Heating & cooling cycles in cool cluster cores

Prateek Sharma (IISc)
Collaborators: Deovrat Prasad, Arif Babul

COOL CORE CYCLES: COLD GAS AND AGN JET FEEDBACK IN CLUSTER CORES

THE ASTROPHYSICAL JOURNAL, 811:108 (21pp), 2015 October 1

DEOVRAT PRASAD[1], PRATEEK SHARMA[1], AND ARIF BABUL[2]
[1] Joint Astronomy Program and Department of Physics, Indian Institute of Science, Bangalore, 560012, India; deovrat@physics.iisc.ernet.in, prateek@physics.iisc.ernet.in
[2] Department of Physics and Astronomy, University of Victoria, Victoria, BC V8P 1A1, Canada; babul@uvic.ca

Received 2015 April 12; accepted 2015 July 28; published 2015 September 28

Cold gas condensation

- allows feedback to act sufficiently fast, unlike Bondi
- t_{cool}/t_{ff}~threshold around 10 seems robust (at least in sims)
- cooling & heating cycles
- push ε to smallest allowed by observations
- cold gas inflows & outflows
- angular momentum: stochastic cold accretion

AGN jet-ICM sims.

$$\frac{\partial \rho}{\partial t} + \nabla \cdot \rho \mathbf{v} = S_\rho$$ mass

$$\rho \left(\frac{\partial \mathbf{v}}{\partial t} + \mathbf{v} \cdot \nabla \mathbf{v} \right) = -\nabla p - \rho \nabla \Phi + S_\rho v_{\rm jet} \hat{\mathbf{r}}$$ momentum

$$\frac{p}{\gamma - 1} \frac{d}{dt} \ln(p/\rho^\gamma) = -n^2 \Lambda$$

source terms to mimic injection by feedback AGN jets

AGN jet-ICM sims.

$$\frac{\partial \rho}{\partial t} + \nabla \cdot \rho \mathbf{v} = S_\rho$$ mass

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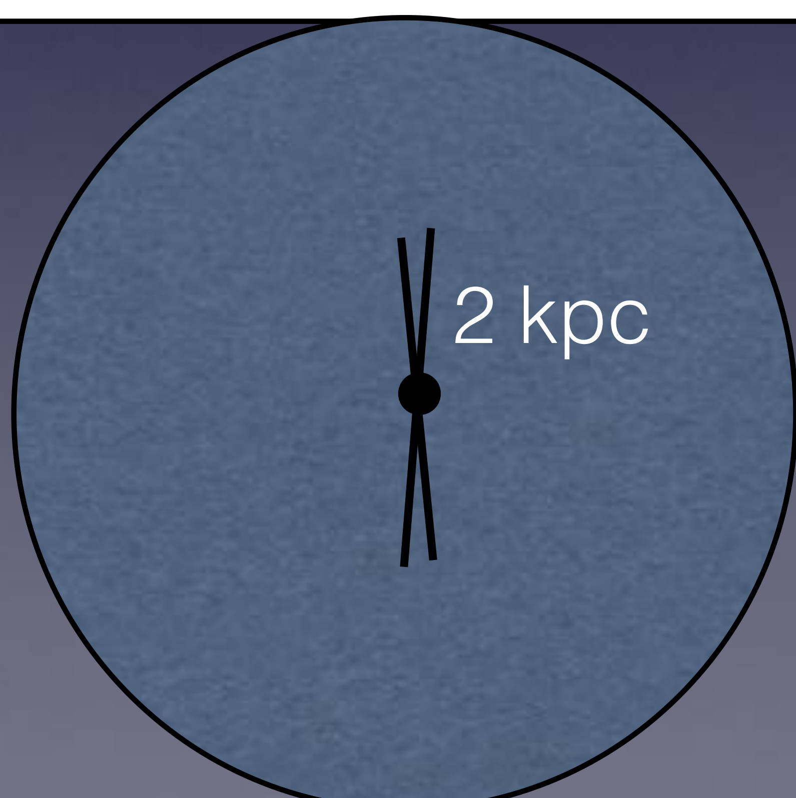
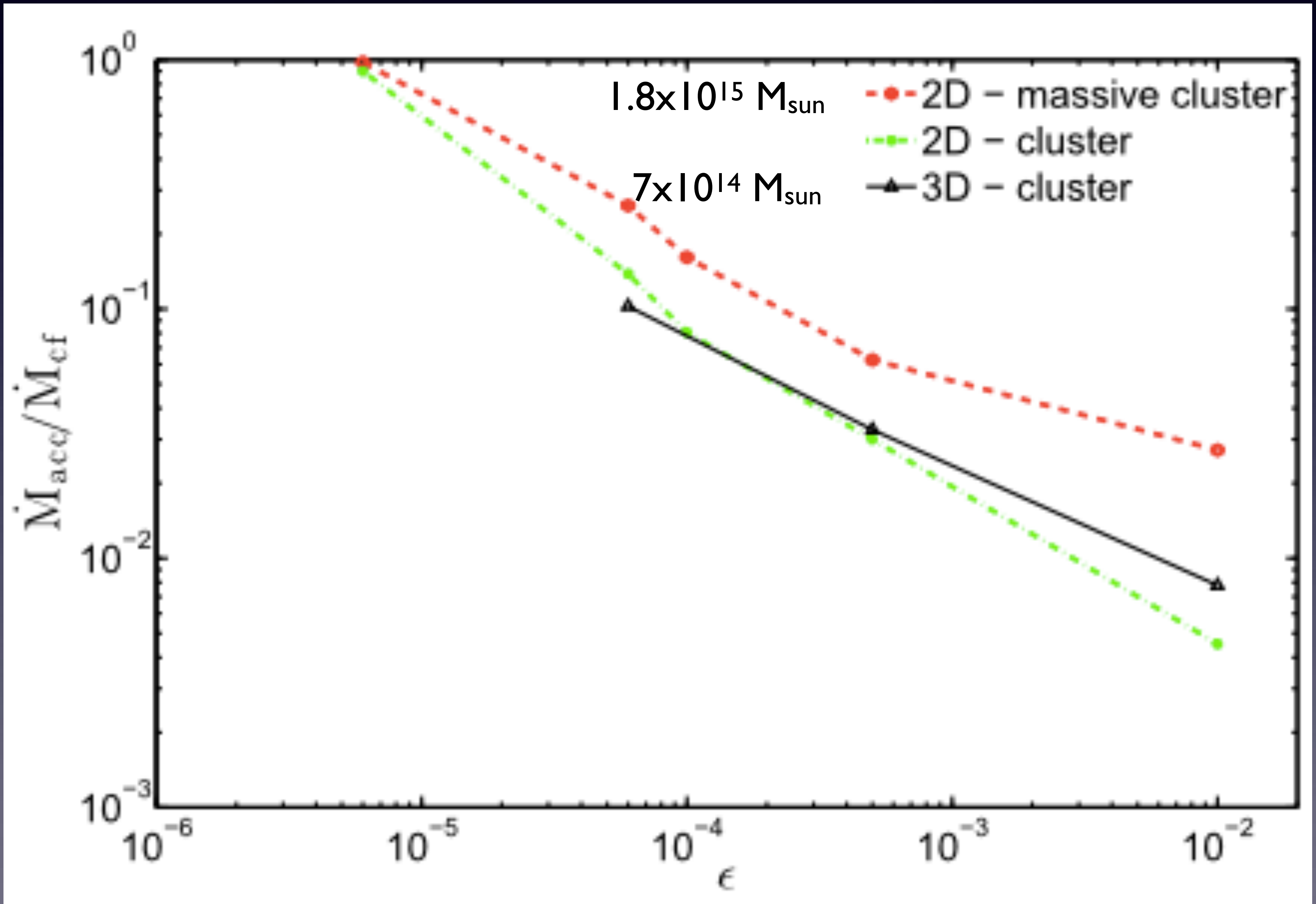


source term applied in a small bipolar cone at the center: opening angle of 30^0, size 2 kpc

$$\dot{M}_{\rm jet} v_{\rm jet}^2 = \epsilon \dot{M}_{\rm acc} c^2$$

v_{jet}=0.1c, $\varepsilon=6\times10^{-5}$, $r_{in,out}$=1, 200 kpc
robust to variations

