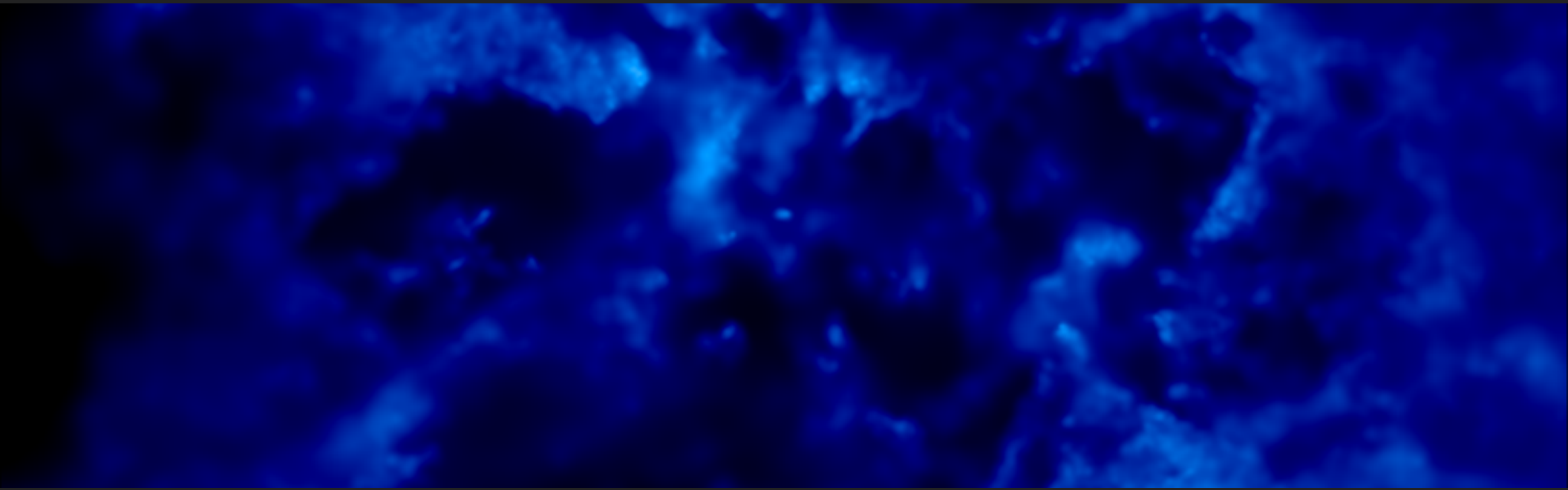


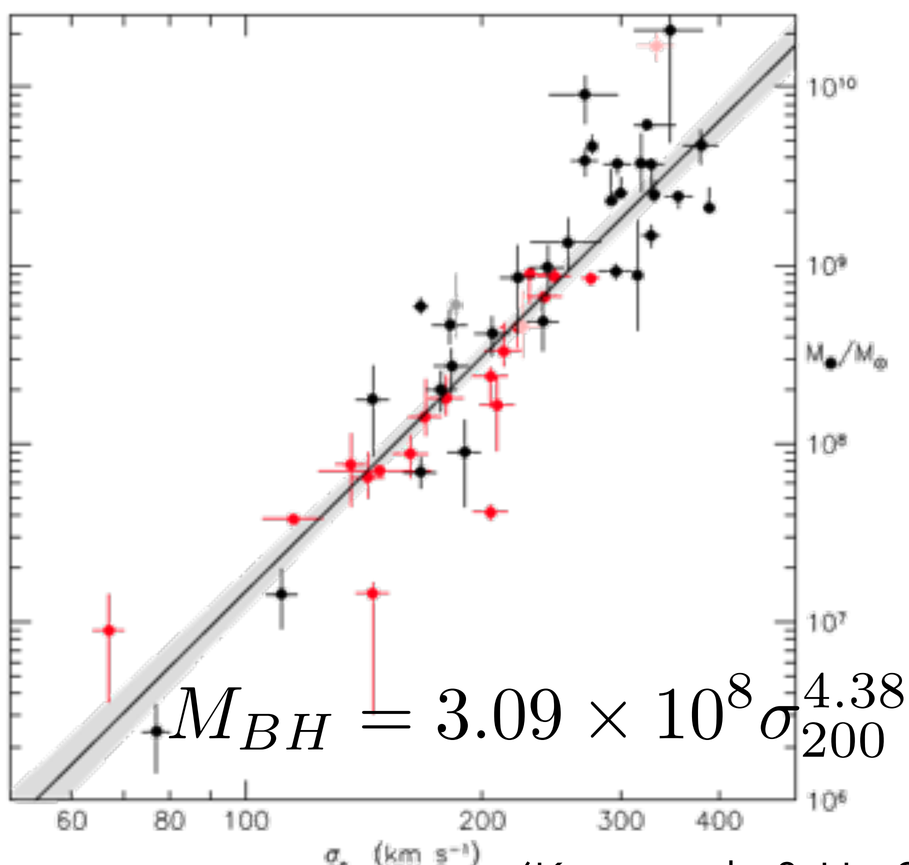
MARTIN BOURNE

DEBORA SIJACKI, MIKE CURTIS, SERGEI NAYAKSHIN, ALEX HOBBS & KASTYTIS ZUBOVAS

SHAPING GALAXIES WITH BLACK HOLE FEEDBACK

CONSTRAINING FEEDBACK MODELS

SCALING RELATIONS



$$M_{BH} = 3.09 \times 10^8 \sigma_{200}^{4.38} M_\odot$$

(Kormendy & Ho 2013)

$$\frac{E_{\rm BH}}{E_{\rm gas}} \sim \frac{\eta M_{\rm BH} c^2}{f_{\rm g} M_{\rm b} \sigma^2} \sim 10^3 - 10^4$$

LARGE SCALE OUTFLOWS

- Range of states and velocities
  - Ionised ~ 3000 km/s
  - Neutral atomic ~ 1000 km/s
  - Cold molecular ~ 1000 km/s

$$\dot{M}_{\rm out} \sim 100 - 1000\ {\rm M_\odot\ yr^{-1}}$$

$$\dot{E}_{\rm out} \sim 0.05 L_{\rm AGN}$$

$$\dot{p}_{\rm out} \sim 20 \frac{L_{\rm AGN}}{c}$$

e.g. Feruglio et al., 2010, Sturm et al., 2011,Rupke & Veilleux, 2011, 2013 a,b, Cicone et al., 2012, 2014, 2015, Faucher-Giguére et al., 2012, Maiolino et al., 2012, Arav et al., 2013, Liu et al., 2013, Harrison et al., 2014 ,Carniani et al., 2015, Tombesi et al., 2015

CONSTRAINING FEEDBACK MODELS

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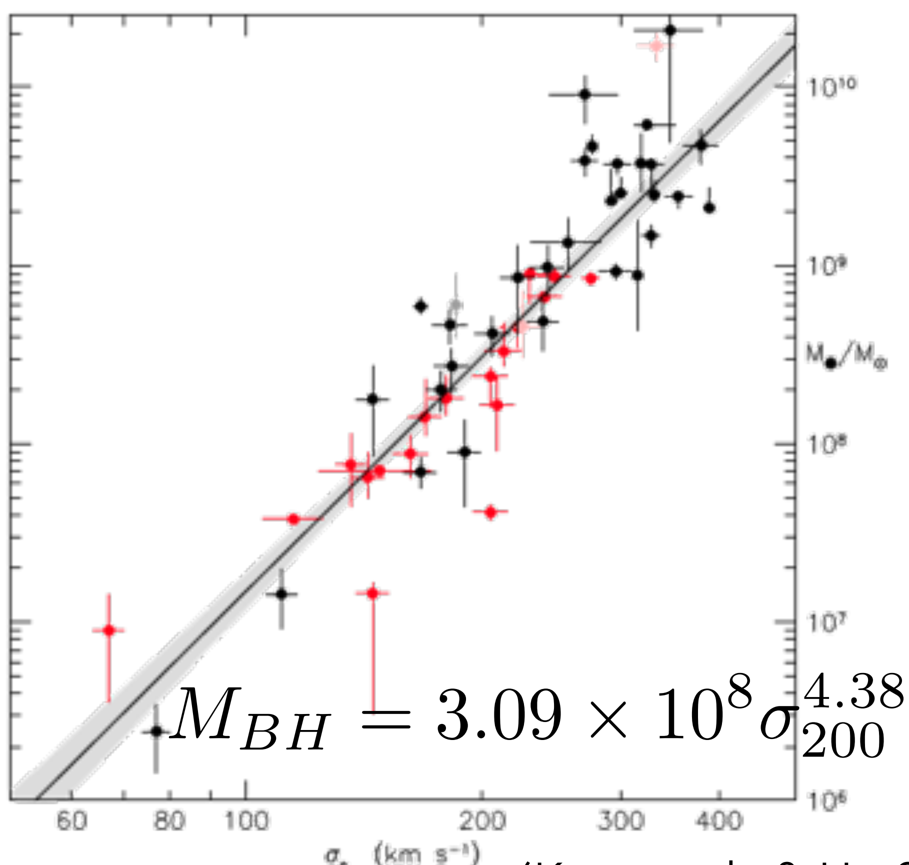

