CHAOTIC COLD ACCRETION ONTO SMBHS

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RAINING ONTO SMBHS

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OUTLINE

FEEDING ?

- cold versus hot mode
- linking group scale to sub-pc scale
- beyond classic Bondi and thin disc
- cooling, heating, rotation, turbulence: **chaotic cold accretion [CCA]**

MG+2013-2015

FEEDBACK ?

- amount of energy released
- deposition of energy
- mechanical versus thermal
- bubbles, shocks, metal uplift, turbulence, L_x-T_x <---> observations

MG+2009-2015

SELF-REGULATED LOOP

ON SPHERICALLY SYMMETRICAL ACCRETION

H. Bondi

(Received 1951 October 3)

Summary

The special accretion problem is investigated in which the motion is steady and spherically symmetrical, the gas being at rest at infinity. The pressure is taken to be proportional to a power of the density. It is found that the accretion rate is proportional to the square of the mass of the star and to the density of the gas at infinity, and varies inversely with the cube of the velocity of sound in the gas at infinity. The factor of proportionality is not determined by the steady-state equations, though it is confined within certain limits. Arguments are given suggesting that the case physically most likely to occur is that with the maximum rate of accretion.

$$\dot{M}_{\rm B} = 4\pi\lambda_{\rm c}\frac{(GM_{\rm BH})^2}{c_{\rm s,\infty}^3}\rho_\infty \quad \propto K_\infty^{-3/2}$$

"For simplicity, ... "
(mathematical)

$$4\pi r^2 \rho v = \text{constant}$$

$$\frac{v^2}{2} + \int_{p_\infty}^{p} \frac{dp}{\rho} - \frac{GM}{r} = \text{constant } (=0).$$

$$p/p_\infty = (\rho/\rho_\infty)^\gamma$$

"For complexity, ... "
(physical)

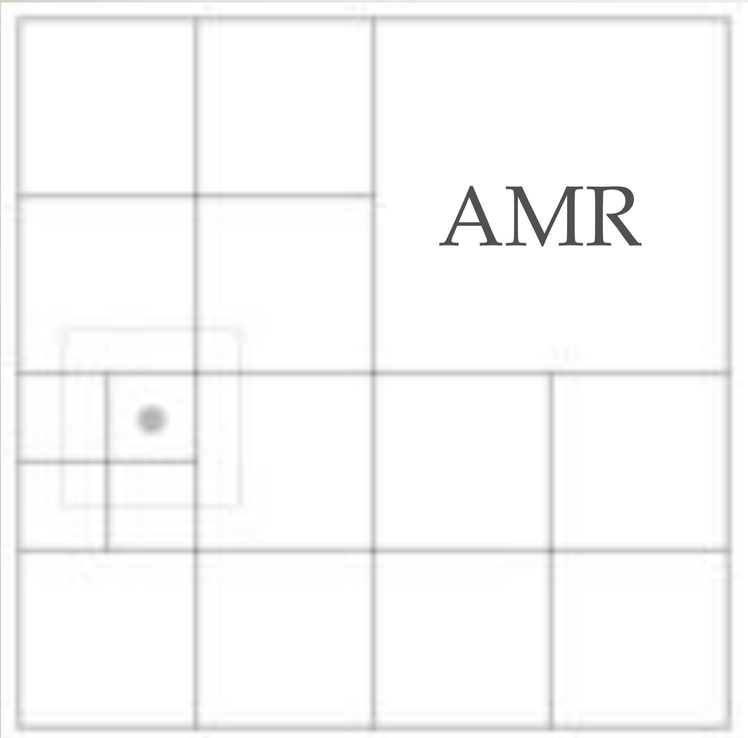
$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \boldsymbol{v}) = \alpha \rho_* - q \frac{\rho}{t_{\rm cool}} + S_{1,\rm jet}, \tag{1}$$

$$\frac{\partial \rho \boldsymbol{v}}{\partial t} + \nabla \cdot (\rho \boldsymbol{v} \otimes \boldsymbol{v}) + \nabla P = \rho \boldsymbol{g}_{\rm DM} + S_{2,\rm jet}, \tag{2}$$

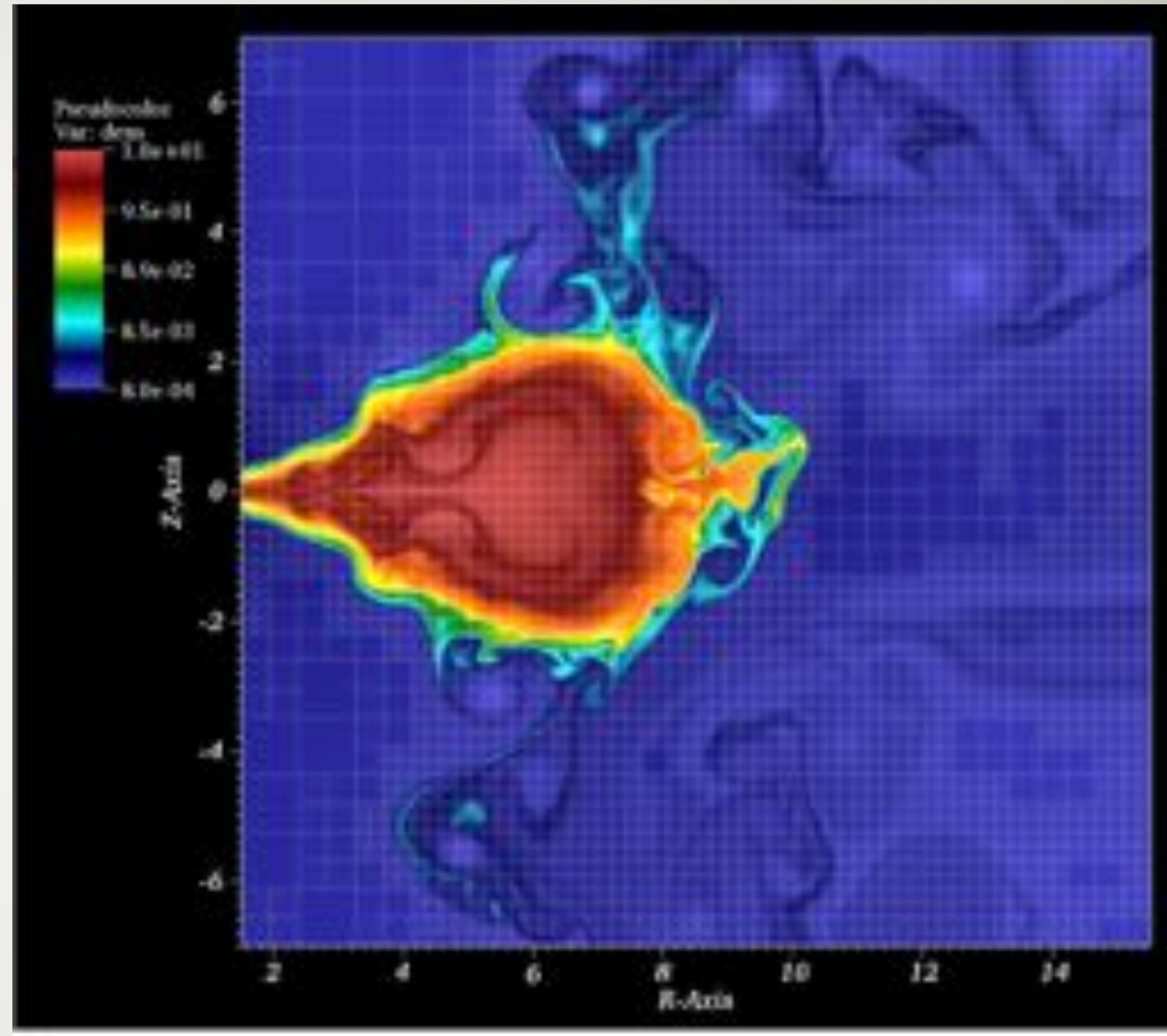
$$\frac{\partial \rho \varepsilon}{\partial t} + \nabla \cdot [(\rho \varepsilon + P) \boldsymbol{v}] = \rho \boldsymbol{v} \cdot \boldsymbol{g}_{\rm DM} + \alpha \rho_* \left(\varepsilon_0 + \frac{\boldsymbol{v}^2}{2} \right) - n_{\rm e} n_{\rm i} \Lambda(T, Z) + S_{3,\rm jet}, \tag{3}$$

$$P = (\gamma - 1) \rho \left(\varepsilon - \frac{\boldsymbol{v}^2}{2} \right). \tag{4}$$

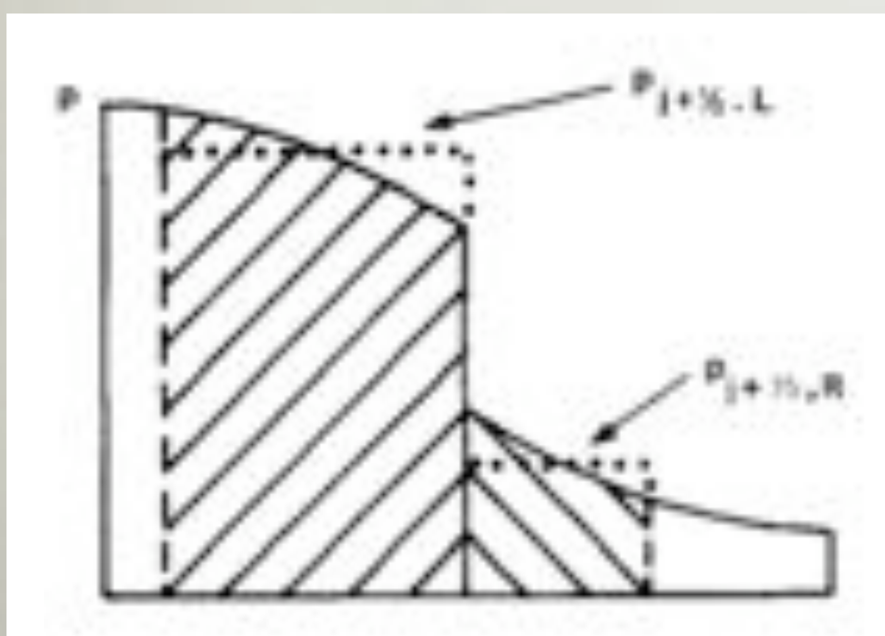
Flash4 code



AMR blocks:
high scalability
(100k+ CPUs)



$$\int_{x_1}^{x_2} \mathbf{U}(x,t_2)\,dx = \int_{x_1}^{x_2} \mathbf{U}(x,t_1)\,dx + \int_{t_1}^{t_2} \mathbf{F}(\mathbf{U}(x_1,t))\,dt - \int_{t_1}^{t_2} \mathbf{F}(\mathbf{U}(x_2,t))\,dt$$



PPM

PIECEWISE PARABOLIC METHOD
(III order; Woodward & Colella 1984)

- **Integral** form of the hydro equations (cell averages)
- Perfectly suited to study: **shocks** & **discontinuities**
- Optimal **conservation** of mass, momentum and energy

FEEDING: SMBH ACCRETION

FLASH4 simulations

MG+2013-2015

- concentric SMR zooming: **box = 50 kpc → dx ~ 20 R_S - 0.1 pc**

  ~10 million range 600 r_B and 200 t_B

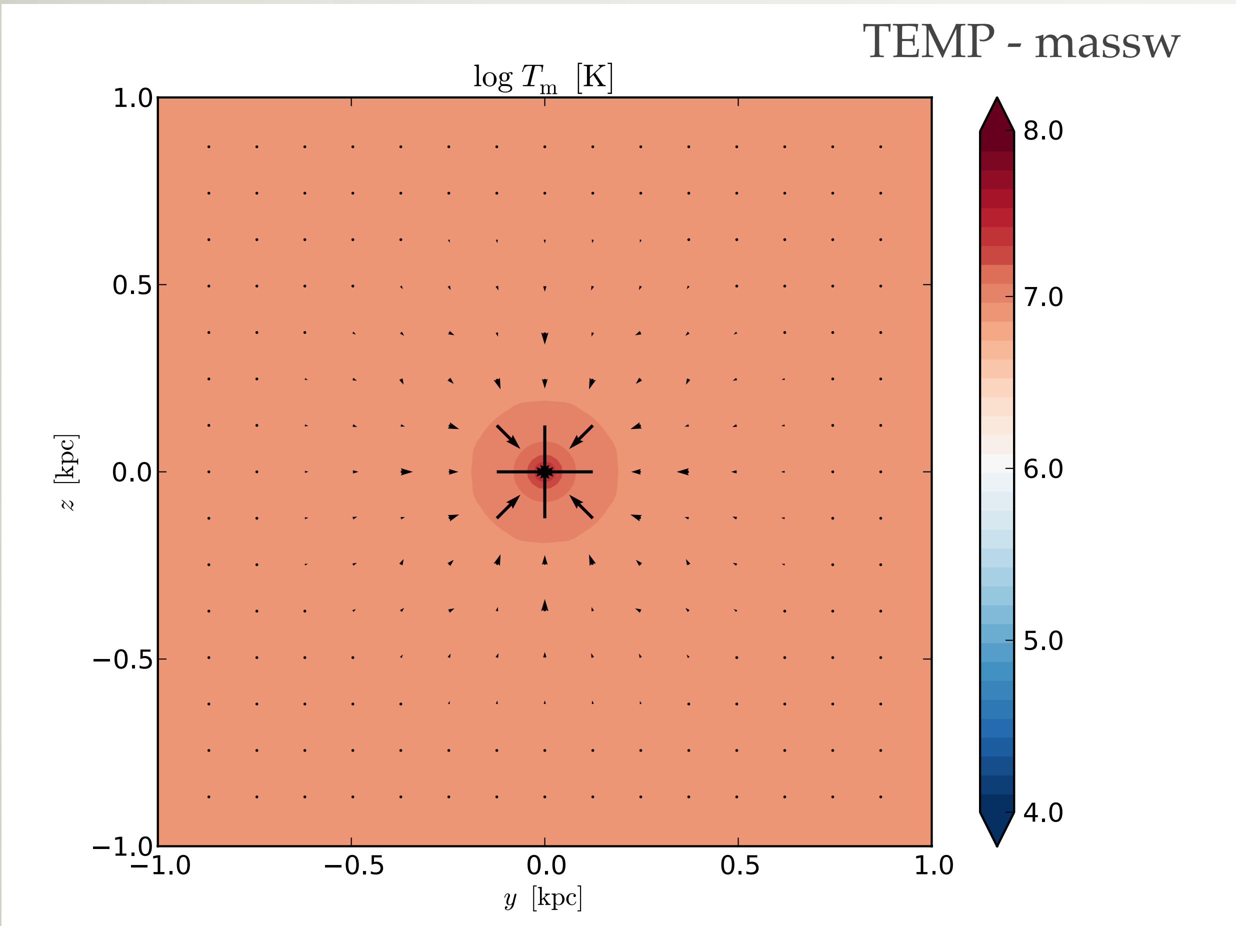
- 3D eulerian gas dynamics: unsplit PPM (3rd order) + varying physics
- massive galaxy group with dark matter halo: $M_{vir} = 4\text{x}10^{13}\ M_\odot$
- central elliptical galaxy (NGC 5044): $M_{star} = 3.4\text{x}10^{11}\ M_\odot$
- SMBH: $M_{bh} = 3\text{x}10^{9}\ M_\odot$ ⟶ relativistic PW: $\phi_{PW} = -GM_{bh}/(r - R_S)$
- observed gas $T(r)$ [cool-core] ⟶ $n(r)$ via hydrostatic equilibrium

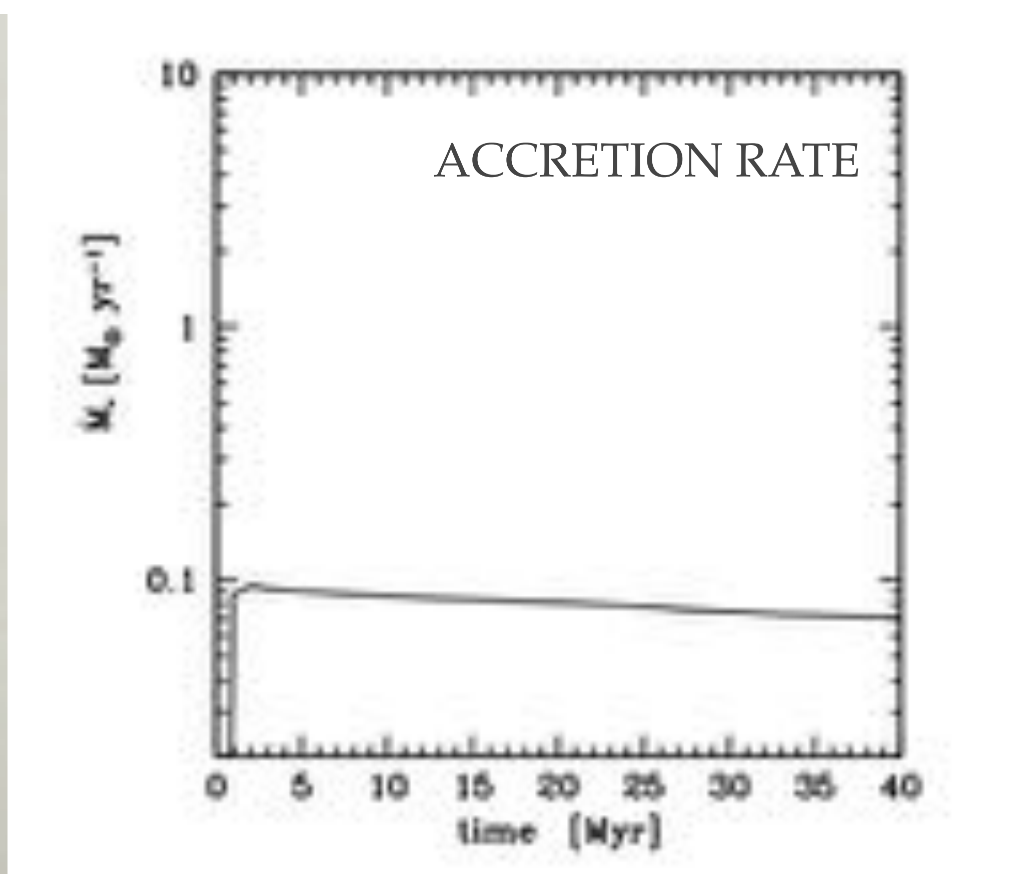
1.

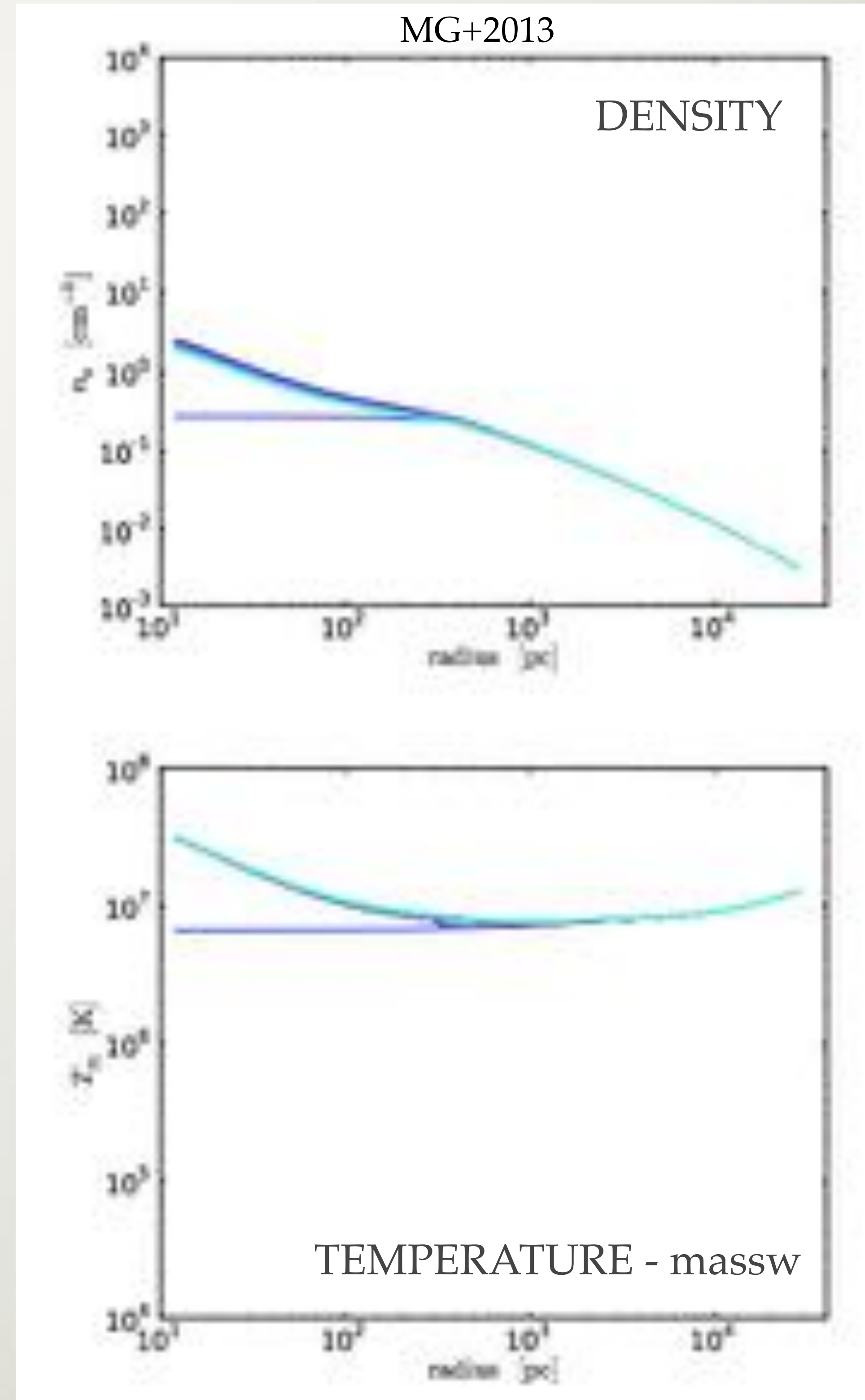
~~CONSTANT BOUNDARIES~~

STRATIFICATION

PURE HOT MODE (BONDI)

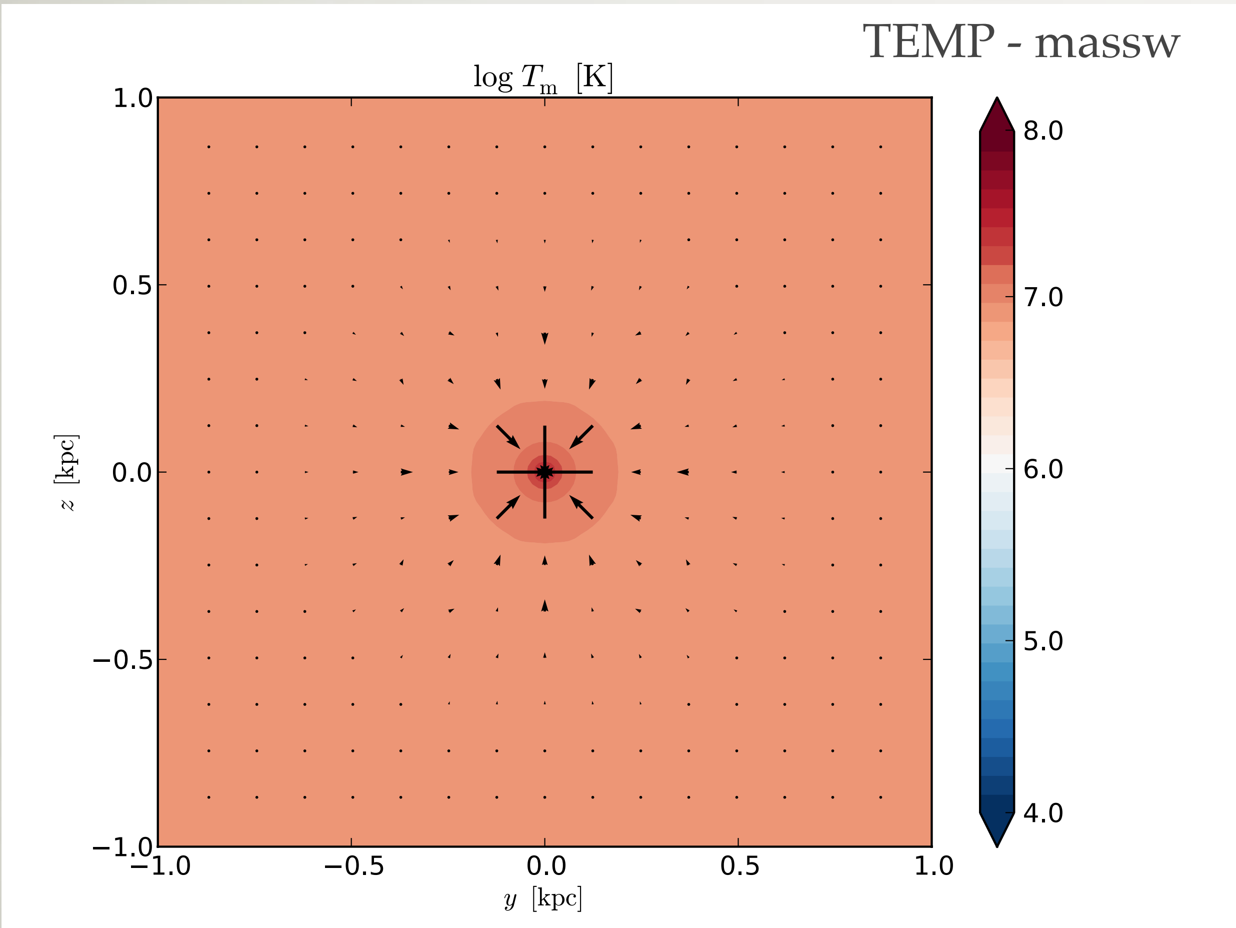


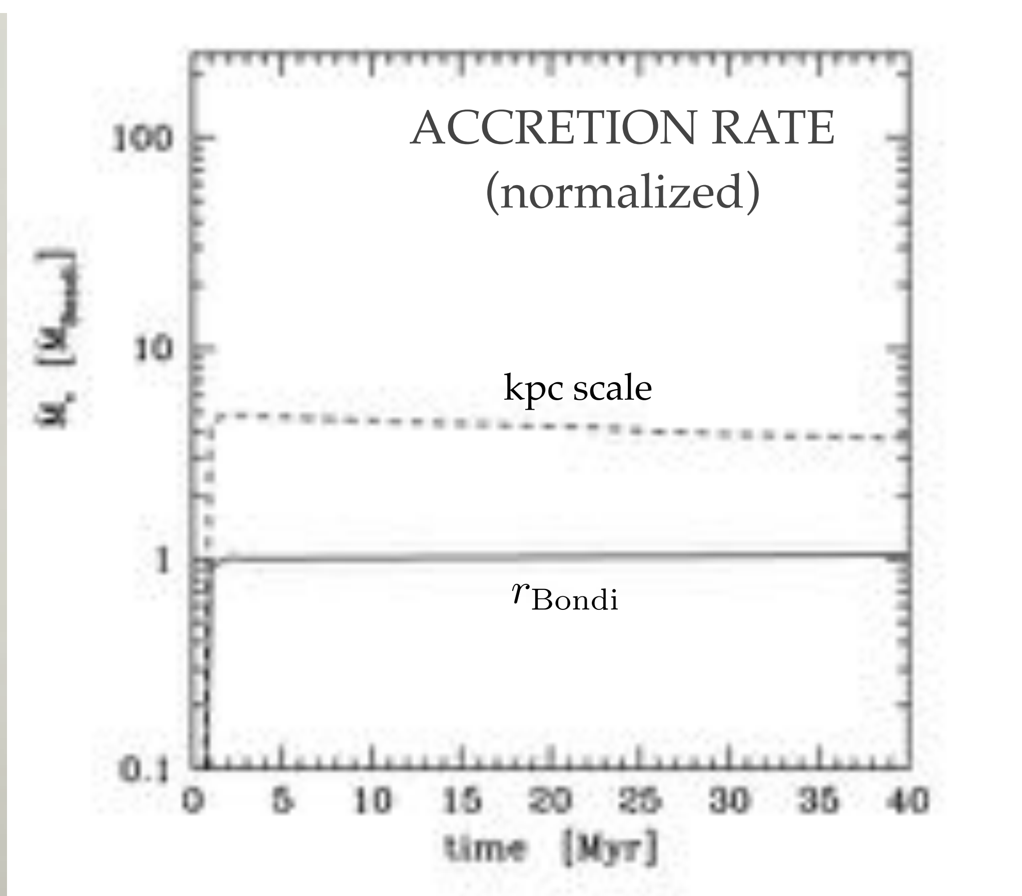


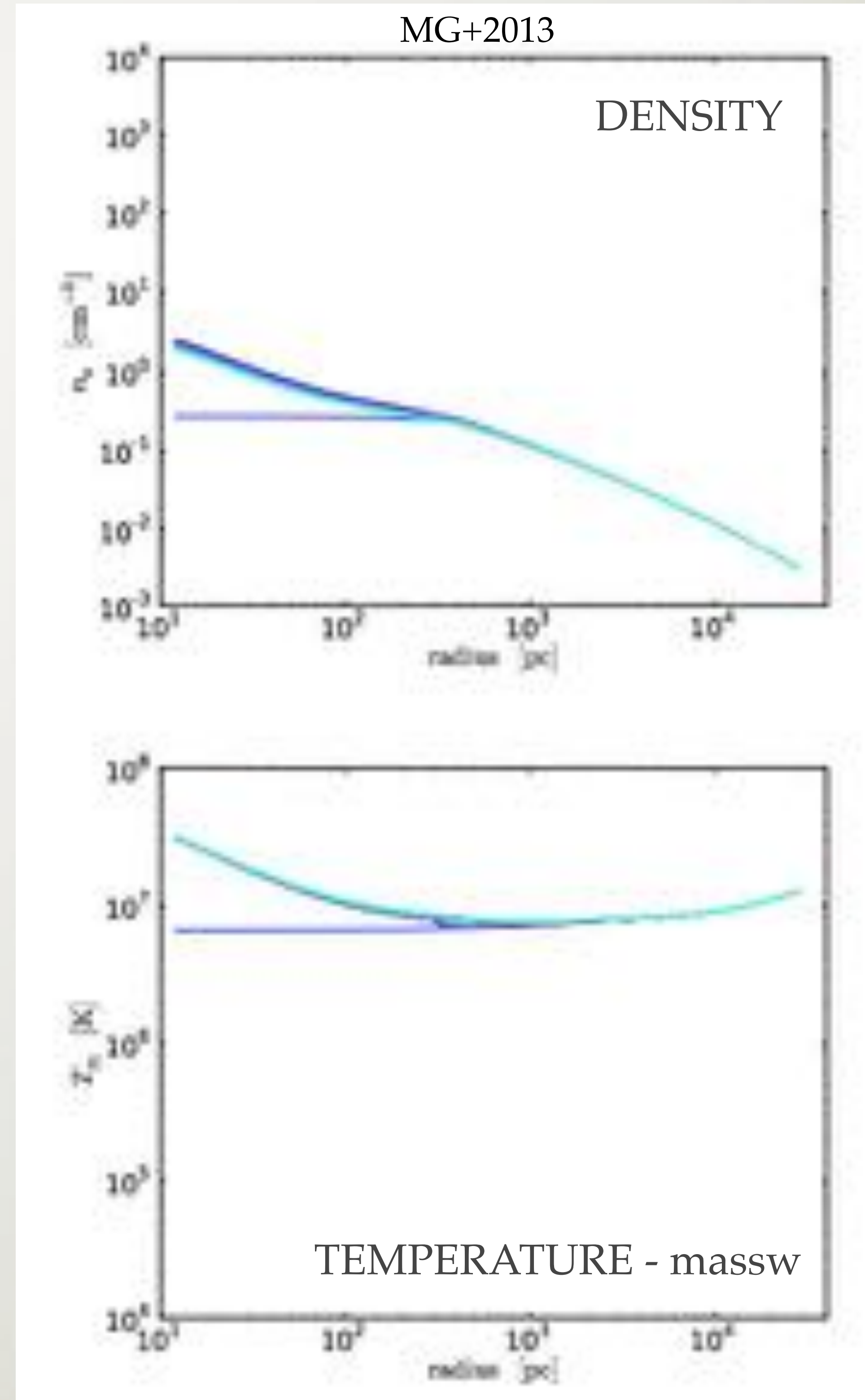


$$\dot{M}_{\rm Bondi} = 4\pi (G M_{\rm BH})^2 \rho_\infty / c_{s,\infty}^3$$

PURE HOT MODE (BONDI)

