Heating & cooling cycles in cool cluster cores

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

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Cold gas condensation

- allows feedback to act sufficiently fast, unlike Bondi
- $t_{cool}/t_{ff} \sim 10$ seems robust
- 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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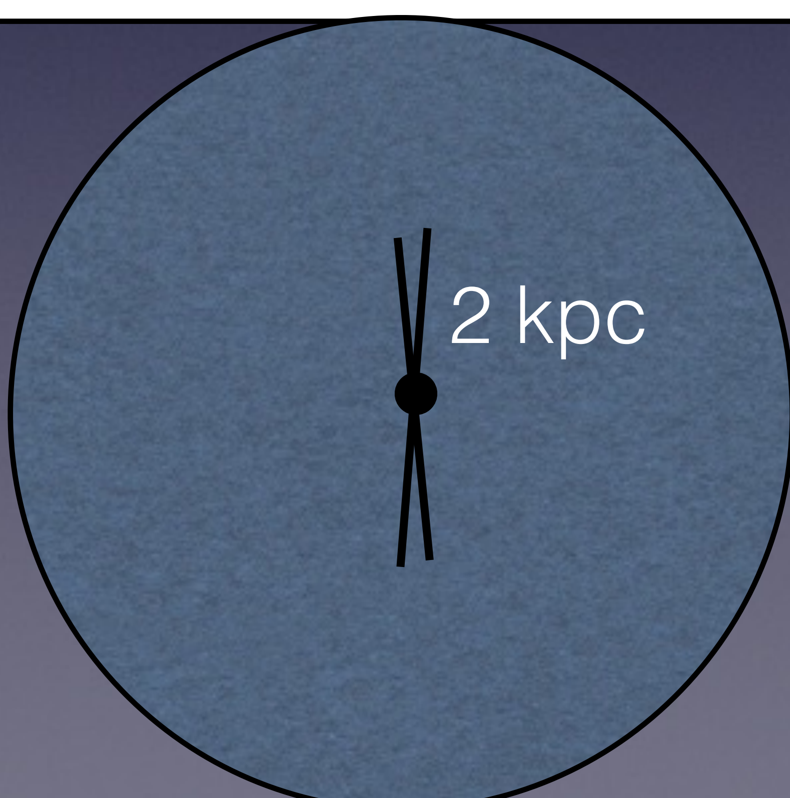
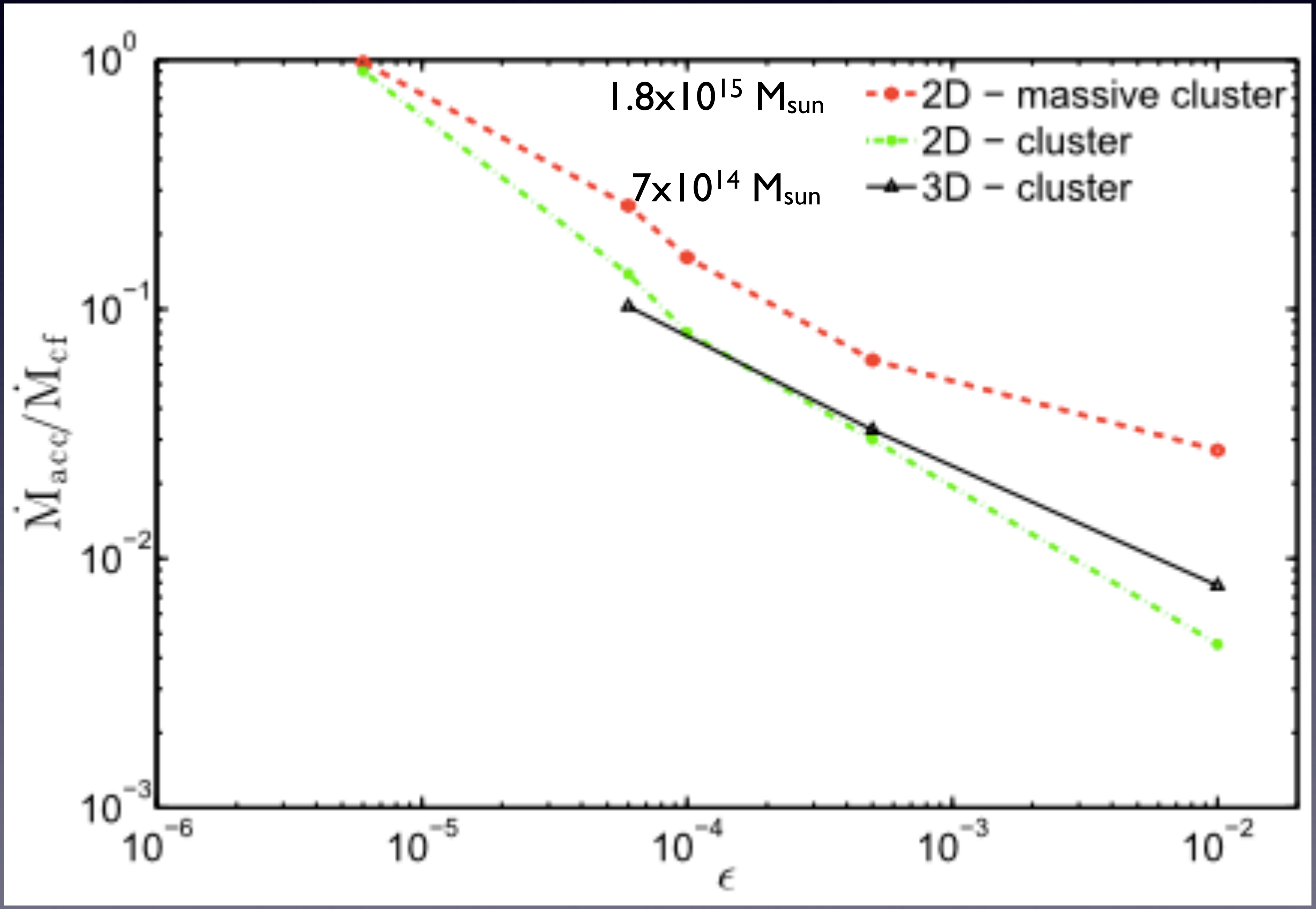


source term applied in a small bipolar cone at the center: opening angle of 30^0, size 2 kpc

