Black Hole Weather

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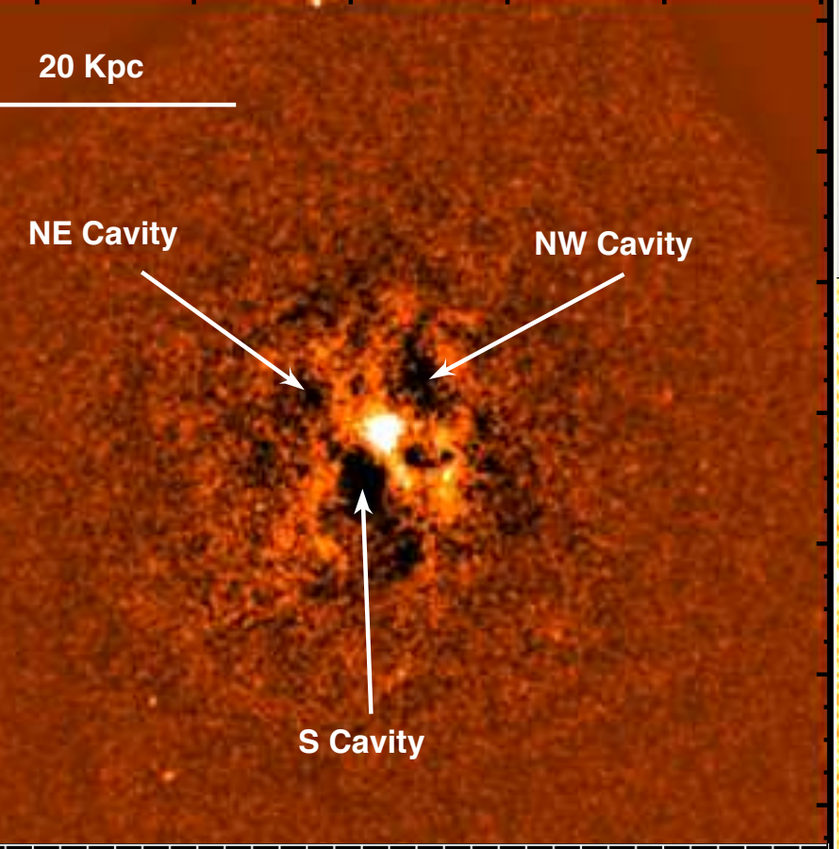
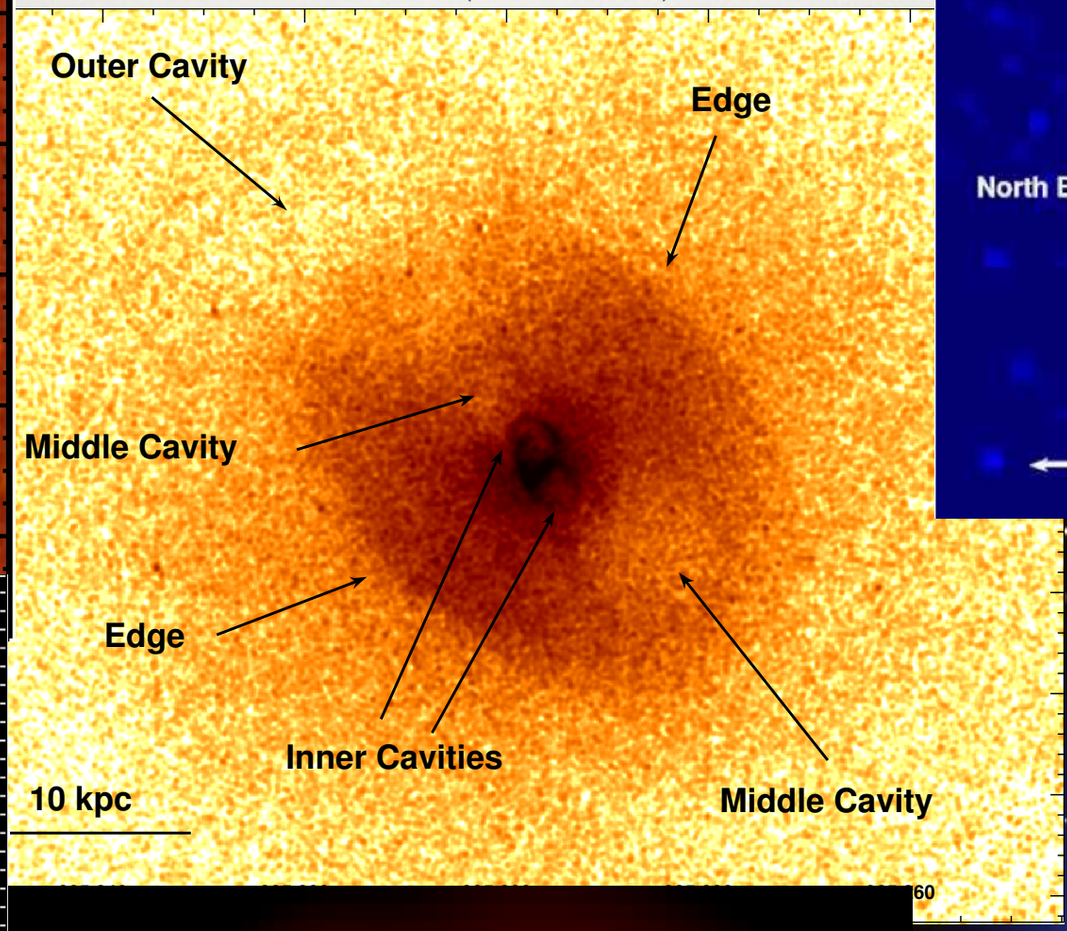
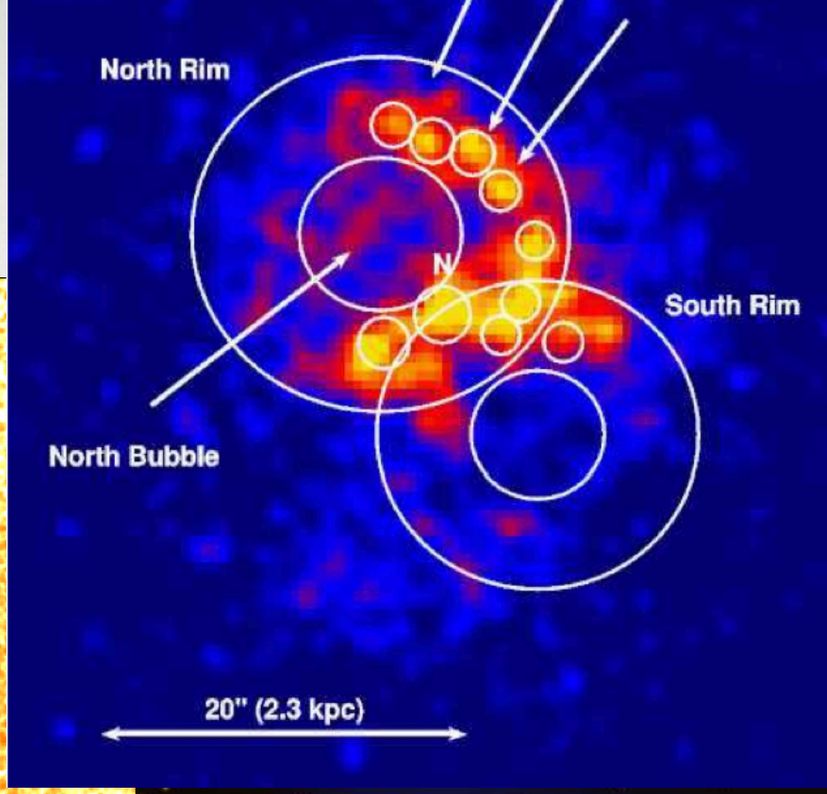
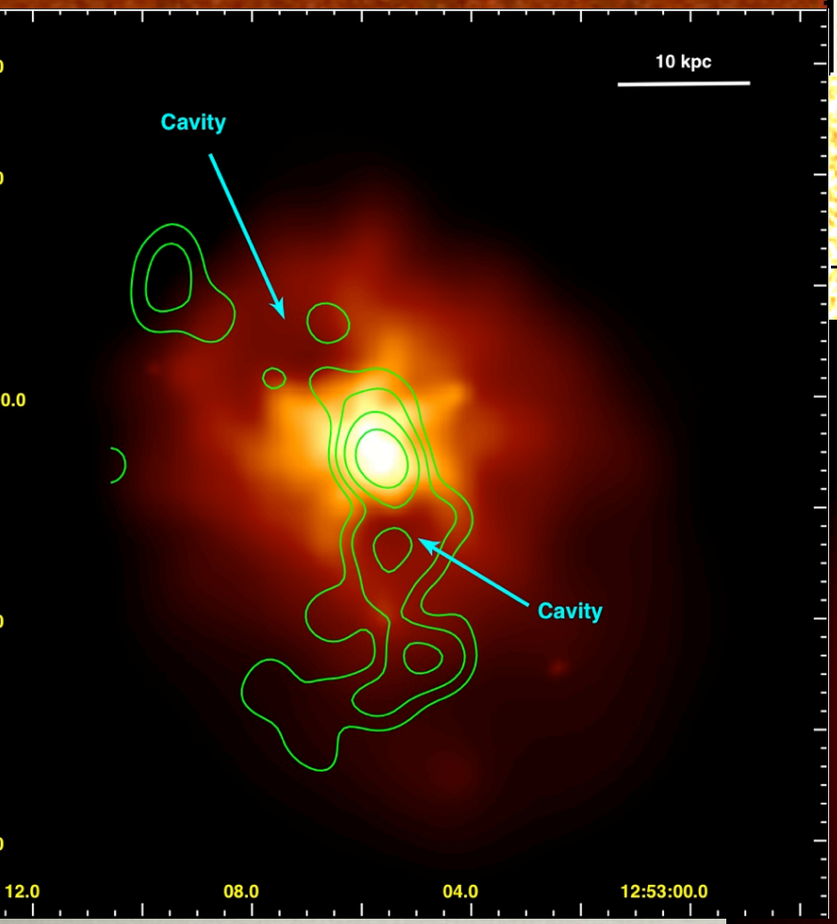
HOT HALOS

NGC 5044 (David+09) NGC 5846 (Machacek+11)
NGC 5813 (Randall+11)

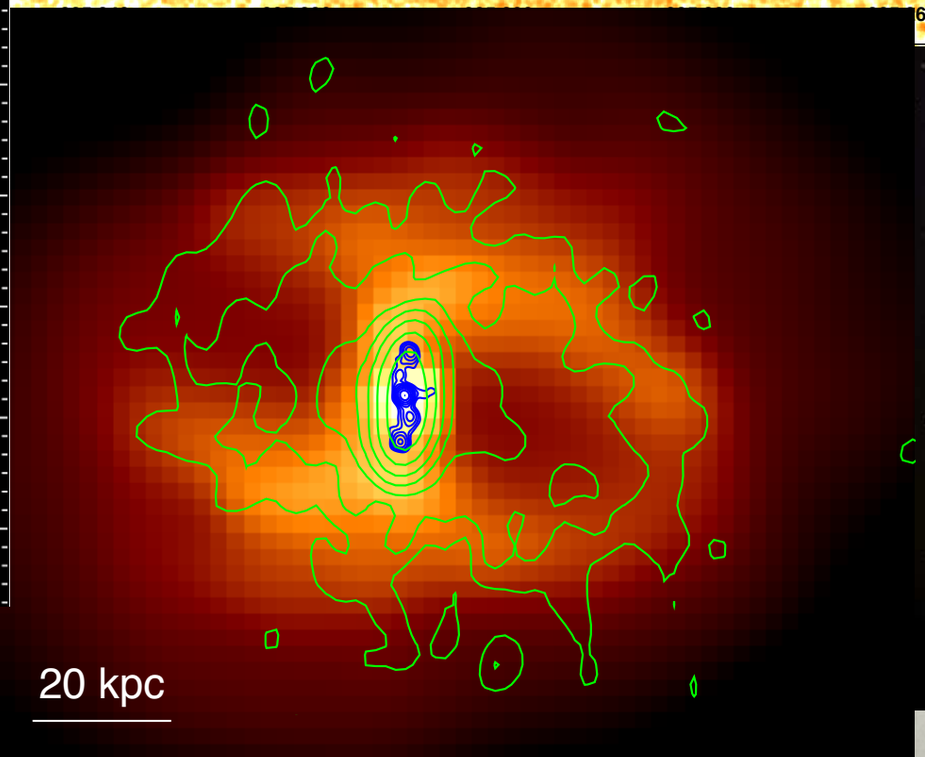




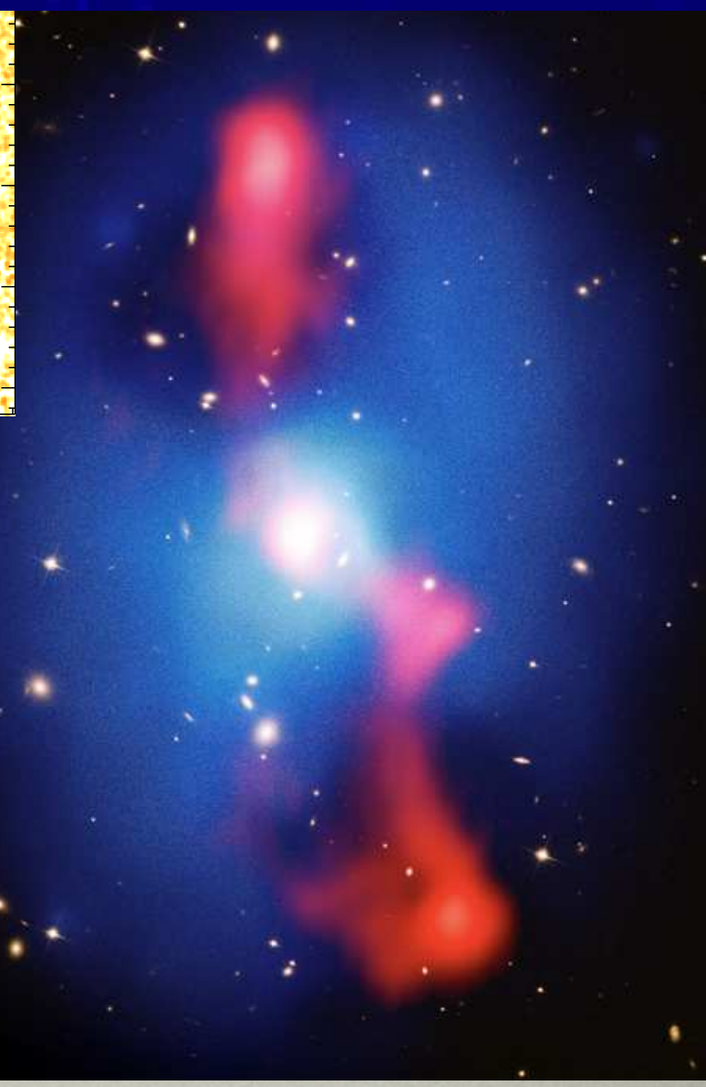




HCG 62 (Gitti+10)



