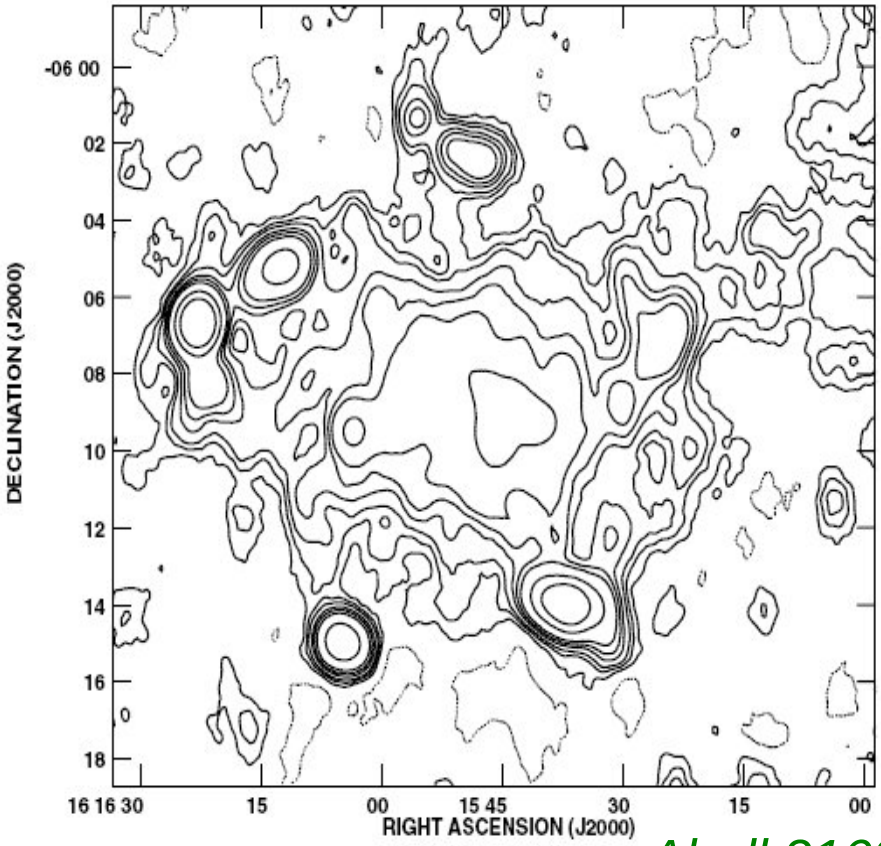
Non-thermal processes in galaxy clusters

cosmic rays, ***dark matter***, *turbulence, magnetic fields, ...*

Bullet Cluster



Abell 2163

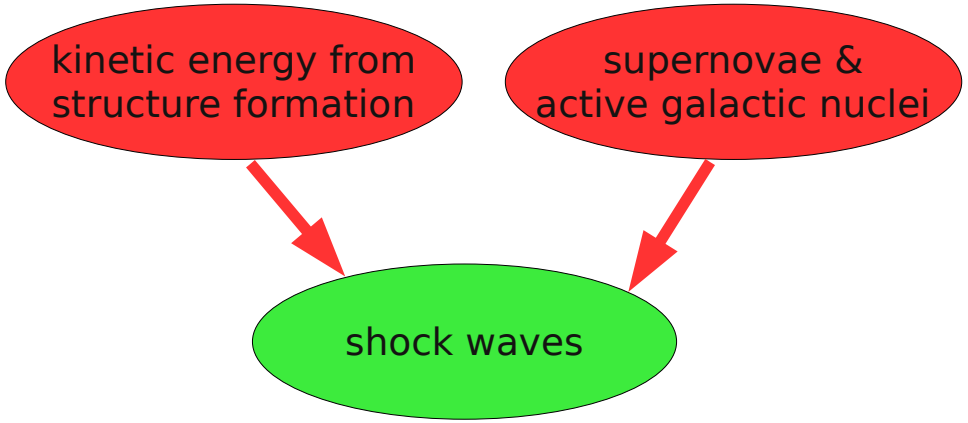
Anders Pinzke

CGE Inaugural Workshop
Irvine, March 1-2, 2011

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

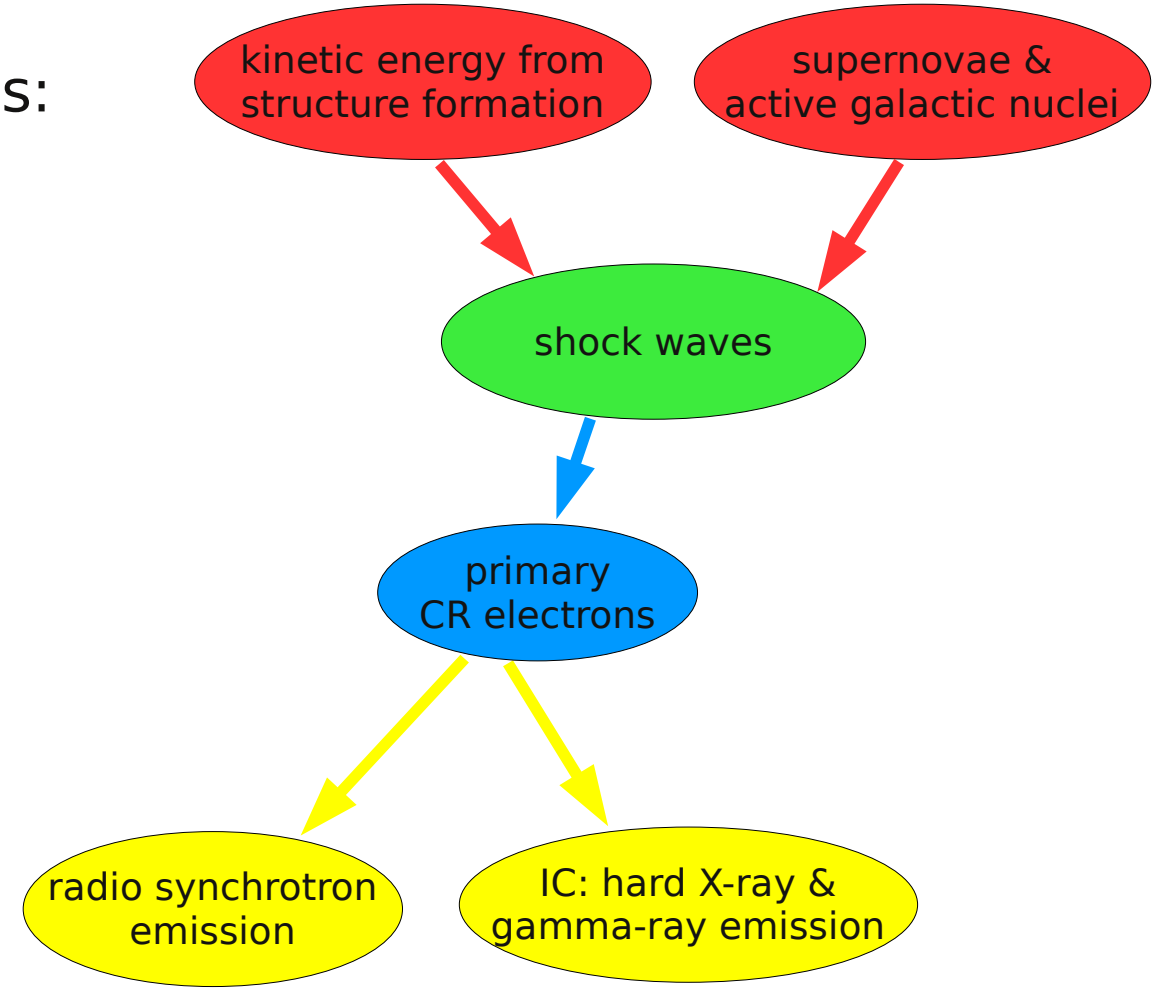
Relativistic populations and radiative processes in clusters:

Energy sources:

Plasma processes:

Relativistic particle pop.:

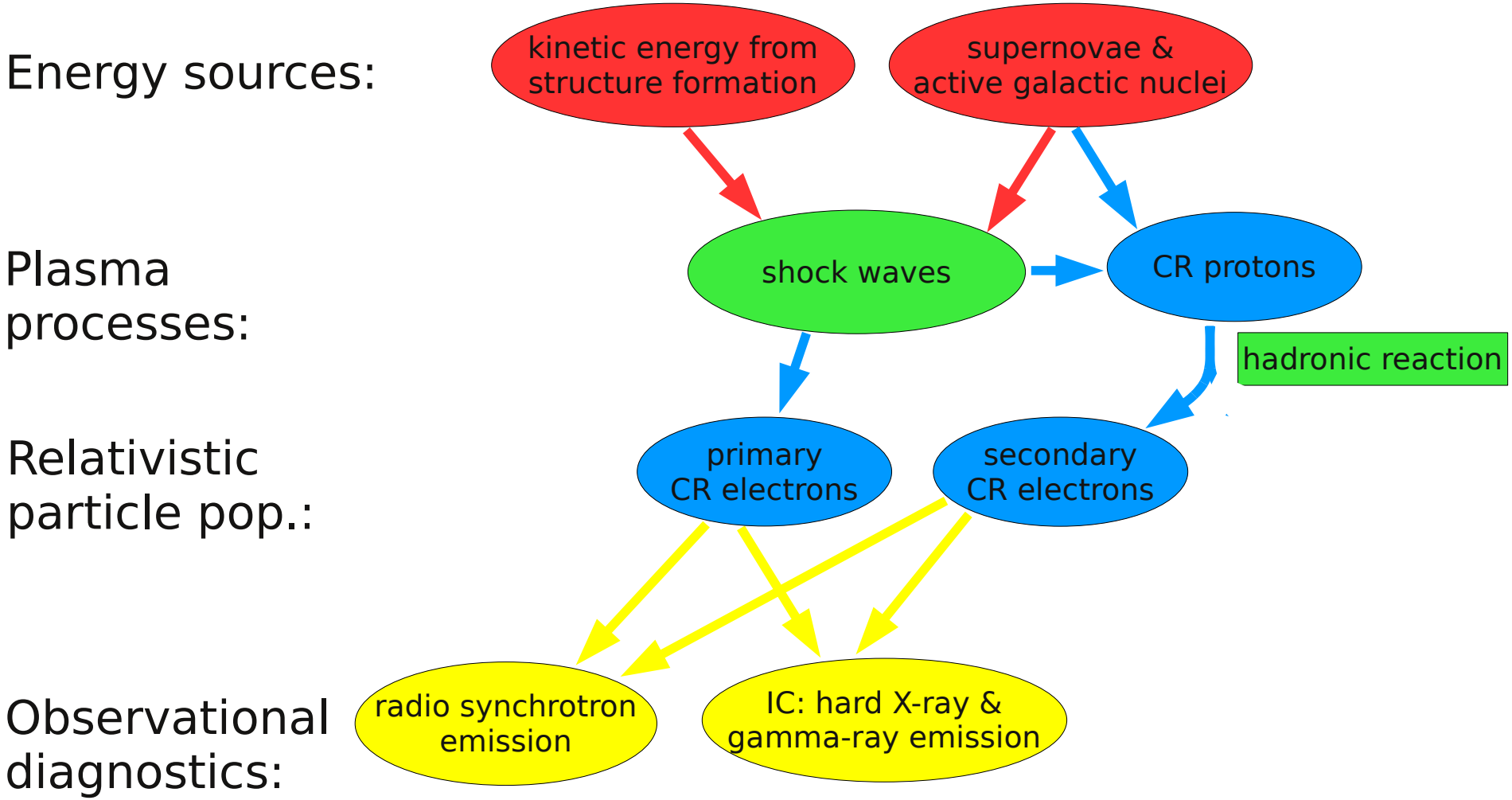
Observational diagnostics:



Pfrommer et al. 2008

Cosmic rays in clusters of galaxies

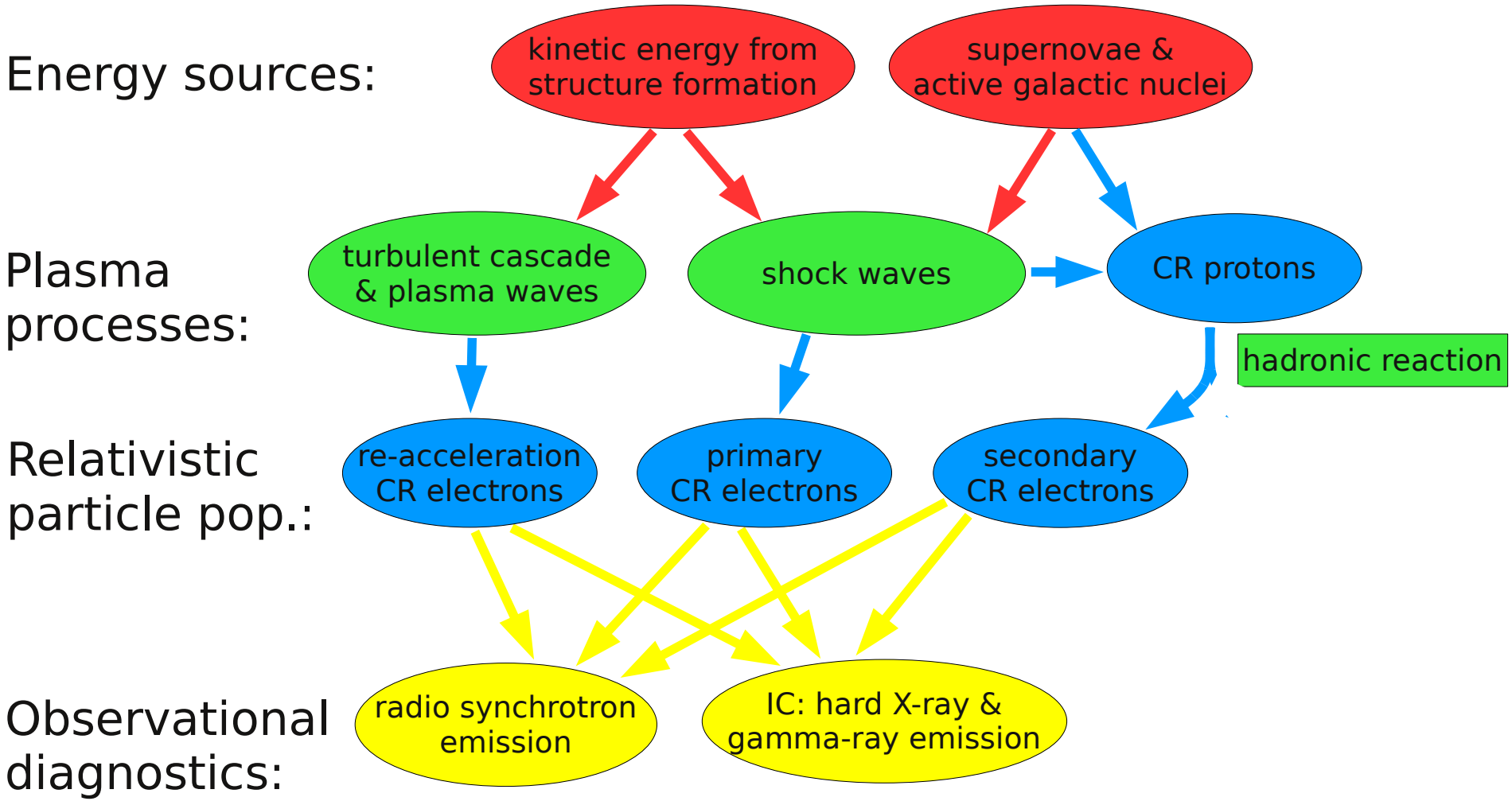
Relativistic populations and radiative processes in clusters:



Pfrommer et al. 2008

Cosmic rays in clusters of galaxies

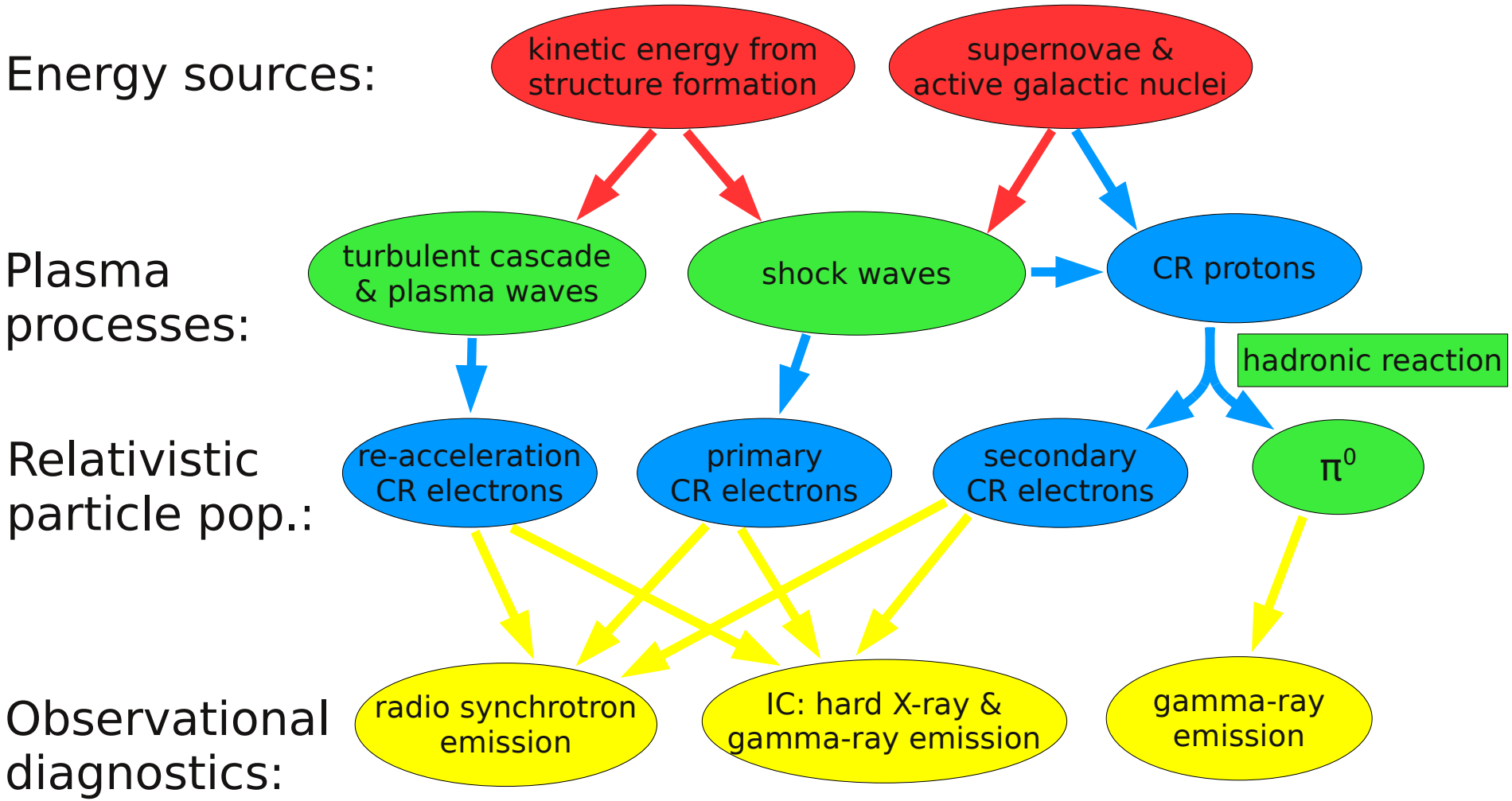
Relativistic populations and radiative processes in clusters:



Pfrommer et al. 2008

Cosmic rays in clusters of galaxies

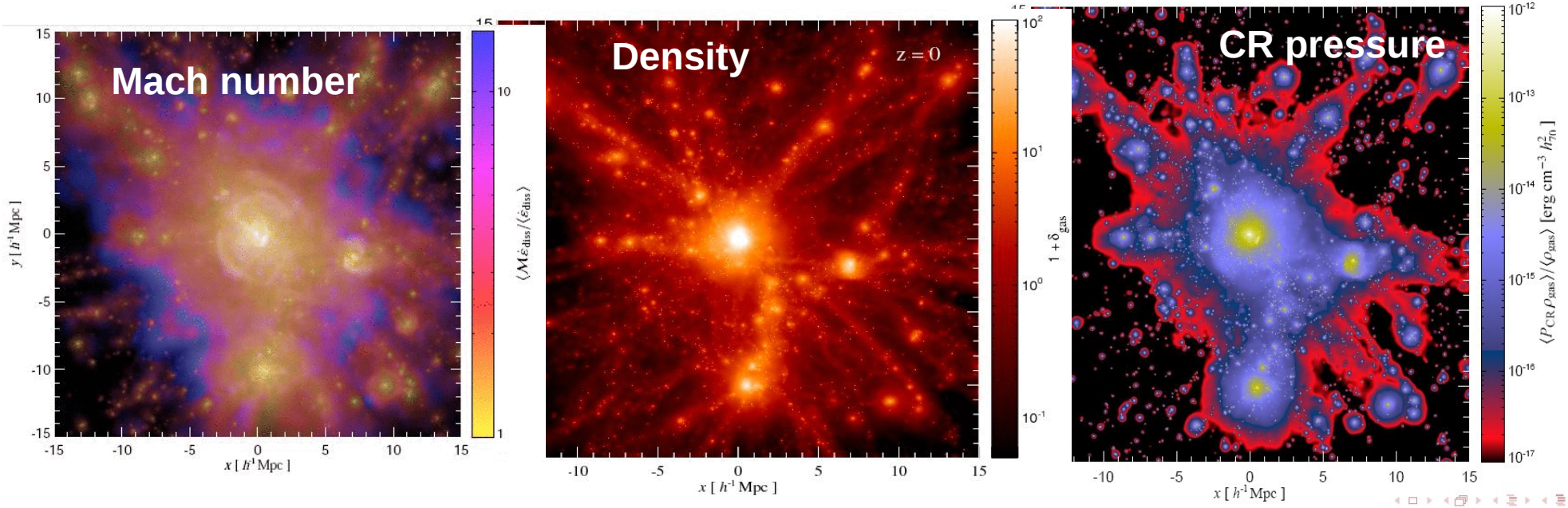
Relativistic populations and radiative processes in clusters:



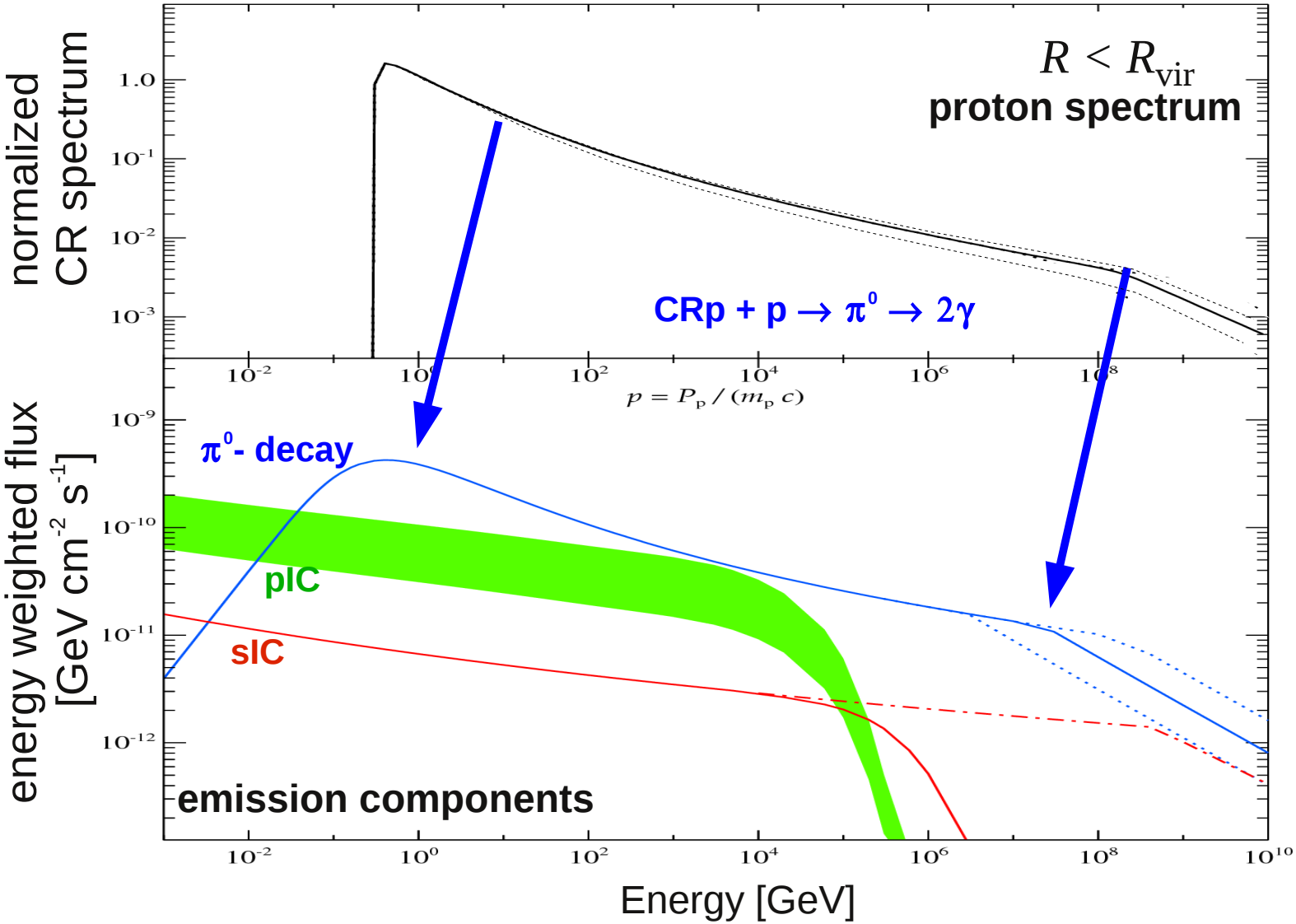
Pfrommer et al. 2008

Galaxy cluster simulations

- Gadget3
  - *parallel TreeSPH code*
  - *updated cosmic ray physics (spatial and spectral information)*
  - *radiative hydrodynamics*
- Simulate 14 high-resolution galaxy clusters
  - *full cosmological environment*
  - *variety of dynamical stages*
  - *mass range of almost two orders of magnitudes*



CR proton/gamma-ray spectra

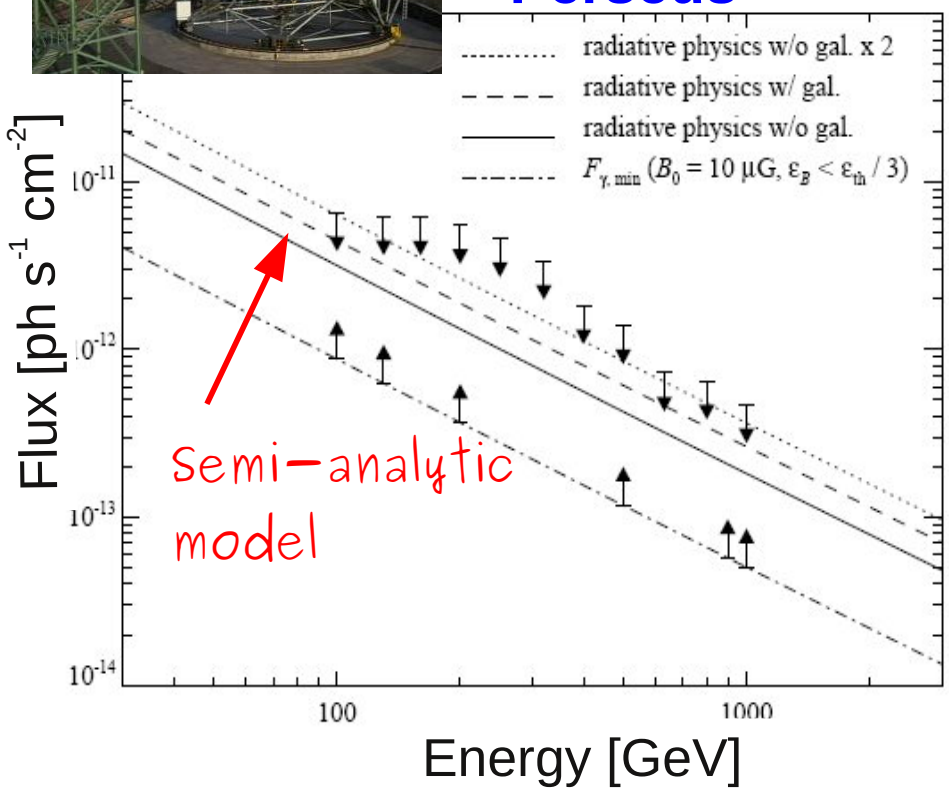


Pinzke, Pfrommer 2010

Gamma-ray observations of clusters

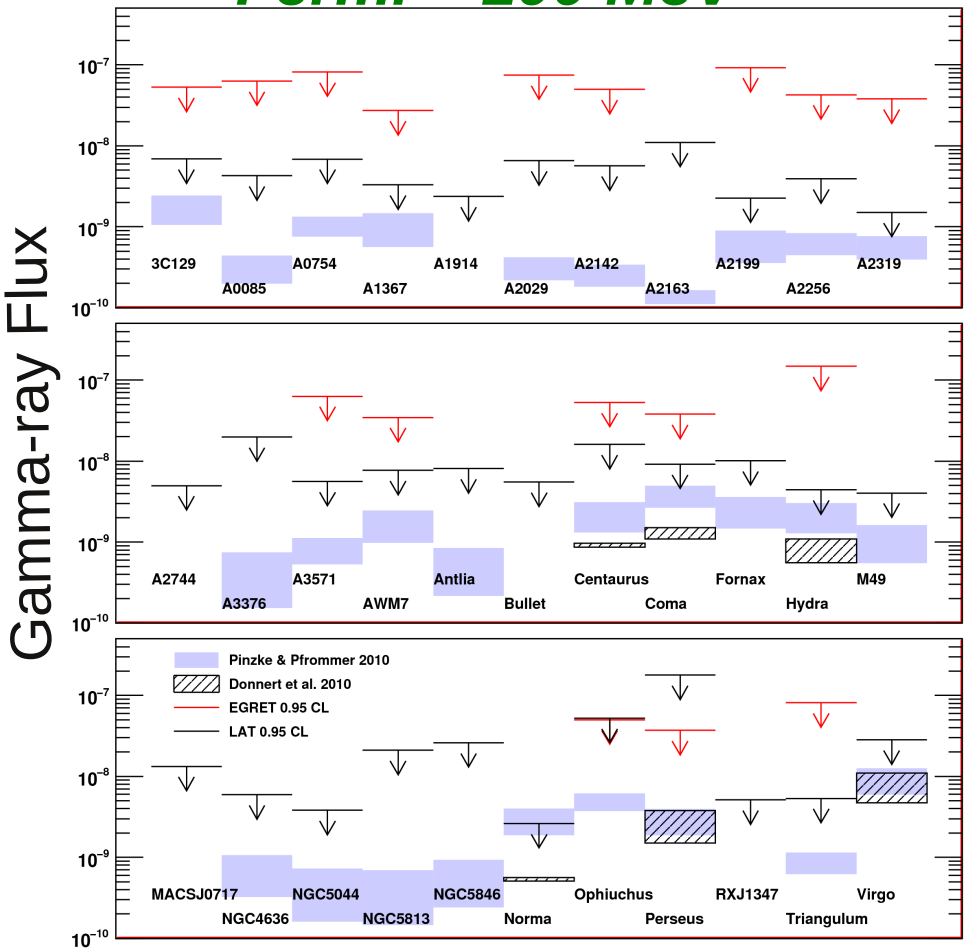
MAGIC IACT

Perseus



Aleksic et al. 2009

Fermi – 100 MeV



Ackermann et al. 2010

Annihilating dark matter - substructures

Large luminosity contribution from substructures.

The cold dark matter scenario predicts a smallest size for halos of $M_{min} \sim 10^{-6}\ M_{\odot}$.

