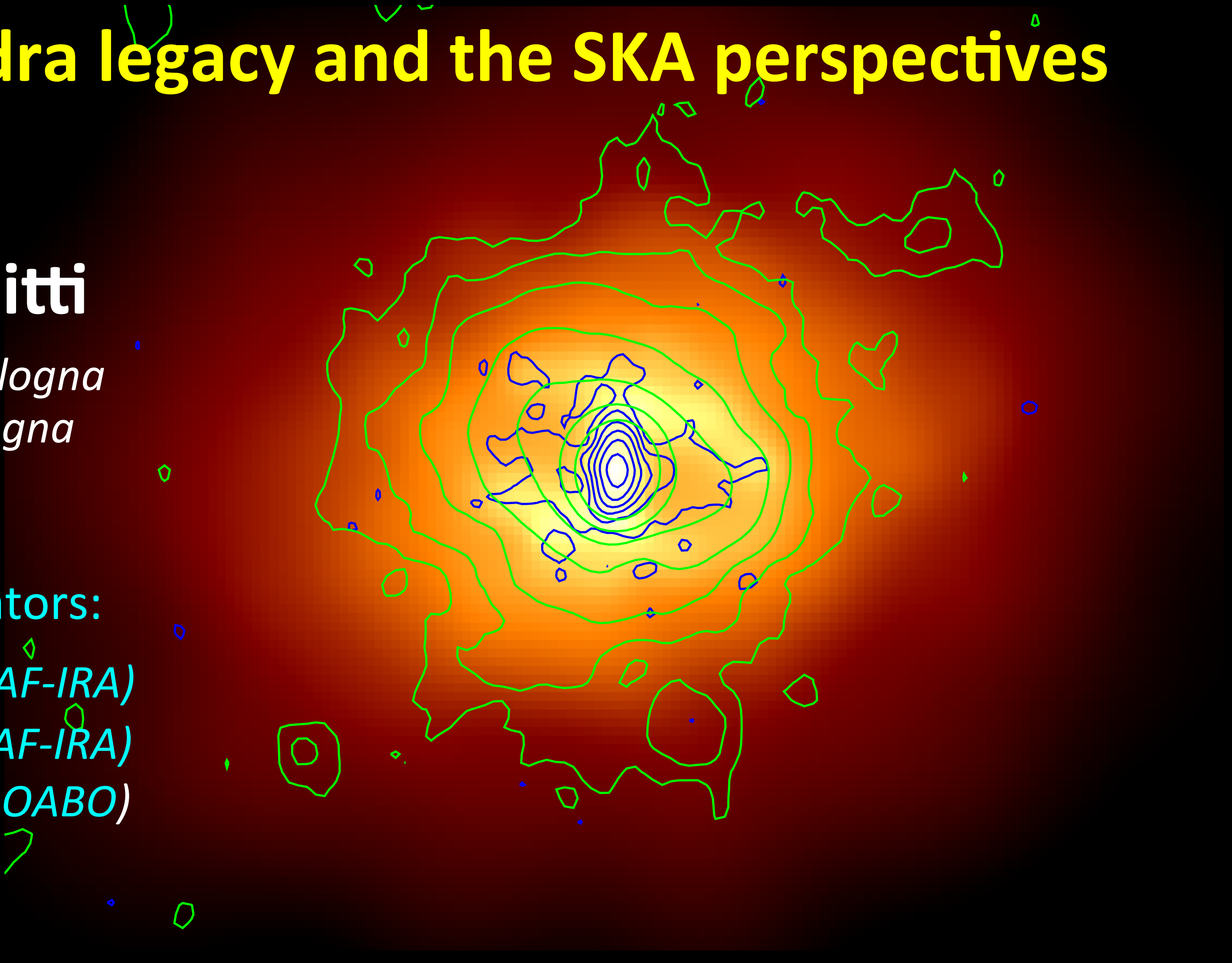
Radio mini-halos and AGN feedback in cool-core galaxy clusters:

the Chandra legacy and the SKA perspectives



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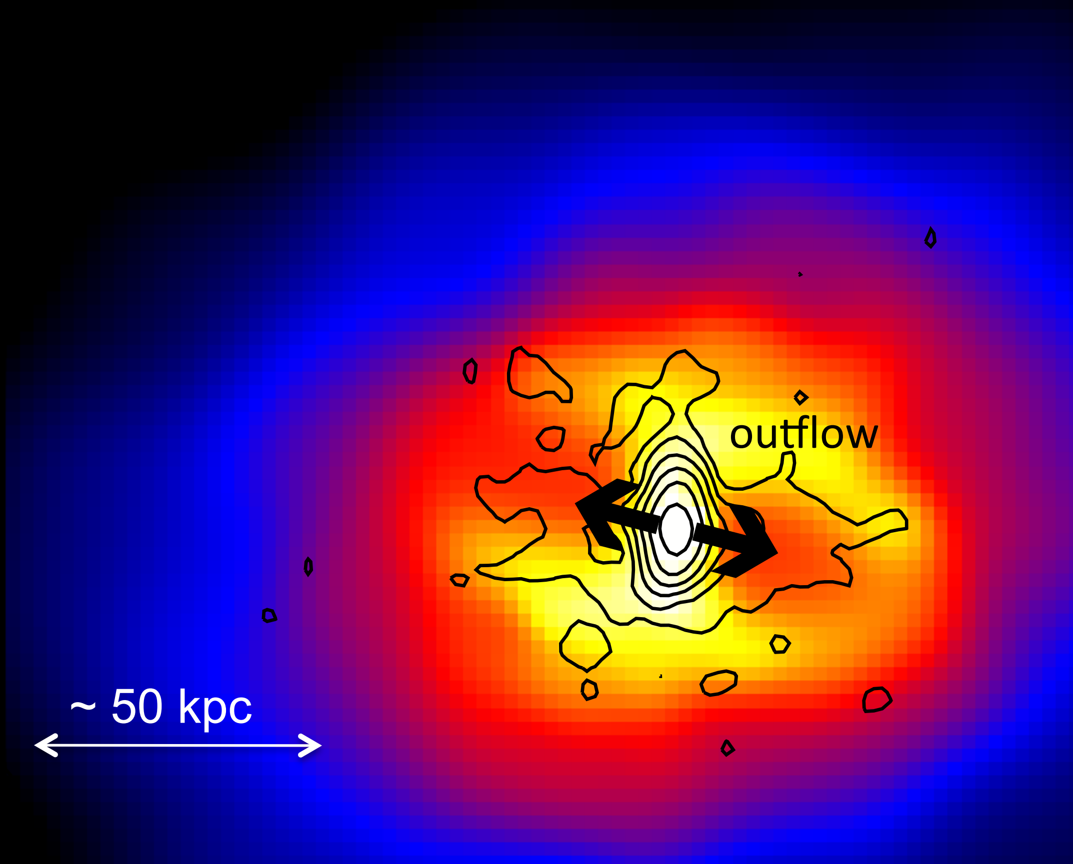
Non-thermal emission from cool-core (CC) clusters: (not only) **radio-loud AGN**



RBS 797 *(Gitti et al. 2013)*
Chandra X-ray
VLA 4.8 GHz (black)

