Substructures associated with the sloshing cold front in the Perseus cluster

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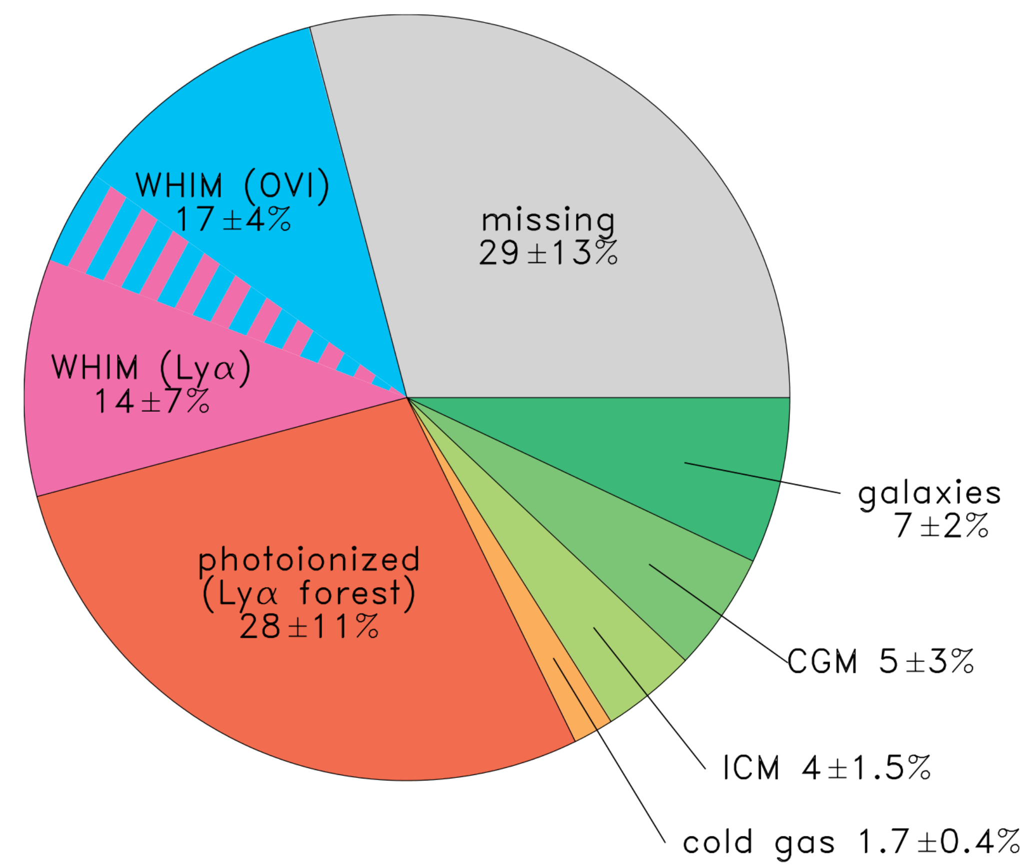
Clusters of galaxies and ICM

- Most of the baryons are in the form of diffuse intergalactic plasma (IGM)

- Clusters of galaxies
  - largest gravitationally-bound objects in the Universe
  - grow by merger and/or accretion
  - 85% dark matter, 12% ICM, 3% galaxies and stars

- Intracluster medium (ICM)
  - high-temperature (10^7-10^8 K), low-density (10^{-4}-10^{-1} cm^{-3}) plasma
  - shines in X-ray -> most accessible IGM
  - its fundamental microphysics is still not well known

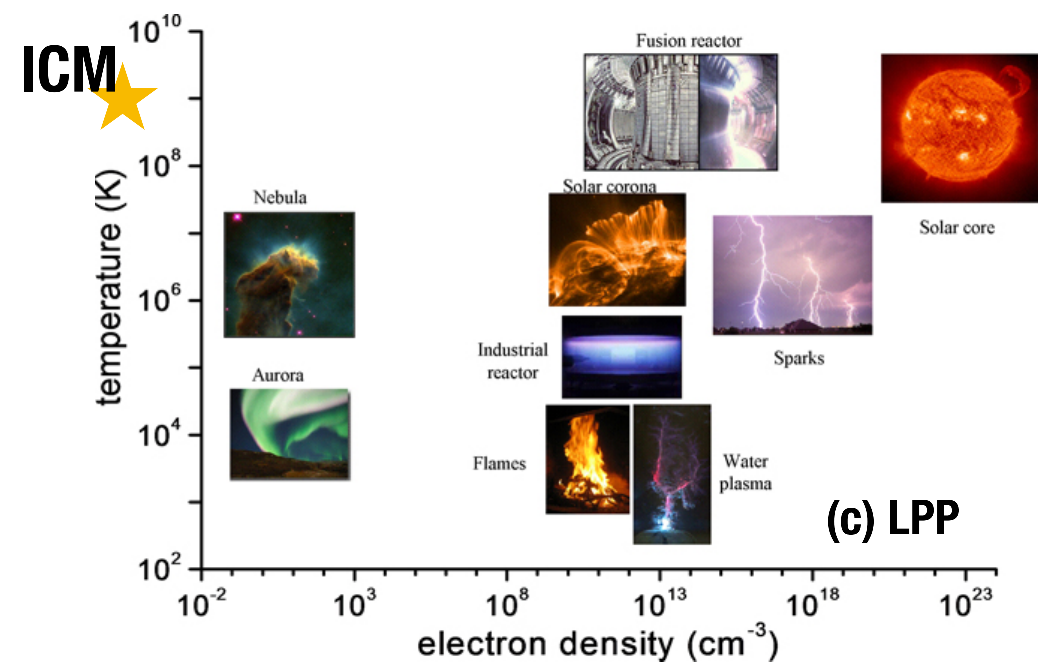
Baryon census (Shull+12)



ICM microphysics

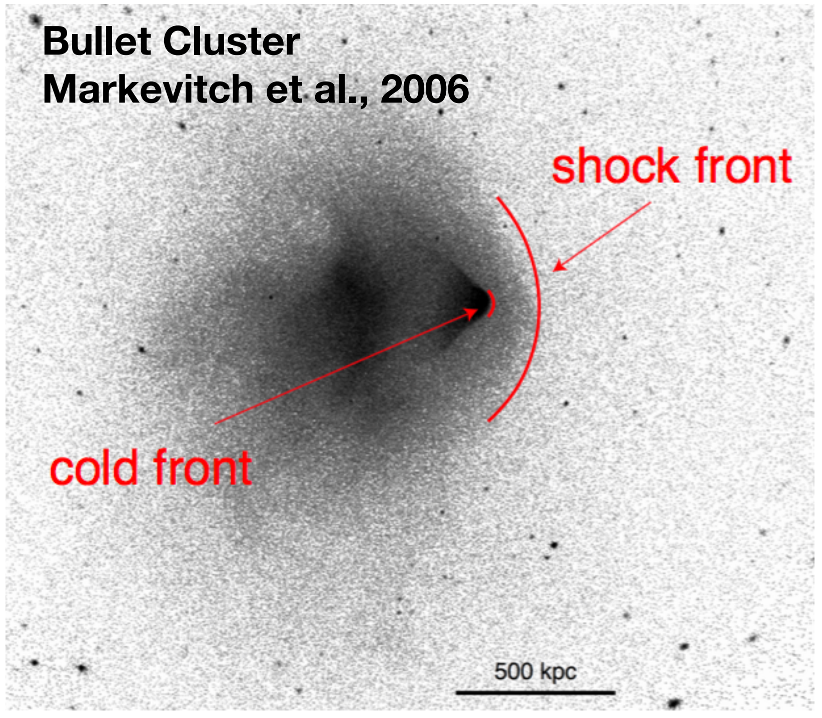
viscosity, conductivity, magnetic fields, turbulence, inhomogeneity etc.

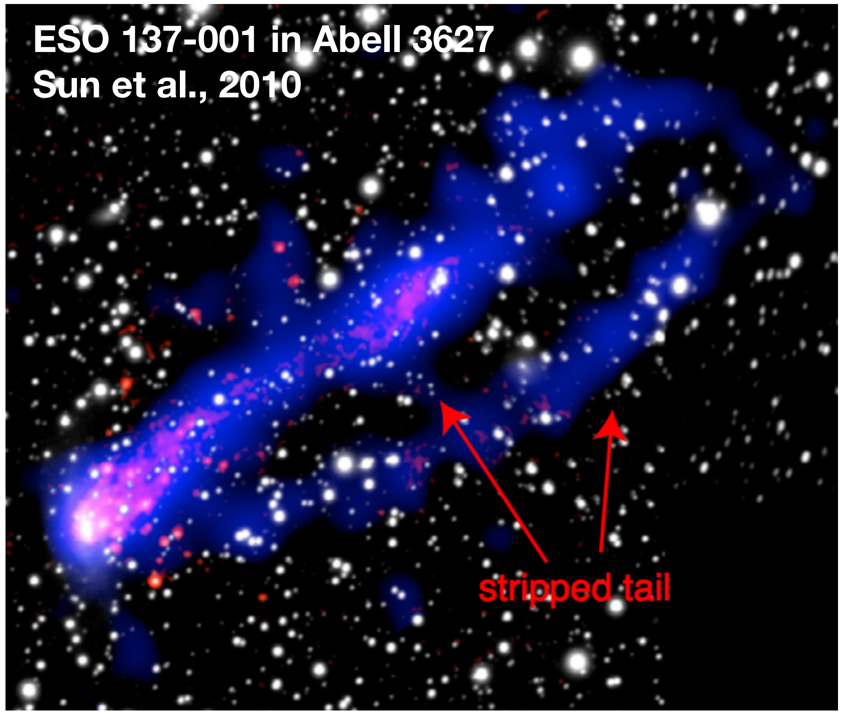
- fundamental parameters of the most dominant phase of baryon
- important in astrophysics
  - how energies branch into other forms of energy
  - how efficiently the energy transportation takes place
- important in cosmology
  - HSE mass estimation
- important in plasma physics
  - high-temperature and low-density end of the plasma phase space
  - cannot be reproduced in labs

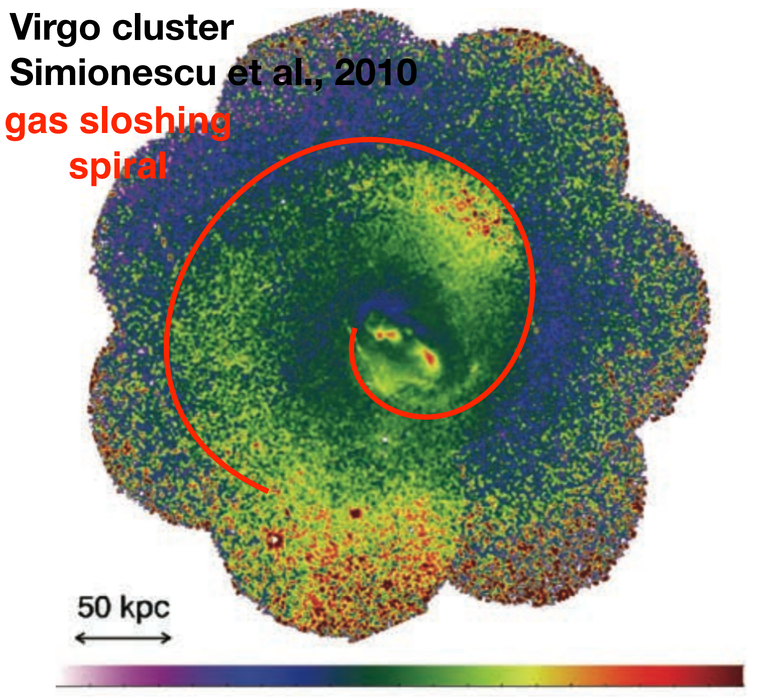


X-ray substructure

ICM must respond to thermal/kinematic disturbance
the response emerges as X-ray substructure, reflecting ICM microphysics



