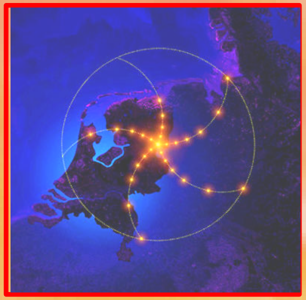
# *Statistics of radio halos and future low frequency observations*



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*"Astrophysics in the LOFAR era''* **23 - 27 April 2007, Emmen (NL)**

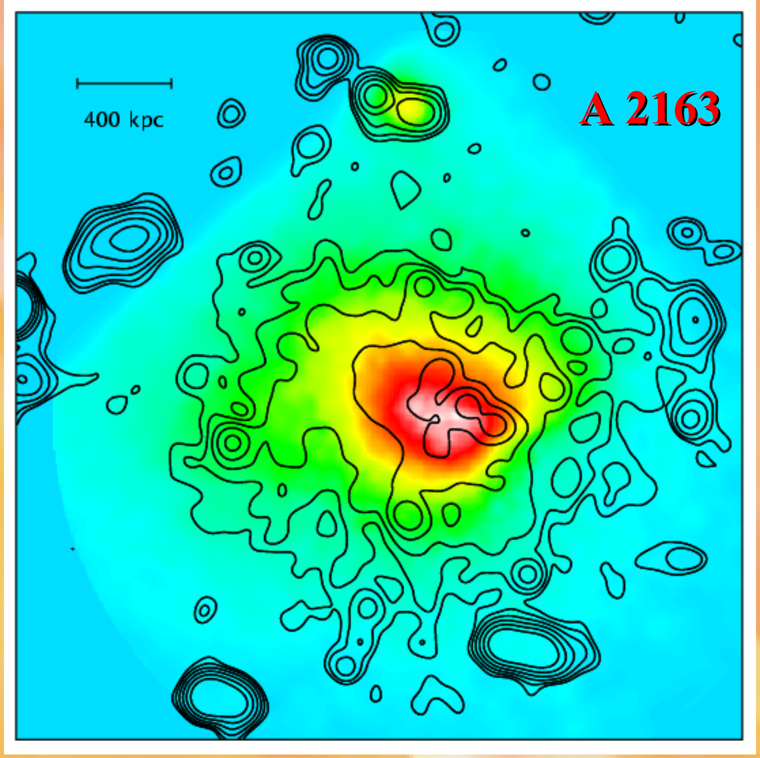
# *Giant Radio Halos (RH) in galaxy clusters*

**Diffuse synchrotron radio cluster sources:**

•Low surface brightness (μJy arcsec$^{-2}$ at 1.4 GHz)

•Not associated with any individual galaxy

•Permeate the cluster volume, similarly to the hot X-ray gas ( **~Mpc size**)




*Feretti et al. 2001*

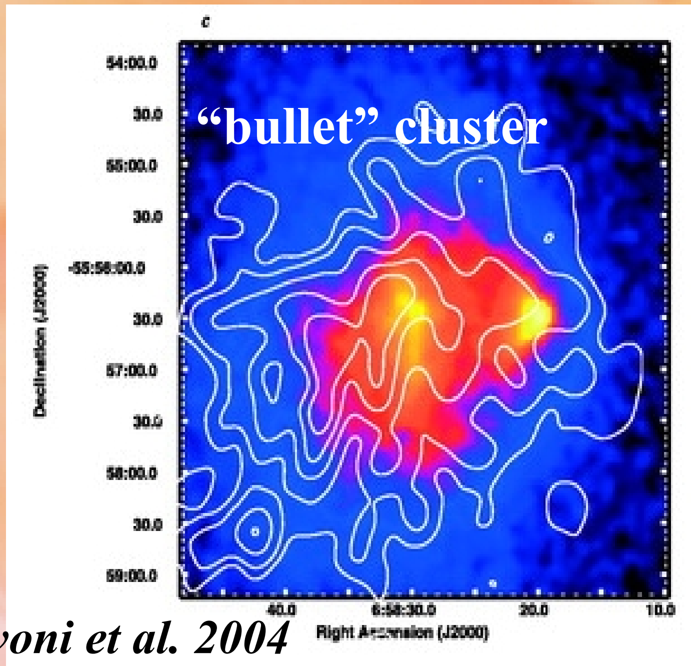
**Properties of host clusters:**

X-ray luminosities: **~3 ·10$^{44}$- 3 ·10$^{45}$ erg/s**

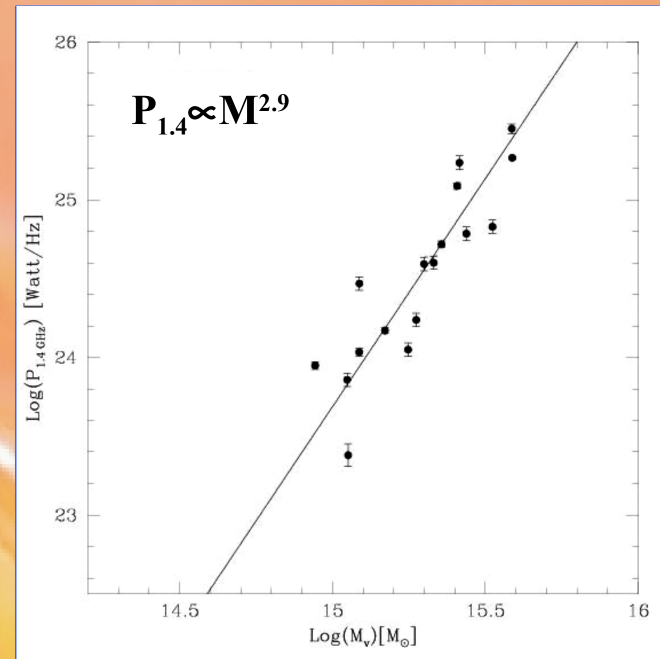
X-ray temperatures: **~ 6-13 keV**

Virial cluster mass: **~ 10$^{15}$ - 4 ·10$^{15}$ $M_{\odot}$**

# *RHs and cluster-cluster mergers*




***Govoni et al. 2004***




Evidence of evidence of dynamical evolution: **recent/ ongoing cluster mergers** (*Schuecher et al. 2001, Markevitch et al. 2002, Boschin et al. 2003 Govoni et al. 2004*)

The 1.4 GHz synchrotron radio power of GRH increases with the cluster mass ($L_X$, T). First found by *Liang et al. 1999*.

**GRH are rare:** only 5% of clusters (z=0.05-0.2) in the XBAC sample show a diffuse radio emission in the NVSS.
"*The percentage of clusters showing diffuse radio emission is higher in clusters with higher X-ray luminosity.*" (***Giovannini et al. 1999***)

**RHs are the most spectacular evidence for the existence of non-thermal components in galaxy clusters: GeV relativistic electrons and μG magnetic field !**

**The Diffusion Problem:** diffuse non-thermal emission on Mpc scale

$T_{diff}$ ($\sim 10^{10}$ yr) >> $T_{v}$ ($\sim 10^{8}$ yr)

**One possibility :** ***in situ*** **re-acceleration by MHD turbulence developed in the cluster volume during the merger events**
**(e.g.,** *Brunetti et al. 2001, 2004; Brunetti & Blasi 2005; Petrosian 2001; Ohno et al. 2002; Fujita et al. 2003***)**

**Second possibility:** *secondary models,* **relativistic electrons continuously injected in the ICM by inelastic proton-proton collisions through productions and decay of charged pions**
**(e.g.,** *Dennison 1980, Blasi & Colafrancesco 1999, Dolag & Ensslin 2000***)**

**Re-acceleration models are able to reproduce several observed *morphological* and *spectral* properties of RHs (*radio brightness profiles, integrated and radial spectral steepenings, mergers connection*).**

**What about the statistical properties of the RHs population???**

General properties: RHs **should be transient phenomena!**

Cut-off frequency-merger energy: **occurrence of RHs should depend on the frequency!**

# *Outline of the talk*

- Electron re-acceleration model and statistics of giant radio halos

- Revised occurrence of radio halos from **NVSS**+**GMRT** deep observations

- Statistics of radio halos at low (**LOFAR**) radio frequencies from electron re-acceleration model

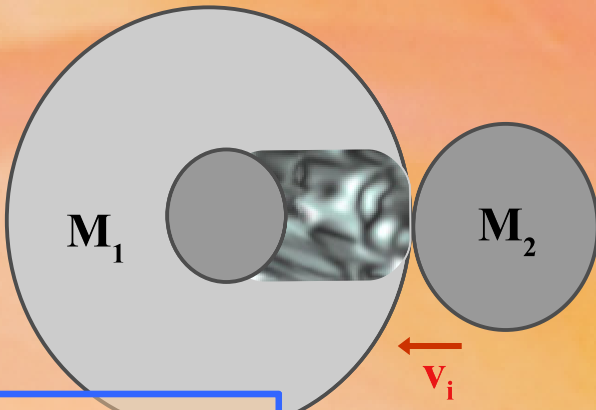
# *Basis of the statistical calculations for giant RH*

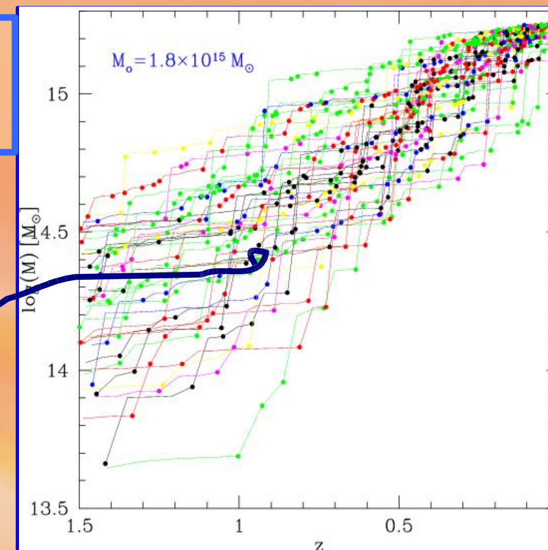
*(Cassano & Brunetti 2005; Cassano 2007-PhD thesis)*

$R_H \sim 500\ h_{50}^{-1}$

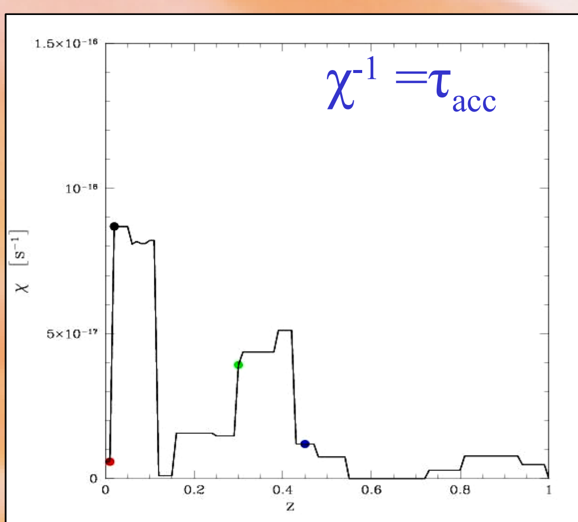
Extended PS theory

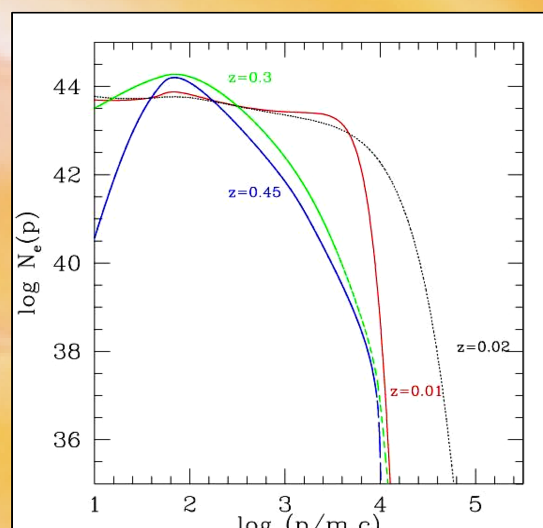
⇒ **merger trees**

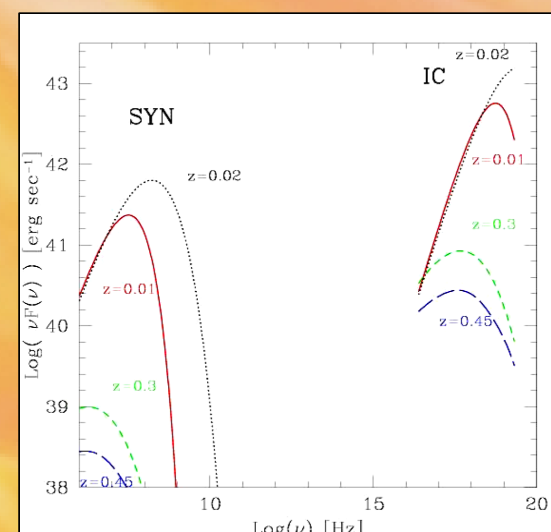


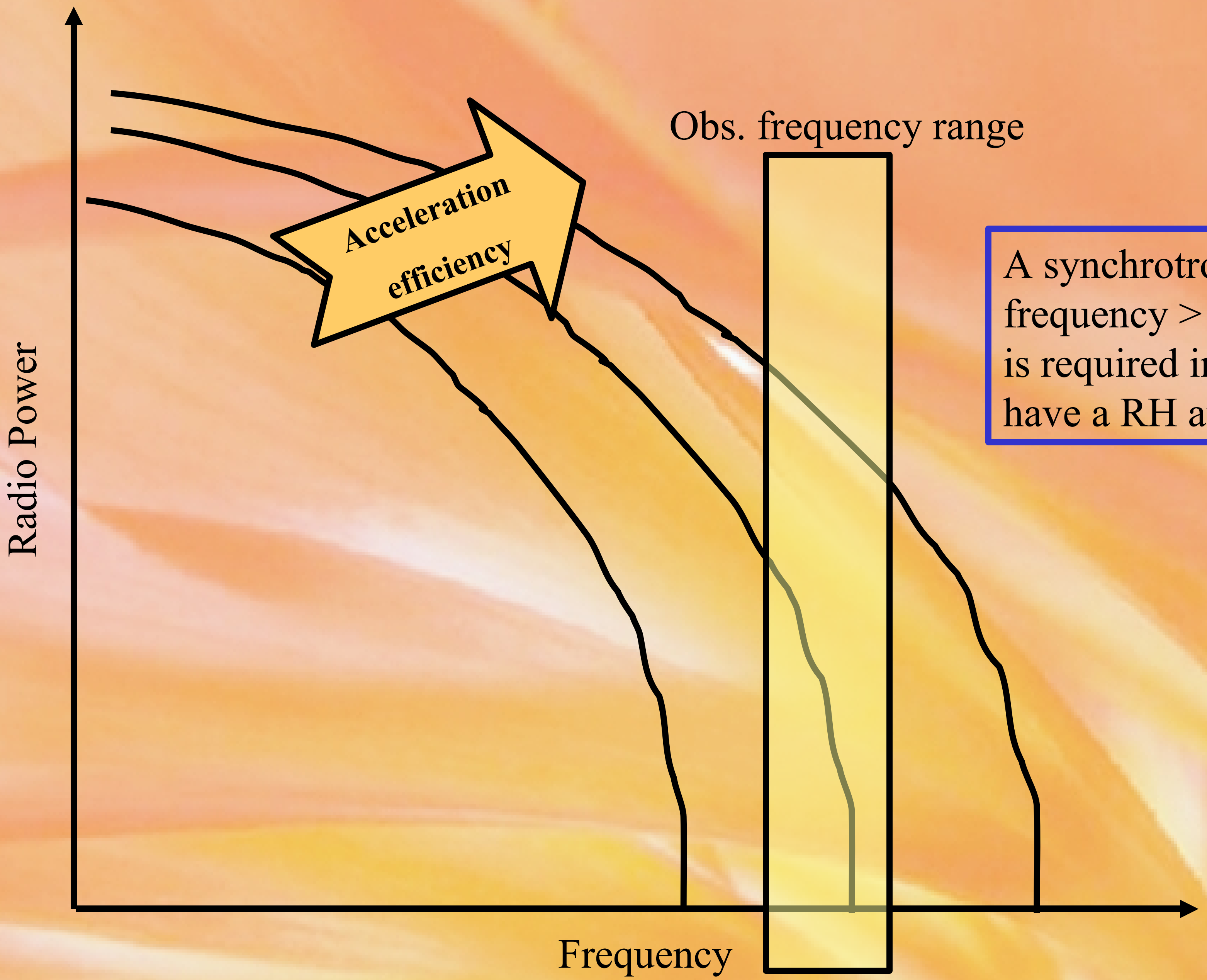

$E_t \sim \eta_t <\rho>_{ICM} v_i^2 V_t$



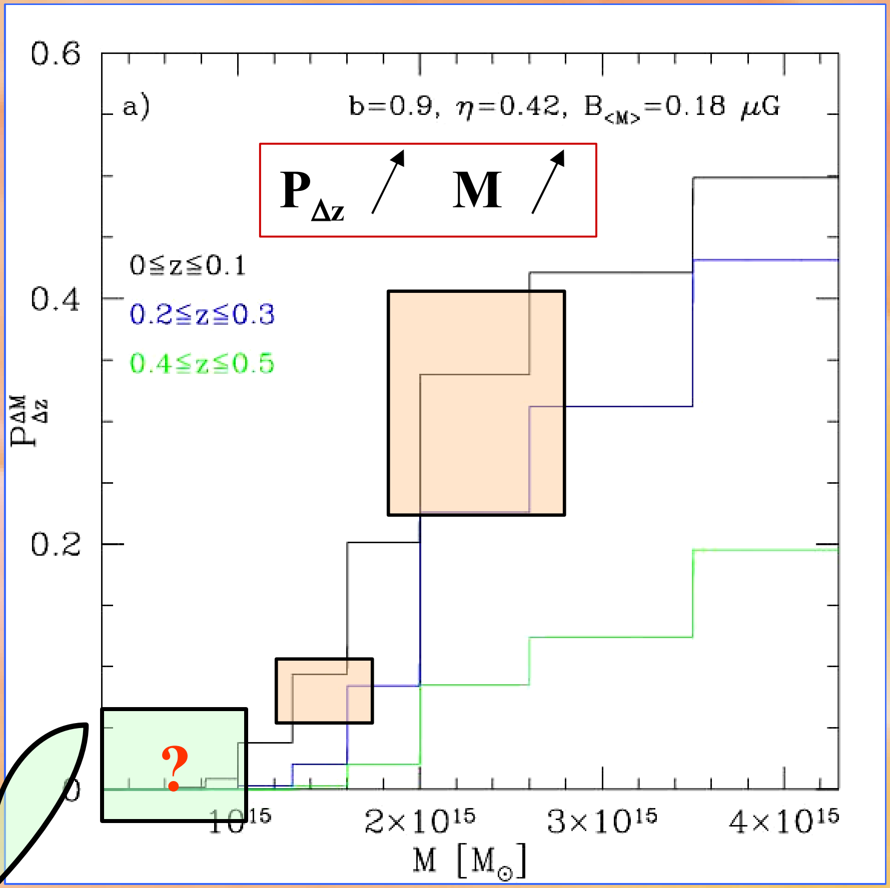



# Defining a Radio Halo




A synchrotron break frequency > **200 MHz** is required in order to have a RH at ~ GHz.

# *Increasing probability to have giant RH with cluster mass* *(Cassano, Brunetti, Setti 2006)*




The expected probability to form RH naturally increases with the cluster mass (and $L_X$).

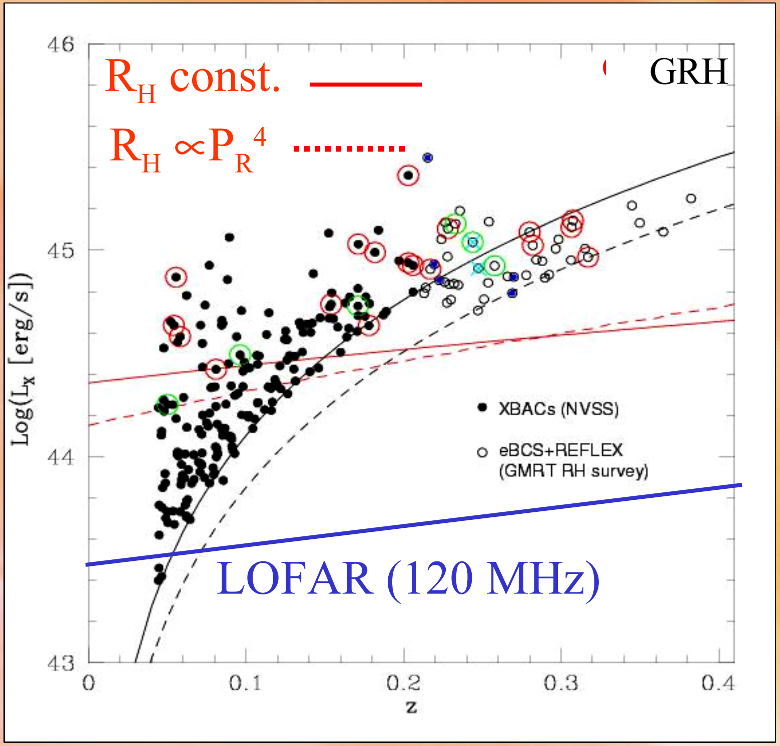
In particular, at **z<0.2** is **~30-40%** in the massive galaxy clusters (**M ~2·10$^{15}$ M$_{\odot}$**) and a few % in less massive ones.

