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Fermi Gamma-ray Space Telescope

A Combined Analysis on Clusters of Galaxies
Gamma Ray Emission from Cosmic Rays and Dark Matter

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and

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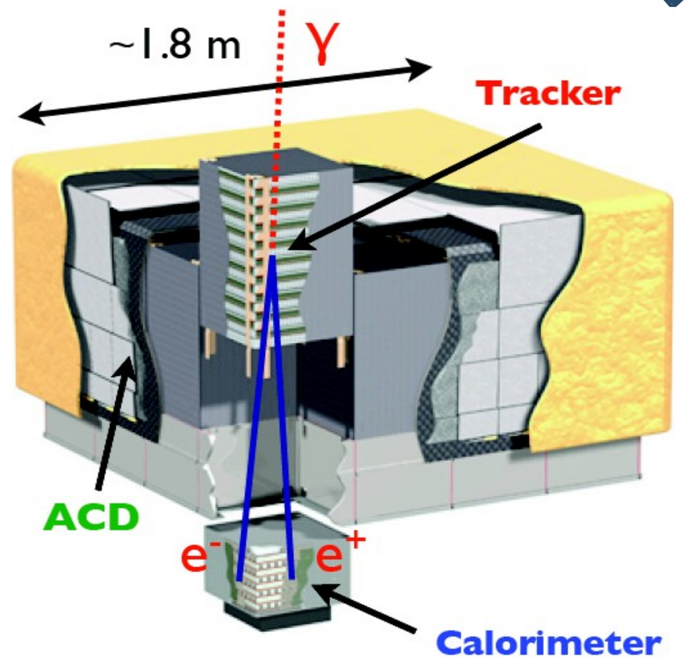
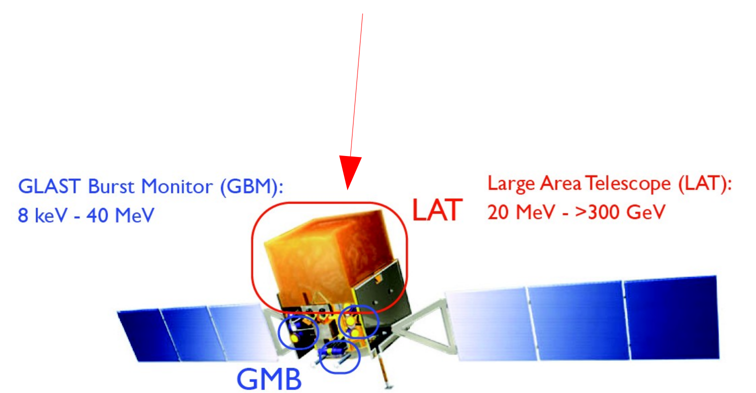
The Fermi-LAT

- Fermi Gamma-ray Space Telescope launched on June 11th, 2008 at Cape Canaveral, FL
- 16 identical modules in a 4x4 array, consists of tracker (direction) & calorimeter (energy) → pair-conversion telescope
- Energy Range: 20 MeV - 300 GeV
- Large effective area ~$1 m^2$
- All-Sky monitor ~3h for 2 orbits, FoV ~2.4 sr (@ 1 GeV)
- Gamma Ray Burst Monitor energy coverage 8 keV to 40 MeV, serves as trigger for GRBs





