The SKA view of cool core clusters
Evolution of radio mini-halos and AGN feedback

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Radio-loud BCG: “bubbles” filling the X-ray cavities

thermal and non-thermal components are spatially separated

Radio-mode AGN feedback

(McNamara & Nulsen 2012, Gitti et al. 2012, Fabian 2012)
RBS 797 (z=0.35): diffuse radio emission on larger scale

Radio mini-halos (MH):
- diffuse, faint, amorphous (roundish) in shape,
- synchrotron radio emission surrounding the radio-loud BCG in a number of cool-core galaxy clusters
- MH size \(\sim 100 \div 500\) kpc
- \(\approx\) cooling region

\[VLA\ 1.4\ GHz\ (green)\]
\[VLA\ 4.8\ GHz\ (black)\]
\[Gitti\ et\ al.\ 2012,\ 2013\]
RBS 797 ($z=0.35$): diffuse radio emission on larger scale

Radio mini-halos: not directly connected with the radio bubbles, but truly generated from the ICM

→ thermal plasma and relativistic electrons are mixed

VLA 1.4 GHz (green)
VLA 4.8 GHz (black)
Gitti et al. 2012, 2013
At present:

~20 mini-halos (or candidates) known, all at $z < 0.6$ (Giacintucci et al. 2014)

radio-mode feedback studies limited to $z < 0.7$, with very few cases at high $z$
(Hlavacek-Larrondo et al. 2012)

On the other hand:

• virialized clusters detected up to $z \sim 1.6$ (Tozzi et al. 2014)
• cool cores already well-developed at $z \sim 1$ (Santos et al. 2010, 2012)

➔ with SKA we expect to be able to trace the non-thermal emission and radio-mode feedback activity in clusters up to the highest redshift where clusters are found
Origin of radio mini-halos

MHs resemble small-scale versions of giant halos (*see Cassano’s talk*) ..but MHs always found in CCs → mergers do not play a major role

• **Leptonic models**:  
  Rel. electrons injected by the radio BCG and re-accelerated by turbulence in the CC region  
  and/or (e.g., Brunetti & Jones 2014)

• **Hadronic models**:  
Statistics of radio mini-halos

Current MH sample: 16 objects

Observational bias limits our present ability of detecting mini-halos complicated by the need of separating their low surface brightness emission ($\sim \mu$Jy/arcsec$^2$) from the bright BCG

$\Rightarrow$ this requires:
- very good sensitivity to diffuse emission
- high dynamic range
- good spatial resolution

$\Rightarrow$ SKA
How many mini-halos await discovery?

All known MHs are hosted in clusters with central entropy $K_0 = kT_0 n_0^{-2/3} \leq 25$ keV cm$^2$ $\rightarrow$ strong cool cores (SCC) (Giacintucci et al., in prep.)

Cluster statistics in terms of X-ray properties, available from Chandra and XMM studies, can be exploited to forecast future detections of radio mini-halos, provided an intrinsic relation between the thermal and non-thermal cluster properties exists.
1.4 GHz radio power vs. the CC-excised X-ray bolometric luminosity for the observed MH cluster sample

\[ \log P_{1.4} = 1.72(\pm 0.28) \log L_X - 2.20(\pm 0.46) \]  
(bisector BCES regression)

\[ P_{\text{MH,1.4}} \propto L_X^{1.72} \]

Is this valid for the whole population of SCC clusters?
Our basic assumption: every SCC cluster powers a radio mini-halo

The $P_{1.4}$-$L_X$ correlation is still valid

- observed MHs
- GMRT upper limits
  \[
  \text{rms} = 0.05 \div 0.1 \text{ mJy} \\
  \vartheta_b = 18'' \div 25''
  \]
  \(\text{(Kale et al. 2013)}\)
- estimated upper limits for the Chandra ACCEPT SCC clusters assuming they are undetected by current follow-up obs.
  \[
  \text{rms} = 25 \mu \text{Jy} \\
  \vartheta_b = 10''
  \]
SCC clusters in the Chandra ACCEPT sample

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Observed MHs

SCC clusters in the Chandra ACCEPT sample

$L_x (10^{44} \text{ erg s}^{-1})$

$z$

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Observed MHs

Current MH detection limit on the population of SCC clusters (from upper limits on $P_{1.4}$ by means of the $P_{1.4} \propto L_X^{1.7}$ correlation)

$$\text{rms} = 25 \, \mu\text{Jy}/\text{bm}$$
$$\theta_b = 10''$$

$\Rightarrow$ at present we are seeing only the tip of the iceberg
Observed MHs

SKA1-MID surveys at confusion limit
(from upper limits on $P_{1.4}$ by means of the $P_{1.4} \propto L_X^{1.7}$ correlation)

$$\text{rms} = 2 \, \mu\text{Jy/bm}$$
$$\theta_b = 8''$$

$\Rightarrow$ SKA1 will detect all MHs above
$\sim 10^{23} \, \text{W Hz}^{-1}$ up to redshift 0.6

