RADIO HALOS IN GALAXY CLUSTERS

Seeing beyond the tip of the iceberg

"Diffuse synchrotron emission in clusters of galaxies What's Next?

Rossella Cassano

INAF-IRA, Bologna, ITALY

Coll.s: G. Brunetti, T. Venturi, S.Giacintucci, D.Dallacasa, S. Ettori, Giocoli, V, Cuciti, G. Bernardi, …R.Kale, G. Pratt; M. Markevitch; K. Dolag; H. Röttgering, M.Brüggen, V, Cuciti, G. Bernardi, …

Leiden, 23-27 October 2017

Outline of the talk

Present theoretical picture for giant RH in GC

Importance of statistical studies

Observations of "statistical" RH populations

(occurrence, radio-X-ray/mass correlations, etc…)

What's Next?

Future Surveys

(LOFAR… SKA)

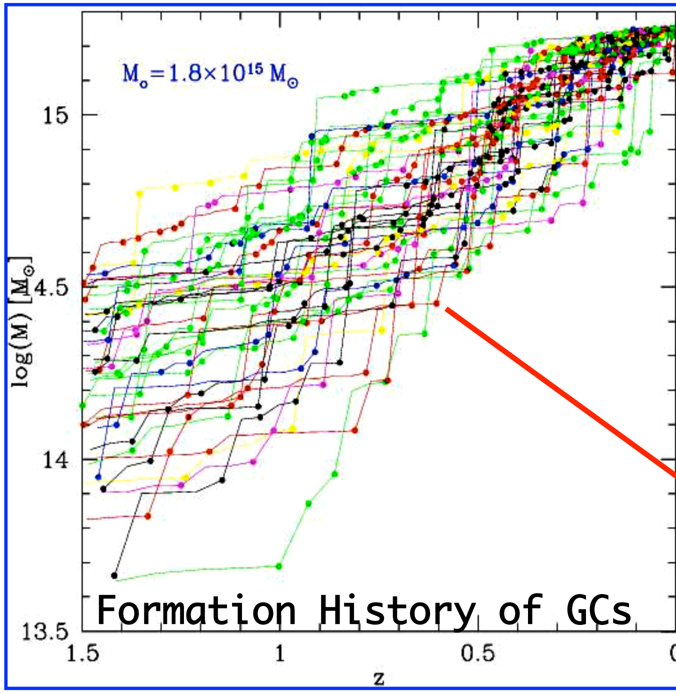
RH as probes of the cluster merging rate ?

Can we use RH to understand cluster mergers properties ?

(first attempts)

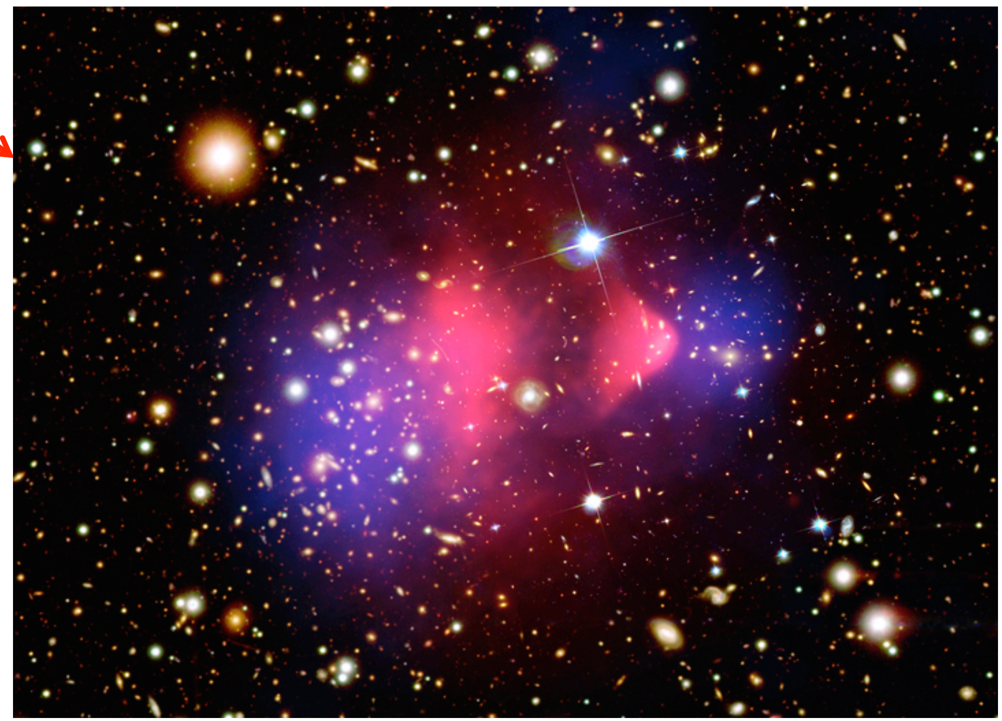
Theoretical (cartoon) picture for GRH in GCs

Brunetti & Jones 14 for a review



- **Giant Radio Halos** are generate in connection with galaxy cluster **mergers**
- Mergers drive **turbulence** and **shocks** in the ICM

Stochastic turbulent re-acceleration of CRe (fossil and secondaries) via Fermi II-type mechanisms generates **Giant Radio Halos (GRH)**



Clowe et al. 06; Markevitch 2010

Theoretical (cartoon) picture for GRH in GCs

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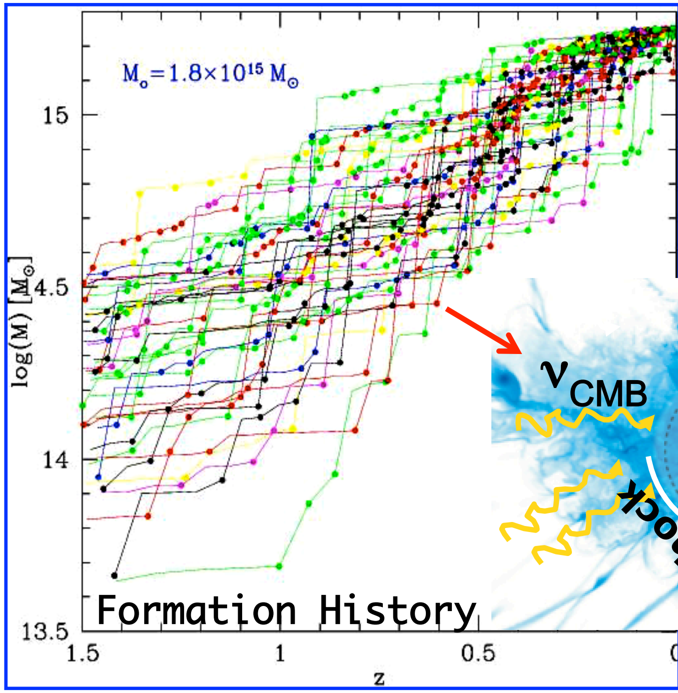

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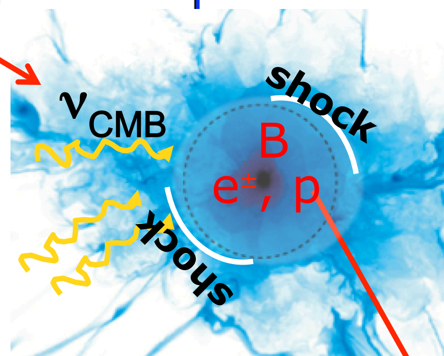
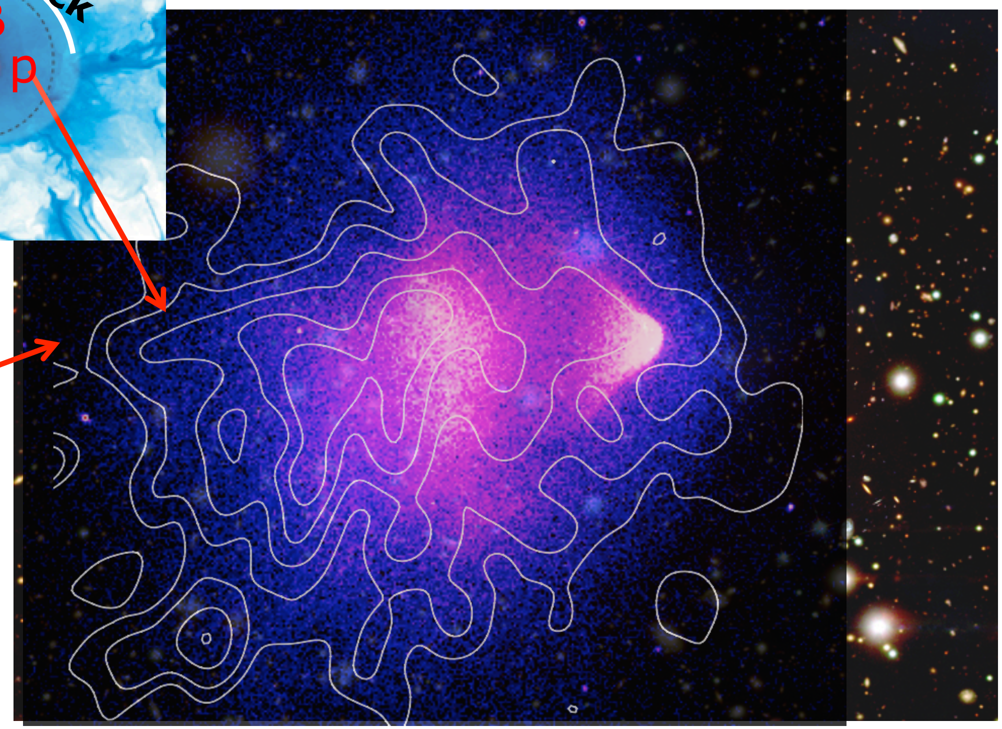
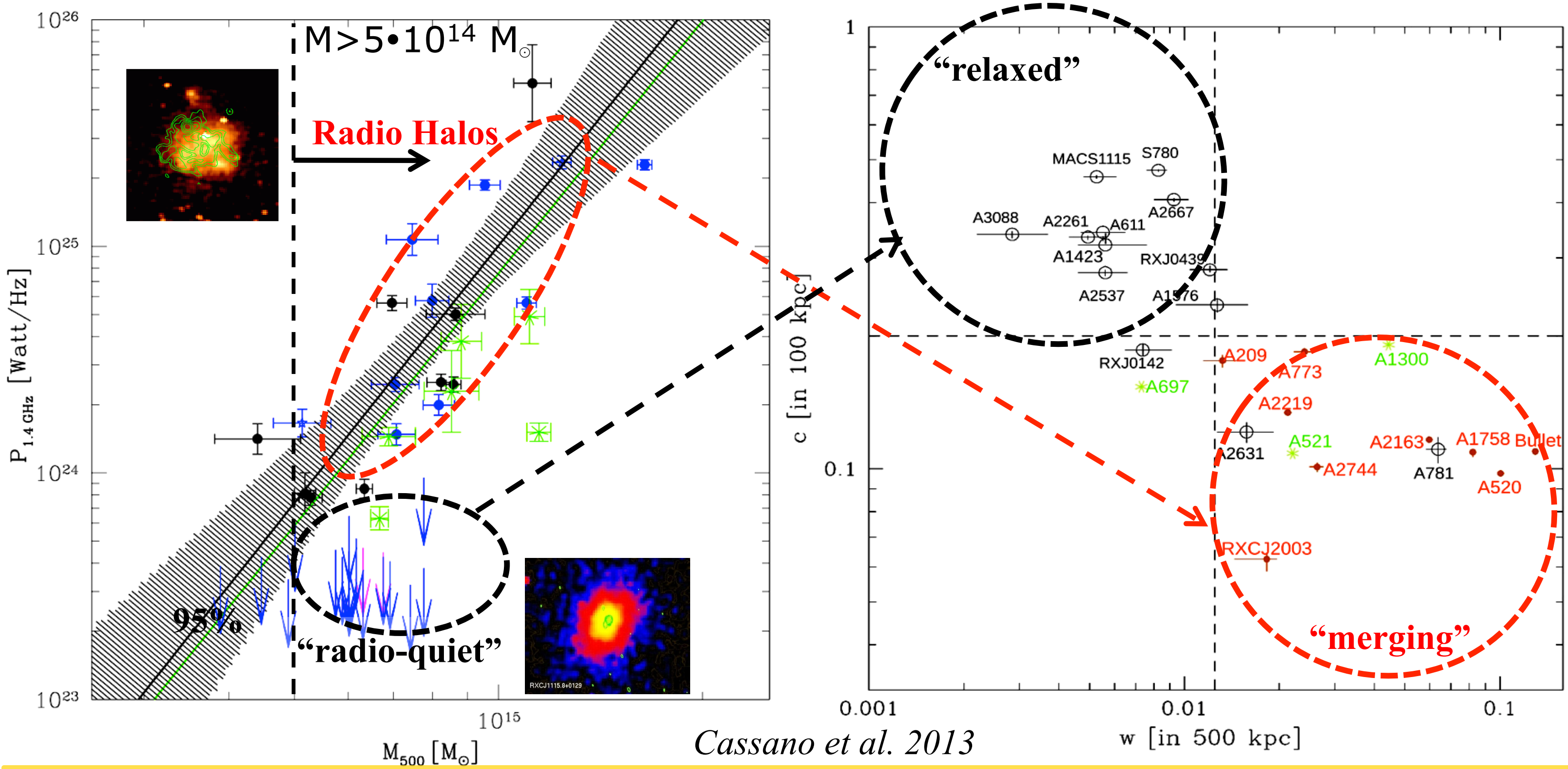




