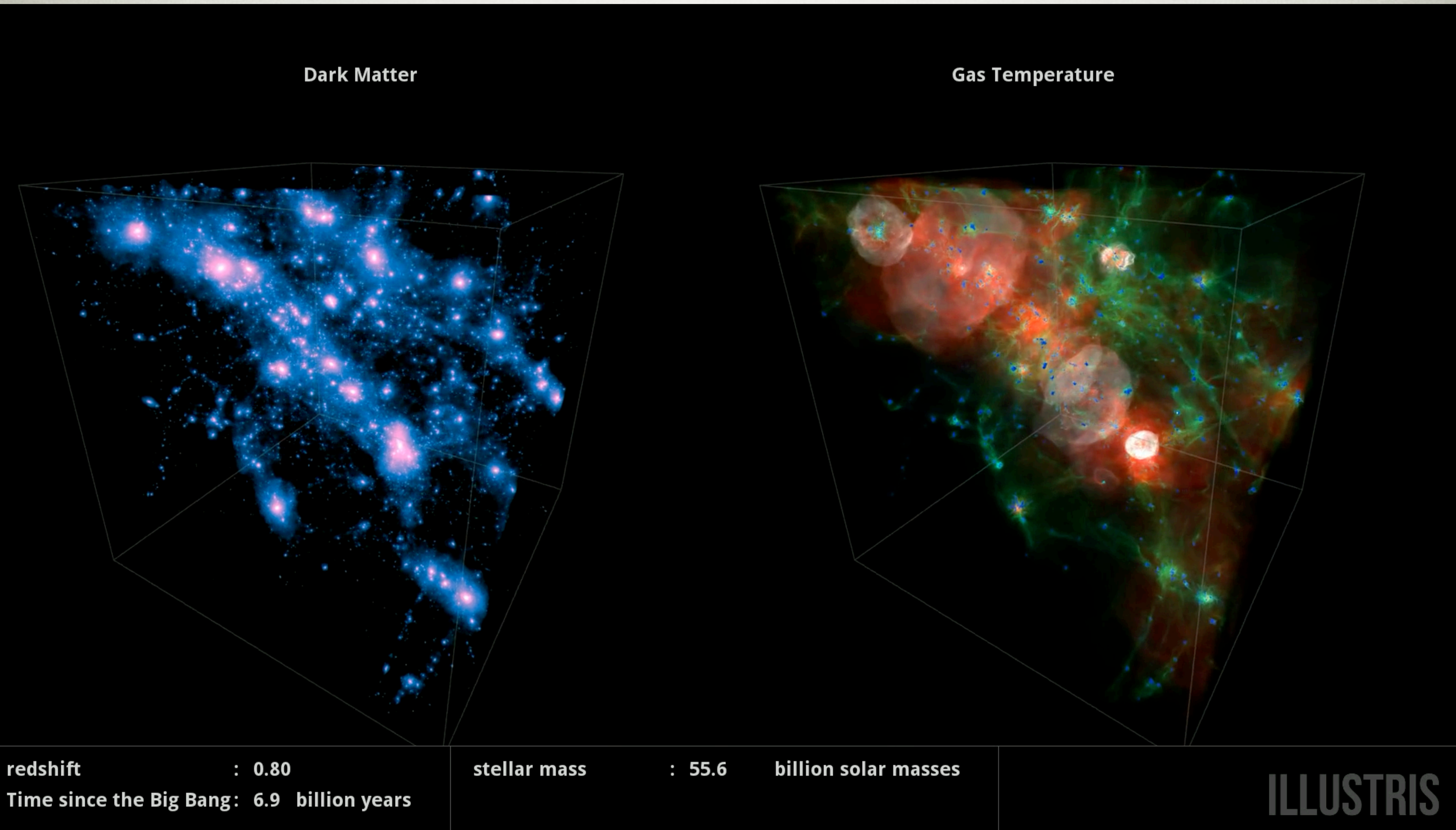
CHAOTIC COLD ACCRETION ONTO BLACK HOLES

Massimo (Max) Gaspari

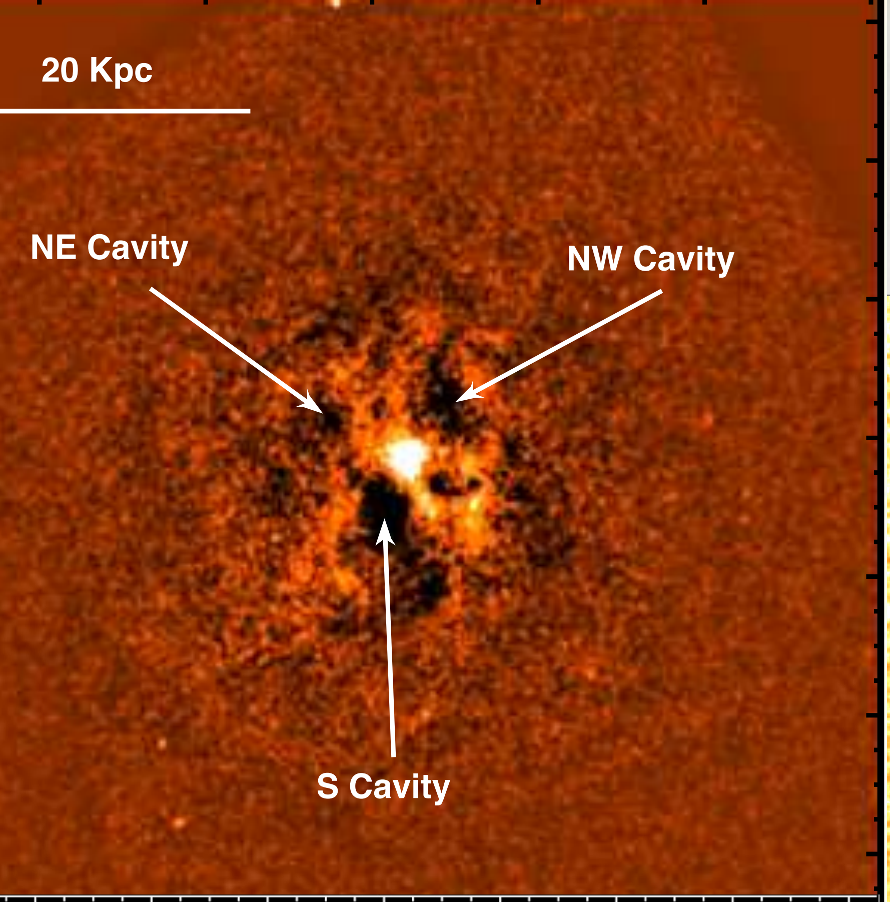
Princeton University

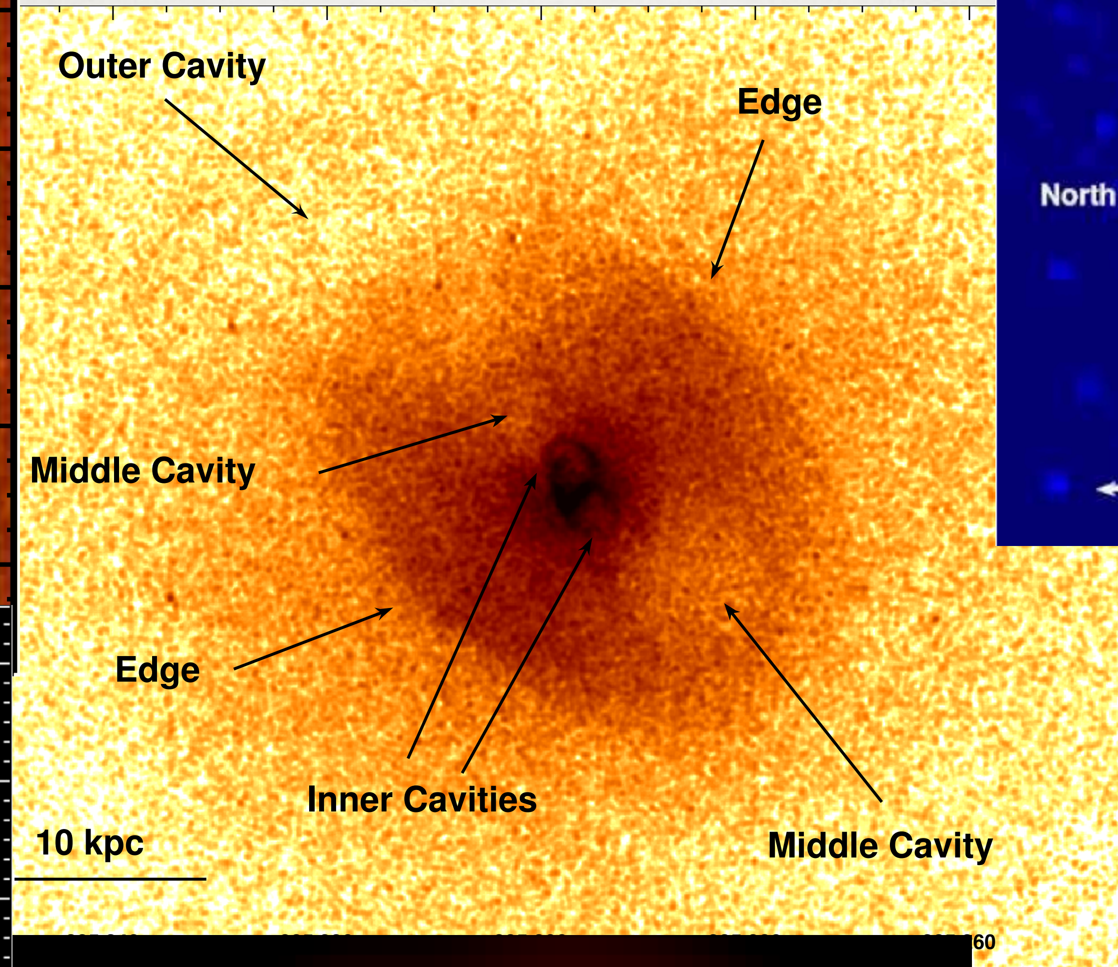
HOT PLASMA HALOS

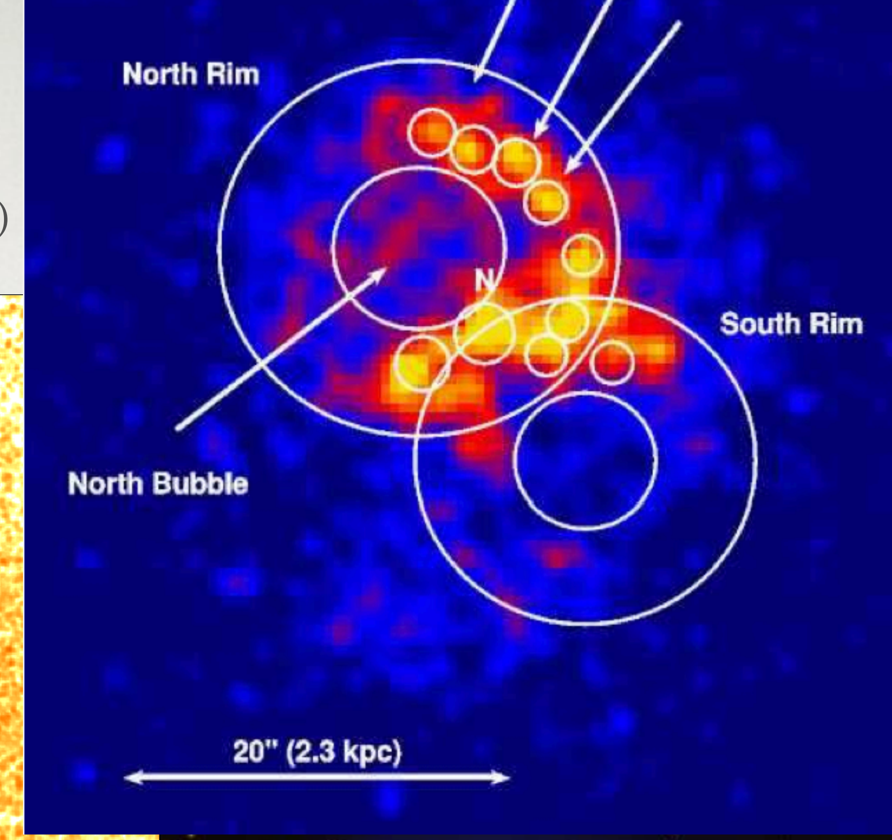


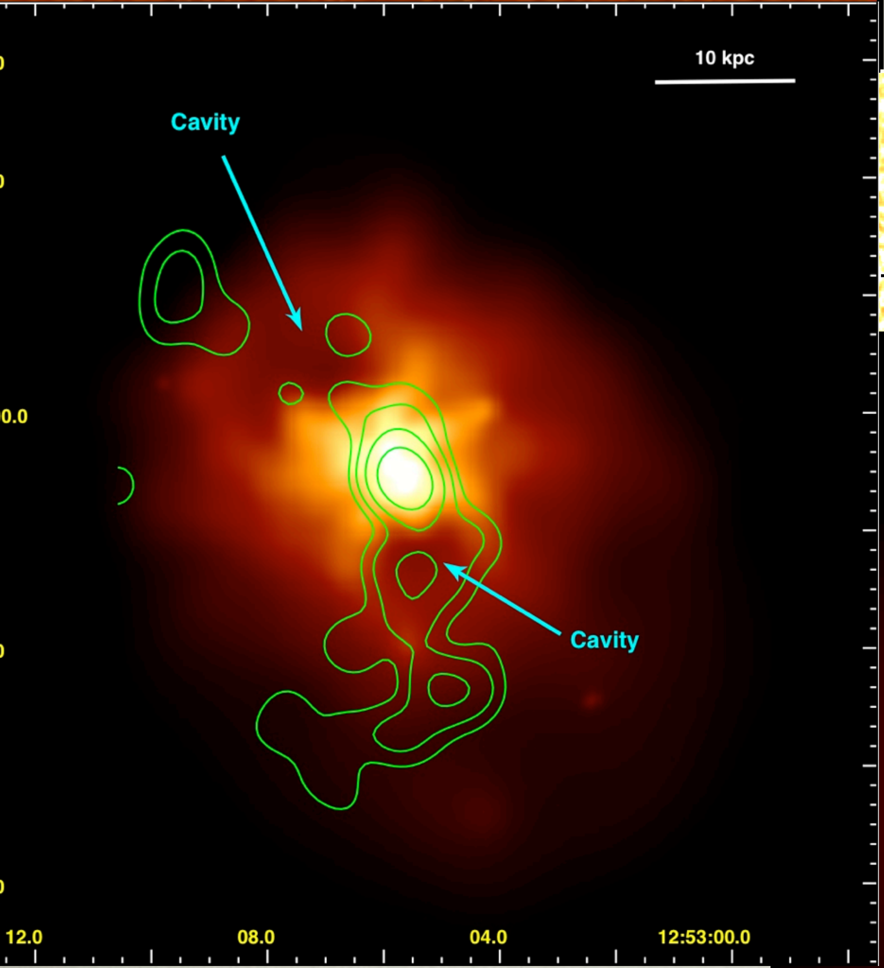
HOT HALOS

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

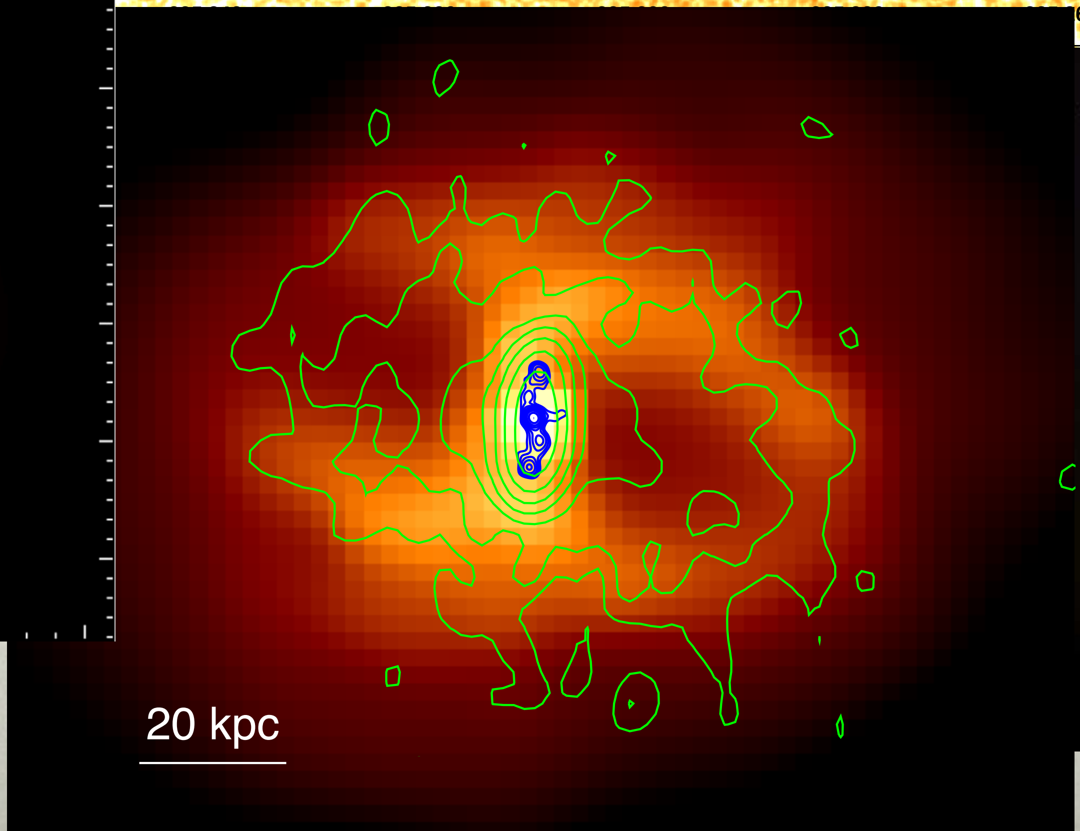




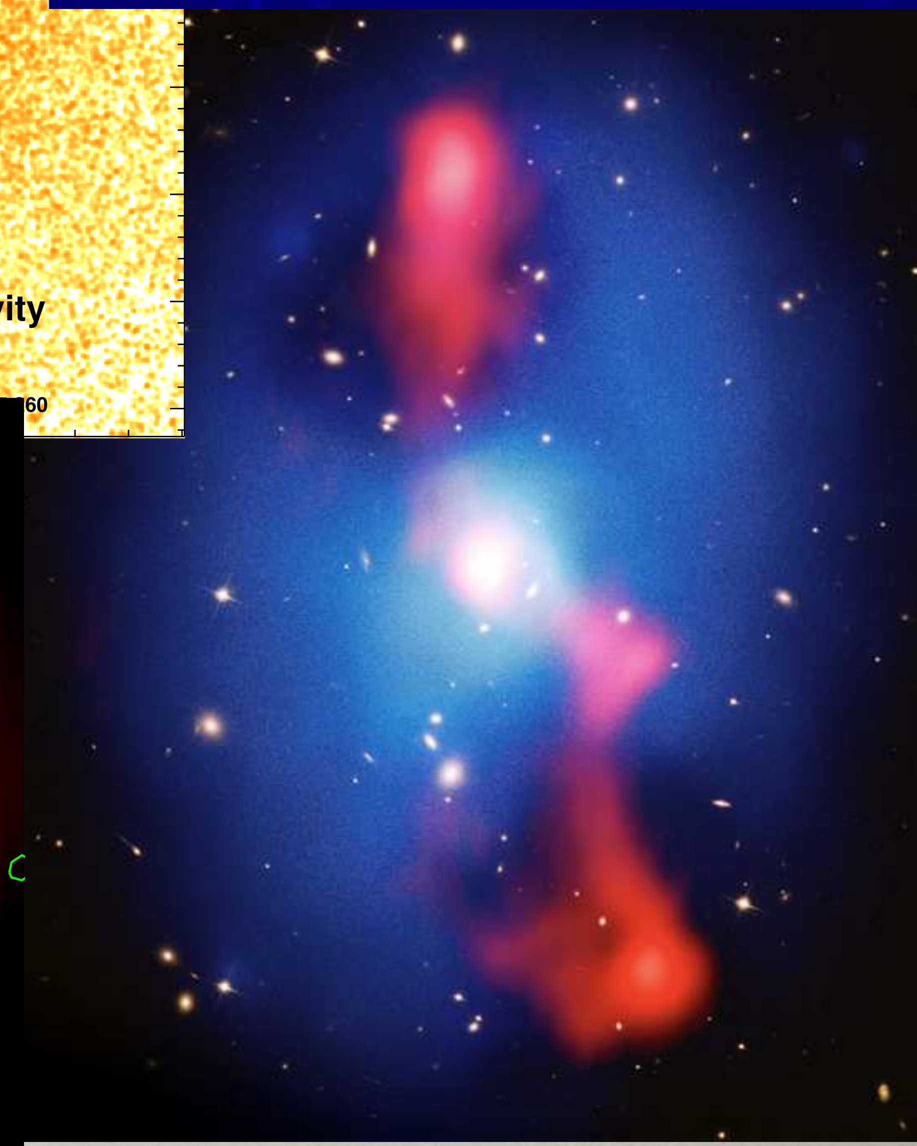




HCG 62 (Gitti+10)



RBS 797
(Gitti+11)



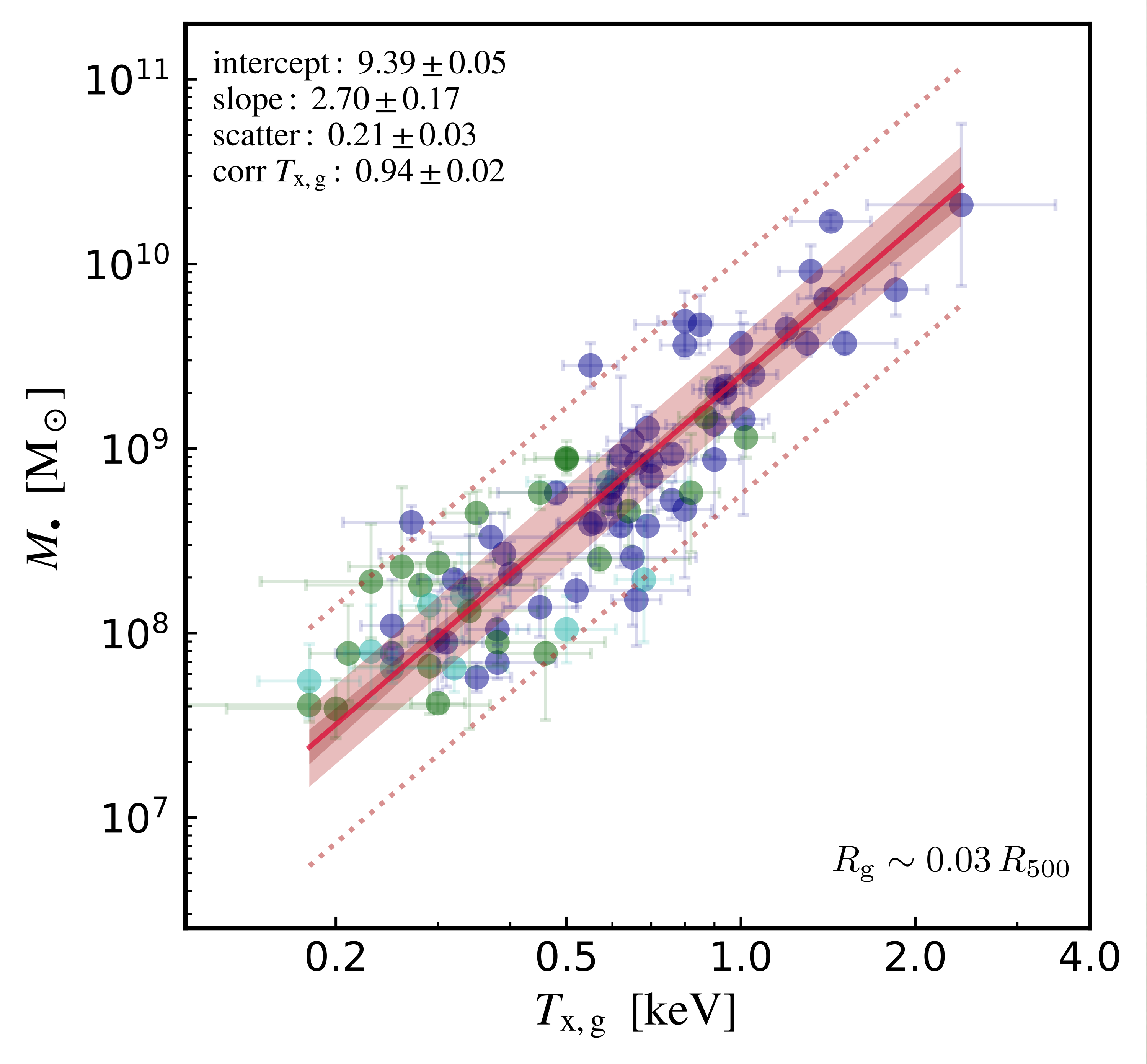
MS0735.6 cluster (McNamara+05)

SCALING RELATION: HOT HALO - SMBHS

Bayesian analysis:
85 galaxies, groups, clusters

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

dynamical BLACK HOLE (BH) MASS



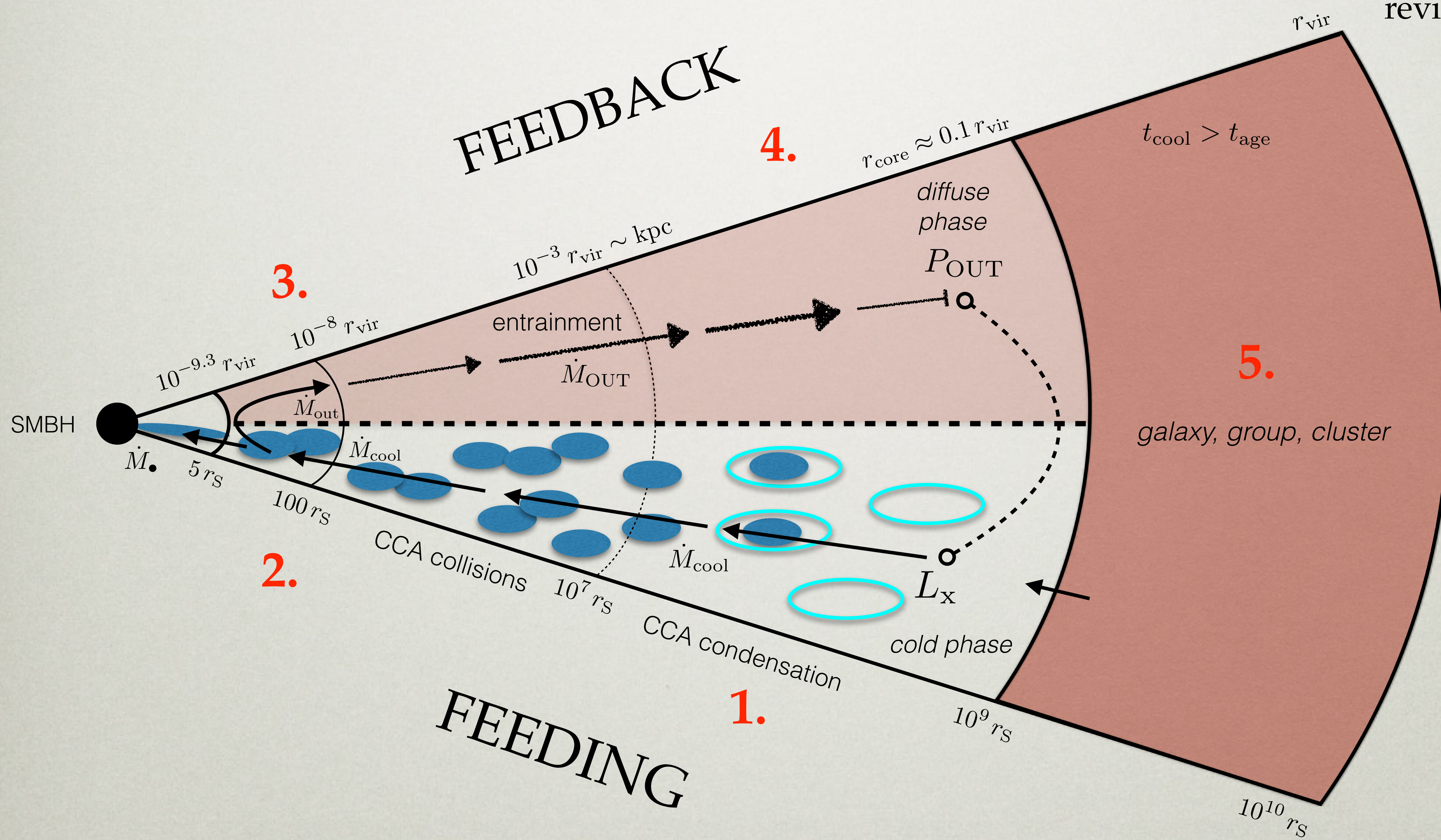
X-RAY TEMPERATURE

Gaspari et al. 2019

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

"BLACK HOLE WEATHER" PROGRAM

Gaspari+20
Nature Ast.
review/overview



GOAL 1: first-principle multi-scale simulations

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

MG+2011-2023

“For complexity, … ”
(physical)

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

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

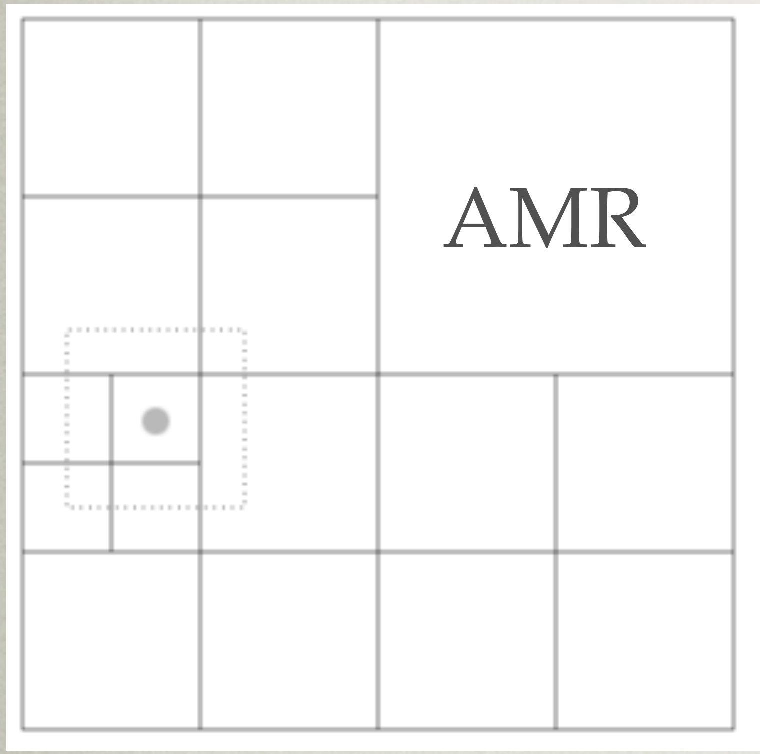
$$\begin{aligned} \frac{\partial \rho \varepsilon}{\partial t} + \nabla \cdot [(\rho \varepsilon + P)\, \boldsymbol{v}] = \rho \boldsymbol{v} \cdot \boldsymbol{g}_{\rm DM} + \alpha \rho_* \left(\varepsilon_0 + \frac{\boldsymbol{v}^2}{2} \right) \\ - n_{\rm e} n_{\rm i} \Lambda(T, Z) + S_{3,\rm jet},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

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

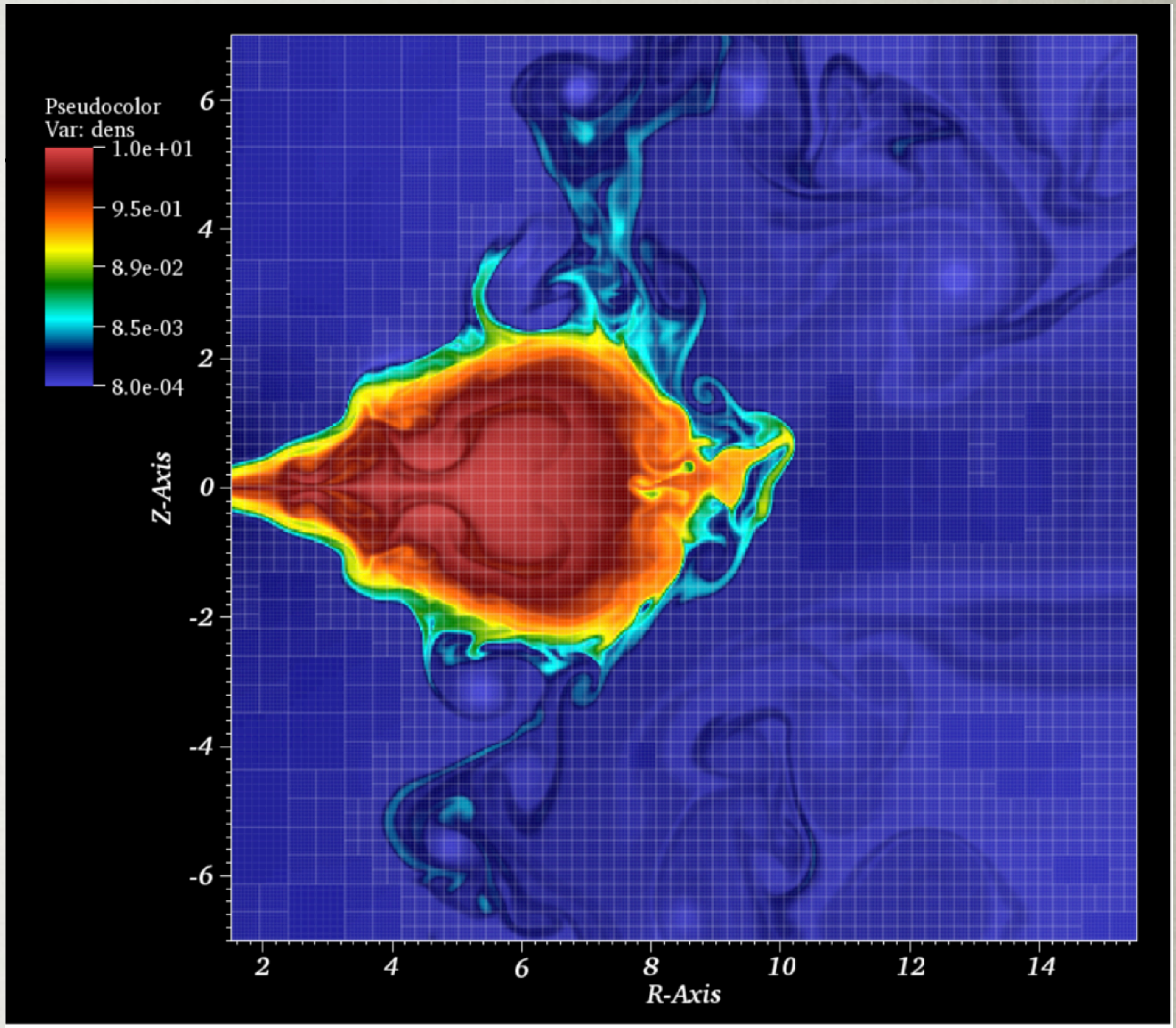
KEY: SIMULATIONS AS CONTROLLED EXPERIMENTS

