# The quest for gamma-ray emission in galaxy clusters

*Anders Pinzke*

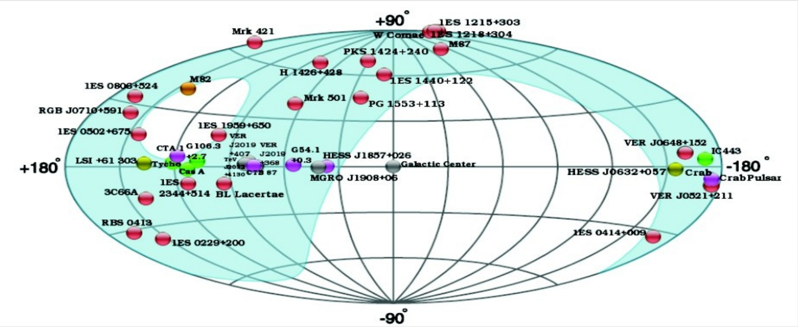
*Stockholm*
*Oct 24, 2013*

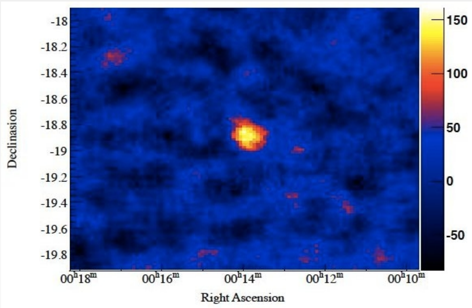
Dark Cosmology Centre

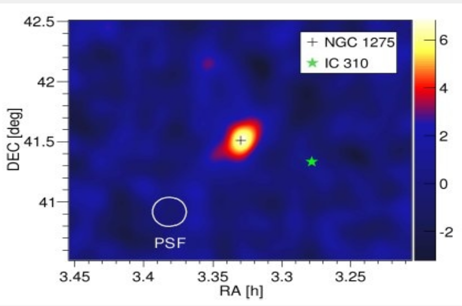
Stockholm University

# Gamma-rays from clusters – origin

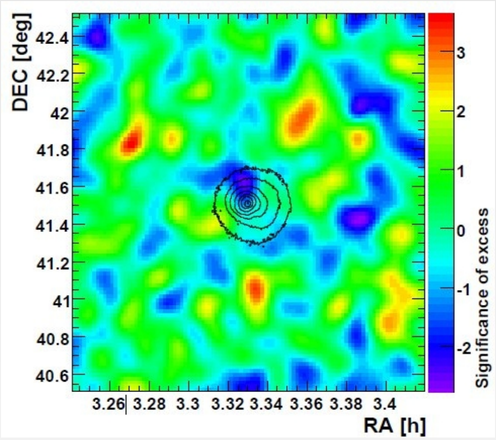
***Point sources:***
AGNs,
gamma-ray bursts
**OBSERVED**

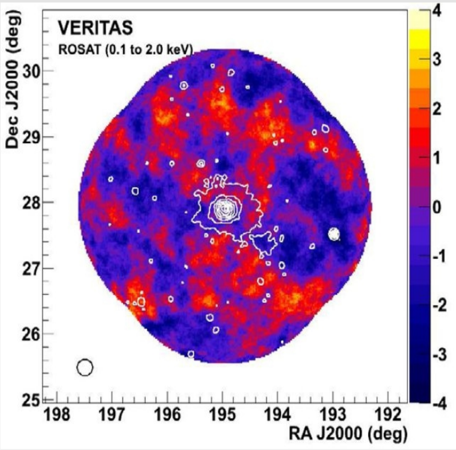


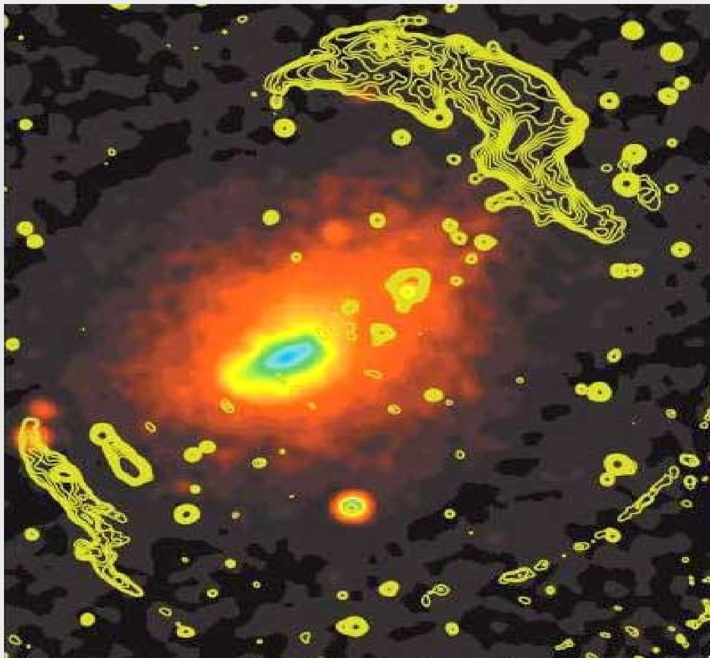

***Dark matter:***
massive/high densities,
boosted by substructures?
**NOT OBSERVED**




***Cosmic-rays:***
signs of non-thermal activity
**NOT OBSERVED**

# Signs of non-thermal activity in galaxy clusters

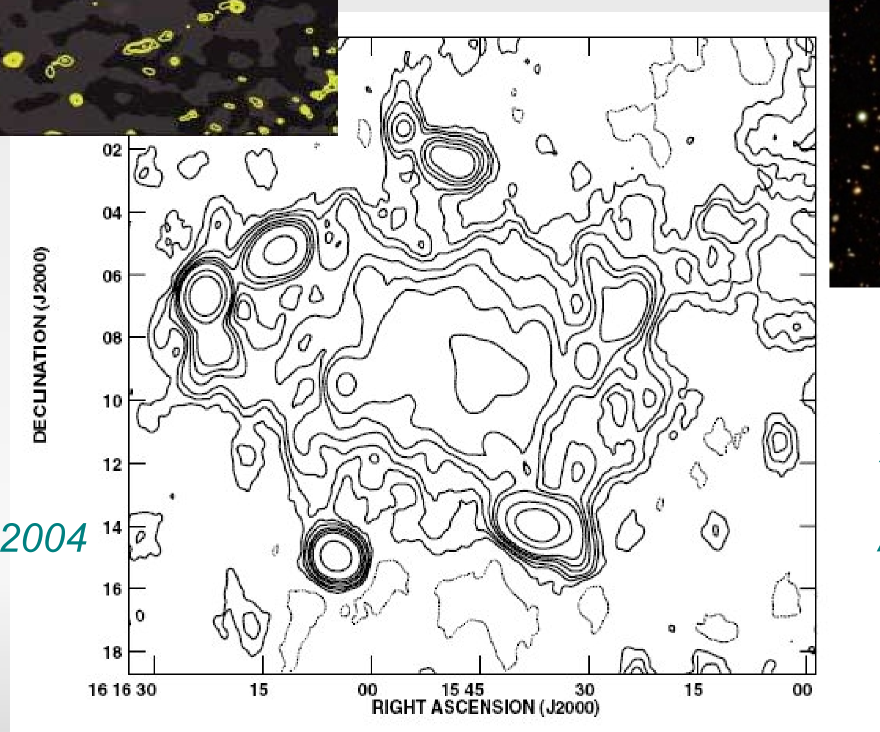


A 3667

**Radio:** *Johnston-Hollitt.;*
**X-ray:***ROSAT/PSPC.*

Bullet Cluster

**X-ray:***NASA/CXC/CfA/Markevitch et al.;* **Optical:***NASA/STScI;Magellan/U.Arizona /Clowe et al.;* **Lensing:***NASA/STScI; ESO WFI; Magellan/U.Arizona/Clowe et al.*



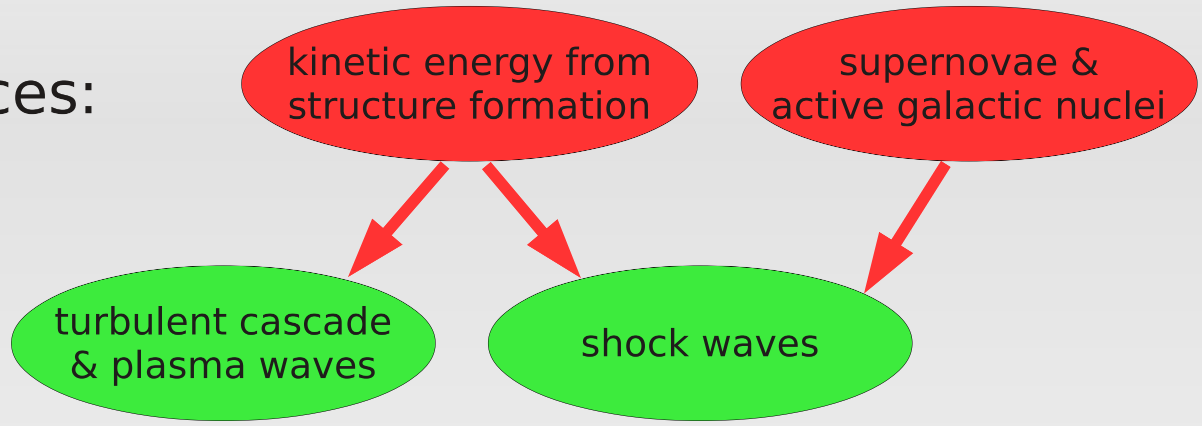

A 2163

***Radio:*** *Feretti at al, 2004*

# Cosmic rays in clusters of galaxies

Relativistic populations and radiative processes in clusters:

Energy sources:




Plasma processes:

Relativistic particle pop.:

Observational diagnostics:

