Physical processes in merging galaxy clusters

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Main topics of the talk

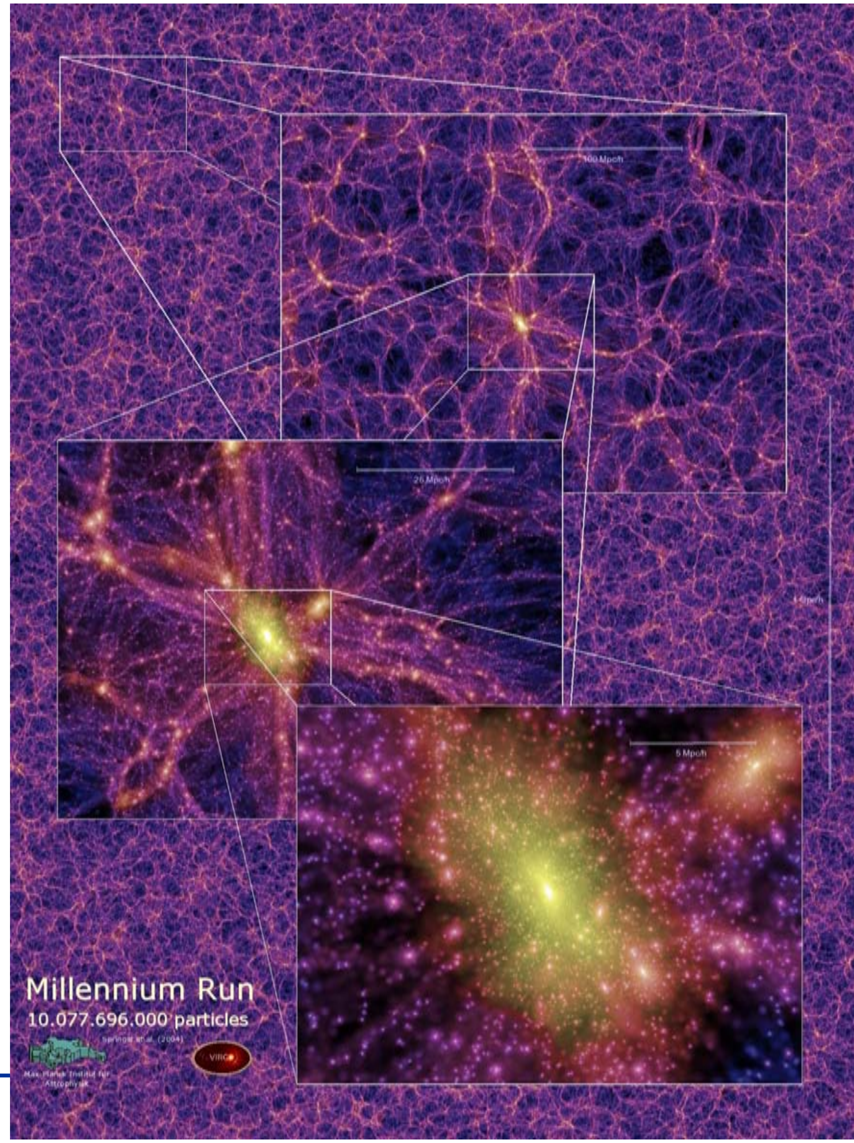
✓ Formation and evolution of clusters and their galaxies

- Study of the complex physics of cluster formation and evolution
  <u>In collaborations with:</u> OCA (FR), INAF (IT), MPE (DE), University of Cambridge (UK), SAp/CEA (FR)
- Cluster merging and star formation
  <u>In collaborations with:</u> OCA (FR), INAF (IT), University of Sydney (AU)
- New tracers of structure formation: metallicity maps
  <u>In collaborations with:</u> Innsbruck Universität (AT)

✓ Diffuse and extended radio emission in galaxy clusters

- Radio halos and relics
  <u>In collaborations with:</u> INAF (IT), University of Innsbruck, University of Sydney (AU), OCA(FR), Max-Plank Institut für Kernphysik (DE)

Hierarchical model of structure formation



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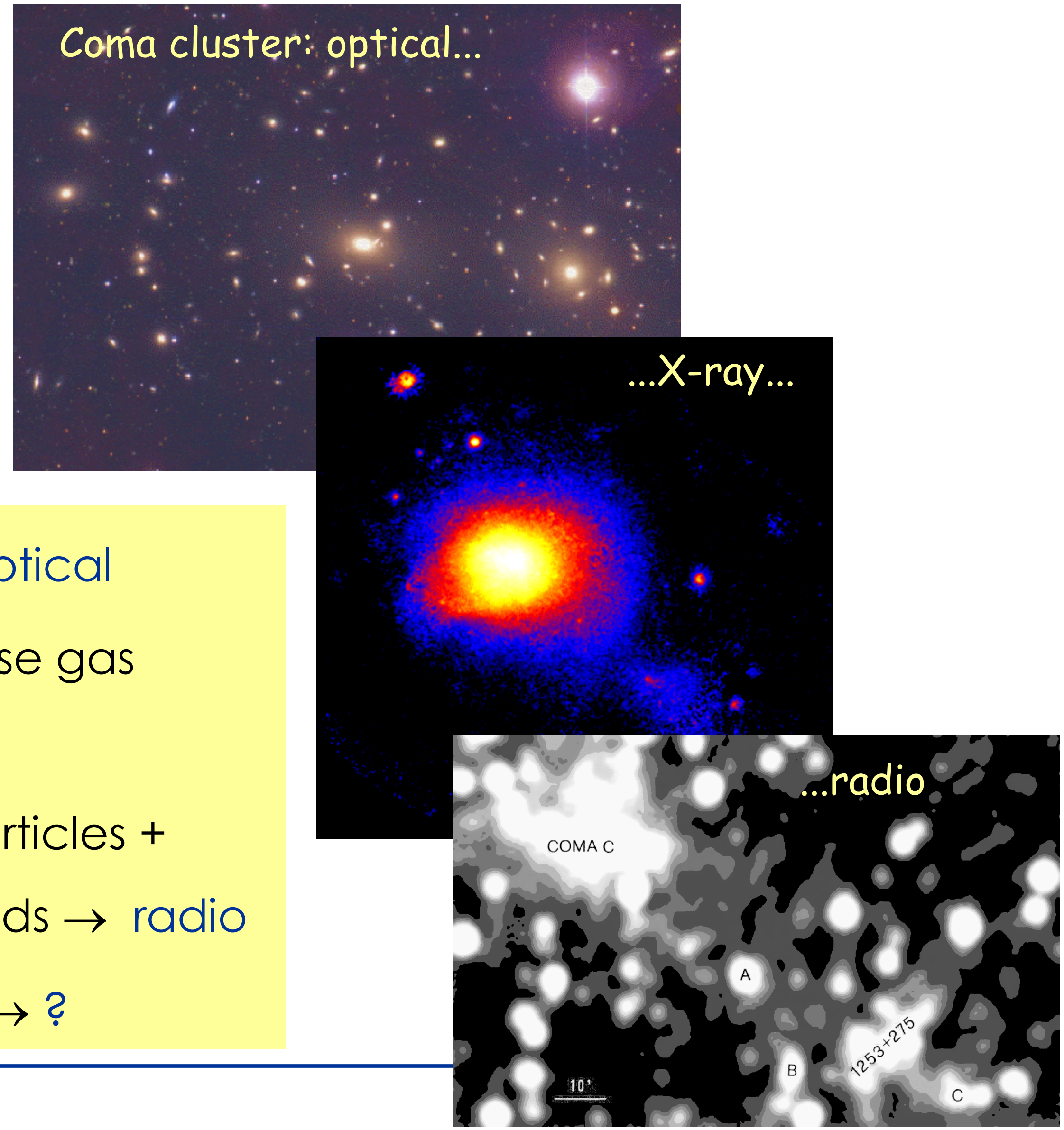


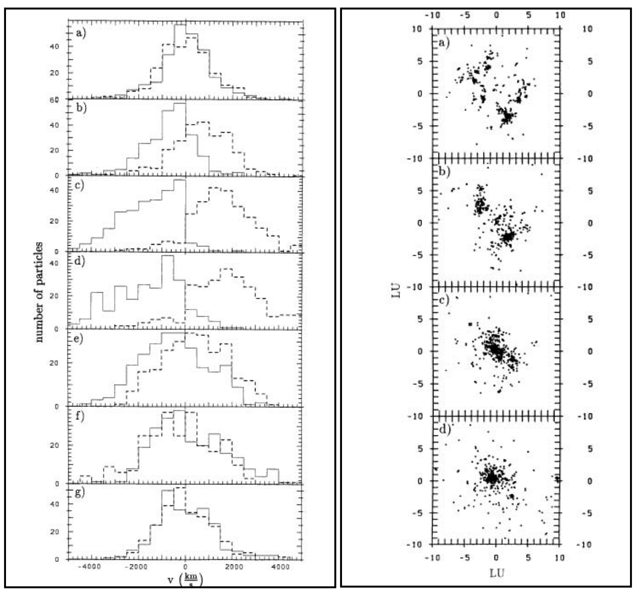
- ✓ 3% $M_{cluster}$: galaxies → optical
- ✓ 16% $M_{cluster}$: hot and diffuse gas (ICM) → X
- ✓ ~0% $M_{cluster}$: relativistic particles + magnetic fields → radio
- ✓ >80% $M_{cluster}$: dark matter → ?

Physics of merging clusters

Effects of the merging process on global cluster properties:

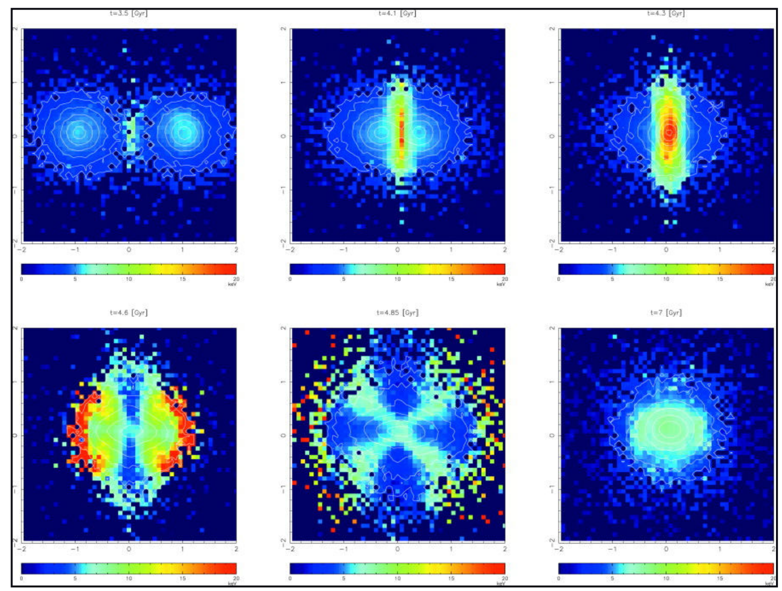
- ✓Galaxy dynamics and spatial distribution → optical observations
- ✓ICM density and temperature distribution → X-ray observations

} dynamical state of clusters



Numerical simulations:
spatial and velocity distribution of cluster galaxies

Schindler & Müller 1993



Numerical simulations:
ICM temperature maps & density contours

Takizawa et al. 1999

Physics of merging clusters

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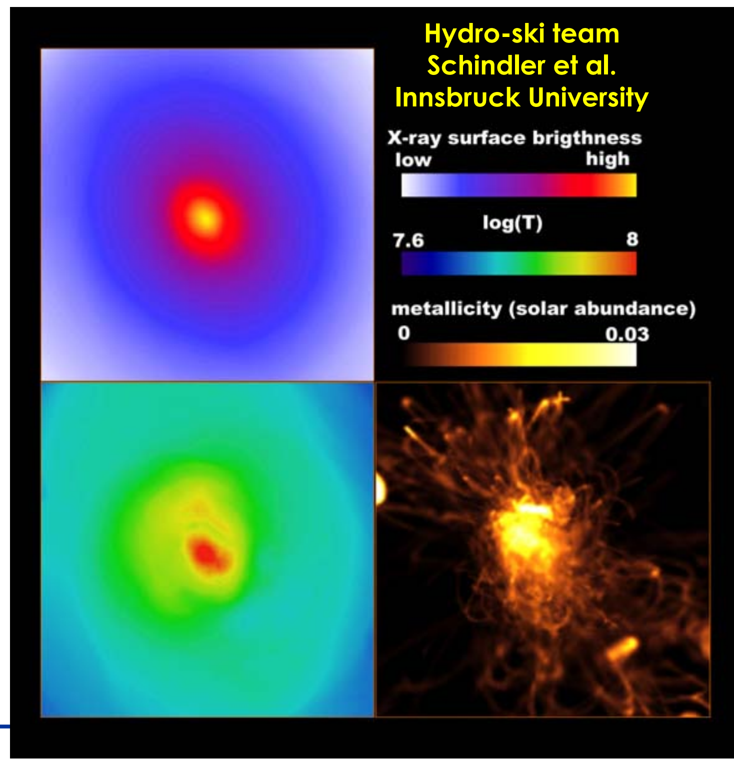
- ✓ICM metallicity distribution → X-ray observations



Physics of merging clusters

Effects of the merging process on global cluster properties:

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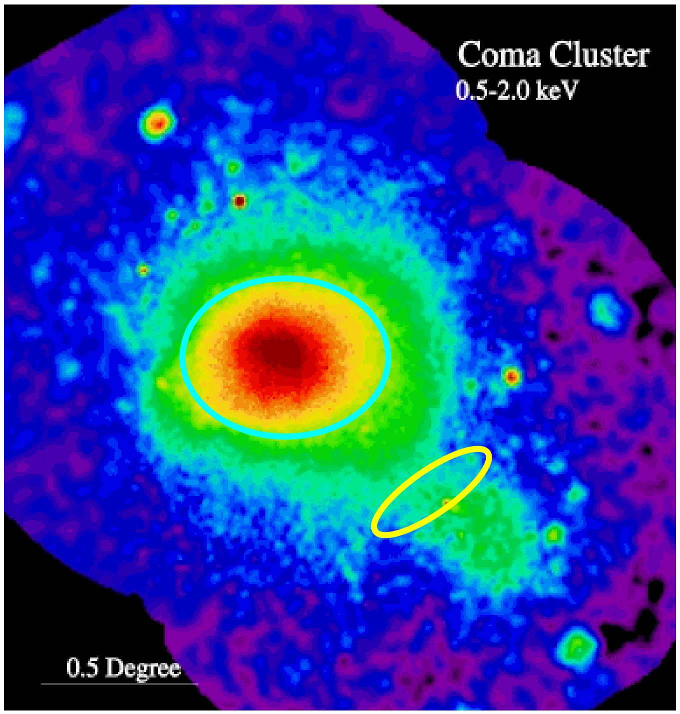
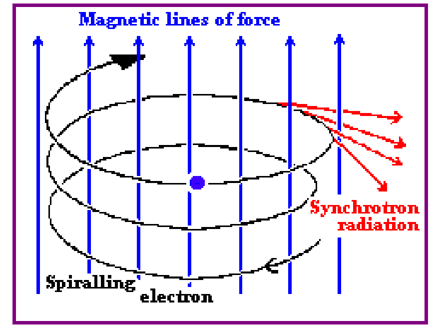
} dynamical state of clusters

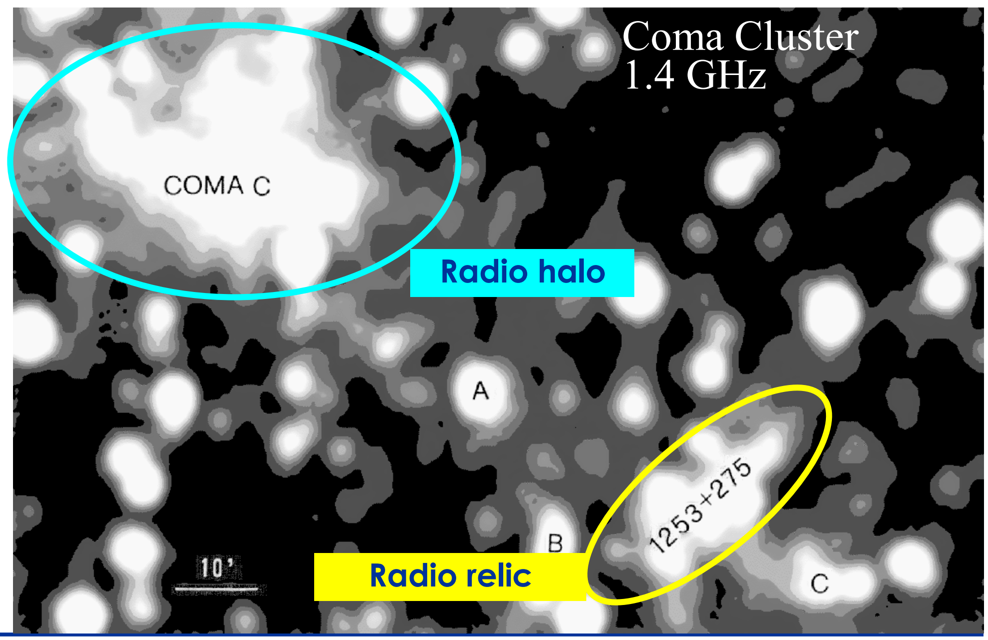
- ✓ICM metallicity distribution → X-ray observations
- ✓Non-thermal component of the ICM → radio observations

