What shall we see in galaxy clusters with SKA?

Marguerite PIERRE DAP

Journée SKA – 10 mai 2023

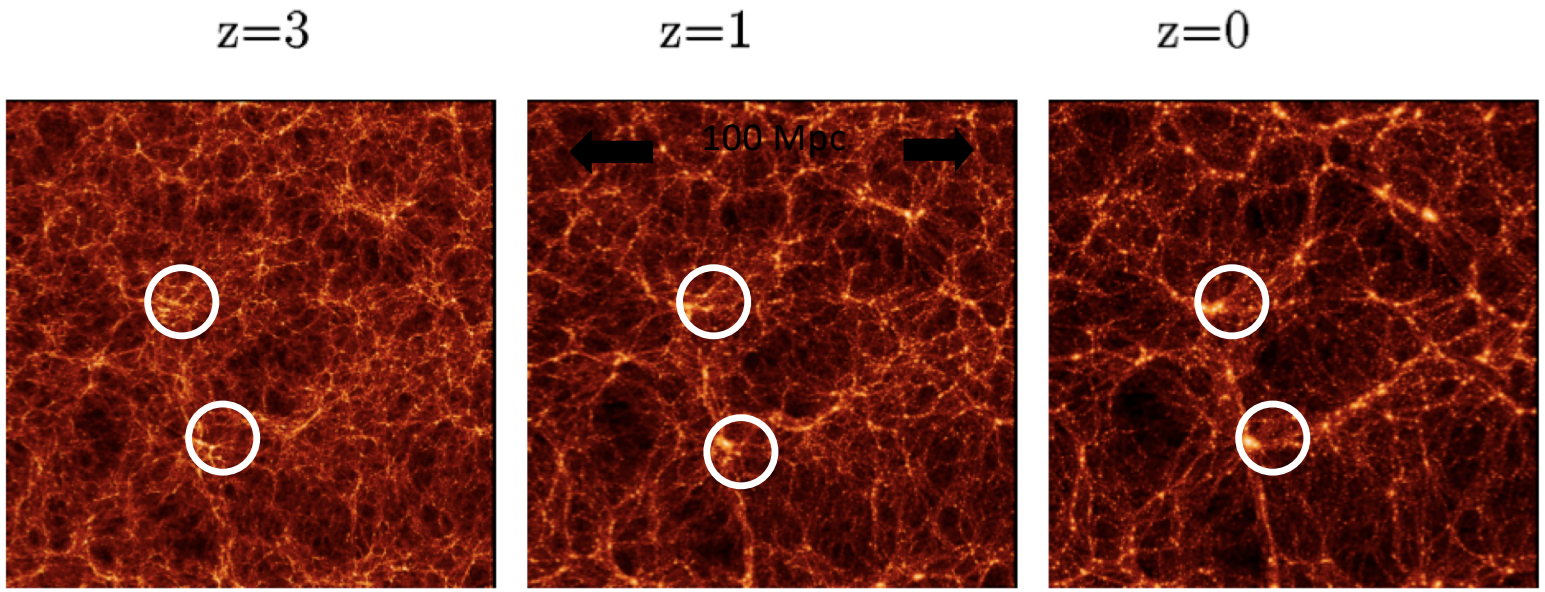
A vast question !
Layout

1. Reminder about custers

2. SKA: deeper insights into physical phenomena related to structure formation

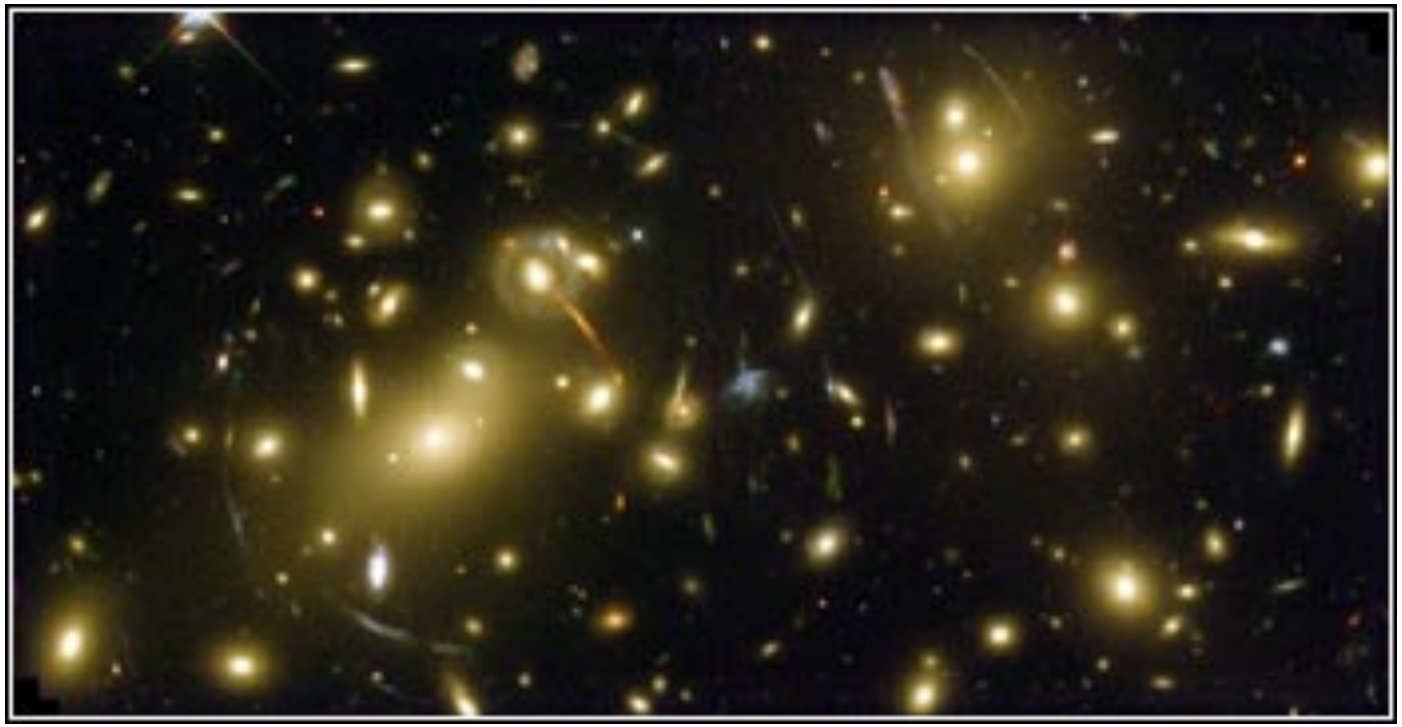
3. Synergy between SKA and Athena

Clusters of galaxies
= nodes of the cosmic structre



Most massive objects in the universe

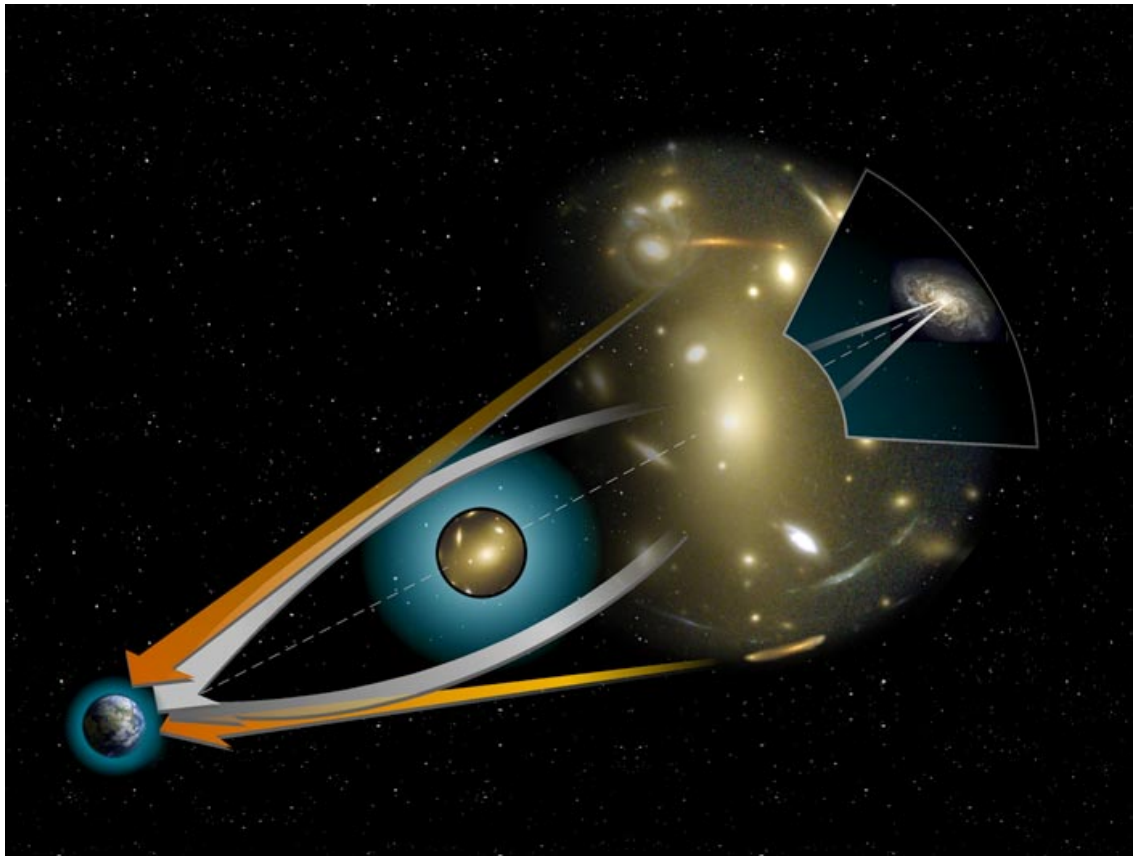
