Probes of rain and turbulence in multiphase halos via 3D spectroscopy

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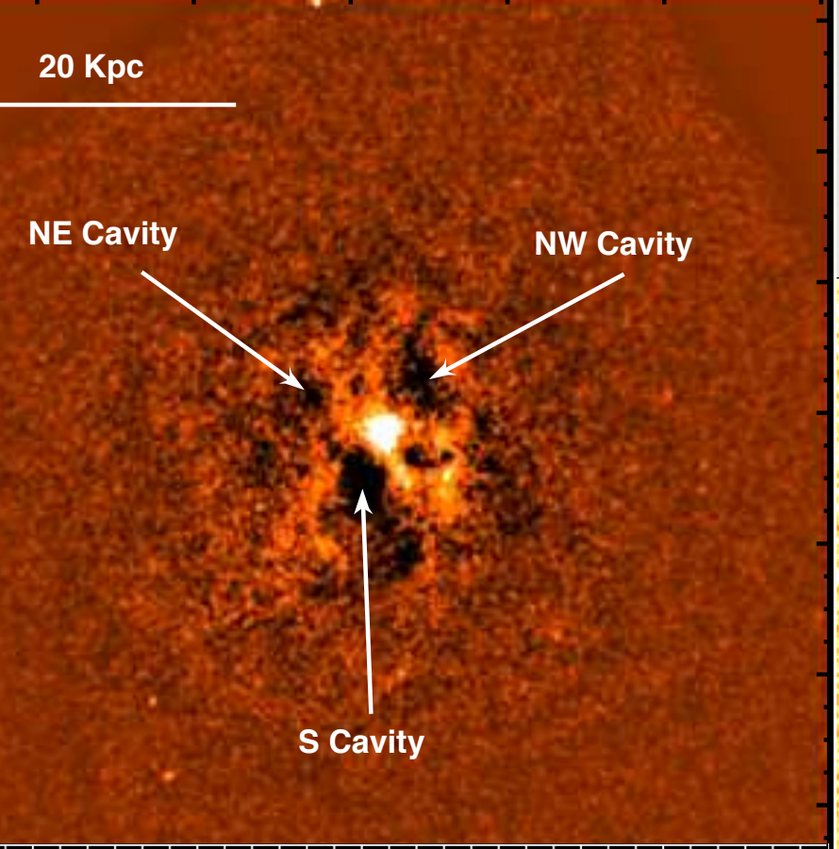
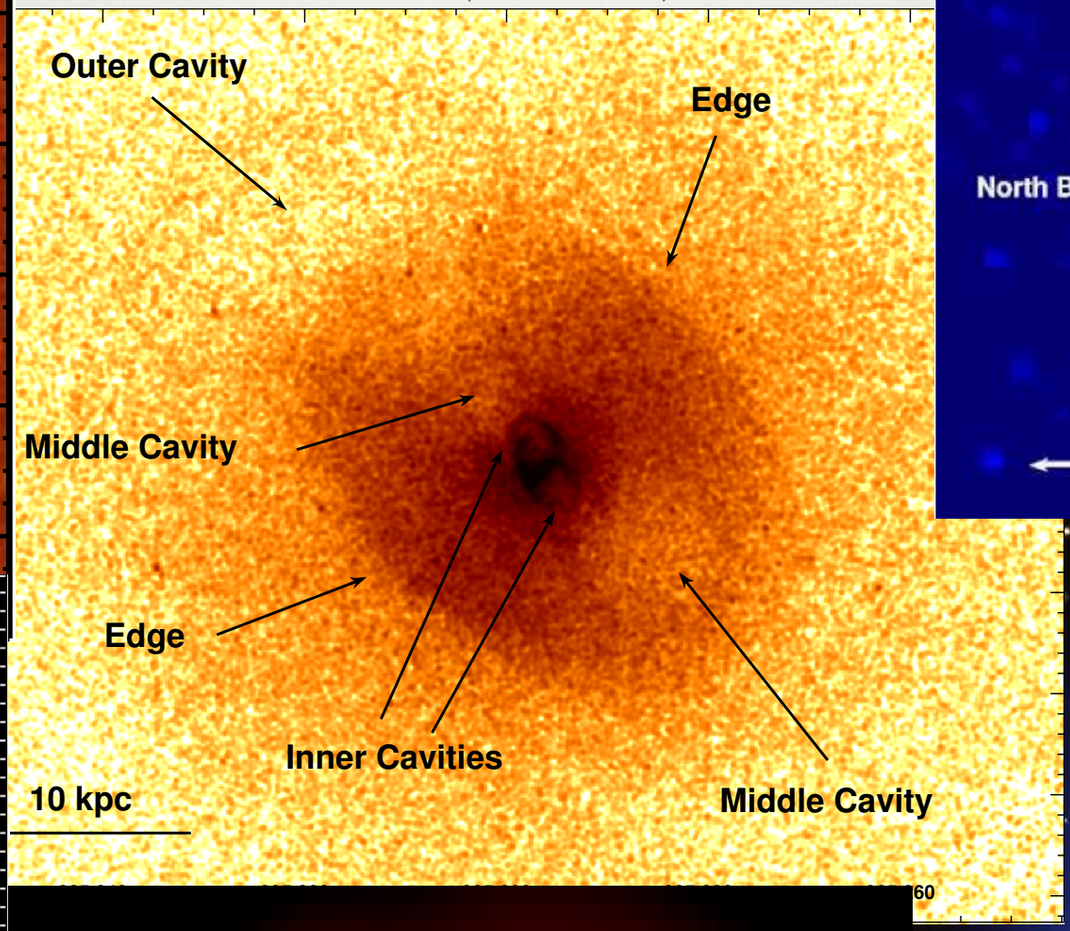
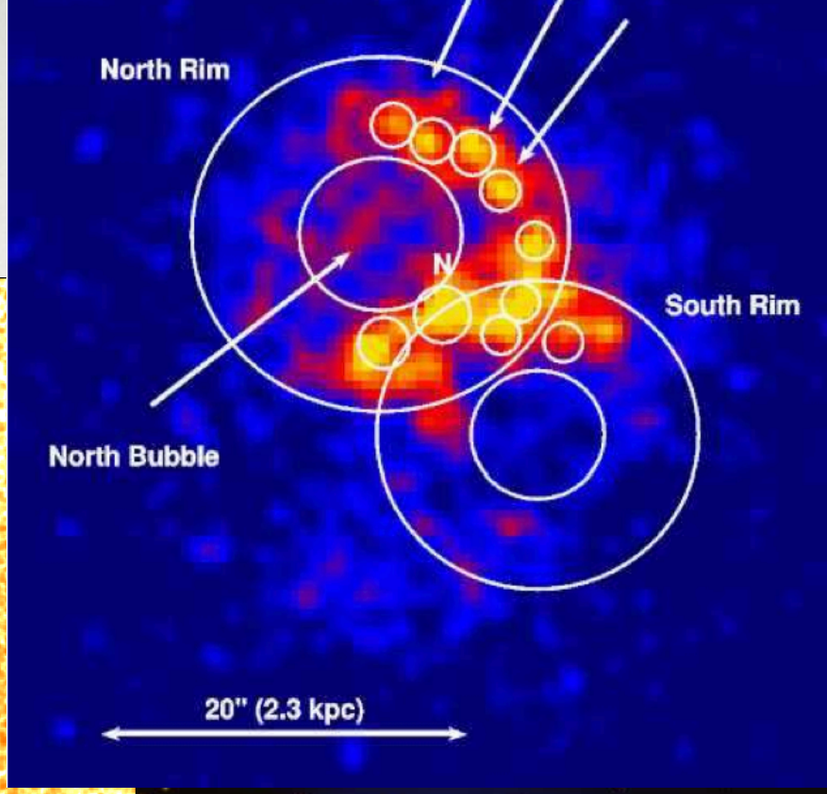
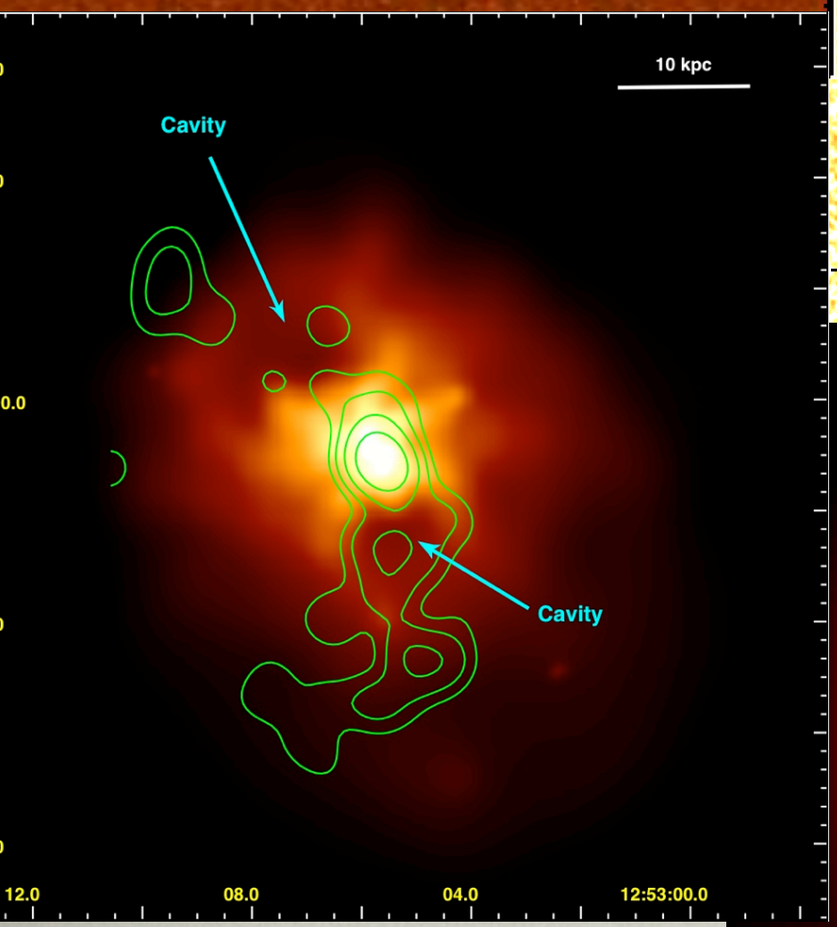
HOT HALOS

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

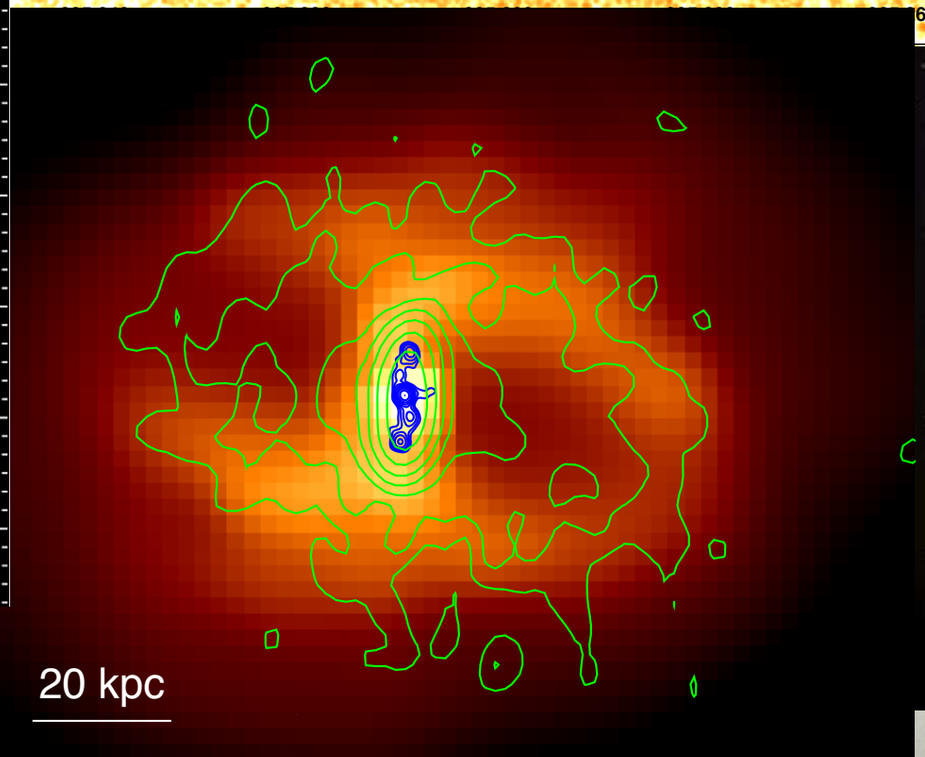




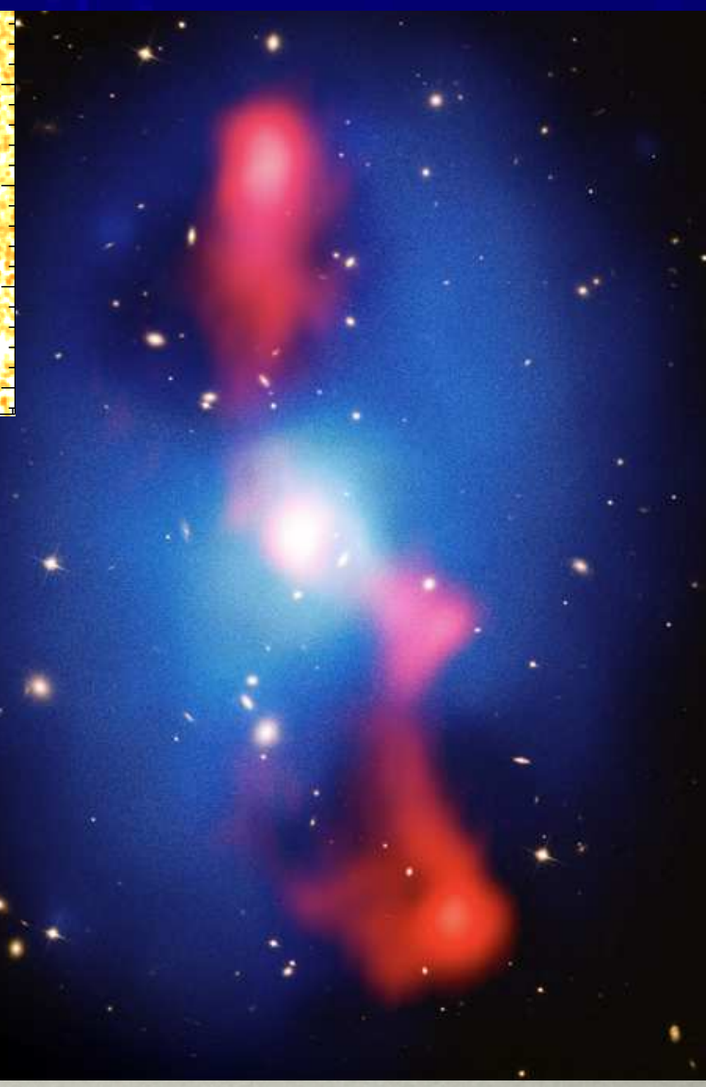




HCG 62 (Gitti+10)