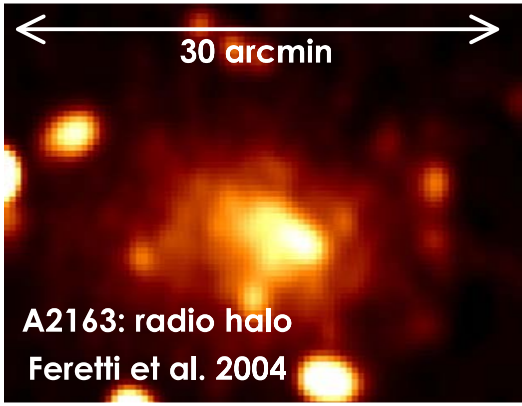
Extended and diffuse radio emission in galaxy clusters

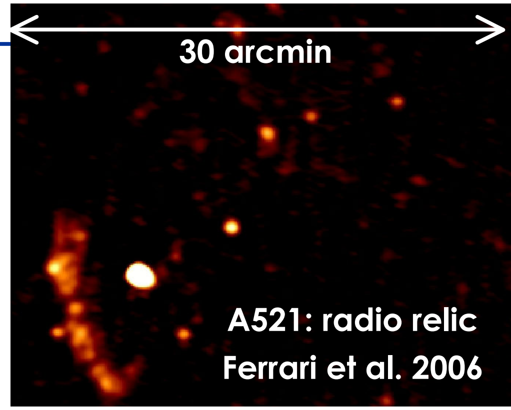


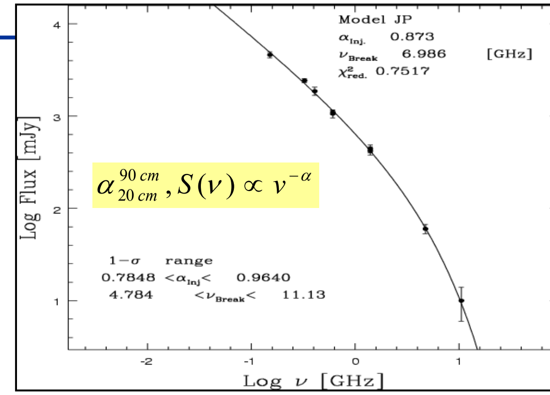
- ✓ magnetic field (μGauss)
- ✓ relativistic electrons (GeV)











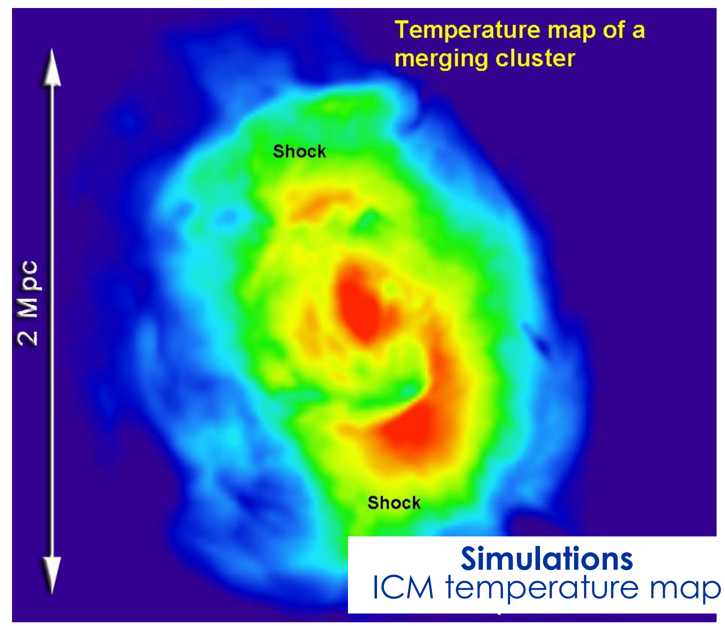
Dimensions: ~1 Mpc

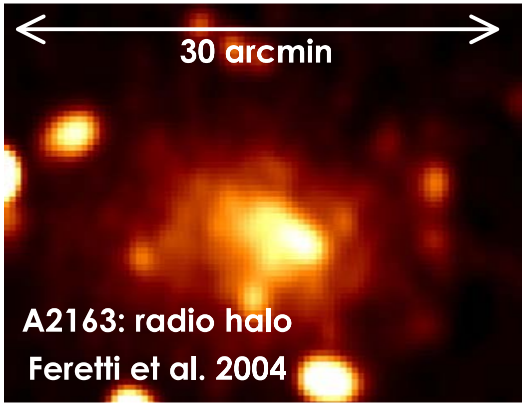
Crossing time e⁻: ~9.5 Gyr

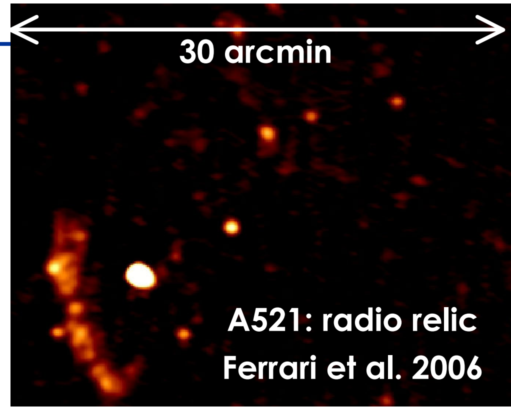
Life time of e⁻: ~0.1 Gyr

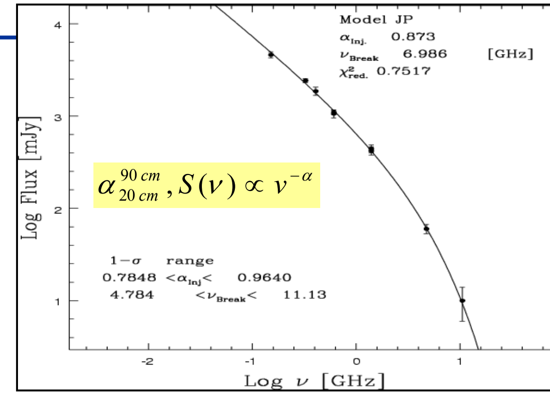
Possible acceleration mechanisms:

- ✓ Primary: (re-)acceleration due to shocks/turbulences
  (e.g. Tribble 1993, Brunetti et al. 2001, Fujita et al. 2003)
- ✓ Secondary: hadronic collisions of relativistic p^+ with the ICM
  (e.g. Blasi & Colafrancesco 1999, Dolag & Enßlin 2000)









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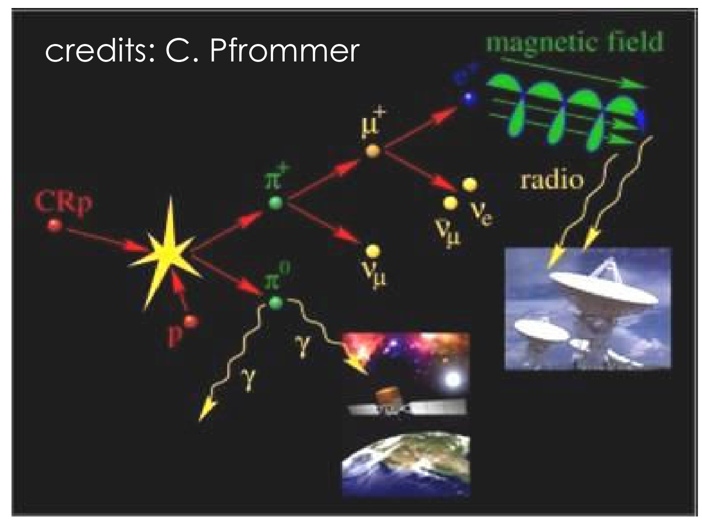
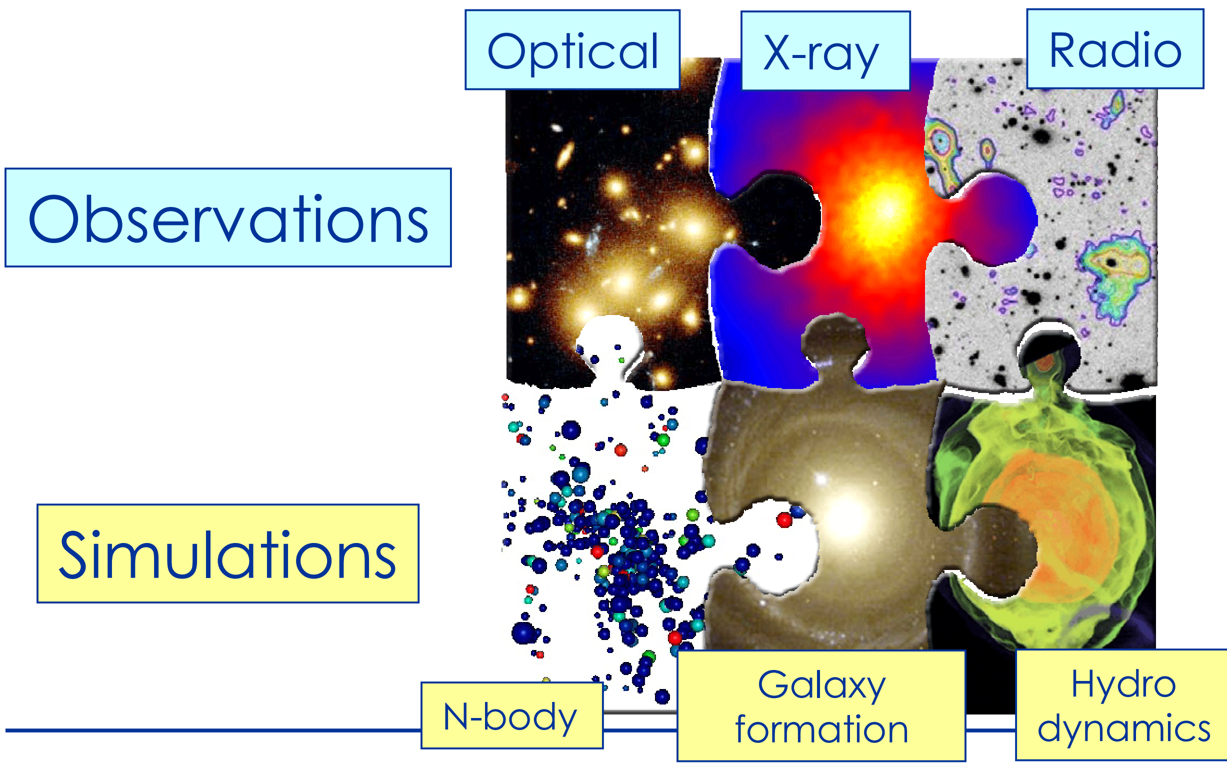


Physics of merging clusters

Effects of cluster mergers on:

- ✓ Galaxy dynamics and spatial distribution → optical observations
- ✓ ICM density, temperature and metallicity distribution → X-ray observations
- ✓ Non-thermal component of the ICM → radio observations



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⇒ characterisation of the merging process

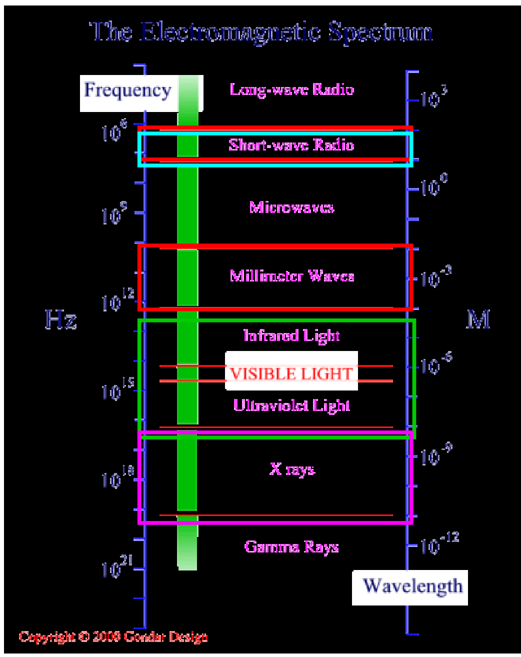
⇓

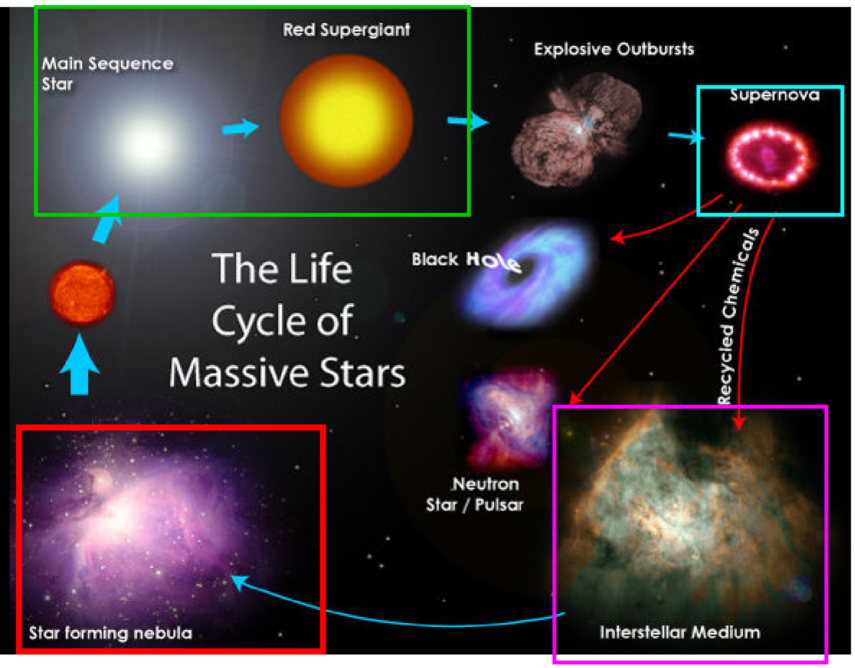
✓ Evolution of the internal properties of galaxies: colour, star-formation rate (SFR), morphology...

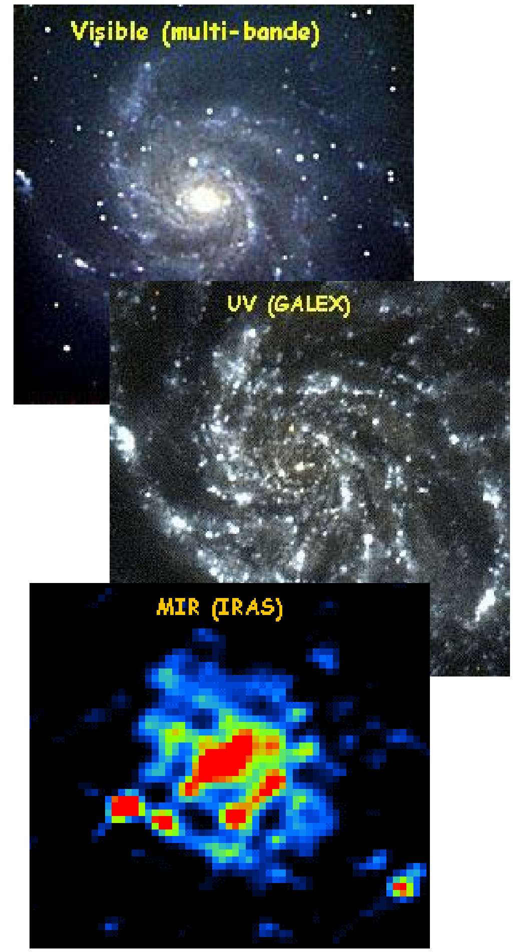
Evolution of cluster galaxies with z: connection with cluster mergers ?

