# THE SELF-REGULATED AGN FEEDBACK LOOP: CHAOTIC COLD ACCRETION

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# THE SELF-REGULATED AGN FEEDBACK LOOP: RAINING ONTO BLACK HOLES

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# SELF-REGULATED AGN FEEDBACK

AMR zoom-in 3D simulations (FLASH)

## FEEDING

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

MG+2013-2015 sims

## FEEDBACK

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

MG+2009-2015 sims

**SELF-REGULATED LOOP**

$$P_{\rm out} = \epsilon \dot{M}_{\rm BH} c^2$$

# FEEDING: SMBH ACCRETION

FLASH4 simulations — MG+2013-2015

- concentric AMR 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 group dark matter halo: $M_{vir} = 4x10^{13}$ $M_\odot$
- central elliptical galaxy (NGC 5044): $M_{star} = 3.4x10^{11}$ $M_\odot$
- SMBH: $M_{bh} = 3x10^9$ $M_\odot$ ⟶ relativistic PW: $\phi_{PW} = -GM_{bh}/(r - R_S)$
- observed gas $T(r)$ [cool-core] ⟶ $n(r)$ via hydrostatic equilibrium

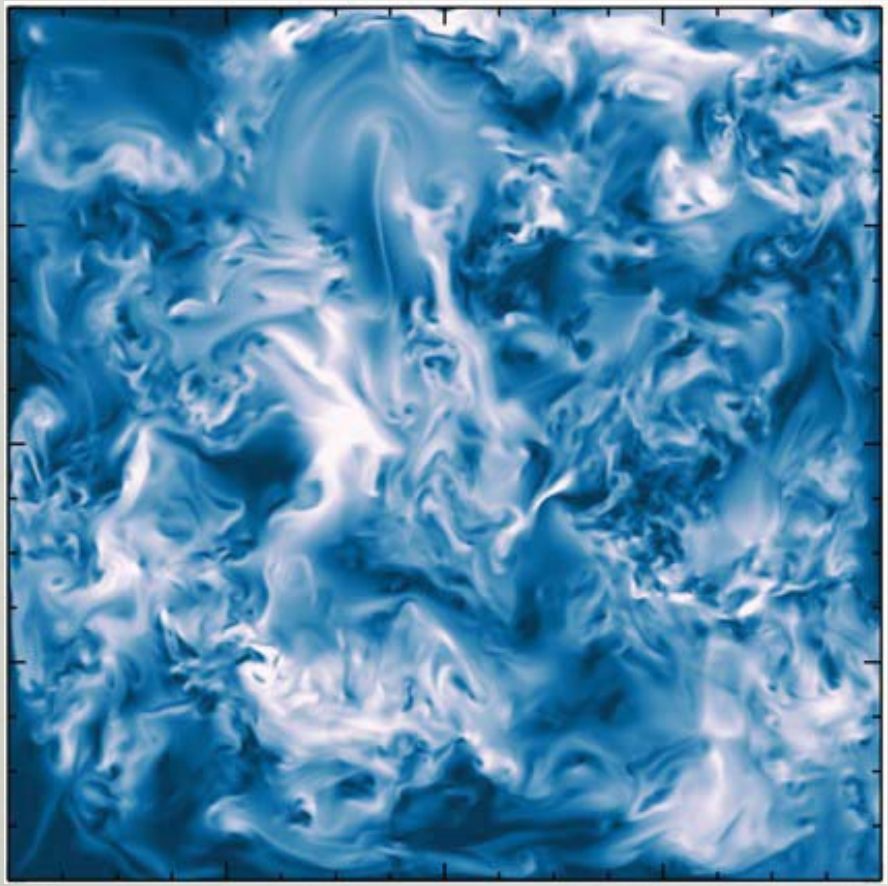
# TURBULENCE IN HOT HALOS

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

**subsonic (~100 km $s^{-1}$ )**

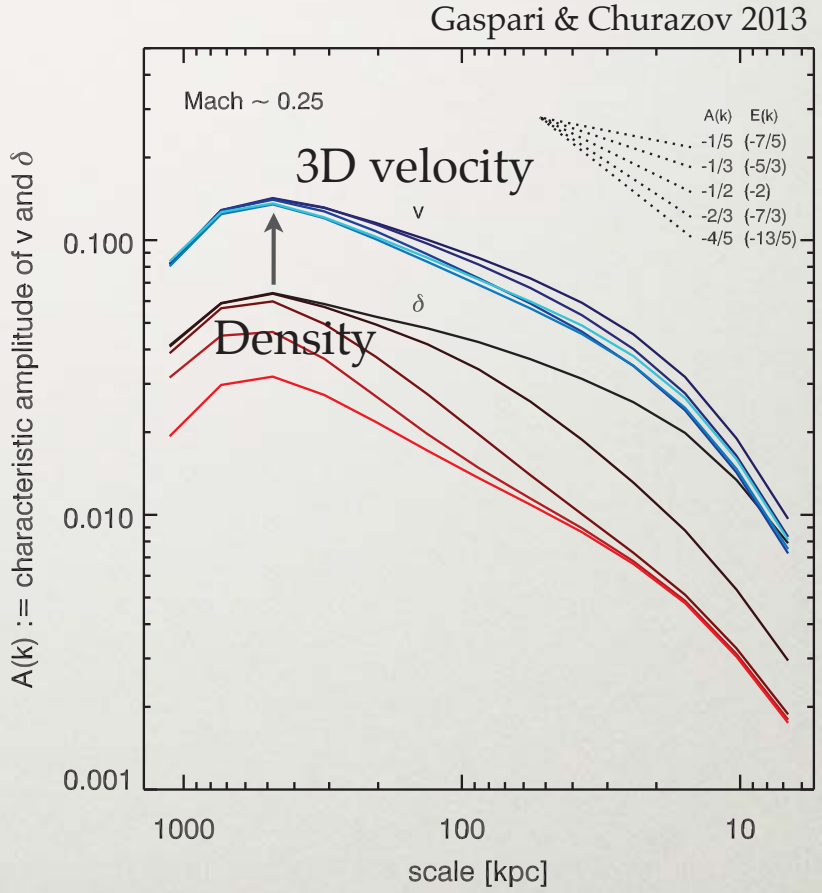
ICM turbulence

MG+2014



|v| cut

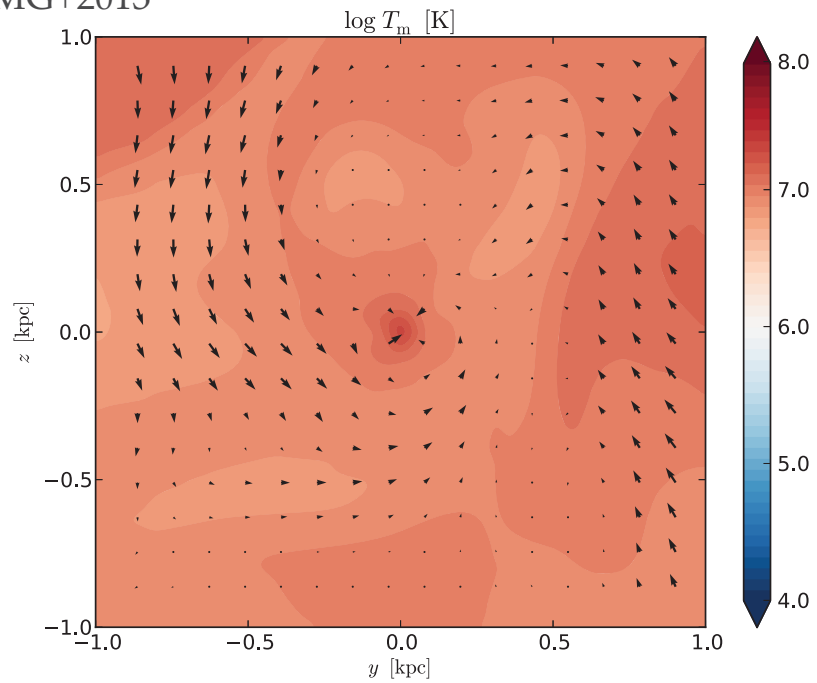
Gaspari & Churazov 2013



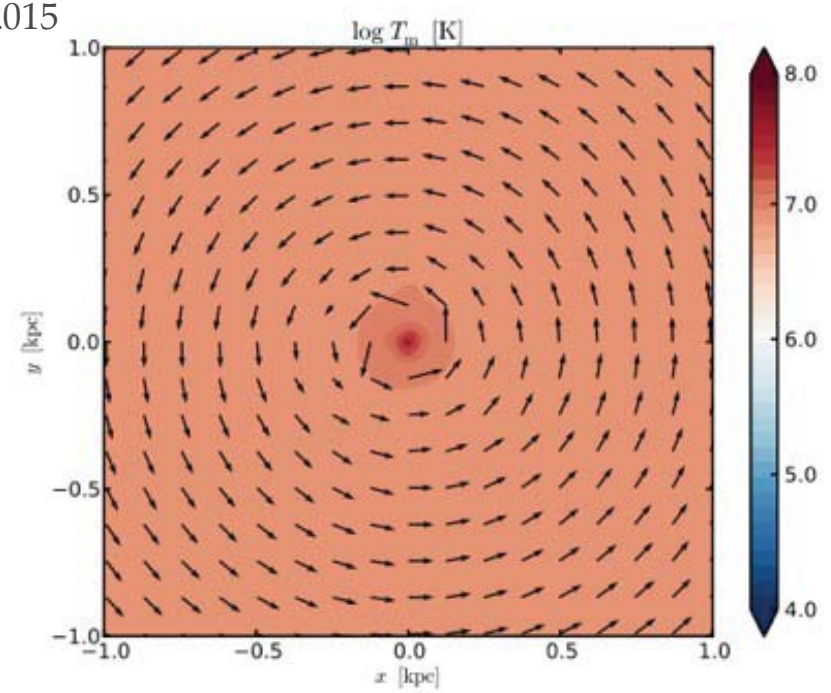

$$\delta\rho/\rho \sim \mathrm{Mach}_{1\mathrm{D}}$$

# HOT ACCRETION

MG+2013



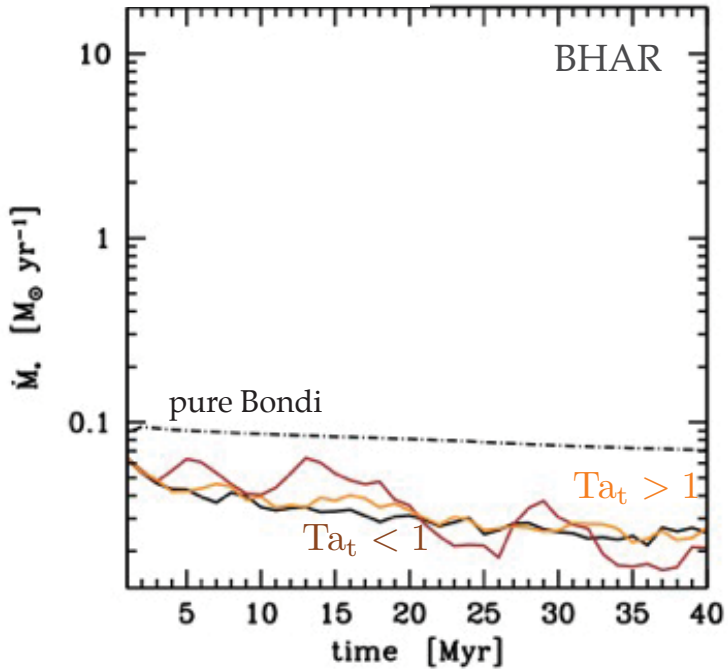

MG+2015




rotation < **turbulence**

$$\mathrm{Ta_t} \equiv v_{\rm rot}/\sigma_v < 1$$

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

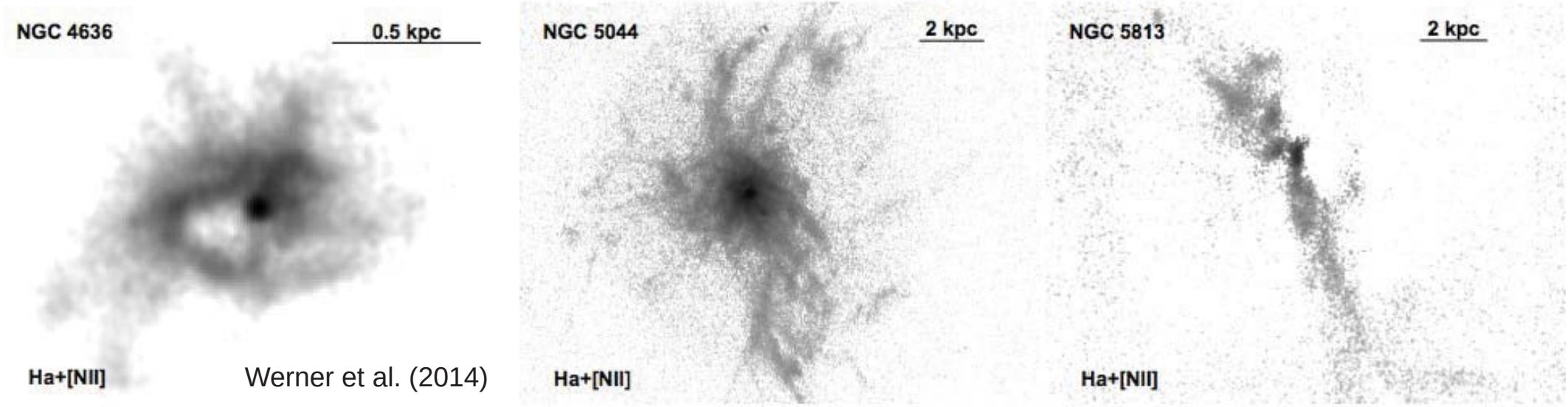



**rotation** > turbulence

$$\mathrm{Ta_t} \equiv v_{\rm rot}/\sigma_v > 1$$

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

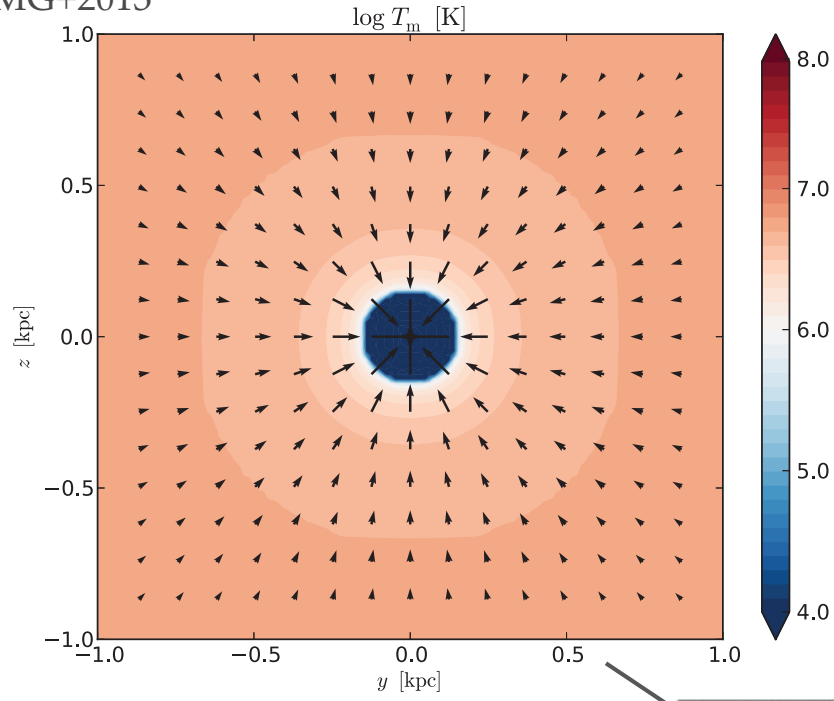
$$\dot{M}_{\rm Bondi} = 4\pi (G M_{\rm BH})^2 \rho_\infty / c_{s,\infty}^3$$


Werner et al. (2014)

