Galaxy / Cluster Ecosystem

Ming Sun
(University of Alabama in Huntsville)

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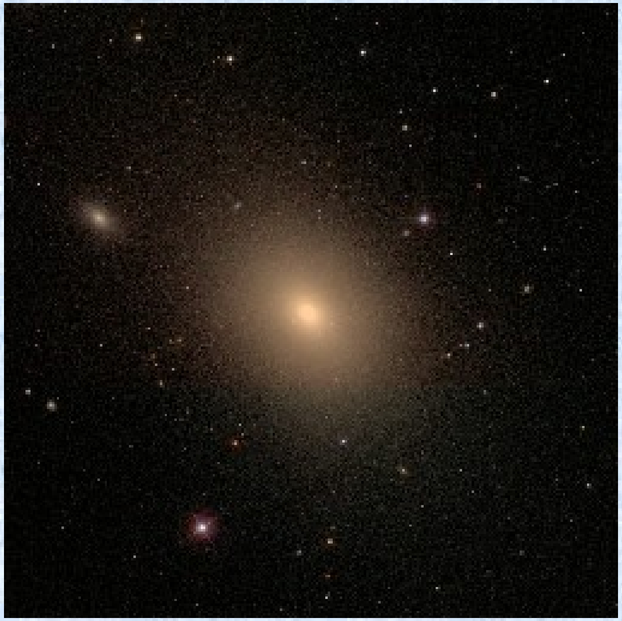
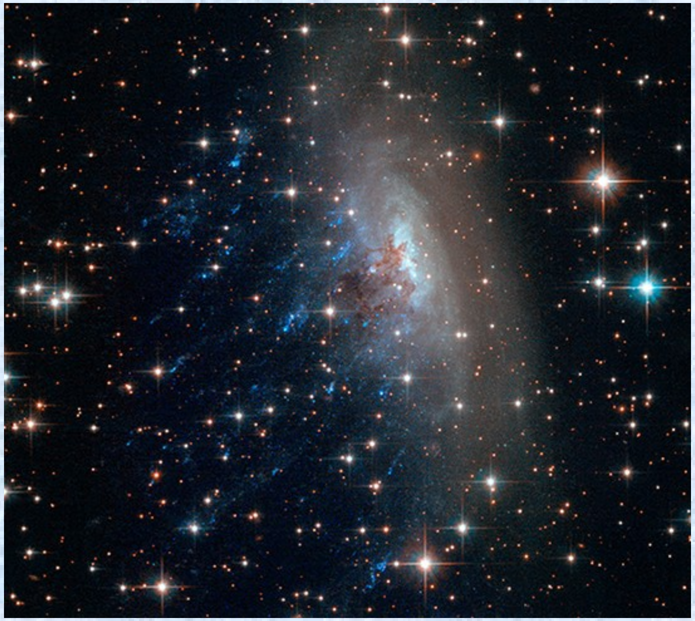
Why study galaxy / cluster ecosystem ?

1) Galaxies inject energy into the intracluster medium (ICM), with AGN outflows, galactic winds, galaxy motion etc.
2) Galaxies also dump heavy elements and magnetic field in the ICM.
3) Clusters also change galaxies, e.g., density - morphology (or SFR) relation, with e.g., ram pressure stripping and harassment.
4) Great examples to study transport processes (conductivity and viscosity)





Summary

Environment

UMBHs

Radio AGN

Stripping

Conduction

B Draping

Turbulence

Ram pressure

stripped tails

(multi-phase

gas and SF)

You have heard a lot of discussions on thermal coronae of early-type galaxies in this workshop. What about early-type galaxies in clusters? Are they “naked” without gas? --- **No** firm detections of coronae in hot clusters before *Chandra* !

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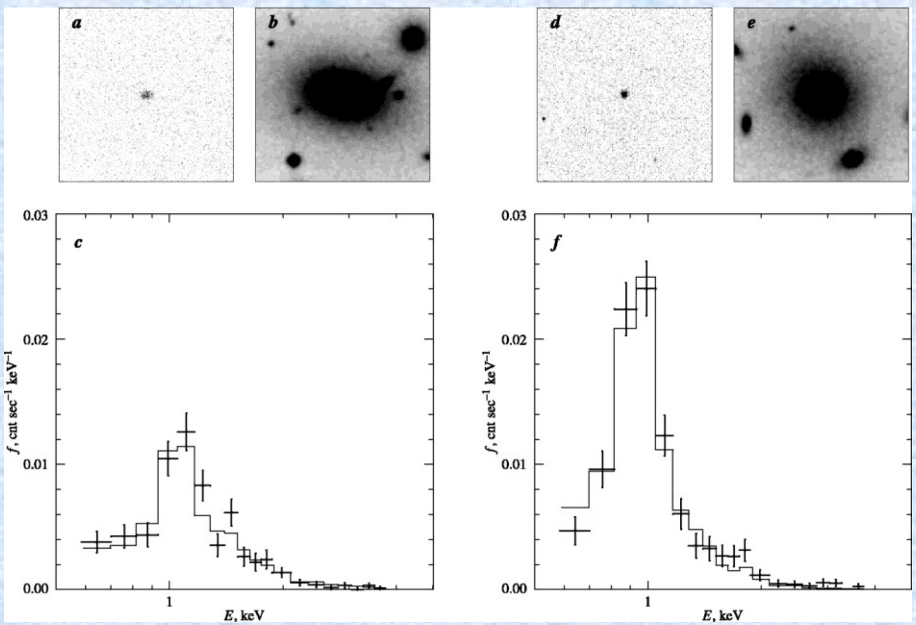

Vikhlinin + 2001

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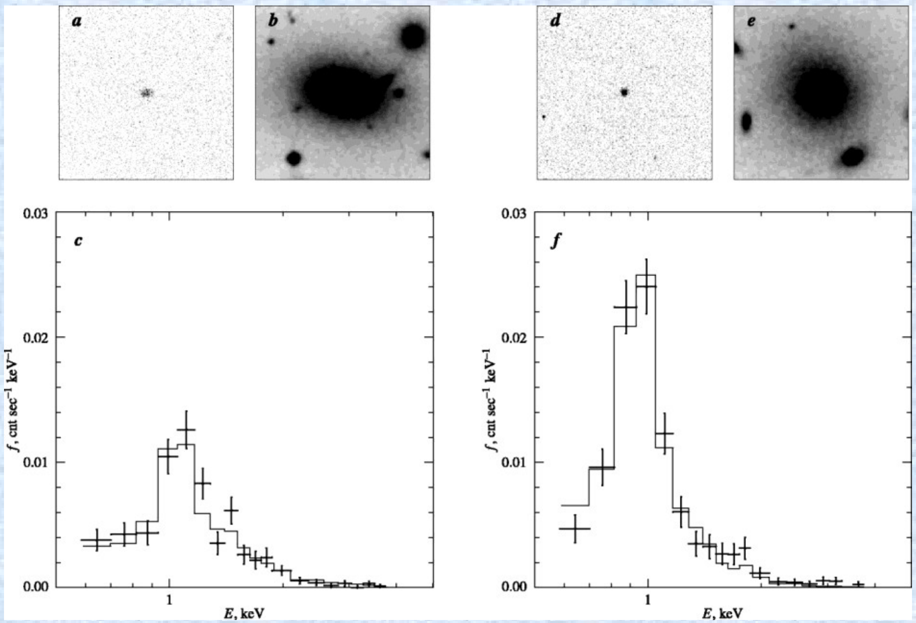

Vikhlinin + 2001

Later more embedded coronae discovered (Yamasaki+2002; Sun+2002, 2005, 2006) and the first sample in Sun+2007

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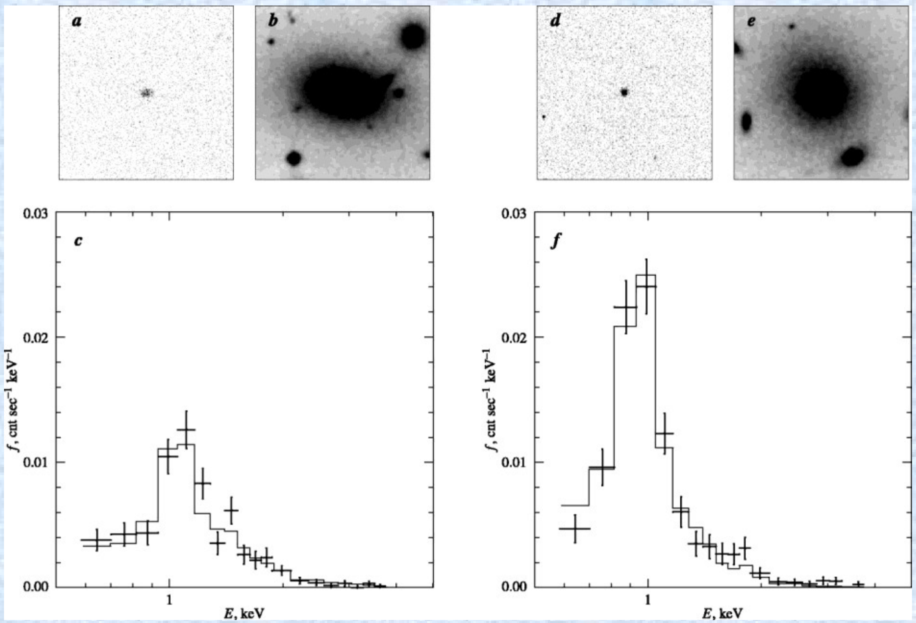

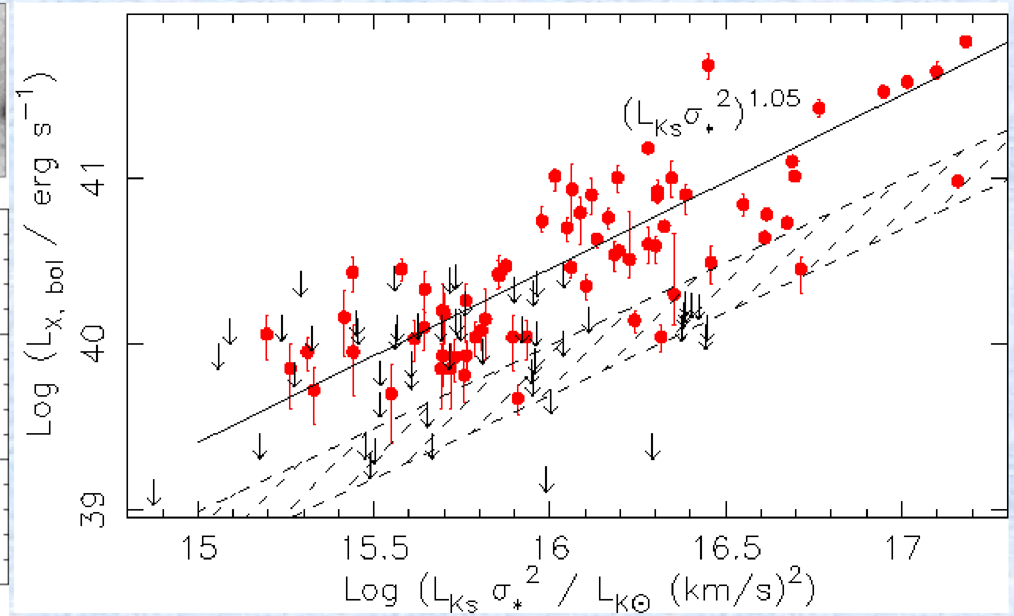

Vikhlinin + 2001

Sun + 2007

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OUTWIT OUTPLAY
SURVIVOR
OUTLAST
OUTWIT · OUTPLAY
SURVIVOR
OUTLAST
OUTWIT OUTPLAY
SURVIVOR
THE AUSTRALIAN OUTBACK
OUTLAST
OUTWIT OUTPLAY
SURVIVOR
AFRICA
OUTLAST
OUTWIT OUTPLAY
SURVIVOR
MARQUESAS
OUTLAST
OUTWIT OUTPLAY
SURVIVOR
THAILAND
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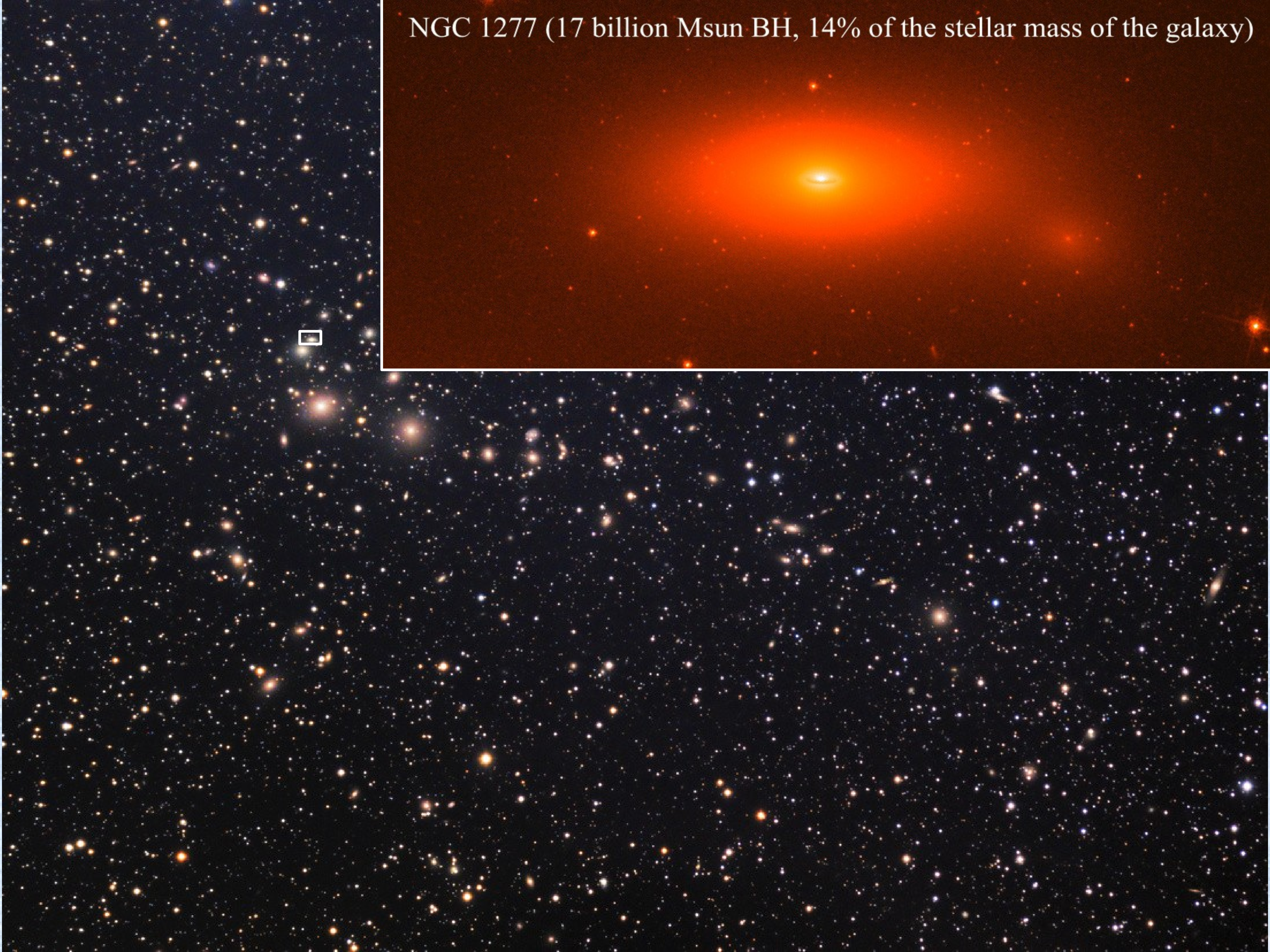
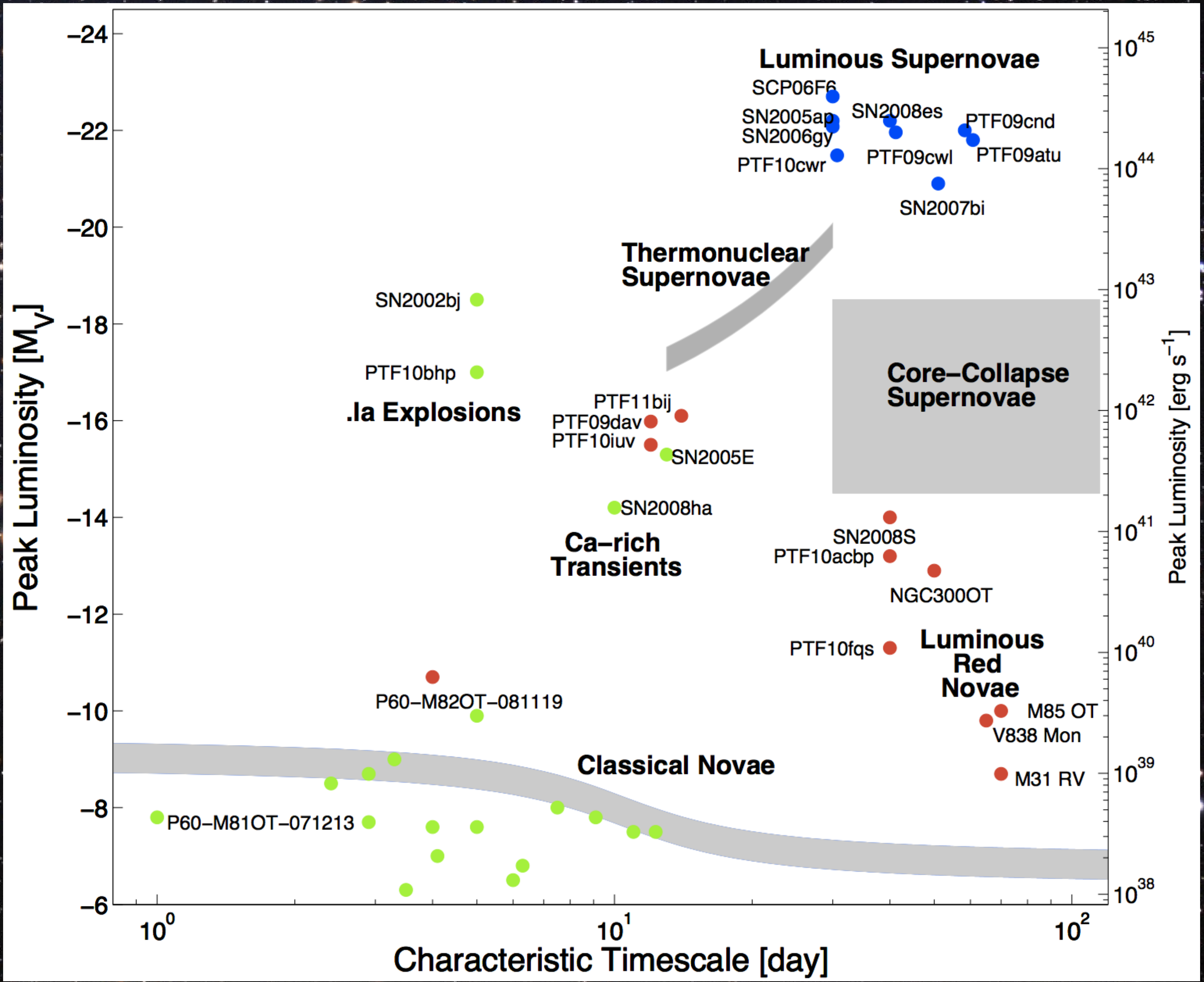
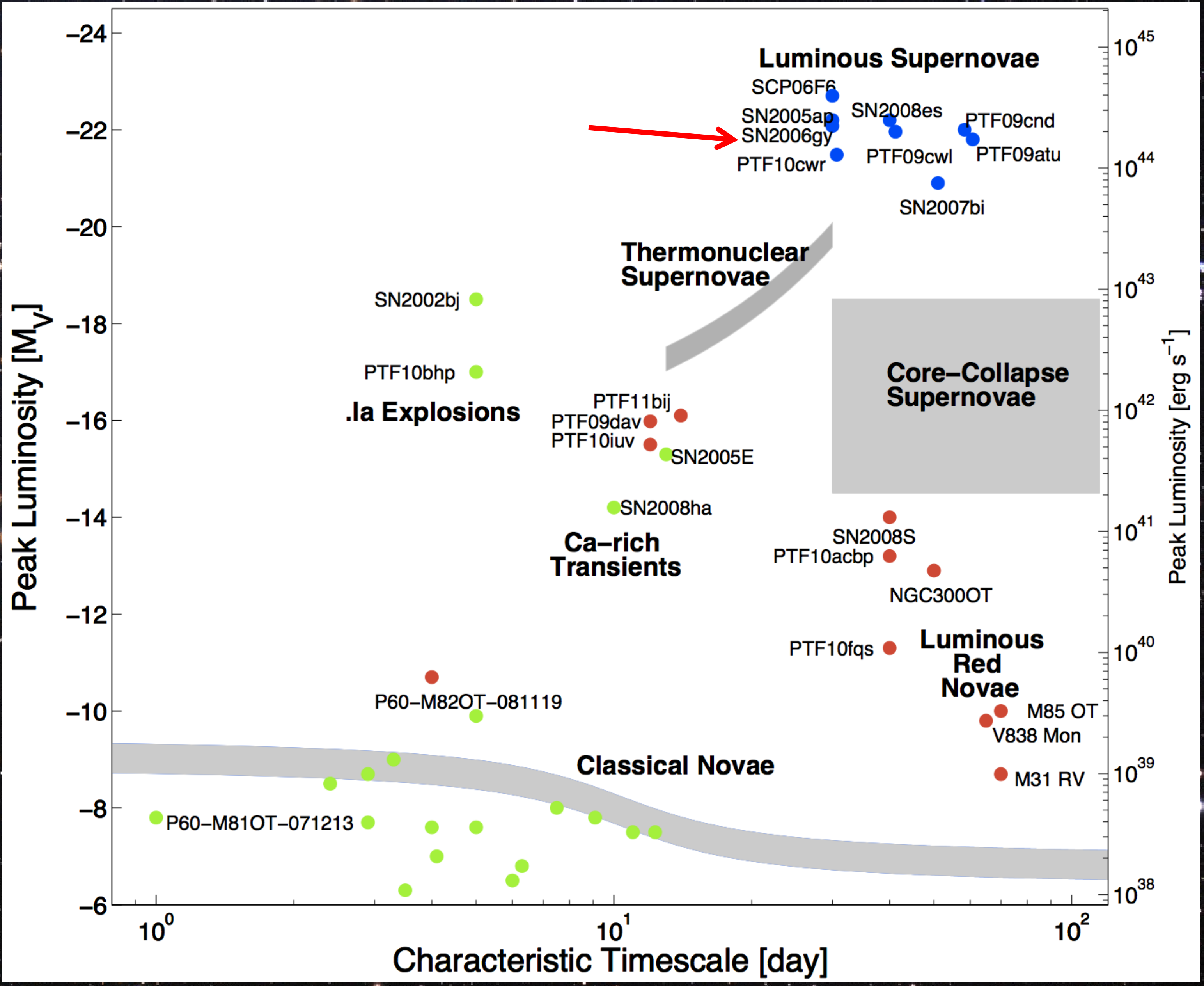
OUTWIT OUTPLAY
SURVIVOR
THE AMAZON
OUTLAST
OUTWIT OUTPLAY
SURVIVOR
PEARL ISLANDS
OUTLAST
OUTWIT OUTPLAY
SURVIVOR
ALL-STARS
OUTLAST
OUTWIT OUTPLAY
SURVIVOR
VANUATU
ISLANDS OF FIRE
OUTLAST
OUTWIT OUTPLAY
SURVIVOR
PALAU
OUTLAST
OUTWIT OUTPLAY
SURVIVOR
GUATEMALA
THE MAYAN EMPIRE
OUTLAST
OUTWIT OUTPLAY
SURVIVOR
PANAMA
EXILE ISLAND
OUTLAST
OUTWIT OUTPLAY
SURVIVOR
Cook Islands
OUTLAST
OUTWIT OUTPLAY
SURVIVOR
FIJI
OUTLAST
SURVIVOR
CHINA
OUTWIT OUTPLAY
SURVIVOR
MICRONESIA
FANS vs FAVORITES
OUTLAST
OUTWIT OUTPLAY
SURVIVOR
GABON
earth's last eden
OUTLAST
OUTWIT OUTPLAY OUTLAST
SURVIVOR
TOCANTINS
THE BRAZILIAN HIGHLANDS
OUTWIT OUTPLAY
SURVIVOR
SAMOA
OUTLAST