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FAST NUCLEAR WINDS – MOMENTUM VS ENERGY DRIVING

$$v_{\rm wind} \sim 0.1c$$

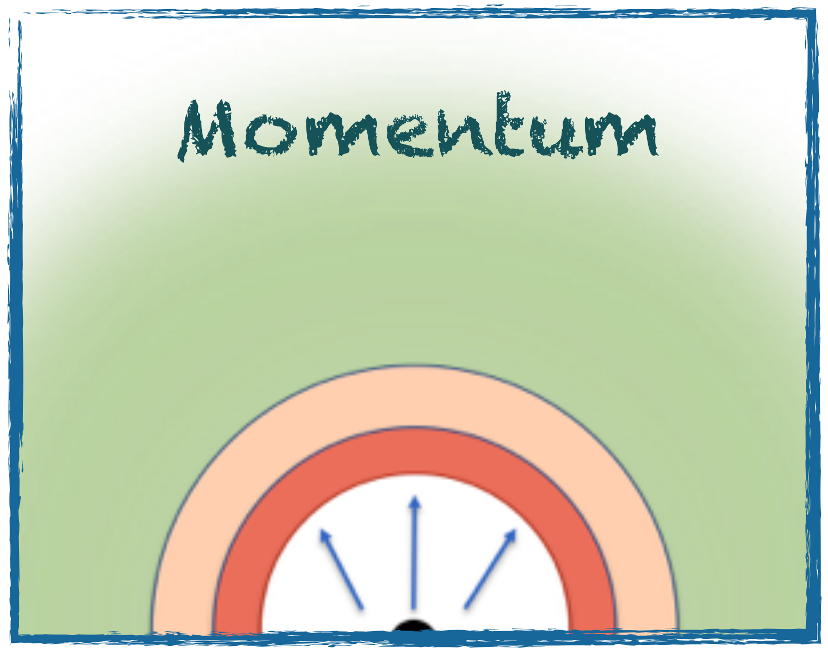
$$\dot{p}_{\rm wind} \simeq \frac{L_{\rm AGN}}{c}$$

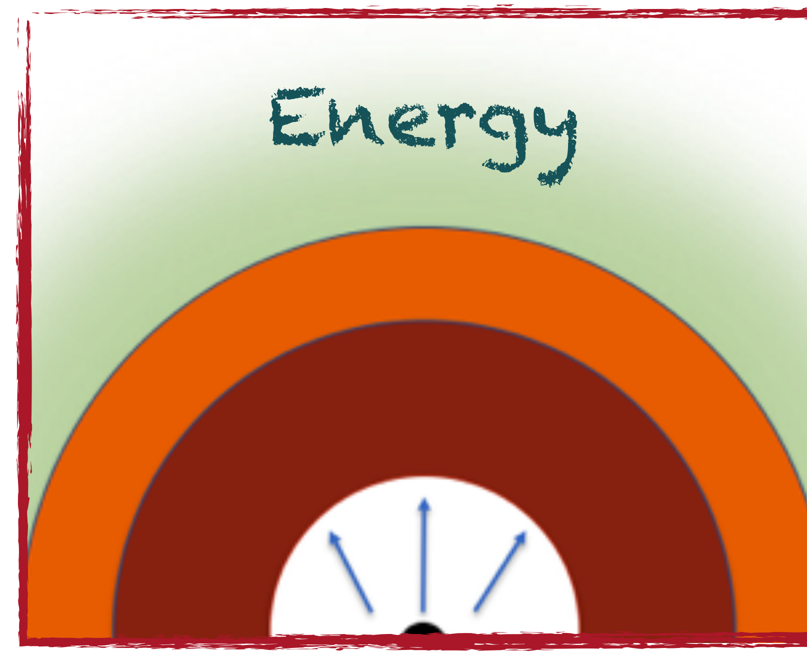
$$\dot{E}_{\rm wind} \sim 0.05 L_{\rm AGN}$$

(e.g. King 2010, King & Pounds 2015)

- X-rays - UFOs
  - Pounds et al., 2003a,b
  - Pounds & Reeves, 2009
  - Tombesi et al., 2010a,b, 2015
  - King & Pounds, 2015 (Review)

FAST NUCLEAR WINDS – MOMENTUM VS ENERGY DRIVING





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(e.g. King 2010, King & Pounds 2015)

e.g. efficient inverse-Compton cooling within ~1kpc (King 2003, 2005)

$$M_\sigma = \frac{f_{\rm g}}{\pi \kappa G^2}\sigma^4$$

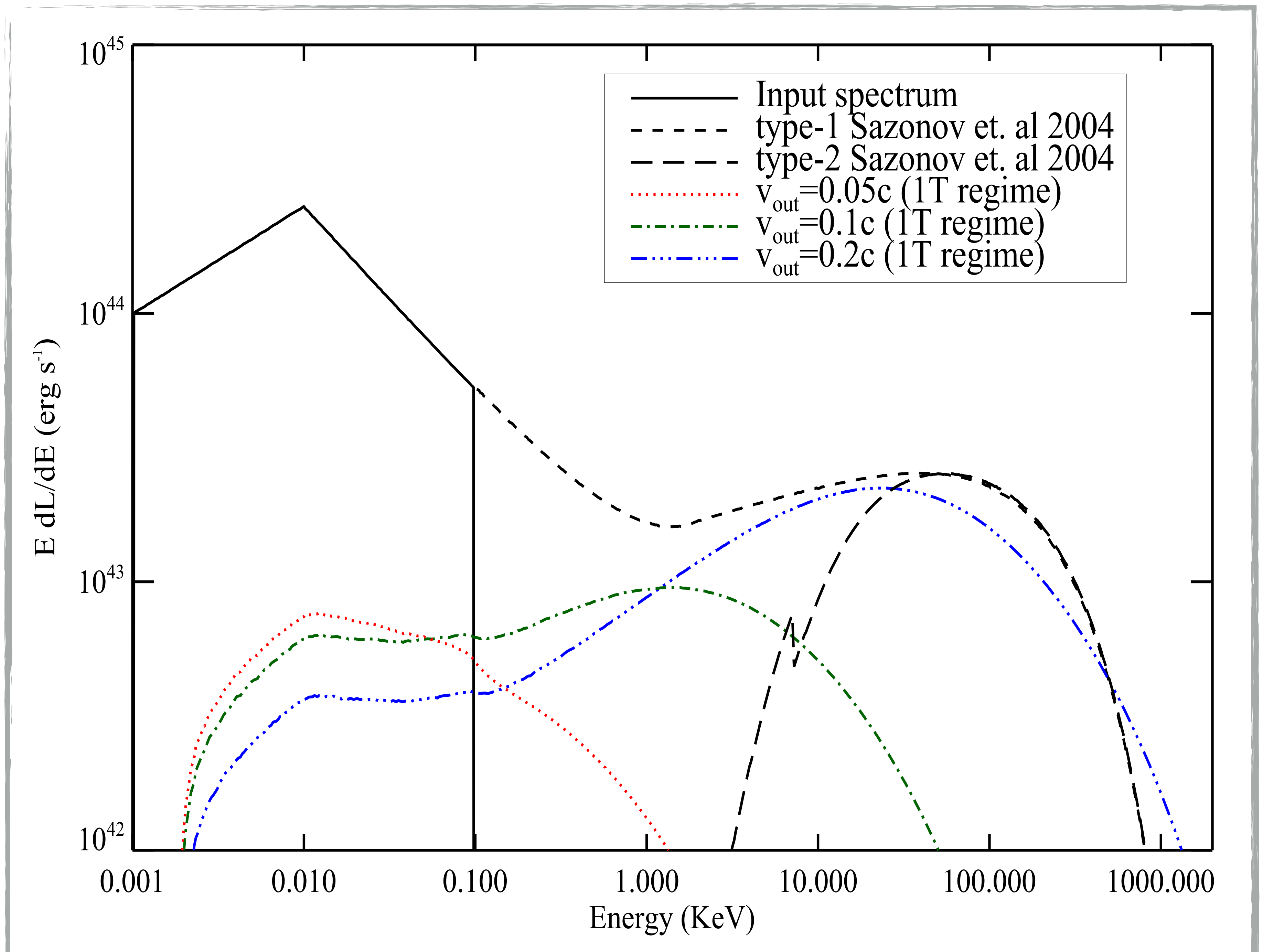
King 2003, 2005
(see also Murray et al. 2005)

