Searching for Dark Matter with Gamma-Ray and X-ray Observations of Clusters

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Gamma-ray Space Telescope

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Outline

- Signals from dark matter

- Limits on dark matter models from Fermi gamma-ray observations of clusters
(first year and more recent results)

- Can we constrain dark matter with X-ray observations?

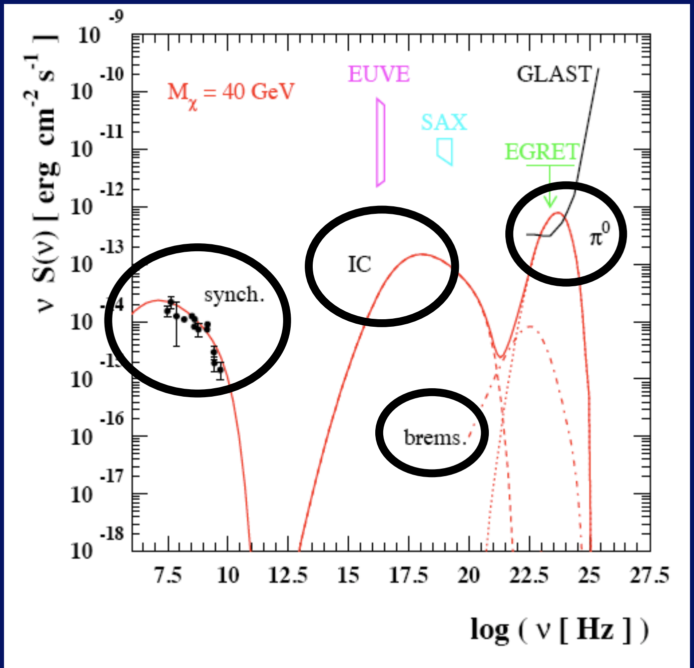
- Cosmic rays in clusters – limits from Fermi

Observing Dark Matter

➢ Dark matter can annihilate or decay to Standard Model particles potentially giving observables signatures.

➢ Dark matter annihilation/decay can lead to a broad spectrum of emission.

Gamma-ray: π^0 decay, direct production
X-ray: IC scattering of CMB by energetic e^+e^- produced
radio: synchrotron emission



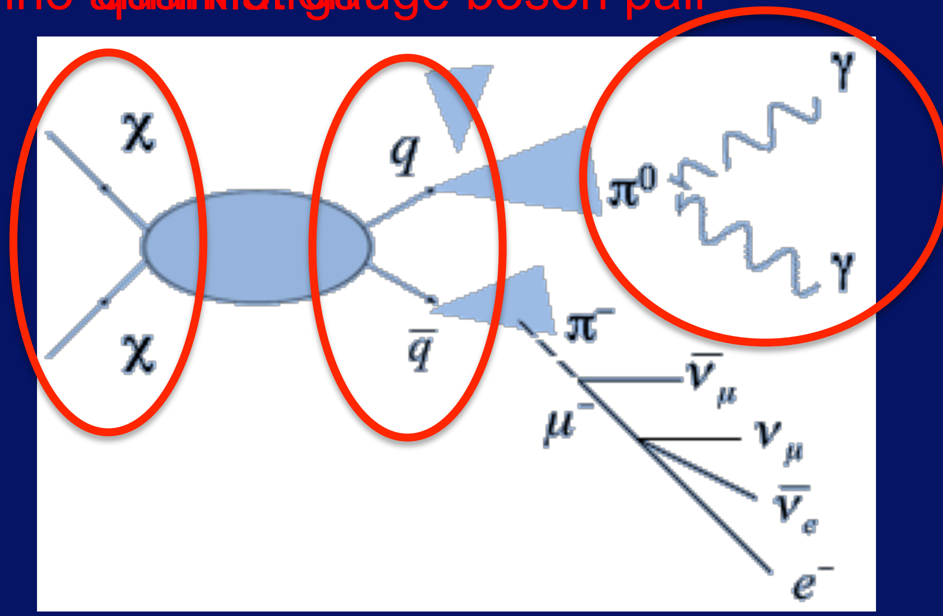
Example spectrum of DM annihilation in the Coma cluster (Colafrancesco et al. 2006)

Gamma Rays from Dark Matter Annihilation

π^0 decay to γ

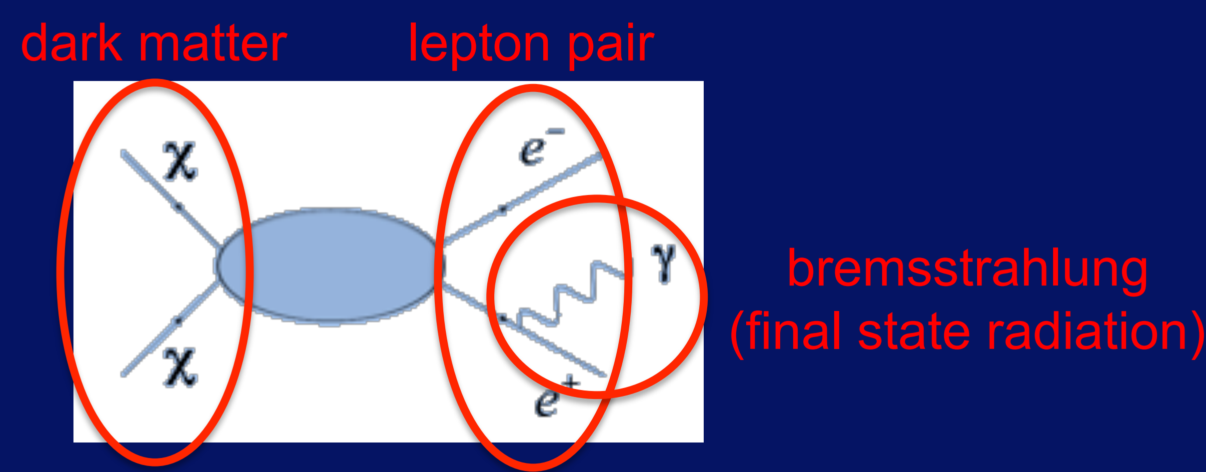
neutralino annihilation

quark or gauge boson pair



Secondary gamma rays from π_0 decays

Gamma Rays from Dark Matter Annihilation



Lepton pair production

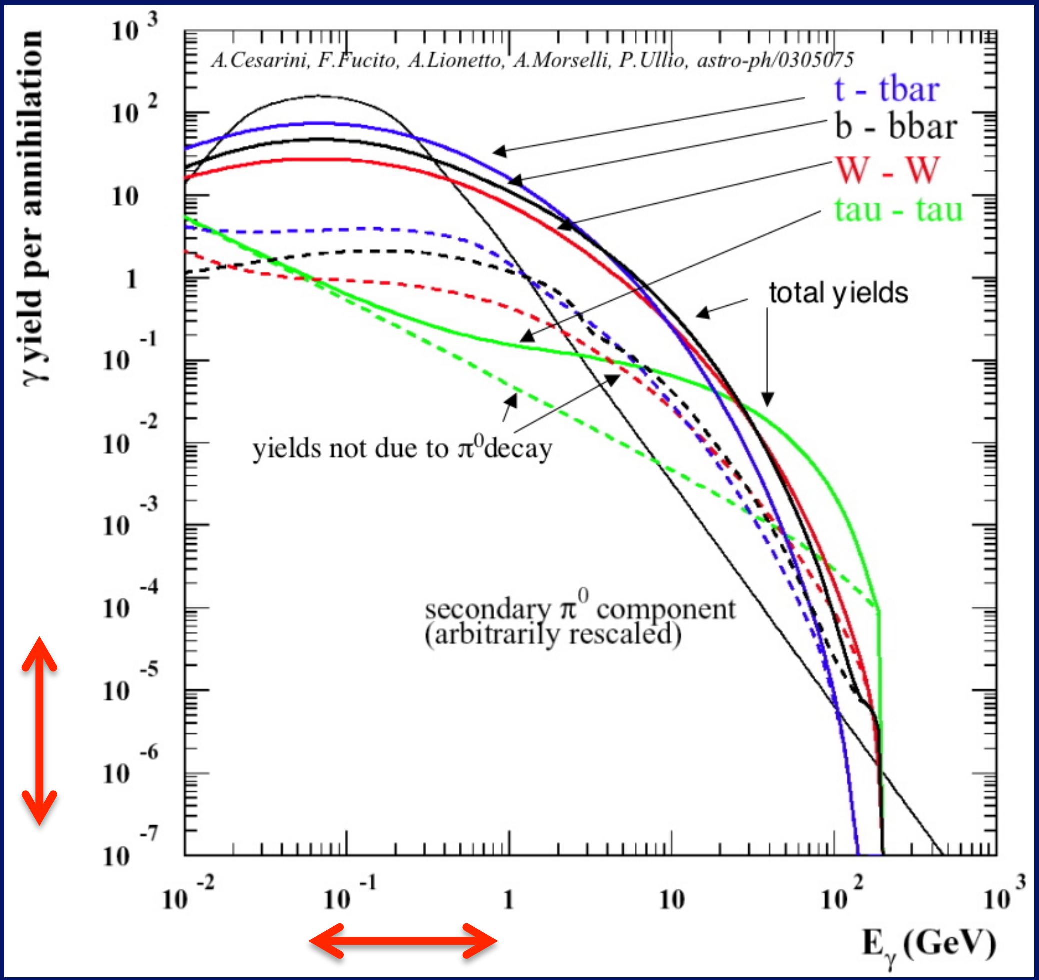
("leptophilic", not typical for neutralino annihilation, but popular as an explanation of the PAMELA positron excess)