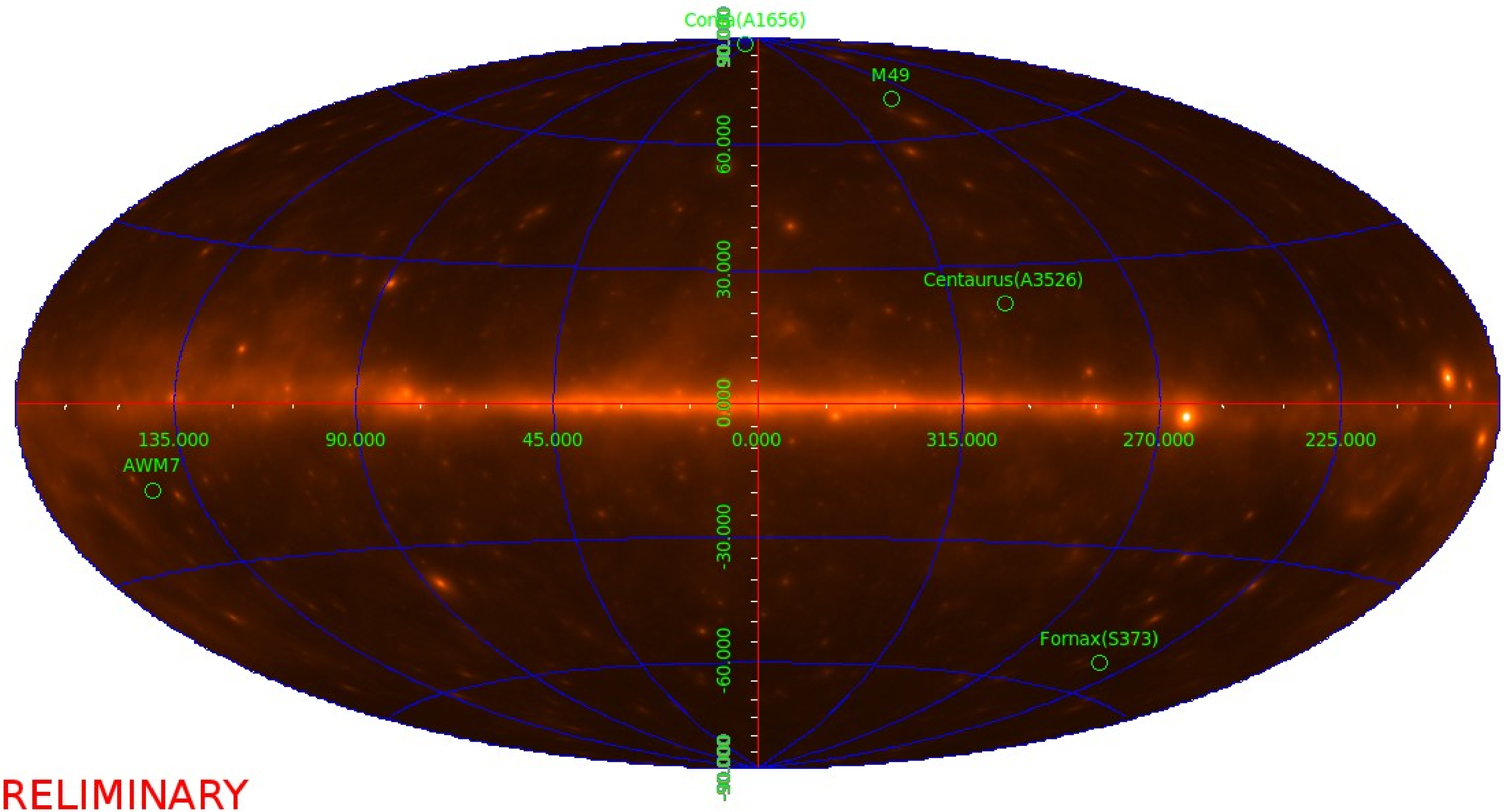
Clusters of Galaxies

- Largest **virialized** and **most massive** structures in the universe
- Lensing and X-Ray observations indicate **large dark matter (DM)** content, can be traced through γ-rays → good candidate for searches
- **Radio emission** indicates presence of **relativistic electrons** → cosmic ray (CR) population with potentially **high γ-ray emission**
- **No γ-Ray Emission** from Clusters seen so far
- Only **small sample** for starters – to be extended

Cluster	Mean Distance (Mpc)	Mass Estimate M_{500} (10^{14}) $M_\odot$	CR Ranking*	DM Ranking**
M49	16.1	0.41	1	2
Coma	99.0	11.99	2	4
Centaurus	51.2	2.39	3	3
AWM7	69.2	3.79	4	5
Fornax	19.0	0.87	5	1

* based on flux predictions from Pinzke & Pfrommer
** inferred from J-value

Cluster Locations in the Sky



PRELIMINARY

Skymap showing 24 months of Fermi-LAT data smoothed with LAT Point-Spread Function
overlaid with NASA/IPAC Extragalactic Database locations of clusters

γ-Ray Emission Models – Dark Matter

- The γ-ray flux from self-annihilating Dark Matter can be expressed as:

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

Astrophysical factor

Particle physics factor

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

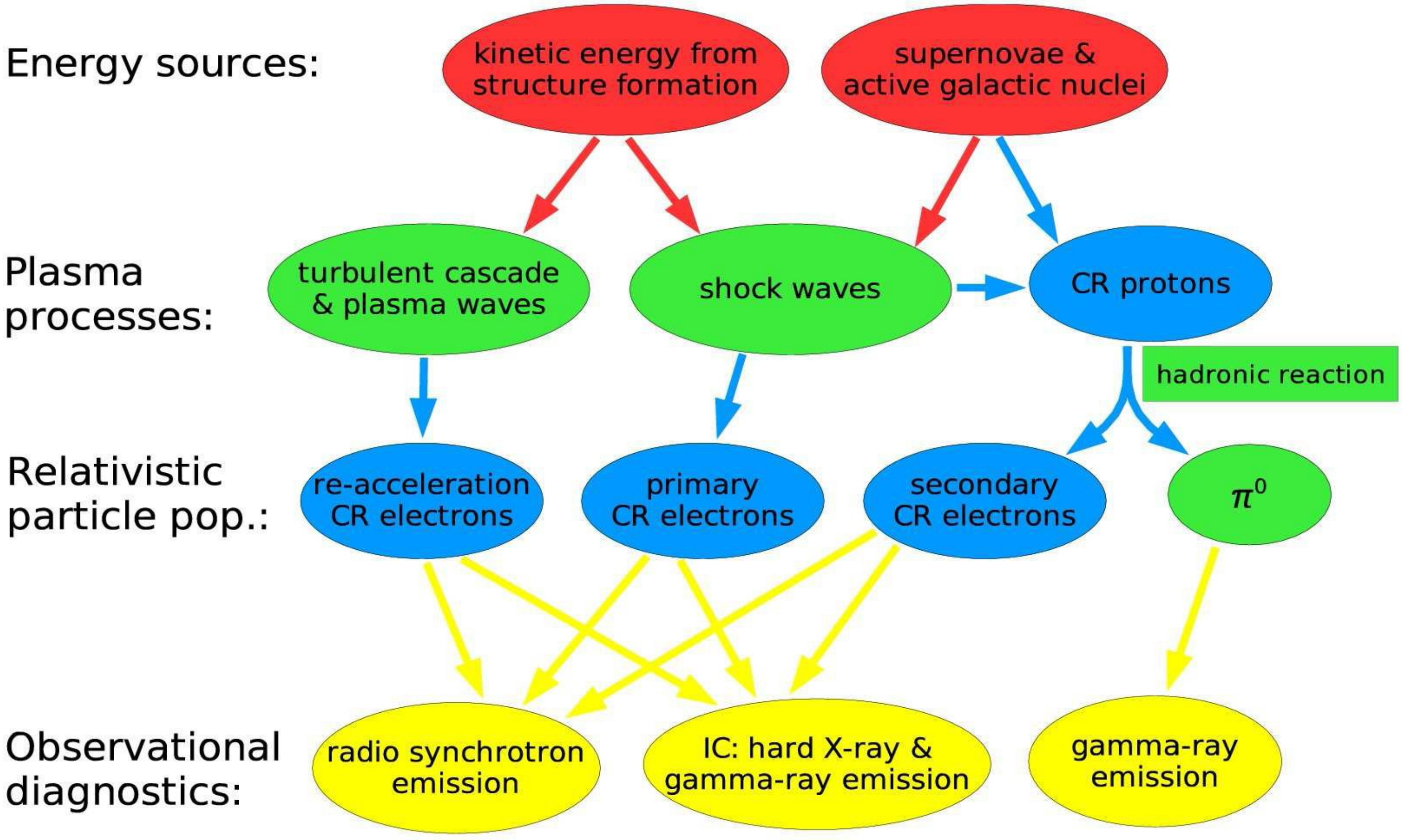
$$\Phi^{PP}(E) = \frac{1}{2}\frac{\langle \sigma v \rangle}{m_{WIMP}^2} \sum_f \frac{dN_f}{dE} B_f$$