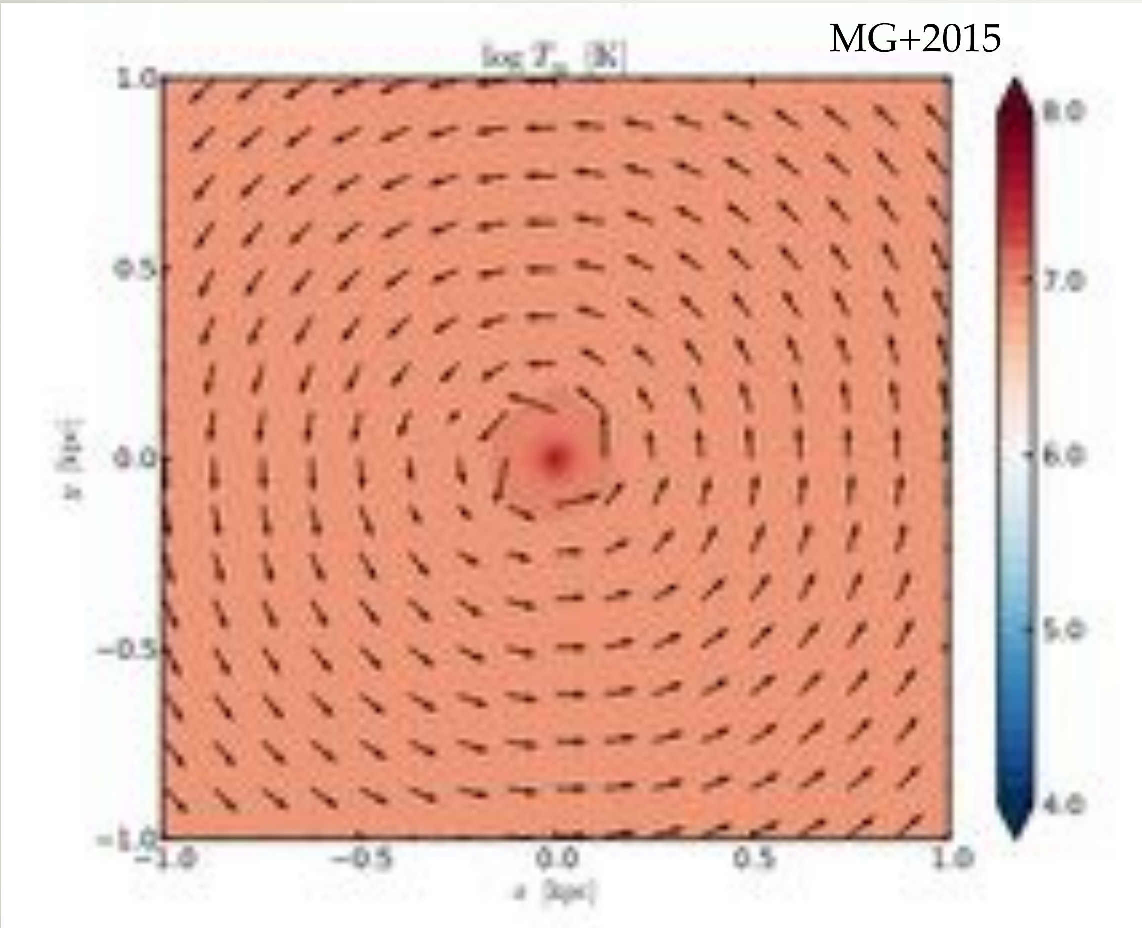




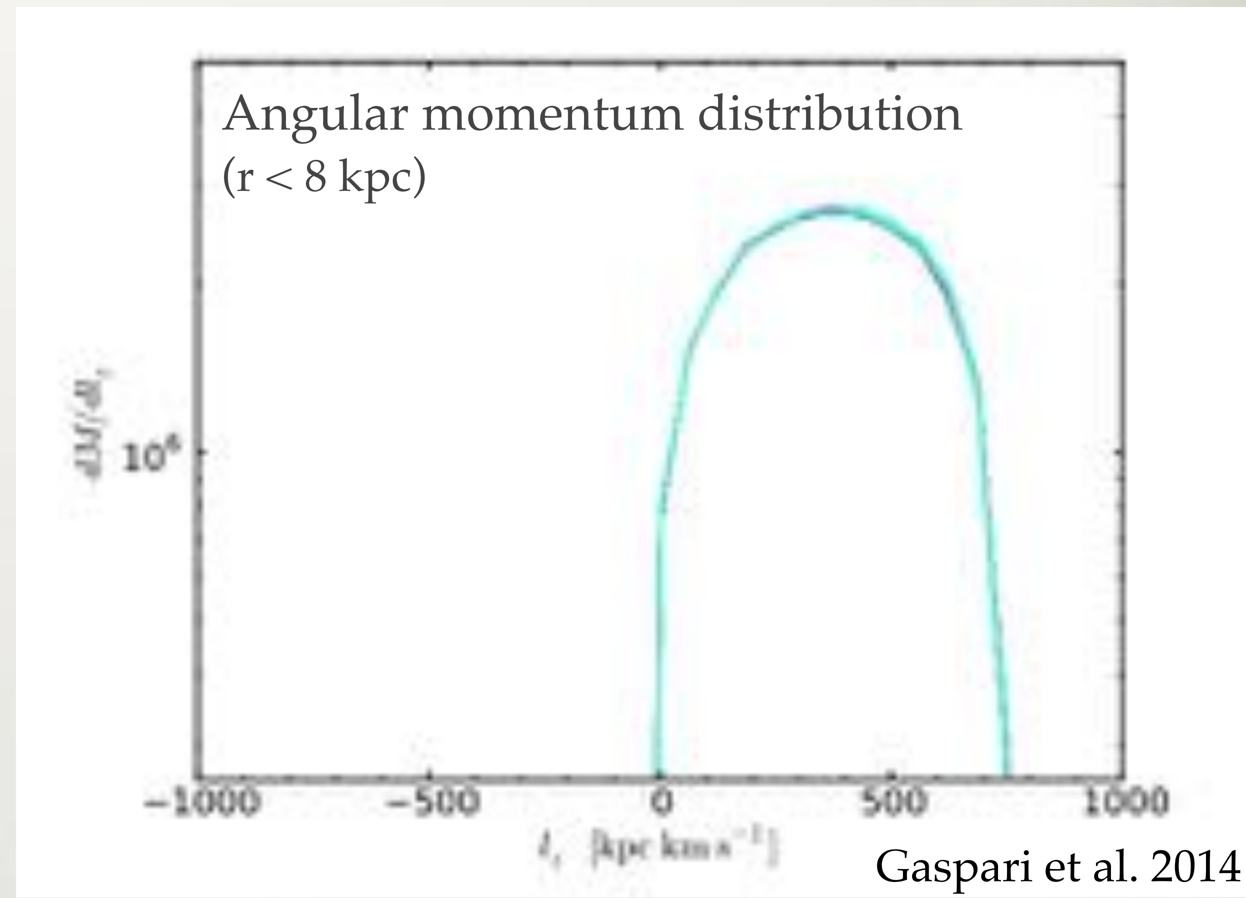


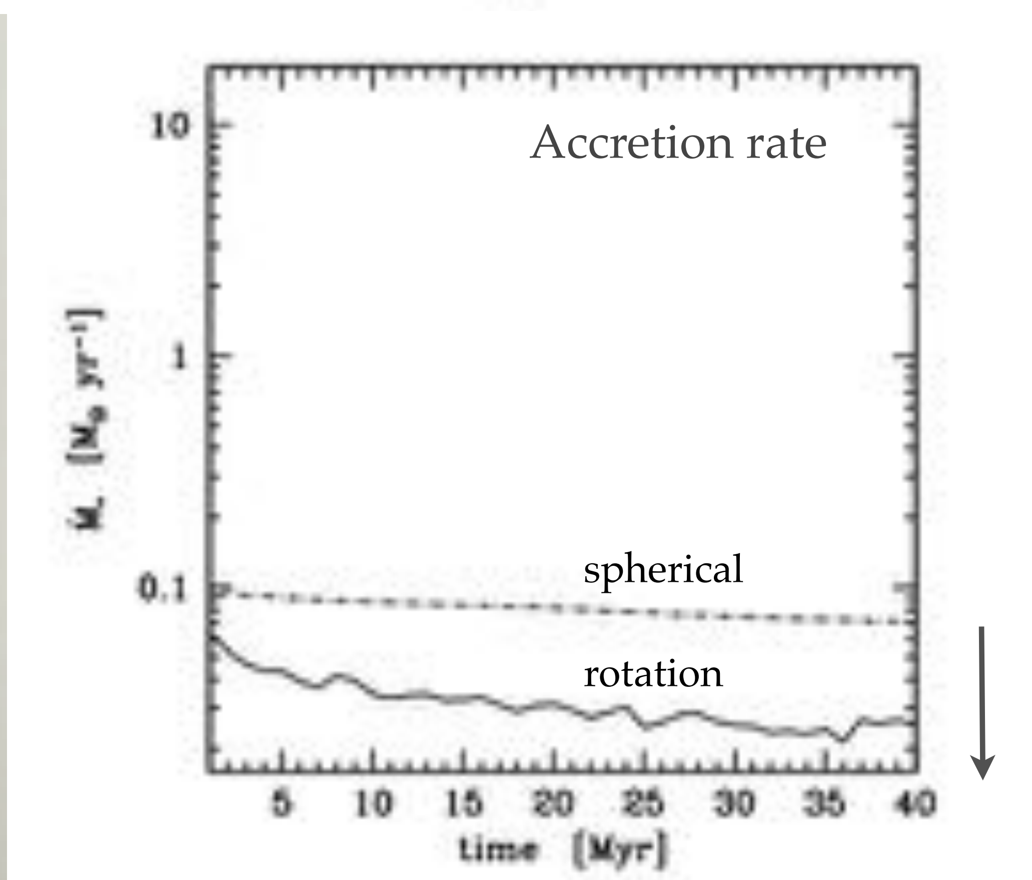
$$\dot{M}_{\text{Bondi}} = 4\pi(GM_{\text{BH}})^2 \rho_\infty / c_{s,\infty}^3$$

PURE HOT MODE (ROTATING)



$$v_{\rm rot,gas} \approx 100\ {\rm km\,s^{-1}}$$
$$\sim 0.3\, v_{\rm circ}$$





1/3 suppression:

geometrically thick toroidal region: ~ invariant with initial rotation

accretion through a funnel with $\theta \sim \pi/4$

unstable structure: mild variability

2.

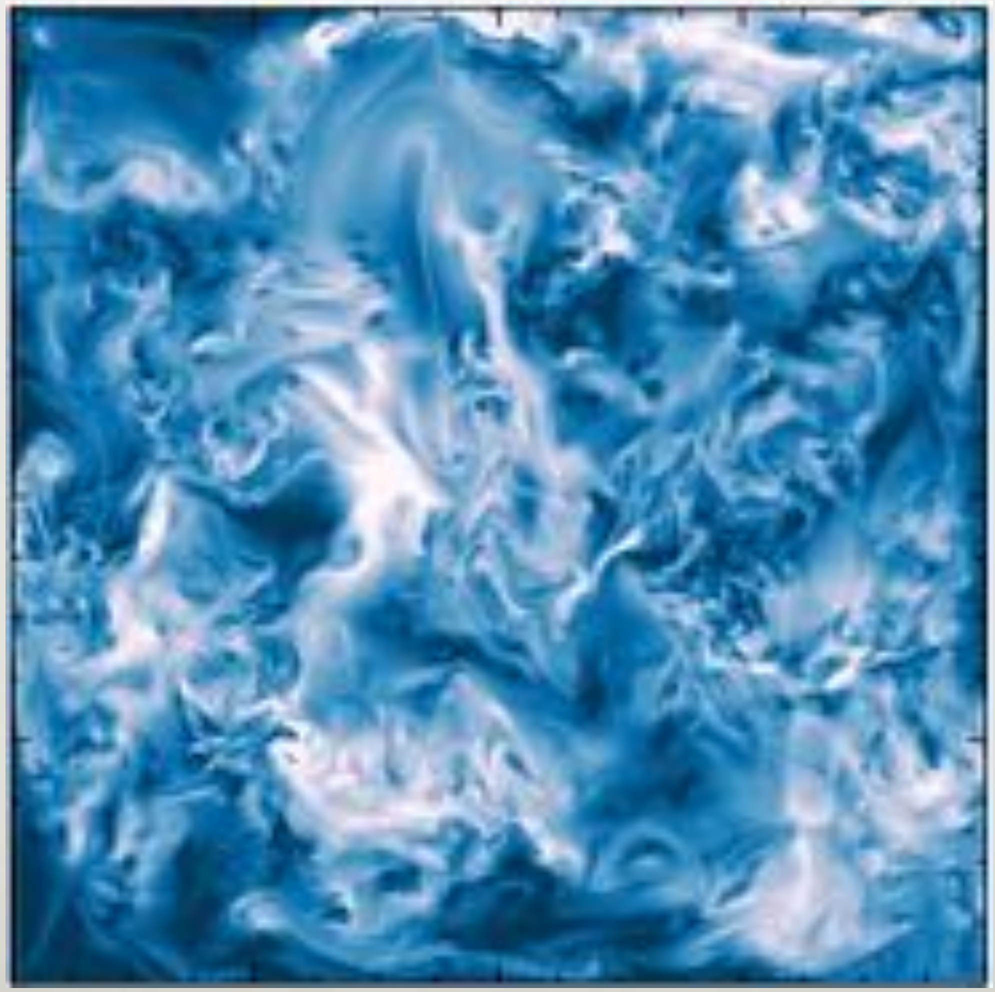
~~STEADY & SPHERICAL~~

TURBULENCE

AGN feedback, SNe, mergers, galaxy motions, ...

subsonic (~100 km s^{-1}) ⟶ spectral forcing

Simulations & Observations: e.g. Sanders & Fabian 2013, Norman & Bryan 1999, Lau et al. 2009, Ruszkowski & Oh 2010, 2011, Vazza et al. 2011, Gaspari et al. 2012b

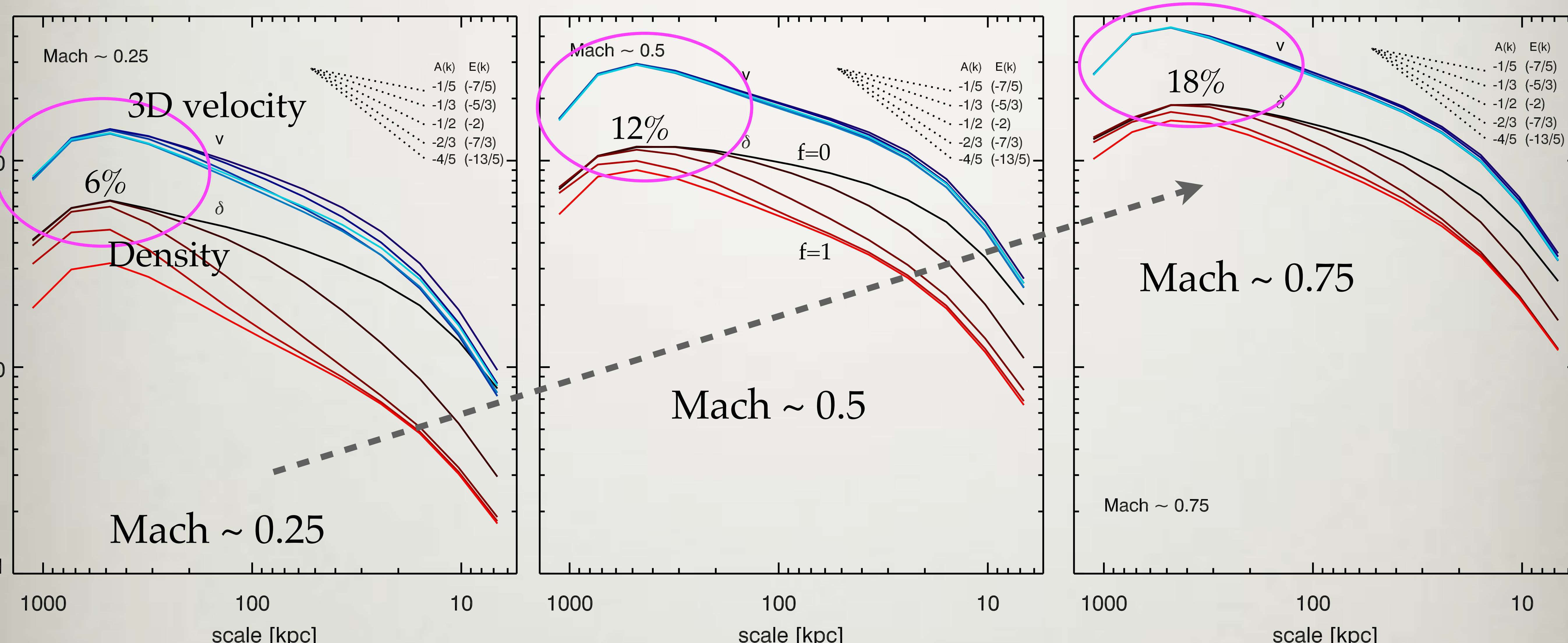


galaxy cluster turbulence

MG+2014

|v| cut

ICM power spectrum



$$\delta\rho/\rho \sim \mathrm{Mach}_{1\mathrm{D}}$$

globally self-similar over Mach and L_{inj}

(density perturbations relative to the underlying radial profile)

REAL CASE: COMA CLUSTER

mild turbulence:

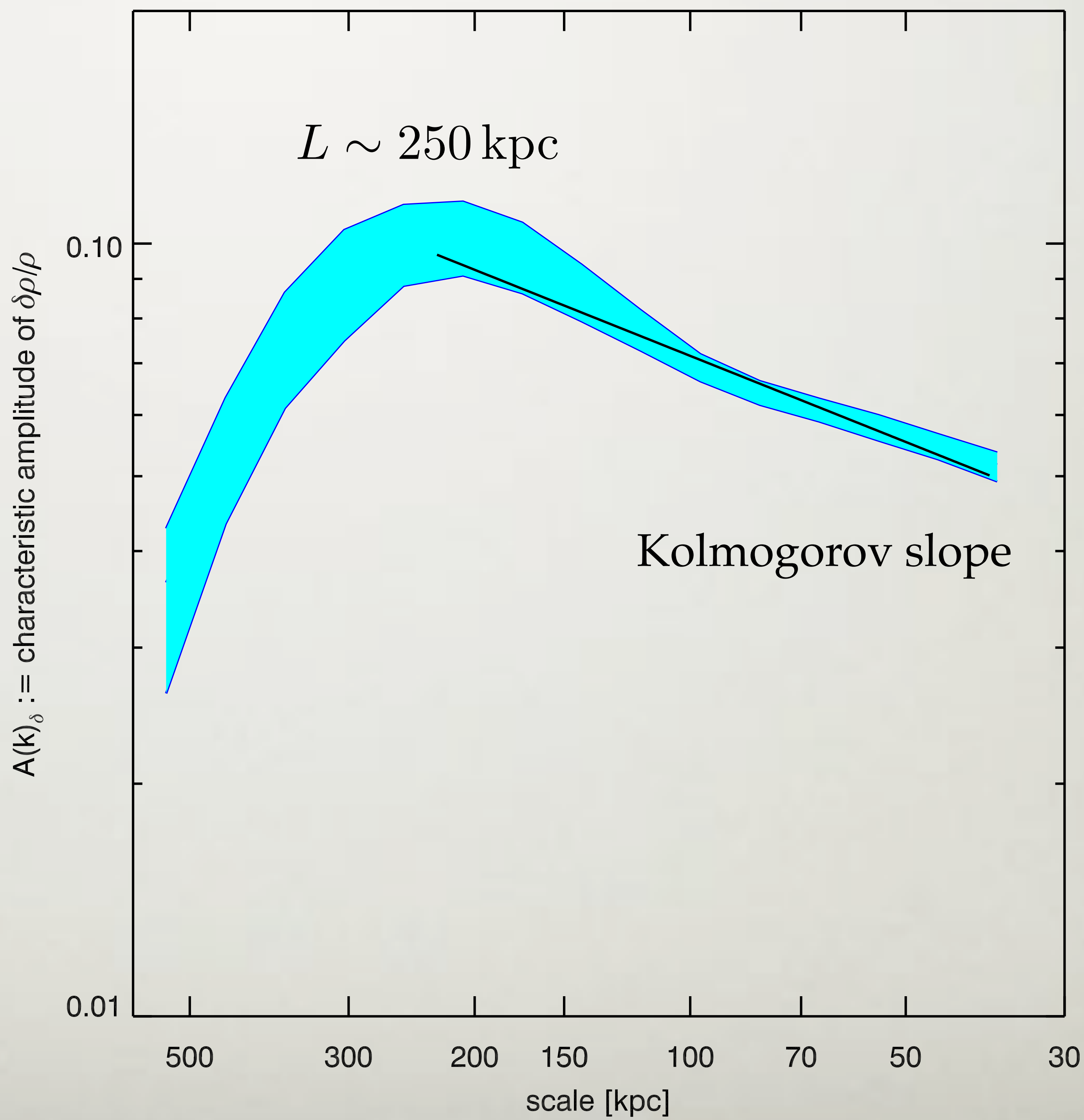
$$M \simeq 0.45$$

$$E_{\rm turb} \simeq 0.11\, E_{\rm th}$$

strongly suppressed conduction:

$$f \sim 10^{-3}$$

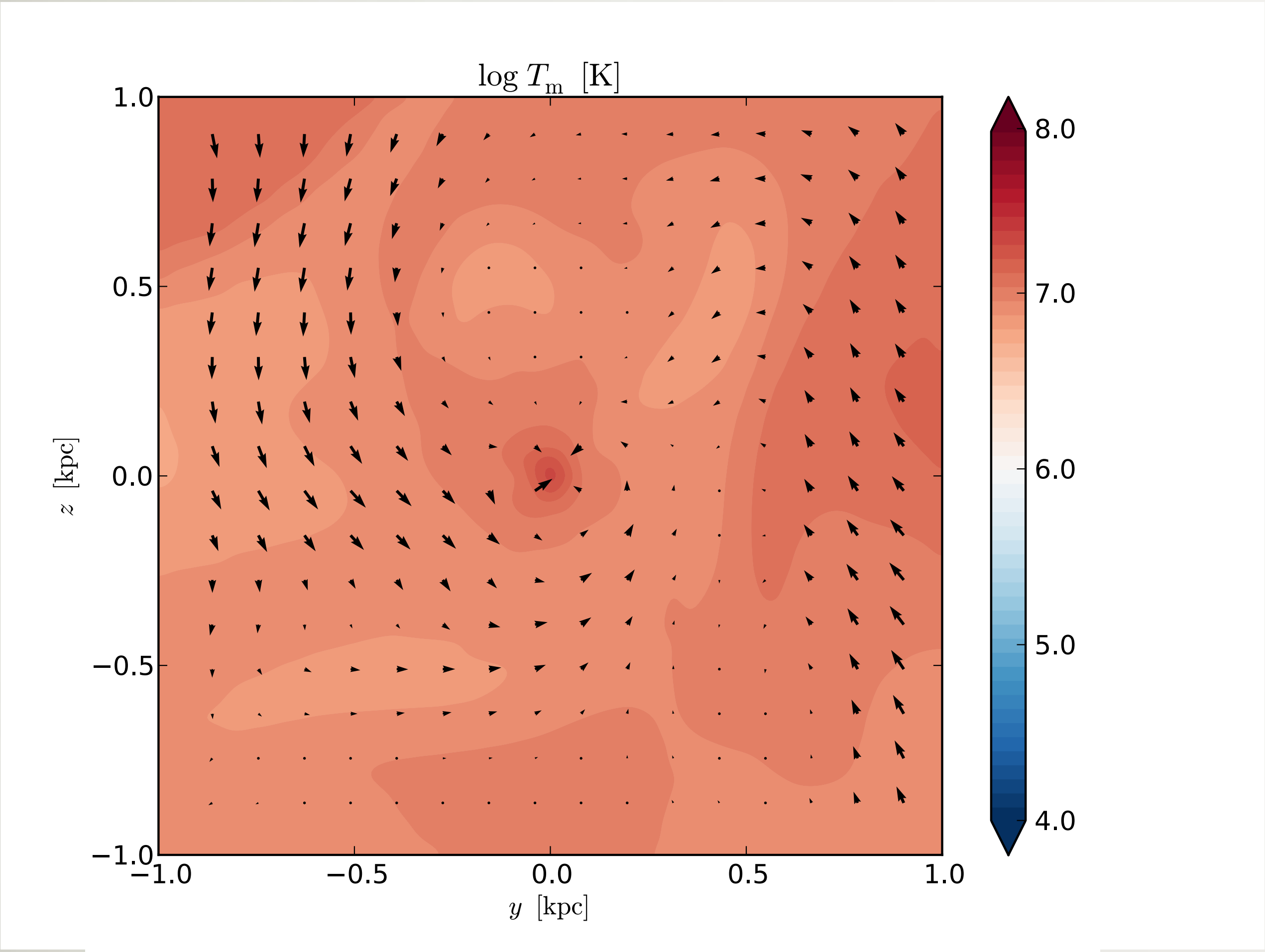
MG+2013-2014

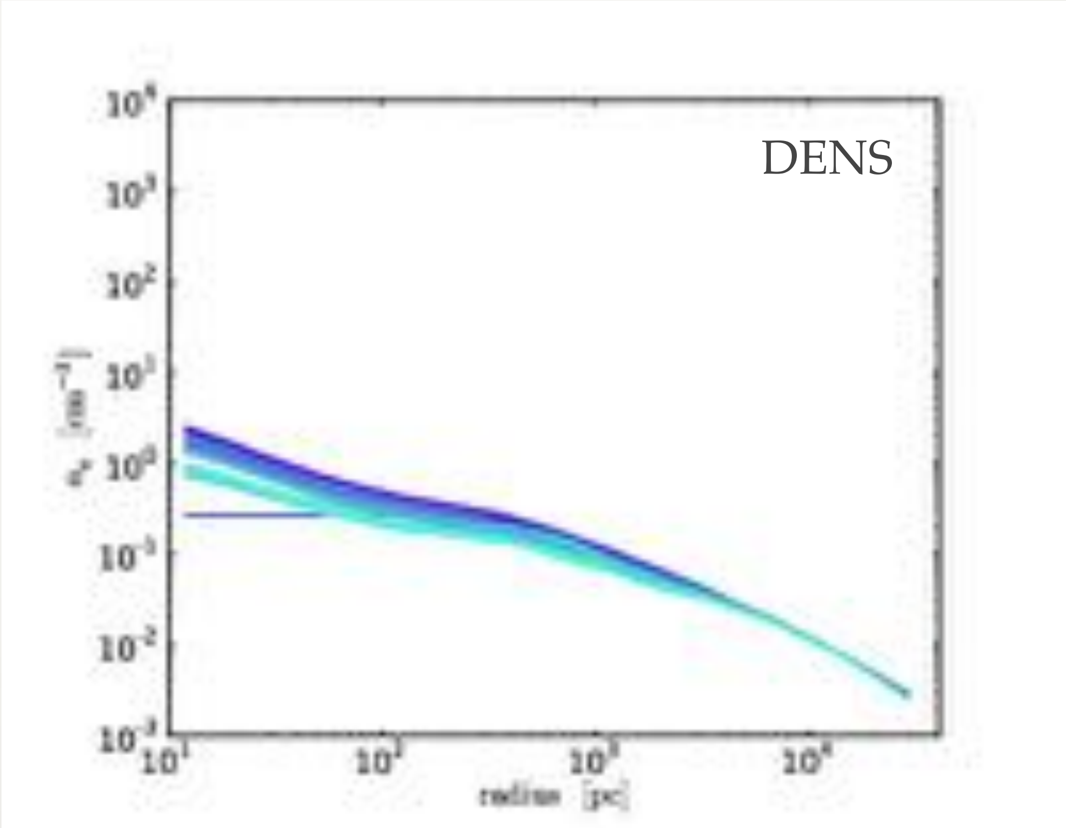


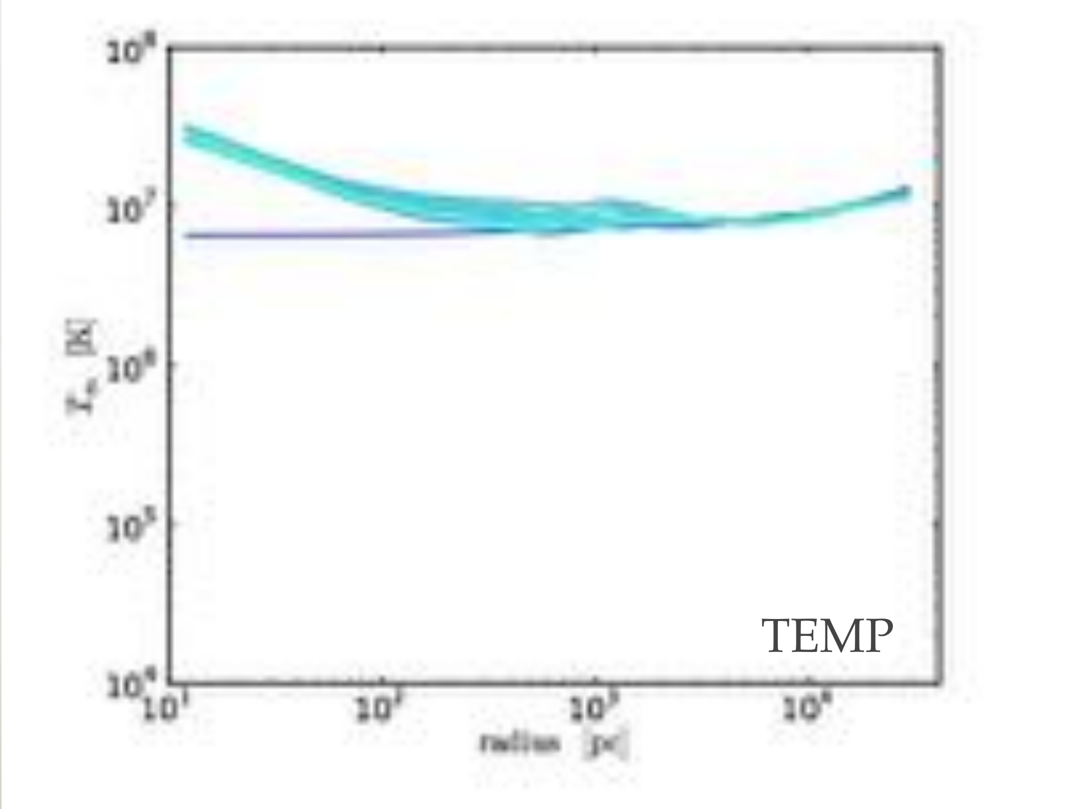
~500 ks

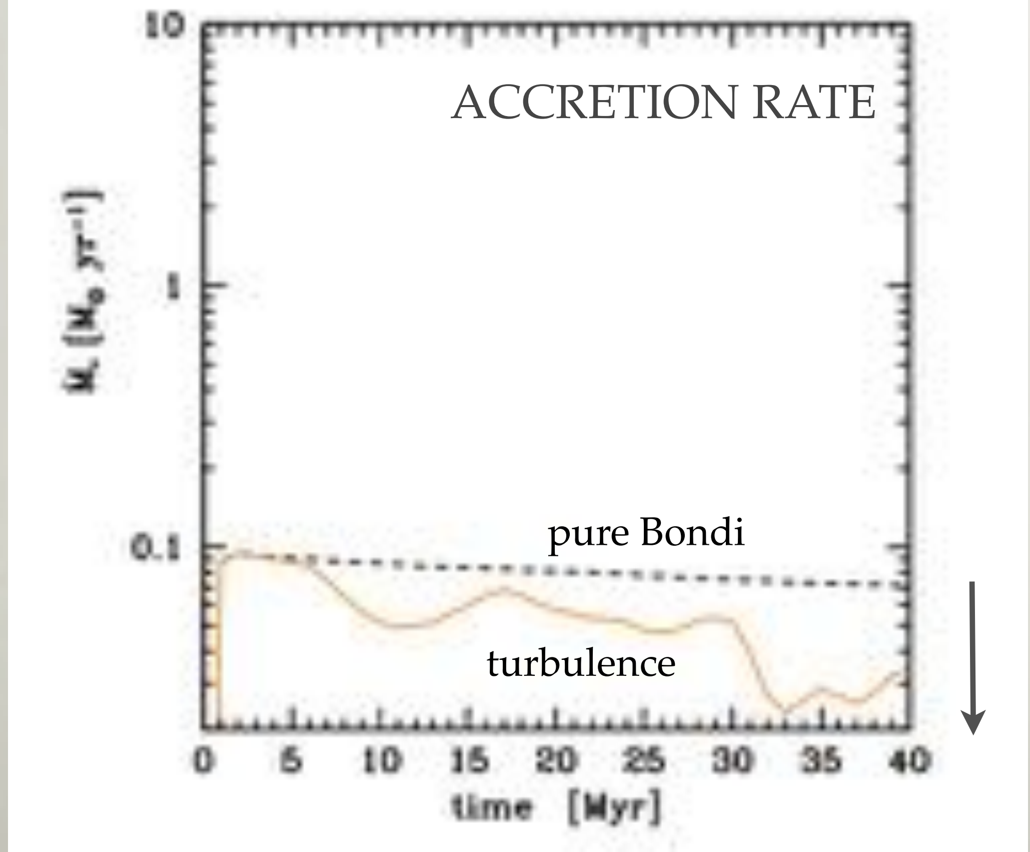
TURBULENT HOT MODE

subsonic turbulence $\sigma_v \sim 100\,\mathrm{km\,s^{-1}}$







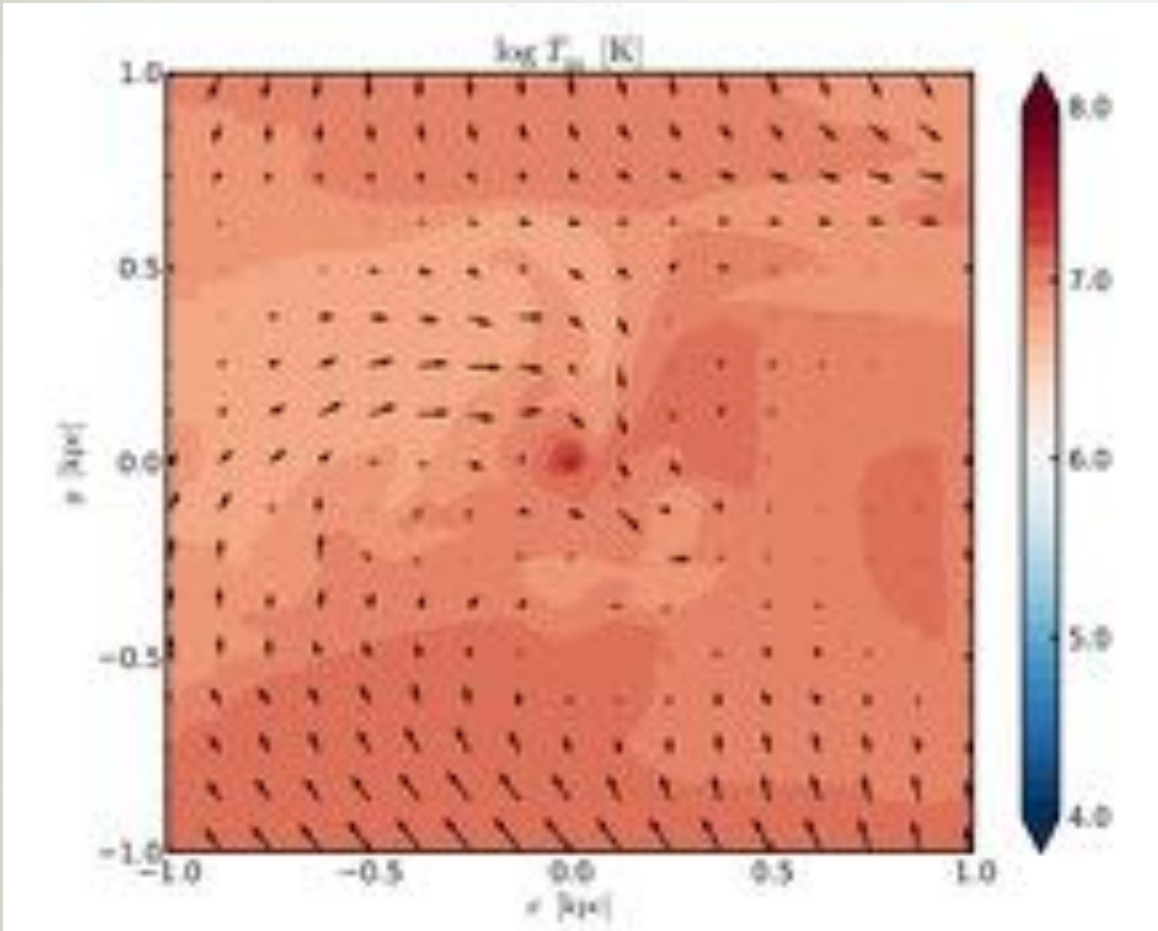


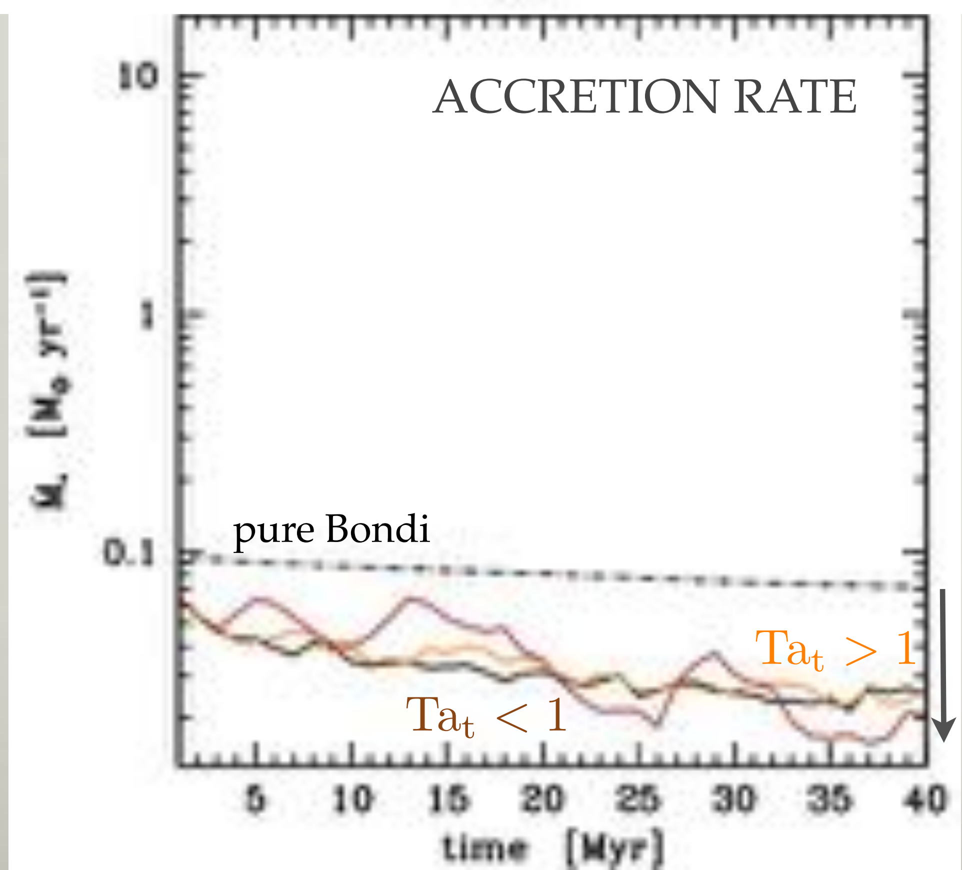
MG+13

TURBULENT HOT MODE (ROTATION)

$$\mathrm{Ta_t} \equiv v_{\mathrm{rot}}/\sigma_v$$

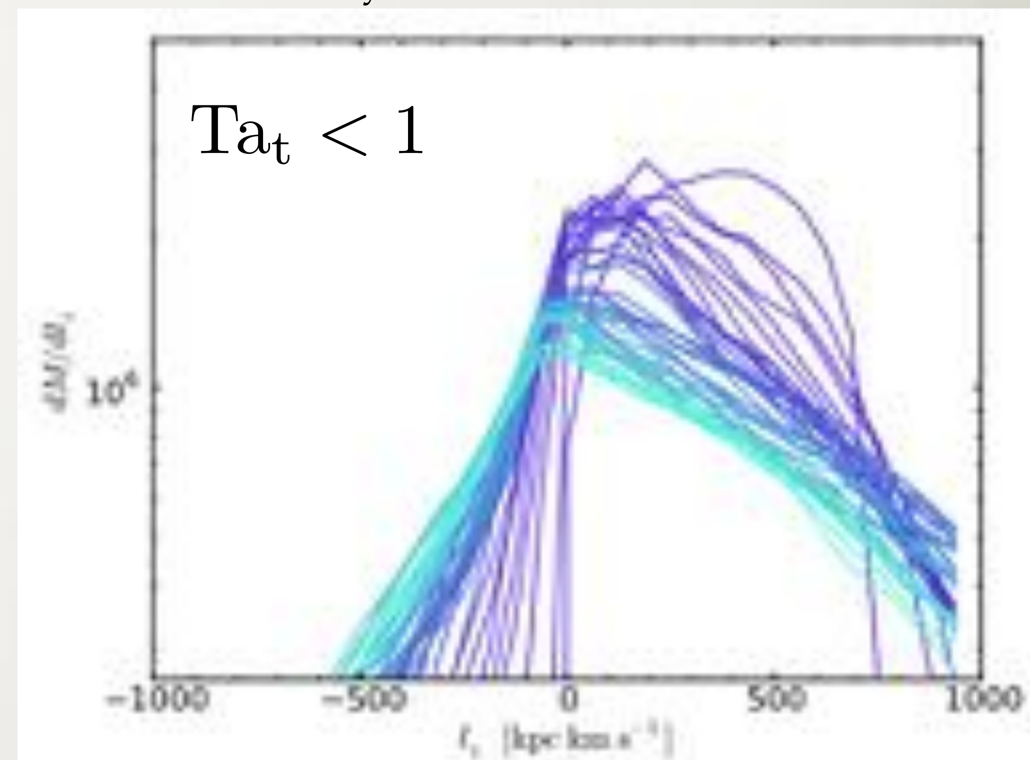
turbulent Taylor number



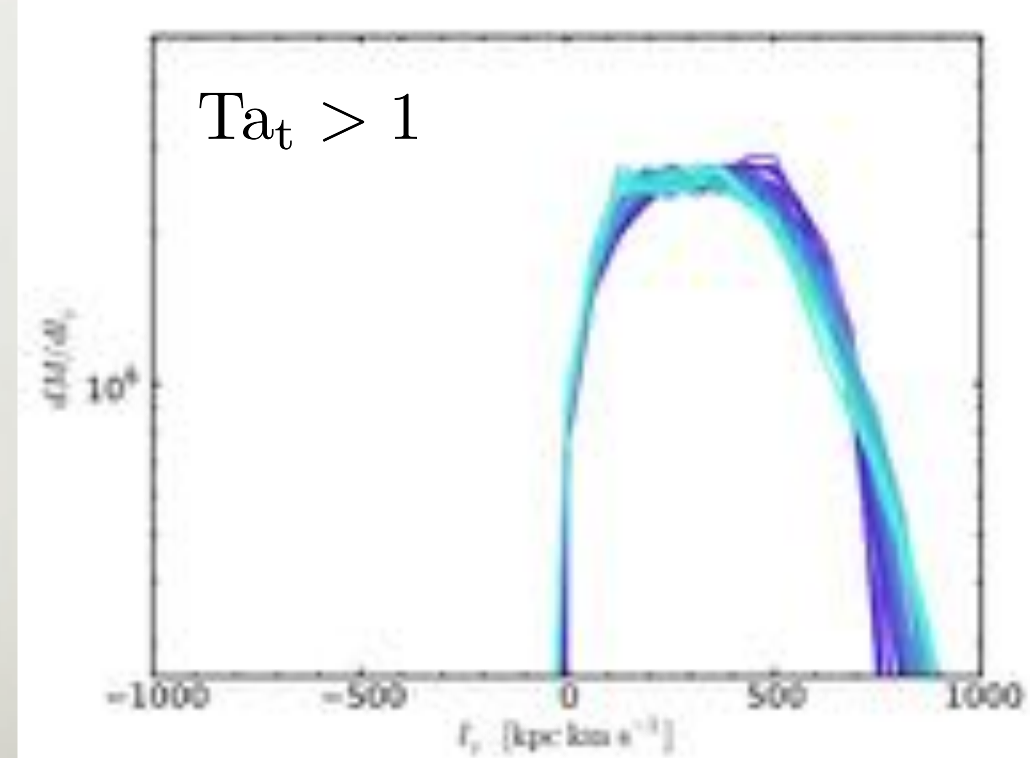


generation of local vorticity: again ~1/3 suppression

similar to purely rotating run (solid black line)



broadening allows retrograde motions



MG+15

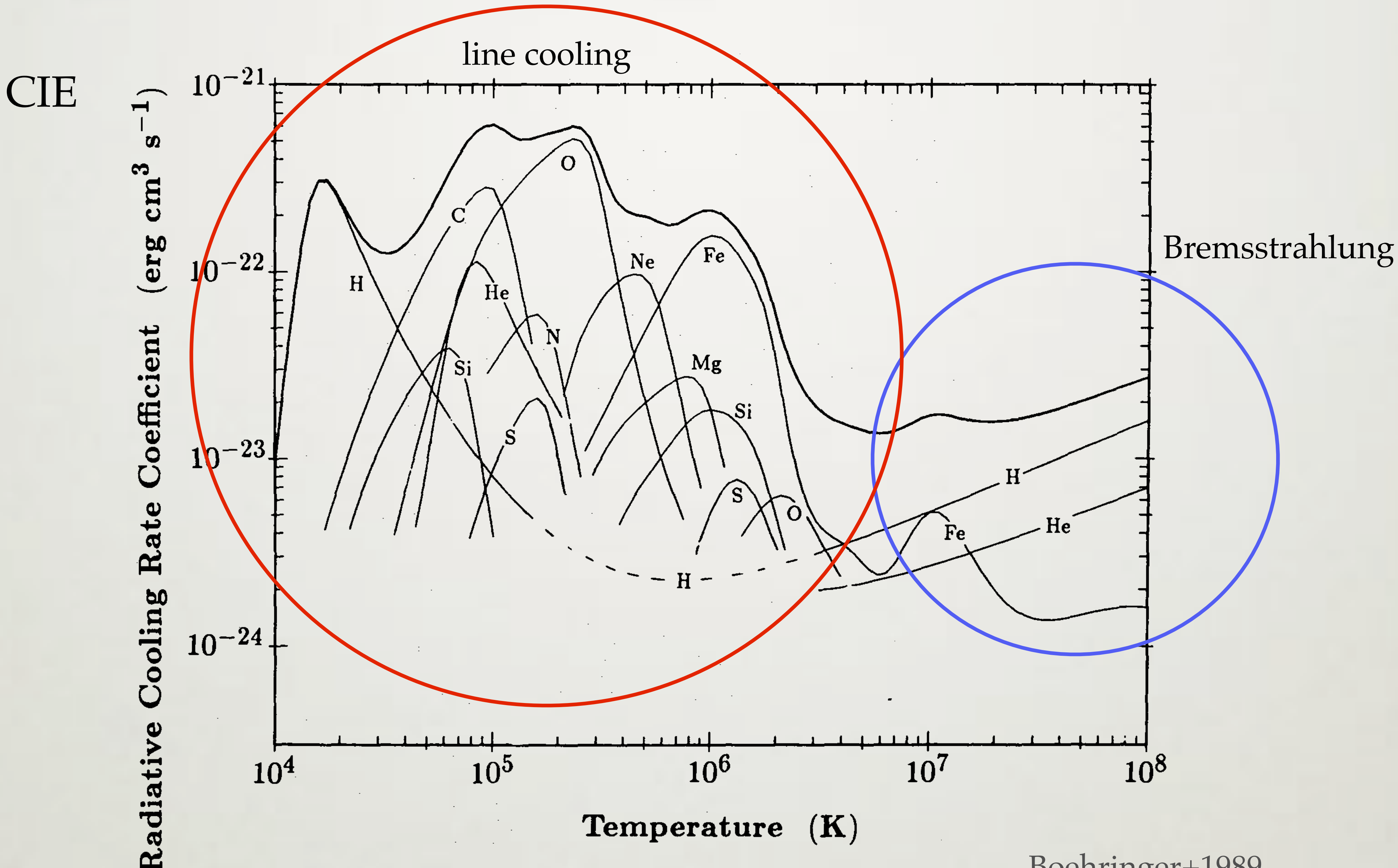
3.

~~ADIABATIC~~

COOLING

$$\mathcal{L} = -n_e n_i \Lambda(T, Z)$$

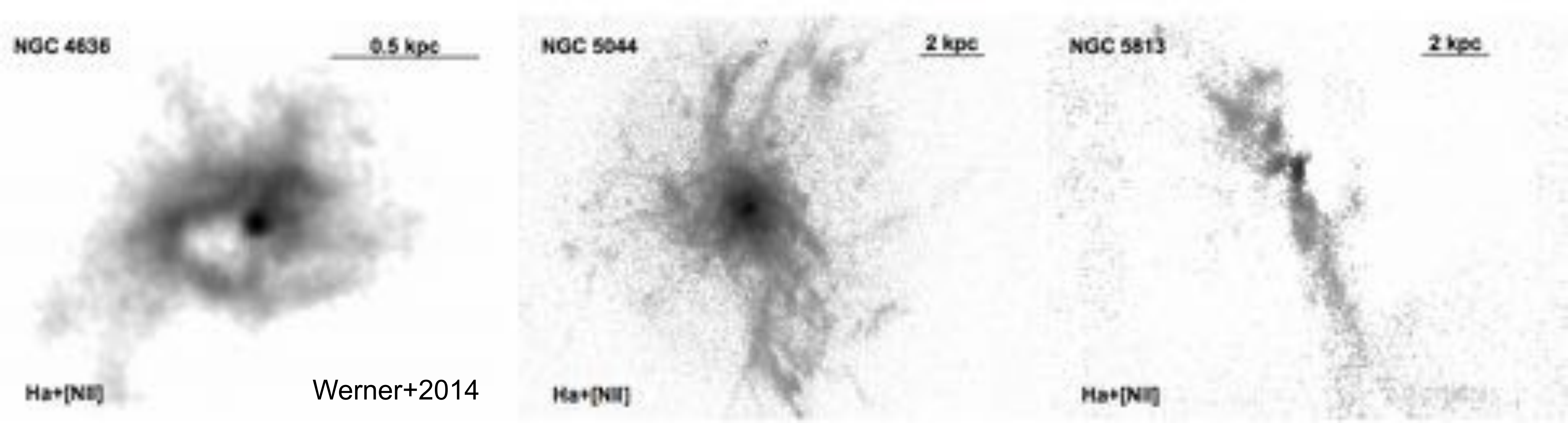
Radiative Cooling



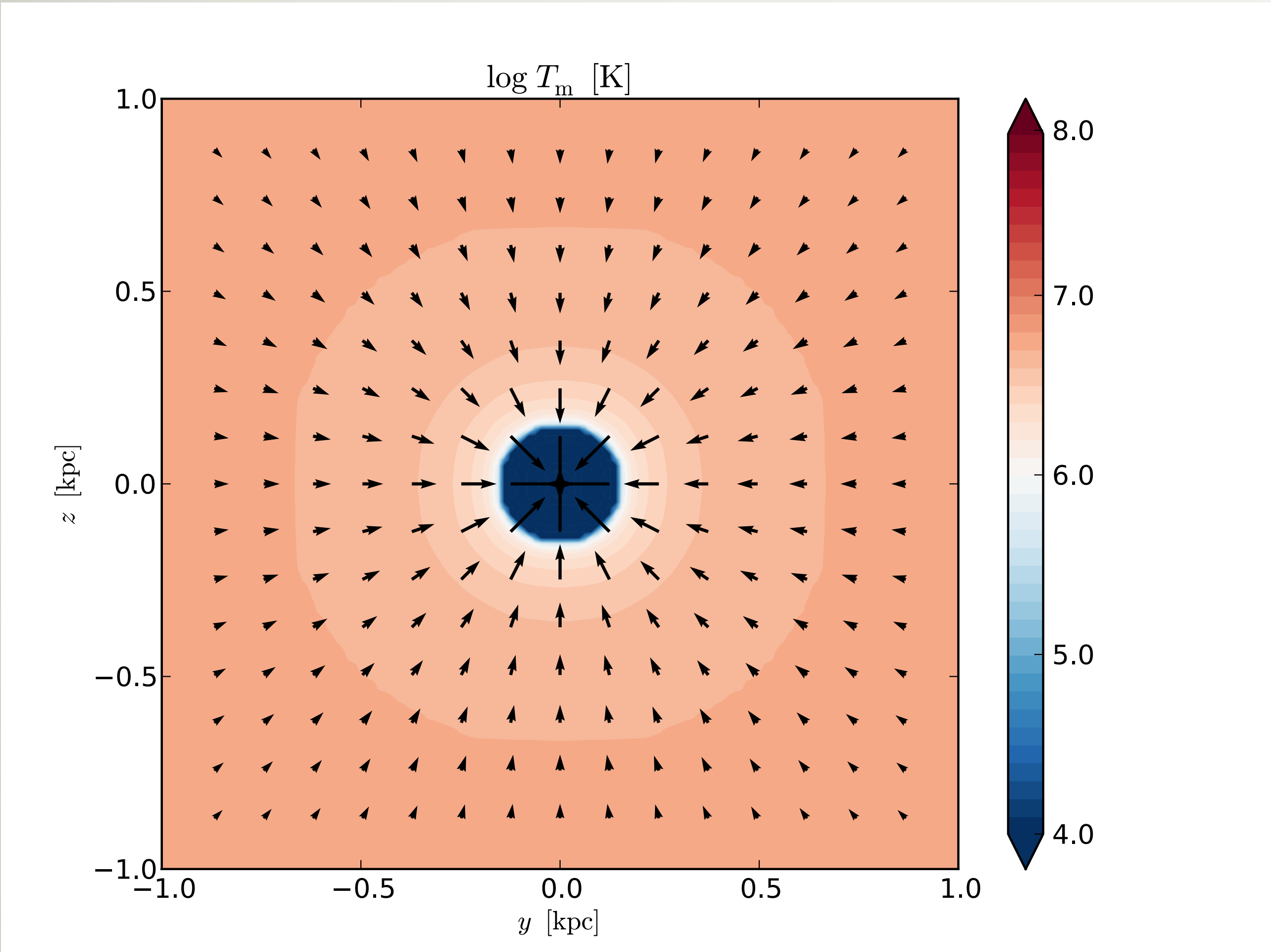
Boehringer+1989

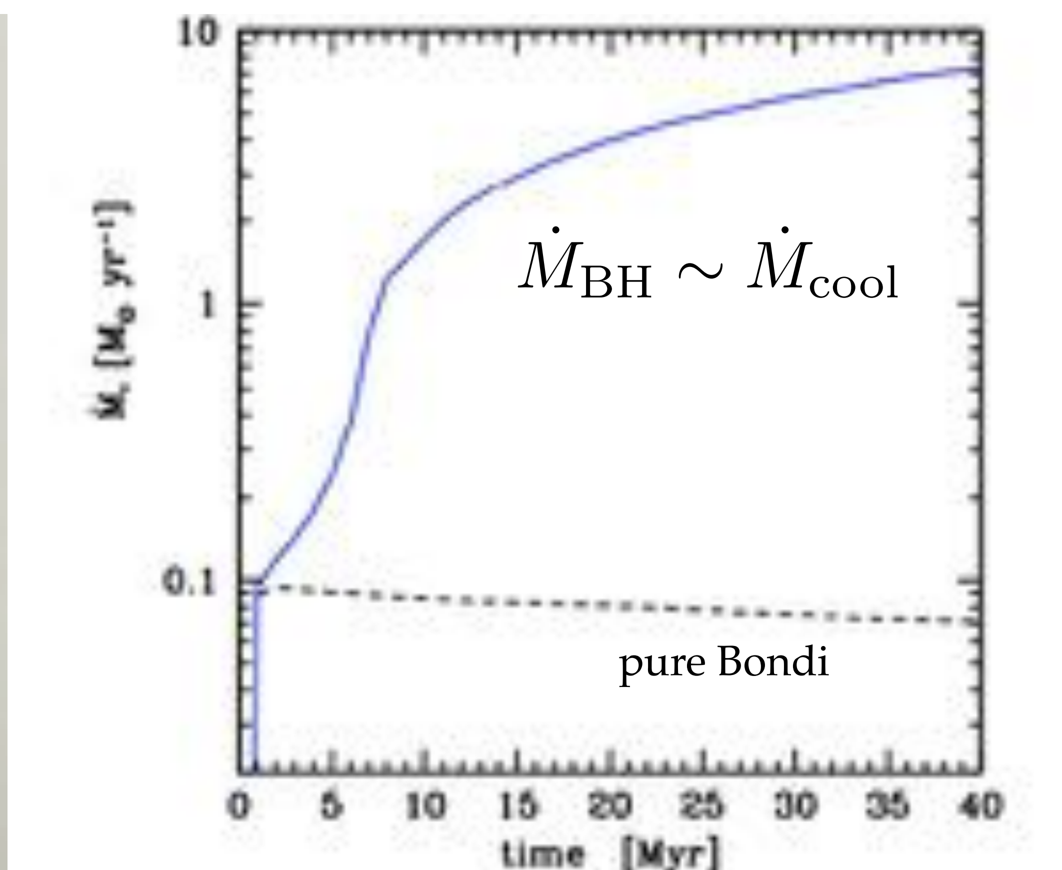
$$\mathcal{L} = -n_e n_i \Lambda(T, Z) \qquad \mathrm{erg\,s^{-1}cm^{-3}}$$