Gamma-ray Spectrum

Gamma-ray yield for a 200 GeV WIMP

- cutoff at WIMP mass
- quark and gauge boson final states give similar spectra

DM density distribution
annihilation cross-section



particle mass
final state

Signal from Dark Matter

$$\Phi_{WIMP}(E,\Psi) = J(\Psi) \times \Phi^{PP}(E)$$

Astrophysical factor

$$J(\Psi) = \int_{l.o.s} dl(\Psi)\,\rho^2(l)$$

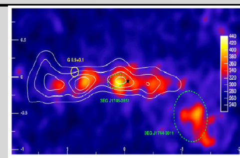
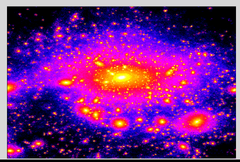
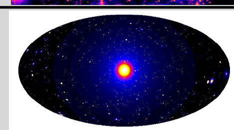
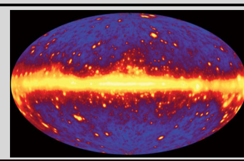
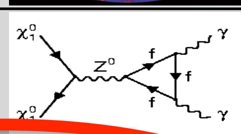
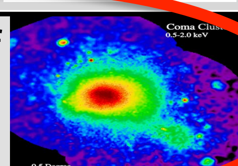
Particle physics factor

$$\Phi^{PP}(E) = \frac{1}{2}\frac{\langle \sigma v \rangle}{m^2_{WIMP}} \sum_f \frac{dN_f}{dE} B_f$$

depends on DM density distribution in a given object

depends on pair annihilation cross-section, particle mass, and final state

Indirect Dark Matter Searches

Search Technique	advantages	challenges
Galactic center 	Good Statistics	Source confusion/Diffuse background
Satellites, Subhalos 	Low background, Good source id	Low statistics
Milky Way halo 	Large statistics	Galactic diffuse background
Extra-galactic 	Large Statistics	Astrophysics, galactic diffuse background
Spectral lines 	No astrophysical uncertainties, good source id	Low statistics
Clusters of Galaxies 	Low background, Good source id	Low statistics

Clusters for Dark Matter Searches

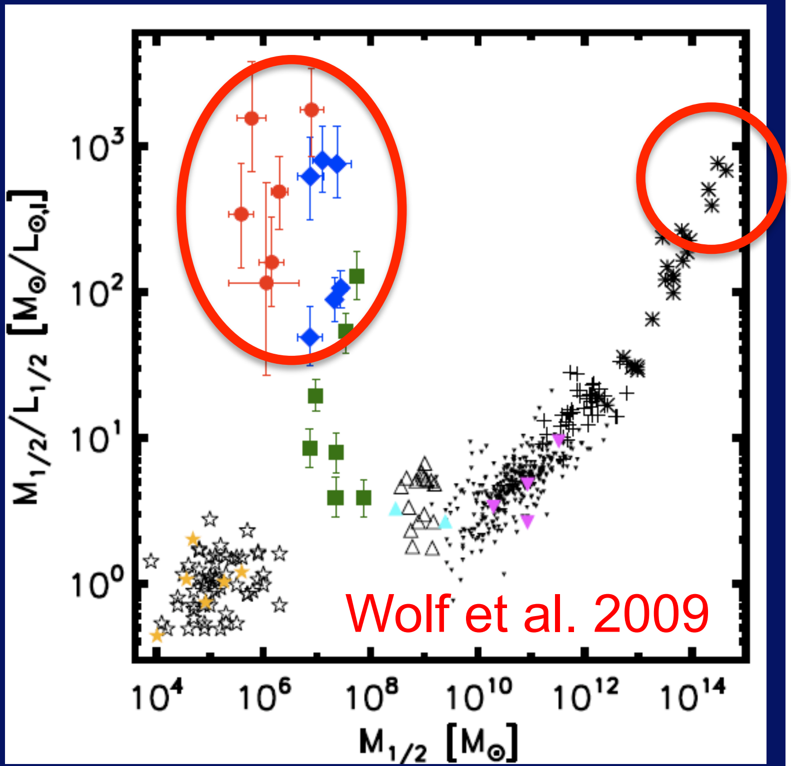
Clusters of galaxies are:

➢ The most massive collapsed objects and dark matter dominated

➢ Isolated and many lie in regions of low gamma-ray backgrounds

(similar to dwarf spheroidal galaxies)

dwarfs clusters

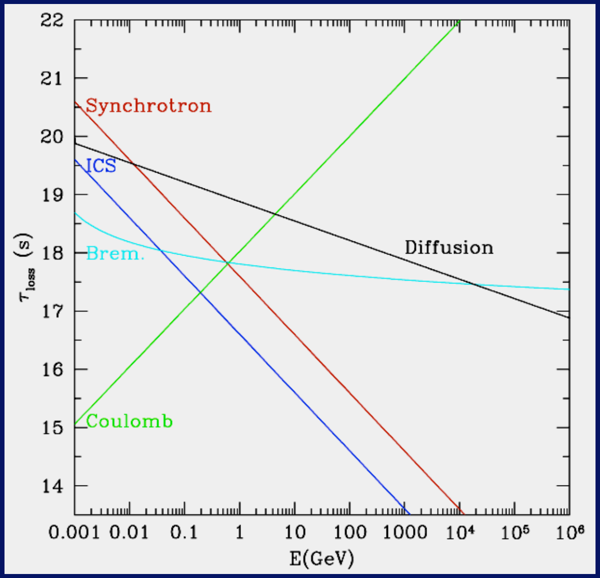


Clusters for Dark Matter Searches

Clusters are particularly powerful for constraining:

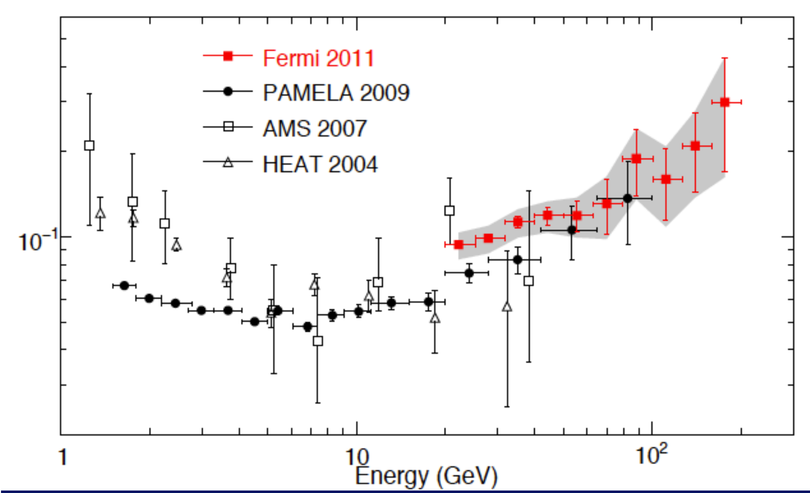
1. dark matter decay
2. leptophilic dark matter when IC emission dominates

(Diffusion of e^+e^- not important, because the energy loss timescale via IC scattering is much shorter than the diffusion time)