RBS 797
(Gitti+11)

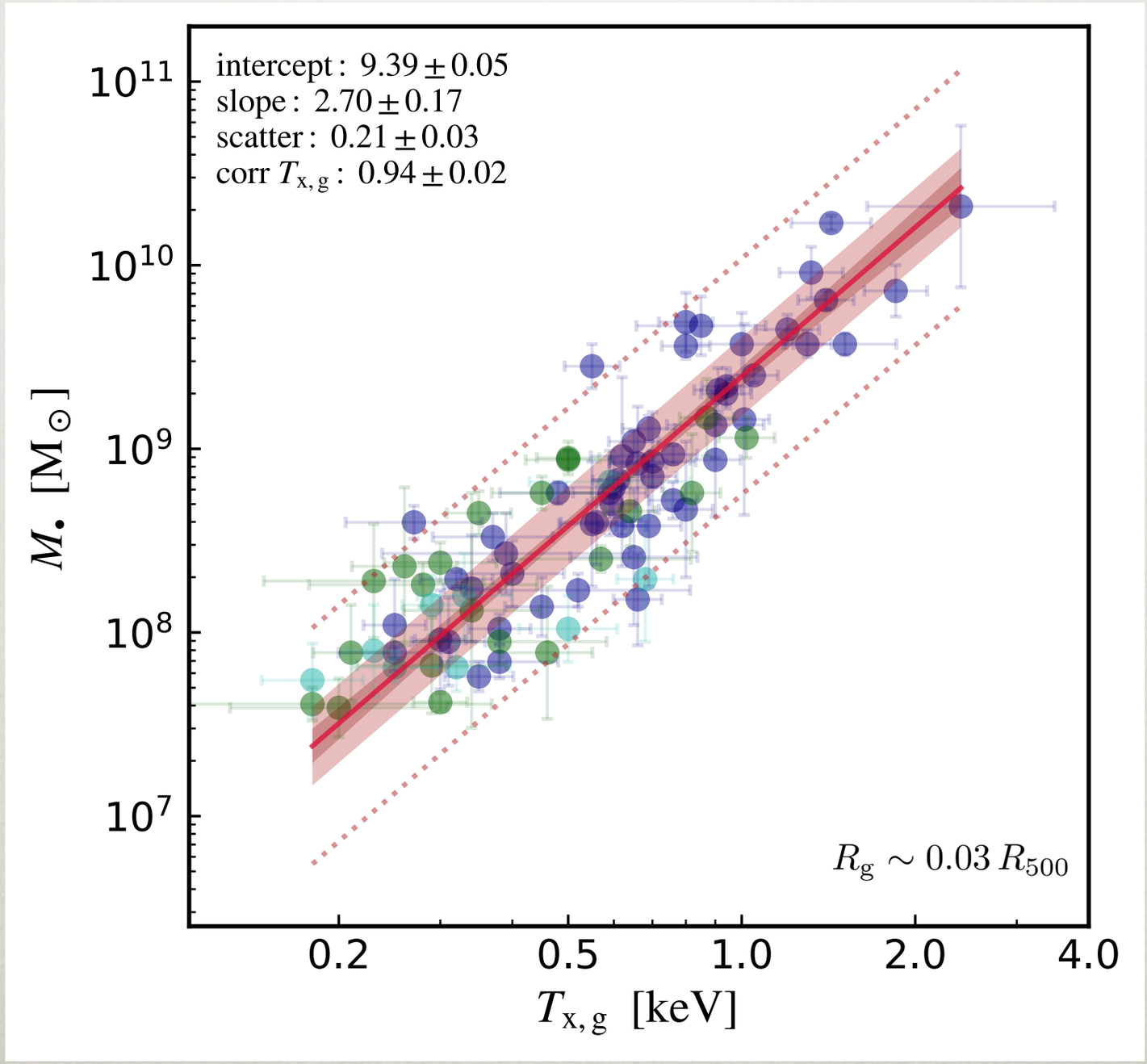


MS0735.6 cluster (McNamara+05)

SCALING RELATION:
HOT HALO - SMBHS

Bayesian analysis:
85 galaxies, groups, clusters

ETGs (blue), S0s (green), Ss (cyan)



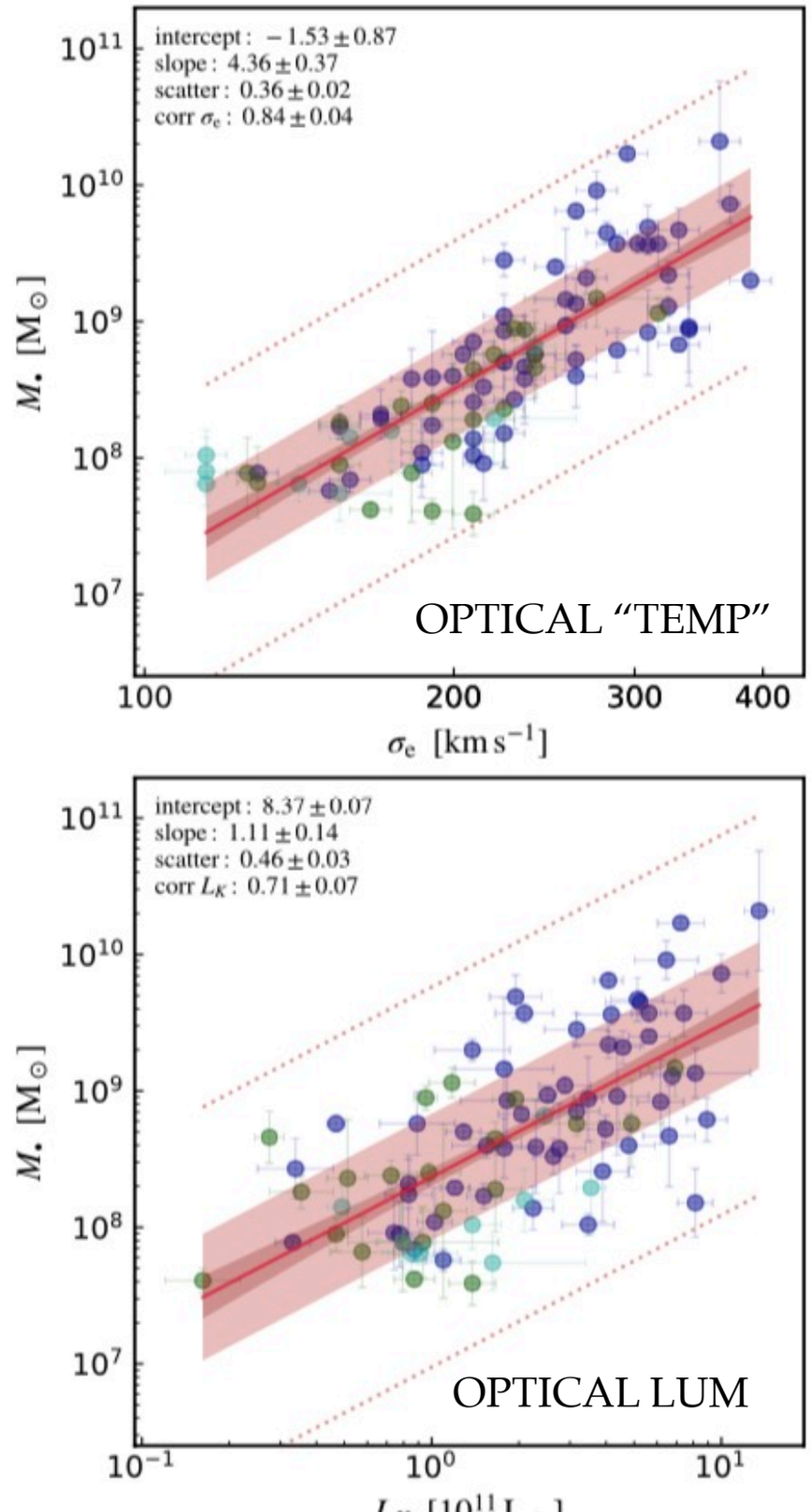
dynamical BLACK HOLE (BH) MASS

X-RAY TEMPERATURE

Gaspari et al. 2019

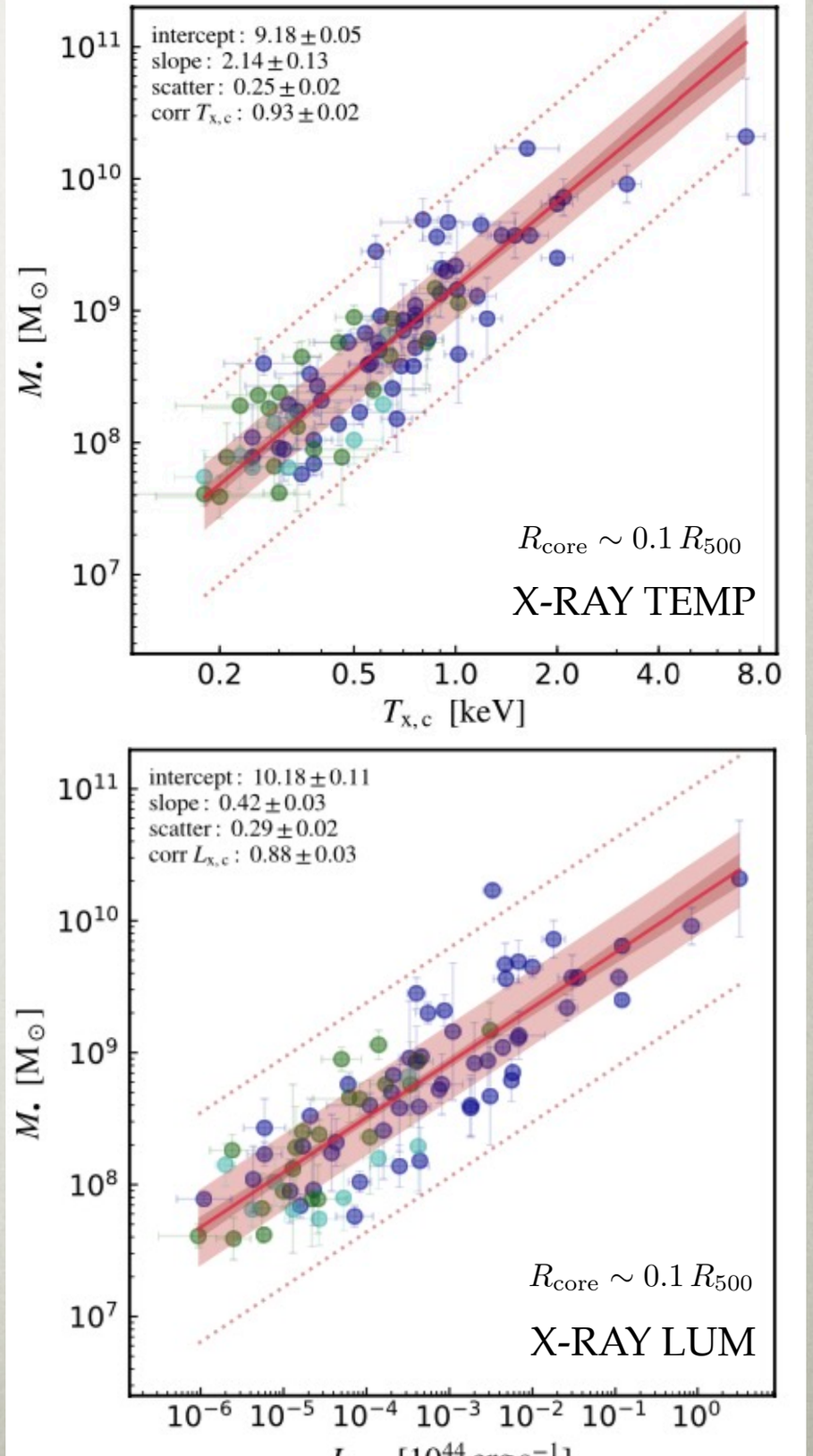
X-ray scalings lower scatter + larger corr than optical scalings

HOT HALO SCALING RELATIONS OF SMBHs



X-ray scalings lower scatter + larger corr than optical scalings!

