Probes of Rain and Turbulence in Hot Halos

Massimo (Max) Gaspari

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... and SMBH co-evolution

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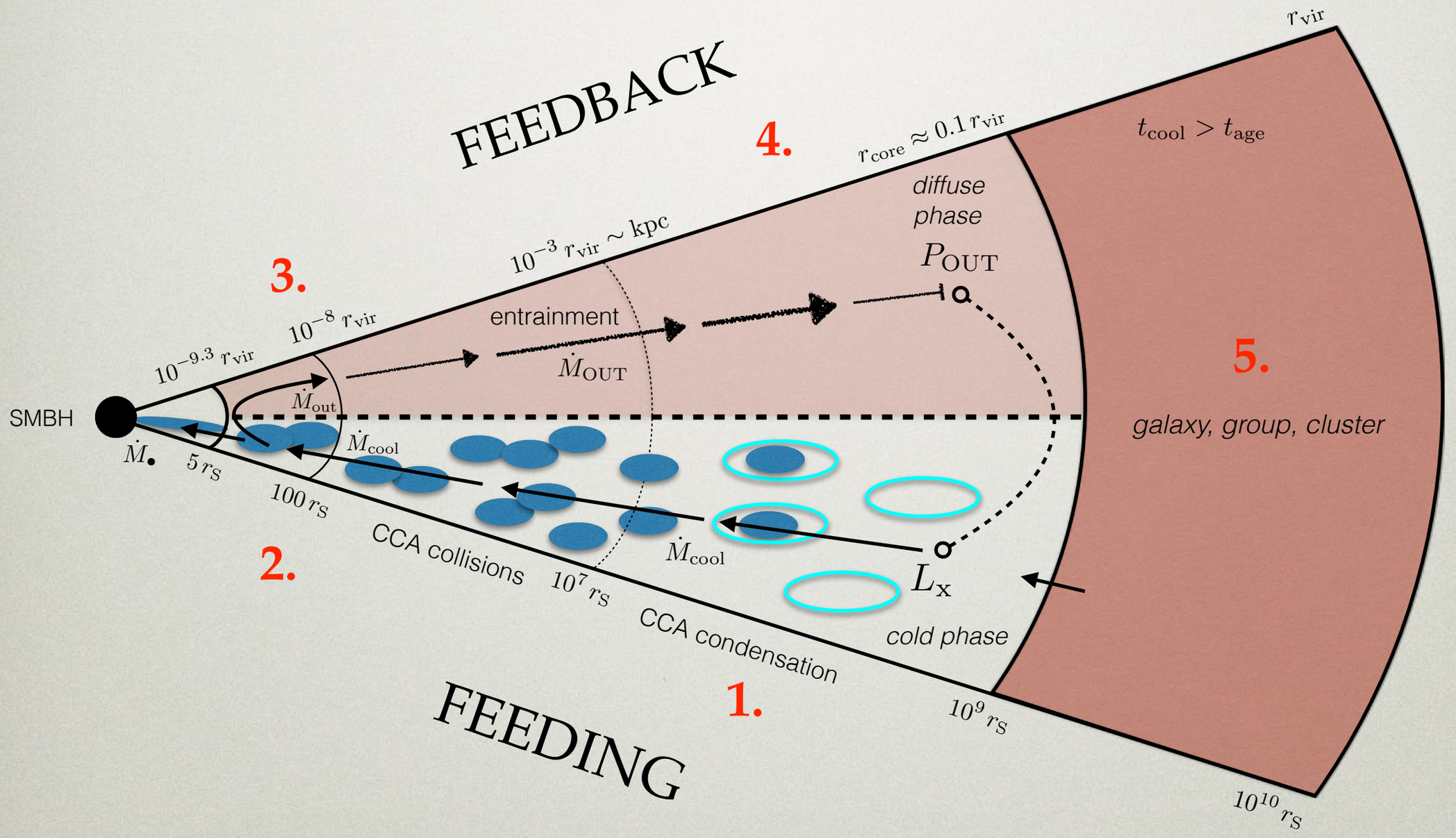
"BLACK HOLE WEATHER" PROGRAM

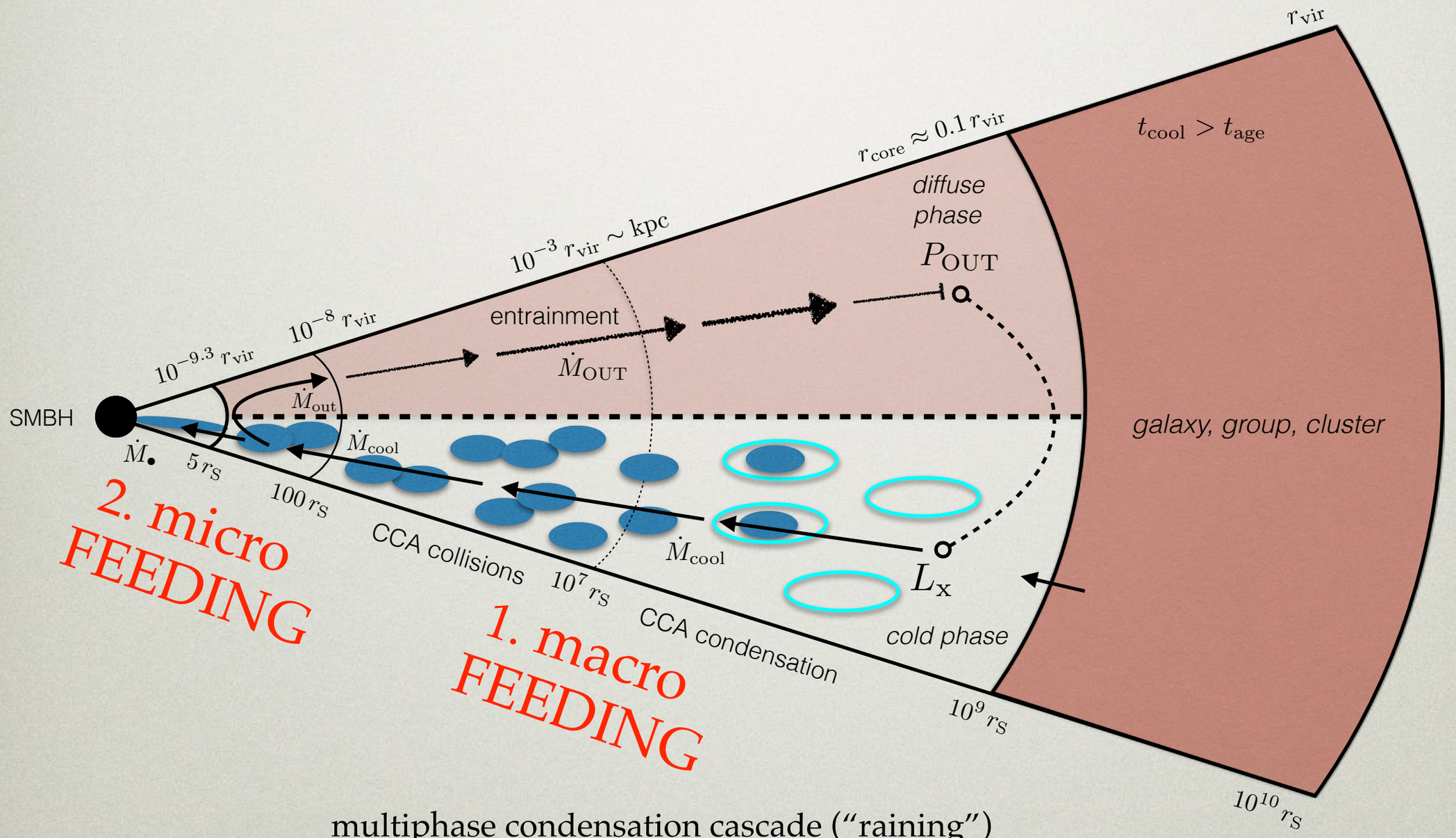


GOAL 1: first-principle multi-scale simulations

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

MG+2011-2019

“BLACK HOLE WEATHER” PROGRAM



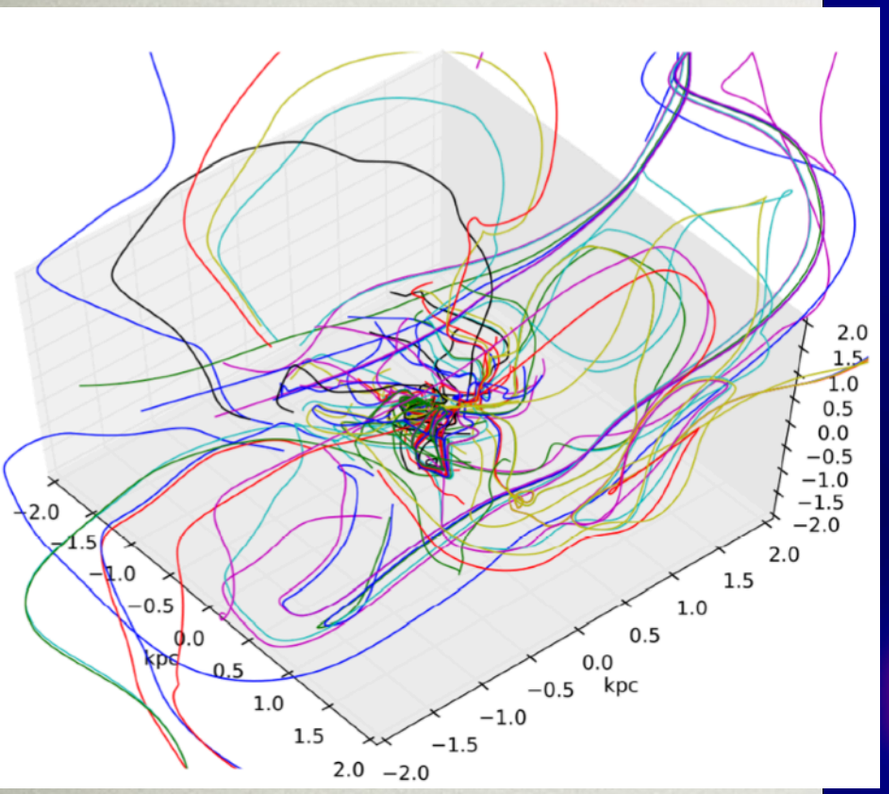
multiphase condensation cascade (“raining”)

