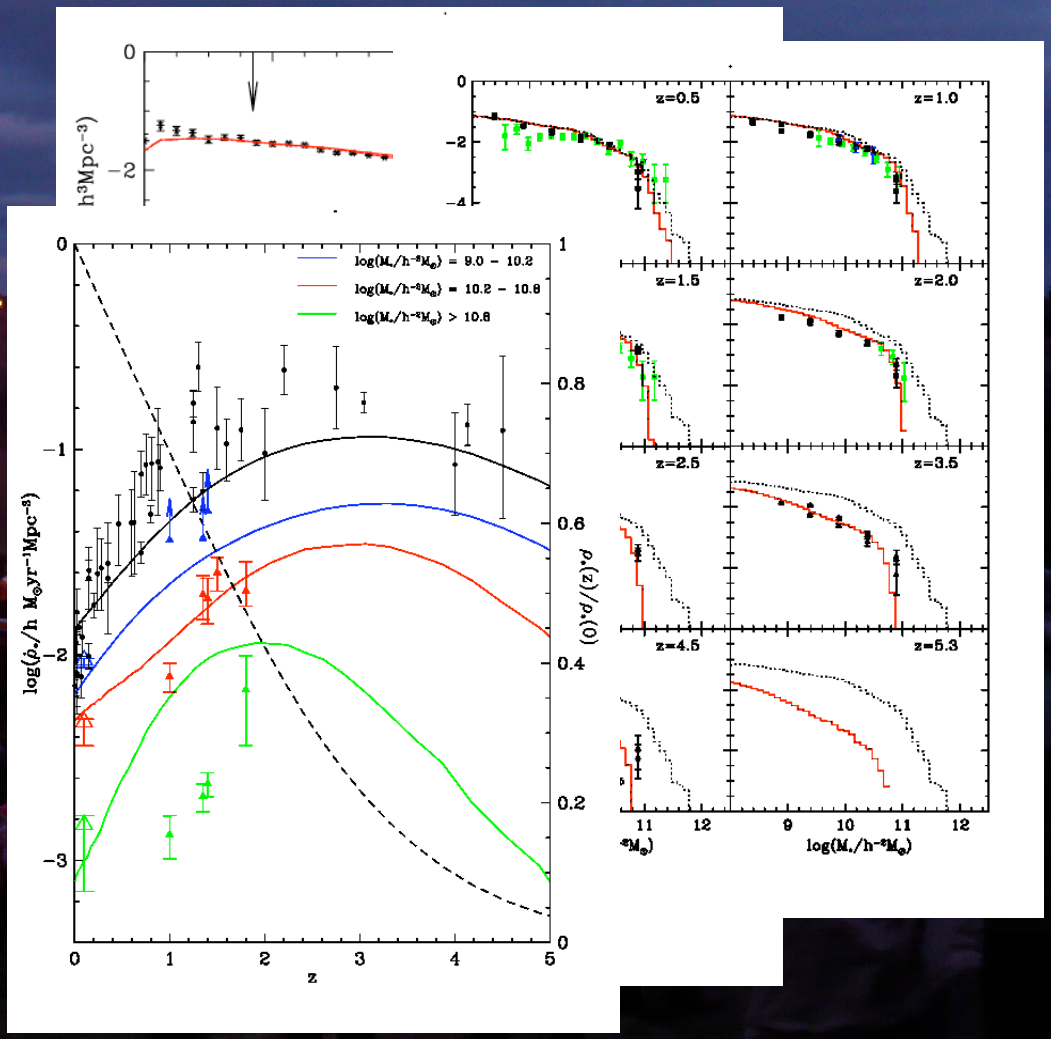
Keres et al 2005; Dekel & Birnboim 2005; Binney 2004

“radio mode” feedback

- The “radio mode” suppresses cooling in massive haloes
  - Generates a sharp break in the luminosity function.
  - Natural scale set by hydrostatic vs rapid cooling.
  - Simply preventing cooling inconsistent with thermal X-ray emission from groups and clusters.
  - Does not fix-up the properties of faint galaxies. Still need SNe to do that.
- See Nikos Fanidakis’ talk for discussion of AGN properties in the model.

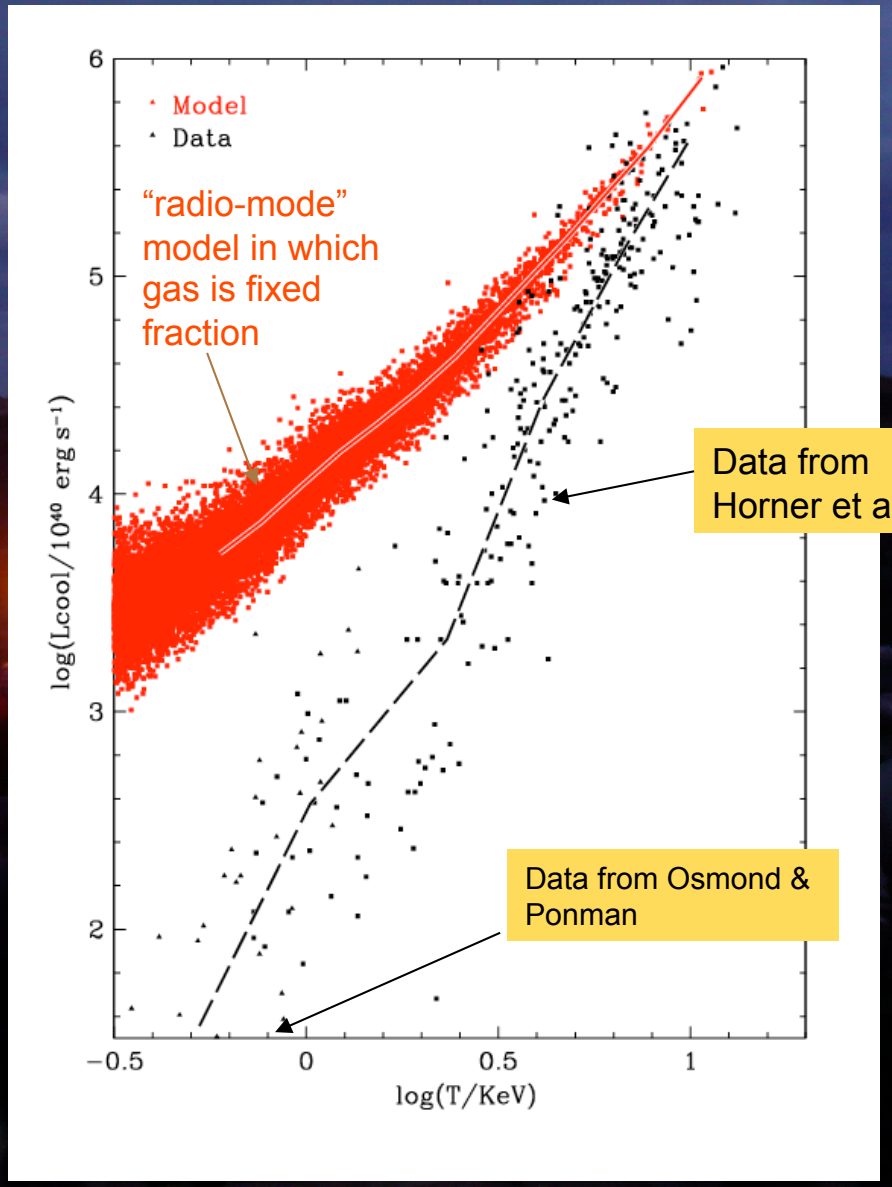


See also Croton et al., Cattaneo et al., De Lucia et al.; Kitzbichler et al., Somerville et al.


Part III
Beyond galaxy properties:
The (thermal) X-ray universe

Beyond Galaxy Properties

- But a successful model needs to do more that explain the observed properties of galaxies.
- The observed gas distribution in groups is puffed-up compared to clusters.
  - Simply preventing cooling in hydrostatic haloes is not enough - they actually contain fewer baryons.



Bower etal 08, Short & Thomas 08

The AGN feedback loop

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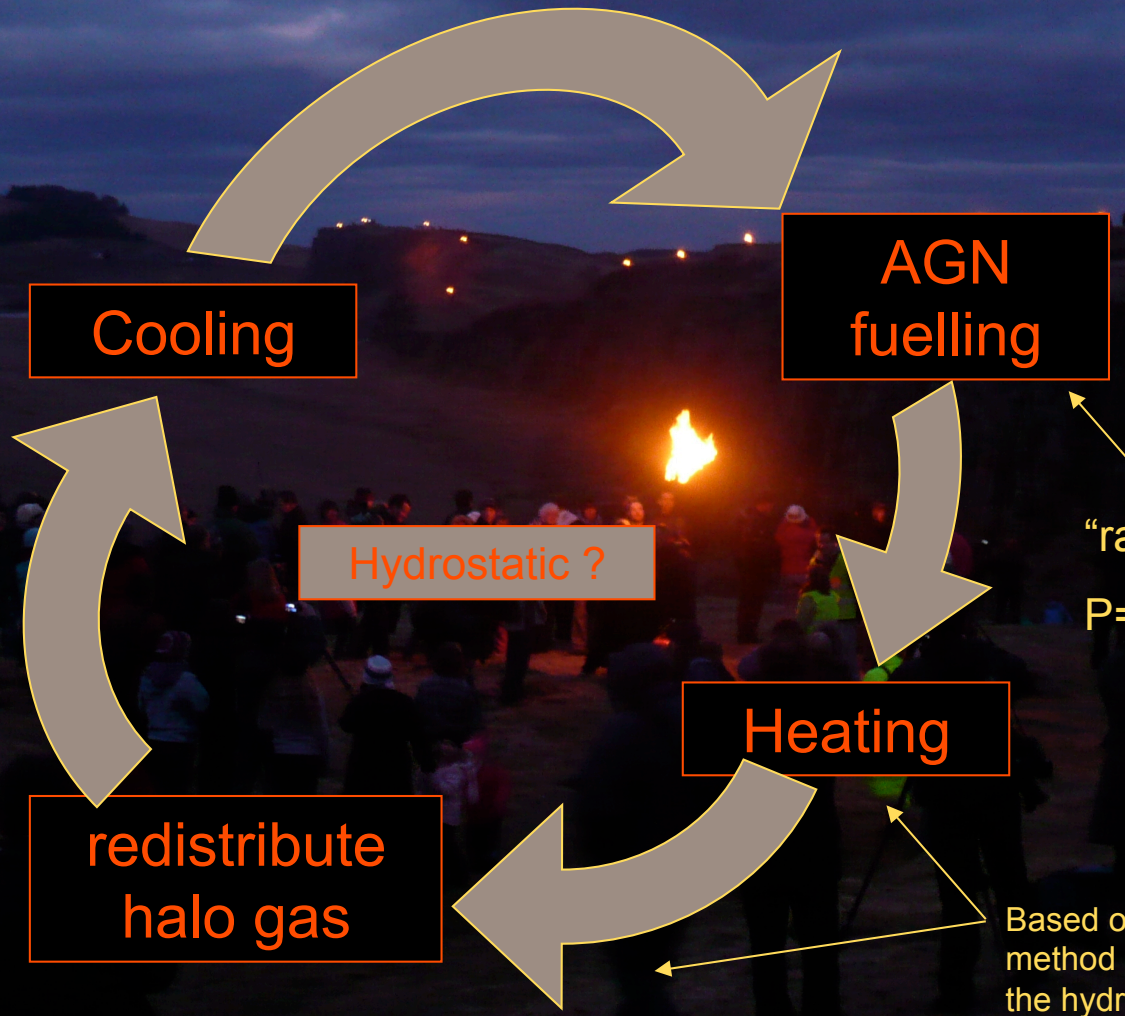
The AGN feedback loop (new version)