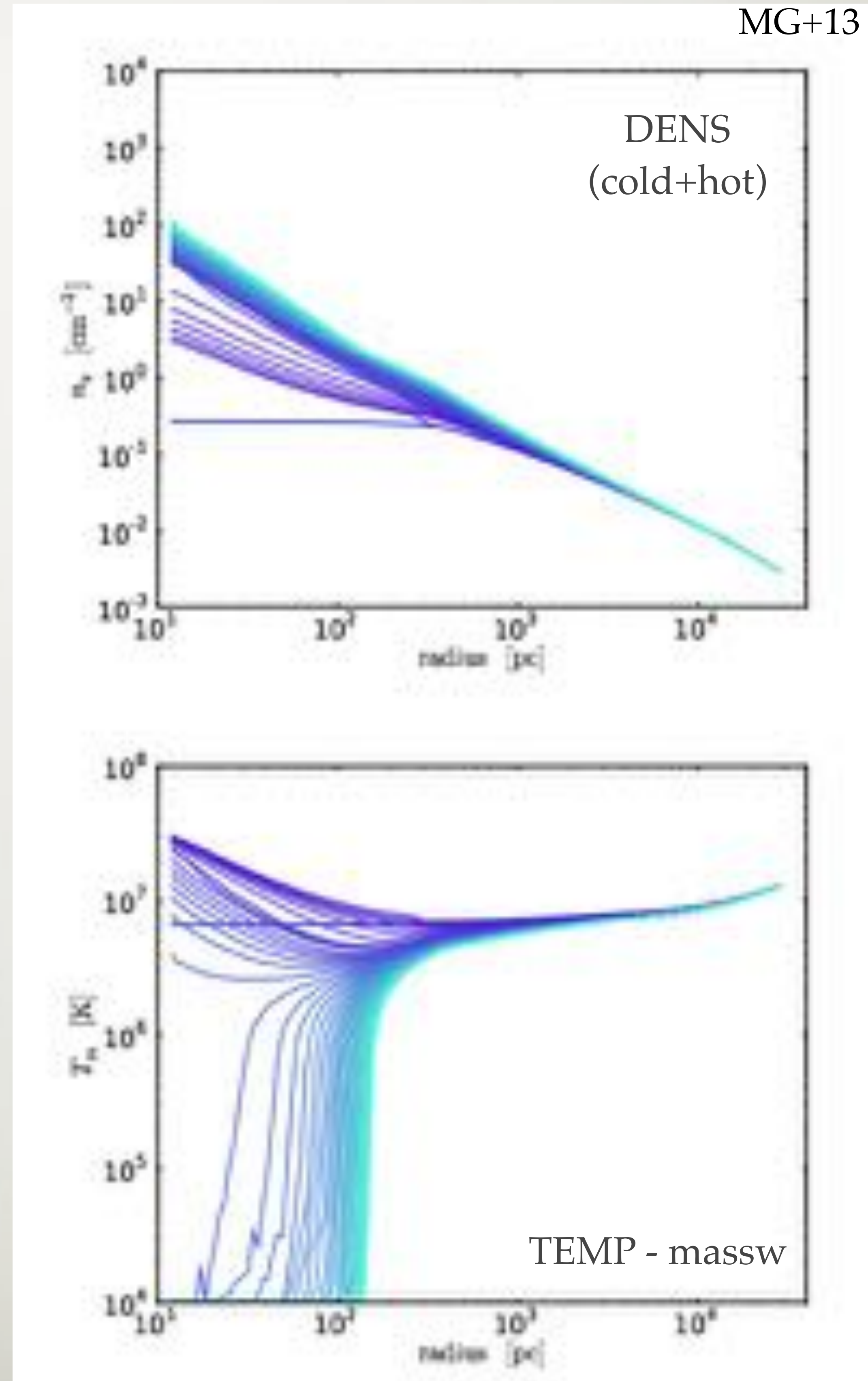

Perseus
Fabian et al.


NGC 4636
0.5 kpc
Ha+[NII]
Werner+2014
NGC 5044
2 kpc
Ha+[NII]
NGC 5813
2 kpc
Ha+[NII]

PURE COLD MODE



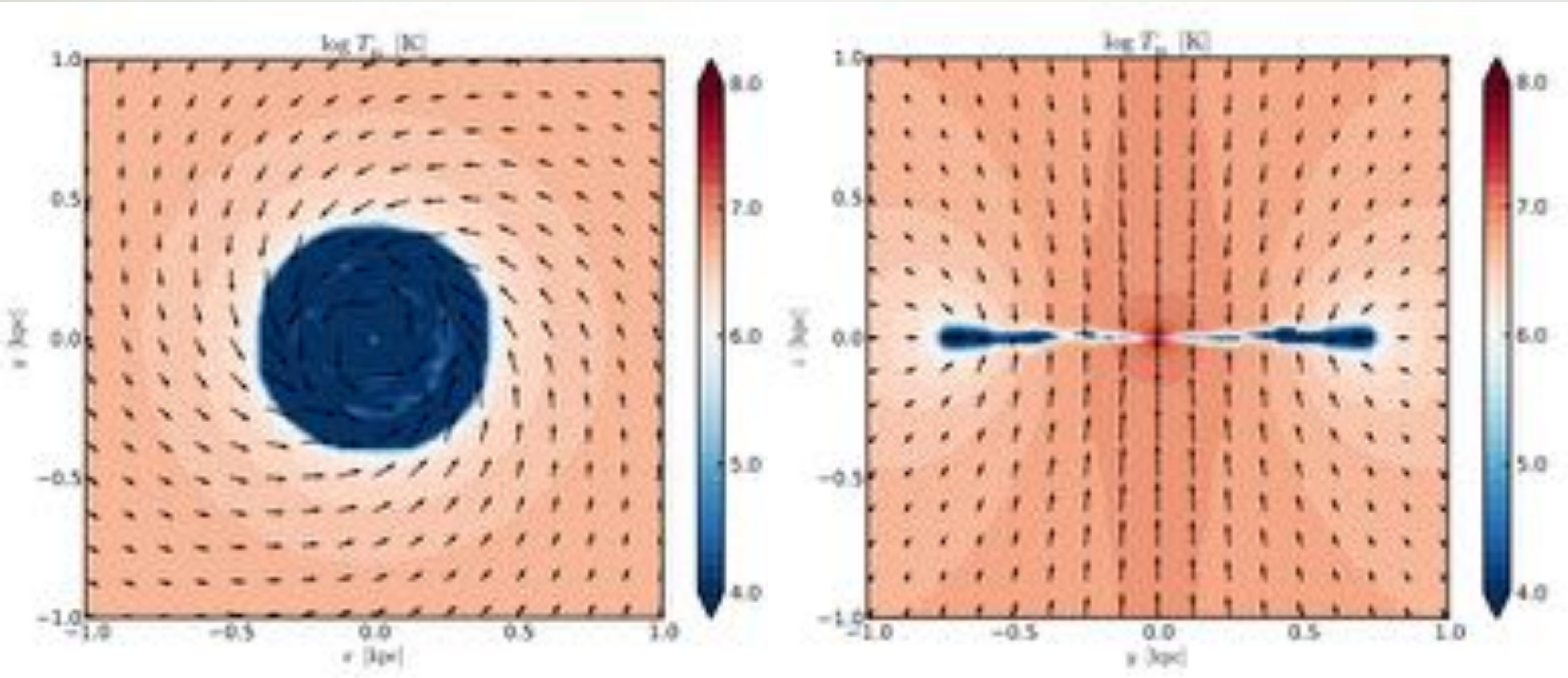


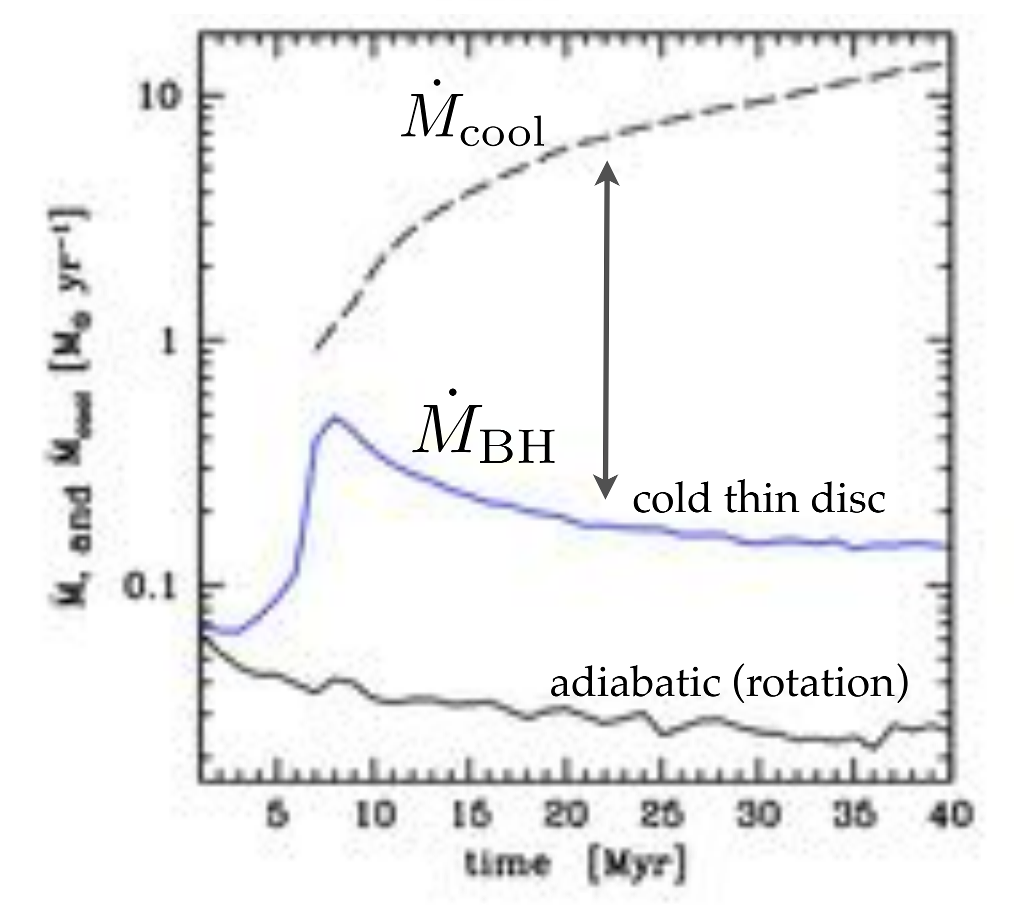


MG+13

PURE COLD MODE (ROTATION)

MG+15





COLD THIN DISC

size of the disc: how long the cooling-dominated phase has lasted (low heating and turbulence)

many elliptical galaxies with inner discs:
Mathews & Brighenti 2003; Young et al. 2011; Alatalo +2013; NGC 6868 and NGC 7049: Werner+2014

4.

~~PURE COOLING~~

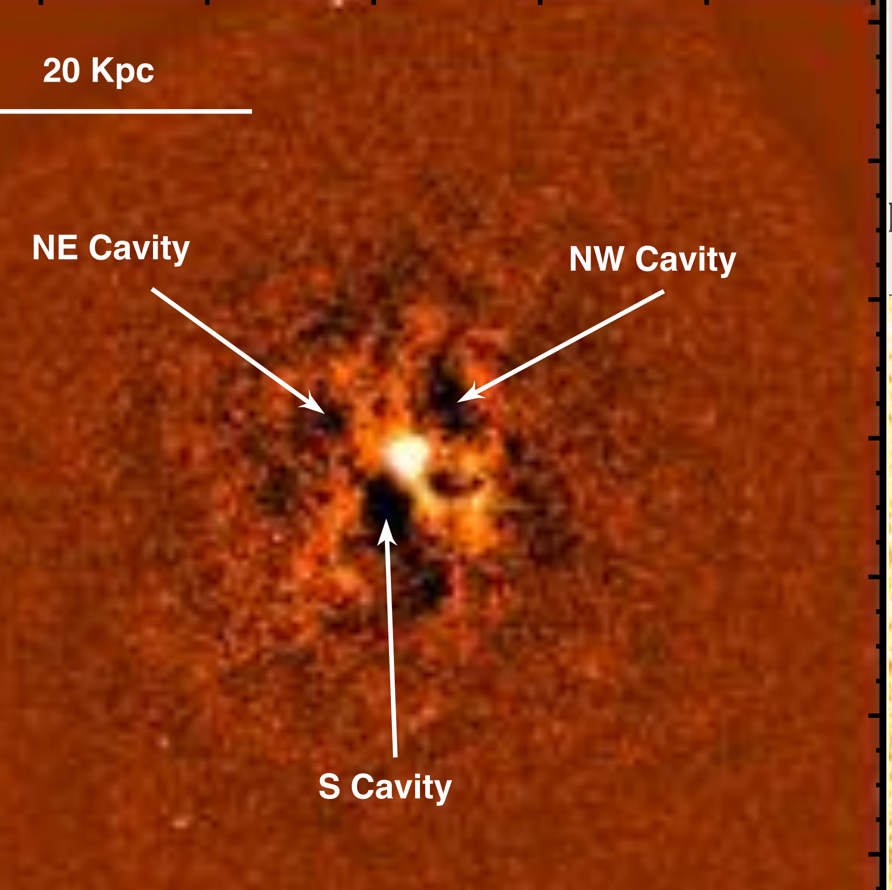
HEATING

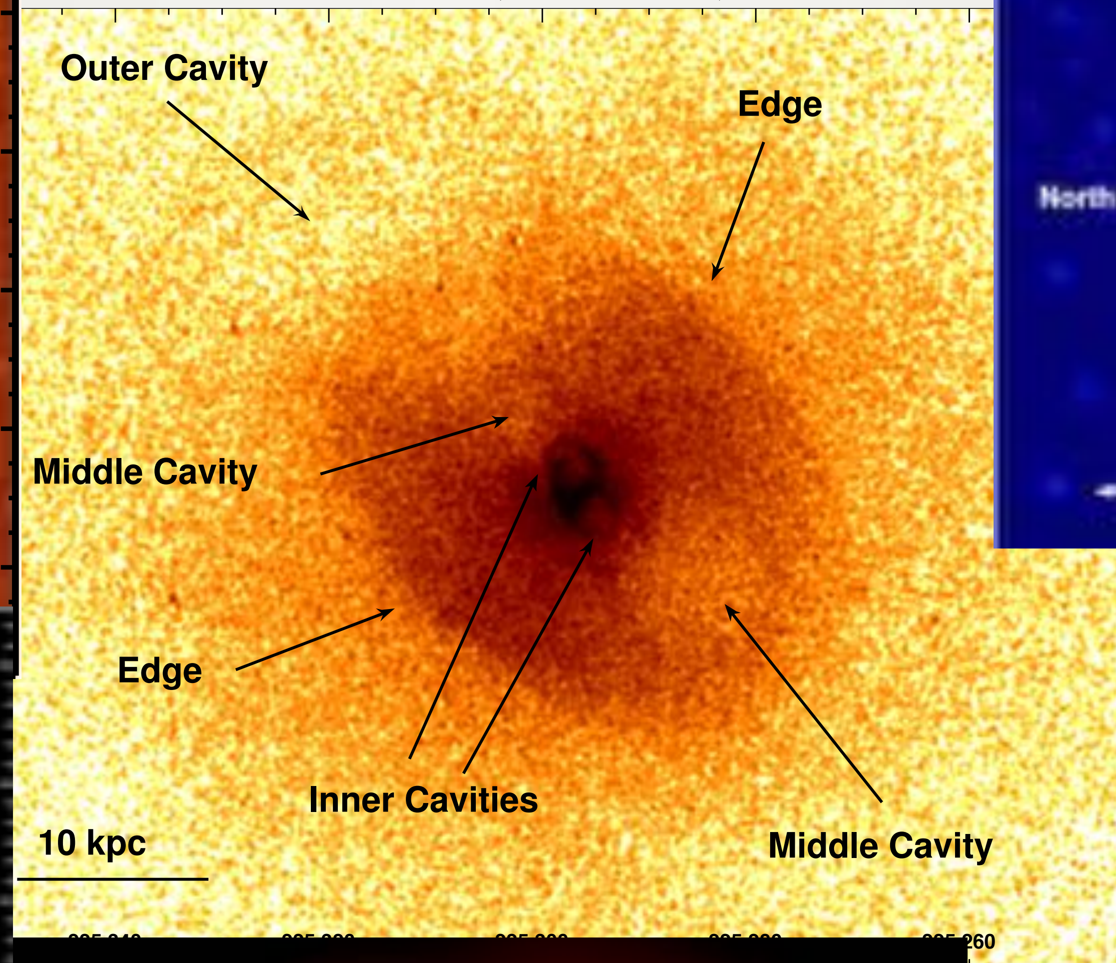
<u>AGN feedback</u>: outflows, shocks, turbulence

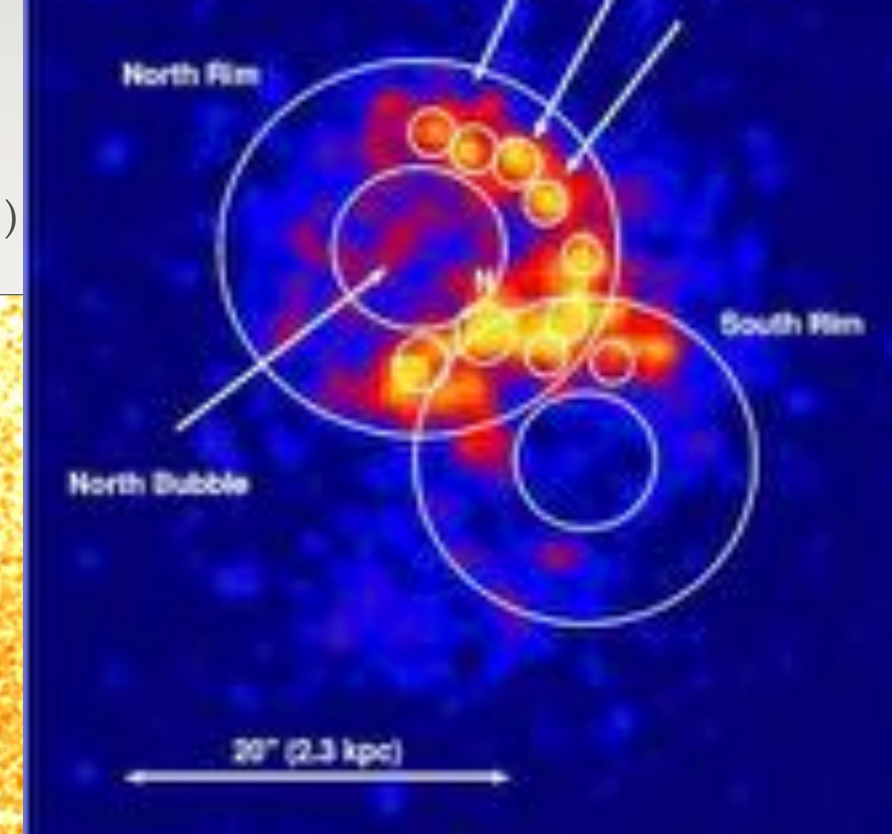
SNe, mergers, conduction, cosmic rays can contribute

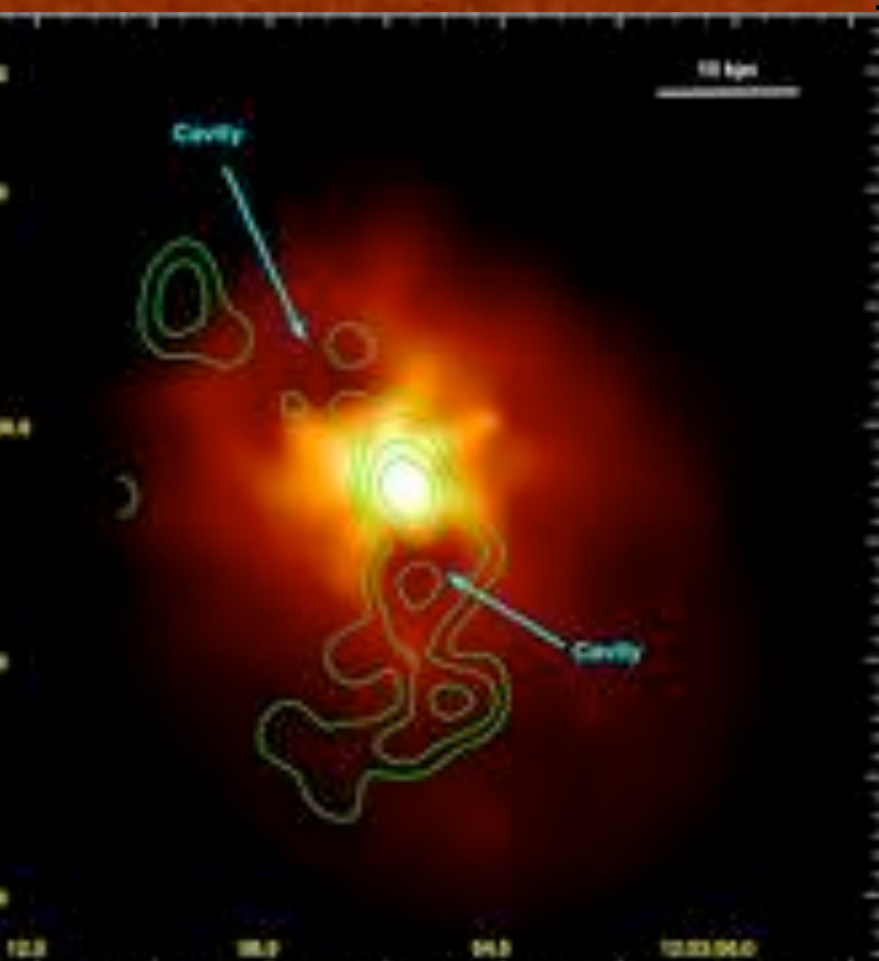
AGN Feedback

NGC 5044 (David+2009) NGC 5846 (Machacek+11)
NGC 5813 (Randall+11)

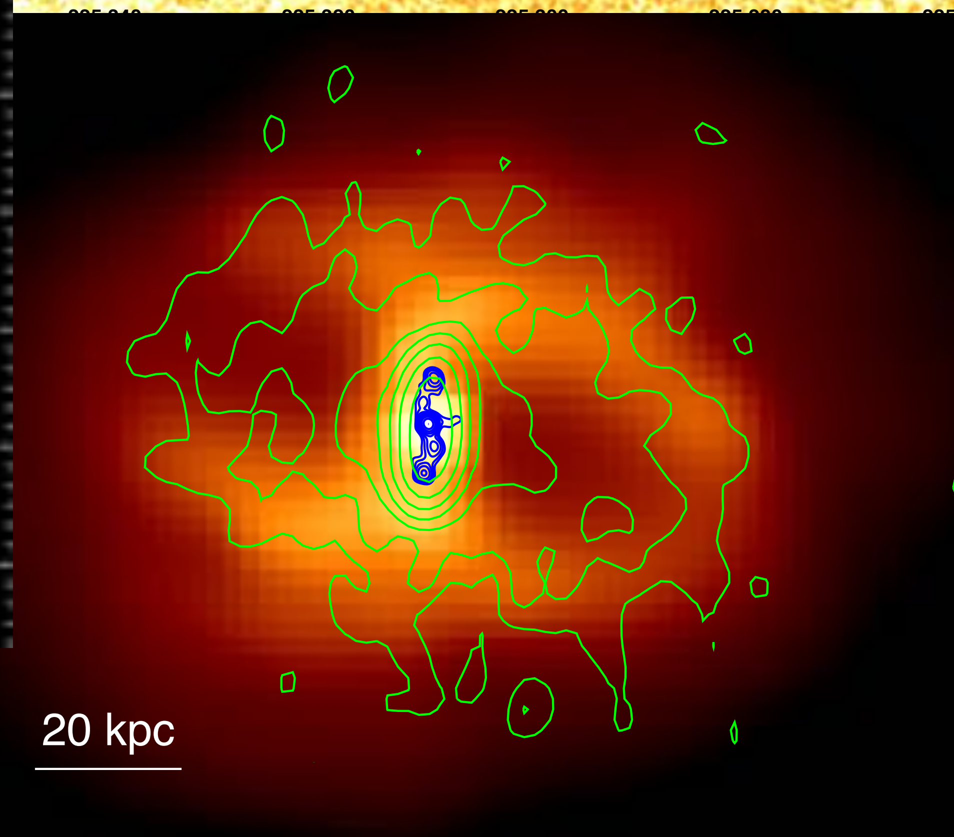




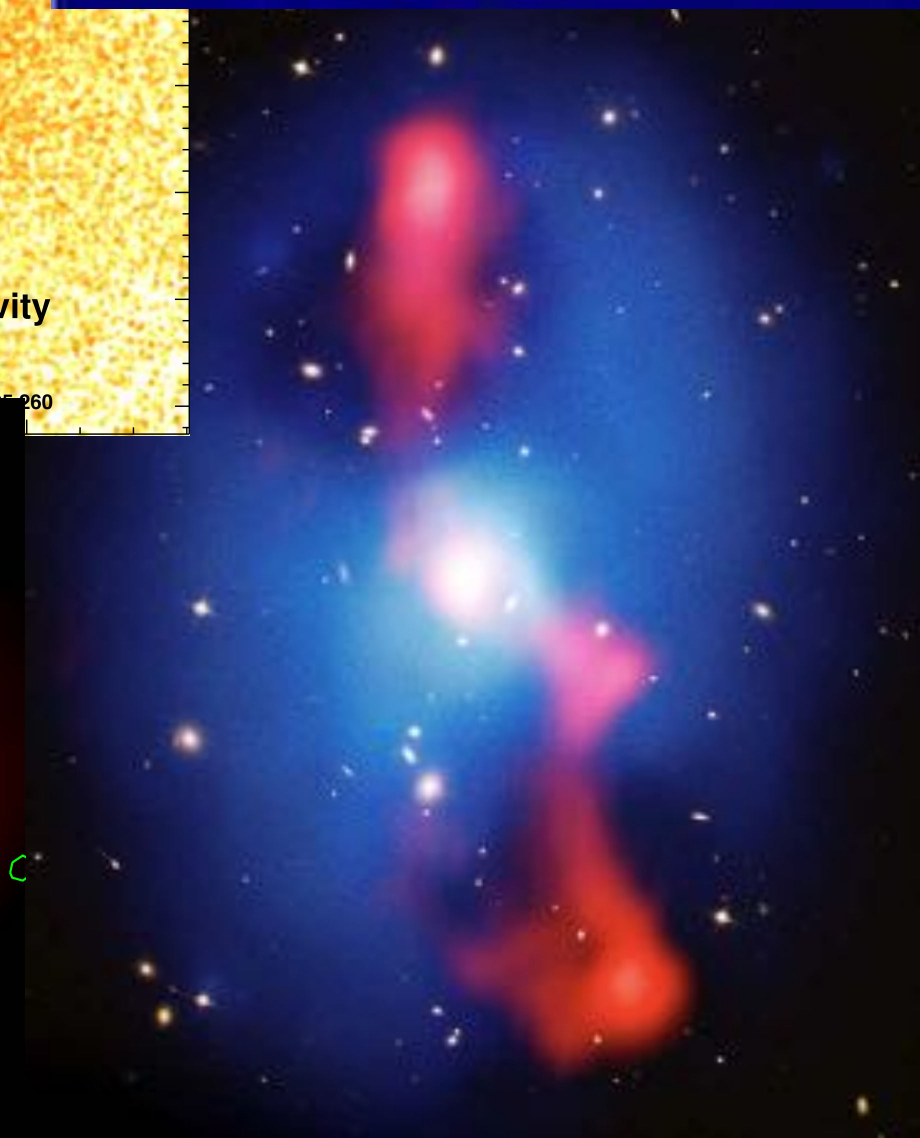




HCG 62 (Gitti+10)