*Pfrommer et al. 2008*

# Cosmic rays in clusters of galaxies

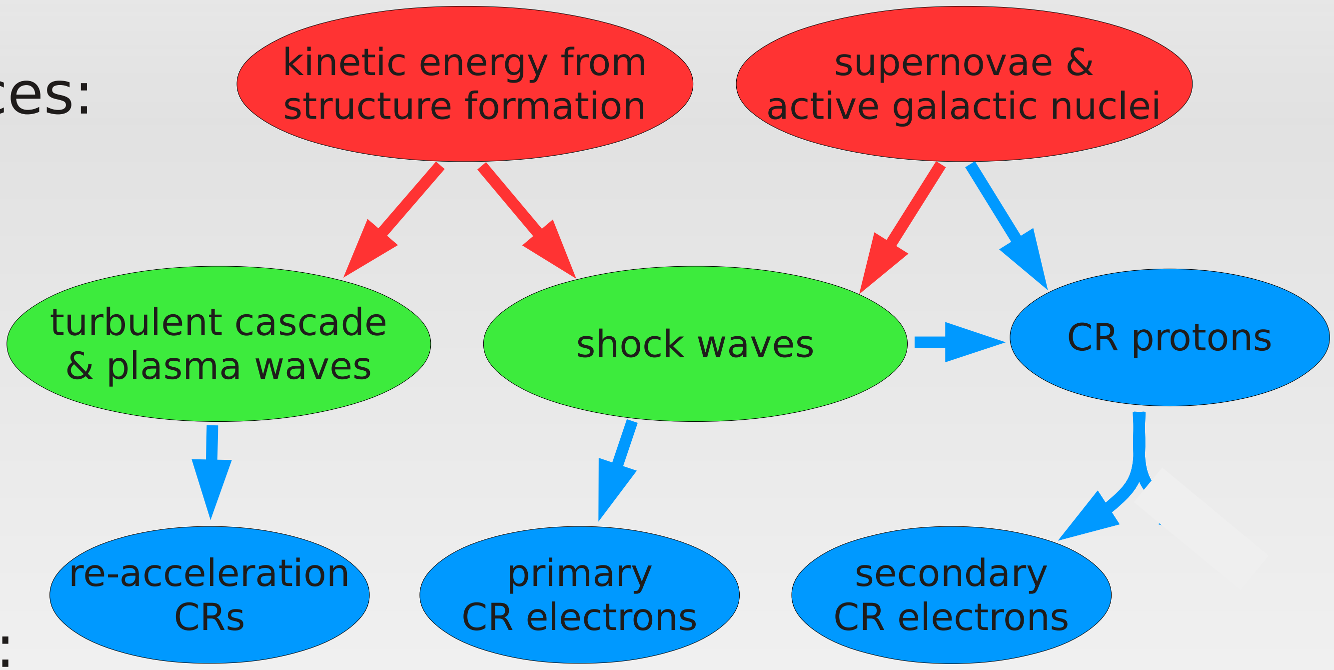
Relativistic populations and radiative processes in clusters:

Energy sources:

Plasma processes:

Relativistic particle pop.:

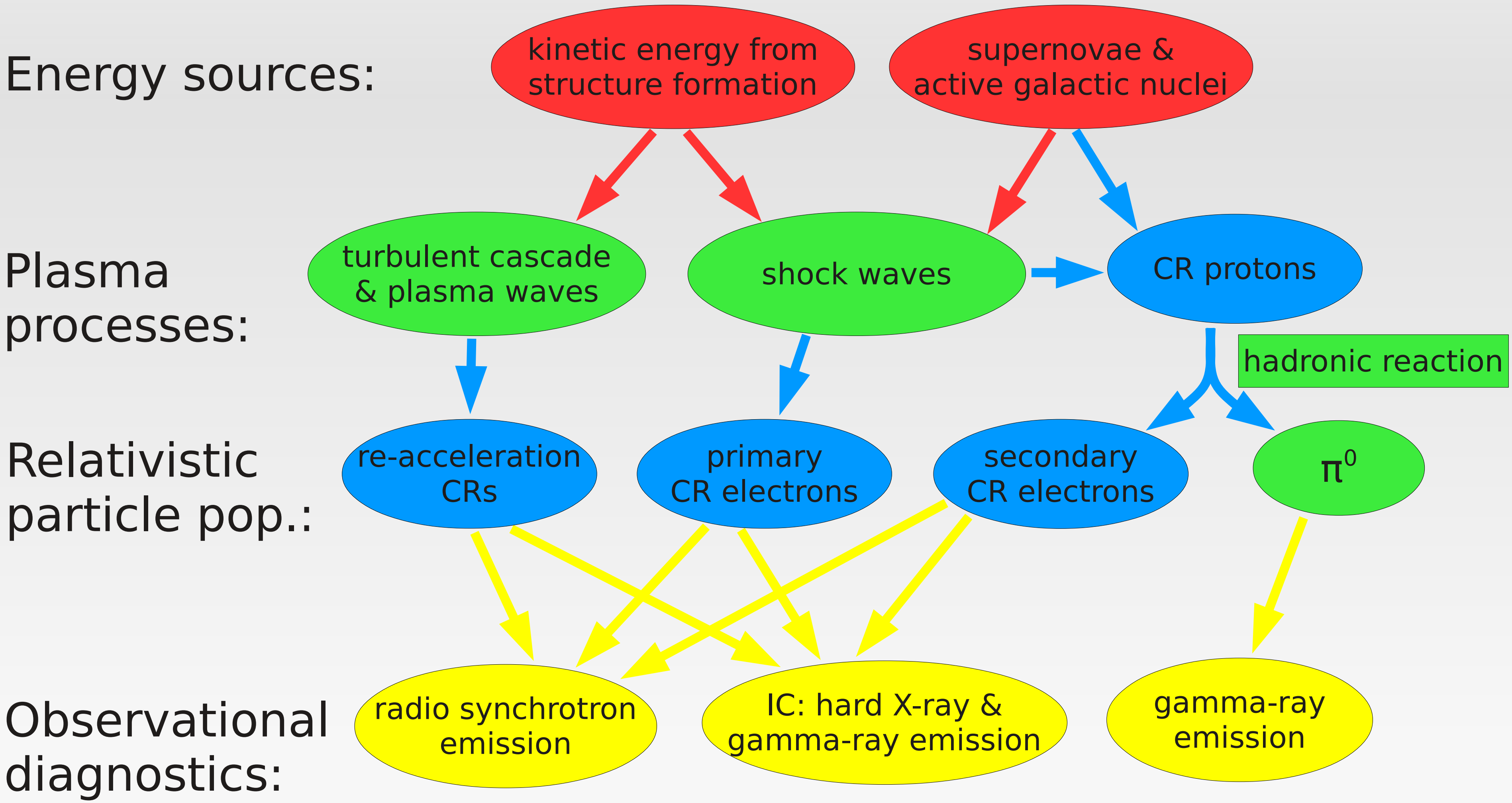
Observational diagnostics:




*Pfrommer et al. 2008*

# Cosmic rays in clusters of galaxies

Relativistic populations and radiative processes in clusters:

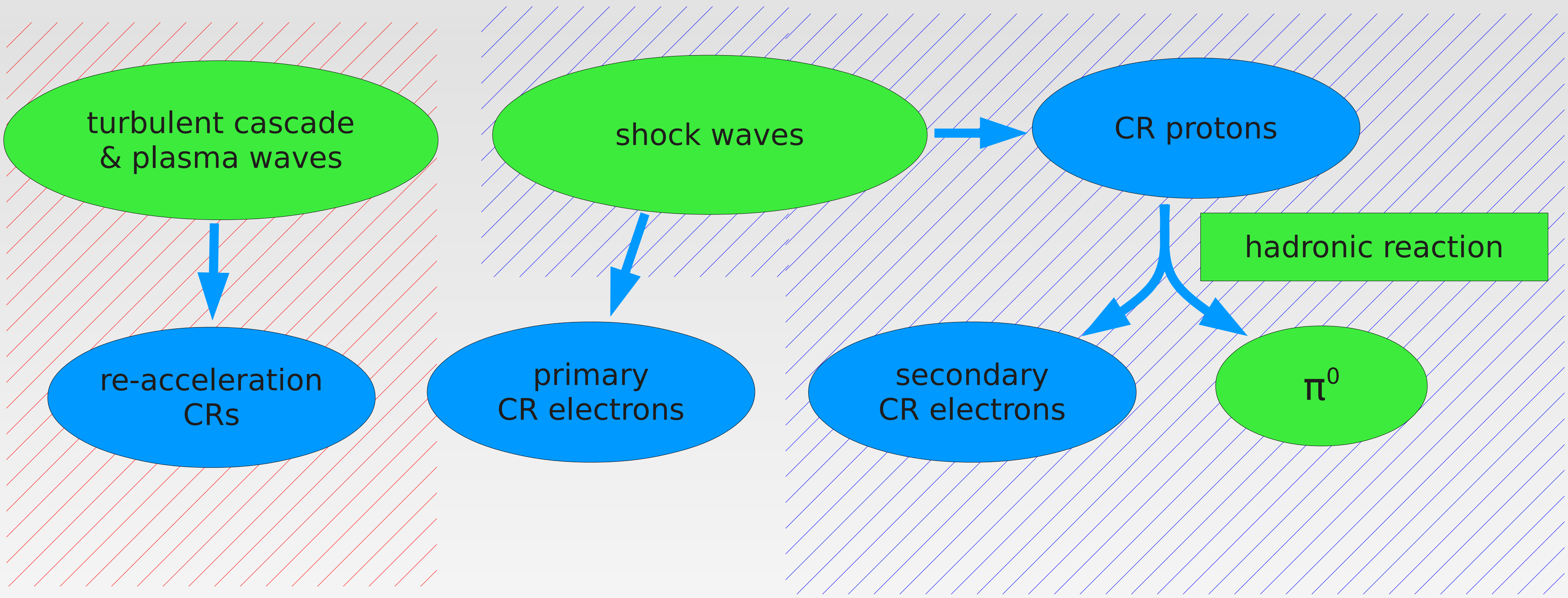



*Pfrommer et al. 2008*

# Cosmic rays in clusters of galaxies

**Which CR population is dominating?**

Two main models with different radio and gamma-ray signatures




## Reacceleration models

*e.g. Brunetti+ 2001,2004,2012, Brunetti and Lazarian 2007, 2011, Petrosian 2001, Cassano and Brunetti 2005*

## Hadronic models

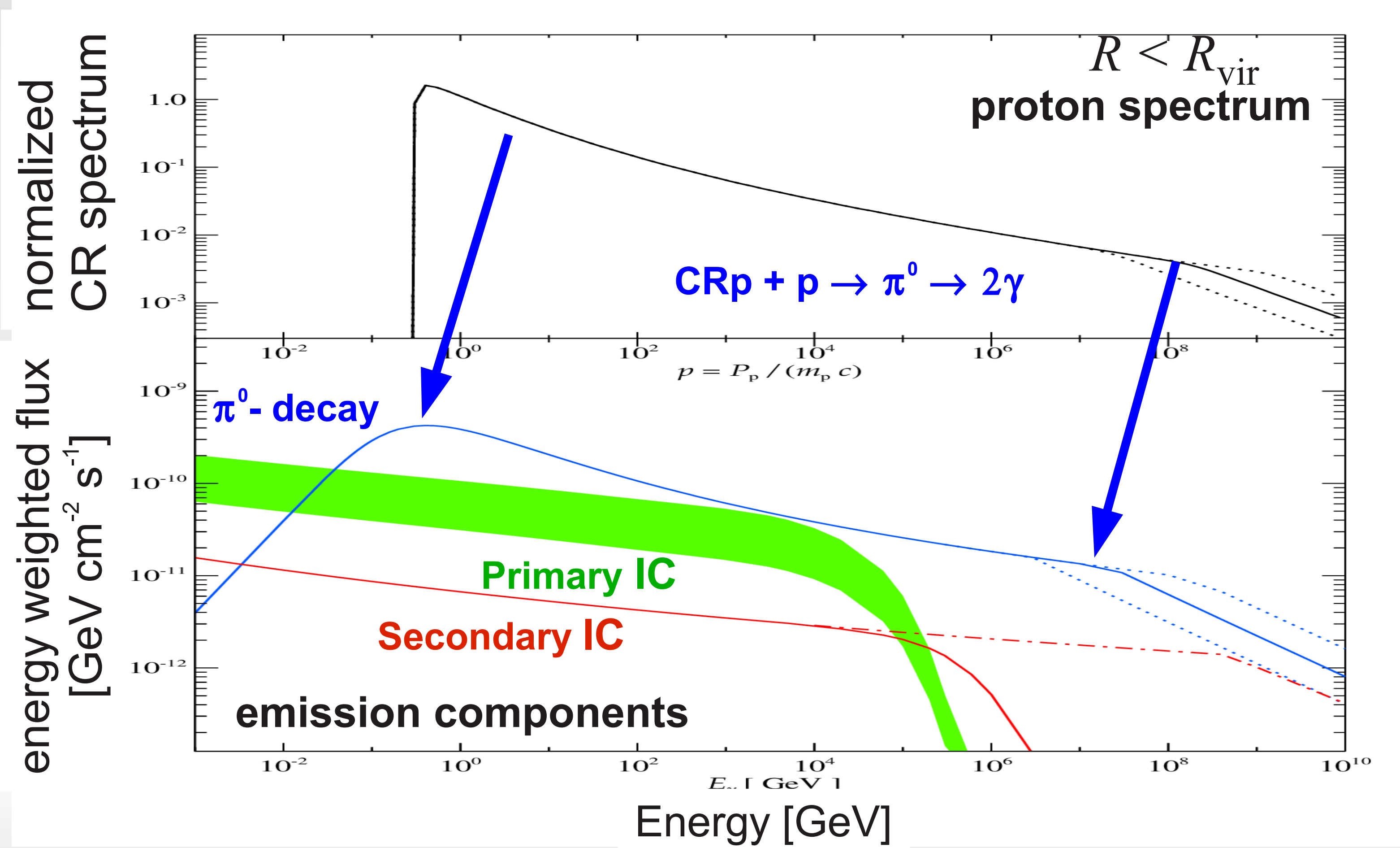
*e.g.Ensslin+ 2011, Wiener+ 2013, Zandanel+ 2013, Pinzke and Pfrommer 2010, Pinzke+ 2012, Pfrommer+ 2004,2008*