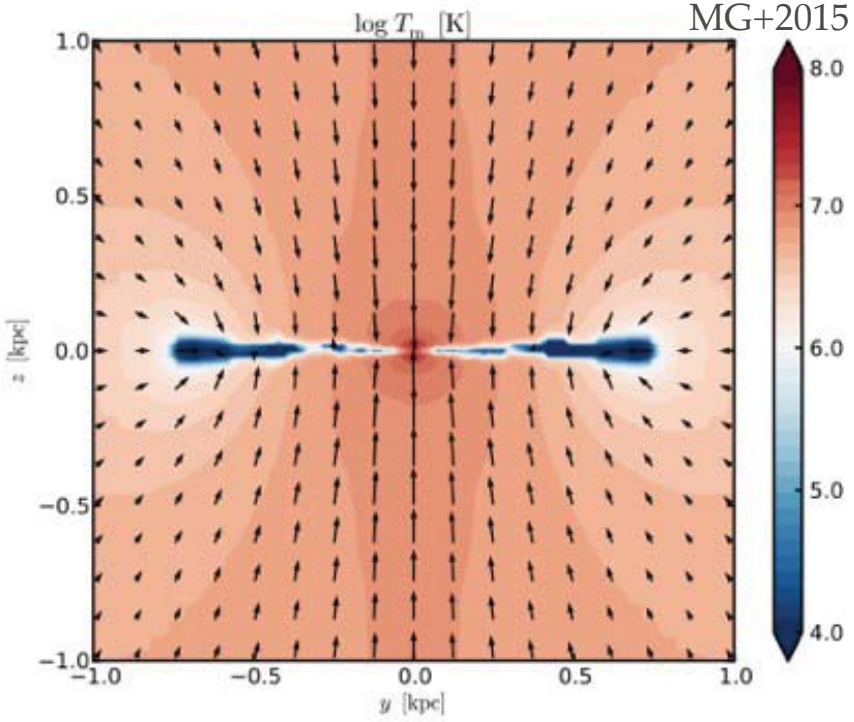
# PURE COLD ACCRETION

MG+2013

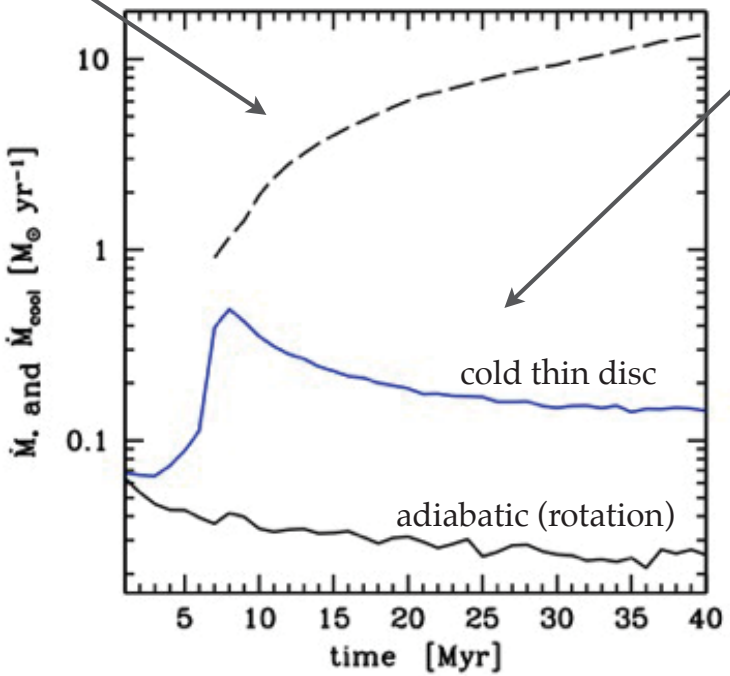



no rotation

MG+2015

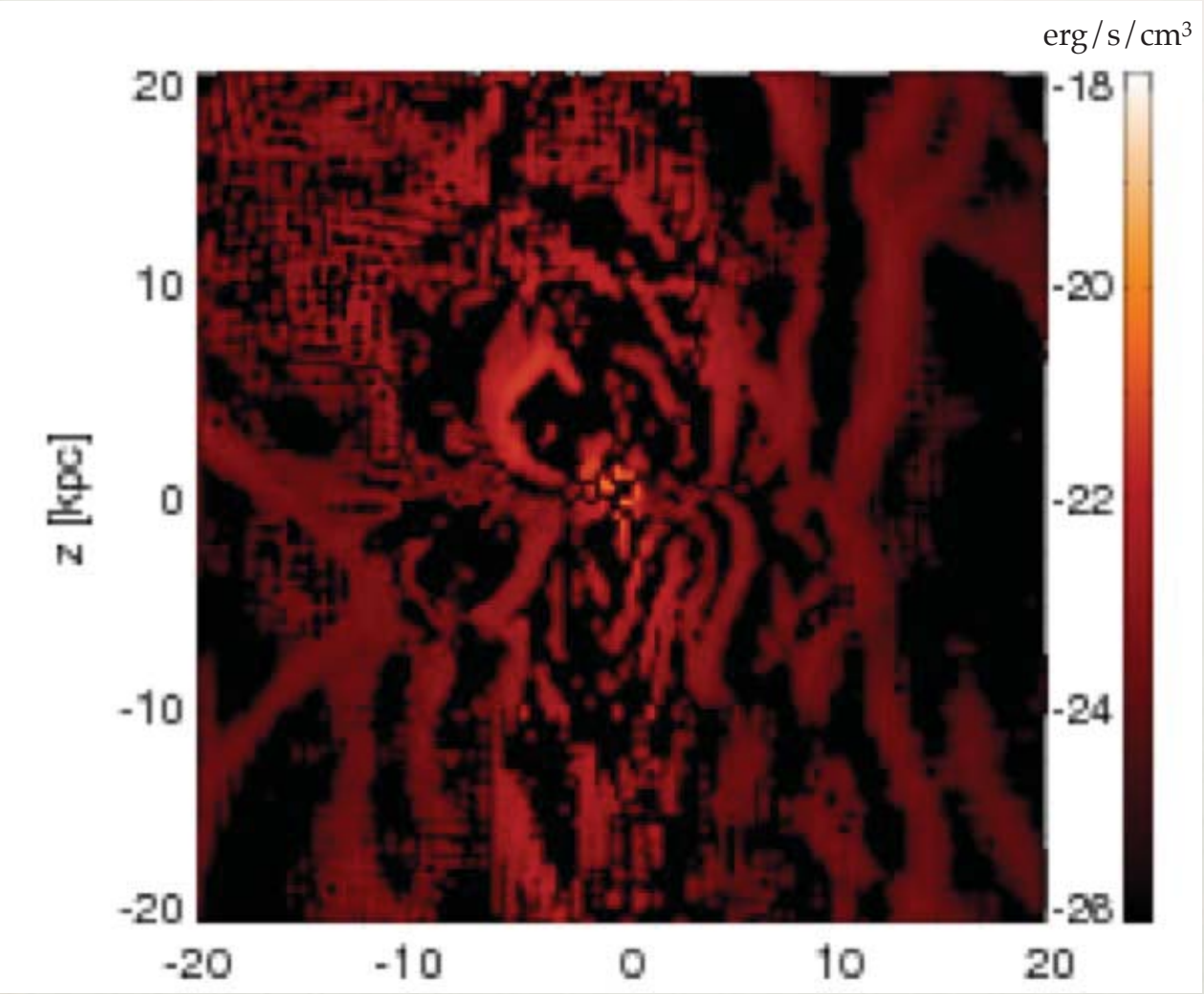



rotation



# Global thermal equilibrium

AGN outflow feedback: net heating deposition

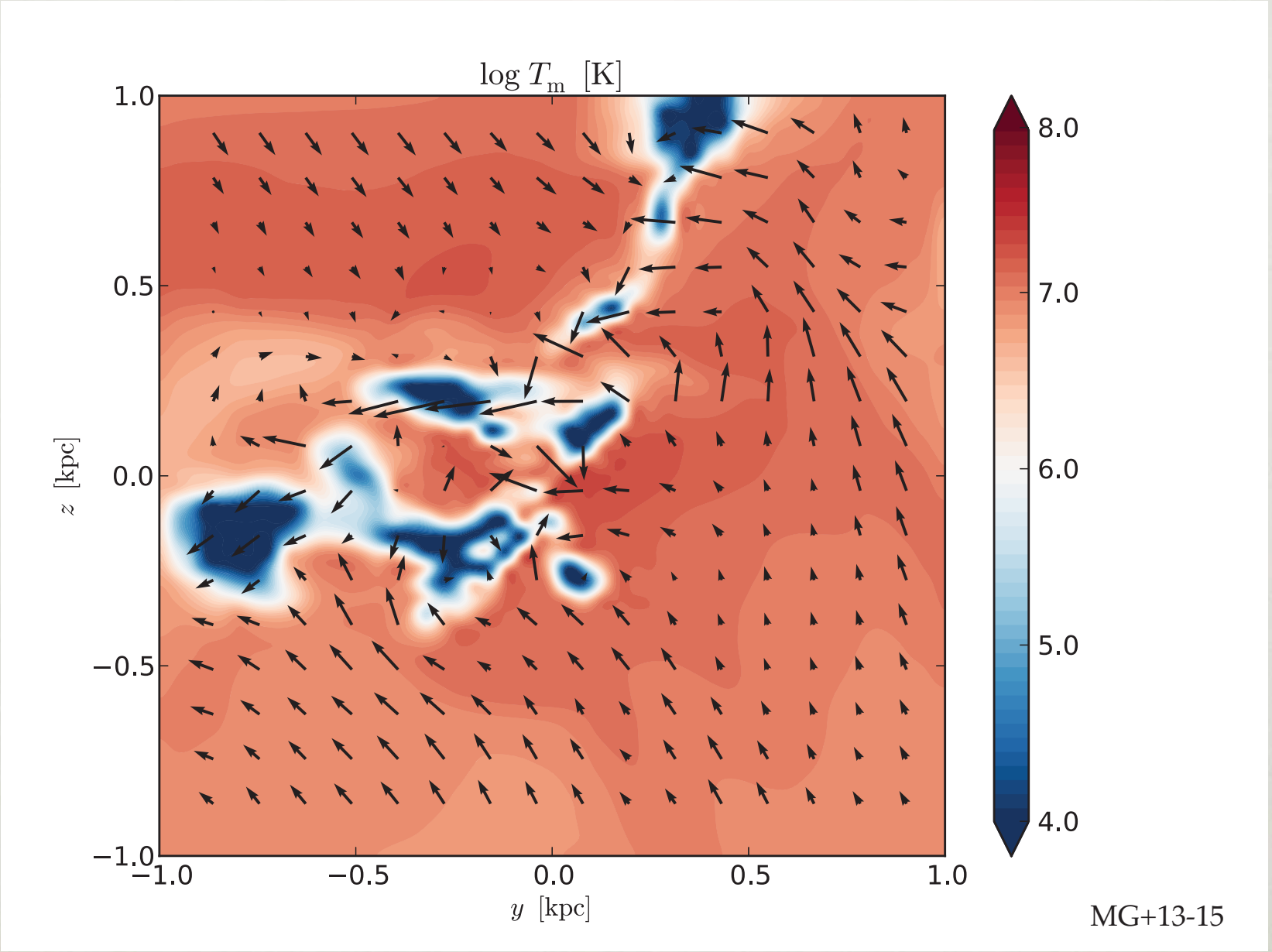



internal energy increase
(averaged over 1 Gyr)

MG+2012

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

# CHAOTIC COLD ACCRETION [CCA]



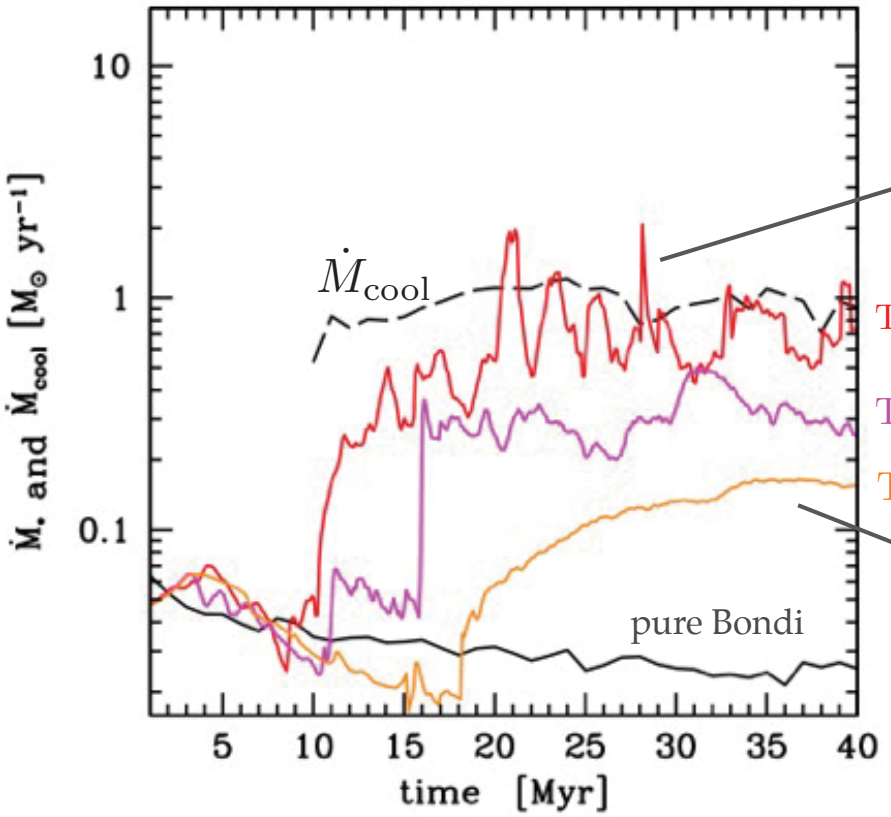

COOLING + TURBULENCE + AGN HEATING

$\sigma_v \sim 100\,\mathrm{km\,s^{-1}}$ $\mathcal{H} \sim \langle \mathcal{L} \rangle$

