# Do radio mini-halos and AGN heating in cool-core clusters have a common origin?

**Myriam Gitti**

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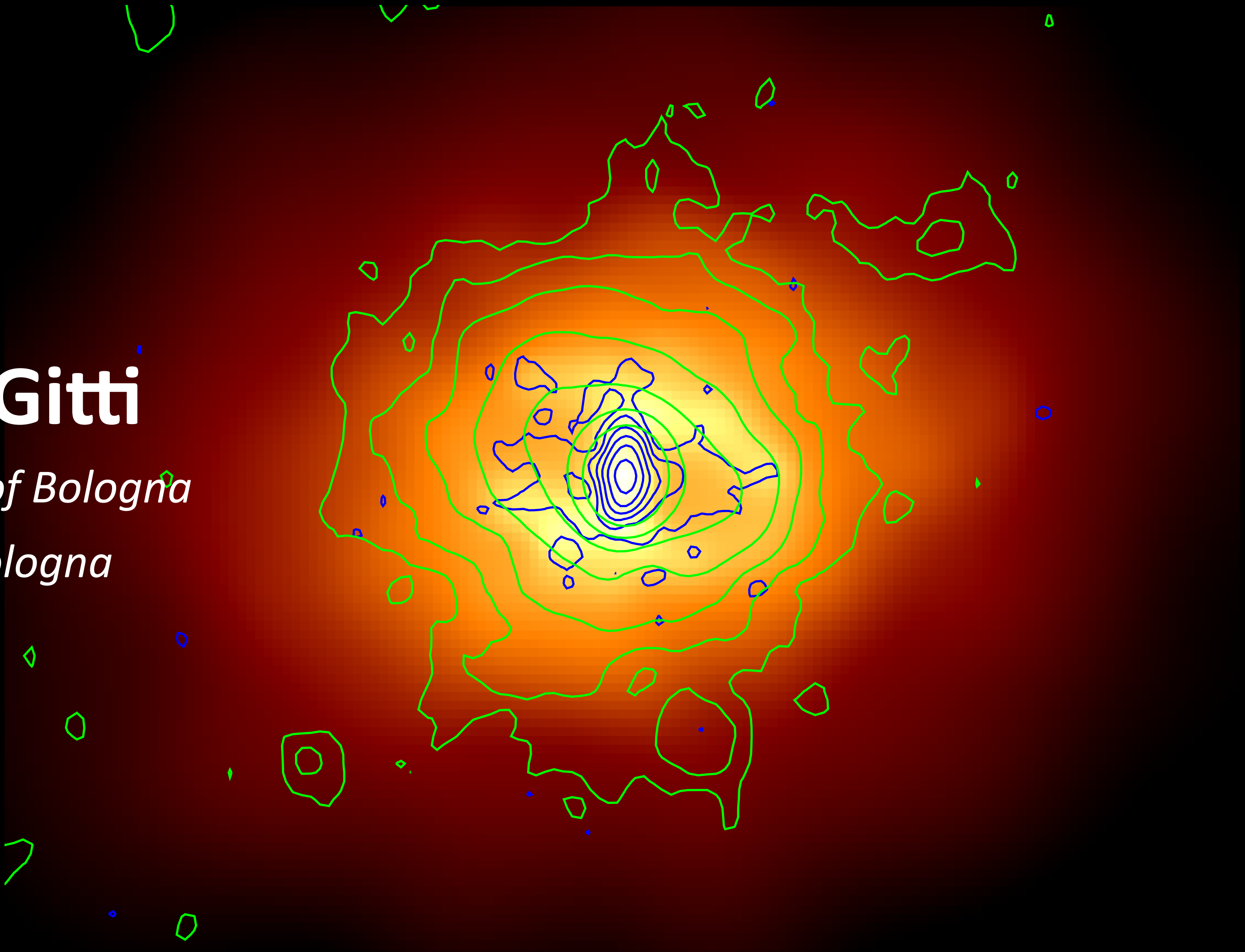


# Cooling Flow (CF) – standard model

- **cooling time** $t_{cool}$ : characteristic time of energy radiated in X-rays ≈ $T^{1/2} / n_e$
- **cooling radius** $r_{cool}$ : radius at which $t_{cool}$ = age of the cluster ~ $t_H$
- **cooling region :**

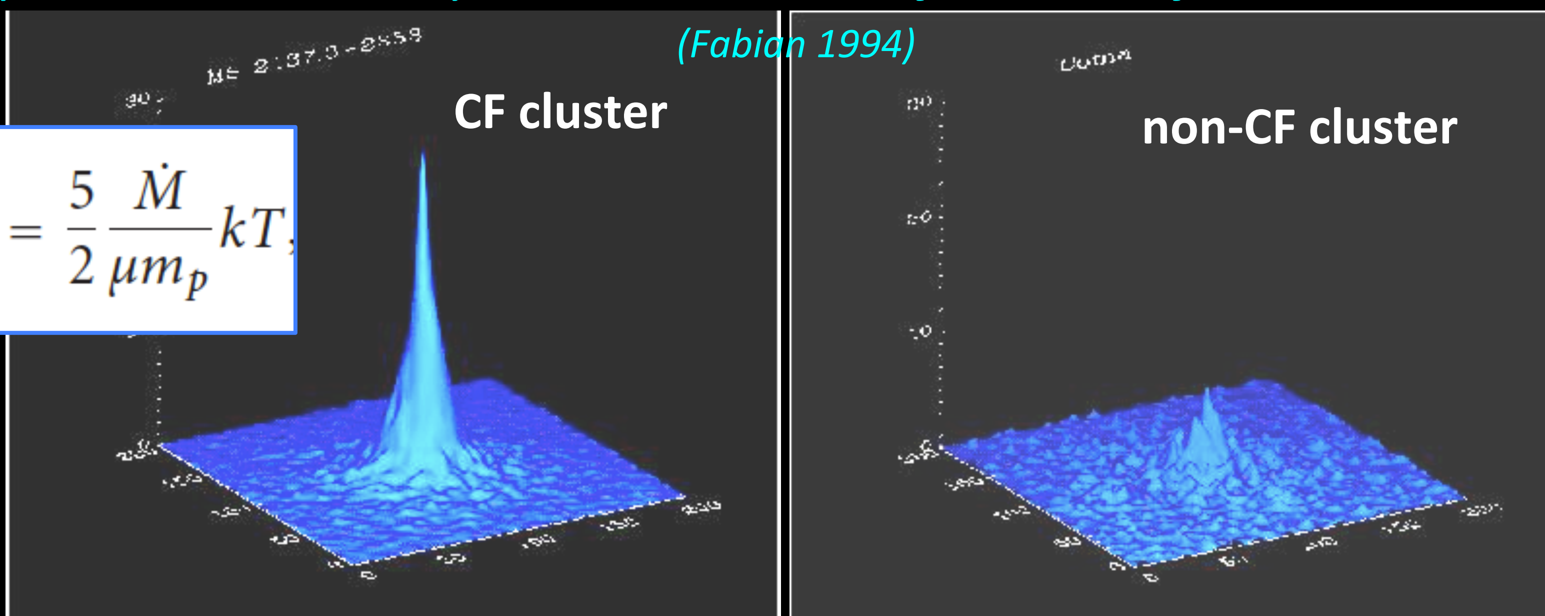
actually, time for which the **system has been relaxed** (e.g., time since last major merger)

within $r_{cool}$ : $t_{cool} \ll t_H$ → (hydrostatic eq.) cooling gas flows inward with mass accretion rate $\dot{M}$ and compressed

Compression ⇒ density increases ⇒ **X-ray emissivity** ($\propto n^2 \Lambda$) **increases !**

(Fabian 1994)

$$L_{\rm cool} = \frac{5}{2}\frac{\dot{M}}{\mu m_p}kT,$$



# Cooling Flow Problem

BUT.. *observed* lack of cold gas !

XMM/RGS failed to show strong emission lines expected from Fe XVII as the gas cooled below 0.7 keV

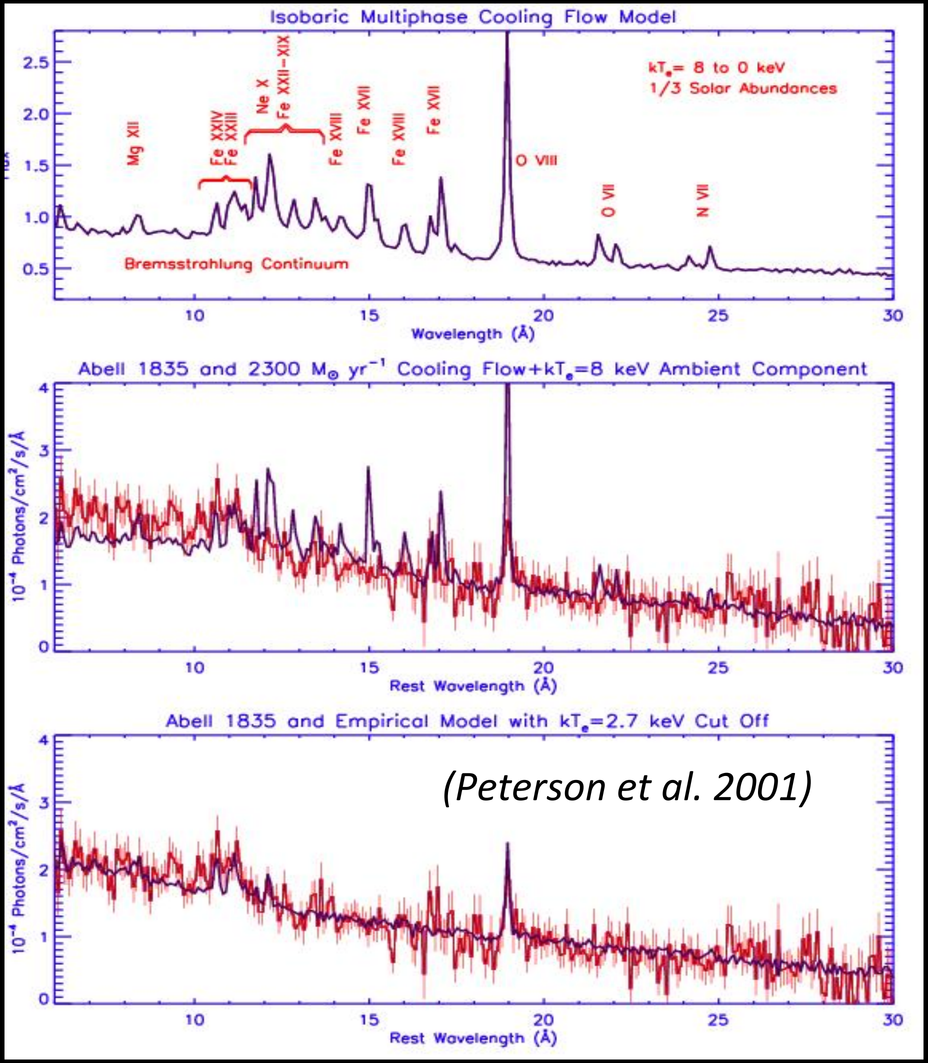
T gas drops only to $T_{min} \sim 0.3\ T_{vir}$
( *Chandra* spectra consistent)

$\dot{M}_{(<Tmin)} \sim (0.1\text{-}0.2)\ \dot{M}_X$

## ⇒ CF problem:

why, and how, is the cooling of gas below $T_{min}$ suppressed?

