Prospects of detecting gamma-ray emission from galaxy clusters: cosmic rays and dark matter annihilations

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Collaborators: *C. Pfrommer, L. Bergström, F. Zandanel (Magic)*

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UCSB

Outline

Gamma-rays from cosmic rays and annihilating dark matter in clusters:

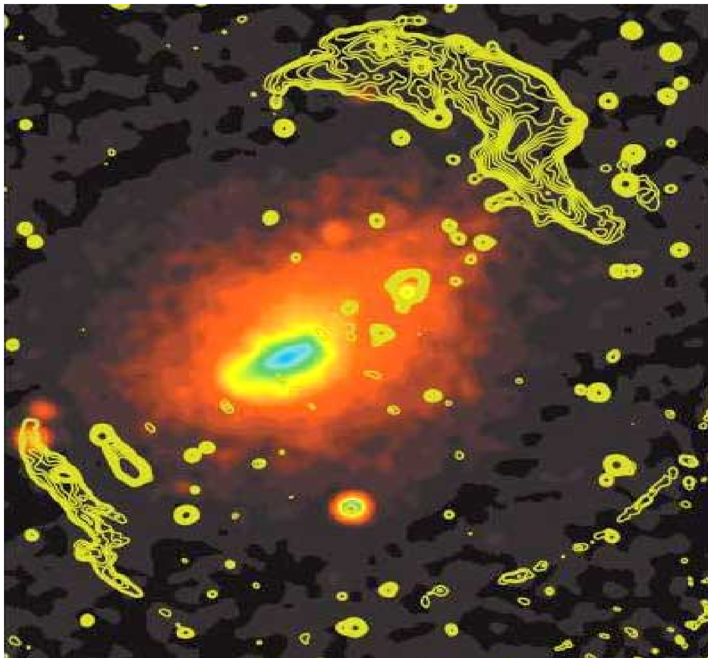
- **Introduction**
- **Tools for gamma-ray detection** (*Pinzke, Pfrommer, and Bergström 2011*)
  - *spectral properties*
  - *emission morphology*
  - *cluster selection*
- **Summary**

Prospects for detecting gamma-ray emission from clusters!
What can we learn from these observations?

Part 1

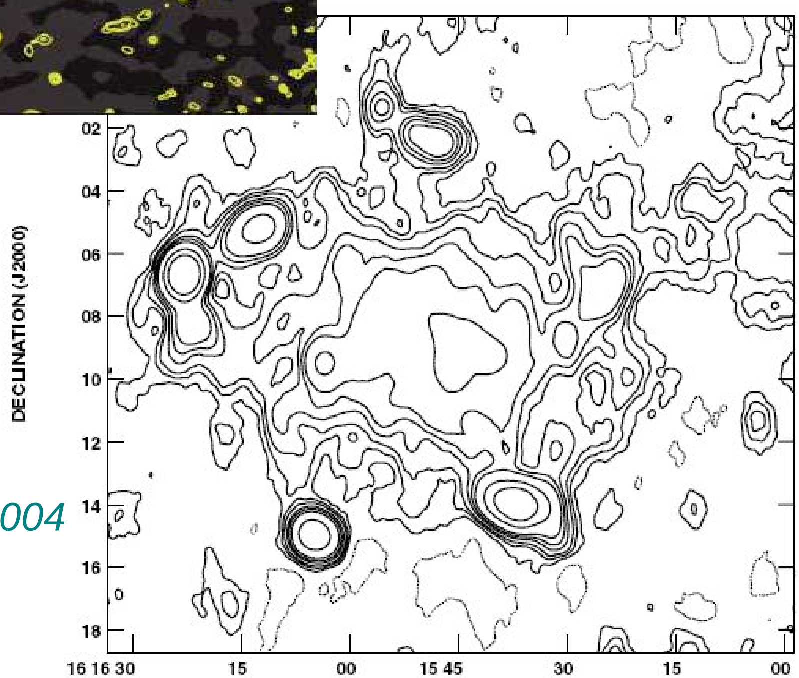
Cosmic ray induced gamma-ray emission

Signs of non-thermal activity in galaxy clusters



A 3667

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



A 2163

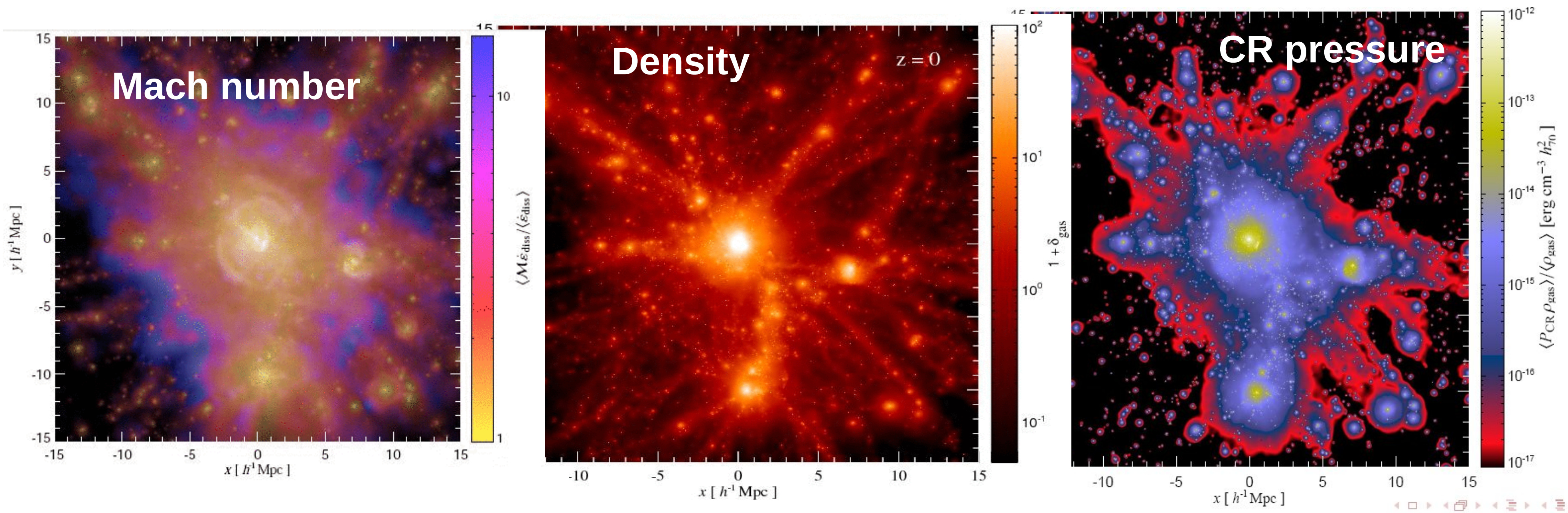
Radio: *Feretti at al, 2004*

Bullet Cluster

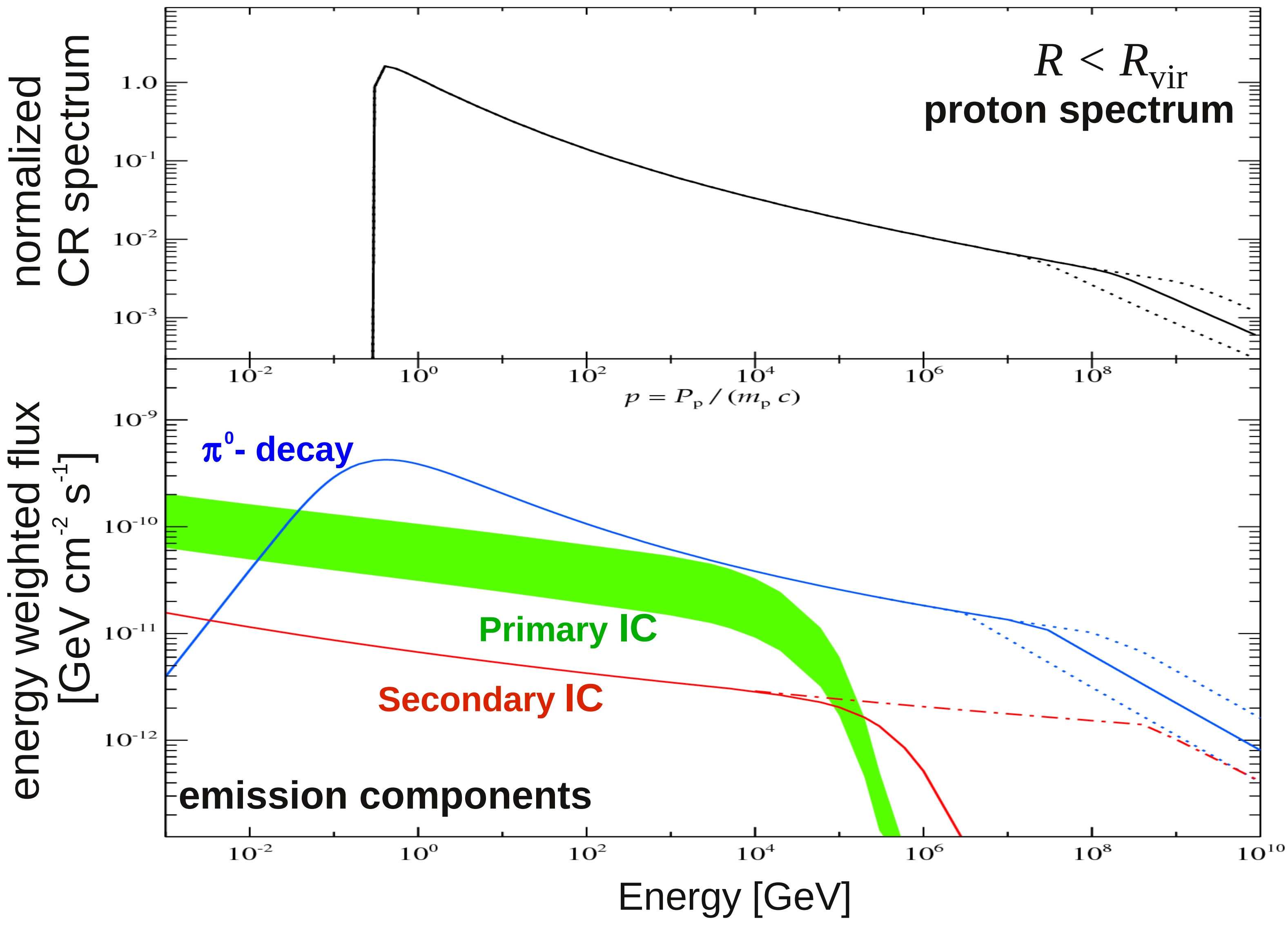
X-ray:*NASA/CXC/CfA/Markevitch et al.*;
Optical:*NASA/STScI;Magellan/U.Arizona /Clowe et al.;* **Lensing:***NASA/STScI; ESO WFI; Magellan/U.Arizona/Clowe et al.*