- And for Decaying dark matter (the decay spectrum is roughly equivalent to the annihilation spectrum of a particle with half the mass):

$$J_D(\Psi) = \int_{l.o.s.} dl(\Psi)\,\rho(l) \quad \Phi_D^{PP}(E) = \frac{1}{m_{WIMP}\,\tau} \sum_f \frac{dN_f}{dE} B_f$$

γ-Ray Emission from Clusters of Galaxies

Relativistic populations and radiative processes in clusters:



C. Pfrommer et al., MNRAS, 378:285-408 (2007) [modified]

γ-Ray Emission from Clusters of Galaxies

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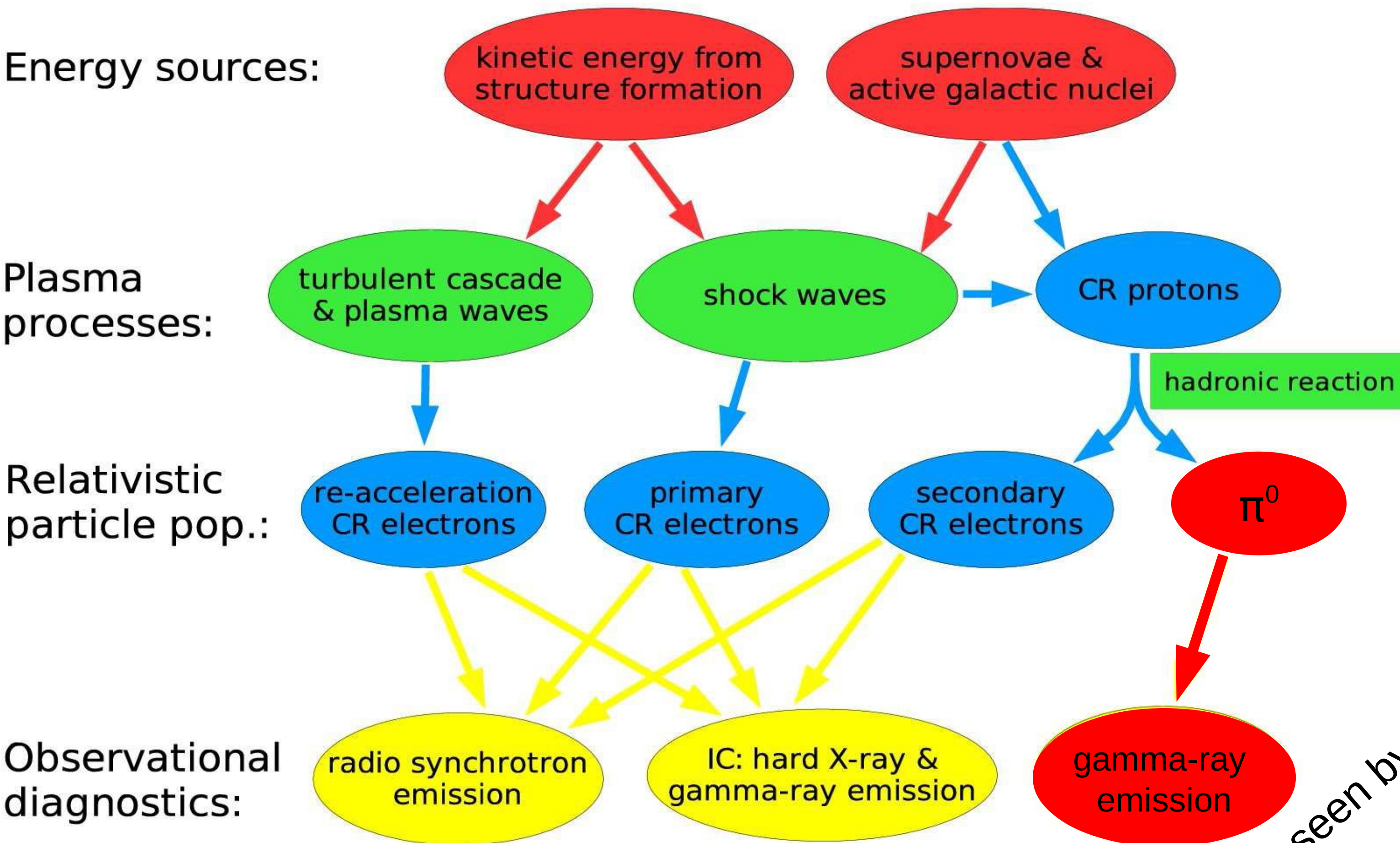


C. Pfrommer et al., MNRAS, 378:285-408 (2007) [modified]

Could be seen by the LAT!