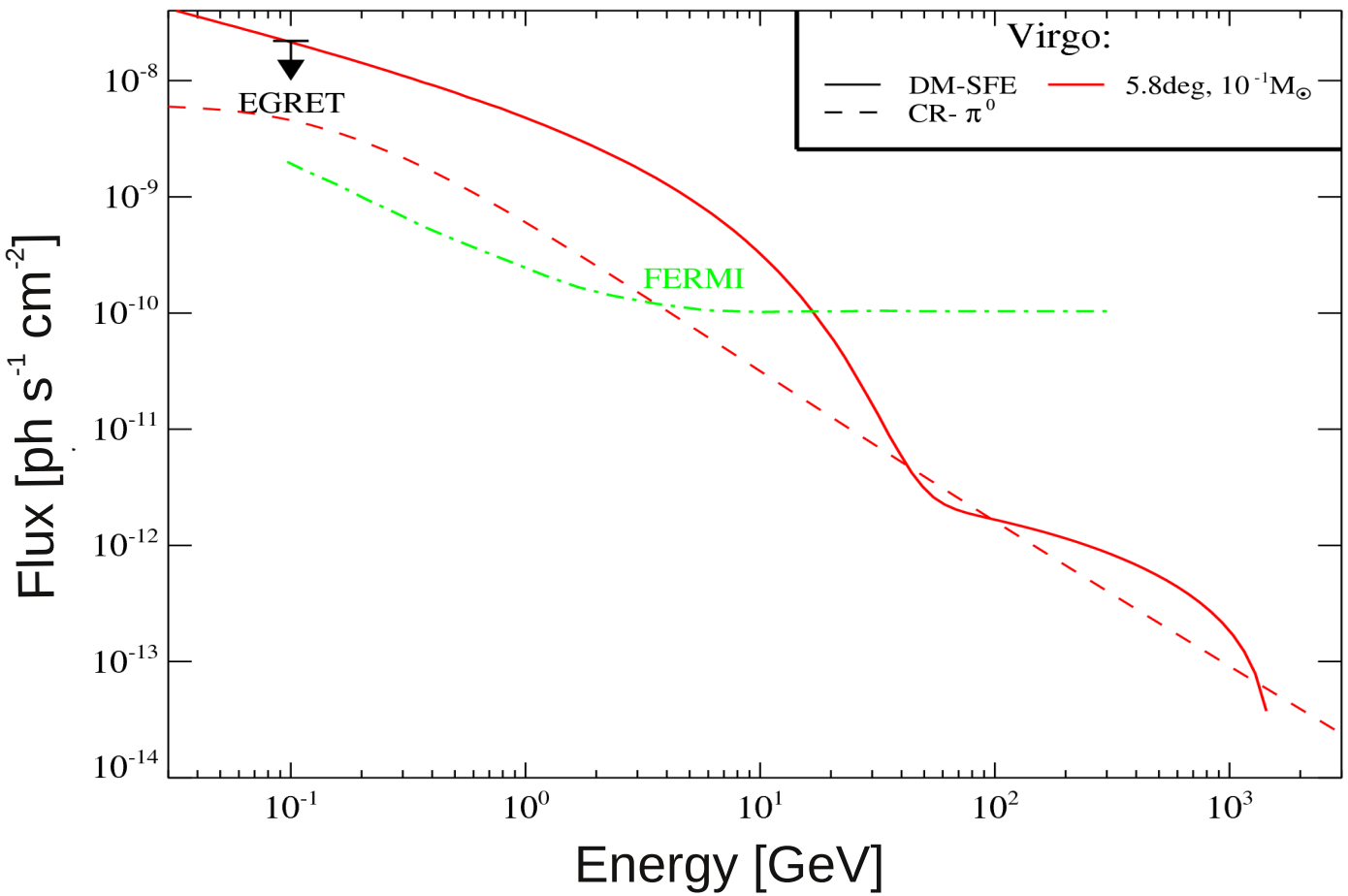
Hofmann, Schwarz and Stöcker, 2008
Green, Hofmann and Schwarz, 2005

Extrapolating simulations to these scales:

–> luminosity boosted by **200**

Springel et al., 2008

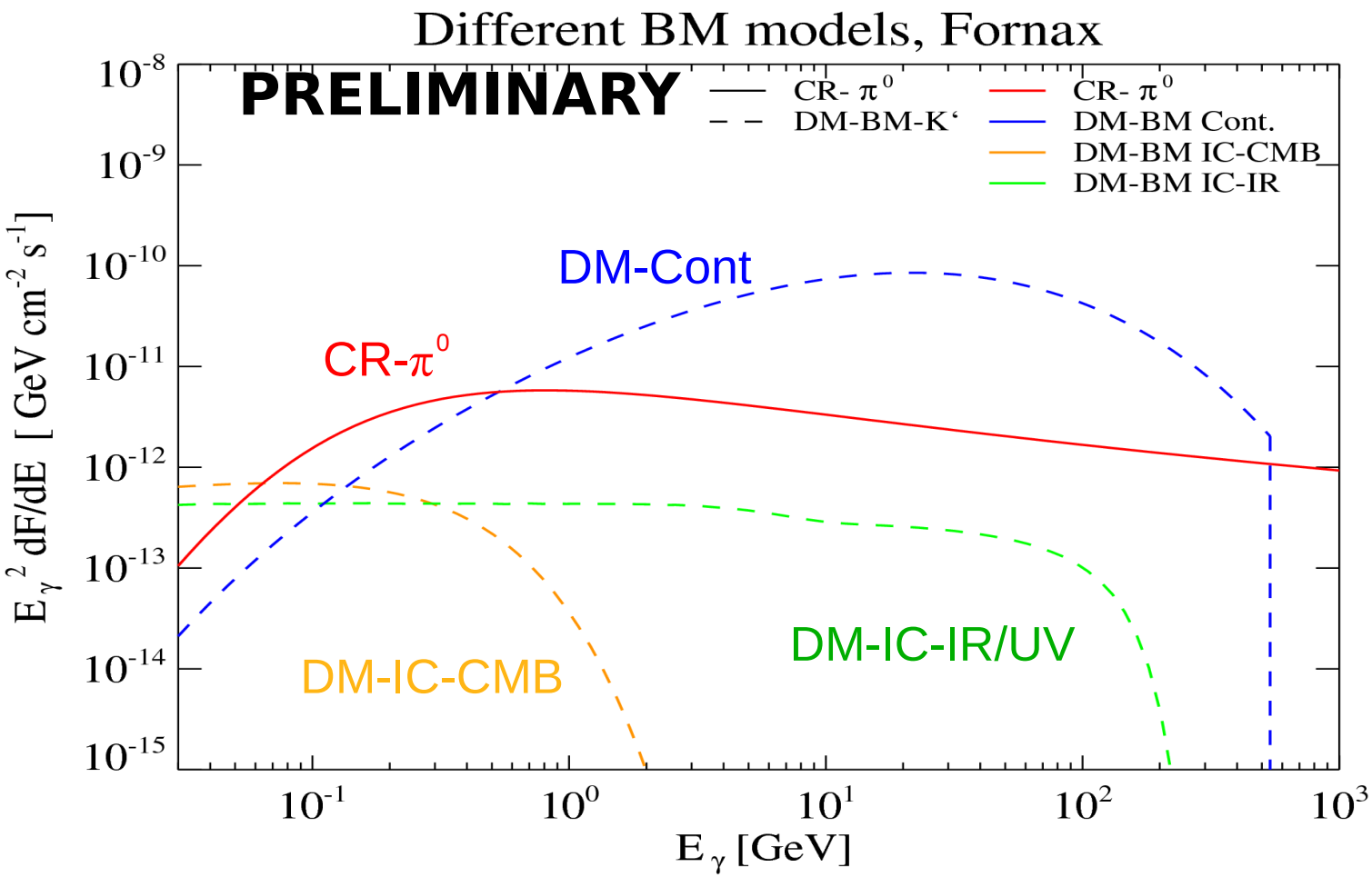
Constraining the DM halos size



Pinzke, Pfrommer and Bergström, 2009

- Gamma-ray upper limit from EGRET → $M_{min} > 10^{-2}\ M_\odot$ (*lower limit on substructure mass*)
- Fluxes well above Fermi limits, however there are non trivial resolution effects and a more detailed analysis of extended sources would be needed.

Annihilating DM vs. CR interactions



Pinzke, Pfrommer and Bergström, in preparation

Bright prospects for detecting DM:
CR induced signal does not swamp the DM annihilation signal

→ **Fornax is a prime candidate for annihilating dark matter**

Ongoing/Future

Experiments:

-) Fermi - stacked cluster analysis

Limited by AGNs?

-) Major Cherenkov telescope observations

Observation time and target selection

-) More sensitive radio observations; statistics, polarization, lower luminosities

-) Better Faraday Rotation measurements; remove degeneracy for non-thermal emission

Theories/simulations:

-) Detailed model for CR proton transport – diffusion, streaming,...

-) MHD simulations; impact of B fields on relativistic populations

-) Simulations that can resolve smaller substructures

–> improve estimates of the substructure boost;

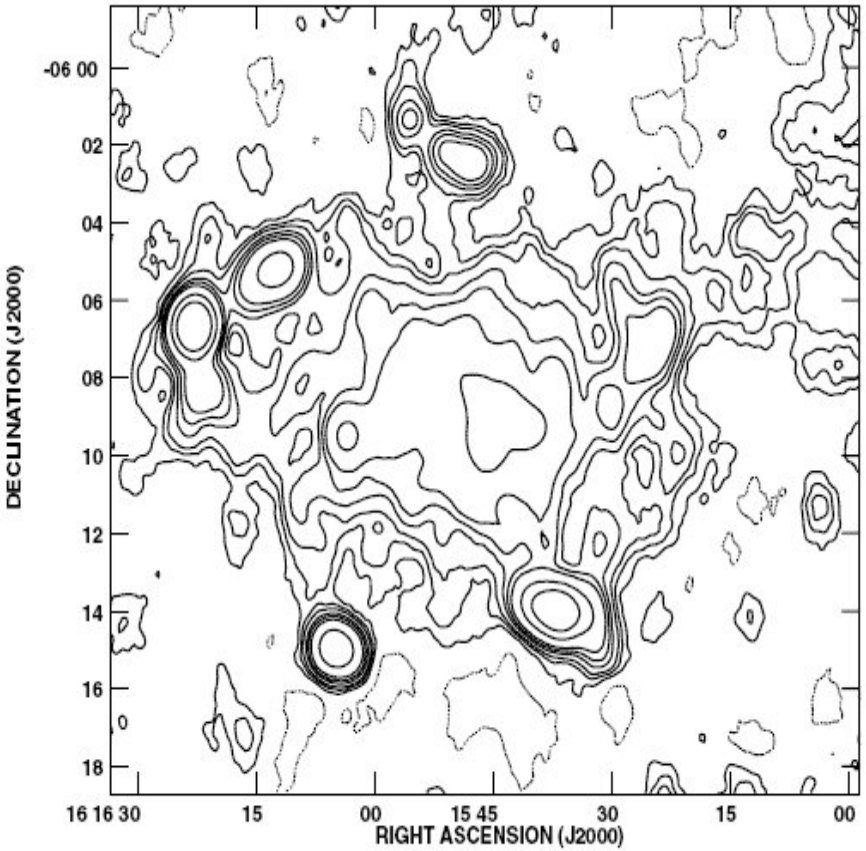
key ingredient for cosmological DM searches

Extra Slides

Signs of non-thermal activity in galaxy clusters

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.*



Abell 2163

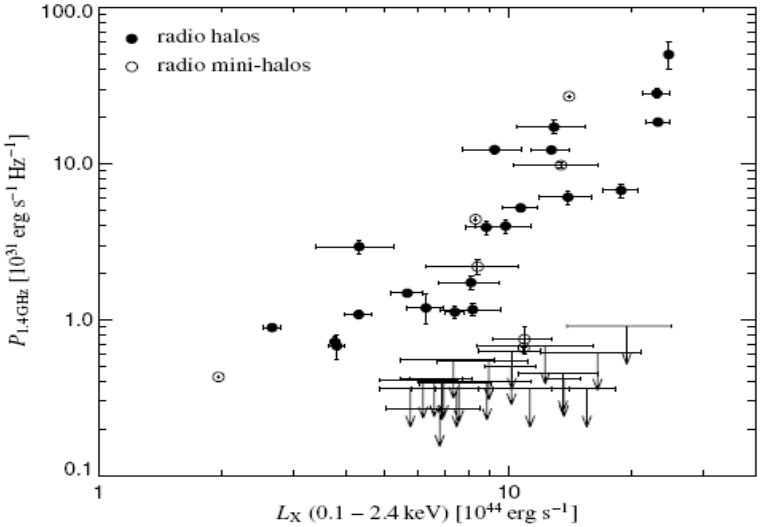
Radio: *Feretti at al, 2004*

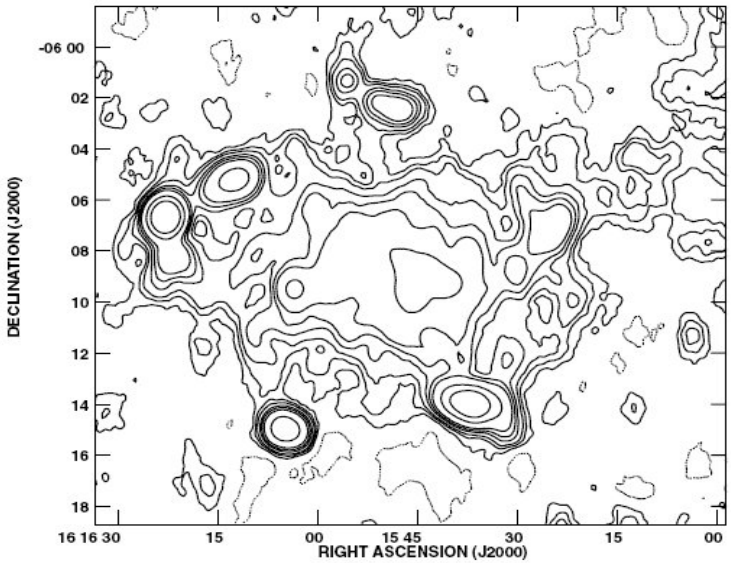
Radio halos - origin

Radio observations alone can not distinguish the emission from re-accelerated electrons from the secondary electrons.