This is in agreement with present observations (*Giovannini et al. 1999*)

Possible problem with sensitivity of present radio surveys (at least in the case the mass-radio power correlation holds at these masses)?

# *Revised statistics of RHs: work in progress…*

**(Cassano et al., in prep.)**




**Deep GMRT observations (rms=0.03-0.1 mJy/b) at 610 MHz of a complete flux-limited X-ray sample of 50 massive clusters (0.2<z<0.4) from REFLEX & eBCS catalogues.**

**(see D. Dallacasa's talk)**

**+**

**Past study of XBACs clusters with the NVSS (rms=0.45 mJy/b) at z<0.2 (Giovannini et al. 1999)**

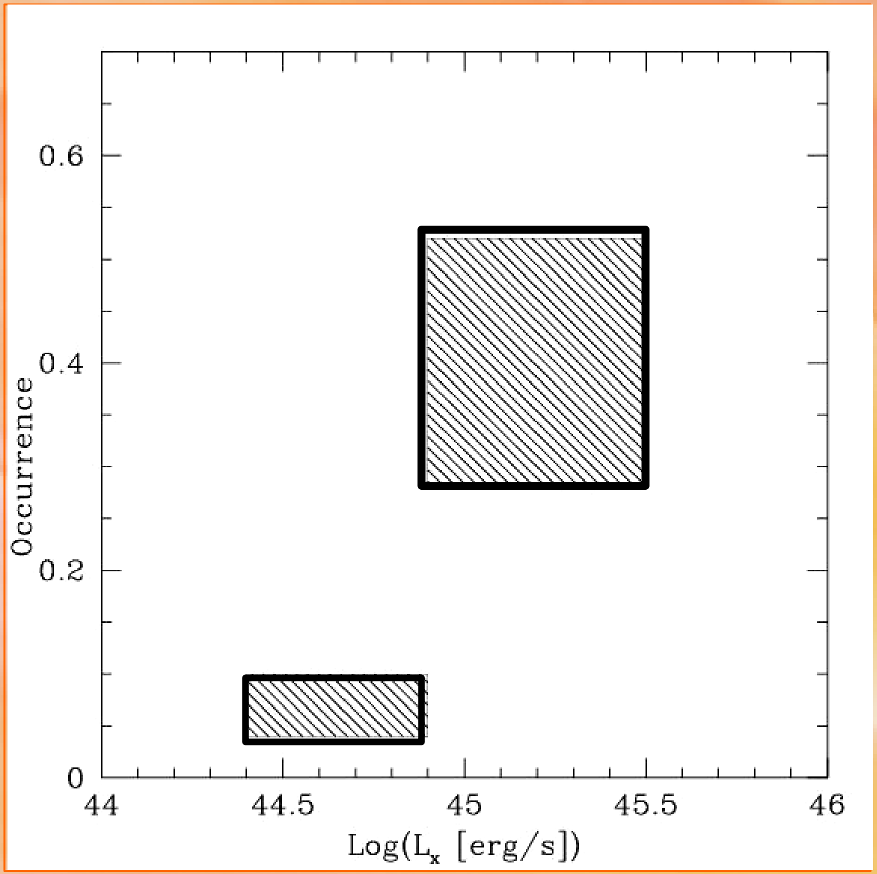
**total sample of ~ 220 clusters**

While the NVSS is not expected to detect halos in low X-ray luminous clusters if the $\mathbf{P_{1.4} \propto L_x^{1.97 \pm 0.25}}$ correlation holds, LOFAR should be able to detect these sources down to $\mathbf{P_{1.4} \sim 10^{22}}$ **Watt/Hz.**

Most important no detection of ***giant radio halos*** in low X-ray luminous clusters would be an important test of the re-acceleration scenario for the formation of these sources!

# *Occurrence of giant RHs in galaxy clusters…*

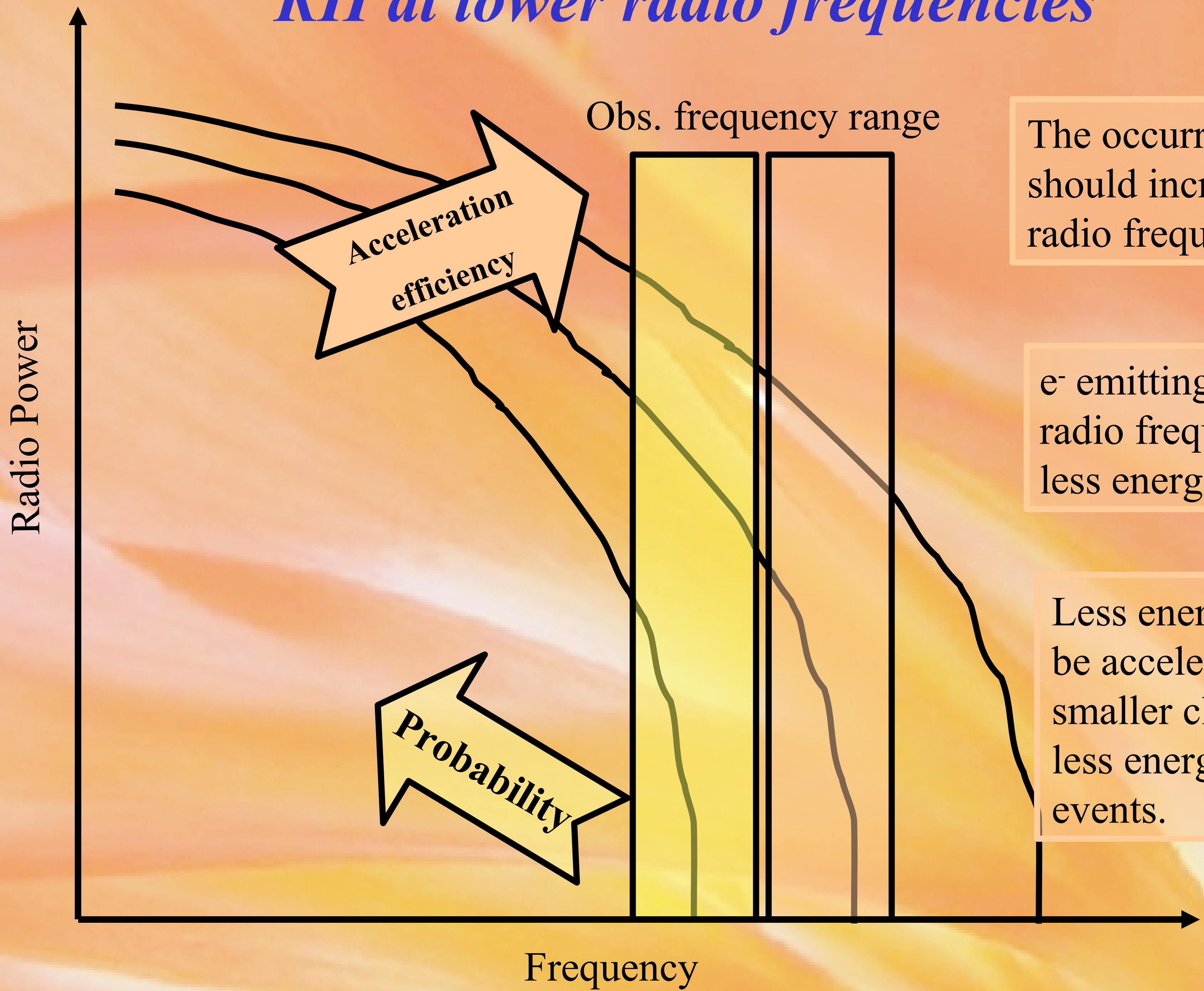
**(Cassano et al., in prep.)**




Our study **confirms** that the occurrence of RHs increases with the cluster X-ray luminosity (mass) within z<0.35:

in particular the probability to find a RH is ~ **5-10 %** for clusters with $M<2\cdot10^{15} M_{\odot}$ and ~ **30-50 %** for clusters with $M>2\cdot10^{15} M_{\odot}$

# *RH at lower radio frequencies*



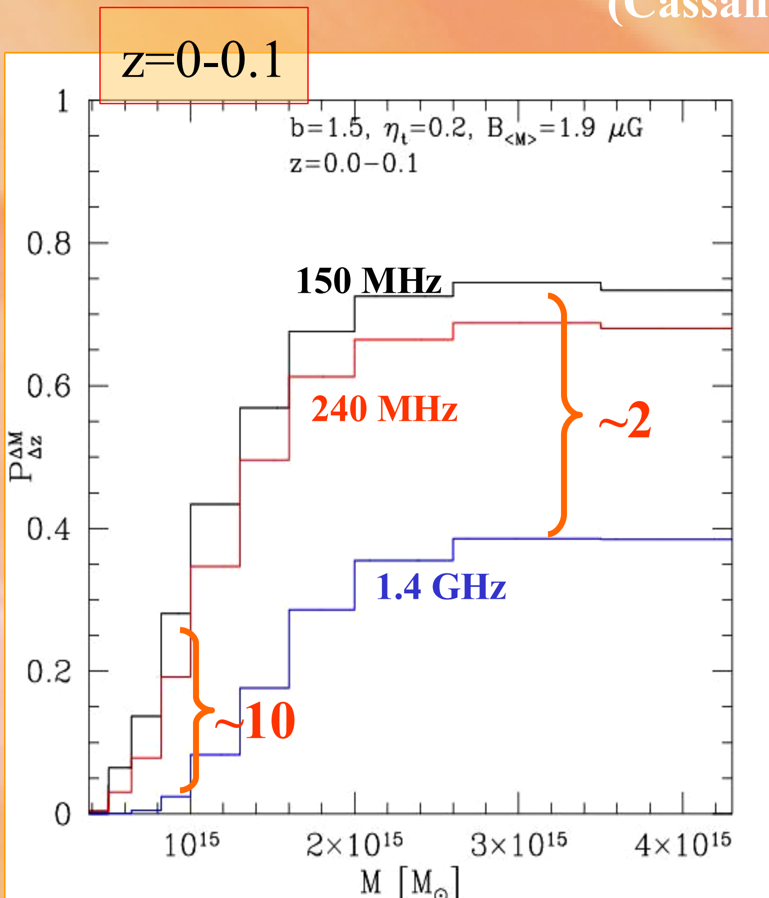

The occurrence of RHs should increase at lower radio frequencies

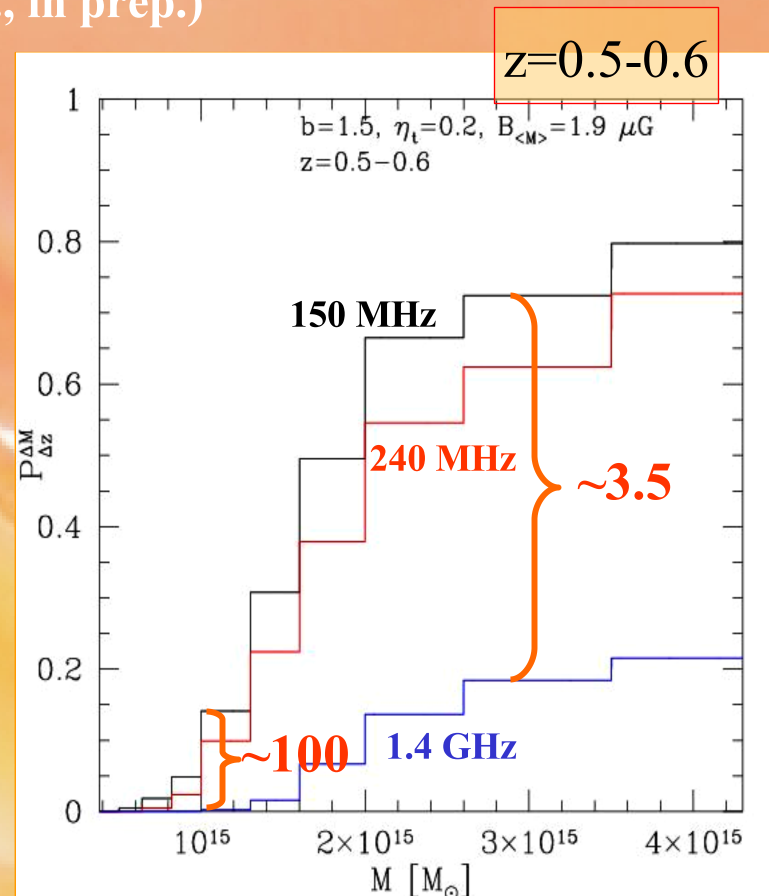
$e^-$ emitting at lower radio frequencies are less energetics.

Less energetic $e^-$ may be accelerated also in smaller clusters and in less energetics merger events.

# *Occurrence of RHs at lower radio frequencies*

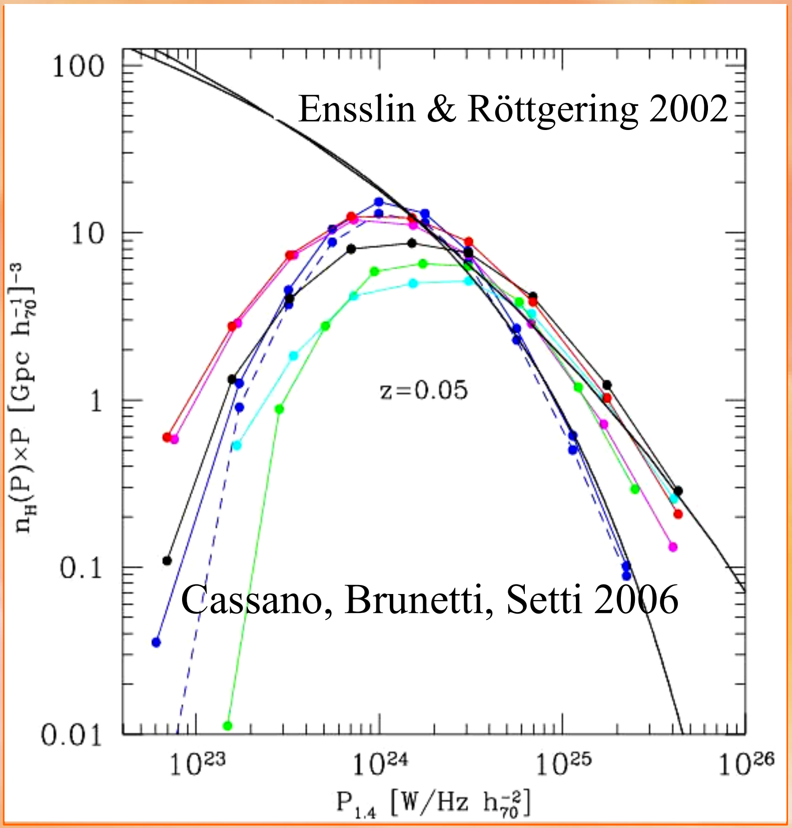
(Cassano et al., in prep.)

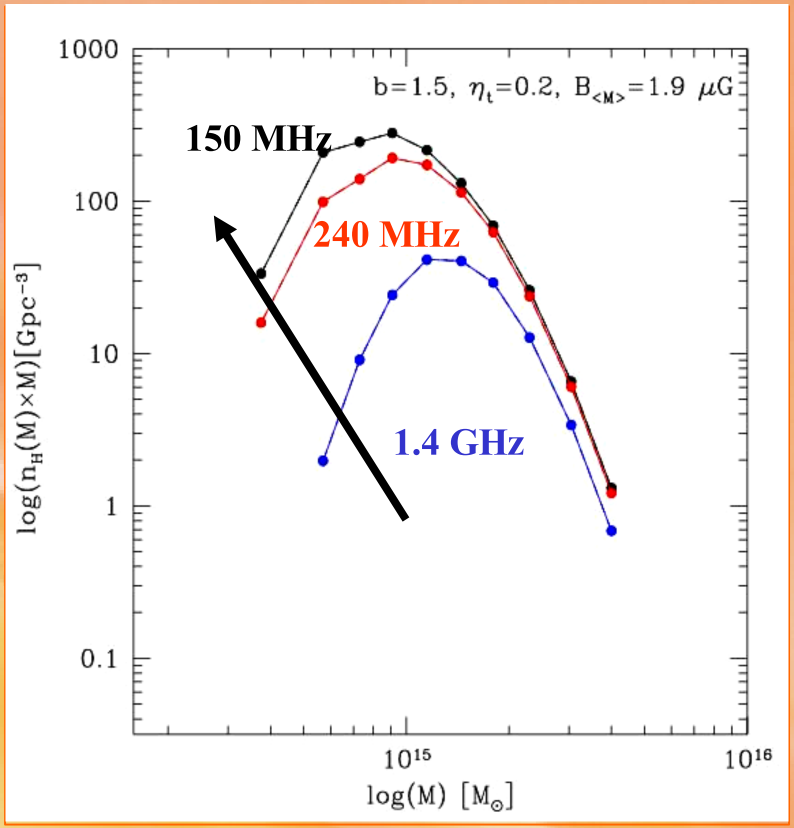



The occurrence of RHs increases at lower radio frequencies!
This increase is even stronger for **smaller clusters** ($M<10^{15} M_{\odot}$) !
This increase is even stronger at **higher redshift** ($z>0.4$)!

# *Luminosity functions of RHs at low radio frequency*

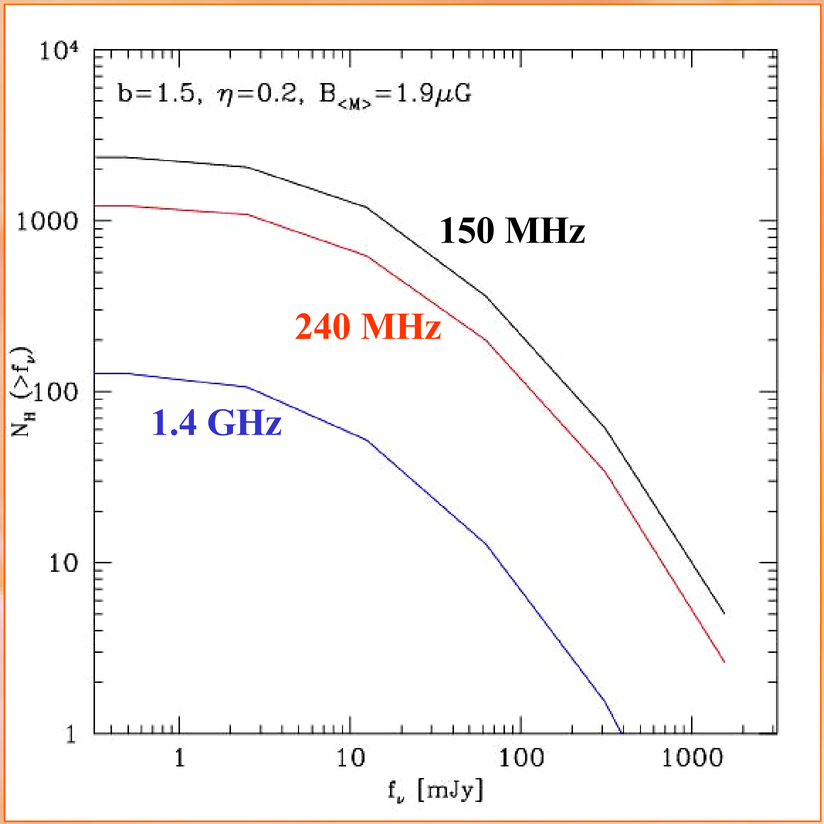


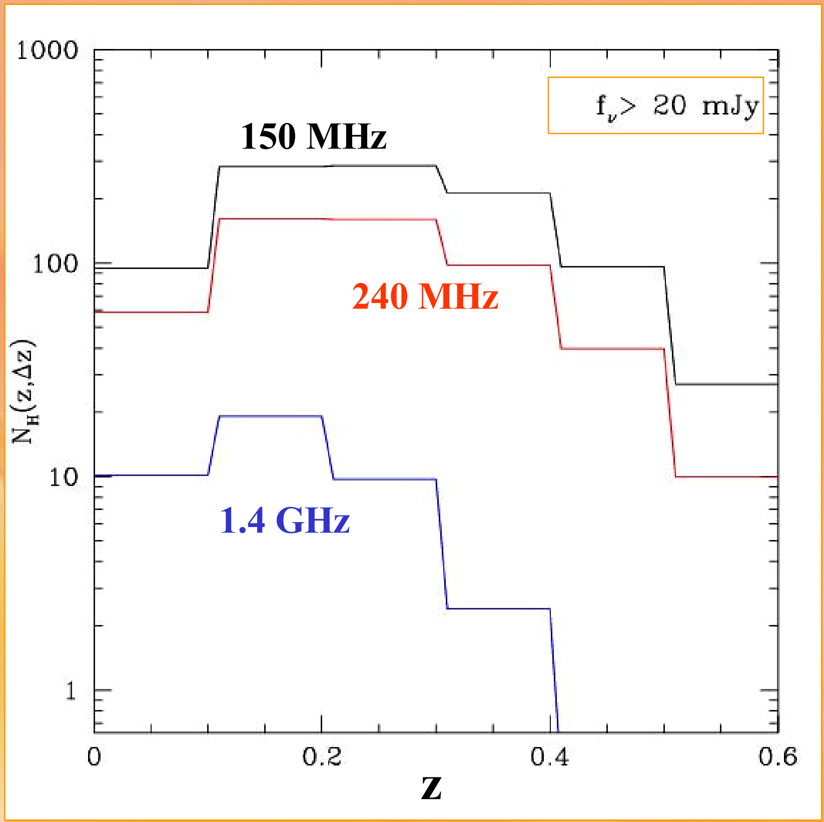




The expected RHLFs show the presence of a cut-off at low radio power due to the decrease of the efficiency of the particles acceleration in the case of less massive galaxy clusters.

