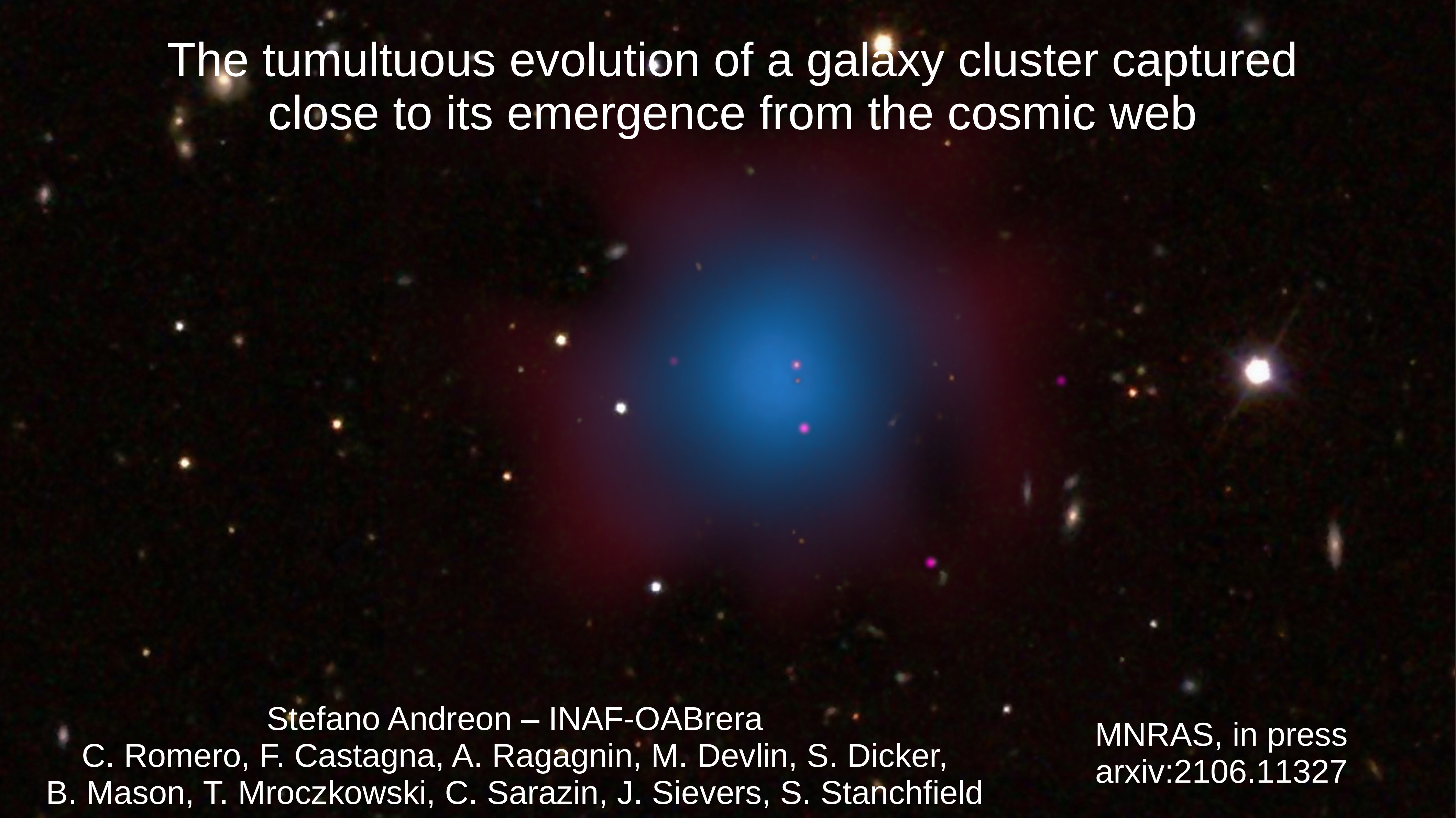
The tumultuous evolution of a galaxy cluster captured close to its emergence from the cosmic web



Stefano Andreon – INAF-OABrera
C. Romero, F. Castagna, A. Ragagnin, M. Devlin, S. Dicker,
B. Mason, T. Mroczkowski, C. Sarazin, J. Sievers, S. Stanchfield

MNRAS, in press
arxiv:2106.11327

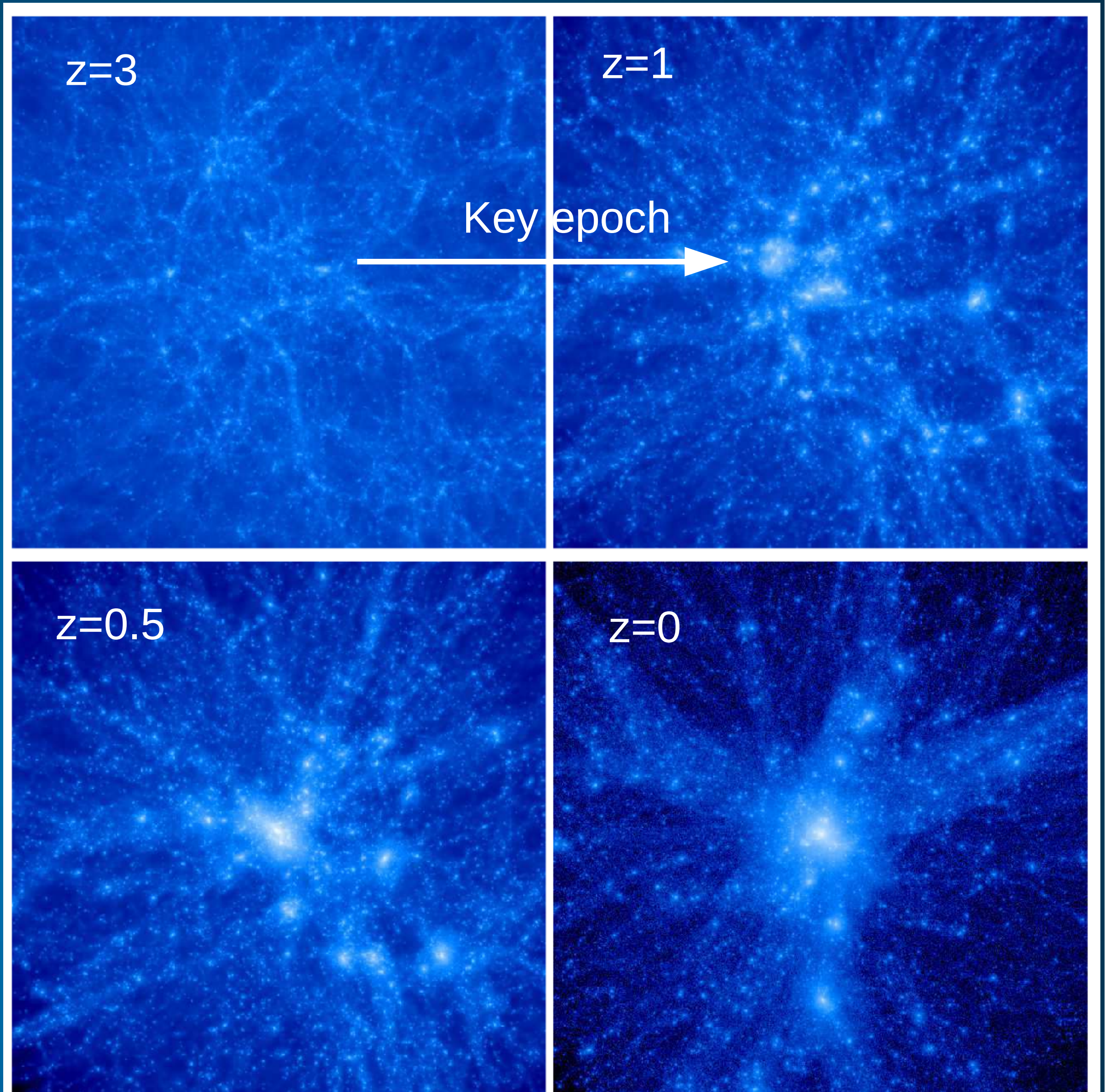


Image credit: Kravtsov & Borgani (2012)

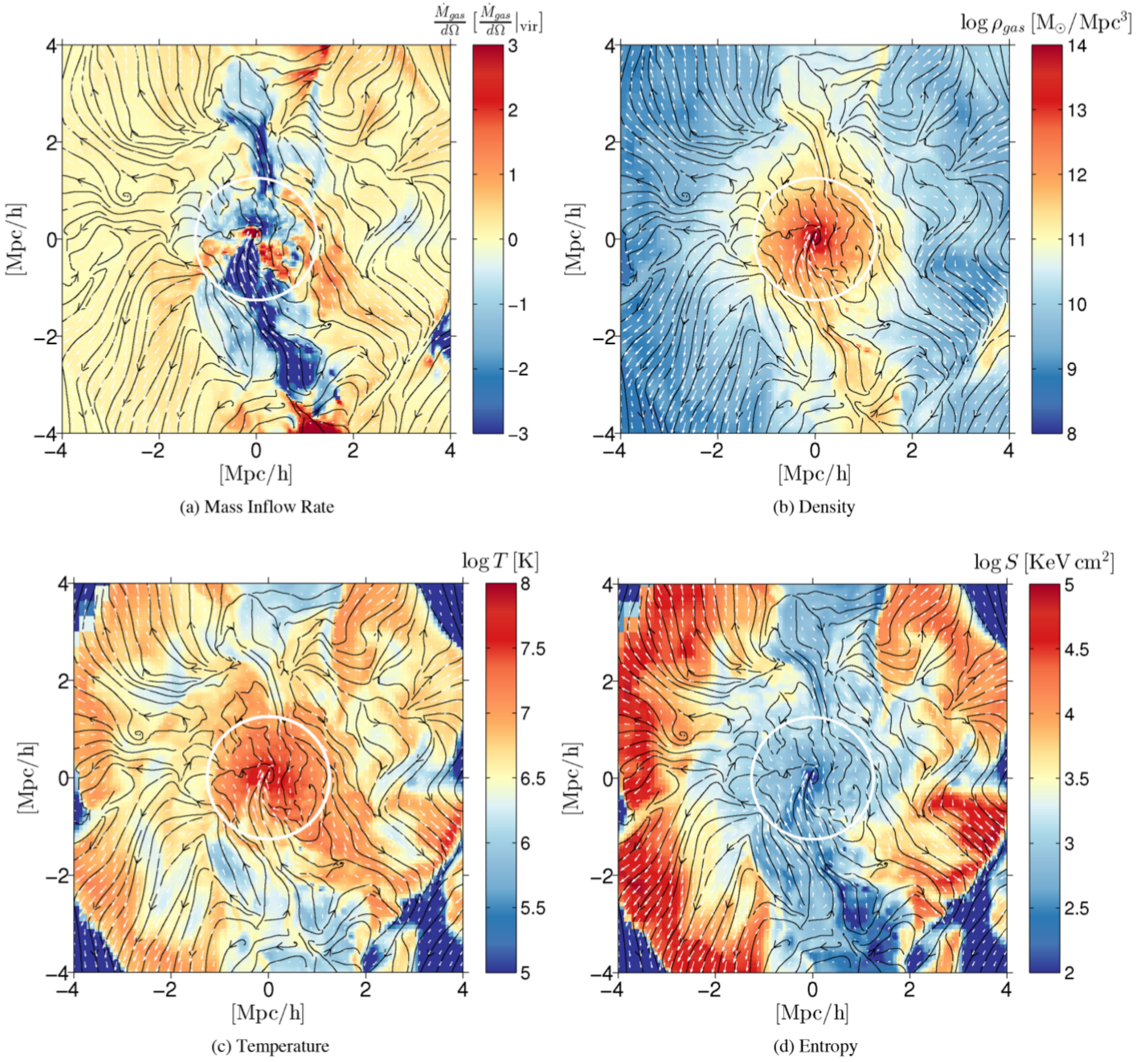
Cluster growth

(Cold gas) accretion

From simulations:

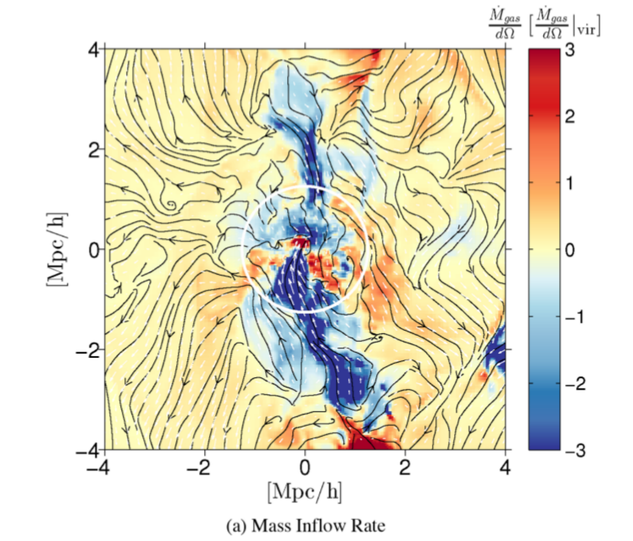
Cold, low entropy, dense gas feeds the cluster through streams along the cosmic web

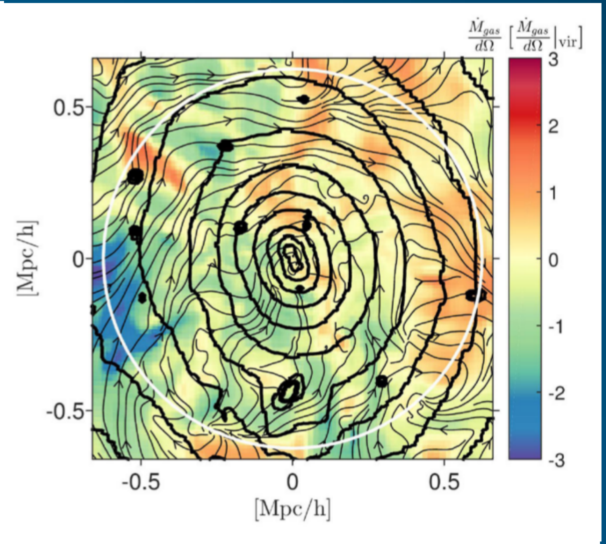
Figure from Zinger et al. (2016)



High redshift Low redshift

Theory

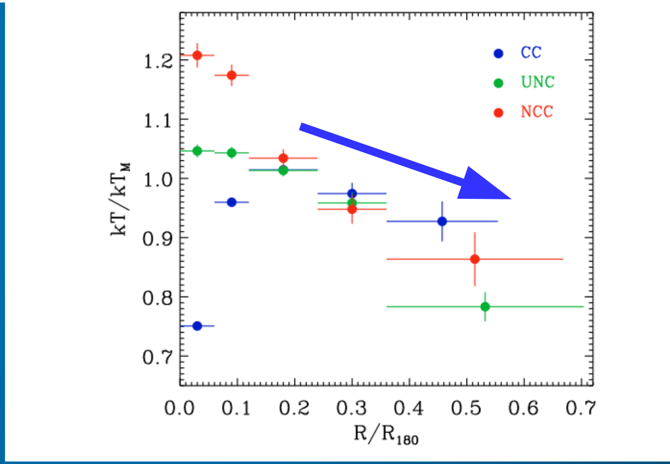




Zinger et al. 16

Obs.

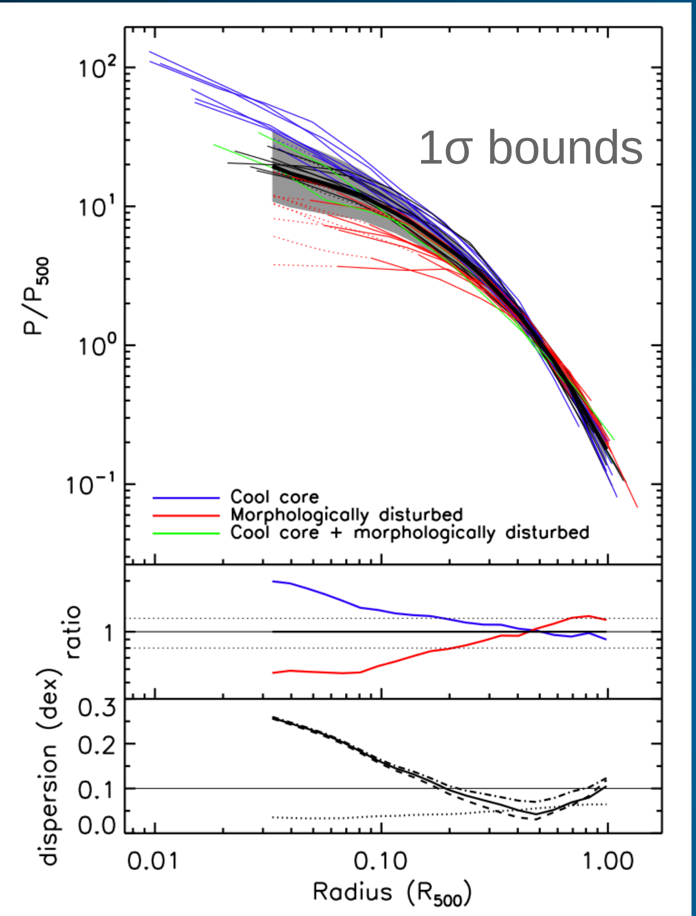
?



Leccardi & Molendi 2008

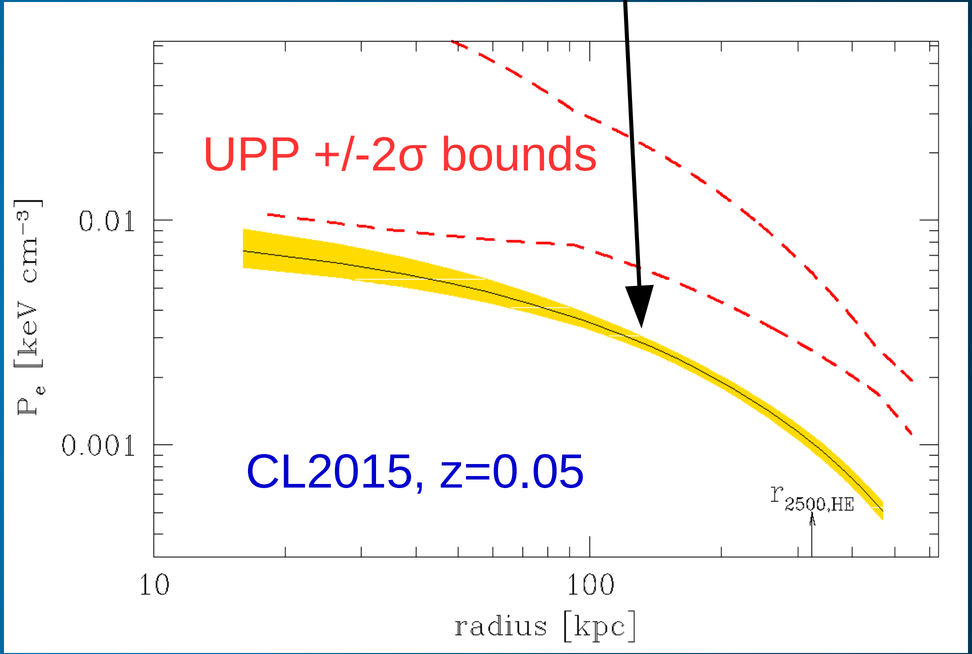
Universal (at low z) Pressure Profile

Arnaud et al. 2010



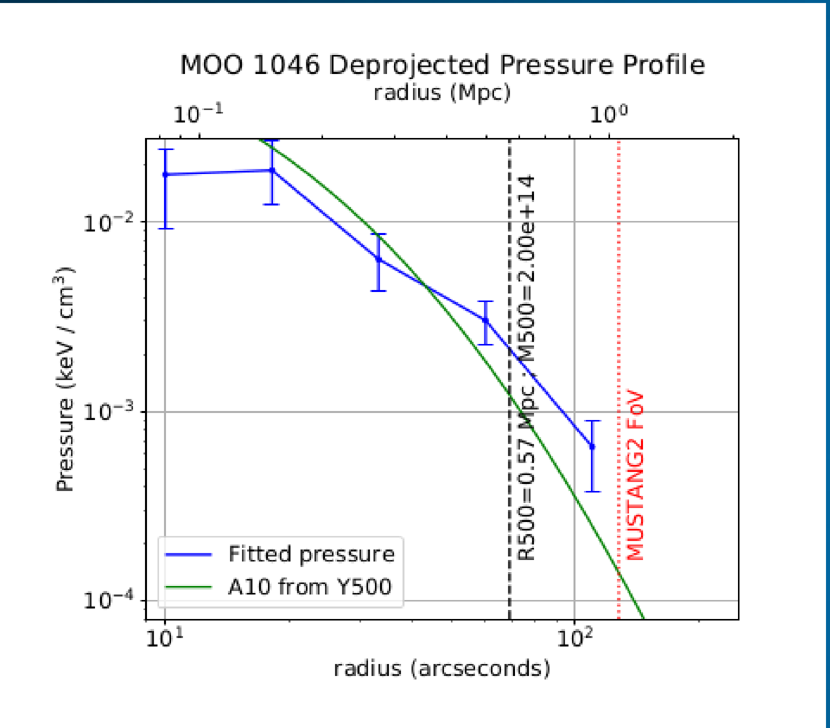
exploited to detect clusters in SZ surveys or to estimate cluster mass from them.

