ADVANCEMENTS IN CHAOTIC COLD ACCRETION & MULTIPHASE CONDENSATION

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SELF-REGULATED AGN FEEDBACK

SMR zoom-in 3D hydro simulations (FLASH)

FEEDING

- cold vs hot mode
- linking 100 kpc scale to sub-pc scale
- beyond Bondi and thin disc assumptions
- physics interplay, e.g., heating vs cooling (plasma, **neutral**, and **molecular**)
- dynamical stages: rotation vs turbulence **chaotic cold accretion [CCA]**

MG+2013-2016 sims
galactic 52 kpc --> 20 R_s
short term: < 80 Myr

FEEDBACK

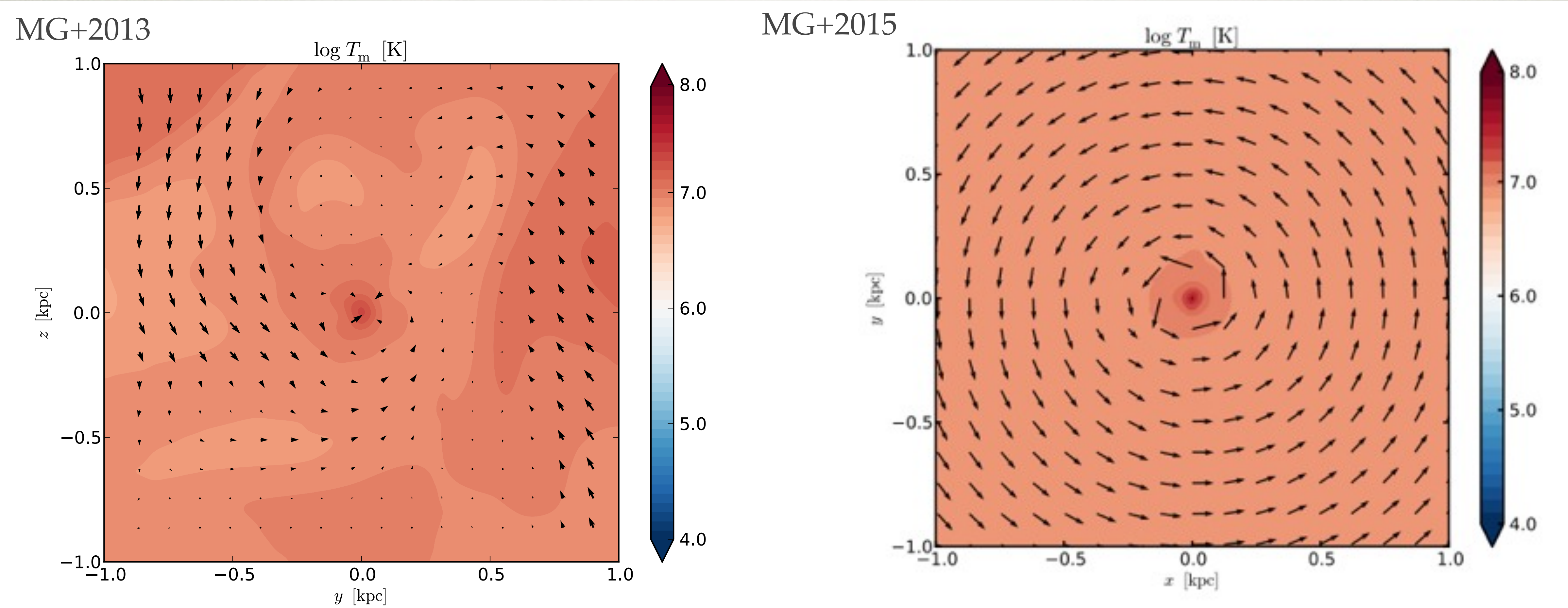
- amount of energy released
- deposition of energy
- mechanical versus thermal
- buoyant bubbles, shocks, metal uplift, turbulence and mixing
- scaling relations (L_x-T_x, ...)

MG+2009-2015 sims
large scales: 100 pc --> 2 Mpc
long term: > 7 Gyr

SELF-REGULATED LOOP

$$P_{\rm out} = \epsilon \, \dot{M}_{\rm BH} c^2$$

HOT ACCRETION



rotation < **turbulence**

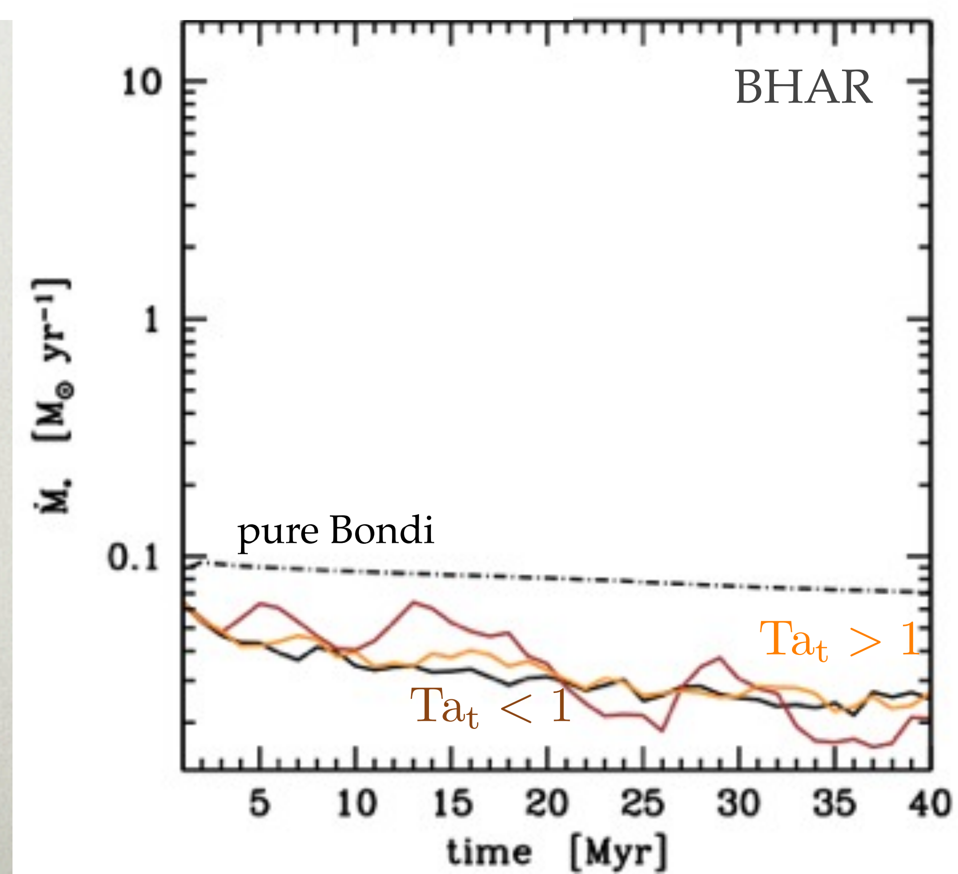
$\mathrm{Ta_t} \equiv v_{\rm rot}/\sigma_v < 1$

$\sigma_v \sim 100\,\mathrm{km\,s^{-1}}$

rotation > turbulence

$\mathrm{Ta_t} \equiv v_{\rm rot}/\sigma_v > 1$

$v_{\rm rot,gas} \approx 100\ \mathrm{km\,s^{-1}}$



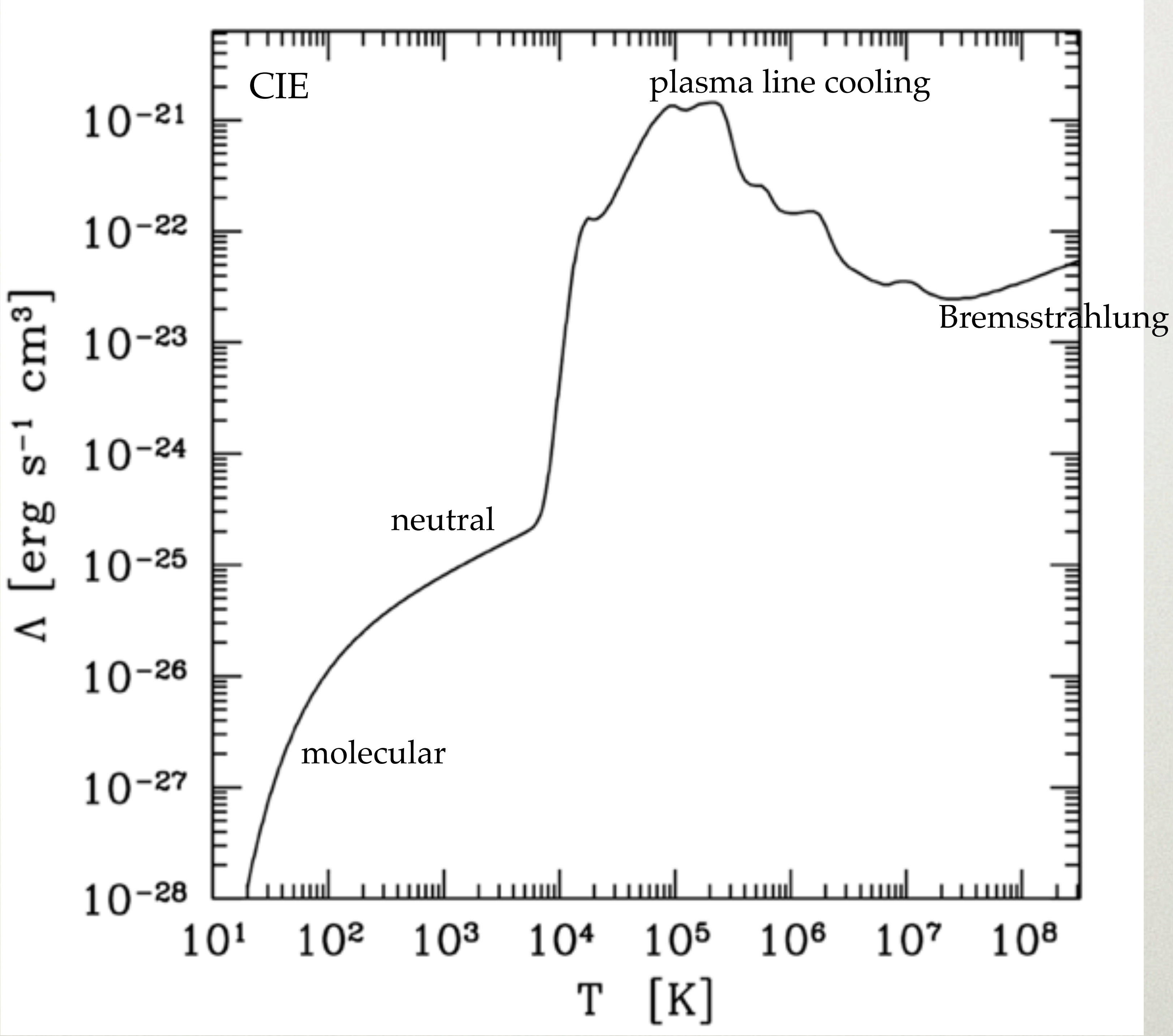
massive ETG (NGC 5044)

SMBH: $M_{bh} = 3\times10^9\ M_\odot$

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

in all cases: suppressed Bondi
highly inefficient BHAR

RADIATIVE COOLING

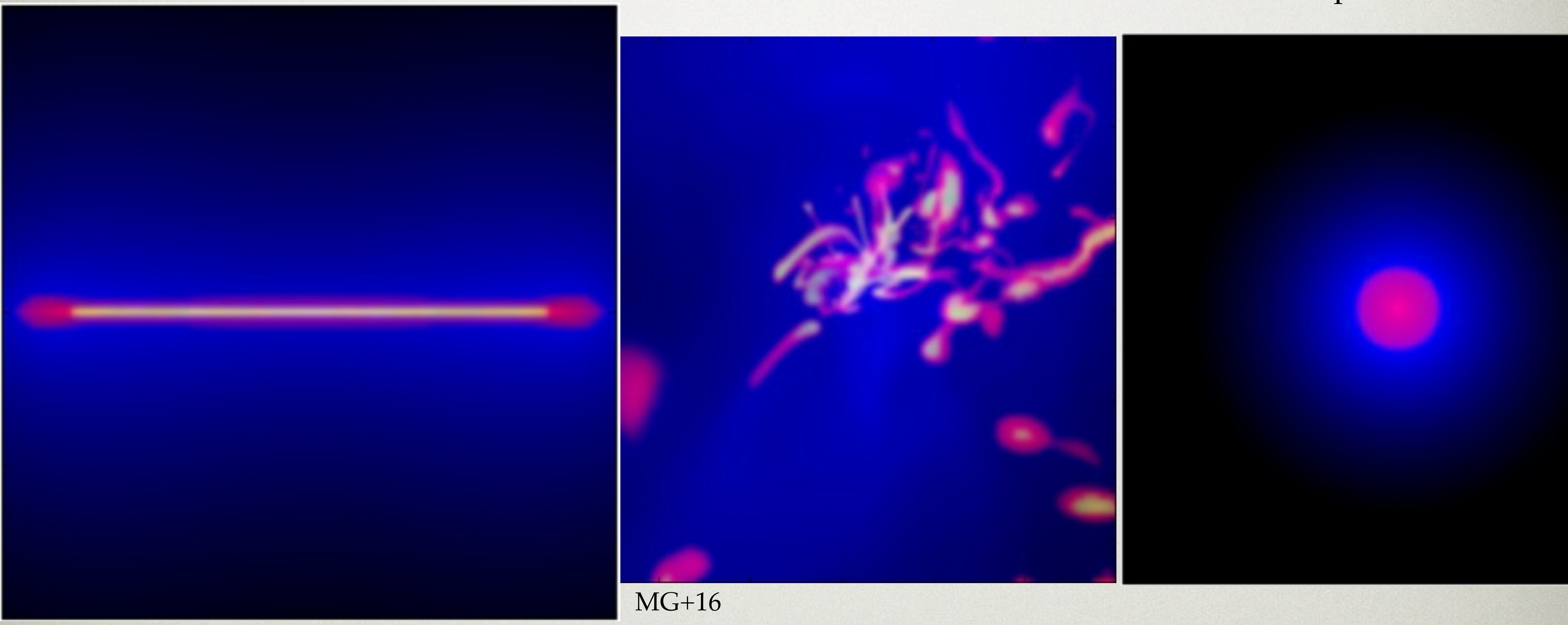


Gaspari, Brighenti, & Temi (2016)