γ-Ray Emission – Cosmic Rays

- **The γ-ray flux from π^0 decay in clusters as predicted in (Pinzke & Pfrommer 2010) can be described as:**

$$\Phi_\gamma = \int d^3 r \, A(R) \lambda_{\pi^0 - \gamma}(E)$$

- **Where $\lambda_{\pi 0\text{-}\gamma}$(E) contains universal spectral model including η (maximum hadronic injection efficiency)**
- **η should be identical for all clusters → common parameter**
- **A(R) denotes the cluster-specific normalization:**

$$A(R) = C_M(R) \frac{\rho(R)^2}{\rho_0^2}$$

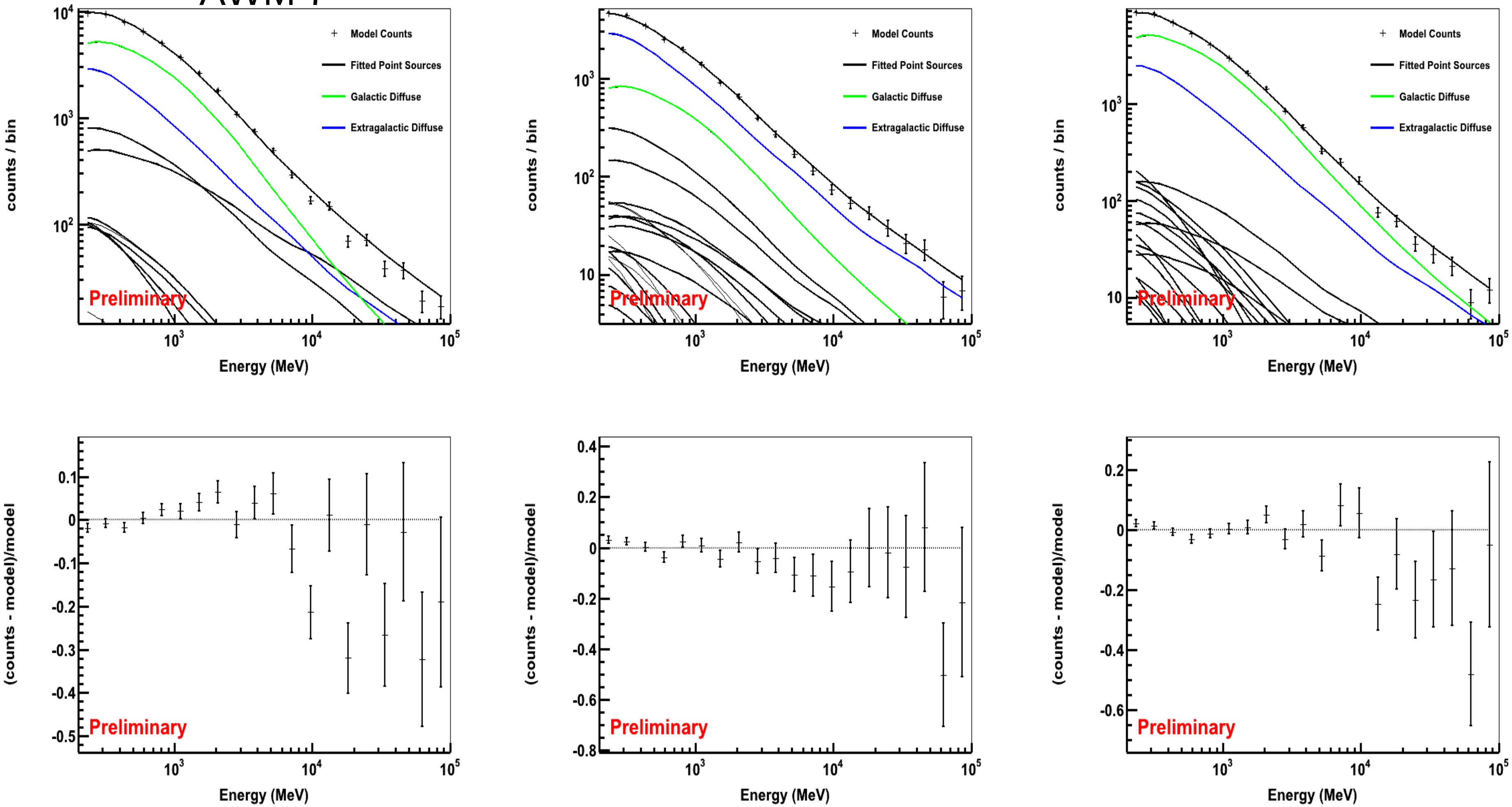
- **C_M(R) derived for different cluster masses in the model, ρ(R) is the gas density profile; from X-ray observations or in simplified forms (AWM7, Centaurus), see Jeltema et al. 2009 (arXiv: 0812.0597)**