Eulerian MHD codes

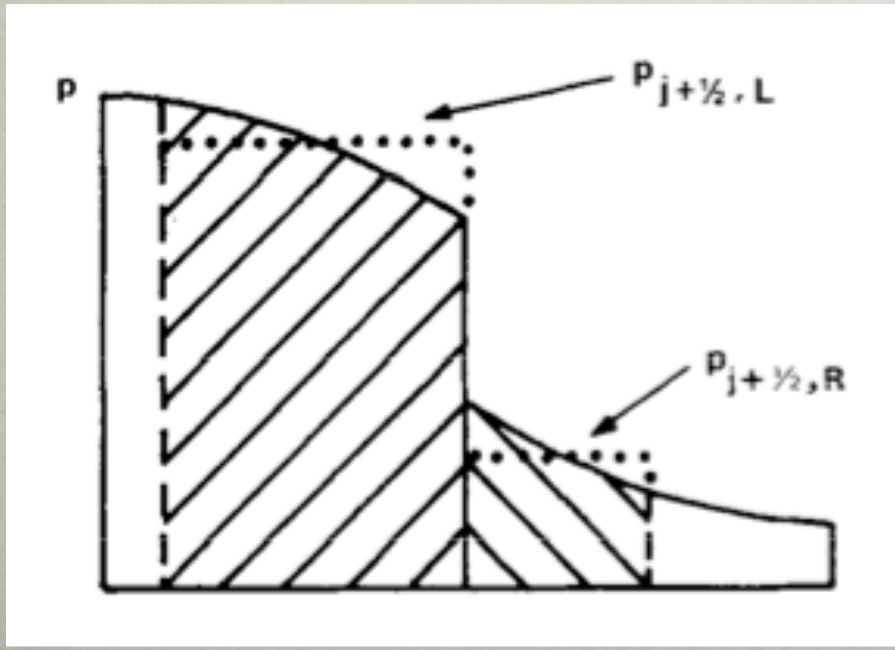
(FLASH4, ATHENA++, GAMER2)



AMR blocks:
high scalability
(100k+ CPUs)



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

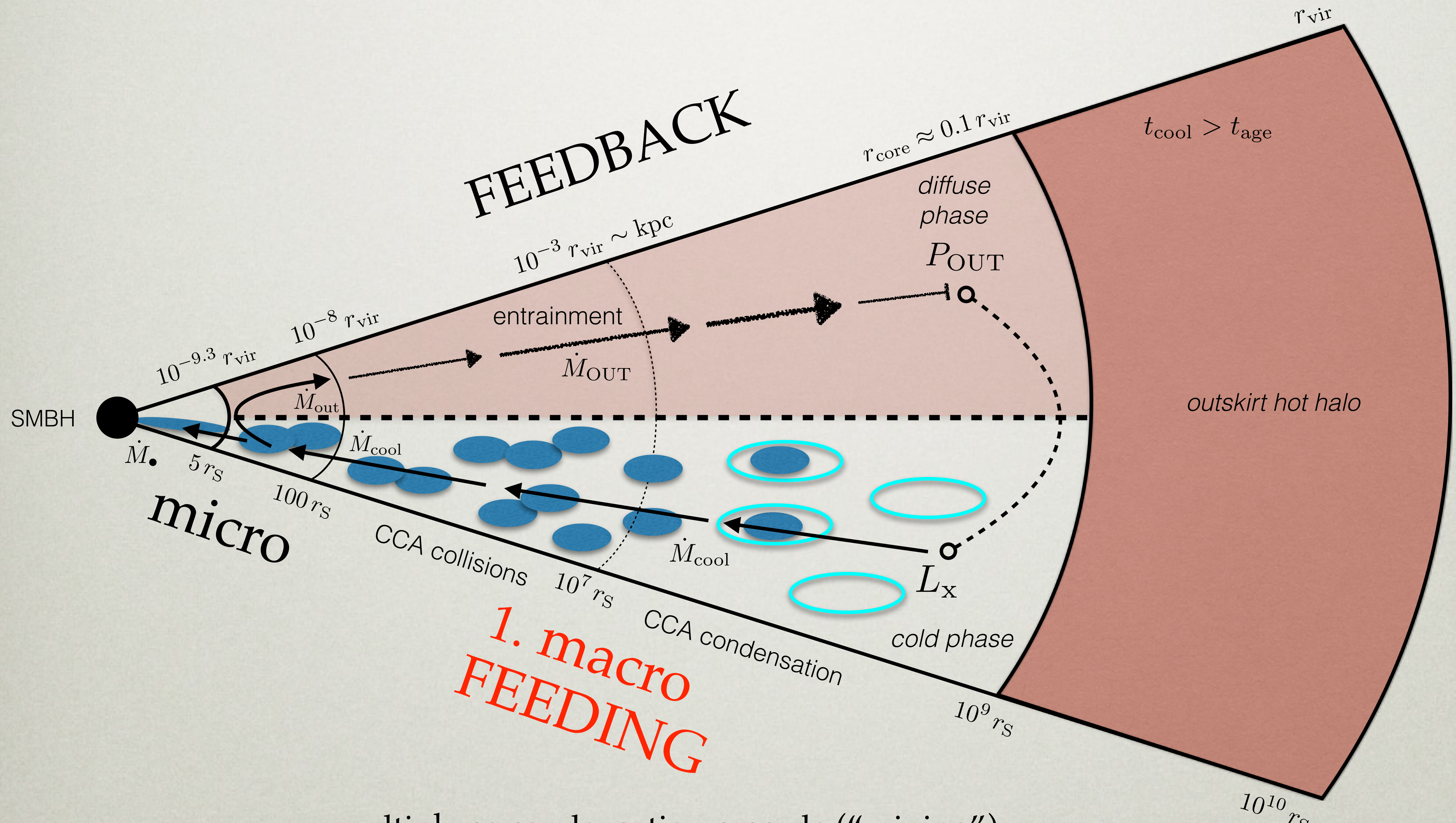


PPM

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

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

BH FEEDING AND FEEDBACK UNIFICATION



multiphase condensation cascade ("raining")

CCA = CHAOTIC COLD ACCRETION

MG+2011-2023

FEEDING SIMULATION

typical massively parallel run:

- concentric SMR zooming: **box = 100 kpc $\longrightarrow$ dx ~ 0.1 pc**

  ~10^6 range

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

SIMS AS CONTROLLED EXPERIMENTS

ON SPHERICALLY SYMMETRICAL ACCRETION

H. Bondi

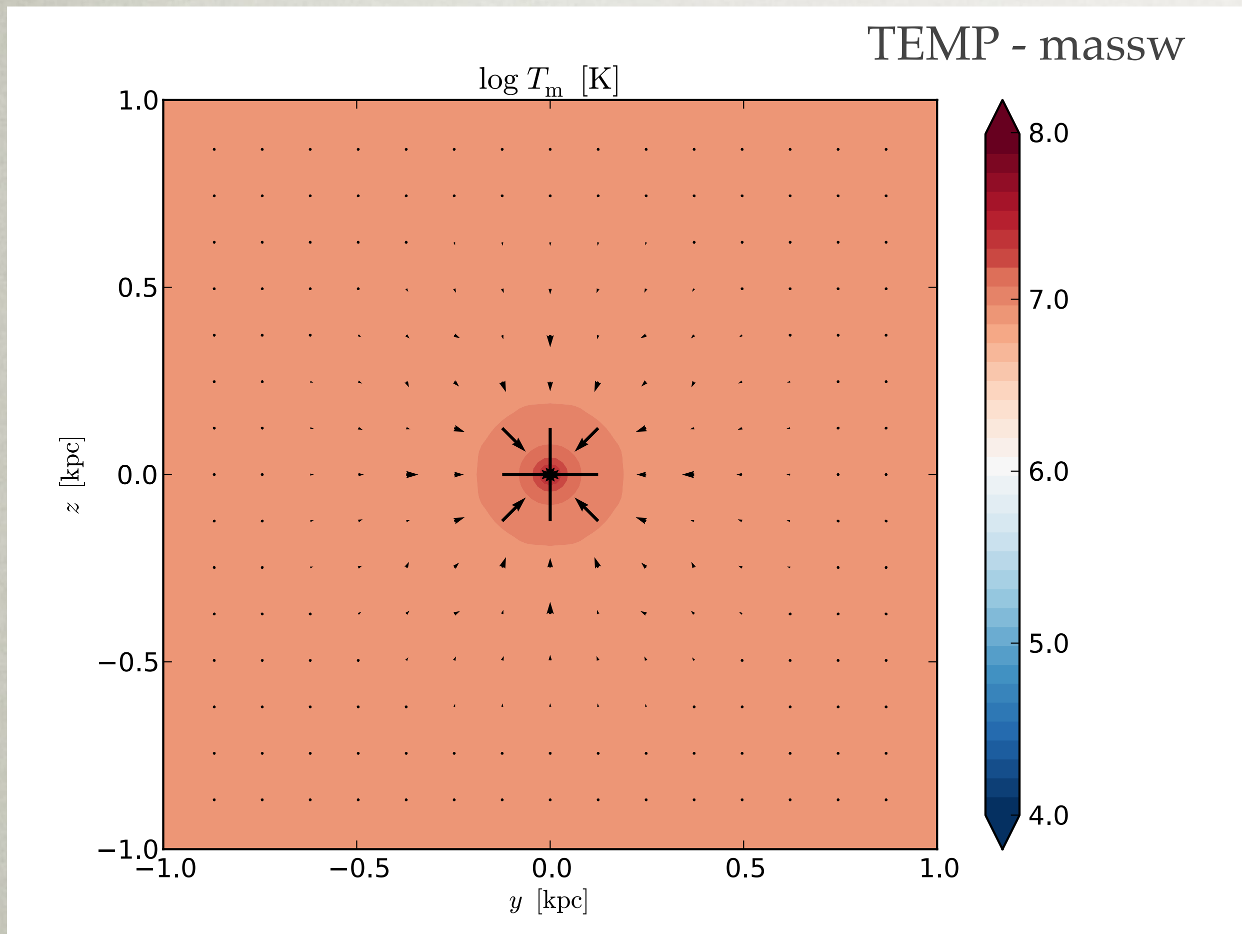
(Received 1951 October 3)

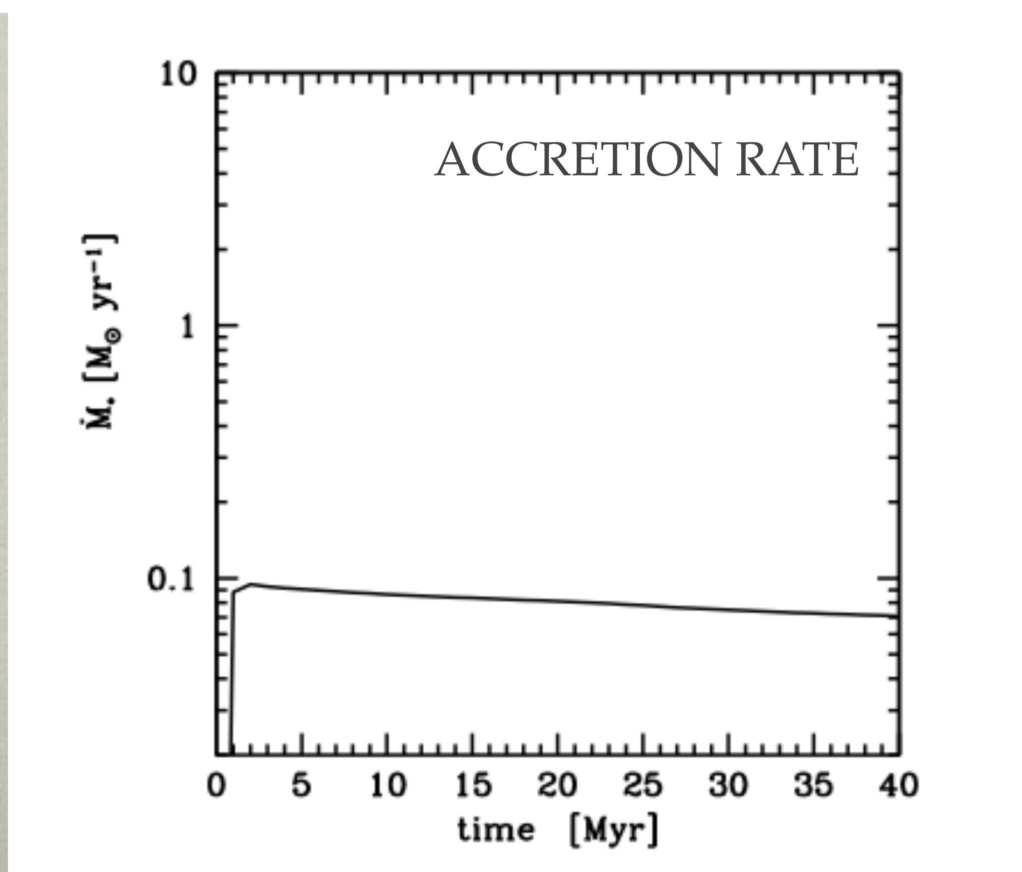
Summary

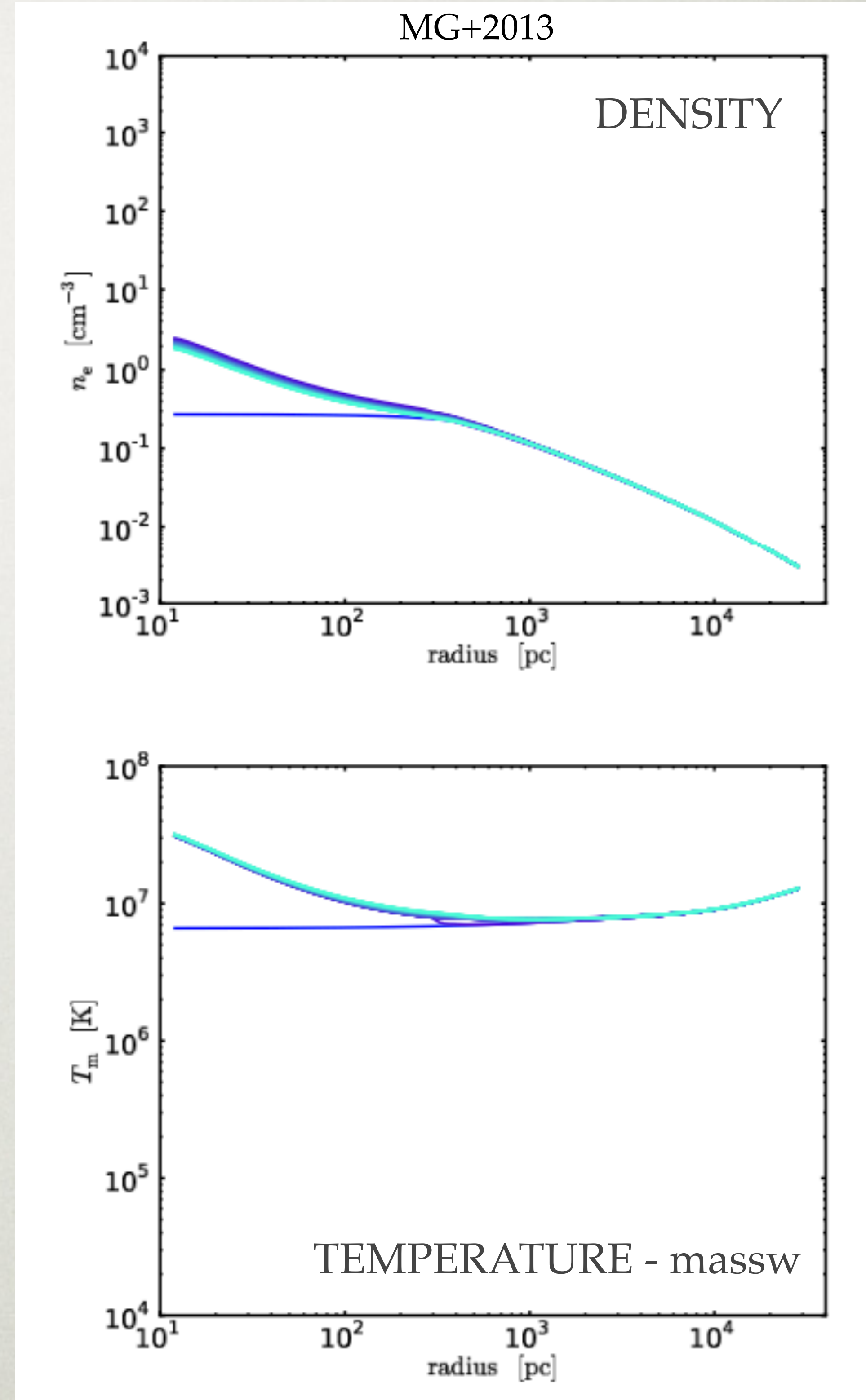
The special accretion problem is investigated in which the motion is steady and spherically symmetrical, the gas being at rest at infinity. The pressure is taken to be proportional to a power of the density. It is found that the accretion rate is proportional to the square of the mass of the star and 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.

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

PURE HOT MODE (BONDI)

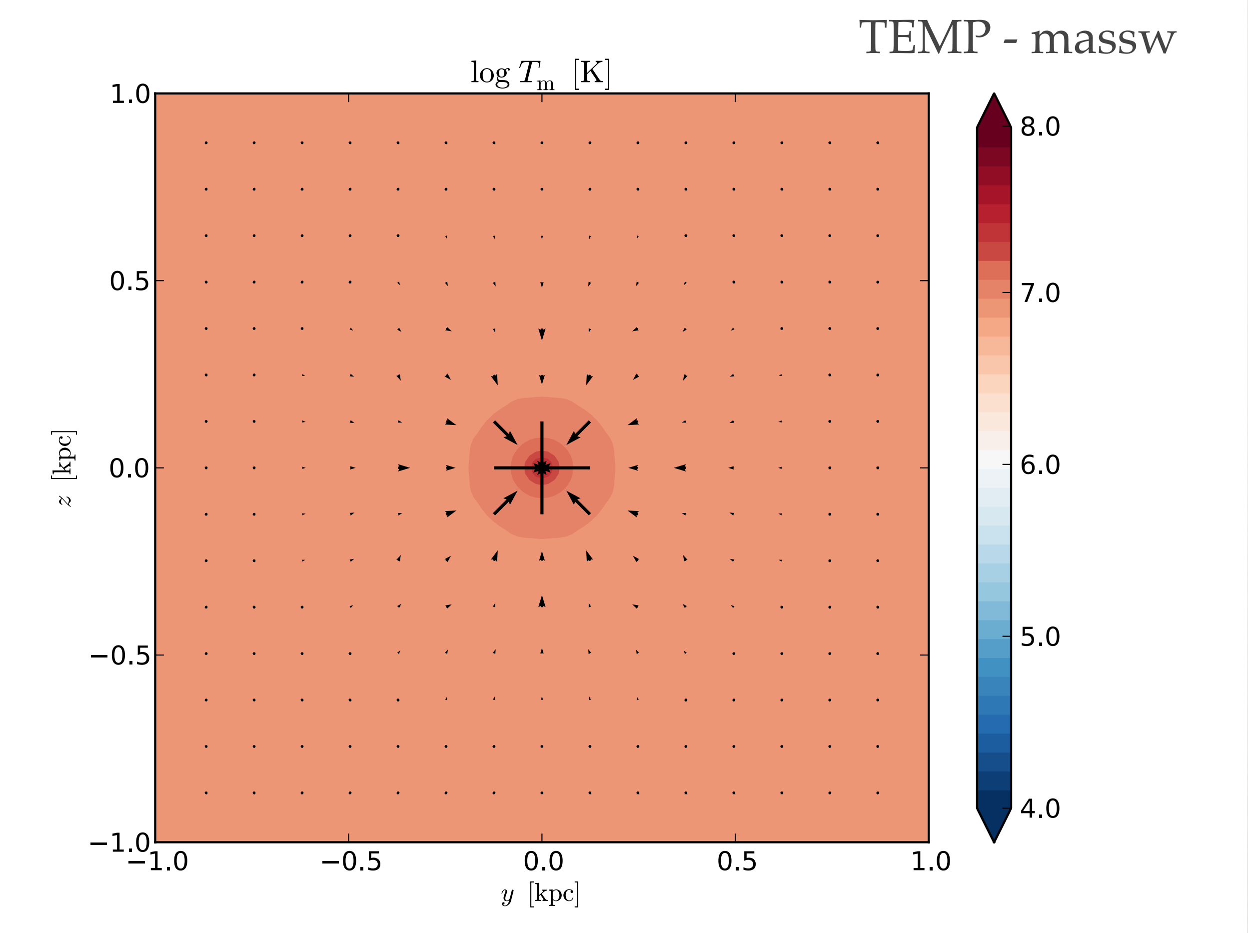


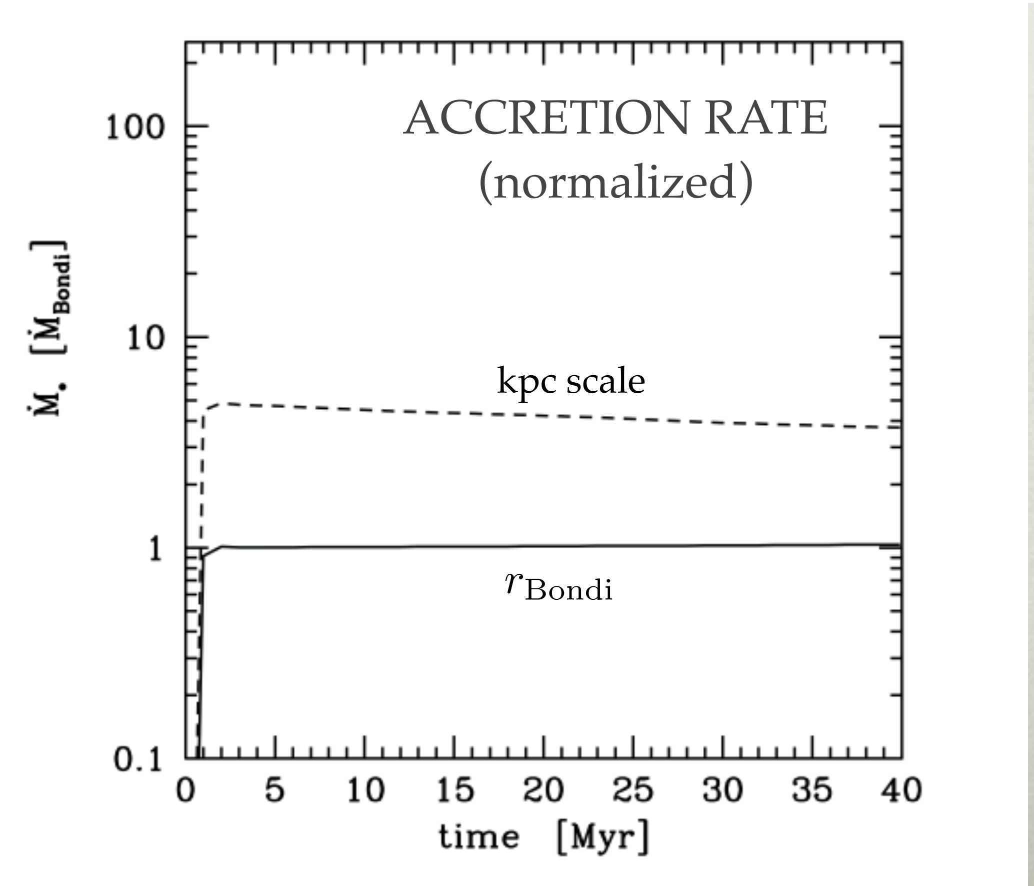


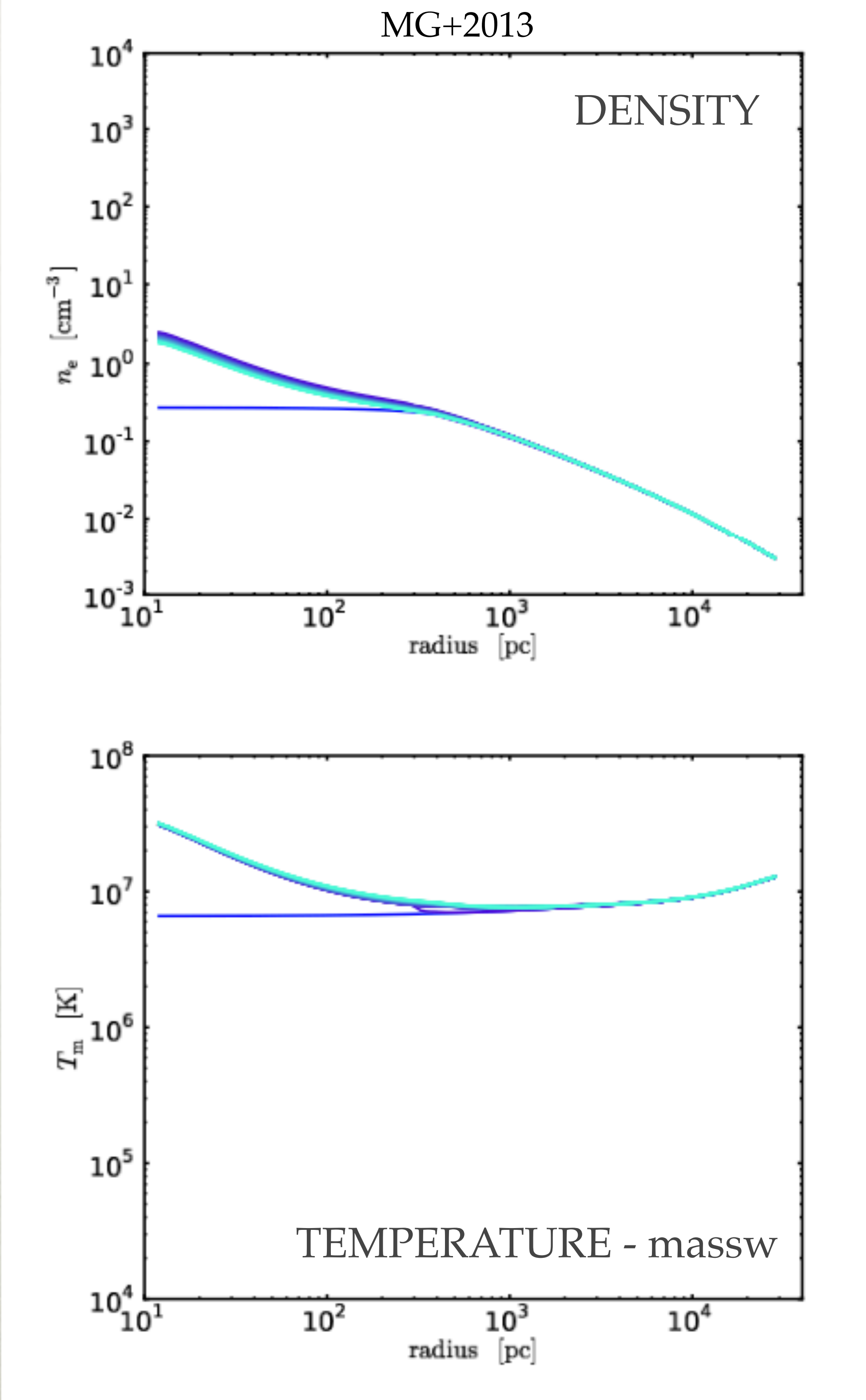


$$\dot{M}_{\rm Bondi} = 4\pi (G M_{\rm BH})^2 \rho_\infty / c_{s,\infty}^3$$

PURE HOT MODE (BONDI)