The number density of RH incraeses toward low radio frequencies and the low mass cut-off is shifted toward low massive clusters.

# *Number Counts of RHs at lower radio frequencies*




**The number of expected RHs increases at lower frequencies by about a factor 10!**

**LOFAR should be able to catch the bulk of RHs!**

**The bulk of RHs emitting at GHz frequencies is expected at relatively low redshift: 0.1-0.3.**
**At lower radio frequencies a number of RHs is expected to be discovered at relatively higher redshifts z>0.4.**

# *Conclusions I*

- An increasing occurrence of giant RHs with cluster mass is expected in the framework of the re-acceleration model.
This is in agreement with results of a statistical unbiased analisys of NVSS+GMRT observations for **$M> \sim 10^{15} M_{\odot}$** ($L_X > \sim 3 \cdot 10^{44} h_{70}^{-2}$ erg/s) clusters.

- Possible problems with the sensitivity of present radio surveys in the detection of **giant RHs** in **$M< \sim 10^{15} M_{\odot}$** clusters (at least if the mass-radio power correlations holds also for these systems).
**LOFAR** should be able to detect giant RH in $M< 10^{15} M_{\odot}$ clusters.
Test of the re-acceleration scenario!

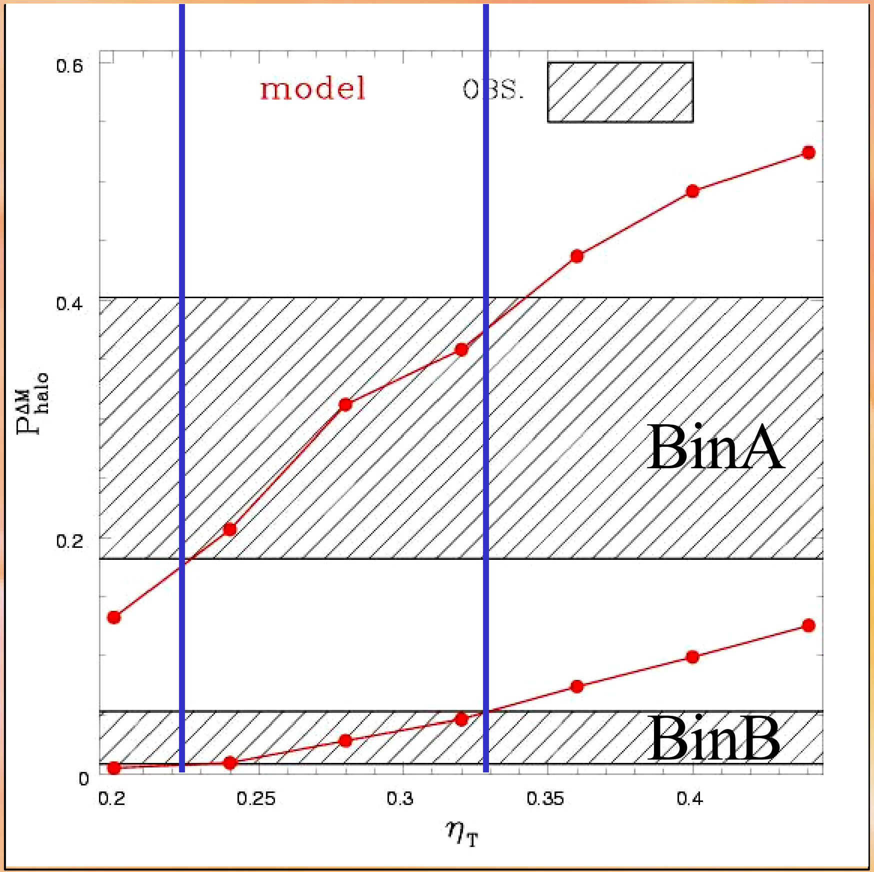
# *Conclusions II*

- A unique feature in the RHLFs expected by the re-acceleration model is the presence of a **low radio power cut-off** with respect to extrapolations of present data.

- The expected number of giant RHs in the whole universe at **$f_{1.4}$> few mJy** at 1.4 GHz is **~100**. This number increases by a factor of **~10** at 240 and 150 MHz (LOFAR).

- The bulk of RHs emitting at GHz frequencies is expected at z ~ **0.1-0.3**, while a large number of RH at higher redshifts z>0.4 is expected to be discovered at lower (LOFAR) radio frequencies.

# Occurrence of RADIO HALOS with mass:




binA~[2 – 3.6] $10^{15}$ $M_\odot$

binB~[0.9 – 2] $10^{15}$ $M_\odot$

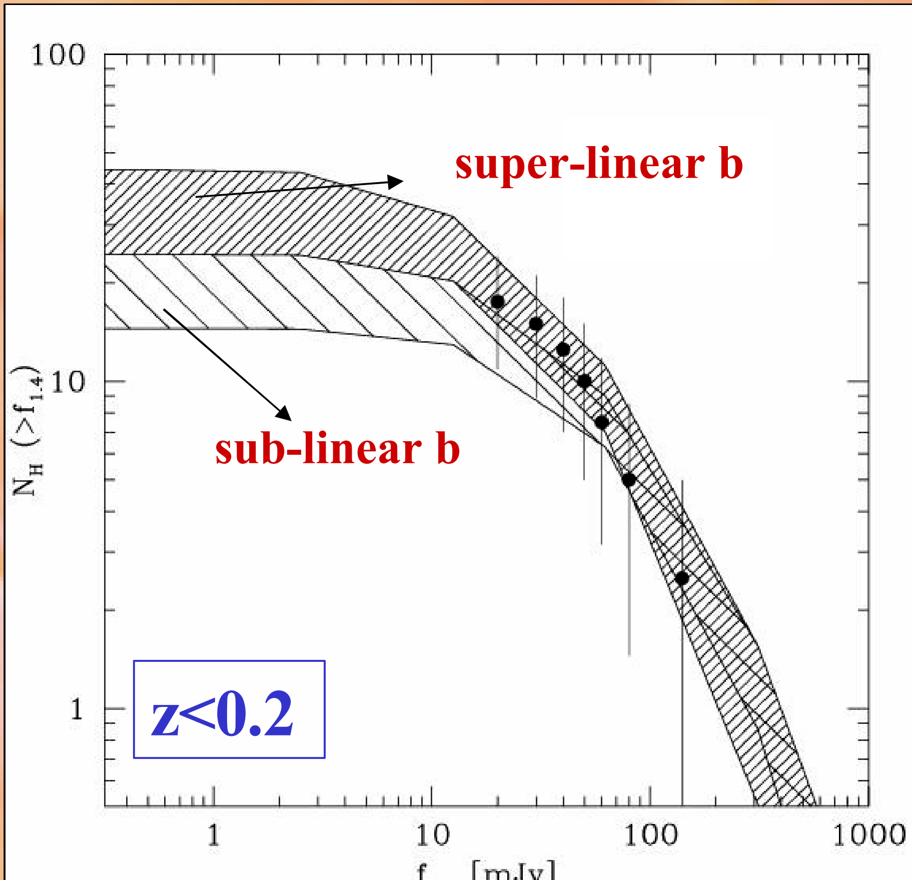
**z<0.2**

For **$\eta_t$=[0.23-0.33]** our predictions match the observations in both the mass bins.

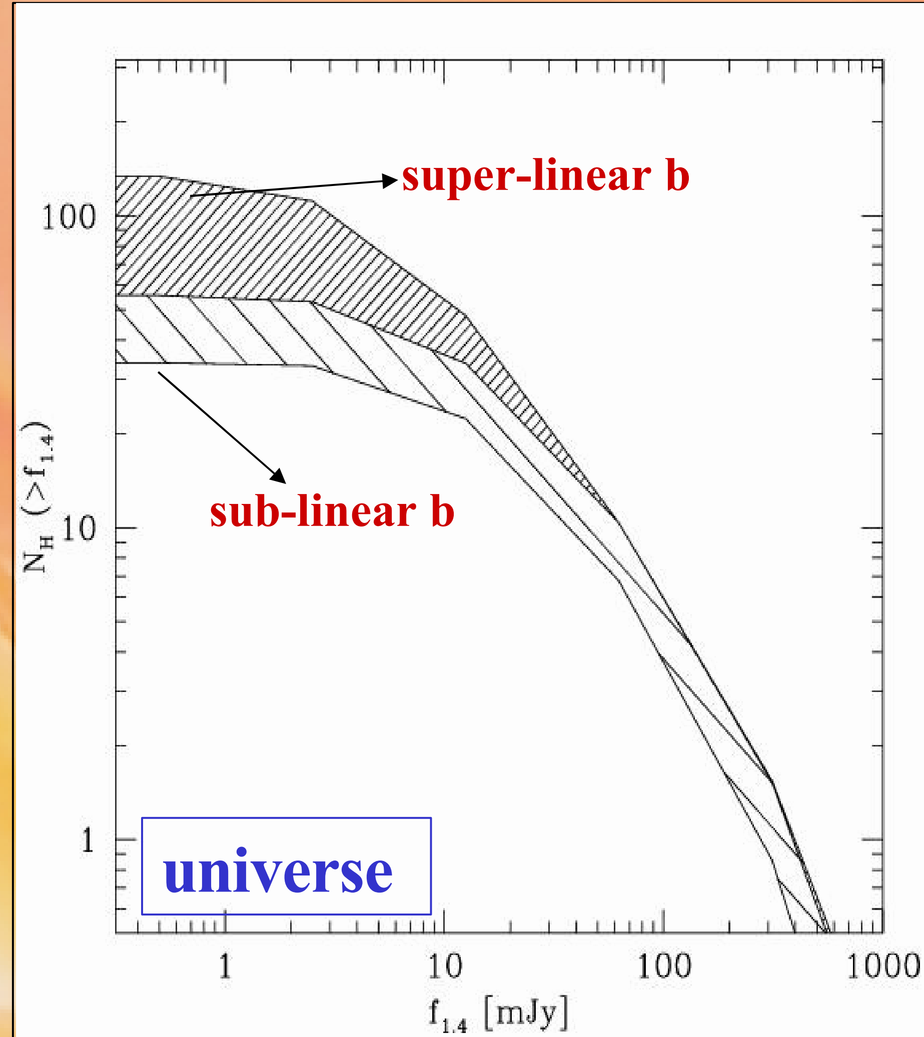
The expected probability to form radio halos naturally increases with the cluster mass. In particular, at **z<0.2** is **~ 30-40 %** in the more massive galaxy clusters (**M ~2·$10^{15}$ $M_\odot$**) and a few % in less massive ones.

This is in good agreement with observations (*Giovannini et al. 1999*)

# Number Counts




*The RHNCs at z≤0.2, at f> 30 mJy are in good agreement with observations. A number of RHs at lower fluxes is expected to be discovered with future radio observations .*

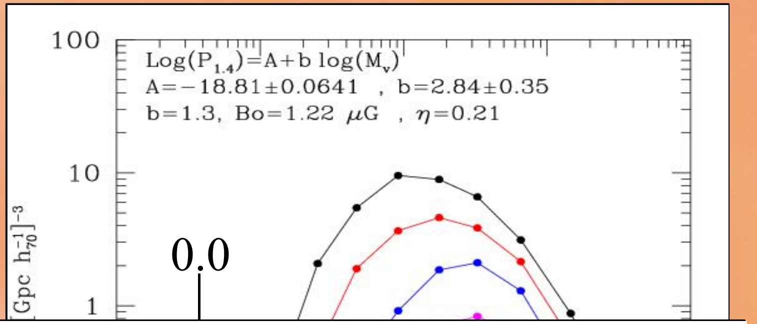


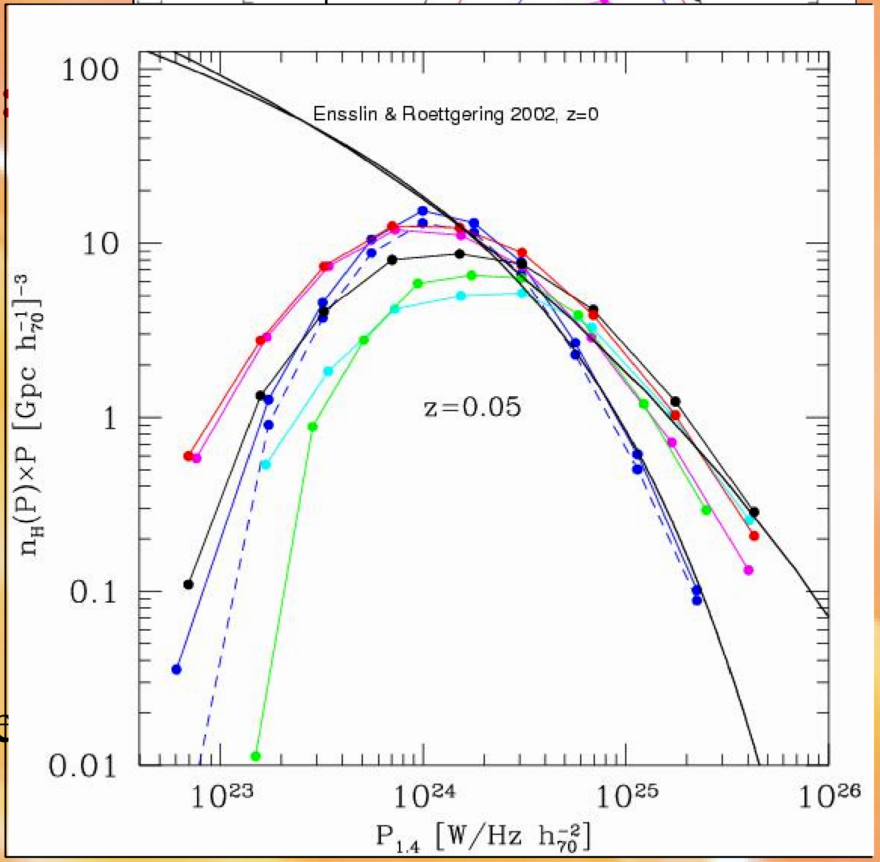

*The expected RHNCs in the whole universe, at f> 1 mJy is ~100 depending on b. Future deeper radio observations will thus be useful to futher constrain the possible values of b.*

# The Luminosity Functions of GRHs (RHLFs)

*The efficiency of the injection of turbulence increases with cluster mass* *(Cassano & Brunetti 2005).*

***We predict the presence of a low radio power cut-off due to the decrease of the efficiency of the particles acceleration in the case of less massive galaxy clusters*** **(*Cassano, Brunetti, Setti 2006; see also Cassano, Brunetti, Setti 2004, JKAS 37, 589*).**



# Deep GMRT survey at 610 MHz of a complete flux-limited X-ray sample of 50 clusters

**Selection criteria:**

1) $L_X$ [0.1-2.4 keV] $\geq 5 \cdot 10^{44}$ erg/s
2) $0.2 < z < 0.4$
3) $\delta > -30°$ (good u-v coverage)

The clusters are extracted from X-ray catalogues, REFLEX (**27** clusters, *Böhringer et al. 2004* ) and extended BCS (**23** clusters, *Ebeling et al. 1998* & *2000*).

**THE AIMS OF THE PROJECT ARE:**

a) Obtain for the first time the statistical occurrence of GRHs at z=0.2-0.4

c) Constrain the dependence of their occurrence with cluster mass

d) Combine the results with the statistics at $z \leq 0.2$ (*Giovannini et al. 1999*) and test the theoretical expectations of the re-acceleration model

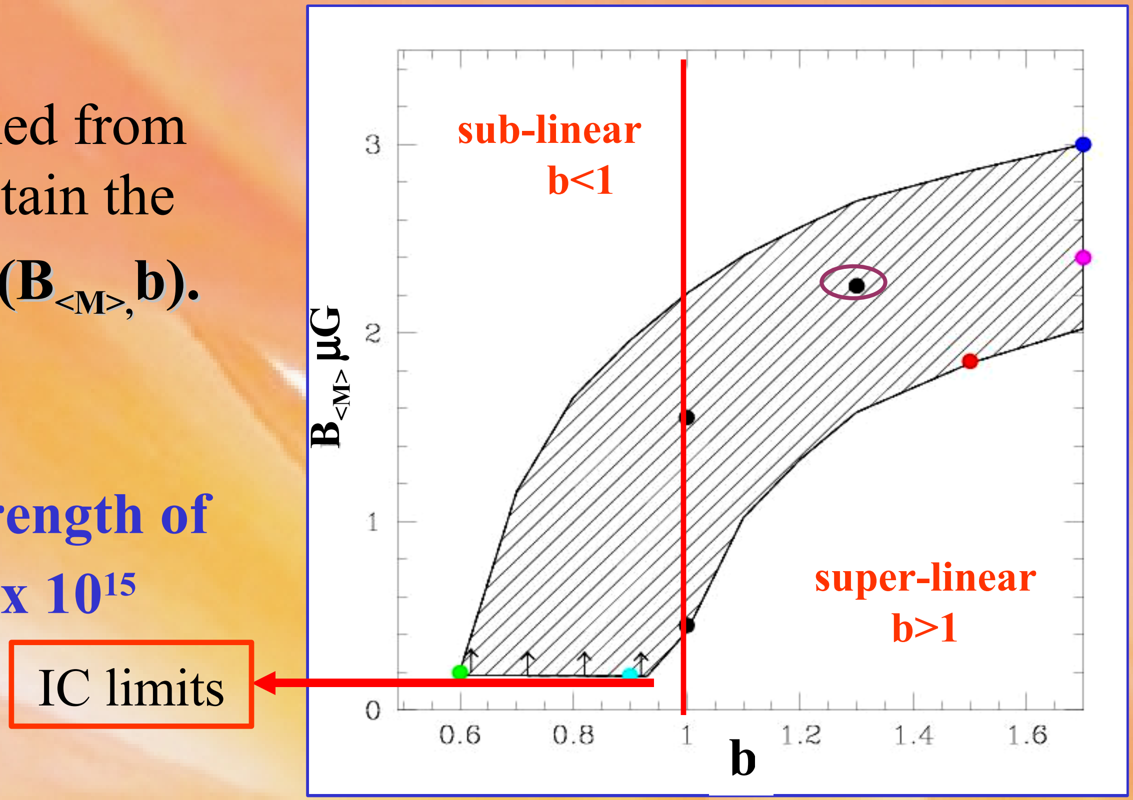
e) Understand the relationship between cluster mergers and the formation of RHs.

**Preliminary Results of Observations (Venturi et al. 2007, A&A 463, 937)**

# Constraints from the $P_R$-M correlation to the parameters <B> and b:

Considering the limit obtained from the $P_R$-$M_v$ correlation we obtain the allowed region in the plane **($B_{<M>}$, b).**

**$B_{<M>}$ rms magnetic field strength of a cluster of mass <M>=1.6 x $10^{15}$ $M_{\odot}$**




***In the shadowed region of the plane ($B_{<M>}$, b) the model can reproduce:***

1. ***the observed radio-X-ray correlations;***
2. ***the observed probability to form radio halos at z≤0.2***

# Expected probabilities to form radio halos

Radio Halos in the synthetic cluster population are identified with those objects with a synchrotron cut-off **$\nu_b \geq 200$ MHz** in a region of 1 Mpc $h_{50}^{-1}$ size.