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*

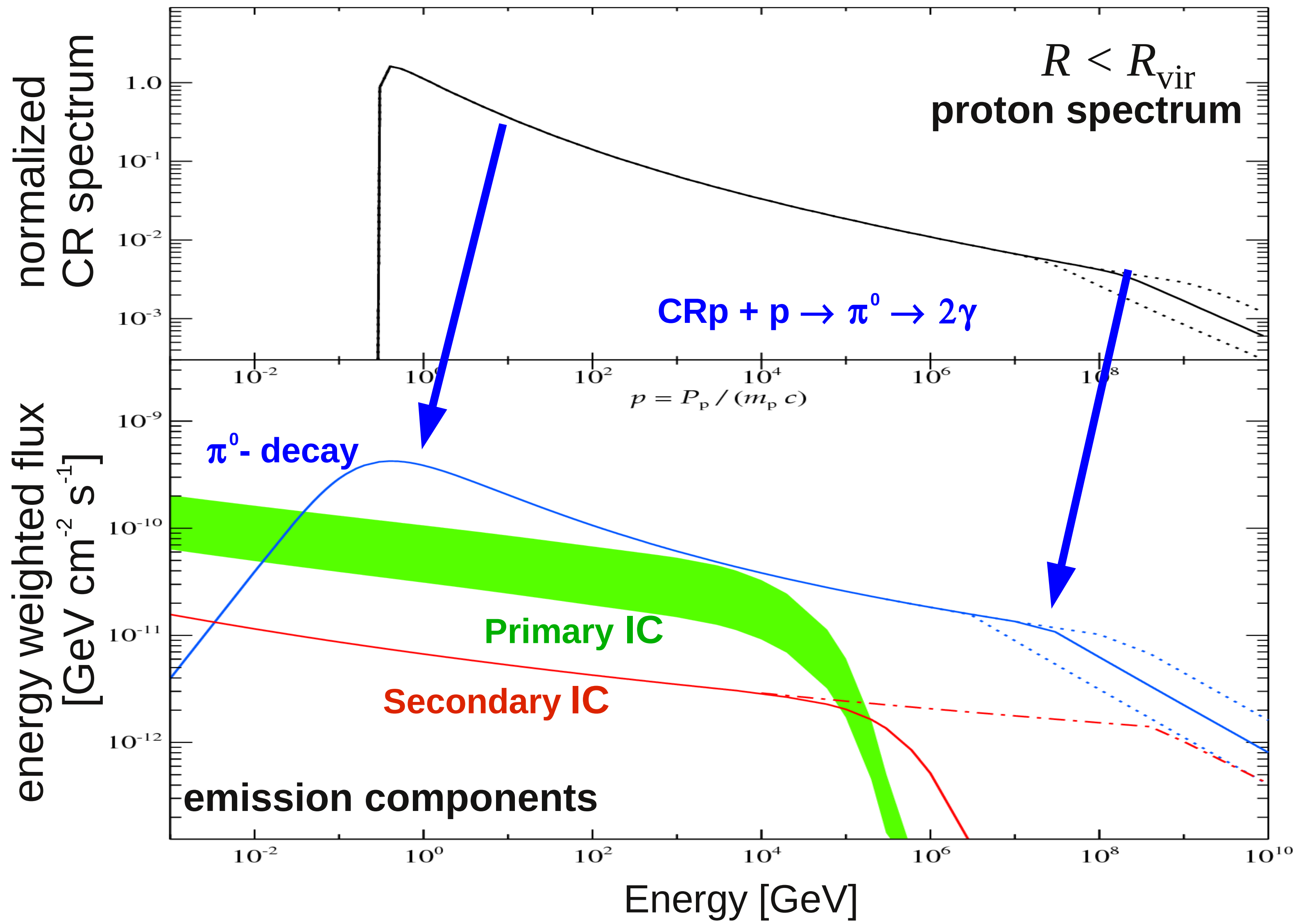


CR proton/gamma-ray spectra



Pinzke, Pfrommer 2010

CR proton/gamma-ray spectra



Pinzke, Pfrommer 2010

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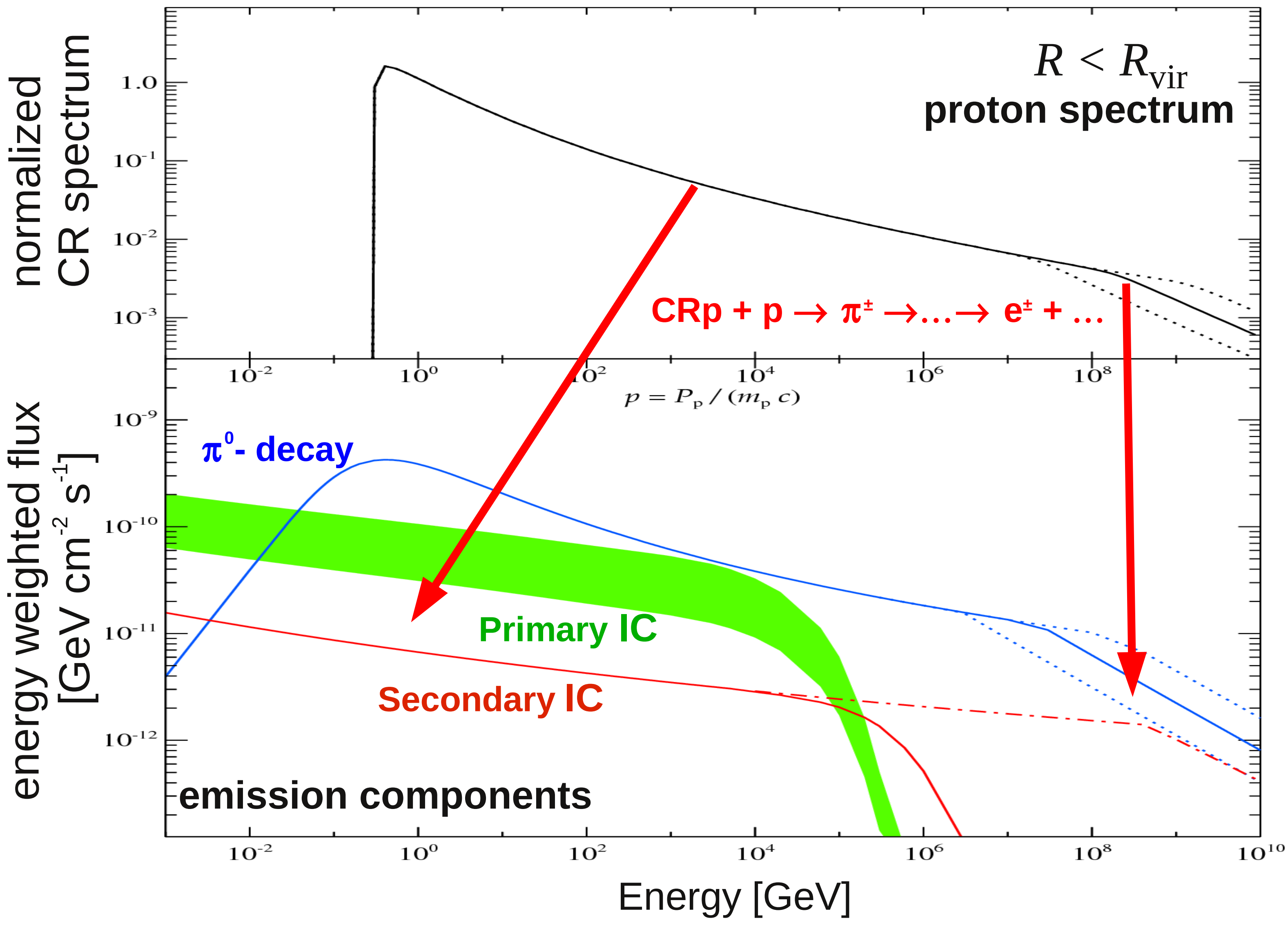
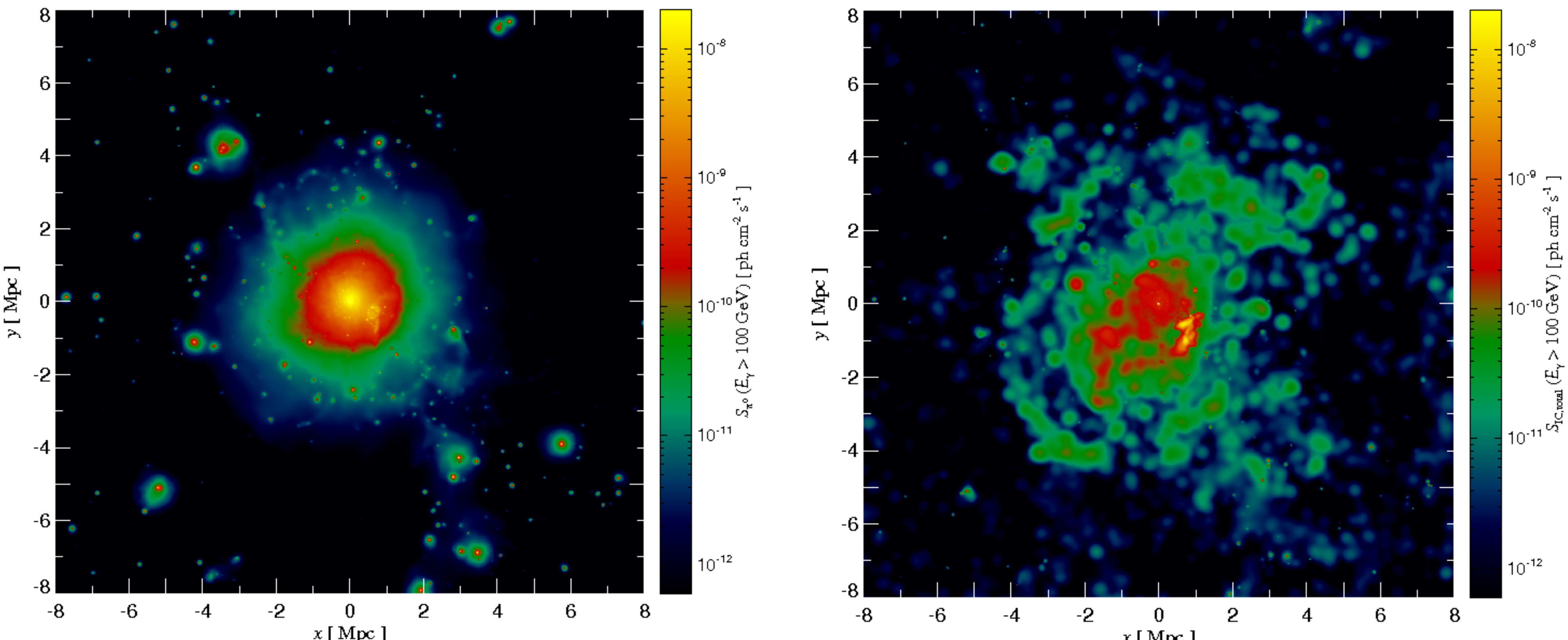


Pinzke, Pfrommer 2010

Surface brightness for E > 100 GeV