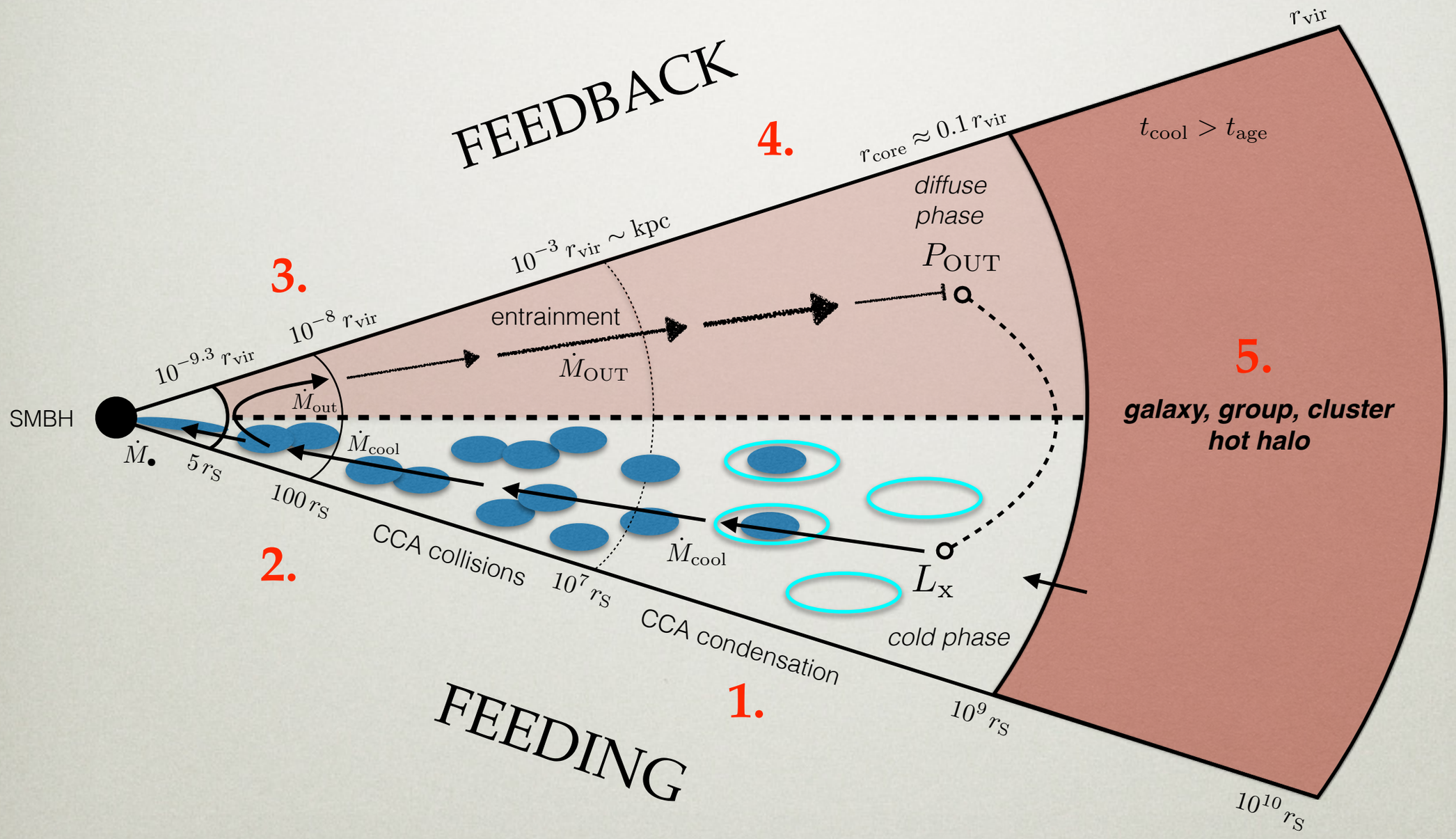


RBS 797
(Gitti+11)



MS0735.6 cluster (McNamara+05)

"BLACK HOLE WEATHER"

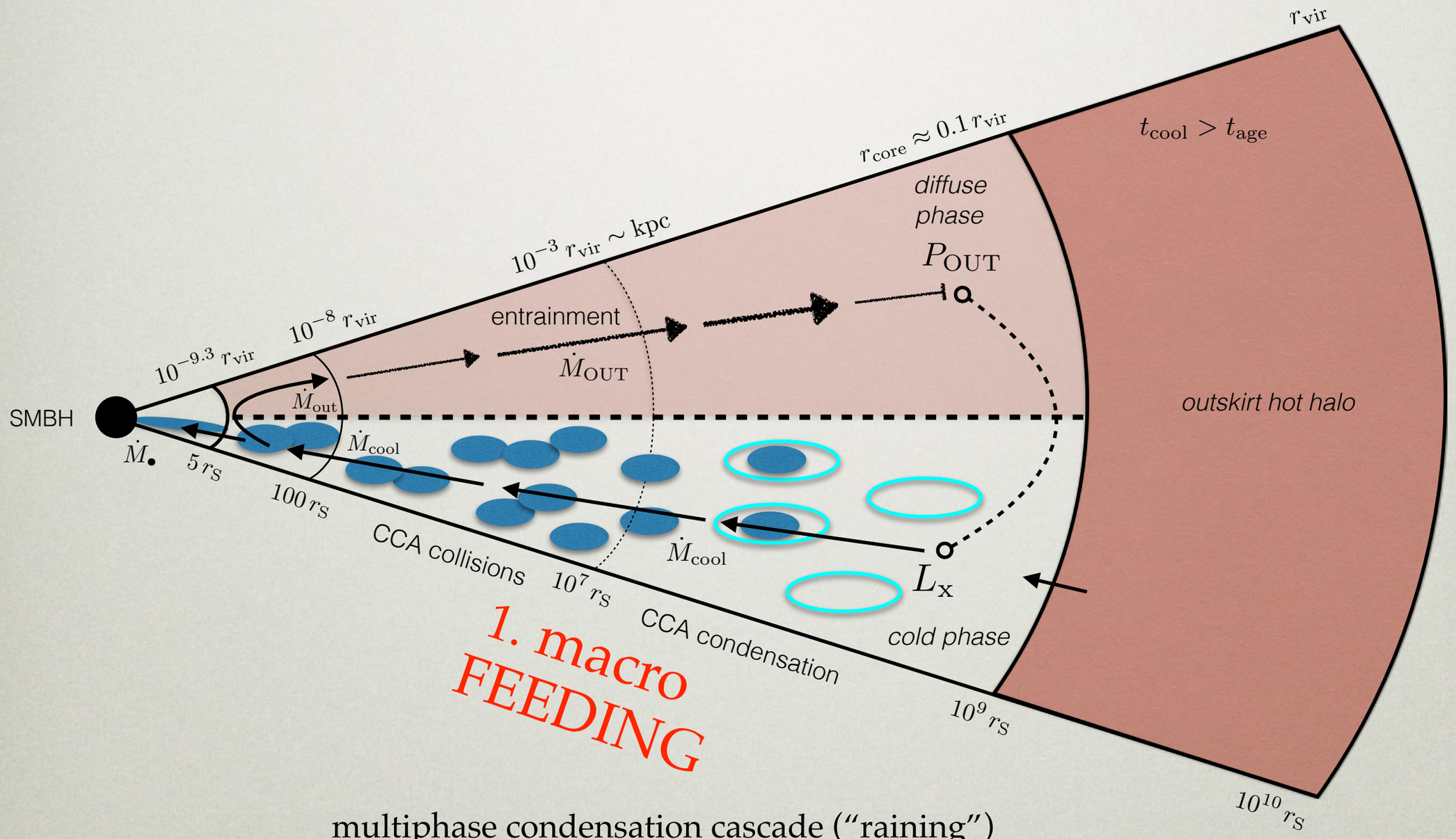


GOAL 1: first-principle multi-scale simulations

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

MG+2011-2019

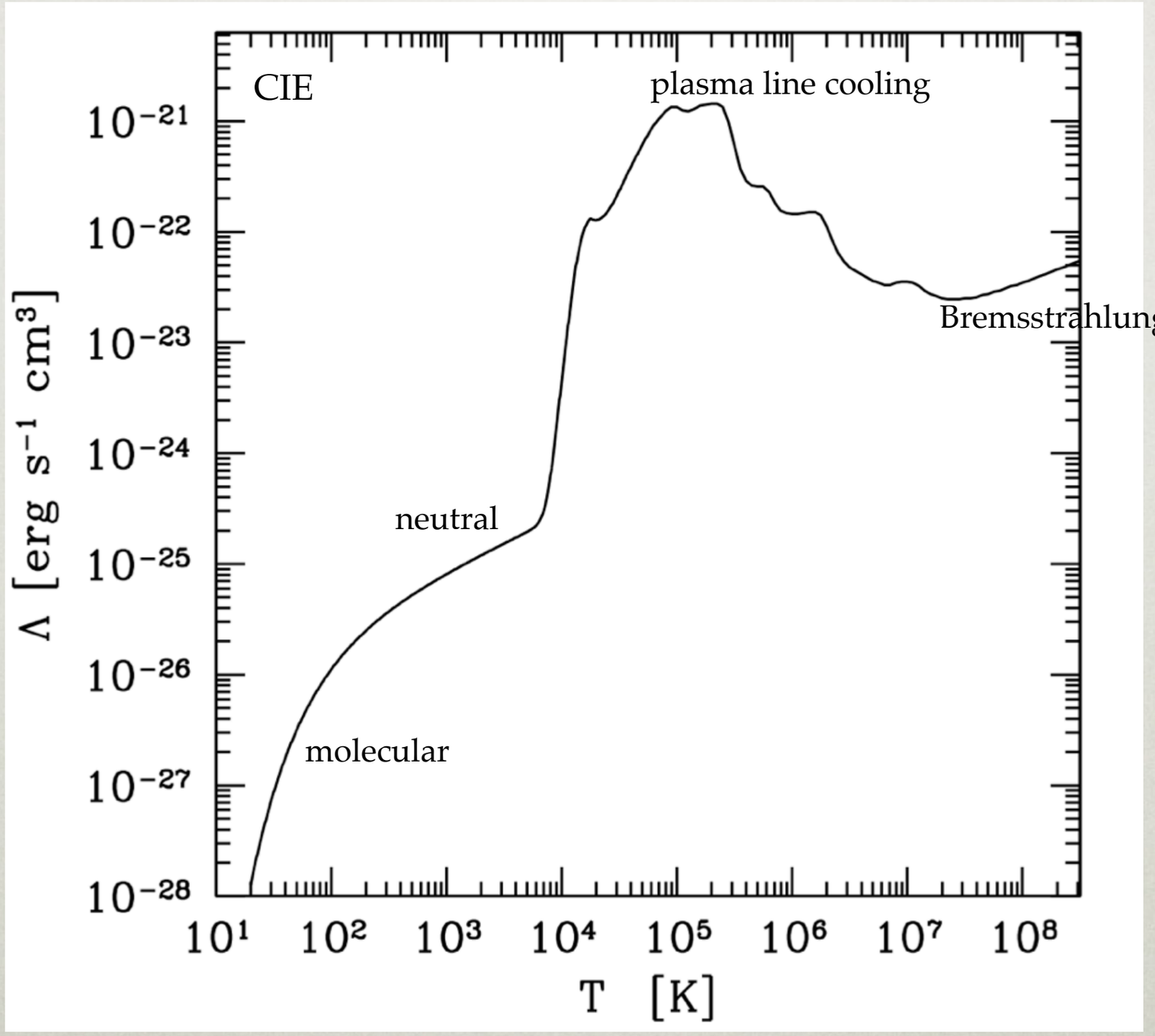
BH FEEDING AND FEEDBACK UNIFICATION



multiphase condensation cascade (“raining”)

CCA = CHAOTIC COLD ACCRETION

RADIATIVE COOLING

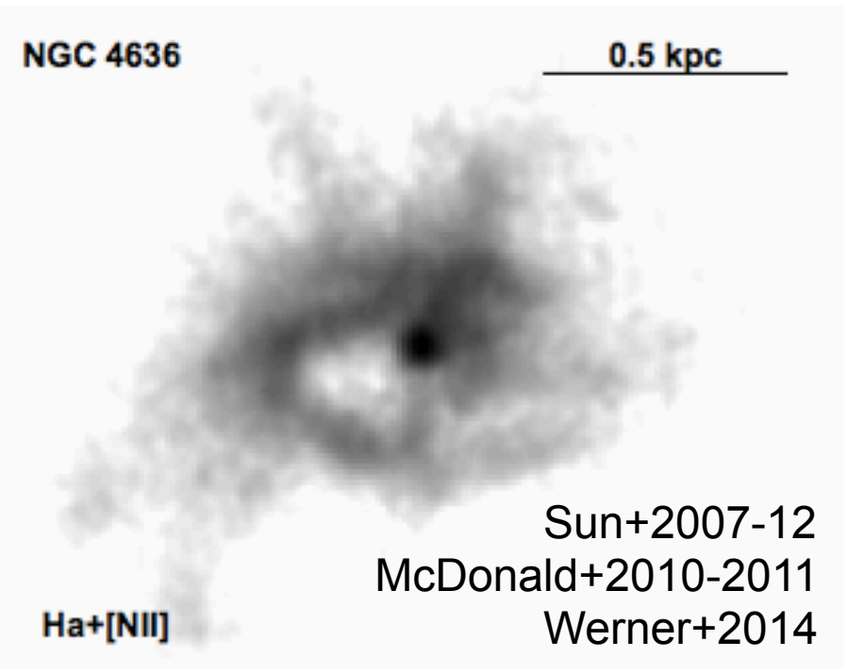


Sutherland & Dopita 1993
Inoue & Inutsuka 2008

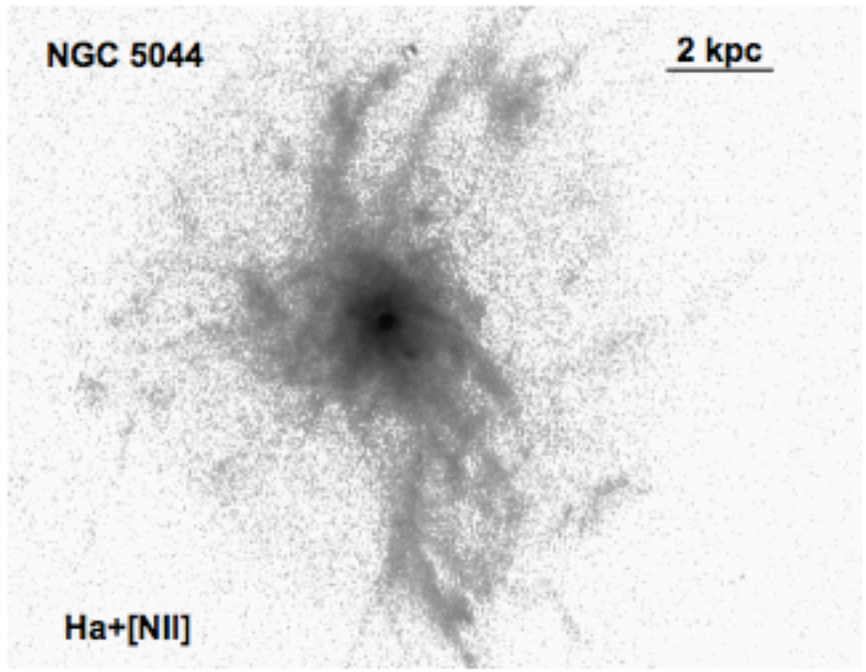
$$\mathcal{L} \simeq -n^2 \Lambda \qquad \mathrm{erg\,s^{-1}cm^{-3}}$$

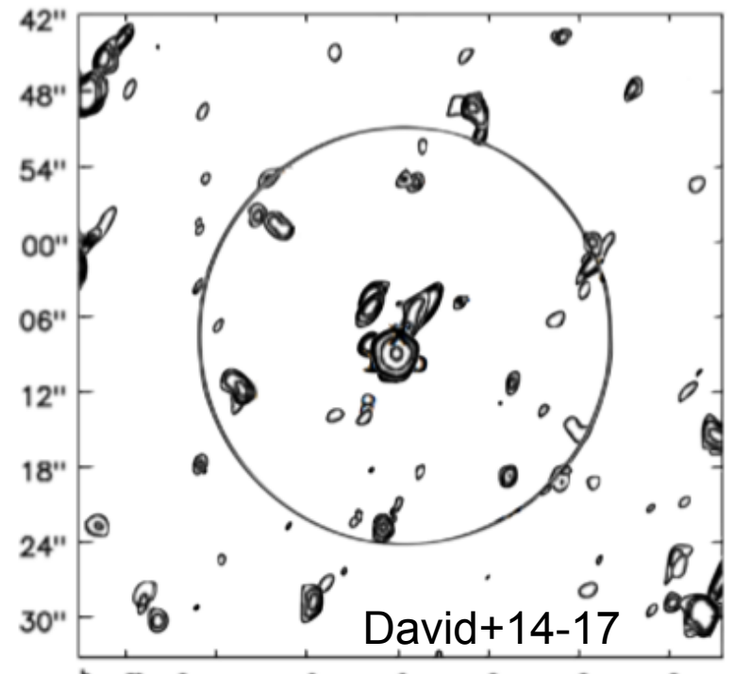
RADIATIVE COOLING

Perseus
Fabian et al.