Stochastic turbulent re-acceleration of CRe (fossil and secondaries) via Fermi II-type mechanisms generates **Giant Radio Halos (GRH)**

Clowe et al. 06; Markevitch 2010

RADIO BIMODALITY: radio halos in merging systems

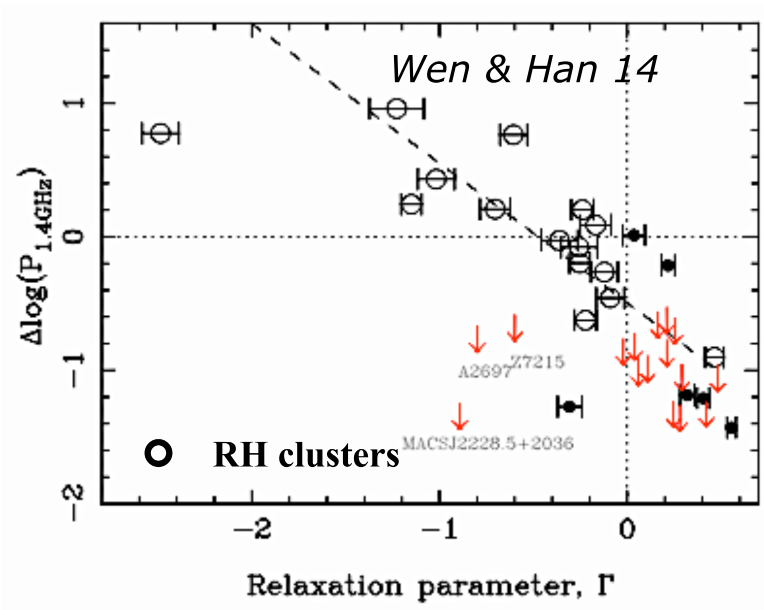


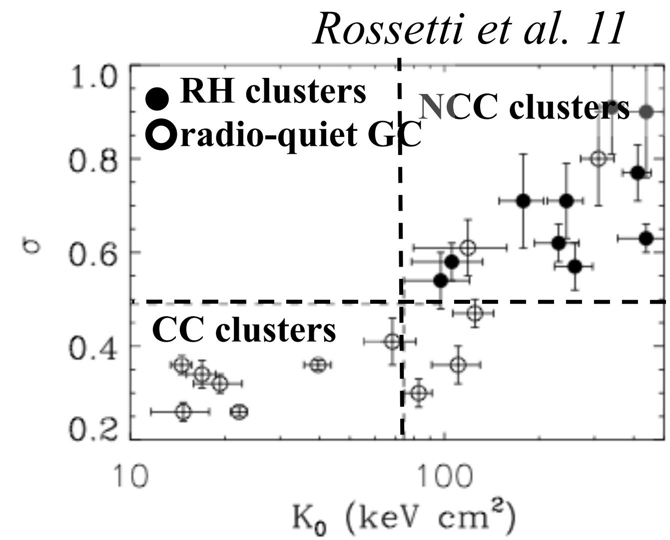
Cassano et al. 2013

GRH are statistically found in merging clusters while clusters without RH (with upper limits to diffuse radio flux) **reside in more "relaxed" clusters** (*Brunetti et al.07, Venturi et al. 07, 08; Kale et al. 2015; Cassano et al. 10, 13; Cuciti et al. 15*).

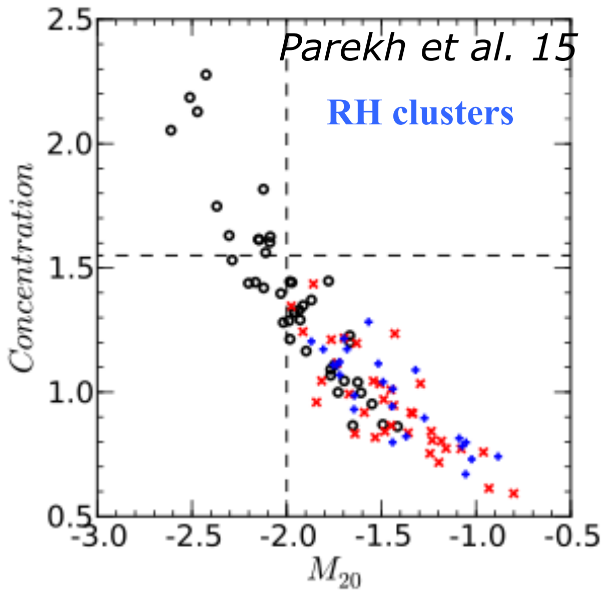
There are however a few controversial examples (see e.g.; Bonafede et al. 14, Sommer et al. 16). + **talk by Cuciti**

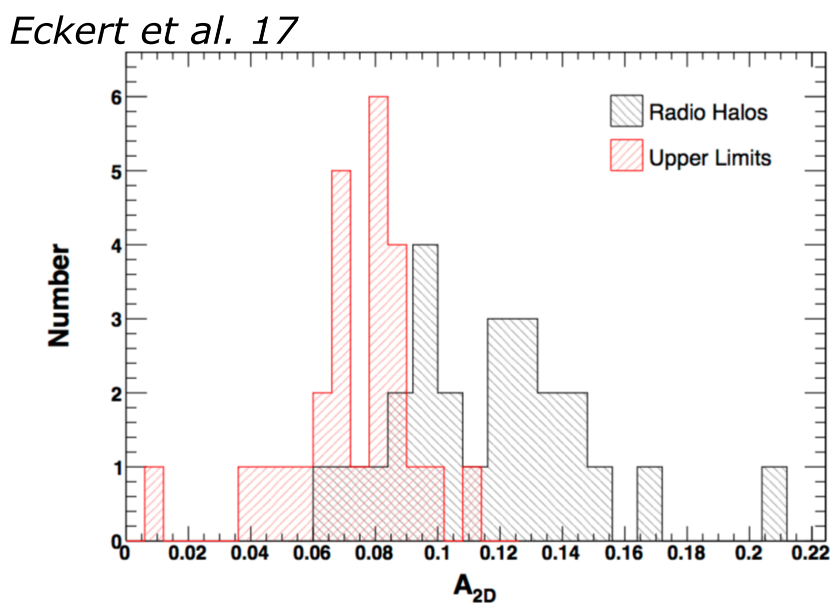
Radio Halo-merger connection





These results have been confirmed by independent groups using different methods and different samples.





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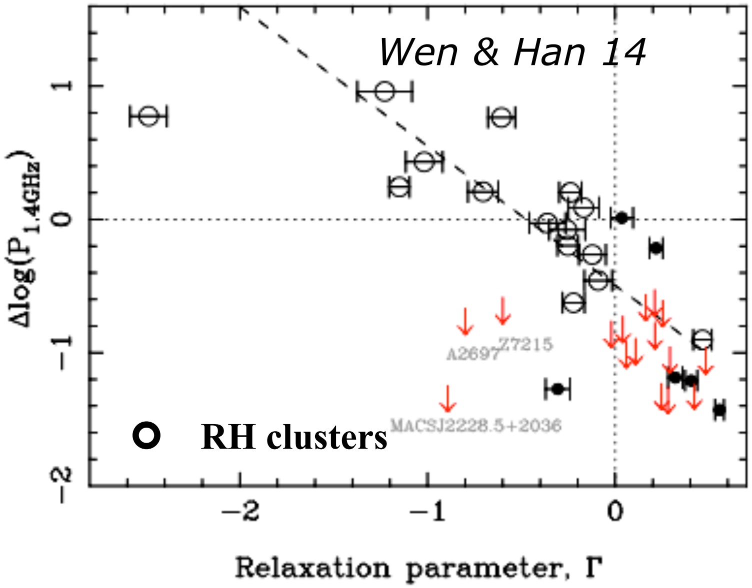

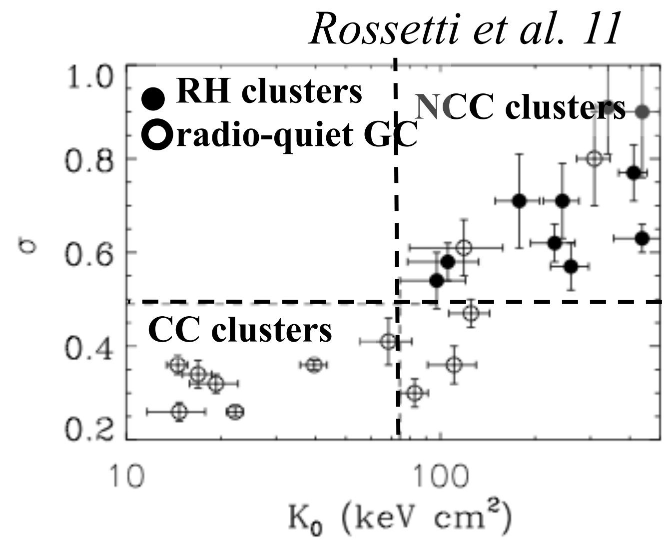

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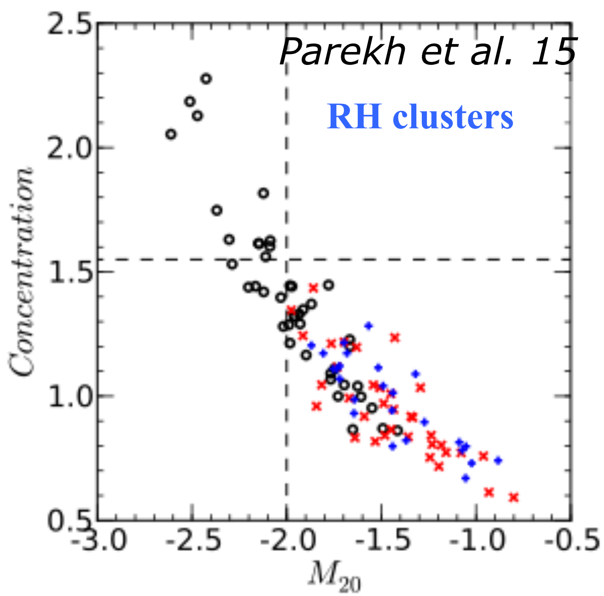
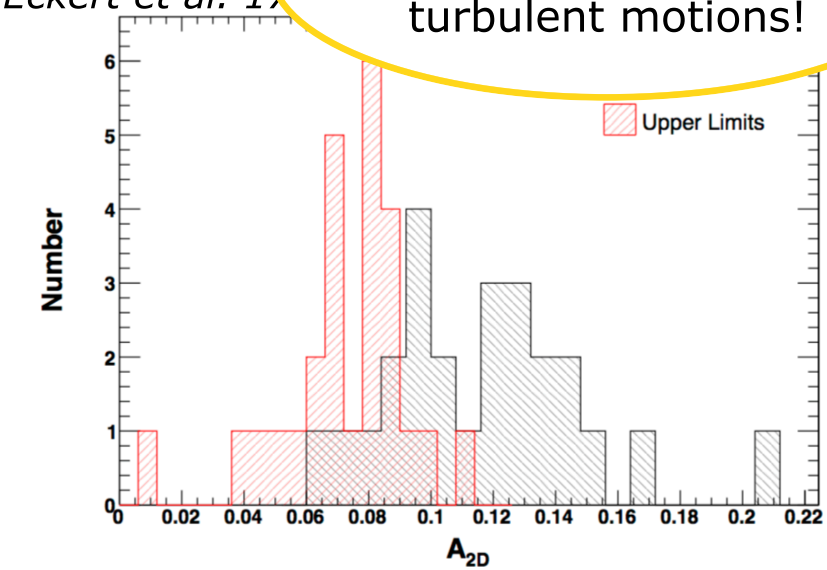
First attempt to connect GRH to turbulent motions!