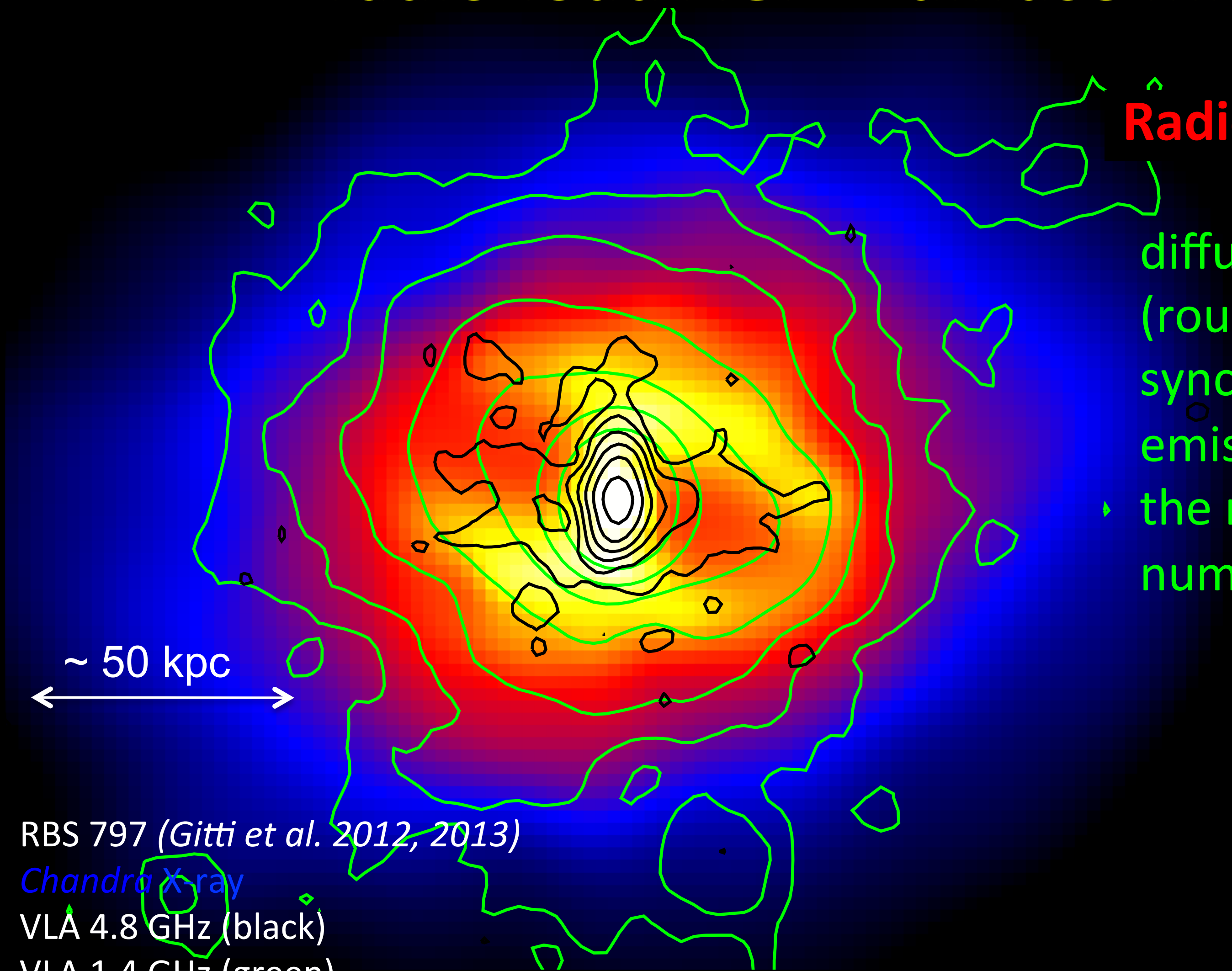
Radio-mode AGN feedback:

massive subrelativistic bipolar outflows from the BCG core

- inflate large radio bubbles while carving X-ray cavities and driving weak shocks
- heat the ICM
- likely drive **turbulence** in the ICM which may contribute to heat it *(Zhuravleva+14, Nature)*
- induce circulation of gas and metals on scales ≈100s kpc

(e.g., reviews by *McNamara & Nulsen 2007,2012*; *Gitti et al. 2012; Fabian 2012*)

Non-thermal emission from cool-core (CC) clusters: radio-loud AGN + diffuse mini-halos



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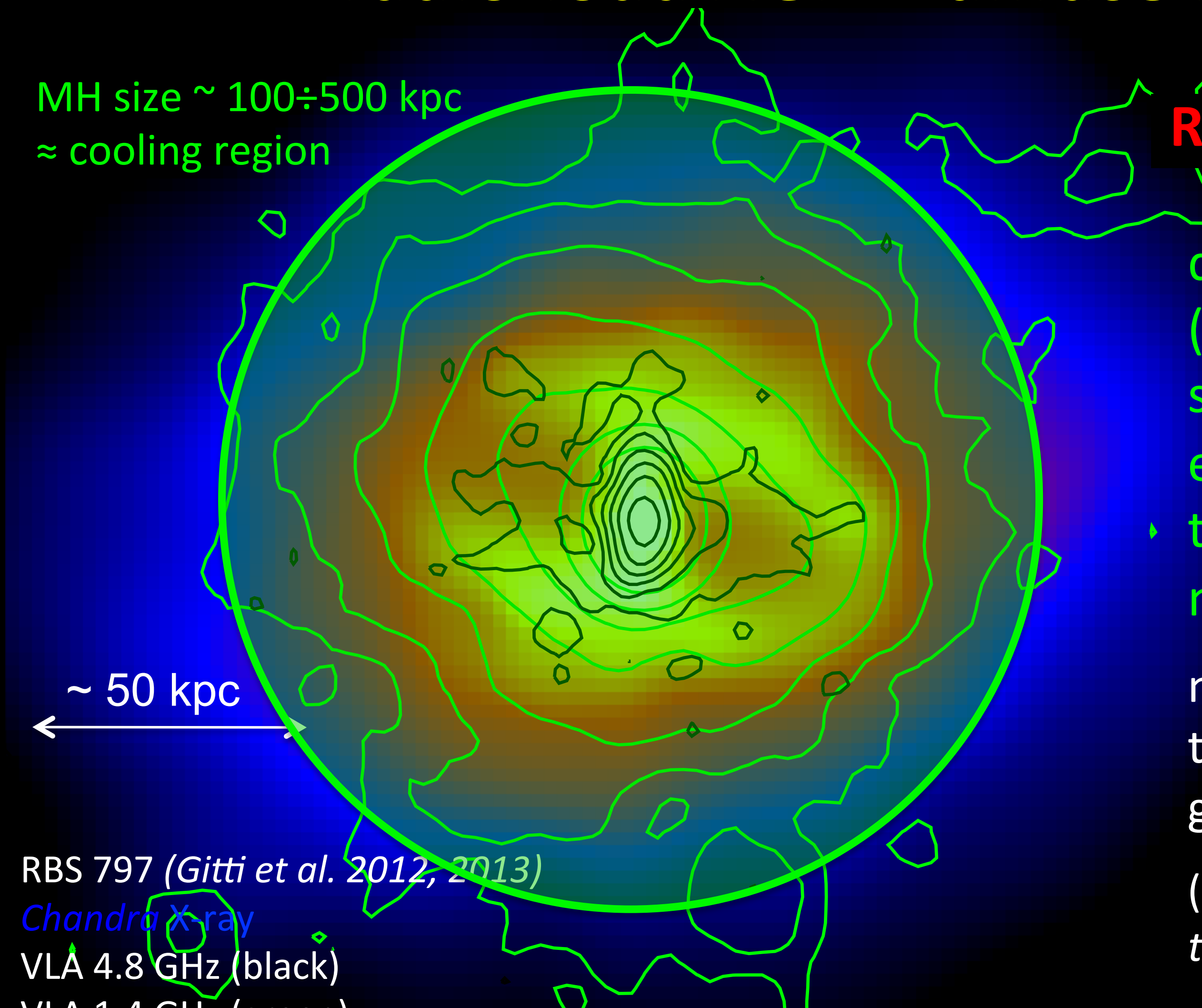
VLA 4.8 GHz (black)
VLA 1.4 GHz (green)

Radio mini-halos (MH):

- diffuse, faint, amorphous (roundish) in shape, synchrotron radio emission surrounding the radio-loud BCG in a number of CC clusters

Non-thermal emission from cool-core (CC) clusters: radio-loud AGN + diffuse mini-halos

MH size ~ 100÷500 kpc
≈ cooling region



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VLA 4.8 GHz (black)
VLA 1.4 GHz (green)

Radio mini-halos (MH):

diffuse, faint, amorphous (roundish) in shape, synchrotron radio emission surrounding the radio-loud BCG in a number of CC clusters

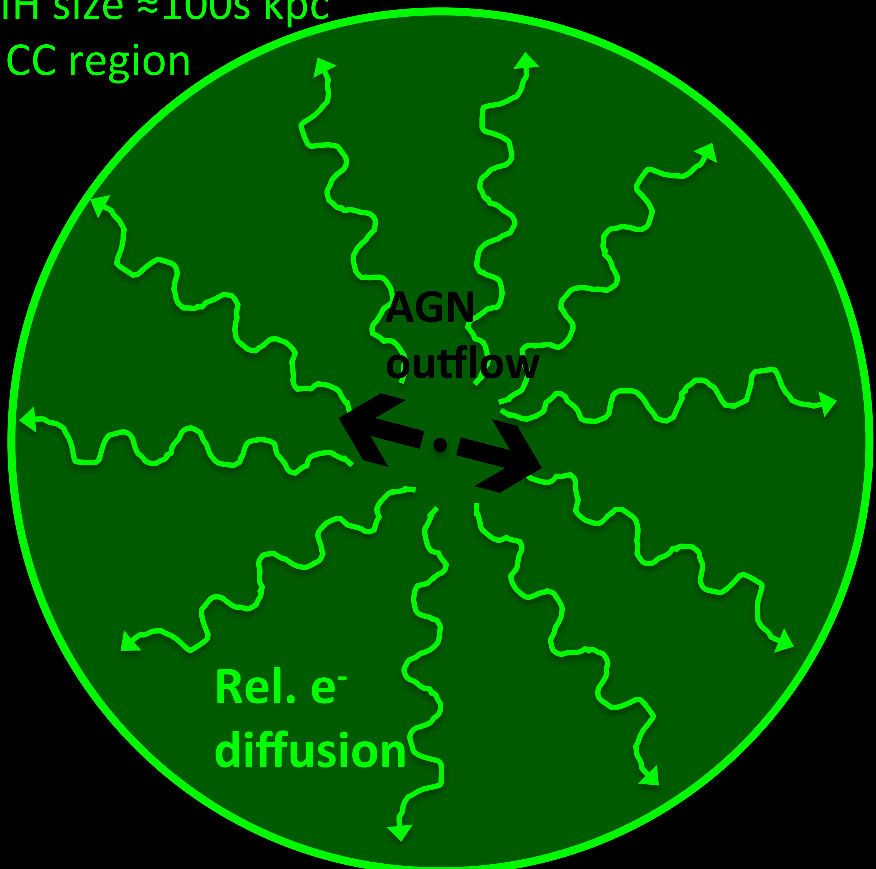
not directly powered by the central AGN, but truly generated from the ICM