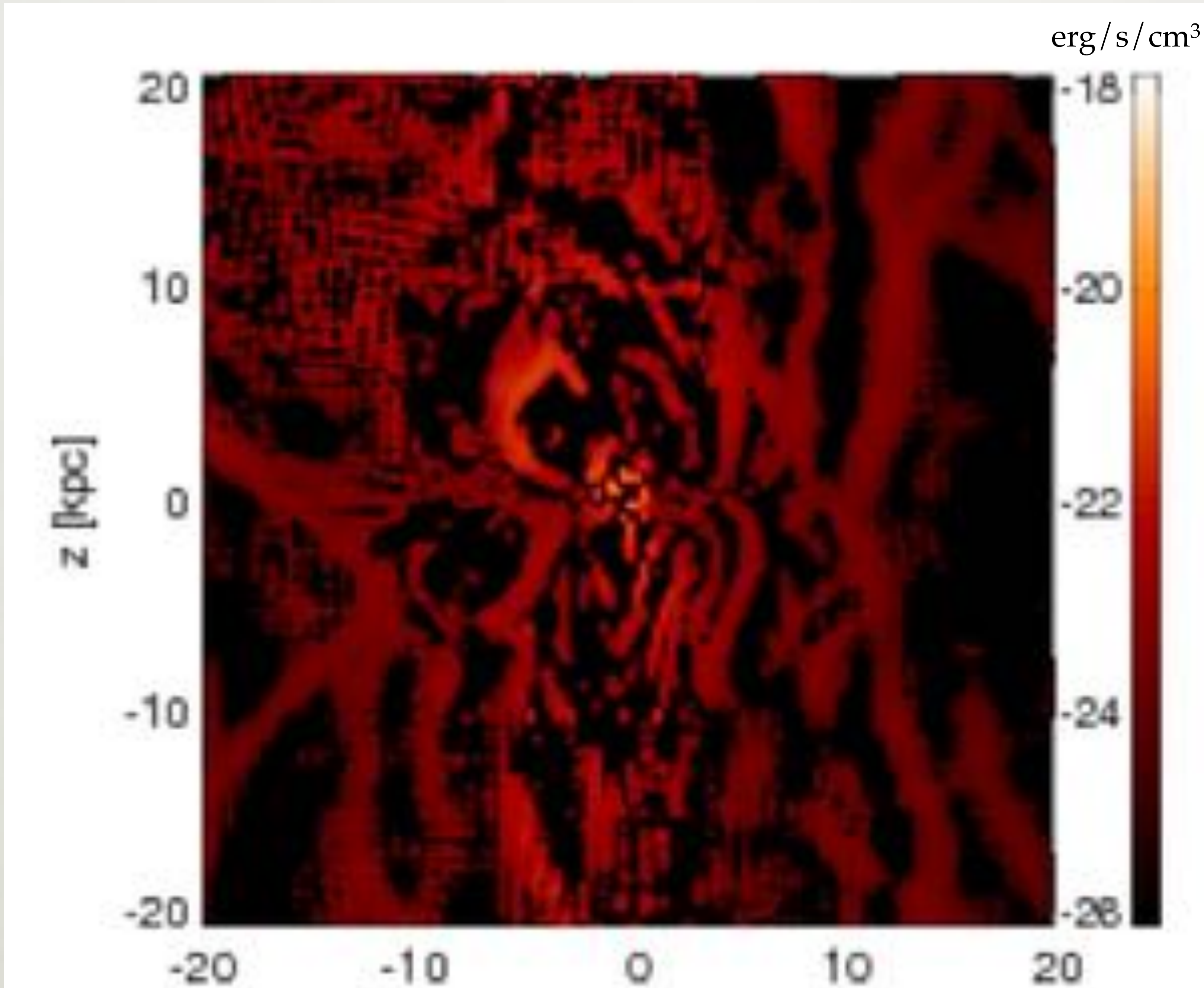
RBS 797 (Gitti+11)



MS0735.6 cluster (McNamara+05)

Global thermal equilibrium

AGN outflow feedback: net heating deposition

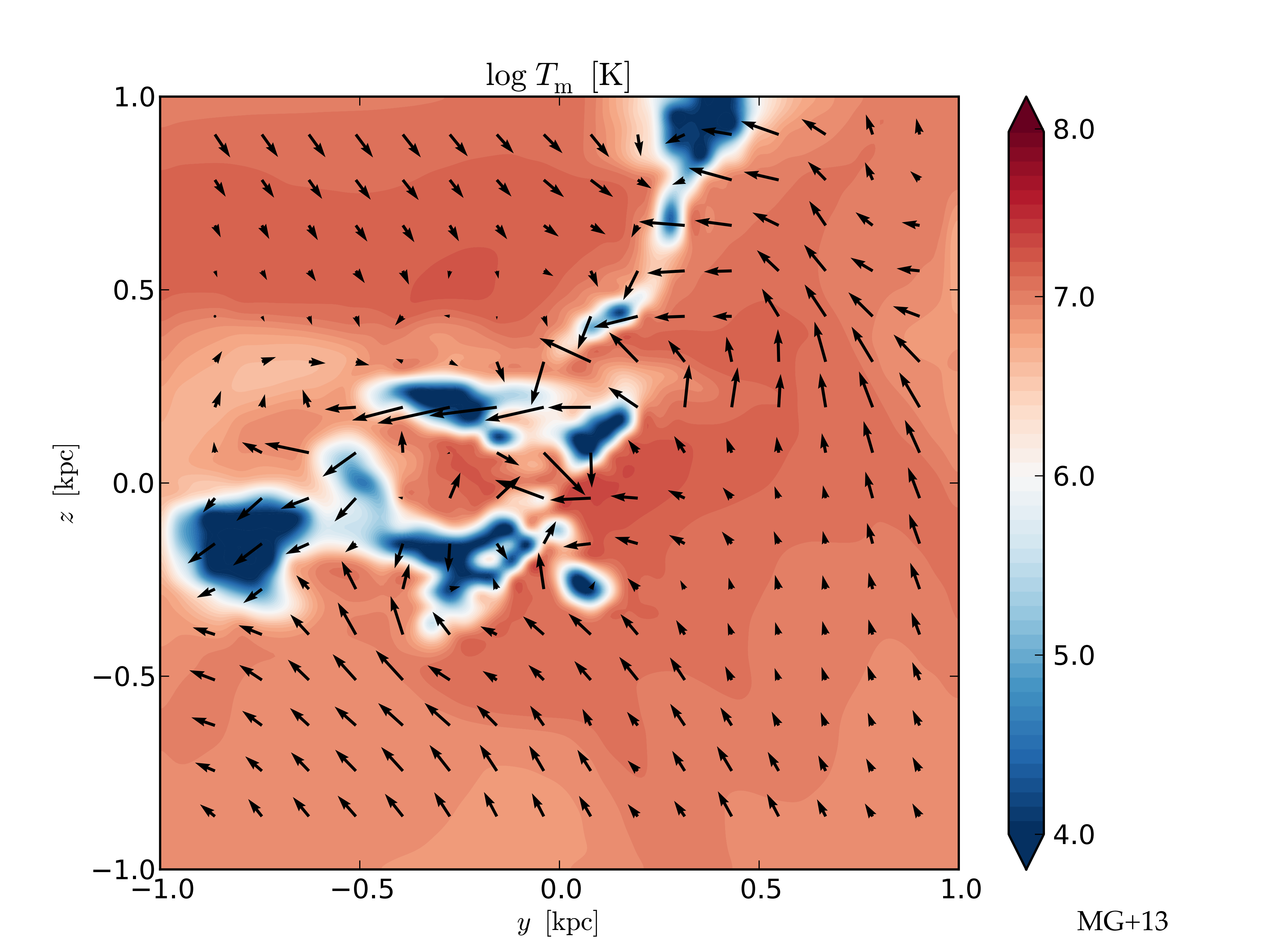


internal energy increase
(averaged over 1 Gyr)

MG+2012

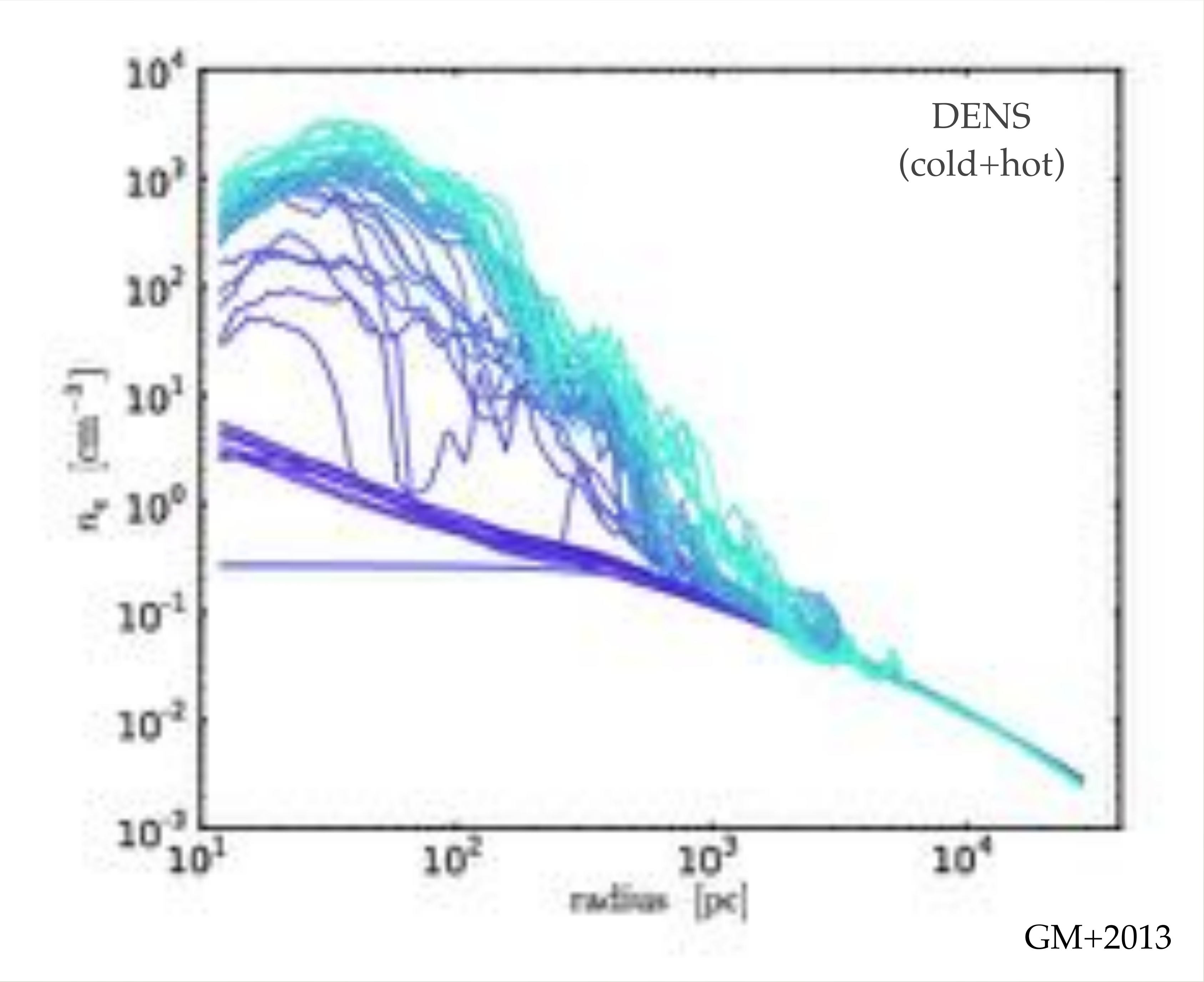
$$\mathcal{H} \sim \langle \mathcal{L} \rangle$$

CHAOTIC COLD ACCRETION ("CCA")



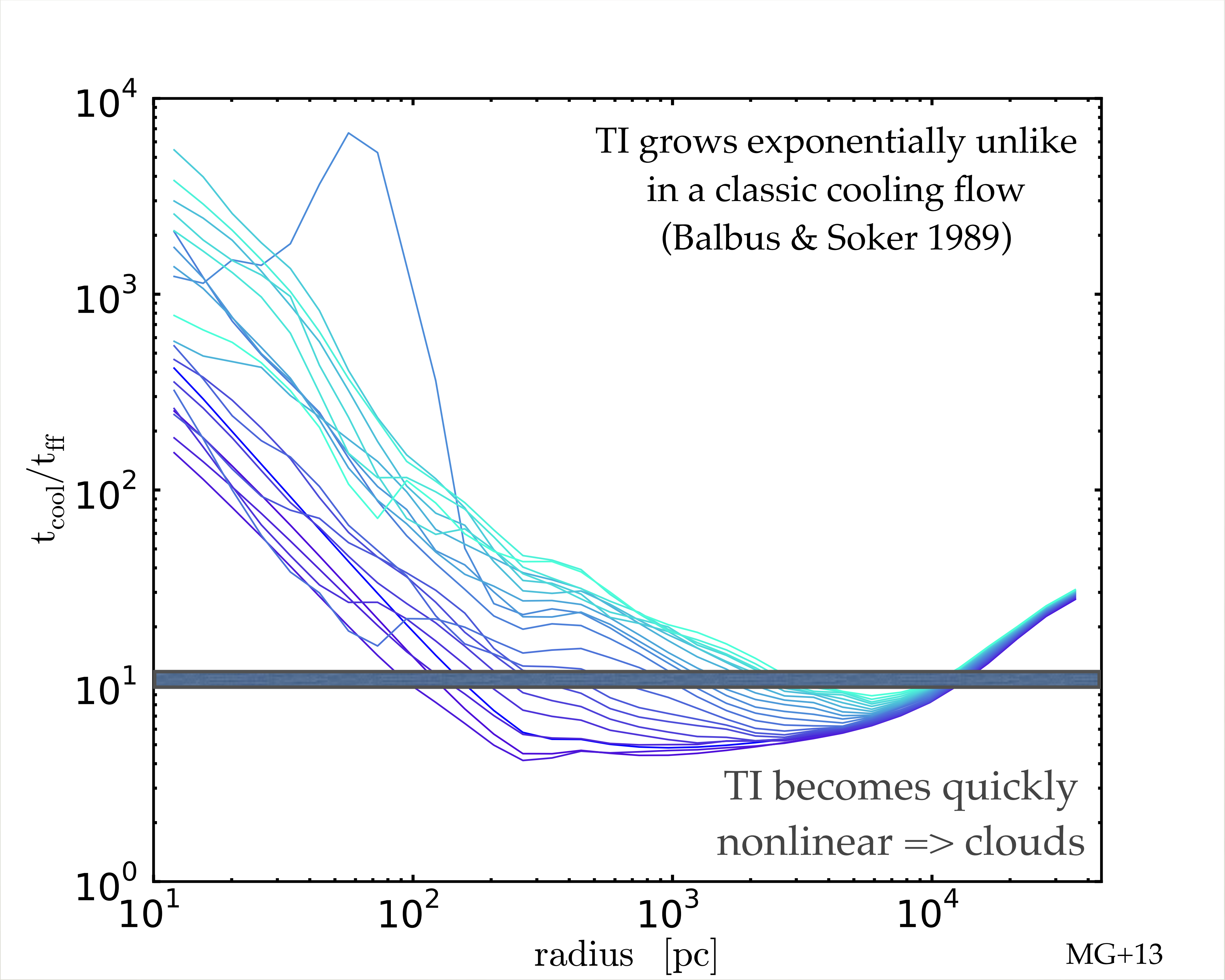
COOLING + HEATING + TURBULENCE

CHAOTIC COLD ACCRETION



condensation up to several kpc

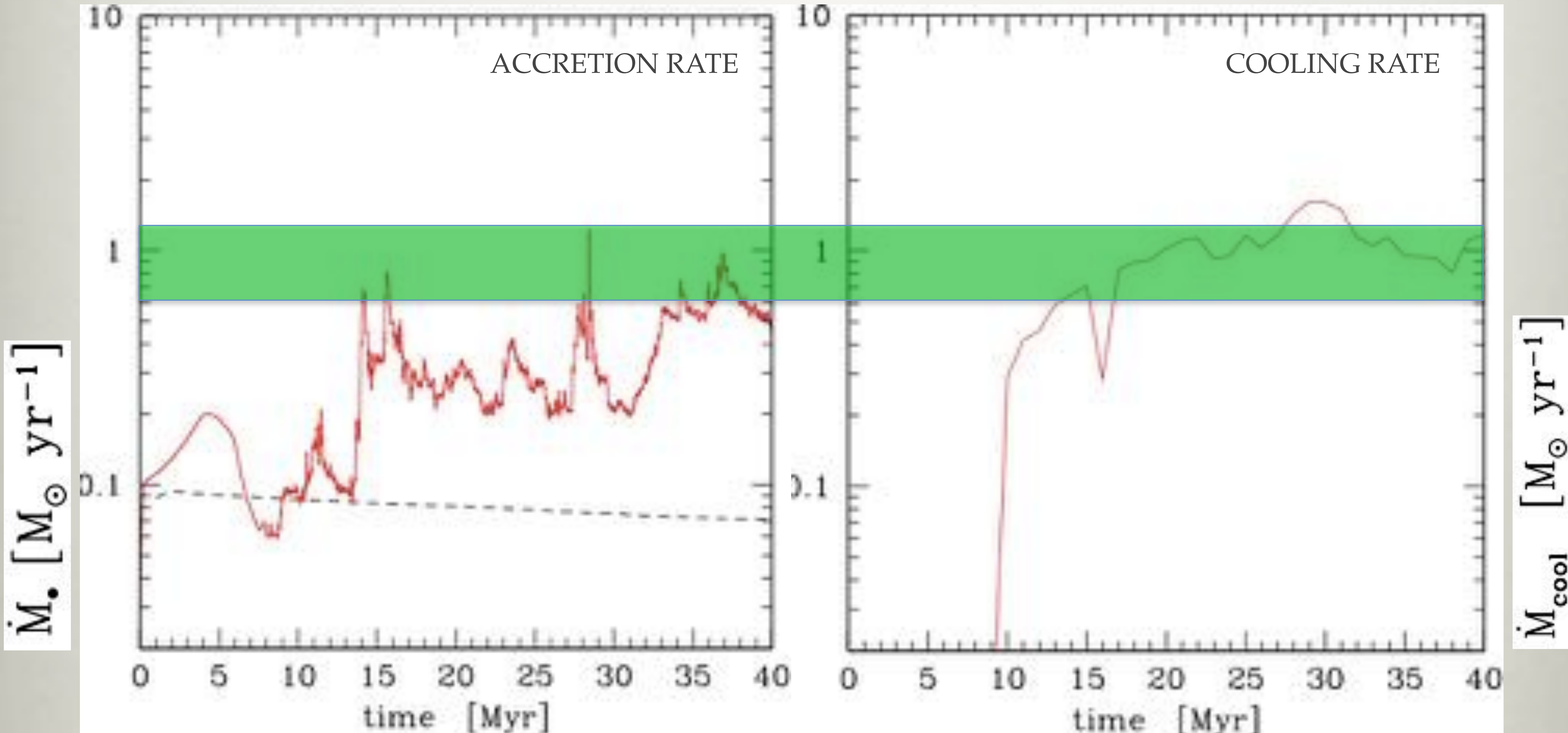
CHAOTIC COLD ACCRETION



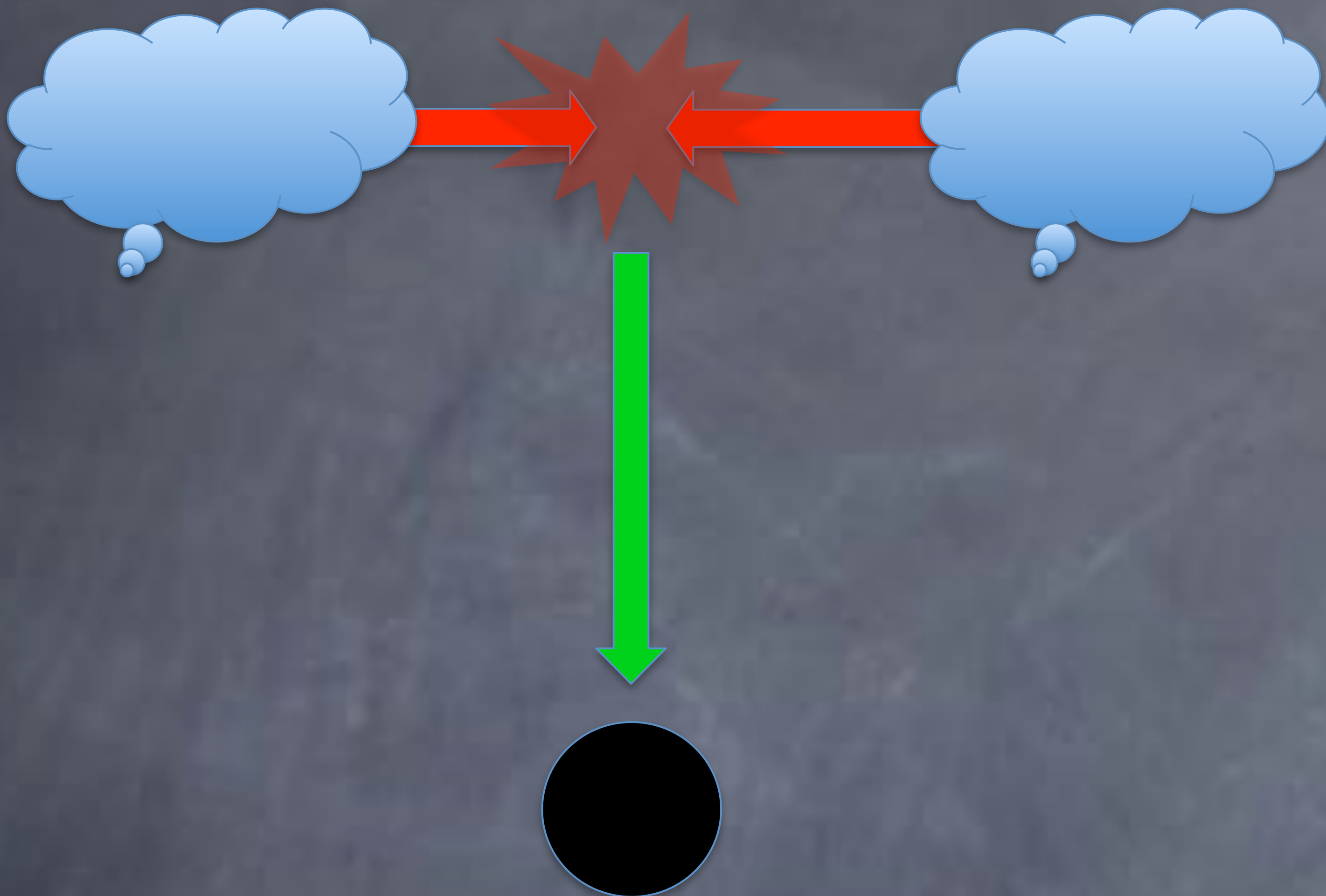
Thermal Instability (TI): $t_{\rm cool}/t_{\rm ff} < 10$

