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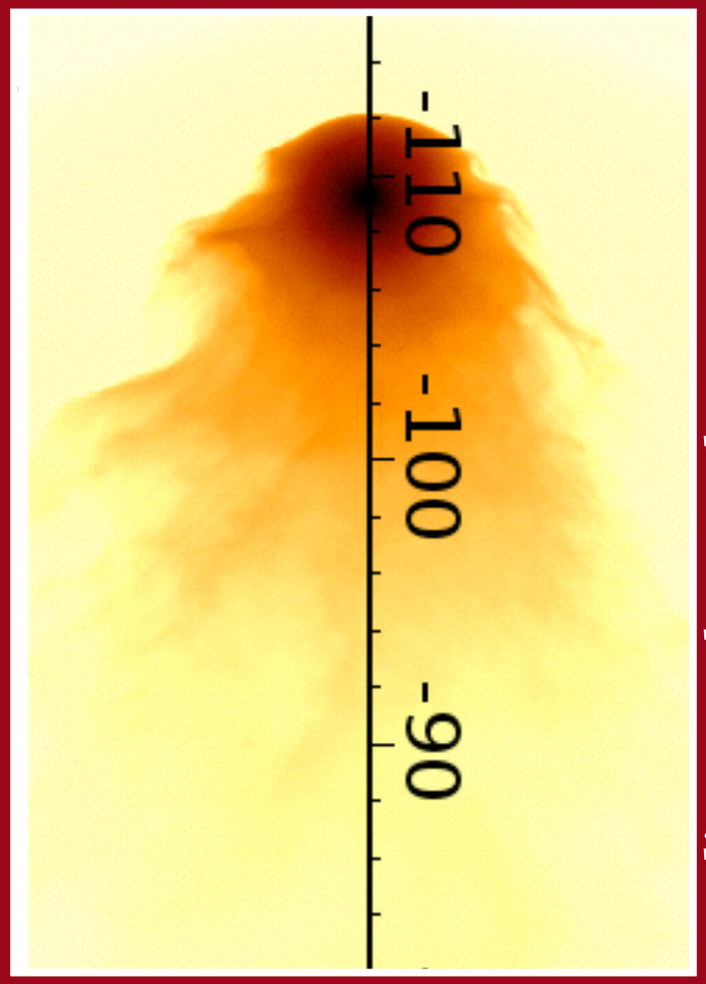
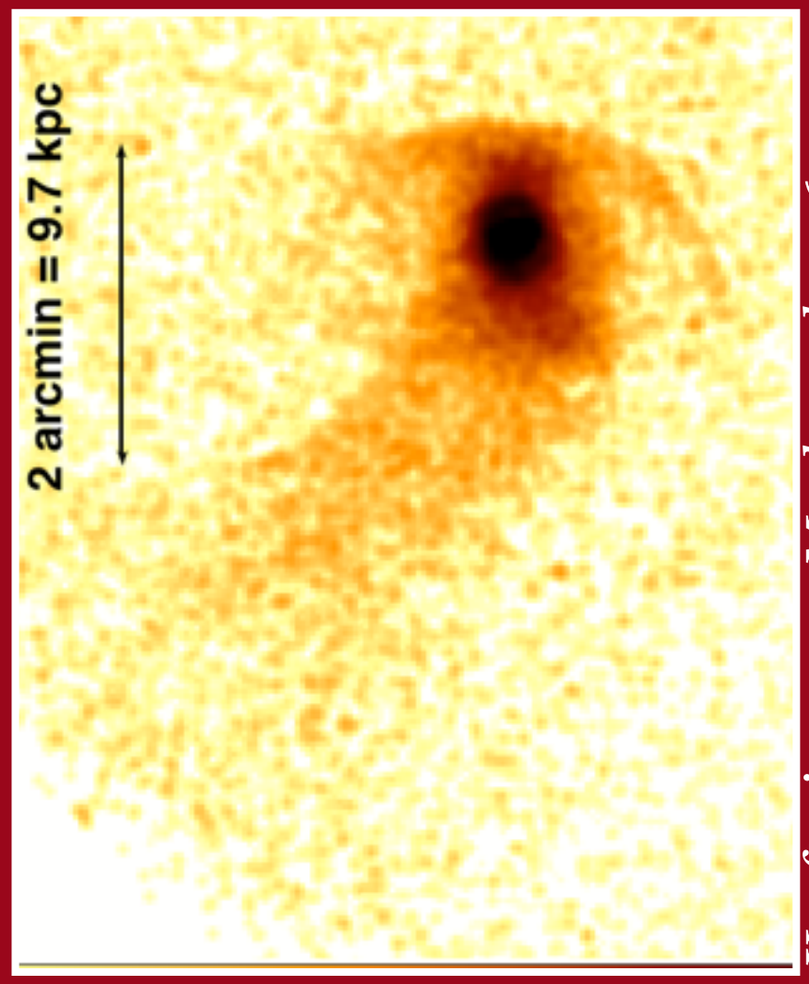
Fluid *dynamics* in the ICM



Roediger et al. 2015ab



Kraft+ in prep., Machaceck+ 06

van Dyke - Album of Fluid Motion

Elke Roediger (E. A. Milne Centre for Astrophysics, University of Hull), Ralph Kraft (CfA), Yuanyuan Su (CfA), Alexander Sheardown (E. A. Milne Centre, Hull), Paul Nulsen (CfA), Bill Forman (CfA), Eugene Churazov (MPA)

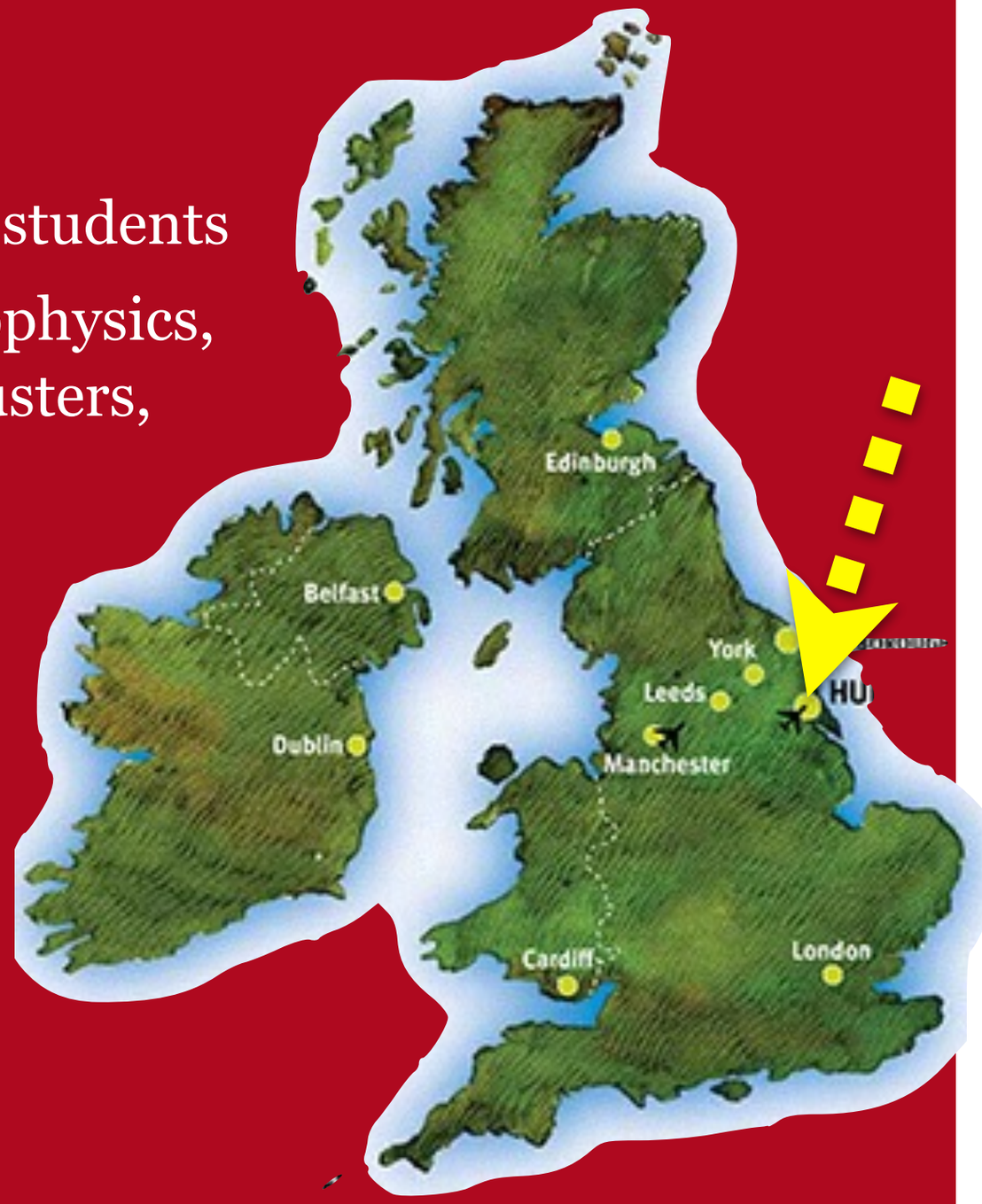
New team members:

Yuanyuan Su
Postdoc at CfA

Alexander Sheardown
PhD student at
E. A. Milne Centre, Hull

E. A. Milne Centre for Astrophysics, University of Hull

- named after Edward Arthur Milne (1896-1950)
- Opened Oct 2015
- 8 staff, 2 postdocs, 10 PhD students
- solar physics, nuclear astrophysics, galaxy evolution, galaxy clusters, cosmology, string theory



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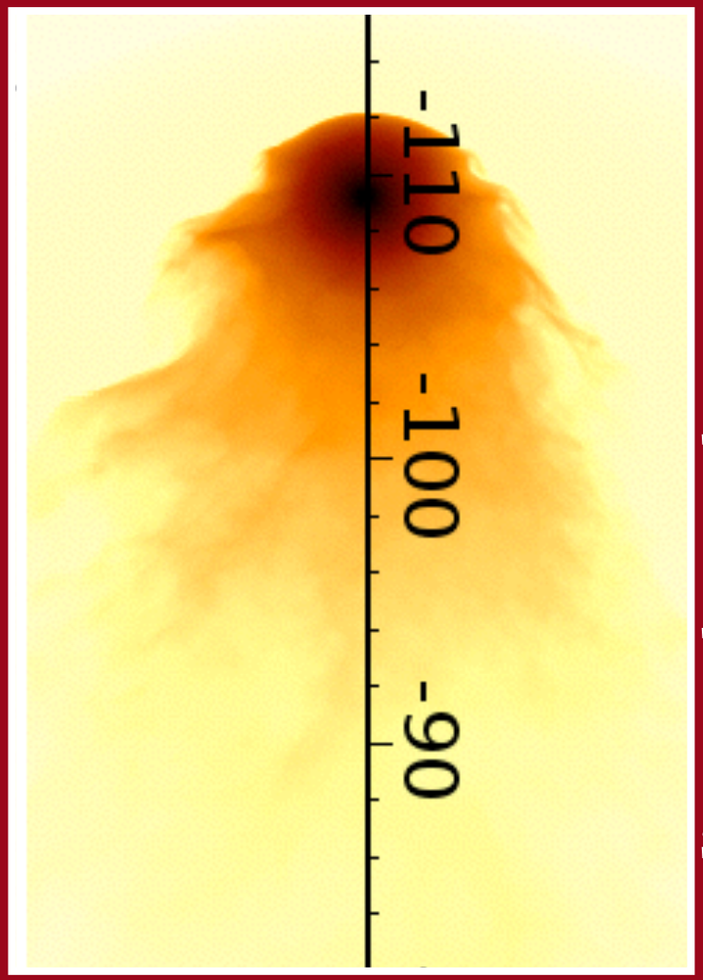
Fluid *dynamics* in the ICM



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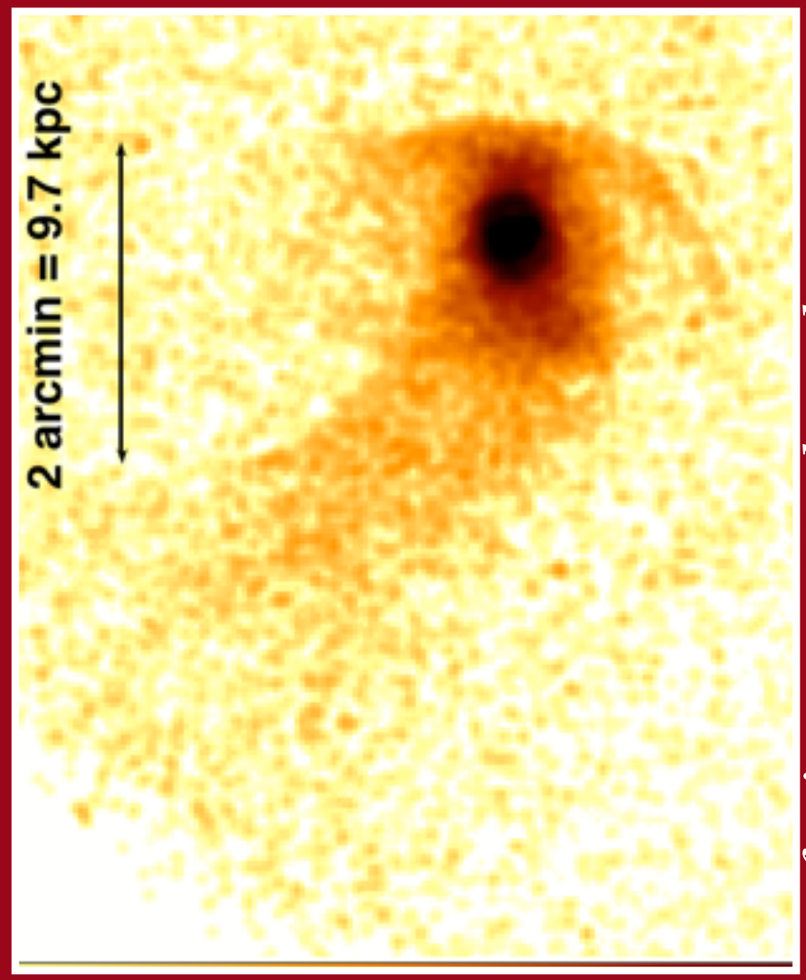


Kraft+ in prep., Machaceck+

van Dyke - Album of Fluid Motion

Goal of this talk: How far can we push pure hydrodynamics model of ICM?

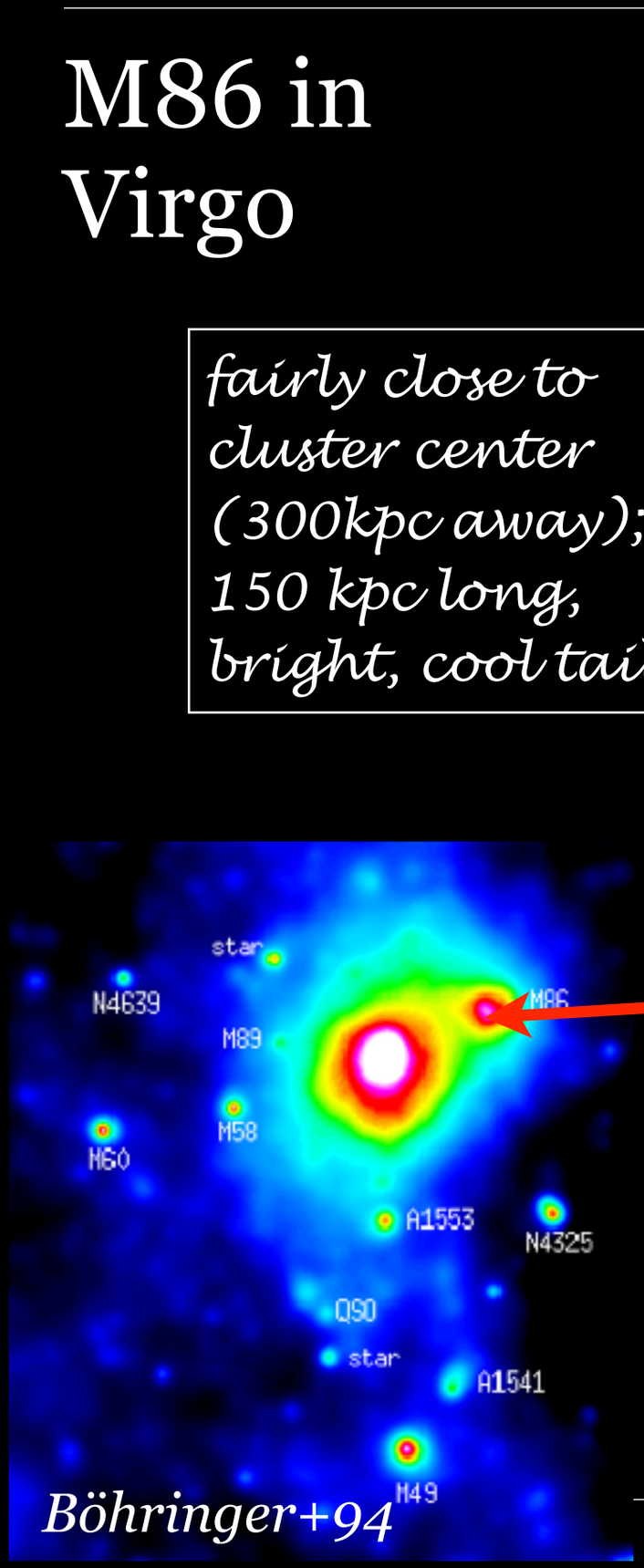
- look at example of infall and gas stripping of elliptical galaxies/small groups; compare observations, simulations, fluid lab experiments
- take-home message: pure hydro simulations at high Reynolds number reproduce observed objects in great detail if correct dynamical context is used, i.e., correct infall stage, gravitational potentials, gas contents, orbits
- Provocative question — which additional ICM physics do we really need?

Next slides: some observed examples

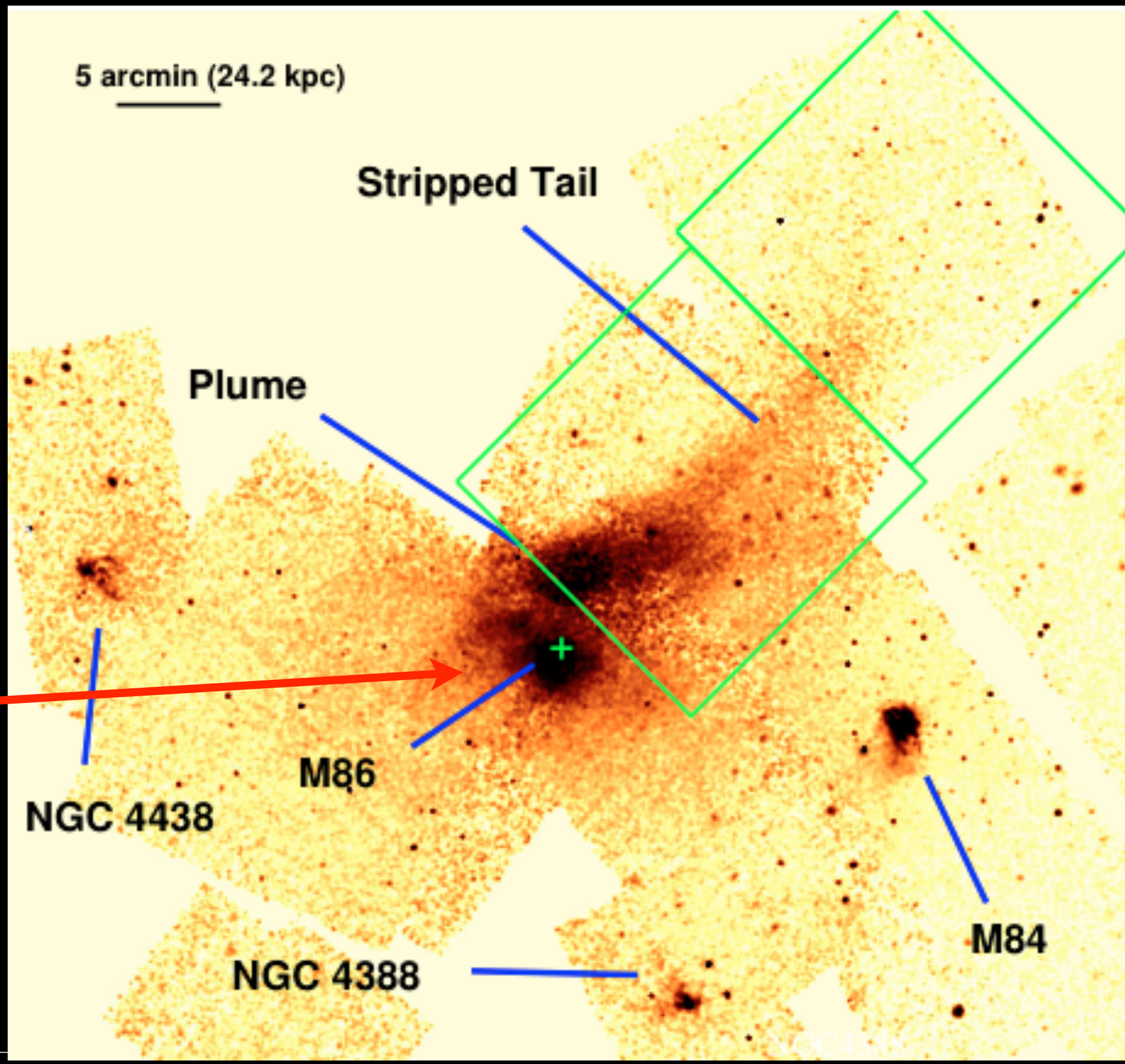
- sorted by near cluster center/in cluster outskirts
- point out differences

M86 in Virgo

fairly close to cluster center (300kpc away); 150 kpc long, bright, cool tail



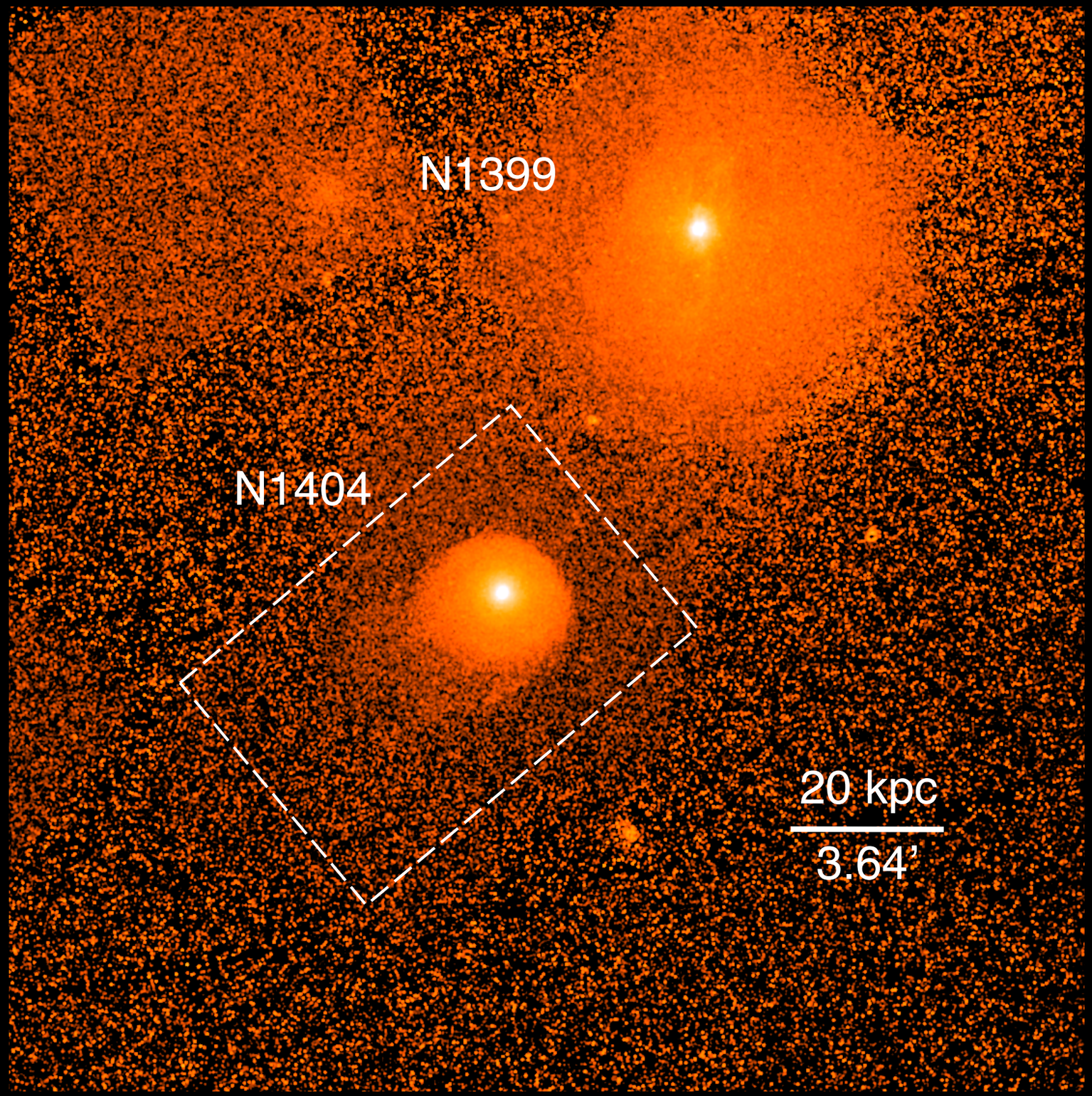
Böhringer+94



Chandra mosaic, Randall+08

NGC 1404 in Fornax

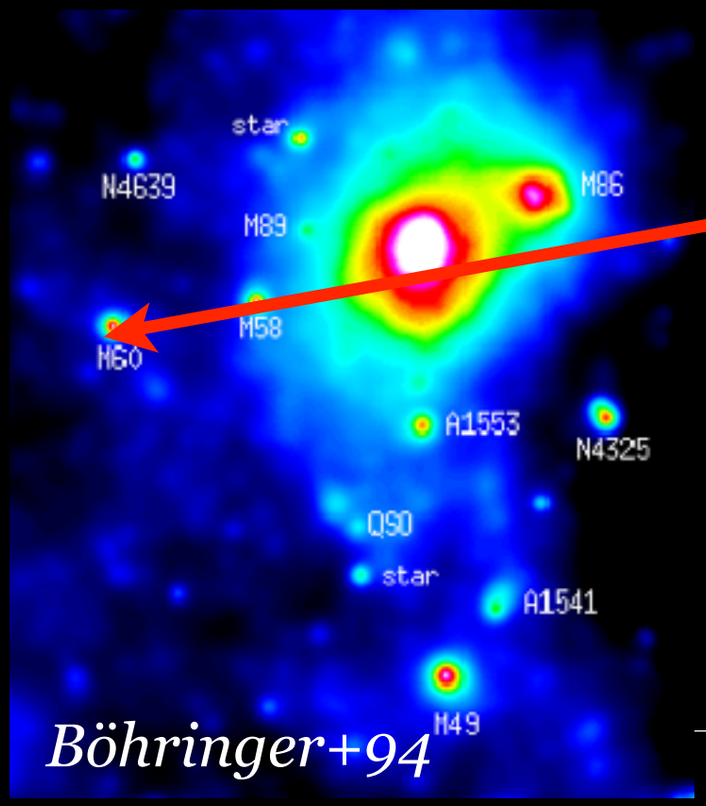
even closer to cluster center, but very short, faint tail — very different from M86



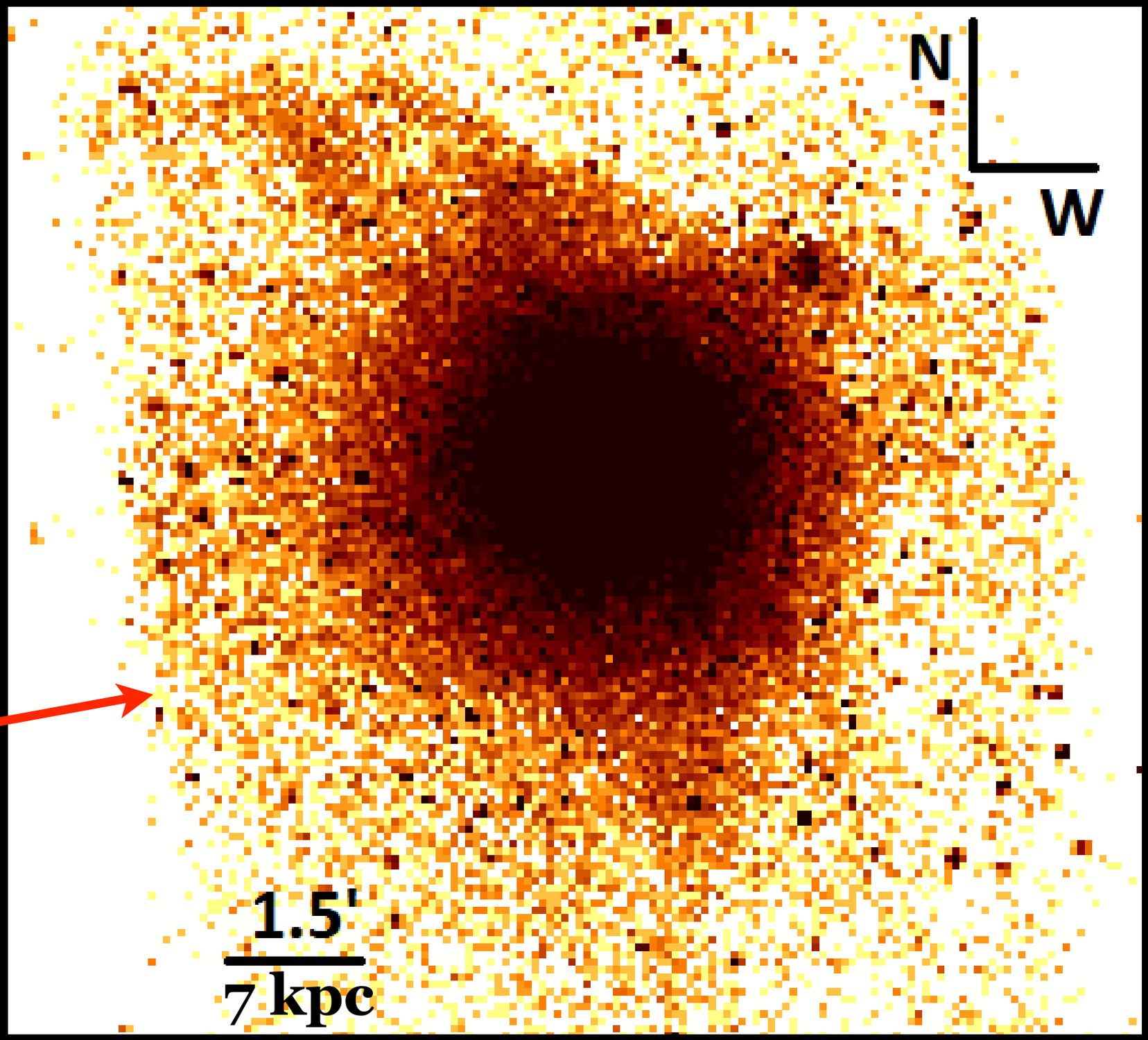
Chandra mosaic, Machachek+05 Su+16ab, in prep.

