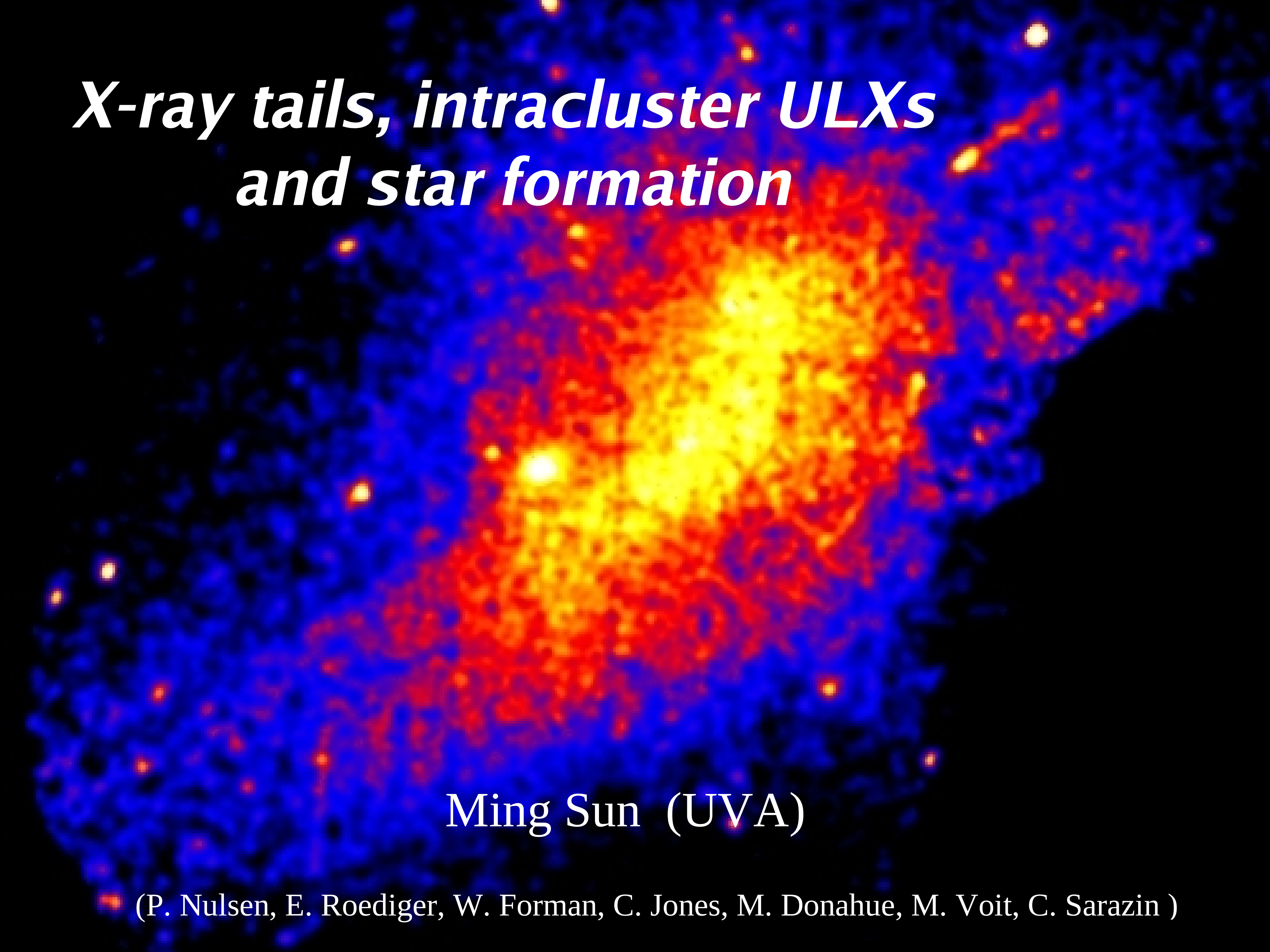
X-ray tails, intracluster ULXs and star formation



Ming Sun (UVA)

(P. Nulsen, E. Roediger, W. Forman, C. Jones, M. Donahue, M. Voit, C. Sarazin)

Outline:

Only discuss late-type galaxies in clusters

1) ESO 137-001 in Abell 3627
  (X-ray/Hα/H_2 tails, turbulence, intracluster ULXs and star formation, galaxy transformation)
  (New data: deep *Chandra*, *Gemini*, *Hubble* WFC3/ACS and SOAR)

2) General relation of gaseous trails

Why care?

1) Galaxy evolution and transformation, intracluster light

2) Multi-phase gas, similar to cool cores

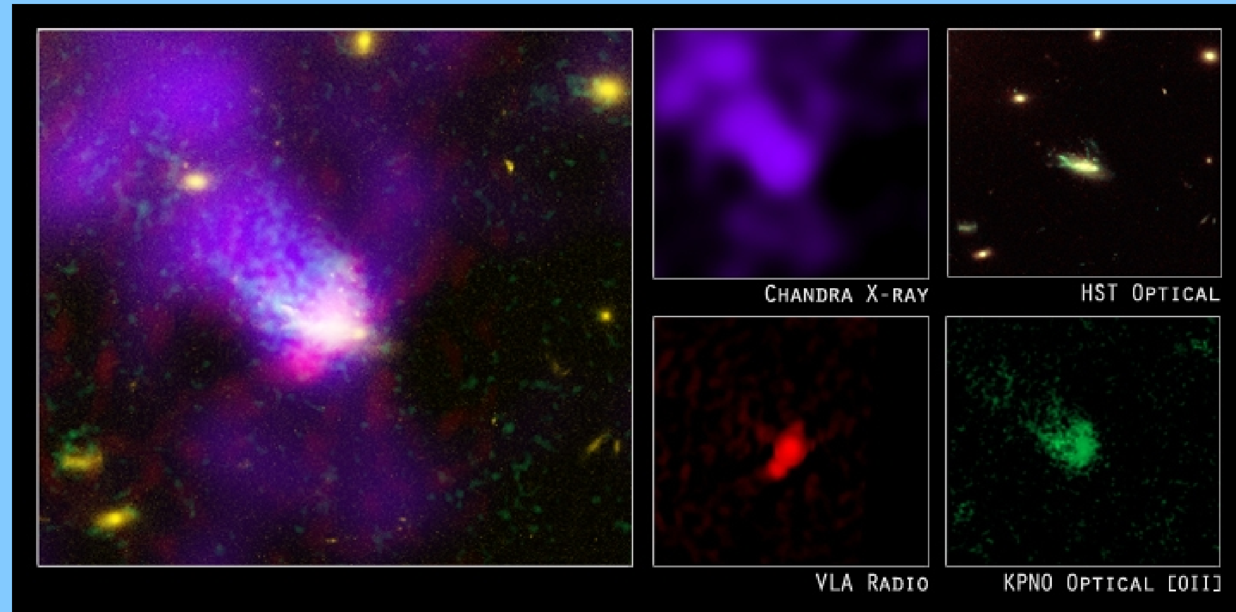
3) Probe ICM turbulence

Radio: HI emission or continuum --- to show the cold gas, B field
missing HI problem in the Virgo cluster
H-alpha: diffuse emission to link X-ray and HI gas; intracluster SF
MIR/FIR: Dust, PAH and molecular hydrogen
X-ray: X-ray tail originates from mixing of cold ISM and hot ICM?
give constraints on mixing, evaporation and the thermal history; abundance

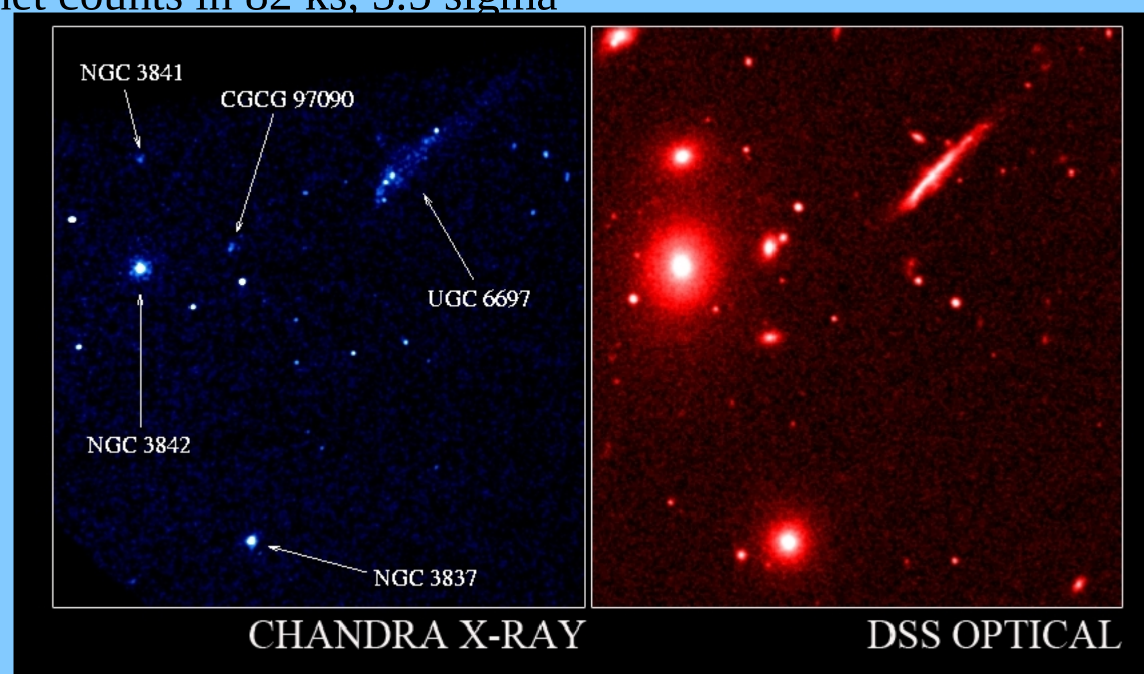
--- combine all to understand the interaction and the fate of the stripped ISM!

Interaction signature:
1) leading edge, easiest to see
2) tail
3) collisionless bow shock (not detected in galaxy scale yet !)