NGC 1277 (17 billion Msun BH, 14% of the stellar mass of the galaxy)


Luminous Supernovae
SCP06F6
SN2005ap
SN2006gy
SN2008es
PTF09cnd
PTF10cwr
PTF09cwl
PTF09atu
SN2007bi
Thermonuclear Supernovae
SN2002bj
PTF10bhp
.Ia Explosions
PTF11bij
PTF09dav
PTF10iuv
SN2005E
Core–Collapse Supernovae
SN2008ha
Ca–rich Transients
SN2008S
PTF10acbp
NGC300OT
PTF10fqs
Luminous Red Novae
P60–M82OT–081119
M85 OT
V838 Mon
Classical Novae
M31 RV
P60–M81OT–071213
Peak Luminosity [M_V]
Peak Luminosity [erg s^{-1}]
Characteristic Timescale [day]
−24
−22
−20
−18
−16
−14
−12
−10
−8
−6
10^{45}
10^{44}
10^{43}
10^{42}
10^{41}
10^{40}
10^{39}
10^{38}
10^0
10^1
10^2



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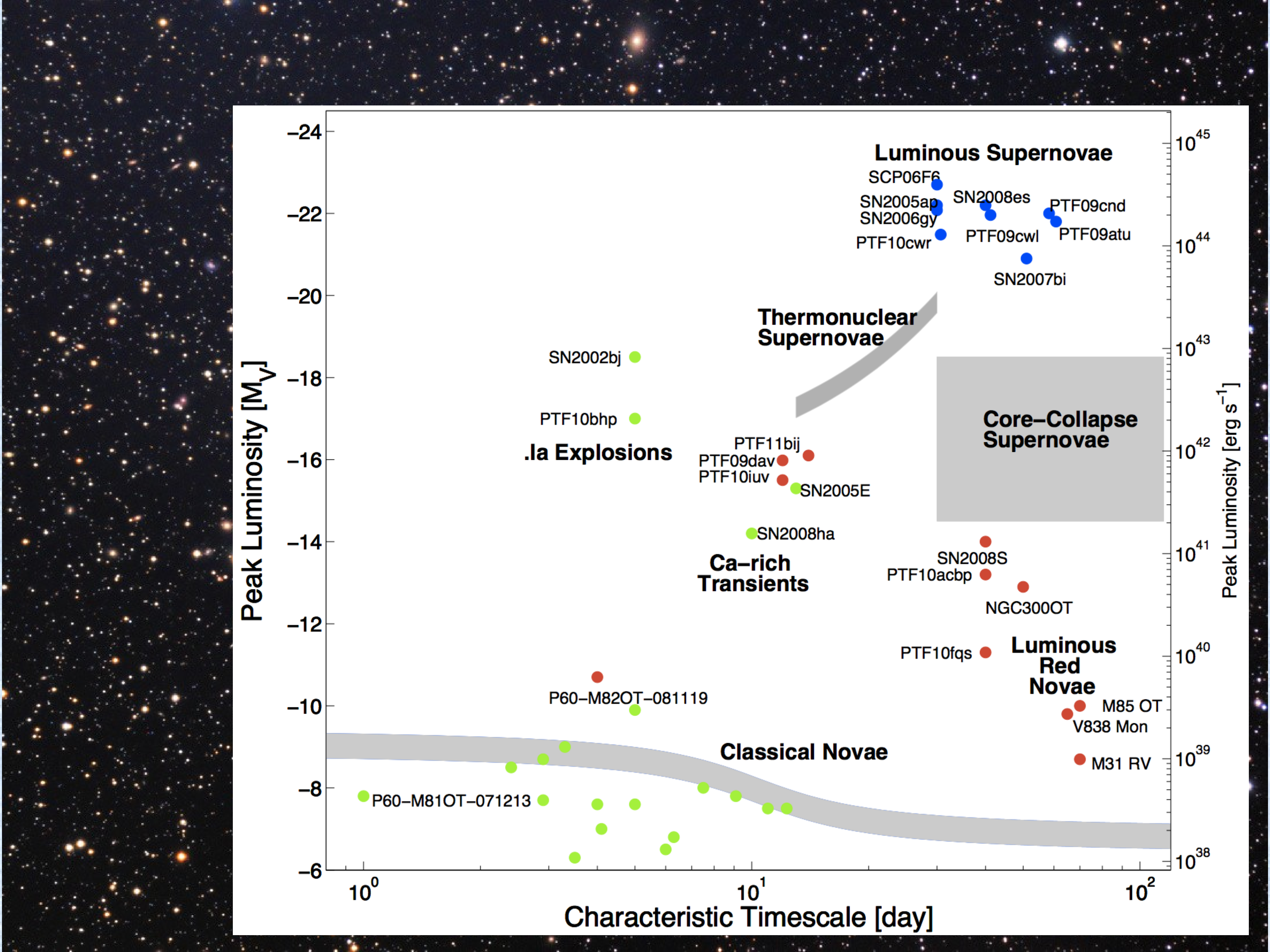
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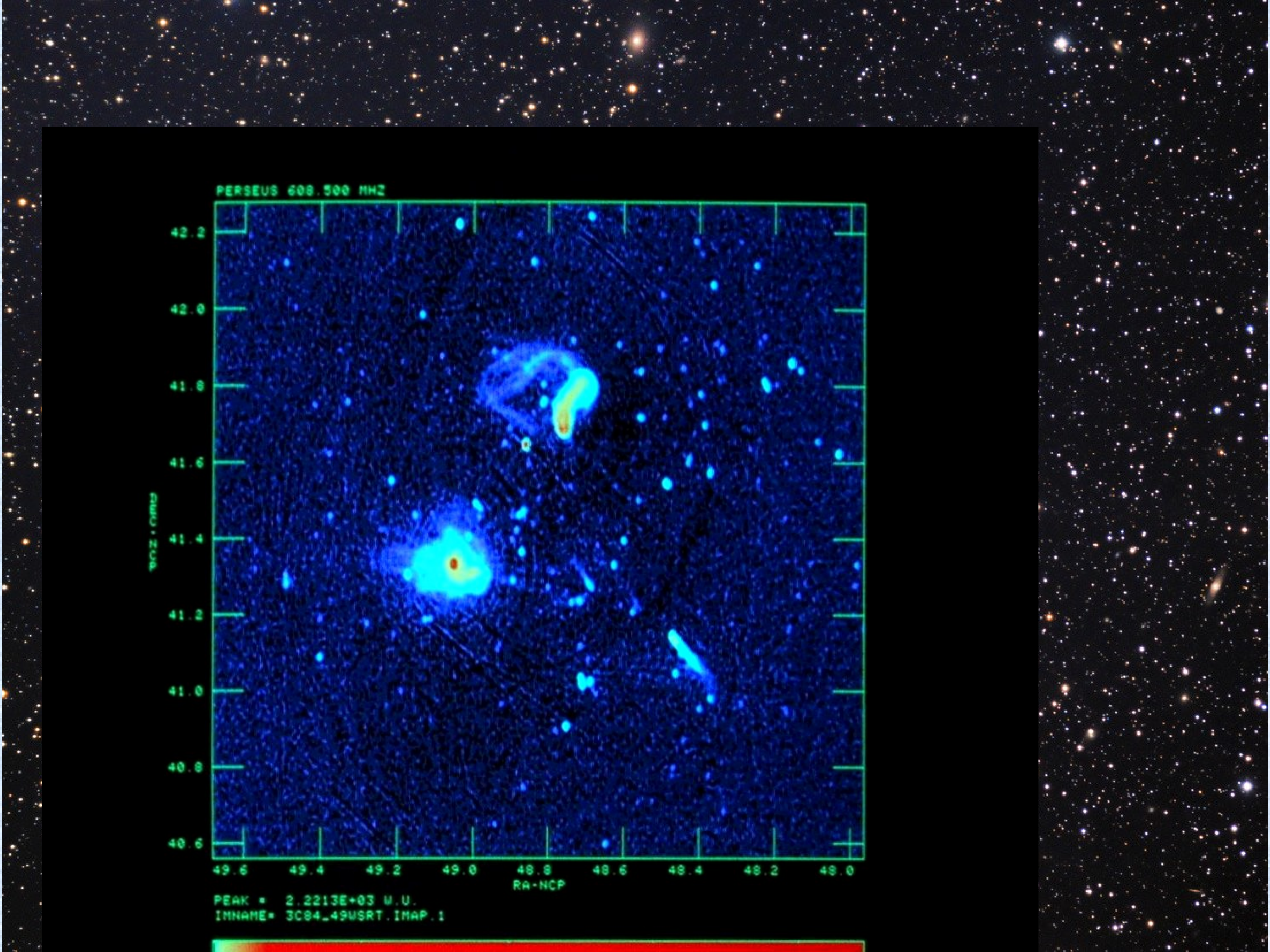
10^1
10^2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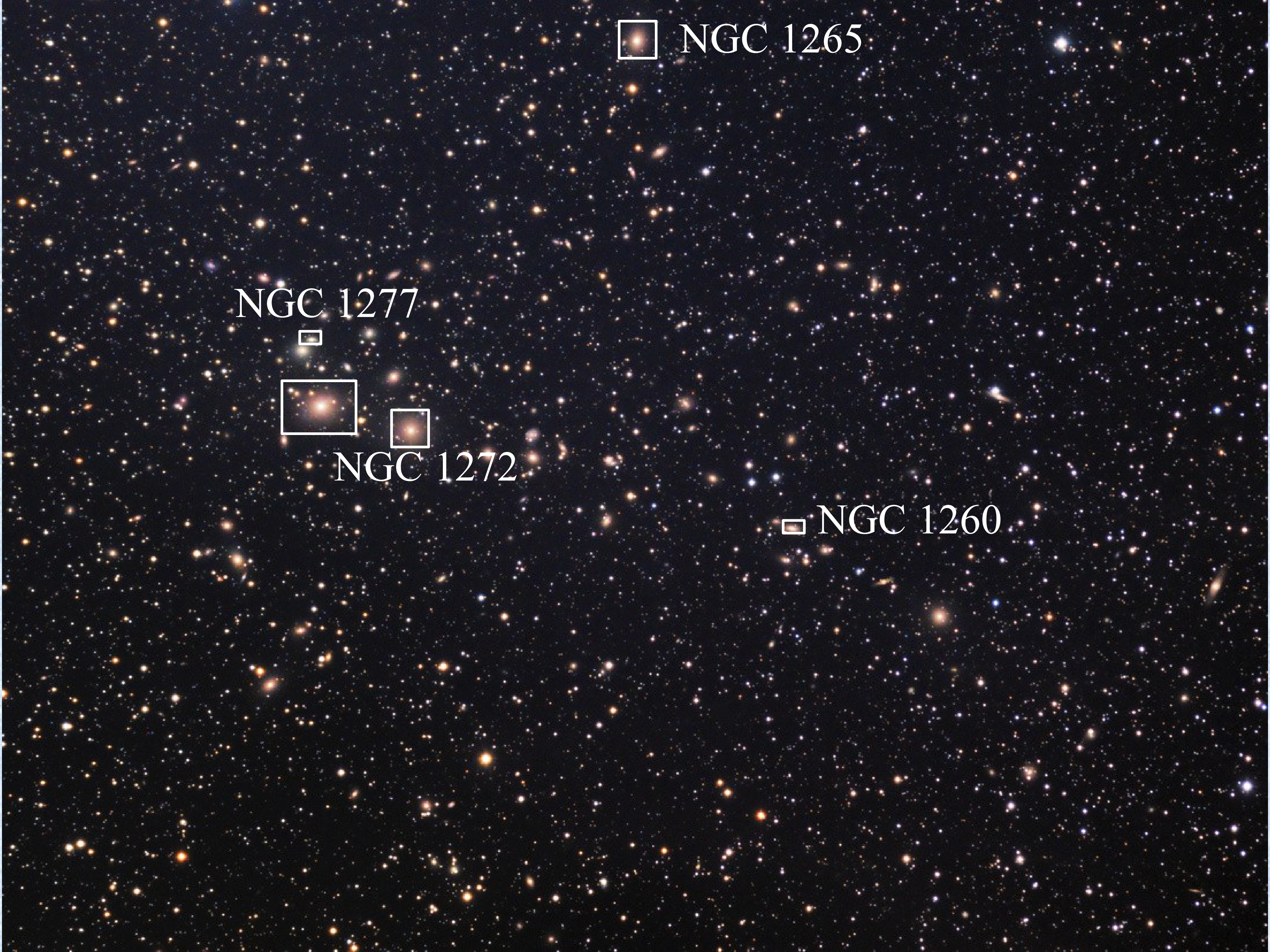
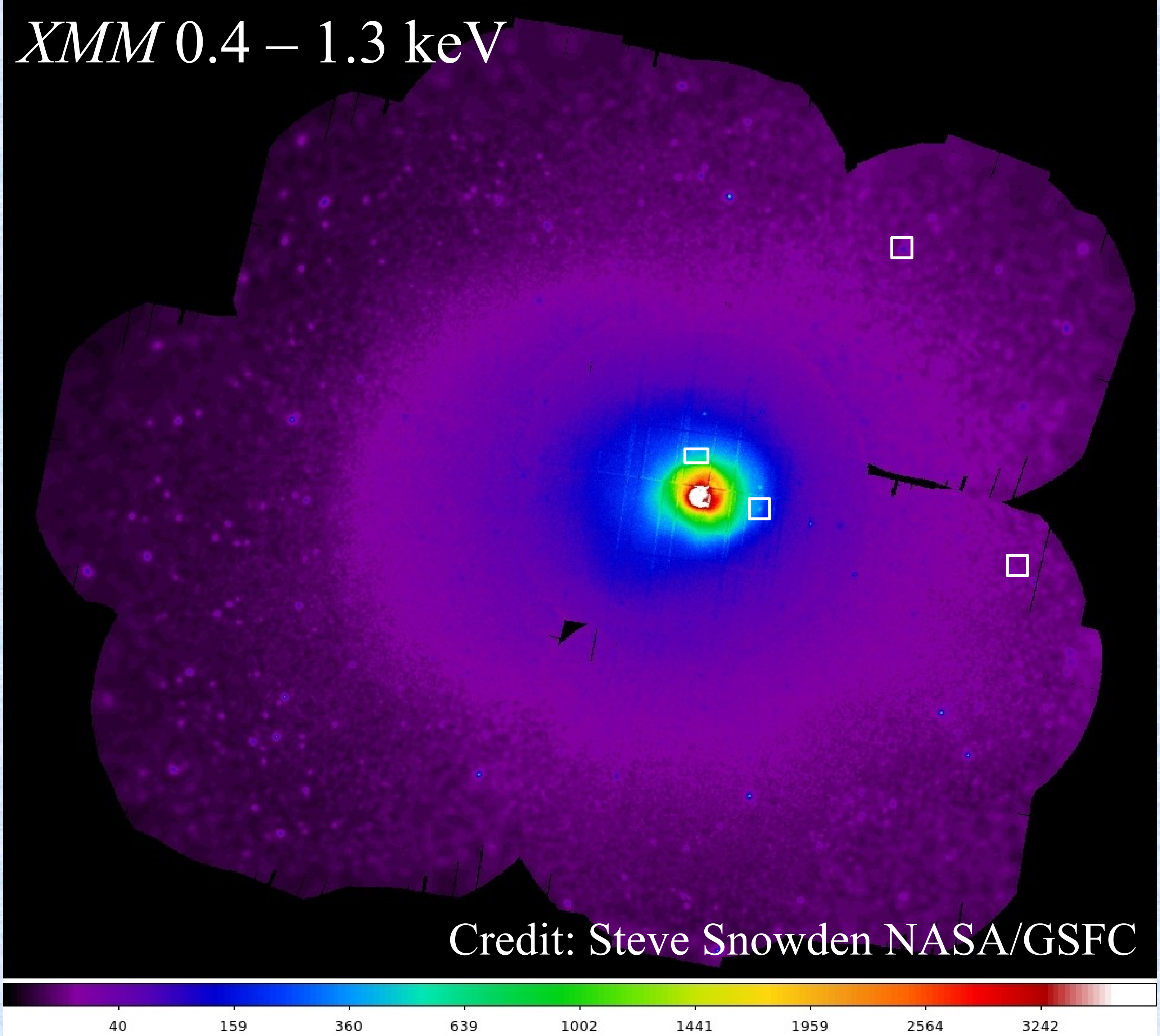
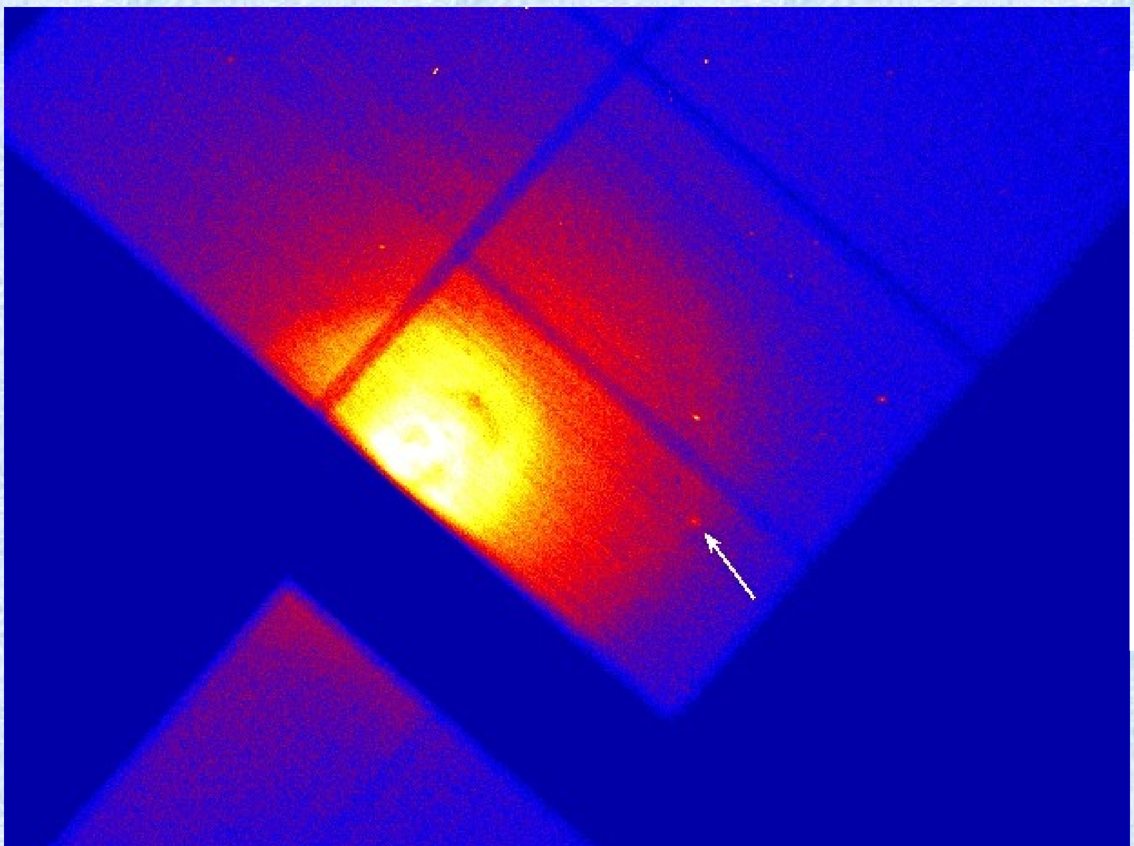
DEC-NCP
RA-NCP
PEAK = 2.2213E+03 W.U.
IMNAME= 3C84_49WSRT.IMAP.1

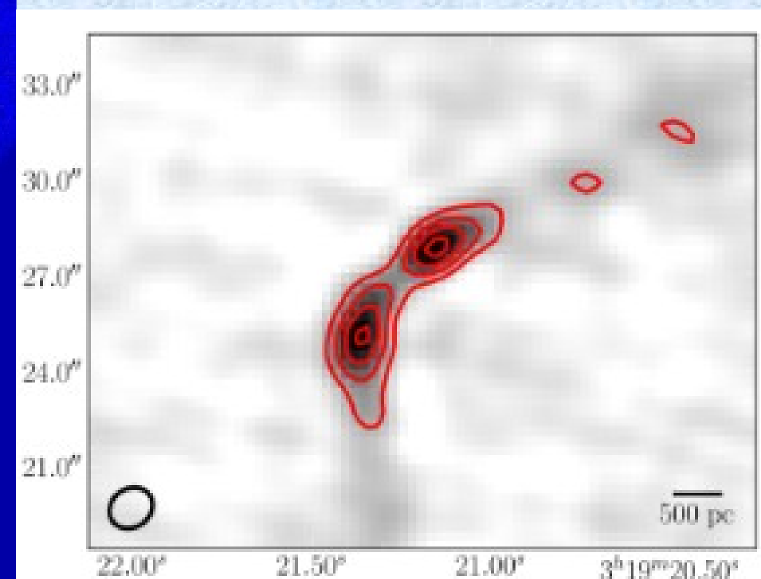

NGC 1265
NGC 1277
NGC 1272
NGC 1260


XMM 0.4 – 1.3 keV
Credit: Steve Snowden NASA/GSFC
40
159
360
639
1002
1441
1959
2564
3242