M60 in Virgo

in cluster outskirts, not much of a tail, but atmosphere truncated all around



Böhringer+94



Chandra mosaic, Wood+, in prep.

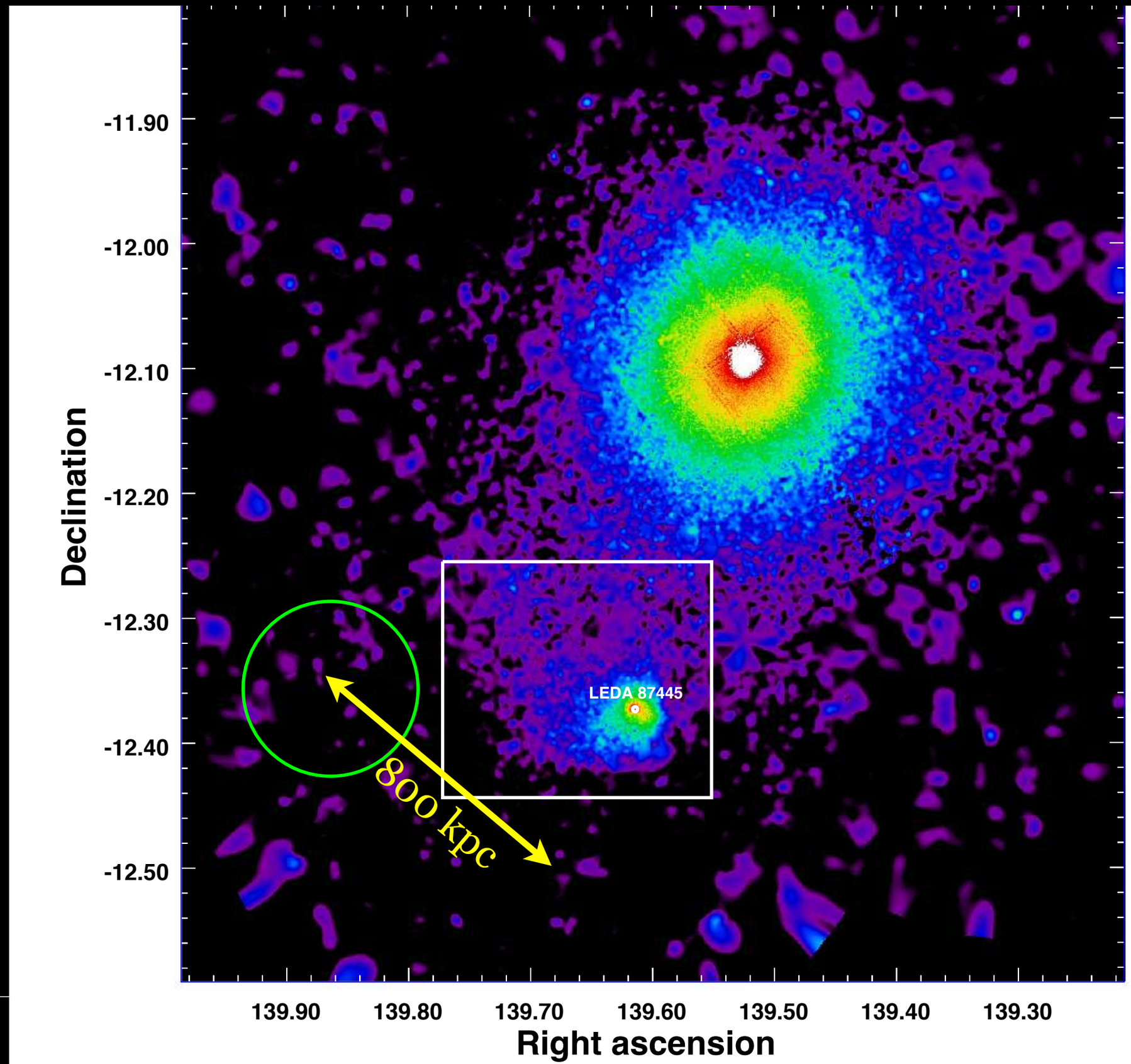
Elke Roediger

UNIVERSITY OF Hull

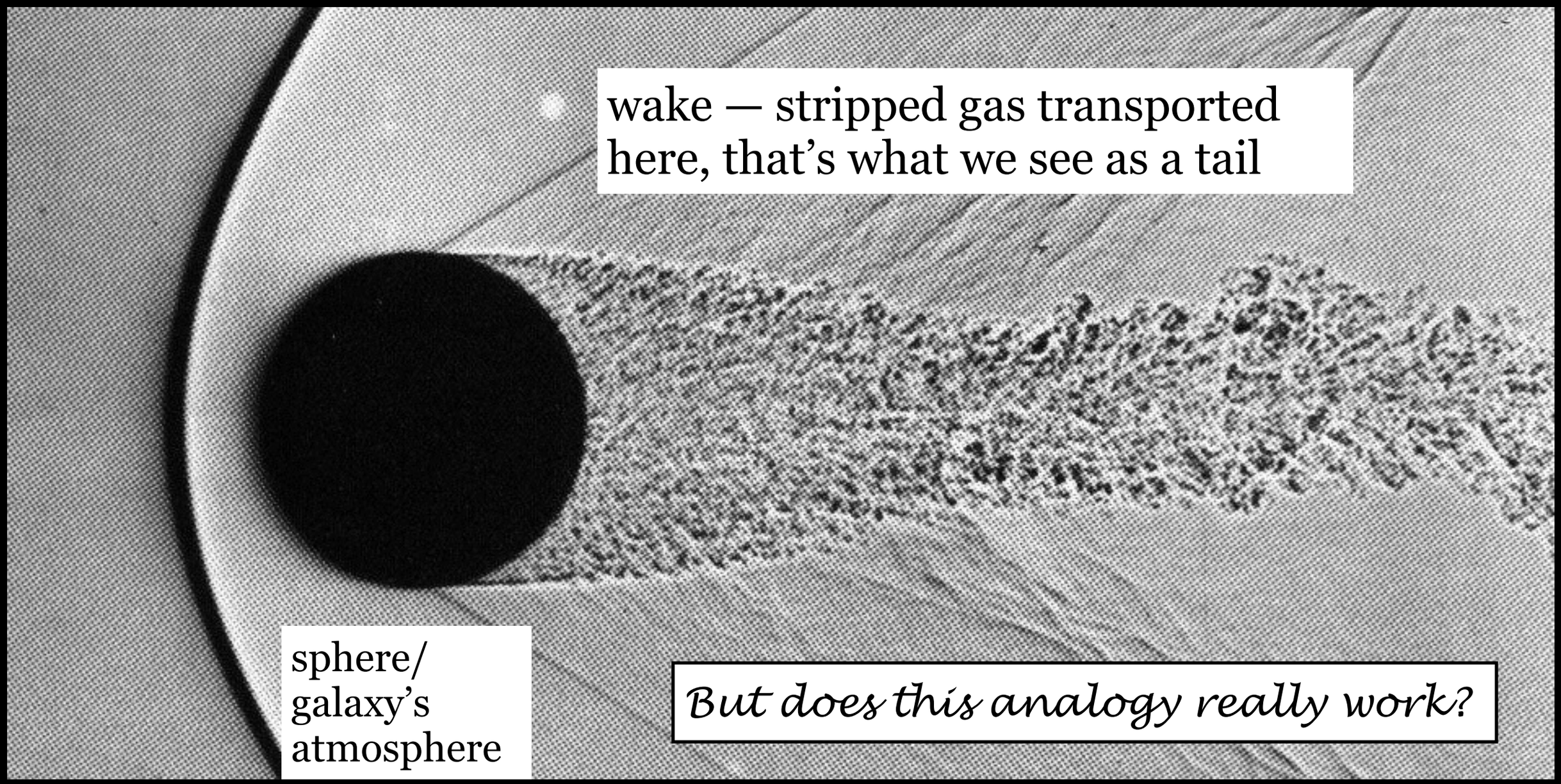
LEDA 87445 in Hydra A

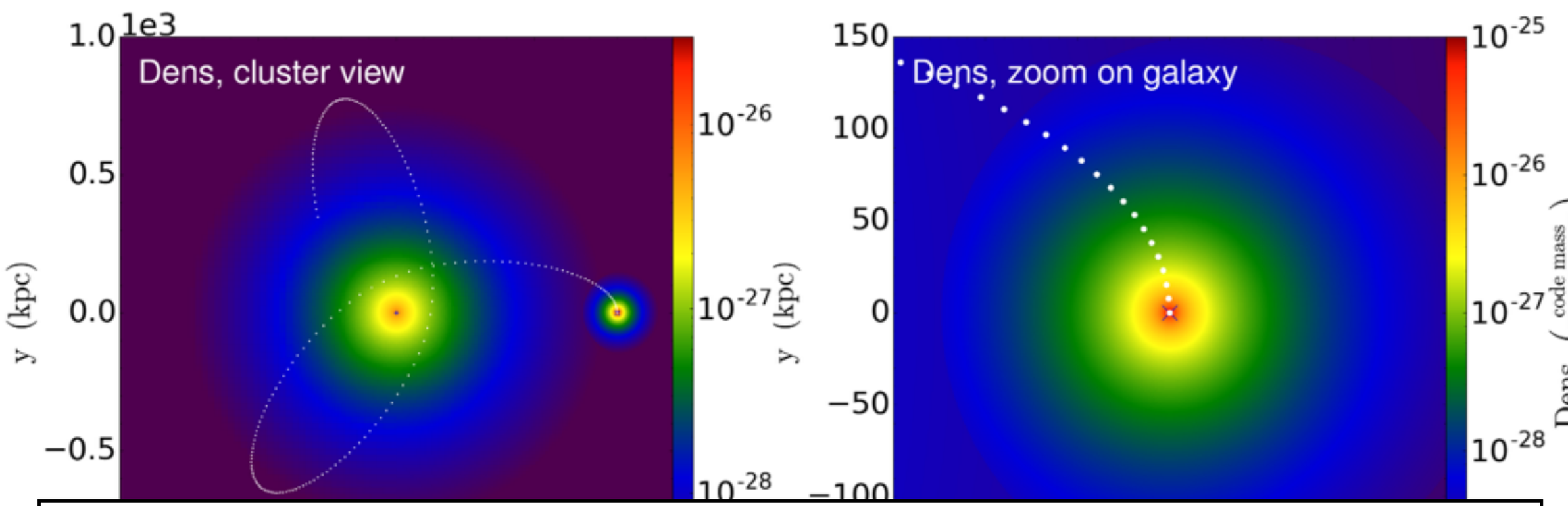
group in cluster outskirts, with a very long, TANGENTIAL tail — how can the tail be tangential? What orbit is this galaxy on?

XMM, De Grandi+2016



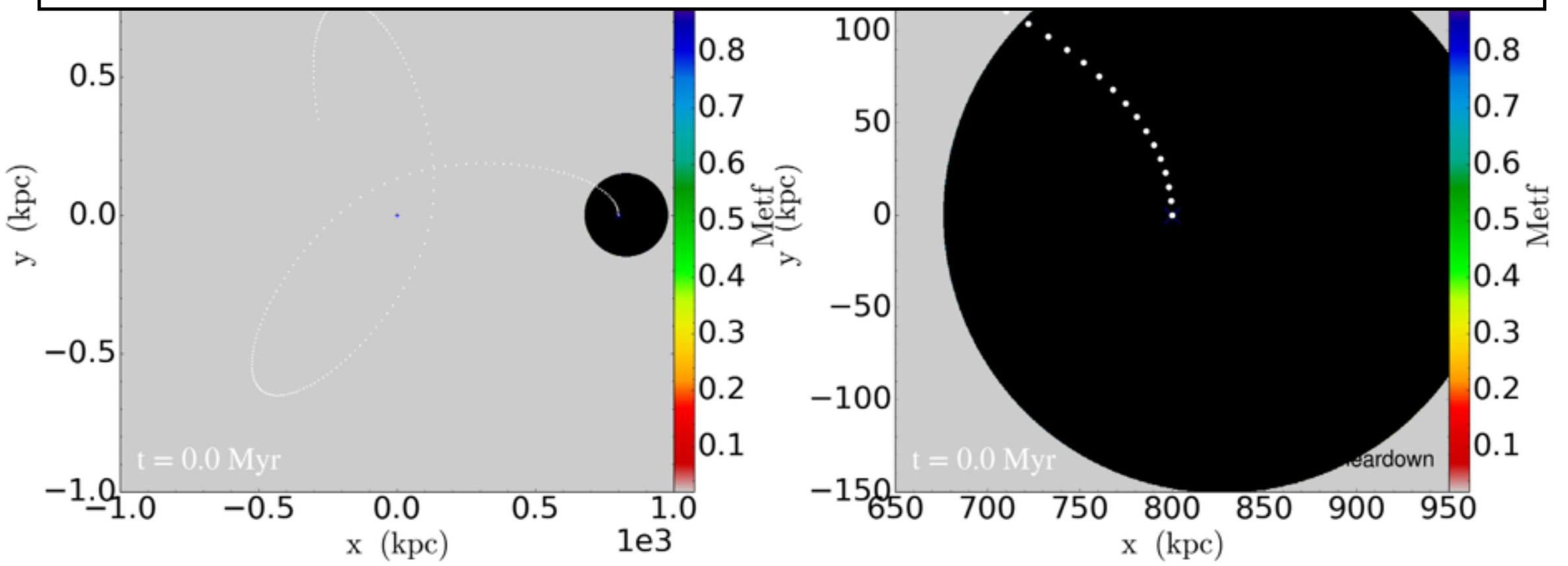
Basic expectation — theory/lab experiments — flow around a sphere:





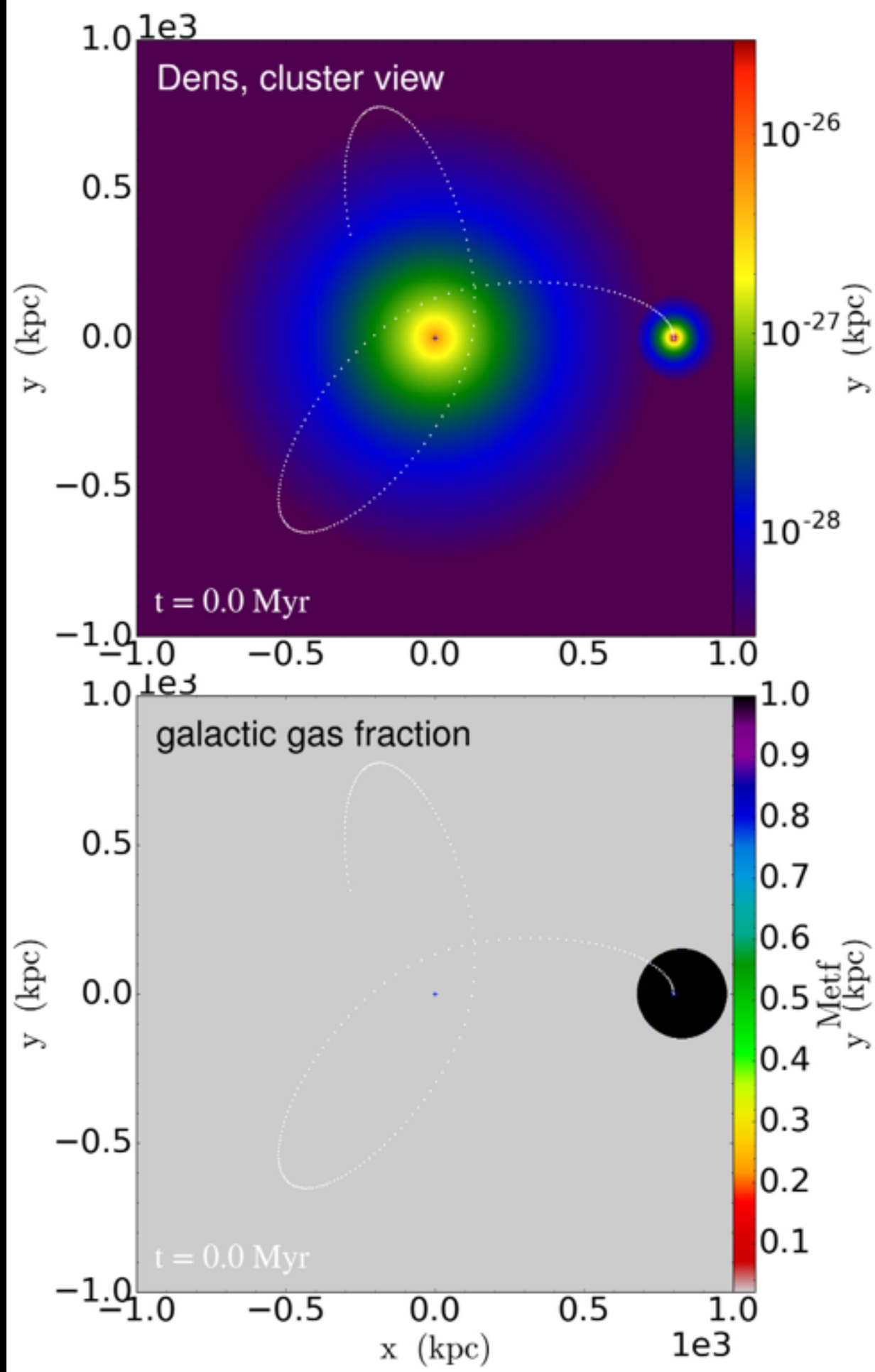
Snapshots from simulation on next slides – movies to appear on homepage of Alex Sheardown soon.

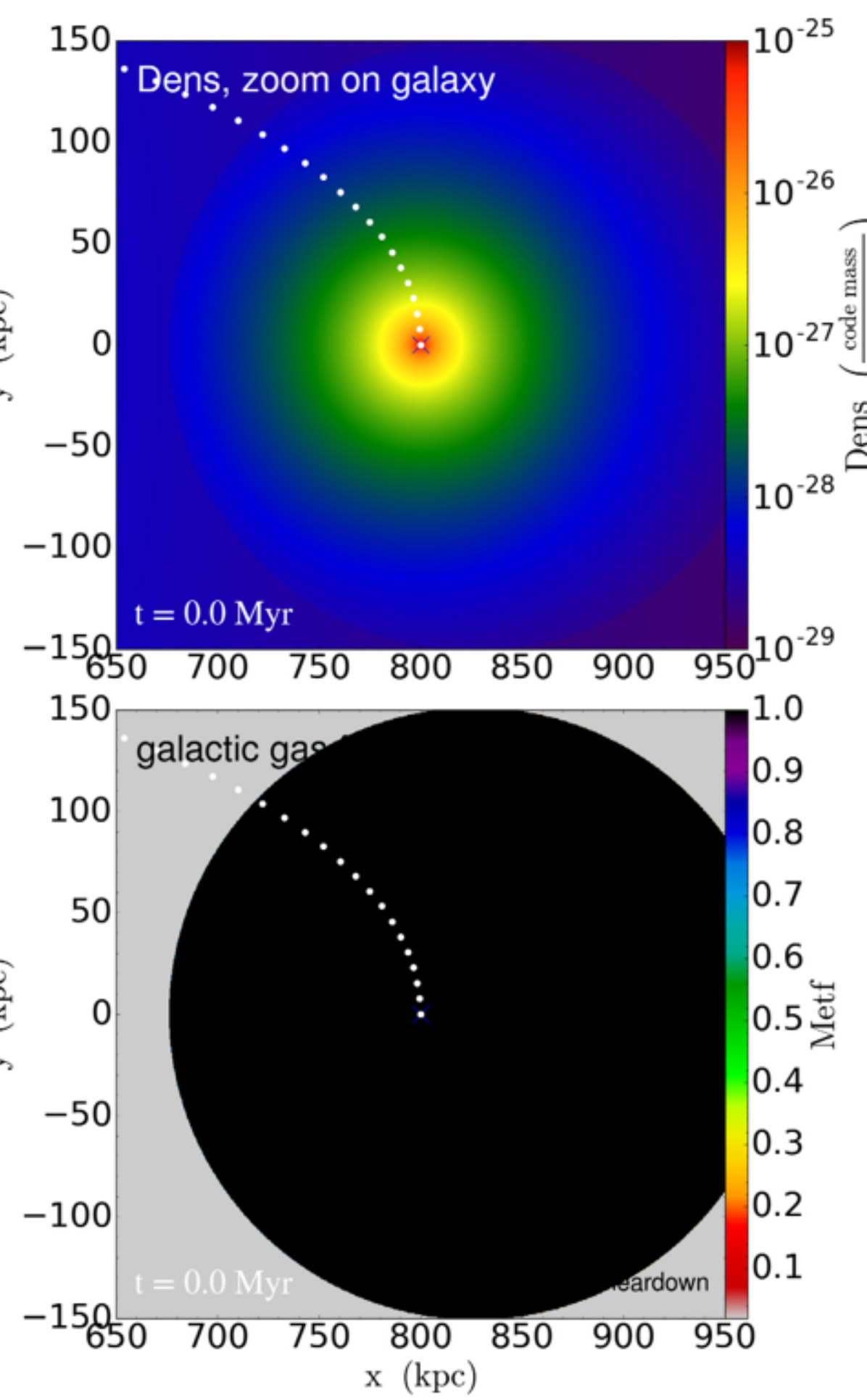
Simulation aims at N1404 in Fornax.



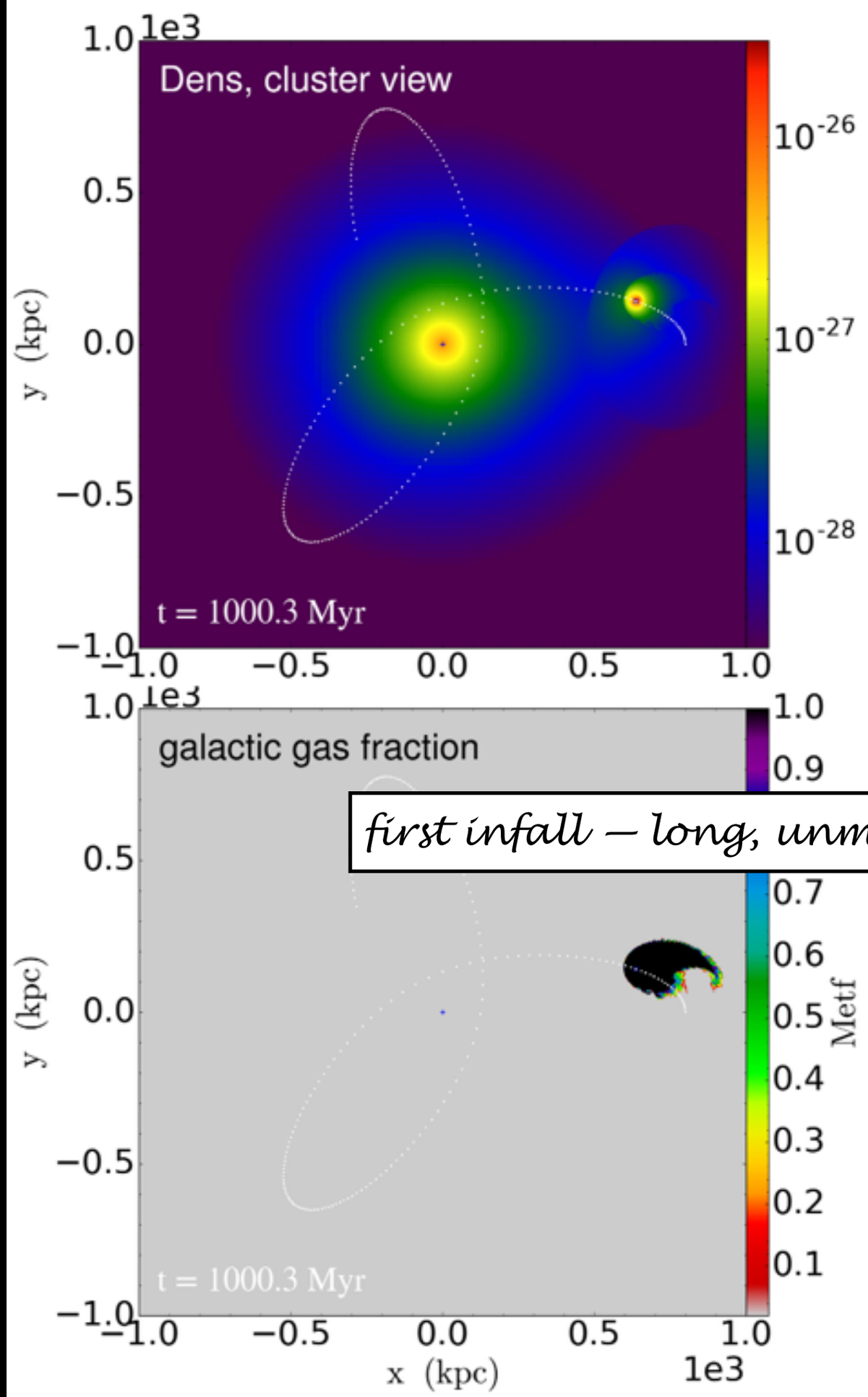
Sheardown+, in prep.