CCA = CHAOTIC COLD ACCRETION

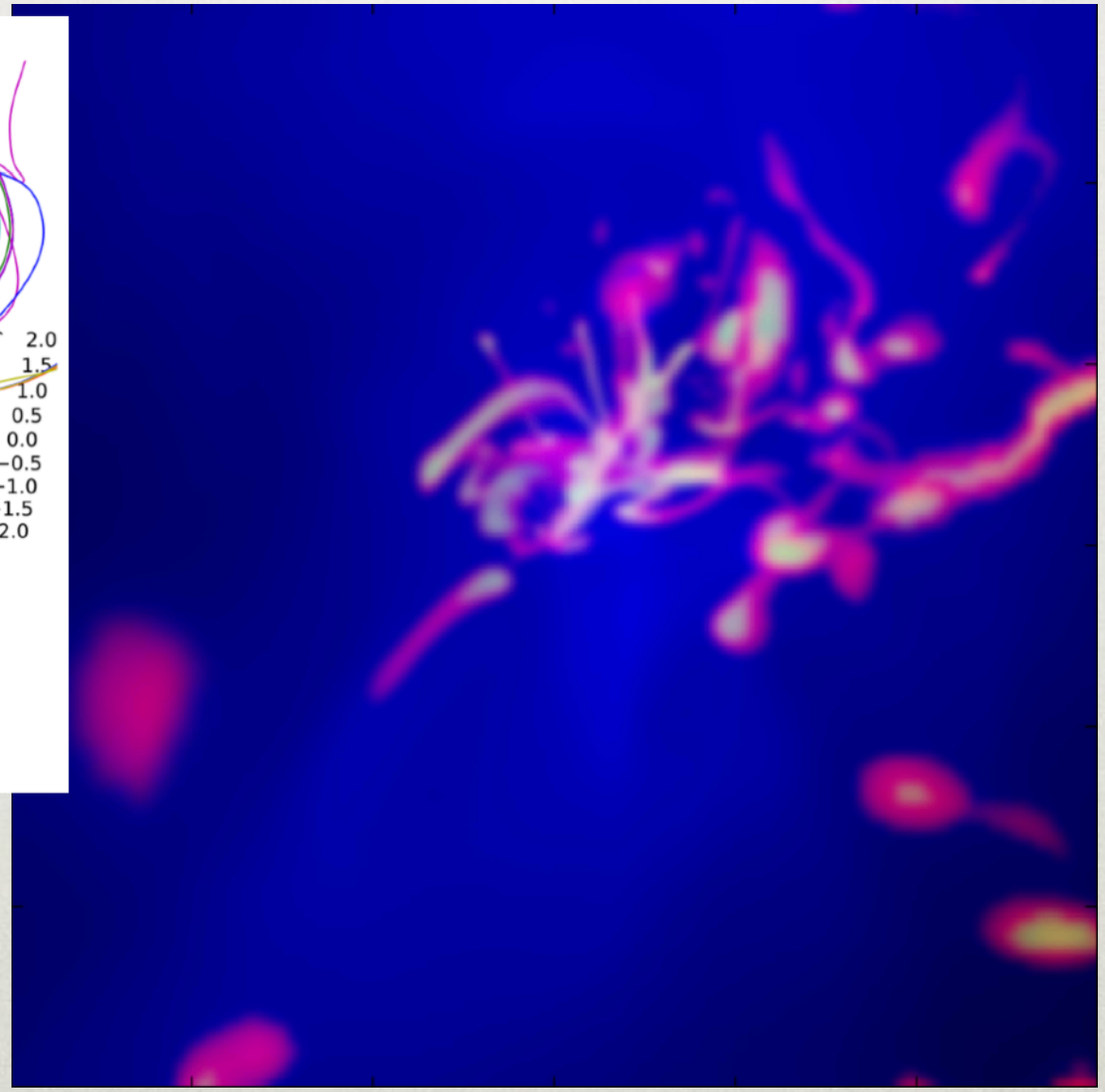
MG+2011-2019

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

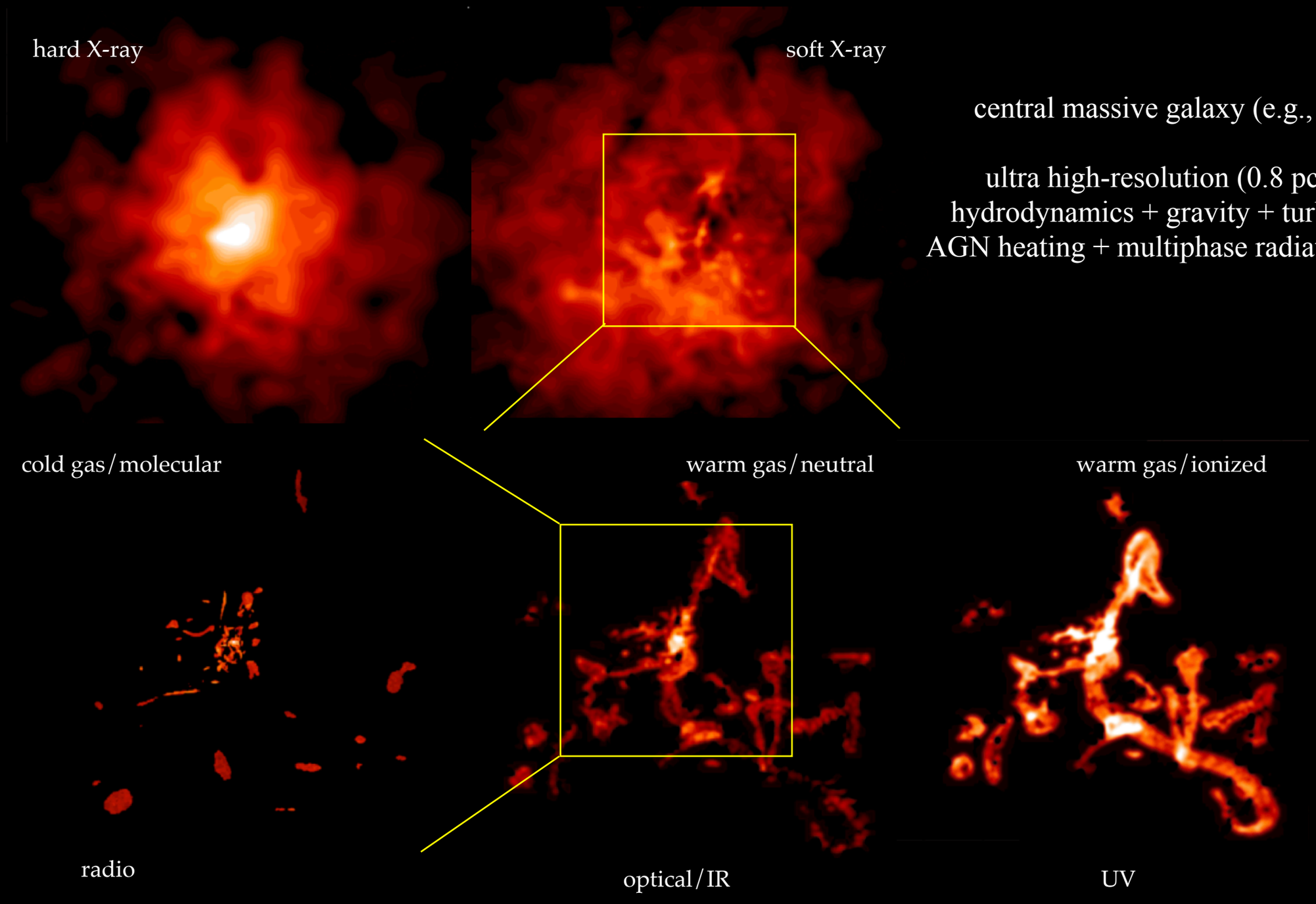
turbulence ~150 km/s, as found (a posteriori) by *Hitomi*

MG+17

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

Since 2013, 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

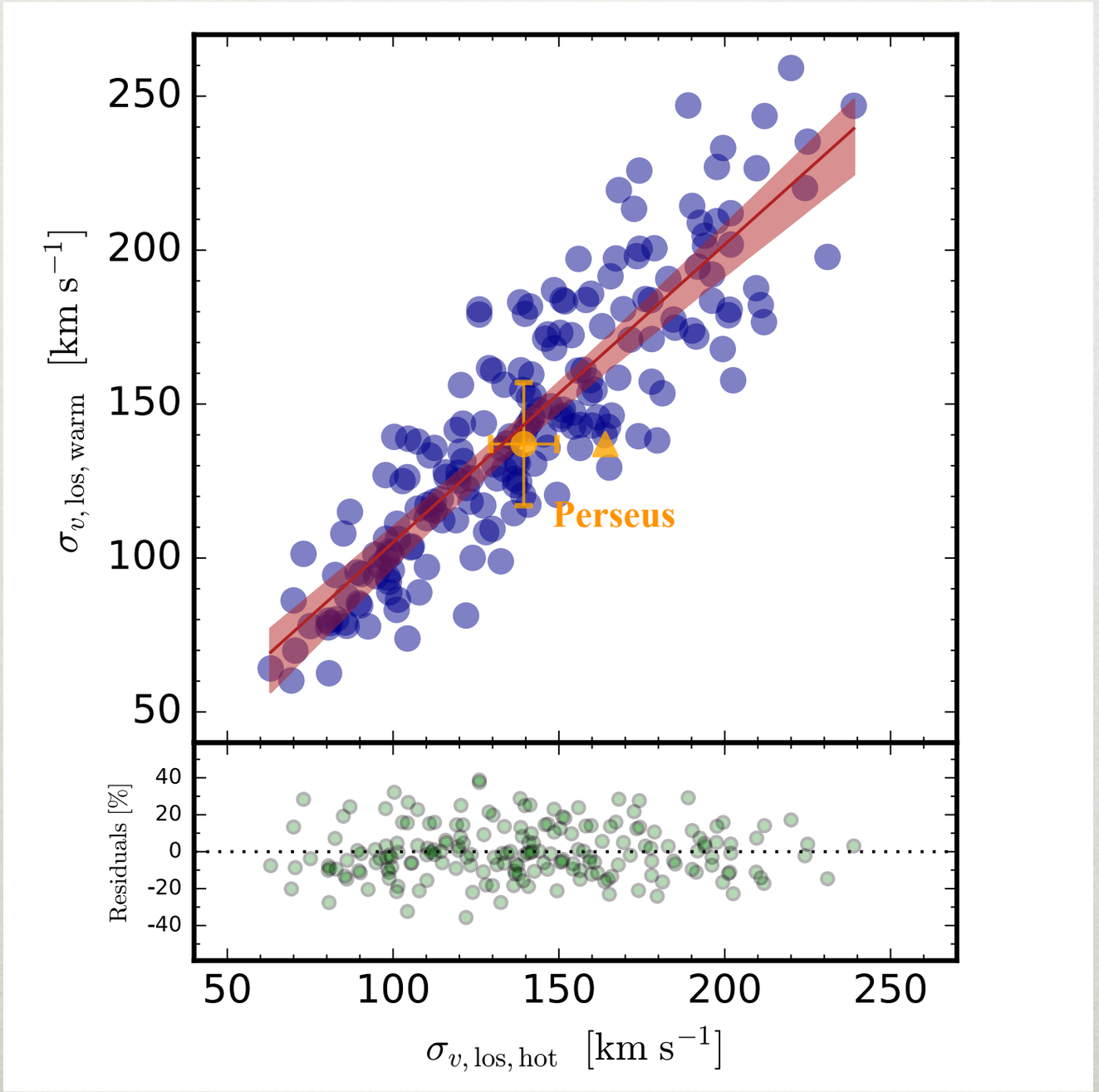
"shaken snow globes"

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

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

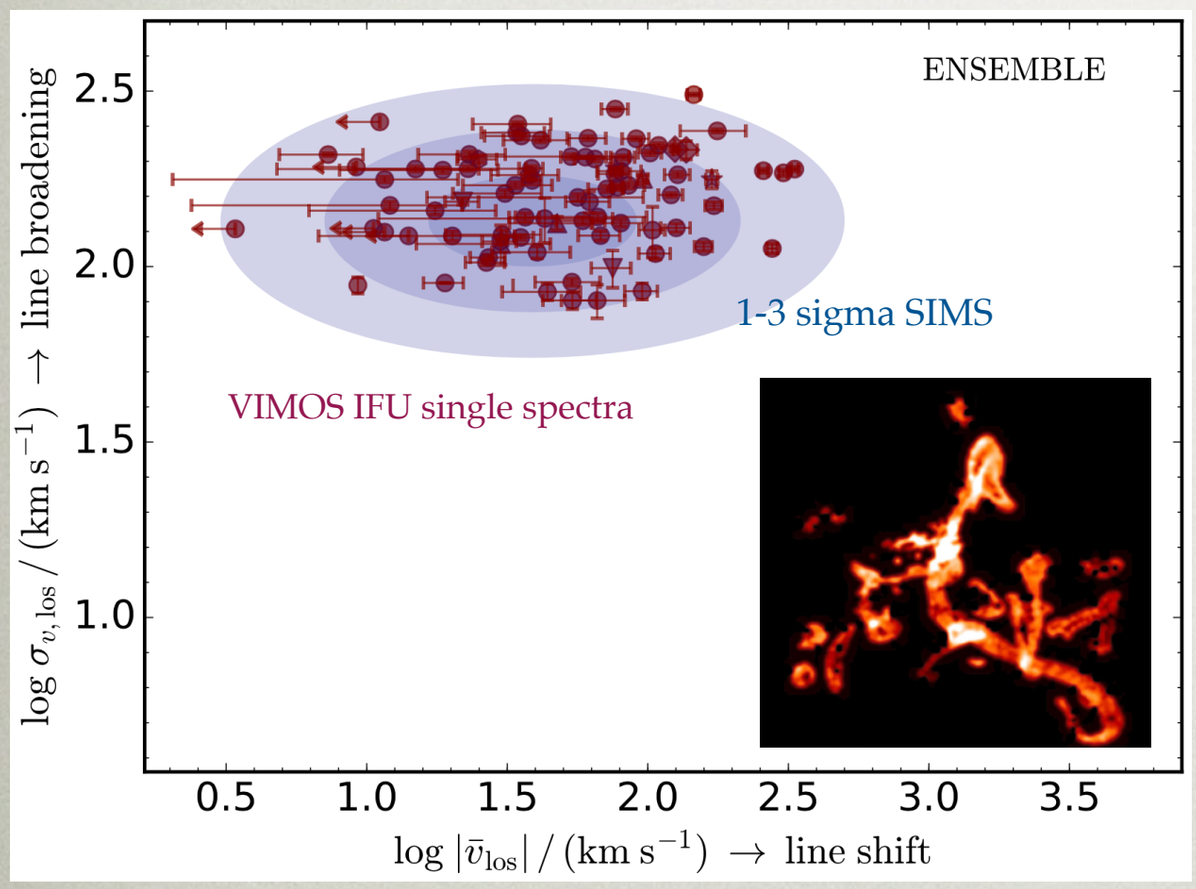
KINEMATIC TRACERS - RAIN/CCA

observational tests

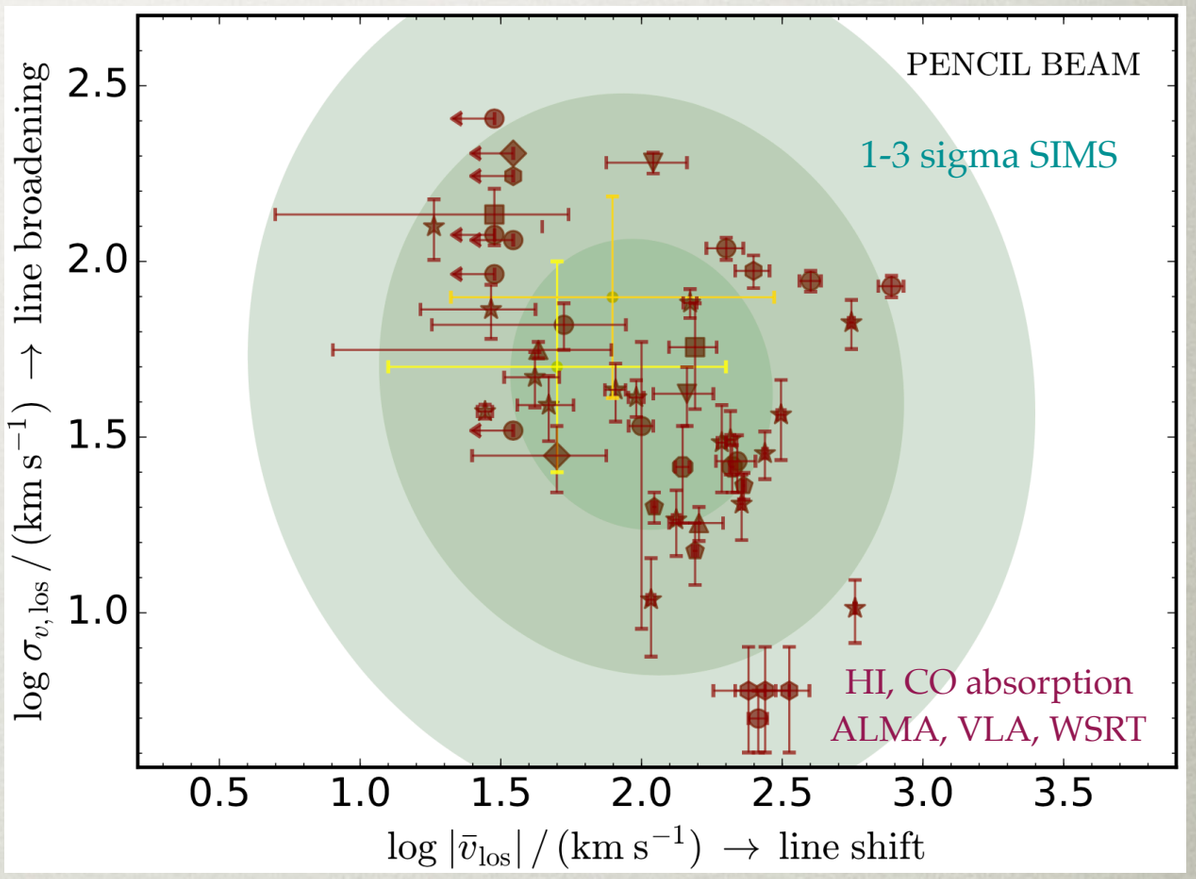
(massive galaxies in groups and clusters)