# CHAOTIC COLD ACCRETION [CCA]

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

MG+15



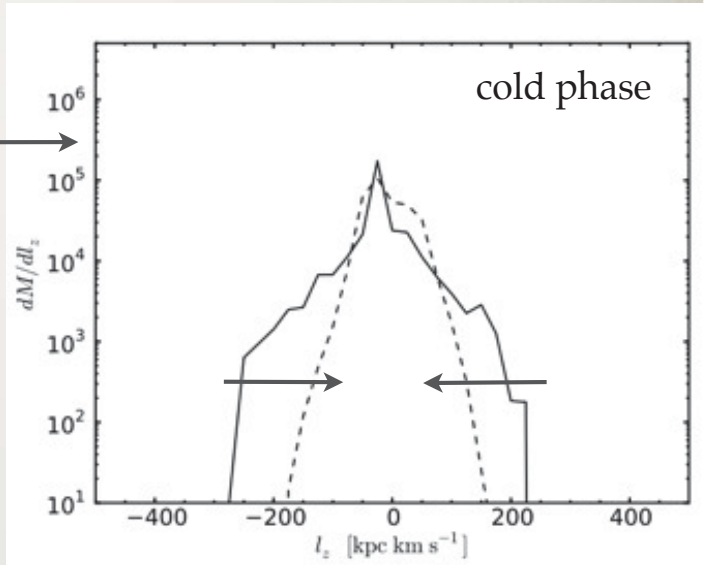

$\mathrm{Ta_t} \sim 0.75$

$\mathrm{Ta_t} \sim 1.5$

$\mathrm{Ta_t} \sim 3$

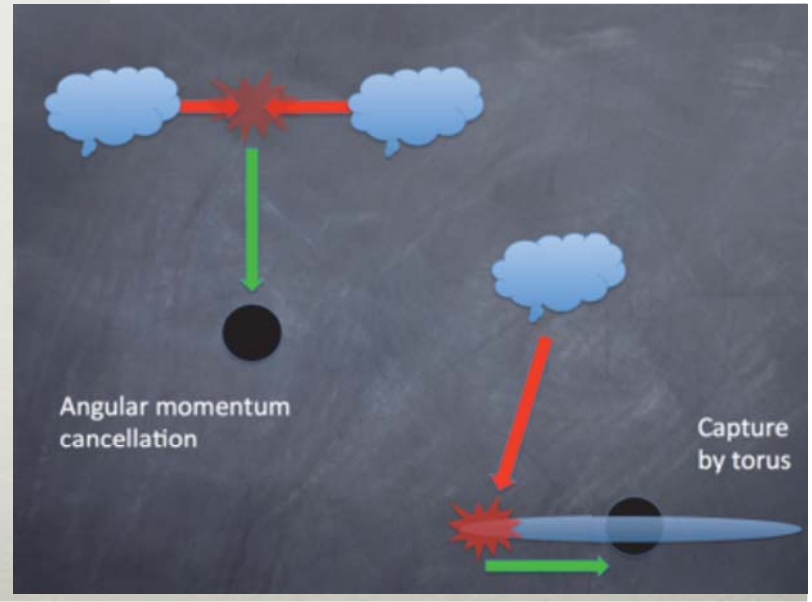
$\mathrm{Ta_t} < 1$

**CCA dominates**




$\mathrm{Ta_t} > 1$

**disc dominates**

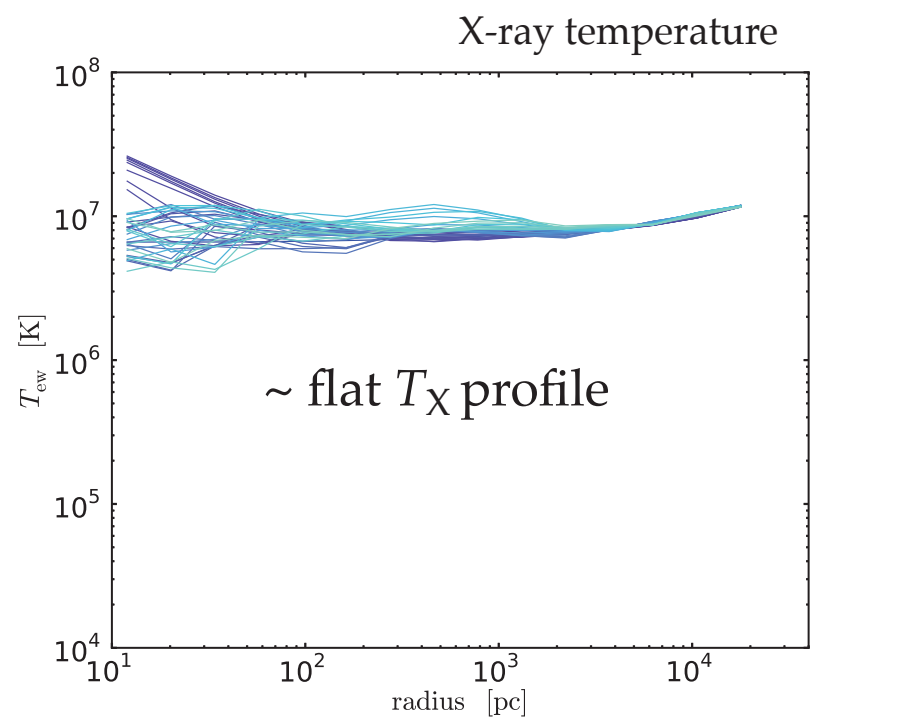


# COLD vs HOT ACCRETION

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

**chaotic cold accretion**

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

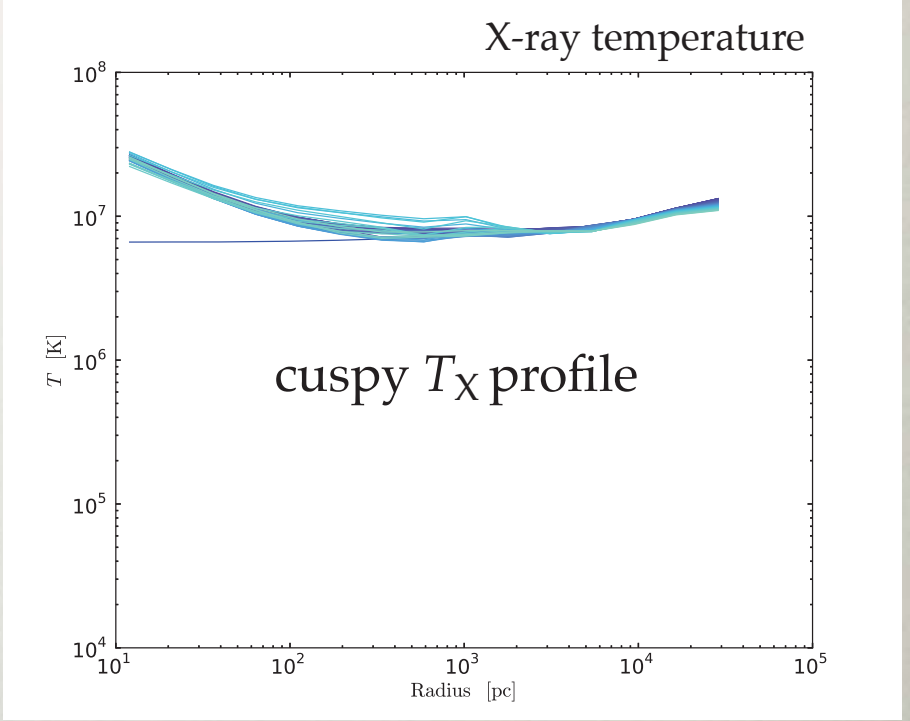



e.g. NGC 3115 (Wong et al. 2014)
NGC 4261, 4472 (Humphrey et al. 2009)
M87 (Russell et al. 2015)