$$\dot{E}_{\rm out} \sim 0.05 L_{\rm AGN}$$

$$\dot{p}_{\rm out} \sim 20\frac{L_{\rm AGN}}{c}$$

Zubovas & King 2012, Faucher-Giguere & Quataert 2012

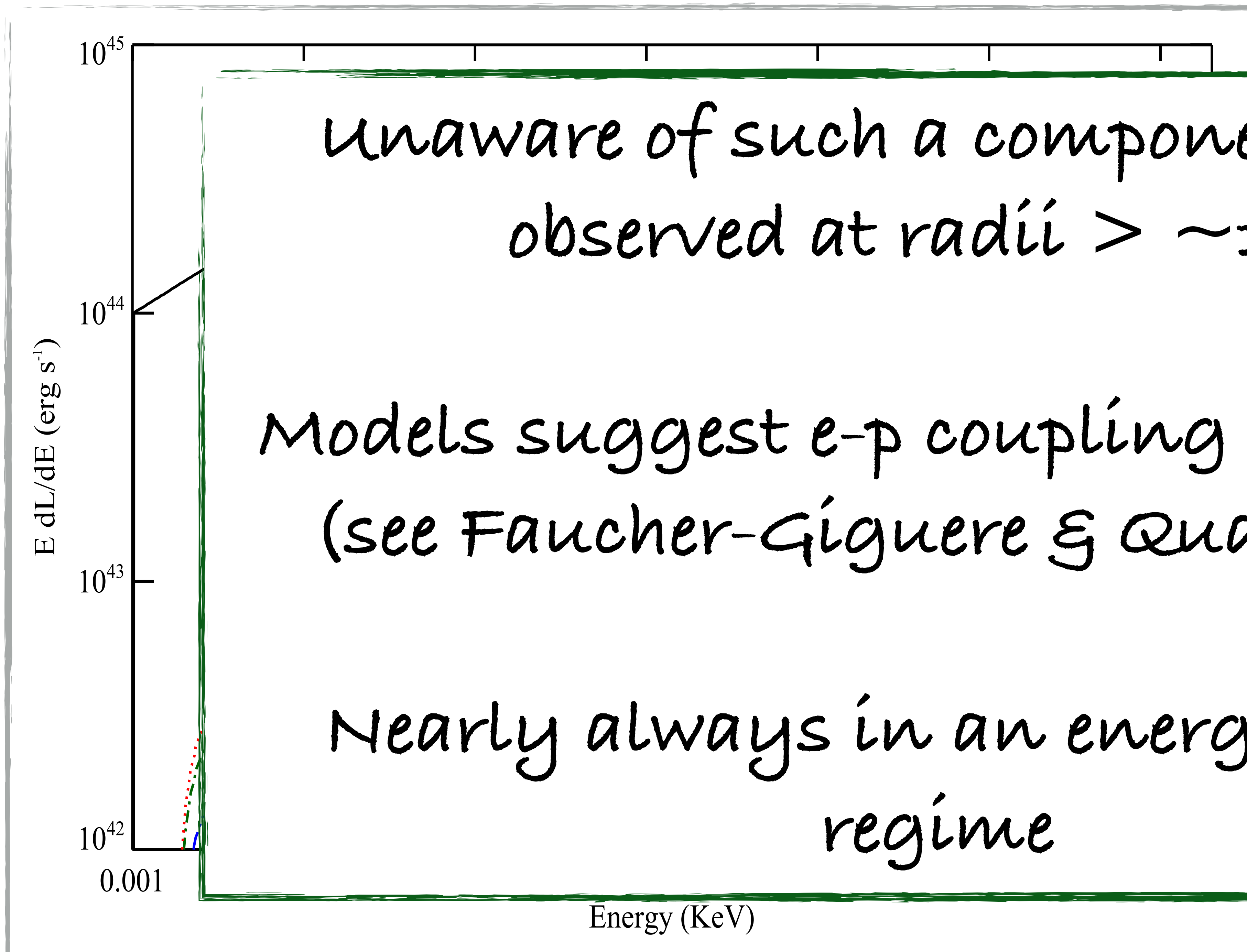
INVERSE COMPTON COMPONENT



- Efficient e-p coupling - 1T shock
- Input spectrum modeled by obs Type 1 AGN, 1-100 eV
- If $R_{shock} > R_{torus}$ still expect to observe spectra at low energies in Type 2 AGN

(Bourne & Nayakshin, 2013)

OBSERVATIONAL SIGNATURES – 1T SHOCK



Unaware of such a component being observed at radii > ~1 pc

Models suggest e-p coupling inefficient (see Faucher-Giguere & Quataert 12)

Nearly always in an energy driven regime

pling -

Type

ill

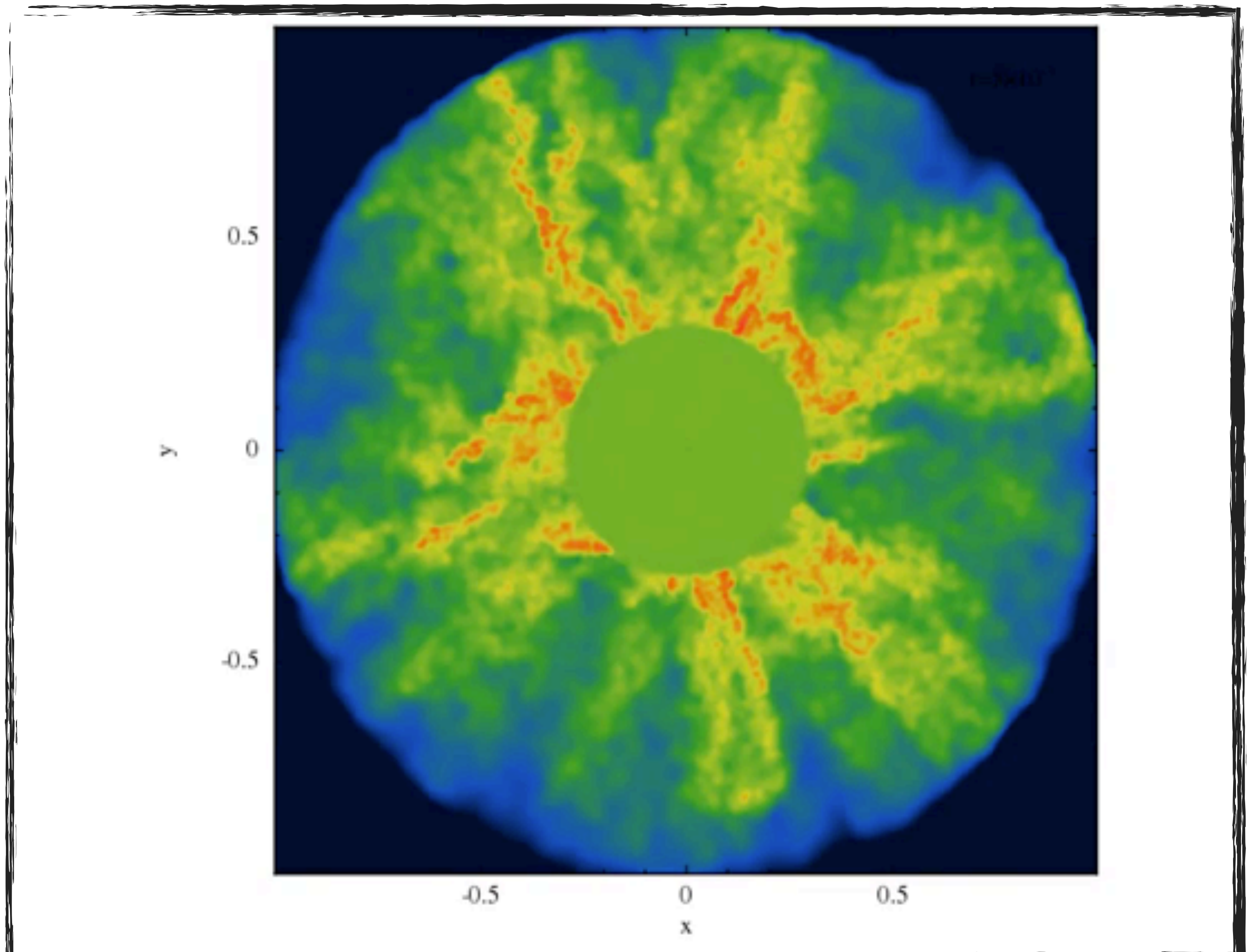
e

2

- variability - light crossing time

(Bourne & Nayakshin, 2013)

HOW RESILIENT ARE GALAXIES? – SET UP



(Bourne, Nayakshin & Hobbs, 2014)

- Use Gadget-3 (Springel 05) to perform SPHS (Read et al. 10 & 12) simulations to study effects of a shocked UFO on ambient medium
- Hot bubble of gas used to model hot shocked wind
- Apply turbulent velocity field to ambient gas & evolve to form ``clumpy'' medium
- Energy escapes through paths of least resistance
- High density material not kicked out but can be compressed and ablated