COOLING CURVE

DYNAMICAL STAGES

rotating chaotic spherical



MG+16

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

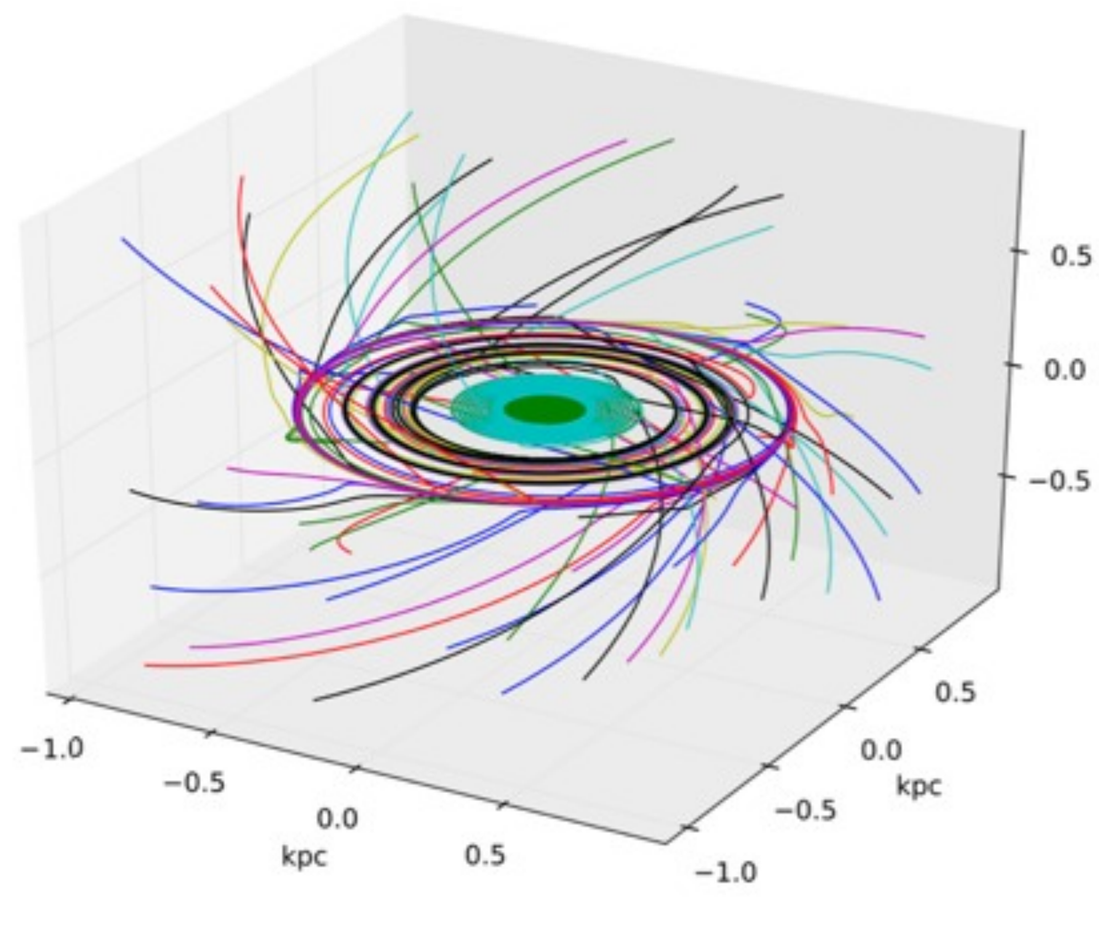
MULTIPHASE DISC

ROTATION + COOLING

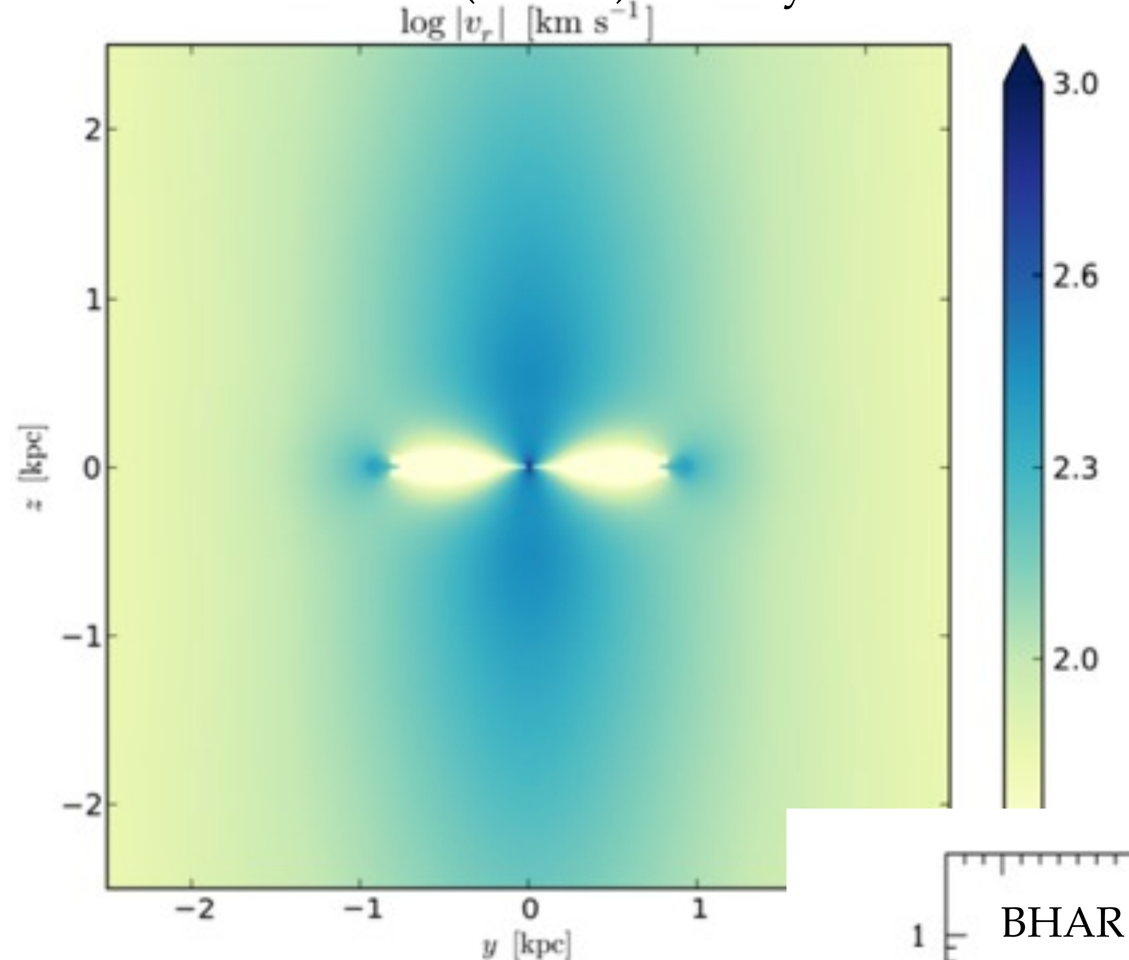
$\mathrm{Ta_t} > 1$

MG+2016

streamlines

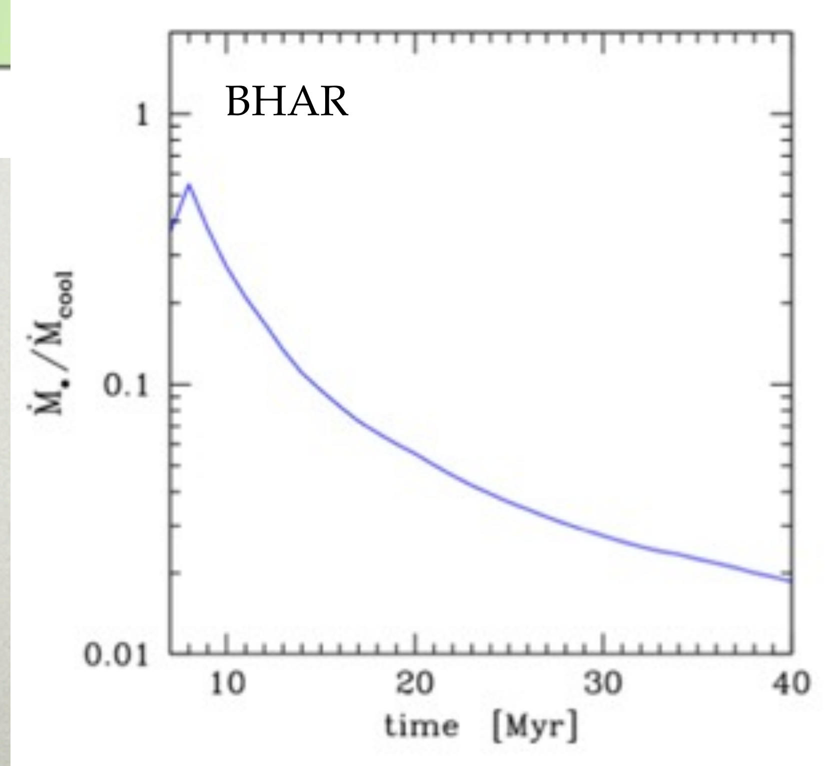


radial (inflow) velocity



equatorial circularization

accretion through <10° polar funnel



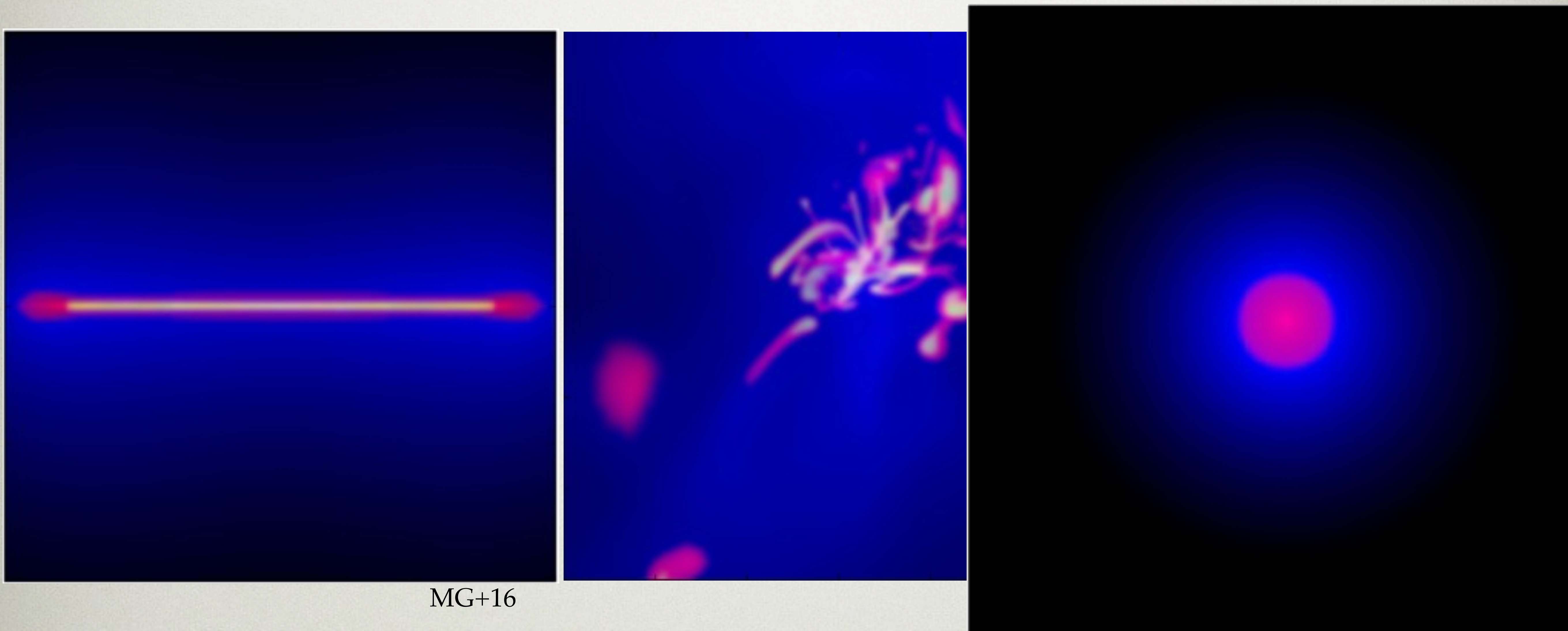
helical condensation forming a stratified disc