=> cosmology



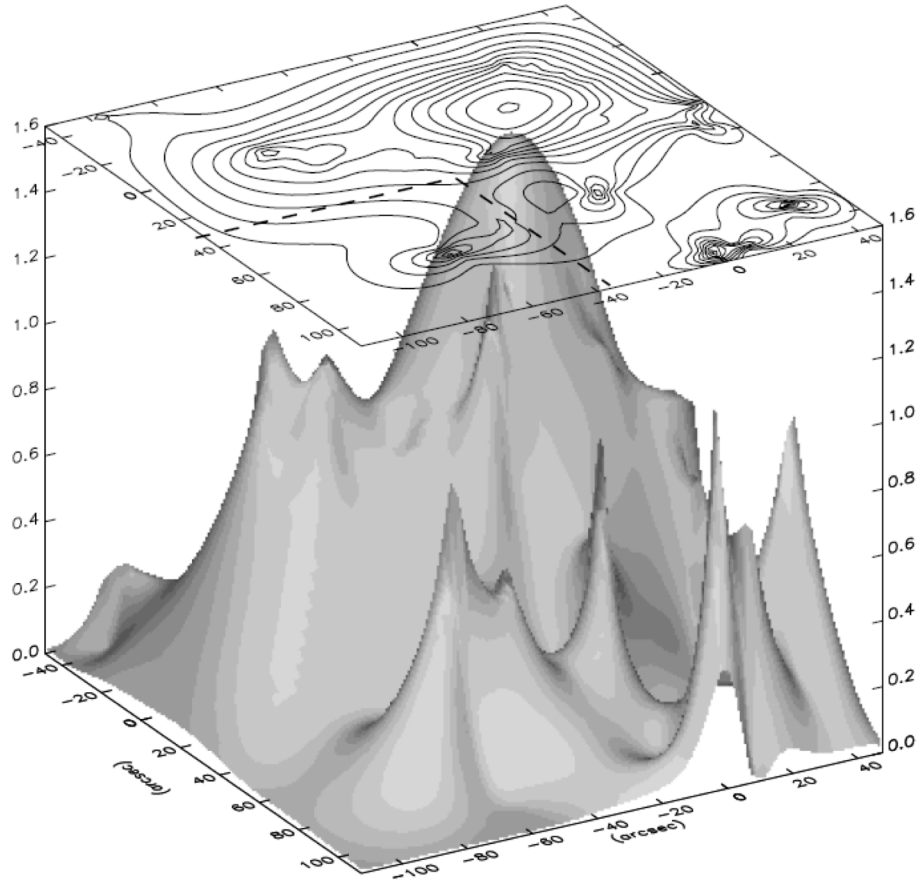
The center of A2218 as seen by the HST

z = 0.176

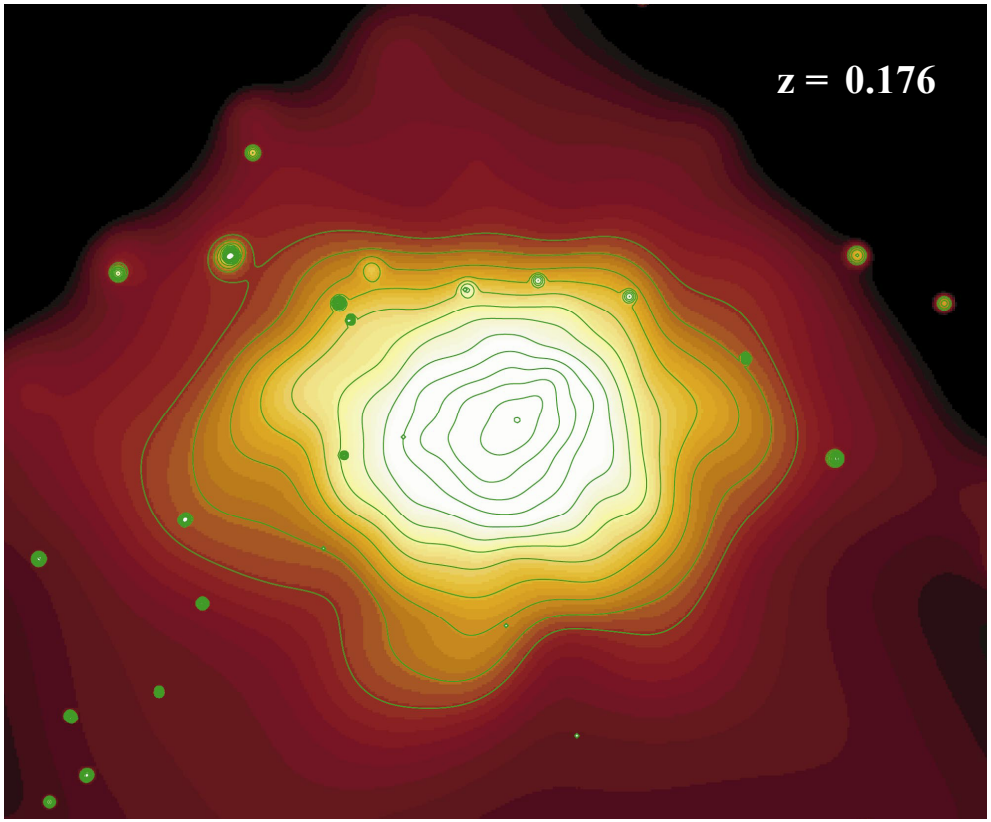
The dark matter acts as a lens



The shear measurement allows us to measure (total) cluster masses



X-ray image of A2218



Gas = optically thin plasma

T ~ 50 million degrees

n ~ 1 atom per liter

Emission : **thermal** Bremsstrahlung (free-free)

Simplistic (?) hypothesis: the gas is in hydrostatic equilibrium in the cluster potential

Mass fraction:

Galaxies : 5%

Gas = ICM : 15%

Dark Matter : 80%

Clusters of galaxies in the radio waveband = non-thermal emission

- The cluster radio ‘zoo’
  - Tailed galaxies
  - Diffuse extended sources : halos and relics
  - Radio bubbles filling cavities in the ICM

➔ How do these non-thermal components
  - Affect the properties of the ICM ?
  - Depend on the dynamical properties of the clusters ?