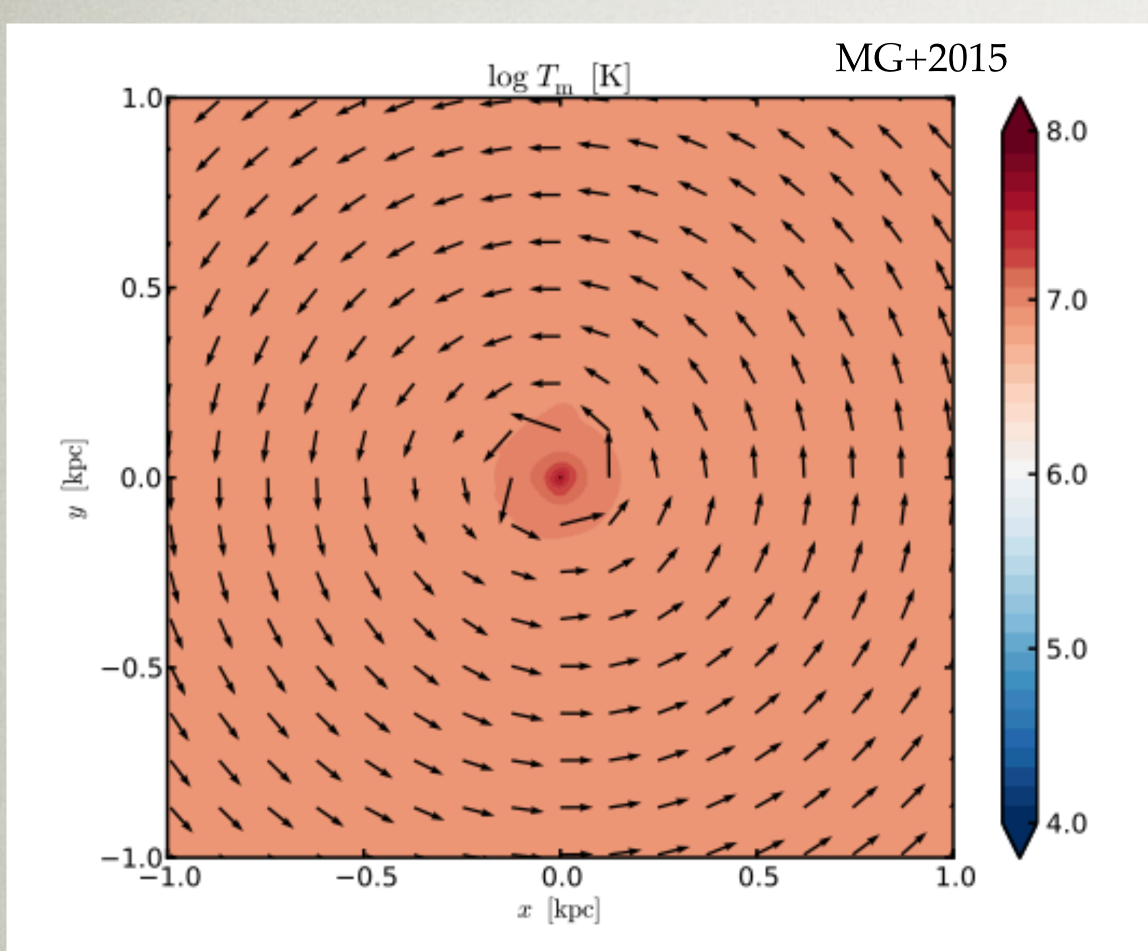




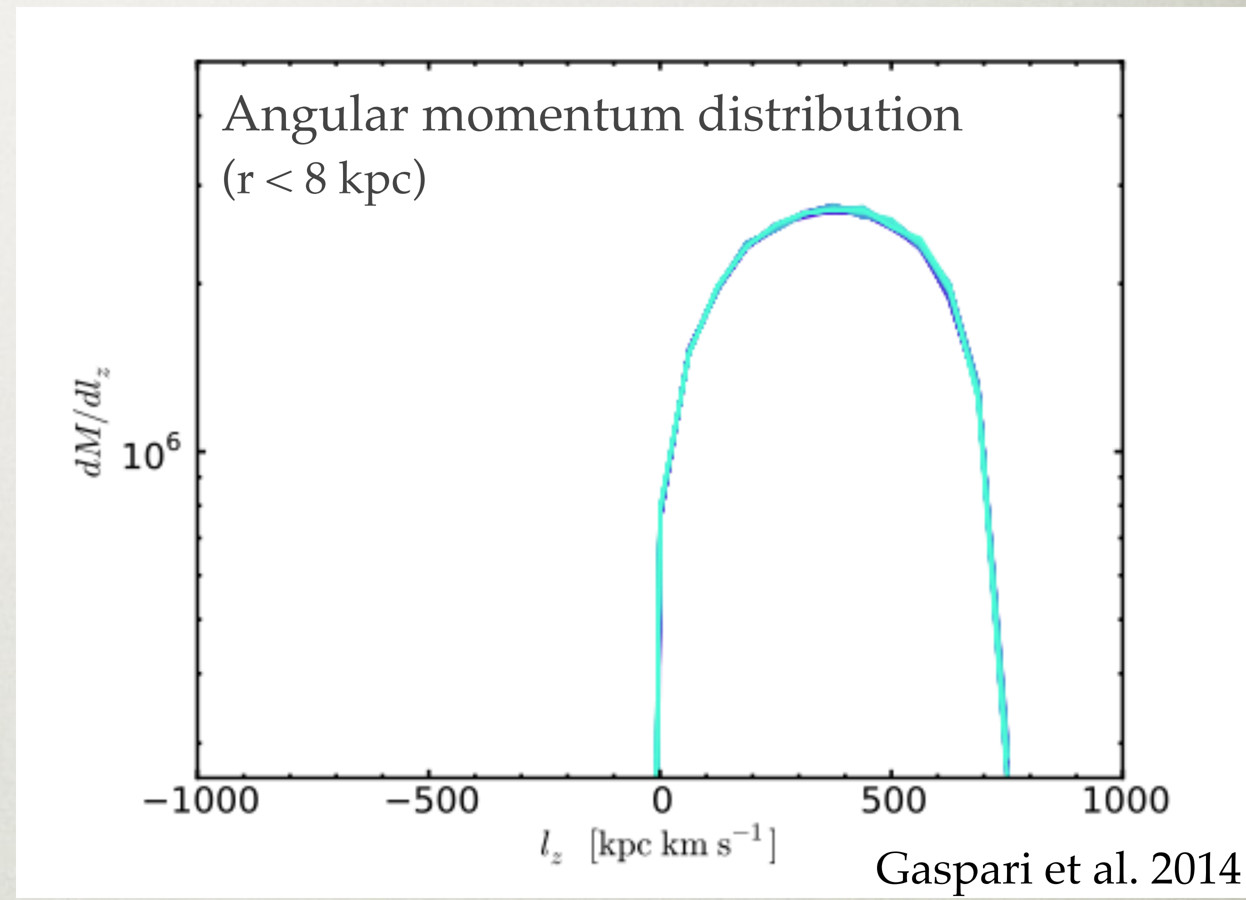


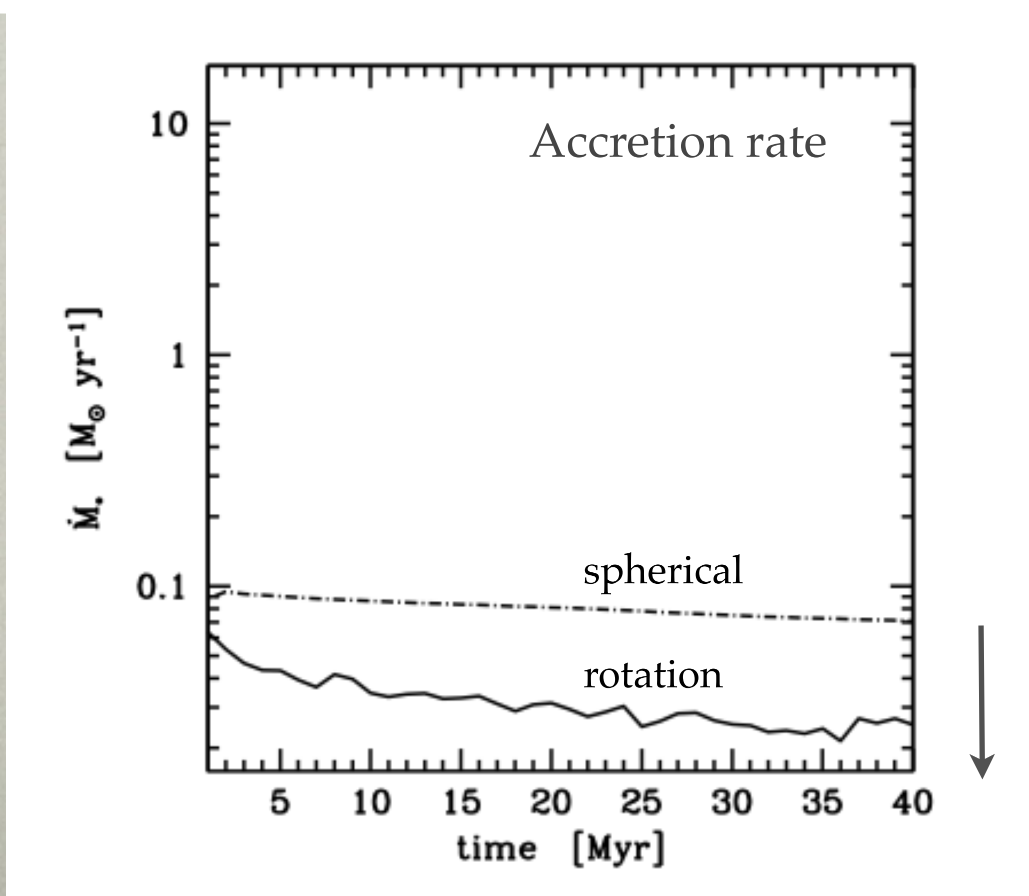
$$\dot{M}_{\rm Bondi} = 4\pi (G M_{\rm BH})^2 \rho_\infty / c_{s,\infty}^3$$

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

TURBULENCE IN HOT HALOS

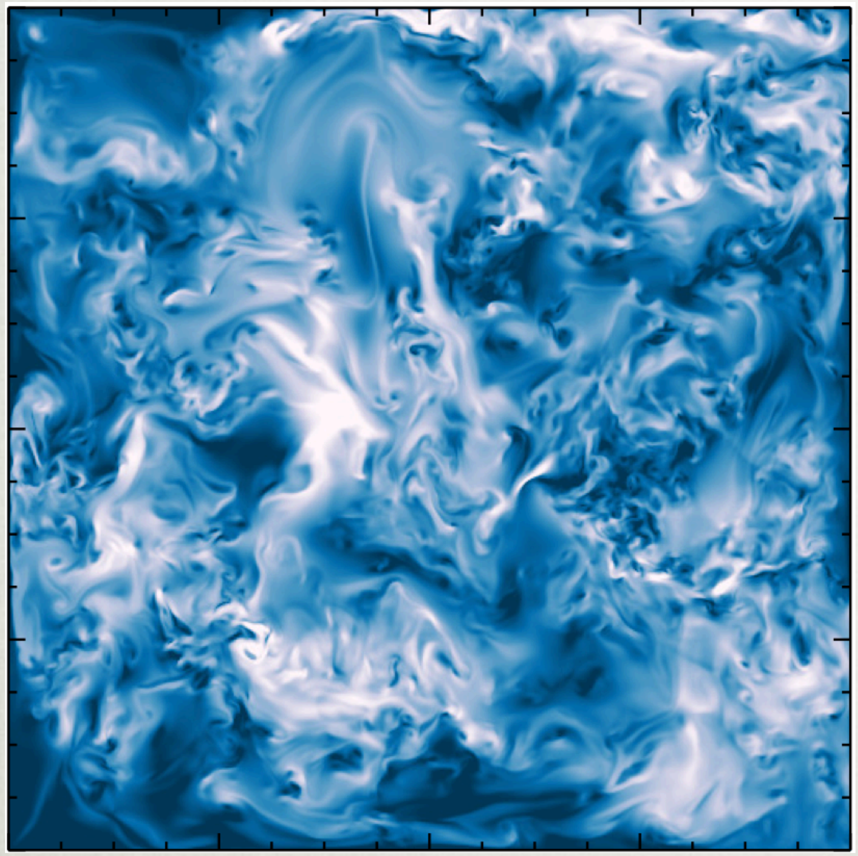
AGN feedback, SNe, mergers, galaxy/group infall

subsonic (100s km/s)

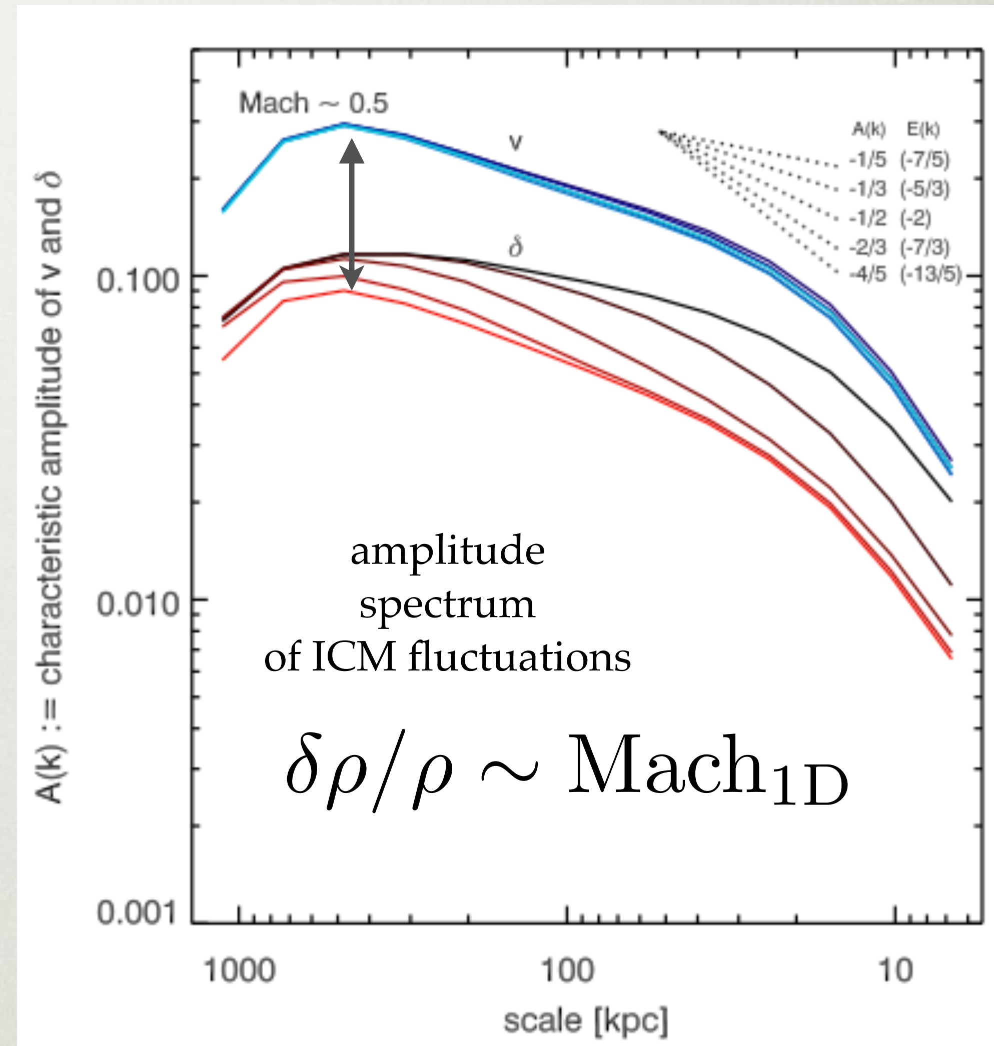
Simulations: e.g.,
Norman & Bryan 1999,
Lau, Nagai et al. 2009,
Vazza et al. 2011,
MG+2012b, Miniati+13

simulated
galaxy cluster

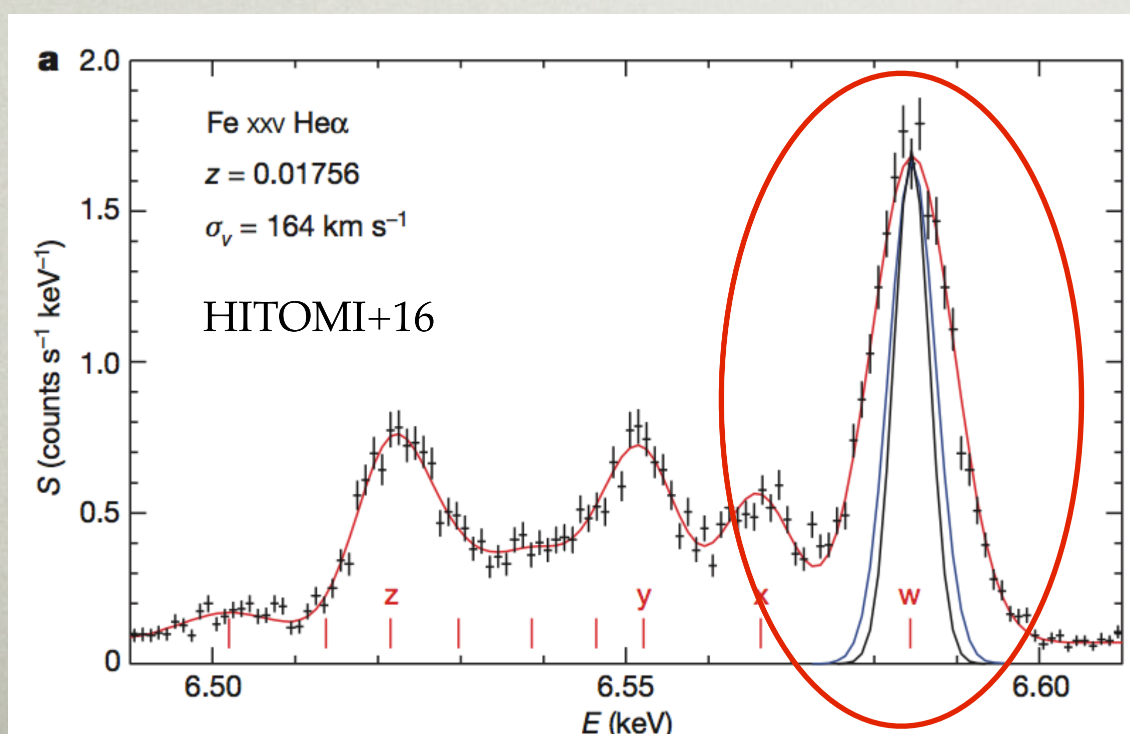
|v| cut



MG+14



MG+13,14,16



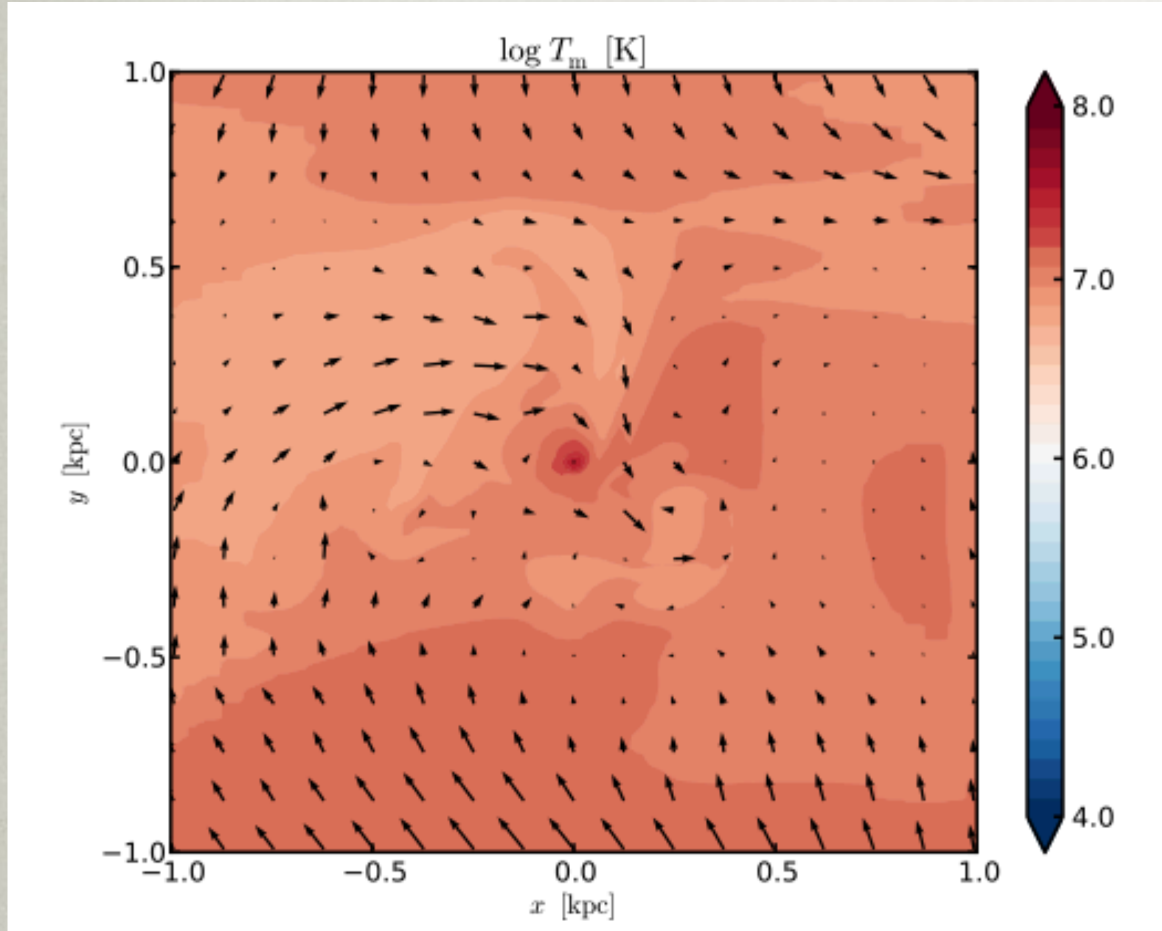
Typically, relaxed to unrelaxed systems -> Mach_{3D}~0.2-0.5

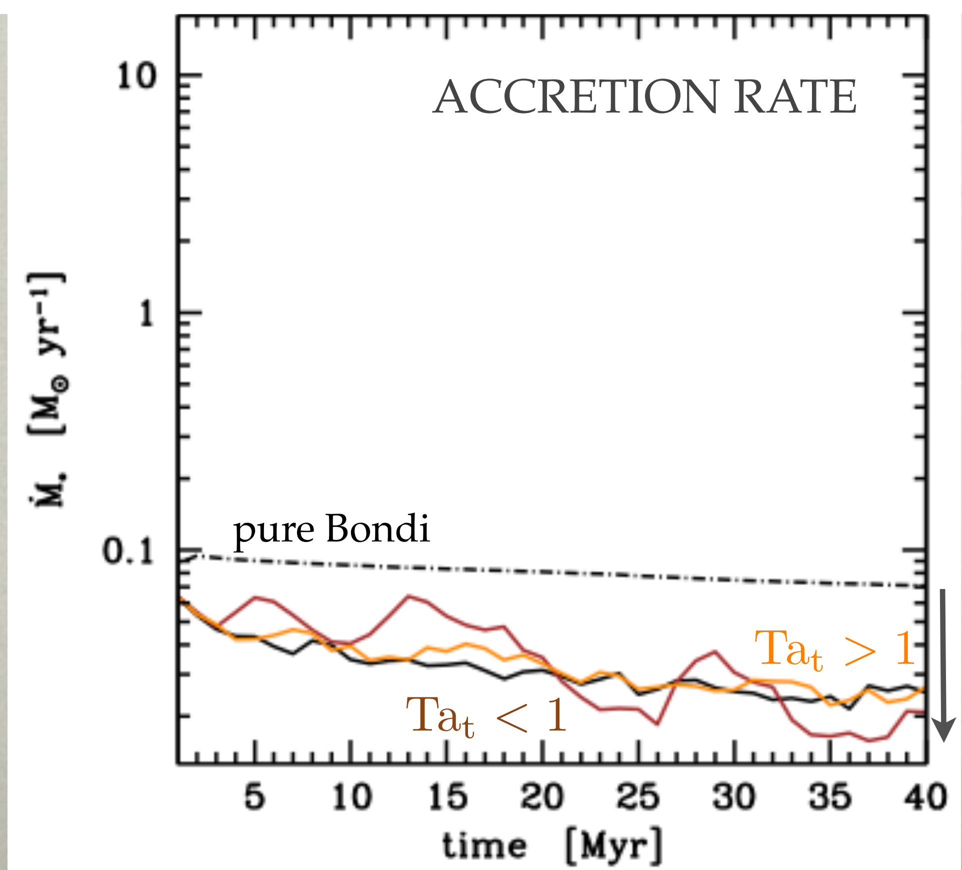
see also recent Ogorzalek+17 for similar RGS constraints in ETGs

TURBULENT HOT MODE (ROTATION)

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

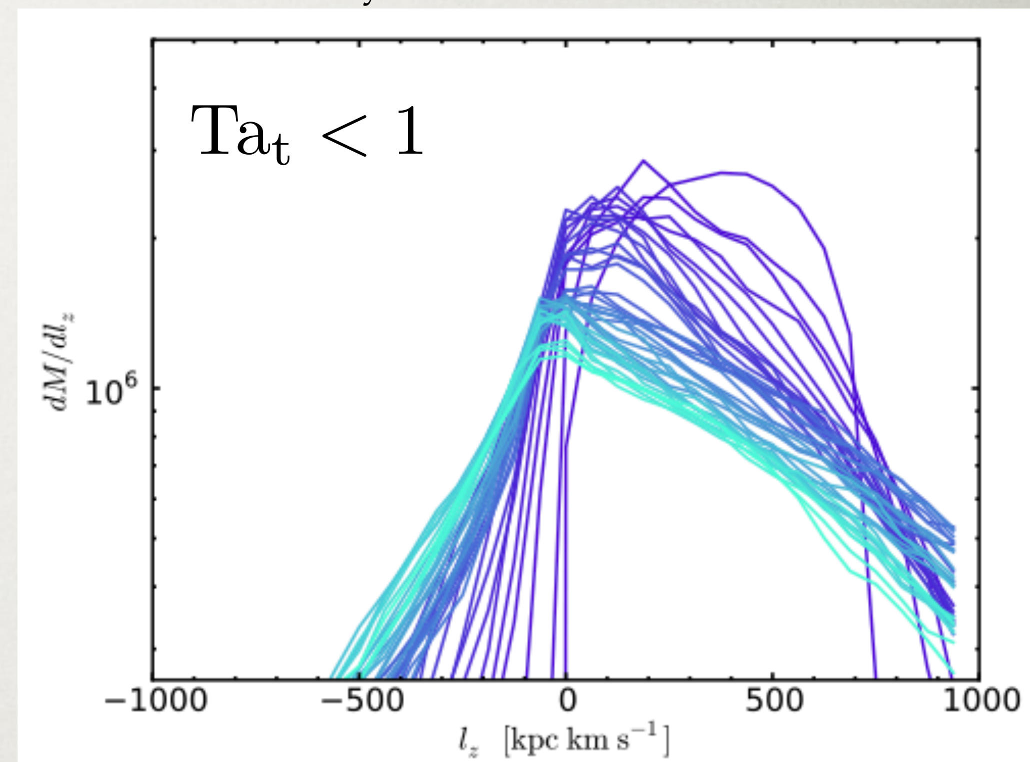
turbulent Taylor number



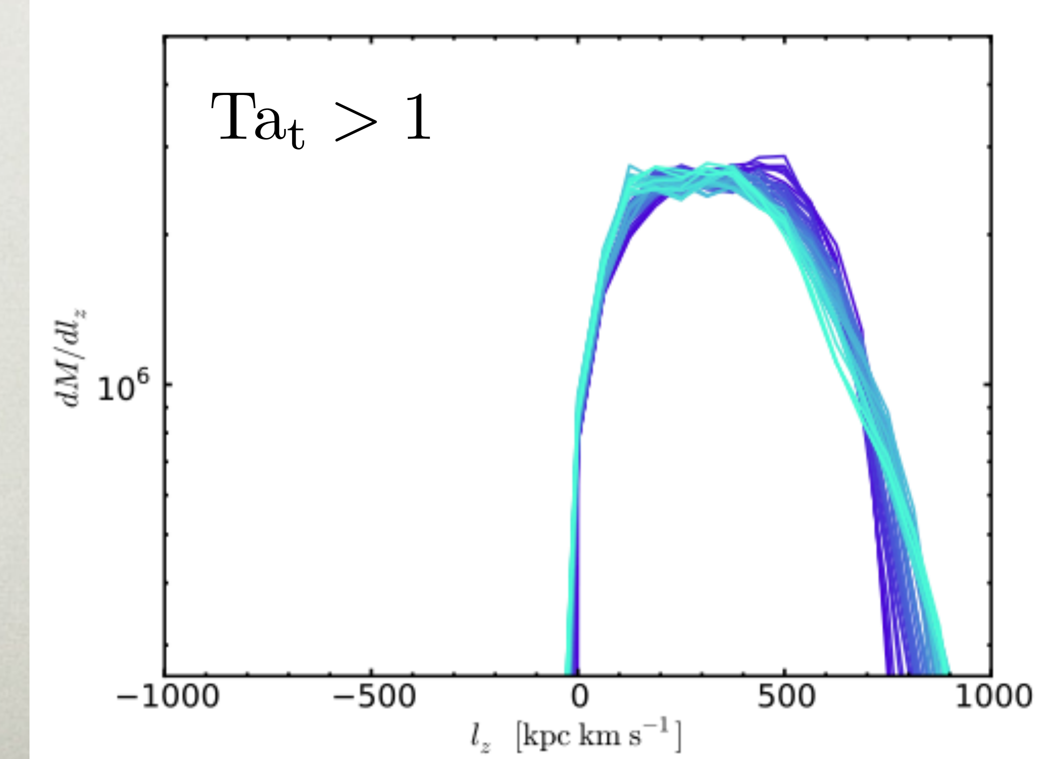


generation of local vorticity: again ~1/3 suppression

similar to purely rotating run (solid black line)

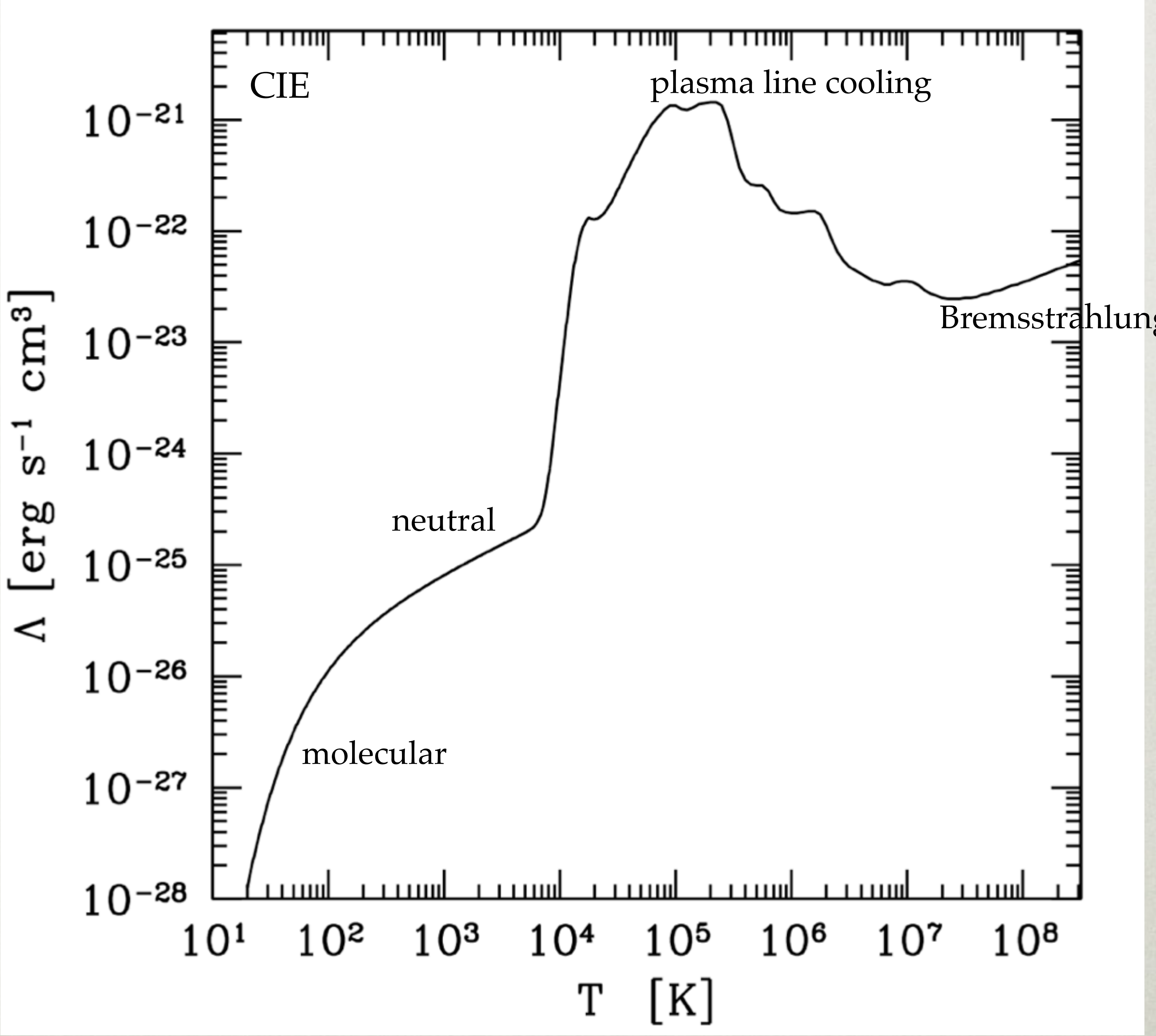


broadening allows retrograde motions



MG+15

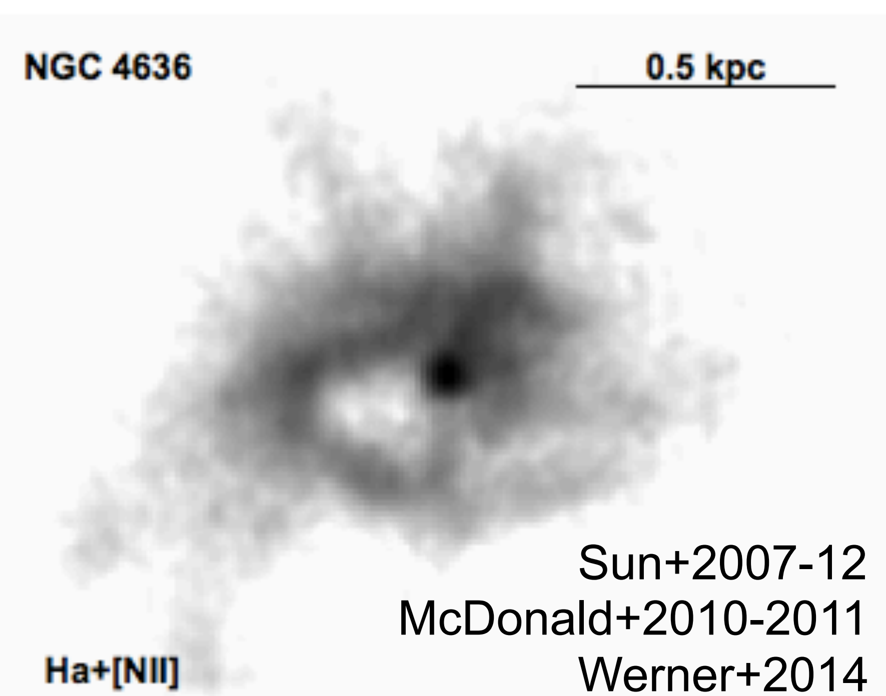
RADIATIVE COOLING

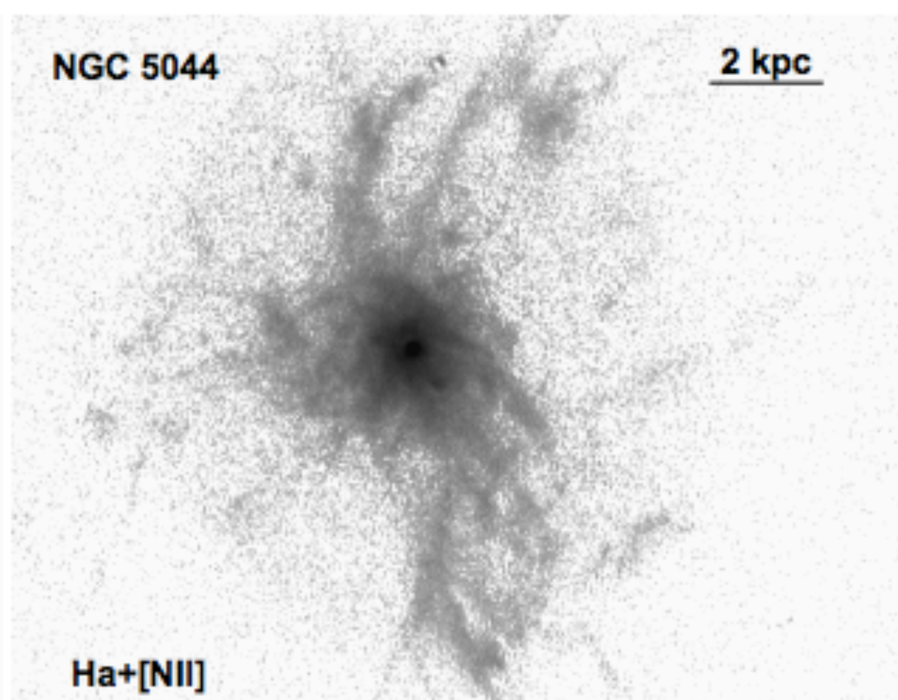


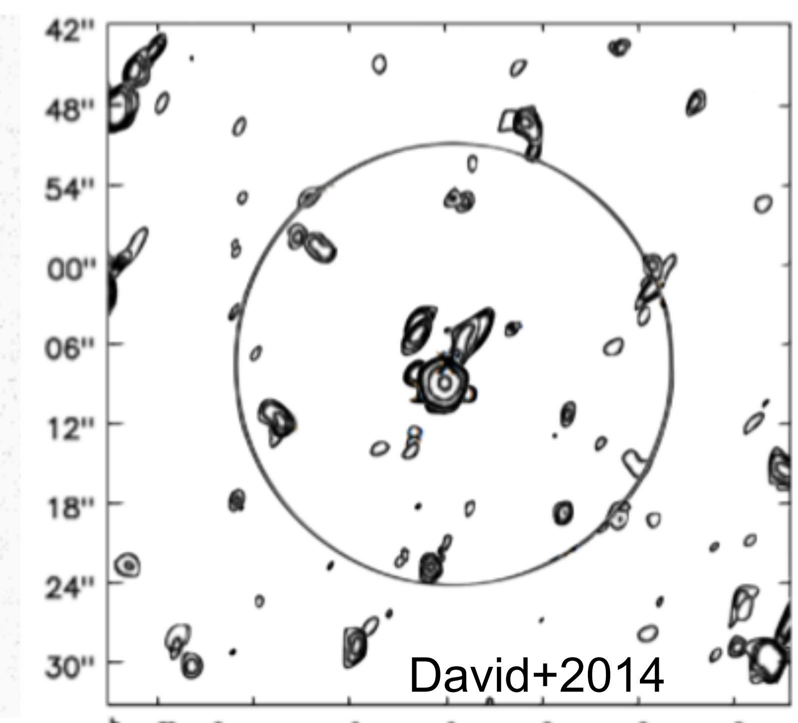
Sutherland & Dopita 1993
Inoue & Inutsuka 2008

$$\mathcal{L} \simeq -n^2\Lambda \qquad \mathrm{erg\,s^{-1}cm^{-3}}$$


RADIATIVE
COOLING
Perseus
Fabian et al.

