Star formation in the brightest cluster galaxies and the intracluster space

Ming Sun
(University of Virginia)

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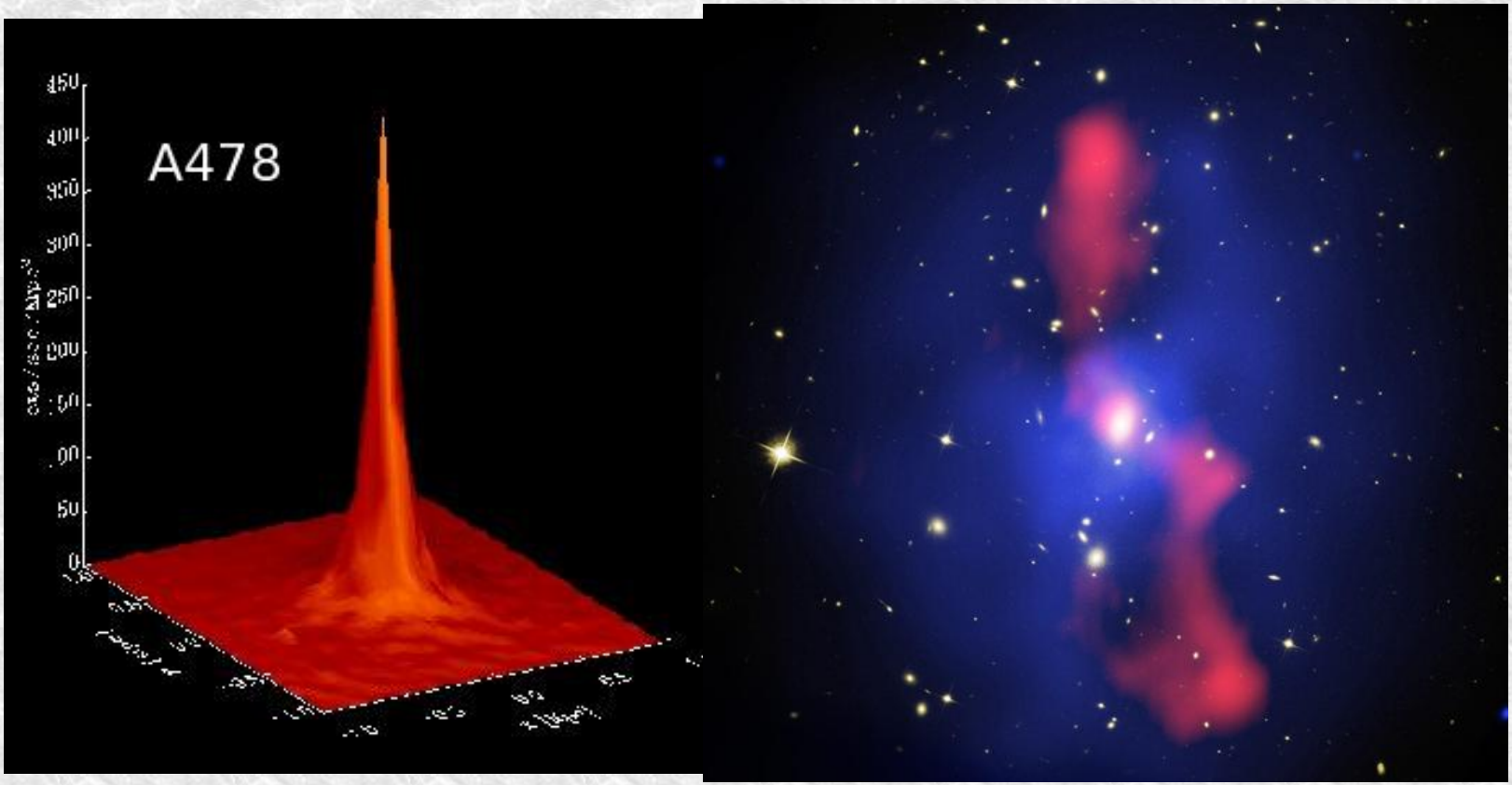
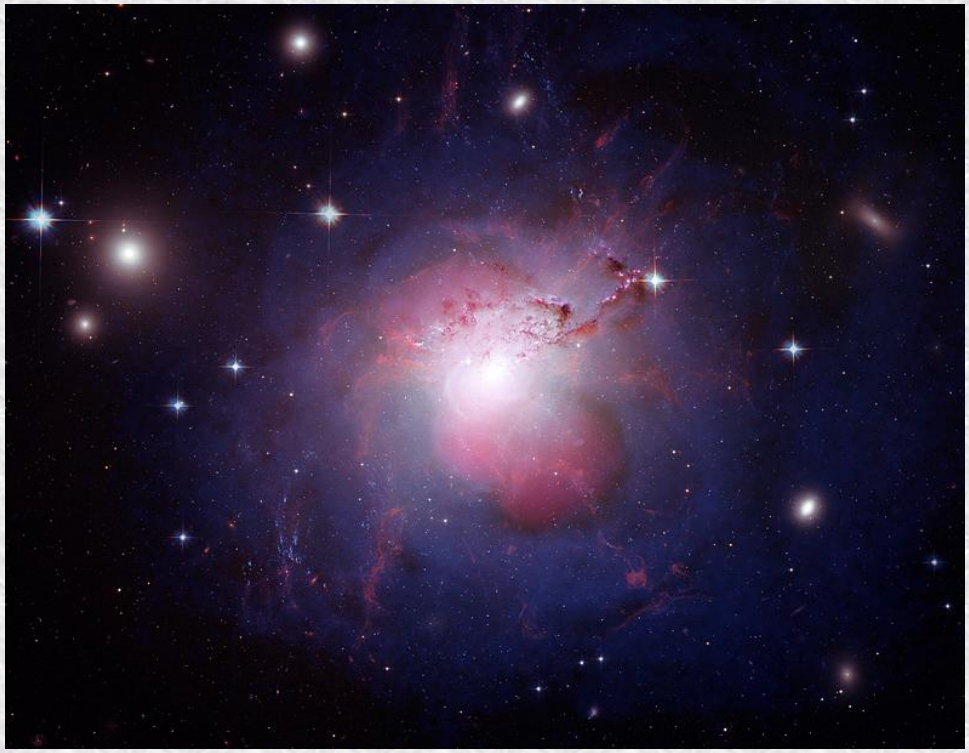
X-ray “cooling-flow” problem



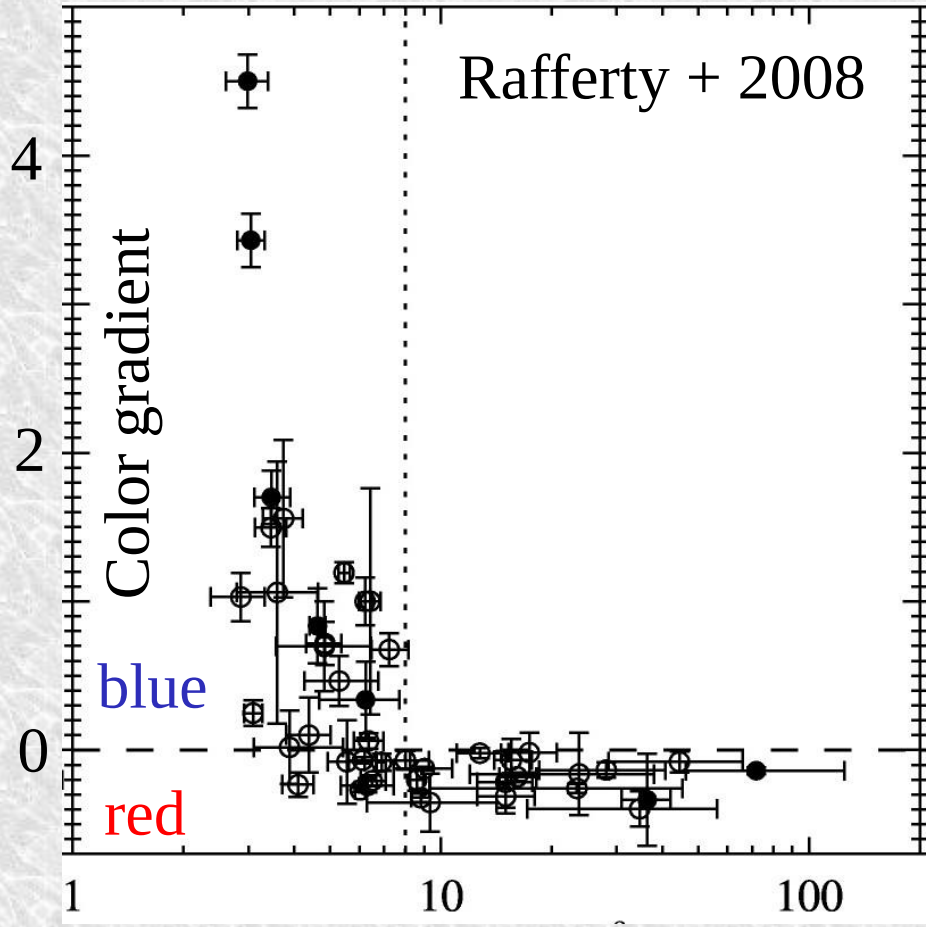
Why doesn't most gas with short cooling time cool out of hot phase rapidly ?

SMBH outbursts reheat cooling gas !

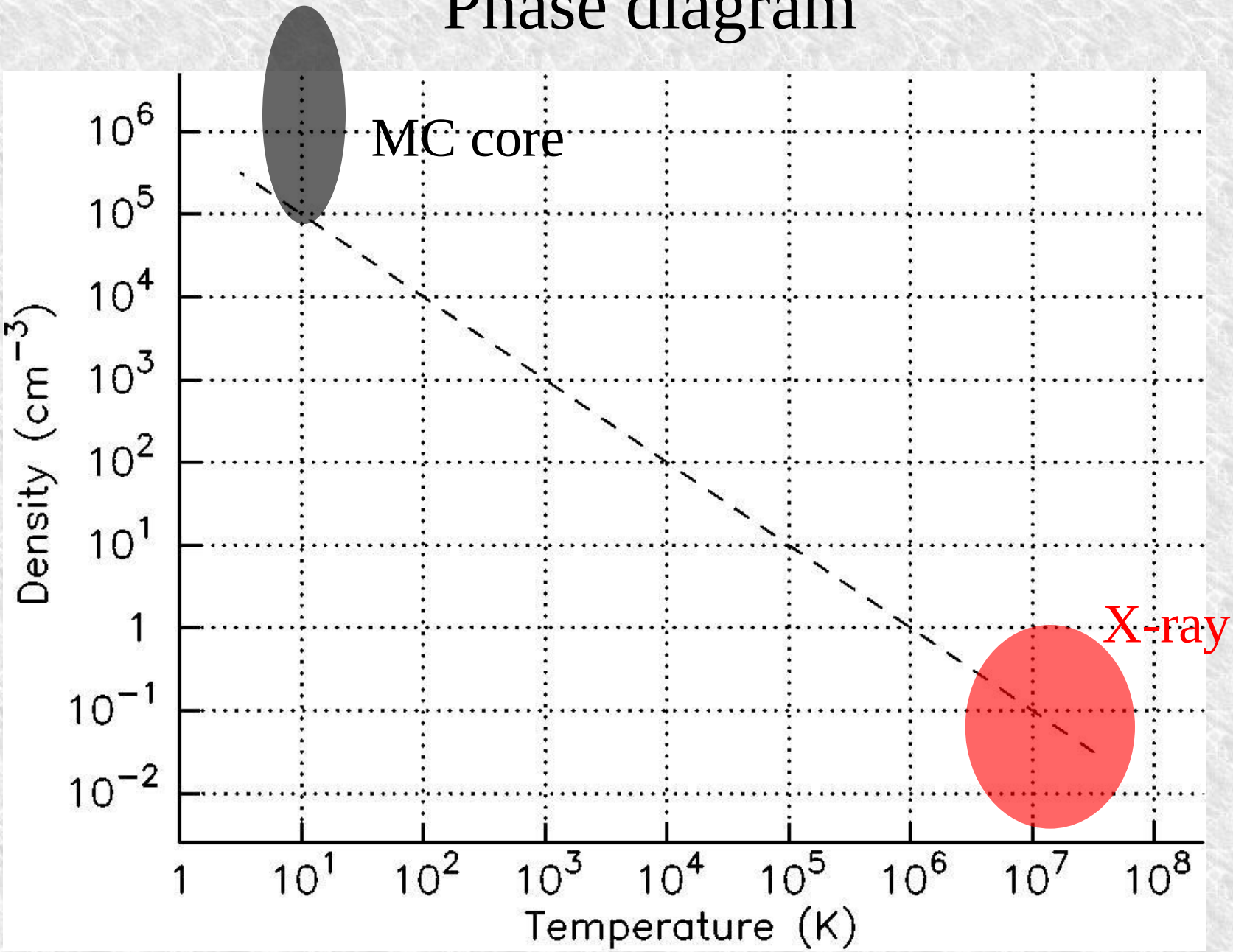
But residual cooling still happens and some stars still form …