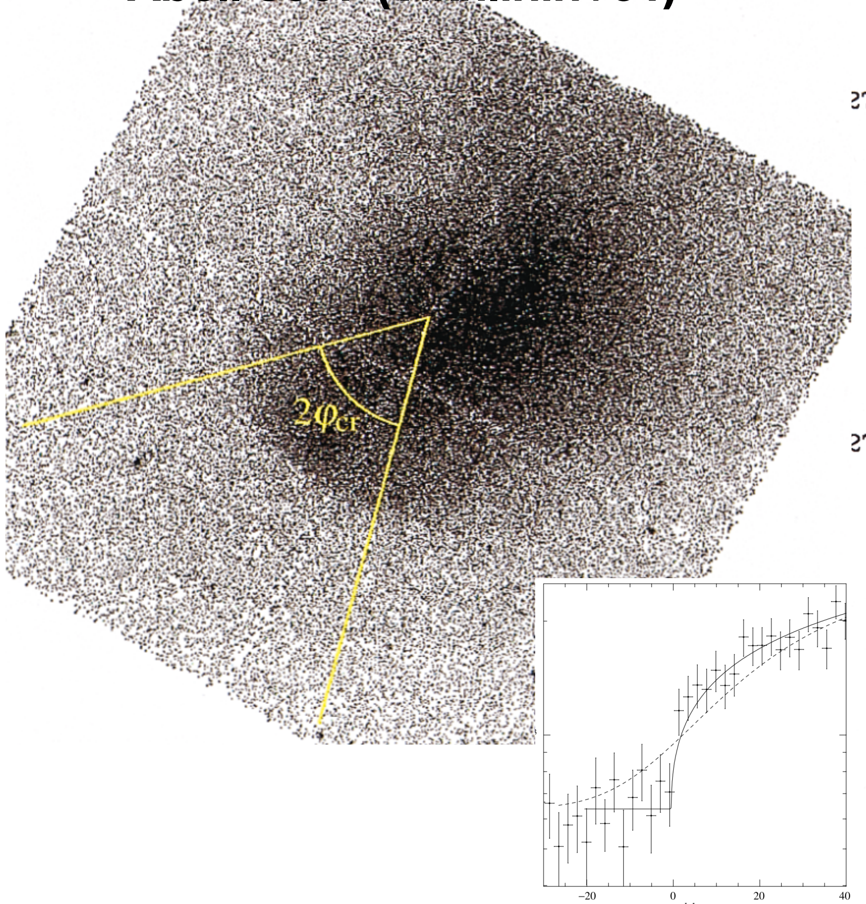




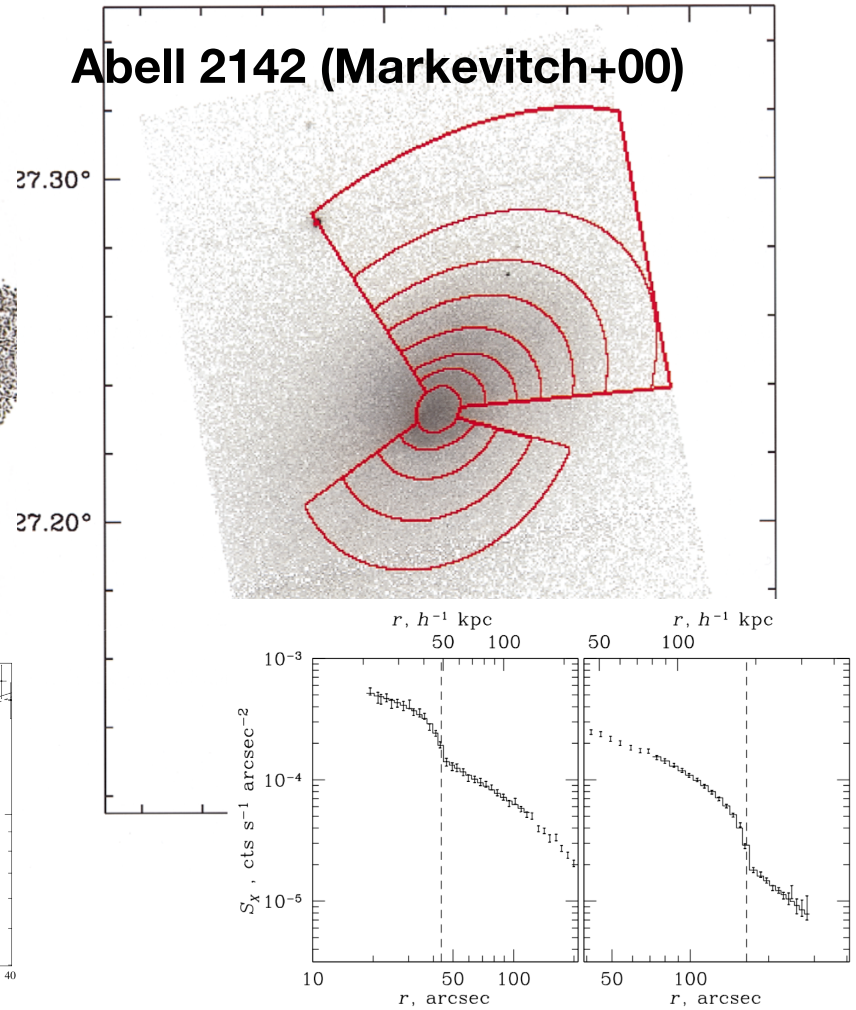
- supersonic motion -> shock
- ram pressure stripping -> stripped tail
- merger with non-zero impact parameter -> gas sloshing spiral
- cool gas moving in the hot ambient medium -> cold front

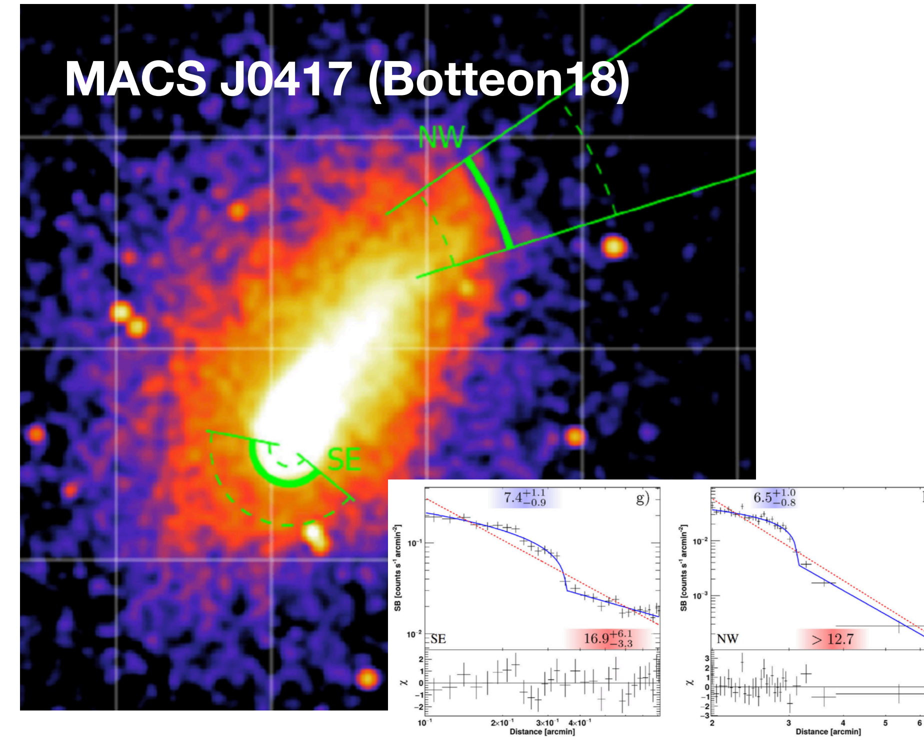
Cold fronts

Abell 3667 (Vikhlinin+01)

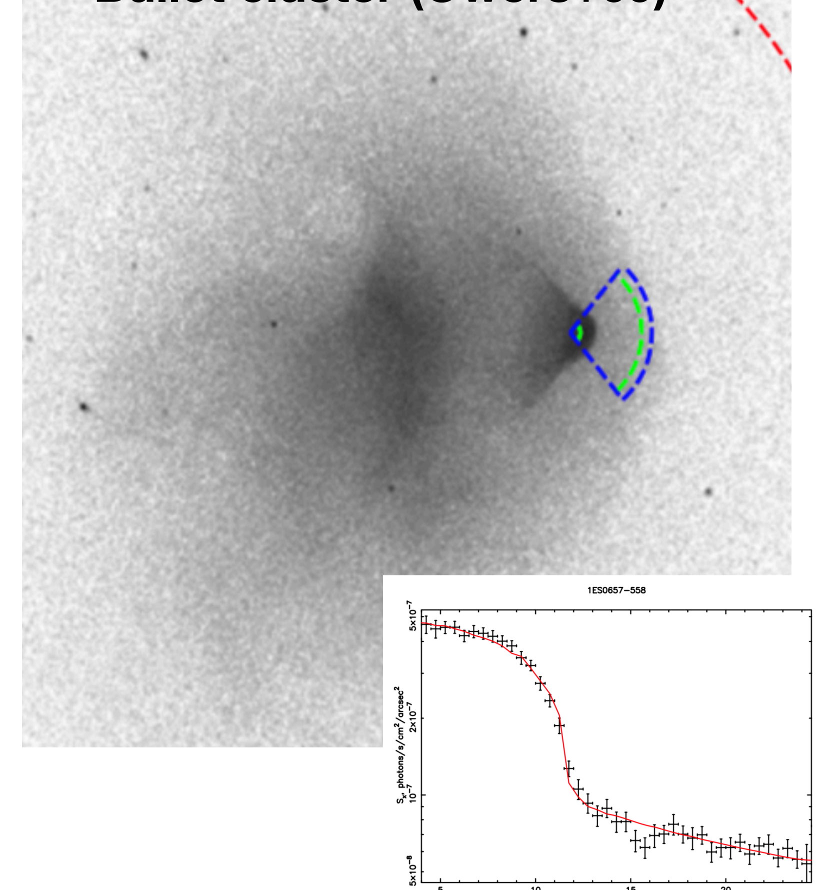


Abell 2142 (Markevitch+00)





Bullet cluster (Owers+09)



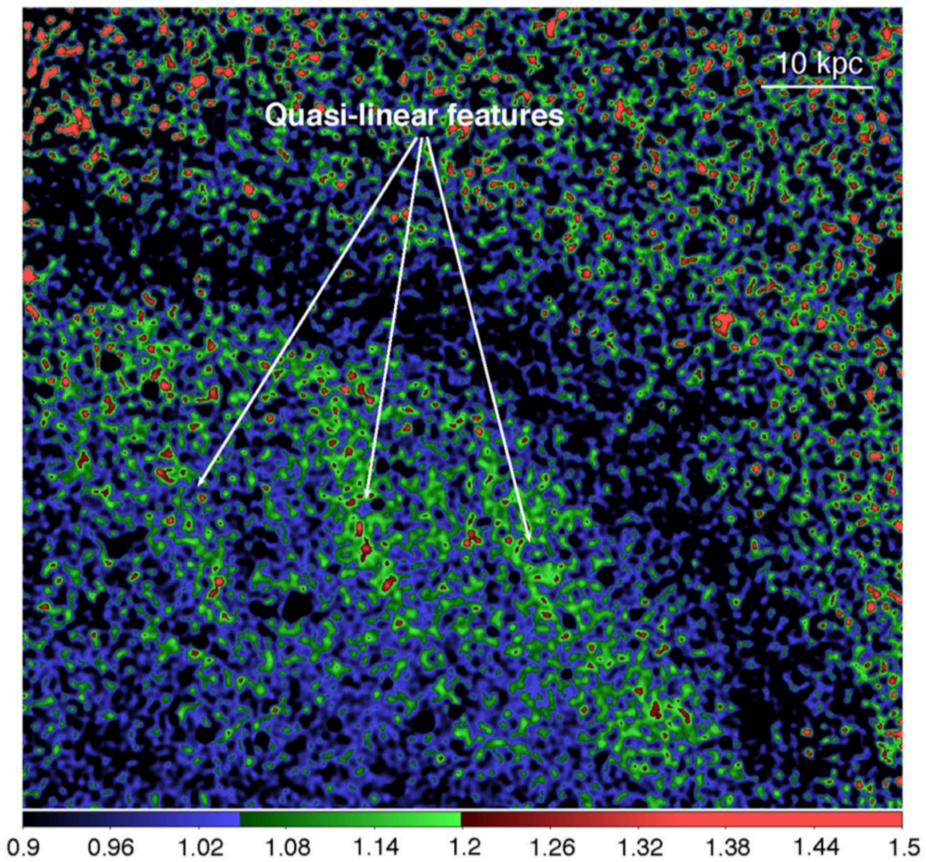
- sharp ($<\lambda_{mfp}$) contact discontinuity
- widely used to probe ICM microphysics
  - transport process suppressed due to magnetic field (Vikhlinin+01)
  - thermal conductivity suppressed by a factor of 250-2500 (Ettori+00)

have mostly been treated as single objects

Cold front substructures

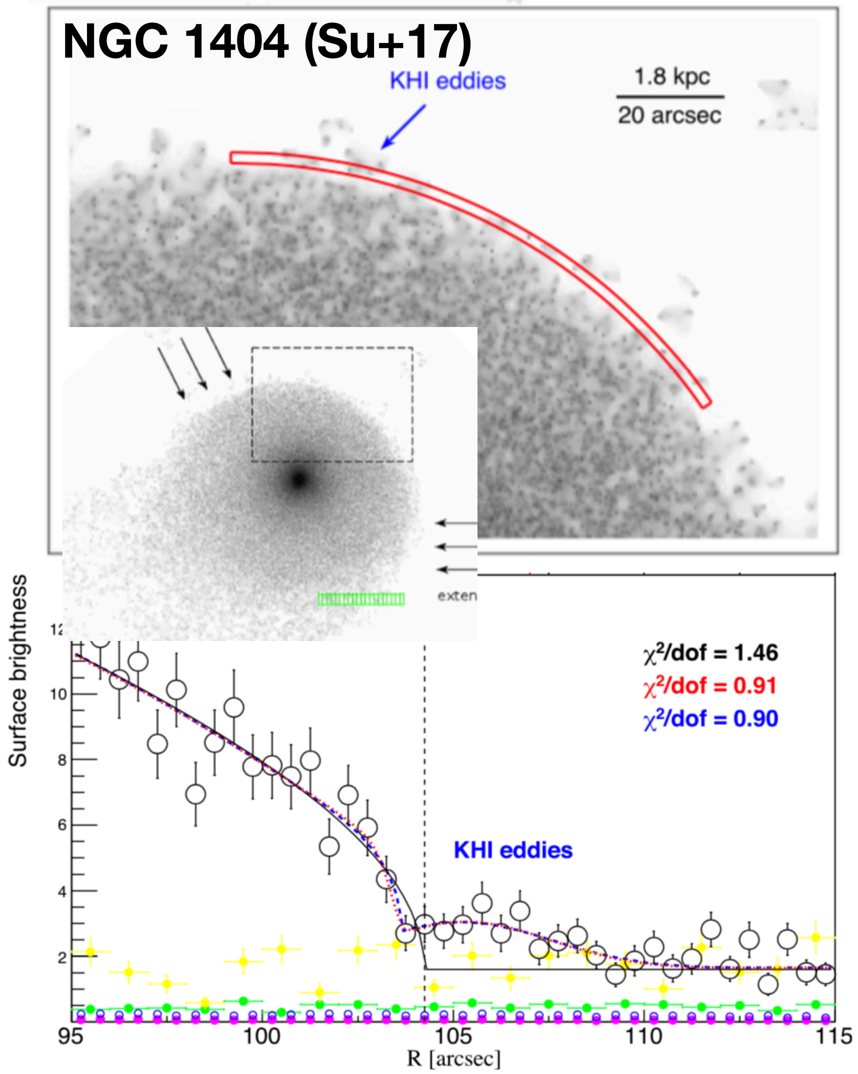
Cold fronts are not just simple ICM substructures
-- they themselves have substructures!