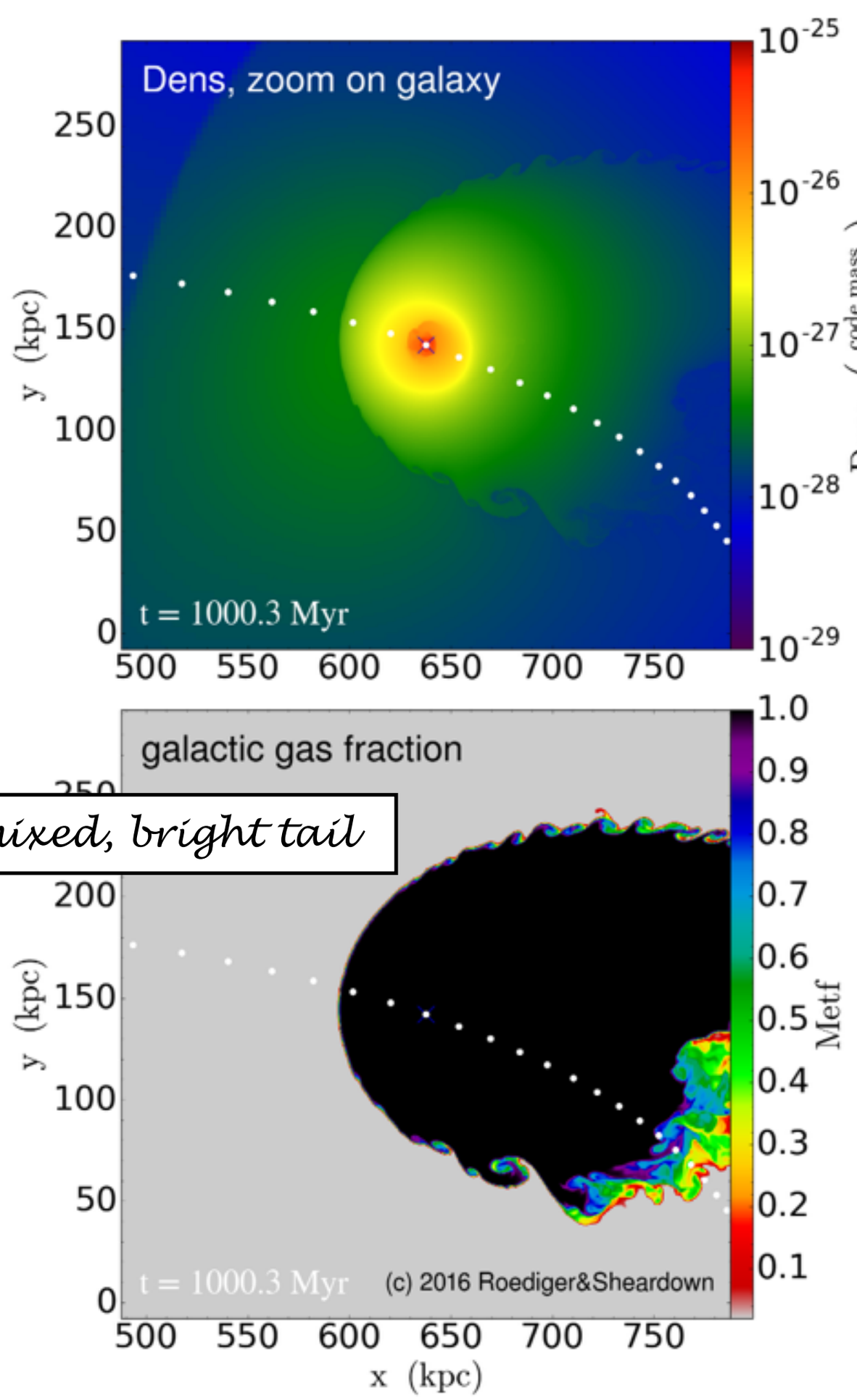
Sheardown+, in prep.





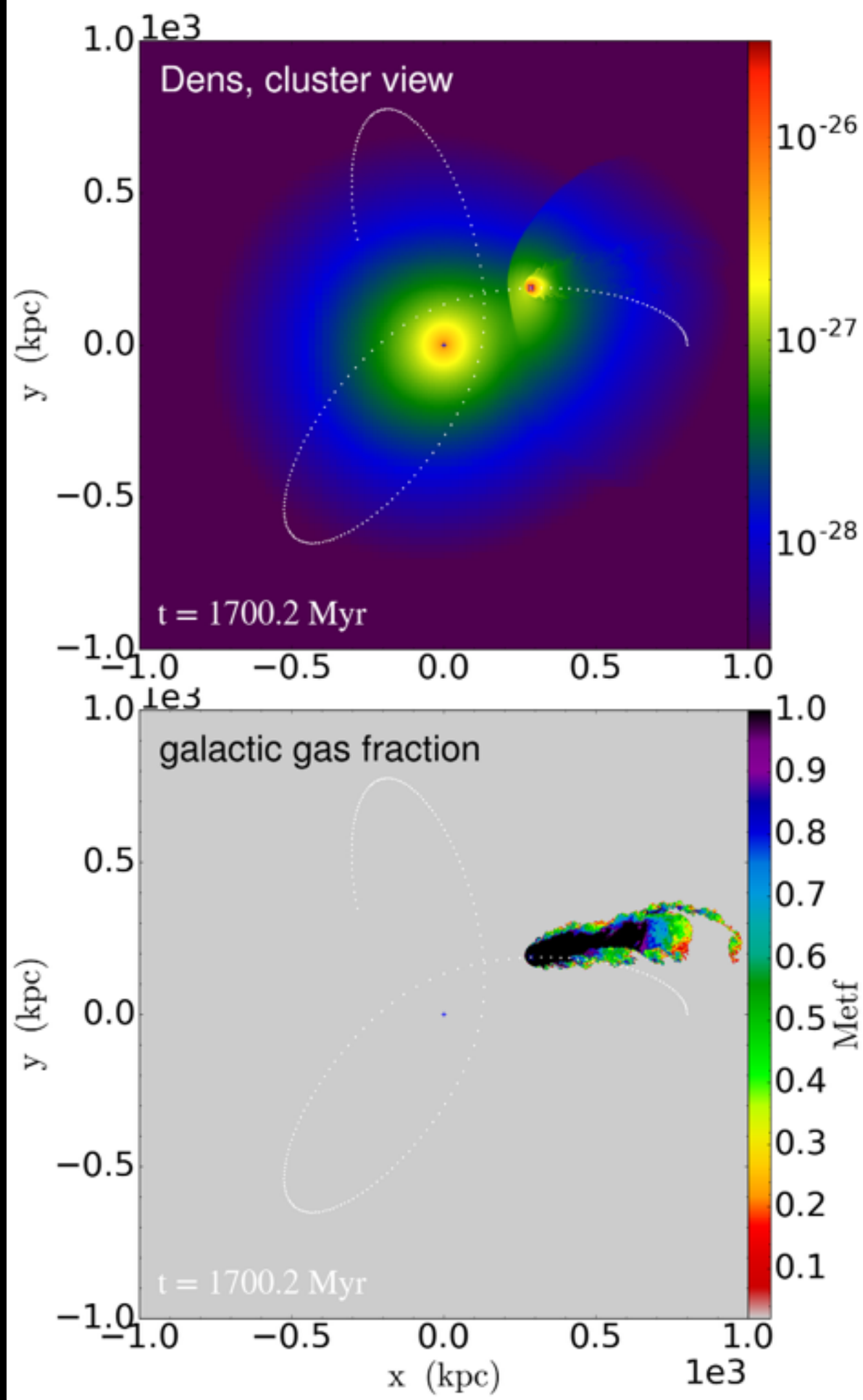
Sheardown+, in prep.

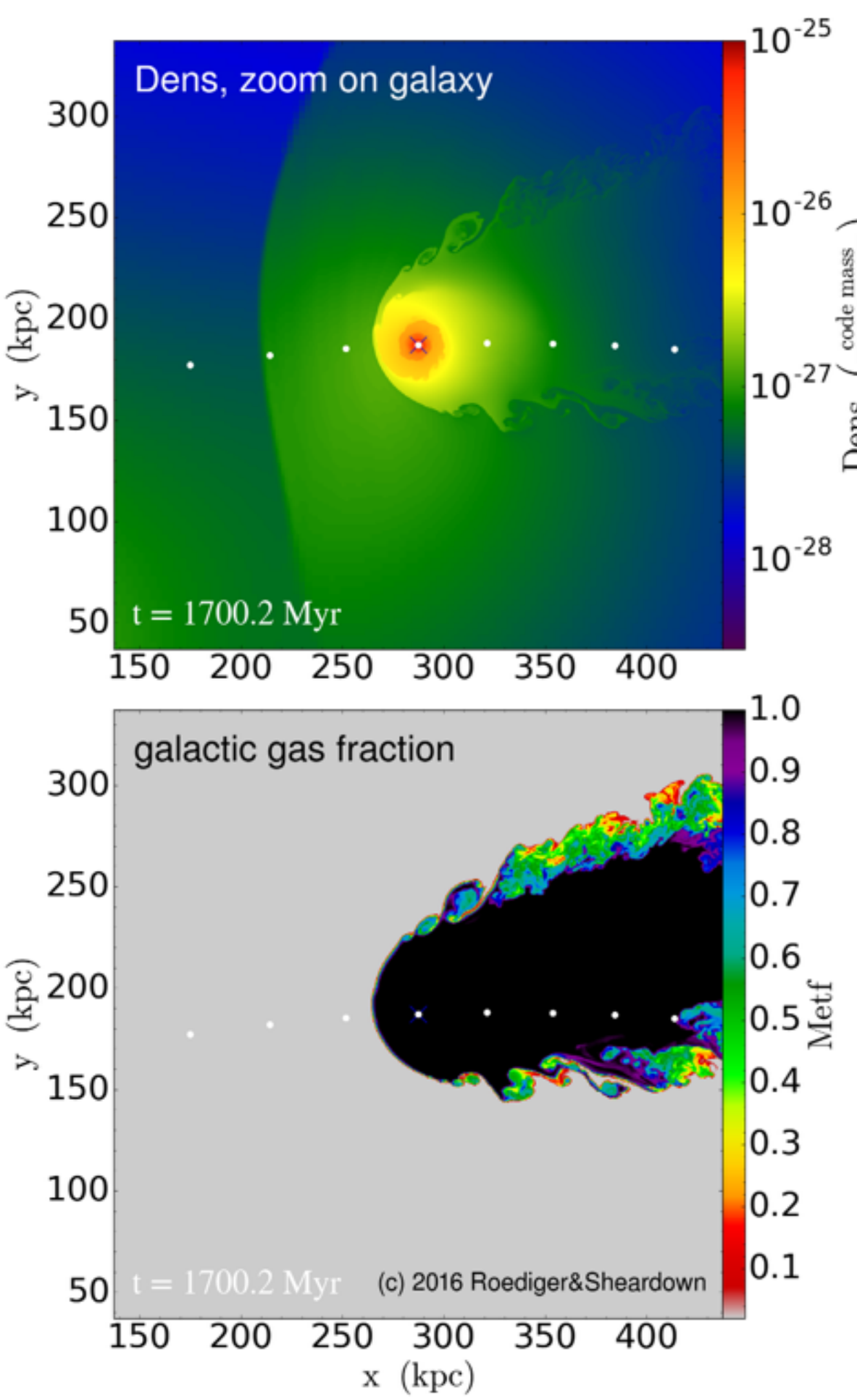




first infall – long, unmixed, bright tail

Sheardown+, in prep.





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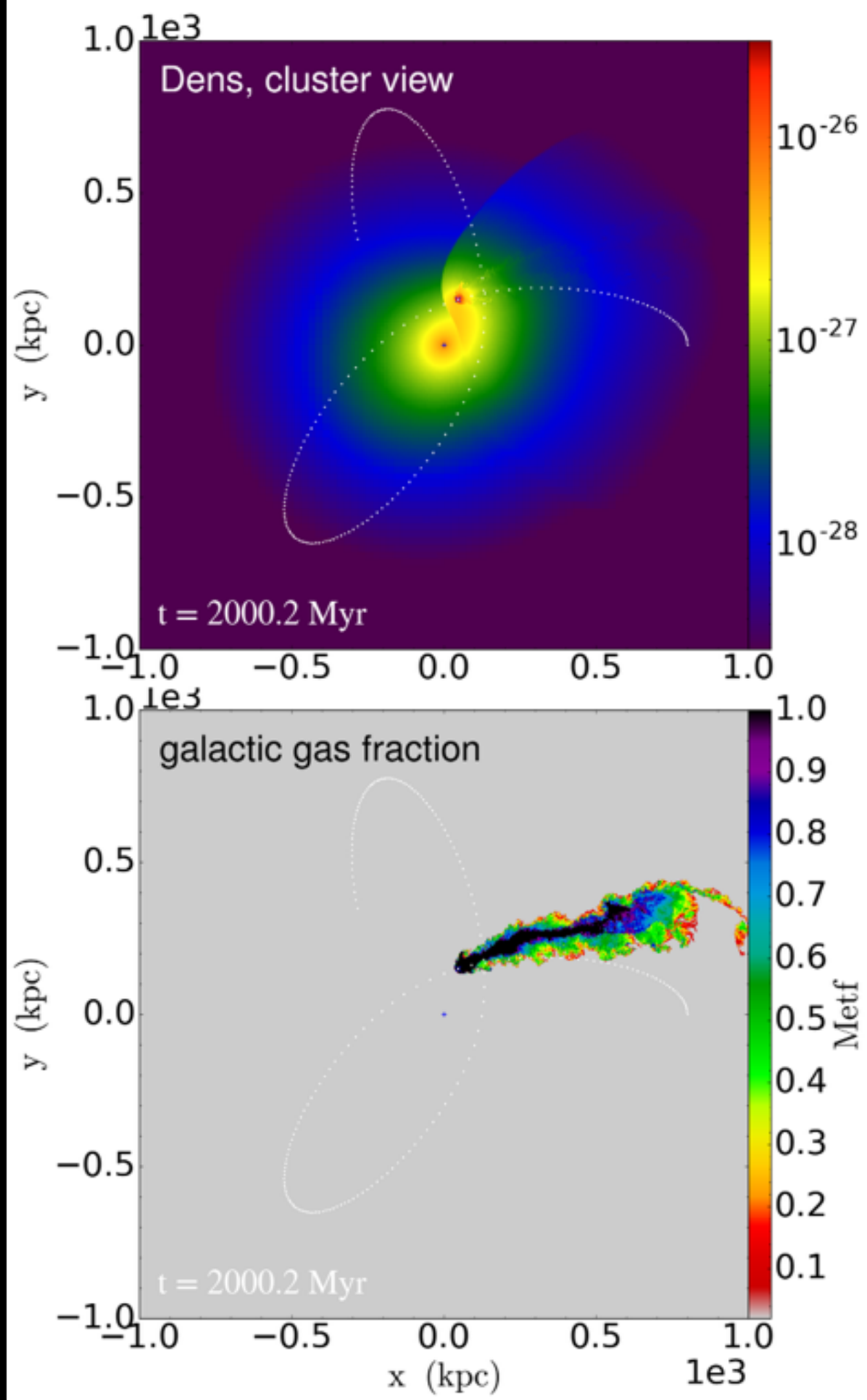

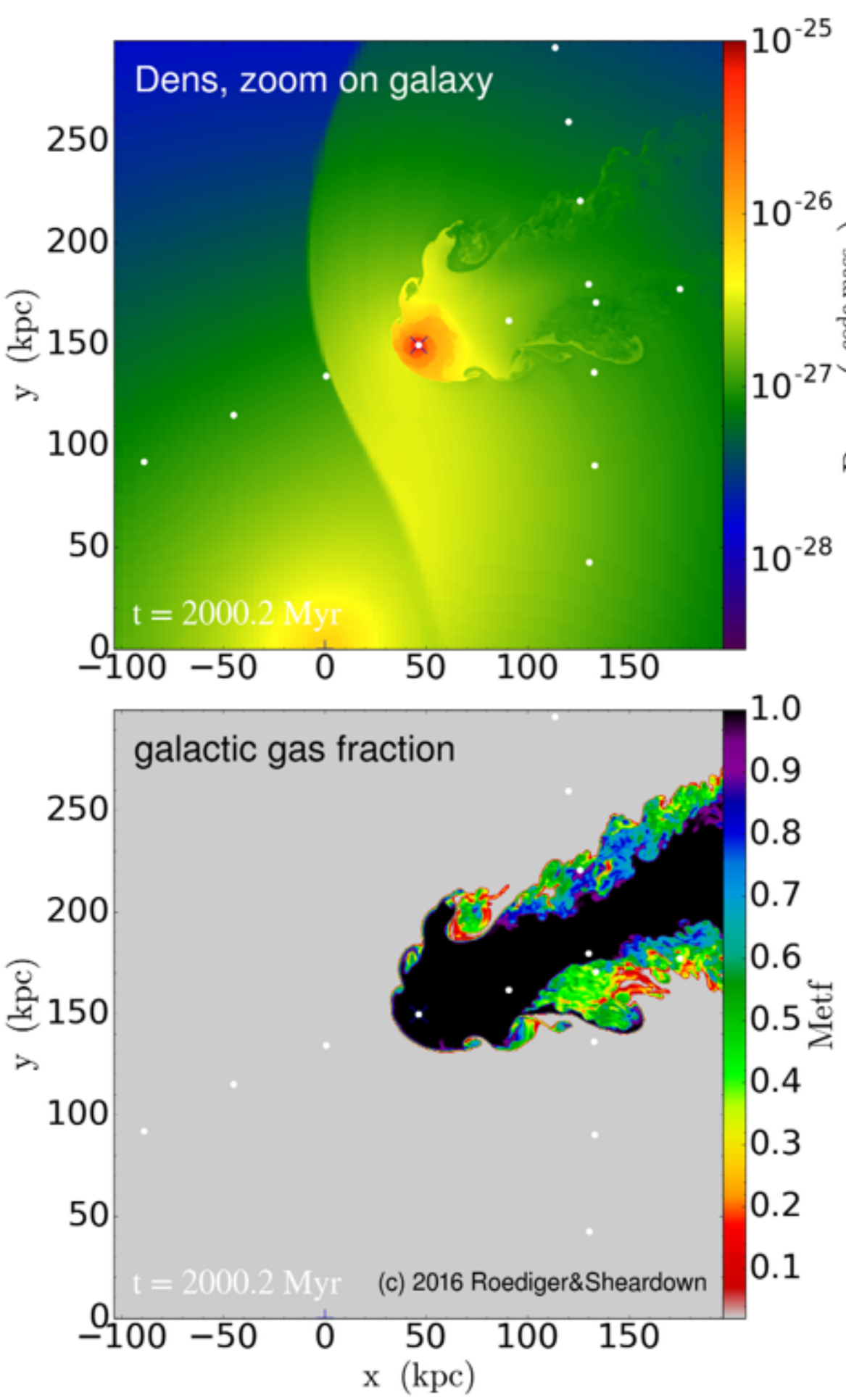

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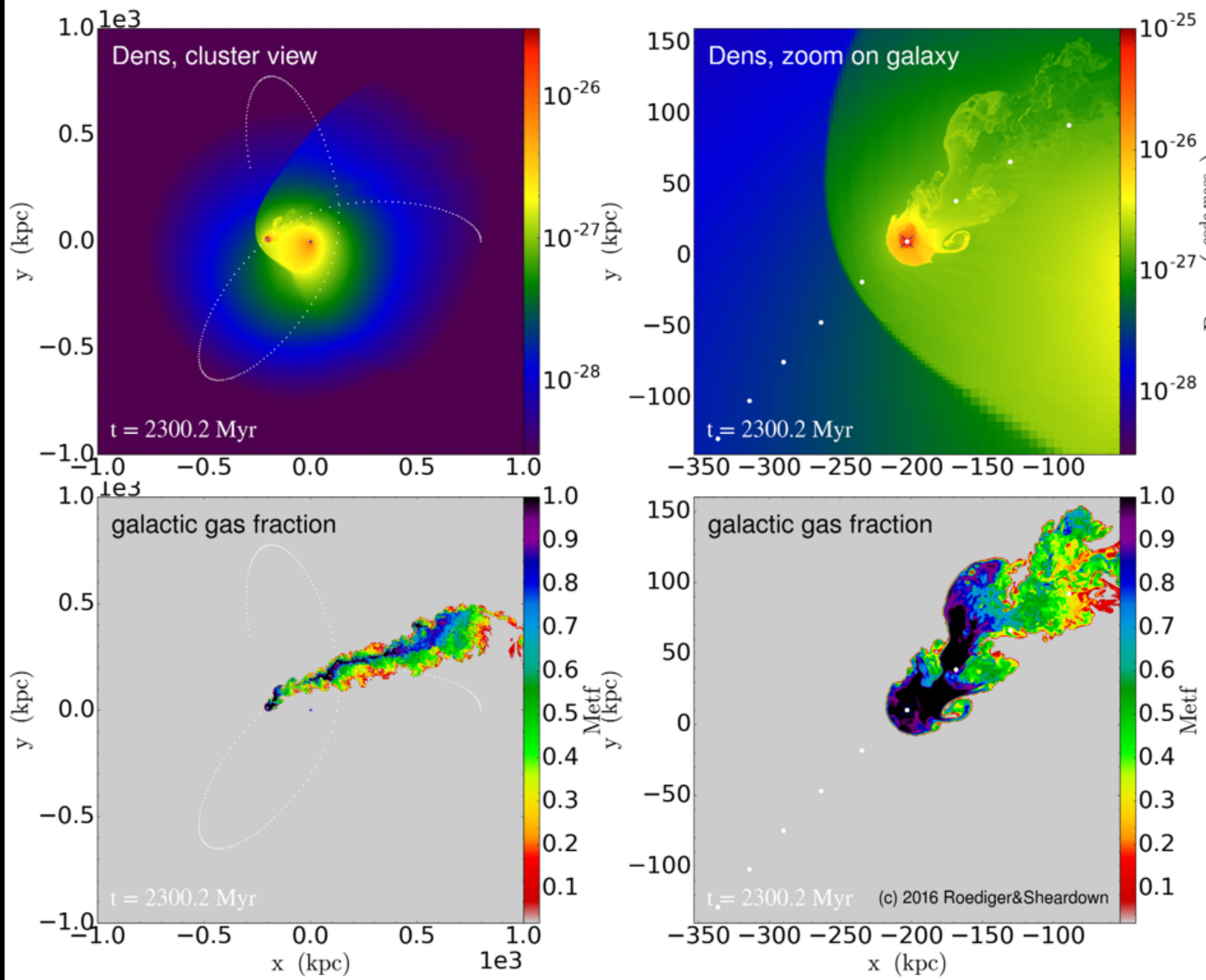

