Gamma-ray emission from clusters of galaxies – a competition between cosmic rays and dark matter

Anders Pinzke

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FermiLab
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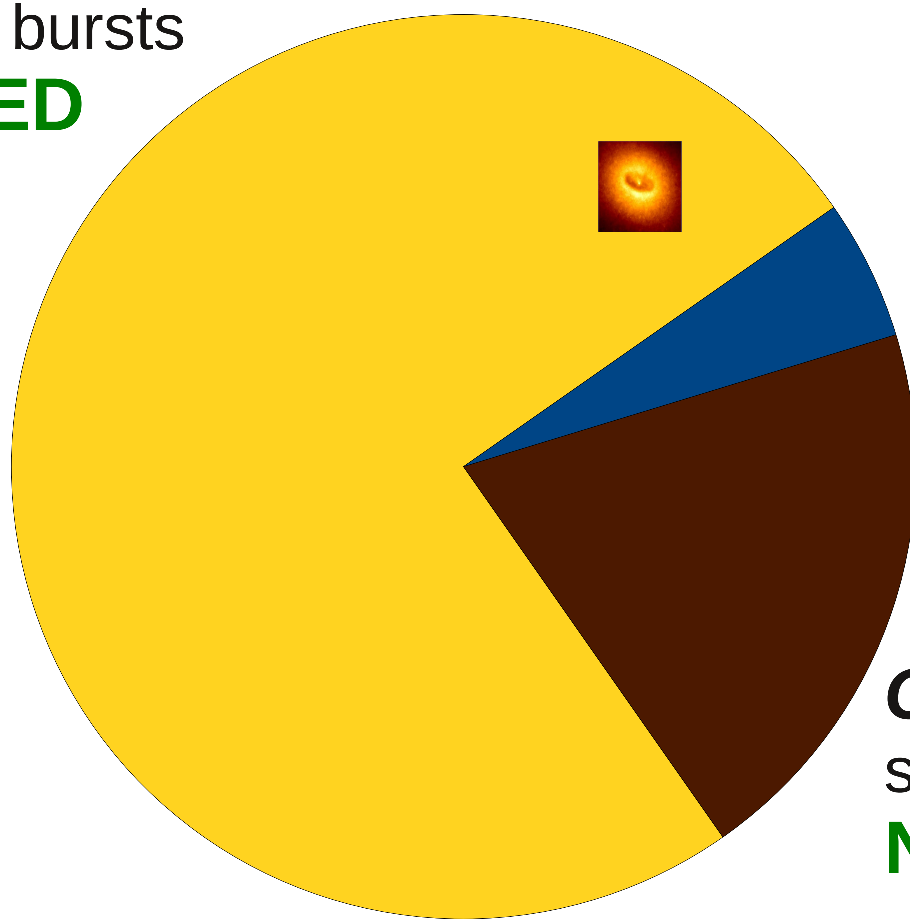
UCSB

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

Part 1

Cosmic ray induced gamma-ray emission

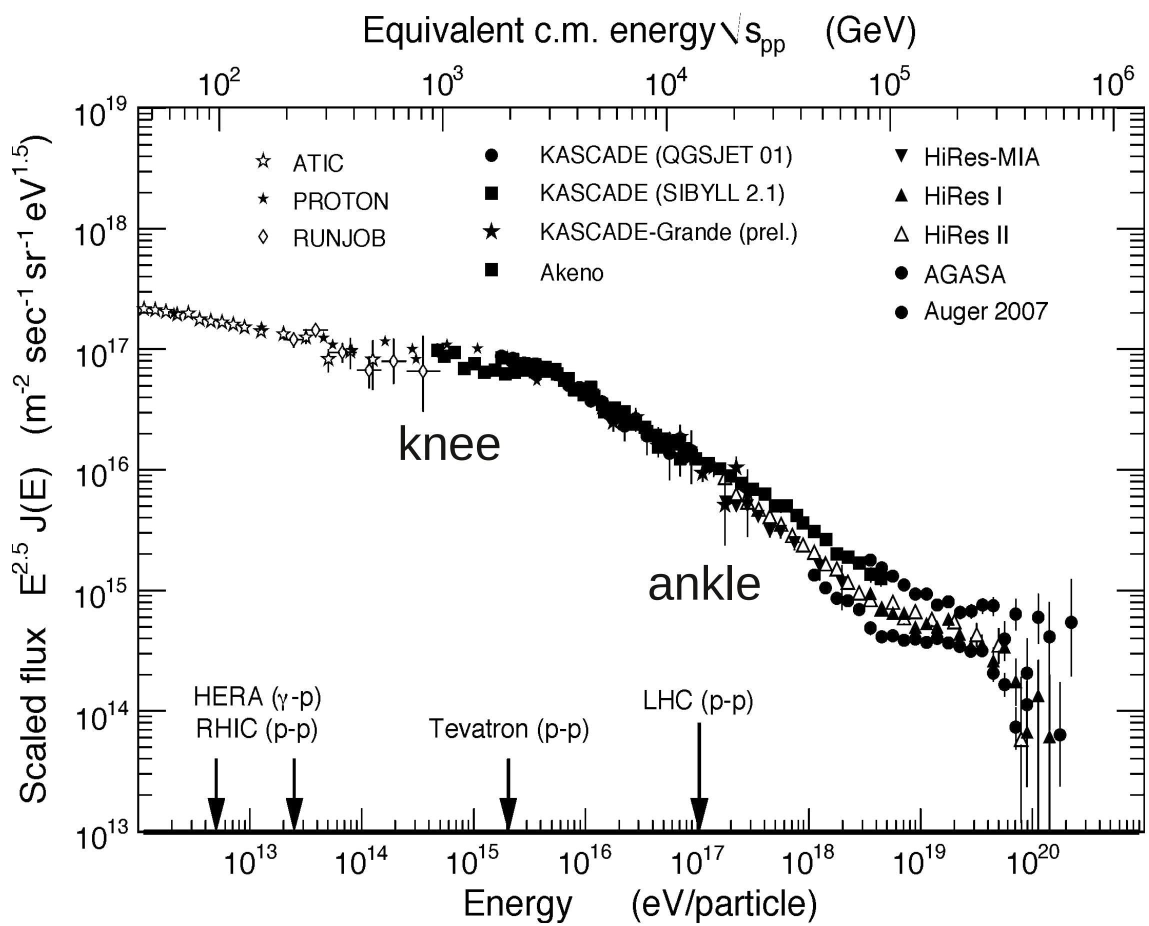
Galactic cosmic rays

SN remnants

diffusive shock acceleration

Relativistic particles:

$e^{\pm}$, p, α, ...



R. Engel 2008

Galactic cosmic rays

SN remnants

diffusive shock acceleration

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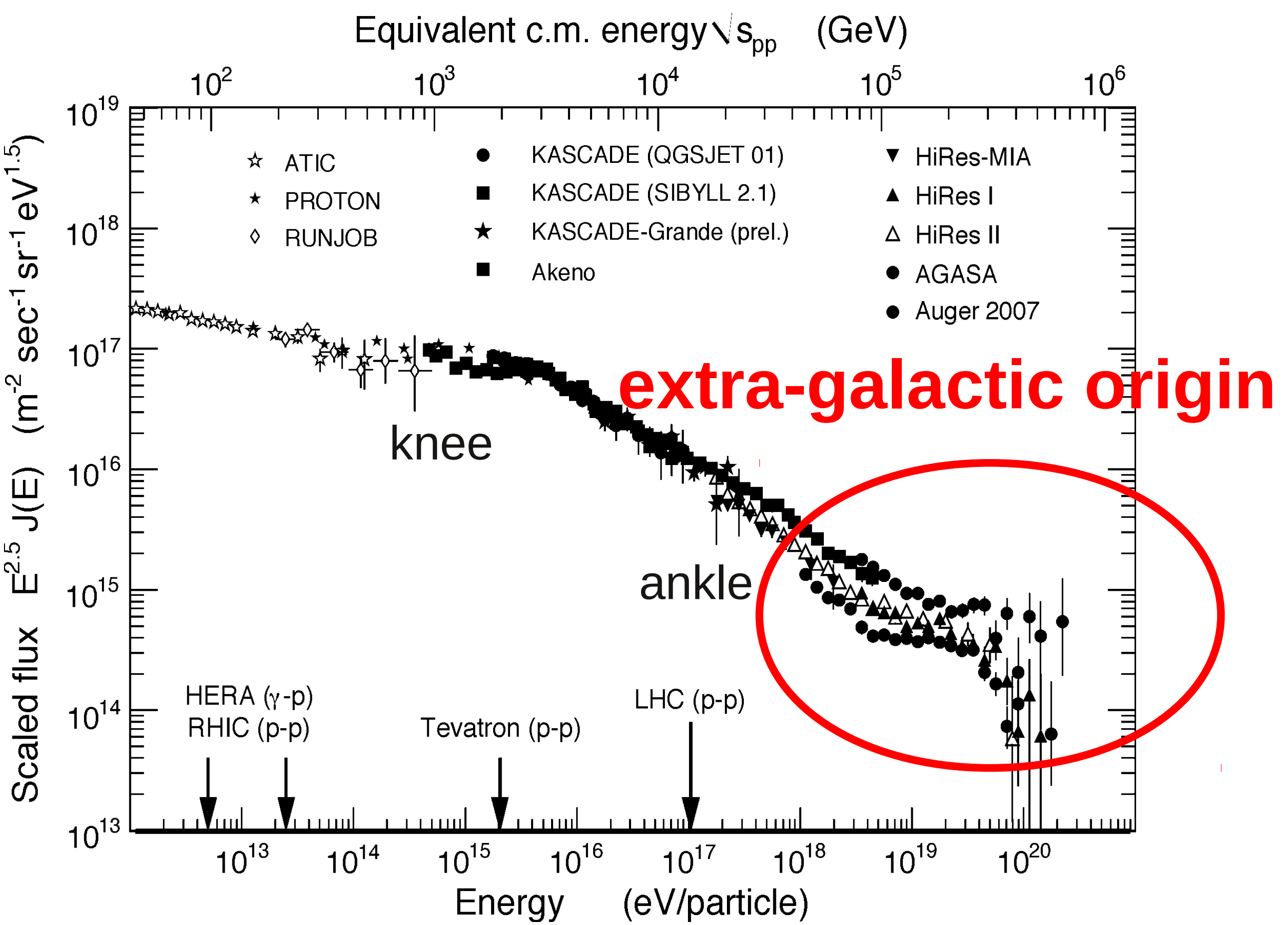
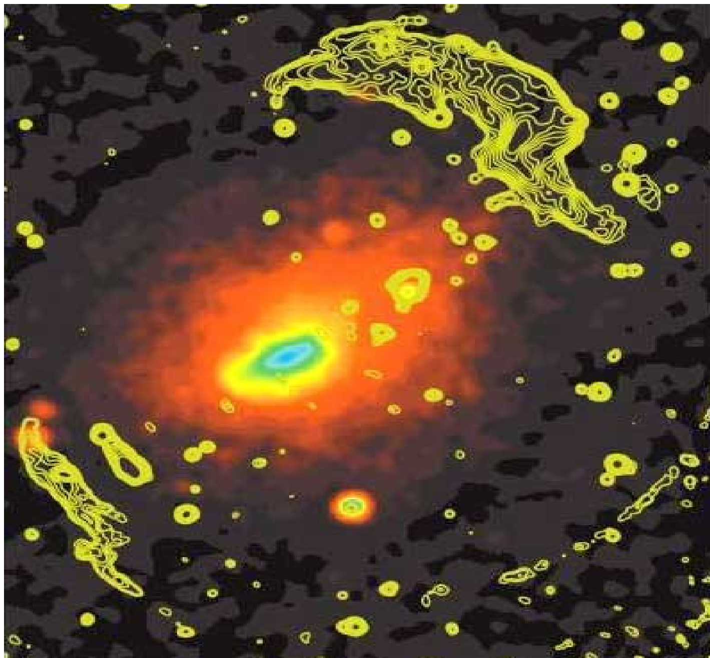


R. Engel 2008

Signs of non-thermal activity in galaxy clusters

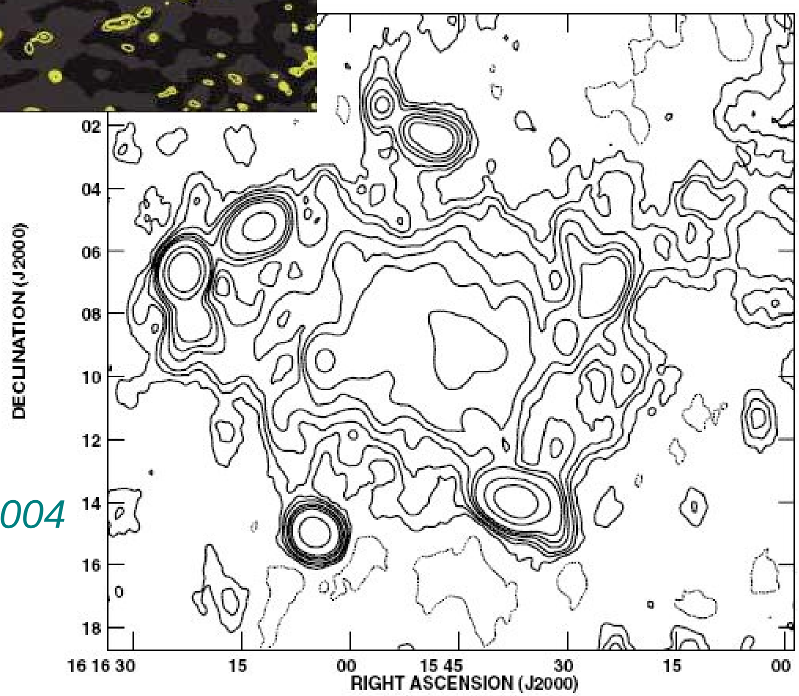


A 3667

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.*



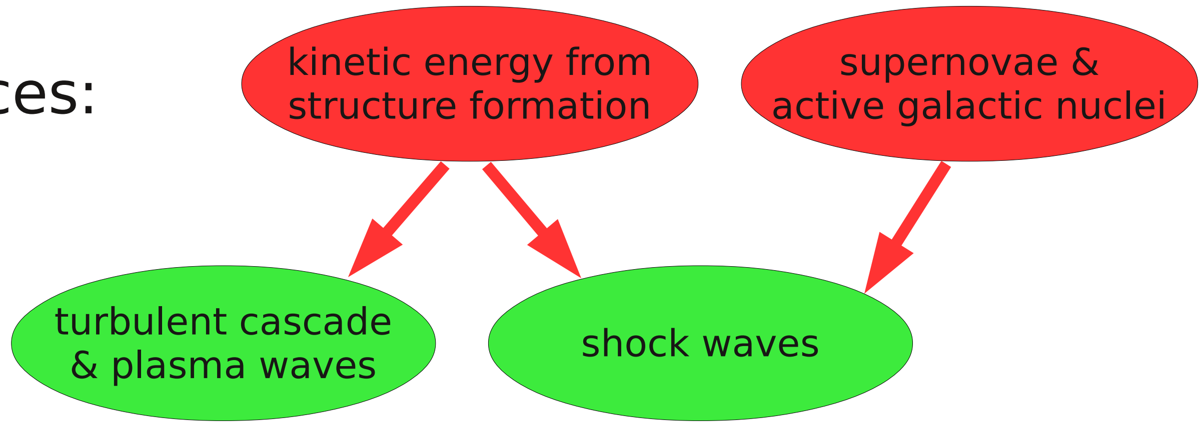
A 2163

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

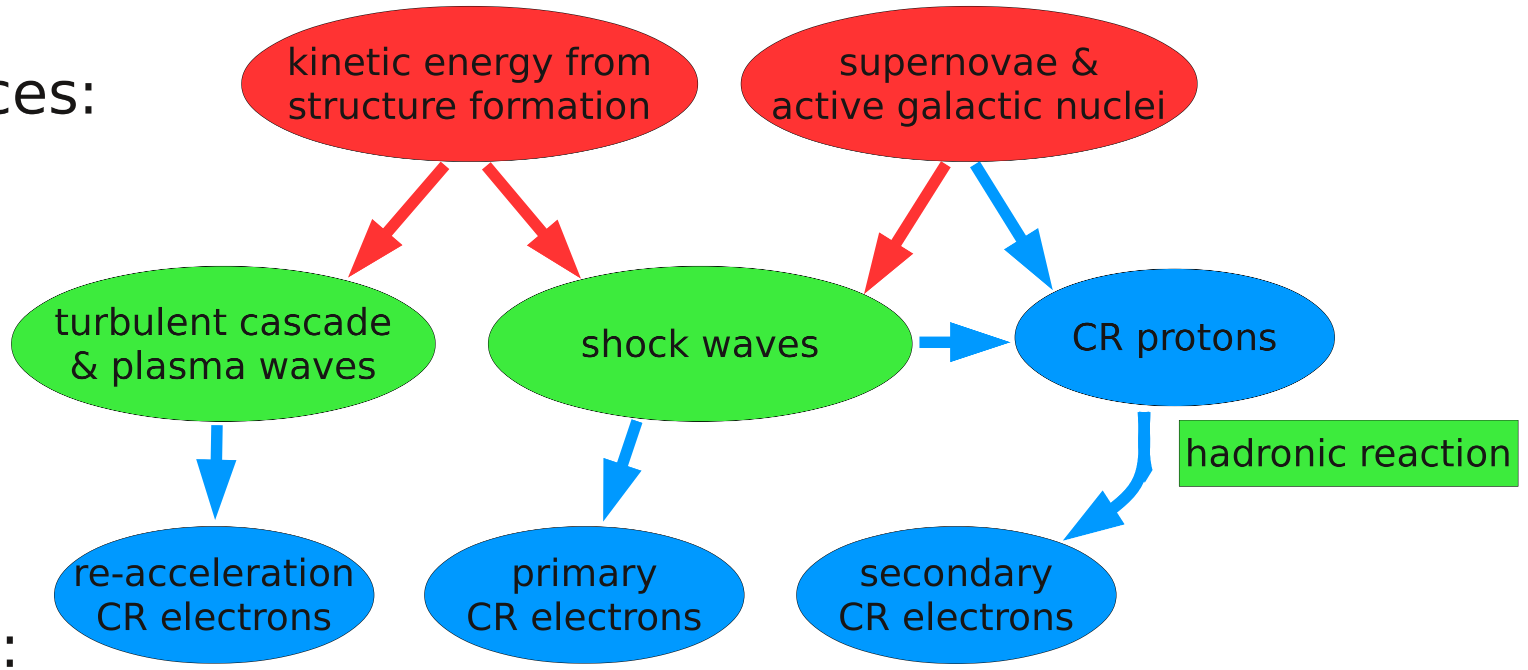
Cosmic rays in clusters of galaxies

Relativistic populations and radiative processes in clusters:

Energy sources:

Plasma processes:

Relativistic particle pop.:

