Raining on Galaxies & Black Holes

unifying the micro and macro properties of agn feedback & feeding

Massimo (Max) Gaspari

Princeton University

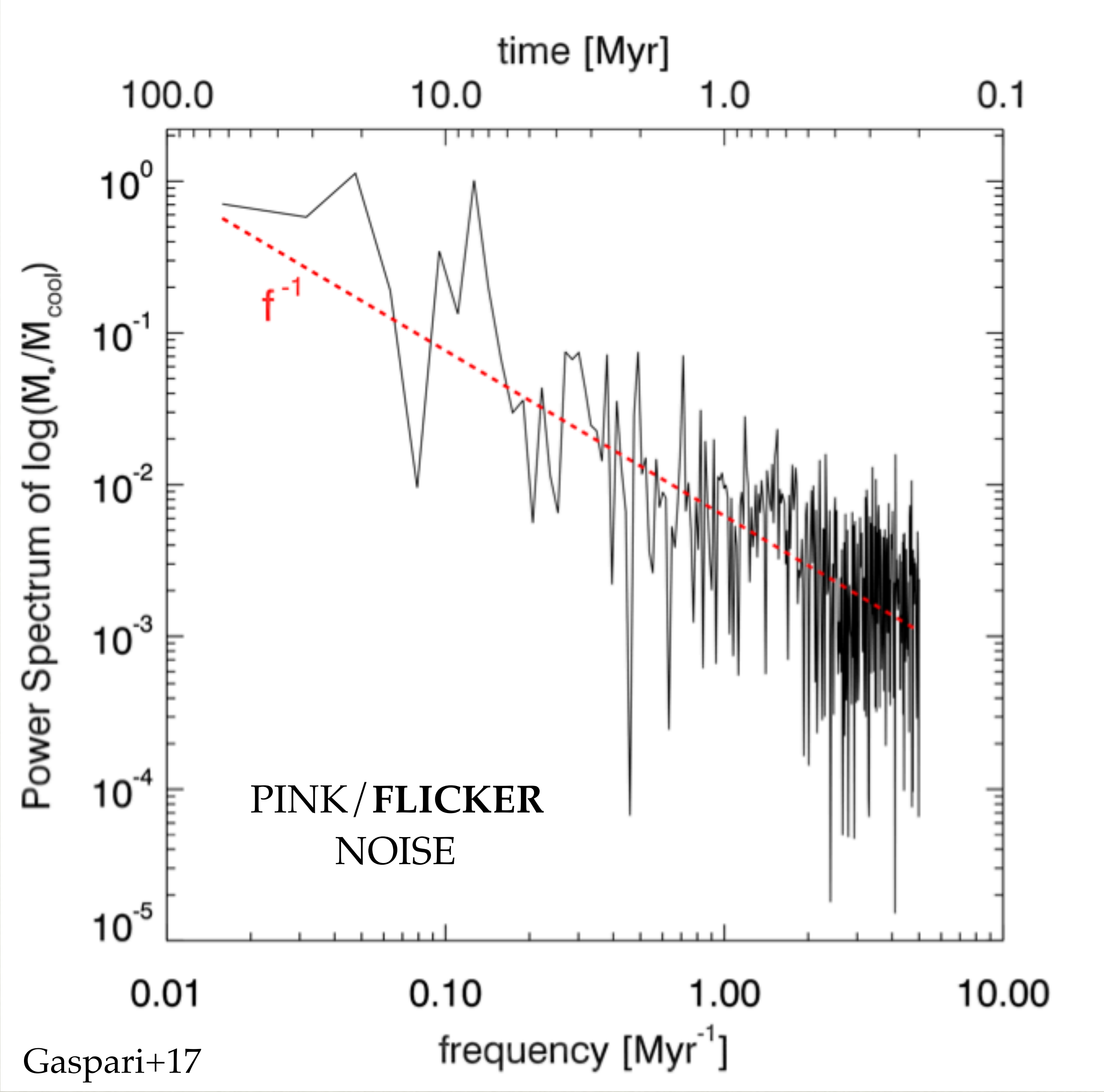
Einstein & Spitzer Fellow

natural RAIN sound (link to click)

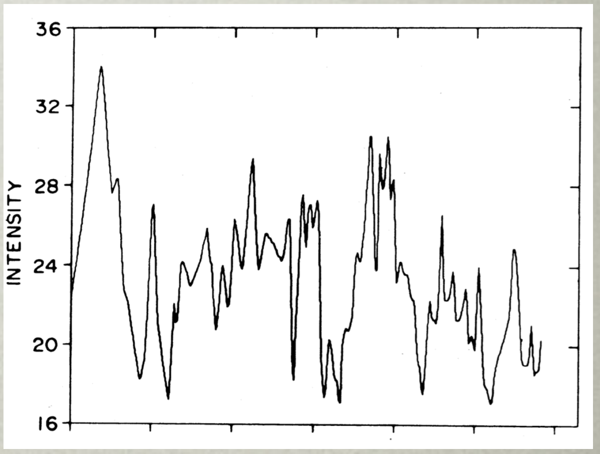
RAINING on SMBHs - CCA sound (link to click)

CHAOTIC COLD ACCRETION - [CCA]

RAINING ON BLACK HOLES AND GALAXIES

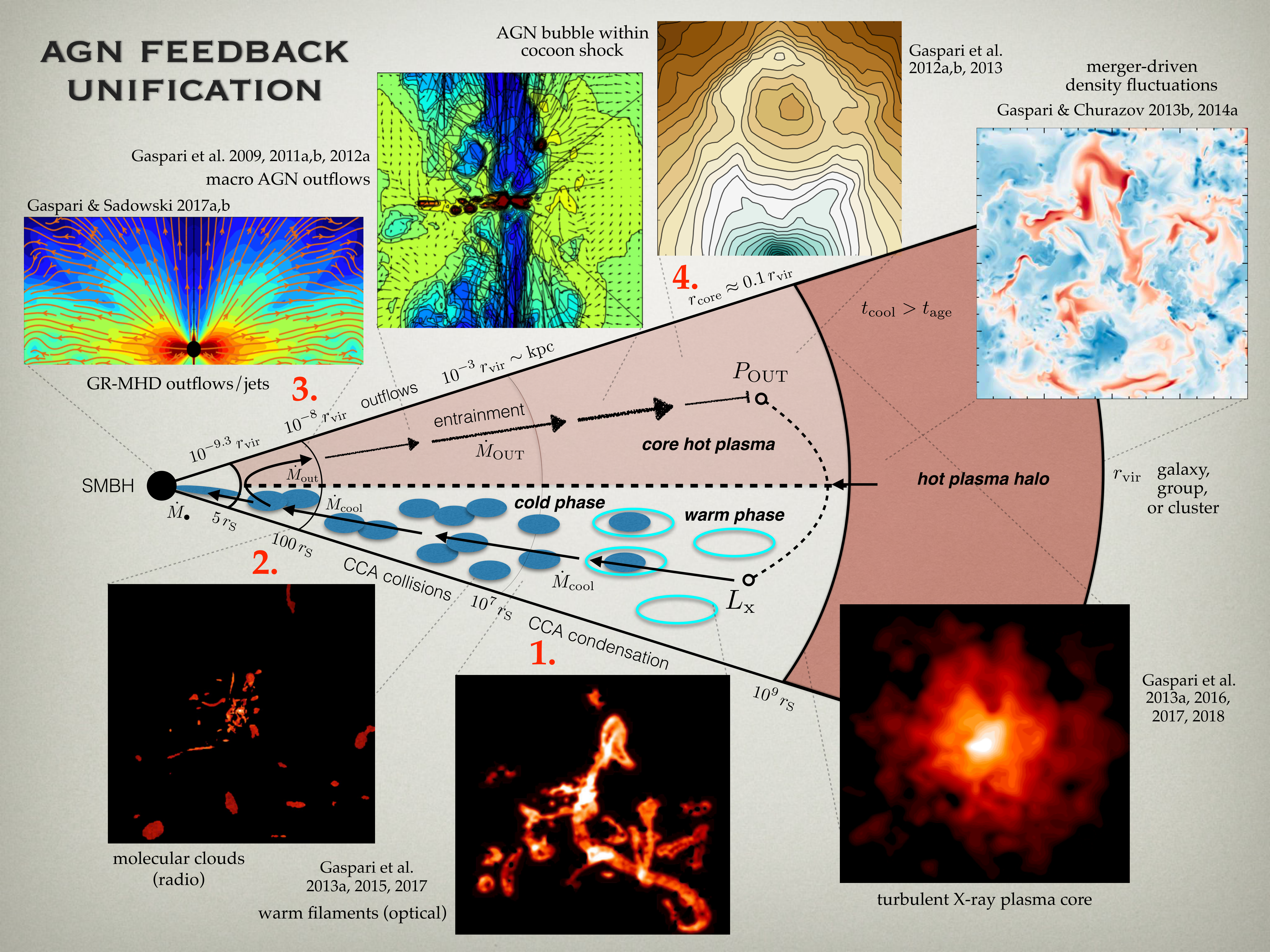


beautiful case: 3C273



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

quasars, sunspots, meteorological data/**RAINFALLS**, heart beat rhythms, neural activity, stock market, …


AGN FEEDBACK UNIFICATION
AGN bubble within cocoon shock
Gaspari et al. 2012a,b, 2013
merger-driven density fluctuations
Gaspari & Churazov 2013b, 2014a
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macro AGN outflows
Gaspari & Sadowski 2017a,b
GR-MHD outflows/jets
3.
4.
$r_{\rm core} \approx 0.1\, r_{\rm vir}$
$t_{\rm cool} > t_{\rm age}$
$10^{-3}\, r_{\rm vir} \sim$ kpc
outflows
$10^{-8}\, r_{\rm vir}$
$10^{-9.3}\, r_{\rm vir}$
entrainment
$P_{\rm OUT}$
$\dot{M}_{\rm OUT}$
core hot plasma
$\dot{M}_{\rm out}$
SMBH
hot plasma halo
$r_{\rm vir}$
galaxy, group, or cluster
$\dot{M}_{\rm cool}$
cold phase
warm phase
$\dot{M}_\bullet$
$5\, r_{\rm S}$
$100\, r_{\rm S}$
2.
CCA collisions
$\dot{M}_{\rm cool}$
$10^7\, r_{\rm S}$
$L_{\rm x}$
CCA condensation
1.
$10^9\, r_{\rm S}$
Gaspari et al. 2013a, 2016, 2017, 2018
molecular clouds (radio)
Gaspari et al. 2013a, 2015, 2017
warm filaments (optical)
turbulent X-ray plasma core

FEEDING SIMULATION

MG+2013-2018

typical massively parallel FLASH run
(8000+ cpu-cores)

- concentric SMR zooming: **galactic 50 kpc → dx ~ 0.1 pc**

  ~5x10^5 range

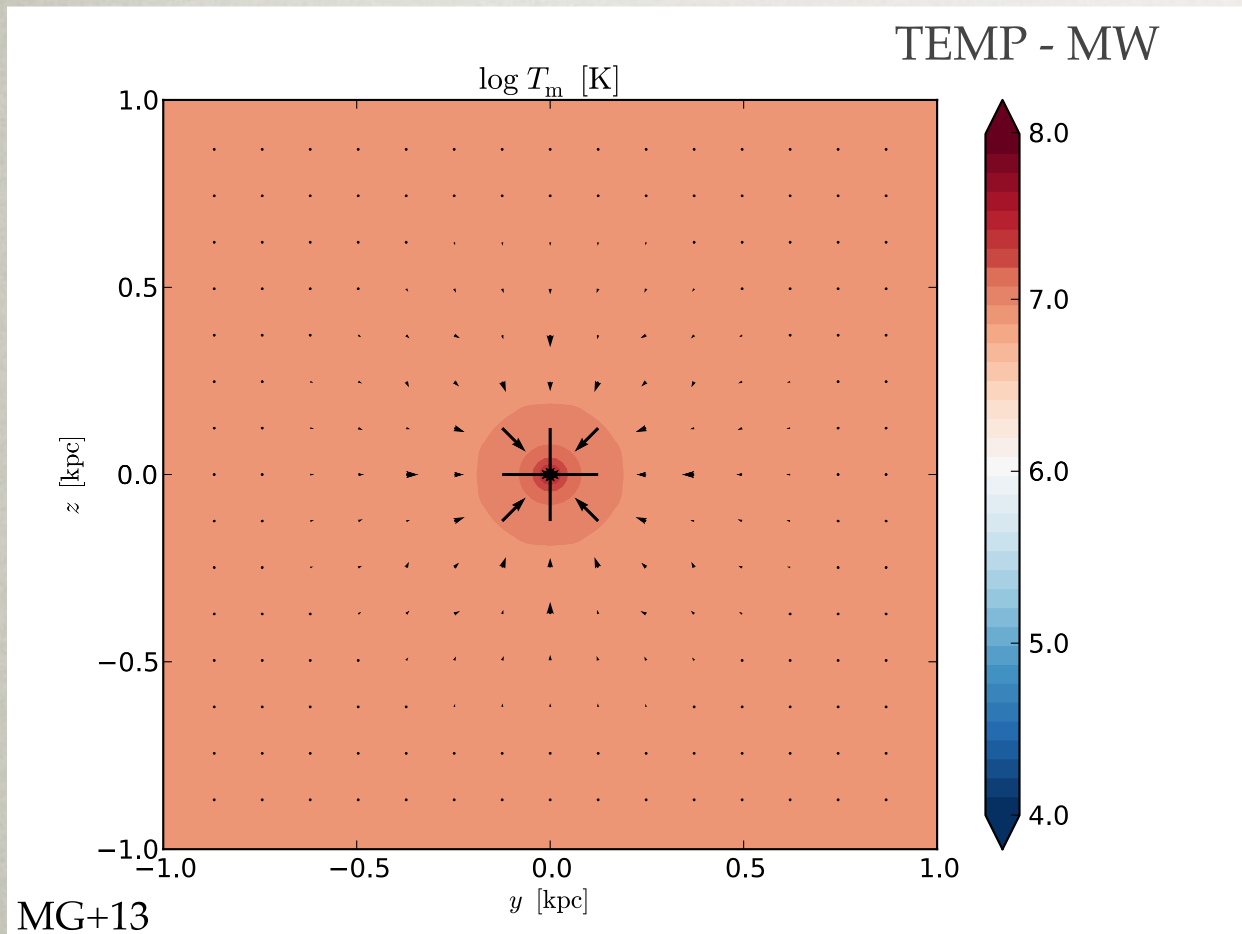
- 3D gas dynamics: unsplit PPM (3rd order) + progressively varying physics
- massive galaxy group with dark matter halo: $M_{vir} = 4x10^{13}\ M_{\odot}$
- central elliptical galaxy (NGC 5044): $M_{star} = 3.4x10^{11}\ M_{\odot}$
- SMBH: $M_{bh} = 3x10^9\ M_{\odot}$ ⟶ PW potential: $\phi_{PW} = -GM_{bh}/(r - R_S)$
- observed gas $T(r)$ [cool-core] ⟶ $n(r)$ via hydrostatic equilibrium