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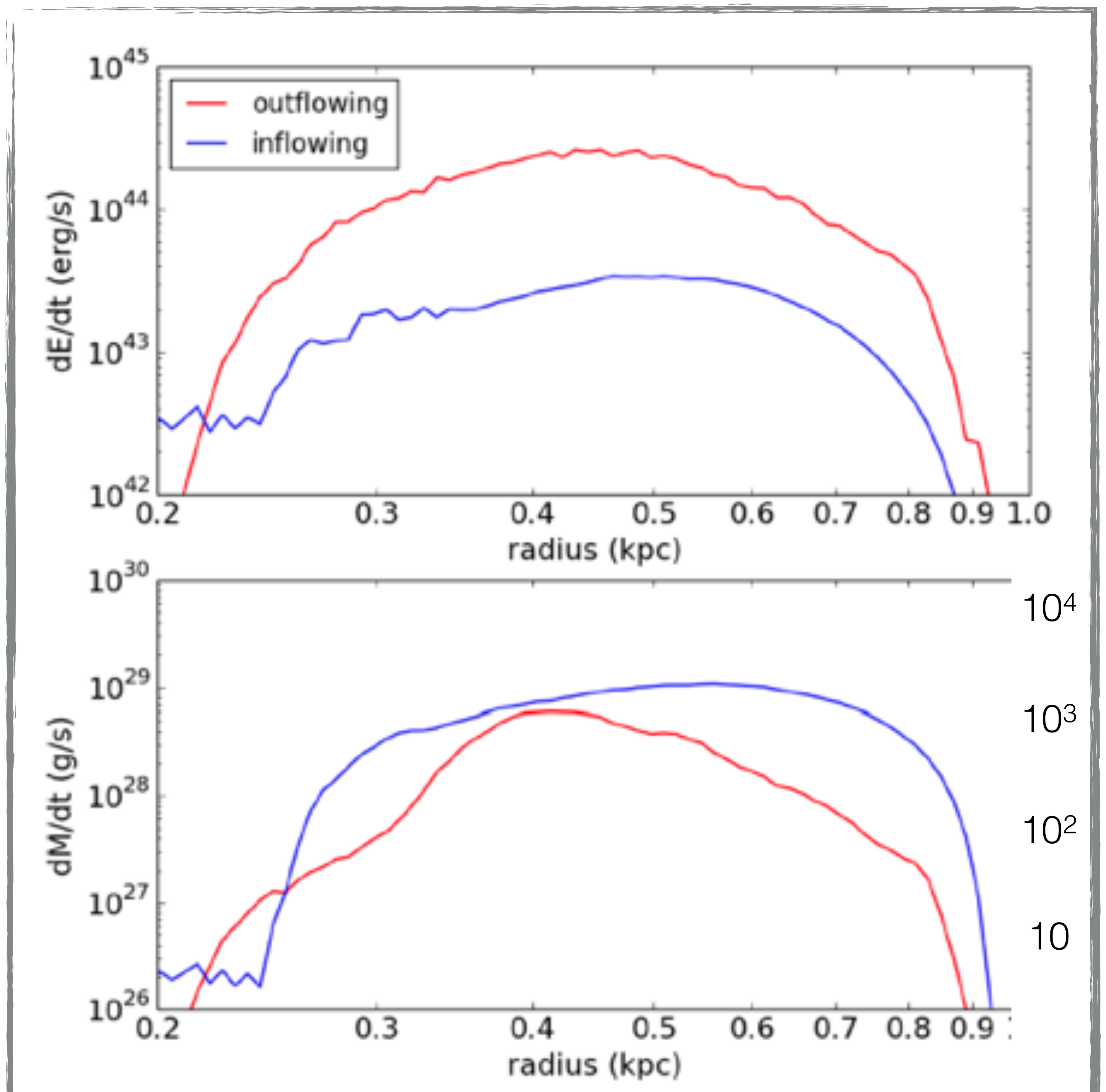
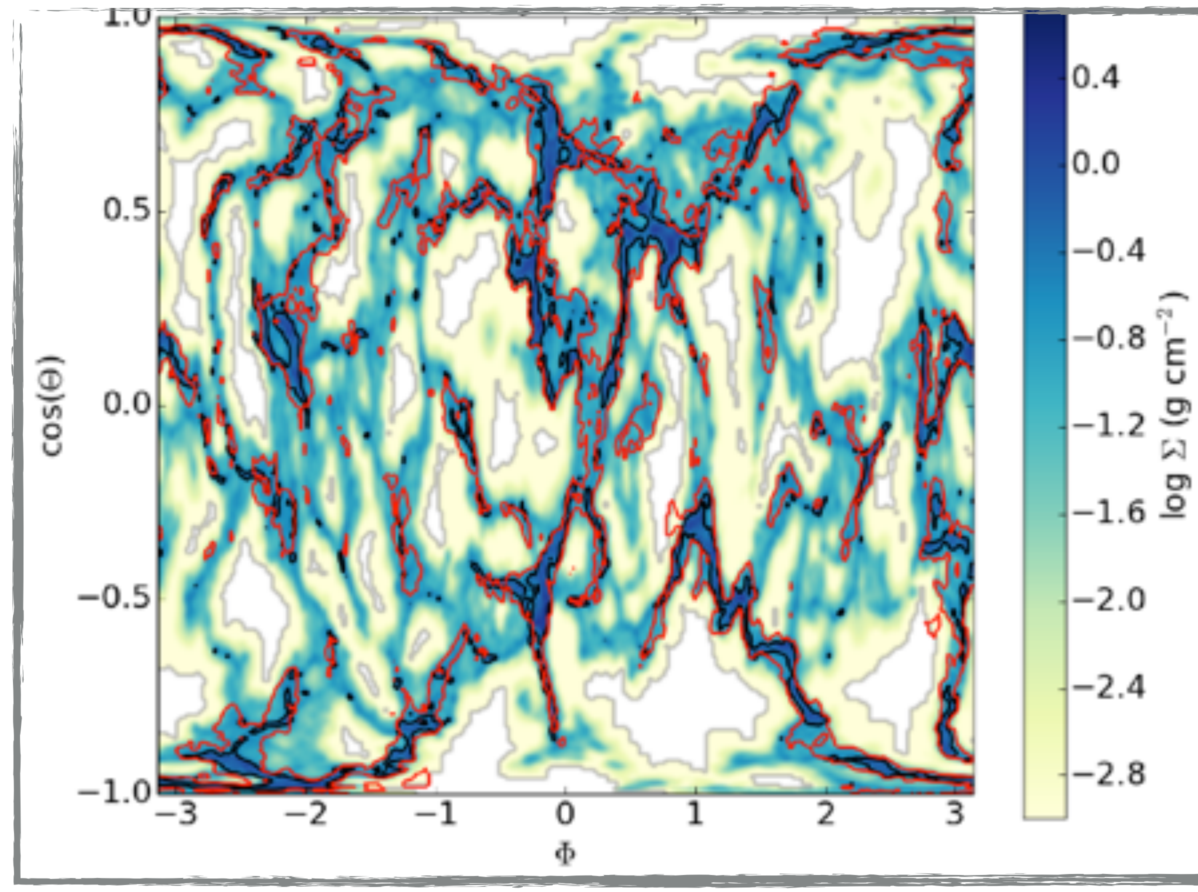
HOW RESILIENT ARE GALAXIES? – FLOW PROPERTIES



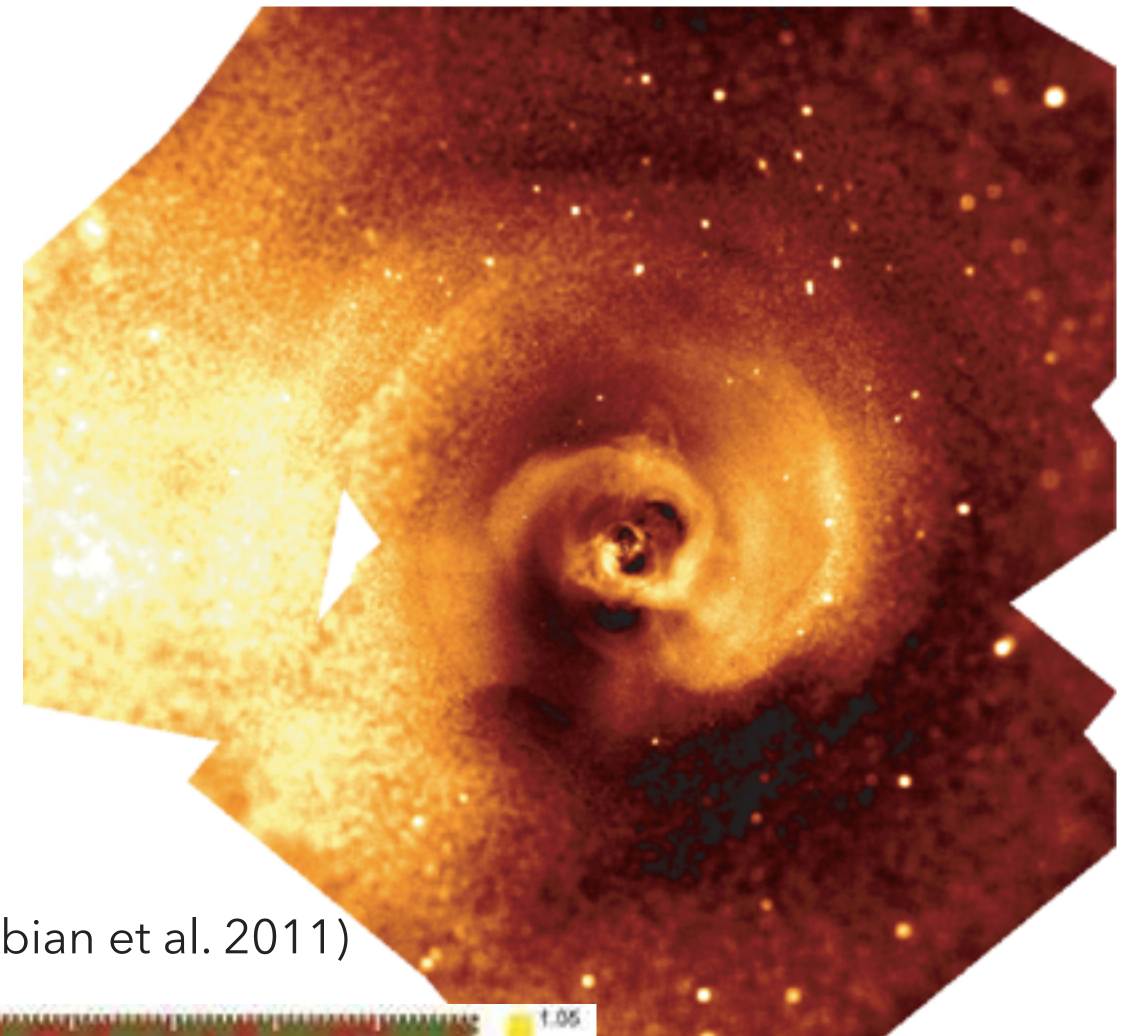


- Mass and energy flows de-couple
- Ram pressure of the outflow acts upon high density clumps (see also, McKee & Cowie 1975, Wagner et al. 2012, 2013, Nayakshin et al. 2014)