Sun+2007-12
McDonald+2010-2011
Werner+2014



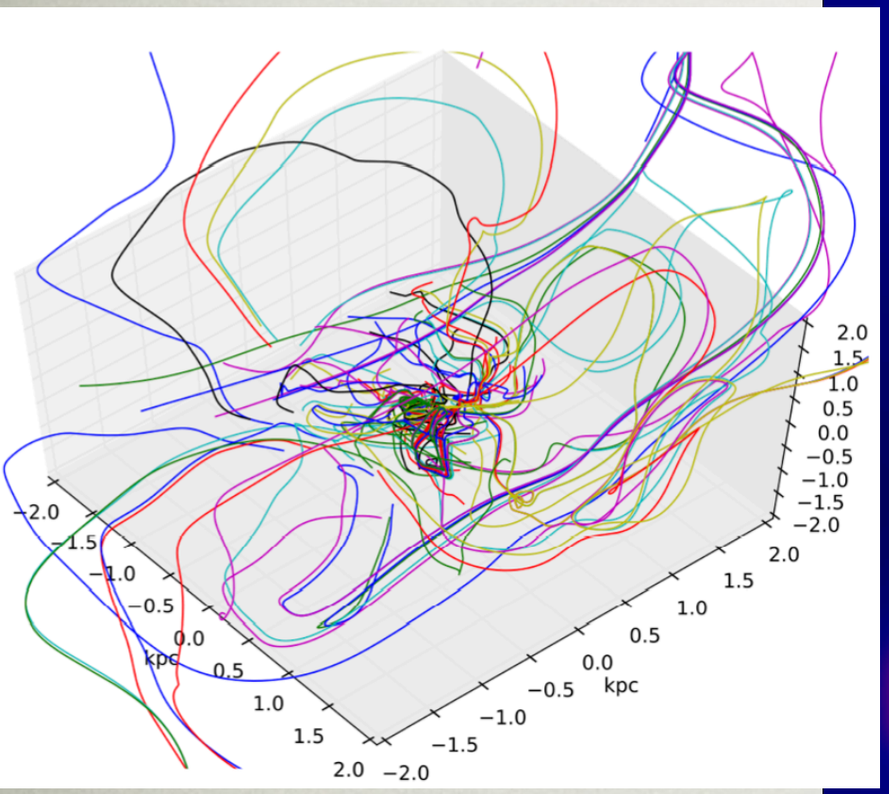


CO
ALMA

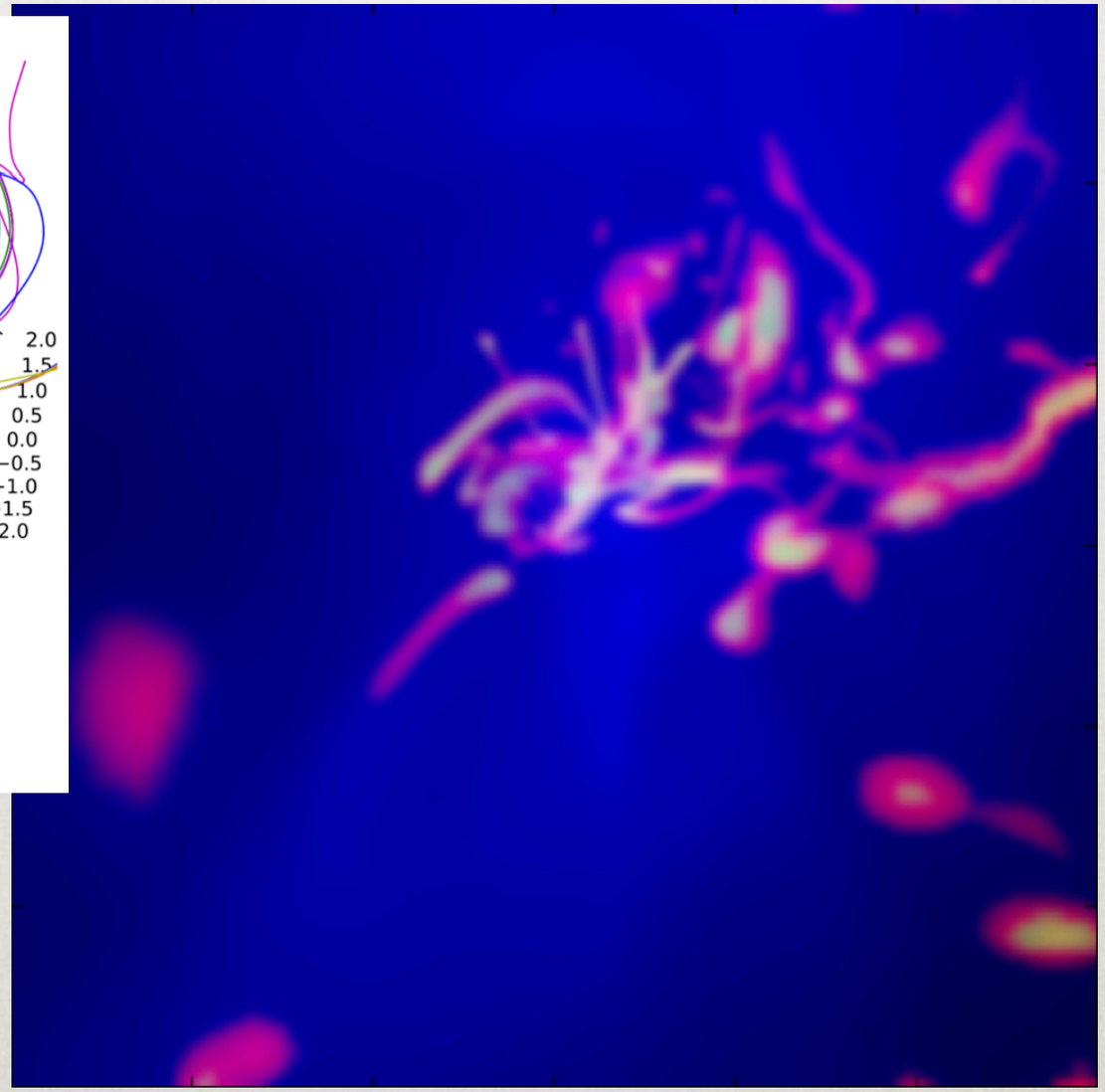
David+14-17

RAINING ON BLACK HOLES

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



chaotic streamlines => recurrent multiphase gas interactions



TURBULENCE > ROTATION

$\mathrm{Ta}_t < 1$

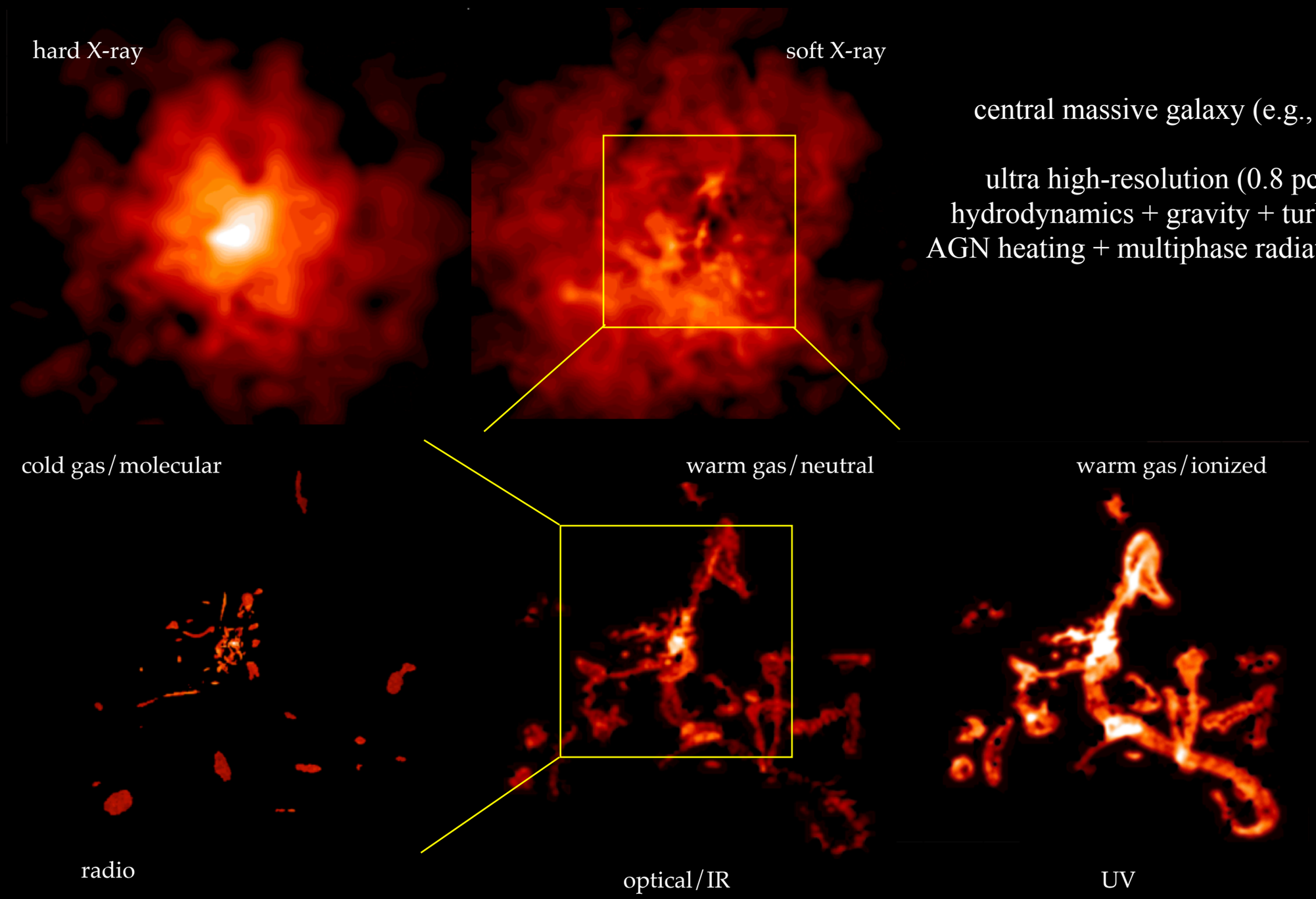
COOLING ~ AGN HEATING

turbulence ~150 km/s, as found (a posteriori) 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+18; Maccagni+18; Nagai+19; Rose+19a,b; Storchi-Bergmann+19 (review), …

TOP-DOWN MULTIPHASE GAS CONDENSATION RAIN



central massive galaxy (e.g., N5044)

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

Gaspari et al. 2017

KINEMATIC TRACERS

MULTIPHASE RAIN

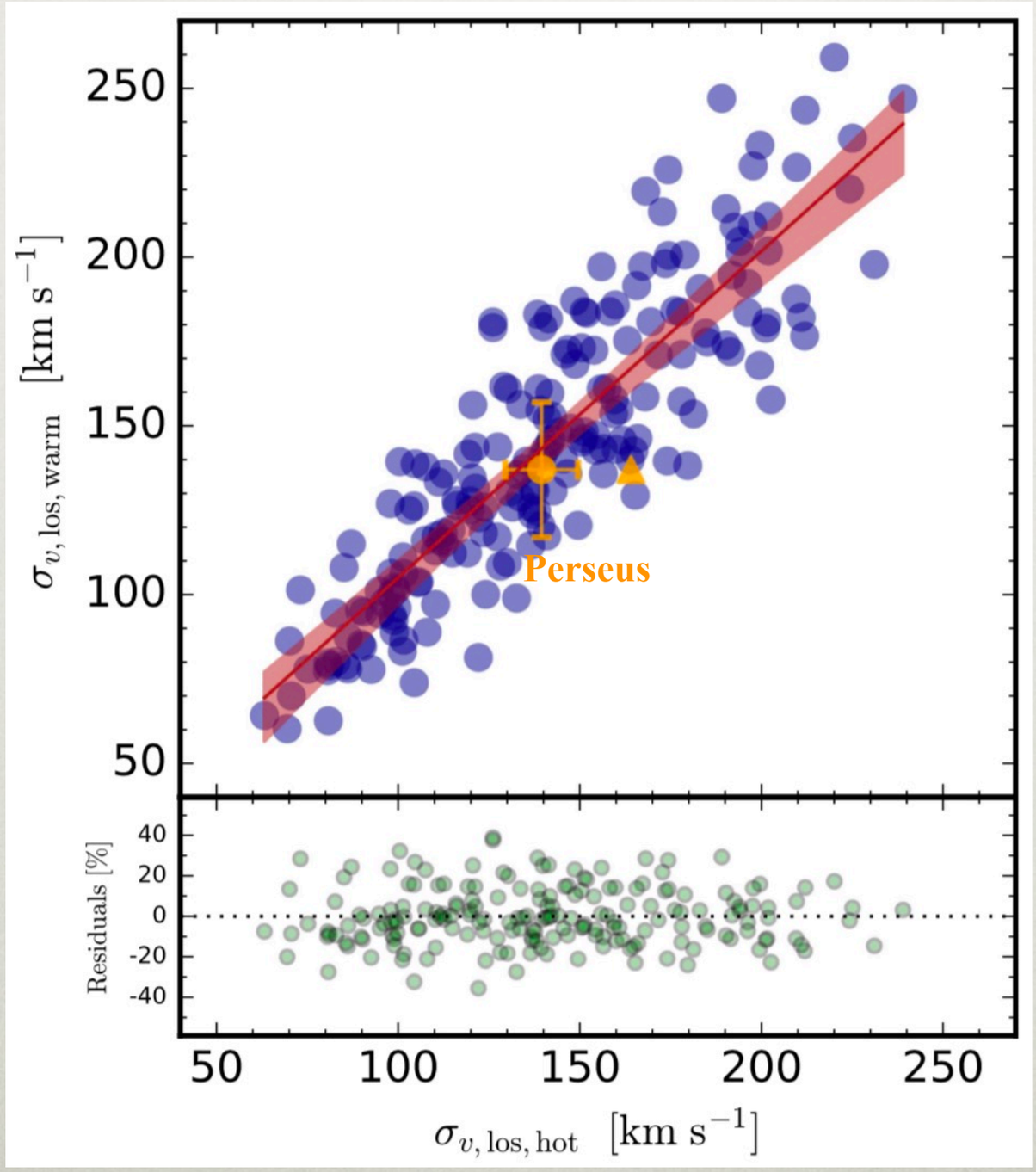
"shaken snow globes"

Gaspari et al. 2018

ENSEMBLE beam
(R < 50 kpc,
arcmin scale)

novel method to constrain
turbulence in the hot phase

spectral line broadening
= turbulent motions



self-regulated
AGN jet feedback run

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

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

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

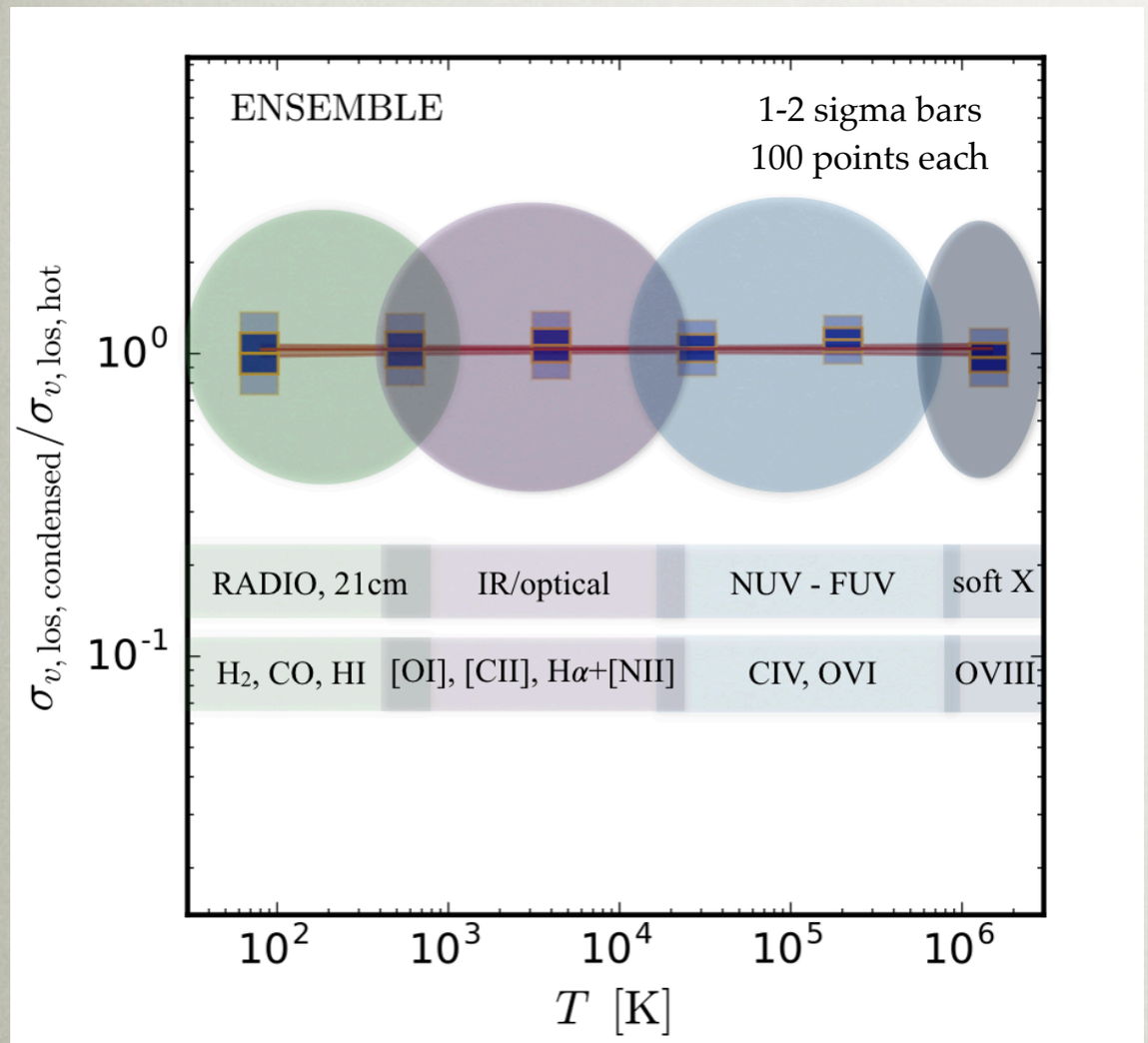
KINEMATIC TRACERS

Velocity dispersion in different phases compared with the turbulence driven in the hot plasma