- ✓ Increasing fraction of star-forming (SF) / post-star-forming (PSF) cluster galaxies with z
- ✓ Increasing population of blue galaxies in clusters with z (Butcher-Oemler effect)
- ✓ Both observations and simulations suggest that cluster mergers can either weaken or trigger SF (e.g. Gavazzi et al. 2003; Venturi et al. 2003; Giacintucci et al. 2004; Evrard 1991; Fujita 1999; Bekki 1999)
- ✓ Some of the possible physical mechanisms (see Boselli & Gavazzi 2006 for a review):
  - ram-pressure of the ICM on the ISM ($\propto \rho_{ICM} \times v_{Gal}^2$): compression or stripping (Evrard 1991; Fujita et al. 1999)
  - interactions, collisions and merging between galaxies (e.g. Combes 2004 for a recent review)
  - tidal effects due to rapid changes in the gravitational field of merging clusters (Bekki 1999)

Evolution of cluster galaxies: star-formation

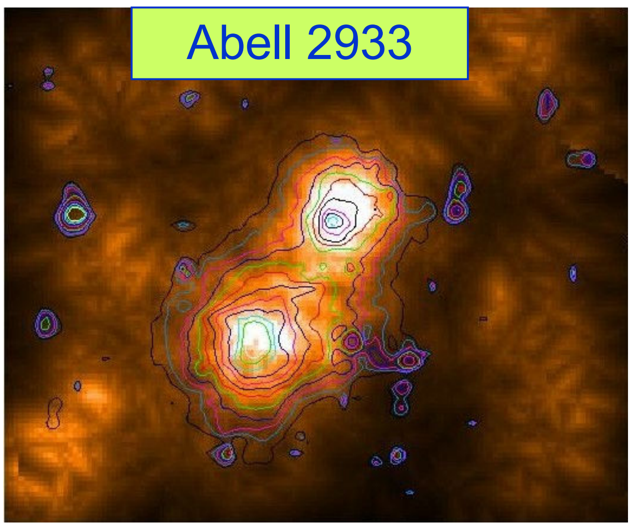


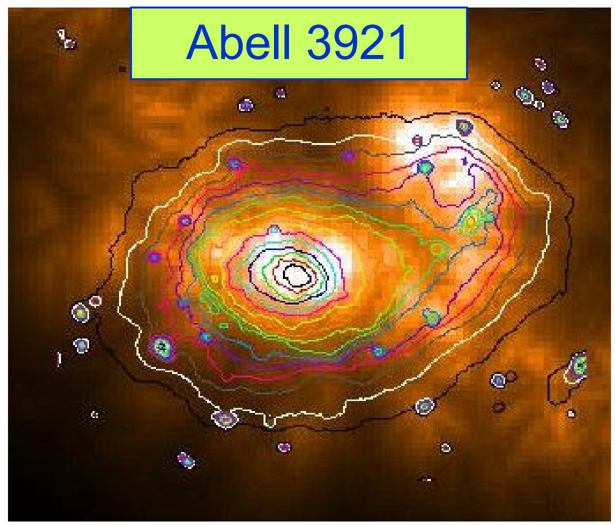


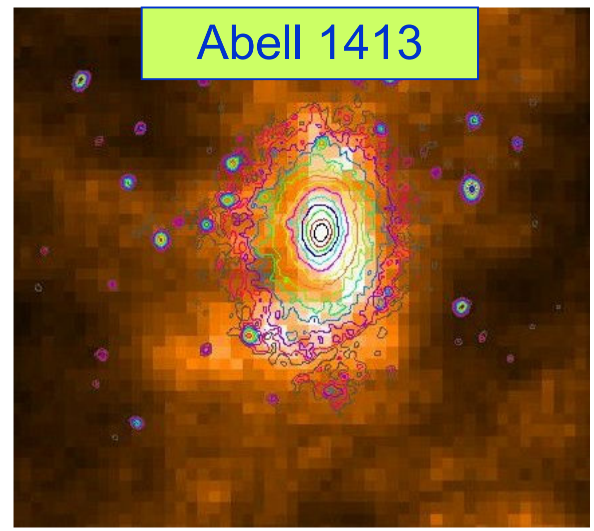


MUSIC:
Multi-wavelength Sample of Interacting Clusters

In collaboration with:
OCA (optical) + Saclay (X-ray) + IRA/Un.Sydney (radio) + Innsbruck (numerical simulations)







Pre-merging → **Merging** → **Post-merging**

Optical iso-density maps + X-ray contours

X-ray:

- Sauvageot, Arnaud (SAp, F)
- Belsole (Uni.Cambridge, UK)
- Bourdin (Uni.Roma, I)
- Pratt (MPE, D)
- Ferrari (Uni.Innsbruck, A)

Large-scale (~Mpc) physical processes

Optical:

- Maurogordato, Benoist, Mars, Slezak (OCA, F)
- Ferrari (Uni.Innsbruck, A)
- Cappi (Oss.Bologna, I)

X-ray:

Spectro-imaging:

- XMM
- Chandra

Large-scale (~Mpc) physical processes

Optical:

- Multi-band imaging:
  - **ESO (WFI@2.2m)**
  - **CFHT (CfH12K)**
- Multi-object spectroscopy:
  - **ESO(EFOSC2@3.6m & VIMOS@VLT)**
  - **CFHT (MOS@3.6m)**
  - **2dF(AAT)**

X-ray:

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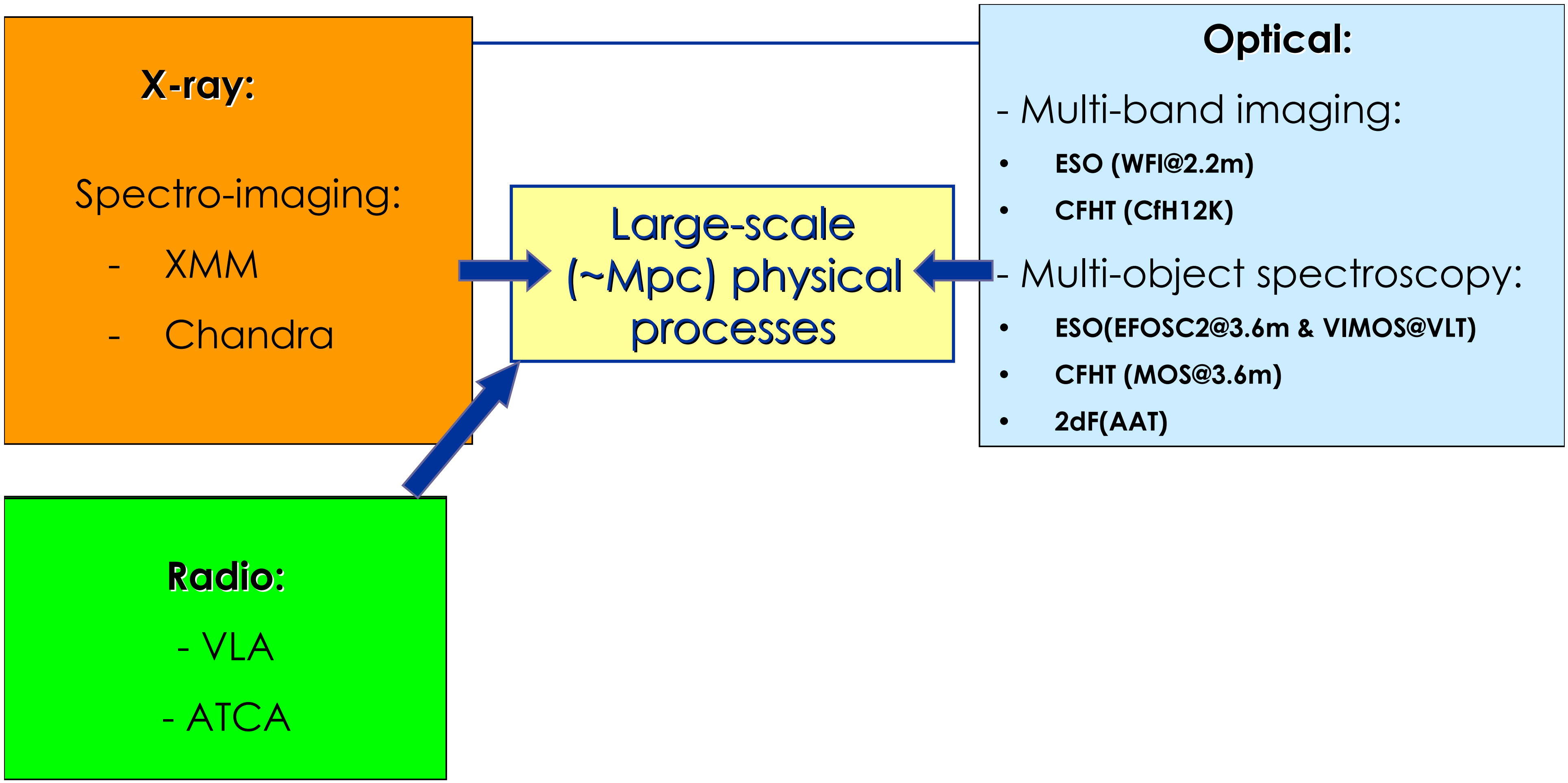
- Cappi (Oss.Bologna, I)

Radio:

-Ferrari (Un. Innsbruck,A)

-Feretti (IRA, I)

-Hunstead (Uni.Sydney, AU)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Large-scale (~Mpc) physical processes
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Radio:
- VLA
- ATCA

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Radio:

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Large-scale (~Mpc) physical processes

Star-formation in merging galaxy clusters

Comparison

observations-numerical simulations:

Ferrari, Schindler & *Hydro-Ski team*

(University of Innsbruck)

MUSIC: observations

Optical Spectroscopy	EFOSC2@3.6m ESO	2dF@AAT	VIMOS@VLT
	P.I. or Co.I.	**P.I.**	Co.I.
Optical Imaging	CFH12k@CFHT	WFI@2.2m ESO	
	Co.I	Co.I	
X-ray	Chandra	XMM	
	P.I. or Co.I.	Co.I.	
Radio continuum	ATCA	VLA	
	P.I.	**P.I.**	

Main topics of the talk

- ✓ Formation and evolution of clusters and their galaxies
  - Study of the complex physics of cluster formation and evolution
    <u>In collaborations with:</u> **OCA (FR), INAF (IT), MPE (DE), University of Cambridge (UK), SAp/CEA (FR)**
  - New tracers of structure formation: metallicity maps
    <u>In collaborations with:</u> **Innsbruck Universität (AT)**
  - Cluster merging and star formation
    <u>In collaborations with:</u> **OCA (FR), INAF (IT), University of Sydney (AU)**

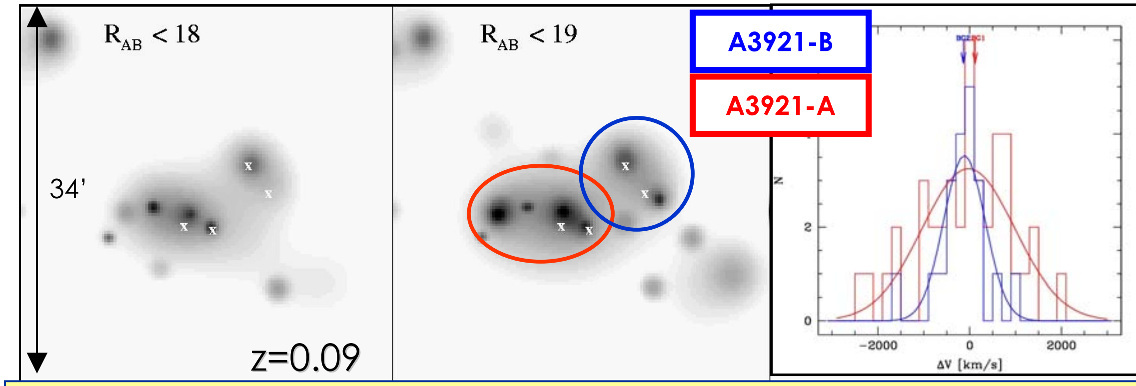
- ✓ Diffuse and extended radio emission in galaxy clusters
  - Radio halos and relics
    <u>In collaborations with:</u> **INAF (IT), OCA(FR), University of Copenhagen (DK), University of Sydney (AU)**

Abell 3921:

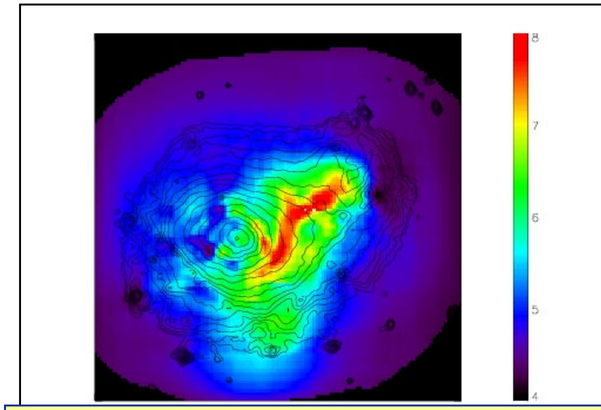
the effect of cluster collisions on star formation

- ✓ Optical (ESO) : Ferrari, Benoist et al., 2005, A&A, 430, 19
- ✓ X-ray (XMM) : Belsole, Sauvageot et al., 2005, A&A, 430, 385
  - ✓ X-ray (Chandra) : Ferrari et al., in prep.
- ✓ Radio (ATCA) : Ferrari, Hunstead et al., 2006 A&A, 457, 21
- ✓ Simulations : Kapferer, Ferrari et al., 2006, A&A, 447, 827

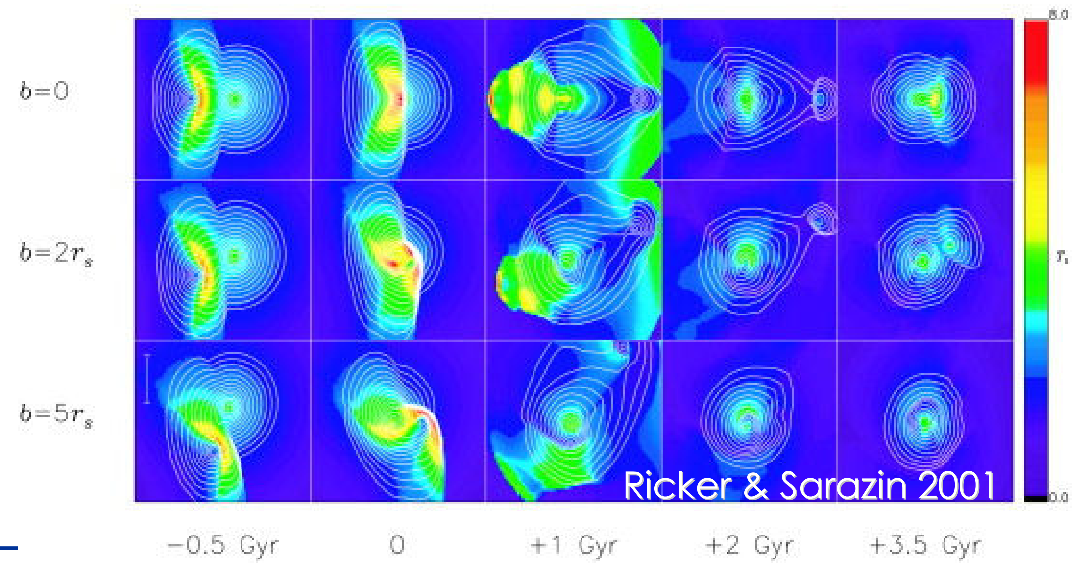
Dynamical state of A3921



Left: Projected galaxy density maps (red-sequence galaxies)
Right: Velocity distributions of the two sub-clusters
(Ferrari et al. 2005)



Temperature map of A3921
(Belsole et al. 2005)



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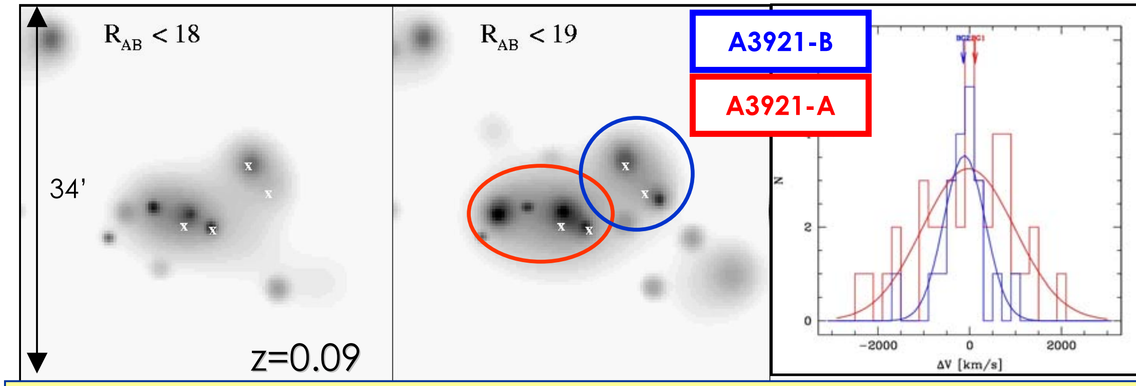