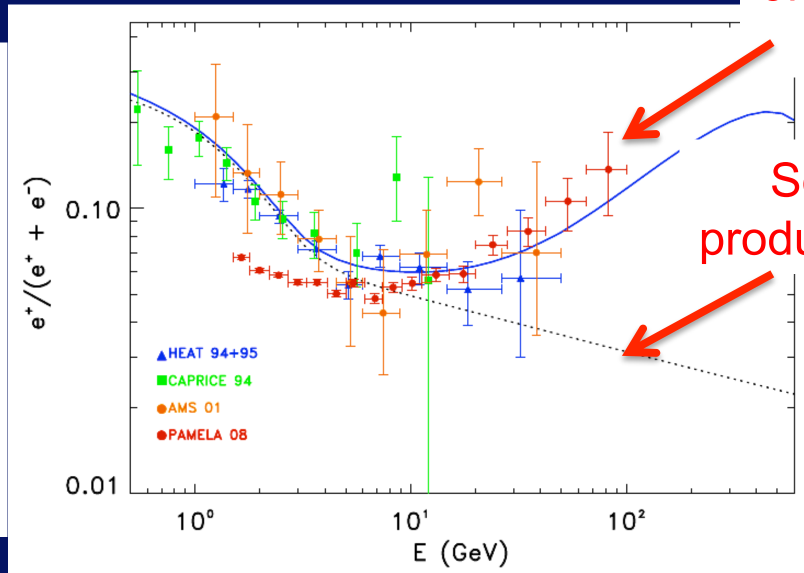


Colafrancesco et al. 2006

The Positron Excess



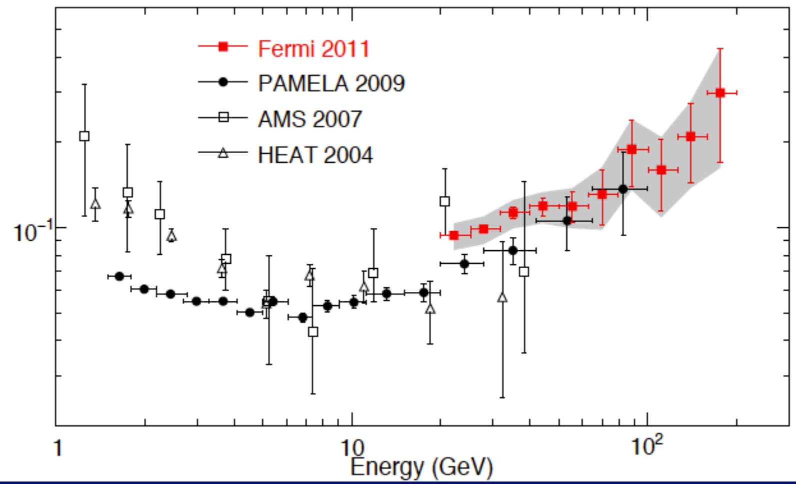
Ackermann et al. 2011



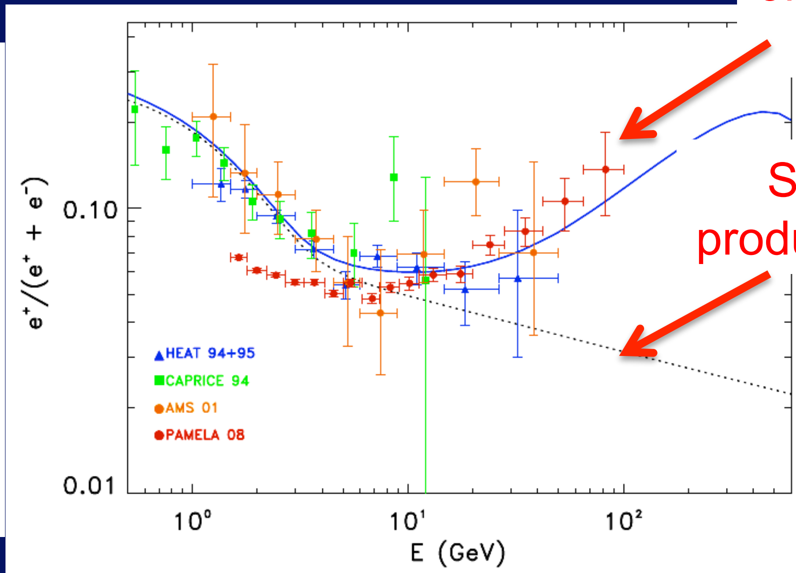
Adriani et al. 2009

- Positron fraction increases with energy above 10 GeV
- Several potential explanations (nearby pulsars, SNR), including DM annihilation or decay

The Positron Excess



Ackermann et al. 2011



Local source of primary e^+e^- needed

Secondary production in MW

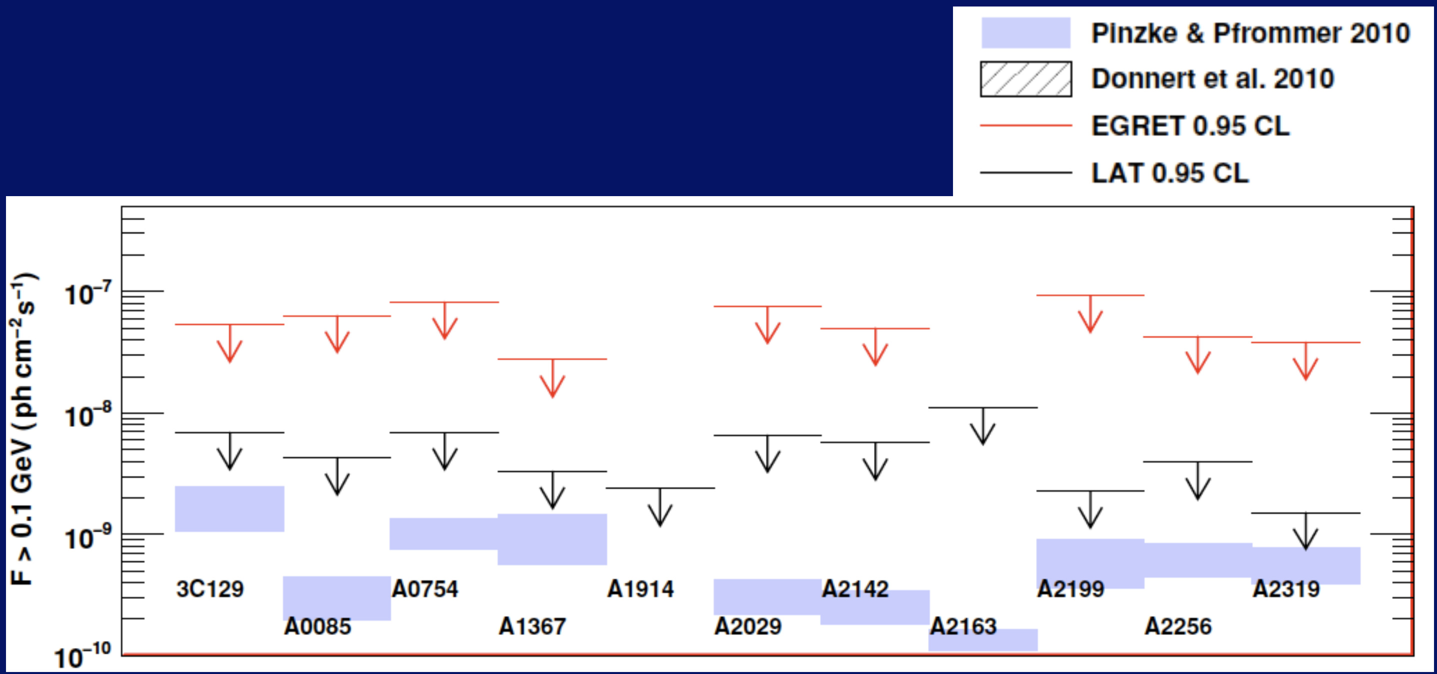
Adriani et al. 2009

➢ Fitting the e^+ excess as dark matter (without violating other constraints) prefers a leptonic final state and a high particle mass.

Limits on Dark Matter Models with the Fermi-LAT

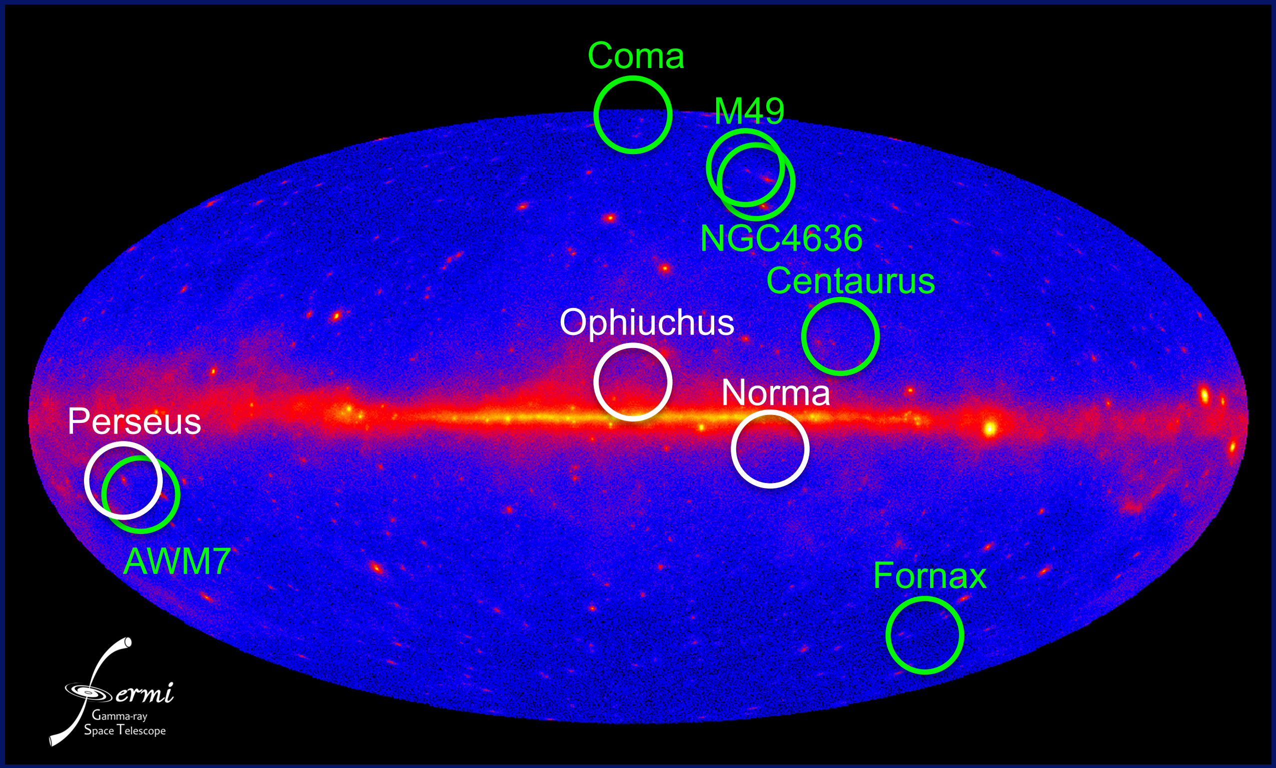
Limits on Gamma-Ray Emission

- Fermi-LAT does not detect clusters in gamma rays.
- Limits an order of magnitude deeper than EGRET.