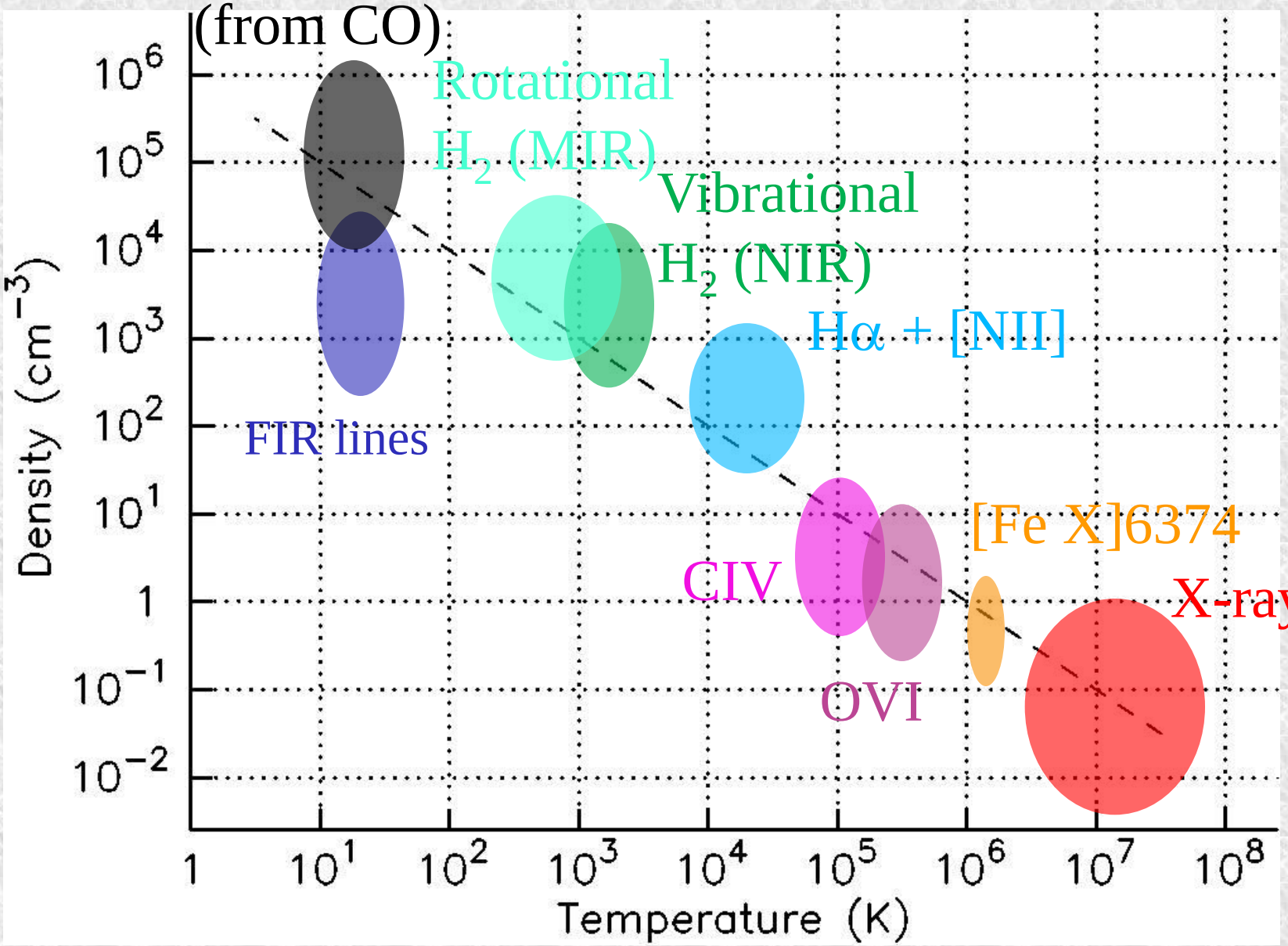
Fabian +



Phase diagram

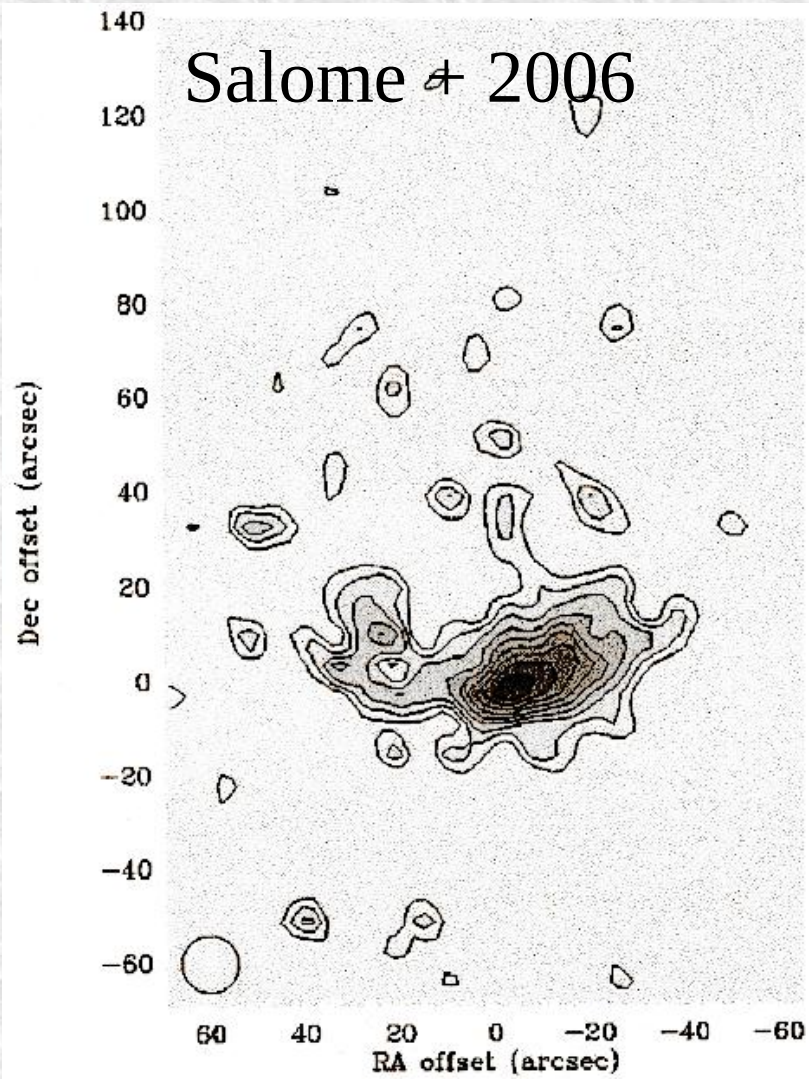


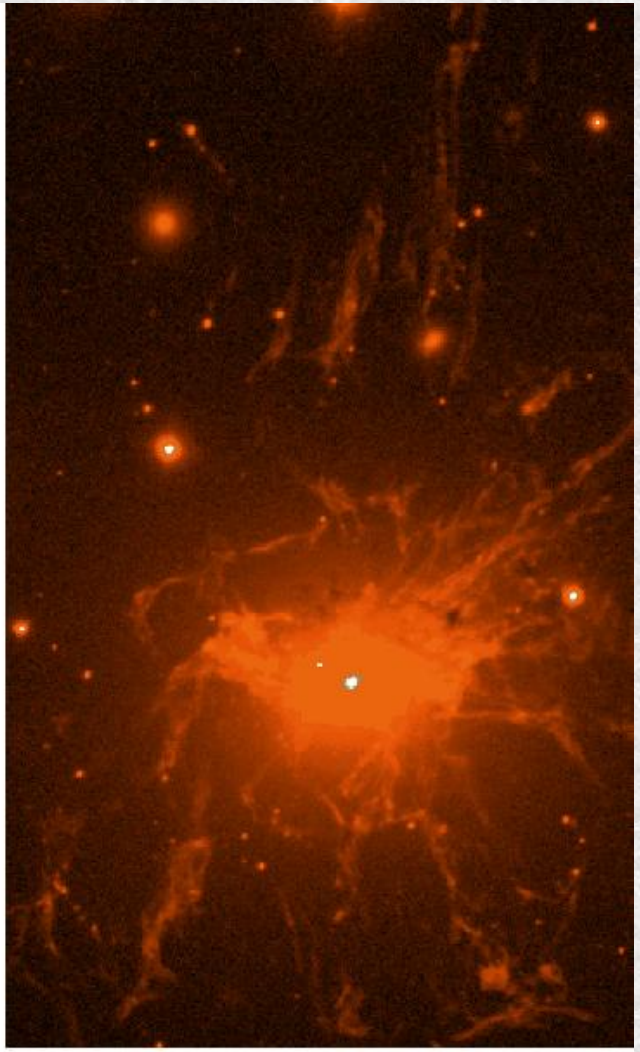
Phase diagram



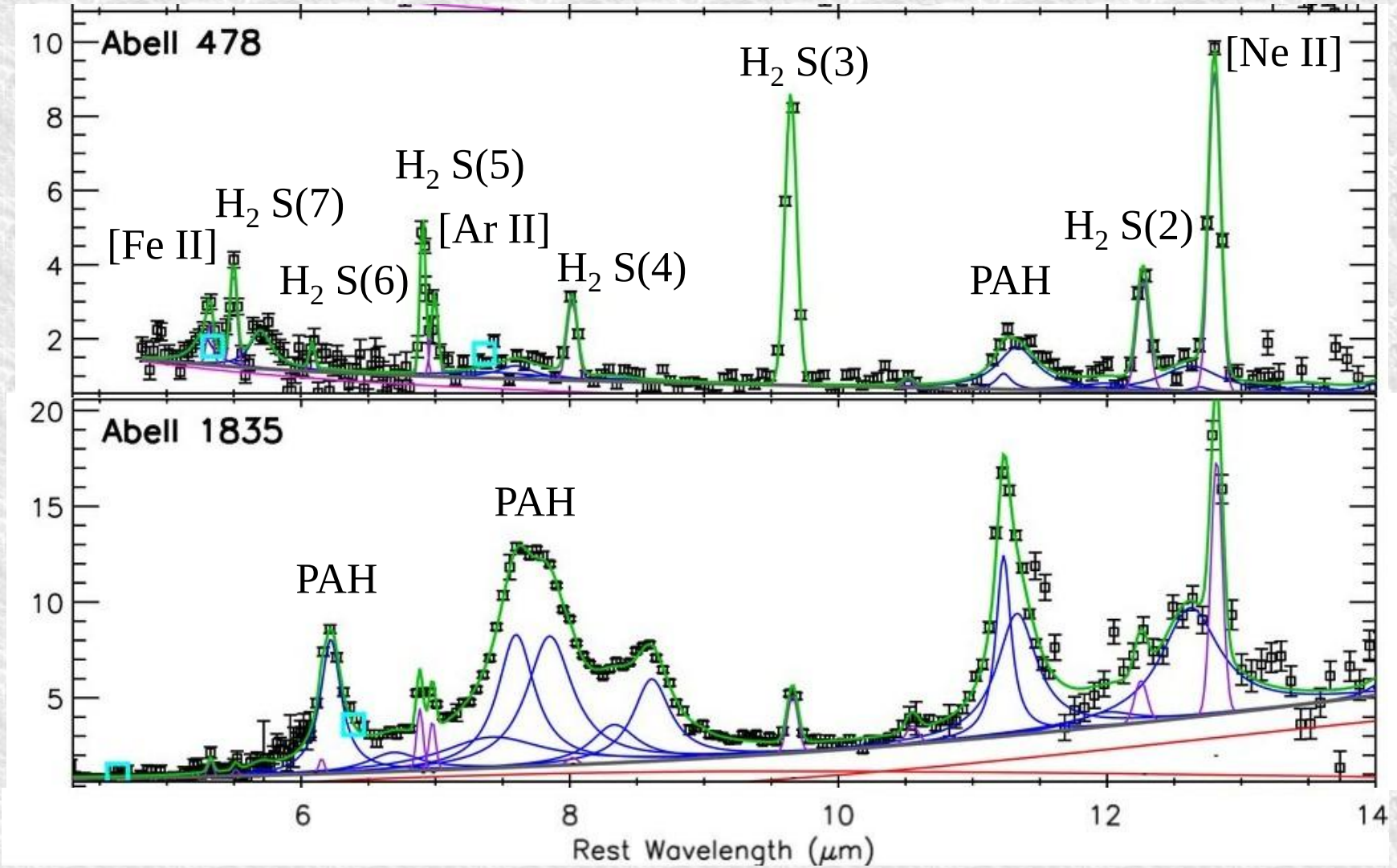
Cold H_2 (from CO)

Detected in many cool core clusters/groups,
$10^{7.5}$ – $10^{10.5}$ $M_\odot$ (Edge +; Salome, Combes +; Lim +)



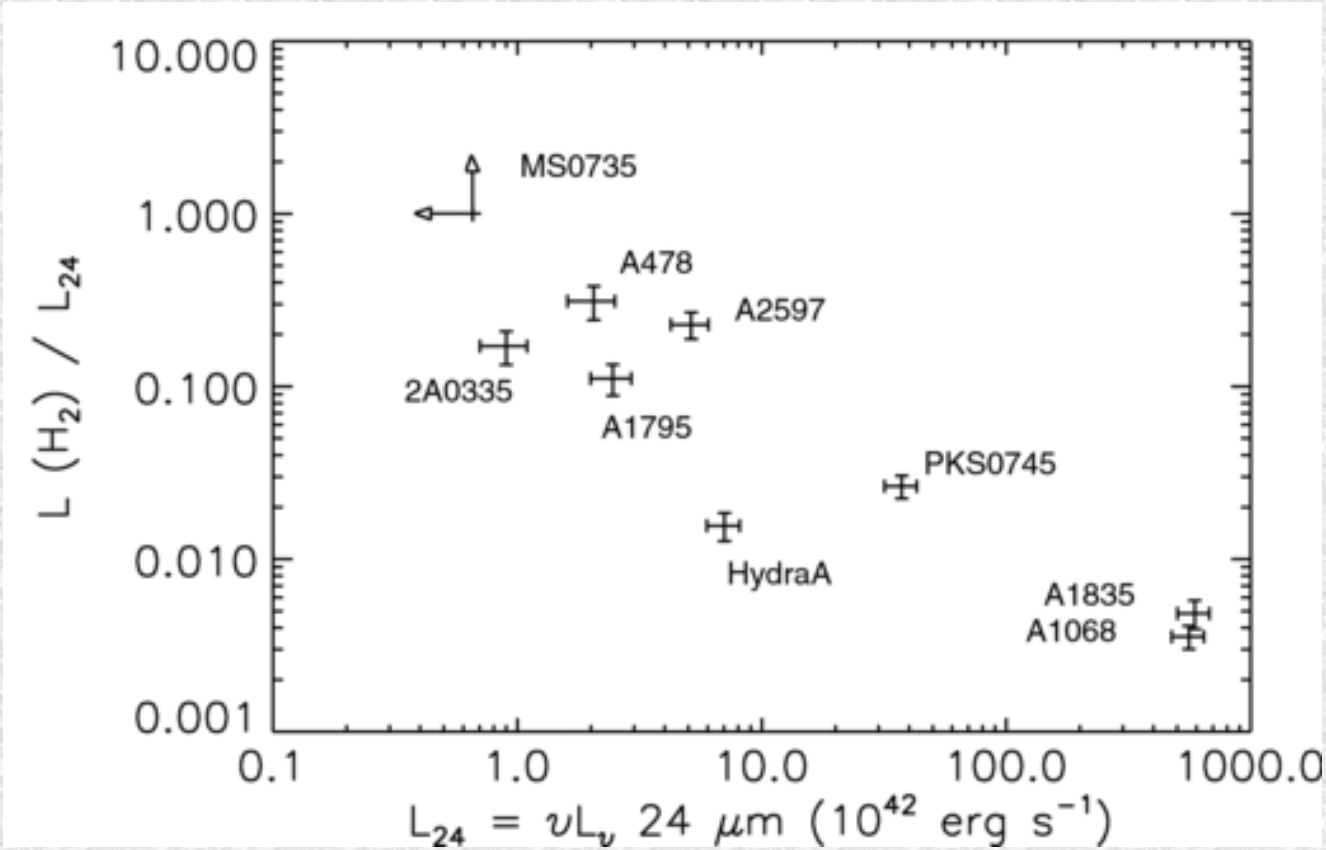


Warm molecular H_2 , PAH and ionized gas in MIR



(T ~ 300 - 2000 K, Donahue et al. 2011)

- BCGs have stronger rotational H_2 and [Ne] lines than SF galaxies with similar L_{IR}
  --- another heating source besides SF
  (CRs, heat conduction, MHD waves …)

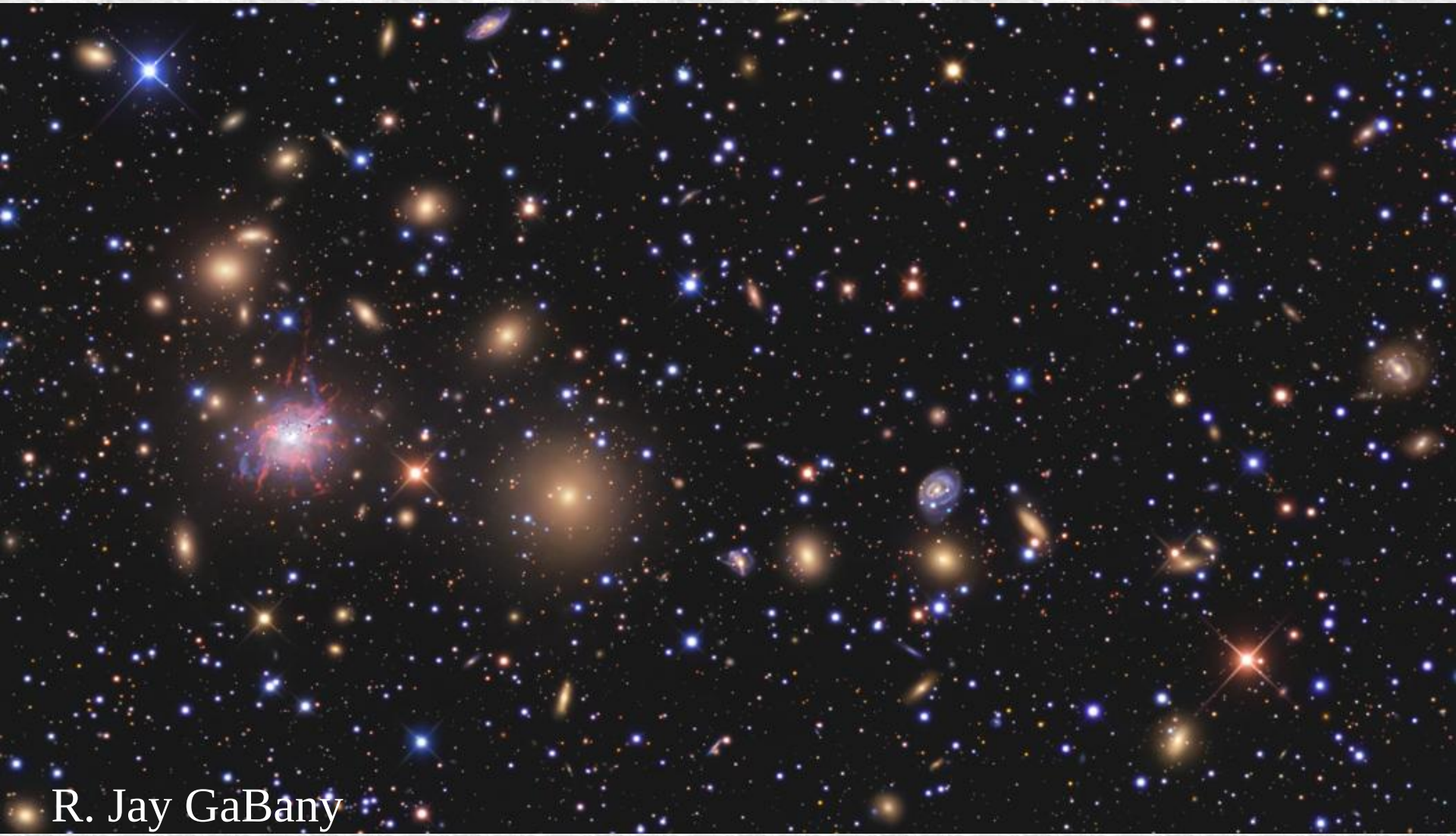


~ 0.001 for SF

Donahue et al. 2011

Hα optical filaments

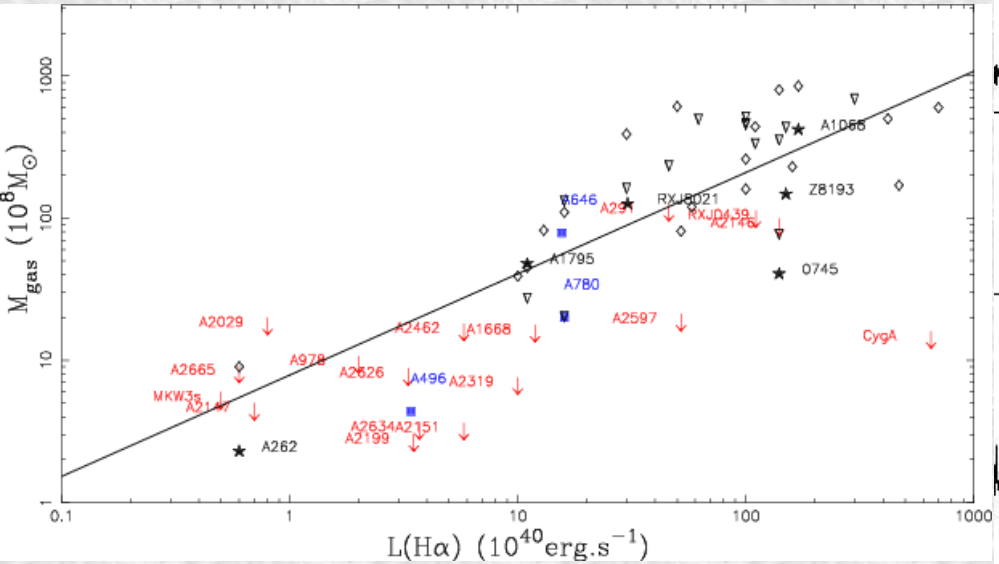
First seen in NGC 1275 (Baade & Minkowski 1954)



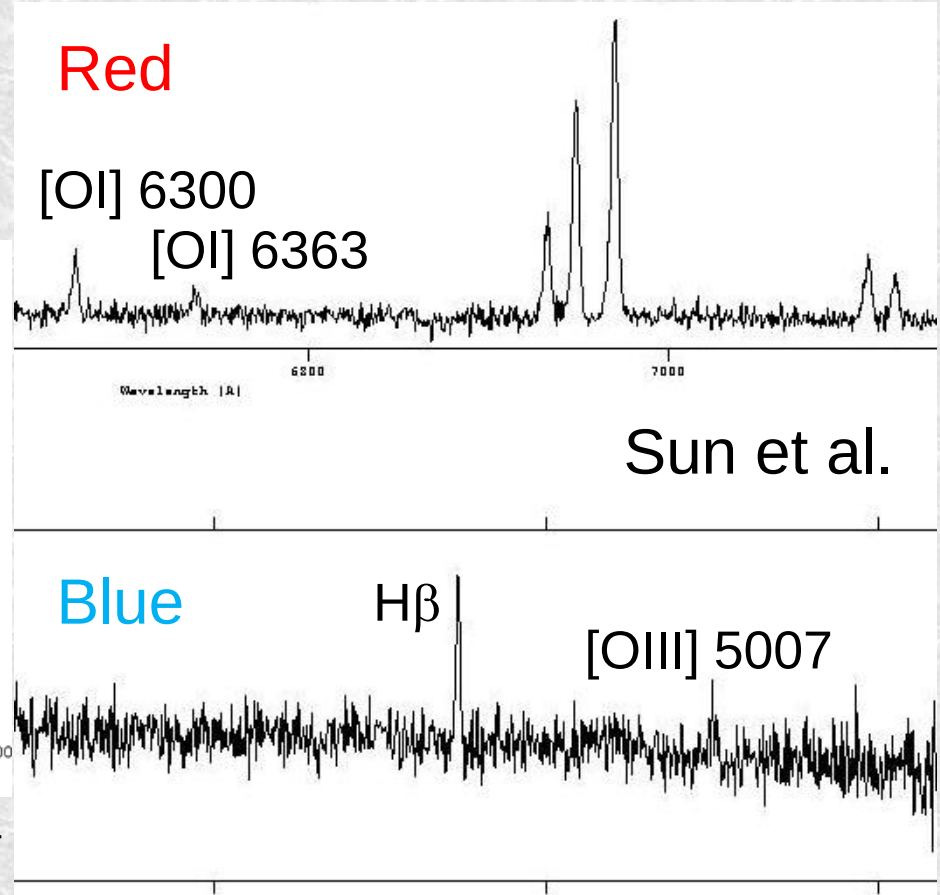
Hα optical filaments

- Now detected in many cool core clusters/groups
- Markers of cold gas
- Strong low-ionization emission lines