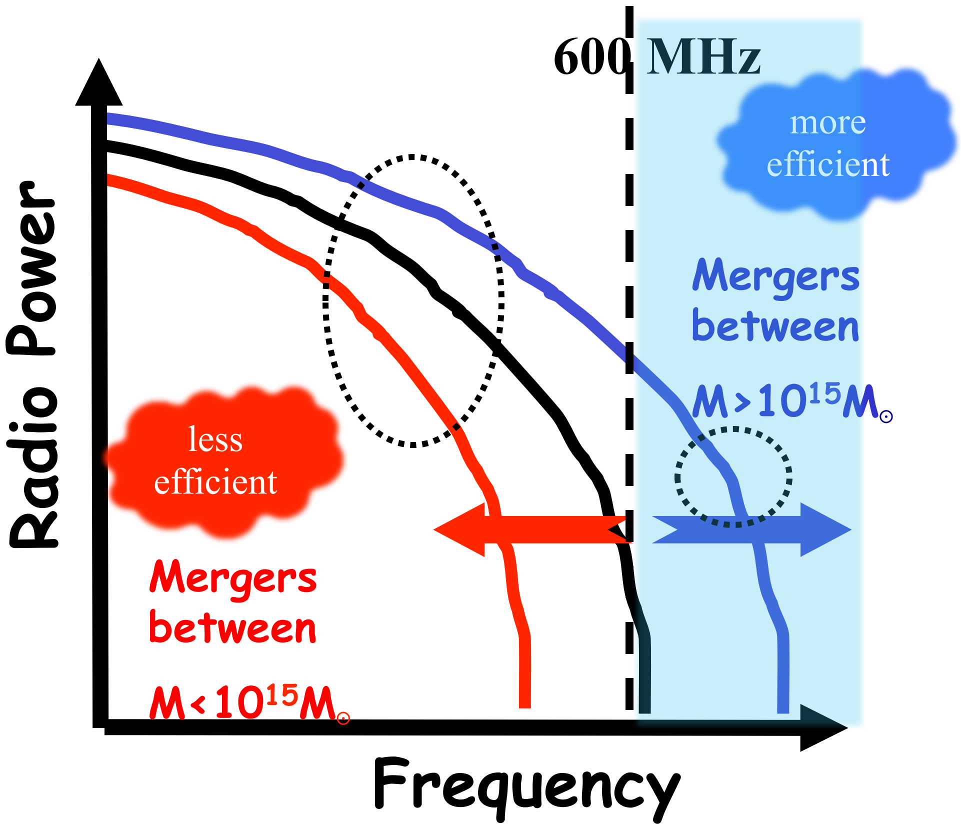




talk by Zimmer (Ekert)

Basic theoretical expectations (turbulence)

Cassano & Brunetti 05; Cassano et al. 2006, 2010, 2012



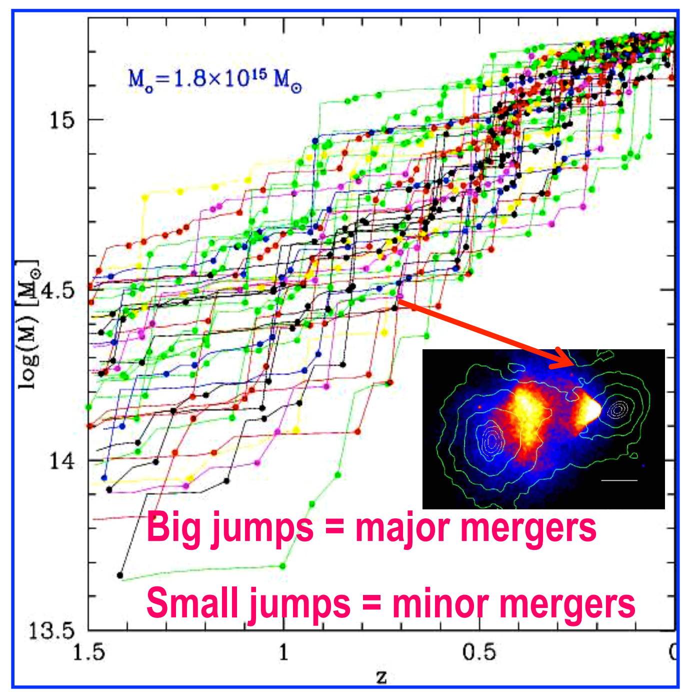
Acceleration efficiency

$\chi \approx 1/\tau_{acc}$

Steepening frequency

$$\nu_s \propto \langle B \rangle \gamma_{max}^2 \propto \frac{\langle B \rangle \chi^2}{\left(\langle B \rangle^2 + B_{cmb}^2 \right)^2}$$

Semi-analytic models to describe the formation history of galaxy clusters



At **GHz frequency**

✔ RH common in massive-merging GCs

✔ RH rare in less massive-merging GC

=> **drop of fraction of RHs at lower masses**

«mass sets the energy available»

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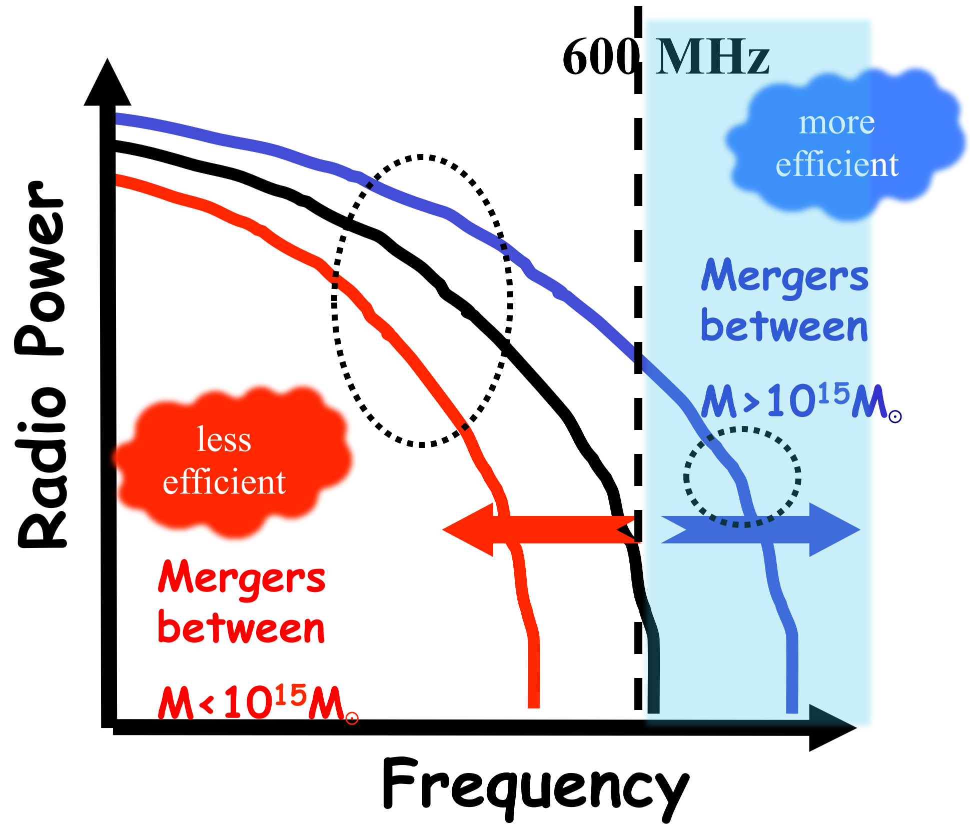

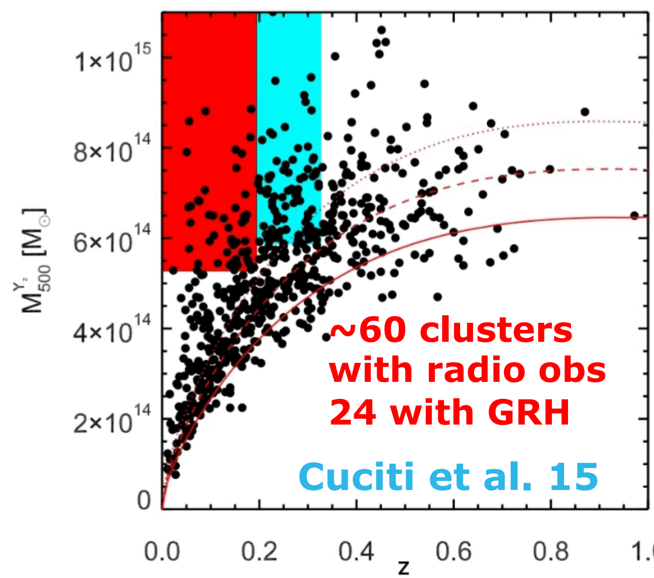

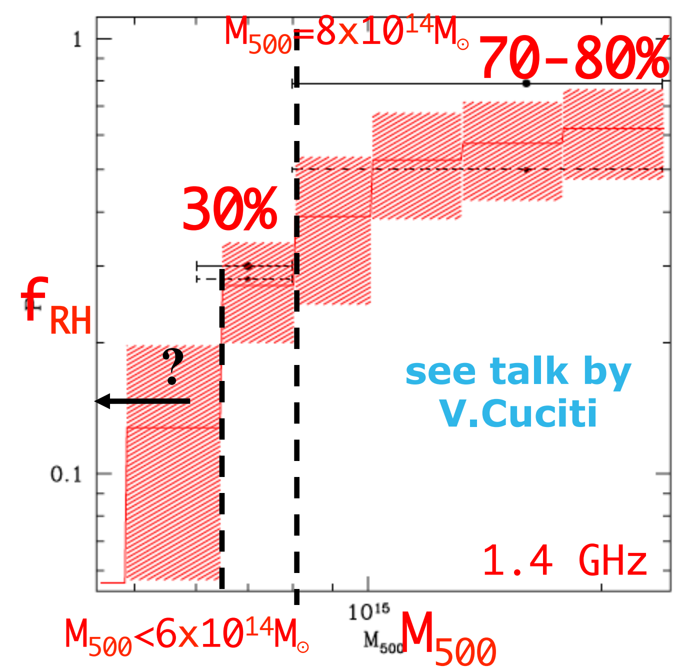

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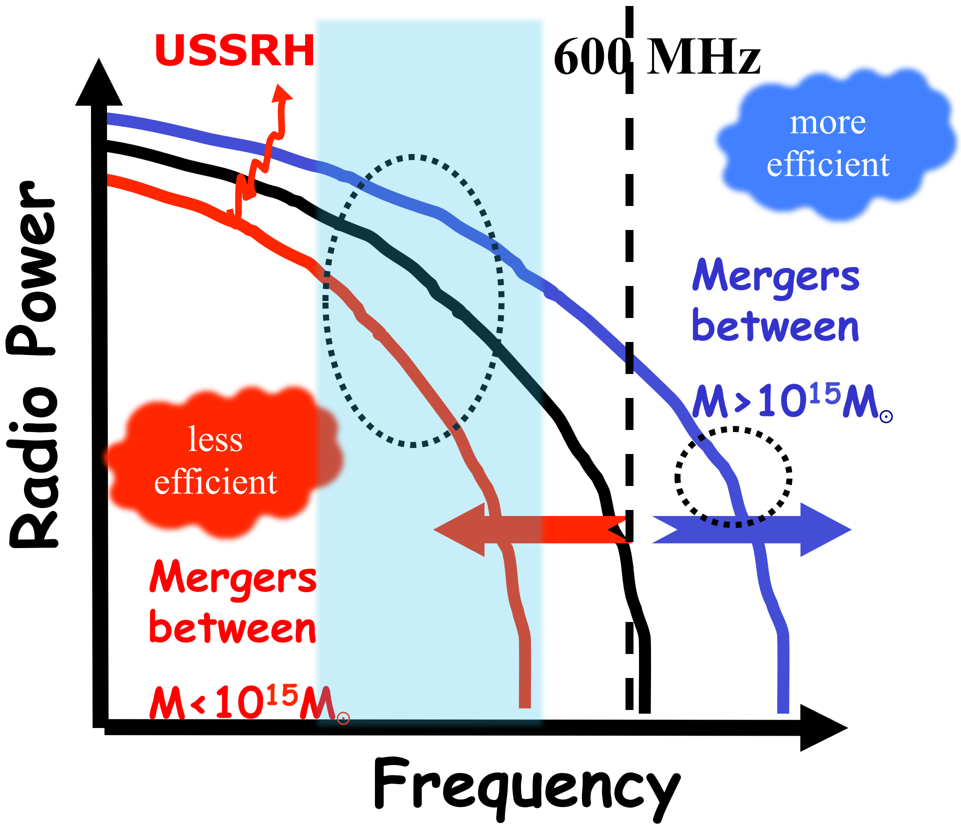