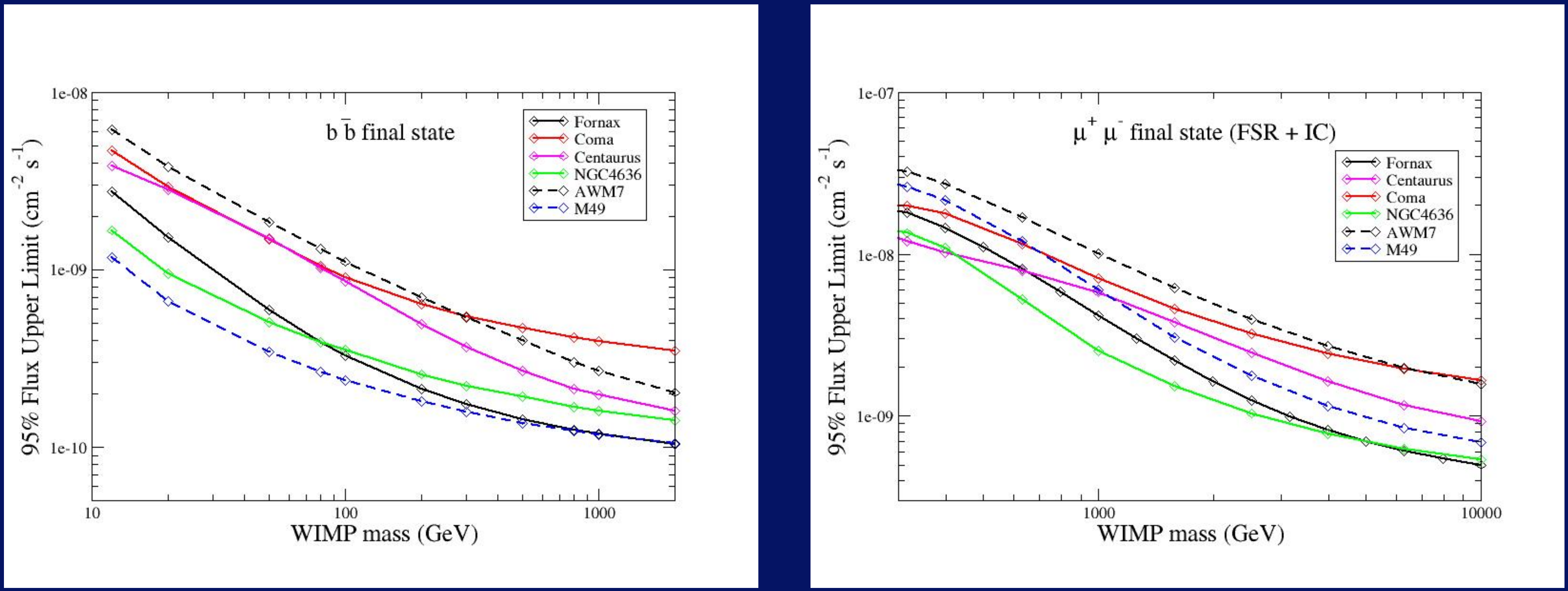
Ackermann et al. 2010a

Cluster Sample



- Brightest predicted clusters/groups (Jeltema et al. 2009)
- Remove Perseus (NGC1275), Ophiuchus (near GC), and Norma (near Galactic plane)

Flux Upper Limits – DM Annihilation



- Derive 95% confidence limits on the gamma-ray flux for a grid of particle masses and representative final states

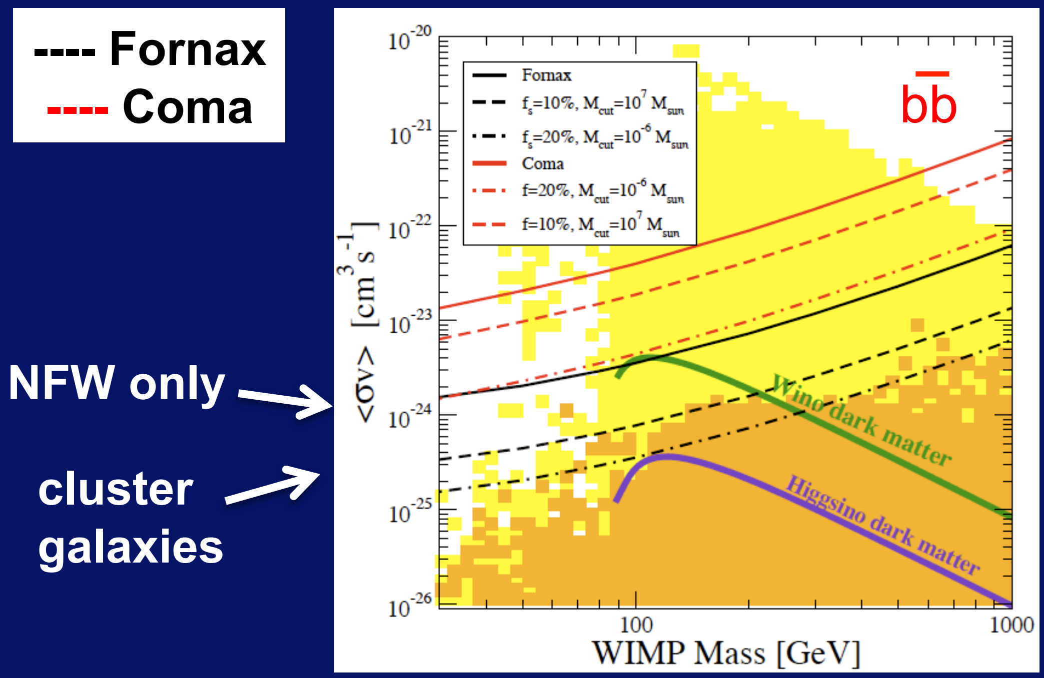
Flux limits depend on assumed spectrum!

Ackermann et al. 2010b

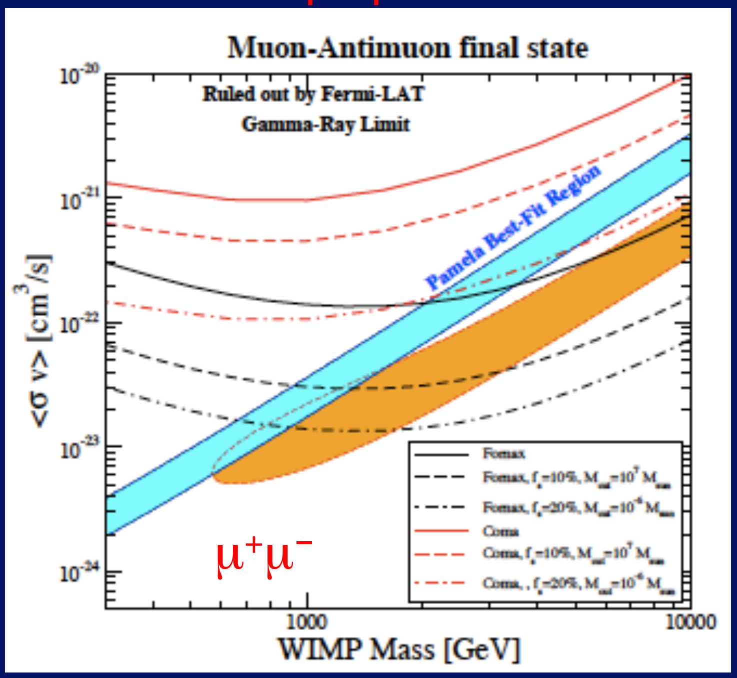
Limits on Dark Matter Annihilation

Results from the 1st Year

MSSM



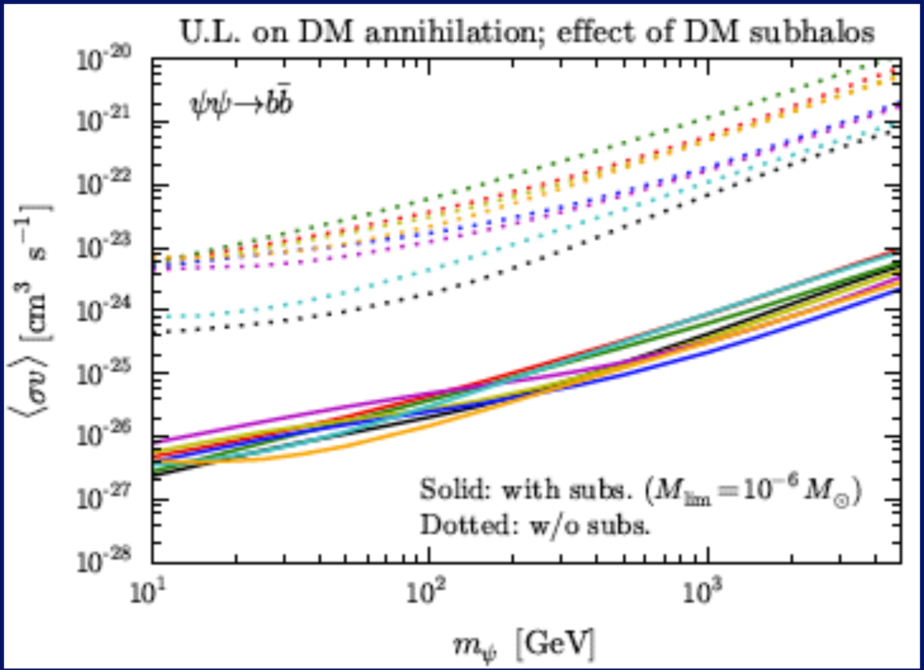
leptophilic



- ➢ Exclude models fitting PAMELA data with mass > 1-2 TeV
- ➢ Constraints on MSSM models depending on substructrue