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

v_{jet}=0.1c, ε=6x10^{-5}, $r_{in,out}$=1, 200 kpc
robust to variations

Dependence on halo mass & efficiency

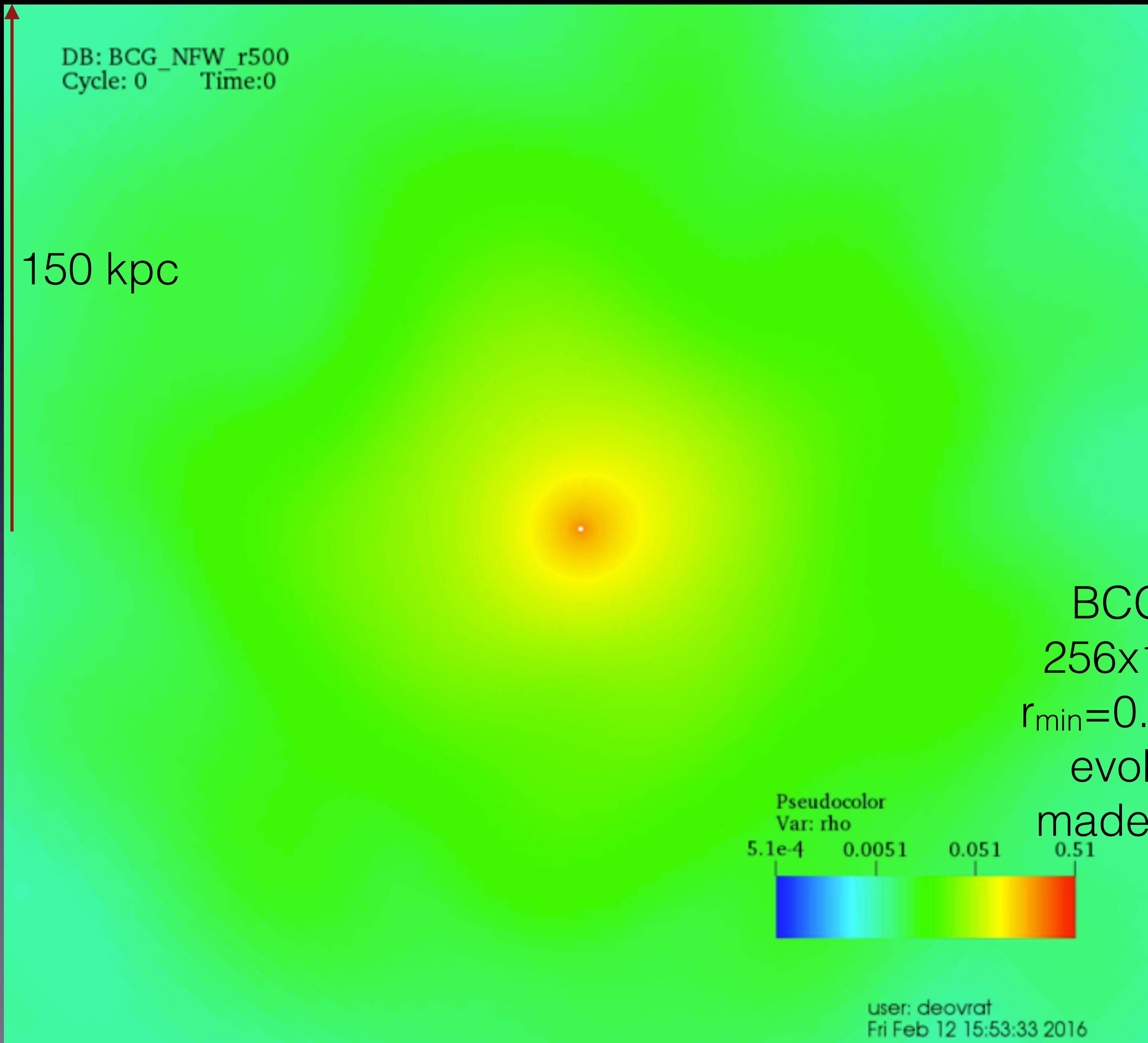


larger ε suppresses accretion

more massive halos require larger ε

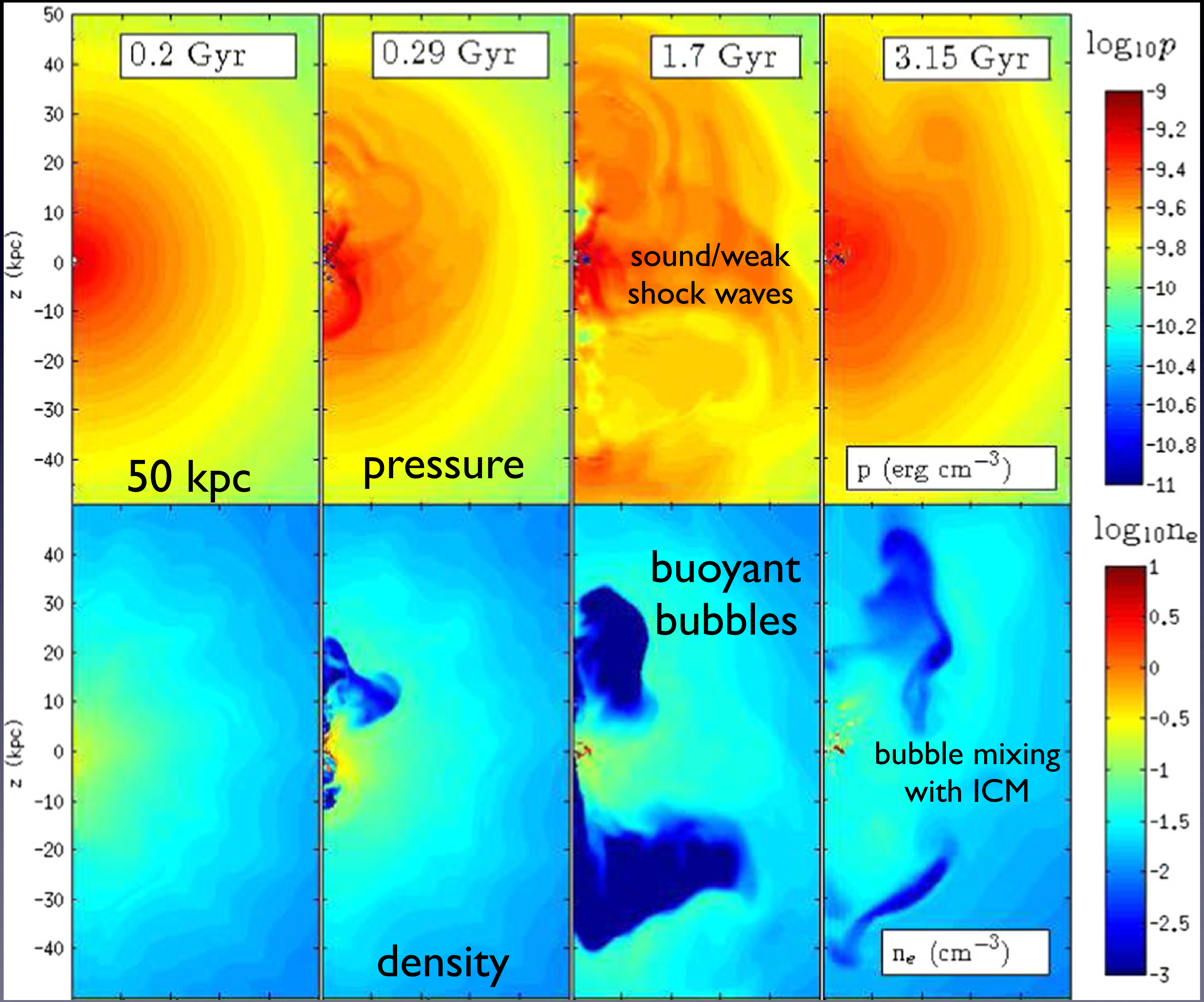
depends on where Mdot calculated

Density movie



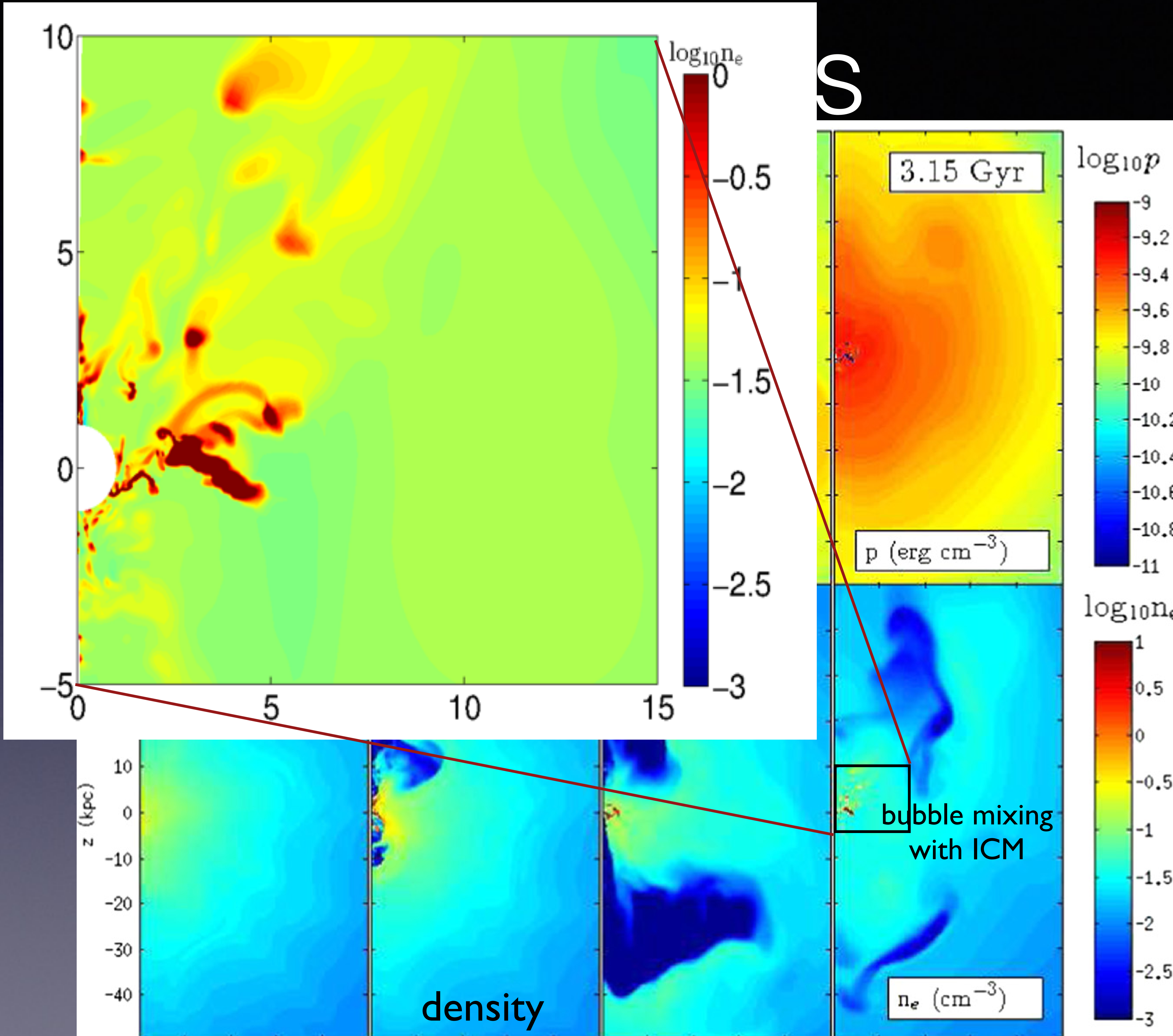
BCG+NFW in PLUTO