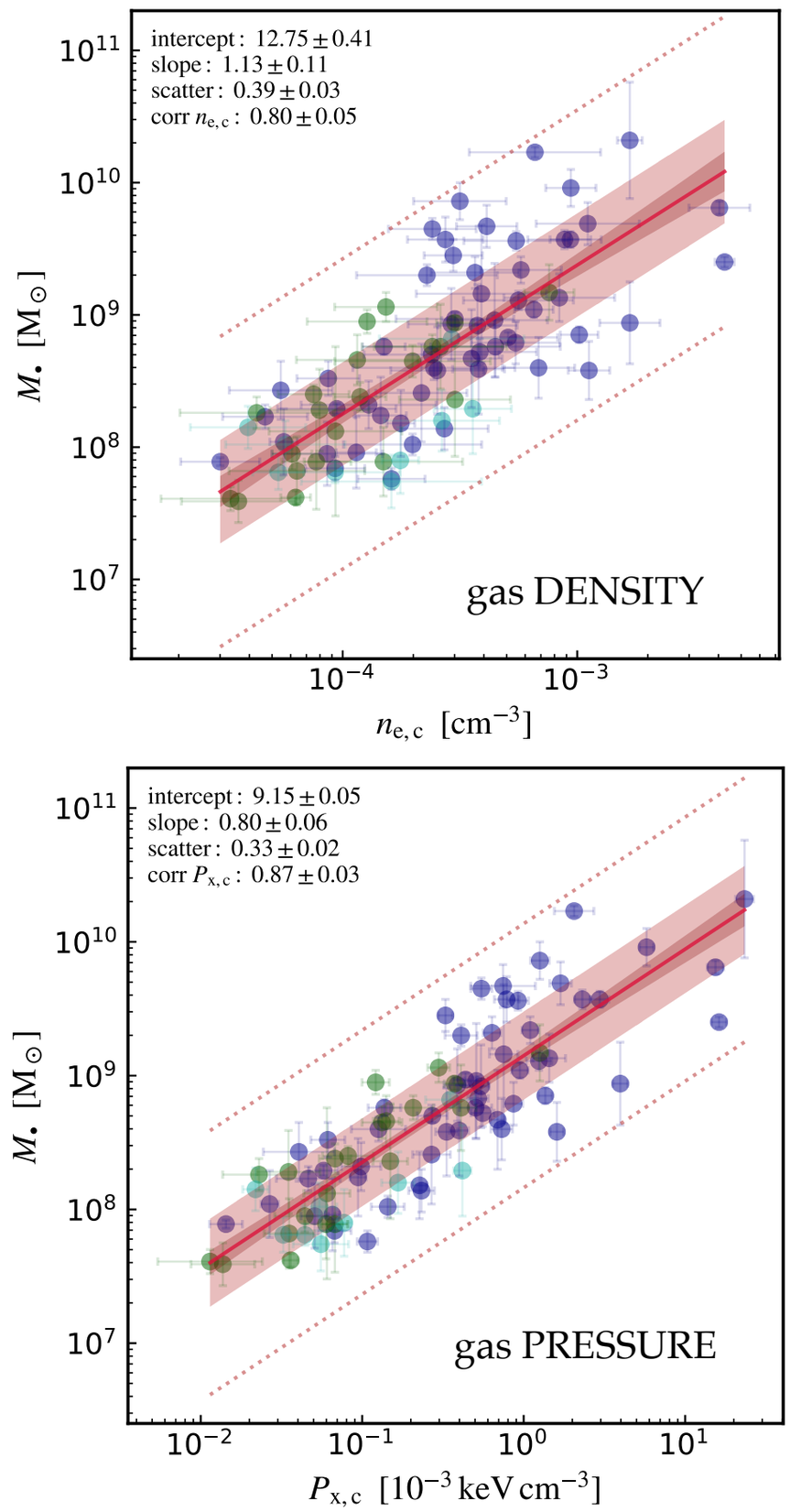
Gaspari et al. 2019

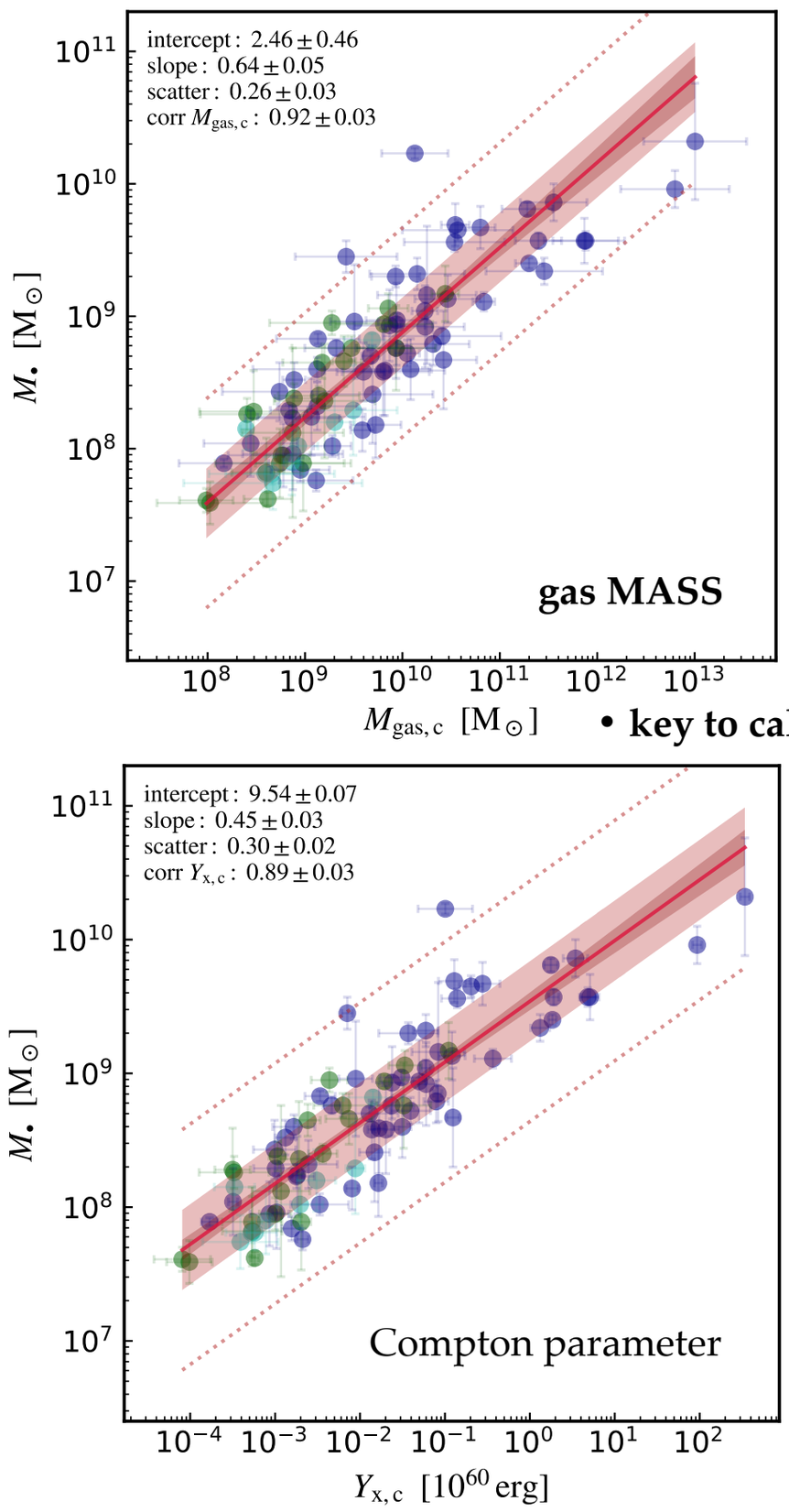


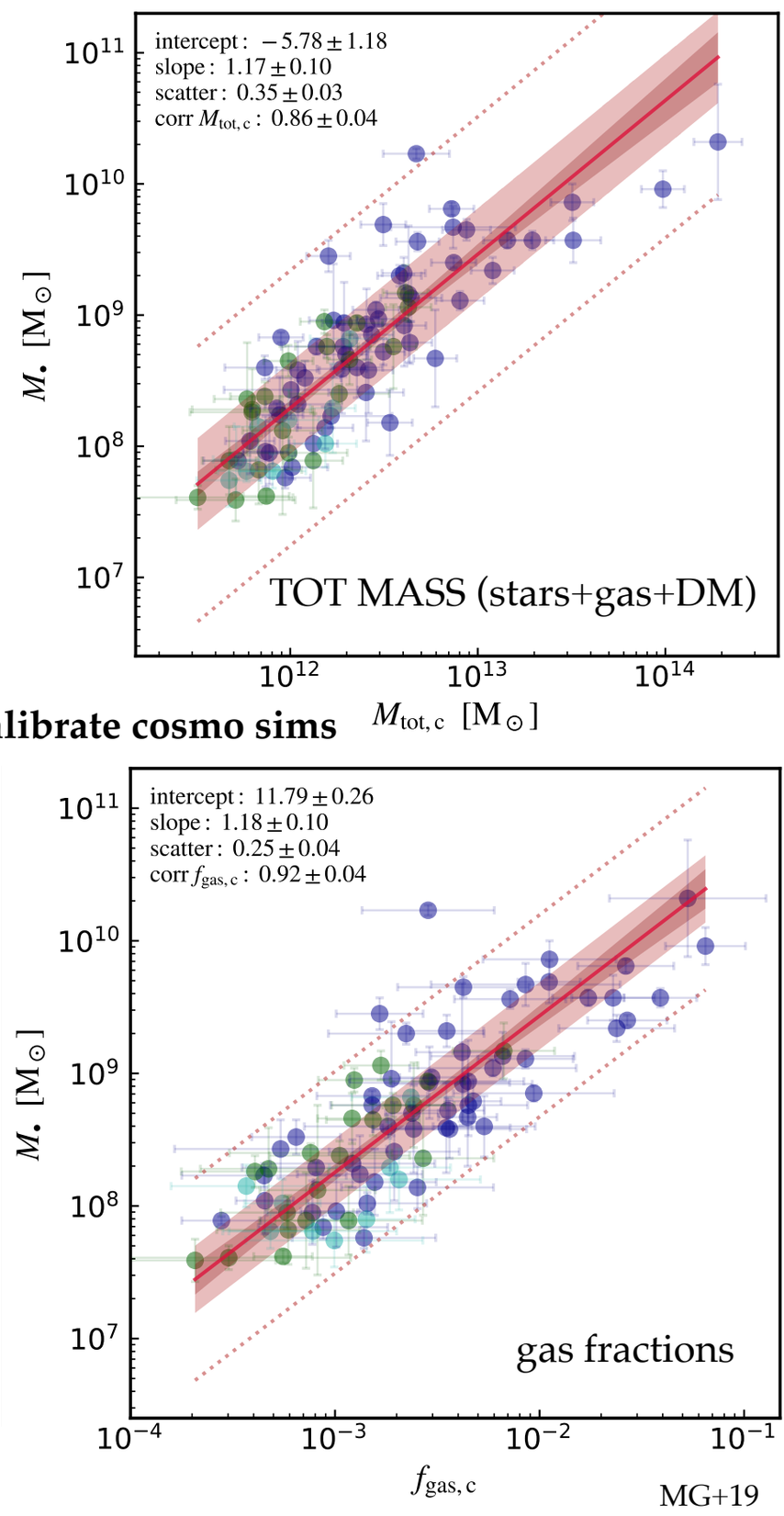
X-RAY HALO SCALING RELATIONS OF SMBHs

(indirect properties, within core)