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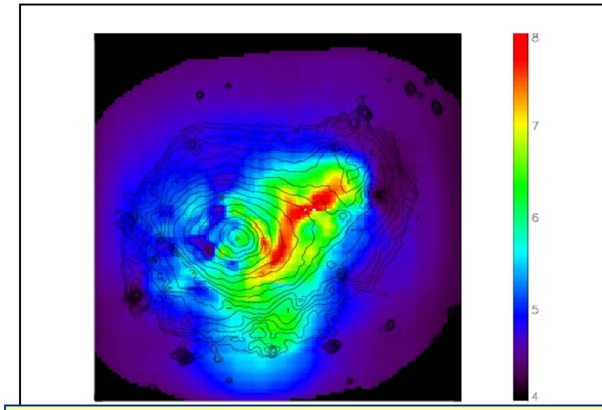

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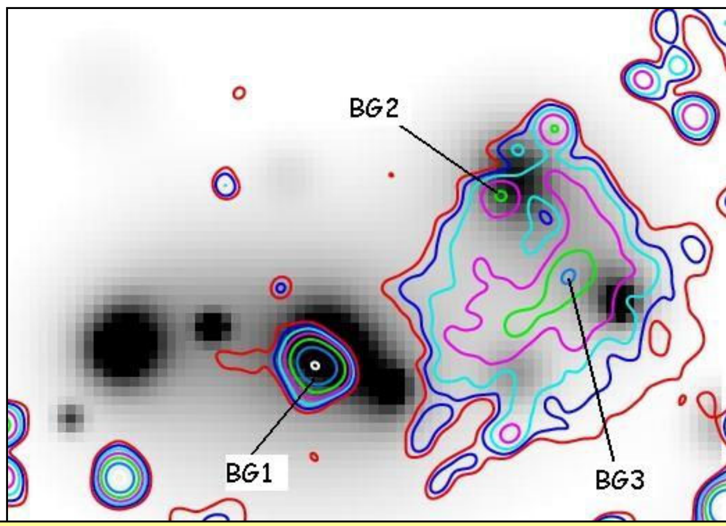


Projected galaxy density map (Ferrari et al. 2005) + X-ray residuals after subtraction of a 2D-β model
(Belsole et al. 2005)

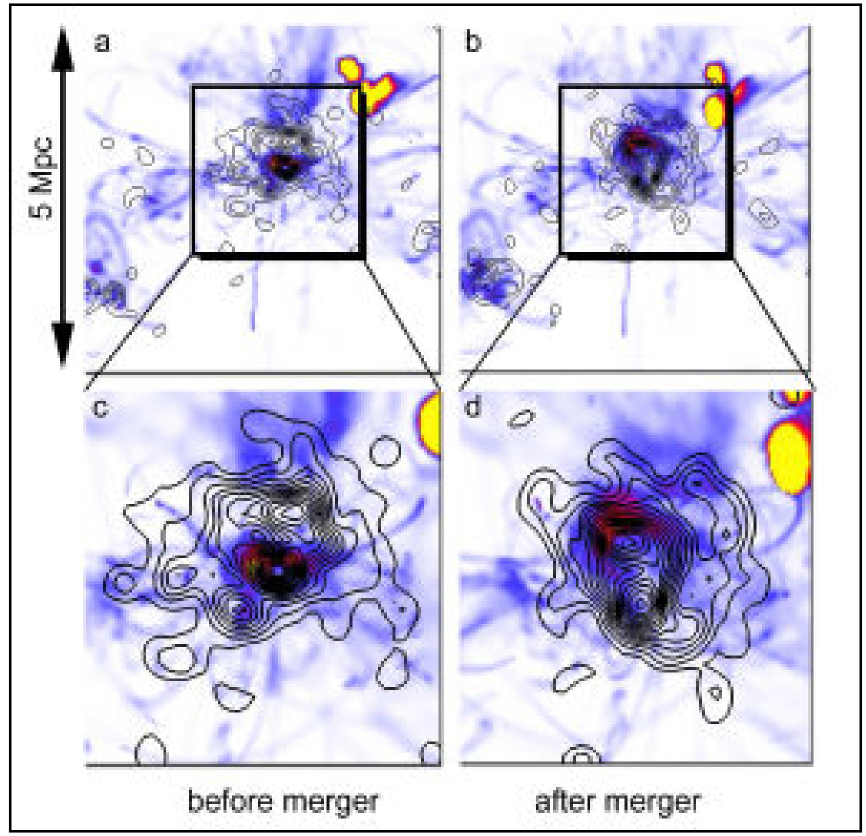
- ✓ The merger is in its central phase (0.0 ± 0.3 Gyr)
- ✓ Off-axis collision on the plane of the sky

Metallicity maps ↔ dynamical state of clusters

Numerical simulations:

X-ray weighted metal maps + galaxy iso-density contours

(Kapferer, Ferrari et al. 2006)



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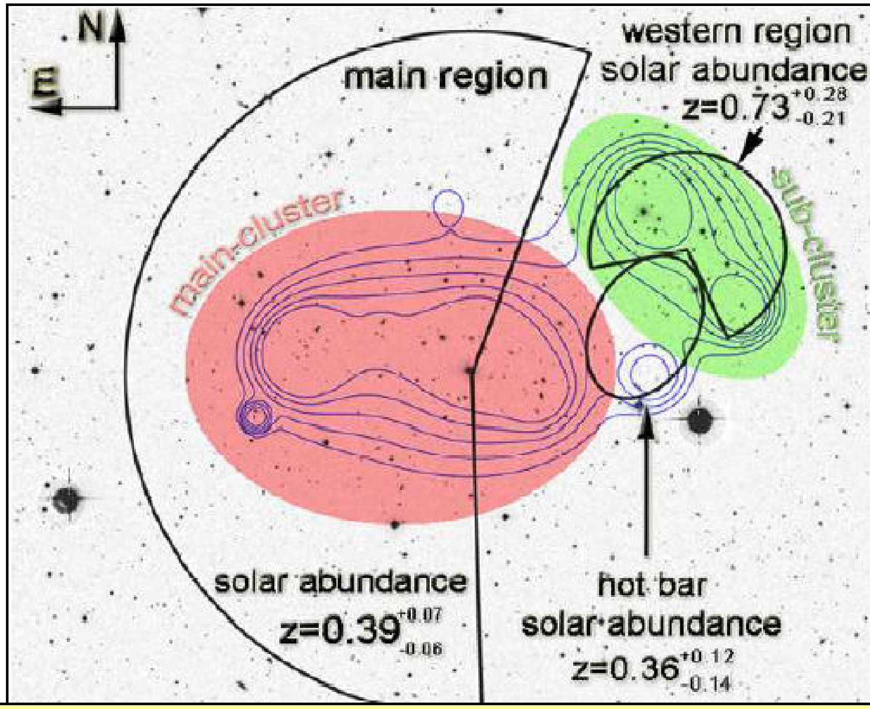
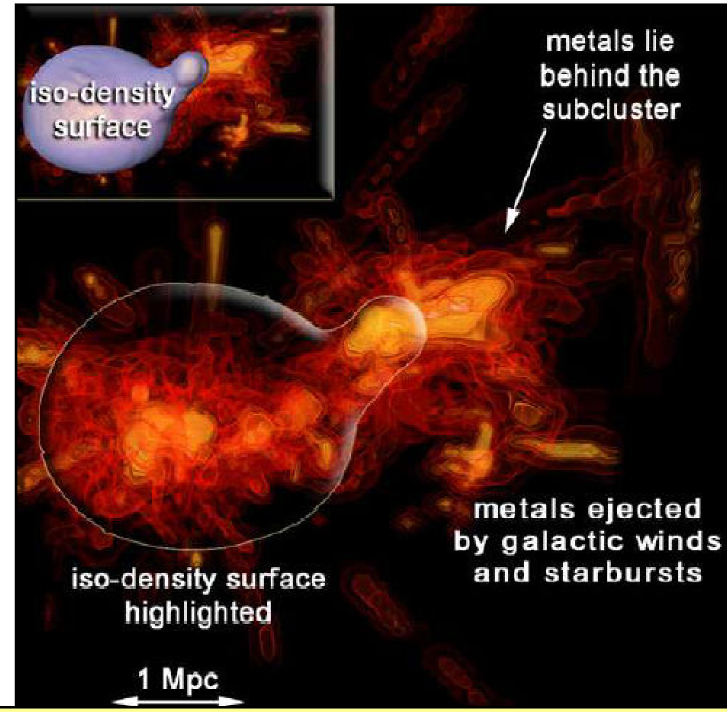


Observations of A3921:

R-band image + optical iso-density contours (Ferrari et al. 2005) + metallicity distribution (Belsole et al. 2005)



Simulations of A3921:

Metallicity distribution + ICM density iso-surface (Kapferer, Ferrari et al. 2006)

The closest core encounter has not yet happened

Merging & star formation in A3921

optical observations (EFOSC2@3.6m ESO)

A3921 galaxies divided in different spectral types based
[OII] and Hδ equivalent widths

(following Dressler et al. 1999 & Poggianti et al. 1999):

1) k (passive, old population of stars) – 71 %

2) k+a (recent star formation) – 16 %

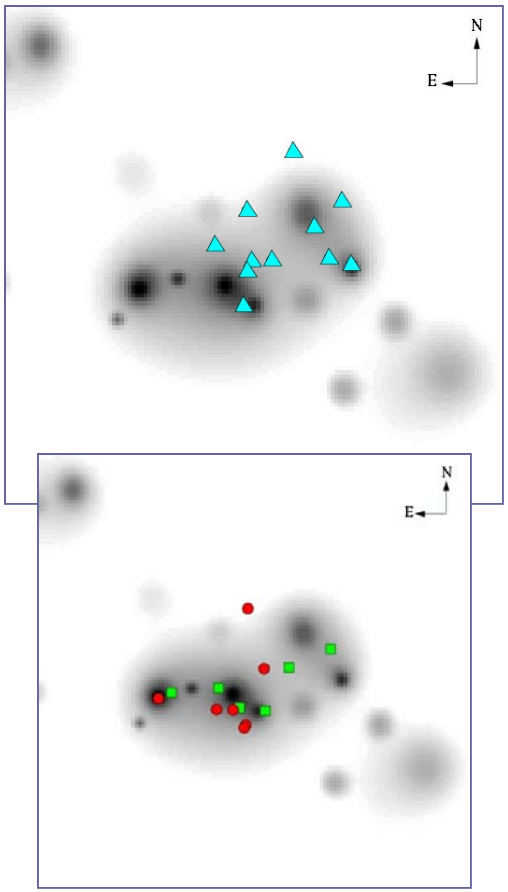
3) e (ongoing star formation) – 13 %

(2–3) Comparable to higher z clusters!
(z_{A3921}=0.09)

Ferrari, Benoist et al., 2005, A&A, 430, 19

Emission-line galaxies

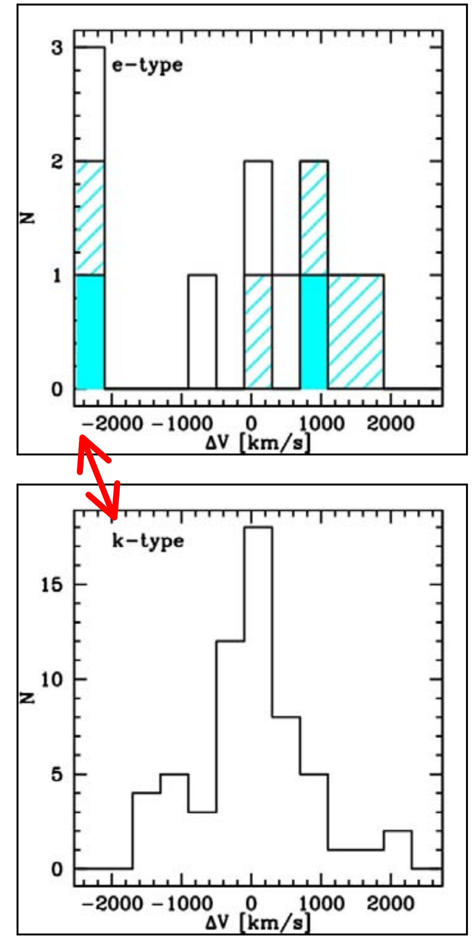
(on-going star formation)



- share neither the kinematics nor the projected distribution than passive cluster members

- they are concentrated in the collision region

Star formation ↔ merging event



However:

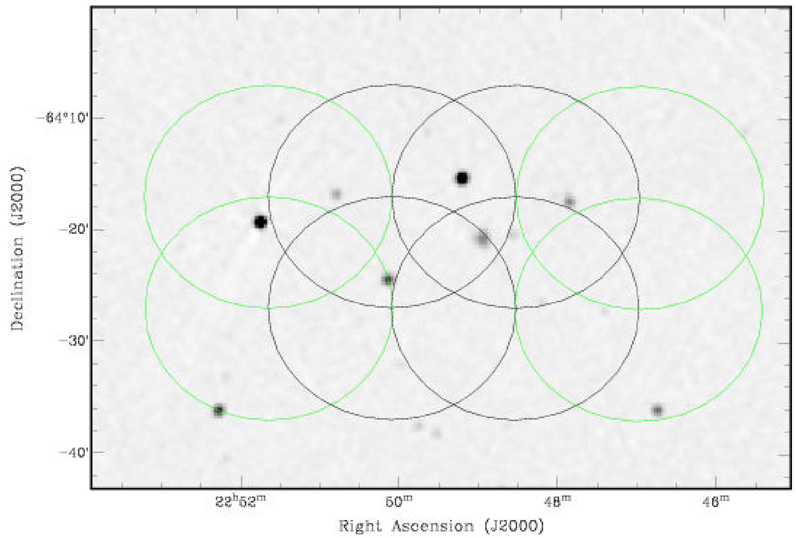
[OII] is not the best estimator of star formation...

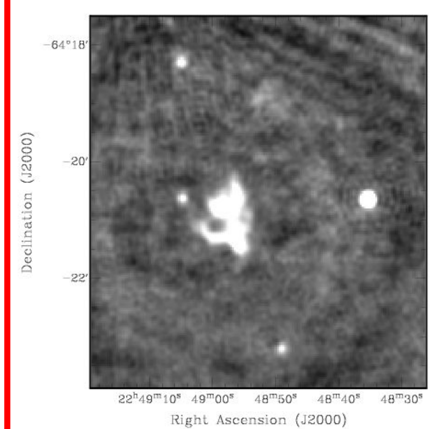
Radio observations

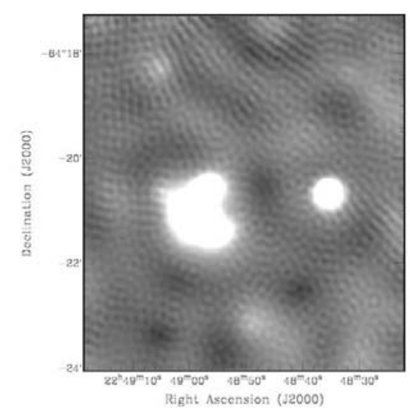
(no dust extinction)

ATCA observations

(22 & 13 cm - 4×12 h)



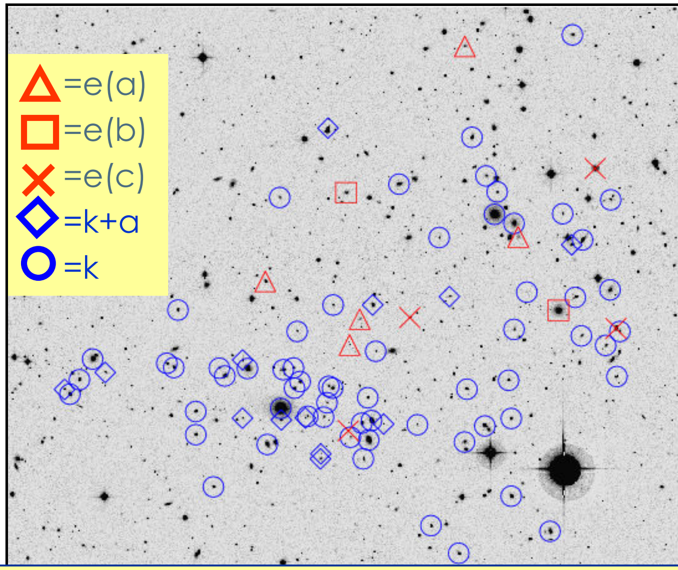




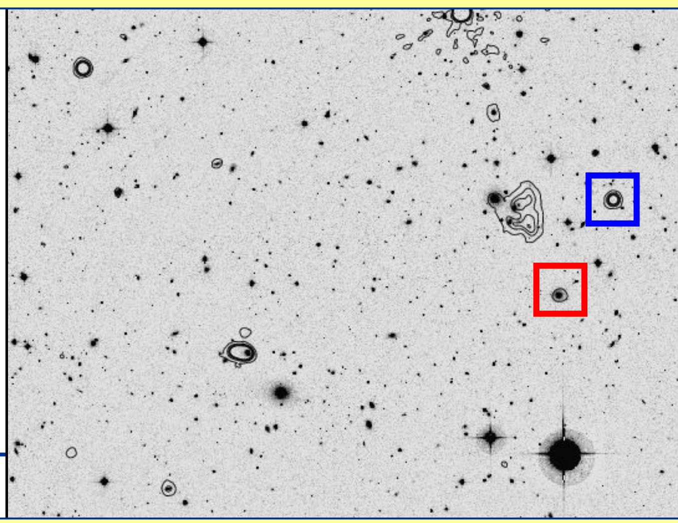
- ✓ May 2004: 6C configuration ← Highest spacing between antennas!
- ✓ July 2004: 6A configuration
- ✓ November 2004: 750C configuration
- ✓ December 2004: 1.5 D configuration ← Most compact configuration!