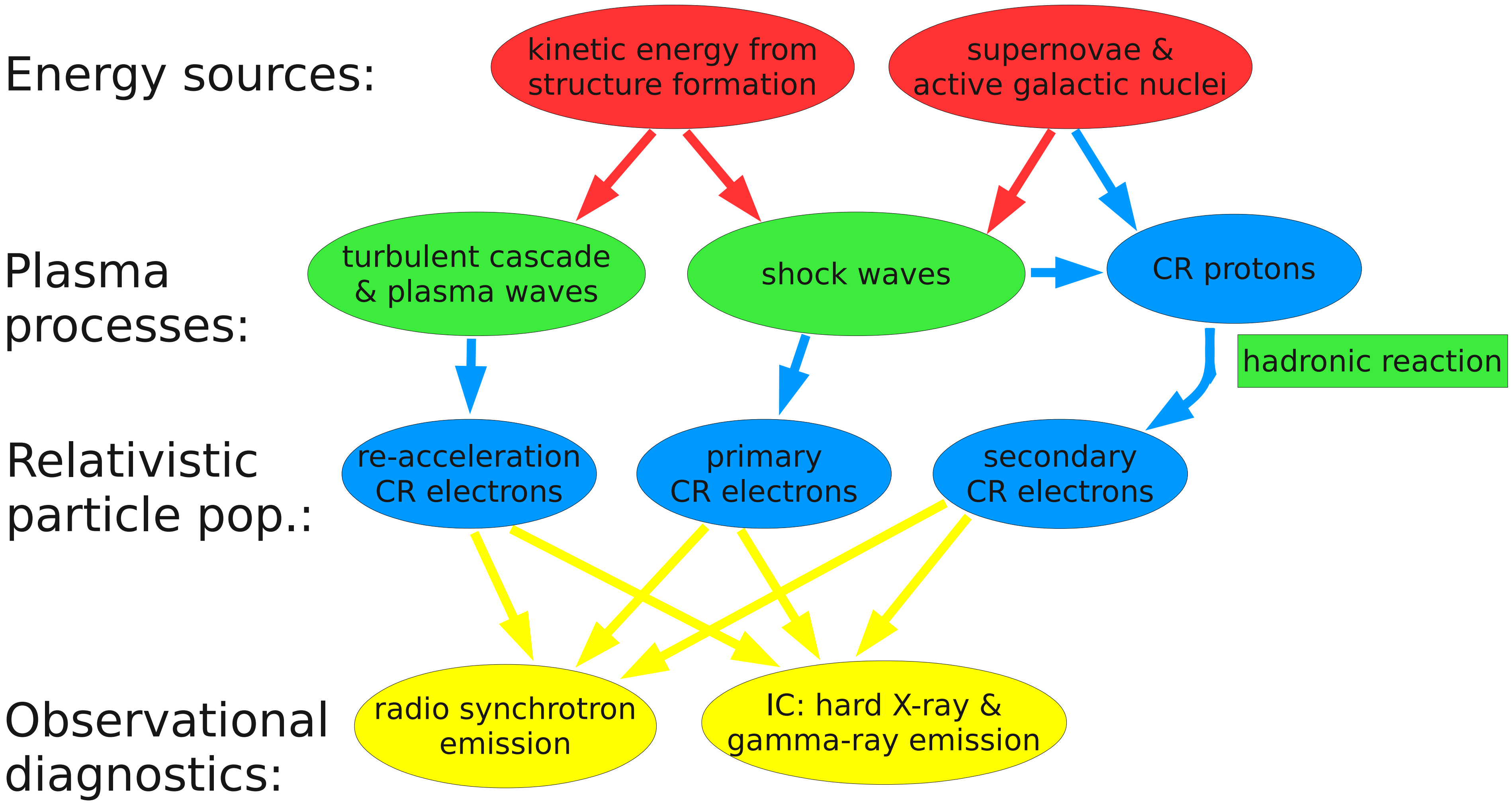


Observational diagnostics:

Pfrommer et al. 2008

Cosmic rays in clusters of galaxies

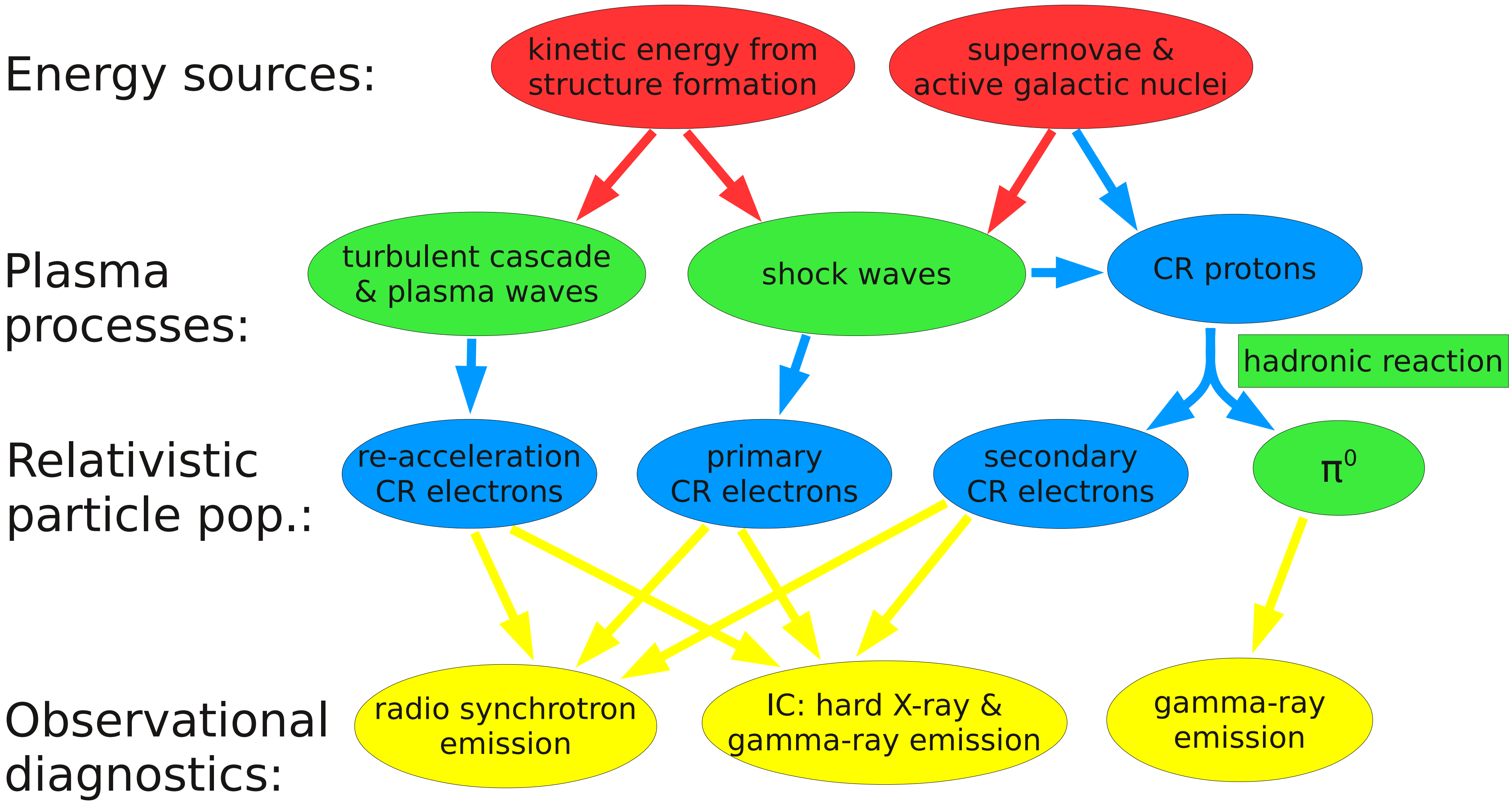
Relativistic populations and radiative processes in clusters:



Pfrommer et al. 2008

Cosmic rays in clusters of galaxies

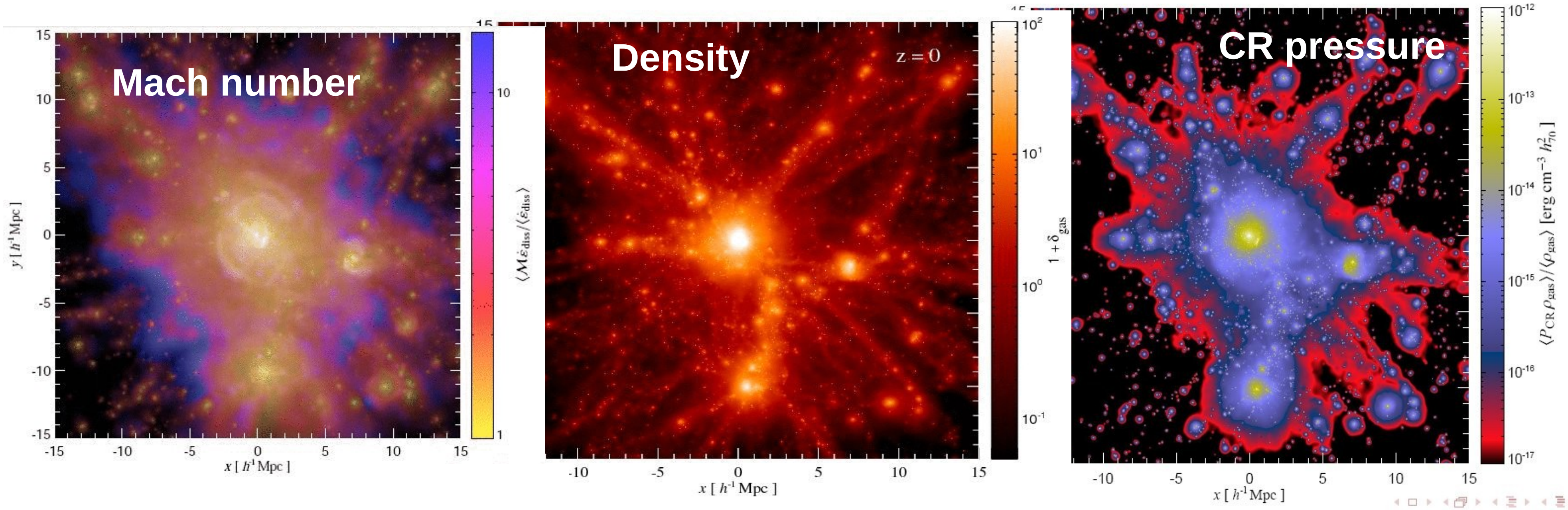
Relativistic populations and radiative processes in clusters:



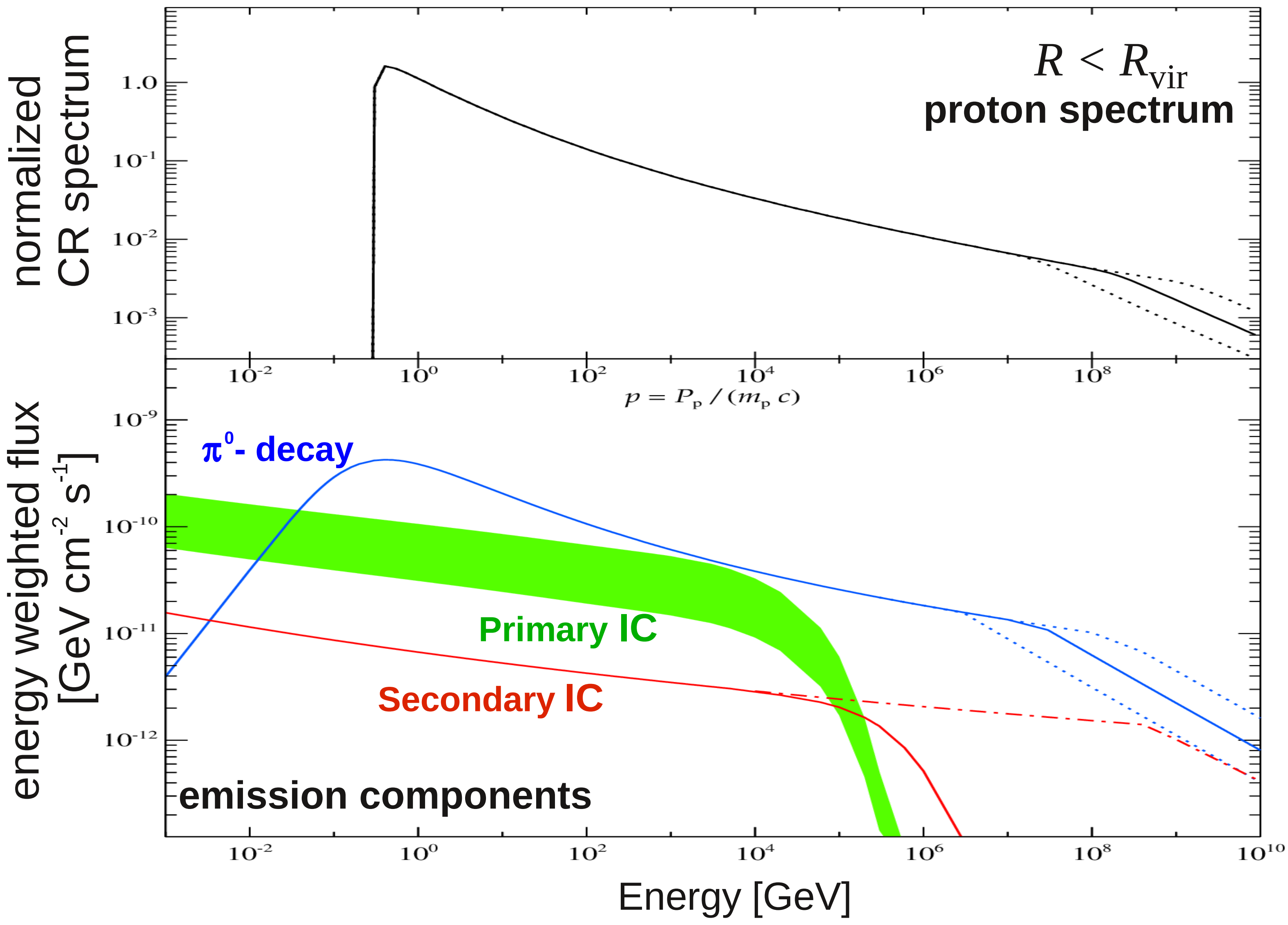
Pfrommer et al. 2008

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

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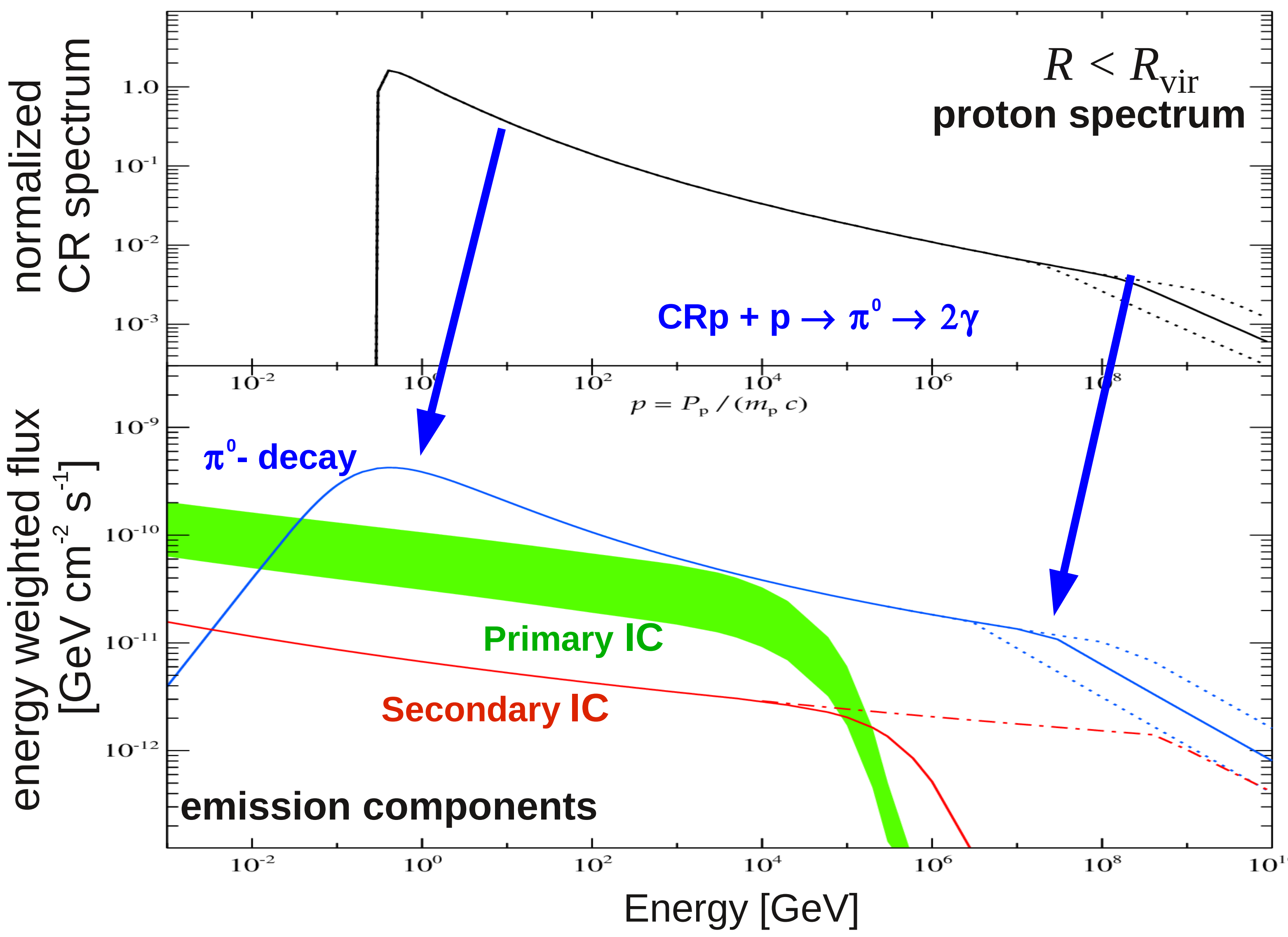
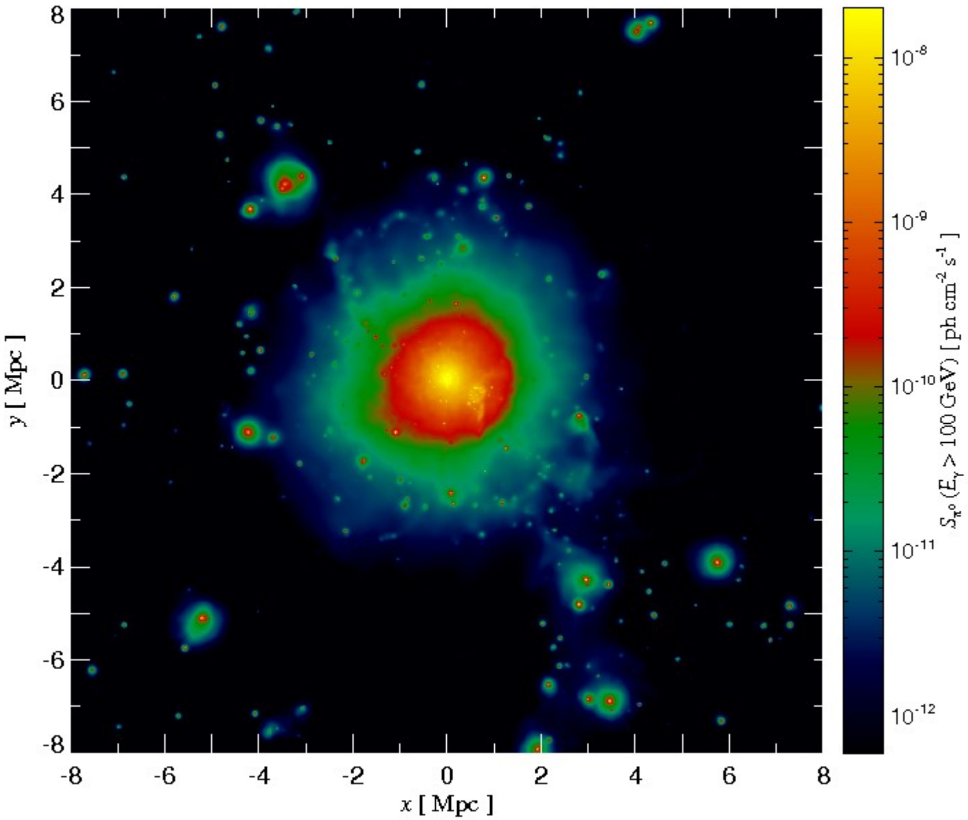