X-ray "tails" of late-type galaxies in clusters:
Wang et al. 2004; Sun et al. 2005



C153 in A2125 (z=0.247), Wang et al. 2004; Owen et al. 2006;
60 net counts in 82 ks, 5.5 sigma

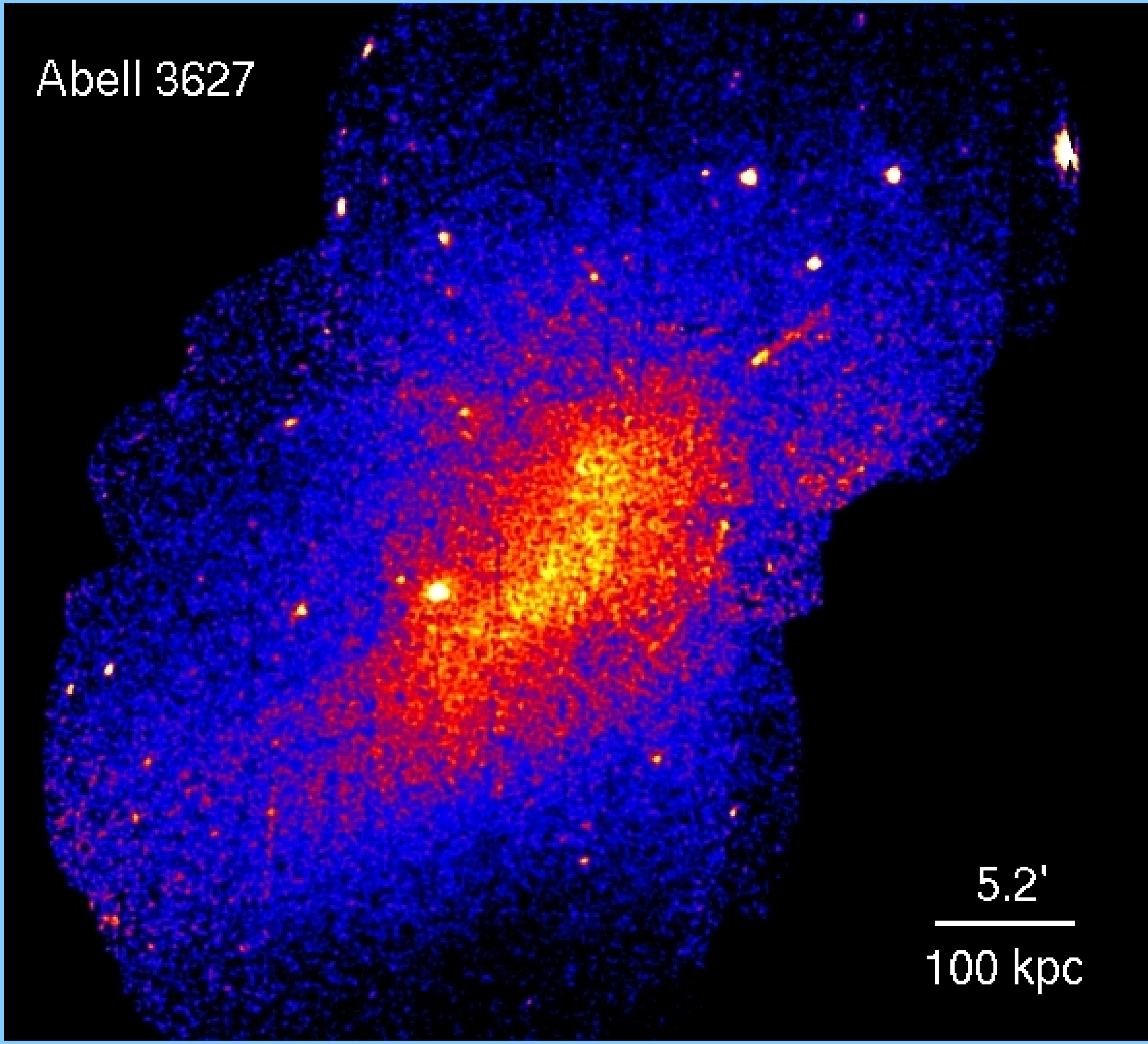


UGC 6697 in A1367 (z=0.021), Sun & Vikhlinin 2005

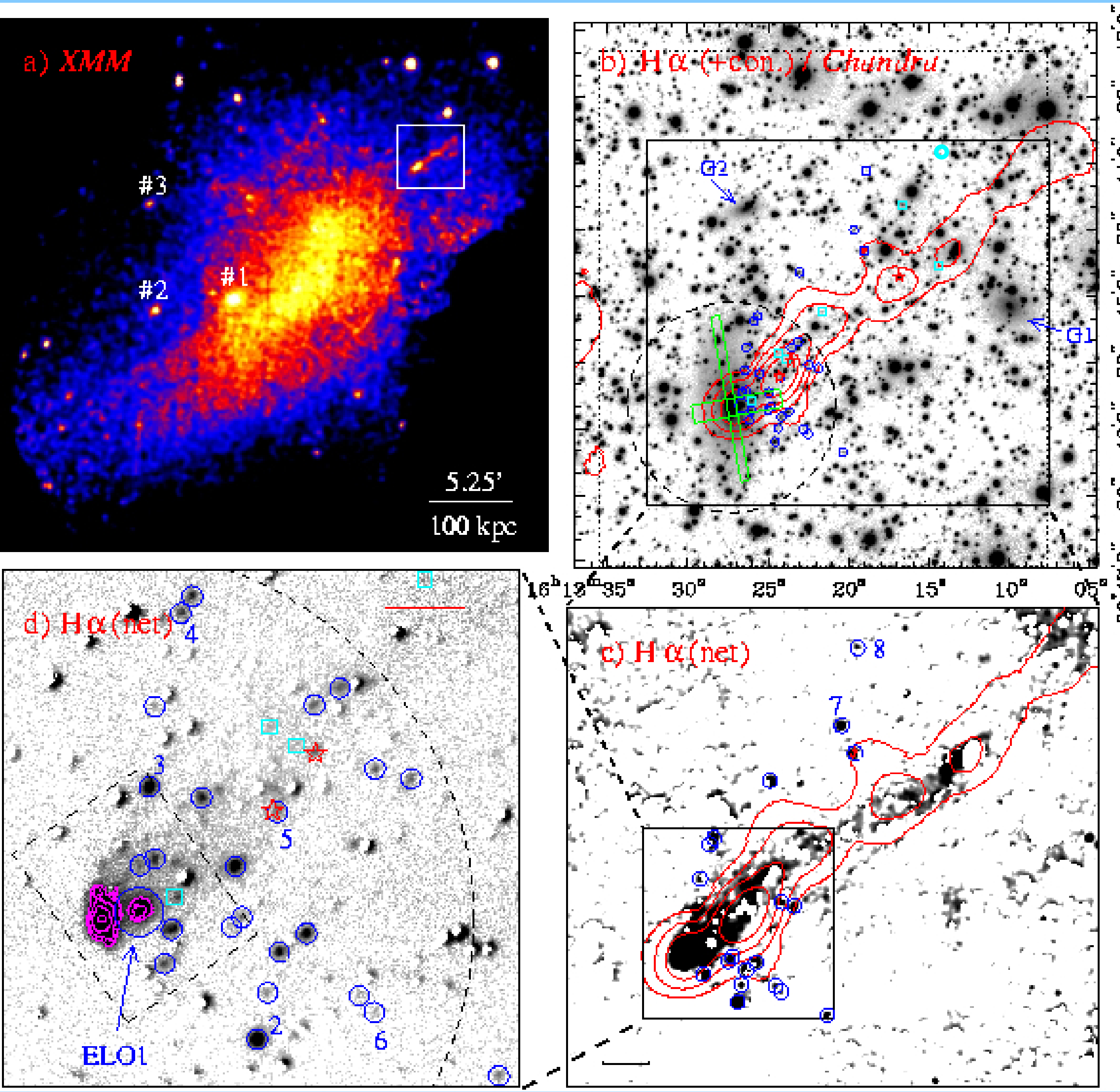
<u>The first unambiguous extended X-ray tail is ...</u>

ESO137-001 (z=0.0154) in A3627 (6 keV)

• A 70 kpc tail with a 10:1 length-to-width ratio
• A blue starburst galaxy (SFR: 1-2 $M_\odot$/yr) with a stellar mass of ~ 0.07 M*
• 0.7 keV tail, the brightest X-ray tail of a cluster late-type galaxy



Sun et al. 2006 (*Chandra* + *XMM*)