# Hadronic models - CRs

Acceleration mechanism: diffusive shock acceleration

Simulation based CR proton model with adiabatic transport

*Ensslin et al. 2006, Pfrommer et al. 2008, Pinzke et al. 2010, 2012*

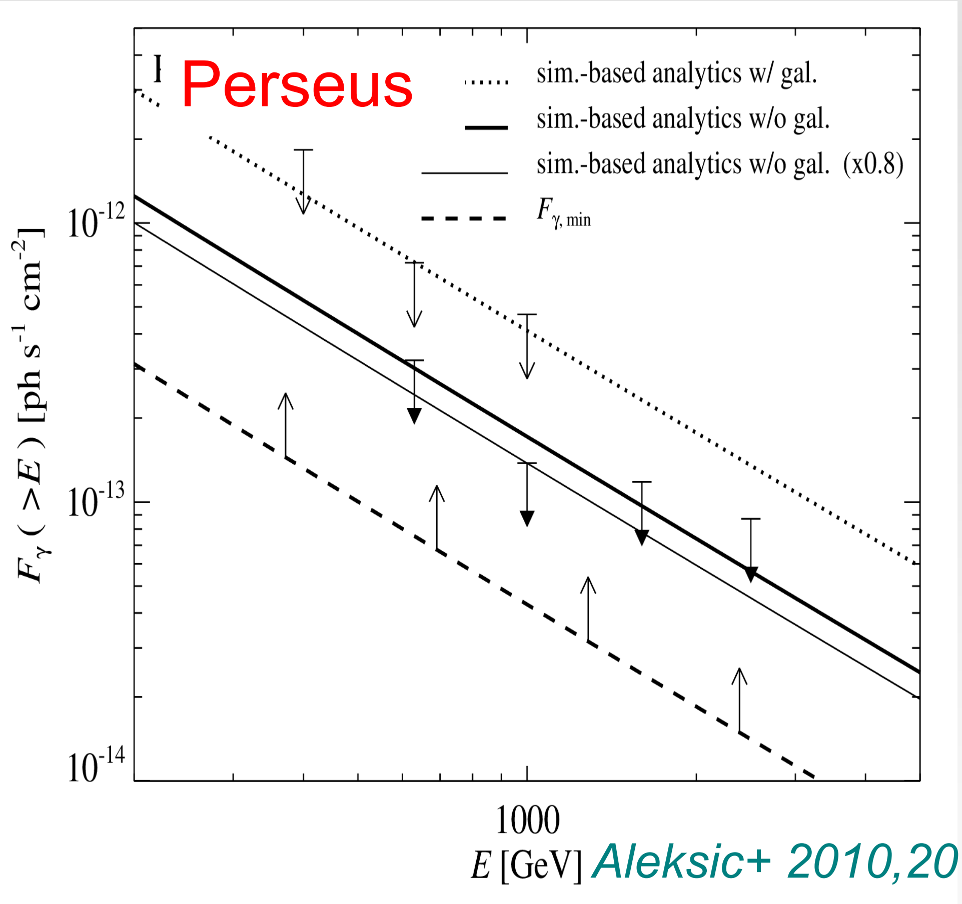



*Pinzke, Pfrommer 2010*

Gamma-ray emission dominated by decaying $\pi^0$:s

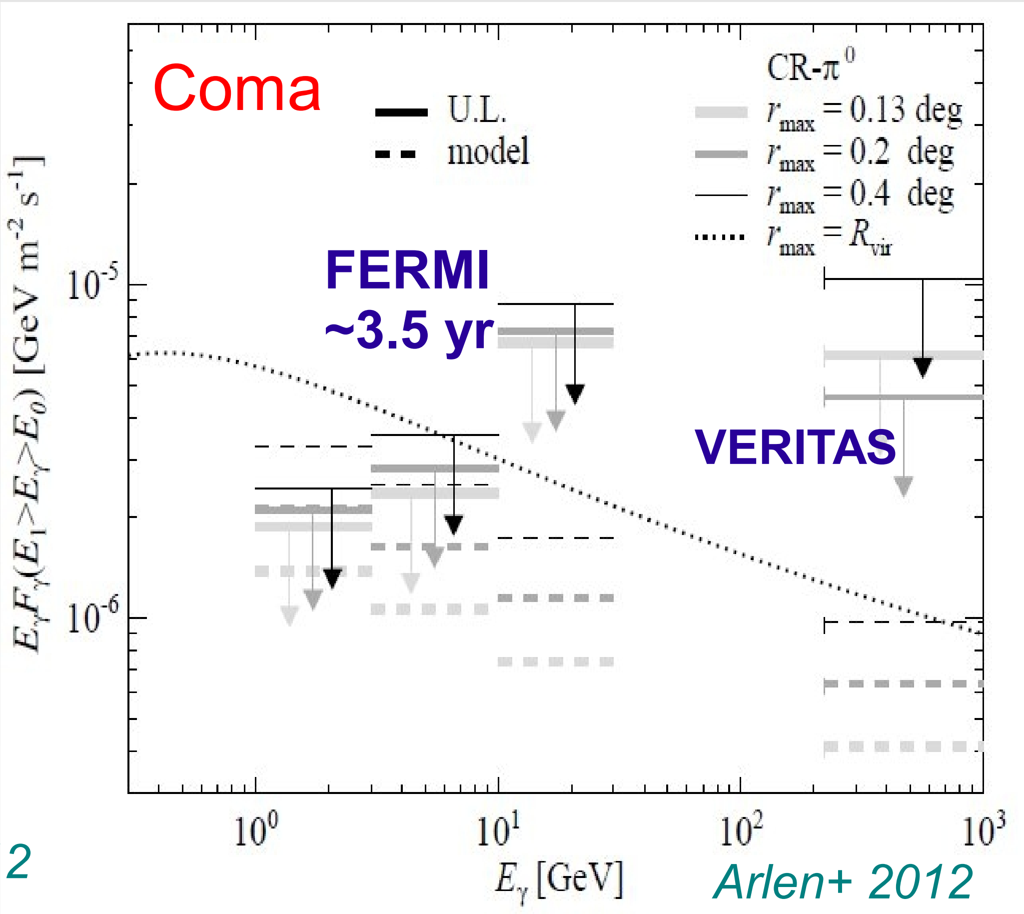
# Hadronic models – gamma rays

**Magic** *Observation time*: 85 h
***deepest observation of a cluster ever***




*Aleksic+ 2010,2012*

**Veritas** *Observation time*: 19 h

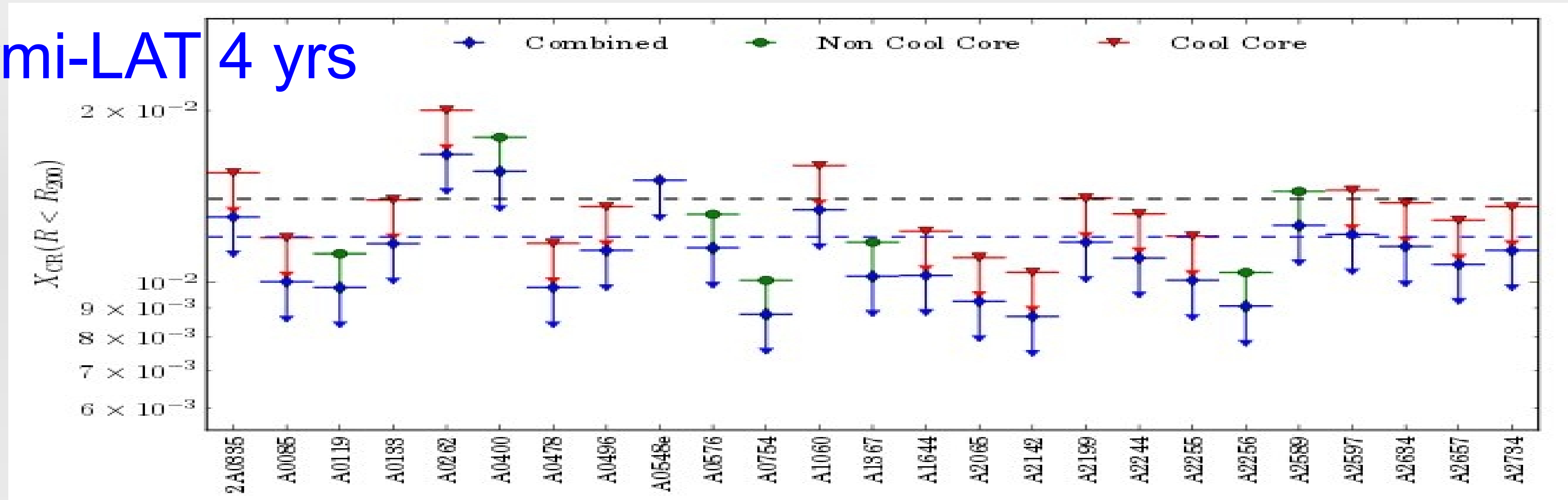


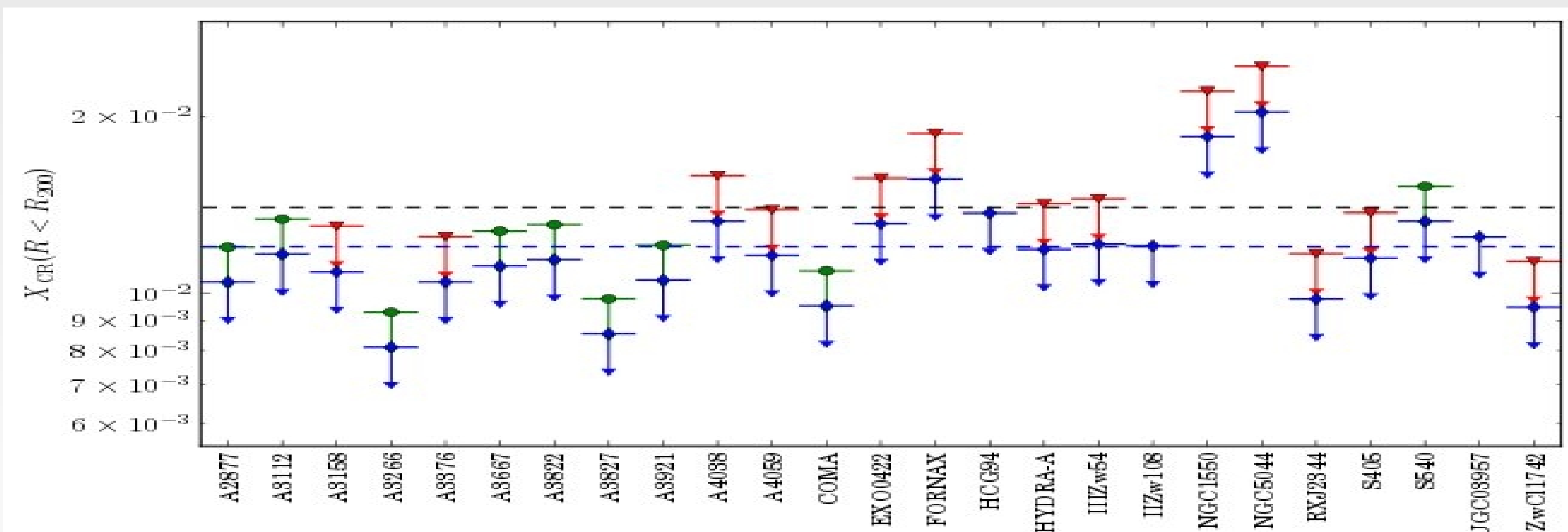

*Arlen+ 2012*

➔ IACT and Fermi-LAT start to constrain CR proton model
➔ Magic factor ~3 from minimum gamma-ray flux

# Hadronic models – gamma rays

Fermi-LAT 4 yrs



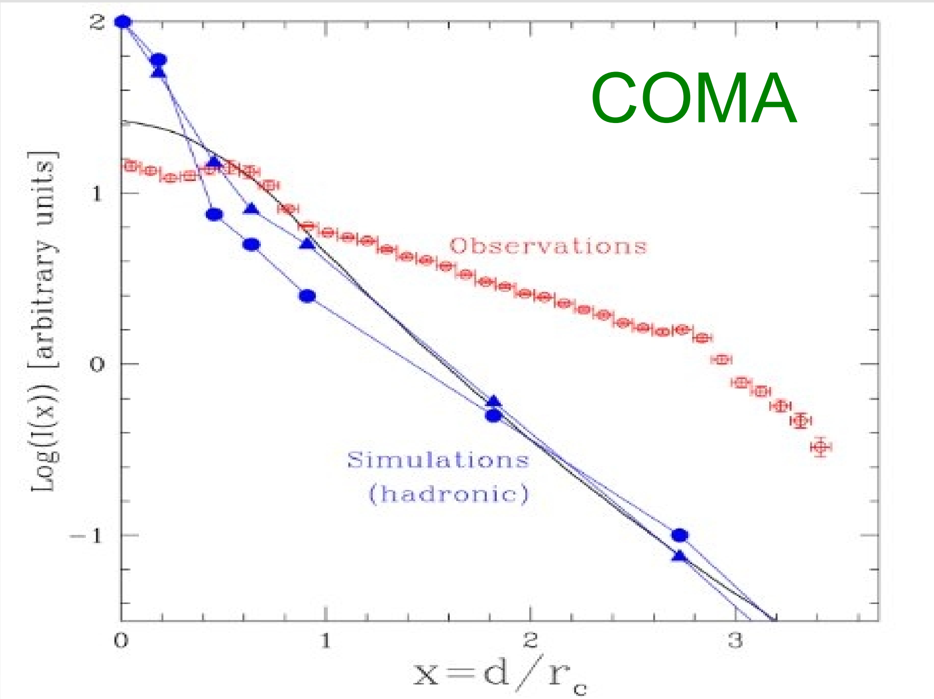




*Zimmer et al. (Fermi-LAT) 2013*

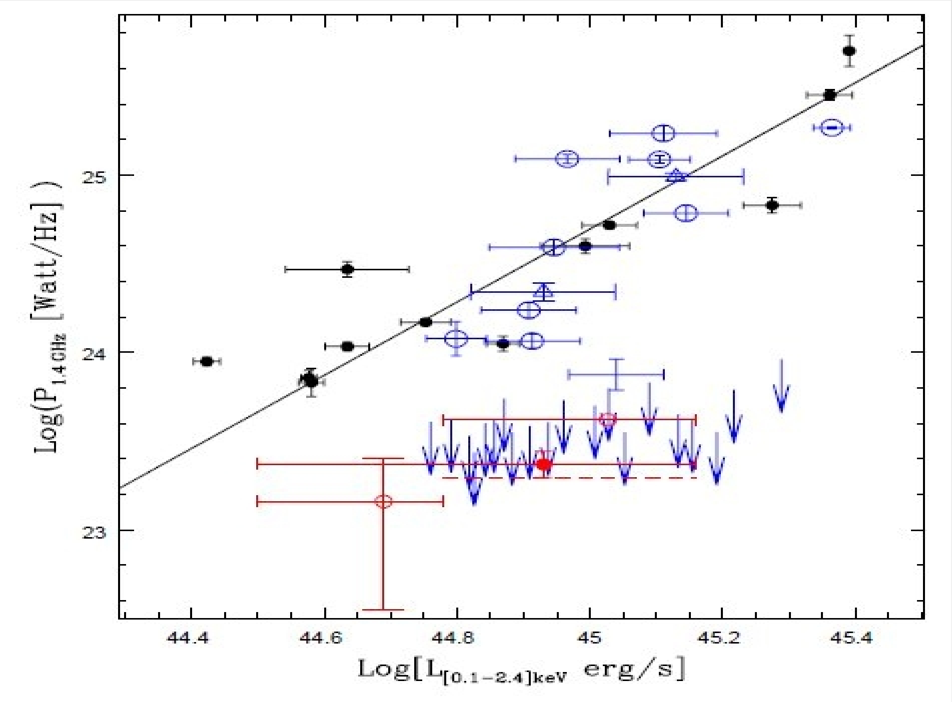
- ➔ $P_{CR}/P_{th}$ and $E_{CR}/E_{th}$ < few percent