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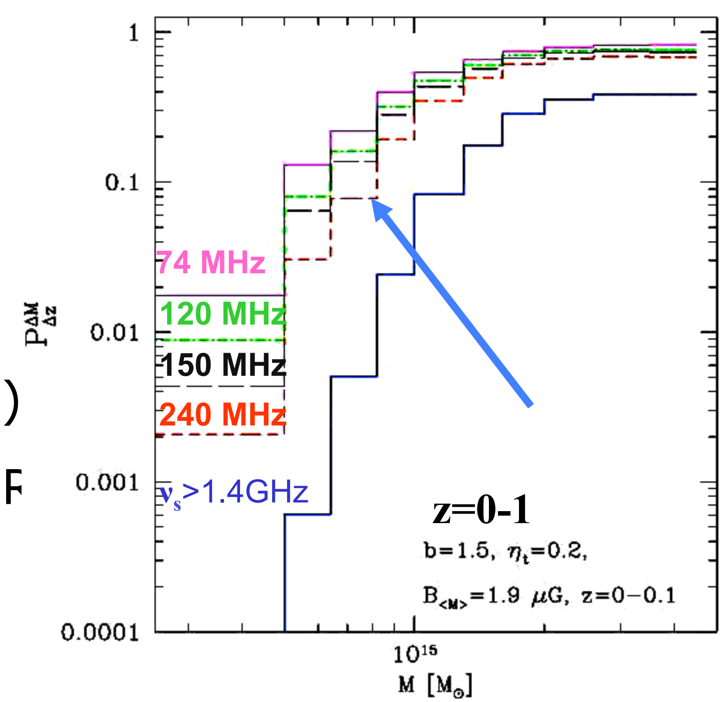
Steepening frequency

$$\nu_s \propto \langle B\rangle \gamma_{max}^2 \propto \frac{\langle B\rangle \chi^2}{\left(\langle B\rangle^2 + B_{cmb}^2\right)^2}$$

Radio Halos with very steep spectrum (**α>1.5, USSRH**) in the classical radio band must exist (Cassano et al.06; Brunetti et al. 2008, Nature **455, 944**)

Cassano et al. 10



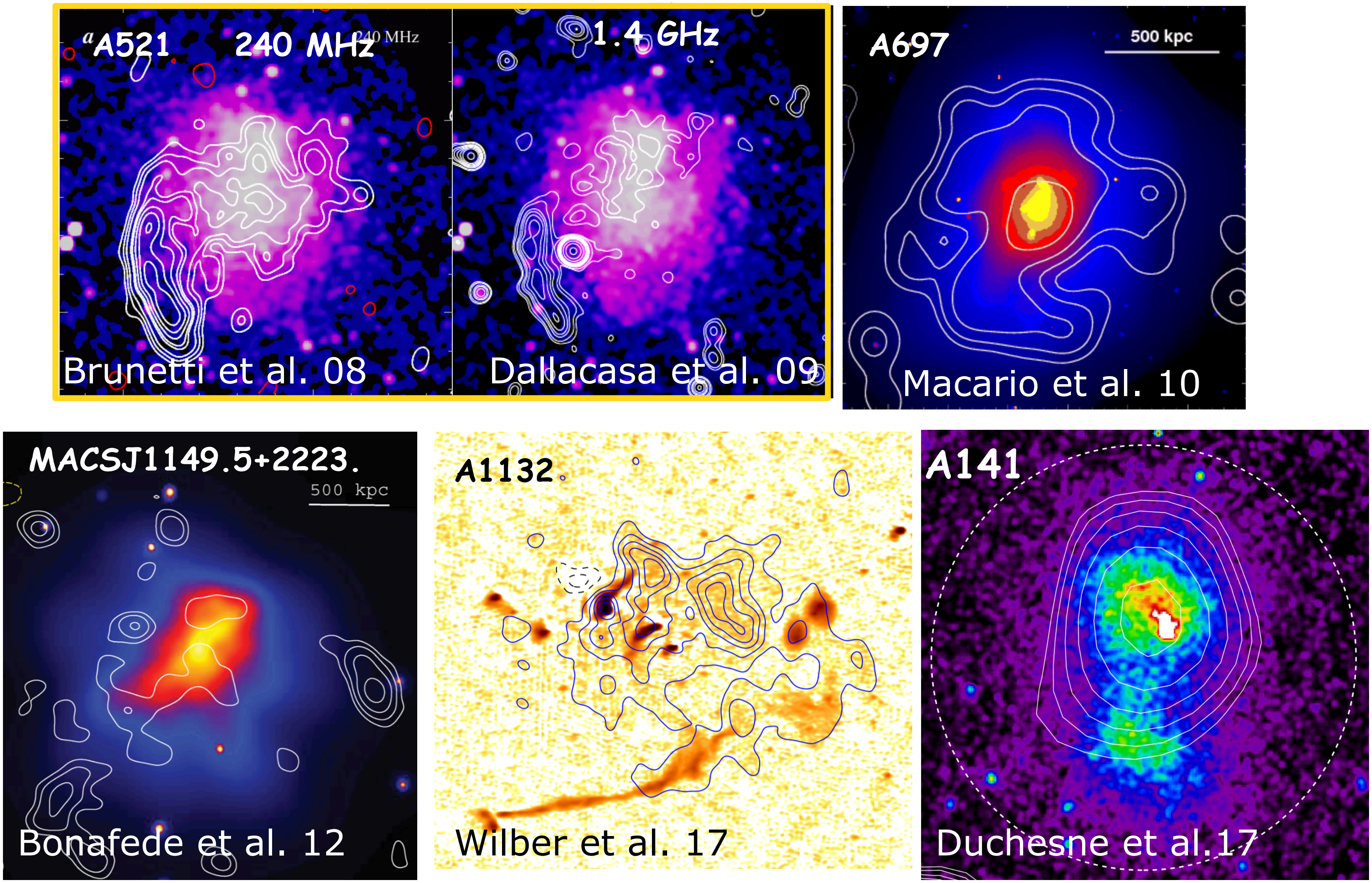
At **low (<1 GHz) frequency**

✔ A complex population of RH (different spectra)

✔ RH more common, increase of the fraction of R

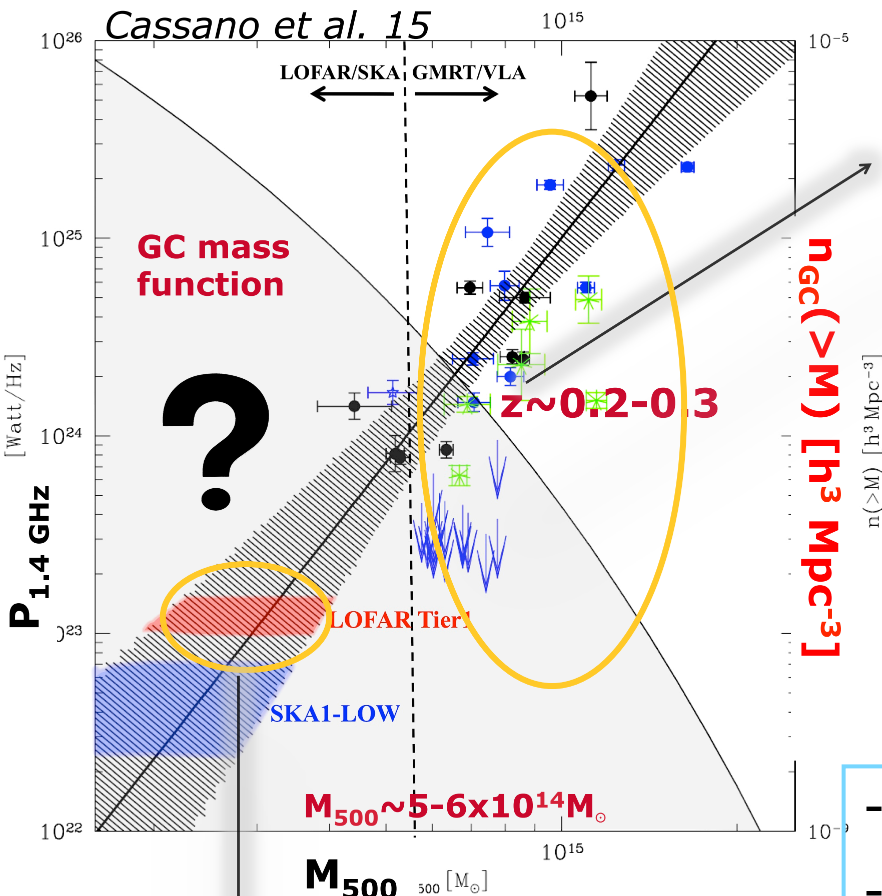
✔ ultra-steep spectrum RH (USSRH, **α>1.5**)

Ultra-Steep Spectrum RHs discoveries so far
(not a complete list)



+ candidates (see e.g.; talks by de Gasperin, Johnston-Hollitt)

What's next?

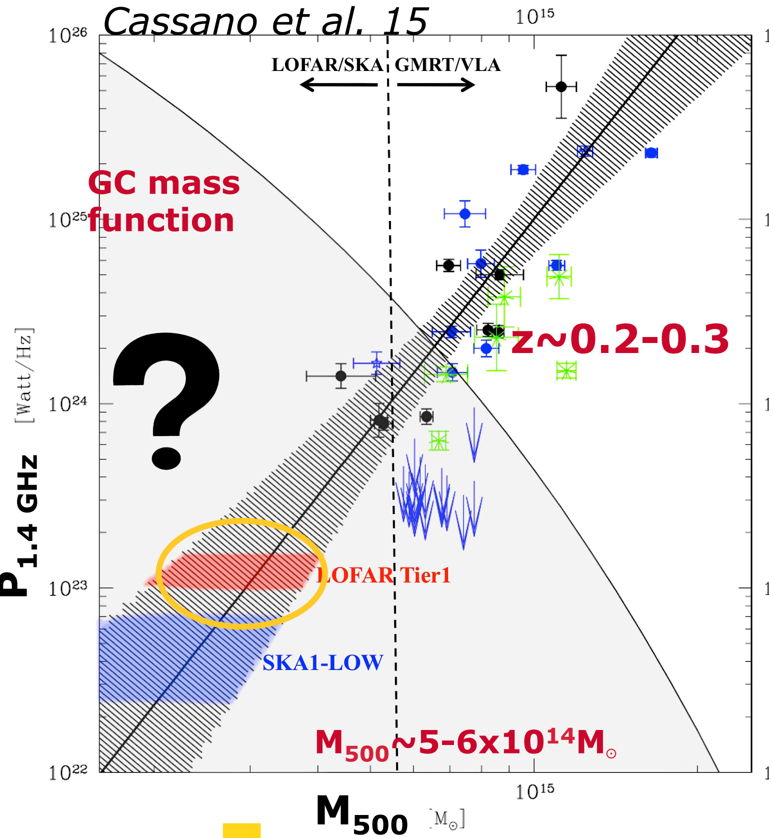


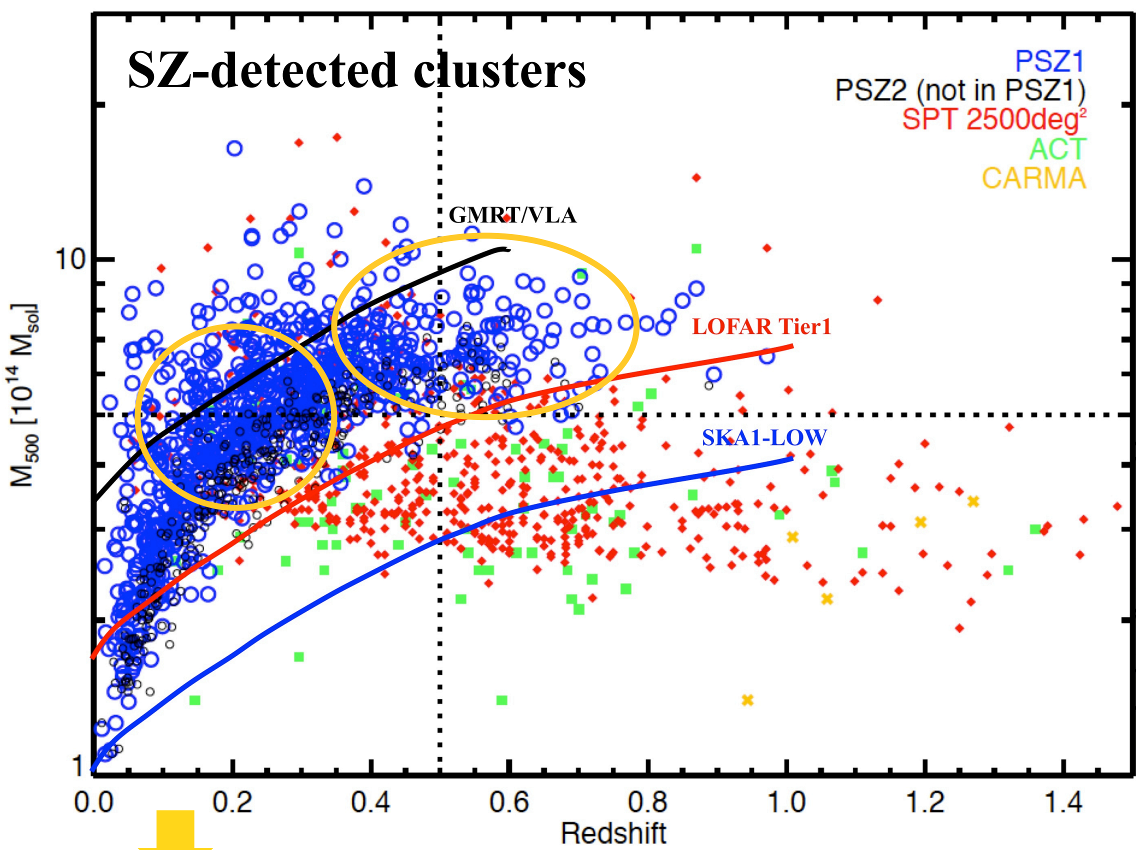
Current statistical studies of diffuse radio emission in GCs are **limited to massive M_{500}~5-6x$10^{14}$$M_\odot$ (and ~nearby) systems** which are only a small fraction of the clusters in the Universe !