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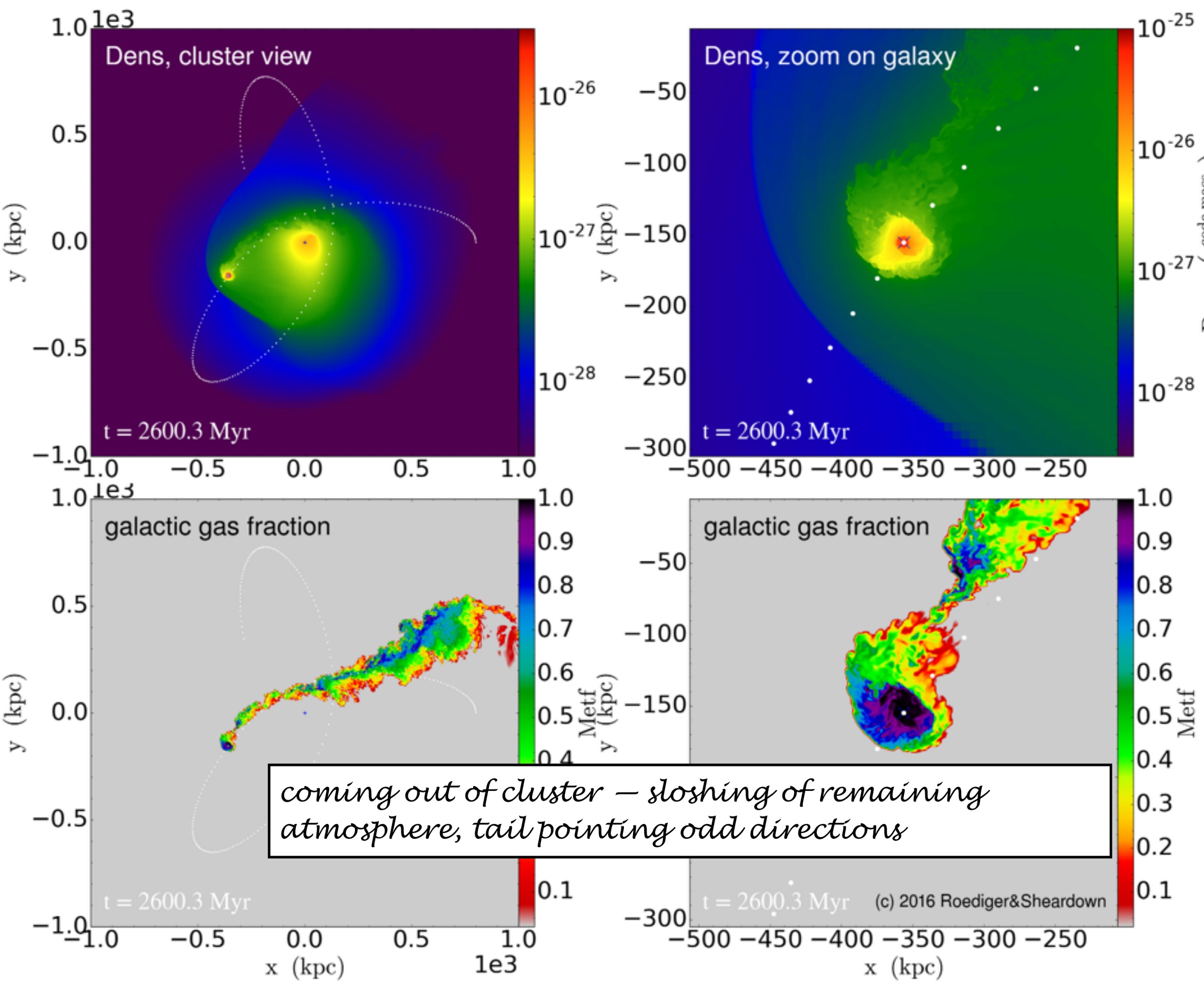
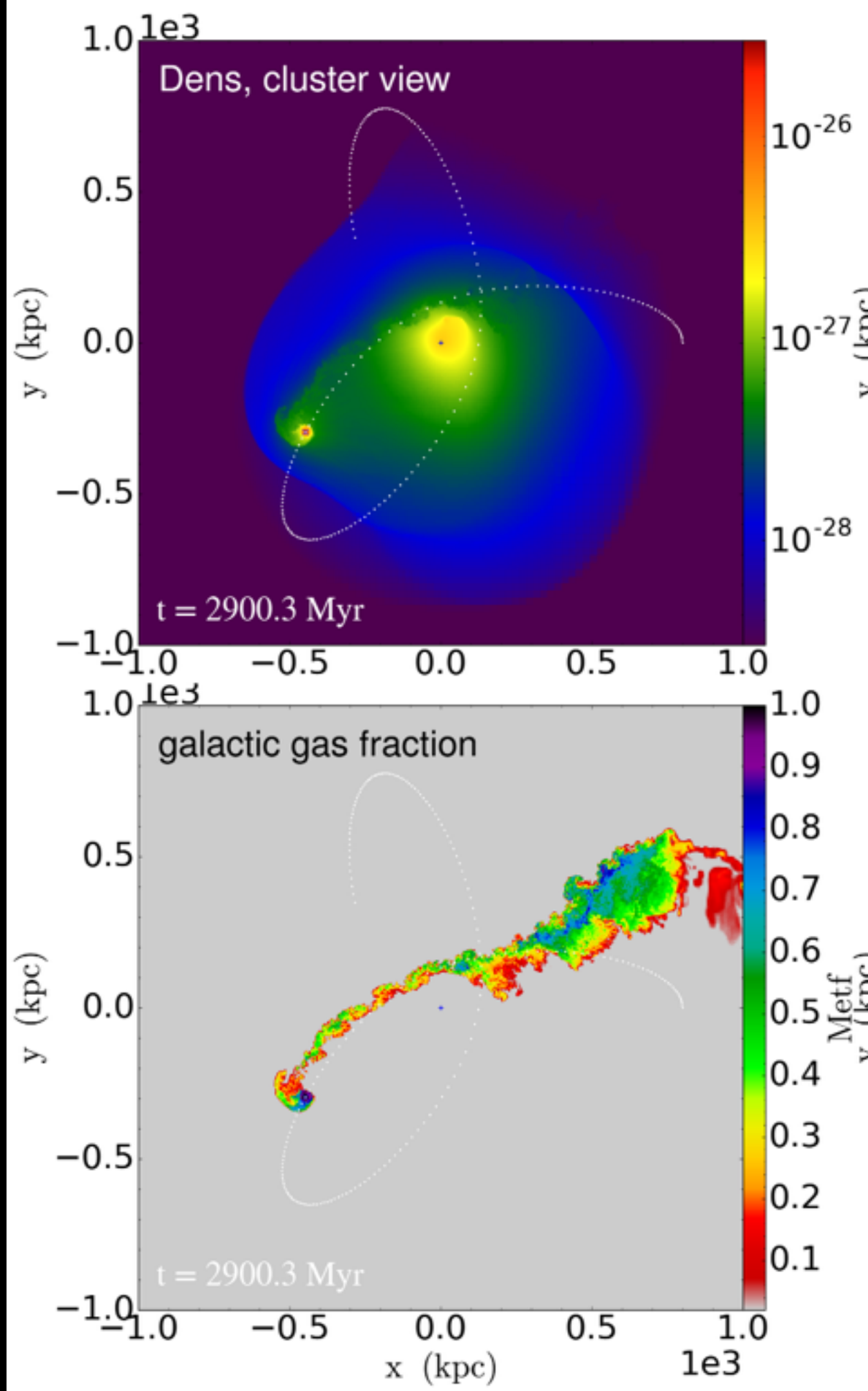
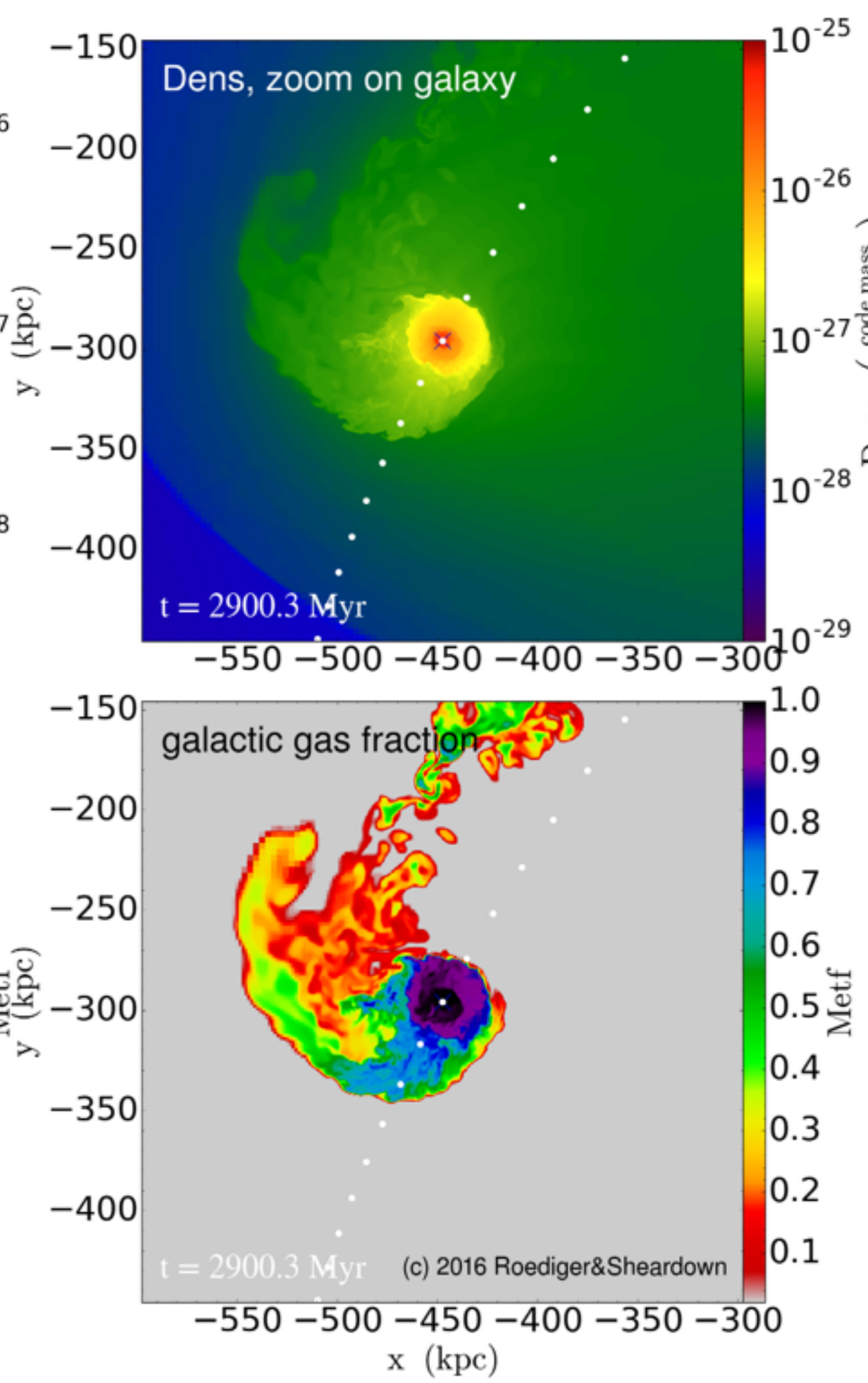


coming out of cluster – sloshing of remaining atmosphere, tail pointing odd directions

Sheardown+, in prep.





Dens, cluster view

t = 3600.3 Myr

Dens, zoom on galaxy

t = 3600.3 Myr

galactic gas fraction

t = 3600.3 Myr

galactic gas fraction

t = 3600.3 Myr

(c) 2016 Roediger&Sheardown

y (kpc)

x (kpc)

1e3

Metf

Dens (code mass)

Sheardown+, in prep.

Dens, cluster view

t = 4000.4 Myr

Dens, zoom on galaxy

t = 4000.4 Myr

galactic gas fraction

t = 4000.4 Myr

galactic gas fraction

t = 4000.4 Myr

(c) 2016 Roediger&Sheardown

y (kpc)

x (kpc)

Metf

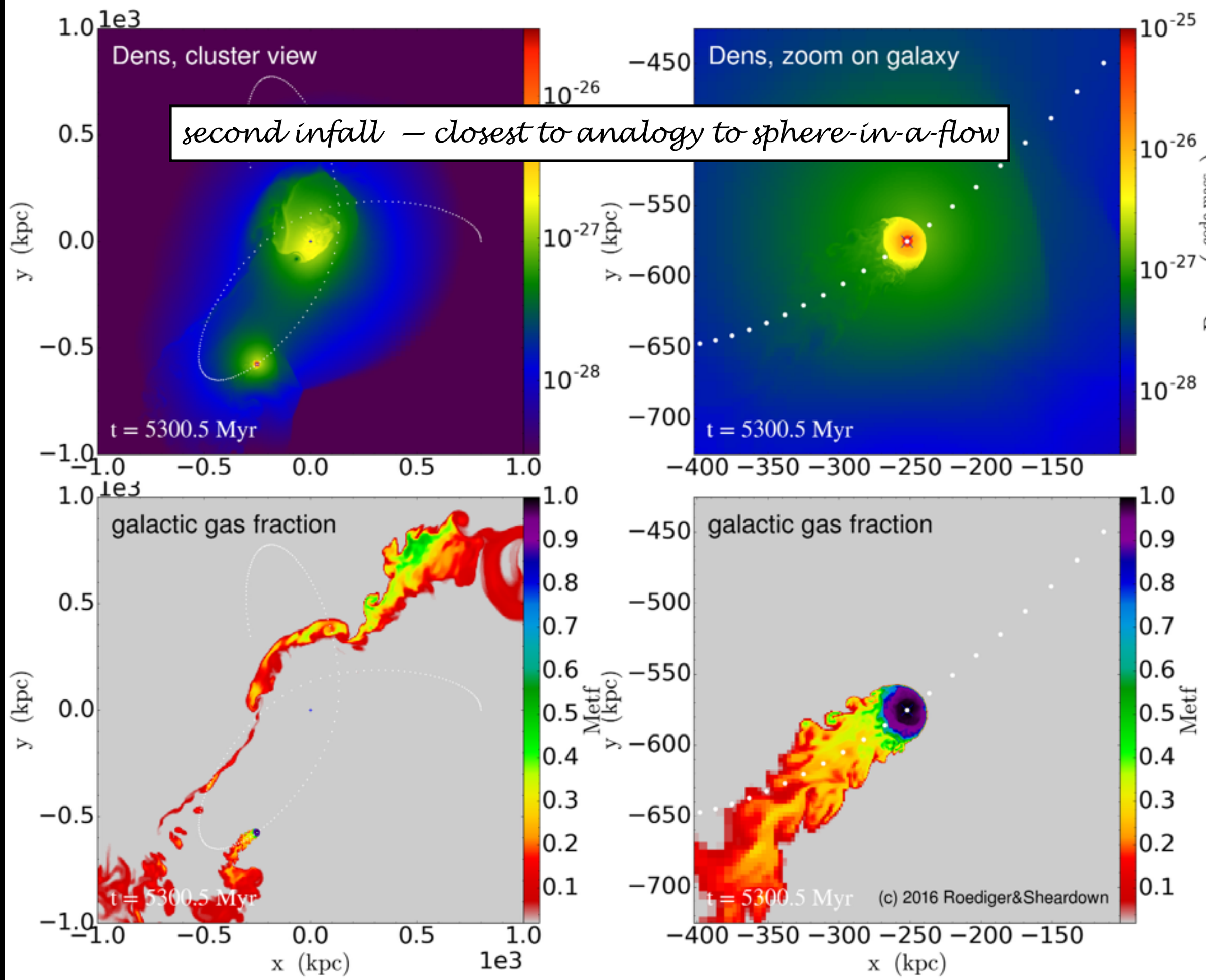
Dens (code mass)

1e3

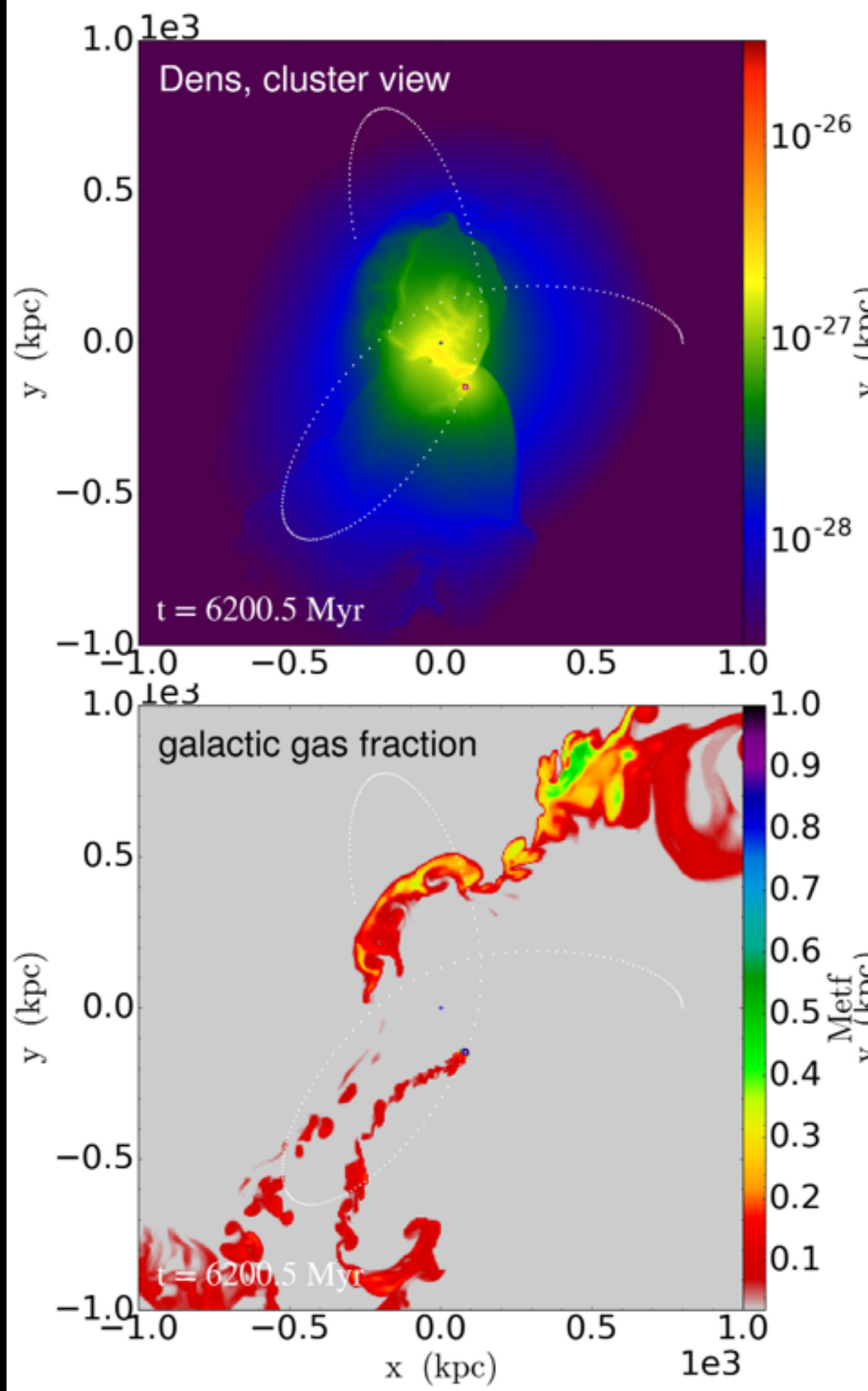
Sheardown+, in prep.

Sheardown+, in prep.

second infall – closest to analogy to sphere-in-a-flow



Sheardown+, in prep.



Dens, cluster view

t = 6400.5 Myr

Dens, zoom on gálaxy

t = 6400.5 Myr

galactic gas fraction

t = 6400.5 Myr

galactic gas fraction

t = 6400.5 Myr

y (kpc)

x (kpc)

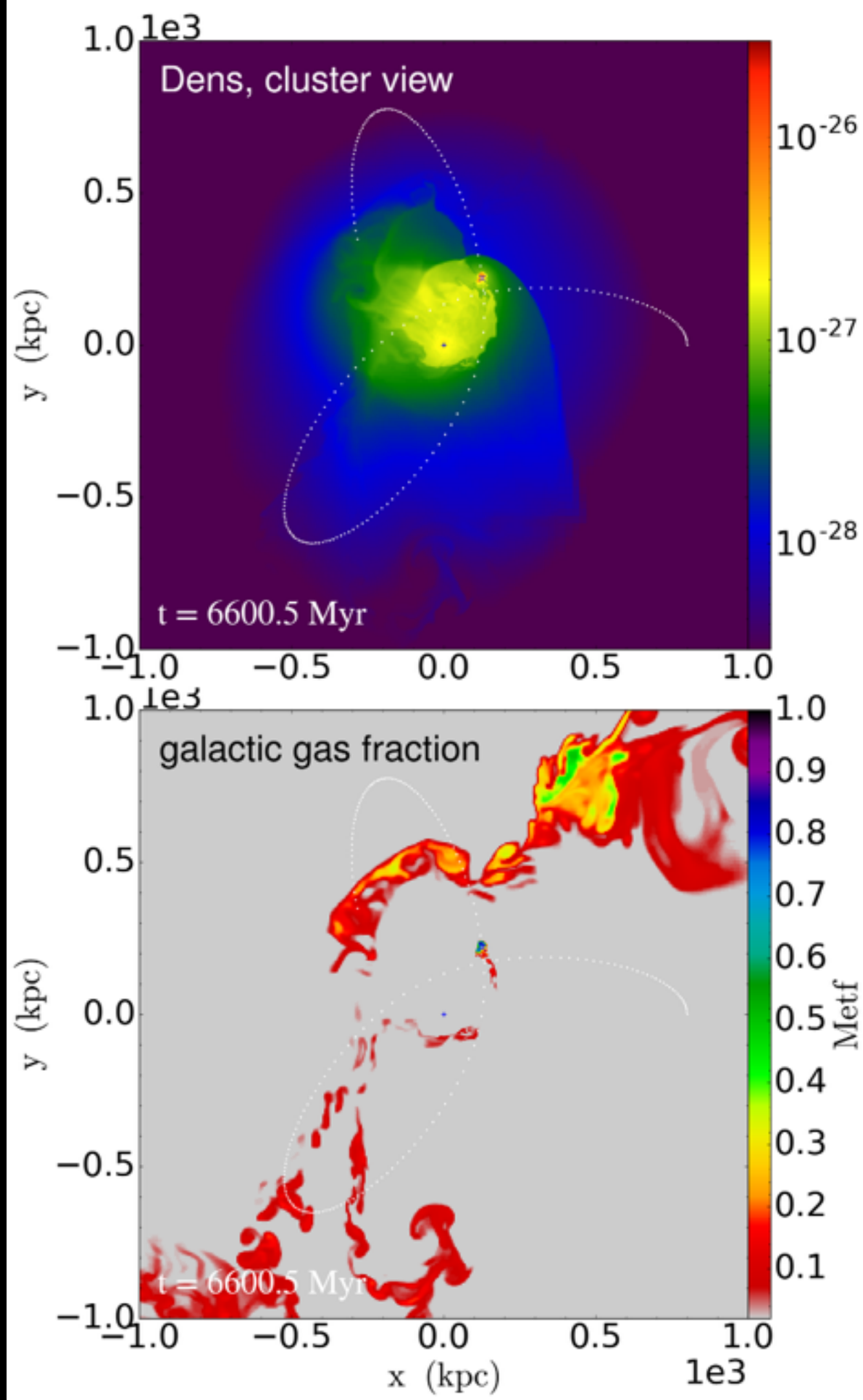
1e3

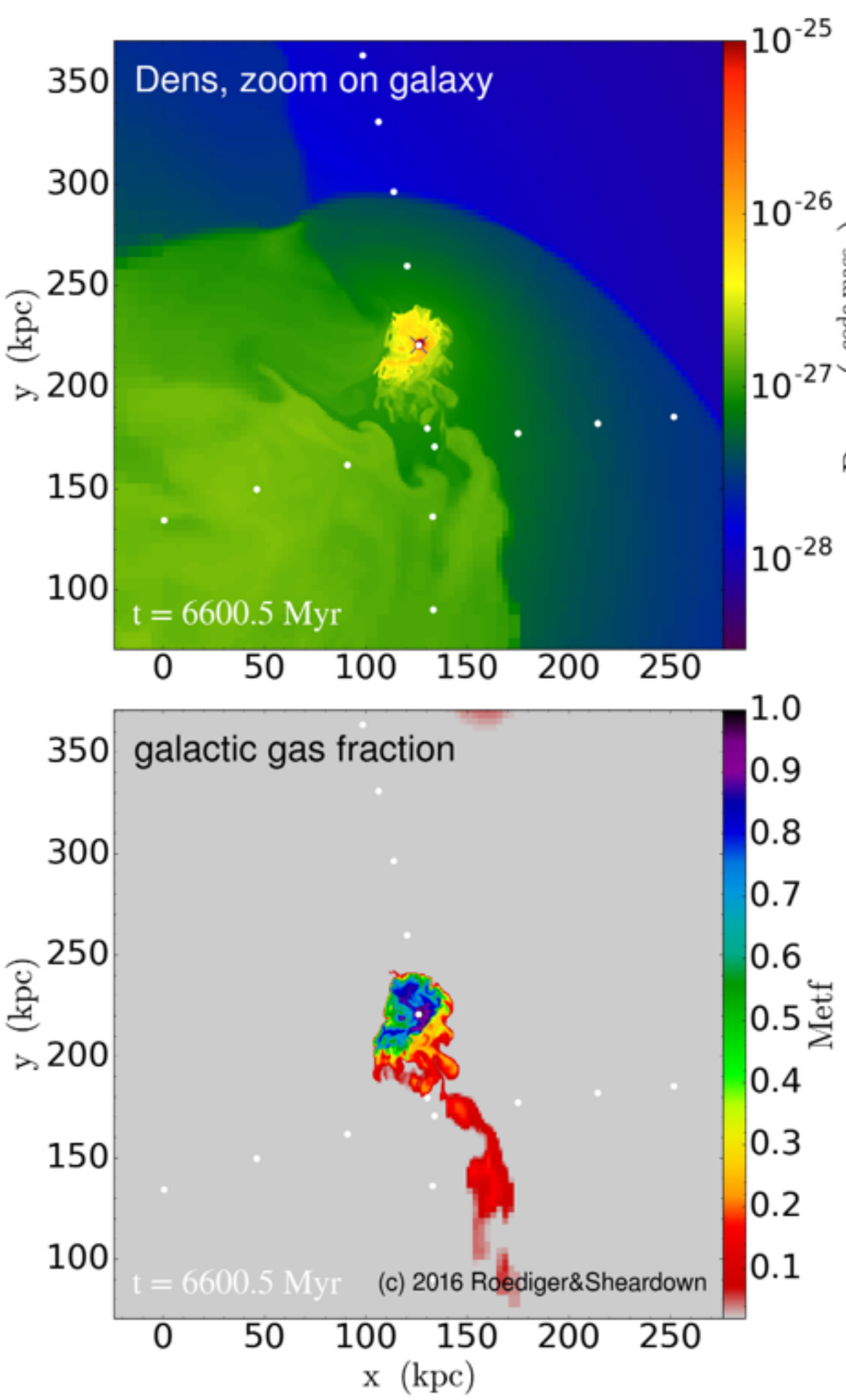
Dens (code mass)

Metf

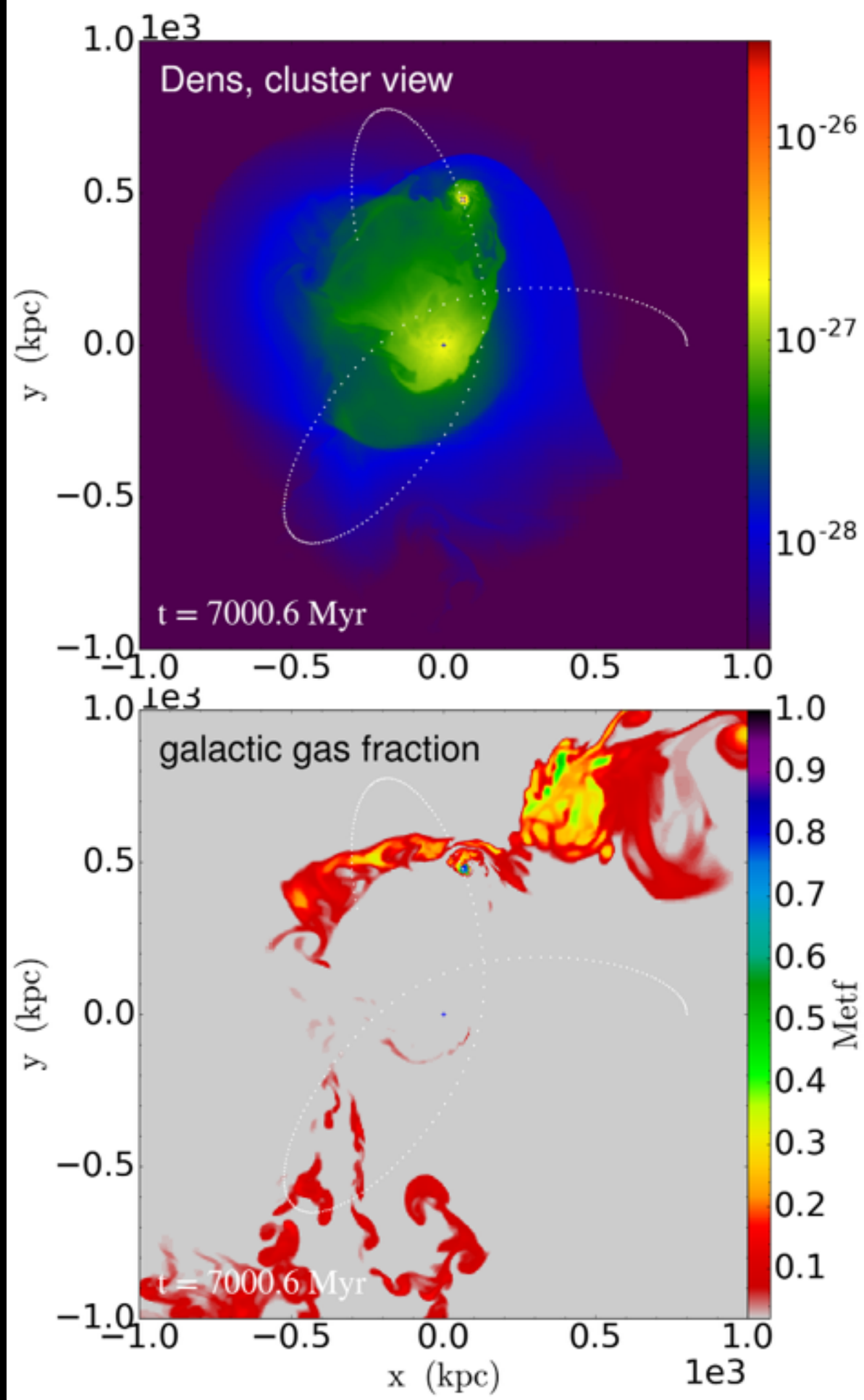
Sheardown+, in prep.