(need a hard and distributed ionizing source, e.g., CRs, conduction, MHD waves)



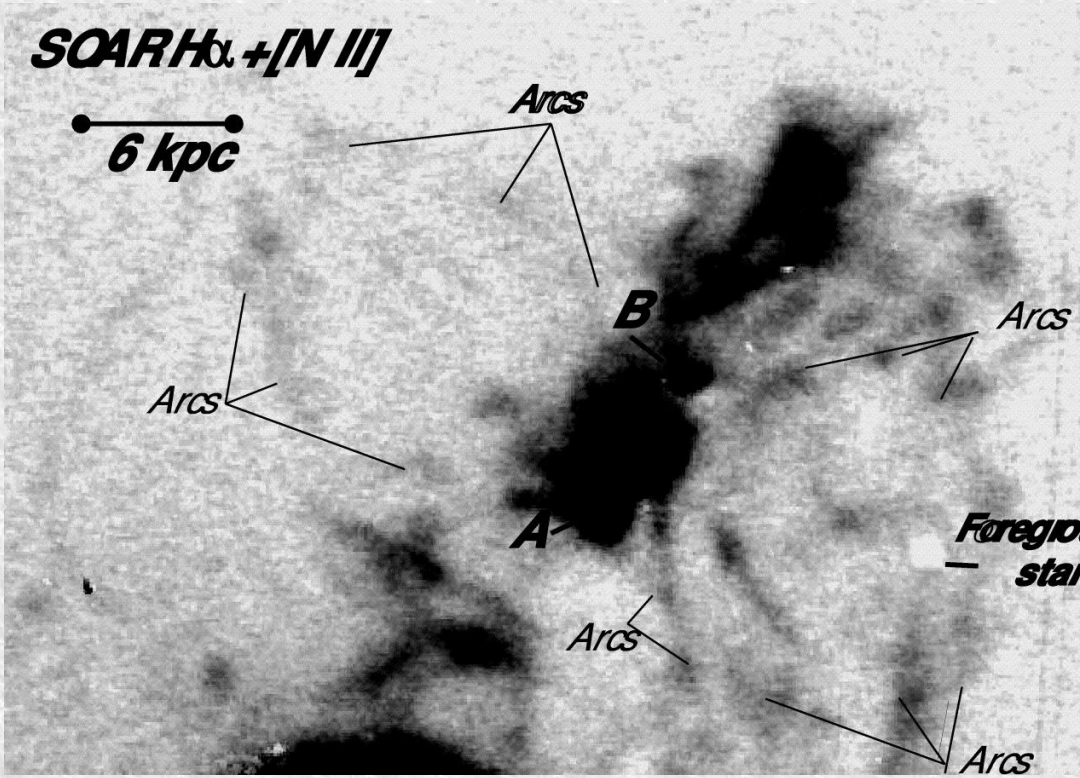
Salome & Combes 2003, also Edge +



SOAR observations of X-ray cool cores

(narrow-band imaging with SOI + spectroscopy with Goodman)

2A0335+096
(Donahue, Sun et al. 2007)
REXCESS sample
(Donahue et al. 2010)
NGC 5813
(Randall et al. 2011)
NGC 5044
(David et al. 2011)
AS1101
(Werner, Sun et al. 2011)
NGC 5846
(Machacek et al. 2011)
Galaxy groups
(Sun et al. 2011)

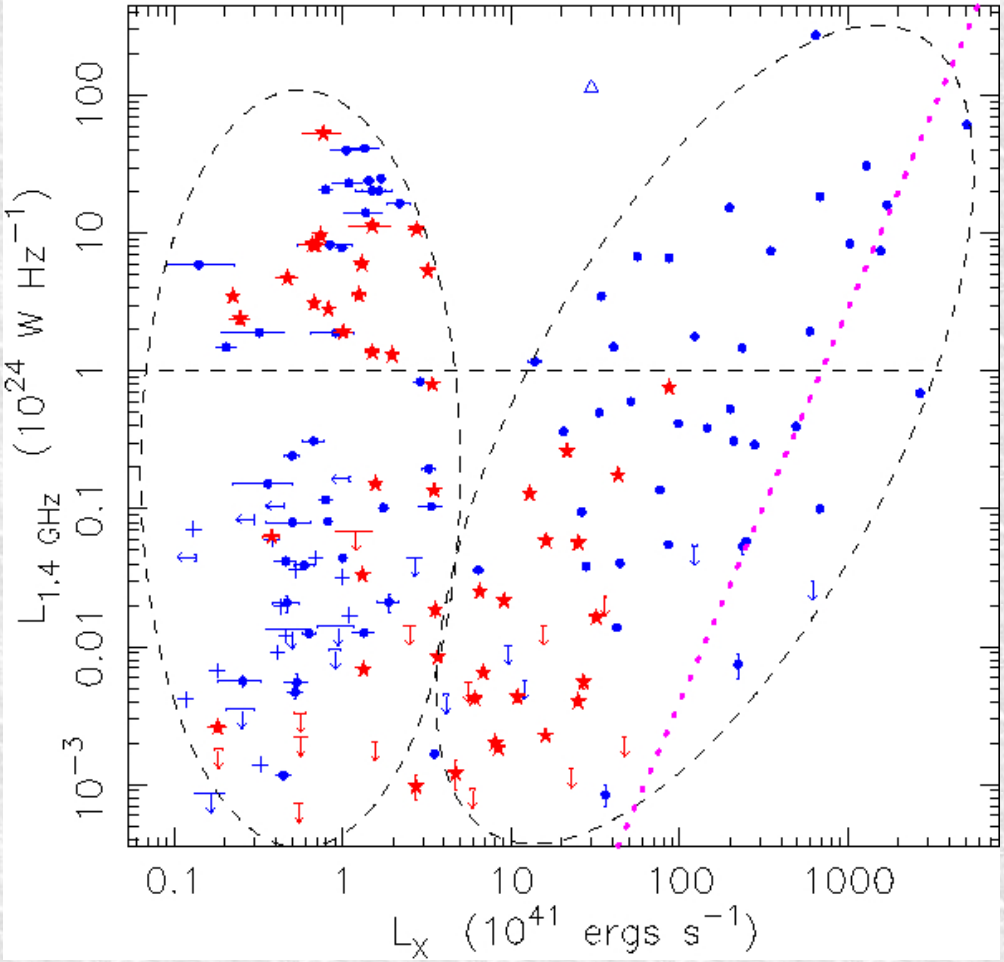


Donahue, Sun et al. 2007

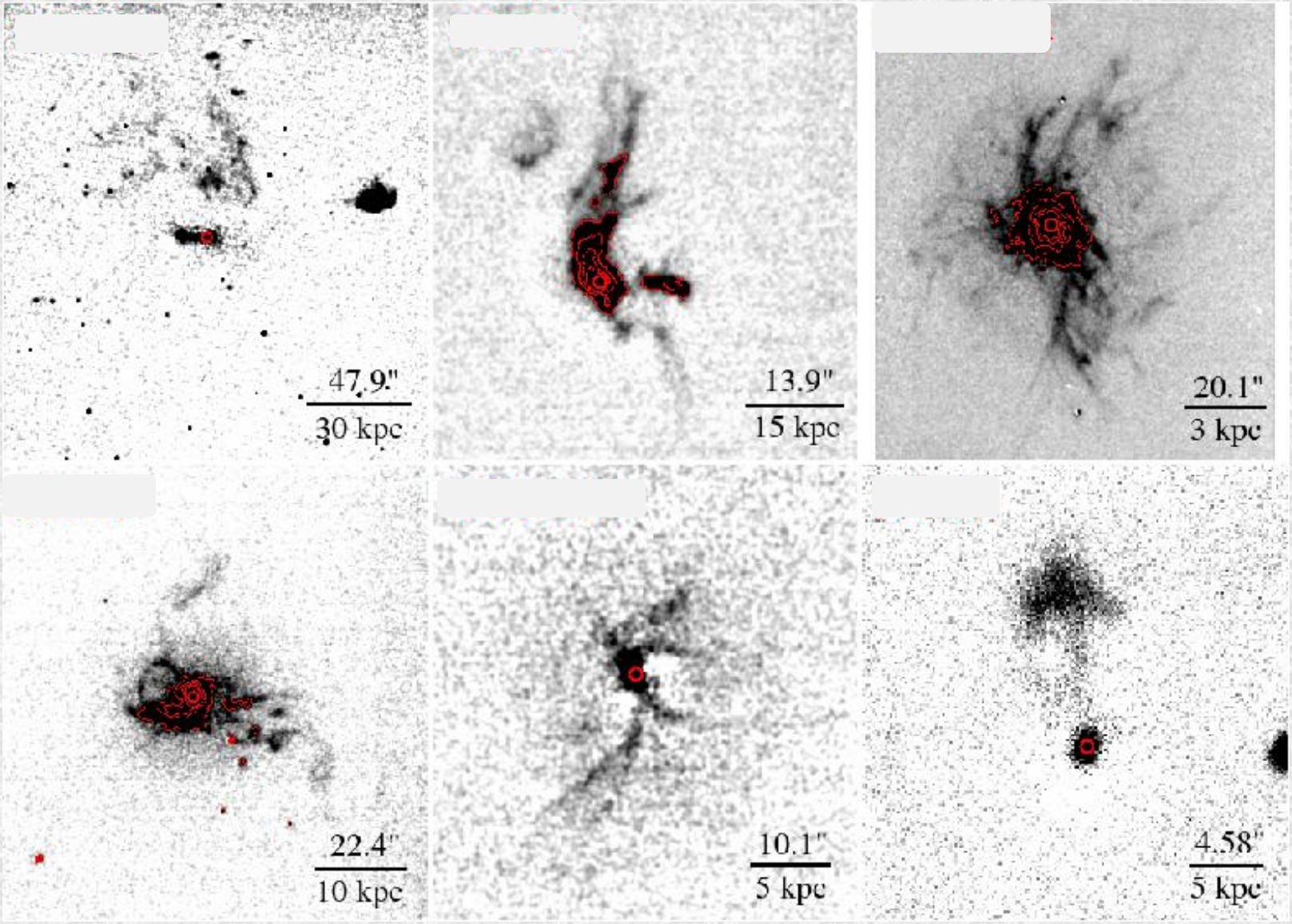
Hα + [NII] imaging of nearby group cool cores (SOAR, Sun et al.)

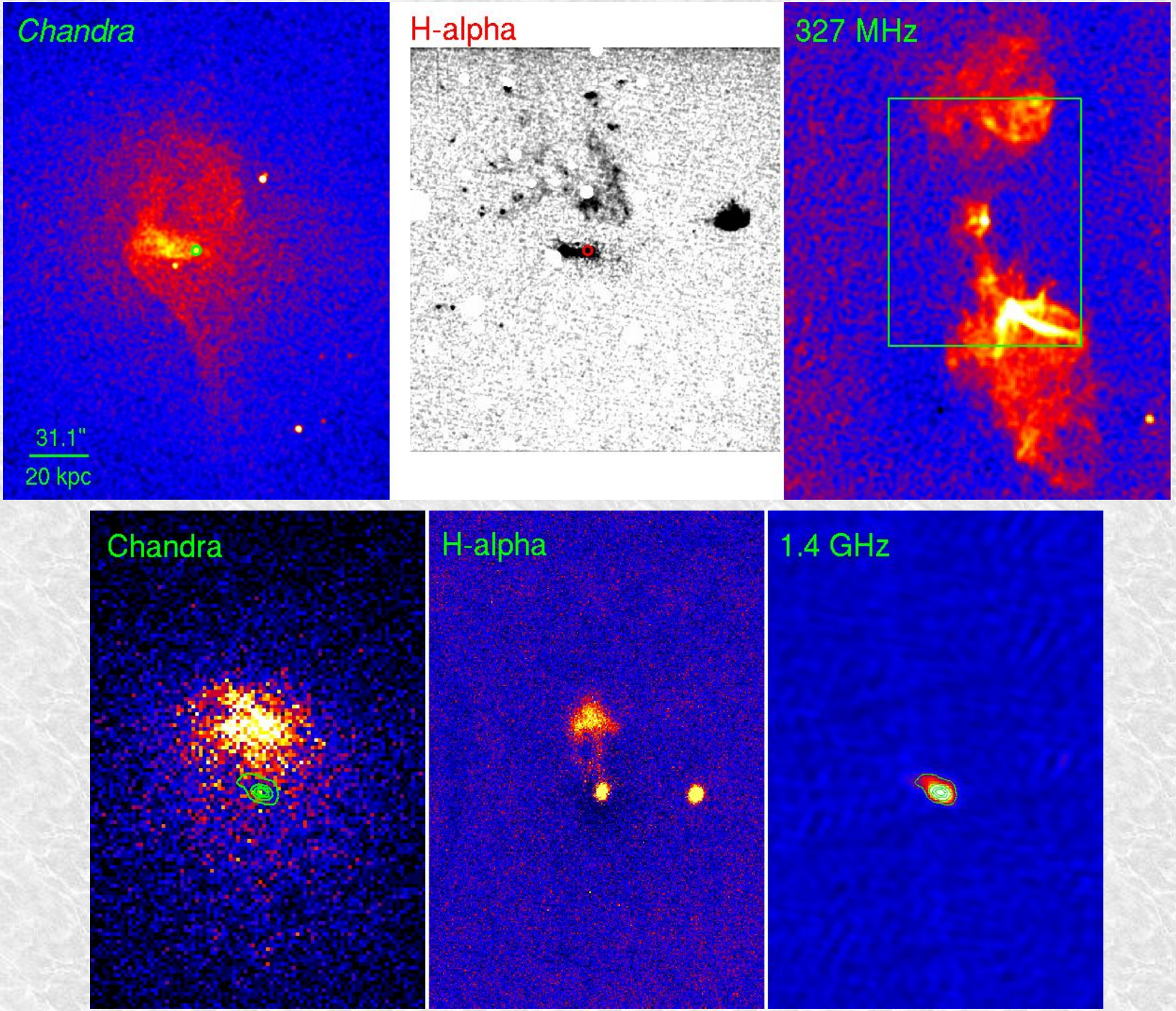
Why galaxy groups ?

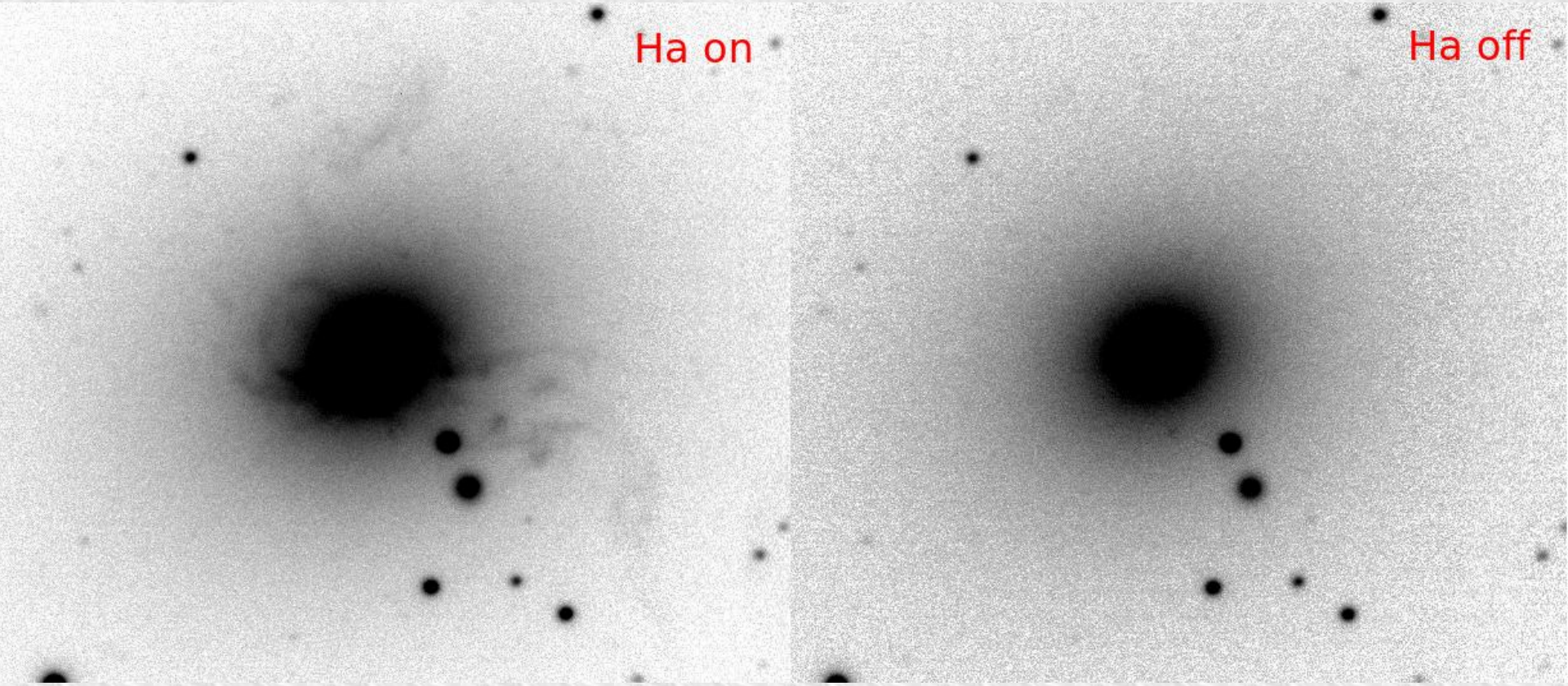
1) Lower $T \Rightarrow$ weaker heat conduction
2) Generally weaker radio AGNs
3) Closer (good for detailed studies)



Red: $kT < 2$ keV, Blue: $kT > 2$ keV (Sun 2009)