Low-z exceptions start to be found (SA et al. 2016, 2017a, 2017b, 2019)

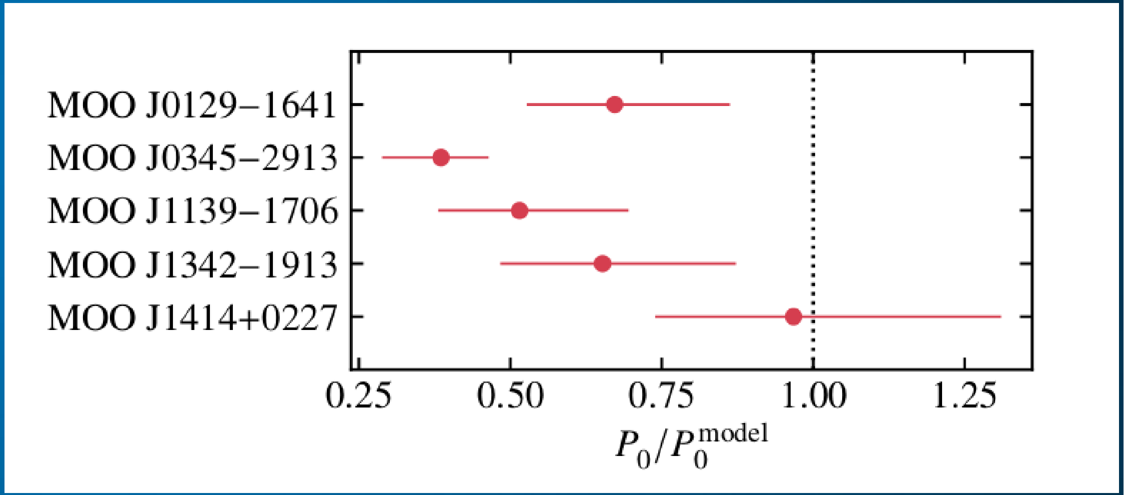


Indirect or weak evidence of non UPP profiles at intermediate redshift (z~1)

Dicker et al. 2020 (deviation from the average, not from the library)

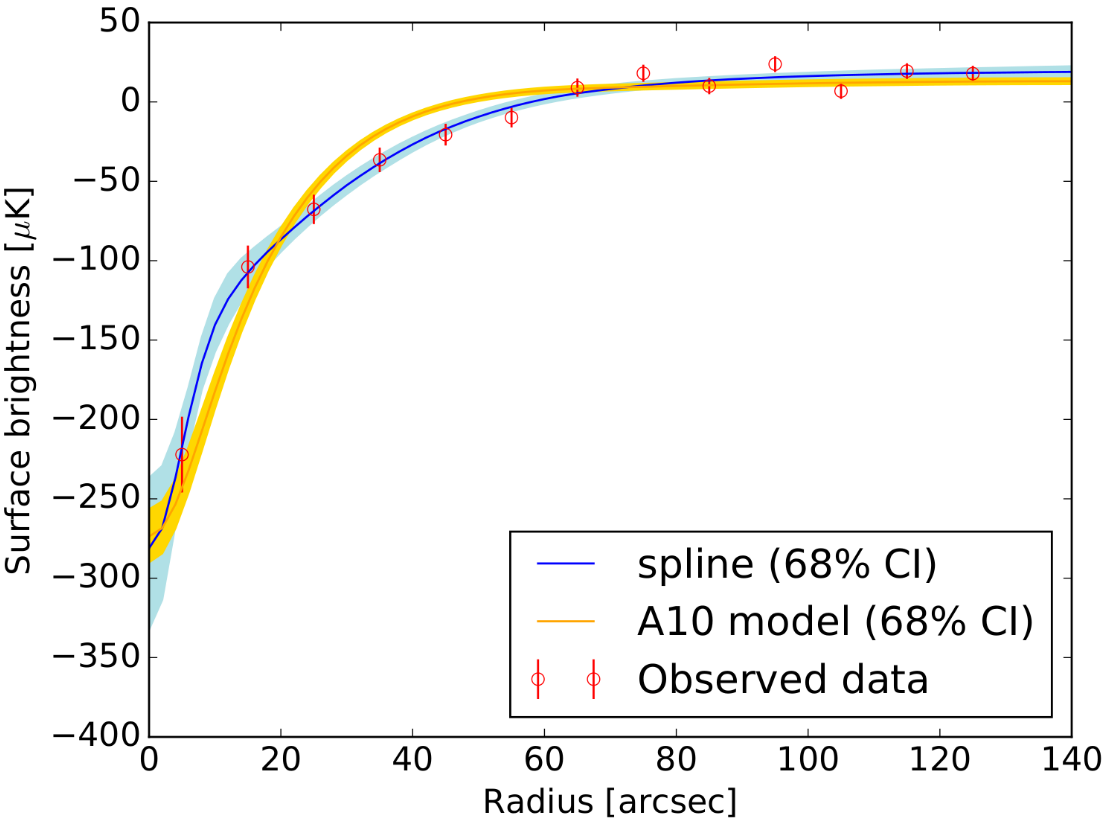


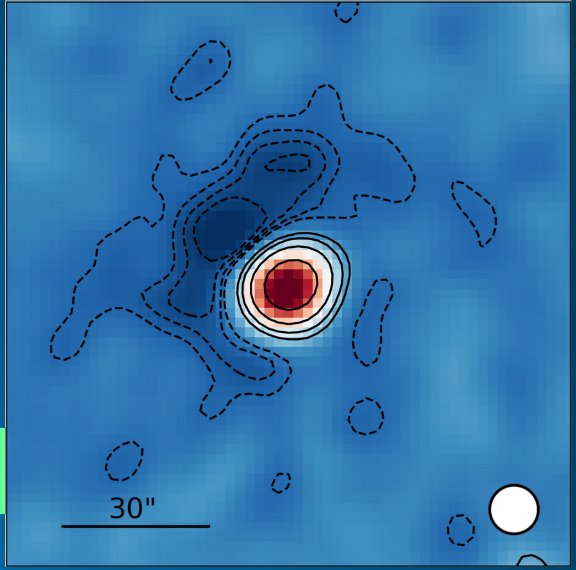
Central pressure over expected pressure (given some assumptions)< 1 Di Mascolo et al. 2020



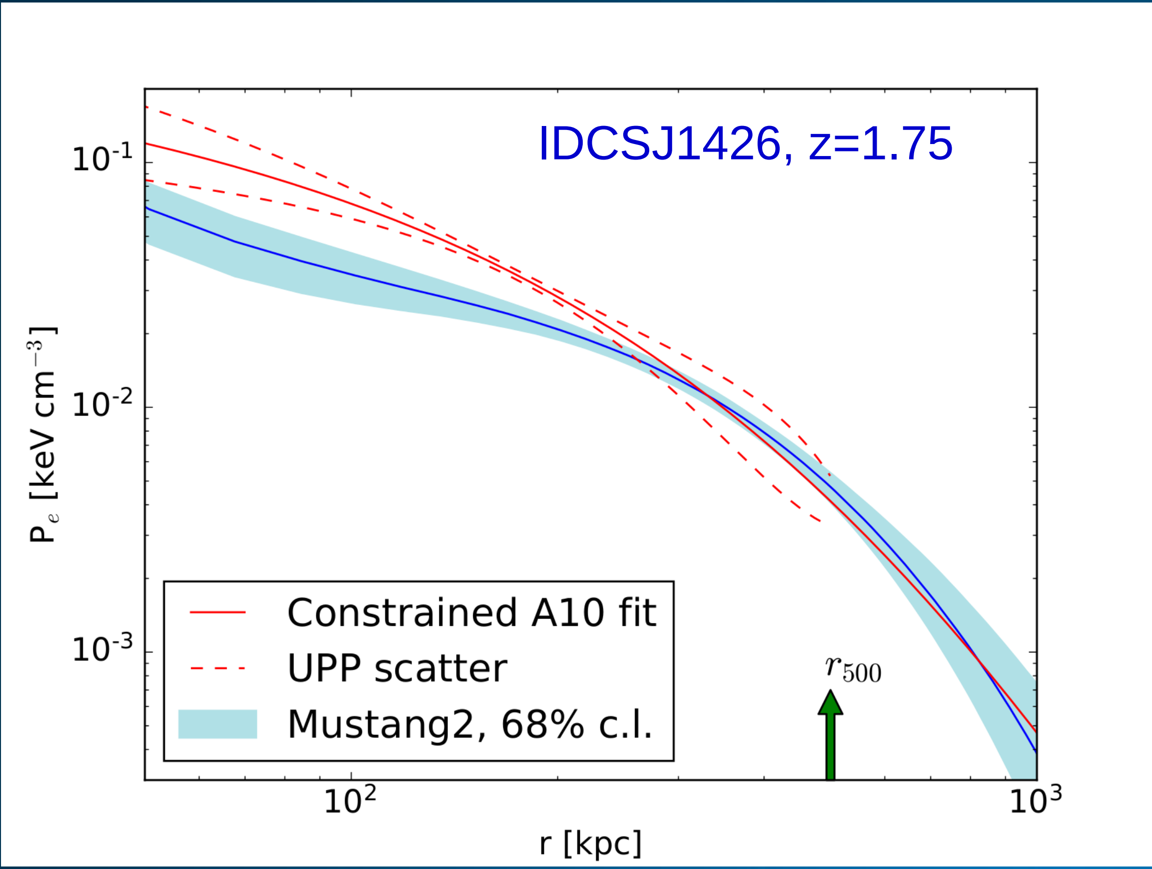
IDCS J1427.5+3508

z=1.75, M_{500}~2.5 10^{14} M_{sol}, massive for its z





Mustang2@GBT



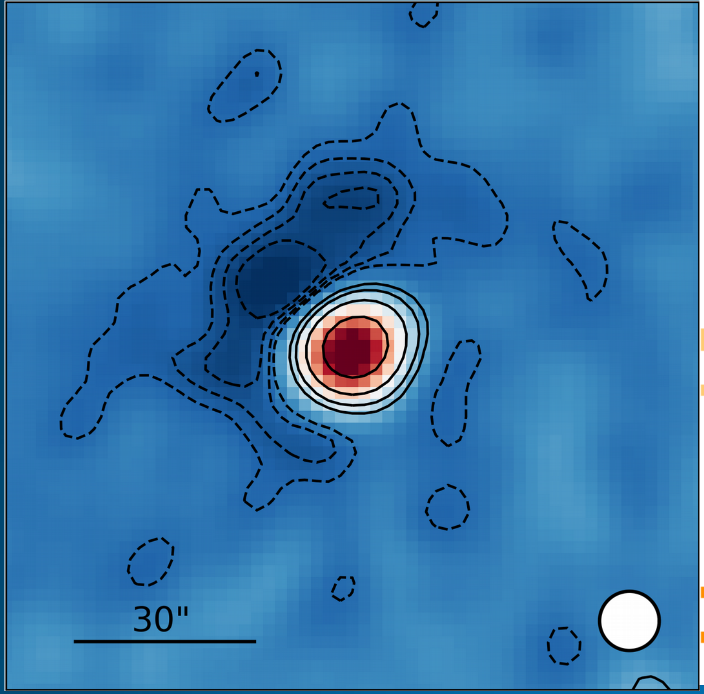
Cluster is “depressed”, far from UPP

χ^2/dof=3.3 for UPP
P(r) outside 3σ bounds at several radii

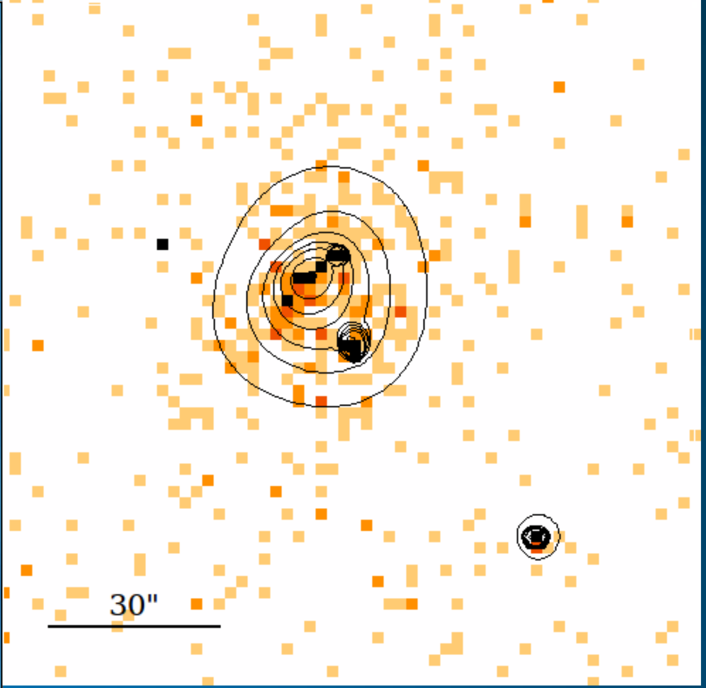
relevant for

-cosmology (easier to miss than assumed, or with a biased mass for its SZ signal) and

-astrophysics (next slides)



Mustang2@GBT



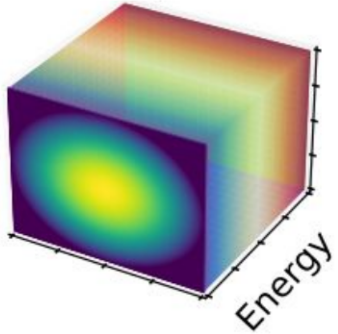
Chandra

Fully joint analysis of X-ray data cubes, SZ image, accounting for background and calibration systematics, PSF and transfer function, etc. (adapted version of JoXCS, Castagna & Andreon 2020, on github, see Castagna talk).