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

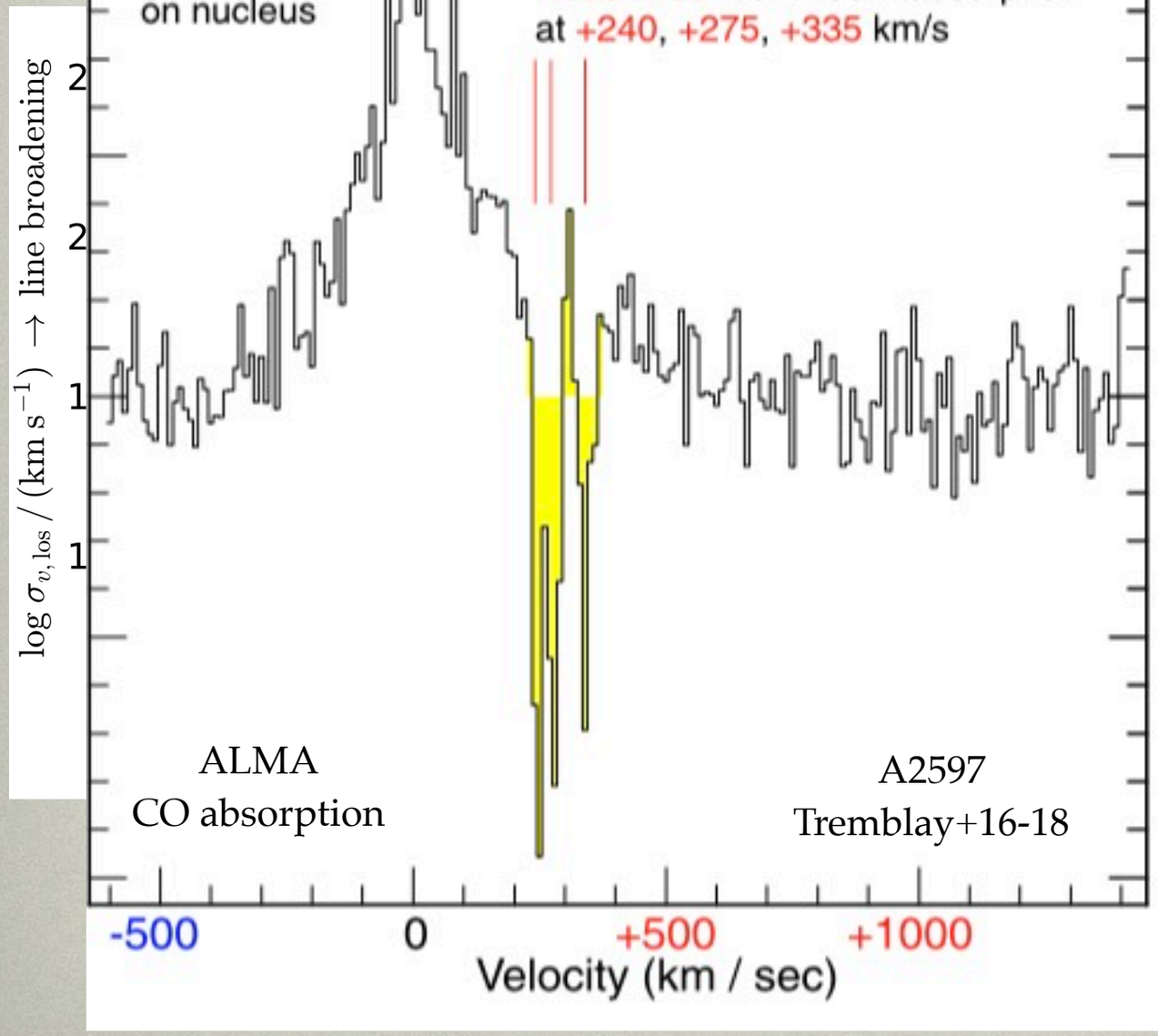
- r < 100 pc **funneling** of clouds with 100s km/s (recently probed by ALMA, e.g., N5044, A2597)

KINEMATIC TRACERS - RAIN/CCA

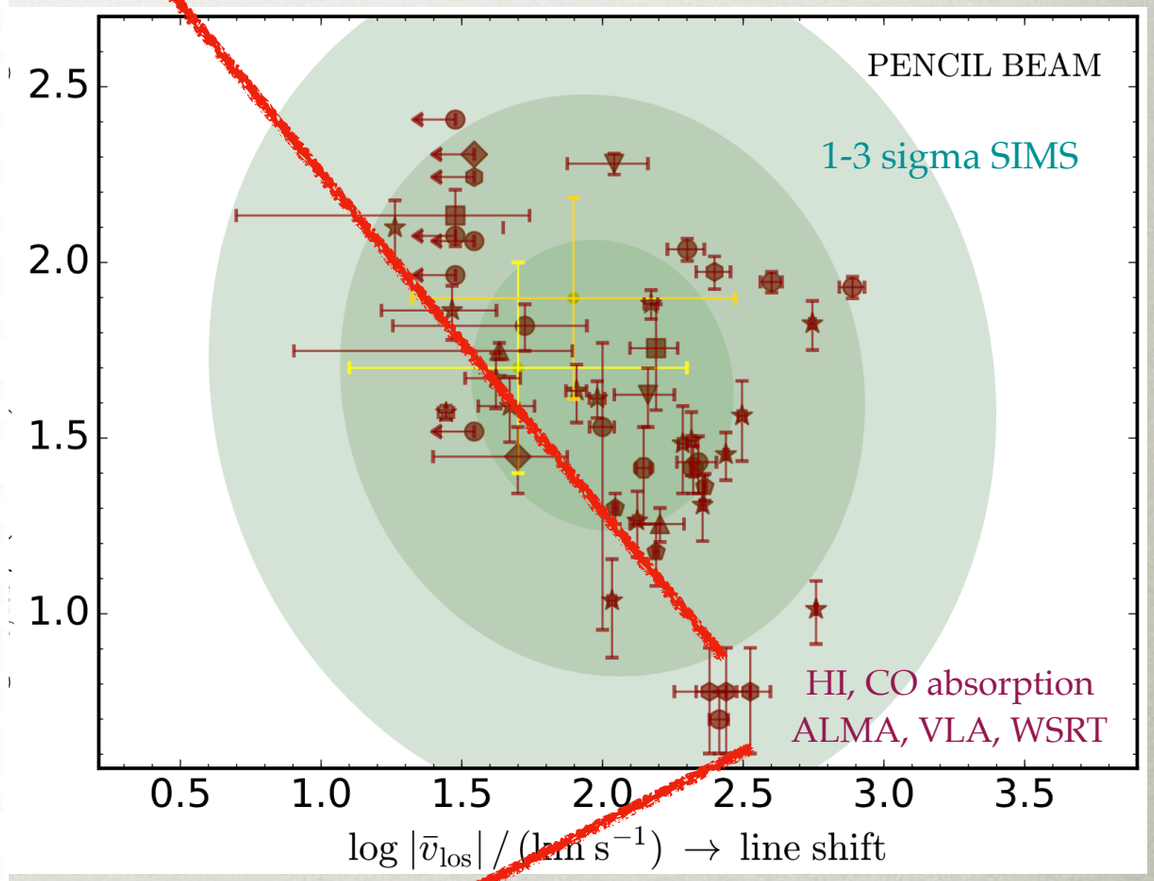
observational tests

(massive galaxies in groups and clusters)

MG+



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



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es) — contours: SIMS lognormal distributions

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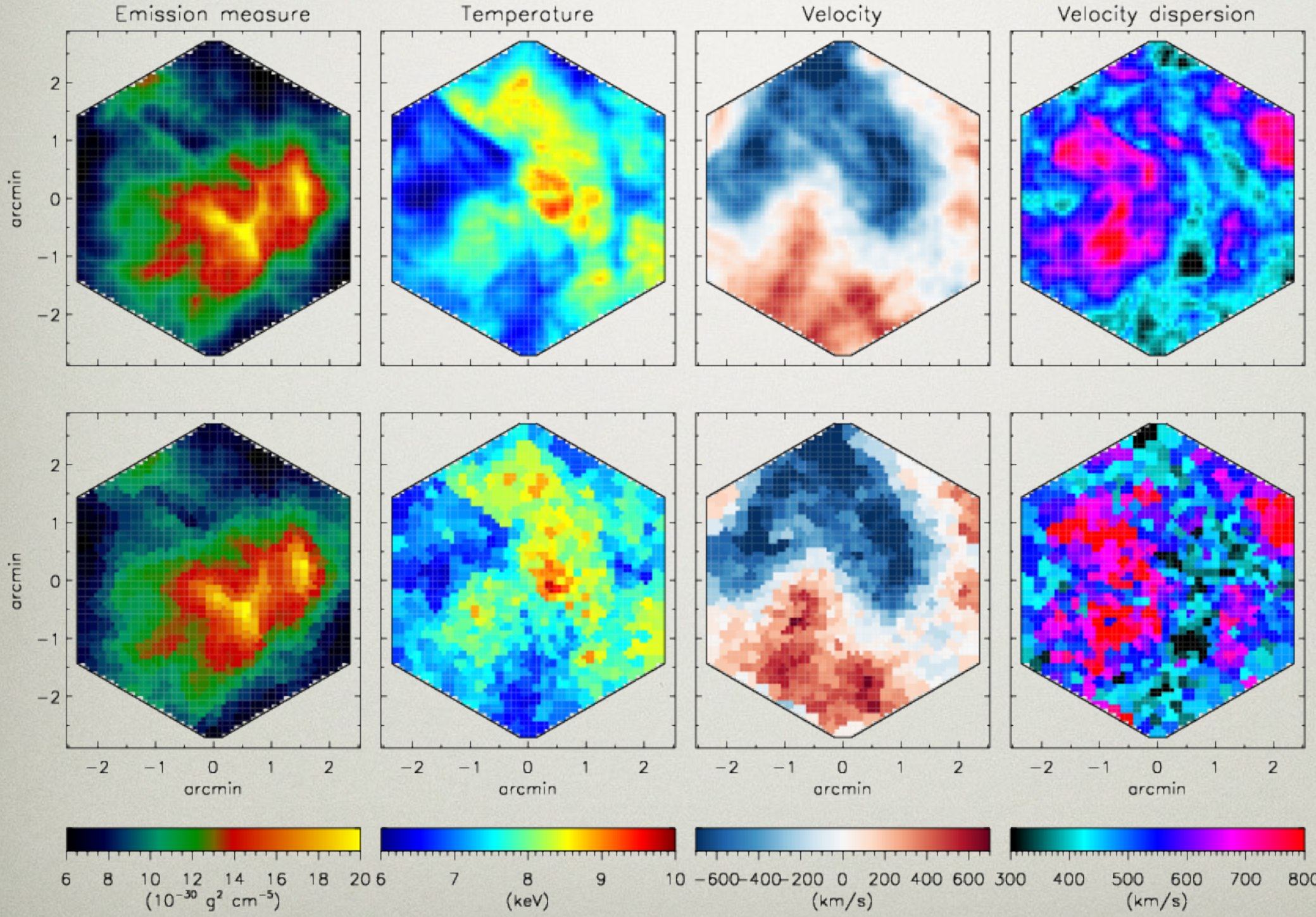
ATHENA X-IFU

SYNTHETIC OBSERVATIONS



"real"
(3D hydro sims)