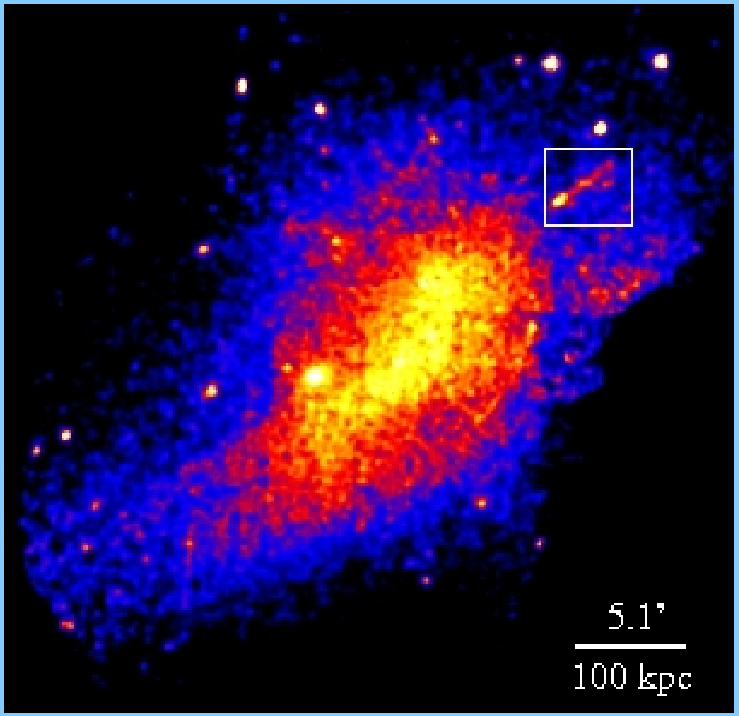
A 40 kpc Hα tail

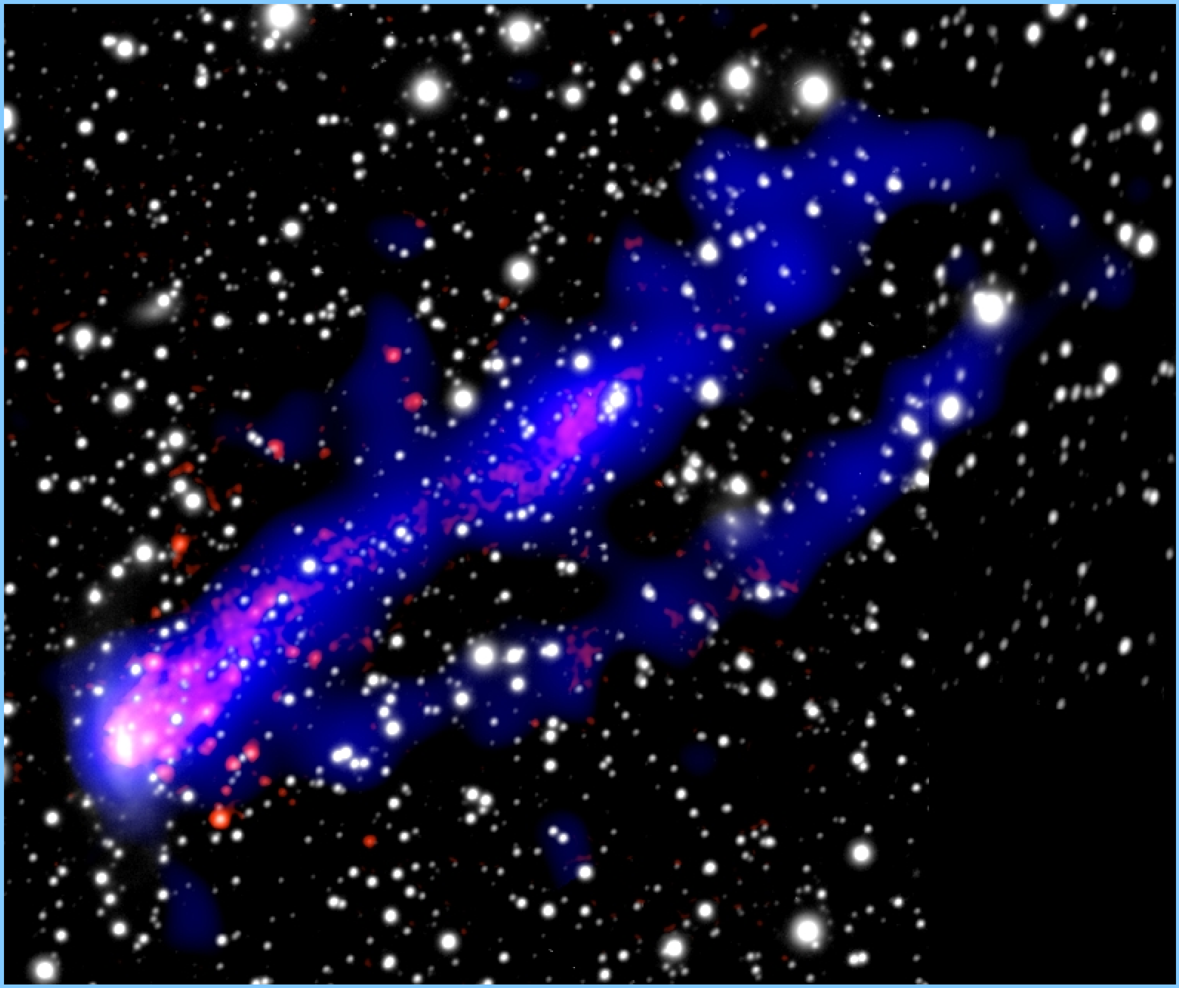
35 emission-line objects with a bow-like front, downstream of the galaxy, SFR~0.6 $M_{\odot}$ / yr

Little residual Hα nebula (0.9 kpc x 1.5 kpc in radius)

Sun et al. 2007

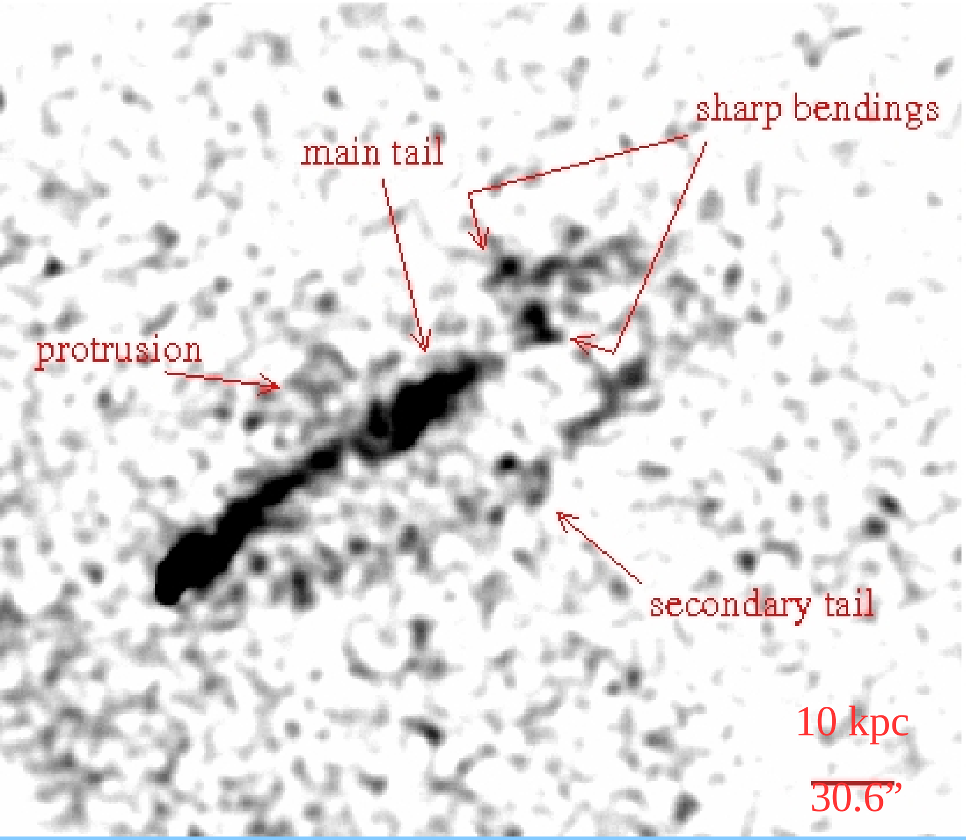
A new 140 ks *Chandra* observation (PI: MS) reveals...