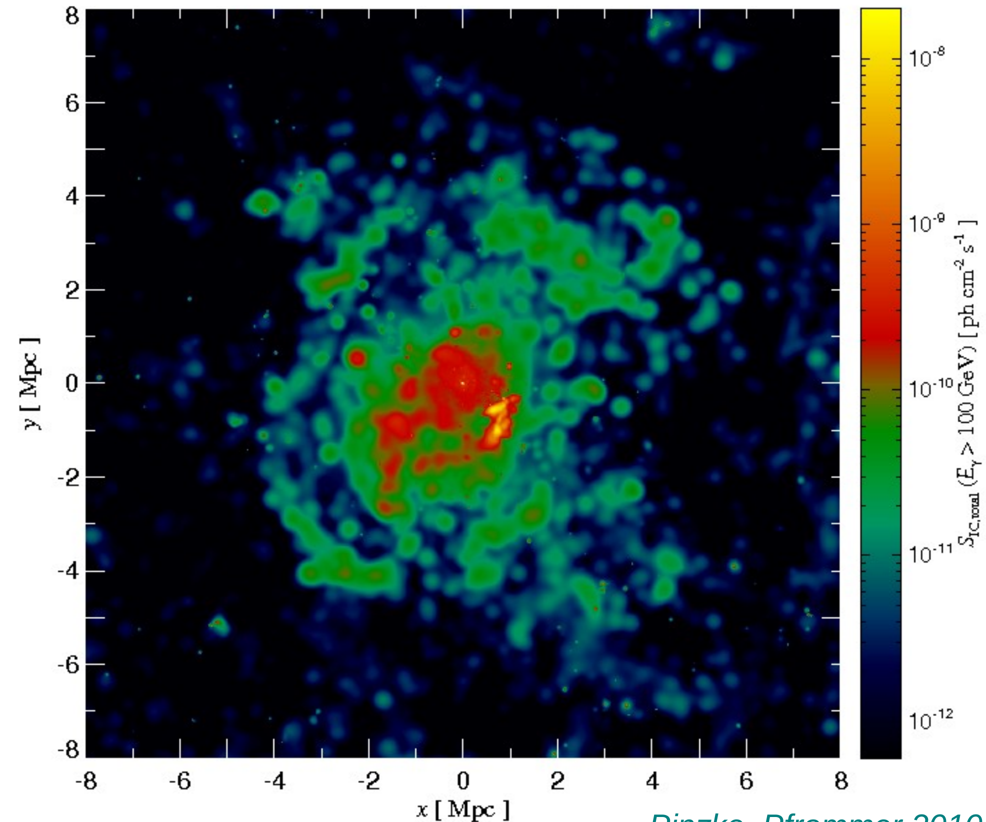
Pinzke, Pfrommer 2010

Surface brightness for E > 100 GeV

Pion decay induced emission



Total inverse Compton emission

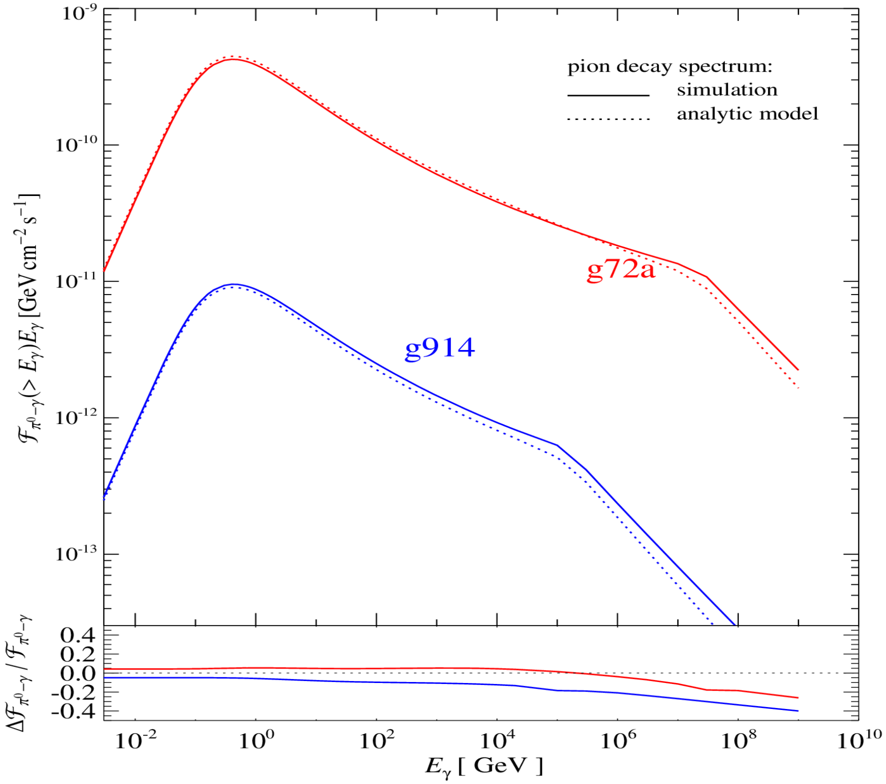


Pinzke, Pfrommer 2010

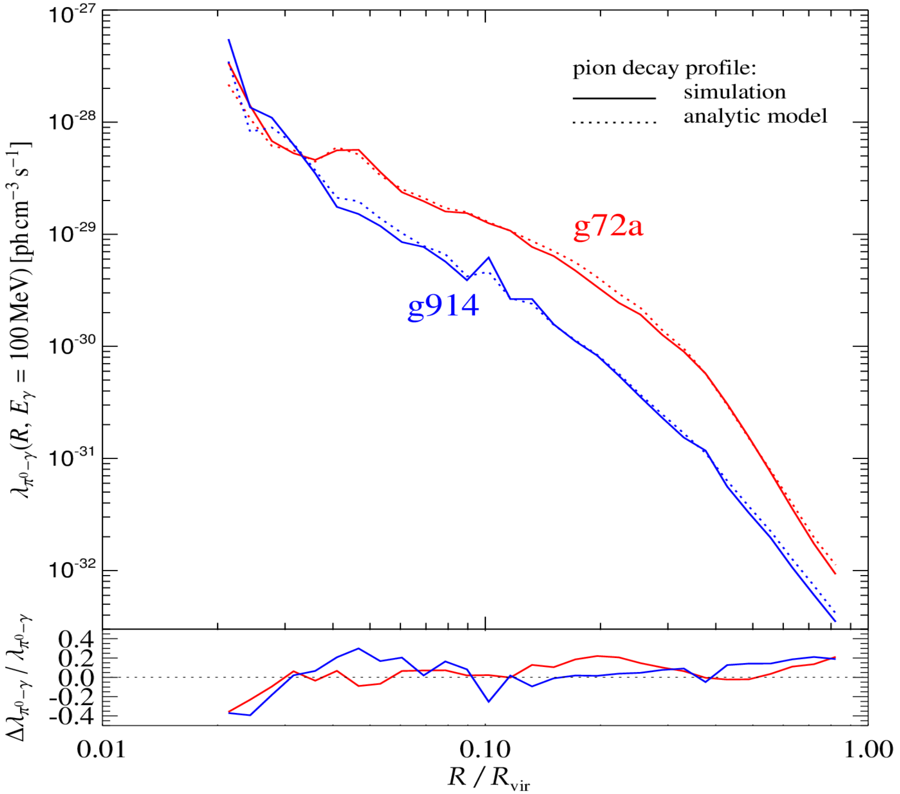
- Pion decay gamma-rays dominate inside virial radius
- The strong magnetic field in the center suppress inverse Compton due to CRs cooling through synchrotron radiation
- Primary inverse Compton contribute substantially in the cluster periphery

Test of analytic gamma-ray model

Spectral comparison



Spatial comparison

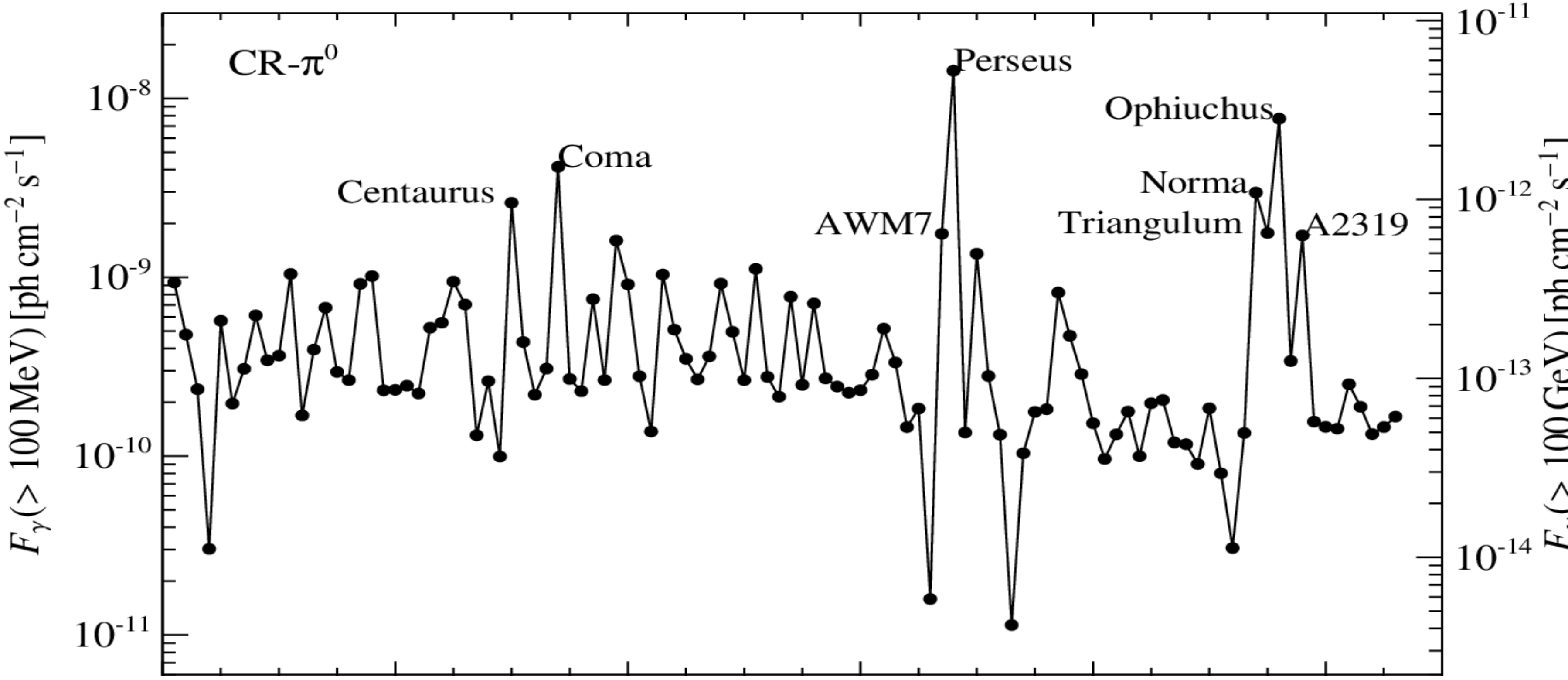


Pinzke, Pfrommer 2010

Very good agreement between analytic model and simulations

Gamma-ray flux predictions

Flux within $\Delta\Phi = R_{vir}$



Pinzke, et al. 2011

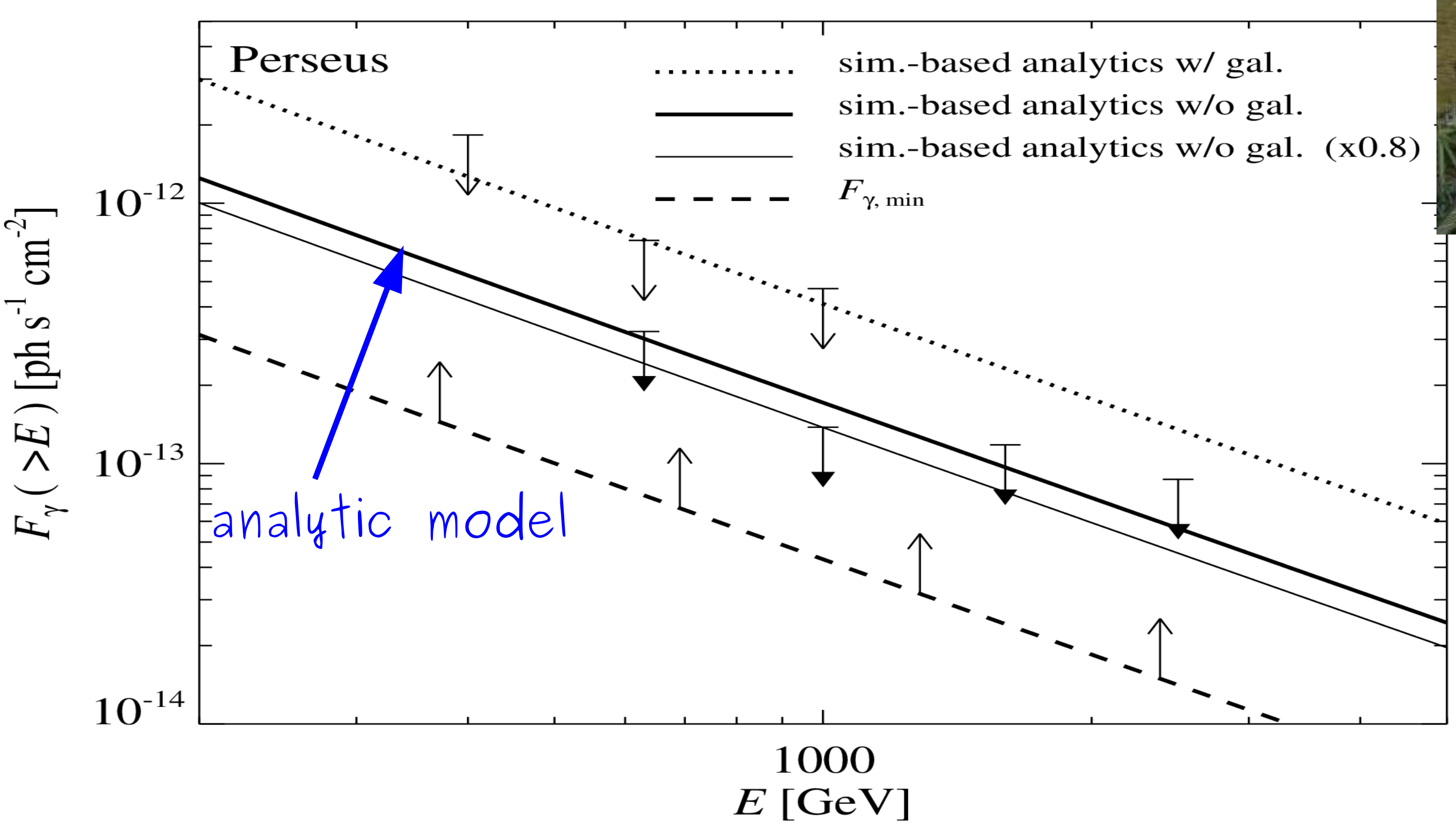
Using CR model to predict gamma-ray emission from a sample of the brightest 107 X-ray clusters (extended HIFLUGCS)

High central target densities for pion production in ***Perseus.***

→ Brightest cluster in gamma-rays!

Predictions for Perseus cluster

Magic - Imaging Air Cerenkov Telescope
Observation time: 85 h (effective hours); ***deepest observation of a cluster ever***
Flux upper limits: $1.4{\times}10^{-13}$ [ph cm^{-2} s^{-1}] for $\Gamma=-2.2$ (E > 1 TeV)
Aleksic et al. 2012; Aleksic et al. 2010



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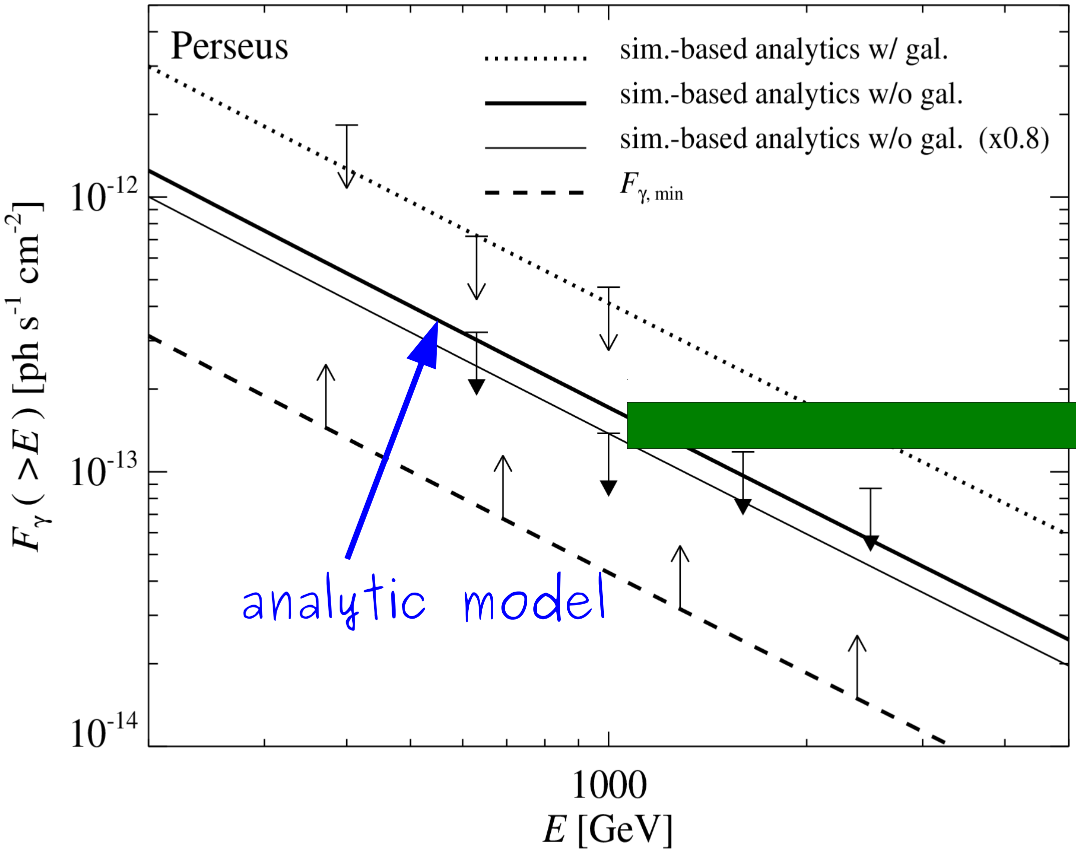
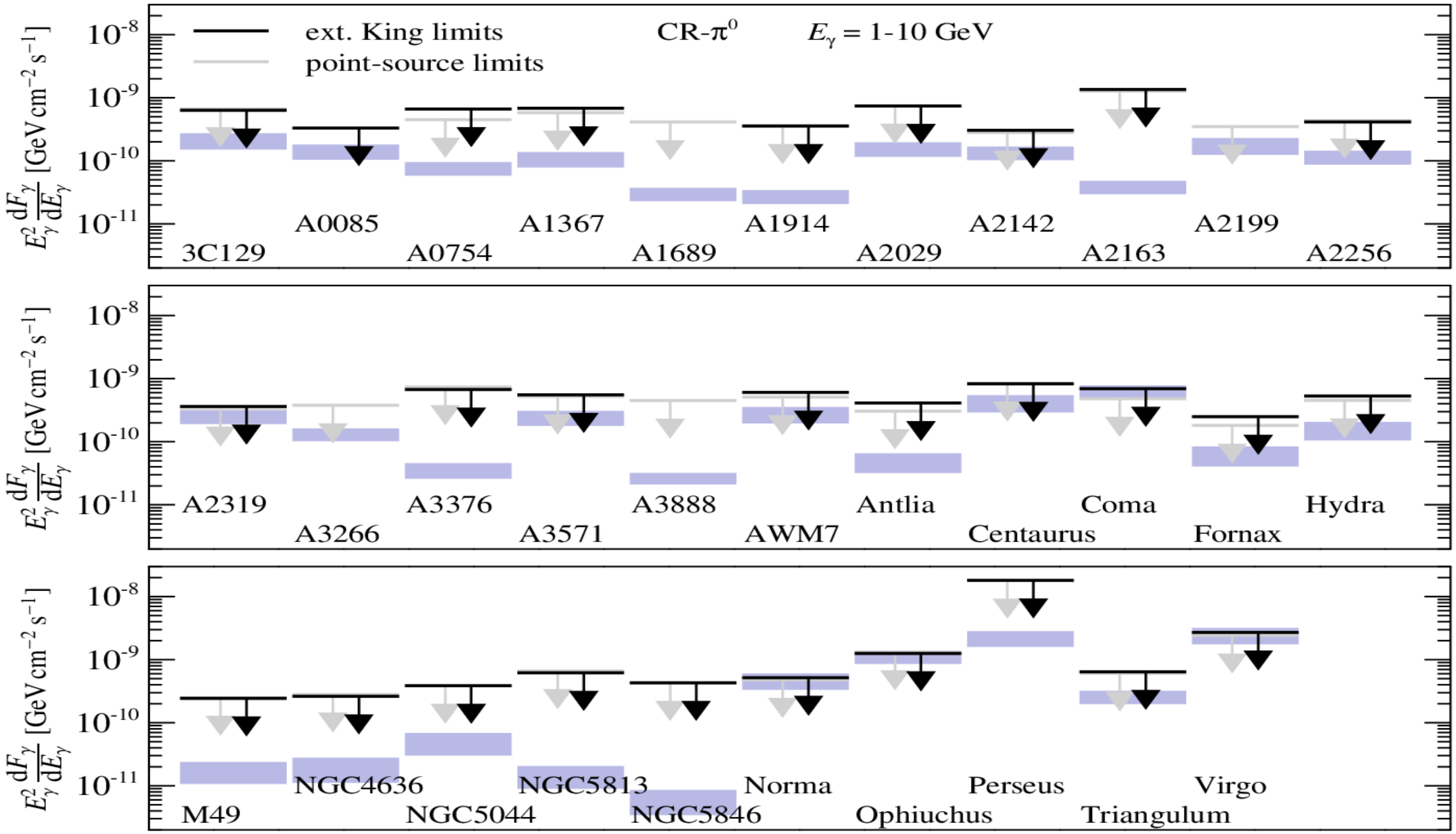