Derivation of thermodynamic profiles

$$S_X \propto \int n_e^2\, T_e^{1/2}\, \partial\ell$$

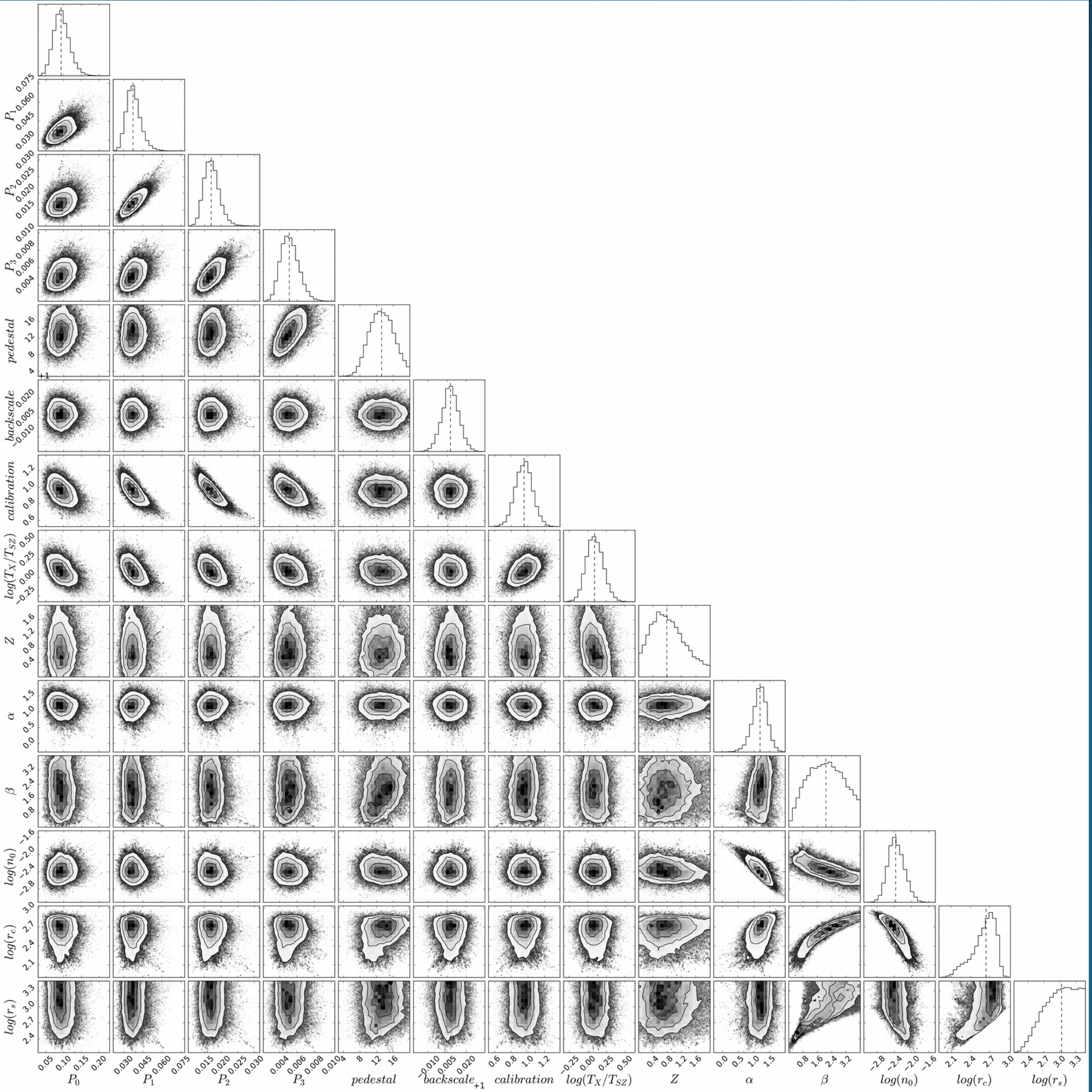
X-ray
Bremsstrahlung emission



$$y \propto \int n_e\, T_e\, \partial\ell$$

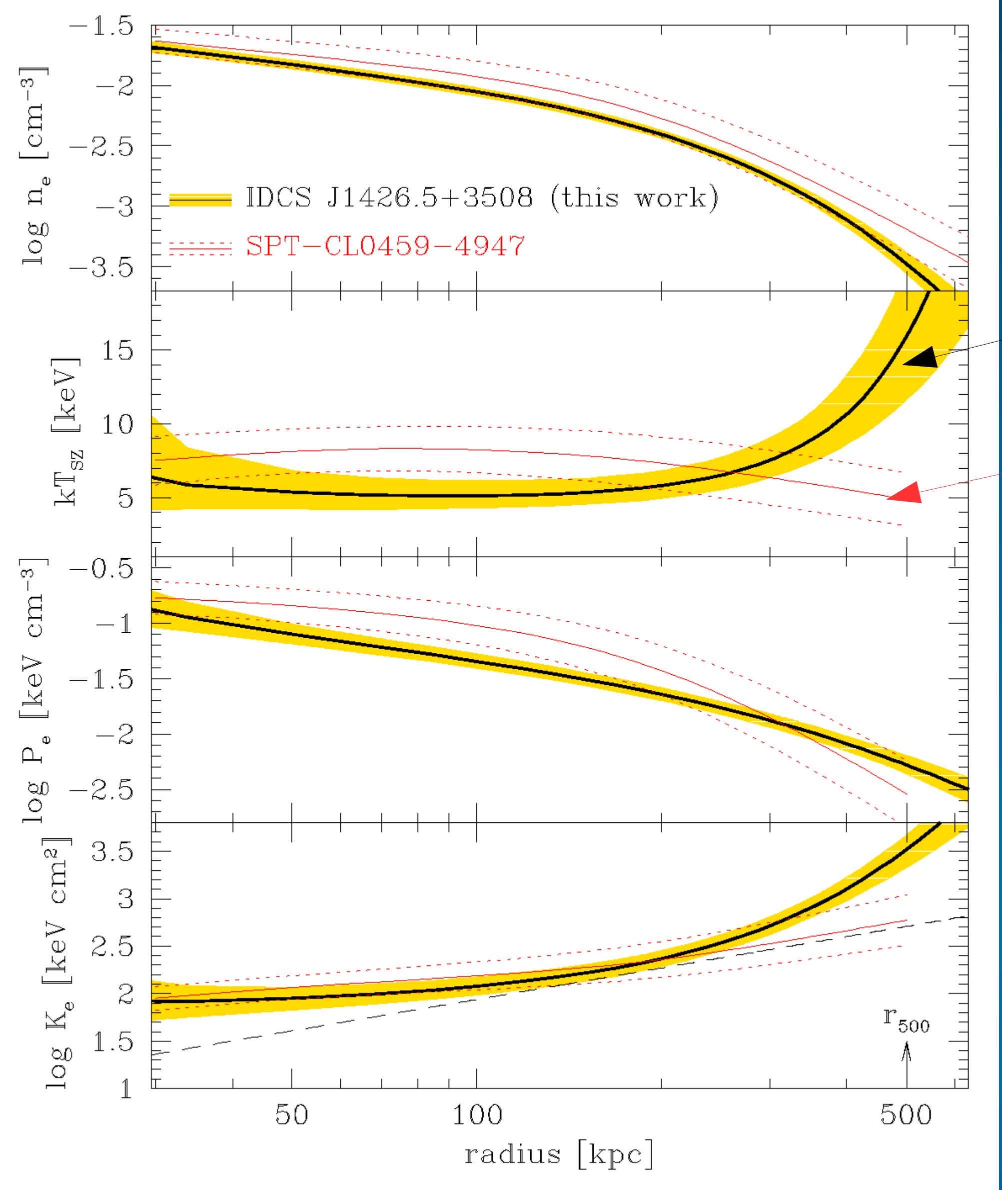
mm
Sunyaev-Zeldovich effect

>2 equations in two unknows (n_e ,T_e), plus a number of technical details (PSF, transfer function, X-ray+SZ calibration & background systematics, T(r)-dependence of conversion from Y to brightness, etc.). Pressure and entropy are derived from (n_e ,T_e)



Joint and marginal posterior, joint fit

(JoXSZ)

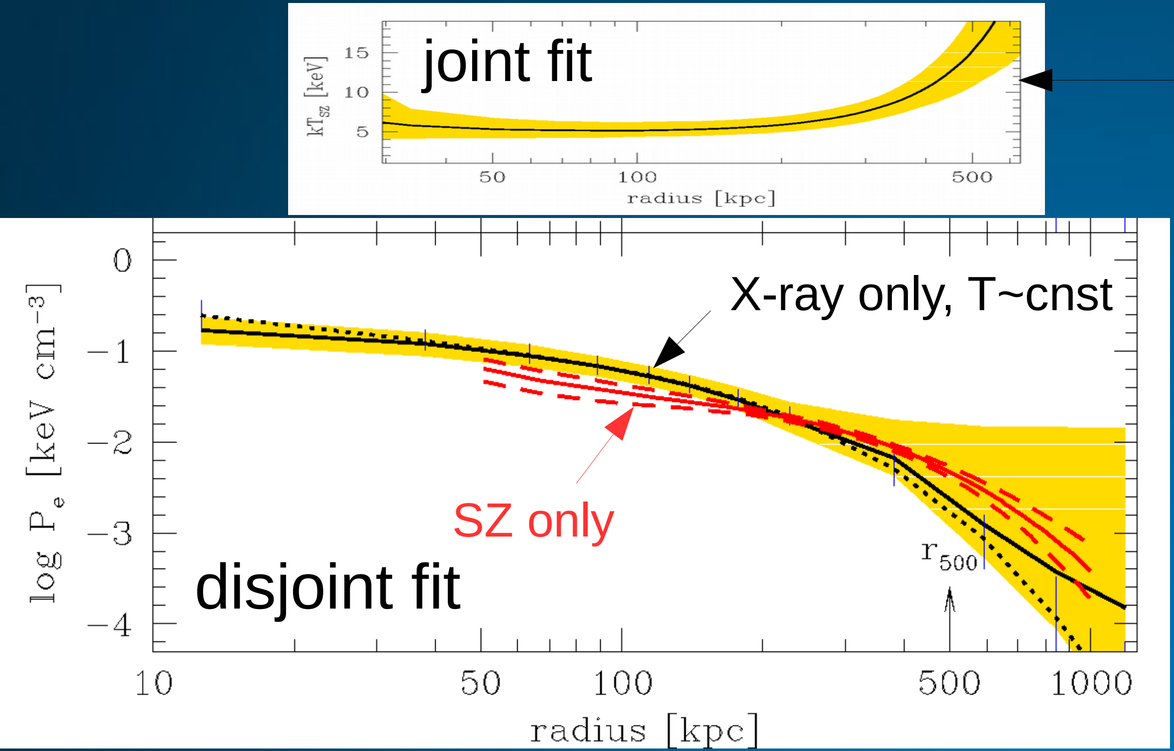


Efficiency of SZ+Xray

Black: IDCS, z=1.75, 100 ks Chandra + 36 ks Mustang2. 1σ errors shaded.