(*relativistic electrons and thermal plasma are* *mixed)*

Origin of radio mini-halos

Diffusion time ≫ Radiative lifetime → ***Slow diffusion problem***
(≫ 10^9 yr) (≈10^8 yr)

MH size ≈100s kpc
≈ CC region



- ***Leptonic* models** :

  Rel. electrons injected by radio BCG are re-accelerated by turbulence in CC region

  (Gitti et al. 02, 04, 07; Cassano & Gitti 08; Mazzotta & Giacintucci 08; ZuHone et al. 13)

and/or *(e.g., Brunetti & Jones 2014)*

- *Hadronic* models :

  Secondary electrons generated by p-p collisions in cluster vol.

  (Pfrommer & Enßlin 04, Zandanel et al. 13)

Origin of radio mini-halos

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($\gg 10^9$ yr) ($\approx 10^8$ yr)

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Gitti, Brunetti & Setti (2002) model
→ **CF process powers MHs** :

re-acceleration by Fermi II mechanisms associated with MHD turbulence amplified by (frozen-in) magnetic field compression in the CC region

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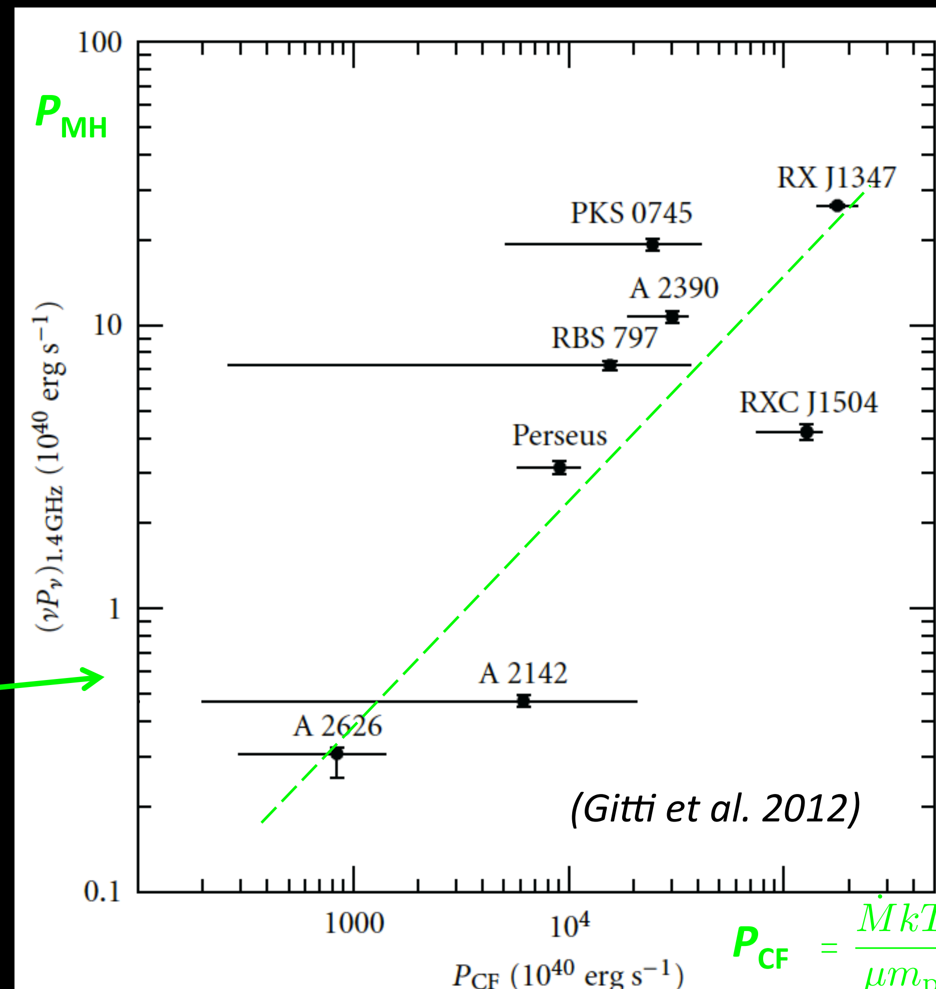
Trend P_{MH} – P_{CF} *(Gitti et al. 04, 12)*:
connection *thermal* CCs and *non-thermal* MHs ?



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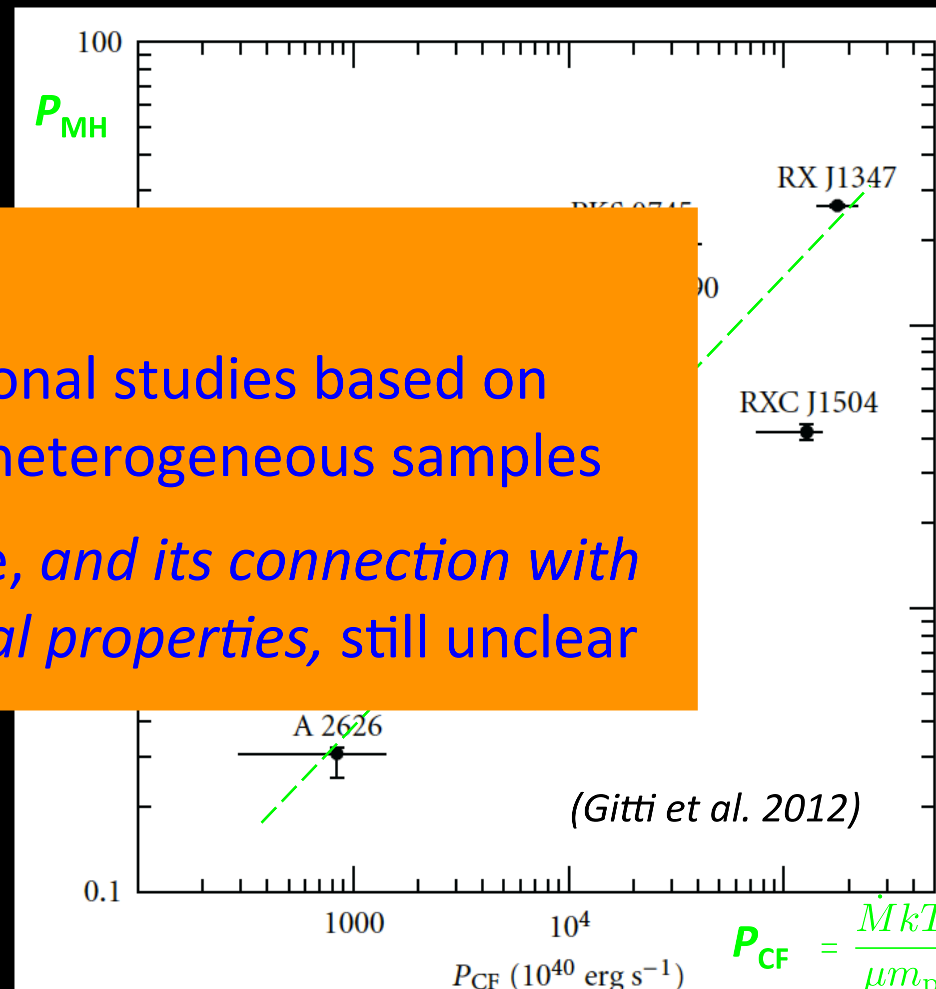


<u>C A V E A T S</u> :

- previous observational studies based on small (≈5-10 MHs), heterogeneous samples
- origin of turbulence, *and its connection with CC thermodynamical properties,* still unclear

Trend $P_{MH} - P_{CF}$ *(Gitti et al. 04, 12)*:
connection *thermal* CCs and *non-thermal* MHs ?