"radio" mode

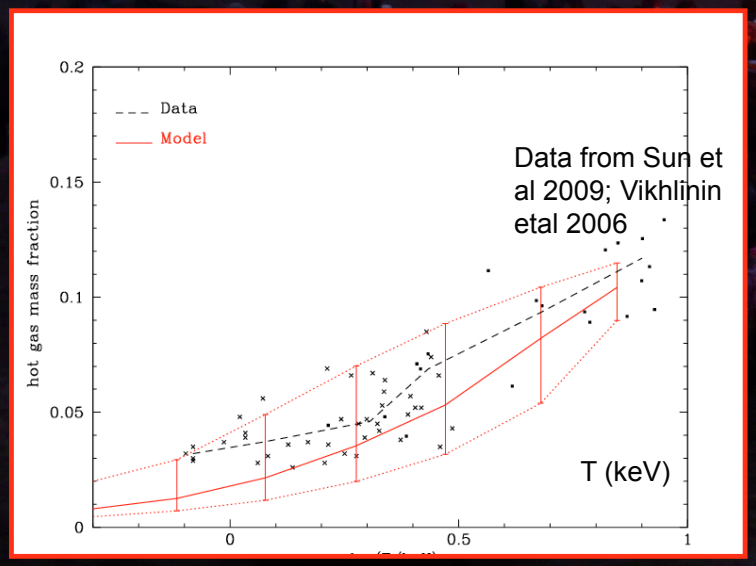
$P=\min(\varepsilon L_{edd}, \eta M_{cool})$

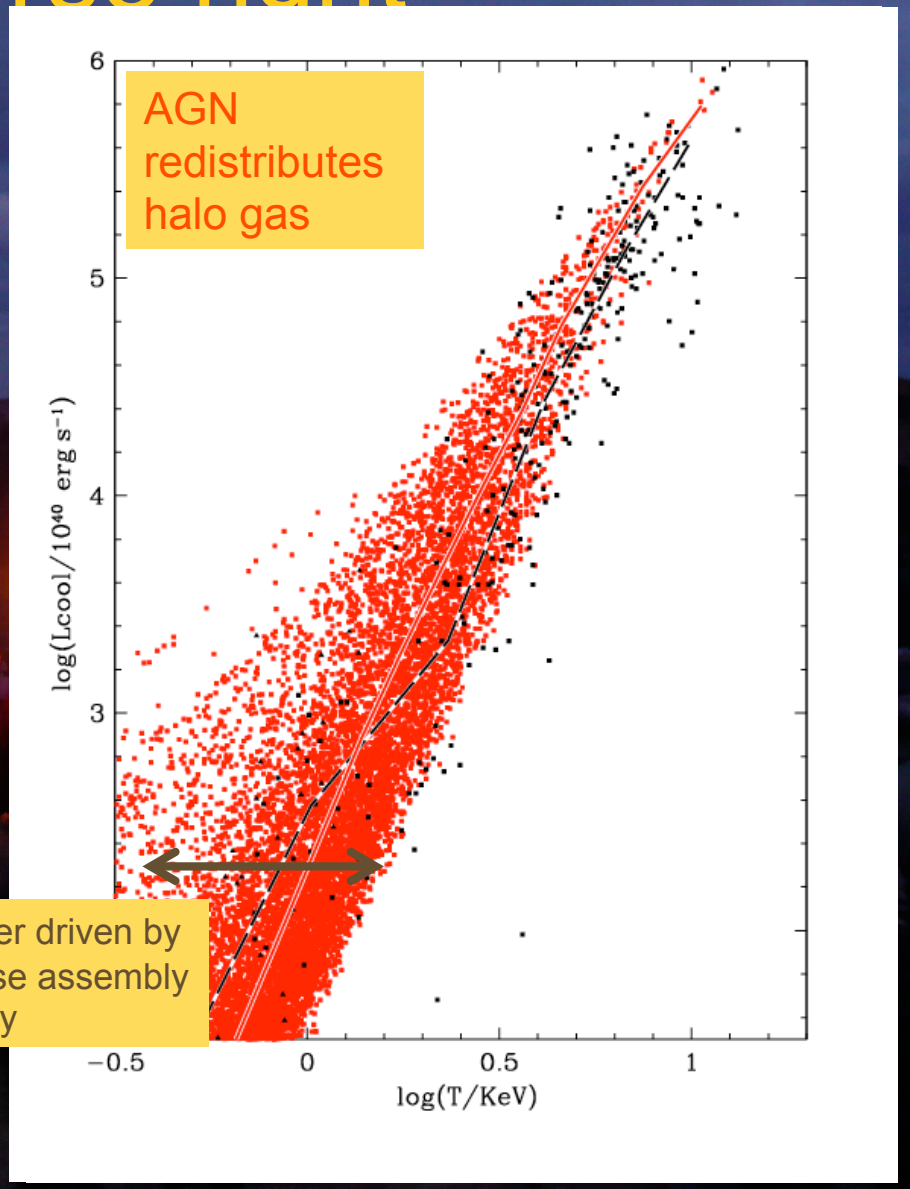
Based on the "excess energy" method (Wu et al 1999), plus the hydrostatic criterion

As seen in numerical sims: Puchwein et al 2008; McCarthy et al 2009

Getting the (thermal) X-ray Universe right

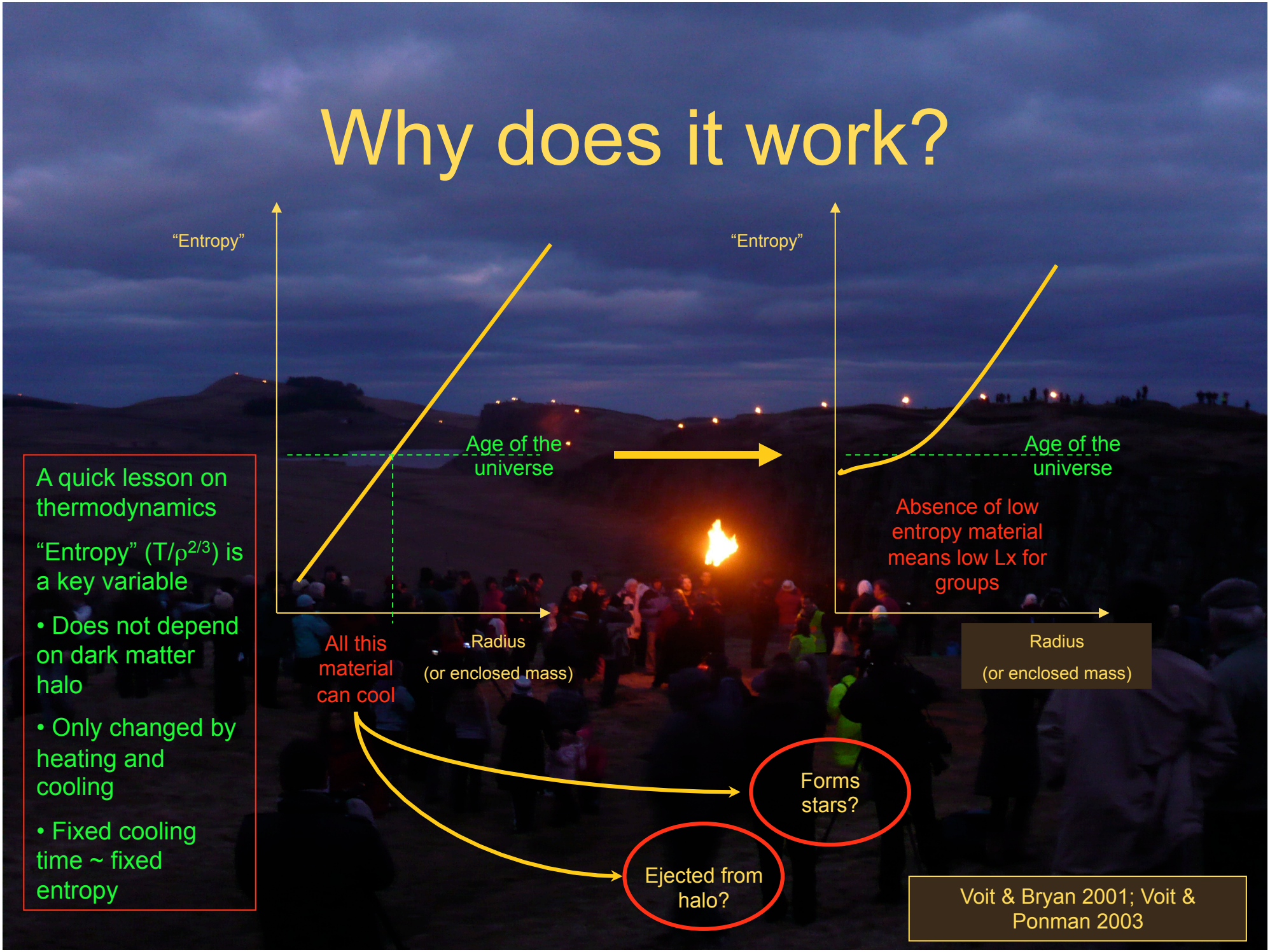
- Expulsion feedback does more than offset the cooling luminosity of the clusters
- Rather the cooling rate is reduced by ejecting material from the halo until the cooling rate becomes small
- This model gets both the galaxy properties and the halo X-ray emission correct.





Bower etal 08, Short & Thomas 08

Why does it work?