- How much the present view is biased ?
- Are we seeing the tip of the iceberg?
- How many RH await discovery?

LOFAR and SKA1 pathfinders will explore low massive clusters (M_{500}~10^{14} $M_\odot$) that are ~100+ times more numerous than clusters observable by present facilities.

What's next?





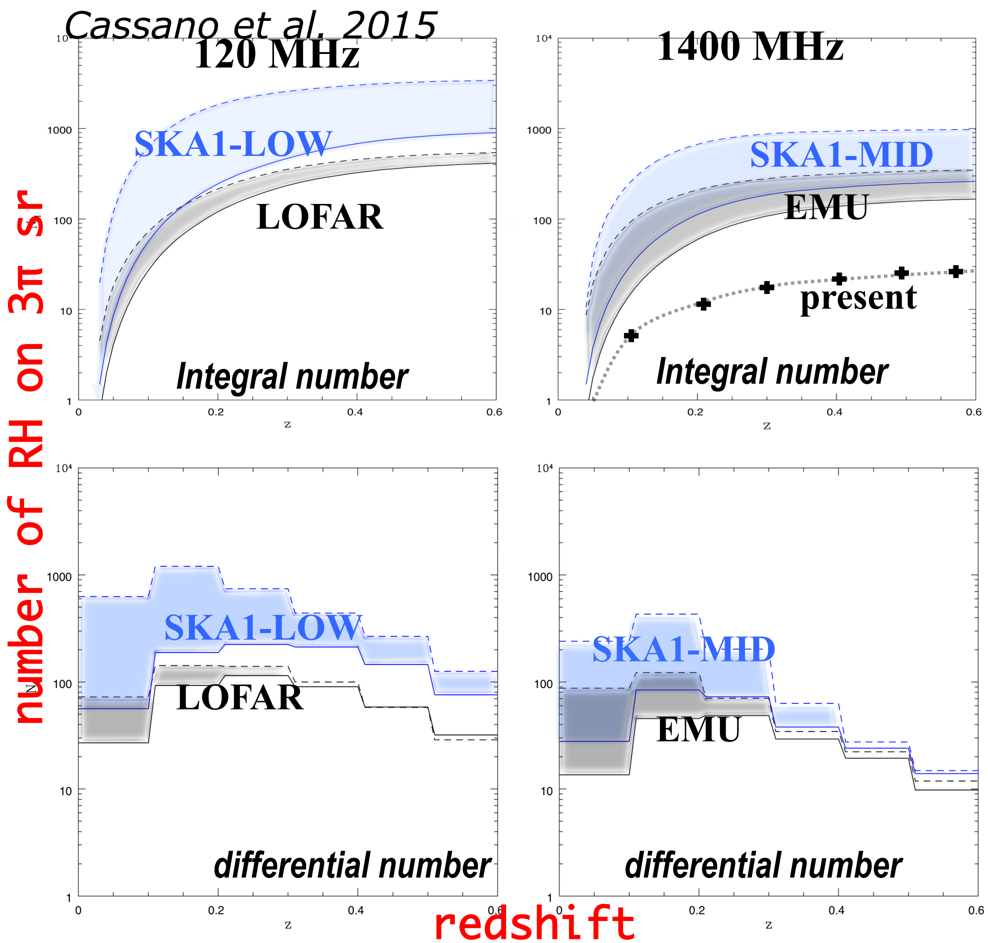
LOFAR should discover GRH mainly in:

M_{500} > 2-3x$10^{14}M_\odot$ (z~0.2-0.3) ➡ low massive GC

M_{500} ≥ 5x$10^{14}M_\odot$ (z>0.4-0.5) ➡ high-z GC

How many RHs await discovery in future radio surveys?

from Monte Carlo simulations (see also *Cassano et al. 10, 12, 15***)**



We know about 30-40 RH

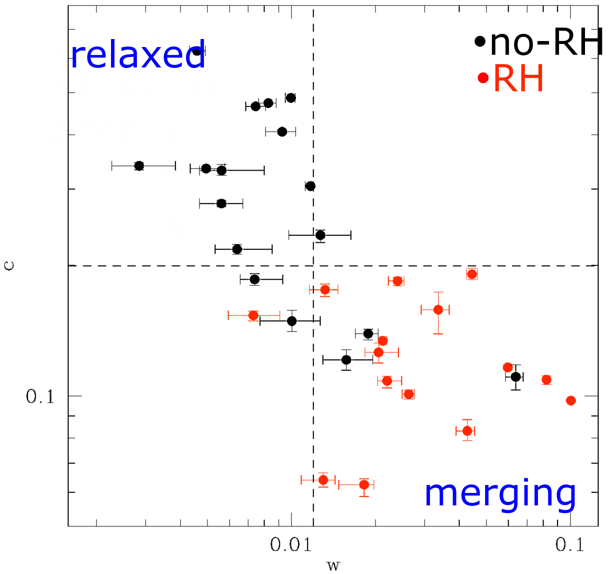
ASKAP(EMU) => ~300
SKA1-MID => ~750
1-2 GHz

LOFAR => ~500
SKA1-LOW => ~2600
150-200 MHz

configurations	rms μJy/beam	θ_b arcesc
LOFAR (120 MHz)	400	25
SKA1-low (120 MHz)	20	10
EMU (1.4 GHz)	13	15
SKA1-MID (1.4 GHz)	5	15

LoTSS (LOFAR Two-metre Sky Survey) will cover 2π sr **(~20,627 deg²)**,
with 0.1 mJy/beam and 5” =>
~400-500 GRH (with 0.2 mJy/beam and ~20” or with 0.1 mJy/beam and ~10”)

GRH as probe of cluster merging rate with cosmic time ?



The observed **RH-cluster merger** connection suggests that RH can be used to probe the cluster merging rate with cosmic time. However, not every merging cluster hosts a giant RH.

Idea: to combine the observed fraction of merging clusters and of RHs with the merging rate predicted by cosmological simulations, and we attempt to infer constraints on the merger properties of clusters that appear disturbed in the X-rays and of those hosting RHs.

OBSERVATIONS

The clusters sample: 54 clusters with $M_{500}>6 \cdot 10^{14} M_{\odot}$ and $0.2<z<0.33$ from the PSZ1 catalogue (80% complete; Plank Collaboration 2014).

- **94%** of the clusters have deep radio (GMRT 610 MHz/ VLA 1.4 GHz) and X-ray (41 Chandra+10 XMM) data

-fraction of clusters with **RH**:
$\mathbf{f_{RH}=33\text{-}41\%}$
- fraction of merging clusters
$\mathbf{f_m=65\text{-}69\%}$

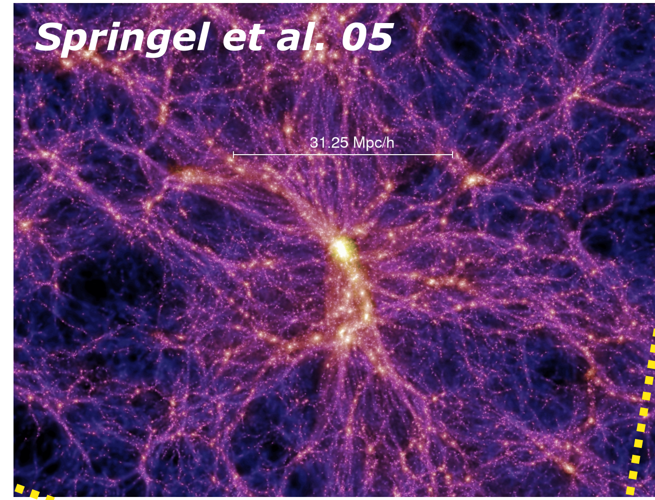
Cassano, Brunetti, Giocoli, Ettori 2016

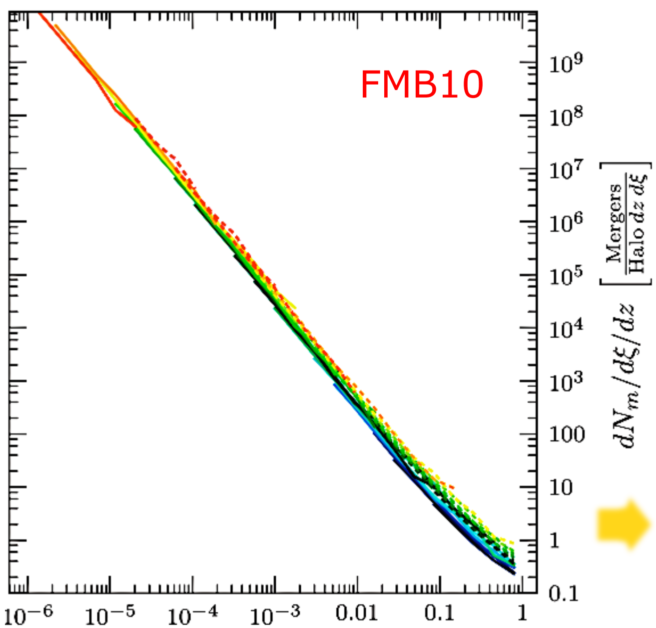
GRH as probe of cluster merging rate with cosmic time

THEORY

Fakhouri, Ma & Boylan-Kolchin 10 (FMB10) used merger trees from the combined Millennium and Millennium-II (Springel et al. 05;Boylan-Kolchin et al. 09) simulations to derive the mean merging rate per halo, i.e.; the mean number of mergers per unit halo per unit z per unit ξ, with ξ being the progenitor mass ratio:

$$\frac{dN_m}{d\xi dz}(M,\xi,z) = A\left(\frac{M}{10^{12}M_\odot}\right)^{\alpha} \xi^{\beta} \exp\left[\left(\frac{\xi}{\tilde{\xi}}\right)^{\gamma}\right](1+z)^{\eta},$$



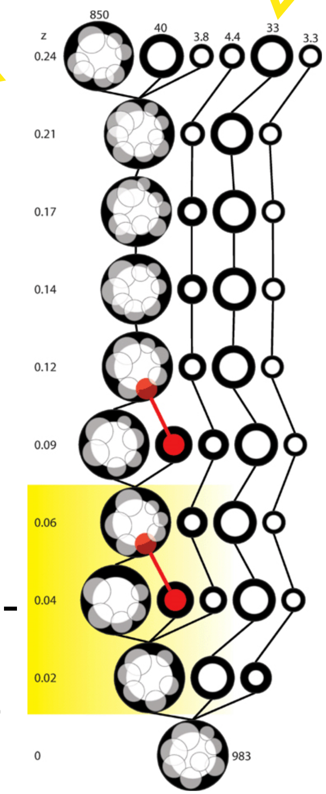


$\xi= M_i/M_1 \leq 1$

The best-fitting parameters: α=0.133, β=−1.995, γ=0.263, η=0.0993 and A=0.0104, $\tilde{\xi}$=9.72×~10^{-3}

The mass ratio $\xi= M_i/M_1 \leq 1$
ξ=0.3 => major mergers (1:3)
ξ=0.1 => minor mergers (1:10)

- Negligible dependence on the halo redshift
- Nearly independent of the mass
- strongest dependence on the mass ratio



Fakhouri & Ma 08

GRH as probe of cluster merging rate with cosmic time

The expected **fraction of mergers** with $\xi \geq \boldsymbol{\xi_{min}}$ in our sample can be derived by integrating the mean mearging rate per halo for each cluster of the sample with mass M_0 at z_0 up to the redshift z corresponding to the merger timescale τ_m:

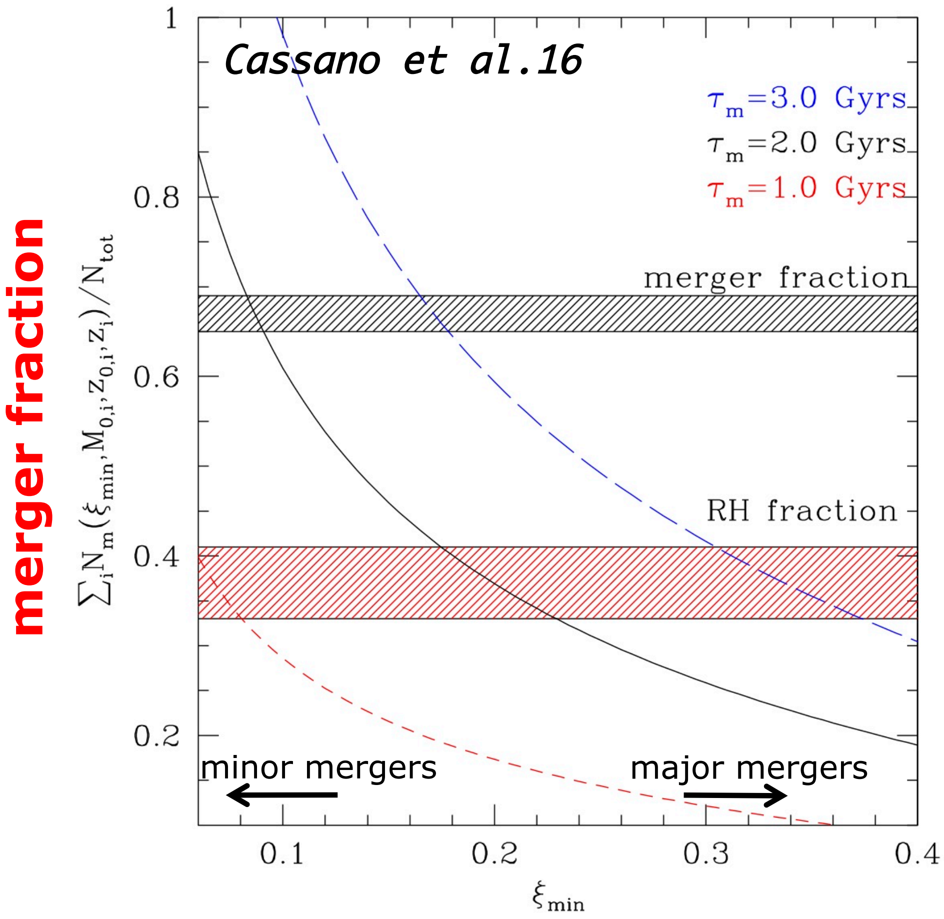
$$N_m(\xi_{min}, M_0, z_0, z) = \int_{z_0}^{z} dz \int_{\xi_{min}}^{1} d\xi \frac{dN_m}{d\xi dz}(M(z), \xi, z),$$

and then computing $\sum_i N_m(\xi_{min}, M_{0,i}, z_{0,i}, z_i)/N_{tot}$

The merger timescale, $\boldsymbol{\tau_m}$, is the timescale associated with the duration of the morphological disturbance that we infer from X-ray images, we use it as free parameter.

Cassano, et al.2016

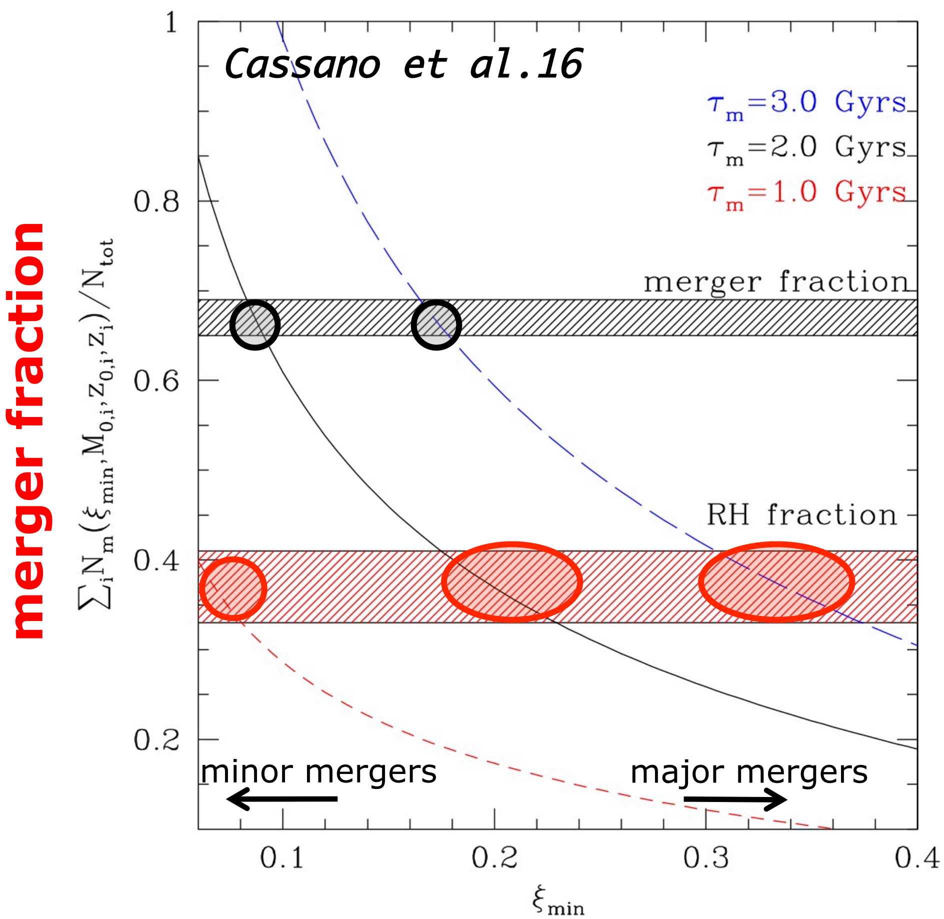
GRH as probe of cluster merging rate with cosmic time



- The predicted **merger fraction** decreases for larger mass ratios simply because major mergers are less common than minor mergers and it obviously increases by assuming larger timescales.

- There is a degeneracy between τ_m and ξ_{min} =>we can find combination of (τ_m , ξ_{min}) to explain the observed merger fraction and RH fraction

GRH as probe of cluster merging rate with cosmic time



- The predicted **merger fraction** decreases for larger mass ratios simply because major mergers are less common than minor mergers and it obviously increases by assuming larger timescales.

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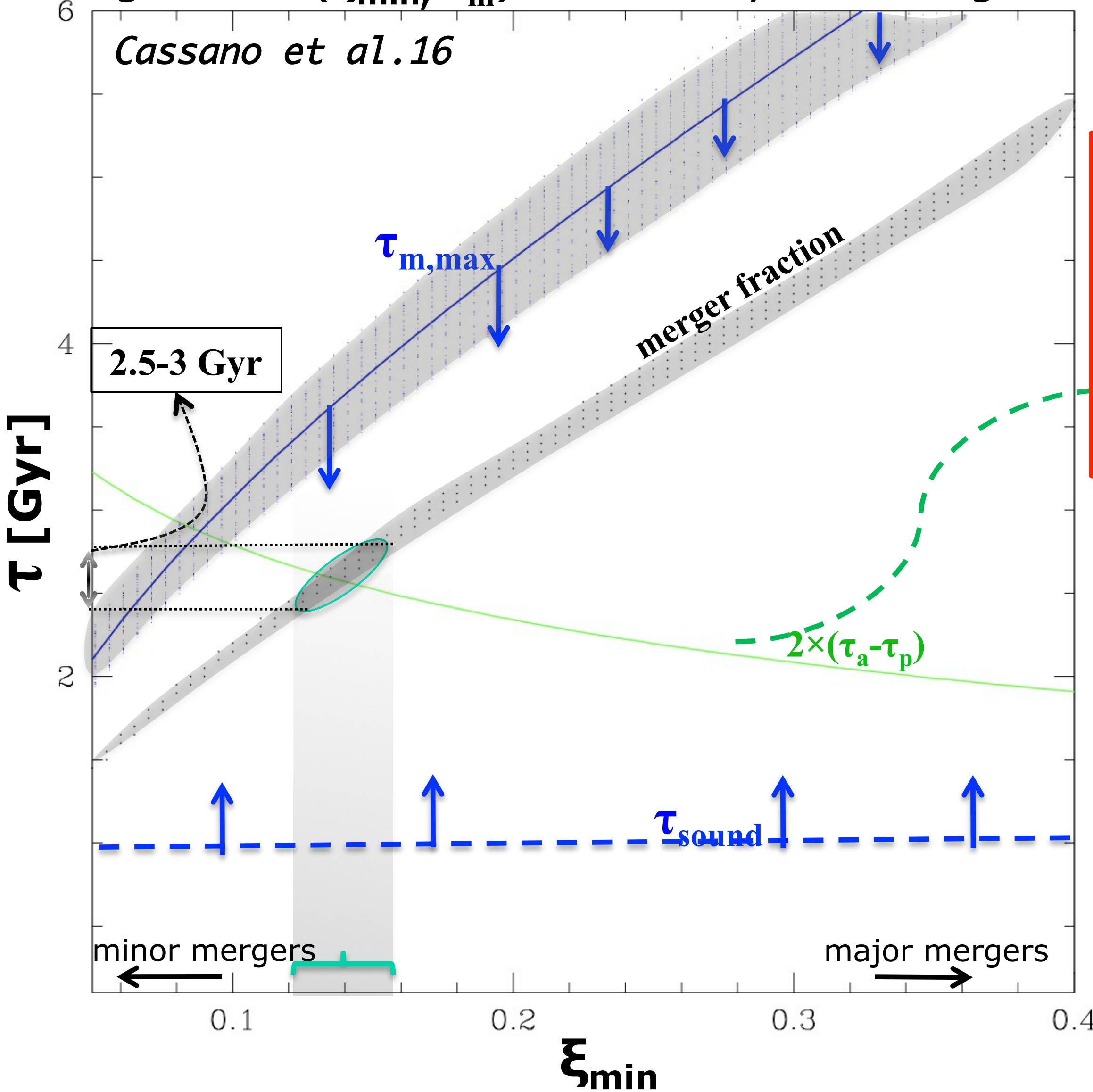
GRH as probe of cluster merging rate with cosmic time

Allowed regions of (ξ_{min}, τ_m) derived by matching theory and observations.



How to break the ξ_{min}-τ_m degeneracy?

τ_m constrained by cosmological simulations (Tormen et al. 04)

$\tau_m \sim$ 2.5-3 Gyr

$\xi_{min} \sim$ 0.12-0.16

Or a 1:8 - 1:6 merger

Cassano et al.16

GRH as probe of cluster merging rate with cosmic time

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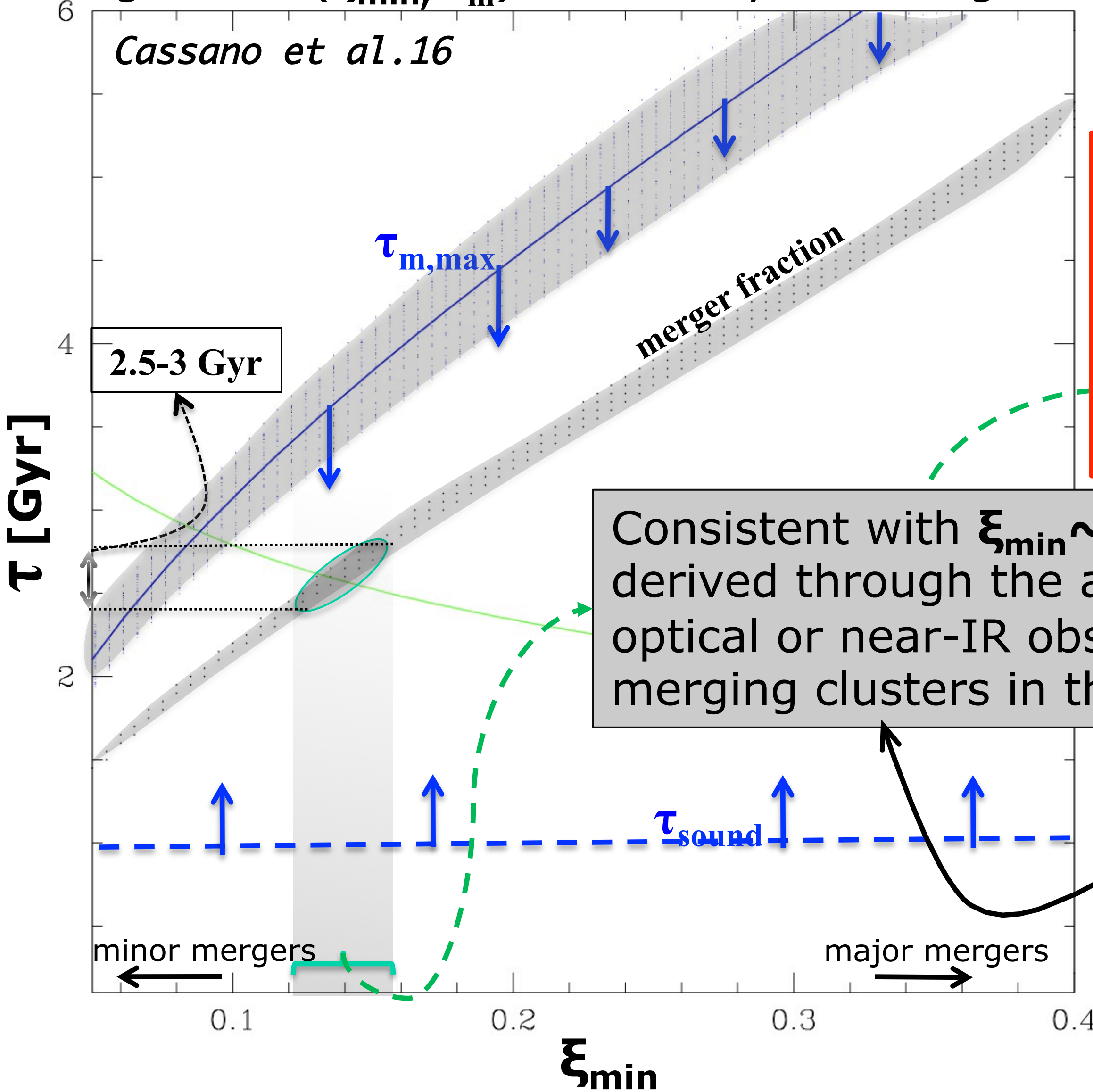

How to break the ξ_{min}-τ_m degeneracy?