Virgo cluster (Werner+16)



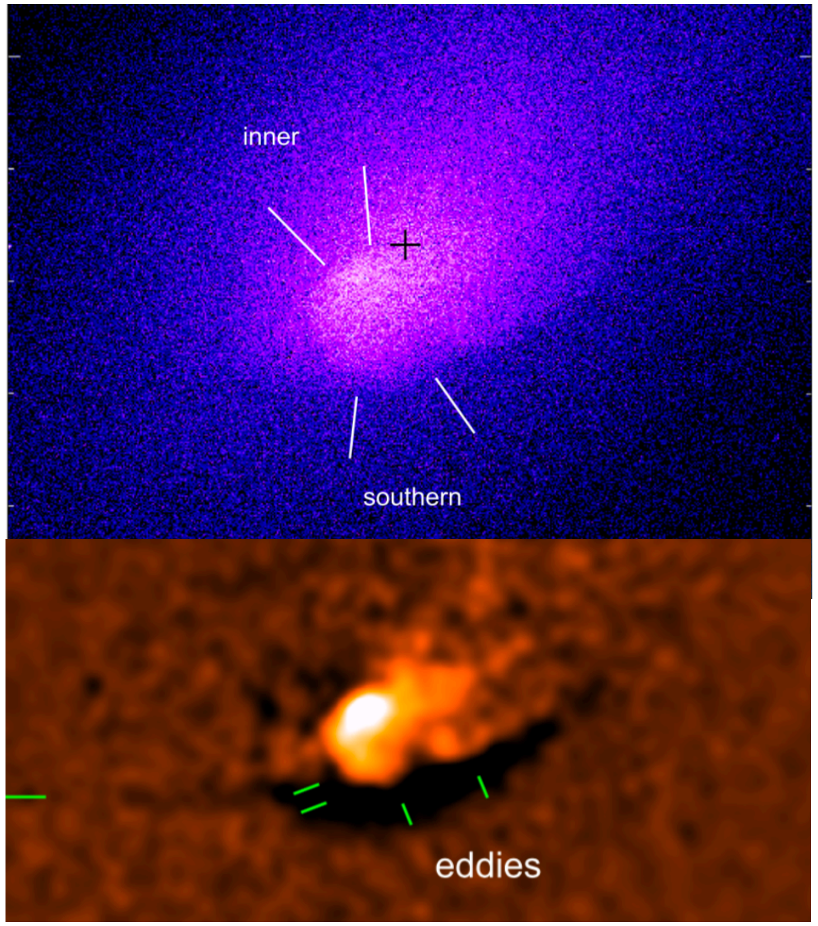
linear features below the front

NGC 1404 (Su+17)



bumpy SB profile

Abell 2142 (Wang+18)

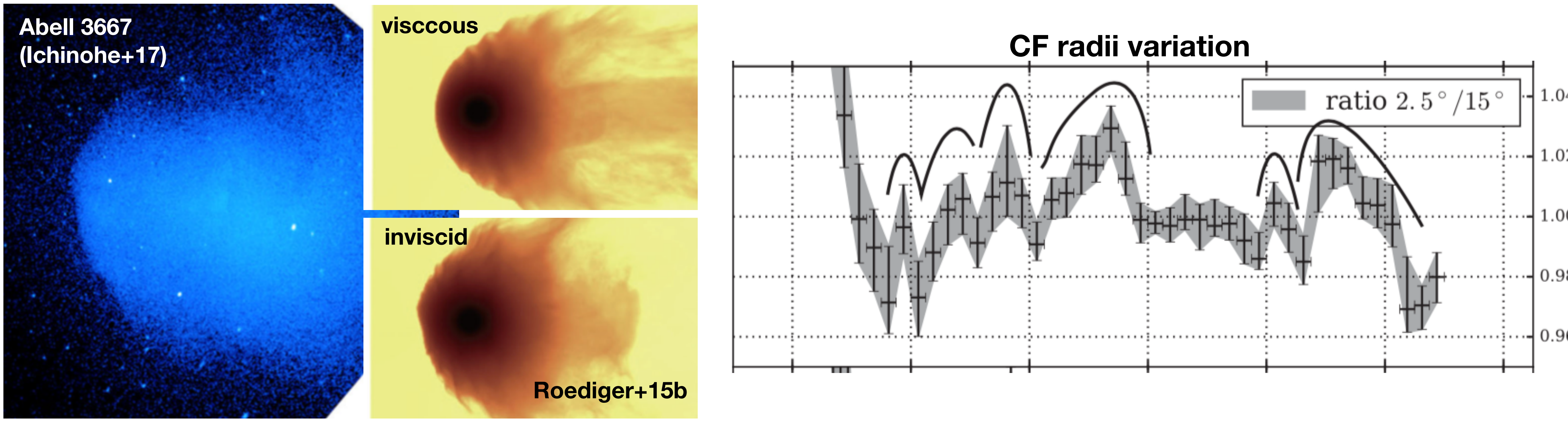


bumpy interface

- Kelvin-Helmholtz instabilities
- plasma depletion layer

Using CF substructures to infer ICM microphysics

e.g. azimuthal variation of the cold front in Abell 3667 (Ichinohe+17)



- azimuthally resolved SB / deprojected thermodynamic profile
- likely KHI
  - -> upper limit of ICM viscosity ~200 g/cm/s (5% Spitzer)
    - < 5% Spitzer (NGC 1404, Su+17)
    - < 20% Spitzer (A2142, Wang+18, consistent with Braginskii)

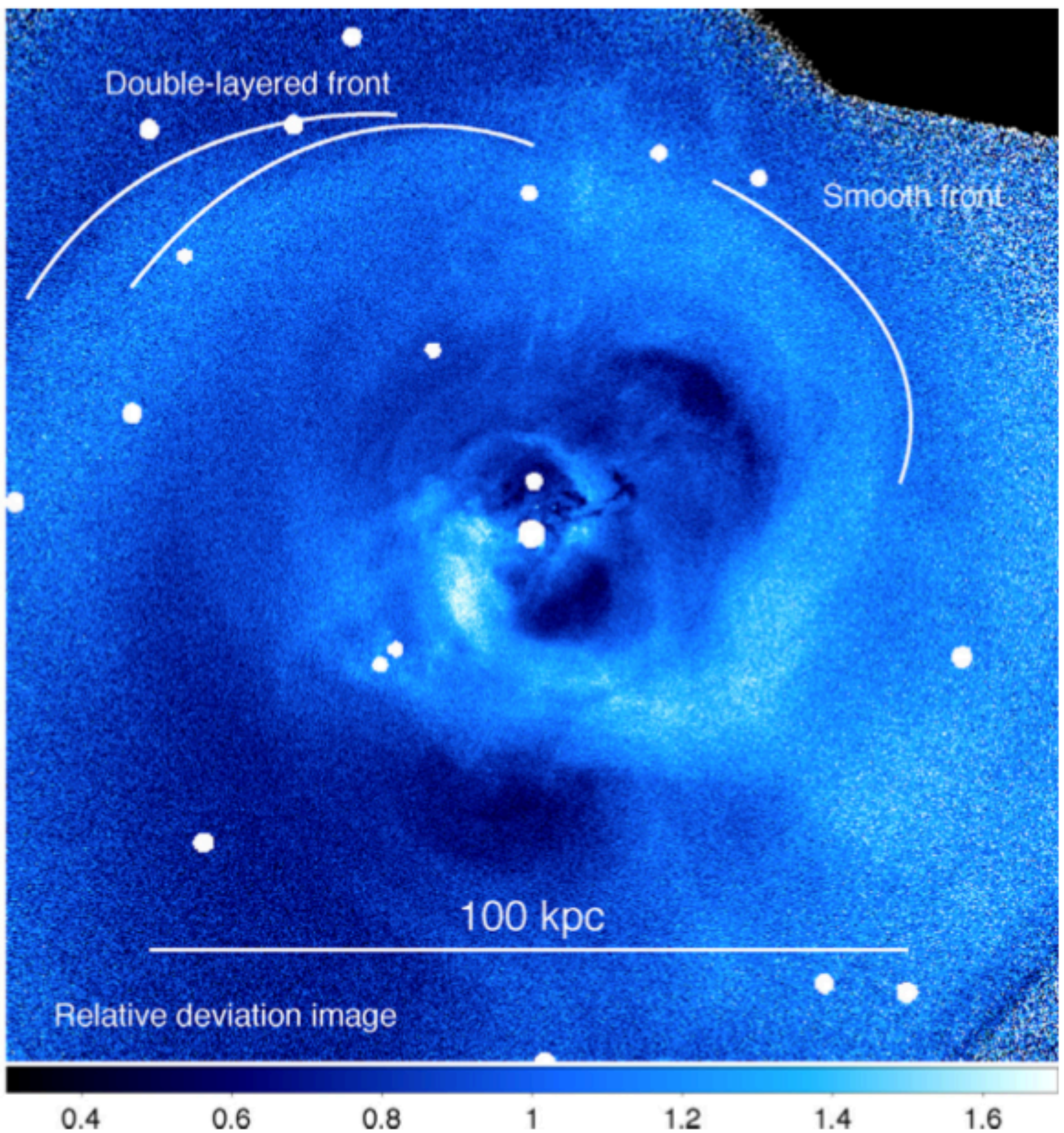
using substructures, quantitative estimations are becoming possible
but small -- difficult to measure thermodynamic properties

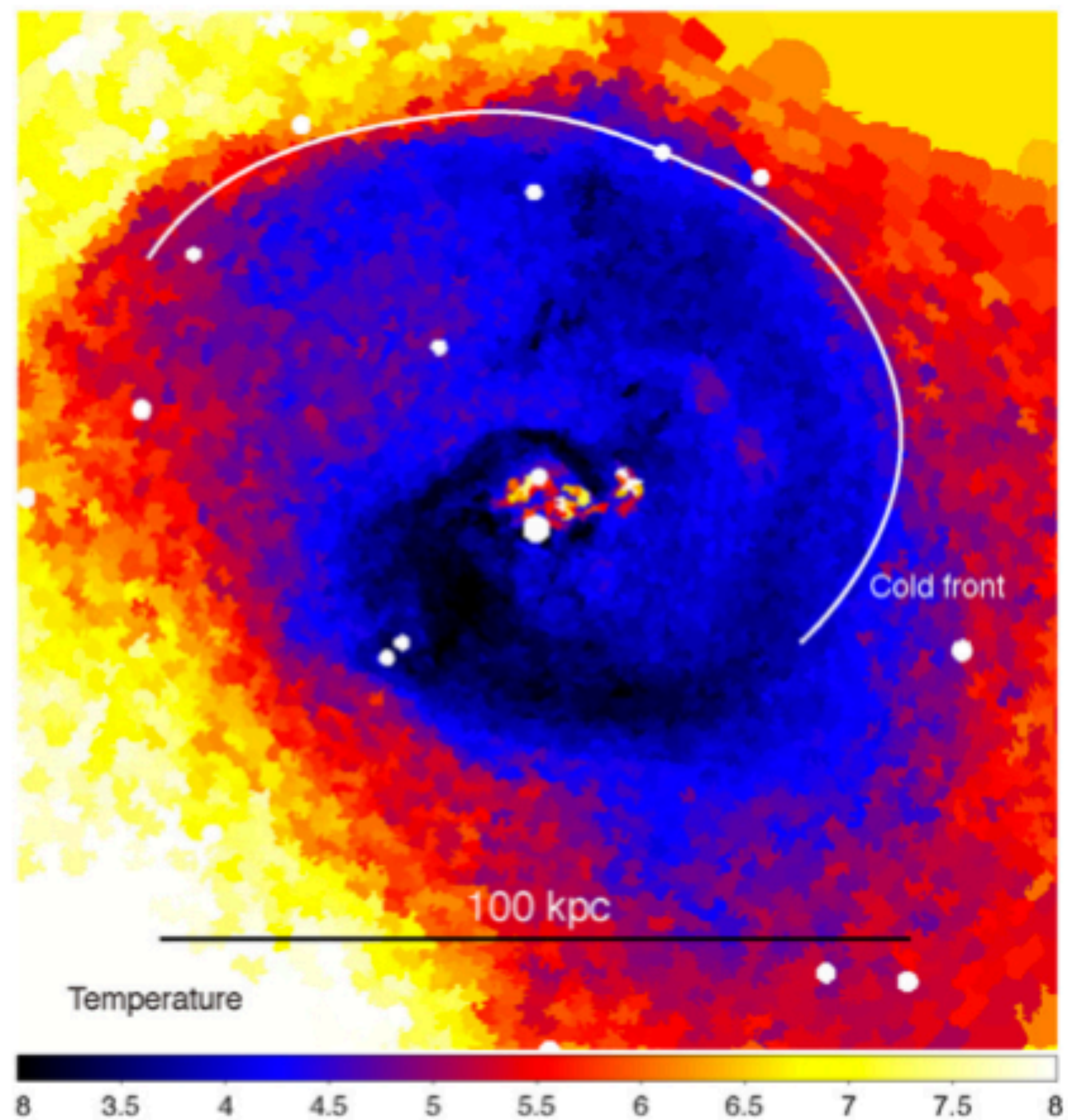
Sloshing cold front in the Perseus cluster

What else can be quantitatively constrained using CF substructures?

Perseus: nearby (z~0.0173), X-ray brightest, >Msec Chandra obs.

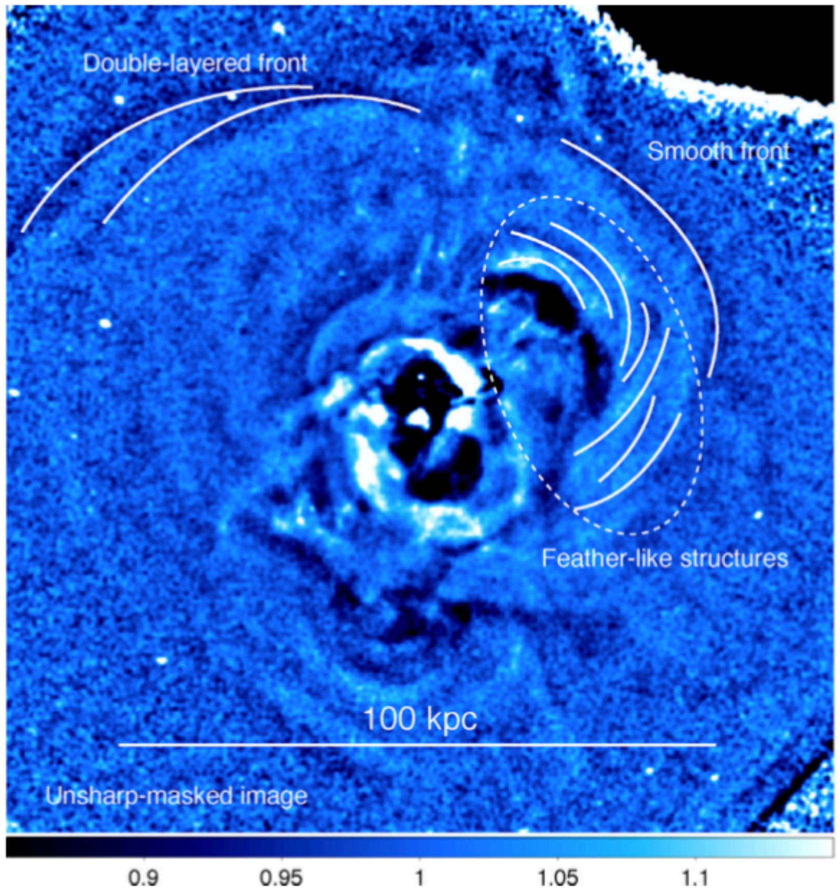
-> ideal target for thermodynamic studies of individual substructures