Re-acceleration models predict:
Low X-ray luminous clusters should not exhibit radio halos.

Hadronic models predict:
The radio halo emission should always be accompanied by some level of gamma-ray flux, emerging from the hadronic production of neutral pions that decay into gamma-rays.

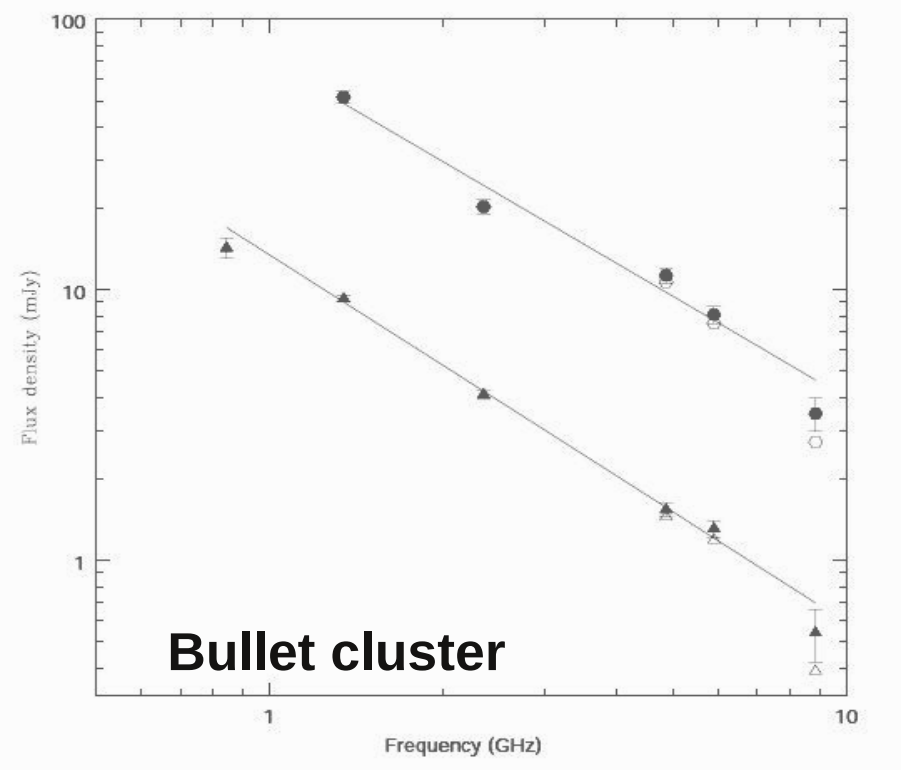




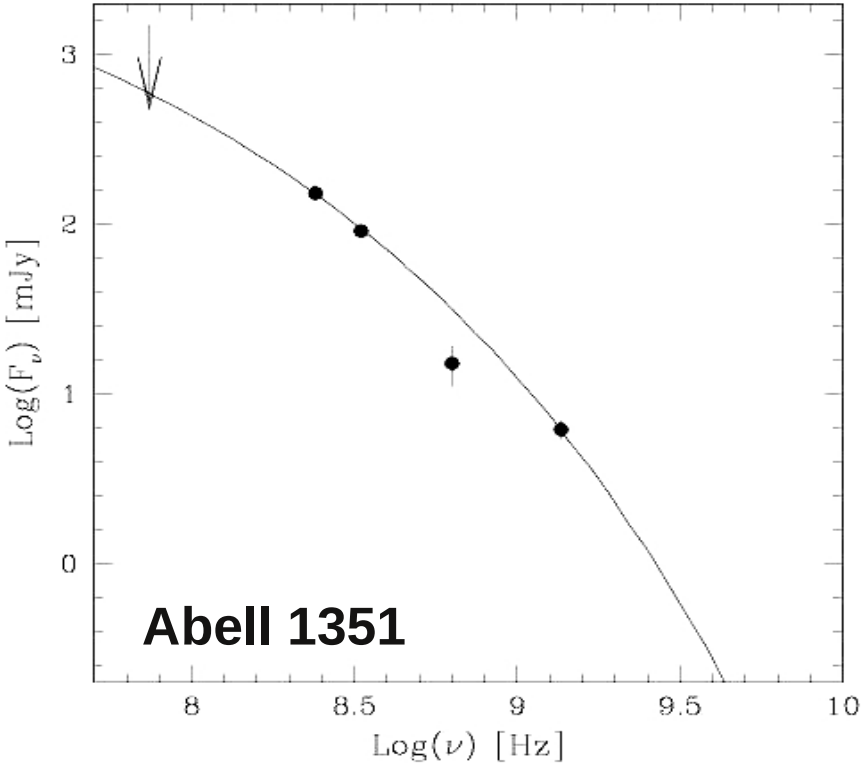
Origin of radio halos – observations I

Radio spectra

Liang et al., 2000



Radio spectra

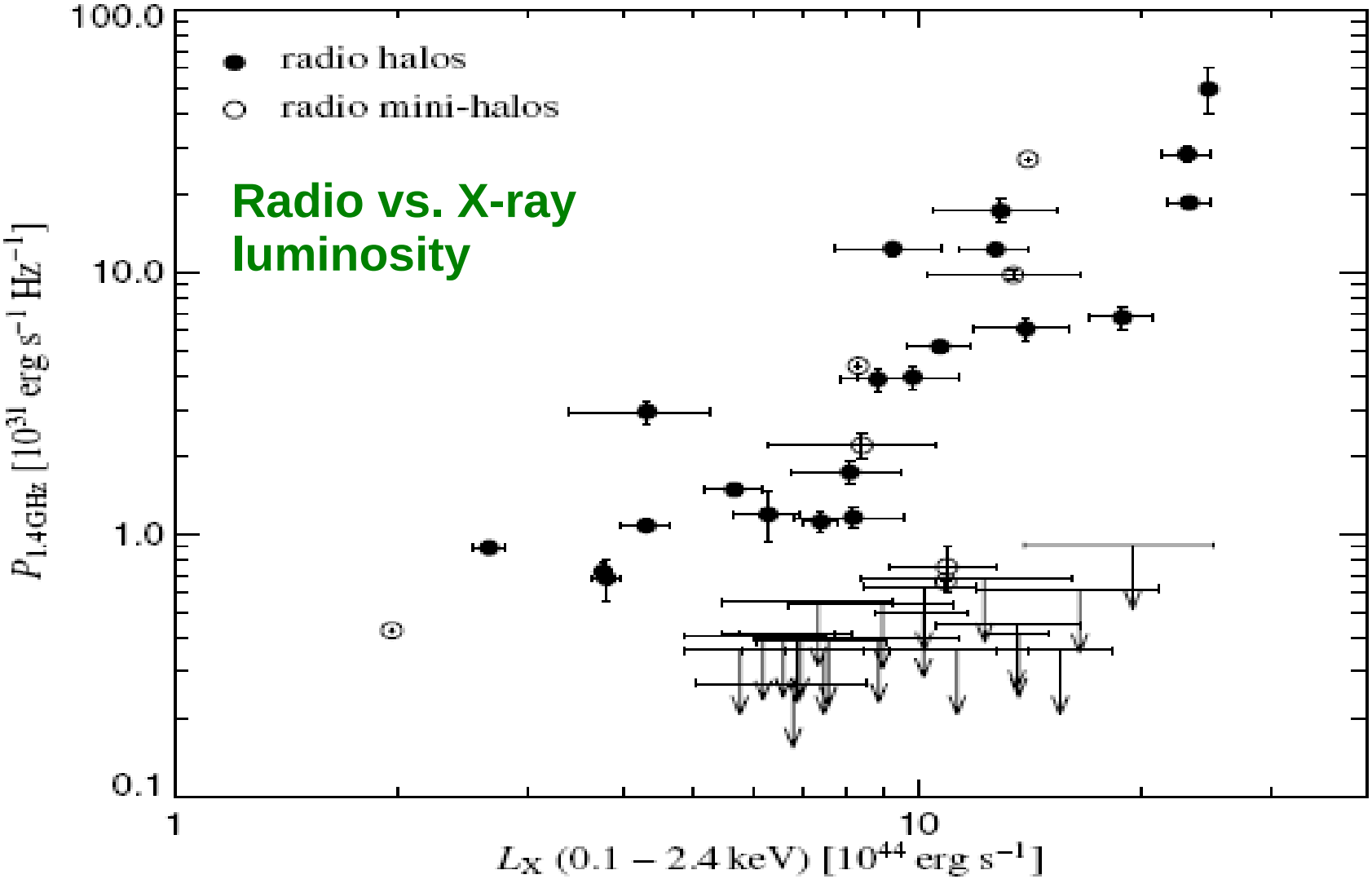


Dallacasa et al., 2009

Most clusters are best fitted with a rather flat radio power-law spectrum.
However, some clusters show a much steeper spectrum.

Potential bias in radio observations:
Interpretation: relics?
Measurements: point source bias, reduced sensitivity at large frequencies

Origin of radio halos – observations II



Ensslin et al., 2011

Bimodality of extended radio halo emission

Origin of radio halos – re-acc. model

Strength:

- all required ingredients available:
  radio galaxies and relics inject CRes, turbulence and plasma waves,...
- reported complex radio spectra emerge naturally
- less turbulence $\longrightarrow$ clusters without a radio halo

Weakness:

- Fermi II acceleration is inefficient and CRes cool rapidly
- observed radio power-law spectra require fine tuning
- ...

Hardest prediction:

Low X-ray luminous clusters should not exhibit radio halos

Cassano et al. 2006, 2008

Should become testable with upcoming sensitive radio telescope arrays

Origin of radio halos – hadronic model

Strength:

- all required ingredients available:

shocks inject CRps, gas protons as targets, magnetic fields,...

- predicted luminosities and morphologies agree with observations without any tuning
- Power-law spectra as observed

Weakness:

- simple CRp models predict that all clusters have a radio halo
- does not explain all reported spectral features
- ...