τ_m constrained by cosmological simulations (Tormen et al. 04)

Consistent with ξ_{min}~ **0.14-0.16** derived through the analysis of optical or near-IR observations of merging clusters in the sample

$\tau_m \sim$ **2.5-3 Gyr**

$\xi_{min} \sim$ **0.12-0.16**

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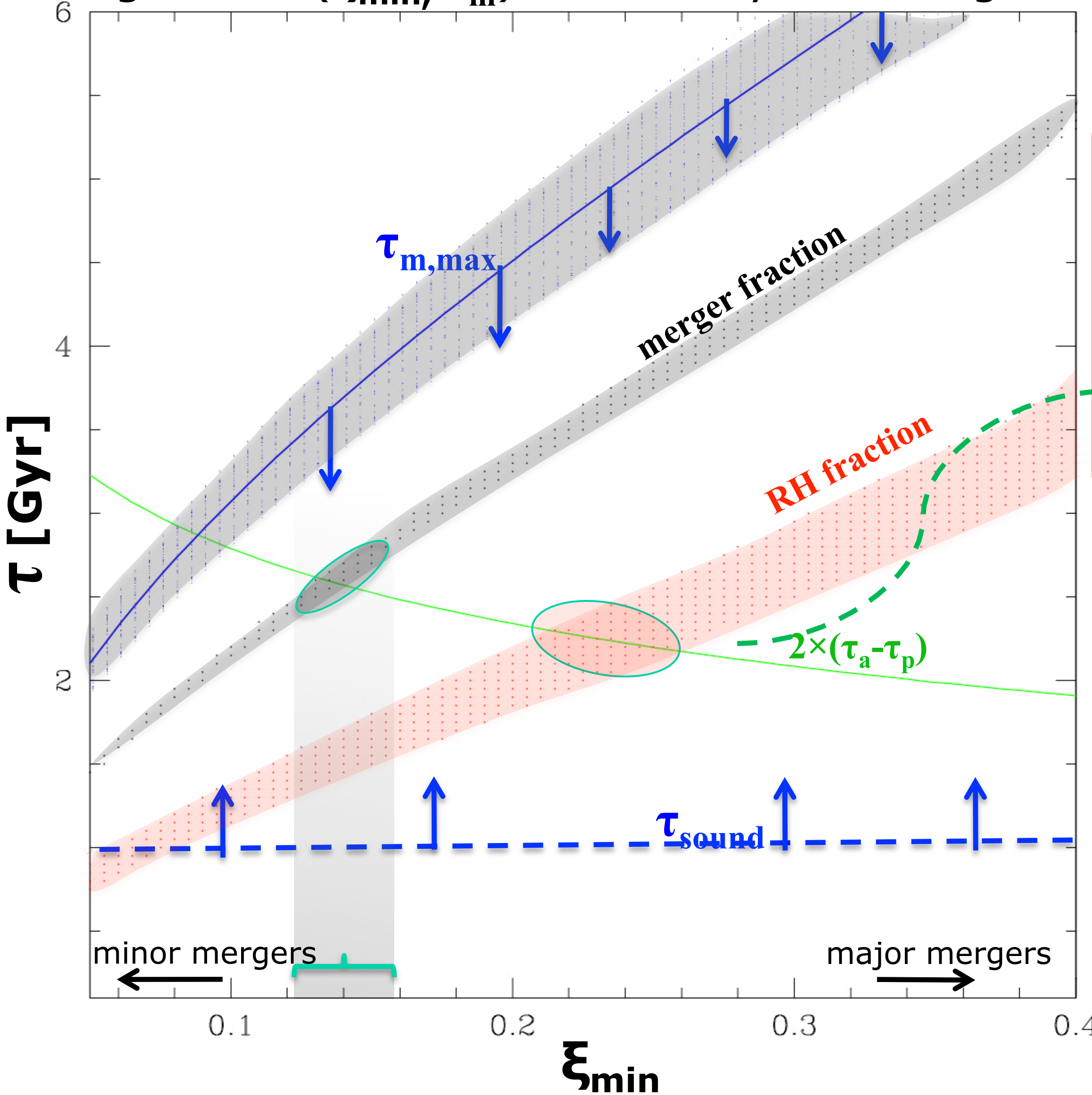


How to break the ξ_{min}-τ_m degeneracy?

τ_m constrained by cosmological simulations (Tormen et al. 04)

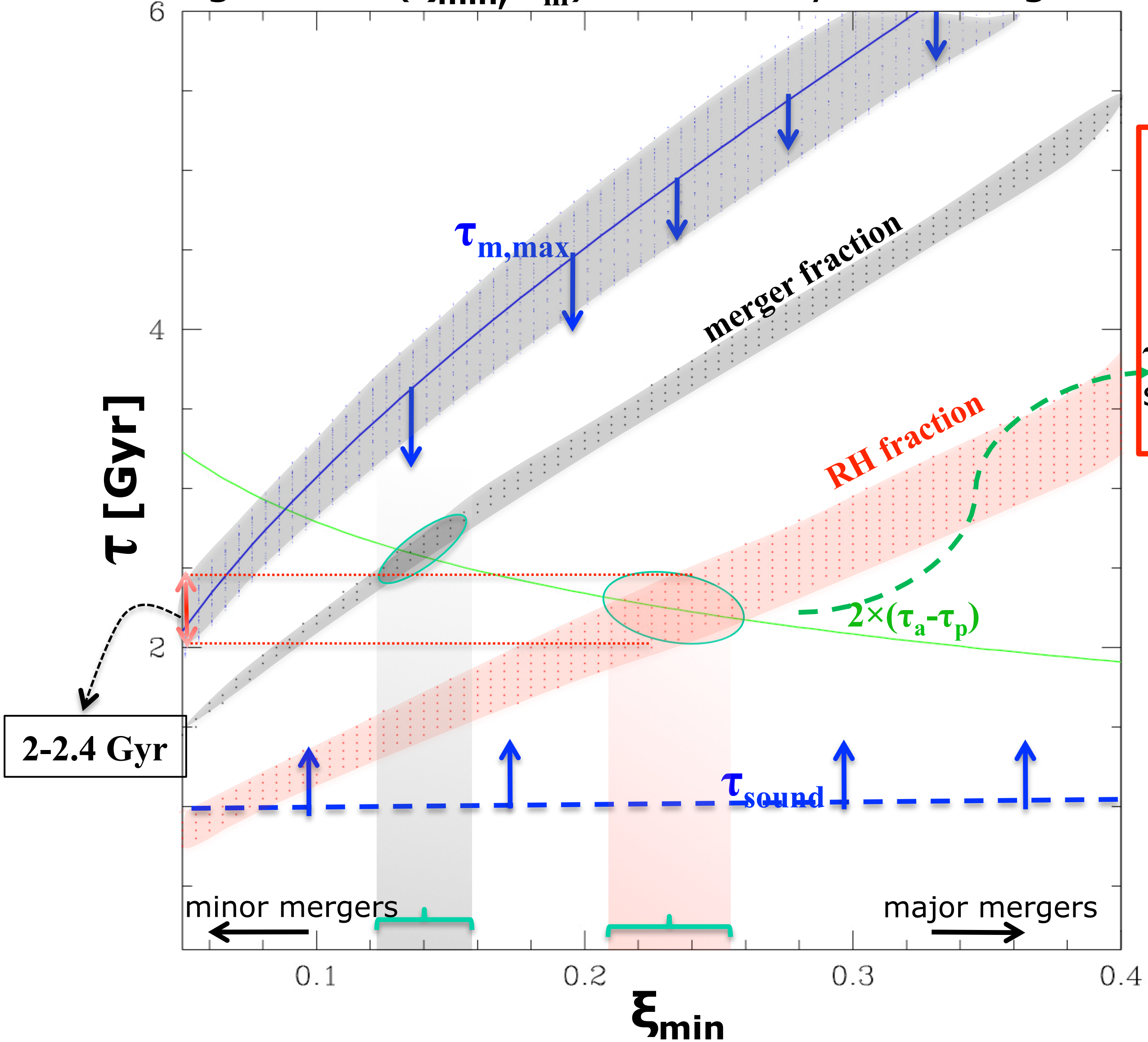
<u>1st possibility</u>

$\tau_{RH} \sim \tau_m$ => RHs are generated in those systems that have larger ξ_{min} among merging clusters in our sample.

Cassano et al.16

GRH as probe of cluster merging rate with cosmic time

Allowed regions of (ξ_{min}, τ_m) derived by matching theory and observations.



How to break the ξ_{min}-τ_m degeneracy?

τ_m constrained by cosmological simulations (Tormen et al. 04)

1st possibility

$\tau_{RH}\sim$ 2-2.4 Gyr

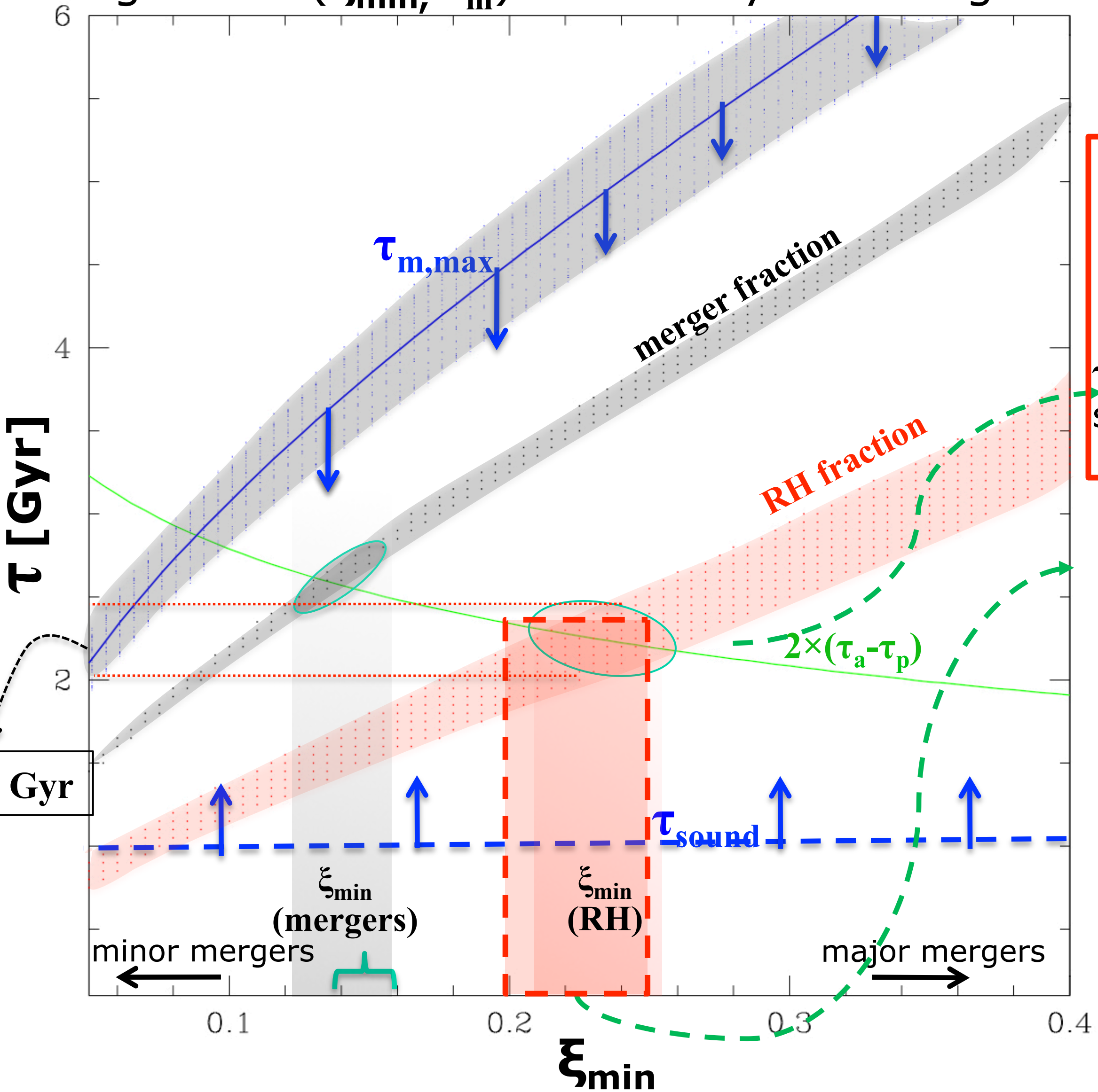
$\xi_{min}\sim$ 0.21-0.26

Or a 1:5 – 1:4 merger

Cassano et al.16

GRH as probe of cluster merging rate with cosmic time

Allowed regions of (ξ_{min}, τ_m) derived by matching theory and observations.