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

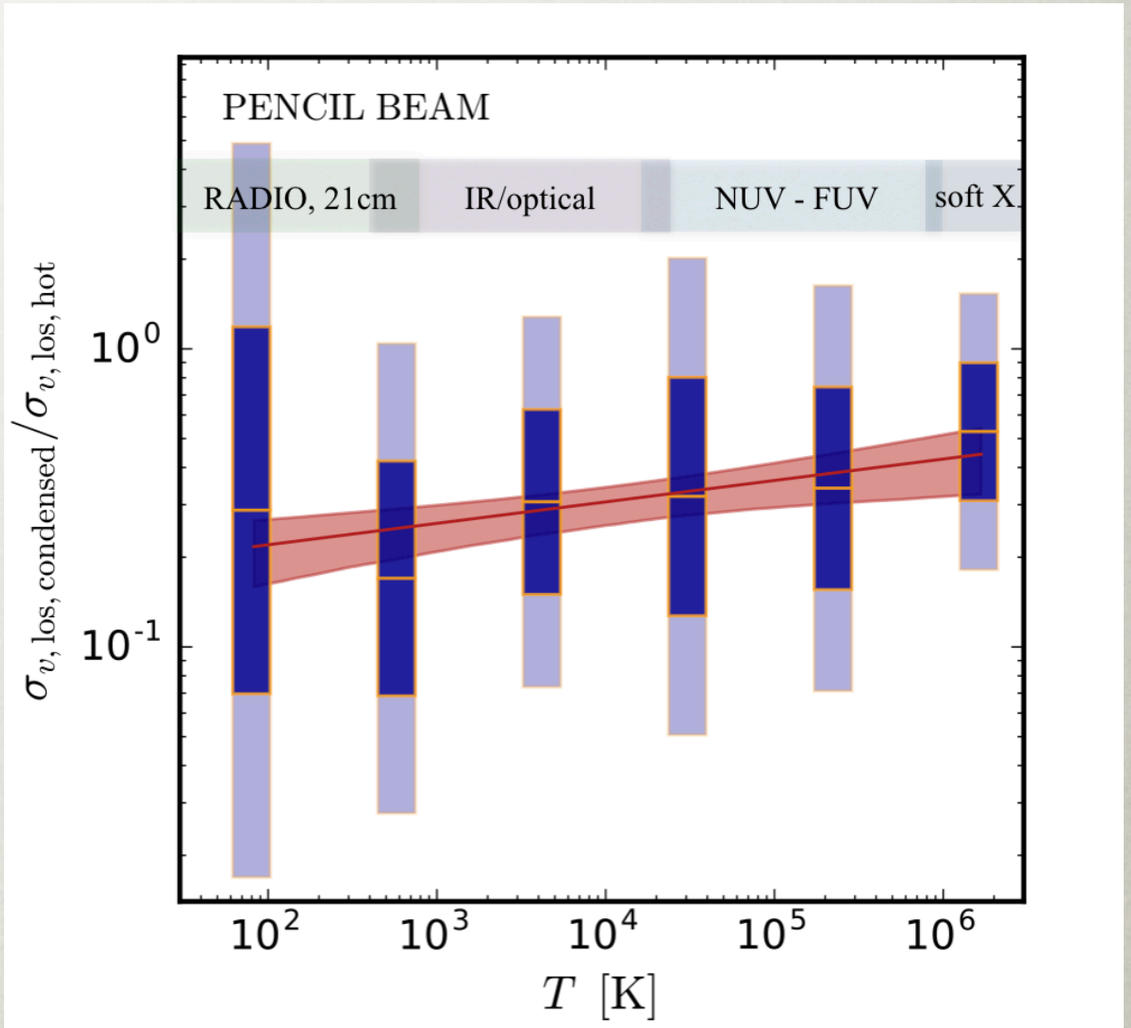
short-term (100 Myr): ultra high-resolution (0.8 pc) CCA runs

MG+18



wide aperture (R < 15 kpc or ~ arcmin)

- small scatter: tracing large-scale volume-filling turbulence
- tight correlation among all phases during CCA



small aperture (R < 25-100 pc or ~ arcsec)

- large scatter: tracing the small scale clouds, infalling onto the SMBH or drifting at large radii
- following the turbulent eddy Kolmogorov cascade

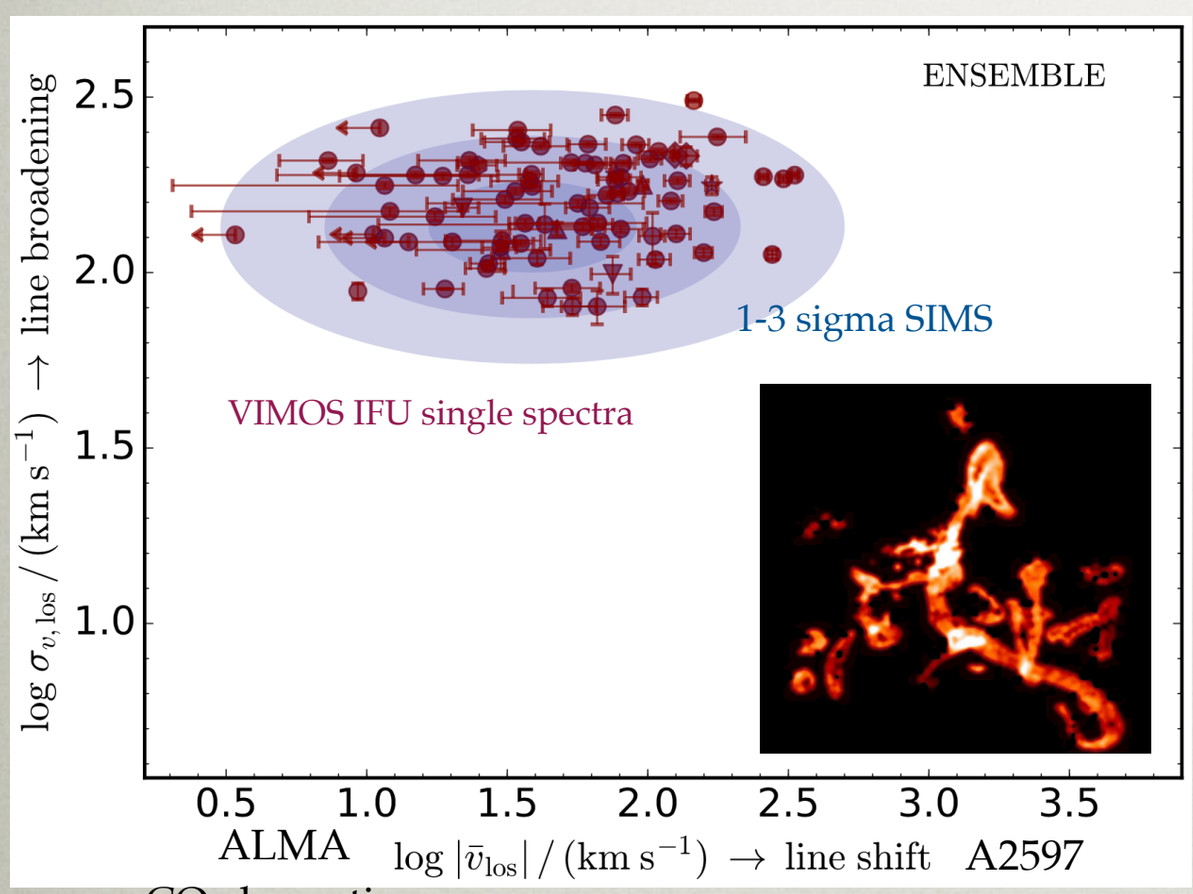
KINEMATIC TRACERS - RAIN/CCA

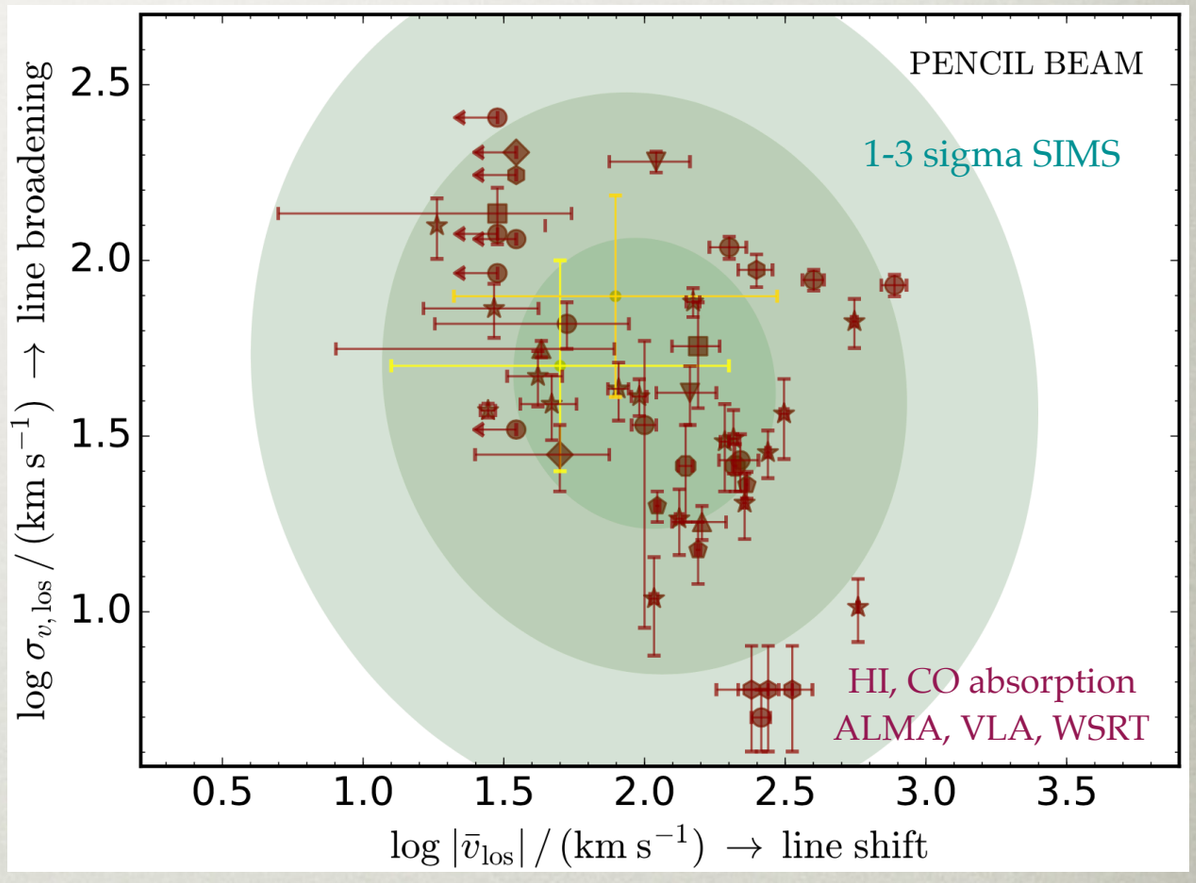
observational tests

(massive galaxies in groups and clusters)

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

MG+18





Tremblay+16-18

substantial line broadening and small scatter

large line shifts and narrow broadening: accreting clouds

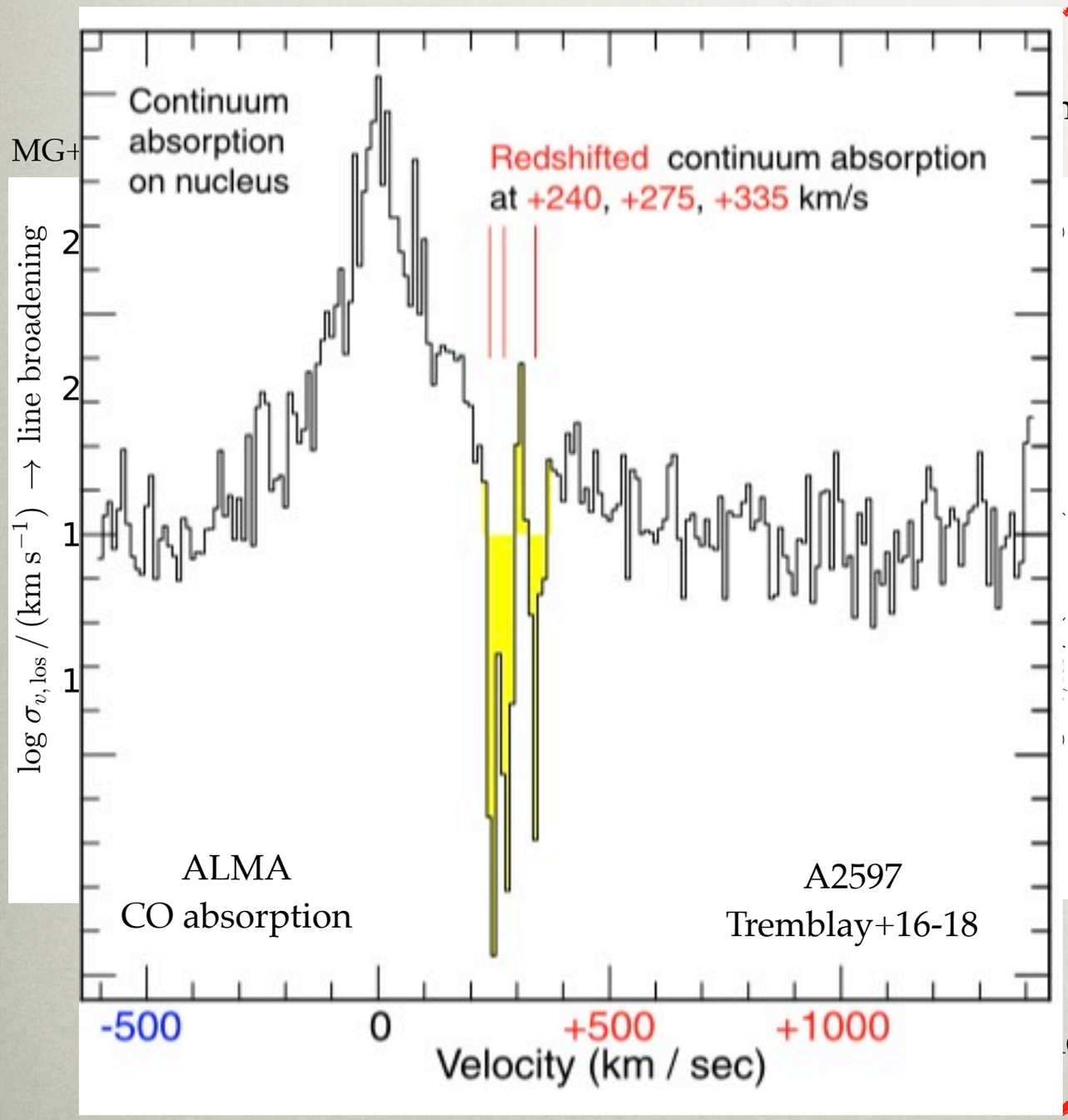
red points: ~80 systems (Hα+[NII], HI, CO, [CII] lines) — contours: SIMS lognormal distributions

