Probes of CCA, AGN Bubbles, & Turbulence

Massimo (Max) Gaspari

Princeton University

Lyman Spitzer Jr. Fellow

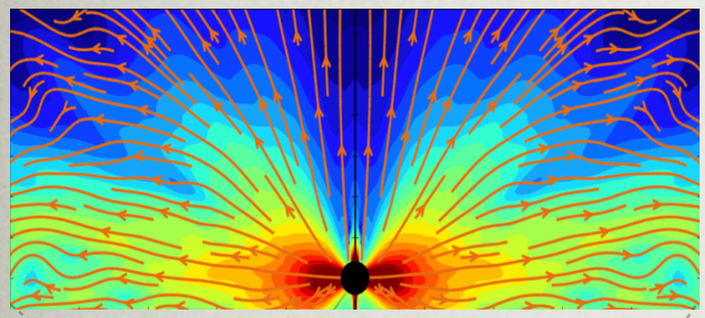
"BLACK HOLE WEATHER"

(PI: M. GASPARI)

Gaspari et al. 2009, 2011a,b, 2012a

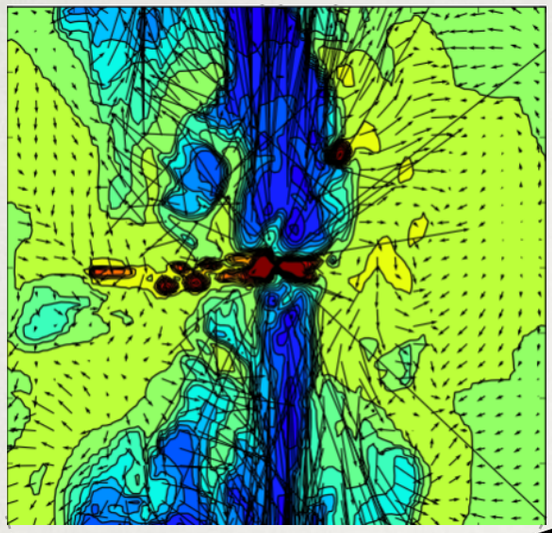
macro AGN outflows

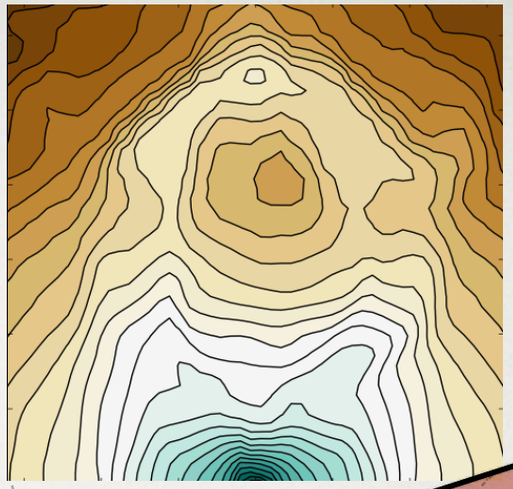
Gaspari et al. 2017a,b



GR-MHD outflows/jets

AGN bubble within cocoon shock

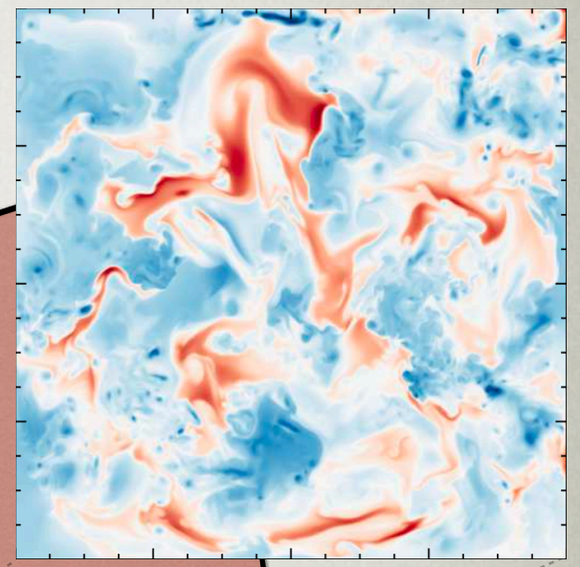




Gaspari et al. 2012a,b, 2013

merger-driven density fluctuations

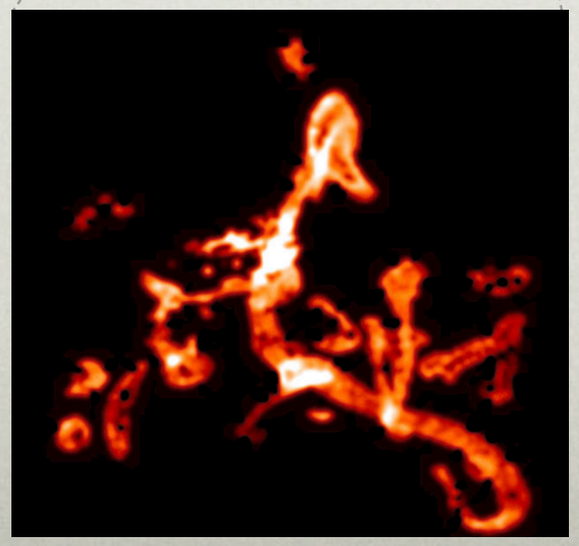
Gaspari et al. 2013b, 2014a

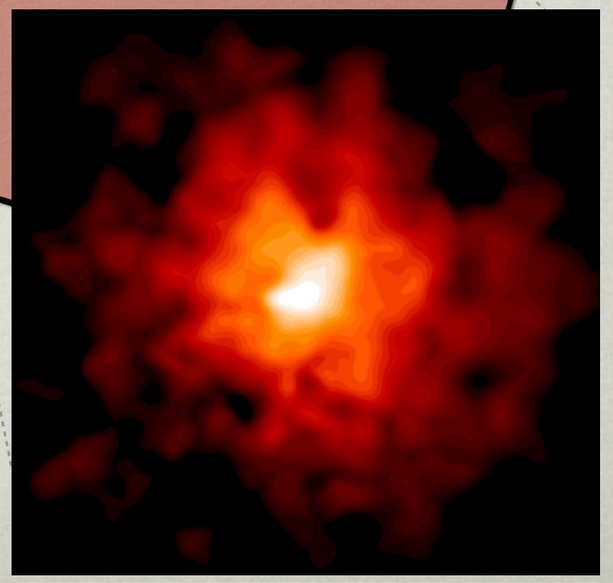


molecular clouds (radio)

Gaspari et al. 2013a, 2015, 2017a

warm filaments (optical)