Constraining the average cosmic ray-to-thermal pressure to < 1.7% for the entire cluster

Flux predictions vs. observations

Flux within $\Delta\Phi = R_{vir}$

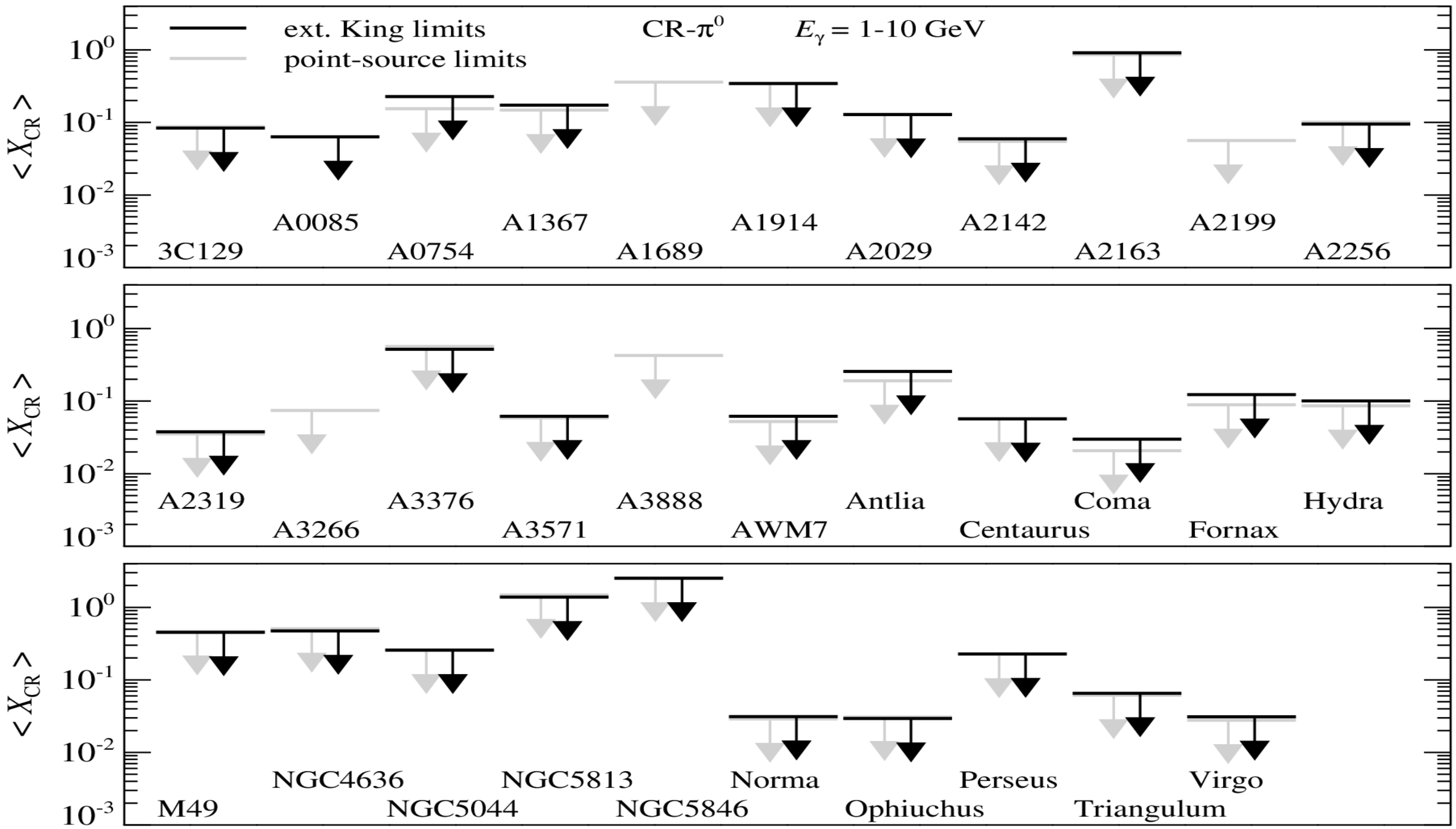


Pinzke et al. 2011

Upper limits set by Fermi-LAT after ~18 months of operation approach predicted gamma-ray fluxes. In the coming years we can seriously can probe the expected gamma-ray emission with Fermi-LAT.

Constraints on relative CR pressure

Derived from flux within $\Delta\Phi = R_{vir}$

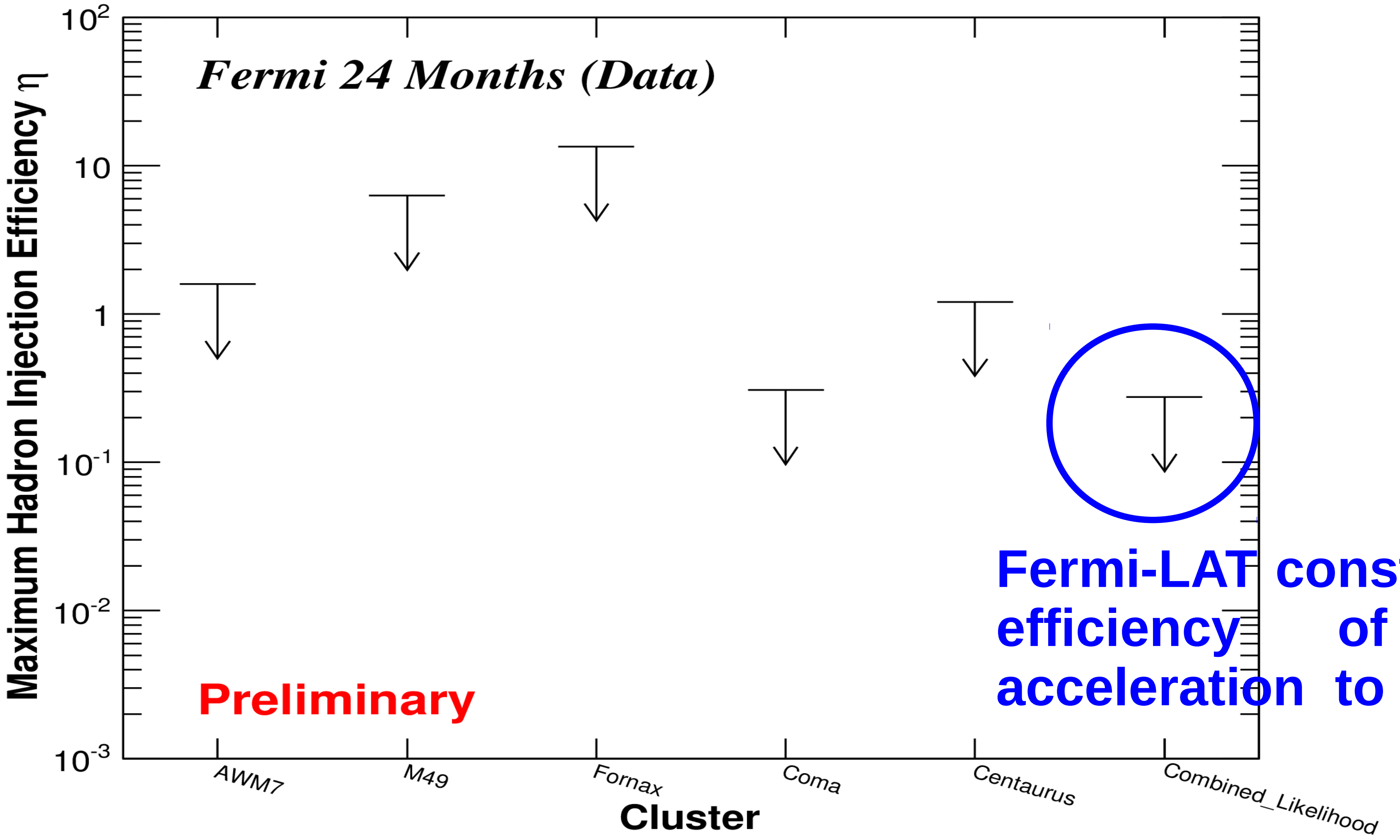


Pinzke et al. 2011

The best limits on relative CR pressure $X_{CR}=P_{CR}/P_{th}$ are found in Norma, Coma, Ophiuchus, A2319 (and Virgo) of the order few percent, with typical limits around 10%.

Constraints from stacking clusters

maximum injection efficiency



Fermi-LAT constrains efficiency of CR acceleration to $\lesssim$30%

Zimmer+ in preparation

Conclusions – CR part

CR proton induced π^0:s decaying into gamma-rays dominate the total gamma-ray emission above 100 MeV in clusters. The emission trace the gas, hence dominated by the central/core regime in clusters.

→ Good targets for Cherenkov telescopes with a small viewing angle and for Fermi-LAT with peak sensitivity close to the pion bump.

Constraints from Observations:

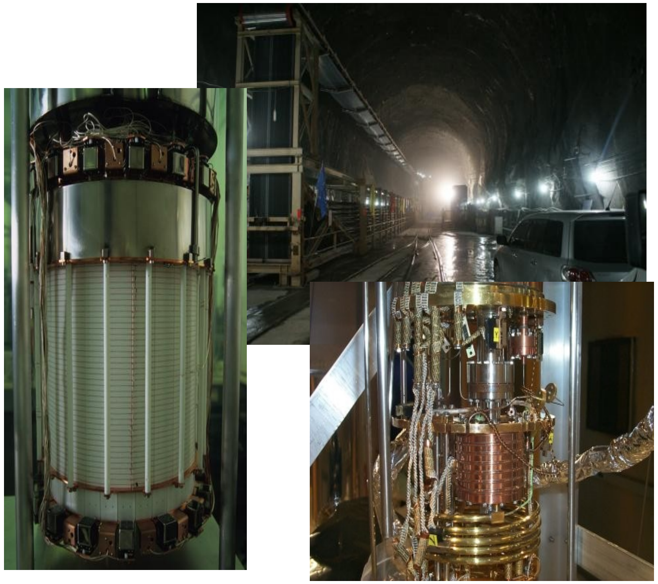
- **Fermi-LAT** 18 month data constrain the cosmic ray-to-thermal pressure to a few percent in a few clusters. Stacking clusters constrains acceleration efficiency to $\lesssim$ 30%.
- **MAGIC** observations of ***Perseus*** constrain the cosmic ray-to-thermal pressure to < 1.7% and starts constraining NT physics.

Part 2

Gamma-rays from annihilating dark matter

Searching for DM

indirect detection



direct detection

accelerators

Detecting CDM indirectly – annihilation radiation

Supersymmetric particles are Majorana particles

⇒ 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

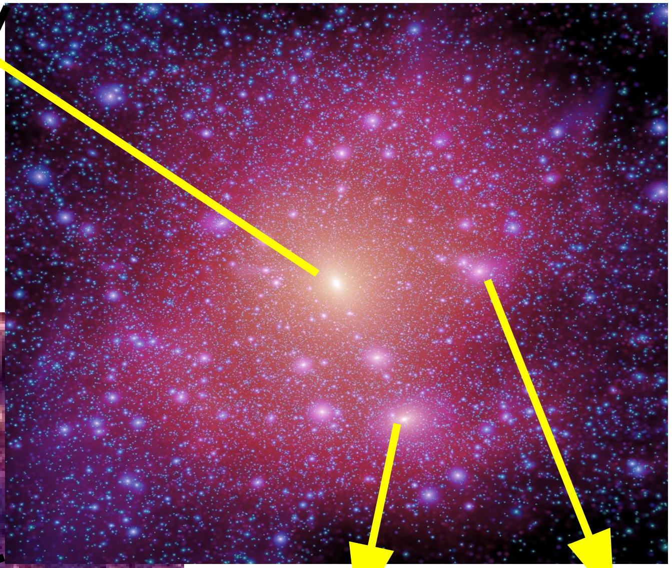
⇒ Theoretical expectation requires knowing $\rho(x)$

⇒ High resolution N-body simulations of halo formation from CDM initial conditions

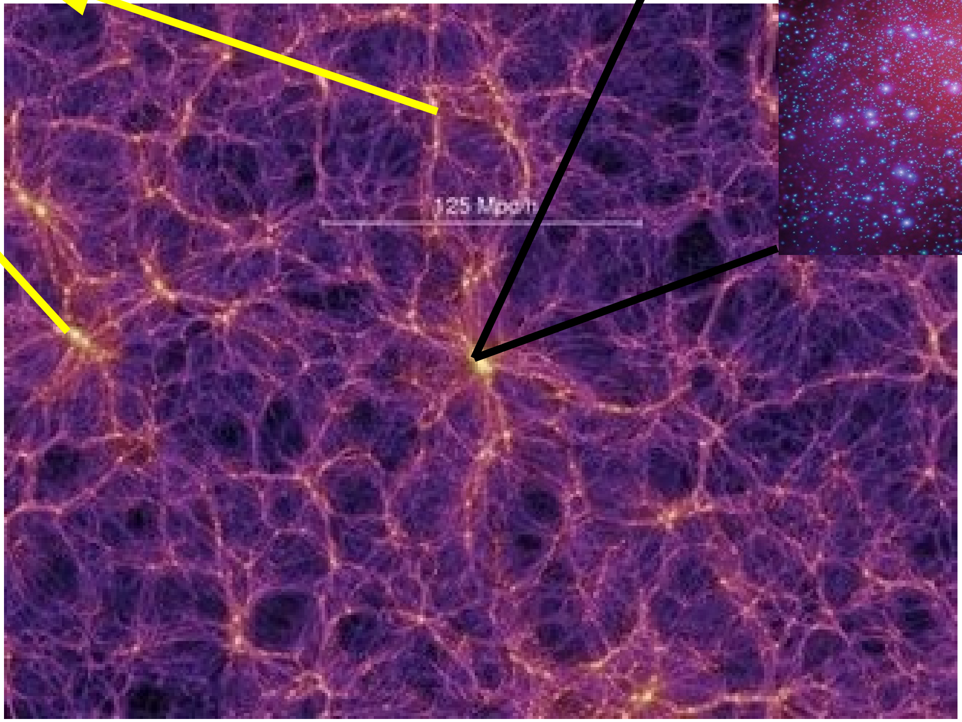
Indirect DM searches

Milky Way halo:
Very good statistics, but diffuse background

Galactic center:
Good statistics, but source confusion and diffuse background



Galaxy clusters:
Low background, but low statistics

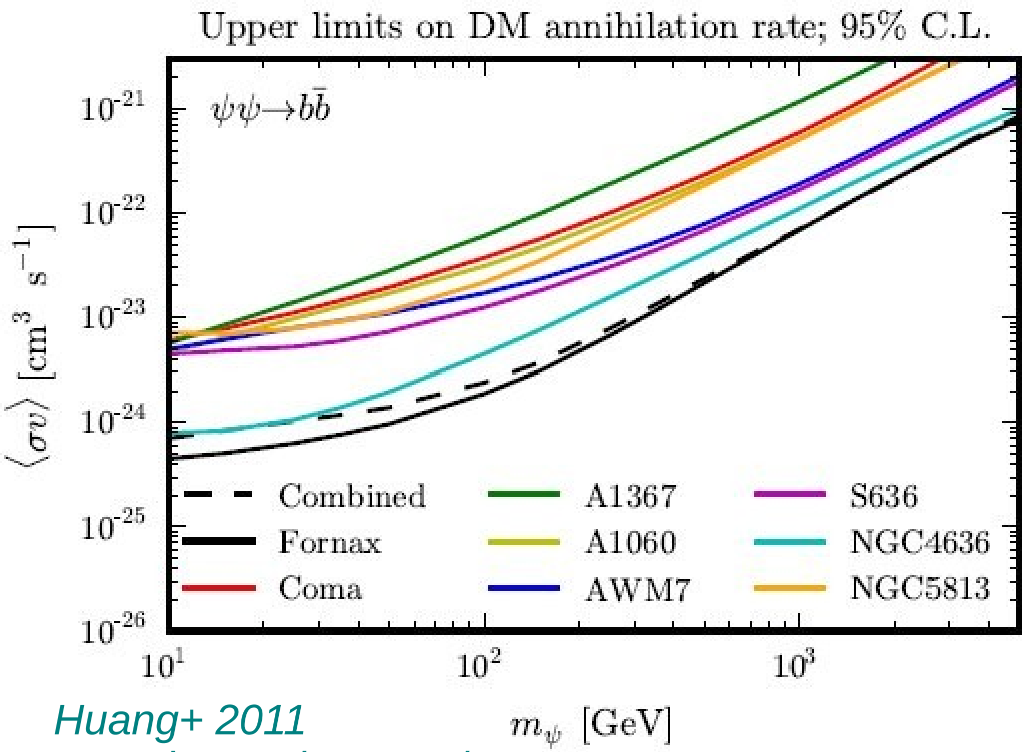


Satellites:
Low background, but low statistics

Extra galactic:
Very good statistics, but astrophysics and galactic diffuse foregrounds

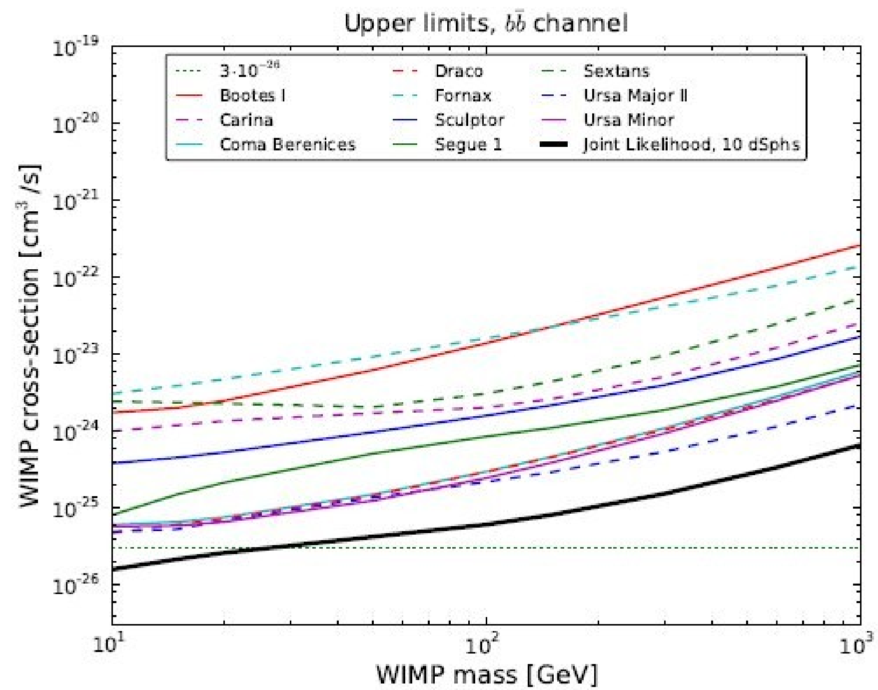
Why search for DM in galaxy clusters?