Young+11 (ATLAS[3D]): ~1/3 of ETGs have an inner CO disc

2 dex BHAR suppression compared with cooling rate

DYNAMICAL STAGES

rotating chaotic spherical

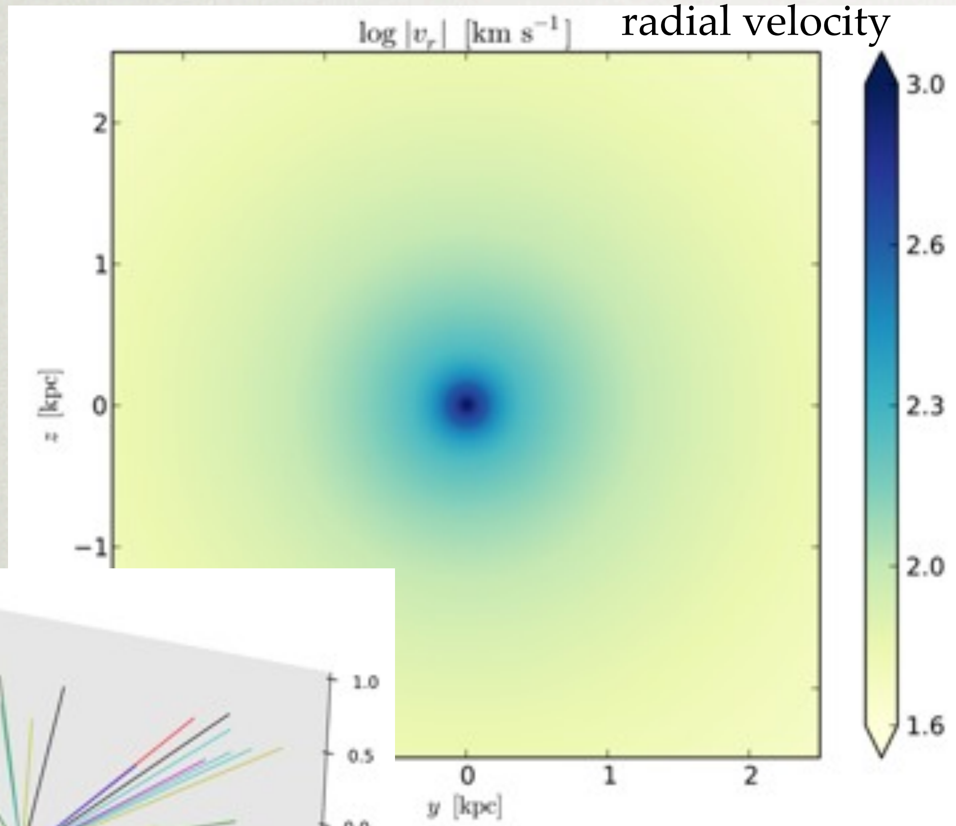


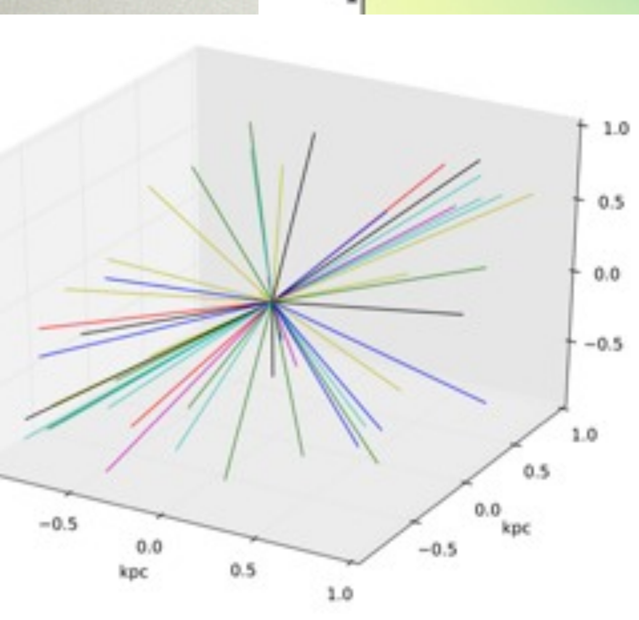
MG+16

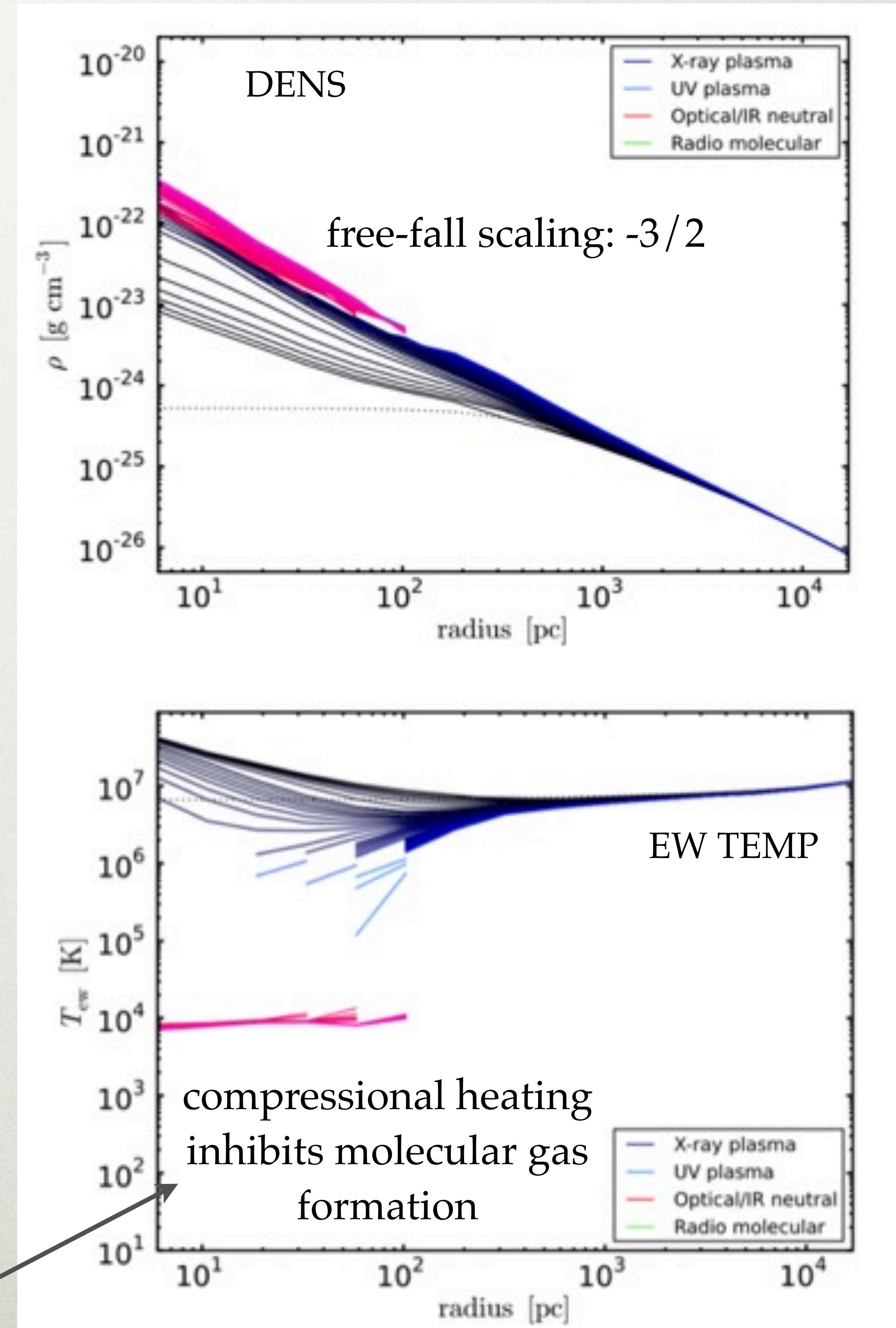
RGB surface density: plasma (blue), warm gas (red), cold gas (green)

MULTIPHASE COOLING FLOW

NO ROTATION + COOLING







$$\dot{M}_{BH} \simeq \dot{M}_{\rm cool}$$

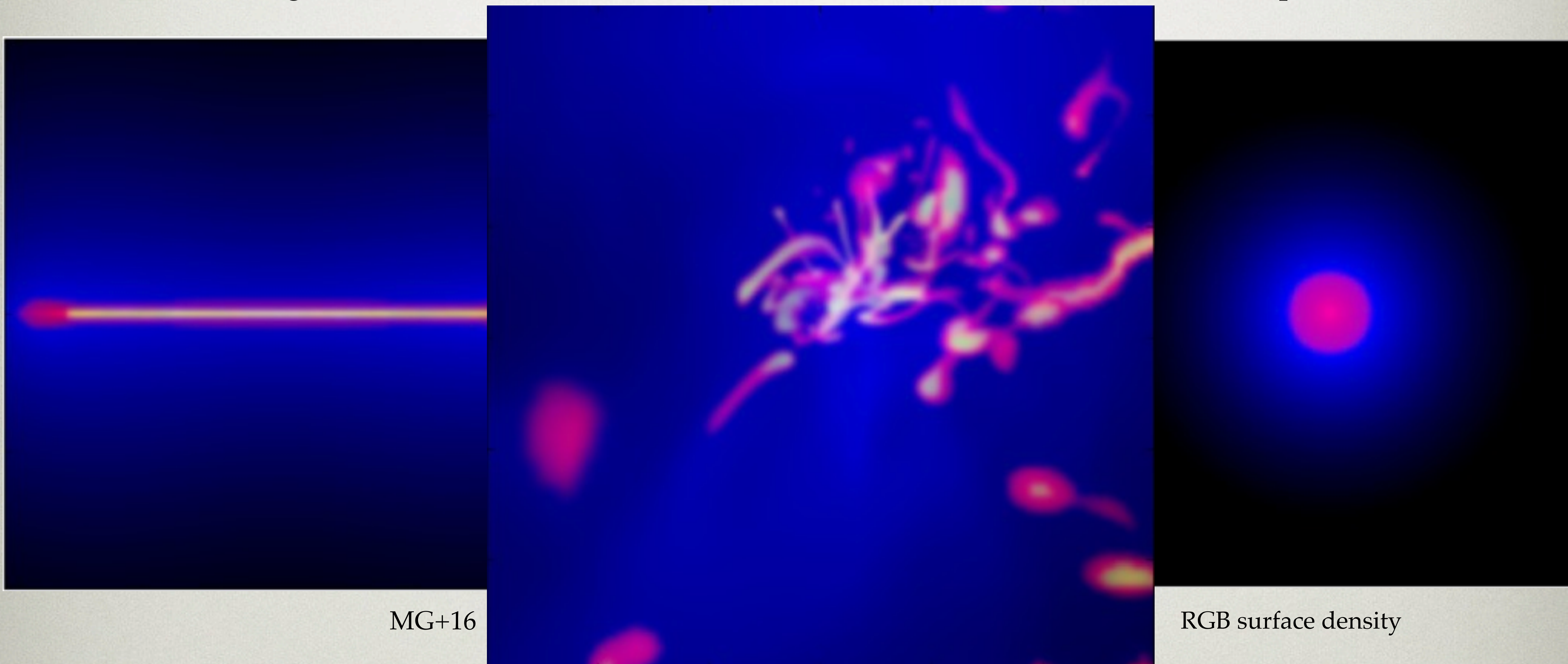
Werner+12-14: quiescent ETGs typically have a compact Hα core

Young+11 (ATLAS[3D]) : quiescent galaxies have low CO detection rates

$$\mathcal{H}_{\rm comp} \equiv -P\,(\boldsymbol{\nabla}\cdot\boldsymbol{v}) = -P\,\frac{v_r}{r}\left(\frac{\partial \ln v_r}{\partial \ln r}+2\right) \approx \frac{3}{2}\,P\,\frac{v_{\rm ff}}{r} > \mathcal{L}_{\rm cold}$$

DYNAMICAL STAGES

rotating | chaotic [CCA] | spherical



MG+16 | RGB surface density

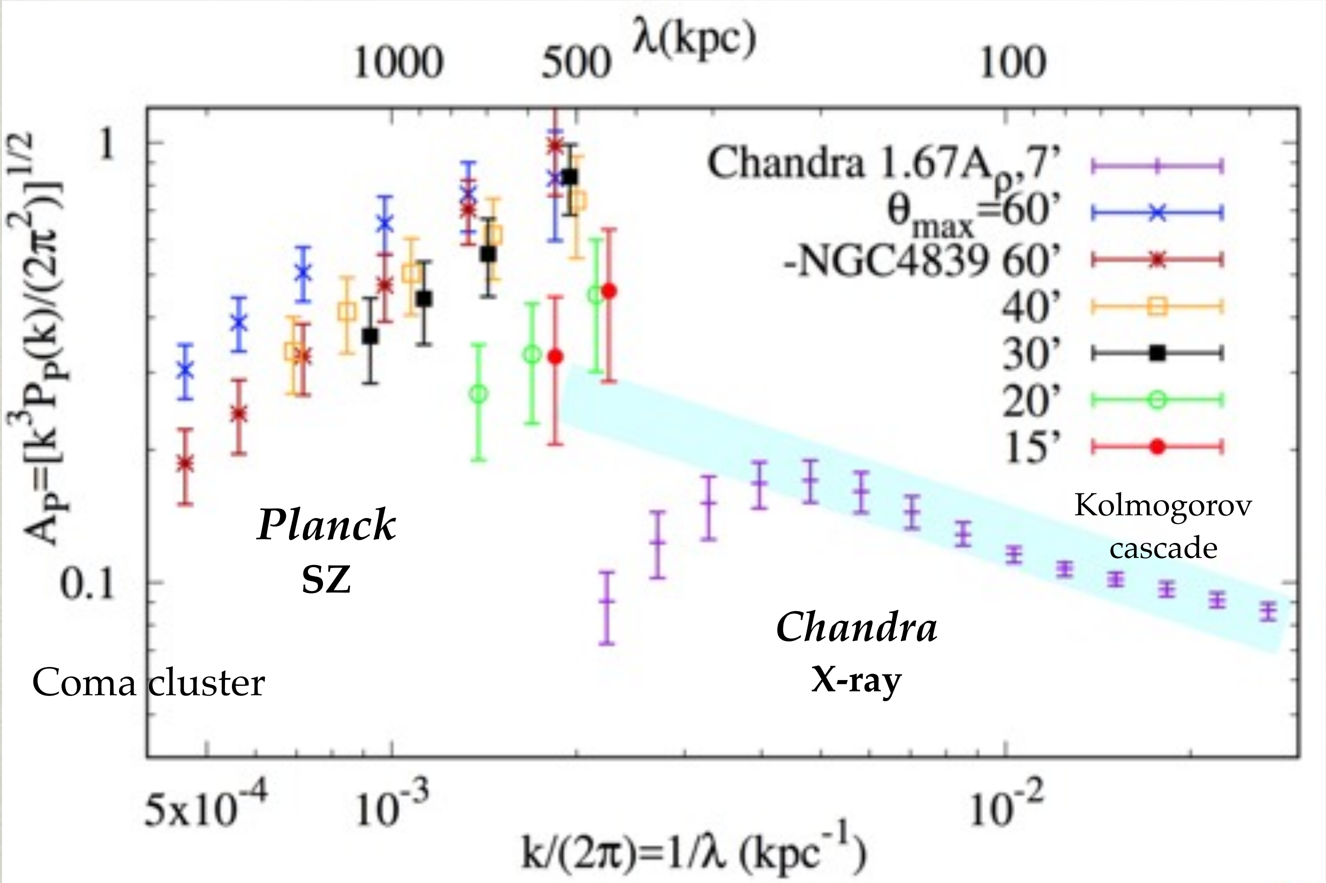
Since 2012, CCA has been corroborated and extended by several independent observational and theoretical/simulation studies: e.g., Voit & Donahue 2015, Voit 2015a,b,c, 2016; Werner+14; David+14; Li & Bryan 2014, 2015; Wong+2014; Russell +2015; Valentini & Brighenti 2015; Yang+2015; Meece+2016; Tremblay+2015, 2016; etc.