CHAOTIC COLD ACCRETION

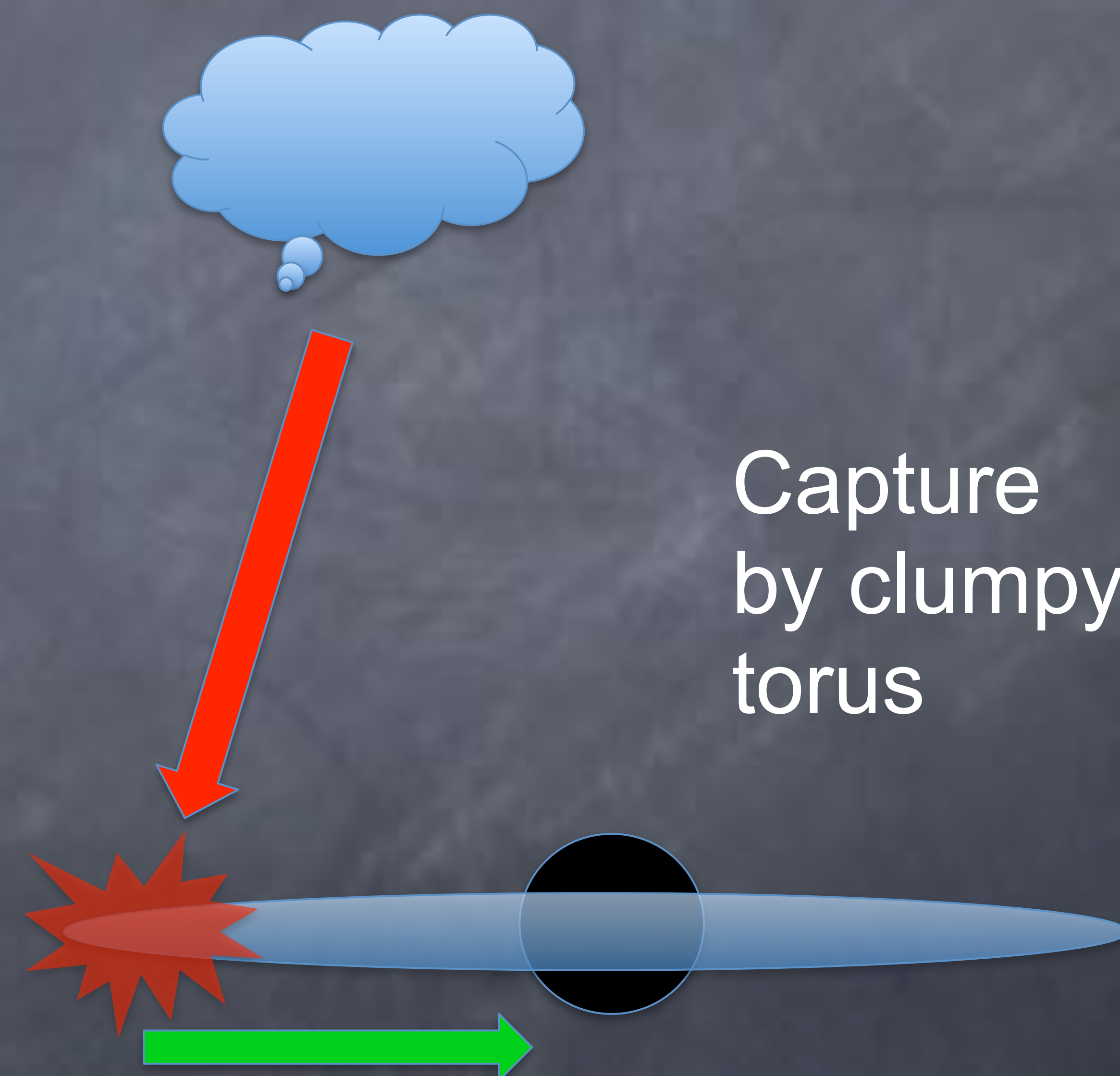
MG+13



$$\dot{M}_{\rm BH} \sim \dot{M}_{\rm cool}$$

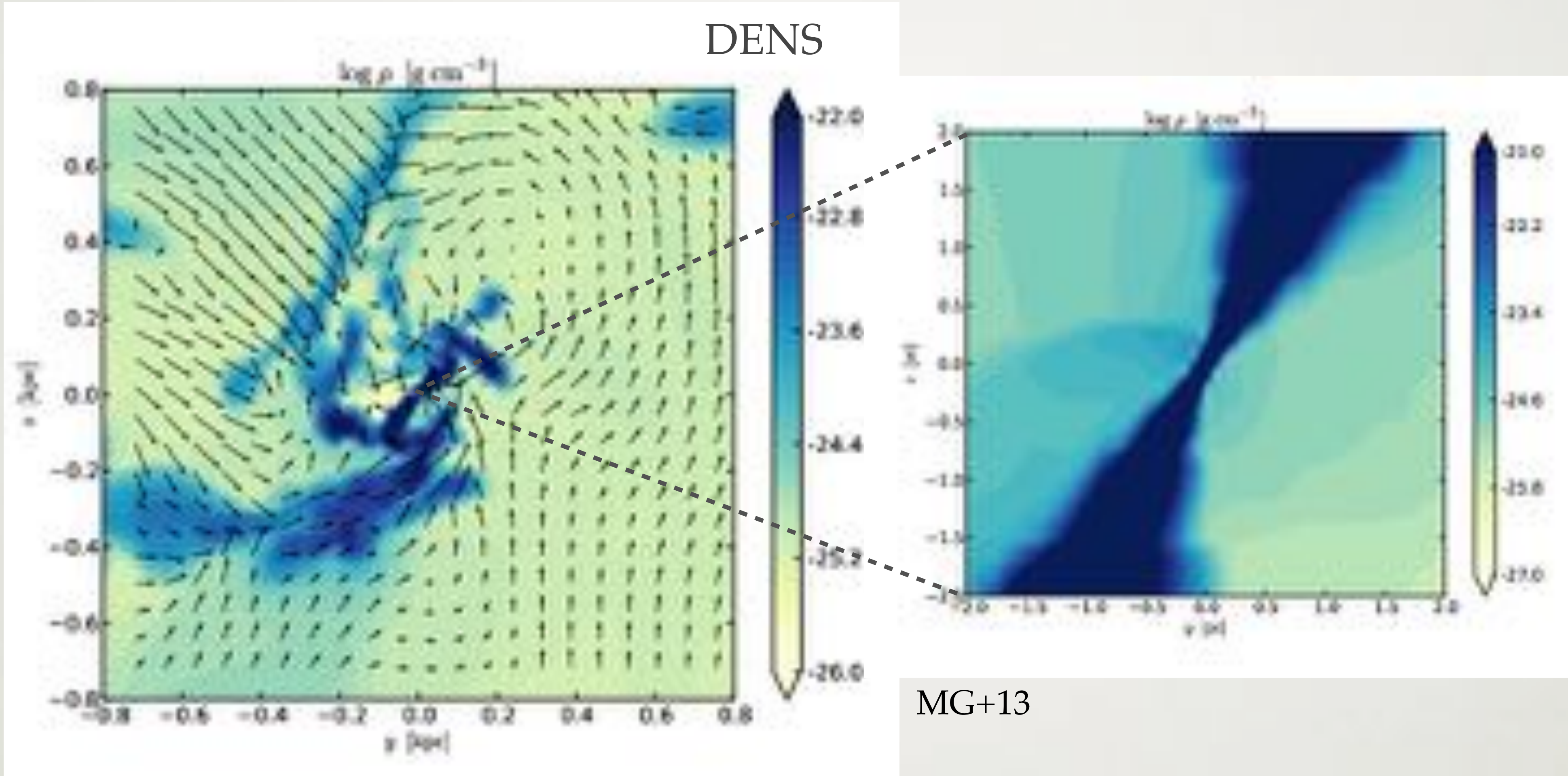


Angular momentum cancellation



Capture by clumpy torus

CHAOTIC COLD ACCRETION



MG+13

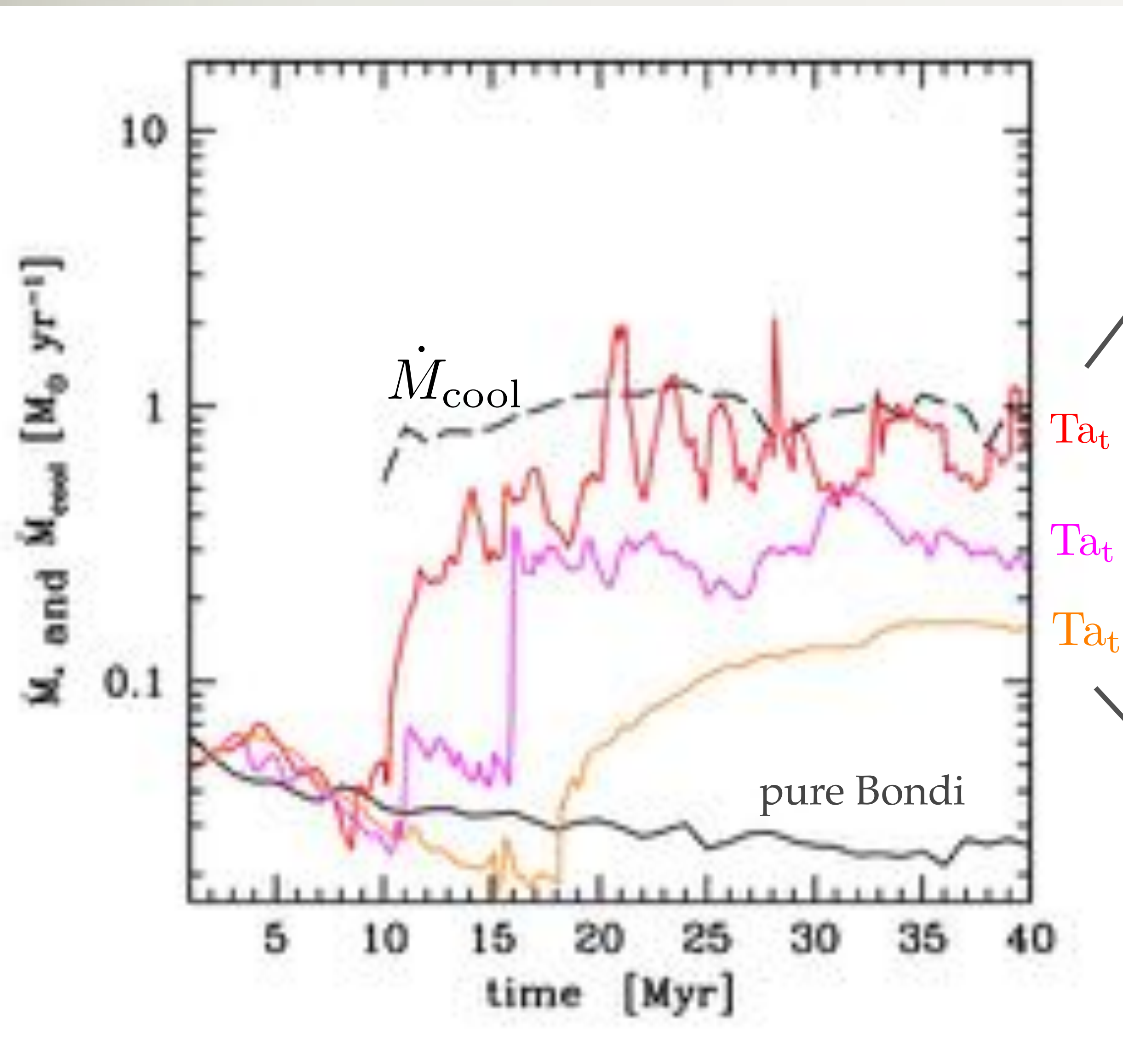
- Accretion driven by **inelastic collisions**: cloud-cloud and cloud-torus
- Very clumpy & turbulent torus (crucial for the AGN unification theory)
- Cold clouds may form the BLR/NLR or HVC
- Deflection of jets/outflows & BH spin changes

CHAOTIC COLD ACCRETION (ROTATION)

MG+2015

$\dot{M}_{\rm BH} \sim 100\,\dot{M}_{\rm Bondi} \sim \dot{M}_{\rm cool}$

efficient collisions



$\mathrm{Ta_t} \sim 0.75$

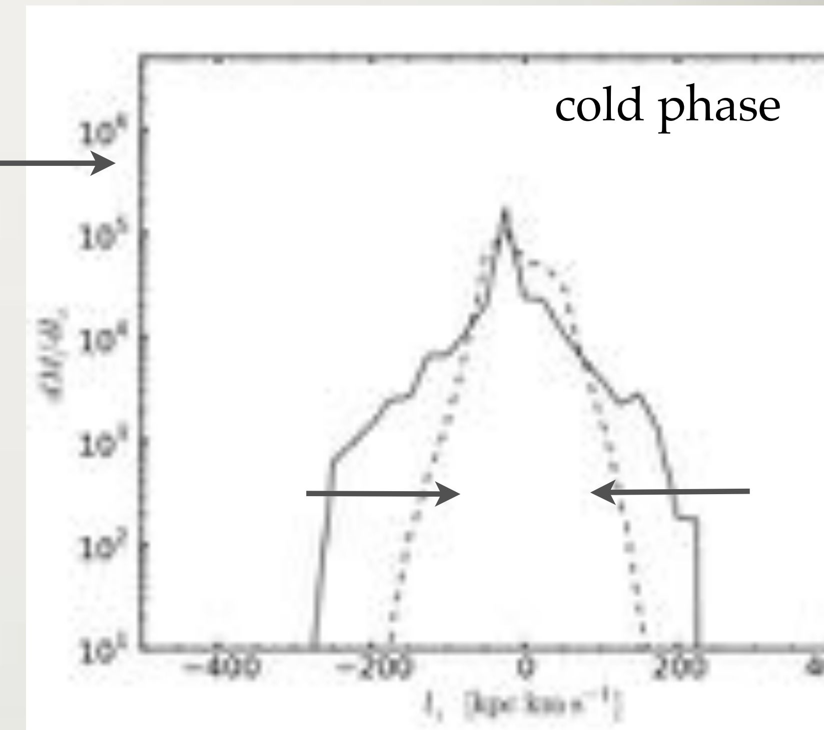
$\mathrm{Ta_t} \sim 1.5$

$\mathrm{Ta_t} \sim 3$

CCA dominates:

$\mathrm{Ta_t} < 1$

$\dot{M}_\bullet \propto \mathrm{Ta_t}^{-1}$



shrinking of angular momentum PDF
(20-27 Myr: 3 major accretion peaks)

$\mathrm{Ta_t} > 1$

rotating structure dominates:

1. weaker turbulent broadening
2. less efficient collisions
3. TI are weaker as rotation dominates: vertical infall => radial compression is marginal => lower TI threshold $t_{\rm cool}/t_{\rm ff} < 1$ (non-spherical case; McCourt et al. 2012)

sub-Eddington accretion rates: 3.e-4 - 3.e-2 --> covers well the mechanical mode regime (e.g. Russell+13)

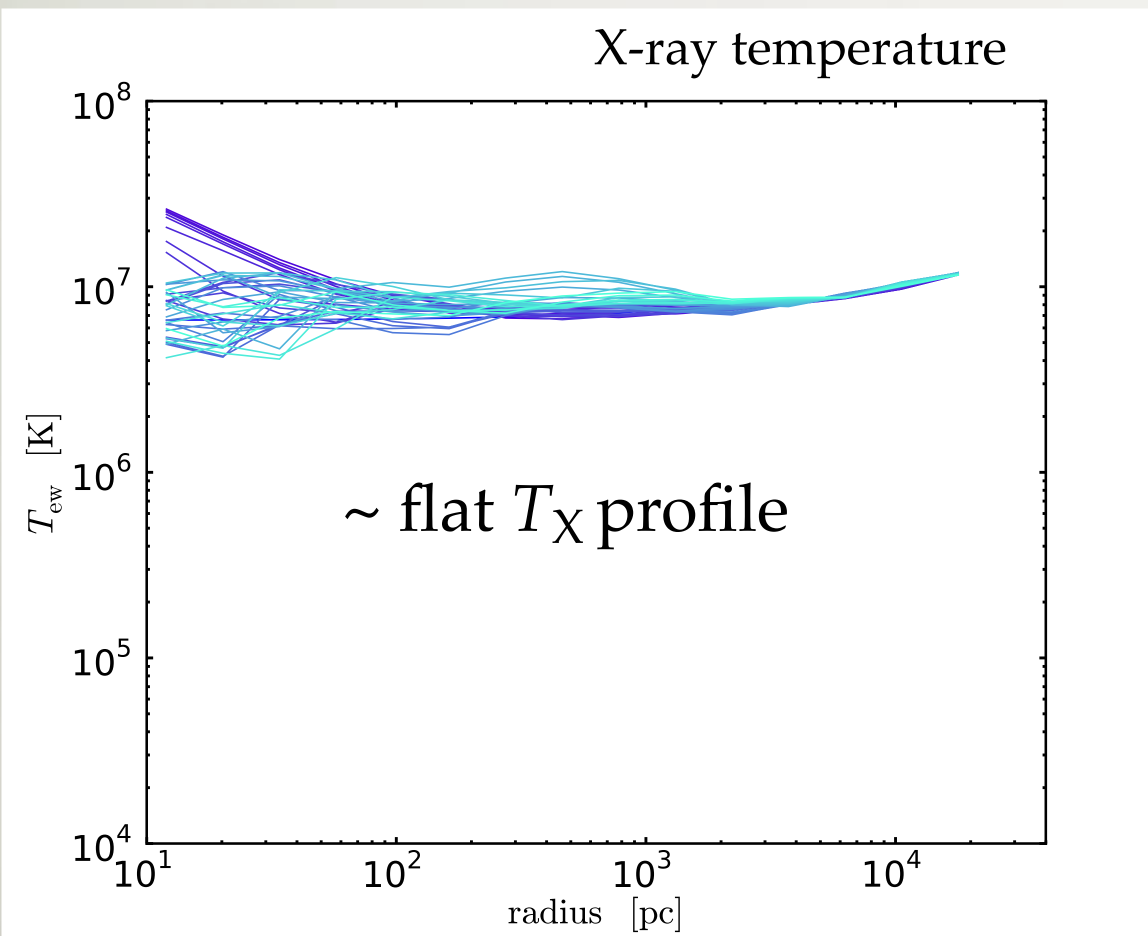
COLD vs HOT

ACCRETION

- $t_{\rm cool}/t_{\rm ff}$ **< 10 => condensation & TI**

chaotic cold accretion

$$\dot{M}_{\rm BH} \sim 100\,\dot{M}_{\rm Bondi}$$

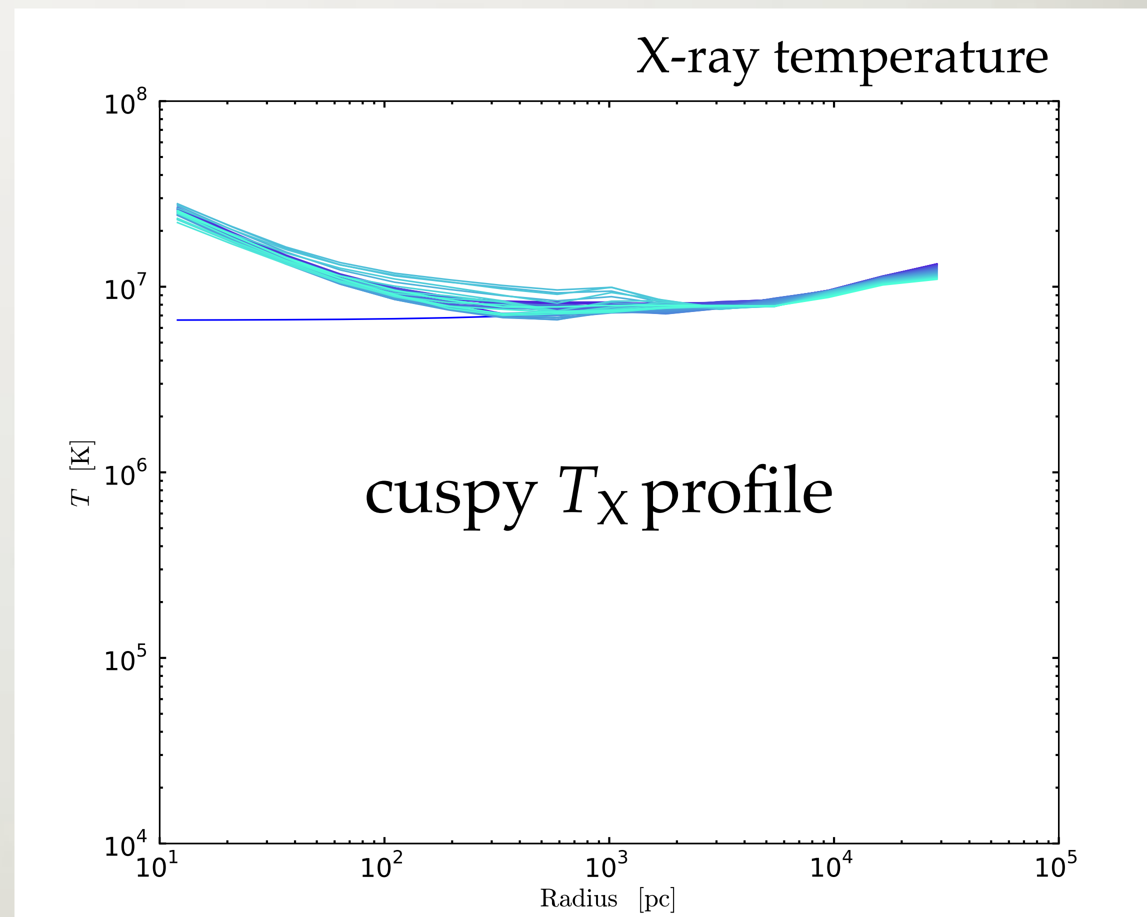


e.g. NGC 3115 (Wong et al. 2014)
NGC 4261, 4472 (Humphrey et al. 2009)
M87 (Russell et al. 2015)

- $t_{\rm cool}/t_{\rm ff}$ **>> 10 => overheated phase**

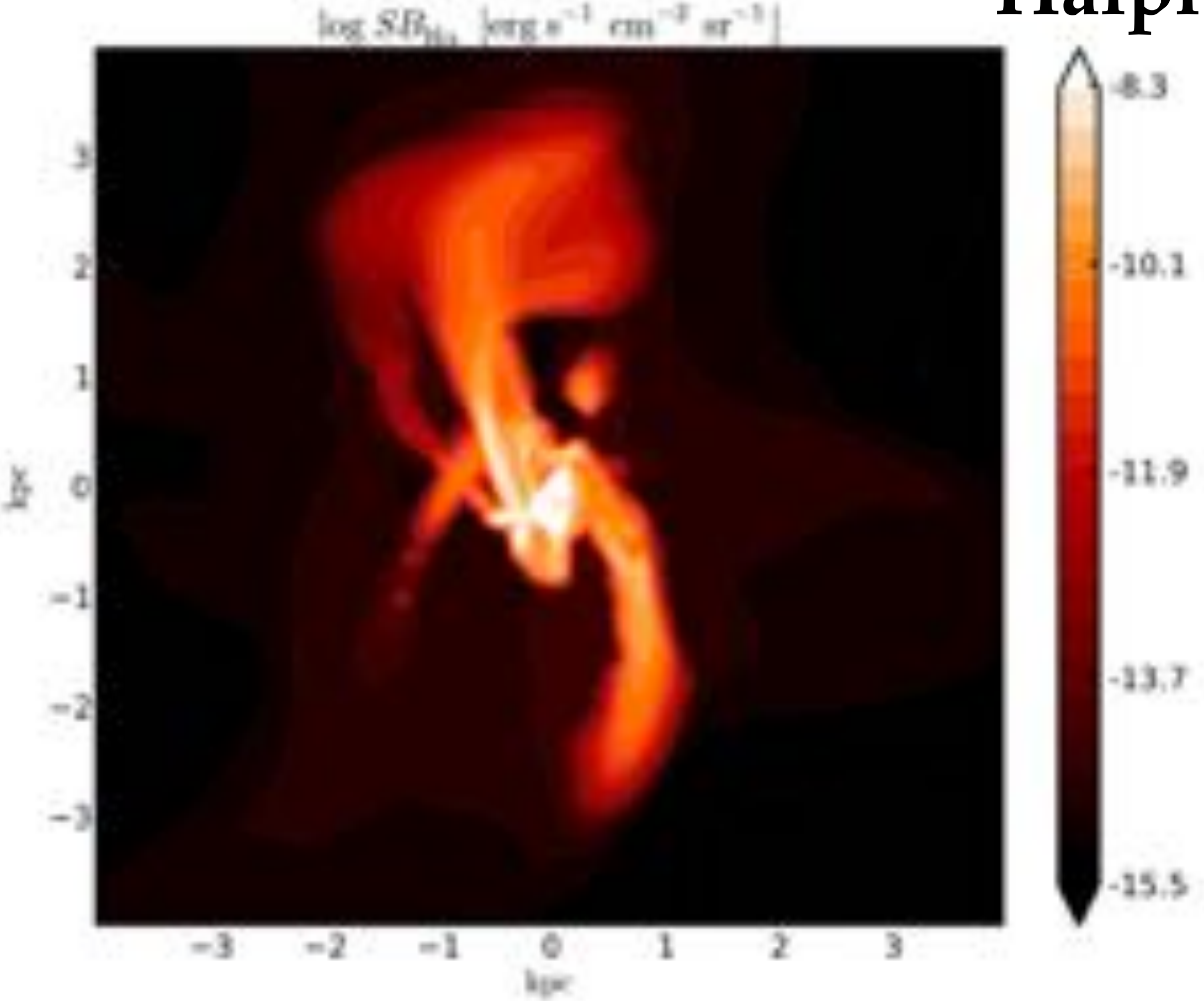
stifled Bondi/hot accretion

$$\dot{M}_{\rm BH} \lesssim 1/3\,\dot{M}_{\rm Bondi}$$



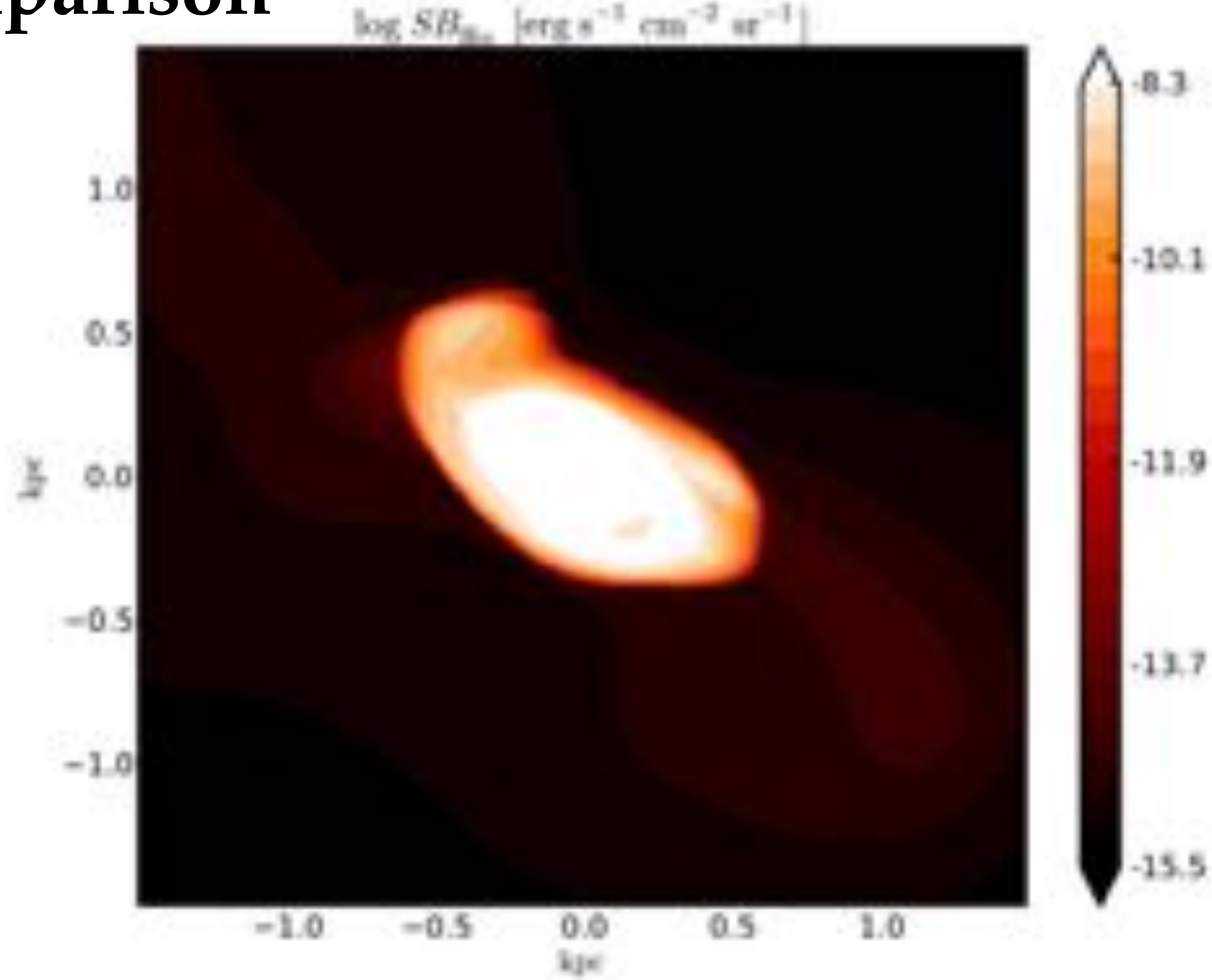
e.g. NGC 4649 (Humphrey et al. 2008)
NGC 1332 (Humphrey et al. 2009)

Halpha comparison

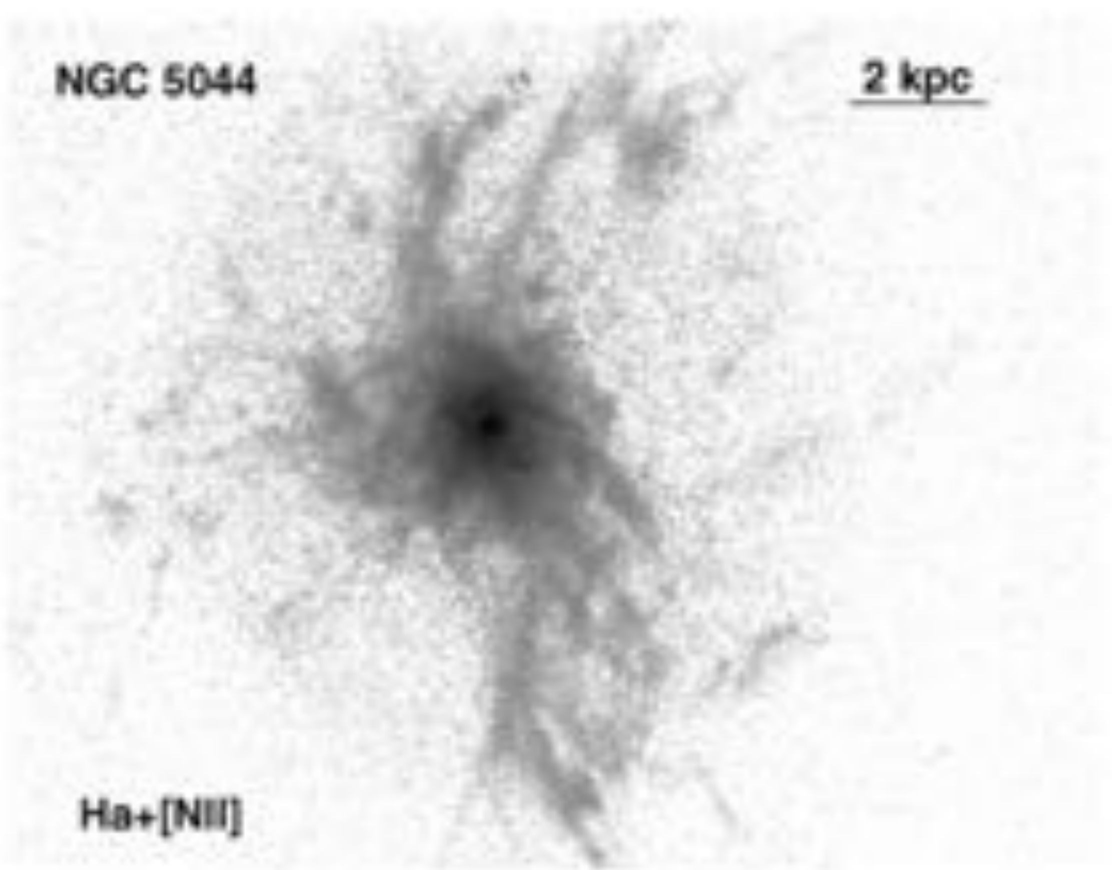


full CCA

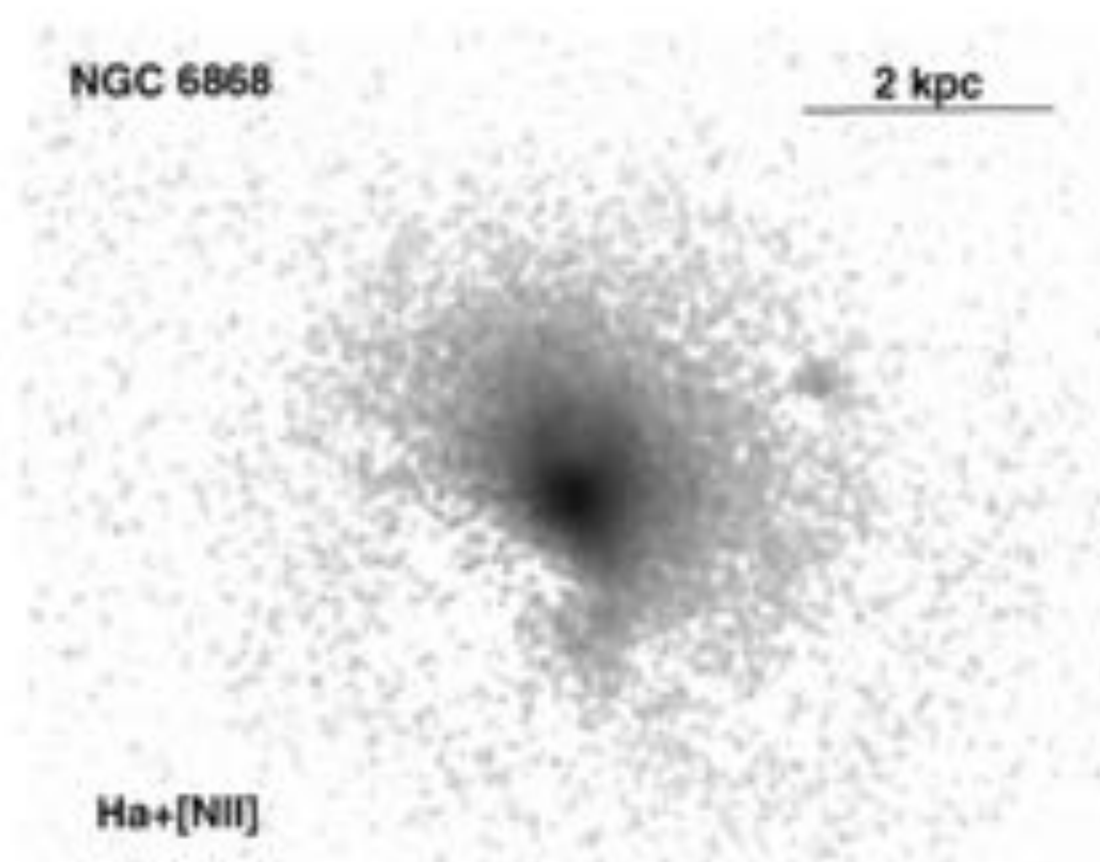
SIMS
MG+15



disc mode



SOAR DATA
Werner+14



5.