Pion decay induced emission | **Total inverse Compton emission**

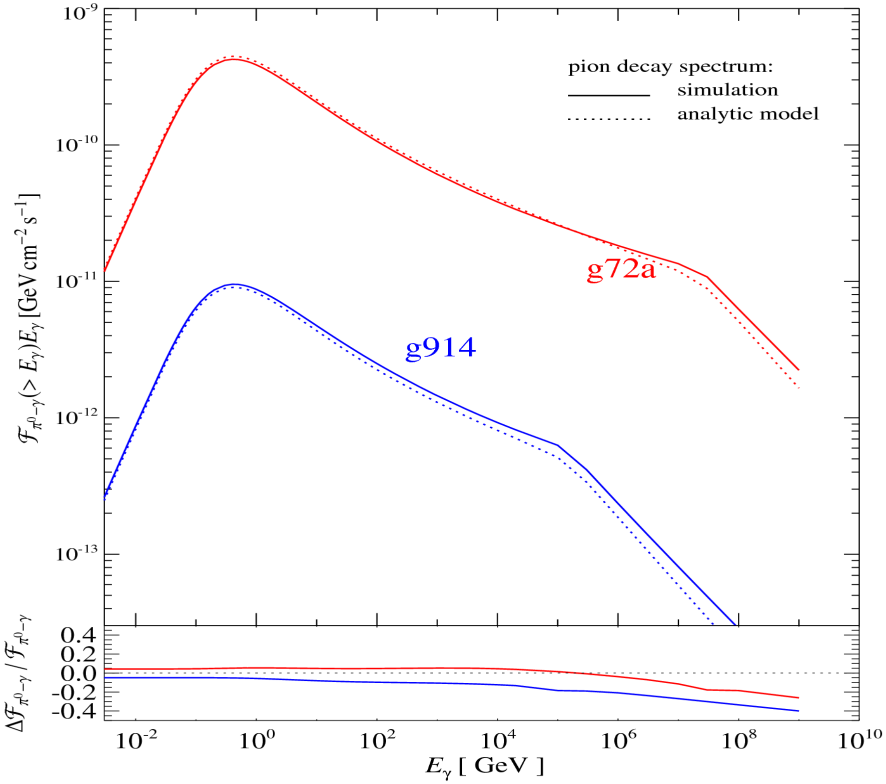


Pinzke, Pfrommer 2010

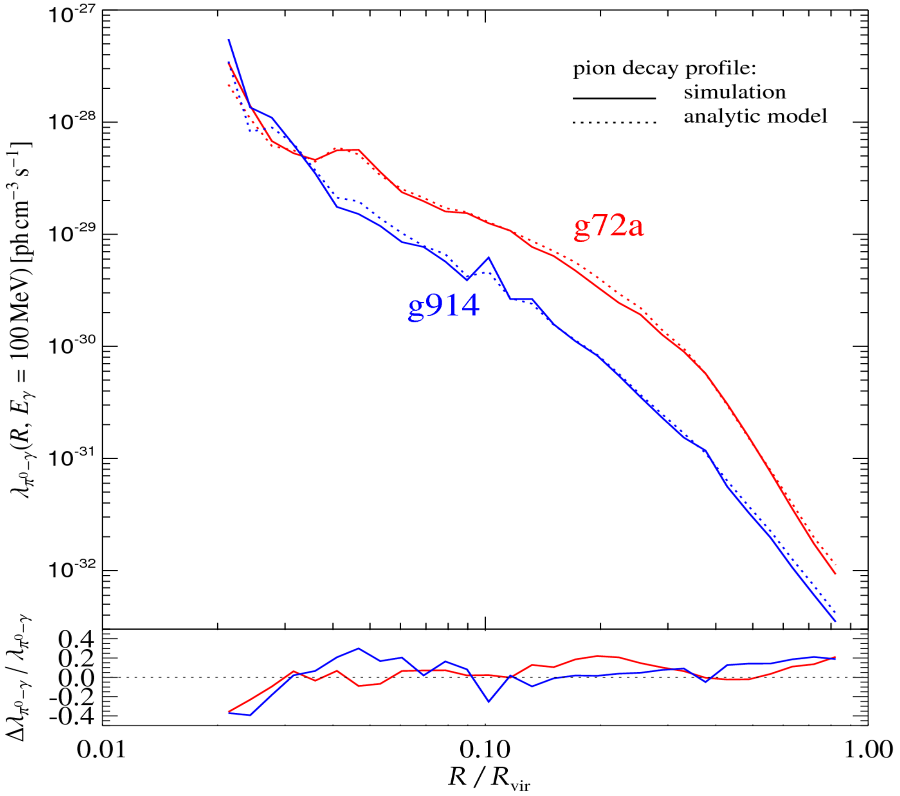
- Pion decay gamma-rays dominate inside virial radius
- The strong magnetic field in the center suppress inverse Compton due to CRs cooling through synchrotron radiation
- Primary inverse Compton contribute substantially in the cluster periphery