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 boost the gamma-ray flux and potentially make clusters several orders of magnitude brighter than dwarf galaxies.

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}).

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

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

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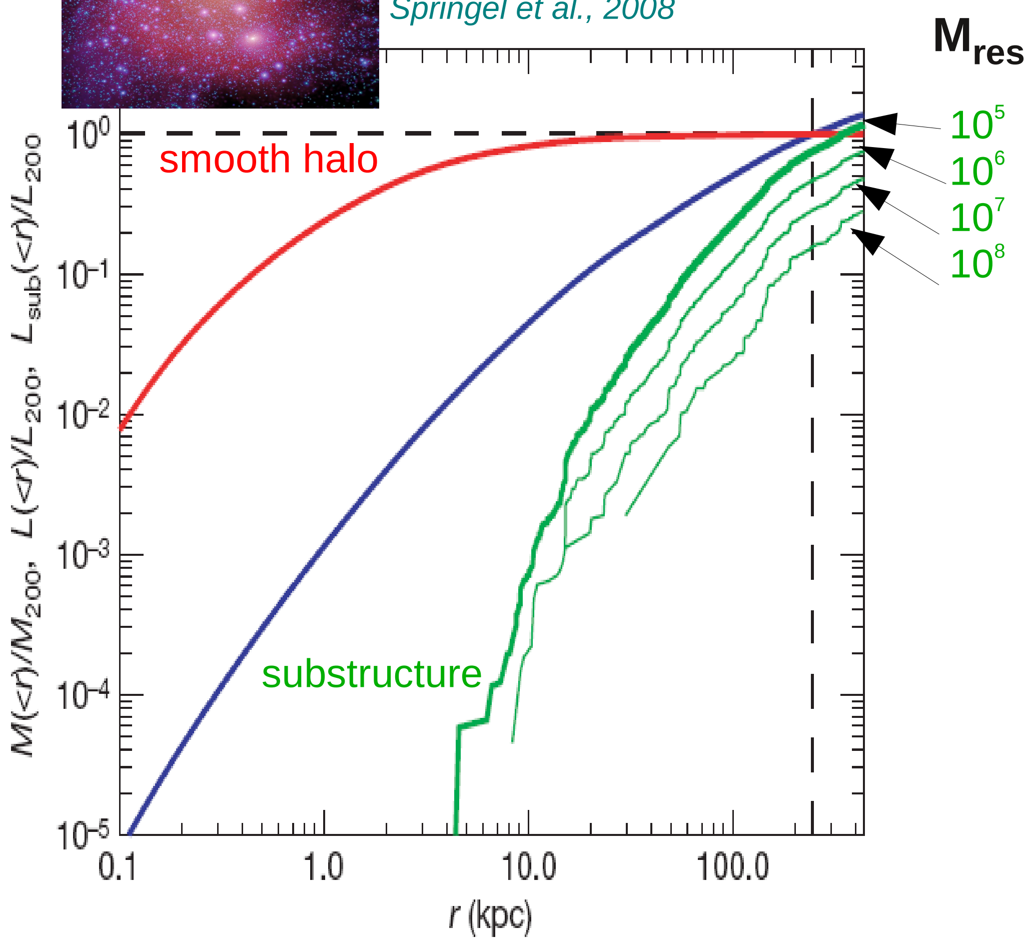

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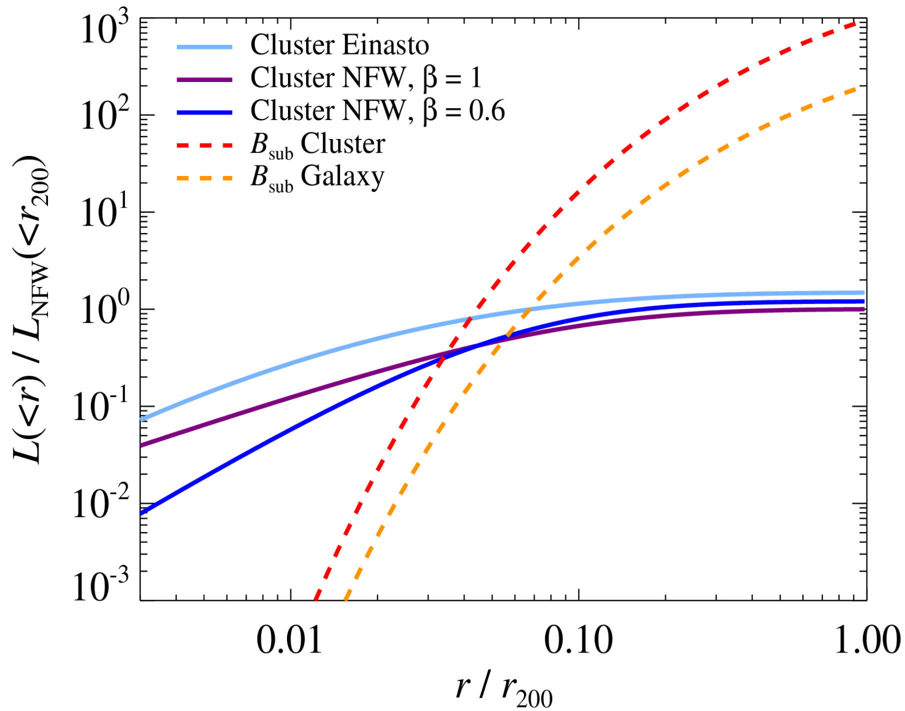
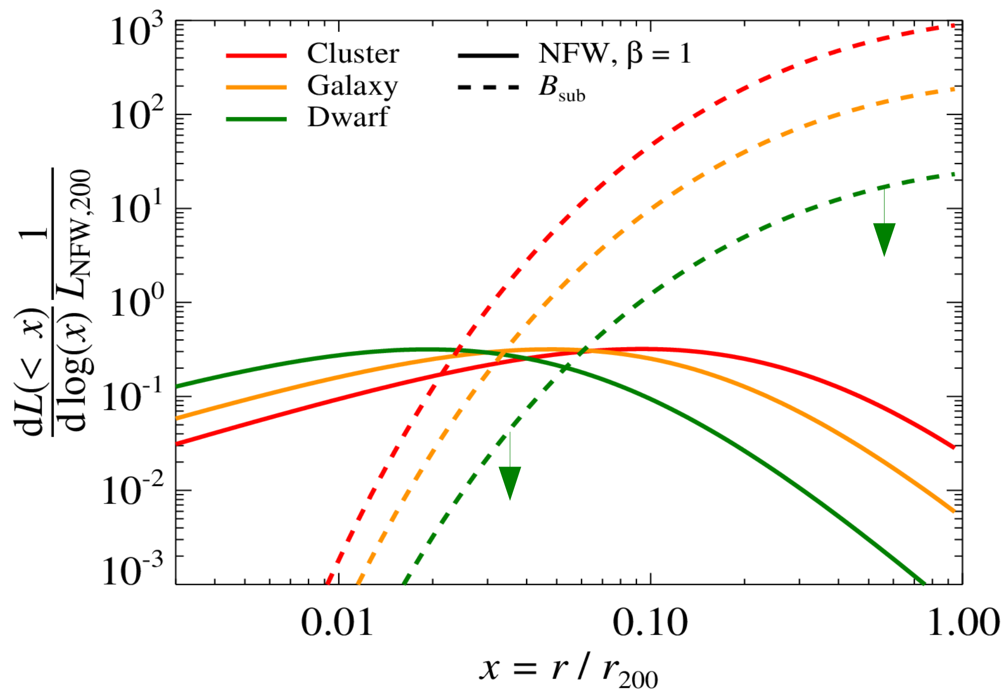
Pinzke et al. 2011, Gao et al 2011

Spatial distribution of DM





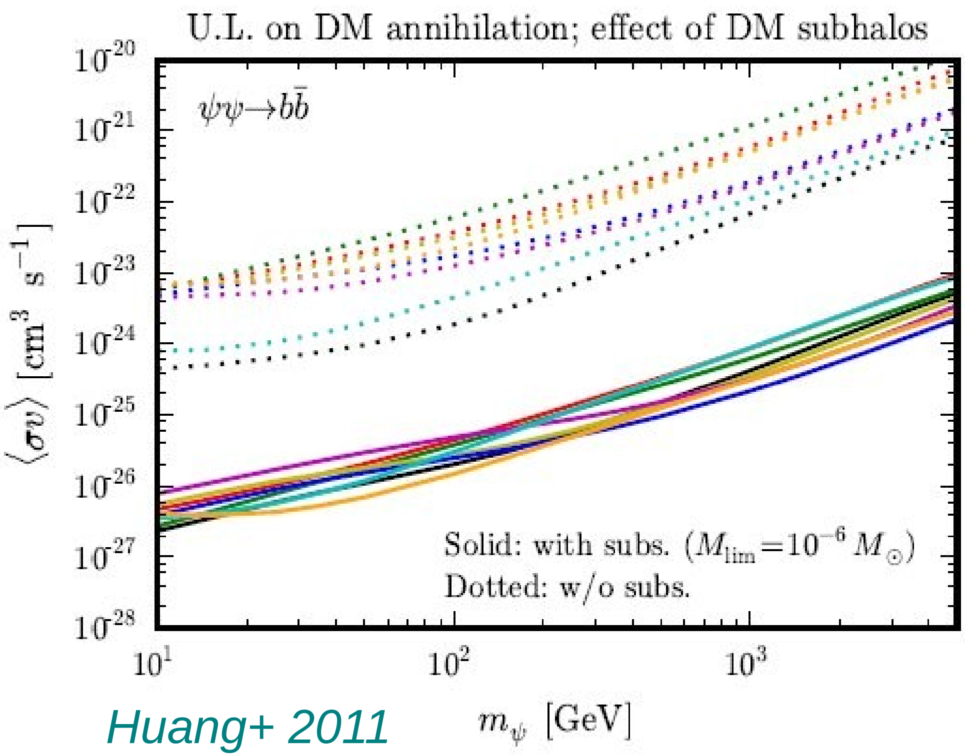
- Choice of smooth density profile minor impact on annihilation luminosity outside center.
- Large boost from substructures in clusters (~1000), and smaller for galaxies (~200).
- Majority of flux from smooth halo delivered by region around r_s / 3.
- Emission from substructures dominated by outer regions.

Spatially extended!

→ challenging for IACTs

Clusters incl. substructures Vs Dwarfs

GALAXY CLUSTERS



Huang+ 2011
See also Ando&Nagai 2012

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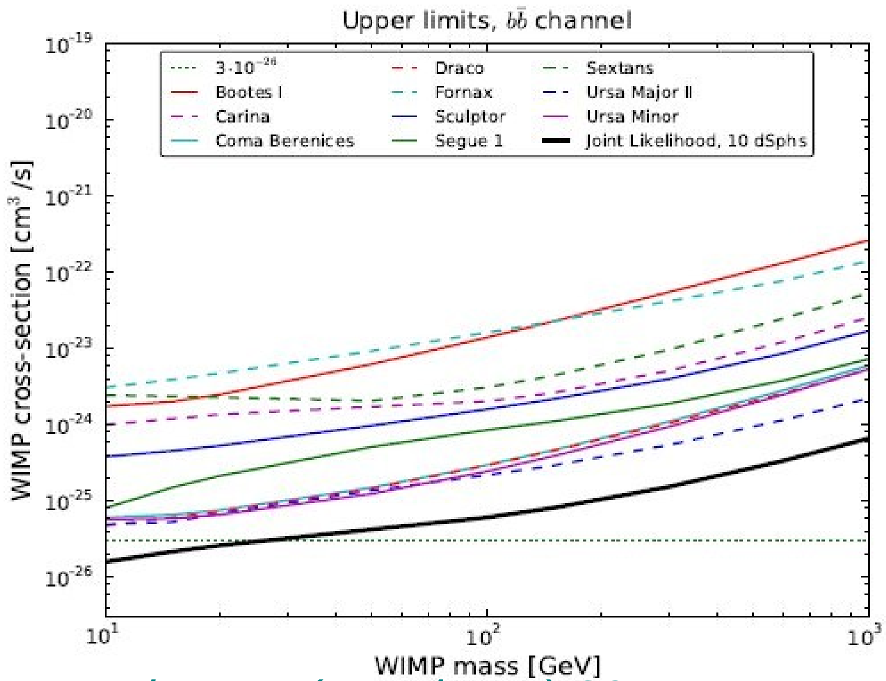
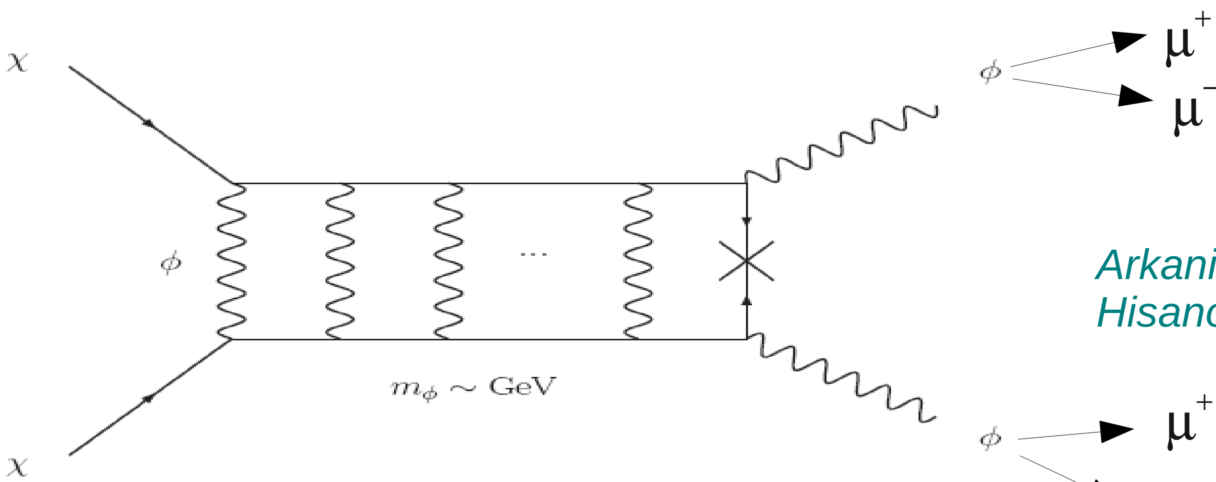


Ackerman(Fermi-LAT) 2011
See also Geringer-Sameth+ 2011

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

Sommerfeld enhancement



ladder diagrams with unknown force carrier

Arkani-Hamed et al. 2009
Hisano, Matsumoto, and Nojiri 2004

$$\langle\sigma v\rangle \approx \langle\sigma v\rangle_0 \times (c/v)$$

$$v = 960\ \text{km/s} \times (M_{200}/10^{15}\ M_\odot)^{1/3}$$

$$\Downarrow$$

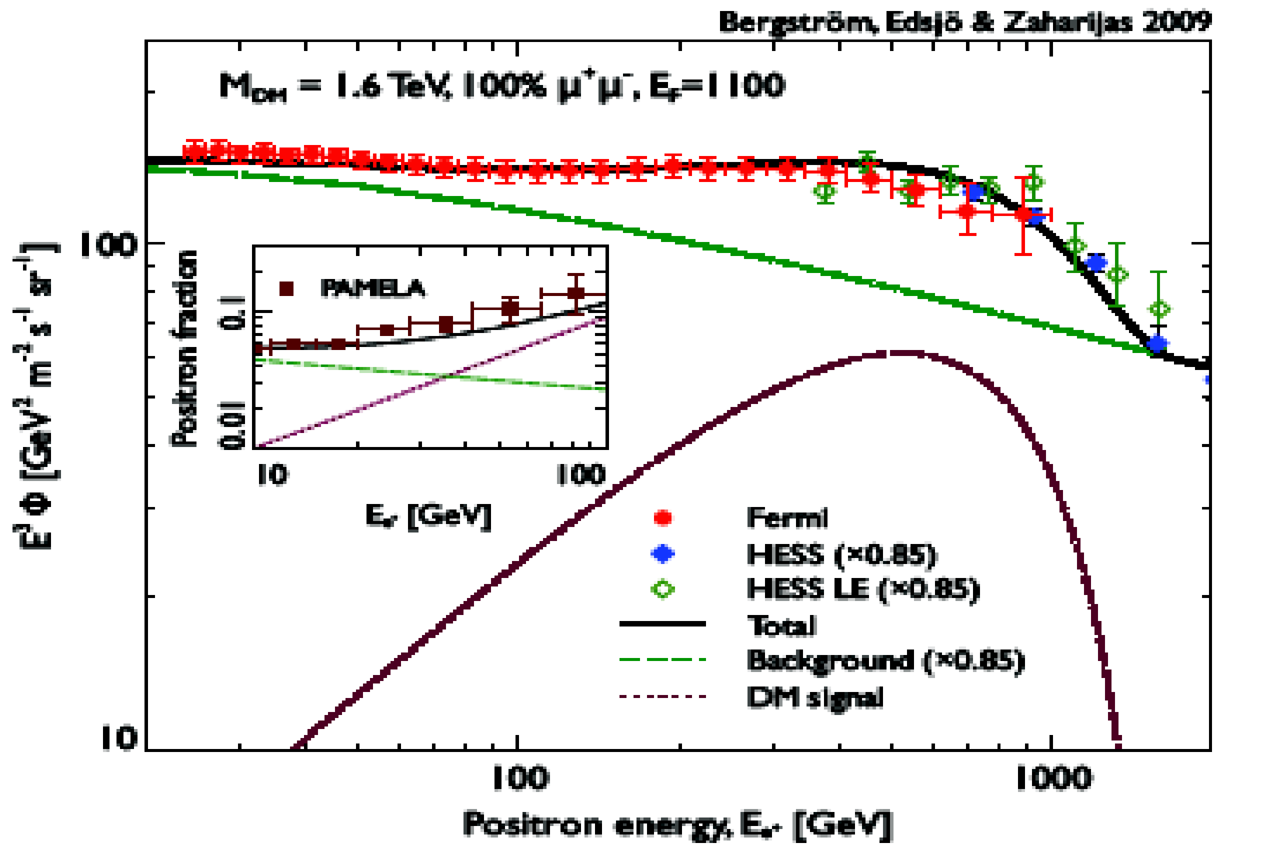
$$L_{xx} \sim \langle\sigma v\rangle \int dV\ \rho^2$$

Boost from sommerfeld enhancement (SFE) in the Milky Way DM halo is limited to $\lesssim$400. Saturated boost can be larger.