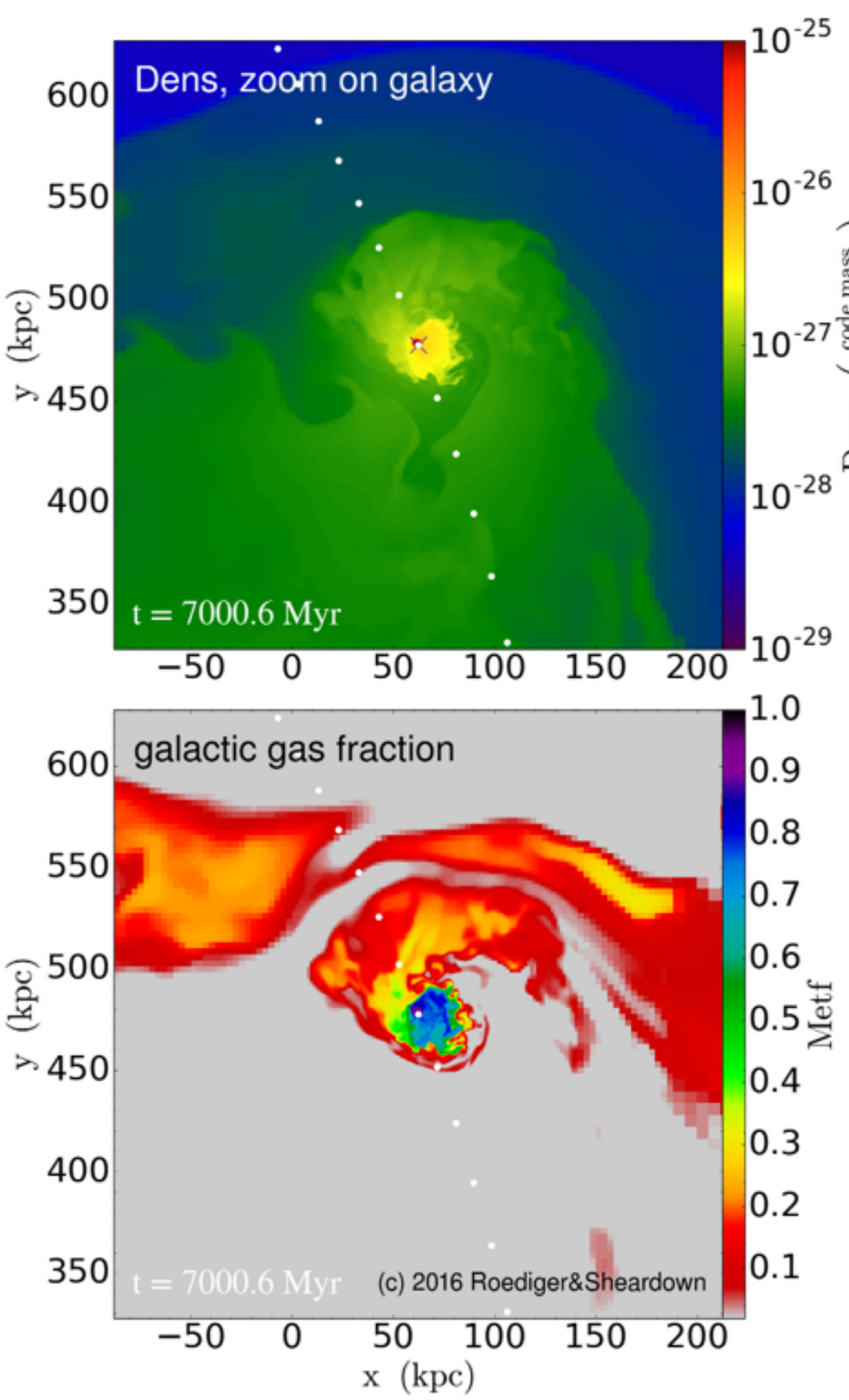
Sheardown+, in prep.





Sheardown+, *in prep.*





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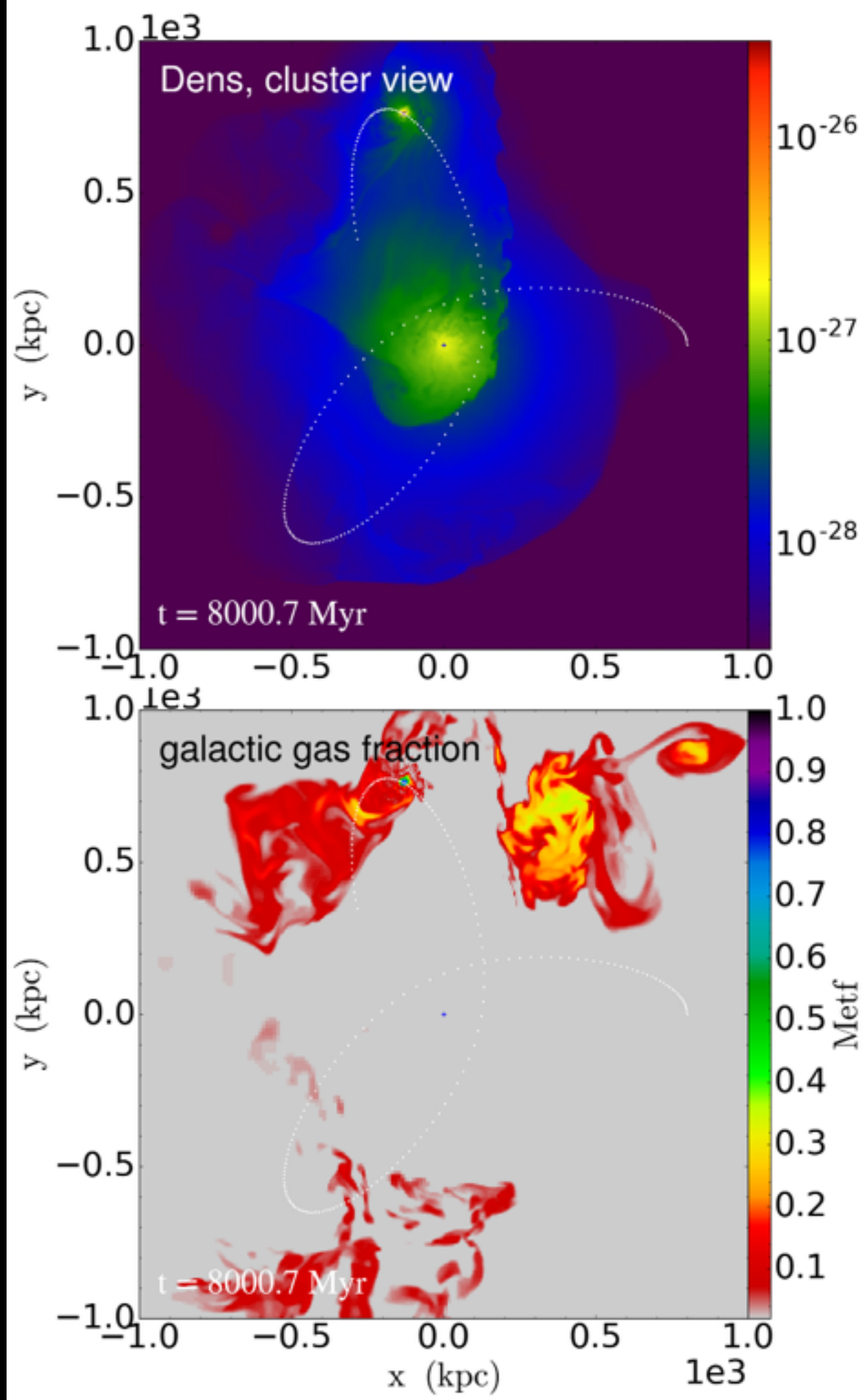

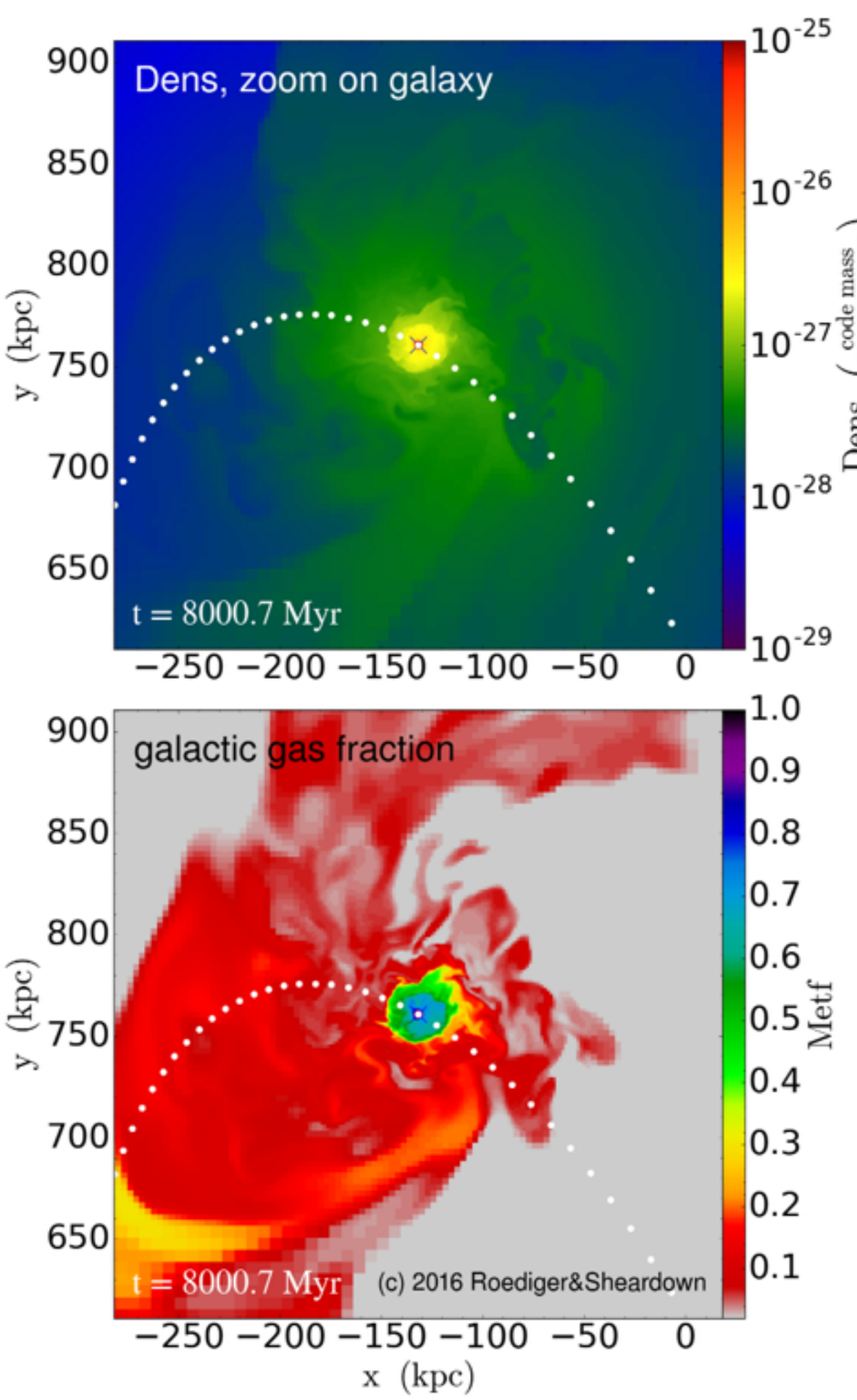

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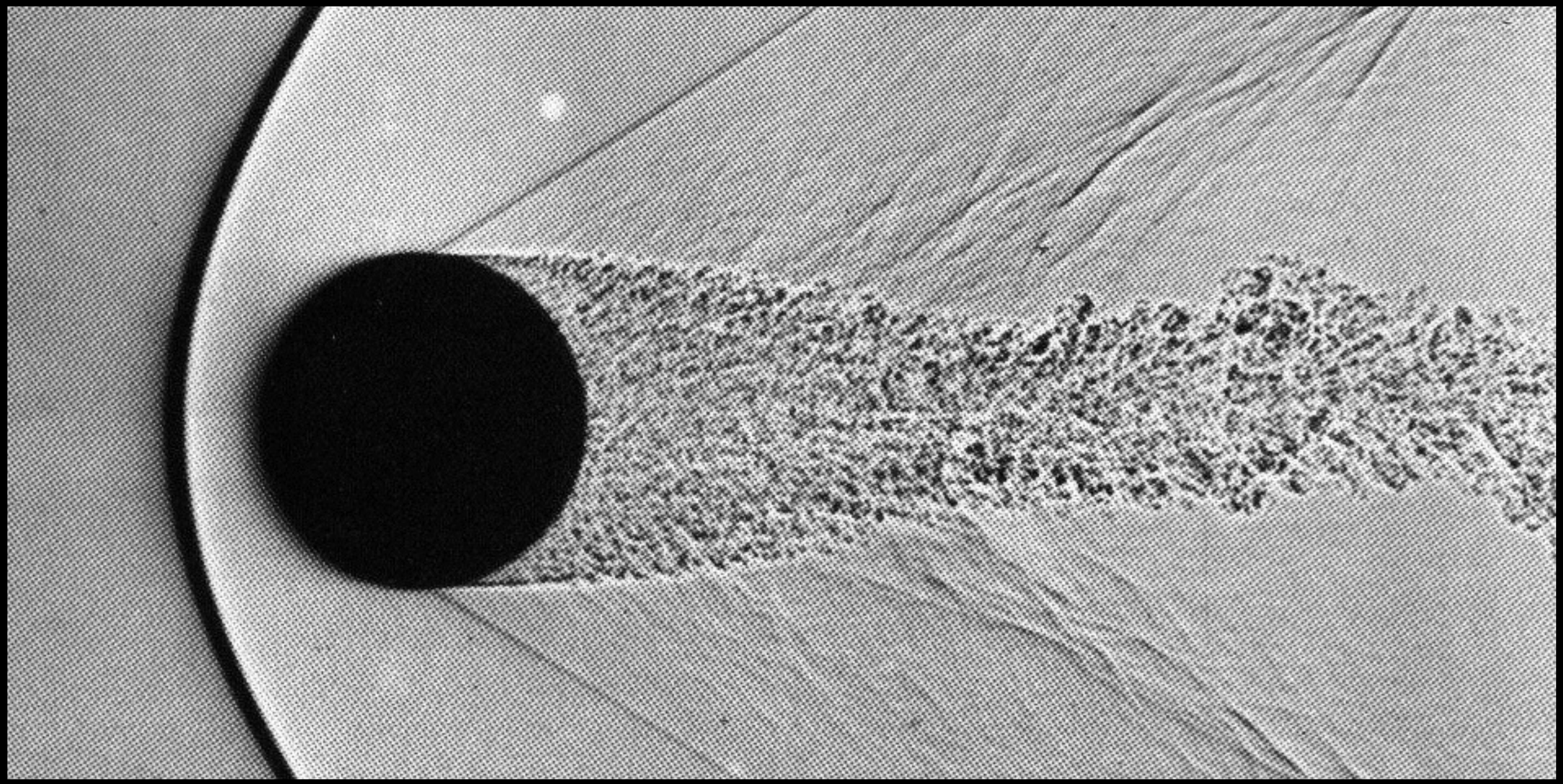
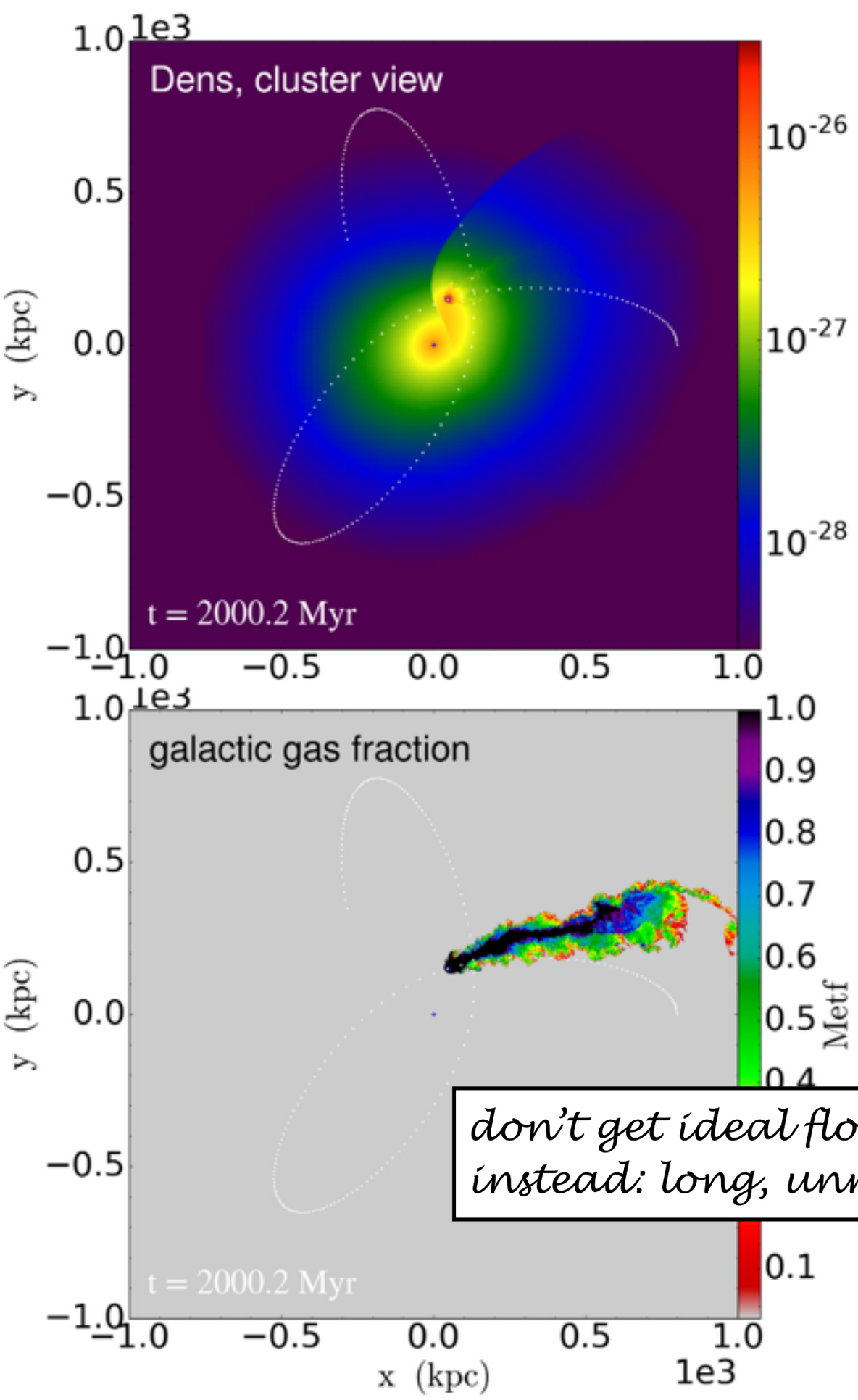
Do we get this flow pattern during *first infall*?

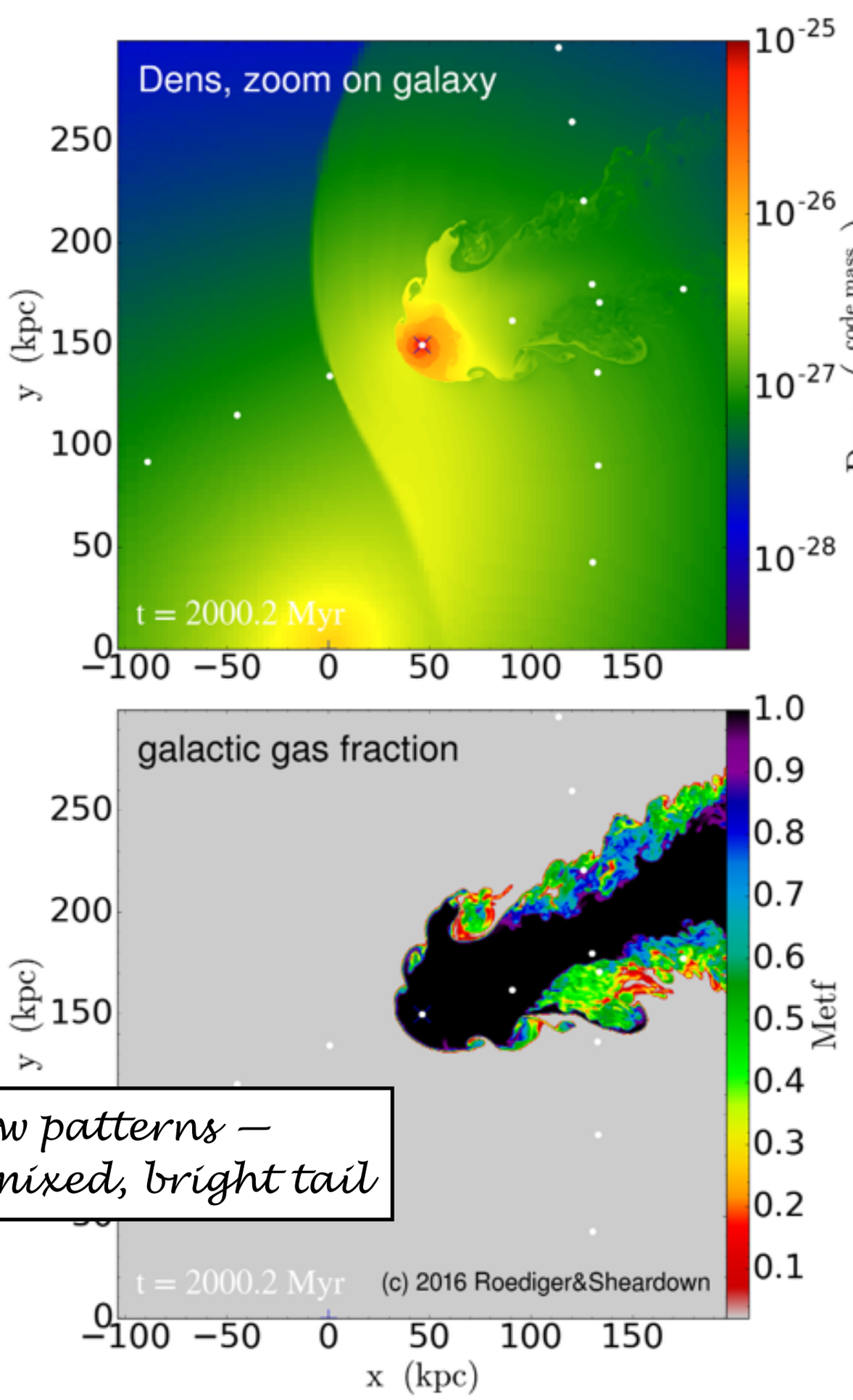


van Dyke - Album of Fluid Motion

Elke Roediger

Sheardown+, in prep.





don't get ideal flow patterns –
instead: long, unmixed, bright tail

First infall

- ✓ no solid obstacle but galactic atmosphere undergoes gas loss and *deformation* — SHIELDING of downstream atmosphere

- ✓ no steady flow but increasing ram pressure

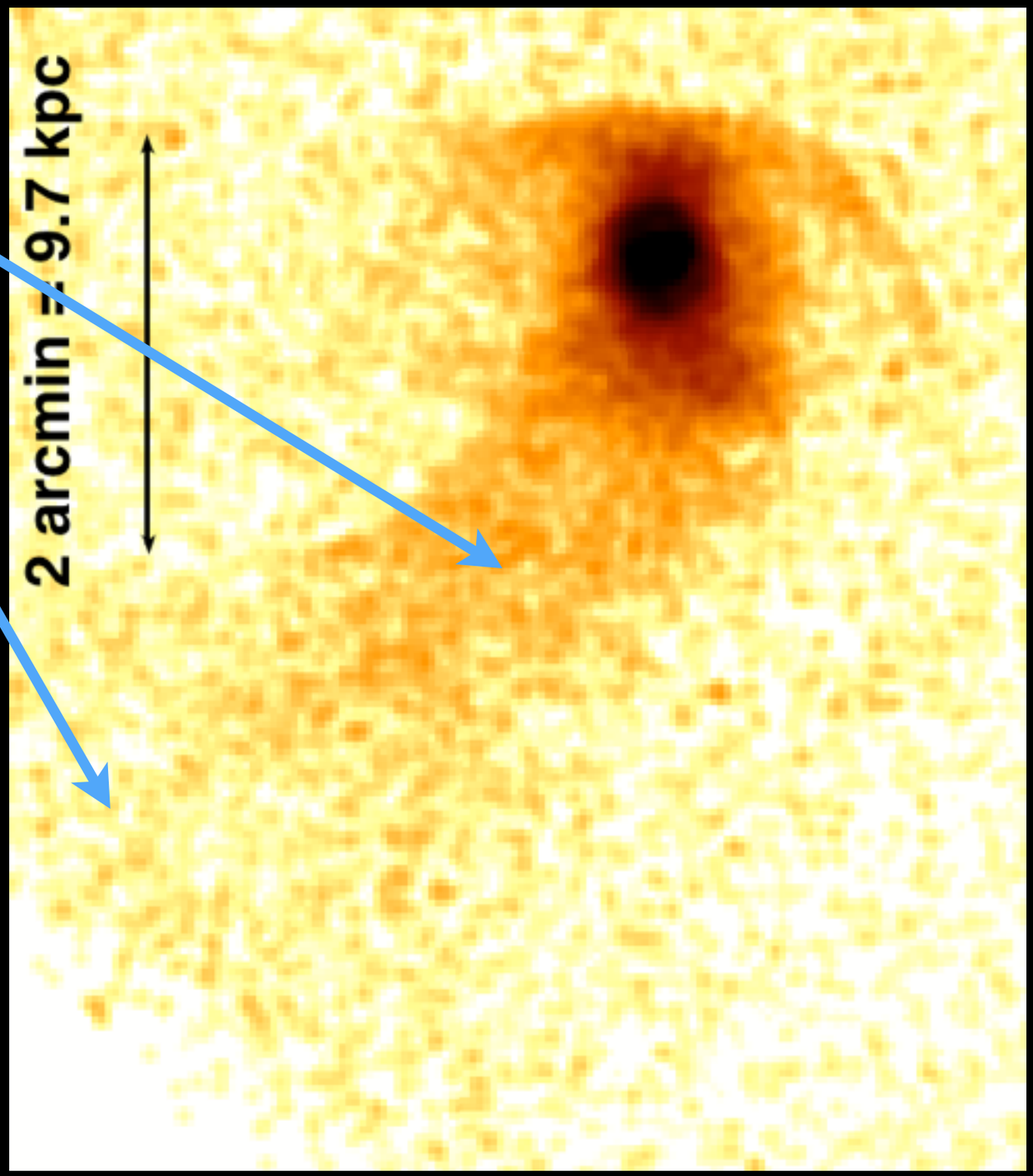
Consequence: long, dense, cool, bright *remnant* tail

Observed? Yes!