Ferrari et al., A&A, 2006 A&A, 457, 21

Merging & star formation in A3921



R-band image + cluster members



R-band image + 5σ radio contours (22 cm)

$$\left[\frac{SFR(M \geqslant M_{Sun})}{M_{Sun}\, yr^{-1}}\right] = 1.4\times10^{-34}\left(\frac{L_{[OII]}}{W}\right) \simeq 2.0\times10^{-12}\frac{L_B}{L_{B_{Sun}}} EW([OII])E(H_\alpha)$$

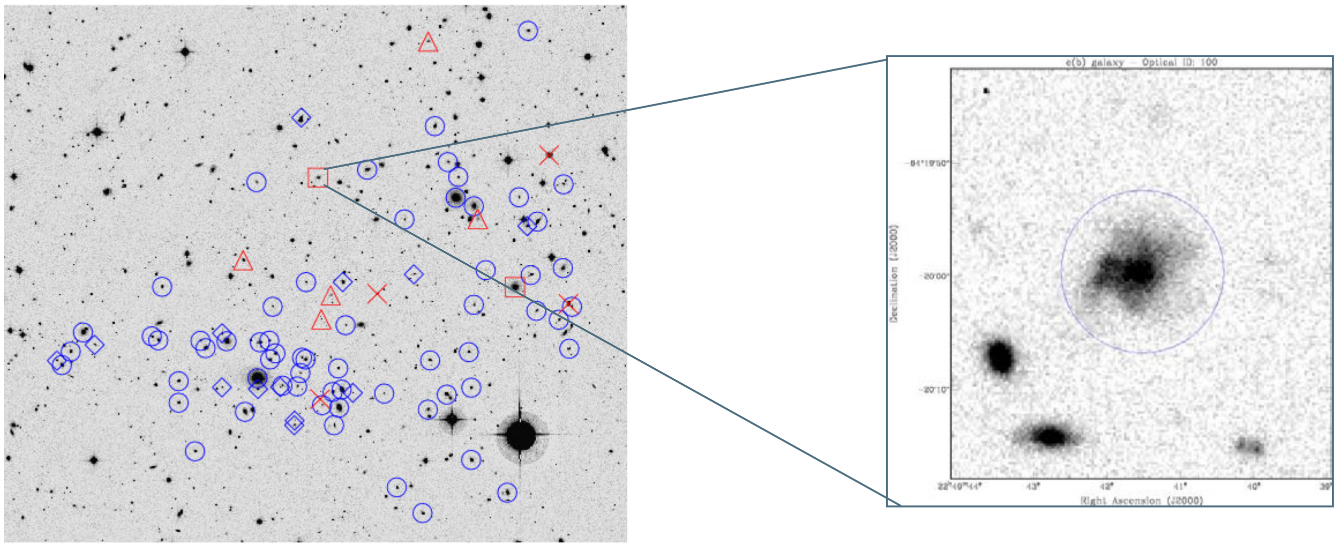
$$\left[\frac{SFR(M \geqslant M_{Sun})}{M_{Sun}\, yr^{-1}}\right] = 1.1\times10^{-21}\left(\frac{L_\nu}{W\,Hz^{-1}}\right)\left(\frac{\nu}{GHz}\right)^{-\alpha}$$

Spectral Type	SFR([OII])	SFR(1.4 GHz)
e(a)	0.28	< 3.68
e(a)	0.05	< 3.93
e(a)	0.16	< 4.11
e(a)	0.12	< 2.98
e(a)	0.17	< 4.20
e(b)	0.70	< 3.05
e(c)	0.04	< 2.98
e(c)	0.26	< 3.76
e(c)	0.10	< 3.76
e(b)	5.64	50.35
e(c)	0.25	7.85

Ferrari et al., A&A, 2006 A&A, 457, 21

Merging & star formation in A3921

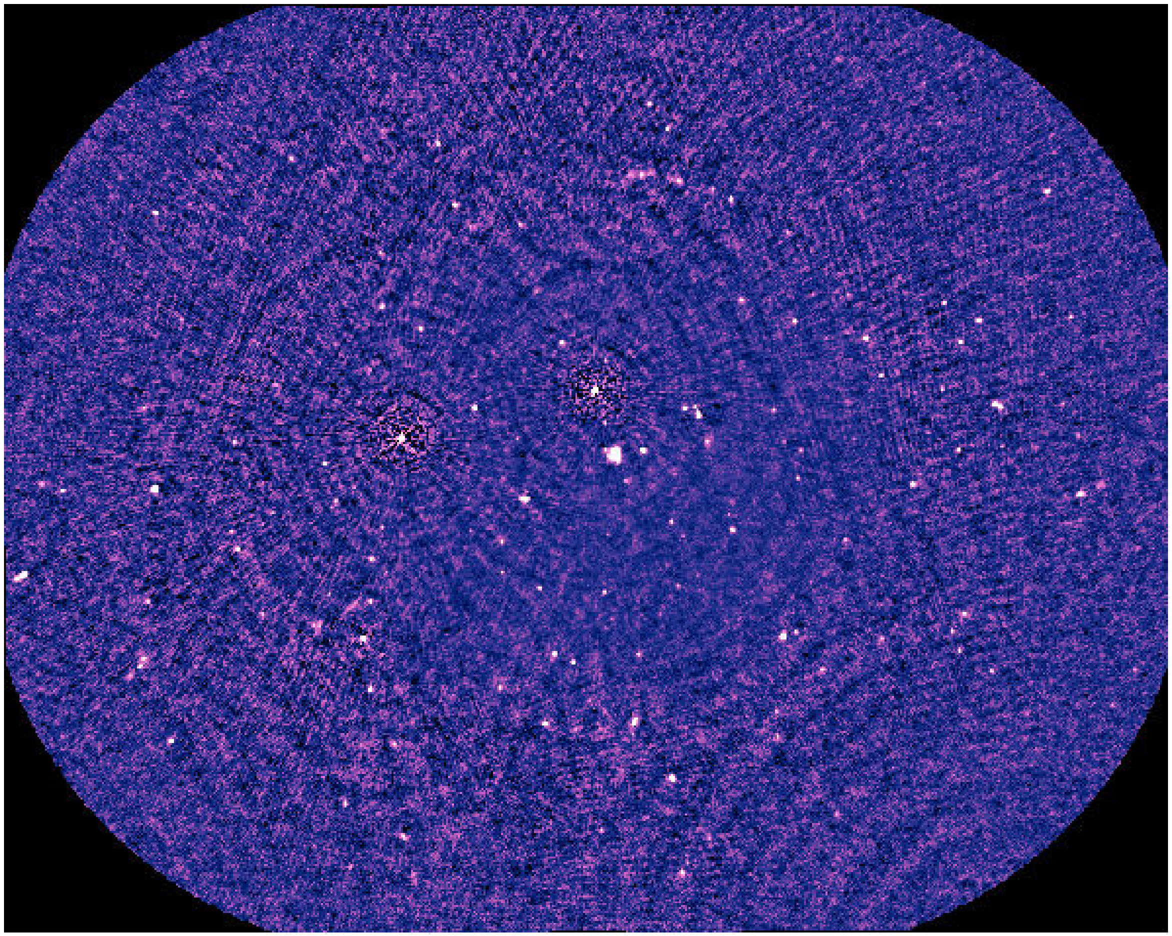
Conclusions

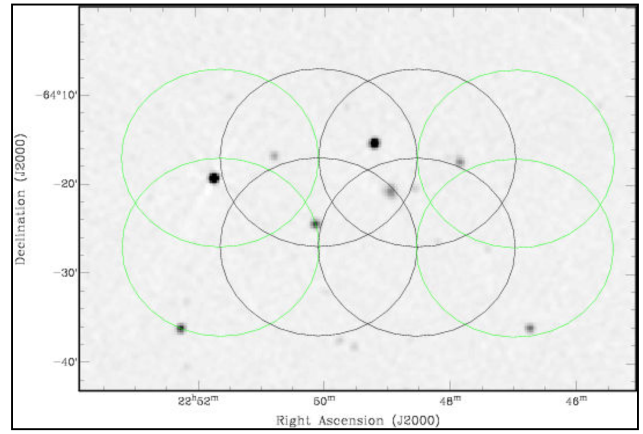


- ✓ k+a not detected at radio wavelegths $\rightarrow$ galaxies with recent, and not on-going, star formation (Poggianti et al. 1999, Duc et al. 2002)
- ✓ Emission-line galaxies:
  - One (BG3) is a starburst (high SFR_{Radio} (~50 M_{Sun}/yr), wide [OII] emission, thermal X-ray spectrum)
  - One is a spiral (spectral properties, SFR_{Radio}, morphology, colour)
  - The other (9) have not been detected at 1.4 GHz $\rightarrow$ SFR < 3 M_{sun} yr^{-1}
  - These galaxies are located between the two sub-clusters of A3921

Large scale optical and radio analyses

2dF@AAT and ATCA observations



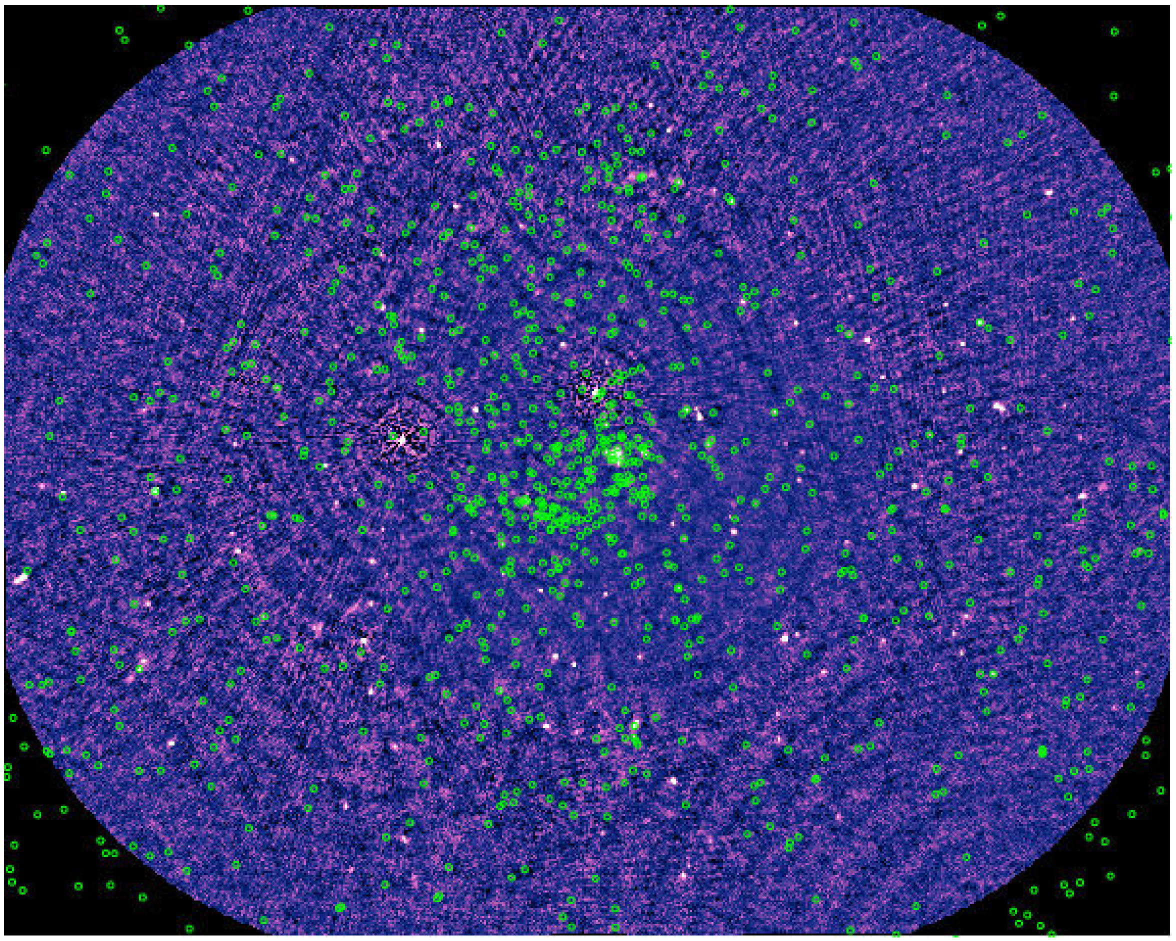


1.4 GHz map of the central 1.8x1.5 deg^2 of A3921

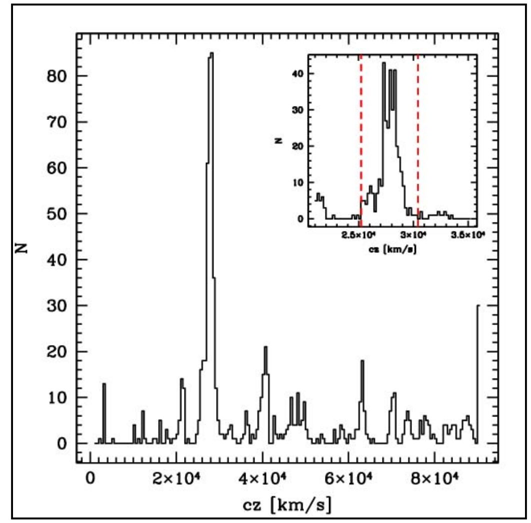
Ferrari, Hunstead et al., in prep.

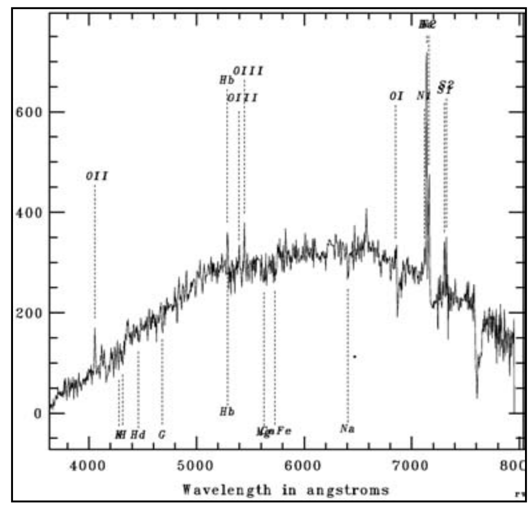
Large scale optical and radio analyses

2dF@AAT and ATCA observations



1.4 GHz map of the central 1.8x1.5 deg^2 of A3921+ available redshifts (1160)





Ferrari, Hunstead et al., in prep.