(Bourne, Nayakshin & Hobbs, 2014)

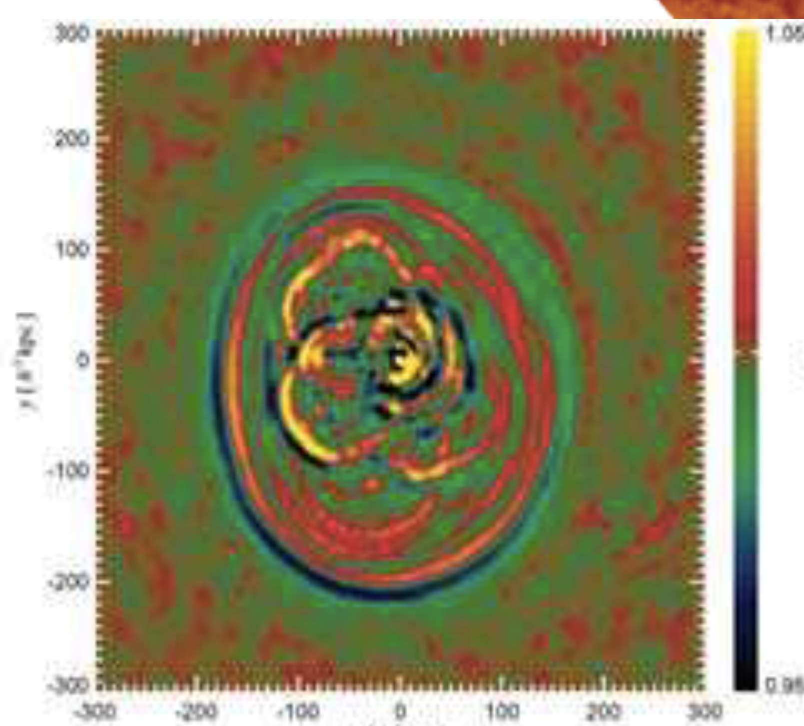
JET MODE FEEDBACK

- Many galaxy clusters contain giant X-ray cavities associated with radio Jets.
- Jets and the cavities they inflate play an important role in regulating the cooling of the ICM and hence the evolution of the host galaxy.
- How jet energy is efficiently communicated to the ICM is not well understood (see e.g., McNamara & Nulsen 2007; Fabian 2012 for reviews).



(Fabian et al. 2011)

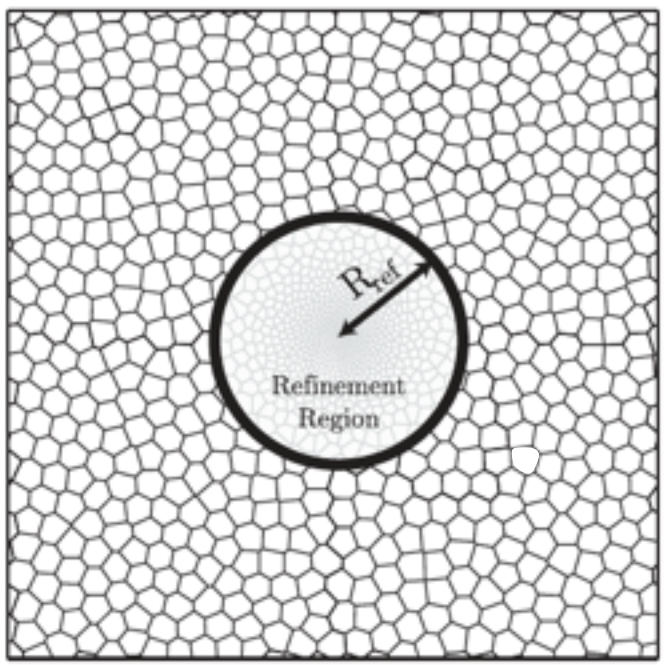
Credit: NASA, ESA, S. Baum and C. O'Dea (RIT), R. Perley and W. Cotton (NRAO/AUI/NSF), and the Hubble Heritage Team (STScI/AURA) - See more at: http://www.space.com/18861-hercules-a-galaxy-radio-jets.html#sthash.adgIuy50.dpuf



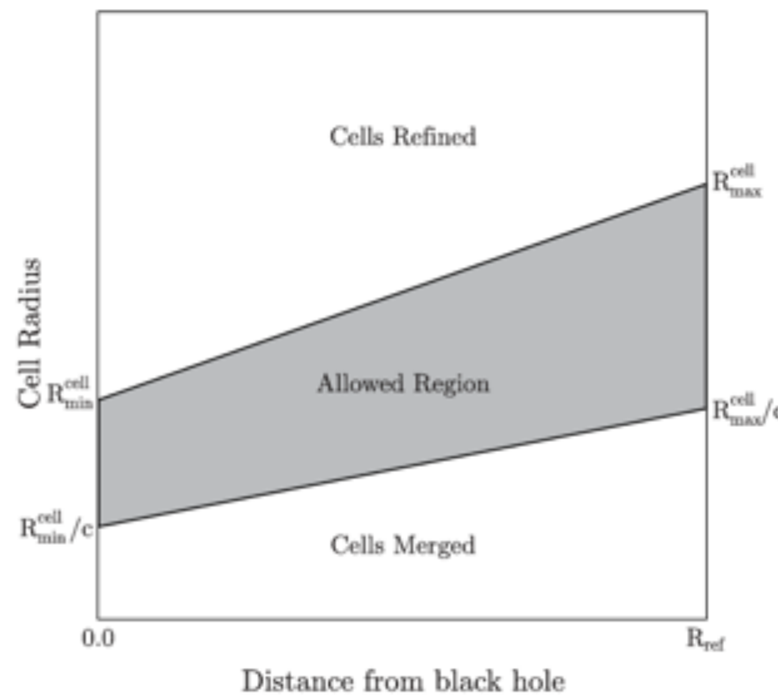
(Sijacki et al. 2007)

Previous simulations, e.g.:
Churazov et al. 2001, 2002
Omma et al. 2004,
Vernaleo & Reynolds 2006,
Cattaneo & Teyssier 2007,
Dubois et al. 2010, 2012
Yang & Reynolds 2016

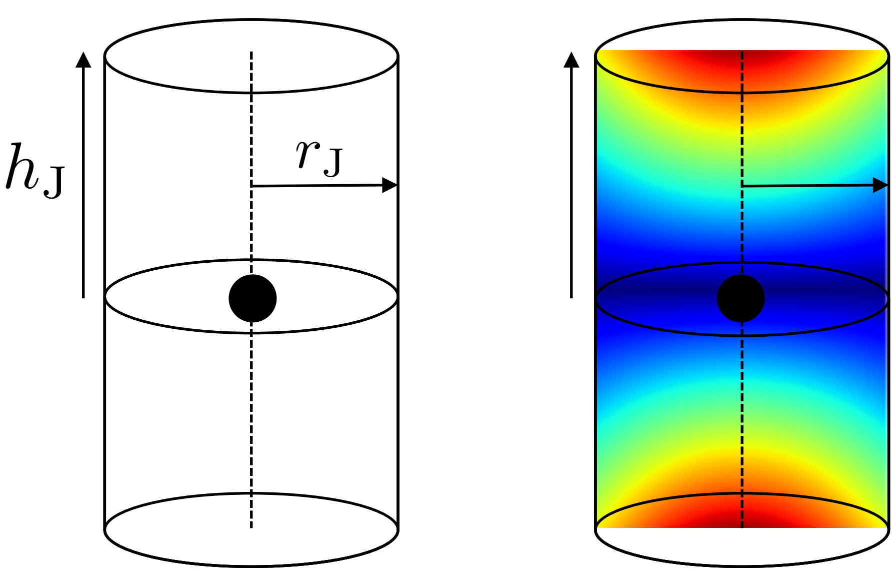
SIMULATION OF JET FEEDBACK – THE METHOD



(Curtis & Sijacki 15)



(Curtis & Sijacki 15)