Dependence on halo mass & efficiency

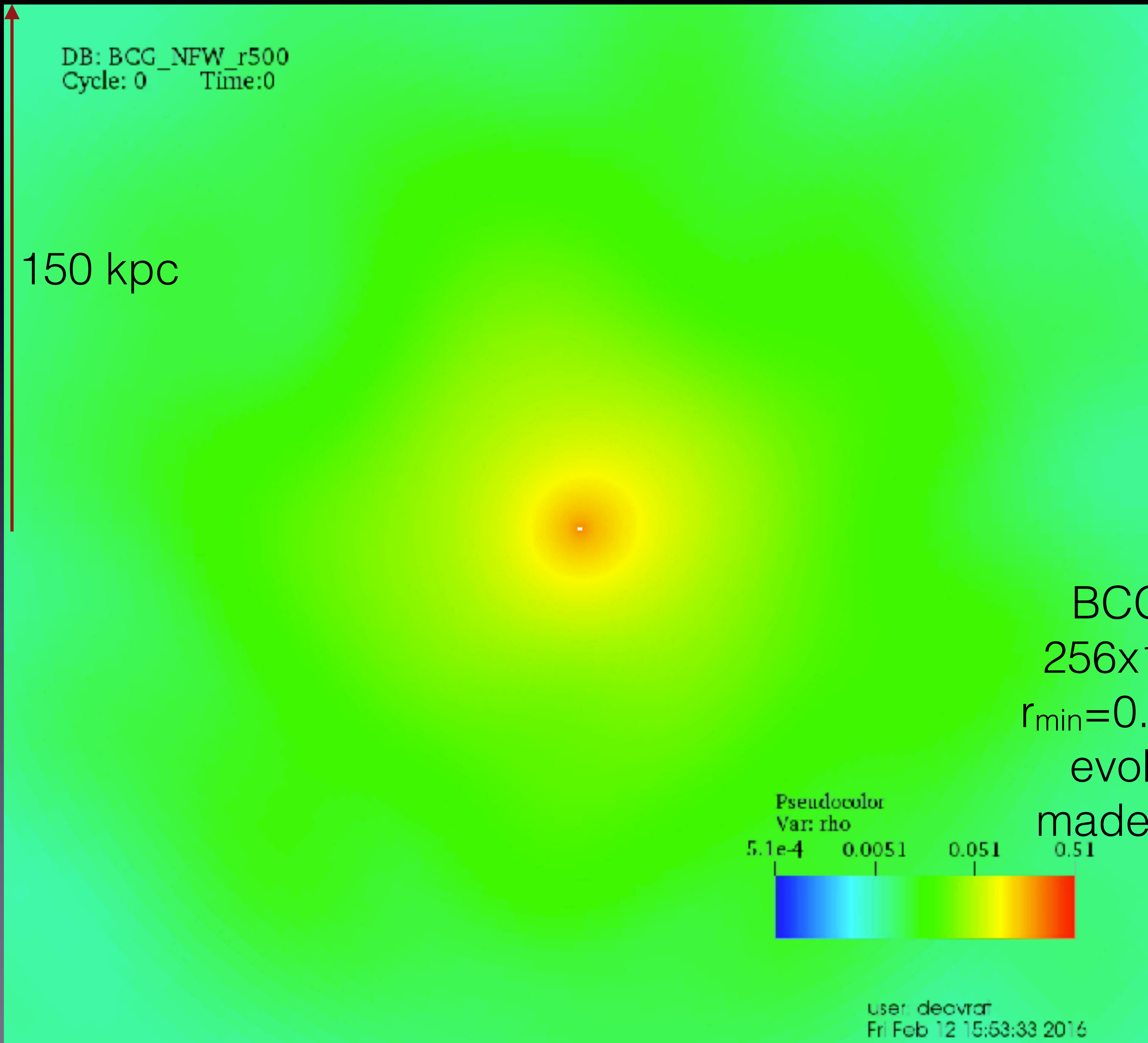


larger ε suppresses accretion

more massive halos require larger ε

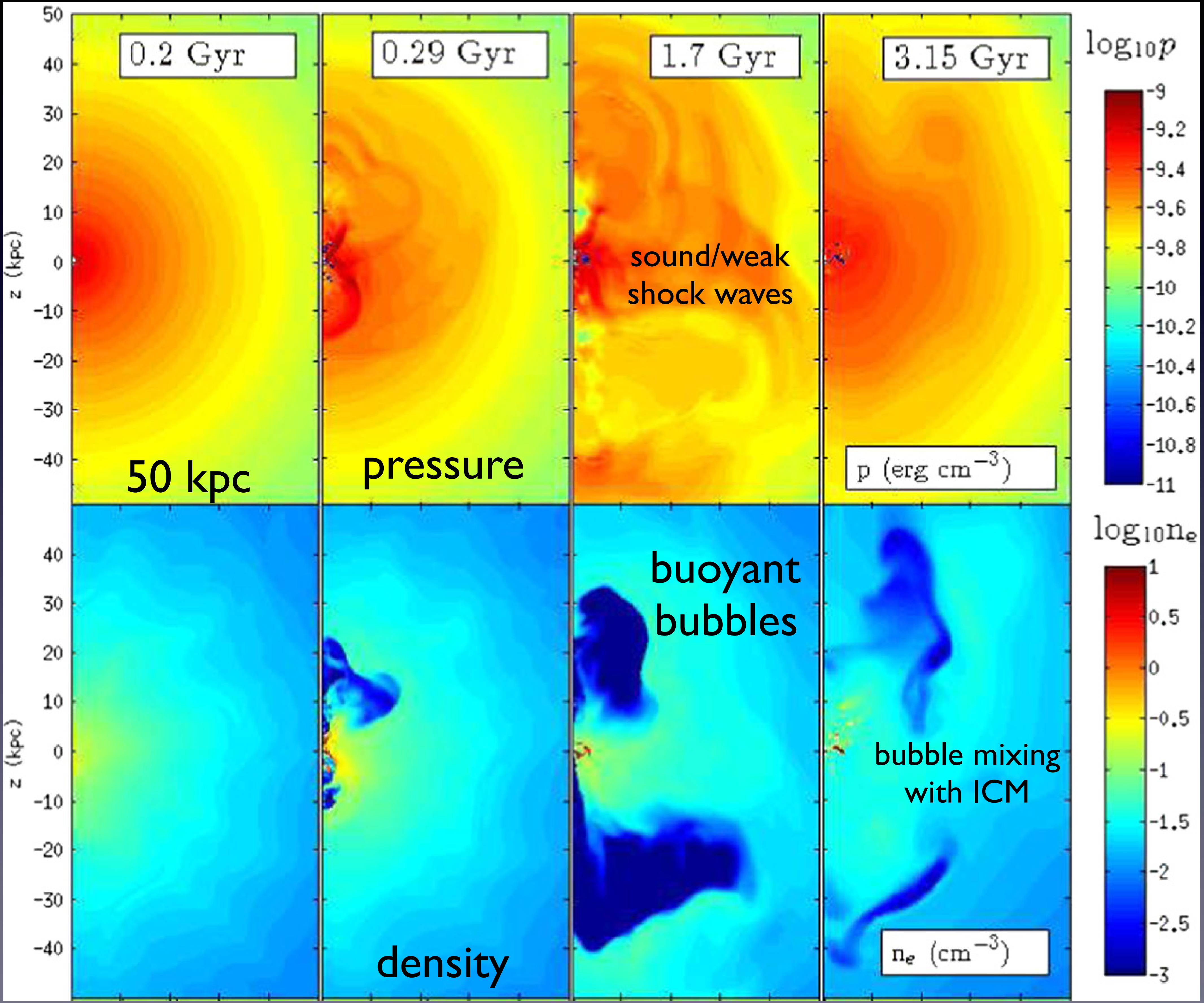
depends on where Mdot calculated

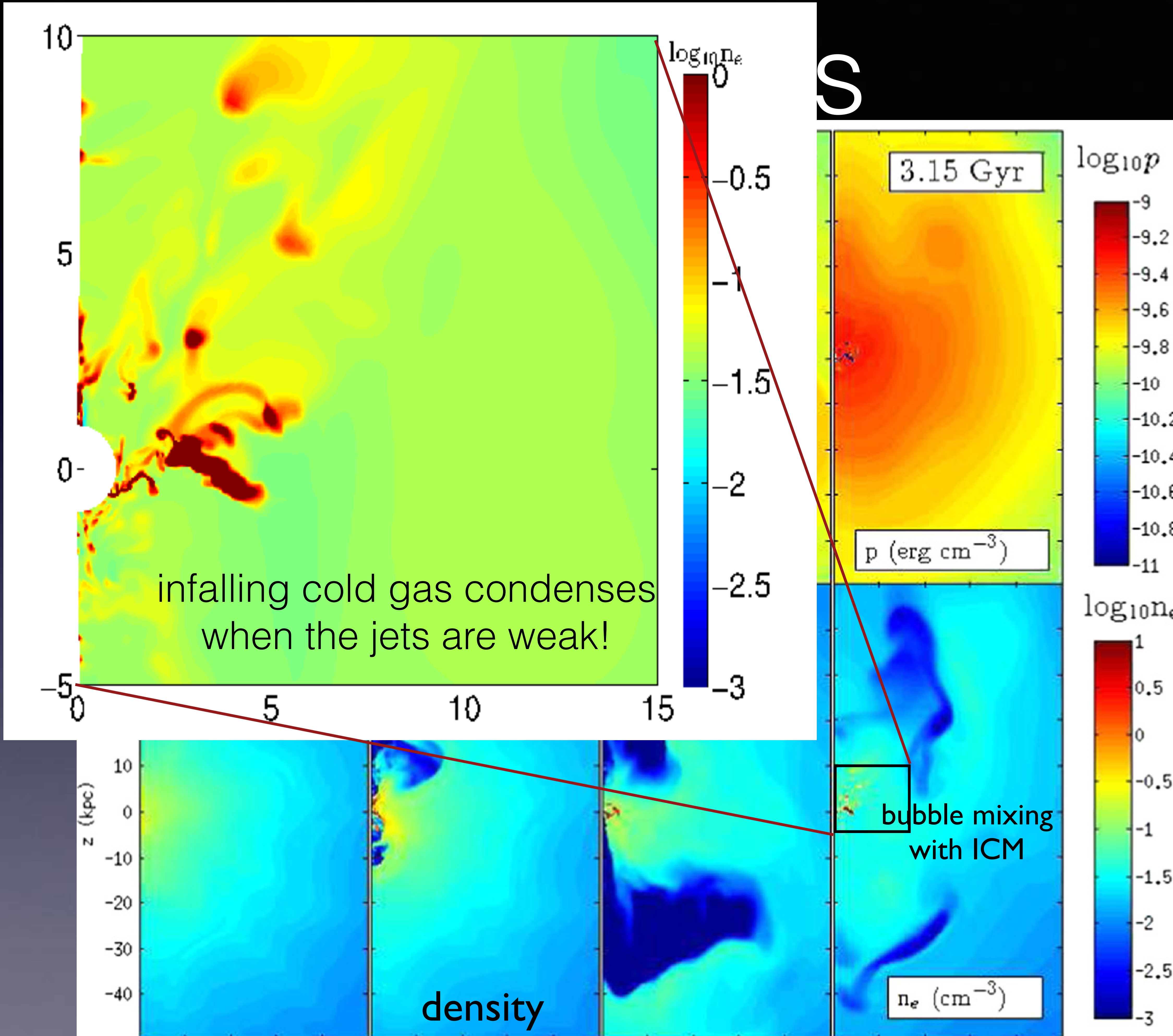
Density movie



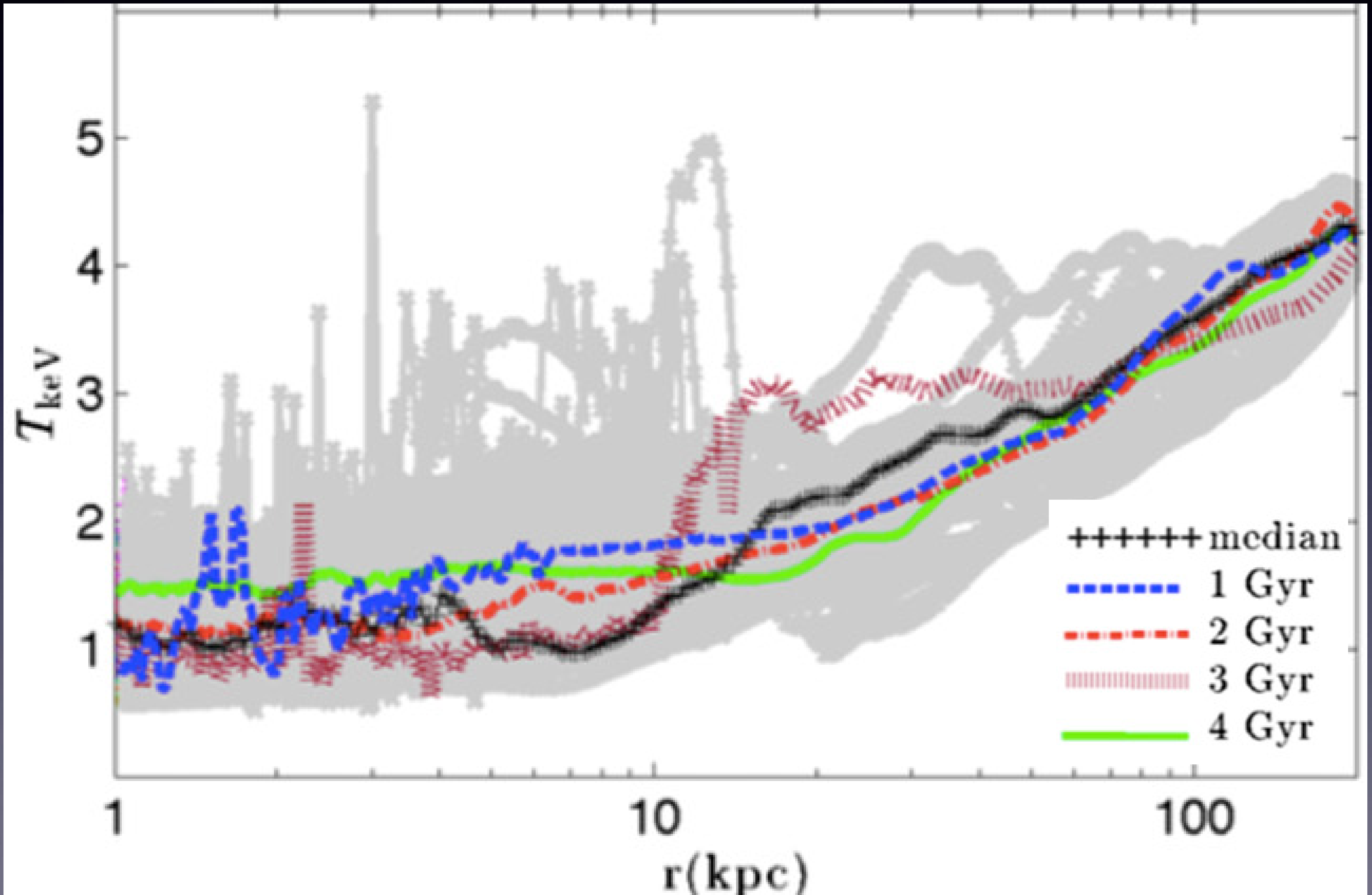
BCG+NFW in PLUTO
256x128x32 in (logr,θ,ϕ)
r_{min}=0.5 kpc, r_{max}=0.5 Mpc
evolution for ~2.8 Gyr
made by Deovrat Prasad

r-θ slices

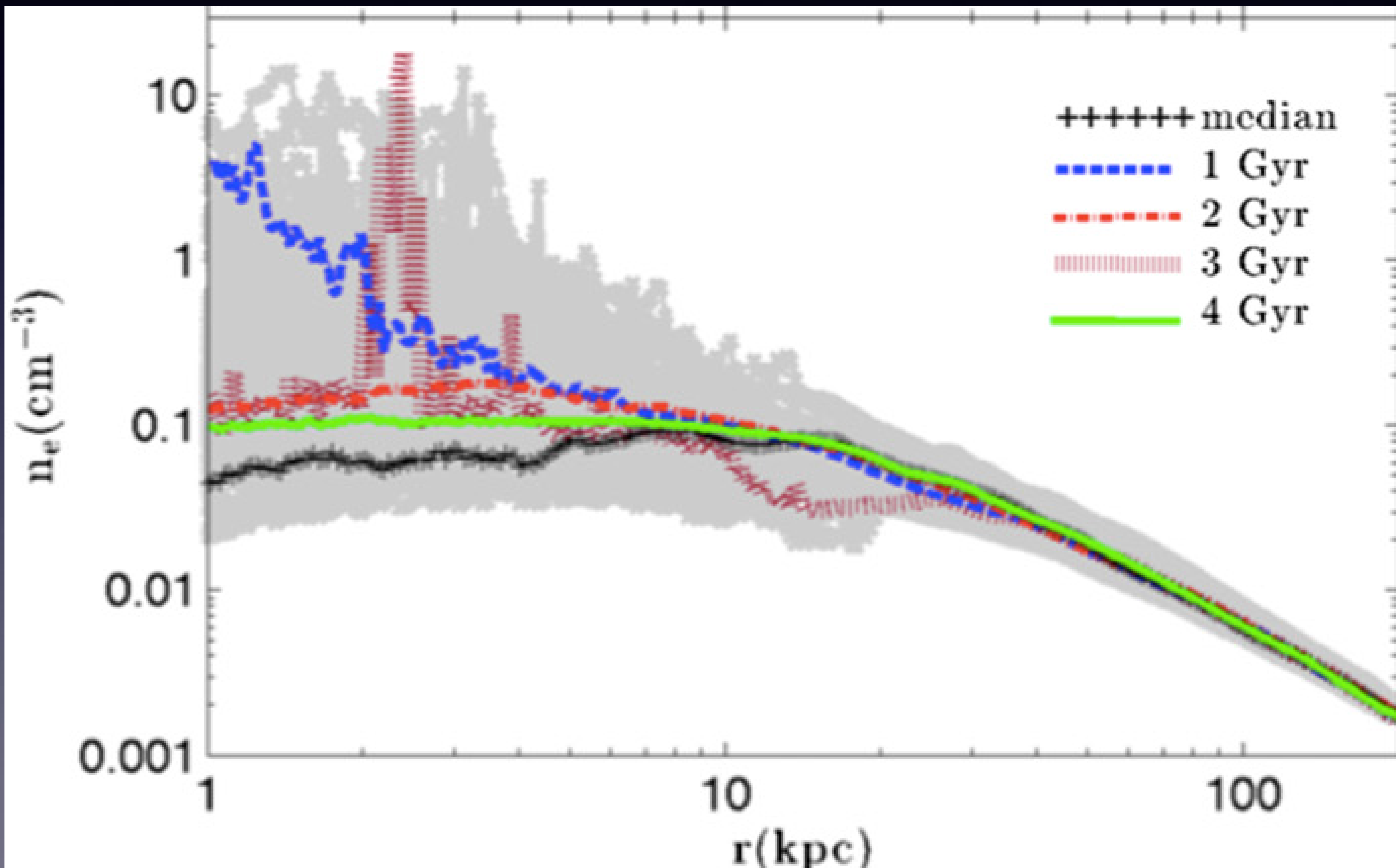

0.2 Gyr
0.29 Gyr
1.7 Gyr
3.15 Gyr
log10p
-9
-9.2
-9.4
-9.6
-9.8
-10
-10.2
-10.4
-10.6
-10.8
-11
z (kpc)
50
40
30
20
10
0
-10
-20
-30
-40
sound/weak
shock waves
50 kpc
pressure
p (erg cm−3)
log10ne
1
0.5
0
-0.5
-1
-1.5
-2
-2.5
-3
buoyant
bubbles
bubble mixing
with ICM
density
ne (cm−3)


S
log10ne
0
−0.5
−1
−1.5
−2
−2.5
−3
10
5
0
−5
0
5
10
15
infalling cold gas condenses
when the jets are weak!
3.15 Gyr
log10p
-9
-9.2
-9.4
-9.6
-9.8
-10
-10.2
-10.4
-10.6
-10.8
-11
p (erg cm−3)
log10ne
1
0.5
0
-0.5
-1
-1.5
-2
-2.5
-3
z (kpc)
10
0
-10
-20
-30
-40
bubble mixing
with ICM
density
ne (cm−3)