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

KINEMATIC TRACERS - RAIN/CCA

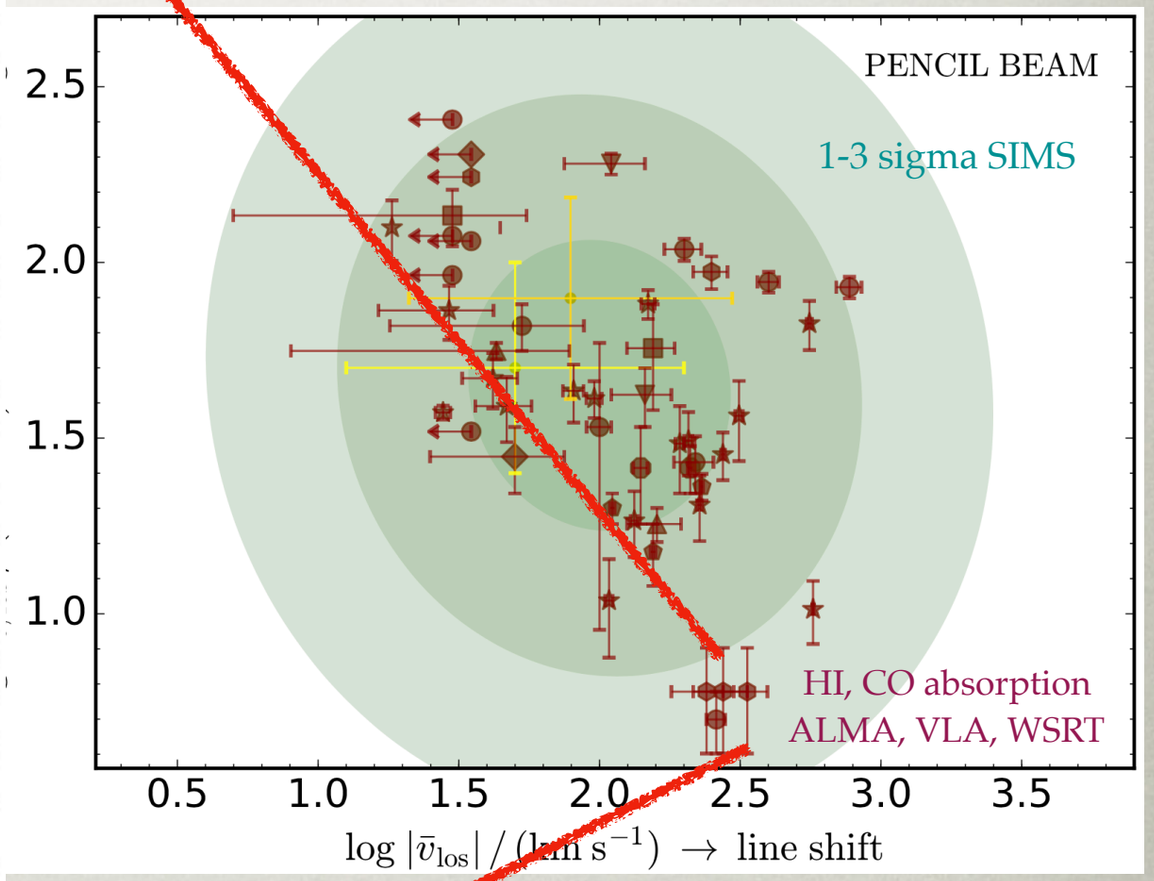
observational tests

(massive galaxies in groups and clusters)



MG+

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

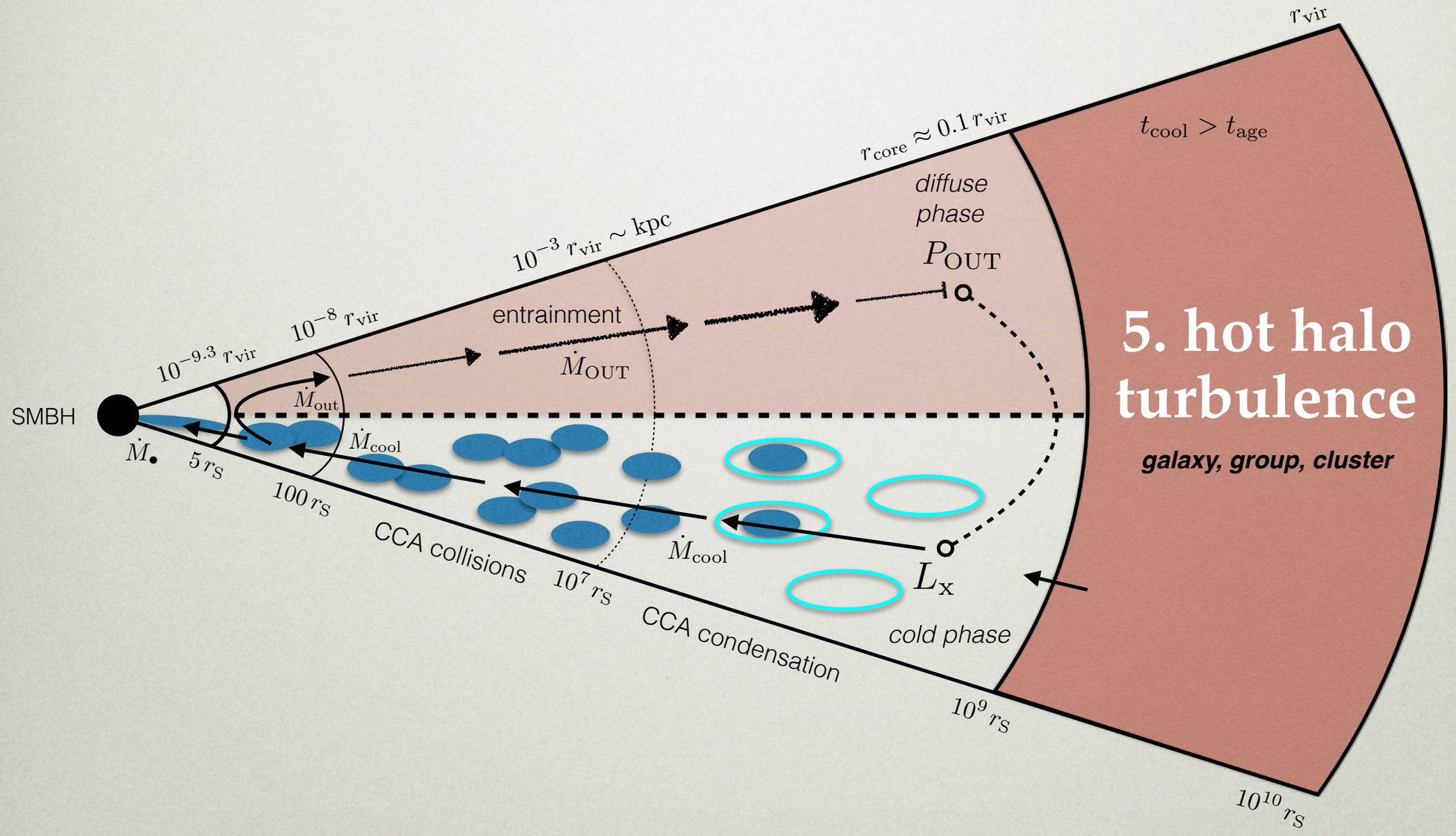


large line shifts and narrow broadening: accreting clouds

es) — contours: SIMS lognormal distributions

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

BLACK HOLE FEEDING AND FEEDBACK UNIFICATION



MG+2011-2019

ICM DENSITY FLUCTUATIONS

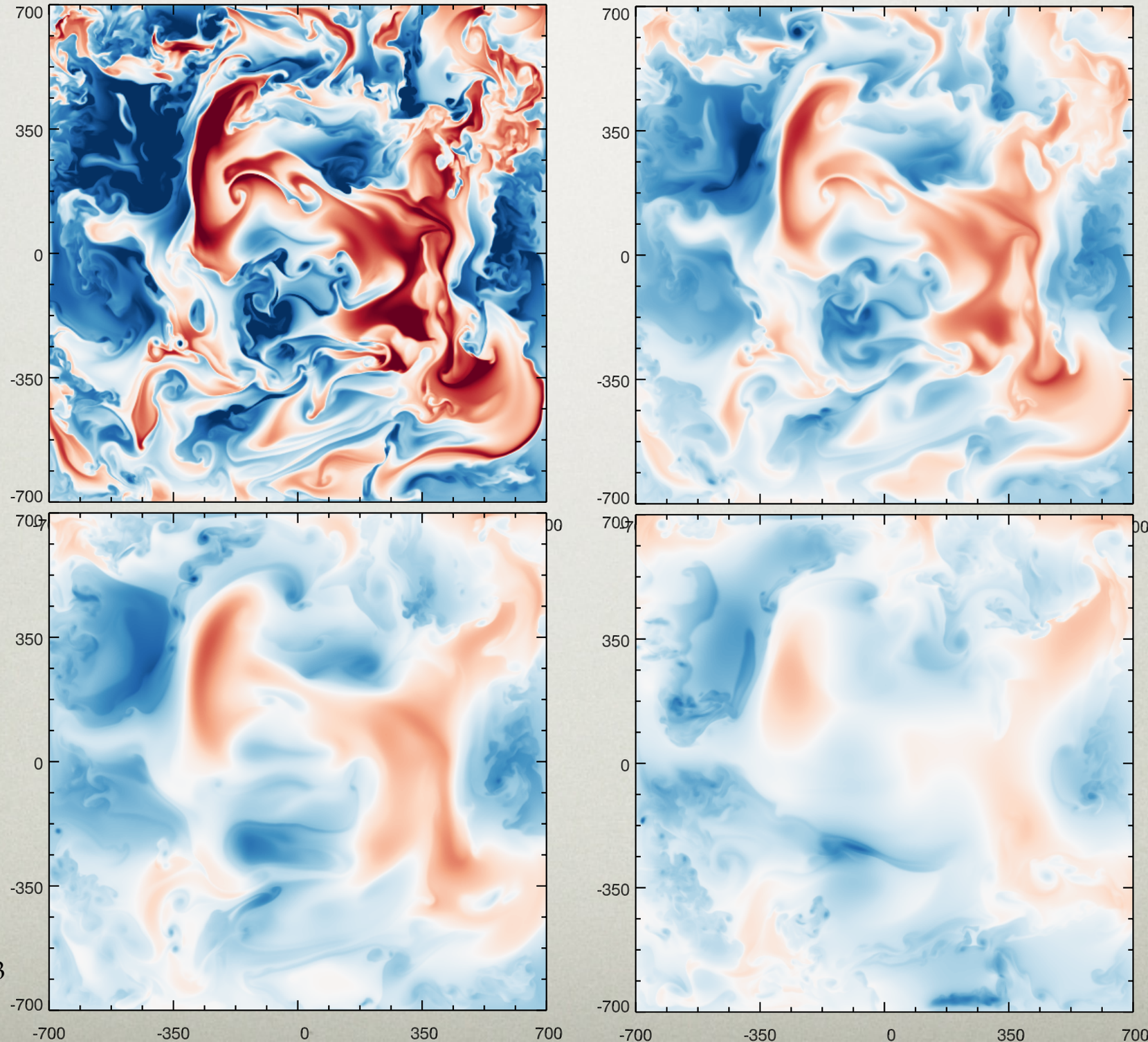
(REAL SPACE)

Mach ~ 0.25

hydro

isobaric fluctuations

$\delta\rho/\rho$ slices



f = 0.001

f = 0.01

f = 0.1

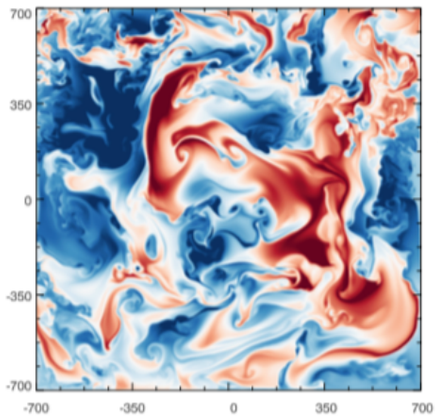
ele-ion plasma
3D simulation

isothermal fluctuations

Gaspari & Churazov 2013

A complete end-to-end X-IFU simulator

Simulated cluster



Emission model

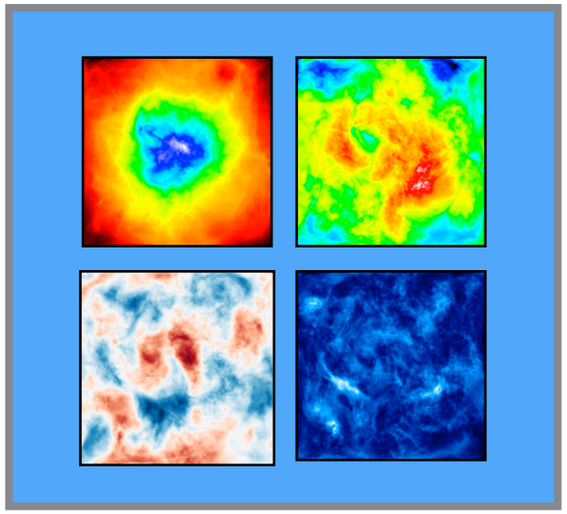
redshift

(x,y,E) data cubes

Z, n_H, t_{exp}

SIXTE

Projected ph. quantities



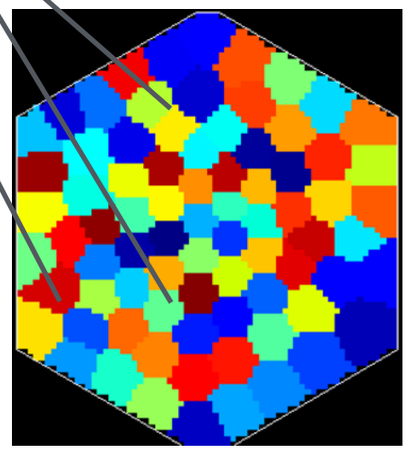
? ? ? ?