- ➔ Fermi-LAT upper limit constrain hadronic models (acc.eff. < 50%)

# Hadronic models – missing pieces

**However**, simple CR model is in tension with some observations of giant radio halos




*Brunetti et al. 2013*




*Brown et al. 2011*

BUT - large uncertainty in B-field (e.g. turbulence might amplify B-field *Keshet 2009*) might explain COMA profile

=> need gamma-ray observations to unambiguously probe the CR protons

# Hadronic models – Streaming CRs

Acceleration mechanism: diffusive shock acceleration

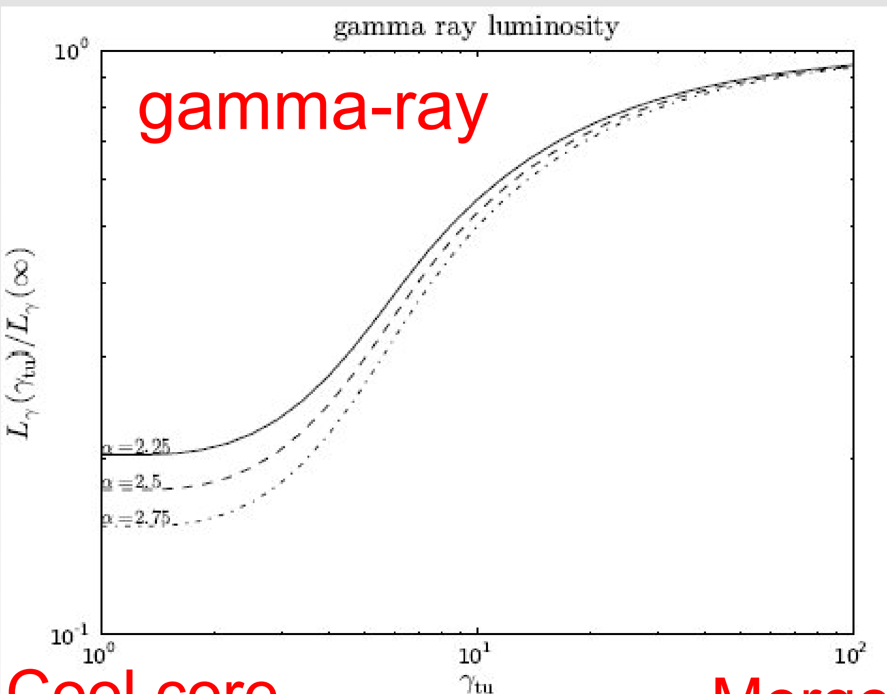
Simulation based CR proton model with adiabatic transport

**+ streaming and diffusion**

*Ensslin et al. 2011, Zandanel et al. 2013, Wiener et al. 2013*

$$\frac{\tau_{\rm st}}{\tau_{\rm tu}} \equiv \gamma_{\rm tu}$$

gamma-ray




Cool core

Merger

**COMA** - radio

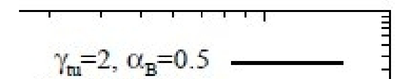



Figure only available off-line

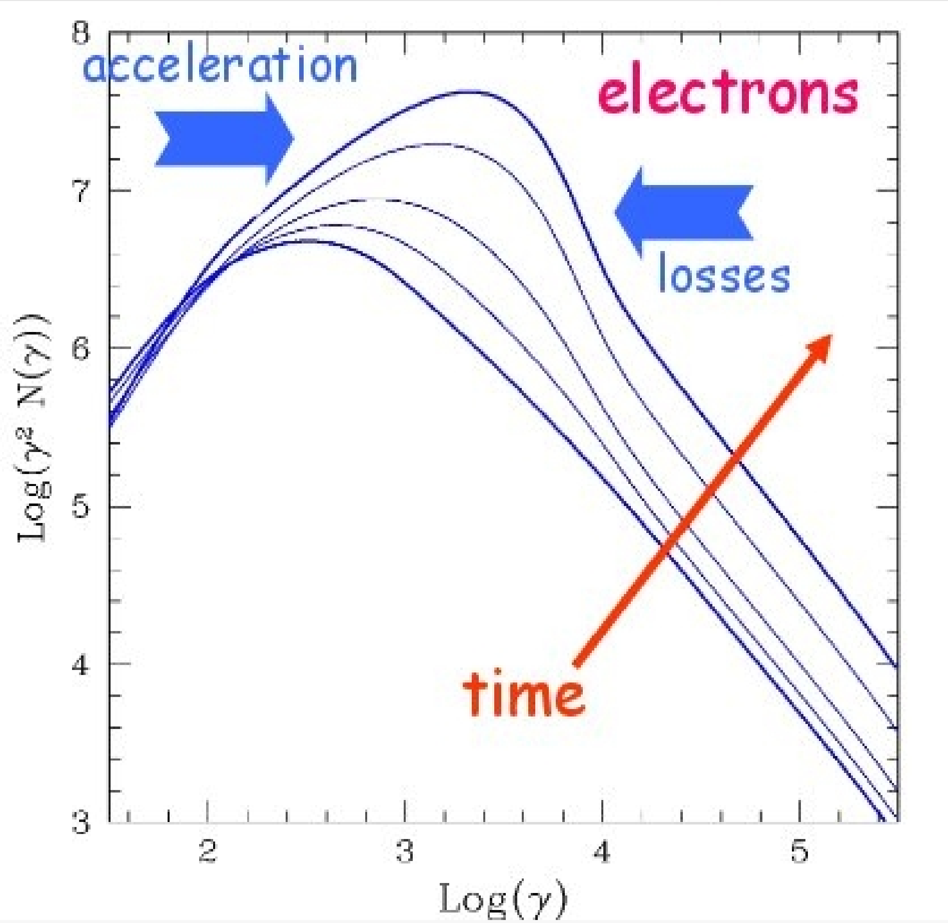
Gamma-ray emission suppressed by ~ 10 in low turbulent clusters