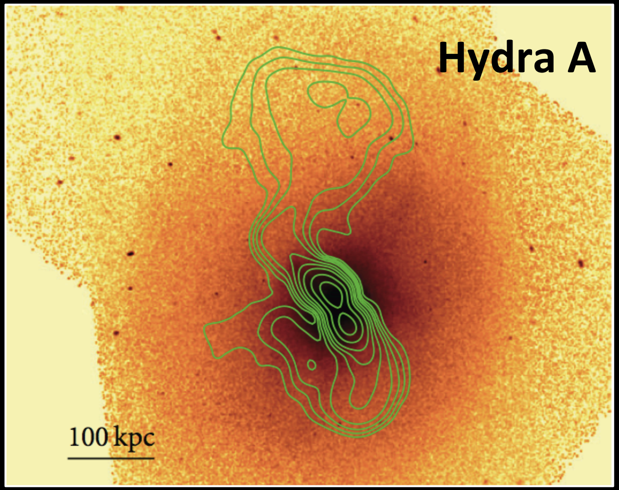
[ new nomenclature → **COOL CORE (CC)** ]



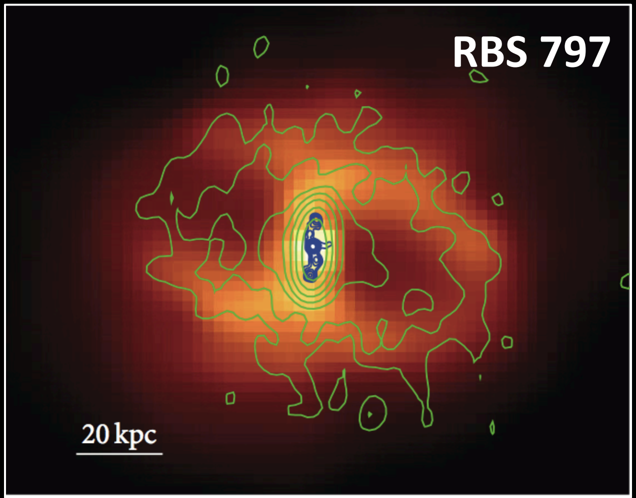

*(Peterson et al. 2001)*

# Radio-AGN / ICM interaction in cool cores

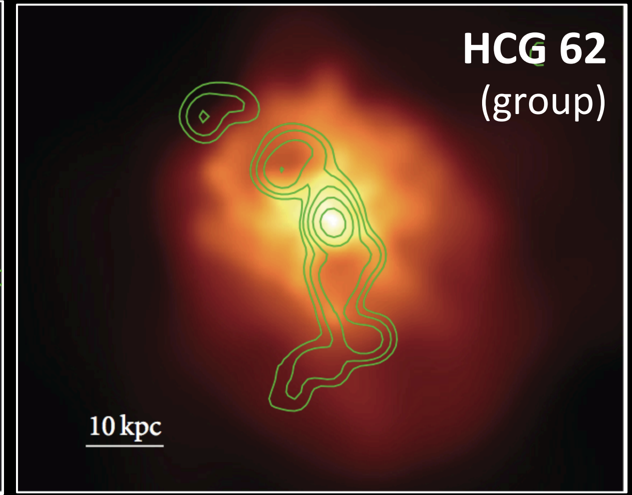
- in most (~70%) CC clusters the brightest cluster galaxy (BCG) is radio loud
- in most (≳70%) CC clusters the central intra-cluster medium (ICM) shows "holes" often coincident with BCG radio lobes




*Wise et al. 2007*
*Gitti et al. 2011*




*Gitti et al. 2006, 2013*
*Doria et al. 2012*




*Gitti et al. 2010*
*Giacintucci et al. 2011*

→ radio "**bubbles**" displace the ICM, creating X-ray "**cavities**"

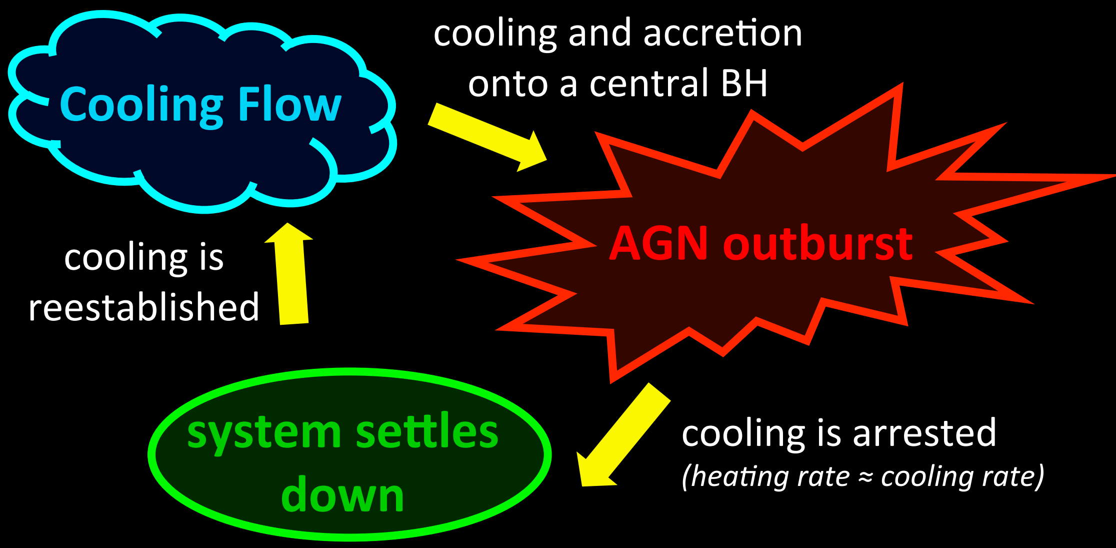
(e.g., reviews by *McNamara & Nulsen 2007,2012*; *Gitti, et al. 2012; Fabian 2012*)

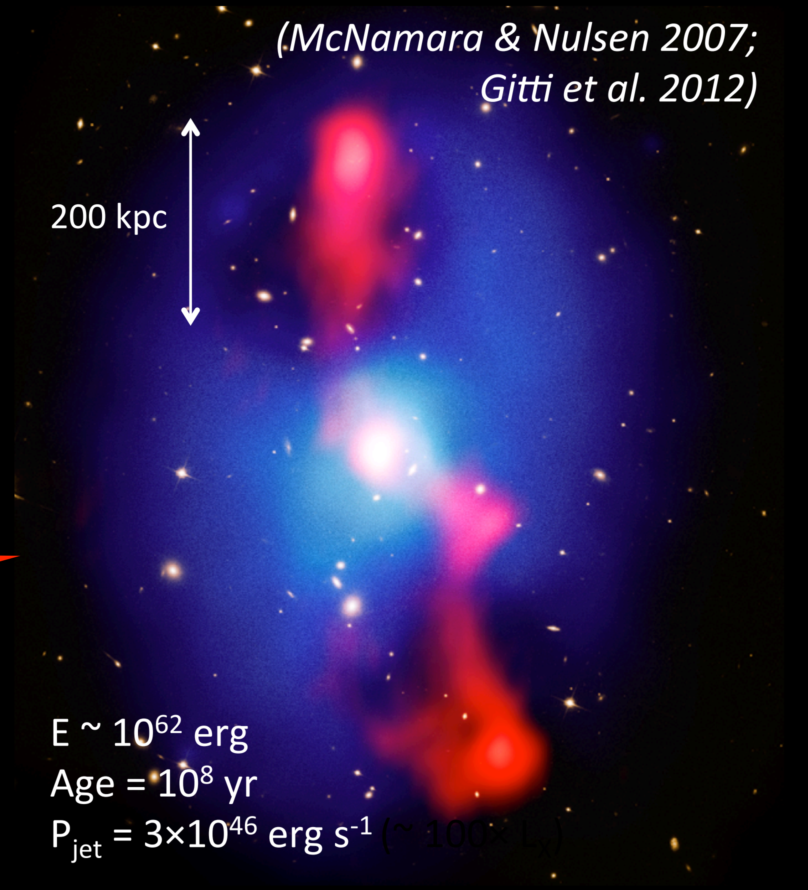
# Cooling flow regulation in galaxy clusters

Main candidate to solve the *CF Problem:*

**Feedback by AGN**

*"The AGN is fueled by a CF that is itself regulated by feedback from the AGN"*

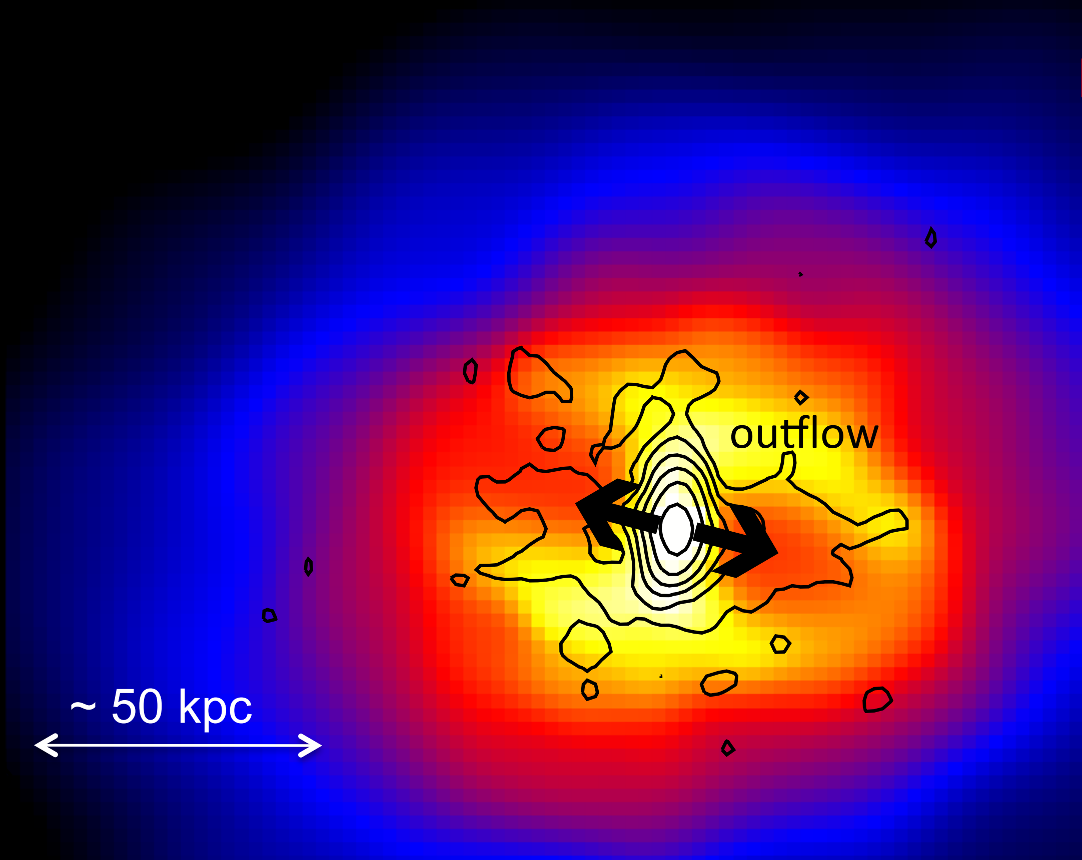



*(McNamara & Nulsen 2007; Gitti et al. 2012)*

**Self-regulated feedback loop** : (recurrent) outbursts from the radio-loud AGN hosted by the BCG at the center of (almost) every CC cluster

# Non-thermal emission from 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 emerging from the BCG core, that

- inflate large radio bubbles while carving X-ray cavities and driving weak shocks
- heat the ICM
- induce a circulation of gas and metals on scales of ≈100s kpc

*..but many details are still unclear..*

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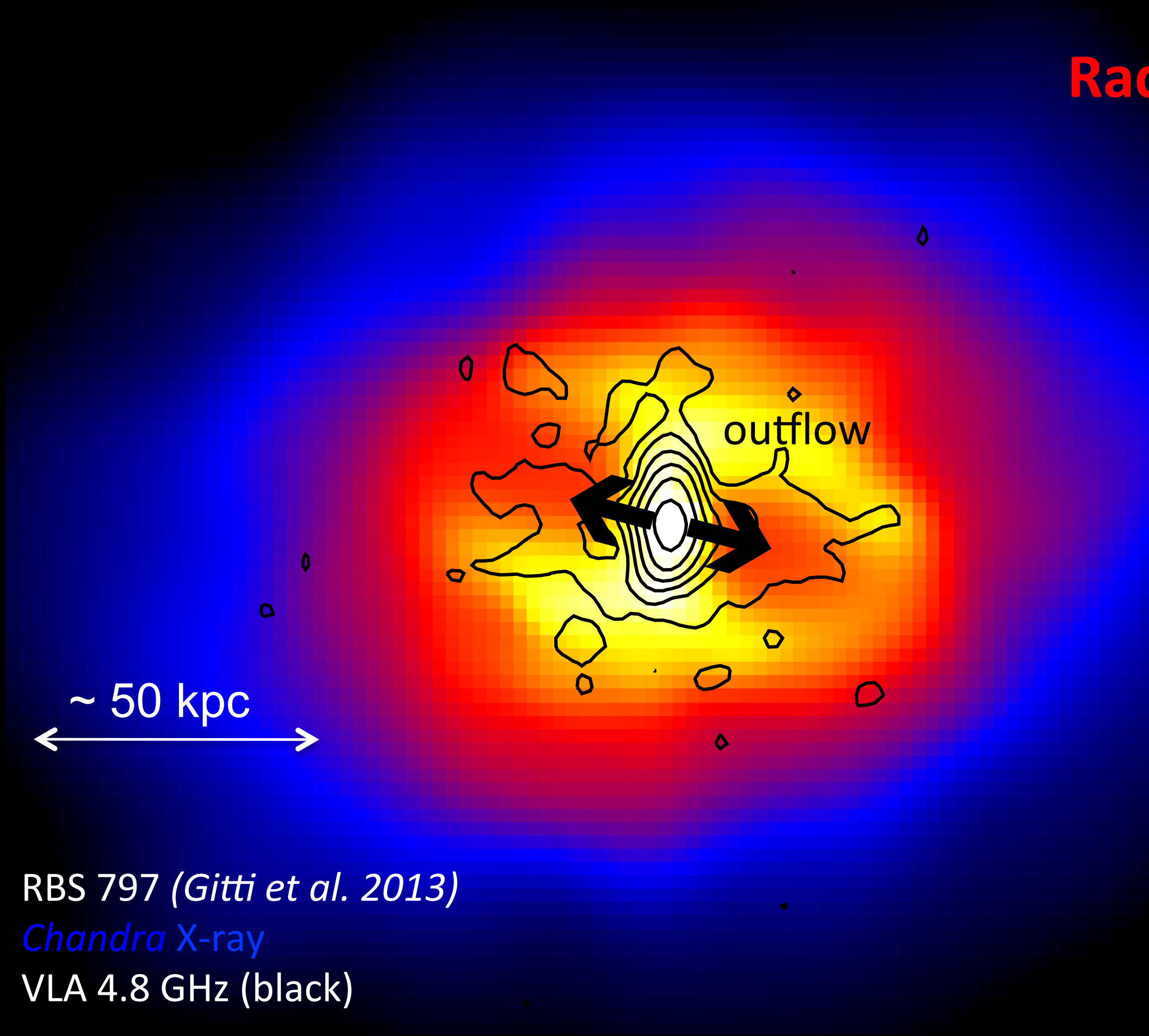