Chaotic cold accretion drives AGN feedback

FEEDBACK

FLASH4 simulations

MG+2009-2015

$$\textbf{Cluster} \rightarrow \ M_{\rm vir} \approx 10^{15}\ M_\odot,\ R_{\rm vir} \approx 2.5\ \rm Mpc$$

$$\textbf{Group} \rightarrow \ M_{\rm vir} \approx 4 \times 10^{13}\ M_\odot,\ R_{\rm vir} \approx 0.9\ \rm Mpc$$

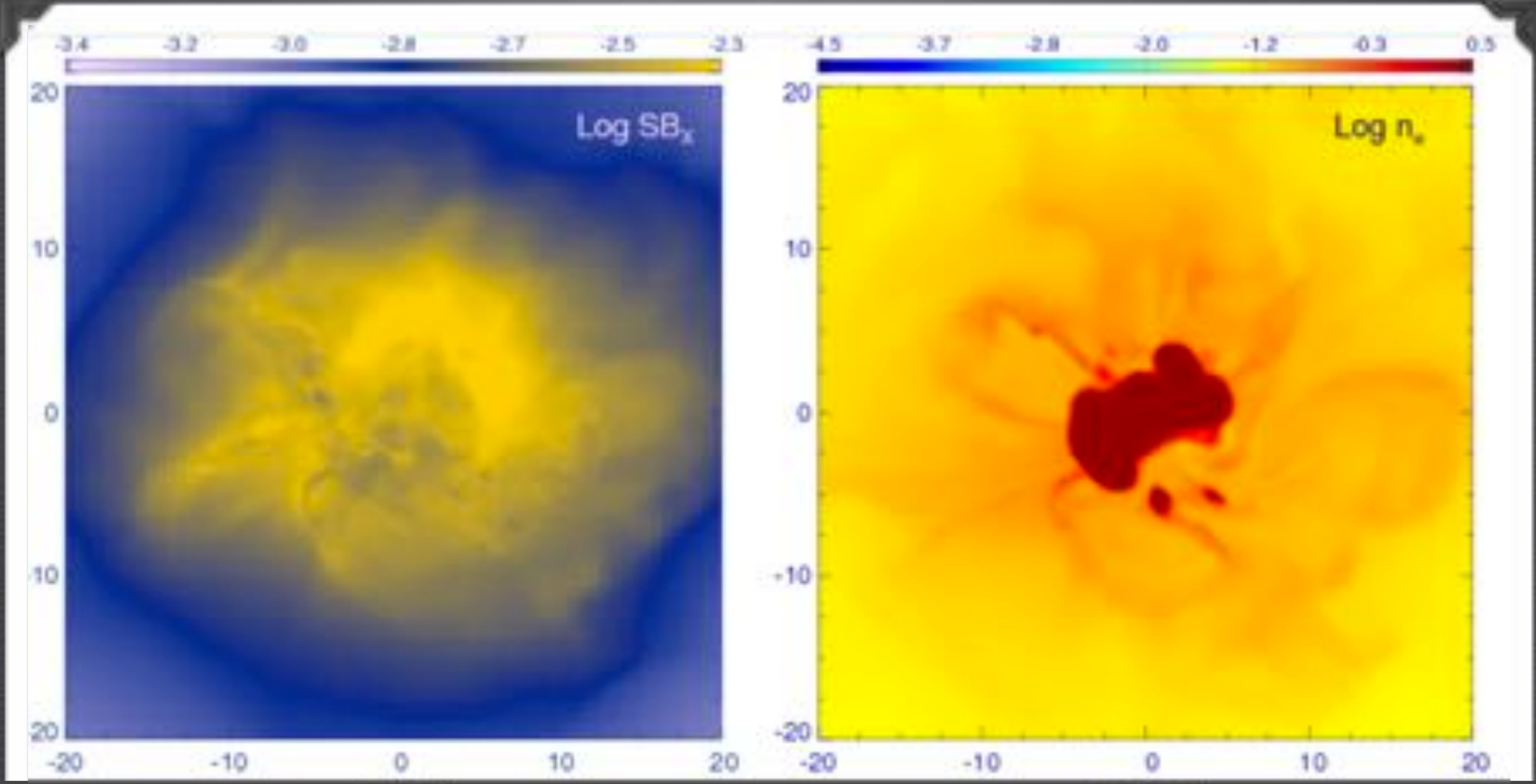
$$\textbf{Elliptical} \rightarrow \ M_* \approx 3 \times 10^{11}\ M_\odot,\ R_{\rm eff} \approx 10\ \rm kpc$$

- large-scale runs: 100 pc - 2 Mpc
- Dark matter + central galaxy potential
- Radiative cooling
- Stellar evolution: heating + mass loss
- **Bipolar AGN outflows + self-regulation:**

$$\frac{1}{2}\dot{m}_{\rm jet} v_{\rm jet}^2 = \boxed{P_{\rm jet} = \epsilon\, \dot{M}_{\rm acc} c^2}$$

$$\dot{M}_{\rm acc} \sim \dot{M}_{\rm cool}$$

Pure Cooling Flow evolution



z (kpc)

x (kpc)

x (kpc)

AGN Heating

KEY OBSERVATIONAL CONSTRAINTS

- **Quenching** the pure cooling flow for several (> 7) Gyr
- **Self-regulated** feedback (quasi thermal equilibrium)
- Preserve the **cool-core** structure (T and n profiles)
- Naturally producing typical **observed features**:

  bubbles, shocks, metals dredge-up, cold gas, turbulence

AGN feedback Cycle

$\mathcal{L} > \mathcal{H}$

↓

$t_{\rm cool} / t_{\rm ff} \lesssim 10$

↓

thermal instabilities

↓

cold clumps

↓

feed SMBH

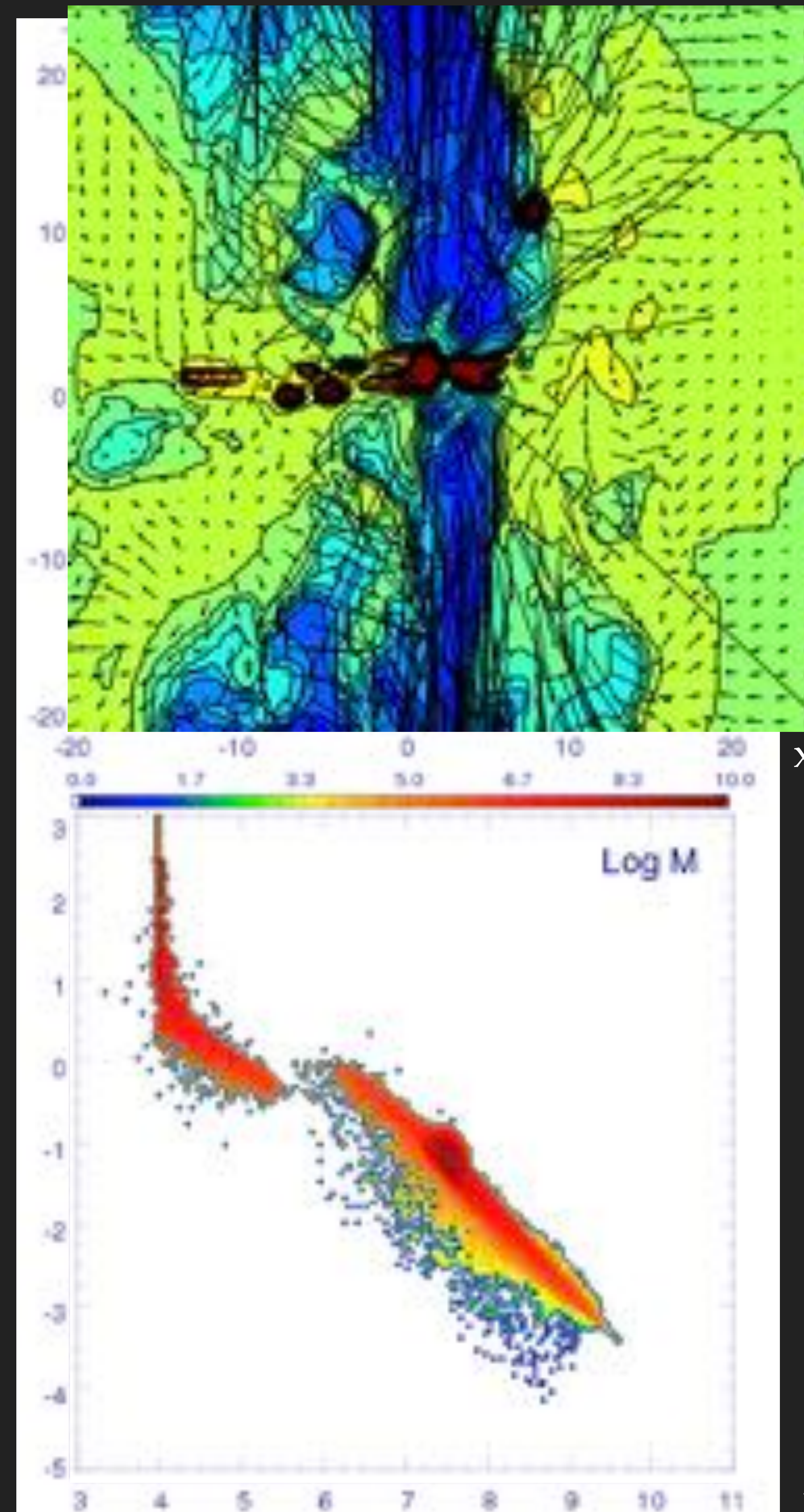
↓

feedback boosted

↓

$\mathcal{L} < \mathcal{H}$

MG+2012



AGN OUTFLOWS
+
CCA FEEDBACK

<u>Solving the cooling flow problem (mass sink)</u>

- Quenched cooling: < 5-10% CF

- Cool core preserved

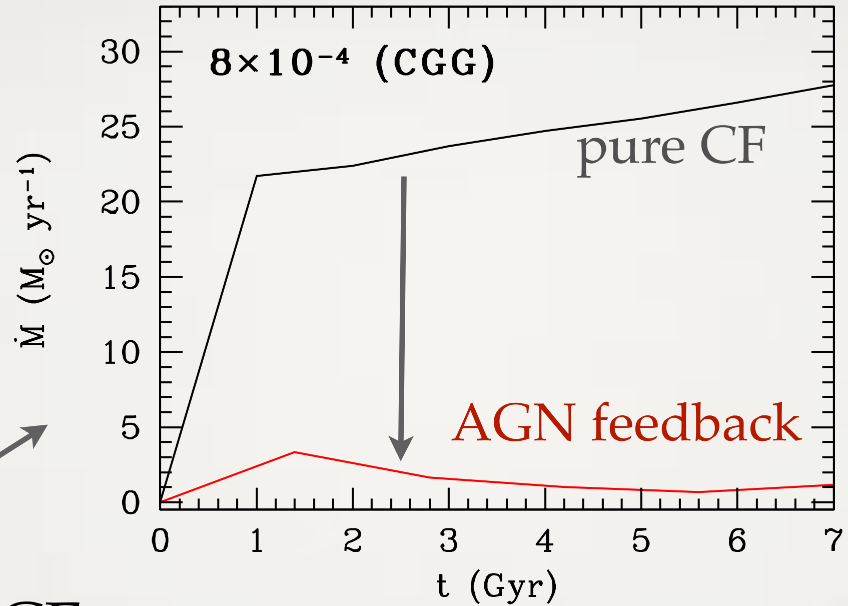
- Mechanical efficiencies:

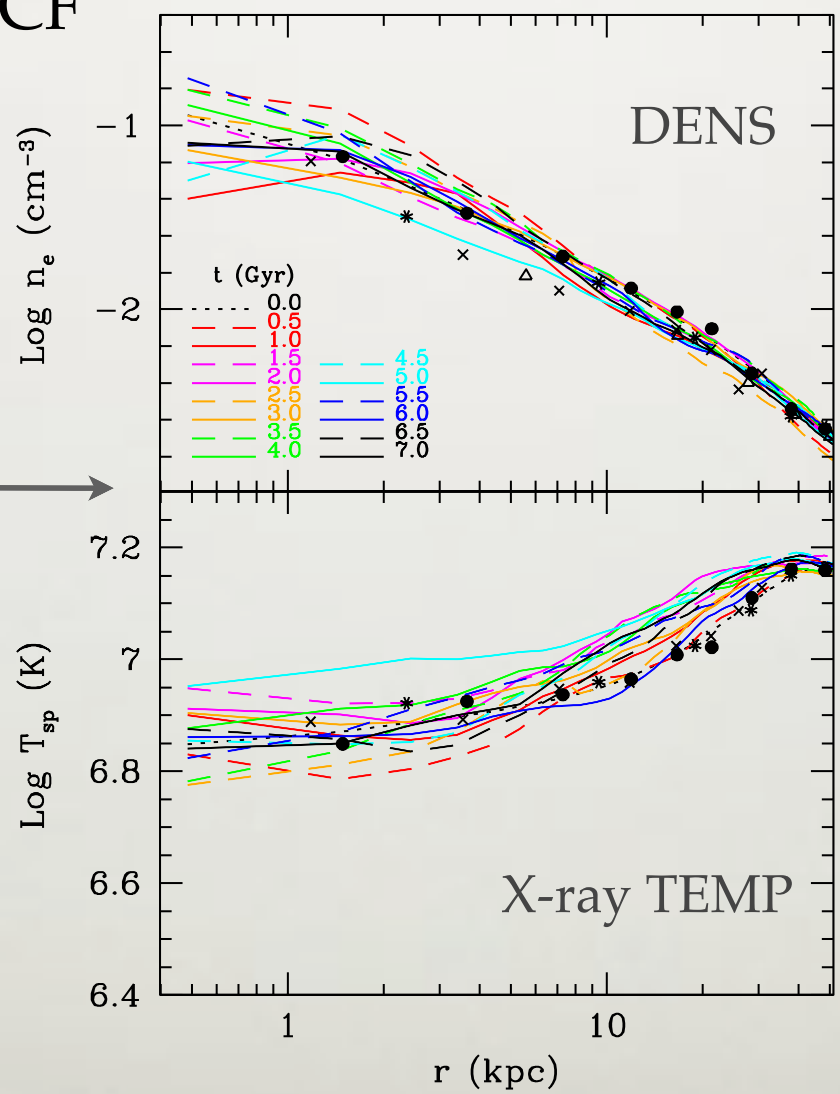
  ~ 5×10^{-4} - 5×10^{-3}

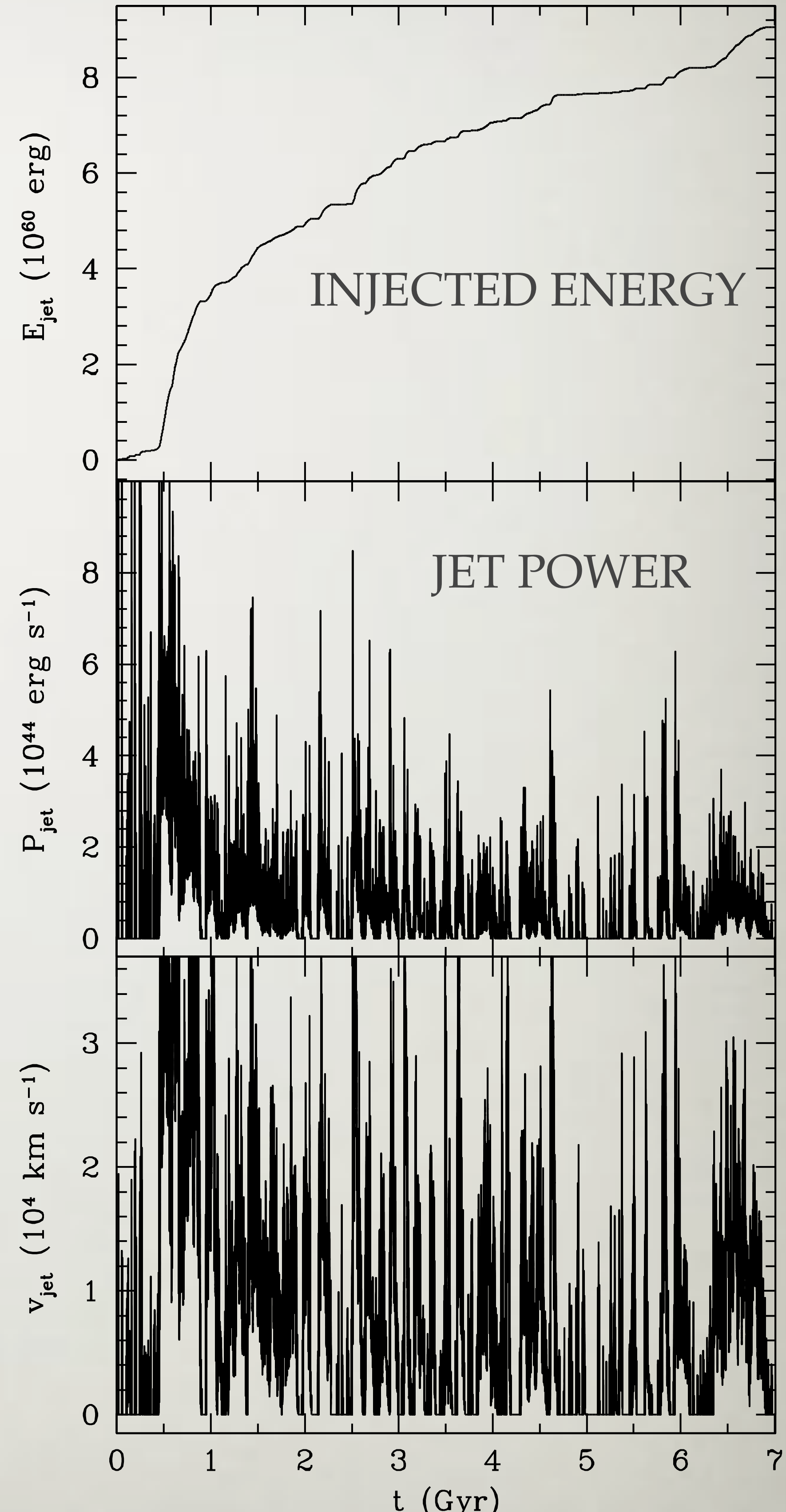
  isolated galaxies ---> clusters

galaxy group NGC 5044

MG+2012

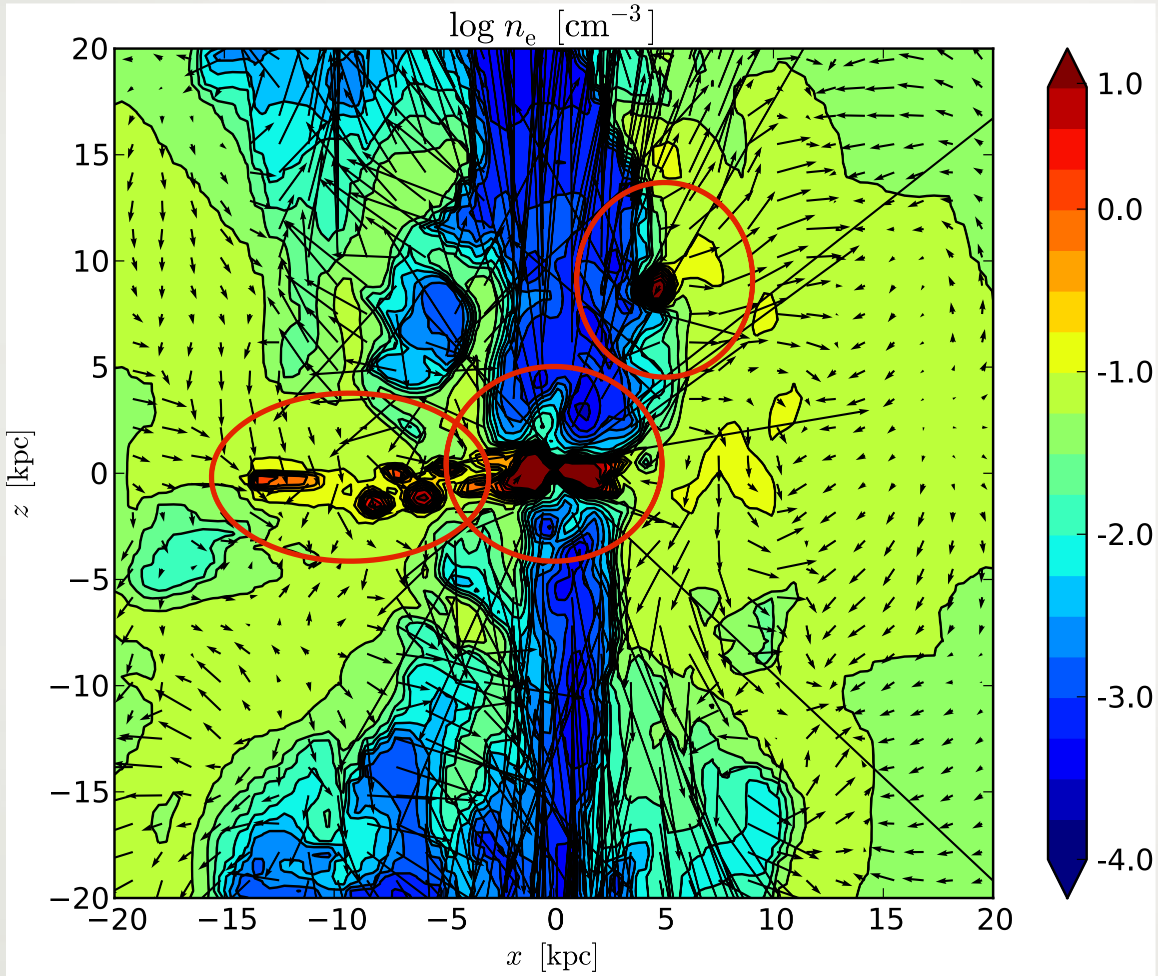






JET VELOCITY

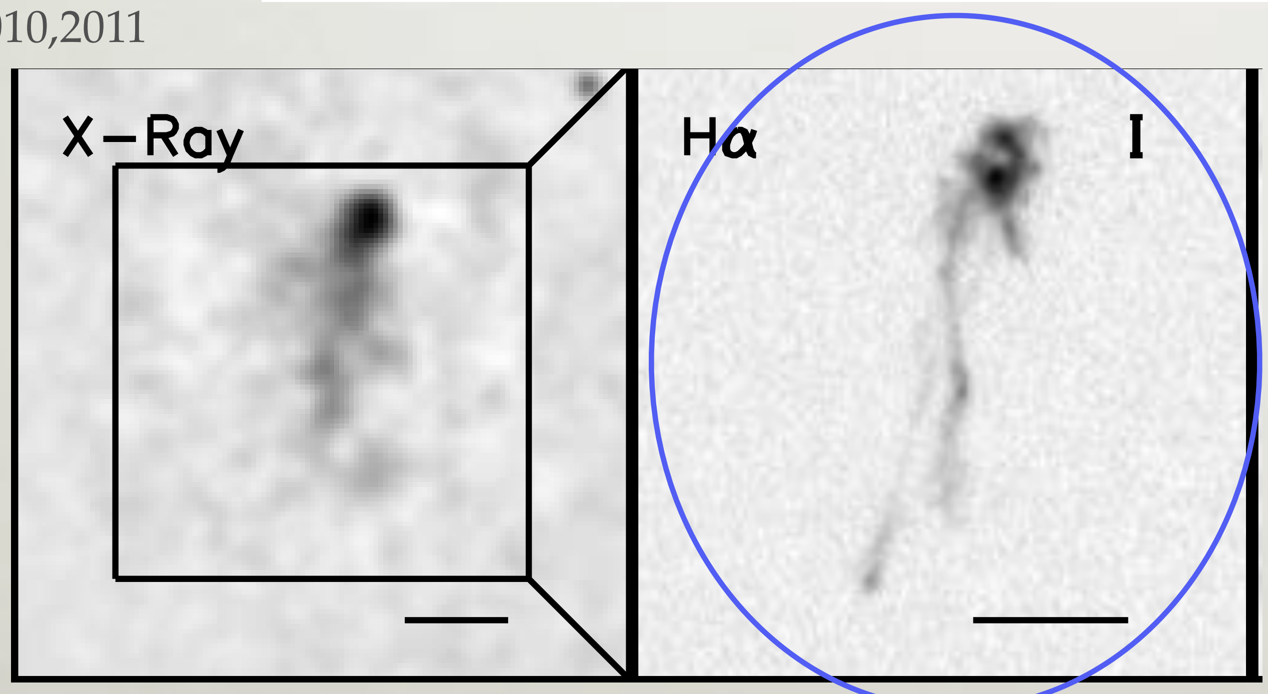
Cold gas: by-product and fuel of feedback

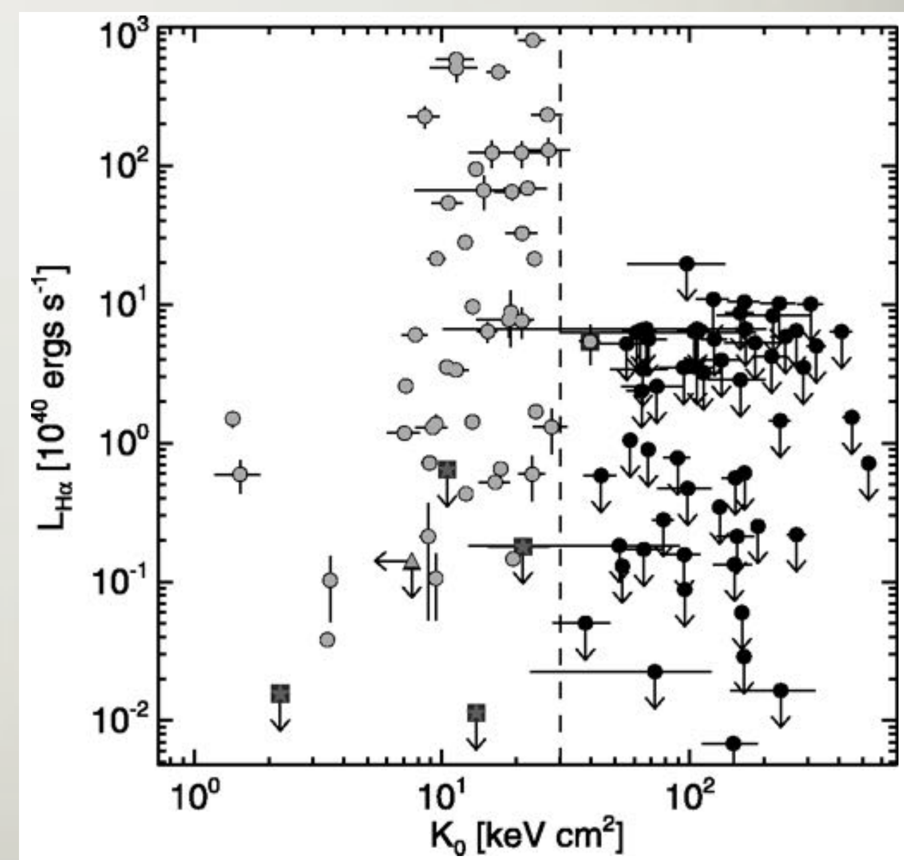


MG+2012

- Extended + Nuclear
- Cold mass $\lesssim 10^{11}\ M_\odot$ for clusters (Salomé+2003; Edge+2001)
- Cold >> hot accretion