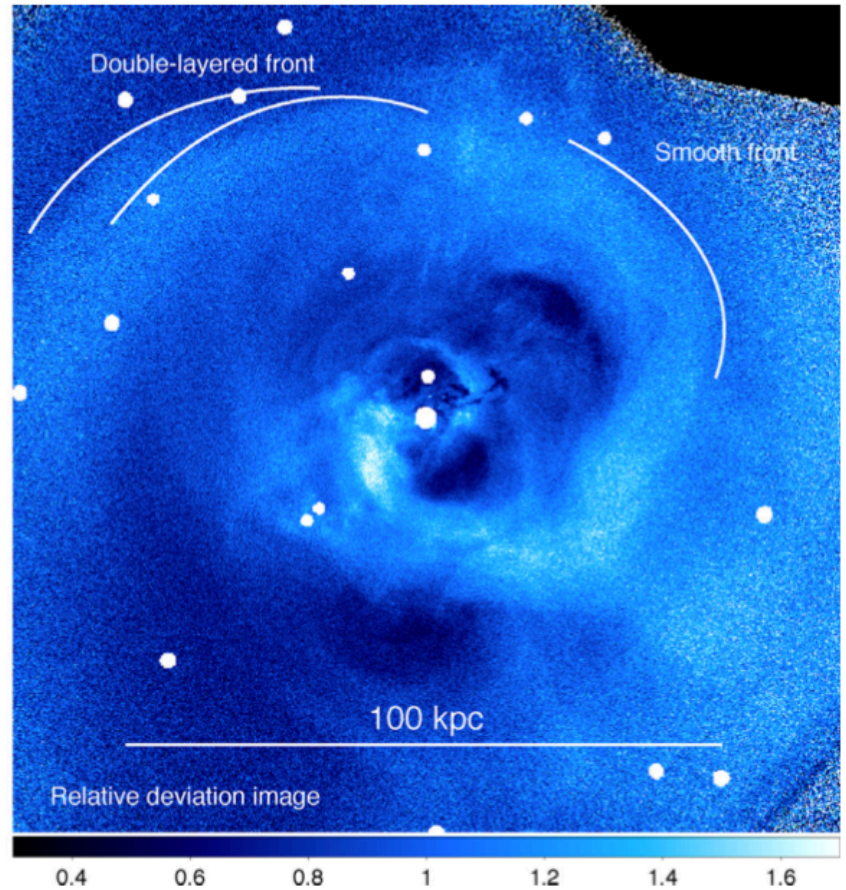


Sloshing cold front in the Perseus cluster

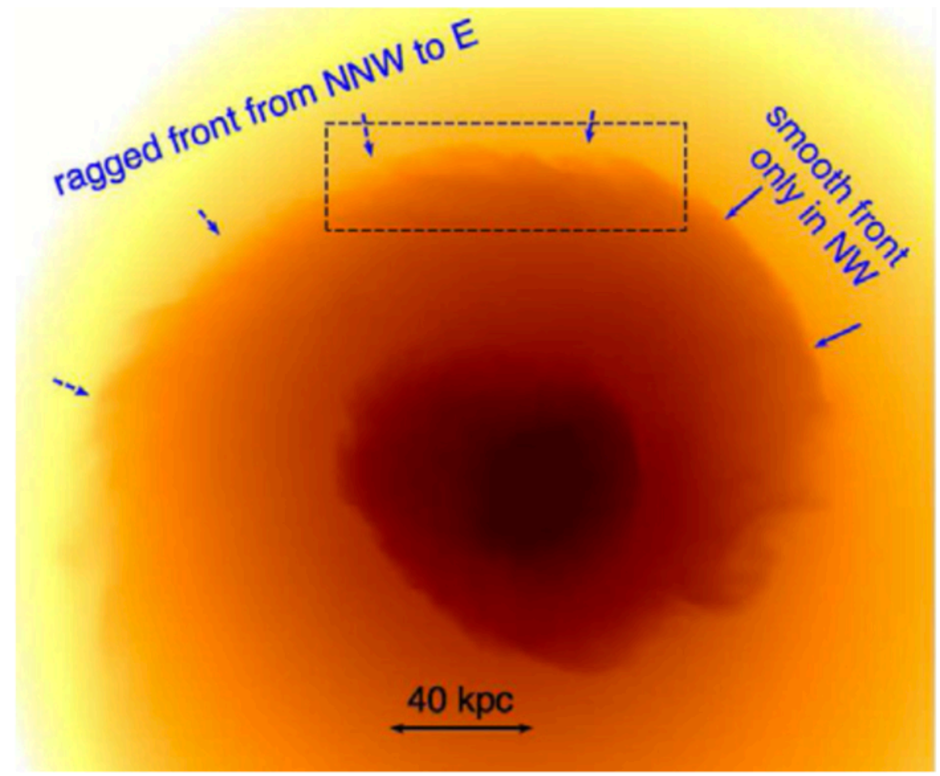
unsharp masked image



relative deviation image



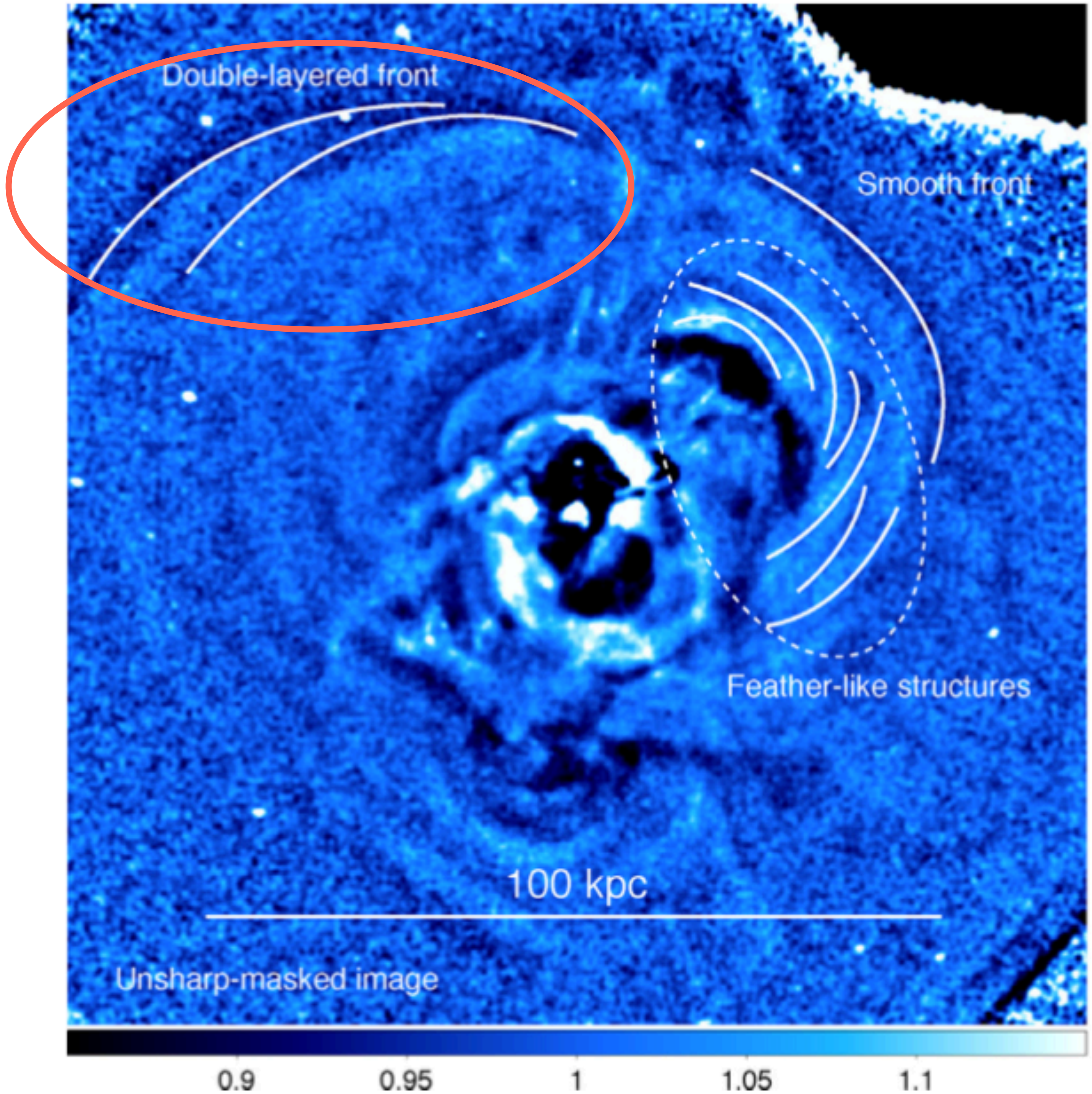
low viscosity simulation (Roediger+13b)



- morphologically similar to recent numerical simulations
  - smooth interface vs. layered morphology -- KHI?

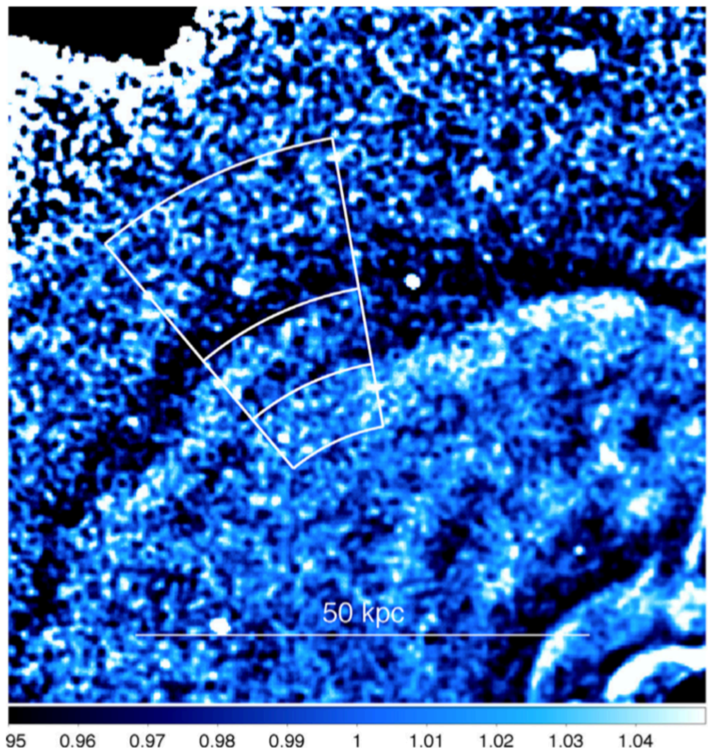
- Feathers & brightness dip -- magnetic amplification?

1. Double-layered interface



Double-layered interface -- SB profile

unsharp masked image



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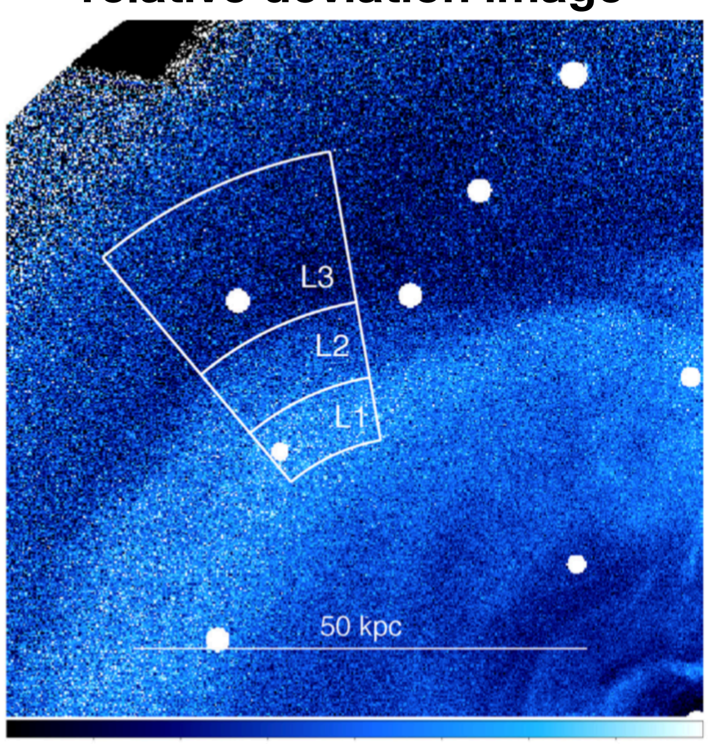
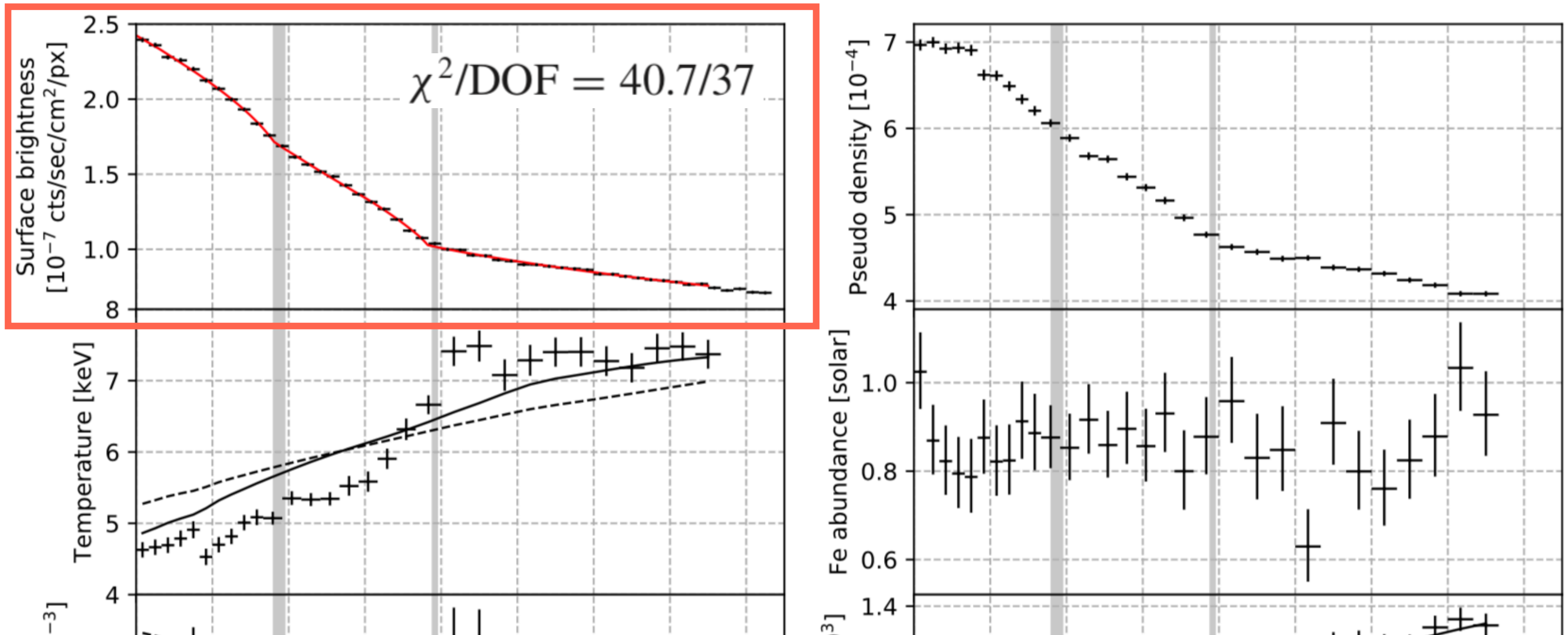
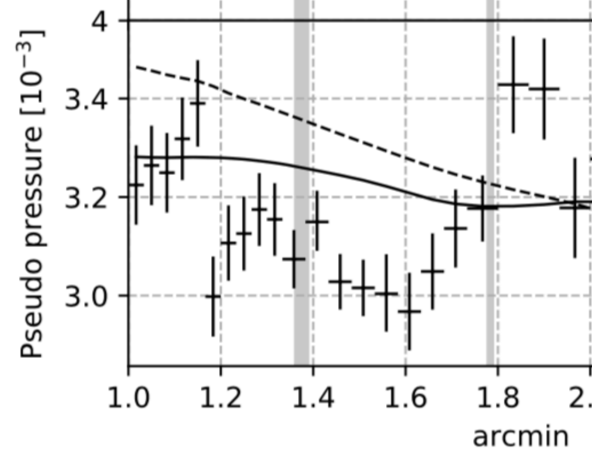