Analysis Details

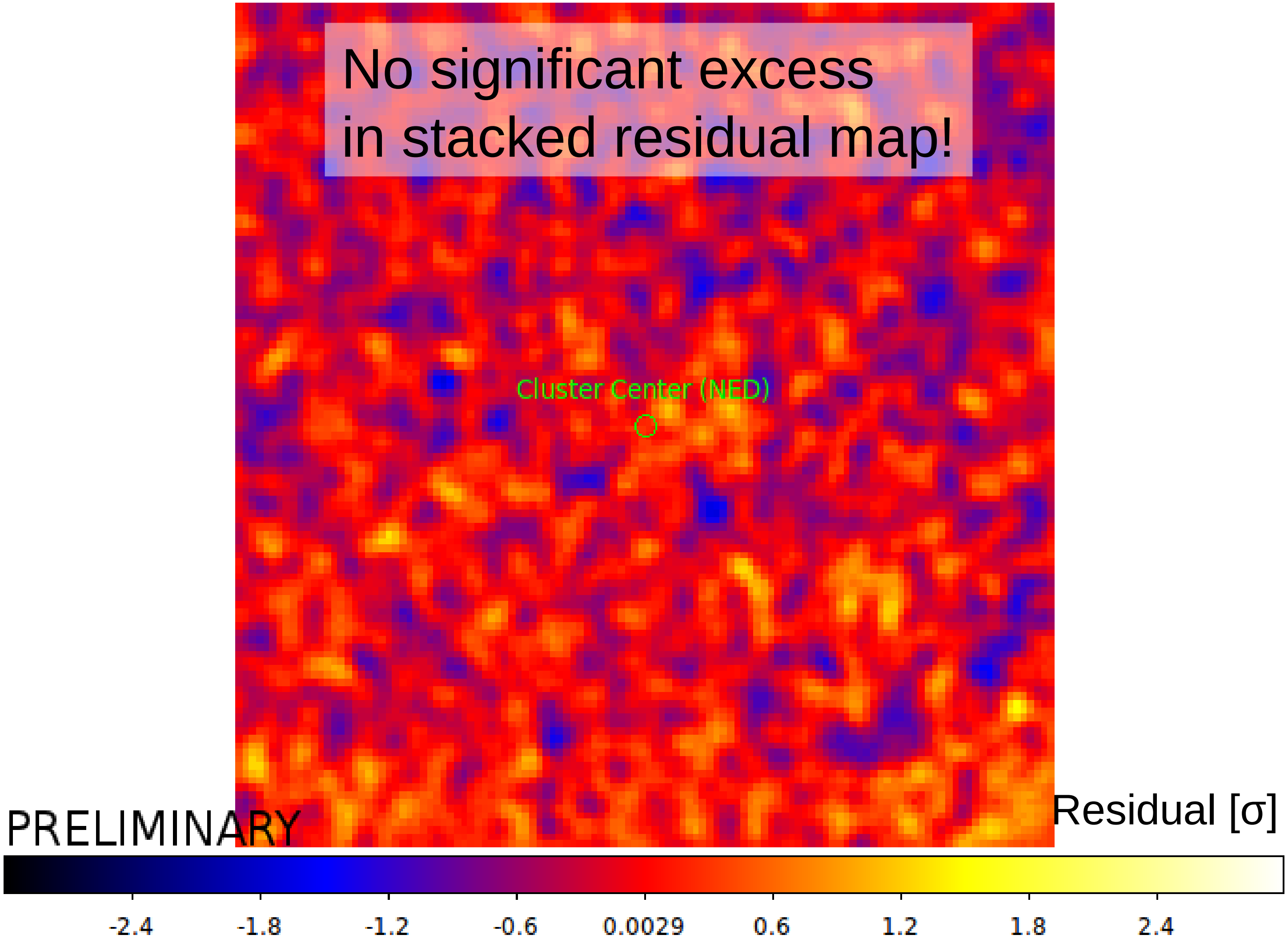
- Dark Matter Analysis:
  - 24 Months of Fermi-LAT data, p6v11 Diffuse class Events
  - Binned analysis, 10 deg ROI, 20 Energy Bins from 200 MeV – 100 GeV
  - Point Sources within 15 degrees included, free normalization for sources within 5 degrees
  - J-factors from NFW profile, no uncertainties included
  - Assume Standard WIMP for $b\bar{b}$ final states
  - Model Clusters as Point Source
- Cosmic Ray Part
  - Follow Hadronic Universal Cosmic Ray Model by Pinzke & Pfrommer (MNRAS 277, 2010) for Spectral Form
  - Perform same analysis as in DM case for CR spectra

Individual Fit Results (500 GeV DM Mass)

AWM 7 | Coma | Centaurus



Looking at the 'Stacked Residual Map'