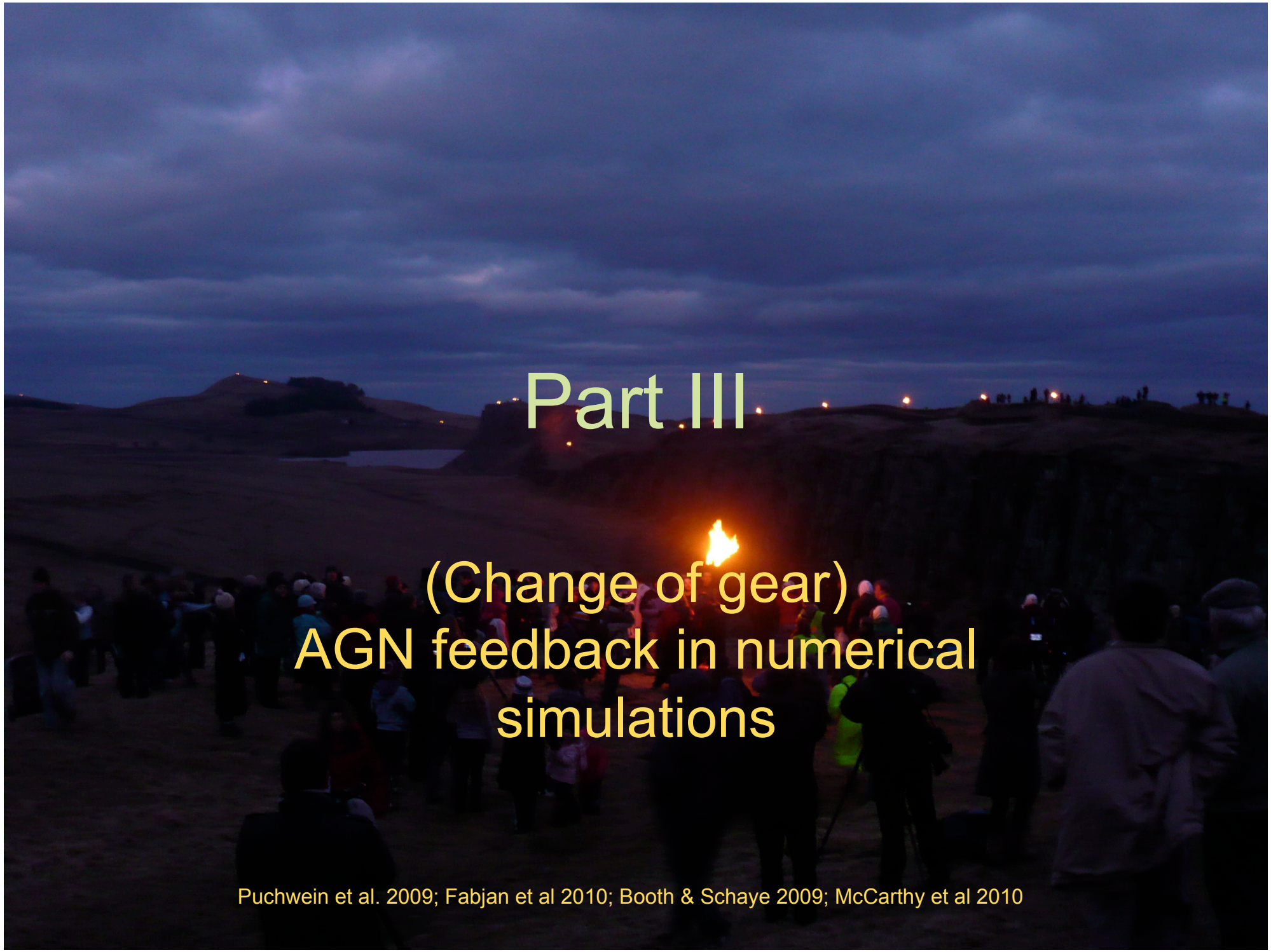


A quick lesson on thermodynamics

"Entropy" ($T/\rho^{2/3}$) is a key variable

- Does not depend on dark matter halo
- Only changed by heating and cooling
- Fixed cooling time ~ fixed entropy

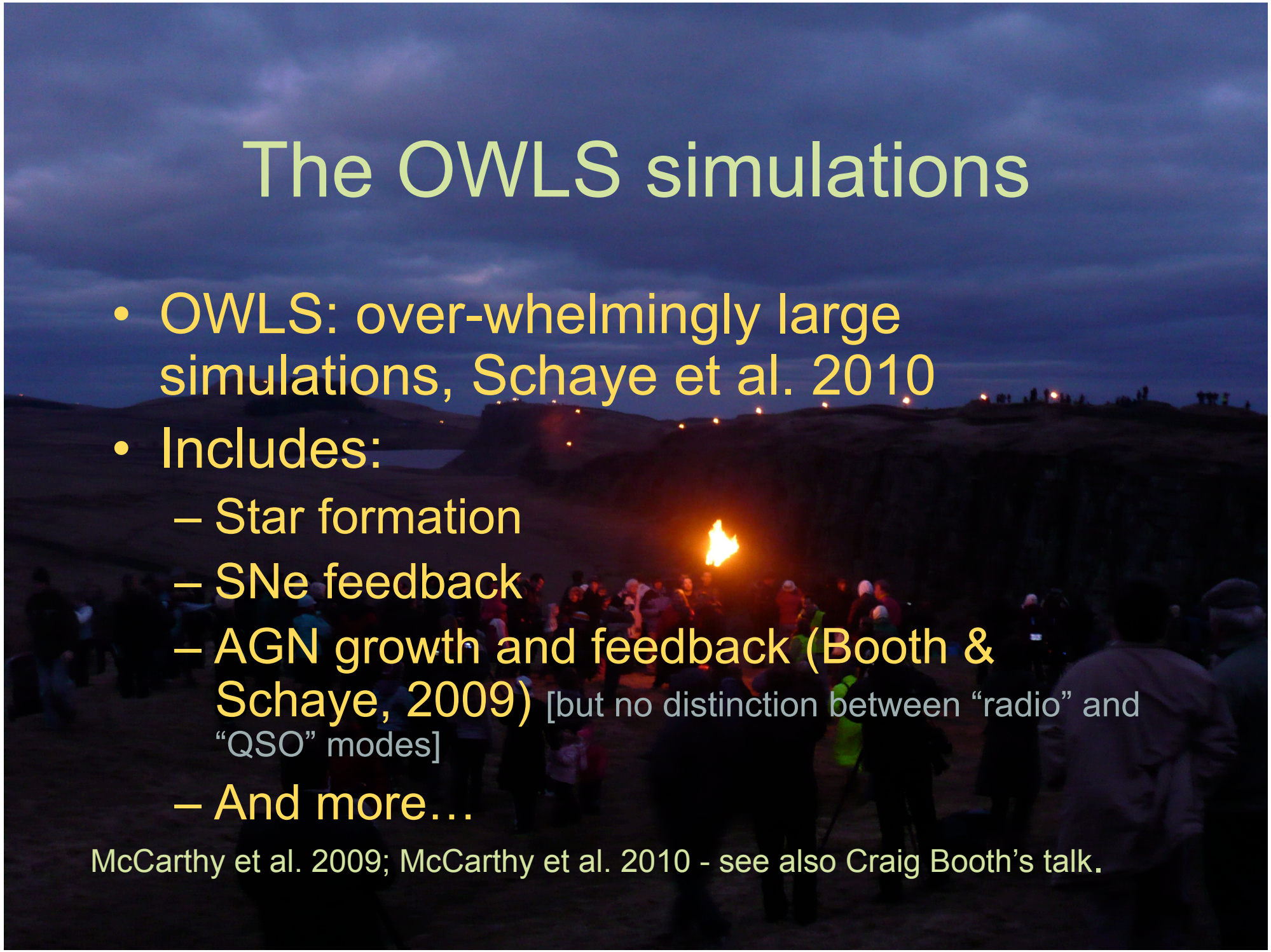
Voit & Bryan 2001; Voit & Ponman 2003



Part III

(Change of gear)
AGN feedback in numerical simulations

Puchwein et al. 2009; Fabjan et al 2010; Booth & Schaye 2009; McCarthy et al 2010



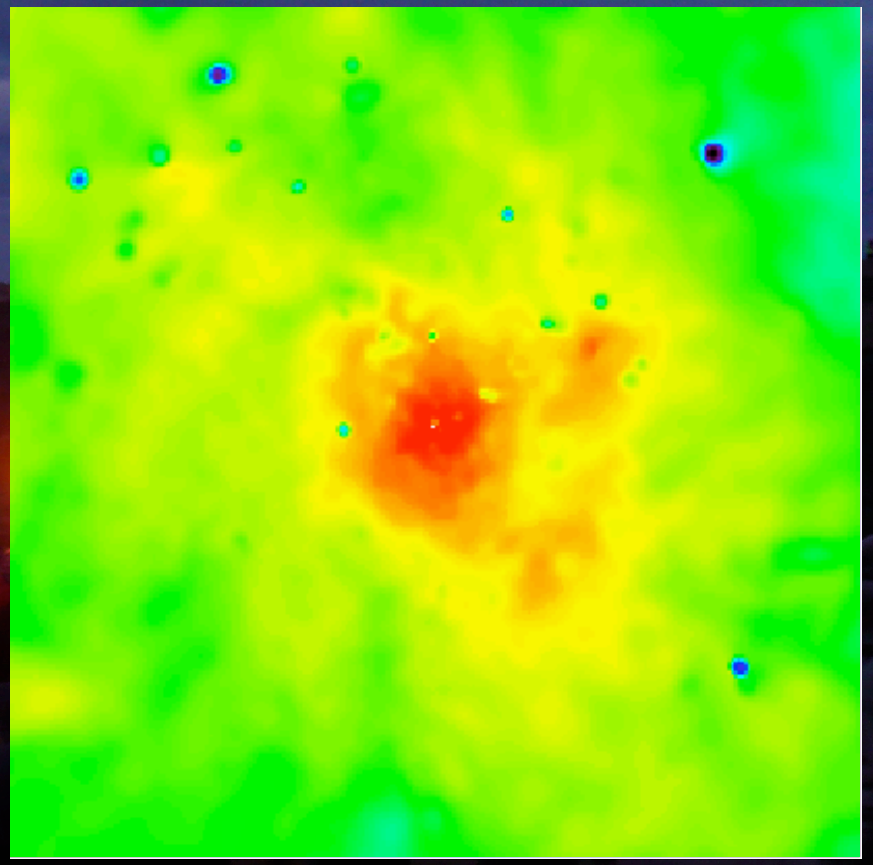
The OWLS simulations

- OWLS: over-whelmingly large simulations, Schaye et al. 2010
- Includes:
  - Star formation
  - SNe feedback
  - AGN growth and feedback (Booth & Schaye, 2009) [but no distinction between “radio” and “QSO” modes]
  - And more…

McCarthy et al. 2009; McCarthy et al. 2010 - see also Craig Booth’s talk.

(thermal) X-ray properties

- Generate X-ray spectral-images
  - Measure temperature
  - Density
  - “Entropy”
- Scale to quantities at r500 in ideal halo



X-ray surface brightness map

X-ray spectroscopic-like temperature [0.5-7.0 keV band]

McCarthy et al. 2009; McCarthy et al. 2010.

$$S \equiv \frac{k_B T}{n_e^{2/3}}$$

What does the AGN do?