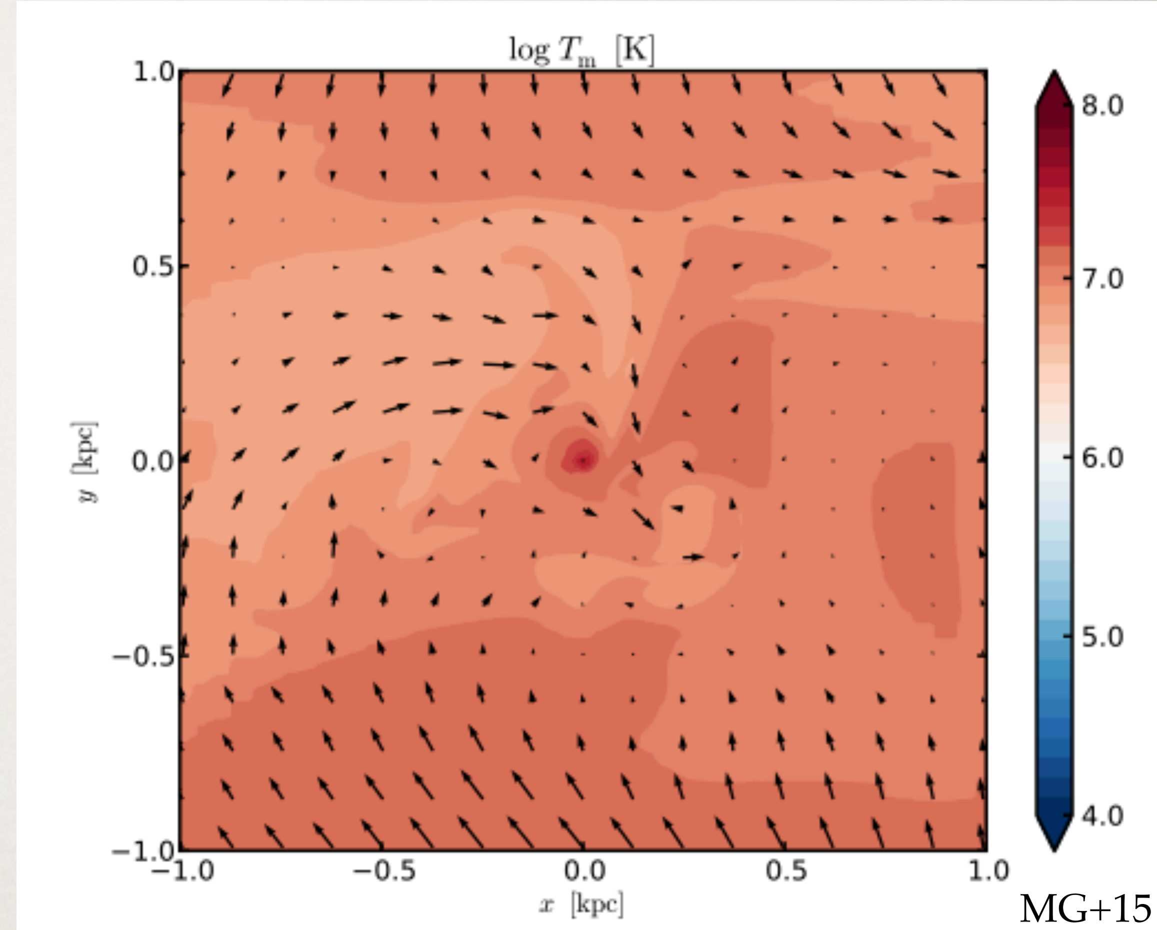
SIMS AS CONTROLLED EXPERIMENTS

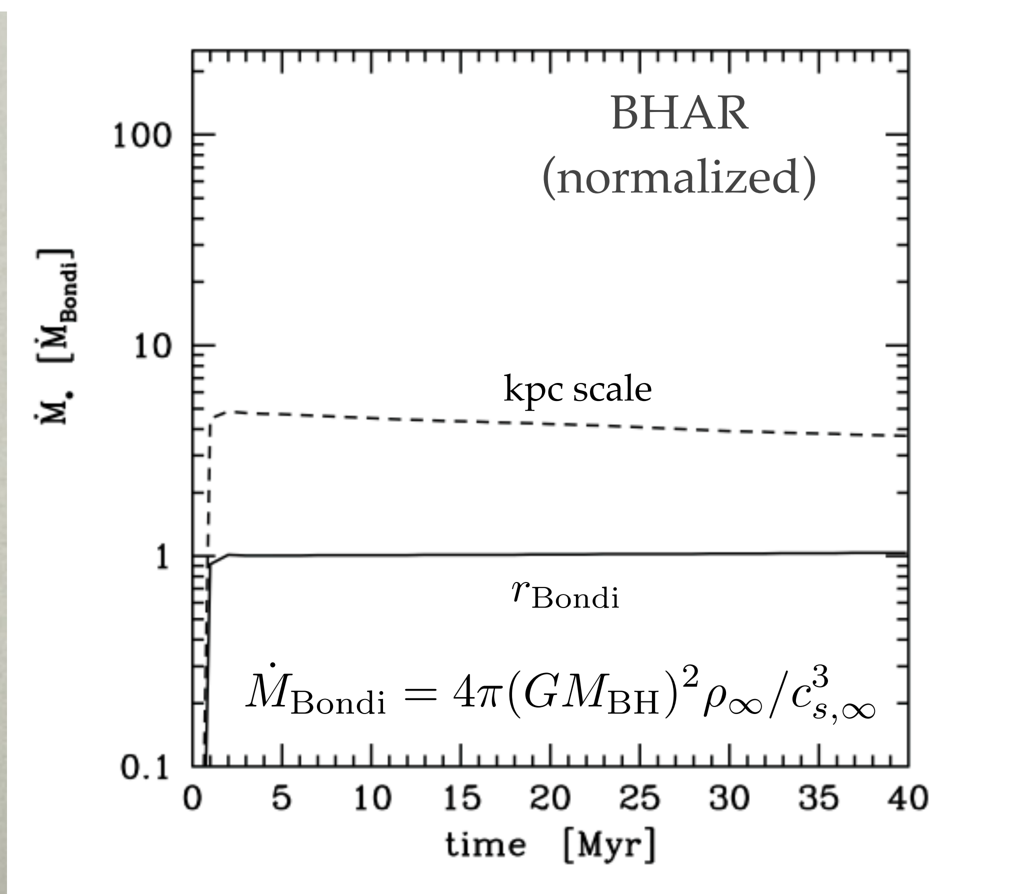
AGN FEEDING: HOT MODE

quiescent

turbulent or rotating

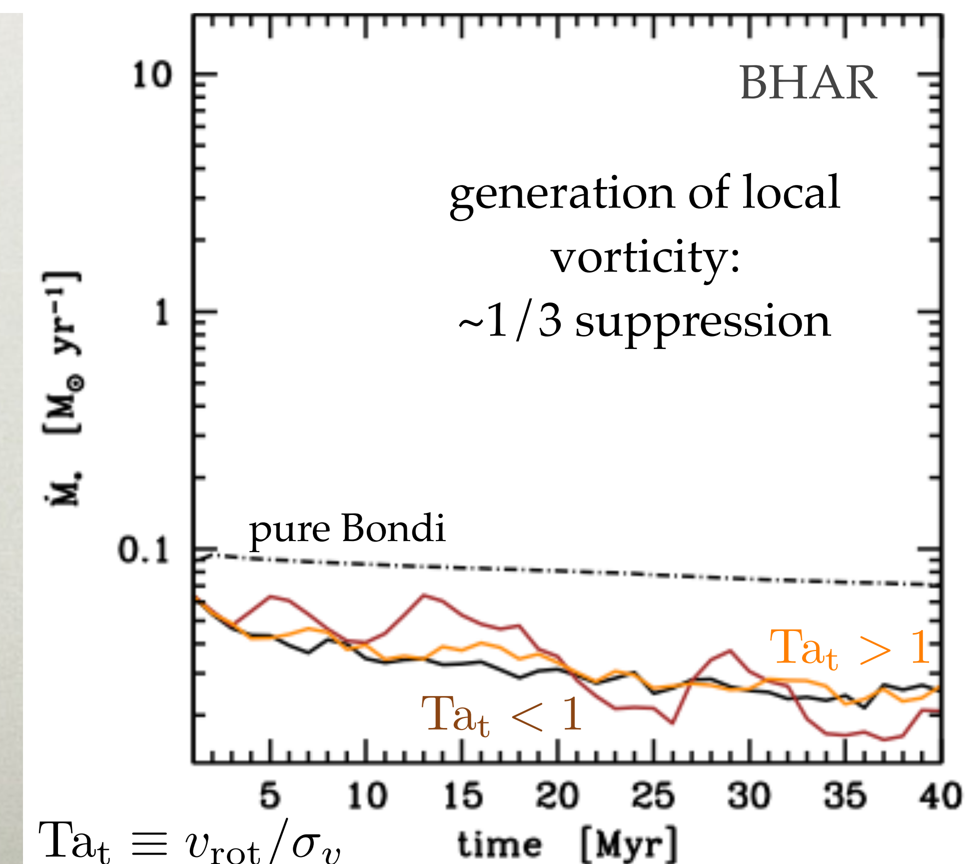






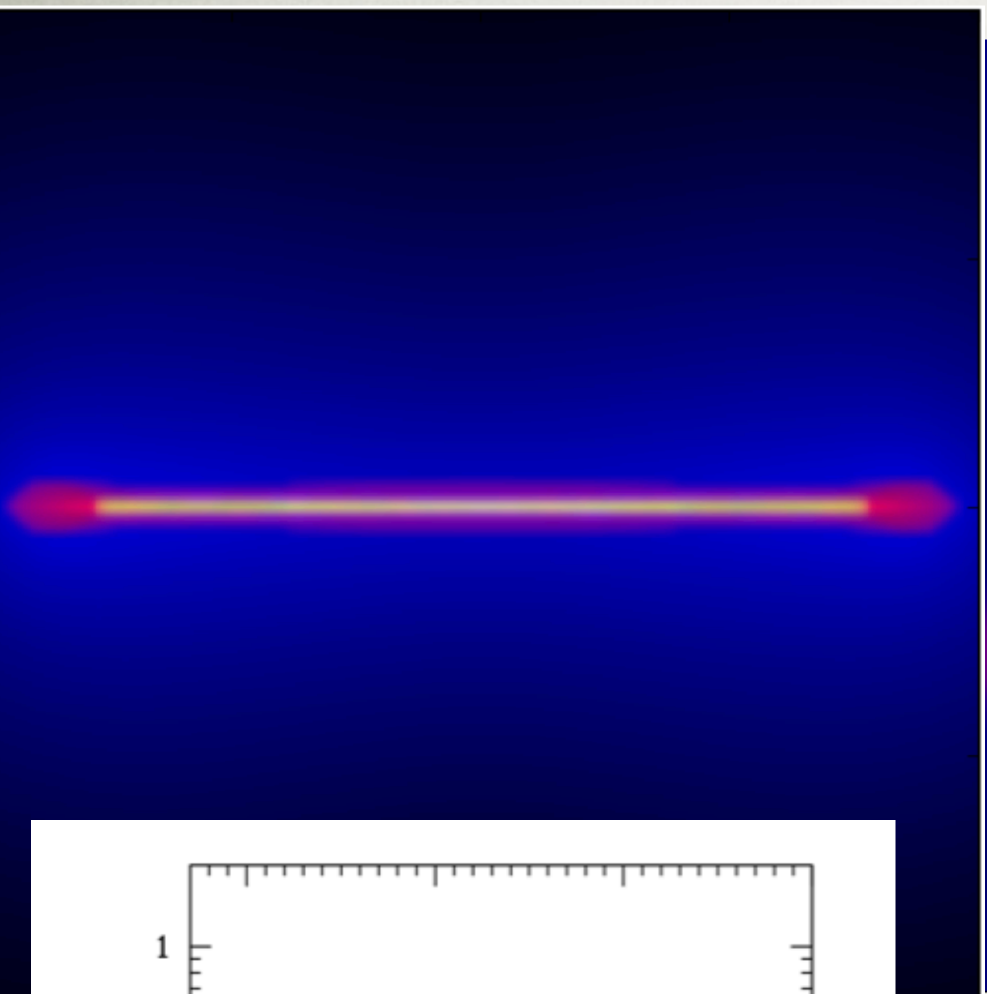
HIGH-RES HD SIMULATION
massive galaxy

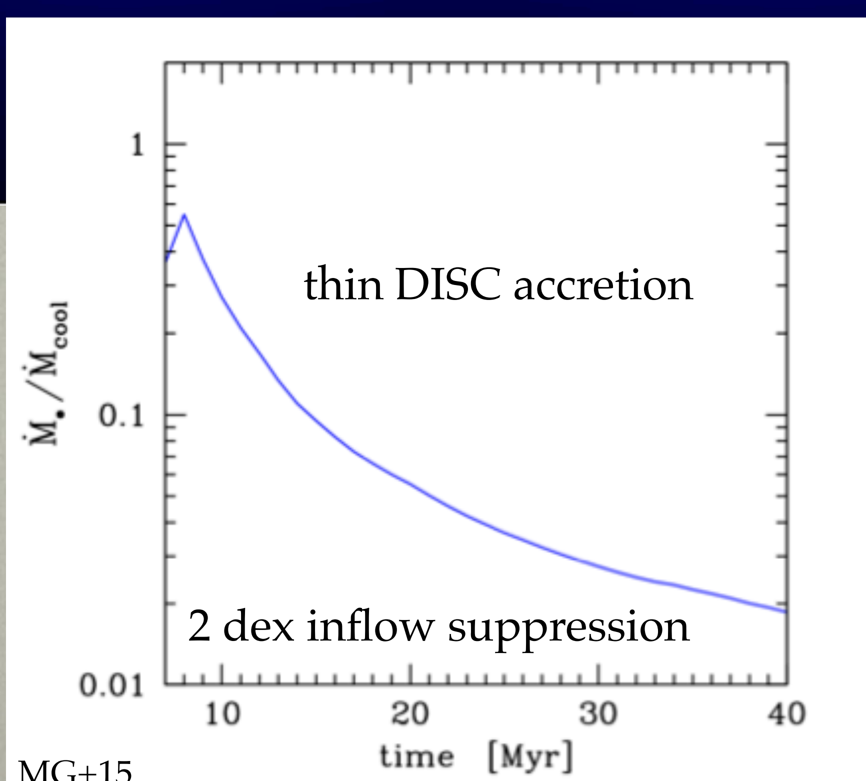
overall:
too weak
and smooth



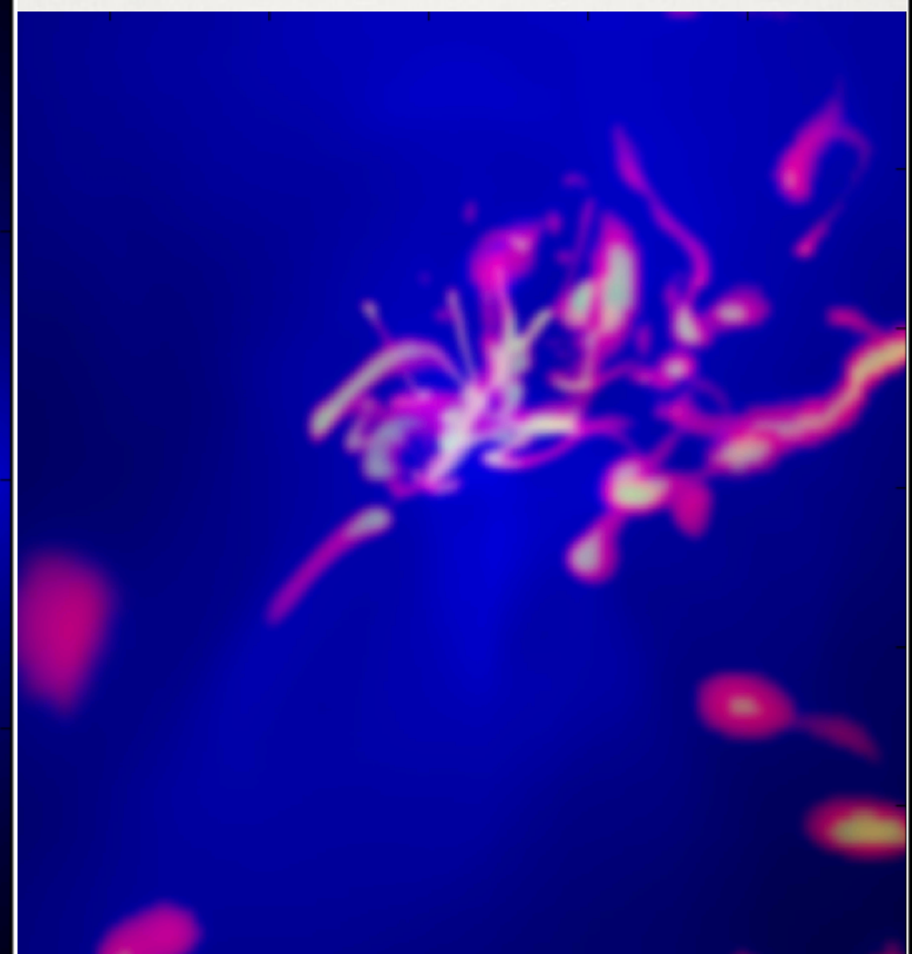