256x128x32 in (logr,θ,ϕ)
r_{min}=0.5 kpc, r_{max}=0.5 Mpc
evolution for ~2.8 Gyr
made by Deovrat Prasad

r-θ slices



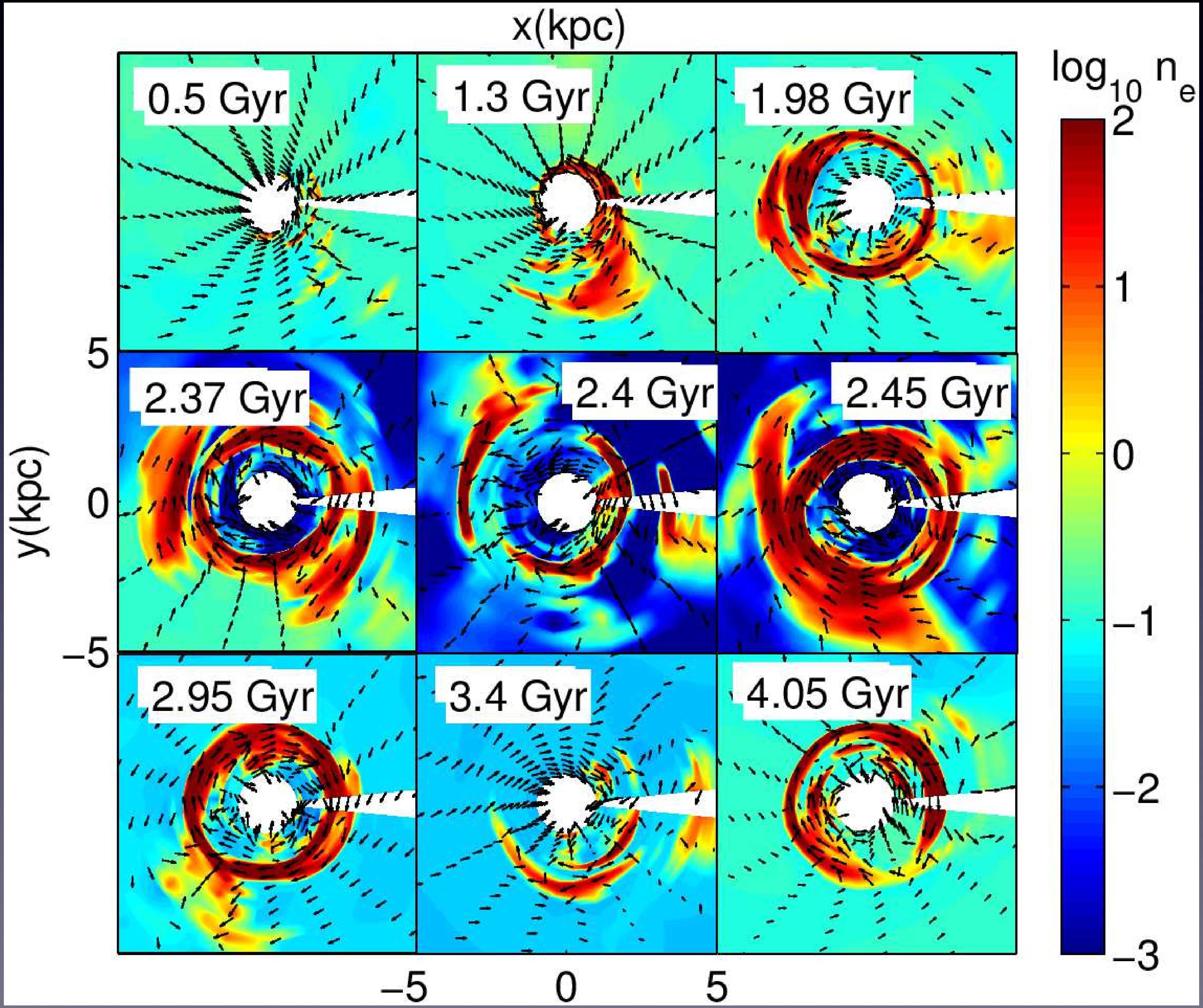
0.2 Gyr
0.29 Gyr
1.7 Gyr
3.15 Gyr
log10p
-9
-9.2
-9.4
-9.6
-9.8
-10
-10.2
-10.4
-10.6
-10.8
-11
z (kpc)
50
40
30
20
10
0
-10
-20
-30
-40
sound/weak shock waves
50 kpc
pressure
p (erg cm^-3)
log10ne
1
0.5
0
-0.5
-1
-1.5
-2
-2.5
-3
buoyant bubbles
bubble mixing with ICM
density
ne (cm^-3)