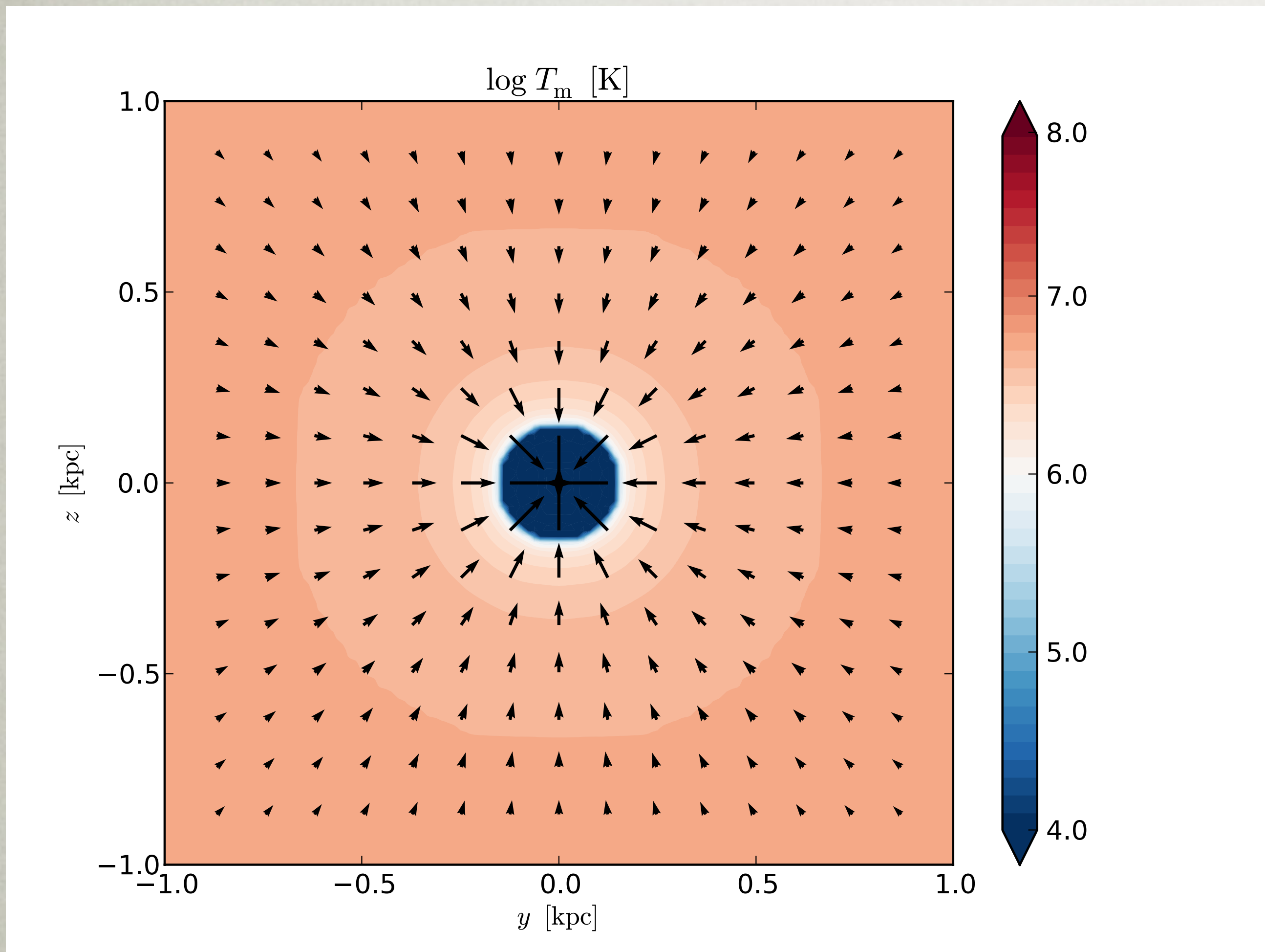

NGC 4636
0.5 kpc
Ha+[NII]
Sun+2007-12
McDonald+2010-2011
Werner+2014

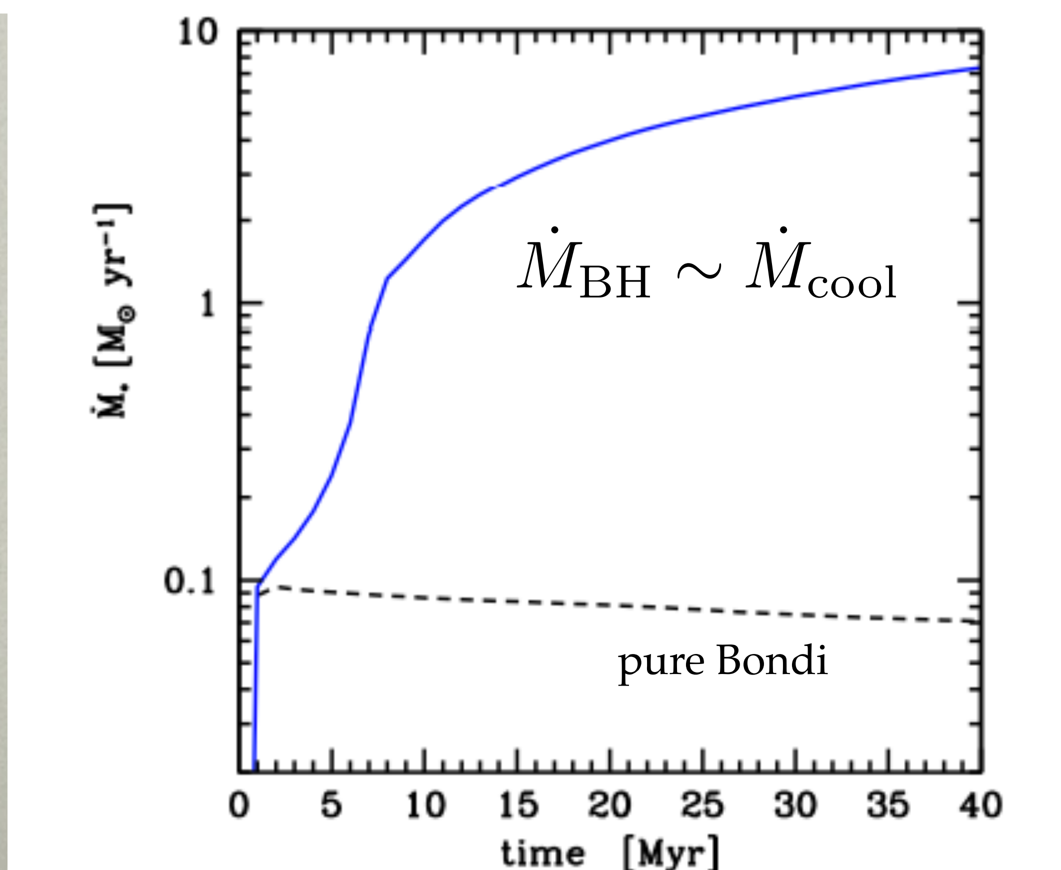

NGC 5044
2 kpc
Ha+[NII]

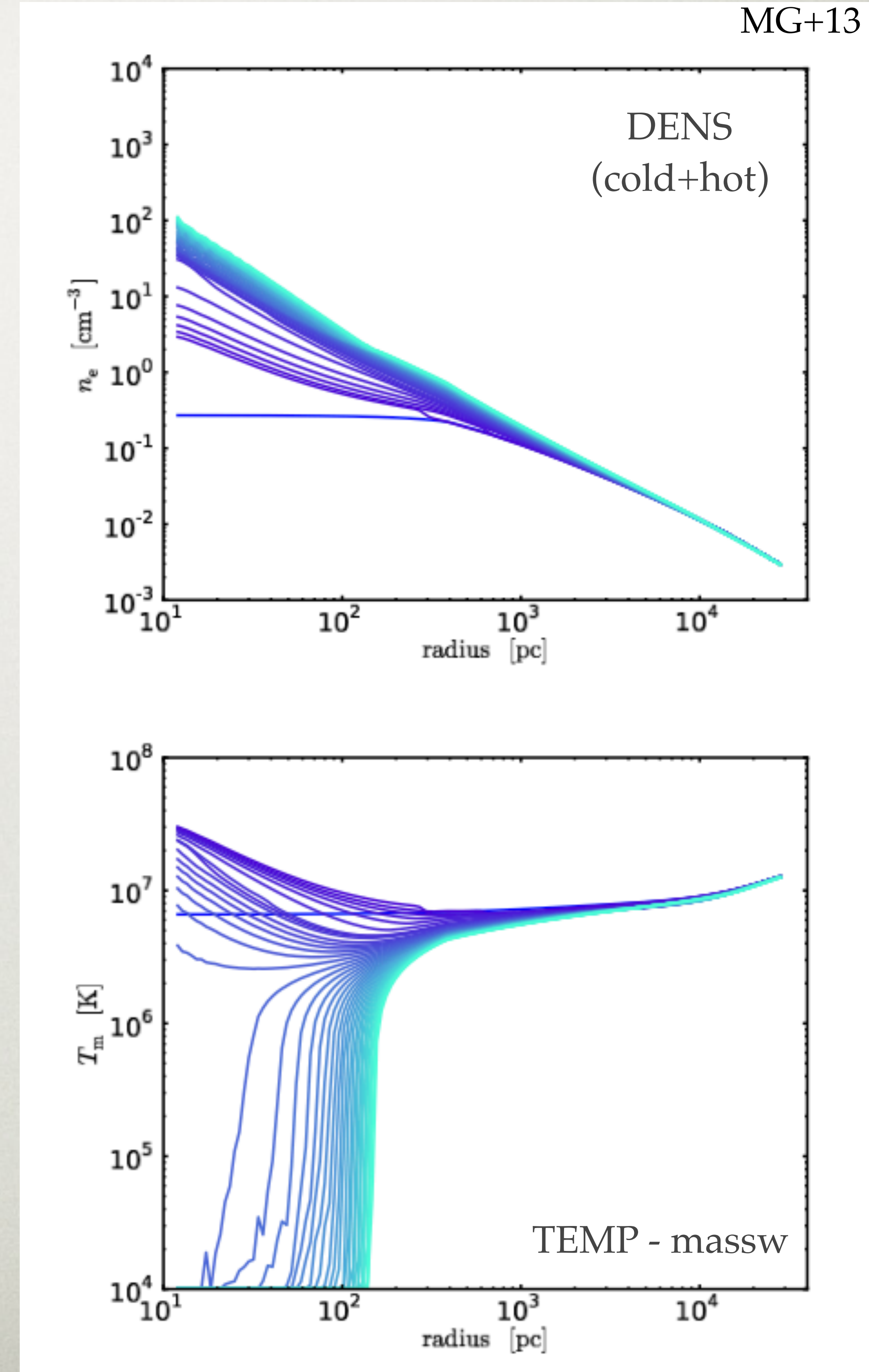

42"
48"
54"
00"
06"
12"
18"
24"
30"
David+2014

CO
ALMA

PURE COLD MODE

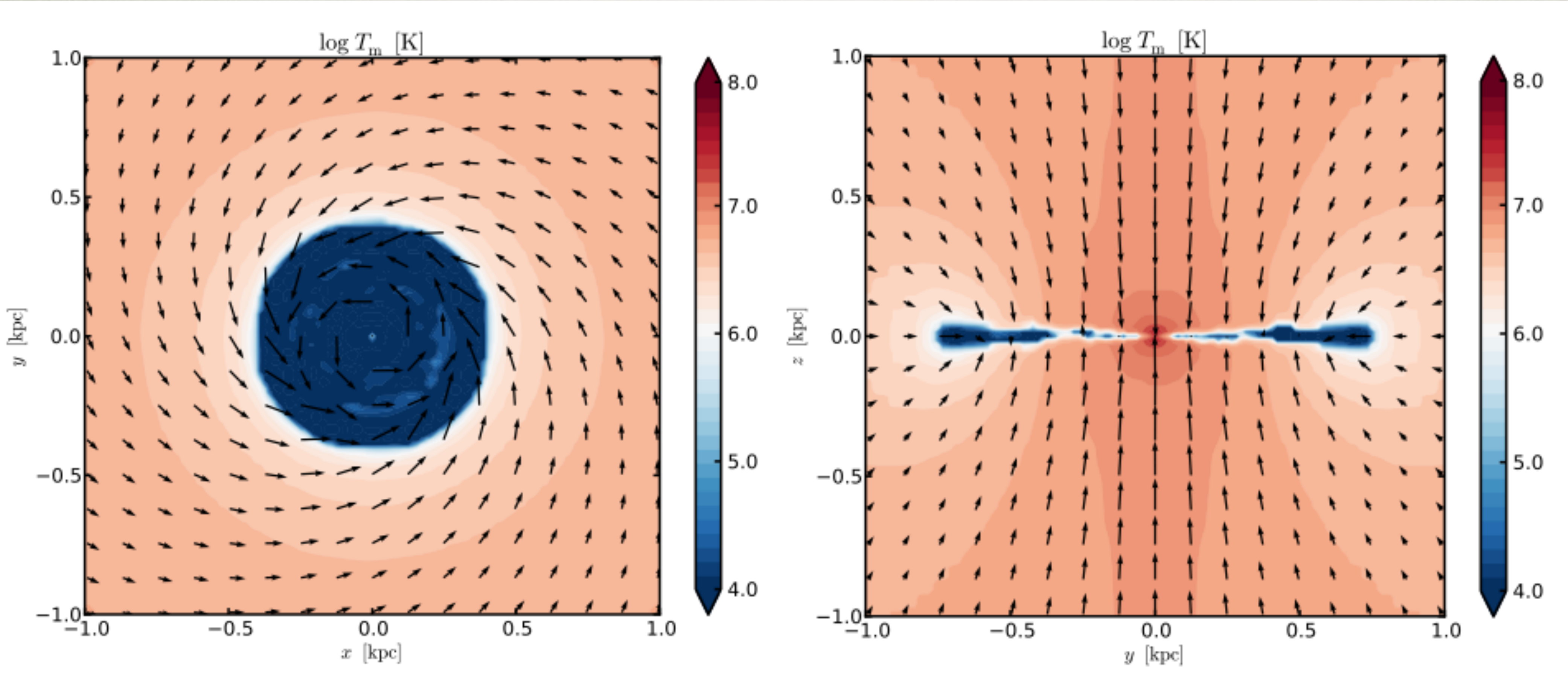




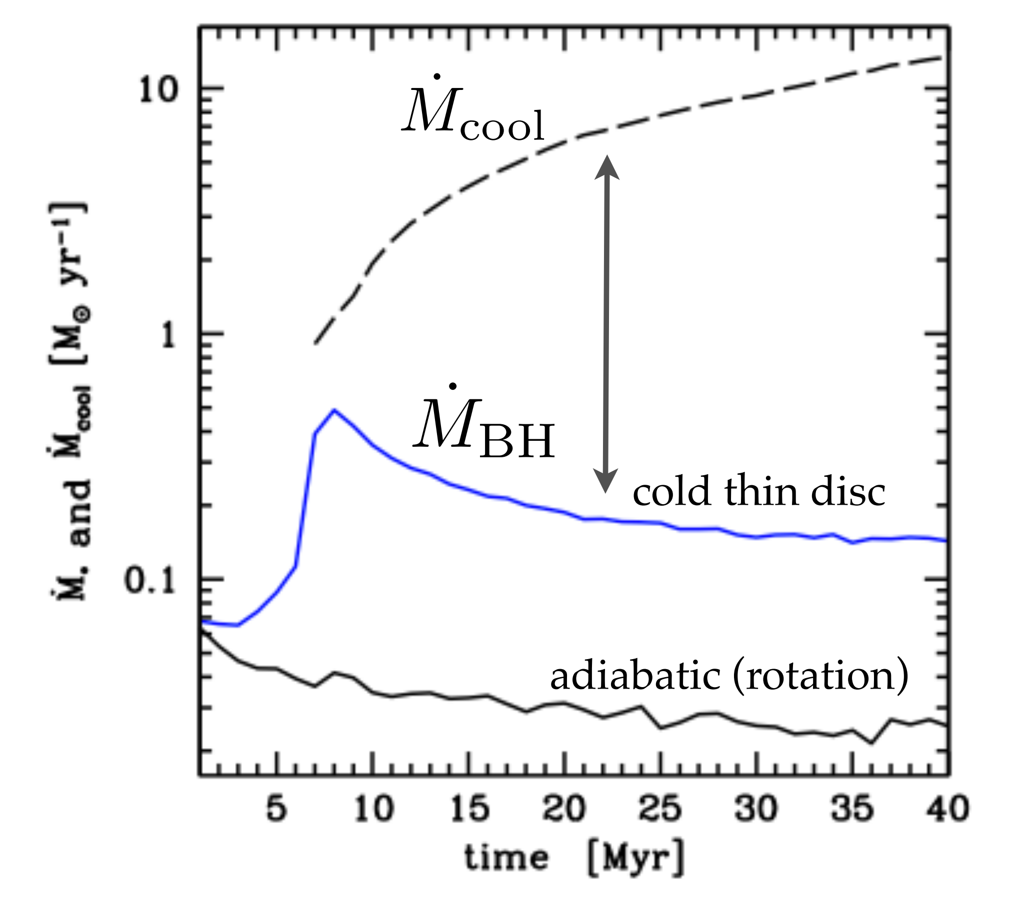


MG+13

PURE COLD MODE (ROTATION)



MG+15



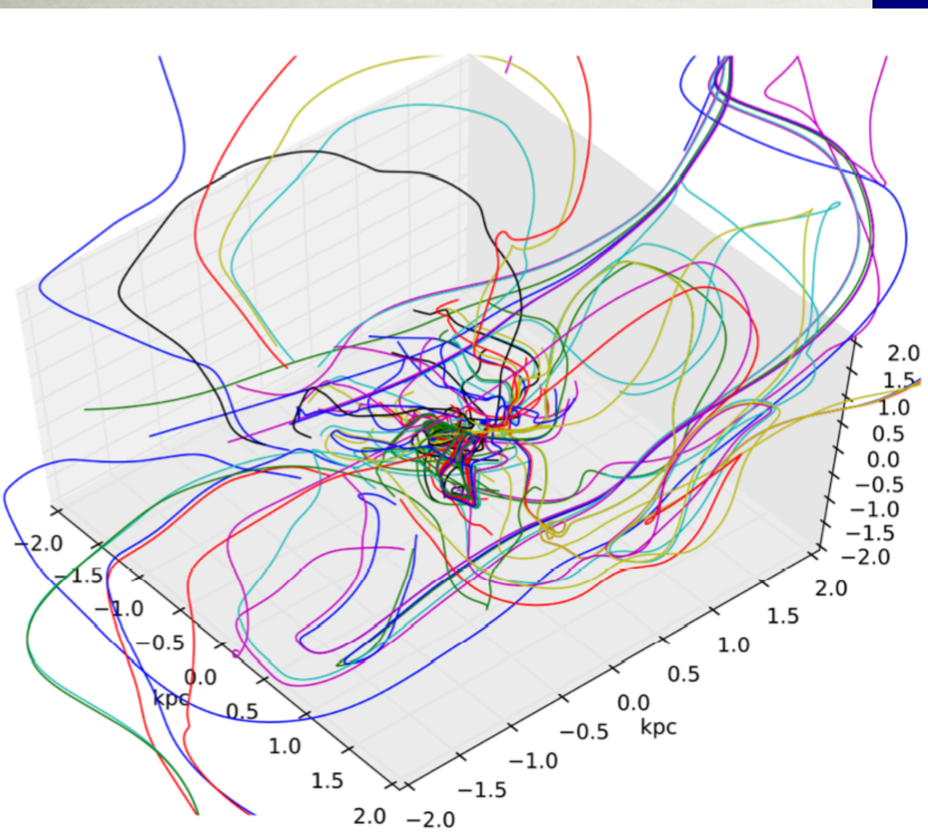
COLD THIN DISC

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

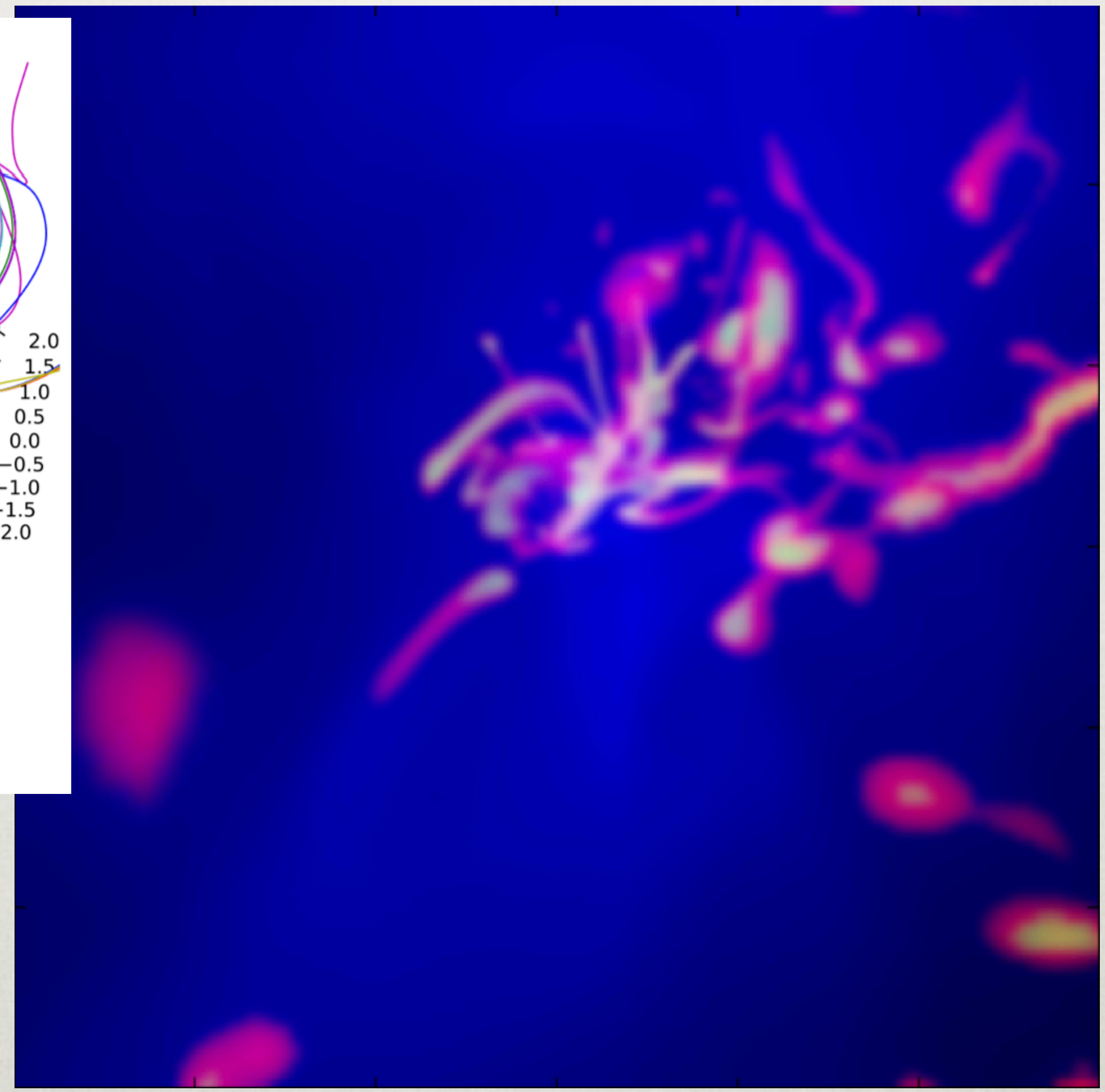
many elliptical galaxies with inner discs:
Mathews & Brighenti 2003; Young et al. 2011; Alatalo+2013; NGC 6868 and NGC 7049: Werner+2014

RAINING ON BLACK HOLES

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



chaotic streamlines => recurrent multiphase gas interactions



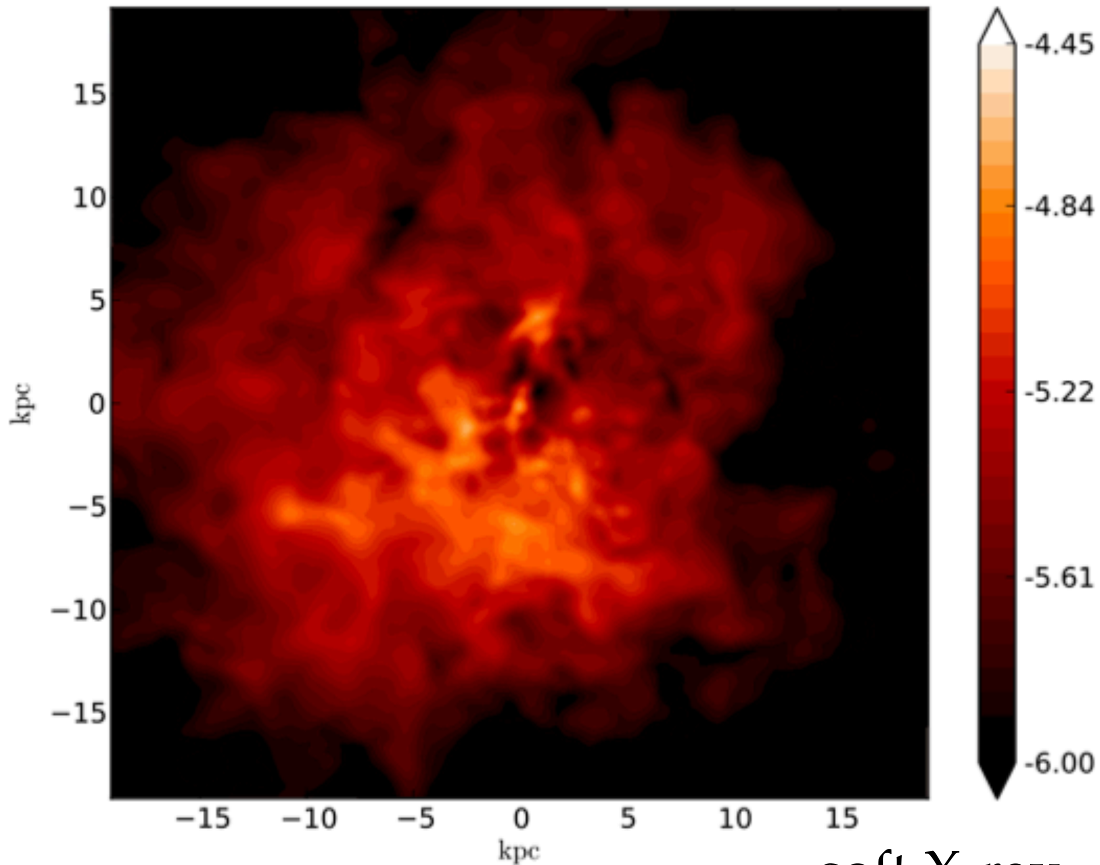
TURBULENCE + COOLING

σ_v ~150 km/s
as found by *Hitomi*

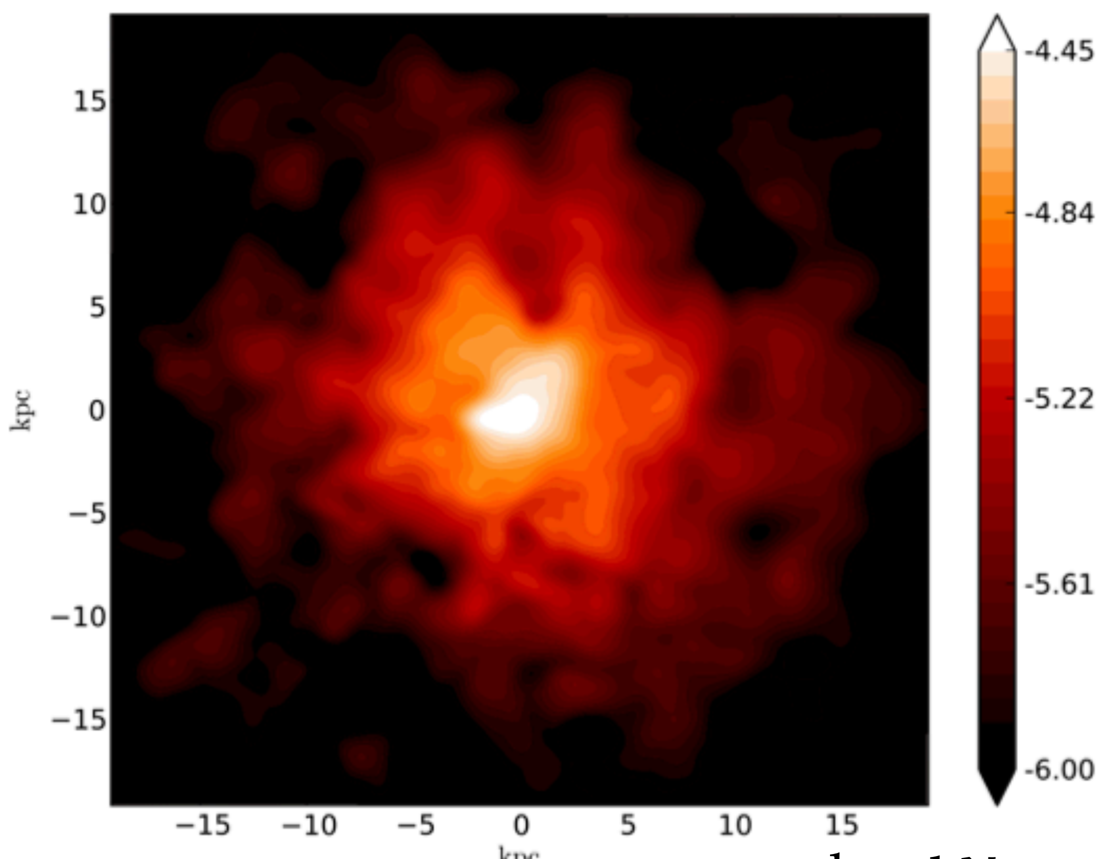
RGB surface density: plasma (blue), warm gas (red), cold gas (green)

CCA has been tested and corroborated by many subsequent observational and theoretical studies, e.g.:
Voit & Donahue 2015; Voit 2015-2018; Werner+2014; David+2014, Li & Bryan 2014, 2015; Wong+2014; Russell+2015; Valentini & Brighenti 2015; Yang+2015-2016; Meece+2016; Tremblay+2015-2018; Prasad+2016; David+2017; McDonald+2018-2021; Maccagni+2018-2021; Nagai+2019; Rose+2019, 2020; Storchi-Bergmann+2019; Juranova+2019-2020; Schellenberger+2020; Olivares+2019-2022; Temi+22; McKinley+2022; Fiore+2023