AGN FEEDING WITH COOLING: 3 DYNAMICAL STAGES

rotating



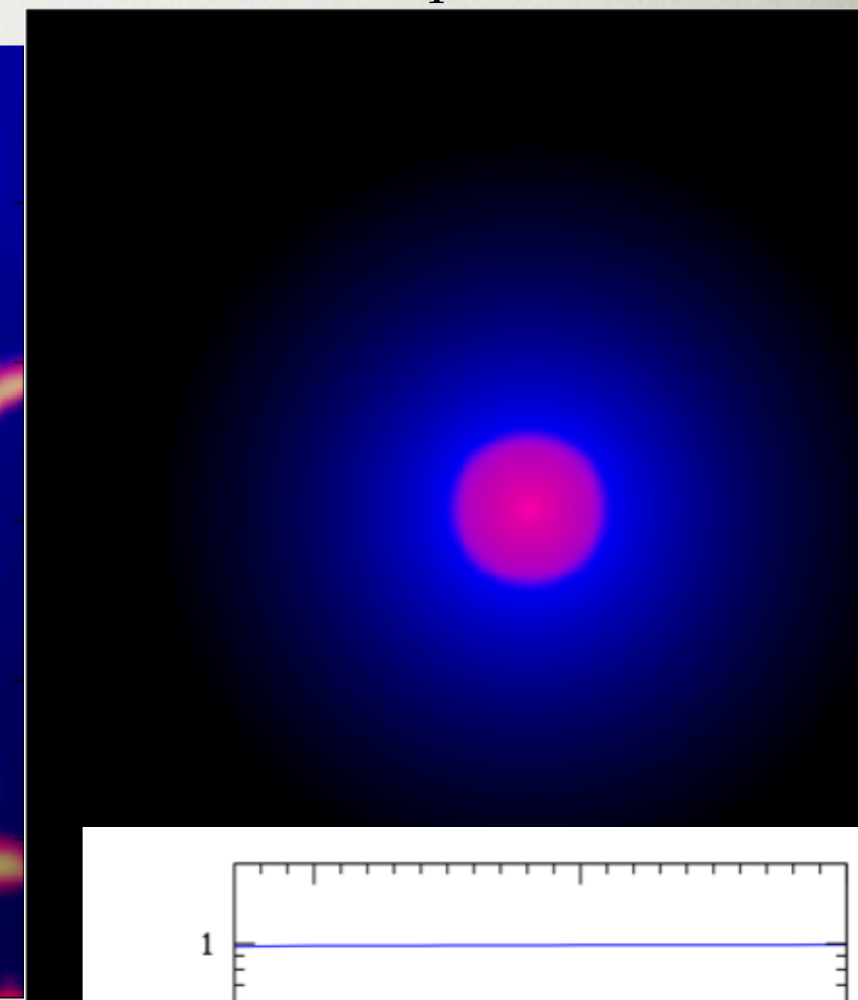


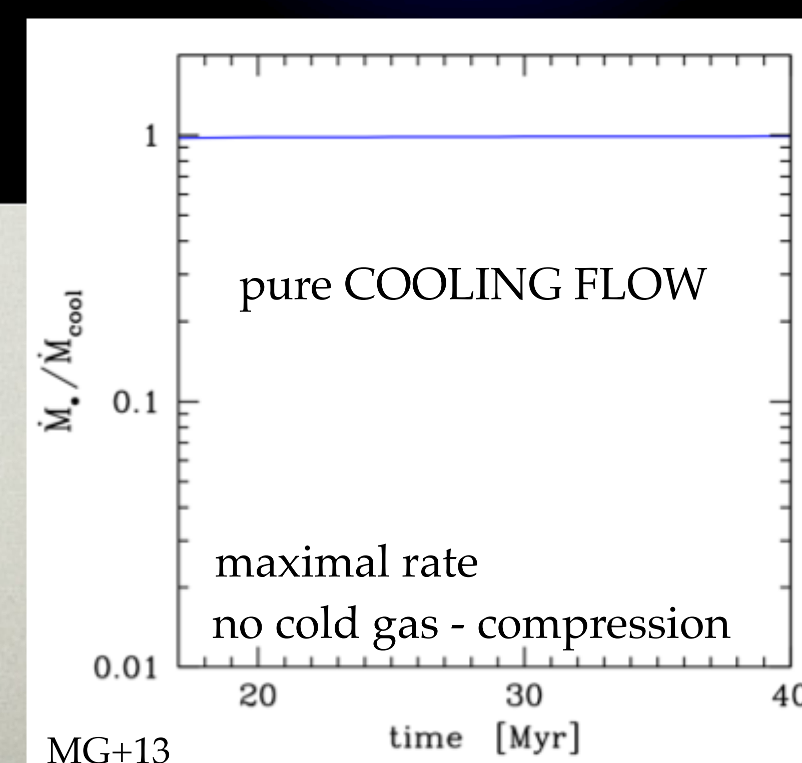
turbulent



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

quiescent





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Chaotic cold accretion on to black holes

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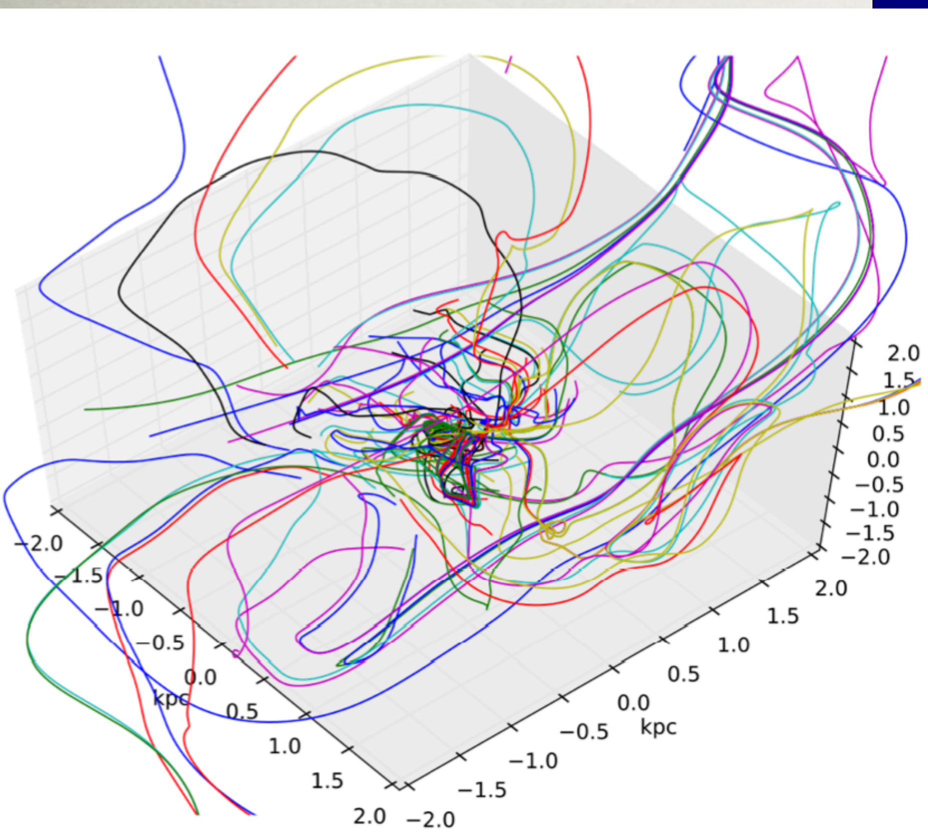
ABSTRACT