47.9"
30 kpc
13.9"
15 kpc
20.1"
3 kpc
22.4"
10 kpc
10.1"
5 kpc
4.58"
5 kpc


Chandra
31.1"
20 kpc
H-alpha
327 MHz
Chandra
H-alpha
1.4 GHz

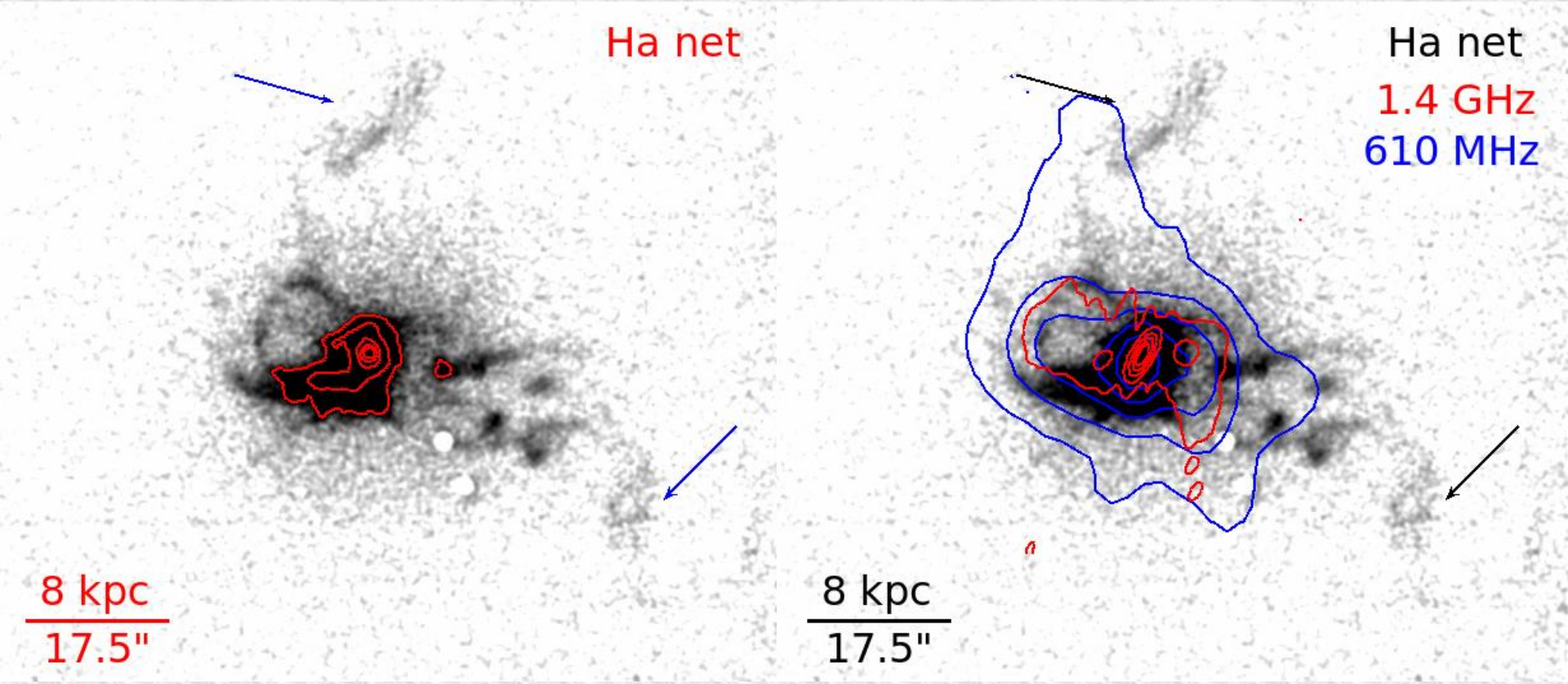


The most X-ray luminous cool core for $kT < 2$ keV systems at $z < 0.1$

SFR ~ 1.4 $M_\odot$ / yr from Hα

~ 0.9 $M_\odot$ / yr from *IR* (*WISE*, 12 μ + 22 μ)

(Hα, *Chandra*, *EVLA*, *GMRT*, *HST* and more, PI: Sun)



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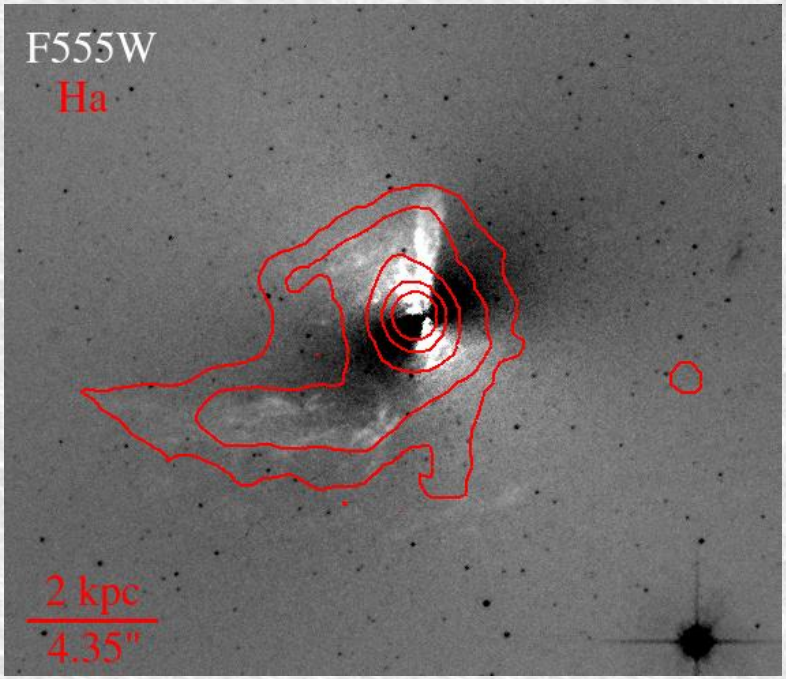
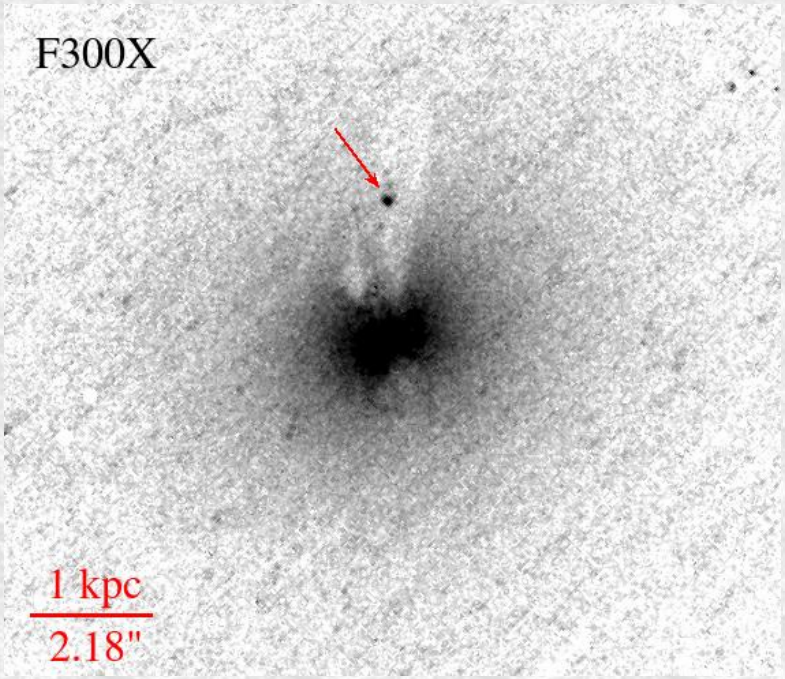
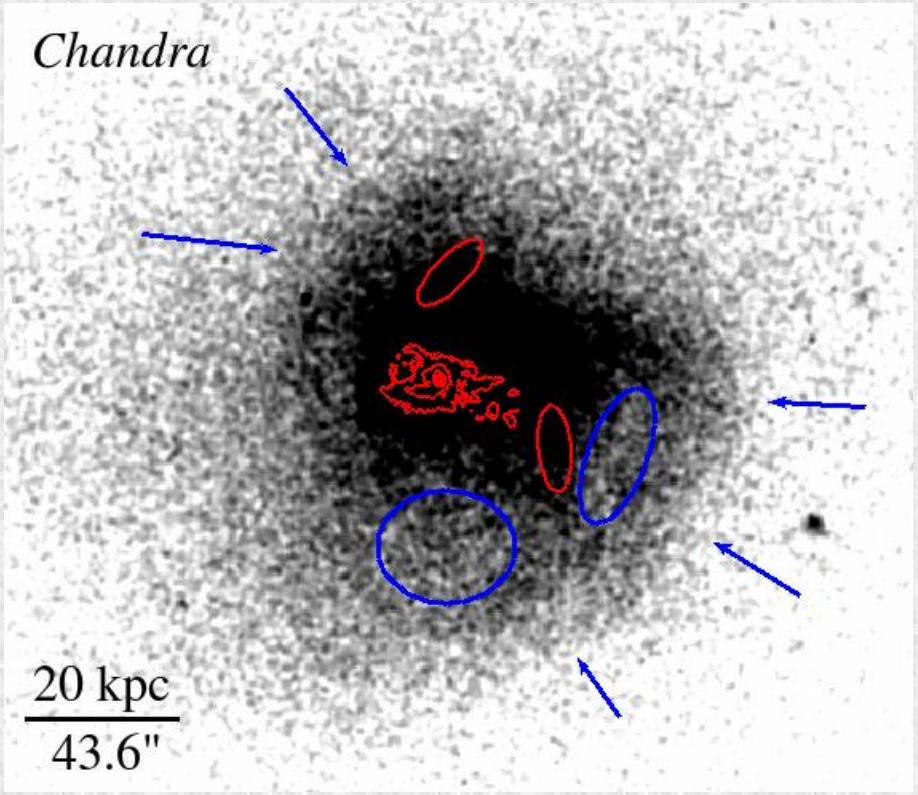
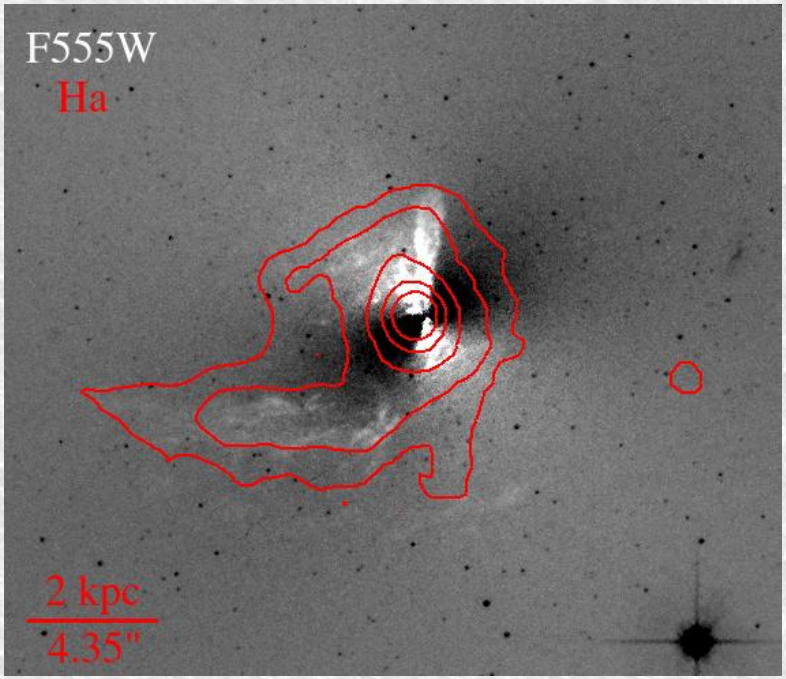
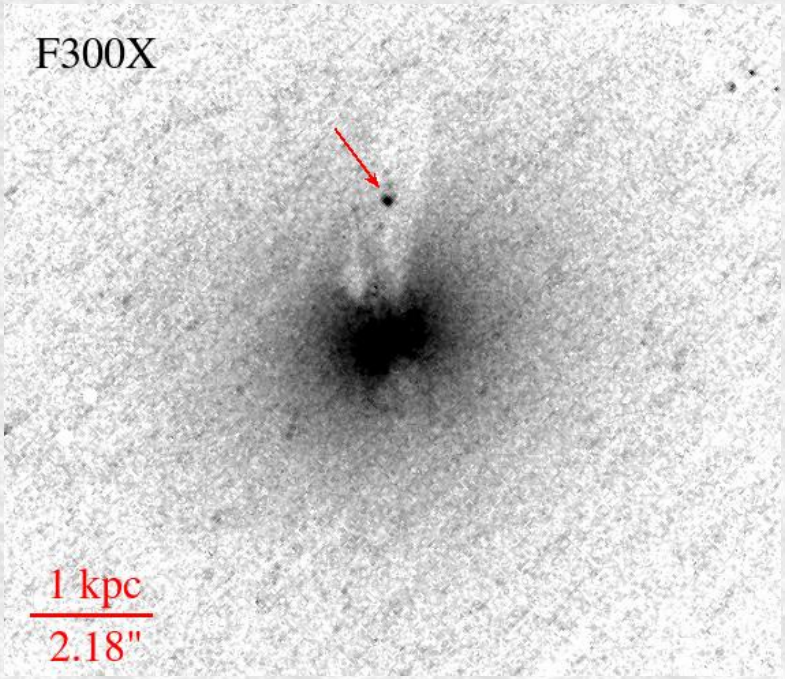
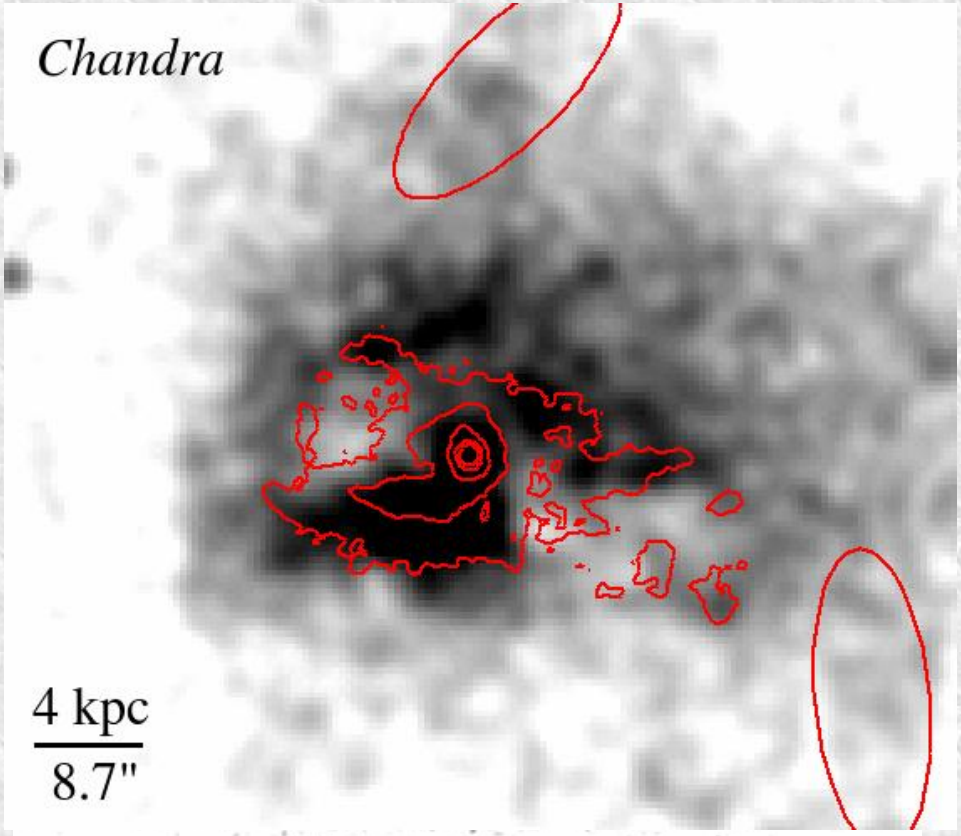

F555W
Ha
2 kpc
4.35"


F300X
1 kpc
2.18"


Chandra
20 kpc
43.6"


F555W
Ha
2 kpc
4.35"

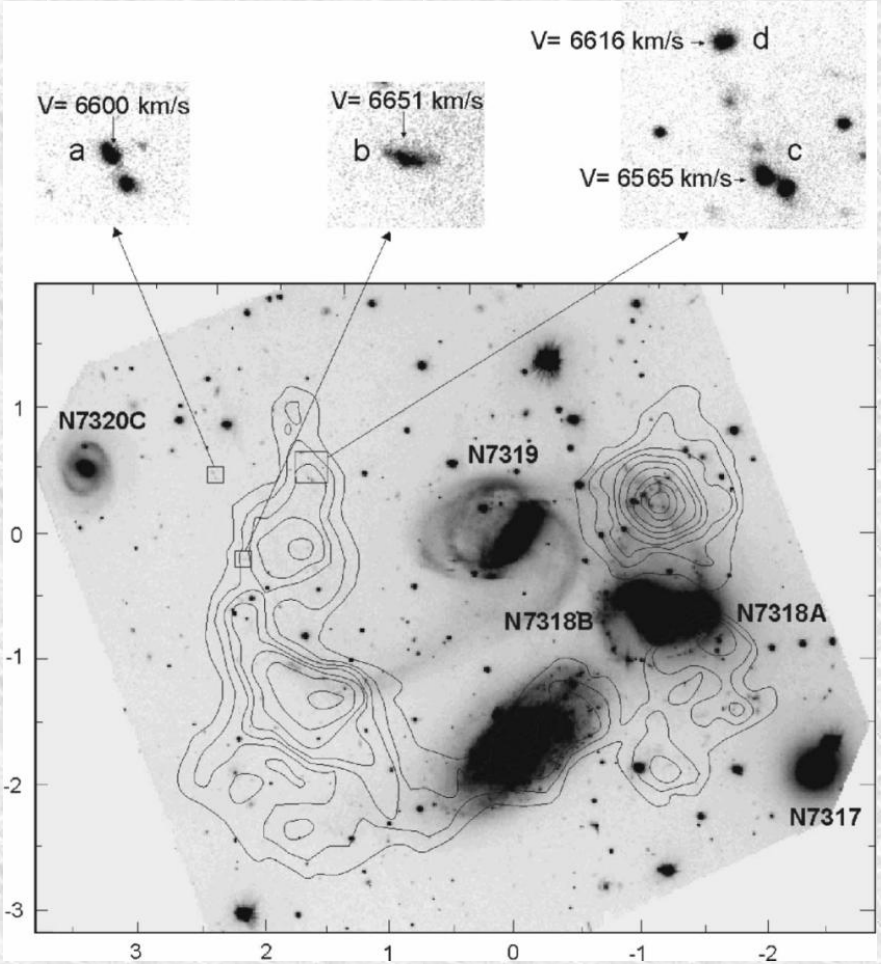

F300X
1 kpc
2.18"


Chandra
4 kpc
8.7"

Conclusions (I)

1) We have collected multi-wavelength data (including SOAR) for samples of groups and clusters. BCGs in cool cores can host spectacular emission-line nebulae. SF is revealed from the UV and IR data, but emission lines requires another ionizing mechanism.