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

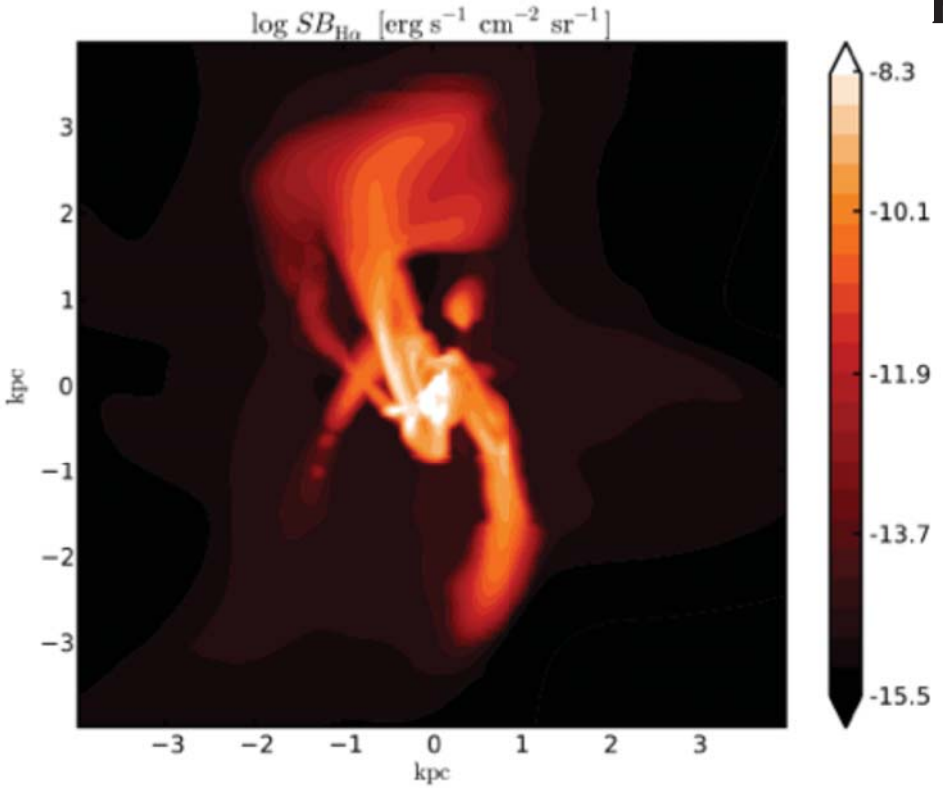
**stifled Bondi/hot accretion**

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



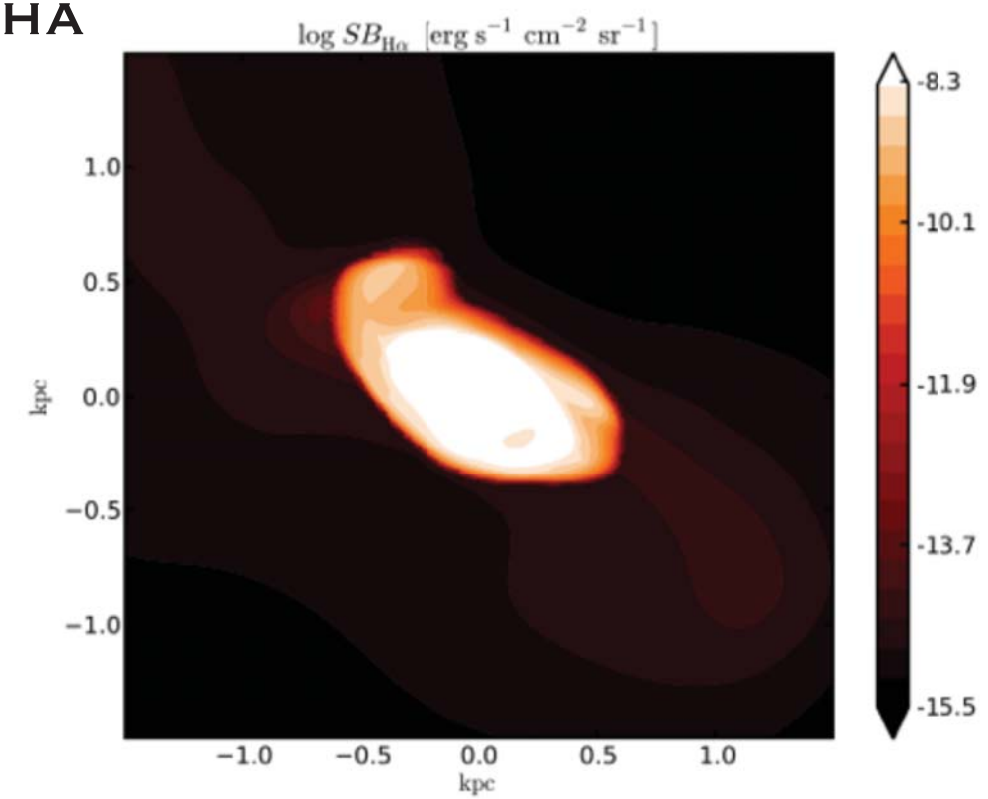

e.g. NGC 4649 (Humphrey et al. 2008)
NGC 1332 (Humphrey et al. 2009)

# Halpha

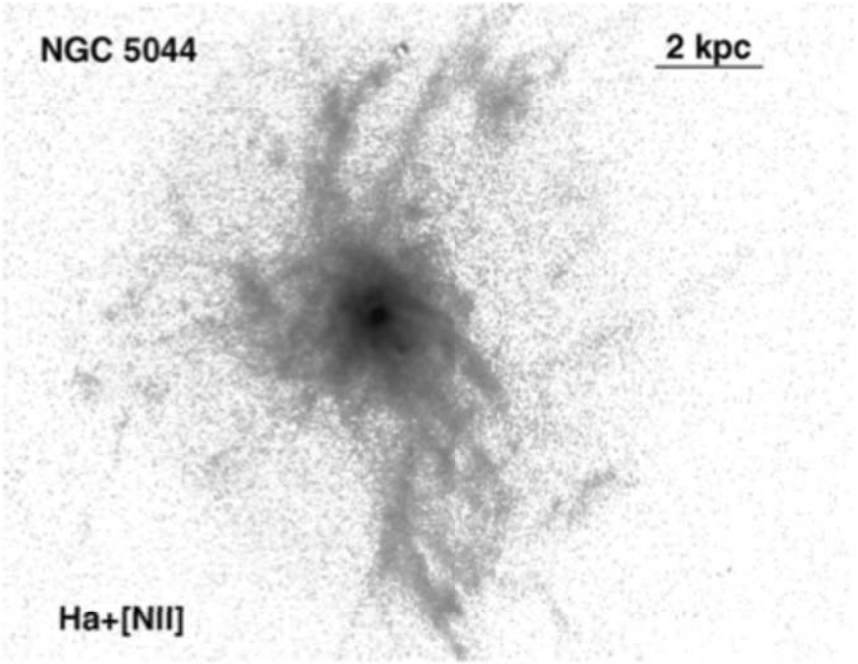



full CCA

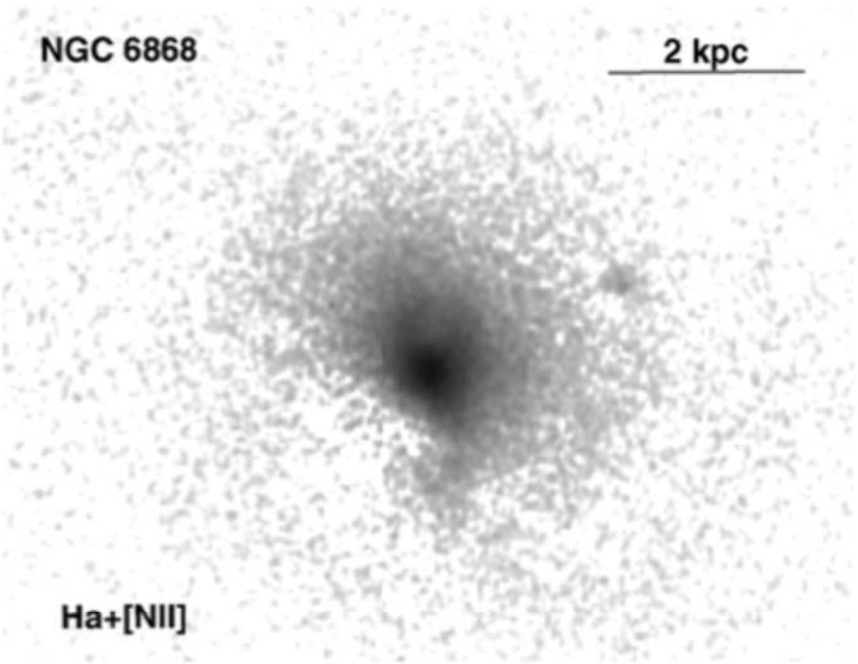
**SIMS**
MG+15



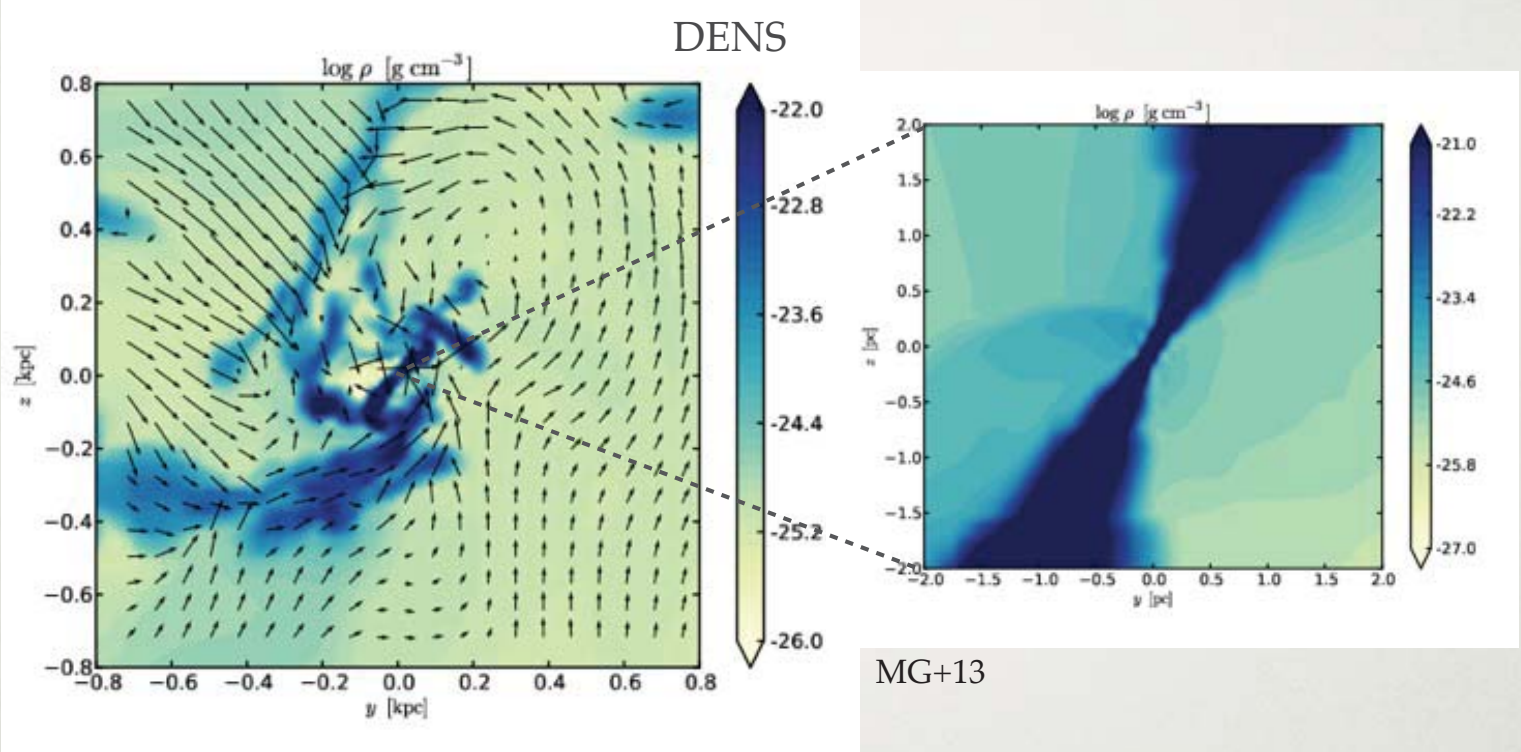

disc mode




**SOAR DATA**
Werner+14



# "Raining on to black holes"




- Highly clumpy & turbulent torus (key for AGN unification theory)
- Cold clouds can form the BLR/NLR or HVC & induce rapid variability in $L_{\rm AGN}$
- Tight **symbiosis** between the BH and the <u>whole</u> galaxy: $M_{\rm BH} \propto M_{\rm cold} \propto M_*$
- Fast communication time BH - galaxy and boosted accretion $\dot{M}_{\rm BH} \sim \dot{M}_{\rm cool}$