NGC 1272

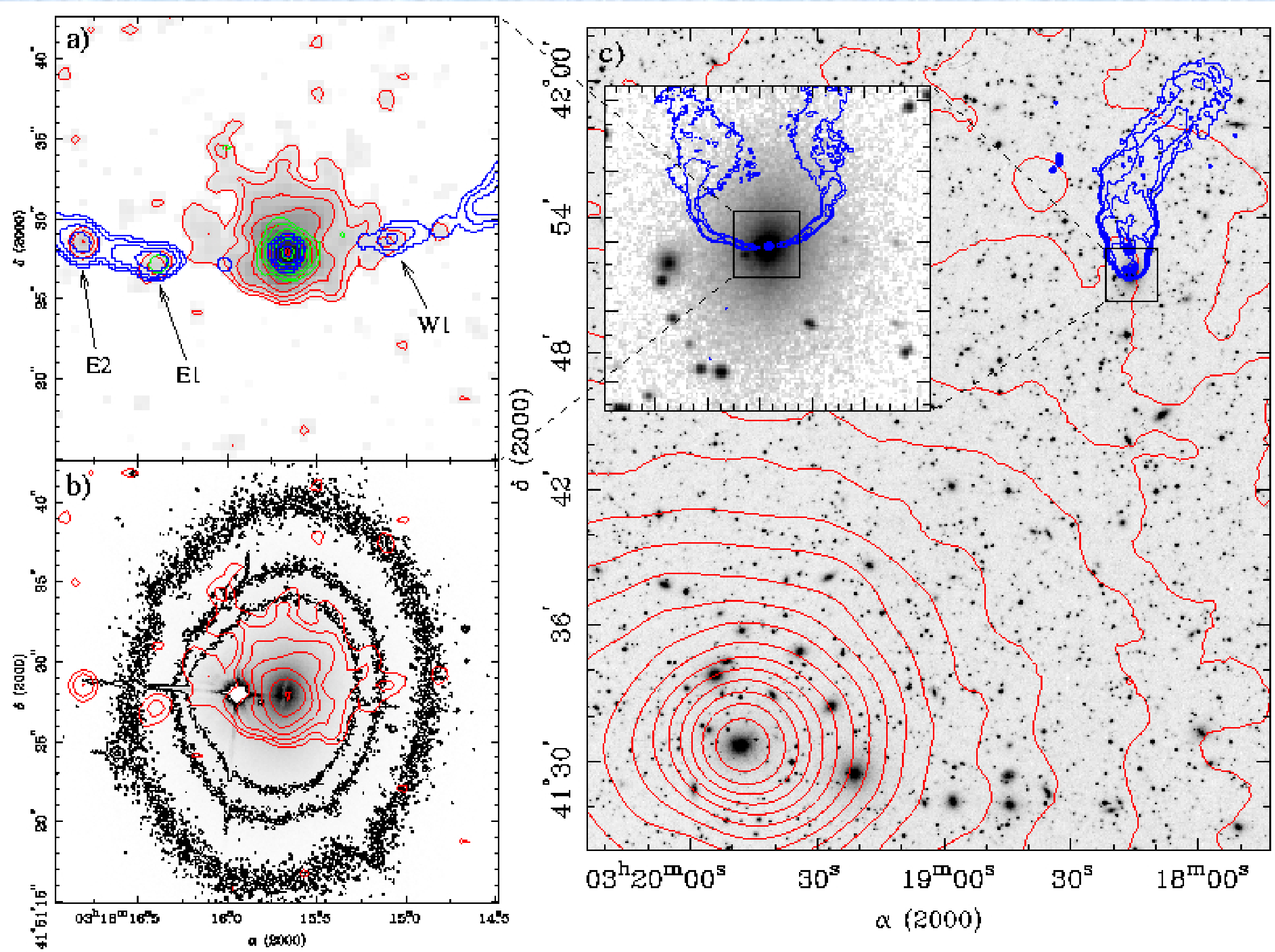
- The second most massive galaxy in the Perseus cluster (~ 60% of NGC 1275's light, velocity: -1551 km/s)
- An X-ray corona (kT ~ 0.56 keV) and a small wide-angle radio galaxy (WAT)





(Radio image from McBride & McCourt 2014)

NGC 1265 (3C83.1B) in Perseus --- “**Bullet galaxy**”



A 0.6 keV mini cool core (central cooling time ~ 10 Myr) embedded in the 6.7 keV ICM.

A sharp edge 0.8 kpc south of the nucleus.

Galaxy’s velocity vs. Perseus’s: + 2170 km/s --- Mach number of ~ 3 --- a Bullet galaxy !

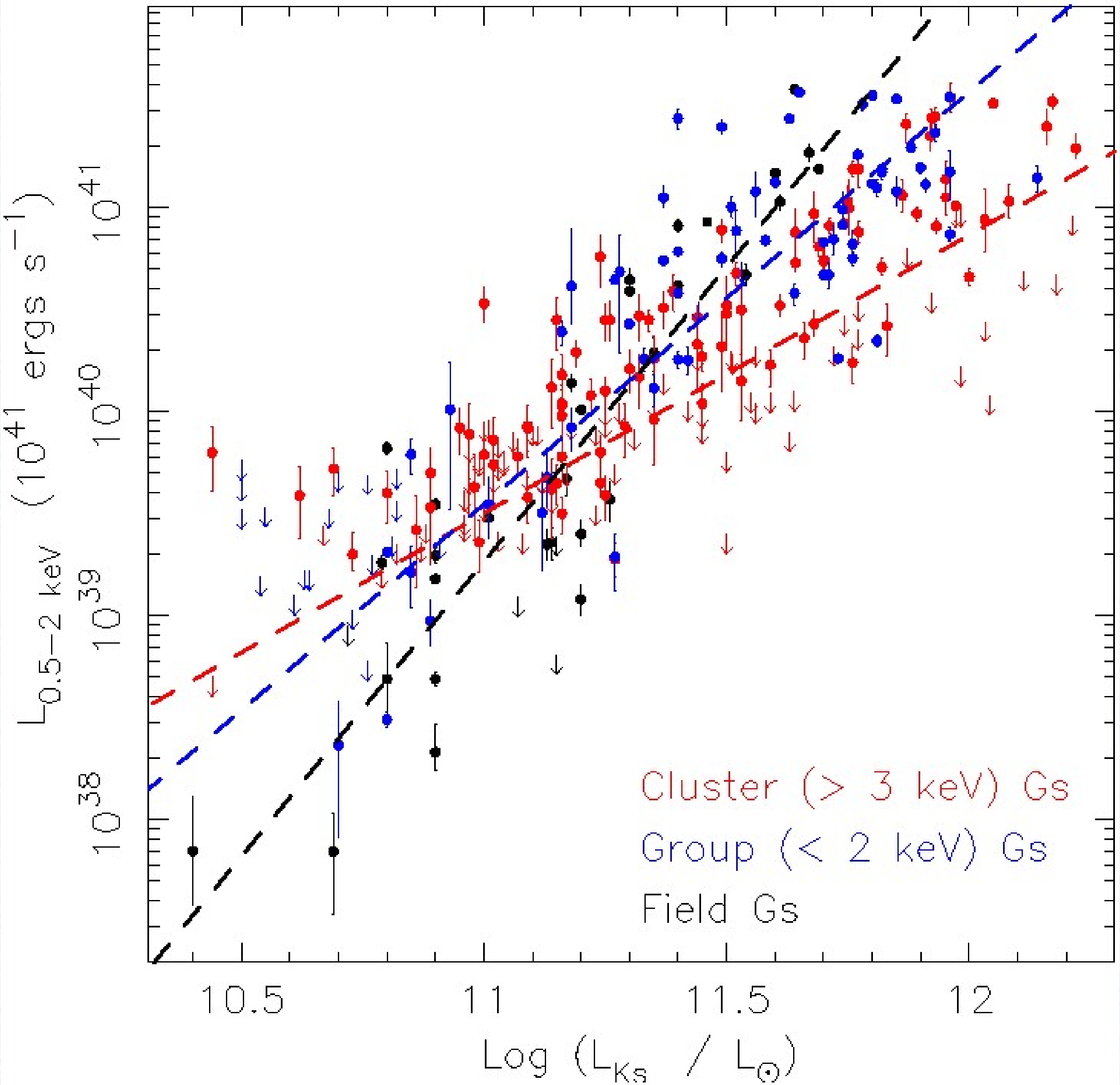
Soft X-ray Radio Optical

Sun, Jerius & Jones 2005

Known knowns

- Coronae survived for many cluster galaxies, esp. massive ones (e.g., > 60 % for L > 2 L* galaxies); they are metal rich (~ solar) and hotter than stars ($\beta_{spec} = 0.3 - 1.1$).
- Origin: a) galactic cool cores (stellar mass loss); b) remnants of large cool cores after stripping or AGN heating?
- Embedded coronae are mini cool cores with boundary conditions. Conduction is suppressed over the boundary (~ 100 x on average).
- The prevalence of coronae for massive galaxies implies these mini cool cores are long-lived. Possible heat sources include weak **AGN outbursts** and SN (with caveats).
- Radio AGN in clusters and groups that do not reside in large cool cores are generally associated with small coronae. Strong radio AGN in groups do not co-exist with strong, large cool cores. They are generally associated with coronae.

Environmental effect ?

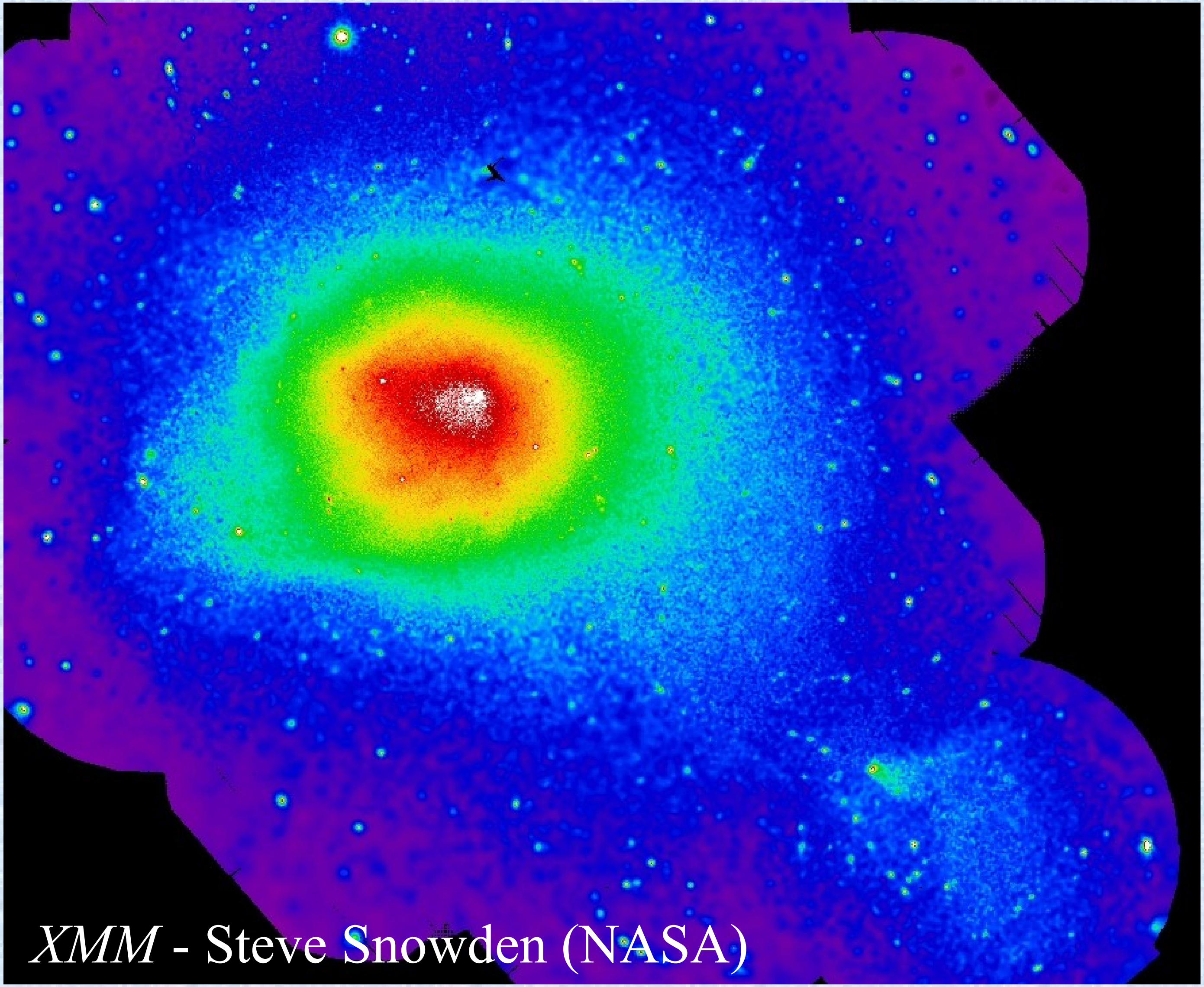


Slopes:

~ 1.4 (clusters)
~ 2.0 (groups)
~ 2.9 (field)

But be aware of limitations of data ! (data from Sun+2007; Jeltema+2008 Sun 2009; Mulchaey+2010; Boroson+2011; Li+2012)

What environmental effect ? Stripping for sure !



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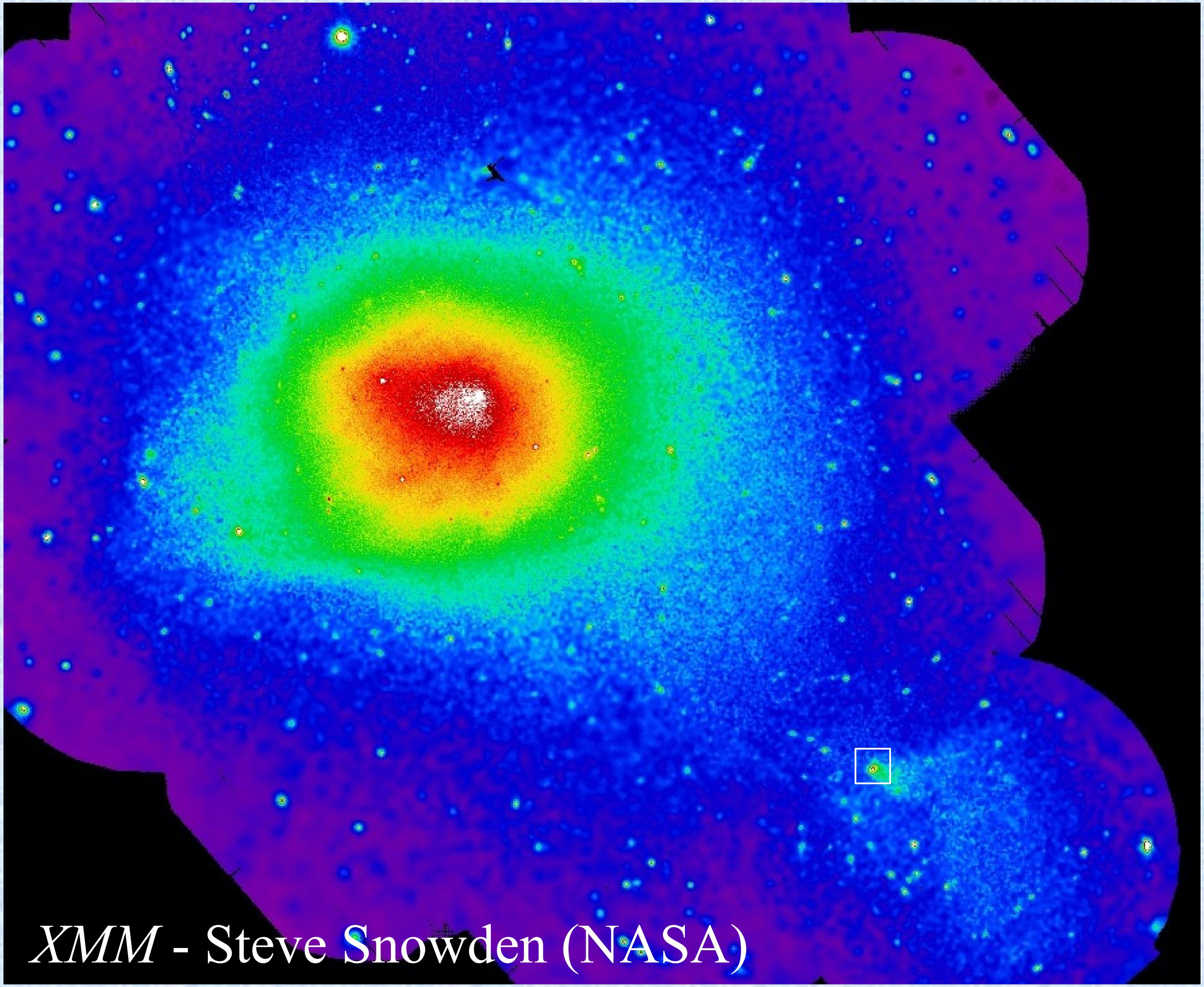

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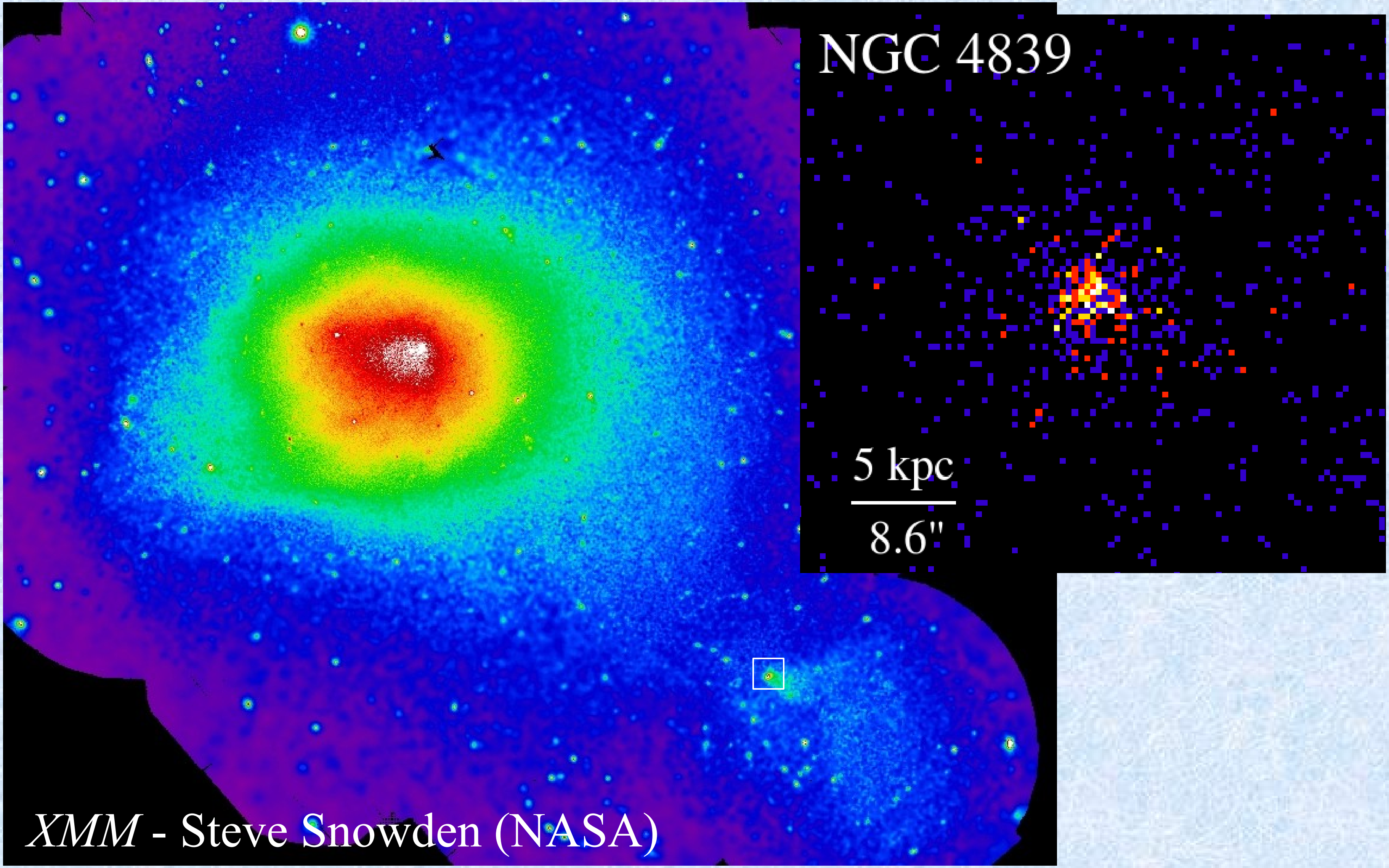