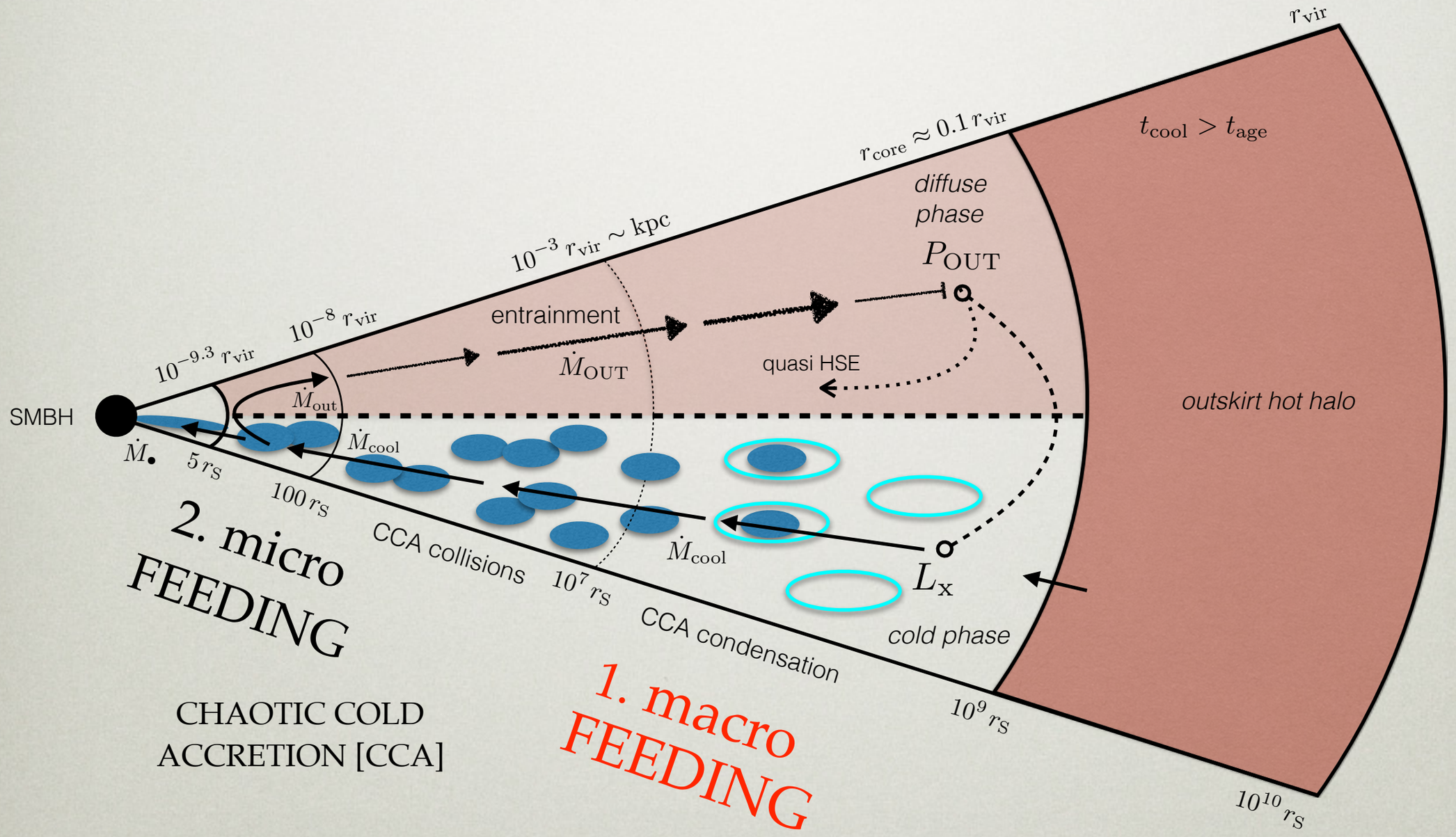




turbulent X-ray plasma core

Gaspari et al. 2013a, 2016, 2017a,b, 2018

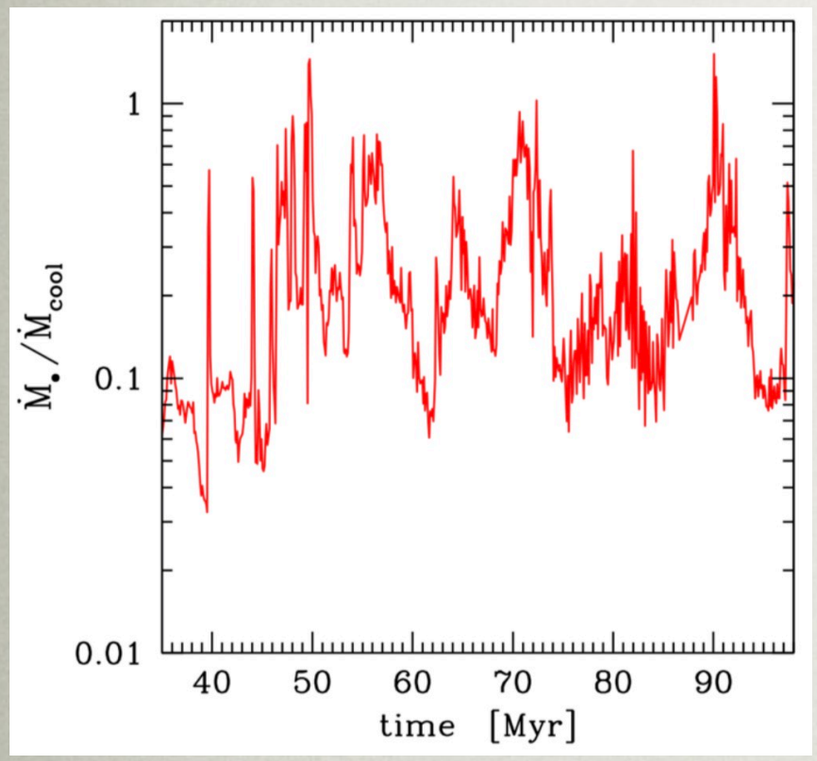
“BLACK HOLE WEATHER” PROGRAM



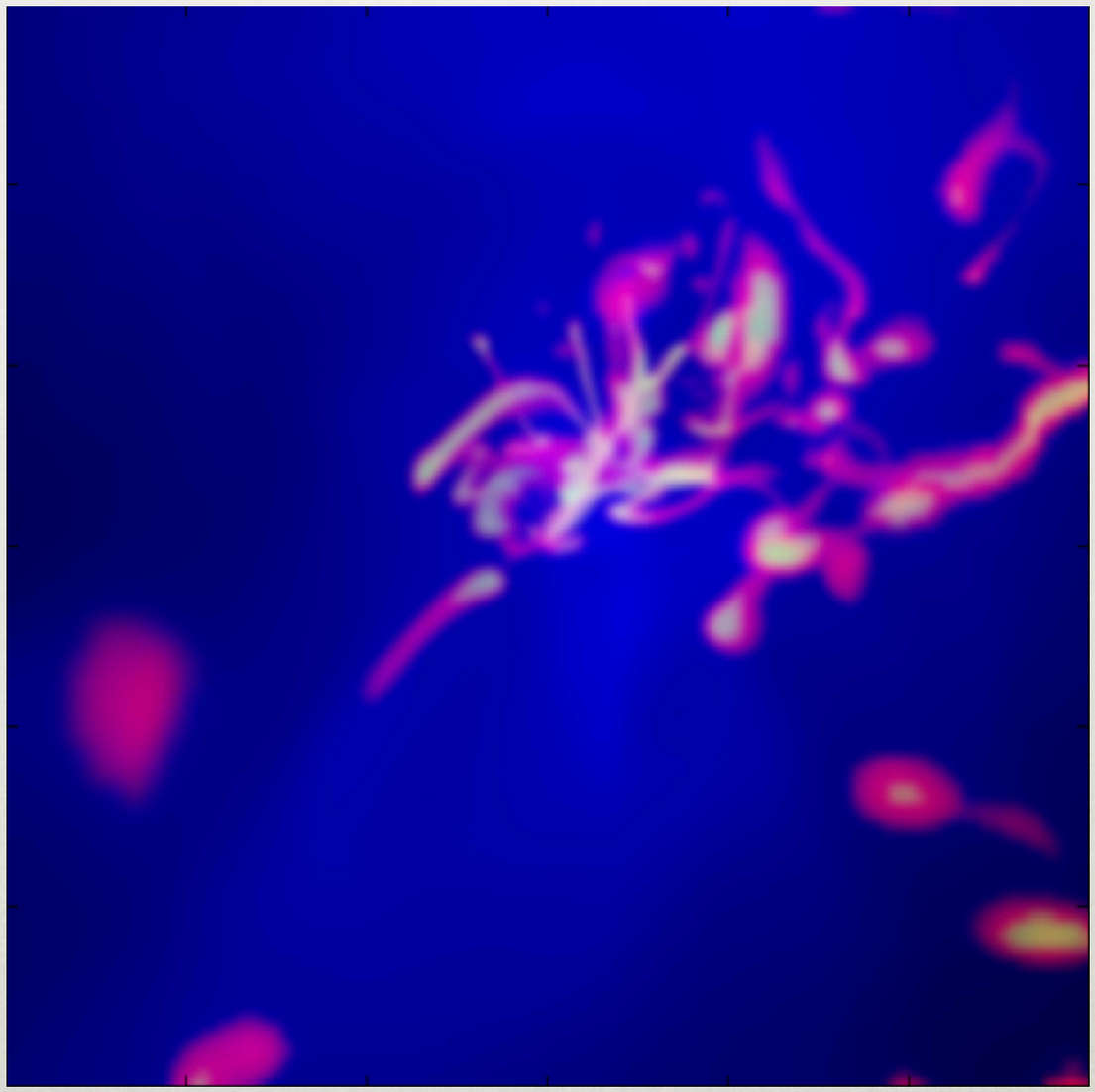
MG+2011-2019

RAINING ON BLACK HOLES

a.k.a. Chaotic Cold Accretion [**CCA**] — Gaspari, Ruszkowski, & Oh 2013



chaotic collisions => recurrent
2 dex boost in accretion rate
~ 100x Bondi rate



TURBULENT and heated atmosphere

turbulence ~150 km/s

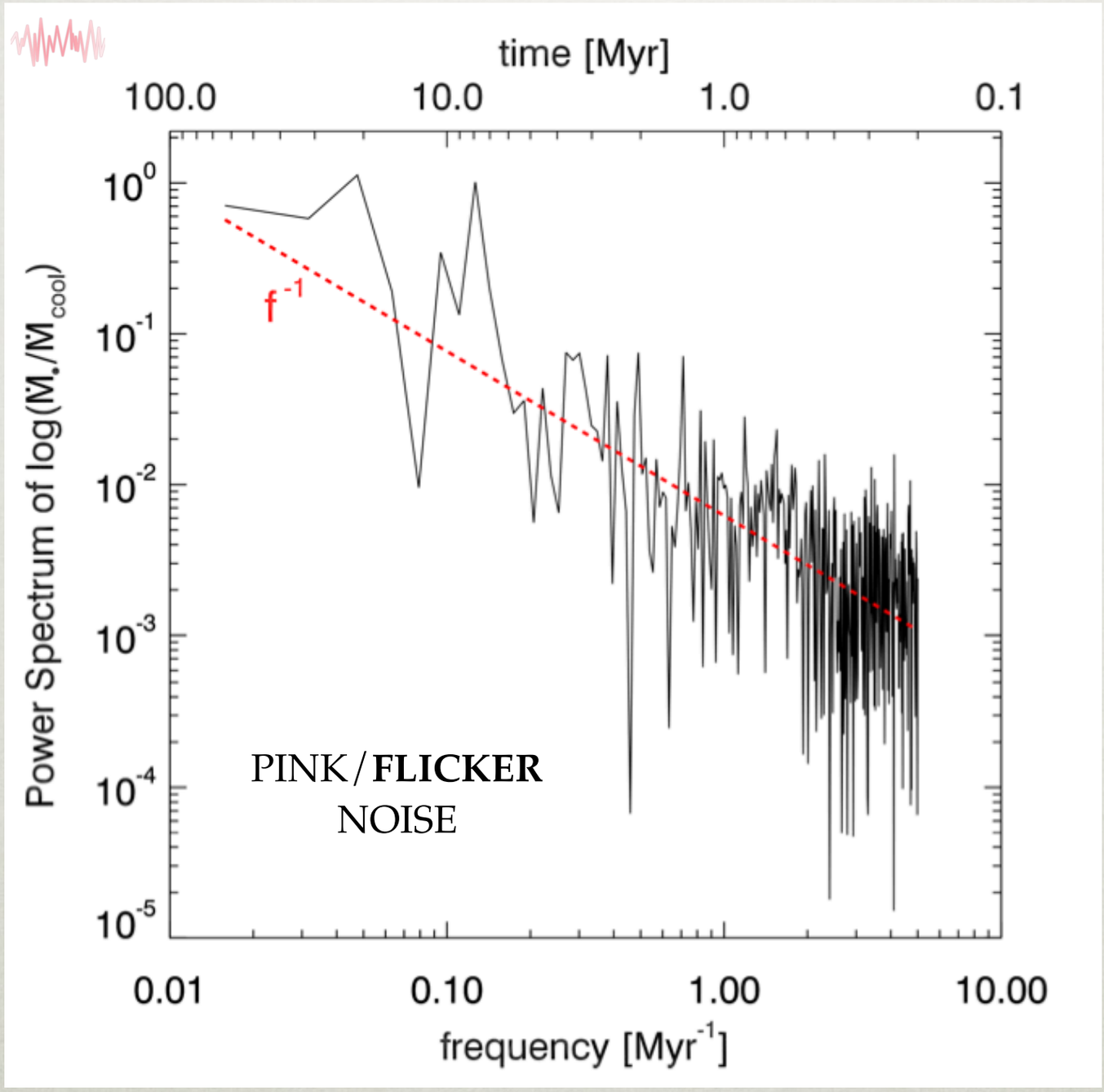
Gaspari+2017

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

CHAOTIC COLD ACCRETION

VARIABILITY

Gaspari+2017



natural explanation for the ubiquitous rapid variability of AGN

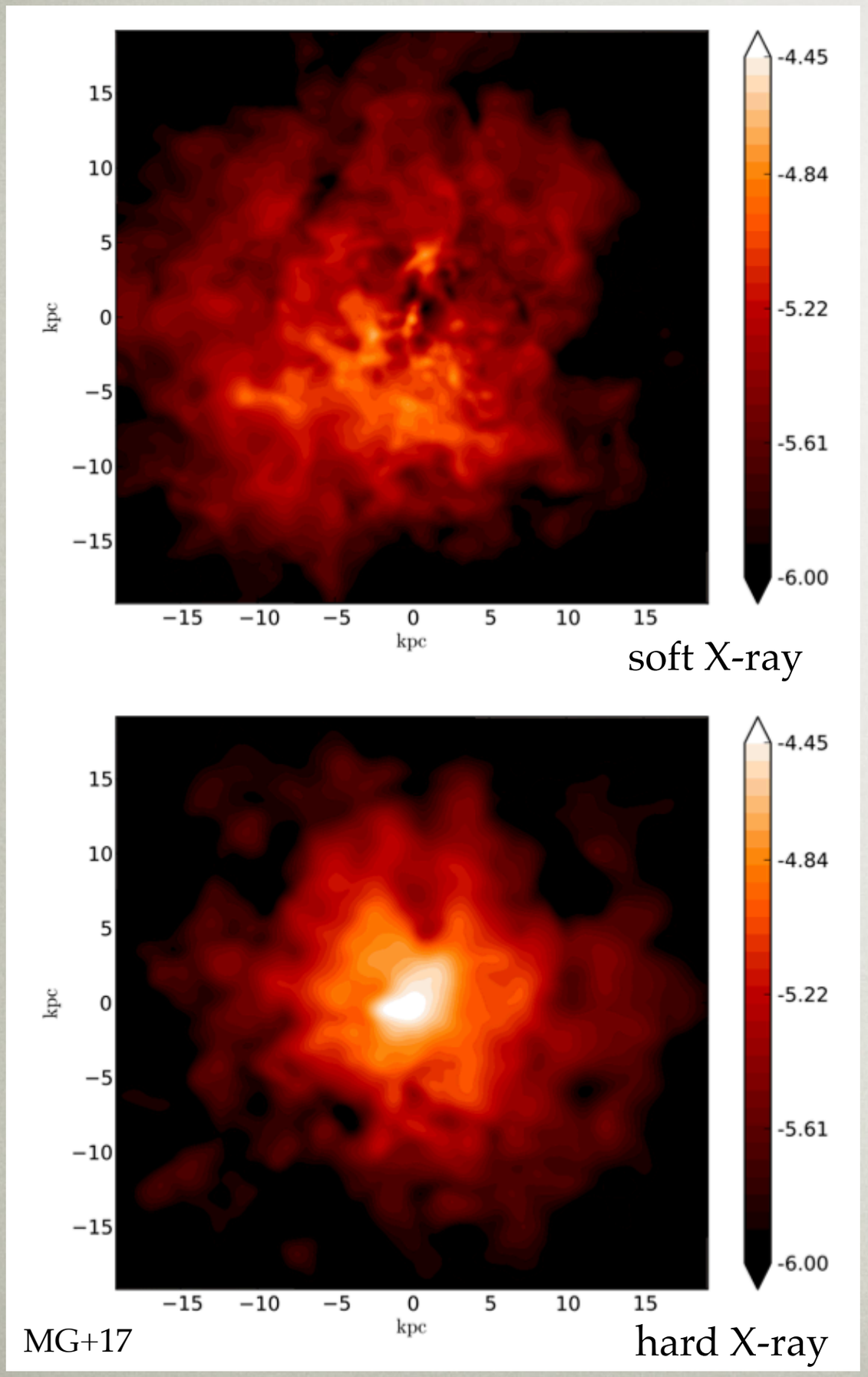
constant variance per log interval => large self-similar variability on different timescales

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

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

MULTIPHASE RAIN:
1. HOT PLASMA

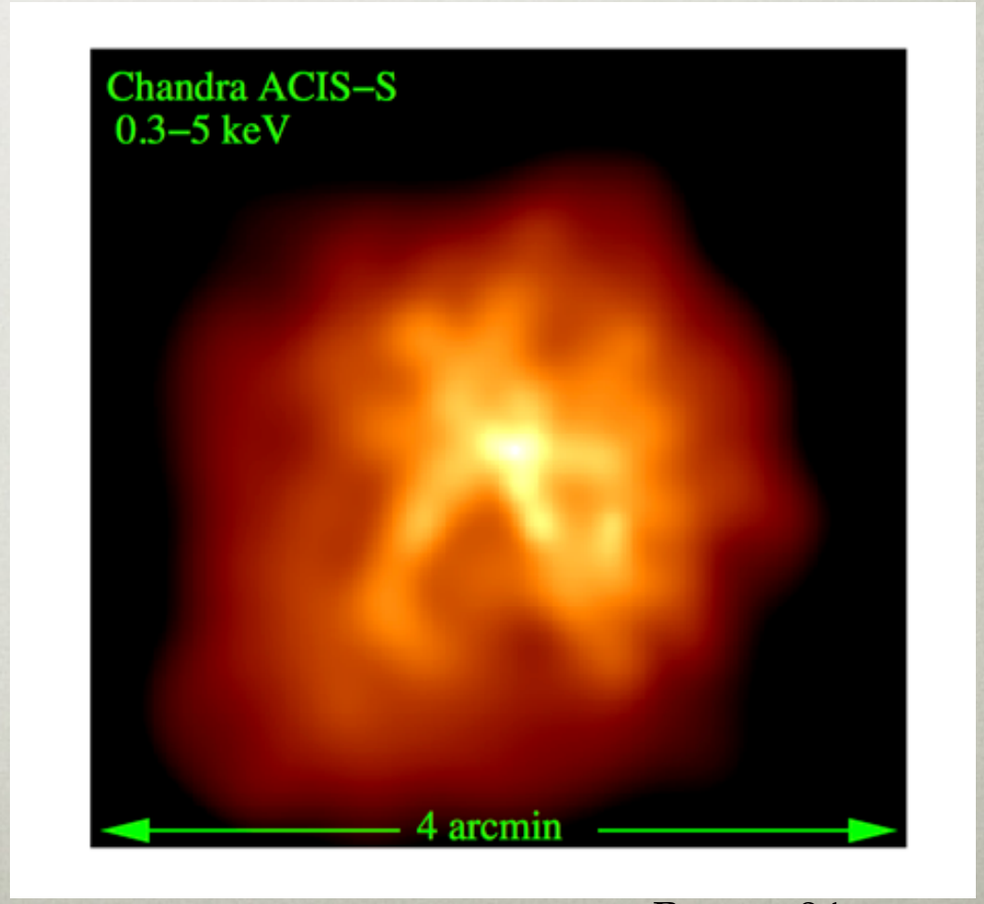
- turbulent eddies imprint => naturally create “cavities” /”fronts”
- X-ray “filaments” start to appear below 0.5 keV
- weak subsonic turbulence is enough to trigger CCA