The break frequency is given by: $\nu_b \propto \gamma_b^2 B \propto \chi^2 B/(B^2+B_{cmb}^2)^2$ thus

given $\chi$ in our model $\nu_b$ can be expressed (for $r_s \geq R_H$):

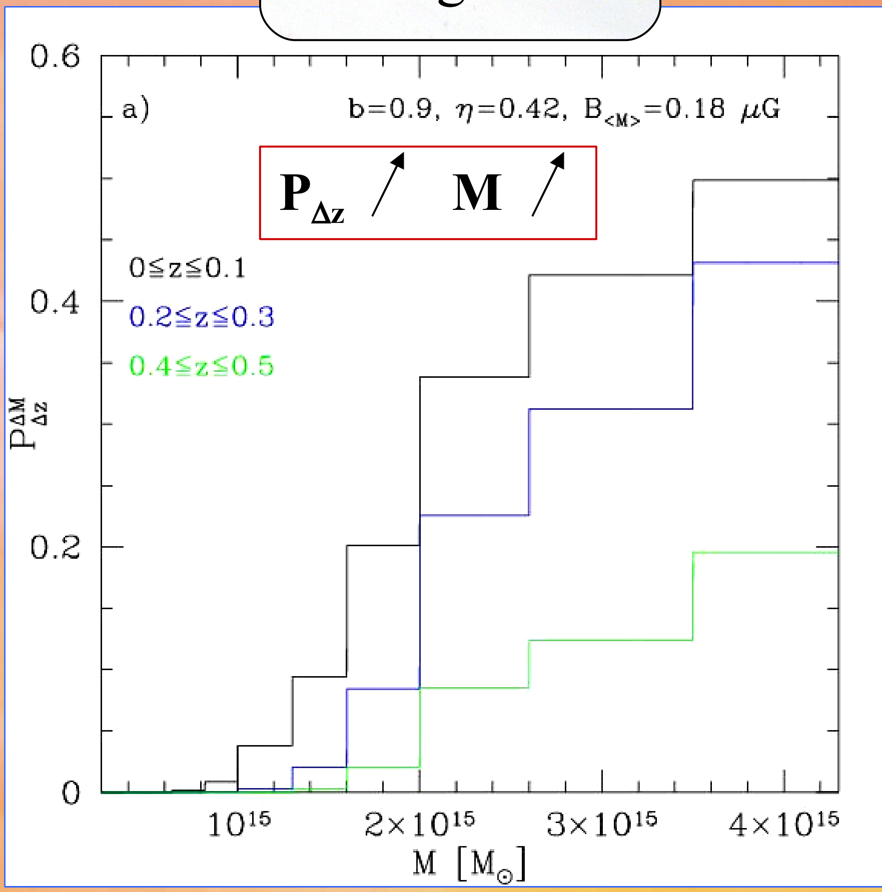
$$\nu_b \propto M^{2-\Gamma} \frac{B \eta_t^2}{(B^2 + B_{cmb}^2)^2}$$

**$B_{cmb} = 3.2(1+z)^2$ μG**

**Thus the probability to form giant radio halos shoul depend on B, on M and on z.**

# Expected probabilities to form GRHs versus M & z

sub-linear scaling **b=0.9**

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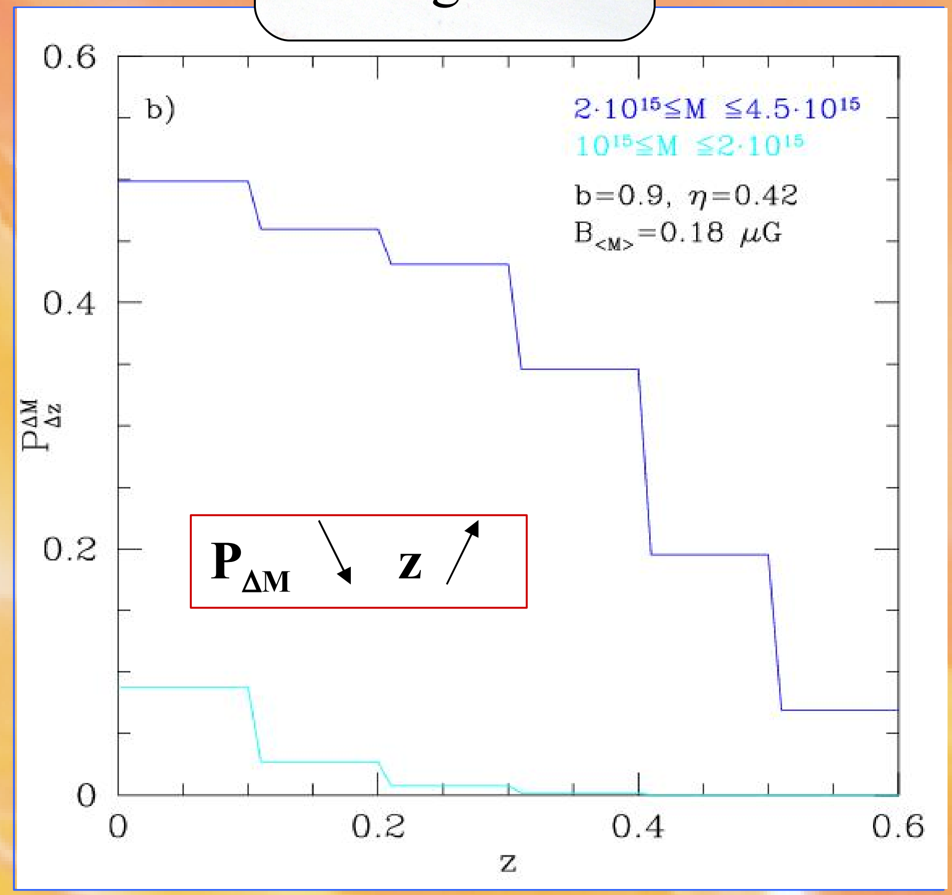


# Model expectations for $P_R$-$M_v$ correlation

In the case of giant Radio Halos (**$R_H \geq 500/h_{50}$ kpc**) it can be shown that the expected correlation **$P_R$-$M_v$** (Cassano & Brunetti 2005):

$$P_R \propto \frac{M_v^{2-\Gamma} B^2 n_e}{(B^2 + B_{cmb}^2)^2}$$

where $\mathbf{T} \propto \mathbf{M}^{\Gamma}$

$\Gamma \sim 2/3$ (virial scaling) or 0.56

We can assume that:

- **$n_e$** (the number density of relativistic electrons) is independent of the cluster's mass;
- **$B = B_{<M>} \cdot (M/<M>)^b$**, the rms magnetic field strength depends on the mass.

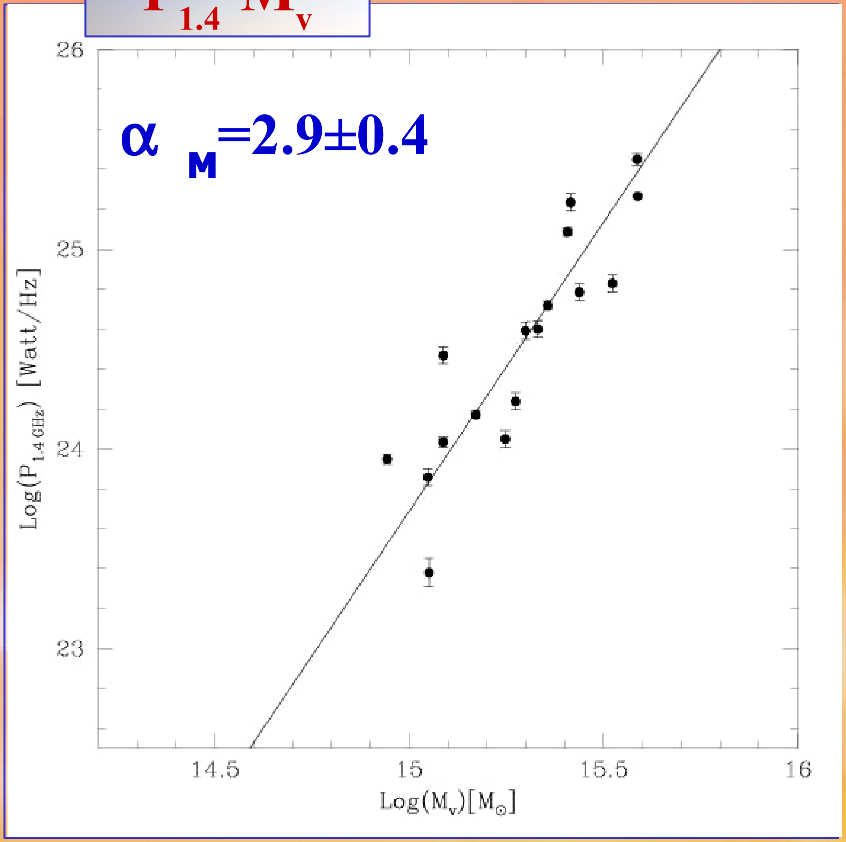
The expected slopes of the $P_R$-M correlations is thus given by:

$$\alpha_{1,2} = \frac{\log(P_1/P_2)}{\log(M_1/M_2)} = f(B,b)$$

which can be directly compared with the observed value and which can be used to constrain B and b.

# Observed $P_R$-$M_v$ correlation

$P_{1.4}$-$M_v$




Radio power-virial mass relation $P_{1.4GHz} \propto M_v^{\alpha_M}$

best-fit value : $\alpha_M = 2.9 \pm 0.4$ ;

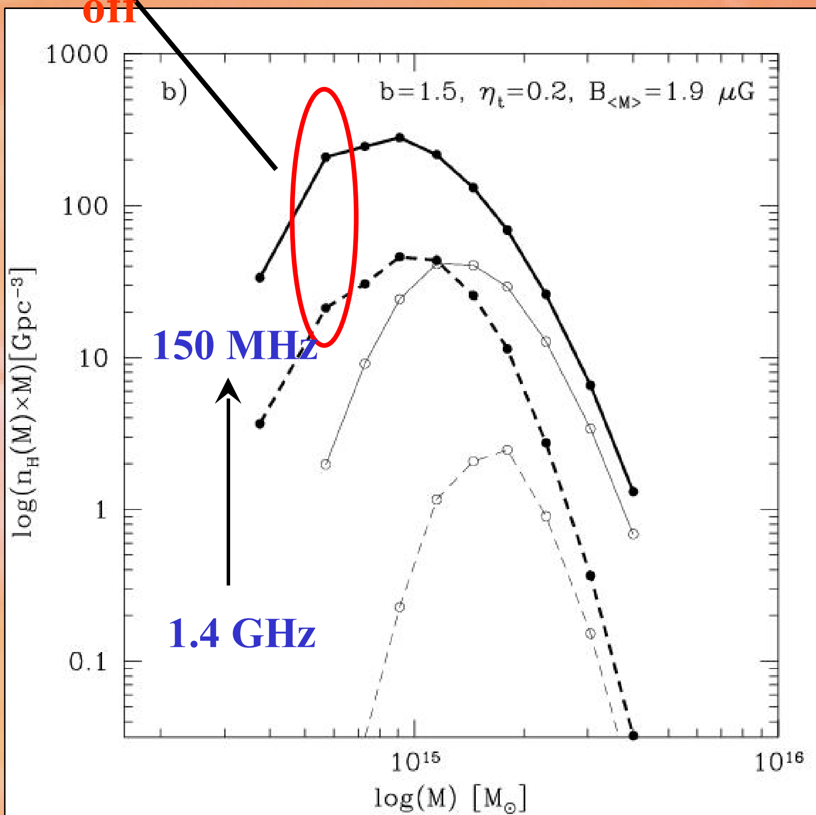
# Towards low radio frequencies: expectations at 150 MHz

**(*Cassano et al. 2006; Cassano et al. in prep.*)**

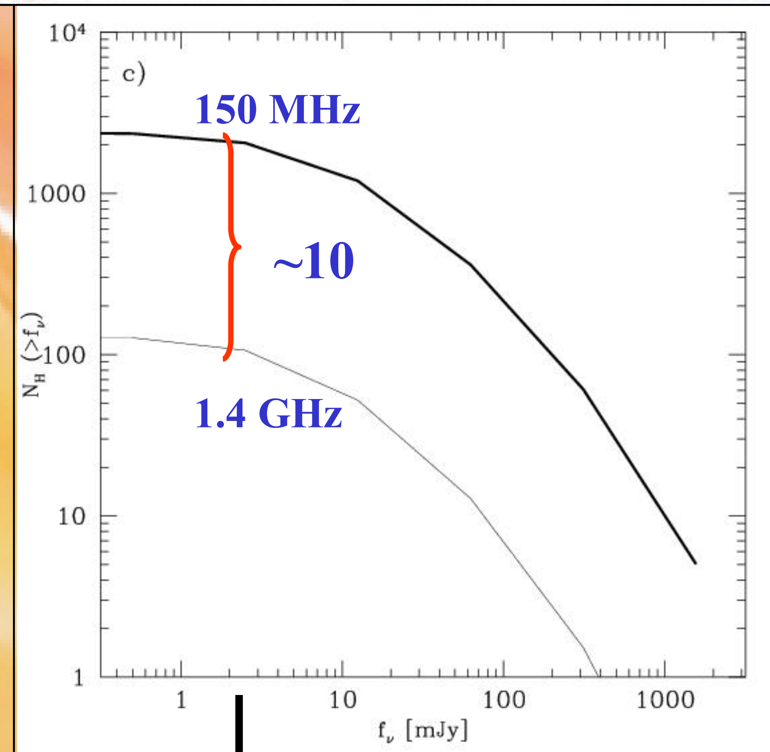
low-mass cut-off

—— z=0-0.1

------- z=0.4-0.5



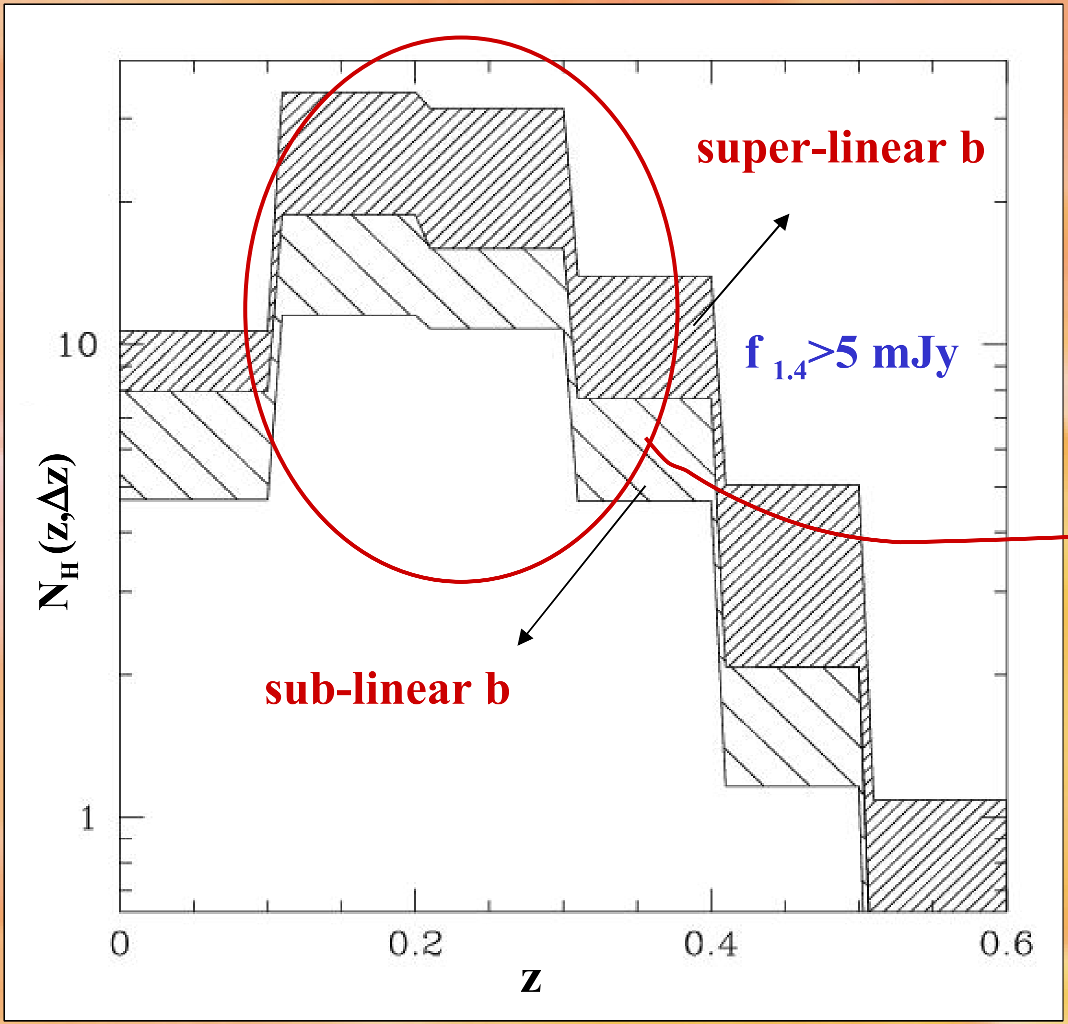

Tentatively, we assume the same $P_r$-$M_v$ scaling observed at 1.4 GHz, scaled at 150 MHz with an average spectral index $\alpha_\nu \sim 1.2$.




**The number density of GRHs incraeses from 1.4 GHz to 150 MHz!!!**

**LOFAR will be able to detected diffuse emission on Mpc scales at 150 MHz down to few mJy.**
**Sufficient to catch the bulk of GRHs !!!?**

# At which z we expect to find the bulk of GRHs?




**Bulk of GRHs between z~0.1-0.4**

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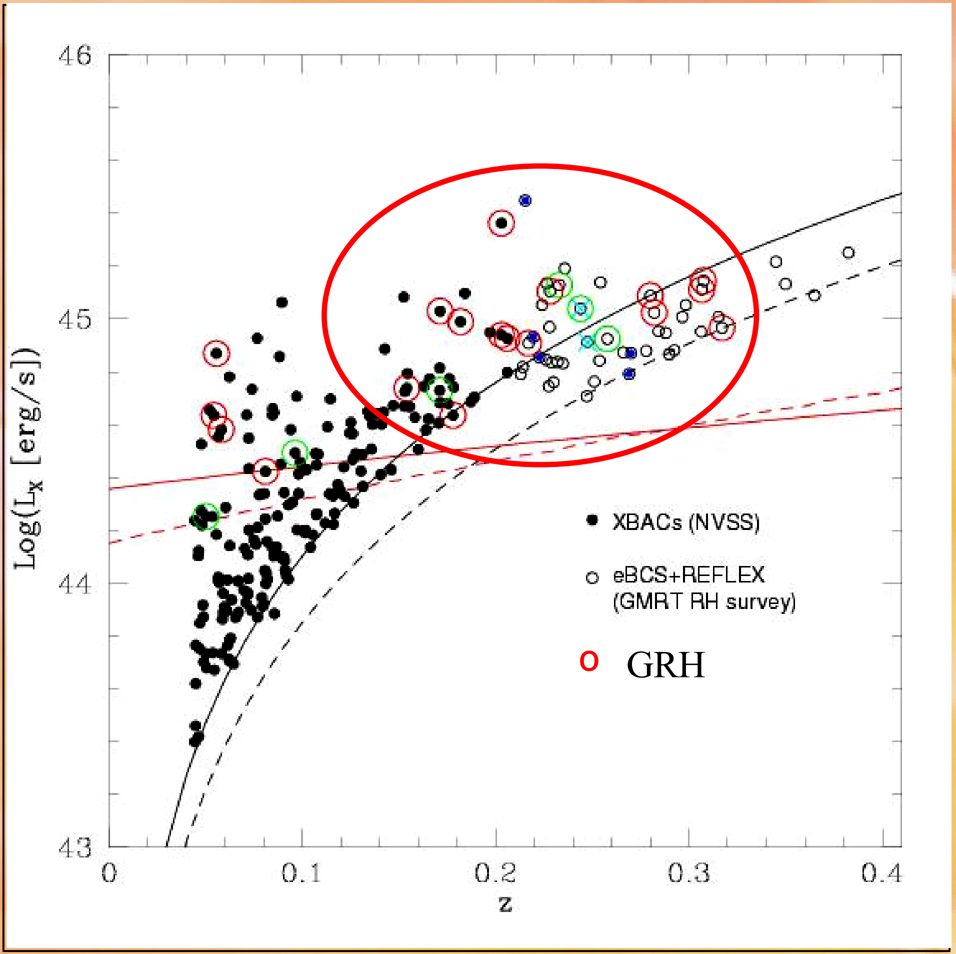
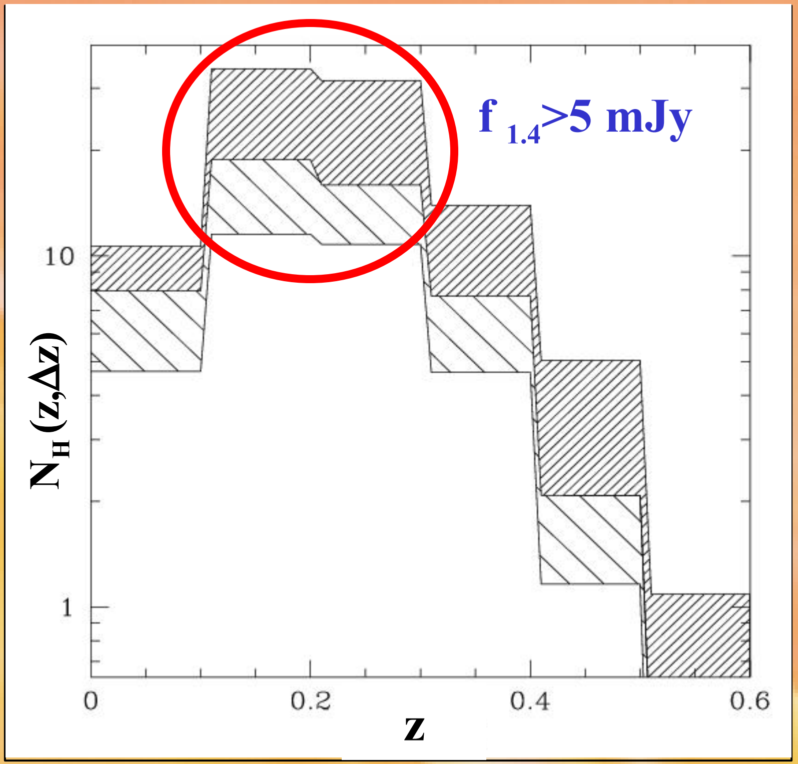
# Revised statistics of GRHs: work in progress…

## (Cassano, Setti, et al., in prep.)



# Simplified version of the re-acceleration model & new correlations for GRHs

***(Cassano, Brunetti, Setti, Govoni, Dolag 2006; submitted)***

Monte-Carlo based methods do not allow to have a spatially resolved modelling of particle re-acceleration and RH formation (fixed size of RHs).