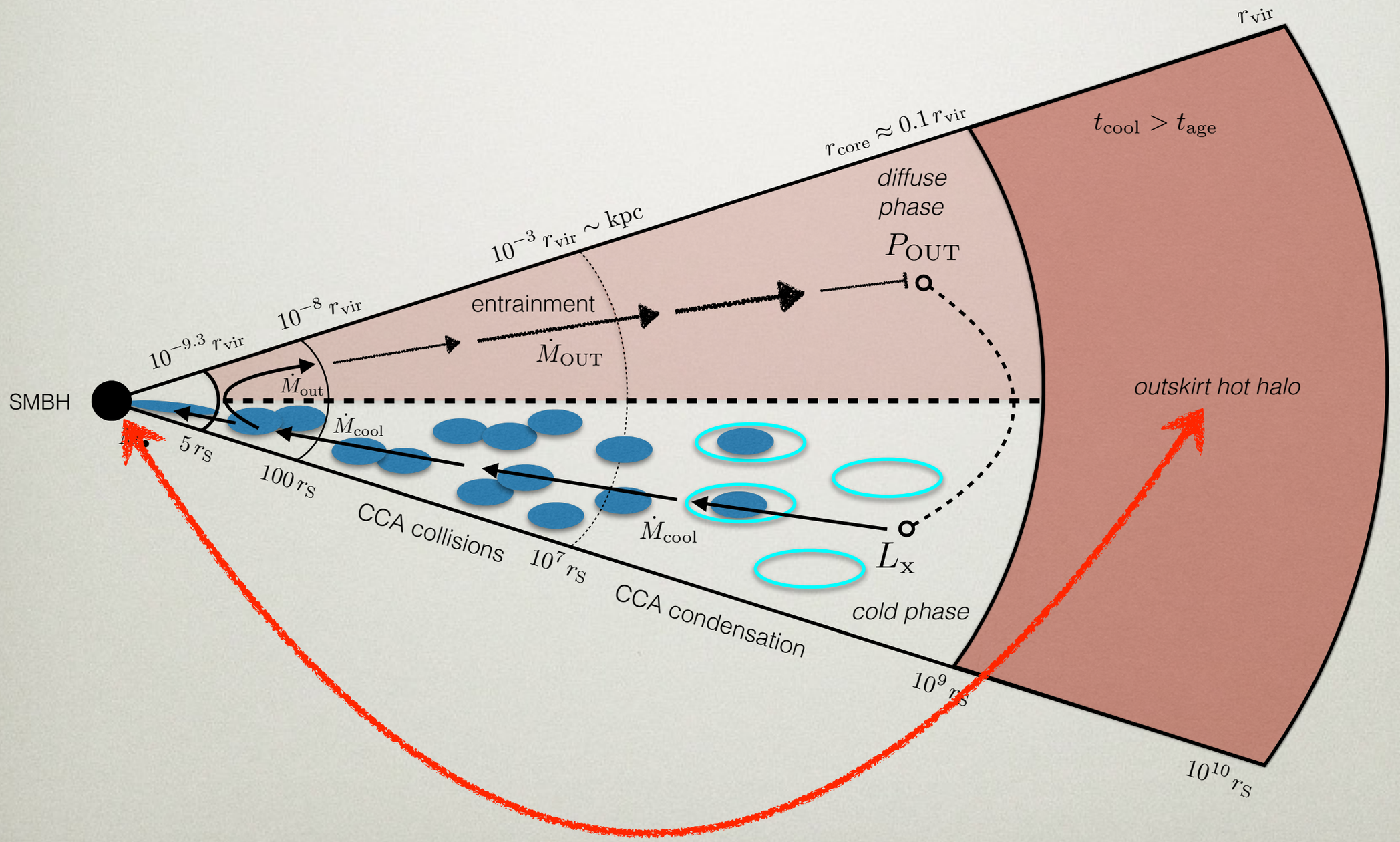
synthetic

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

Roncarelli, Gaspari, Ettori, et al., 2018

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

“BLACK HOLE WEATHER” PROGRAM

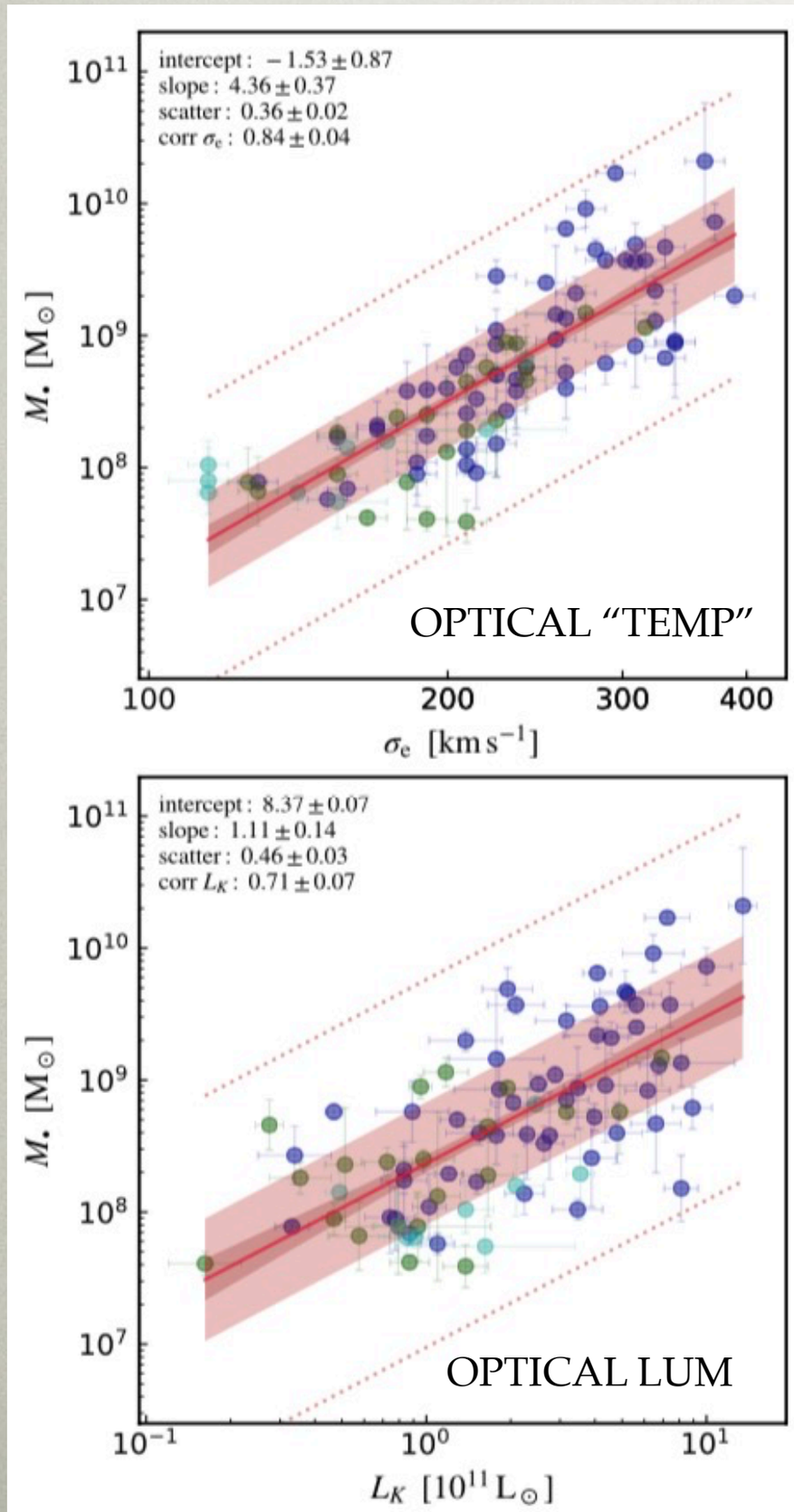


5. self-regulation

Gaspari et al. 2019

X-RAY HALO SCALING RELATIONS OF SMBHs

Gaspari et al. 2019

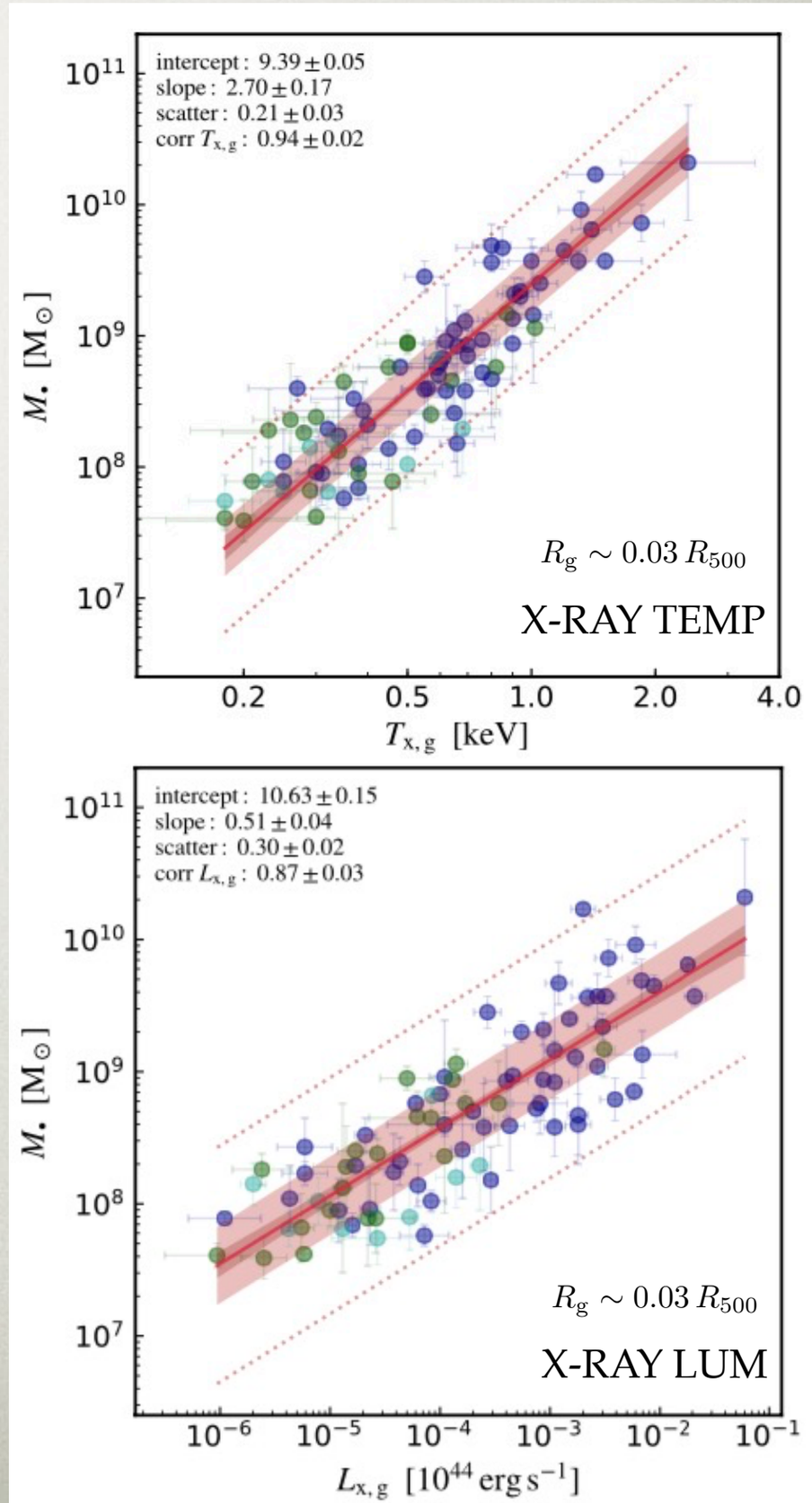


Bayesian analysis:
85 galaxies,
groups, clusters

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

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

X-ray scalings lower scatter and larger correlation



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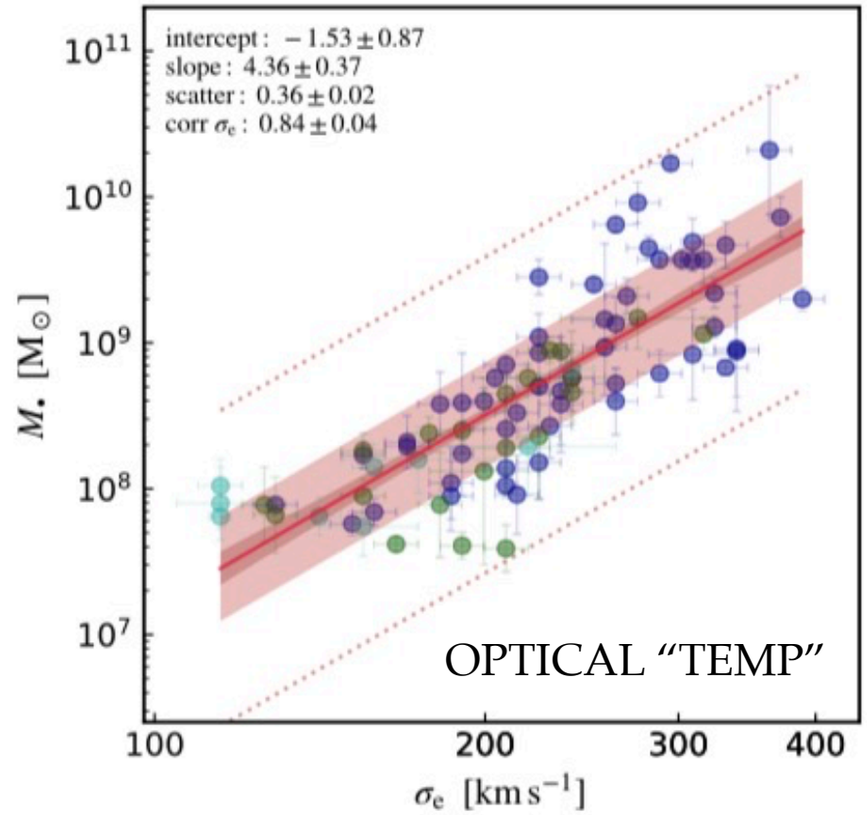
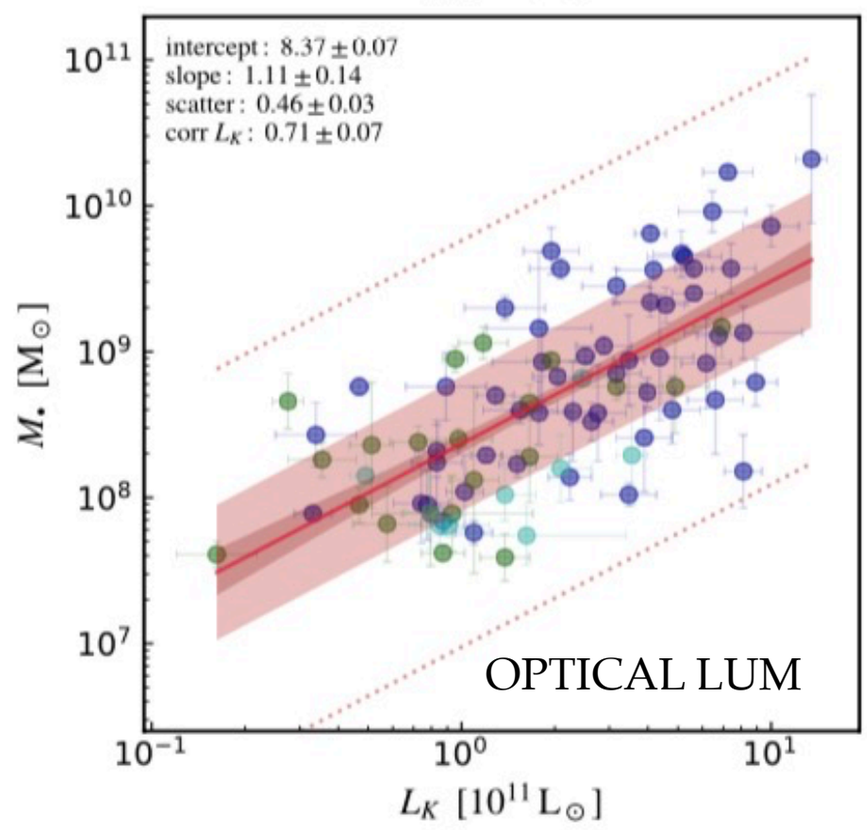
Gaspari et al. 2019