S



log10ne
log10p
3.15 Gyr
p (erg cm−3)
ne (cm−3)
z (kpc)
bubble mixing
with ICM
density

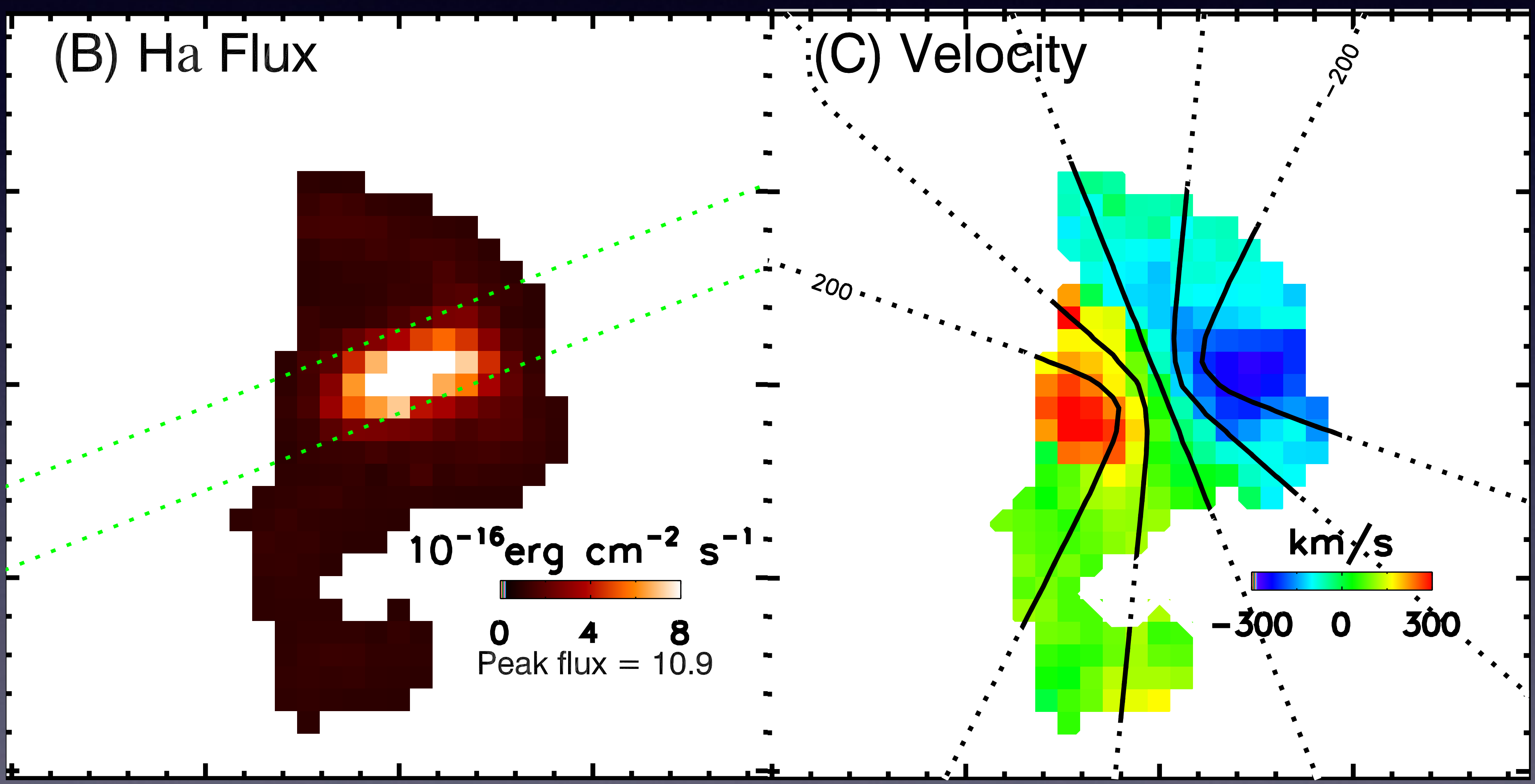
Cold rotating torus



few kpc scale
molecular torus

Cold torus in Hydra A

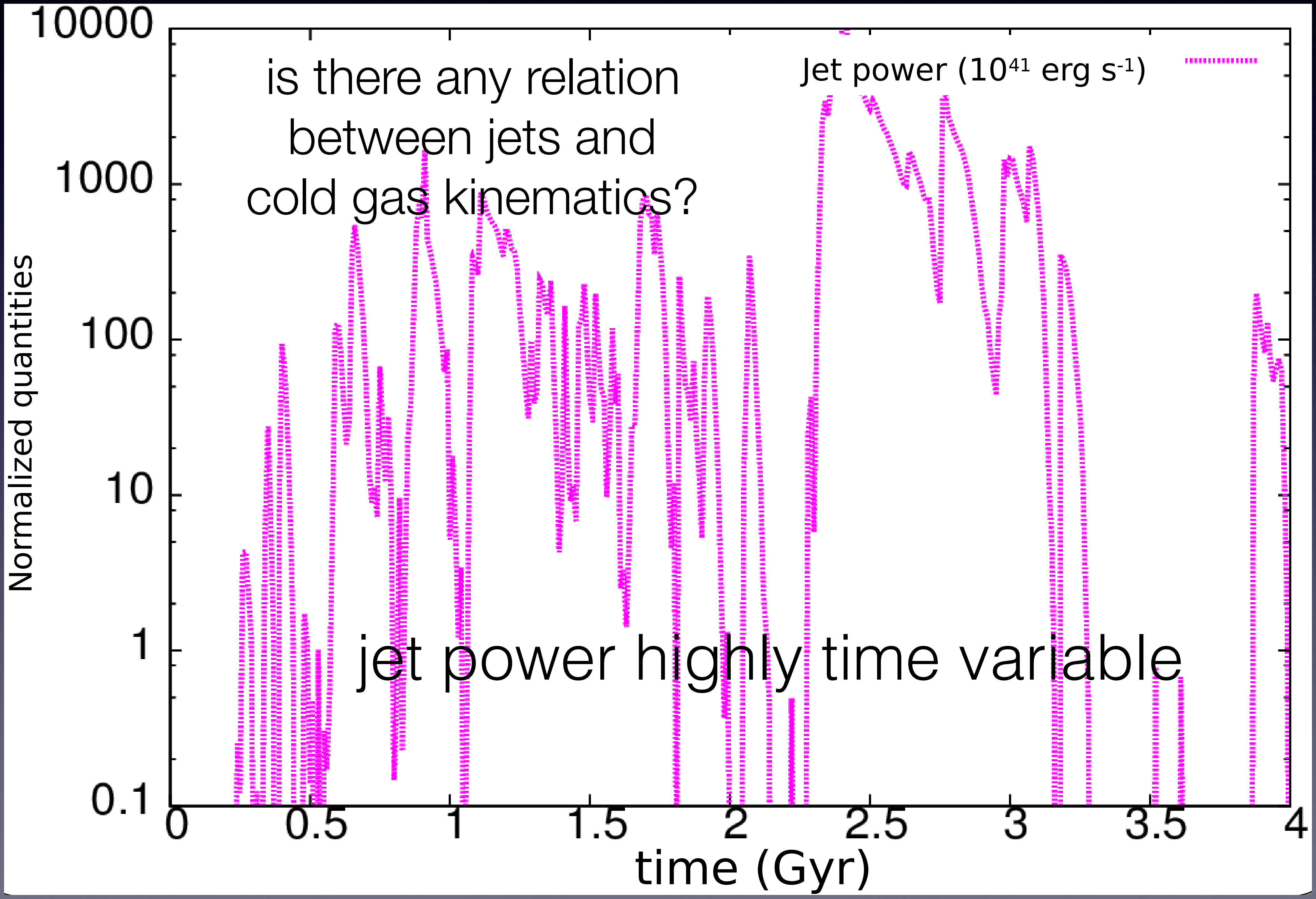
[Hamer et al. 2014]