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- Why?
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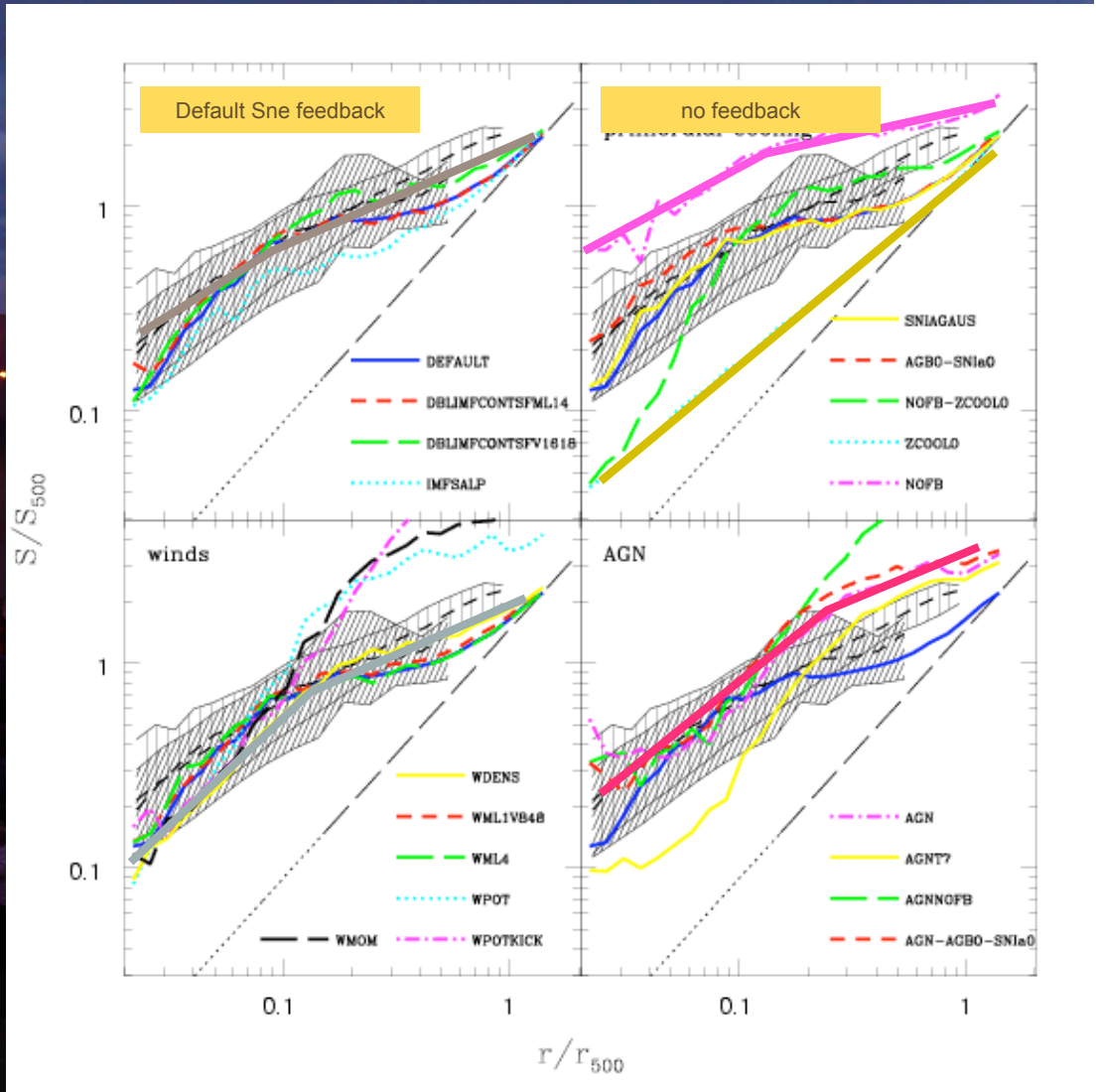

McCarthy et al 2009

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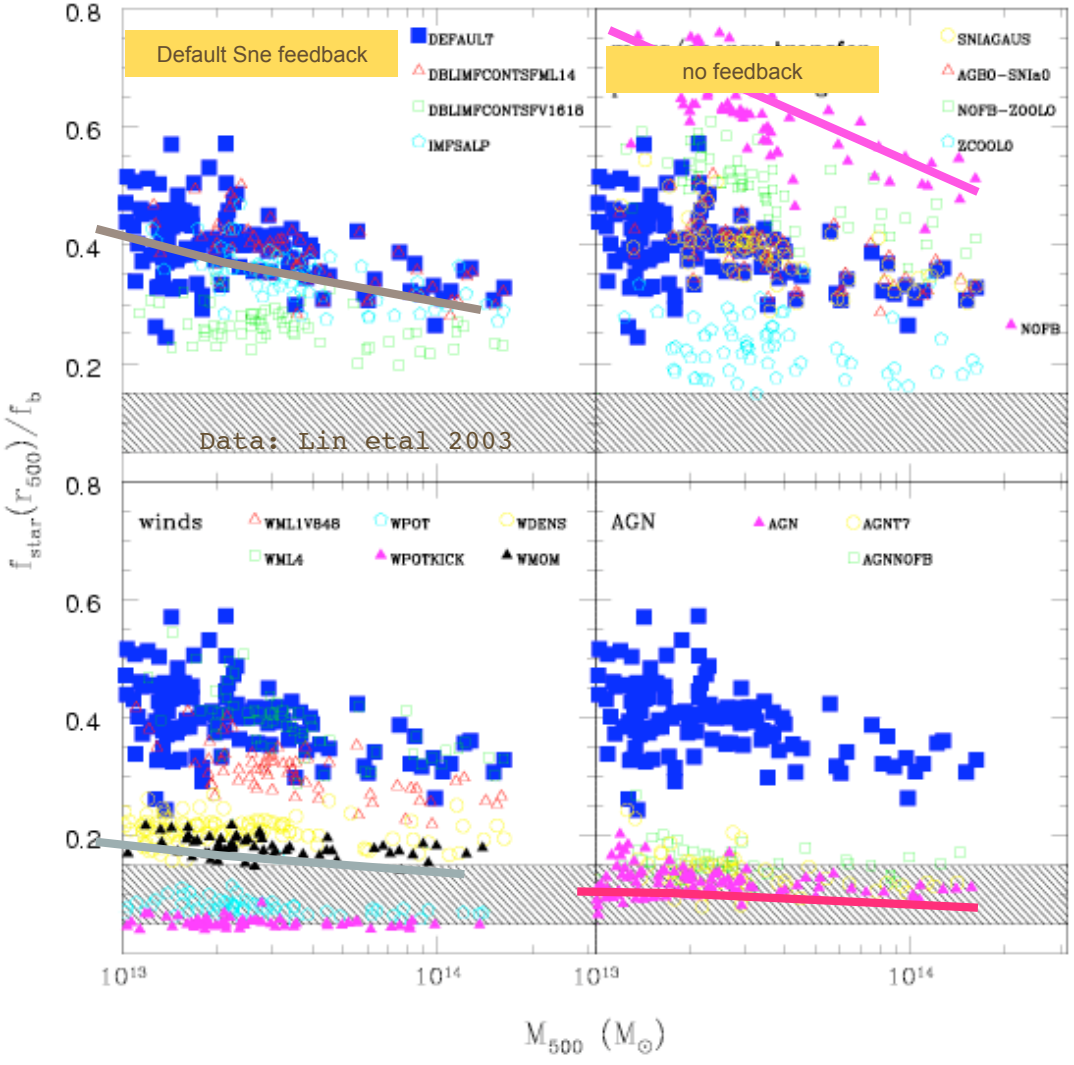
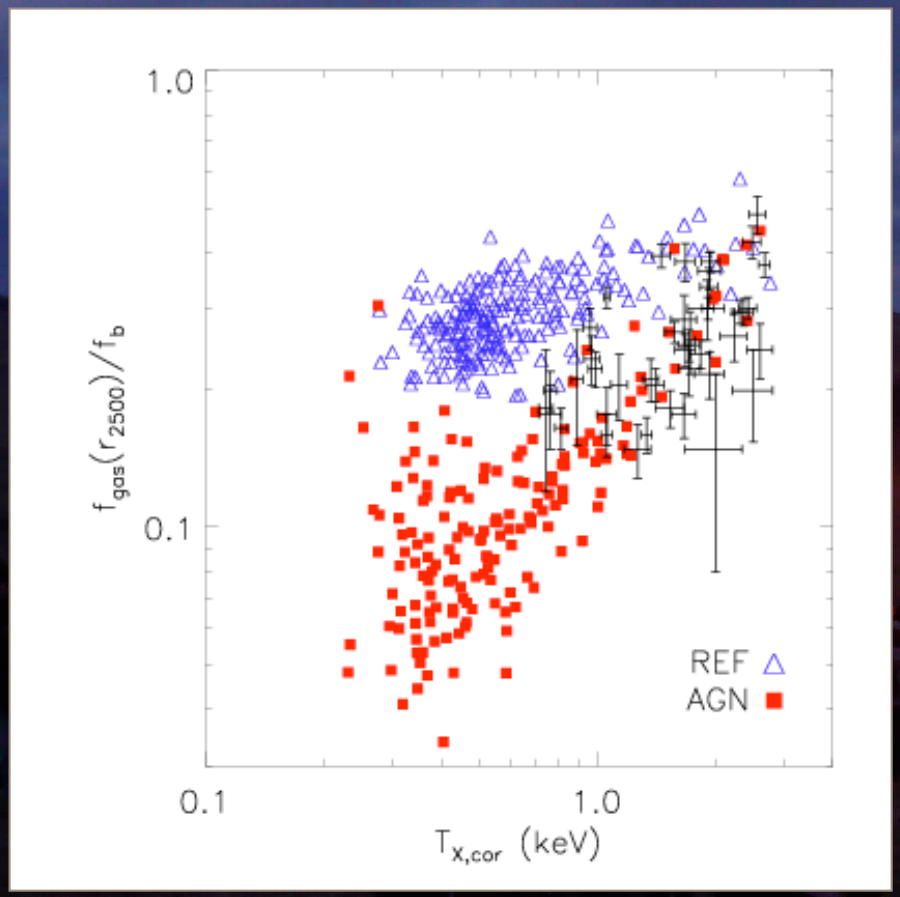
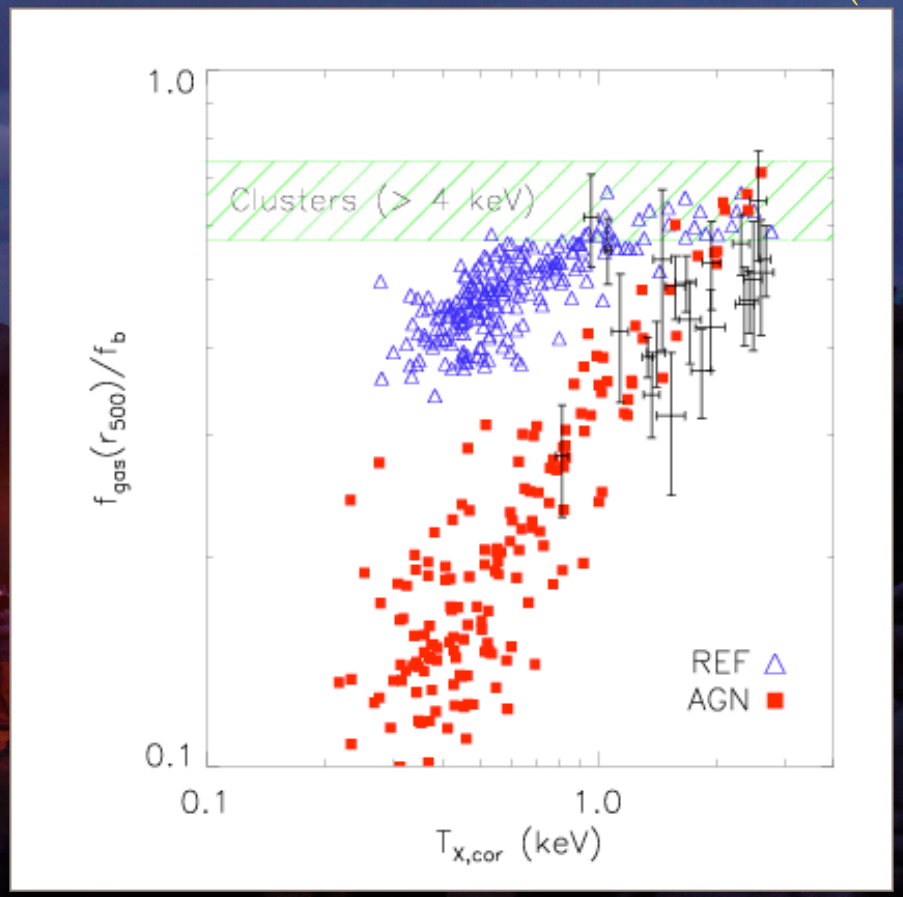