Conclusions and Perspectives

Formation and evolution of clusters and their galaxies

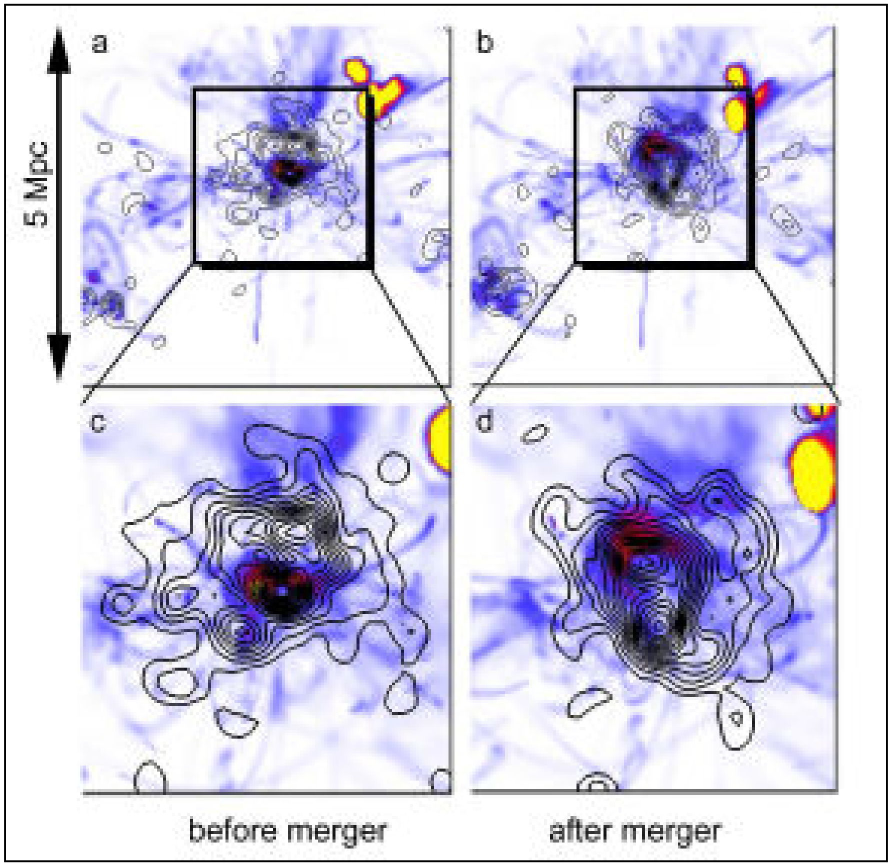
✓ Multi-wavelength analysis + numerical simulations

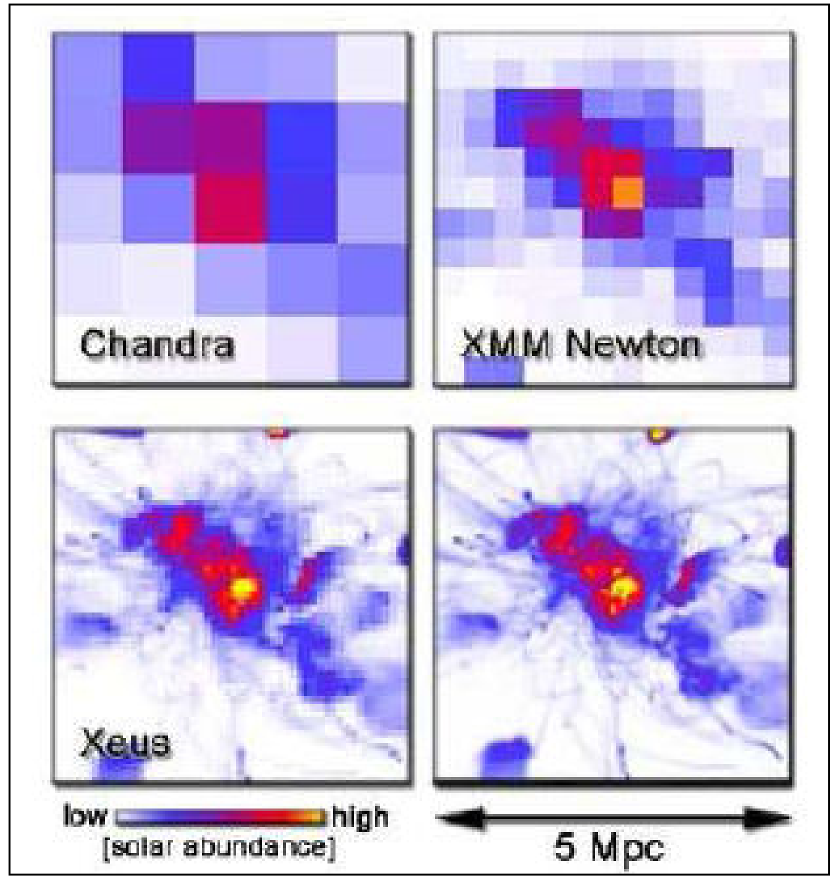
→ precise characterisation of the dynamical state of galaxy clusters:

- Geometry and phase of cluster collisions
- Mass ratio of the merging sub-structures
- New tracers of the dynamical state of clusters and corresponding physical processes (e.g. ICM metallicity maps: Kapferer, Ferrari et al.)

✓ Merging process ↔ star formation

- SFR increased during the central phases of cluster mergers
- Why? How long? (ICM compression of the ISM, tidal effects related to cluster collisions, galaxy-galaxy interactions… ?)
- Need of complementary multi-wavelength analyses (UV, FIR, mm et sub-mm)
- Next generation IR, sub-mm, radio telescopes (Herschel, ALMA, LOFAR, SKA…) : SFH unhindered by dust obscuration





Kapferer, Ferrari et al., A&A, 2006, 447, 827

Main topics of the talk

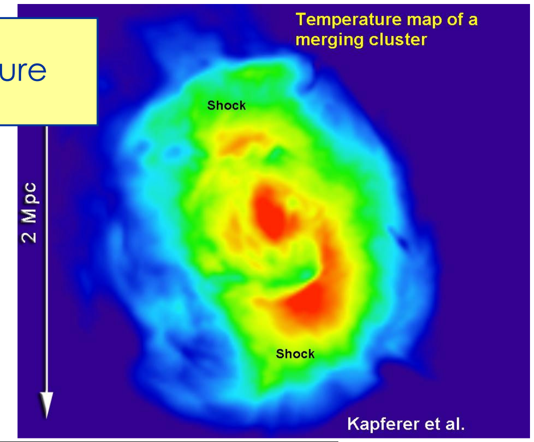
- ✓ Formation and evolution of clusters and their galaxies
  - Study of the complex physics of cluster formation and evolution
    <u>In collaborations with:</u> OCA (FR), INAF (IT), MPE (DE), University of Cambridge (UK), SAp/CEA (FR)
  - New tracers of structure formation: metallicity maps
    <u>In collaborations with:</u> Innsbruck Universität (AT)
  - Cluster merging and star formation
    <u>In collaborations with:</u> OCA (FR), INAF (IT), University of Sydney (AU)

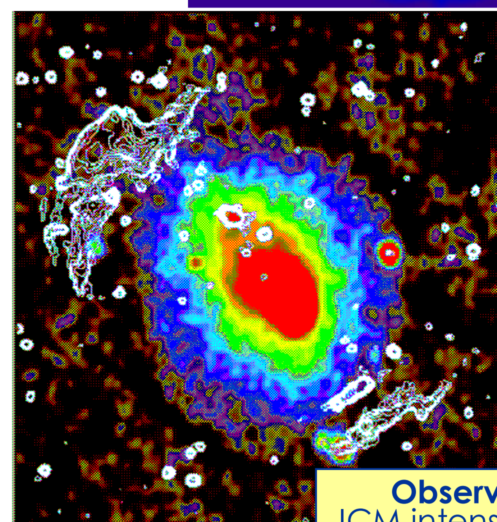
- ✓ Diffuse and extended radio emission in galaxy clusters
  - Radio halos and relics
    <u>In collaborations with:</u> INAF (IT), OCA(FR), University of Copenhagen (DK), University of Sydney (AU)

Physics of galaxy clusters: non-thermal component

- ✓ Acceleration mechanisms:
  - Secondary: hadronic collision of relaivistic p^+ with the ICM
  - Primary: (re-)acceleration due to shocks/turbulences
- ✓ Tracers of structure formation
- ✓ Non-thermal component & complex physics of clusters:
  - cluster merger ❓↔ non-thermal component
  - inter-connection between the thermal and relativistic plasma
- ✓ Intra-cluster magnetic fields

Simulations
ICM temperature map

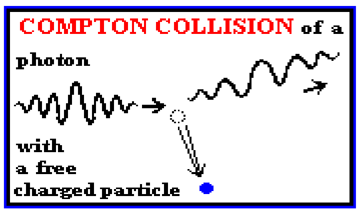


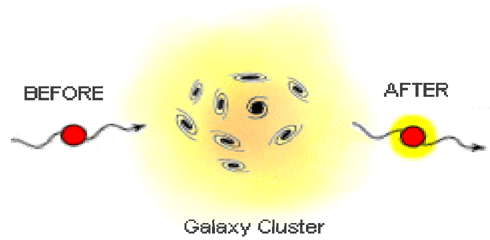


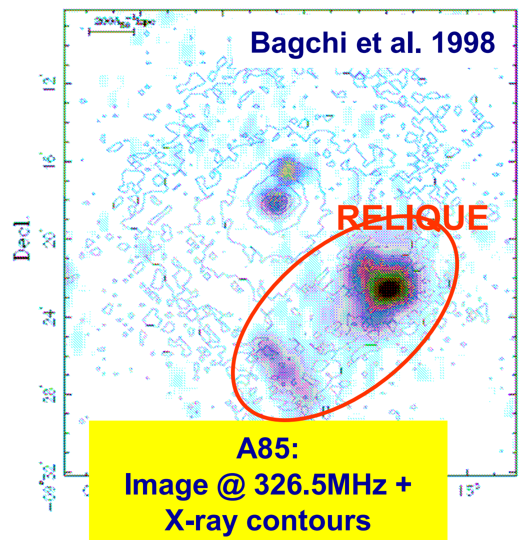
Observations
ICM intensity map + radio contours (relics)

Intra-cluster magnetic fields

- ✓ Inverse Compton scattering of CMB photons
- ✓ Rotation measure
- ✓ Morphology and polarization maps of halos







Inverse Compton scattering of CMB photons

$$f_S = 1.64 \times 10^{-14} \frac{N_0 V}{4\pi D^2} B^2 a(3) \quad (10 - 100 \text{ MHz})$$
$$f_{IC} = 1.36 \times 10^{-29} \frac{N_0 V}{4\pi D^2} T^4 b(3) \quad (0.5 - 2.4 \text{ keV}).$$

$$B = 2.97 \times 10^{-6} \left(\frac{f_S}{f_{IC}}\right)^{\frac{1}{2}} \mathrm{G} = (0.95 \pm 0.10) \times 10^{-6} \mathrm{G}.$$

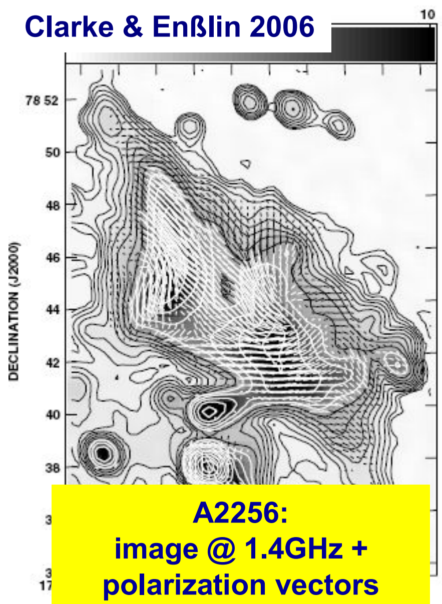
Radio emission (synchrotron)

X-ray emission (Inverse Compton)

Intra-cluster magnetic fields

- ✓ Inverse Compton scattering of CMB photons
- ✓ Rotation measure
- ✓ Morphology and polarization maps of halos

Clarke & Enßlin 2006



A2256: image @ 1.4GHz + polarization vectors

$$\Psi_\lambda = \Psi_{\rm int} + RM\,\lambda^2$$

$$RM = 812 \int_0^L n_e H_{\parallel} \mathrm{d}l \quad \mathrm{rad/m^2}$$

$$\sigma_{RM} = \frac{441 H n_0 r_c^{1/2} l^{1/2}}{(1 + r^2/r_c^2)^{(6\beta-1)/4}} \sqrt{\frac{\Gamma(3\beta - 0.5)}{\Gamma(3\beta)}}$$

Γ: Gamma function
r_c: core radius of the cluster
l: dimension of magnetic field cells
n_0: ICM central density
H: magnetic field intensity

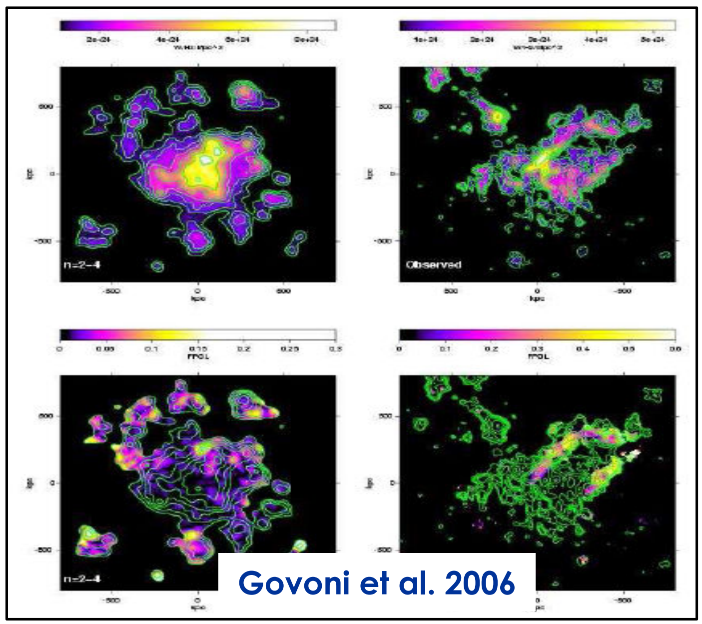
Intra-cluster magnetic fields

- ✓ Inverse Compton scattering of CMB photons
- ✓ Rotation measure
- ✓ Morphology and polarization maps of halos

Simulations | Observations

Radio surface brightness

Fraction of polarization + radio surface brightness (contours)



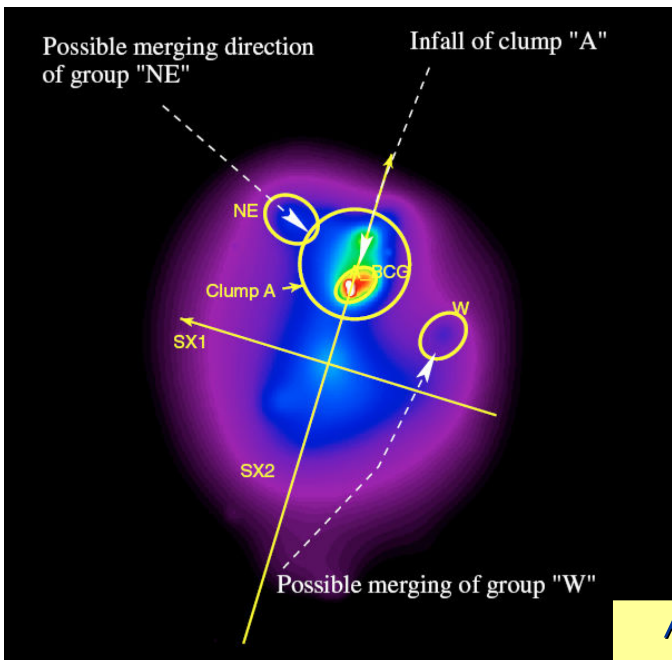
Govoni et al. 2006

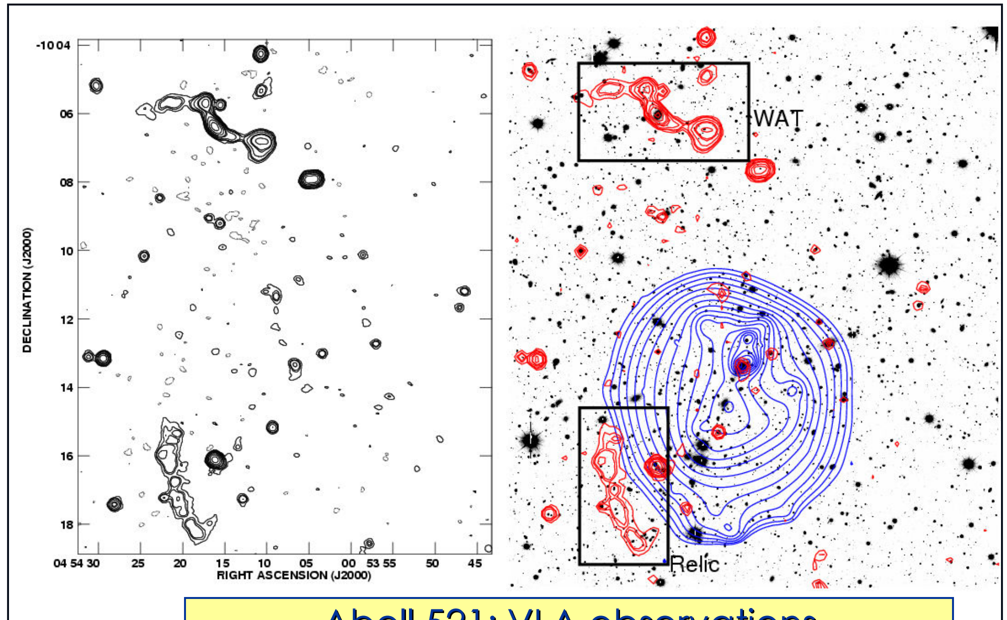
$|B_k|^2 \propto k^{-n}$
n=2-4

First results of the radio follow-up of MUSIC

Abell 521:
a multiple merging cluster

- ✓Optical (ESO) : Ferrari et al., 2003
- ✓ X-ray (Chandra) : Ferrari et al., 2006a
- ✓ Radio (VLA) : Ferrari et al., in prep.