A new study of the largest MH sample

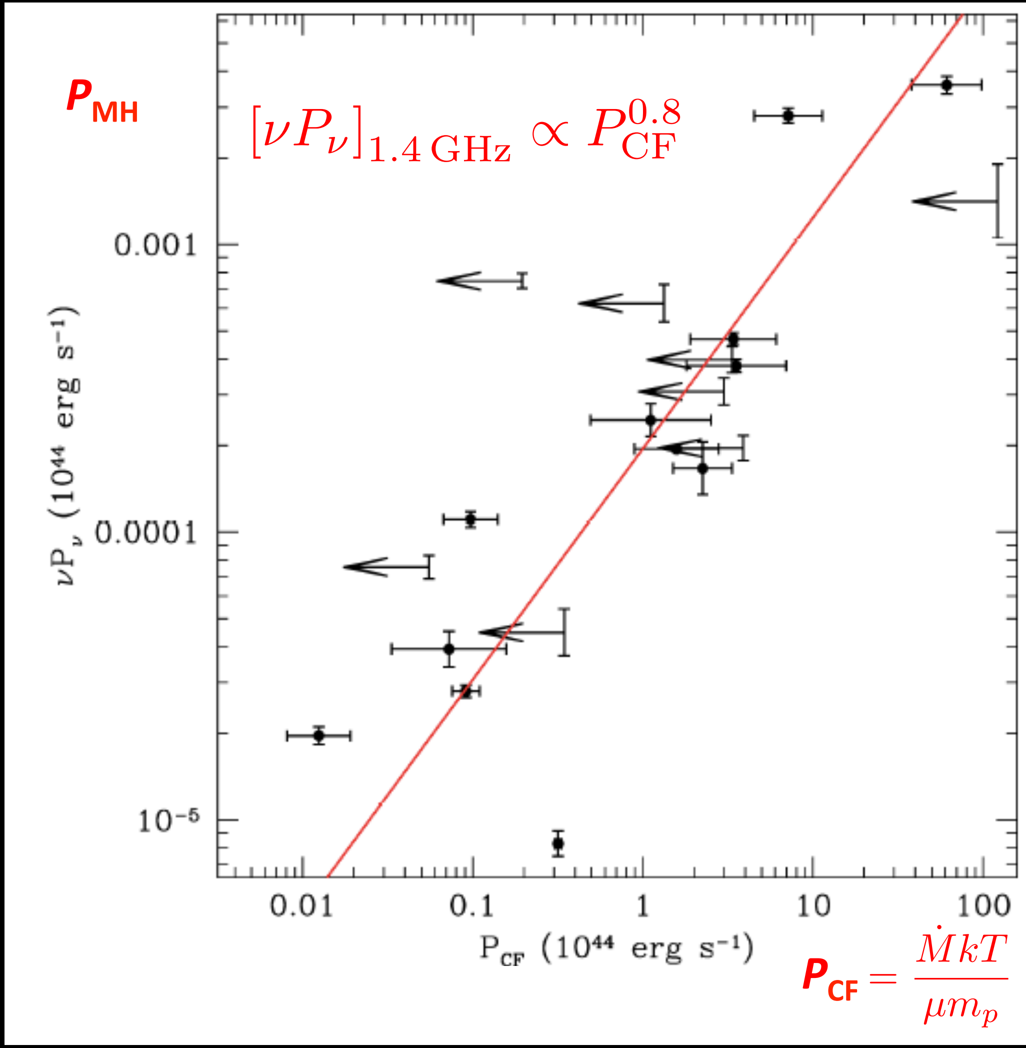
We exploit the increased MH statistics *(Giacintucci et al. 2014, van Weeren et al. 2014)*

⬇

Homogeneous analysis of archival Chandra data of the largest existing sample (~ 20 objects) of MH clusters

➔ **Correlation $P_{MH} – P_{CF}$:** connection between *thermal* CCs and *non-thermal* MHs

(Bravi, Gitti, Brunetti 2016)



Proposed scenario: turbulence is responsible for both MH origin and CF quenching

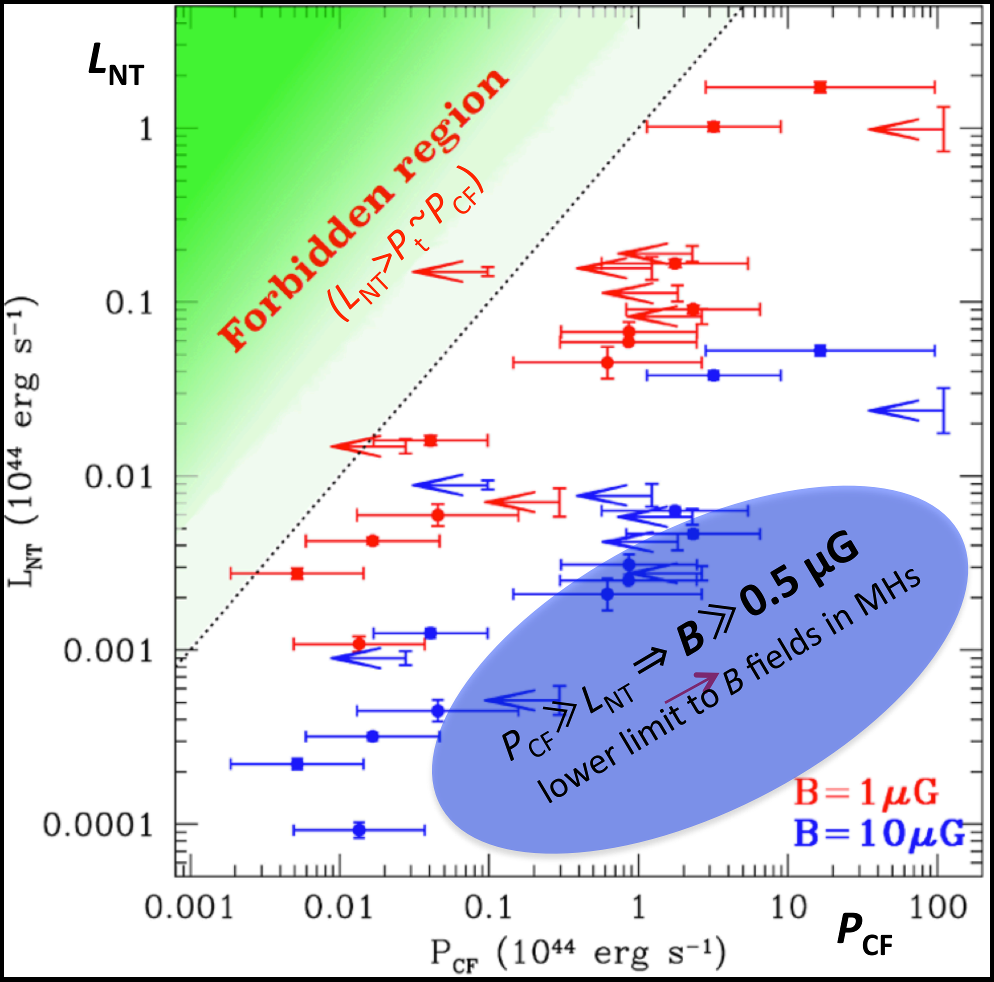
- We argue that particle acceleration and gas heating in CCs may be due to the dissipation of the *same* turbulence (heating power $P_H \gtrsim P_{CF}$)

- P_{CF} ≈ upper limit to non-thermal luminosity L_{NT} in the MH region:

$$L_{\rm NT} = L_{\rm Syn} + L_{\rm IC} = L_{\rm Syn}\left[1 + \left(\frac{B_{\rm CMB}}{B}\right)^2\right]$$

~ 3.2 μG

(Bravi, Gitti, Brunetti 2016)



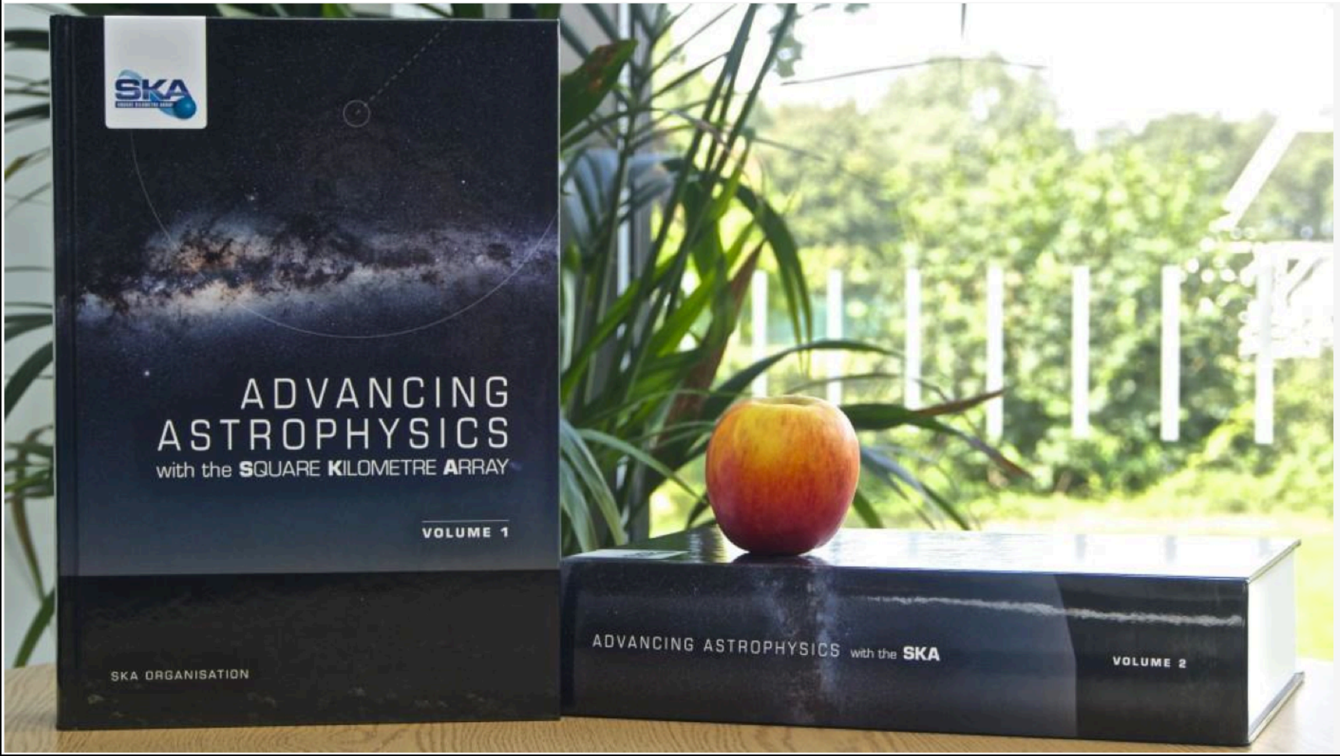
The (near) future: Square Kilometre Array