MULTIPHASE RAIN:
1. HOT PLASMA



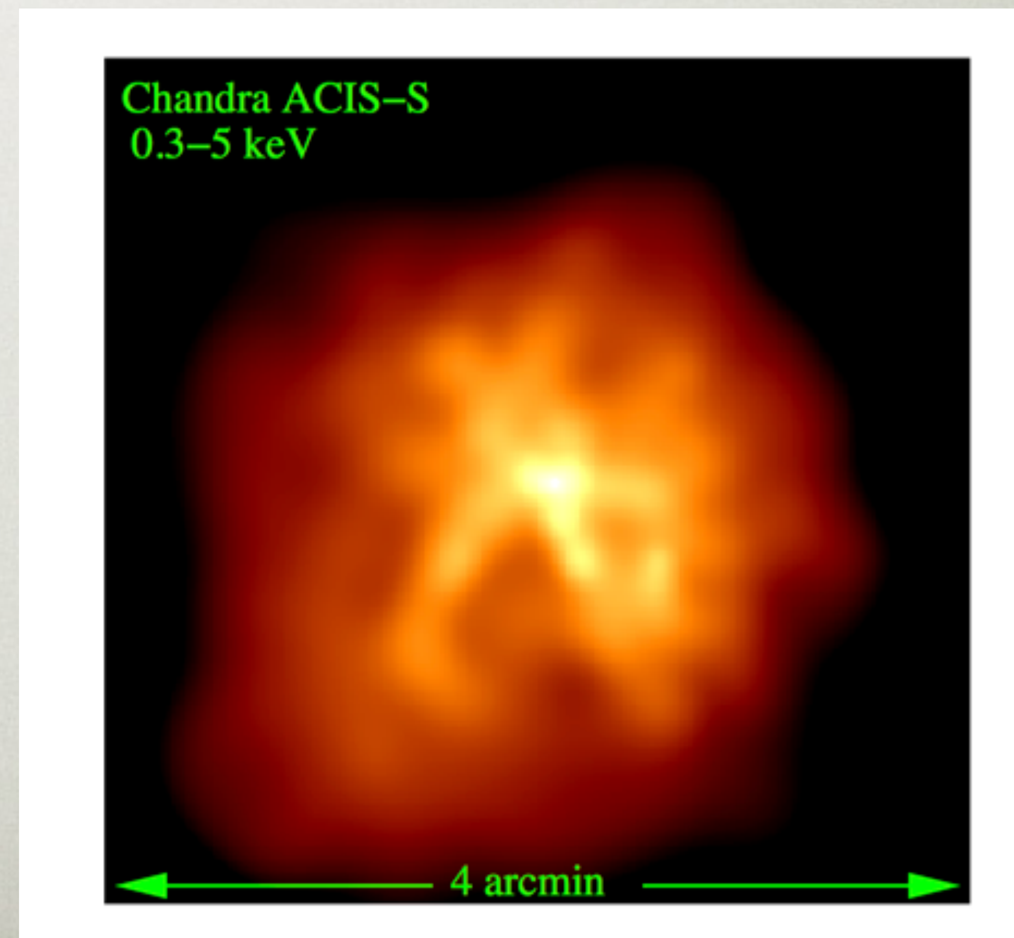
soft X-ray



MG+17

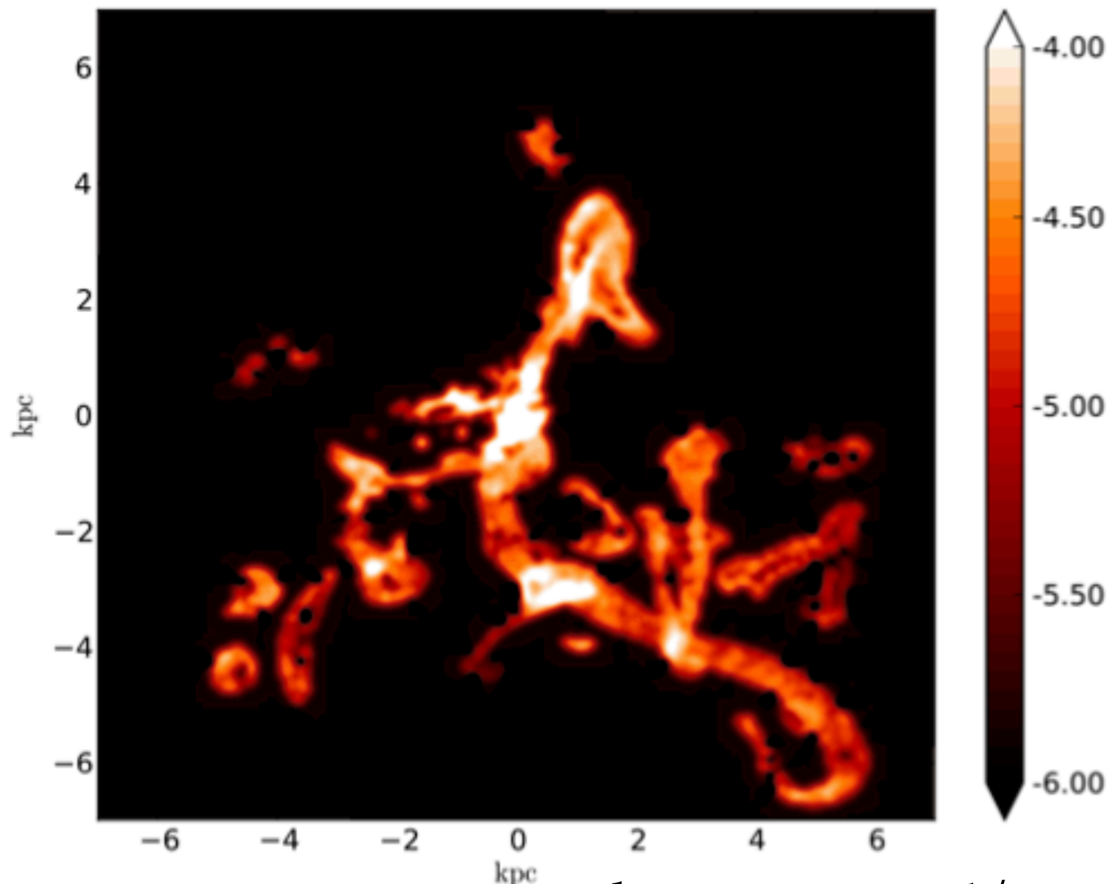
hard X-ray

- turbulent eddies imprint => naturally create "cavities"/"fronts"
- X-ray "filaments" start to appear below 0.5 keV
- weak subsonic turbulence is enough to trigger CCA

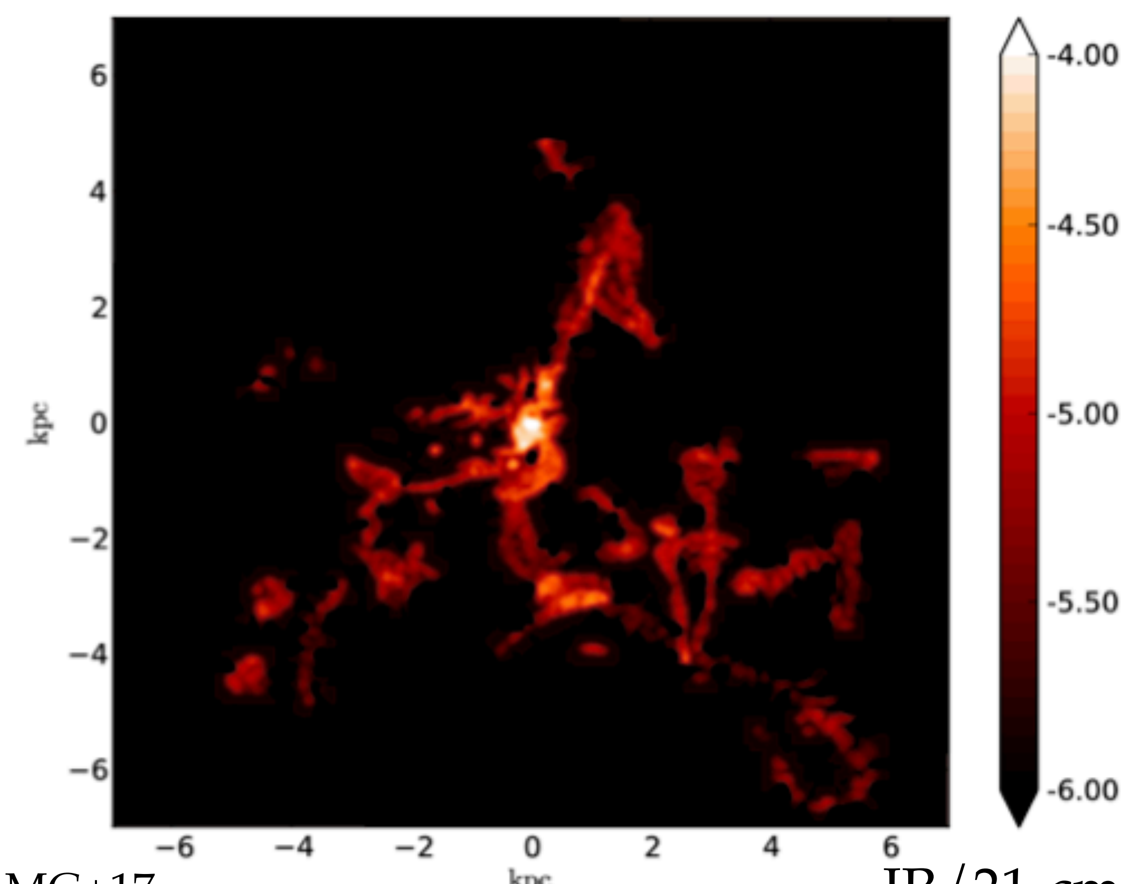


Buote+04

MULTIPHASE RAIN: 2. WARM PHASE



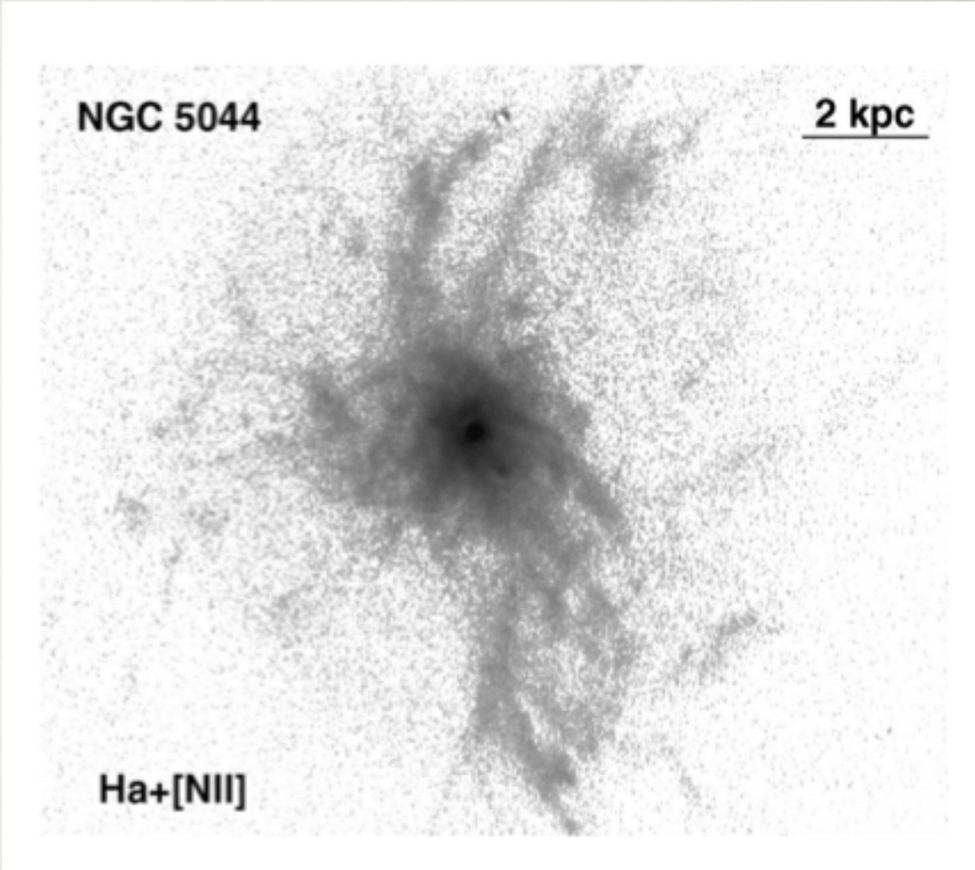
ionized warm phase optical/UV



MG+17 IR/21-cm

neutral warm phase

Werner+14: SOAR



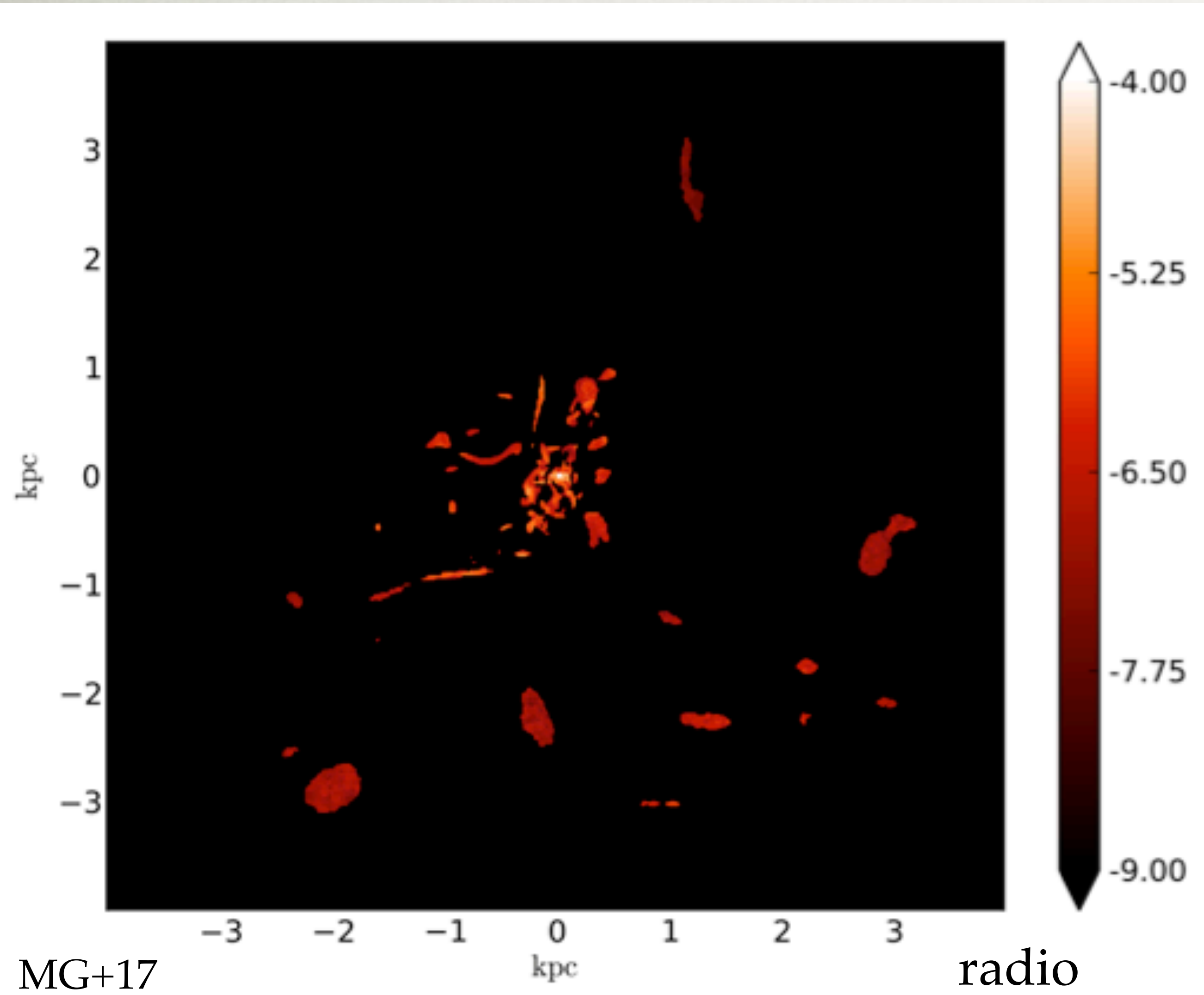
- robust thermal instability/ **multiphase condensation criterion**: MG+18

$$C \equiv t_{\rm cool}/t_{\rm eddy} \approx 1$$

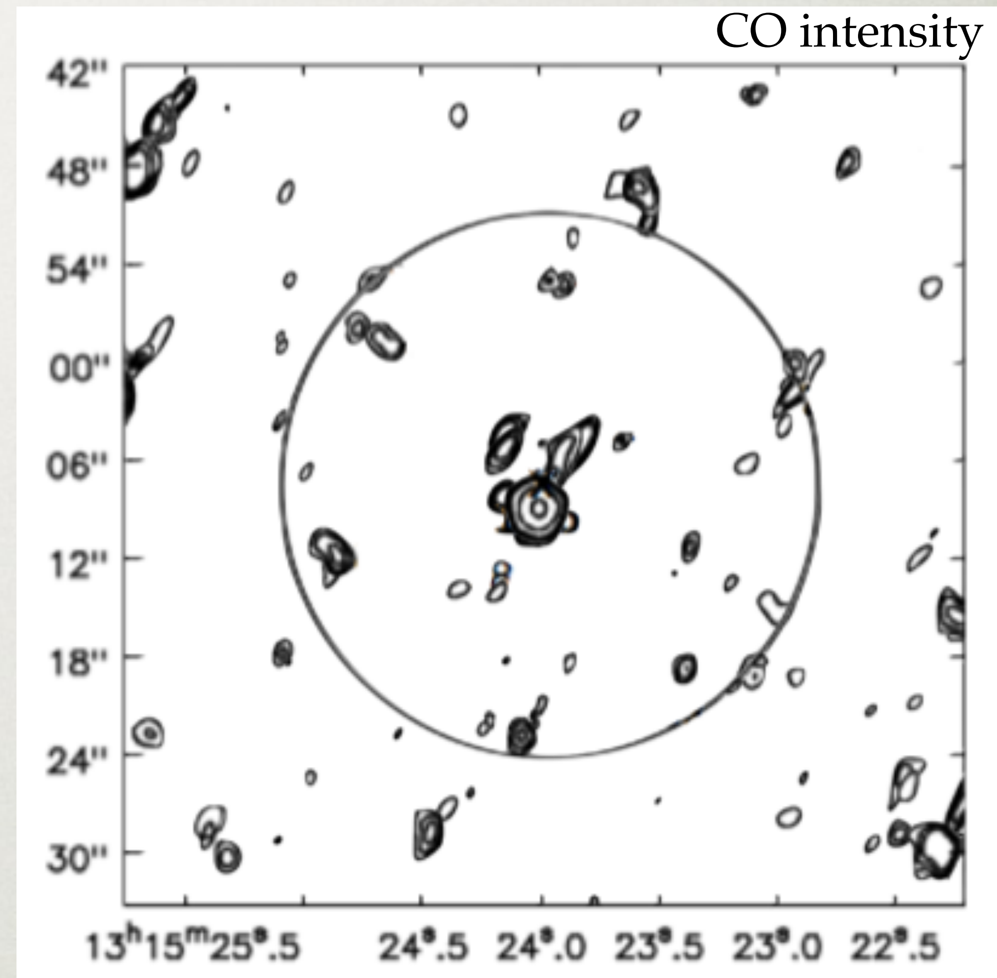
- **top-down** condensation: ionized skin envelops neutral filaments

- **filaments** naturally form out of the interacting sheets between large-scale eddies

MULTIPHASE RAIN:
3. COLD/MOLECULAR PHASE



David+14-17, Schellenberger+20: ALMA



- GMAs (**giant molecular associations**), radius < 50-70 pc with surface density ranging 50-200 Msun/pc^2 (~galactic clouds)
- **cospatial** with warm phase and soft X-ray plasma, though more compact
- **dynamically supported** (virial parameter >> 1) — turbulent pressure dominant

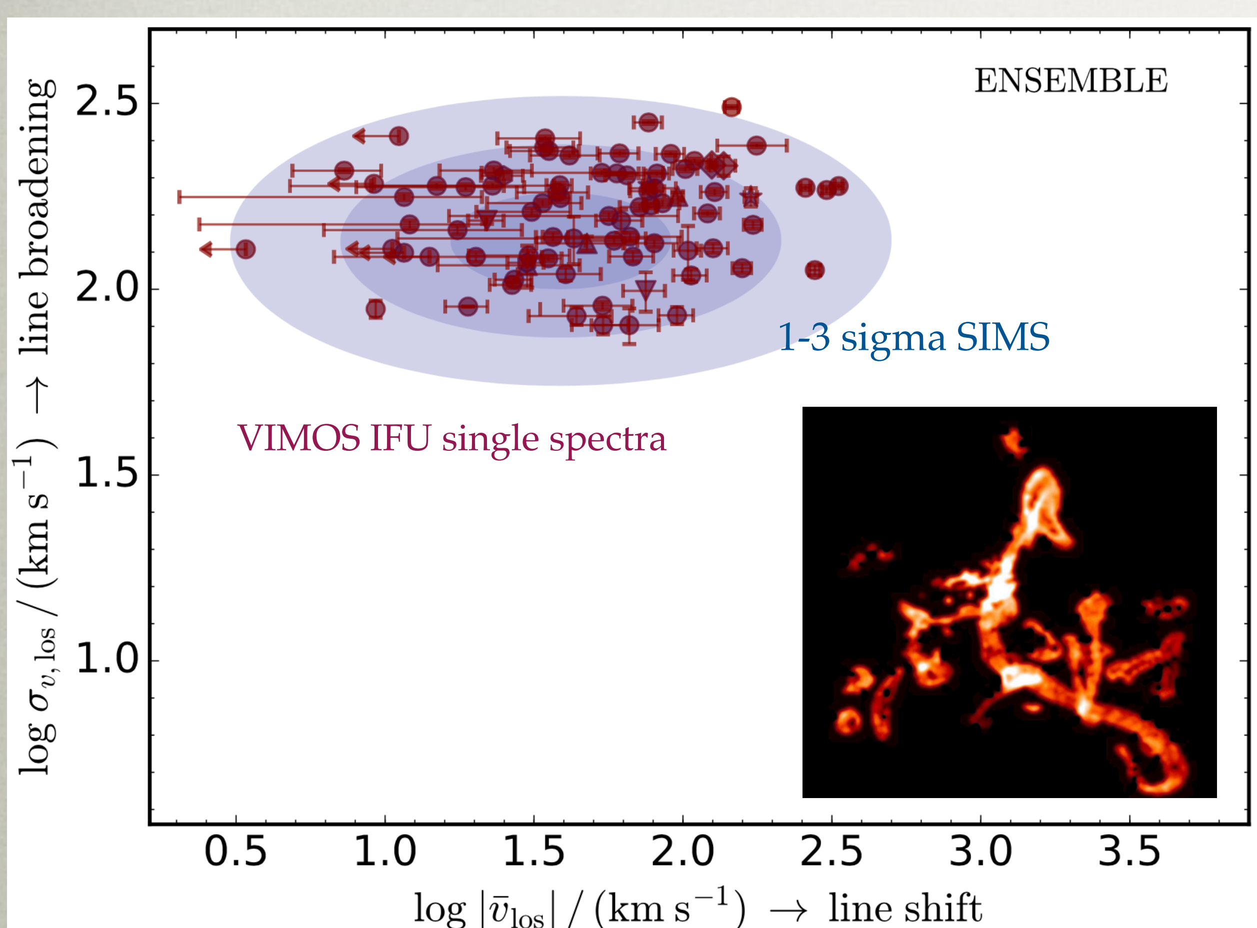
KINEMATIC TRACERS - RAIN/CCA

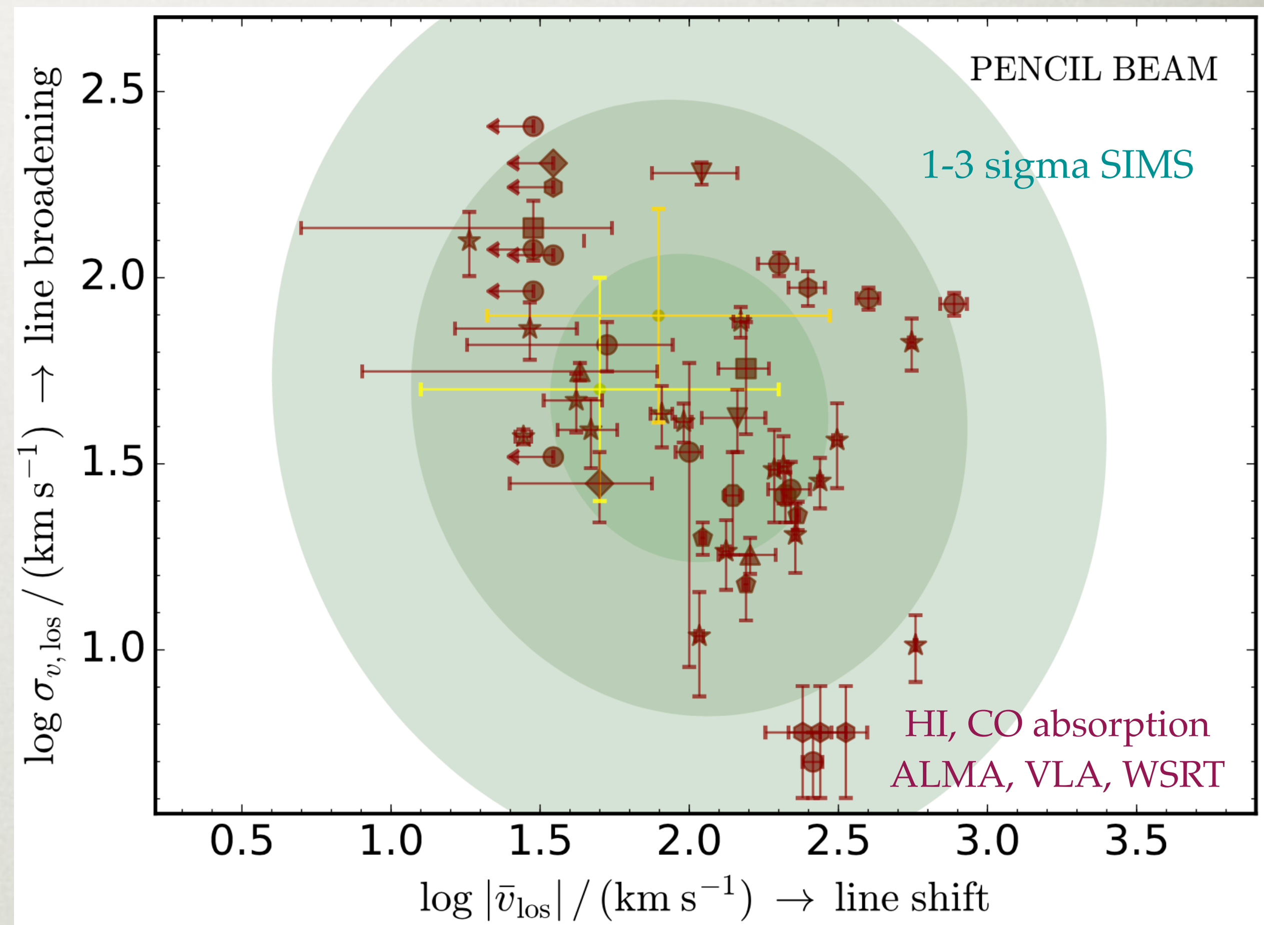
observational tests

(massive galaxies in groups and clusters)

spectral line **broadening** = turbulent motions vs. line **shift** = bulk motions

MG+18





substantial line broadening and small scatter

large line shifts and narrow broadening: accreting clouds

red points: ~80 systems (Hα+[NII], HI, CO, [CII] lines) — contours: SIMS lognormal distributions

- r < 100 pc **funneling** of clouds with 100s km/s (probed by ALMA, e.g., N5044, A2597)

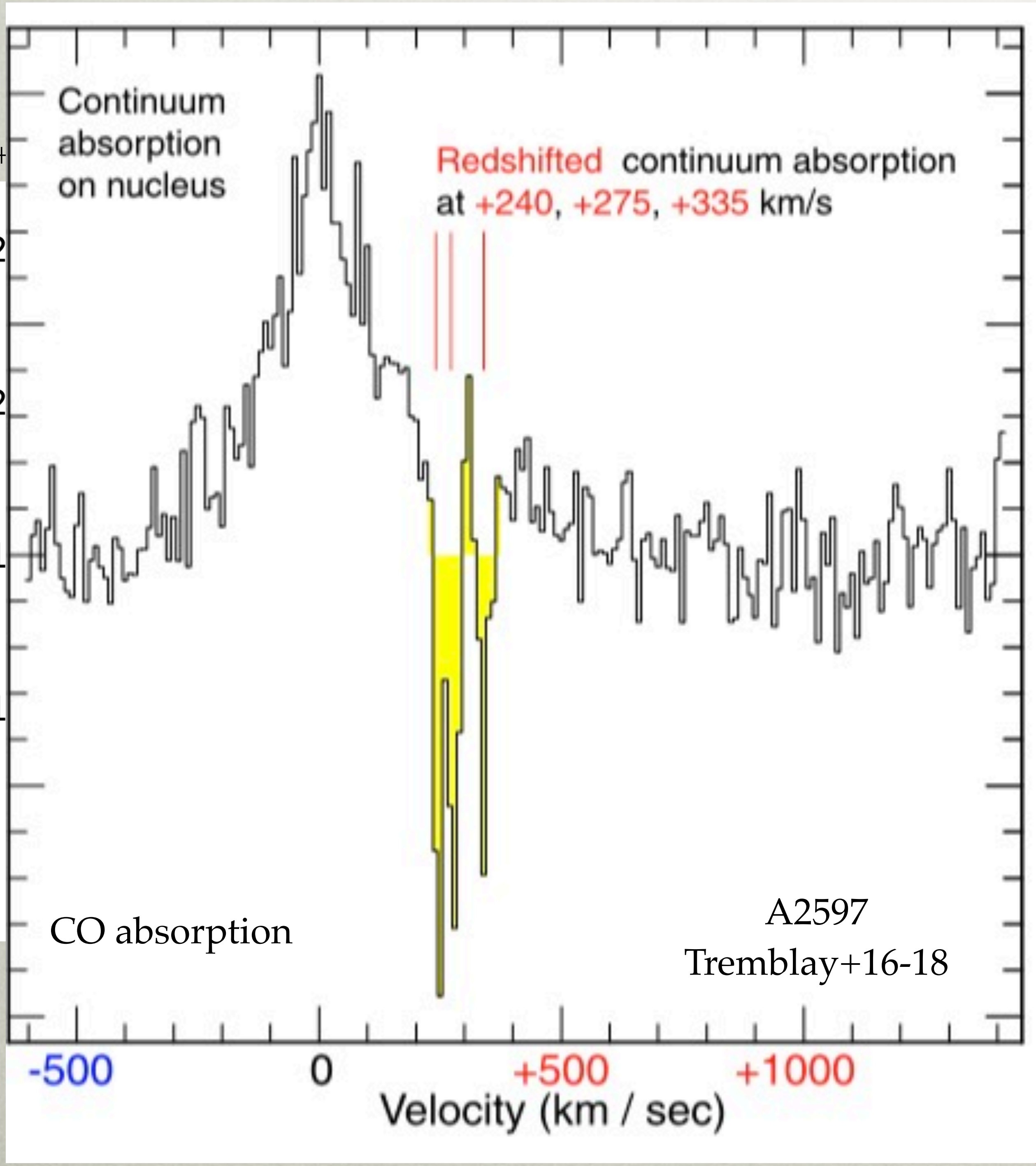
KINEMATIC TRACERS - RAIN/CCA

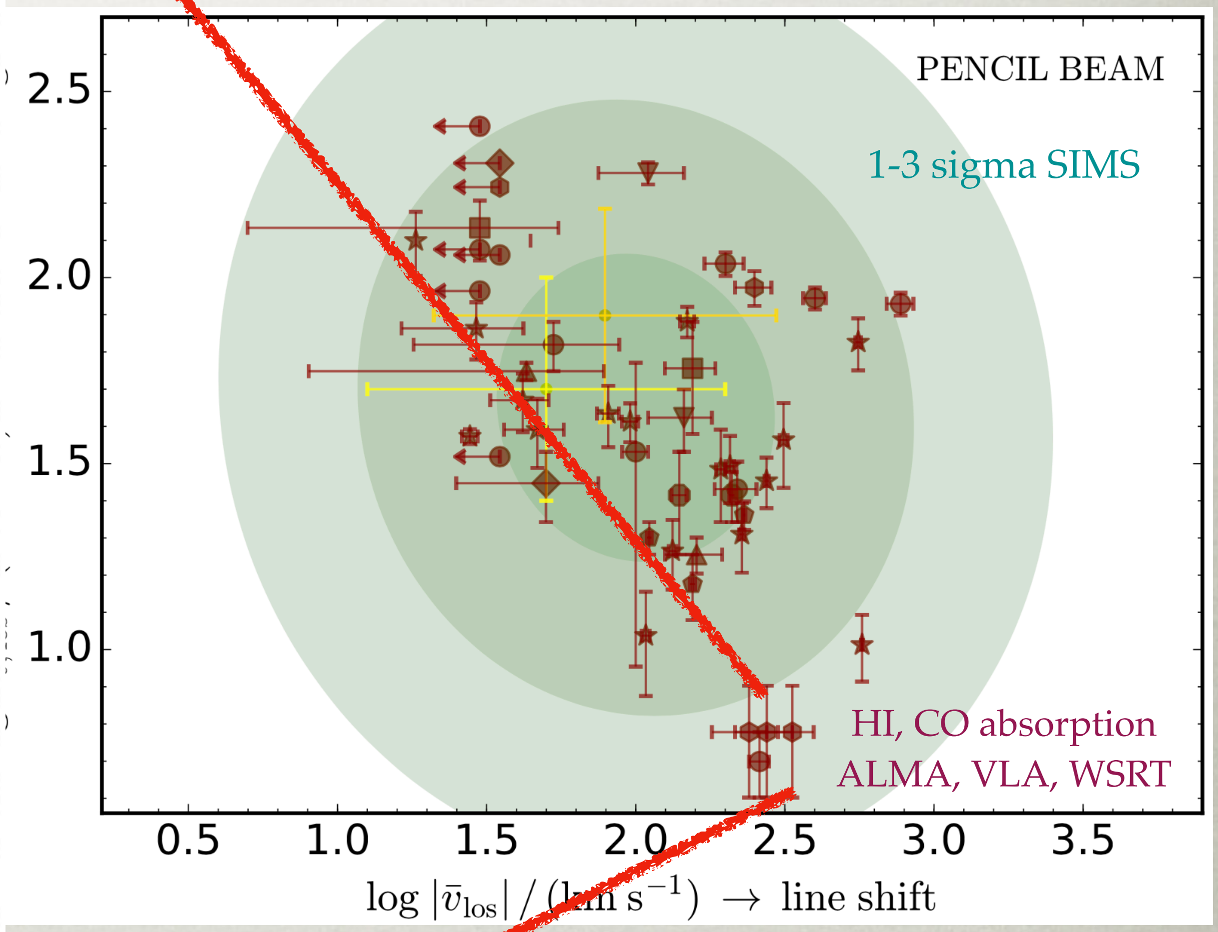
observational tests

(massive galaxies in groups and clusters)