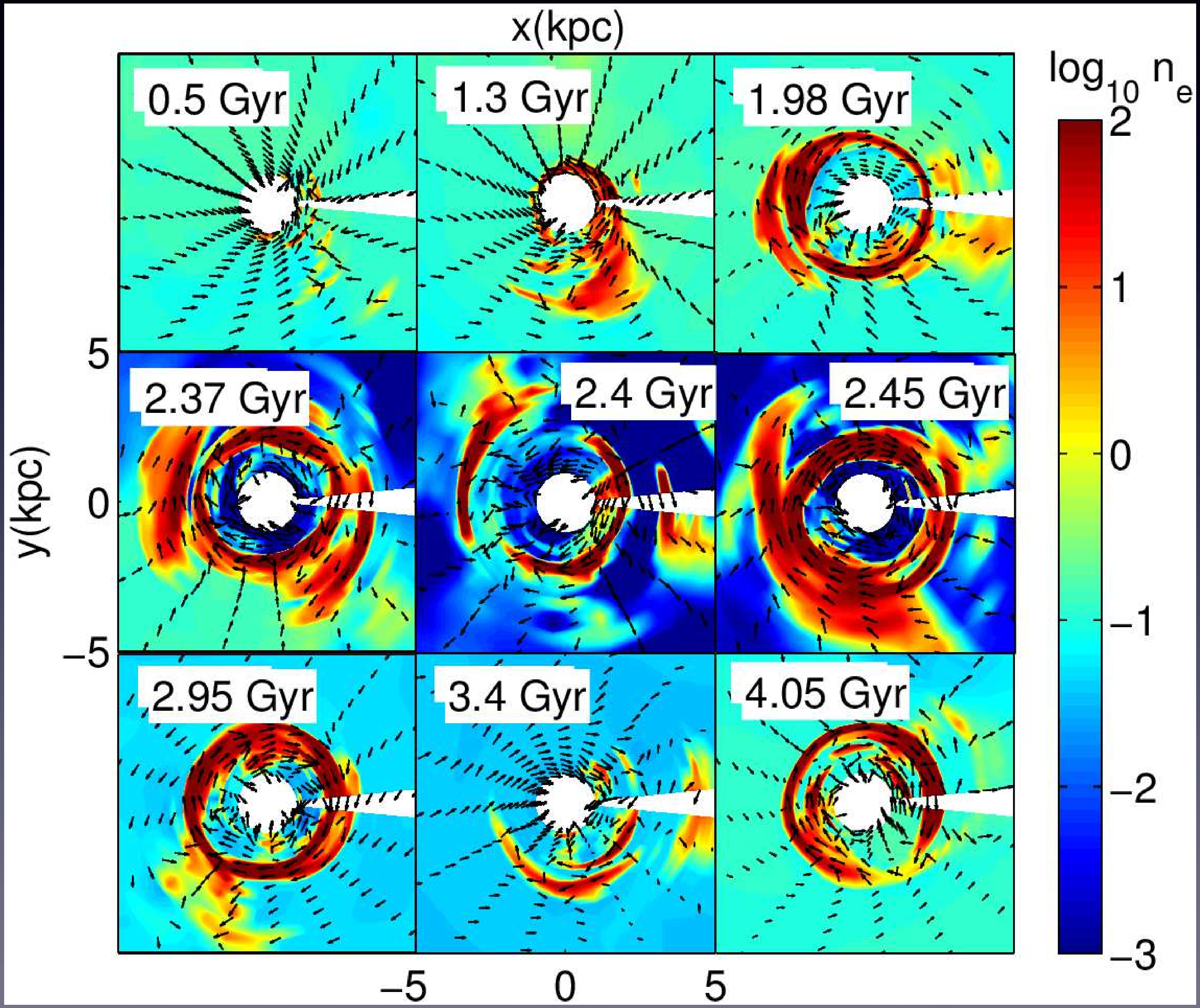
temperature reasonable



density reasonable



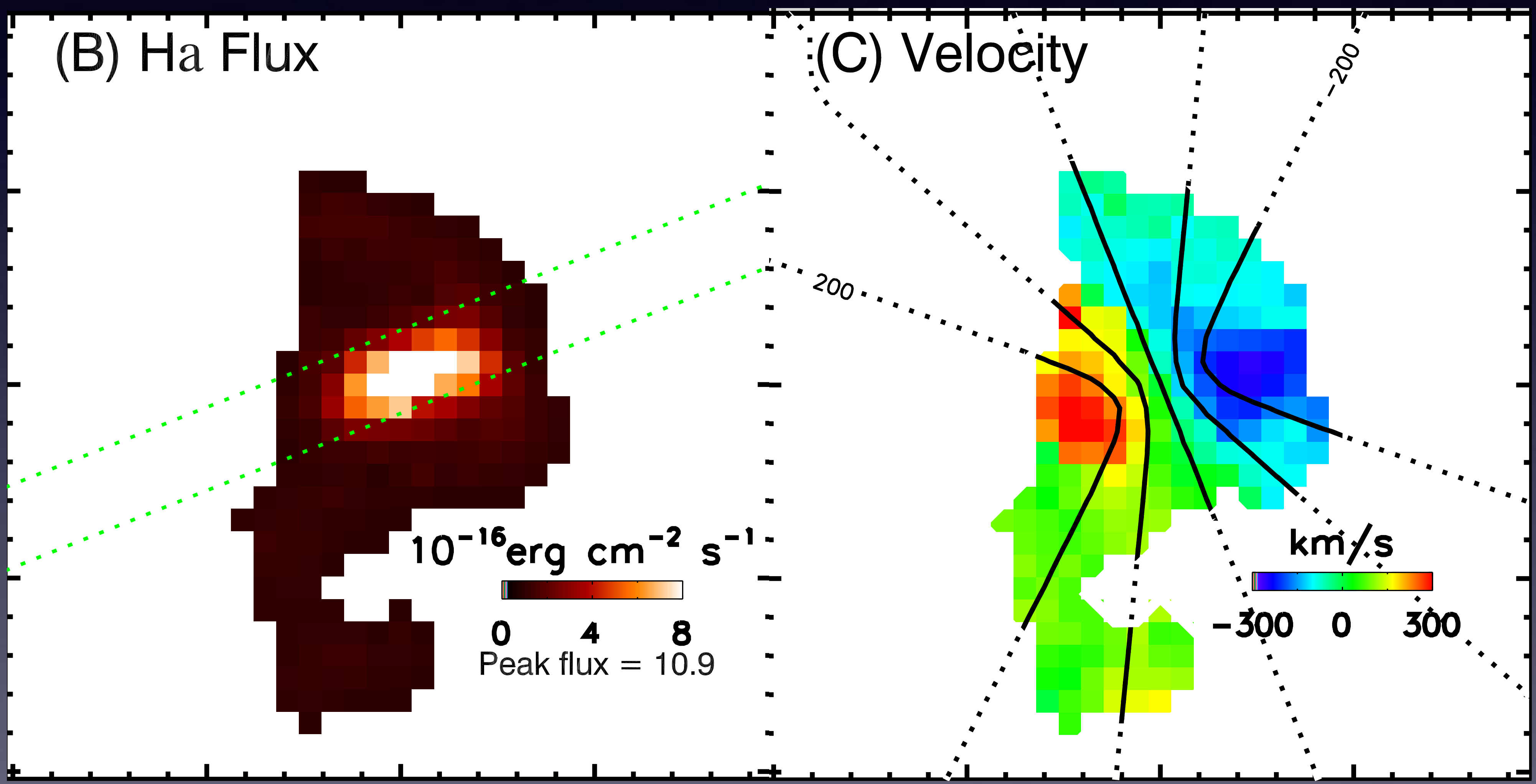
Cold rotating torus



few kpc scale
molecular torus

Cold torus in Hydra A

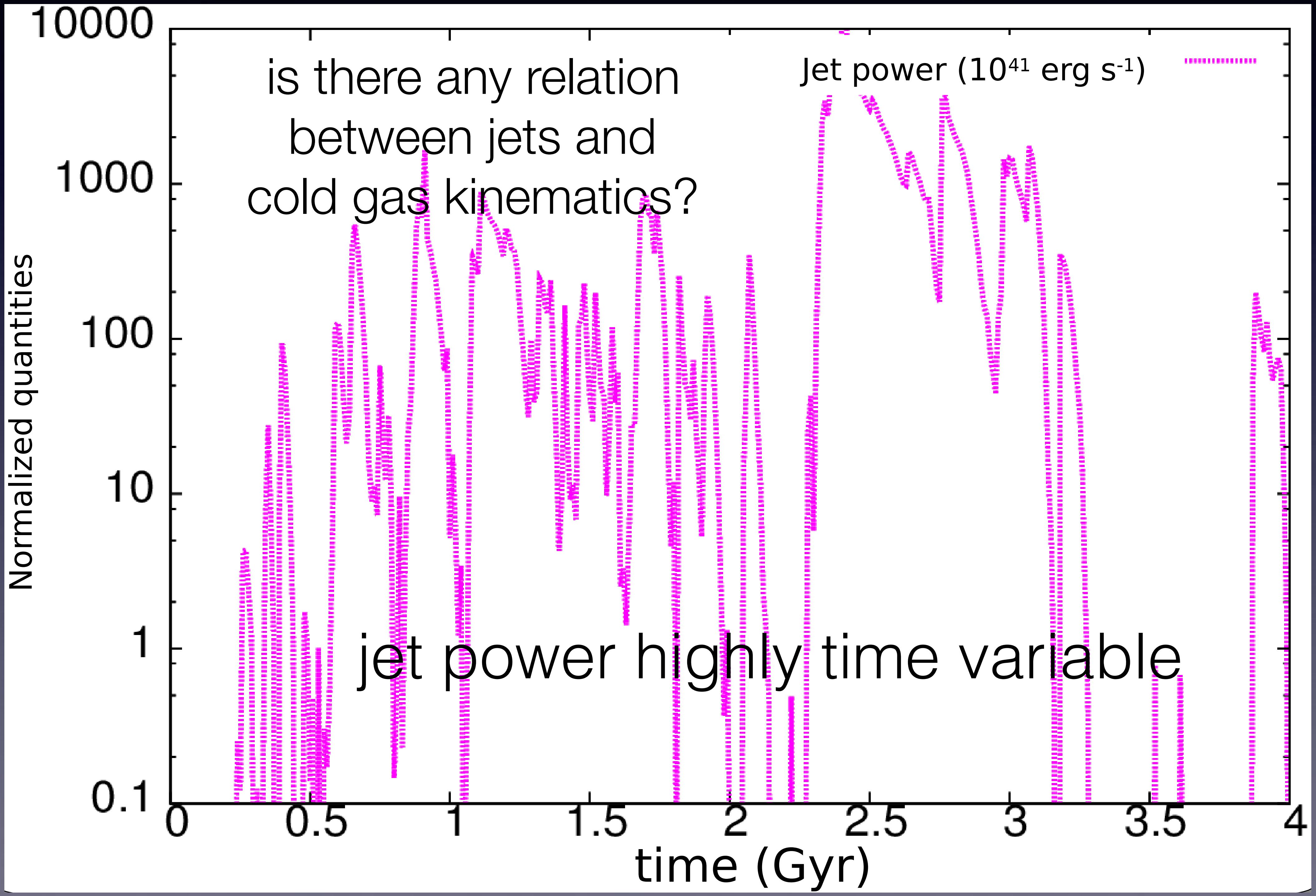
[Hamer et al. 2014]