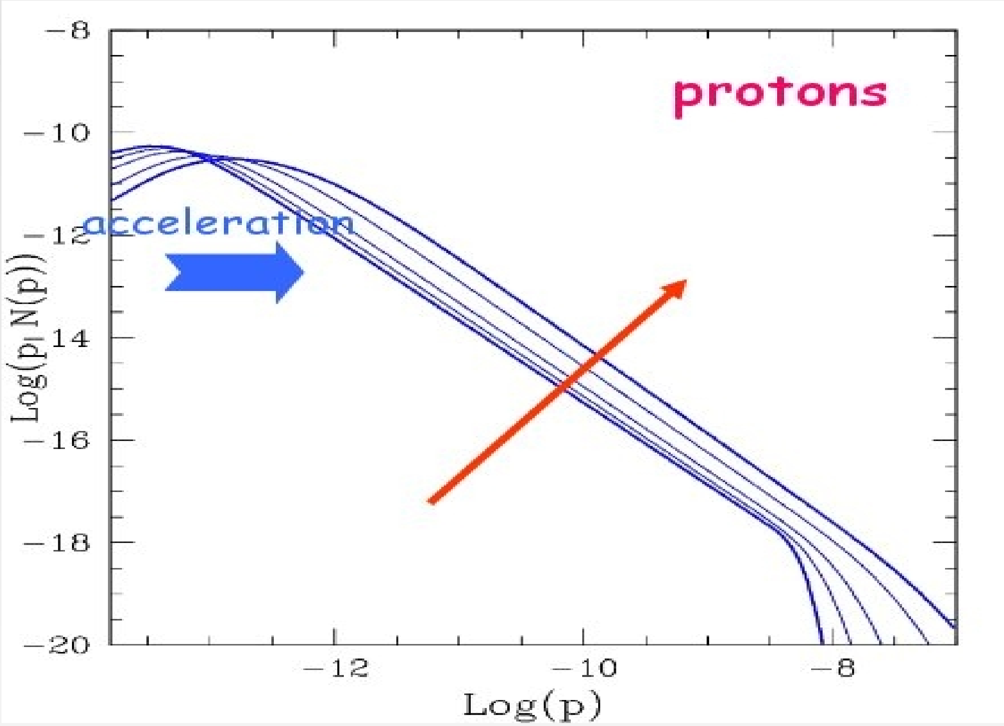
Can reproduce the radio profile in most clusters (COMA a problem)

**Need a leptonic component in cluster outskirts**

# Reacceleration models - CRs

Acceleration mechanism: Compressible MHD turbulence




*Brunetti and Lazarian 2007, 2011*
*Brunetti et al. 2012*

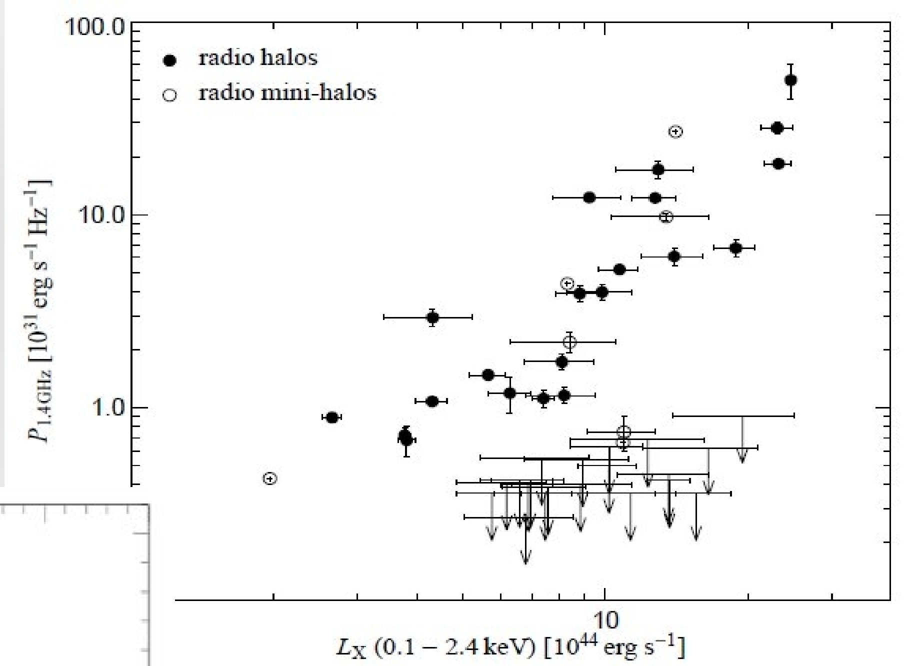
## Uncertainties

- Efficiency acceleration mechanism
- Fossil CRp and CRe spectrum

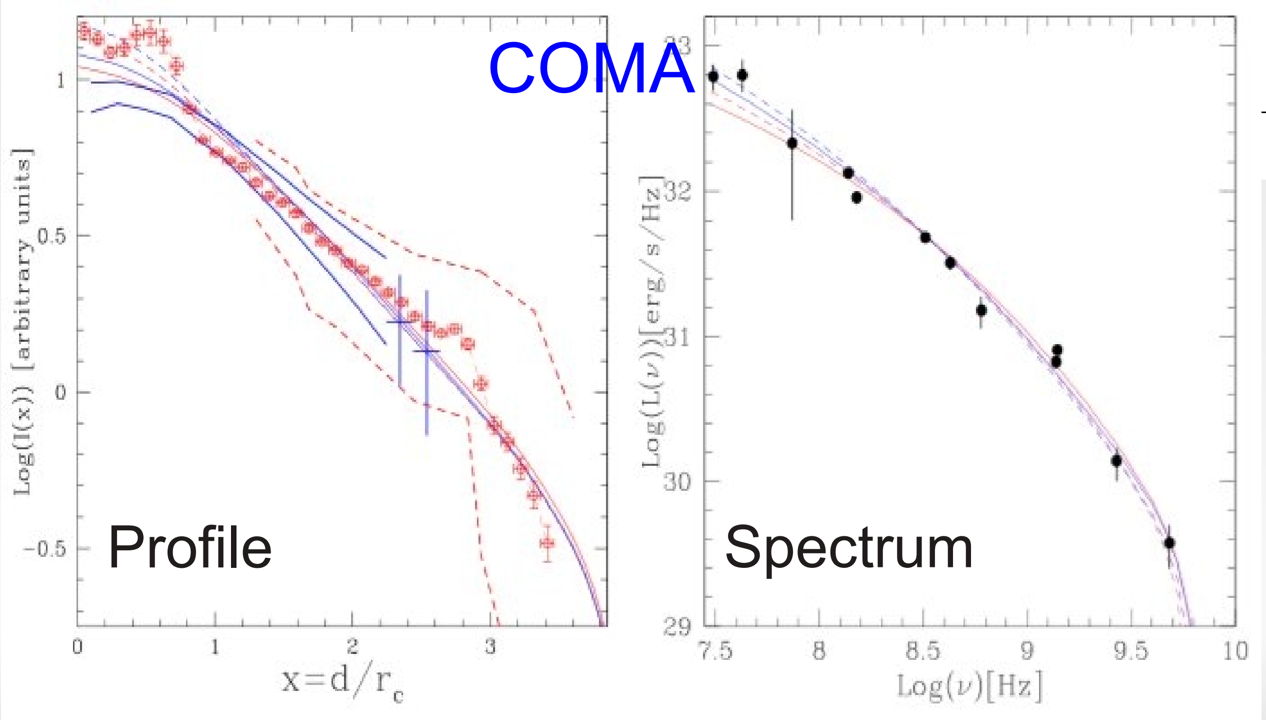
# Reacceleration models - radio

## Characteristics

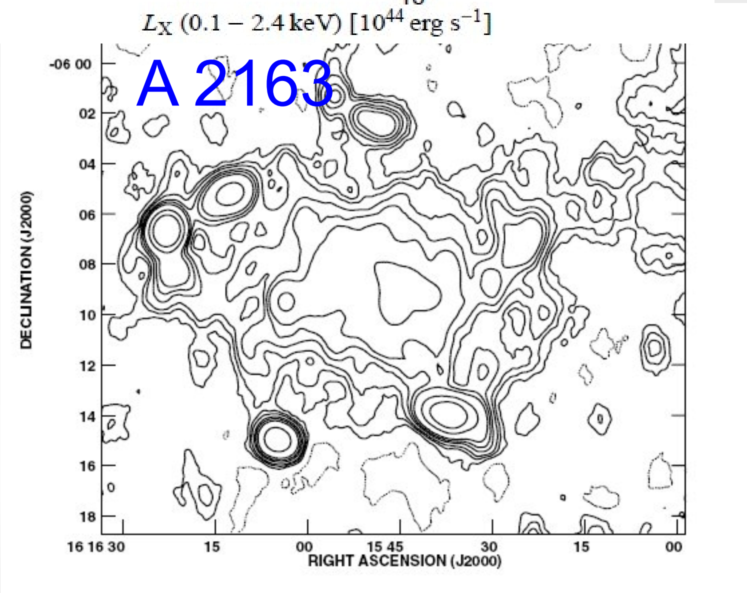
- Bimodality in radio luminosity
- Curved radio spectrum
- Turbulence => complex morphology