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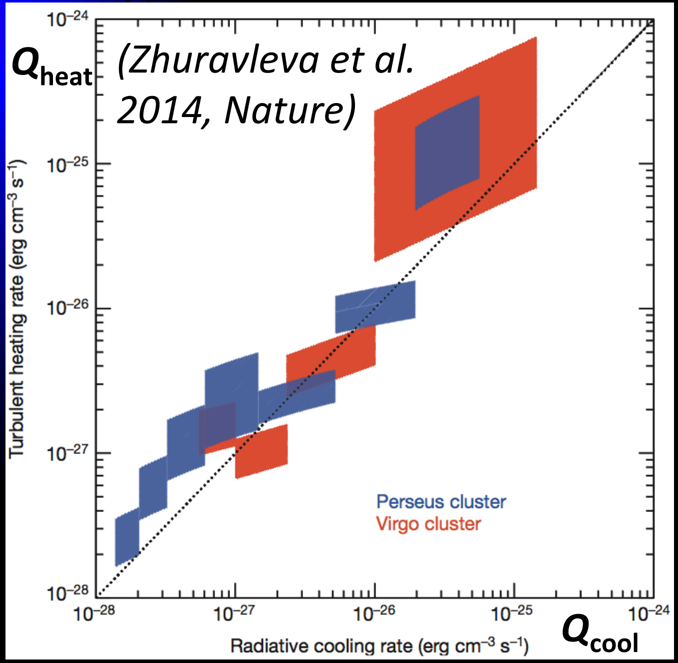
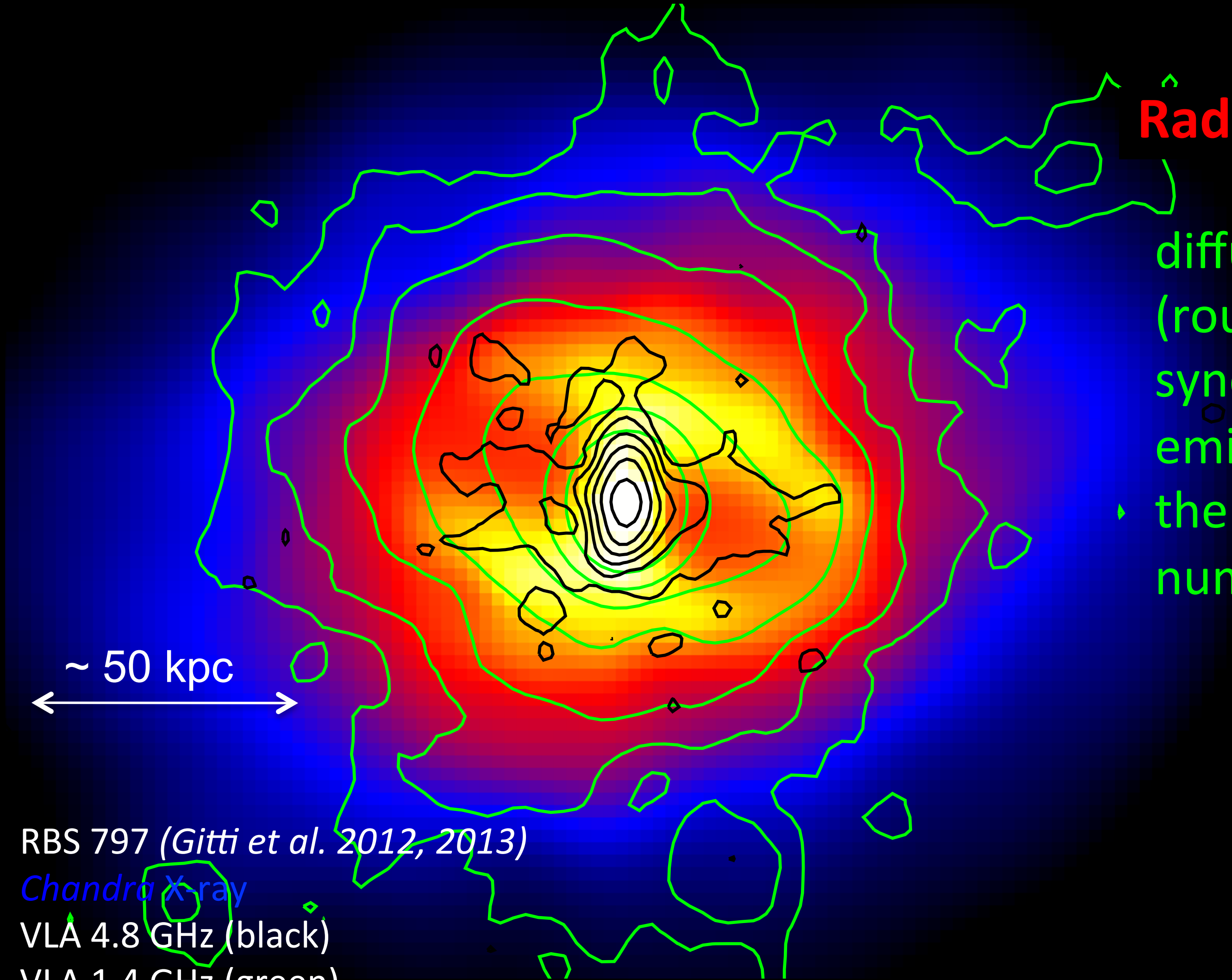
## Radio-mode AGN feedback:

mechanically-powered AGN are also likely to drive **turbulence** in the ICM which may contribute to heat it



# Non-thermal emission from CC clusters: radio-loud AGN + diffuse mini-halos

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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

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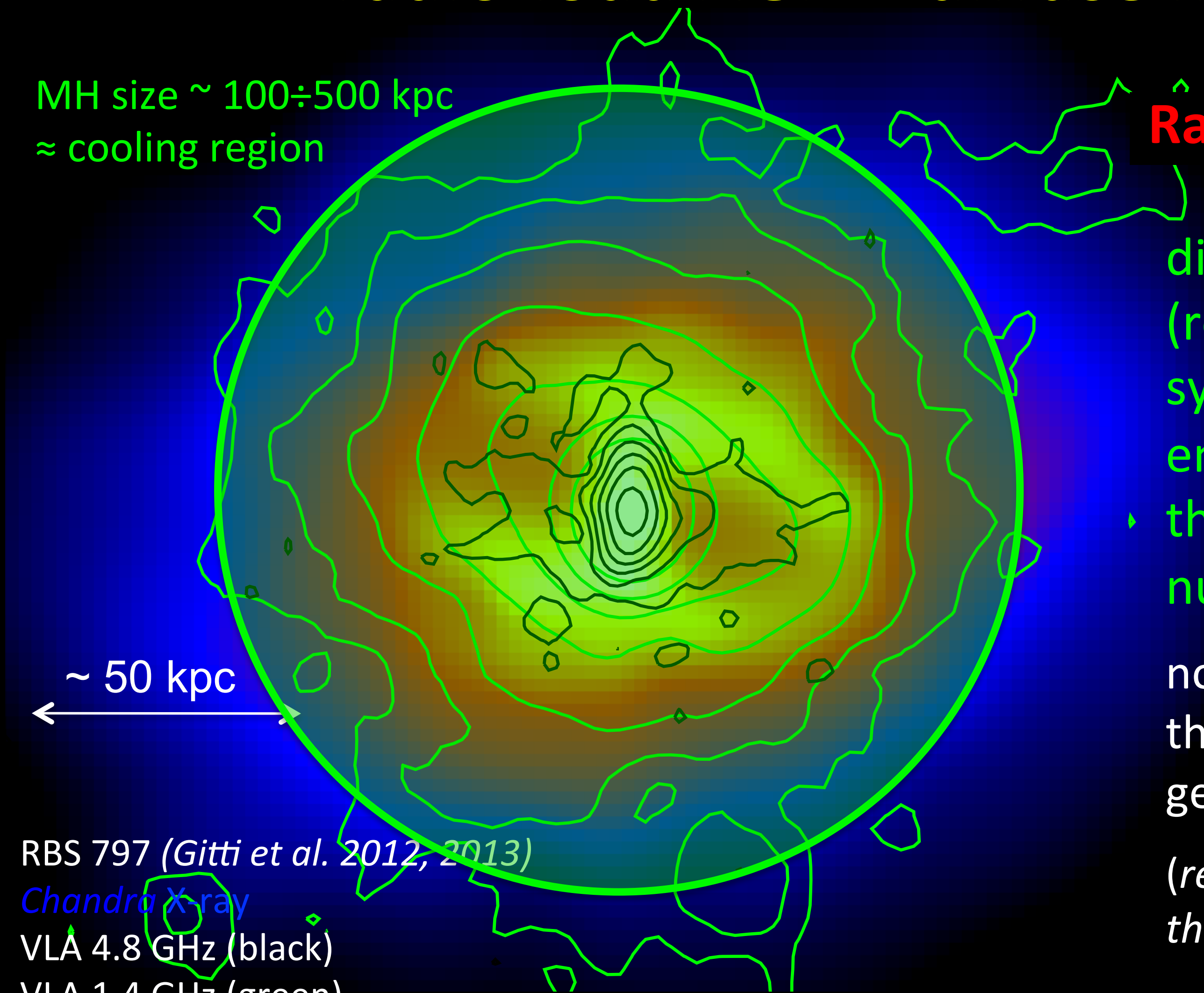


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## Radio mini-halos (MH):

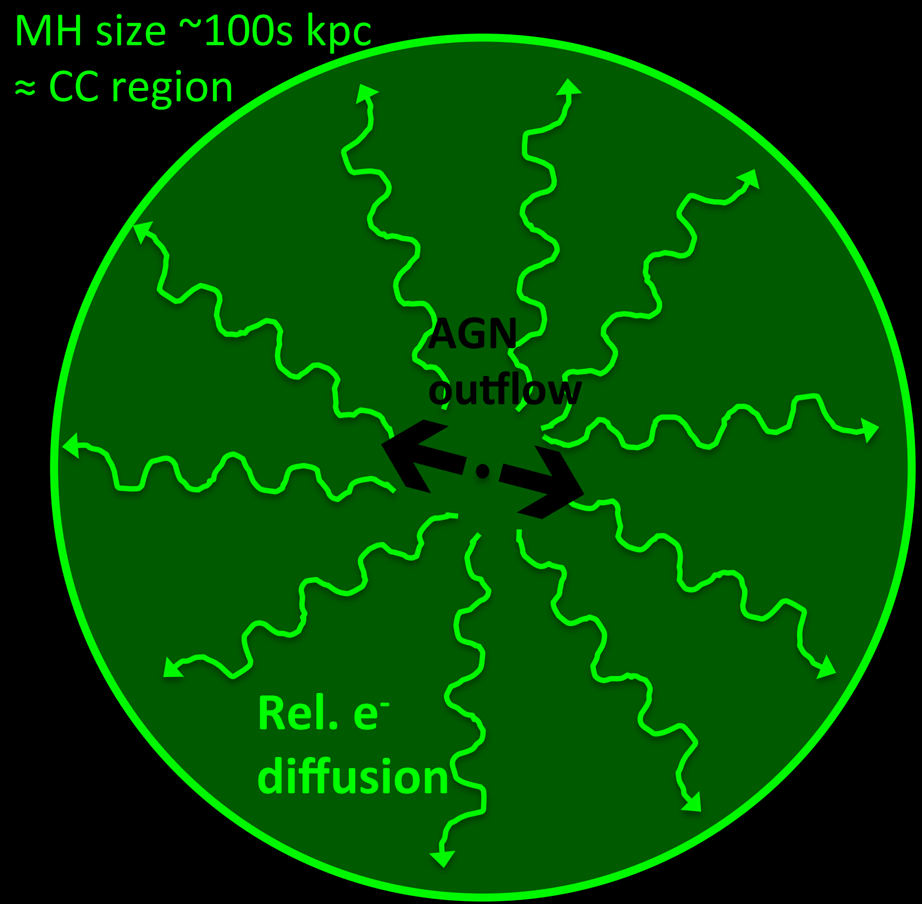
- diffuse, faint, amorphous (roundish) in shape, synchrotron radio emission surrounding the radio-loud BCG in a number of CC clusters