Ackermann et al. 2010b

Dark Matter Annihilation – The Effects of Substructure



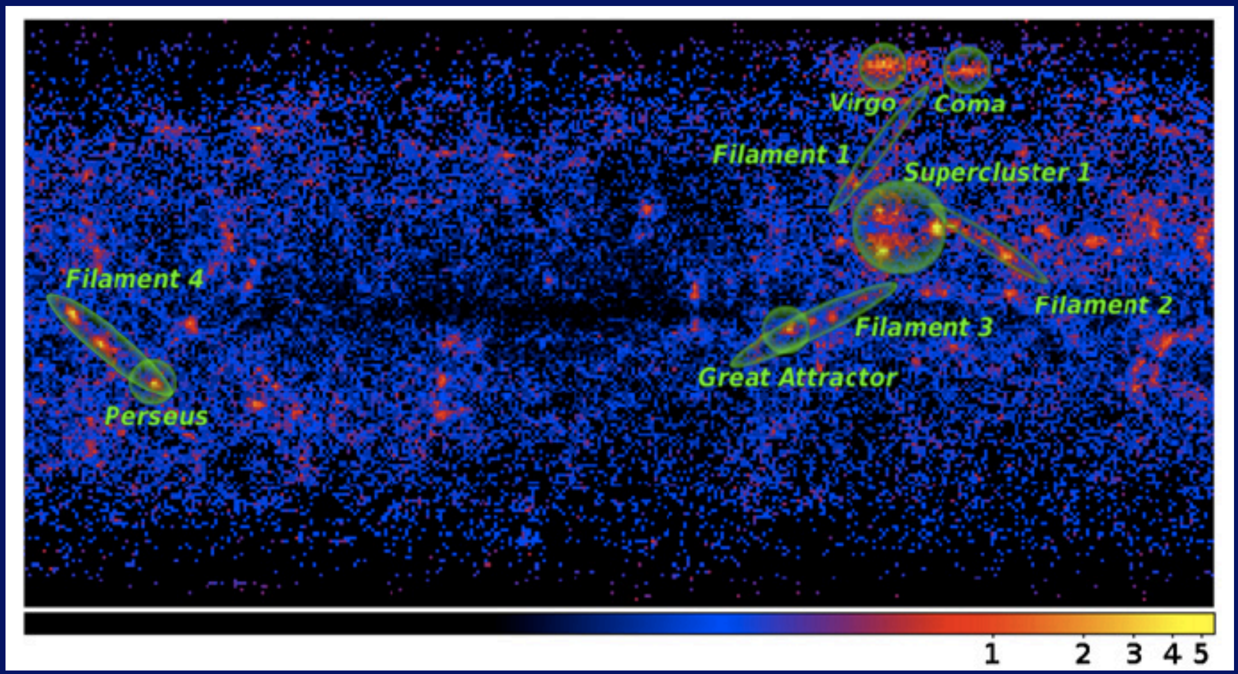
Huang, Vertongen, Weniger 2011

- With substructure predicted by extrapolating simulations, clusters exclude thermally produced WIMPs with masses less than ~150 GeV.

Dark Matter Decay

➢ Clusters and filaments/superclusters are particularly good targets for decay searches (ρ instead of ρ^2).

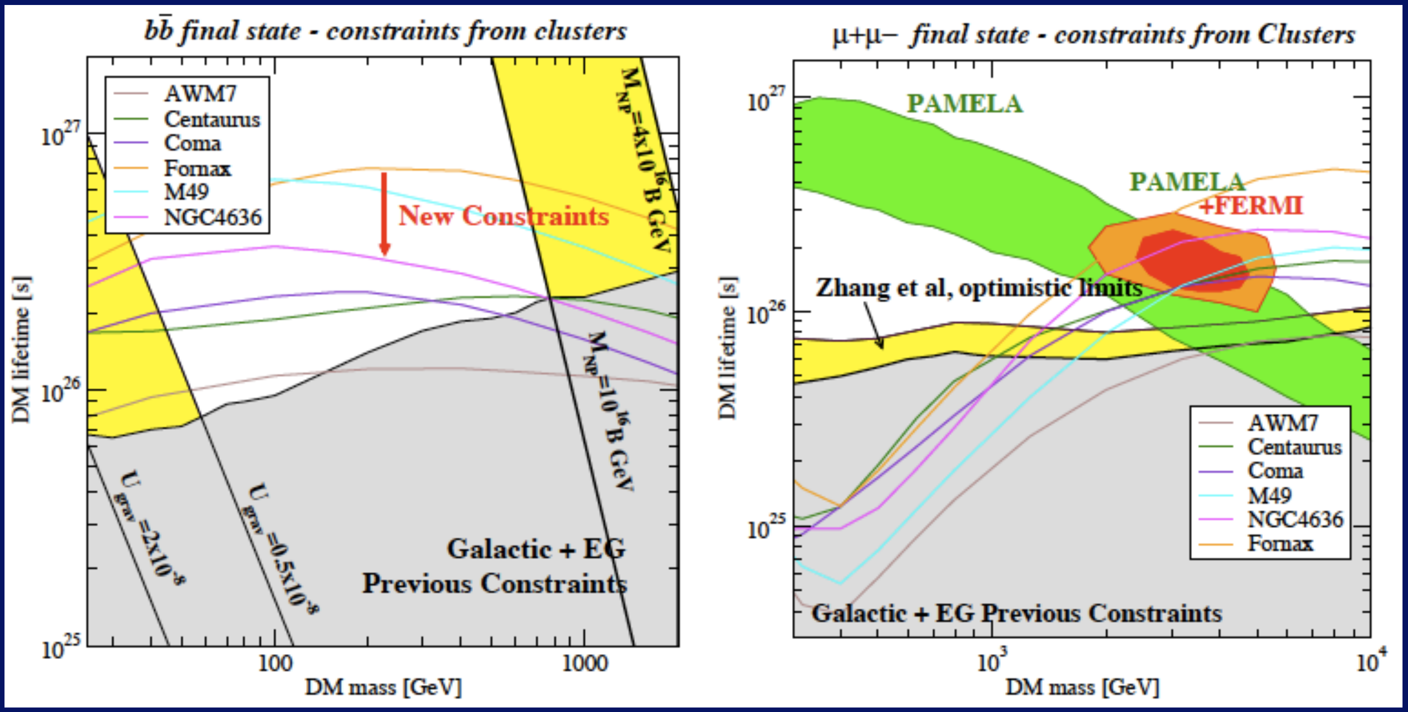
simulated Fermi S/N map



Cuesta et al. 2011

Limits on Dark Matter Decay

Results from the 1st Year

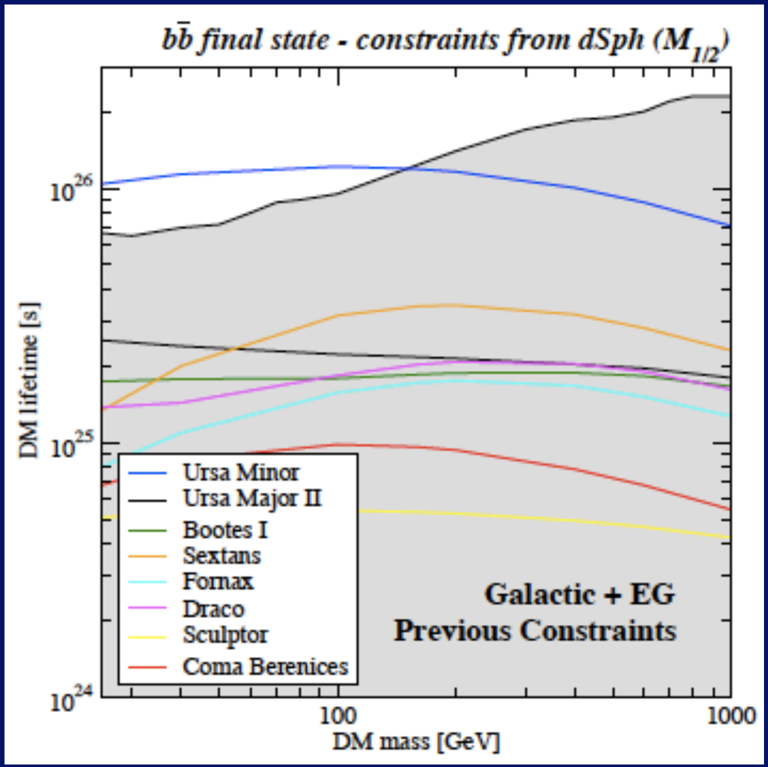


- Strong limits on the dark matter lifetime for a wide range of particle masses and decay final states, including models fitting the e^+ data.