*Ensslin et al. 2011*

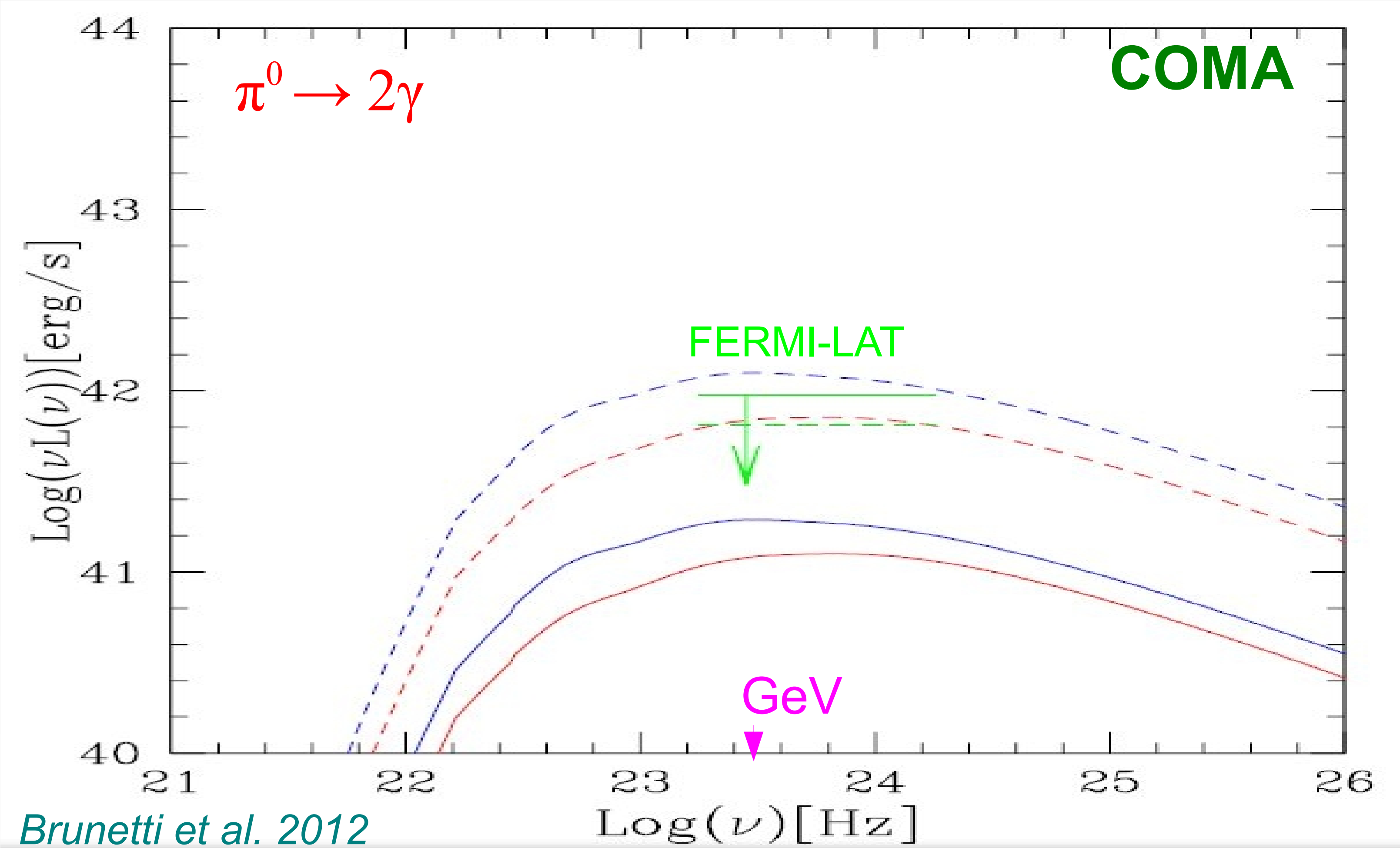



*Brunetti and Lazarian 07,11, Brunetti et al. 2012*




*Feretti at al, 2004*

# Reacceleration models – gamma rays




➔Fermi-LAT (2 yrs) upper limit factor 10 from predictions

➔IACTs will suffer from spatially extended emission (main gamma-ray emission outside $R_c$ ~ 0.2 deg)

# Summary – cosmic rays

Radio observations of clusters can *not* unambiguously determine the non-thermal component → need gamma-ray observations

| Model | Reacceleration | Hadronic *without streaming* | Hadronic *with streaming and primary CRe* |
|---|---|---|---|
| **CRs** | **Mergers** - flat profiles, convex spectra<br>**CC** - suppressed | **Mergers and CC -** trace ICM, concave spectra | **Mergers** - trace ICM, concave spectrum<br>**CC** - flat profiles, concave spectra with cutoff |
| **radio** | ok | ✗ Bimodality<br>✗ Curved spectra<br>✗ COMA profile | ok |
| **γ-ray** | Not detectable in near future by LAT and IACTs<br>Emission > $R_C$<br>Factor few below current LAT limits | Detectable by LAT and IACTs<br>$\pi^0$-decay dominate, ~$R_C$<br>Magic/LAT limit $P_{CR}/P_{th}$ < few % | Mergers detectable by LAT and IACTs<br>$\pi^0$-decay dominate, ~$R_C$<br>Magic/LAT limit $P_{CR}/P_{th}$ < few % |

# Detecting CDM indirectly – annihilation radiation

Supersymmetric particles are Majorana particles

$\Rightarrow$ annihilate and produce gamma-rays

Intensity of annihilation radiation at **x** depends on:

$$\alpha \int \rho^2(\mathbf{x}) \langle \sigma v \rangle \, dV$$

halo density at **x**
*smooth + substructures*

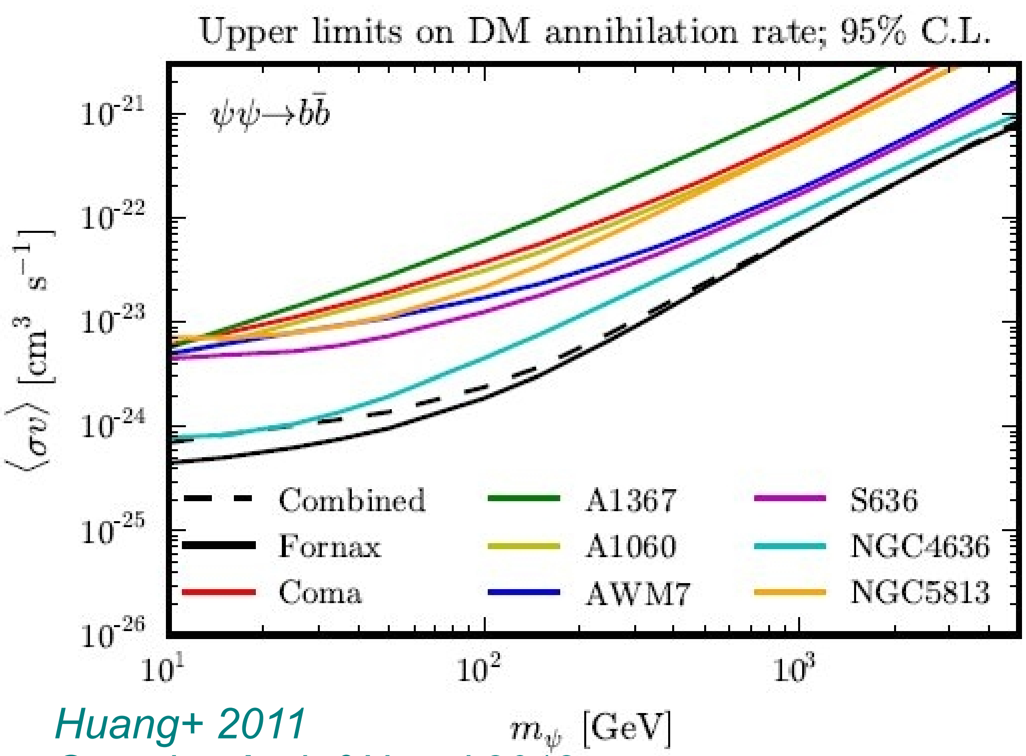
cross-section

$\Rightarrow$ Estimating intensities requires knowing $\rho(x)$

$\Rightarrow$ High resolution N-body simulations of halo formation

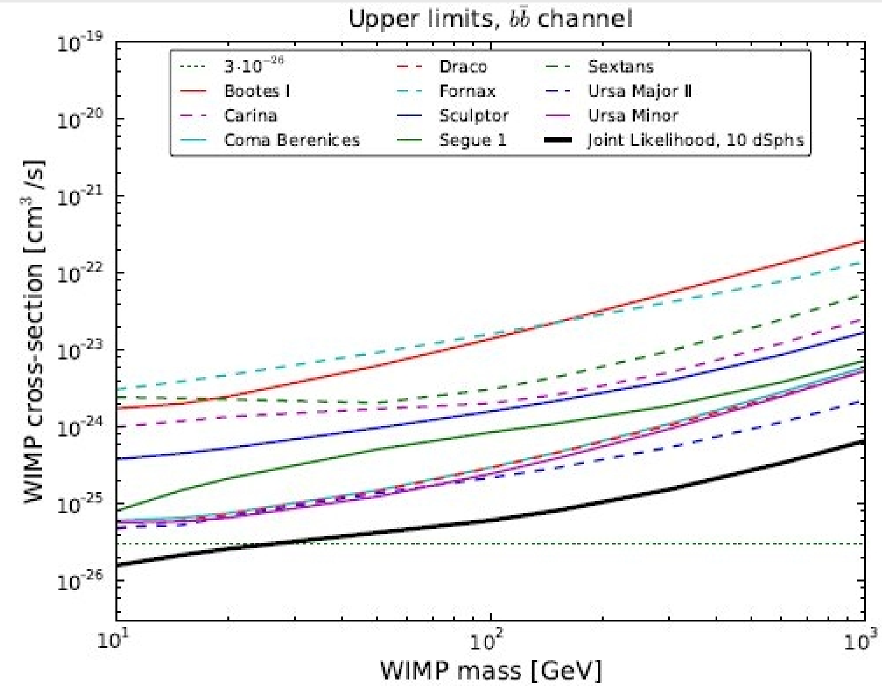
# Why search for DM in galaxy clusters?

## GALAXY CLUSTERS




*Huang+ 2011*
*See also Ando&Nagai 2012*

## DWARF GALAXIES




*Ackerman(Fermi-LAT) 2011*
*See also Geringer-Sameth+ 2011*

Combined limits for dwarf galaxies ~ 20 more constraining

**BUT**

**Very high resolution simulations of galaxy clusters show that CDM substructures could potentially boost the gamma-ray flux in clusters by several orders of magnitude.**

*e.g. Pinzke el al. 2011, Gao et al 2011*

# Enhancement from DM substructures

*Springel et al., 2008*

Constant offset in the luminosity from substructures between different mass resolutions in the simulation ($M_{res}$).

$$\mathrm{Norm} \propto M_{res}^{-0.226}$$

Extrapolate to the minimal mass of dark matter halos ($M_{min}$) that can form.

The cold dark matter scenario suggest $M_{min} \sim 10^{-6}\ M_{\odot}$.