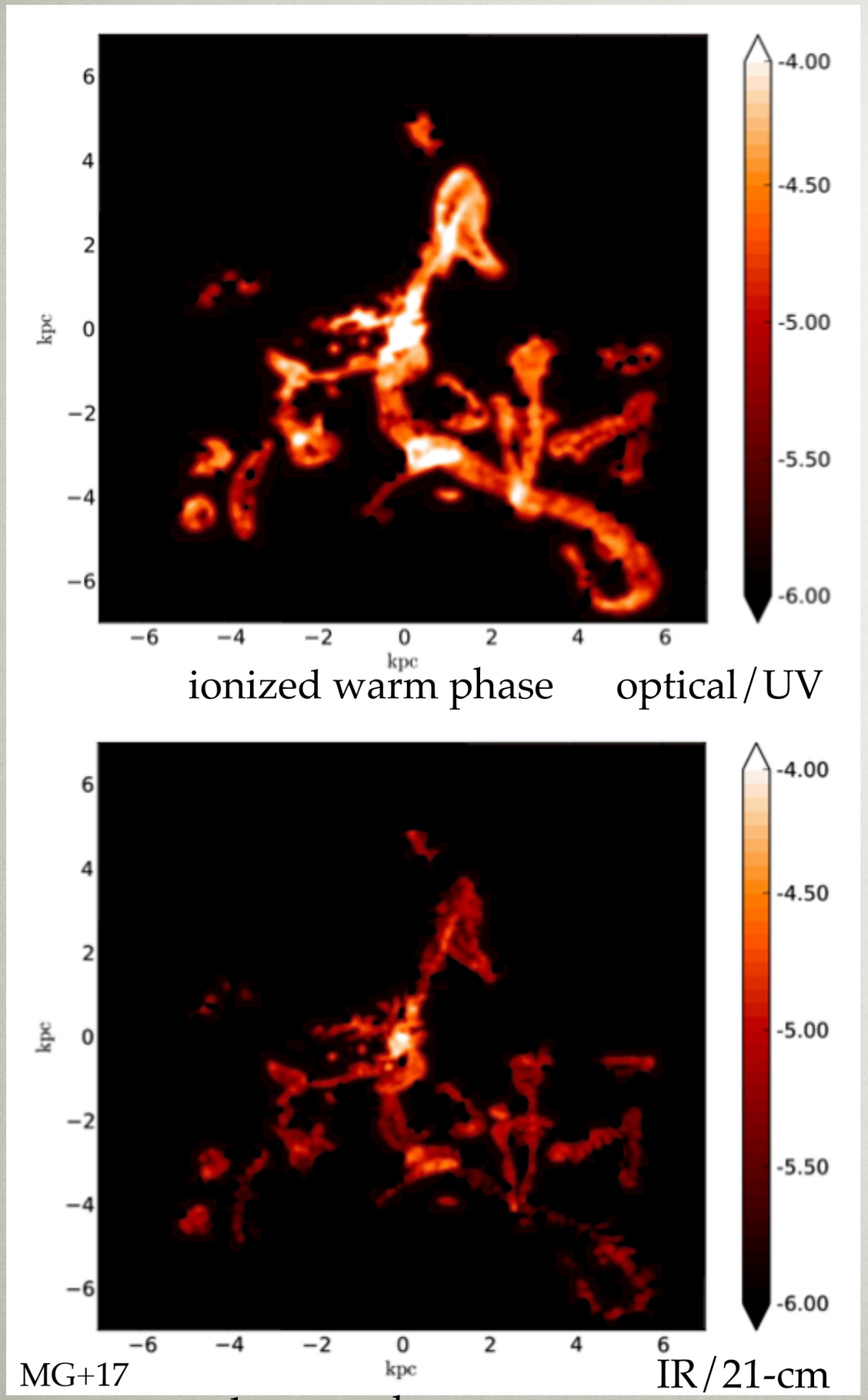
soft X-ray

MG+17

hard X-ray



Buote+04



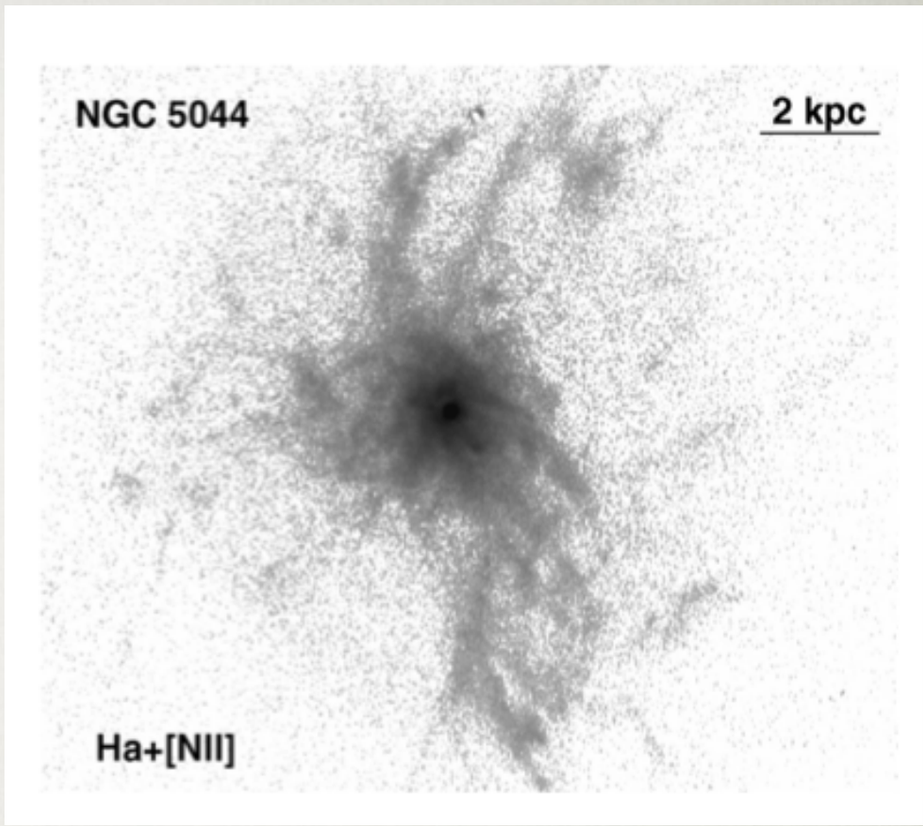
ionized warm phase optical/UV

MG+17

IR/21-cm

neutral warm phase

Werner+14: SOAR



- robust thermal instability/ **multiphase condensation criterion**:

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

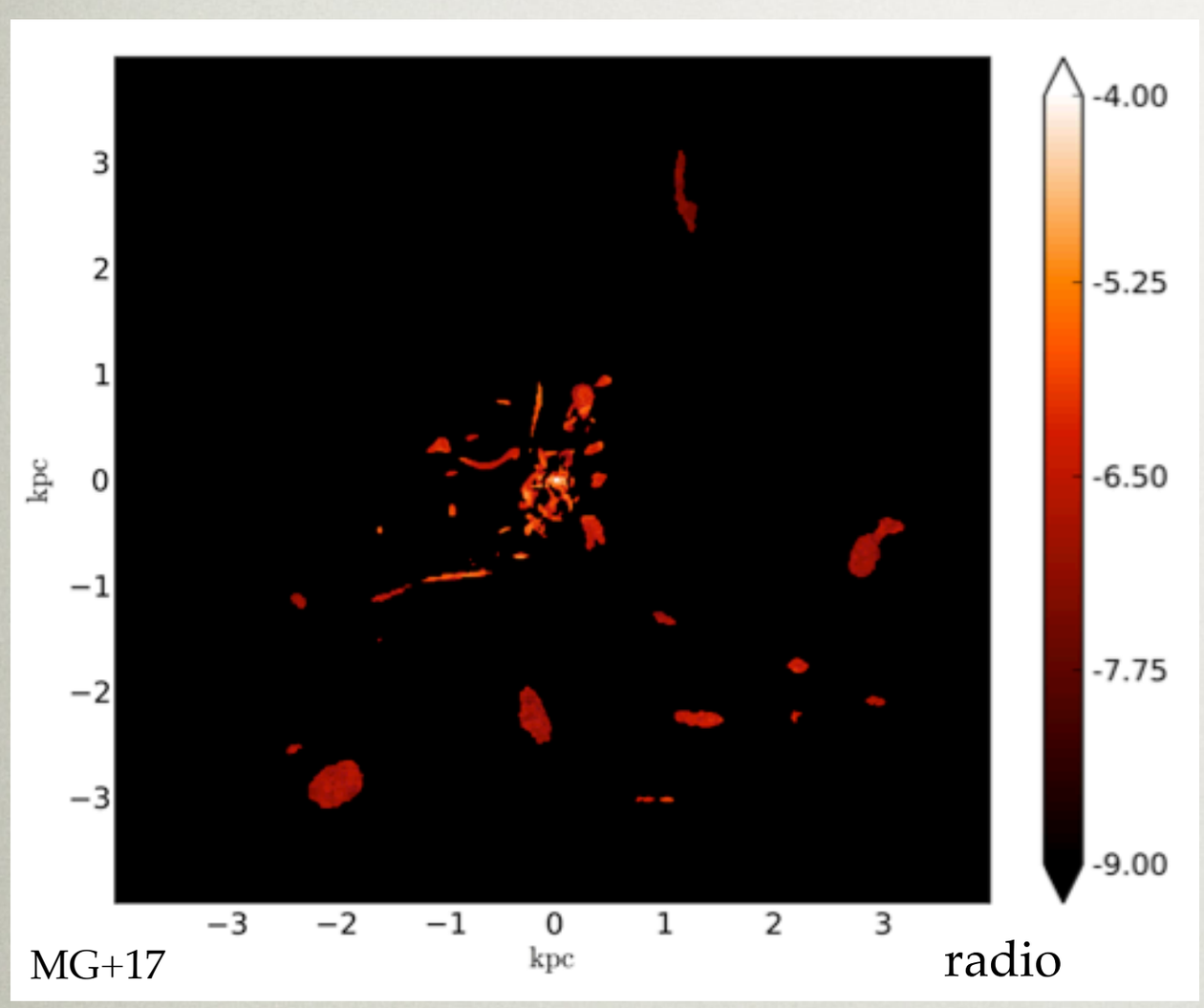
- **top-down** condensation: ionized skin envelops neutral filaments

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

MULTIPHASE RAIN:

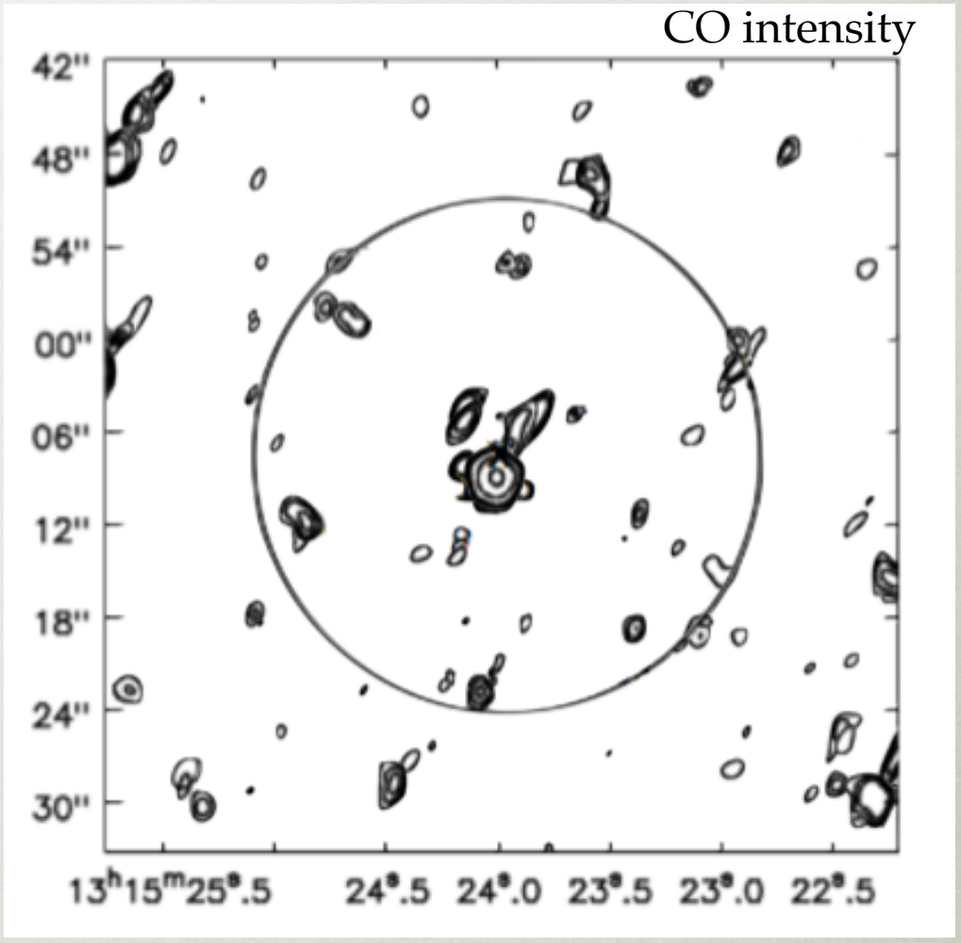
2. WARM PHASE

MULTIPHASE RAIN:
3. COLD/MOLECULAR PHASE



MG+17 radio

David+14-17: ALMA CO intensity



- 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

MULTIPHASE RAIN

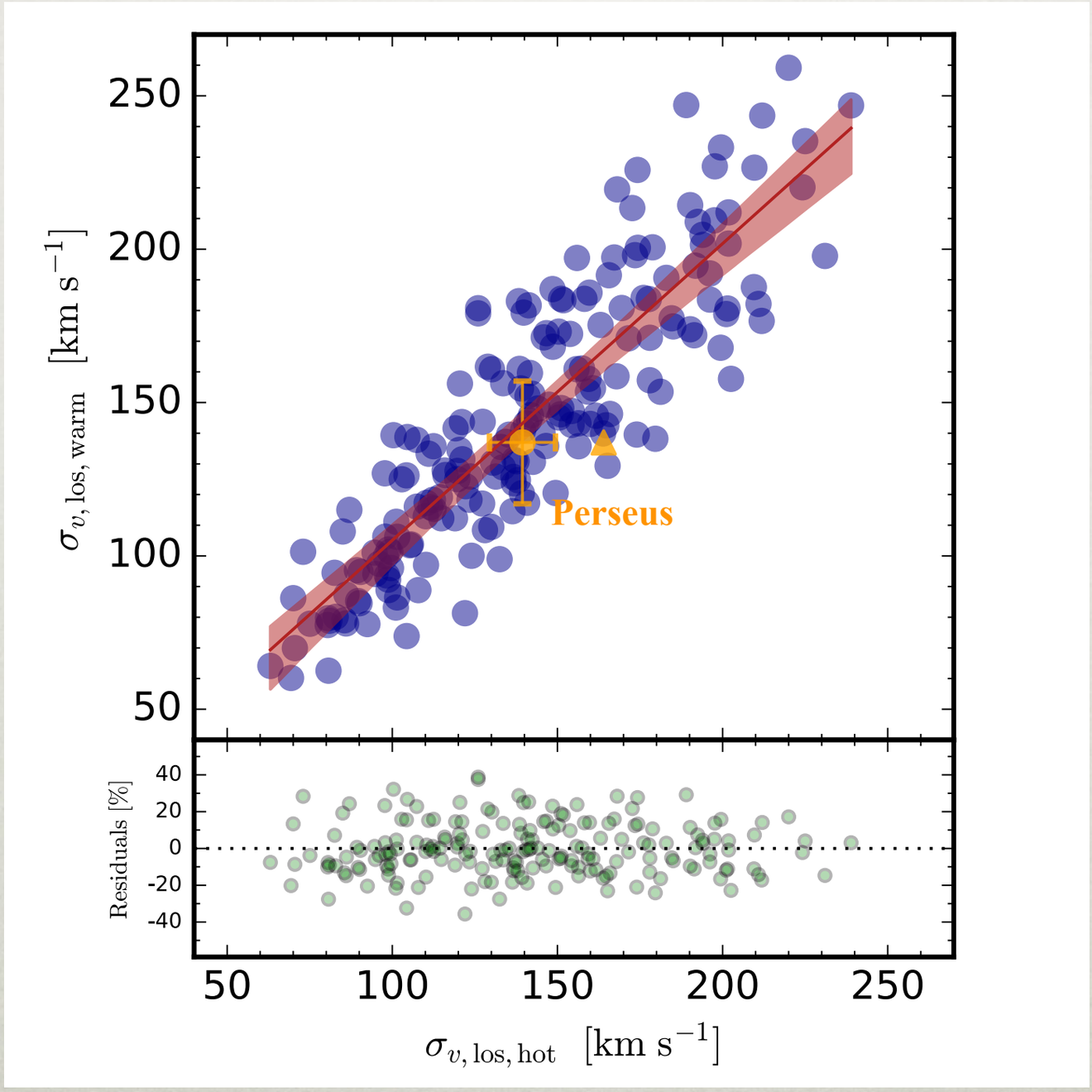
"shaken snow globes"