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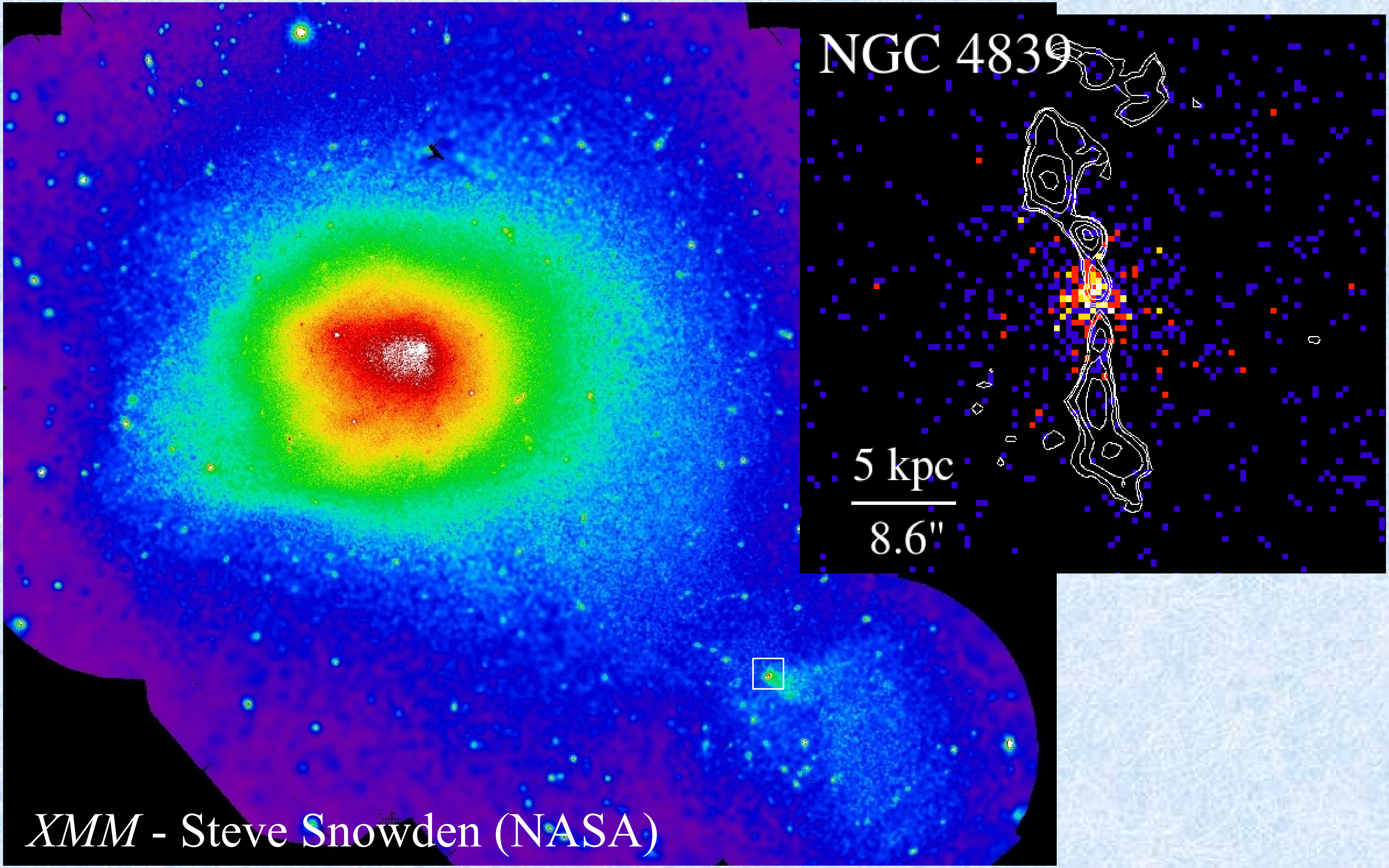
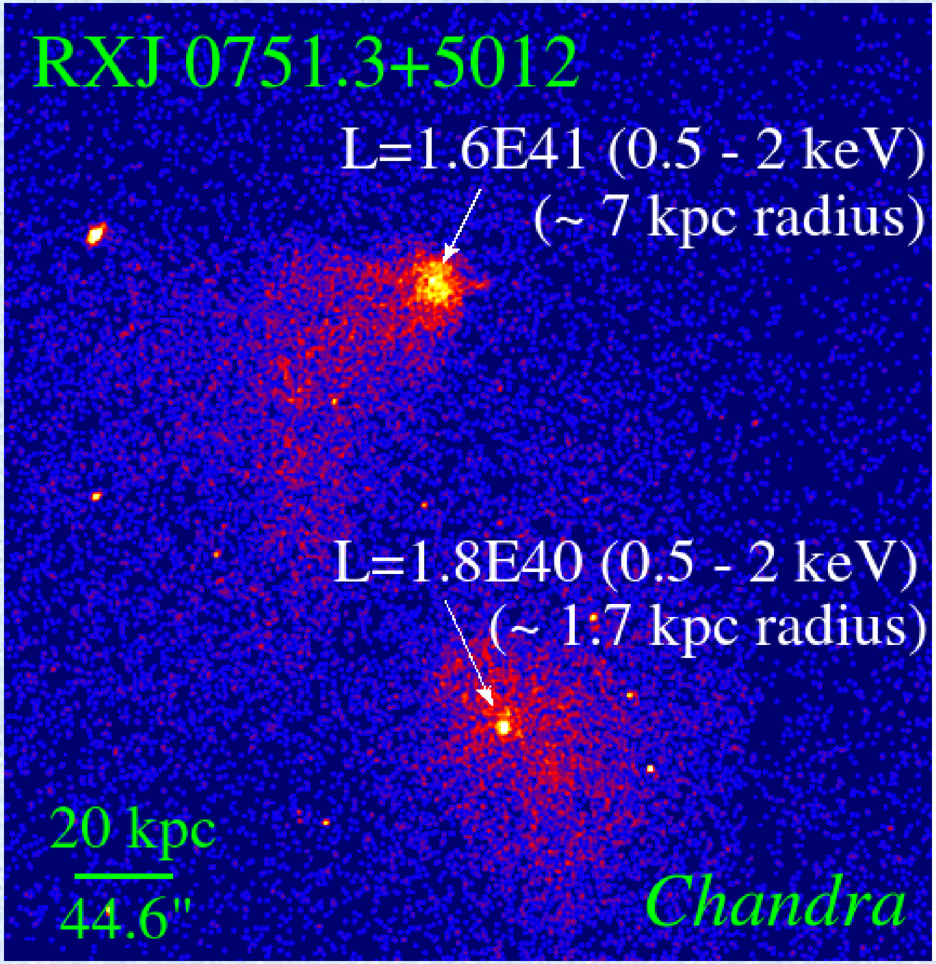
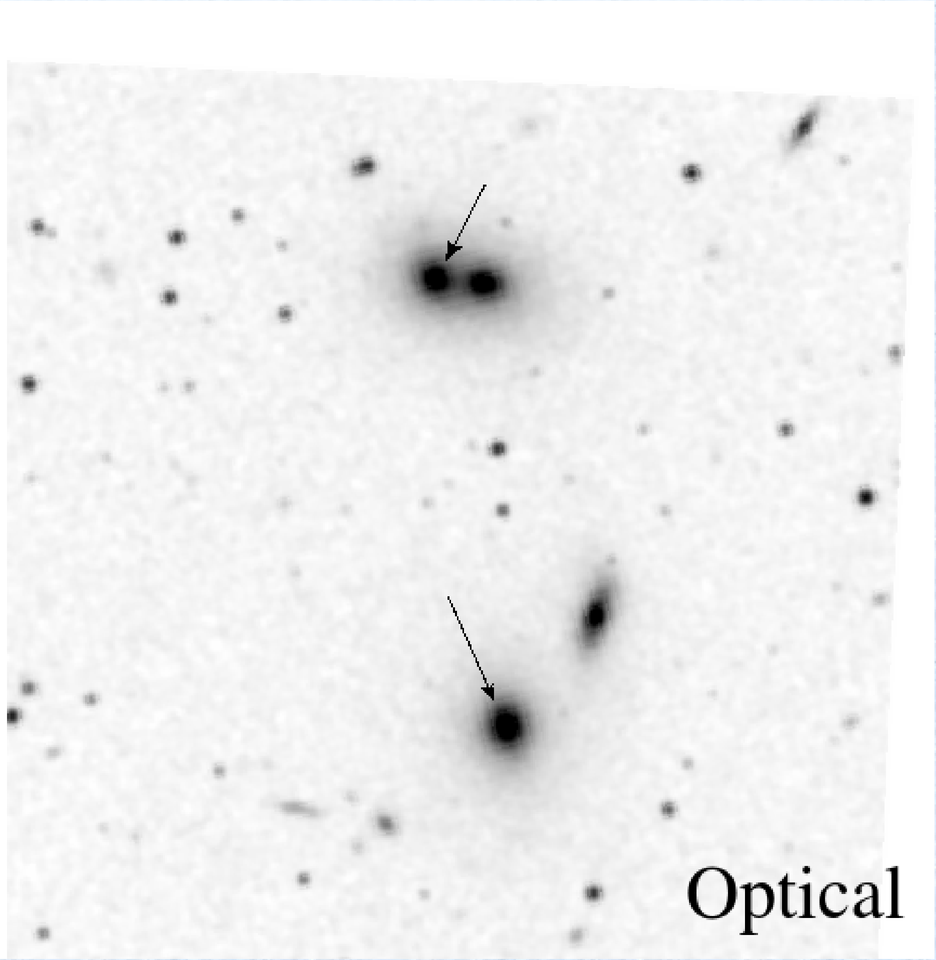






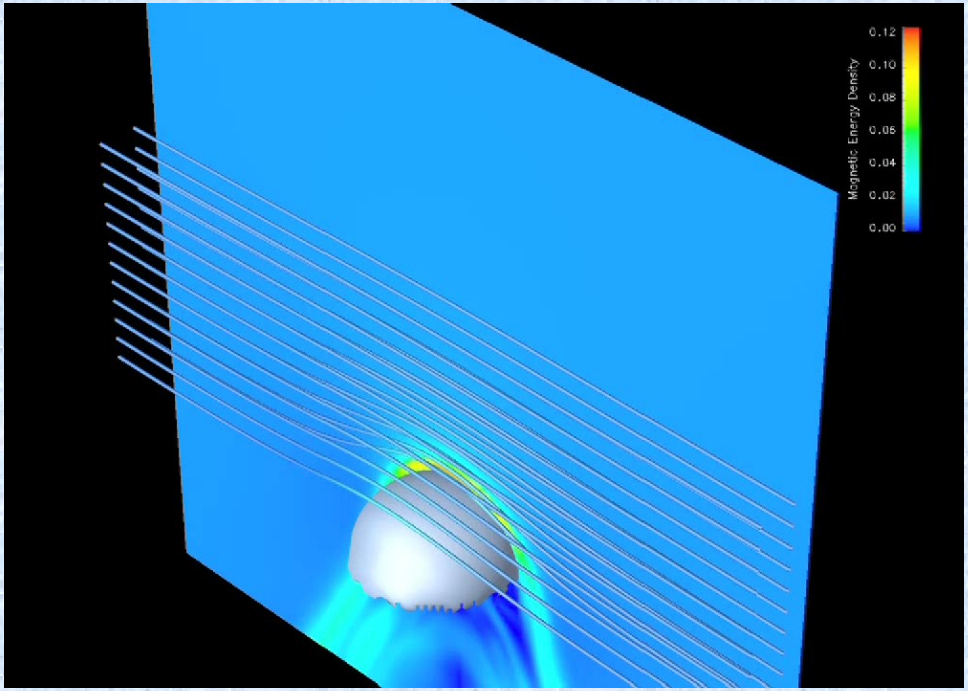
Lloyd-Davies (*XMM*)
Russell (*Chandra*)

Magnetic draping

Ambient ICM magnetic field gets draped around cluster galaxies as they soar through the ICM.
(magnetic draping, see Lyutikov 2006; Ruszkowski + 2007; Dursi & Pfrommer 2008; Pfrommer & Dursi 2010 for cold fronts, radio lobes in cool cores and stripping for late-type galaxies)

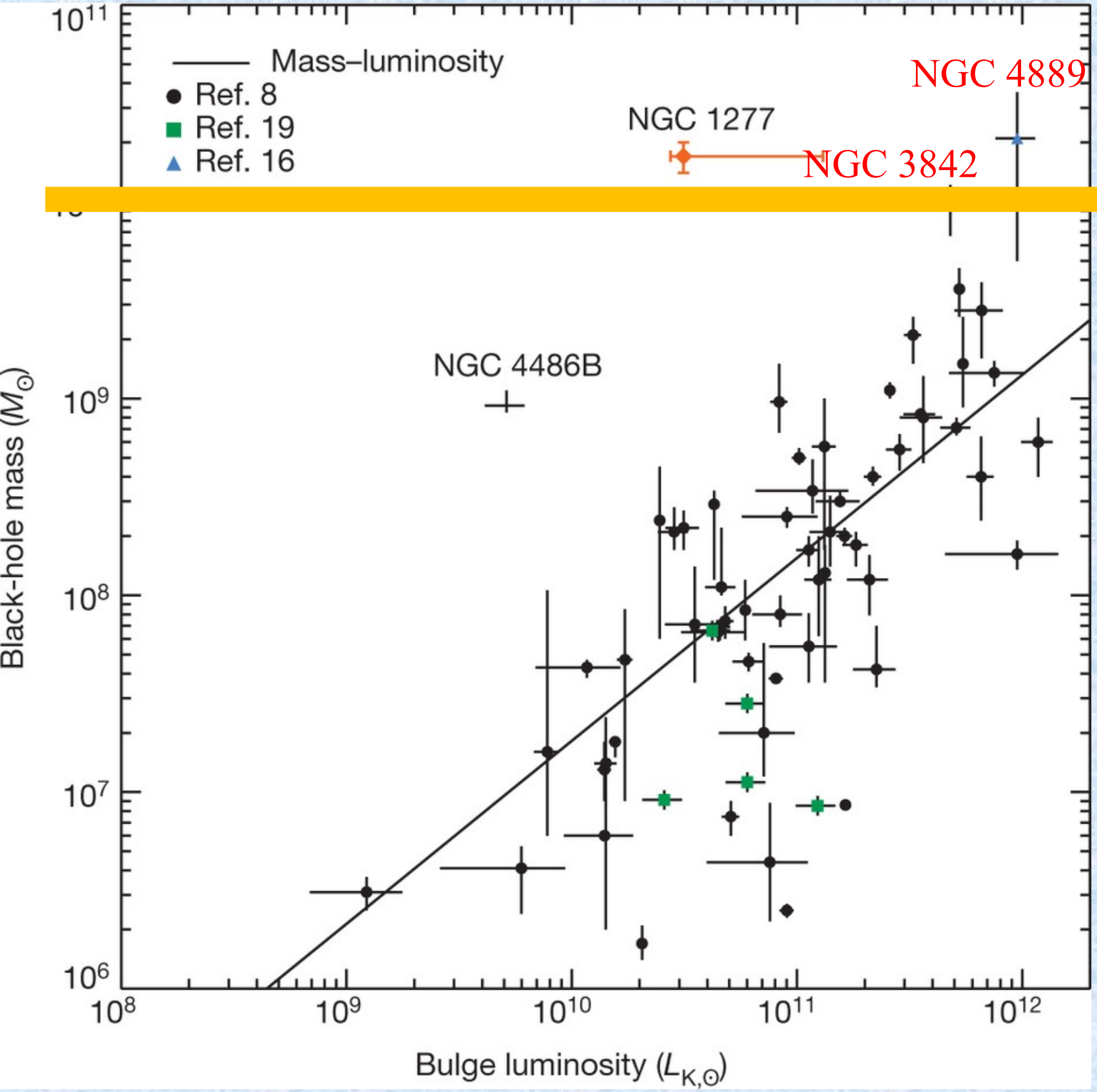
In the magnetic boundary layer, $B = \sqrt{8 \quad \nu^2}$

B = 7.0 μG for $n_e=10^{-4}$ cm^{-3}
and ν_{gal} = 1000 km/s
= 67 μG for $n_e=10^{-3}$ cm^{-3}
and ν_{gal} = 3000 km/s



Dursi & Pfrommer 2008

Ultra-massive black holes (UMBHs)

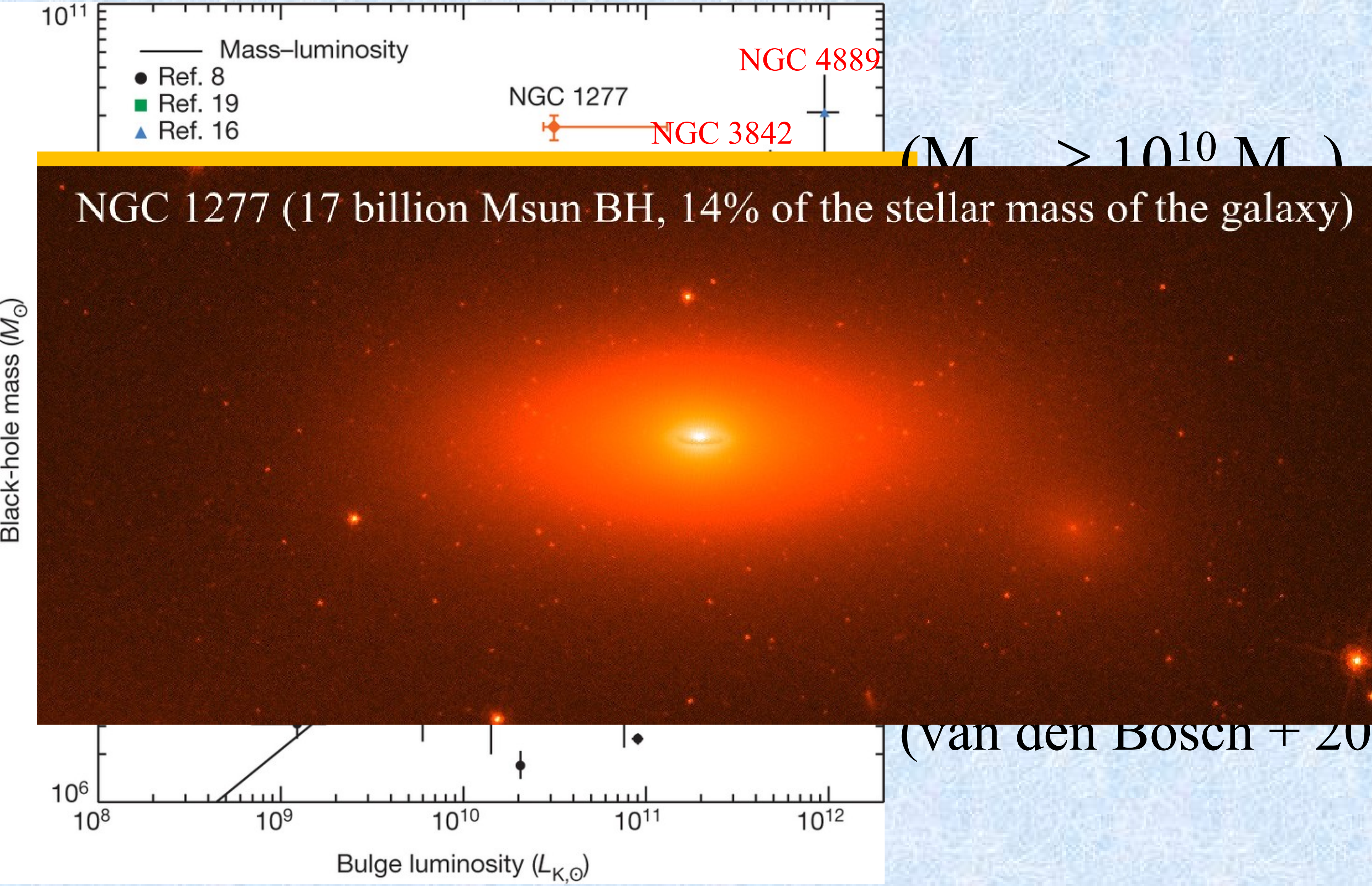


($M_{BH} \geq 10^{10}\ M_\odot$)

NGC3842, NGC4889:
Brightest cluster galaxy
(McConnell + 2011)

NGC 1277:
an 1.4 L* galaxy in the
Perseus cluster
(van den Bosch + 2012)

Ultra-massive black holes (UMBHs)



(M > 10^{10} M)

9:

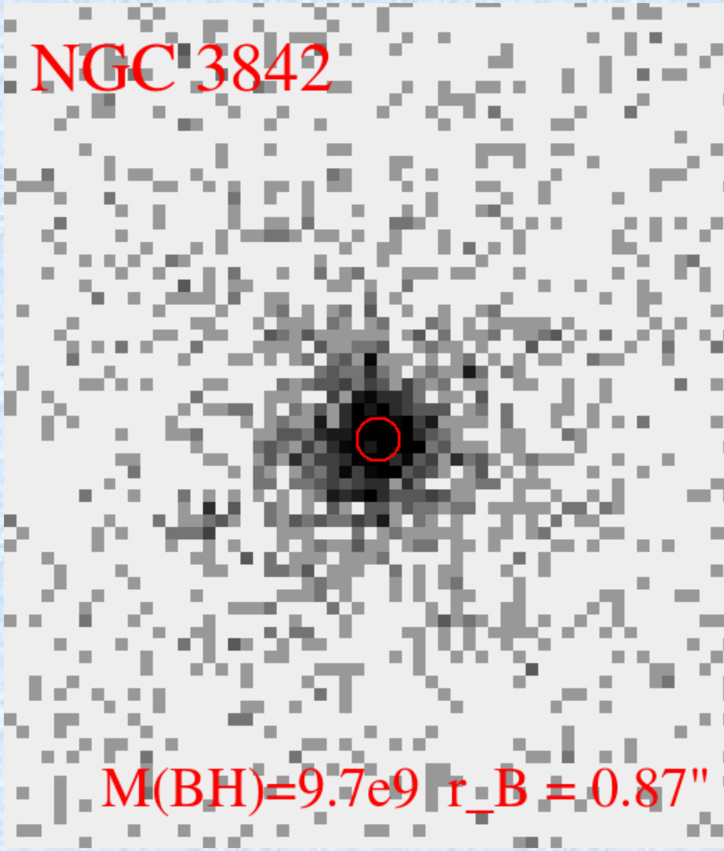
xy

ne

(van den Bosch + 2012)

UMBHs

1) All associated with coronae, with Bondi radius of 0.9" – 1.5" (Sun+2005, 2007; Fabian+2013)
2) Dense cool core + large M_{BH}
   $\rightarrow$ high accretion rate!
   (2.4 – 6.8 × 10^{45} erg s^{-1} if ε = 10%)
3) But these UMBHs are very quiet !
   (ε = 10^{-4} – 10^{-5}, kinetic + radiation
   Eddington ratios < 10^{-7})

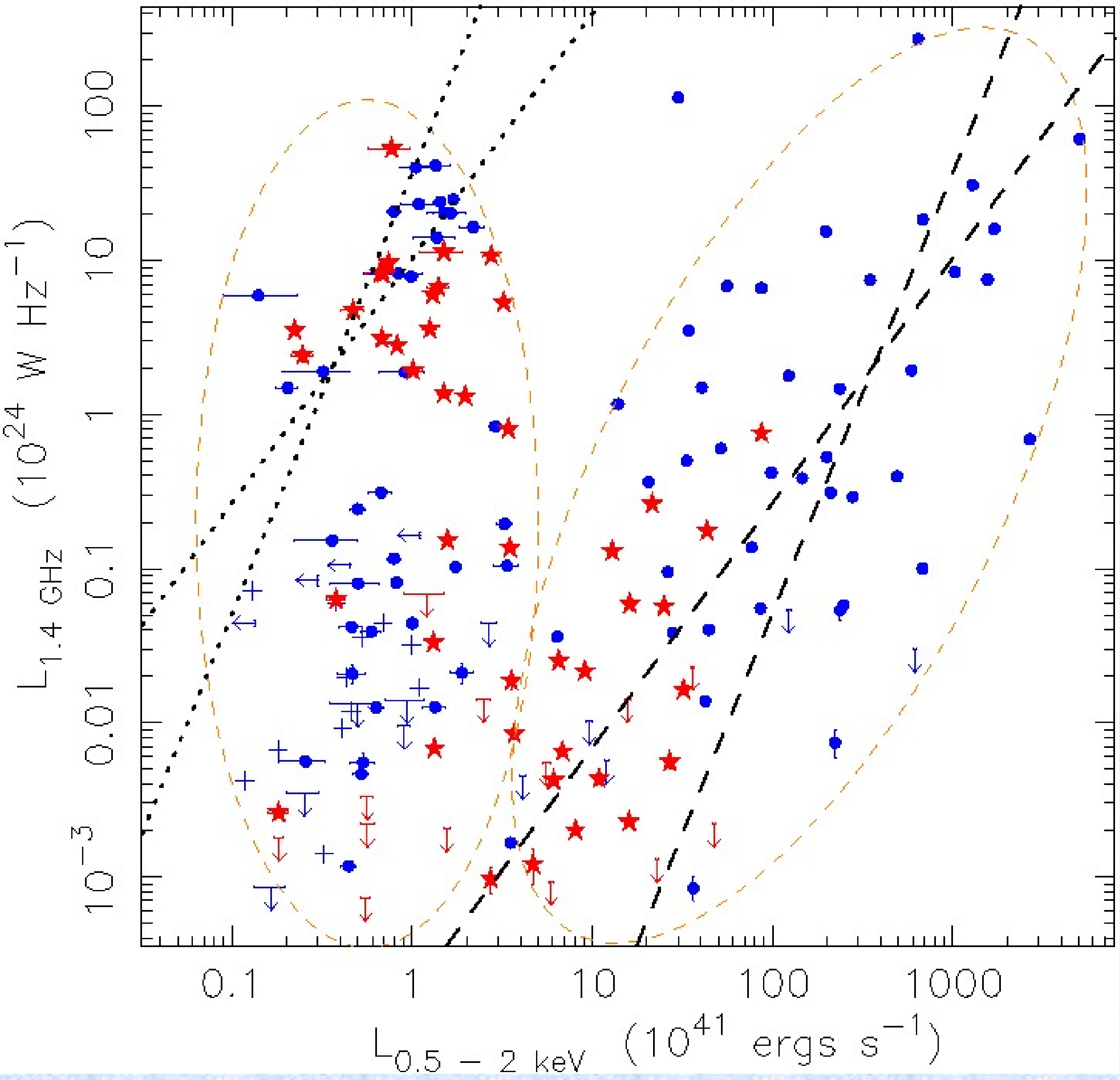


0.38 kpc

Follow-ups with *IRAM*-30m/*PdBI* :