Test of analytic gamma-ray model

Spectral comparison



Spatial comparison

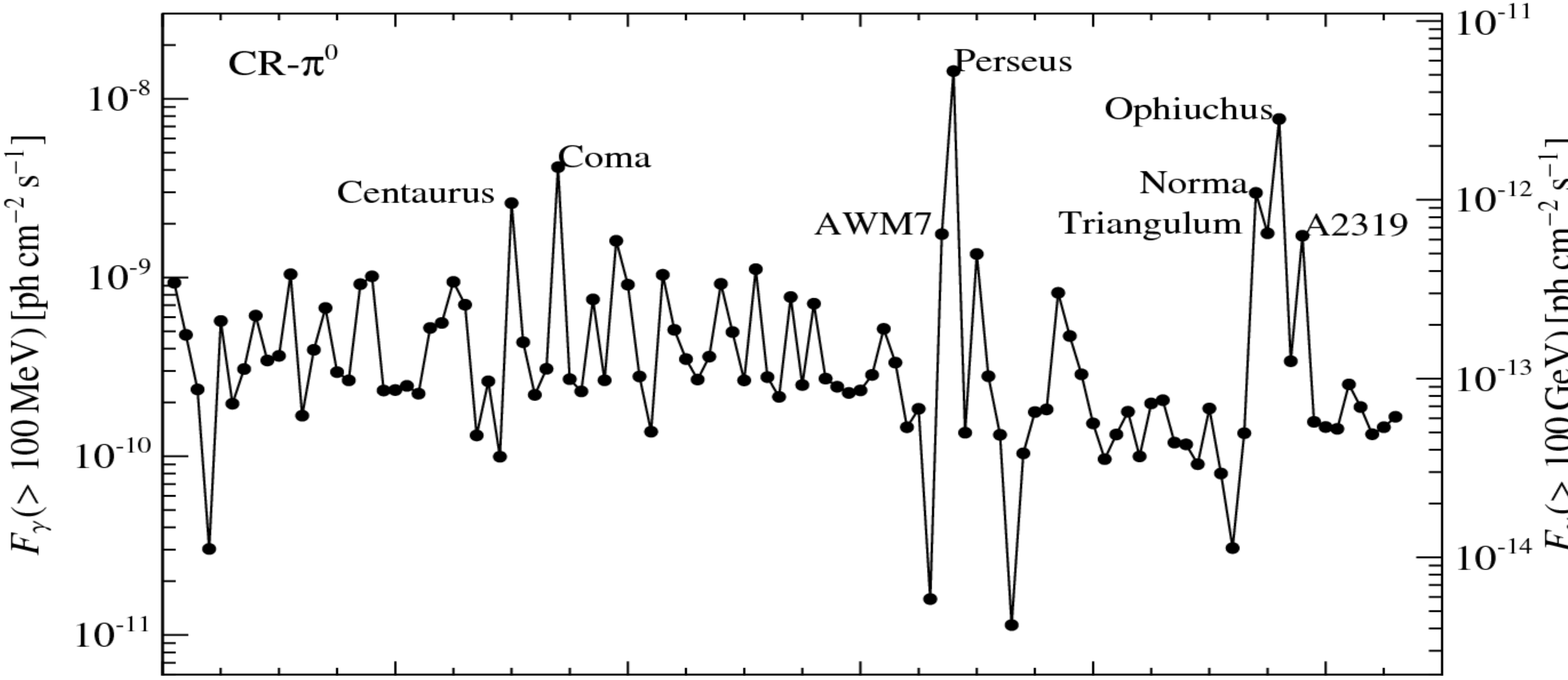


Pinzke, Pfrommer 2010

Very good agreement between analytic model and simulations

Gamma-ray flux predictions

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



Pinzke, et al. 2011

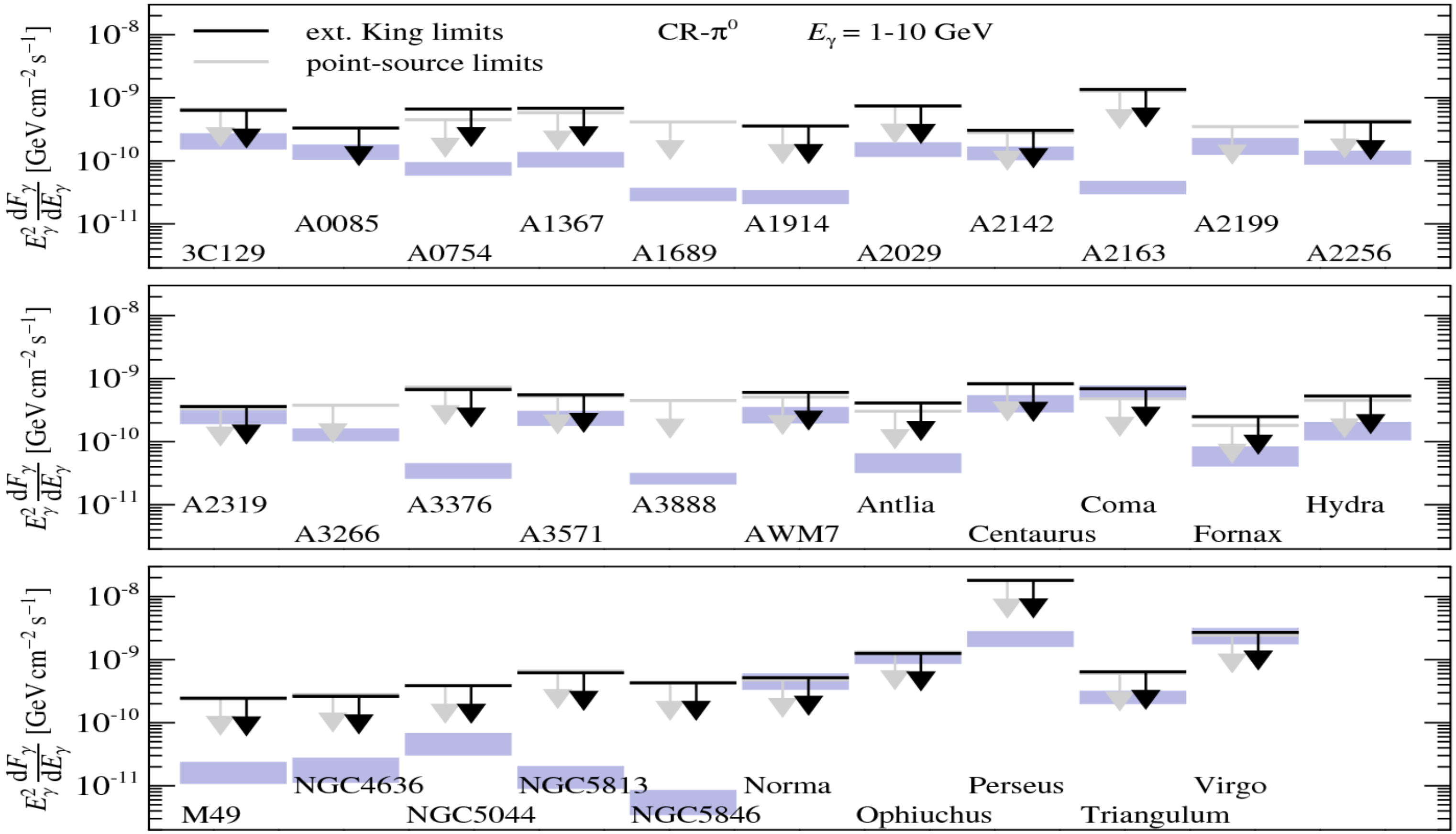
Using gamma-ray mass-luminosity scaling relations on the sample of the brightest 107 X-ray clusters (extended HIFLUGCS)

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

Brightest cluster in gamma-rays!