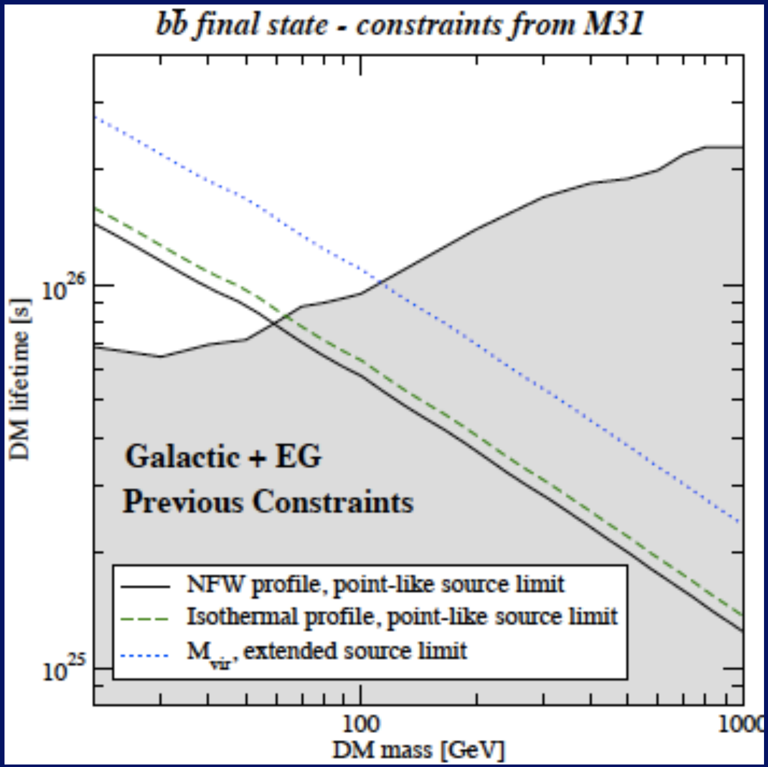
Dugger, Jeltema, & Profumo 2010

Comparison to Dwarfs and M31

Dwarfs



M31

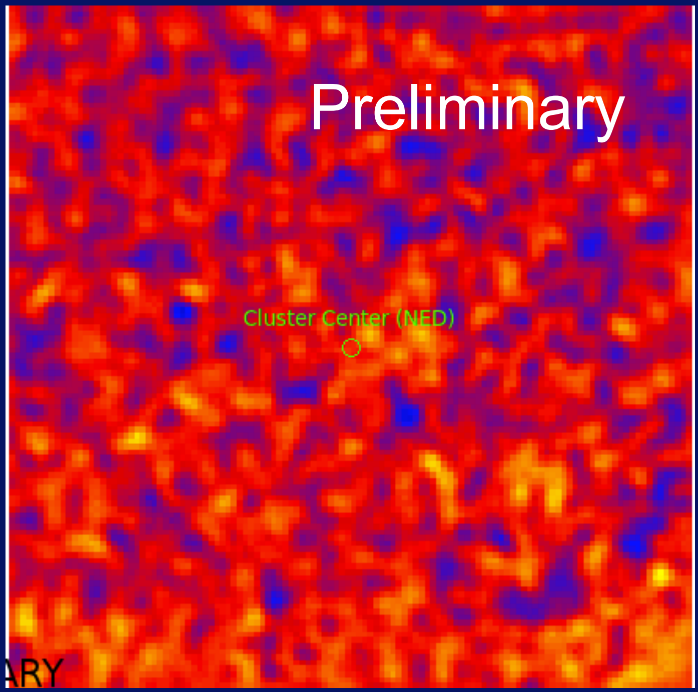


- For DM decay clusters typically give stronger constraints than other isolated extragalactic objects.

Dugger, Jeltema, & Profumo 2010

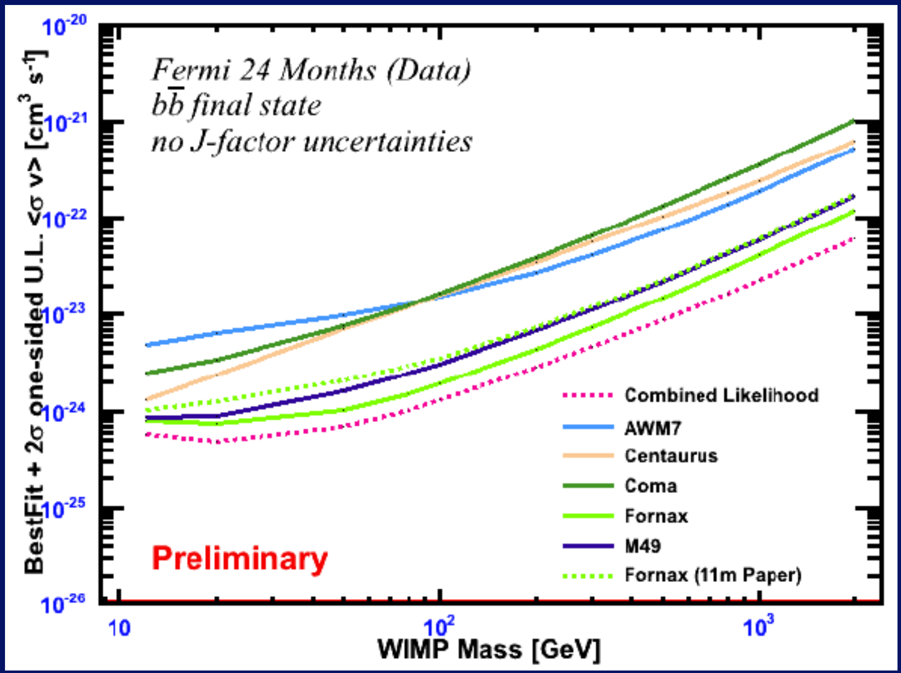
Updates from Fermi: Cluster Stacking

➢ Stacked 24 month data for five clusters: no significant detection of gamma rays