Red: brighter cluster at z=1.71, 190 ks Chandra + 500 ks XMM (from Ghirardini et al. 2021). 1σ errors with corridor.

Compare uncertainties!

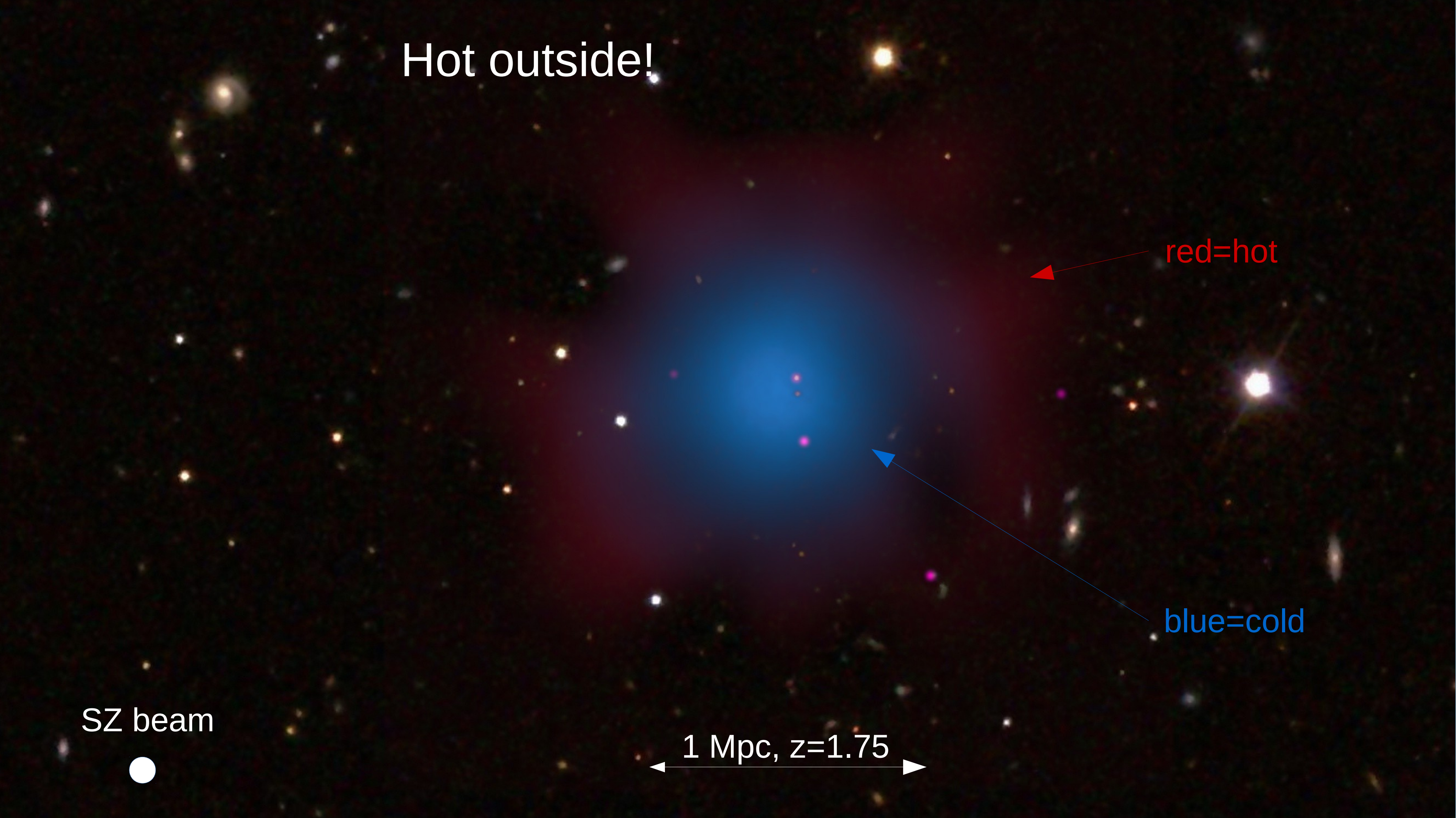


Unusual T profile

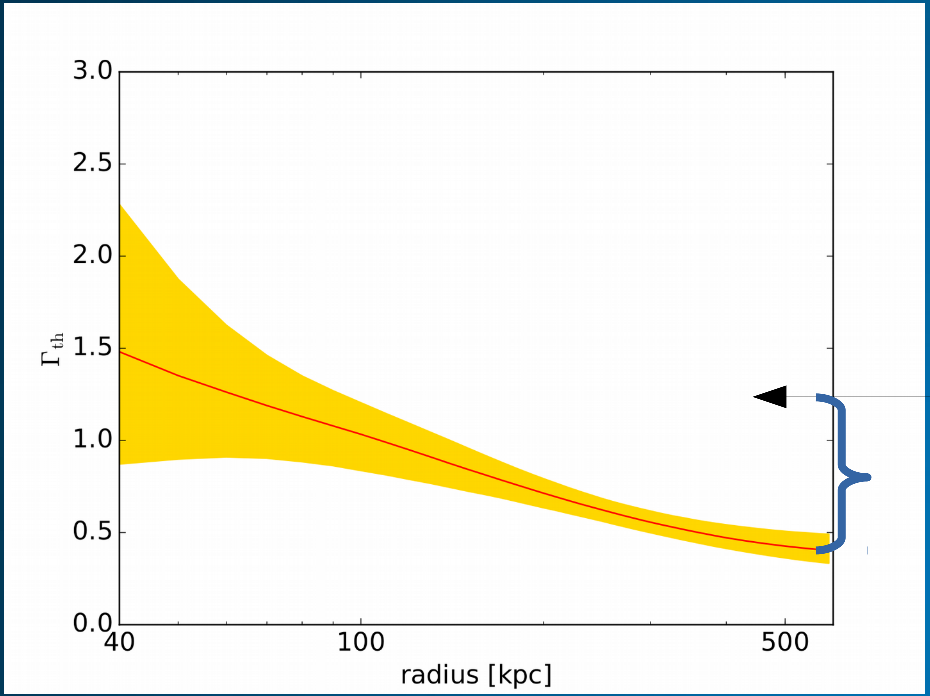
Robust feature: ultimately coming from a P profile shallower than the n_e profile

The SZ-based P profile and the X-ray-based n_e profile are tightly constrained by data.

Uprising T profile, unstable and far from the final configuration (already seen in other clusters, but on smaller spatial scales)


Hot outside!
red=hot
blue=cold
SZ beam
1 Mpc, z=1.75

Polytropic index profile $\Gamma = d \ln P / d \ln n_e$



Expected value in absence of non-thermal pressure support

Δ implies bulk motion/turbulence

An unstable/far from equilibrium cluster

Γ =1 isothermal sphere, Γ=1.67 adiabatic gas

What’s the plausible evolution of IDCSJ142?

Let’s pause and recap what we know about cluster evolution.

A quarter of century ago ...

- we don’t like “to compare unripe apples to ripe oranges in understanding how fruit ripens” (verbatim from Andreon & Ettori, 1999, ApJ). Progenitor vs descendants.
- M_{500} increases with time, at least because of the decreasing $\rho_{crit}(z)$.
- Therefore, evolutions is not to be estimated at fixed mass (as some authors still do) but at fixed progenitor (e.g. $\Delta \log M=0.62$ dex between $z=1.7$ and $z=0$). Scatter in mass accretion history accounted for (and subdominant).

Half a century ago ...

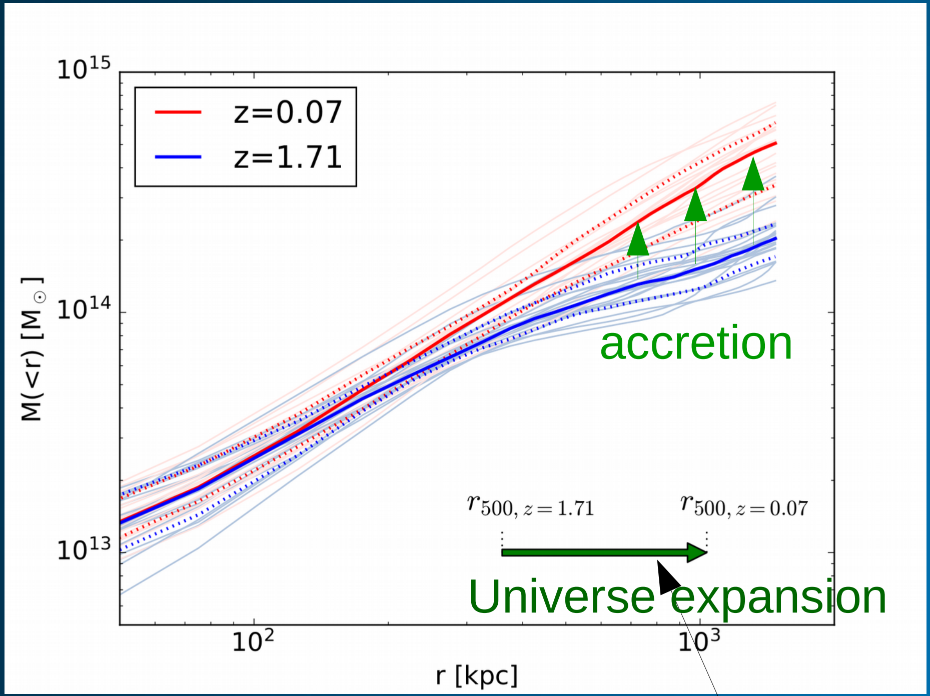
Clusters grow their outer regions but do not expand.