# Simplified version of the re-acceleration model & new correlations for GRHs

***(Cassano, Brunetti, Setti, Govoni, Dolag 2006; submitted)***

- Turbulent energy density (**$\varepsilon_t$**) as a fraction of the PdV work done by the infalling sub-halos $\dot{\varepsilon}_t \propto \frac{\overline{\rho}_H \, \sigma_H^2}{\tau_{cros}}$ (*Cassano & Brunetti 2005*)

- The energy of MS waves damped by the relativistic electrons goes into synchrotron and IC radiation $\dot{\varepsilon}_t (\Gamma_{rel} / \Gamma_{th}) \propto (\dot{\varepsilon}_{syn} + \dot{\varepsilon}_{IC})$

- $B_H \propto M_H^{bh}$

**1)** $$P_R = \int \varepsilon_{syn} \, dV_H \propto \frac{M_H \, \sigma_H^3}{F(z, M_H, b_H)}$$

$$F(z, M_H, b_H) = 1 + \left( \frac{3.2 \, (1+z)^2}{B_H} \right)^2$$

# Observed new correlations

*(Cassano, Brunetti, Setti, Govoni, Dolag 2006; submitted)*

1) $$P_R = \int \varepsilon_{syn}\, dV_H \propto \frac{M_H\, \sigma_H^3}{F(z, M_H, b_H)}$$

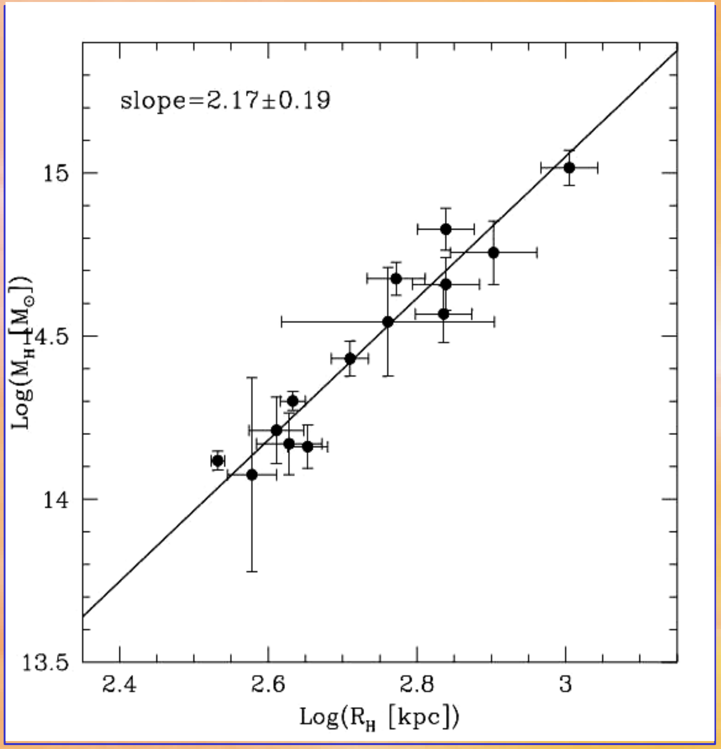
\+ 2) $M_H \propto R_H^{\alpha}$

⇒

a) $P_R$-$R_H$

b) $P_R$-$M_H$

c) $P_R$- $\sigma_H$

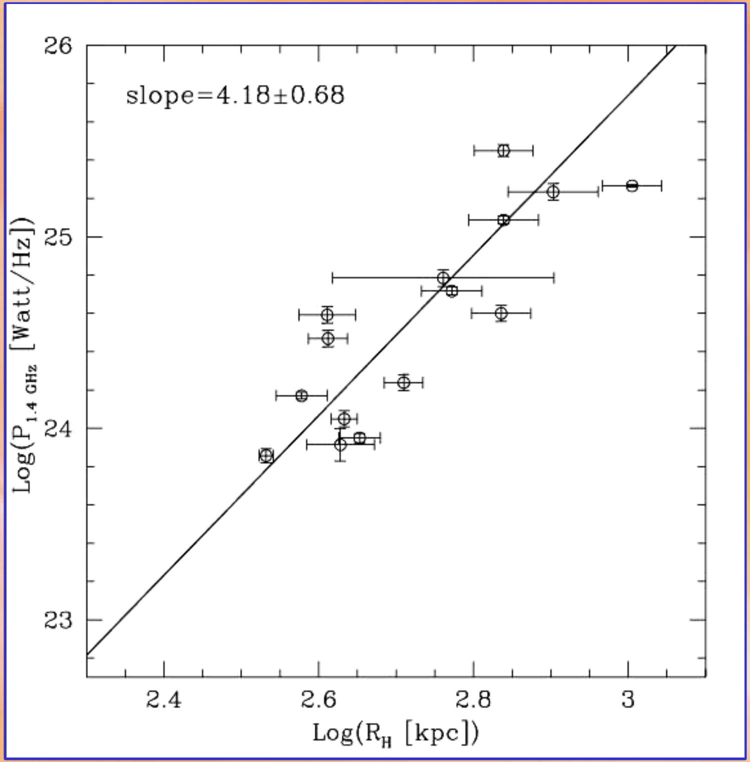



Assuming that the ICM is in hydrostatic equilibrium and is isothermal:

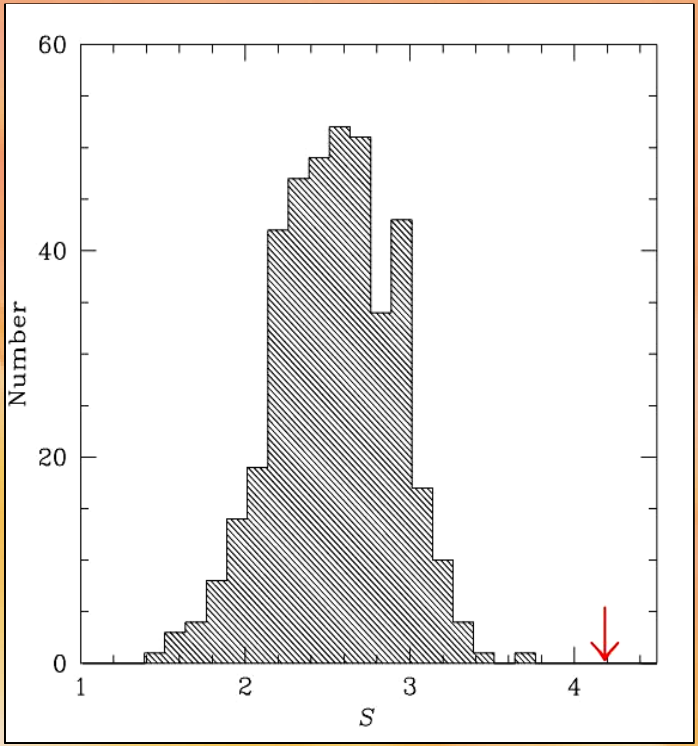
$$M_H = M_{tot}(< R_H) = \frac{3K_B T R_H^3 \beta}{\mu m_p G}\left(\frac{1}{R_H^2 + r_c^2}\right)$$

Observed: $\mathbf{M_H \propto R_H^{2.17 \pm 0.19}}$

# Observed new correlations

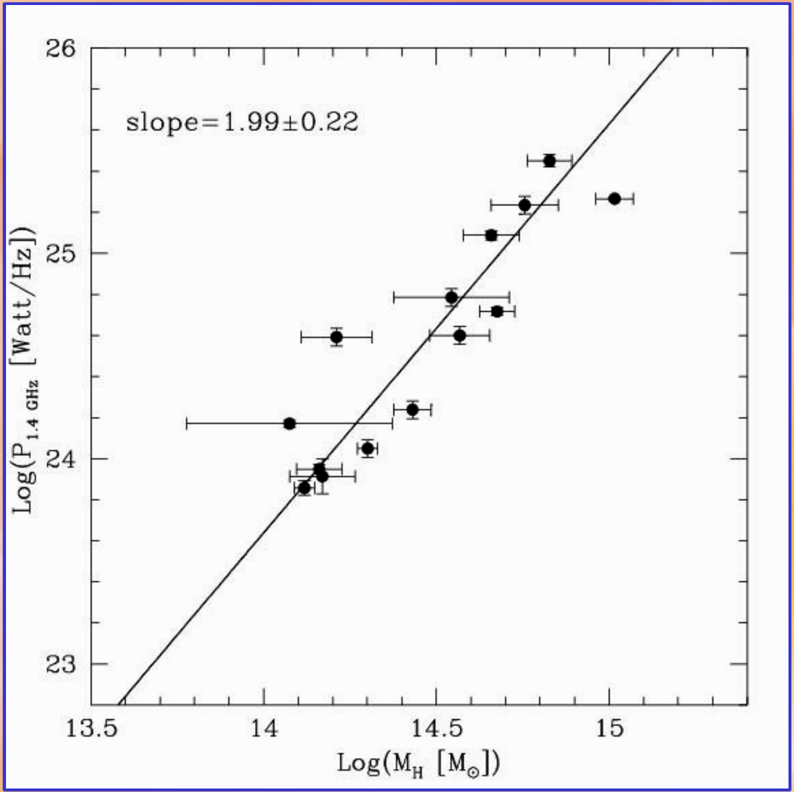


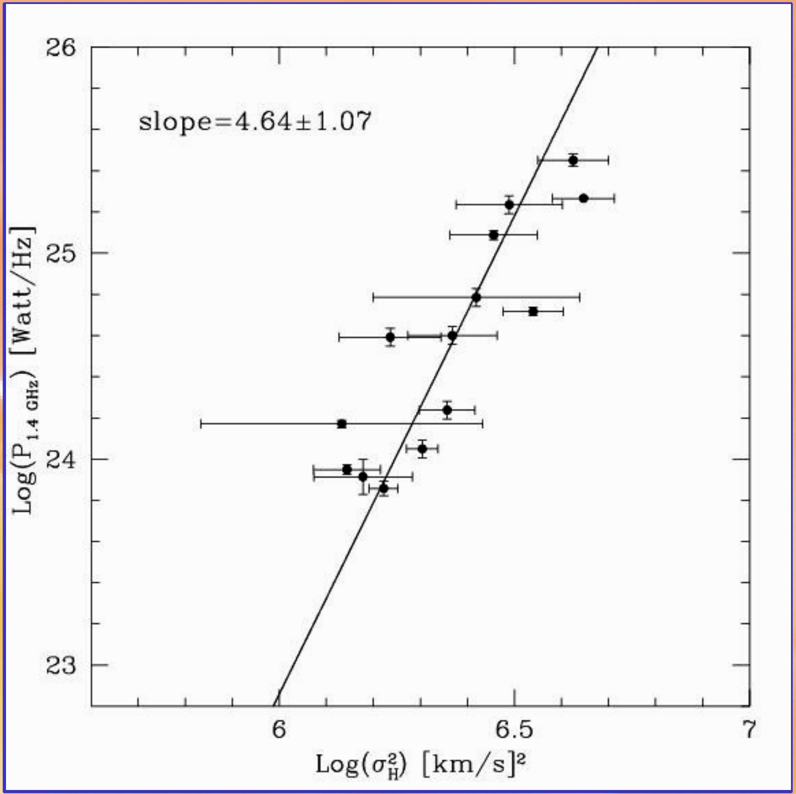

$P_{1.4}$-$R_H$ correlation




The values of the slopes of the $P_{1.4}$-$R_H$ correlation obtained with a Monte-Carlo procedure (~400 trails) are far from the observed value.

# Derived correlations

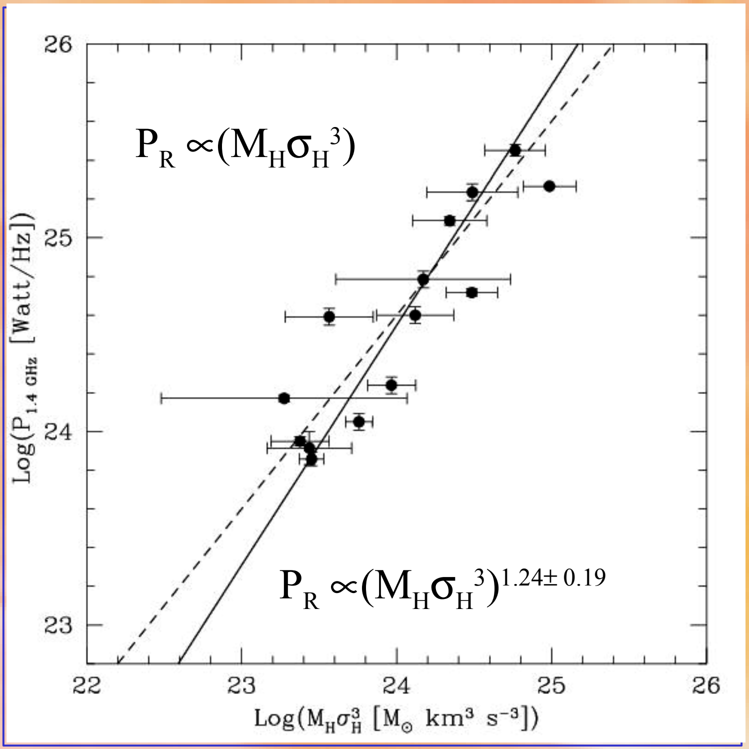



$\sigma_H^2 \approx G\, M_H/R_H$

**Another byproduct correlation is $\sigma_H^2 \propto R_H^{1.17}$**

# Observations vs model predictions




1) $$P_R = \int \varepsilon_{syn}\, dV_H \propto \frac{M_H\, \sigma_H^3}{F(z, M_H, b_H)}$$

with F~const.: $b_h$~0

+

2) $M_H \propto R_H^{\alpha}$ with $\alpha = 2.17$

From **1)** + $M_H \propto R_H^{2.17}$

$P_{1.4} \propto R_H^{3.9}$

$P_{1.4} \propto M_H^{1.8}$

$P_{1.4} \propto (\sigma_H^2)^{3.9}$

***Consistent with the new observed correlations***

# Conclusions I

**Predictions for the statistics of giant radio halos !**

Electron reacceleration model may reproduce for the same choice of the physical parameters:

- the observed probability to form giant radio halos as a function of the cluster mass at $z \leq 0.2$;
- the observed Number Counts of giant radio halos at $z \leq 0.2$.

# Conclusions II

**Predictions for present (VLA, GMRT) and forthcoming radio instruments (LOFAR, LWA, SKA)**

- The RHLFs derived from the re-acceleration model show the presence of a **low radio power cut-off** with respect to extrapolations of present data.

- The expected number of GRHs in the whole universe, at $f_{1.4}>$ **few mJy** is **~100** depending on **b**. This number increases by a factor of **~10** at 150 MHz (LOFAR).

- The bulk of giant radio halos is expected to be discovered between redshift **0.1-0.3**. We start to test this prediction with deep observations of a sample of galaxy clusters with the GMRT at 610 Mhz.

# Conclusions III

- New observed scaling relations for GRHs: $P_R \propto R_H^4$, $P_R \propto M_H^{2.2}$ and $R_H \propto R_v^{2.6}$
- The size of GRHs increases not linearly with the size of the cluster $\Rightarrow$ GRHs are not self-similar
- $B_H$ does not critically depend on $M_H$ $\Rightarrow$ GRHs select regions of the cluster volume in which the magnetic field strength is above some minimum value
- **The electron re-acceleration model, related to the injection of turbulence in the hierarchical formation scenario, provides a basic physical interpretation for all the correlations observed so far for GRHs.**

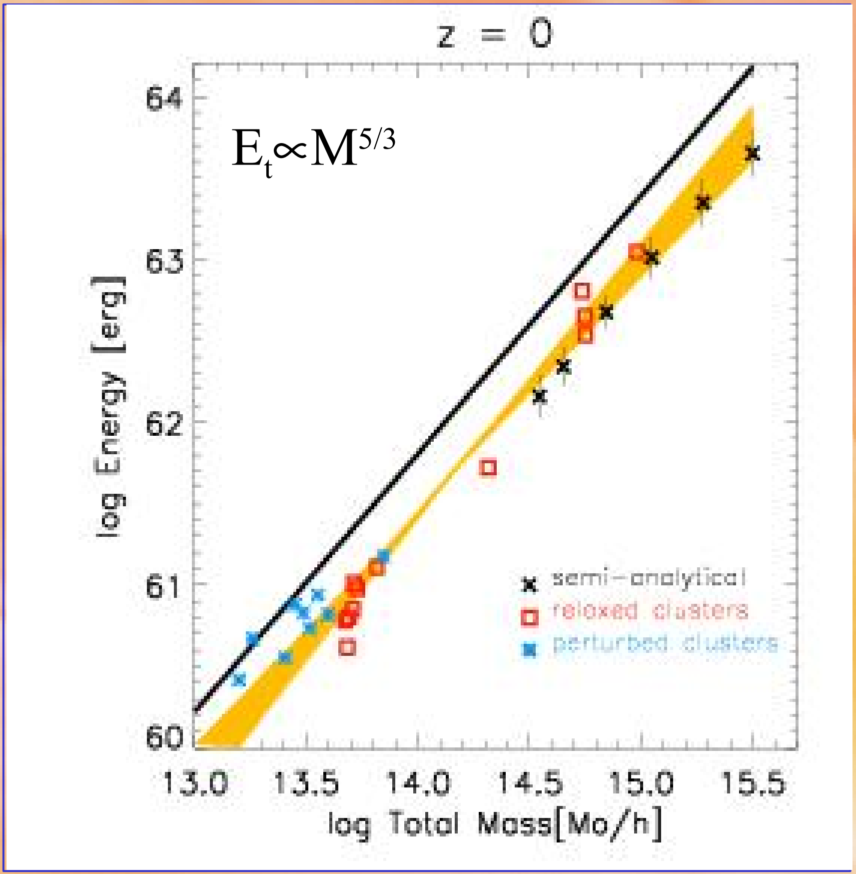
# Future

- Combining NVSS results + GMRT survey will allow us *to calculate an <u>unbiased occurrence</u> of RHs with mass and z, and to compare the observations with model expectations.*

- *Calculate the statistical properties of RHs with mass, z at low radio frequency, which will be crucial to interpret the future LOFAR and LWA data.*

- Calculate *the expected properties of* ***hard X-ray tails*** *with mass and z of the parent clusters, which could be tested* by *future HXR detectors (e.g., Simbol-X)*

# Turbulence and cluster-cluster mergers




*Vazza, Tormen, Cassano, Brunetti & Dolag 2006, MNRAS Letters 369, 14*

× Semi-analytical expectations **(Cassano & Brunetti 2005)**

□ × From the study of turbulent velocity fields in the ICM of a sample of 21 SPH- simulated galaxy clusters. **(Vazza et al. 2006)**

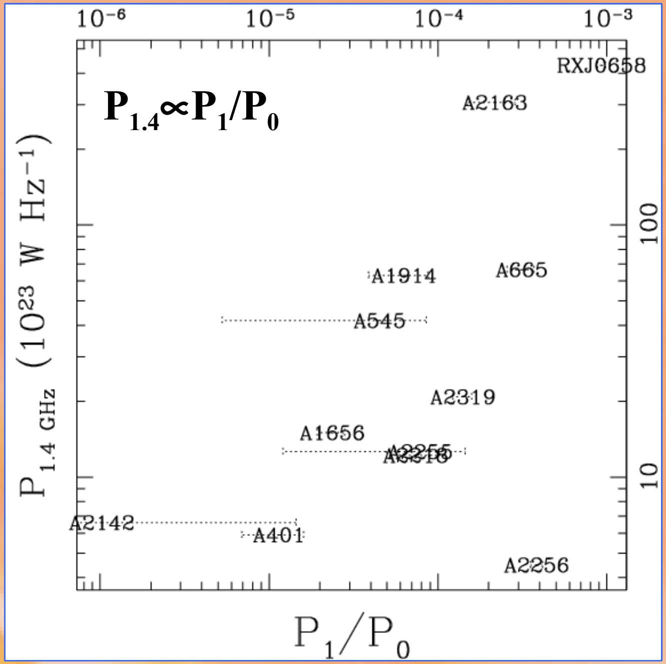
The energy budget injected in turbulence during cluster formation is found to be **~ 15-30 %** of the thermal energy.