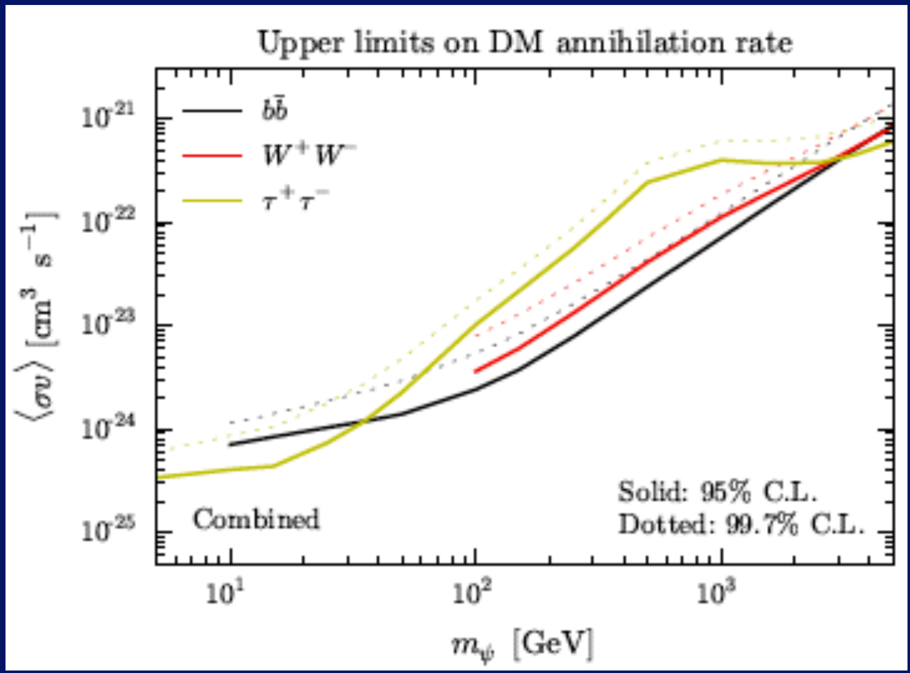


S. Zimmer, TeV Particle Astrophysics 2011

Stacking Limits on DM Annihilation



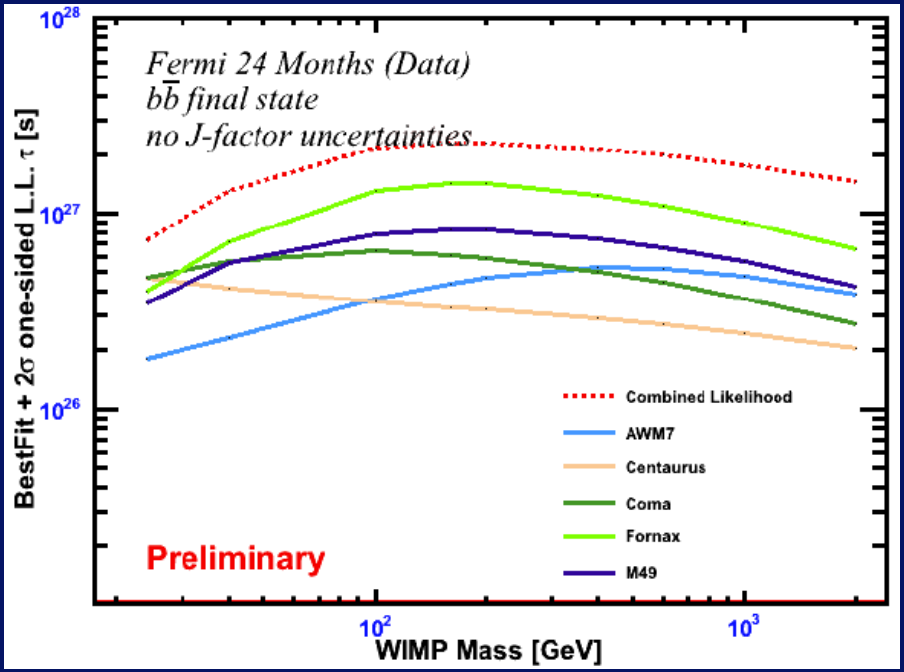
S. Zimmer, TeV PA 2011

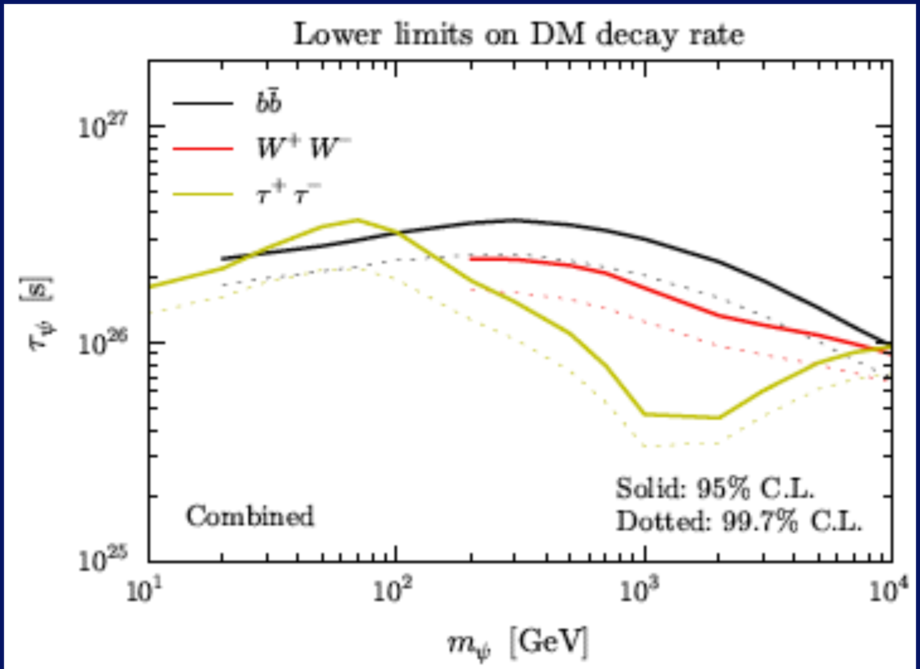


Huang et al. 2011

- Stacking of a few clusters with 2-3 years of data gives a factor of ~ 2-3 improvement in constraints.

Stacking Limits on DM Decay



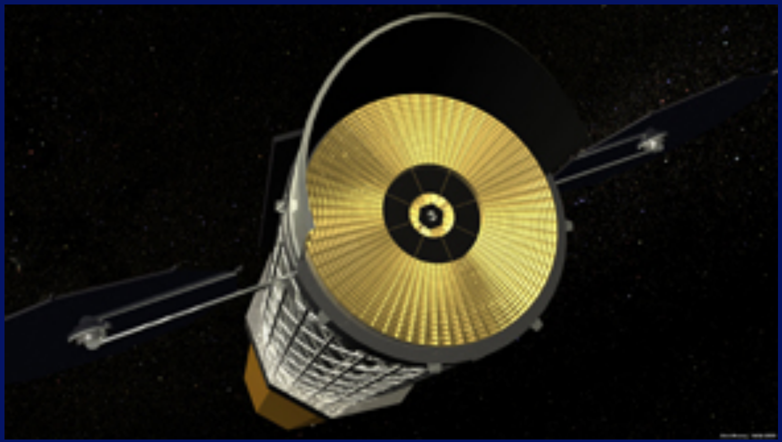


S. Zimmer, TeV PA 2011

Huang et al. 2011

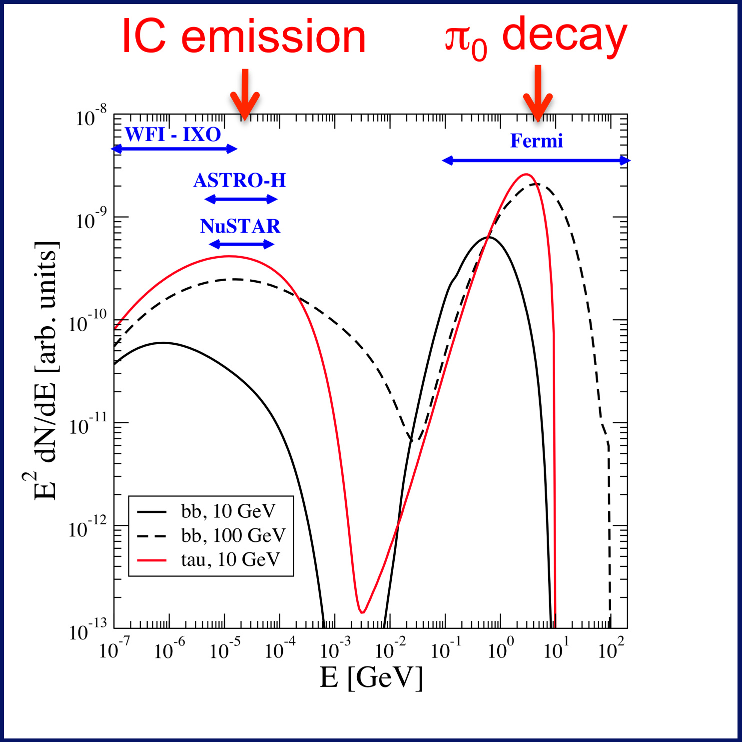
- Larger cluster samples and more data to come!

X-rays from Dark Matter in Clusters and Future Telescopes



X-ray Emission from Dark Matter

➢ For a range of DM models, IC emission from the scattering of the CMB by e^+/e^- produced in DM annihilation and decay peaks in the hard X-ray band.

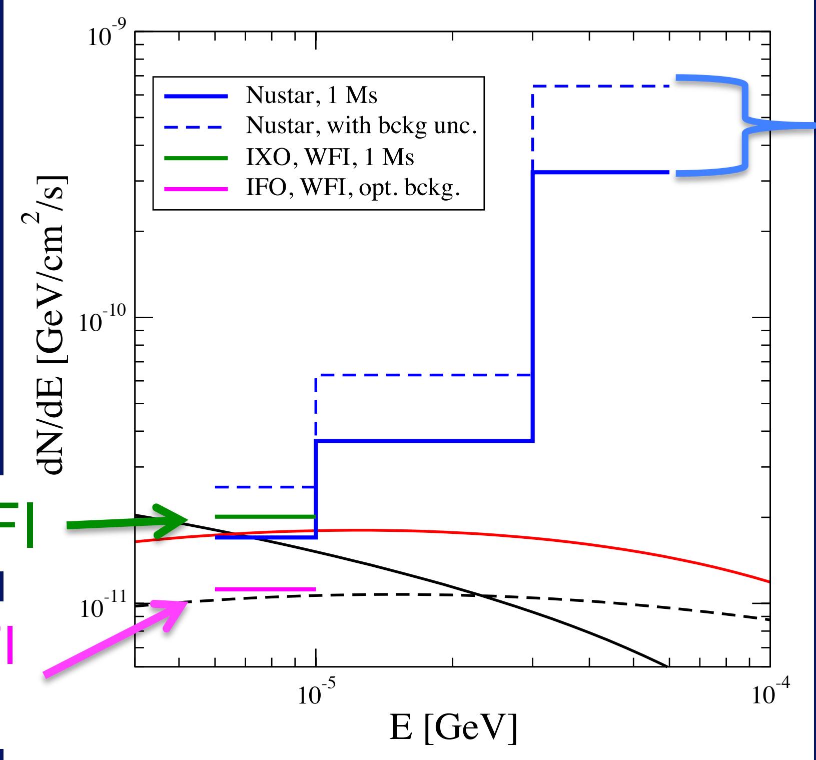


Jeltema & Profumo 2011

Predictions for a long observation of the Fornax Cluster

DM models normalized to Fermi limits:

- bb, 10 GeV
- bb, 100 GeV
- tau, 10 GeV



NuSTAR

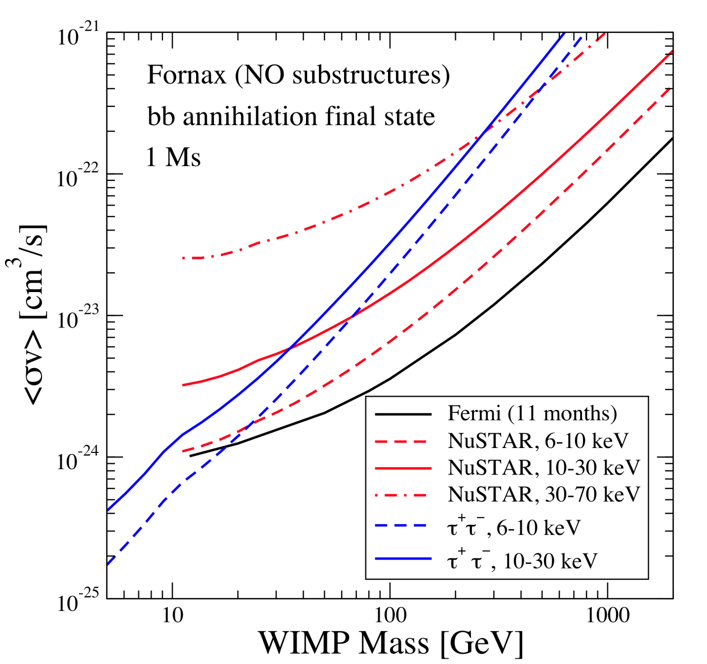
Athena WFI

hypothetical WFI with lower NXB

* 6-10 keV bin includes background from cluster thermal emission.

Jeltema & Profumo 2011

Comparison of NuSTAR and Fermi



➢ Planned X-ray telescopes will have (at best) similar sensitivity to Fermi to low mass WIMPs.