SF in the intracluster space



HII regions were known to exist between galaxies (e.g., Mendes De Oliveira et al. 2004)

What I will discuss is: SF in the cold gas stripped by ram pressure behind cluster galaxies

Cold gas/dust in the intracluster space

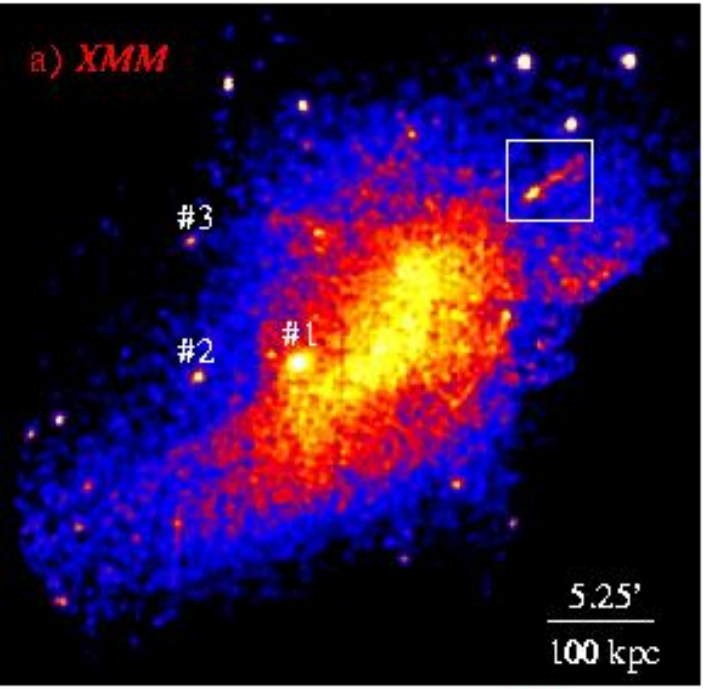
- Ram pressure stripping observed

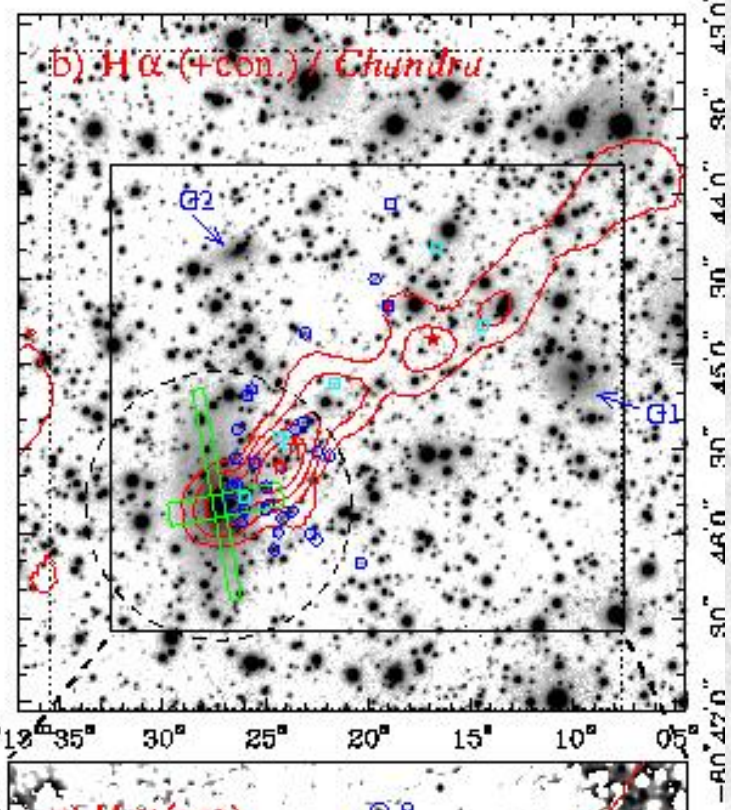
  (HI, Hα, molecular H_2 and X-rays tails ...)

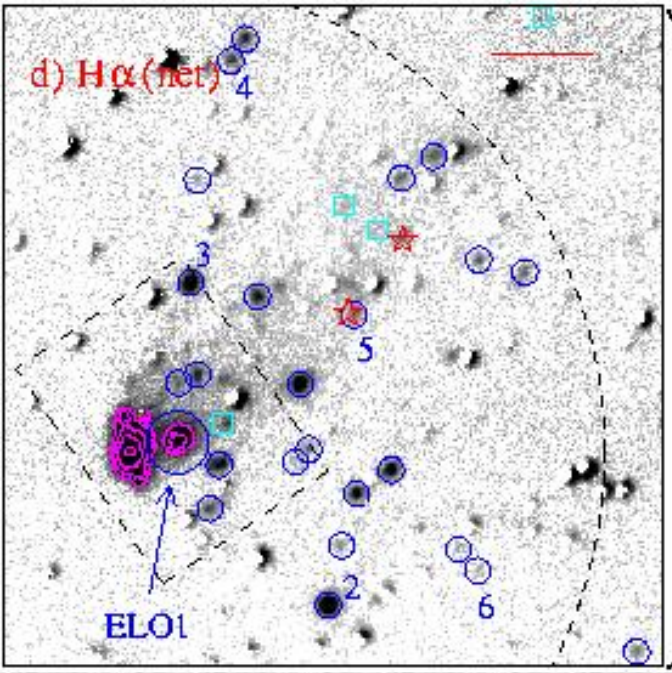
- Deep HI observations see isolated HI clouds in clusters (e.g., ALFAFA)

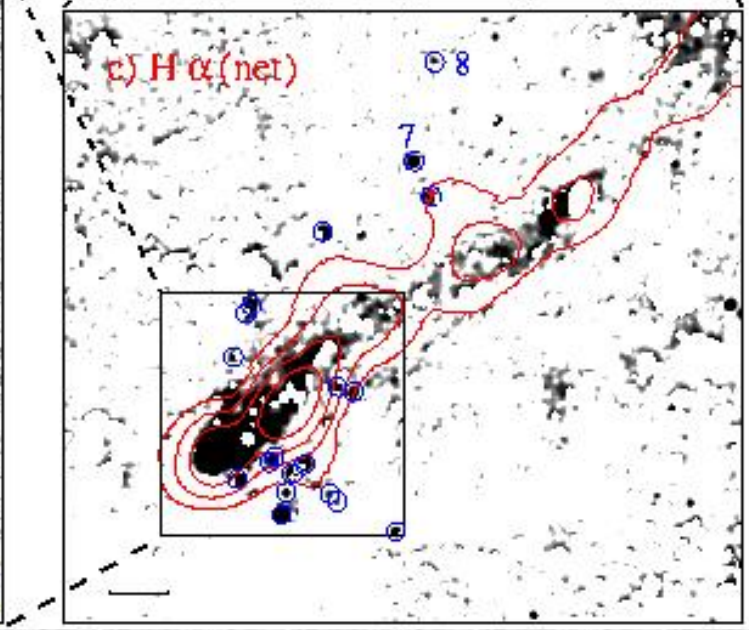
- Intracluster dust exists (from reddening)

The fate of the stripped gas ?









ESO 137-001
In A3627
(z=0.016)

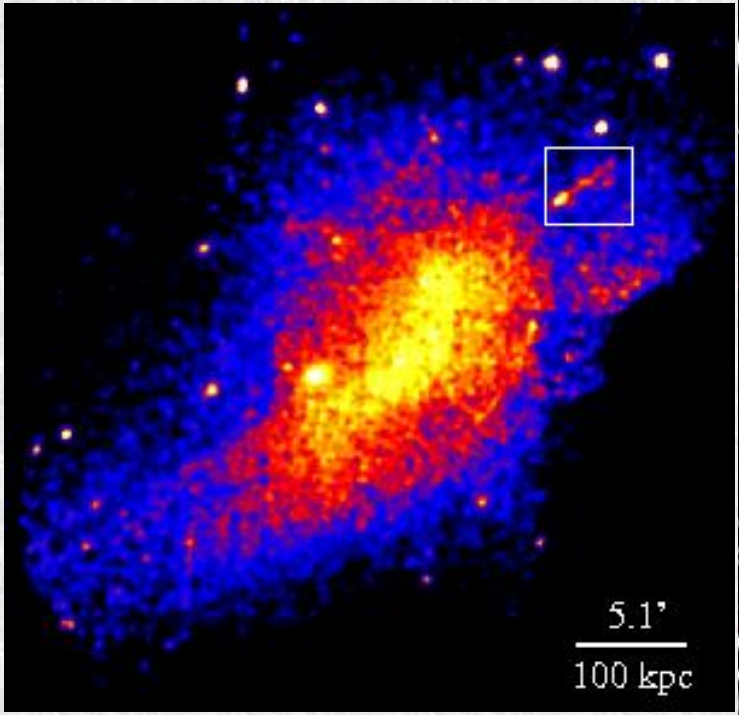
A blue galaxy
(SFR: ~1 $M_{\odot}$/yr),
~0.07 M*

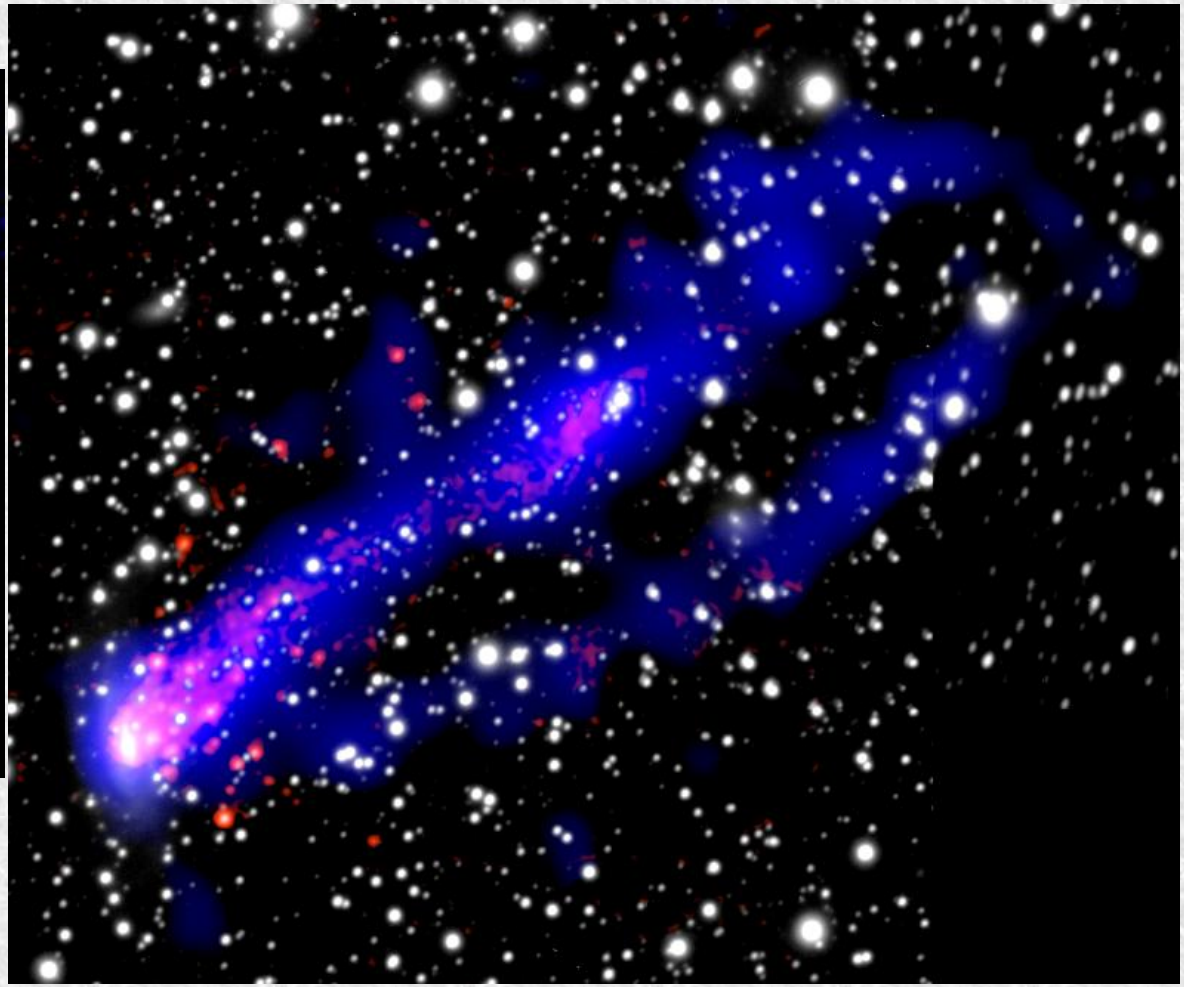
A 70 kpc X-ray
tail + A 40 kpc
Hα tail

35 HII regions
downstream of
the galaxy,
SFR~0.6 $M_{\odot}$ / yr

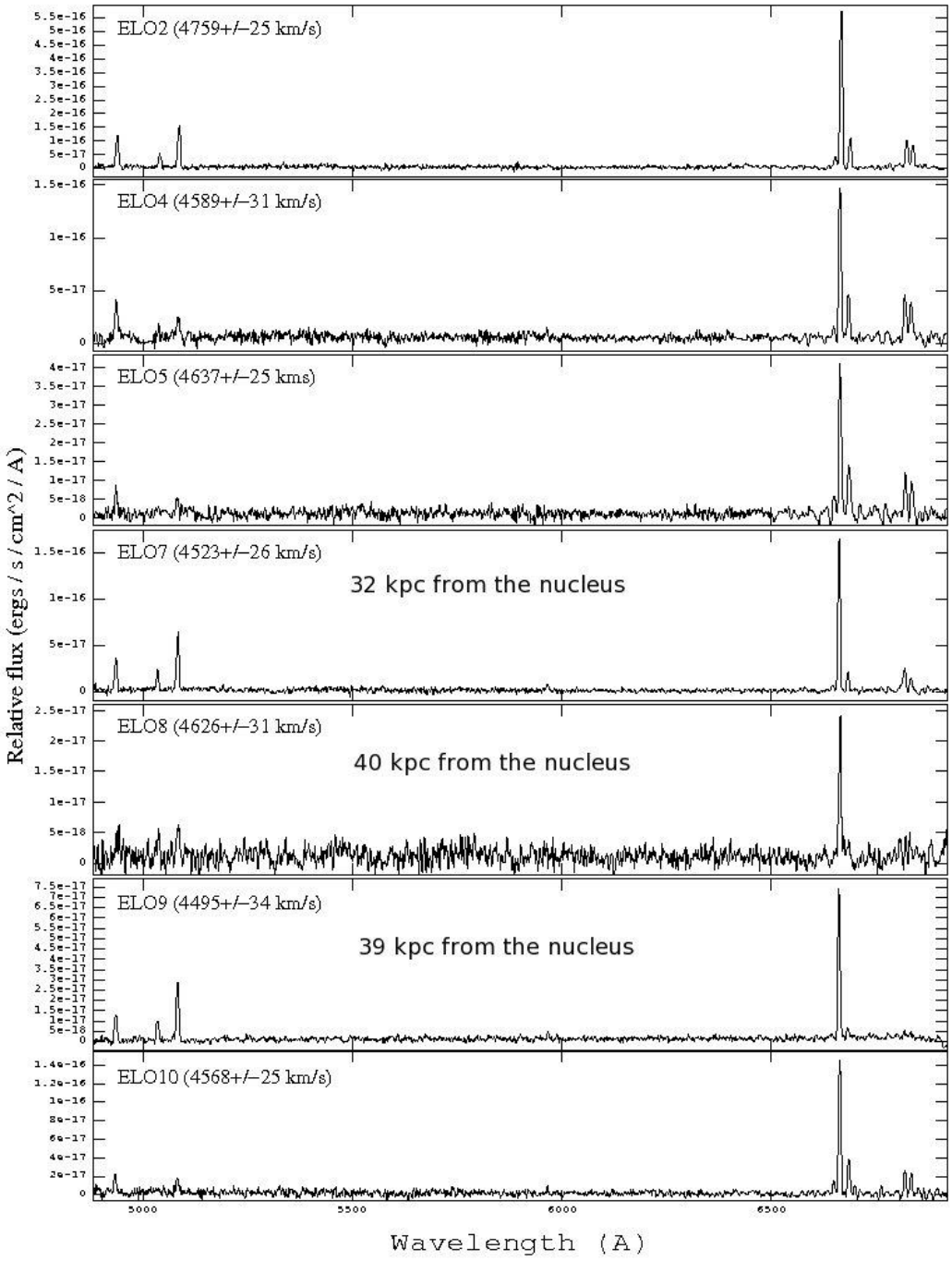
(Sun + 2006,
2007)

Later, an 140 ks *Chandra* observation reveals ...