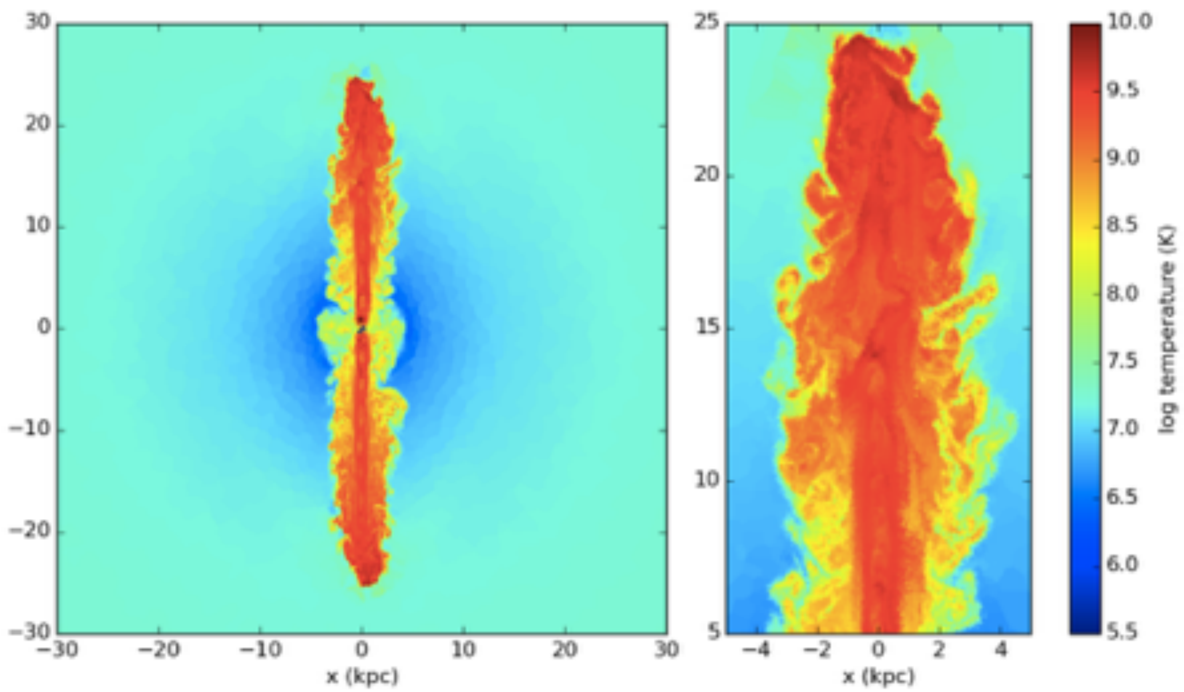


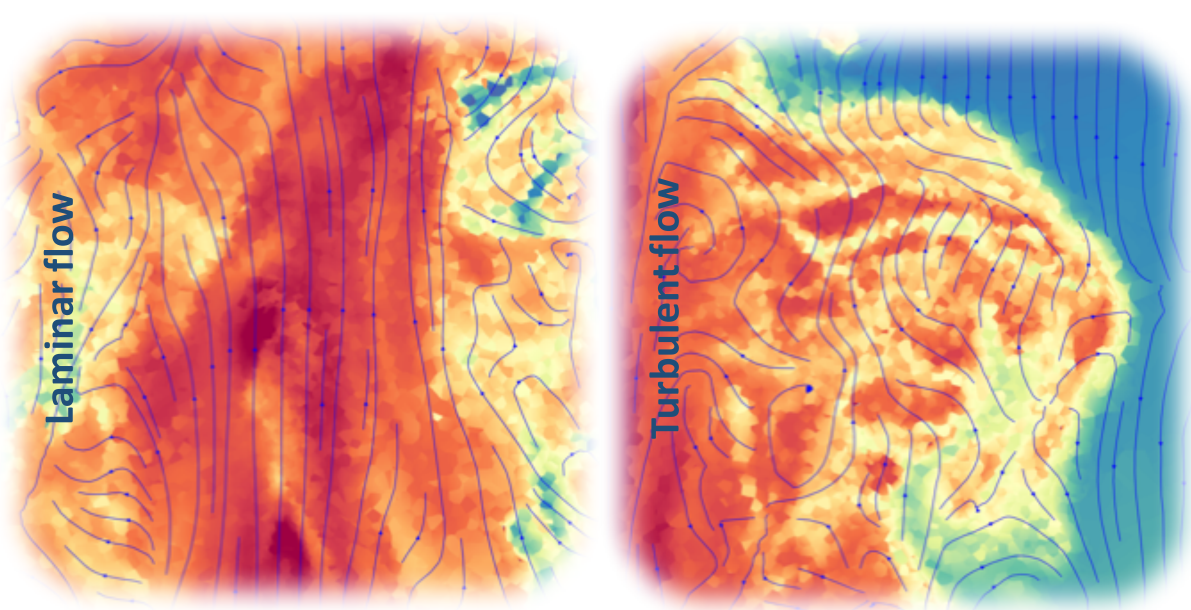
$$W_J(r, z) \propto \exp\left(\frac{-r^2}{2r_J^2}\right) z$$

(e.g., Cattaneo & Teyssier 2007)

- Use AREPO (Springel 2010) to simulate jet feedback from SMBHs
- Refinement technique of Curtis & Sijacki 15
- Inject mass, momentum, thermal and/or kinetic energy into cylinder centered on black hole

SIMULATION OF JET FEEDBACK – EARLY RESULTS





(Bourne,Curtis & Sijacki, in prep)

- Example density and temperature slices for jet simulation
- Inject mass, momentum and kinetic energy
- Jet injected on scales of order 100 pc
- Maintain high resolution within the jet but lower resolution in ICM
- Temperatures reach ~10^{10} K & Density contrasts reach ~10^4

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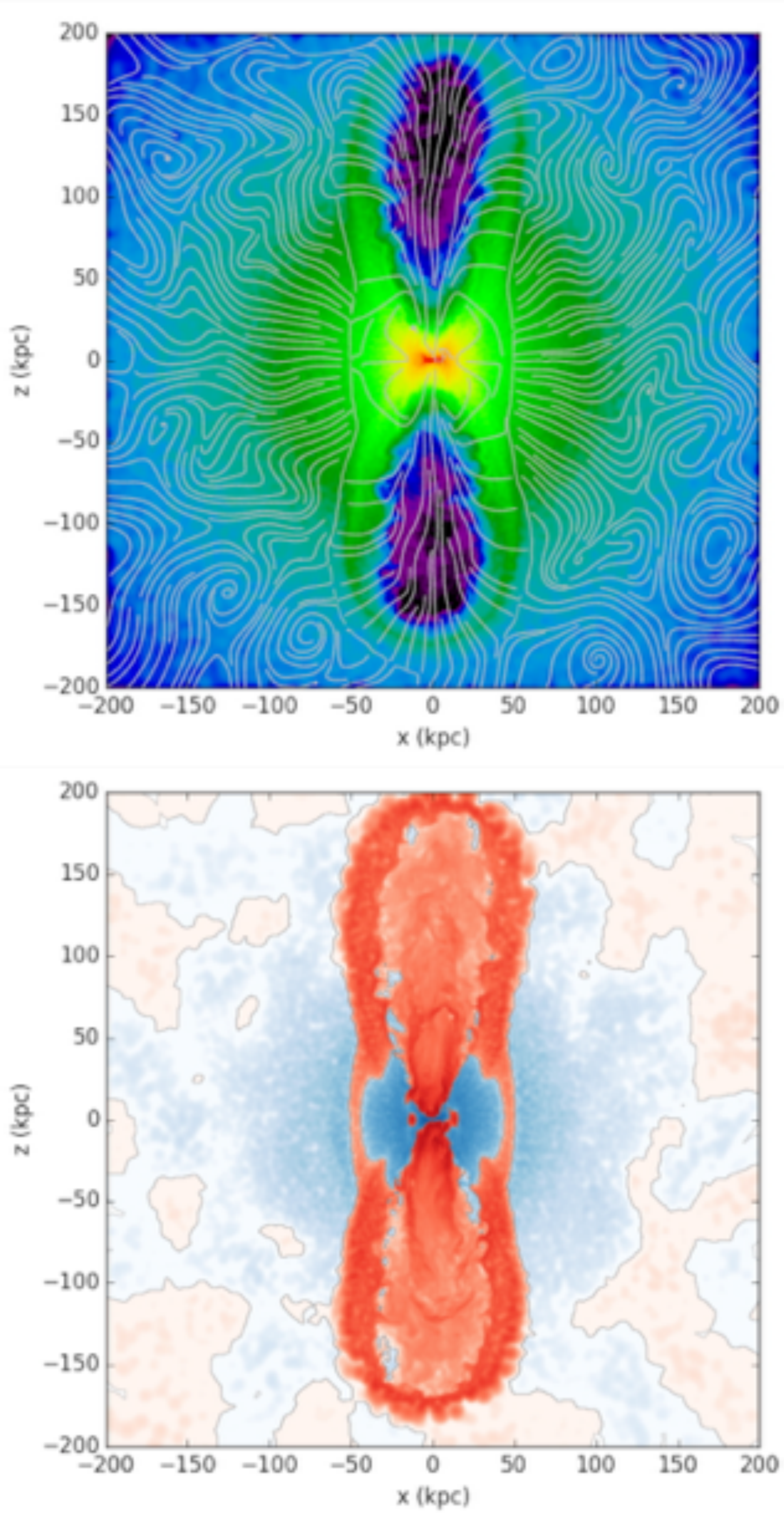
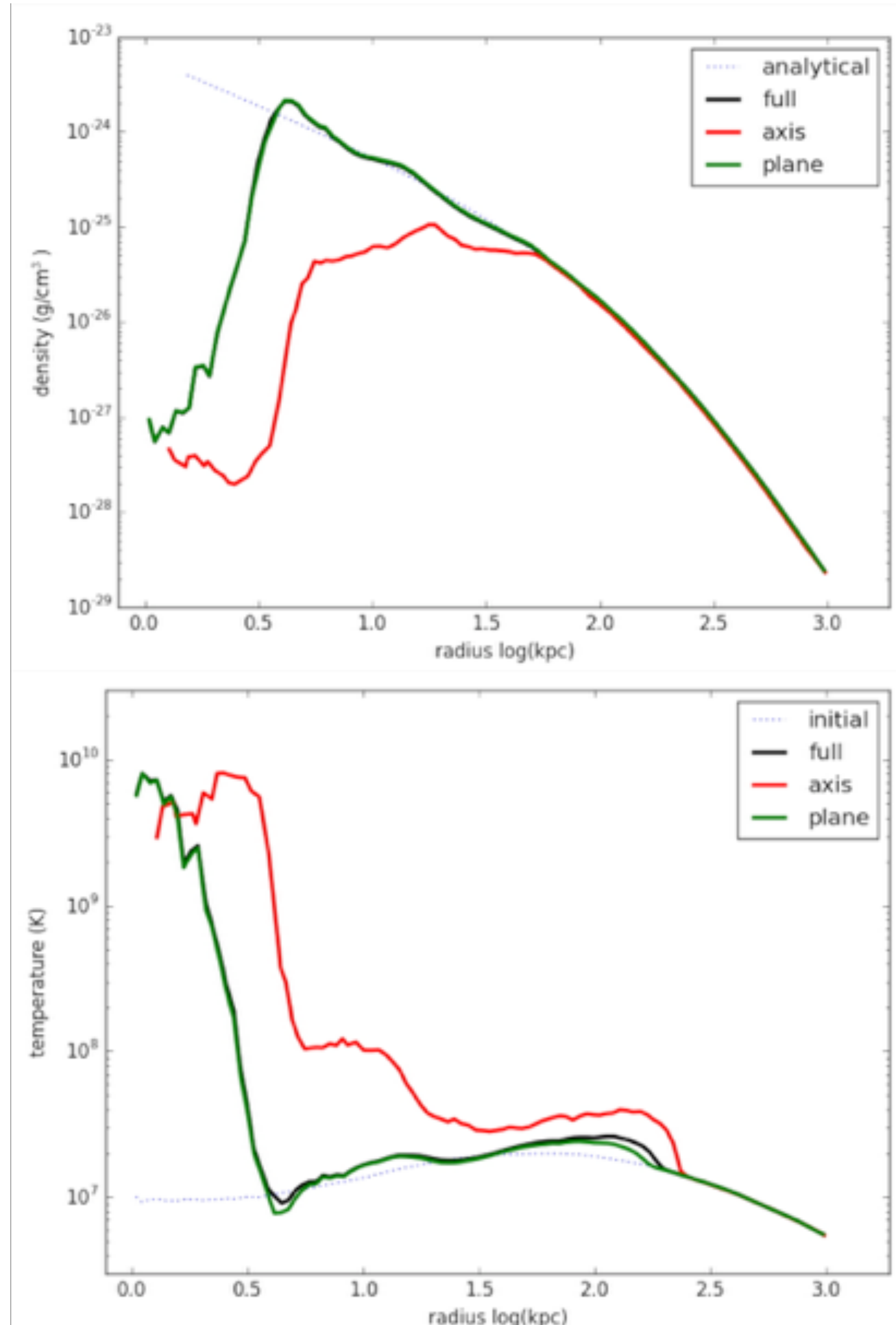
SIMULATION OF JET FEEDBACK – GAS FLOWS