**The energy injected in turbulence, calculated with both semi-analytical and numerical approach, is found to roughly scale with the thermal energy of the cluster.**

**Radio properties** ($H_o$=70 km $s^{-1}$ $Mpc^{-1}$):

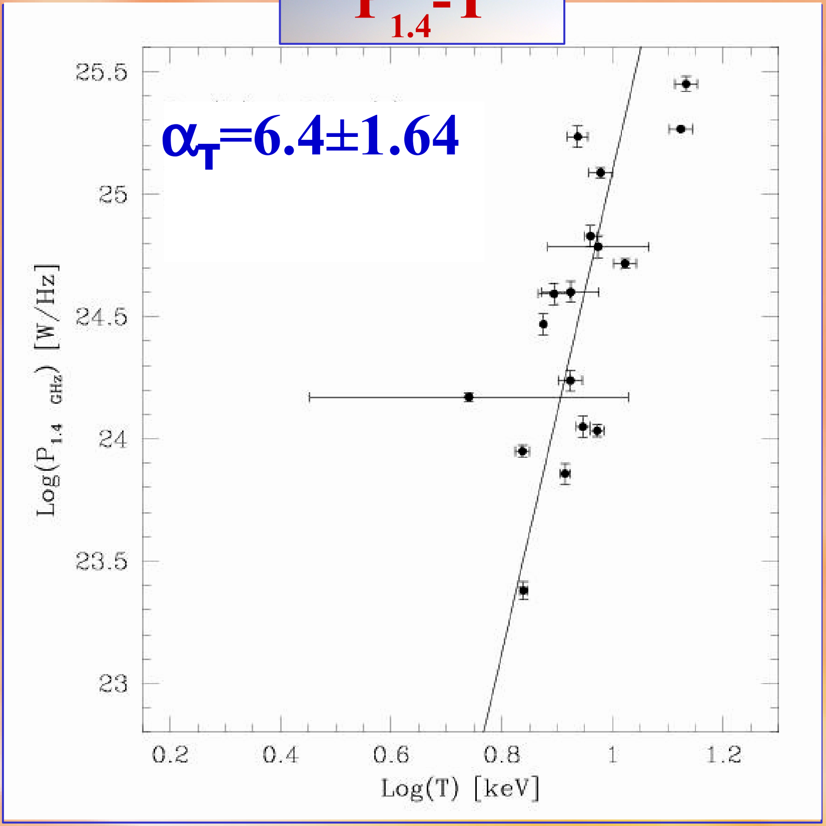
Total Size: **~ 600 kpc - 2 Mpc**

Radio Power at 1.4 GHz: **~ $6 \cdot 10^{23}$-$3 \cdot 10^{25}$ Watt/Hz**




*"The strongest radio halos appear only in those clusters currently experiencing the largest departures from virialized state."* (***Buote 2001***)

# $P_{1.4}$-T




Radio power temperature correlation $P_{1.4GHz} \propto T^{\alpha_T}$ ,
best-fit value: **$\alpha_T$=6.4±1.64**

# The Number Counts of GRHs (RHNCs)

Given the RHLFs the Number Counts of giant RHs are given by:

$$N_H(>f^*_{1.4}) = \int_{z=0}^{z1} dz' \left(\frac{dV}{dz'}\right) \int_{L(f^*,z')} \frac{dN_H(L,z')}{dL\,dV} dL$$

where dV/dz is the comoving volume element in the ΛCDM cosmology.

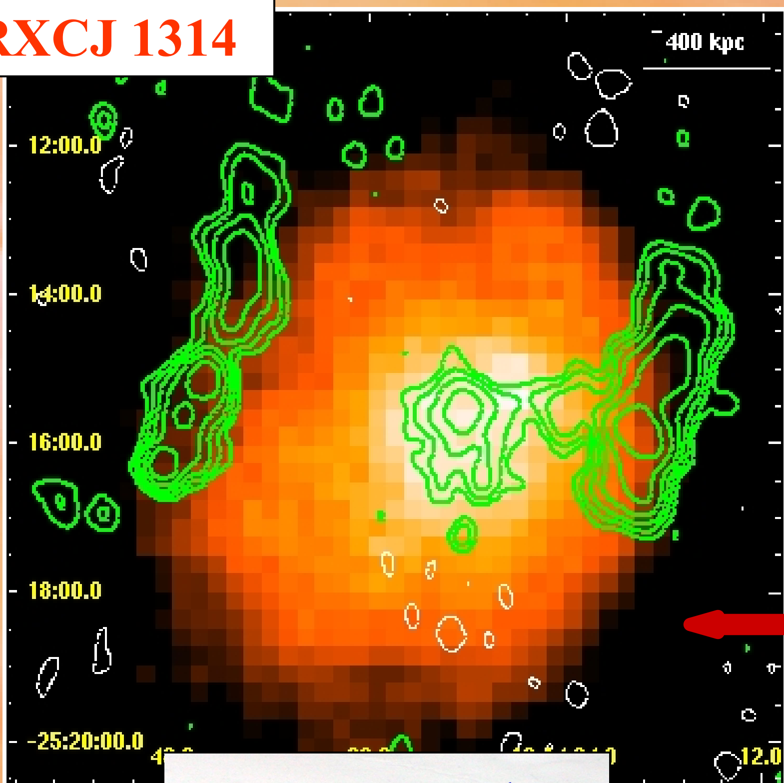
- To compare our prediction with present-day observations, we calculate the integral number of expected GRHs at 1.4 Ghz from a full sky coverage up to $z \leq 0.2$. We take the obseved counts from the statistical analysis of the NVSS by Giovannini et al. (1999) and correct the normalization to account for the incompleteness of their sky-coverage ($\sim 2\pi$ sr).
- We calculate the number of expected GRHs above a given radio flux at 1.4 Ghz in the whole universe.


The End

# Preliminary Results of Observations

(Venturi et al. 2007, A&A 463, 937)

## RXCJ 1314

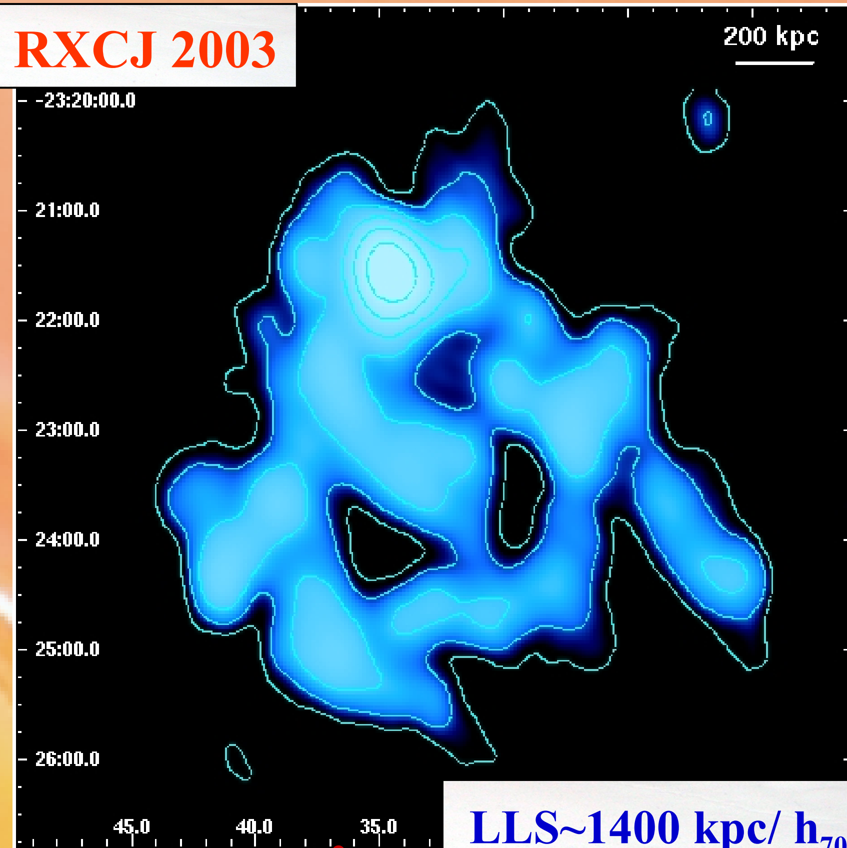



**LLS~460 kpc/ $h_{70}$**

**z~0.24**

Radio contours on ASCA X-ray image. In the radio map: HPWD= **25”**, rms=0.18 mJy/b. Also found by Feretti et al. 2005 (VLA 1.4GHz)

## RXCJ 2003

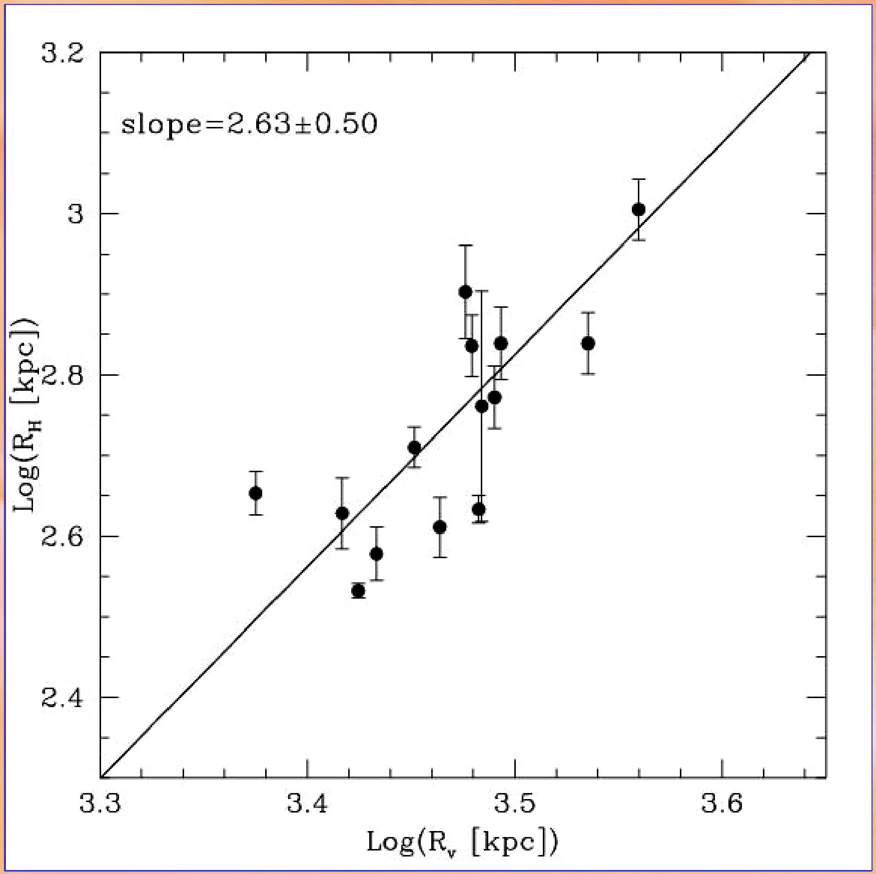



**LLS~1400 kpc/ $h_{70}$**

**z~0.32**

Radio contours and colour image of after subtraction of the discrete sources. HPWD=**32”**, rms=0.1 mJy/b.

# GRH and self-similarity




**Generally, massive clusters are self-similar…** ~~$R_H \propto R_V$~~

The size of the GRH increase not linearly with the cluster virial radius,

$$R_H \propto R_V^{2.63 \pm 0.5}$$

i.e., the fraction of radio emitting volume increase with the cluster mass:

1) radio emitting electrons distributions

2) magnetic field profiles

# A simple explanation from the re-acceleration model

2) turbulent energy density (**$\varepsilon_t$**) as a fraction of the PdV work done by the infalling subhalos (*Cassano & Brunetti 2005; Vazza et al. 2006*)

$$\dot{\varepsilon}_t \propto \frac{\overline{\rho}_H \, \sigma_H^2}{\tau_{cros}}$$

3) turbulence damped by TTD resonance with thermal and relativistic particles

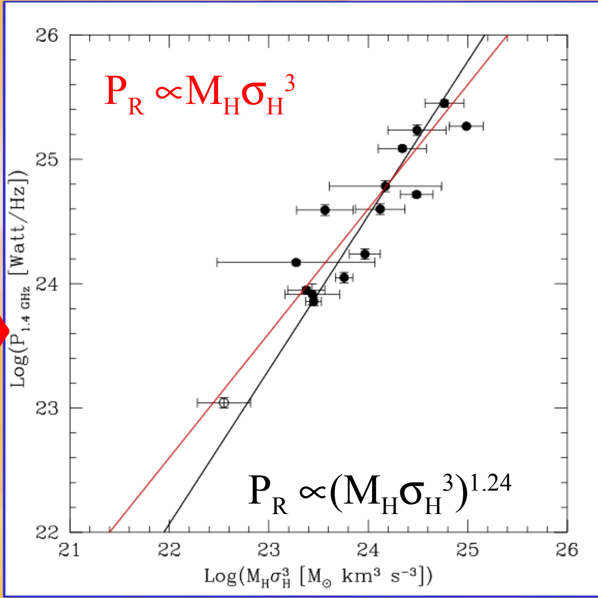
4) $\Gamma_{rel}$ & $\Gamma_{th} >> 1/\tau_{cros}$ & $1/\tau_{acc} \Rightarrow$ stationary condition cab be assumed for **$\varepsilon_t$**

$$\left(\frac{\dot{\varepsilon}_t \, \Gamma_{rel}}{\Gamma_{th} + \Gamma_{rel}}\right) \propto \left(\dot{\varepsilon}_{syn} + \dot{\varepsilon}_{ic}\right)$$

**1)** $$P_R = \int \varepsilon_{syn} \, dV_H \propto \frac{M_H \, \sigma_H^3}{F(z, M_H, b_H)}$$

$$F(z, M_H, b_H) = 1 + \left(\frac{3.2\,(1+z)^2}{B_H}\right)^2$$

$$B_H \propto M_H^{bh}$$



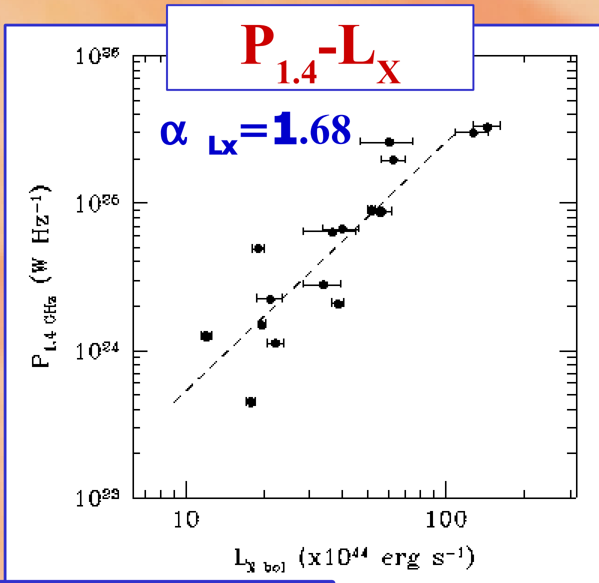

From **1)** + **$M_H \propto R_H^{2.17}$**

$P_{1.4} \propto R_H^{3.9}$ $P_{1.4} \propto M_H^{1.8}$

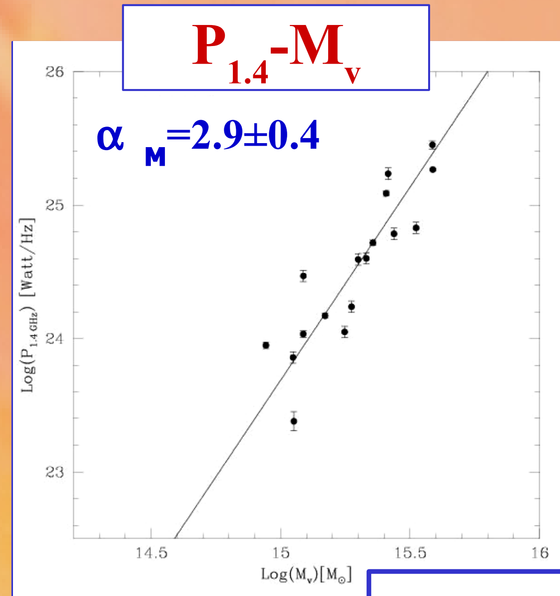
$P_{1.4}$

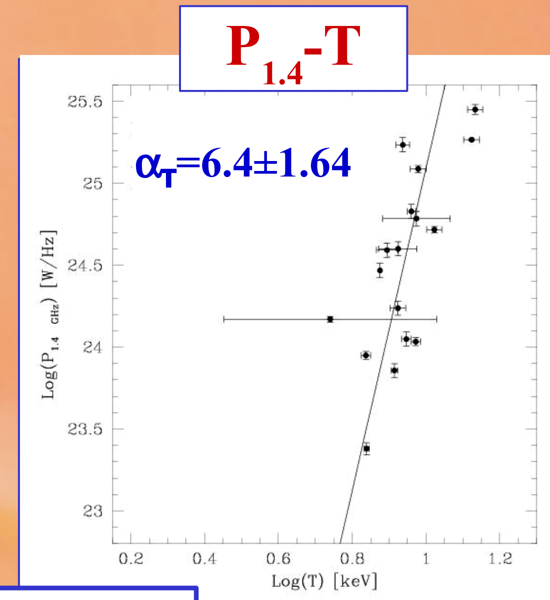
***Consistent with the observed values***

# Observed correlations for GRHs




Bacchi et al. 2003



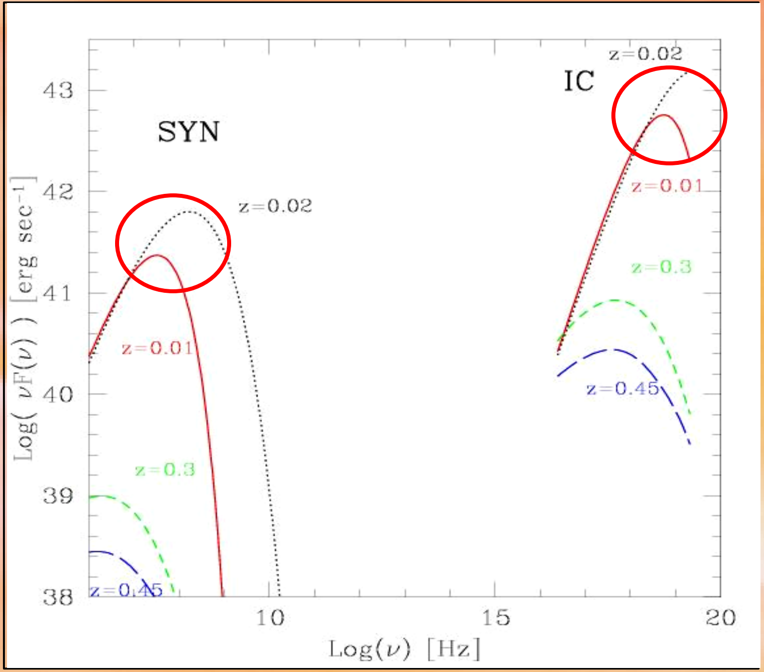

Cassano et al. 2006

**Q: There is a simple explanation of all observed correllations for GRHs in the framework of the re-acceleration model?**

**Starting from new observed correlations for GRH we provide a basic physical interpretation of these new correlations and show that the same interpretation is also valid for all correlations know so far for GRHs (*Cassano et al. 2006; MNRAS Lett. sub*.)**

# First Results of the C&B Model

## *Radio* (Synchrotron) and *Hard X-ray* (IC) emission




The typical observed **$L_R$ ~[$10^{40}$ - $10^{41}$] erg** and **$L_{HX}$ ~ [$10^{42}$ - $10^{44}$] erg $s^{-1}$** can be obtained in massive clusters during merger events, provided that a fraction of the cluster thermal energy (of the order of **3-5 %** ) is channelled into MS waves and that the energy injected into relativistic electrons during the cluster life is at least a few **$10^{-4}$** times the present energy of the thermal pool.