M89 in Virgo

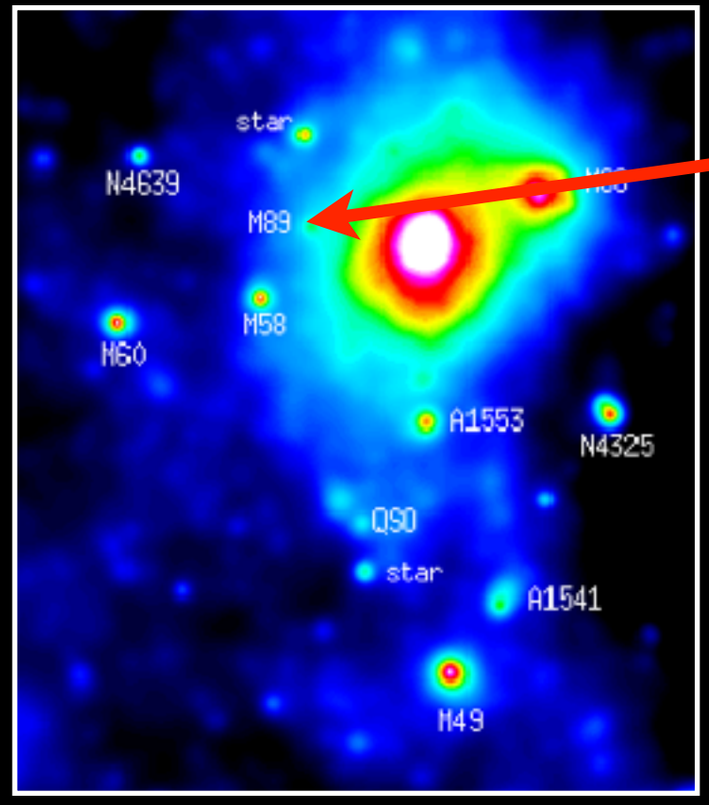
remnant tail, pushed-back part of remnant atmosphere

wake



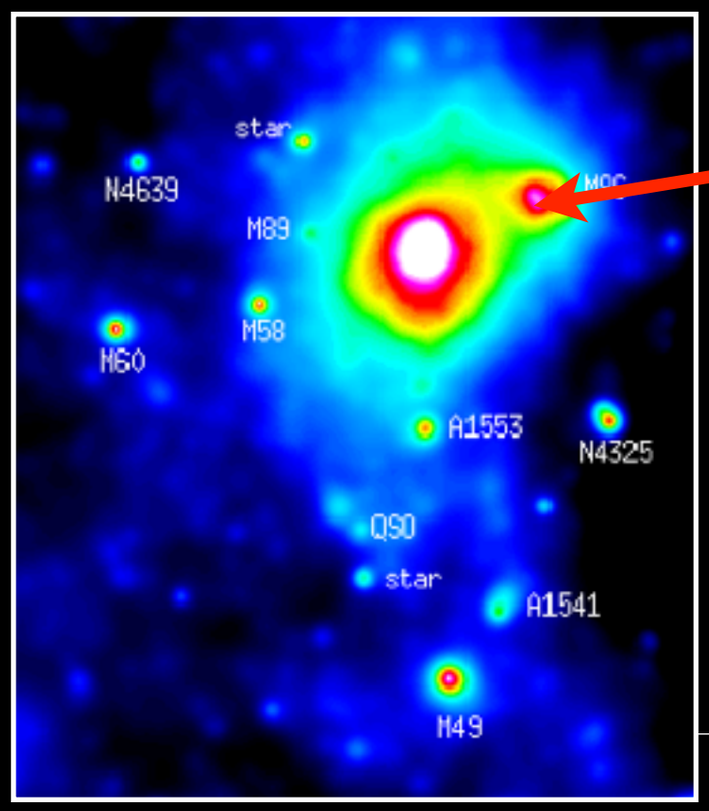
Chandra; Machacek+06, Kraft+, in prep.

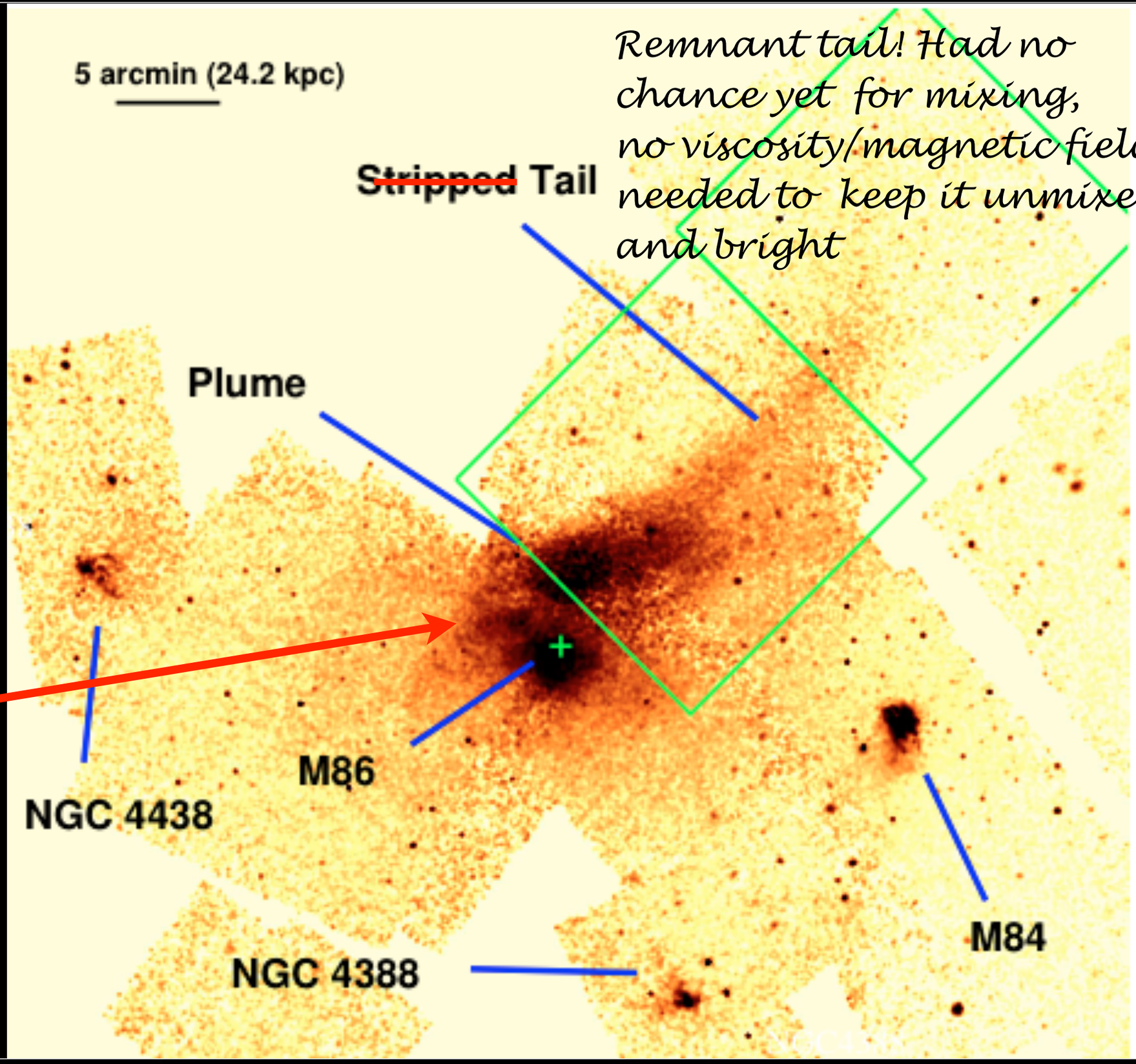
Böhringer+94



M86 in Virgo

Böhringer+94

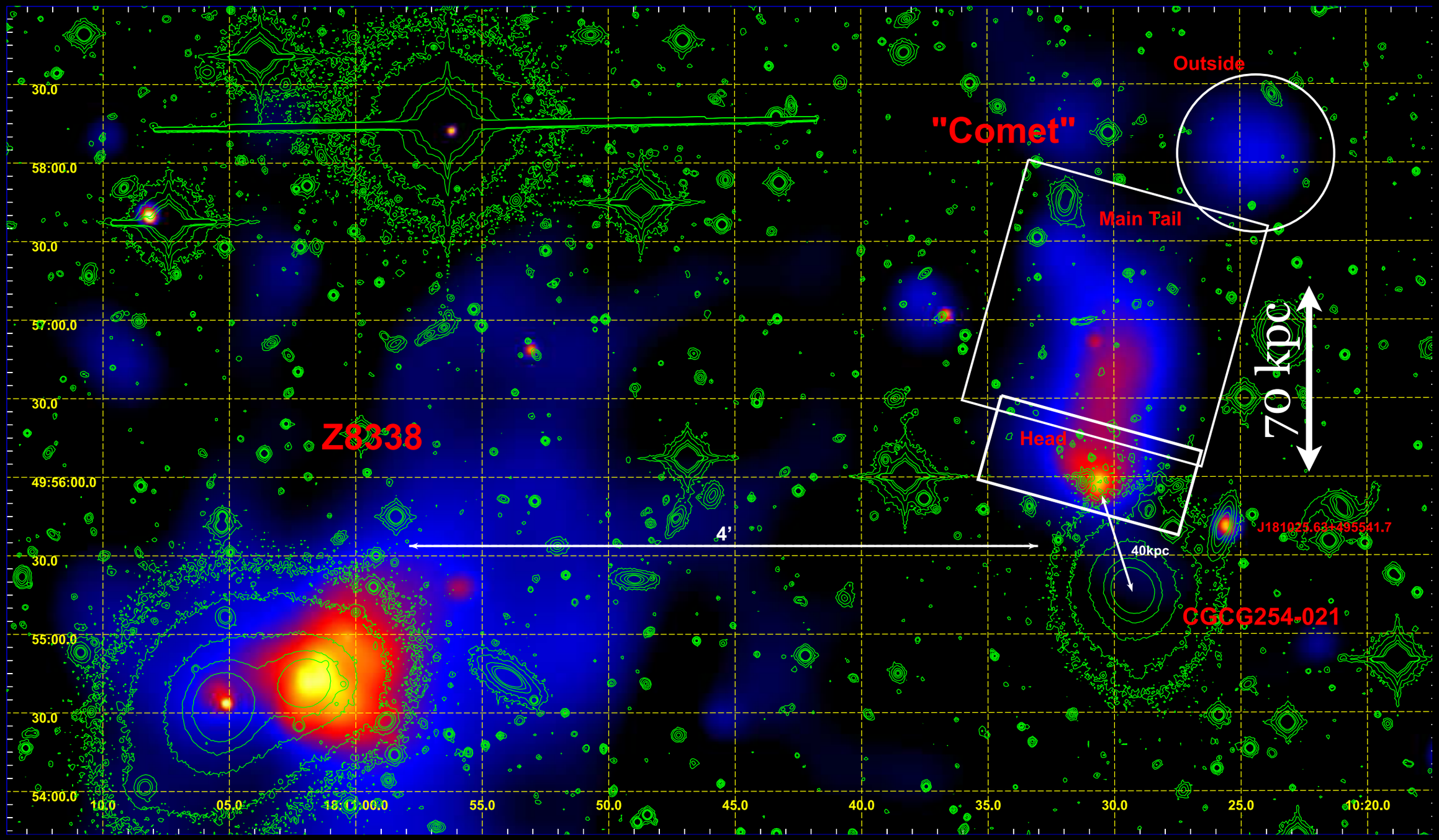




Remnant tail! Had no chance yet for mixing, no viscosity/magnetic fields needed to keep it unmixed and bright

Randall+08

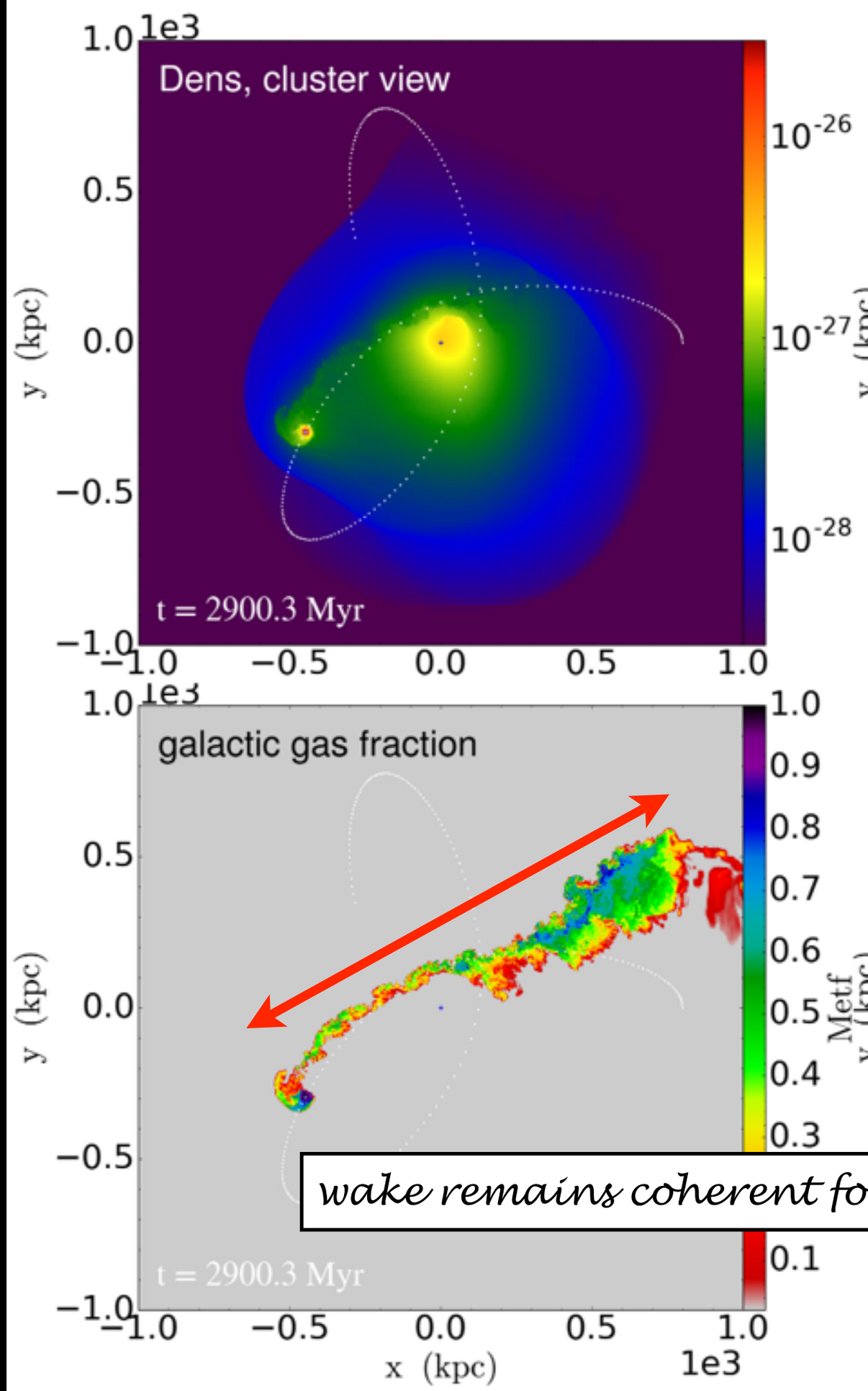
Zw 8338

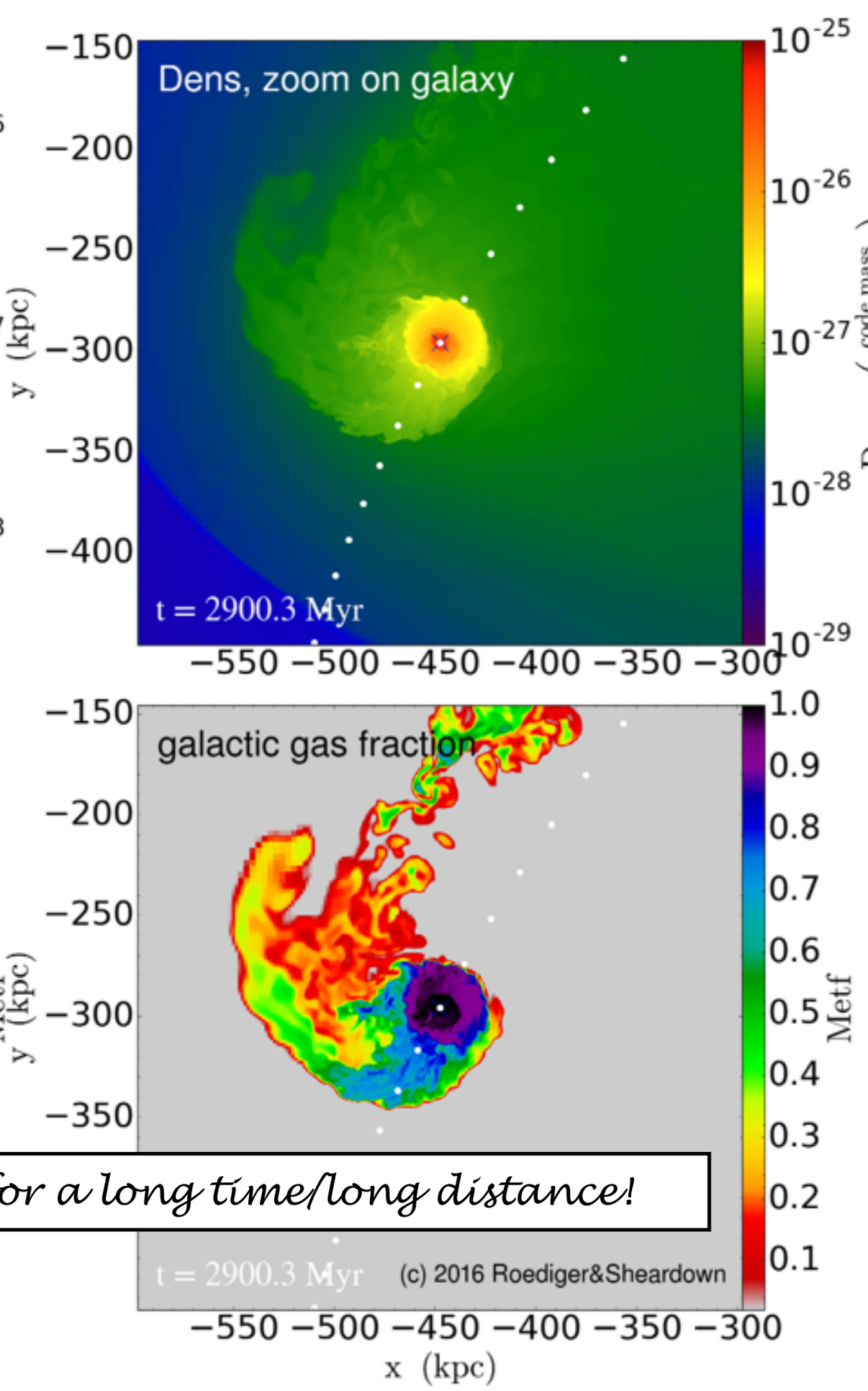


Chandra; Schellenberger&Reiprich 15

The wake very far downstream

Sheardown+, *in prep.*

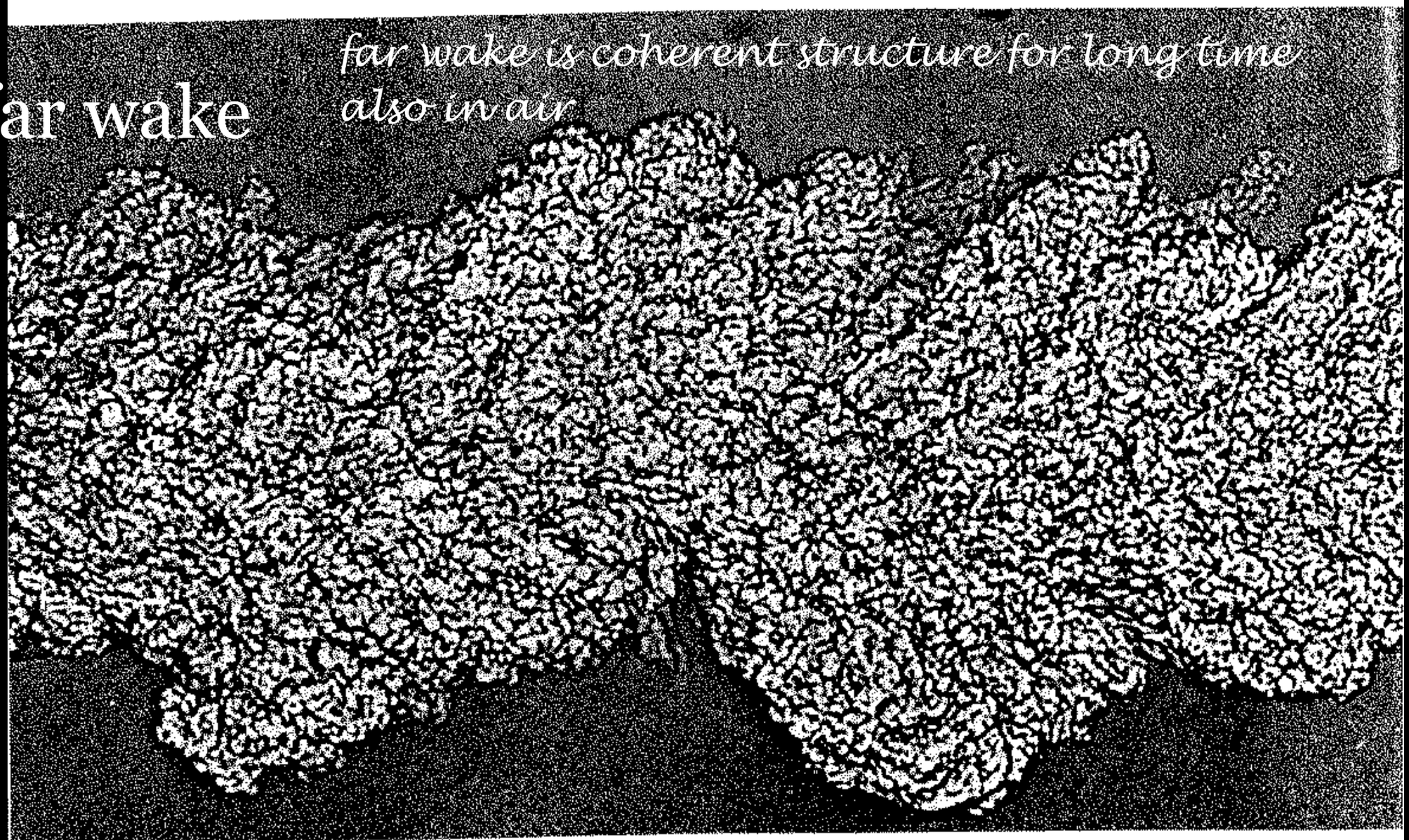




wake remains coherent for a long time/long distance!

Very far wake

far wake is coherent structure for long time
also in air



151. Turbulent wake far behind a projectile. A bullet has been shot through the atmosphere at supersonic speed, and is now several hundred wake diameters to the left. This short-duration shadowgraph shows the remarkable sharpness of the irregular boundary between the highly turbulent wake produced by the bullet and the almost quiescent air in irrotational motion outside. *Photograph made at Ballistic Research Laboratories, Aberdeen Proving Ground, in Corrsin & Kistler 1954*

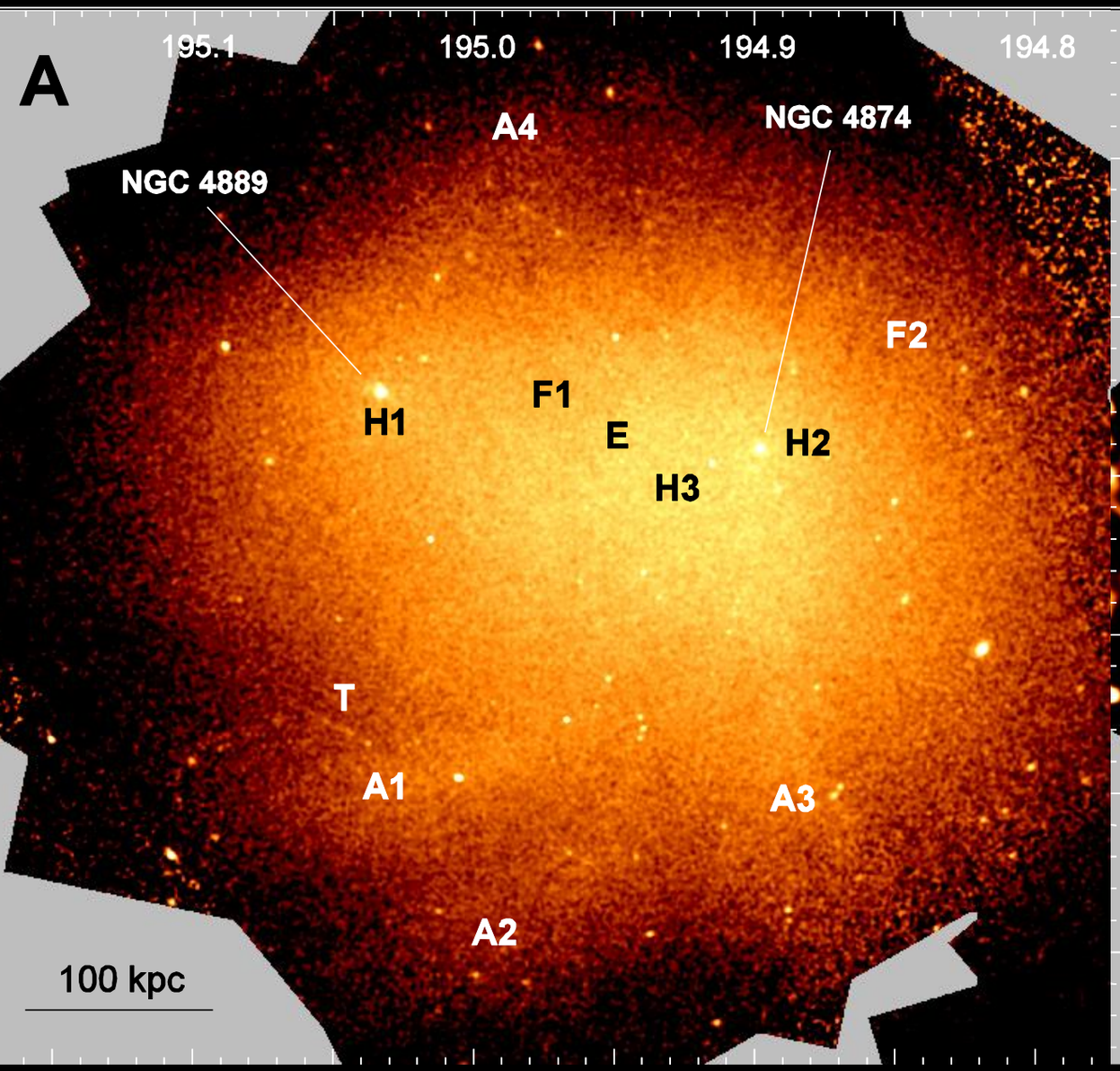
van Dyke - Album of Fluid Motion

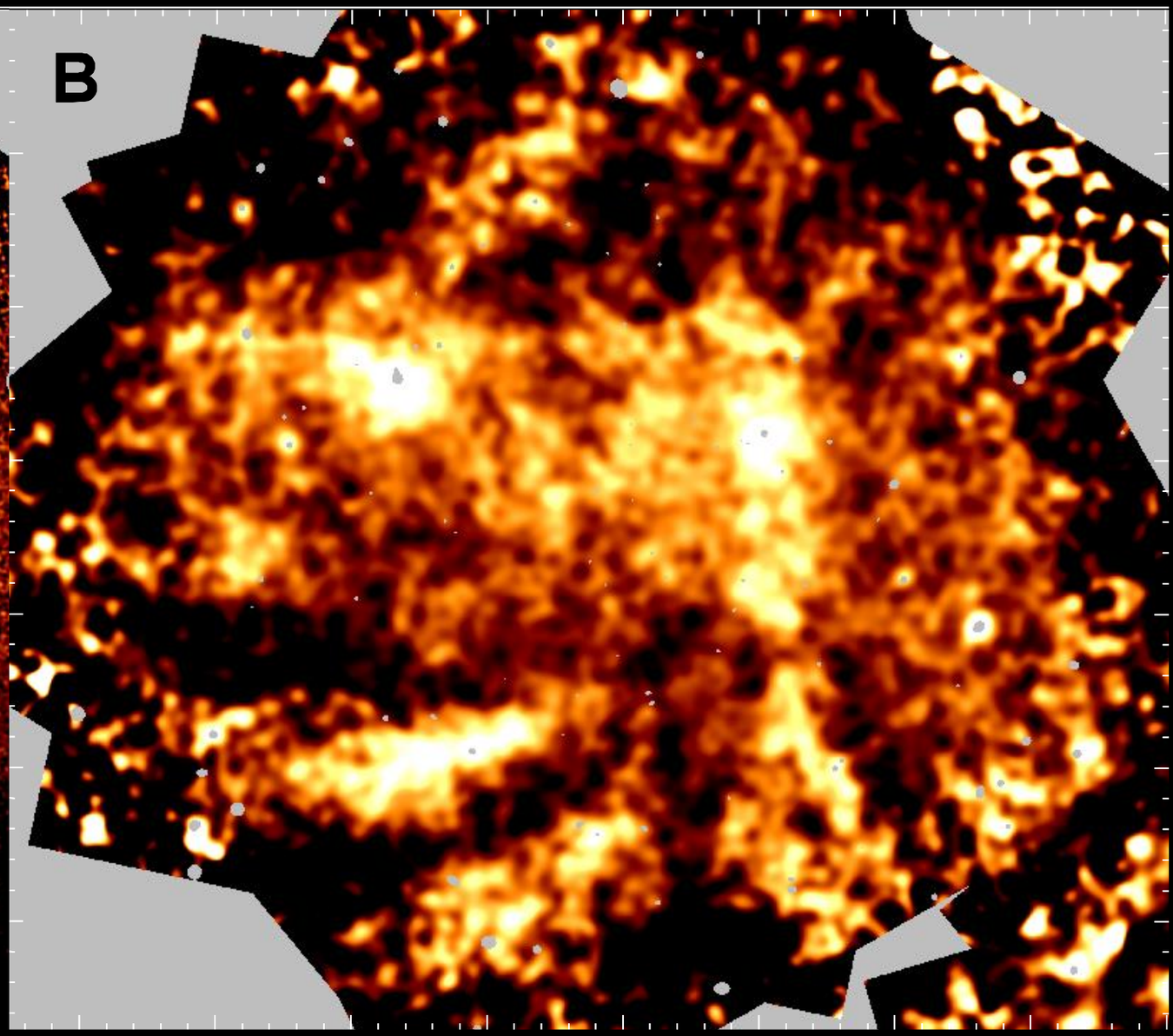
~~Tails~~ Wakes? in Coma

if these are the very far wakes instead of tails, the responsible galaxy may be far away already