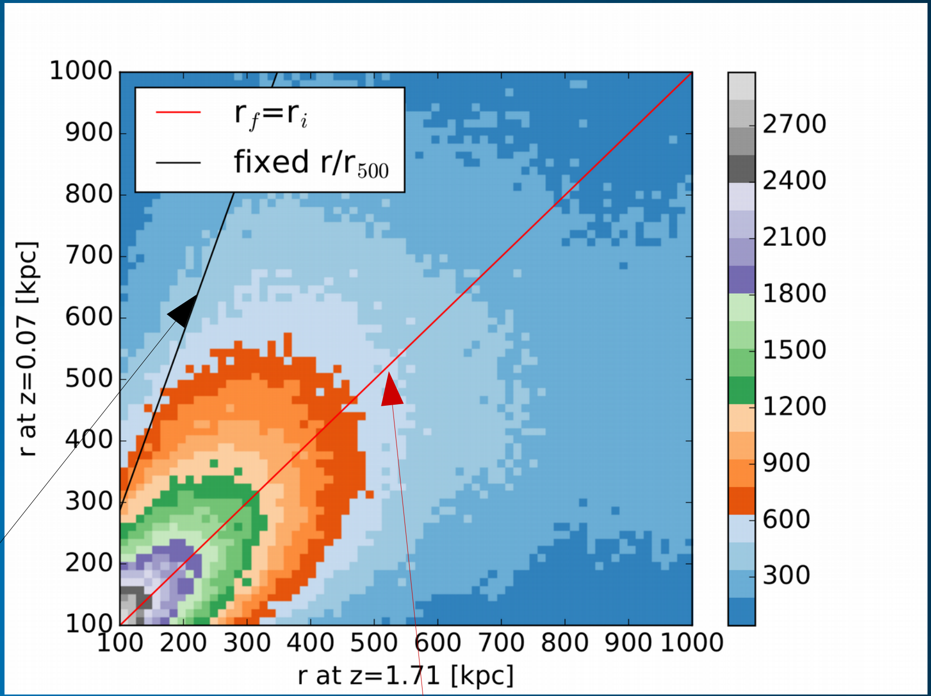
- ✔ known since Gott & Rees 1975, Peebles 1980 book
- ✔ Would clusters become smaller in a contracting Universe?
- ✔ Remember Birckoff theorem.
- ✔ Use a (state of the art) numerical simulation (next slide)

Therefore:

- ✔ Comparison at fixed r (unlike most recent literature, using r/r_{500}).

During pandemia … Clusters continue not to expand





Self-similar choice

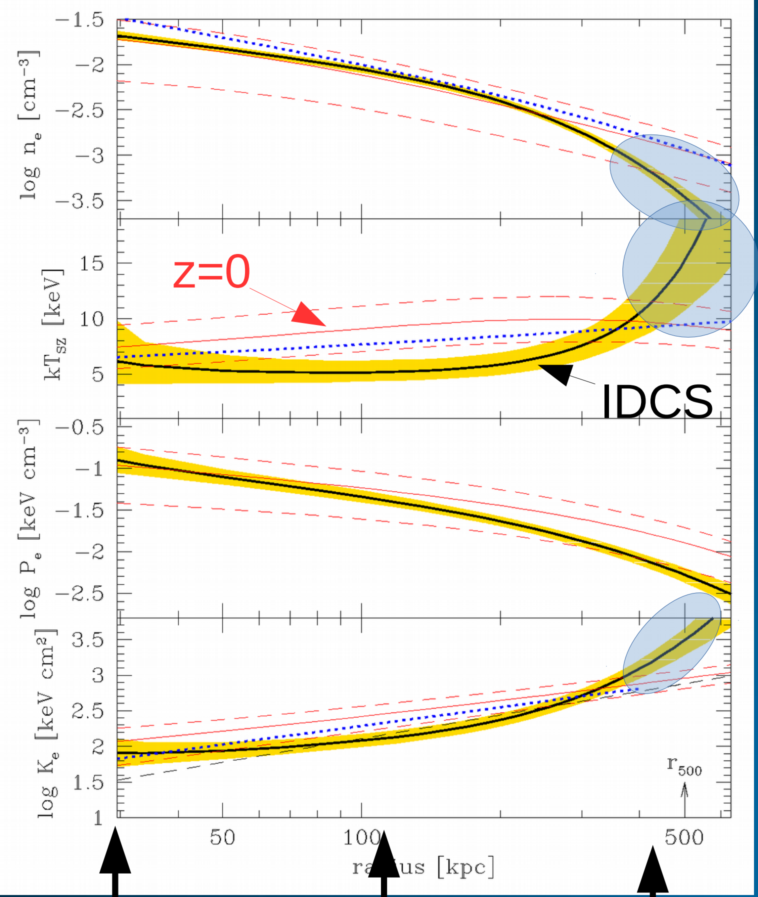
$r_{initial}=r_{final}$

Based on Magneticum (hydro, with baryons) simulations

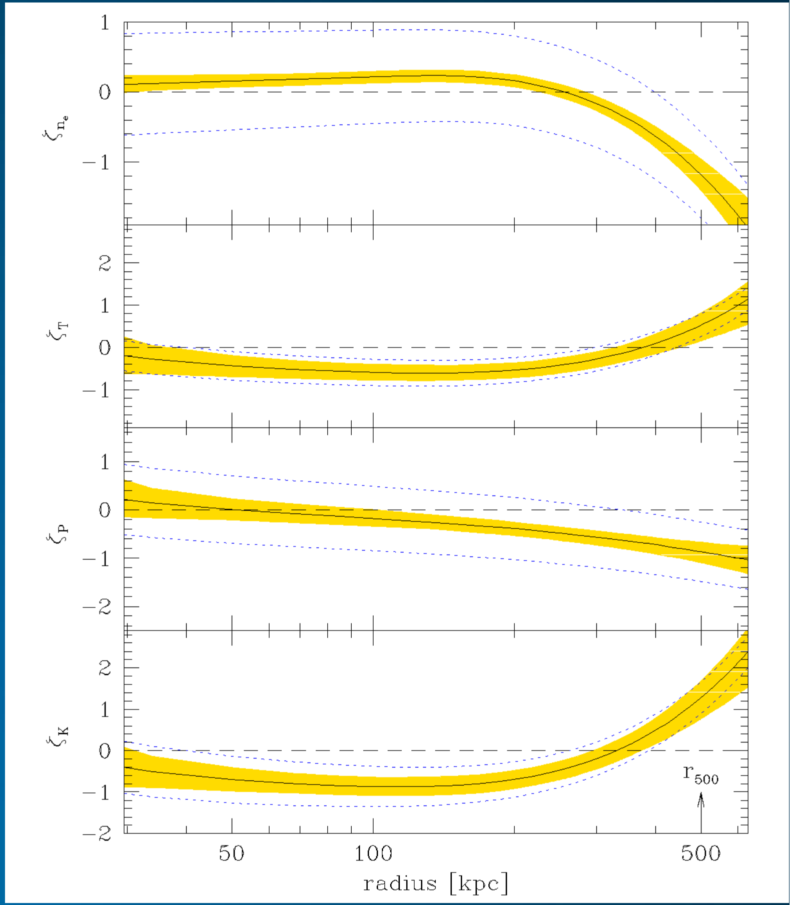
How I computed evolution

- at fixed r. Clusters don’t expand.
- progenitor vs descendants. ΔlogM=0.62 dex between z=1.7 and z=0
- If not, evolution, pseudo-evolution and mass dependence are all mixed up.

- compared one cluster at high z to a library (X-COP) at z=0 with ΔlogM=0.6 dex more massive, shown as ±2σ corridors in next slides



Rates:



$\zeta = d \ln f(r) / d \ln E_z$

ζ=0 means no-evolution (with our choices)

ζ<0 means lower in the past

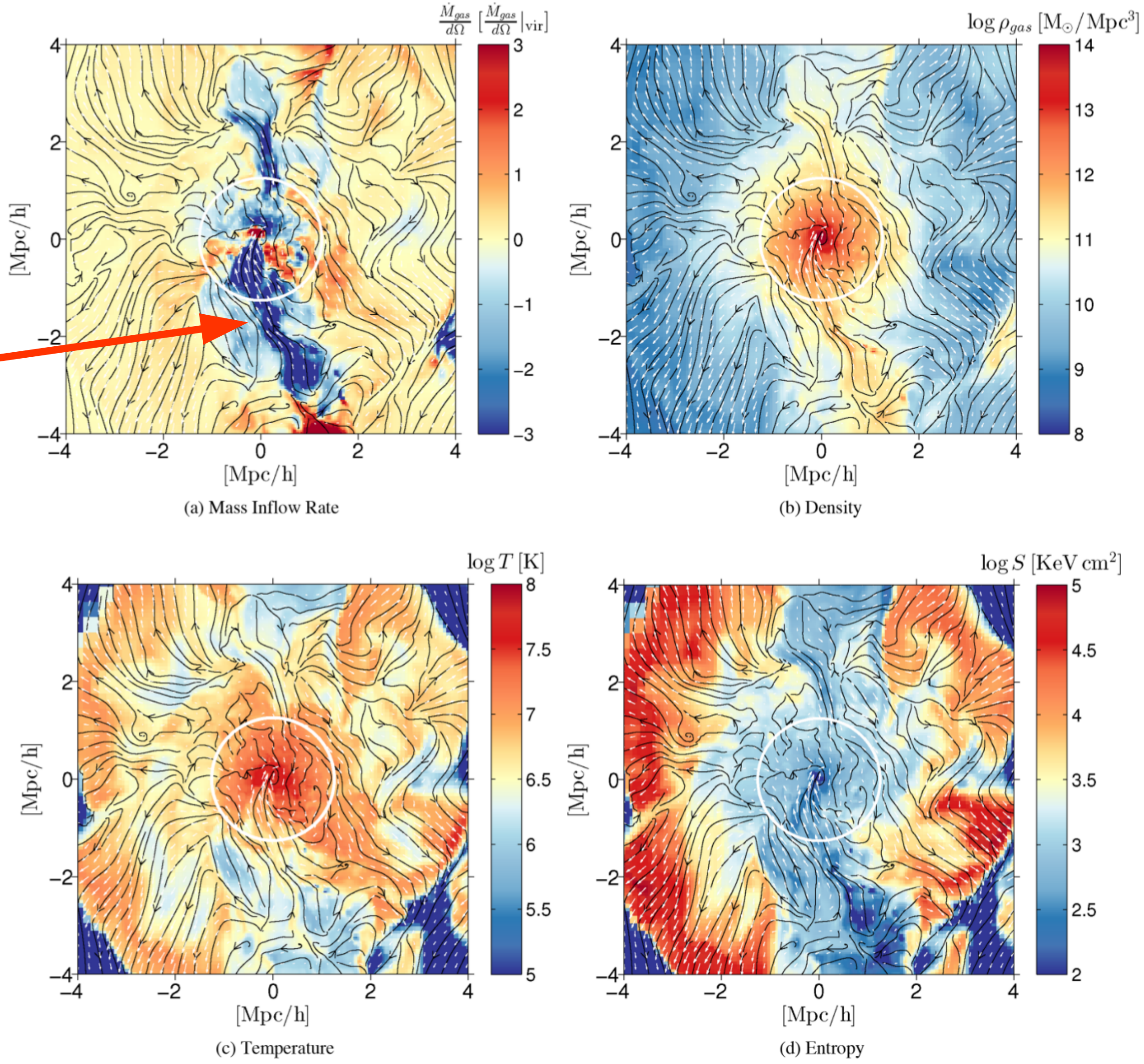
No changes at r~30 kpc

At intermediate r, gas will be heated with little net gas transfer

At large radii, heat should be evacuated, gas accumulated and entropy lowered

(Cold gas) accretion

Polytropic index



heat and entropy is transferred inward with little net gas transfer at intermediate r, whereas at large r n_e grows by accretion of cold, lower entropy gas.