McDonald+2010,2011





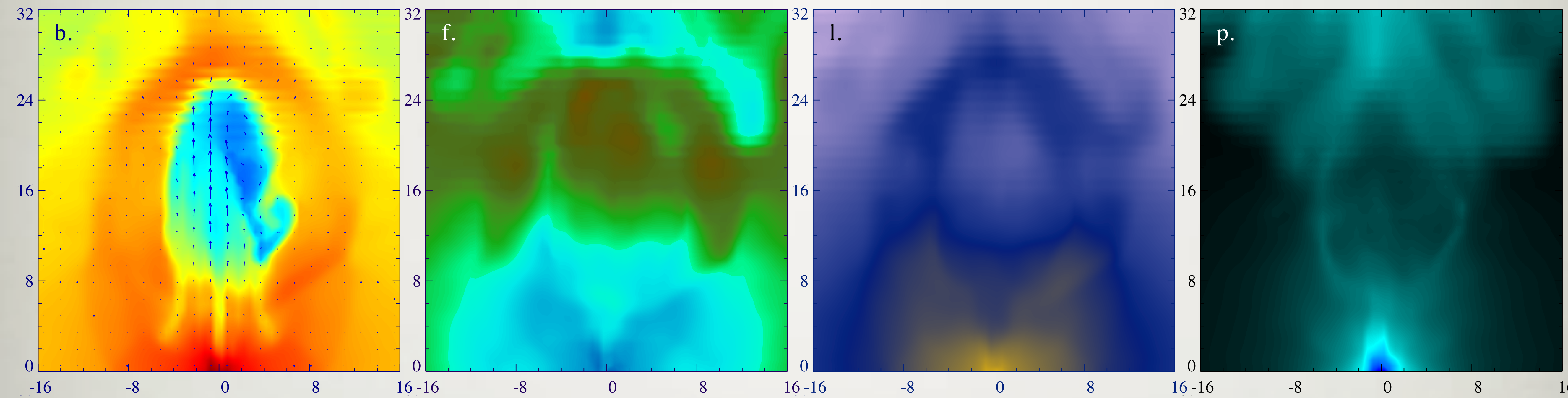
Rafferty, Cavagnolo+2008

$$\mathrm{TI} \Longleftrightarrow t_{\rm cool}/t_{\rm ff} \lesssim 10 \quad \longleftrightarrow \quad K_0 \lesssim 30\ \mathrm{keV cm^2}$$

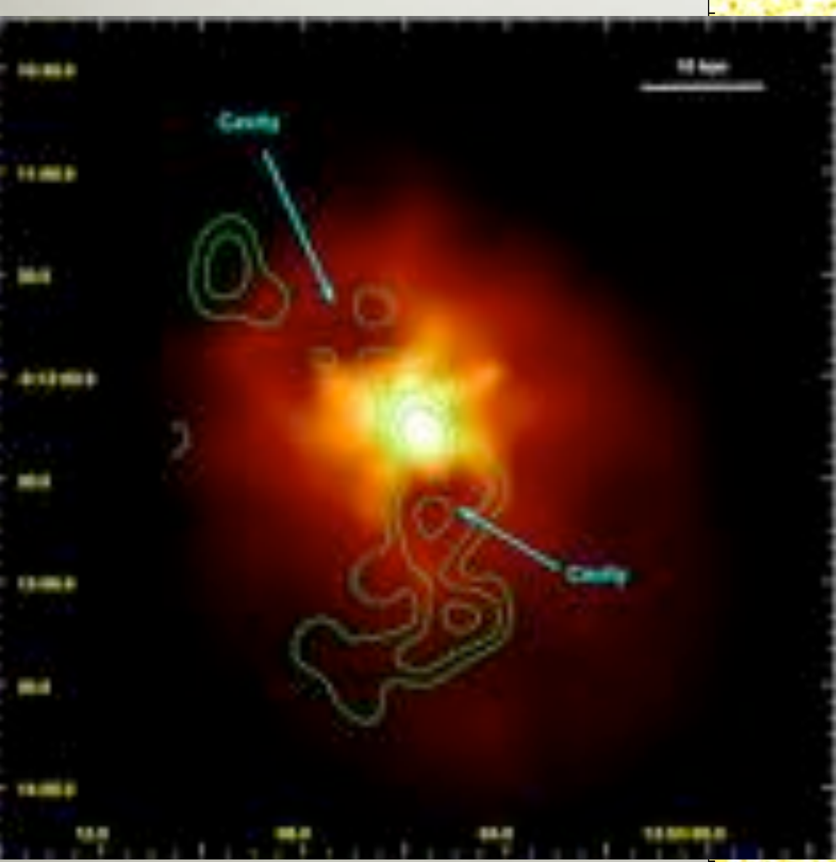
AGN feedback key imprints

cocoon shocks | turbulence | bubbles ~ 10s kpc | metal uplift

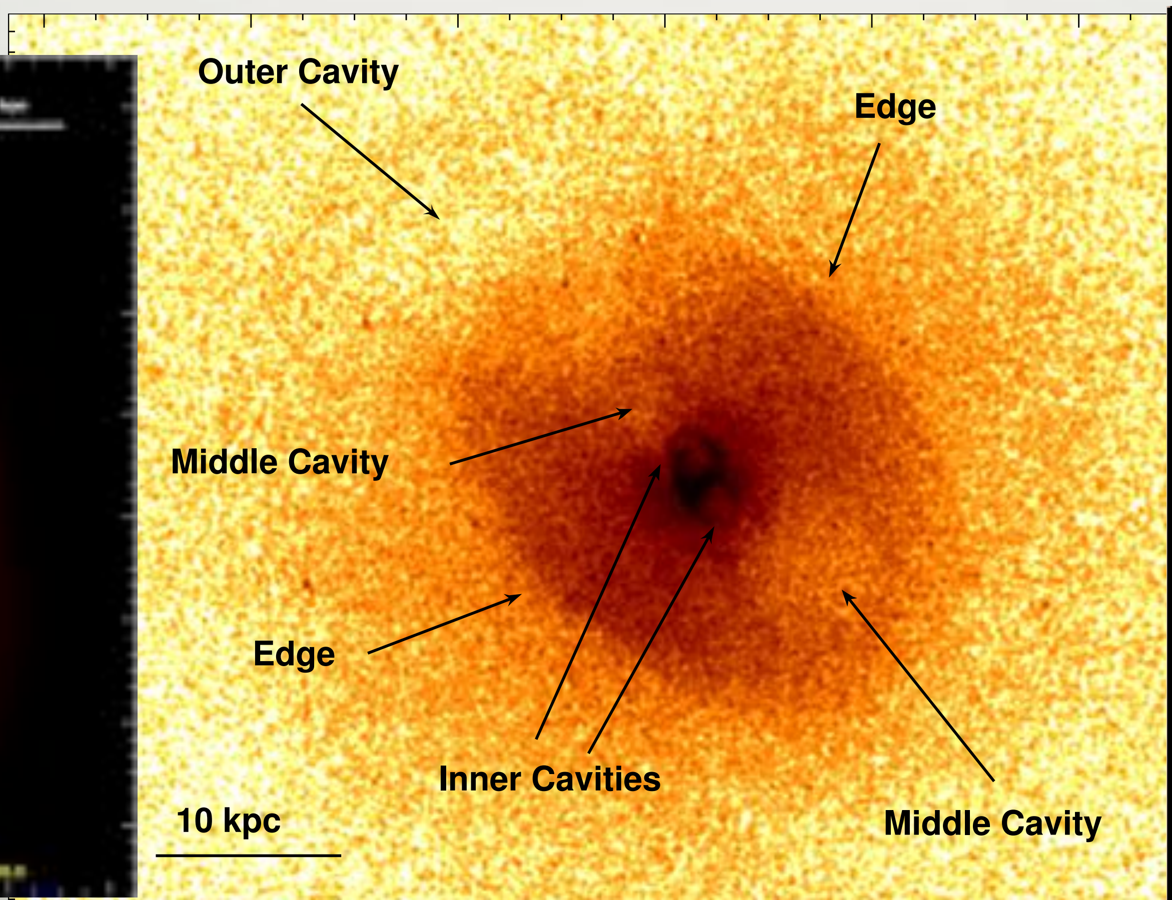
MG+2012 | DENS | X-ray TEMP | X-ray SB | IRON



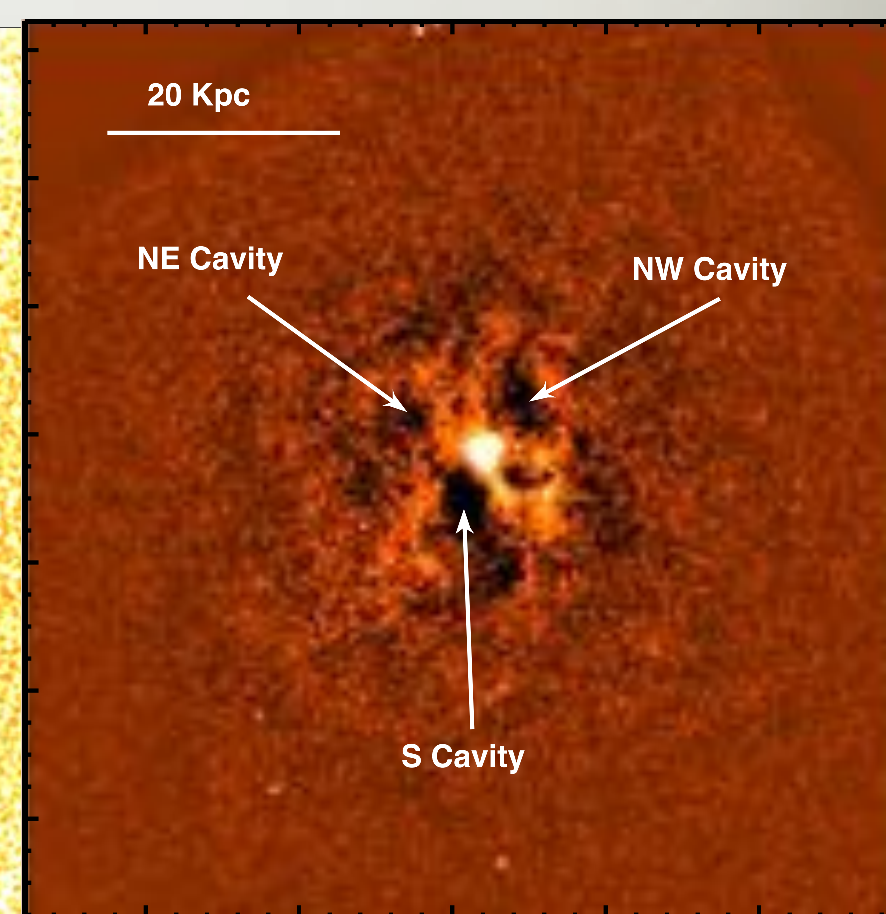
Gitti+2010 - HCG 62



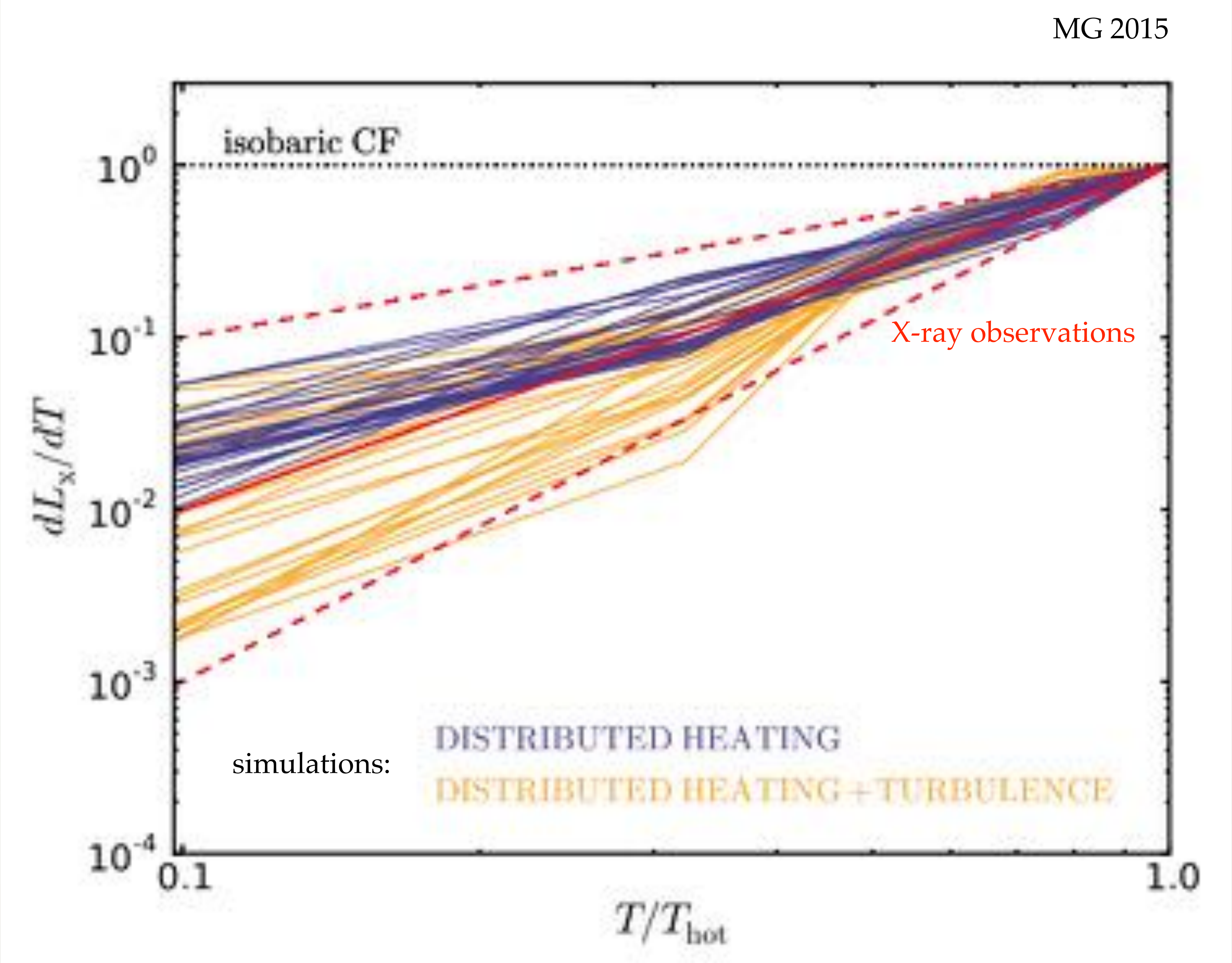
Randall+2011 - NGC 5813



David+2009 - NGC 5044



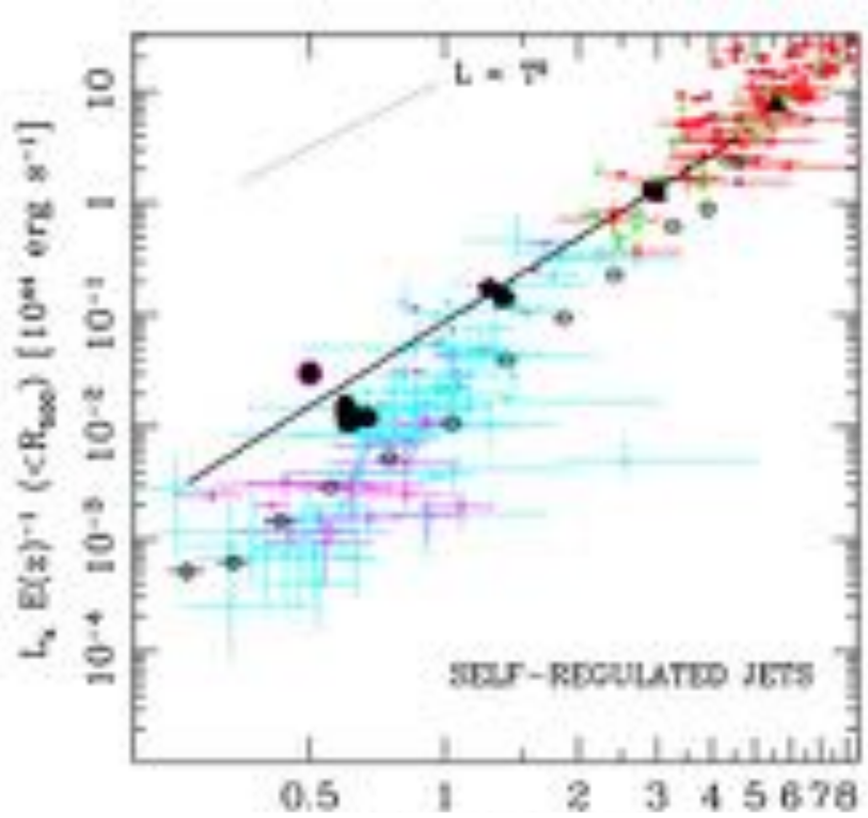
QUENCHING THE SOFT X-RAY SPECTRUM



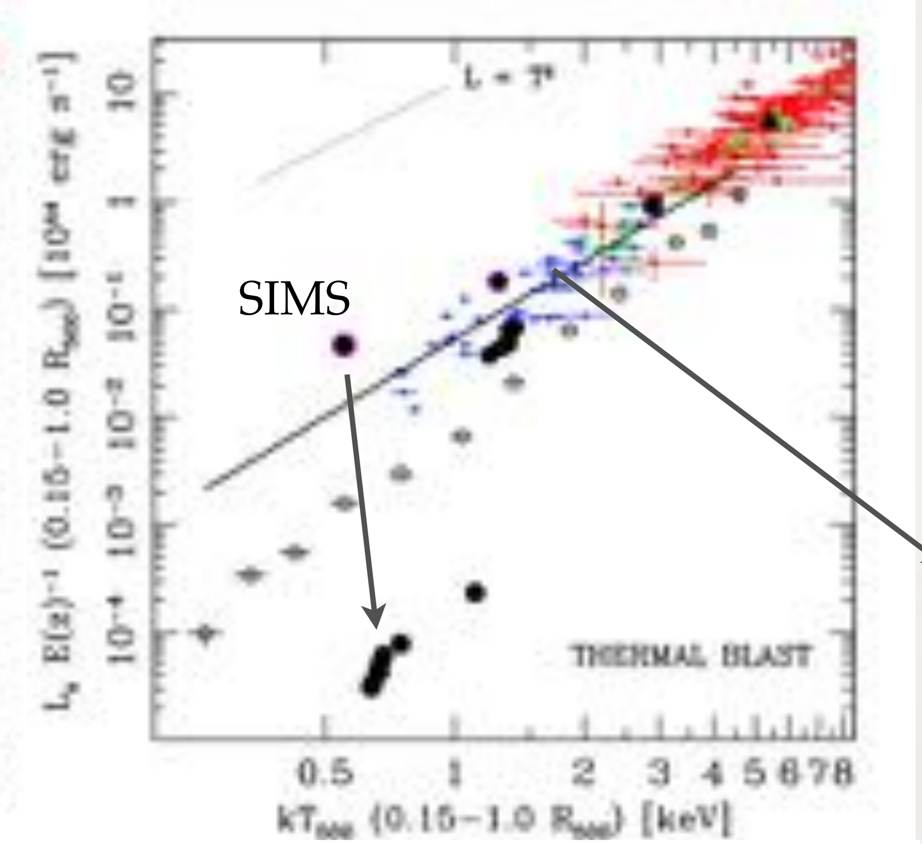
1. AGN outflows deposits relatively more heat in the inner cooler phase
2. turbulence becomes transonic in the cooler phase => stronger diffusion

CAN AGN FEEDBACK "BREAK" SELF-SIMILARITY?

L_x - T_x (core)

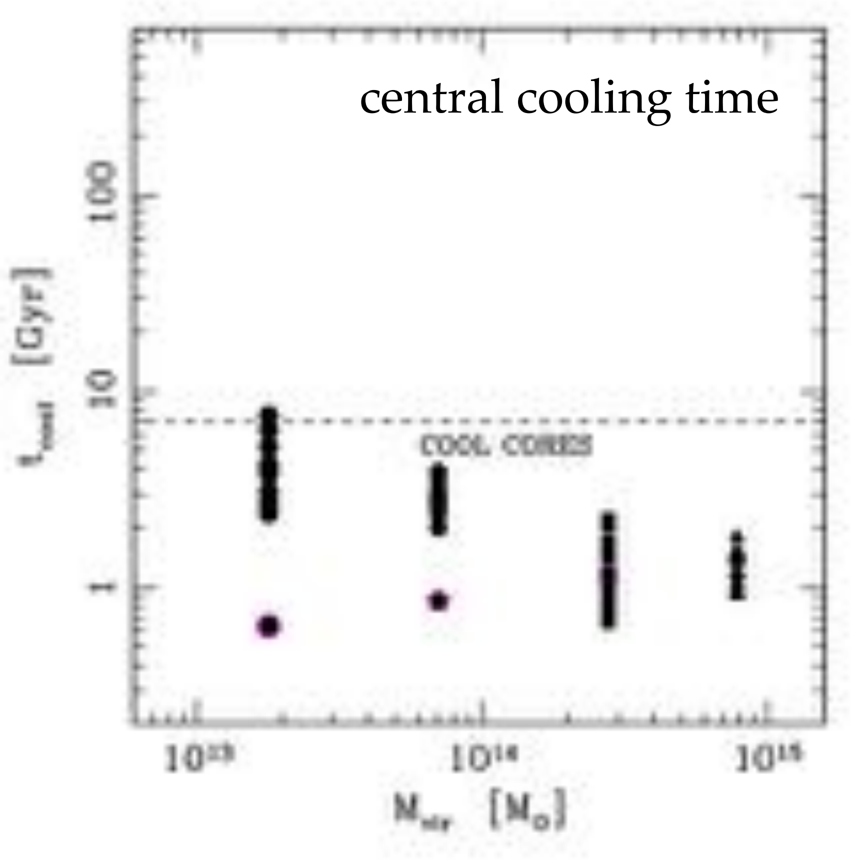


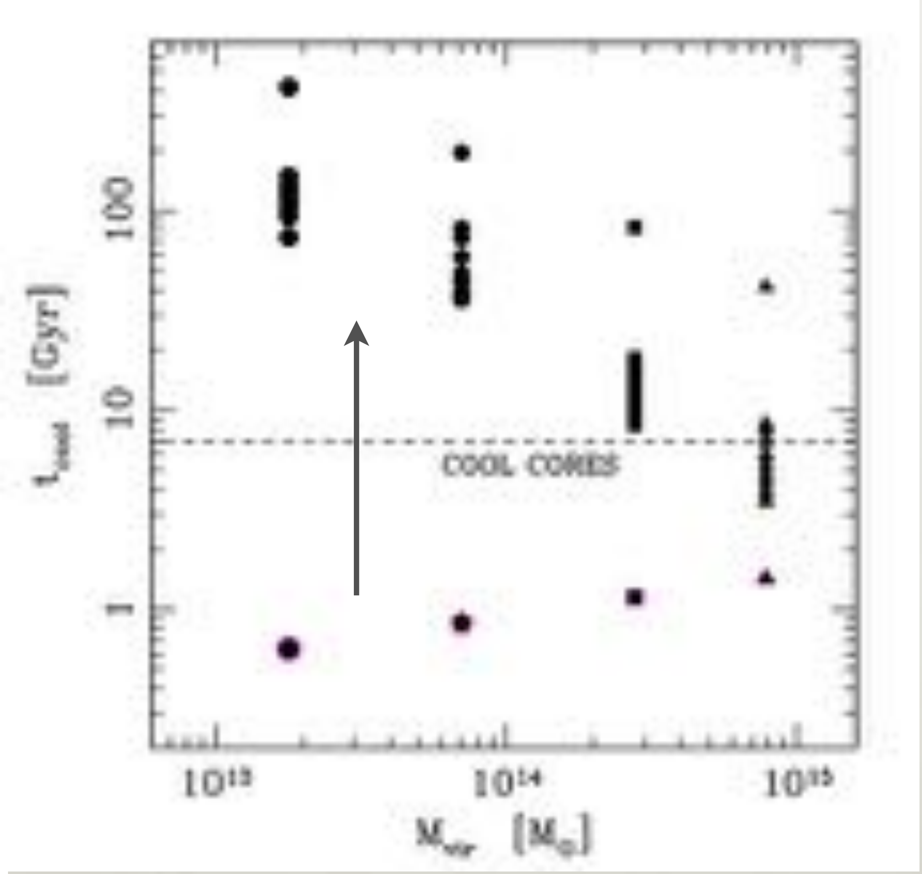
L_x - T_x (no core)



solid line: stacking 250000 central brightest galaxies (X-ray flux-limited)

Anderson, Gaspari, White+15





X-ray data: cool-core structure preserved for several Gyr

MG+14 black filled points: AGN feedback simulations

SELF-REGULATED CCA FEEDBACK

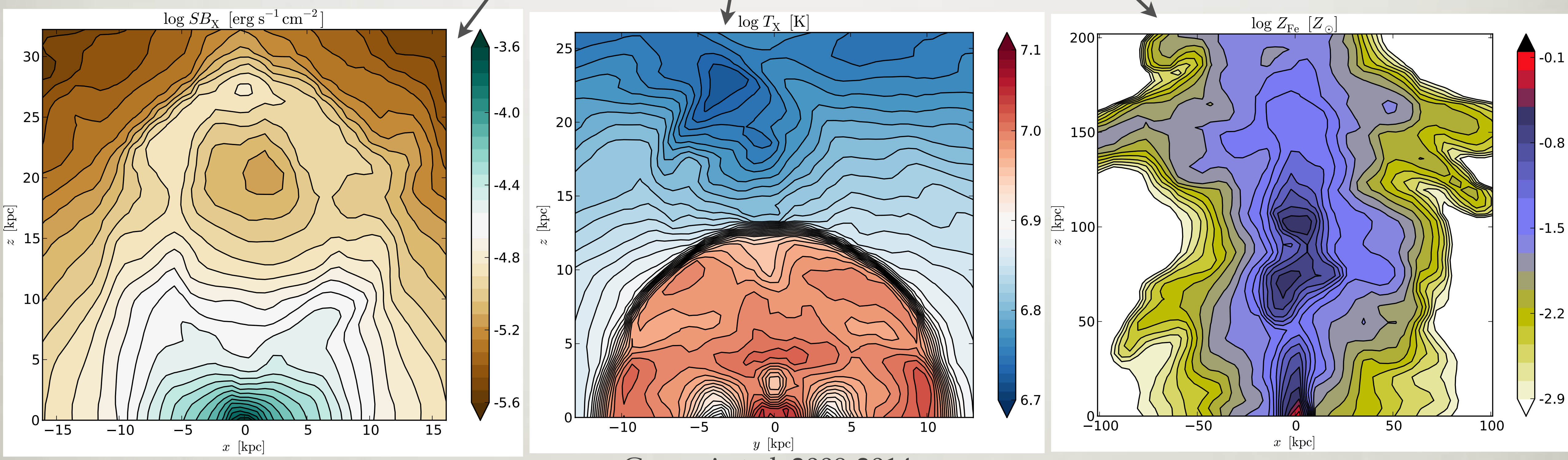
$$\dot{M}_{\rm BH} \sim \dot{M}_{\rm cool}$$

- Simple yet powerful subgrid model, **no need to boost the Bondi rate**:

$$\alpha_{\rm boost} \sim 50 - 100$$

- **Fast** communication time between the gas and the BH

- Rapid **intermittency**: bubbles, shocks, ripples, metal uplift



Gaspari et al. 2009-2014

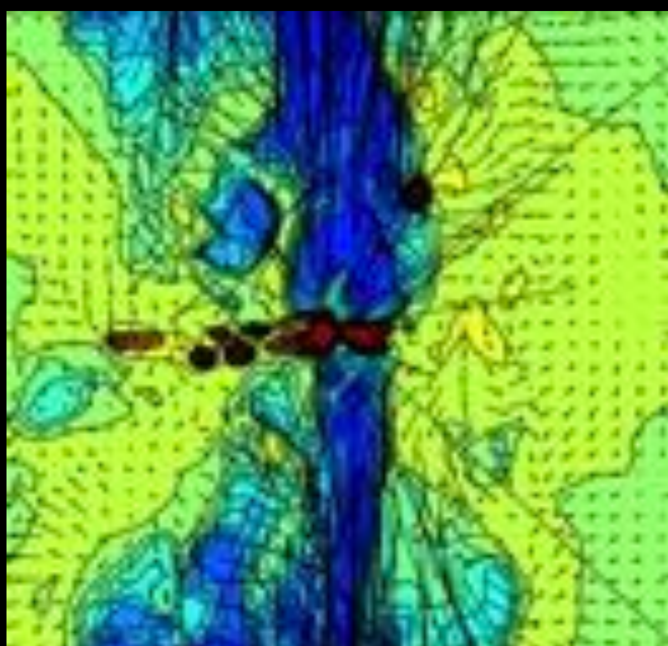
- **Symbiosis** between the BH and the <u>whole</u> galaxy => Magorrian (linear) relation

$$M_{\rm BH} \propto M_{\rm cold} \propto M_*$$

SELF-REGULATED AGN FEEDBACK

MG+2009 --> 2015

chaotic
COLD mode
(flat T_X profile)



disc
COLD mode

stifled
HOT mode
(cuspy T_X profile)

$\mathcal{L} > \mathcal{H}$

↓

t_{cool} / t_{ff} **< 10** ← subsonic turbulence ~ **100 km/s**

↓

extended TI → clumpy torus & filaments (< 10 kpc)
(obs.: McDonald et al. 2011,2012, Werner et al. 2013, Wong et al. 2014)
→ tight and fast symbiosis BH - M_{bulge}

↓

chaotic collisions: $\dot{M}_{\rm BH} \sim 100\ \dot{M}_{\rm Bondi} \sim \dot{M}_{\rm cool}$
Ta_t **< 1**

↓

mechanical feedback → quench the cooling flow and SF
→ bubbles, shocks, metal uplift

↓

Ta_t **> 1** → residual cold disc: $\dot{M}_{\rm BH} \propto \ {\rm Ta}_{\rm t}^{-1}$
(obs.: Young et al. 2011, Alatalo et al. 2013, Werner et al. 2013)

↓

t_{cool} / t_{ff} **>> 10** → system overheated
(obs.: Humphrey et al. 2008, 2009)

↓

$\dot{M}_{\rm BH} < \ \dot{M}_{\rm Bondi}$

↓

$\mathcal{L} < \mathcal{H}$