Finkbeiner et al. 2010

Sommerfeld enhancement

DM annihilating into leptons can explain the excess of e^+/e^- seen by PAMELA/Fermi-LAT/(ATIC).



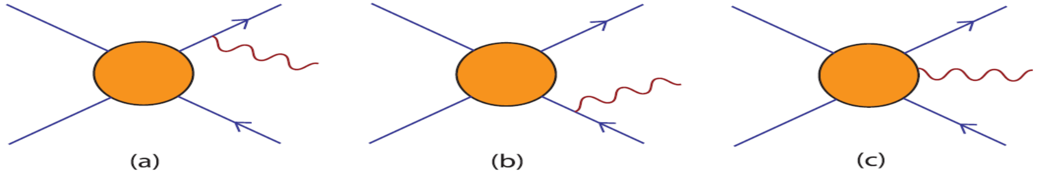
Enough to explain boost required for DM interpretation of e^+/e^- excess.

DM induced gamma-rays
– leptophilic models

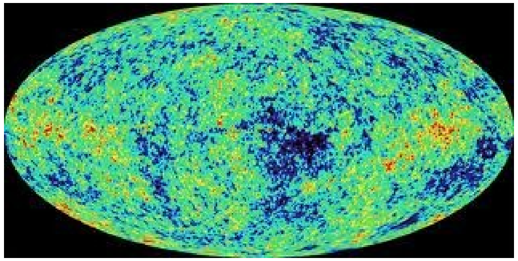
Annihilation rate in these models enhanced by **Sommerfeld effect** as well as **DM substructures**.

Gamma-ray emission components:

- Final state radiation



- IC on background radiation fields (CMB, starlight and dust)



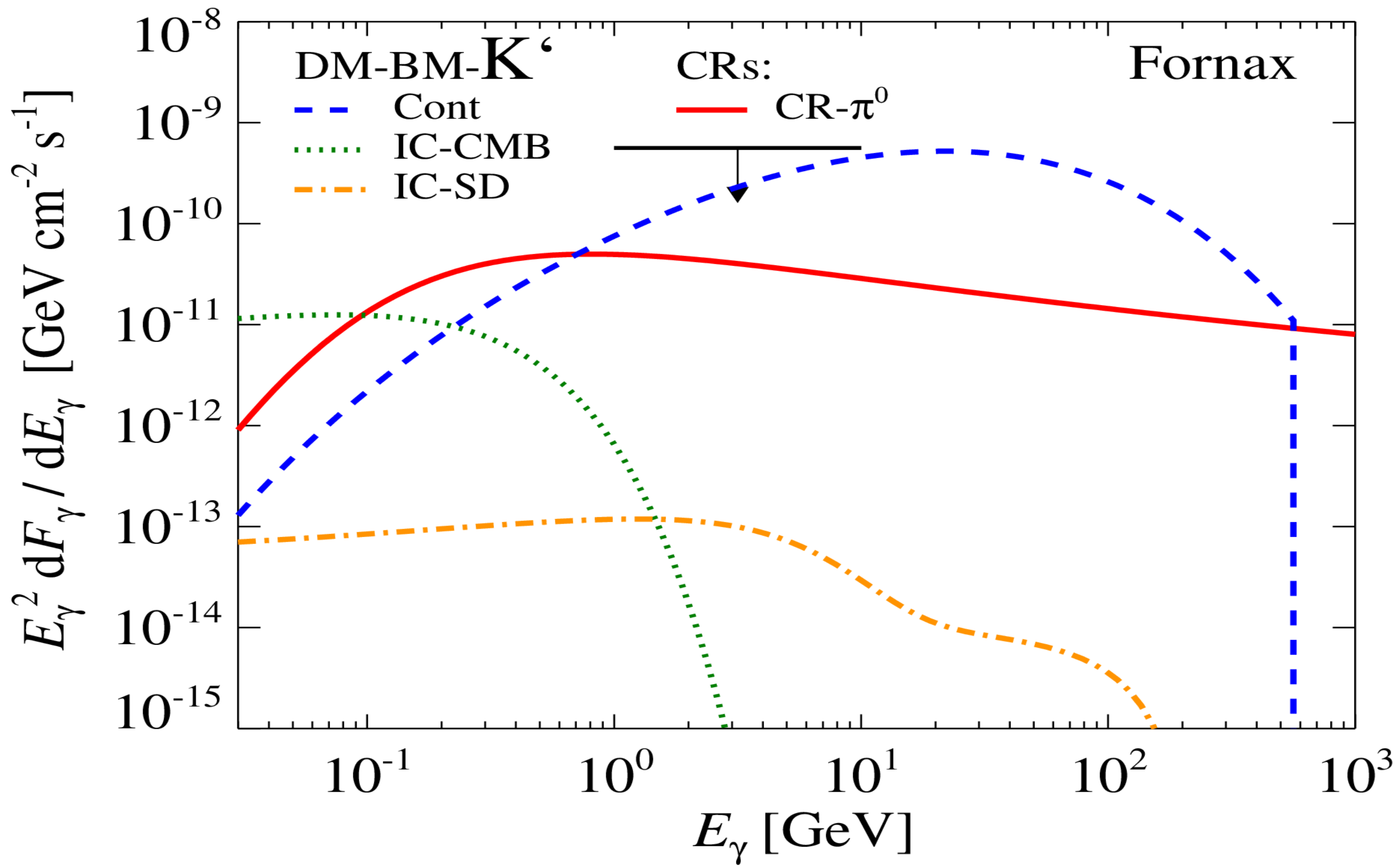
DM induced gamma-rays
– supersymmetric benchmark models

Representation of high mass (~1 TeV) DM models with high gamma-ray emission.

Luminosity **boosted by substructures** in the smooth DM halo.

Gamma-ray emission components:
- Annihilating neutralinos emitting continuum emission
- Final state radiation
- IC on background radiation fields (CMB, starlight and dust)

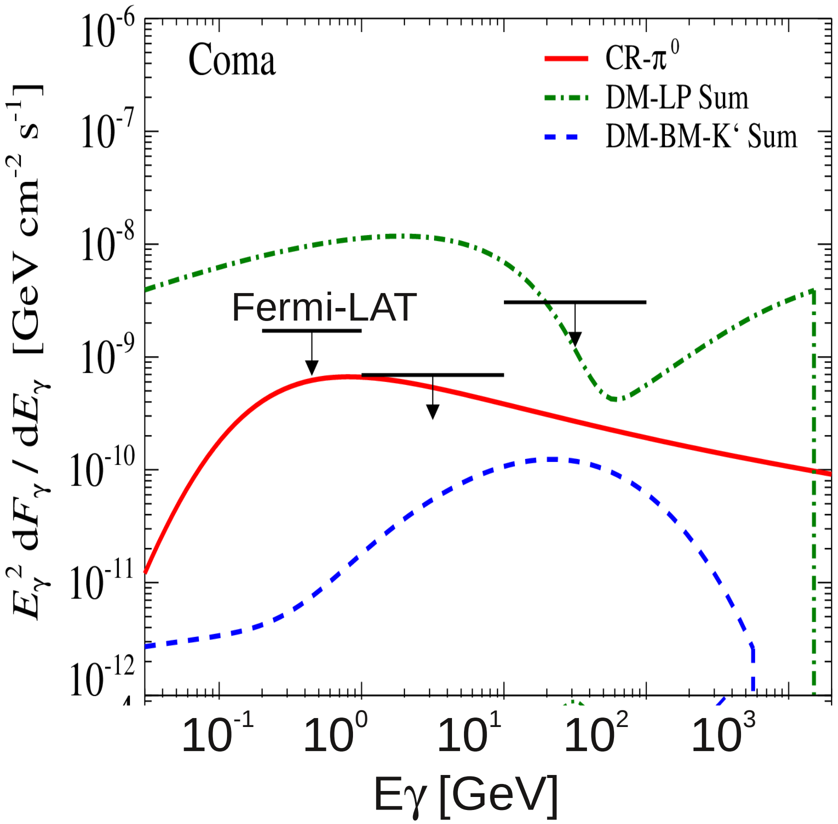
Gamma-ray spectrum from DM vs. CR interactions

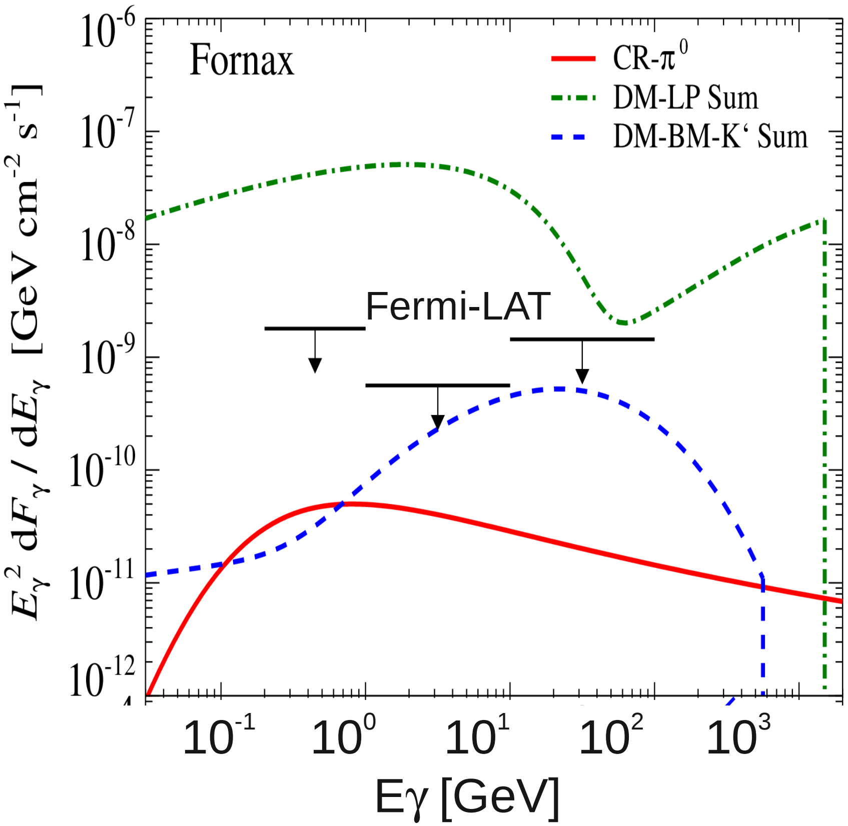


Pinzke et al., 2011

Continuum emission dominates over upscattered starlight and dust (SD). Below GeV energies upscattered CMB dominates DM contribution, however at these energies CR induced emission is expected to dominate.

Comparing clusters and emission processes

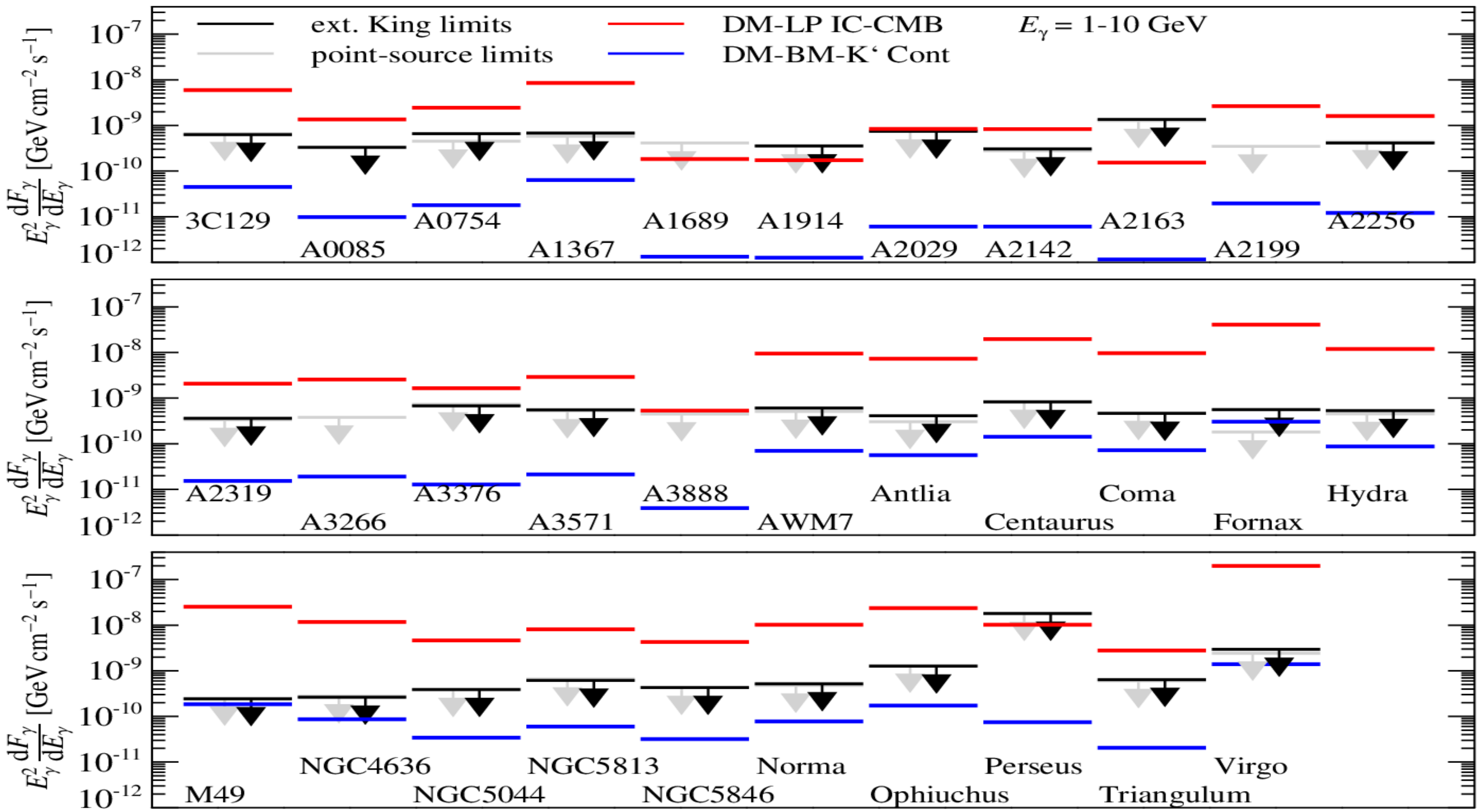




- **Fornax** comparably high DM induced gamma-ray flux and low CR induced gamma-ray flux → enable DM detection or tight limit on DM properties.
- Fermi will start probing CR induced emission in **Coma** the coming years.

DM flux predictions vs. observations

Flux within $\Delta\Phi = R_{vir}$



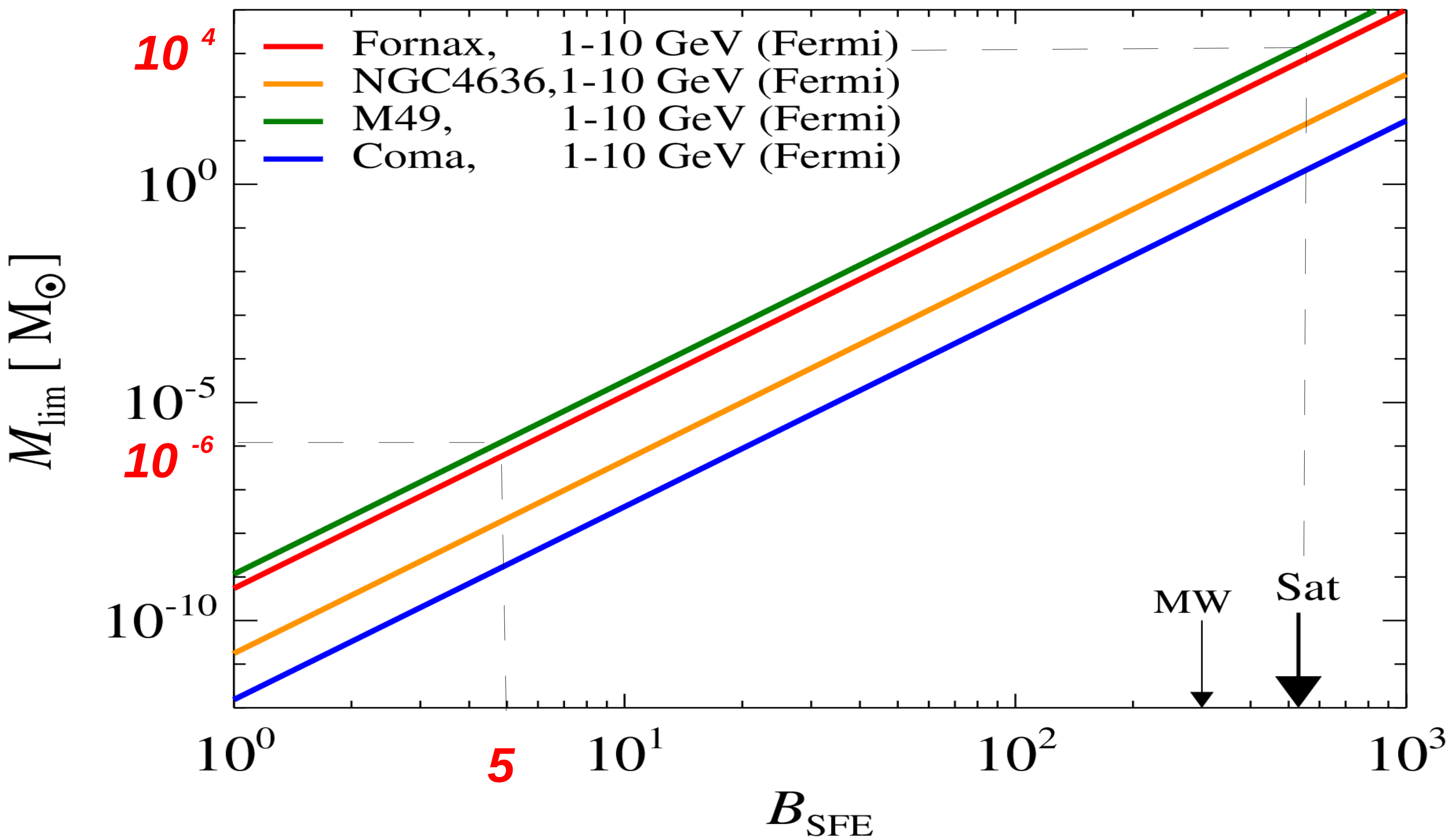
Pinzke et al. 2011

Emission from leptophilic models in most clusters detectable with Fermi-LAT after 18 months of operation.

Supersymmetric DM models will start being probed in coming years.

Brightest clusters: Fornax, Ophiuchus, M49, Centaurus (and Virgo).

Constraining boost factors



Pinzke et al. 2011

- Fornax and M49 constrain the saturated boost from Sommerfeld enhancement (SFE) to $\lesssim 5$.
- Alternatively, if SFE is realized in Nature, this would limit the substructure mass $M_{lim} > 10^4 M_{\odot}$ – a challenge for structure formation.

Conclusions – DM part

We have studied the possibility to detect gamma-ray emission from galaxy clusters, using a variety of DM models.