Diffuse radio Mpc-scale of synchrotron emission: **relativistic particles** and **magnetic fields** associated with the ICM

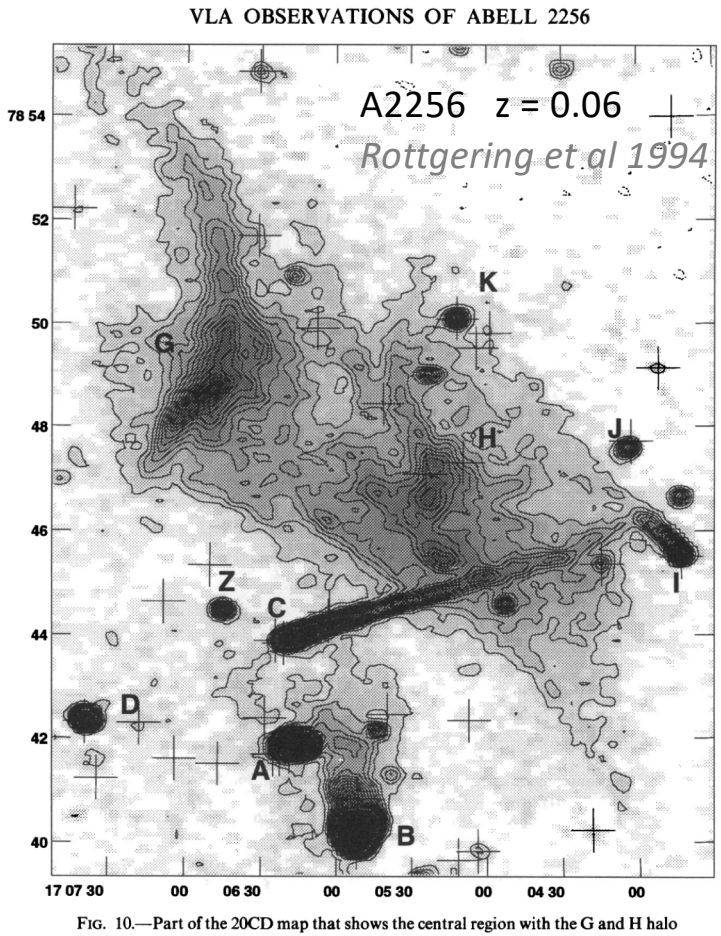
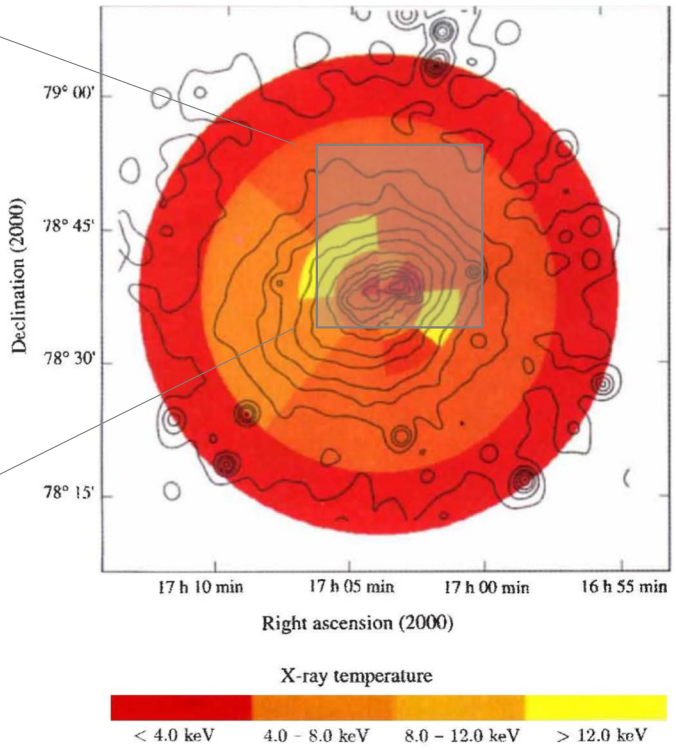


FIG. 10.—Part of the 20CD map that shows the central region with the G and H halo

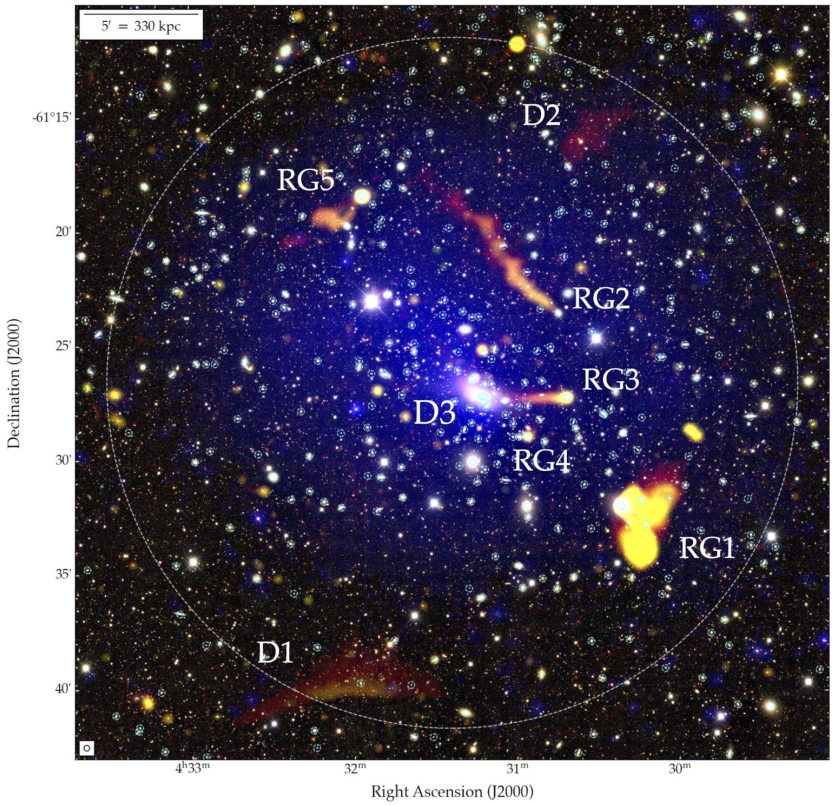
A ROSAT temperature map of the merging galaxy cluster A2256

Briel & Henry 1994, Nature



Observations of nearby objects . . .