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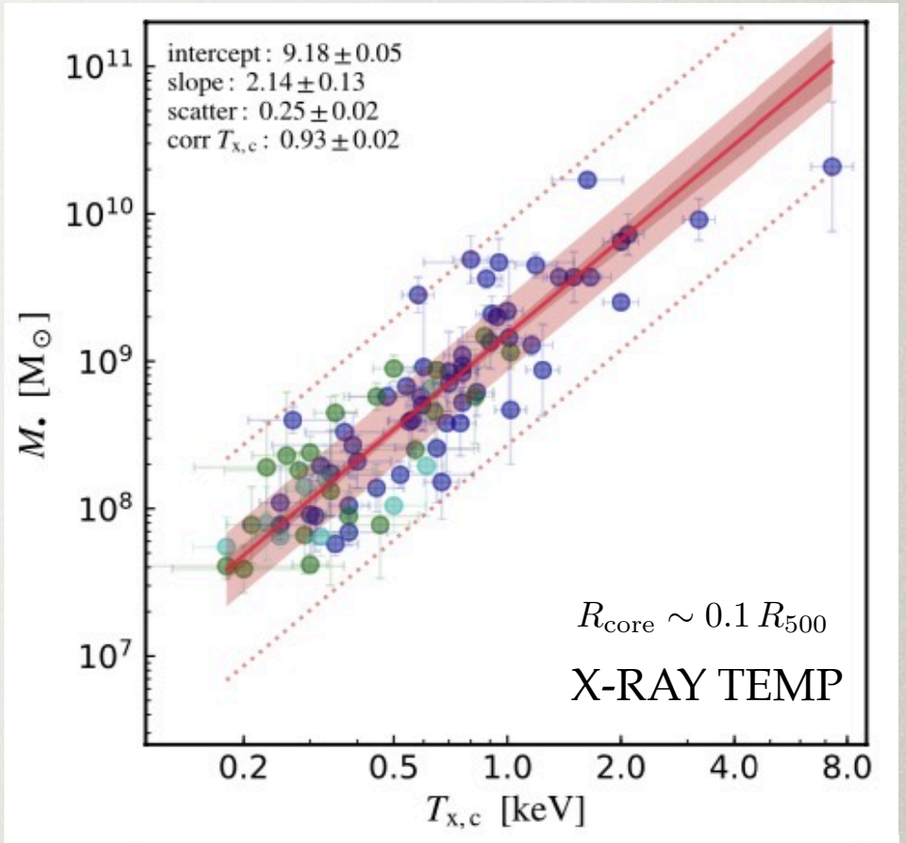
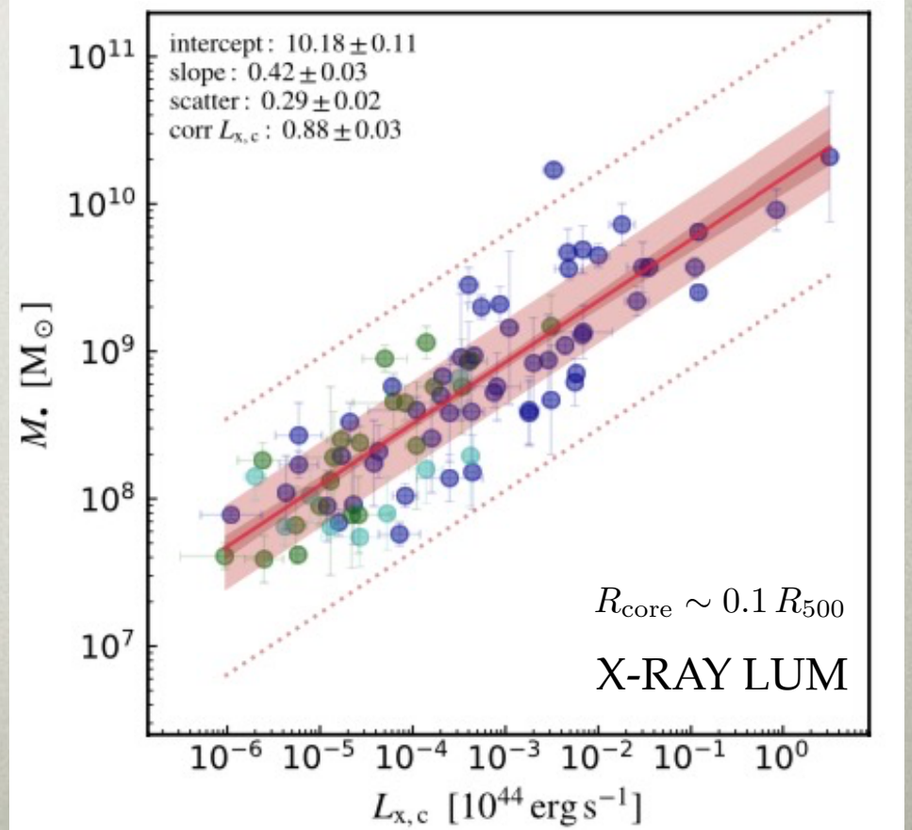
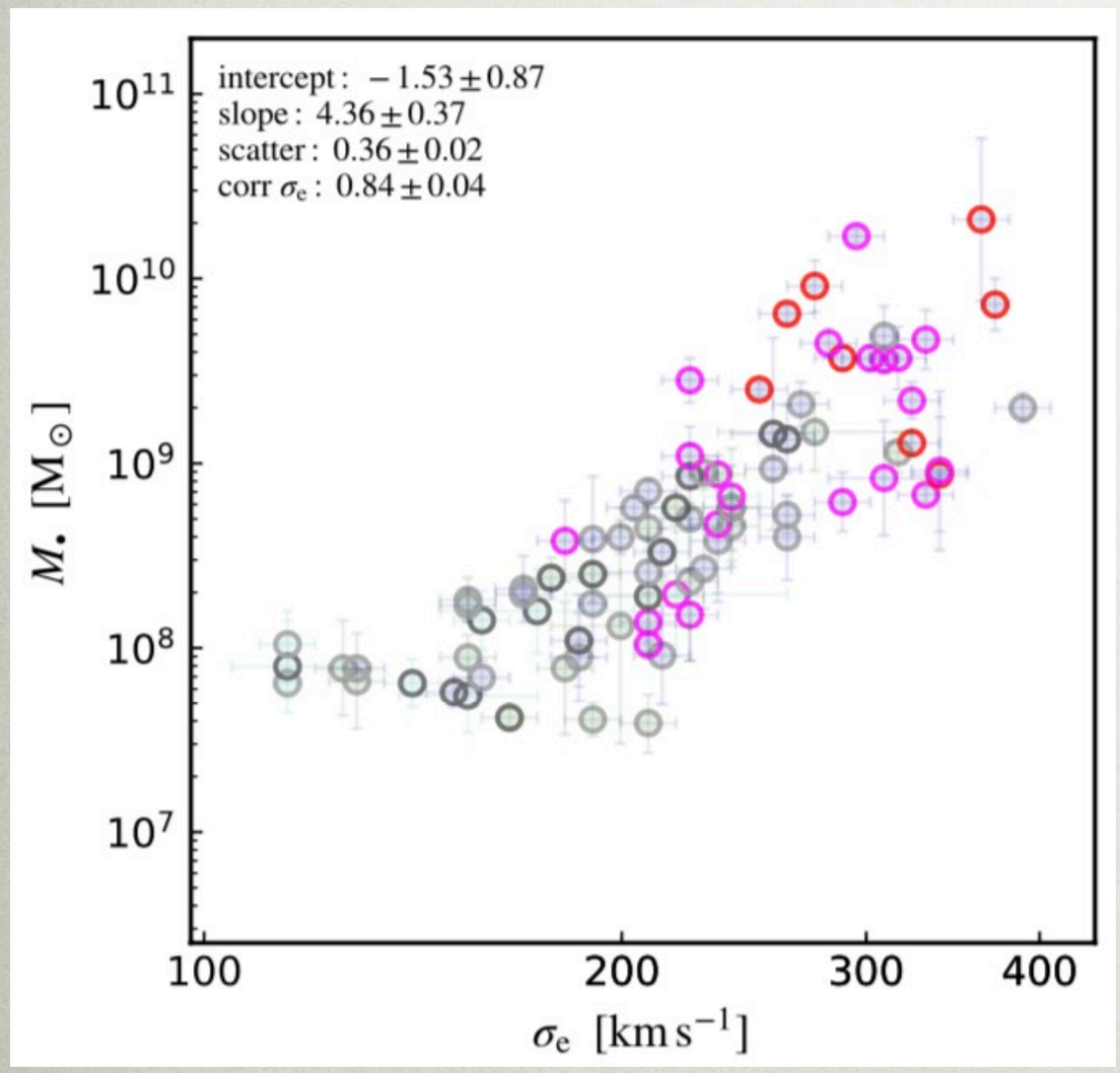
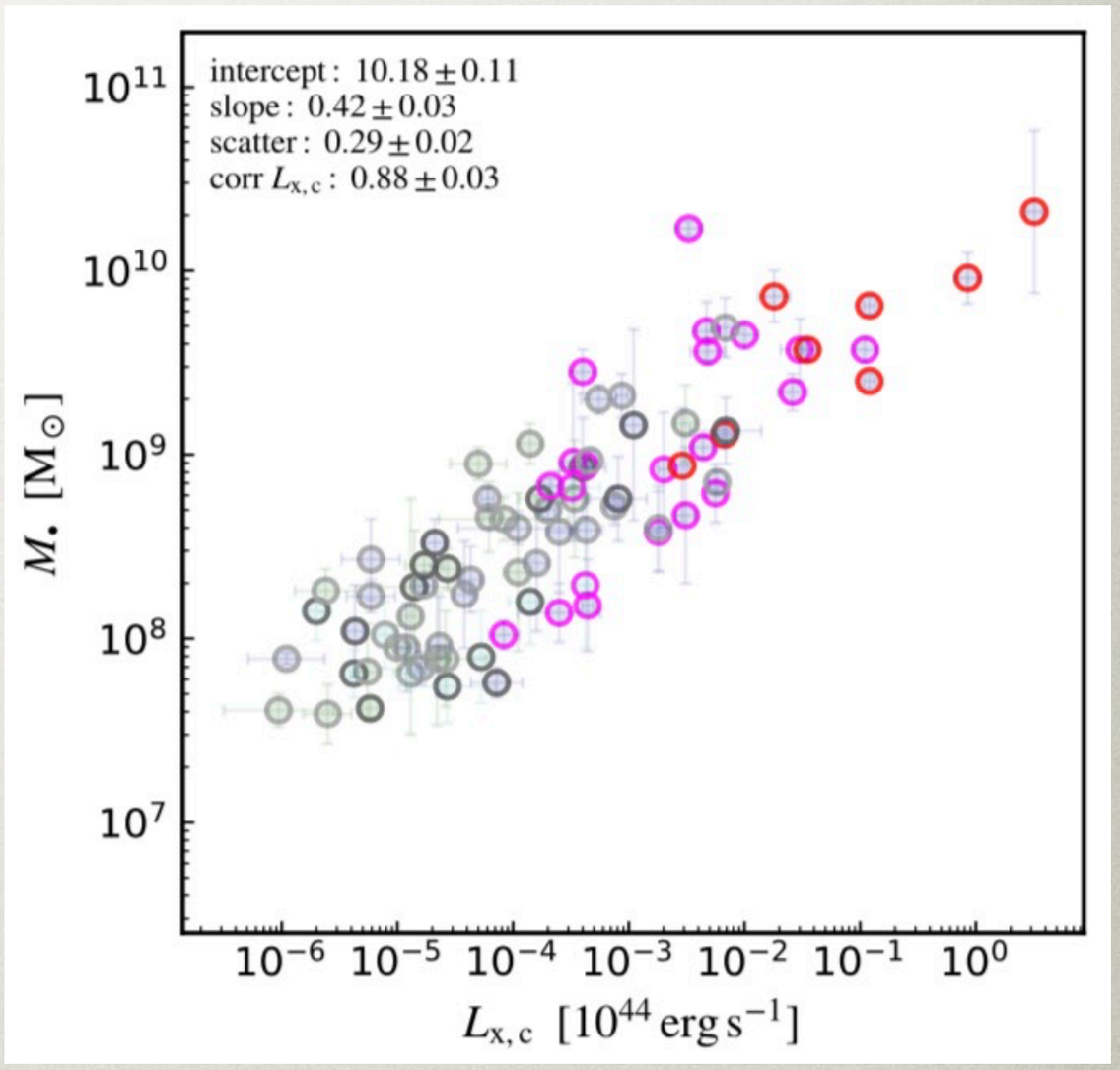




X-RAY HALO SCALING RELATIONS OF SMBHs

Gaspari et al. 2019





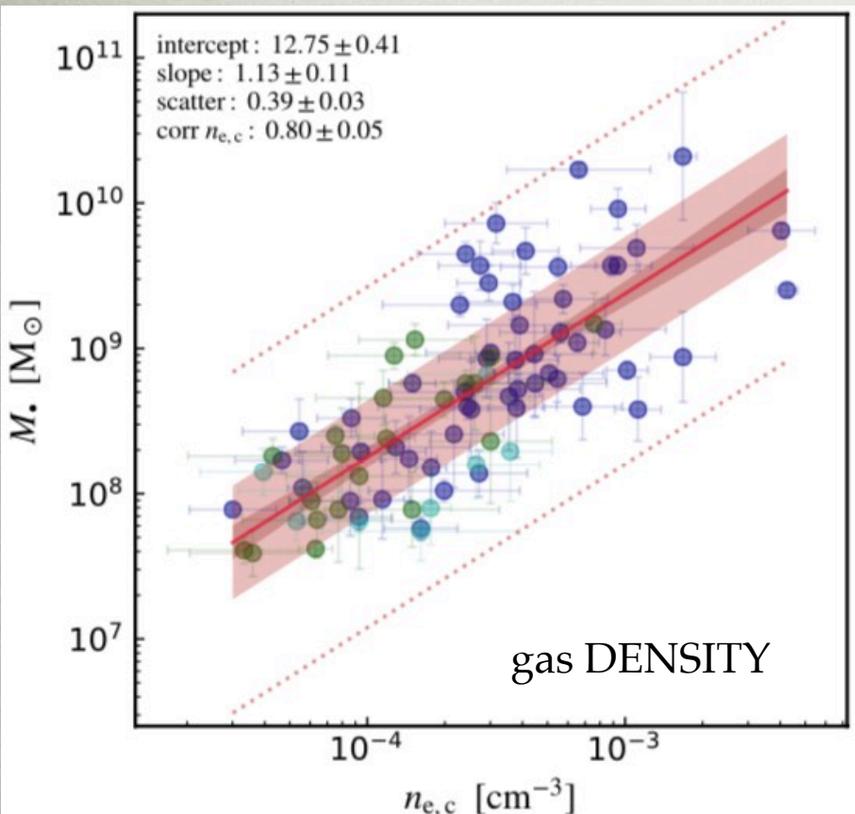
red: BCGs
magenta: BGGs
grey: isolated / field / satellites

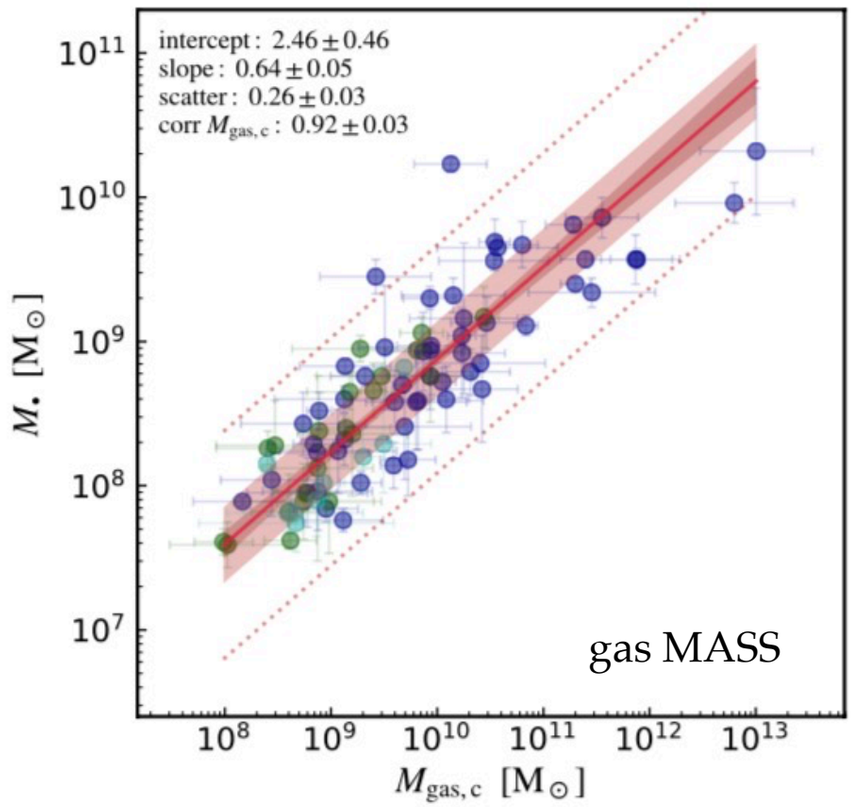
X-RAY HALO SCALING RELATIONS OF SMBHs

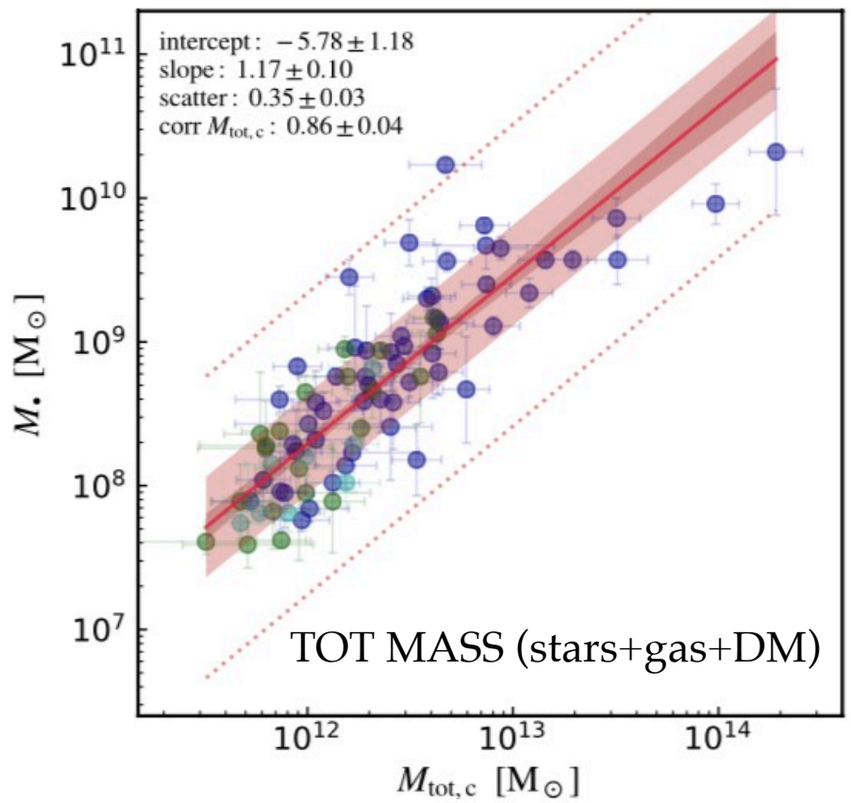
(indirect properties)