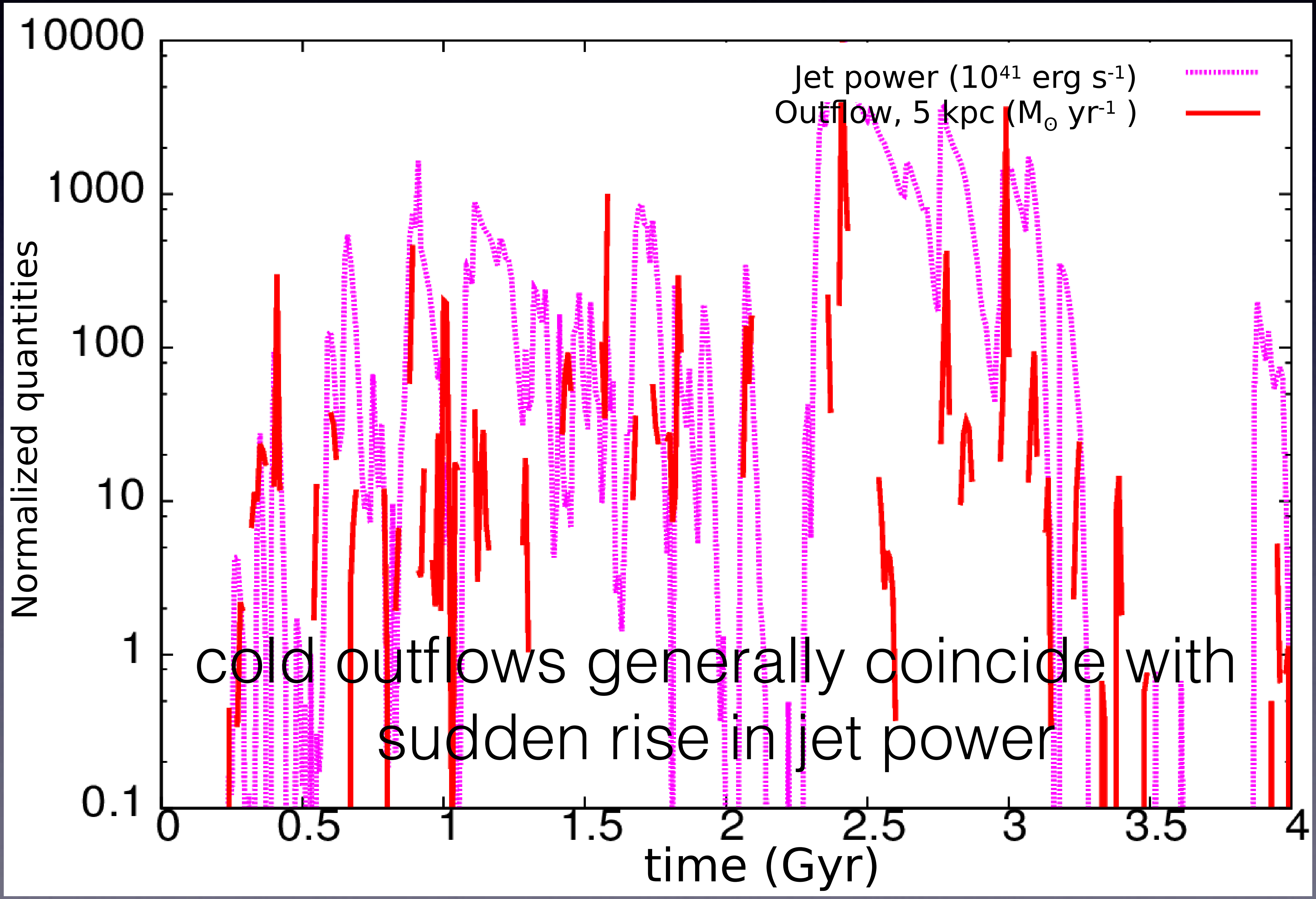
~5 kpc cold torus

more examples from ALMA, Hershel

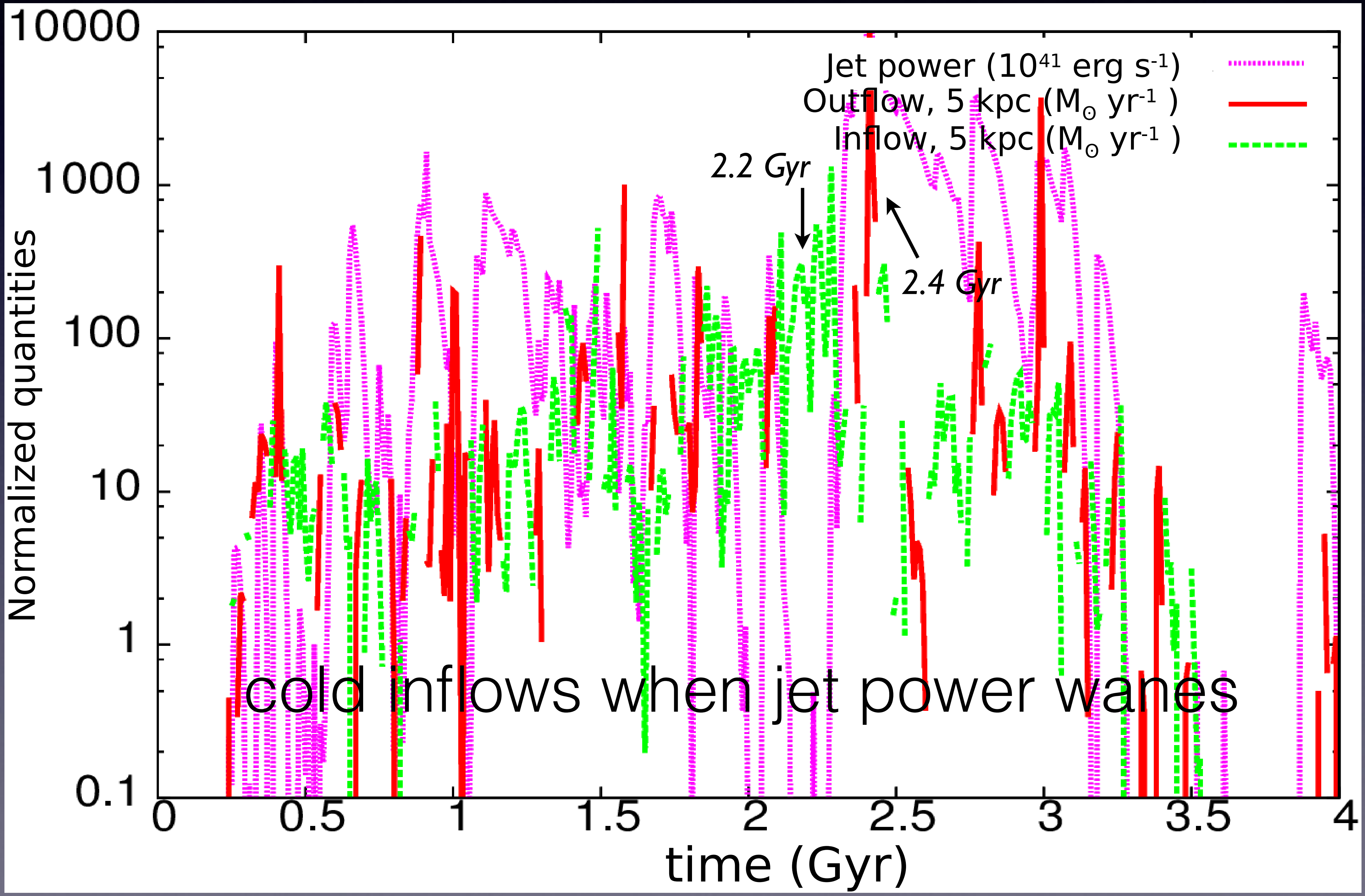
Jets & fast outflows



Jets & fast outflows