unveil the complexity of the mechanisms and interactions



An example : A3266 **z = 0.0594**

Overlaid on a DES optical image :

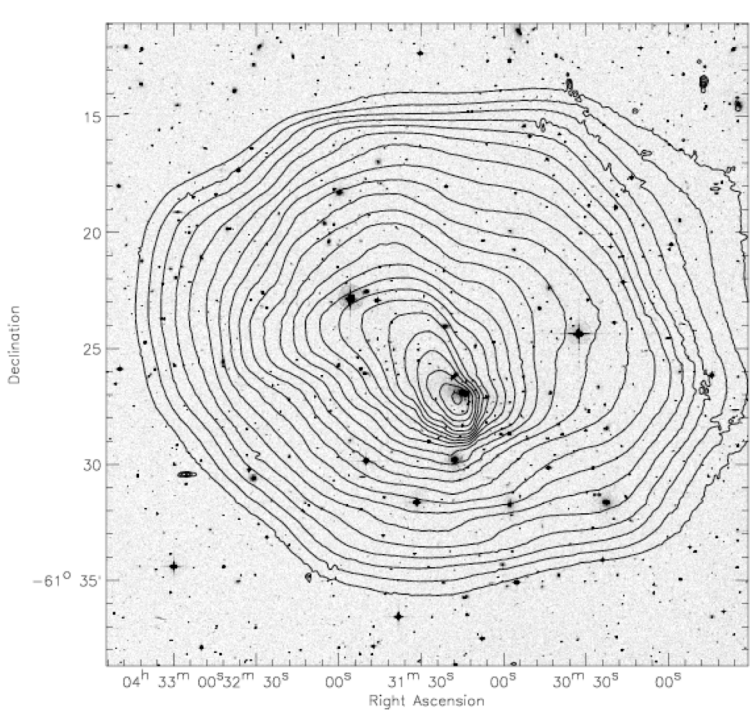
- Blue X-ray : XMM (0.5-2 keV)
- Red radio : ASKAP (943 MHz)

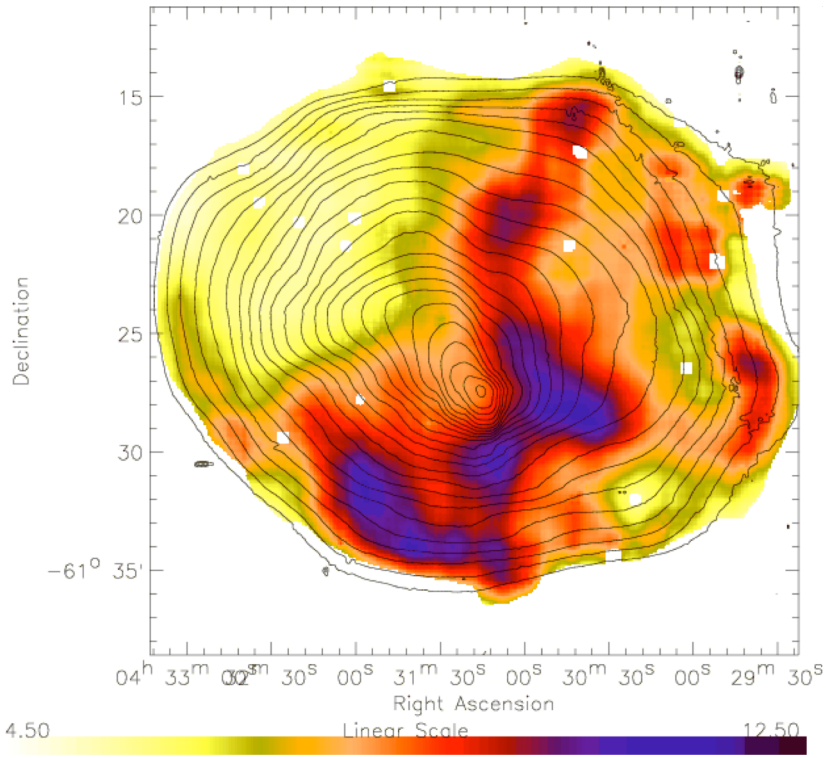
- D: diffuse emission
- RG : Radio galaxy