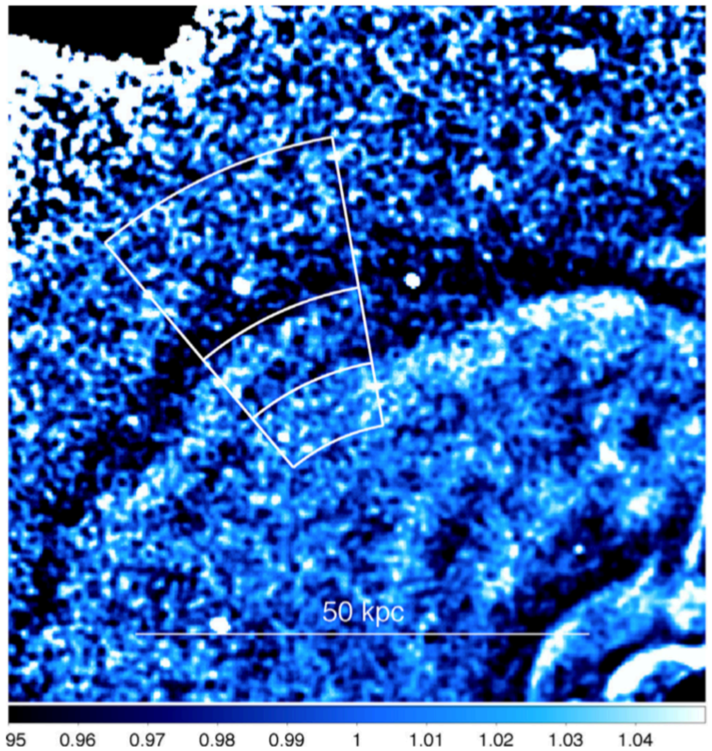


$$
n(r) = \begin{cases} j_{12}\, j_{23}\, n_0 \left(\frac{r_{12}}{r_{23}}\right)^{-\alpha_2} \left(\frac{r}{r_{12}}\right)^{-\alpha_1} & (r \leq r_{12}) \\ j_{23}\, n_0 \left(\frac{r}{r_{23}}\right)^{-\alpha_2} & (r_{12} < r \leq r_{23}) \\ n_0 \left(\frac{r}{r_{23}}\right)^{-\alpha_3} & (r_{23} < r) \end{cases}
$$

- modeling with projected double-broken power law
    - two breaks are actually significant

Double-layered interface -- thermodynamics

unsharp masked image



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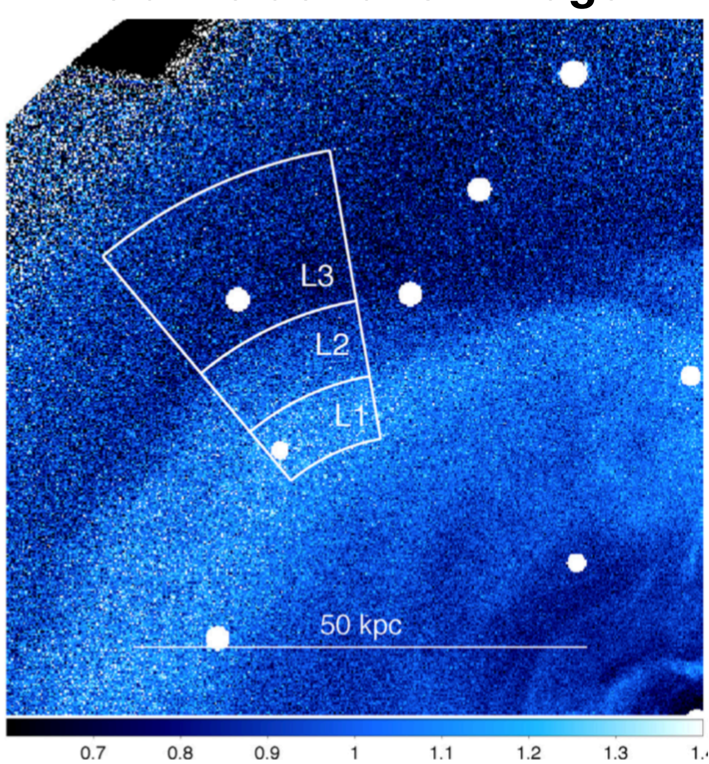
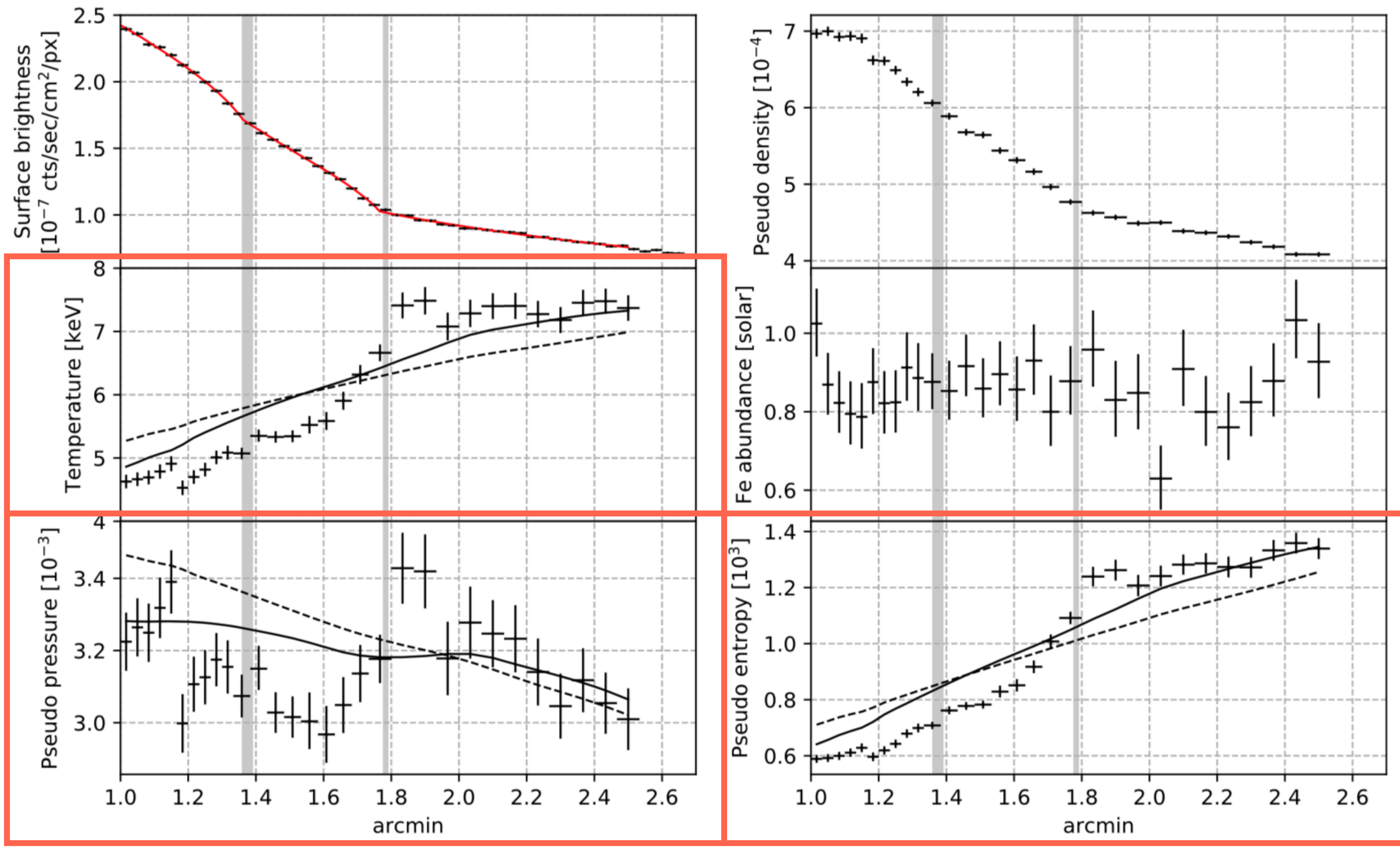
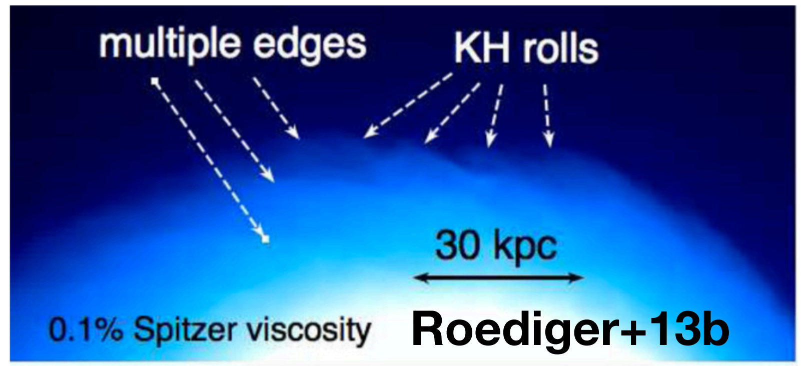




- kT/S slope changes at the breaks
- flat kT/S beyond the second break
- P dip between two breaks

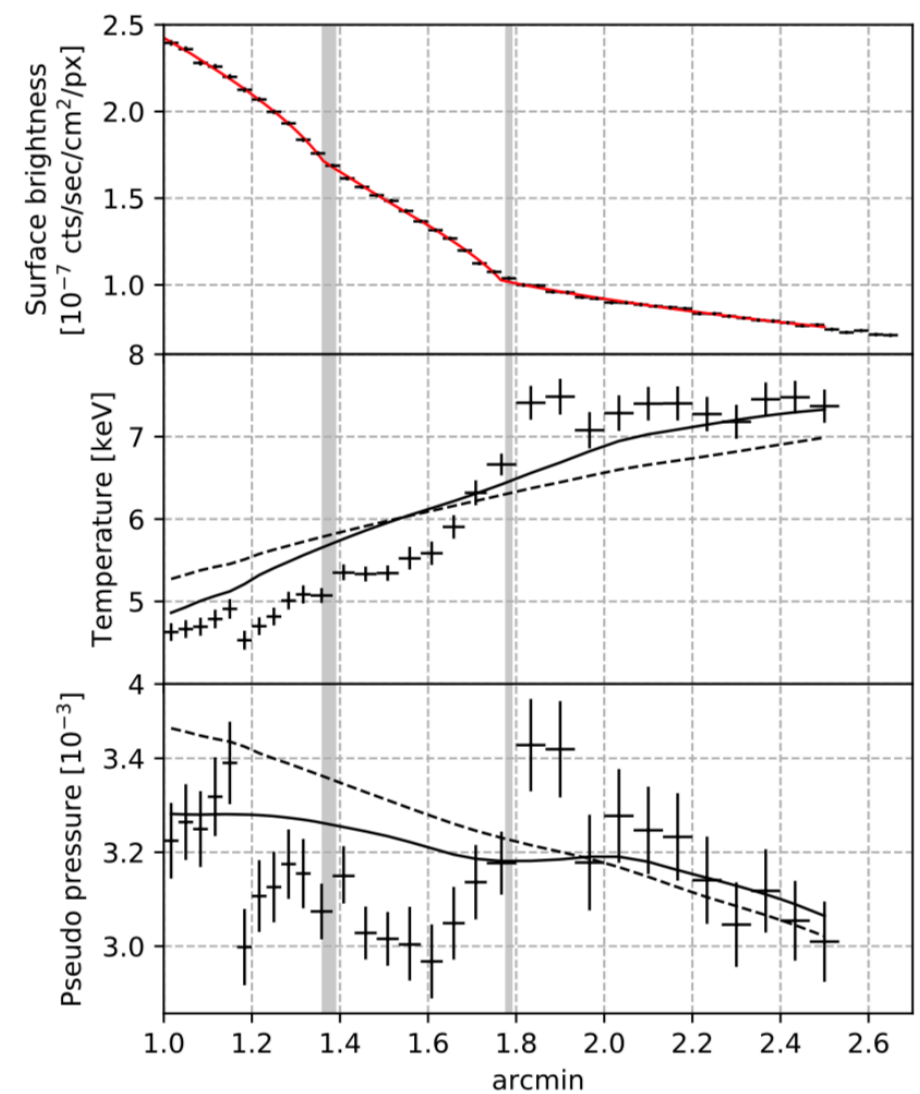
- flat Fe abundance, weak shock

KHI developing on the sloshing CF



what we observed:

- two significant SB breaks
  - multiple edges (sloshing KHI, Roediger+13b)
- first break: kT/S↗, P→, n↘
  - likely (mild) cold front
- second break: kT/S↗, P↗, n↘
  - not cold front (at least in the classical sense)



KHI developing on the sloshing CF

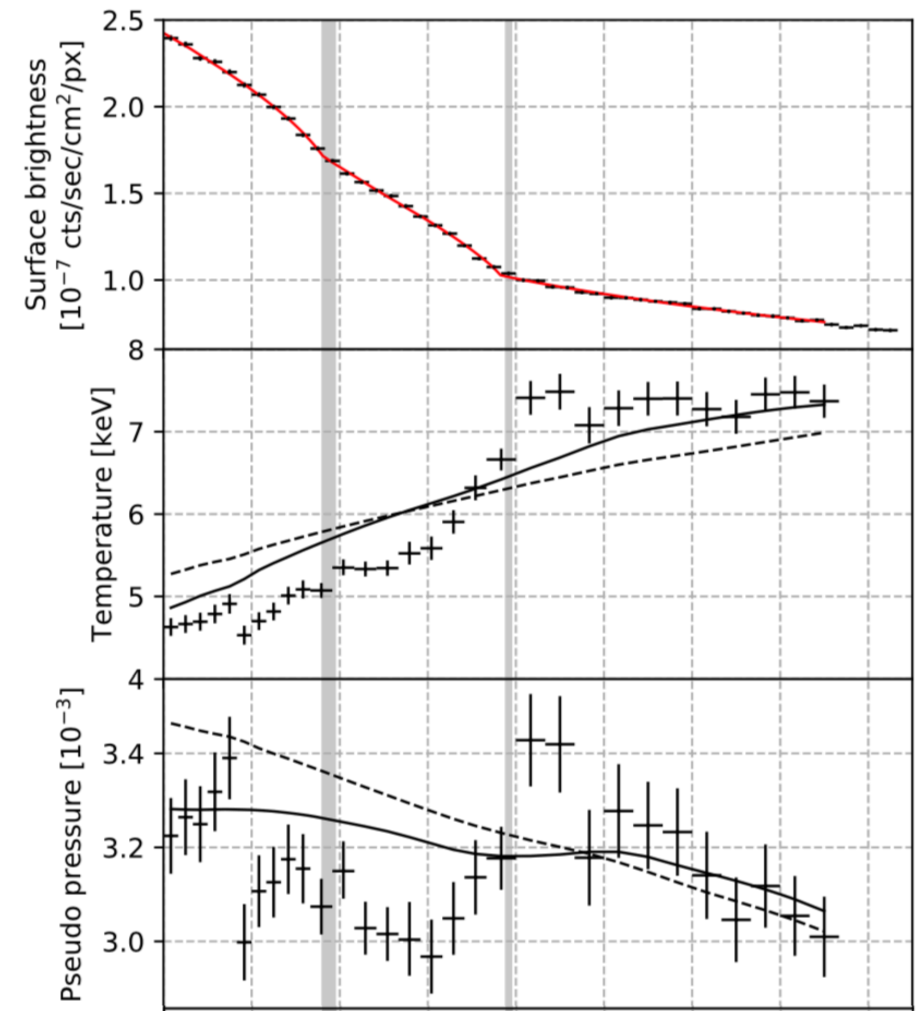
interpretation:
KHI developing on the sloshing cold front

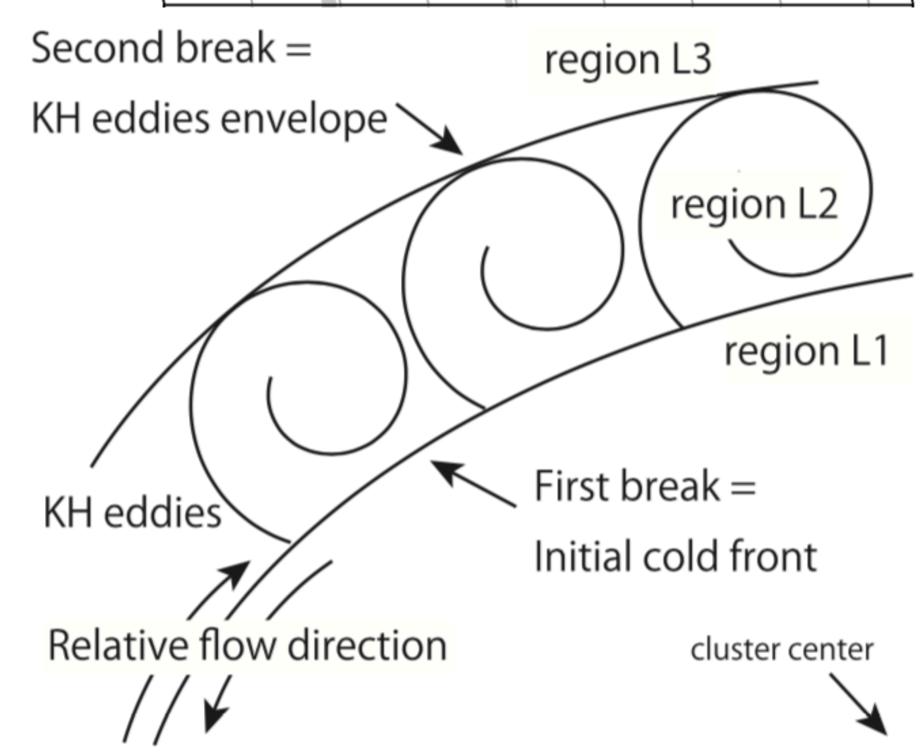
- First break: initial cold front
  - smeared by developing KHI -> no clear jump

- Second break: current KHI eddies envelope
  - induced by the shear at the first front
  - KHI is not coherent -> continuous change

- flat kT/S -> convergent flow (c.f. Virgo CF, Werner+16)

- 2T modeling also supports the scenario
- aspect ratio is consistent with numerical simulation results (Roediger+13a,b)





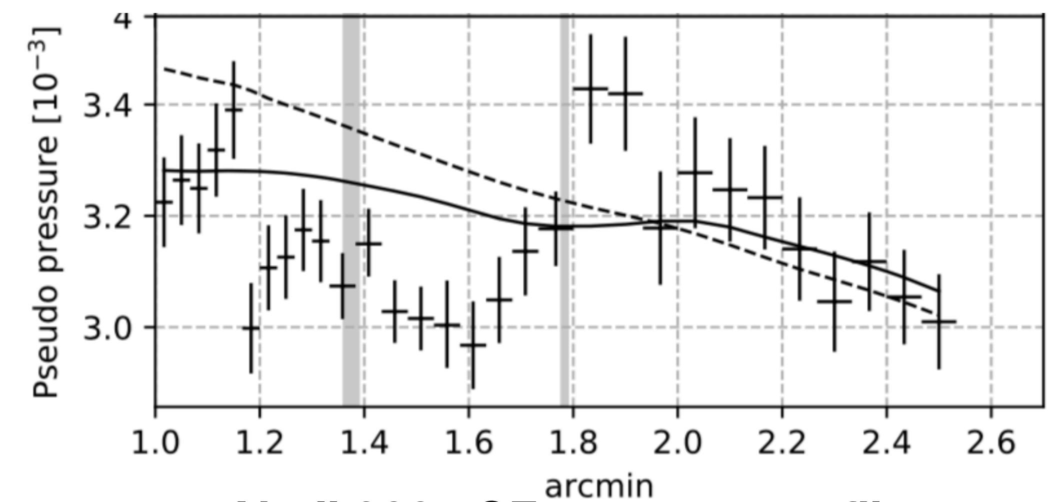
Implications on ICM microphysics

P dip between two breaks

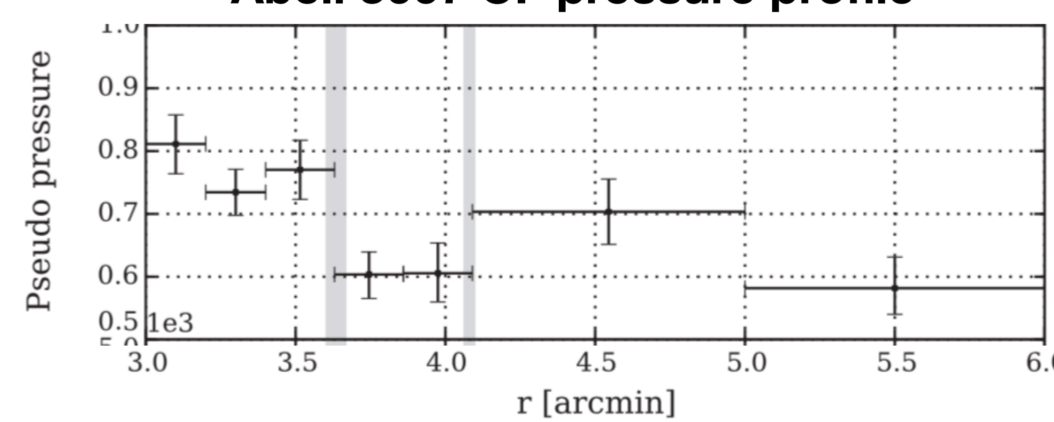
- c.f. A3667, KHI on merger CF

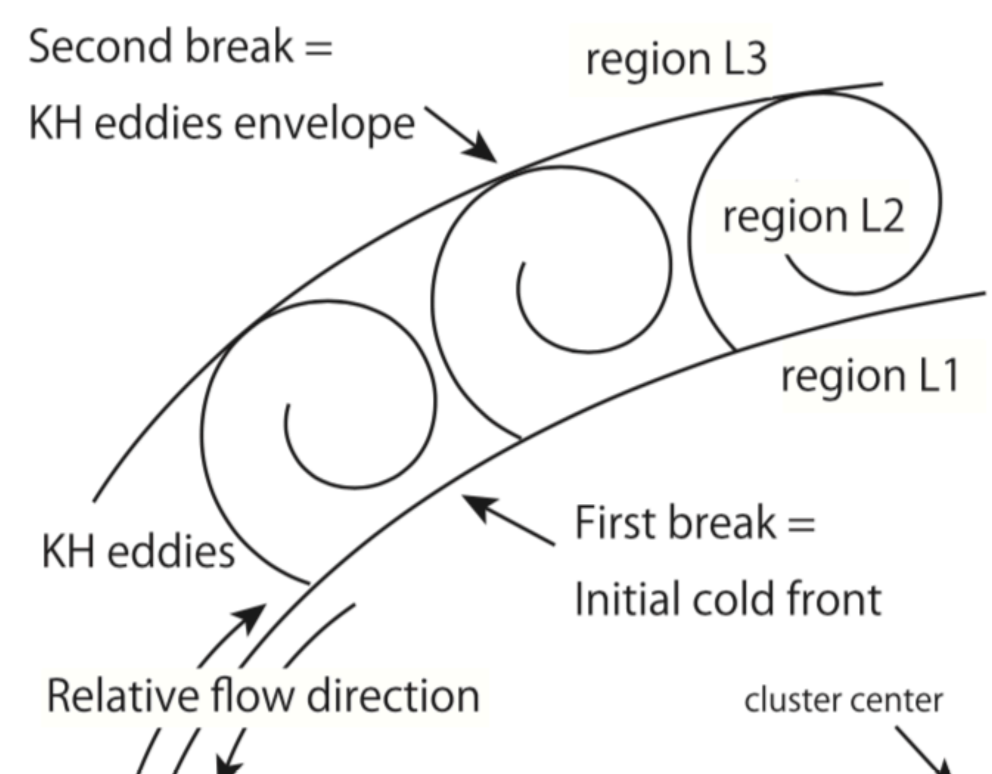
ΔP ~ 10^{-2} keV/cm^3

- turbulence
  - V_{1d} ~ 400 km/s
    - Hitomi 100-200 km/s
- magnetic fields (Keshet+10)
  - B ~ 30 μG
    - consistent with Reiss+14 if the second break is the CF