- **gas mass/Yx tighter than total mass**
- **key to calibrate cosmo sims**

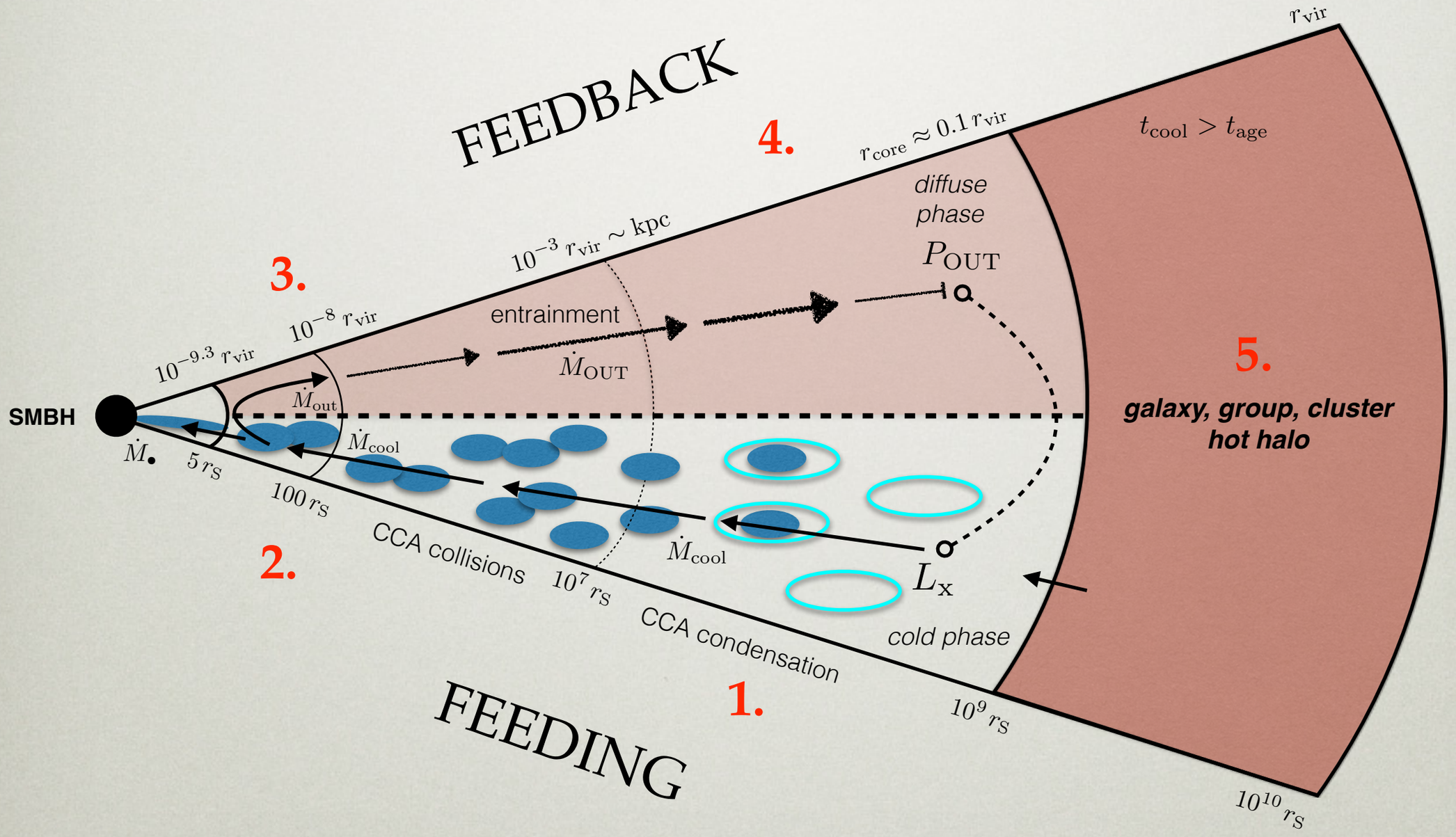






"BLACK HOLE WEATHER" PROGRAM

Gaspari+20
Nature Ast.
review

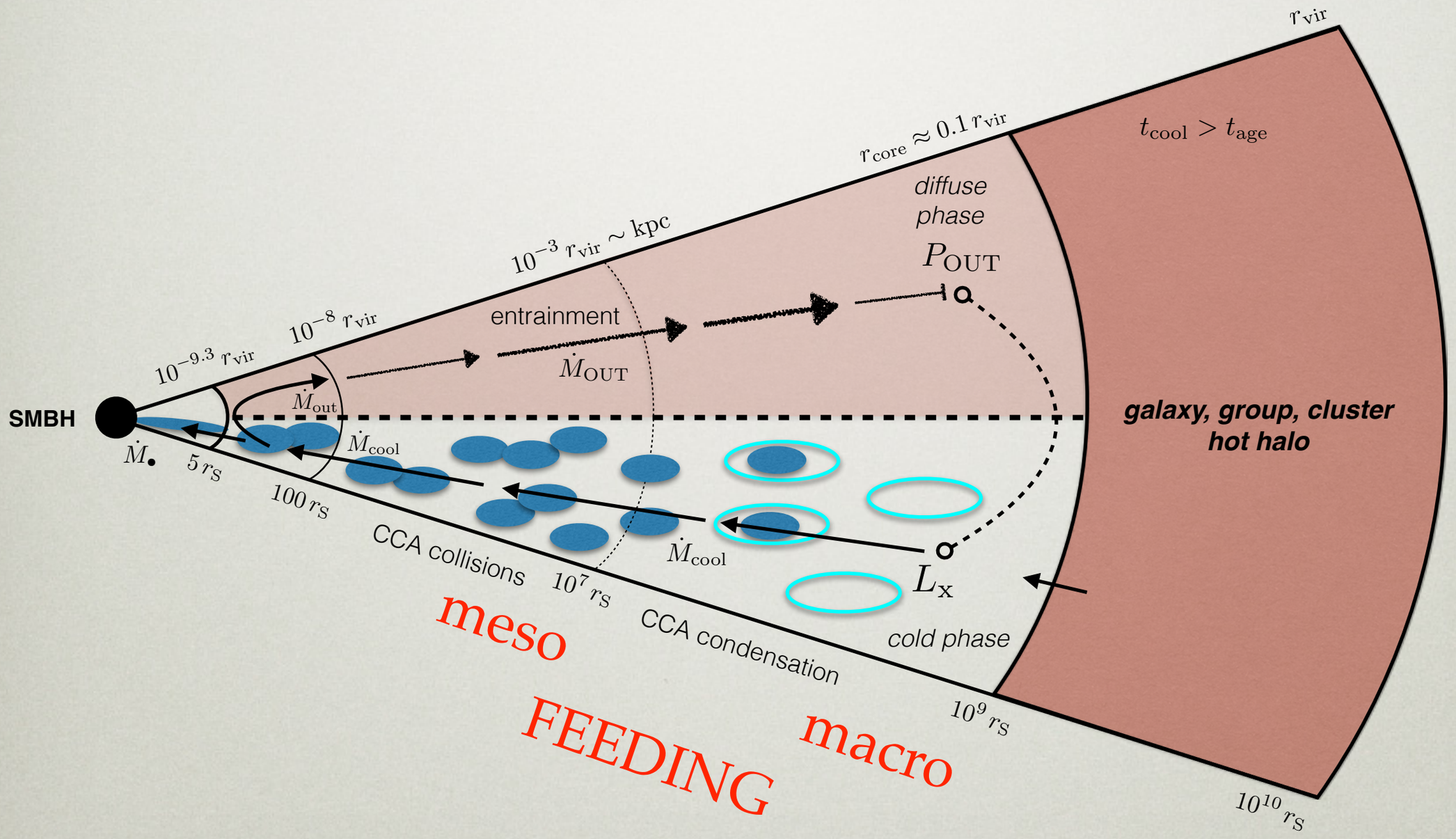


GOAL 1: first-principle multi-scale simulations

GOAL 2: test detailed synthetic models with multi-λ data

MG+2011-2020

“BLACK HOLE WEATHER” PROGRAM



multiphase condensation cascade (“raining”)

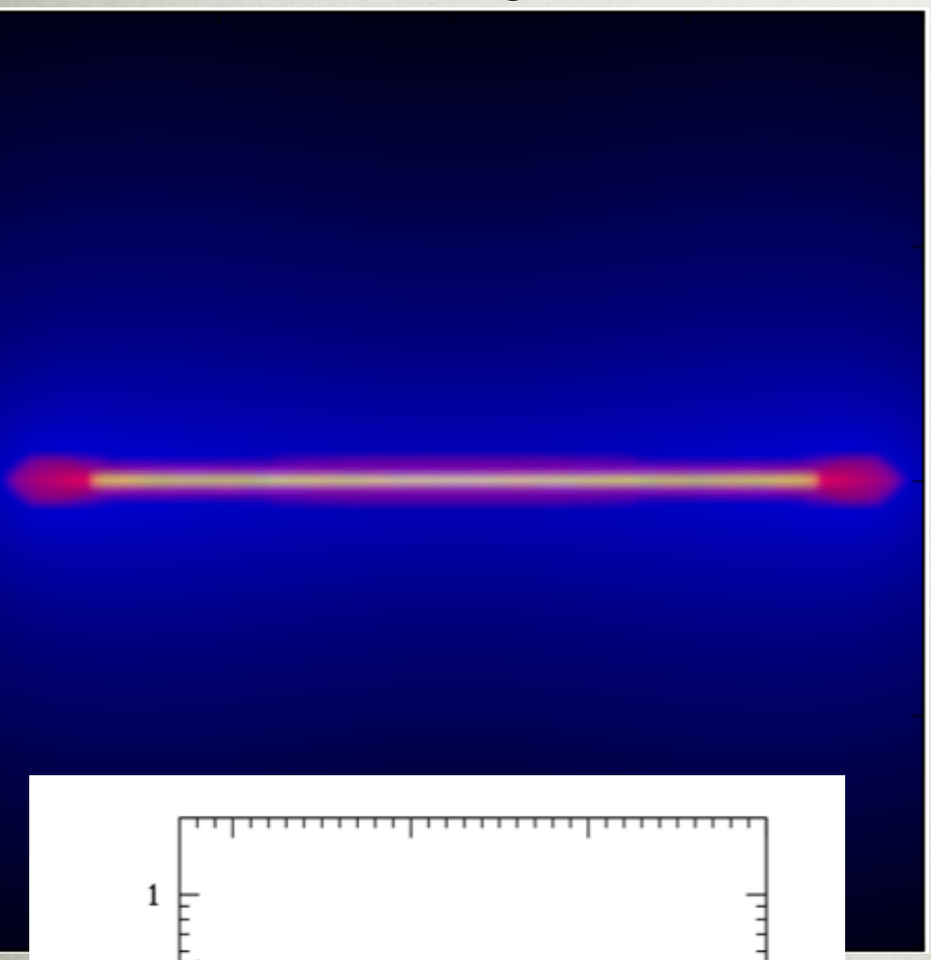
CCA = CHAOTIC COLD ACCRETION

BLACK HOLE FEEDING WITH COOLING: 3 DYNAMICAL STAGES

rotating

turbulent

quiescent



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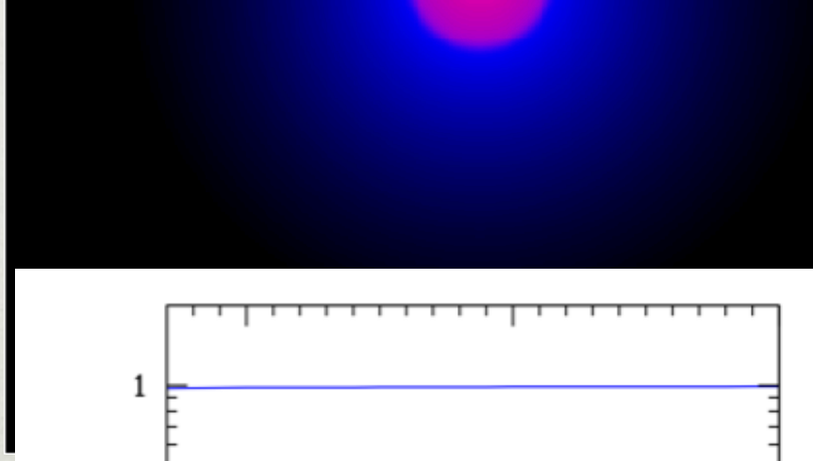
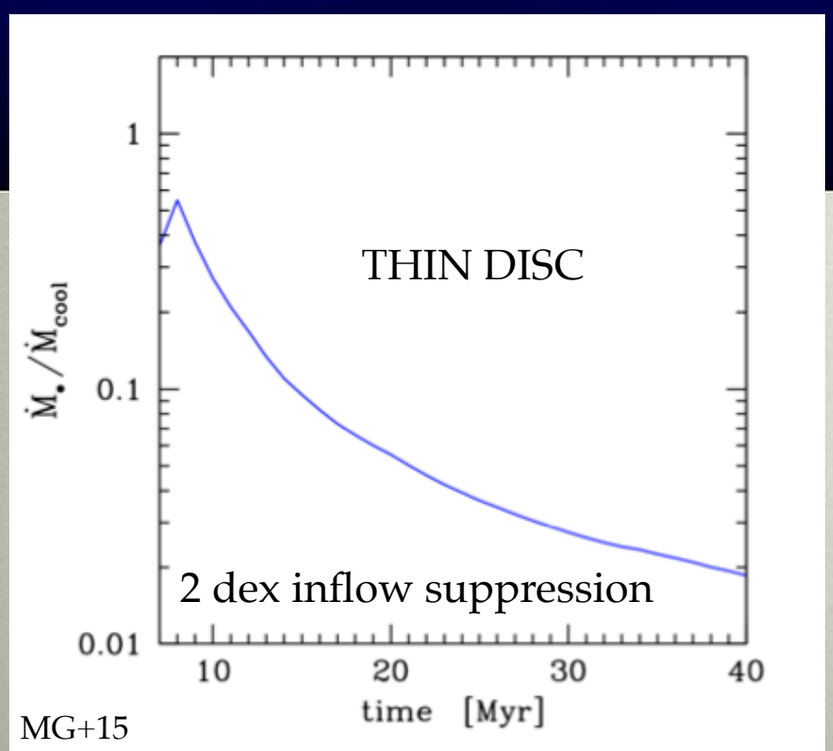
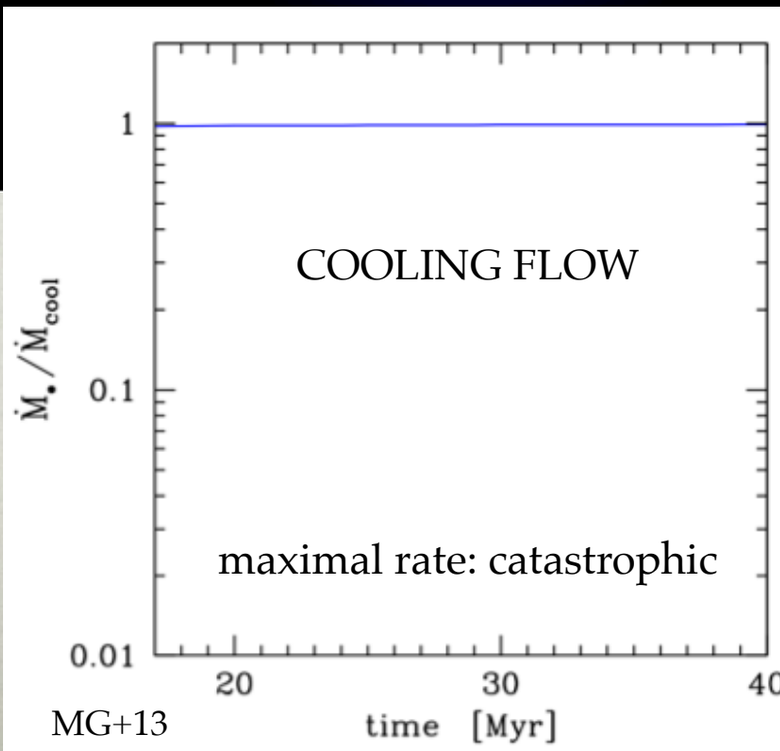




MG+15

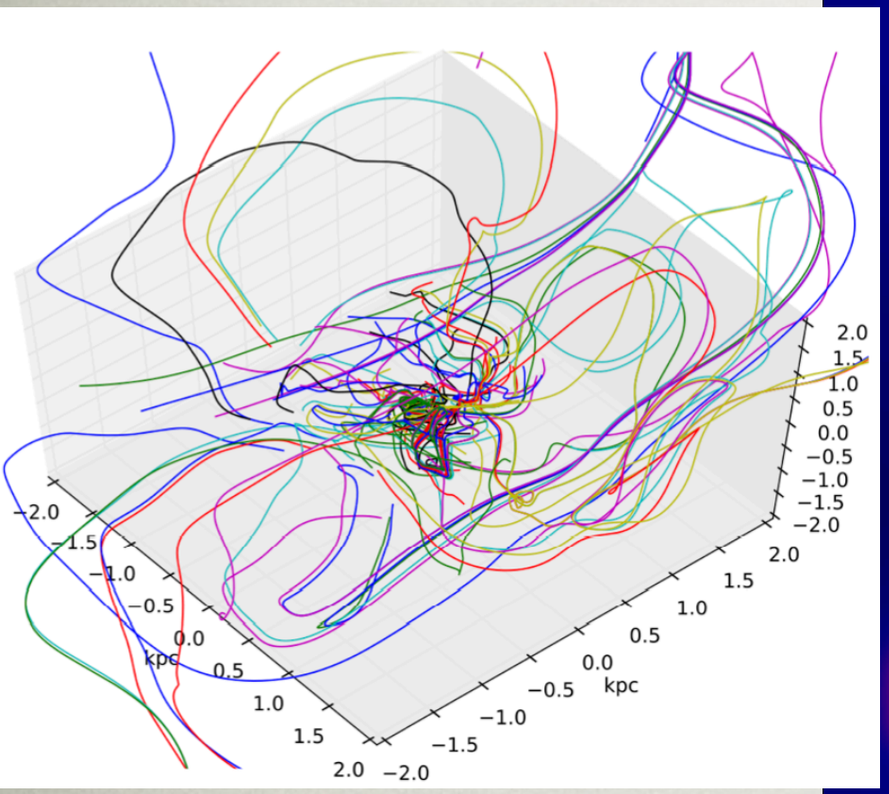
RGB surface density: plasma (blue), warm gas (red), cold gas (green)