Flux predictions vs. observations

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

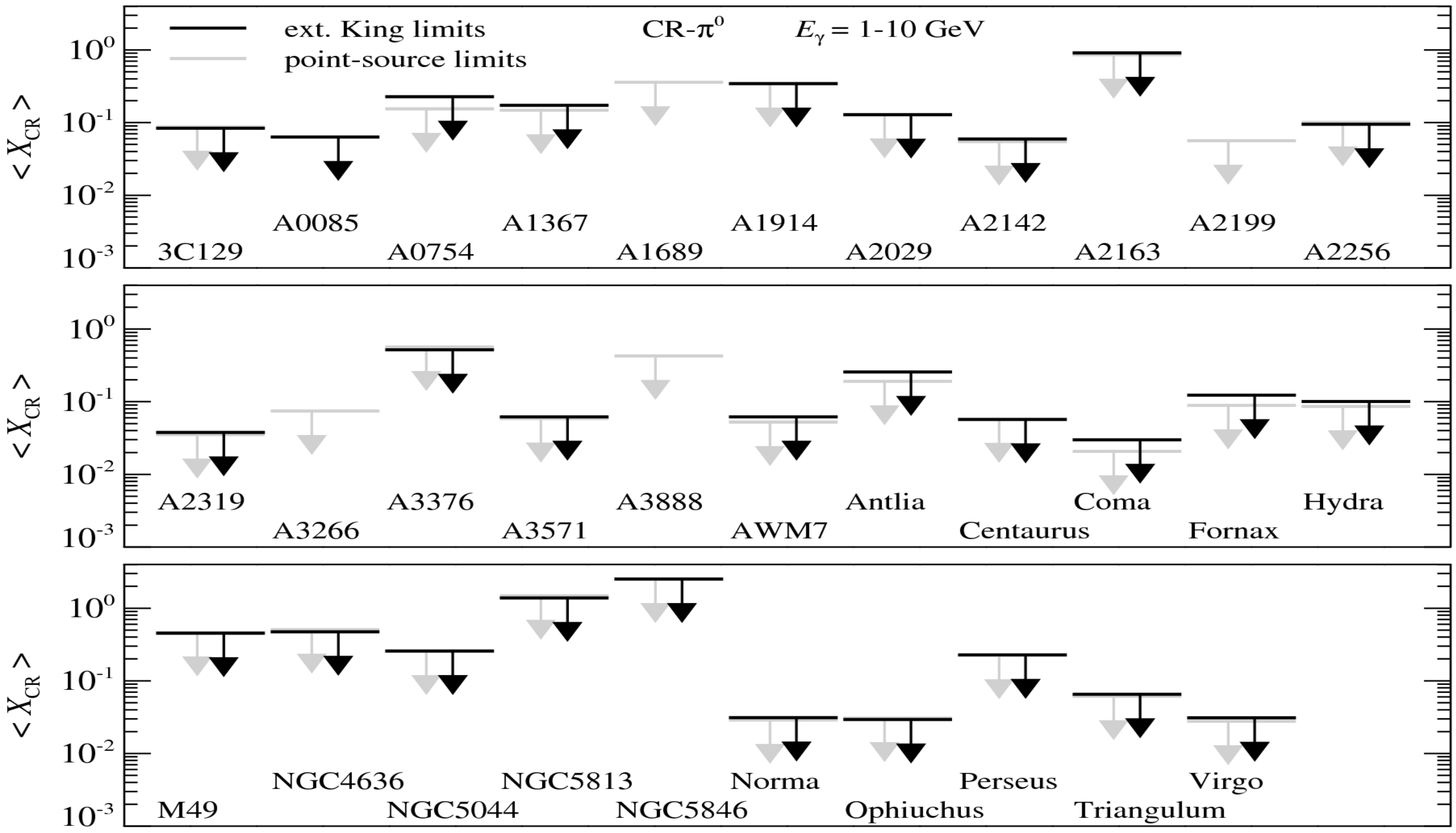


Pinzke et al. 2011

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

Constrain relative CR pressure $X_{CR}=P_{CR}/P_{th}$ using the Fermi-LAT 18 month upper limits. The best limits are found in Norma, Coma, Ophiuchus, A2319 (and Virgo) of the order few percent, with typical limits around 10%.

Magic-Perseus slide removed

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. Coming year will start constraining shock- and CR-physics, as well as magnetic fields.
- **MAGIC** observations of *Perseus* constrain the cosmic ray-to-thermal pressure to few percent and starts constraining NT physics.

Part 2

Gamma-rays from annihilating dark matter

Why search for DM in galaxy clusters?

Clusters of galaxies are the most massive virialized objects in the universe.

$$L_{\rm sm} \sim \int \mathrm{d}V \rho^2 \sim \frac{M_{200}\, c^3}{[\log(1+c) - c/(1+c)]^2} \sim M_{200}^{0.75}$$

Maccio et al. 2008

$$\frac{F_{\rm cluster}}{F_{\rm dwarf}} \simeq \left(\frac{80\,\mathrm{kpc}}{17\,\mathrm{Mpc}}\right)^2 \left(\frac{2 \times 10^{14}\,\mathrm{M}_\odot}{10^8\,\mathrm{M}_\odot}\right)^{0.75} \simeq 1$$

Pinzke, Pfrommer, and Bergström 2009

The large mass of clusters compensates for the larger distances.

The experimental challenge is the larger angular extent of clusters.

DM induced gamma-rays

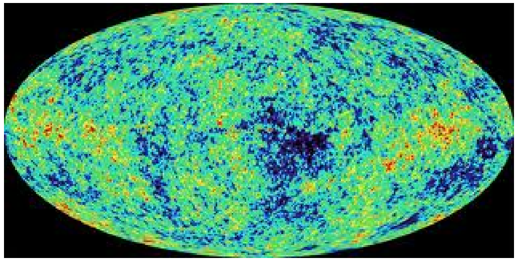
– supersymmetric benchmark models

Representation of DM models with high gamma-ray emission.

Luminosity boosted by substructures in the smooth DM halo.

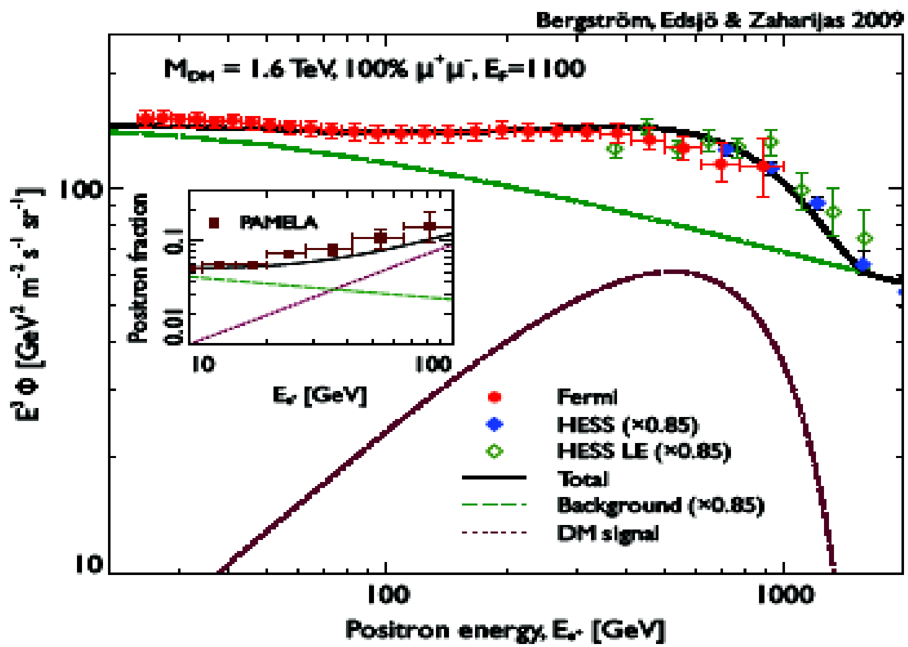
Gamma-ray emission components:

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



DM induced gamma-rays
– leptophilic models

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



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

Gamma-ray emission components:

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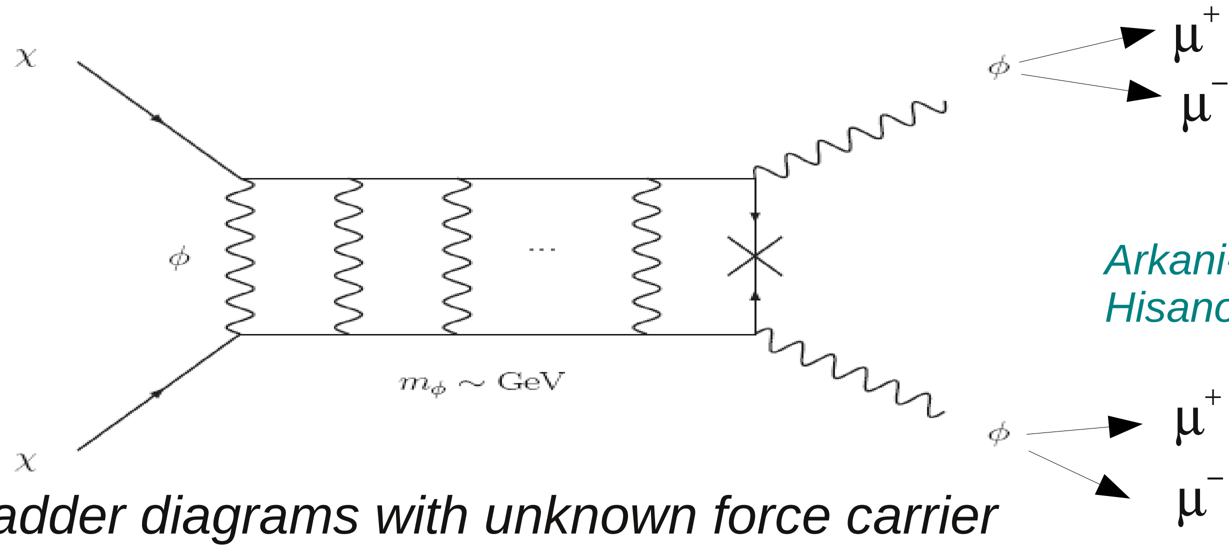
Boost Factors

Sommerfeld enhancement



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

ladder diagrams with unknown force carrier

$$\langle\sigma v\rangle \approx \langle\sigma v\rangle_0 \times (c/v)$$
$$v = 960 \text{ km/s} \times (M_{200}/10^{15}\ M_\odot)^{1/3}$$
$$\Downarrow$$

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

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

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

Boost Factors

Dark matter substructure

Springel et al., 2008

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

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

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, Stöcker 2008
Green, Hofmann, Schwarz 2005