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

*(relativistic electrons and thermal plasma are <u>mixed</u>)*

# Origin of radio mini-halos

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




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

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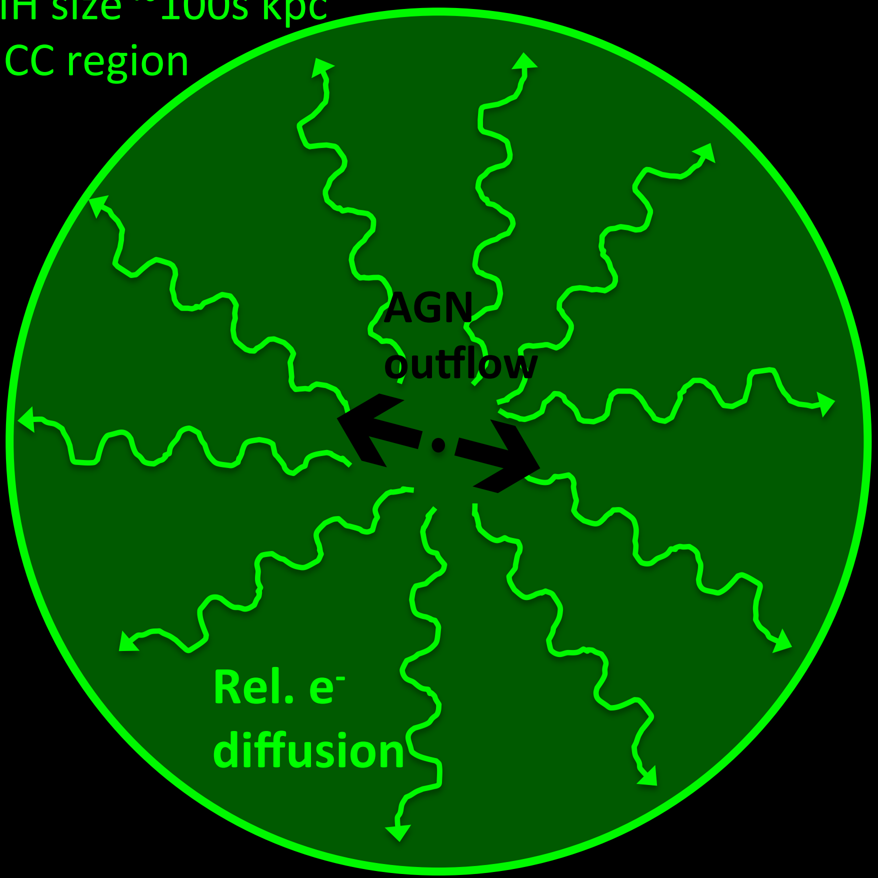
MH size ~100s kpc
≈ CC region




- ***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)*

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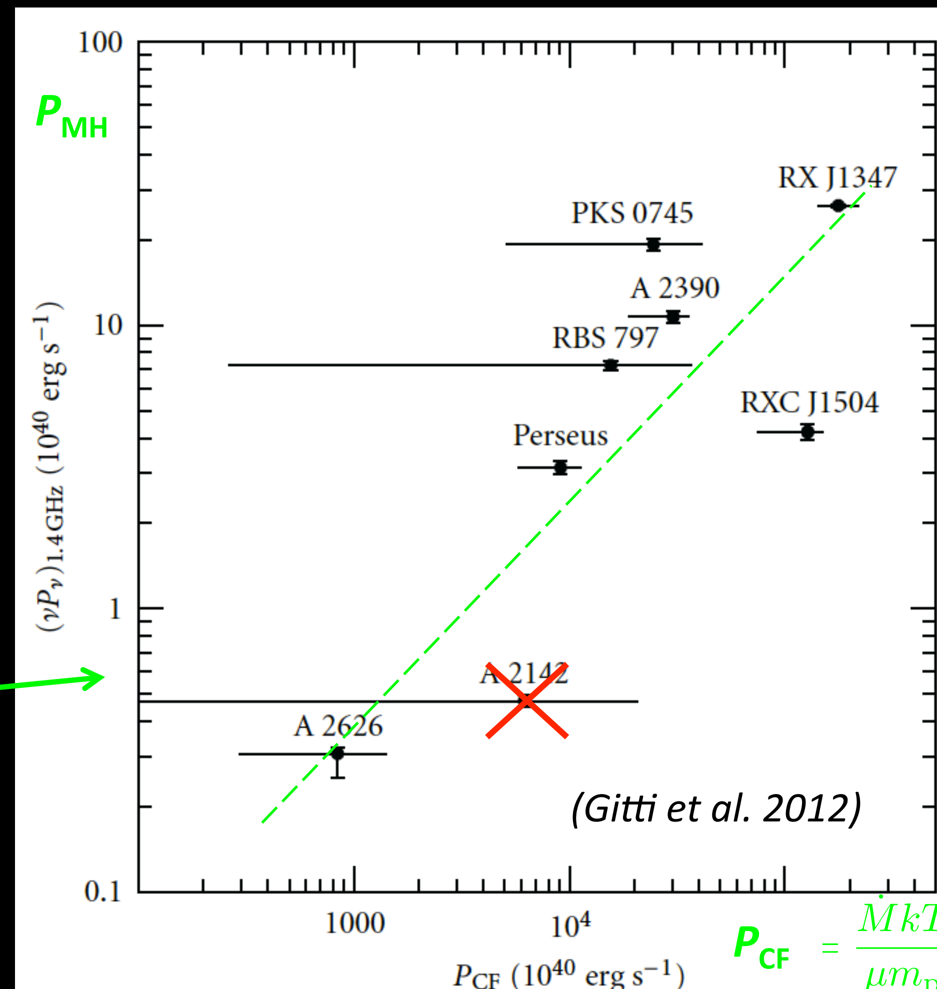
**Trend $P_{MH} - P_{CF}$** *(Gitti et al. 04, 12)*:
connection *thermal* CCs and *non-thermal* MHs ?



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*Gitti, Brunetti & Setti (2002)* ...
→ **CF pr**...

re-acc...
mecha...
MHD tu...
(frozen-...
compres...

**C A V E A T S :**

- **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)*:
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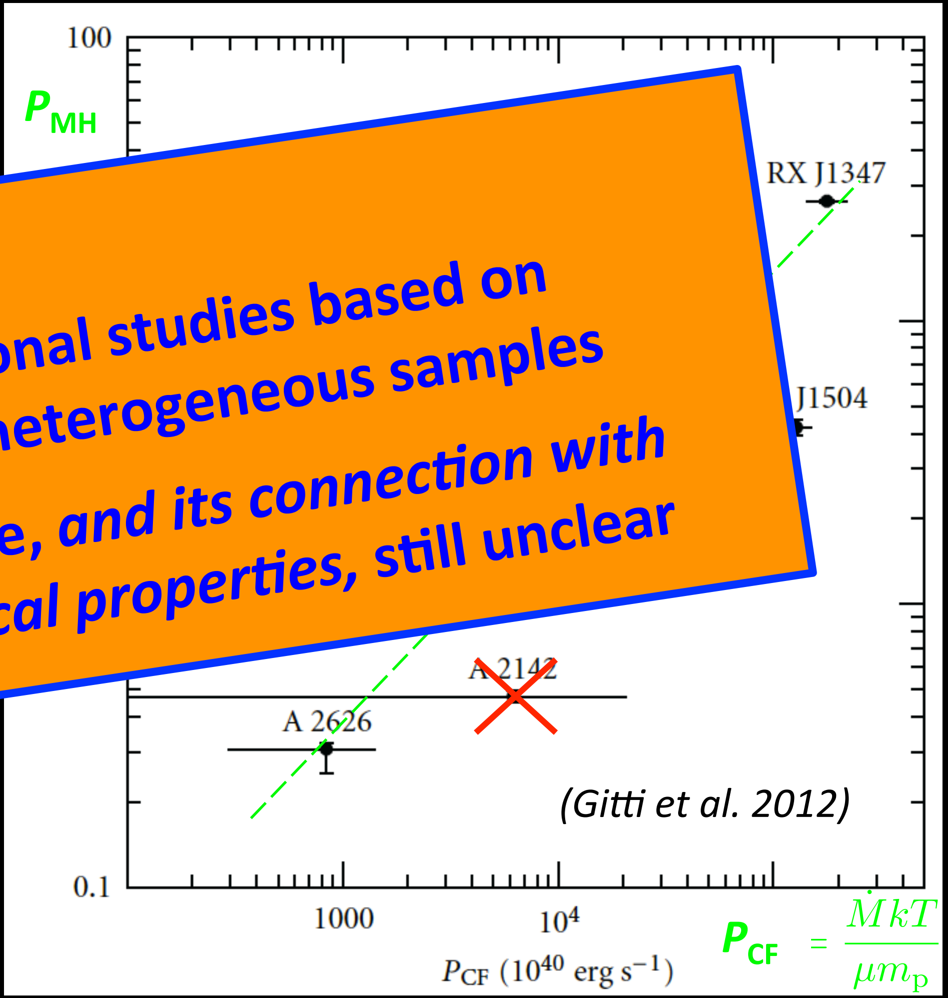



(Gitti et al. 2012)

$$P_{CF} = \frac{\dot{M}kT}{\mu m_p}$$

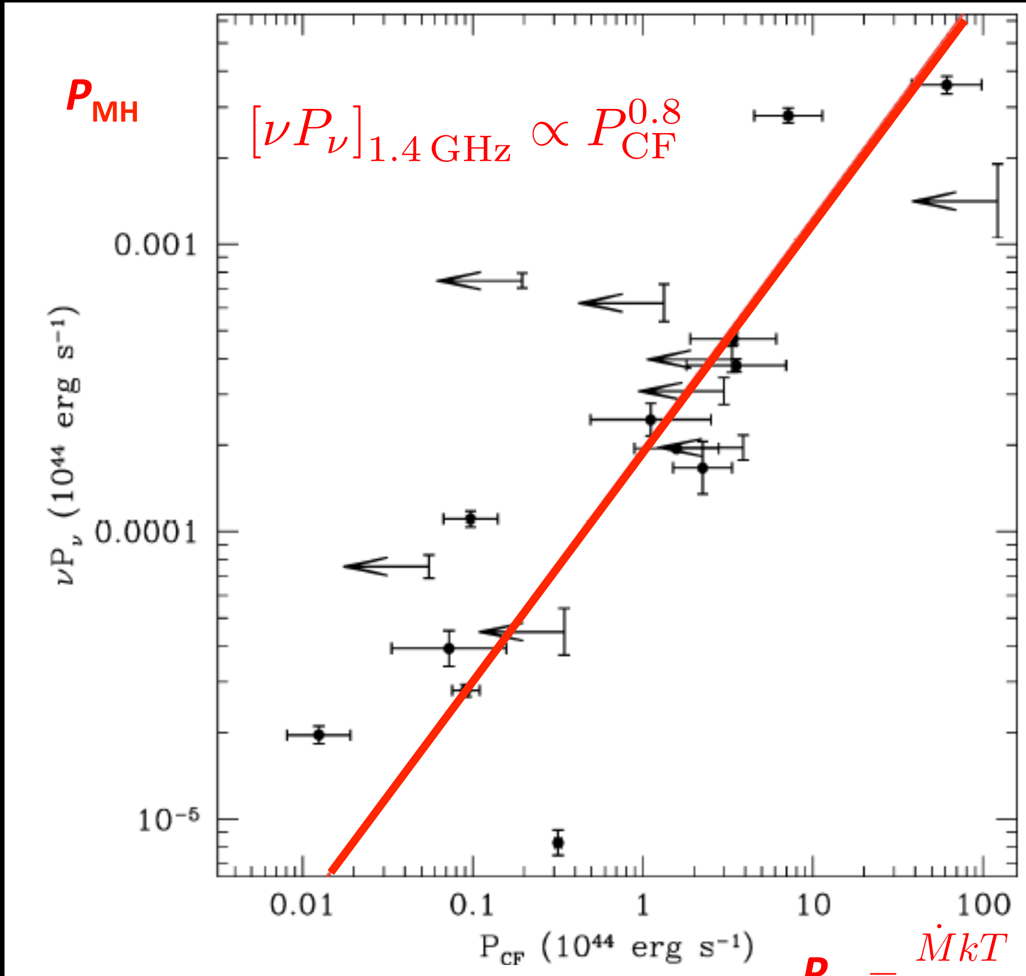
# A new study of the largest MH sample

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

⬇

Homogeneous analysis of X-ray *Chandra* data of the largest existing sample (~ 20 objects) of MH cluster candidates