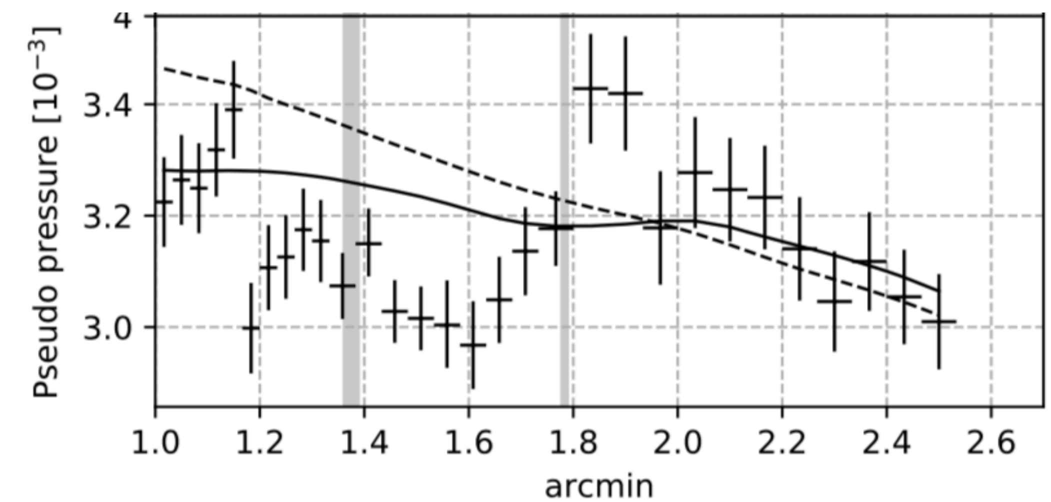


Abell 3667 CF pressure profile

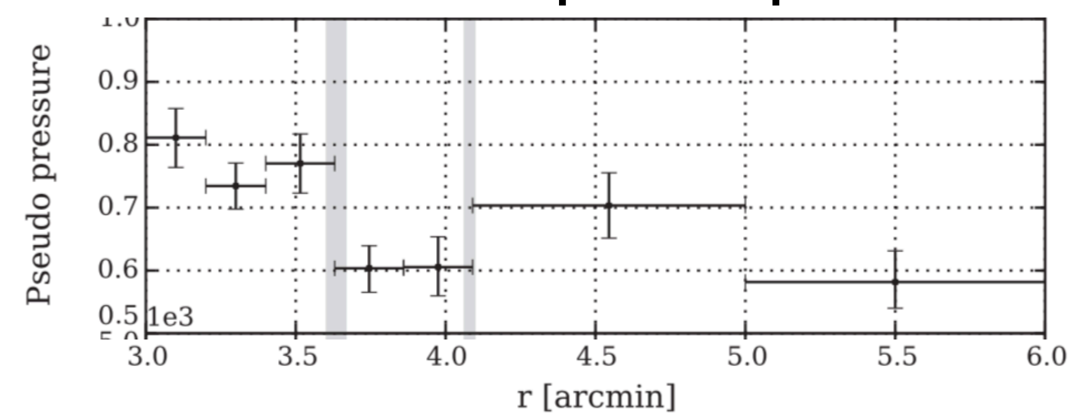


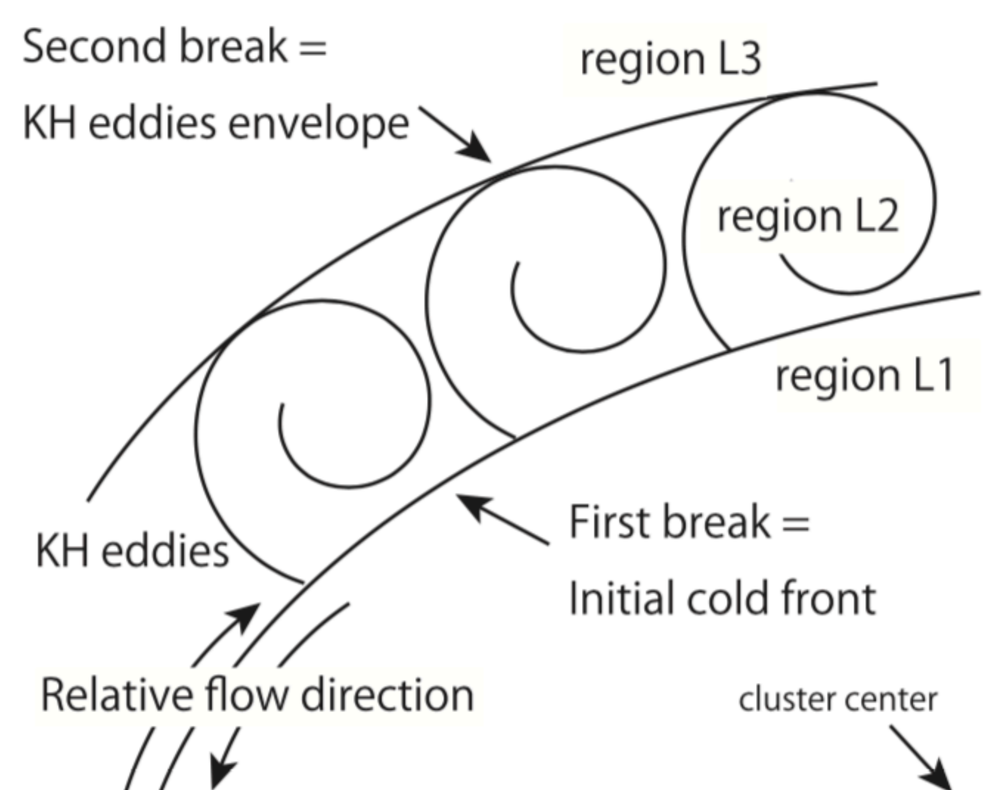


Implications on ICM microphysics



Abell 3667 CF pressure profile





if turbulence

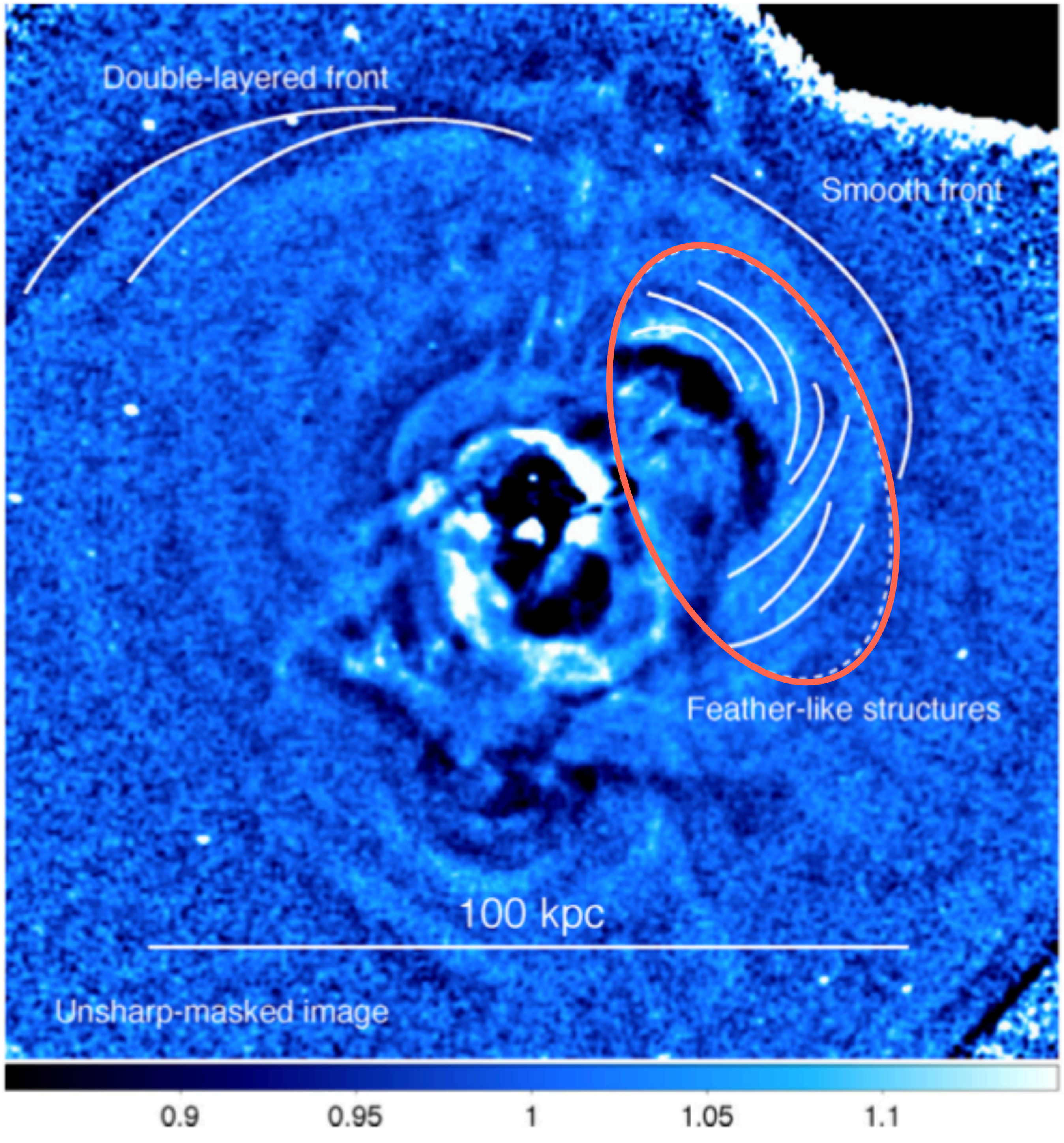
$Q_{turb} = C_Q \rho V_{1d}^3/L \sim 10^{-26}$ erg/cm^3/s

- can support the cooling rate at this radius ~ 10^{-27} erg/cm^3/s
- consistent with Zhuravleva+14 (~10^{-26} erg/cm^3/s, SB fluctuation)

indicating the importance of KHI-induced turbulence (not very much studied observationally)

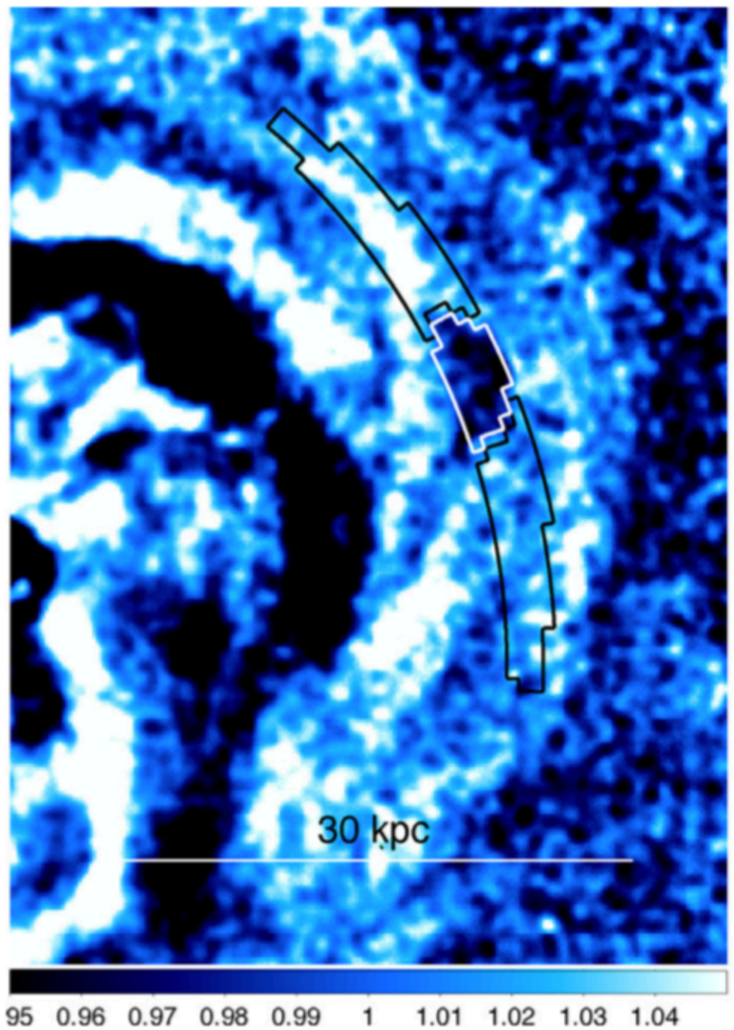
- cannot regulate this process
- other processes are needed