Figure from Zinger et al. (2016)

Summary

a) most accurate resolved (40 kpc resol.) thermodynamic profiles, & for the most distant (z=1.75) cluster (thanks to SZ+X-ray)

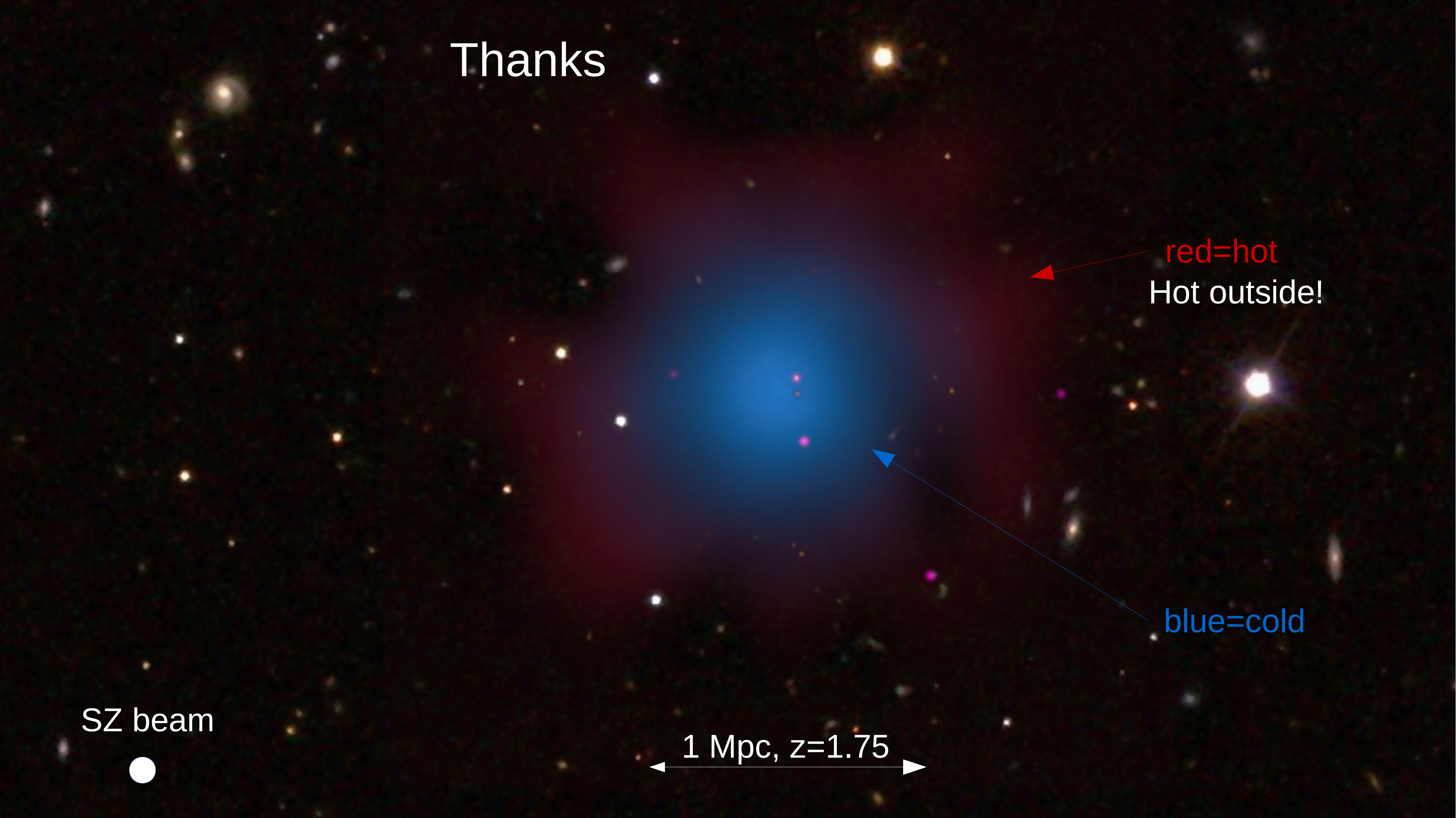
b) far from the final configuration (hotter outside! & Γ profiles), involved the whole cluster, not a (small) part of it

c) fingerprinted cold gas accretion.

d) no evolution at r~30 kpc, unveiling a delicate balance between matter infall and a yet unidentified feedback mechanism

e) clusters grow in mass and don’t expand. Don’t compare at fixed r/r_{500} and/or fixed mass, please.

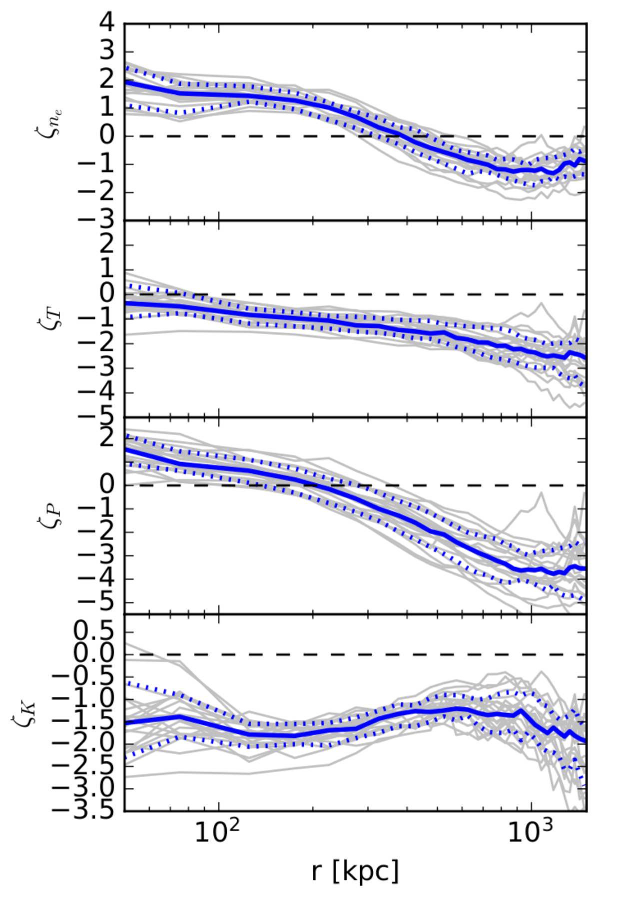
f) Caveat: do not generalize from 1 example (cluster)! One more z>1.7 cluster is coming ...


Thanks
red=hot
Hot outside!
blue=cold
SZ beam
1 Mpc, z=1.75

Backup slides

Rates:

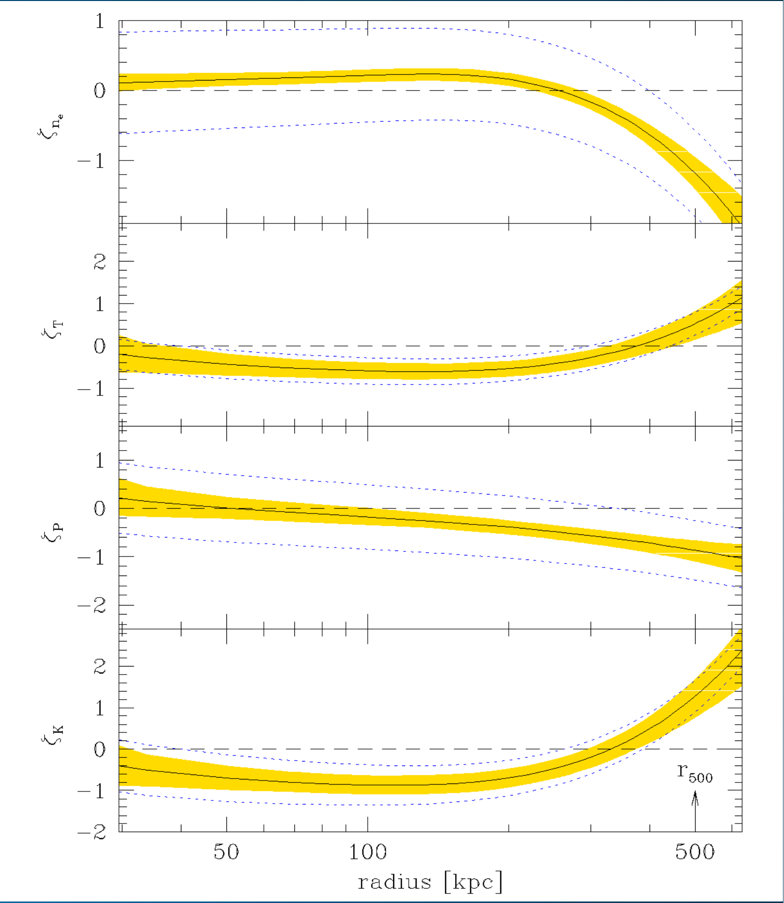
ζ= d ln f (r) / d ln E_z



Expected evolution (Magneticum)