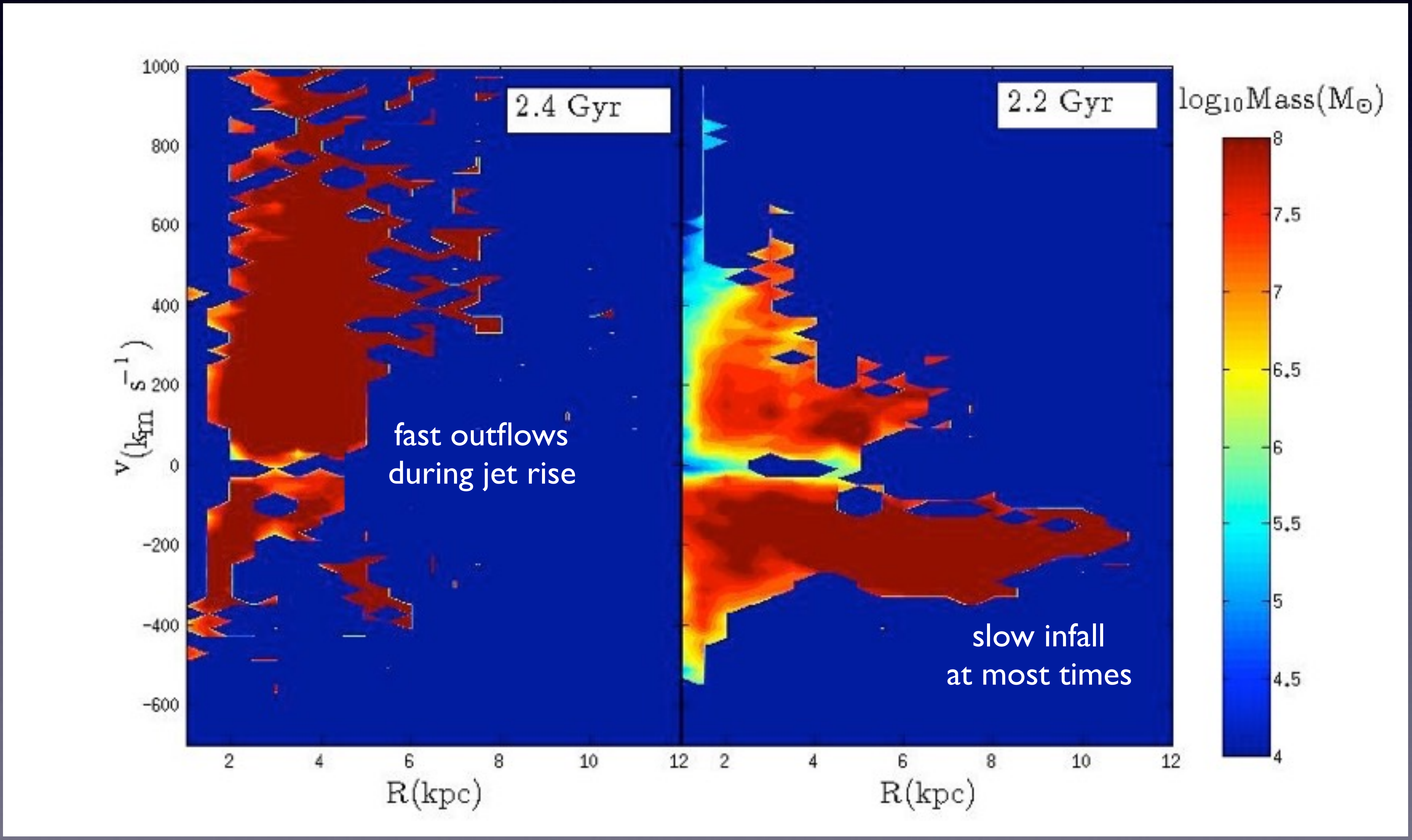
Jets & fast outflows



cold inflows when jet power wanes

Snapshots of inflow/ outflow phases

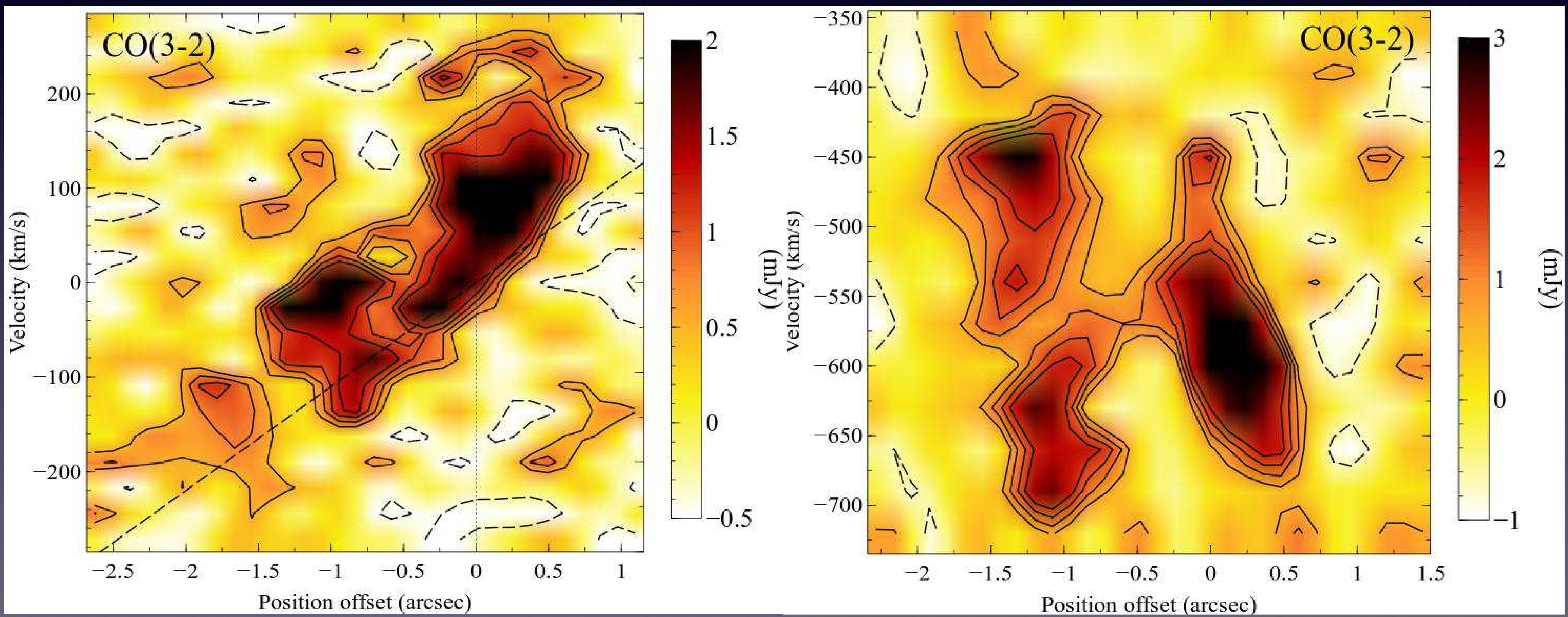