The luminosity contribution from substructures dominates over smooth halo for halo masses $M_{200} > 10^3 M_\odot$.

→ **Luminosity from clusters boosted by ~1000**

→ **Flat brightness profiles and spatially extended**

→ **Challenging for IACTs, better probed by Fermi-LAT**

DM not swamped by astrophysical foregrounds.

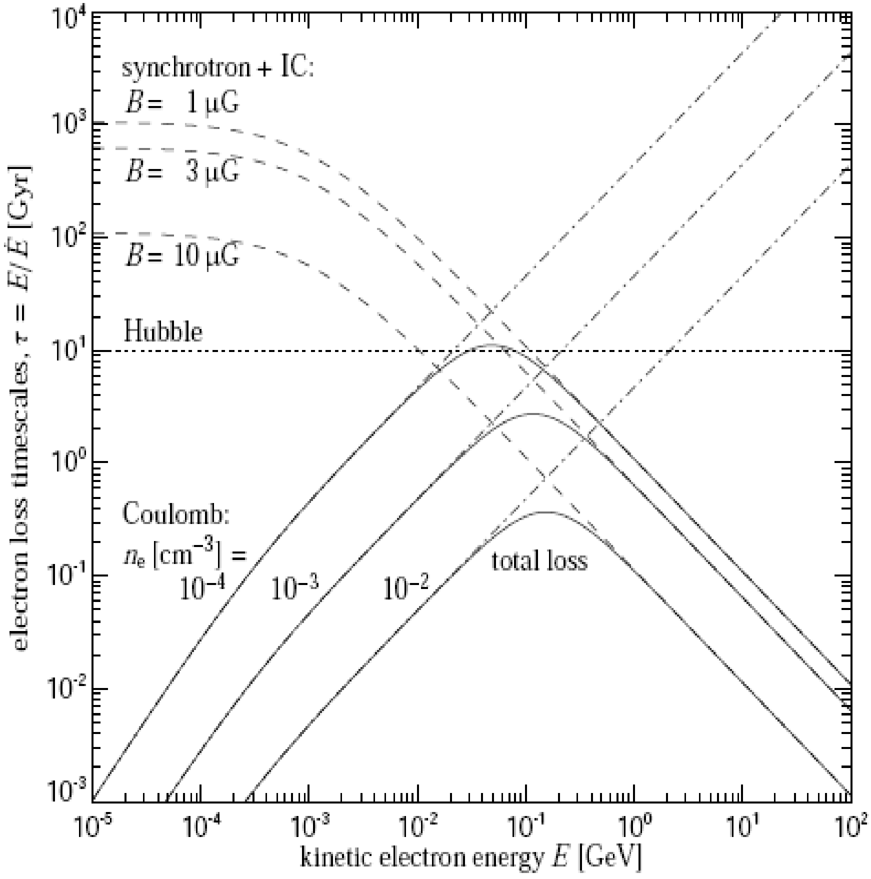
Constraints from Observations:

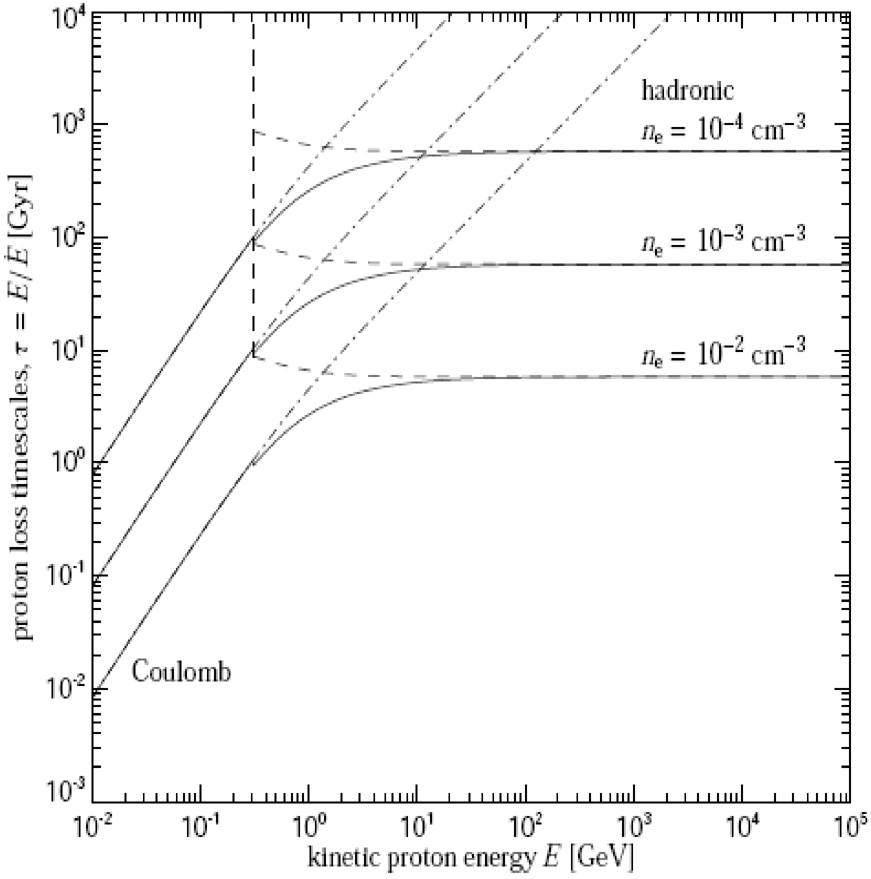
- **Fermi-LAT** will test the leptophilic DM interpretation of the Fermi/HESS/PAMELA data in the next years. The 18 month data constrain the Sommerfeld enhancement to $\lesssim 5$, and if DM interpretation is correct, then smallest subhalos $> 10^4 M_\odot$.

Thank you!!

Extra Slides

CR cooling timescales





Smooth Particle Hydrodynamics

BASIC EQUATIONS

Density estimate:

$$\rho_i = \sum_{j=1}^{N} m_j W(|\mathbf{r}_{ij}|, h_i)$$

Continuity equation fulfilled

Equation of state:

$$P_i = (\gamma - 1)\rho_i u_i$$

Equation of motion:

$$\frac{\mathrm{d}\mathbf{v}_i}{\mathrm{d}t} = -\sum_{j=1}^{N} m_j \left[f_i \frac{P_i}{\rho_i^2} \nabla_i W_{ij}(h_i) + f_j \frac{P_j}{\rho_j^2} \nabla_i W_{ij}(h_j) \right]$$

Springel & Hernquist 2002

$$f_i = \left[1 + \frac{h_i}{3\rho_i} \frac{\partial \rho_i}{\partial h_i} \right]^{-1}$$

Energy and entropy conservation

Add viscosity and non-adiabatic terms to EOM:

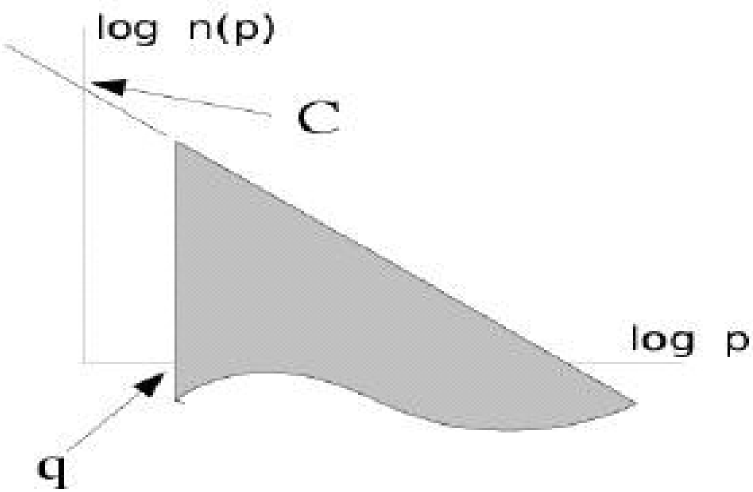
shock waves, radiative energy losses, CR diffusion, ...

Cosmic ray proton physics

SIMPLIFIED COSMIC RAY FORMALISM

CR momentum space

$$f(p) = \sum_i f_i(p) = \sum_i C_i p^{-\alpha_{p,i}} \theta(p - q_i).$$



Cosmic ray pressure

$$P_{CR} = \frac{C\, m_p c_{light}^2}{6} \mathcal{B}_{\frac{1}{1+q^2}}\left(\frac{\alpha-2}{2}, \frac{3-\alpha}{2}\right)$$

Adiabatic evolution

$$q(\rho) = (\rho/\rho_0)^{\frac{1}{3}} q_0 \qquad C(\rho) = (\rho/\rho_0)^{\frac{\alpha+2}{3}} C_0$$

Energy and number density

$$\varepsilon_{CR} = \int_0^\infty \mathrm{d}p\, f(p) T_p(p) \qquad n_{CR} = \int_0^\infty \mathrm{d}p\, f(p)$$

Non-adiabatic processes

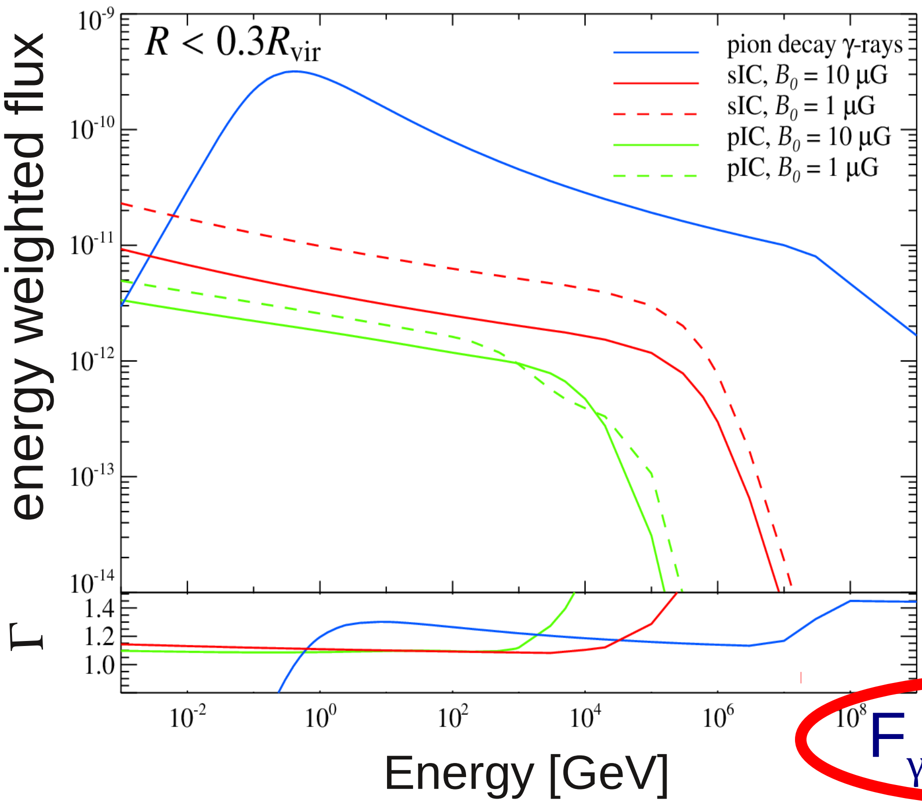
$$\Delta C_0 = C_0 \frac{\Delta \varepsilon_{CR} - T_p(q) \Delta n_{CR}}{\varepsilon_{CR} - T_p(q) n_{CR}}$$

$$\Delta q_0 = \frac{\rho}{\alpha - 1} \frac{\Delta \varepsilon_{CR} - T_{CR} \Delta n_{CR}}{\varepsilon_{CR} - T_p(q) n_{CR}}$$

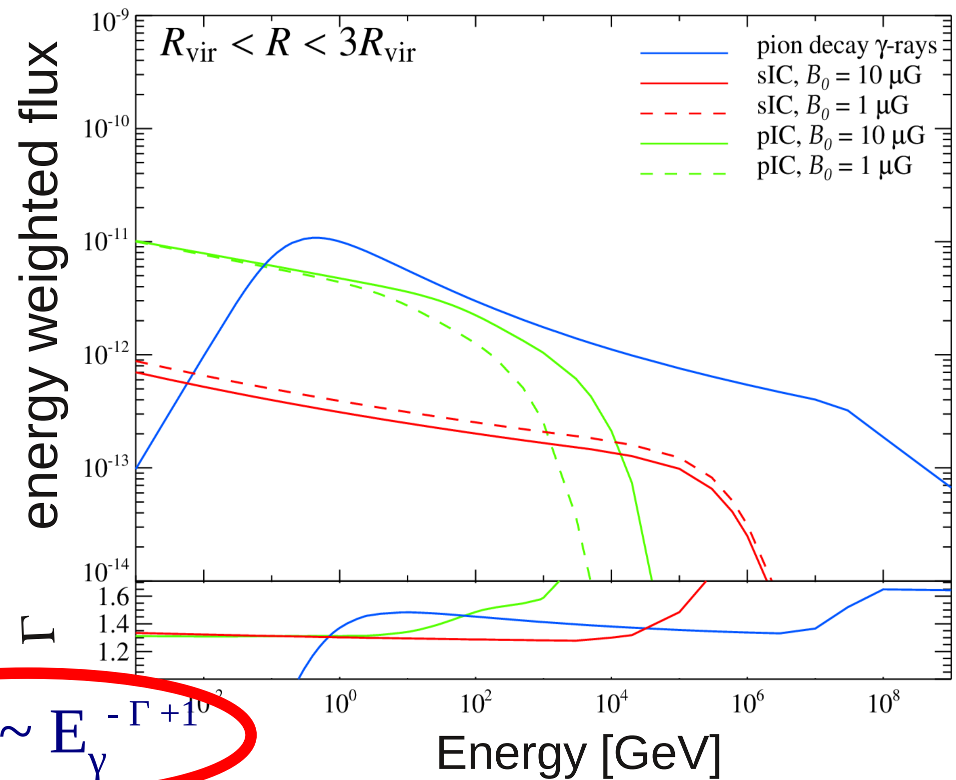
Given by change in energy and number density from gain- and loss-processes

The core vs outer parts

Core region



Cluster outskirts



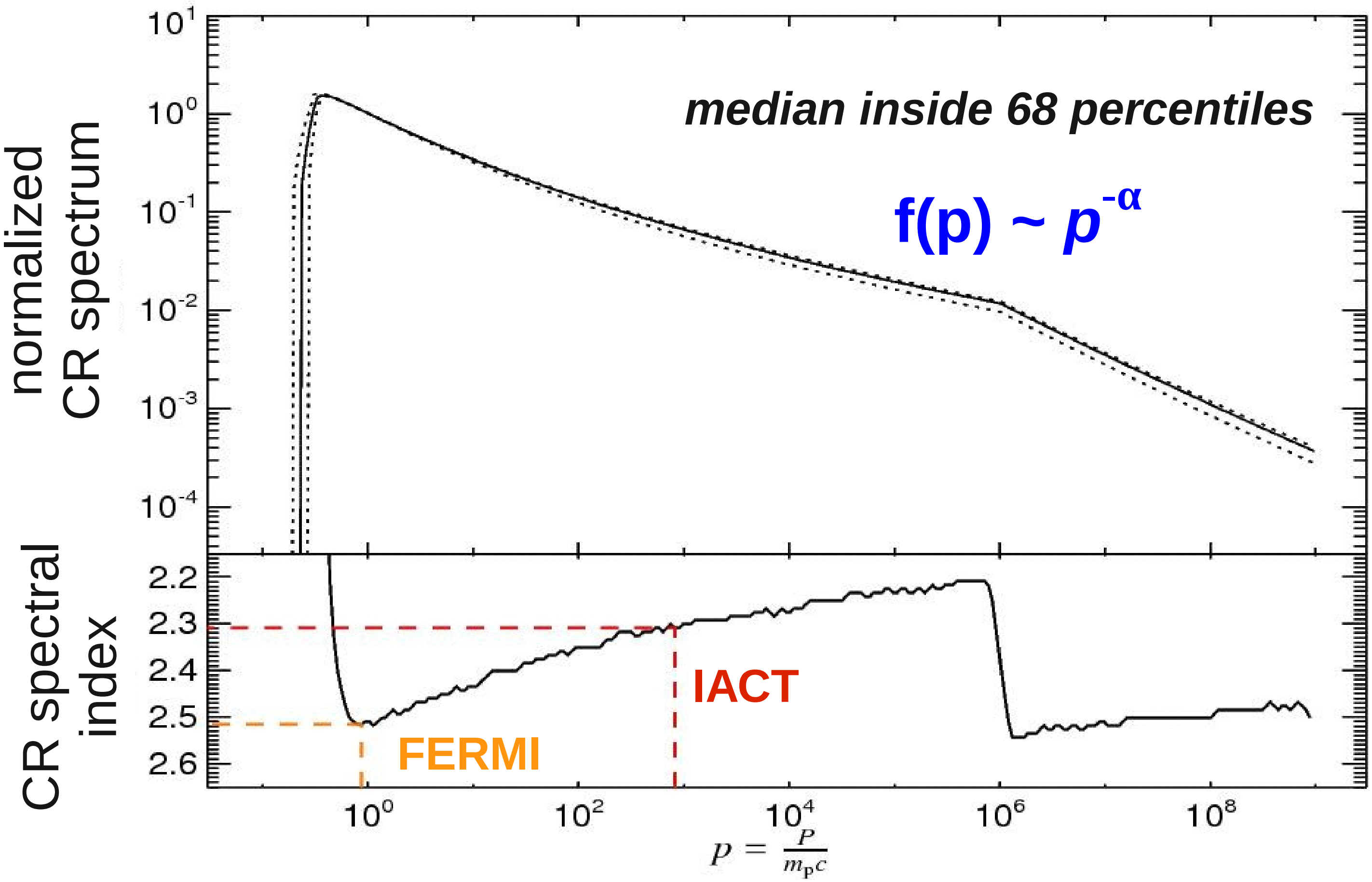
$$F_\gamma E_\gamma \sim E_\gamma^{-\Gamma+1}$$

Pinzke, Pfrommer 2010

- π^0-decay dominate over sIC that is subdominant to pIC
- pIC emission suppressed due to few shocks in the small volume of the core

- Comparable flux from π^0-decay and pIC
- pIC boosted due to great number of shocks in the outer parts of the cluster. These shocks are weaker than in the core which steepens the pIC spectrum.