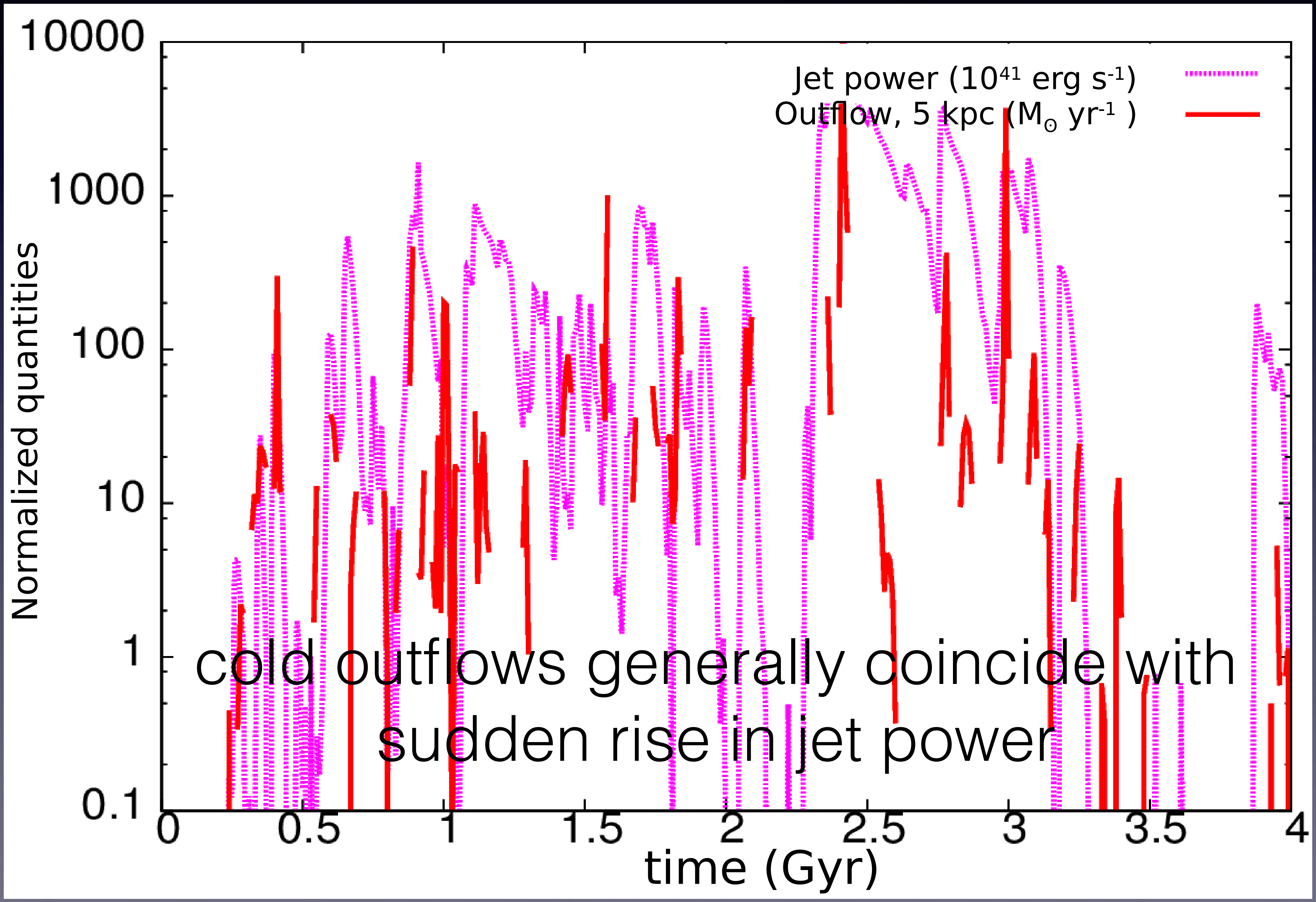
~5 kpc cold torus

more examples from ALMA, Hershel?
may be SF doesn't let a massive torus form

Jets & fast outflows

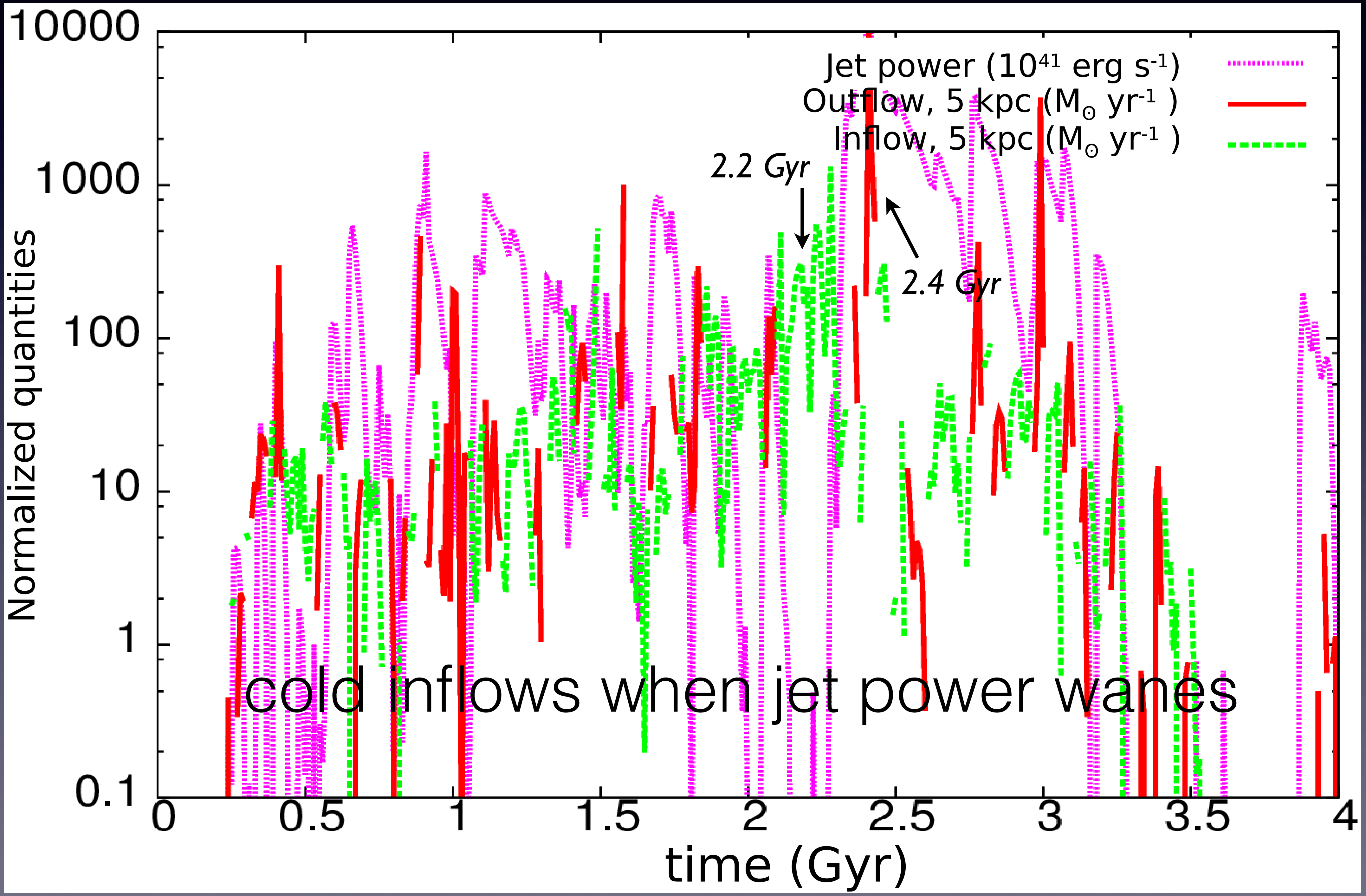


Jets & fast outflows



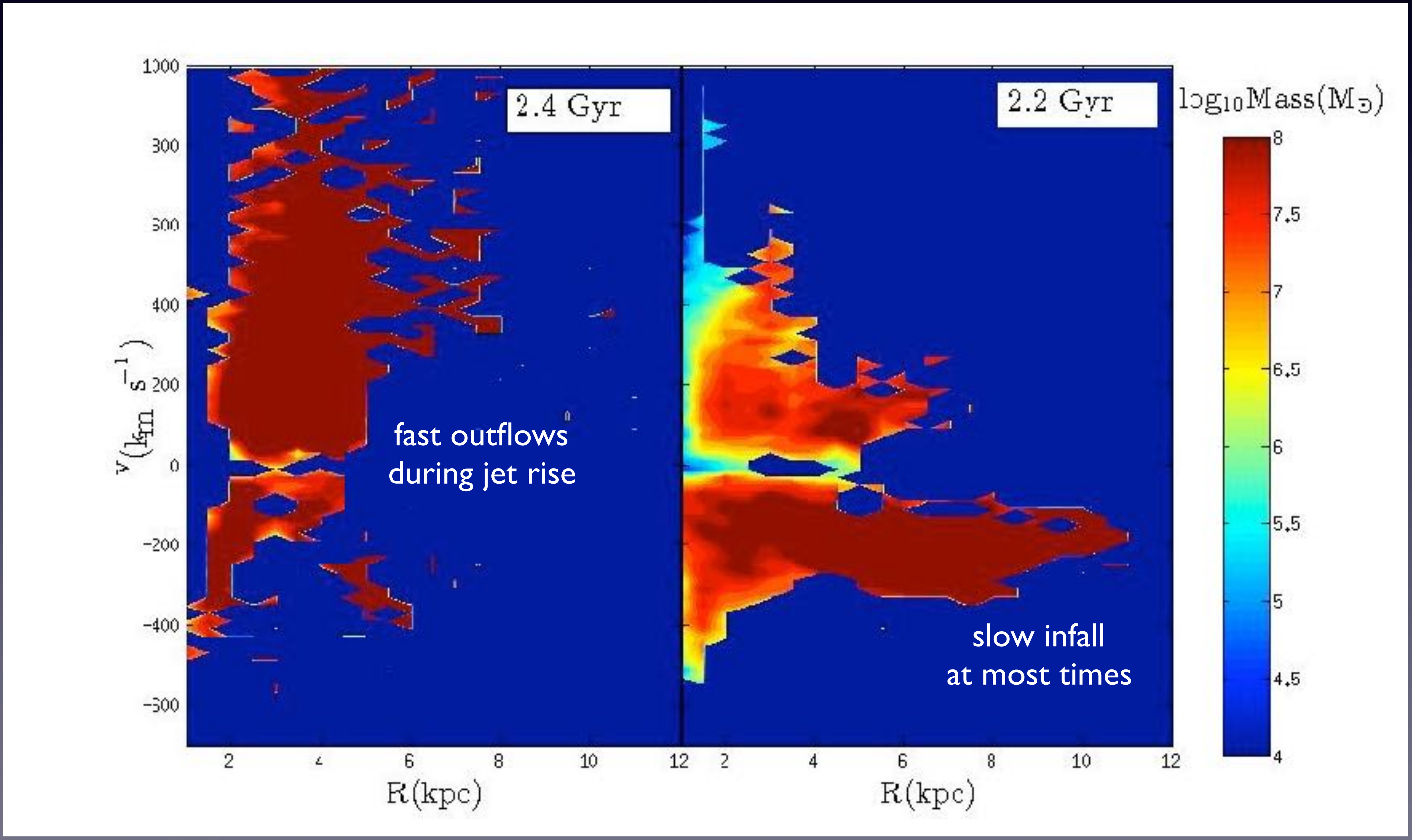
cold outflows generally coincide with sudden rise in jet power