McCarthy et al 2009

Gas mass fractions within r_{2500} and r_{500}

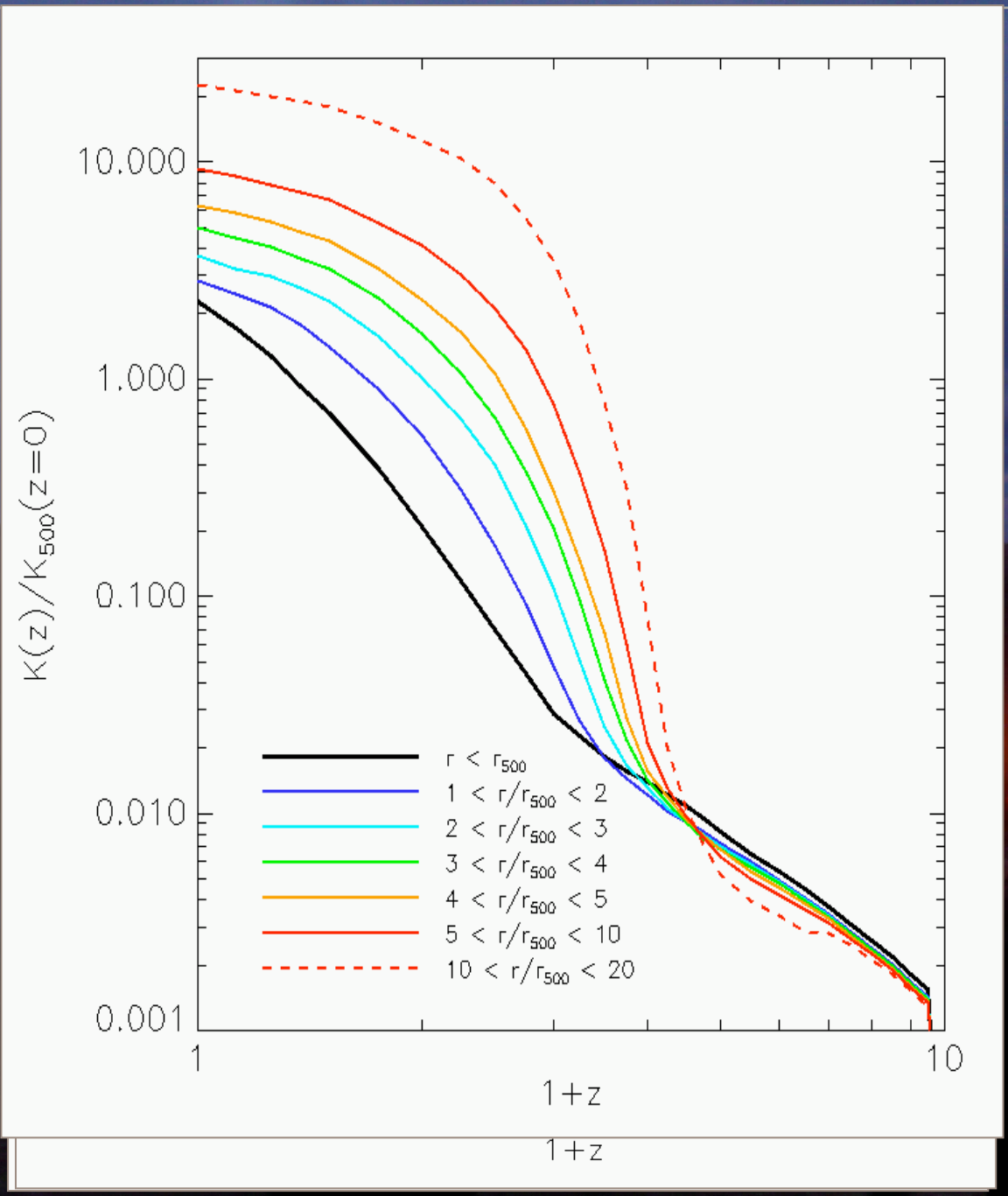
Data from M. Sun et al. (2009)





• Energy input from supermassive black holes yields gas mass fractions in good agreement with observations. Fractions converge to cosmic for M > ~10^{14} M_{sun} : black holes are not powerful enough and the cooling time is long.

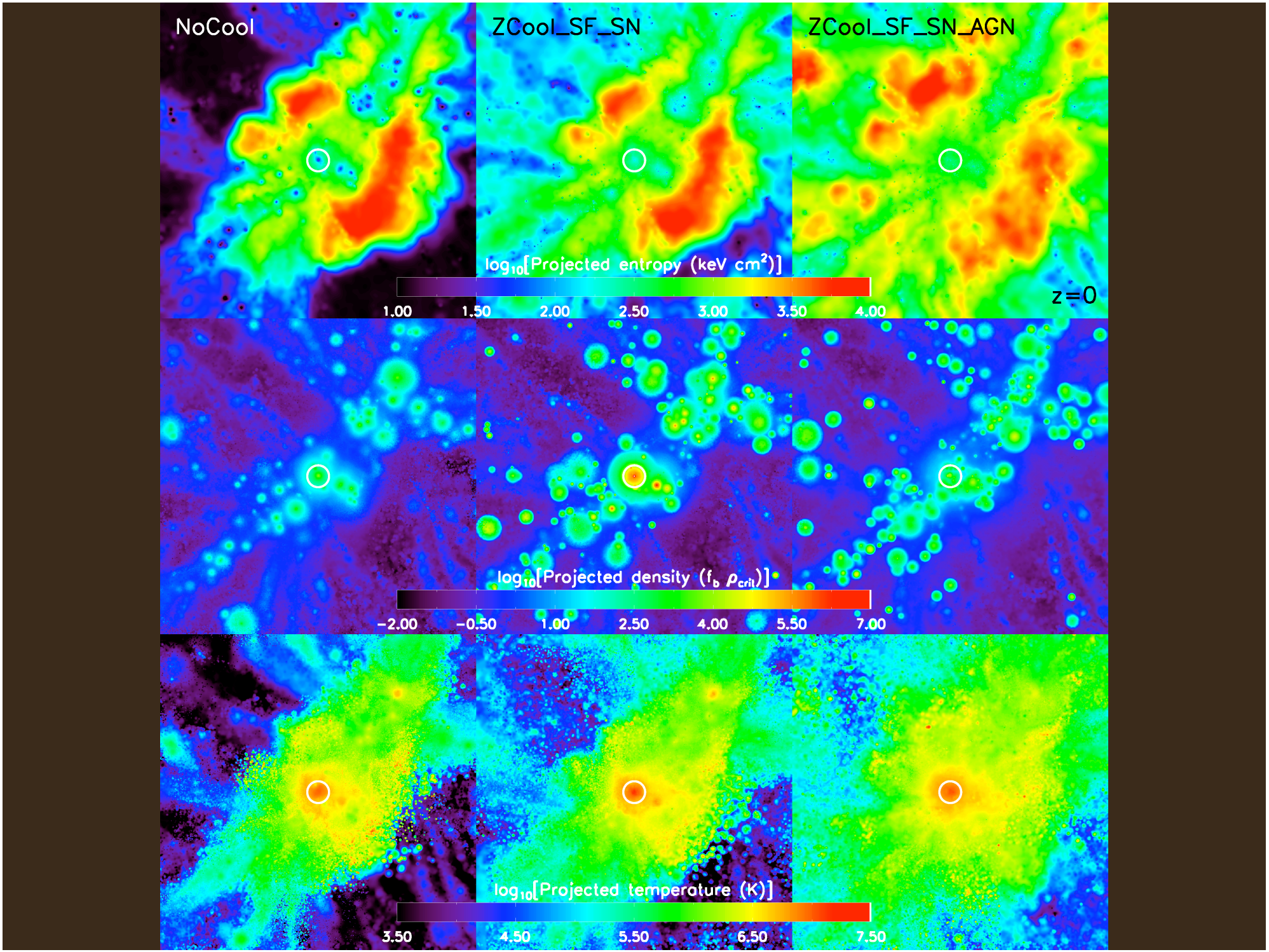
McCarthy et al. (2010), MNRAS, in press

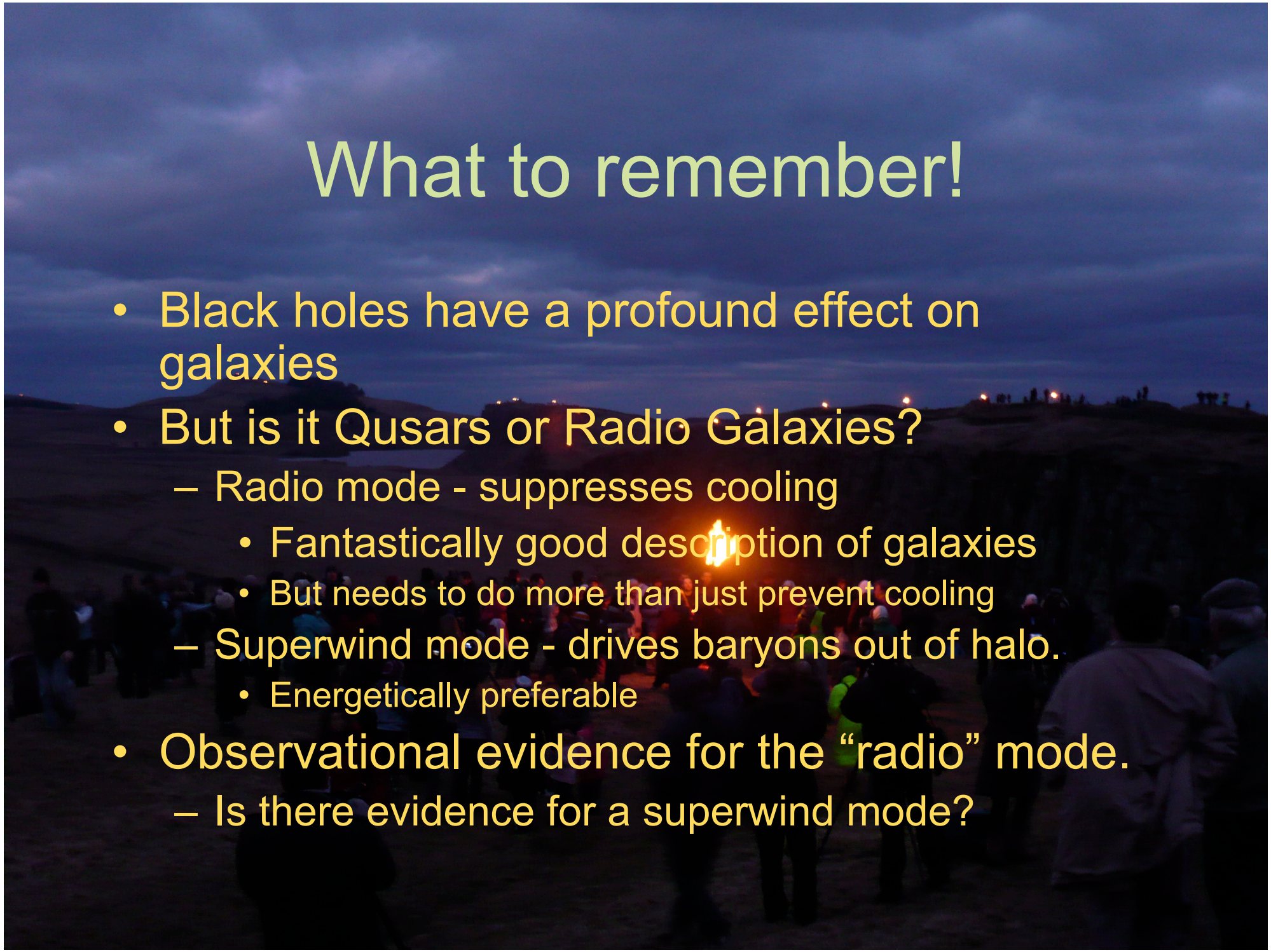


get generated

Simulations have identical ICs. Follow a gas parcel over cosmic time in different sims to isolate effects of feedback, cooling, etc.