radially-dominant component



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

↓

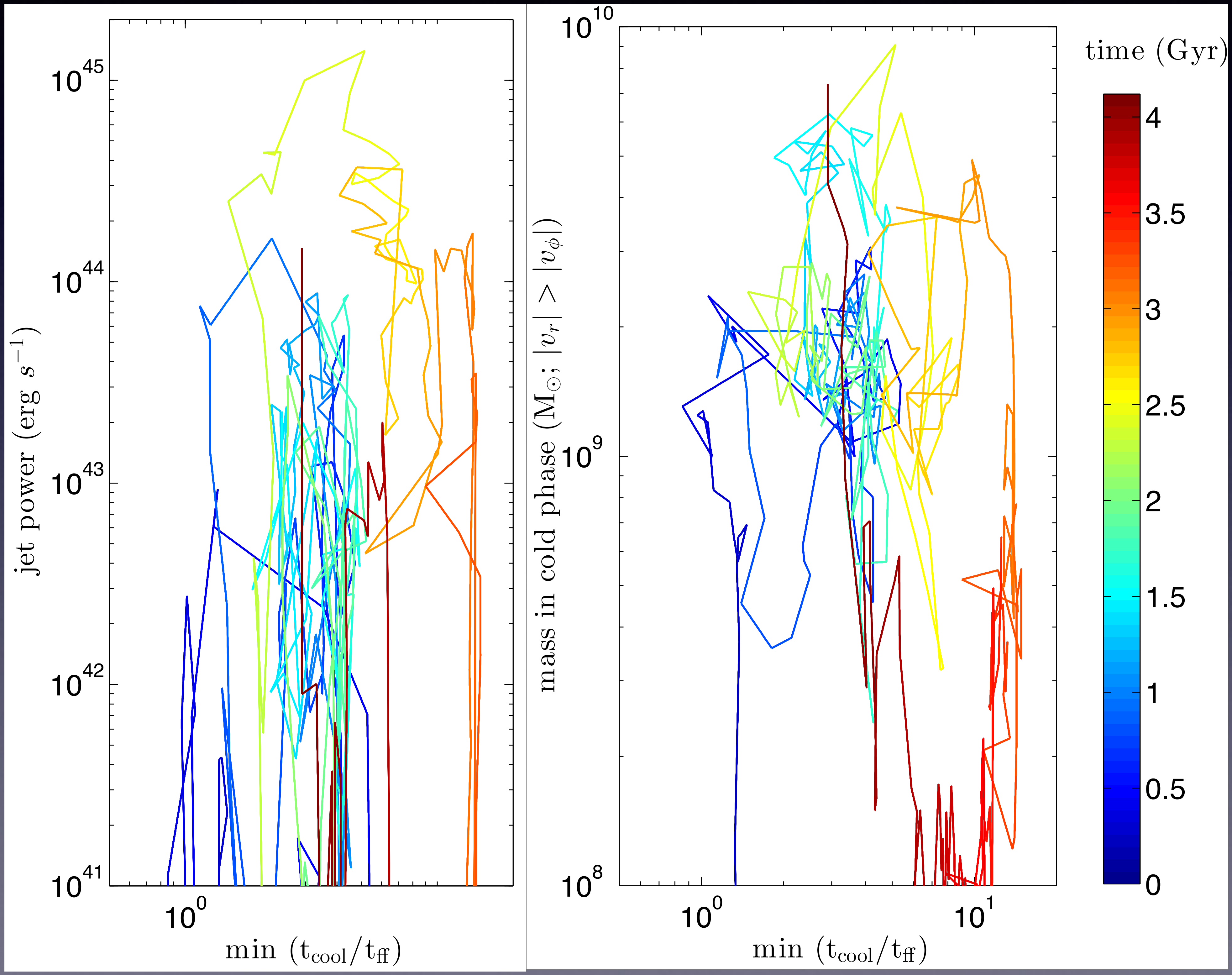
after few cooling times avg. thermal balance in core