Largest and most sensitive radio telescope (cm), on wide frequency range (70 MHz ÷ 10+ GHz), predicted to start operating in 2020 (**SKA1**)

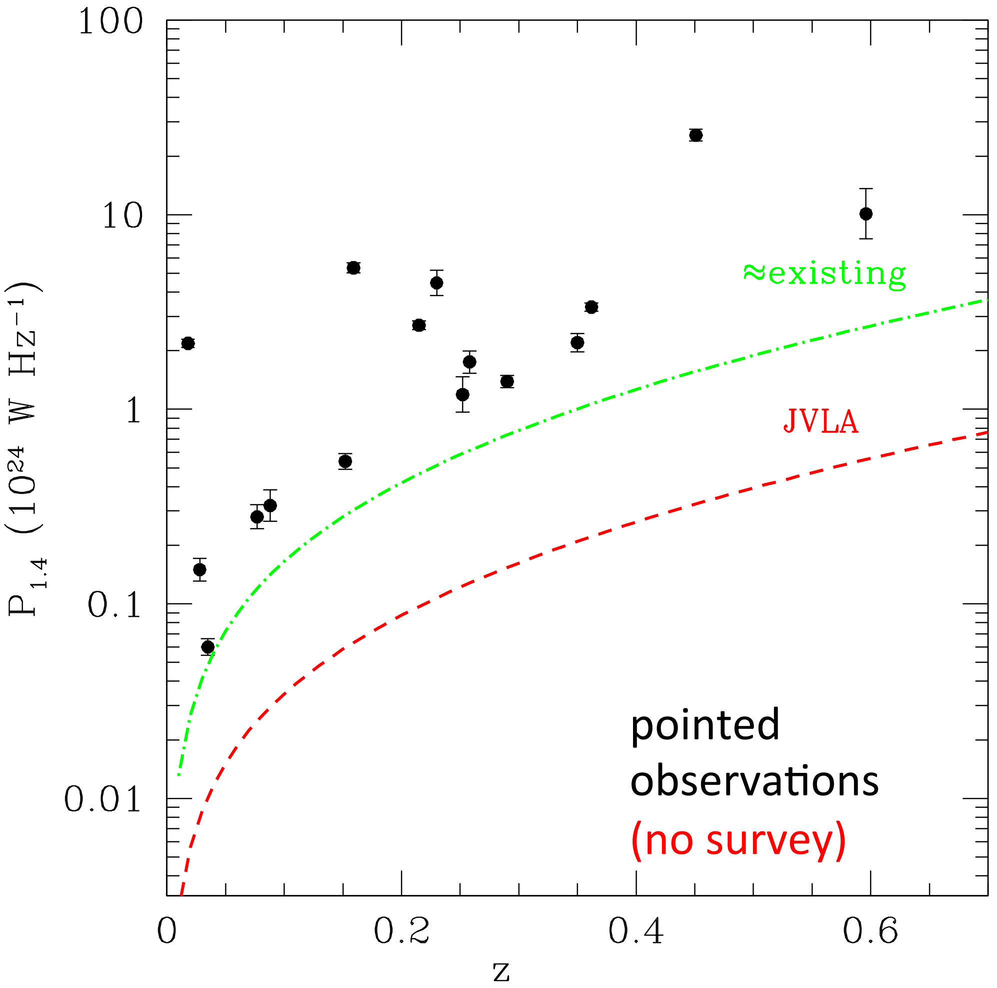
SKA White Book 2015

2000 pages, 135 chapters, 1200 authors, 8.8 kg (19.4 lb)

http://pos.sissa.it/cgi-bin/reader/conf.cgi?confid=215



Statistics of radio mini-halos



Current sample of *confirmed* MHs: 16 objects (all at z < 0.6)

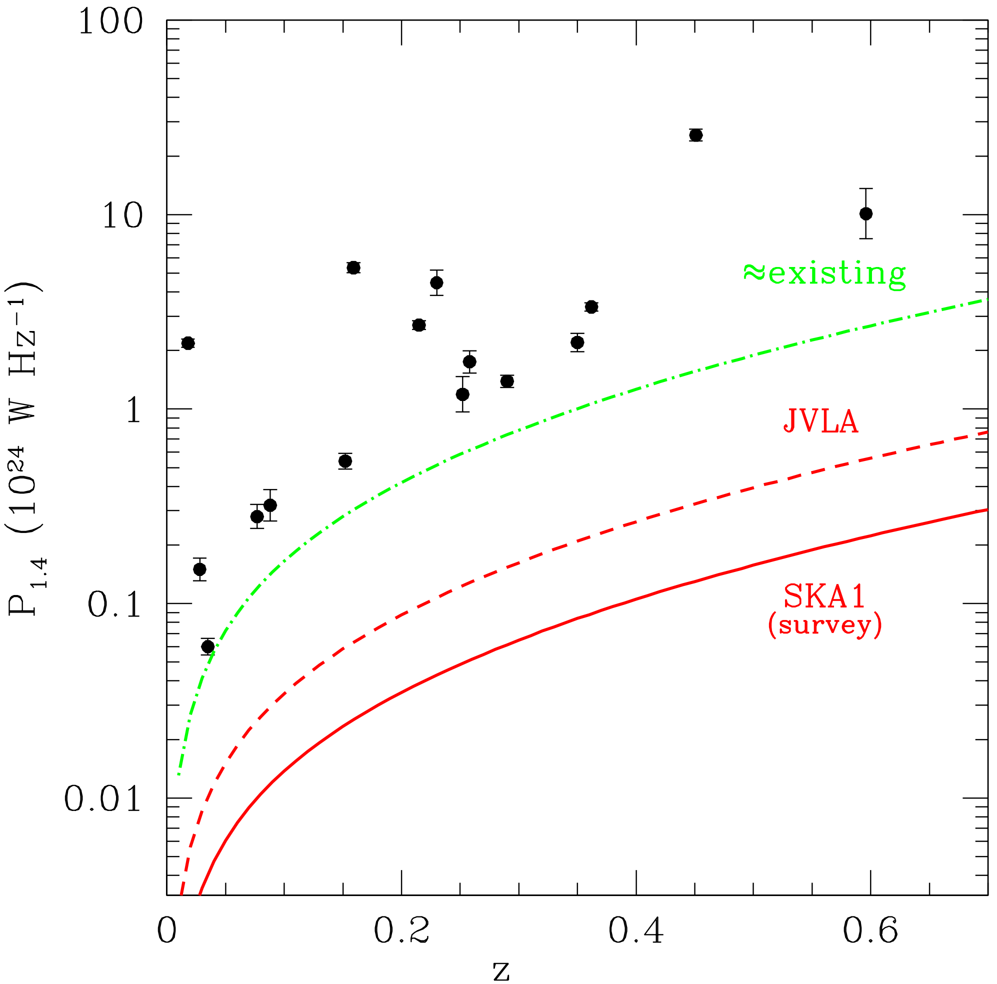
Existing ability of detecting mini-halos is limited
(rms = 30-40 μJy/bm, ϑ_b = 5"-10'')

complicated by the need of separating their low surface brightness emission (~ μJy/''^{2}) from the bright BCG, which requires:

- very good sensitivity to diffuse emission
- high dynamic range
- good spatial resolution

→ SKA pathfinders like JVLA already big improvement
(rms ~ 10 μJy/bm, ϑ_b ~ 8")