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Observed MHs

SKA1-MID surveys at confusion limit
(from upper limits on $P_{1.4}$ by means of the $P_{1.4} \propto L_X^{1.7}$ correlation)

$$\text{rms} = 2 \, \mu \text{Jy/bm}$$
$$\theta_b = 8''$$

$\Rightarrow$ SKA1 “early” (rms ~50% higher) will follow-up > 70% of the SCC sample
SCC clusters in the *Chandra* ACCEPT sample

- **Observed MHs**
- **SKA2-MID surveys at confusion limit**
- (from upper limits on $P_{1.4}$ by means of the $P_{1.4} \propto L_X^{1.7}$ correlation)
- $\text{rms} \sim \text{factor } 10$ better than SKA1

→ SKA 2 will complete the follow-up of the full SCC sample
SCC clusters in the *Chandra* ACCEPT sample

**Observed MHs**

**SKA2-MID surveys** at confusion limit
(from upper limits on $P_{1.4}$ by means of the $P_{1.4} \propto L_X^{1.7}$ correlation)

rms $\sim$ factor 10 better than SKA1

→ SKA 2 will complete the follow-up of the full SCC sample

**Work in progress...**
Comparison with eROSITA and extension to SKA-LOW

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Mini-halos : open questions

• Do all cool-core clusters host a radio MH? How does the MH/CC fraction evolve with redshift?

• What is the role of the central AGN in powering MHs? What is the fraction of MH clusters showing evidence of radio-mode AGN feedback?

• Are MH intrinsically different from giant halos (GH), or just a different evolutionary stage? If non-CCs \(\rightarrow\) CCs, also GHs \(\rightarrow\) MHs?
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  *(power-limited sample with wider redshift distribution, synergy with eROSITA and ATHENA X-ray satellites)*

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  *(spectral studies, radio bubbles filling the X-ray cavities)*

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  *(polarimetric studies, evolutive models and synergy with ATHENA)*

⇒ Surveys with **SKA1** and **SKA2** will address these key points
Mini-halos: open questions

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Radio properties of the BCG as a function of cosmic epoch

A relation exists between the radio power of the BCG and the CC strength (Santos et al 2010)
+ ongoing Chandra/JVLA study of distant (z ~ 1) CC clusters (30 hrs JVLA GO, PI P. Tozzi)

SKA1-MID: Sources above $10^{23}$ W Hz$^{-1}$ can be detected up to $z \sim 1.7$ with rms = 2 μJy

+ complete census of radio properties of the BCGs down to $P_{1.4}=10^{22}$ W Hz$^{-1}$ (duty-cycle of radiogalaxies)
Detection of the radio lobes carving X-ray cavities

a galaxy group: HCG 62 (z=0.0137)  
Cavity size ~ 5 kpc → 0.6″ @ z=1  
Bubble power: $P_{1.4} \sim 2 \times 10^{21}$ W Hz$^{-1}$

a galaxy cluster: RBS 797 (z=0.35)  
Cavity size ~ 12 kpc → 1.5″ @ z=1  
Bubble power: $P_{1.4} \sim 10^{24}$ W Hz$^{-1}$

(Gitti et al. 2006, 2010)
Detection of the radio lobes carving X-ray cavities

Dashed lines: sensitivity limits for SKA1-MID (Deep Fields – 1000 h) at the corresponding resolution

→ SKA1-MID will detect bubbles in clusters at any redshift

→ SKA2 will investigate radio-mode feedback in groups up to $z \sim 1.3$

**Blue line:** flux density per beam (0.75”) for a bubble with $10^{24}$ W Hz$^{-1}$ and 1.5” size → galaxy cluster

**Red line:** bubble with $2 \times 10^{24}$ W Hz$^{-1}$ and 0.6” size → galaxy group
Conclusions

Non-thermal emission from cool-core clusters:
radio-loud BCGs + diffuse radio mini-halos

• **SKA1-MID** surveys with $\text{rms} = 2 \, \mu\text{Jy}$ at confusion limit will be able to detect all sources above $10^{23} \, \text{W Hz}^{-1}$ up to $z \sim 0.6$ for mini-halos and up to $z \sim 1.7$ for radio-loud BCGs

• **SKA2** will perform the radio follow-up of cool cores up to the highest-$z$ where virialized clusters are currently detected

→ SKA will open an unprecedented window on the exploration of mini-halos and radio-mode AGN feedback