(Bourne,Curtis & Sijacki, in prep)

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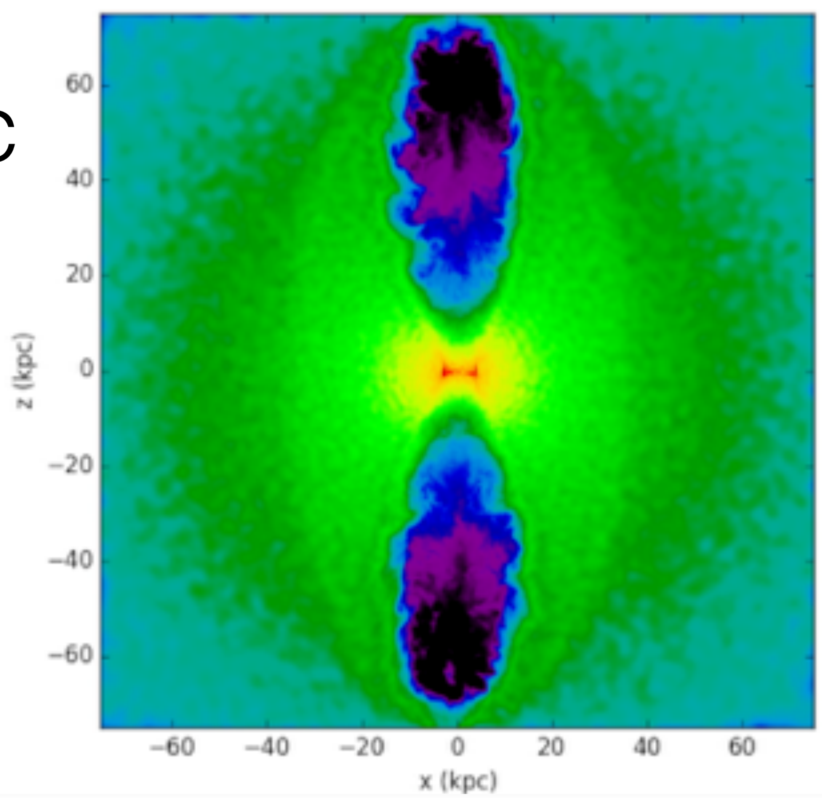
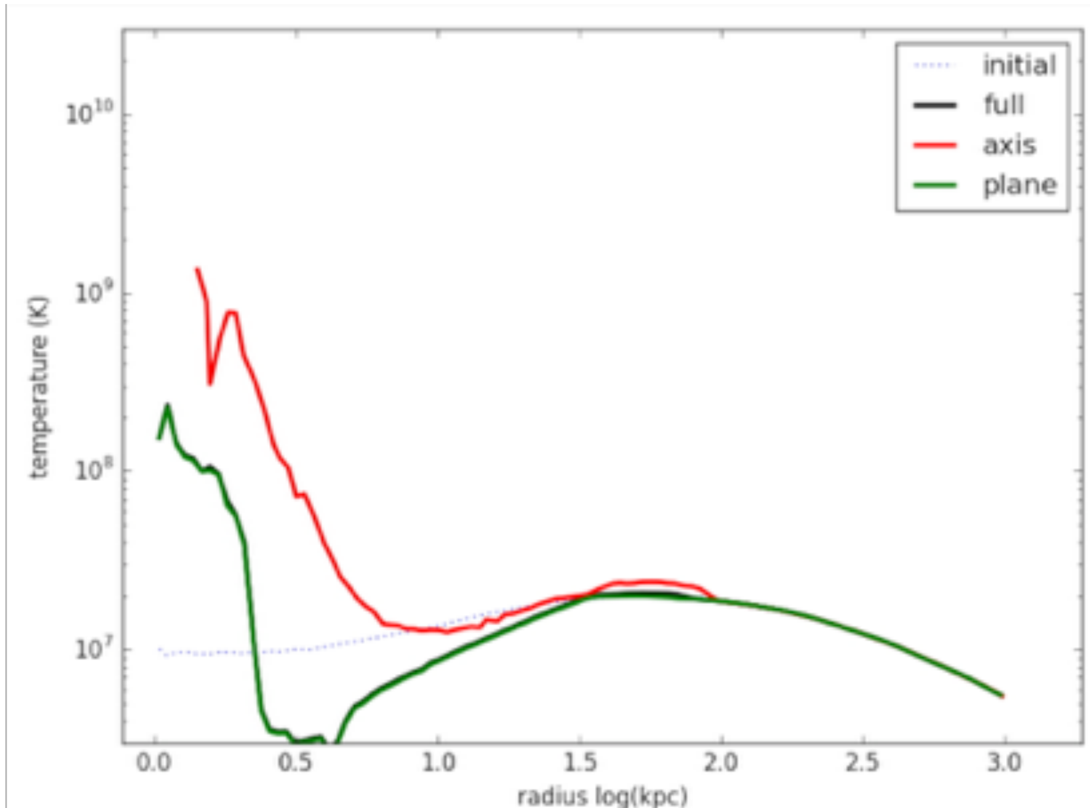
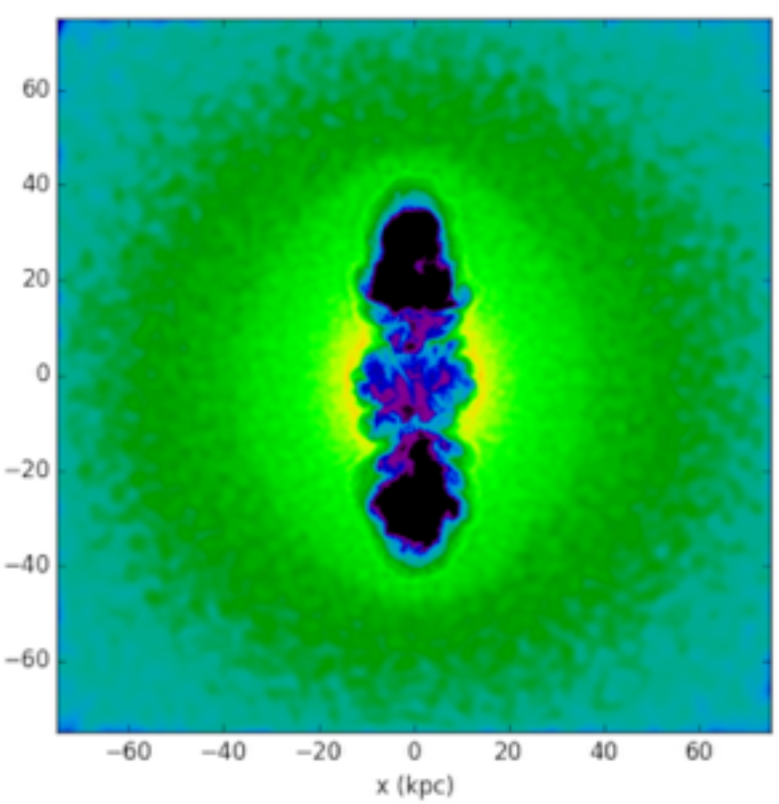
SIMULATION OF JET FEEDBACK - THERMAL VS KINETIC