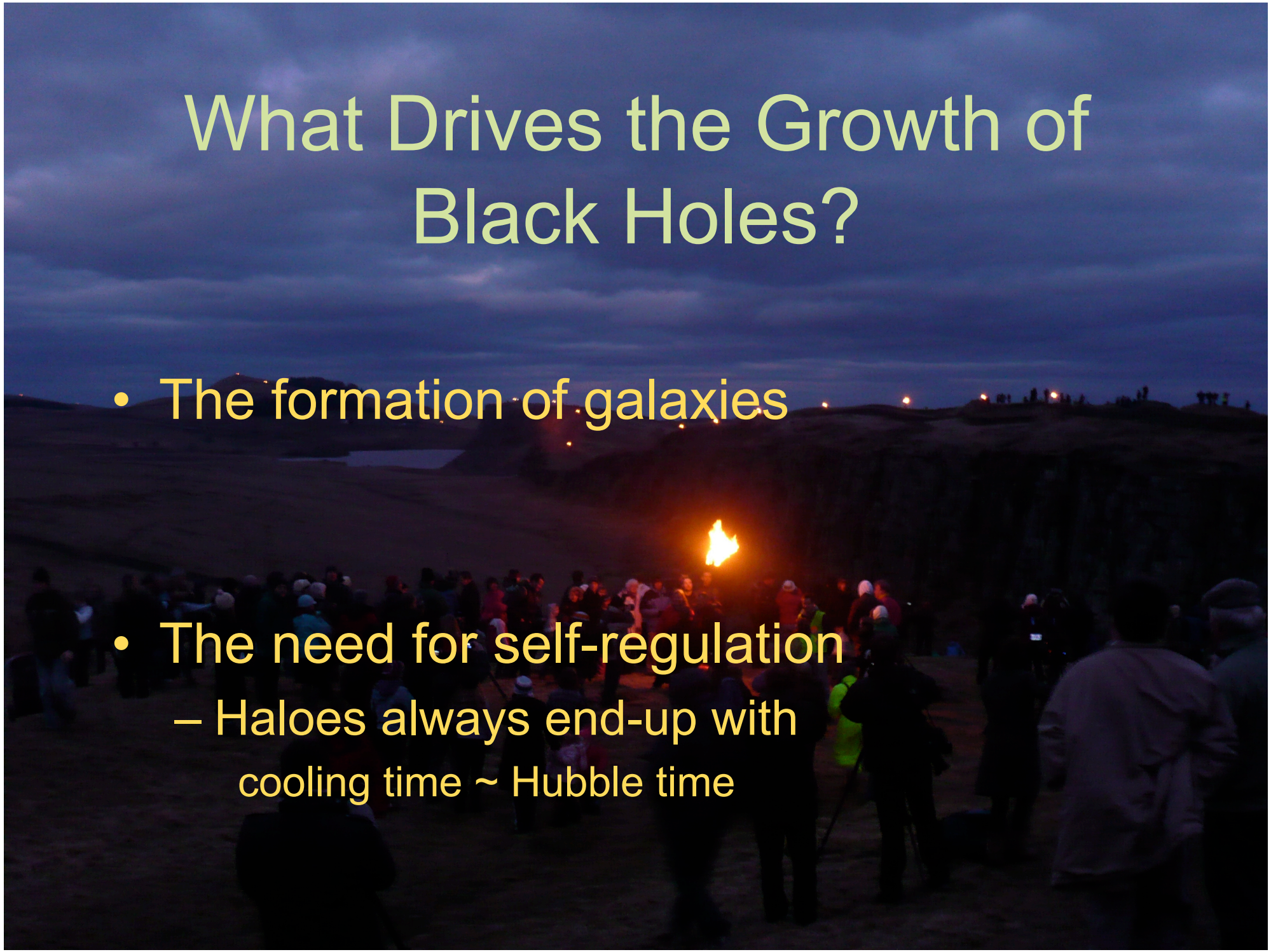
Entropy excess is generated very early - this is feedback by QSO winds. The material then has too much entropy to collapse into group haloes at z=0


NoCool
ZCool_SF_SN
ZCool_SF_SN_AGN
log10[Projected entropy (keV cm2)]
1.00
1.50
2.00
2.50
3.00
3.50
4.00
z=0
log10[Projected density (fb ρcrit)]
−2.00
−0.50
1.00
2.50
4.00
5.50
7.00
log10[Projected temperature (K)]
3.50
4.50
5.50
6.50
7.50



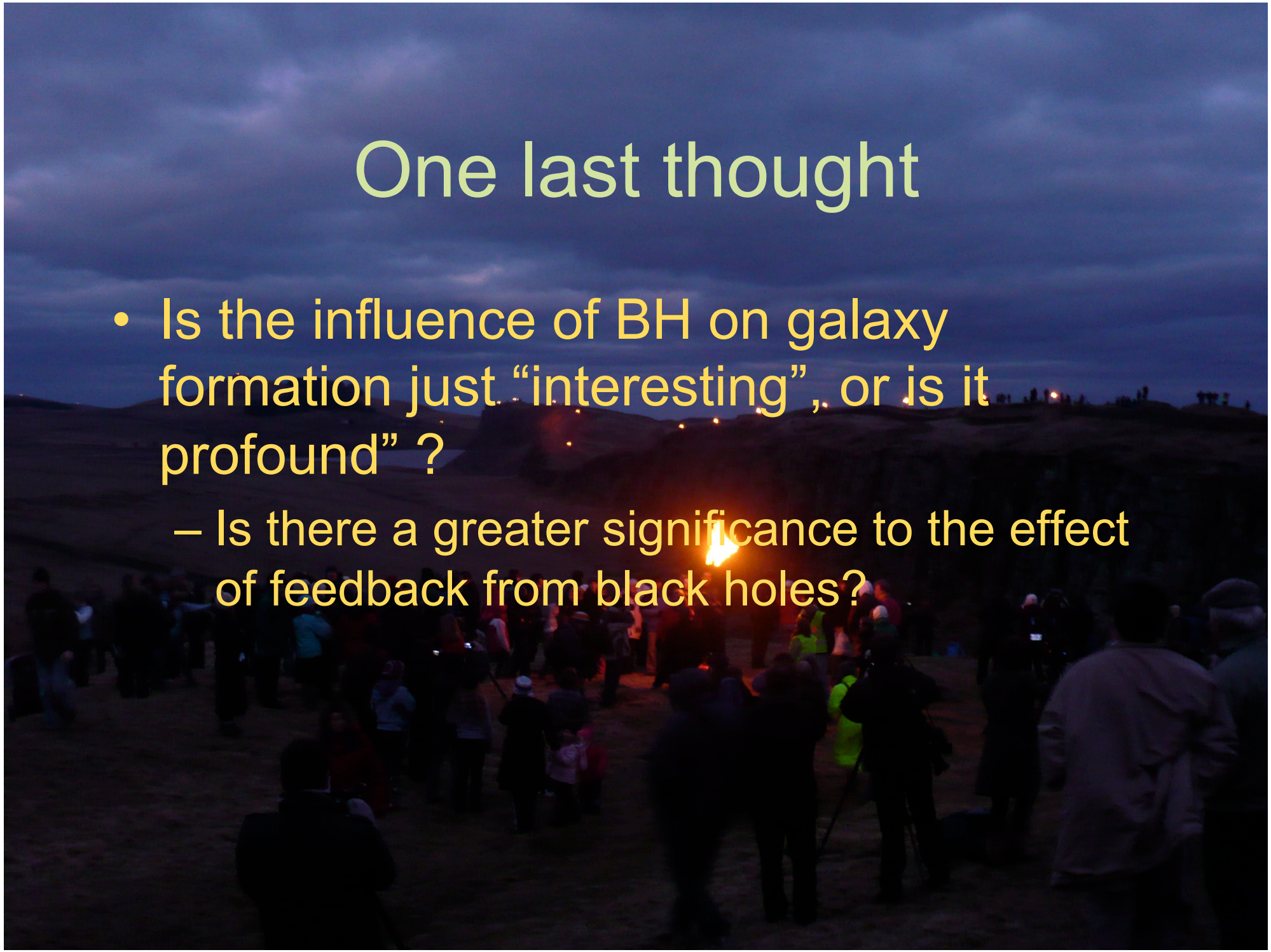
What to remember!

- Black holes have a profound effect on galaxies
- But is it Qusars or Radio Galaxies?
  - Radio mode - suppresses cooling
    - Fantastically good description of galaxies
    - But needs to do more than just prevent cooling
  - Superwind mode - drives baryons out of halo.
    - Energetically preferable
- Observational evidence for the “radio” mode.
  - Is there evidence for a superwind mode?



What Drives the Growth of Black Holes?