2. Feather-like structures

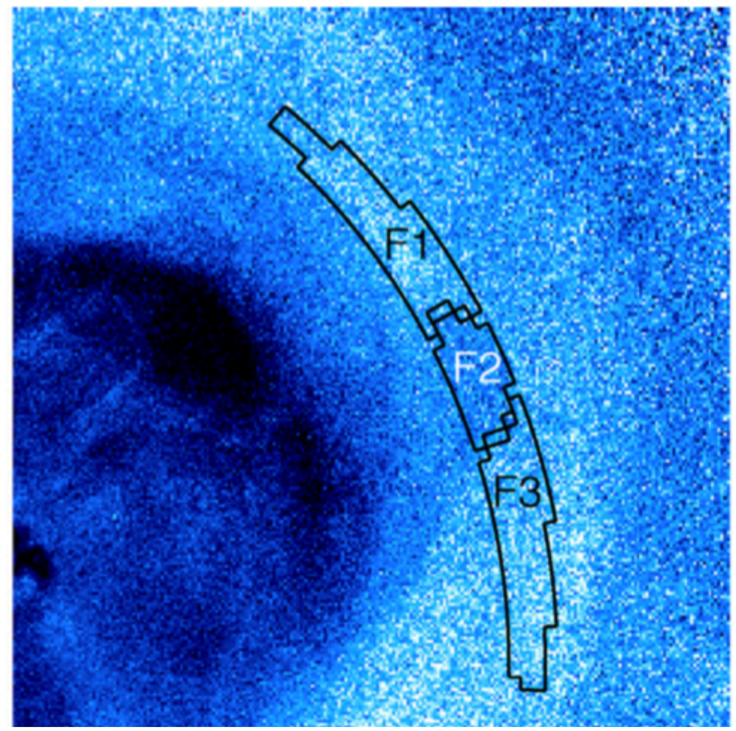


Gas depletion

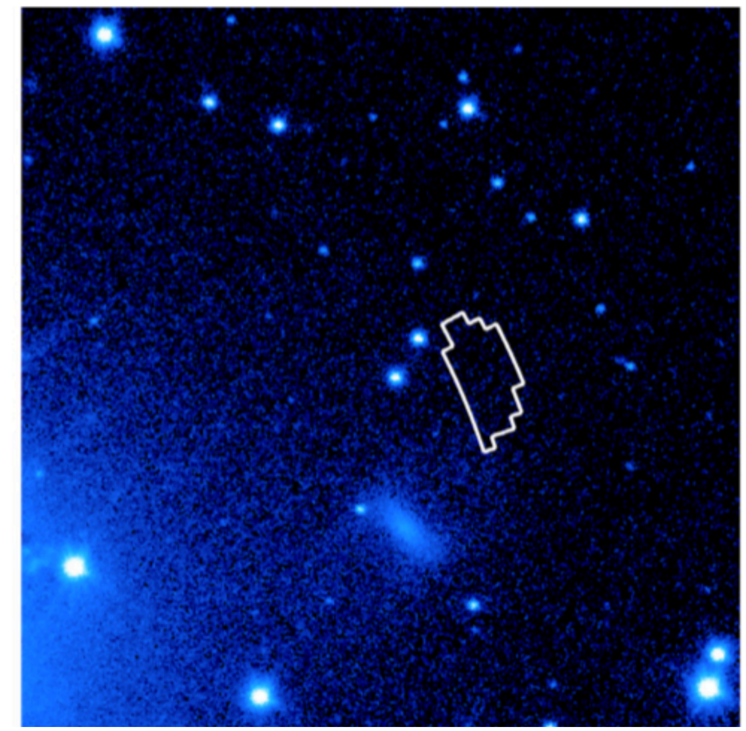
unsharp masked image



relative deviation image



SDSS optical



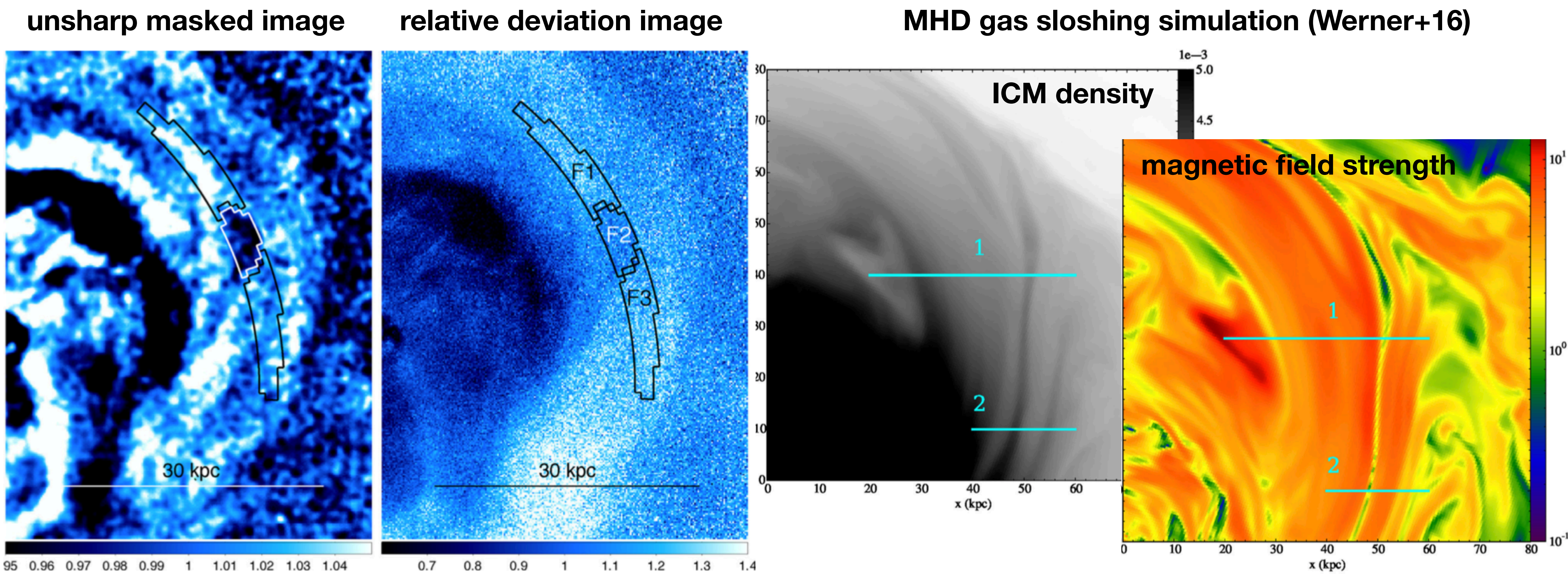
Region	Temperature (keV)	Fe abundance (solar)	Area-normalized apec norm[a] (10^{-6})
F1	3.81 ± 0.03	0.85 ± 0.02	3.49 ± 0.03
F2	3.89 ± 0.05	0.88 ± 0.04	3.15 ± 0.04
F3	3.96 ± 0.03	0.86 ± 0.02	3.53 ± 0.03

Alternating bright and dark regions in the unsharp-masked image

- especially dark at the middle (F2)
- no association with optical / radio
- different from the surroundings only in normalization

-> gas depletion

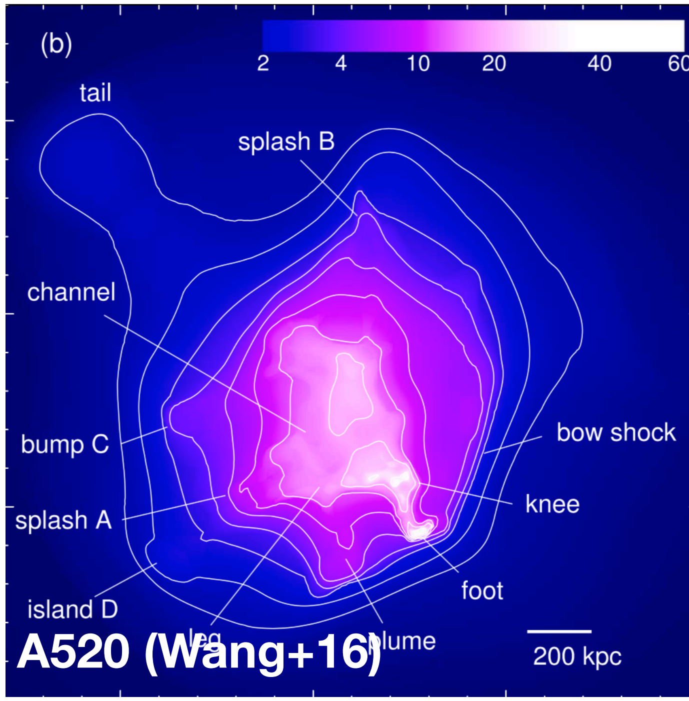
Gas depletion due to magnetic fields



morphologically similar to recent MHD simulations (Werner+16)

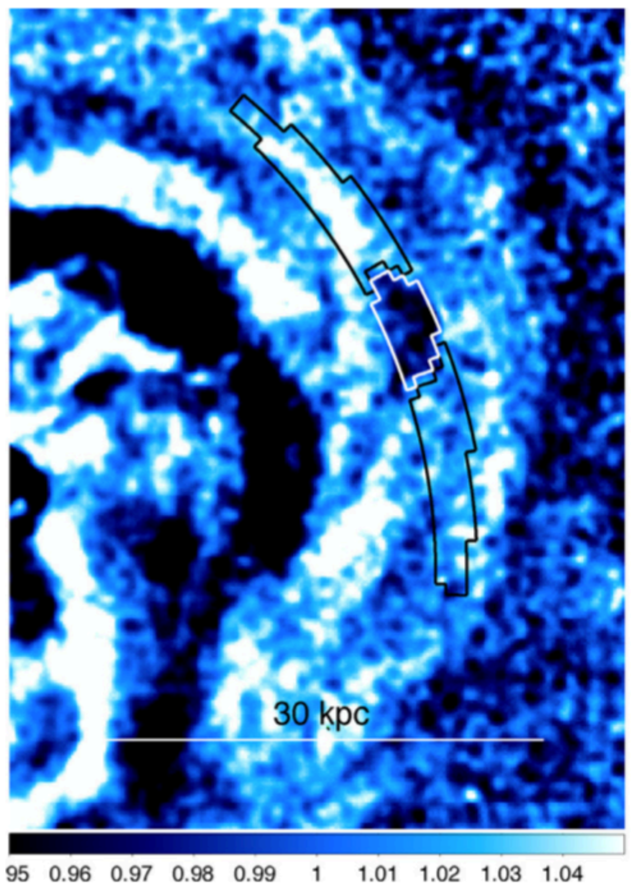
-> projected gas depletion region due to amplified B

- quasi-linear structures in Virgo CF (Werner+16)
- 'channel's in A520, A2142 (Wang+16,18)



Gas depletion due to magnetic fields

unsharp masked image



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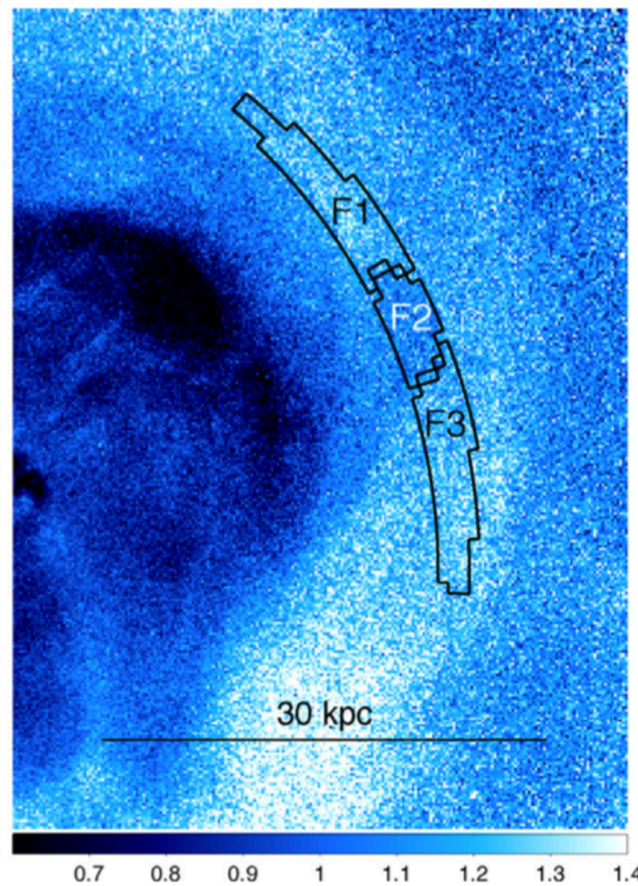
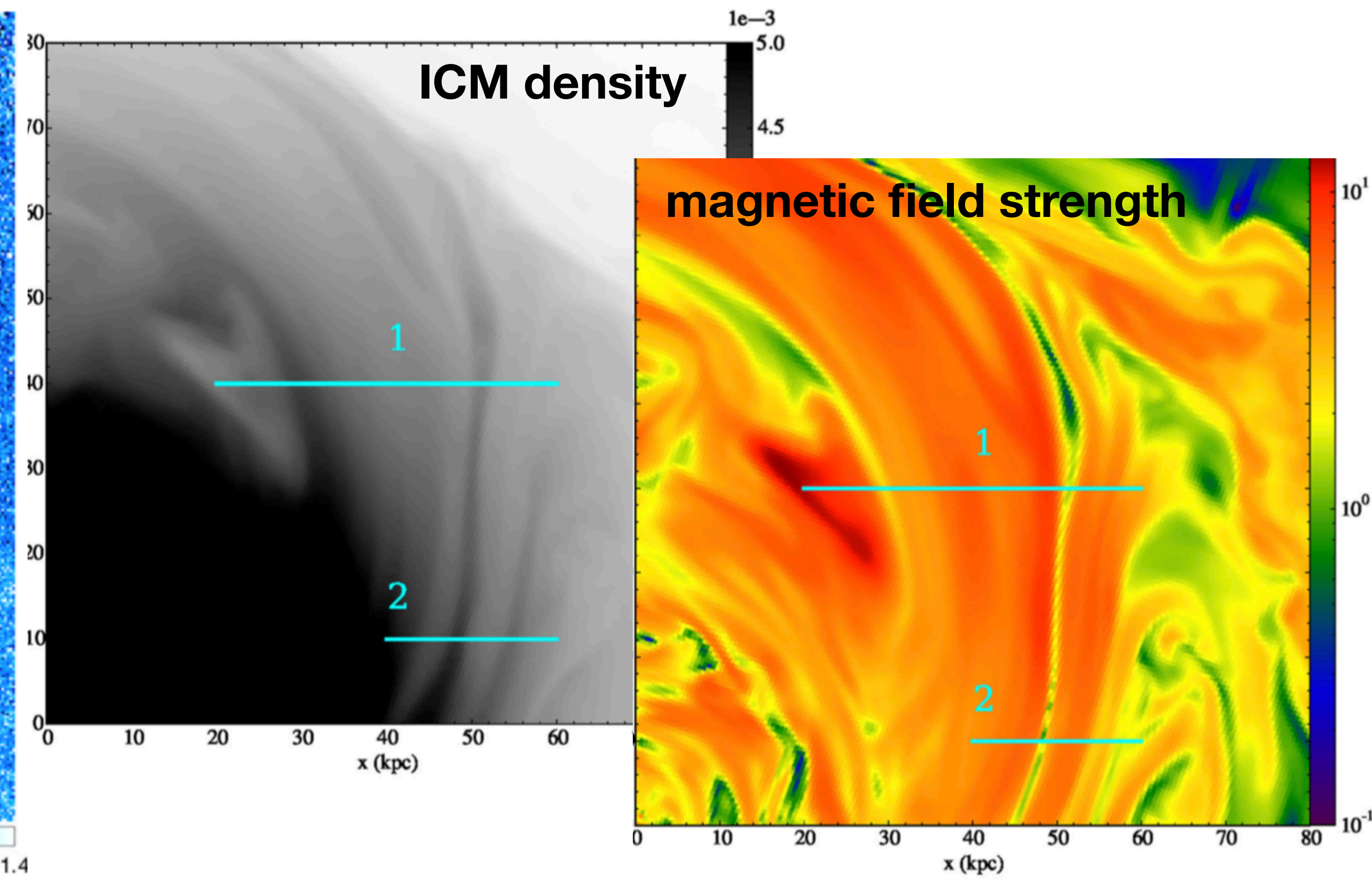
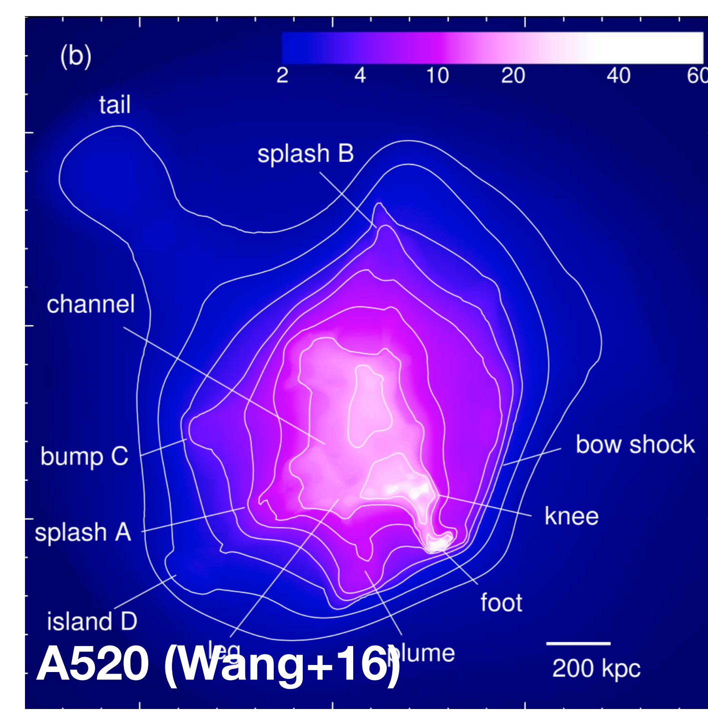


MHD gas sloshing simulation (Werner+16)





- ΔP ~ 10^{-2} keV/cm^3
  - B ~ 30 μG, not implausible (c.f. ZuHone+11)
- other interpretations
  - ghost bubble? too small?
  - turbulence? why localized?

Summary

Substructures of cold fronts (X-ray sub-sub-structure) are useful for quantitative discussion about ICM microphysics.

We analyzed archival >1Msec Chandra data of Perseus and found

1. double-layered structure at the NE rim of the sloshing CF
   - significant multiple edge
   - first break=CF, second break≠CF

   ➡ KHI layer
     - pressure dip -> Q_{turb} ~ 10^{-26} erg/cm^3/s
     - consistent with SB fluctuation result by Zhuravleva+14
     - can support the radiative cooling at this radius

2. feather-like structures below the western half of the CF
   - no association with optical or radio
   - just dark without kT/Z differences

   ➡ projected plasma depletion region
     - B ~ 30 μG
     - not implausible regarding recent MHD simulations