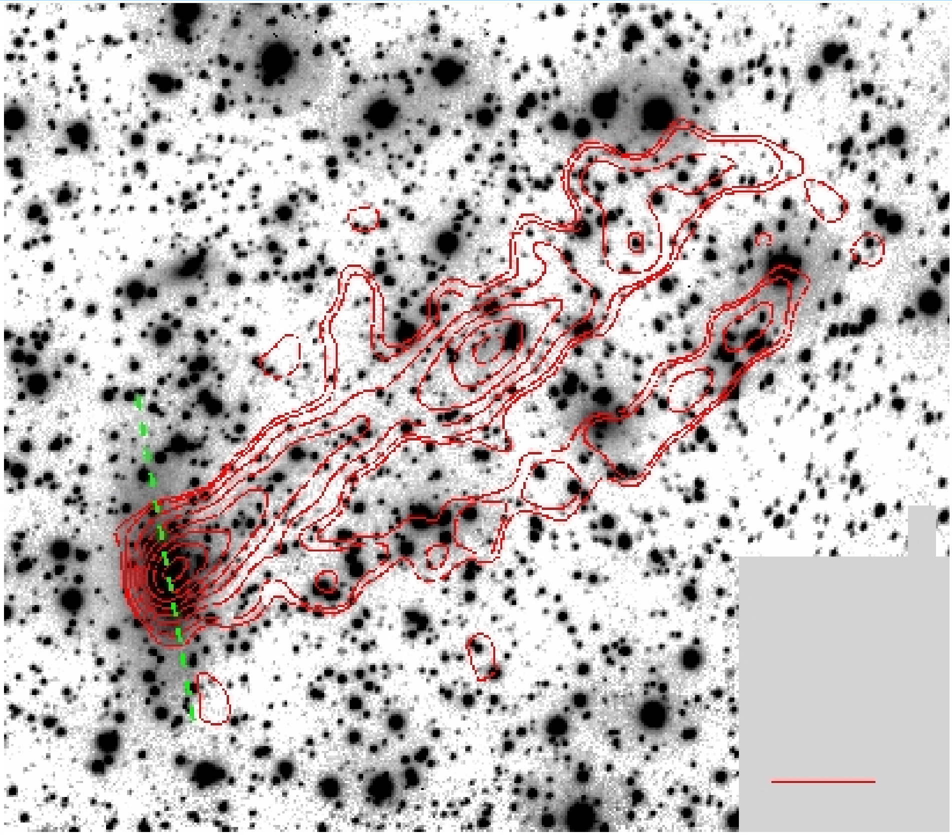




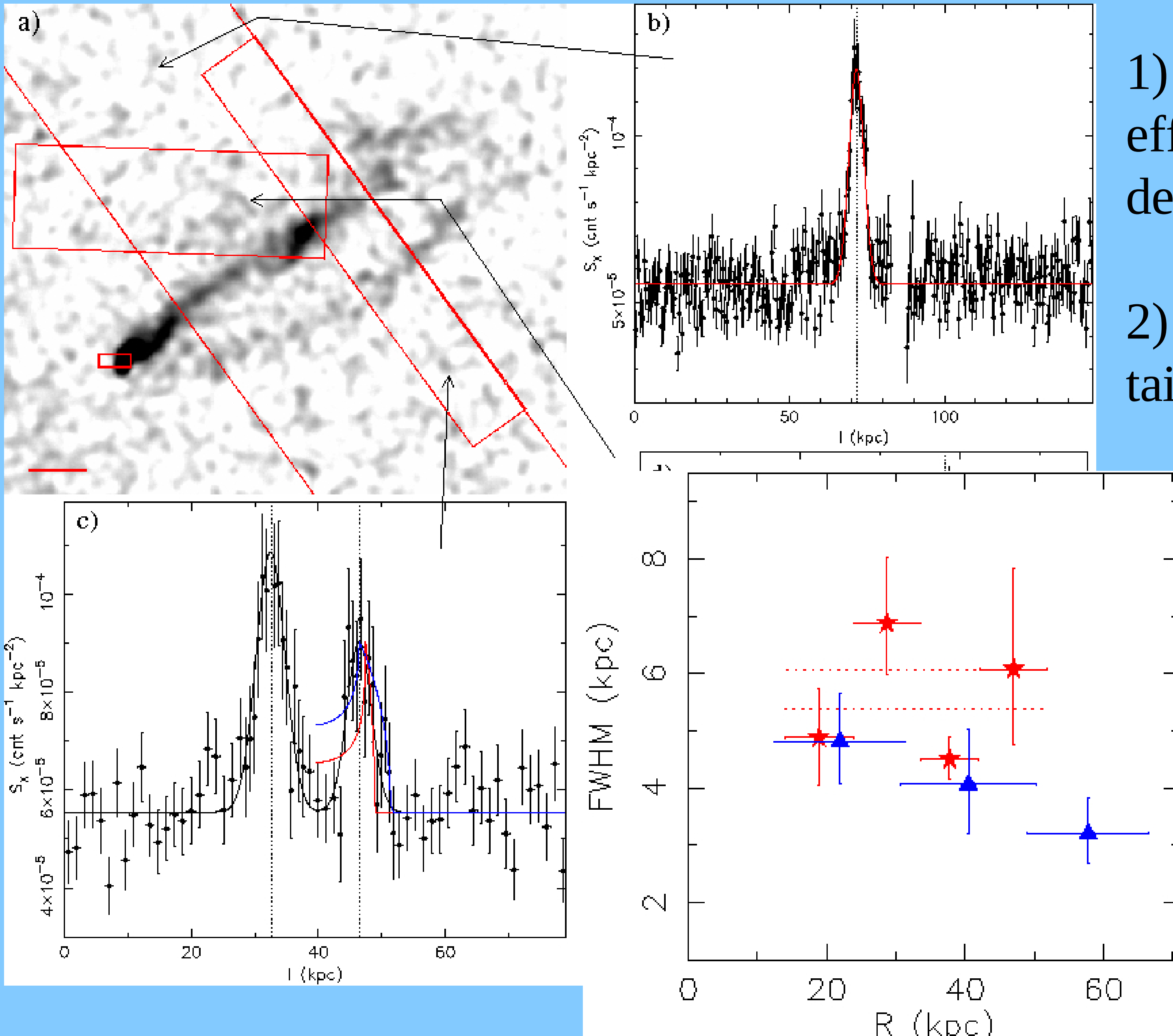
(Sun et al. to be submitted)

~ 4100 counts (0.5-3 keV) from the diffuse gas, ~ 82% from the tail
--- the first spatially spectroscopy for tails of a cluster late-type galaxy



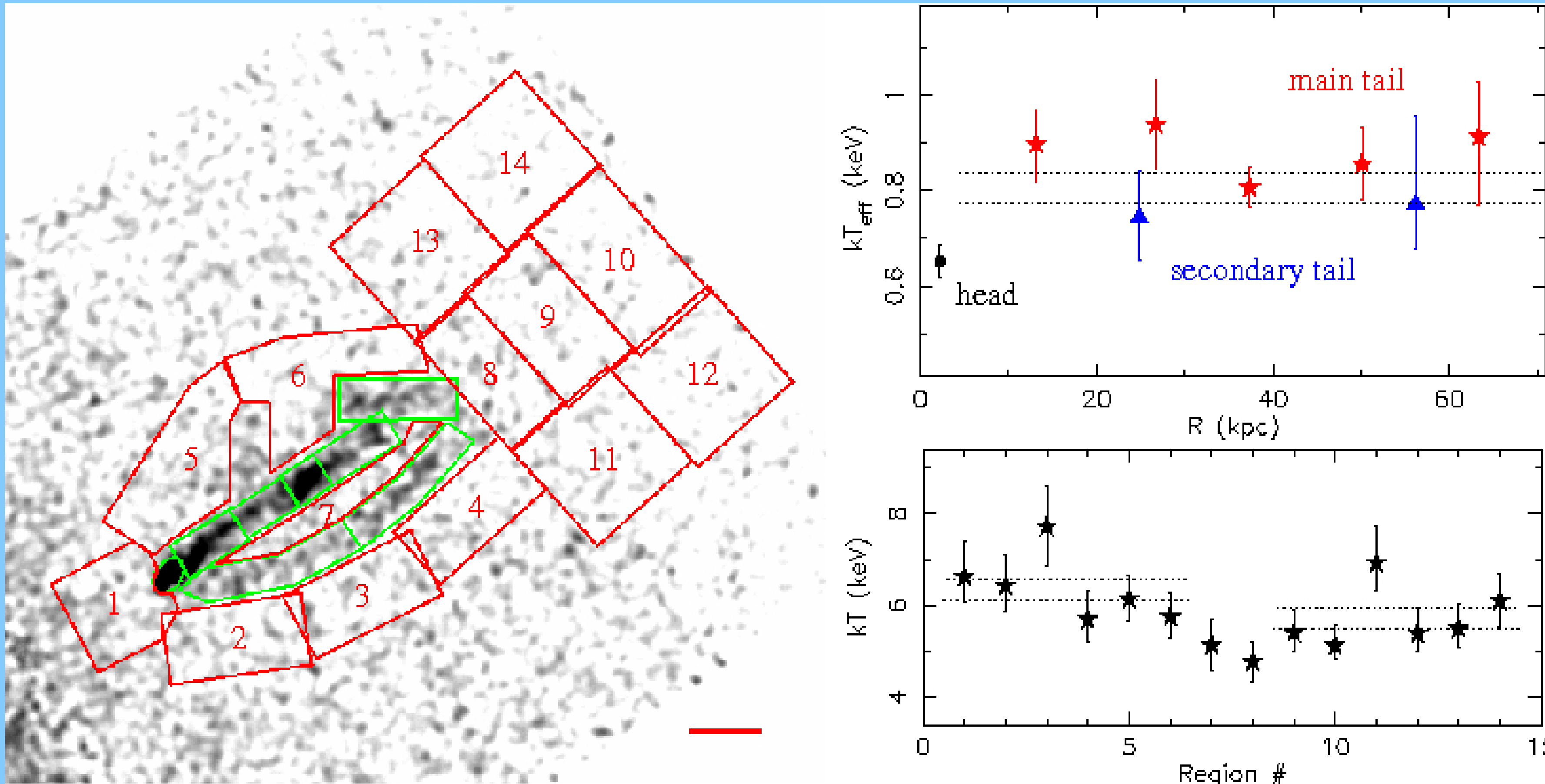


The second tail is ~ 2.1 fainter than the primary one;
The angular extent of the whole tail system: ~ 4.1' or 80 kpc.



1) Not a projection effect (two tails are detached)

2) Width of both tails changes little



1) Little effective heating within ~ 50 Myr (if v = 1500 km/s) !
(mass-weighted temperature: $T_{eff} \approx T_{ICM} / (1+X)$, $X=M_{ISM} / M_{ICM}$)

2) Abundance of the X-ray tails
< 0.1 solar if 1T model, but can be ~ solar if 2 T or DEM models

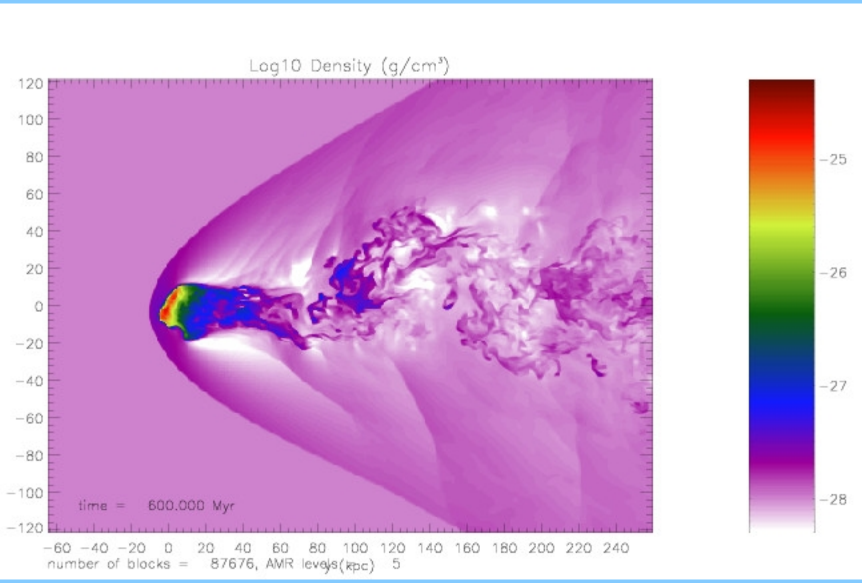
Inconsistency with simulations:

1) double tail

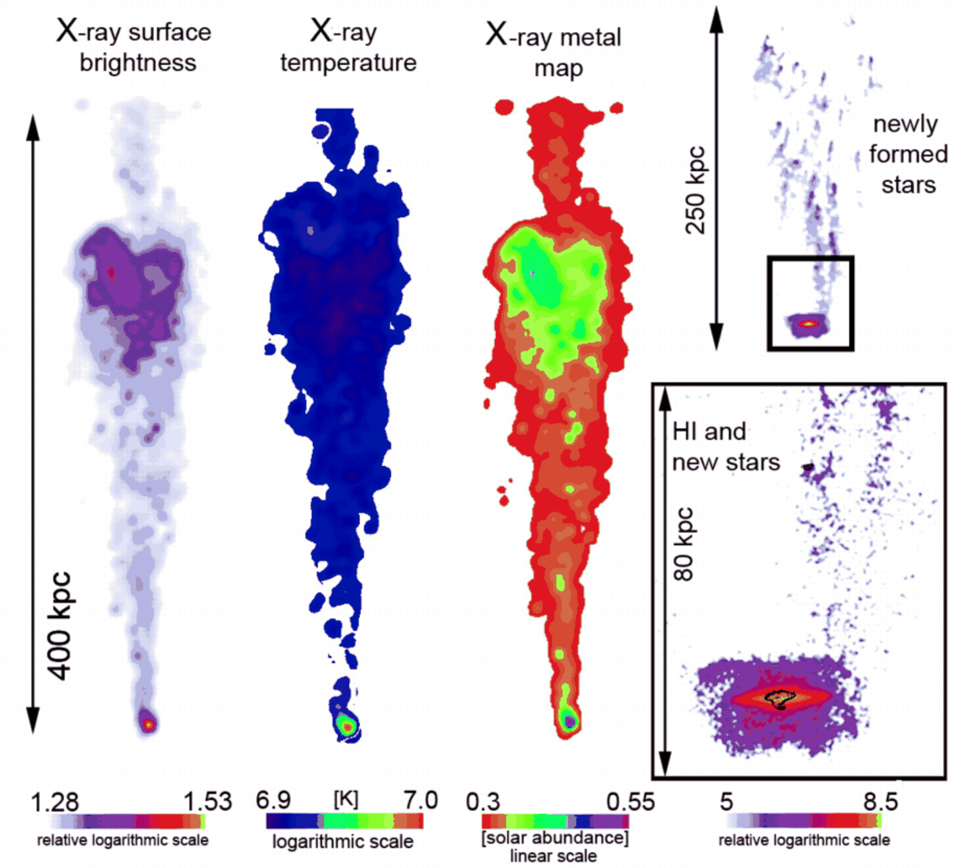
2) width ($\propto d^{1/2\text{-}1/3}$ for laminar or turbulent flow)

3) temperature structure

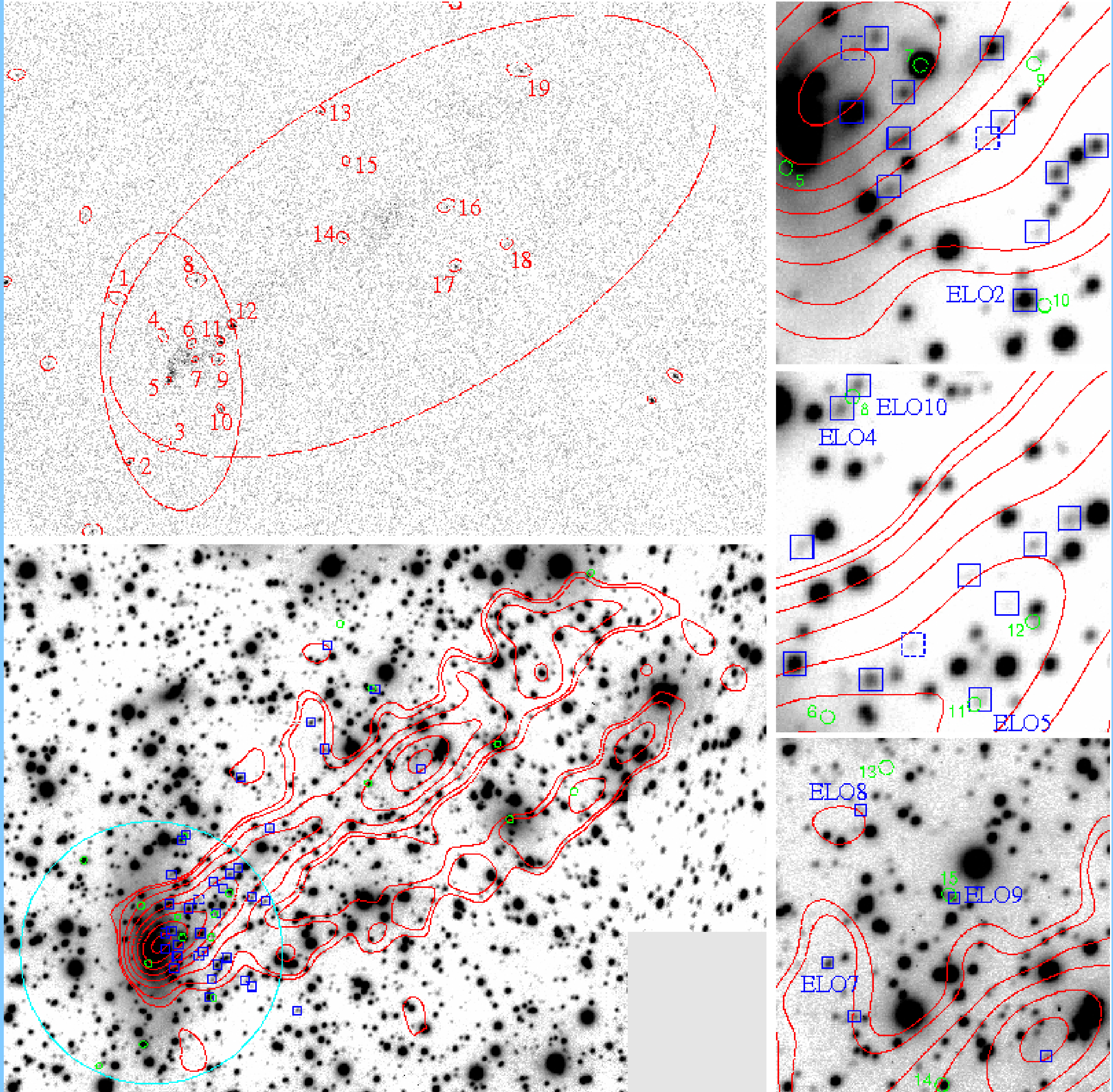
4) SFR (>~ 10% from Kapferer et al. 2009 vs. >~ 1% observed)



Roediger et al. 2006



Kapferer et al. 2009

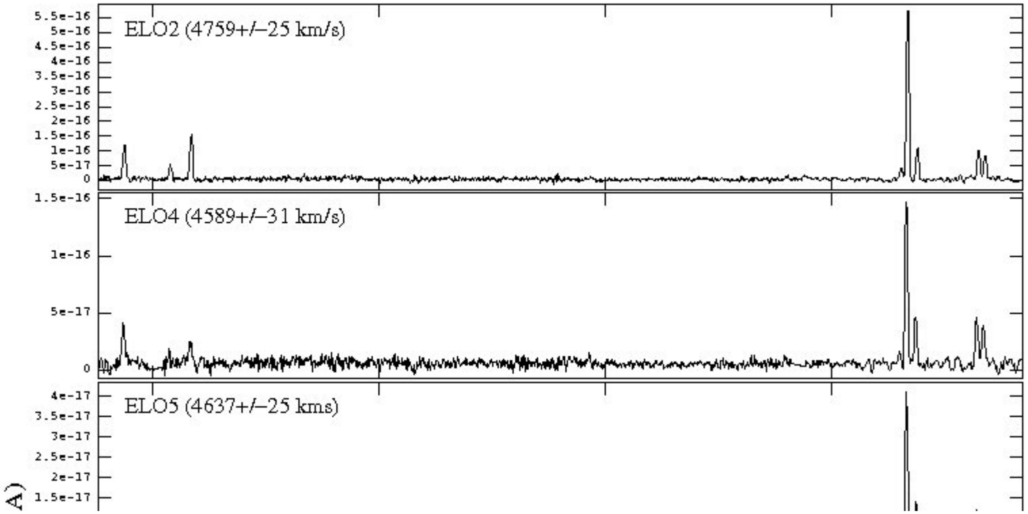


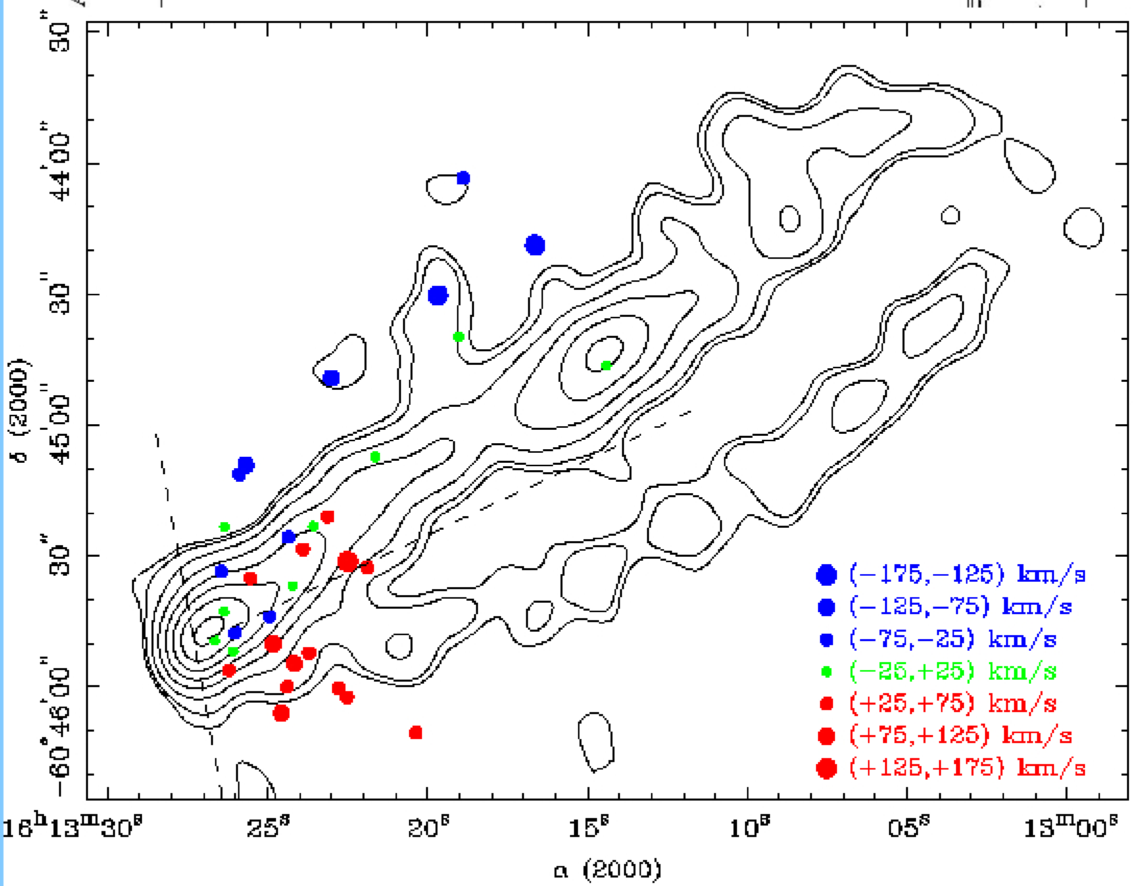
Intracluster ULXs!