notions vs. line **shift** = bulk motions

MG+



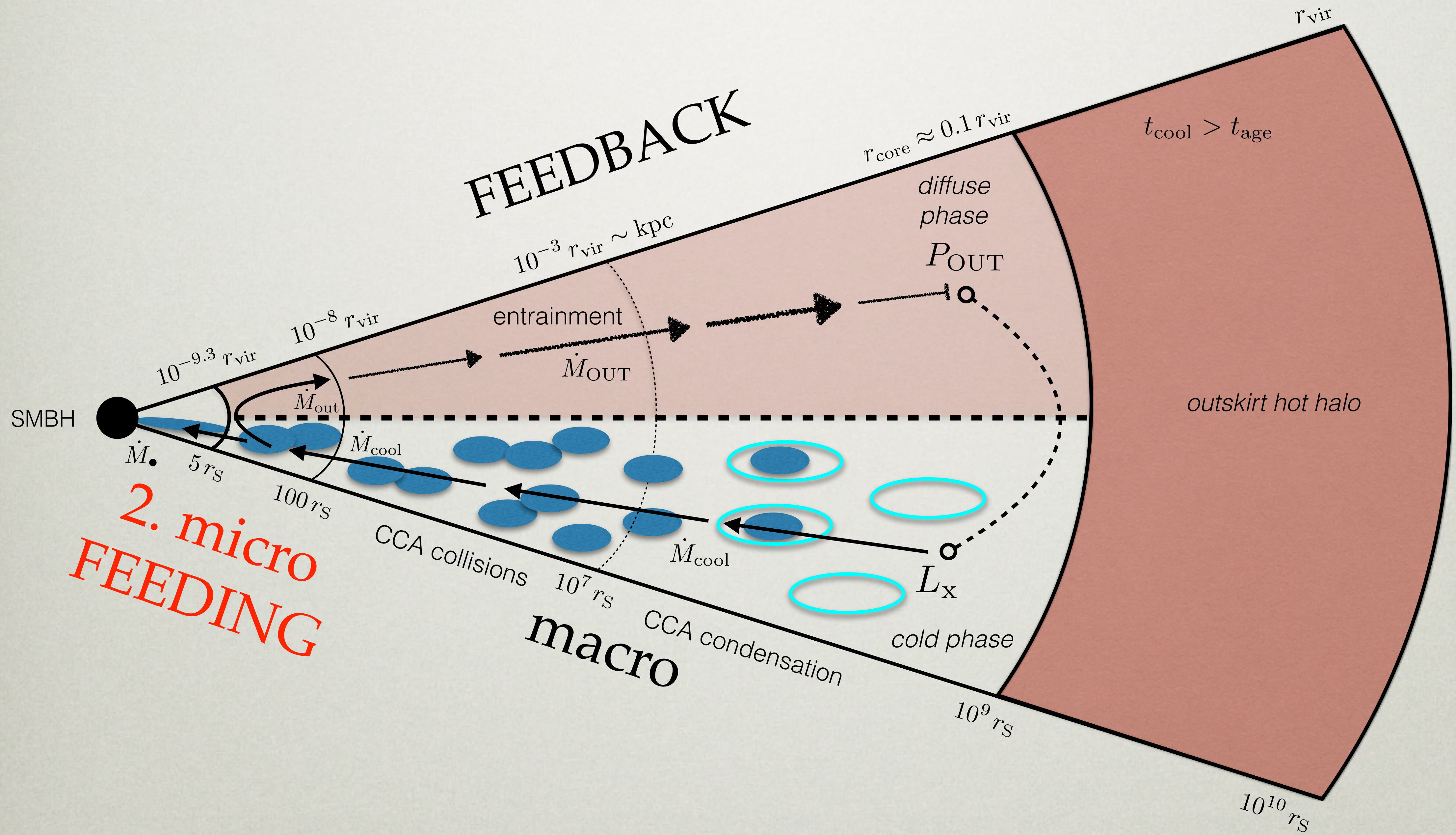


large line shifts and narrow broadening: accreting clouds

es) — contours: SIMS lognormal distributions

- r < 100 pc **funneling** of clouds with 100s km/s (probed by ALMA, e.g., N5044, A2597)

BLACK HOLE FEEDING AND FEEDBACK UNIFICATION



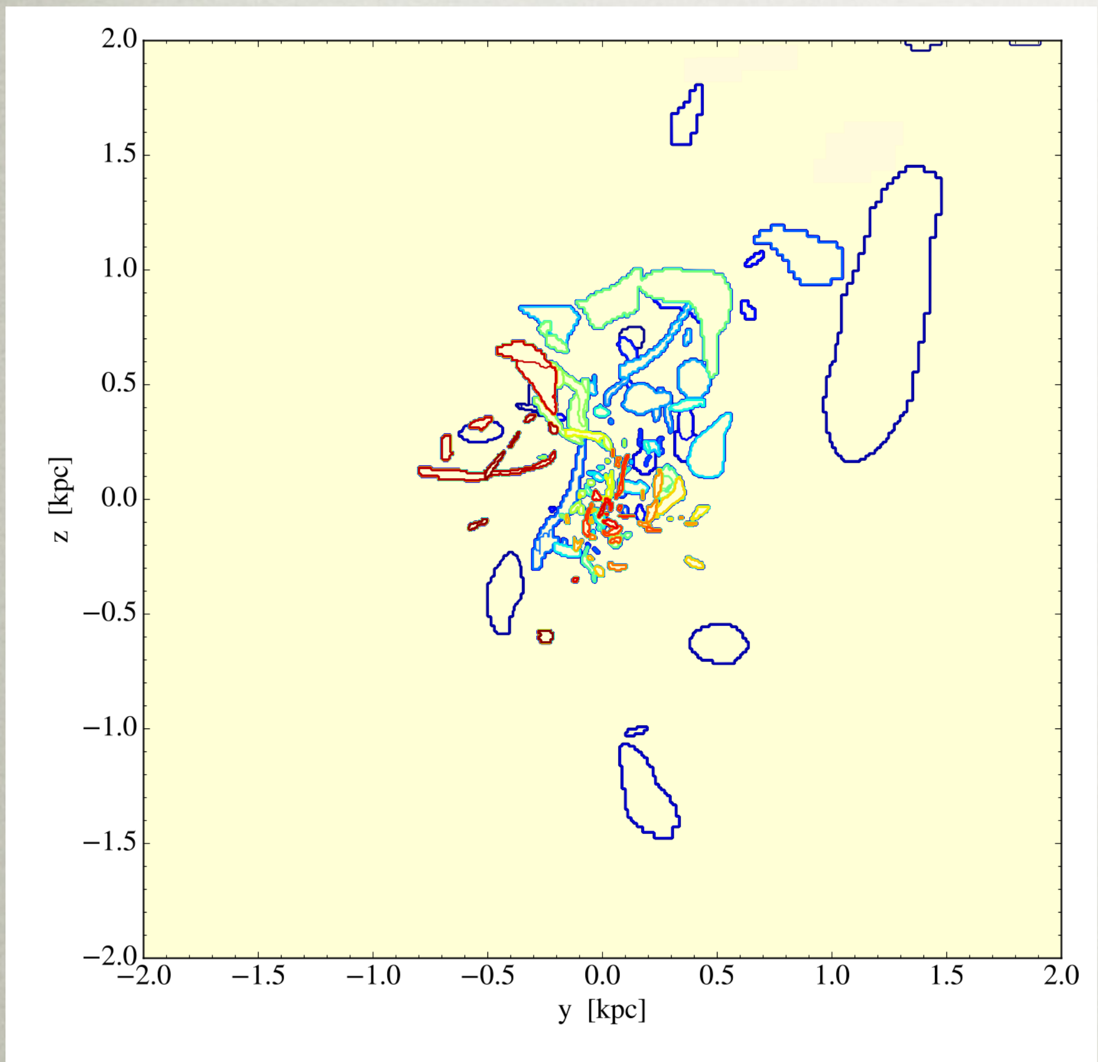
CCA = CHAOTIC COLD ACCRETION

MG+2011-2023

CHAOTIC COLD ACCRETION

DYNAMICS

Gaspari+2017



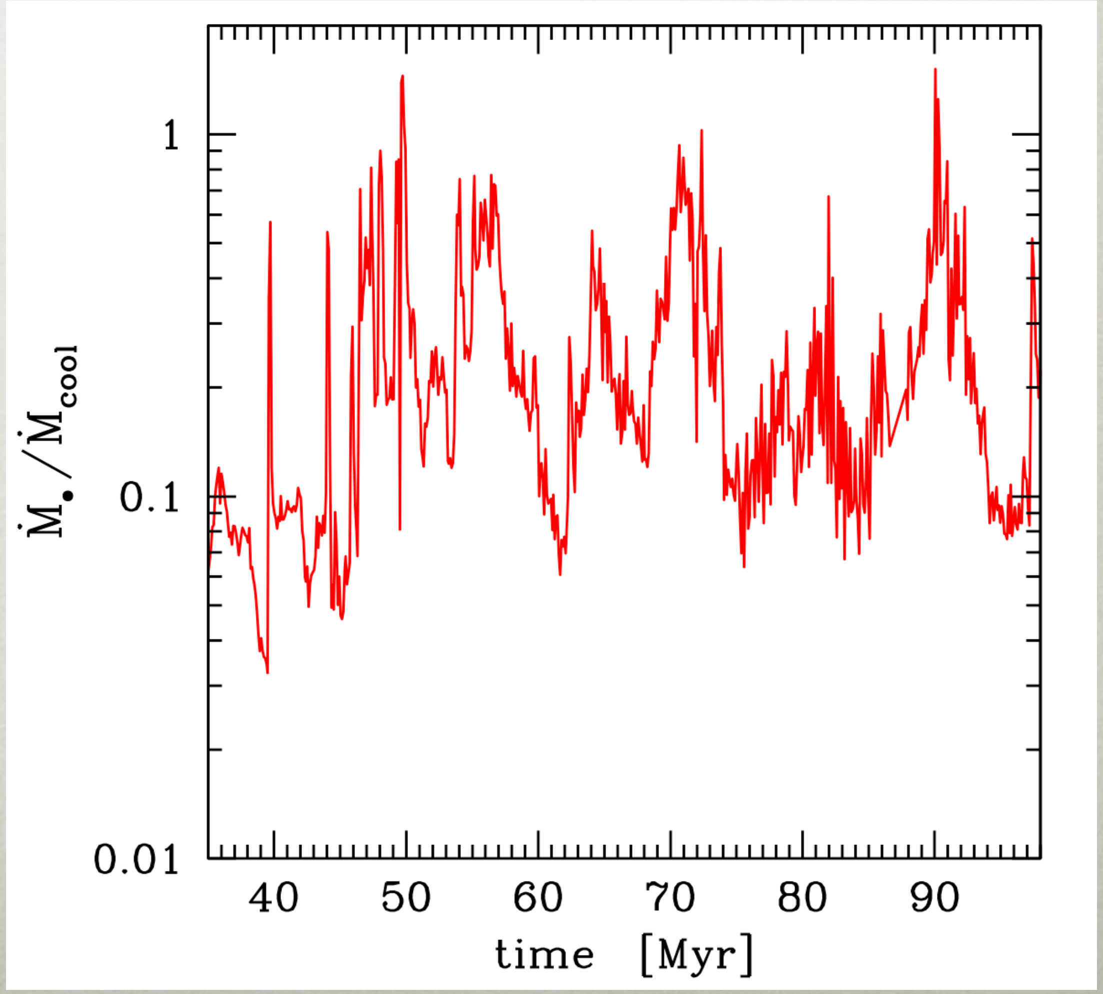
can be modeled as quasi-spherical viscous accretion:

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

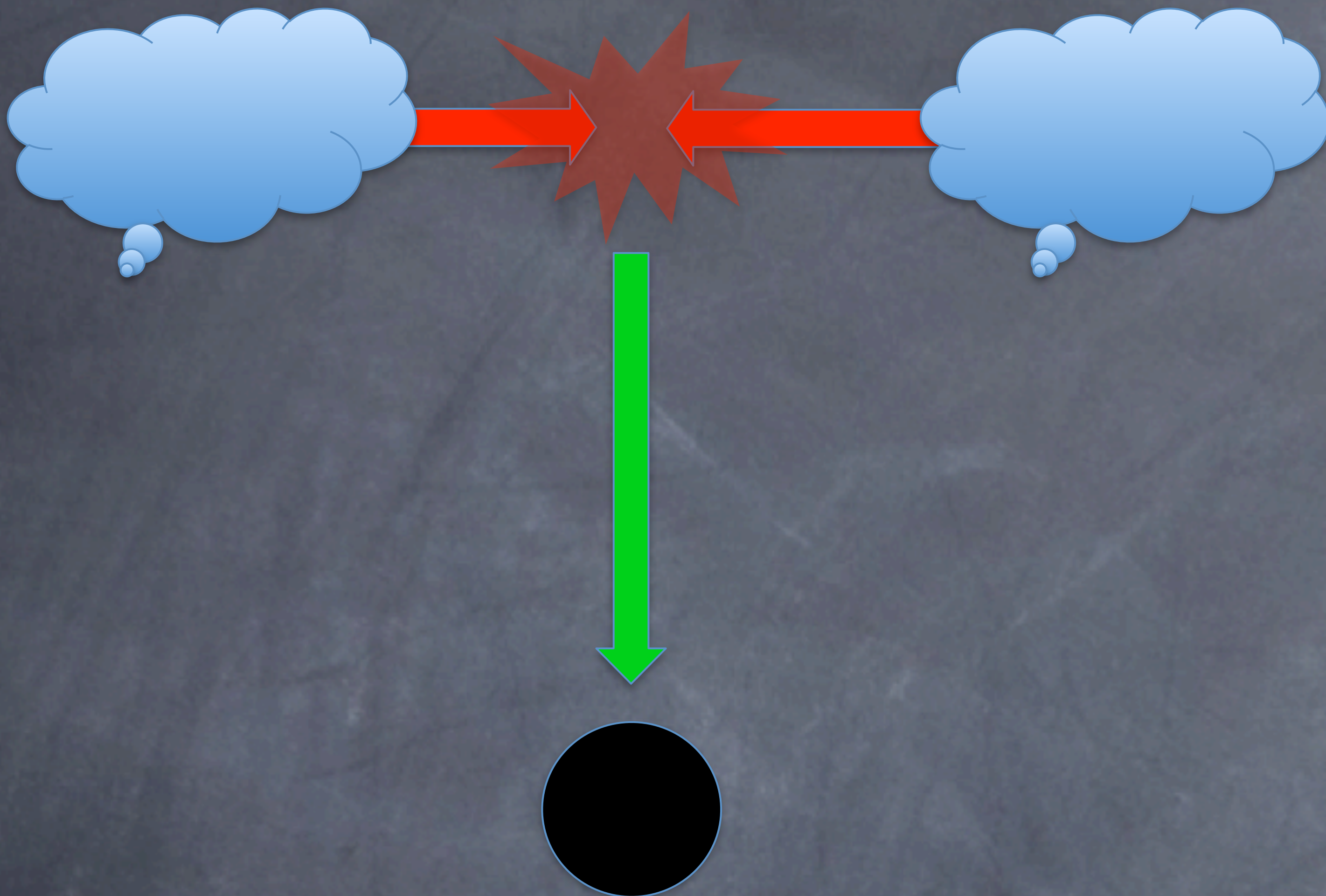
$$\nu_c \equiv \sigma_v\,\lambda_c \simeq 4.5^{+13.3}_{-3.1} \times 10^{27}\ \mathrm{cm^2\,s^{-1}}$$ effective collisional viscosity

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

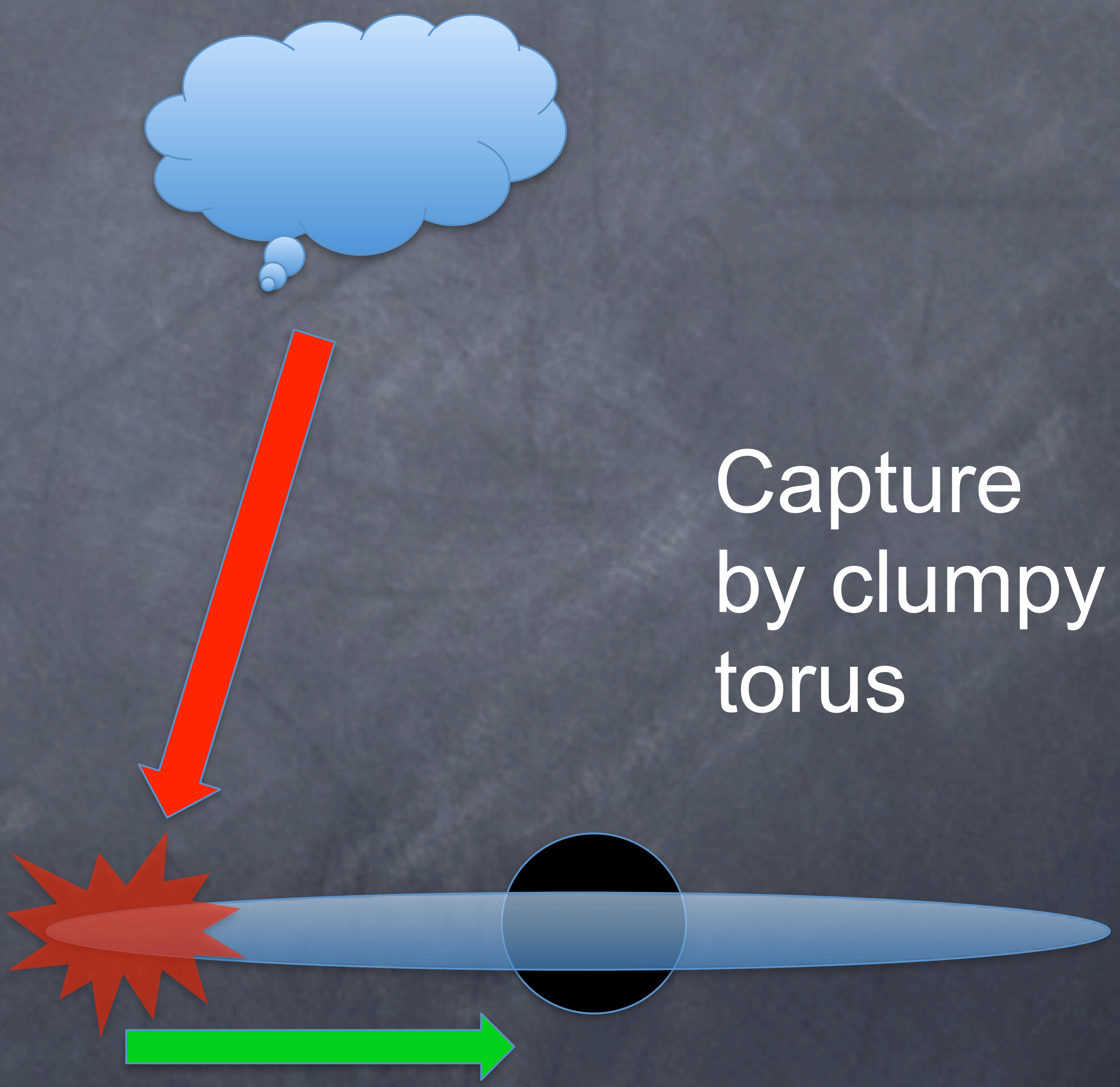
recurrent 2 dex boost in accretion rate ~ 100x Bondi rate



- 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**



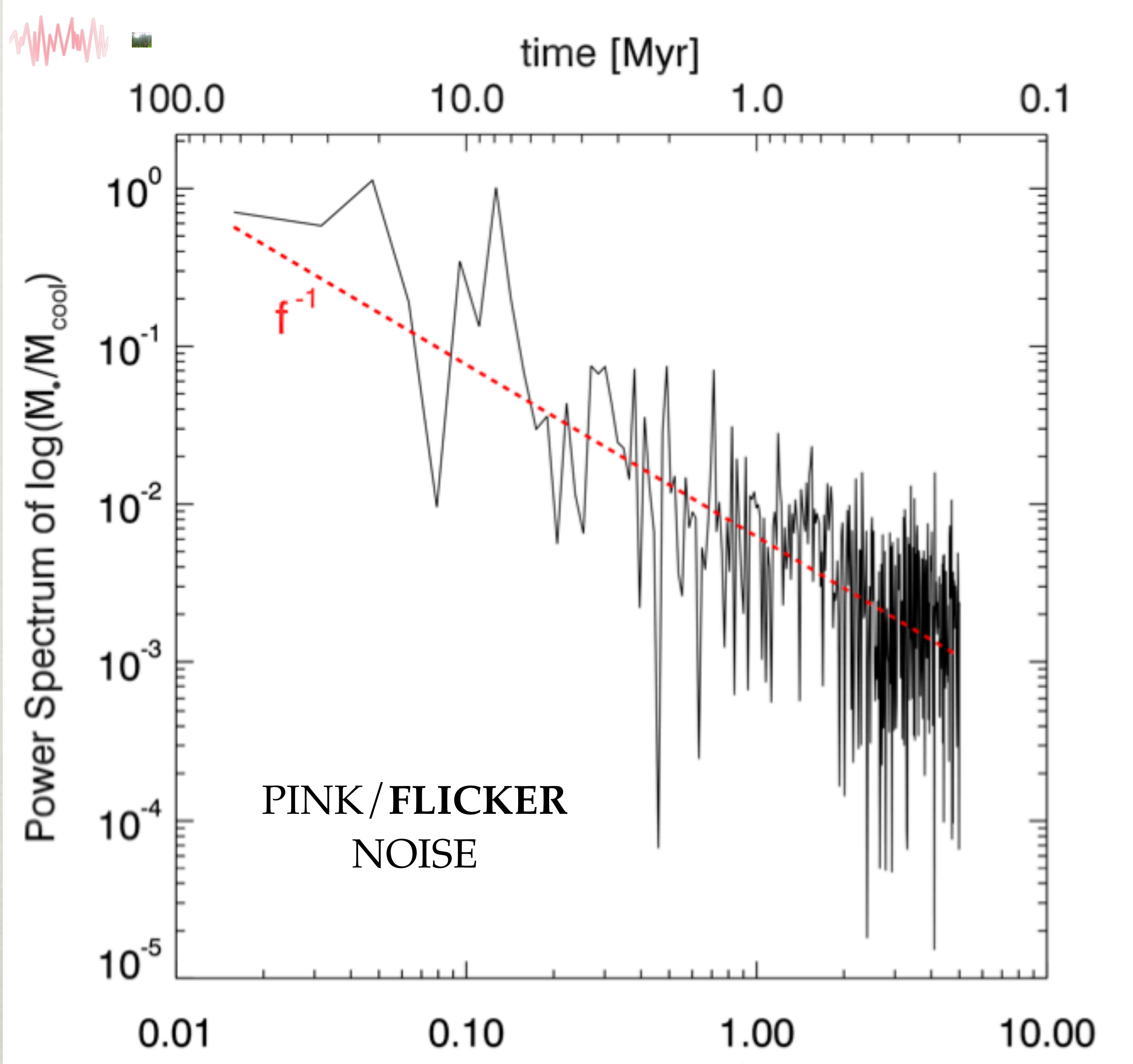
Angular momentum cancellation



Capture by clumpy torus

CHAOTIC COLD ACCRETION

VARIABILITY



MG+17

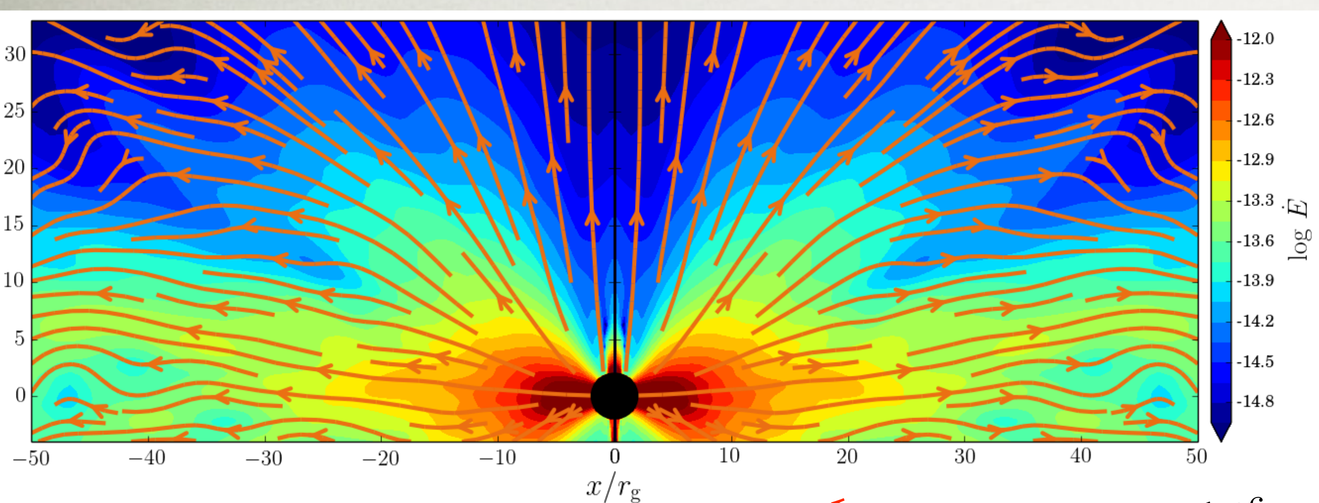
can explain ubiquitous rapid AGN and HMXBs variability

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, …

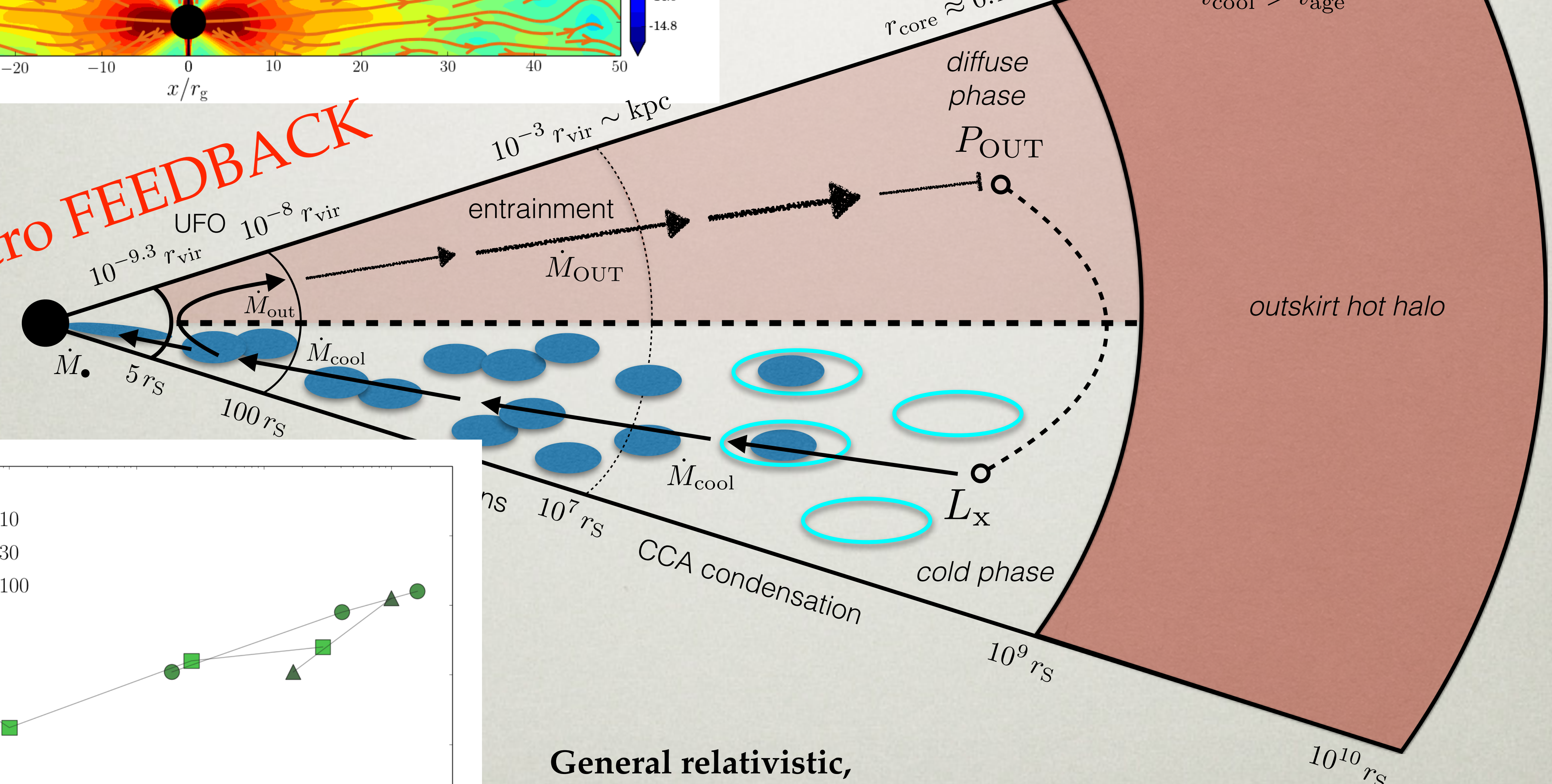
BLACK HOLE FEEDBACK:
MICRO SCALE - GR-RMHD SIMS