⟵Broad similarity ⟶

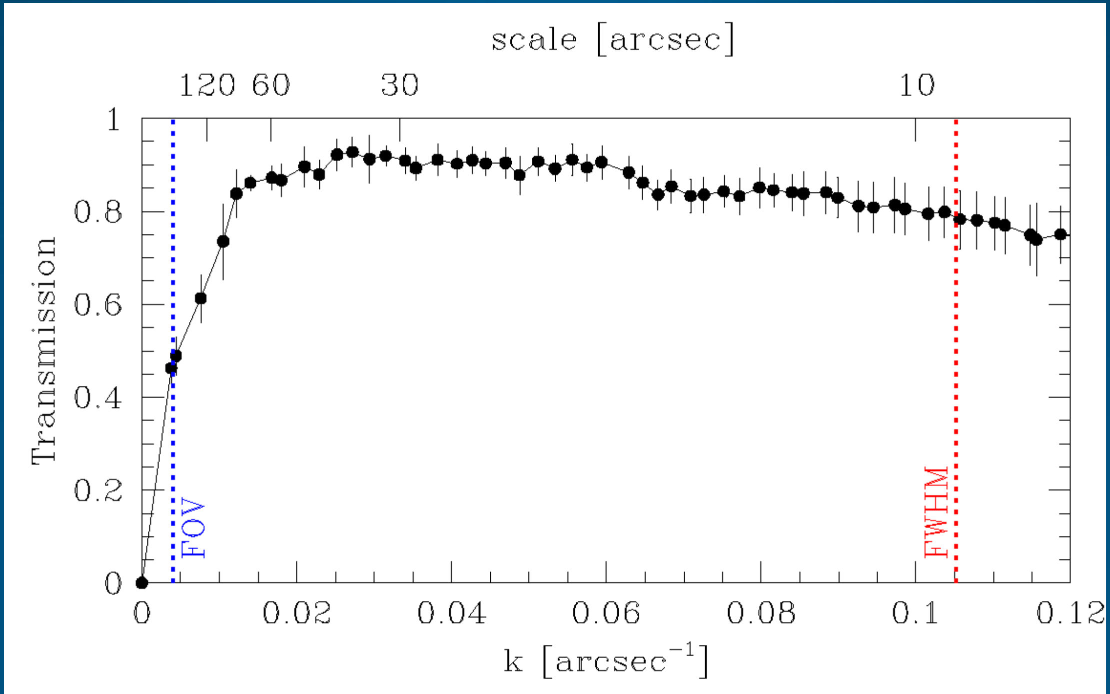
Caveat: qualitative match only



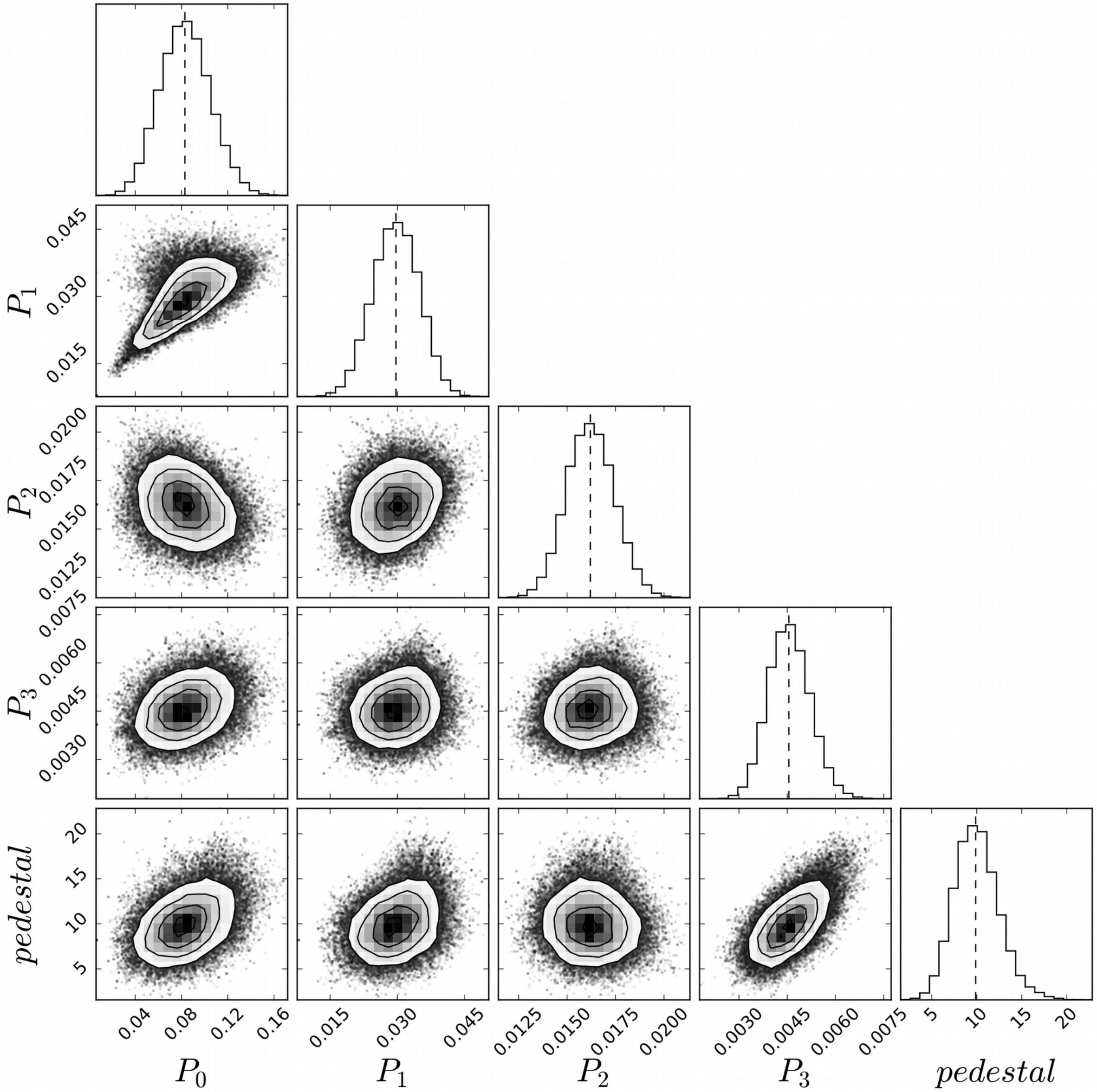
Observed

In simulations, bulk motion can be directly seen (not inferred). As for observations, heat and entropy is transferred inward with little net gas transfer at intermediate r, whereas at large r n_e grows by accretion of cold, lower entropy gas.

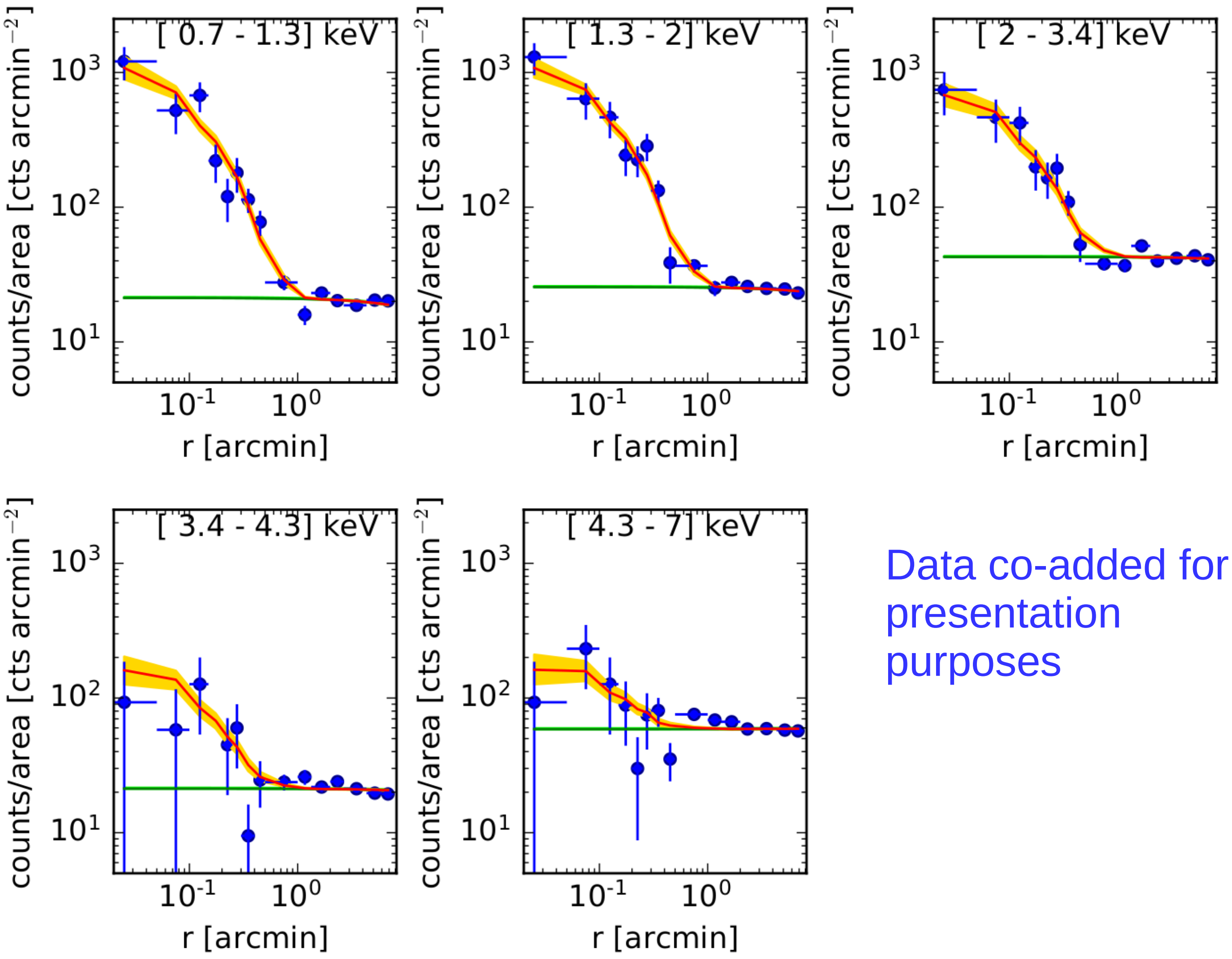
Transfer function



Joint and marginal posterior, SZ fit



X-ray profiles & fit



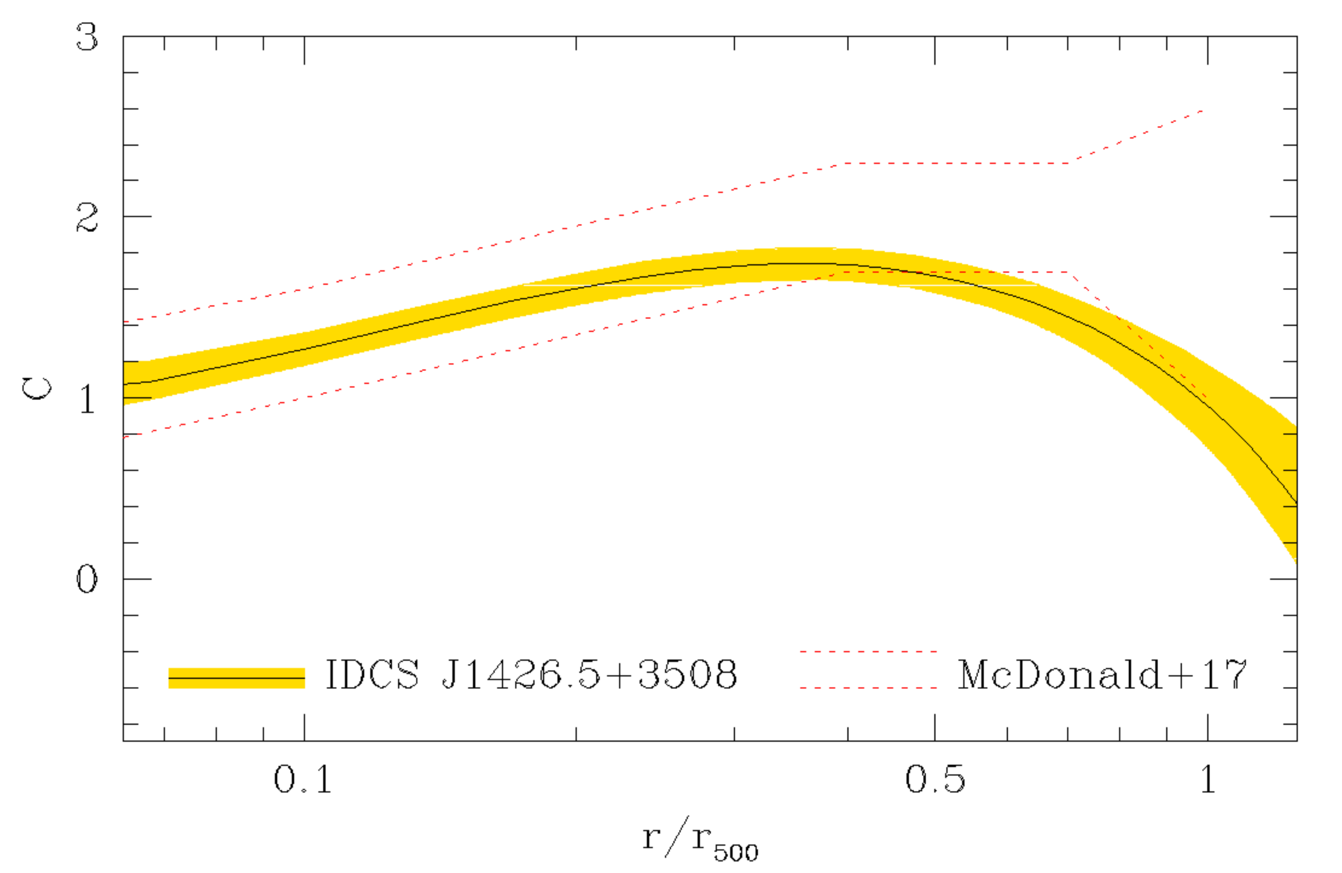
Data co-added for presentation purposes

Fitted cube
==520 net photons,
150x2 data points
== 15x2 spectra with 10 data point each
== 10x2 bands with 15 radial bins.

Fully Poisson stats, background modelled, not subtracted

Pointings jointly fitted, not coadded

Comparison with McDonald+17



n_e only, a few clusters, <z>=1.4

Evolutionary rate C=0 at large r means large growth (not no-evolution)

Larger (than believed) variety in pressure profiles, at z=1.75!