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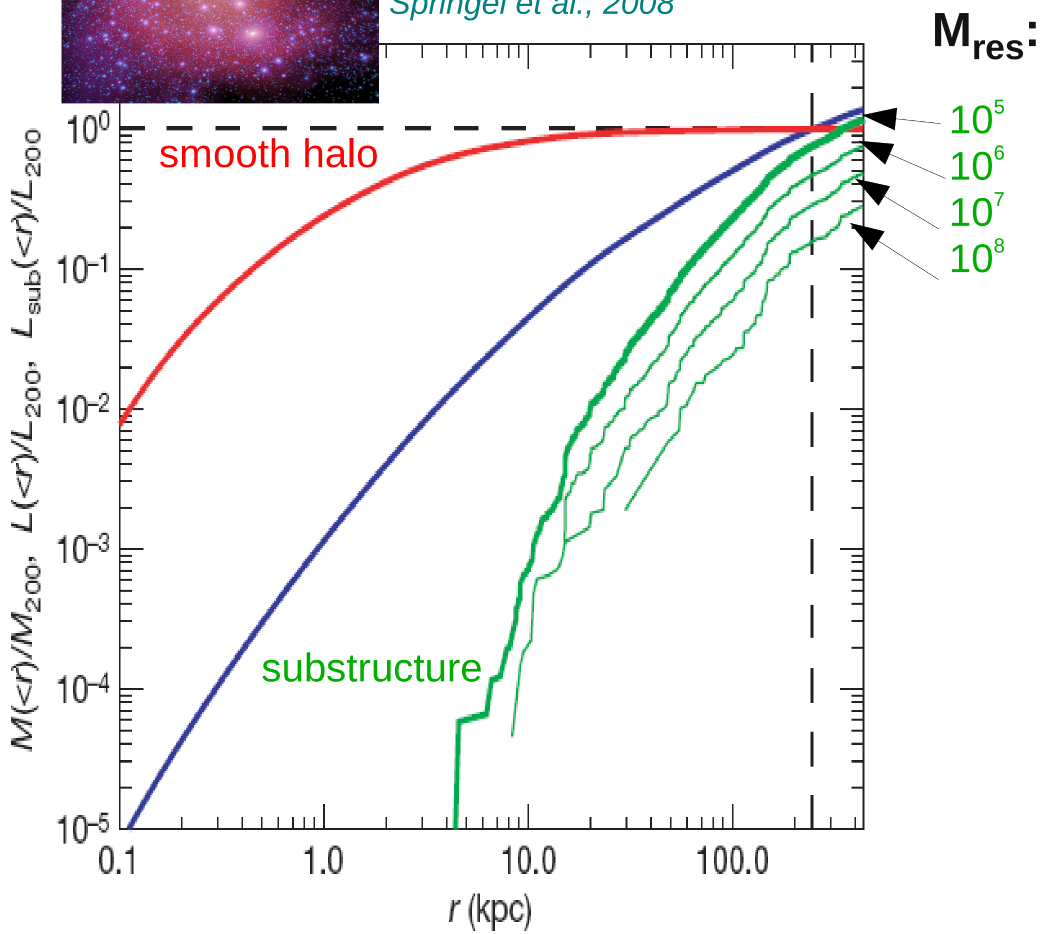

See talk by C. Frenk

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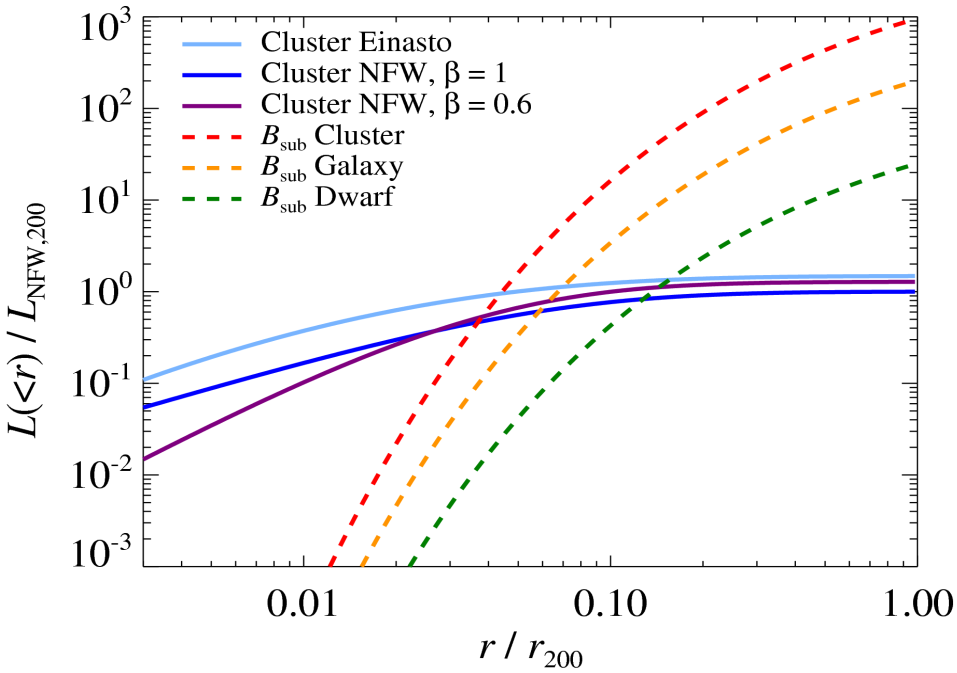
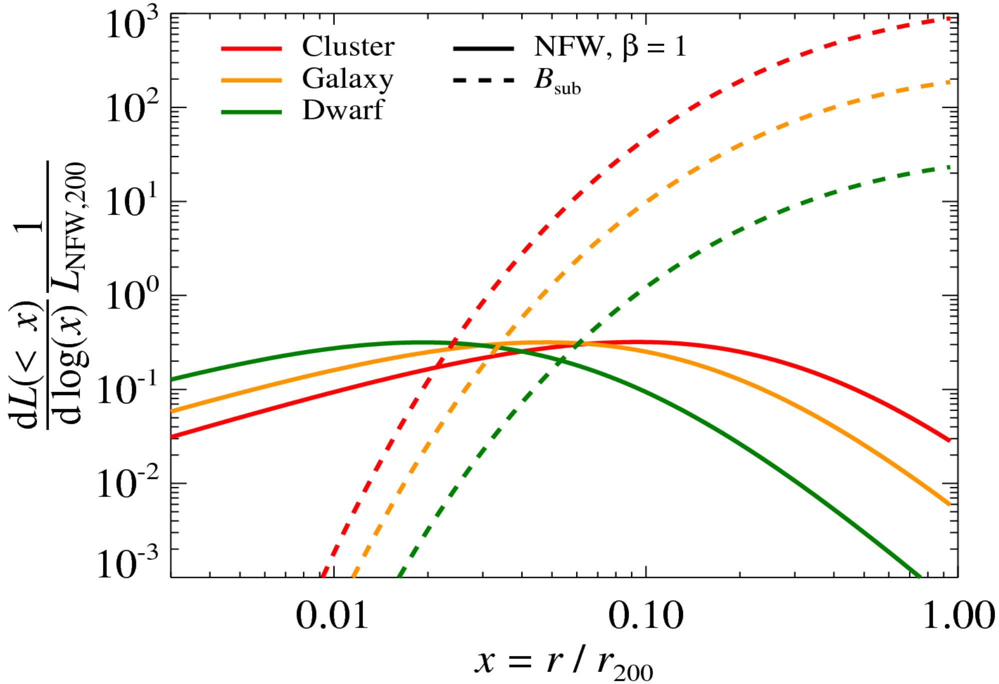
Green, Hofmann and Schwarz, 2005