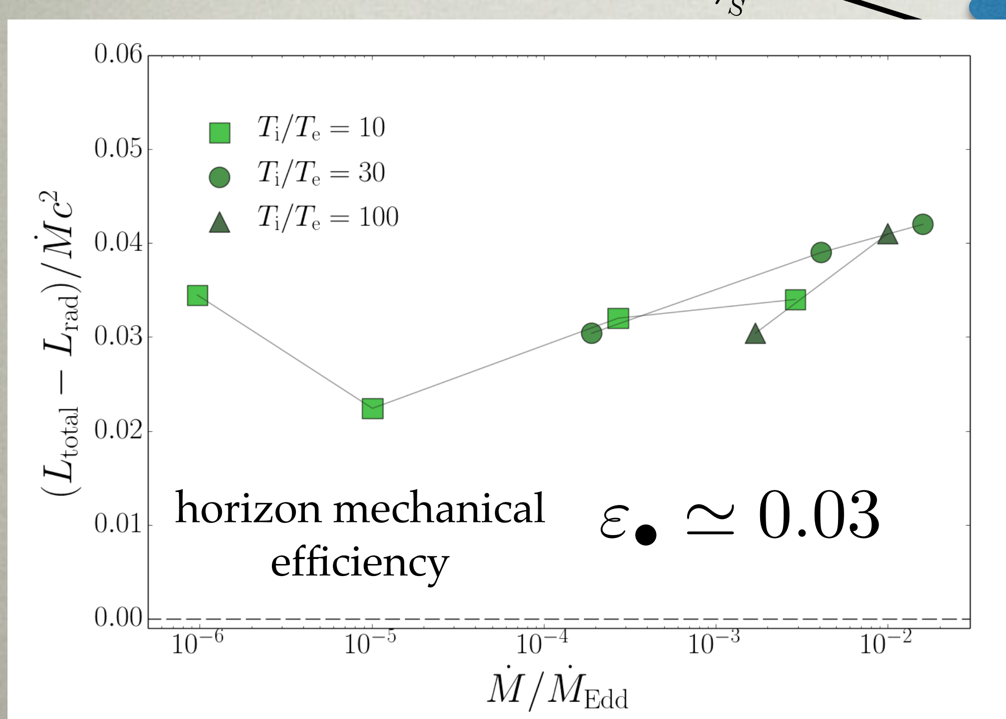


UFO = Ultra-Fast Outflows

magnetically and thermally driven

Sadowski & Gaspari 2017



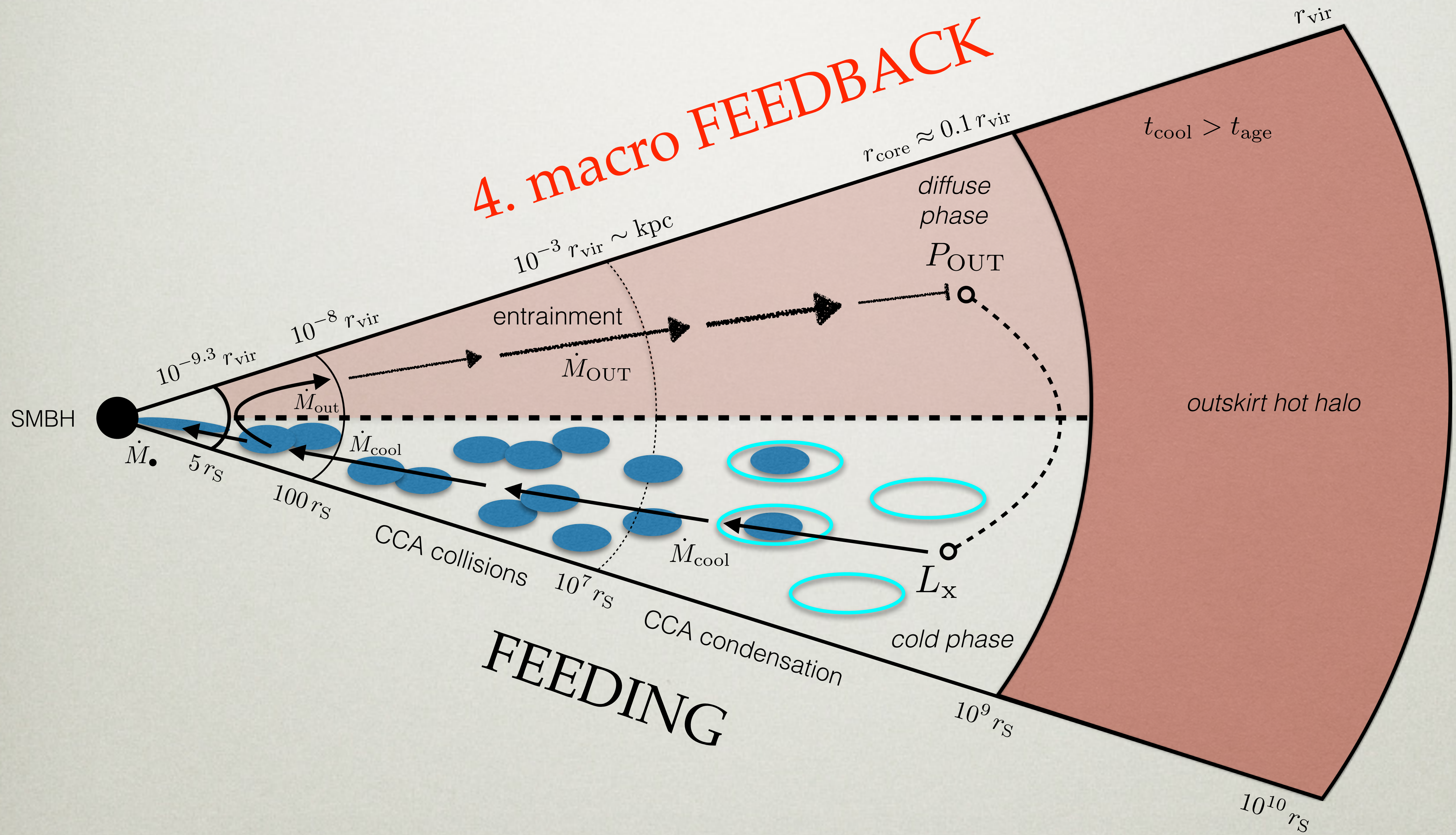


General relativistic, radiative, MHD simulations

(KORAL)

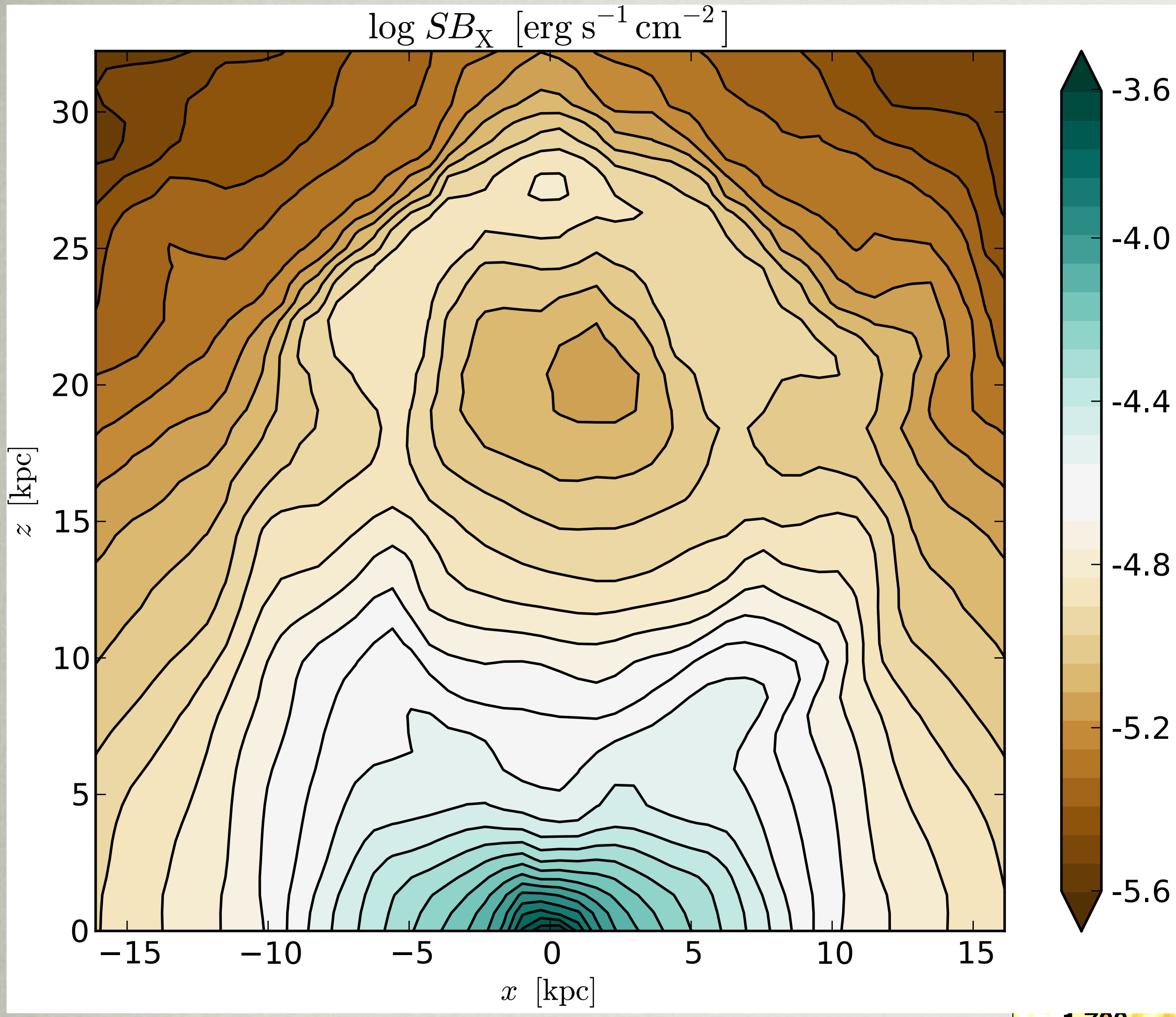
thick accretion flow and nearly null BH spin (due to chaotic accretion)

BLACK HOLE FEEDING AND FEEDBACK UNIFICATION



MG+2011-2023

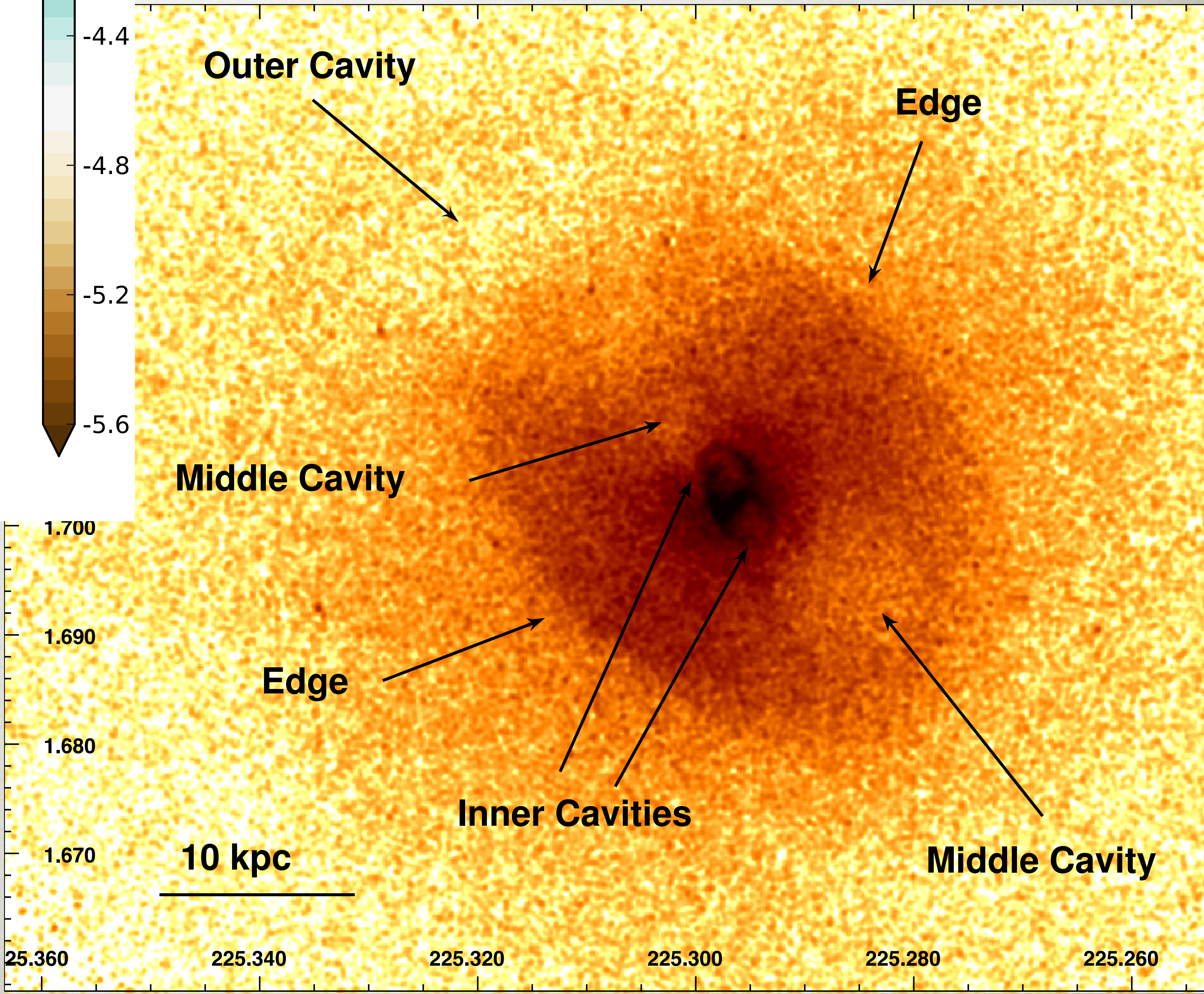
X-RAY BUBBLES



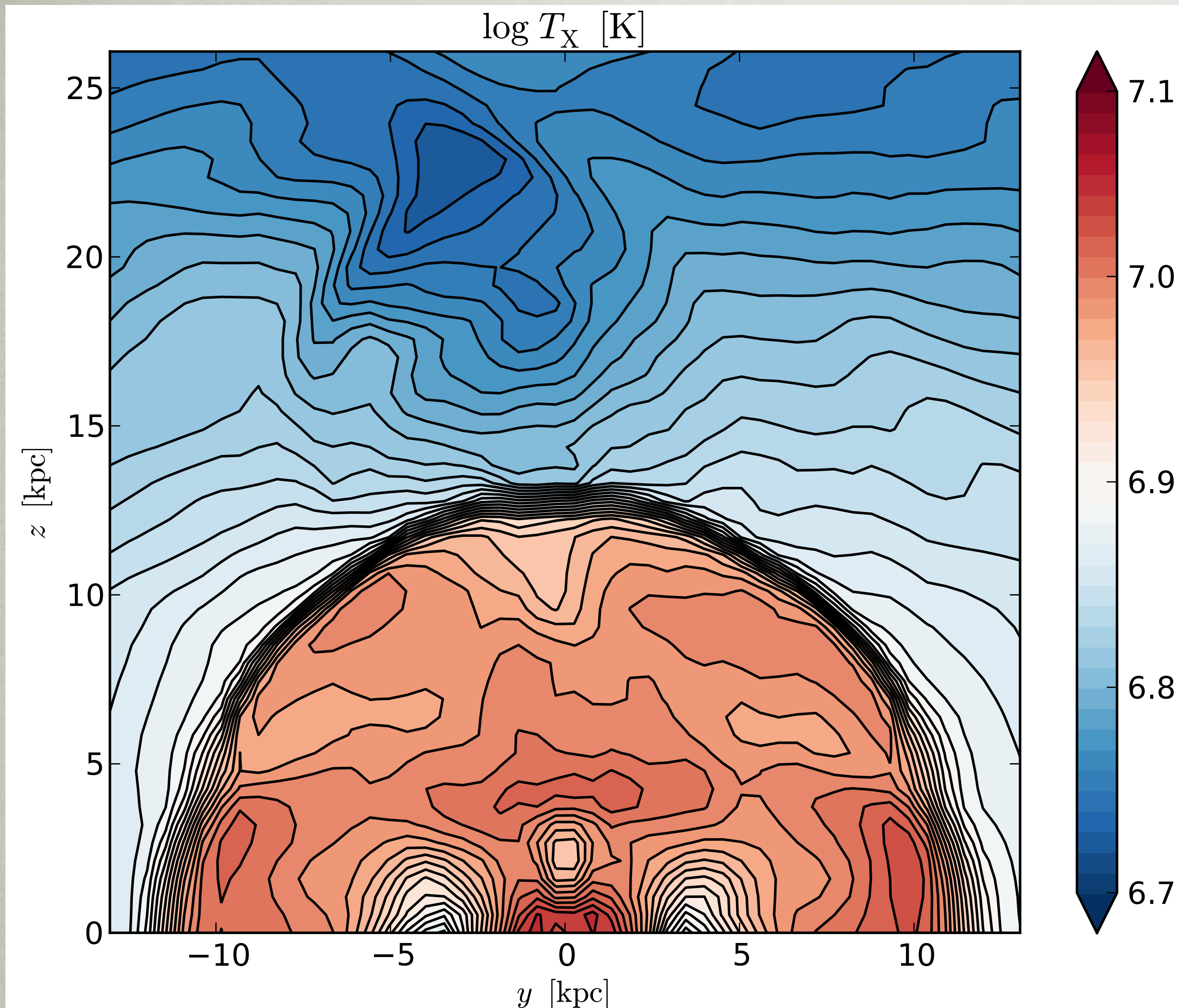
MG+2011b SIMS

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

enthalpy



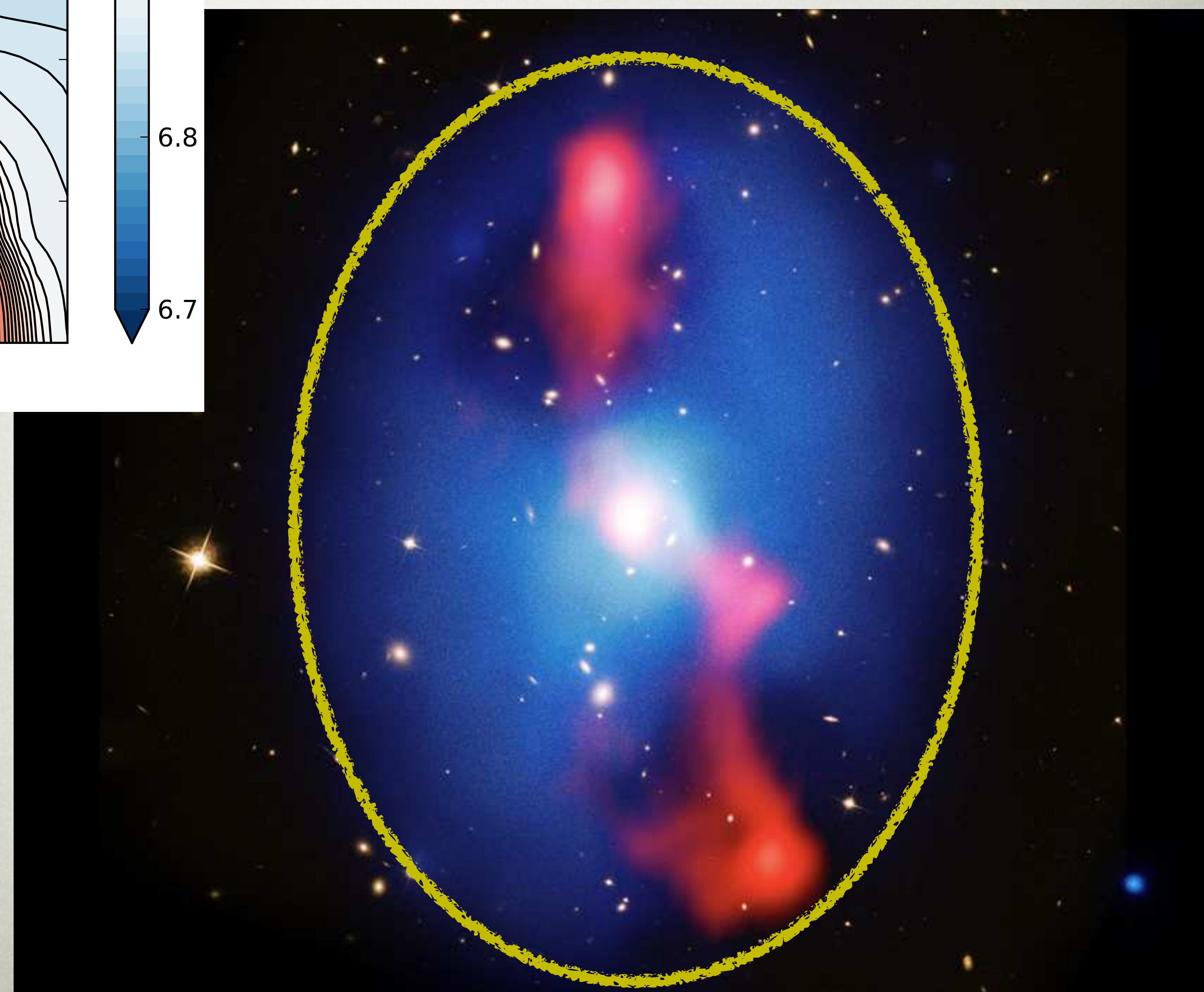
NGC 5813 - Randall+2011



MG+2012b SIMS

COCOON SHOCKS

MS0735.6 cluster (McNamara+2005)

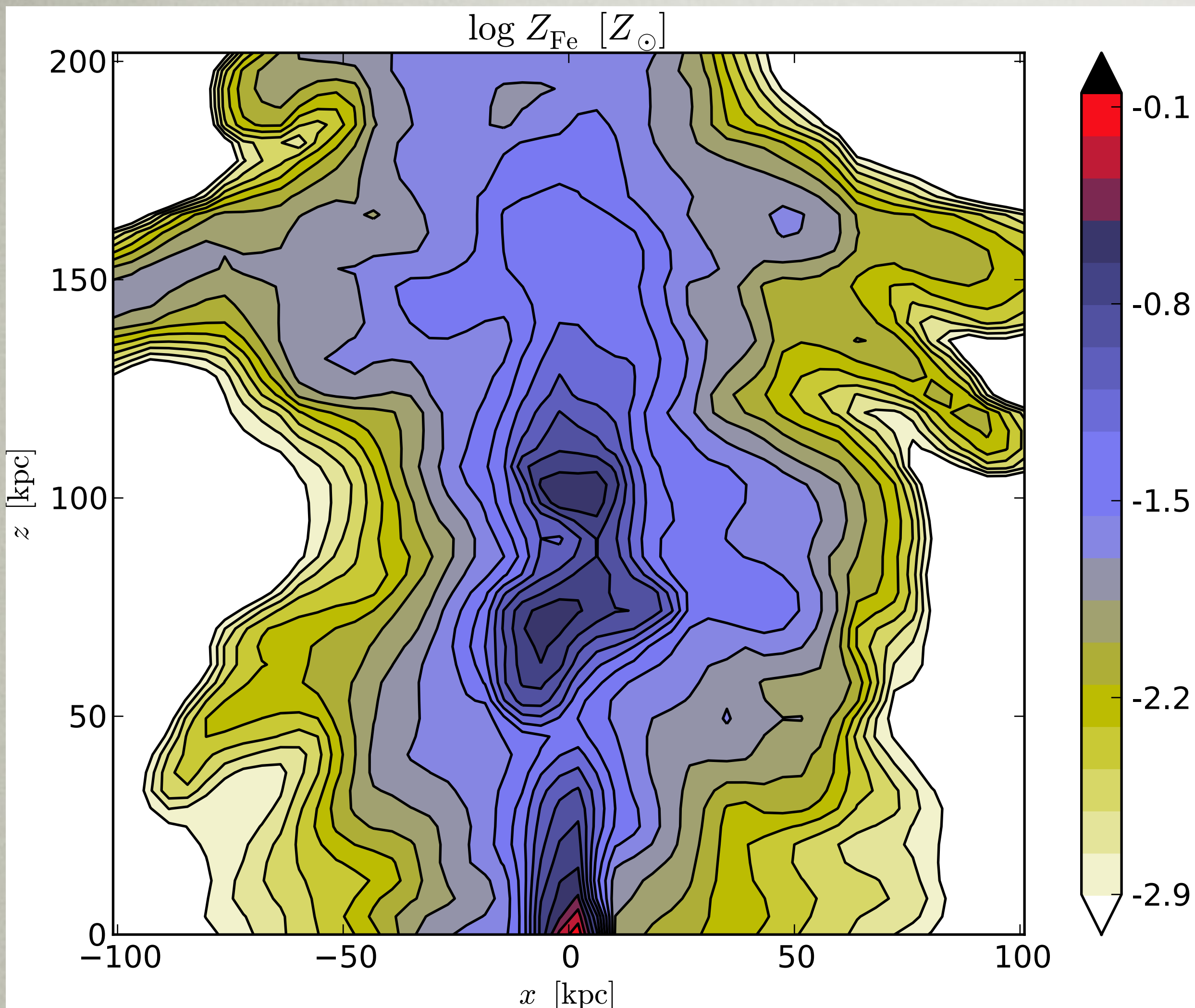


$$\Pi_s = \frac{(\gamma+1)}{12\gamma^2}\frac{\omega p}{2\pi}\left(\frac{\delta p}{p}\right)^3$$

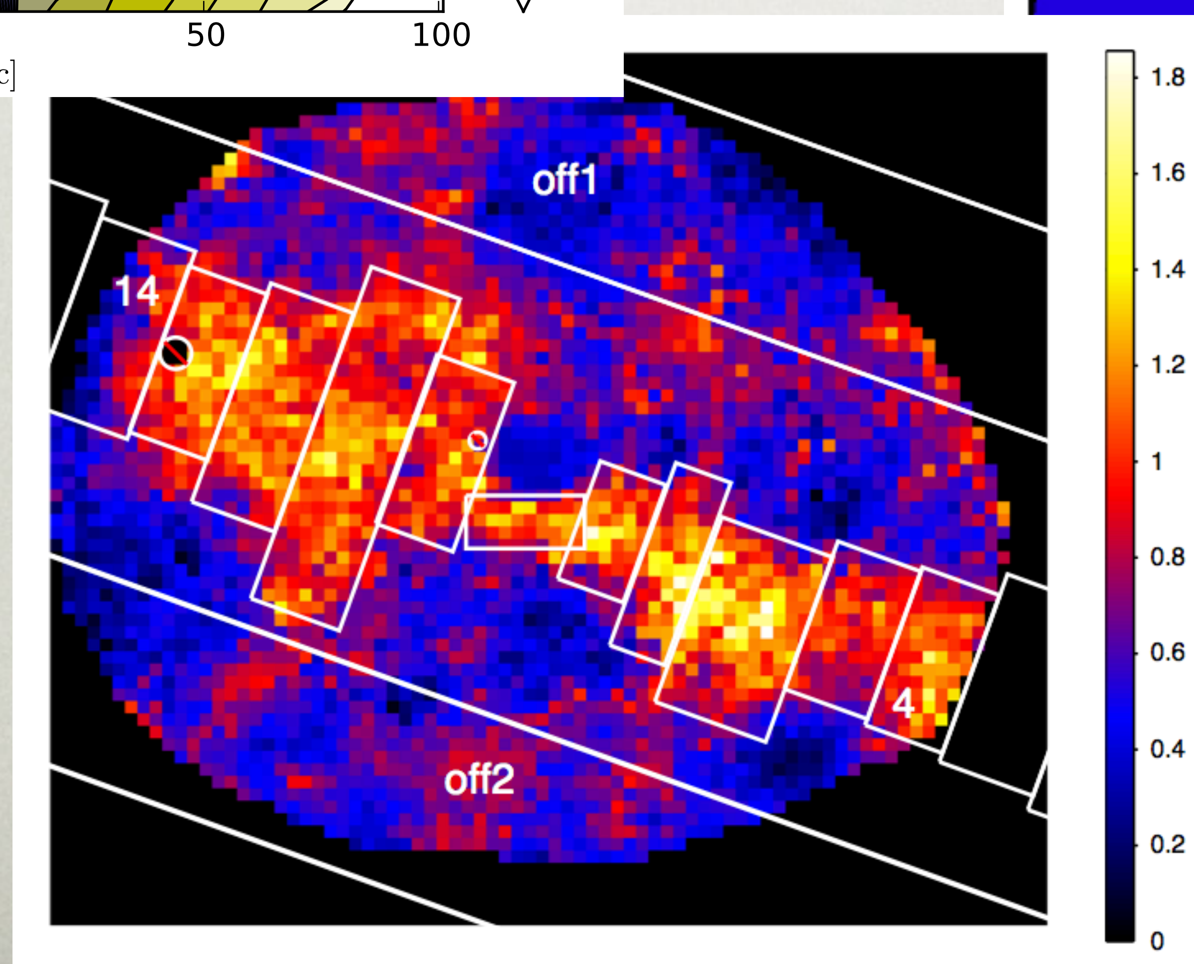
weak shock heating

TURBULENT MIXING

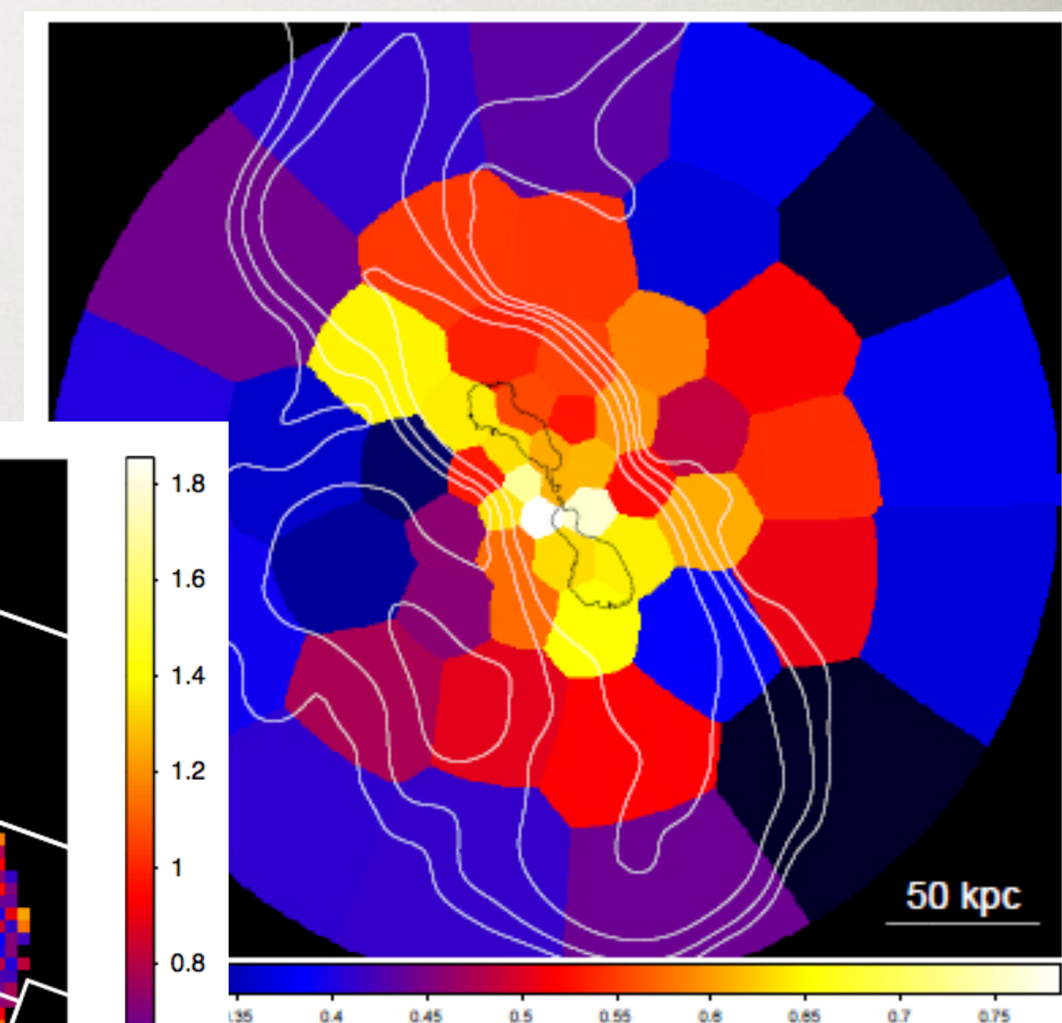
TRACED BY METALS
(passive tracer)