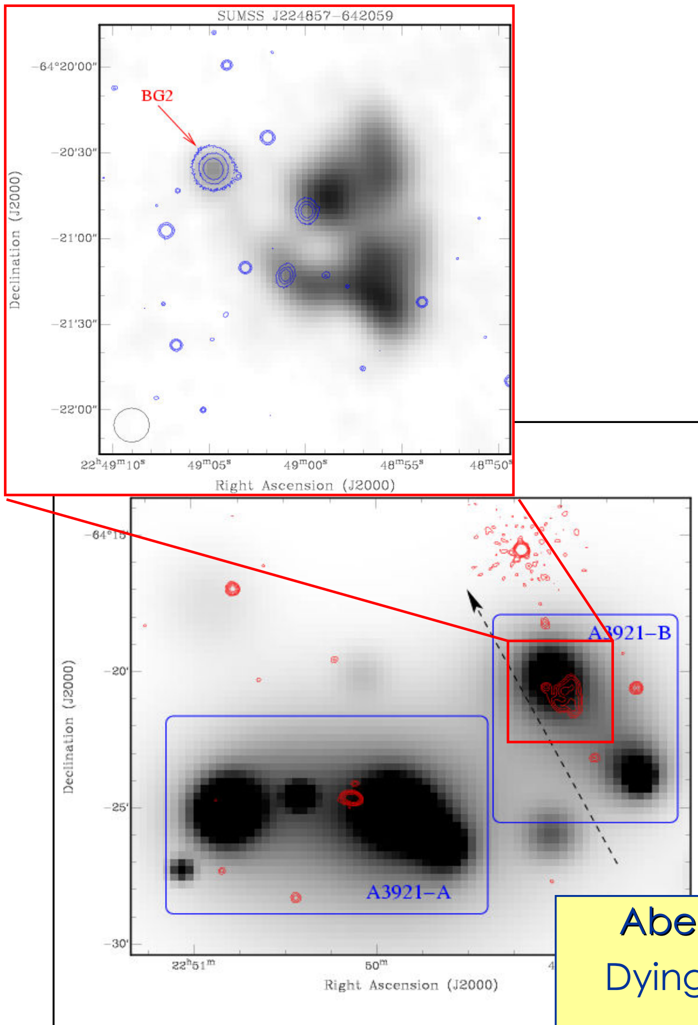


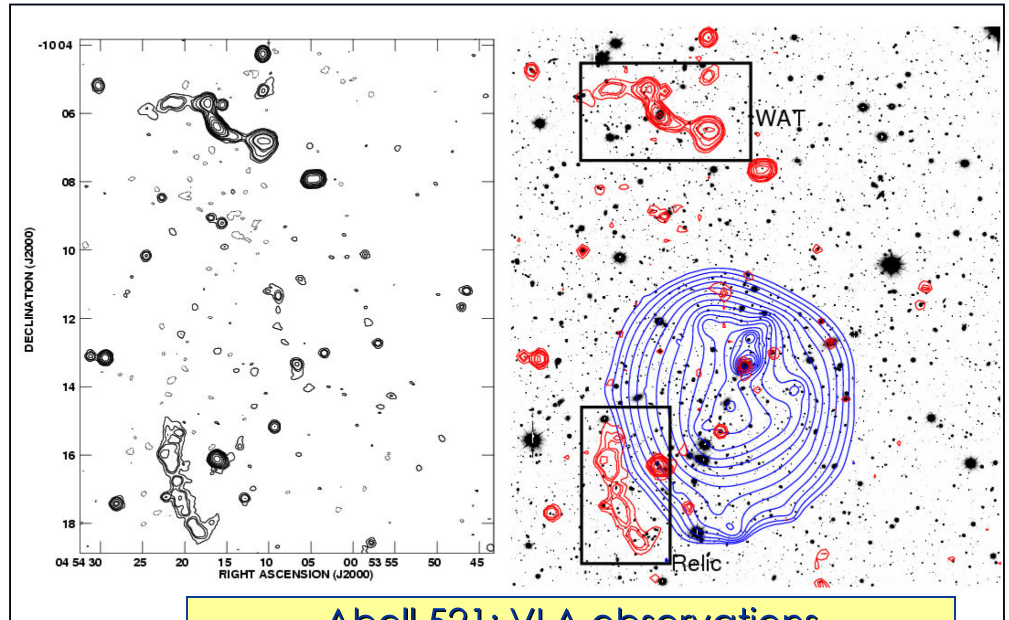


Abell 521: VLA observations
Discovery of a radio relic
Ferrari, Arnaud et al., 2006a

Abell 521: Chandra observations
Ferrari Arnaud et al. 2006a

First results of the radio follow-up of MUSIC





Abell 521: VLA observations

Discovery of a radio relic

Ferrari, Arnaud et al., 2006a

Abell 3921: ATCA observations

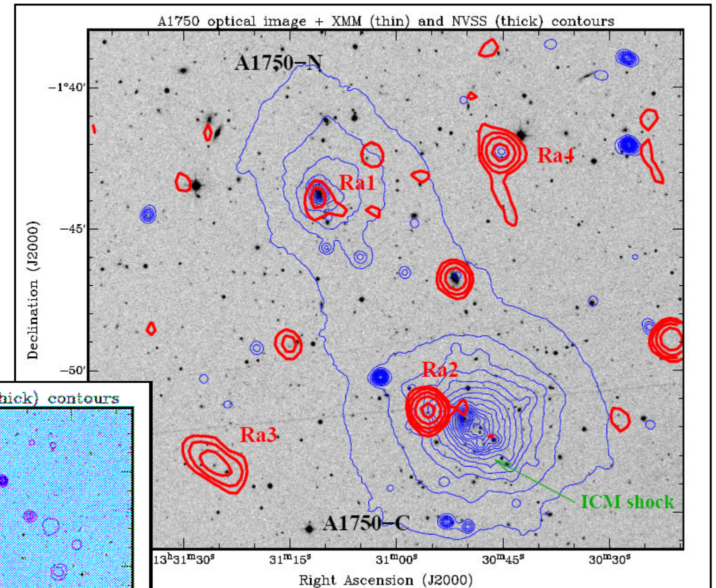
Dying tail of a Narrow Angle Tail radio source

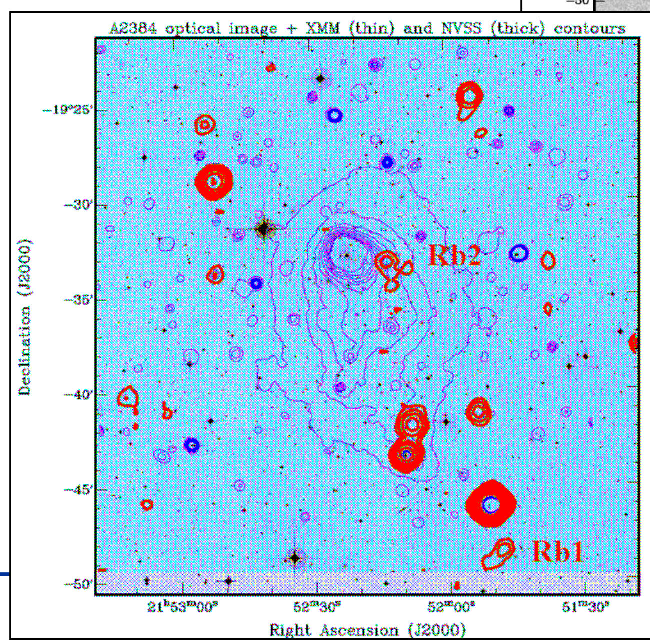
Ferrari, Hunstead et al., 2006b

Diffuse emission in A1750 and A2384: a pre- and a post-merging cluster

VLA – 7 h in D configuration @ 1.4 GHz

Ferrari, Feretti et al. 2007

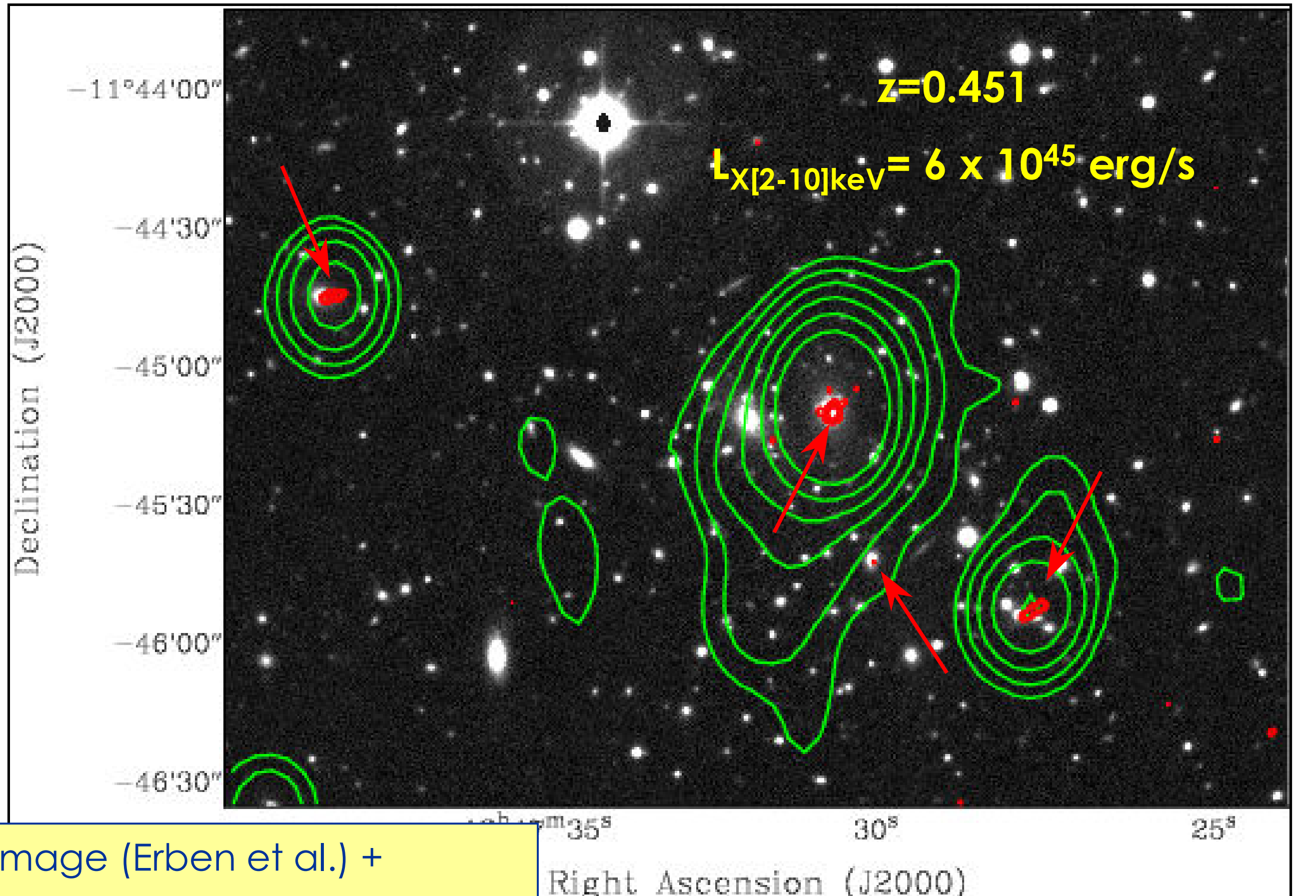




Optical image +
X-ray contours (XMM) +
radio contours (NVSS)

VLA observations of RXJ 1347-1145

Discovery of diffuse radio emission at the centre of the most X-ray luminous cluster

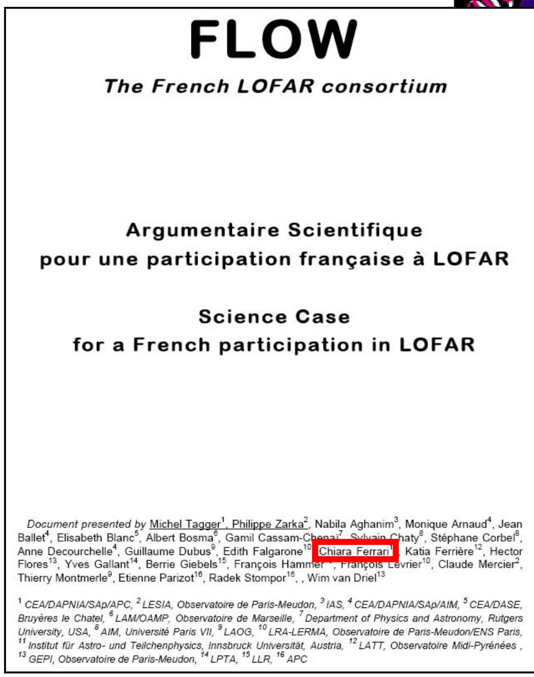


I-band image (Erben et al.) +

5σ radio contours (1.4 GHz) at **high (~1.5")** and **low (~18")** resolution

Gitti, Ferrari et al., in prep.

Perspectives: LOFAR & SKA



FLOW

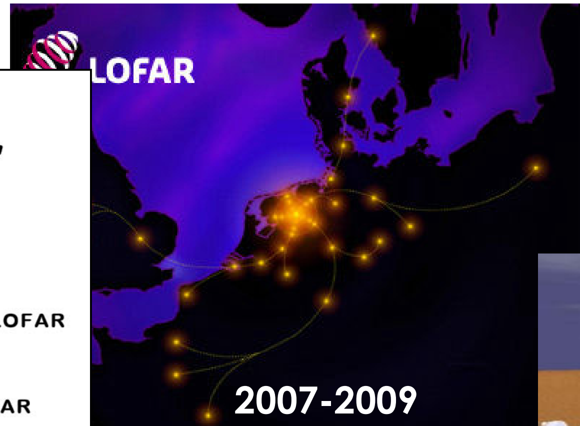
The French LOFAR consortium

Argumentaire Scientifique
pour une participation française à LOFAR

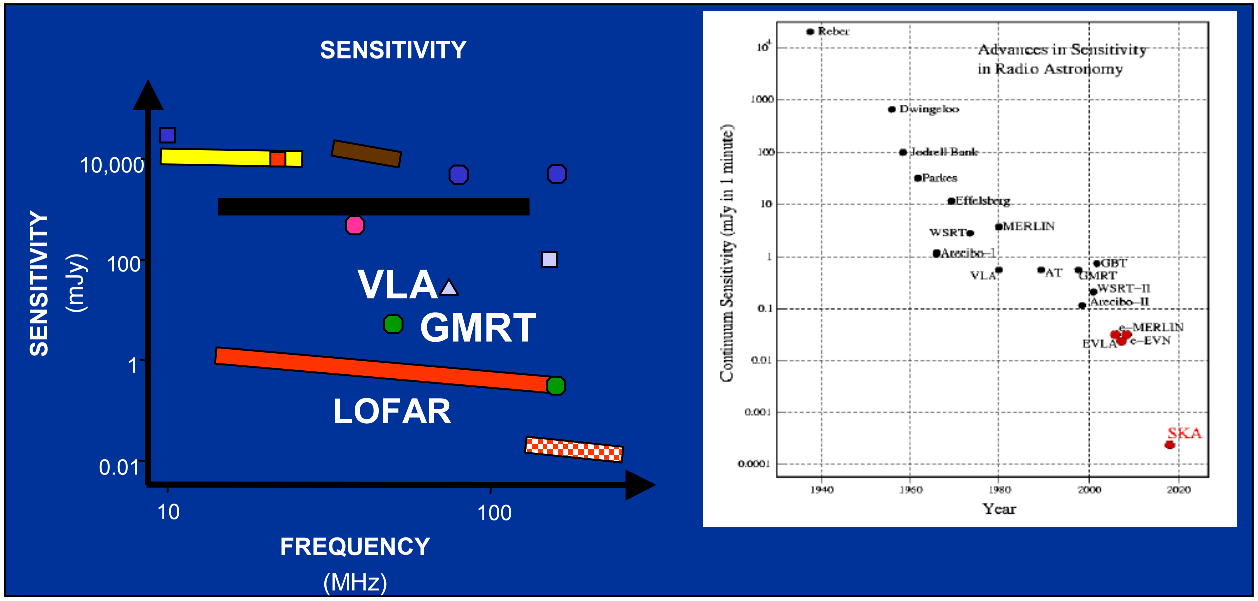
Science Case
for a French participation in LOFAR