Riseley et al 2022

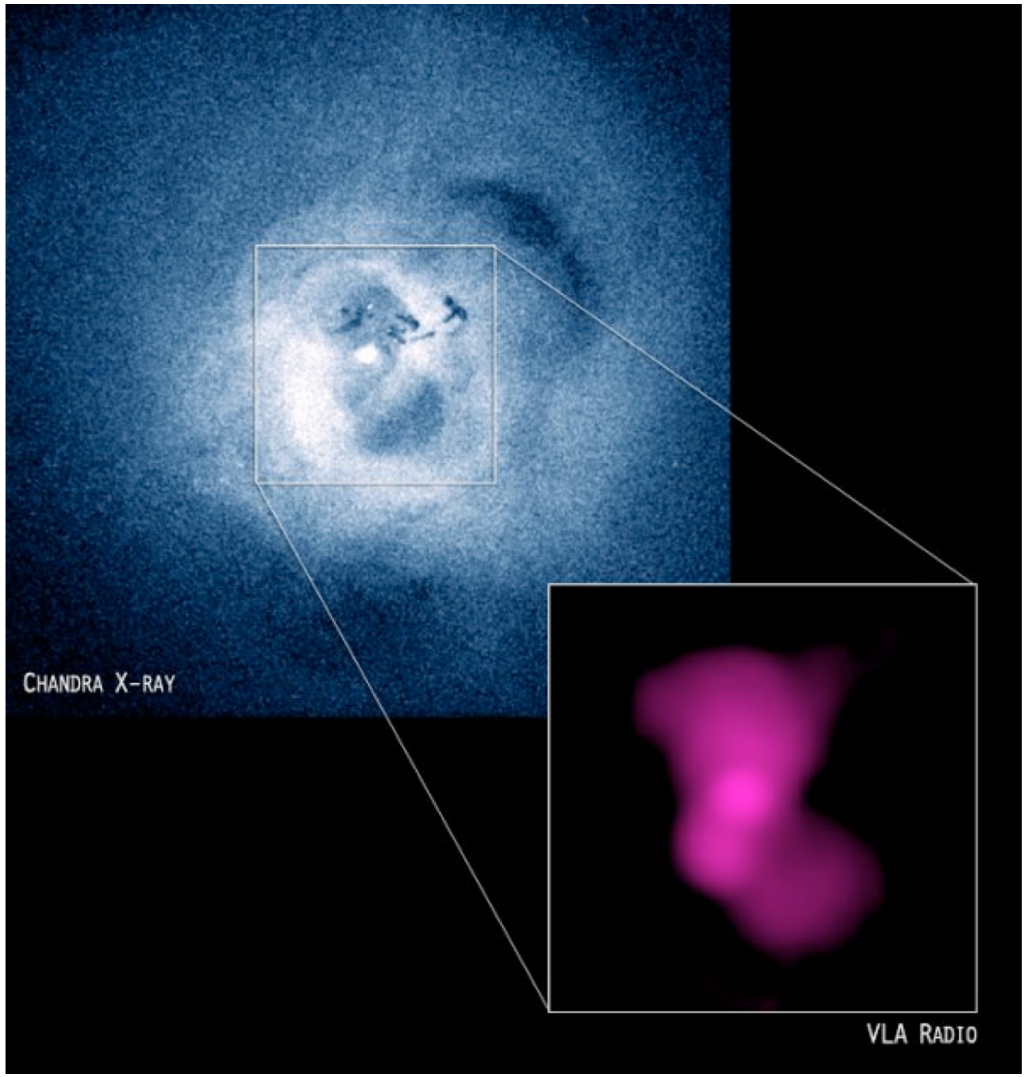
XMM temperature map of A3266 : a late merger

Sauvageot et al 2005





~ 100 kpc



Center of the Perseus cluster

z = 0.018

The radio emission fits neatly inside the cavities in the X-ray emission.

Radio halos and relics

- Radio halos
  - centrally located, largely amorphous,
  - megaparsec-scale synchrotron sources
  - usually exhibit negligible polarisation fraction.
  - the synchrotron emission from haloes generally follows the distribution of the thermal ICM (as traced by X-ray emission), implying a direct connection between thermal and non-thermal components in the ICM

- Radio relics
  - usually located towards the cluster outskirts
  - megaparsec-scale synchrotron sources
  - when imaged at sufficiently high resolution, relics frequently show significant filamentary substructure
  - frequently exhibit a high linear polarisation fraction, with magnetic field vectors aligned with the long axis of the relic, presumably tracing shock compression of magnetic fields
  - often associated with shocks

Question : what is the origin of the cosmic-ray electrons ?

Favoured model: radio halos originate from the re-acceleration of seed cosmic-ray electrons by merger induced **turbulence**

There are two possible scenarios for the origin of the seed electrons

- Primary: CRE are directly injected by accelerators
  - Large scale accretion shocks
  - Escape from the radio jets of the central AGN

- Secondary: CRE injection is dominated by collisions between CR protons and thermal protons of the ICM
  - Disfavored by Fermi (GeV) observations ?
    - Inelastic collisions of CR ions with thermal protons of the ICM produce both neutral and charged pions, which decay almost instantly into γ–rays and electrons/positrons, respectively