MG+2012a SIMS



Zw 1742+3306
Ettori+2013



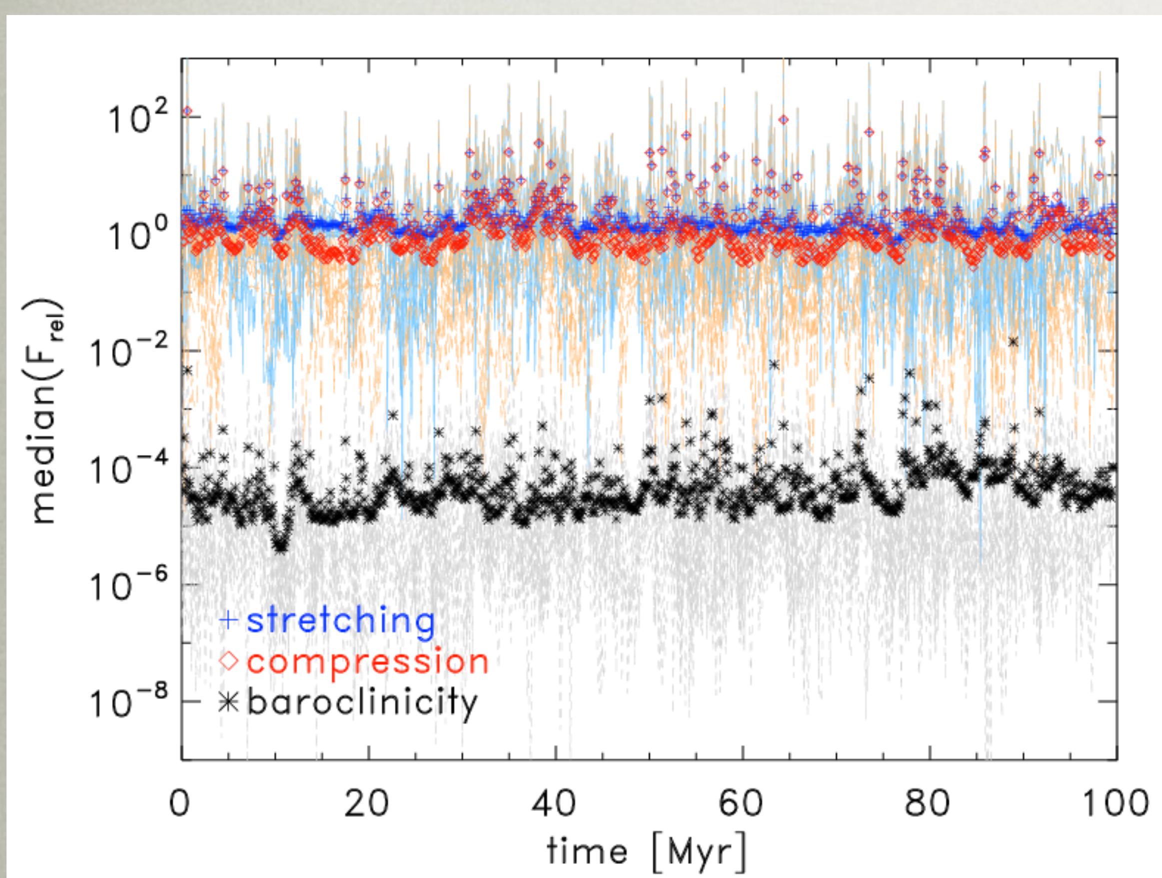
Hydra A - Kirkpatrick+2009, 2011

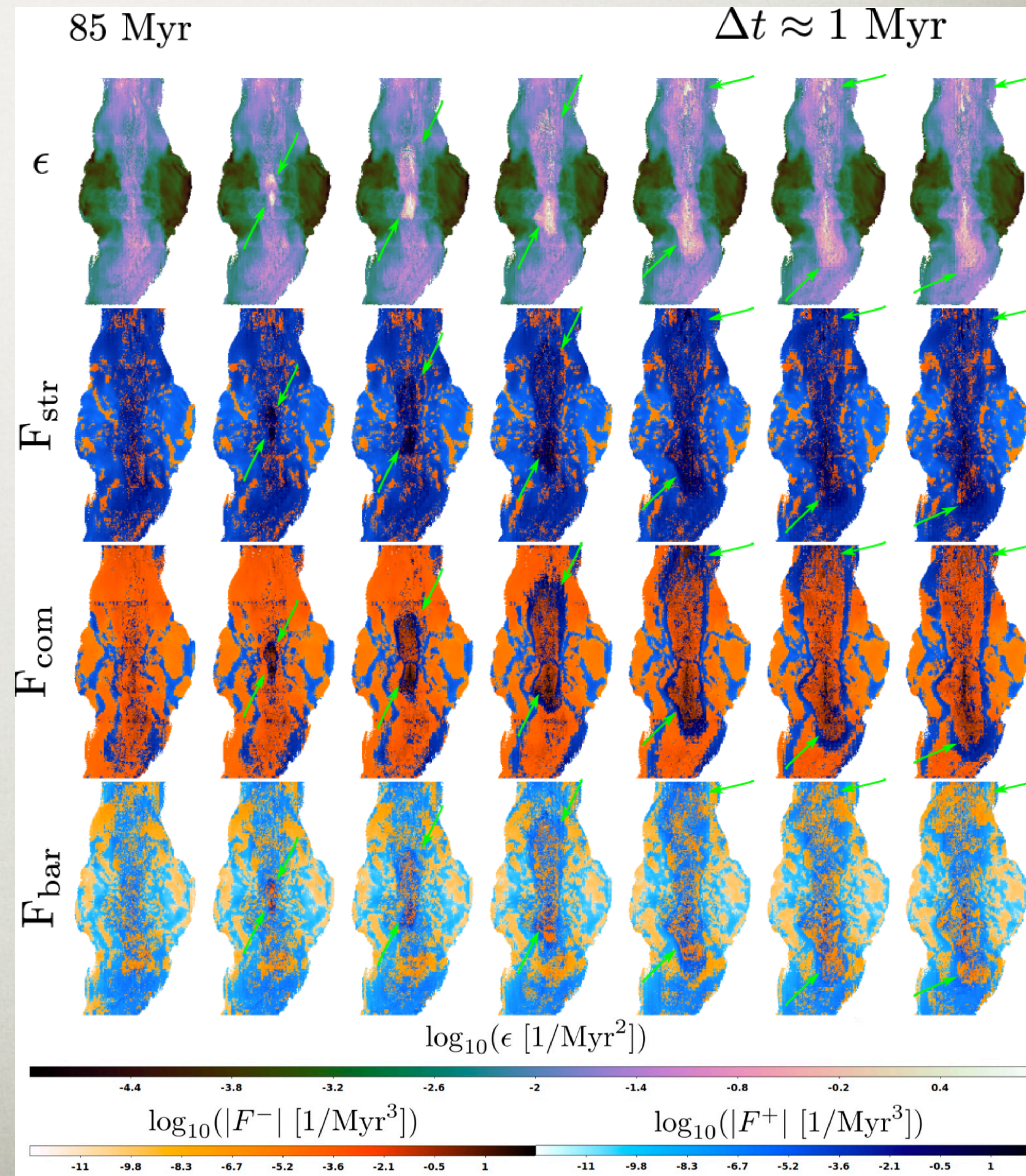
TURBULENCE - ENSTROPHY

Wittor & Gaspari 2020

ENSTROPHY ~ magnitude (squared) of vorticity / turbulence

$$\frac{d\epsilon}{dt} = \underbrace{-2\epsilon(\nabla\cdot\mathbf{v})}_{F_{\rm com}} + \underbrace{2\epsilon\left(\frac{\boldsymbol{\omega}}{|\boldsymbol{\omega}|}\cdot\nabla\right)\mathbf{v}\cdot\frac{\boldsymbol{\omega}}{|\boldsymbol{\omega}|}}_{F_{\rm str}} + \underbrace{\frac{\boldsymbol{\omega}}{\rho^2}\cdot(\nabla\rho\times\nabla P)}_{F_{\rm bar}},$$



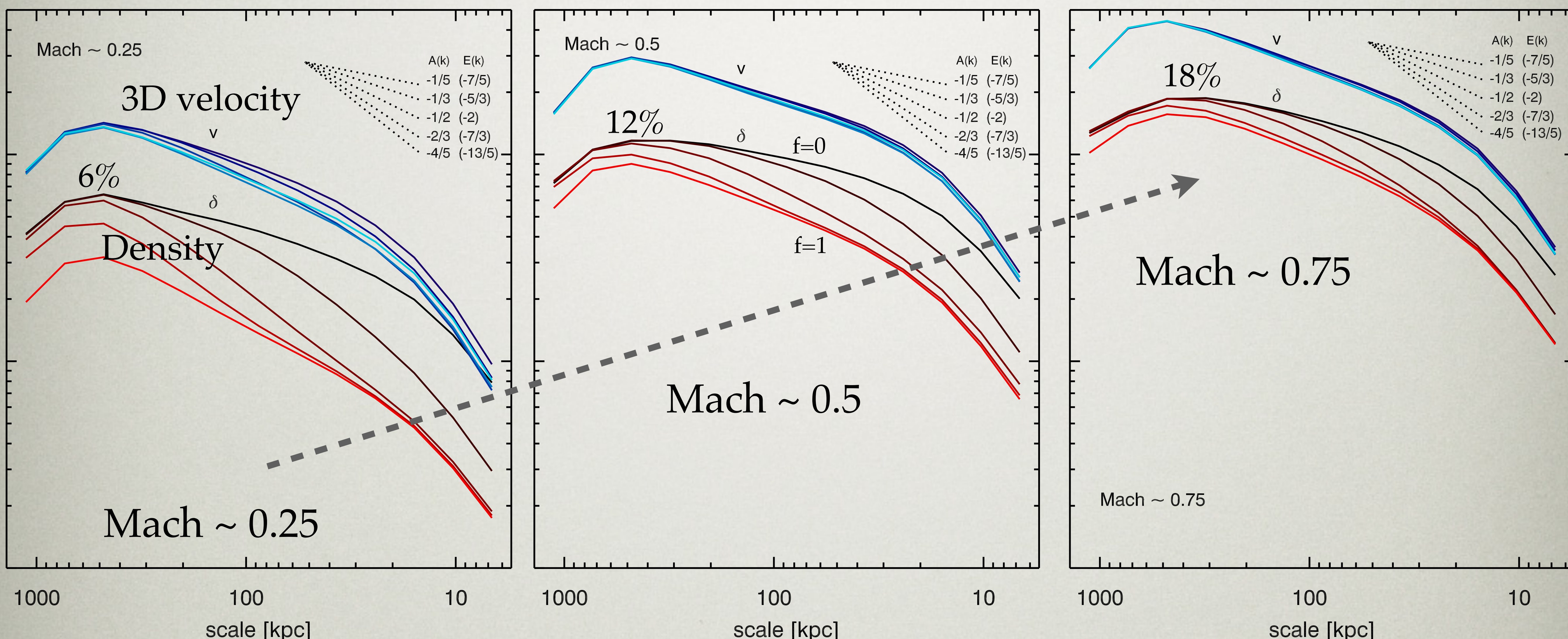


- stretching motions balanced by rarefactions
- baroclinic motions subdominant (except nucleus)

TURBULENCE:

AMPLITUDE SPECTRUM

$$A(k) = \sqrt{P(k)\,4\pi k^3}$$



Gaspari+13-14

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

globally self-similar over Mach and L_{inj}

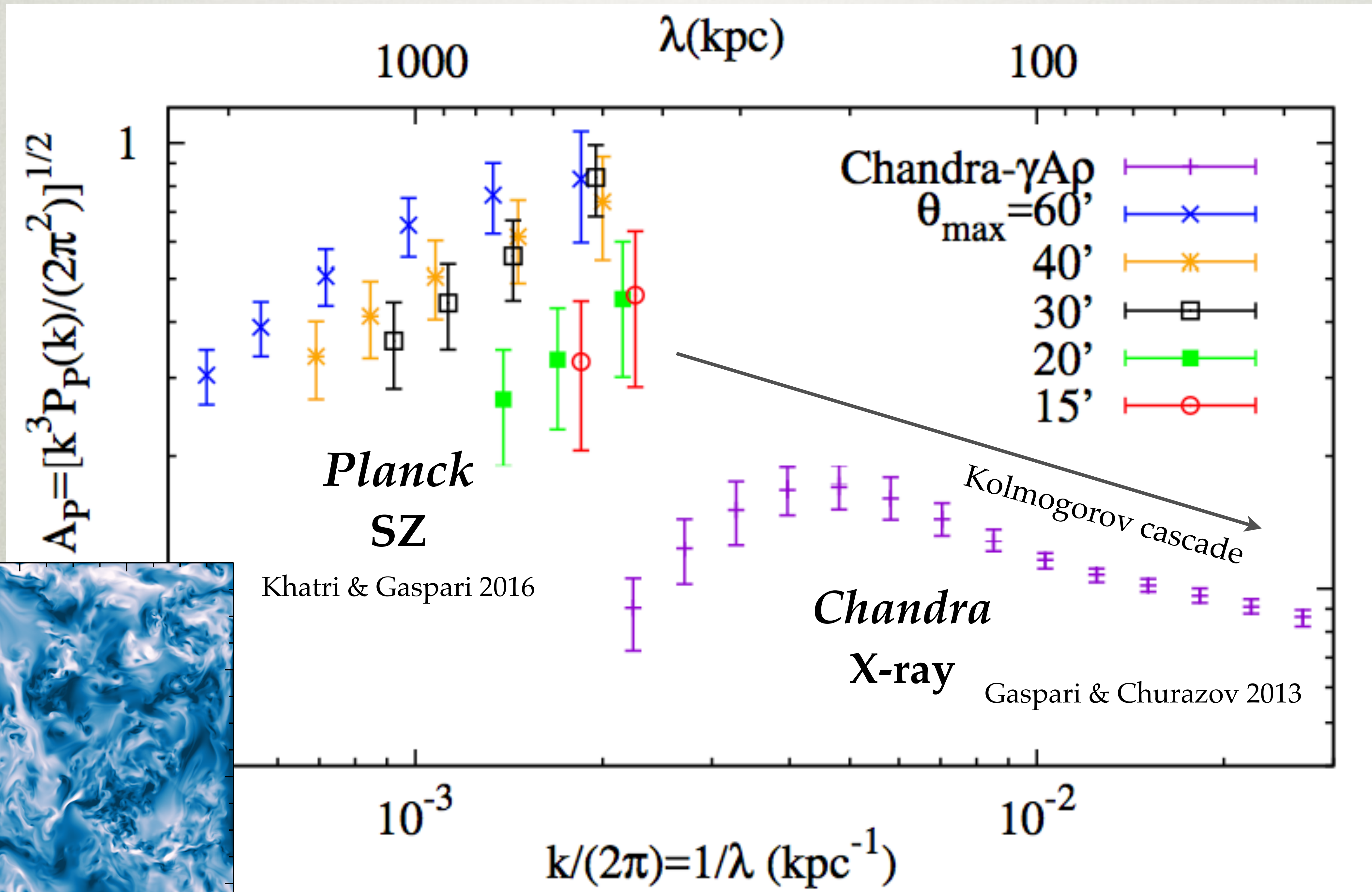
conduction steepens the slope at the meso/micro scale

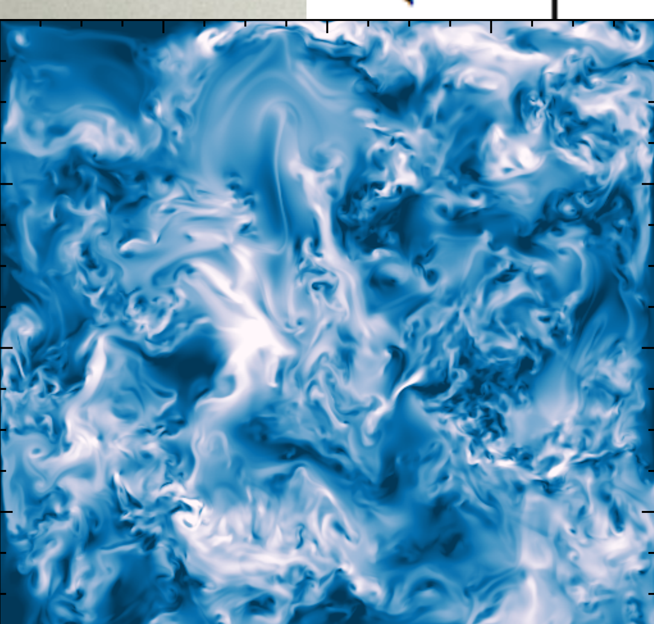
ICM POWER SPECTRUM

PROBING TURBULENCE & CONDUCTION

from 3D hydro simulations: $\boxed{\delta\rho/\rho \sim \mathrm{Mach}_{1\mathrm{D}}}$ [Gaspari & Churazov 2013; Gaspari et al. 2014]

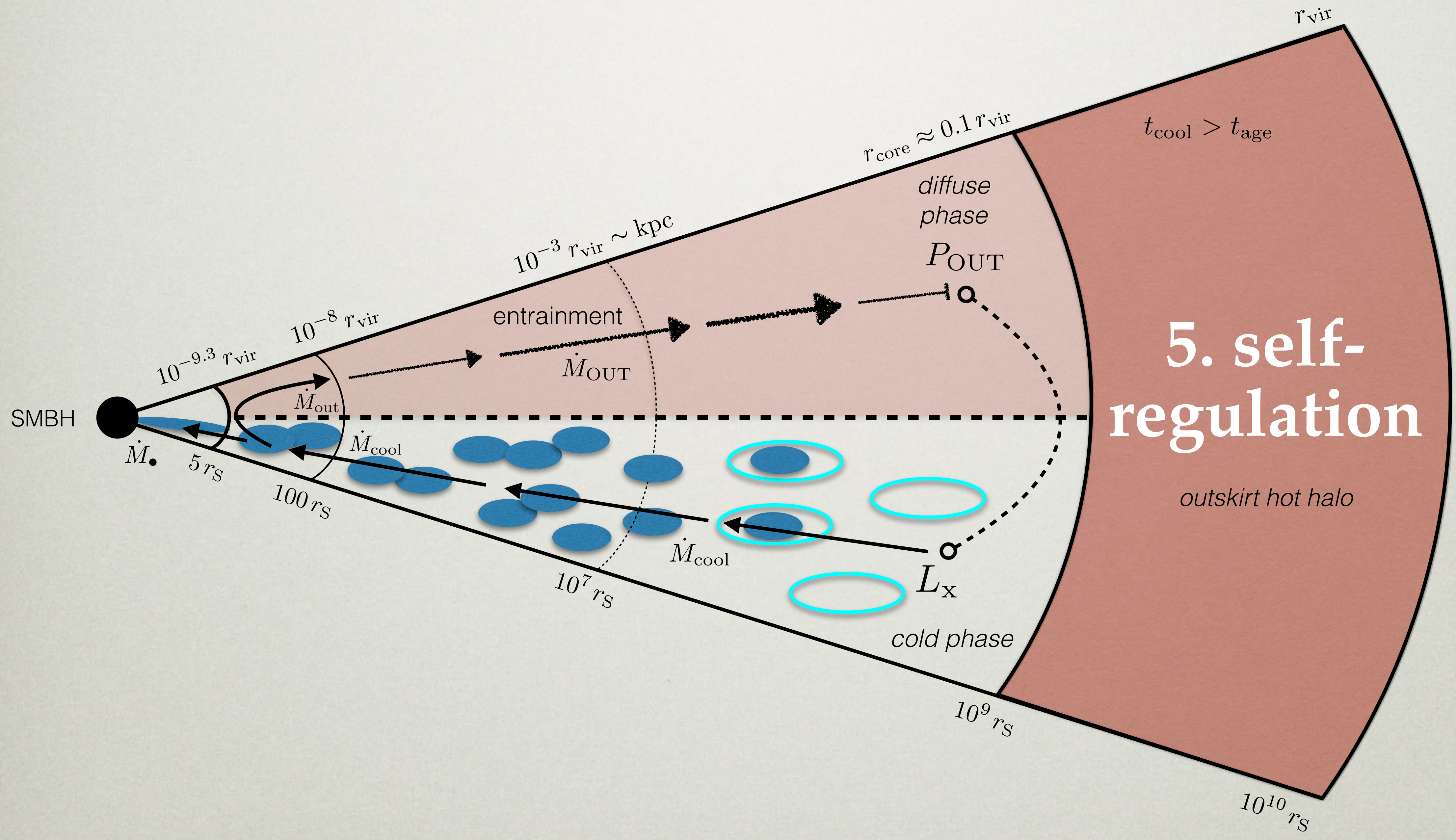
massive CLUSTER





subsonic turbulence

BLACK HOLE FEEDING AND FEEDBACK UNIFICATION



BLACK HOLE FEEDBACK MACRO CYCLE

(> KPC)

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

↓

nonlinear condensation

↓

CCA rain

↓

feed SMBH

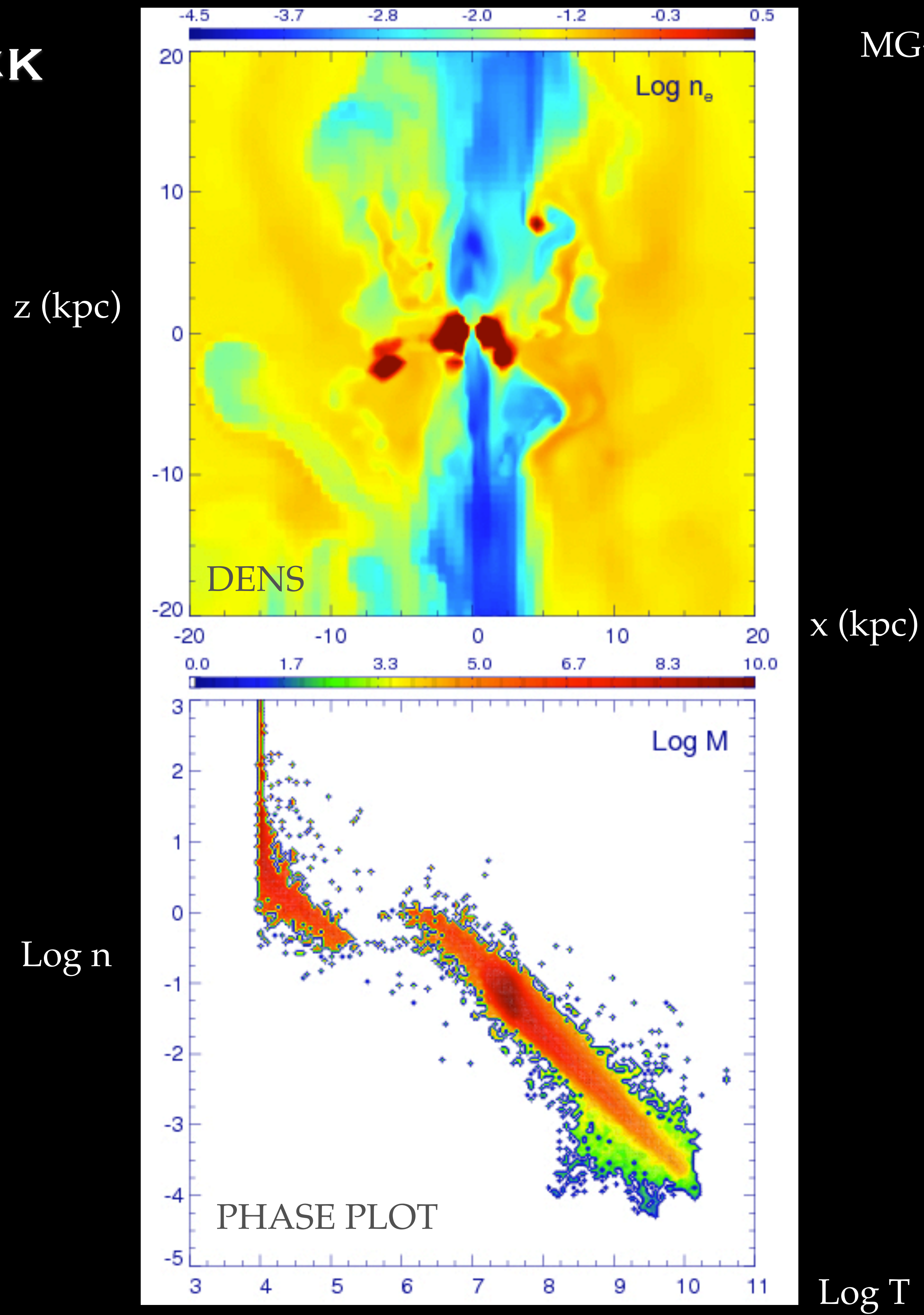
↓

feedback boosted

↓

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

MG+12a



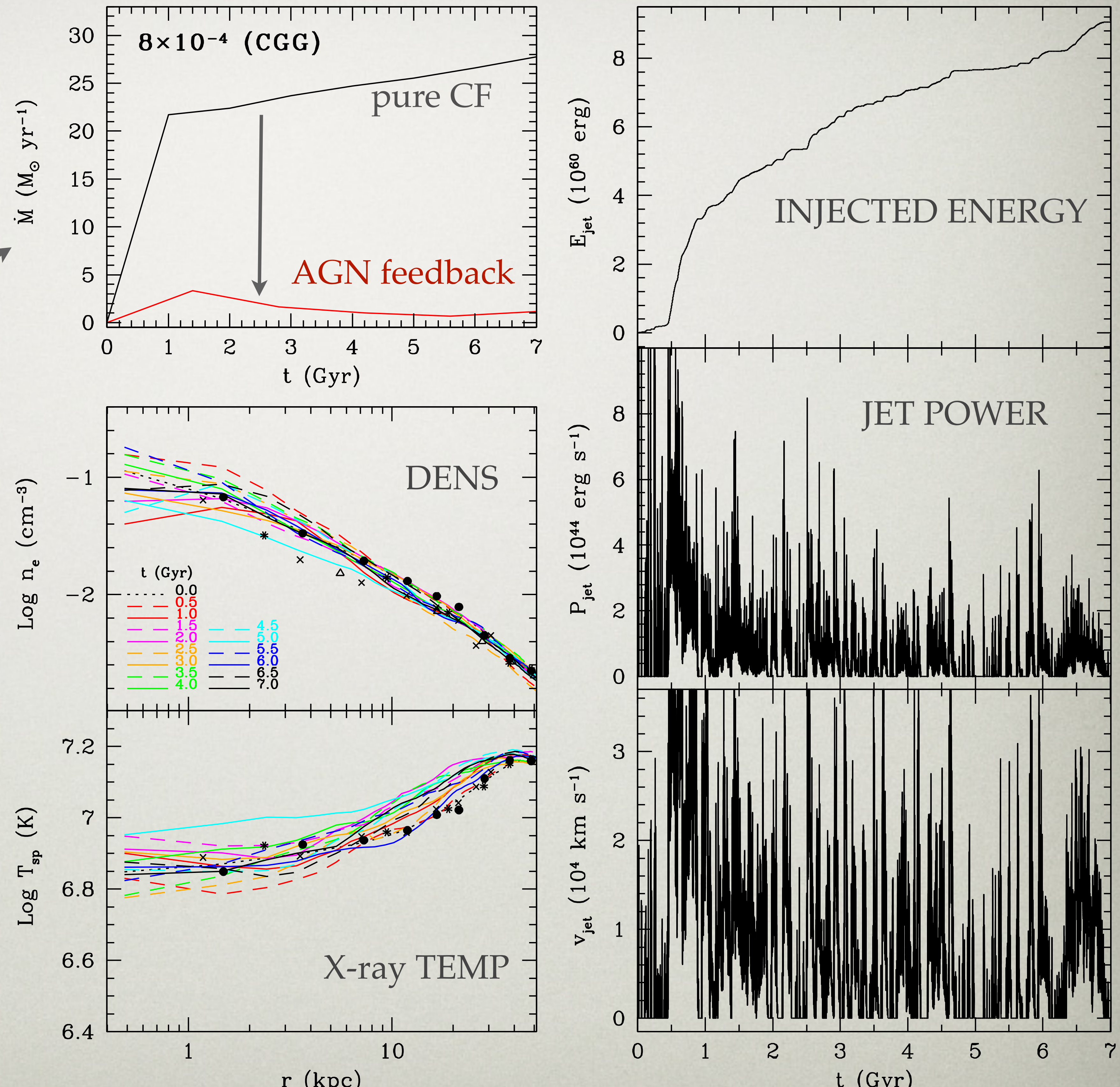
SOLVING THE COOLING FLOW PROBLEM

- 1. Quenching cooling rate (< 10% pure cooling flow)

- 2. Cool core preservation

galaxy group NGC 5044

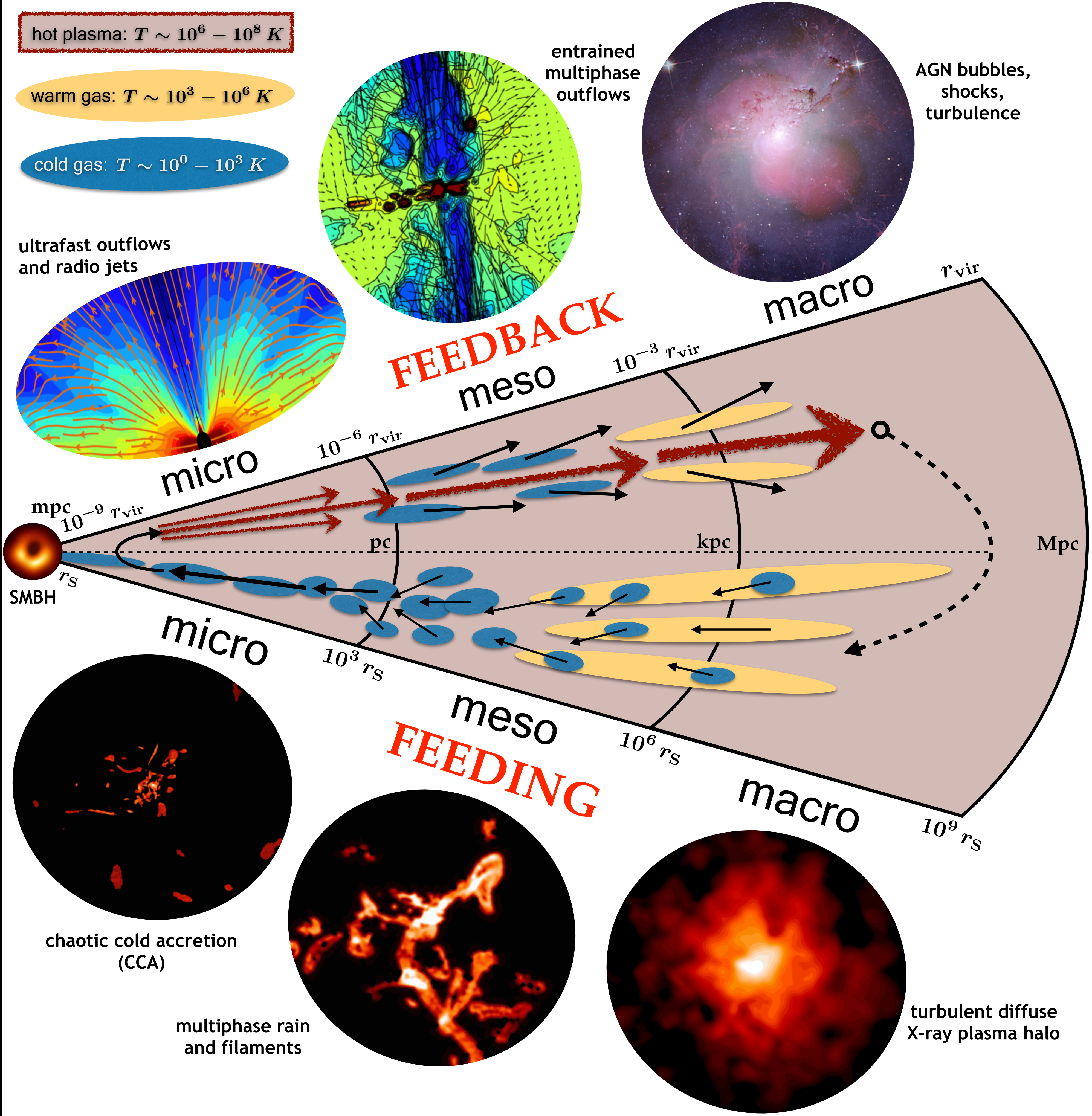
Gaspari+12b



JET VELOCITY

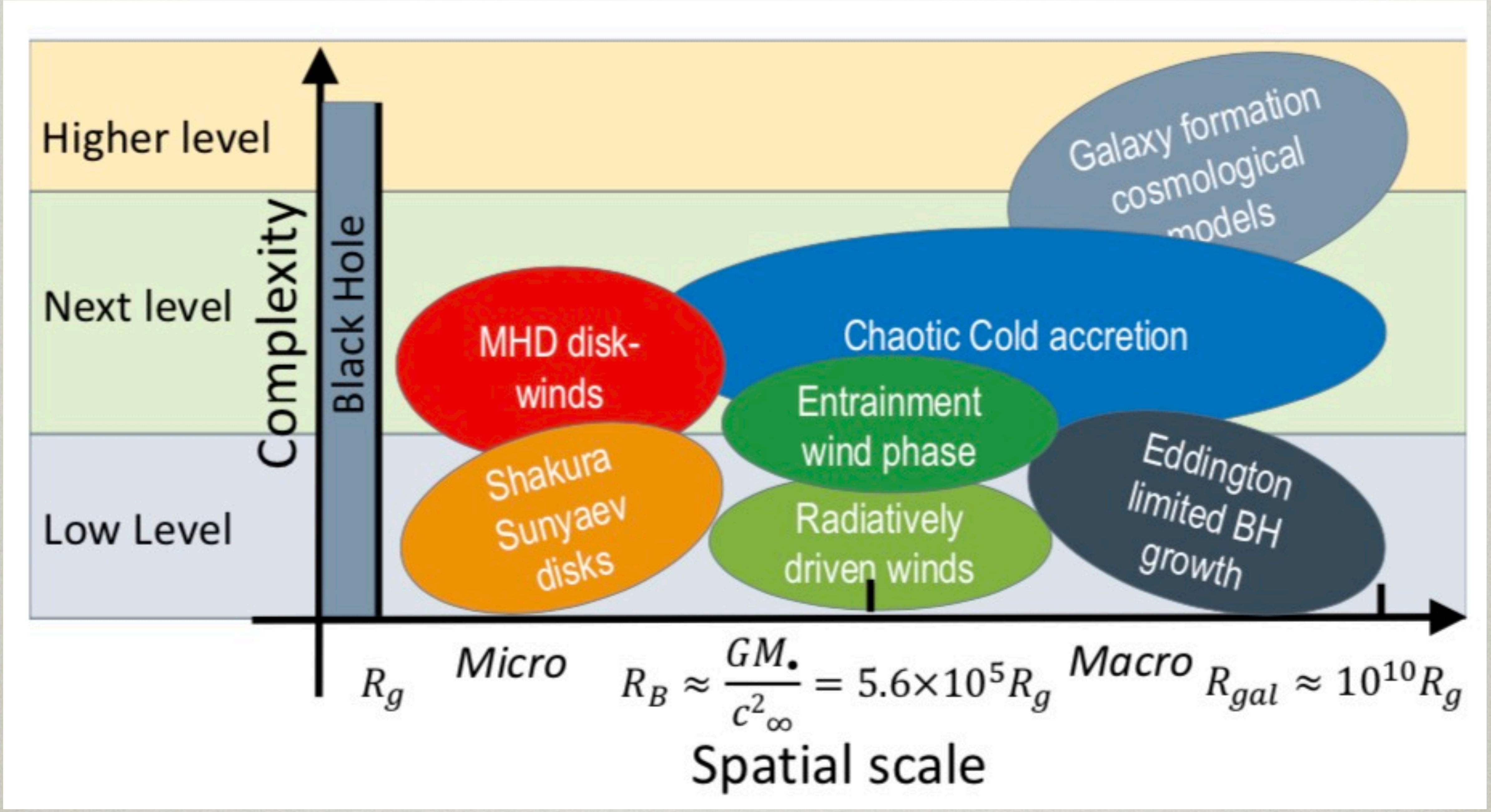
AGN FEEDING
& FEEDBACK
UNIFICATION

SUMMARY



Gaspari+20
Nature Ast.
review

INCREASING COMPLEXITY



How to effectively quantify complexity?

Fiore, Gaspari, Luminari, Tozzi (2023) *A&A*, sub.

WHAT IS COMPLEXITY?

(A FEW IDEAS)

1. **N components very large —** complex systems consist of a large number of interacting elements, making it challenging to understand and predict their collective behavior (highly complex: N ~ 100 billions)

2. **Interconnectedness** — the components of a complex system are highly interconnected, with their interactions often non-linear and difficult to predict (each node 100s-1000s connections)

3. **Emergence** — collective behavior cannot be predicted from the behavior of individual micro components: new properties/"laws" emerge at a coarser macro scale from the interactions between such components

4. **Adaptation** — complex systems are highly dynamic and capable of adapting to changing conditions, leading to further emergent behavior (often in self-similar way)