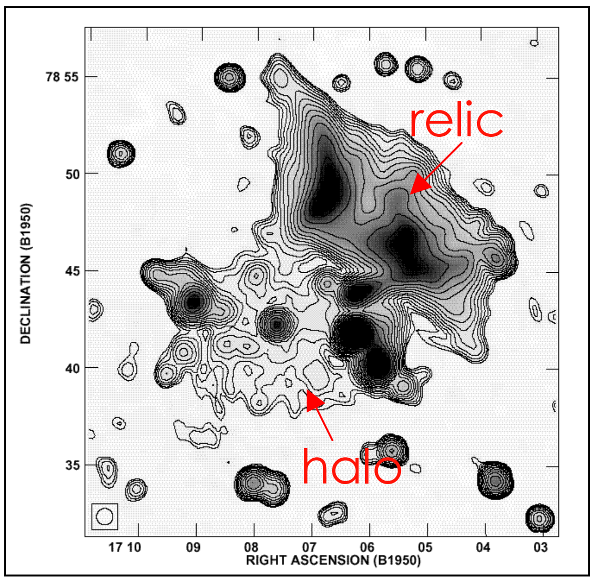
Document presented by Michel Tagger[1], Philippe Zarka[2], Nabila Aghanim[3], Monique Arnaud[4], Jean Ballet[4], Elisabeth Blanc[5], Albert Bosma[6], Gamil Cassam-Chenaï[7], Sylvain Chaty[8], Stéphane Corbel[8], Anne Decourchelle[4], Guillaume Dubus[9], Edith Falgarone[10], Chiara Ferrari[11], Katia Ferrière[12], Hector Flores[13], Yves Gallant[14], Berrie Giebels[15], François Hammer[illegible], François Levrier[10], Claude Mercier[2], Thierry Montmerle[9], Etienne Parizot[16], Radek Stompor[16], , Wim van Driel[13]

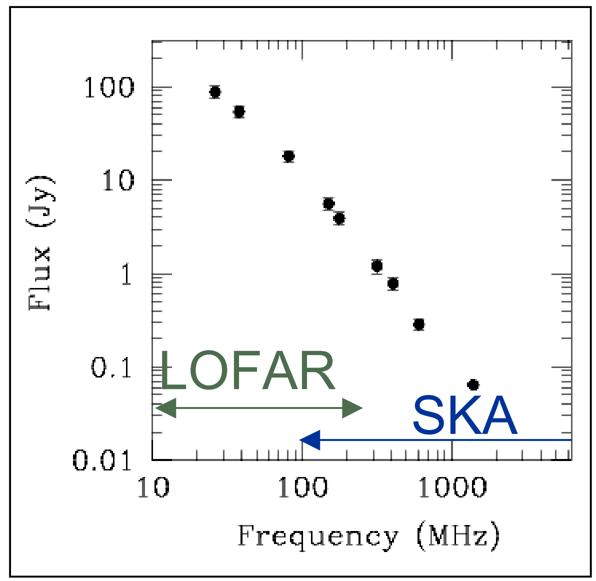
[1] CEA/DAPNIA/SAp/APC, [2] LESIA, Observatoire de Paris-Meudon, [3] IAS, [4] CEA/DAPNIA/SAp/AIM, [5] CEA/DASE, Bruyères le Chatel, [6] LAM/OAMP, Observatoire de Marseille, [7] Department of Physics and Astronomy, Rutgers University, USA, [8] AIM, Université Paris VII, [9] LAOG, [10] LRA-LERMA, Observatoire de Paris-Meudon/ENS Paris, [11] Institut für Astro- und Teilchenphysics, Innsbruck Universität, Austria, [12] LATT, Observatoire Midi-Pyrénées , [13] GEPI, Observatoire de Paris-Meudon, [14] LPTA, [15] LLR, [16] APC

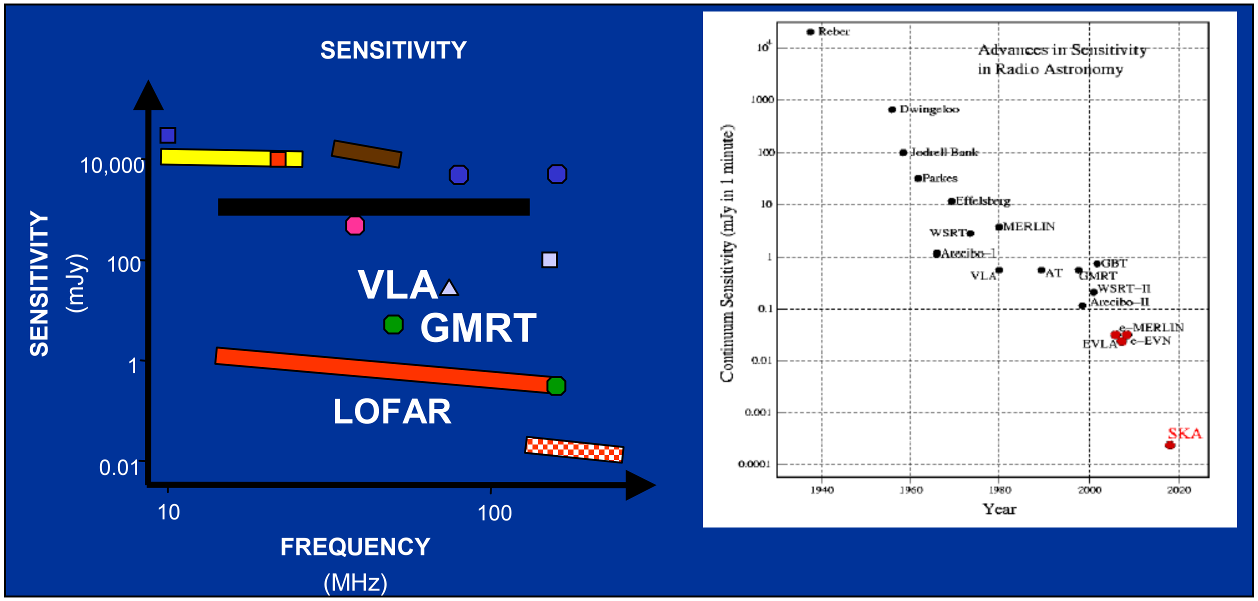


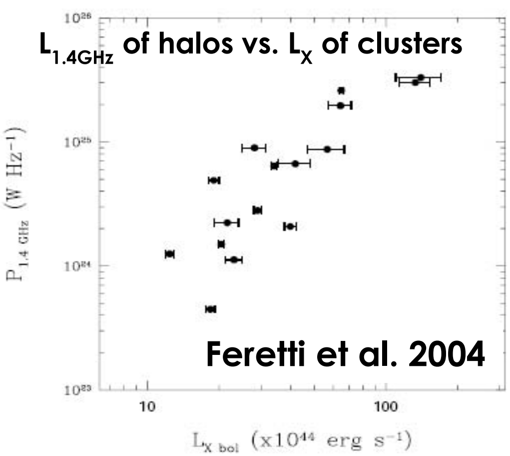
	Frequency Coverage	Sensitivity Improvement	Resolution Improvement	Polarization Purity
LOFAR	20-200 MHz	~100-1000	~100	≥30 dB
SKA	0.1-20 GHz	~100	~10	~40 dB


SENSITIVITY
SENSITIVITY (mJy)
10,000
100
1
0.01
10
100
FREQUENCY (MHz)
VLA
GMRT
LOFAR
Advances in Sensitivity in Radio Astronomy
Continuum Sensitivity (mJy in 1 minute)
Year
Reber
Dwingeloo
Jodrell Bank
Parkes
Effelsberg
WSRT
MERLIN
Arecibo–I
VLA
AT
GBT
GMRT
WSRT–II
Arecibo–II
e–MERLIN
EVLA
e–EVN
SKA


DECLINATION (B1950)
RIGHT ASCENSION (B1950)
relic
halo


Flux (Jy)
Frequency (MHz)
LOFAR
SKA



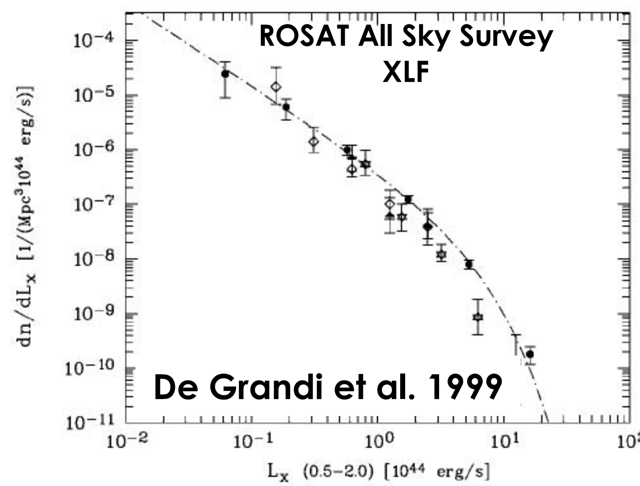


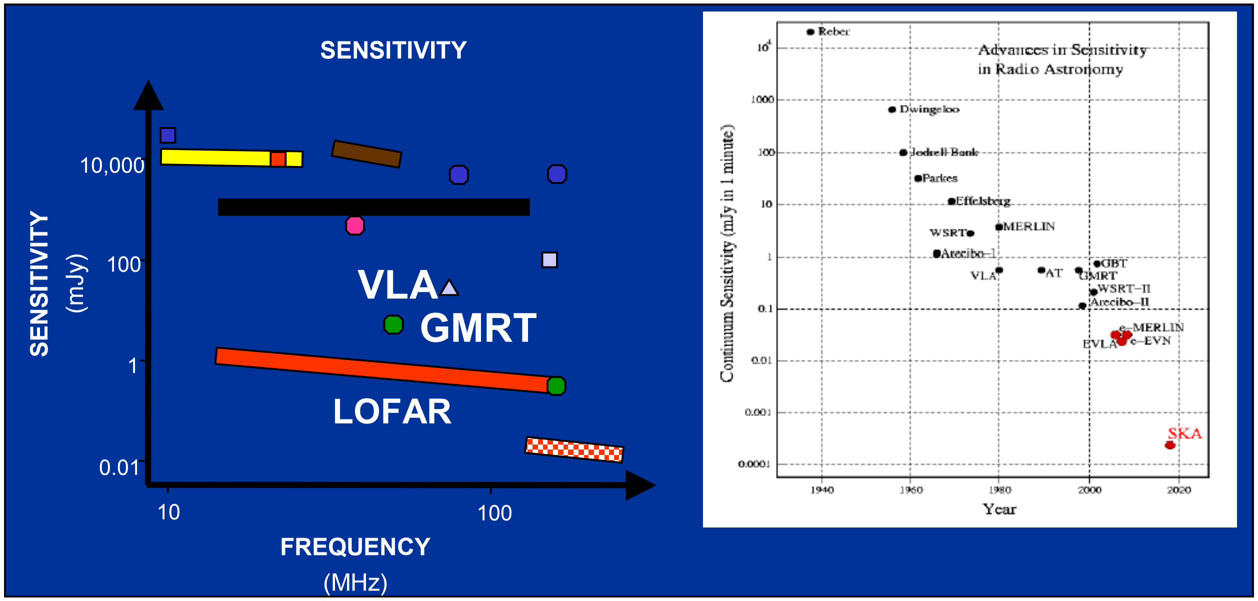
Relics and Halos:

$L_X < 10^{45}$ erg/s

→ $P_{1.4GHz} < 10^{23}$ W/Hz

→ $S_{1.4GHz} < 0.4$ mJy ($z \geq 0.3$)





Luminosity function of halos/relics

S_{tot}	N	N(z>0.3)
1 μJy	23759	10785
10 μJy	6812	2123
0.1 mJy	1654	281
1 mJy	326	21
10 mJy	50	1

LOFAR survey @ 120 MHz:

~10000 halos & relics (z≤2)
~100 halos & relics (0.8<z<1.2)

(Feretti et al. 2004; Röttgering et al. 2007)

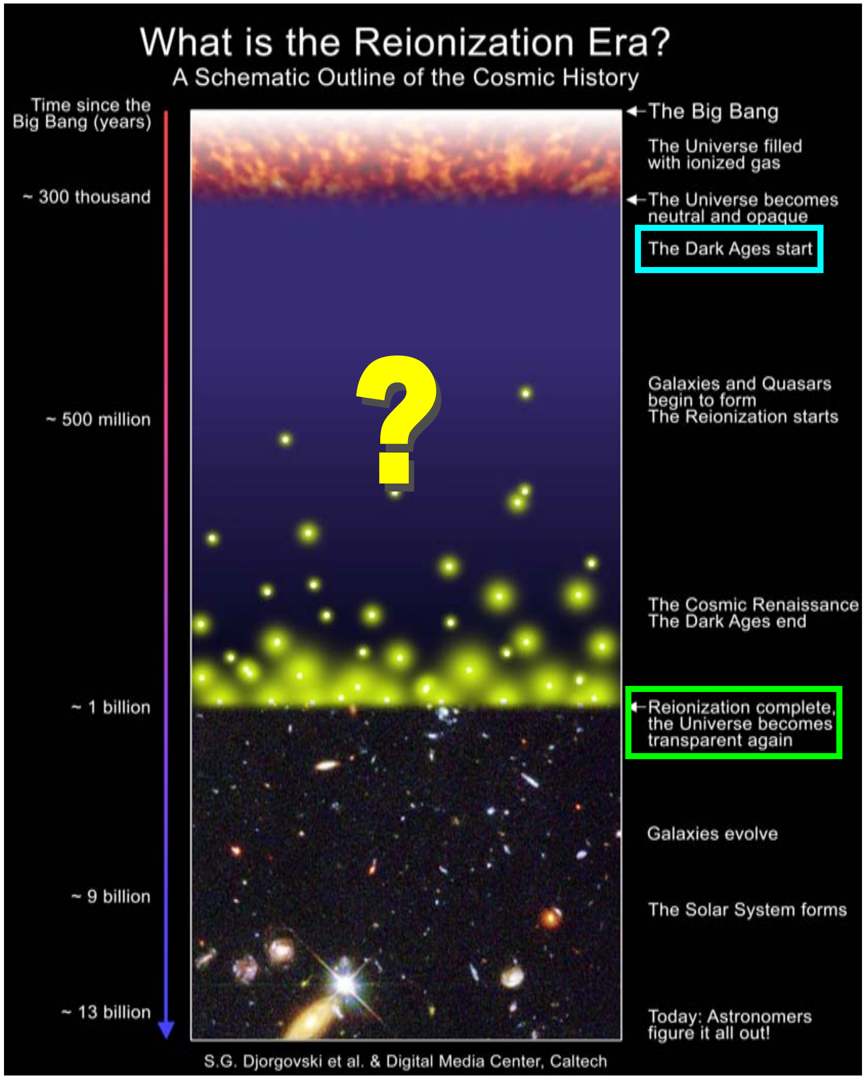
A new window for cosmology: diffuse and extended radio emission in galaxy cluster

- ✓ complex physics of cluster formation and evolution
- ✓ cosmological parameters
- ✓ intra-cluster magnetic field
- ✓ implication for other cosmological studies (e.g. epoch of re-ionization)

Epoch of Reionization (EoR)

z~1000

z~6



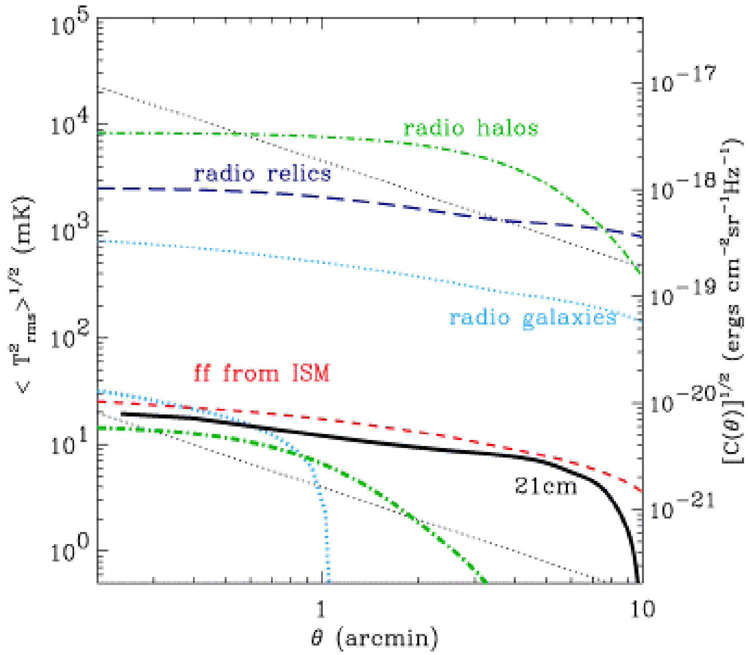
Reionization:

- ✓ Transition from neutral to ionized "intergalactic" medium (z~1000 à z~6)
- ✓ Second of two major phase changes of hydrogen gas in the Universe (first: recombination - CMB)
- ✓ 21cm transition of HI: it allows to trace the neutral gas before and after the reionization

↓ z =1000 – 6

1.4 - 200 MHz

Epoch of Reionization (EoR)



Correlation signal owing to intensity fluctuations of the redshifted 21cm emission and to the different foreground sources

Di Matteo et al. 2004