*Hofmann, Schwarz and Stöcker, 2008*
*Green, Hofmann and Schwarz, 2005*

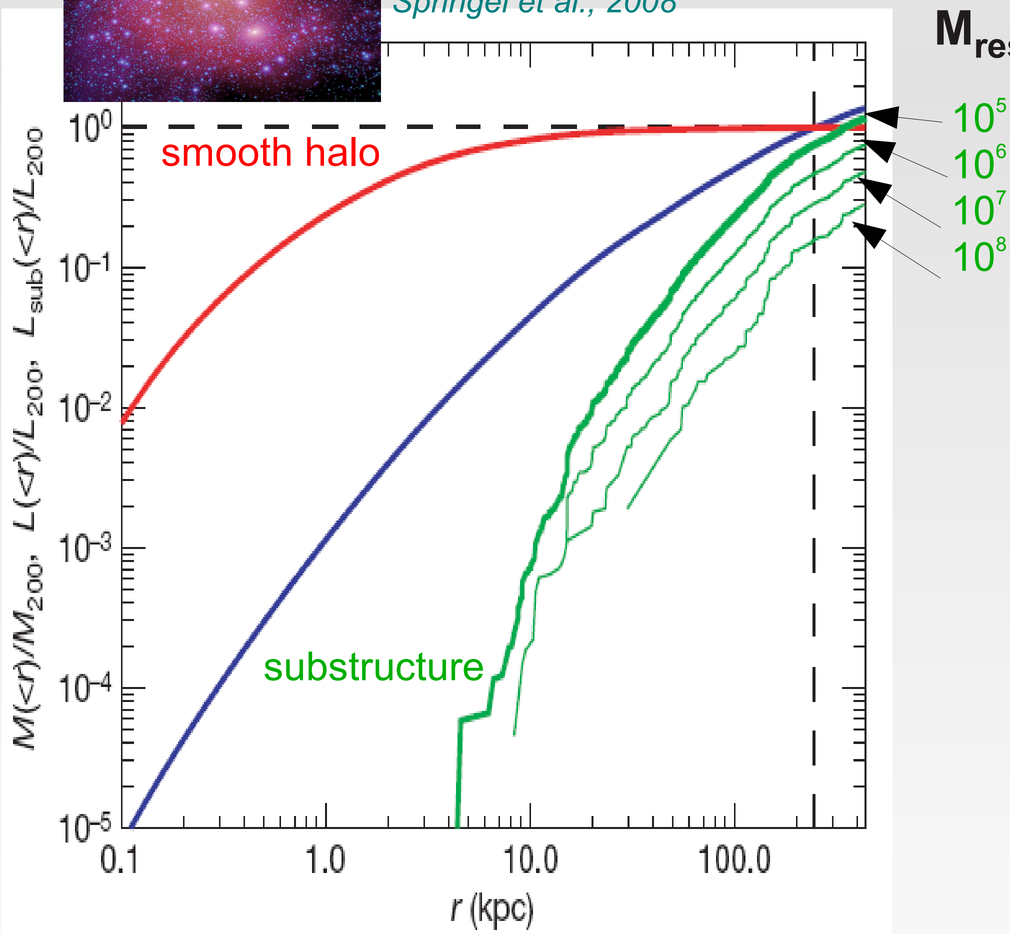
$$L_{sub}(<r)\ \mu\ (M_{200} / M_{res})^{0.226}$$

**Luminosity boosted by ~1000 in clusters**

*Pinzke et al. 2011, Gao et al 2011*

# Enhancement from DM substructures

Springel et al., 2008




$\mathbf{M_{res}}$: Constant offset in luminosity from substructures between different mass cuts in the simulation ($M_{res}$).

$$\text{Norm} \propto M_{res}^{-0.226}$$

Extrapolate to minimal mass of DM halos ($M_{min}$) that can form. The CDM scenario suggest $M_{min} \sim 10^{-6}\ M_{\odot}$.

*Hofmann, Schwarz and Stöcker, 2008*
*Green, Hofmann and Schwarz, 2005*

$$L_{sub}(<r) \propto (M_{200} / M_{res})^{0.226}$$

**Luminosity boosted by ~1000 in clusters**

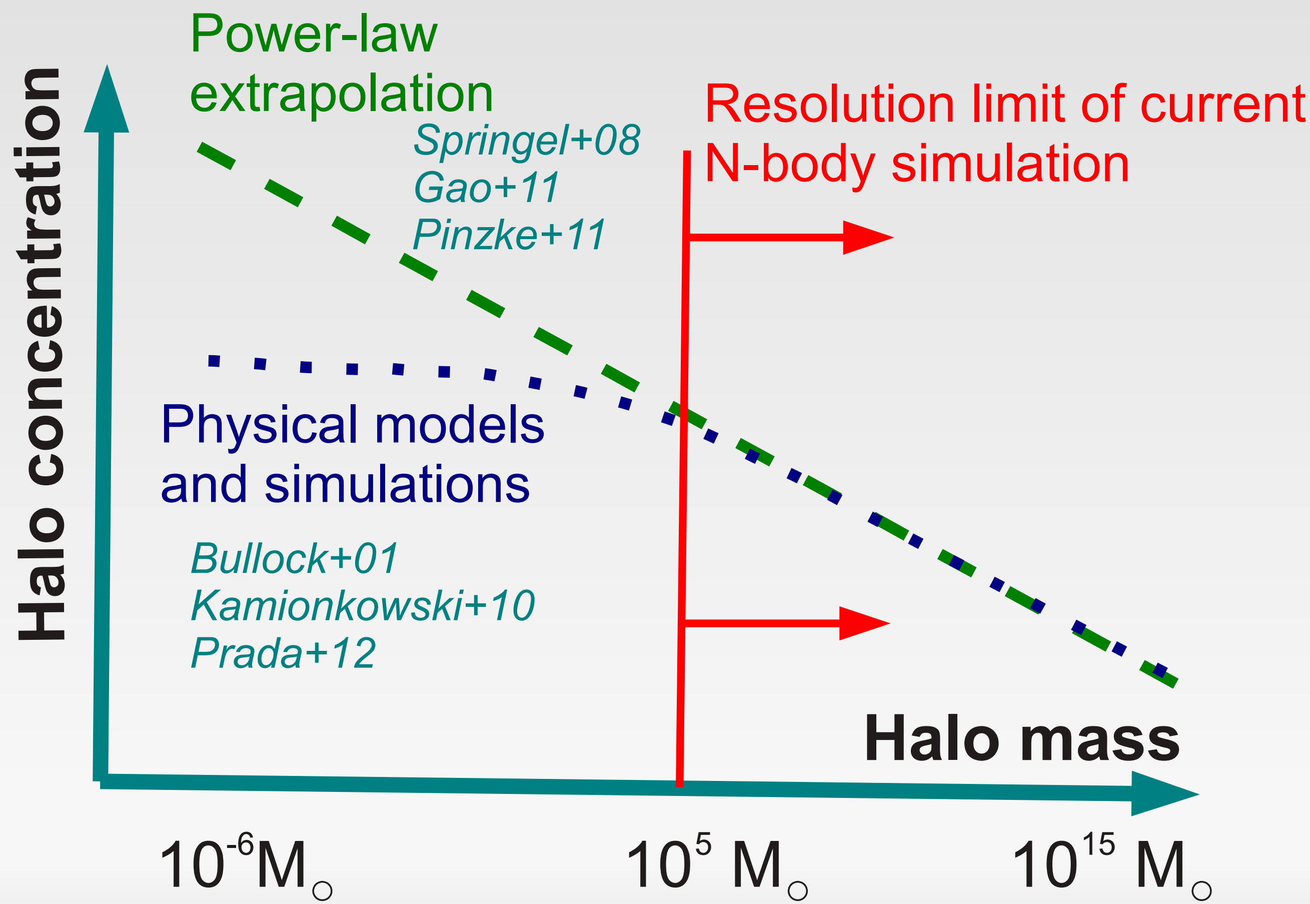
*Pinzke et al. 2011, Gao et al 2011*

# Large uncertainties in extrapolation

Main uncertainty in substructure boost factor from concentration-mass relation of sub $10^5\ M_\odot$ scales

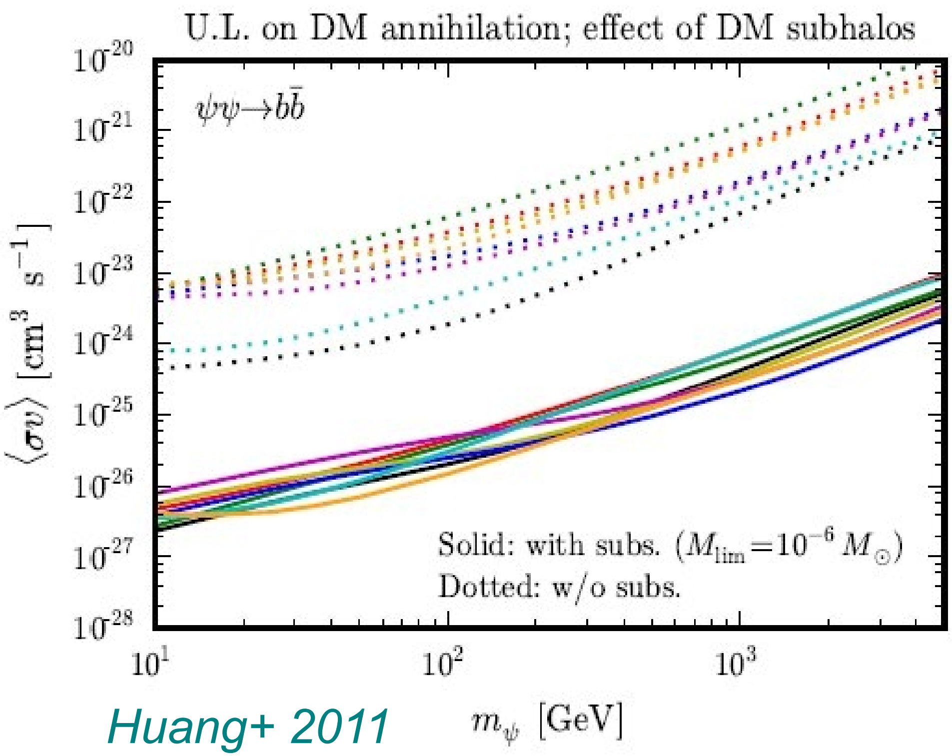
Semi analytic models predict a boost from substructures that is a factor 10-100 smaller than power-law extrapolation

**No data on these scales!**



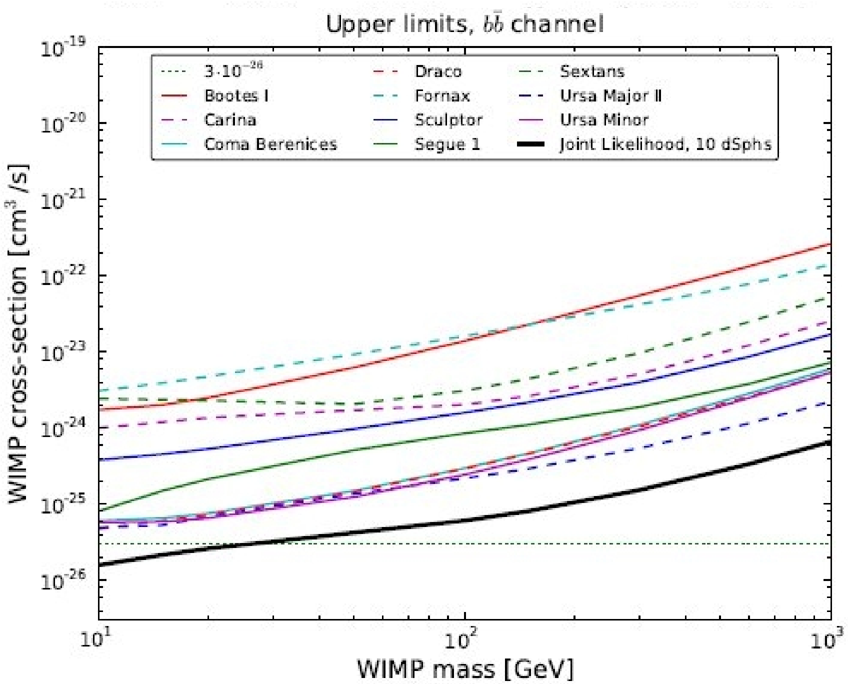
# Clusters incl. substructures vs. Dwarfs