- Detect CO(1-0) significantly in N1277 (Scharwaechter + 2014)
- CO not detected in N3842/N4889

Coronae (mini cool cores) & radio AGN

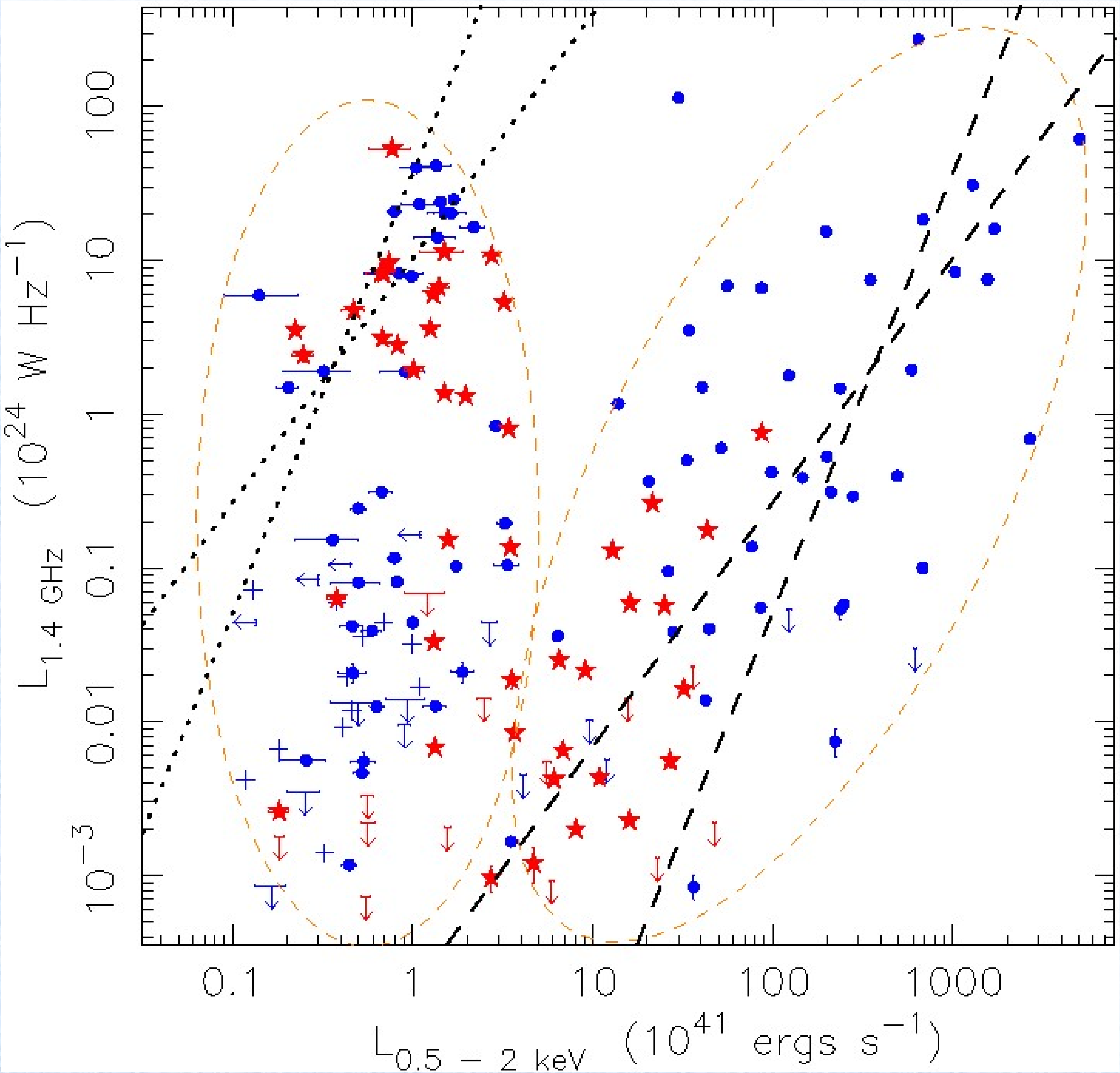


Clusters (kT > 2 keV)

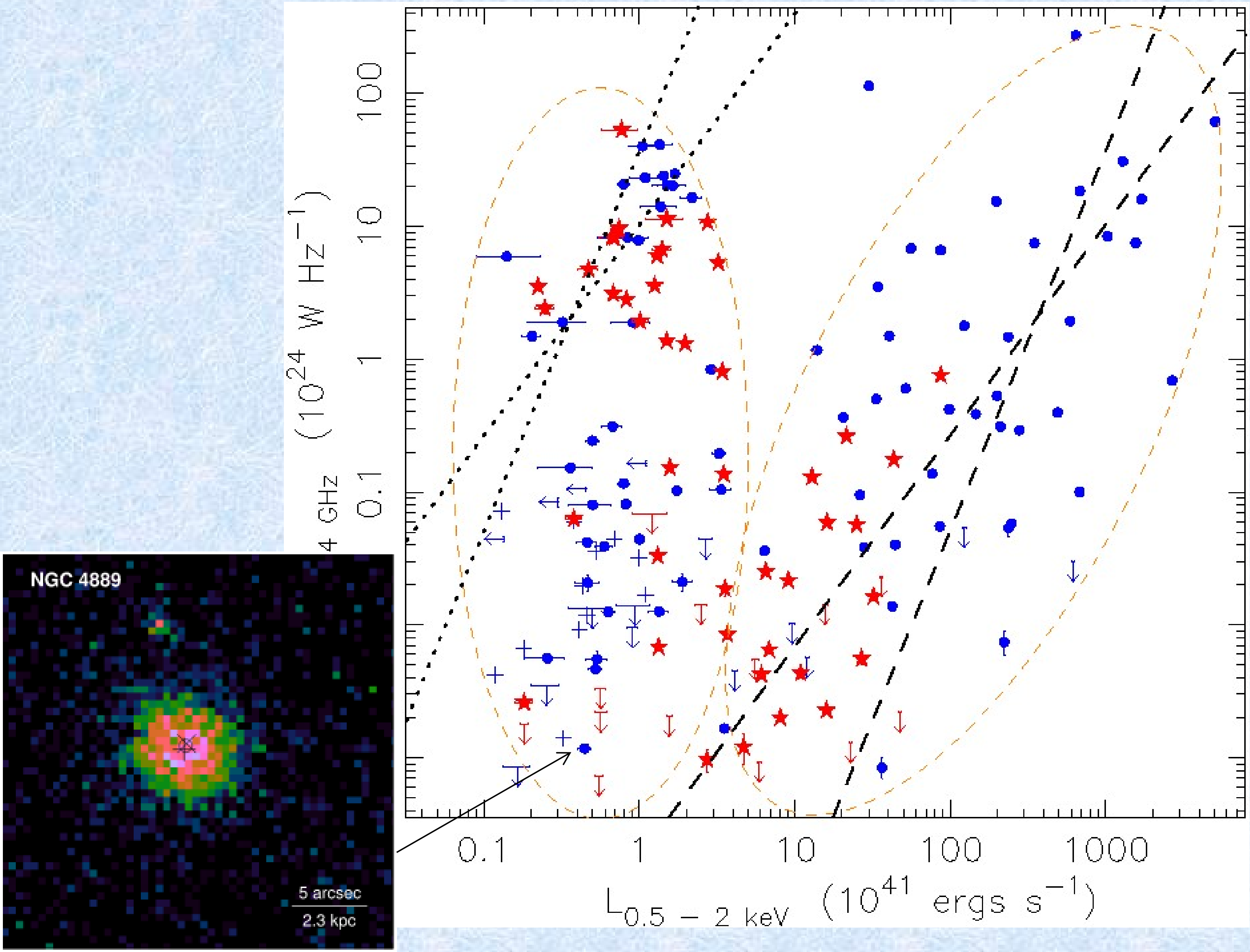
Groups (kT < 2 keV)

Dashed lines from $L_{1.4GHz} - P_{cavity}$ relation from Bîrzan+2008 and O'Sullivan+2011, while dotted lines represent 10^{-3} of the cavity heating power.

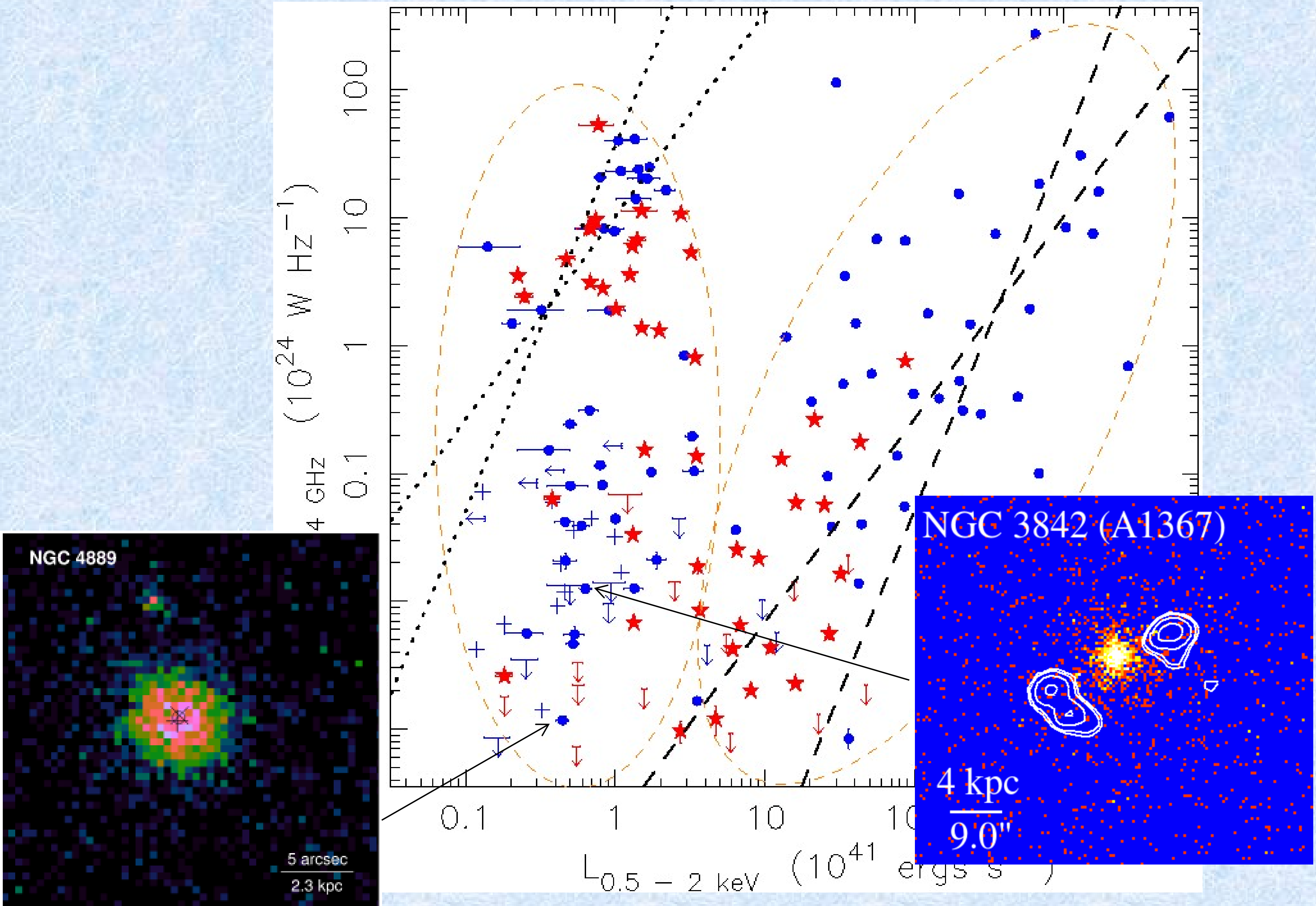
Sun 2009



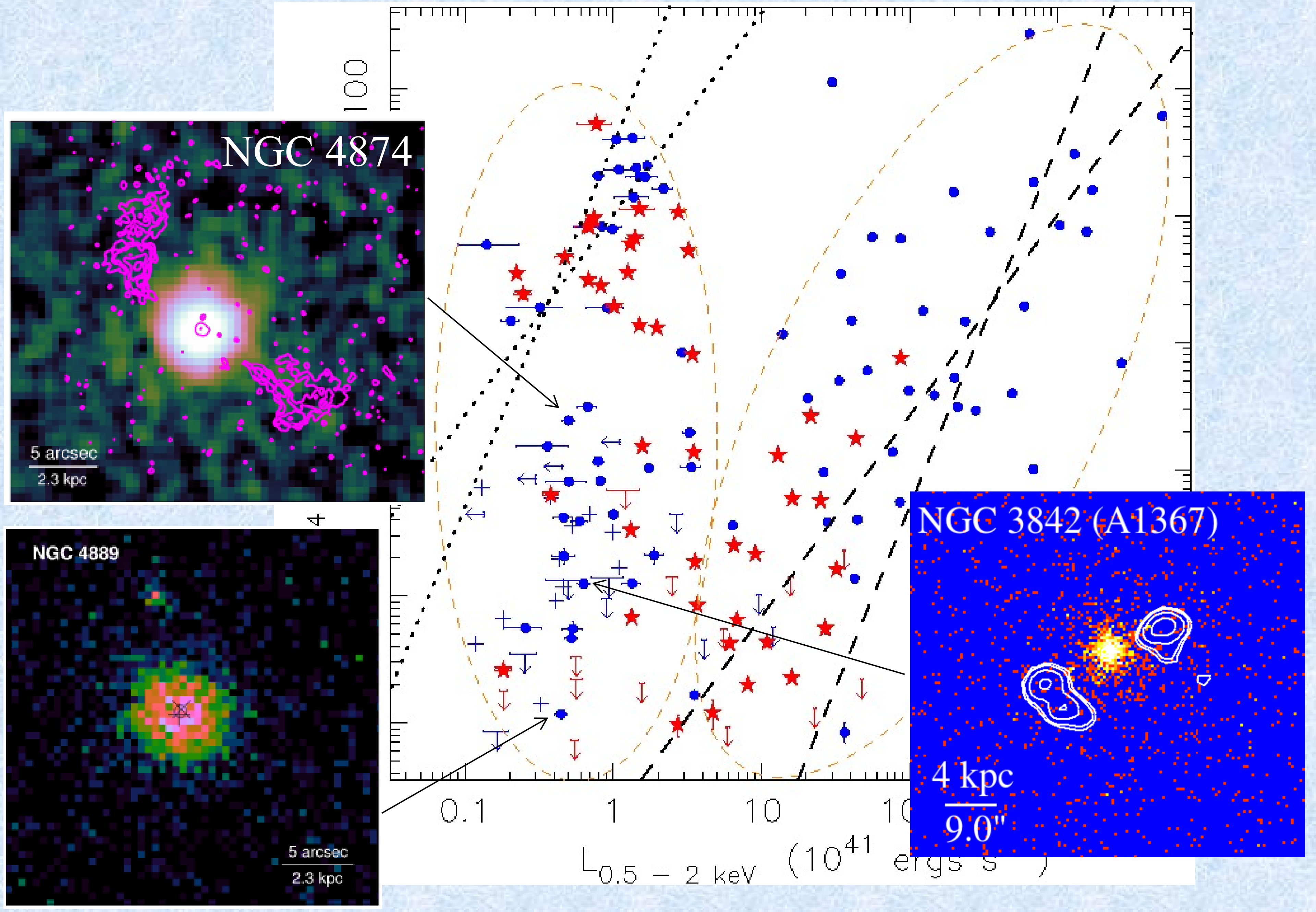
100
10
1
0.1
0.01
10^{-3}
$L_{1.4\ GHz}\ (10^{24}\ W\ Hz^{-1})$
0.1
1
10
100
1000
$L_{0.5-2\ keV}\ (10^{41}\ ergs\ s^{-1})$

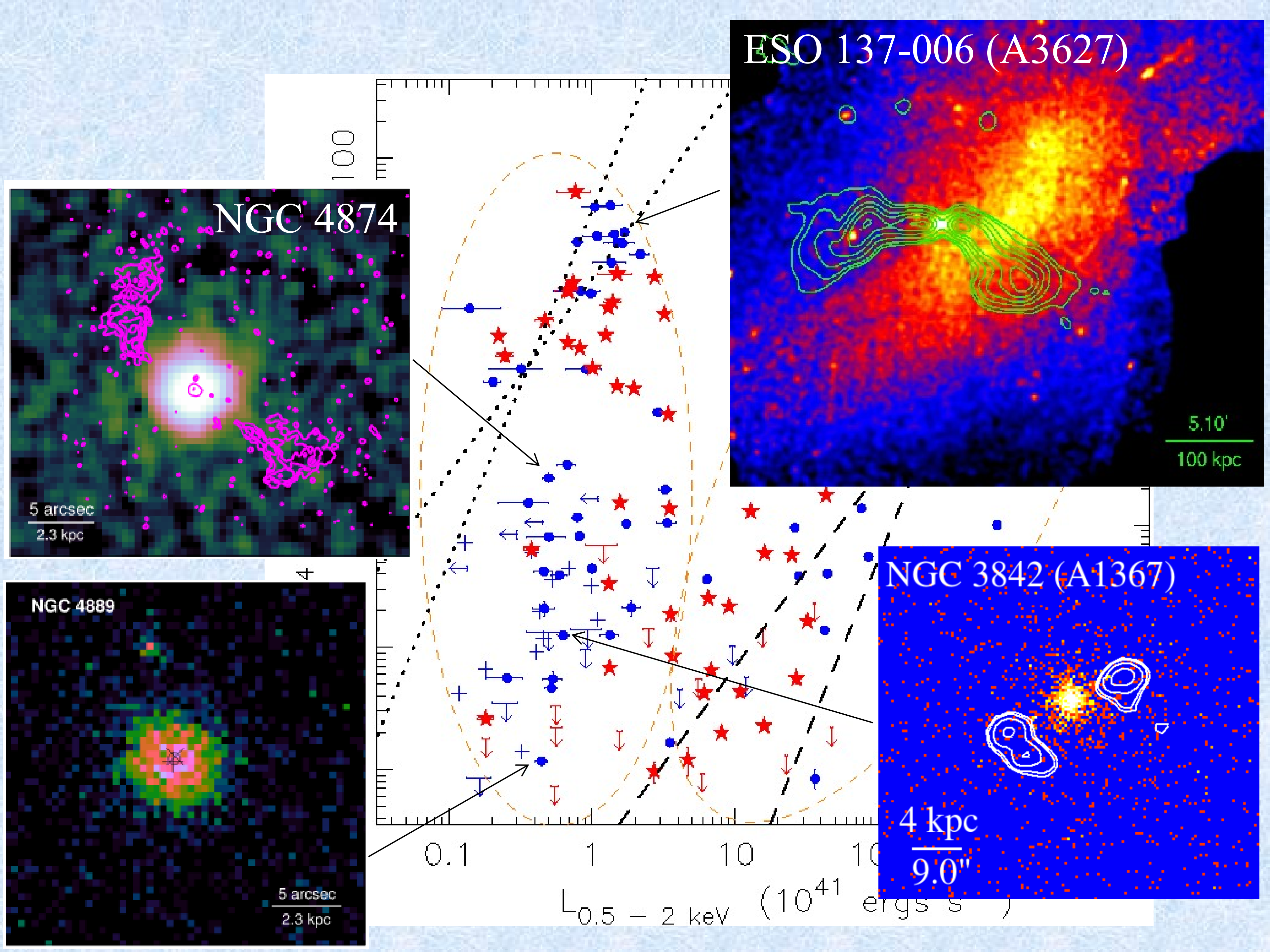


4 GHz (10^24 W Hz^-1)
100
10
1
0.1
0.1
1
10
100
1000
L_0.5 - 2 keV (10^41 ergs s^-1)
NGC 4889
5 arcsec
2.3 kpc



NGC 4889
5 arcsec
2.3 kpc
NGC 3842 (A1367)
4 kpc
9.0"
4 GHz (10^24 W Hz^-1)
100
10
1
0.1
0.1
1
10
L0.5 – 2 keV (10^41 ergs s

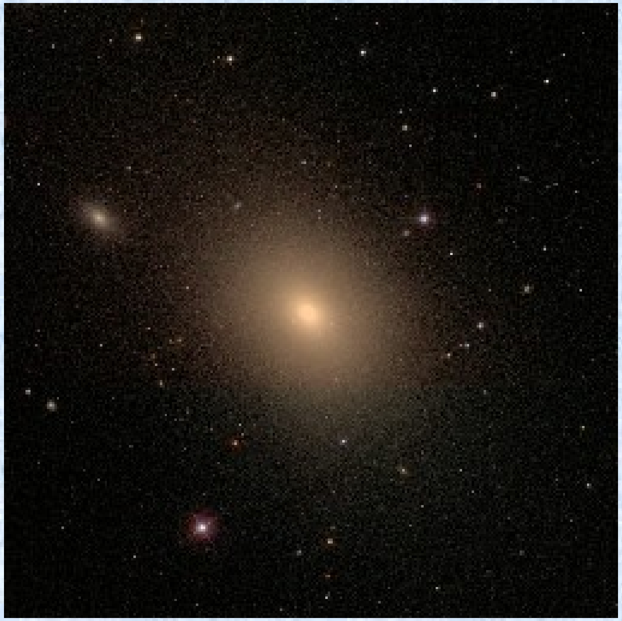

NGC 4874
5 arcsec
2.3 kpc
NGC 4889
5 arcsec
2.3 kpc
NGC 3842 (A1367)
4 kpc
9.0"
100
0.1
1
10
$L_{0.5-2\ keV}$ (10^{41} ergs s^{-1})

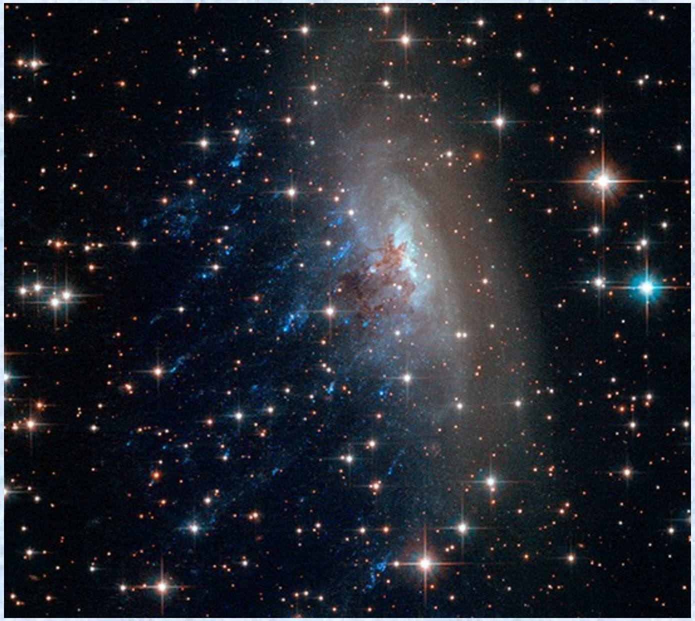


ESO 137-006 (A3627)
5.10'
100 kpc
NGC 4874
5 arcsec
2.3 kpc
NGC 4889
5 arcsec
2.3 kpc
NGC 3842 (A1367)
4 kpc
9.0"
100
0.1
1
10
$L_{0.5-2\ keV}$ (10^{41} ergs s

Known unknowns

- Energy balance in embedded coronae (truncated cool cores)
- Are coronae decoupled from the radio AGN feedback cycle ?
- Hot accretion or accretion of the cold gas cooled from the hot gas ?
- Can small coronae be remnants of large ones? Or seeds?
- Can “naked” galaxies build coronae in clusters/groups ?
- Cooling product in coronae and is SF enhanced?