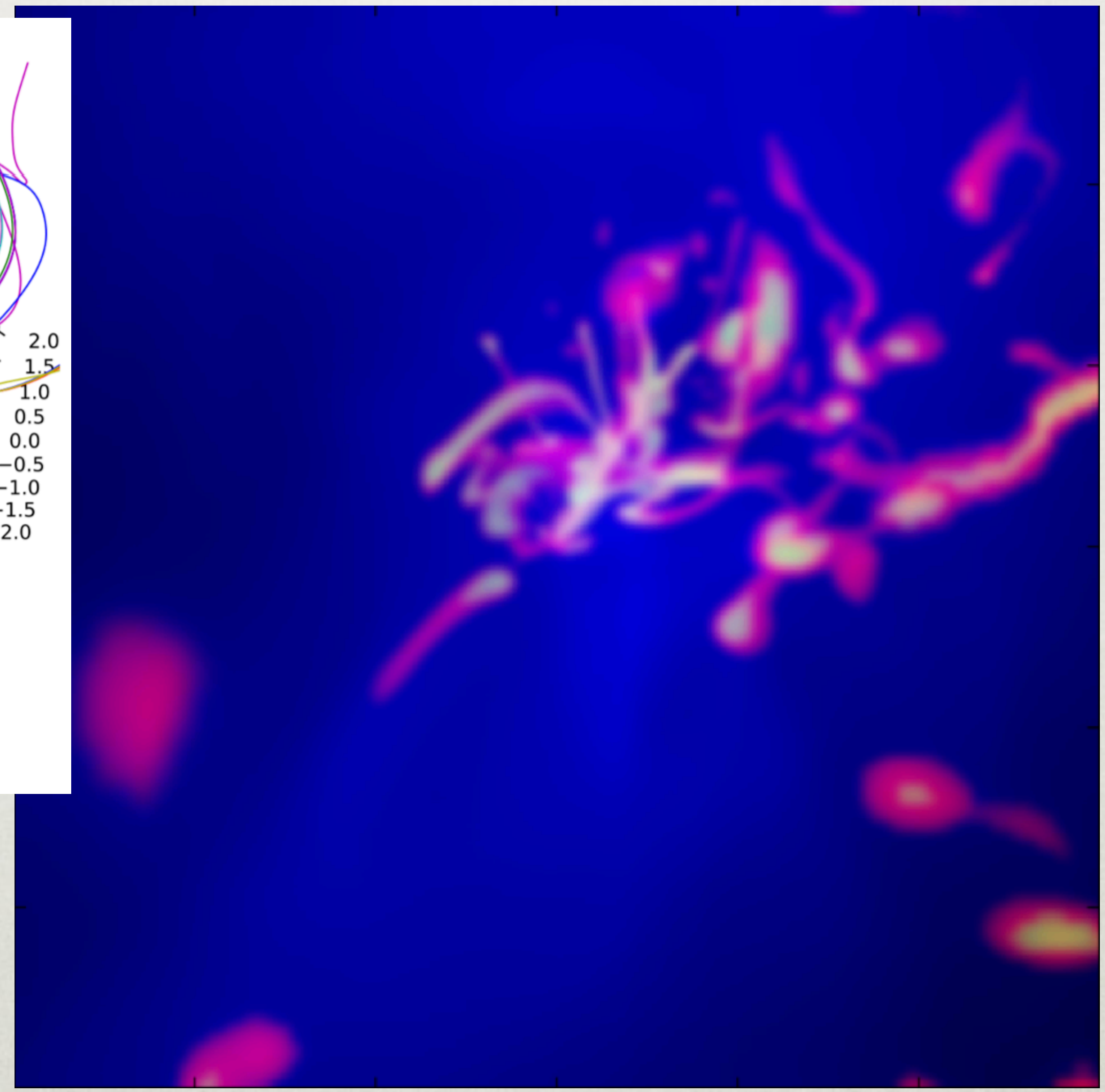
Bondi theory is often assumed to adequately describe the mode of accretion in astrophysical environments. However, the Bondi flow must be adiabatic, spherically symmetric, steady, unperturbed, with constant boundary conditions. Using 3D adaptive mesh refinement simulations, linking the 50 kpc to the sub-parsec (sub-pc) scales over the course of 40 Myr, we systematically relax the classic assumptions in a typical galaxy hosting a supermassive black hole. In the more realistic scenario, where the hot gas is *cooling*, while *heated* and *stirred* on large scales, the accretion rate is boosted up to two orders of magnitude compared with the Bondi prediction. The cause is the non-linear growth of thermal instabilities, leading to the condensation of cold clouds and filaments when $t_{\rm cool}/t_{\rm ff} \lesssim 10$. The clouds decouple from the hot gas, 'raining' on to the centre. Subsonic turbulence of just over 100 km s^{-1} ($M > 0.2$) induces the formation of thermal instabilities, even in the absence of heating, while in the transonic regime turbulent dissipation inhibits their growth ($t_{\rm turb}/t_{\rm cool} \lesssim 1$). When heating restores global thermodynamic balance, the formation of the multiphase medium is violent, and the mode of accretion is fully *cold* and *chaotic*. The recurrent *collisions* and tidal forces between clouds, filaments and the central clumpy torus promote angular momentum cancellation, hence boosting accretion. On sub-pc scales the clouds are channelled to the very centre

RAINING ON BLACK HOLES

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



chaotic streamlines => recurrent multiphase gas interactions



TURBULENCE > ROTATION

$\mathrm{Ta_t} < 1$

COOLING ~ AGN HEATING

turbulence ~160 km/s, as found (a posteriori) by *Hitomi*

MG+17

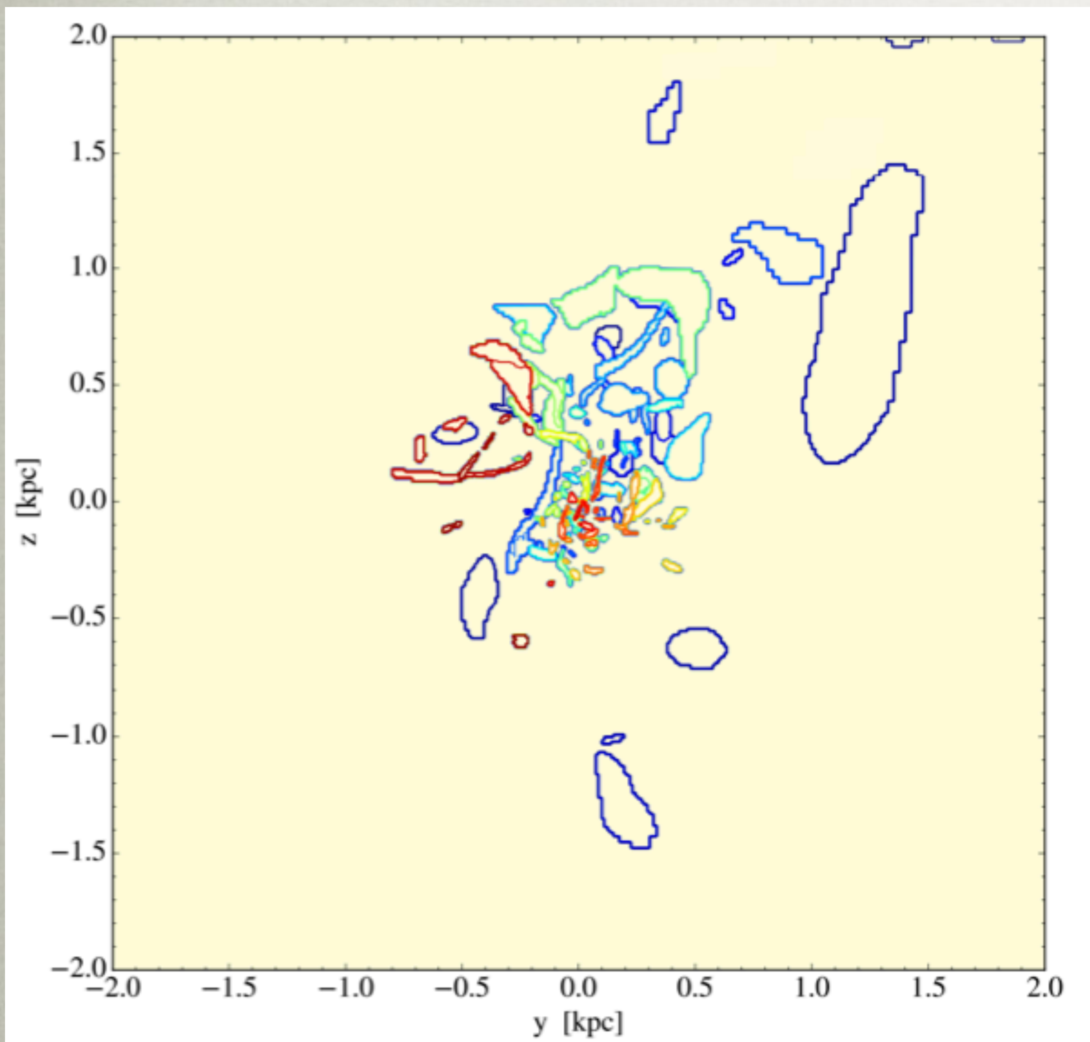
RGB surface density: plasma (blue), warm gas (red), cold gas (green)

Since 2013, CCA has been corroborated by many 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; Prasad+2016; David+2017; McDonald+18; etc.

MULTIPHASE CCA

DYNAMICS

MG+17



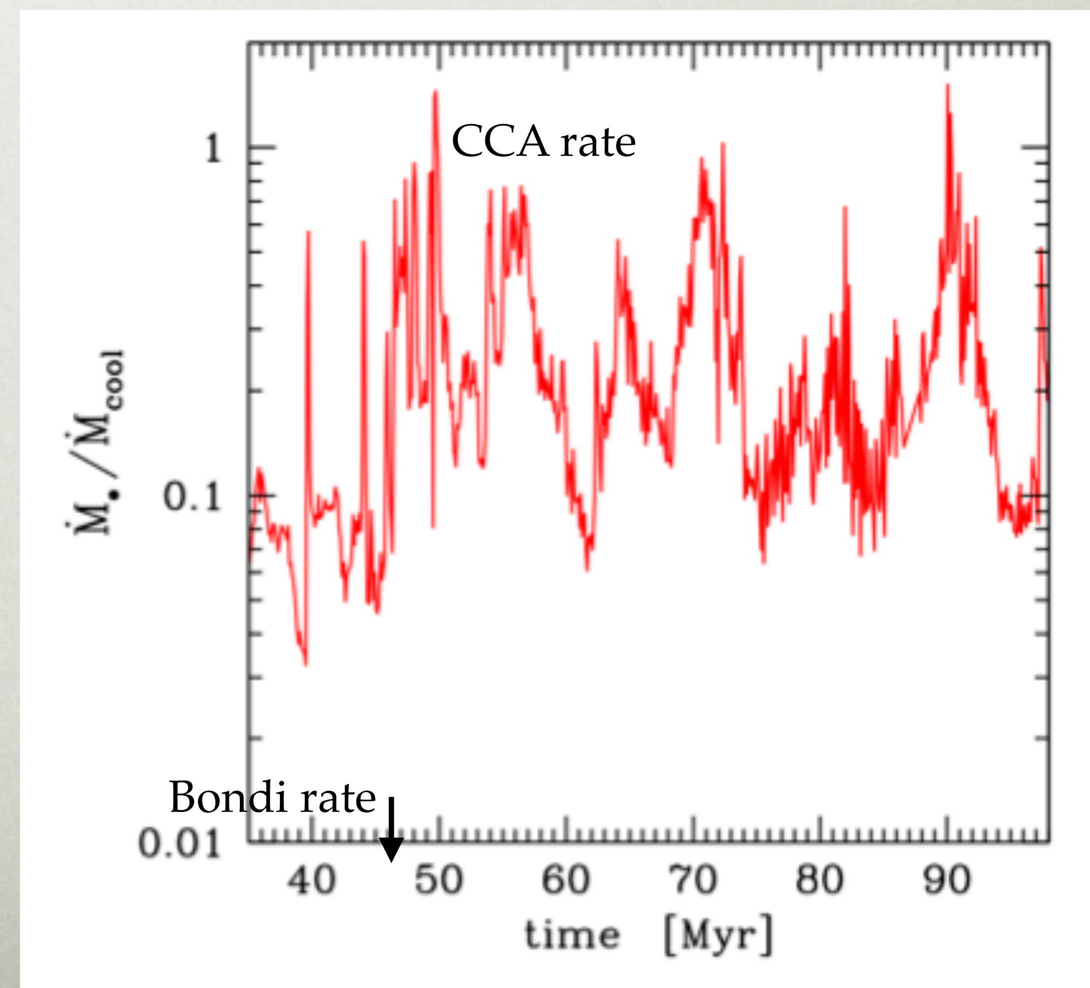
can be modeled as quasi-spherical viscous accretion:

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

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

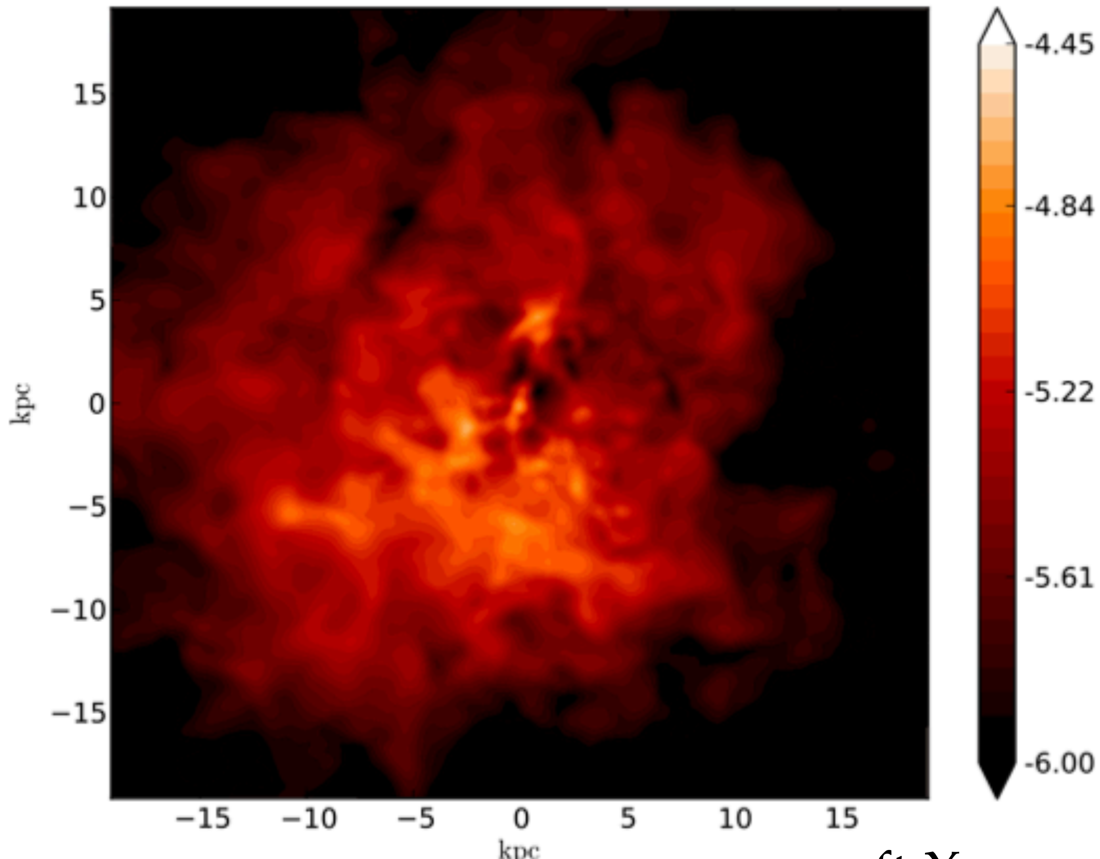
$$\dot{M}_\bullet = 4.8 \times 10^{-3} \, \nu_c \simeq 0.3^{+0.9}_{-0.2} \text{ M}_\odot \text{ yr}^{-1}$$ average inflow rate (for massive ETG)