SKA : decupled sensitivity and resolution

1. Small scale physics thanks to deep high-resolution observations of nearby clusters

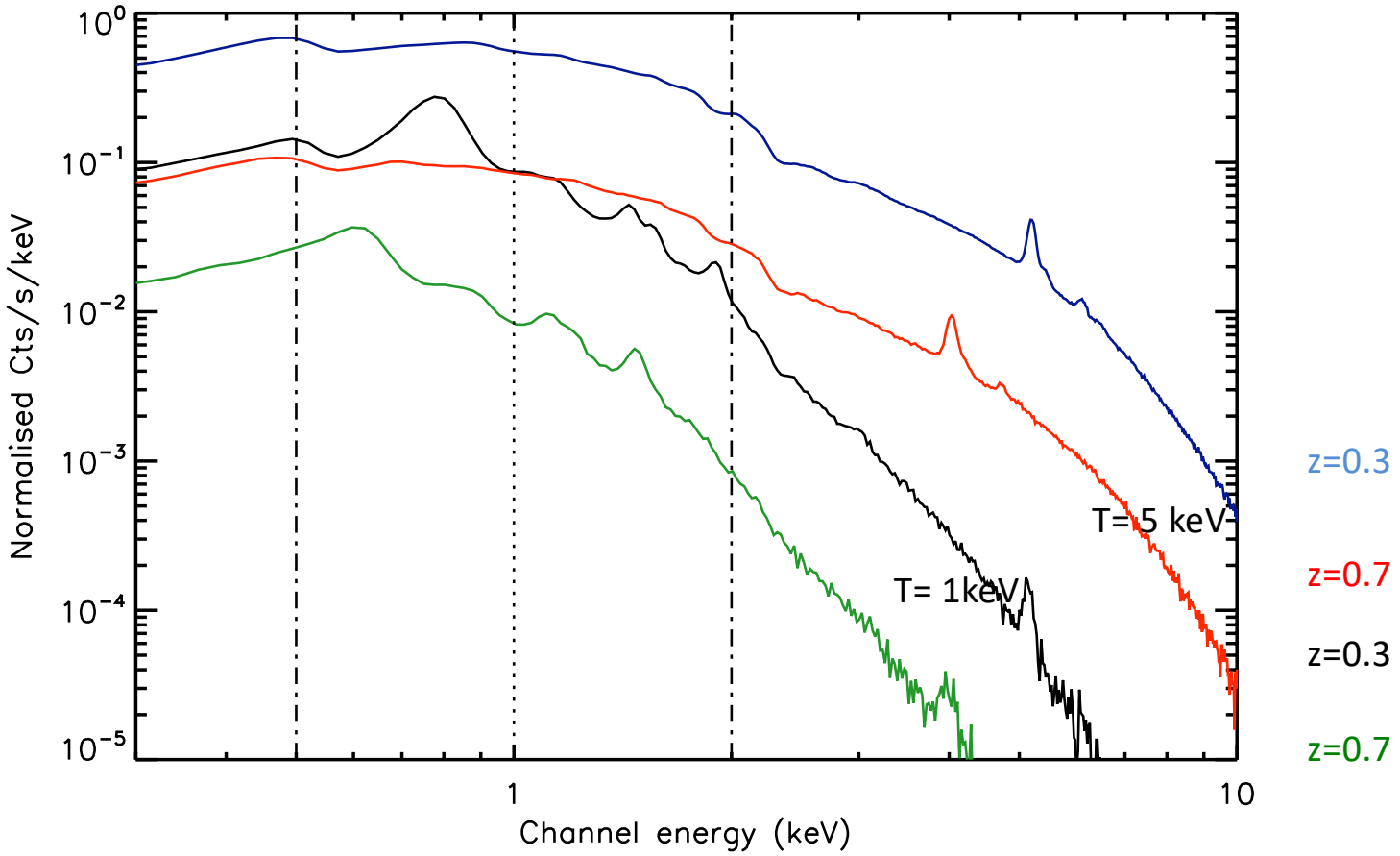
2. Surveys of distant cluster samples : will lead to statistical properties and evolution of the ICM
   - Down to lower masses
   - Up to higher redhsifts

➔ **Cluster physics best addressed in synergy with Athena**

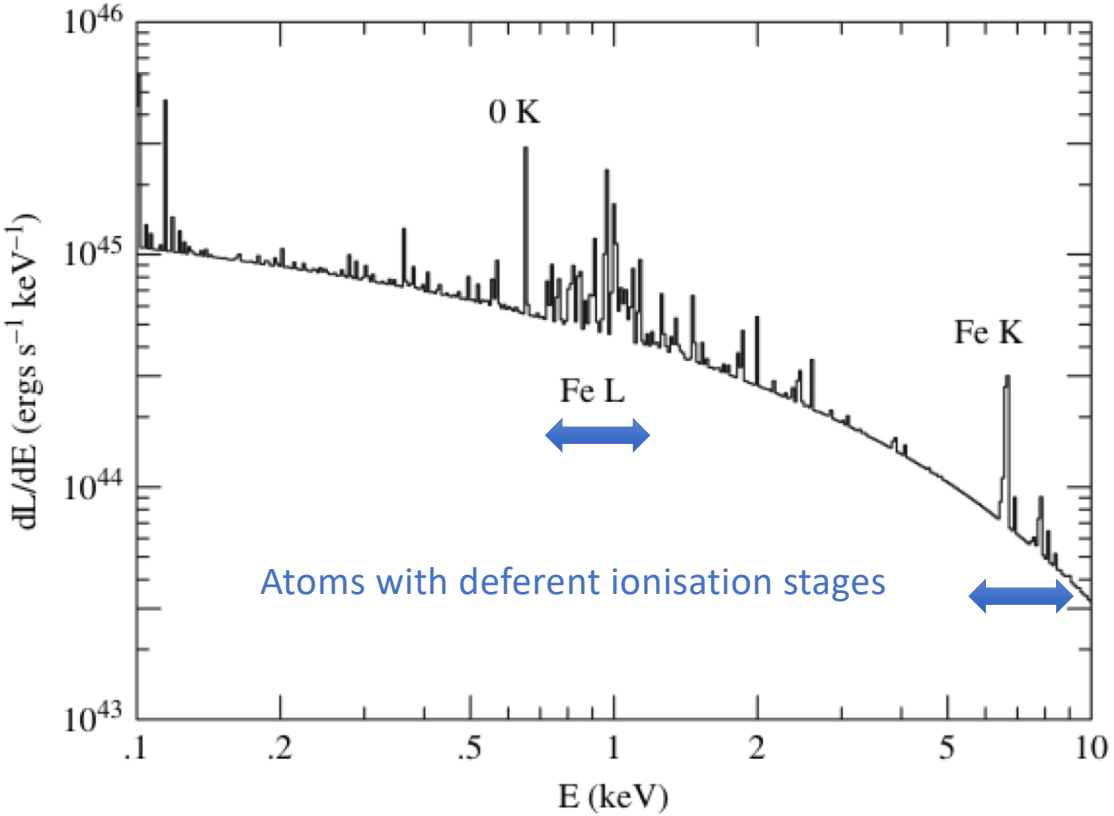
1. WFI
2. **XIFU** : high-sensitivity X-ray spectro-imager => maps of
   - abundances
   - ionisation level
   - velocties and turbulence

Plasma instabilities and kinetic effects play important roles in regulating micro-physical properties