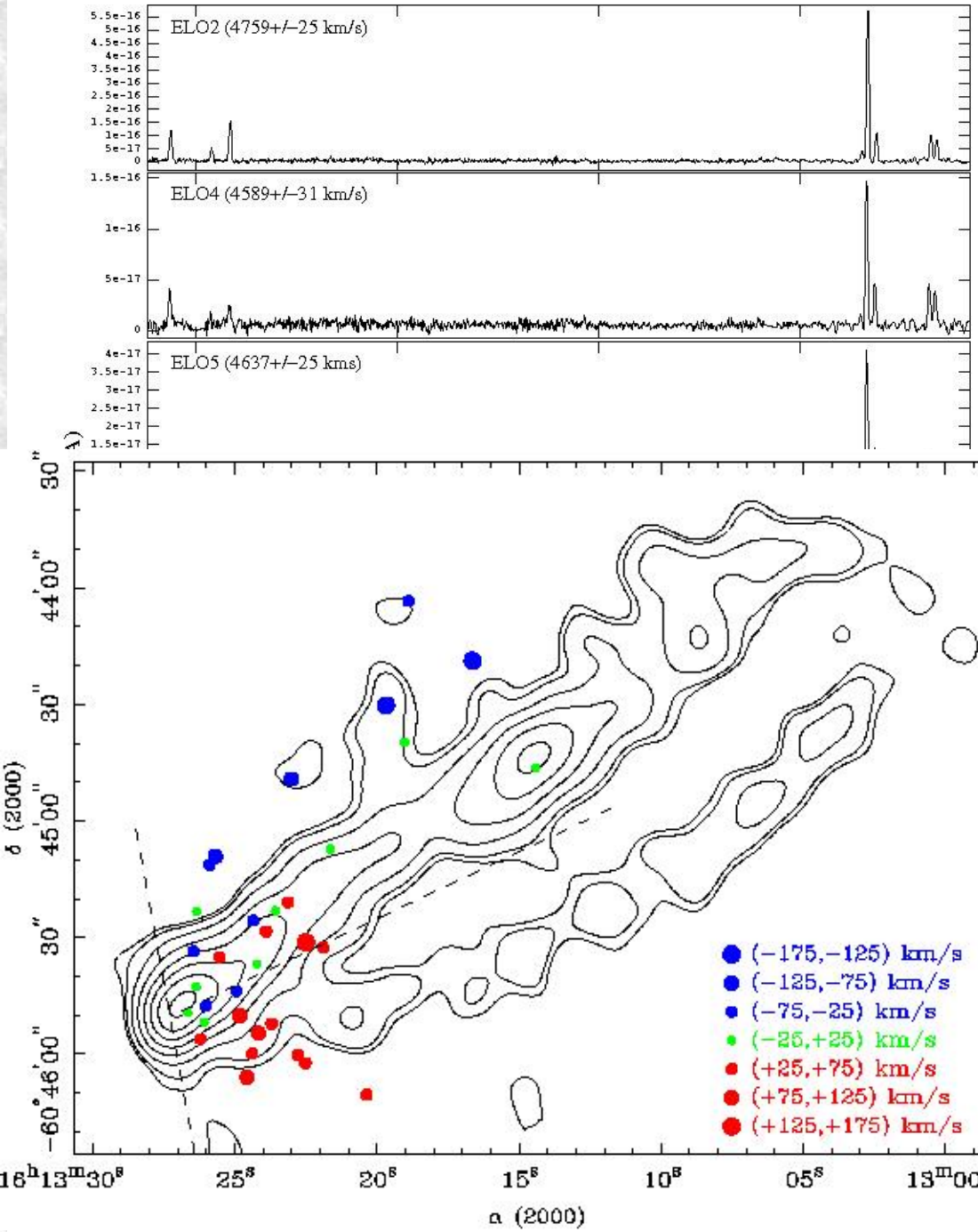
X-ray , SOAR Hα , Sun et al. 2010

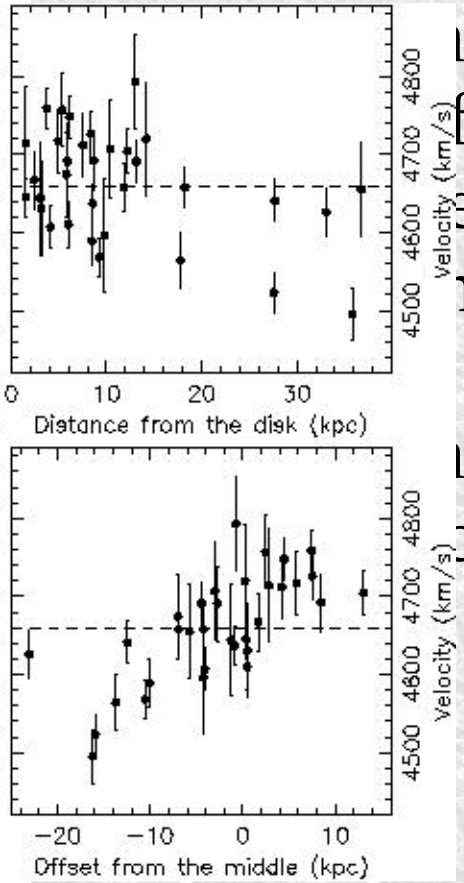


Gemini GMOS

1) All confirmed to be HII regions in A3627

2) Velocity map has the imprint of the rotation curve
and only spans a small range
--- constraint on turbulence ?





Gemini GMOS

1) All confirmed to be HII regions in A3627

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Orphan stars found

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Black Holes
Milky Way Galaxy
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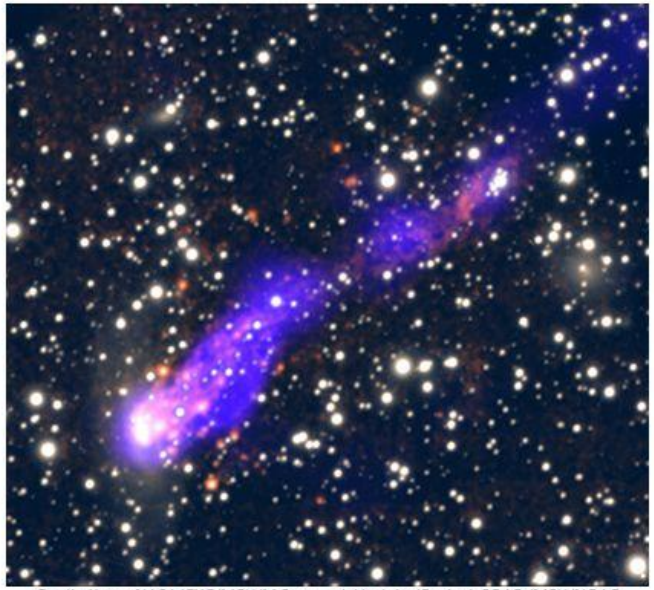
Quasars
Groups of Galaxies
Cosmology/Deep Field
Miscellaneous

Multiwavelength
Sky Map
Constellations
3D Wall

Abell 3627:
Orphan Stars Found in Long Galaxy Tail



Credit: X-ray: NASA/CXC/MSU/M.Sun et al; H-alpha/Optical: SOAR (MSU/NOAO /UNC/CNPq-Brazil)/M.Sun et al.

Two tails to tell

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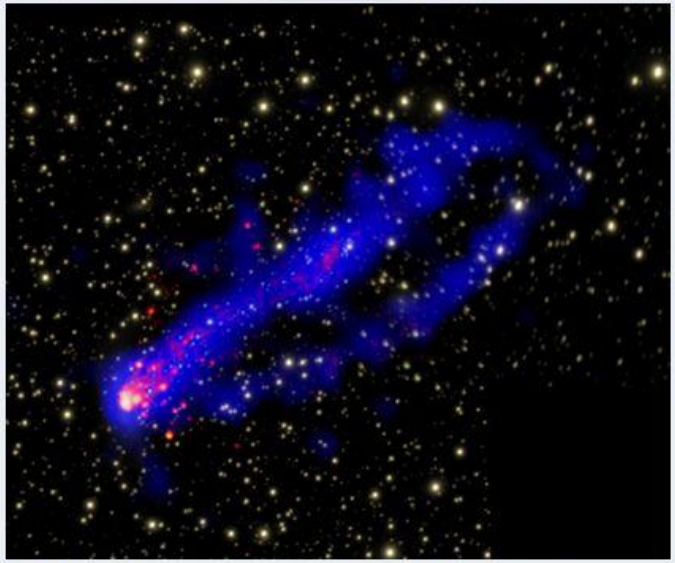
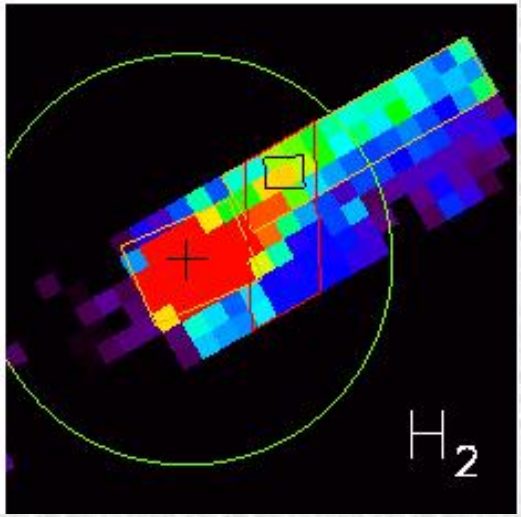
ESO 137-001:
Two Tails to Tell

Wavelengths: Composite | X-ray | H-alpha | Optical



What is it? How far away is it?

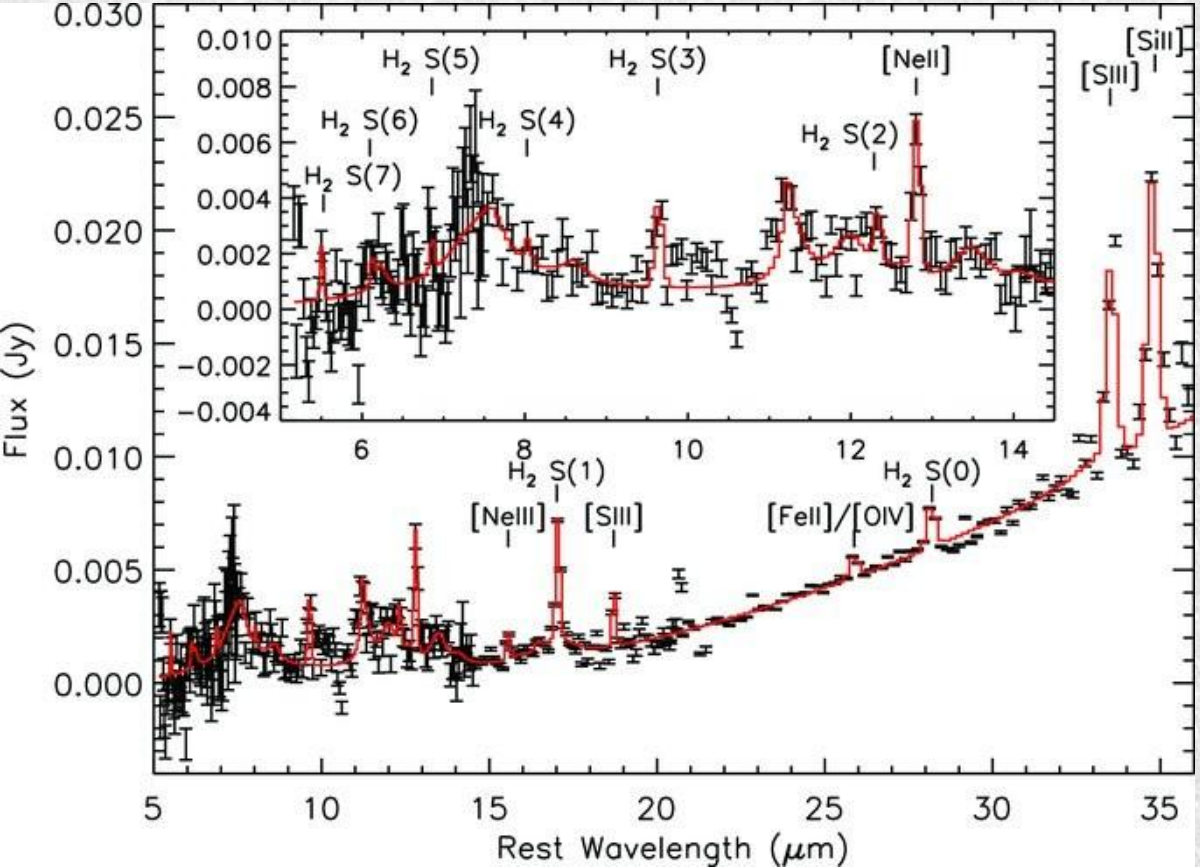
ESPN Tuesday morning Quarterback (Dec. 20, 2007)



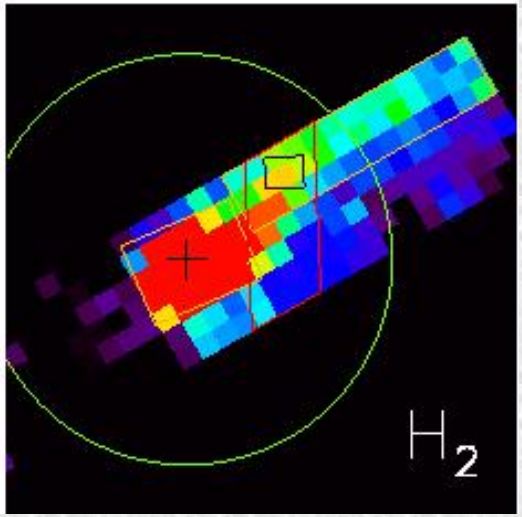
A warm (~ 150 K) H_2 tail with a mass of ~ 2.5×10^7 $M_\odot$ to > 20 kpc

--- the first H_2 tail

Sivanandam, Rieke & Rieke (2010)



Strong rotational H_2 lines



A warm (~
of ~ 2.5x1(
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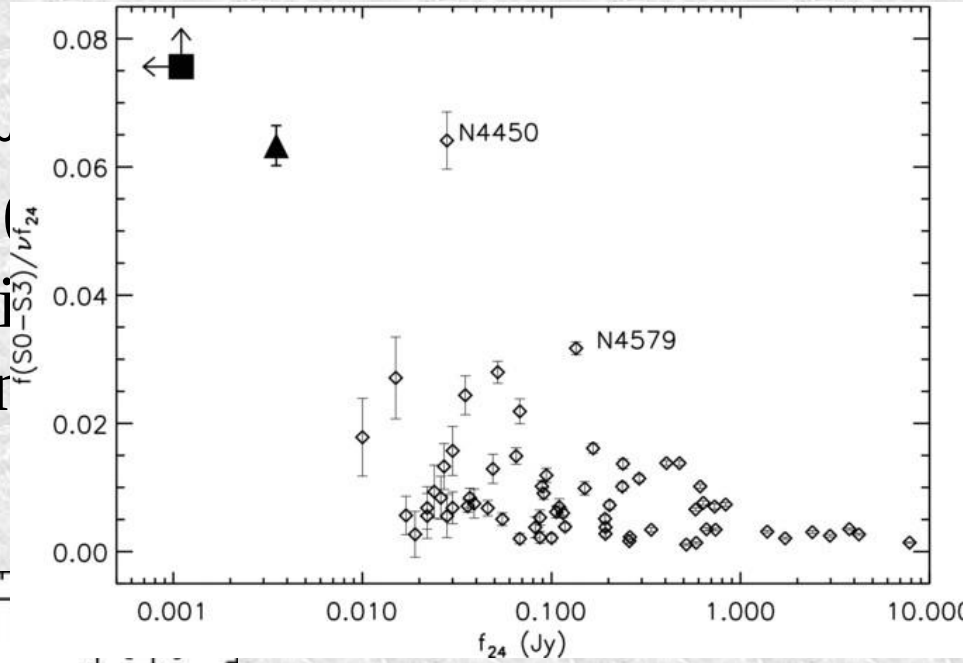
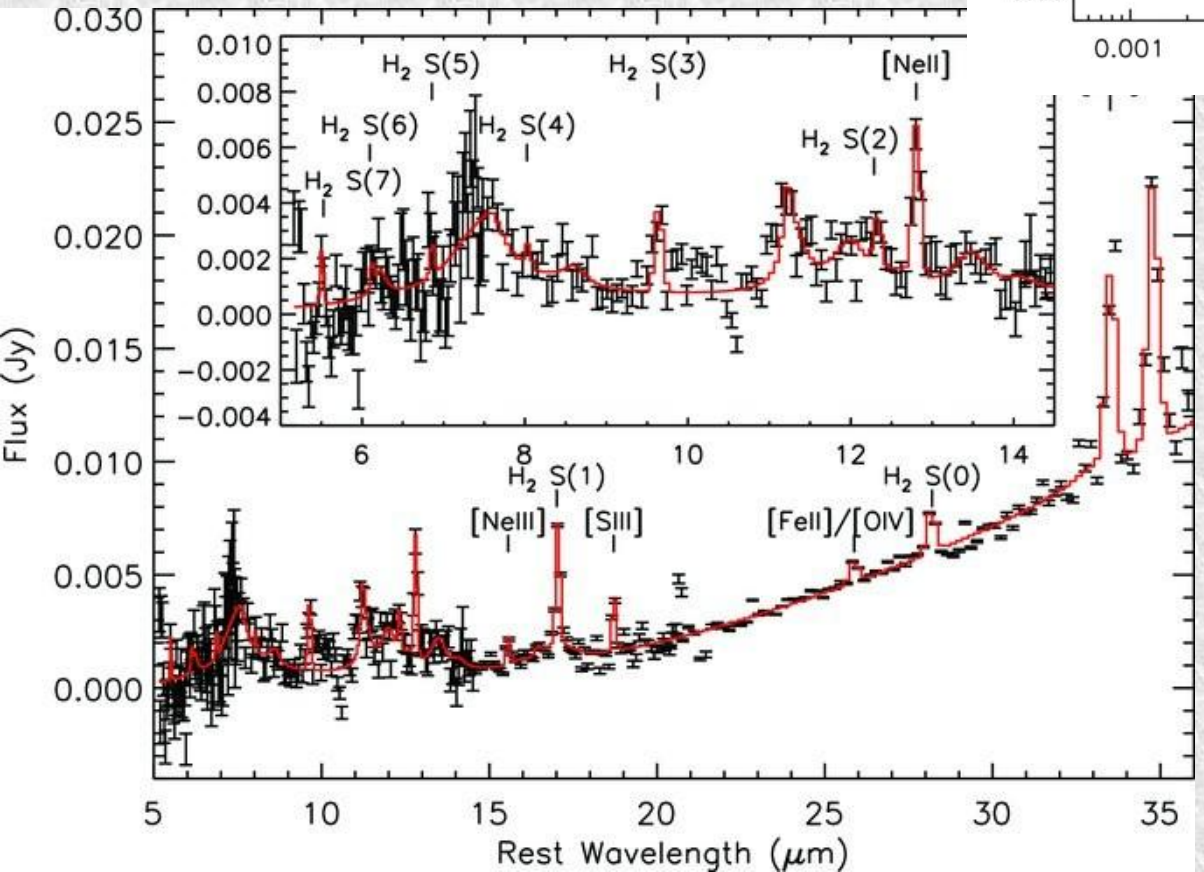
Sivanar