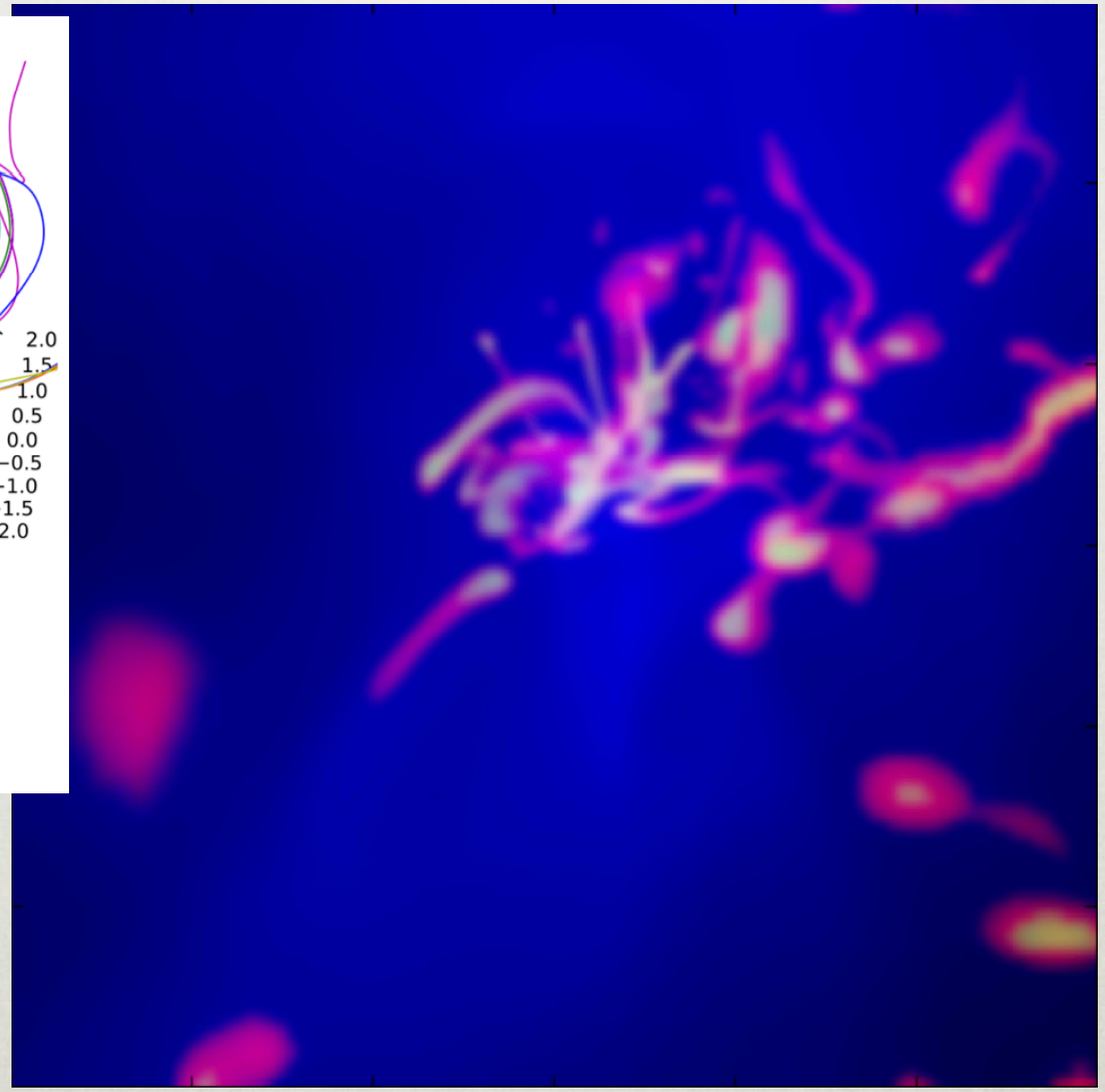
MG+13

RAINING ON BLACK HOLES

a.k.a. **Chaotic Cold Accretion [CCA]** — Gaspari et al. 2013



chaotic streamlines => recurrent multiphase gas interactions



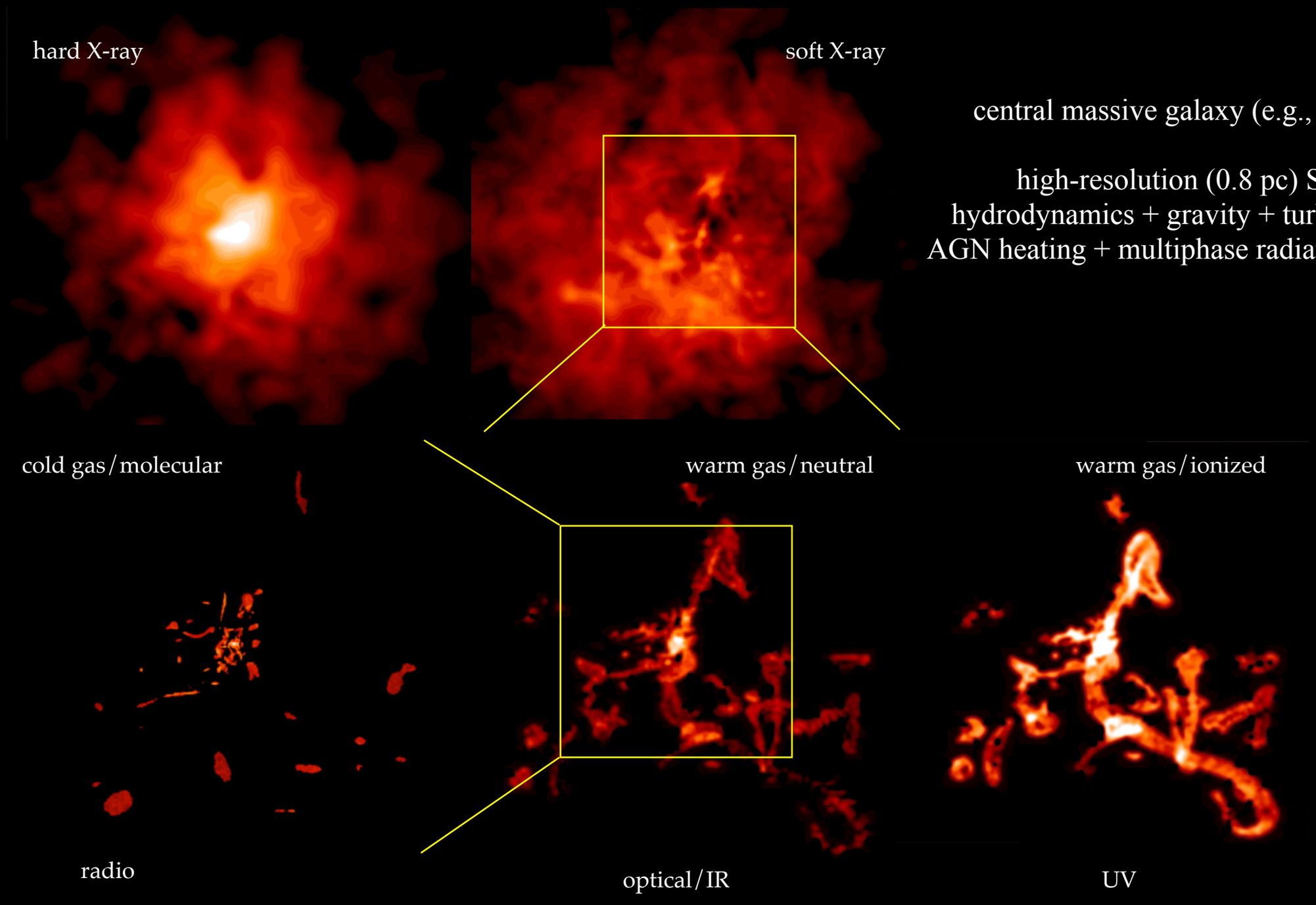
TURBULENCE > ROTATION

σ_v ~150 km/s
as found by *Hitomi*

RGB surface density: plasma (blue), warm gas (red), cold gas (green)

CCA has been corroborated by several independent observational and theoretical/simulation studies: e.g., Voit & Donahue 2015, Voit 2015, 2017, 2018; Werner+2014; David+2014, Li & Bryan 2014, 2015; Wong+2014; Russell+2015; Valentini & Brighenti 2015; Yang+2015-2016; Meece+2016; Tremblay+2015, 2016, 2018; Prasad+2016; David+2017; McDonald+2018; Maccagni+2018; Nagai+2019; Rose+2019-2020; Storchi-Bergmann+2019 (review); Schellenberger+2020, …

TOP-DOWN MULTIPHASE GAS CONDENSATION RAIN:
synthetic imaging



central massive galaxy (e.g., N5044)

high-resolution (0.8 pc) SIM:
hydrodynamics + gravity + turbulence +
AGN heating + multiphase radiative cooling

Gaspari et al. 2017

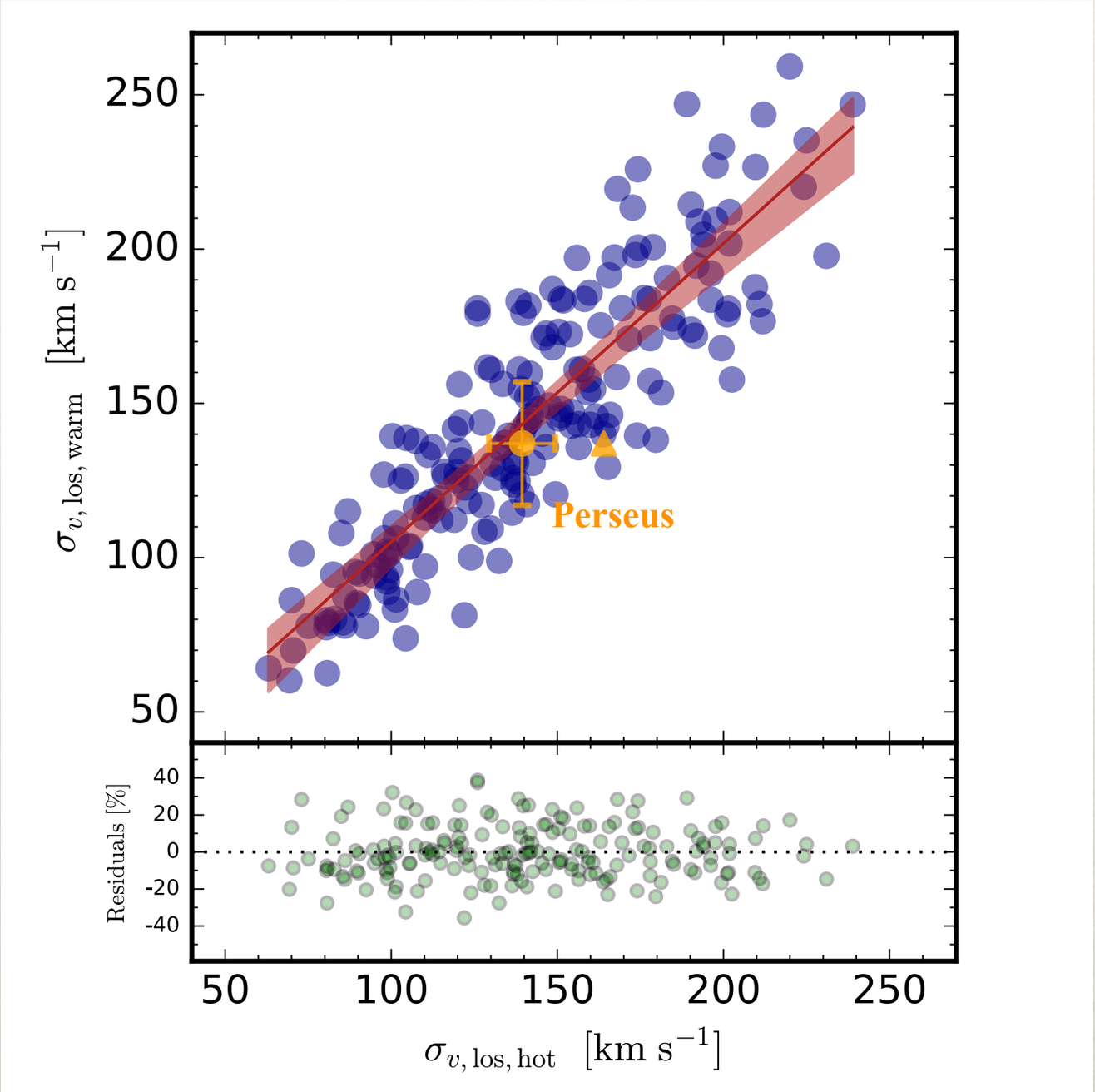
condensation criterion: $C \equiv \frac{t_{\rm cool}}{t_{\rm eddy}} \sim 1$

KINEMATIC TRACERS
MULTIPHASE RAIN

Gaspari et al. 2018

ENSEMBLE beam
(R < 50 kpc ~ arcmin)

spectral line broadening
= turbulent motions



self-regulated
AGN jet feedback sims

global turbulence
kinematics:
ensemble warm phase
and hot/plasma phase
are linearly related

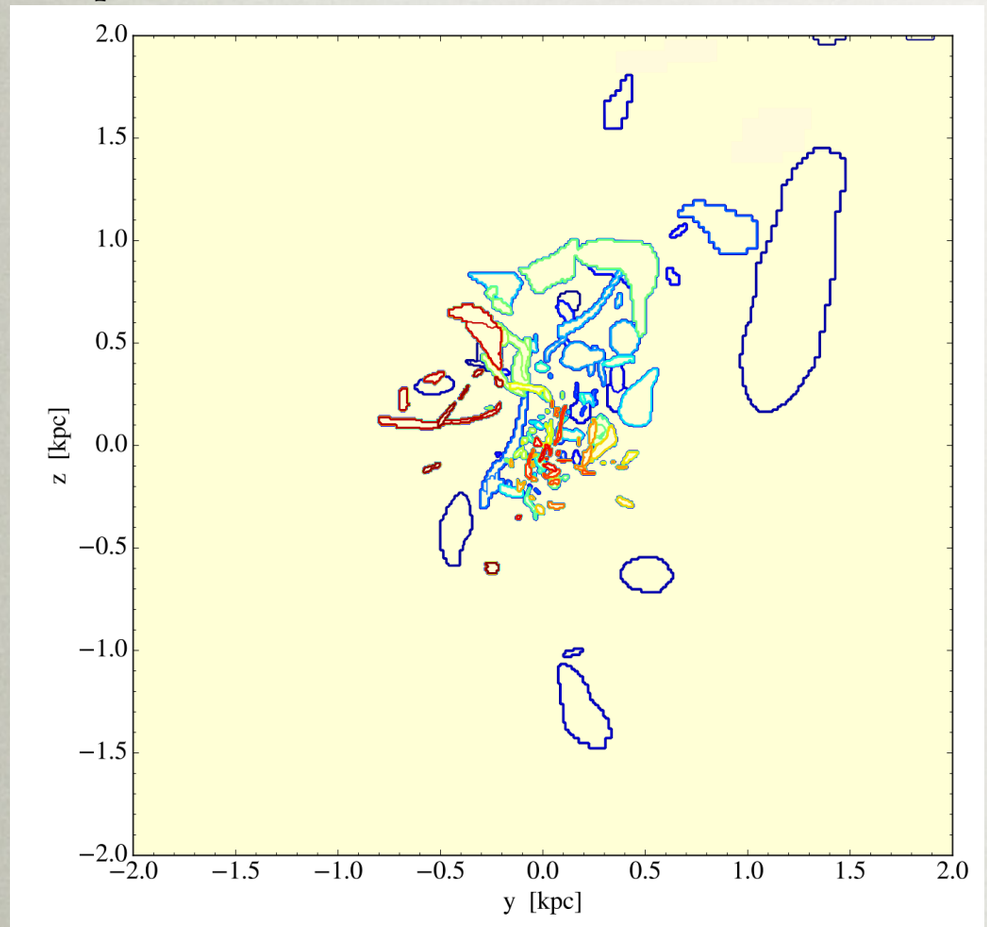
similar can be shown for UV - IR - radio (molecular) phases:

multiwavelength synergies: ATHENA - ALMA - JWST/ELT - VLT/MUSE, SINFONI - SKA

CHAOTIC COLD ACCRETION

DYNAMICS

Gaspari+2017



- leaf clouds via clump finder algorithm
- network of condensed structures
- key for AGN obscuration/unification models (BLR, NLR)
- **angular momentum mixing/cancellation via inelastic collisions**