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



CCA-regulated AGN jet feedback simulation

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

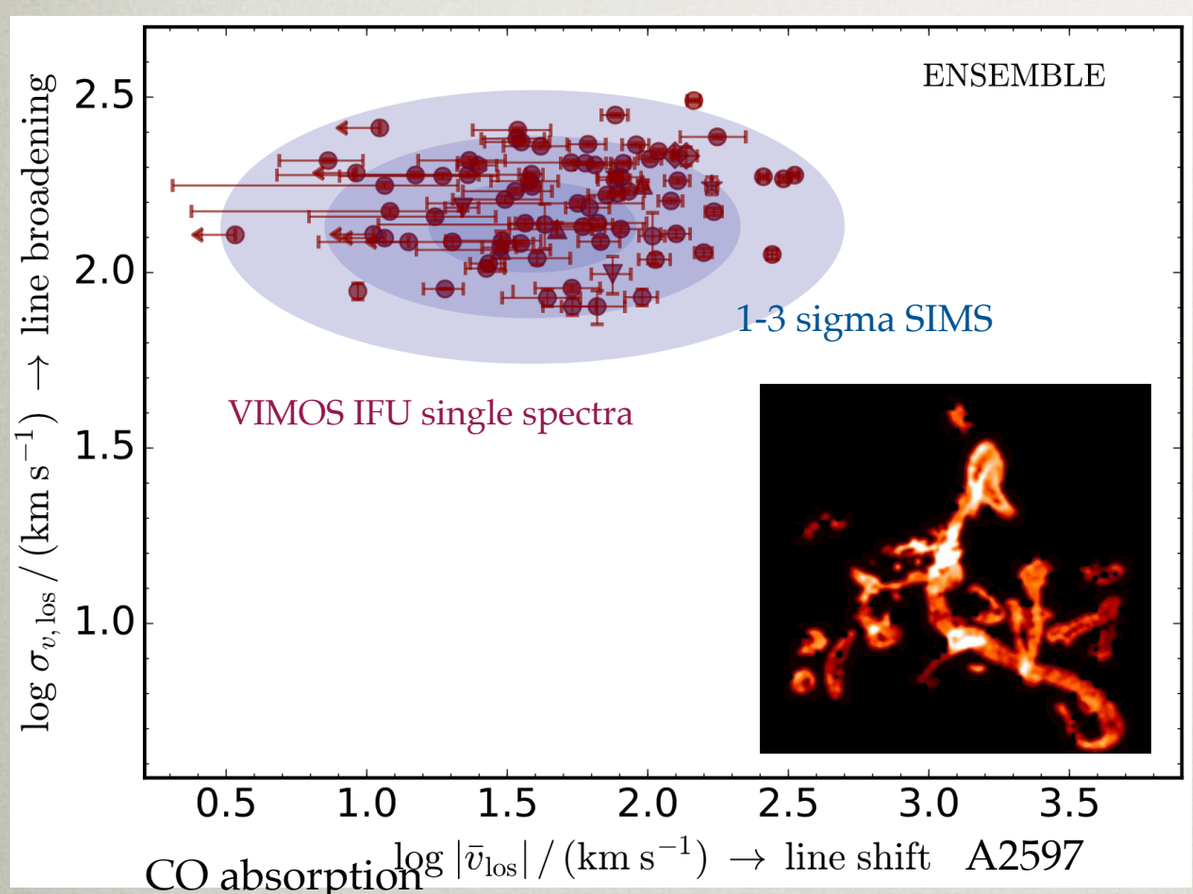
KINEMATIC TRACERS - RAIN/CCA

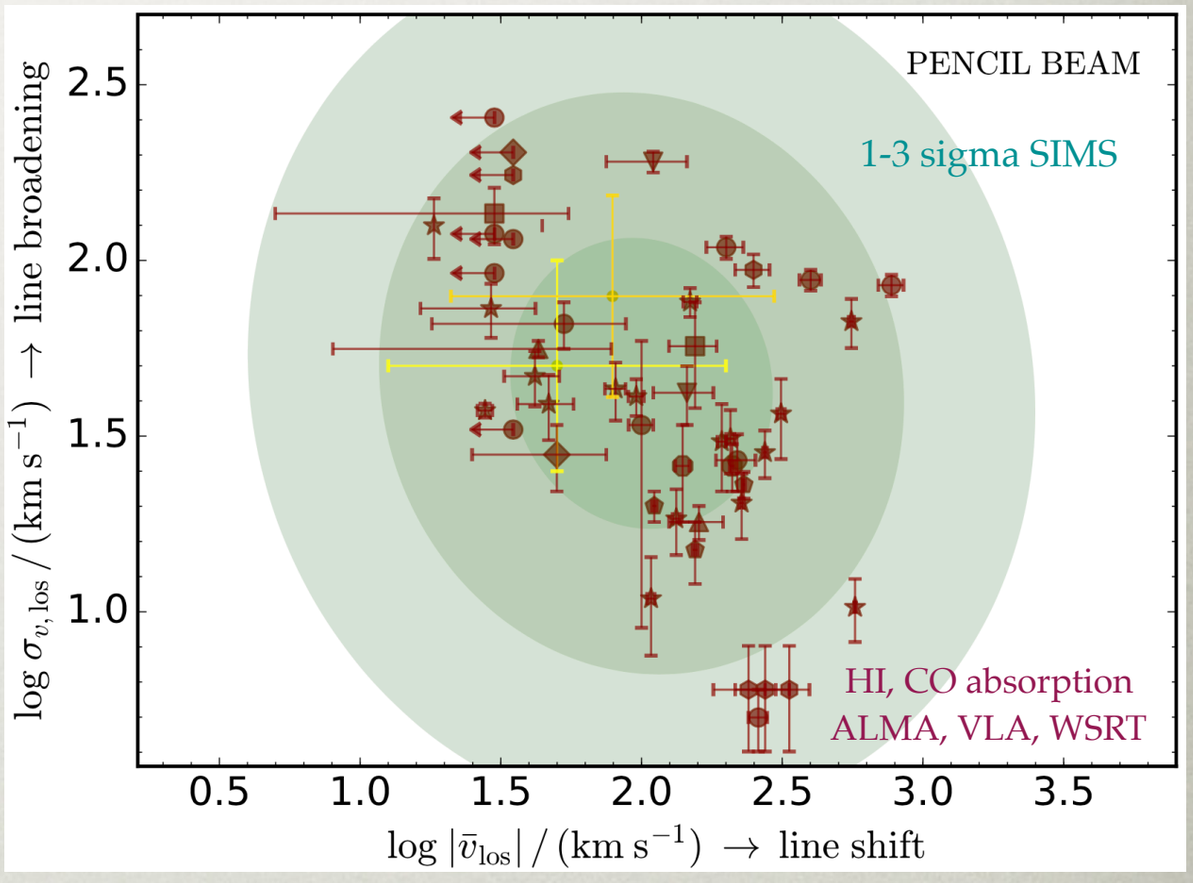
observational tests

(massive galaxies in groups and clusters)

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

MG+18





Tremblay+16-18

substantial line broadening and small scatter

large line shifts and narrow broadening: accreting clouds

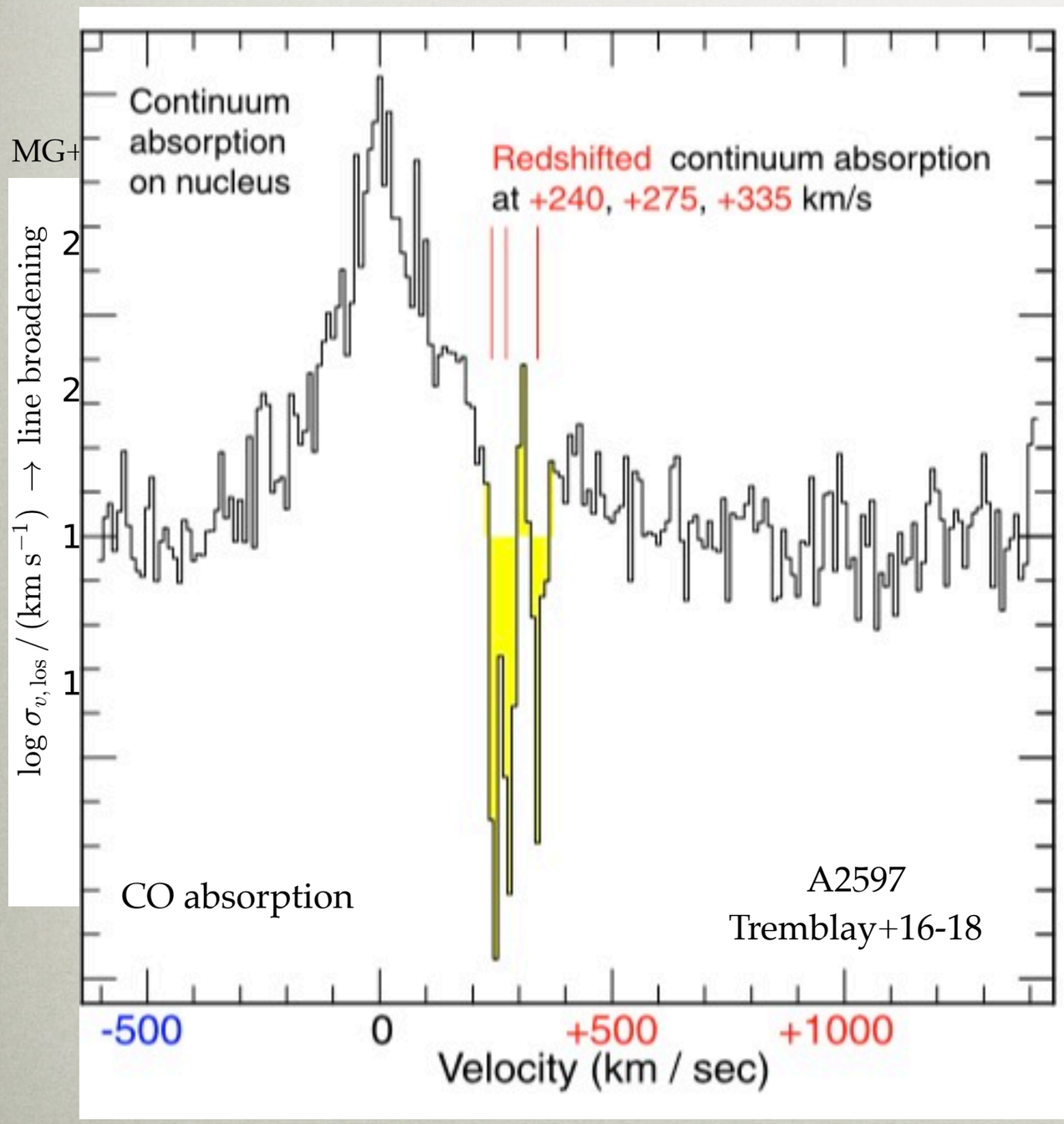
red points: ~80 systems (Hα+[NII], HI, CO, [CII] lines) — contours: SIMS lognormal distributions

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

KINEMATIC TRACERS - RAIN/CCA

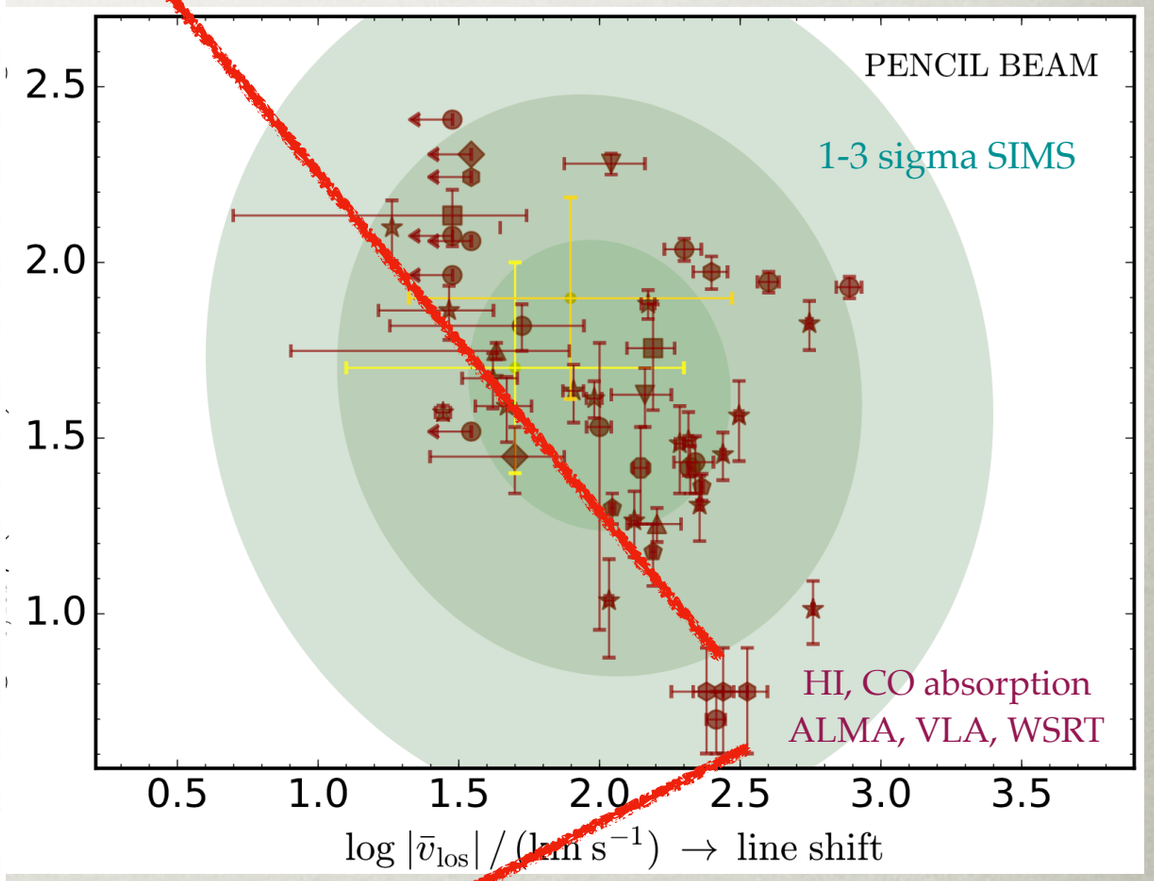
observational tests

(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

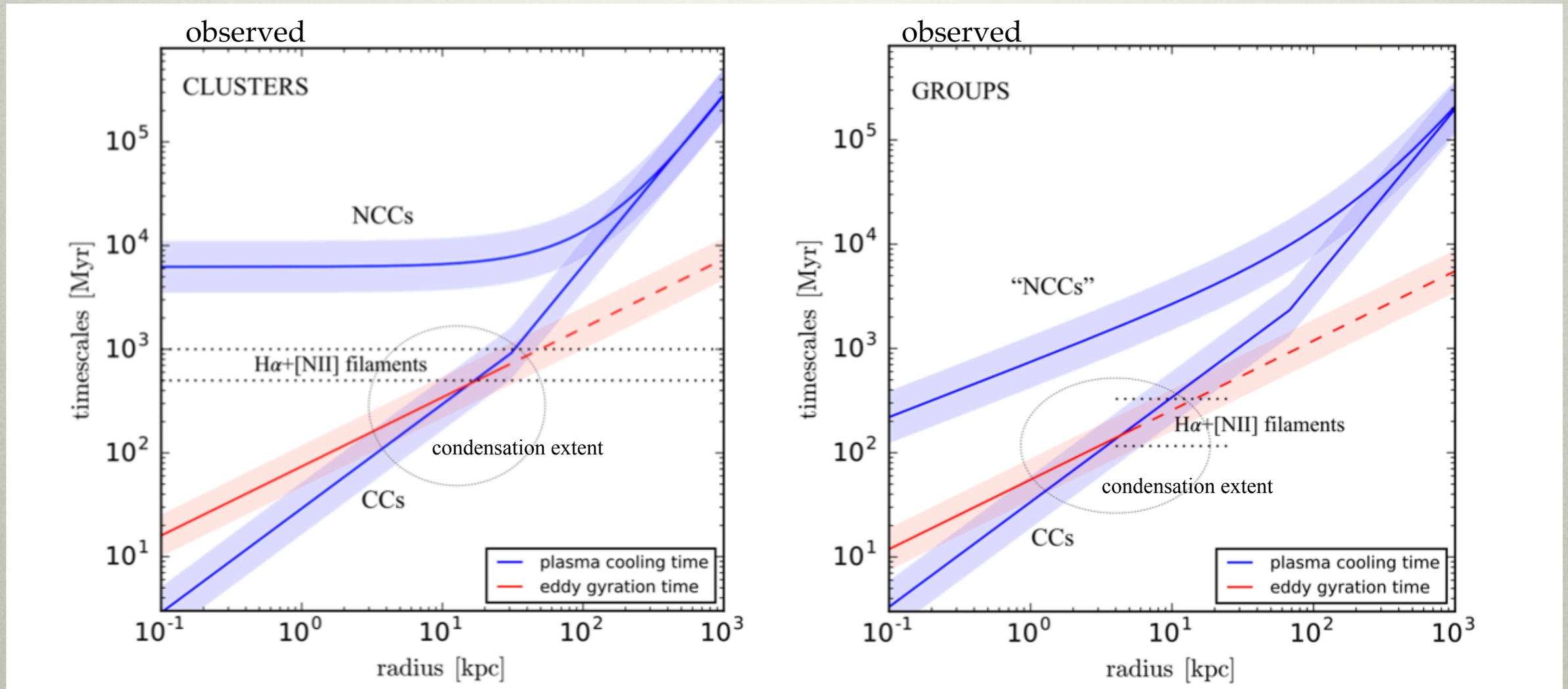
- r < 100 pc **funneling** of clouds with 100s km/s (recently probed by ALMA, e.g., N5044, A2597)