How to break the ξ_{min}-τ_m degeneracy?

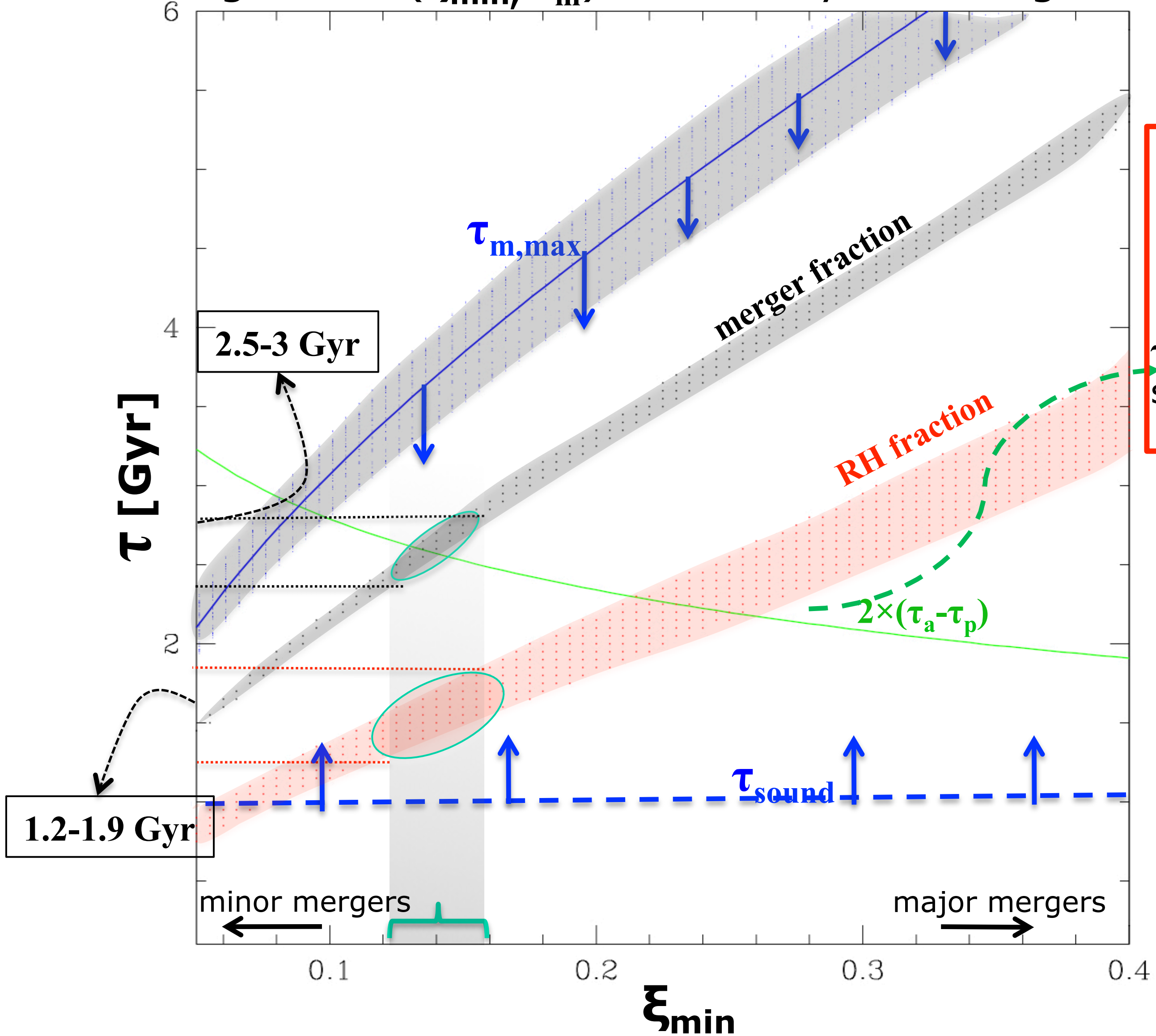
τ_m constrained by cosmological simulations (Tormen et al. 04)

Values of ξ_{min} **~ 0.2-0.25** (~1:5-1:4) are derived through the analysis of optical or near-IR observations of RH clusters in the sample

Cassano et al.16

GRH as probe of cluster merging rate with cosmic time

Allowed regions of (ξ_{min}, τ_m) derived by matching theory and observations.



How to break the ξ_{min}-τ_m degeneracy?

τ_m constrained by cosmological simulations (Tormen et al. 04)

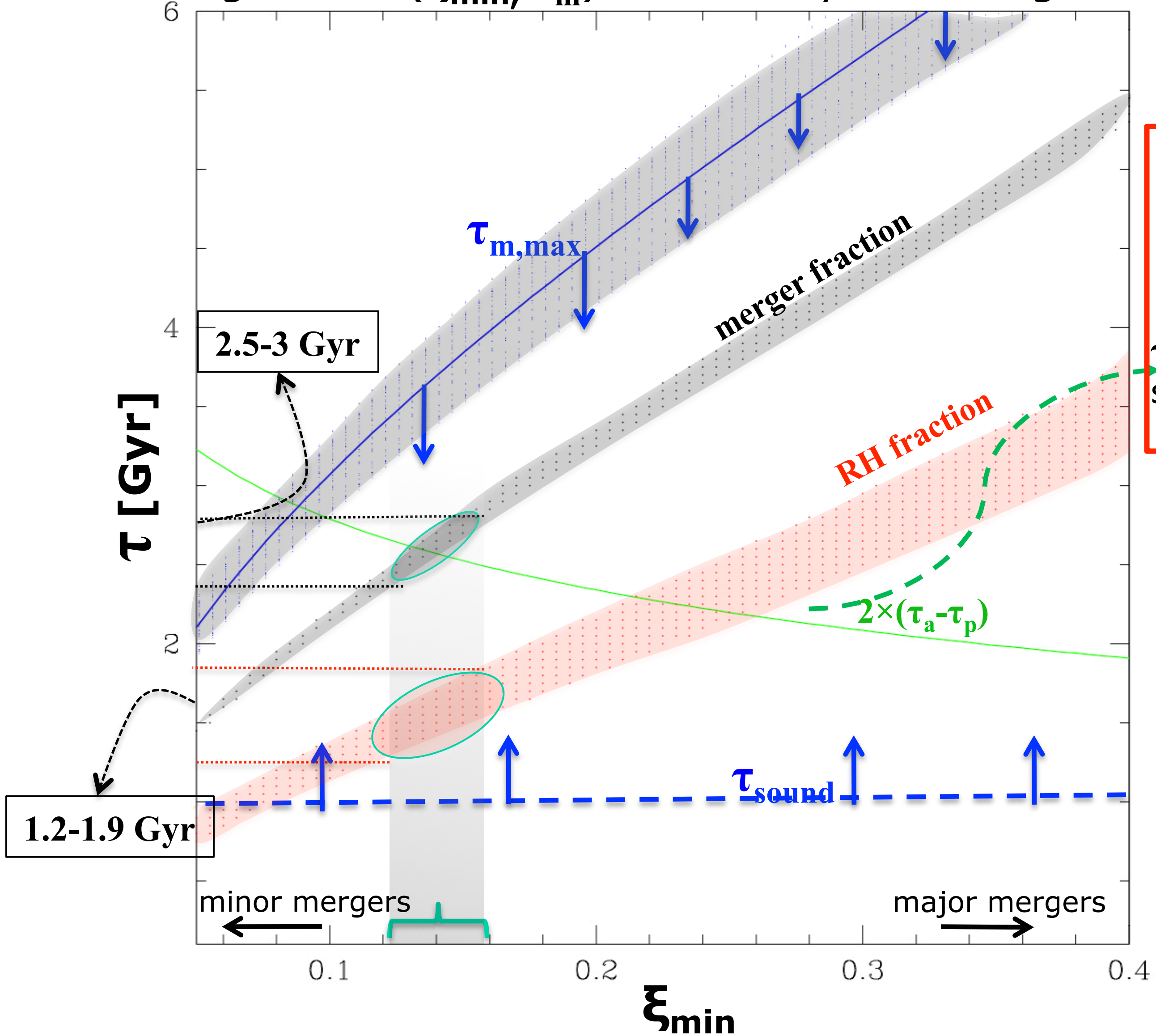
2nd possibility

$\tau_{RH} \sim (f_{RH}/f_m) \times \tau_m$ =>
RHs statistically generated in all merging clusters of the sample but their lifetime is shorter than τ_m

Cassano et al.16

GRH as probe of cluster merging rate with cosmic time

Allowed regions of (ξ_{min}, τ_m) derived by matching theory and observations.



How to break the ξ_{min}-τ_m degeneracy?

τ_m constrained by cosmological simulations (Tormen et al. 04)

2nd possibility

$\tau_{RH} \sim$ 1.2-1.9 Gyr

$\xi_{min} \sim$ 0.12-0.16

Or a 1:8 - 1:6 merger

Cassano et al.16

Conclusions

+ suggestion for discussion session

Present picture: RH form in turbulent merging clusters =>

RH-merger connection
Occurrence of RH depends on cluster mass (M_{500}>~$5 \bullet 10^{14} M_{\odot}$)
Existence of USSRH (increasing examples)

Conclusions

+ suggestion for discussion session

Present picture: RH form in turbulent merging clusters =>

RH-merger connection

Occurrence of RH depends on cluster mass (M_{500}>~5•$10^{14}M_{\odot}$)

Existence of USSRH (increasing examples)

What's Next?

RH in more turbulent GC -> **Athena/X-IFU**

Increase of the RH occurrence from high to low ν } **LOFAR, ...SKA**

Conclusions

+ suggestion for discussion session

First attemps to derive properties of mergers generating RH from the comparison of RH fraction and merger fraction with cosmological merging rate: degeneration between ξ generated and τ_m

- RH are likely generated in "major" merger, means ξ>0.2-0.25 (~or <1:5-1:4) => consitent with weak-lensing measurements of ξ (however not complete info!)
- or RH are statistically generated in all merging systems, however their lifetime is shorter then τ_m, $\tau_{RH} \sim (f_{RH}/f_m) \times \tau_m$ ~1.2-1.9 Gyr

Conclusions

+ suggestion for discussion session

First attemps to derive properties of mergers generating RH from the comparison of RH fraction and merger fraction with cosmological merging rate: degeneration between ξ generated and τ_m

- RH are likely generated in "major" merger, means ξ>0.2-0.25 (~or <1:5-1:4) => consitent with weak-lensing measurements of ξ (however not complete info!)
- or RH are statistically generated in all merging systems, however their lifetime is shorter then τ_m, $\tau_{RH} \sim (f_{RH}/f_m) \times \tau_m$ ~1.2-1.9 Gyr

What's Next?

Remove the degeneracy between ξ generated and τ_m

- through the use of *ad hoc* numerical simulations

- through optical/near-IR observations of merging clusters in the sample

- future radio surveys **(e.g. LOFAR...SKA)** and adequate numerical simulations can really open the door to the use of RH to constrain the cluster merging rate with cosmic epoch.