$\eta_e$=0.003

$R_H$=500 Kpc

B=0.5 μG

$\eta_e$ is the ratio between the energy injected in relativistic electrons during the cluster life and the present day thermal energy of the ICM.

# Theoretical predictions of the re-acceleration model

Principal ingredients:

2) turbulent energy density ($\varepsilon_t$) as a fraction of the PdV work done by the infalling subhalos (*Cassano & Brunetti 2005; Vazza et al. 2006*)

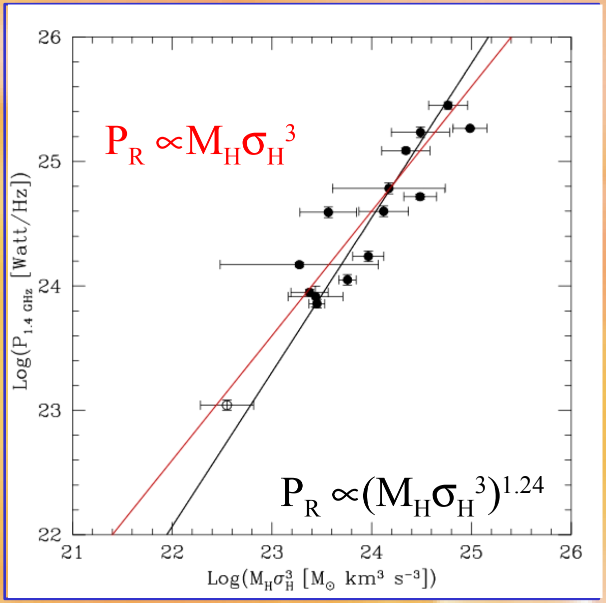
$$\dot{\varepsilon}_t \propto \frac{\overline{\rho}_H \, \sigma_H^2}{\tau_{cros}}$$

3) turbulence damped by TTD resonance with thermal and relativistic particles

4) $\Gamma_{rel}$ & $\Gamma_{th} >> 1/\tau_{cros}$ & $1/\tau_{acc} \Rightarrow$ stationary condition cab be assumed for $\varepsilon_t$

$$\left(\frac{\dot{\varepsilon}_t \, \Gamma_{rel}}{\Gamma_{th} + \Gamma_{rel}}\right) \propto (\dot{\varepsilon}_{syn} + \dot{\varepsilon}_{ic})$$

$$P_R = \int \varepsilon_{syn} \, dV_H \propto \frac{M_H \, \sigma_H^3}{F(z, M_H, b_H)}$$




$$F(z, M_H, b_H) = 1 + \left(\frac{3.2\,(1+z)^2}{B_H}\right)^2$$

$B_H \propto M_H^{b_h}$

- $B_H >> B_{cmb}$ F~const
- $B_H << B_{cmb}$ F~const if $b_h$~0 ⇒ **$0.05 \leq b_h \leq 0.39$**

# Work in progress & Future prospective

**Open questions: what about the approximation of the model?**
**Help from simulations?**

*in collaboration with* ***Klaus Dolag***
(MPA- Garching)

## Merger-trees formalism & ram pressure stripping

- **The P&S formalism is based on the spherical collapse (cluster formation derives from the collapse of spherical perturbations). There are several evidence on the fact that the collapse of structure are not simple spherical.**
- **In addition we use a simple semi-analytical approach to calculate the stripping volume of the subcluster (assuming a beta-model profile for the subcluster, and the mean density for the main one).**

## The simulations can help us to follow the "real" mass accreation history of a cluster.

**In this way will be possible to follow:**

**1) the time evolution of a merger between the cluster and the satellite;**

**2) the disruption of the satellites (mass lost from the satellite and the gas which remain gravitationally self-bound);**

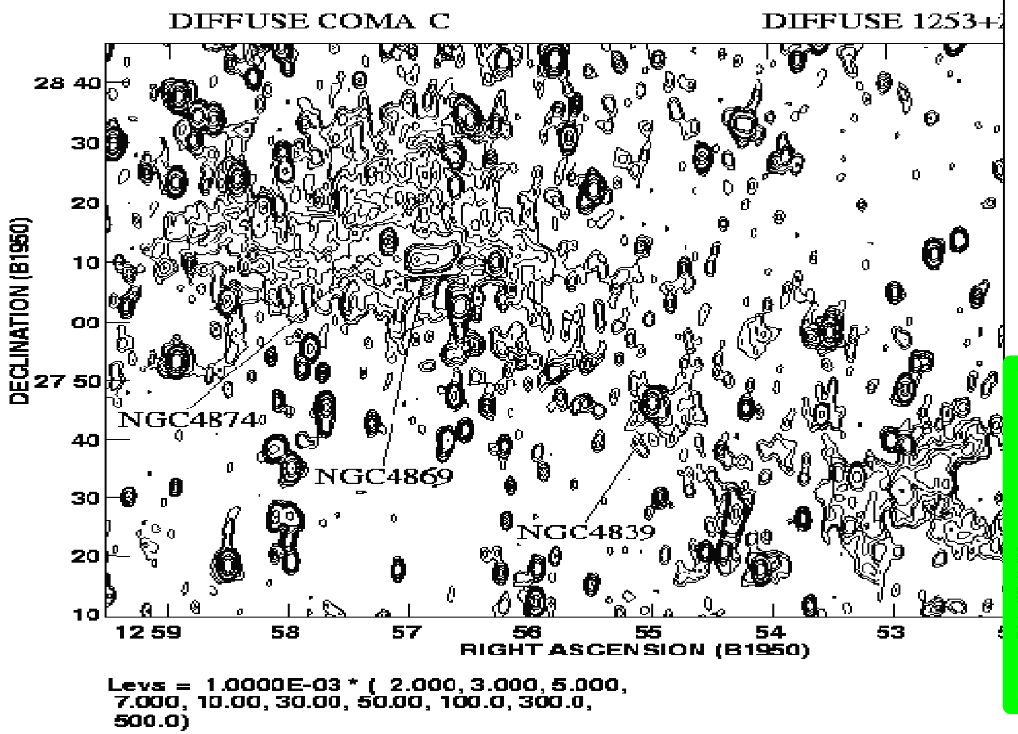
**3) multiple merger events.**

*Fi ne*

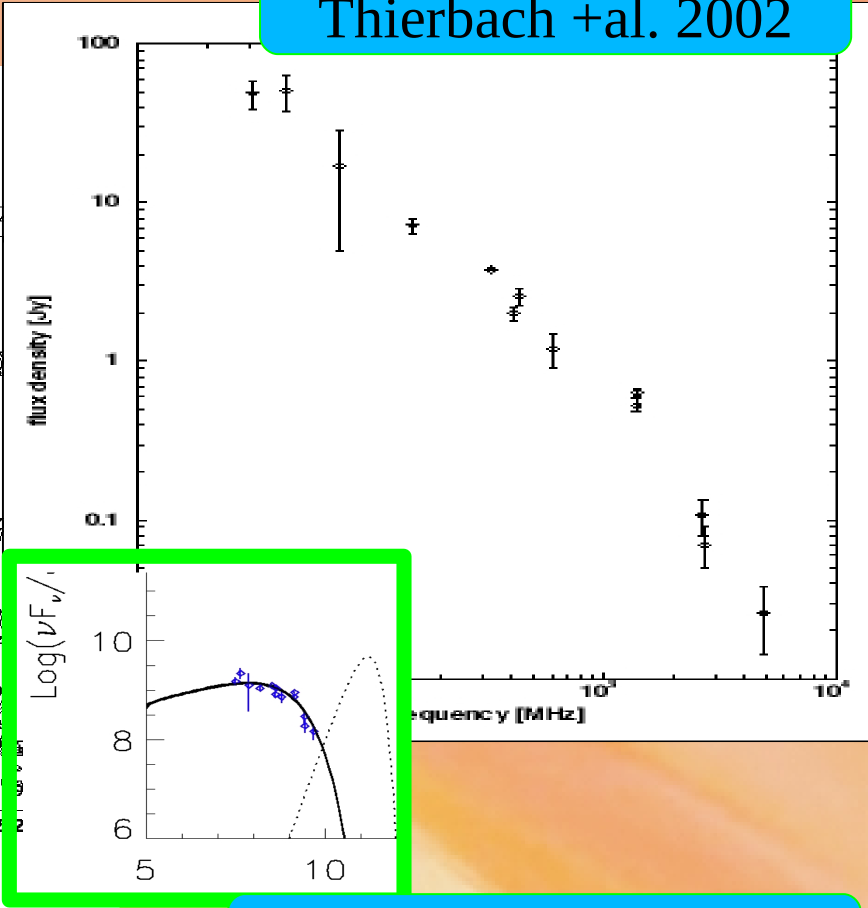
# *Magnetic field in the Coma cluster*

- Statistics of radio halos: **$0.2\ \mu G \leq B \leq 3.7\ \mu G$** ( cental Mpc) if **$B \propto T^2$** (*Dolag et al 2002*) than **$1.7\ \mu G \leq B \leq 3\ \mu G$**
- two-fase model (*Brunetti et al 2001*): **$B \sim 1\text{-}1.5\ \mu G$**
- IC method (*Fusco-Femiano 2001*): **$B_{IC} \sim 0.15\ \mu G$** (volume average magnetic field)
- Rotation mesures (*Kim et al 1990, Feretti et al. 1995*): **$B_{RM} \sim 2\text{-}5\ \mu G$**

RADIO




Thierbach +al. 2002




Reimer +al. 2004

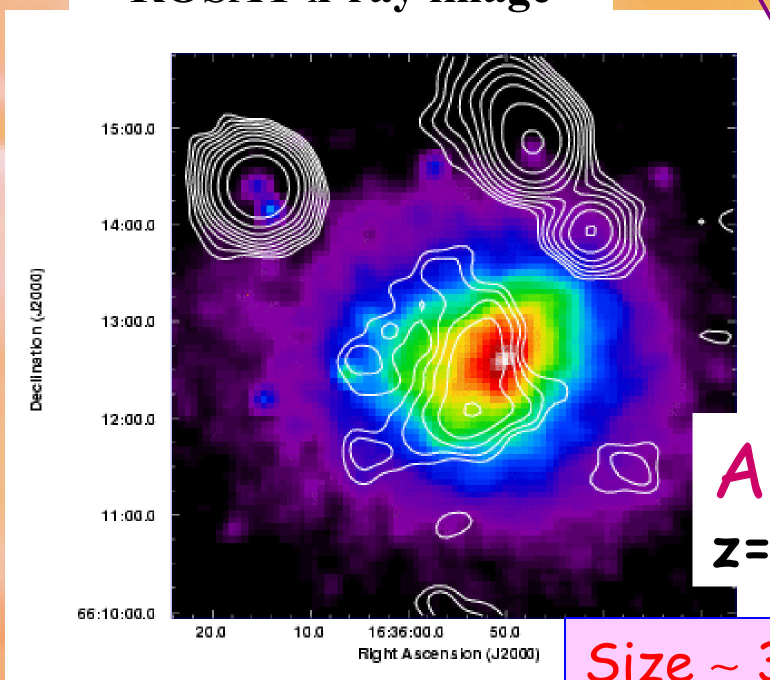
$$\tau_e(\mathrm{Gyr}) \sim 4 \times \left\{ \frac{1}{3}\left(\frac{\gamma}{300}\right)\left[\left(\frac{B_{\mu G}}{3.2}\right)^2 \frac{\sin^2\theta}{2/3} + (1+z)^4\right] + \left(\frac{n_{\rm th}}{10^{-3}}\right)\left(\frac{\gamma}{300}\right)^{-1}\left[1.2 + \frac{1}{75}\ln\left(\frac{\gamma/300}{n_{\rm th}/10^{-3}}\right)\right]\right\}^{-1}.$$

**< 0.1 Gyrs**

# Other diffuse cluster radio source:

## Mini-Halos

VLA 1.4 GHz contours on ROSAT x-ray image




A 2218

z=0.1756

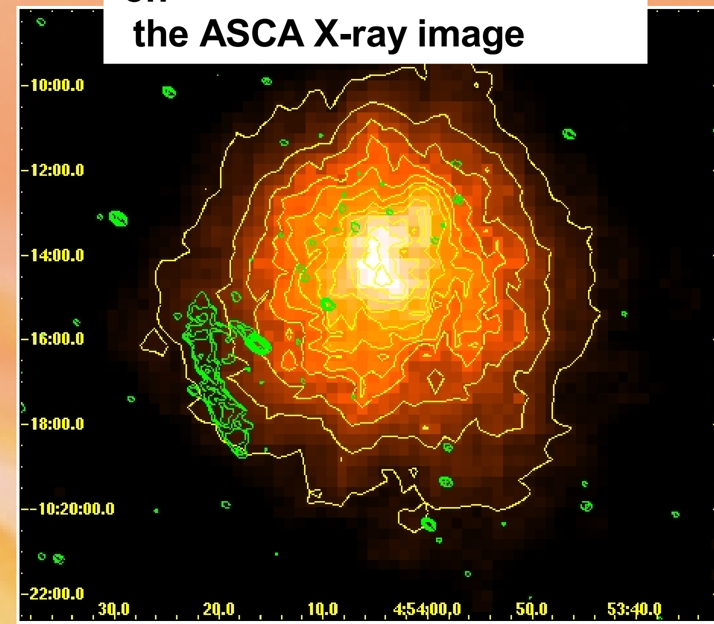
Size ~ 350 $h_{70}^{-1}$ kpc

Giovannini & Feretti 2000

## Relics

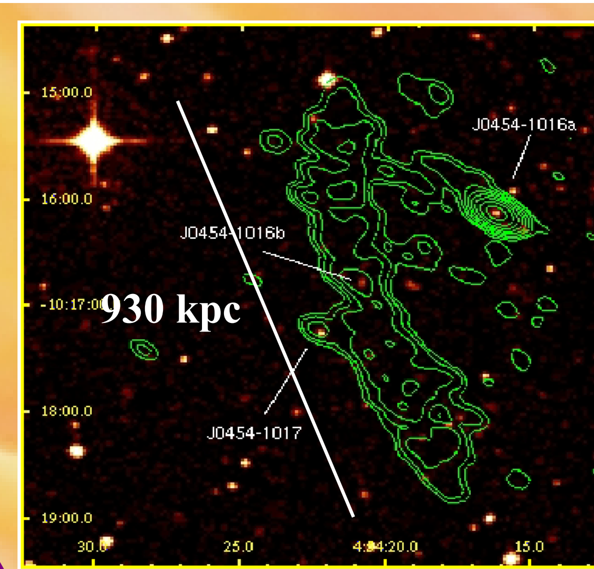
Giacintucci et al. 2005

GMRT 610 MHz contours on the ASCA X-ray image

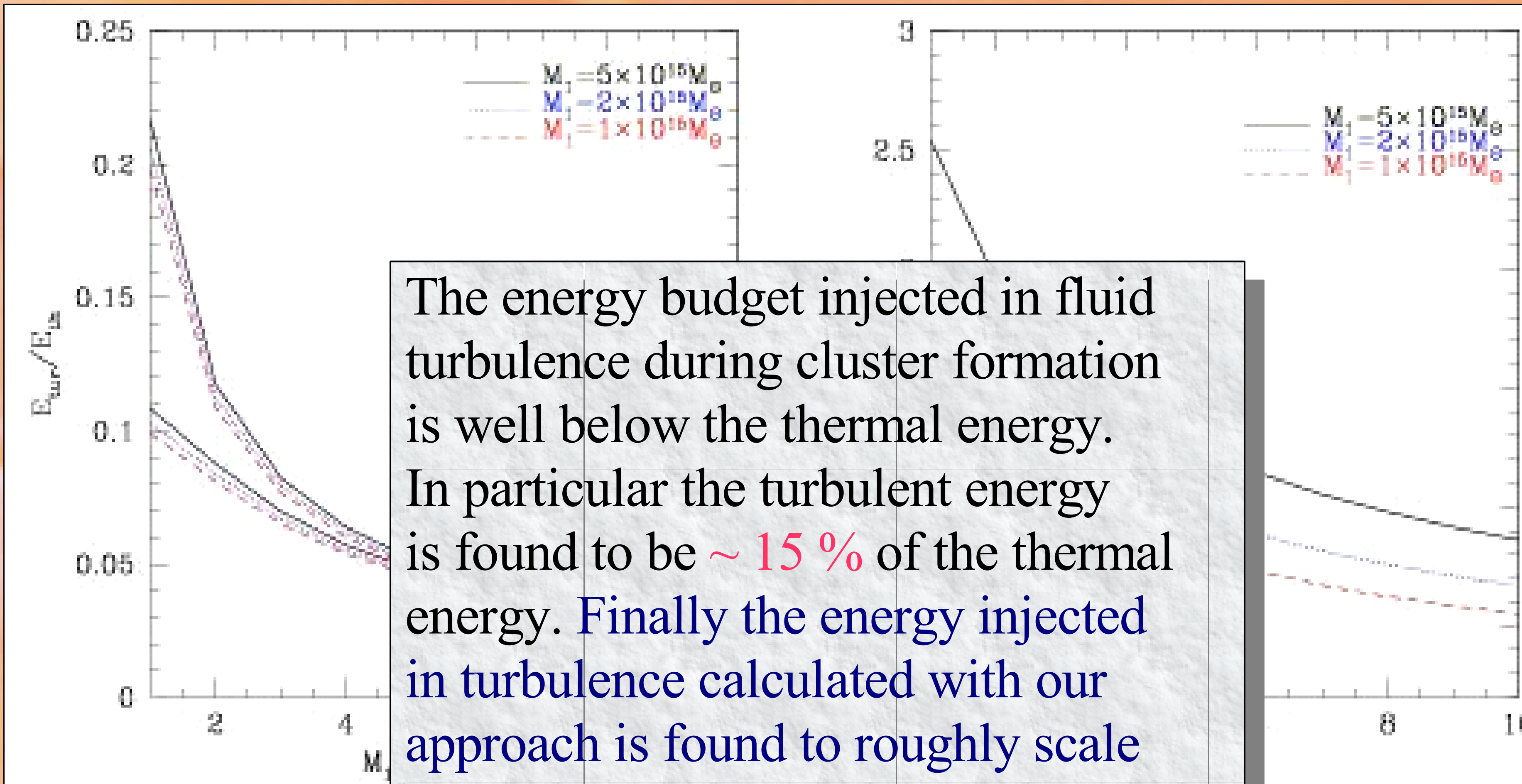



A 521

z=0.247

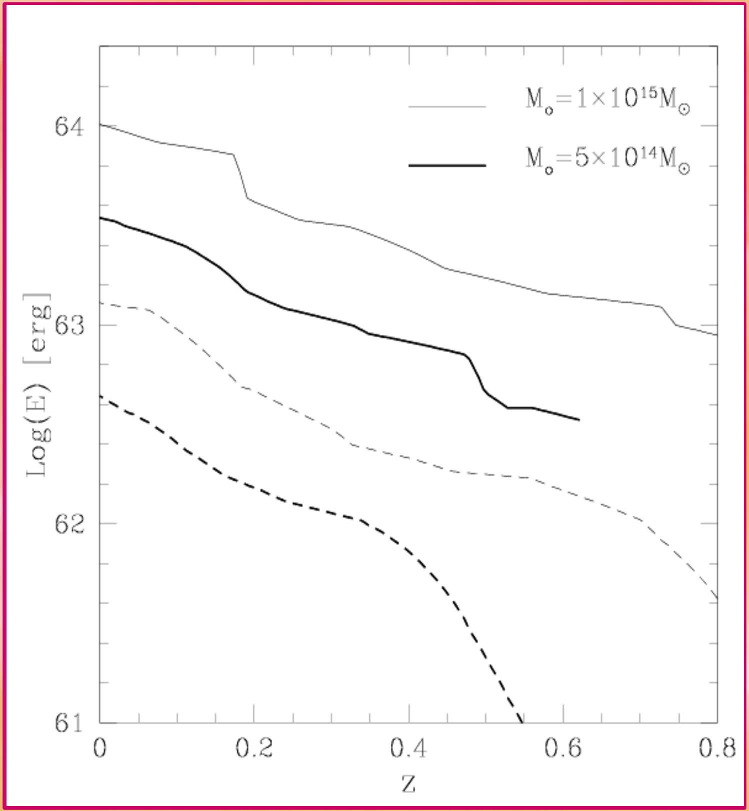


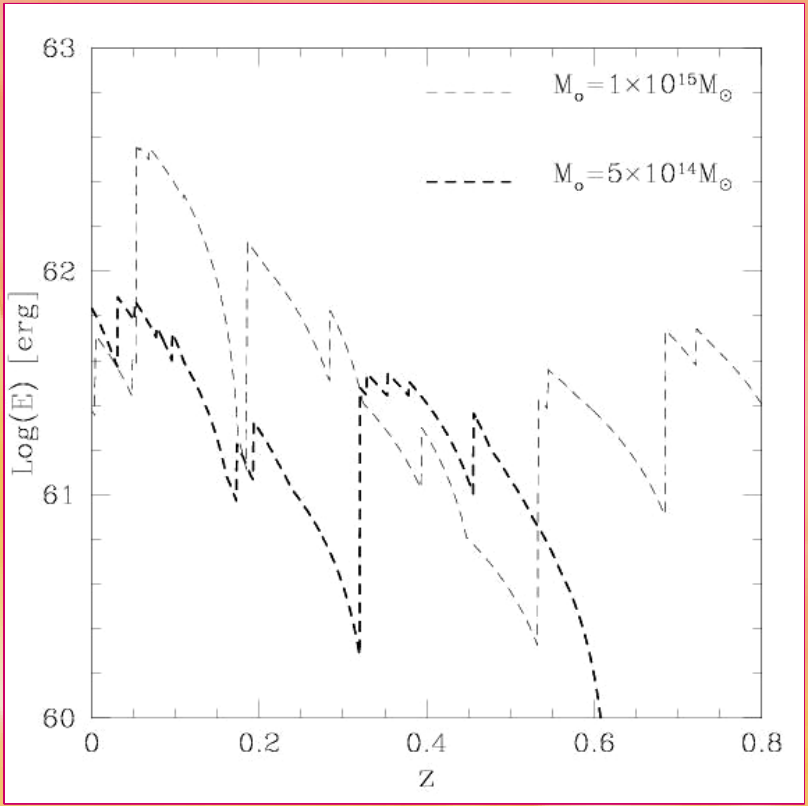
# *Energy budget in fluid turbulence during cluster formation*