KINEMATIC TRACERS:

key physically-motivated condensation criterion

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

Gaspari et al. 2018



plasma cooling time

$$t_{\rm cool} = \frac{3 k_{\rm b} T}{n_{\rm e} \Lambda}$$

versus

eddy gyration time

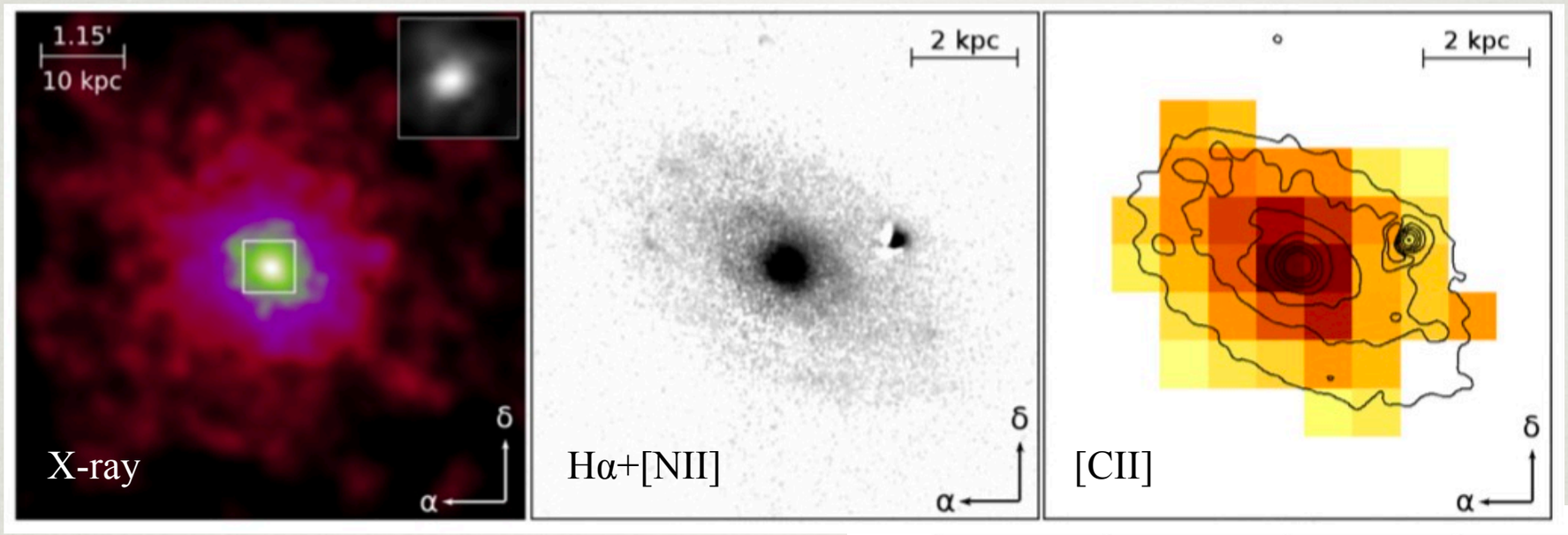
$$t_{\rm eddy} = 2\pi \, \frac{r^{2/3} L^{1/3}}{\sigma_{v,L}}$$

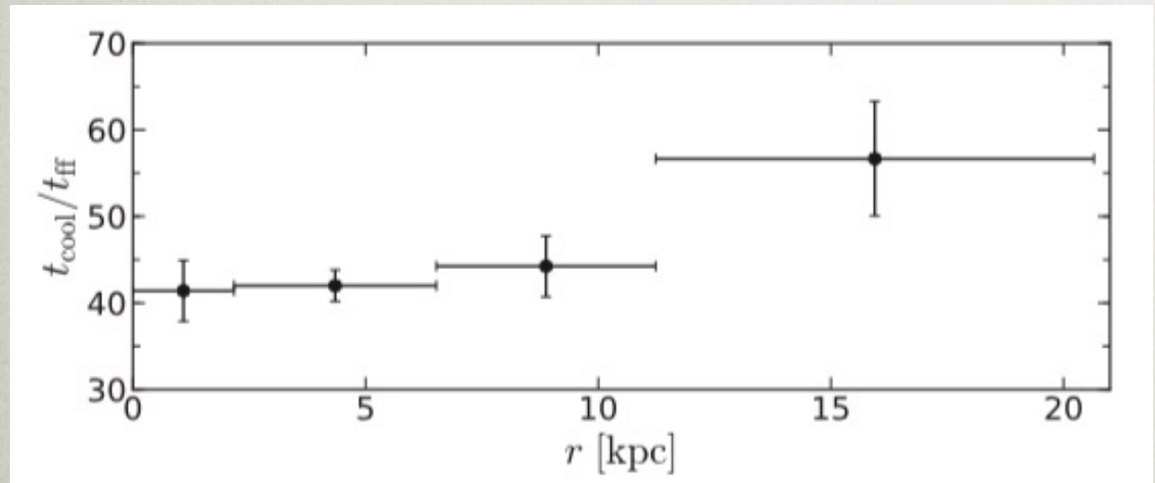
free-fall time likely secondary

CONDENSATION CRITERIA

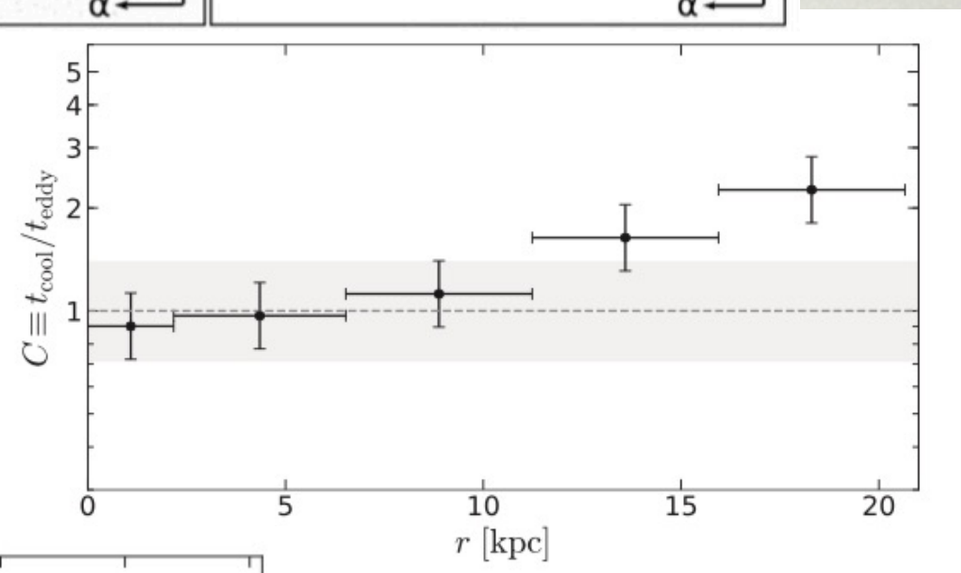
interesting case: NGC 7049 (rotating ETG)