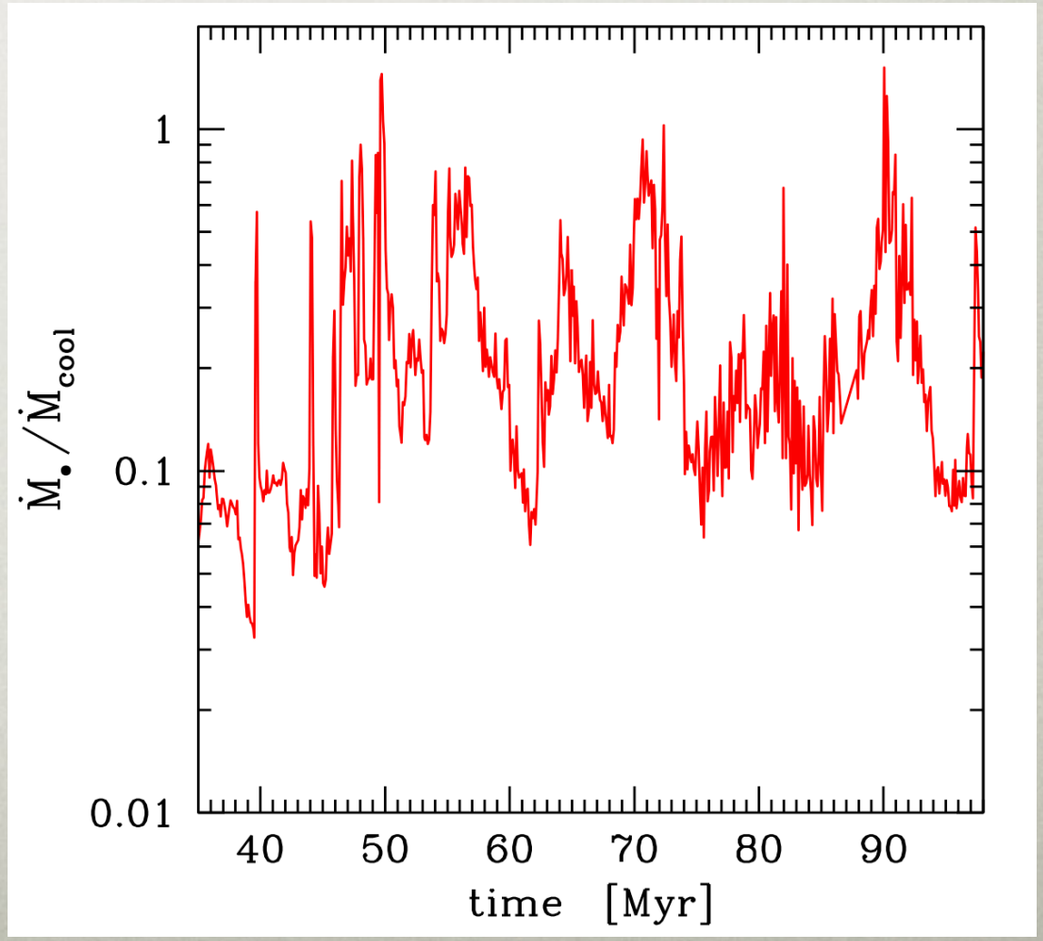
can be modeled as quasi-spherical viscous accretion:

$$\lambda_c \equiv \frac{1}{n_c\,\pi(2\,r_c)^2} = \frac{1}{3}\frac{r_c}{f_V} \simeq 88^{+262}_{-67}\ \mathrm{pc}$$ mean free path

$$\nu_c \equiv \sigma_v\,\lambda_c \simeq 4.5^{+13.3}_{-3.1} \times 10^{27}\ \mathrm{cm^2\,s^{-1}}$$ effective collisional viscosity

$$\dot{M}_\bullet = 4.8 \times 10^{-3}\,\nu_c \simeq 0.3^{+0.9}_{-0.2}\ \mathrm{M_\odot\,yr^{-1}}$$ average inflow rate (for massive ETG)

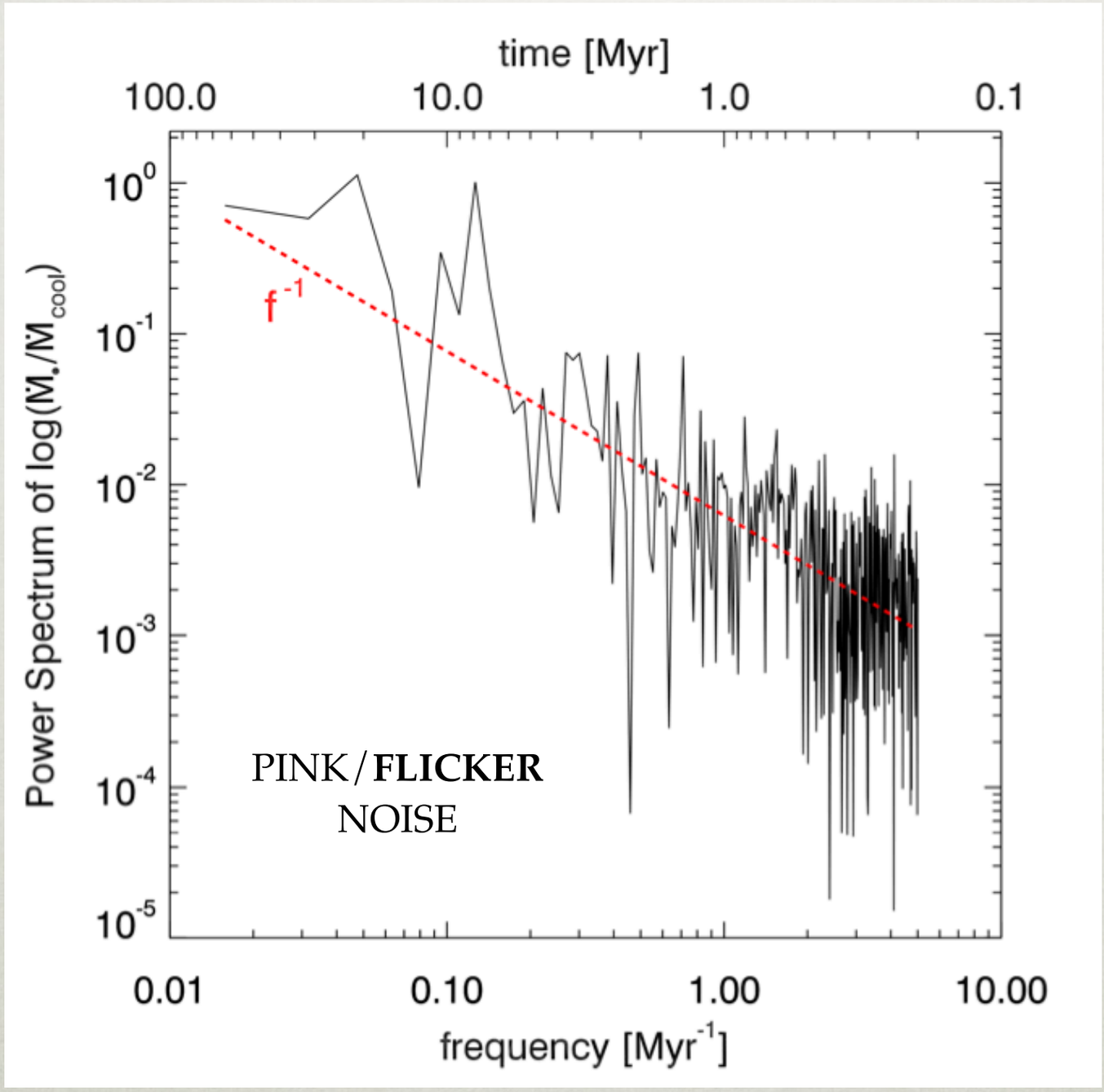
recurrent 2 dex boost in accretion rate ~ 100x Bondi rate



CHAOTIC COLD ACCRETION

VARIABILITY

MG+17



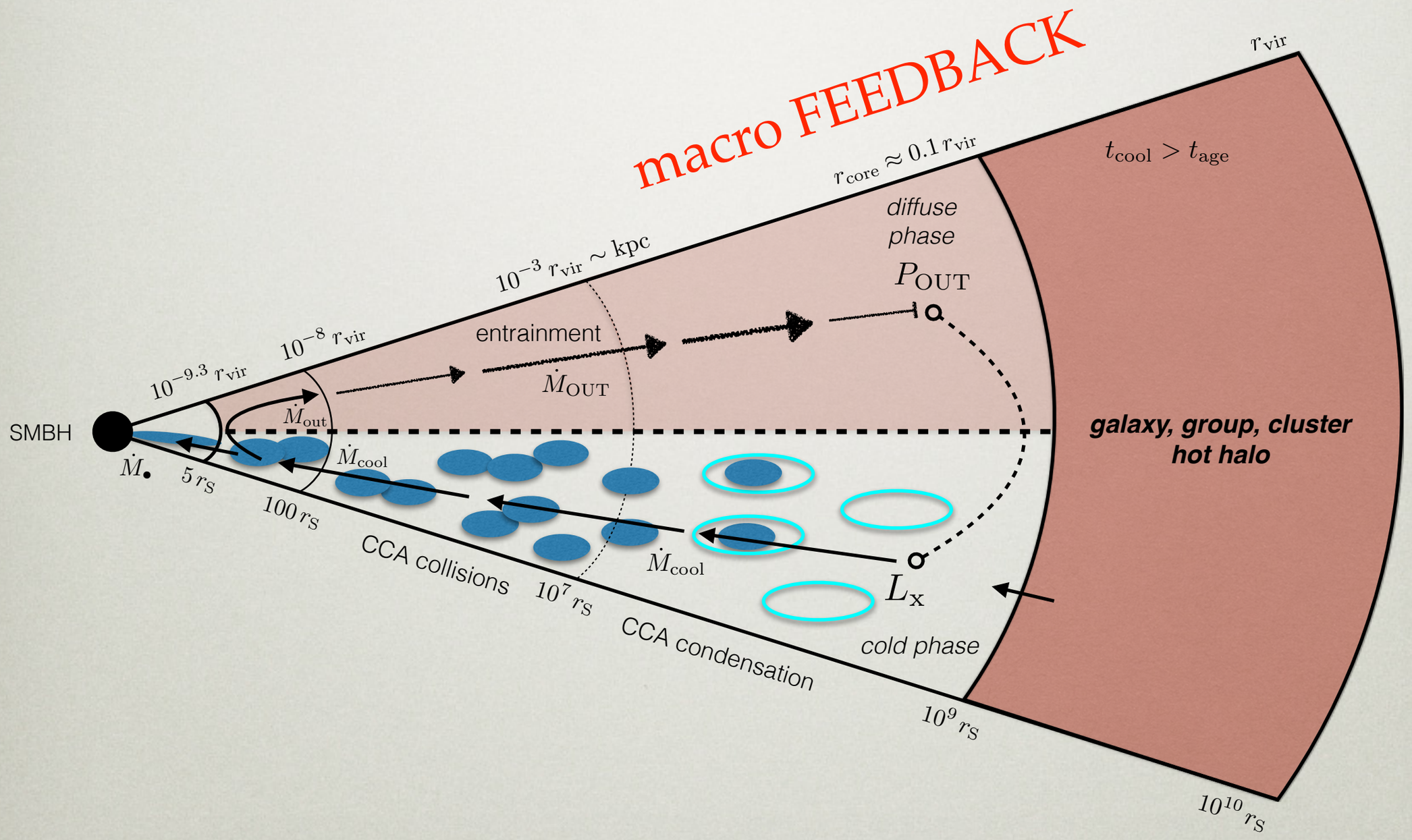
can explain ubiquitous rapid variability of AGN (and HMXBs)

constant variance per log interval => large self-similar variability on different timescales

characteristic of <u>fractal and chaotic phenomena:</u>

quasars (e.g., 3C273), sunspots, meteorological data/**RAINFALLS**, heart beat rhythms, neural activity, stock market, …

BLACK HOLE FEEDING & FEEDBACK
SELF-REGULATION



AGN FEEDBACK CYCLE

(> KPC)