Jets & fast outflows



Snapshots of inflow/ outflow phases

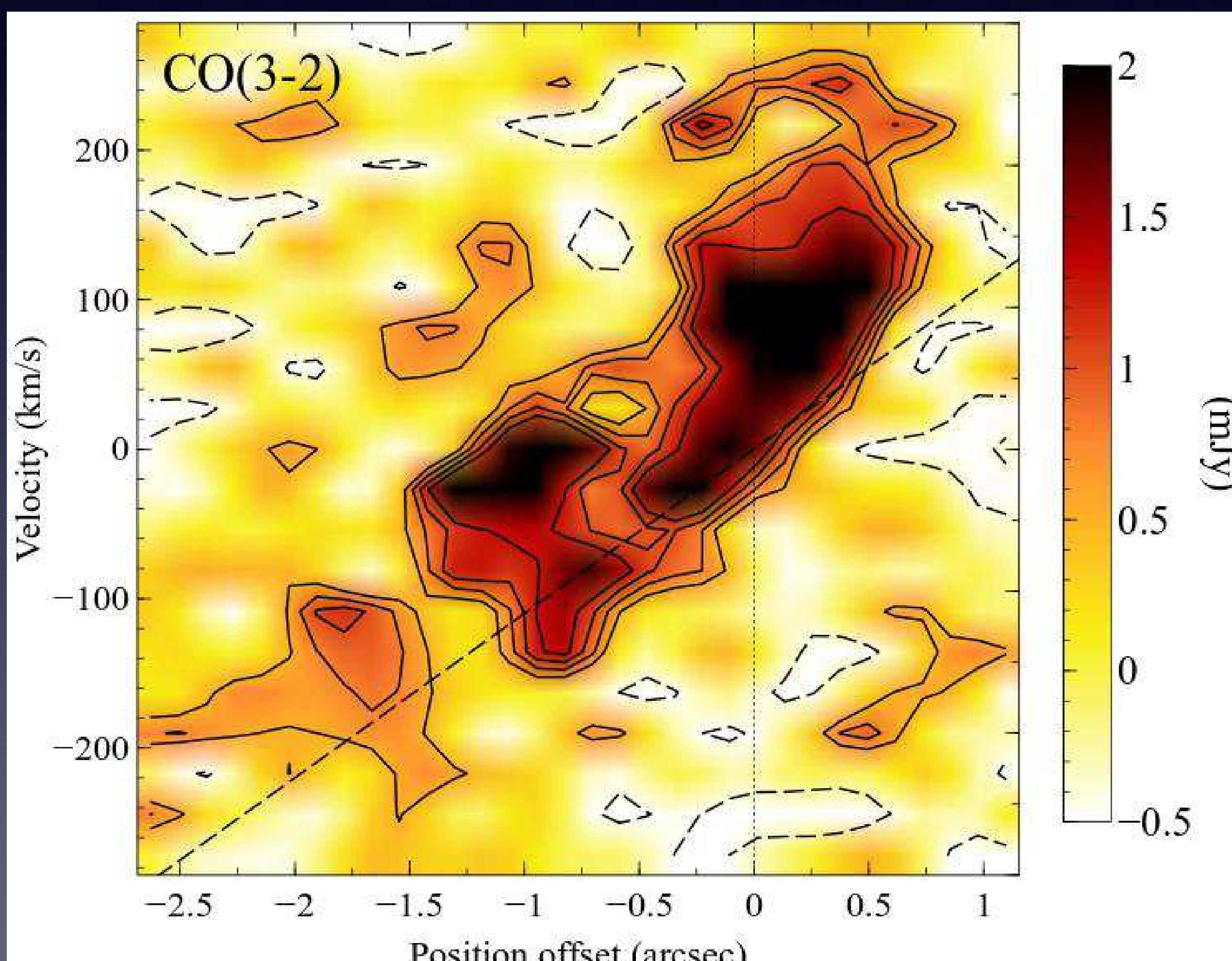
radially-dominant component

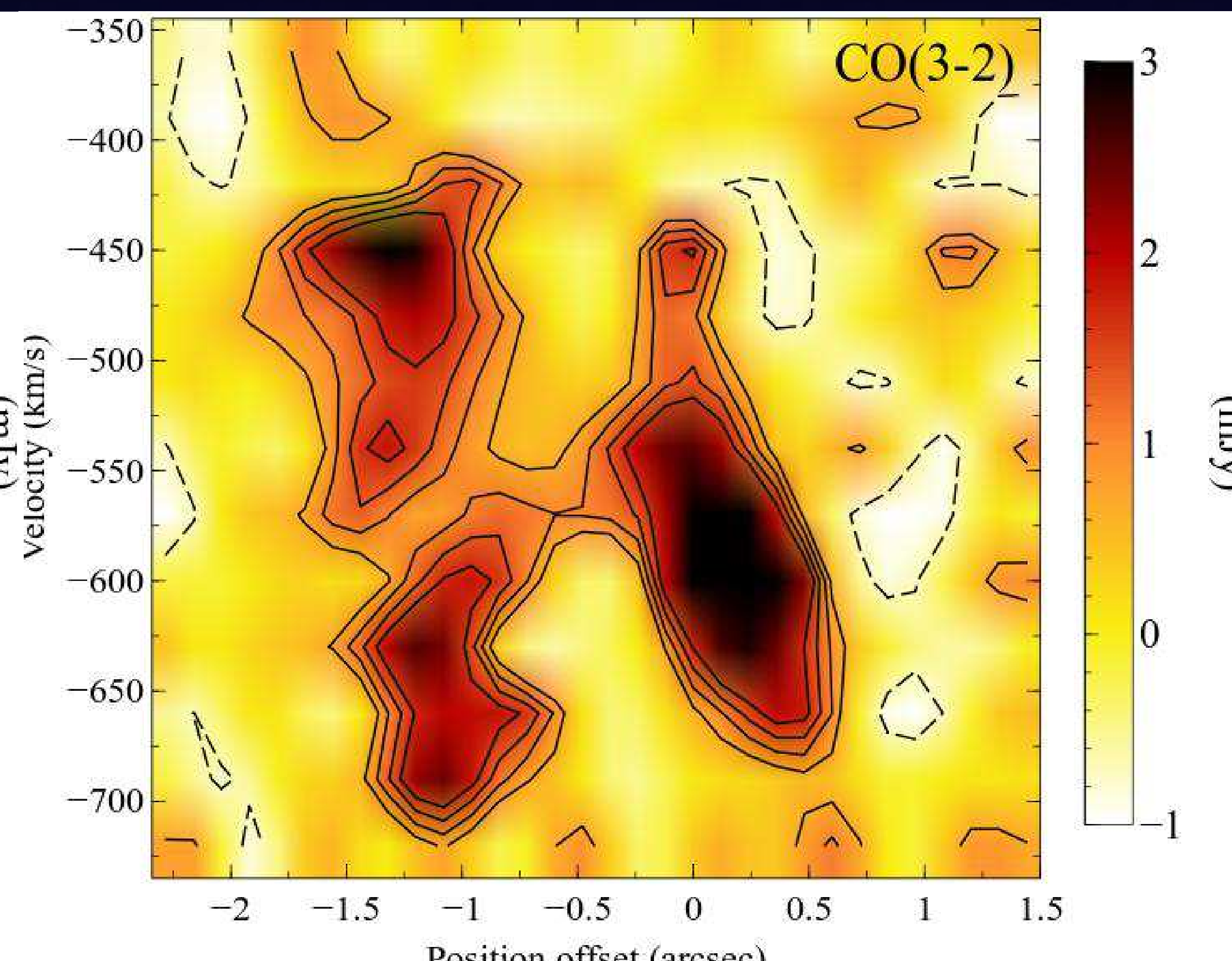


Cold gas observations

10^{10} Msun of molecular gas

A1664 [Russell et al. 2014]