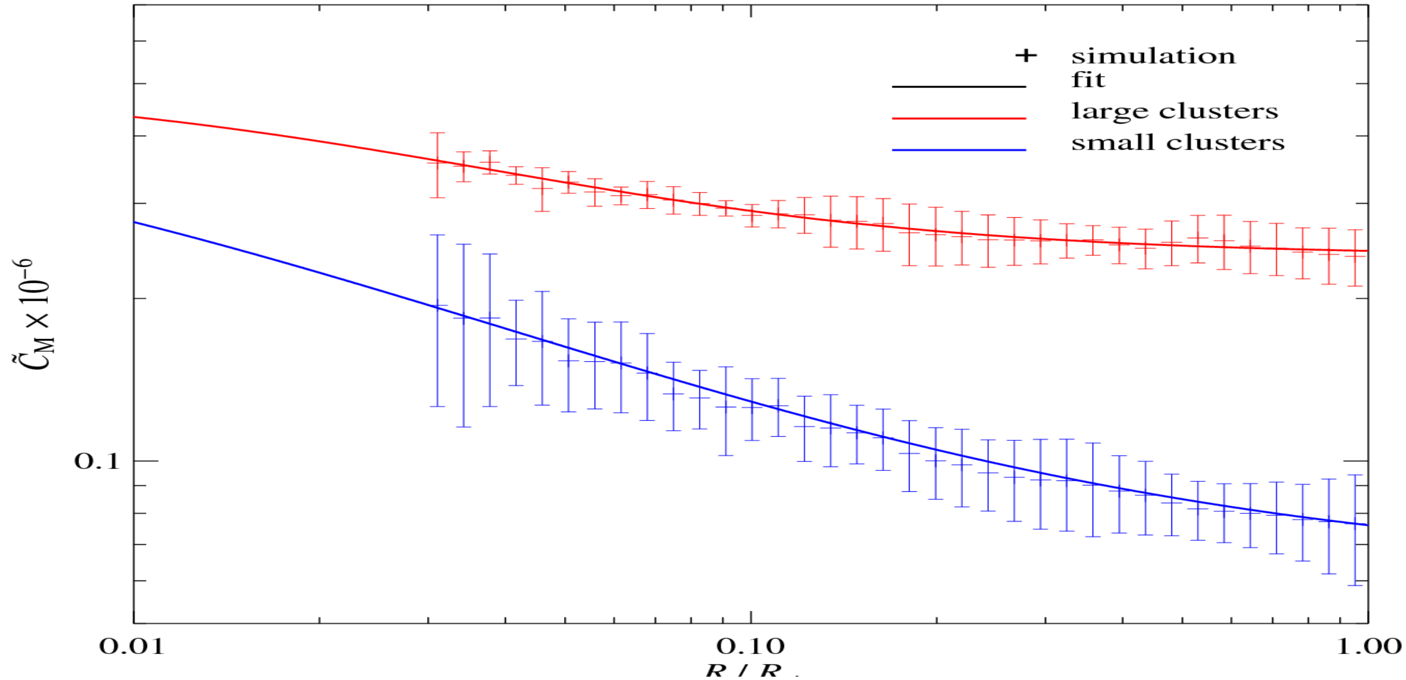
CR spectrum for whole cluster sample



Pinzke, Pfrommer 2010

Universal concave shape and a very small variance!

Spatial CR distribution



Semi-analytic model

CRs spatially and spectrally universal in galaxy clusters

↓

Separate radial and spectral parts in a semi-analytic model

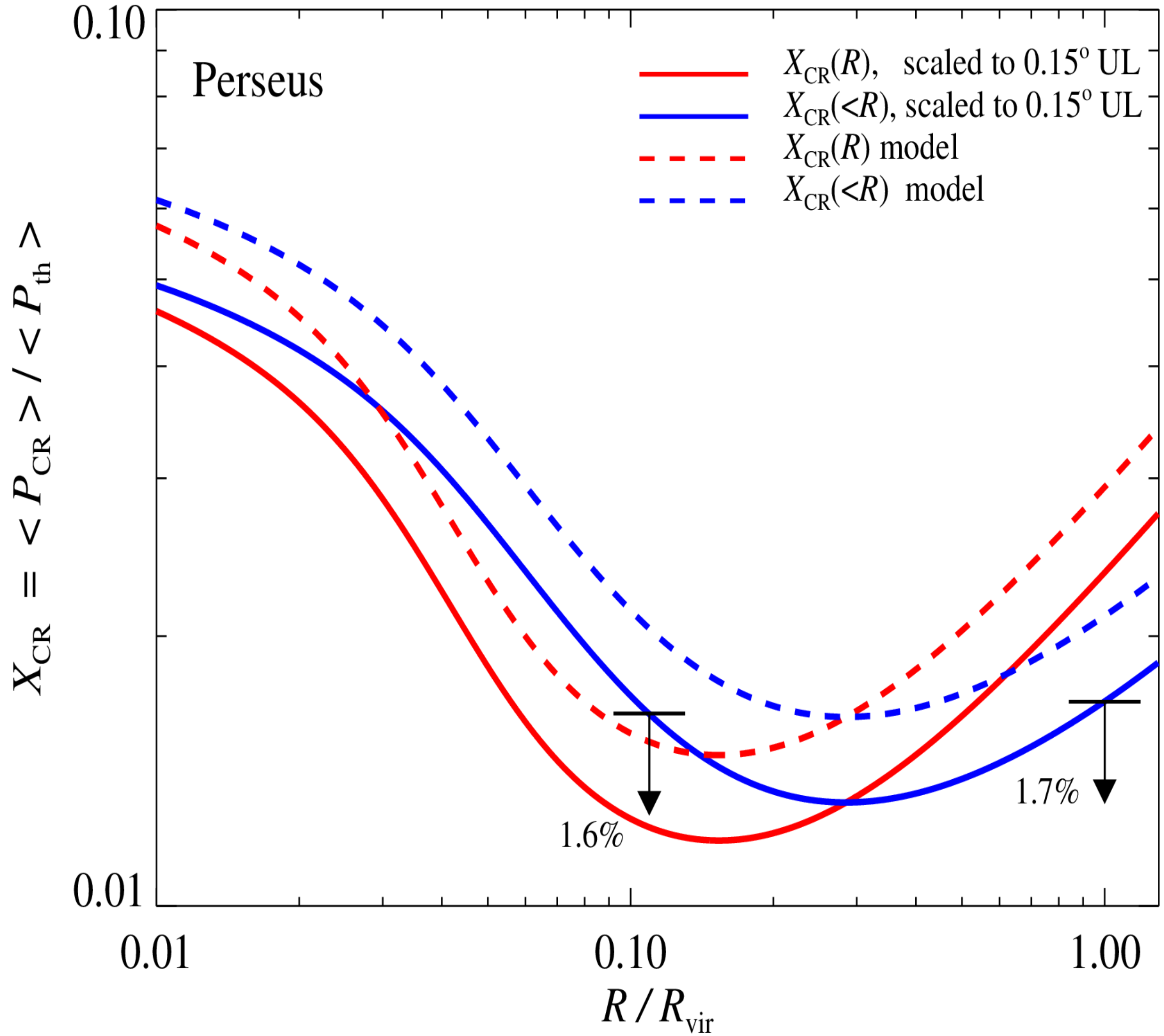
Combining our semi-analytic CR model with density profiles inferred from X-ray measurements

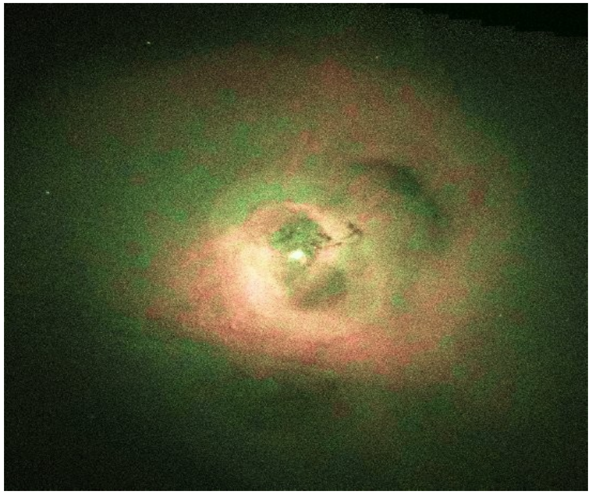
Hadronic model
Pfrommer and Ensslin 2004

Neutrino flux,
Secondary radio

Gamma-ray flux,
Surface brightness

Constraints on relative CR pressure – Perseus





Constraining the average cosmic ray-to-thermal pressure to < 1.7% for the entire cluster

Aleksic et al., 2012

Constraints on relative CR pressure

FORMALISM

CR distribution function:

$f_{CR}(r) \propto C(r)$, where C(r) is the density distribution of CR protons.

Relative CR pressure:

$X_{CR}(r) = P_{CR}(r) / P_{th}(r) \propto C(r) / \rho(r) k_B T(r)$

Gamma-ray flux – **CRp + p → π^0 → 2γ**:

$F_{\pi-\gamma}(<R) \propto \int dV\, C(r)\, \rho(r)$

Use gamma-ray flux upper limits F_{UL} to constrain C(r)!

$A_{max}(<R) = F_{\pi-\gamma}(<R) / F_{UL}(<R)$

Maximum relative CR pressure:

→ $X_{CR,max}(r) \propto A_{max}(<R) C(r) / \rho(r) k_B T(r)$

Constraints on magnetic field – Perseus

- Assume a magnetic field profile $B(r) = B_0[\, n_e(r) \,/\, n_e(0)\,]^{\alpha_B}$.
- Assume a power law CR distribution function.
- Fit CR profile to observed profile of radio synchrotron emission.
- Rescale CR profile to match MAGIC gamma-ray upper limit.
- Adjust magnetic field to again match the observed radio synchrotron emission.

Constrain the magnetic field profile!

$\alpha_B = 0.5 \;\rightarrow\; B_{0,min} > 8.6\text{-}3.1$ [μG] for $\alpha_{CR} = 2.1\text{-}2.5$

$\alpha_B = 0.7 \;\rightarrow\; B_{0,min} > 13.1\text{-}4.7$ [μG] for $\alpha_{CR} = 2.1\text{-}2.5$

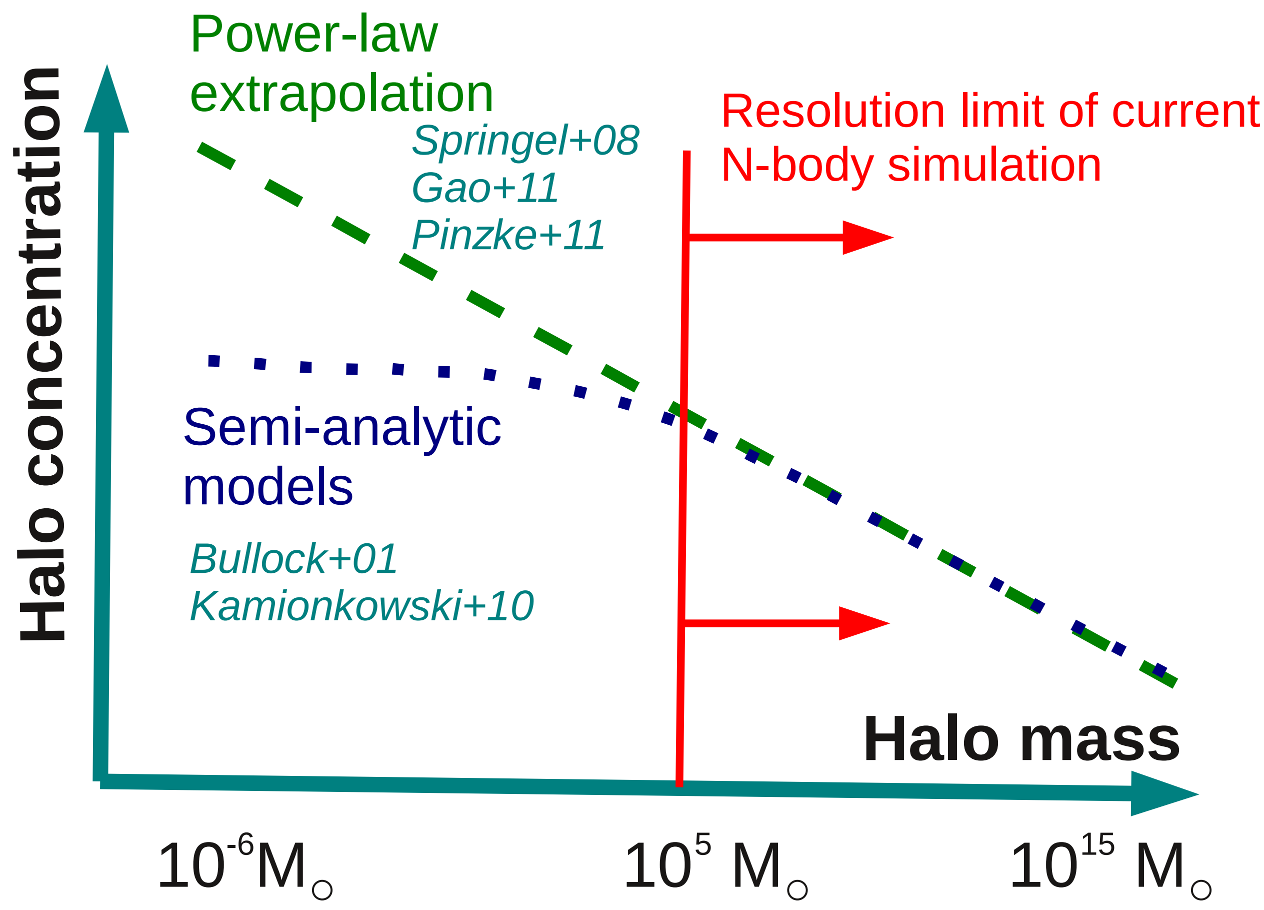
Faraday rotation studies suggest $B_0 \sim 25$ μG. *Taylor et al. 2006*

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!

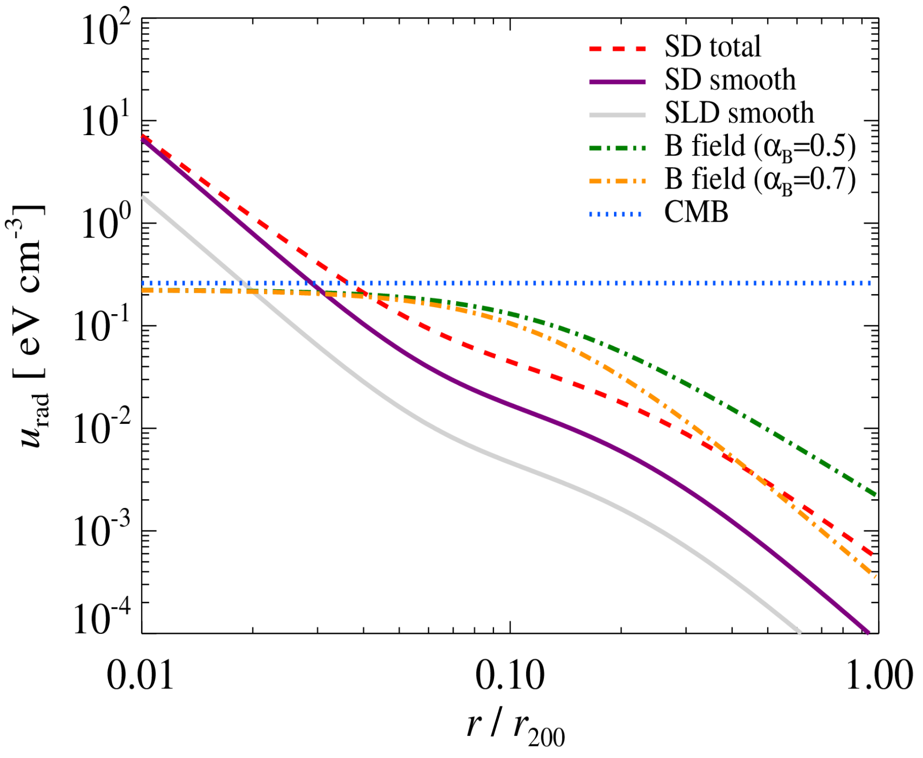


DM induced gamma-rays
– *supersymmetric benchmark models*

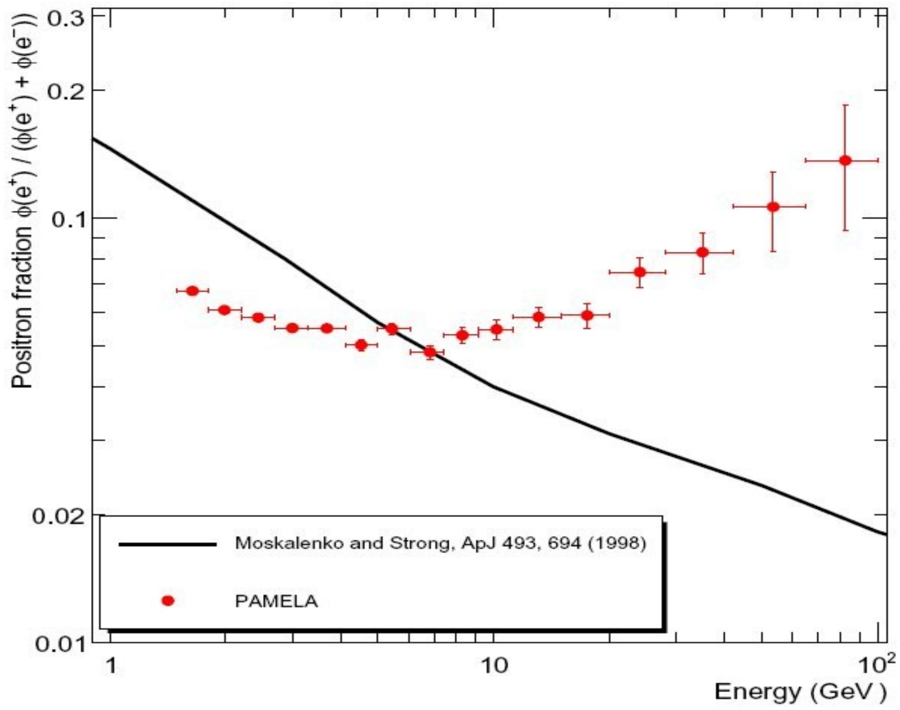
Representation of DM models with high gamma-ray emission.

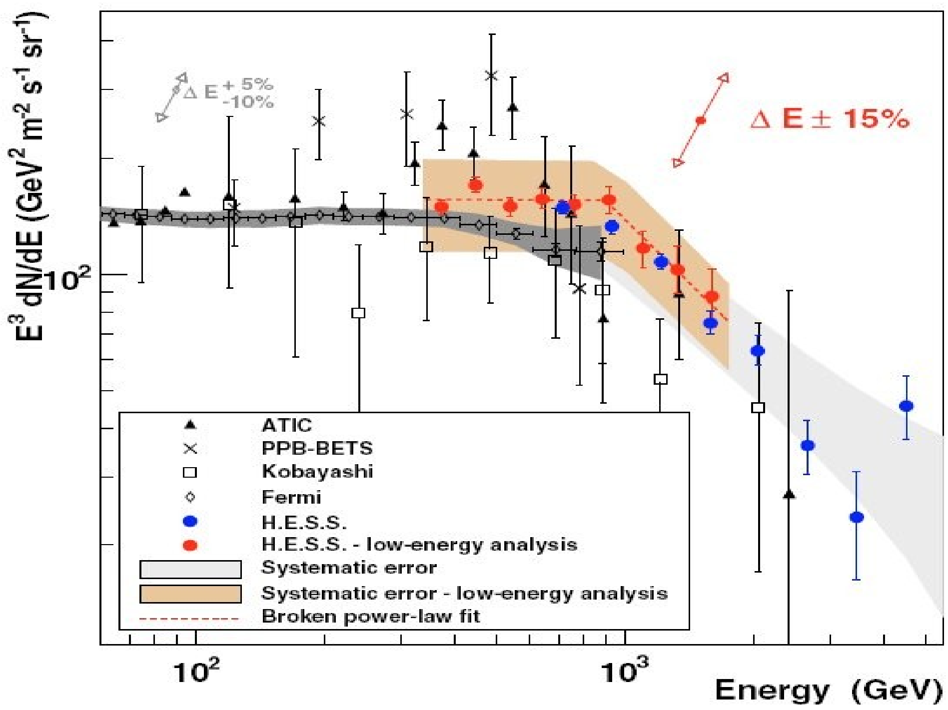
Luminosity boosted by substructures in the smooth DM halo.

Gamma-ray emission components:
- Annihilating neutrinos emitting continuum emission
- Final state radiation
- IC on background radiation fields (CMB, starlight and dust)



PAMELA and HESS data on electrons and positrons





PAMELA: *Adriani et al. 2009*

rasing positron fraction with energy

→ source accelerating e^+/e^- pairs

HESS: *Aharonian et al. 2009*

break in e^+/e^- spectrum

→ maximum energy of accelerating source or DM decaing