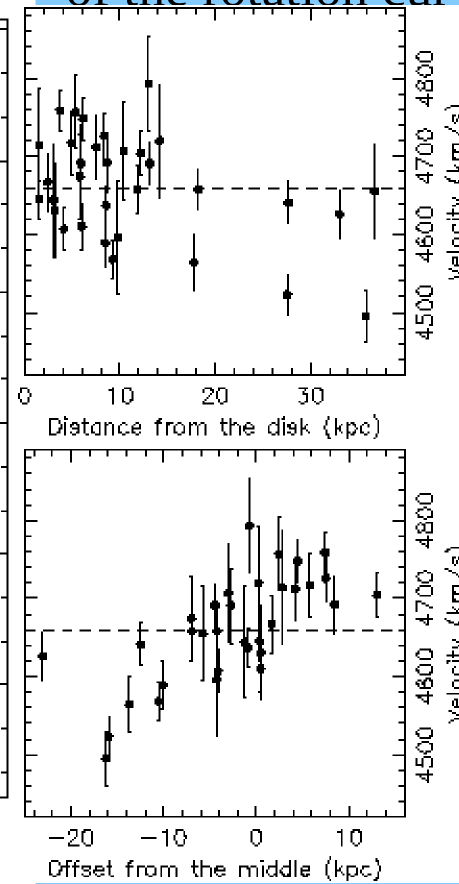
6 X-ray point sources (12 – 410 counts) are close to the confirmed HII regions (<~ 1.3 kpc), with 0.3 – 10 keV luminosities of $5 \times 10^{38} - 2.5 \times 10^{40}$ ergs s^{-1} --- ULXs (up to 39 kpc from the nucleus)

Gemini GMOS data covered 33 objects

Initial results:
1) All 33 targets are confirmed to be HII regions in A3627
2) Velocity map has the imprint of the rotation curve



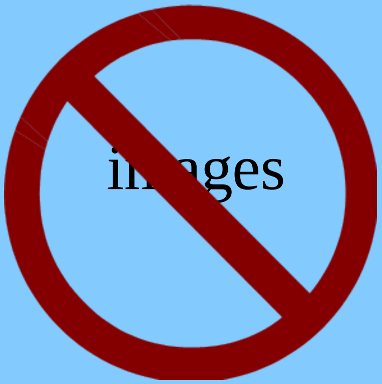




mall range

urbulence?

HST data (F275W/WFC3, F475W/ACS and F814W/ACS)



1) A single galaxy with spiral arms (NO smooth tidal features at both sides of the galaxy)

2) Intracluster HII regions are resolved into blue star clusters, which (and narrow trails) are also found in other places downstream.

3) Dust extinction around the center and skewed to downstream --- in sharp contrast with the smooth upstream

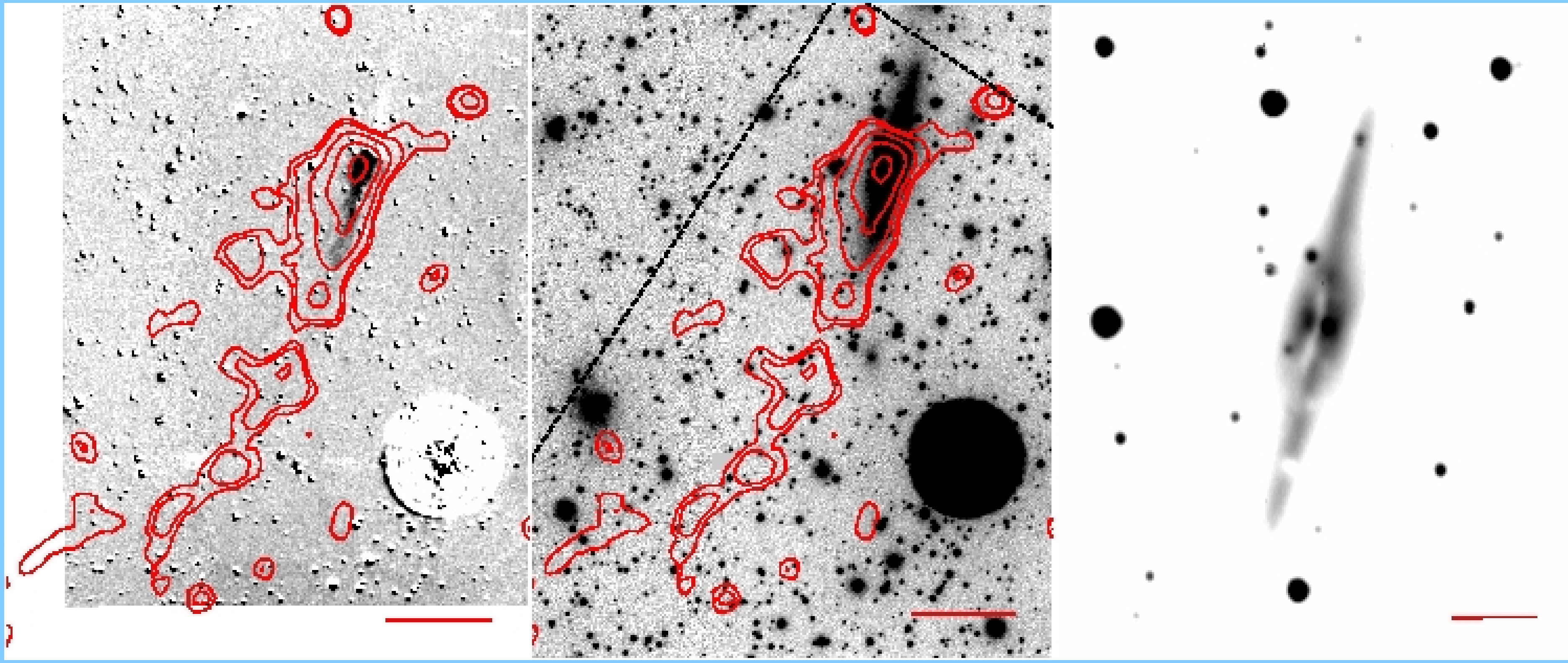
What we now know about ESO 137-001:

1) Double X-ray tails (~ 80 kpc), at least one Hα tail (~ 40 kpc) and at least one H_2 tail (>20 kpc) --- stripping + mixing (wide range of temperatures)
2) For X-ray tails: little change on the tail width (esp. the secondary tail), little change on the tail temperature (~ 0.8 keV), X-ray total mass: ~ $10^9 f^{1/2} M_\odot$.
3) **At least** 33 HII regions downstream of the galaxy (up to 40 kpc in projection)

   total stellar mass >~ $10^7 M_{solar}$ (remember t_{HII} is a few Myr)

   --- stripping of the ISM not only contributes to the ICM, but also adds to the intracluster stellar light through subsequent SF (and also intracluster XRBs) --- for the fist time !
4) Bear constraints on ICM turbulence (from morphology and kinematics)
5) At the same time, building up of a central bulge and losing gas quickly

   --- "blue cloud" region → the low-mass end of the "red sequence"?

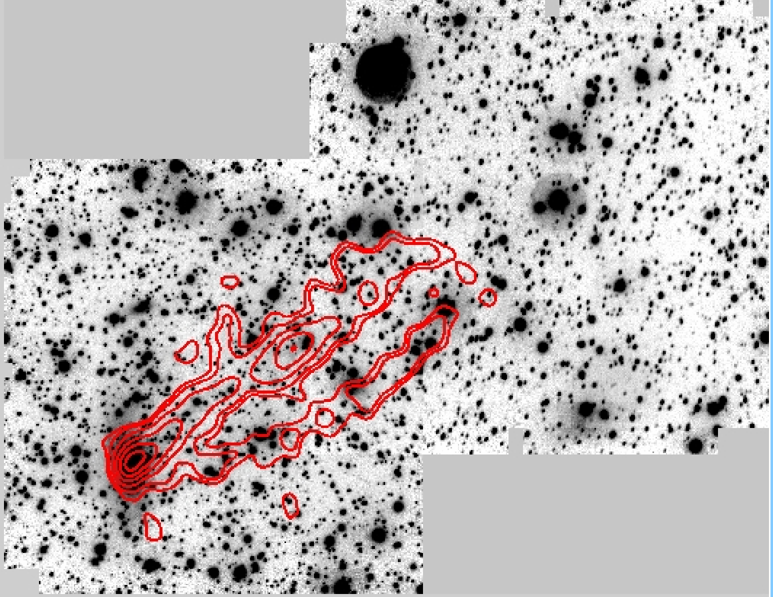


ESO 137-002 also has an X-ray tail (40 kpc at least) and asymmetric Hα emission

ESO 137-001 & ESO 137-002: 6.1' (or 116 kpc) separation; radial velocity difference: 1061 km/s

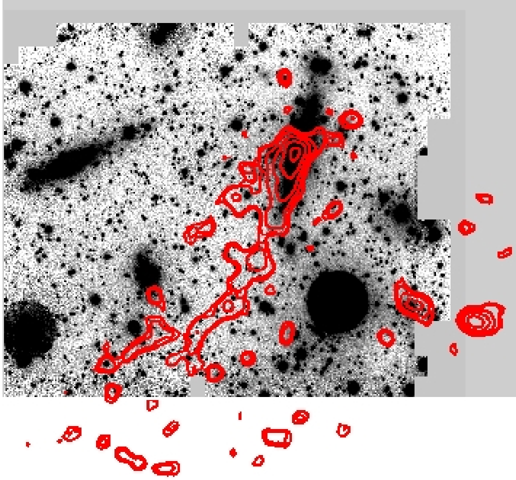
<u>~ 2 keV gas</u> (Z=0.12 solar), half as bright as ESO137-001; M ~ 2 – 5 x10^8 $M_\odot$.