Future statistics of radio mini-halos



→ SKA1-MID All Sky surveys will be able to detect all MHs with $P_{1.4} > 2\times10^{23}$ W Hz^{-1} up to redshift 0.6

SKA1 Continuum Surveys

Instrument	SKA1-MID (Band 2)
Frequency	~1 GHz
Field of View	All Sky
Resolution	2'' - 5''
Sensitivity	4 μJy/b

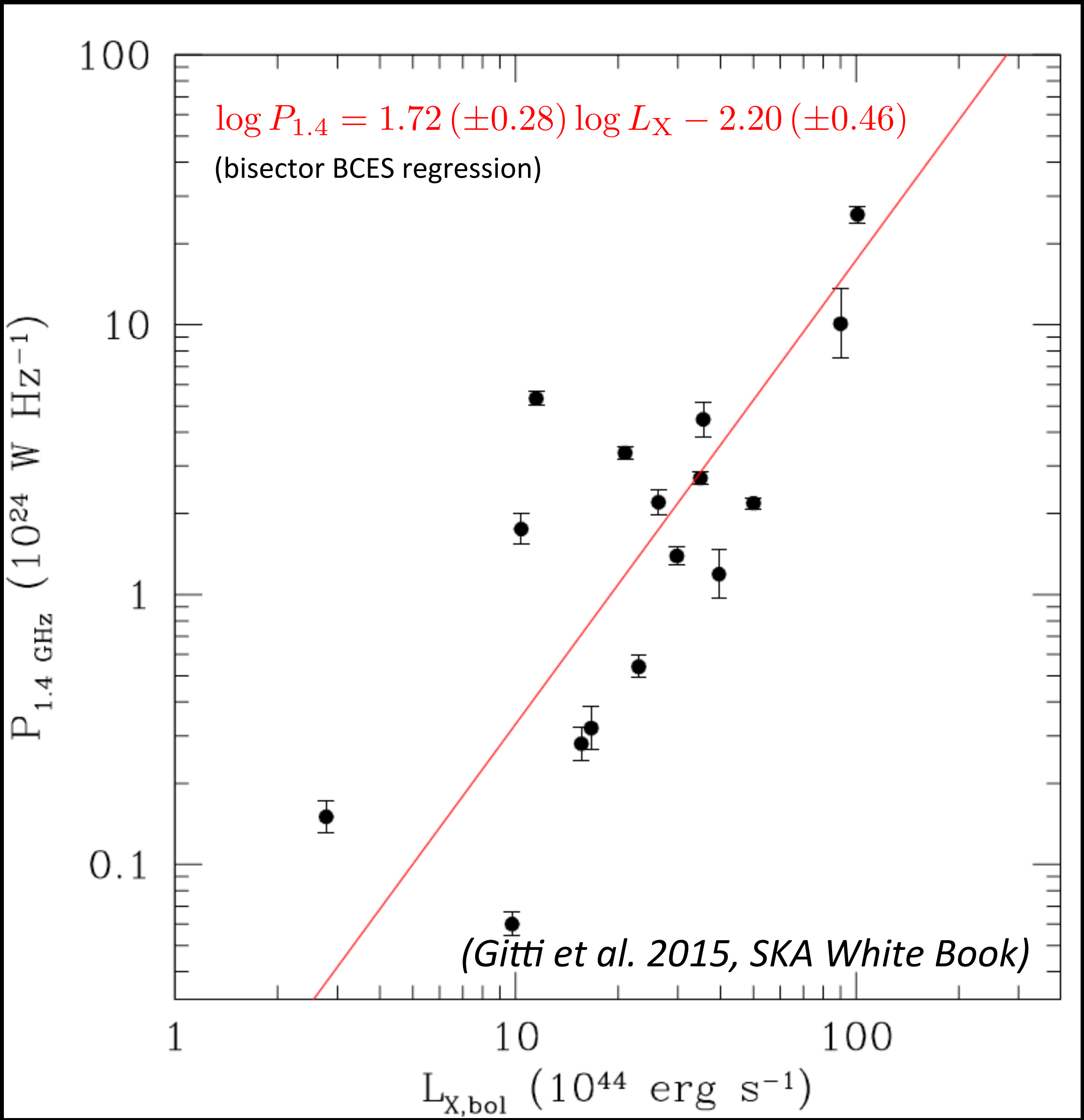
Future statistics of radio mini-halos

All known MHs are hosted in clusters with central entropy
$K0 = kT_0\, n_0^{-2/3} \leq 25$ keV cm^2 → *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

We selected the SCC clusters in the **ACCEPT** sample
Archive of *Chandra* Cluster Entropy Profiles Tables
(Cavagnolo et al. 2009)

Observed $P_{1.4} - L_X$ correlation for MH clusters



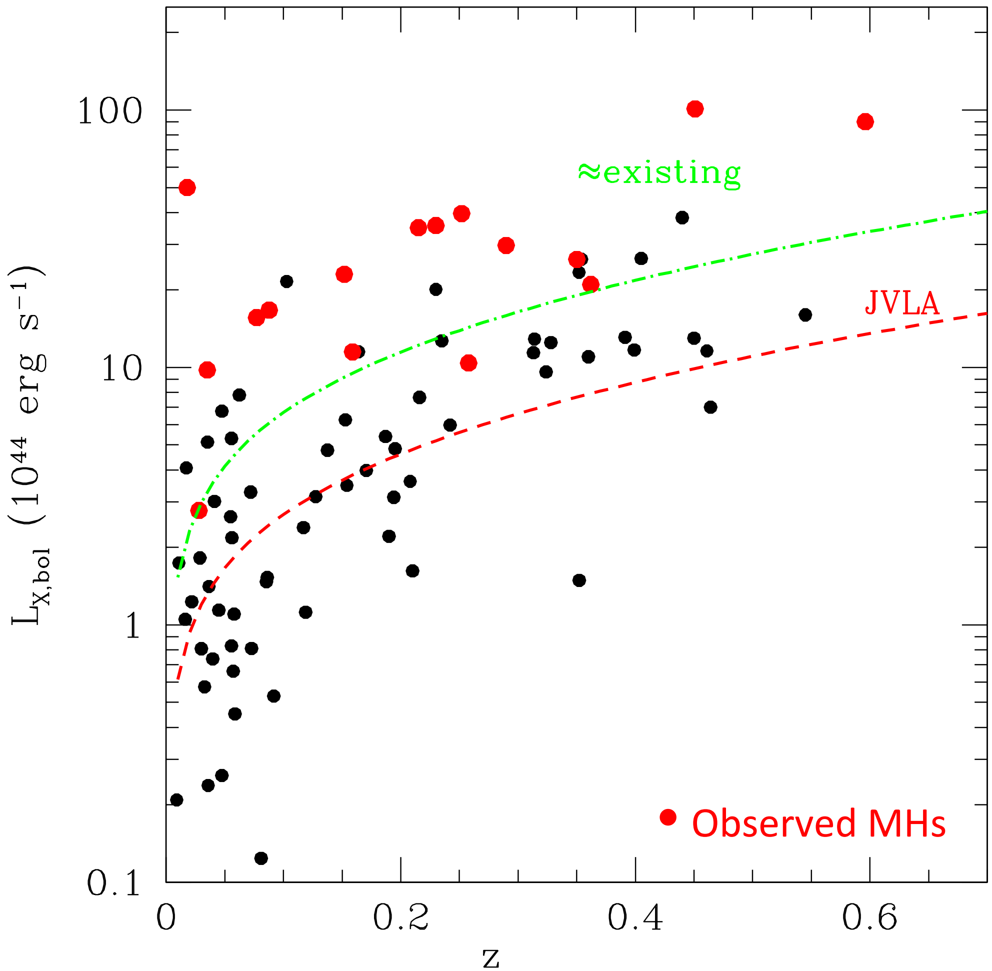
1.4 GHz radio power vs. X-ray luminosity for the observed MH cluster sample

(CC-excised $L_{X,bol}$ from ACCEPT sample, *Cavagnolo et al. 2009*)

$$P_{MH,1.4} \propto L_X^{1.72}$$

→ Our basic assumption:
all SCC clusters host a radio MH that follows the $P_{1.4} - L_X$ correlation

SCC clusters in the Chandra ACCEPT sample
→ candidates to host MHs



→ SKA pathfinders like JVLA already a big improvement (rms ~ 10 μJy/bm, ϑ_b ~ 8")