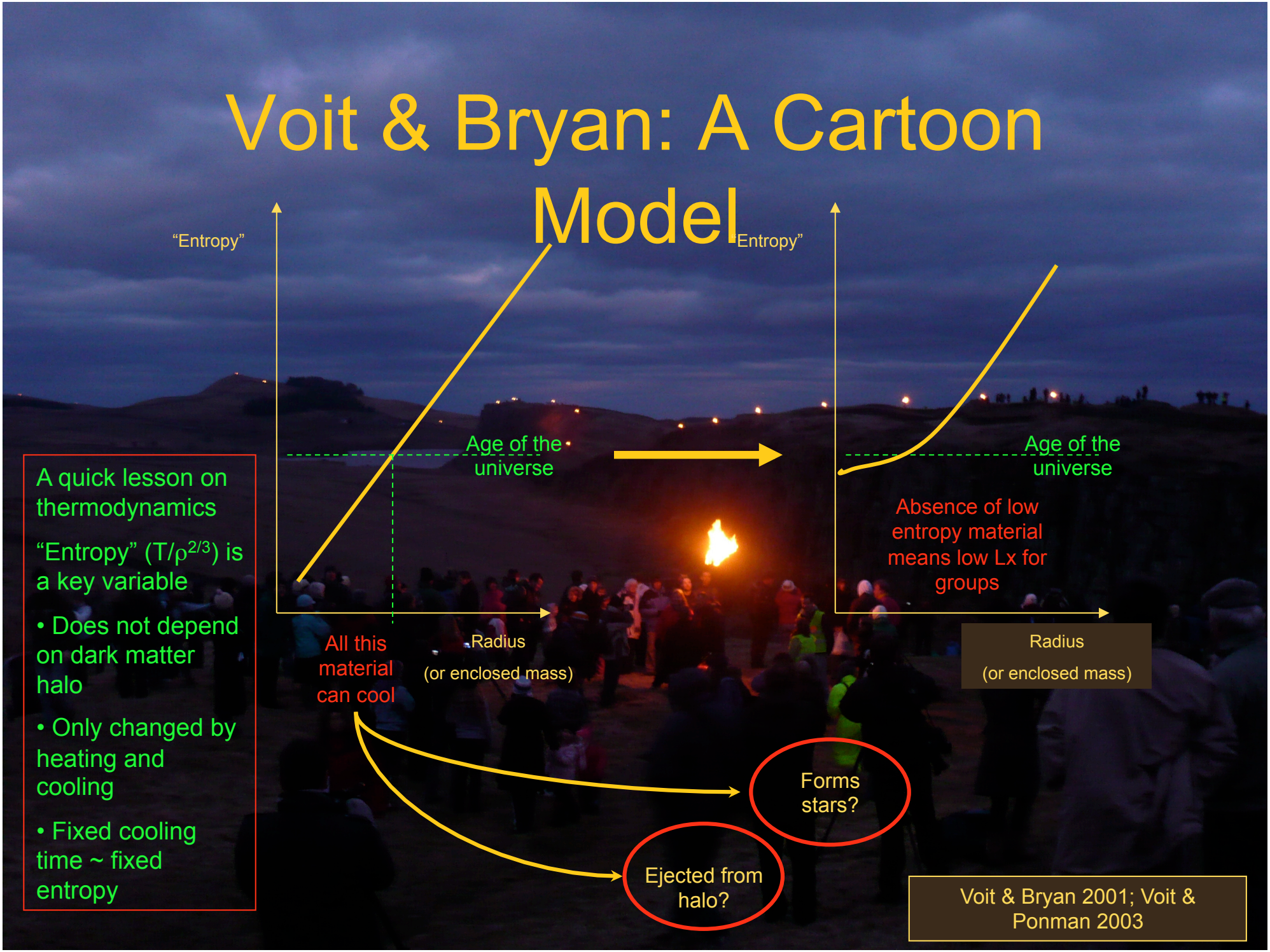
- The formation of galaxies
- The need for self-regulation
  - Haloes always end-up with cooling time ~ Hubble time



One last thought

- Is the influence of BH on galaxy formation just “interesting”, or is it profound” ?
  - Is there a greater significance to the effect of feedback from black holes?

Voit & Bryan: A Cartoon Model



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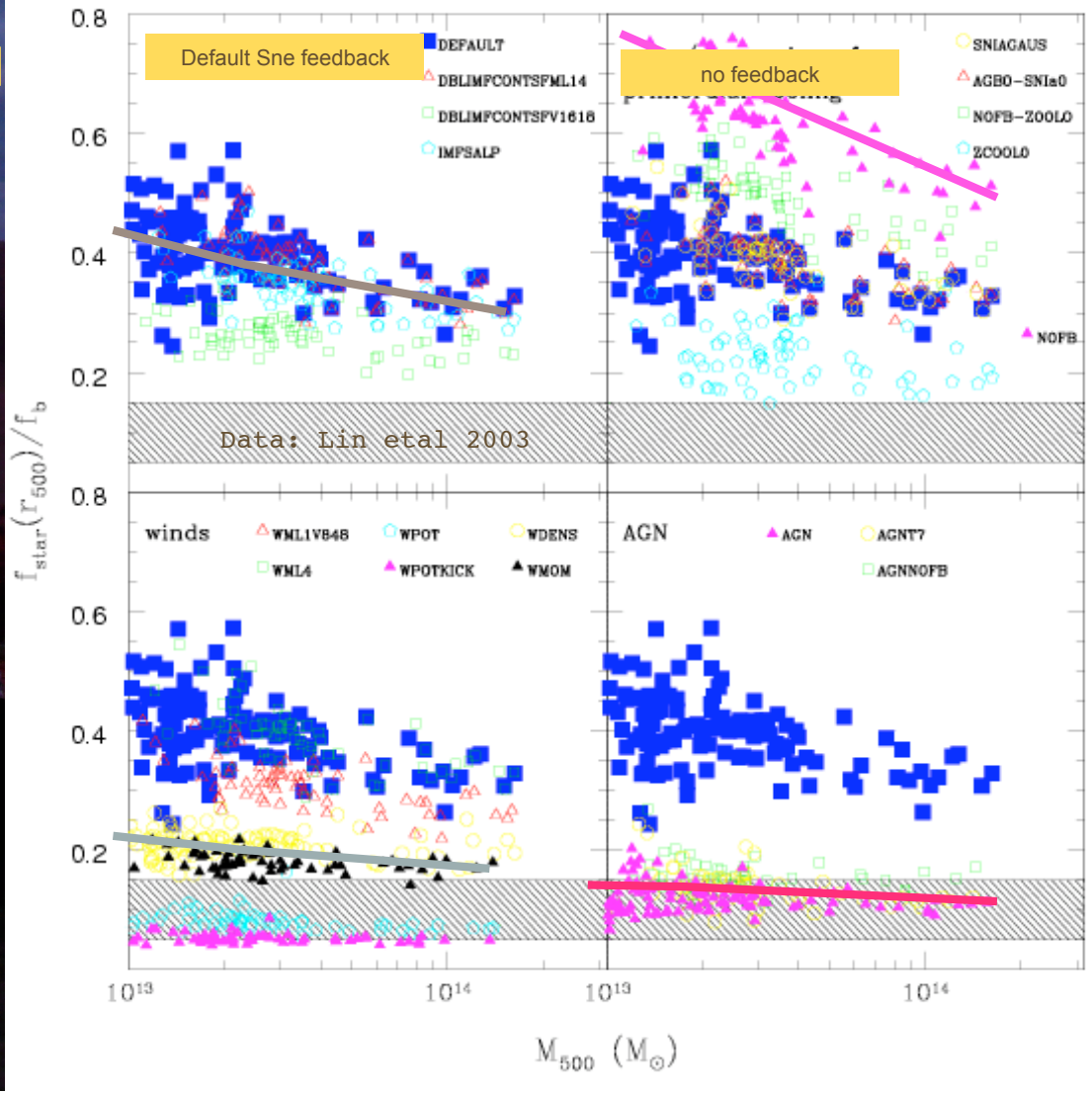