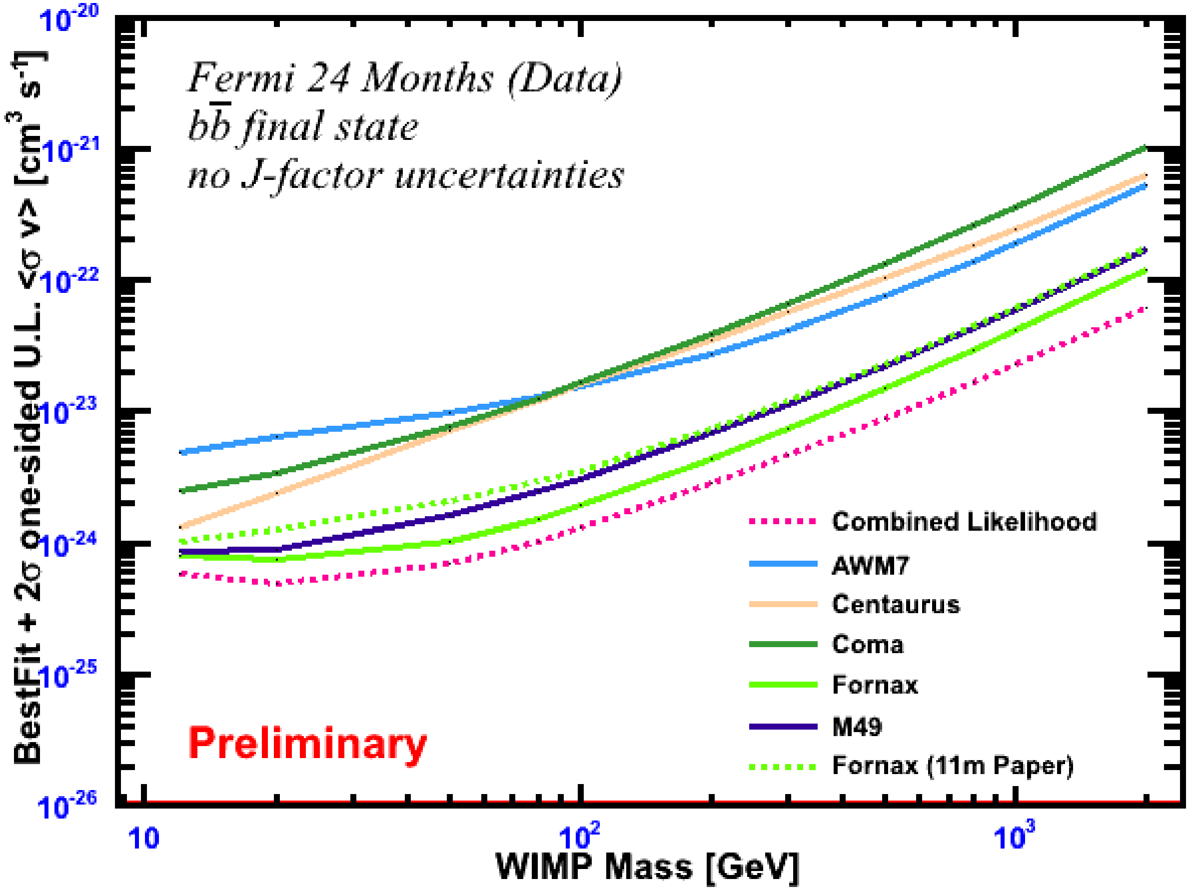
We don't see anything!

The Combined Likelihood Approach

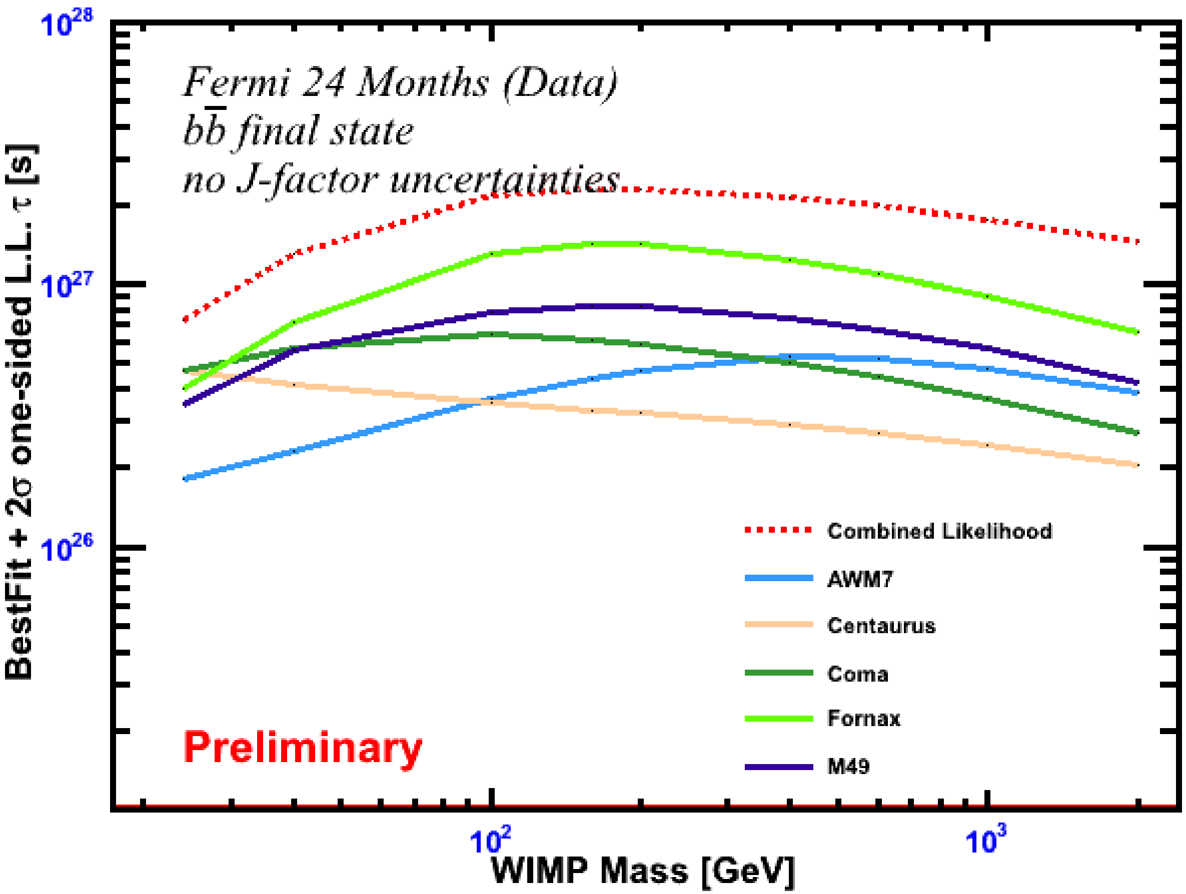
- **Remember, no stacking of data!**
- **Powerful tool that puts tight constraints on a parameter of interest, profiling over nuisance parameters**
- **Implemented in Fermi Science Tools through MINUIT and MINOS**
  - **Common Parameter for all Clusters (e.g. <σv> for DM)**
  - **Individual Nuisance Parameters (e.g. Point Source Parameters, diffuse normalizations)**

$$L(\langle \sigma v \rangle, m_{WIMP} | obs) = \prod L_i(\langle \sigma v \rangle, m_{WIMP}, c, b_i | obs_i)$$