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

↓

nonlinear condensation

↓

CCA rain

↓

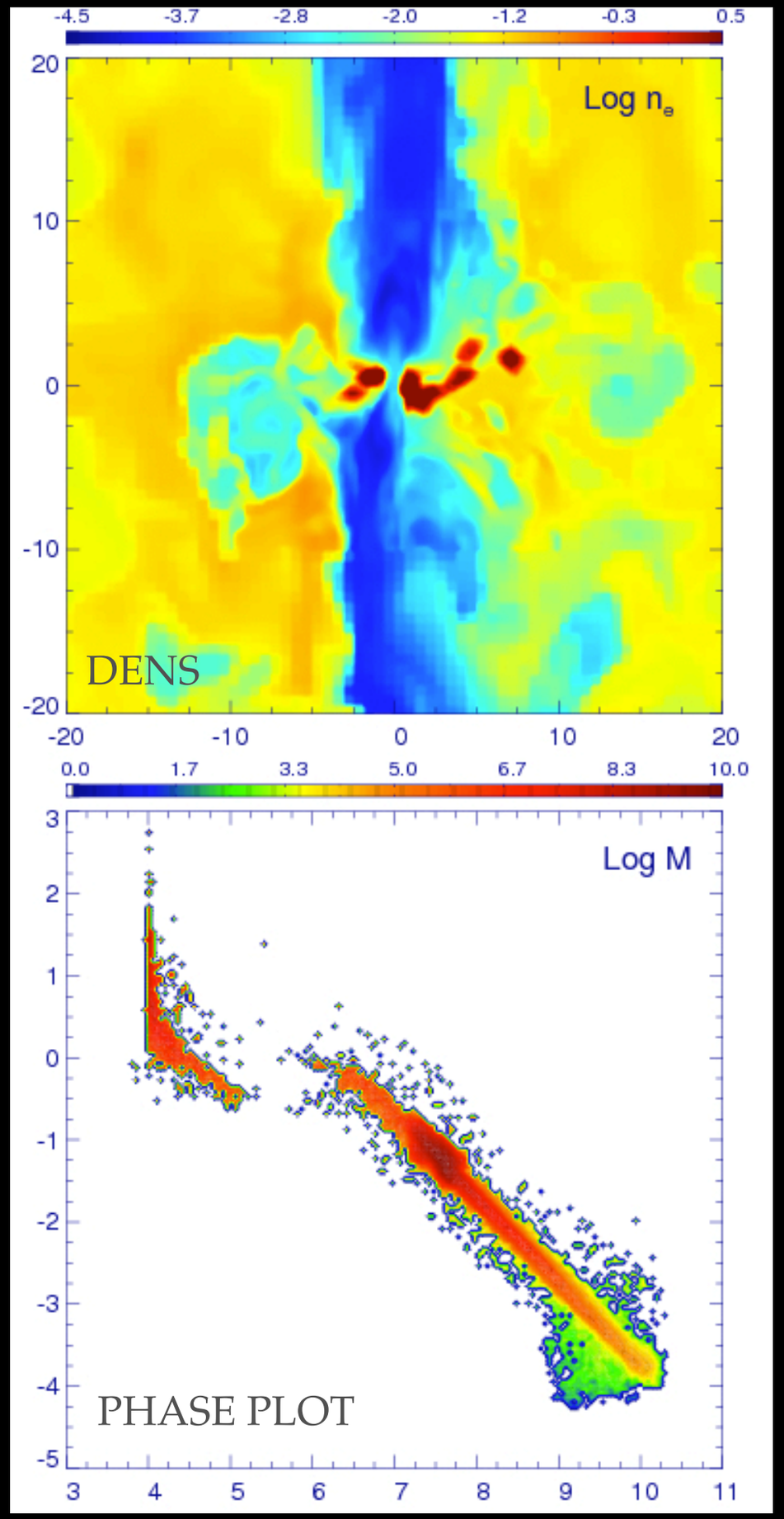
feed SMBH

↓

feedback boosted

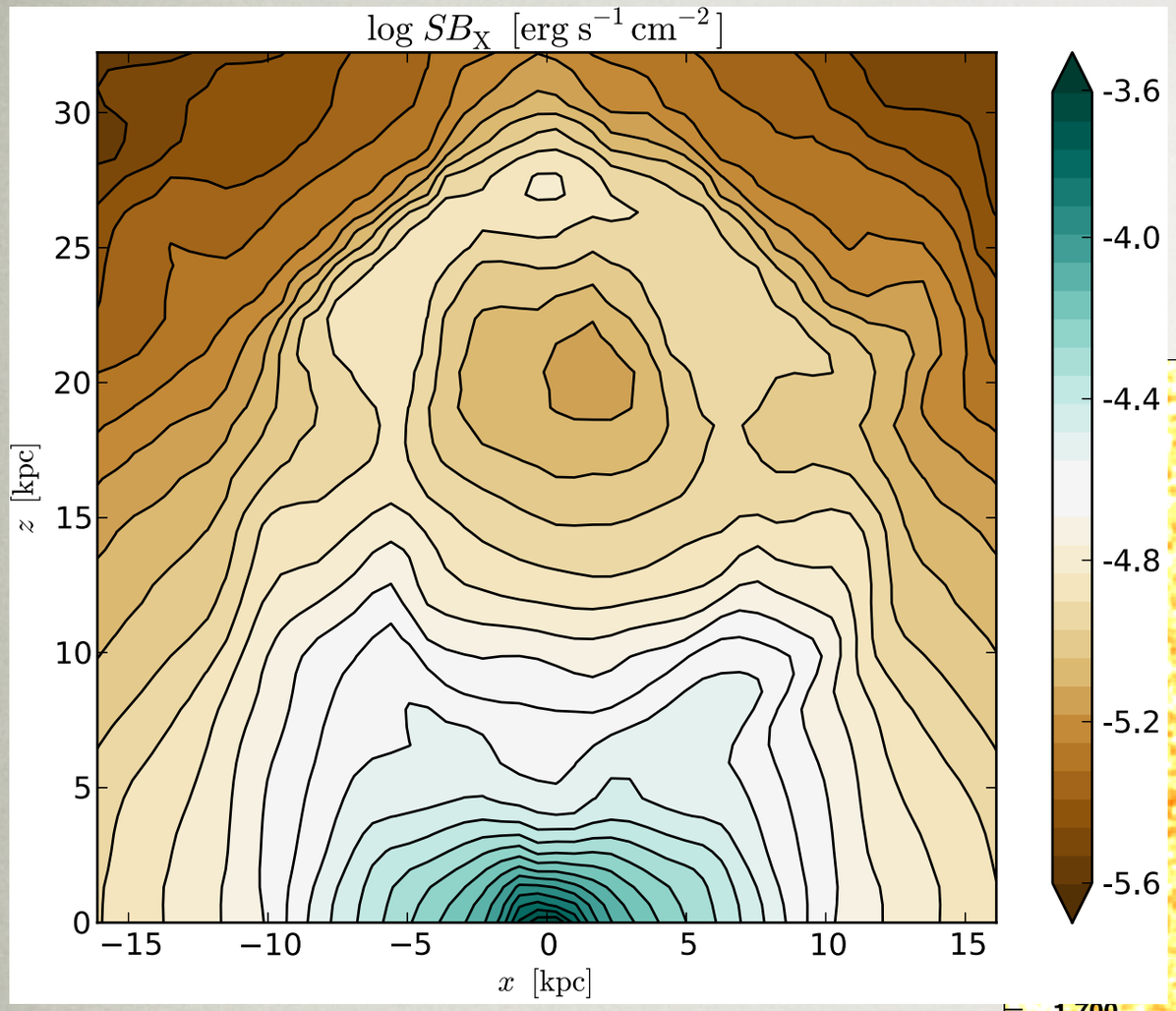
↓

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



Gaspari+12

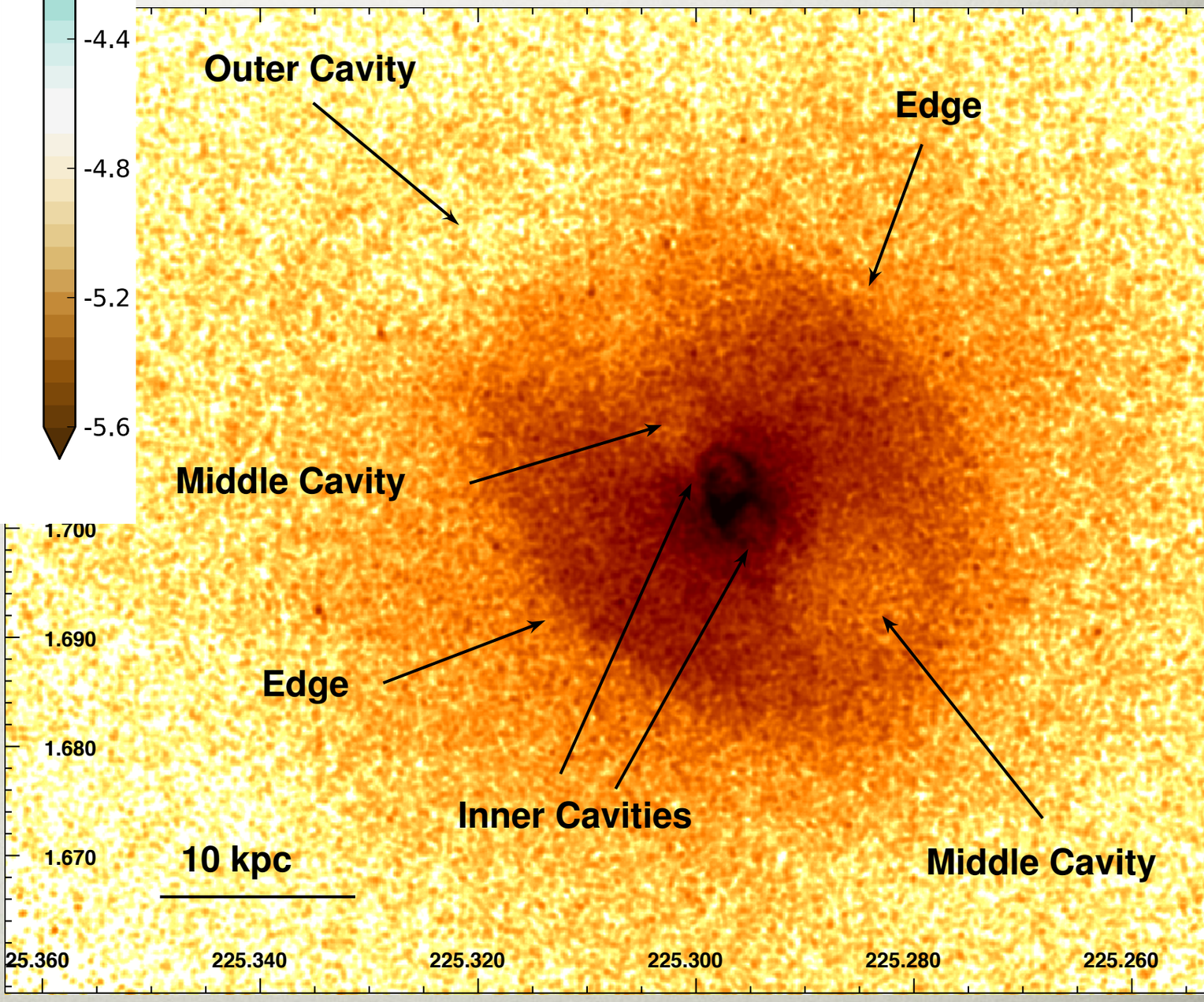
X-RAY BUBBLES



MG+2011b SIMS

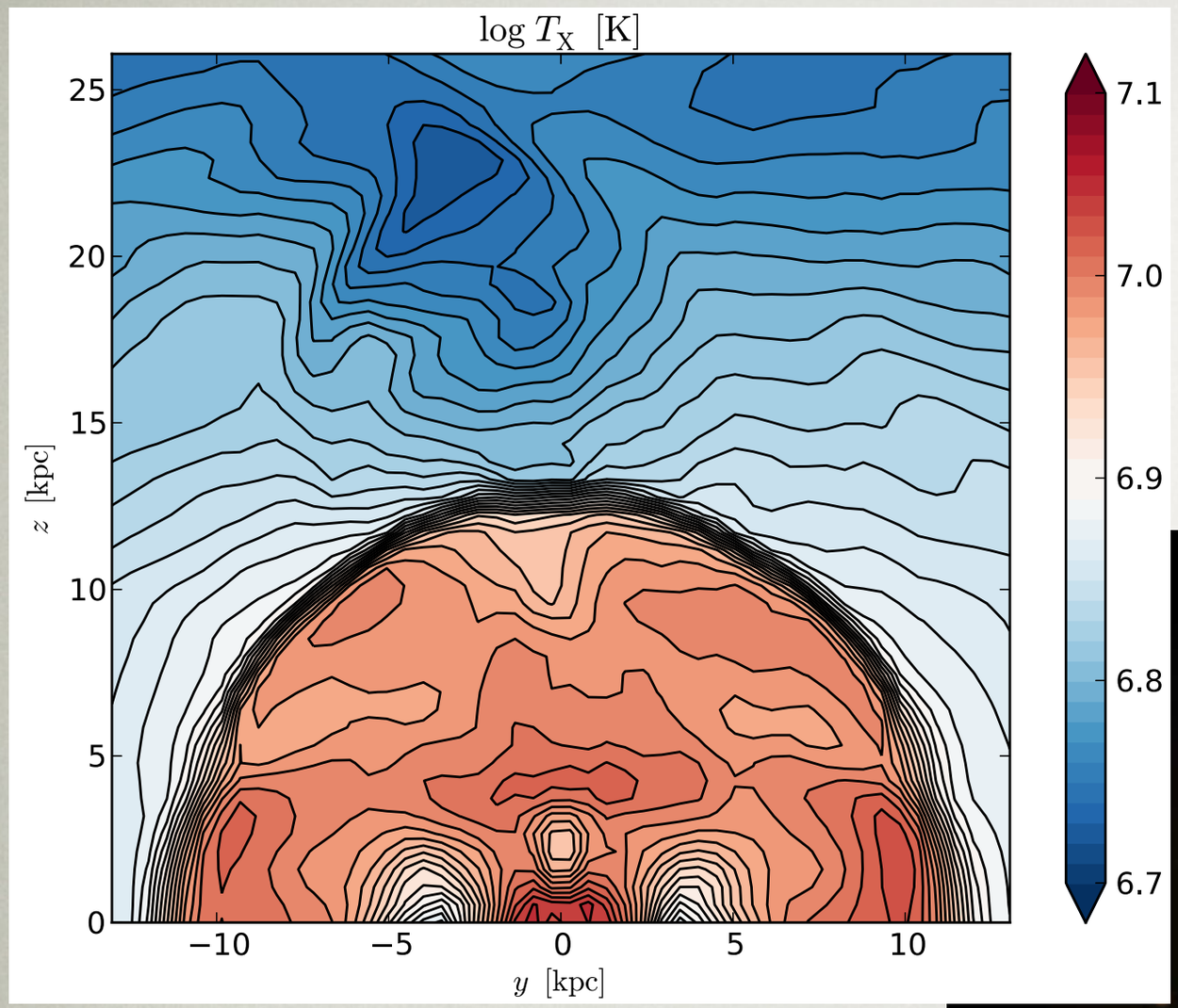
$$E_{\rm cav} = \frac{\gamma}{\gamma - 1} PV$$

enthalpy



NGC 5813 - Randall+2011

COCOON SHOCKS

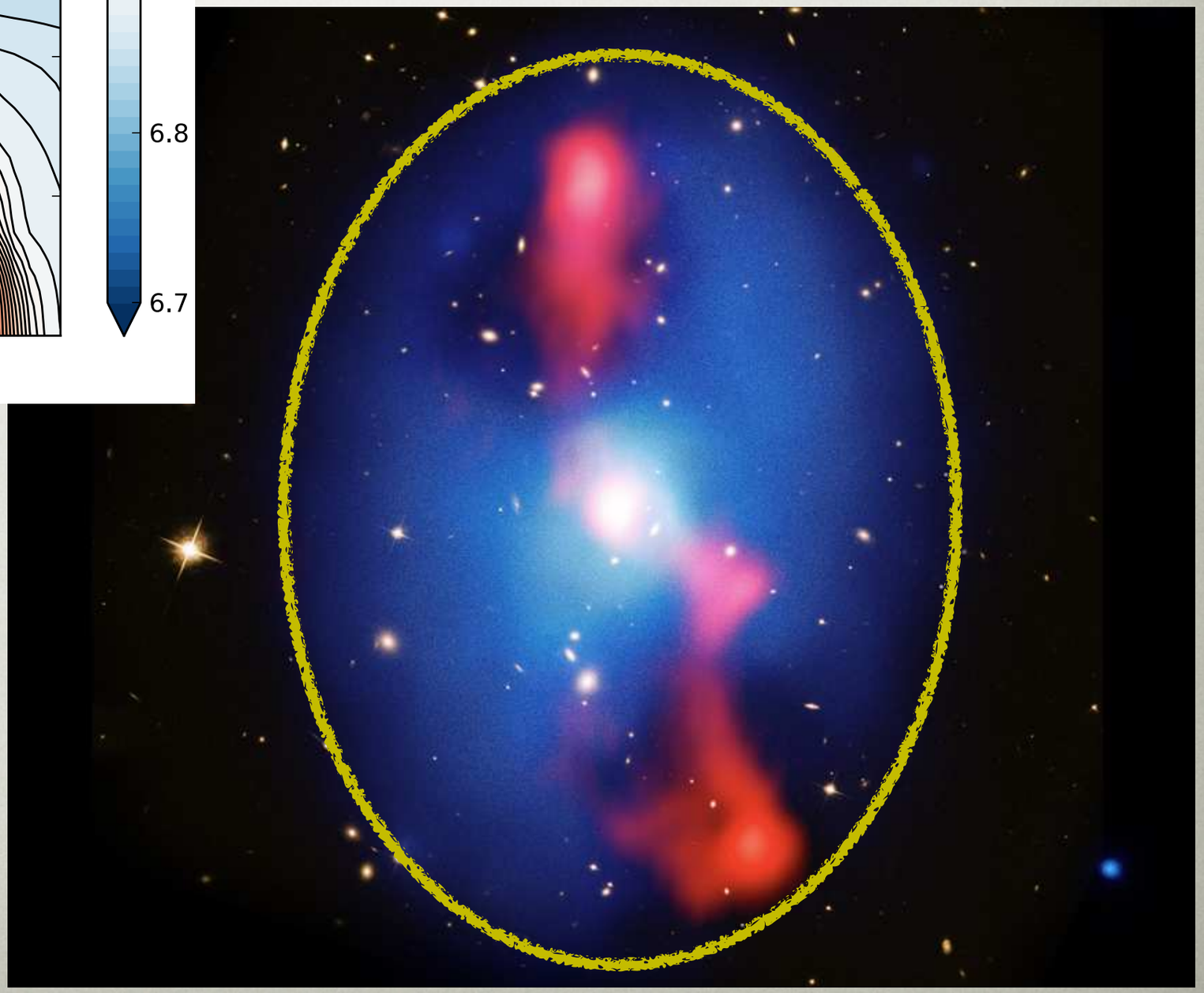


MG+2012b SIMS

$$\Pi_{\rm s} = \frac{(\gamma+1)}{12\gamma^2}\frac{\omega p}{2\pi}\left(\frac{\delta p}{p}\right)^3$$