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

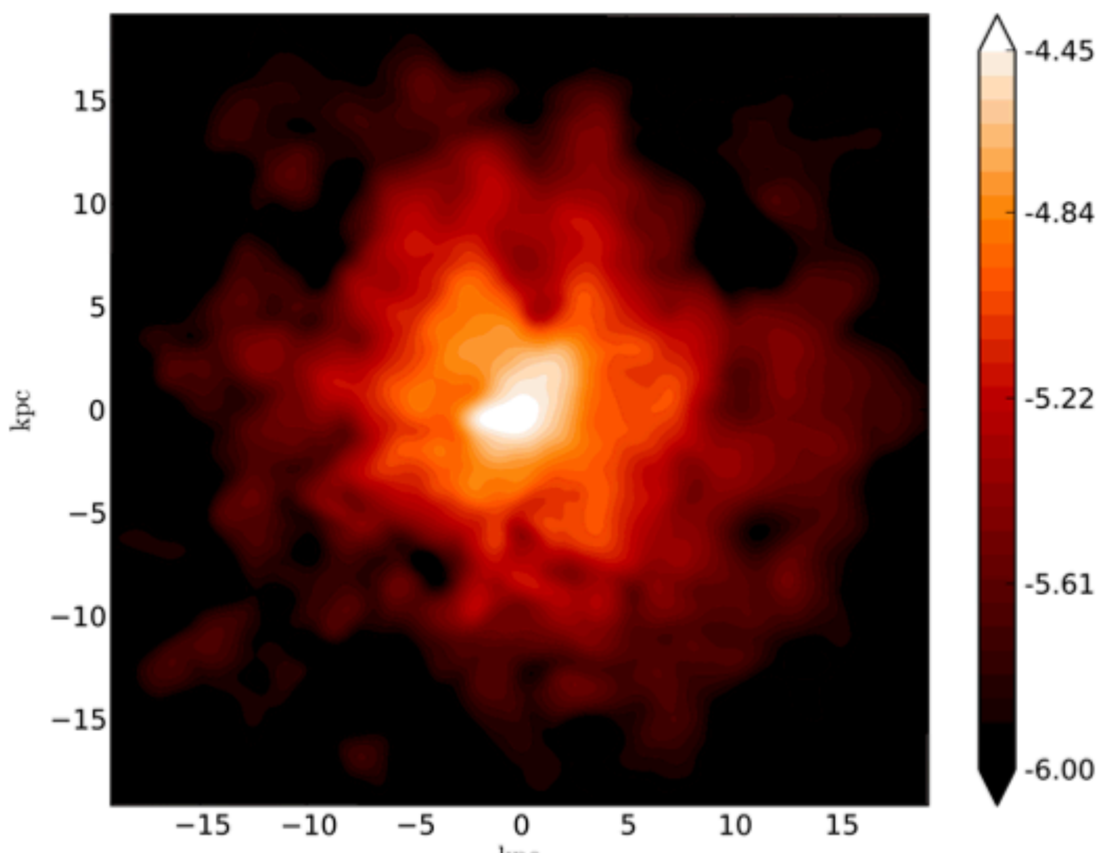


- leaf clouds via clump finder algorithm
- network of condensed structures
- key for AGN obscuration/unification models (BLR, NLR)
- **angular momentum mixing/cancellation via inelastic collisions**

MULTIPHASE CCA:
1. HOT PLASMA



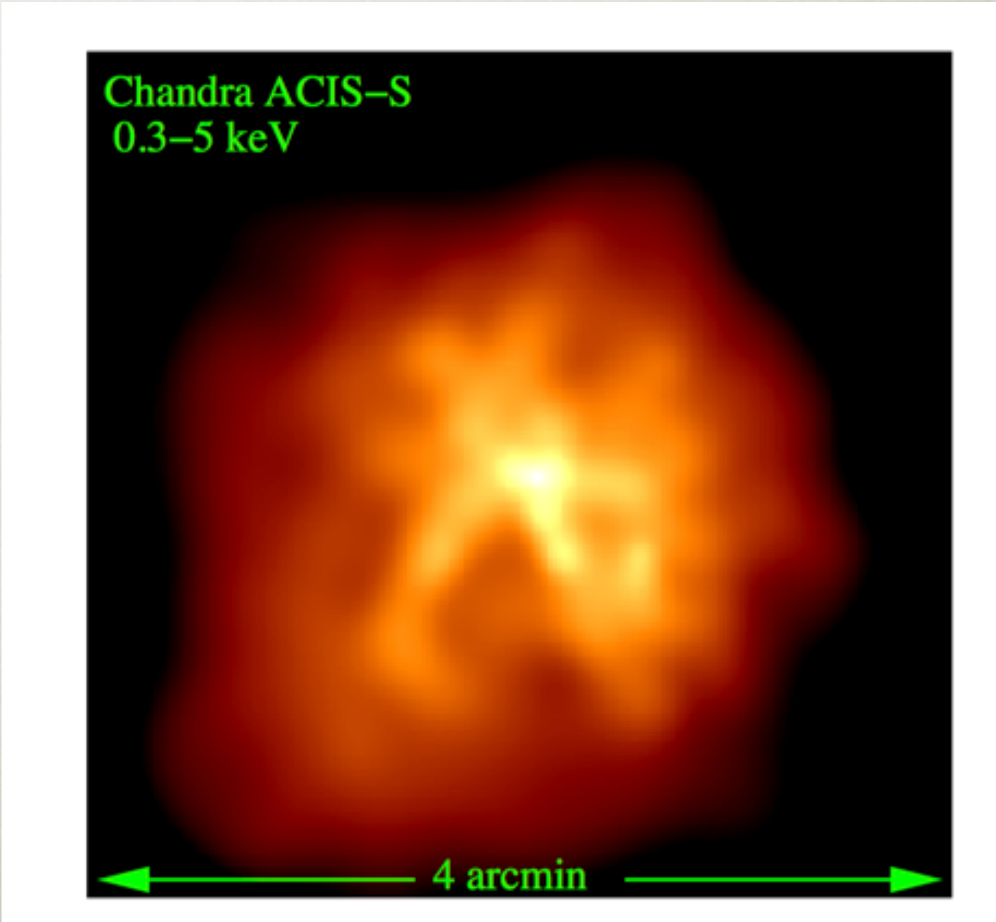
soft X-ray



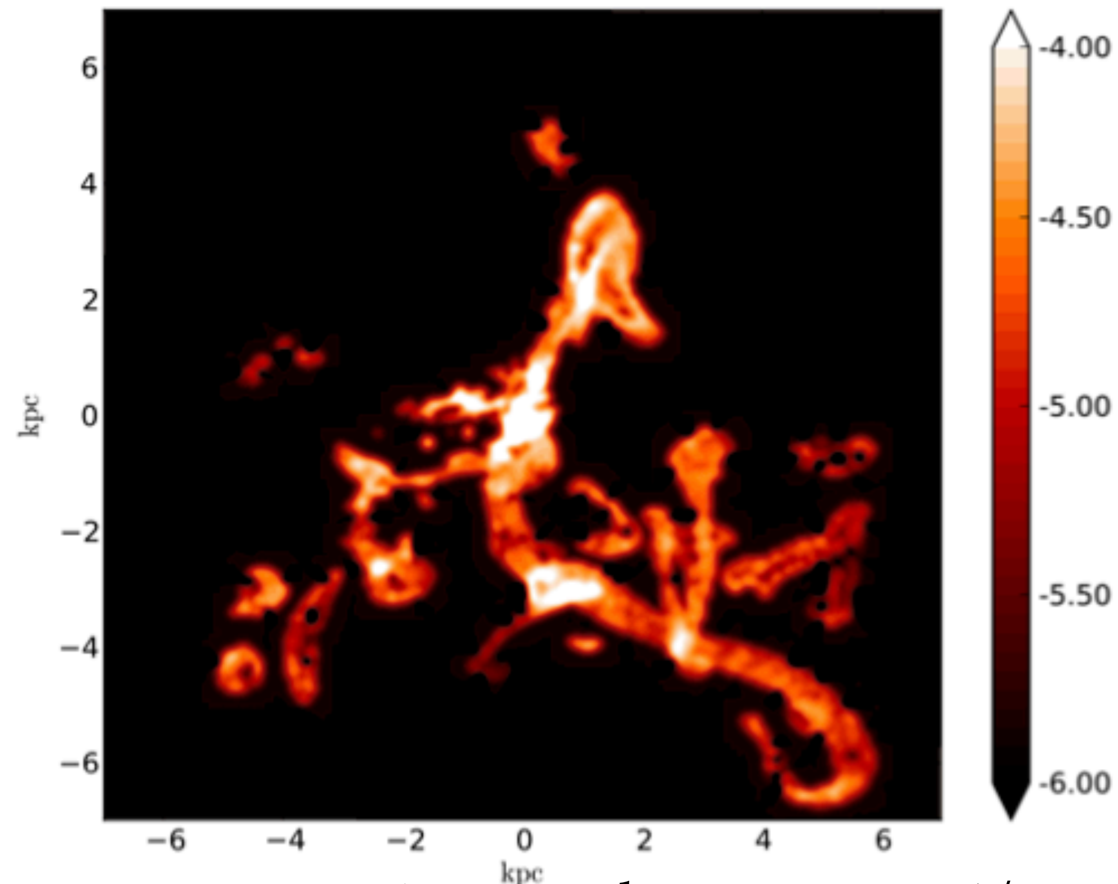
MG+17

hard X-ray

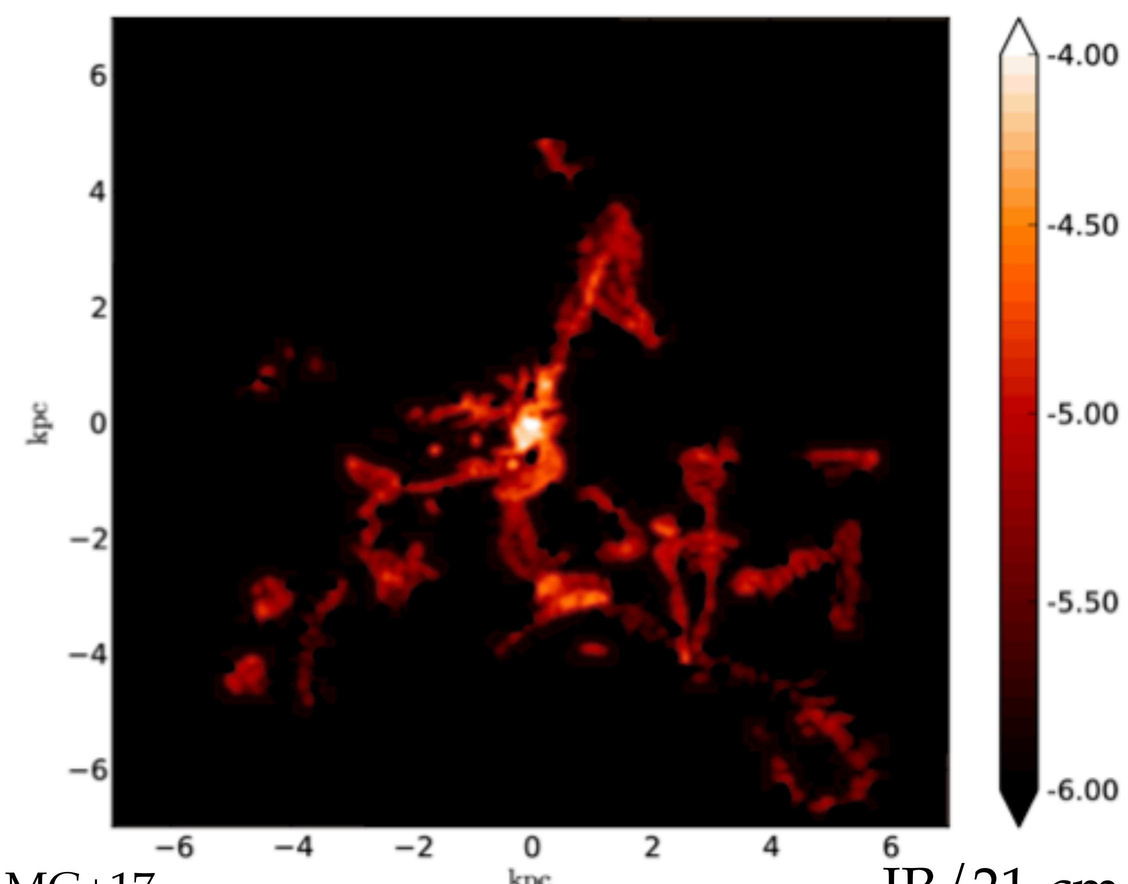
- turbulent eddies imprint => naturally create “cavities”/”fronts”
- X-ray “filaments” start to appear below 0.5 keV
- weak subsonic turbulence is enough to trigger CCA