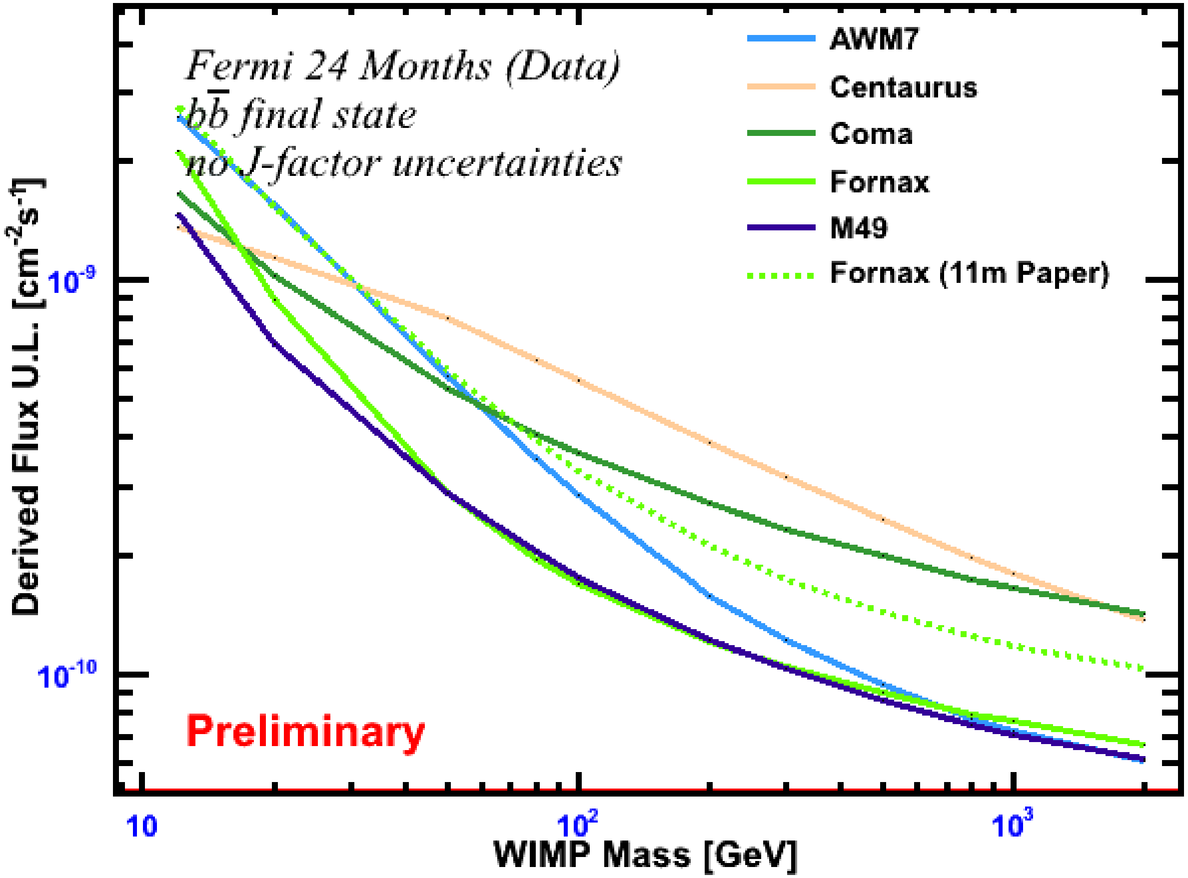
Combined Upper Limits on <σv>



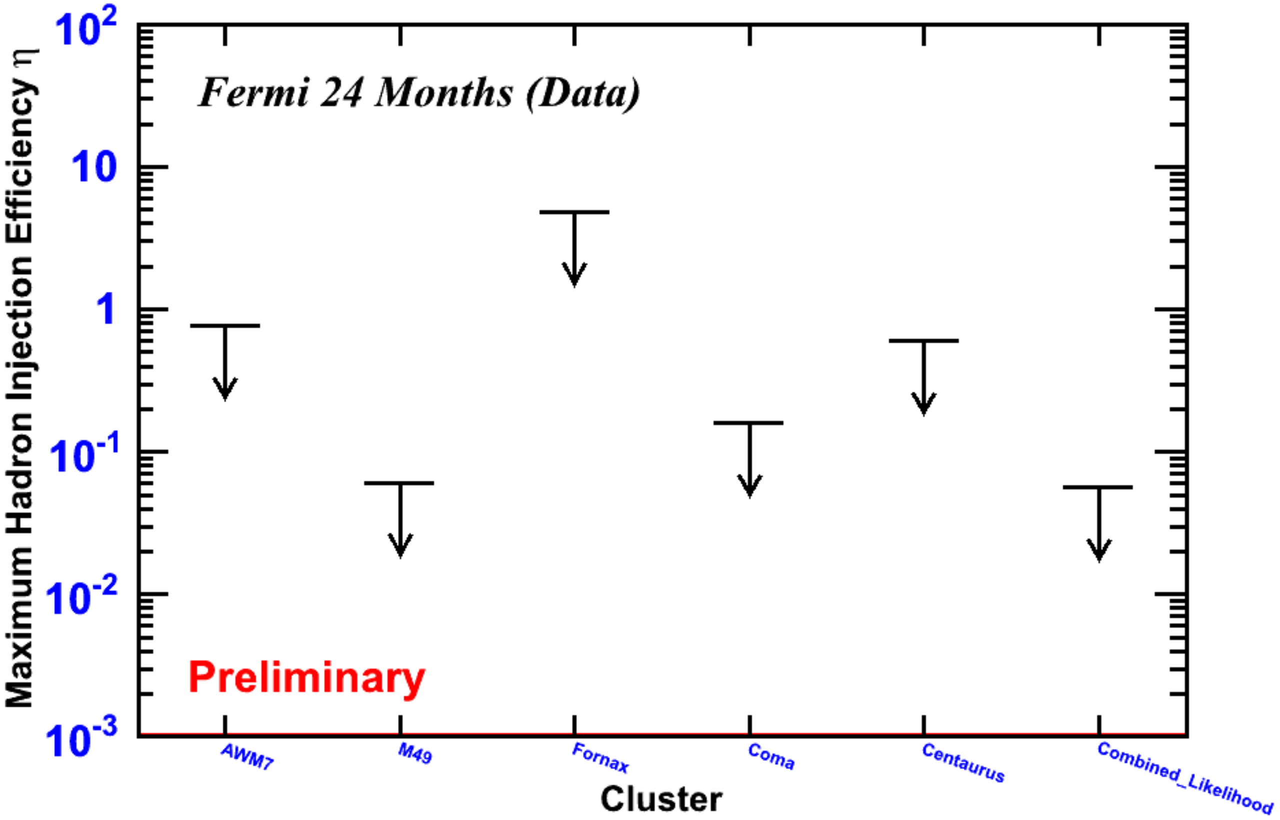
Combined Lower Limits on τ (Decaying DM)



Updated Individual Flux Upper Limits



Constraints on the Maximum Hadronic Injection Efficiency