$\rho \pm \varepsilon$, $T \pm \varepsilon$
$v \pm \varepsilon$ $\sigma_v \pm \varepsilon$

measured quantities

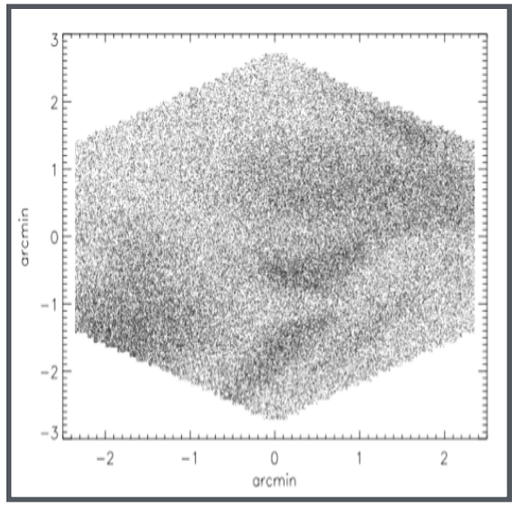
XSPEC fitting

PHA files

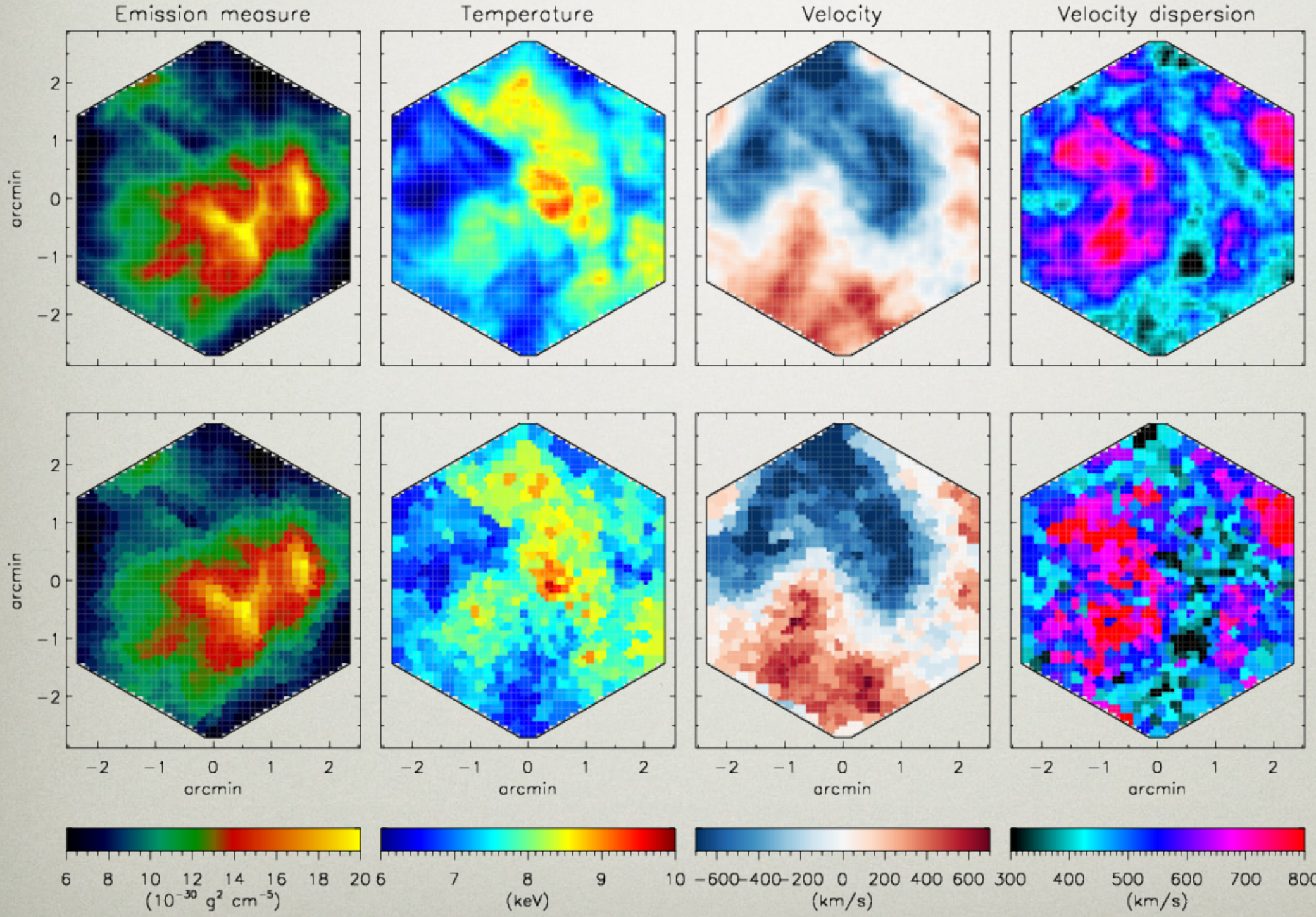


pixel grouping scheme

Mock X-IFU ev. list



ATHENA X-IFU
SYNTHETIC OBSERVATIONS



"real"
(3D hydro sims)

synthetic

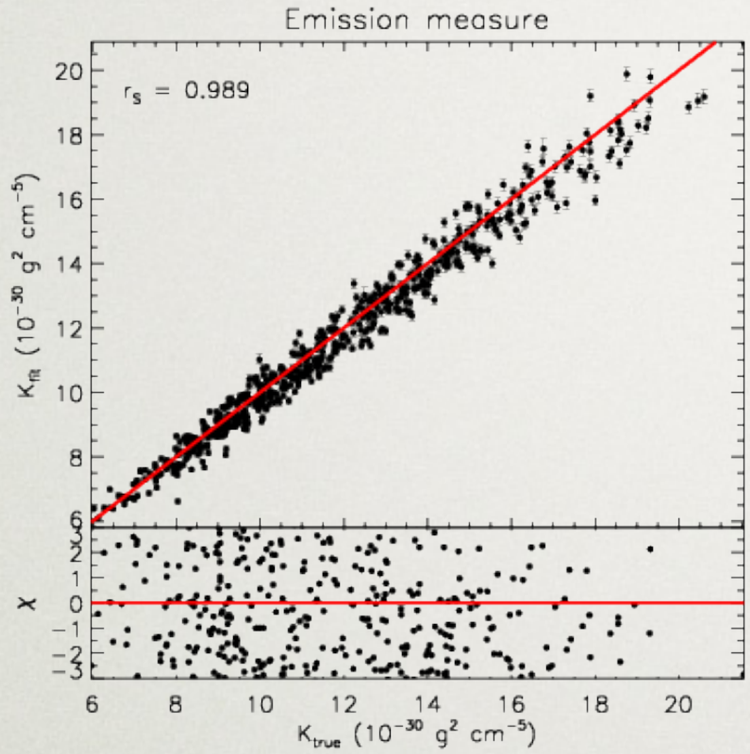
586 Voronoi tessellation (125 arcsec^2), exp. ~ 400 ks

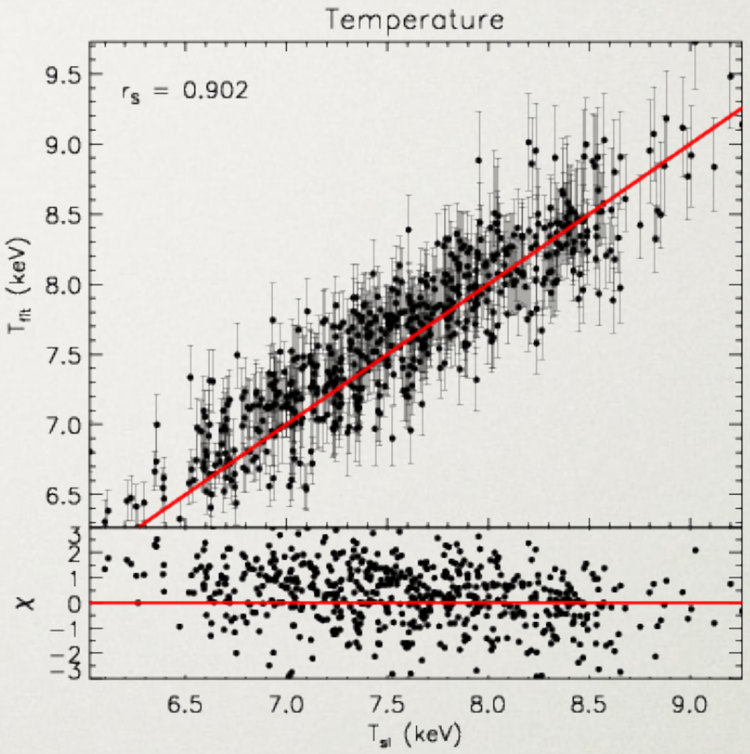
Roncarelli, Gaspari, Ettori+2018

Coma-like cluster - subsonic turbulence (L~500 kpc)

ATHENA X-IFU

SYNTHETIC OBSERVATIONS

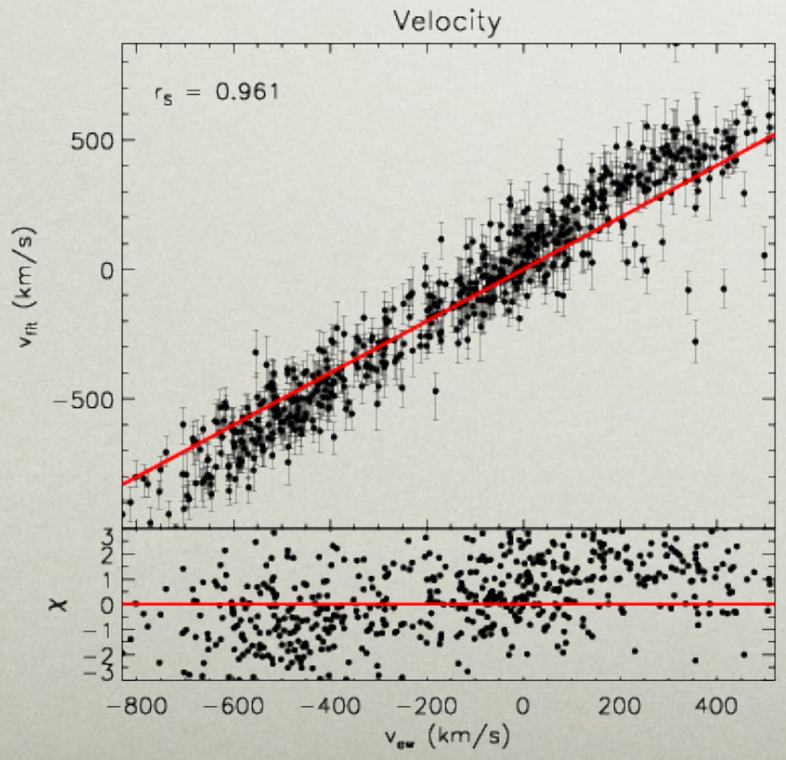


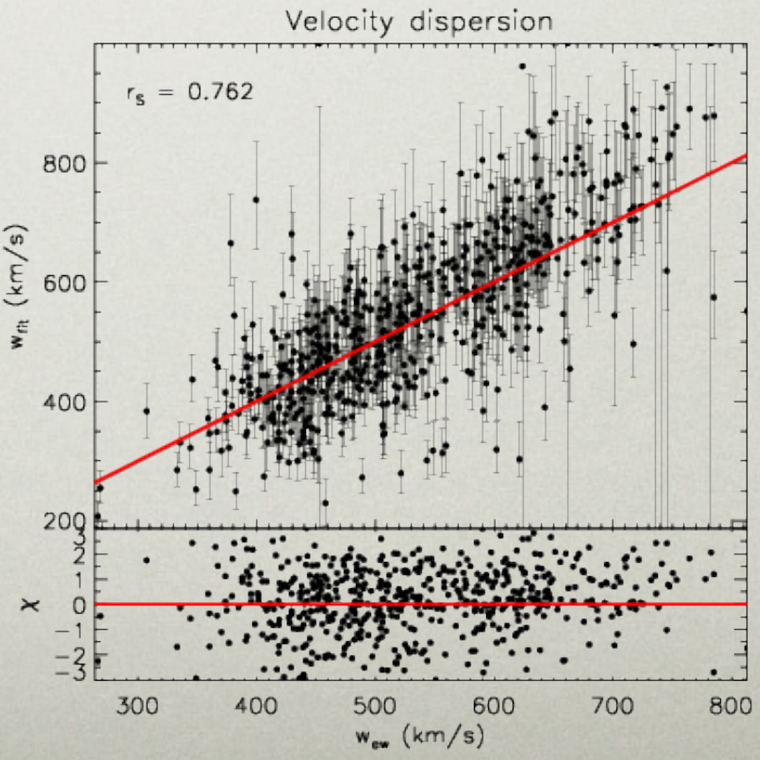


systematics < 4%

synthetic (y-axis)
vs.
"real" (x-axis; EW)

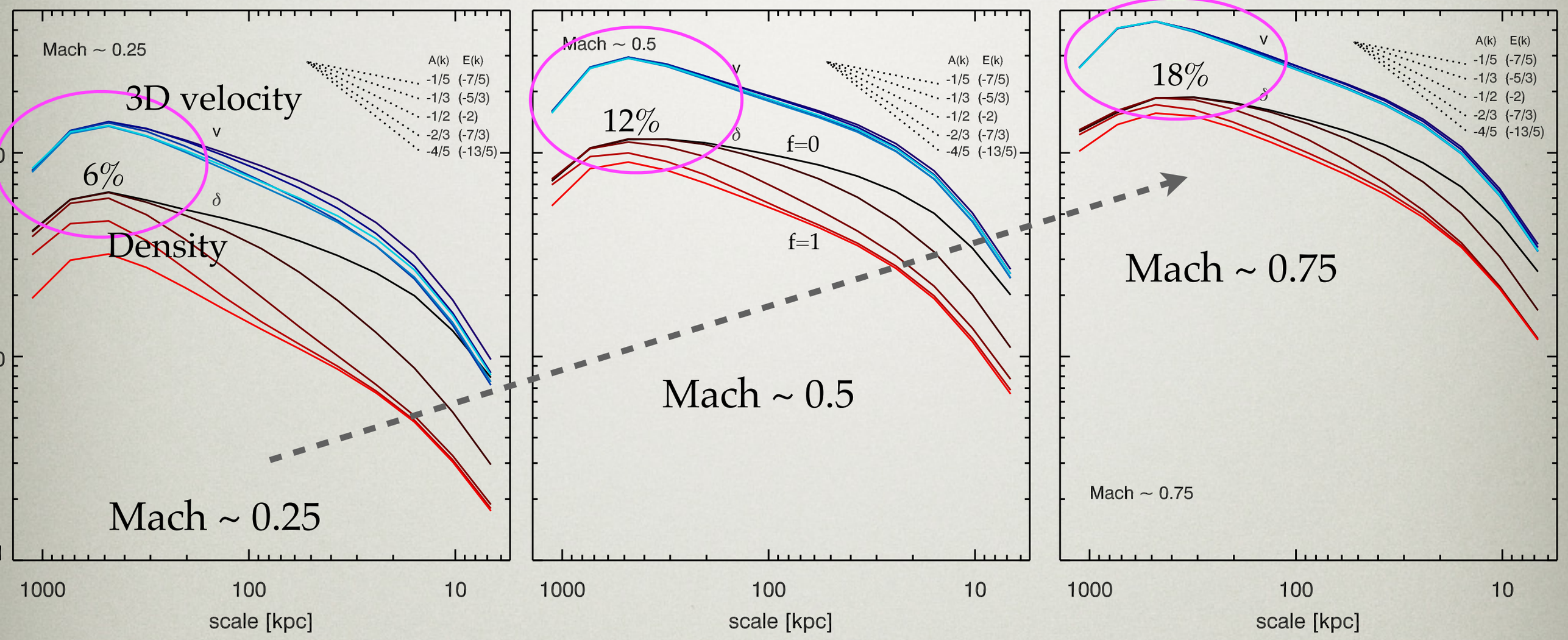
good agreement





systematics < 15%

ICM POWER SPECTRUM



Gaspari & Churazov 2013
Gaspari et al. 2014
Khatri & Gaspari 2016

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

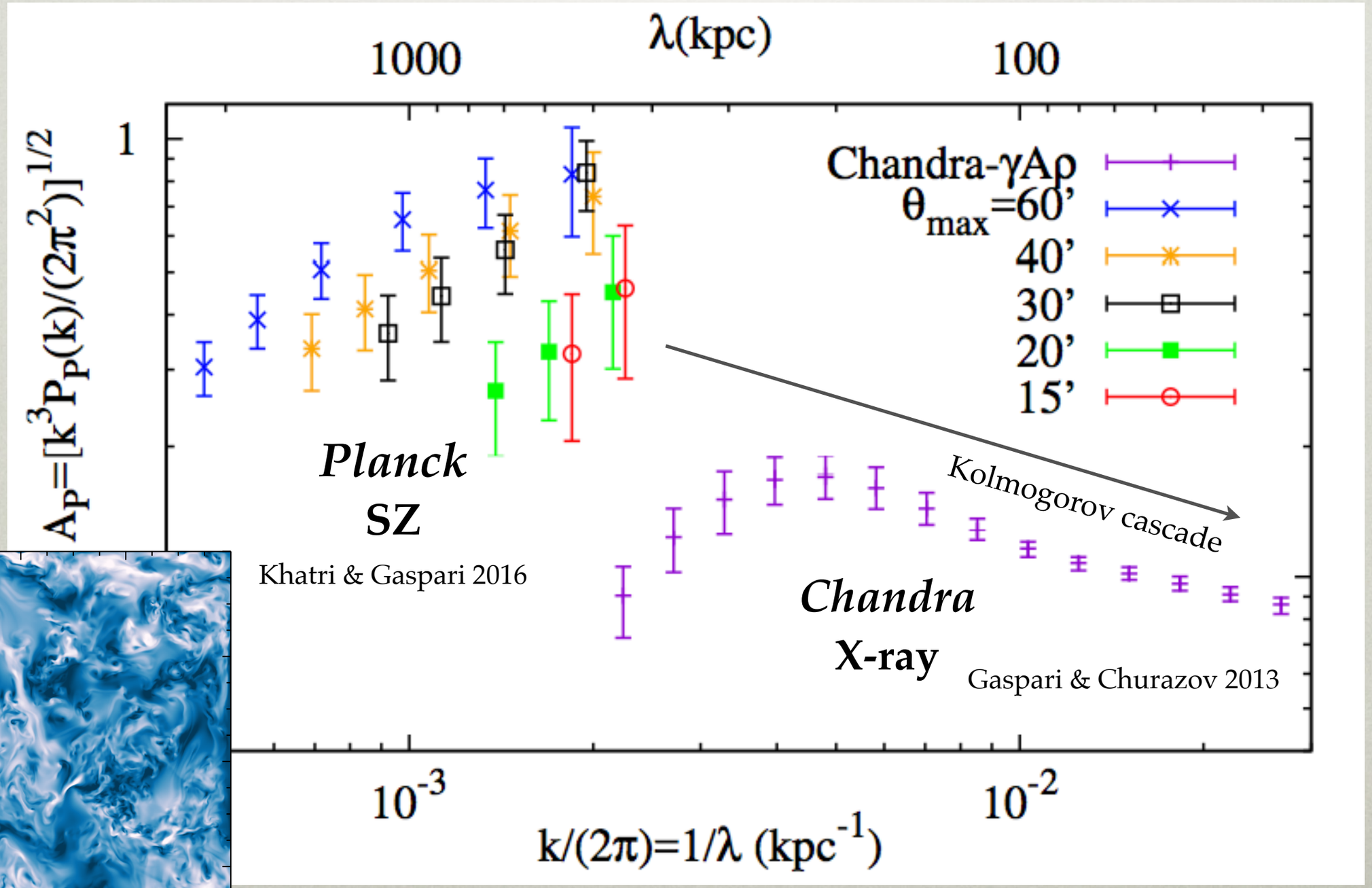
globally self-similar
over Mach and L_{inj}