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

Luminosity boosted by ~1000 in clusters

Spatial distribution of DM



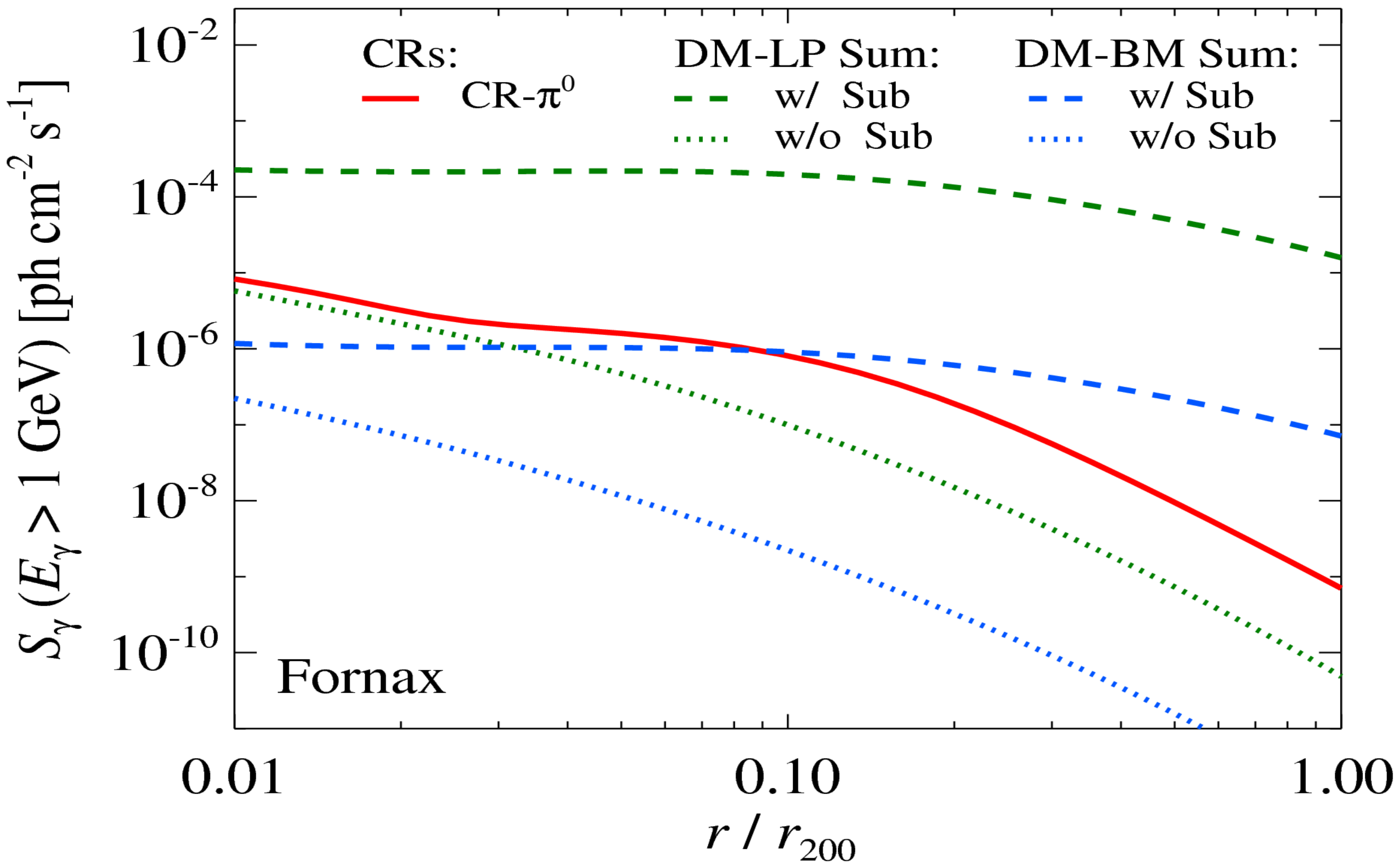


- Choice of smooth density profile minor impact on annihilation luminosity outside center.
- Large boost from substructures in clusters (~1000), and relative small in dwarf galaxies (~20).
- Majority of flux from smooth halo delivered by region around r_s / 3.
- Emission from substructures dominated by outer regions.

Spatially extended!

→ challenging for IACTs

Spatial contribution from substructures

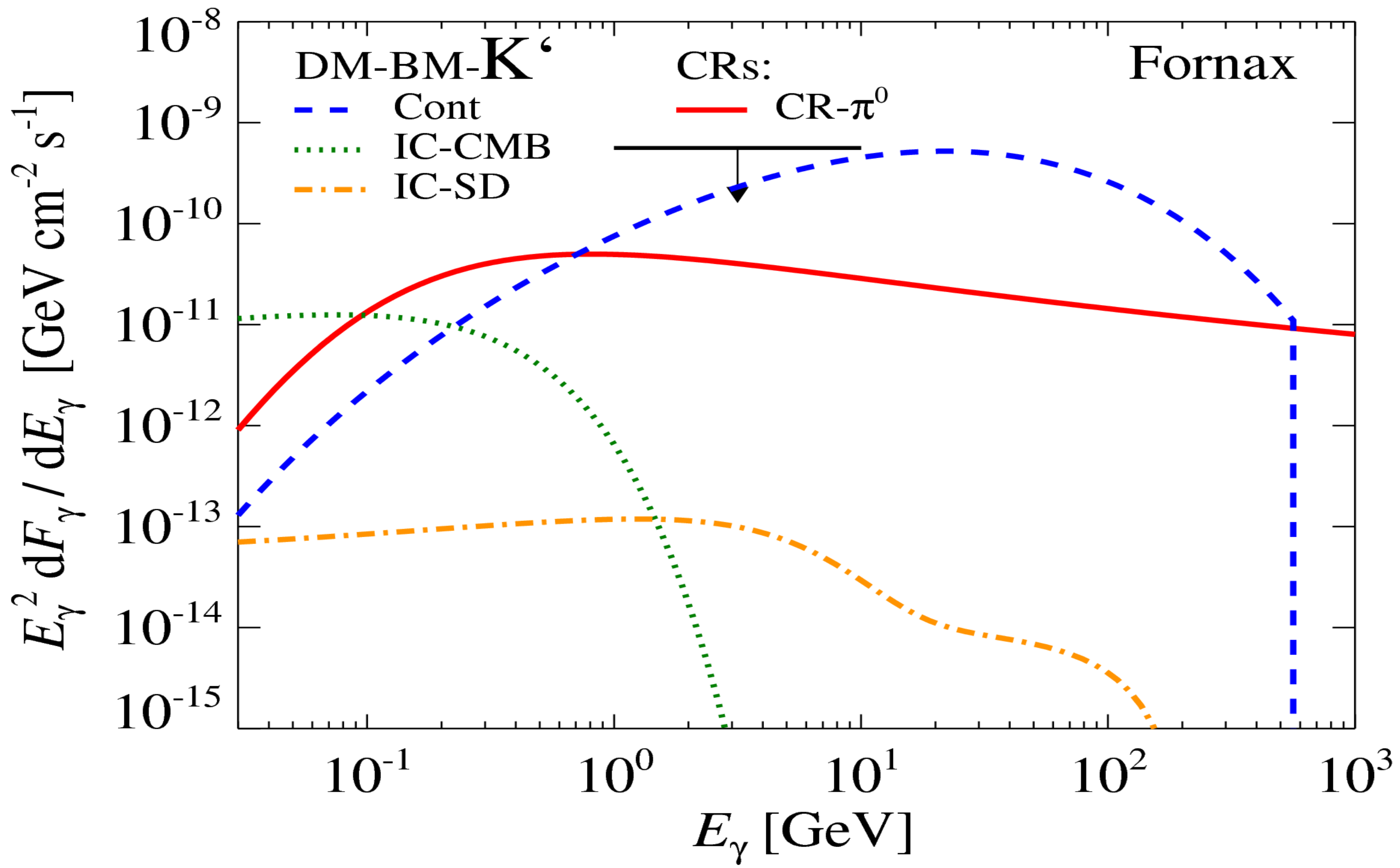


Pinzke et al. 2011

Gamma-rays from DM extends out to the virial radius, while CR induced emission suppressed in the outer parts.

DM substructures flattens DM surface brightness profiles as well as boost the brightness in the center due to line of sight effects.

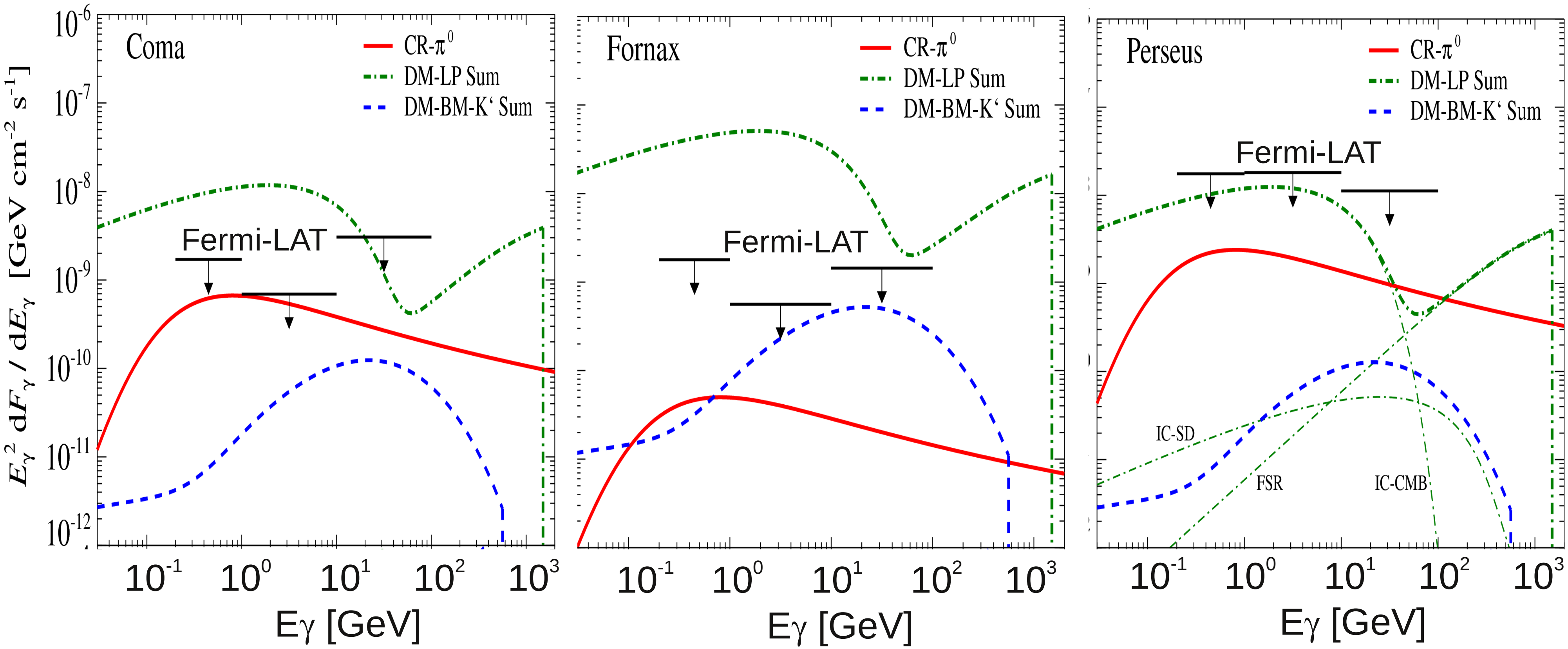
Gamma-ray spectrum from DM vs. CR interactions