Juranova, Werner, Gaspari+2019

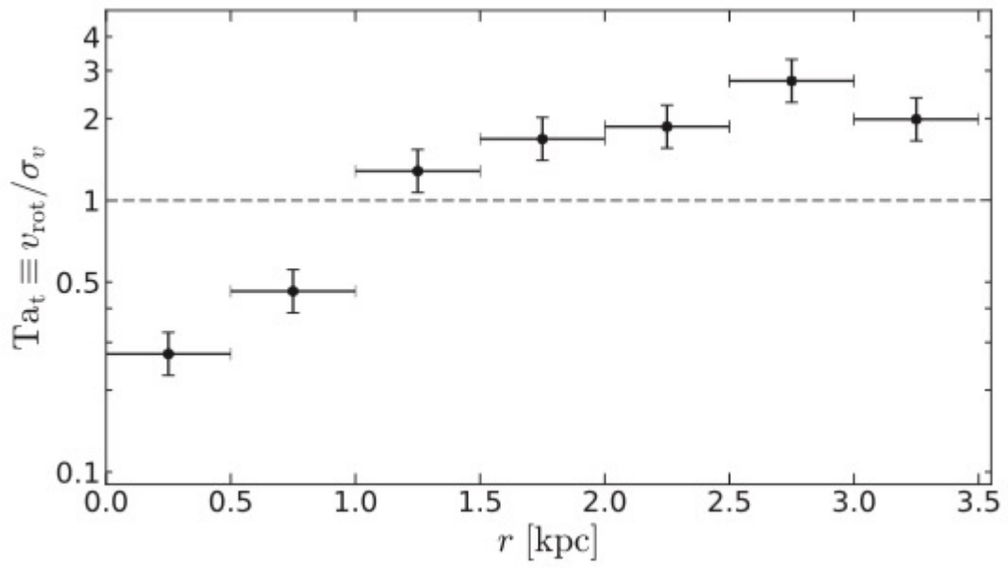




TI-ratio

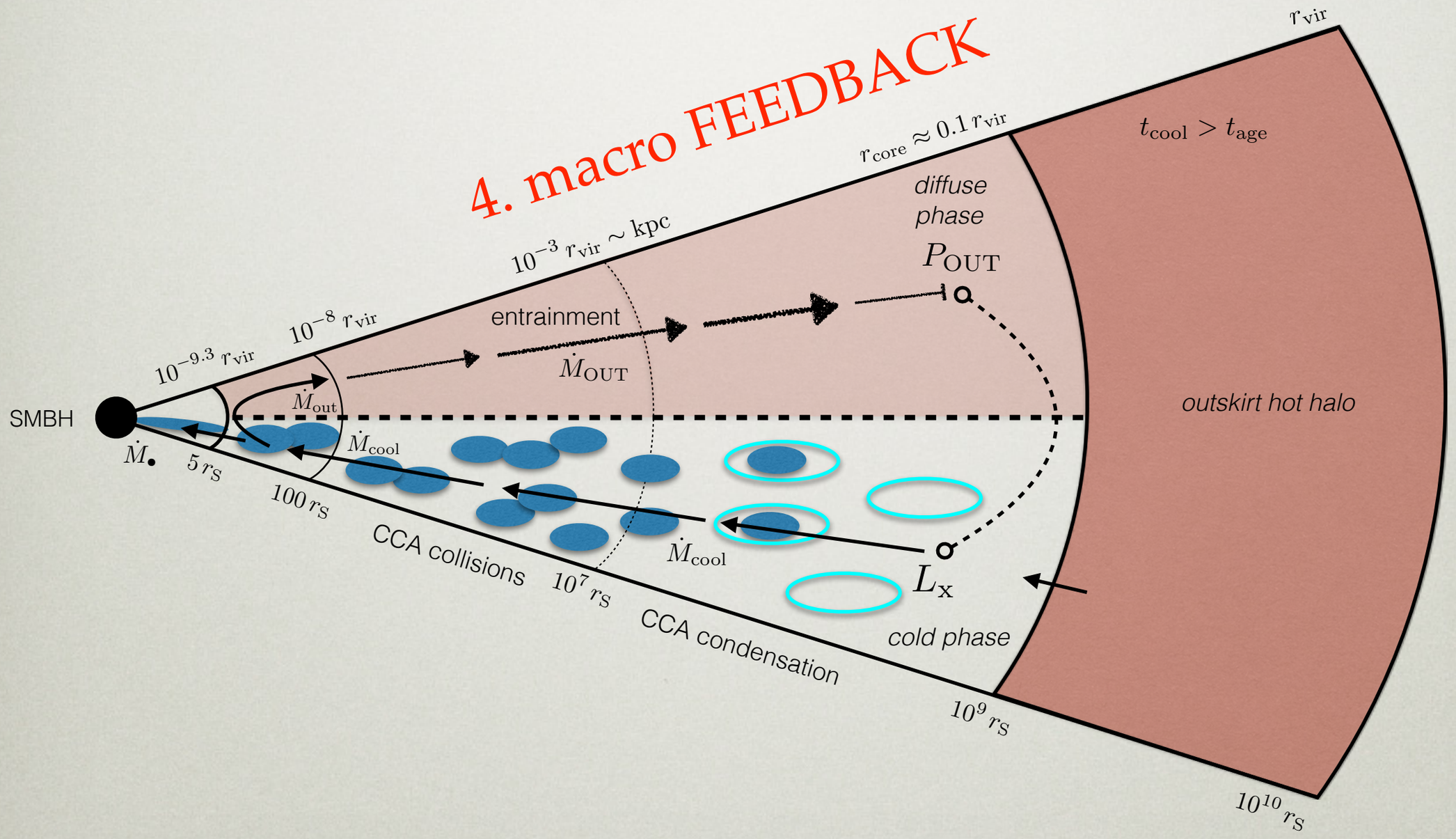


C-ratio



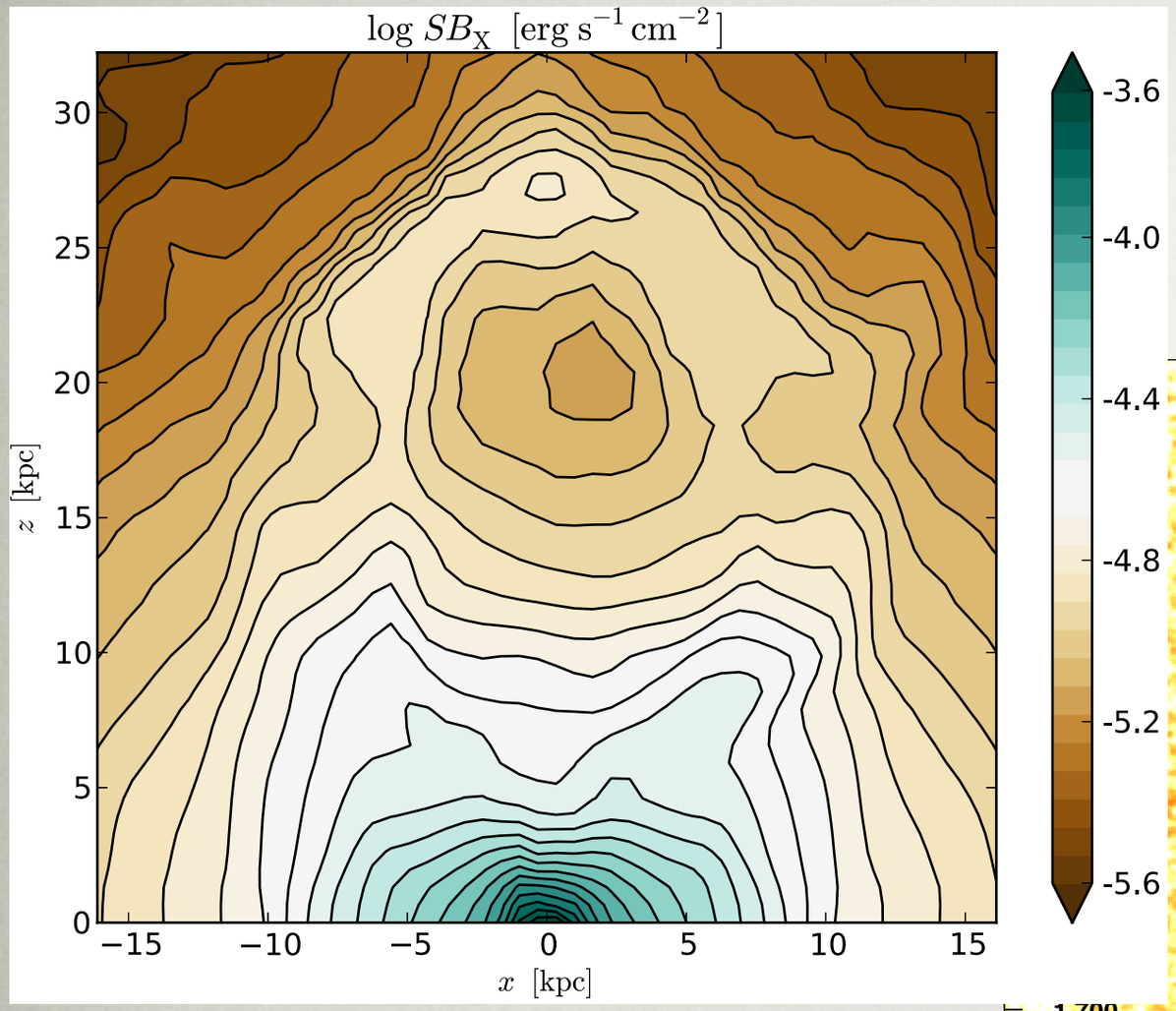
turbulent Taylor number

"BLACK HOLE WEATHER" PROGRAM



MG+2011-2019

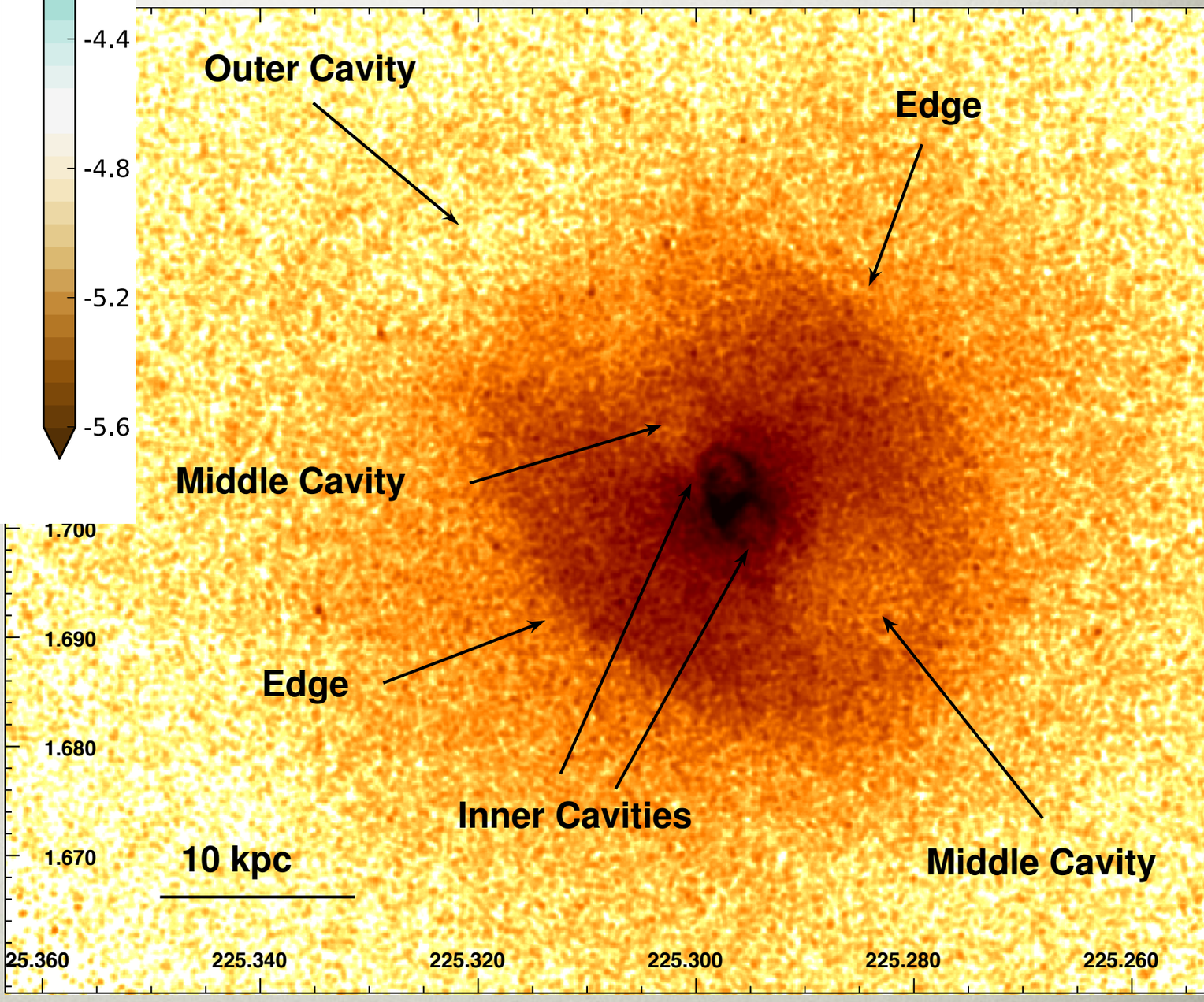
X-RAY BUBBLES



MG+2011/2012
pure hydro simulation

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

enthalpy

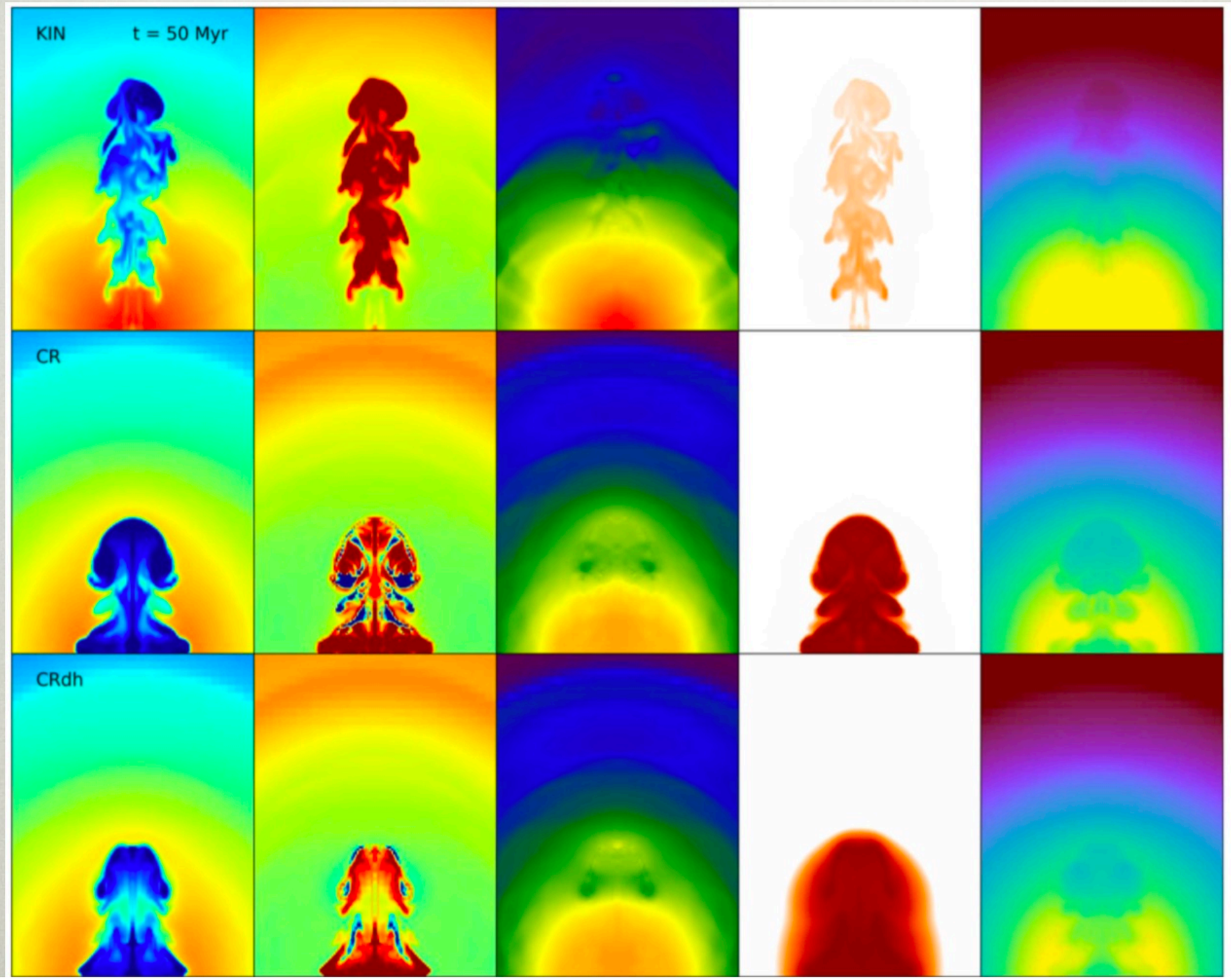


NGC 5813 - Randall+2011

COSMIC-RAY BUBBLES

Yang, Gaspari, & Marlow 2019

60x80 kpc



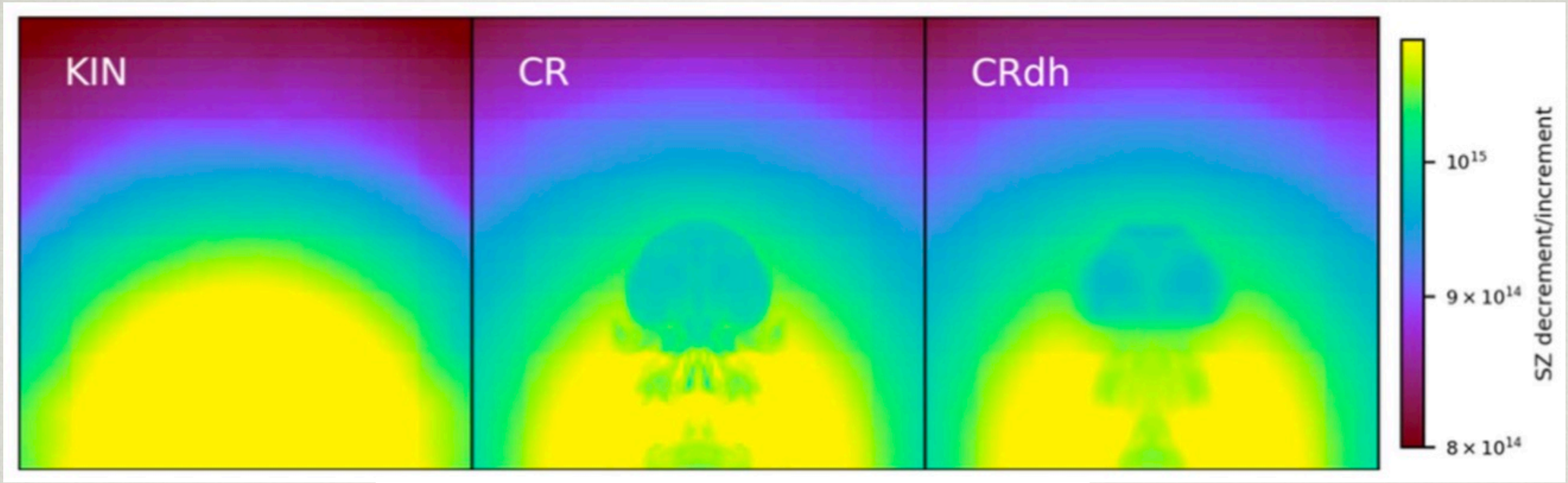
light CR

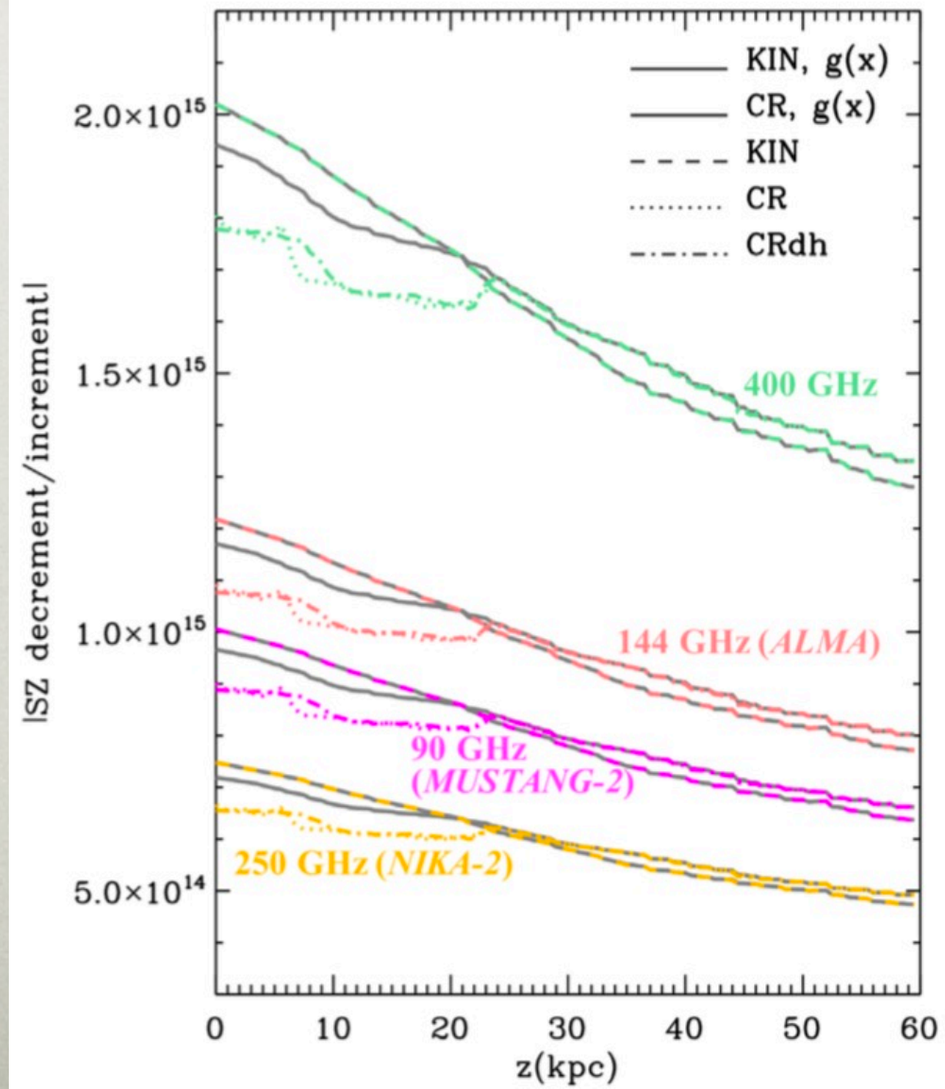
CR dominated (no diffusion)