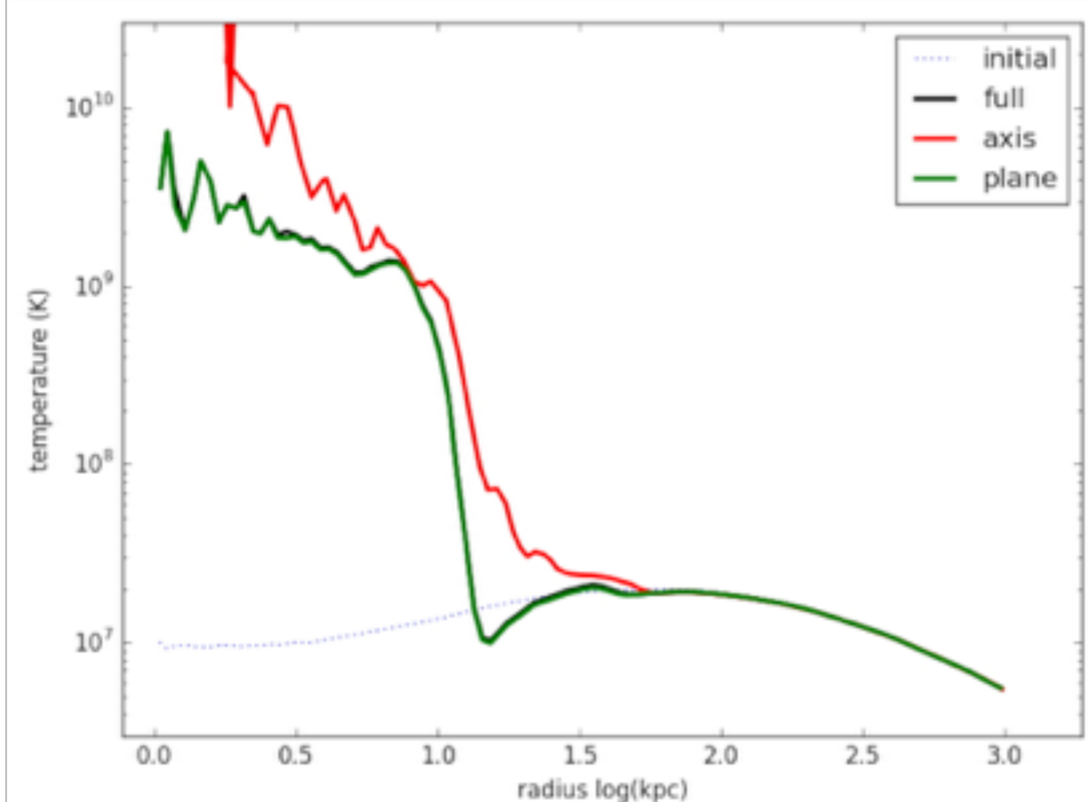
Kinetic





Thermal





(Bourne,Curtis & Sijacki, in prep)

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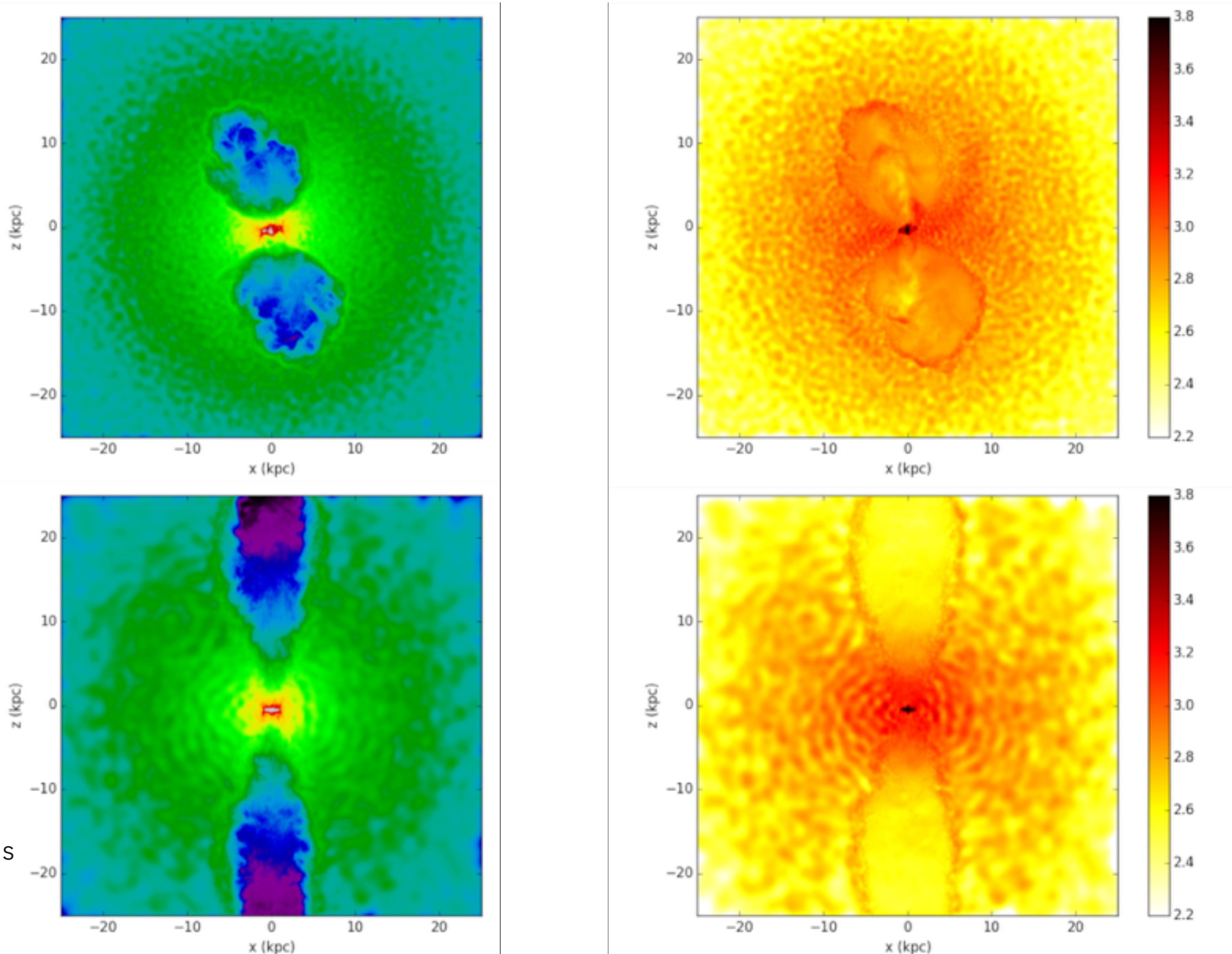
SIMULATION OF JET FEEDBACK –PRECESSING JET



(Bourne,Curtis & Sijacki, in prep)

SUMMARY

- Black hole scaling relations suggest that the coupling between AGN feedback and the ISM must be weak - momentum drives M-σ ?
- IC cooling should produce feature in the X-rays - this has so far not been observed - hint at a lack of IC cooling - due to weak electron-proton coupling? (see Faucher-Giguere & Quataert 2012)
- Modelling the multiphase structure if the ISM in simulations makes it more resilient to AGN feedback, possibly negating the need for IC cooling
- Have implemented jet feedback method into AREPO in combination with refinement scheme that allows the jet to be injected on small scales
- Similar to previous simulations (e.g. Yang & Reynolds, 2015), kinetic jet feedback produces the negative temperate gradient observed in cool-core clusters (e.g. Hudson+ 2010)
- No evidence for jet driven turbulence in the ICM, consistent with findings of Hitomi observations of the Perseus cluster.