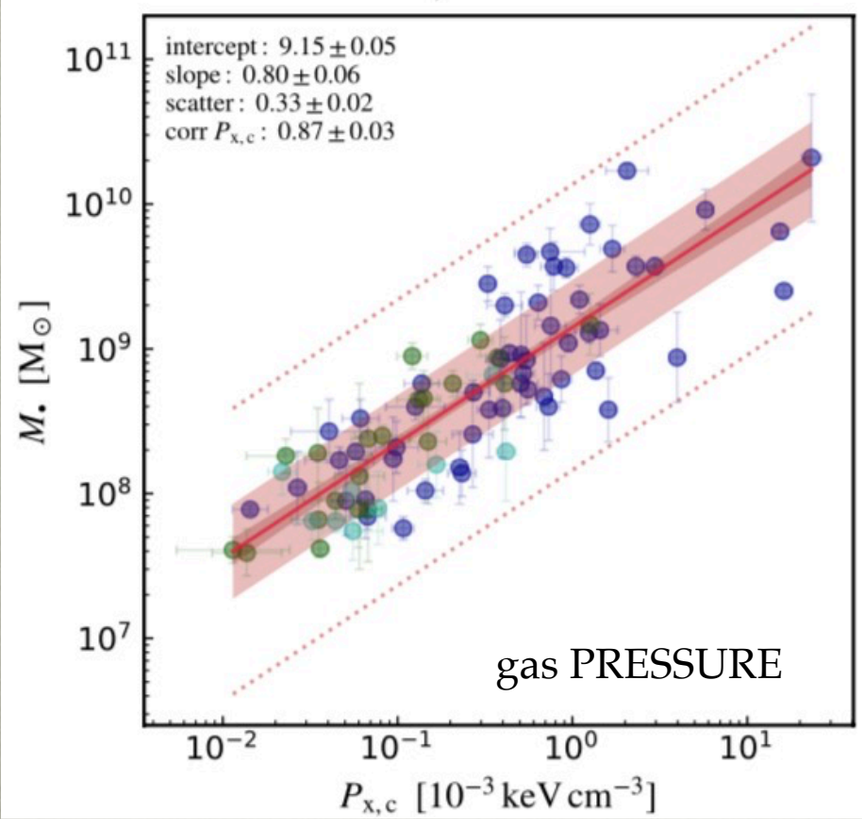
Gaspari et al. 2019

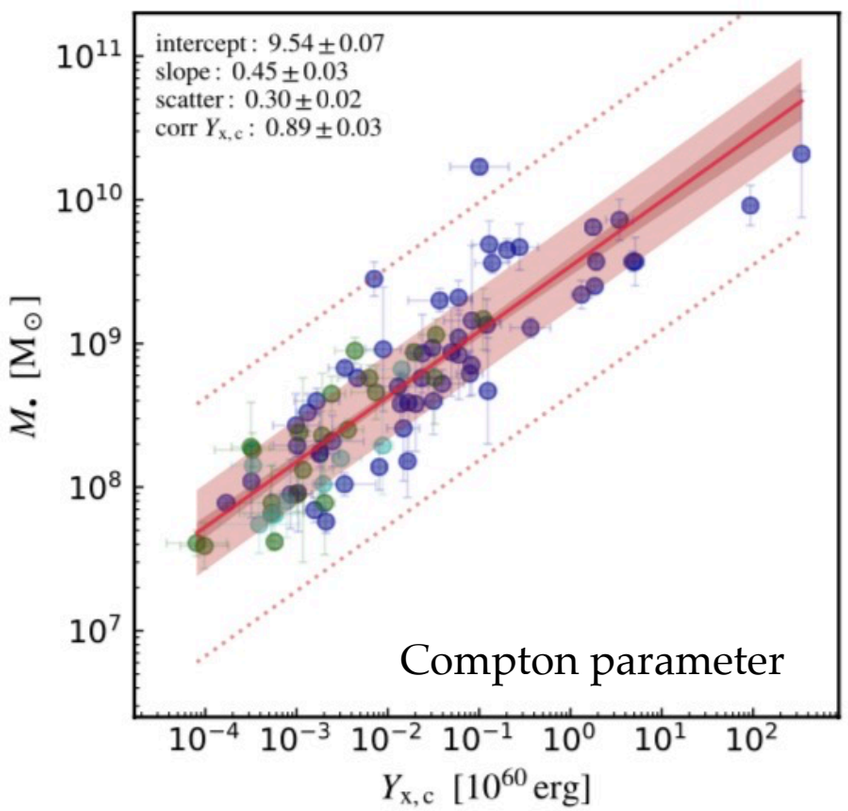
all within core region

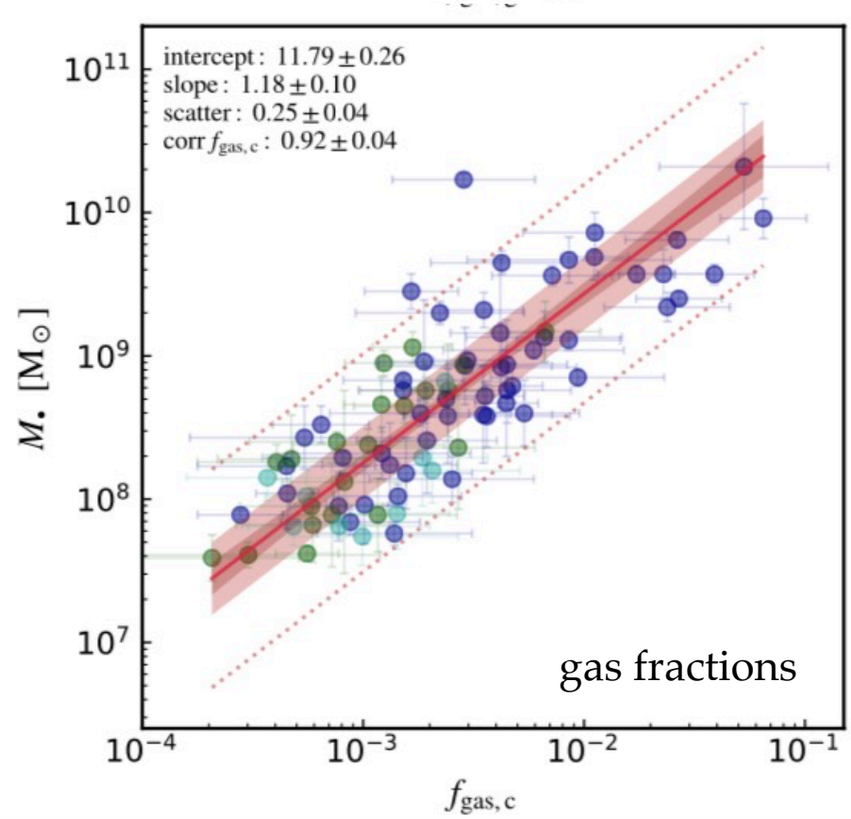












AGN FEEDBACK CYCLE

(> KPC)

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

↓

nonlinear condensation

↓

CCA rain

↓

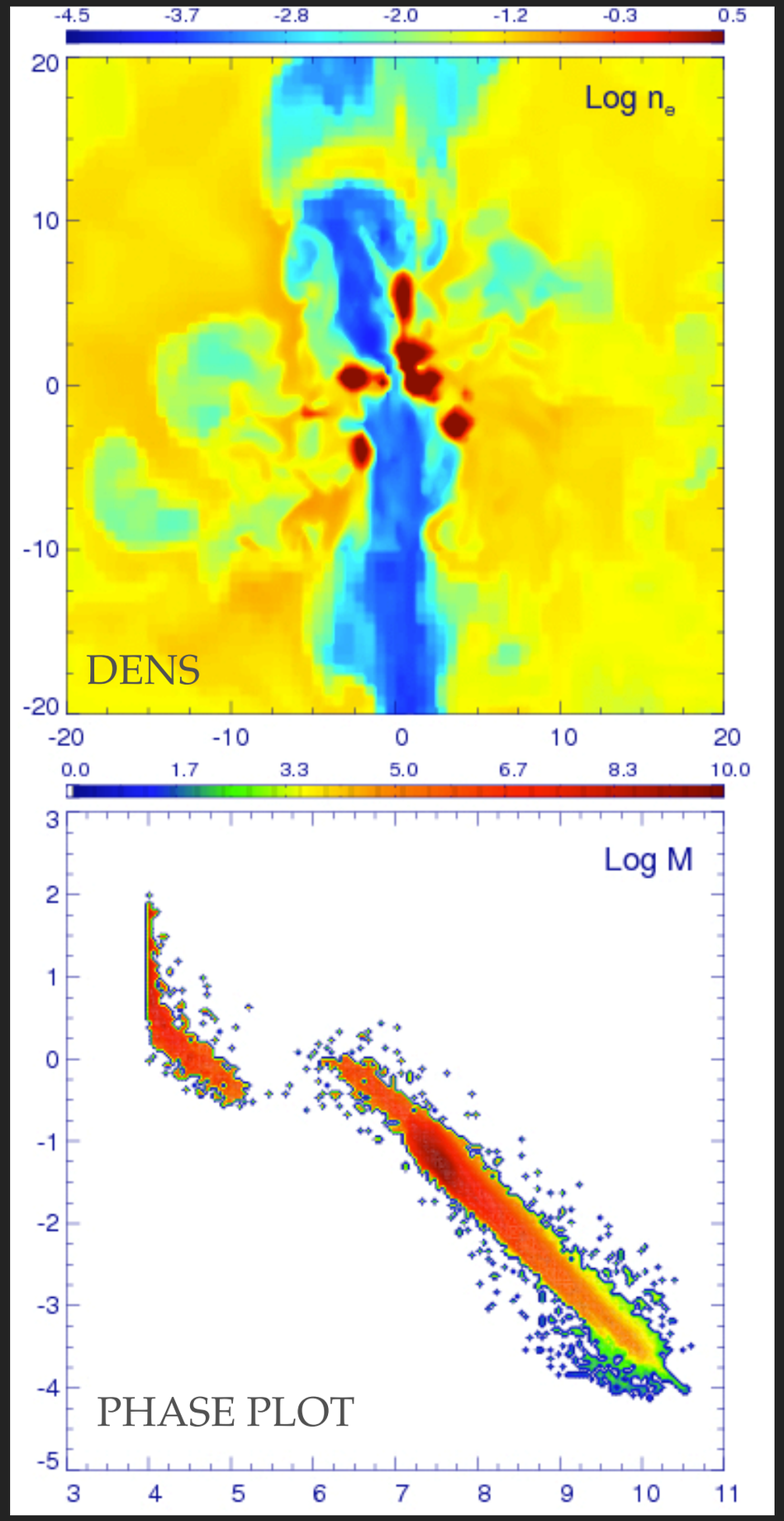
feed SMBH

↓

feedback boosted

↓

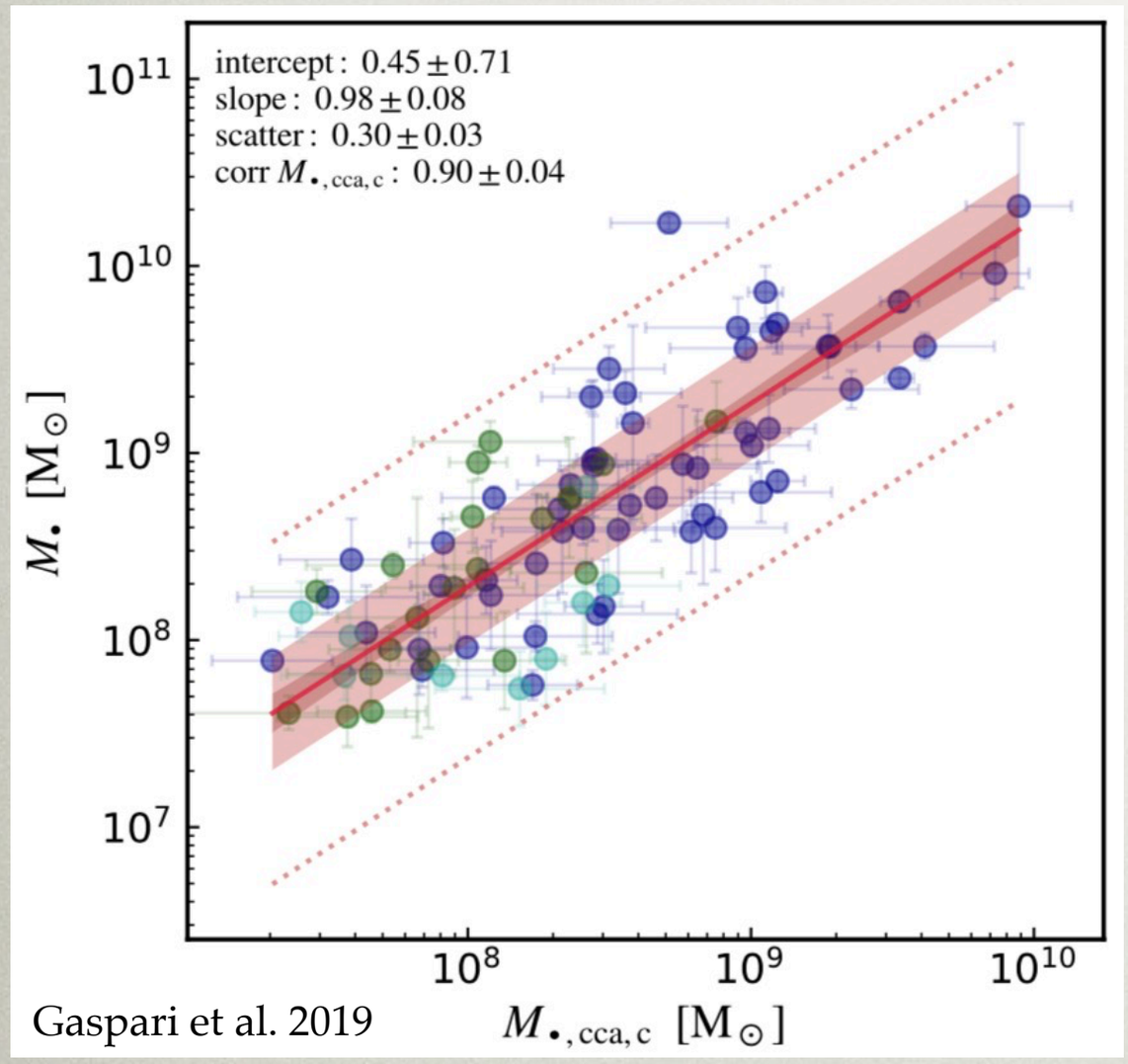
$\mathcal{L} < \mathcal{H}$



MG+2012

X-RAY HALO SCALING RELATIONS OF SMBHs (MODELS)