CR+diffusion/ coll. heating

SZ BUBBLES

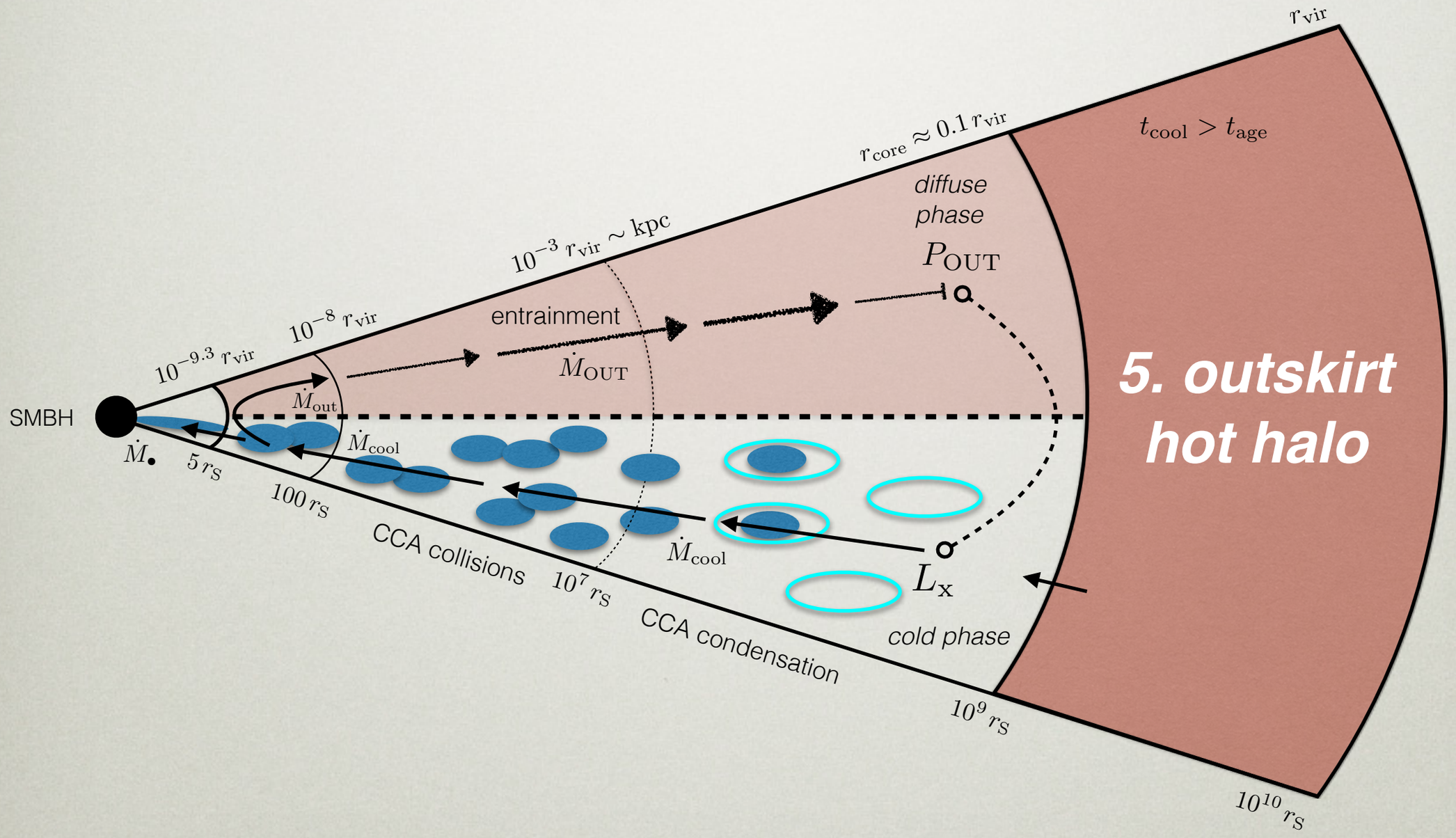
Yang, Gaspari, & Marlow 2019





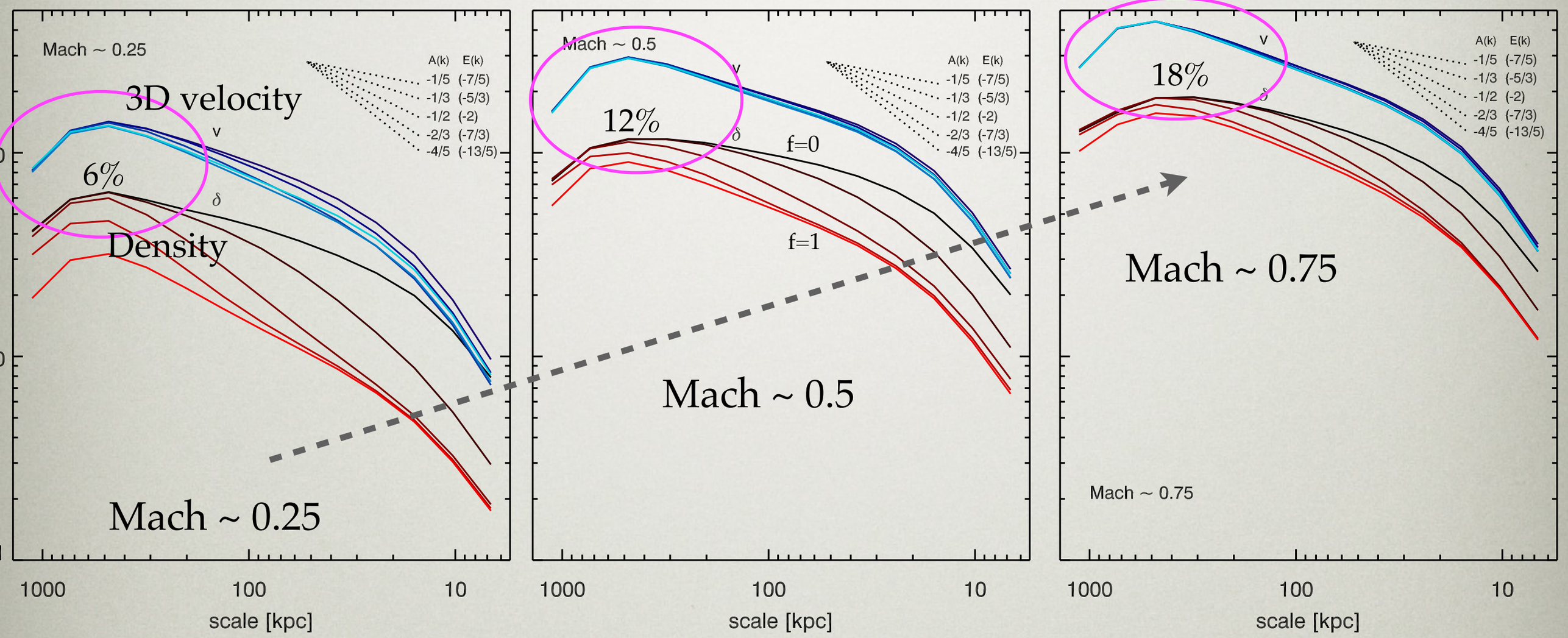
thermal Sunyaev Zel'dovich decrement/increment (major SZ telescopes)

"BLACK HOLE WEATHER" PROGRAM



MG+2011-2019

ICM POWER SPECTRUM: TURBULENCE



Gaspari & Churazov 2013
Gaspari et al. 2014
hydrodynamical simulations —>

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

globally self-similar
over Mach and L_{inj}

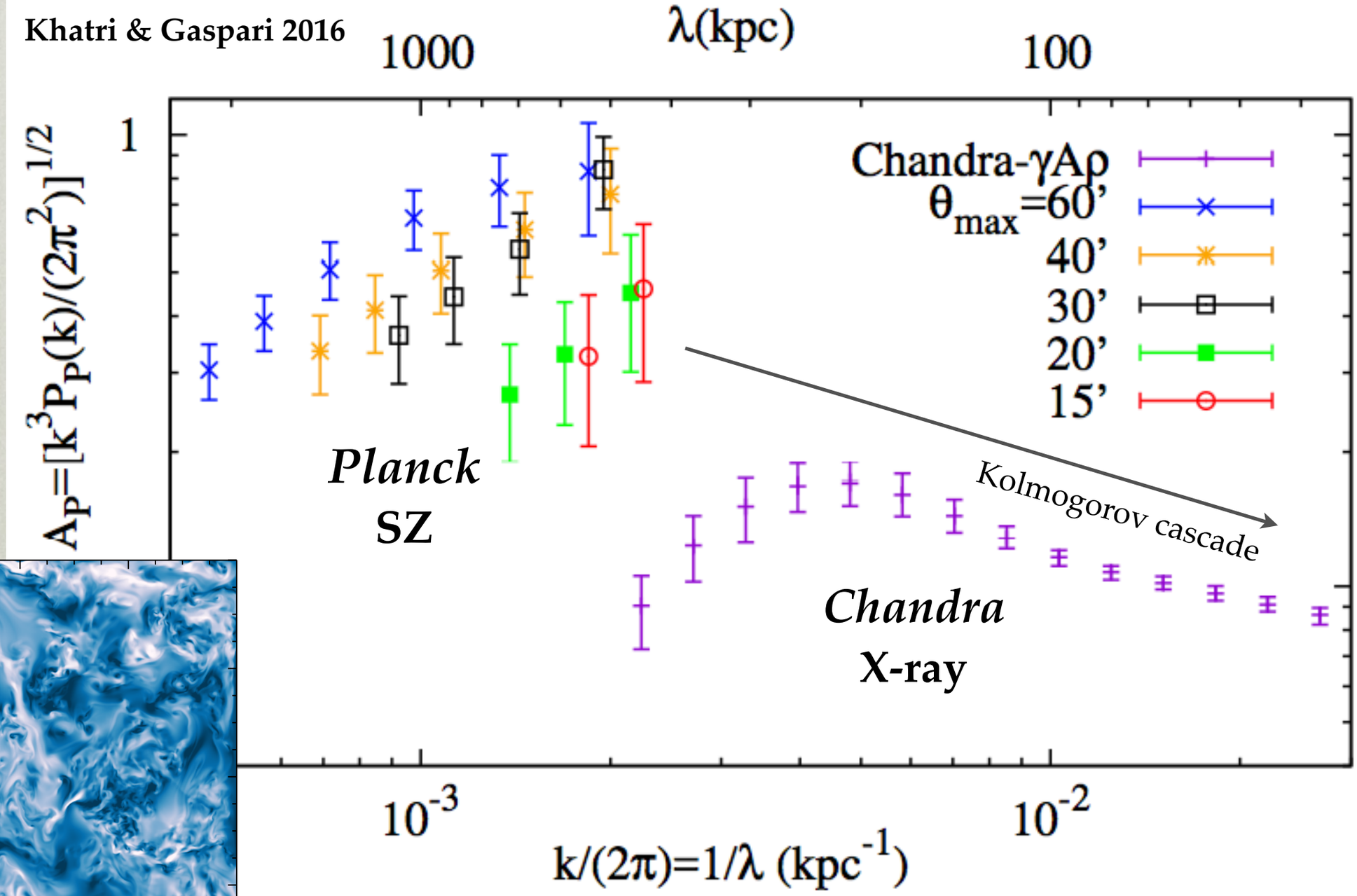
relaxed to unrelaxed clusters: Mach_{3D}~0.3-0.6

ICM POWER SPECTRUM

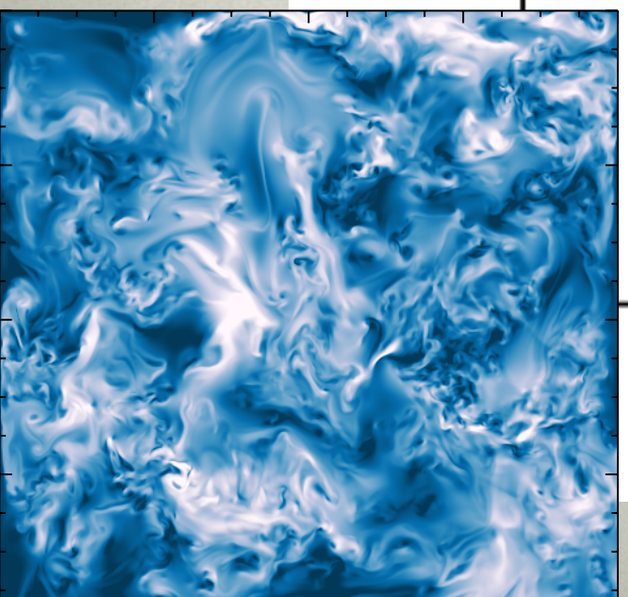
PROBING TURBULENCE & CONDUCTION

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

Khatri & Gaspari 2016



Coma cluster

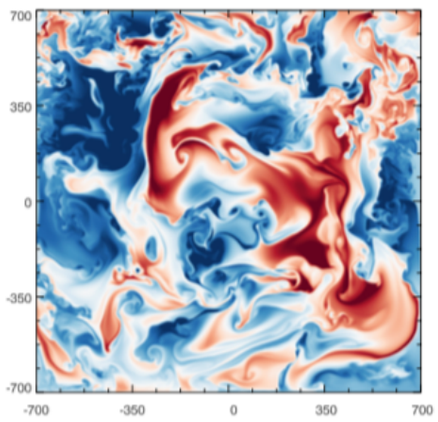


subsonic turbulence

Roncarelli, Gaspari, et al. 2018

A complete end-to-end X-IFU simulator

Simulated cluster



Emission model

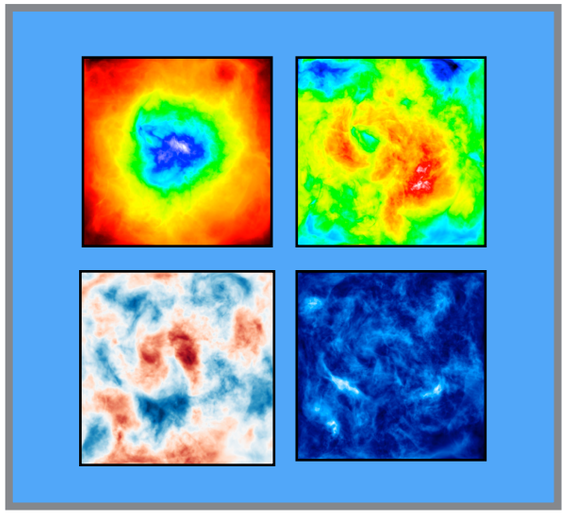
redshift

(x,y,E) data cubes

Z, n_H, t_{exp}

SIXTE

Projected ph. quantities



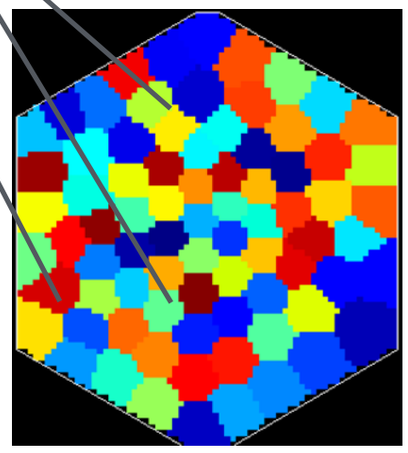
? ? ? ?