TURBULENCE IN HOT HALOS

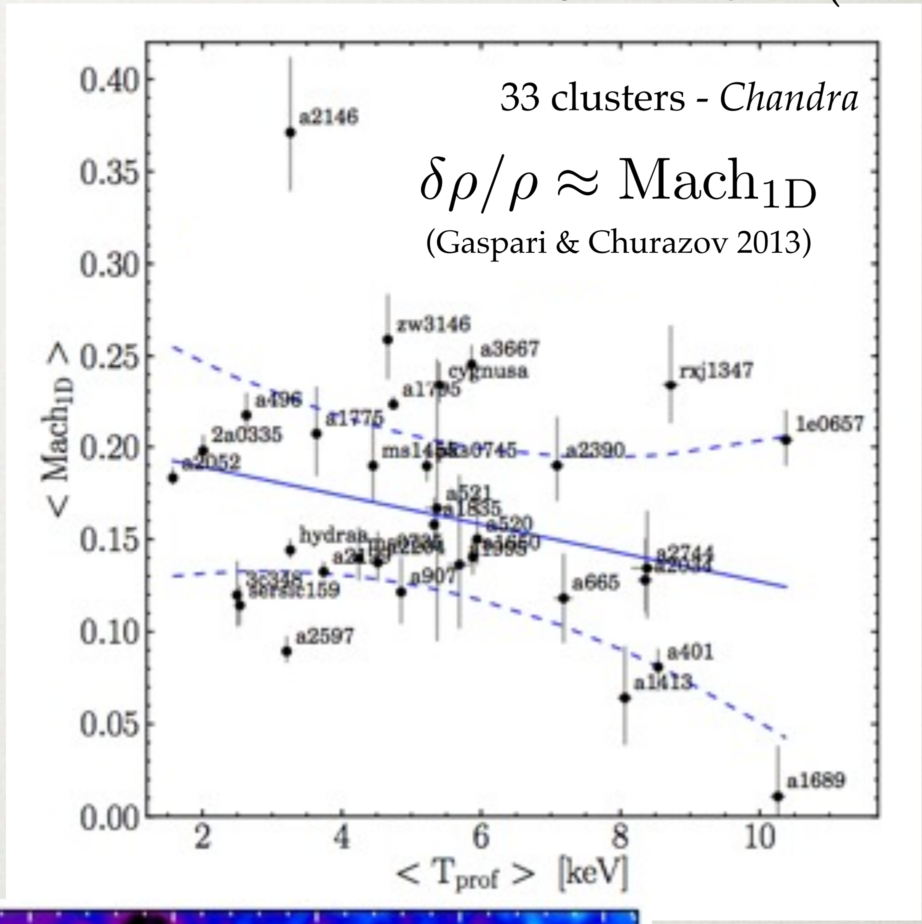
AGN feedback, SNe, mergers, galaxy/group infall

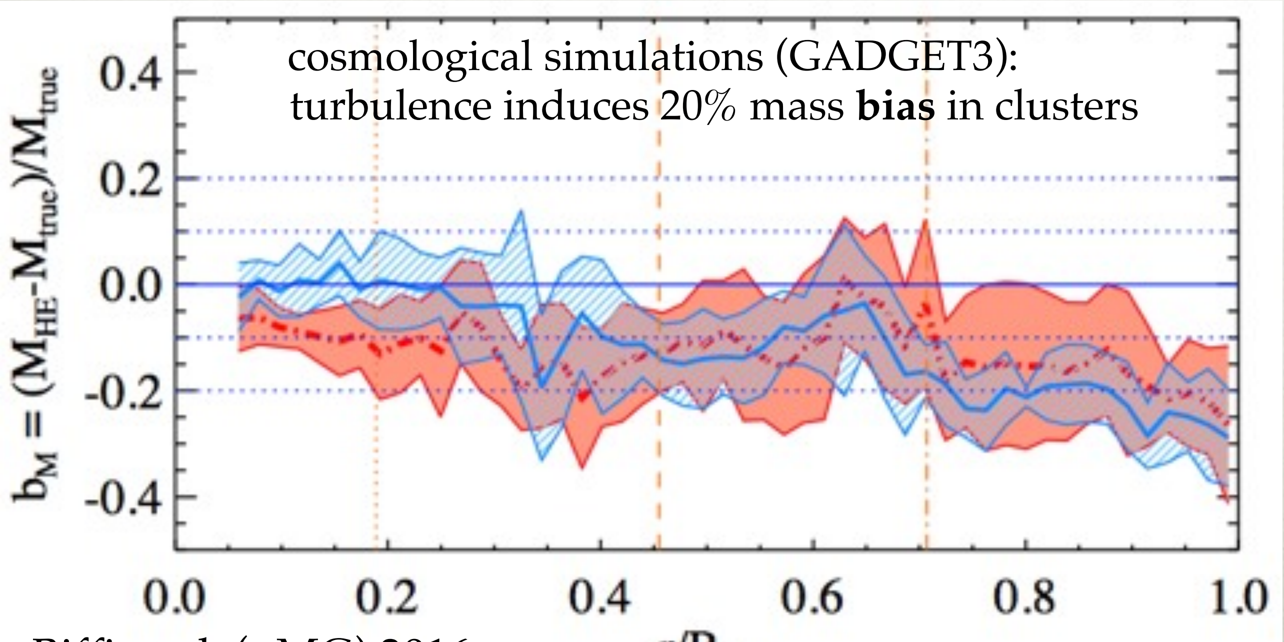
Besides *Hitomi* detection of 164 ± 10 km/s velocity dispersion in Perseus...
we aimed to probe the perturbation physics of hot halos from other angles and methods

Khatri & Gaspari 2016

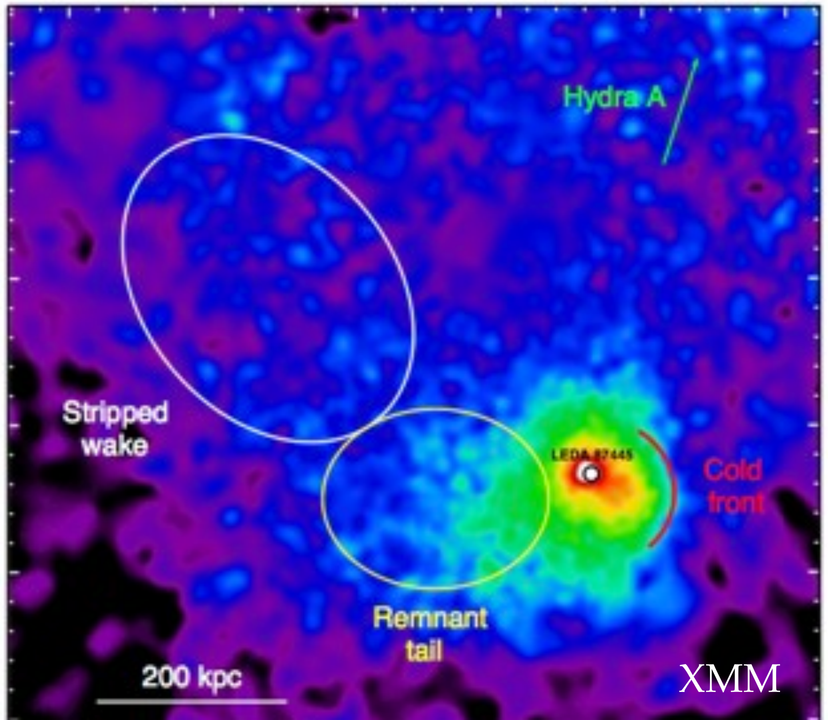


Hofmann et al. (+MG) 2016





Biffi et al. (+MG) 2016



De Grandi et al. (+MG) 2016

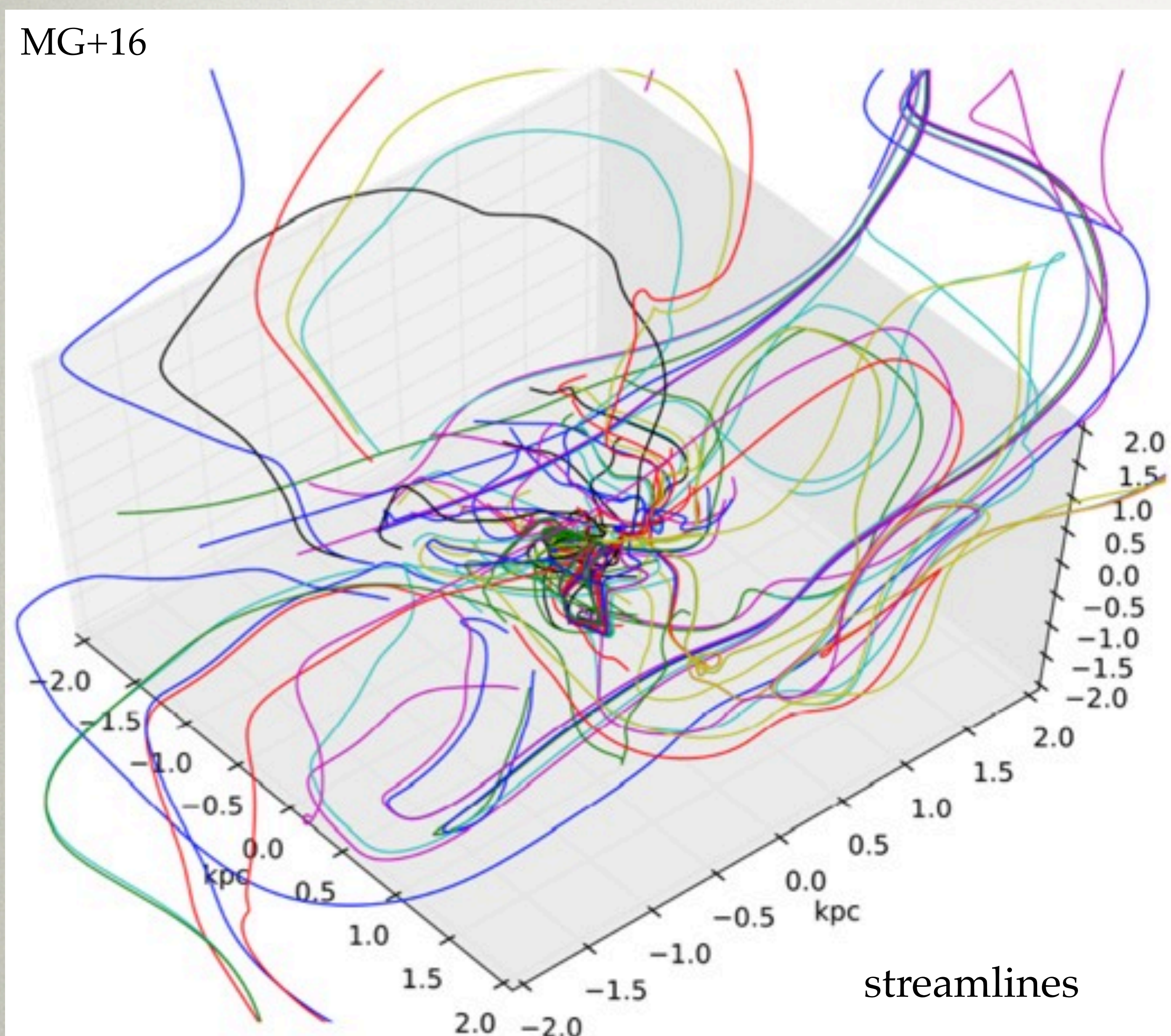
group falling into a massive cluster

MULTIPHASE CCA

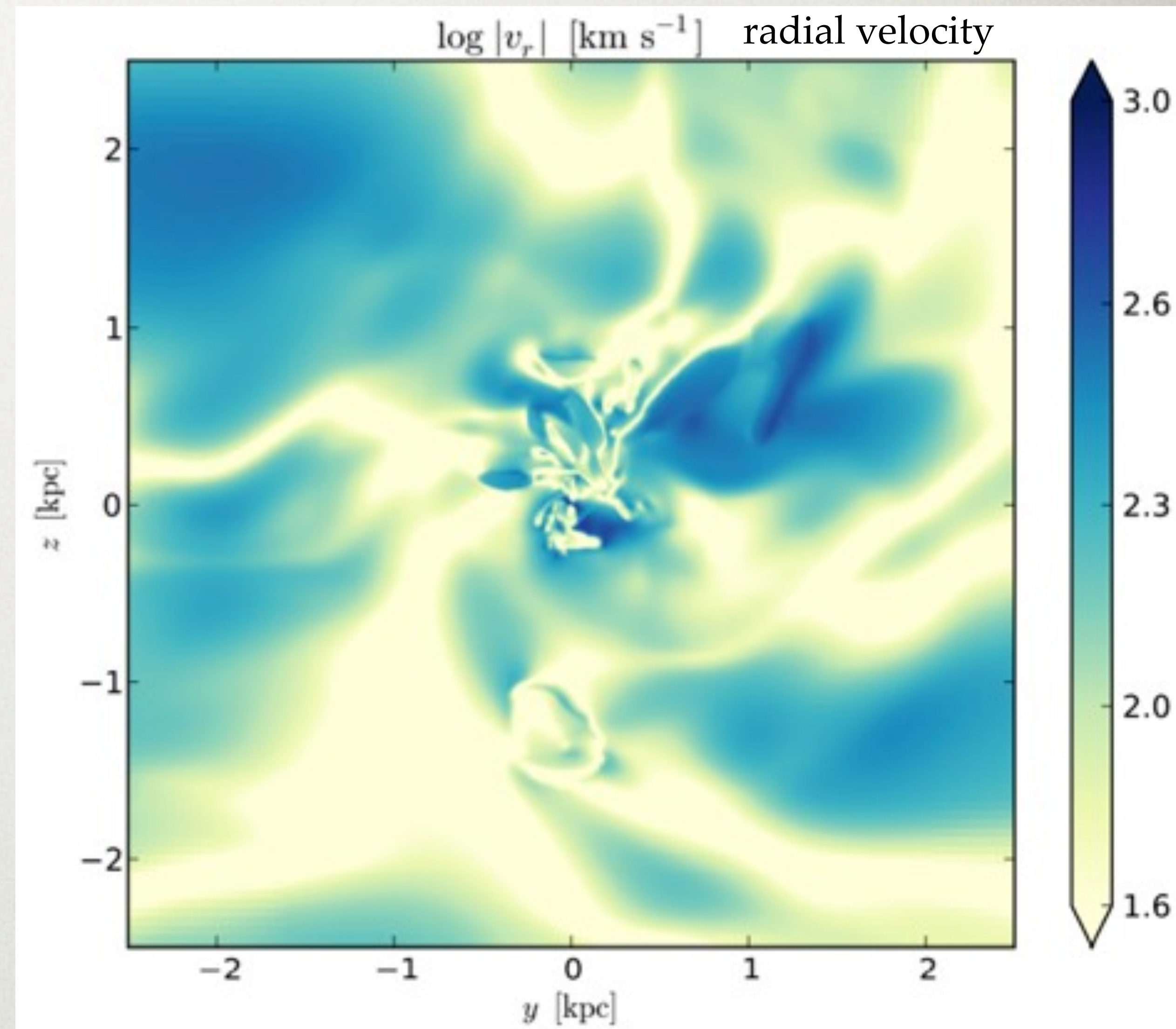
DYNAMICS

ROTATION + COOLING + TURBULENCE + AGN HEATING => Chaotic Cold Accretion [CCA]