CCA(gas)-driven BH growth vs. merger-driven BH growth

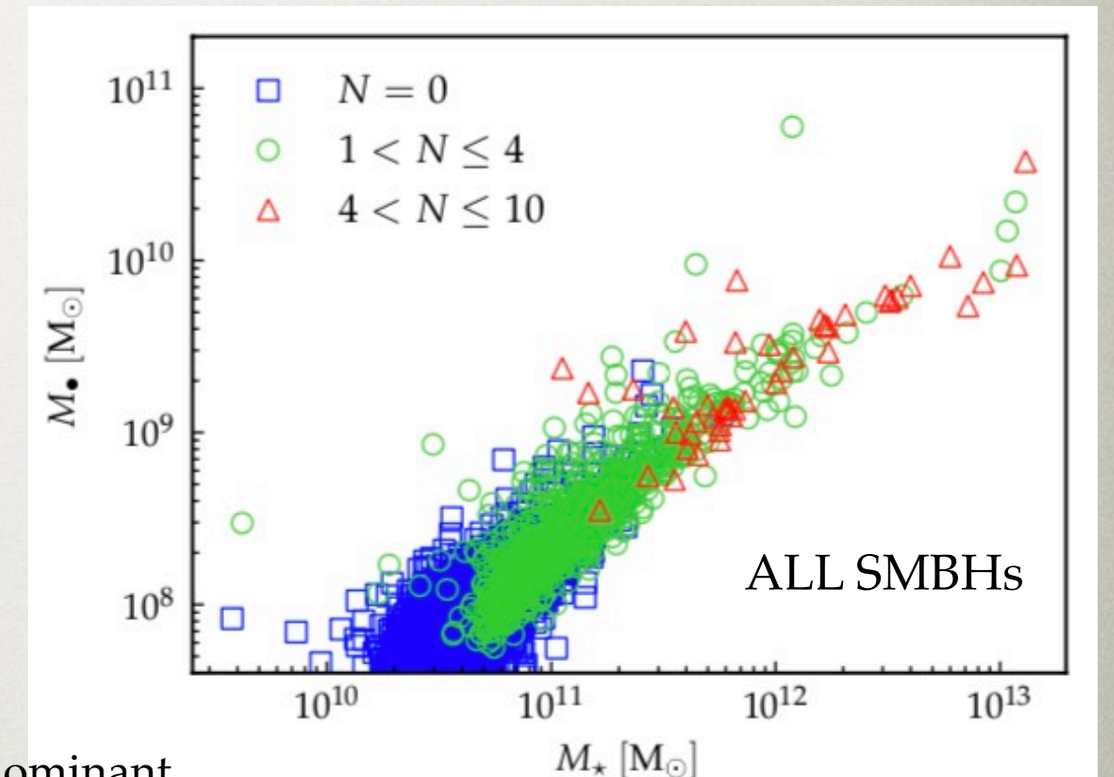


Gaspari et al. 2019

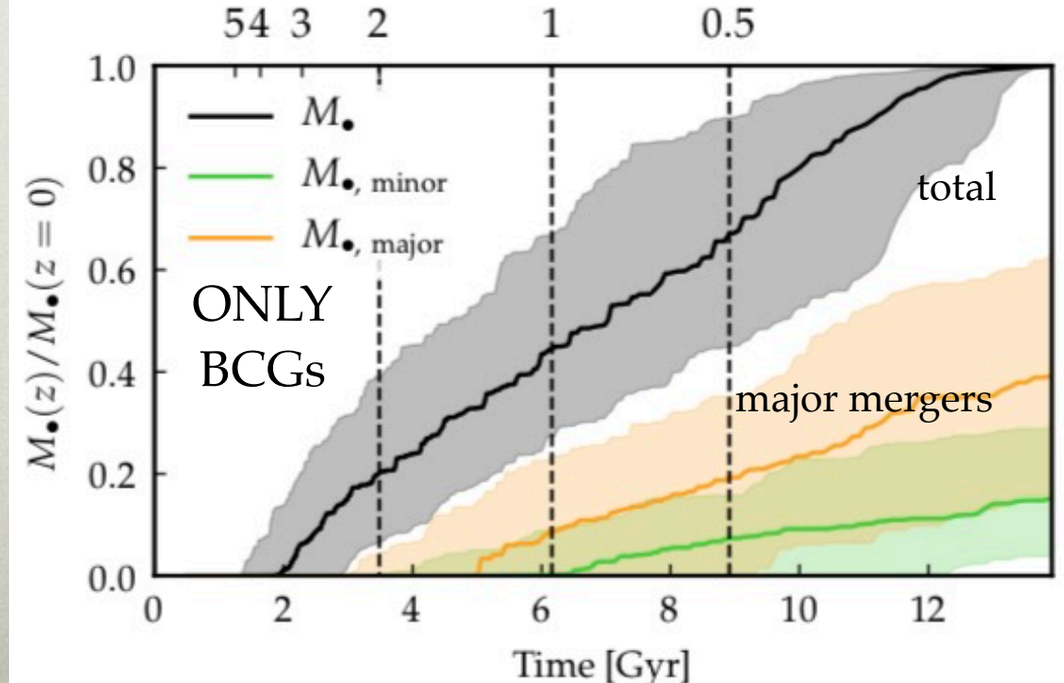
predicts well the observed BH mass

$$M_{\bullet,\mathrm{cca}}(t_\mathrm{H}) \simeq \left[\dot{M}_{\mathrm{cool,now}}\, t_\mathrm{H} \ln(t_\mathrm{H}/t_0)\right] \frac{\nu_\mathrm{cca}}{\tilde{\nu}_\mathrm{cca}}$$

low N mergers + steady scatter also rule out non-causal models (CLT)



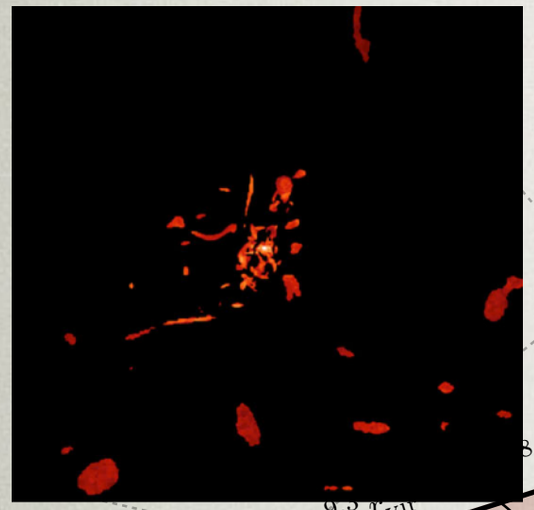
sub-dominant growth channel

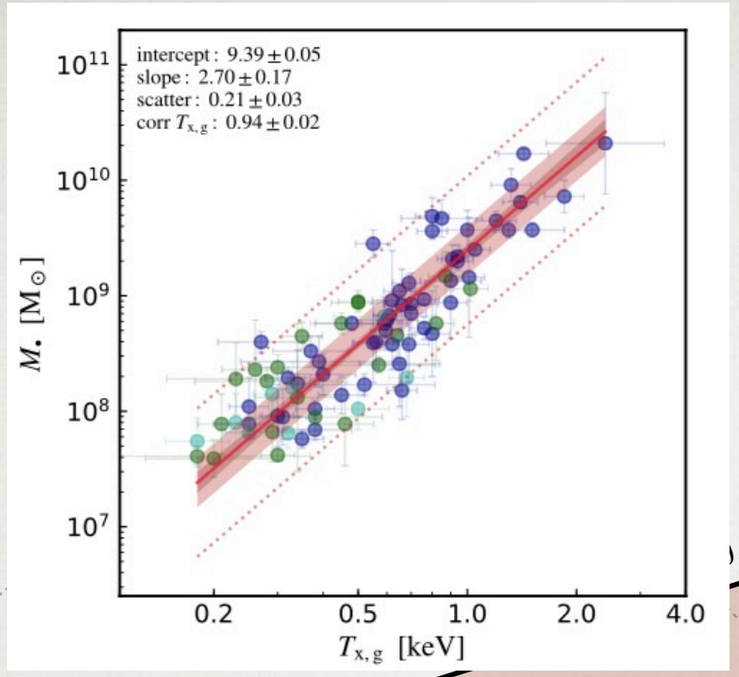


"Black Hole Weather"
discussed results

Gaspari+2017

CCA



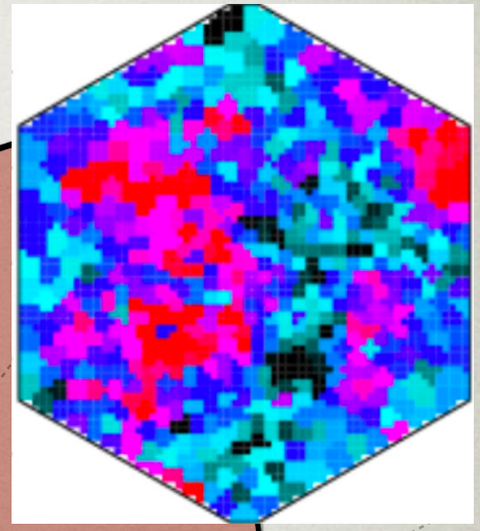


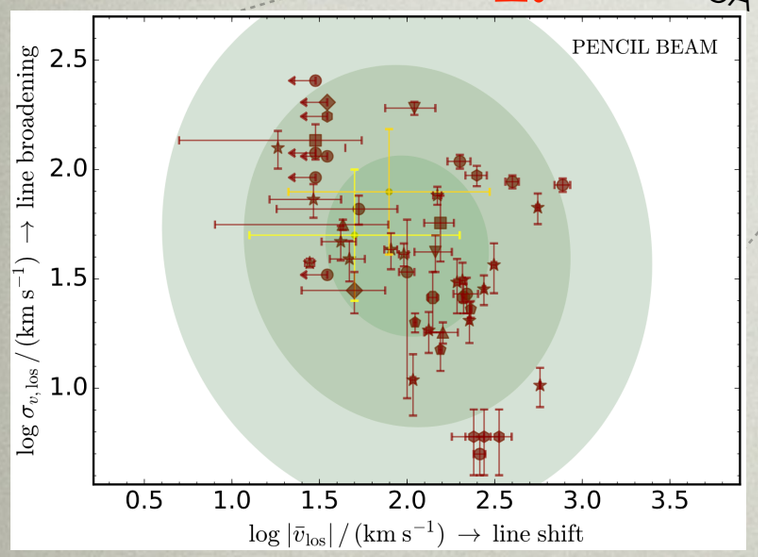
tight X-ray halo scalings of SMBHs

Gaspari+2019

Roncarelli, Gaspari, Ettori+2018

merger-driven turbulence (*Athena*)