Raw XMM cluster spectra



Theoretical X-ray spectrum

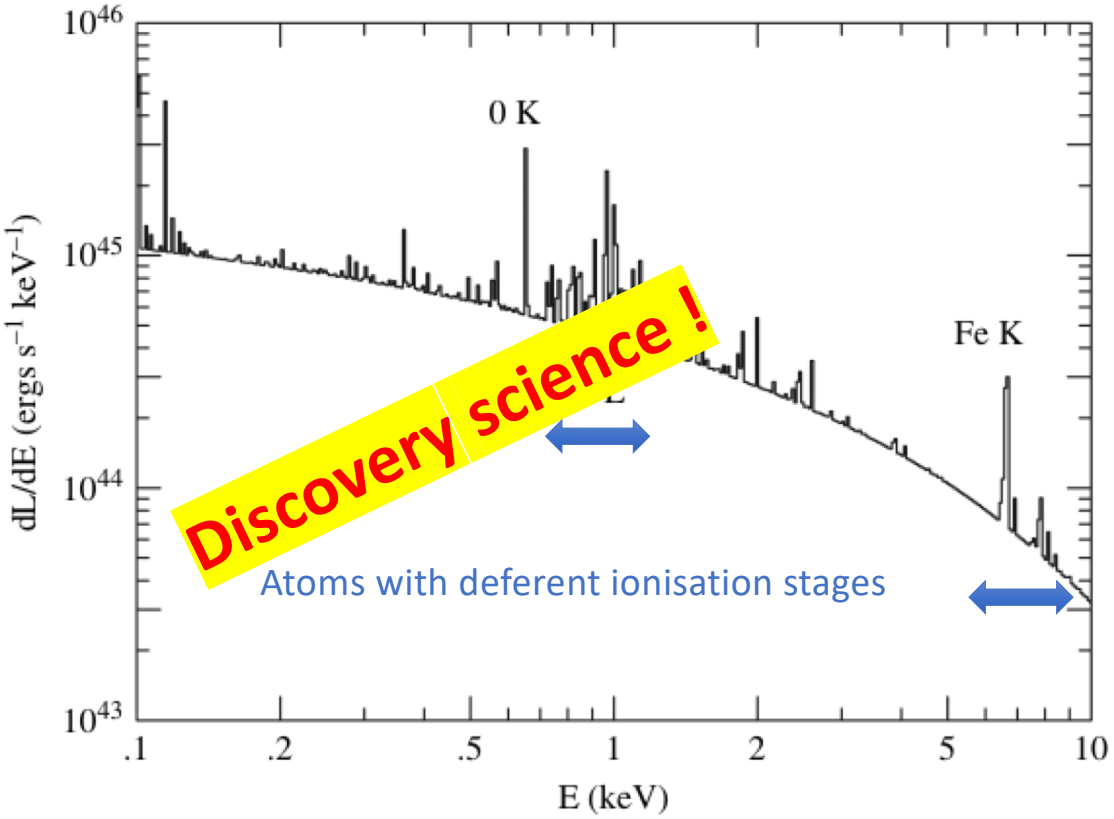


Cluster spectrum = bremsstrahlung continuum + emission lines

Example :
Iron
Atomic number: 26

Stable isotopes
54
56 92%
57
58

Theoretical X-ray spectrum => ~ Athena XIFU



Cluster spectrum = bremsstrahlung continuum + emission lines

Example :
Iron
Atomic number: 26

Stable isotopes
54
56 92%
57
58

Synergy with Athena
I. AGN fedback

SKA-Athena Synergy White Paper, 2018
Cassano, Fender, Ferrari, Merloni et al

- XIFU The impact of jets on the thermodynamic evolution of the ICM
  - Mechanical energy from radio-loud AGN is expected to be responsible for **driving turbulence in the ICM**, which dissipates into heat contributing to offset radiative cooling => How ?
  - Role of **AGN feedback** in the characterisation of **non gravitational physics** (non HSE)
- XIFU Inverse Compton X-ray emission of radio lobes
  - Measure the e-energy distribution and infer B in the radio lobes
- WFI Finding the earliest galaxy groups and clusters efficiently with radio surveys
  - AGN radio-loud point to rich environments (proto-clusters)
  - Compare the X/radio selection functions . . . what can we say beyond z>2 ?

Synergy with Athena
IIa. Diffuse non-thermal phenomena in clusters

Halos & Relics : presence of relativistic particles and magnetic fields

- Investigate the presence of a connection between diffuse radio emission from the ICM and its turbulent state (re-acceleration of e^- and amplification of B)

- **Athena :** Accurate T-jump measurements where relics reside
  insights into the electron-ion non-equilibrium
  shocks
- **SKA**: Spectral and polarization properties of the diffuse emission

New science on the 5”-15” scale, along with numerical simulations:

➔Explain the re-acceleration process (always needed?)

➔Magnetic fields in clusters : structure, origin and evolution

Synergy with Athena
IIb. Diffuse non-thermal phenomena in clusters/mini-halos

- Diffuse radio emission on the scale of cluster cores (< 300 kpc),
- Surround the central AGN
- Often appear bounded by one or two X-ray cold fronts

➔ mini-halos would arise from the reacceleration of seed relativistic electrons in the **magnetized cool core** as a consequence of **sloshing-induced turbulence** (Hitomi observation of the Perseus cluster)

➔ any physical connection between giant halos and mini-halos ? Role of the central AGN ?

Speculations . . . with SKAII ?

Cross-power-spectrum:

- eliminates instrumental effects or irrelevant objects
- stresses common scales

An idea is to investigate the cross-correlation between

1. SKA HI intensity mapping out to z ~ 1 ?
   - redshift ‘slices’ of the universe
   - main issues : foregrounds and sensitivity

2. Athena WFI survey
   - Only cluster and (field) AGN sources
   - No z information but ‘photon-energy slicer’