Summary

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Radio AGN

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Conduction

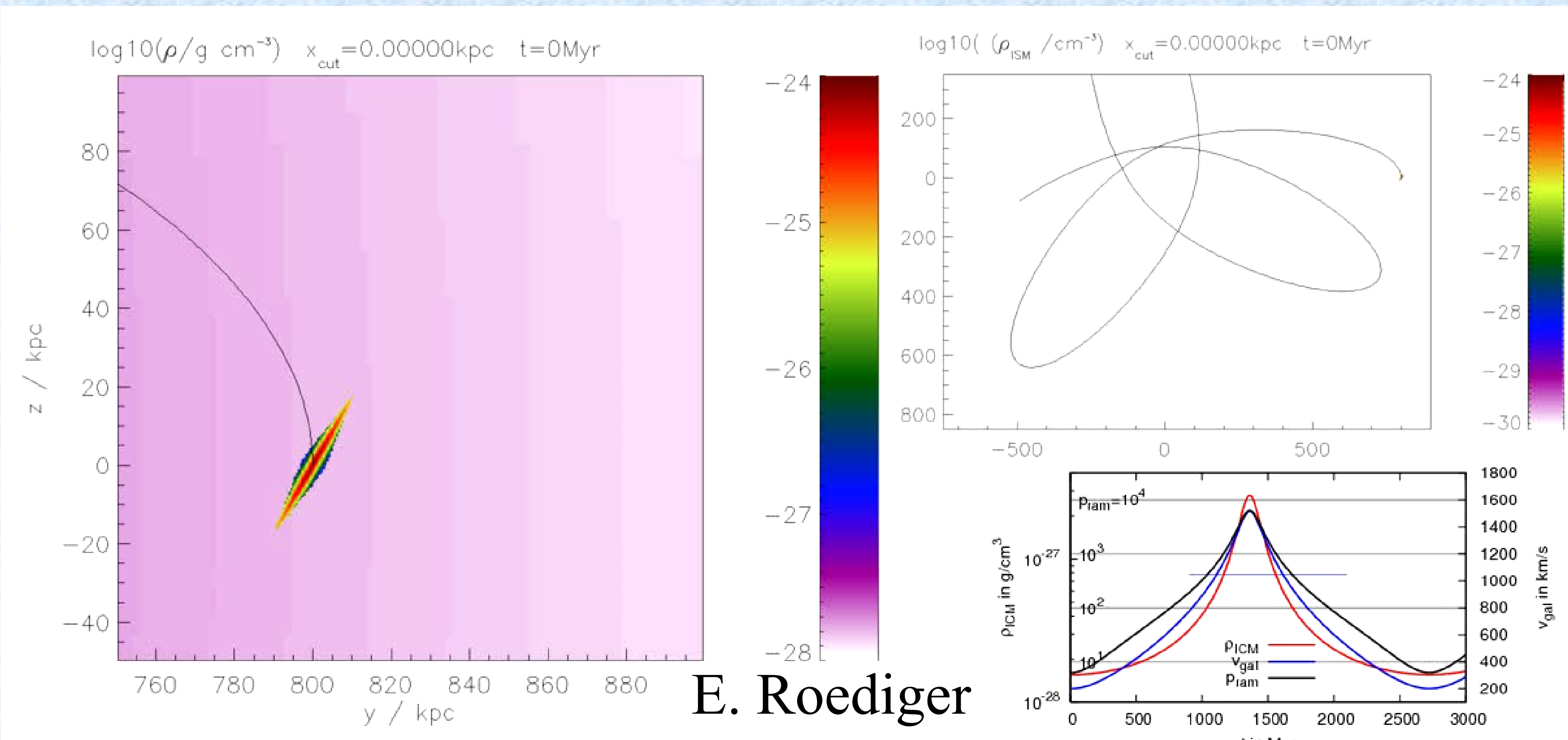
B Draping

Turbulence

Ram pressure stripped tails (multi-phase gas and SF)

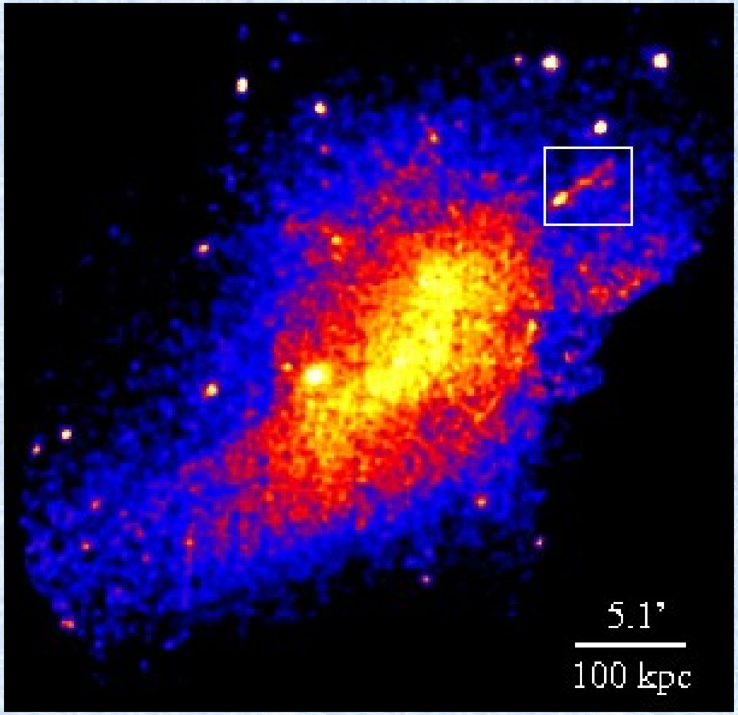
Ram pressure stripping

- $P_{\text{ram pressure}} \approx \rho\, v^2$ (drag force = $0.5\, c_d\, A\, \rho\, v^2$)
- Remove gas (important for galaxy evolution)
- Dump heavy elements, B field into the ICM
- Great sites to study transport processes
- *Fate of the stripped gas ? (heated/mixed with the ICM?)*



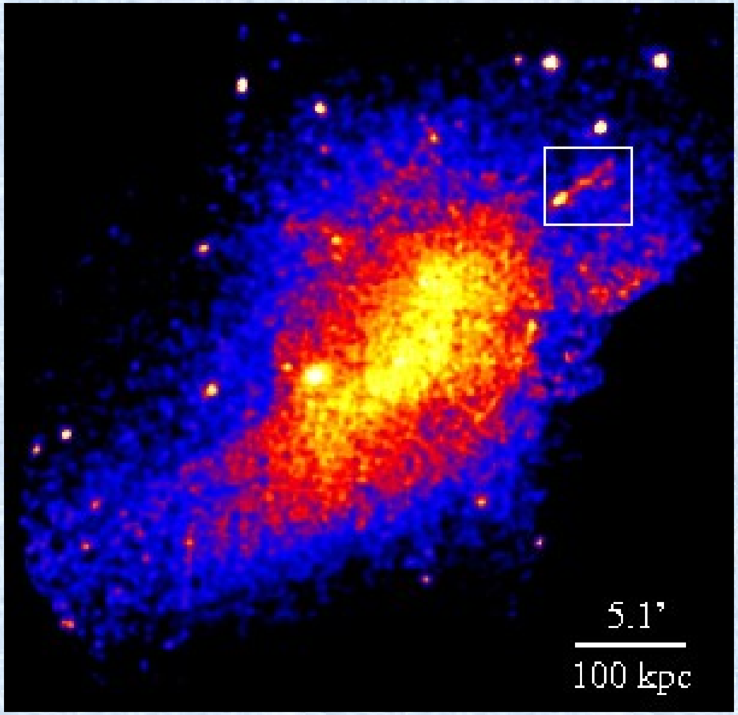
E. Roediger

ESO 137-001 in Abell 3627 (z = 0.016)

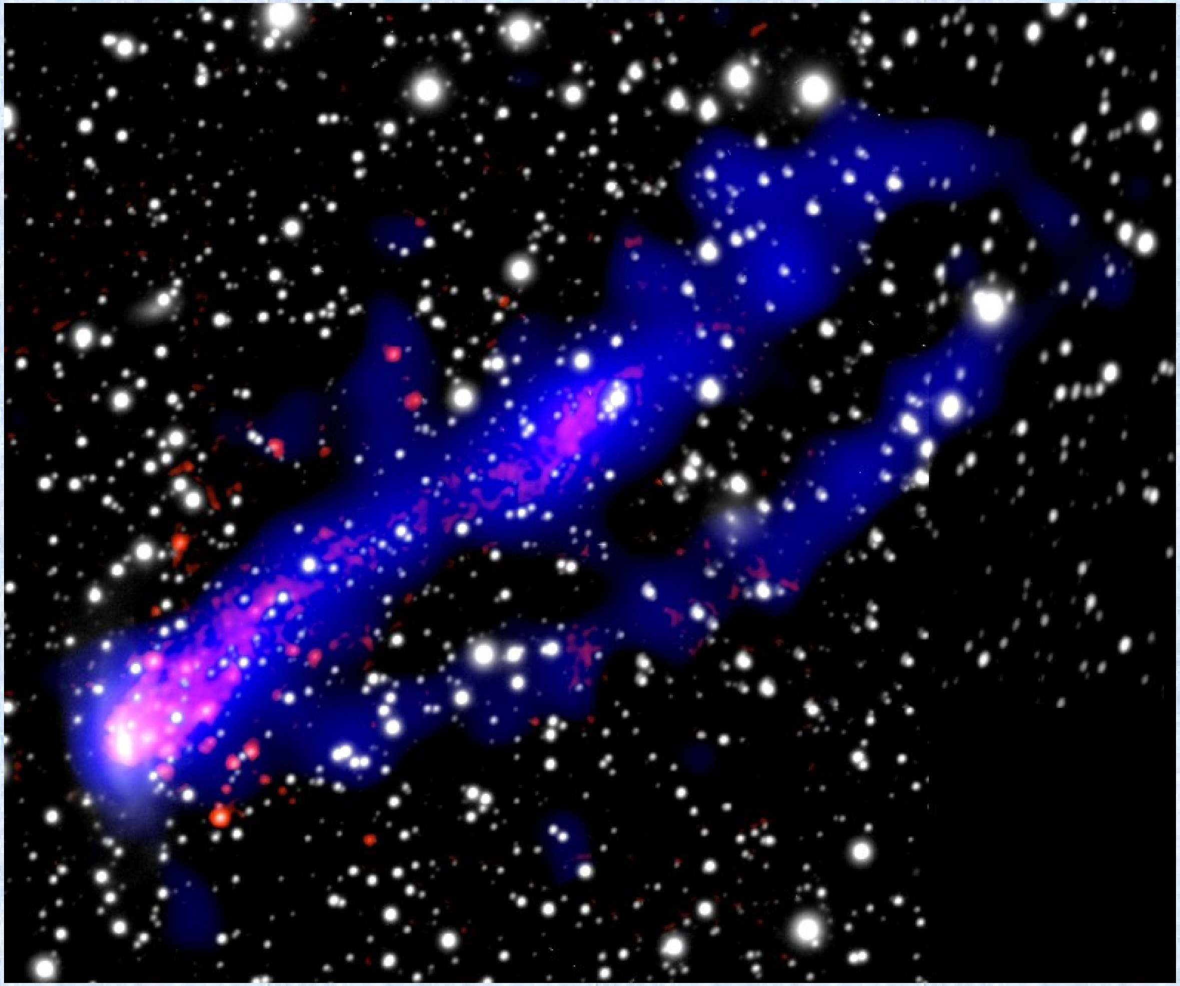


X-rays (*XMM*),
Sun et al. 2006

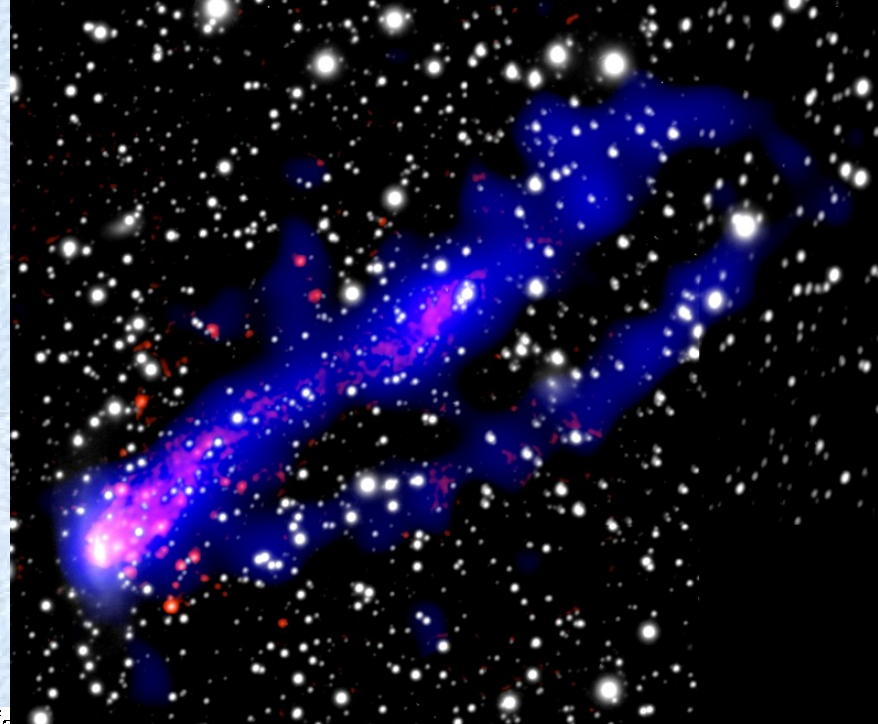
ESO 137-001 in Abell 3627 (z = 0.016)

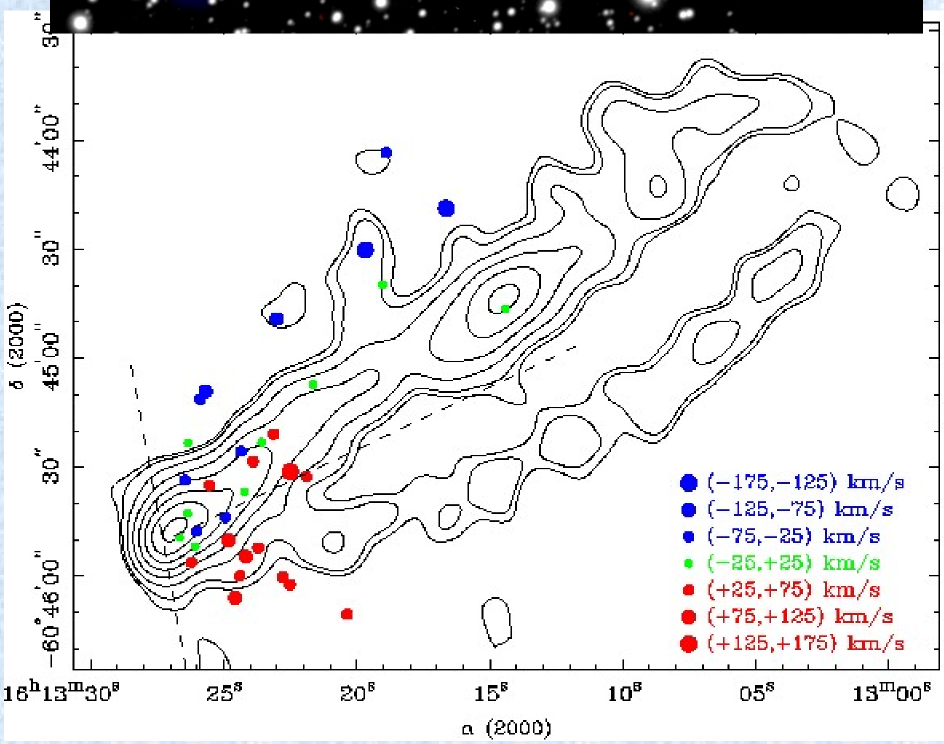


X-rays (*XMM*), Sun et al. 2006



X-ray , Hα , Sun et al. 2007, 2010





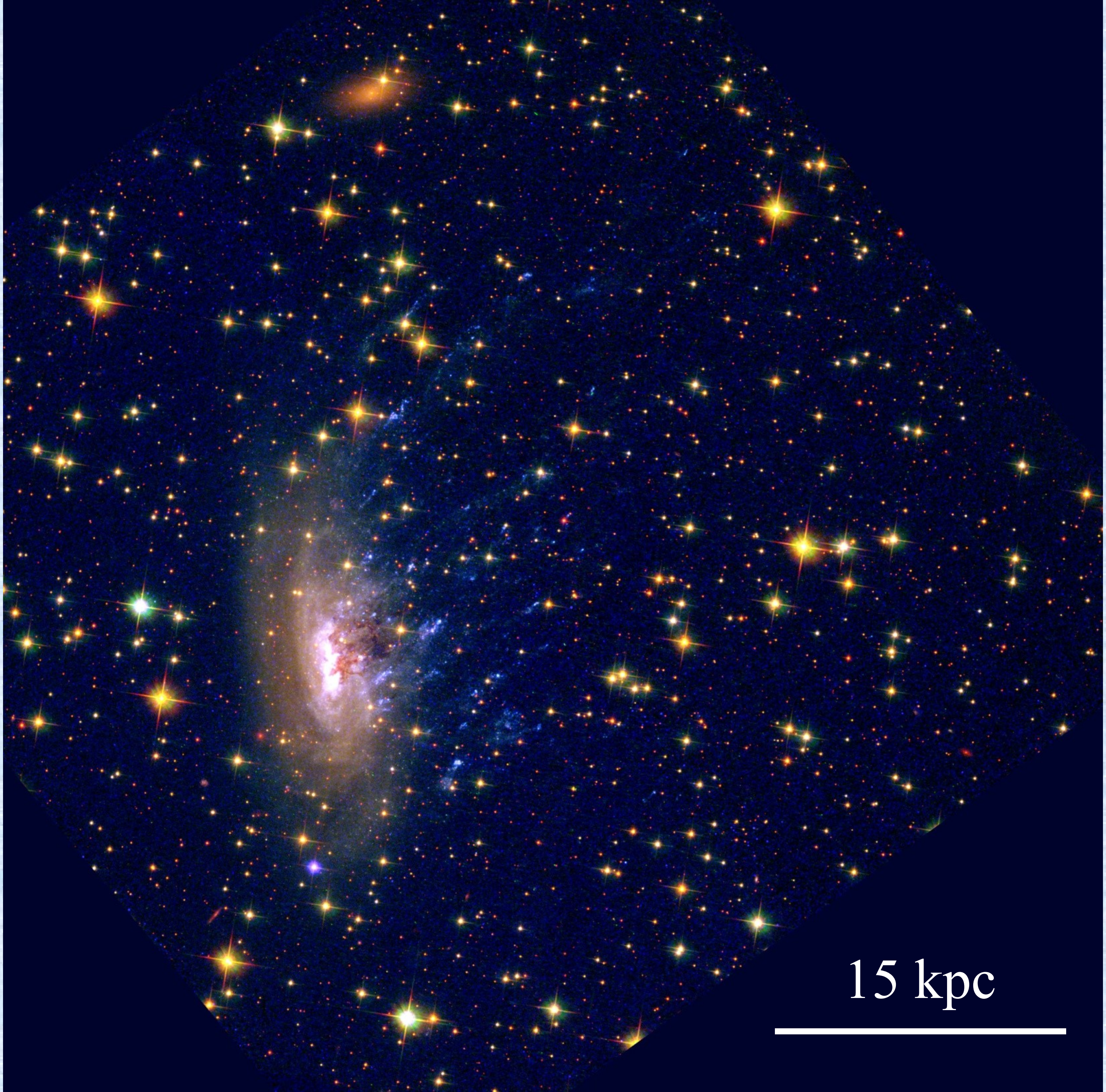
ESO 137-001 in A3627

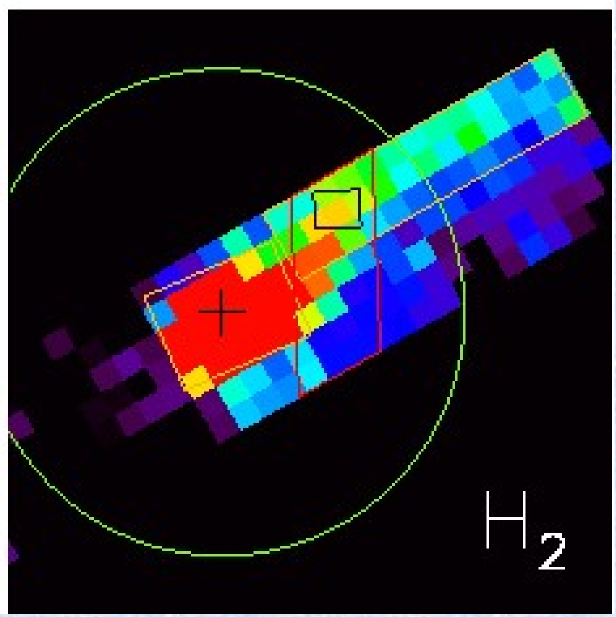
- A blue galaxy (~0.07 M*, SFR: ~ 1 $M_\odot$/yr), in the closest rich cluster A3627 (kT = 6 keV)
- **Two** 80 kpc X-ray tails (~ 0.9 keV) + **two** 40 kpc Hα tails ("*Two tails to tell*")
- **SF in the stripped ISM**: 35 HII regions + > 10 other blue star clusters + 6 ULXs downstream of the galaxy, SFR ~ 1 $M_\odot$ / yr
- **Kinematics**: HII regions show rotation pattern and suggests turbulence not strong