Chandra mosaic

unsharp masked

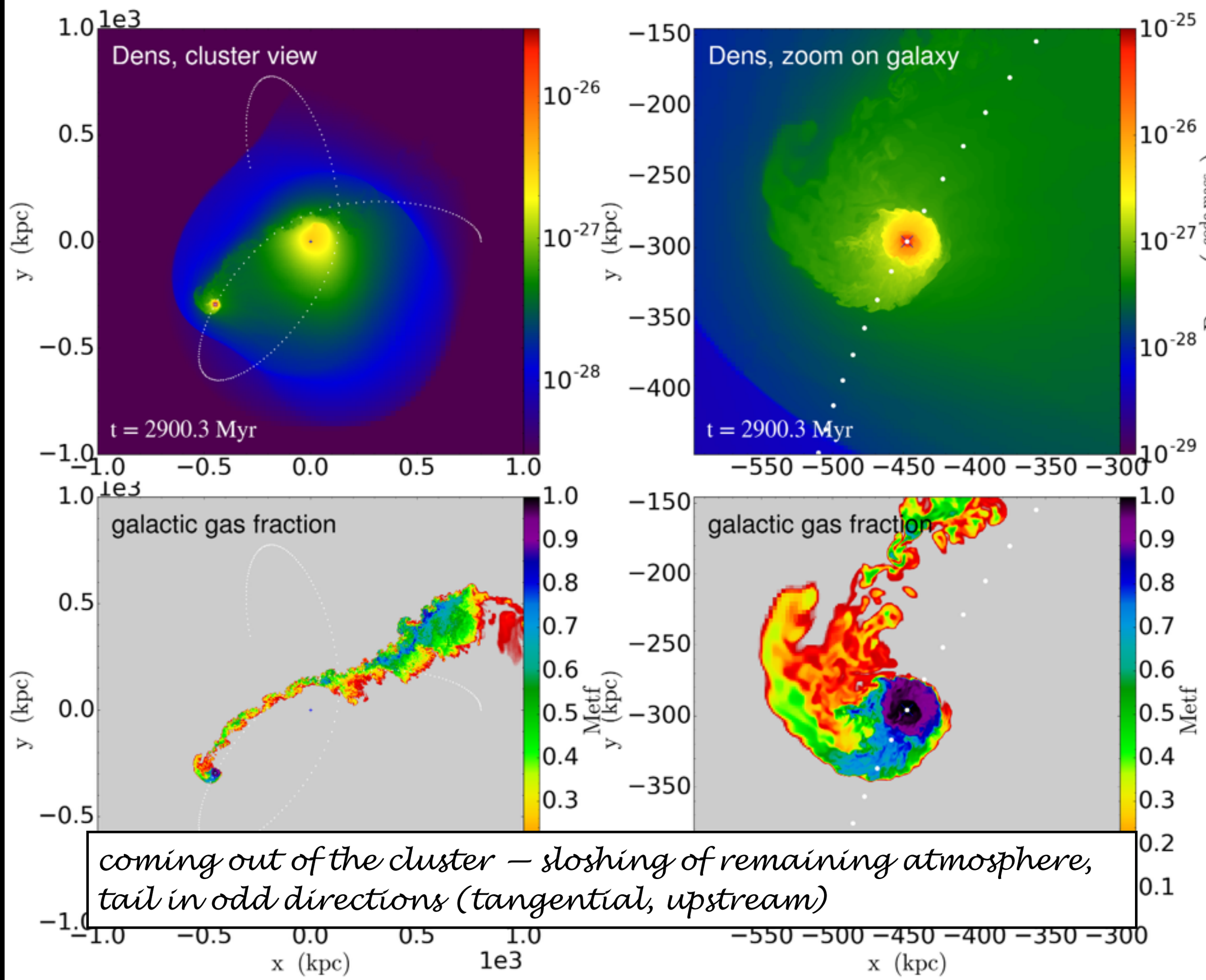




Sanders+2013

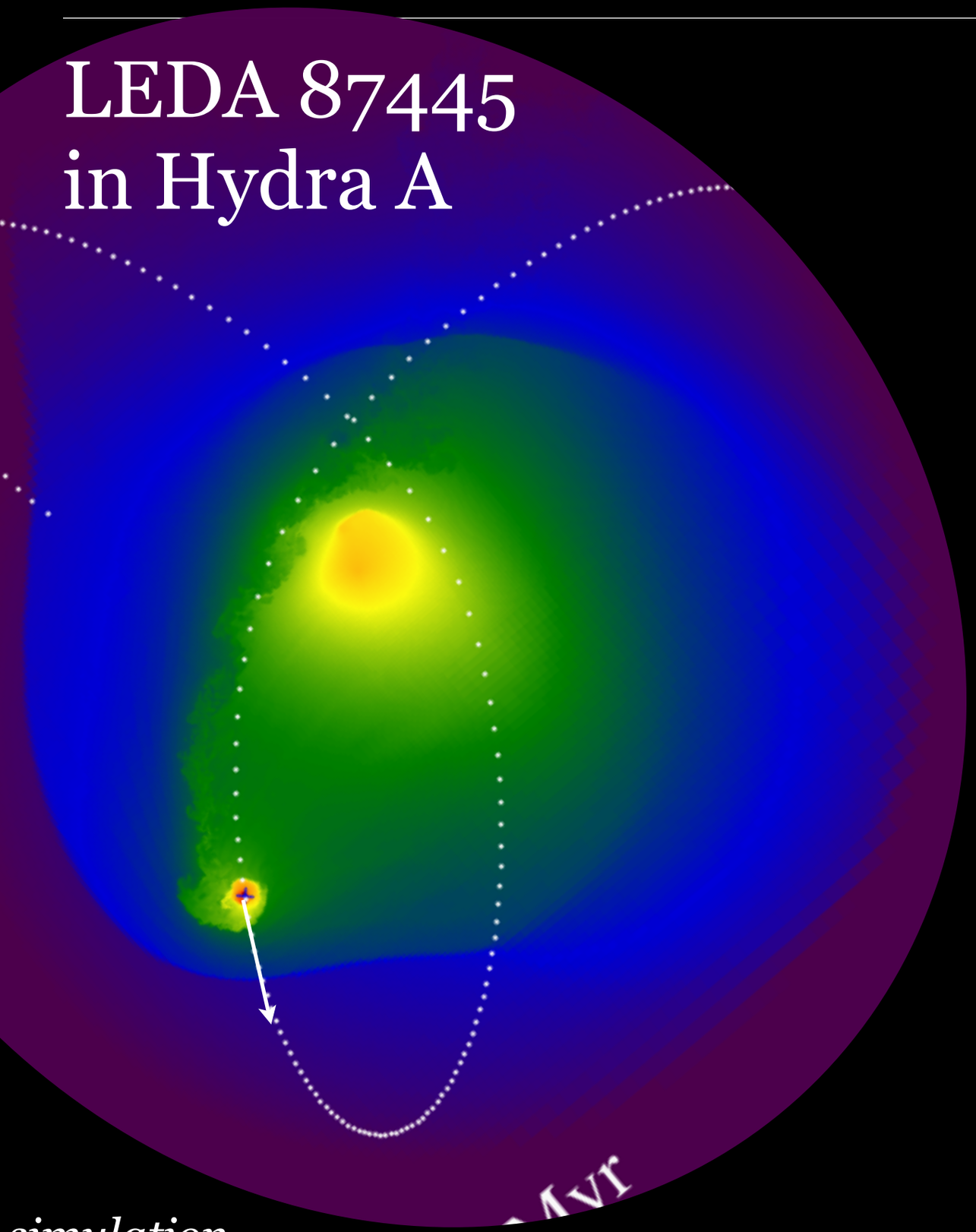
Coming out of the cluster

Sheardown+, *in prep.*

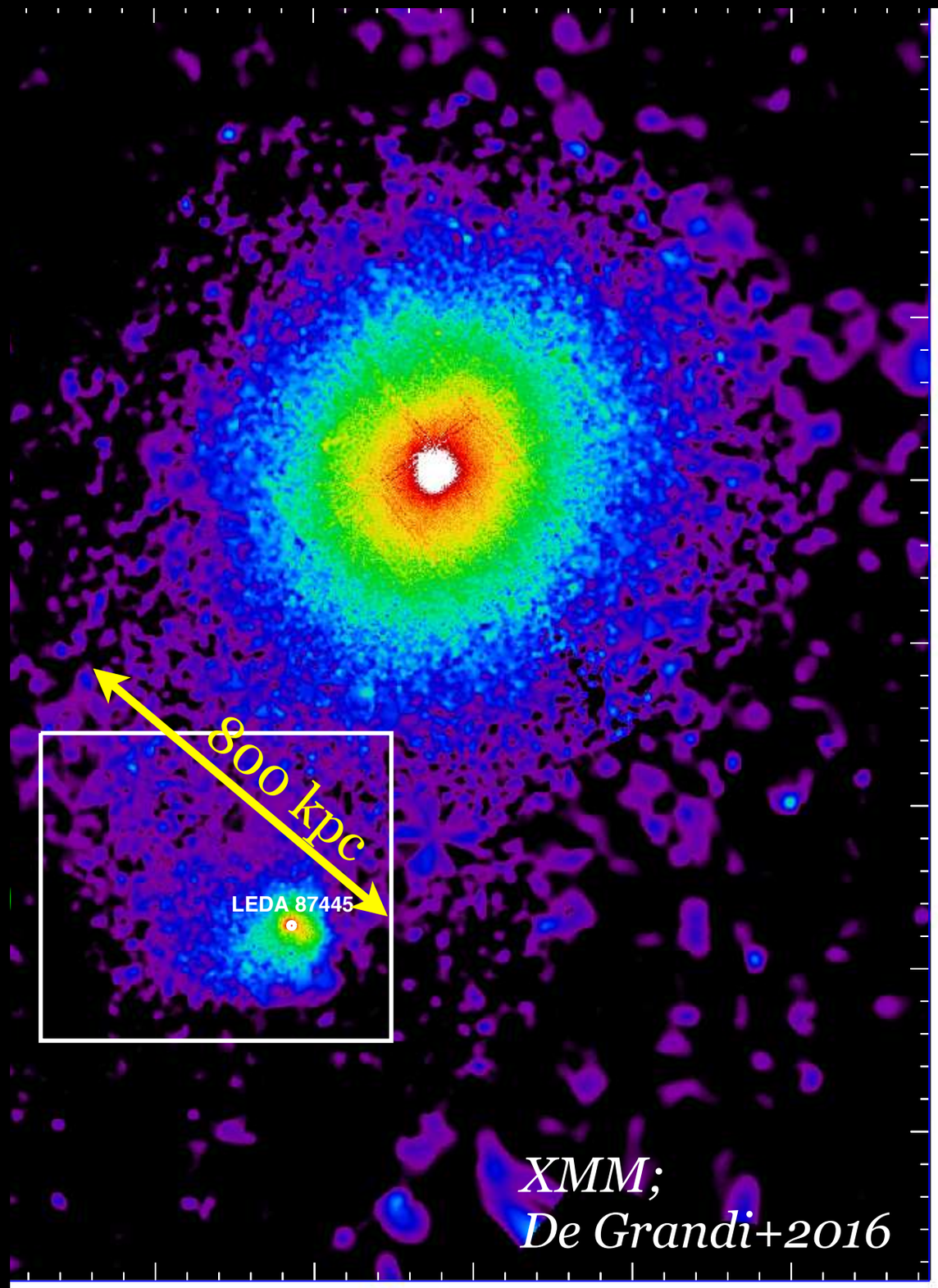


coming out of the cluster – sloshing of remaining atmosphere, tail in odd directions (tangential, upstream)