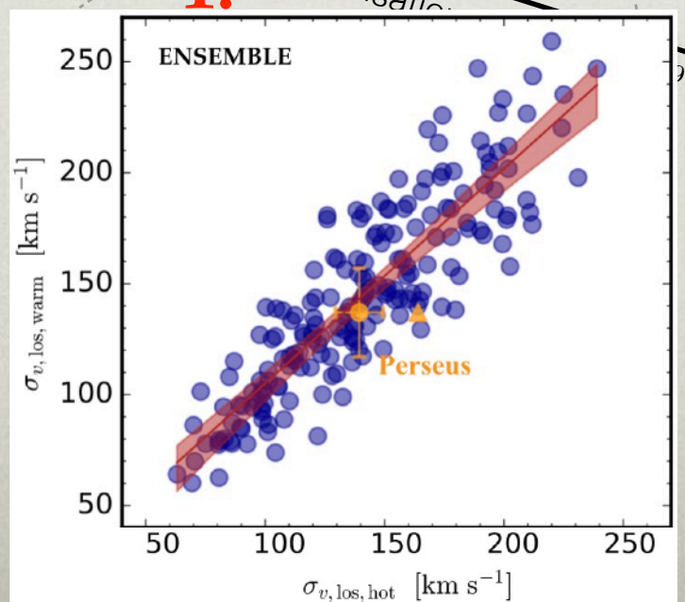


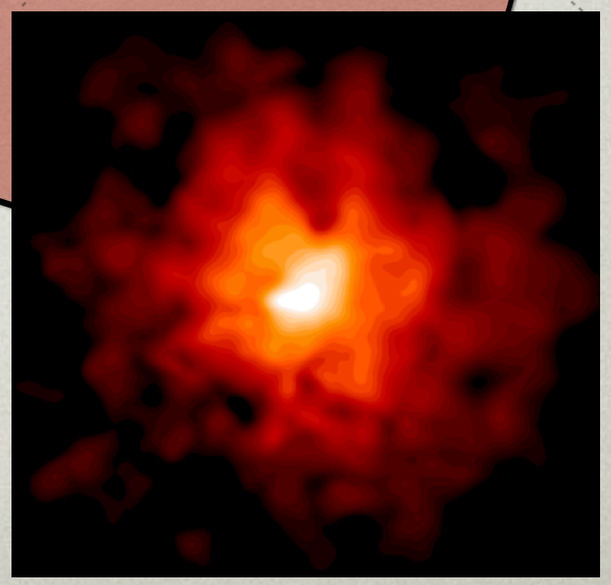


molecular clouds feeding *BH shadows*

Gaspari+2018

warm filaments/hot gas correlations





turbulent hot halos

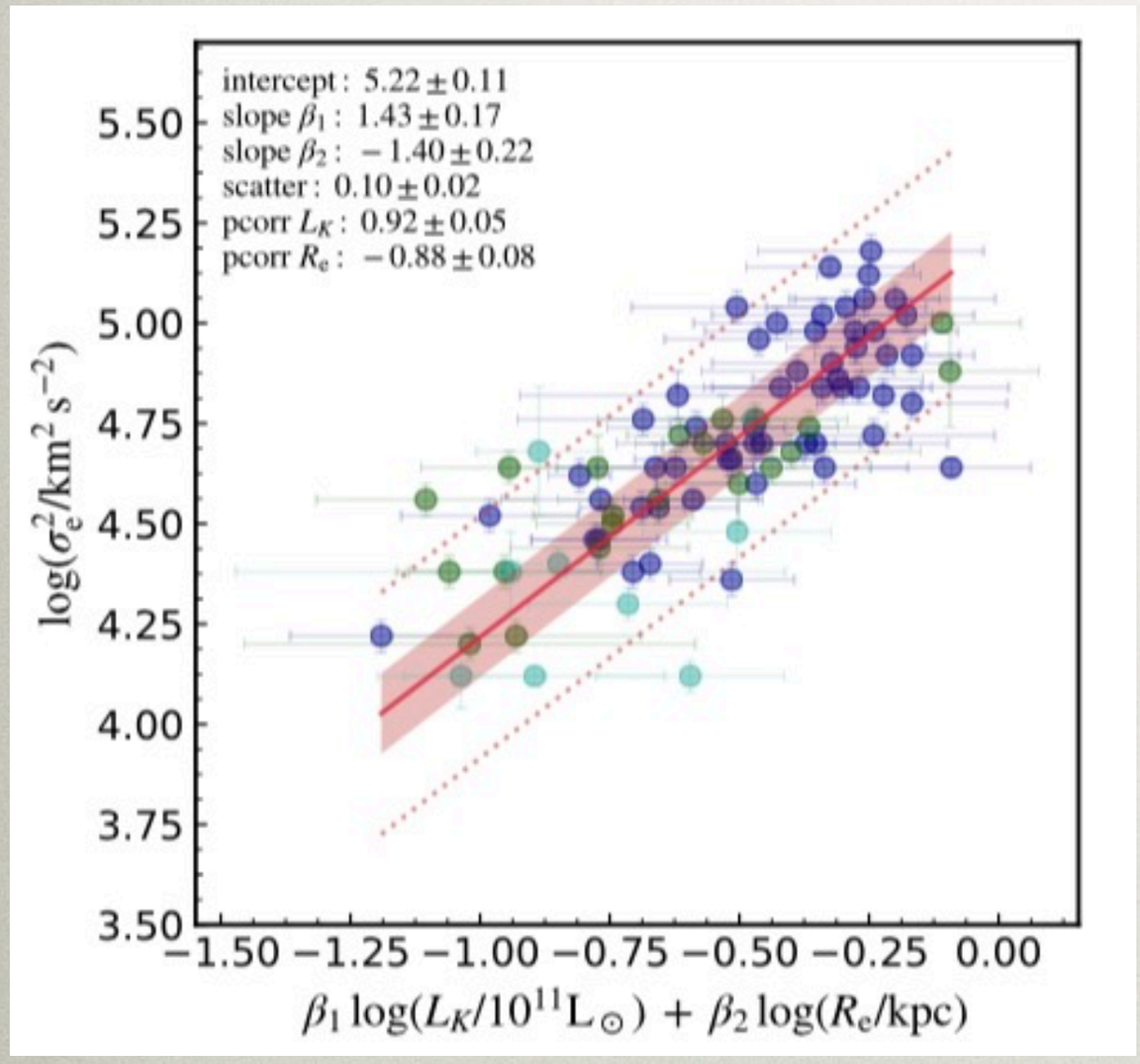
Gaspari+2017

EXTRAS

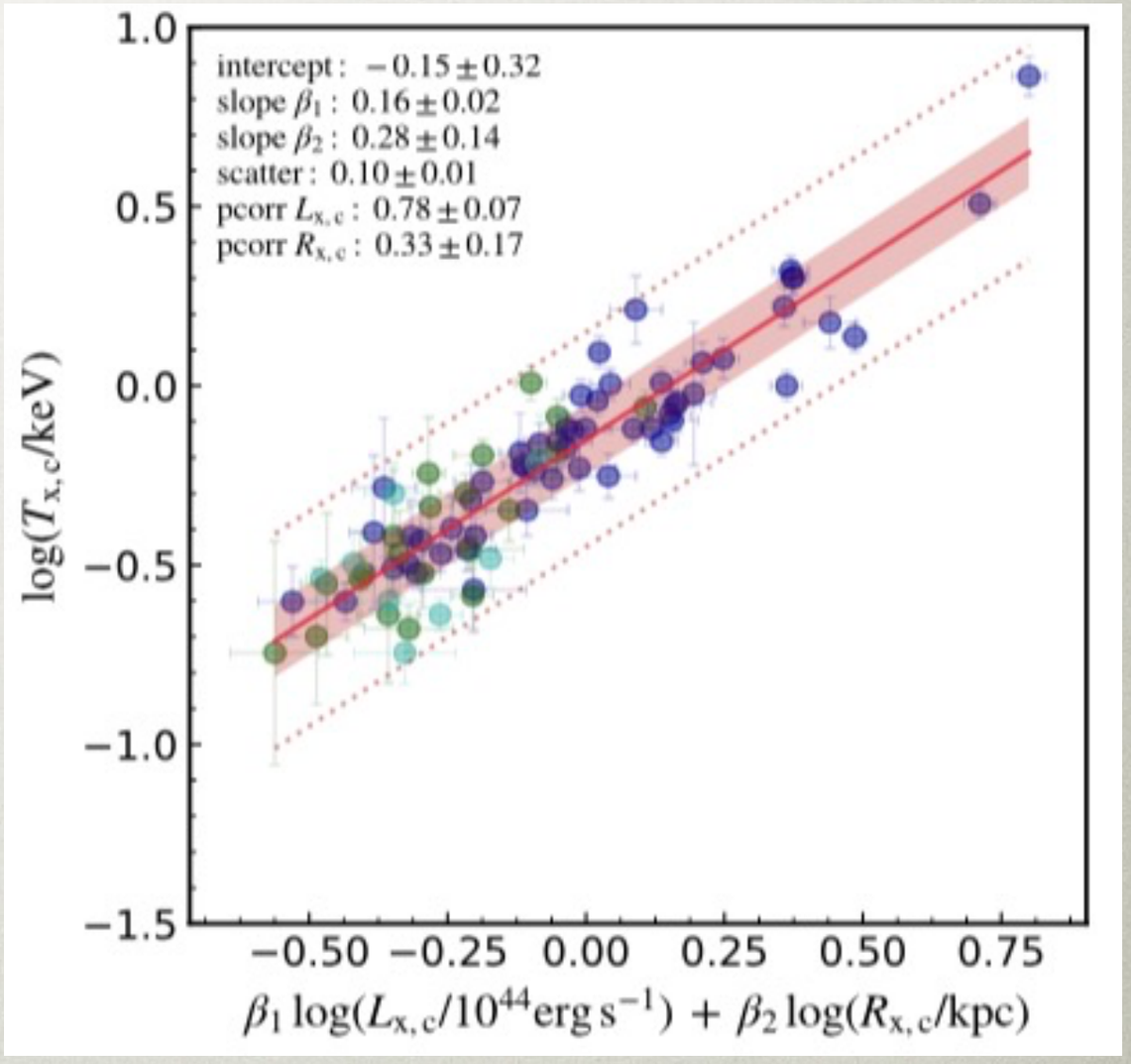
X-RAY HALO SCALING RELATIONS OF SMBHs

FUNDAMENTAL PLANES

Gaspari et al. 2019



optical FP

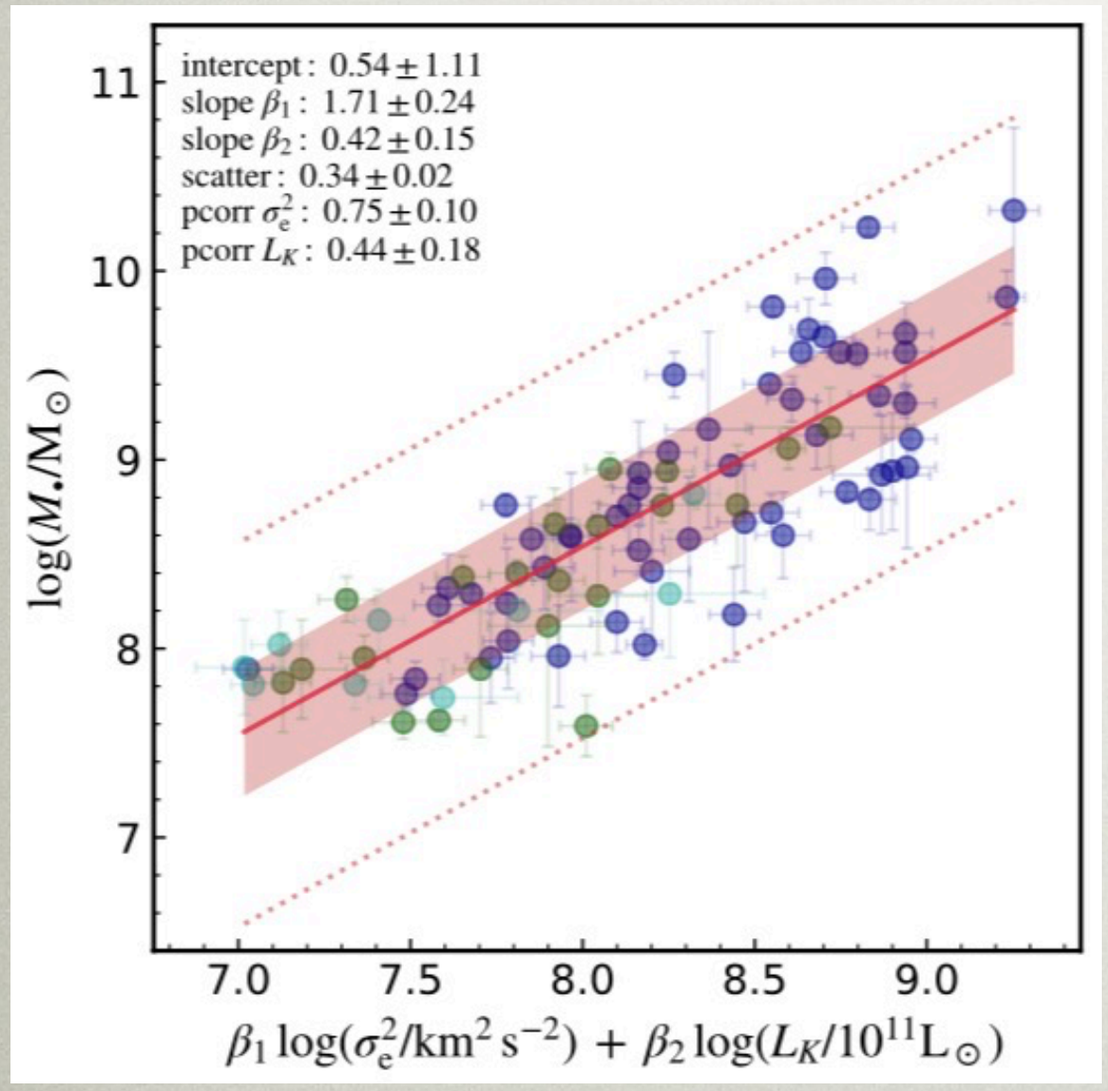


X-ray FP

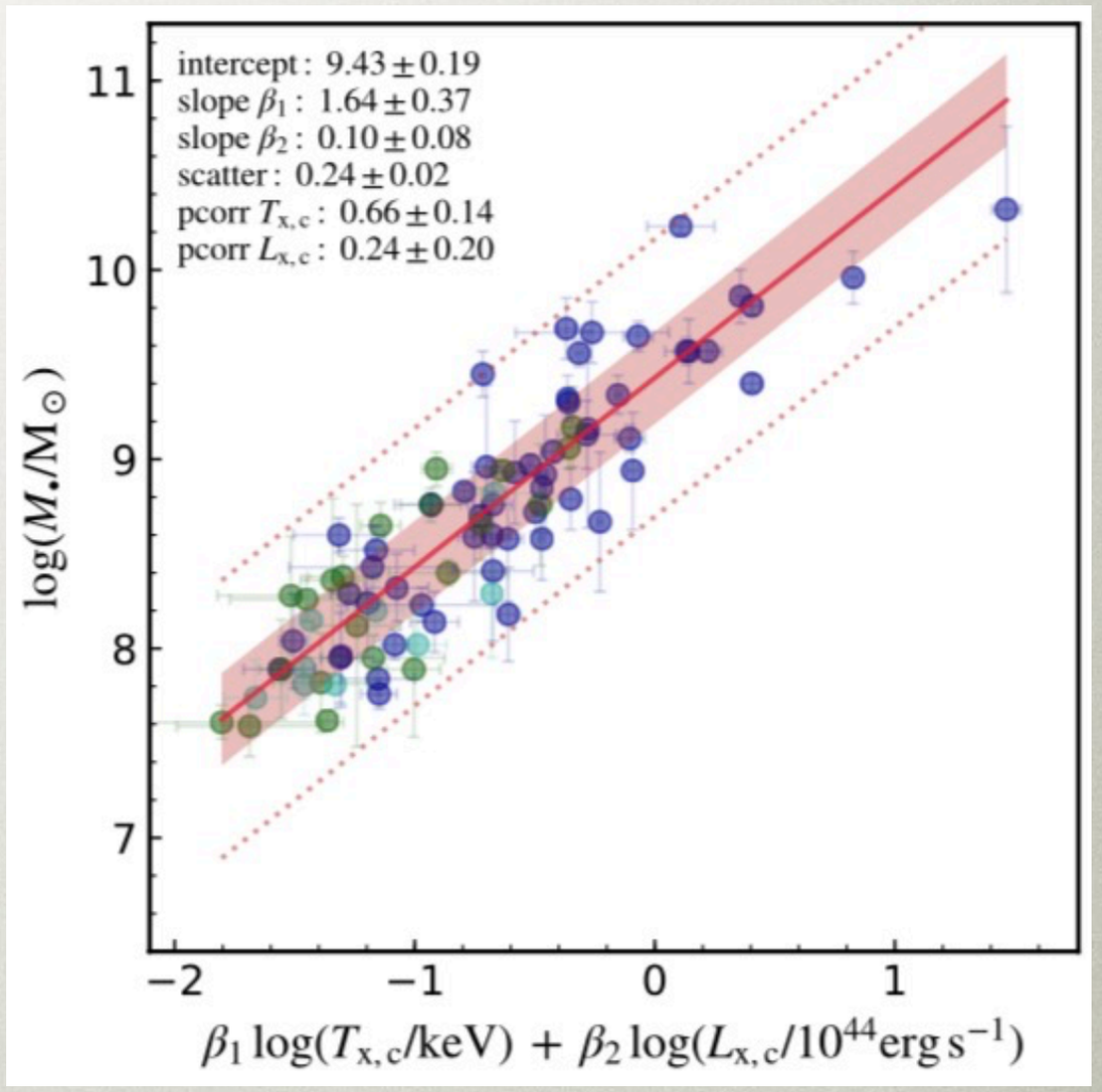
X-RAY HALO SCALING RELATIONS OF SMBHs

MULTIVARIATE CORRELATIONS

Gaspari et al. 2019



optical “fundamental plane”



X-ray “fundamental plane”