**CCA main driver of AGN feedback**

# Feedback

FLASH4 simulations — MG+2009-2015

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

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

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

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

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

# AGN FEEDBACK CYCLE

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

↓

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

↓

thermal instabilities

↓

cold clumps

↓

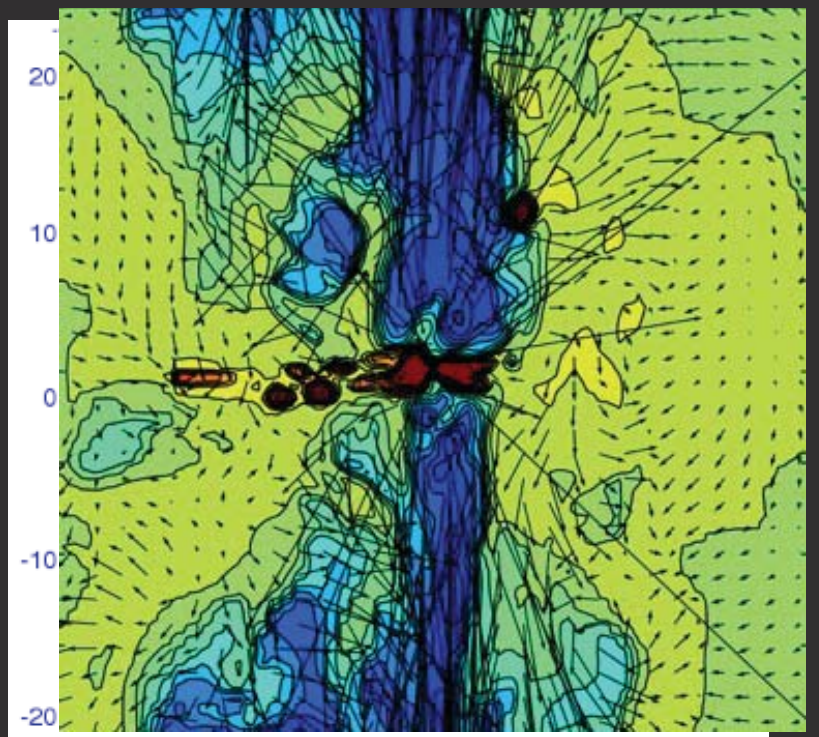
feed SMBH

↓

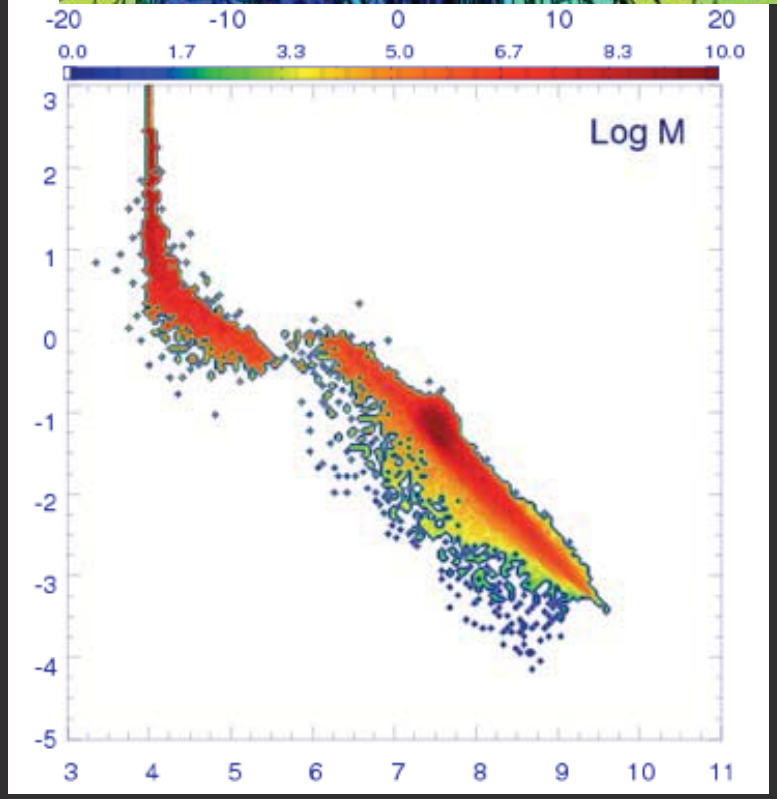
feedback boosted

↓

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



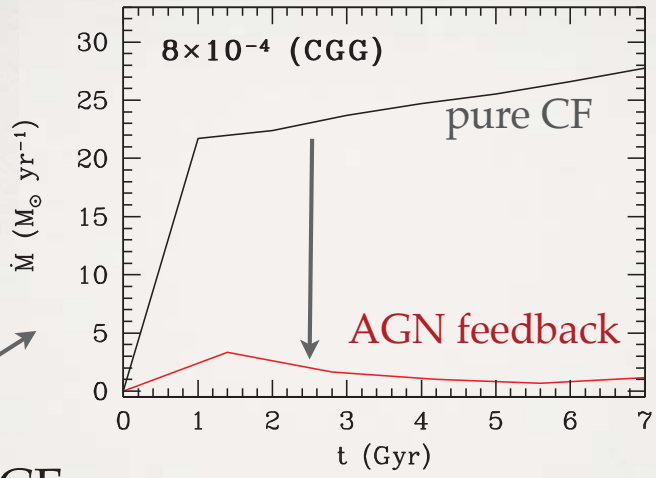

MG+2012

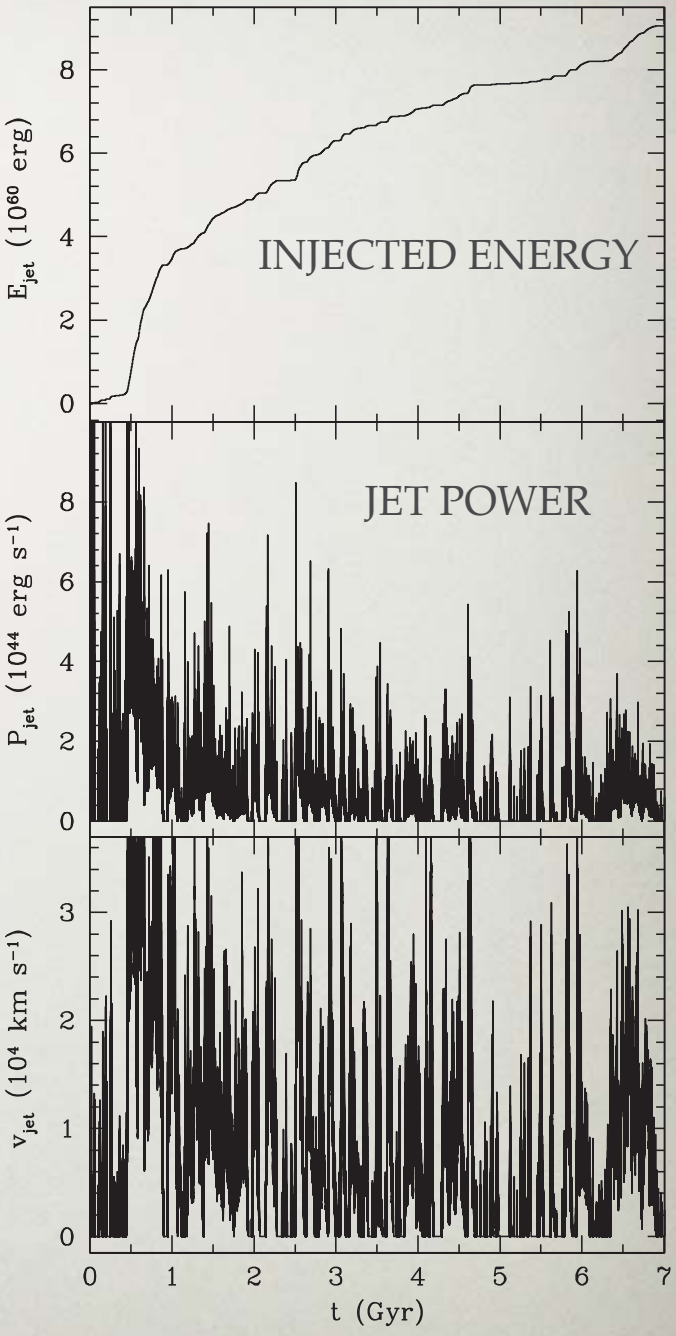


# AGN OUTFLOWS + CCA FEEDBACK

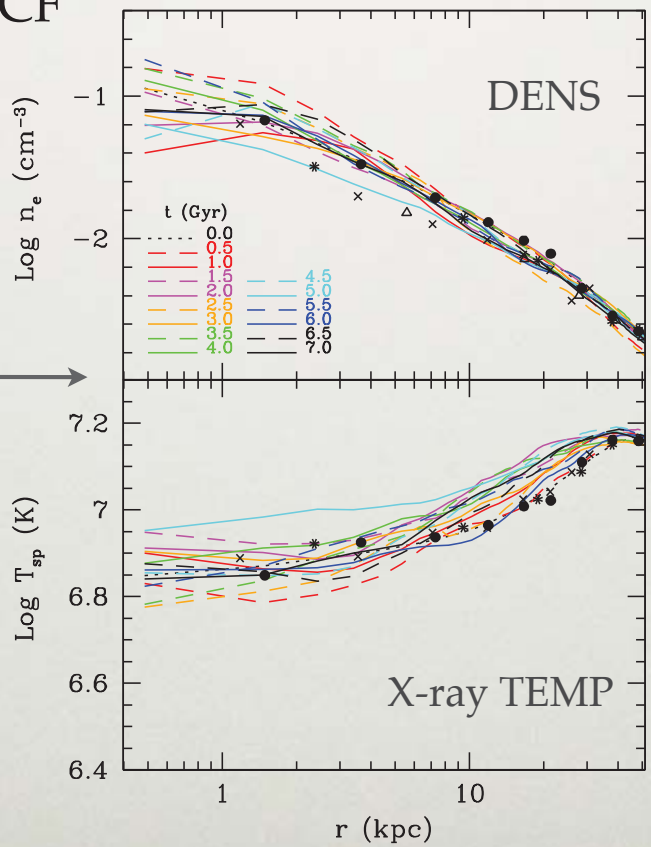
galaxy group NGC 5044

MG+2012




- Quenched cooling: < 5-10% CF




- Cool core preserved

- Mechanical efficiencies:

  ~ 5x10$^{-4}$ - 5x10$^{-3}$

  isolated galaxies ---> clusters

$$P_{\rm out} = \epsilon\, f \dot{M}_{\rm cool} c^2 \approx L_{\rm x} \propto \dot{M}_{\rm cool} T \;\Rightarrow\; \epsilon \approx c_{\rm s}^2 / f c^2$$

# AGN IMPRINTS

cocoon shocks

DENS

turbulence

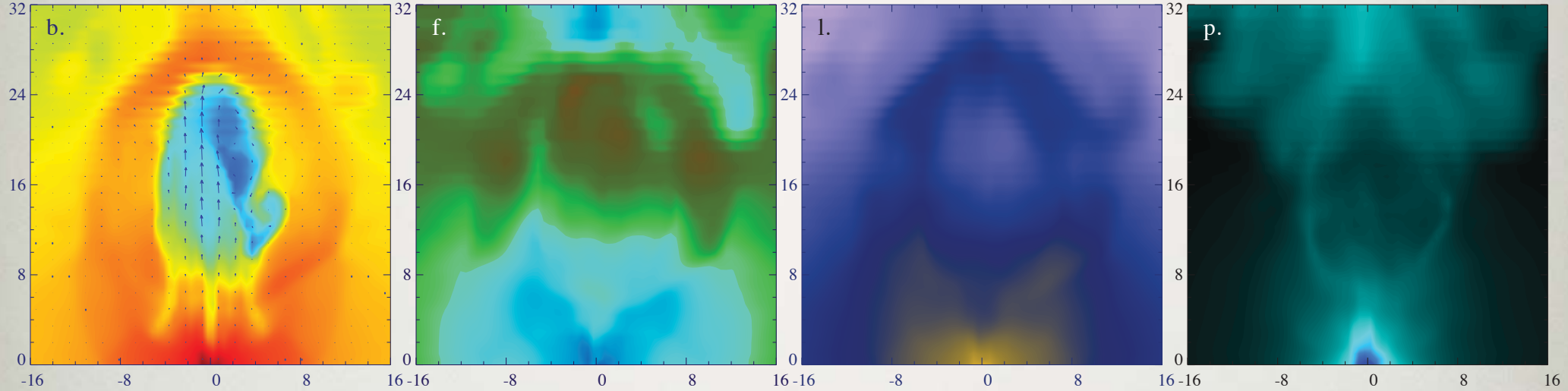
X-ray TEMP

bubbles ~ 5-10 kpc

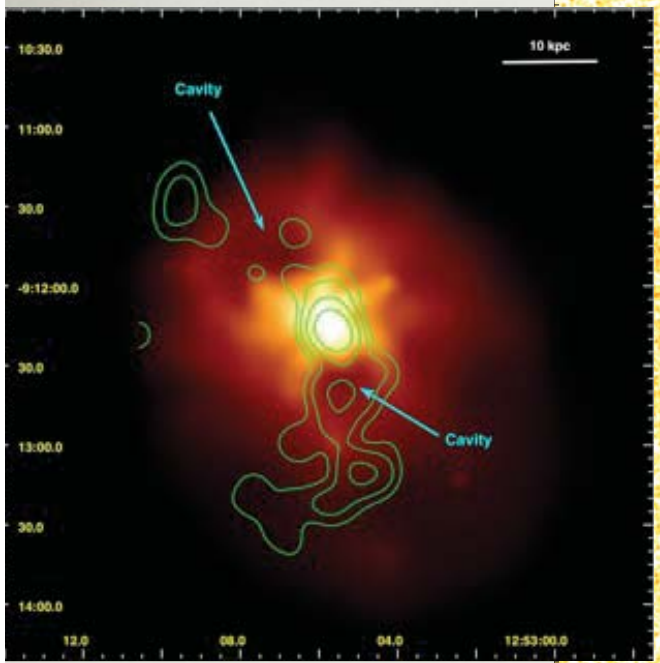
X-ray SB

metal uplift

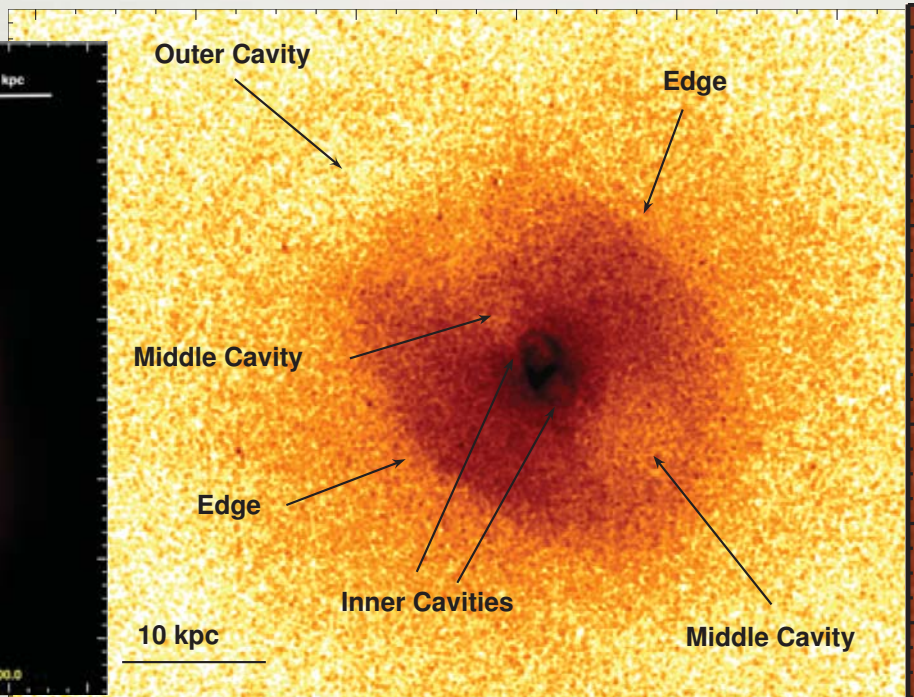
IRON



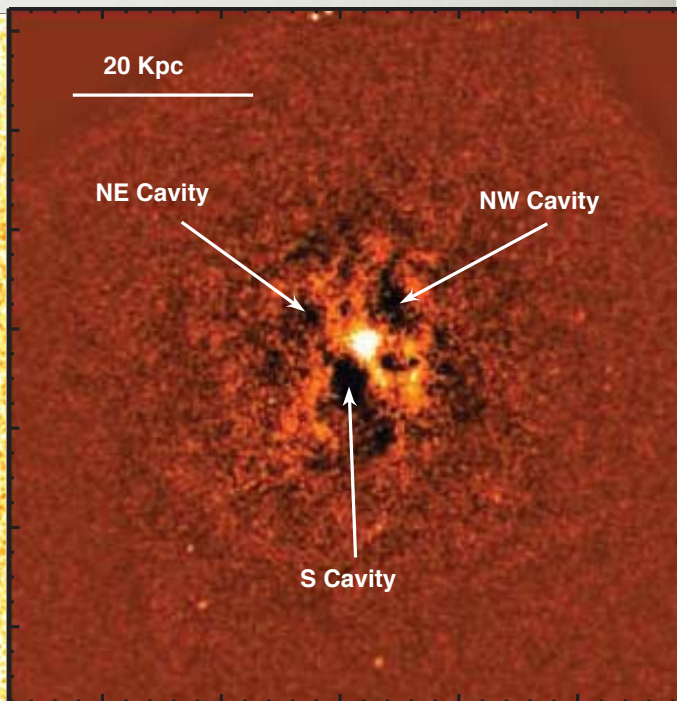

Gitti+2010 - HCG 62



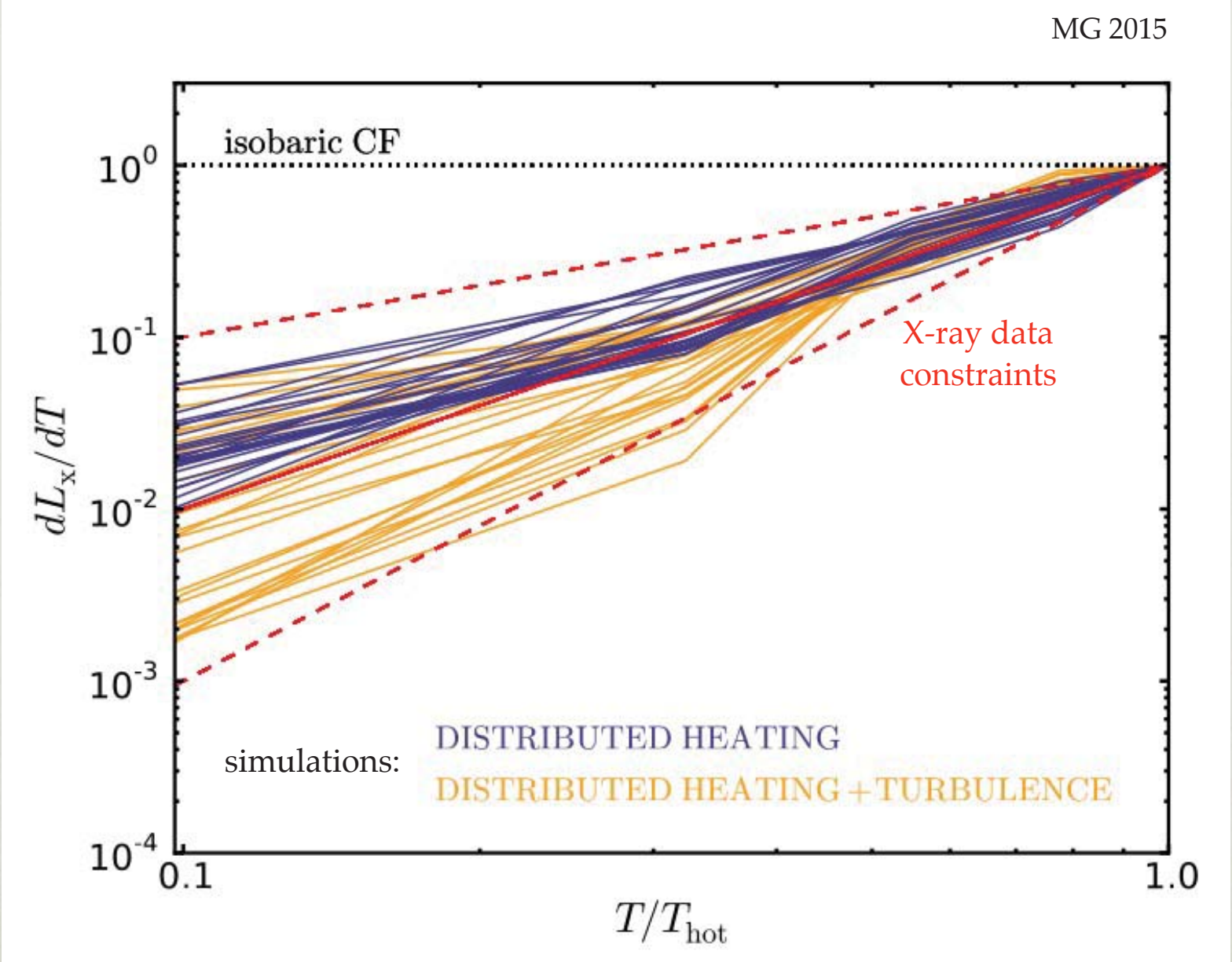

Randall+2011 - NGC 5813




David+2009 - NGC 5044

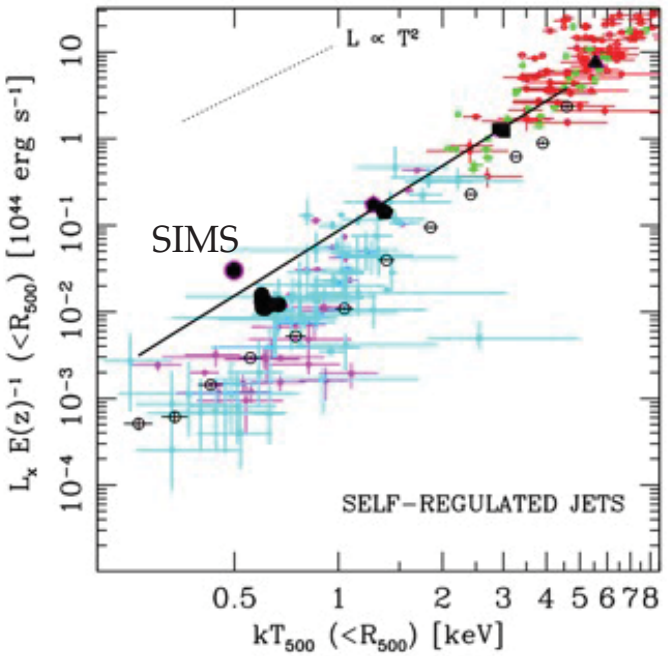


# QUENCHING THE SOFT X-RAY SPECTRUM

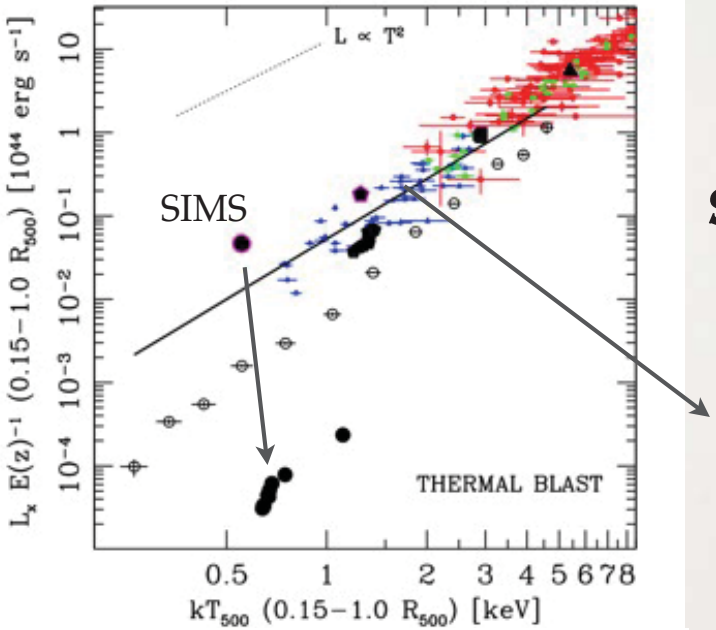


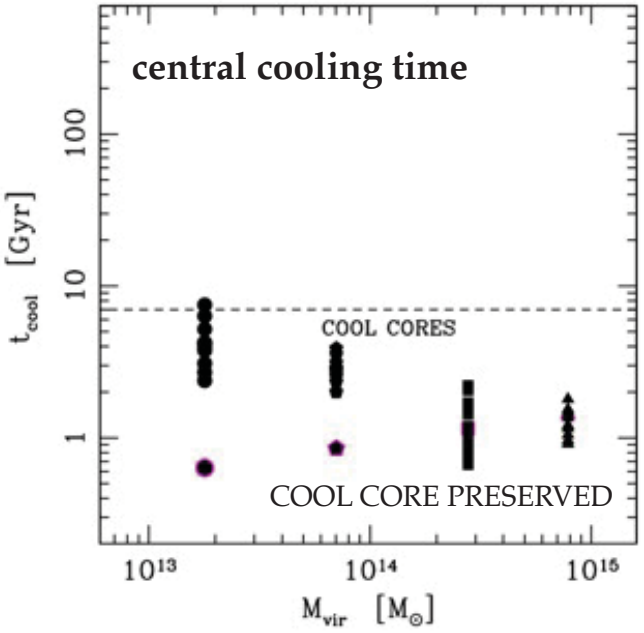

1. AGN outflows deposits relatively more heat in the inner cooler phase