**GALAXY CLUSTERS**




*Huang+ 2011*
*See also Ando&Nagai 2012*

**DWARF GALAXIES**

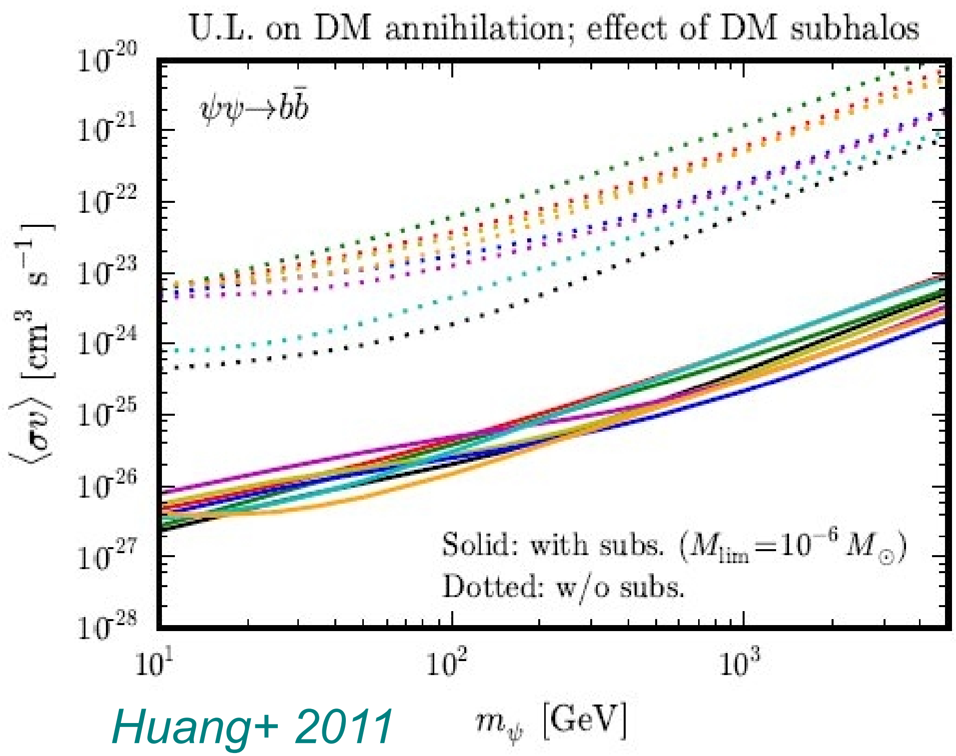



*Ackerman(Fermi-LAT) 2011*
*See also Geringer-Sameth+ 2011*

**Galaxy clusters about factor 10 more constraining than dwarf galaxies when substructures are included!**

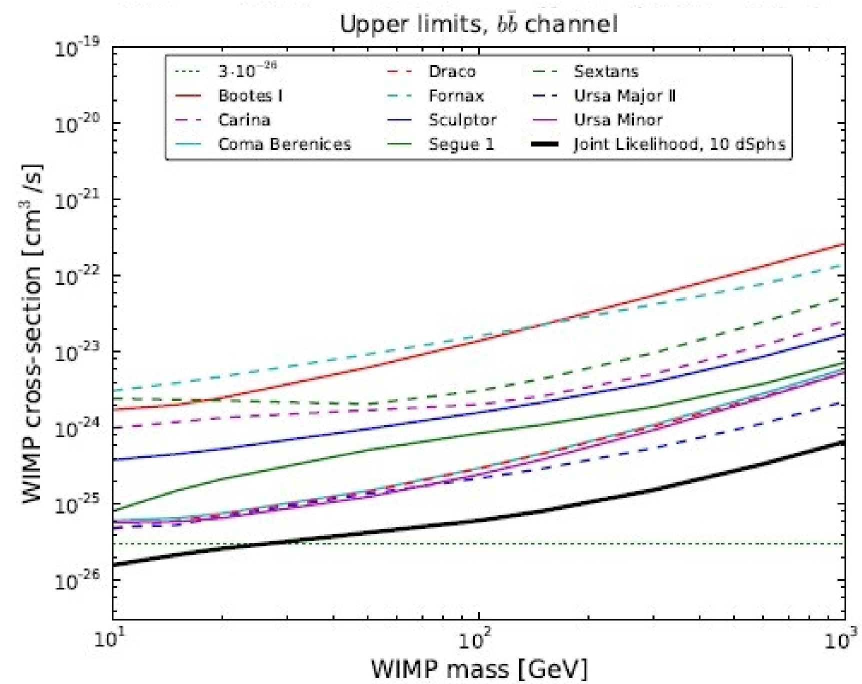
# Clusters incl. substructures vs. Dwarfs

**GALAXY CLUSTERS**




*Huang+ 2011*
*See also Ando&Nagai 2012*

**DWARF GALAXIES**

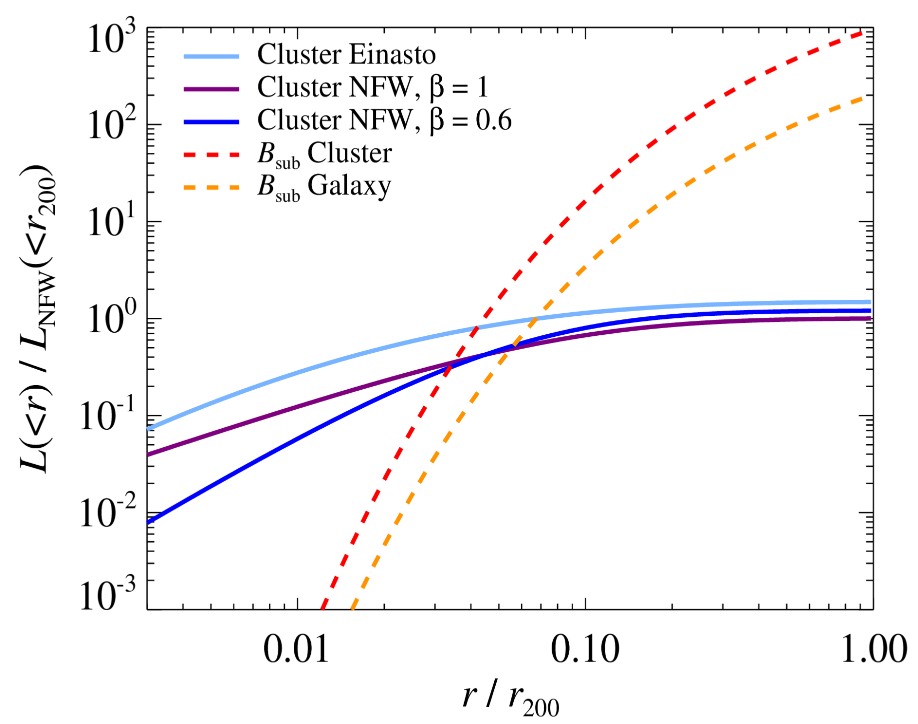


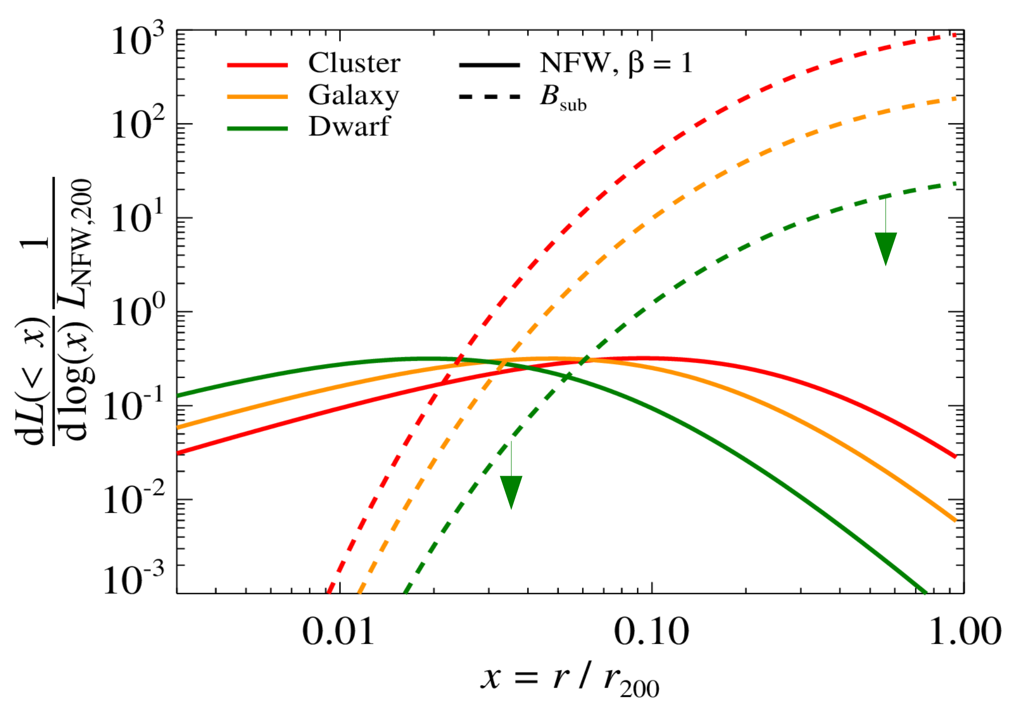

*Ackerman(Fermi-LAT) 2011*
*See also Geringer-Sameth+ 2011*

**Galaxy clusters about factor 10 more constraining than dwarf galaxies when substructures are included!**

**large uncertainty in the boost from substructures**

# Spatial distribution of DM




- Choice of smooth density profile minor impact on annihilation luminosity outside center.
- Large boost from substructures in clusters (~1000), and smaller for galaxies (~200).
- Majority of flux from smooth halo delivered by region around $r_s$ / 3.
- Emission from substructures dominated by outer regions.

Spatially extended!

→ challenging for IACTs

# Summary – dark matter

We have studied the possibility to detect gamma-ray emission from galaxy clusters using annihilating CDM

- **Luminosity from clusters boosted by $\lesssim$ 1000**
- **Flat brightness profiles and spatially extended**
- **Challenging for IACTs, better probed by Fermi-LAT**

*Constraints from Fermi-LAT observations:*

Clusters more constraining than dwarf spheroidals **with substructures** (about factor 20) , less constraining **without** (about factor 20)