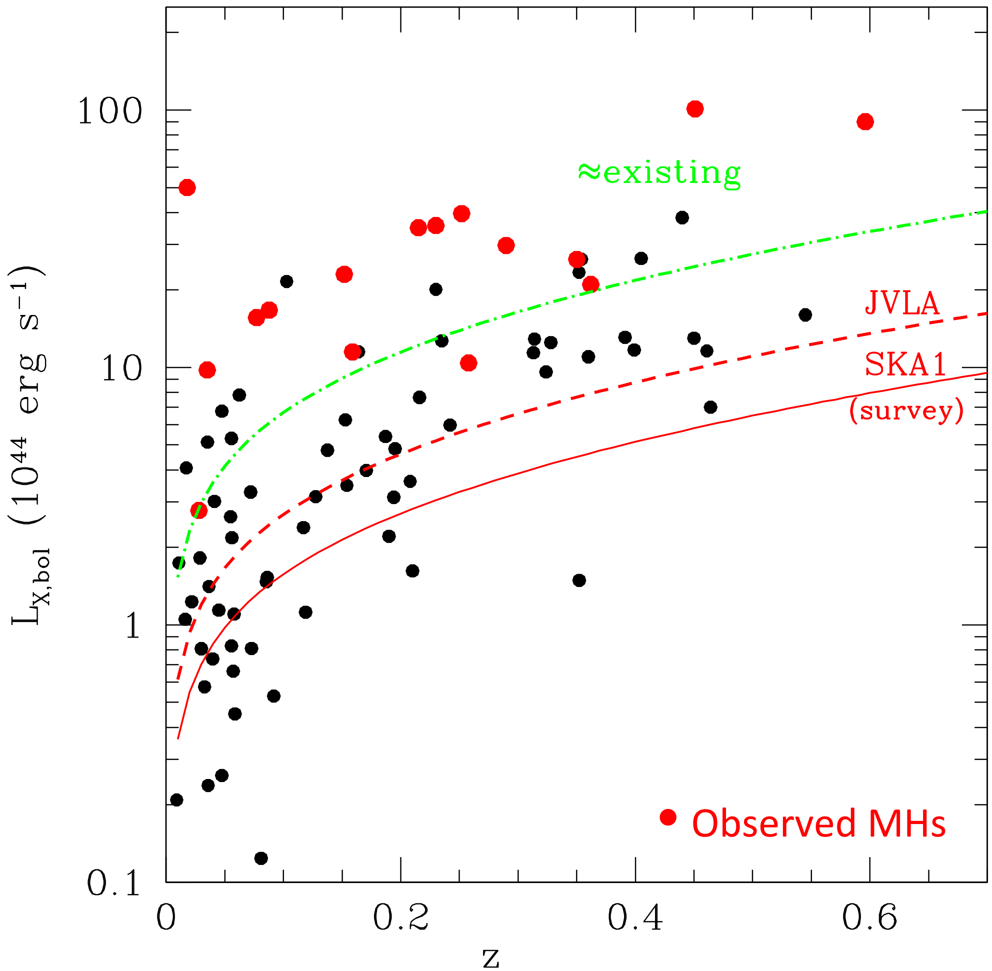
Indicative existing MH detection limit on the population of SCC clusters (rms = 30 μJy/bm, ϑ_b = 5")

↓

at present we are seeing only the ***tip of the iceberg*** of the SCC cluster population

SCC clusters in the Chandra ACCEPT sample

→ candidates to host MHs

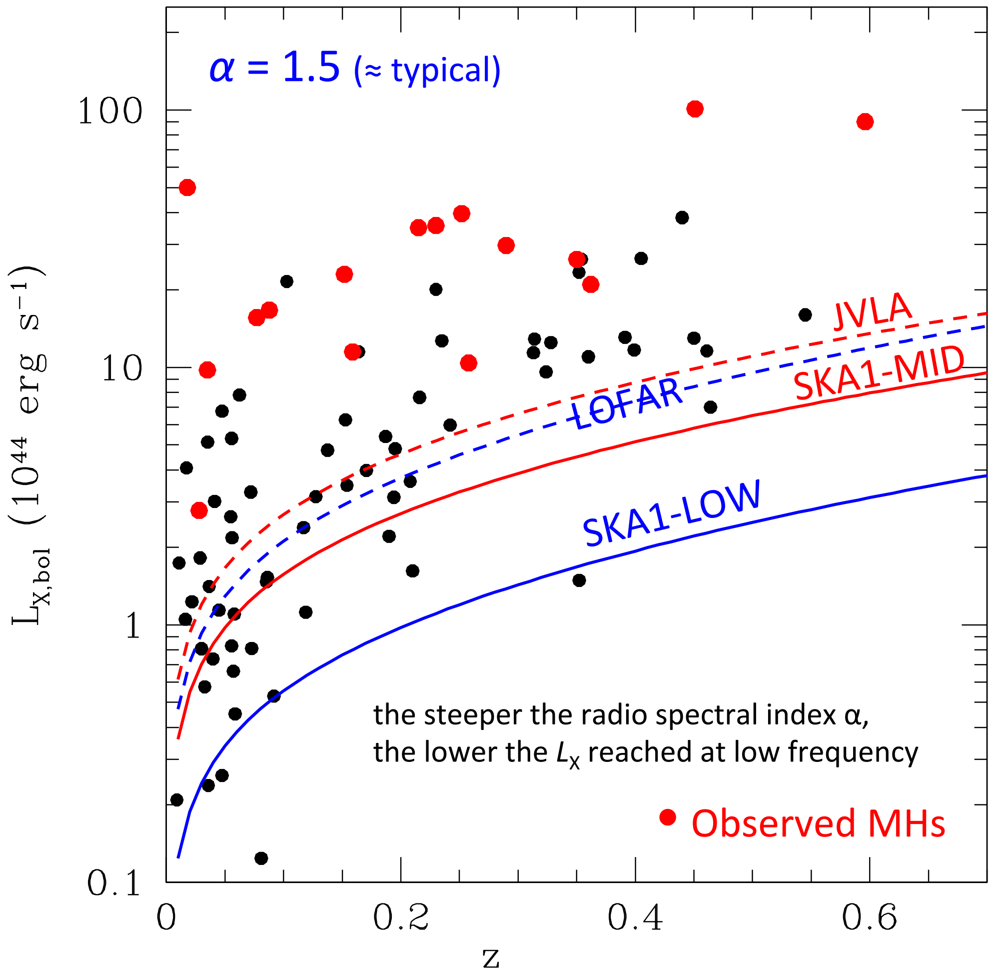


→ SKA1-MID All Sky surveys will be able to follow-up >70% of the ACCEPT sample

SKA1 Continuum Surveys

Instrument	SKA1-MID (Band 2)
Frequency	~1 GHz
Field of View	All Sky
Resolution	2'' - 5''
Sensitivity	4 µJy/b

SCC clusters in the Chandra ACCEPT sample
→ **candidates to host MHs**



→ SKA1-LOW All Sky surveys will be able to complete the follow-up of the ACCEPT sample

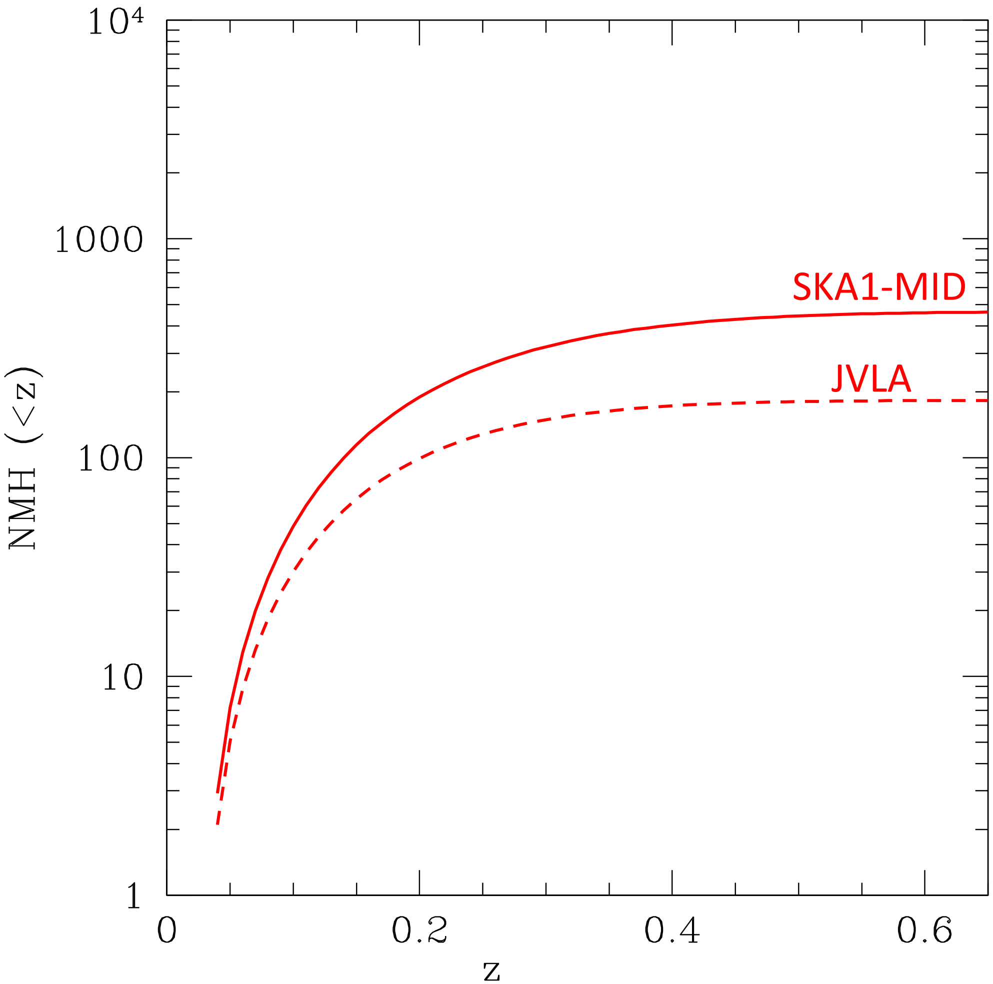
Predictions at low frequency

$S_\nu \propto \nu^{-\alpha}$ the steeper the index α, the brighter the MHs

SKA1 Continuum Surveys

Instrument	SKA1-MID (Band 2)	SKA1-LOW
Frequency	~1 GHz	~150 MHz
Field of View	All Sky	All Sky
Resolution	2'' - 5''	8'' - 10''
Sensitivity	4 μJy/b	20 μJy/b

How many radio mini-halos await discovery ?