2. turbulence becomes transonic in the cooler phase => stronger diffusion

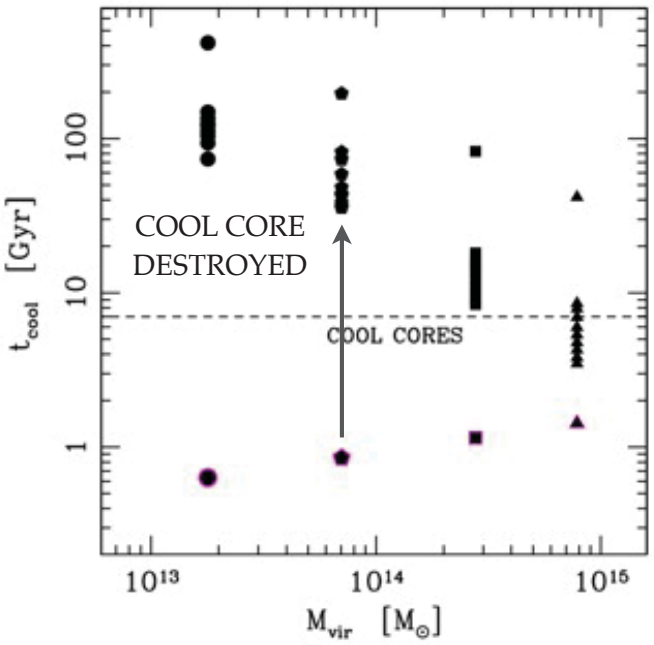
$L_x$ - $T_x$ (core)




$L_x$ - $T_x$ (no core)




black filled points: AGN feedback simulations

# CAN AGN FEEDBACK "BREAK" SELF-SIMILARITY?

MG+2014

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

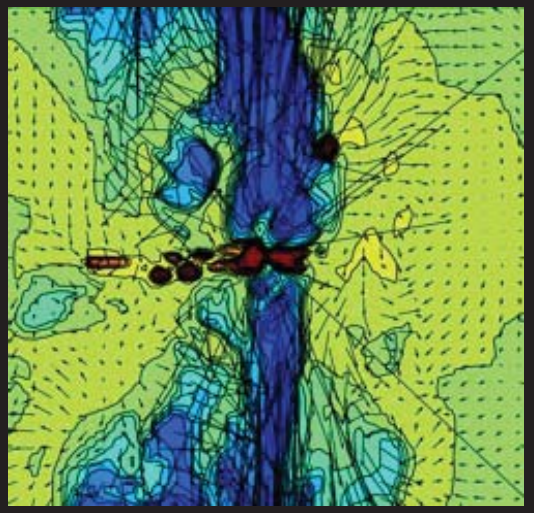
Anderson, Gaspari, White+2015

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

# 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:
$Ta_t < 1$
$\dot{M}_{BH} \sim 100\, \dot{M}_{Bondi} \sim \dot{M}_{cool}$

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

$Ta_t > 1$ → residual cold disc: $\dot{M}_{BH} \propto Ta_t^{-1}$
(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)

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

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