Typically, relaxed to unrelaxed systems -> Mach_{3D}~0.3-0.6

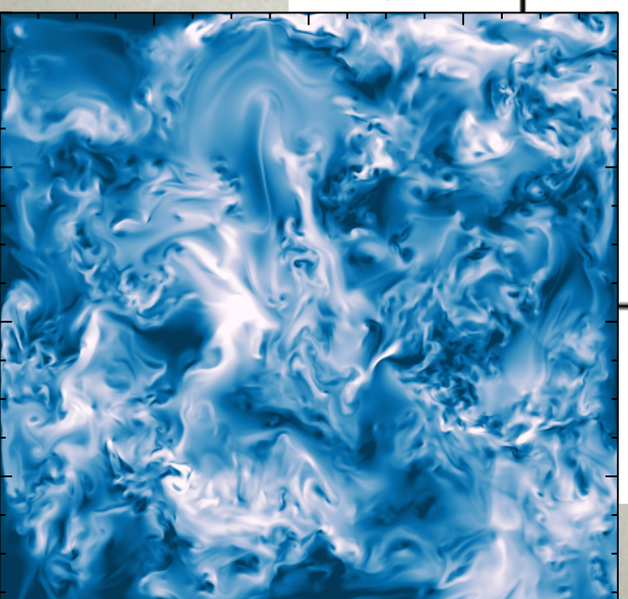
PLASMA POWER SPECTRUM

PROBING TURBULENCE & CONDUCTION

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



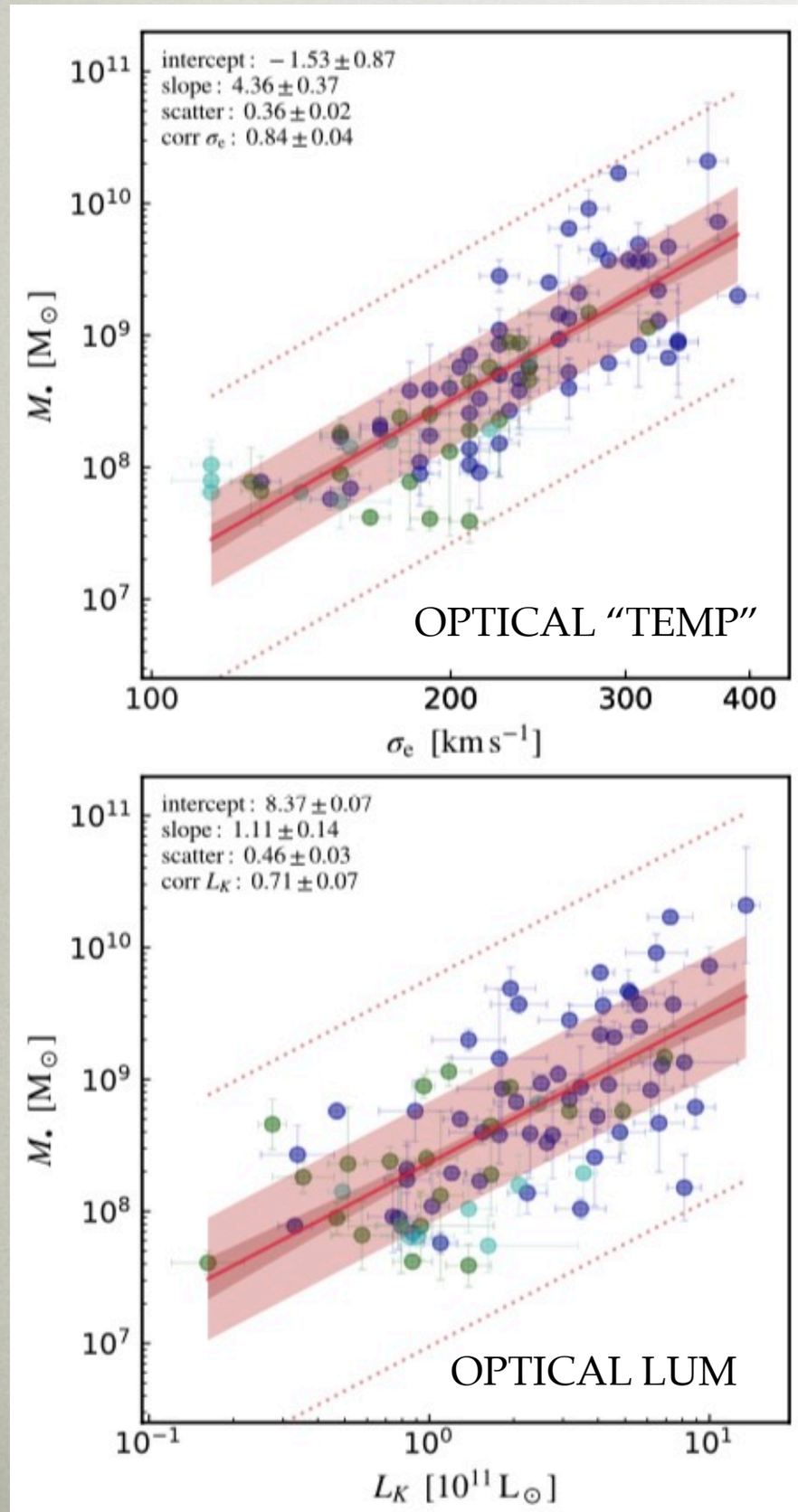
massive CLUSTER



subsonic turbulence

X-RAY HALO SCALING RELATIONS OF SMBHs

Gaspari et al. 2019

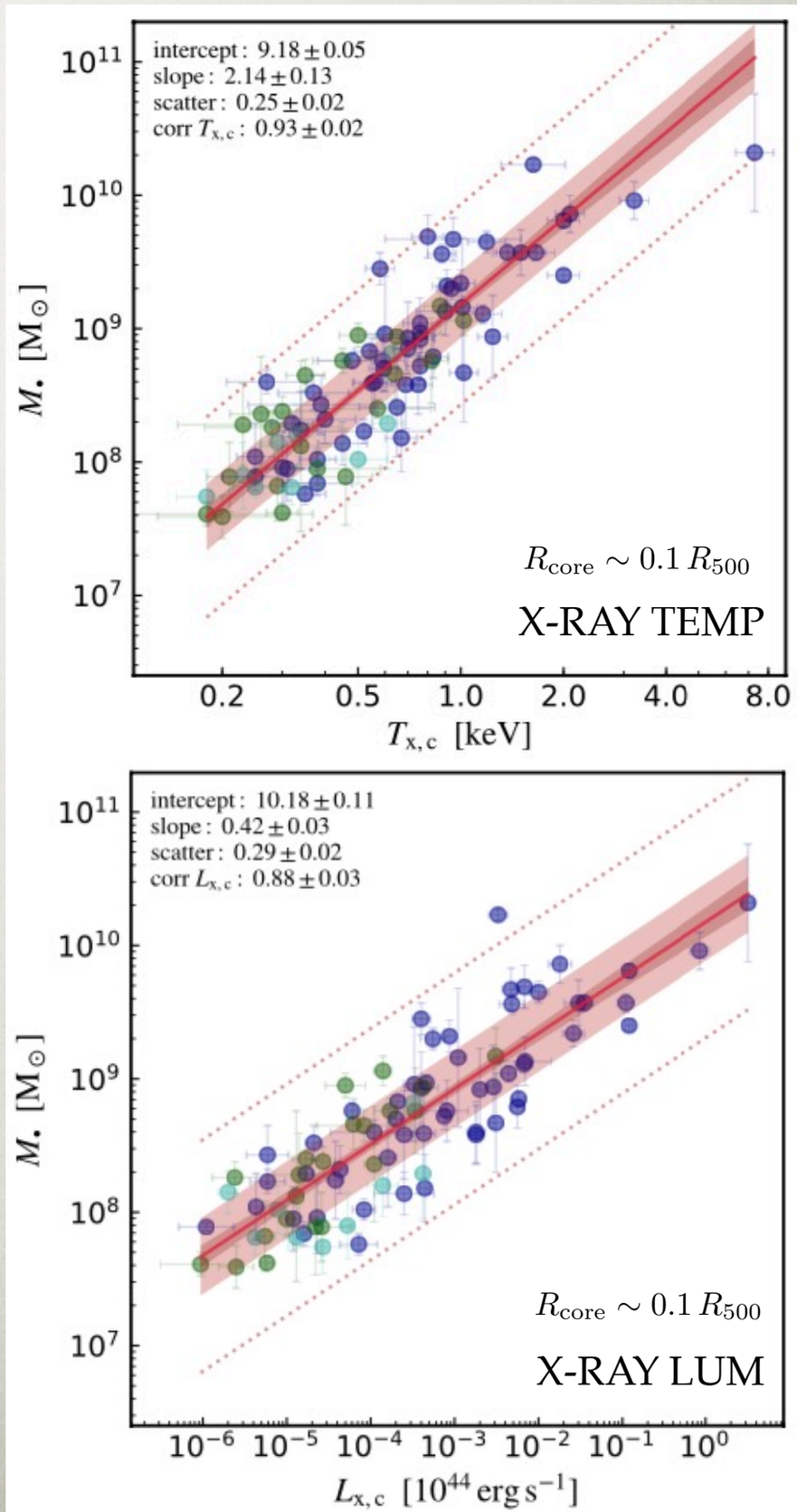


Bayesian analysis:
85 galaxies,
groups, clusters

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

DIRECT BH
MASSES, e.g.,
Kormendy+13,
vBosch+16

X-ray scalings lower scatter and larger correlation

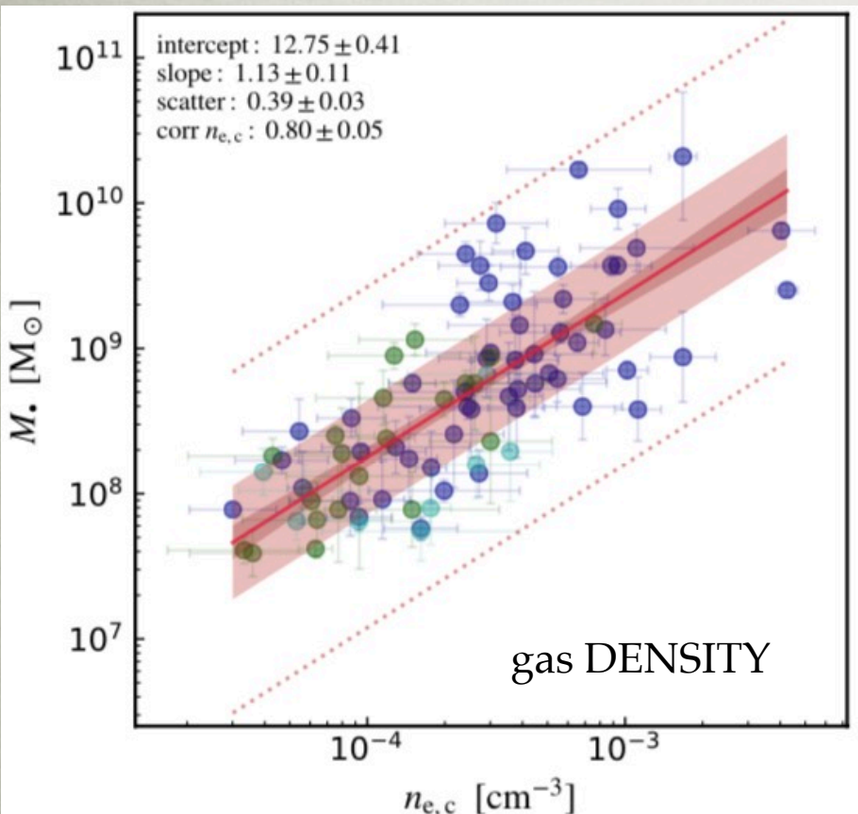


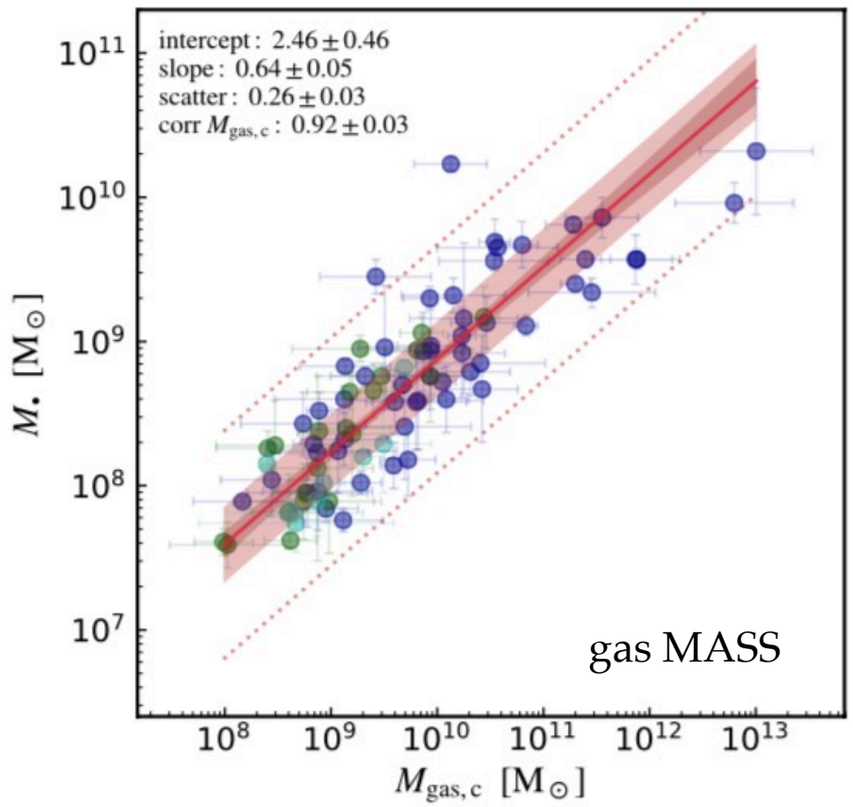
X-RAY HALO SCALING RELATIONS OF SMBHs

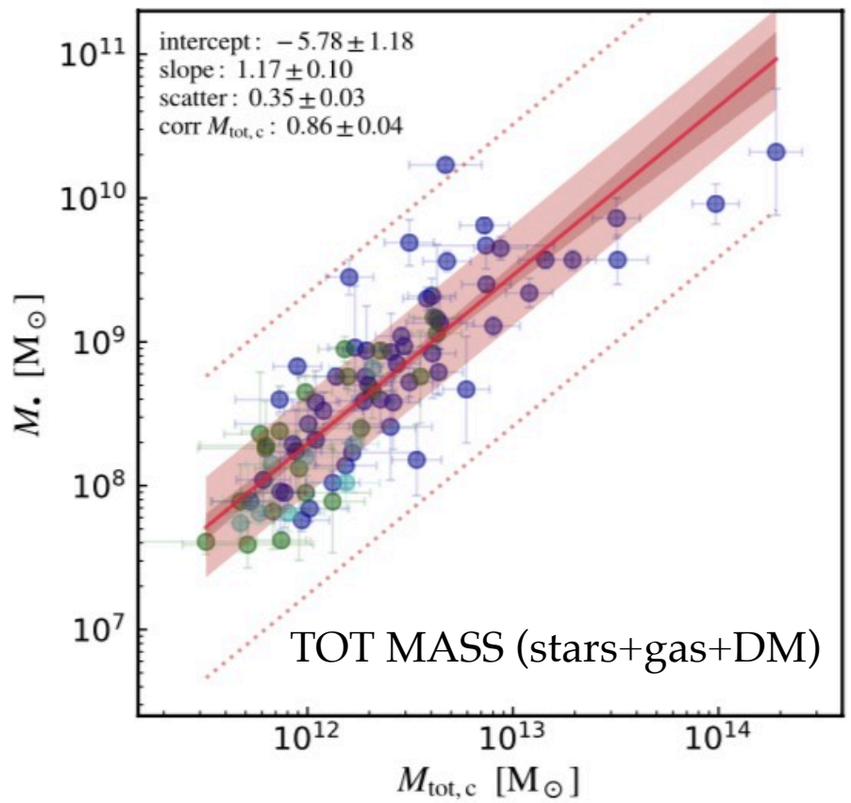
(indirect properties)