Buote+04



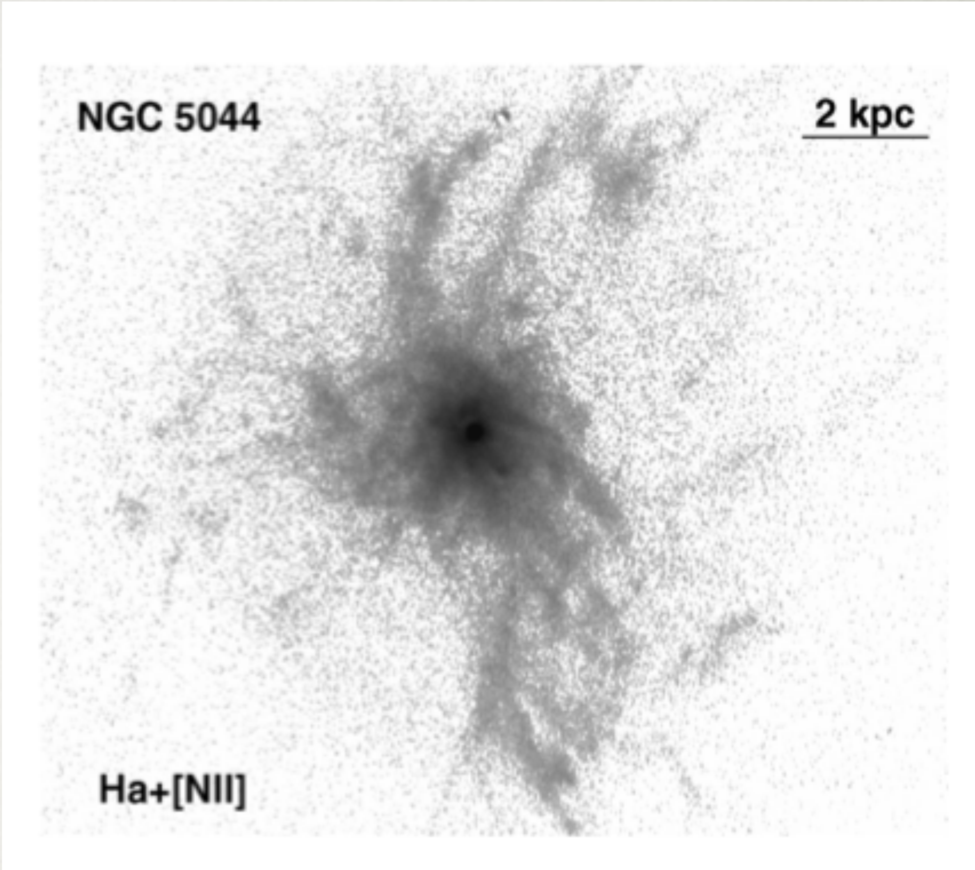
ionized warm phase optical/UV



MG+17 IR/21-cm

neutral warm phase

Werner+14: SOAR



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

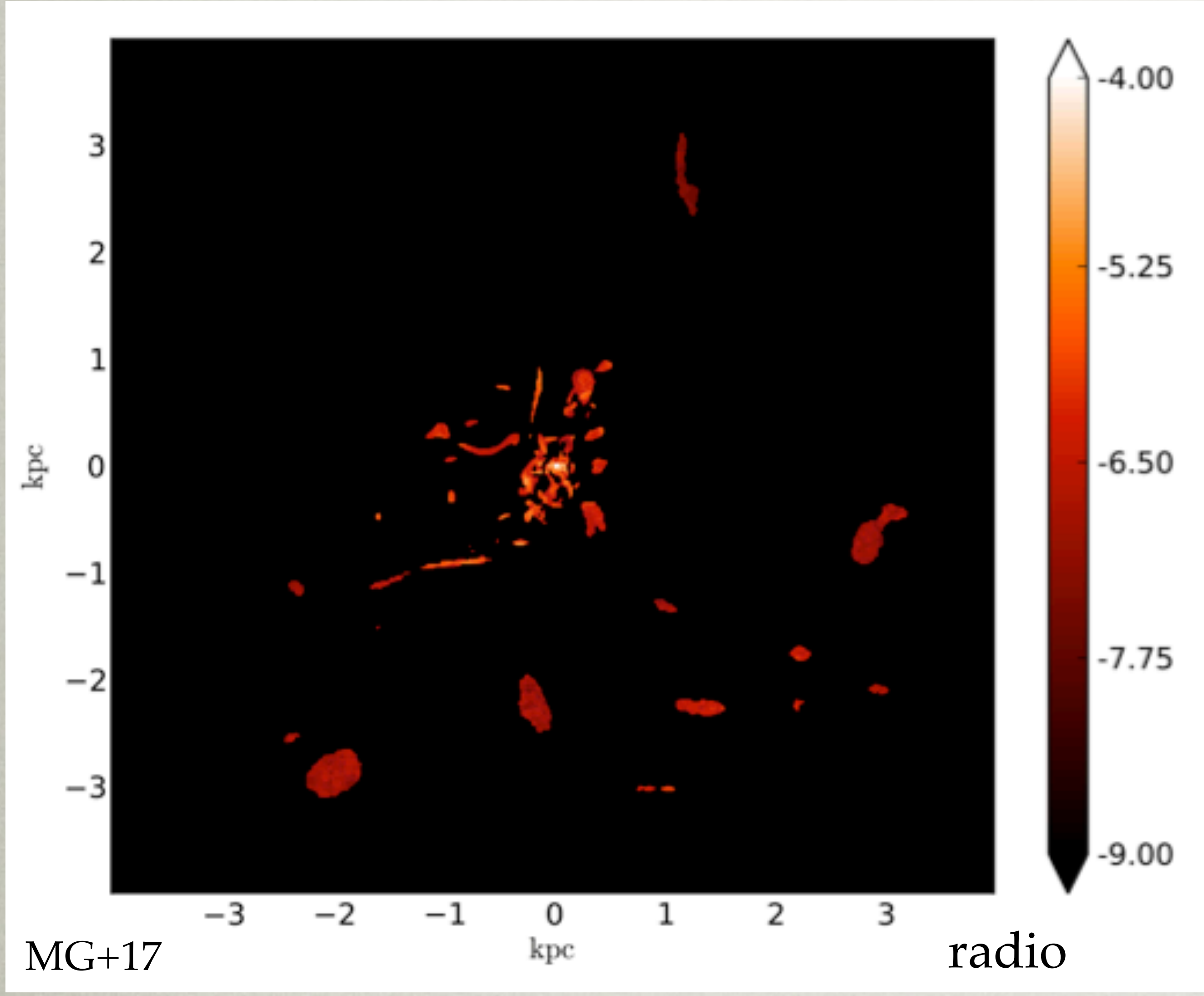
$$C \equiv t_{\rm cool}/t_{\rm eddy} \approx 1$$

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

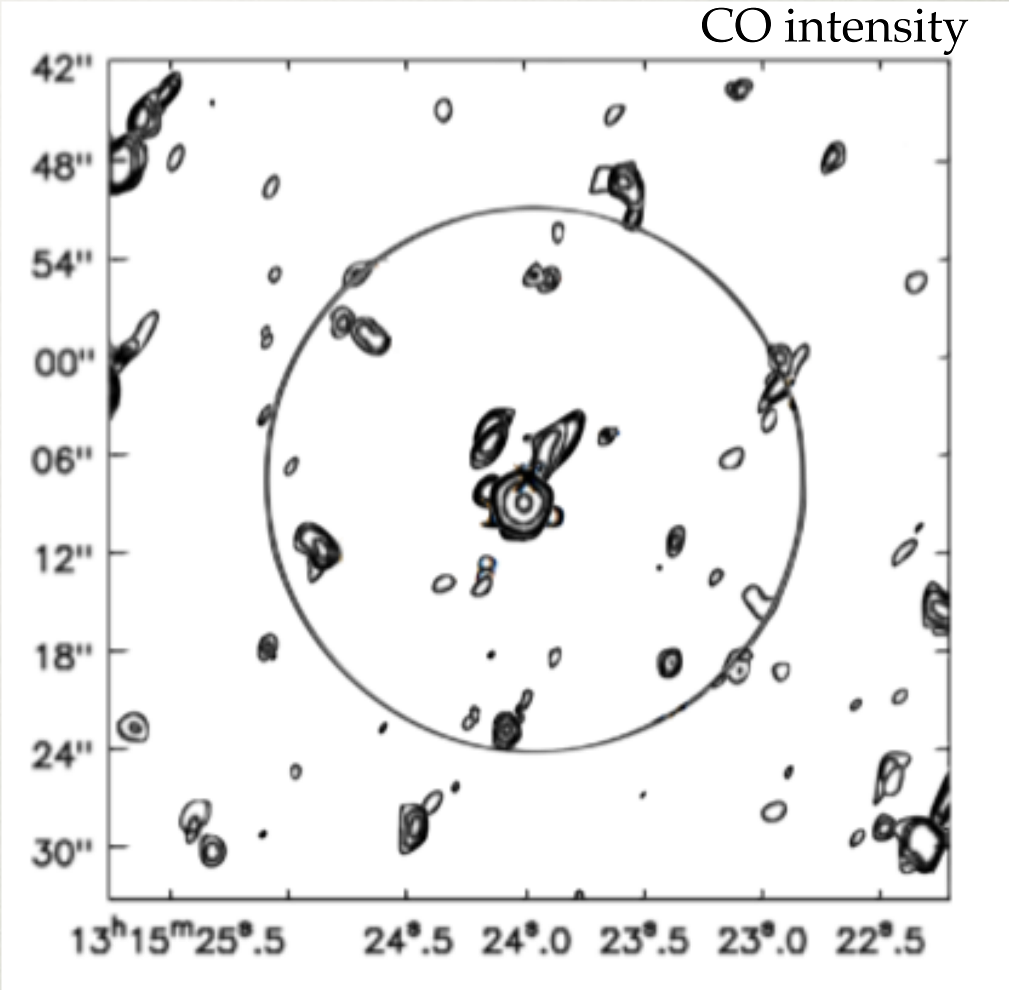
- **filaments** naturally form out of the interacting sheets between large-scale eddies

MULTIPHASE CCA: 2. WARM PHASE

MULTIPHASE CCA:
3. COLD/MOLECULAR PHASE



David+14-17, Temi+18: ALMA



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

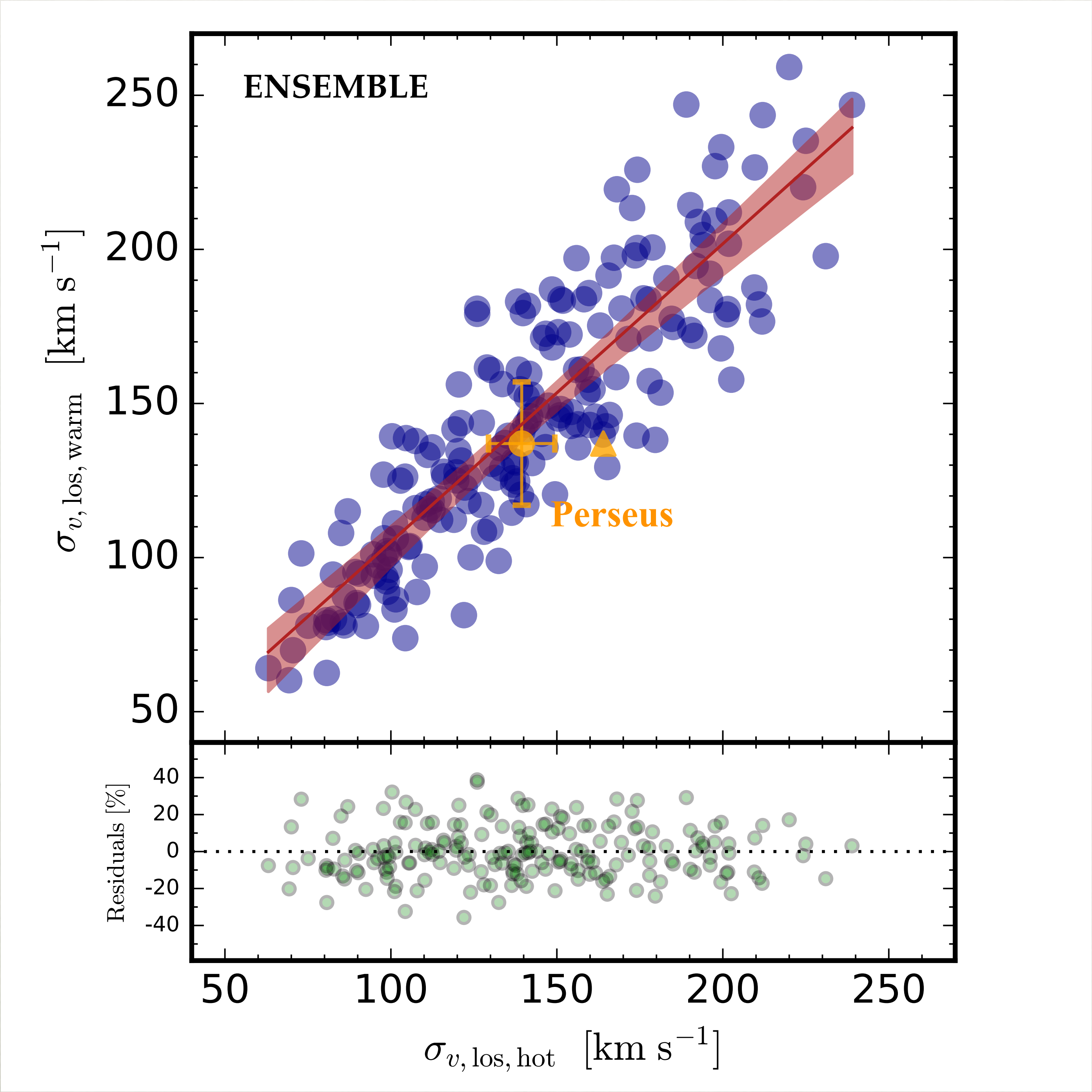
KINEMATIC TRACERS
MULTIPHASE CONDENSATION CASCADE