low (200 km/s) and high (600 km/s) velocity components

AGN feedback cycles

core cooling

↓

large cold accretion onto SMBH

↓

negative FB, heating wins over cooling, energy pumped back in ICM

↓

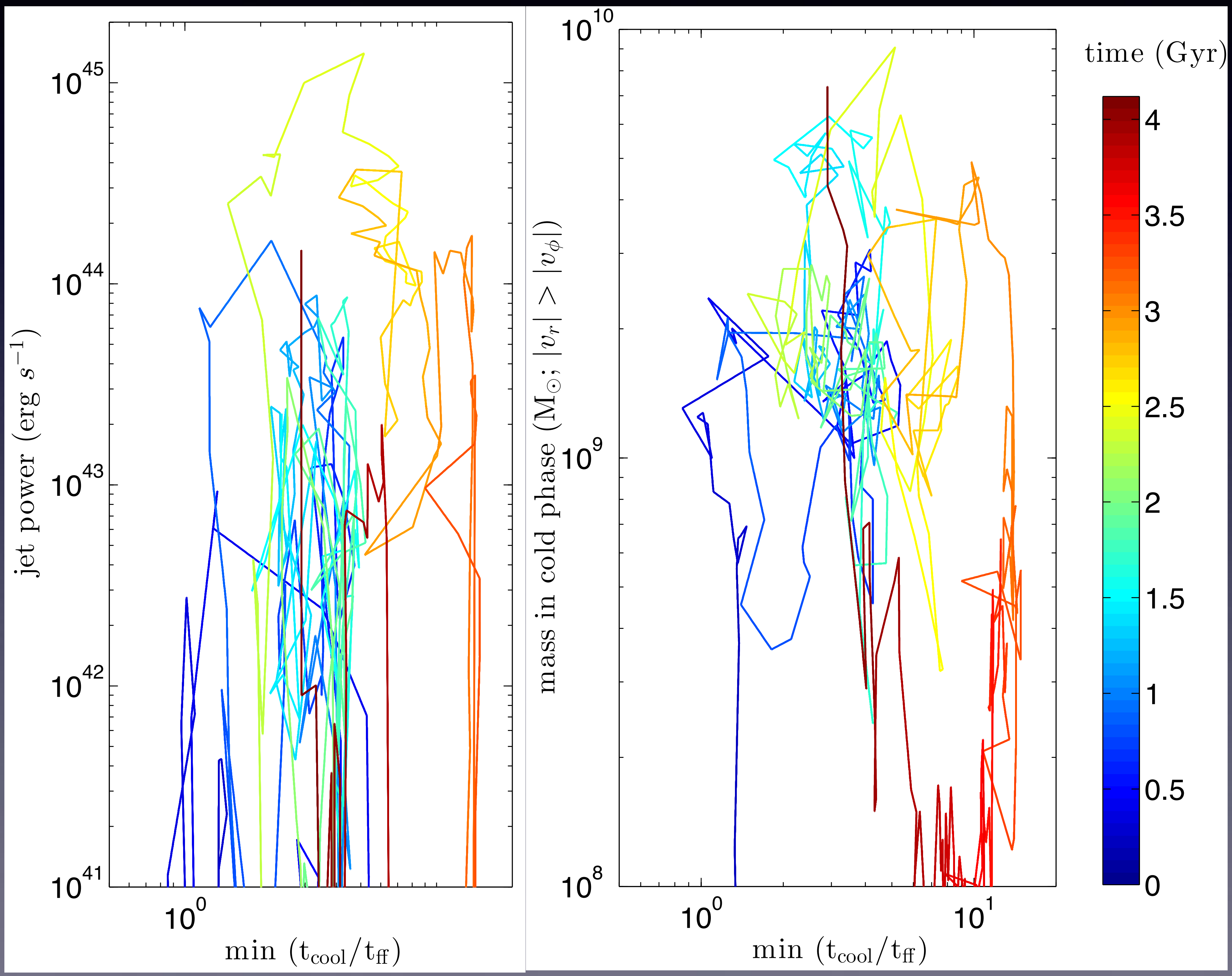
after few cooling times avg. thermal balance in core

↓

cold, multiphase gas condenses if $t_{cool}/t_{ff} \lesssim 10$

cooling & AGN jet heating cycles in cool-core clusters

Cycles in sims.

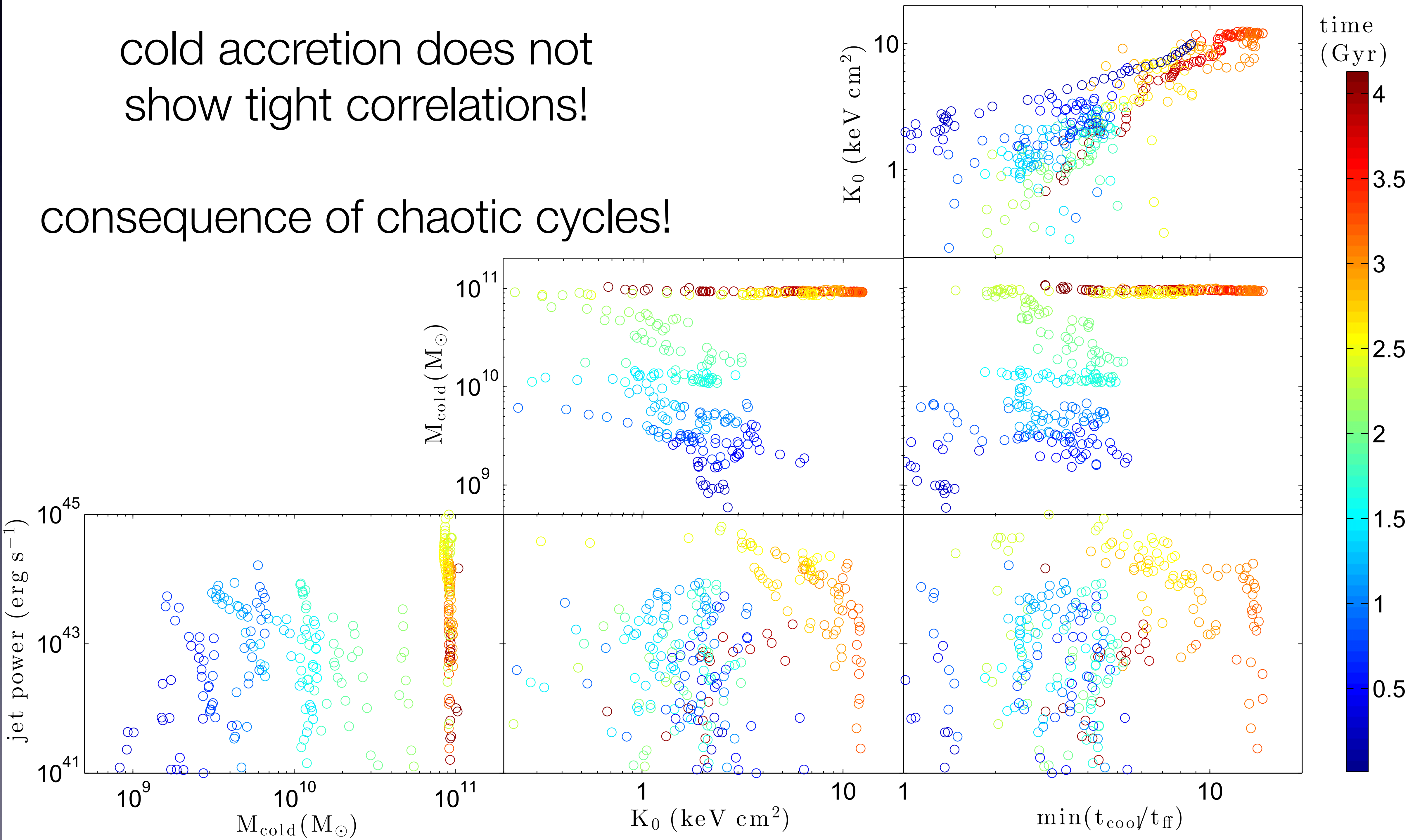


"phase space" of jet power cold gas mass vs. hot gas properties

Huge scatter in sims.

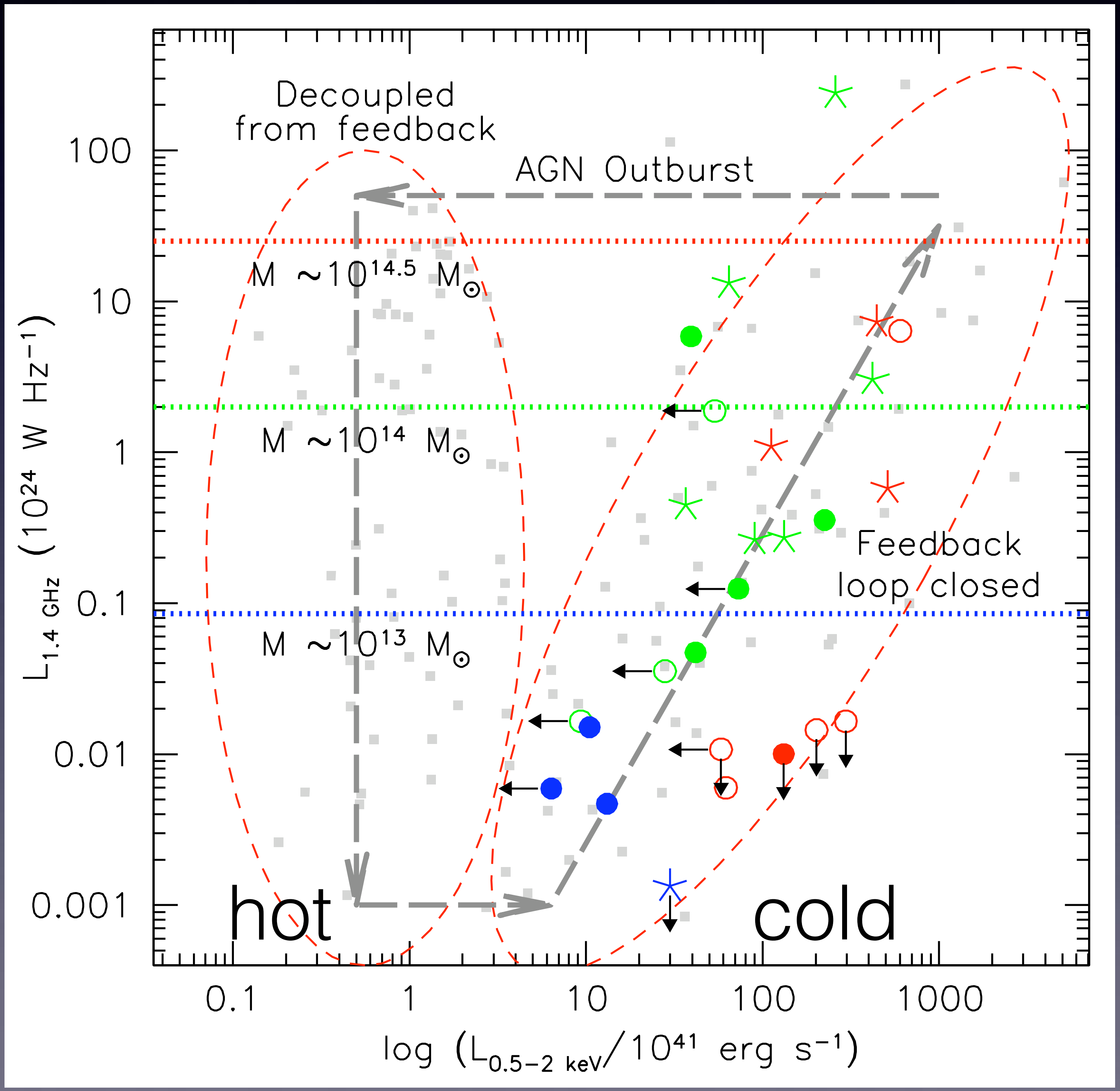
cold accretion does not
show tight correlations!

consequence of chaotic cycles!