(Sun + 2006, 2007, 2010)

Hubble Heritage release (Mar. 2014)

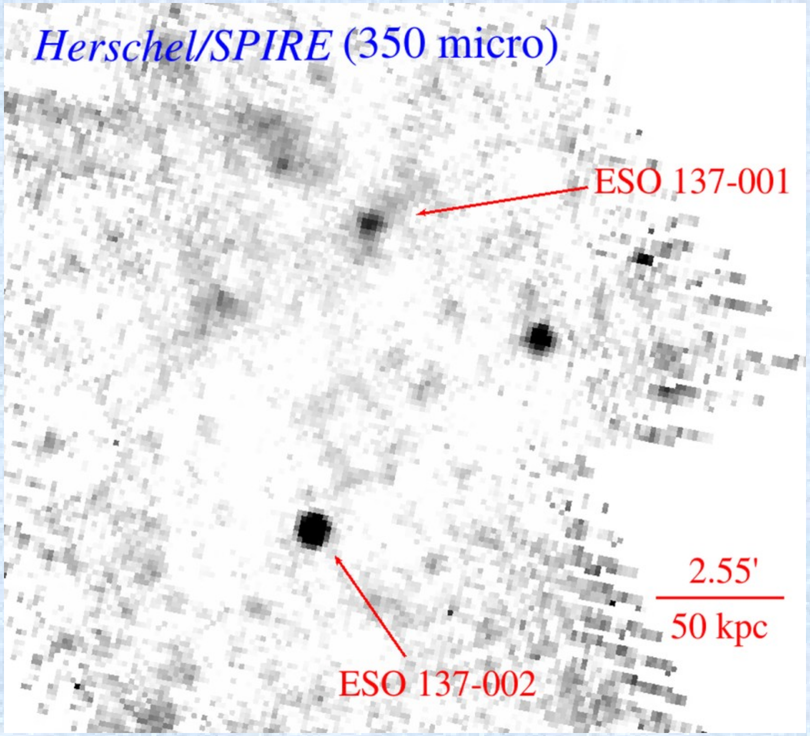
HST





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

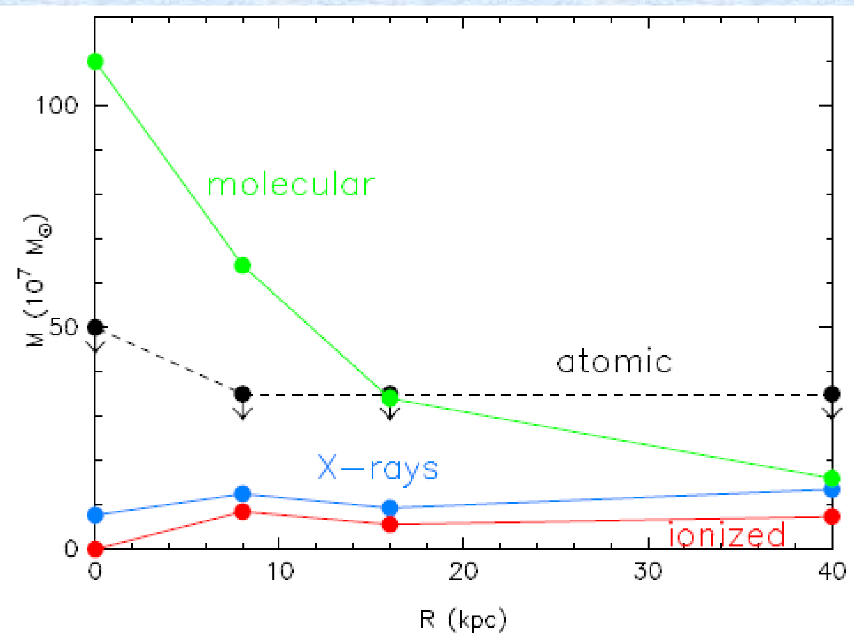
--- the first H_2 tail (Sivanandam+ 2010)

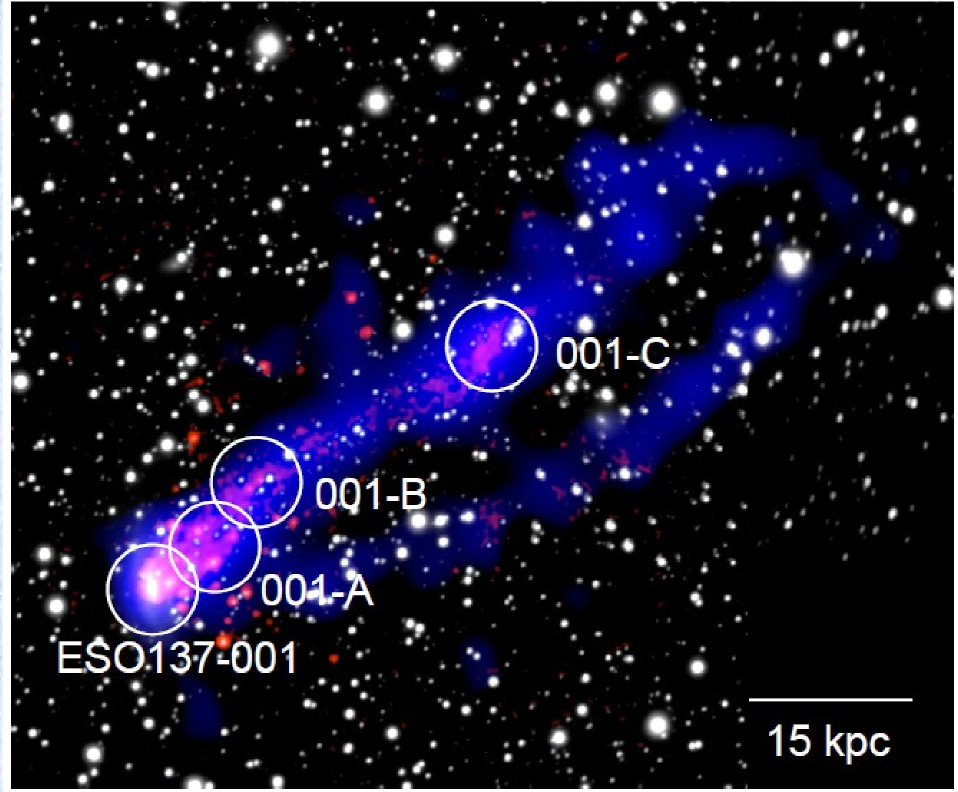


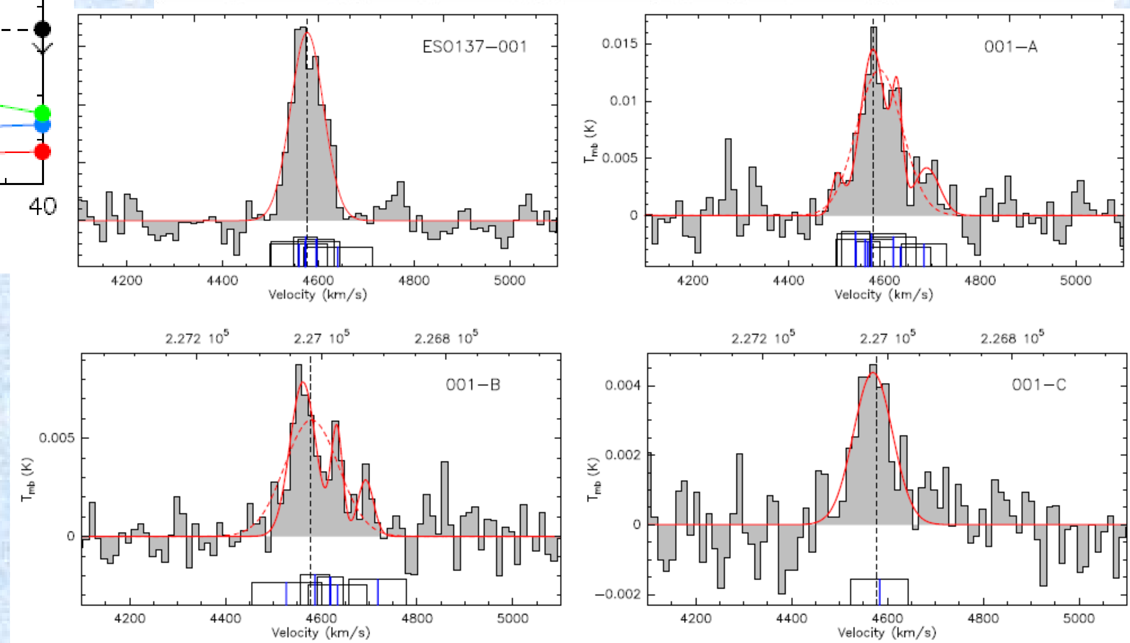
Dusty tail from *Herschel* (Sivanandam, Sun +)

HI + radio continuum data also obtained (Sun, Sivanandam +)

The 1st detection of molecular gas in the tail (formed *in situ* !)







APEX (Jachym + 2014)

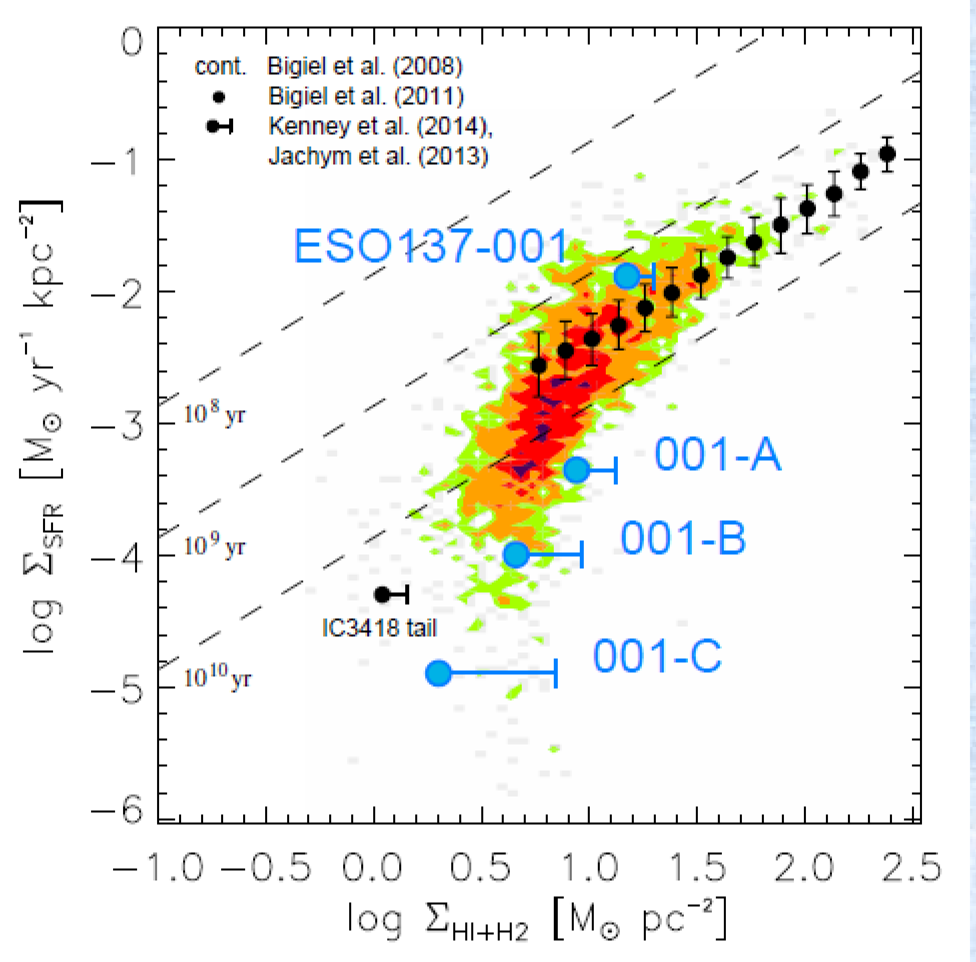
(*Mopra*, Sivanandam +)

- $> 10^9\ M_\odot$ of molecular gas detected in the tail (including $\sim 1.7\text{x}10^8\ M_\odot$ at 40 kpc from the galaxy !)

- Warm-to-cold molecular gas ratio (> 0.1) similar to those in cool cores --- extra heat !

- SF efficiency appears to be low (more studies needed …)
  --- turbulence, B field … ?

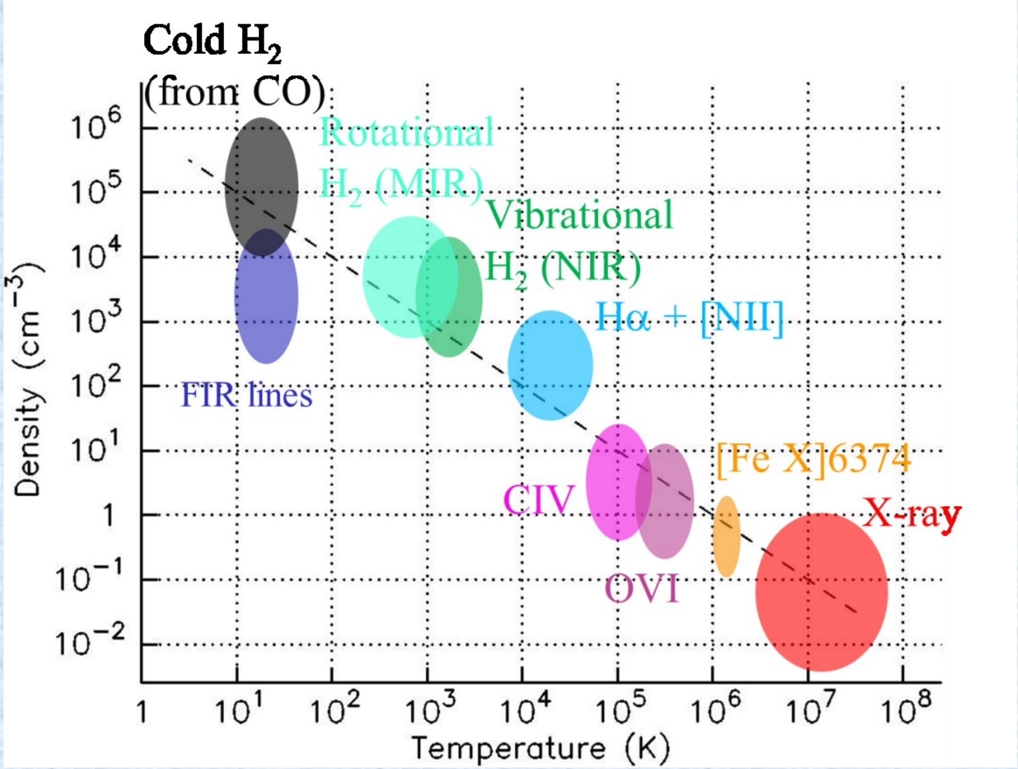
- Kinematics from CO mapping in the future !



APEX (Jachym + 2014)