→ SKA1-MID All Sky surveys will be able to detect ≳ 450 new MHs at z ≤ 0.6

Number of MHs that can be detected from a radio survey:

$$N_{\rm MH}^{\Delta z} = \int_{z_1}^{z_2} dz' \left(\frac{dV}{dz'}\right) \int_{P_m(z')} dP \frac{dN_{\rm MH}}{dPdV}$$

radio luminosity function of MHs:

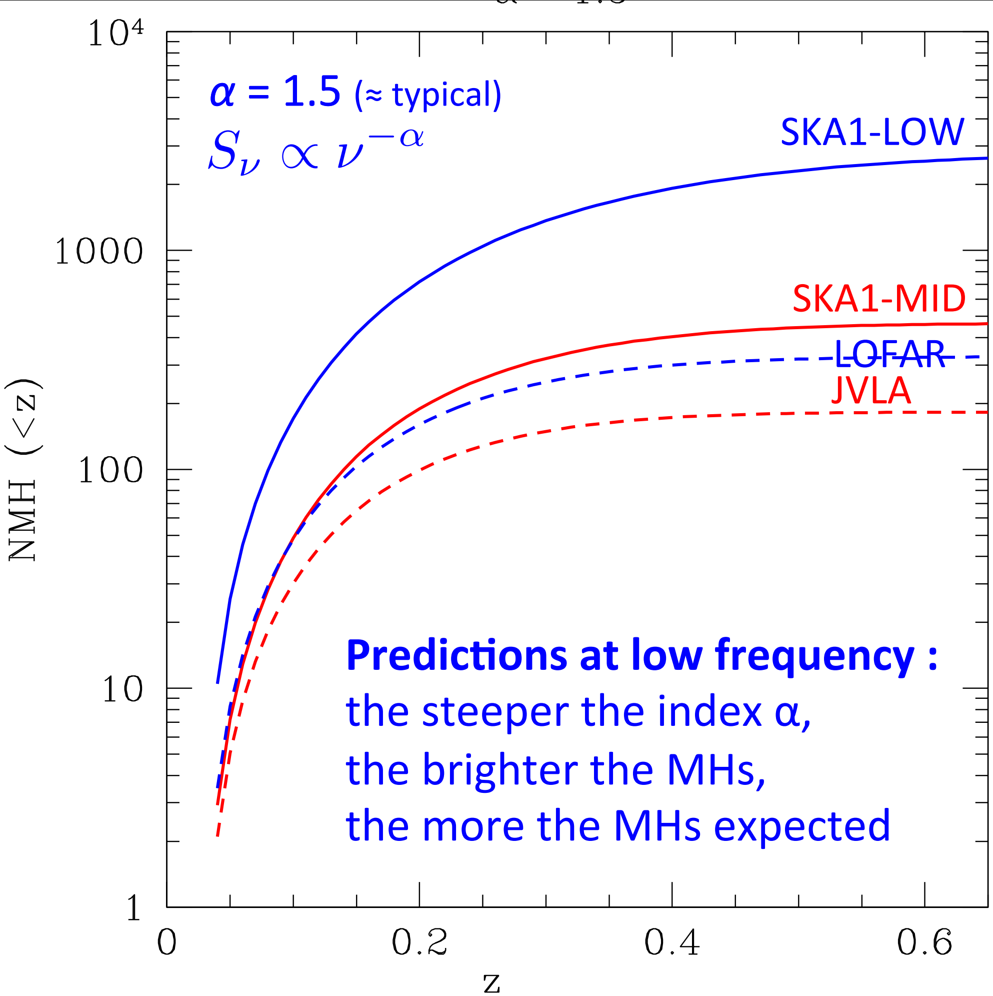
$$\frac{dN_{\rm MH}}{dPdV} = {\rm f_{SCC}} \frac{dN_{\rm cl}}{dL_{\rm X} dV} \frac{dL_{\rm X}}{dP_{1.4}}$$

fraction of clusters with SCC ~ 0.40 *(Hudson et al. 2010)*

X-ray luminosity function of clusters *(Mullis et al. 2004)*

observed MH X-radio power correlation *(Gitti et al. 2015)*

How many radio mini-halos await discovery ?



→ SKA1-LOW All Sky surveys will be able to detect ≳ 2000 new MHs at z ≤ 0.6

Number of MHs that can be detected from a radio survey:

$$N_{\rm MH}^{\Delta z} = \int_{z_1}^{z_2} dz' \left(\frac{dV}{dz'}\right) \int_{P_m(z')} dP \frac{dN_{\rm MH}}{dPdV}$$

radio luminosity function of MHs:

$$\frac{dN_{\rm MH}}{dPdV} = {\rm f_{SCC}} \frac{dN_{\rm cl}}{dL_{\rm X}dV} \frac{dL_{\rm X}}{dP_{1.4}}$$

fraction of clusters with SCC ~ 0.40 *(Hudson et al. 2010)*

X-ray luminosity function of clusters *(Mullis et al. 2004)*

observed MH X-radio power correlation *(Gitti et al. 2015)*

Radio mini-halos : open questions

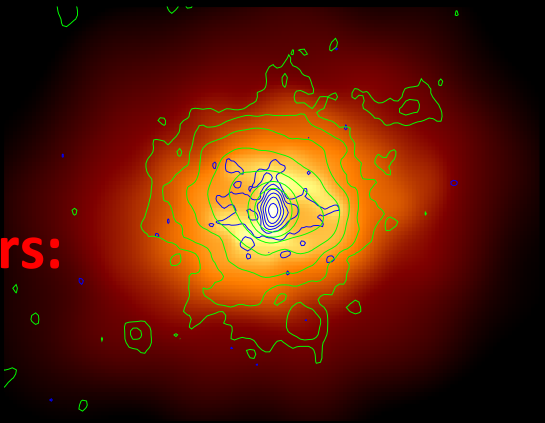
- Do all cool-core clusters host a radio MH?
  How does the MH/CC fraction evolve with redshift?
  (power-limited sample with wider redshift distribution, synergy with Chandra, eROSITA, ATHENA & X-ray Surveyor)

- What is the role of the central AGN in powering MHs?
  What is the fraction of MH clusters with radio-AGN feedback?
  (spectral studies, radio bubbles filling the X-ray cavities)
  SKA1-MID can detect bubbles in clusters at any *z (Gitti+15)*

- Are MH intrinsically different from giant halos (GH), or just a different evolutionary stage? If non-CCs → CCs, also GHs → MHs?
  (polarimetric studies, evolutive models, synergy with Chandra & ATHENA)

→ **unique role of Chandra in the next decade** for X-ray follow-up of radio surveys with SKA (and pathfinders)

Conclusions



Non-thermal emission from cool-core (CC) clusters: radio-loud AGN + diffuse radio mini-halos (MH)

- Homogeneous analysis of X-ray *Chandra* data of the largest existing sample (~ 20 objects) of MH clusters *[Bravi+16, MNRAS]* :
  - ✓ Correlation MH power vs. CF power
  - ✓ Turbulent re-acceleration scenario: rel. electron acceleration (→ **MHs**) and gas heating (→ **CF quenching**) may be due to the dissipation of the *same turbulence*
- Large MH samples are necessary to unveil MH origin and connection with CC thermodynamics *[Gitti+15, POS-AASKA]* :
  - ✓ All Sky Surveys with SKA1-MID @4 μJy rms (SKA1-LOW @20 μJy rms) will be able to detect $\gtrsim$ 450 ($\gtrsim$ 2000) new MHs at $z \leq 0.6$

→ **synergy SKA** (JVLA, LOFAR) **& Chandra**