➢ Interesting constraints could be within reach with an appropriately planned mission.
(low background, large FOV, large EA around 10 keV)

Jeltema & Profumo 2011

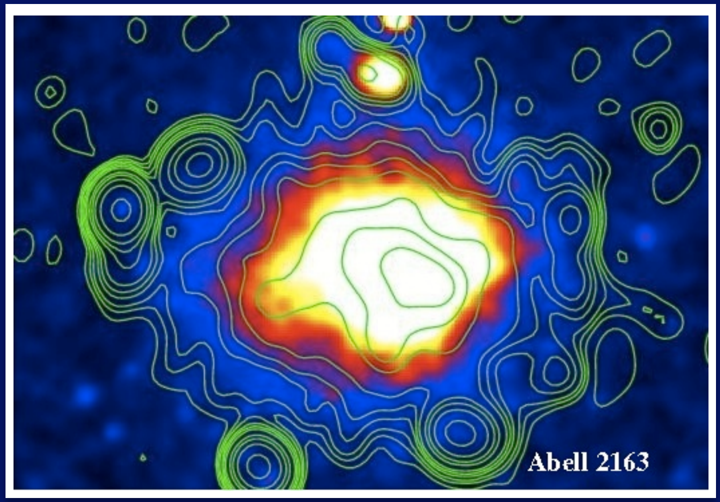
Cosmic Rays in Clusters

- Accelerated in accretion/merger shocks, AGN, and SNe
  - CR protons can survive for a long time and add pressure support to the cluster

- Radio synchrotron emission from CR electrons in the cluster magnetic field

  ➔ observed on Mpc scales!

- Gamma ray emission:
  - CR proton collisions with ICM
  - IC scattering by CR electrons (also hard X-ray)



Arnaud 2008, Feretti et al. 2001

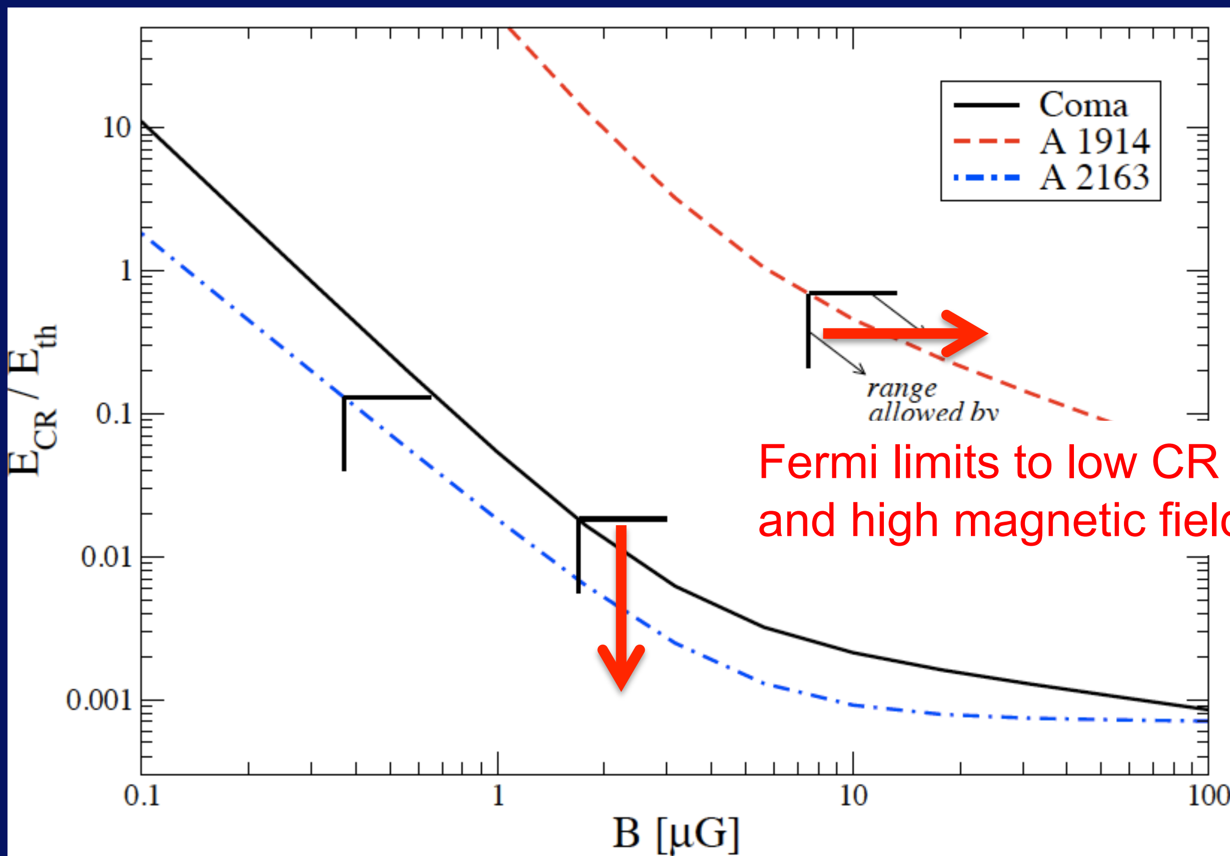
Cosmic Rays: Implications of Fermi Limits

- Low cosmic ray proton densities
  - at most ~ 1-10% of the thermal energy density in nearby clusters
  - little bias in cluster masses = good for cosmology

- Constrains hadronic origin of radio halos
  (i.e. secondary electrons from p-p collisions)
  - To produce the observed radio flux without overproducing gamma-ray emission implies a fairly high minimum average magnetic field in some cases.

Ackermann et al. 2010a, Jeltema & Profumo 2010

Example Constraints for Radio Halos

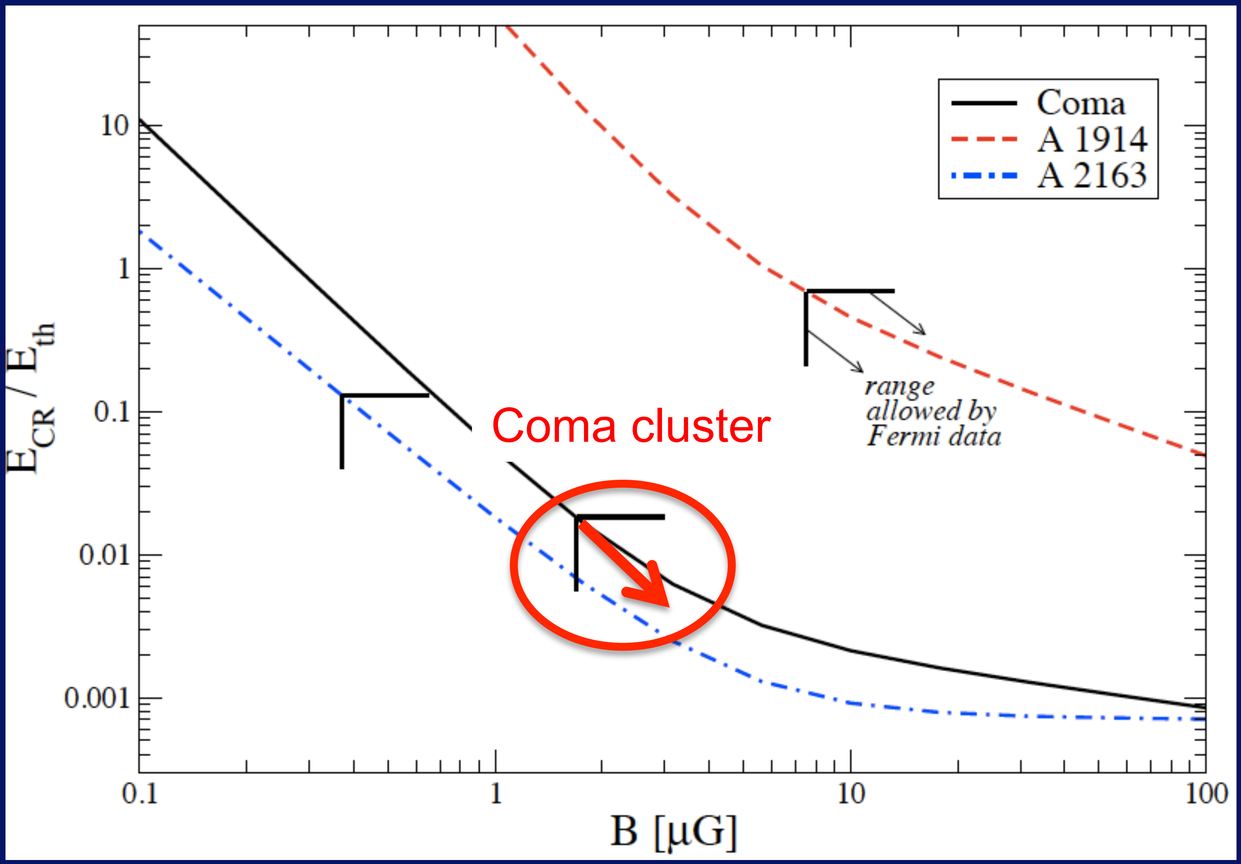


Fermi limits to low CR densities and high magnetic fields

➢ Minimum average magnetic fields as high as ~ 7 μG for nearby radio halo clusters in the hadronic model.

Jeltema & Profumo 2010

Example Constraints for Radio Halos



- CR energy density < 2% and average B > 1.7 μG compared to RM average B ~ 2 μG (Bonafede et al. 2010)

Jeltema & Profumo 2010

Summary

- The non-detection of clusters by Fermi excludes many dark matter models that could explain the local positron excess.

- Clusters are powerful probes of dark matter decay.

- Dark matter searches are something to consider in planning future X-ray telescopes.

- The Fermi limits also imply low cosmic ray energy densities in clusters and place constraints on a hadronic origin of radio halos.