Pinzke et al., 2011

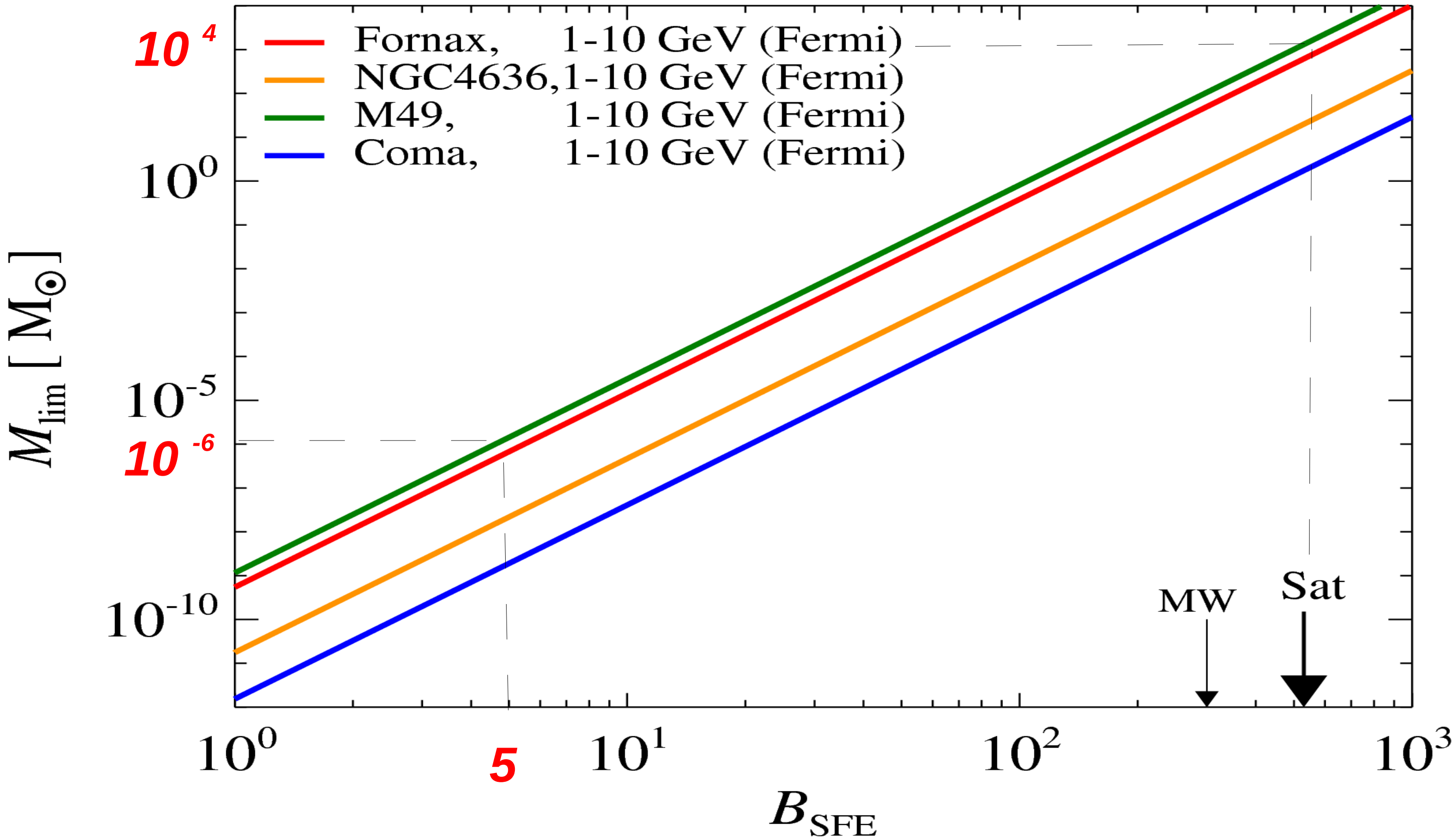
Continuum emission dominates over upscattered starlight and dust (SD). Below GeV energies upscattered CMB dominates DM contribution, however at these energies CR induced emission is expected to dominate.

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.
- The very high CR induced emission in **Perseus** better probed by Cherenkov telescopes due to the central active galaxy NGC 1275.

Constraining boost factors

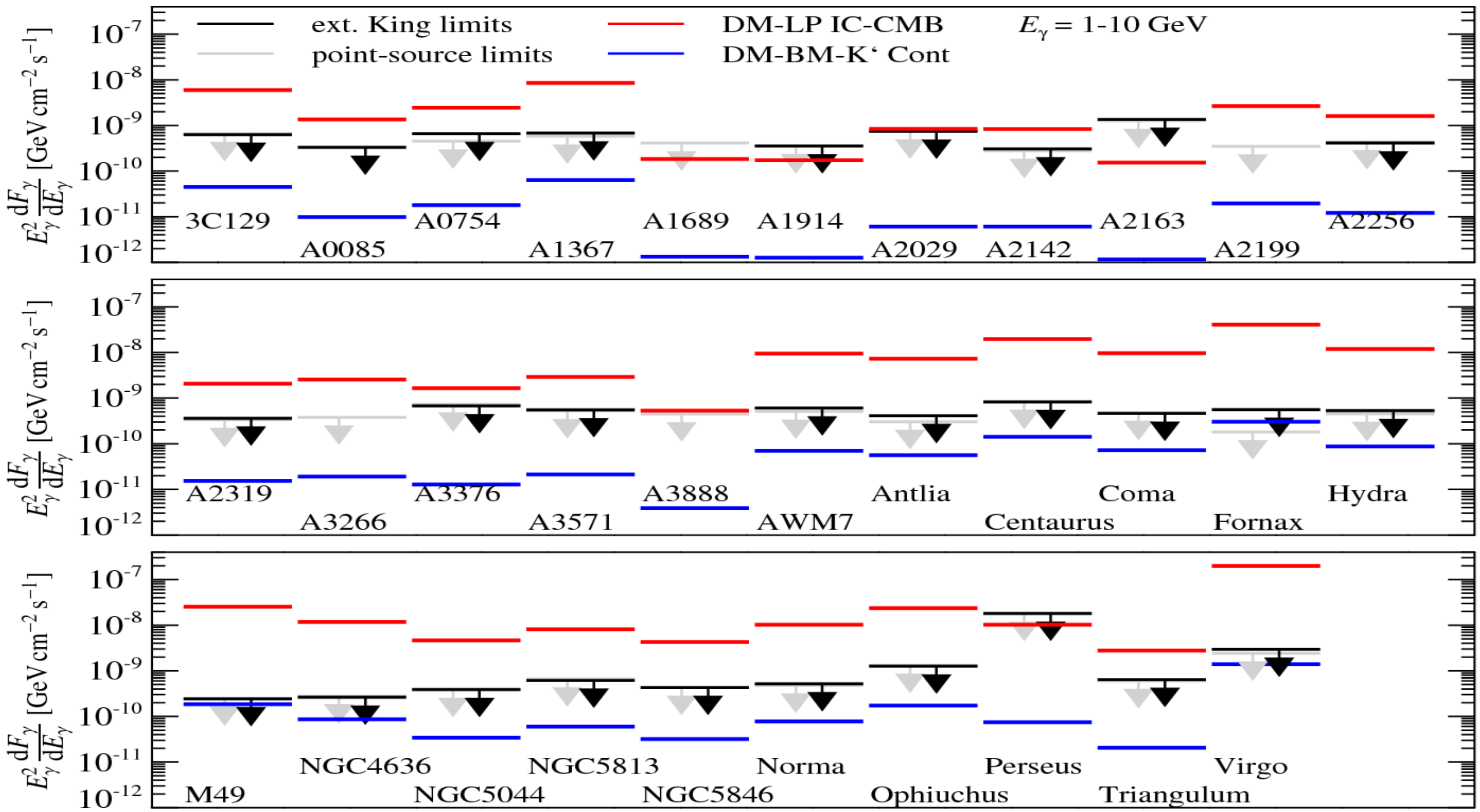


Pinzke et al. 2011

- 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 $M_{\rm lim} > 10^4 M_\odot$ – a challenge for structure formation.

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).

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 $> 10^4 M_{\odot}$.

Future- need to go one step further:

Stacked cluster analysis with Fermi-LAT

-) Improve limits by a factor few

-) "Easy" to separate characteristic pion decay spectra and peculiar DM models from background

-) Bias from time varying sources such as AGNs

Long exposure time of a single cluster with a single IACT

-) sensitive gamma-ray probes

-) problem of AGNs softened

-) hard to get a lot of time

Combining observations of single cluster with different IACTs

-) most sensitive gamma-ray probe

-) technical and political difficulties

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