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

measured quantities

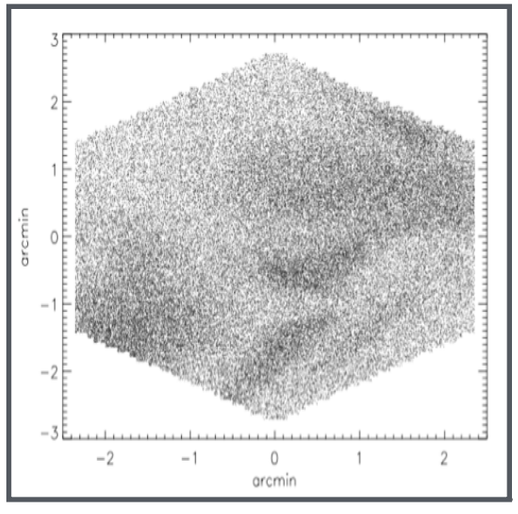
XSPEC fitting

PHA files



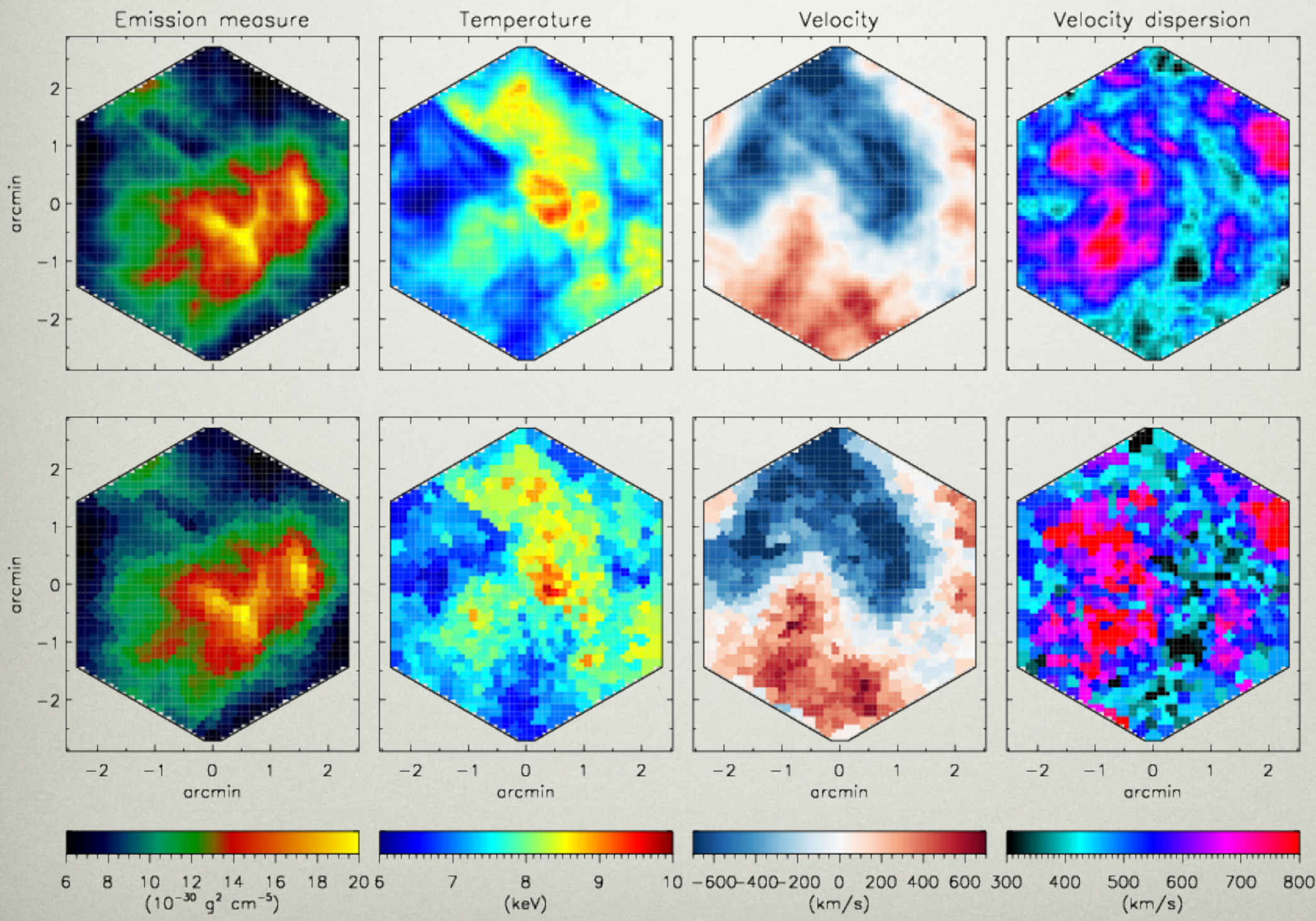
pixel grouping scheme

Mock X-IFU ev. list



ATHENA X-IFU

SYNTHETIC OBSERVATIONS



from
hydro simulation

synthetic

586 Voronoi tessellation (125 arcsec^2), exp. ~200 ks

uncertainties ~1-10%

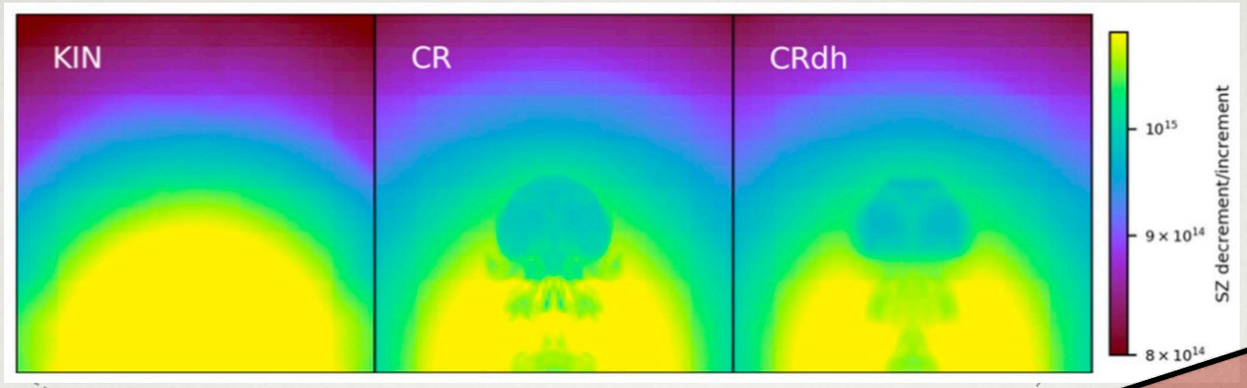
Roncarelli, Gaspari, et al. 2018

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

"Black Hole Weather" discussed areas

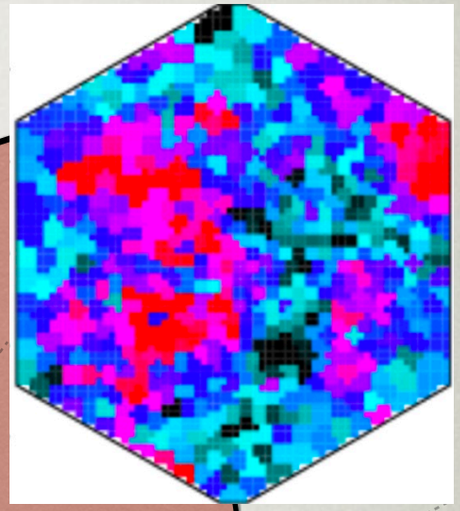
Yang, Gaspari, Marlow 2019

X-ray/SZ AGN bubbles + cosmic rays



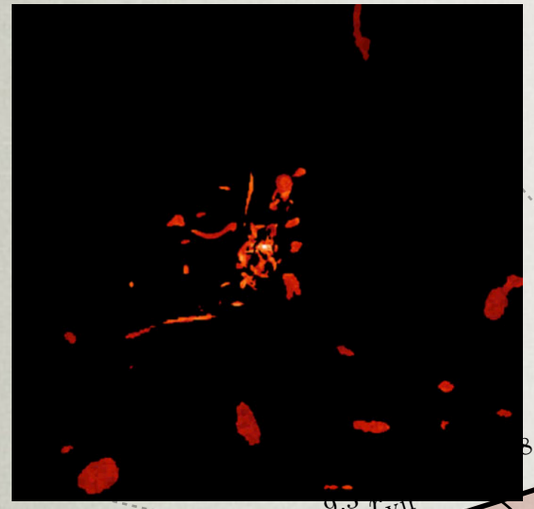
Roncarelli, Gaspari+2018

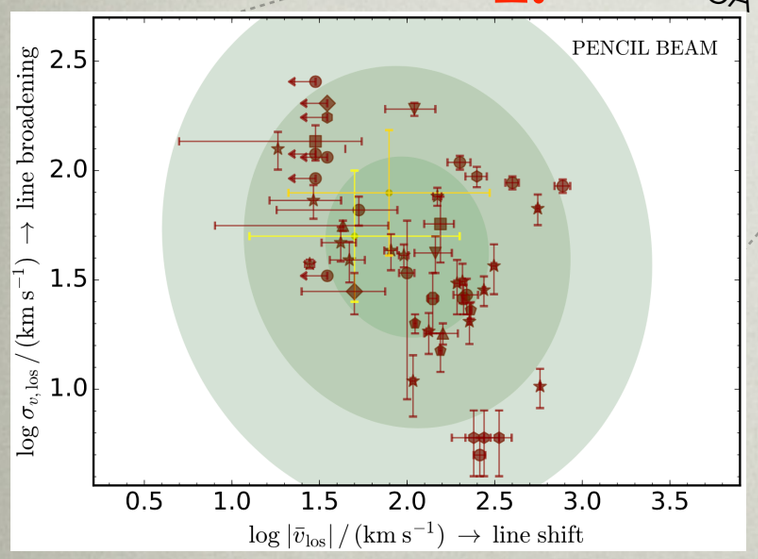
merger-driven turbulence (*Athena*)



Gaspari+2017

CCA flickering

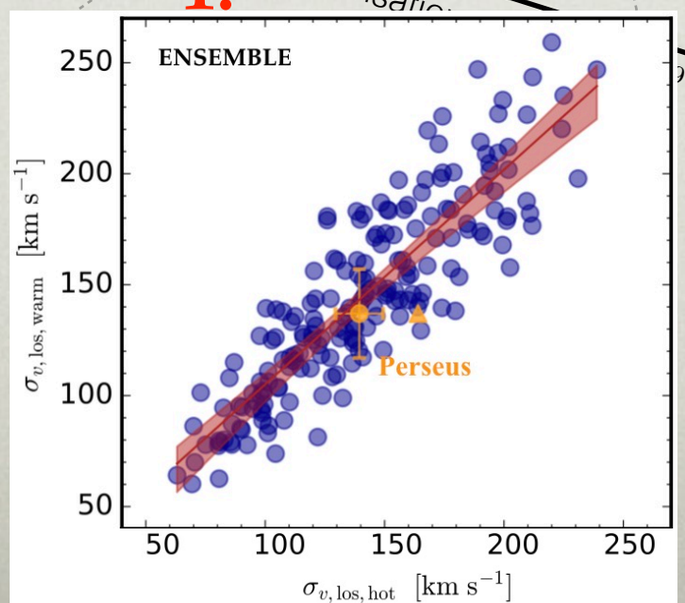


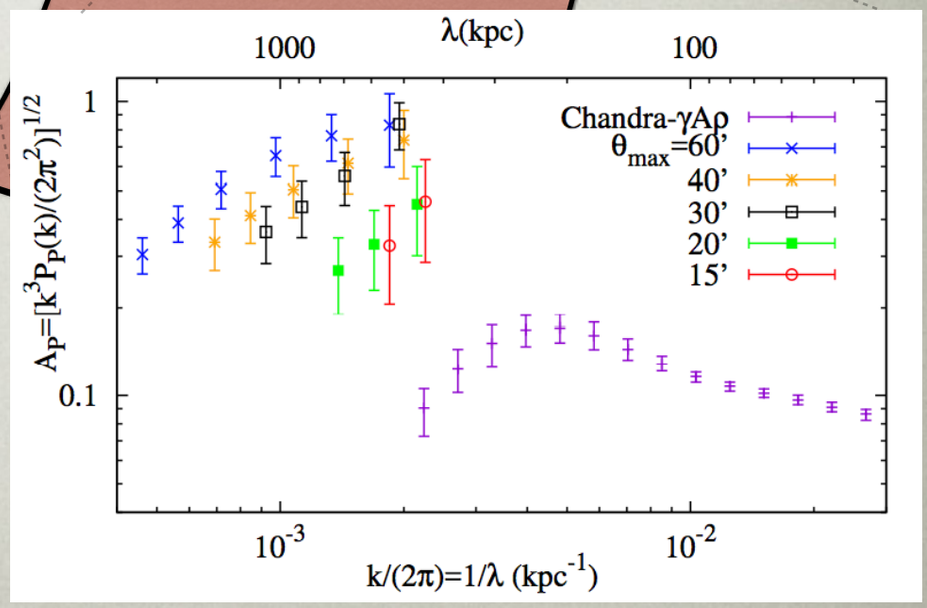


molecular clouds feeding *BH shadows*

Gaspari+2018

warm filaments/hot gas correlations





turbulence and conduction via ICM PS

Gaspari+2013/2014, Khatri & Gaspari 2016