$\sigma_v \sim 160$ km/s $\qquad \mathcal{H} \sim \langle \mathcal{L} \rangle$



chaotic motions => recurrent multiphase gas interactions



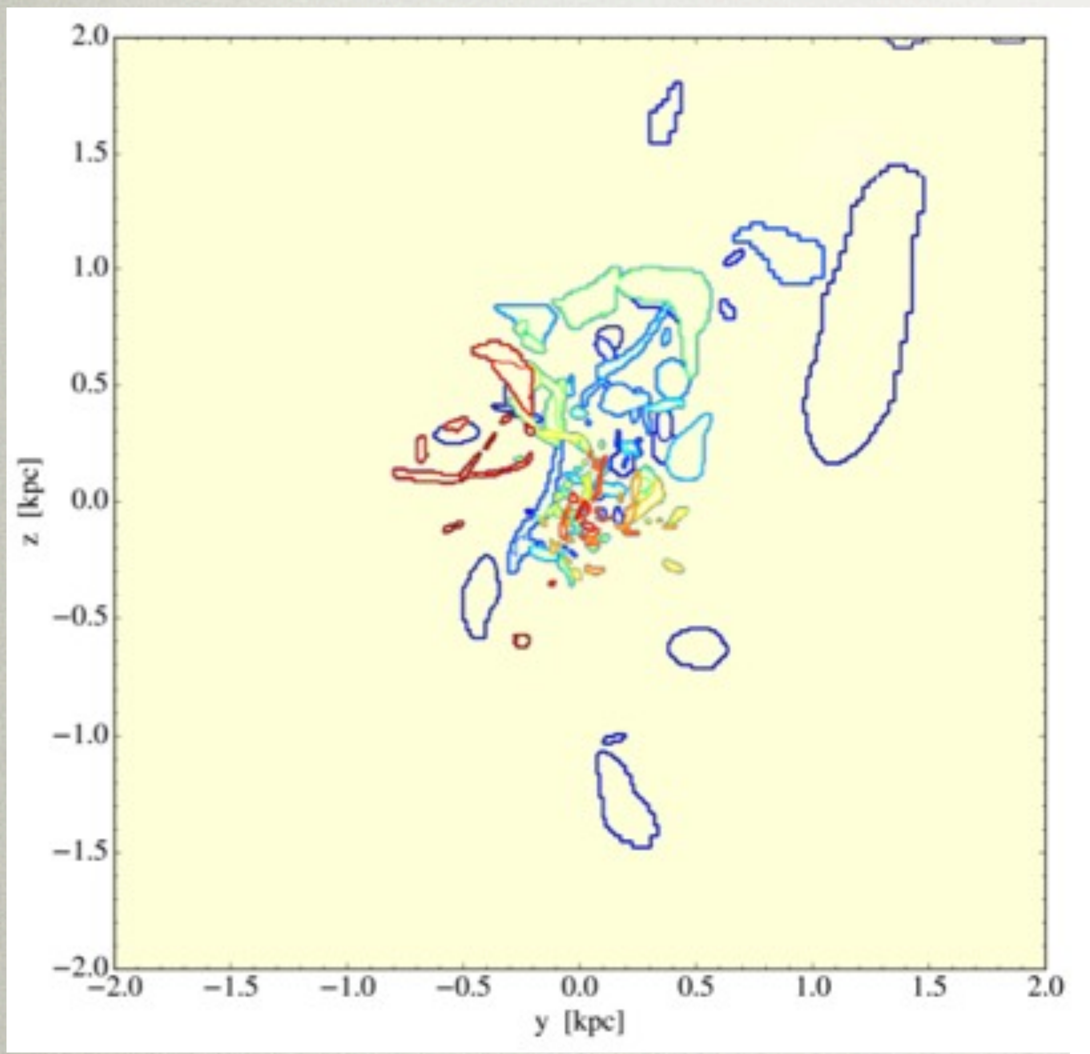
turbulent eddies

injected turbulence ~160 km/s
(similar to *Hitomi* detection)

MULTIPHASE CCA

CLUMPS

MG+16

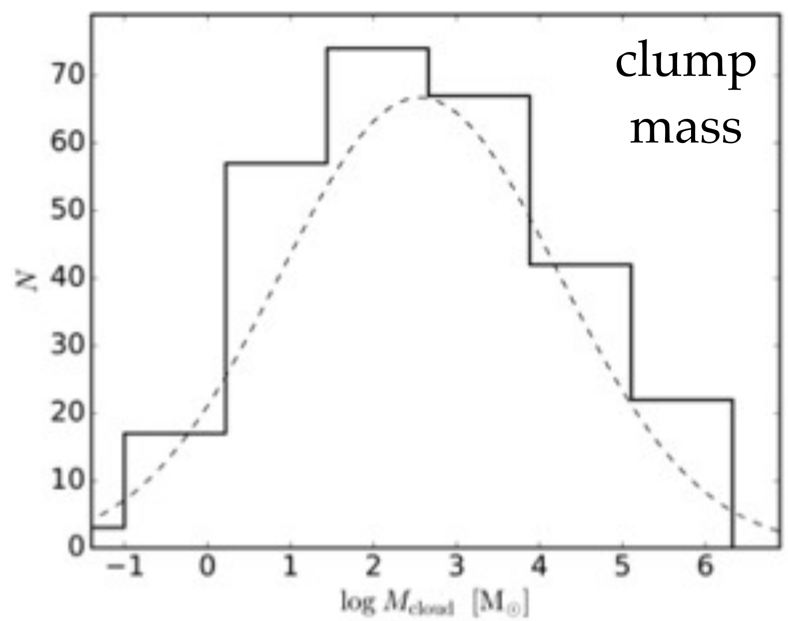


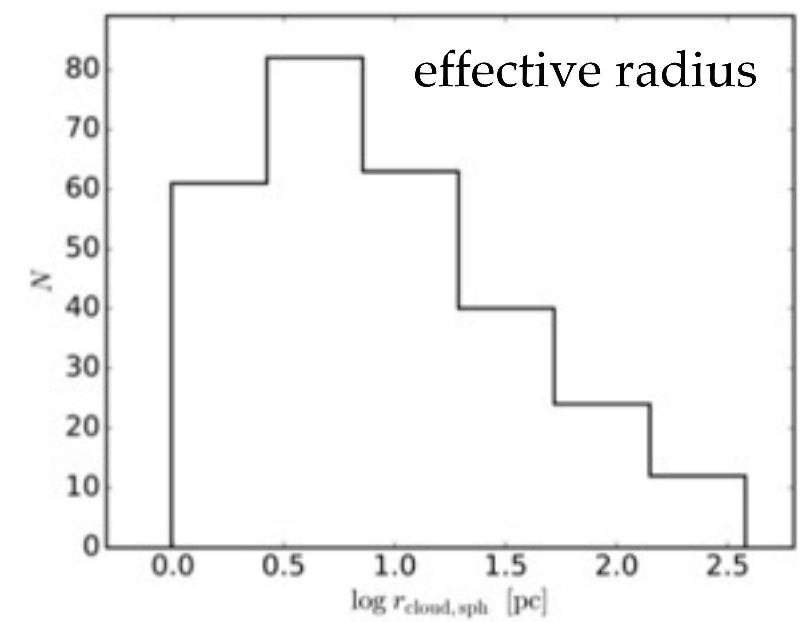
$$\lambda_c \equiv \frac{1}{n_c\,\pi(2\,r_c)^2} = \frac{1}{3}\frac{r_c}{f_V} \simeq 88^{+262}_{-67}\ \mathrm{pc}$$

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

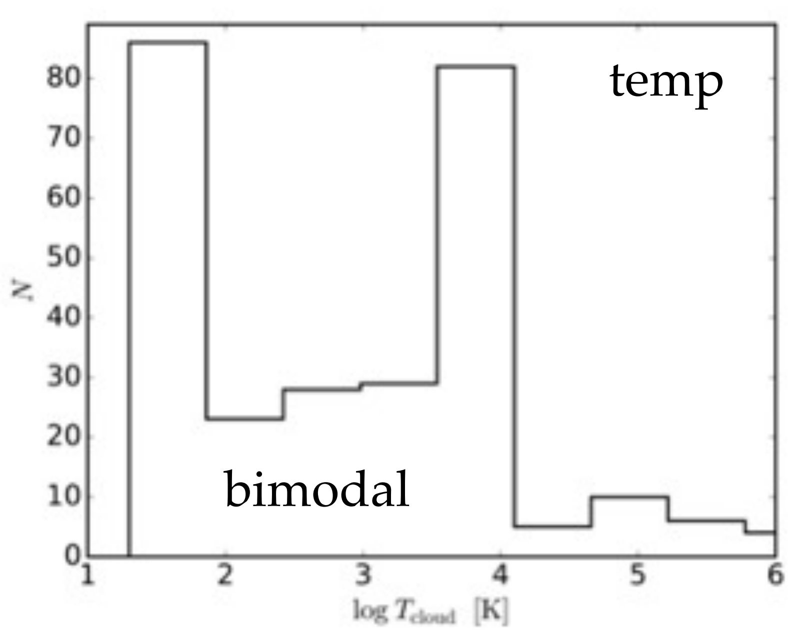
$$\dot{M}_\bullet = 4.8\times10^{-3}\,\nu_c \simeq 0.3^{+0.9}_{-0.2}\ \mathrm{M_\odot\,yr^{-1}}$$

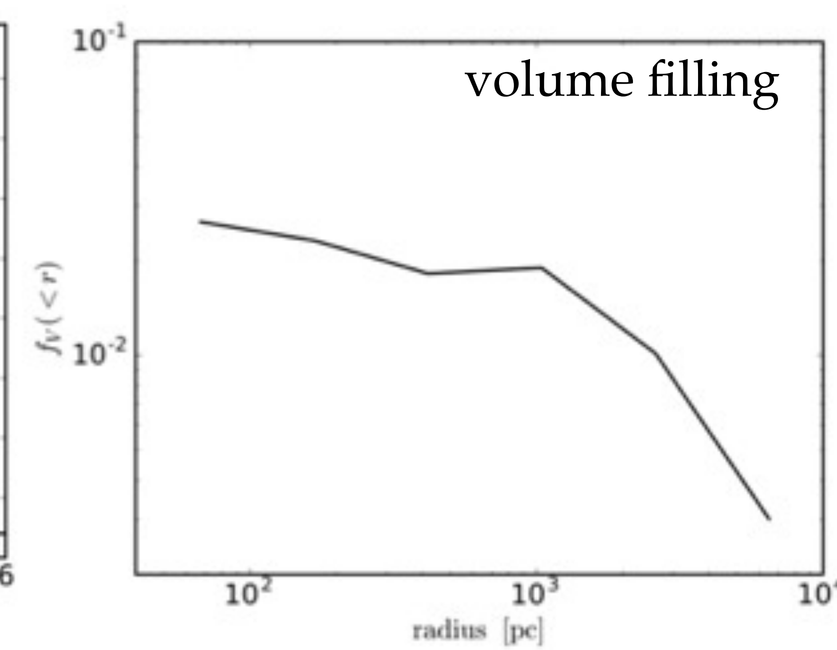
modeled as quasi-spherical viscous accretion