Hardest prediction:

The **radio halo emission** should always be **accompanied by some level of gamma-ray flux**, emerging from the hadronic production of neutral pions that decay into gamma-rays.

Hard X-ray measurements

Several observational claims of an excess to the thermal spectrum in the energy range 20 keV to 300 keV
Kaastra et al. 2008, for a complete review

Although, the presence and origin still remains controversial

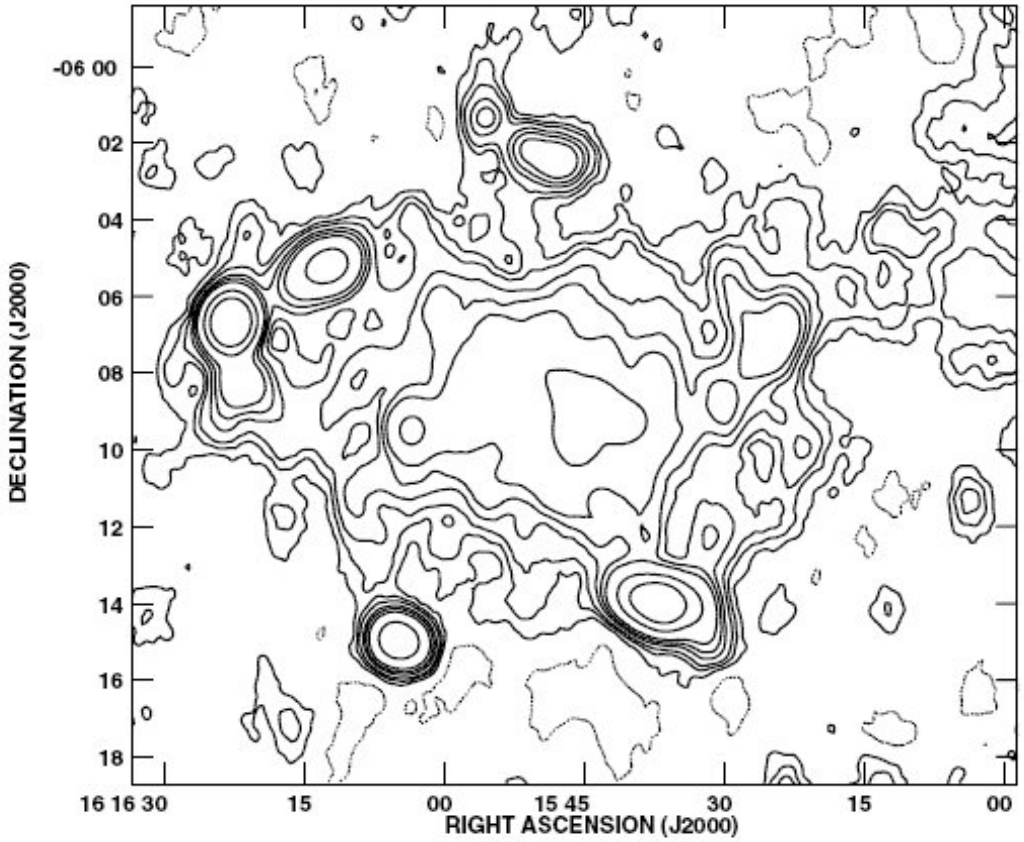
Swift, Chandra and XMM-Newton
"...*in most cases the clusters' emission in the 0.3–200 keV band can be explained by a* ***multi-temperature thermal model***"
Ajello et al., 2010

Suzaku
Do not confirm previus claims of HXR excesses in several clusters
Wik et al., 2009; Nakazawa et al., 2009

Implications: primary electrons, secondary, re-accelerated?

Signs of non-thermal activity in galaxy clusters

Most concrete evidence comes from observations of extended radio halos



A 2163 @ 327 MHz

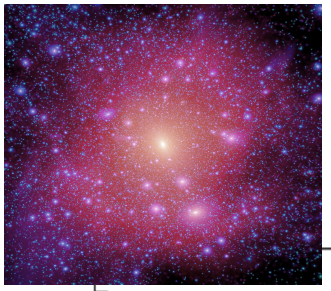
Feretti at al, 2004

About 1/3 of clusters seen in X-rays have an extended radio halo

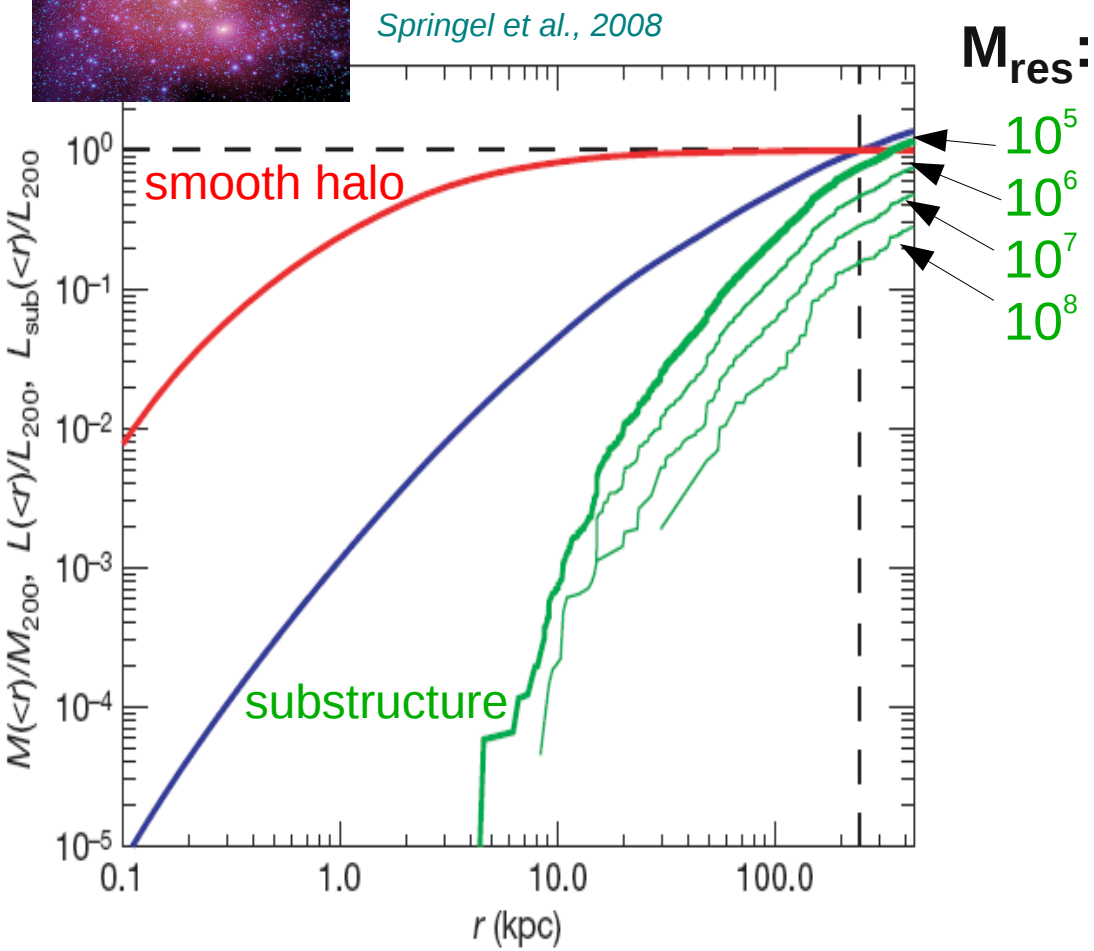
The origin is still disputed!

Ensslin at al, 2011, ...

Annihilating dark matter - substructures



Springel et al., 2008



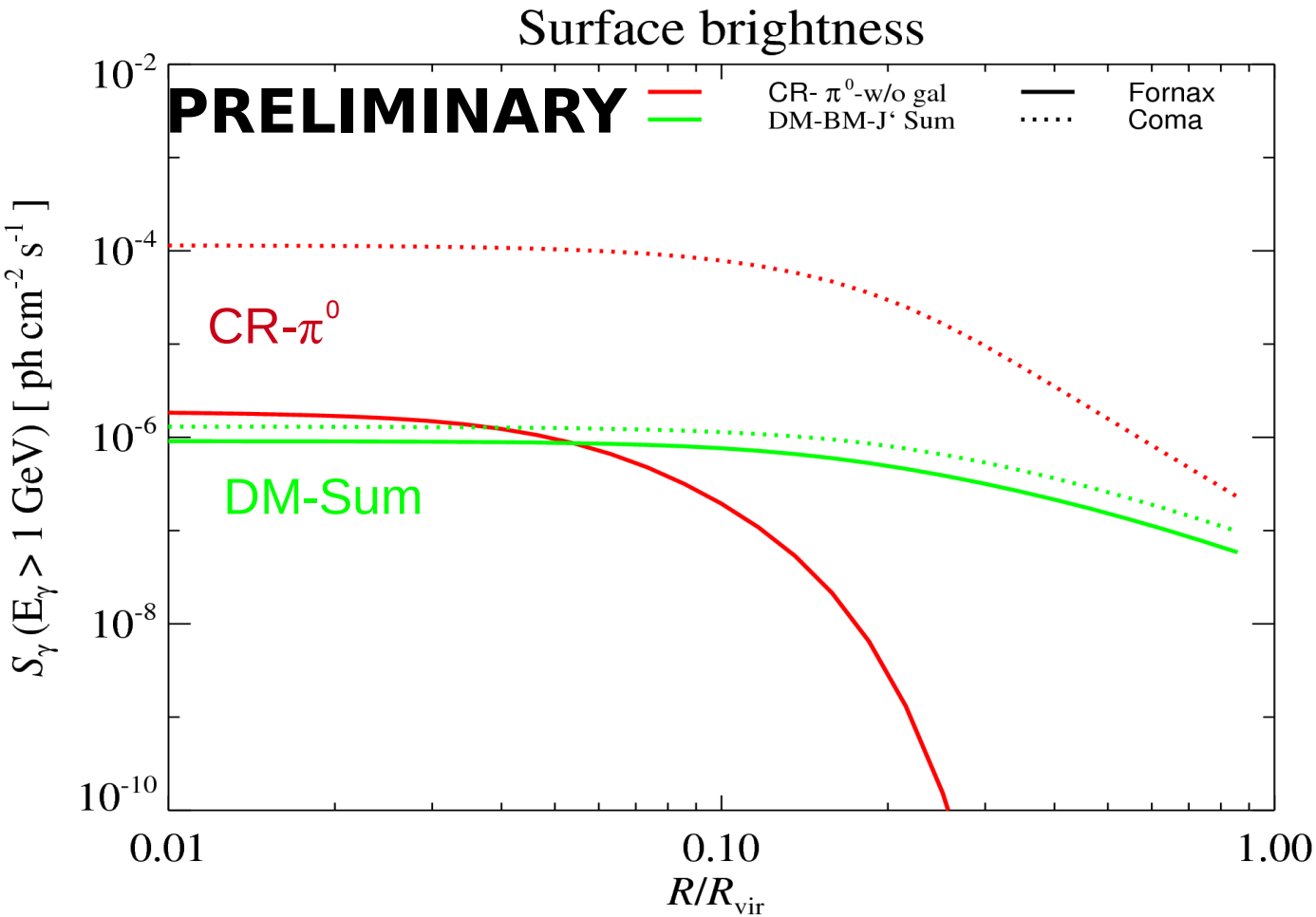
Constant offset in the luminosity from substructures between different mass resolutions in the simulation (M_{res}).