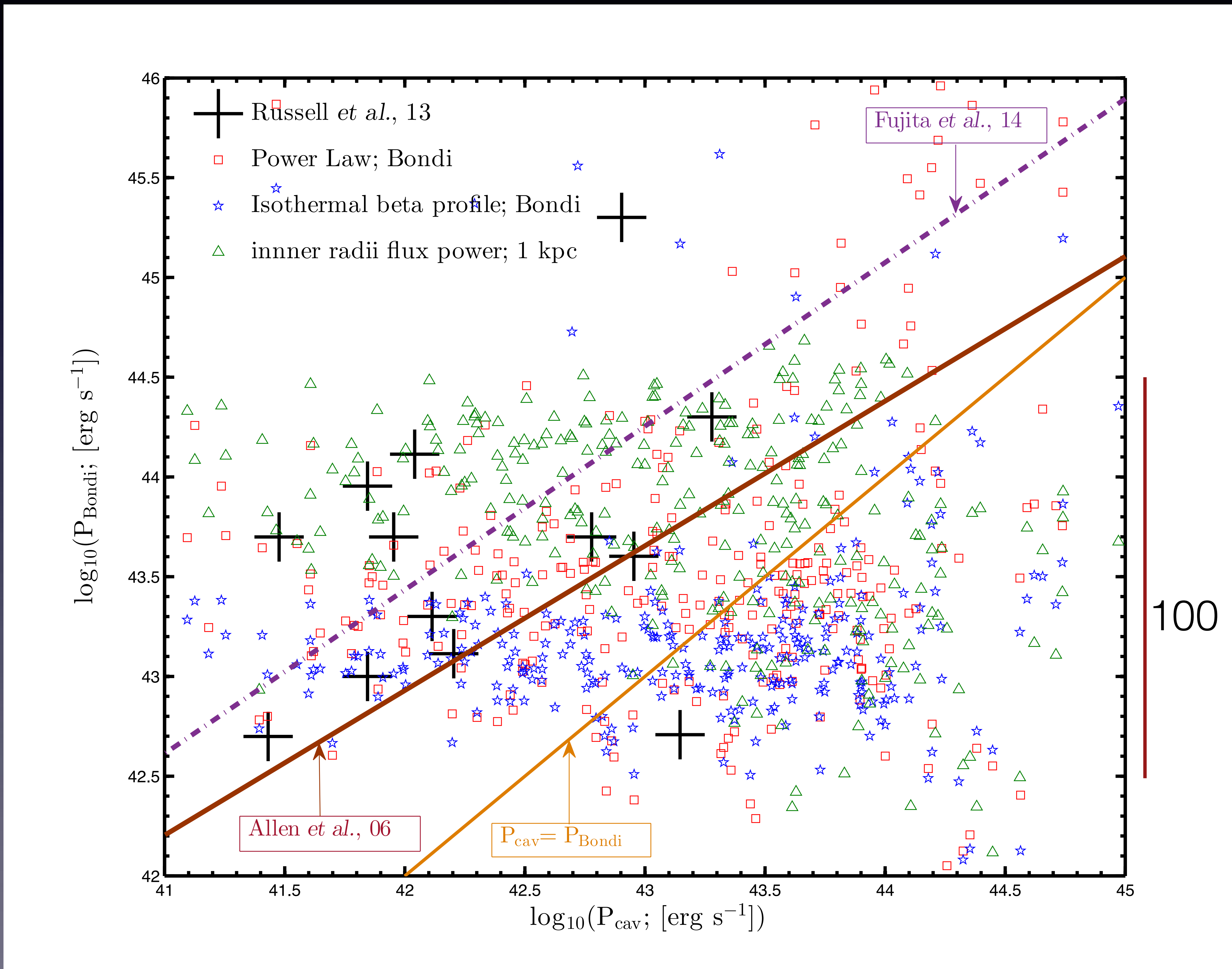
Observations of cycles

[McDonald et al. 2011]



observations of "phase space"

hot accretion inadequate



$$\dot{M}_{\rm BH} \lesssim 0.01 \dot{M}_{\rm Bondi}$$

only a small fraction makes it to SMBH because of outflows

Bondi resolved in Sgr A*, M 87, NGC 3115: all show suppression

Angular momentum problem

$$t_{\rm visc} \sim \frac{1}{\alpha (H/R)^2 \Omega_K}$$

too long if $H/R \sim 10^{-3}$,
of standard AGN thin disks
moreover, star formation
where M_d/M_{BH} exceeds H/R

$$t_{\rm visc} \sim 4.7\ {\rm Gyr}\ \left(\frac{R}{1{\rm pc}}\right)^{3/2} \left(\frac{H/R}{0.001}\right)^{-2} \left(\frac{\alpha}{0.01}\right)^{-1}$$

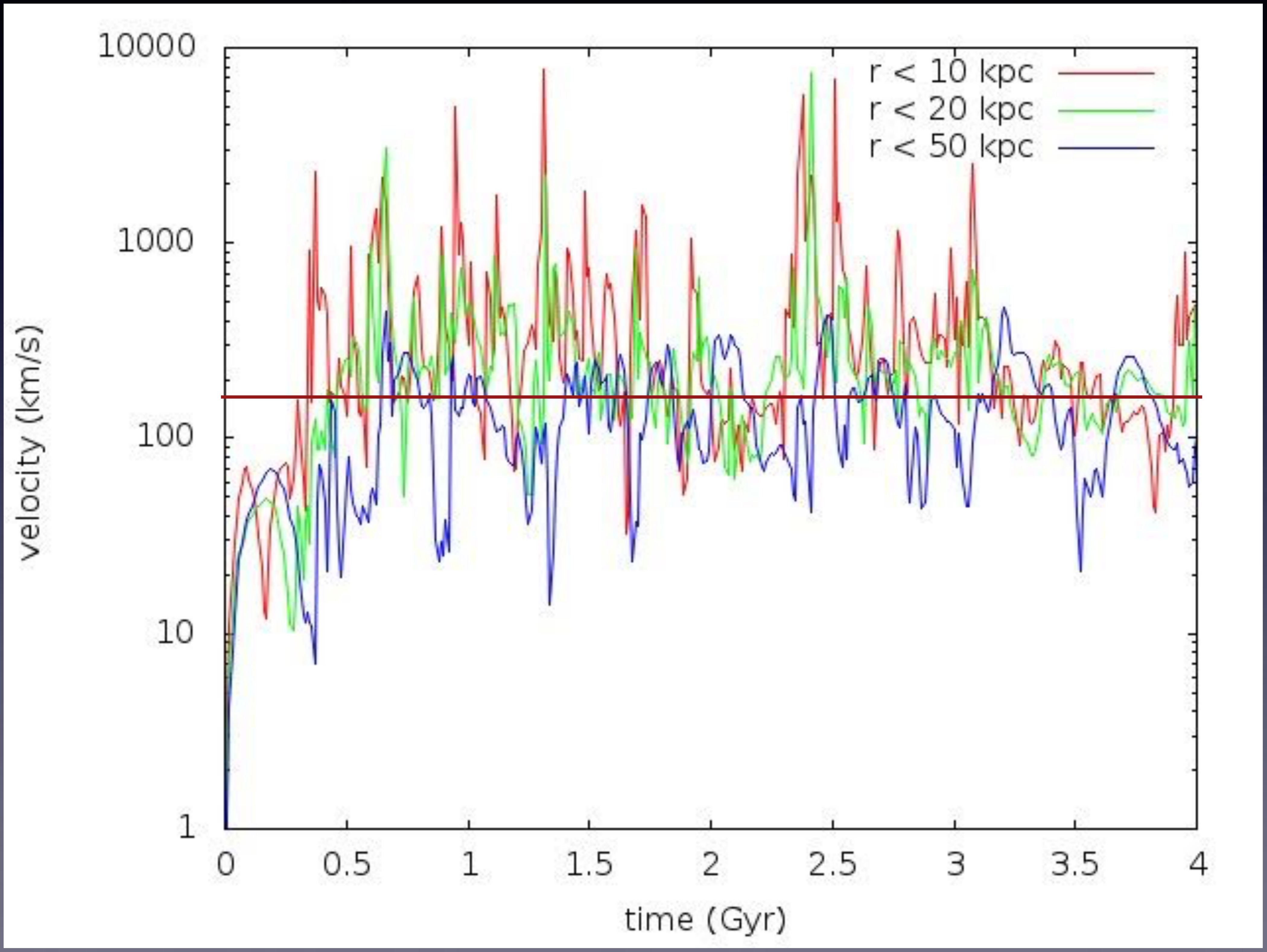
must avoid a large thin disk
t_{visc} $<$ core cooling time

Key issues

- microscopic dissipation: turbulent mixing/heating, shocks, CRs
- conduction, hot accretion secondary
- from 1 kpc to << 1 pc (BH sphere of influence): core to BH accretion
- stochastic cold gas, angular momentum barrier, most cold gas consumed by SF
- relation to radio mini-halos
- spiral structures, cold fronts, sloshing

Thanks!

turbulent velocities



structure of hot gas vs halo mass

[Sharma et al. 2012]