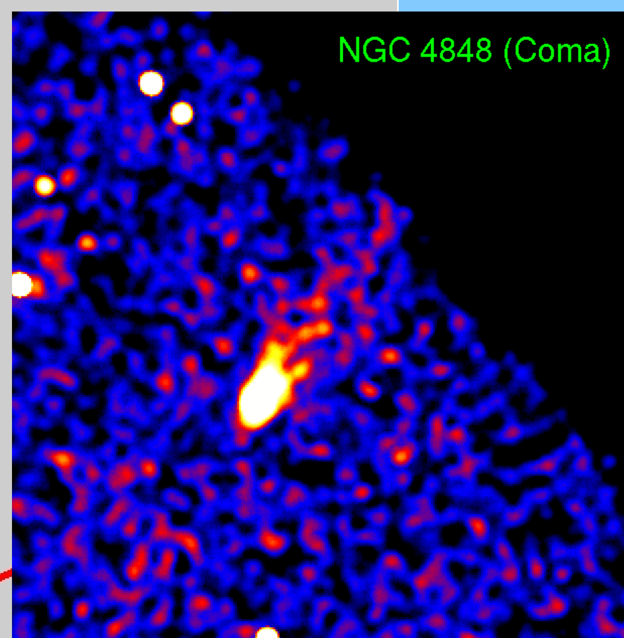
NO high-EW HII regions detected! --- a more advanced stage?

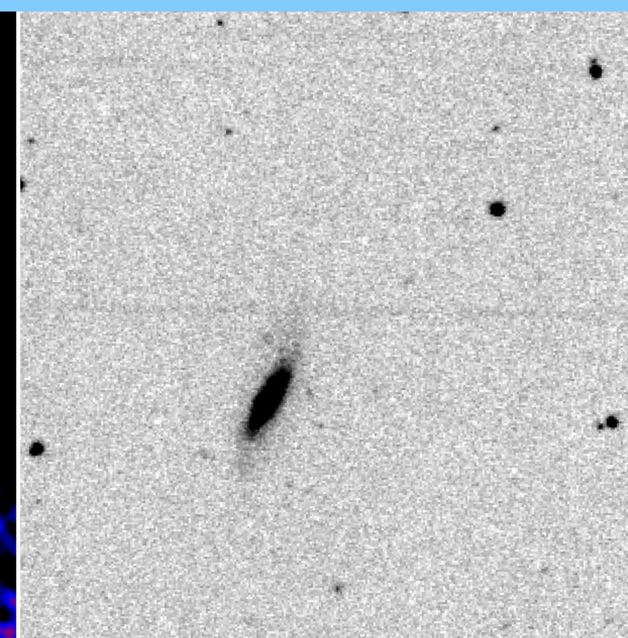


More X-ray tails...