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

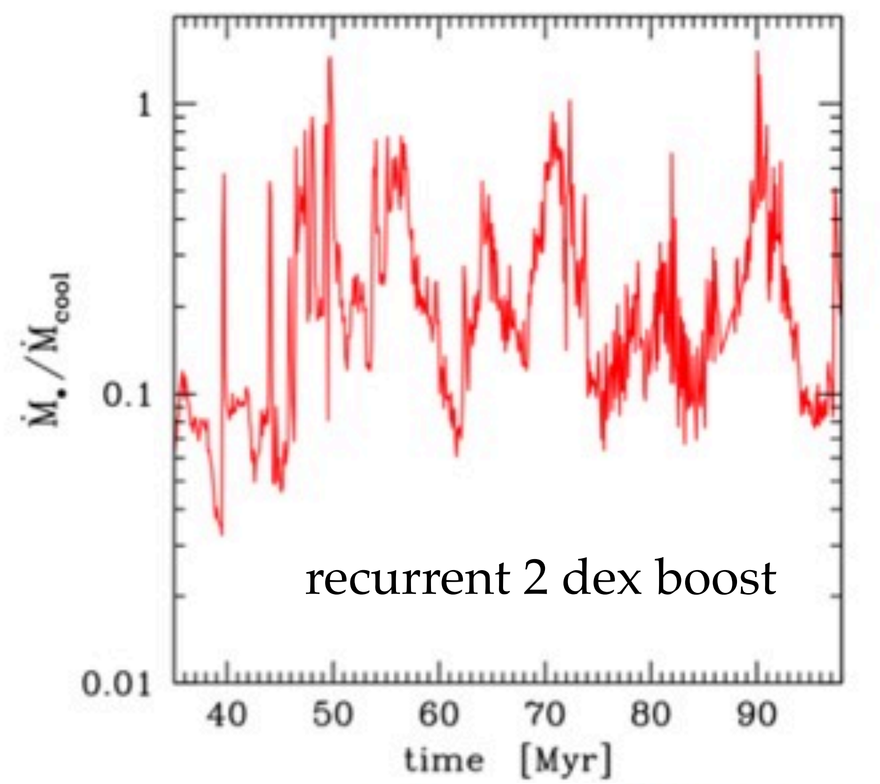




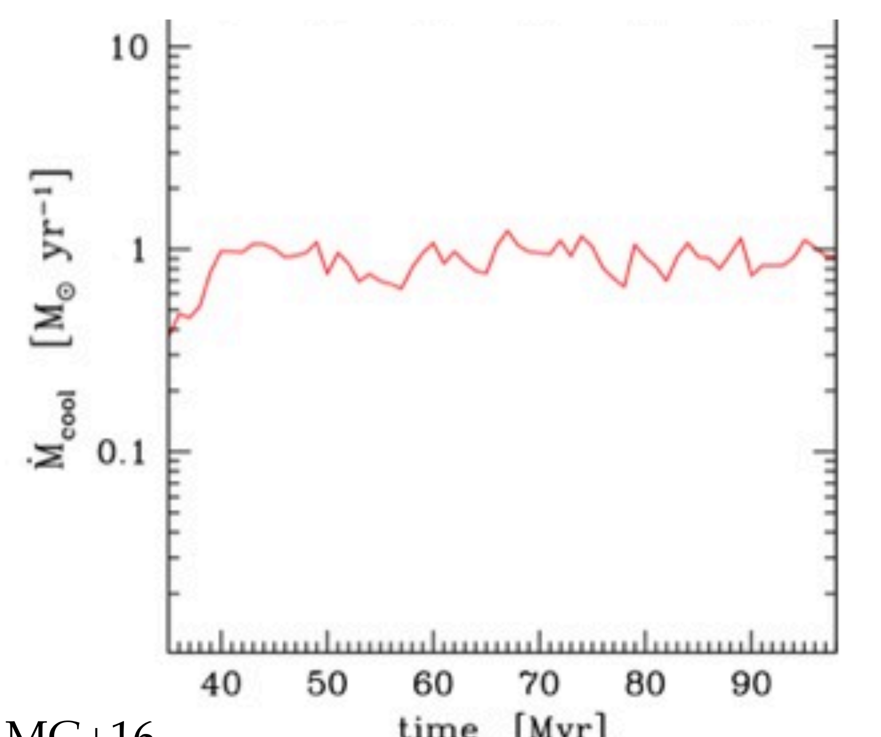
MULTIPHASE CCA

BHAR

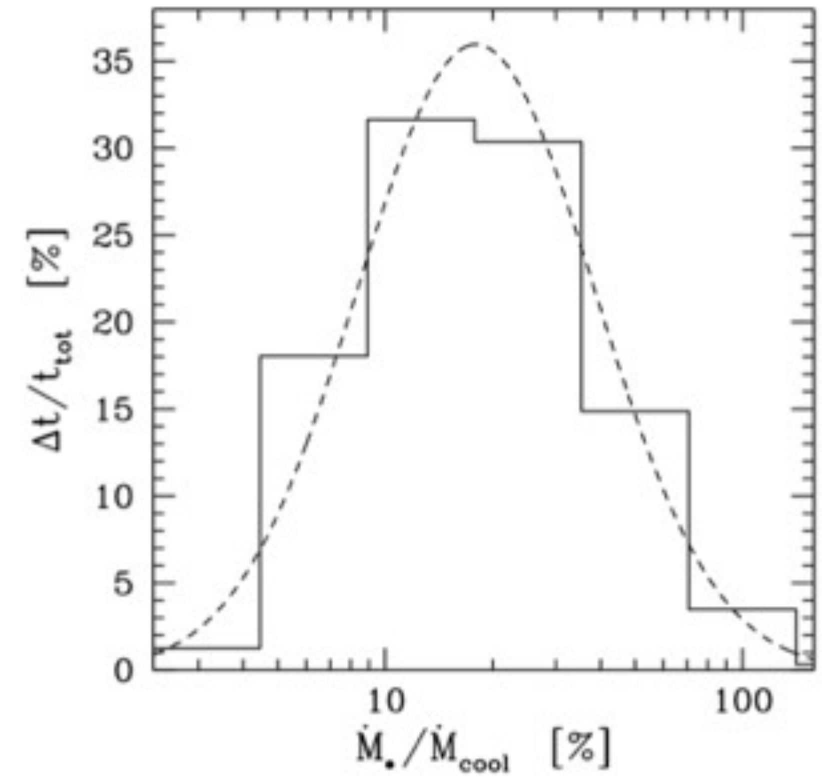
lognormal PDF; turbulence drives the same PDF in fluctuations

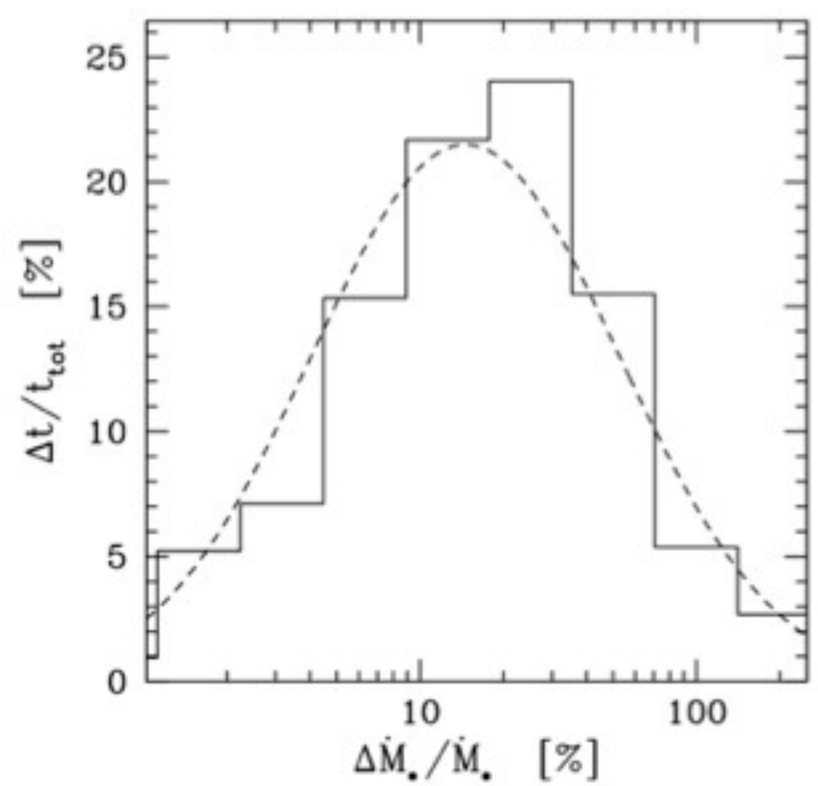


$$\dot{M}_\bullet = 4.8\times10^{-3}\,\nu_c \simeq 0.3^{+0.9}_{-0.2}\ \mathrm{M_\odot\,yr^{-1}}$$



MG+16



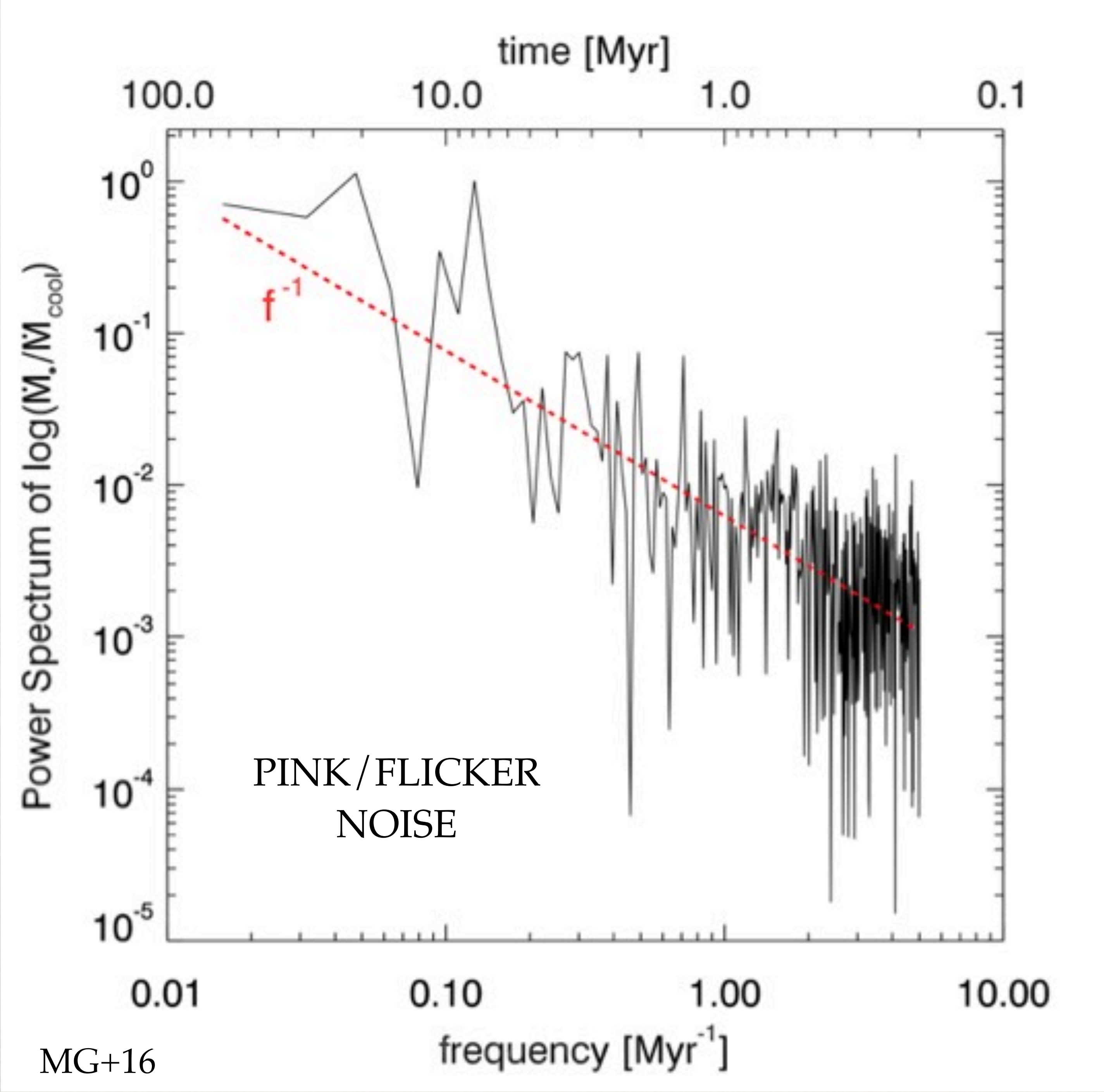


CCA rain - strong similarities with Earth rain

BHAR variation PDF ~ BHAR PDF => fractal

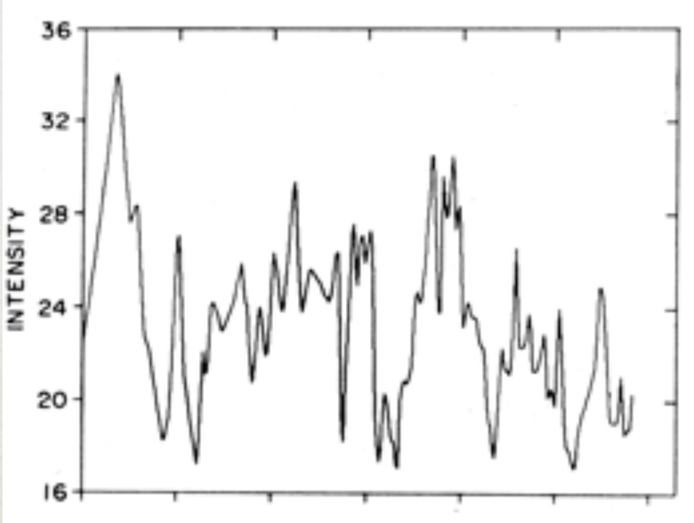
MULTIPHASE CCA

VARIABILITY



can explain ubiquitous rapid AGN and HMXBs variability

beautiful case: 3C273
Press (1978)