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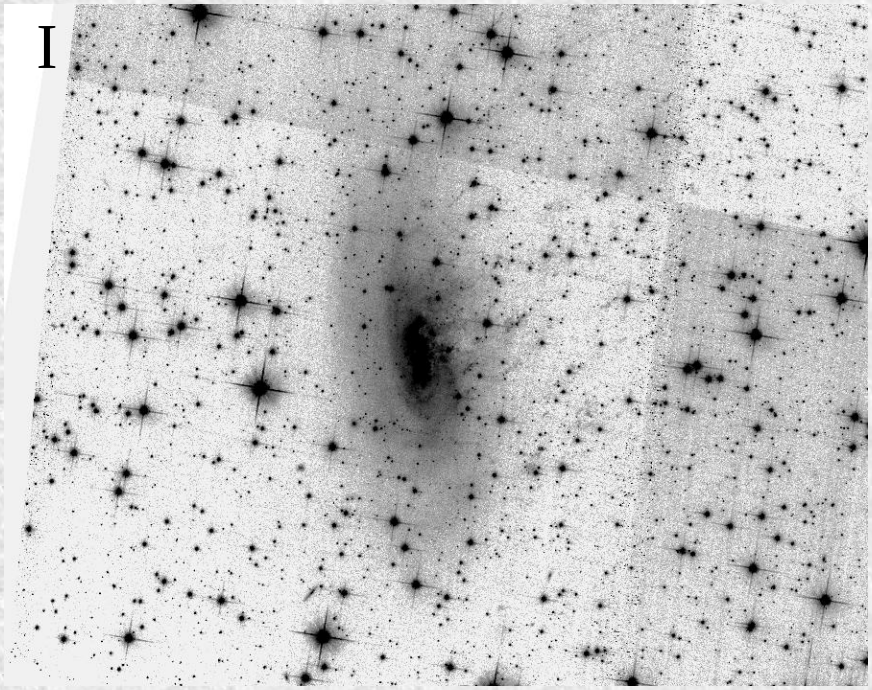
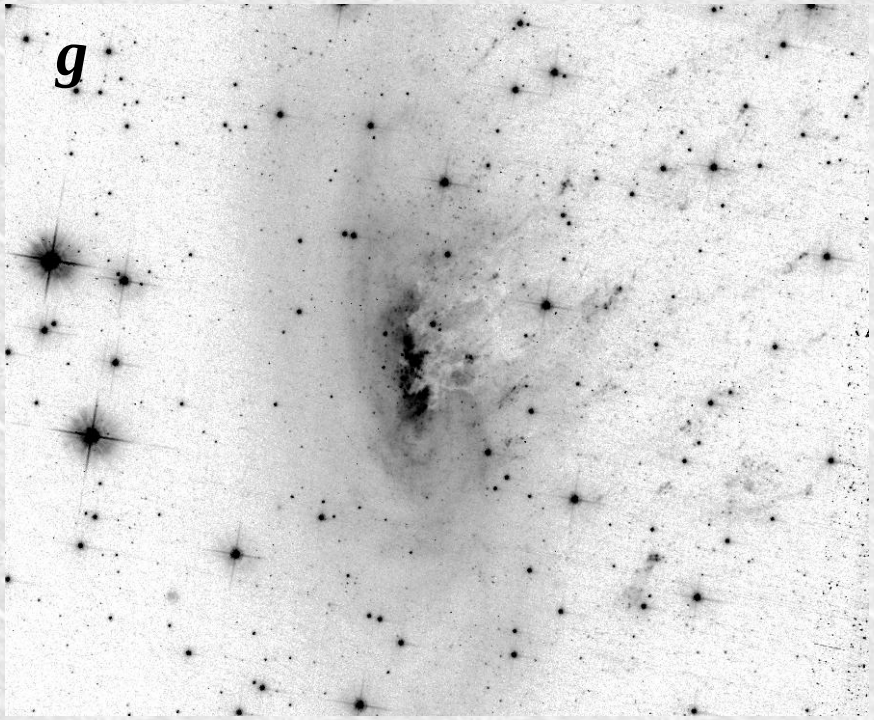
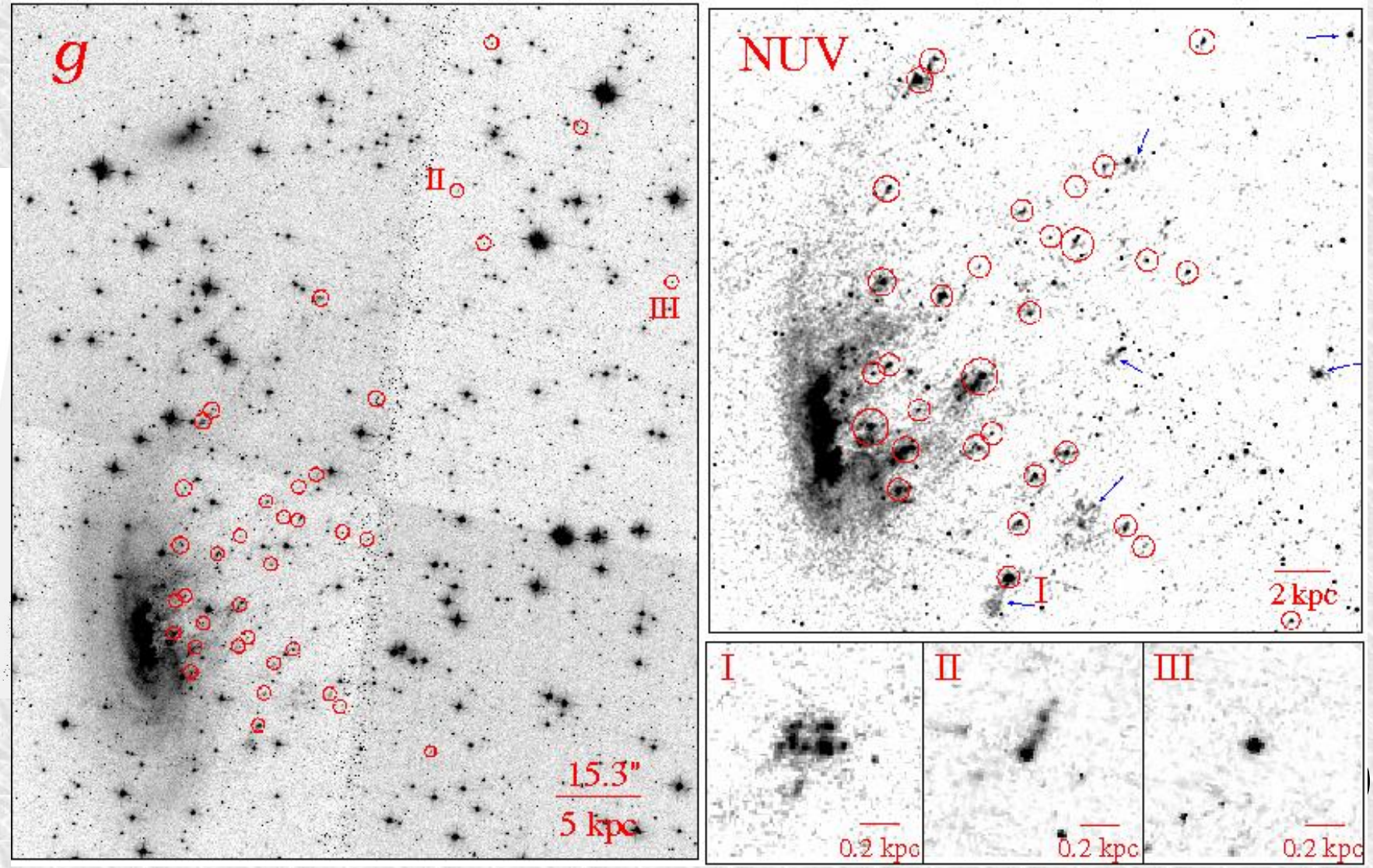




HST data (PI: Sun)

More data: HI (PI: Sun), CO with *Mopra* (PI: Sivanadam, Sun), *Herschel* (PI: Sivanadam, Sun), *JWST*/MIRI GTO



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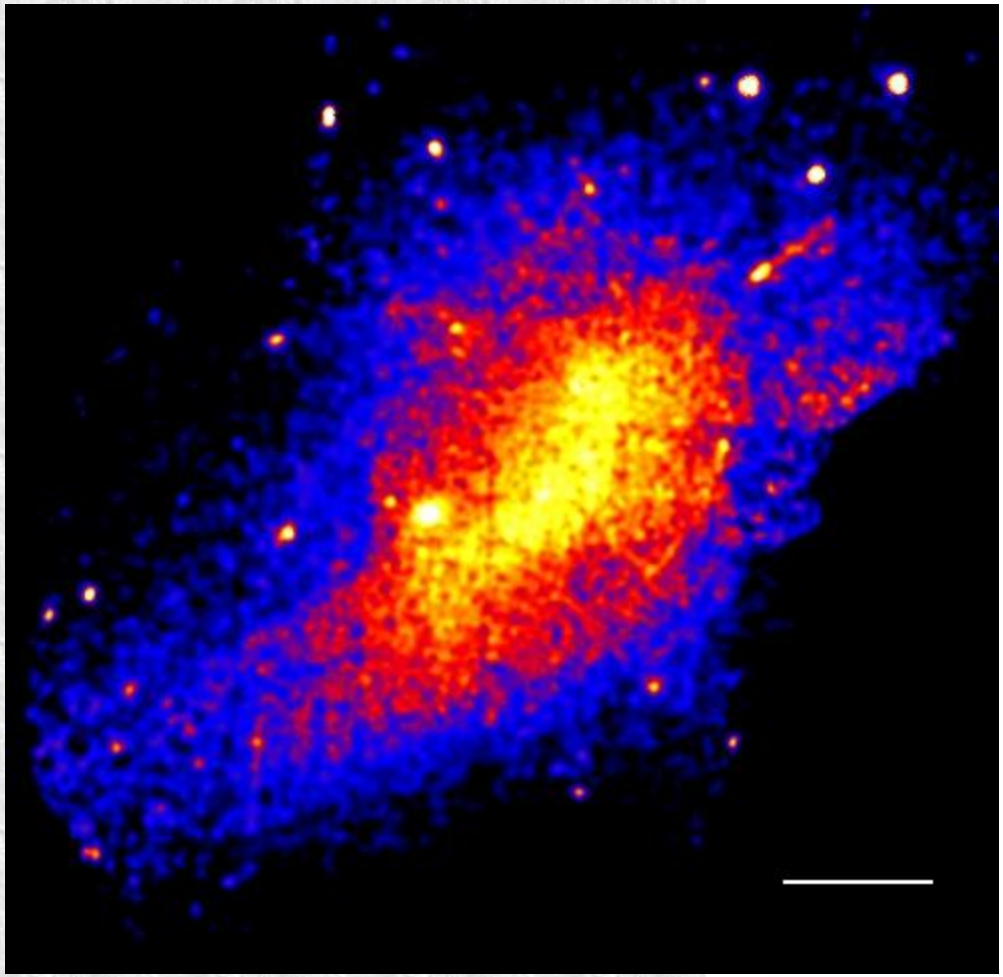
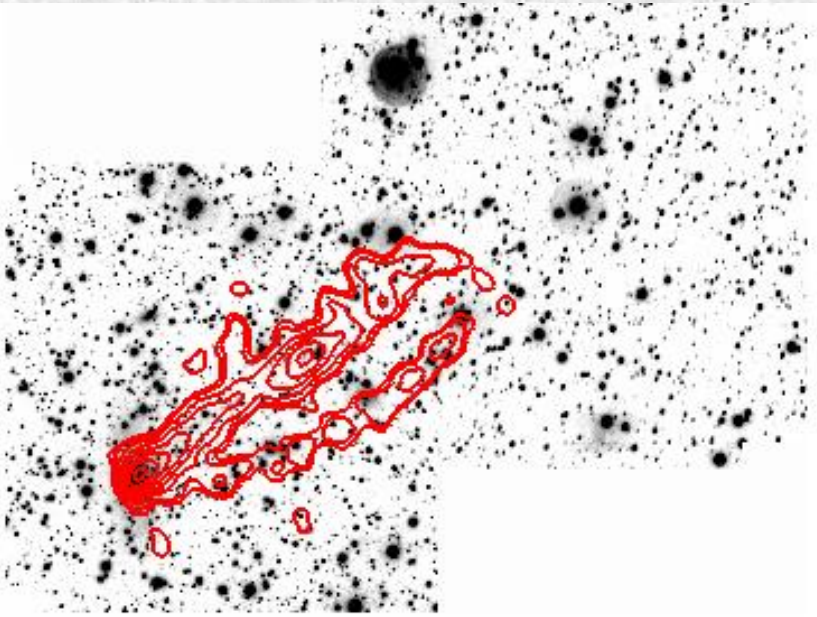
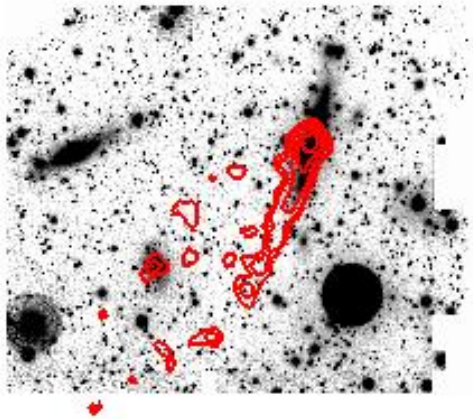


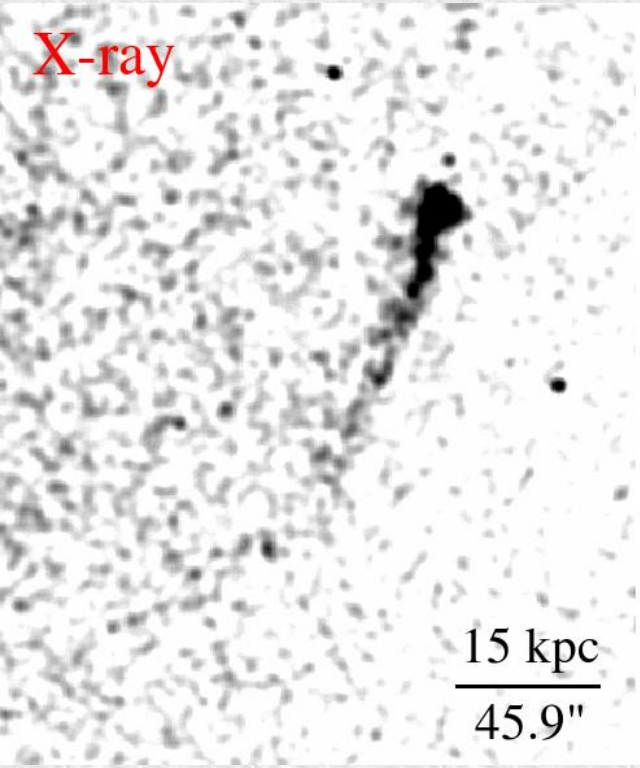


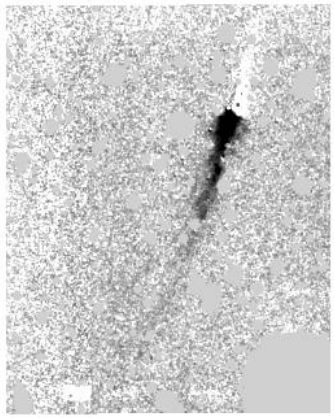
ESO 137-002:
A narrow X-ray tail to >~ 40 kpc

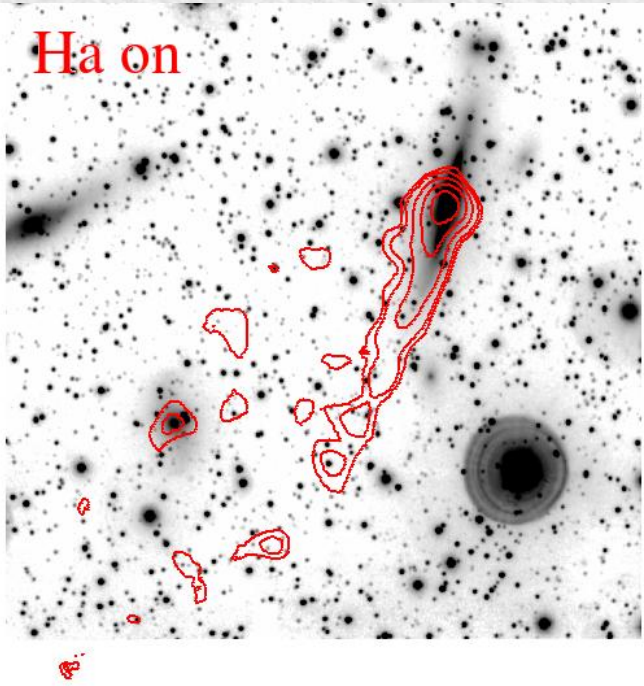


50 kpc
2.55'

ESO 137-002
(a more advanced stage?)

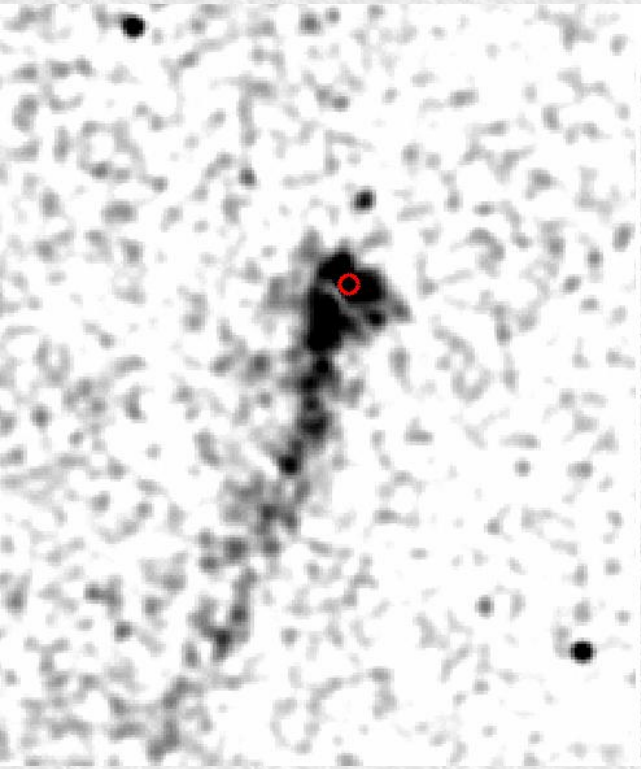


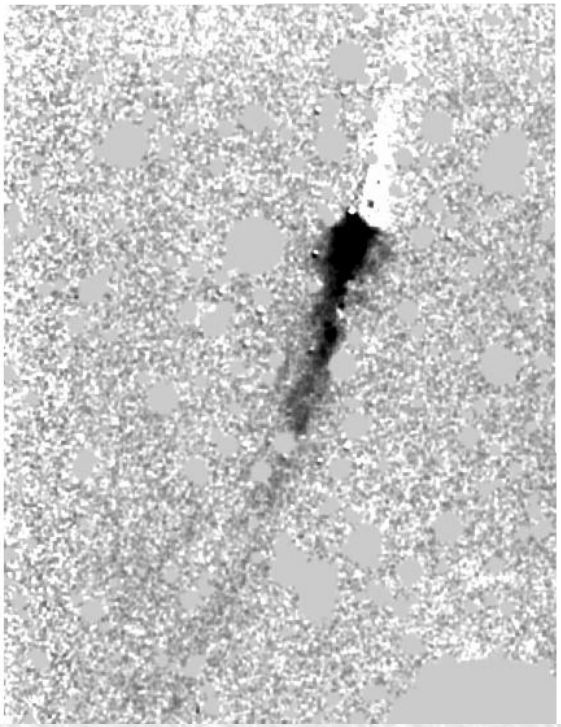


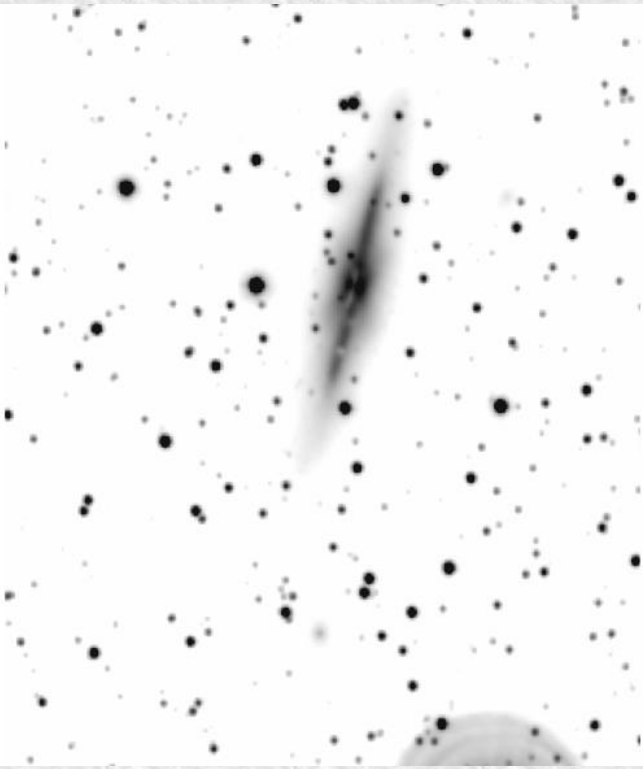


1) A narrow (~ 3 kpc) X-ray tail to > 40 kpc (~ 60 kpc ?)
2) kT ~ 1 keV, ~ 40% X-ray luminosity of ESO 137-001
3) No HII, but double Hα tails to ≥ 25 kpc

ESO 137-002
(a more advanced stage?)