➔ **<u>Correlation</u> $P_{MH} - P_{CF}$ :** connection between *thermal* CCs and *non-thermal* MHs




$$P_{CF} = \frac{\dot{M} k T}{\mu m_p}$$

***(Bravi, Gitti, Brunetti 2015, MNRAS Letter, in press)* → see poster by L. Bravi !!**

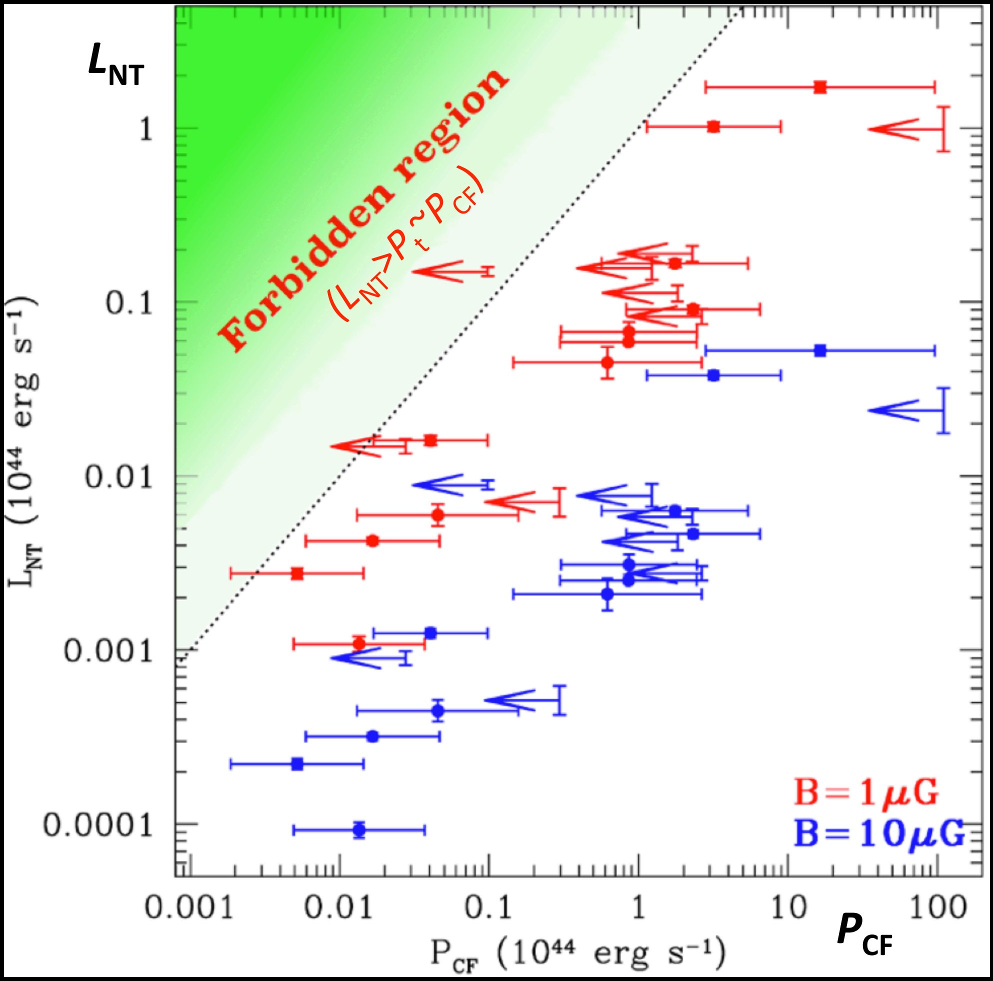
# Proposed scenario: turbulence is responsible for both MH origin and CF quenching

- We argue that particle acceleration and gas heating in CCs are due to the dissipation of the *same* turbulence with power $P_t \gtrsim P_{CF}$

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

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

~ 3.2 μG

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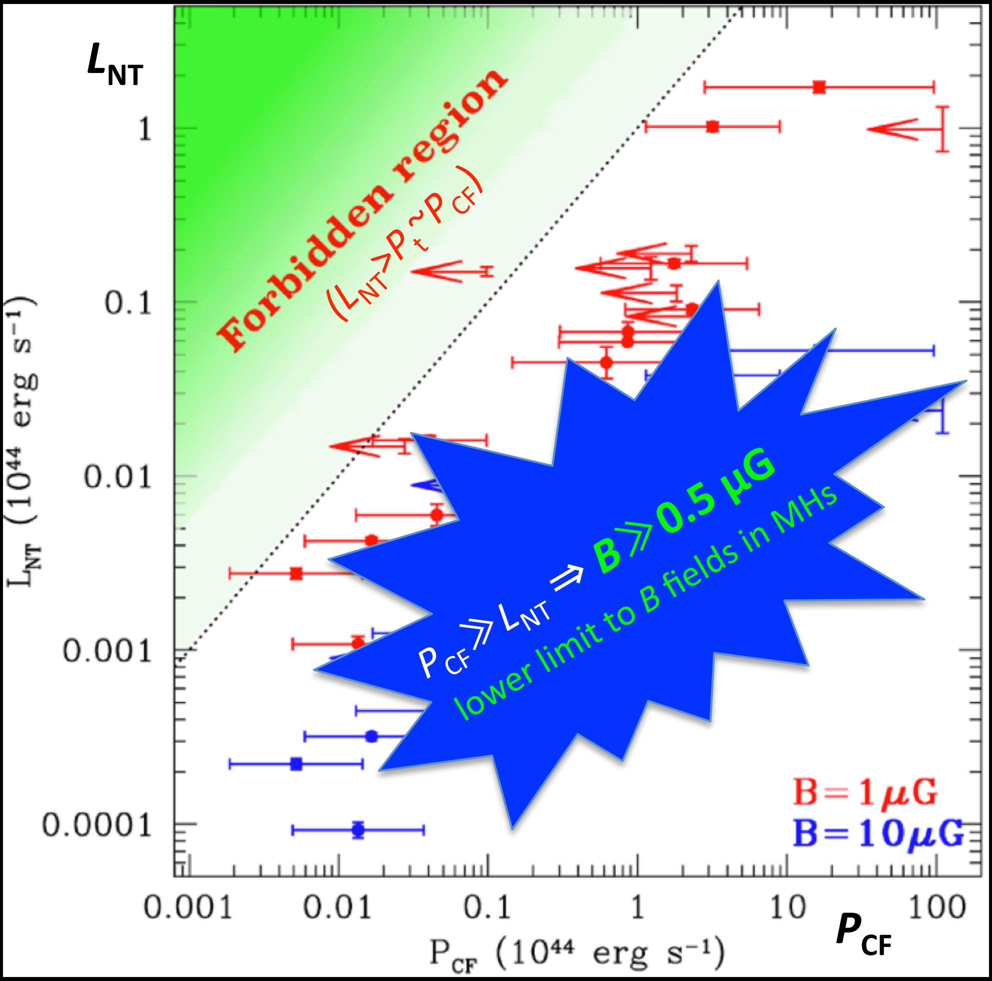


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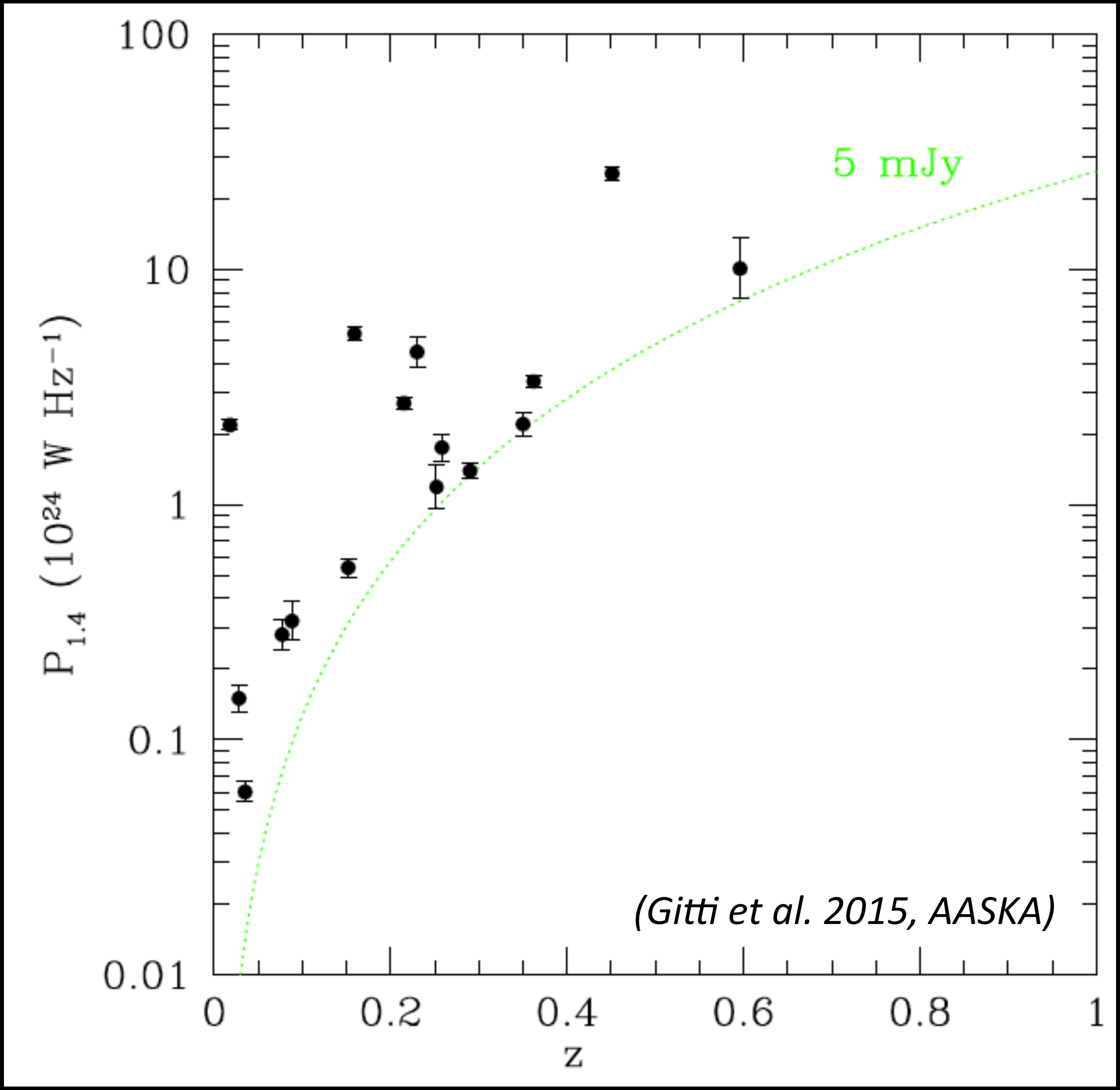
# Statistics of radio mini-halos




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

Observational bias limits our present ability of detecting mini-halos

complicated by the need of separating their low surface brightness emission (~ μJy/″$^2$) from the bright BCG

→ this requires:

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

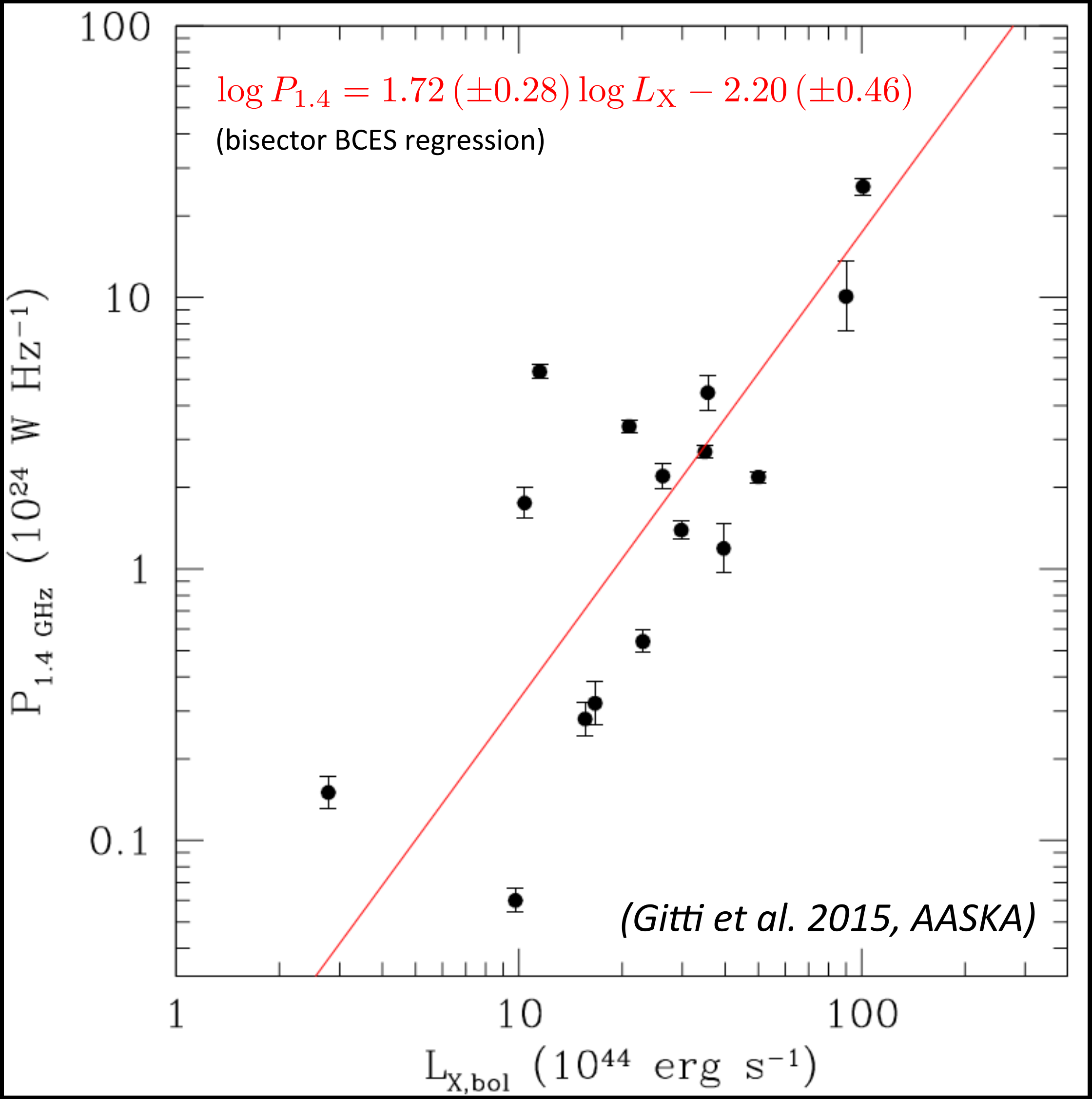
**→ SKA**

# 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

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



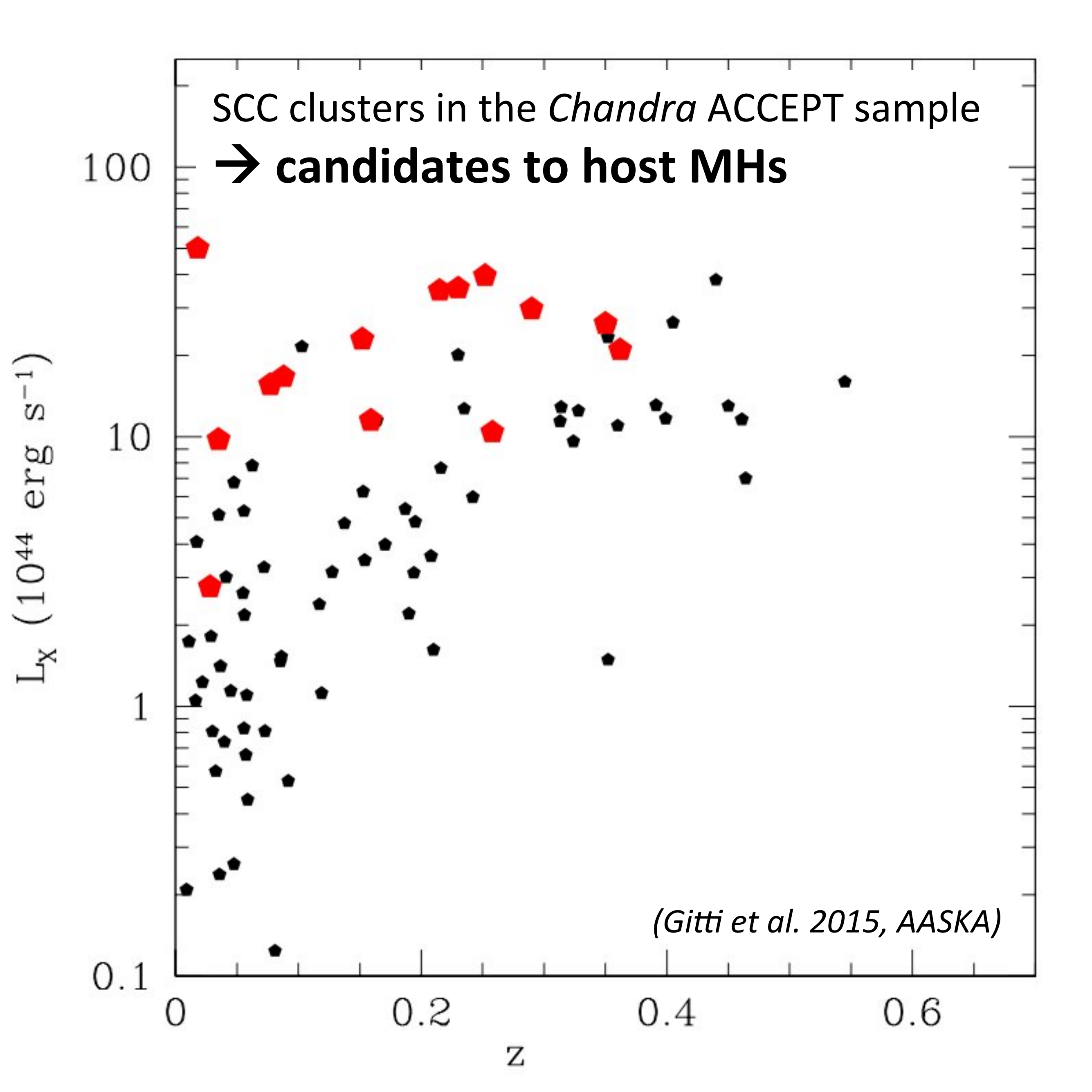

1.4 GHz radio power vs. the CC-excised X-ray bolometric luminosity for the observed MH cluster sample

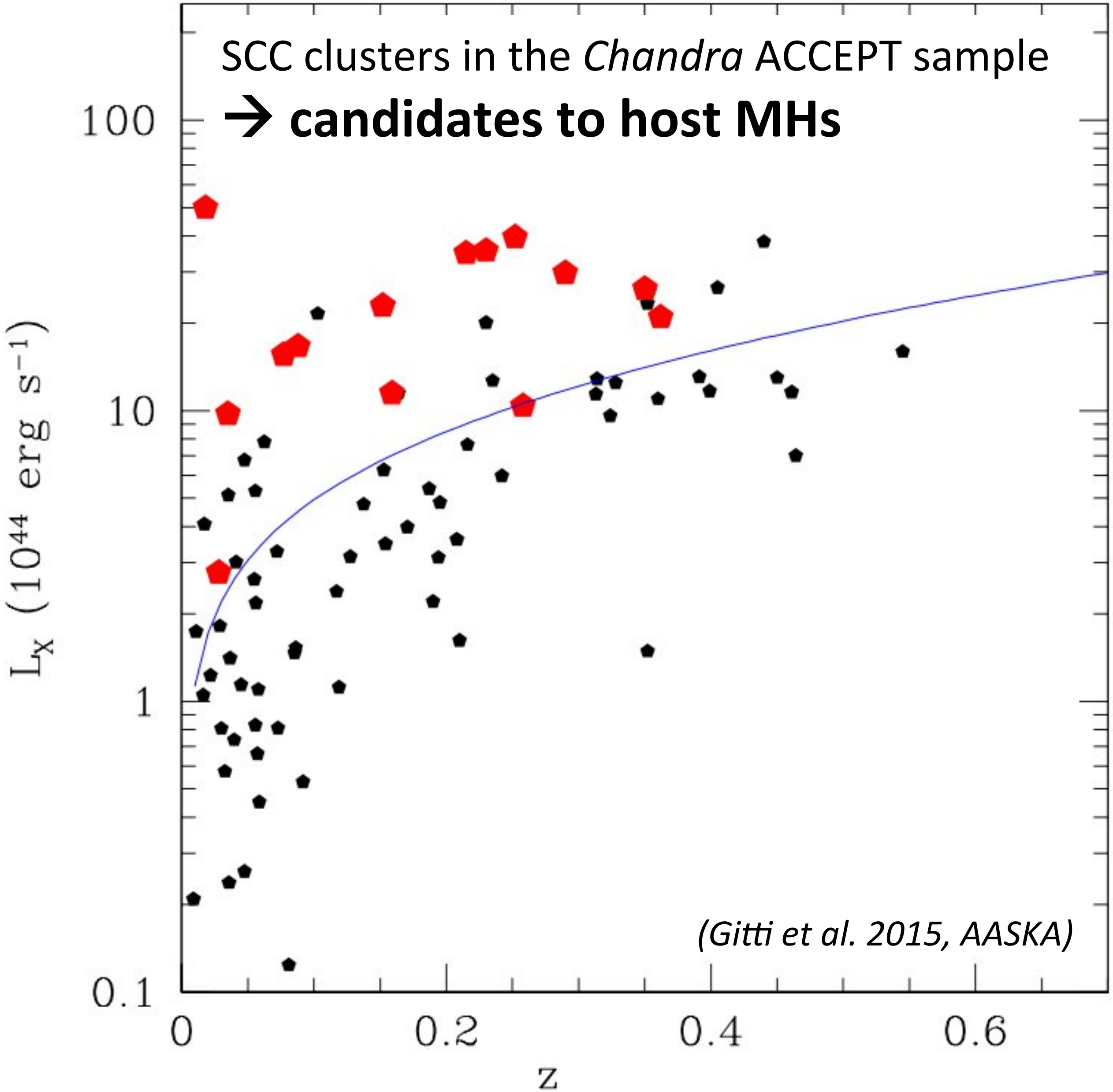
($L_{X,bol}$ from the Chandra ACCEPT sample, *Cavagnolo et al. 2009*)