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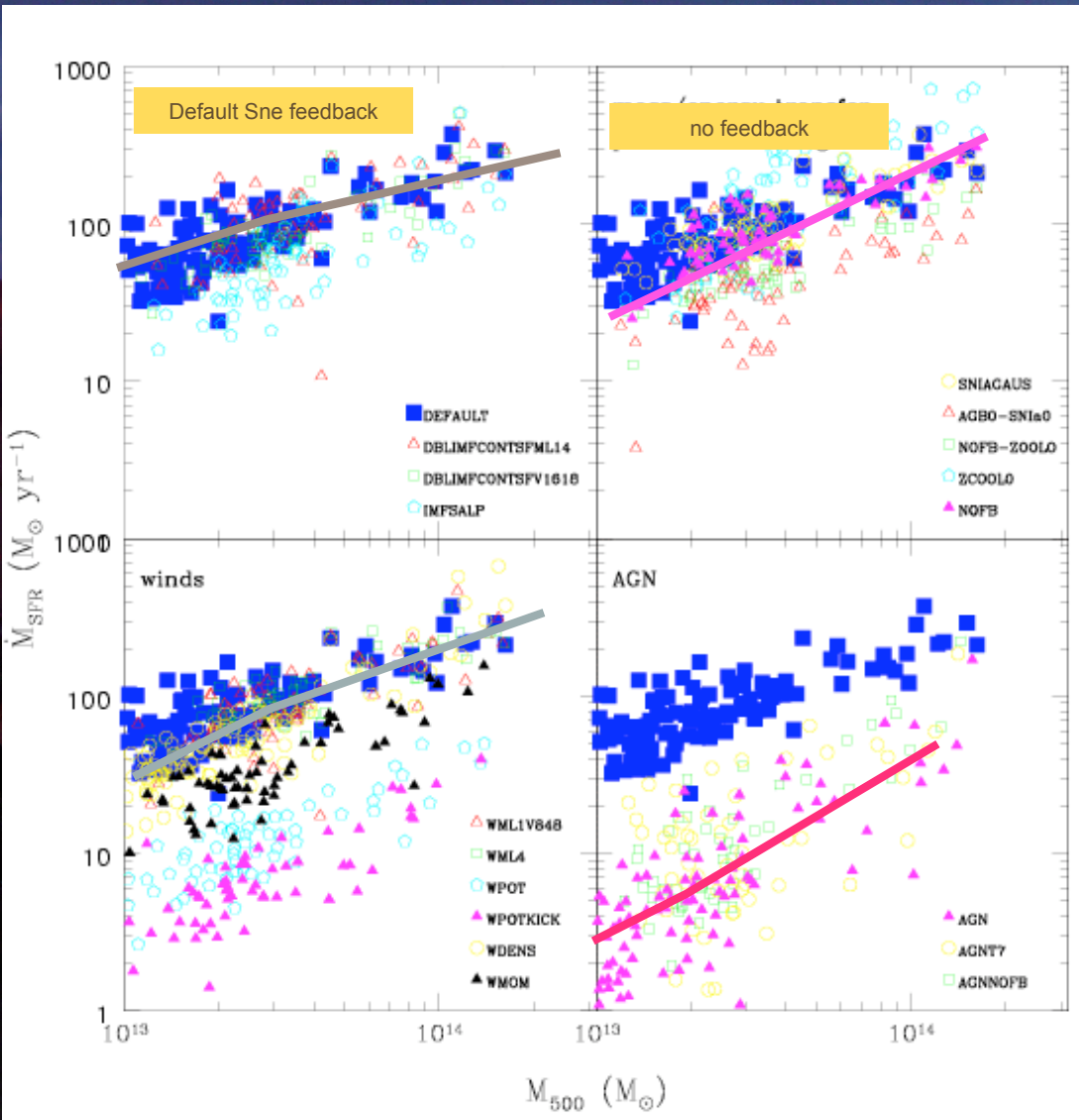
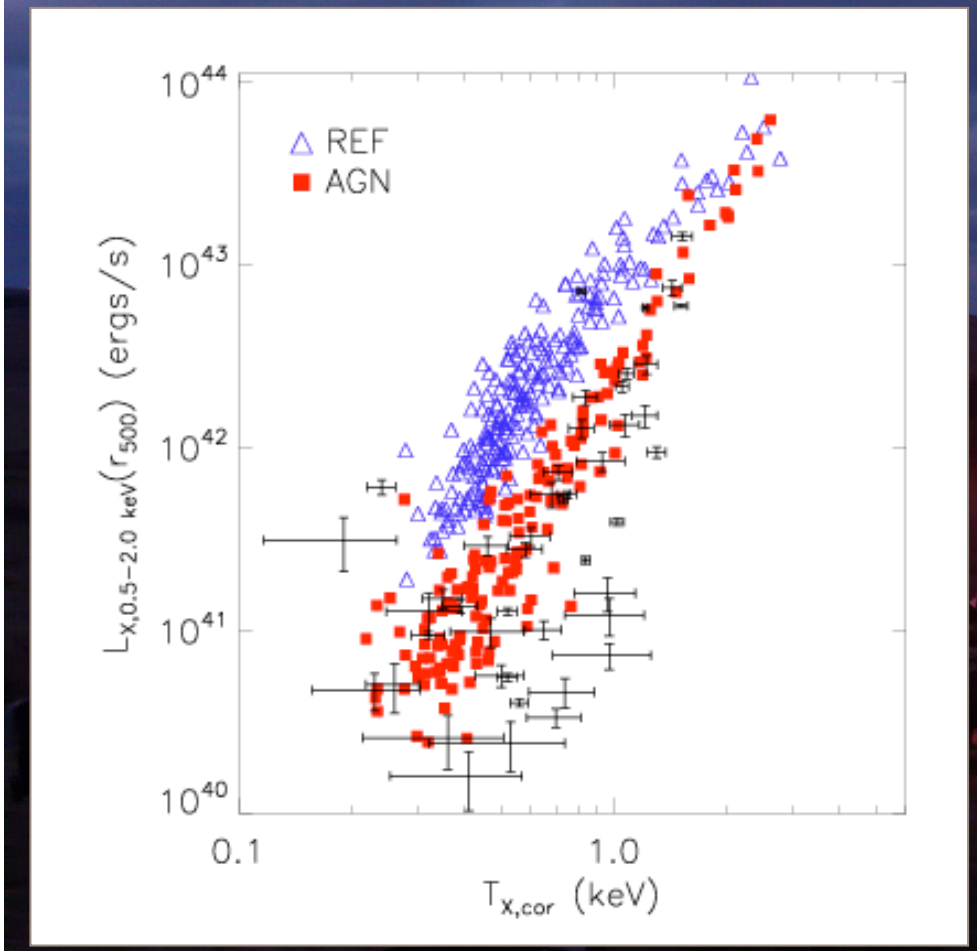
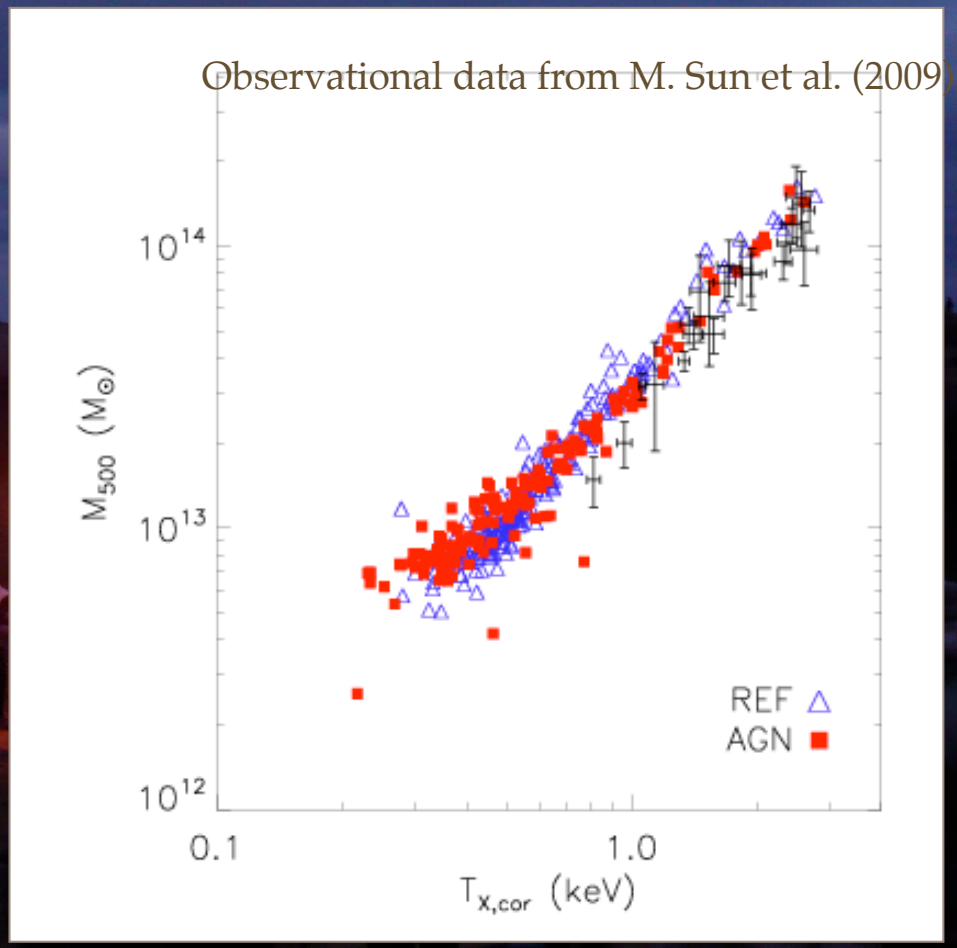


McCarthy et al. (2010), MNRAS, in press

L_X-T and M_{500}-T relations



Observational data from M. Sun et al. (2009)

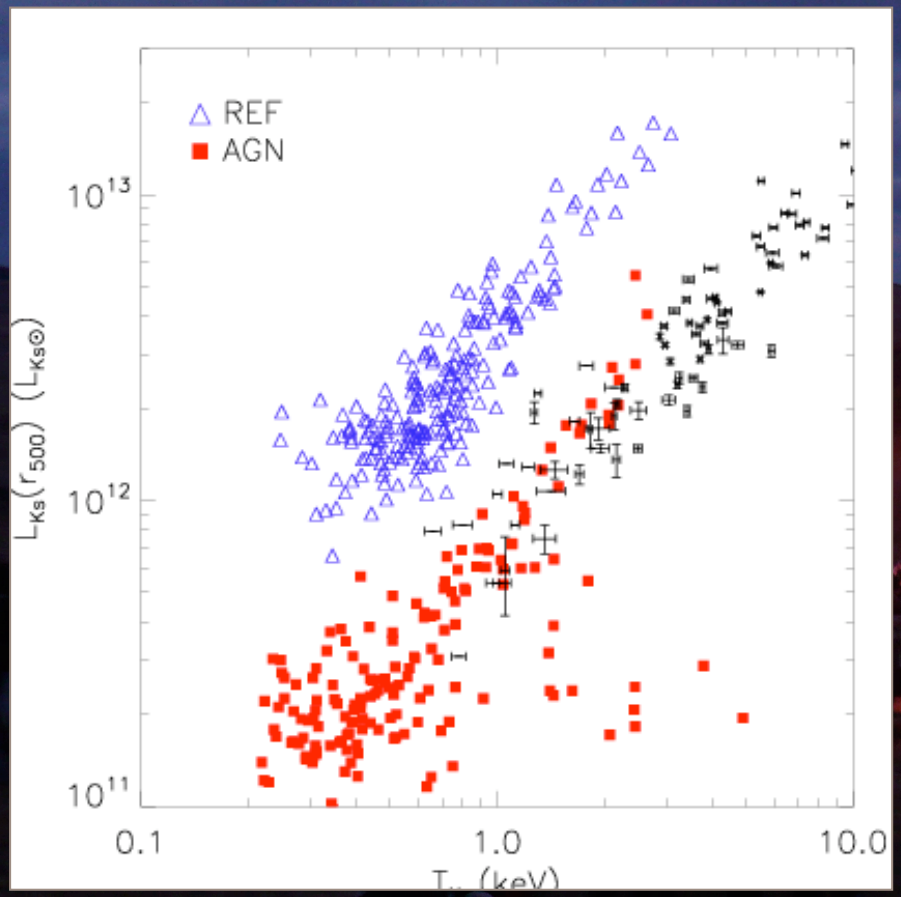


Data from Osmond & Ponman (2004) and M. Sun et al. (2009)

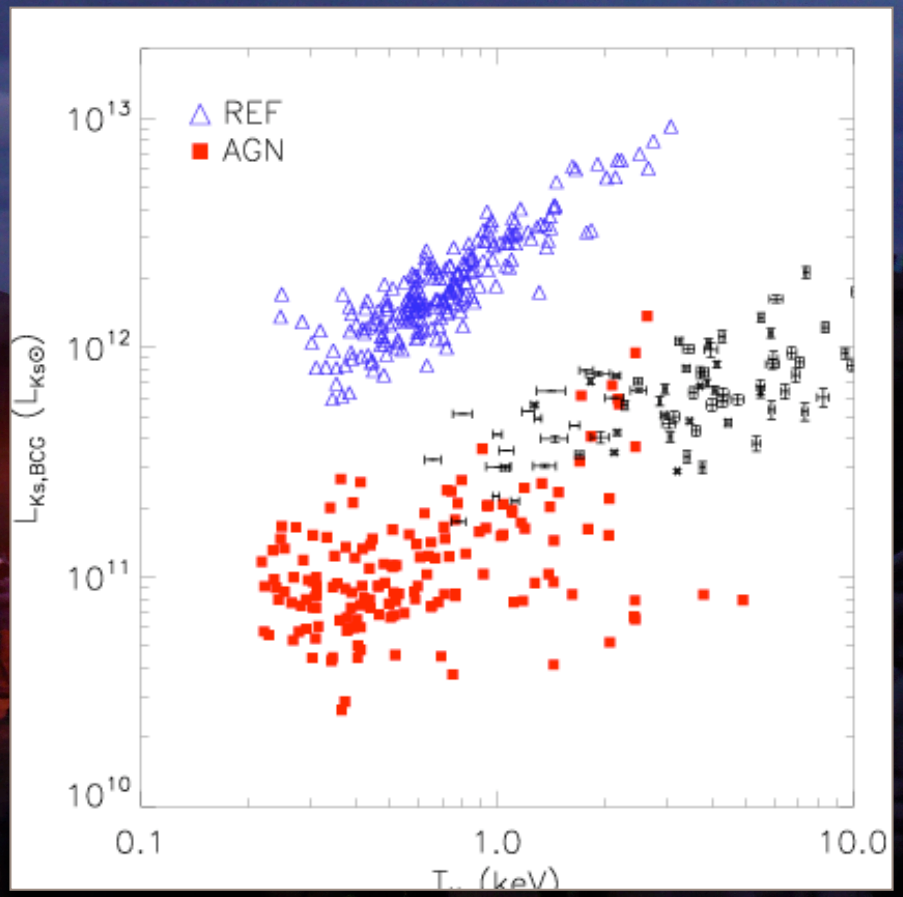
McCarthy et al. (2010), MNRAS, in press

Star formation efficiency: K-band luminosities

Data from Lin & Mohr (2004); Rasmussen & Ponman (2009); Horner (2001)



$L_K(r_{500})$ vs. T_x



$L_{K,BCG}$ vs. T_x

'Cooling crisis' of cosmological simulations is resolved!