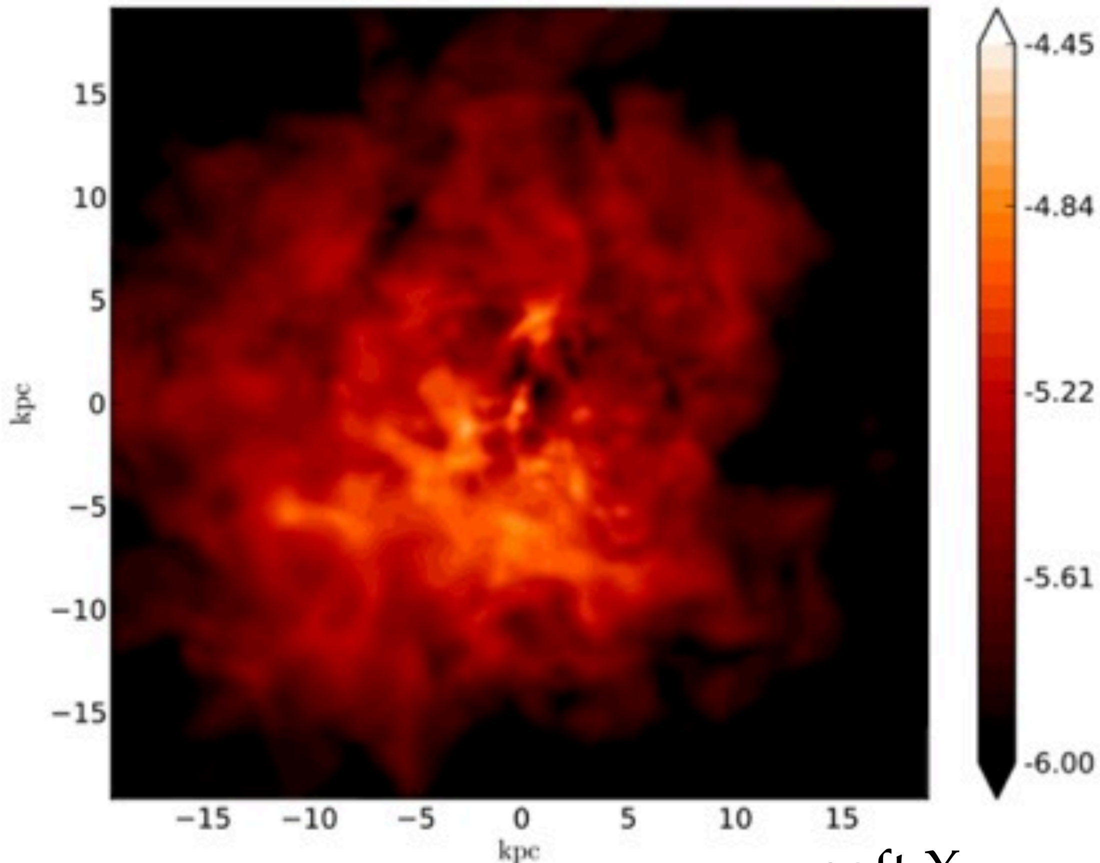


see MG16 for detailed list of variable AGN

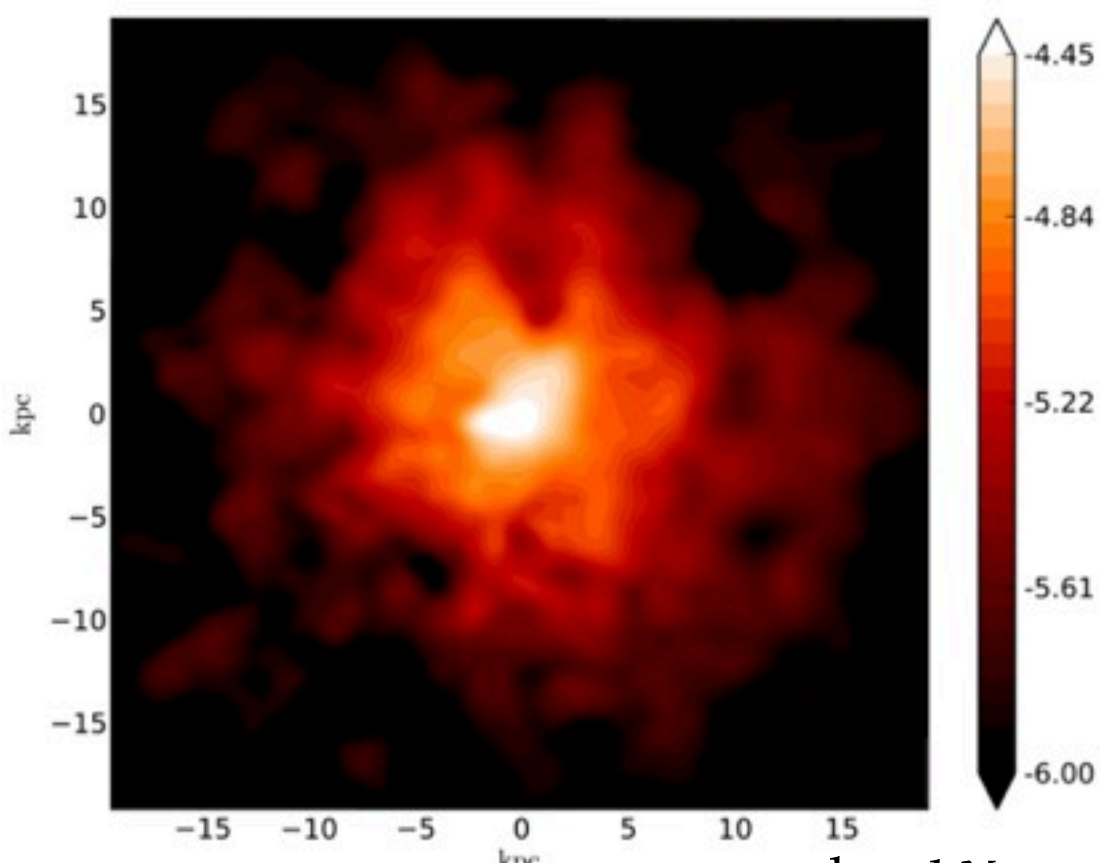
constant variance per log interval => large self-similar variability on different timescales

characteristic of fractal and chaotic phenomena
(quasars, sunspots, meteorological data, heart beat rhythms, neural activity, stock market, ...)

MULTIPHASE CCA: 1. HOT PLASMA



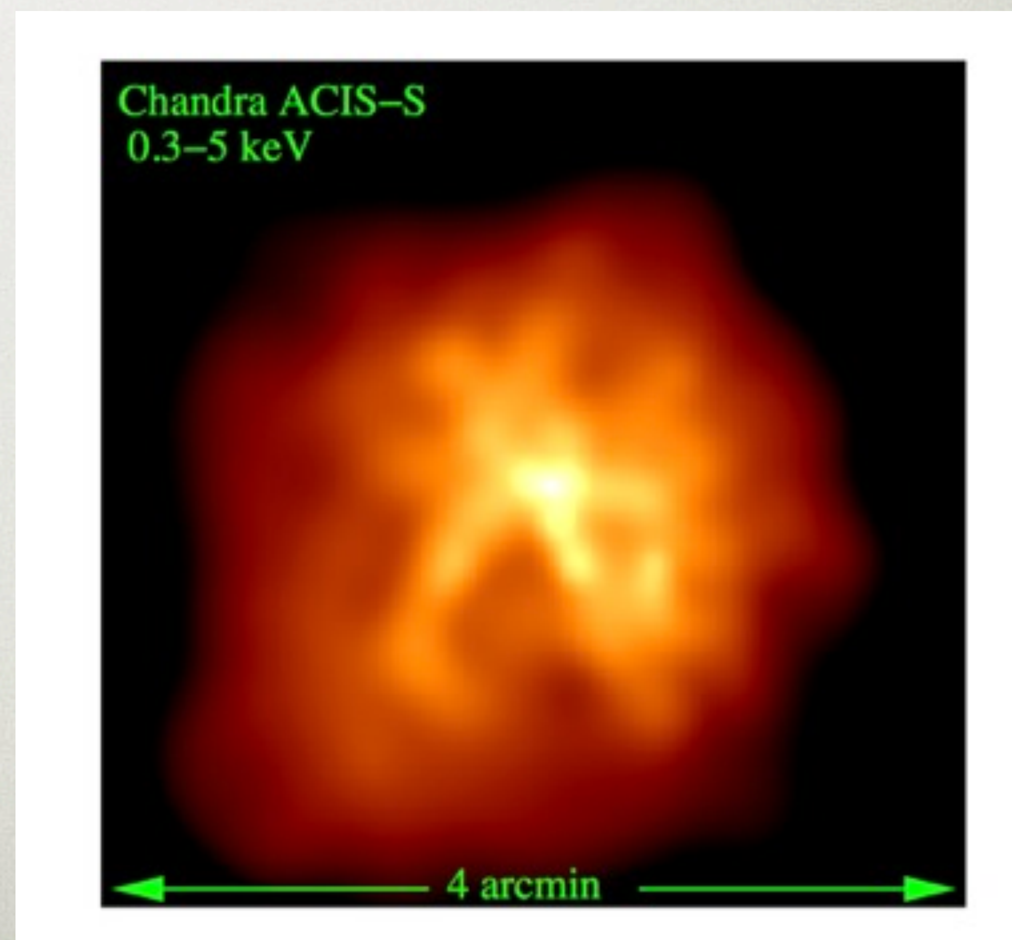
soft X-ray



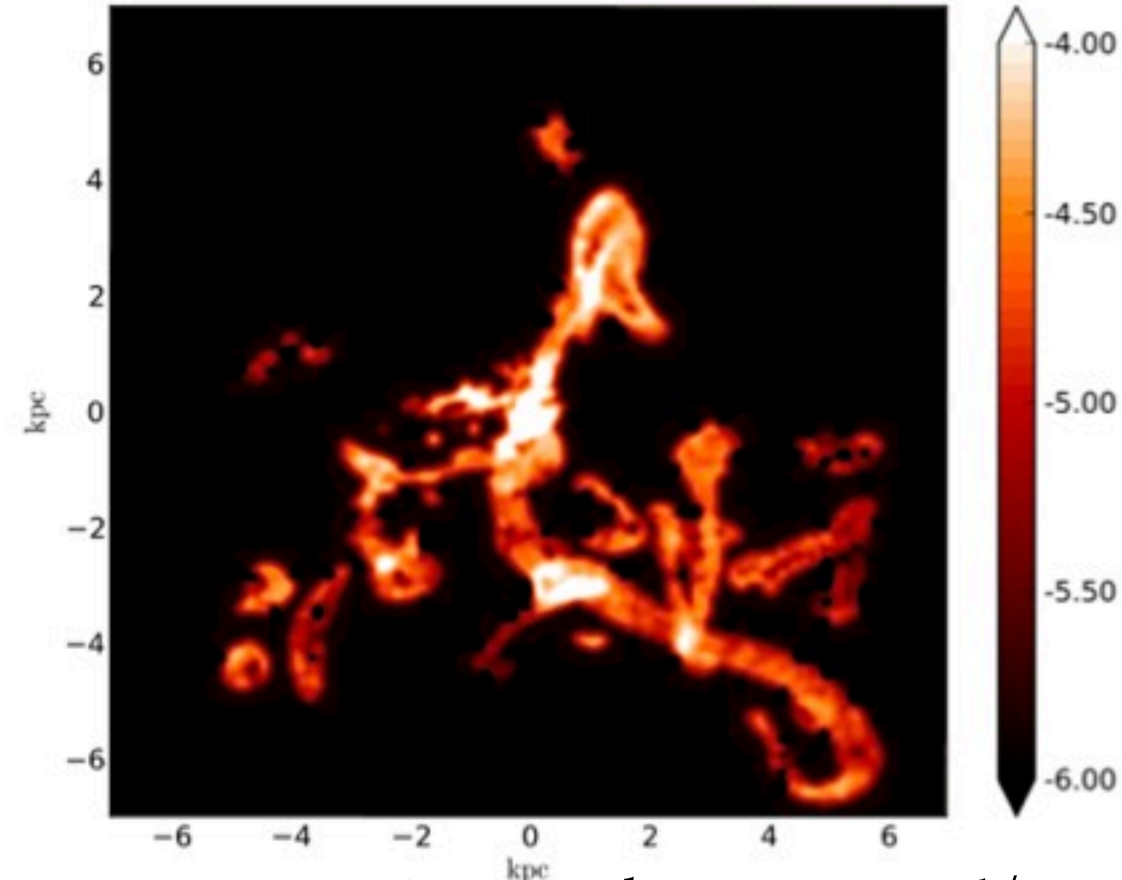
MG+16

hard X-ray

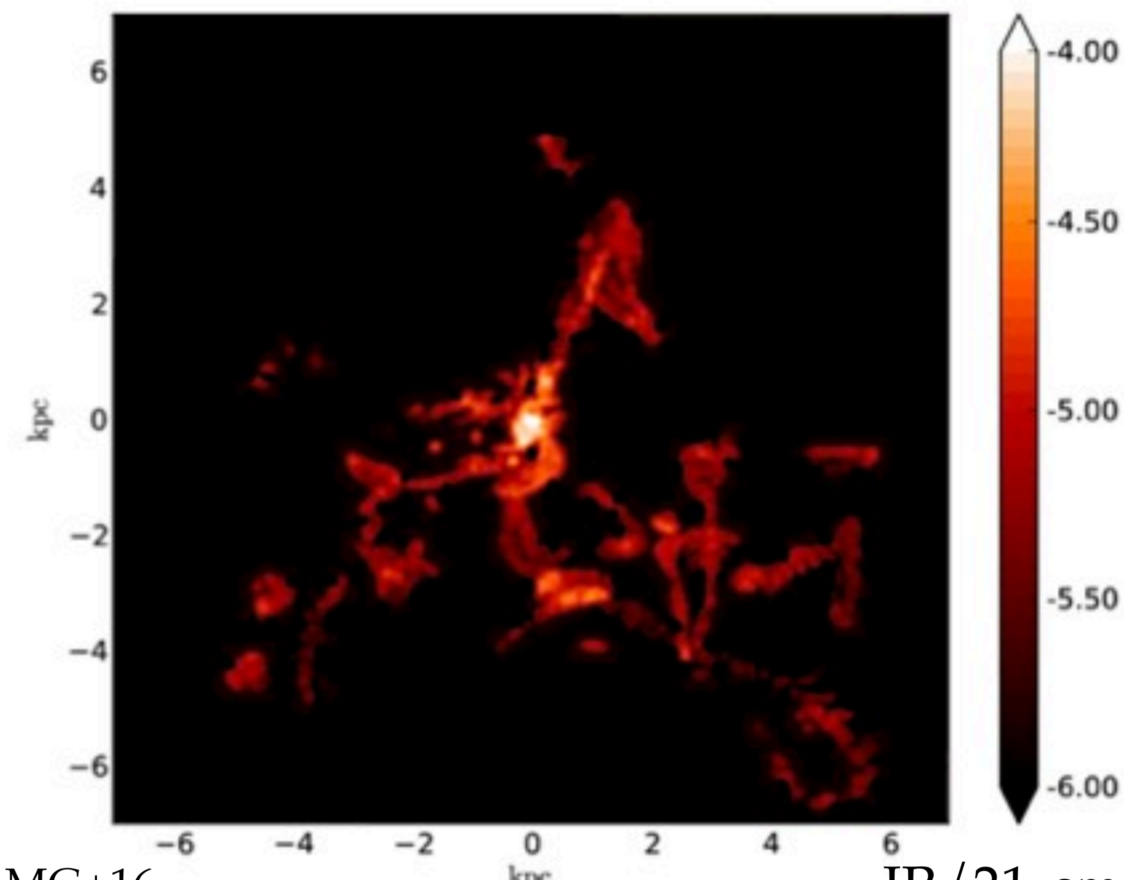
- turbulent eddies imprint => naturally create “depressions” / ”fronts”
- X-ray “filaments” start to appear below 0.5 keV
- flat X-ray T profiles and -1 density slopes: M87, NGC 3115, NGC 4261, NGC 4472, ...
- weak subsonic turbulence is sufficient to trigger CCA



Buote+04



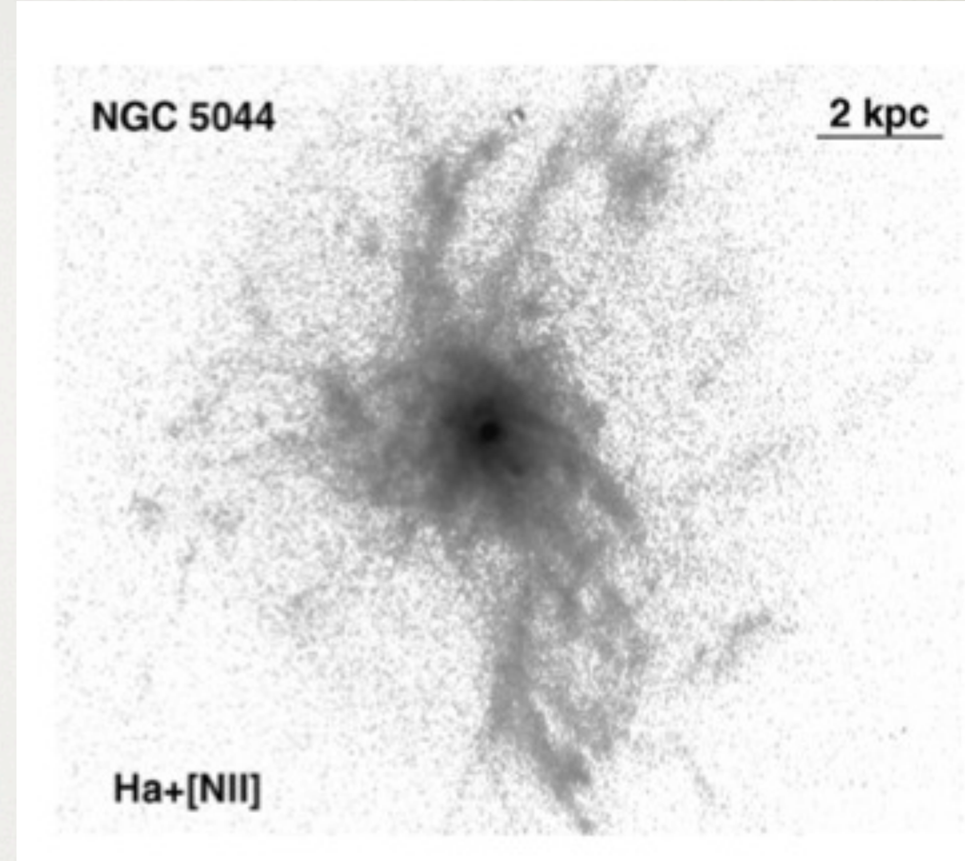
ionized warm phase optical/UV



MG+16 IR/21-cm

neutral warm phase

Werner+14: SOAR



- more reliable thermal instability/ multiphase condensation criterium:

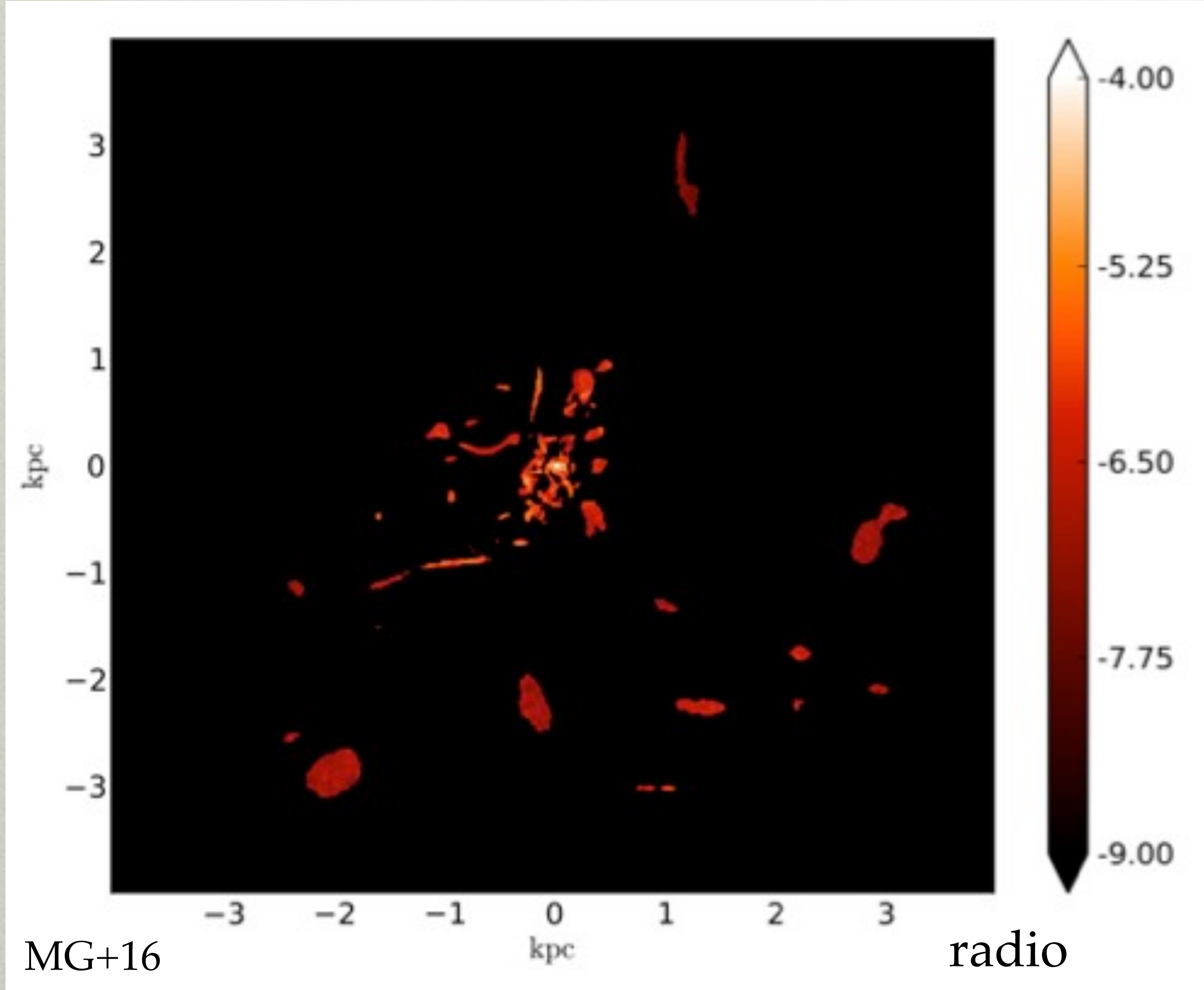
$$t_{\rm cool}(l')/t_{\rm eddy}(l') \equiv \sigma_v(l')/v_{\rm cool}(l') \lesssim 1$$

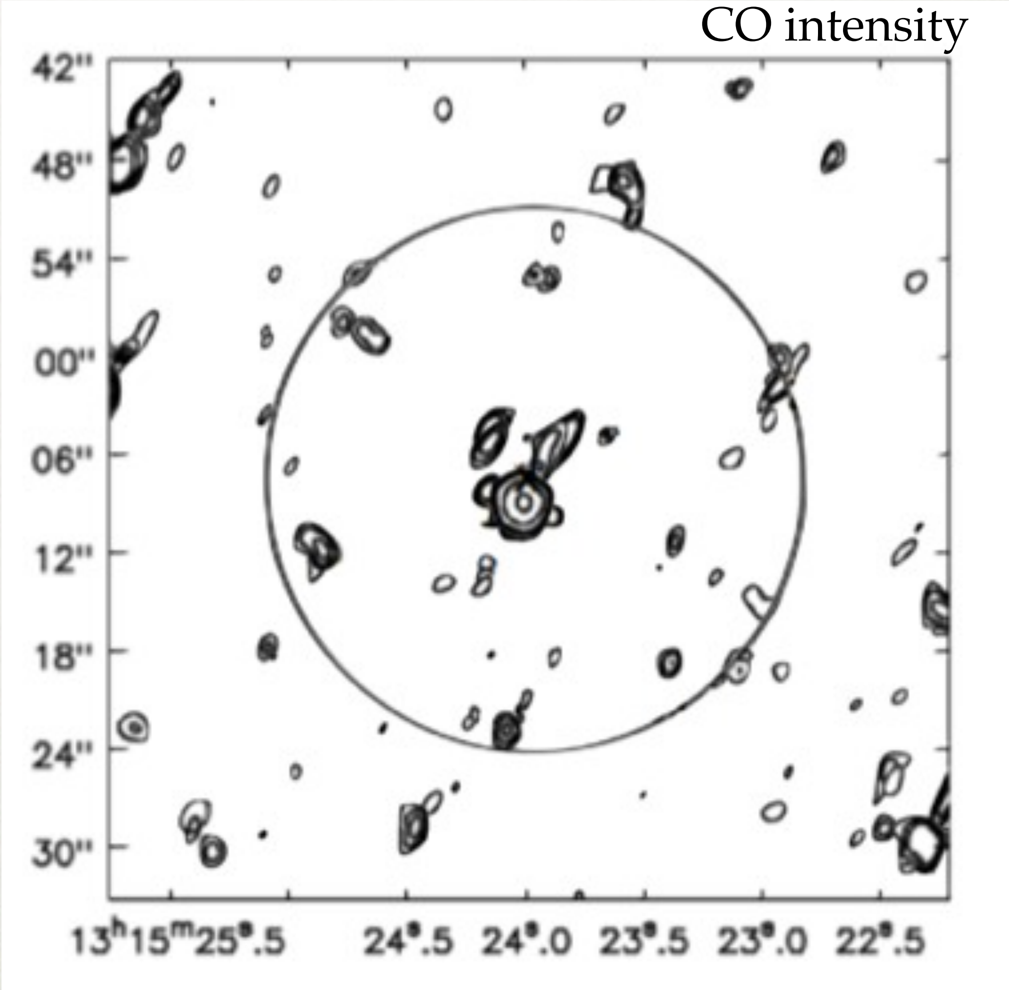
leads to a condensation radius of 7 kpc

- 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





• molecular clouds typically combine in GMAs (giant molecular associations), up to 100 pc with surface density ranging 50-200 Msun/pc^2, as found by ALMA | dominates condensed mass (> neutral gas)

• cospatial with warm phase and soft X-ray plasma, though more compact

• as for the warm gas, ensemble velocity dispersion is inherited by turbulence (150 km/s), while internal dispersion is about 1 dex lower (turbulence cascade) => clouds are **DYNAMICALLY** supported (virial parameter >> 1)

• r < 100 pc rapid **funneling** of clouds, with v~100s km/s (as found in absorption by ALMA in A2597; Tremblay+16)

AGN FEEDBACK CYCLE
VIA CCA FUELING:

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

↓

top-down multiphase condensation →

↓

CCA feeds SMBH

chaotic collisions

↓

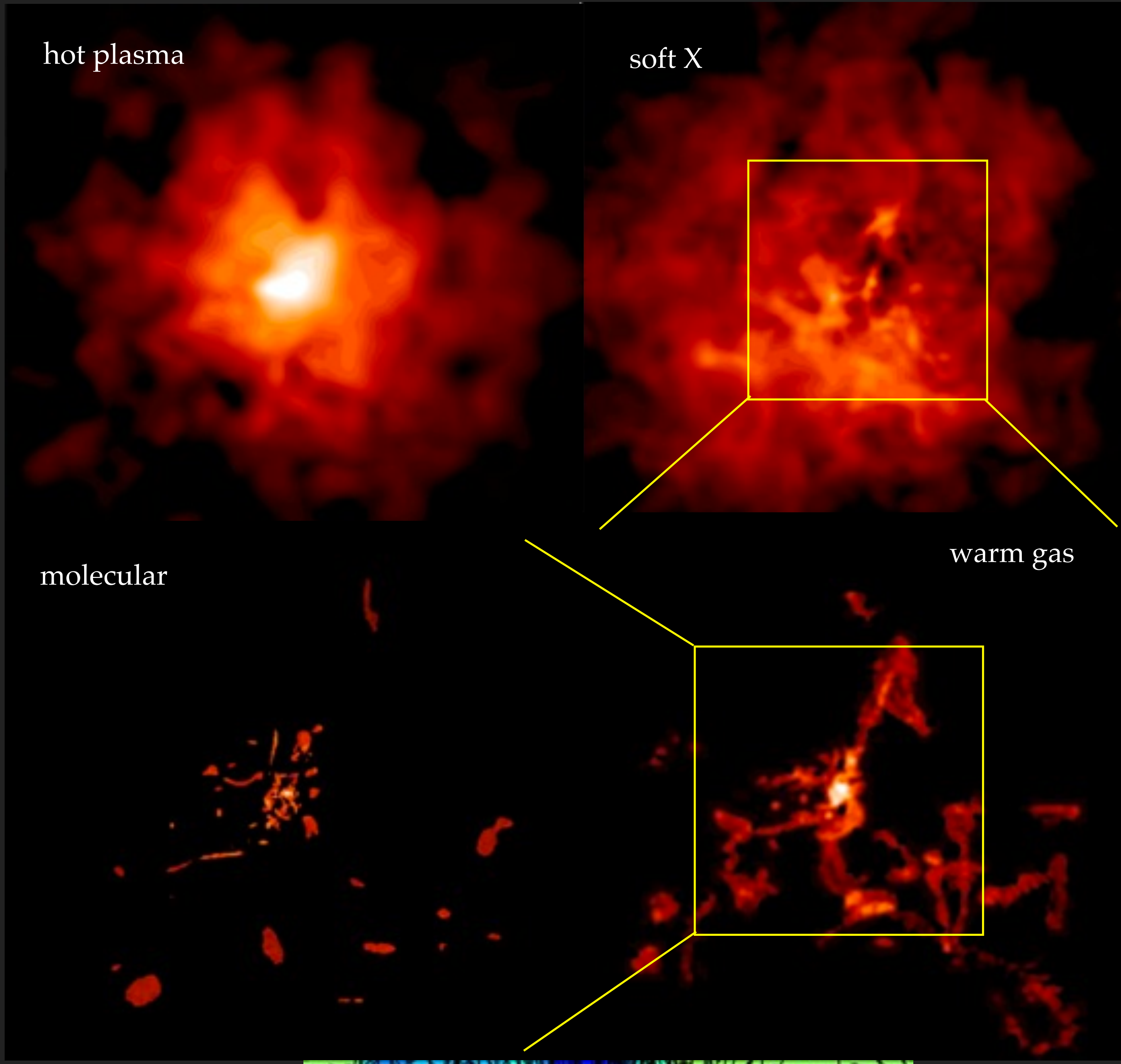
AGN outflows boosted

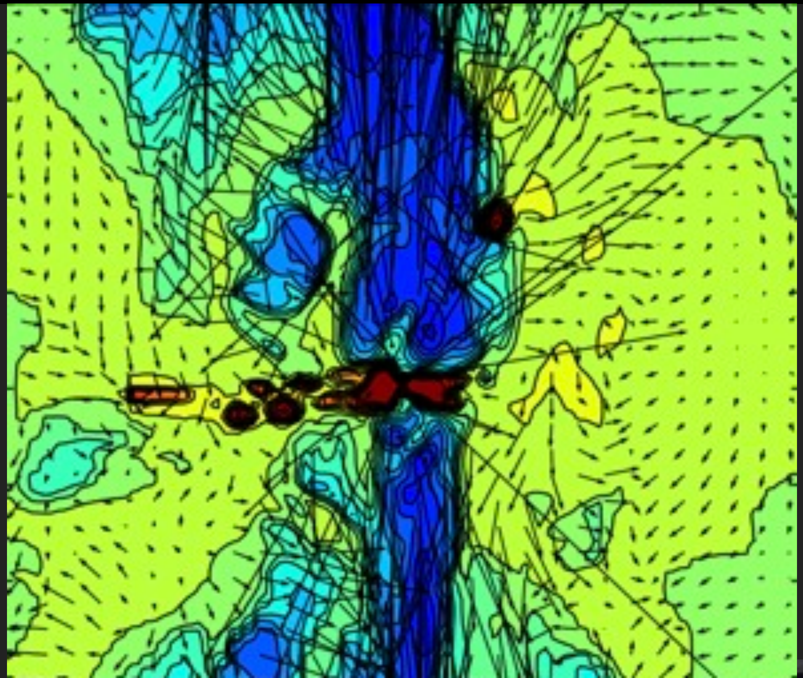
$P_{\rm out} = \epsilon \, \dot{M}_{\rm BH} c^2$ →

↓

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

MG+16





long-term and
large-scale sims