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

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

## Observed MHs





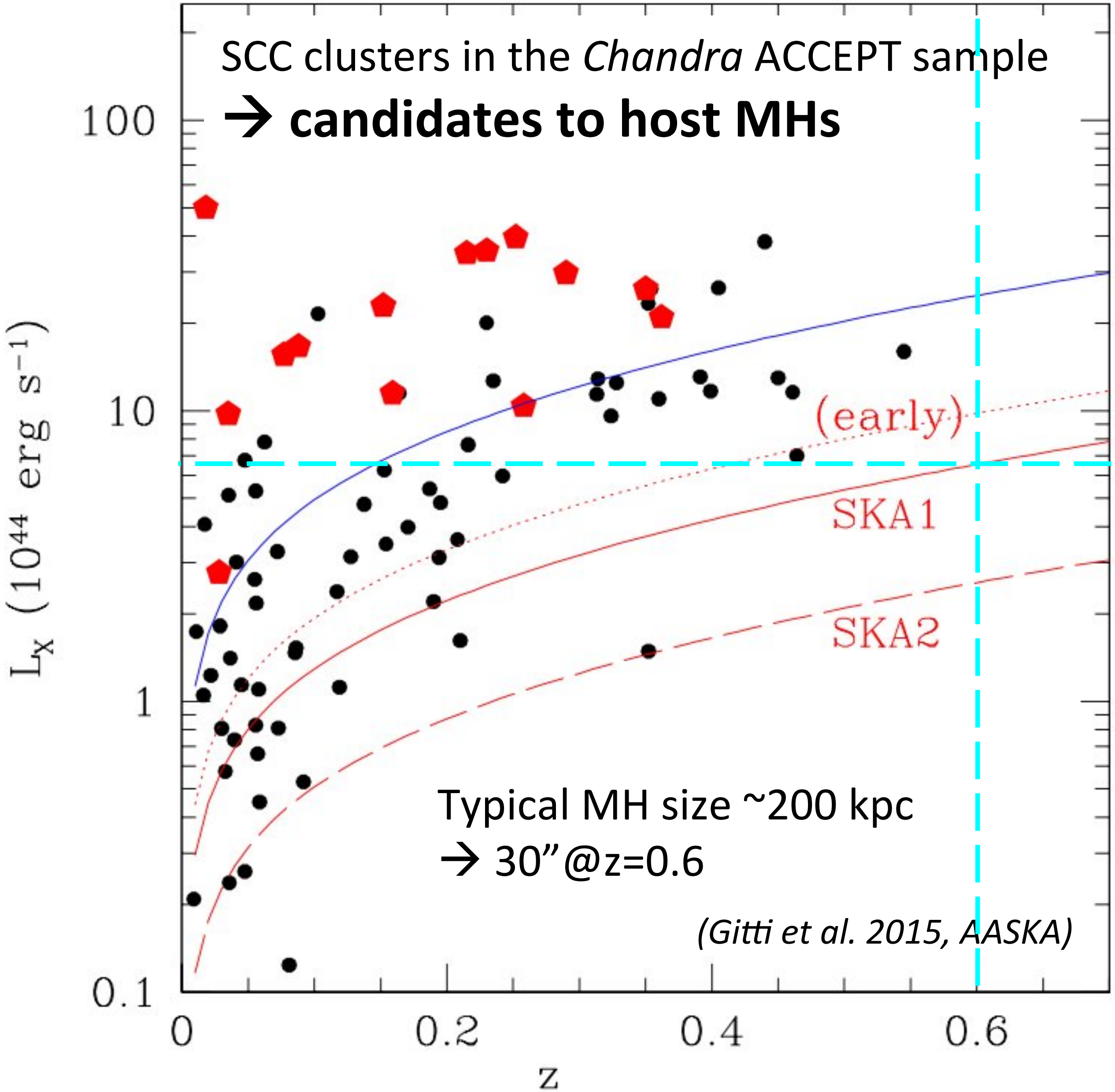

## Observed MHs

*Indicative* current MH detection limit on the population of SCC clusters

*(estimated assuming non- detections by current follow-up observations)*

{ rms = 25 μJy/bm
$\vartheta_b$ = 10"

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




# Observed MHs

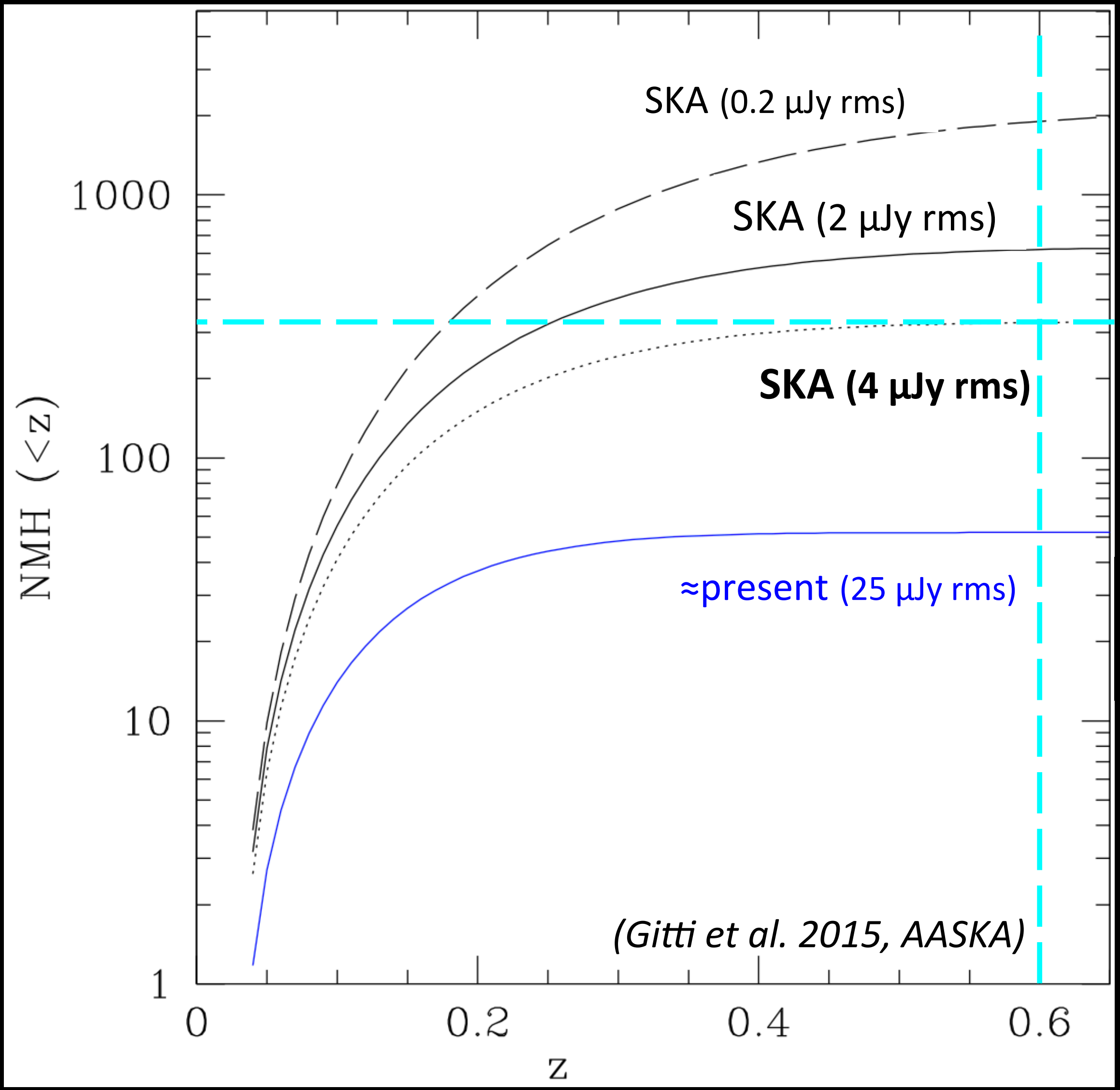
SKA All Sky Surveys at Band 2 :

- **SKA `early'** (4 μJy rms, 2" res. *tapered up to 8"*)
→ will follow-up > 70% of the ACCEPT sample

- SKA1 (2 μJy rms)
→ will detect all MHs above ~ $10^{23}$ W Hz$^{-1}$ up to redshift 0.6

- SKA2 (0.2 μJy rms)
→ will complete the follow-up of the full ACCEPT sample

# How many mini-halos await discovery ?




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:

$$\frac{dN_{\rm MH}}{dPdV} = {\rm f}_{\rm SCC} \left(\frac{dN_{\rm cl}}{dL_{\rm X}dV}\right) \frac{dL_{\rm X}}{dP_{1.4}}$$

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)*

**SKA All Sky Survey at Band 2** (4 μJy rms, 2'' res.) will be able to **detect ≳ 300 new MHs at *z* ≤ 0.6**

# Radio 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 → CCs, also GHs → MHs?

# Radio mini-halos : open questions

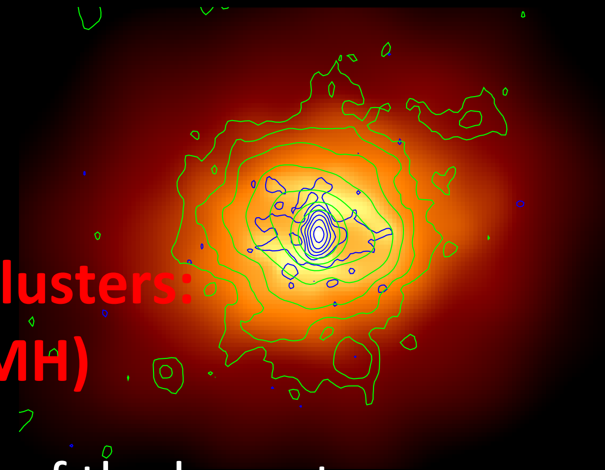
- Do all cool-core clusters host a radio MH?
  How does the MH/CC fraction evolve with redshift?
  *(power-limited sample with wider redshift distribution, synergy with eROSITA and ATHENA X-ray satellites)*

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

- 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 and synergy with ATHENA)*

→ Surveys with **SKA** will address these key points

# Conclusions

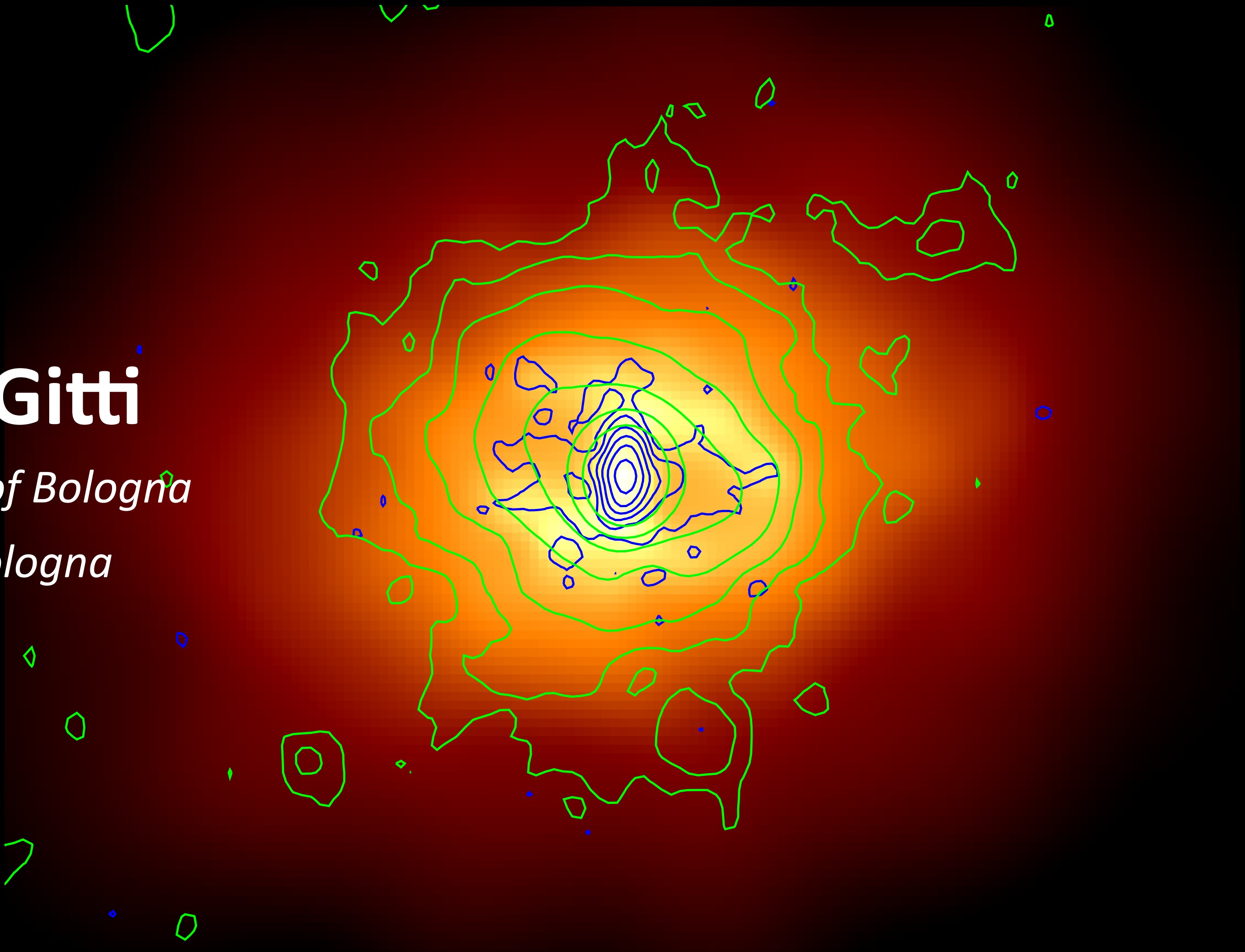


**Non-thermal emission from cool-core (CC) clusters: radio-loud AGN + diffuse radio mini-halos (MH)**

- Homogeneous analysis of X-ray *Chandra* data of the largest existing sample (~ 20 objects) of MH clusters *[Bravi+15, MNRAS]* :
  - ✓ Correlation MH power vs. CF power: $[\nu P_\nu]_{1.4\,\mathrm{GHz}} \propto P_{\mathrm{CF}}^{0.8}$
  - ✓ Turbulent re-acceleration scenario: rel. electron acceleration (→ **MHs**) and gas heating (→ **CF quenching**) are due to the dissipation of the *same turbulence*, provided $B \gg 0.5\ \mu\mathrm{G}$