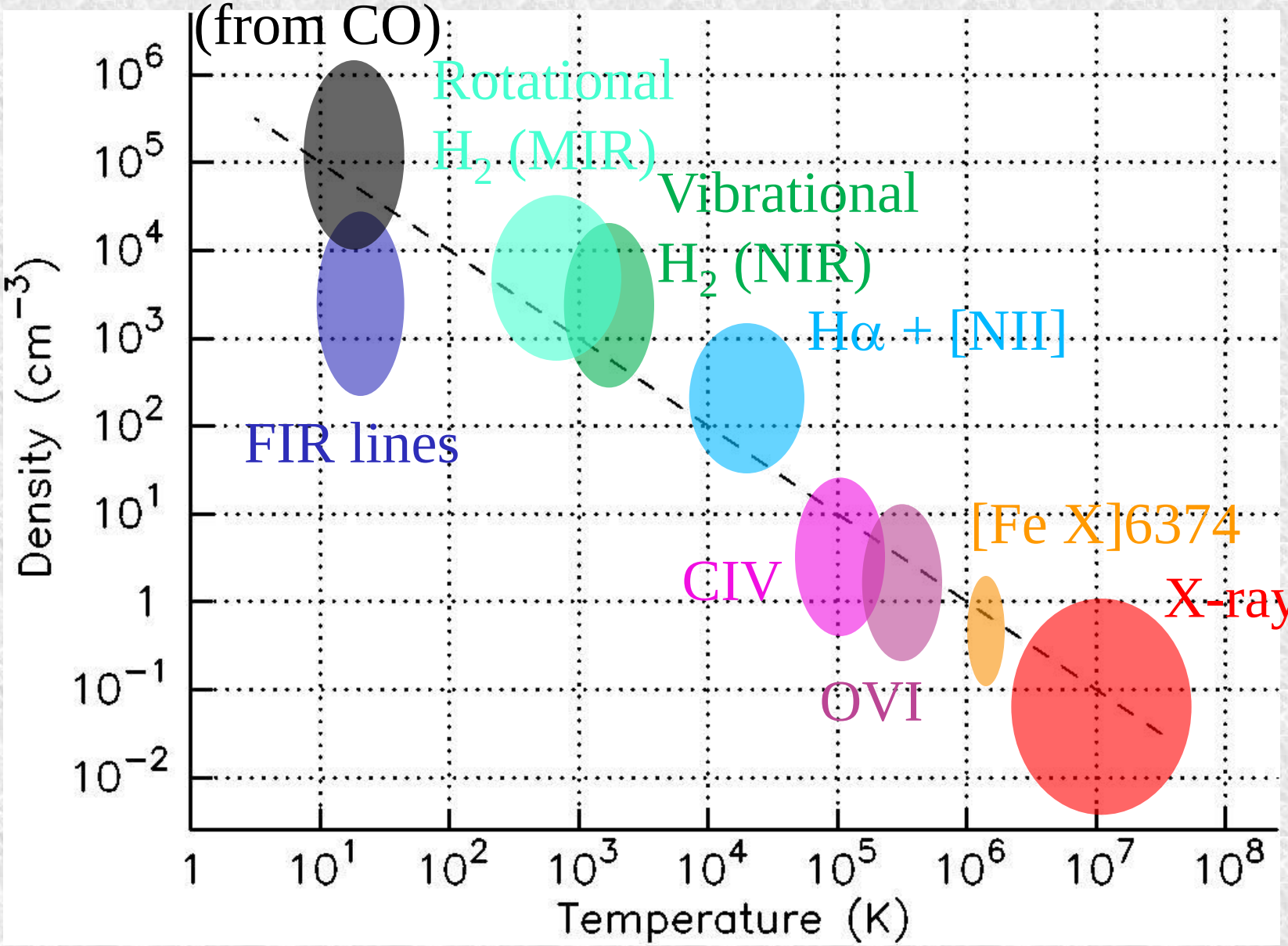




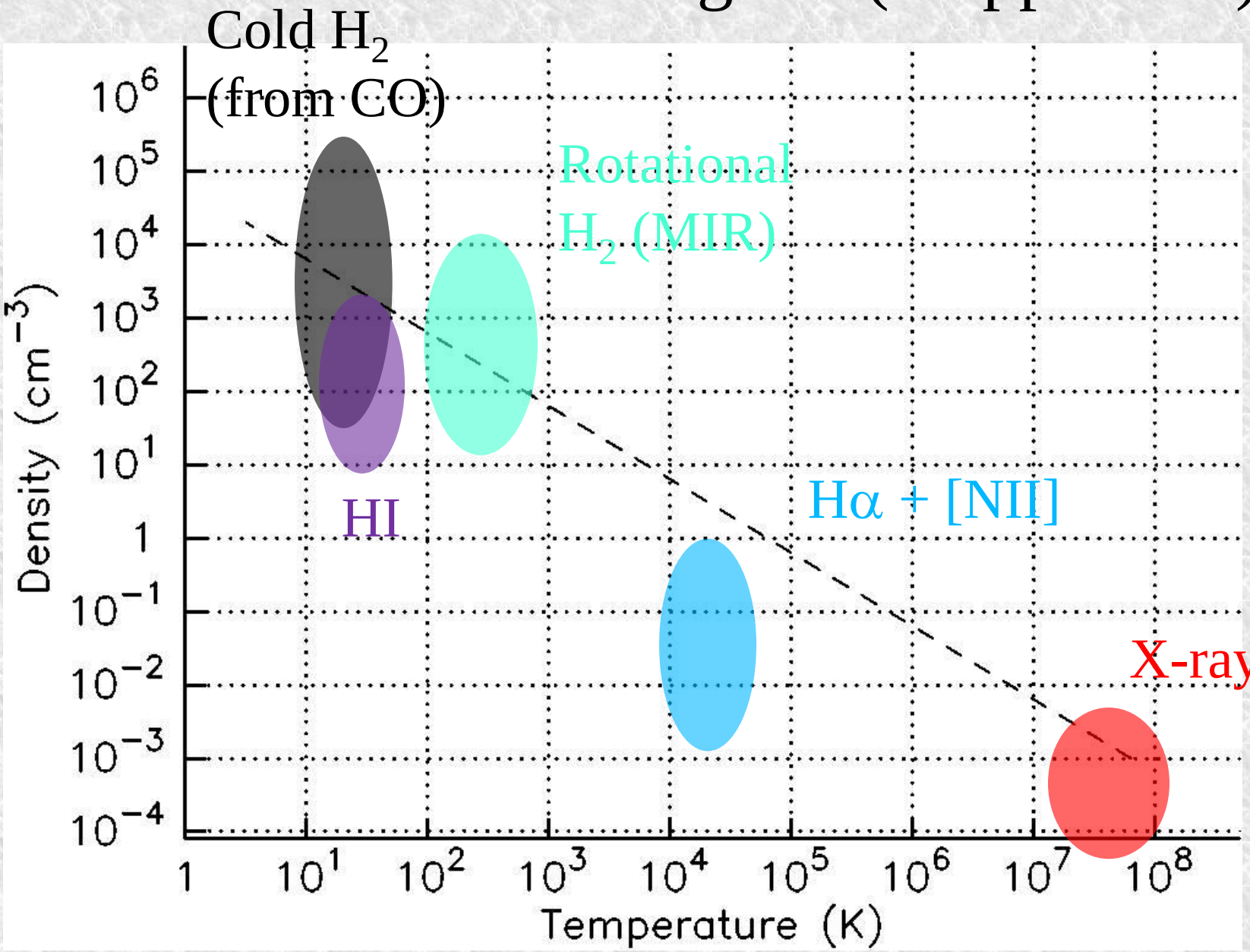


1) A narrow (~ 3 kpc) X-ray tail to > 40 kpc (~ 60 kpc ?)
2) kT ~ 1 keV, ~ 40% X-ray luminosity of ESO 137-001
3) No HII, but double Hα tails to $\geq$ 25 kpc

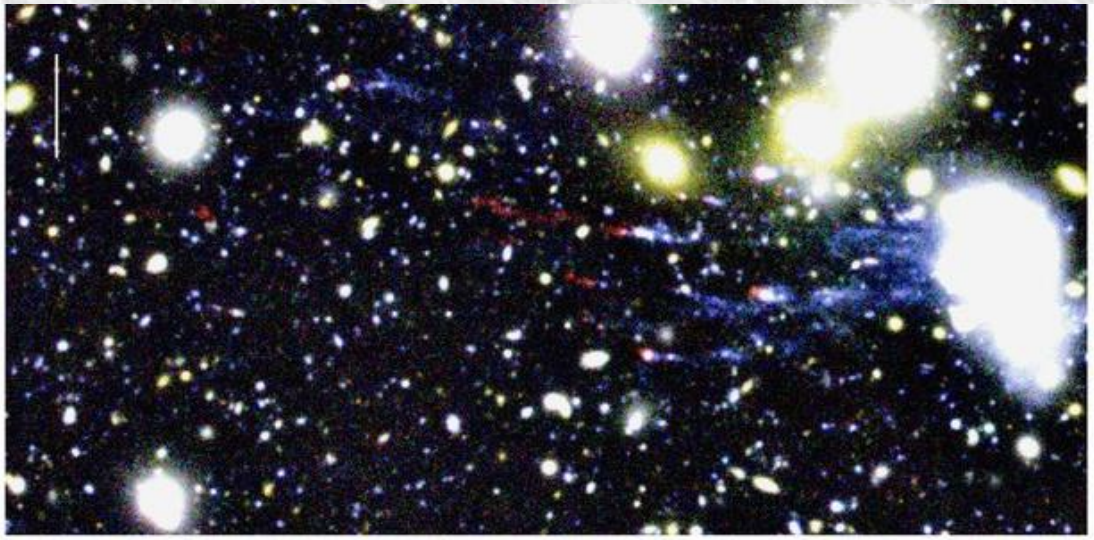
Phase diagram (cool core)

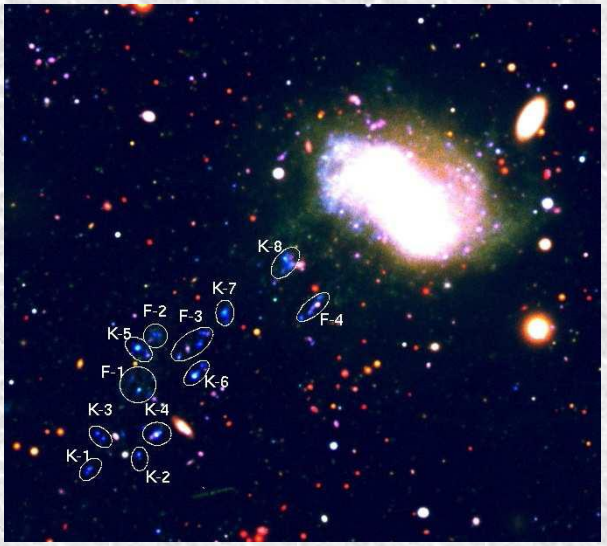


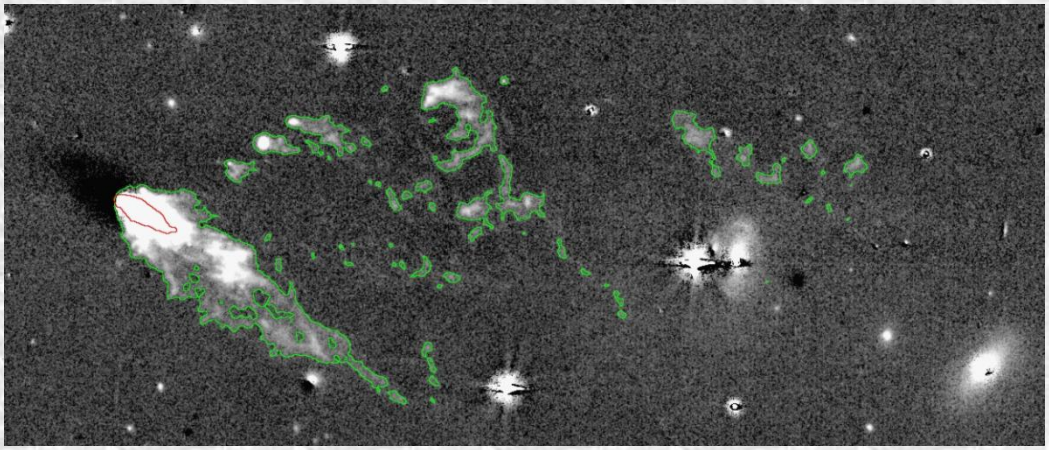
Phase diagram (stripped tail)

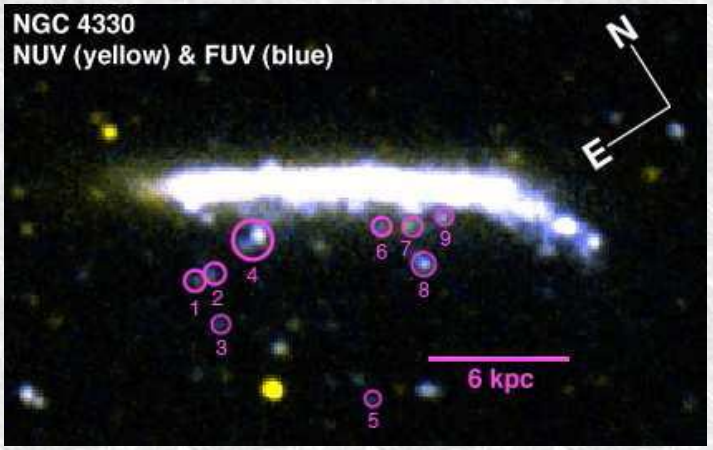


Over 20 more examples of one-sided trails of young star clusters and ionized gas from 2007 ...









one in A2667 and one in A1689 (Cortese + 2007)

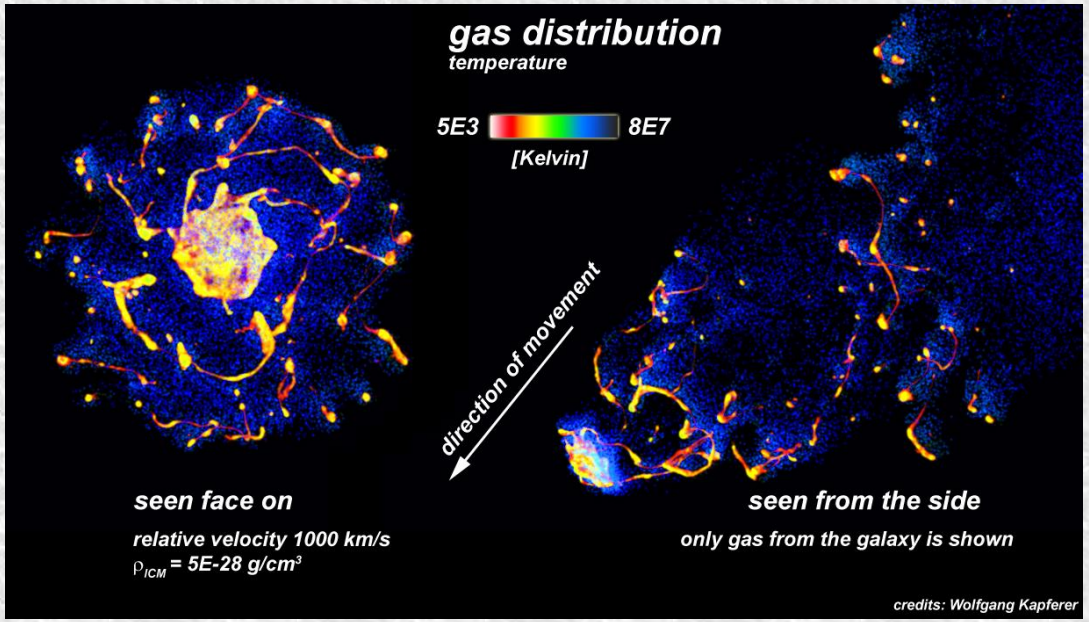
Coma: ~ **20** more (Yoshida + 2008; Yagi + 2010; Smith + 2010)

Virgo: IC 3418 (Hester + 2010; Fumagalli + 2011), N4330 (Abramson + 2011)

If you believe simulations ...

Up to 30% of stars in intracluster light are formed *in situ* (Puchwein et al. 2010)

--- materials stripped out of small infall haloes



Kapferer et al. 2009

Intracluster SF is real but how important?

1) The contribution to the intracluster light depends on the efficiency of SF in stripped gas
2) SF conditions and transport processes
3) Multi-phase gas --- similar conditions as in cool cores

Conclusions

1) BCGs in cool cores can host spectacular emission-line nebulae. SF is revealed from the UV and IR data, but emission lines requires another ionizing mechanism.

2) SF in the stripped ISM is common and will contribute to the intracluster light. But how important ? and a lot of detail to learn

3) Both are great to study energy transfer and micro-physics in multi-phase medium

Many thanks to the whole SOAR consortium and the meeting organizers!