"shaken snow globes"

Gaspari et al. 2018

ENSEMBLE beam
(R < 50 kpc,
arcmin scale)

novel method to constrain
turbulence in the hot phase



self-regulated
AGN jet feedback run

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

same can be shown for
the molecular phase

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

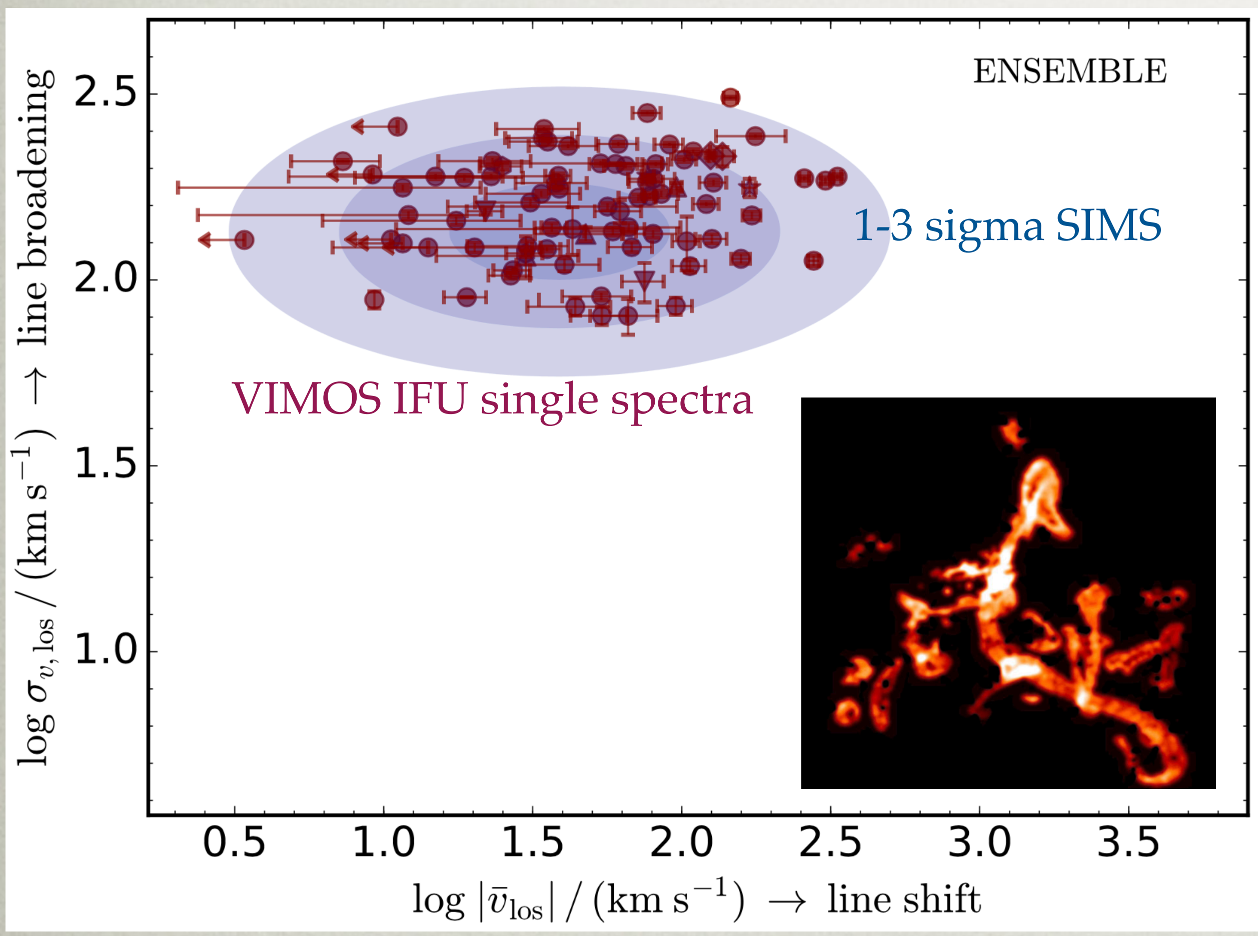
CCA - KINEMATIC TRACERS

observational tests

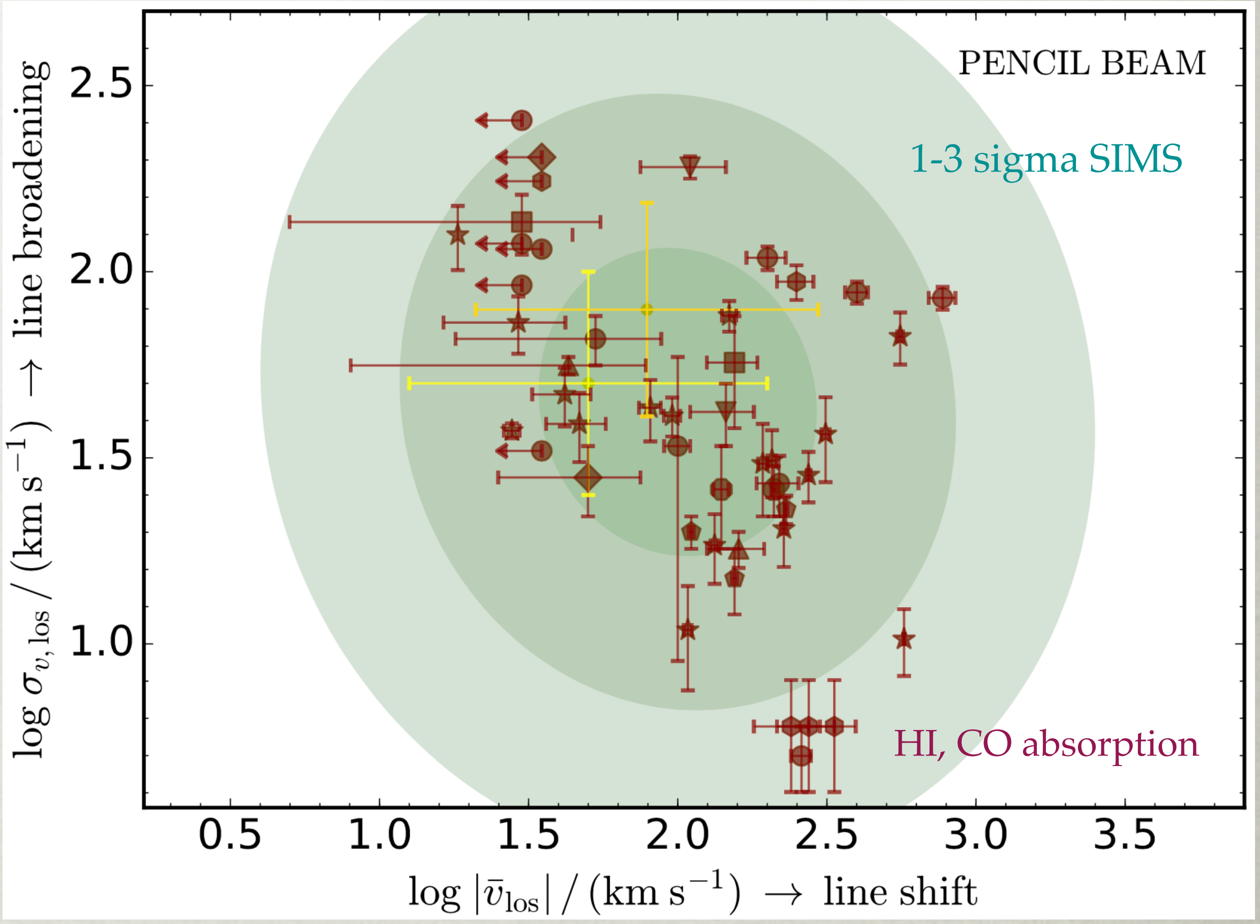
(massive galaxies in groups and clusters)

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

MG+18



substantial line broadening and small scatter

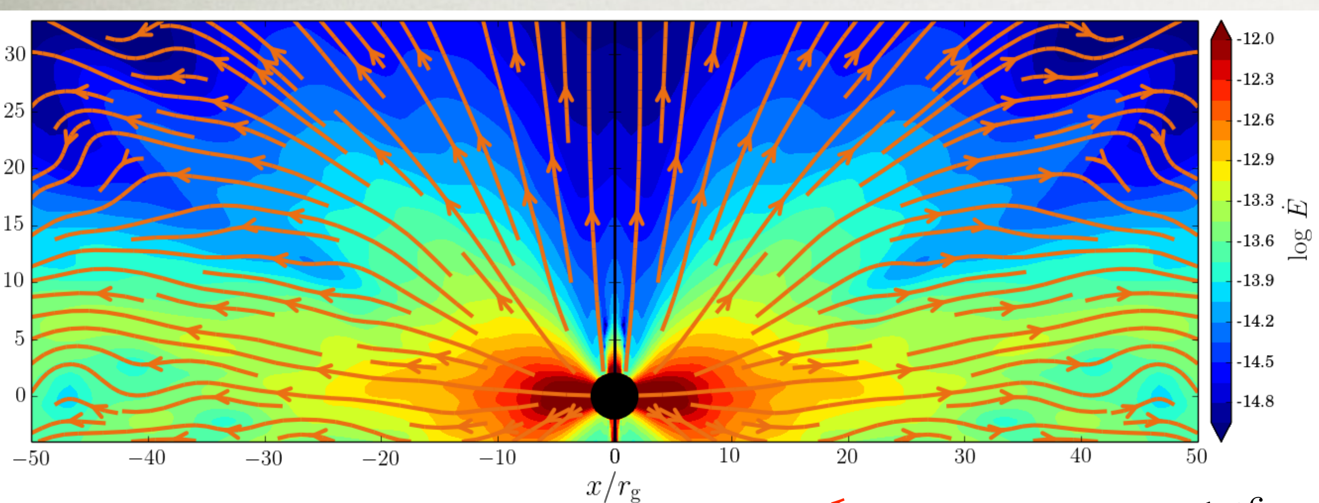


large line shifts and narrow broadening: accreting clouds

- r < 100 pc **funneling** of clouds with 300+ km / s — red-shifted lines (ALMA): A2597, N5044 + **Rose in prep.**

AGN FEEDBACK:

MICRO FEEDBACK - GR-RMHD SIMS

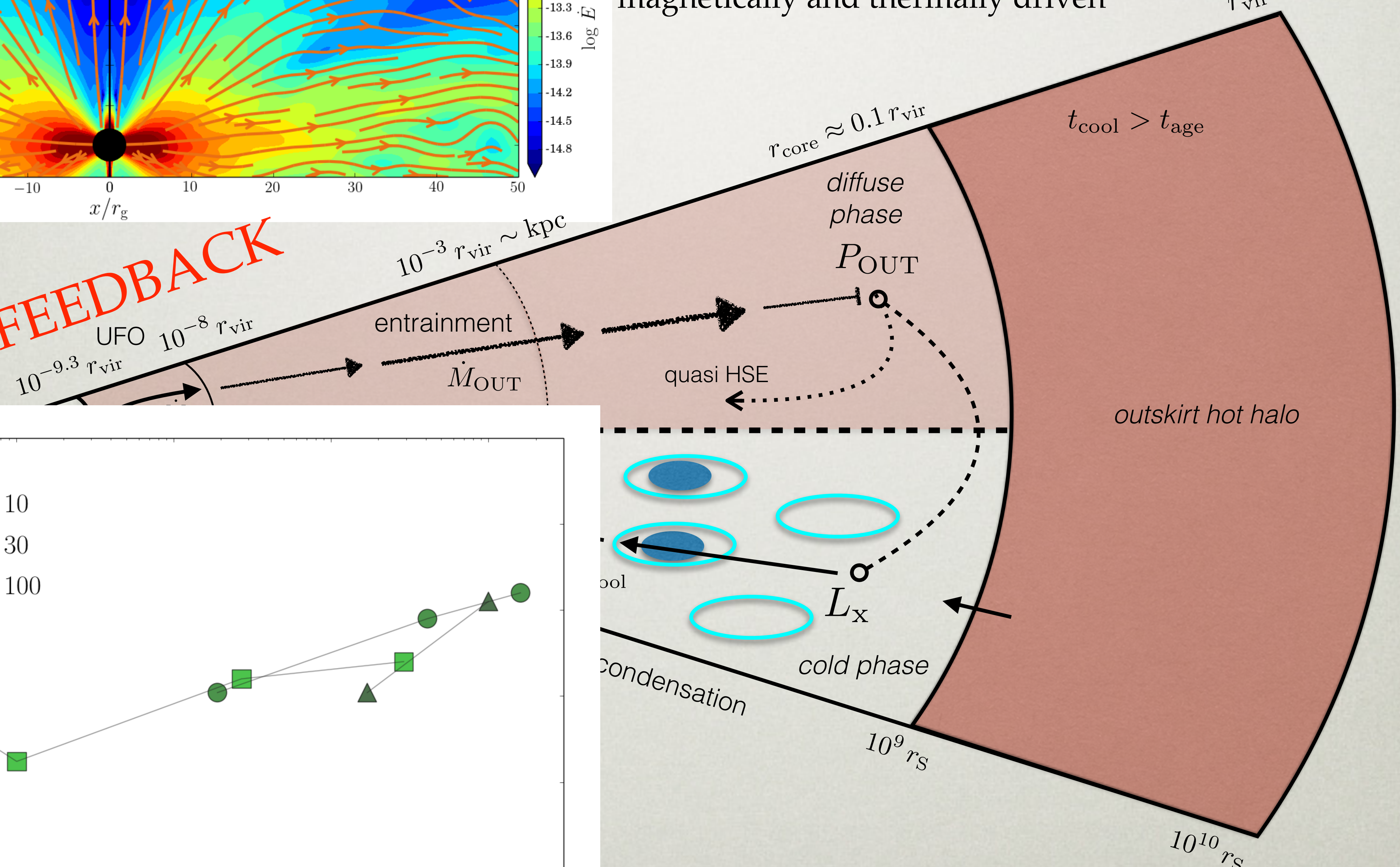


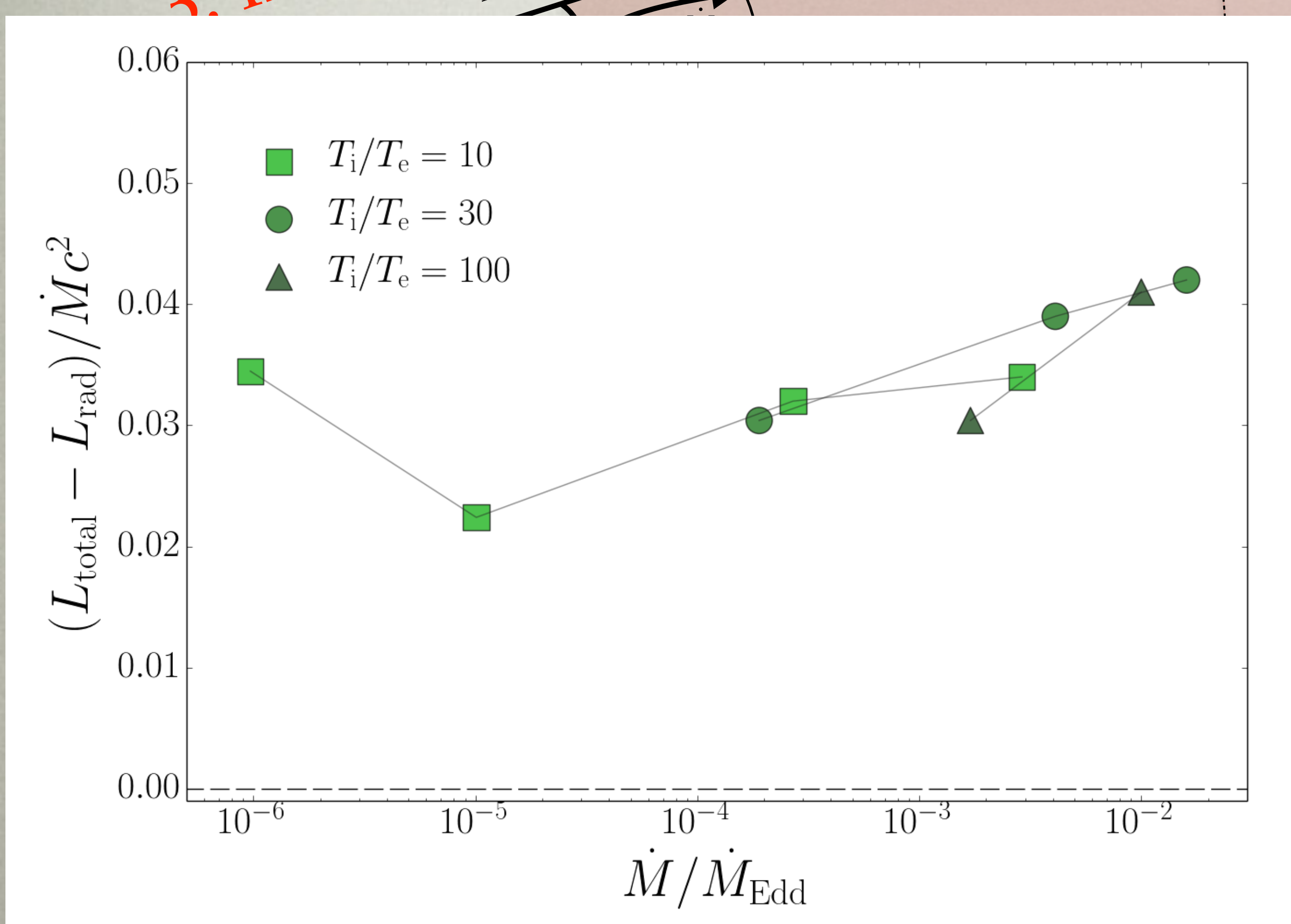
UFO = Ultra-Fast Outflows

magnetically and thermally driven

Sadowski & Gaspari 2017

3. micro FEEDBACK

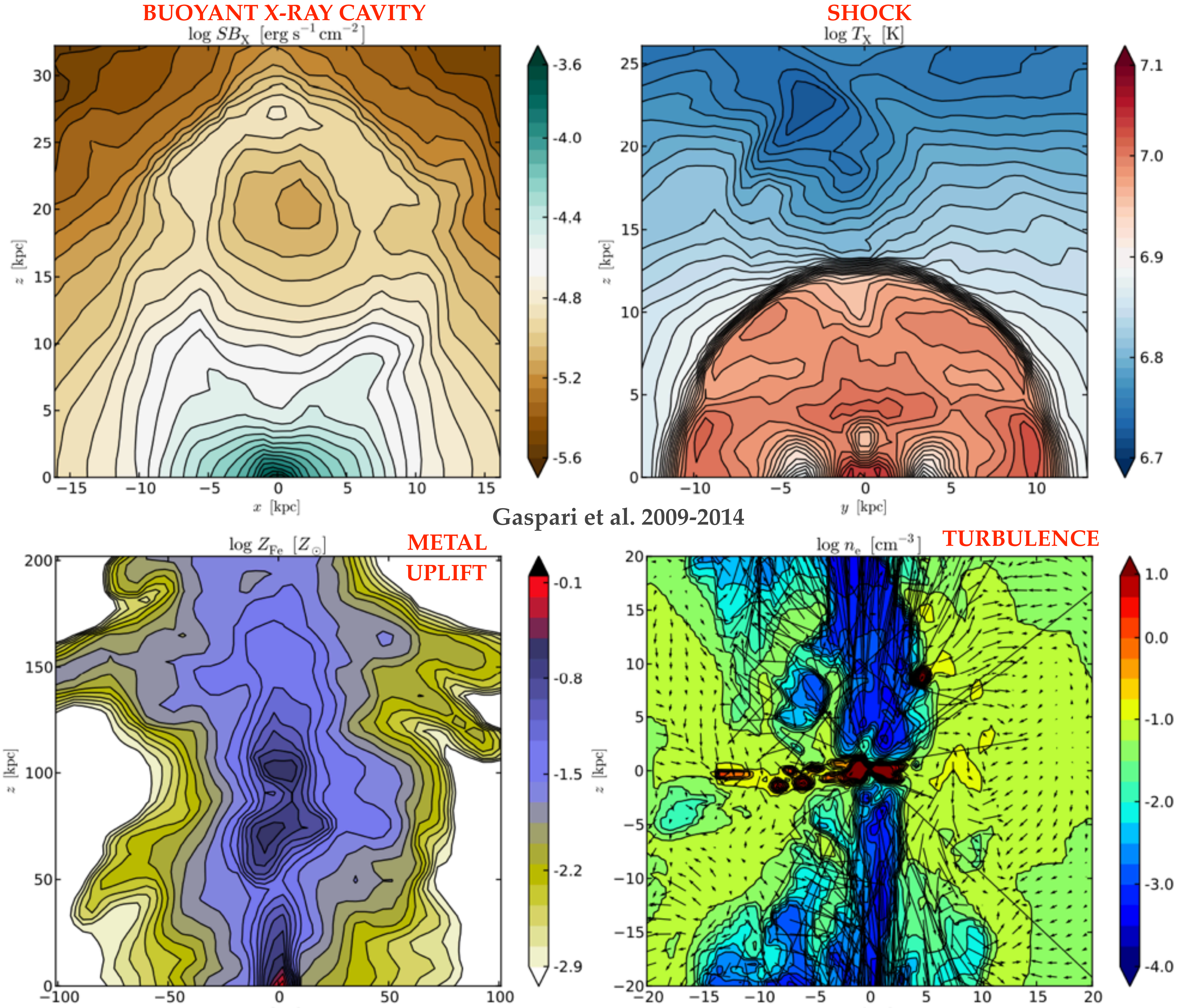




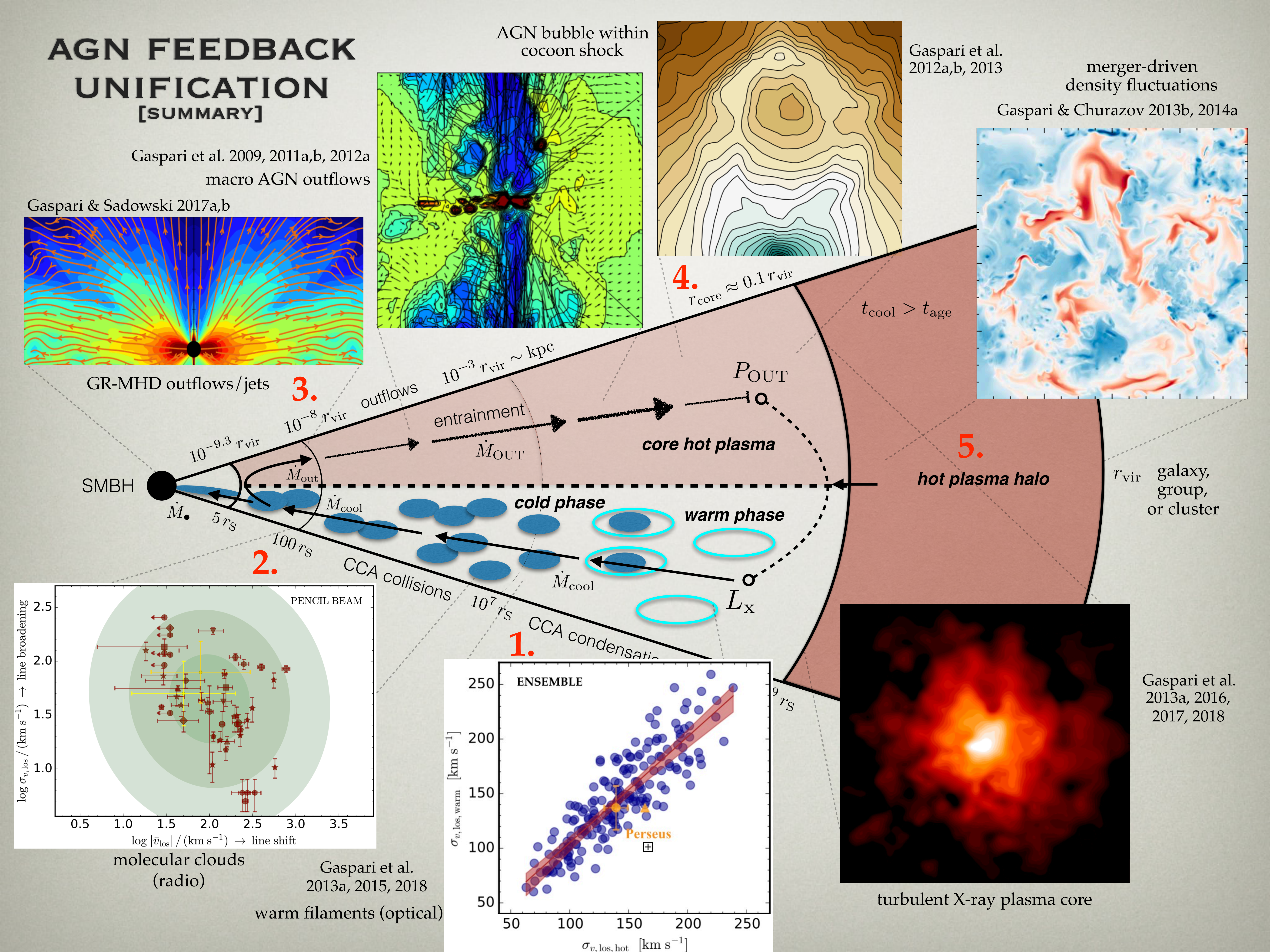
General relativistic, radiative, MHD simulations

(KORAL)

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



Gaspari et al. 2009-2014



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$L_{\rm x}$
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CCA condensation
$10^9\, r_{\rm S}$
1.
PENCIL BEAM
$\log \sigma_{v,\rm los}$ / (km s^{-1}) → line broadening
$\log |\bar{v}_{\rm los}|$ / (km s^{-1}) → line shift
0.5 1.0 1.5 2.0 2.5 3.0 3.5
1.0 1.5 2.0 2.5
molecular clouds (radio)
Gaspari et al. 2013a, 2015, 2018
warm filaments (optical)
ENSEMBLE
Perseus
$\sigma_{v,\rm los,warm}$ [km s^{-1}]
$\sigma_{v,\rm los,hot}$ [km s^{-1}]
50 100 150 200 250
Gaspari et al. 2013a, 2016, 2017, 2018
turbulent X-ray plasma core