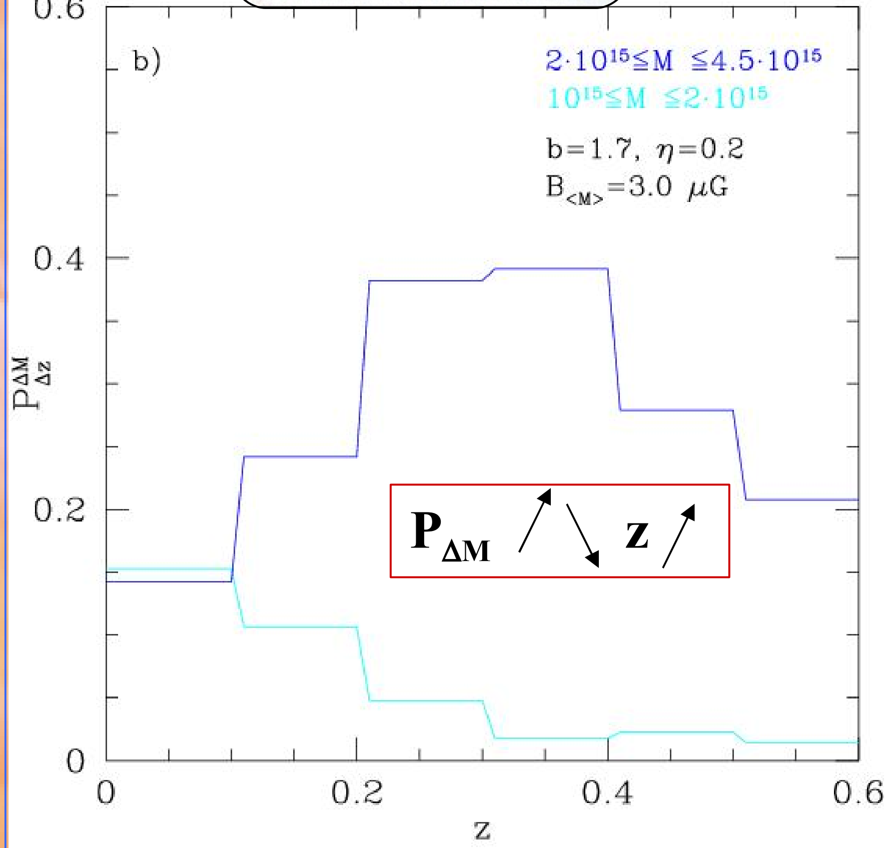

The energy budget injected in fluid turbulence during cluster formation is well below the thermal energy.
In particular the turbulent energy is found to be ~ 15 % of the thermal energy. Finally the energy injected in turbulence calculated with our approach is found to roughly scale with the thermal energy of the cluster.

# Turbulent Energy vs Thermal Energy

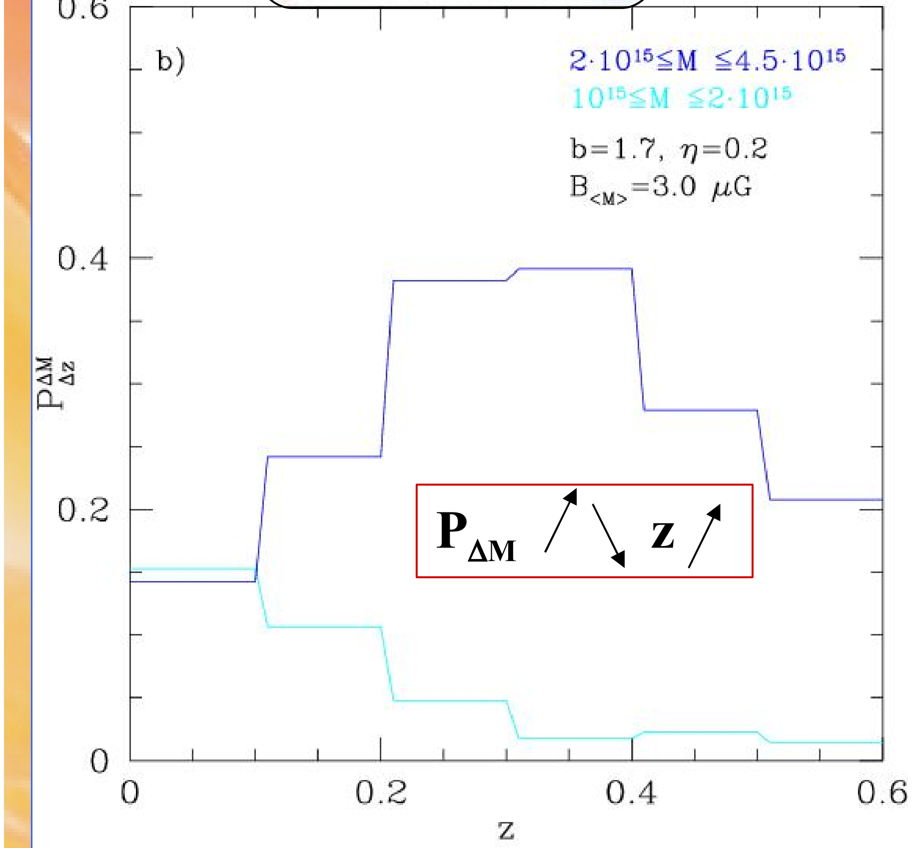


super-linear scaling **b=1.7**




super-linear scaling **b=1.7**



0.6
0.4
0.2
0
$P^{\Delta M}_{\Delta z}$
b)
$2\cdot10^{15} \leq M \leq 4.5\cdot10^{15}$
$10^{15} \leq M \leq 2\cdot10^{15}$
b=1.7, $\eta$=0.2
$B_{<M>}$=3.0 $\mu$G
$P_{\Delta M}$ ↗ ↘ z ↗
0
0.2
0.4
0.6
z

**Assuming** the *Connection with Mergers* **Kuo et al.(2004)** have shown that *Secondary Models* produce **an occurrence of Radio Halos larger than observed**: the life time of a Radio Halo should be of theorder of **1 Gyr**.

## Open questions: what about the approximation of the model? Help from simulations?

### 1) Injection of turbulence

MS waves injected at a maximum scale, $k=k_{min} \sim \pi/r_s$

**The decay time of the MHD turbulence at the maximum/injection scale, $L_{inj} \sim 2r_s$, can be estimated as $\tau_{kk}(L_{inj}) \sim r_s / v_i \eta_t$, one has :**

$$\tau_{kk}(Gyr) \sim 1 \cdot (v_i / 2 \cdot 10^3 \text{ km s}^{-1})^{-1} (r_s / 500 \text{ kpc}) (\eta_t / 0.25)^{-1} \sim \tau_{cros} \Rightarrow$$

***The turbulence diffuse filling a volume of the order of that of RHs (or larger) with a fairly uniform intensity***

To trace the spatial diffusion of the turbulence we need high resolution simulations!!!

## 2) Merger-trees formalism & ram pressure stripping

**The P&S formalism is based on the spherical collapse in which the cluster formation derives from the collapse of spherical perturbations. There are several evidence on the fact that the collapse of structure are not simple spherical. In addition we use a simple semi-analytical approach to calculate the stripping volume of the subcluster (assuming a beta-model profile for the subcluster, and the mean density for the main one)**

**The simulations can help us to follow the 'real' mass accreation history of a cluster.**

**In this way will be possible to follow:**

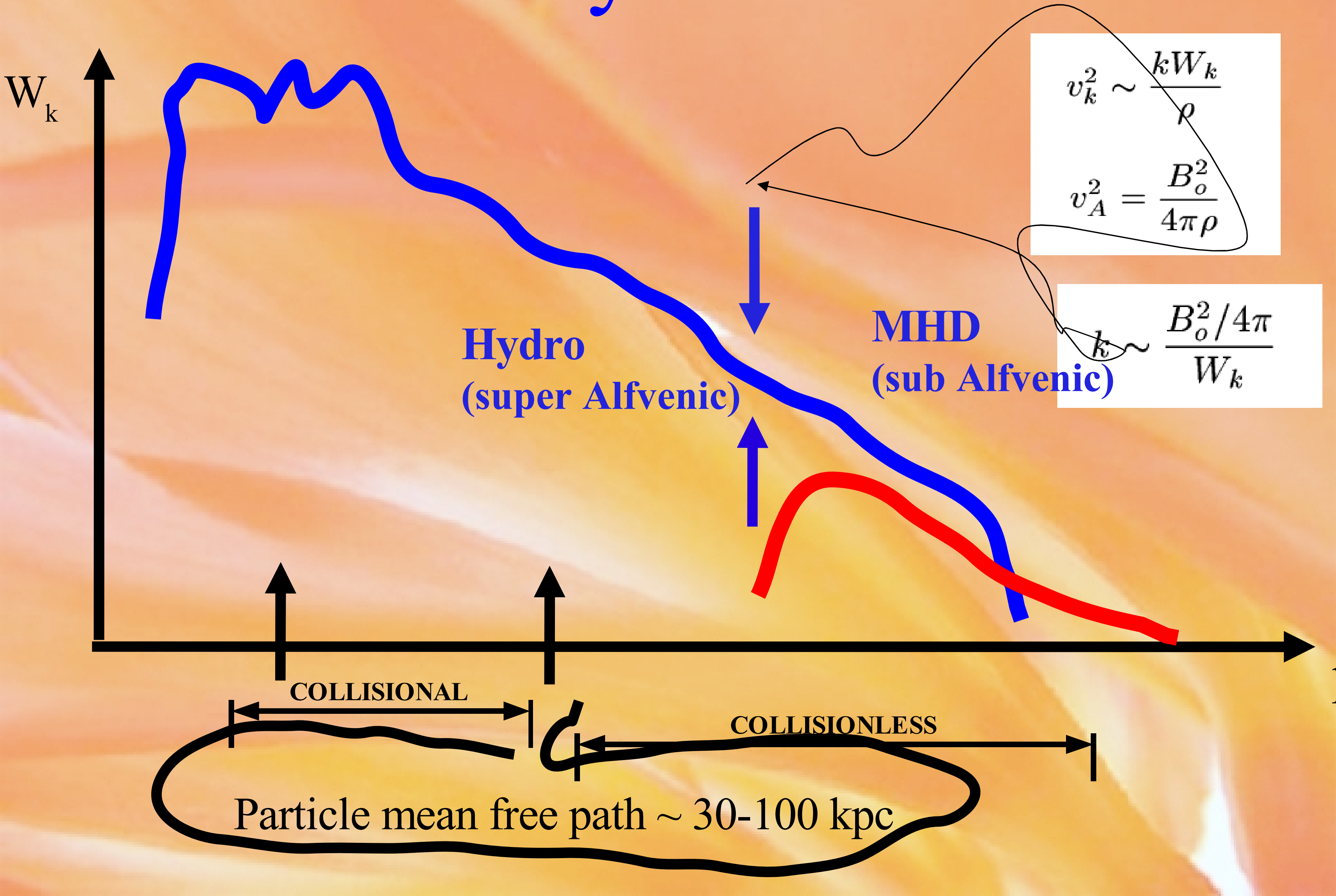
**1) the time evolution of a merger between the cluster and the satellite;**

**2) the disruption of the satellites (mass lost from the satellite and the gas which remain gravitationally self-bound);**

**3) multiple merger events.**

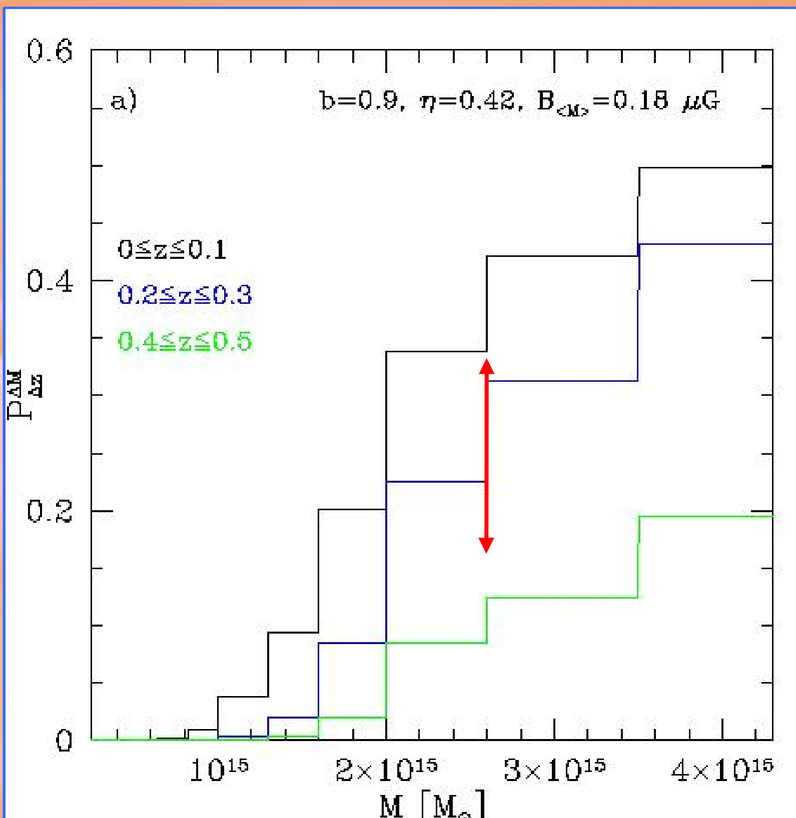
**Part of this work will be done in collaboration with Klaus Dolag in Monaco.**

# Turbulence Physics: BASICS



# PRELIMINARY CONSIDERATIONS ON THE STATISTICS

Radio information is available for **15** out of the **27** clusters of the REFLEX subsample (**11** from our observations and **4** from literature (**3** with a GRH). Among our 11 clusters we have discovered **2 new GRHs,** A209 (see also *Giovannini et al. 2006*) and RXCJ2003, and a RH of smaller size in RXCJ1314 (see also *Feretti et al. 2006*).



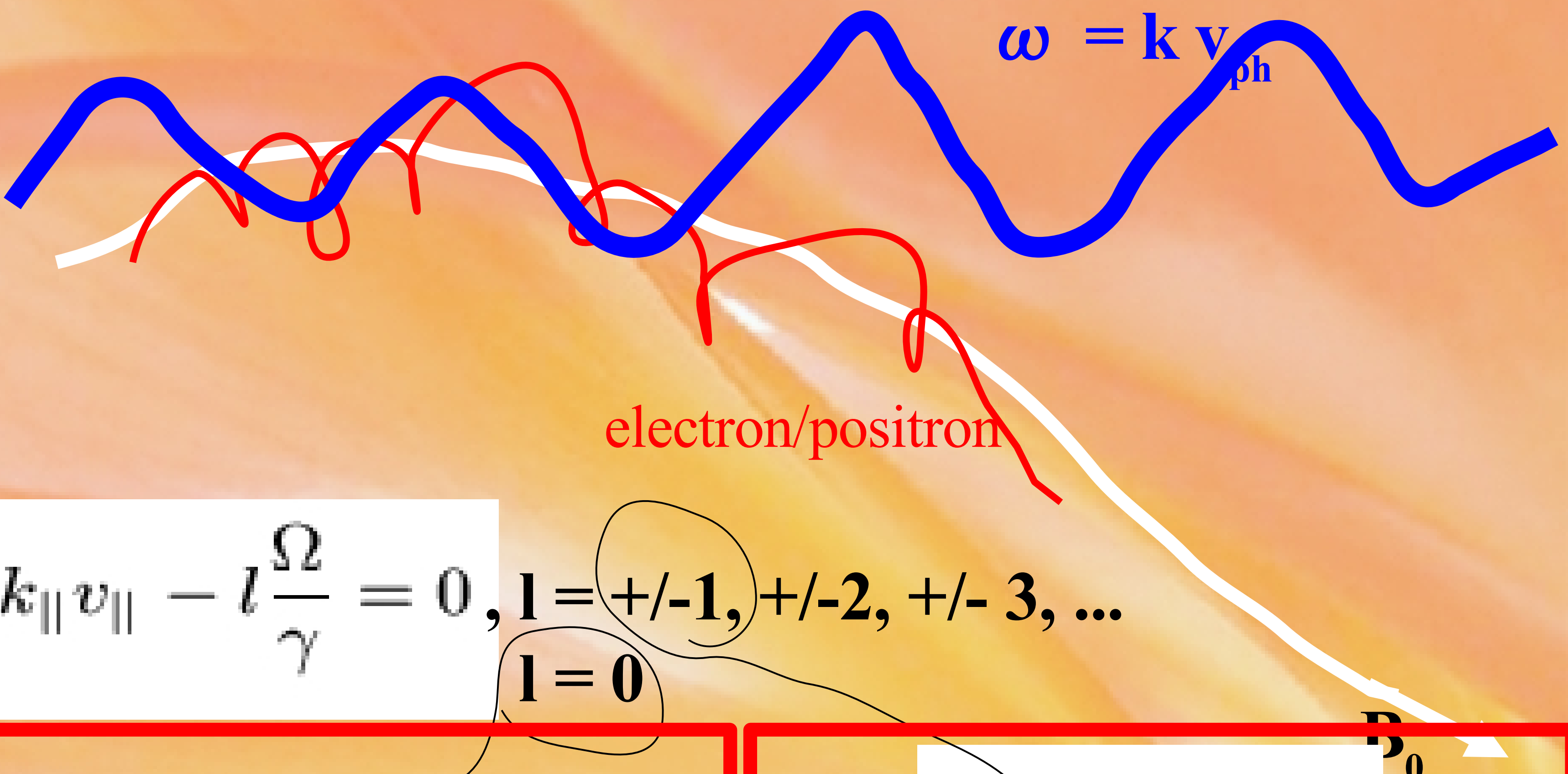

a) if we consider 2 RHs among 11 clusters → $P_H(M)$~18.2±12.8%

b) if we consider 5 RHs among 15 clusters → $P_H(M)$~30±15%

c) if we consider 5 RHs among 27 clusters → $P_H(M)$~18.5±8.3%

**Although we have only a preliminary estimate of the $P_H(M)$ in the range 0.2≤ z ≤0.4, the detected fraction of RHs in the sample is in the range of the above theoretical expectations.**

# MHD Modes (waves): Resonanc




$$\omega - k_{||} v_{||} - l \frac{\Omega}{\gamma} = 0$$

, **l = +/-1, +/-2, +/- 3, ...**

**l = 0**

$$\omega = k_{||} v_{||}$$

$$k_{res} = \frac{\Omega m}{p} \frac{1}{\left(\mu \pm \frac{v_A}{v}\right)}$$

**Alfven, Fast, Slow Modes**

# MHD Modes (waves): Resonance II