↓

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

cooling & AGN jet heating cycles in cool-core clusters

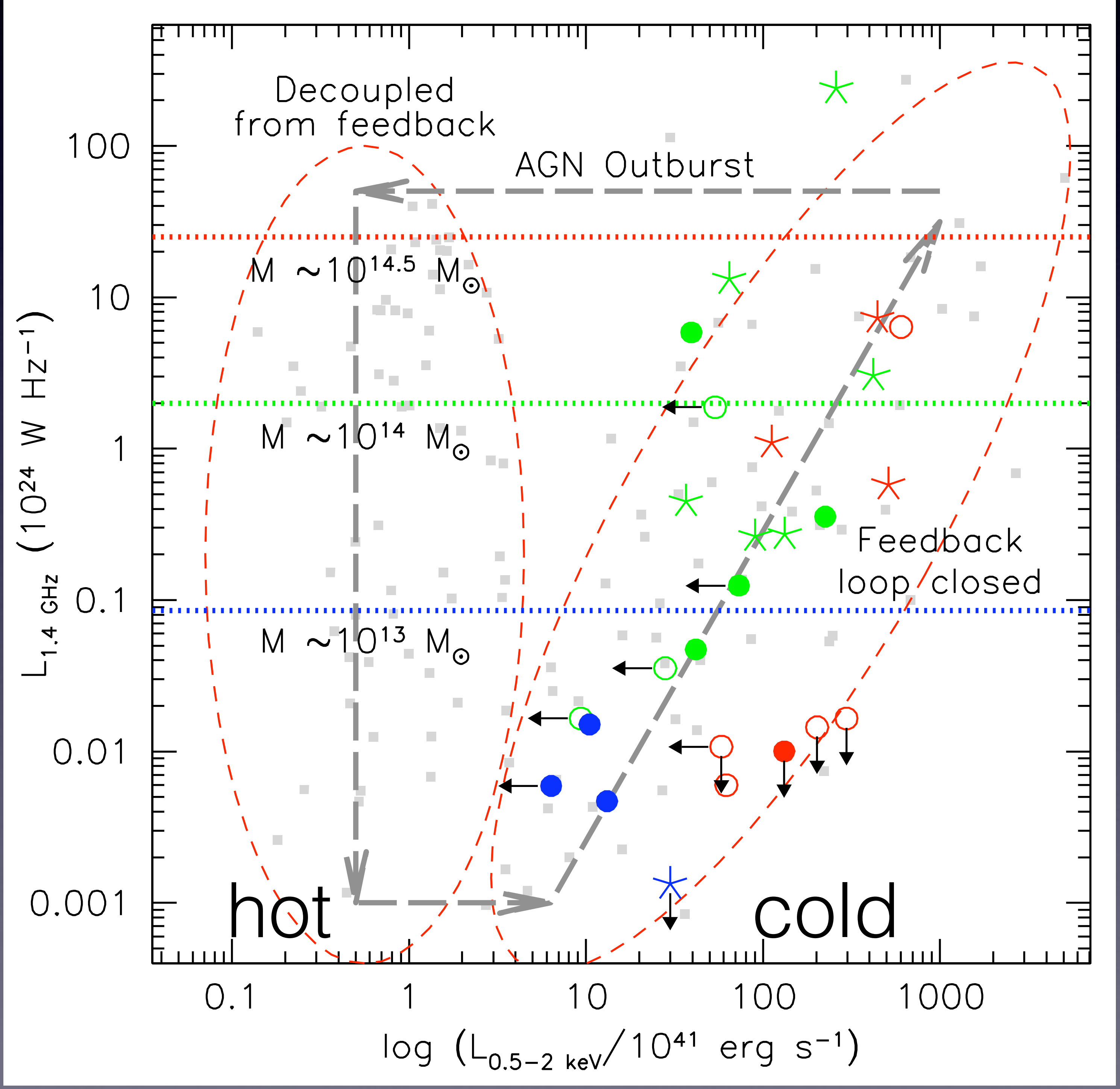
Cycles in sims.



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

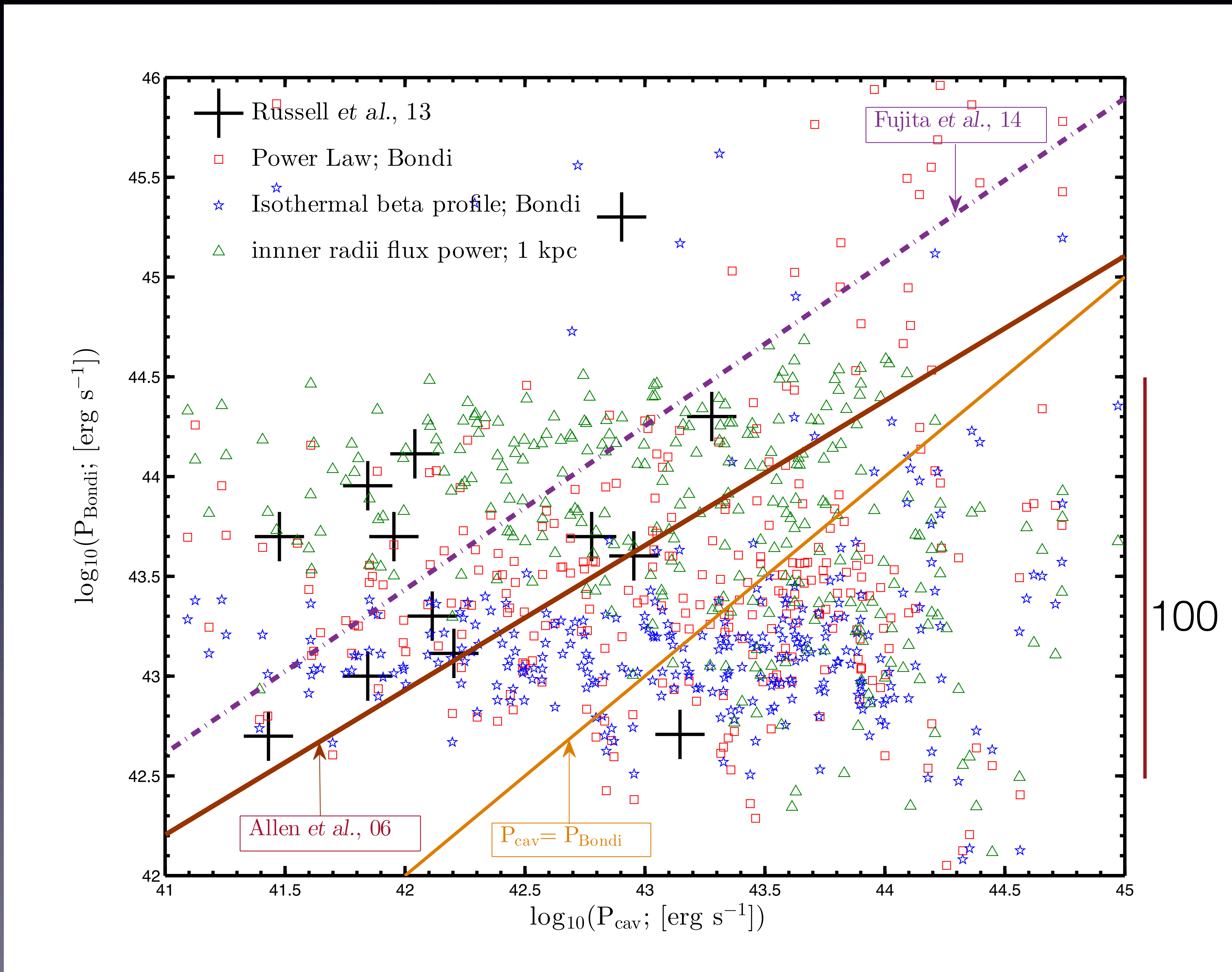
Observations of cycles

[McDonald et al. 2011]



observations of "phase space"

hot accretion inadequate



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

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~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
$t_{\rm visc}$ < 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!