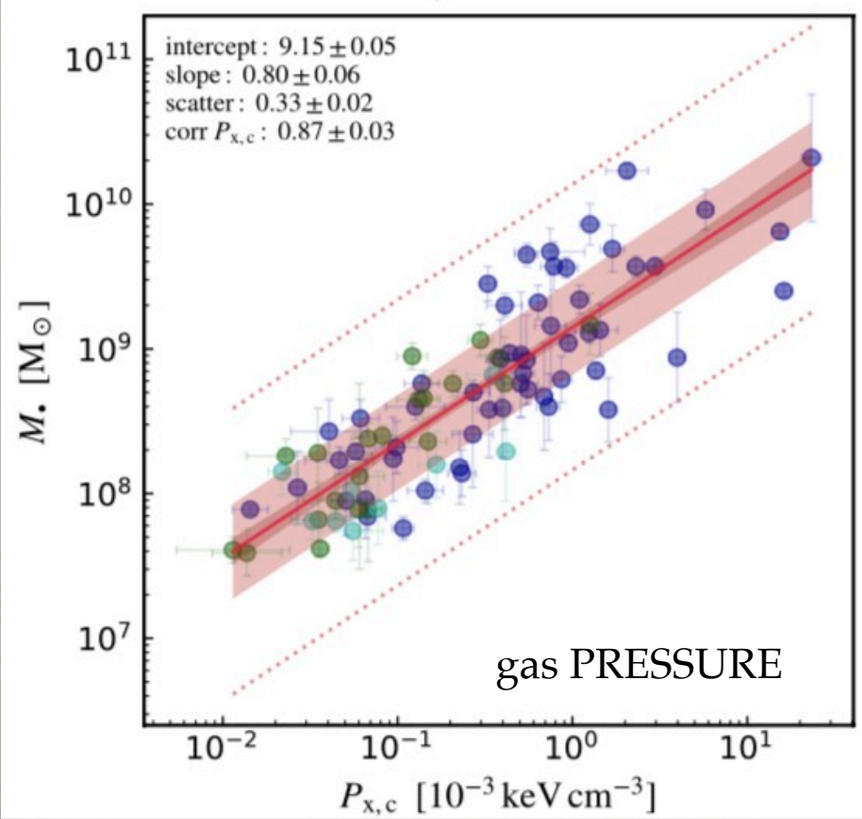
Gaspari et al. 2019

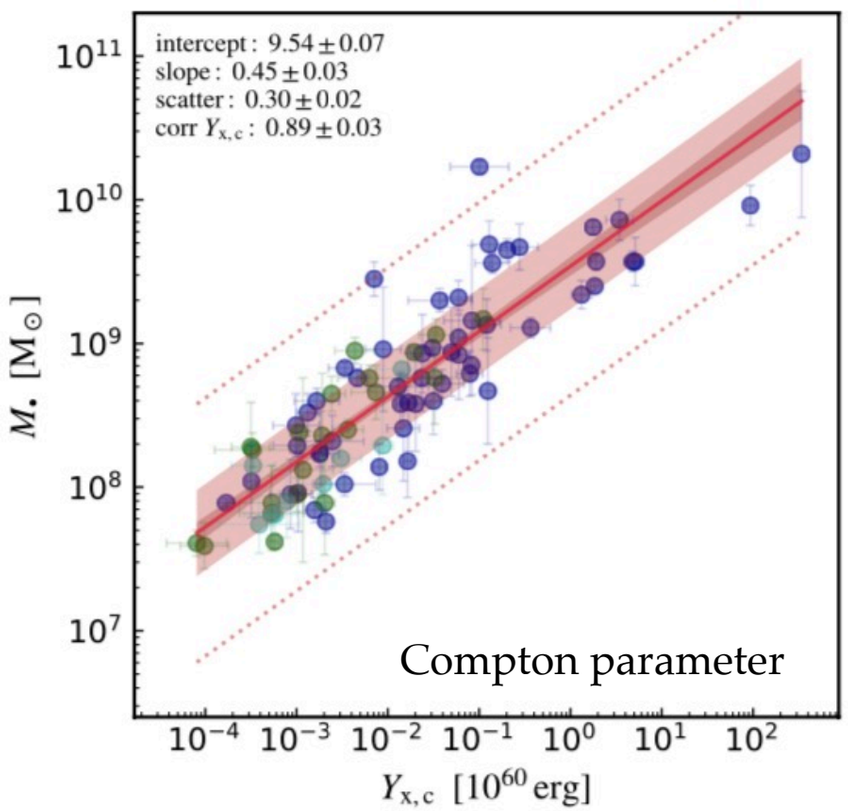
all within core region

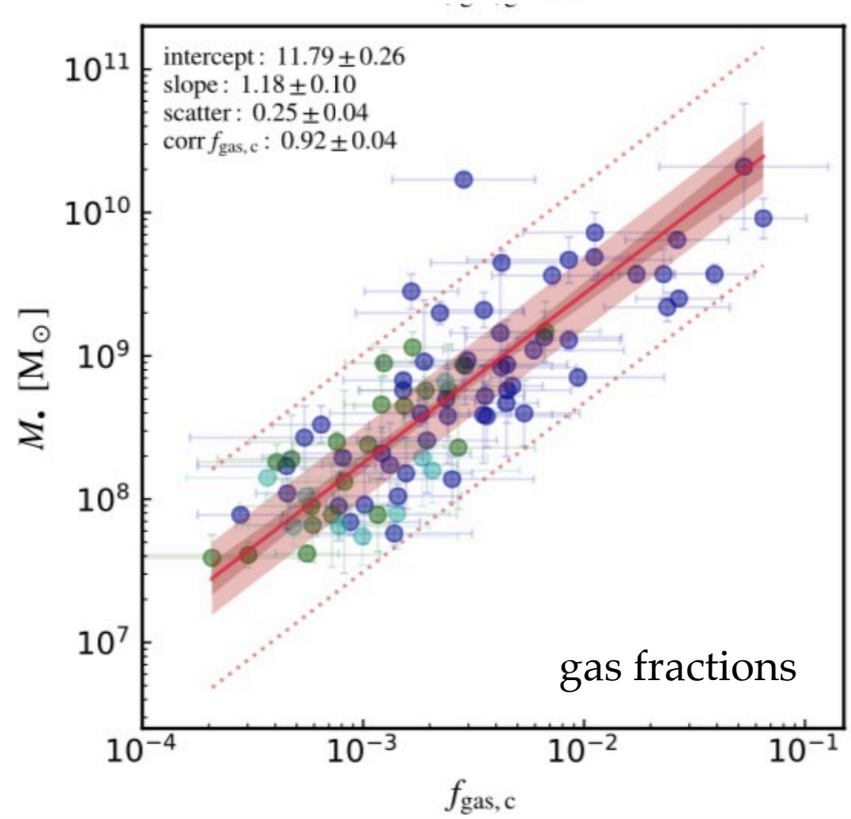




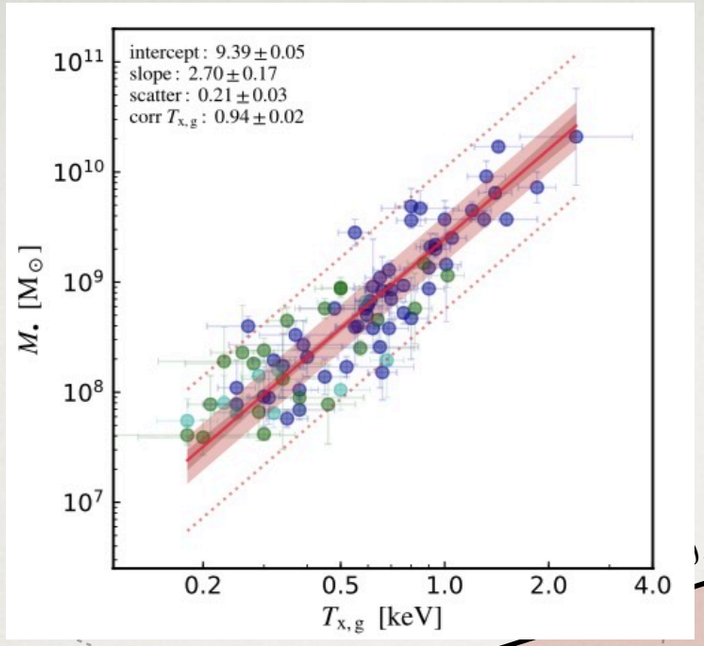






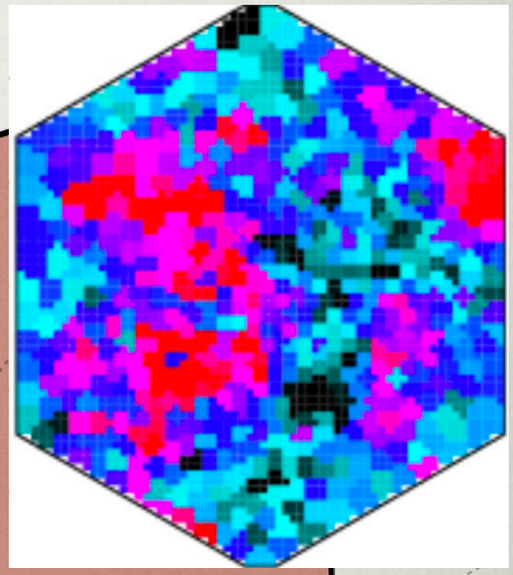


"Black Hole Weather"
discussed areas

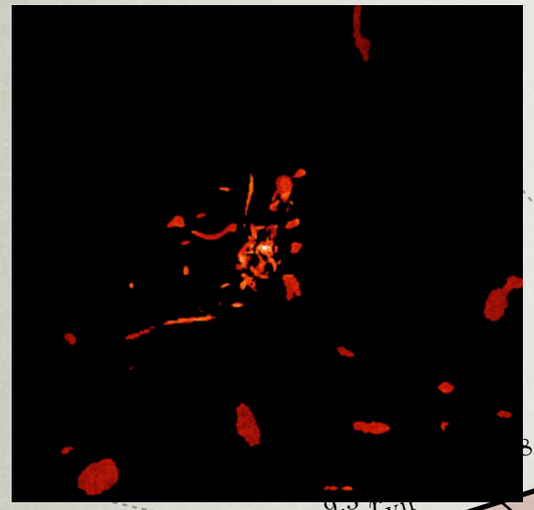


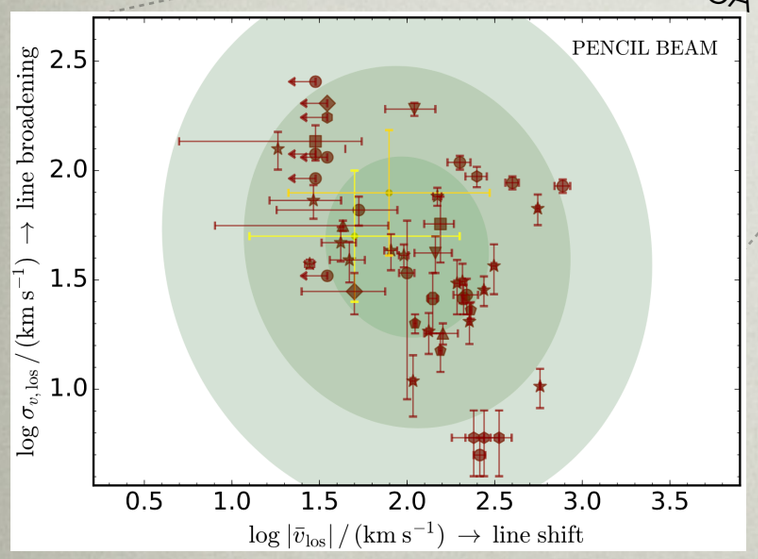
tight X-ray halo scalings of SMBHs

merger-driven turbulence (*Athena*)

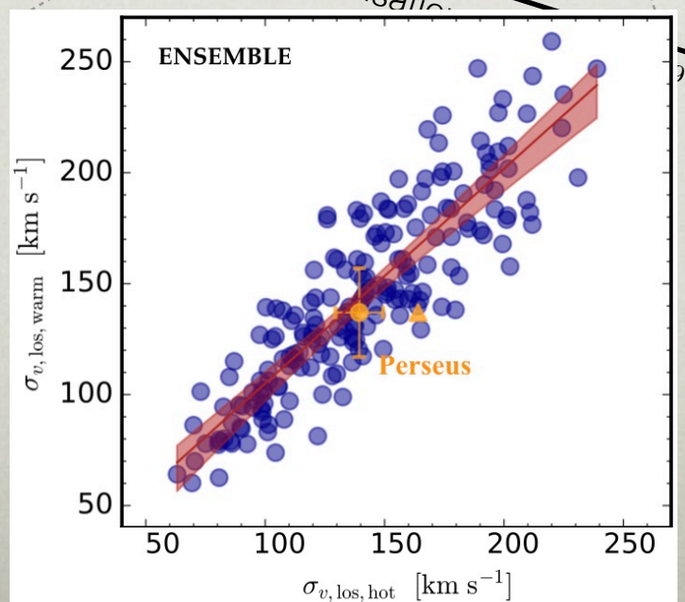


CCA

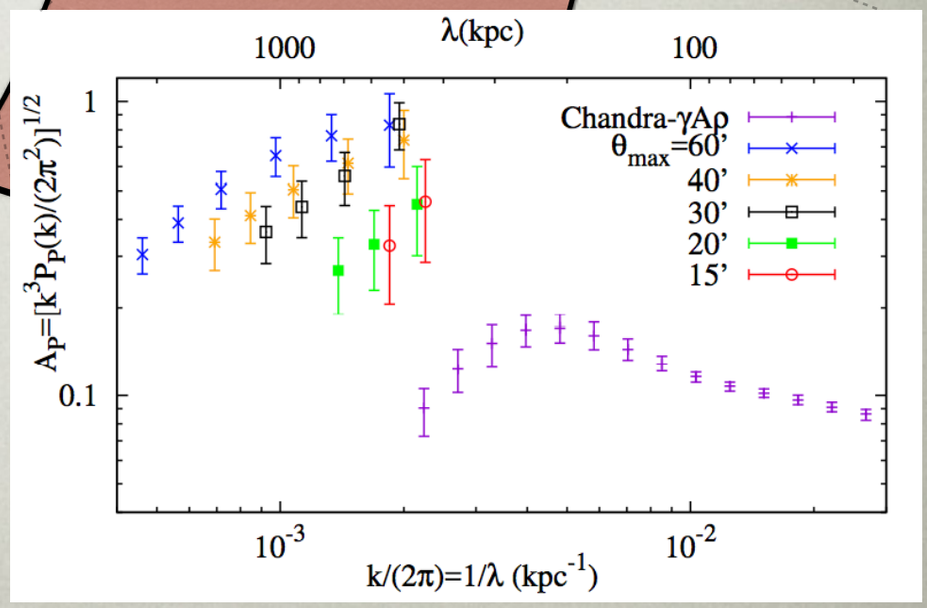




molecular clouds feeding



warm filaments/hot gas correlations



turbulence and conduction via ICM PS