$$\text{Norm} \propto (M_{min} / M_{res})^{0.226}$$

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

DM without Sommerfeld vs. CR interactions



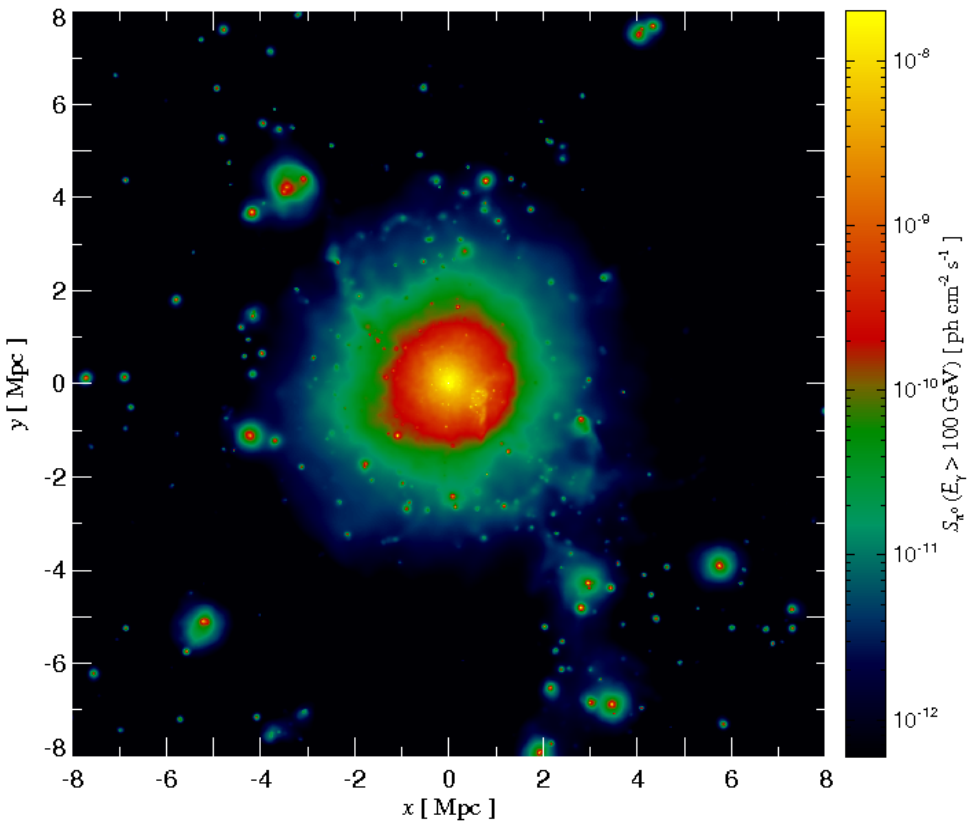
Pinzke, Pfrommer and Bergström, in preparation

The gamma-rays from dark matter extends out to the virial radius, while the CR induced emission is cutoff at about 10% of the virial radius.

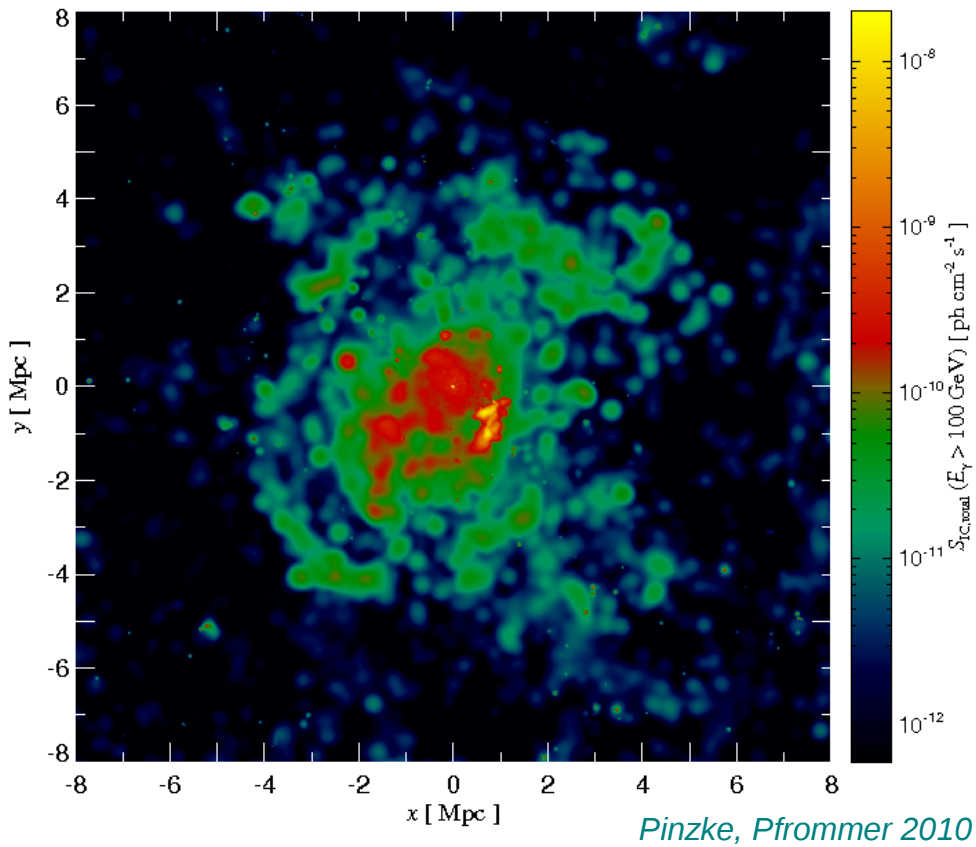
Note the flat surface brightness profile of the DM which is induced by the boost from substructures

Surface brightness for E > 100 GeV

Pion decay induced emission



Total inverse Compton emission

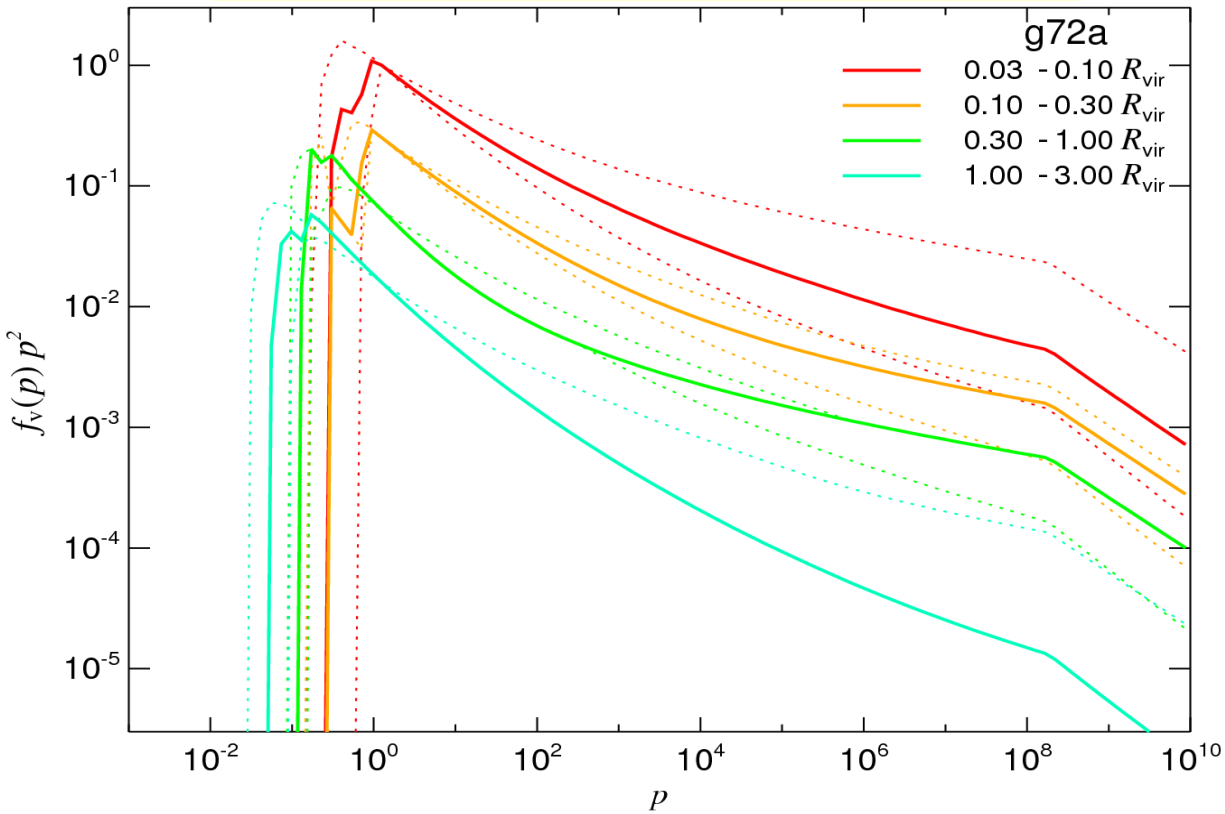


Pinzke, Pfrommer 2010

- Pion decay gamma-rays dominate inside virial radius
- The strong magnetic field in the center suppress inverse Compton due to CRs cooling through synchrotron radiation
- Primary inverse Compton contribute substantially in the cluster periphery

Spatial CR distribution

CR spectra for different radial bins



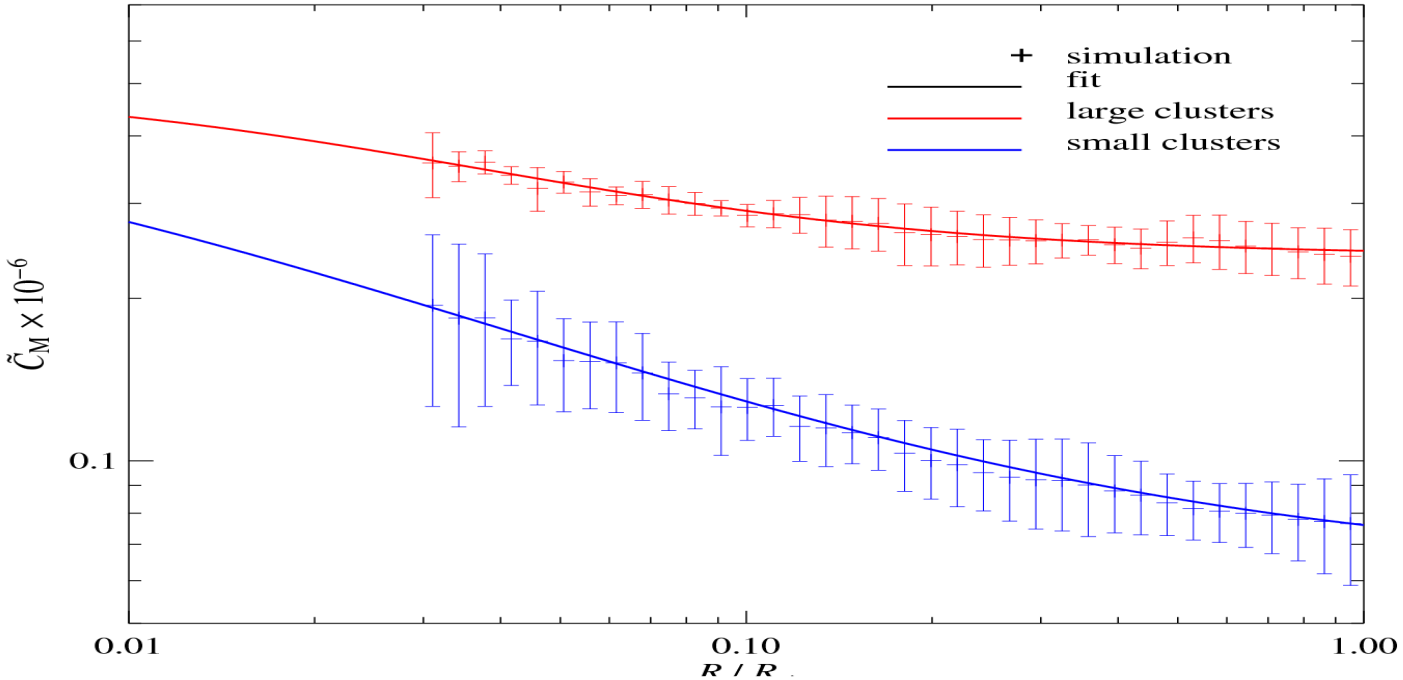
Pinzke, Pfrommer 2010

Similar spectral shape inside R_{vir}

↓

Approximate spatial universal shape!