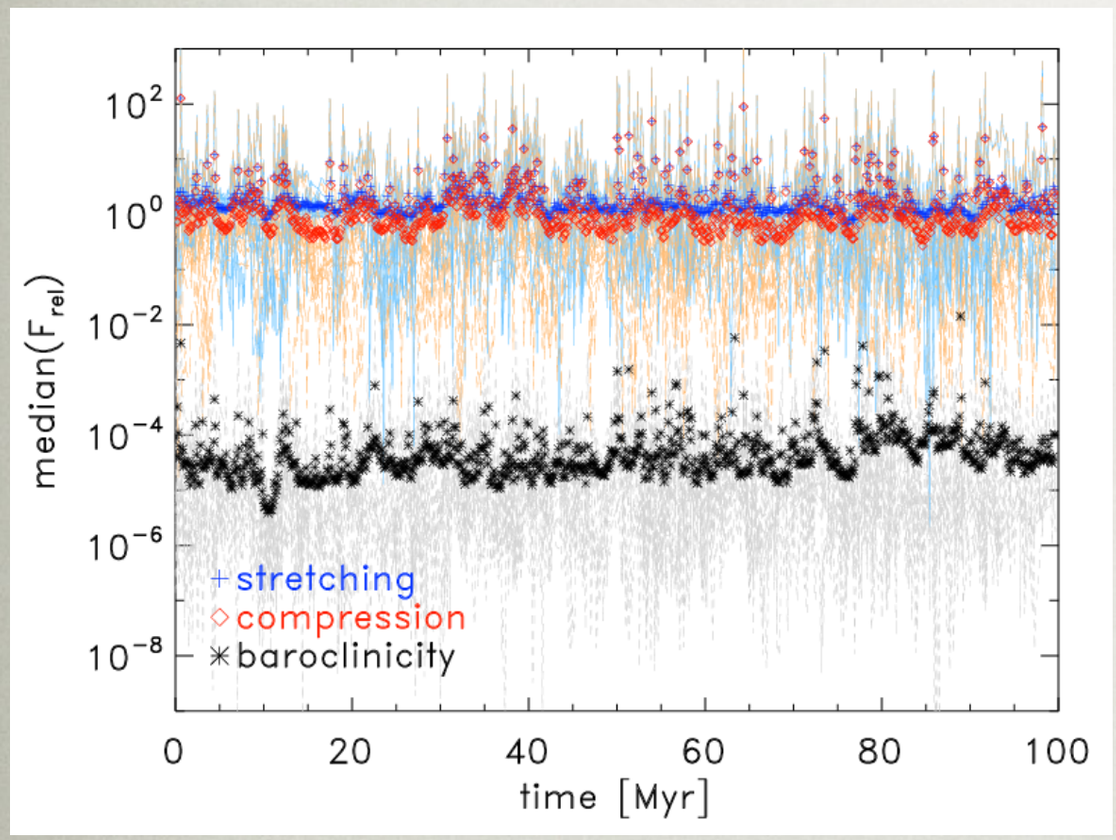
weak shock heating

MS0735.6 cluster (McNamara+2005)



TURBULENCE

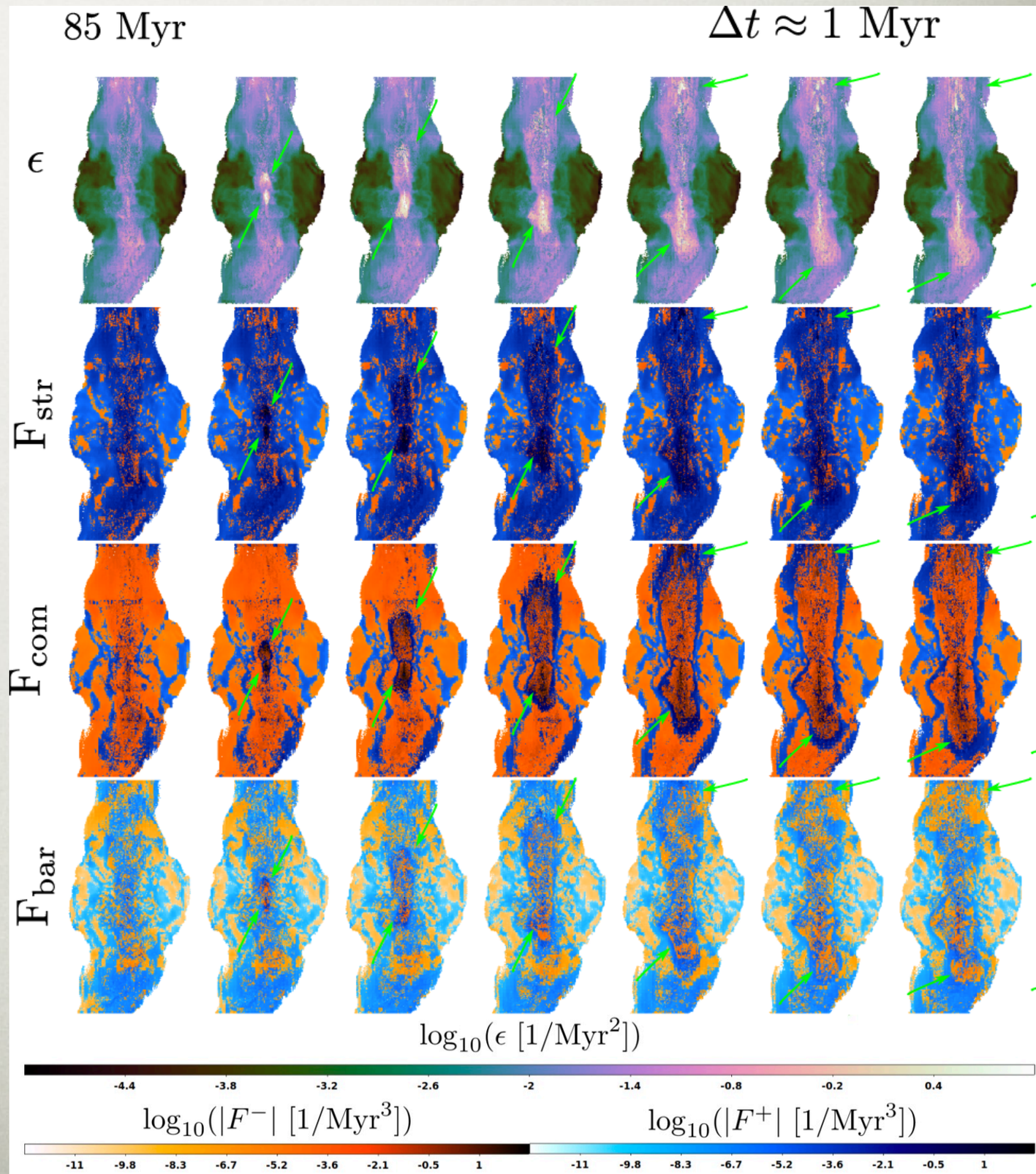
"Enstrophy" ~ magnitude (squared) of vorticity / turbulence



- stretching motions balanced by rarefactions
- baroclinic motions subdominant

Lagrangian tracers on top of AMR hydro simulation

Wittor & Gaspari 2020



AGN FEEDING & FEEDBACK UNIFICATION

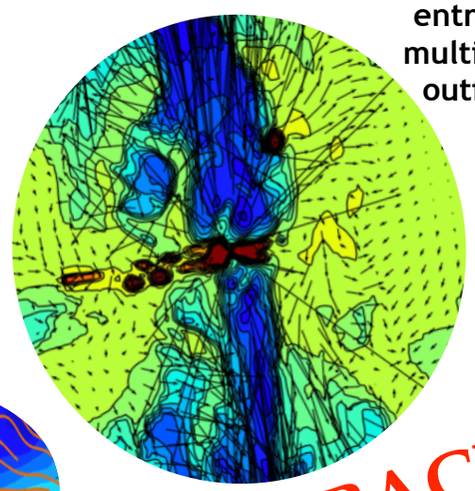
SUMMARY

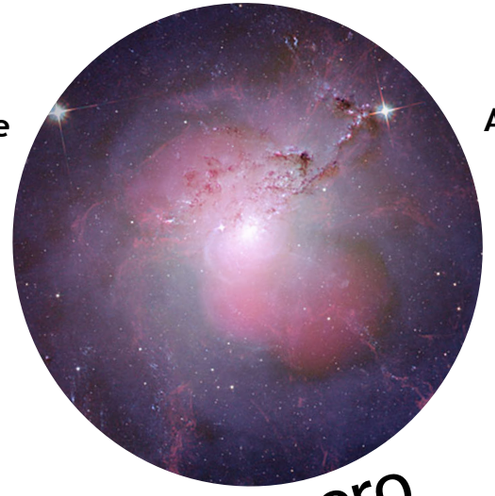
hot plasma: $T \sim 10^6 - 10^8\ K$

warm gas: $T \sim 10^3 - 10^6\ K$

cold gas: $T \sim 10^0 - 10^3\ K$

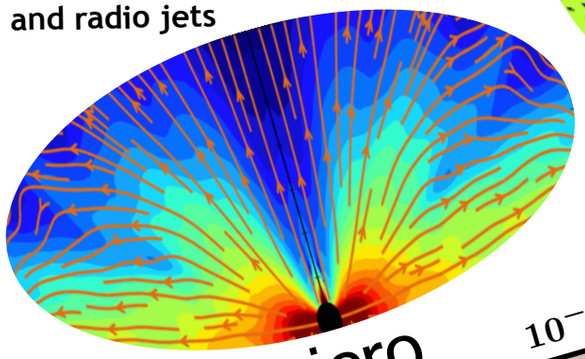
entrained multiphase outflows





AGN bubbles, shocks, turbulence

ultrafast outflows and radio jets



FEEDBACK

micro

meso

macro

r_{vir}

$10^{-3}\ r_{vir}$

$10^{-6}\ r_{vir}$

$10^{-9}\ r_{vir}$

mpc

pc

kpc

Mpc

r_S

SMBH

micro

meso

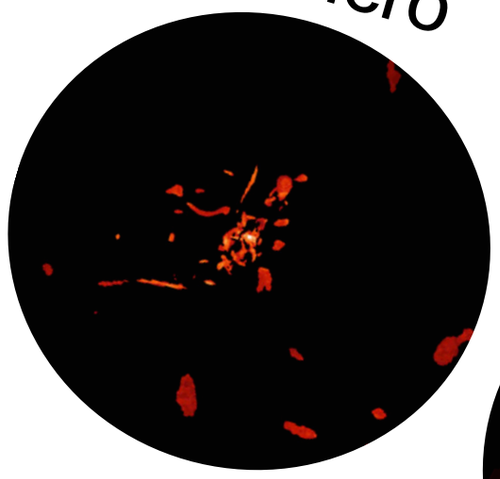
macro

$10^3\ r_S$

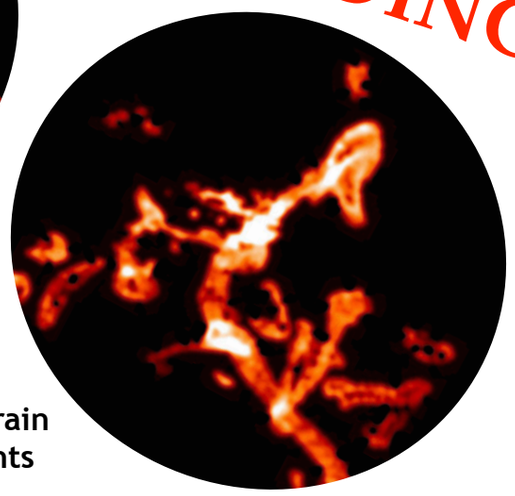
$10^6\ r_S$

$10^9\ r_S$

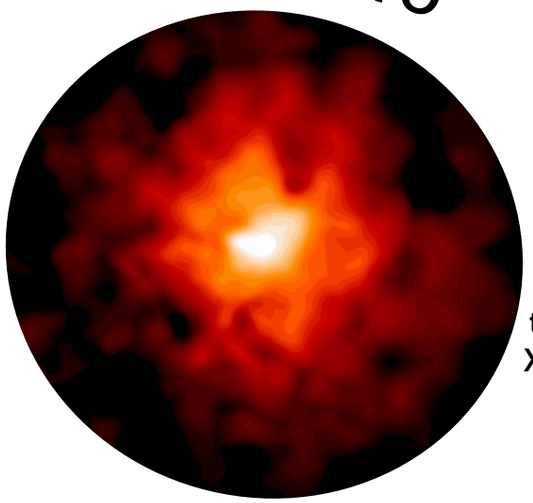
FEEDING



chaotic cold accretion (CCA)



multiphase rain and filaments



turbulent diffuse X-ray plasma halo

Gaspari+20
Nature Ast.
review