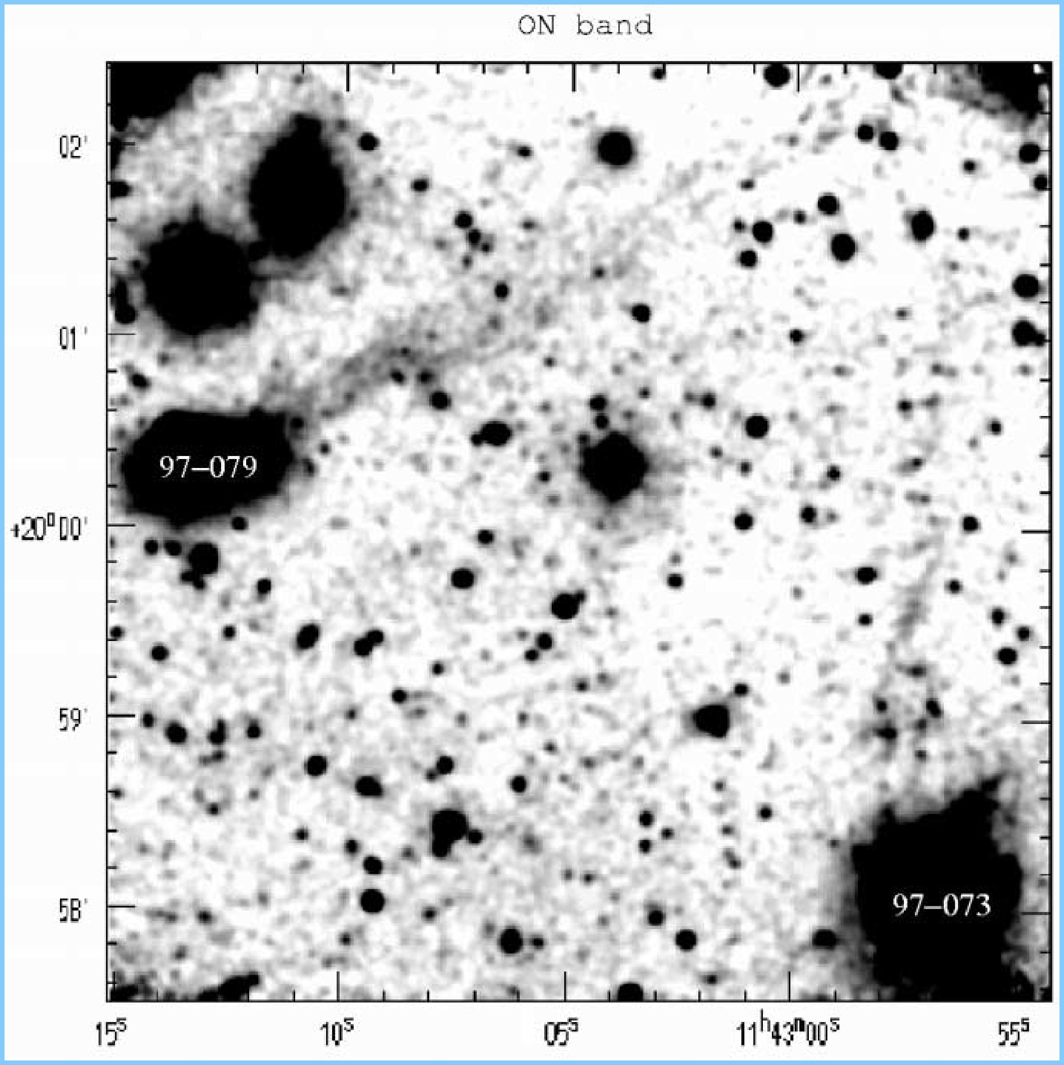
ESO 137-002 in A3627



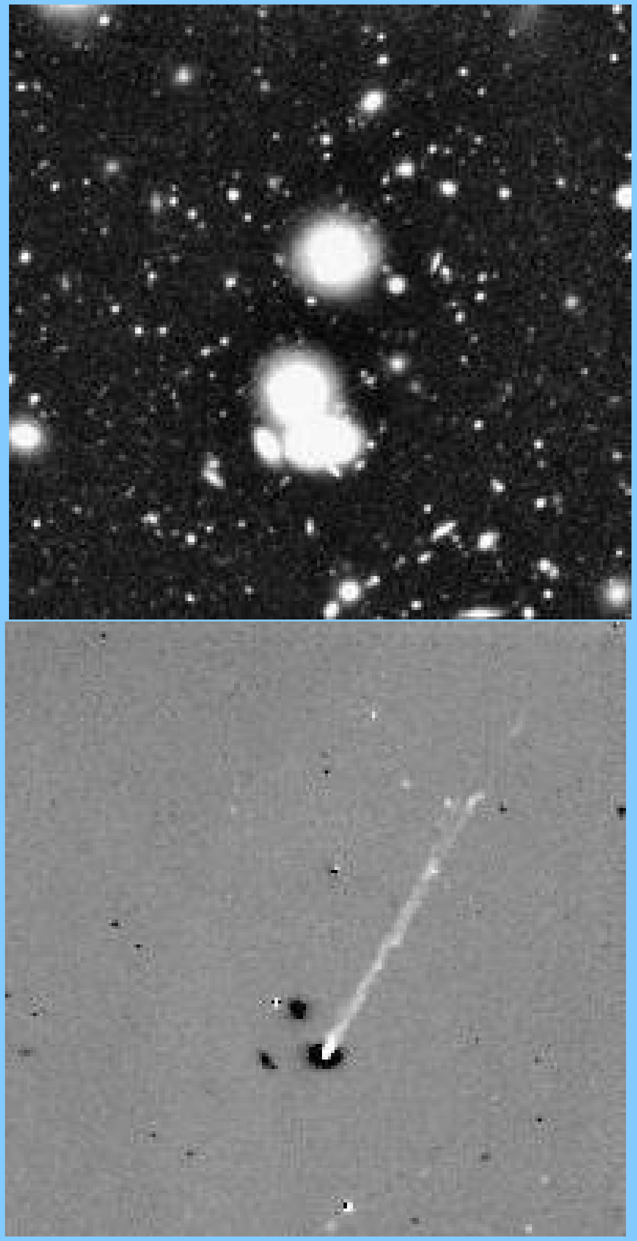




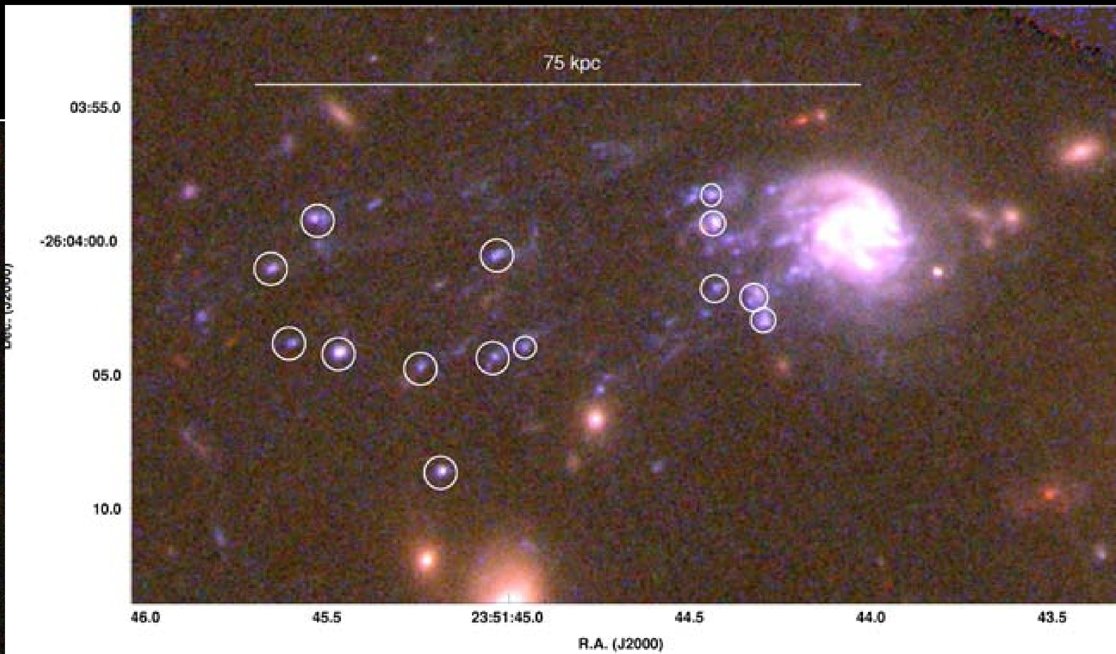
More Hα tail in clusters

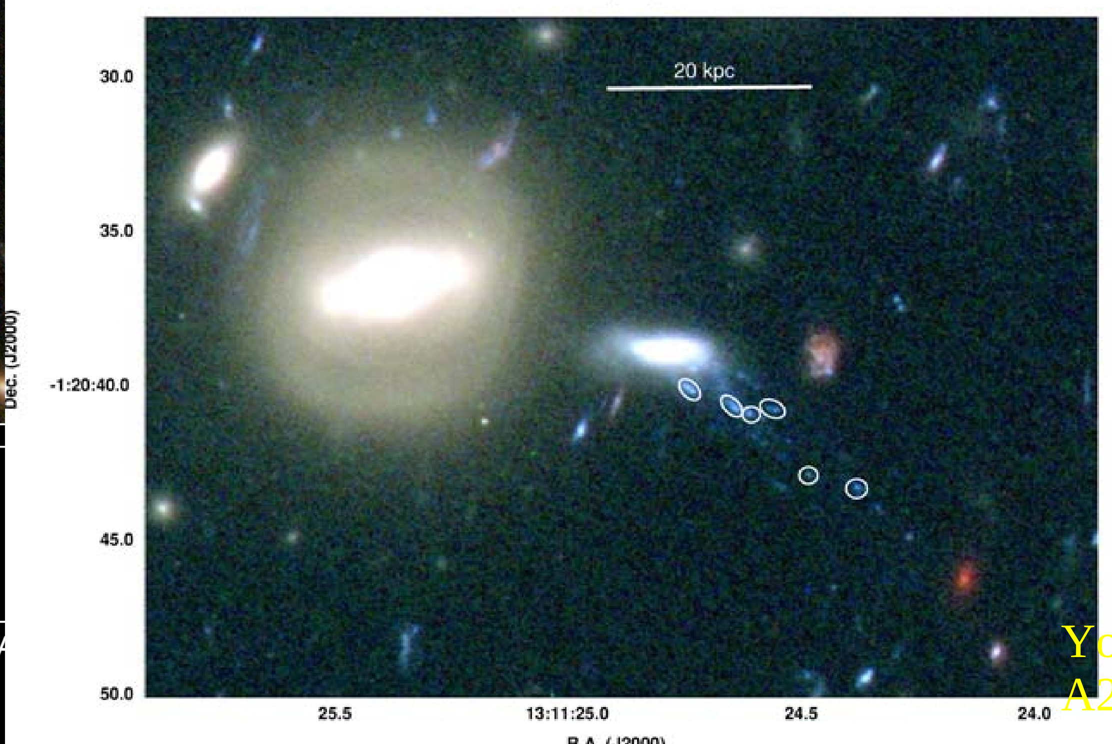


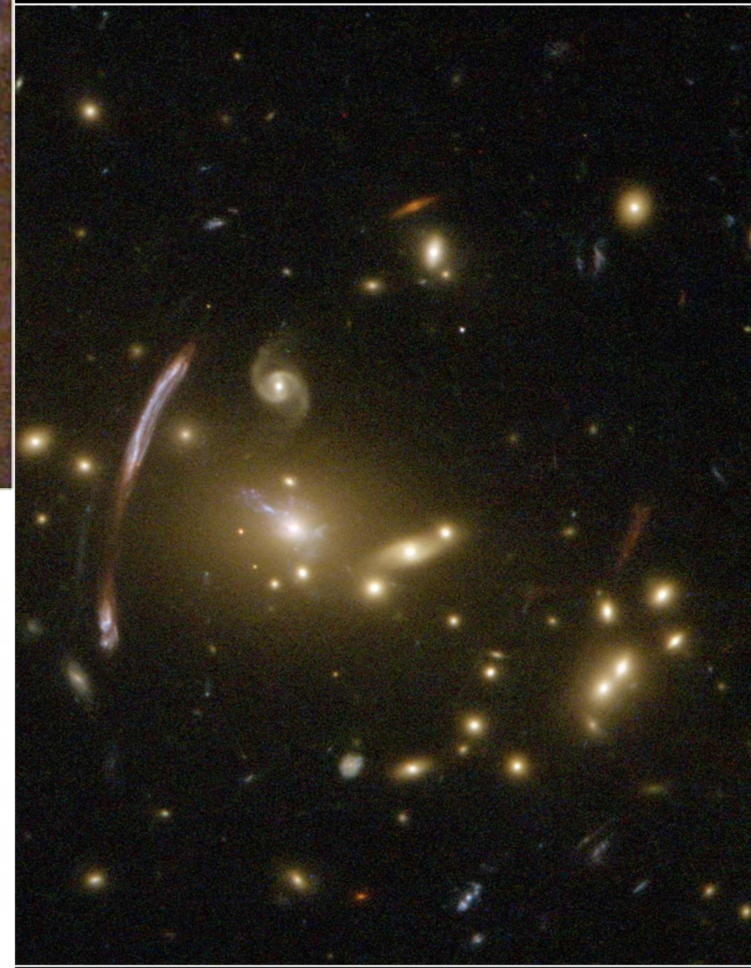
2 starbursts in A1367, Gavazzi et al. 2001



A post-starburst D100 in Coma, Yagi et al. 2007







2667

WFPC2

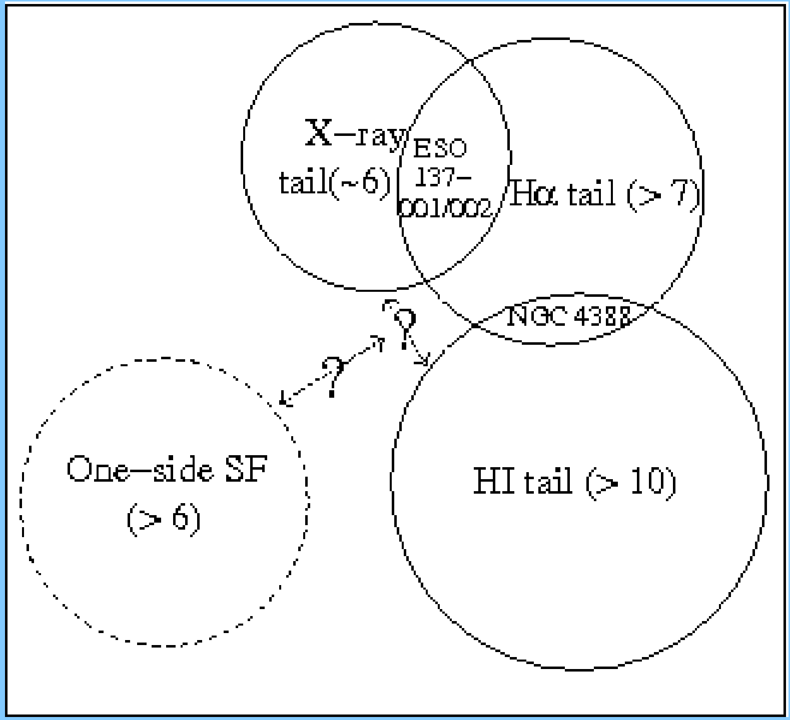
NA

STScI-PRC07-12

Young star clusters in
A2667 and A1689, Cortese et al. 2007

Questions:

* What is the connection of tails in different bands?
(HI, Hα, X-rays and MIR/FIR?)
Will all HI tails have X-ray and Hα tails?
(no significant X-ray tails of late-type galaxies reported in Virgo clusters so far)
a) Cover small number of late-type galaxies with enough depth
b) Projection
c) T_{eff} from mixing is <~ 0.3 keV   d) low pressure



Conclusions:

1) Unambiguous X-ray, H_2 , Hα and HI tails of late-type galaxies do exist in clusters. Need to understand their connection, energy transfer etc.

2) Stripping of cluster late-type galaxies appear more intriguing than what we thought!

3) No sign of heating/evaporation for ESO137-001's tail but ESO137-002's seems to be heated (significant mixing/heating happens at 0.1 – 1 Gyr?); need to understand the X-ray spectra in mixing

4) Ram-pressure-stripping-removed ISM can form stars and high-mass X-ray binaries (and ULXs!) downstream (>~ 1% SF efficiency; if reach ~ 10%, a significant contribution to the intracluster light!), while most stripped gas is mixed with the ICM.