Spatial CR distribution



Semi-analytic model

CRs approximately spatially and spectrally universal in galaxy clusters

↓

Separate radial and spectral parts in a semi-analytic model

$$f_{\rm v}(p,R) = \tilde{C}_{\rm M}(R)\frac{\rho(R)}{m_{\rm p}}\, g(\zeta_{\rm p,max})\, D_{\rm p}(p, p_{\rm break}, q) \sum_i \Delta_i\, p^{-\alpha_i}$$

Combining our semi-analytic CR model with gas density profiles inferred from X-ray measurements

Hadronic model

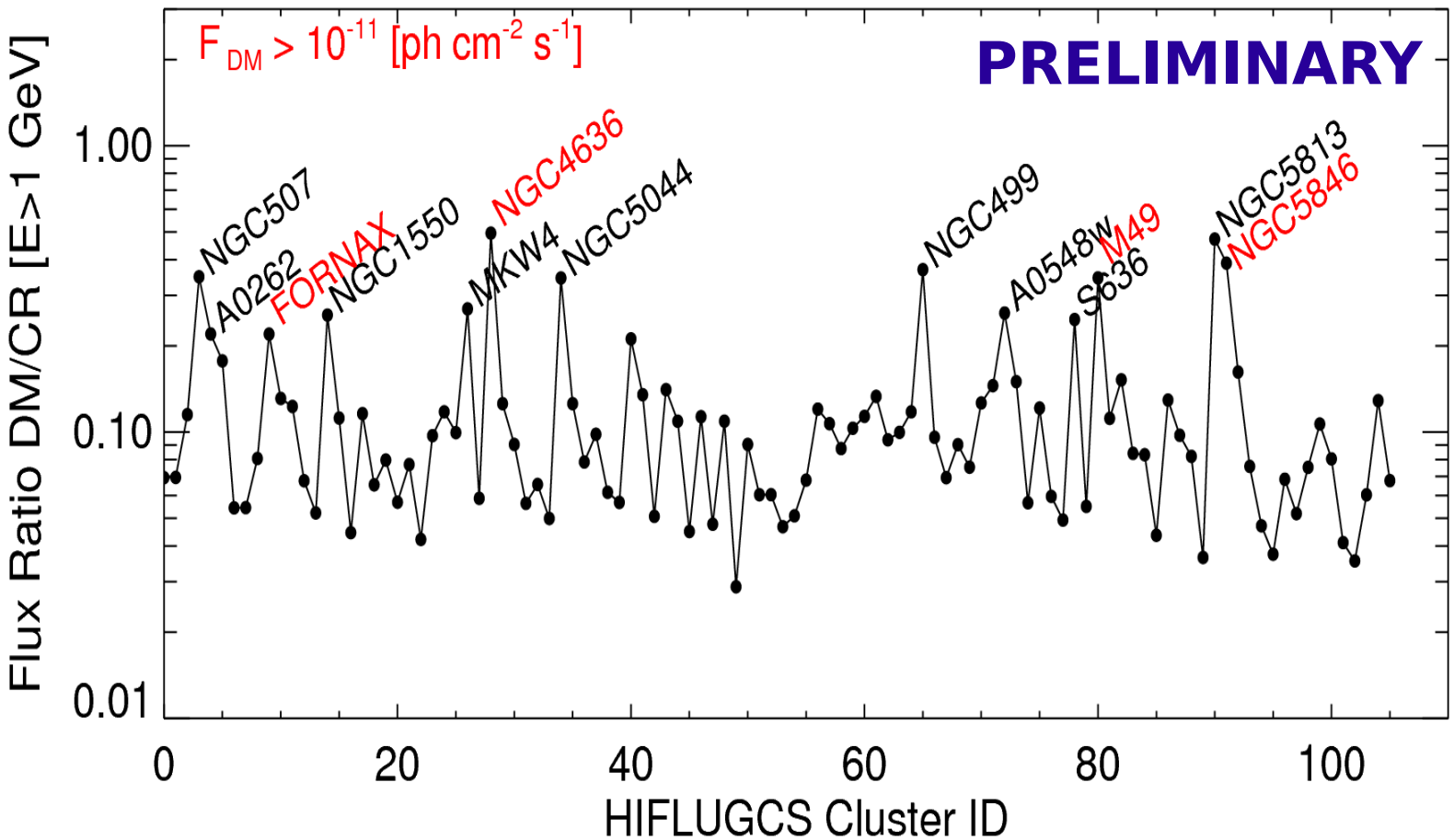
Pfrommer and Ensslin 2004

Neutrino flux,
Secondary radio

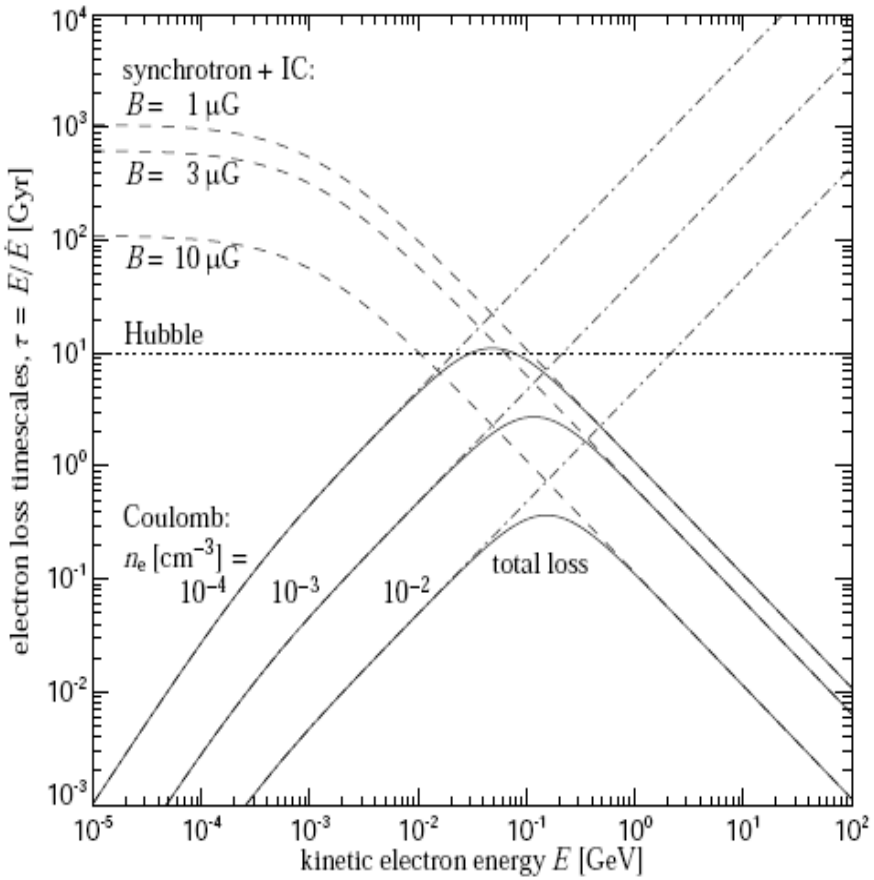
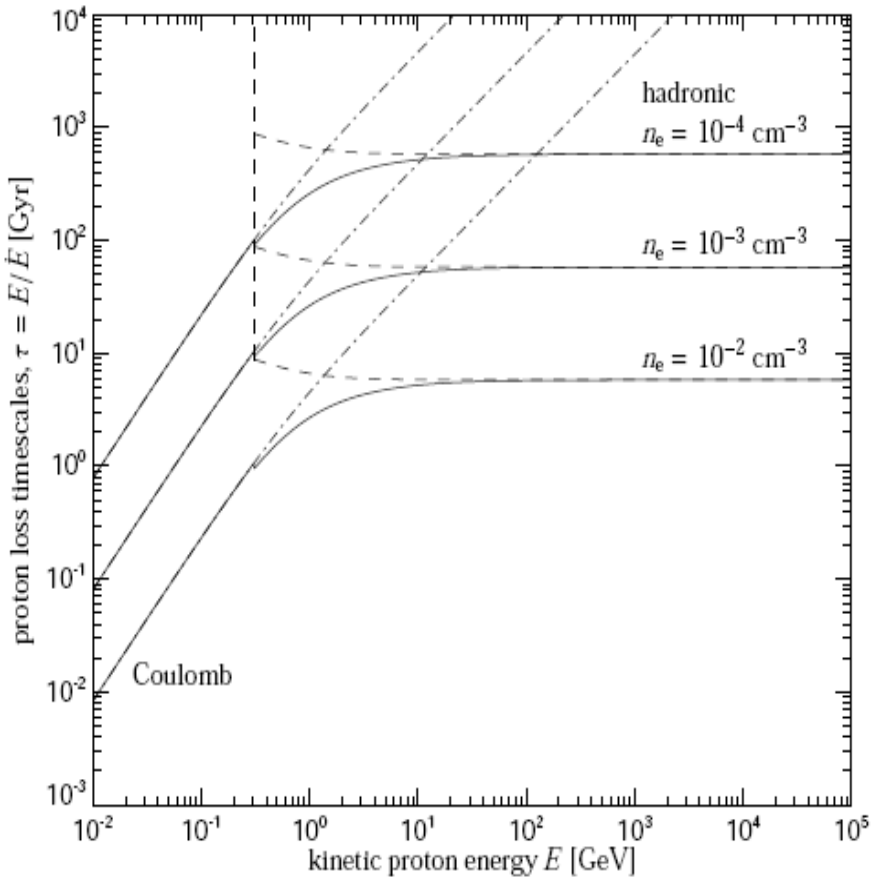
Gamma-ray flux,
Surface brightness

Gamma-ray emission – DM versus CRs

MASS-TO-GAMMA-RAY SCALING RELATIONS



Pinzke, Pfrommer and Bergström, in preparation

CR induced emission dominate in all clusters, however the spread in the scaling relations could potentially increase the ratio for several clusters

CR cooling timescales