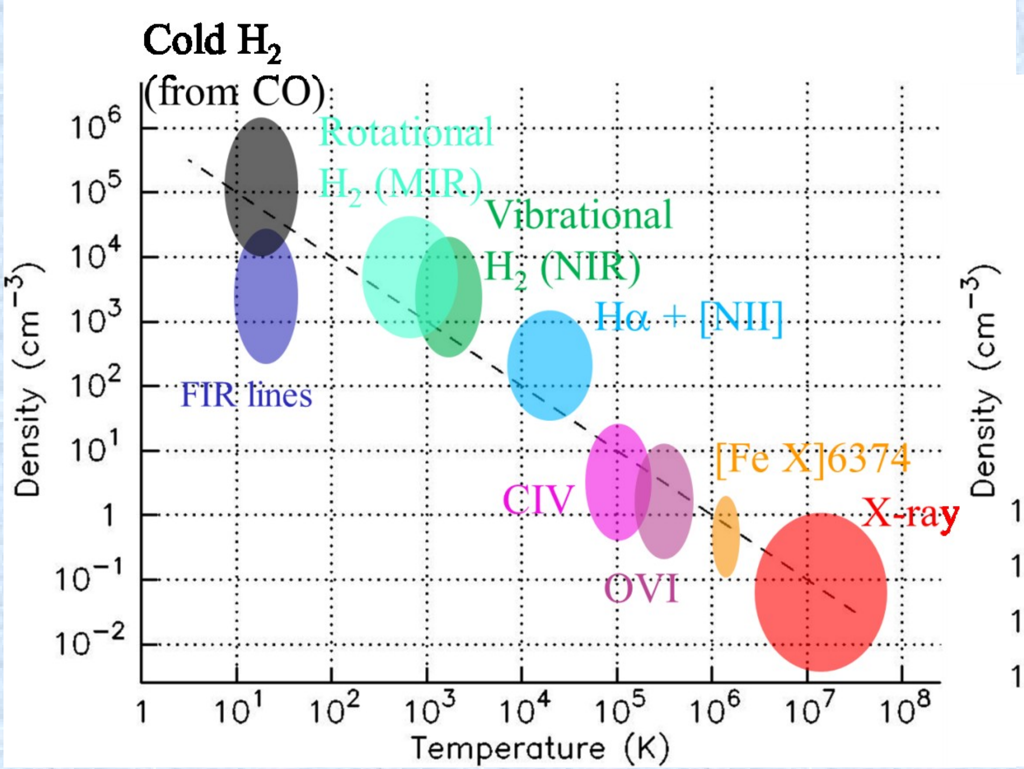
Phase diagram

cool core

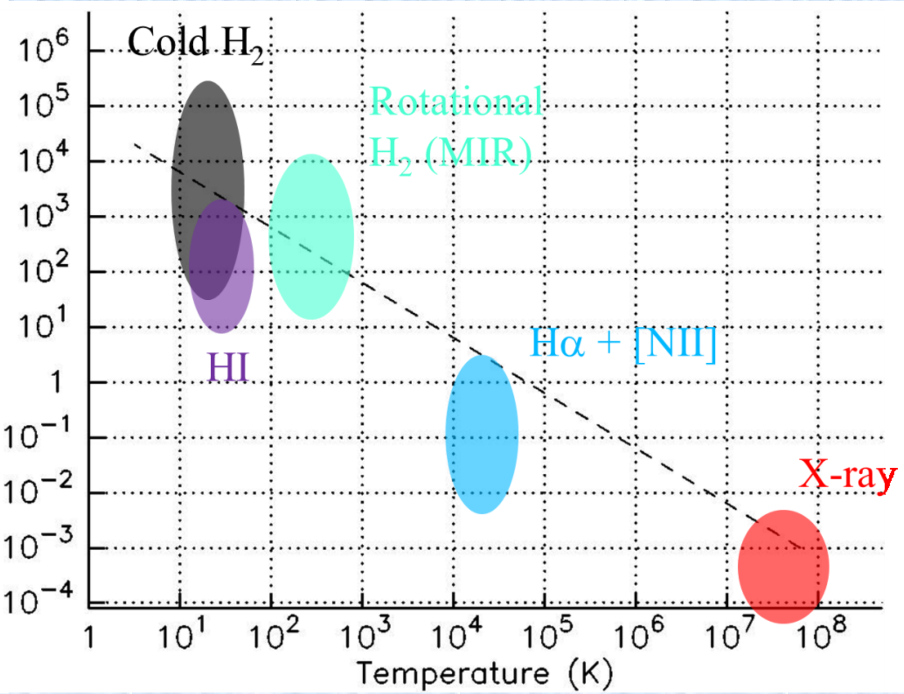


Phase diagram

cool core

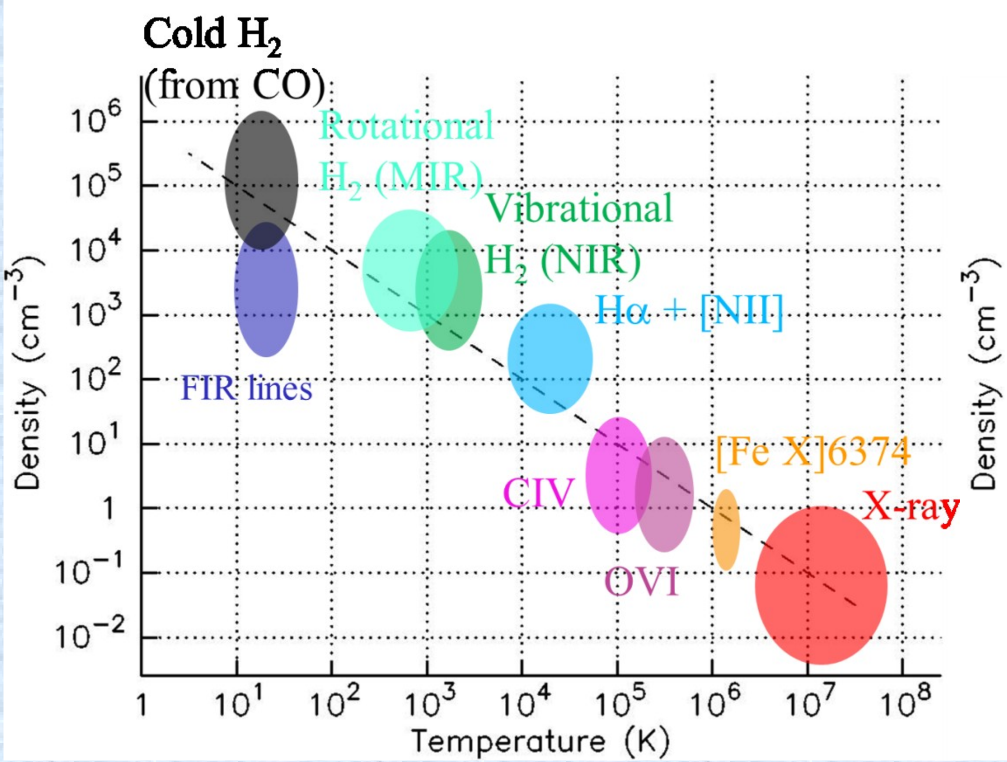


stripped tail

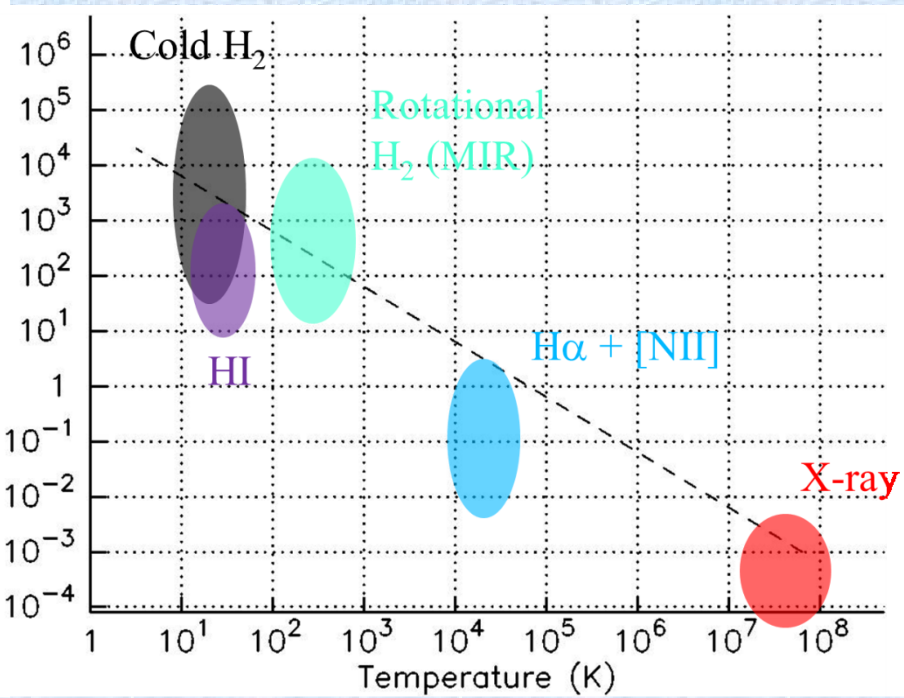


Phase diagram

cool core

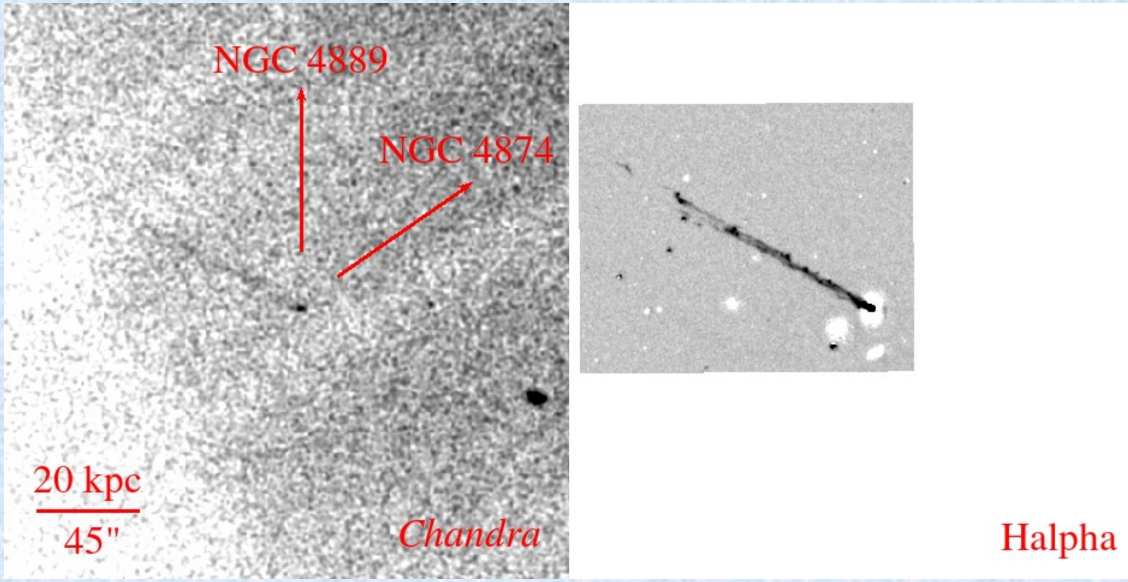


stripped tail



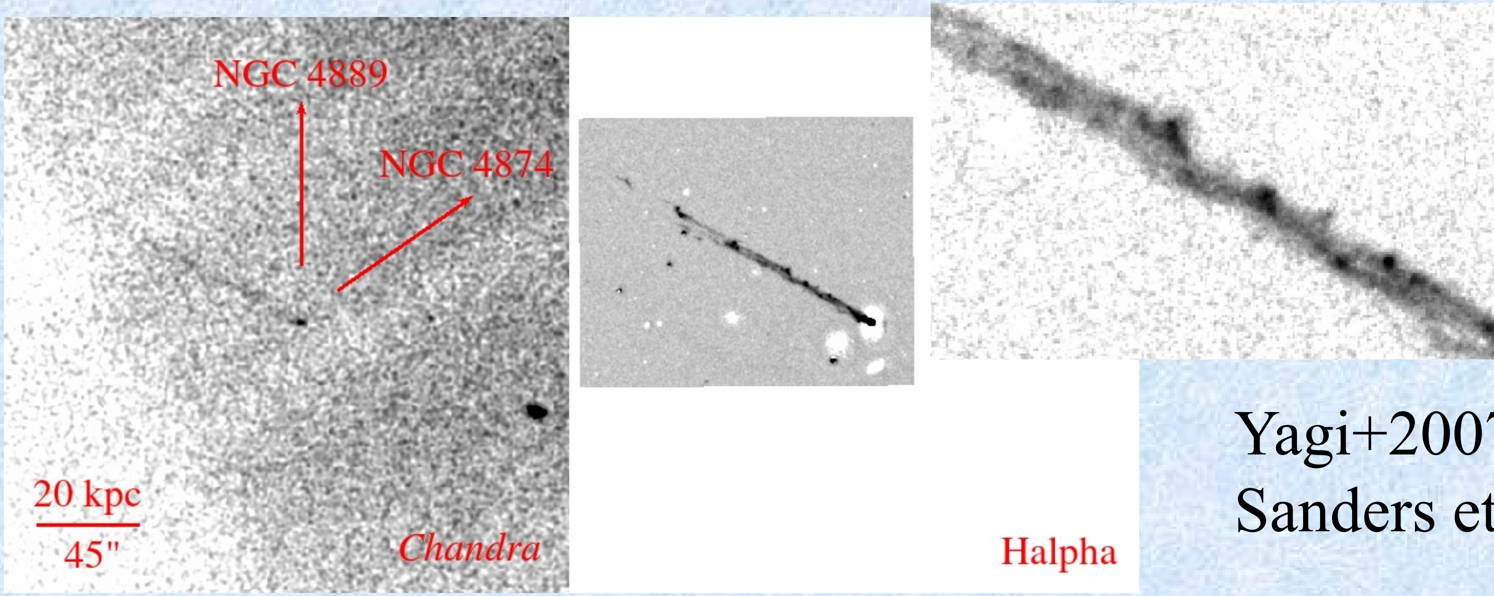
- Several tracer of kinematics
- Star formation conditions / efficiency
- Cooling / heating

Two tails to tell ?



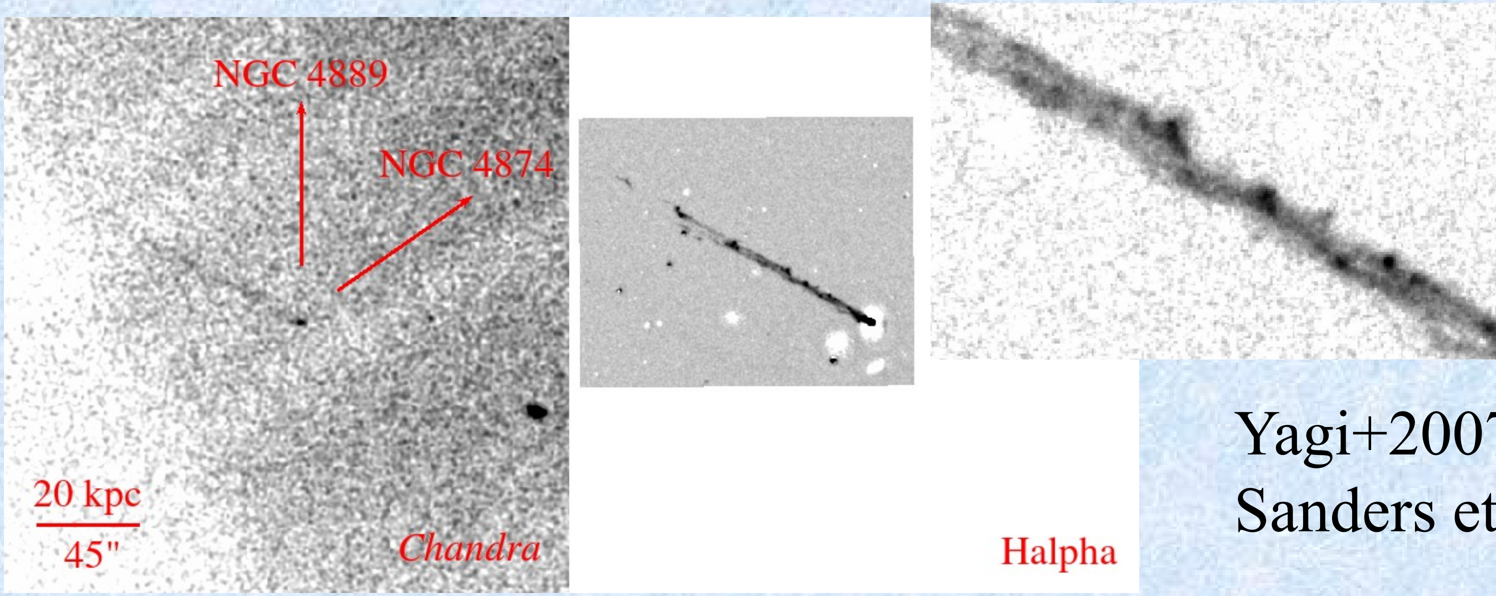
Yagi+2007;
Sanders et al. 2014

Two tails to tell ?

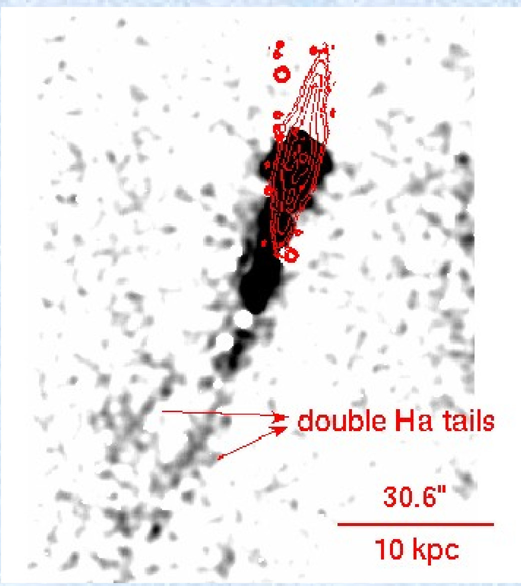


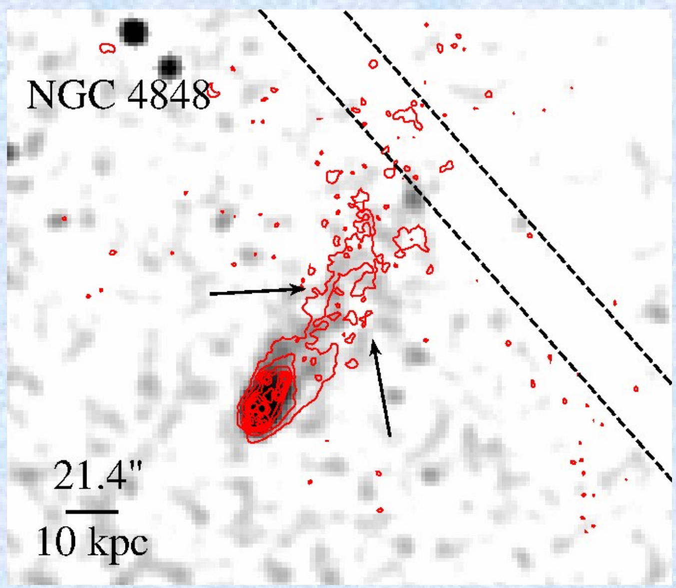
Yagi+2007;
Sanders et al. 2014

Two tails to tell ?



Yagi+2007;
Sanders et al. 2014





ESO 137-002 in A3627
NGC 4848 in Coma
(Sun+2010;
Zhang, Sun+2013)
(NGC 4848
Hα from Fossati +)

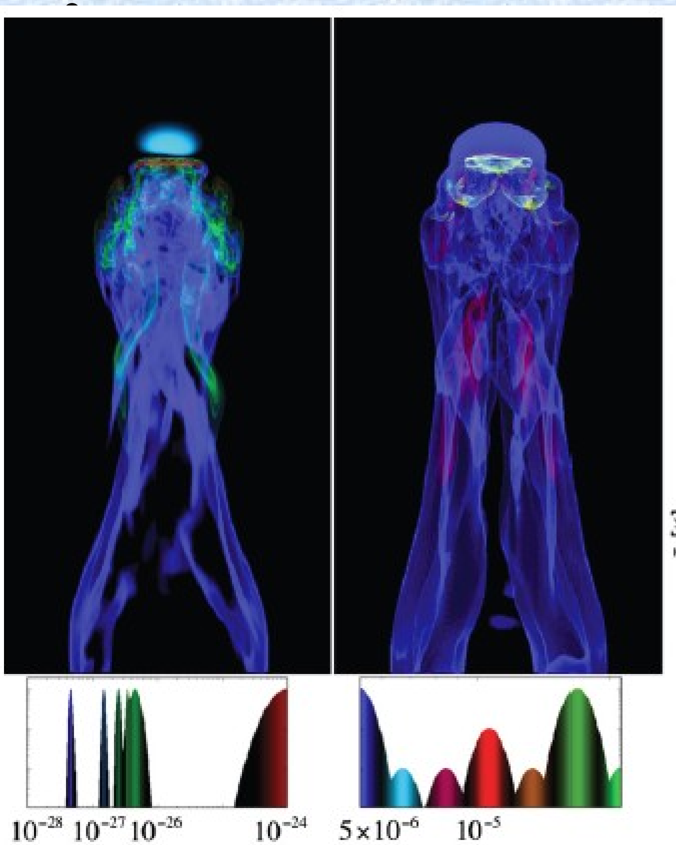
MHD simulations of stripping

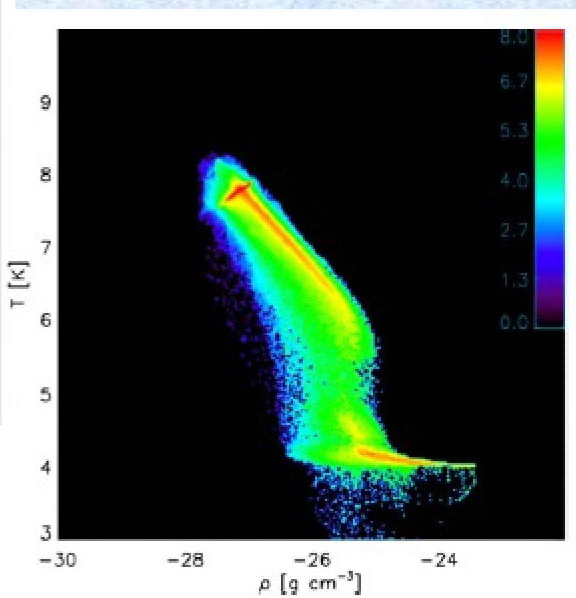
- Ruszkowski+2014: FLASH v4 (ICM B + no Galactic B)

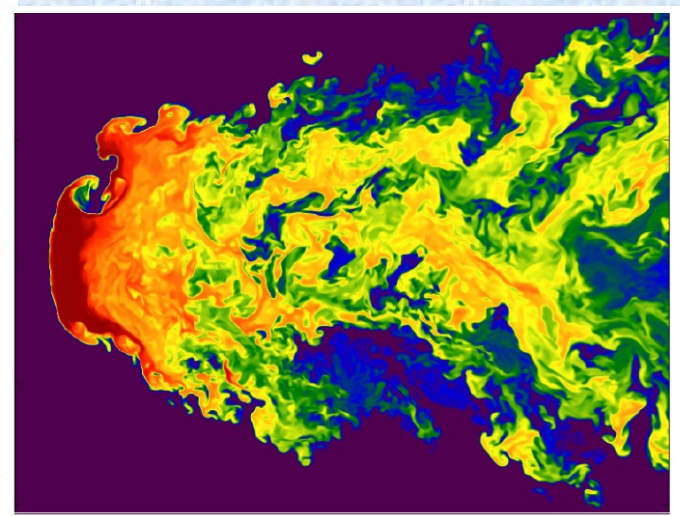
  Clumpy tails in hydro vs. filamentary tails in MHD

  Double tails possible (B field folding)
- Tonnesen & Stone 2014: grid code Athena (Galactic B + no ICM B)

  B field delays mixing; the ram pressure stripped tails can magnetize the ICM.

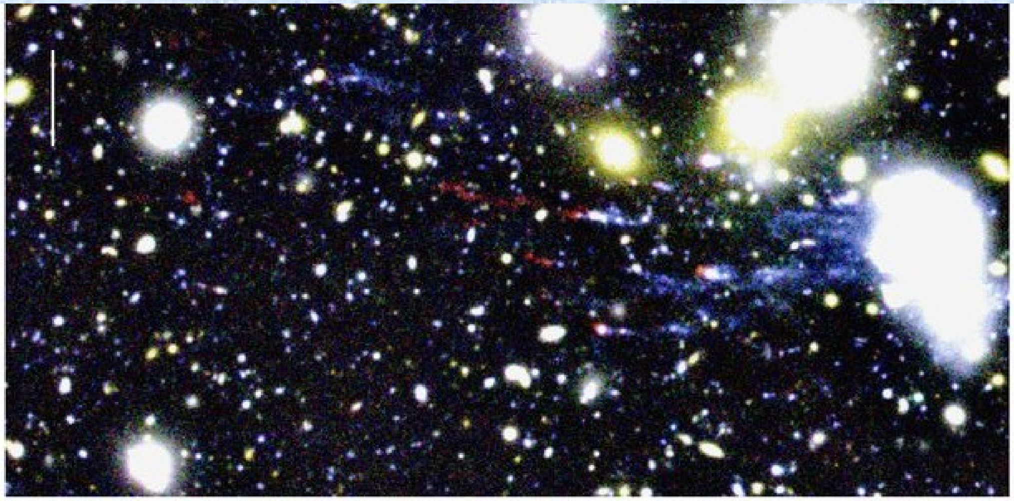


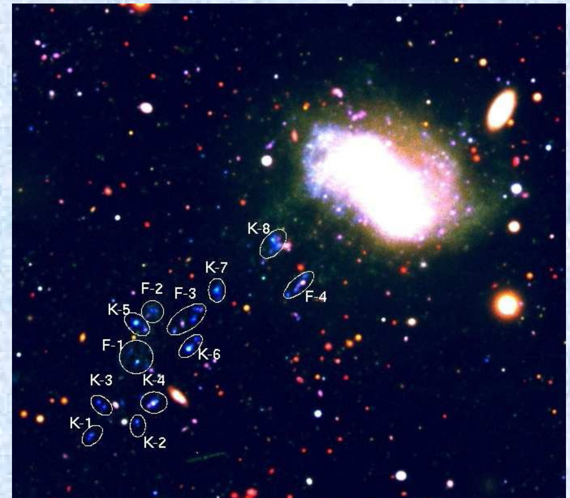


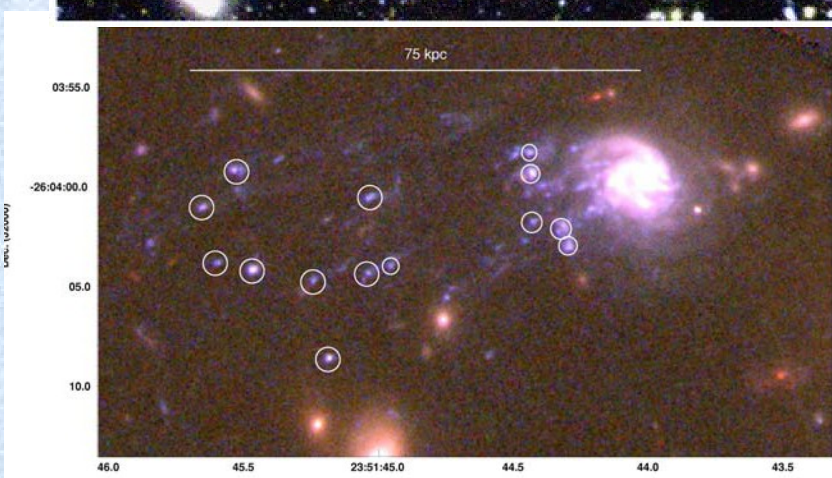


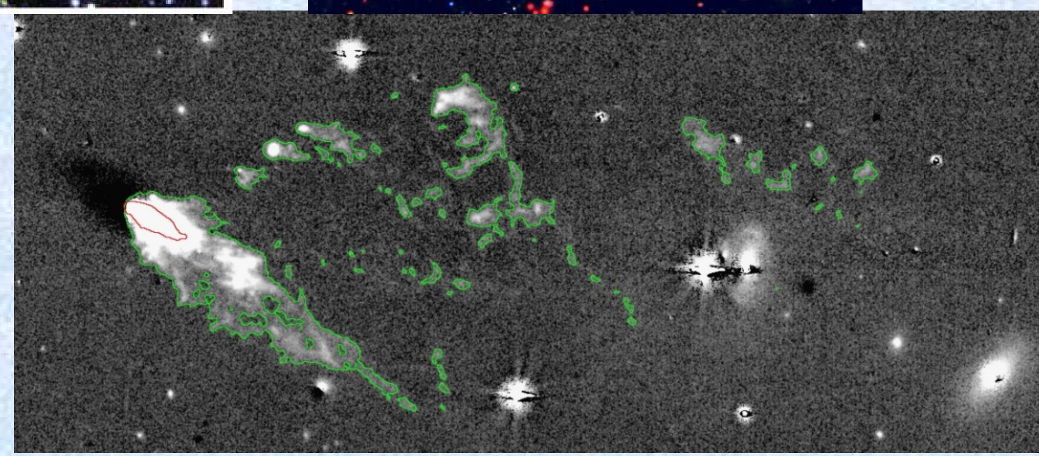
Intracluster Star Formation

> 30 more examples of one-sided trails of young star clusters and ionized gas from 2007 !









(Cortese+2007; Sun+2007; Yoshida+2008; Yagi+2010; Smith+2010; Hester+2010; Abramson+2011; Yoshida+2012; Owers+2012; Ebeling+2013; Kenney+2013)

Known knowns / unknowns

- A lot of more ram pressure stripped tails discovered recently in X-rays, HI, Hα, H_2 and CO !
- Intracluster star formation indeed happens --- another unique place to study star formation, multi-phase medium, turbulence, MHD effects as cool cores ! Intracluster SF efficiency low ? Likely not a major contribution to ICL ?
- Two tails to tell ! ?
- We need magnetic field. The effect of B field on stripping and SF ?