- Large MH samples necessary to unveil MH origin and connection with CC thermodynamics *(synergy SKA-ATHENA)* *[Gitti+15, AASKA]* :
  - ✓ SKA All Sky Survey at Band 2 (4 μJy rms, 2'' res.) will be able to detect $\gtrsim$ 300 new MHs at $z \leq 0.6$

# Thank you



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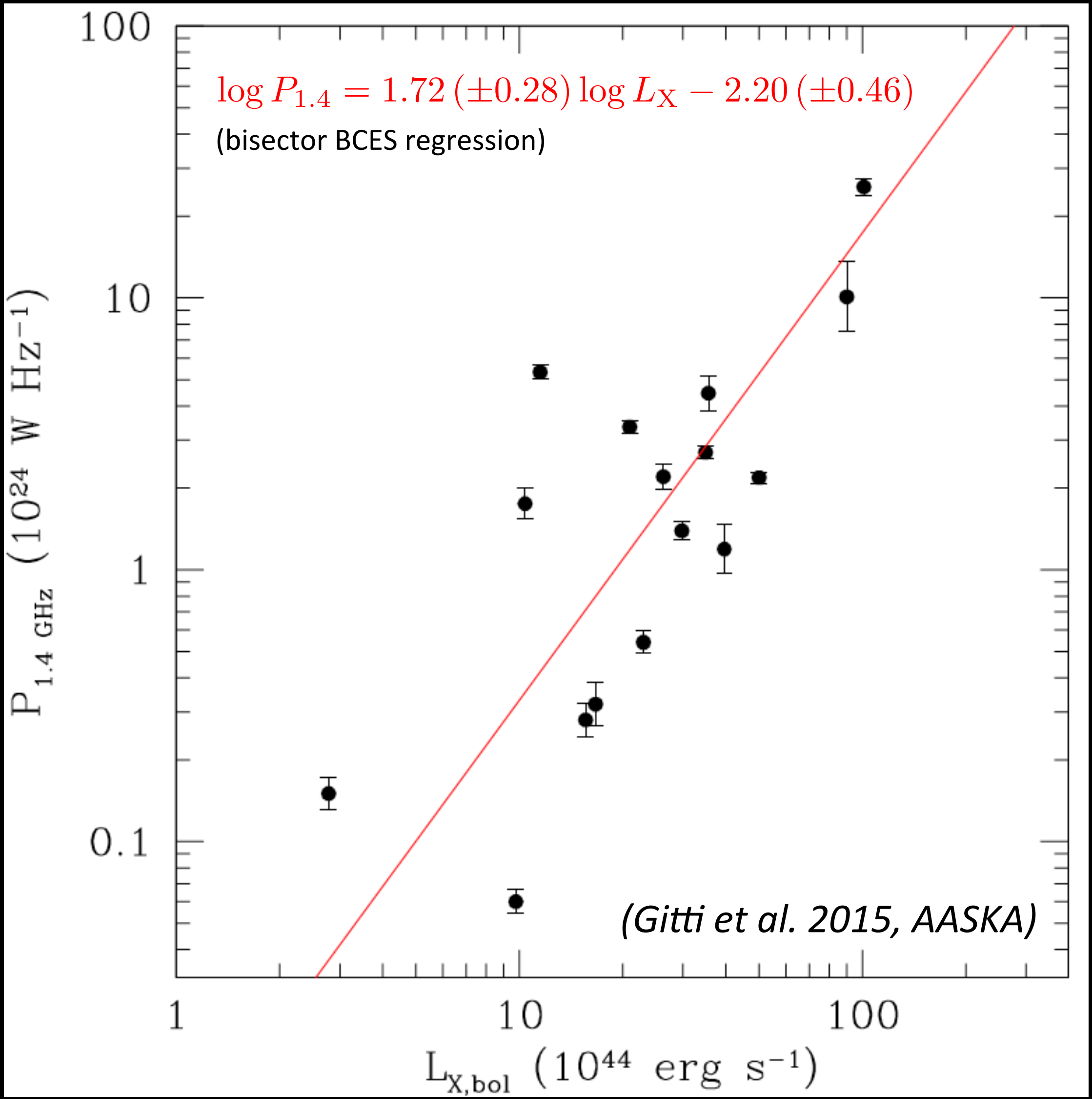


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($L_{X,bol}$ from the Chandra ACCEPT sample, *Cavagnolo et al. 2009*)

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*Is this valid for the whole population of SCC clusters?*

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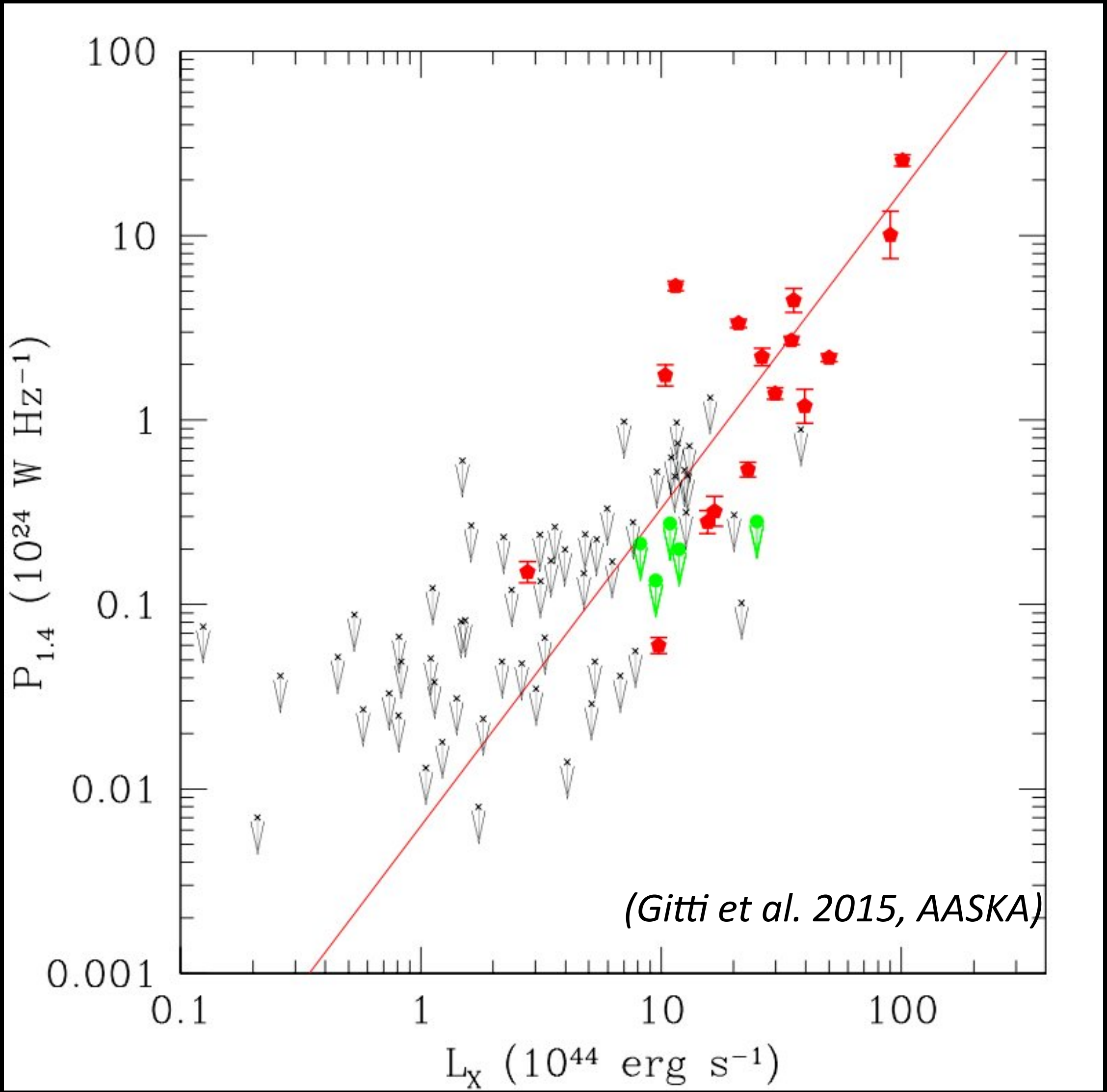


- observed MHs
- GMRT upper limits *(Kale et al. 13)*
  - rms = 0.05 ÷ 0.1 mJy
  - $\vartheta_b$ = 18” ÷ 25”
- *estimated* upper limits for the ACCEPT SCC clusters *assuming they are undetected by current follow-up obs.*
  - rms = 25 μJy
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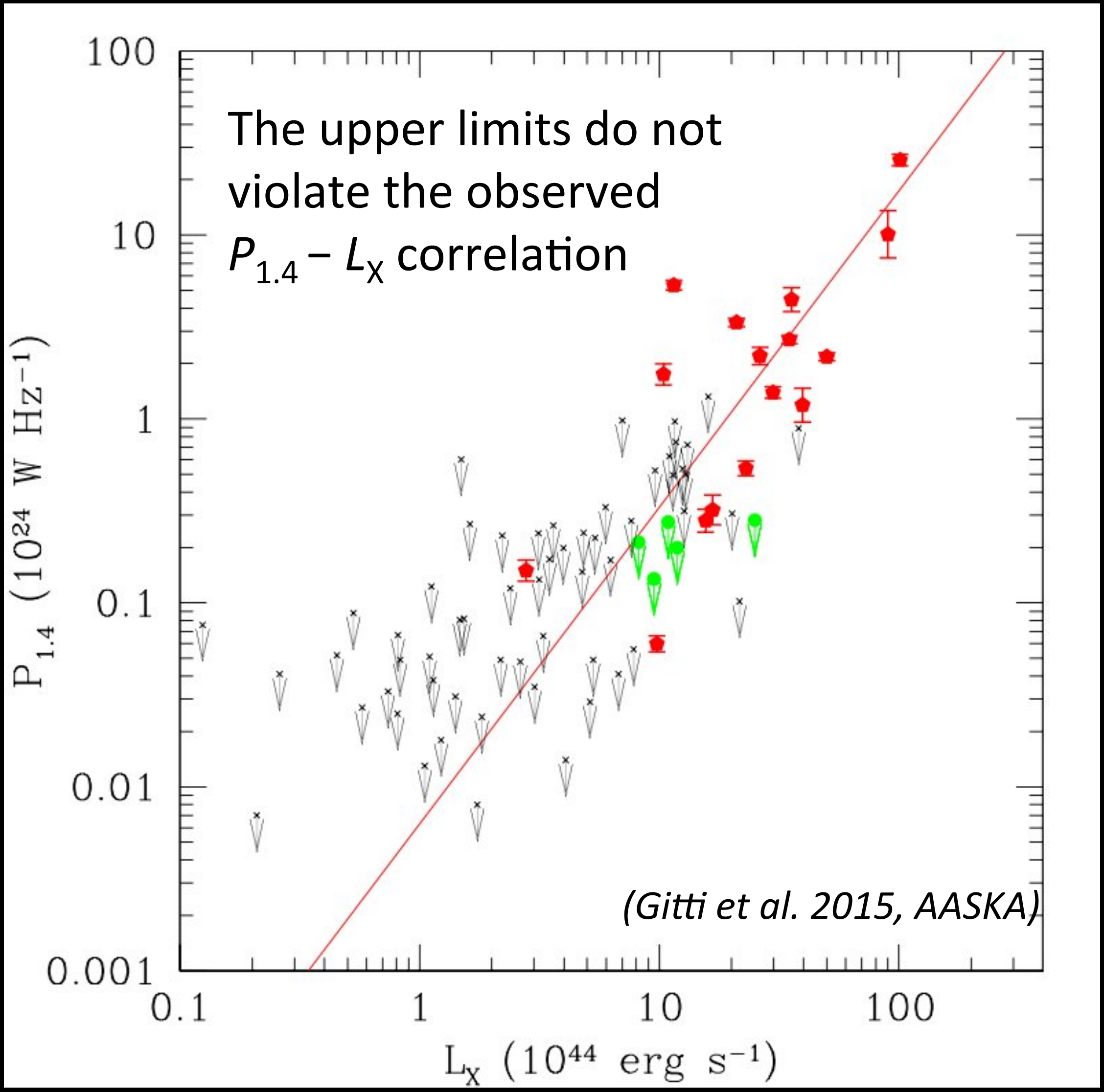


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→ Our basic assumption: **all SCC clusters host a radio MH that follows the $P_{1.4} - L_X$ correlation**

# Conclusions

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

- SKA1-MID surveys with rms = 2 μJy at confusion limit will be able to detect all sources above $10^{23}$ 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

***Work in progress…***

**Comparison with eROSITA and extension to SKA-LOW**