LEDA 87445 in Hydra A

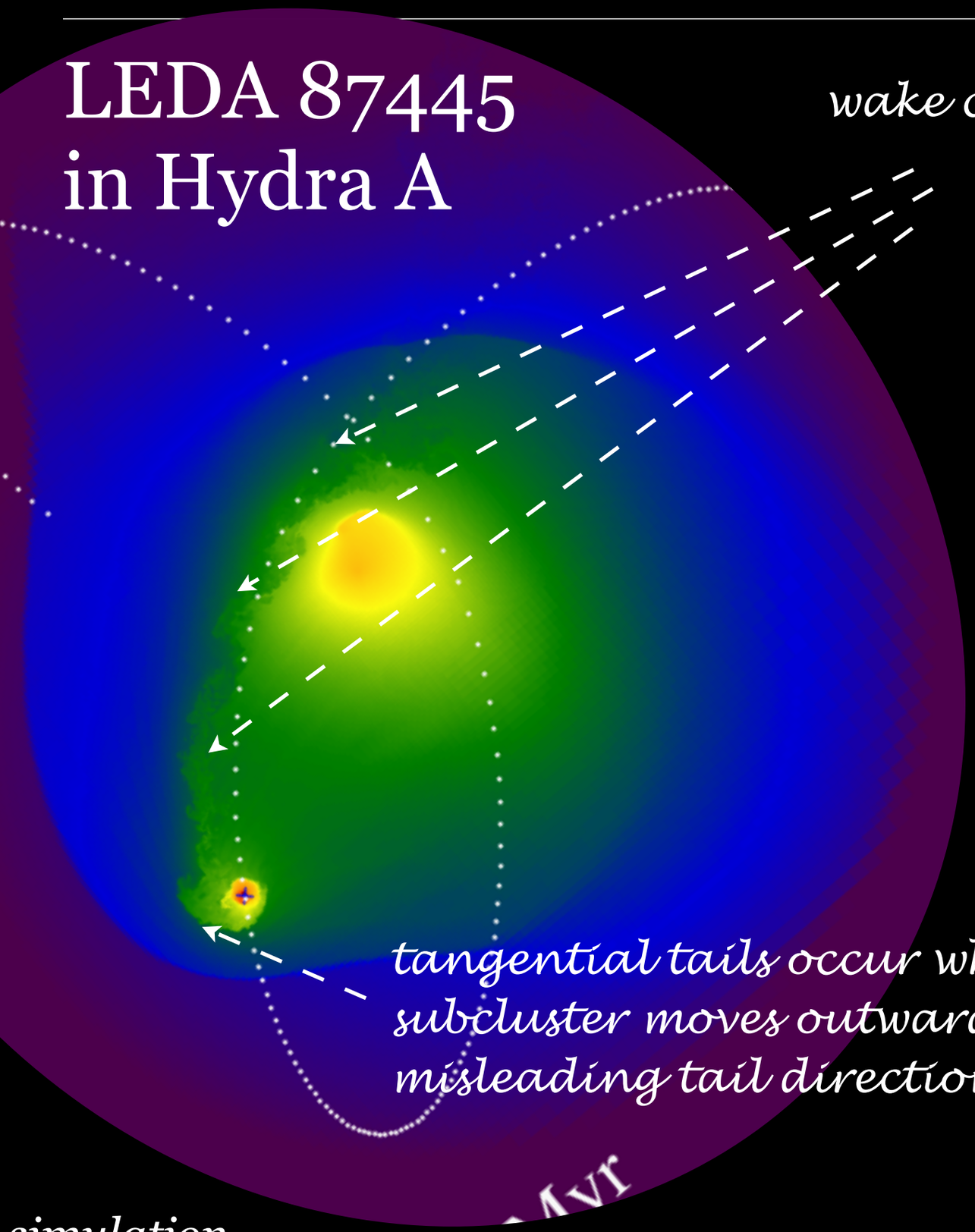


simulation,
galaxy coming out of cluster

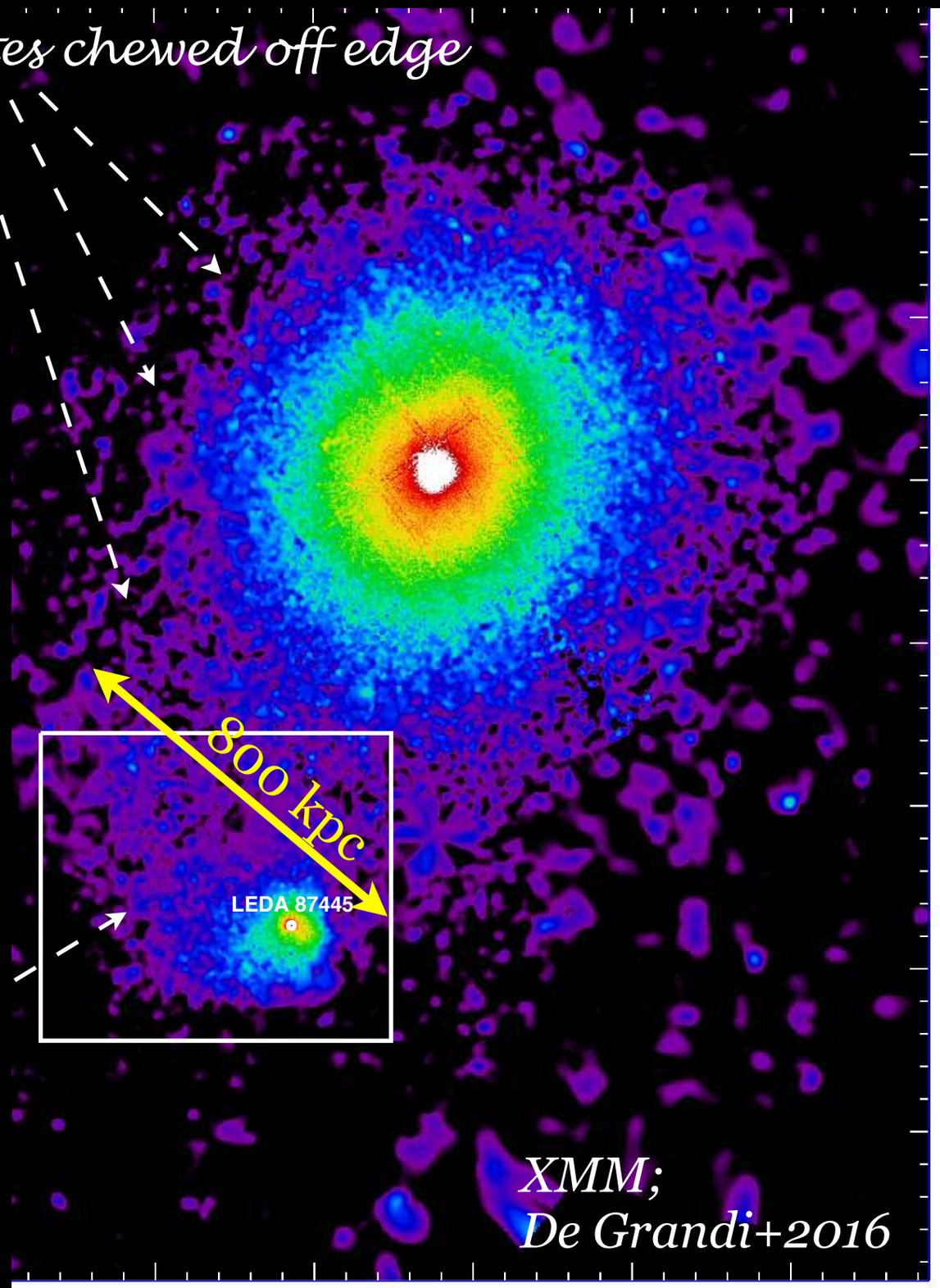


UNIVERSITY OF Hull

LEDA 87445 in Hydra A

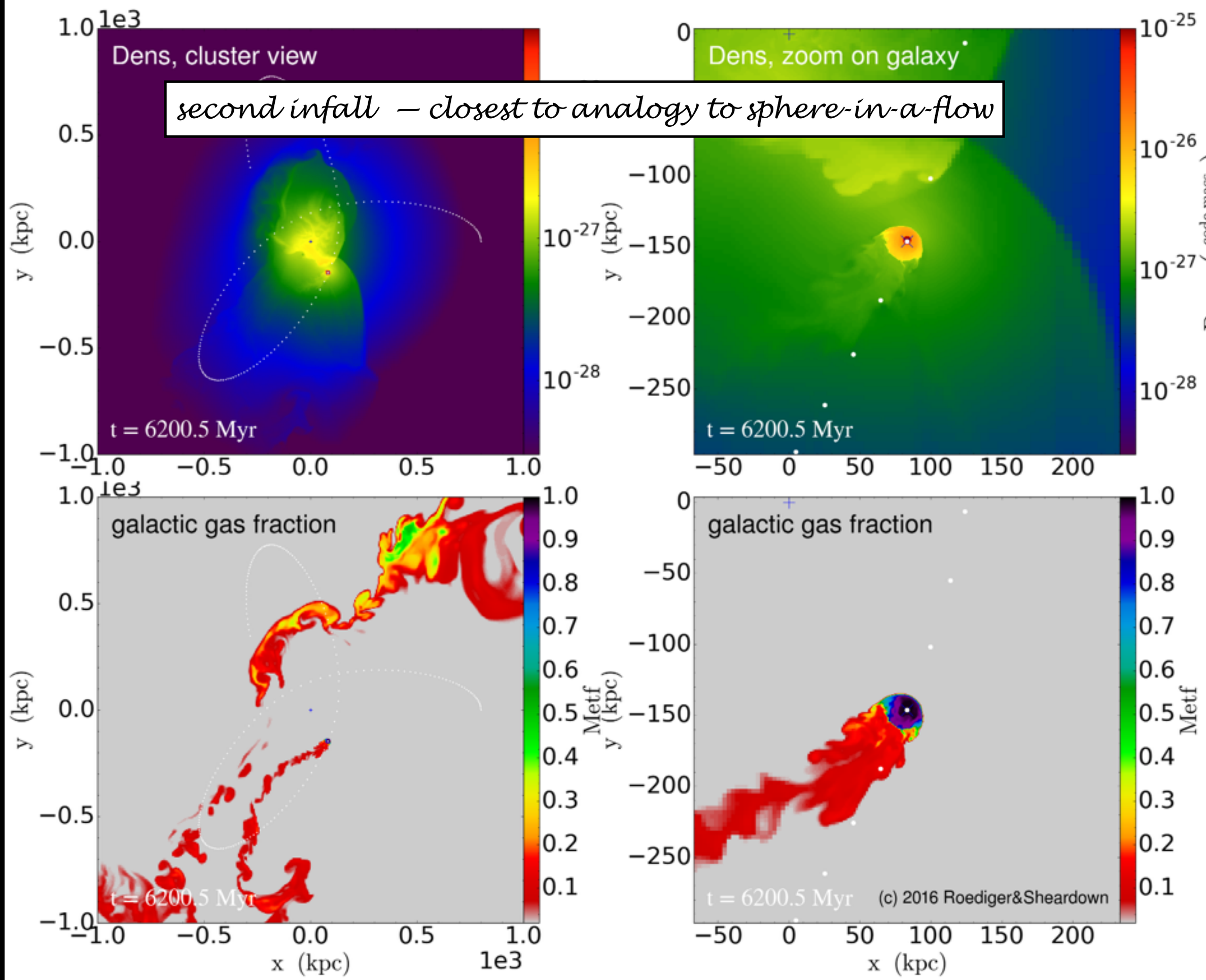


simulation, galaxy coming out of cluster



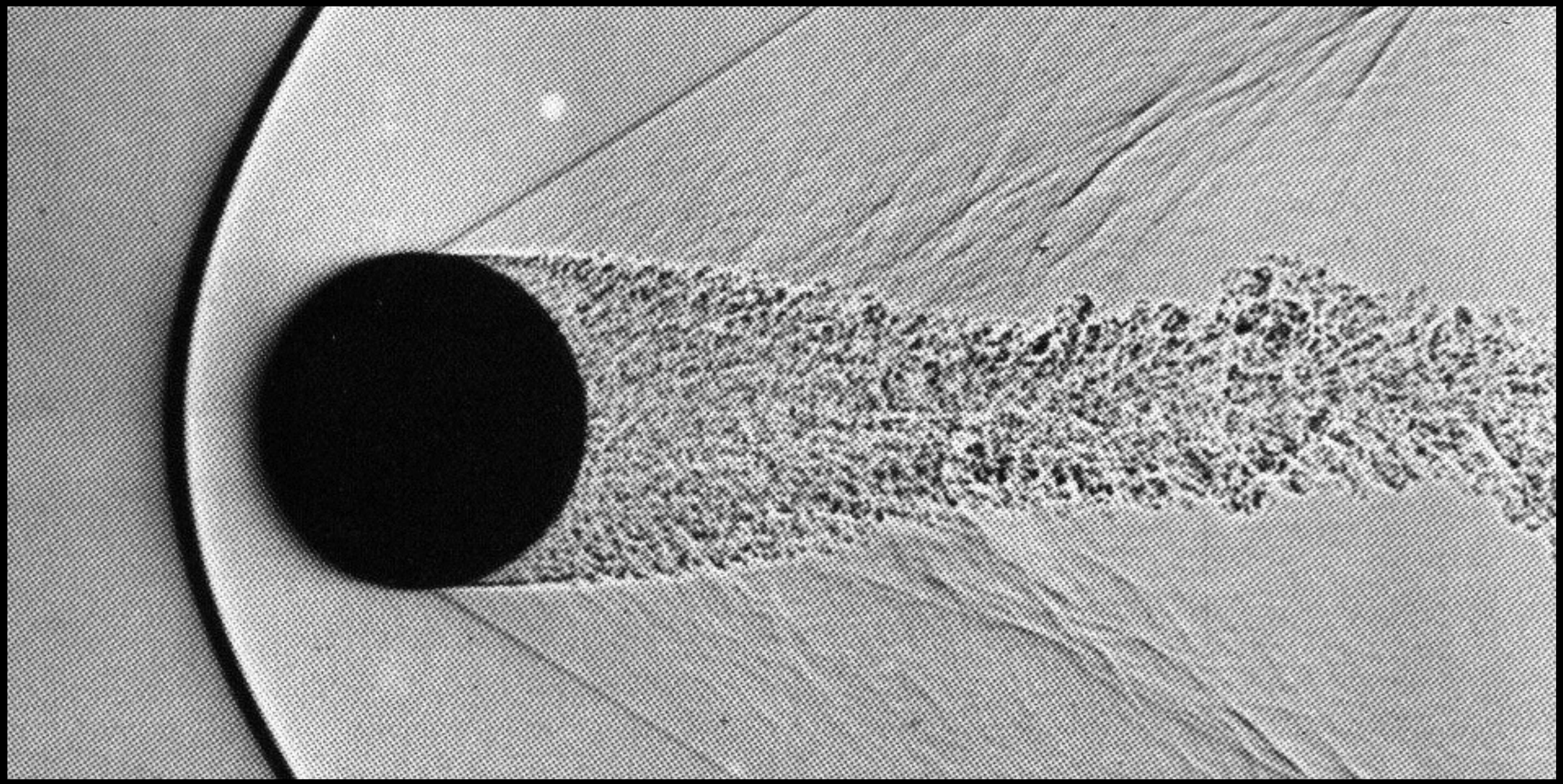
Second infall

second infall – closest to analogy to sphere-in-a-flow



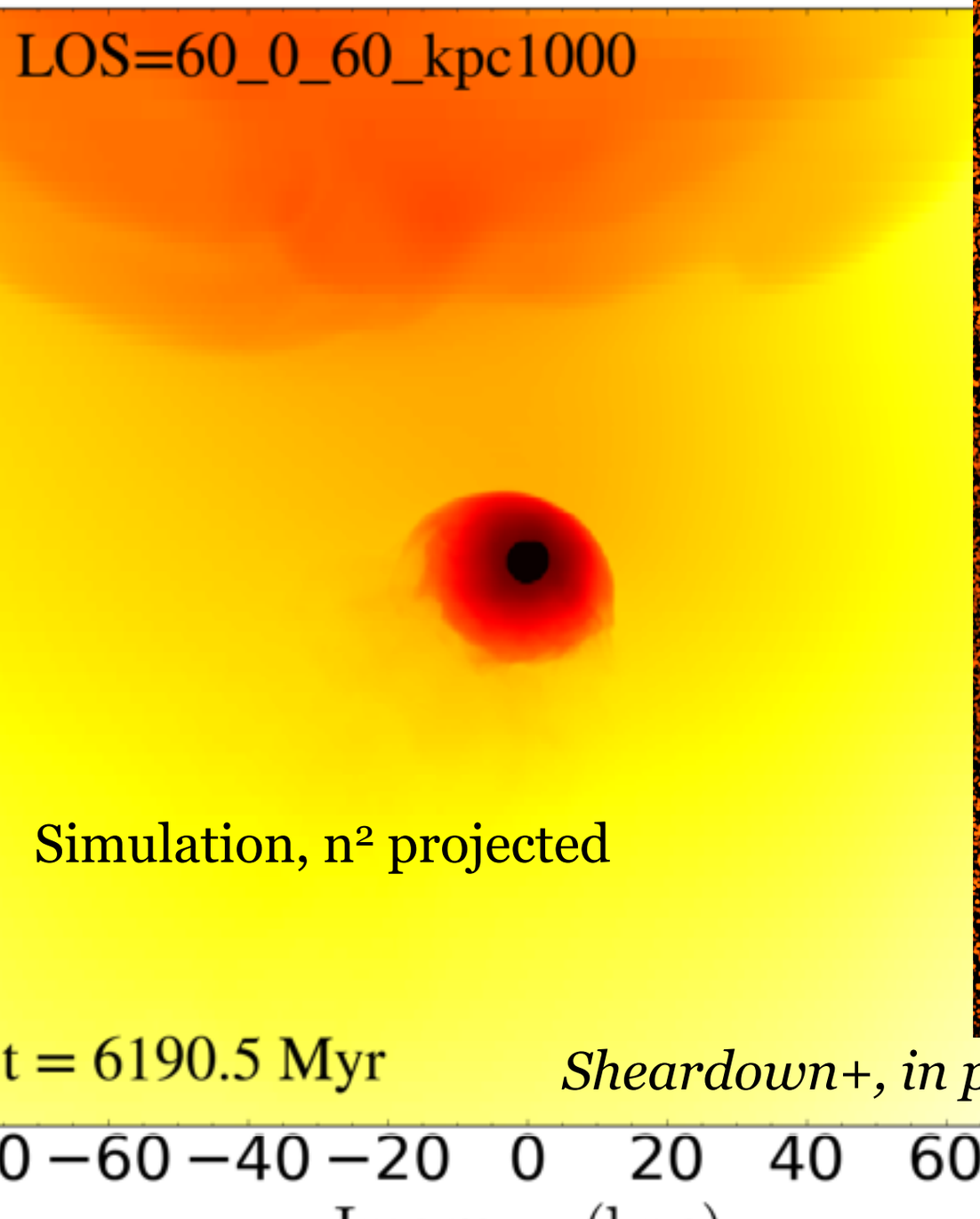
Sheardown+, in prep.

simple analogy applies for second infall

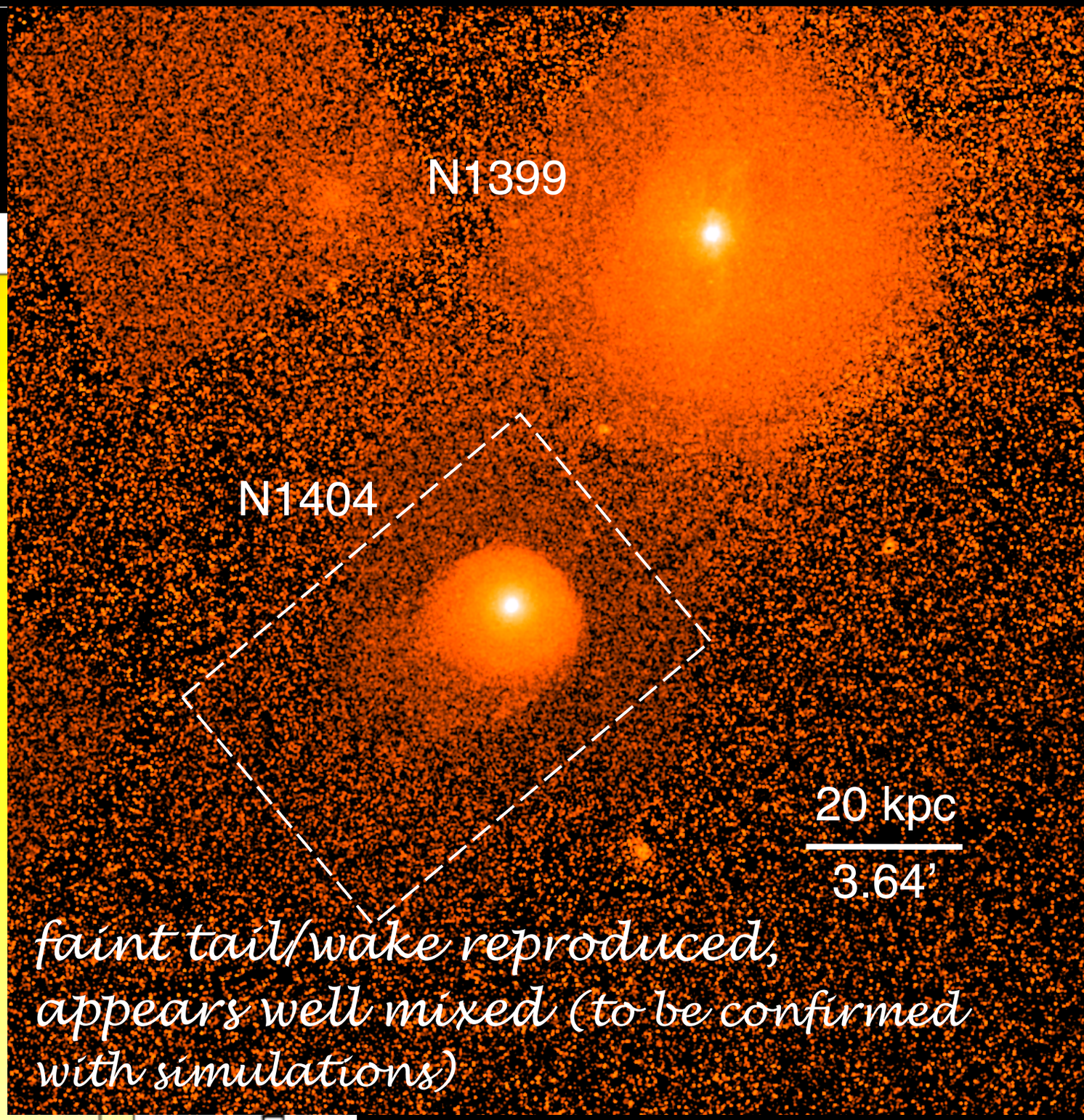


van Dyke - Album of Fluid Motion

NGC 1404 in Fornax



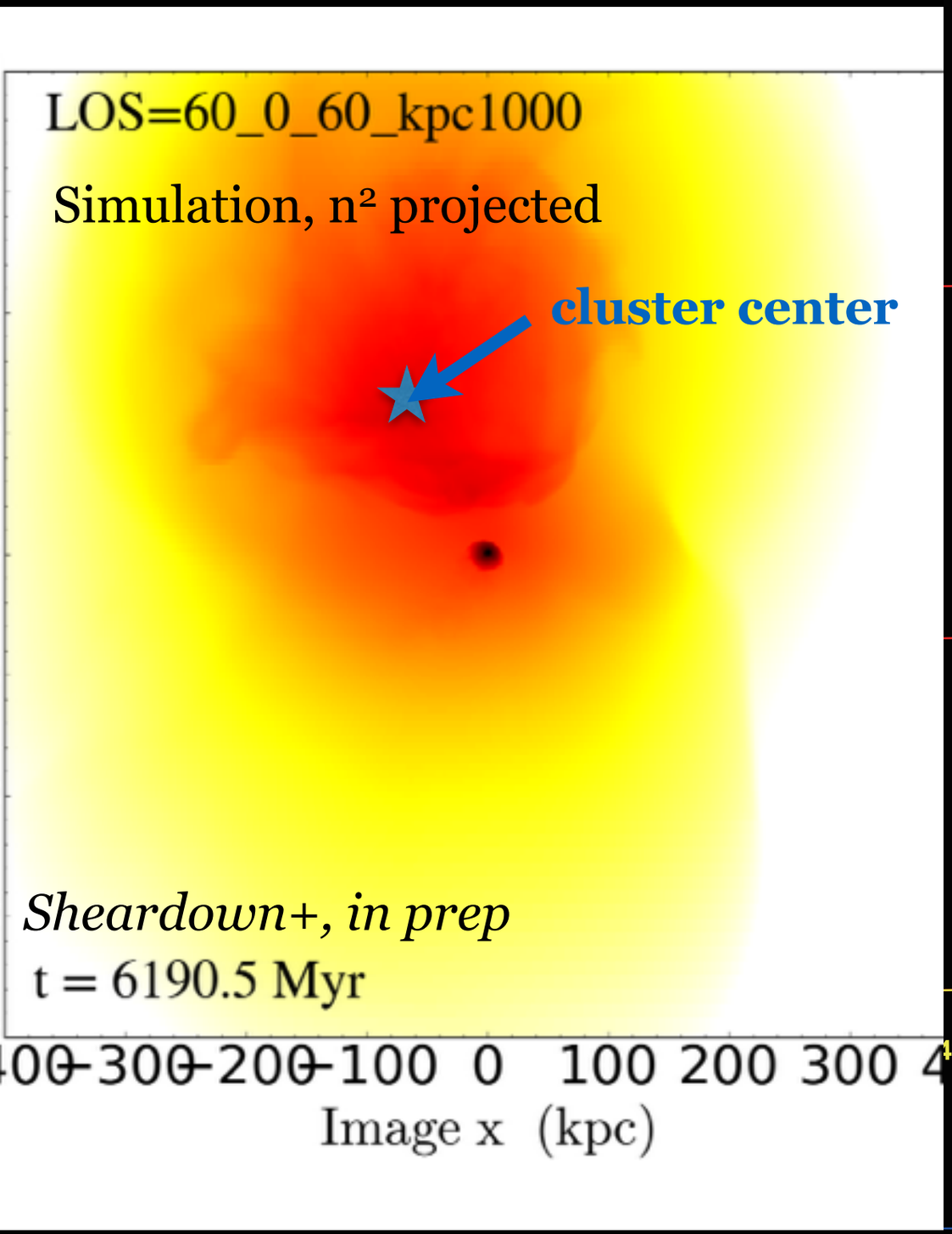
Sheardown+, in prep



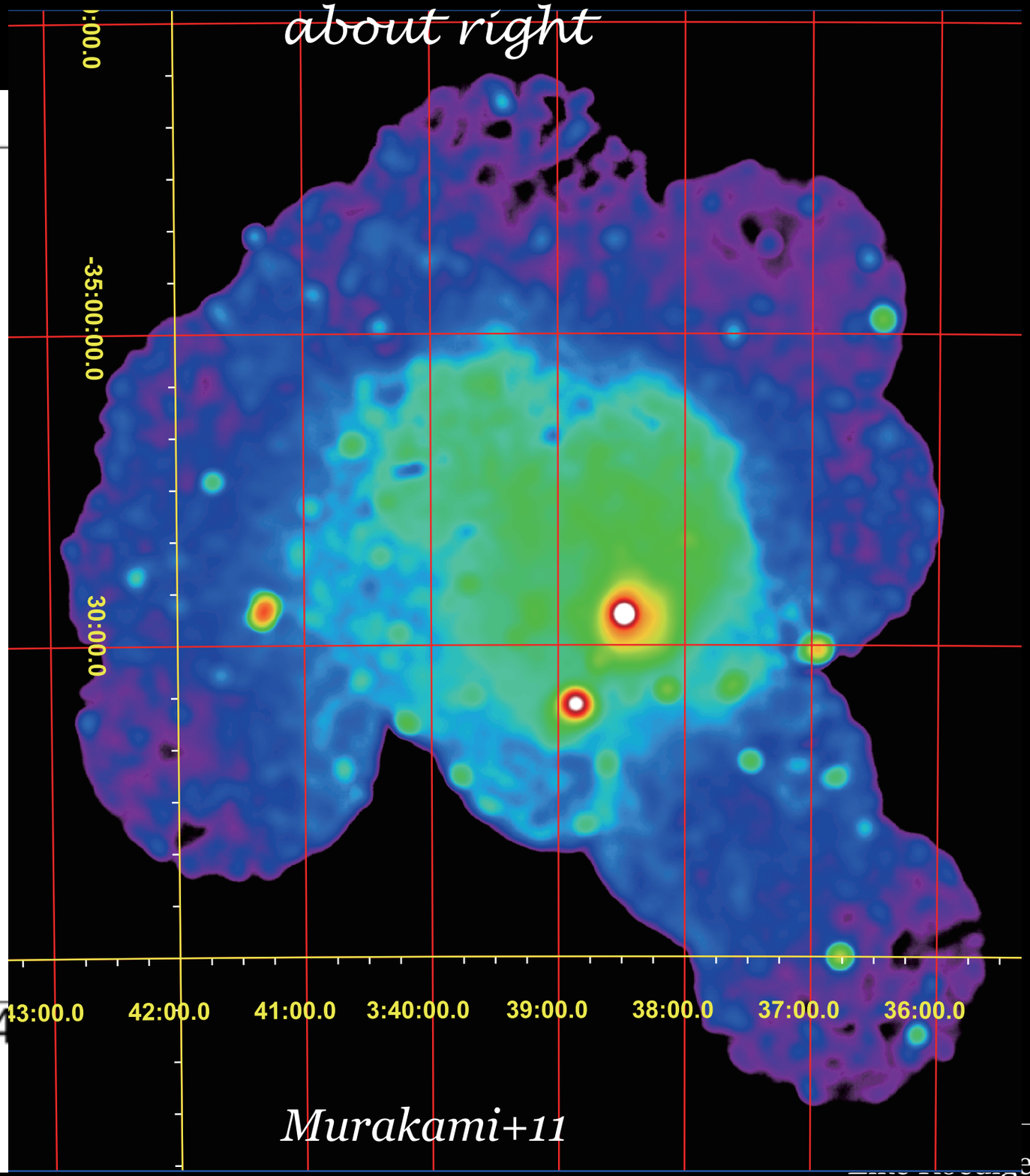
Su+16ab, in prep

Elke Roediger

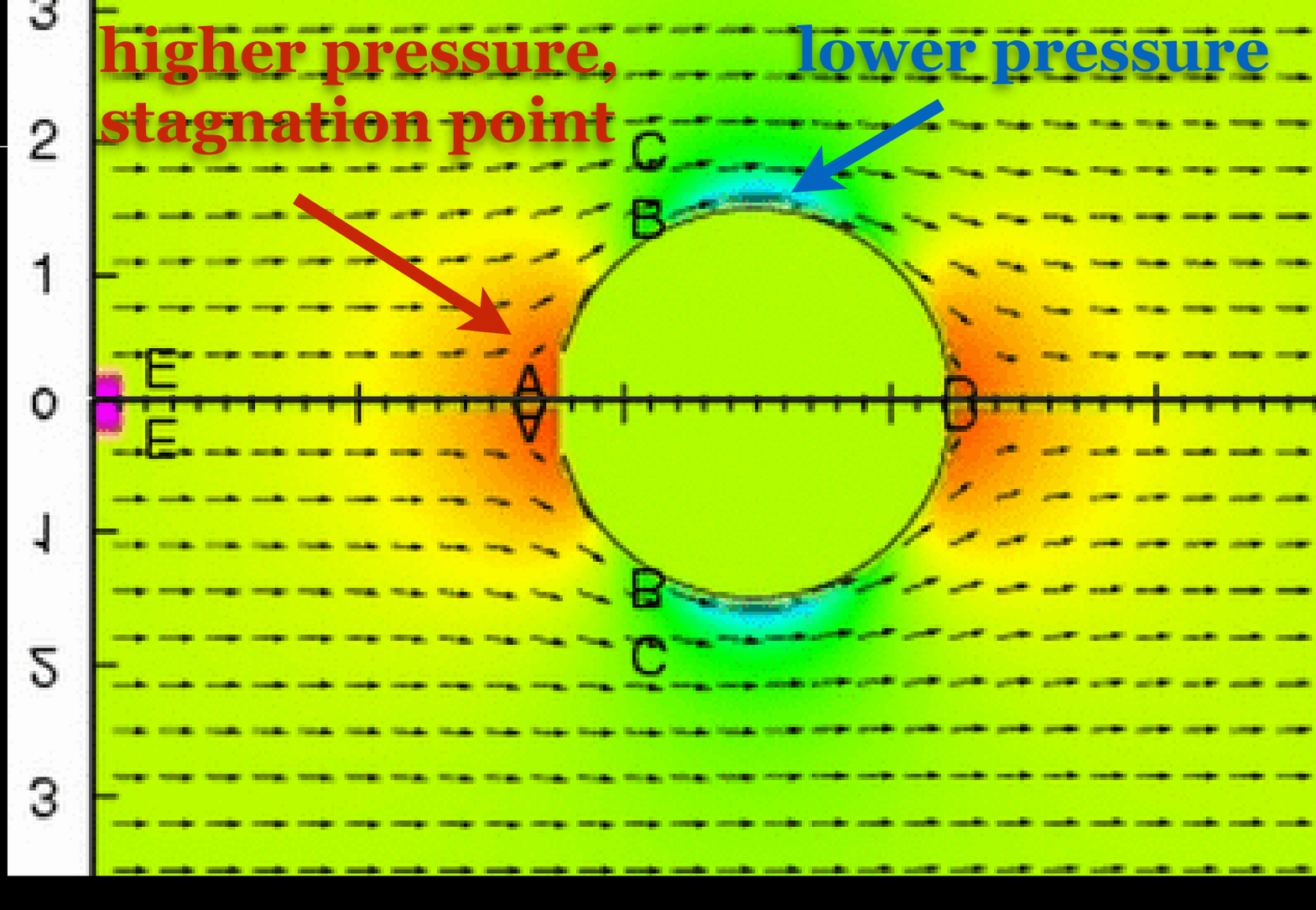
NGC 1404 in Fornax



cluster-scale asymmetry about right

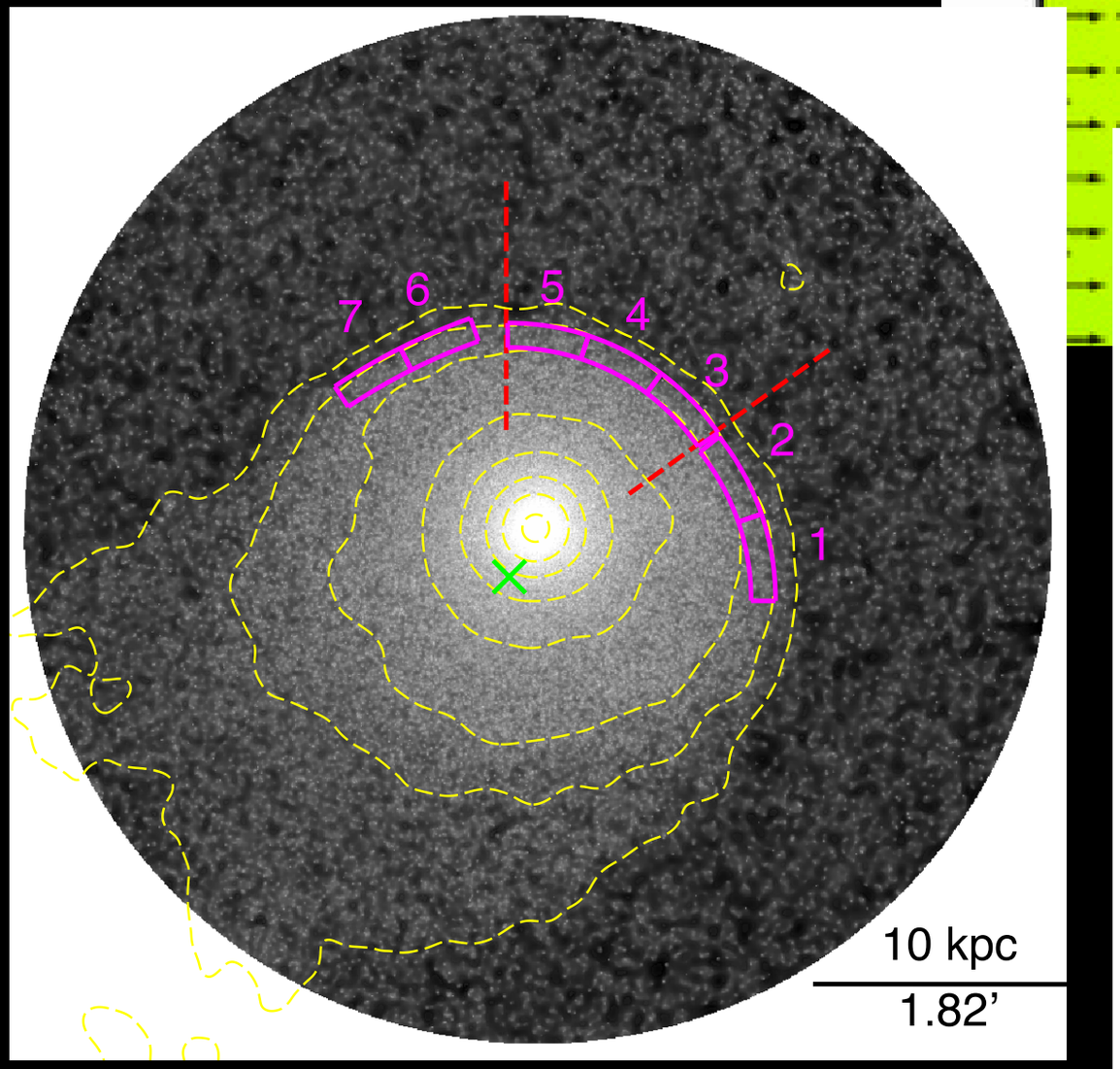


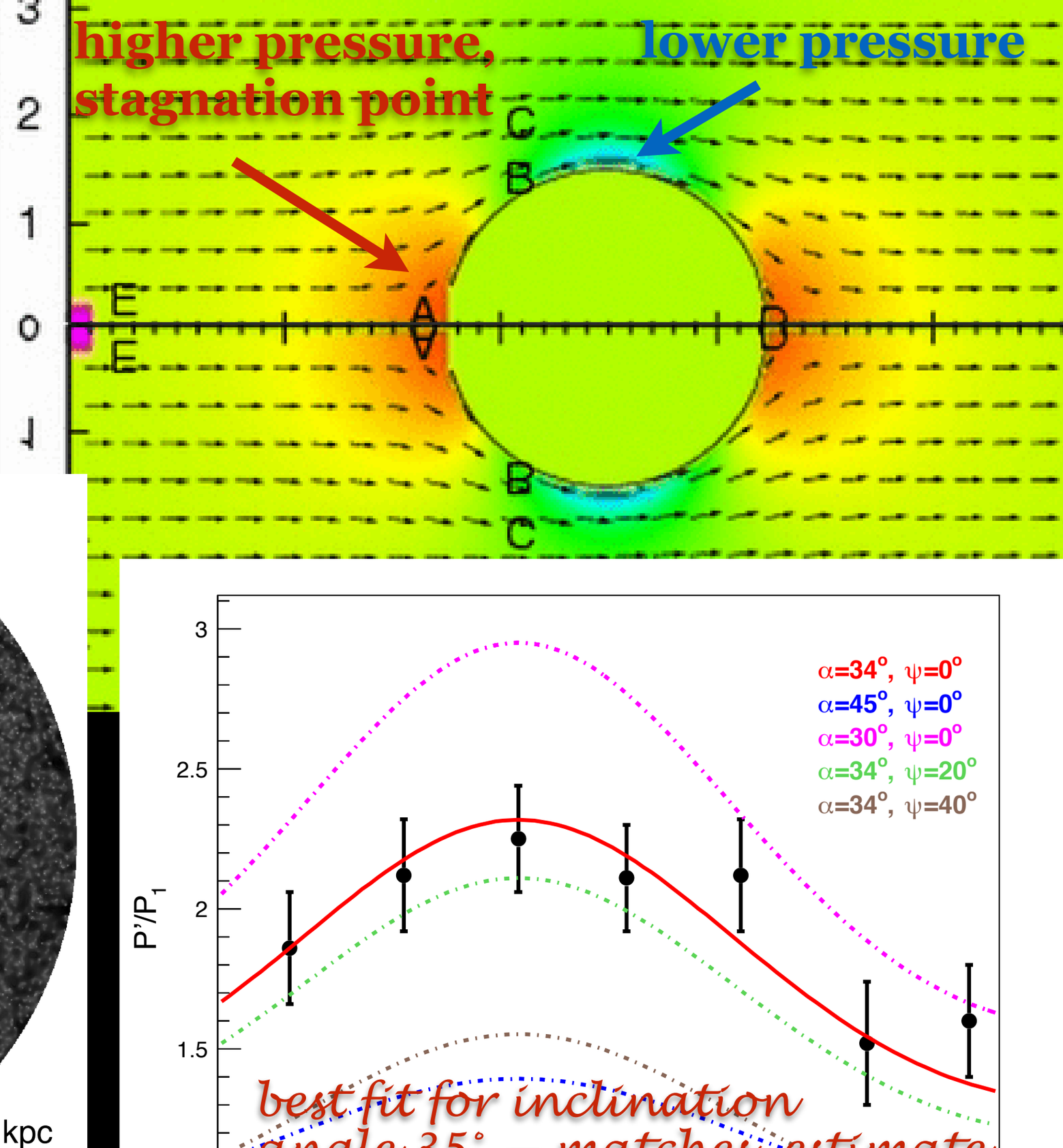
pressure distribution around a sphere in a flow



Elke Roediger

pressure distribution around NGC 1404





Su+16a, in prep.

Summary

- Pure hydro predicts characteristic observable features depending on infall stage:
  - first infall - long, bright, cool remnant tail; very long-lived, long, coherent far wake
  - outgoing - sloshing, odd “tail” directions
  - second infall - closest to “sphere in a flow” analogy, now wake is ideal for studying mixing

- explains many observed features by getting the dynamical context right, without invoking additional ICM physics

To understand observed signatures of ICM physics in individual objects, need to understand dynamics.