Individual limits follow model ranking

Under model assumptions data from Coma & M49 favor $\eta<0.5$

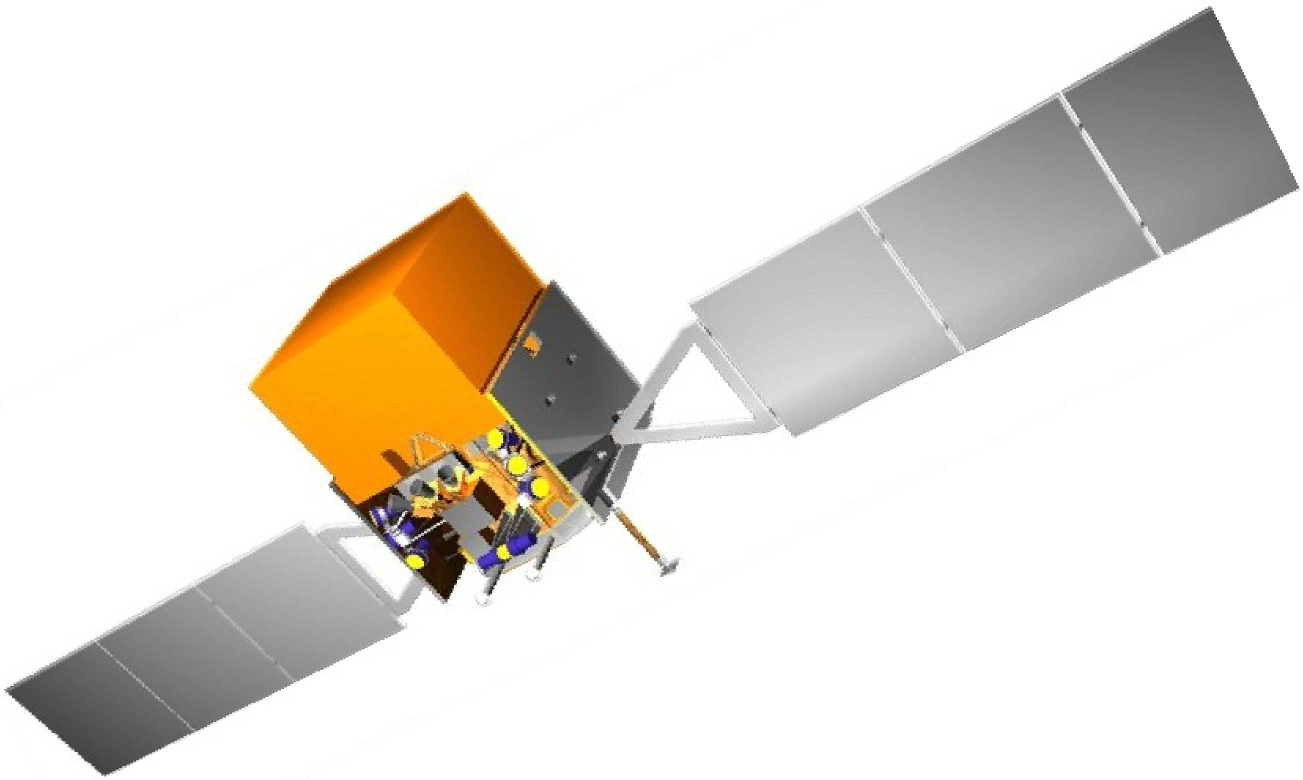
Summary and Outlook

- **Clusters of Galaxies interesting targets both for CR and DM searches but not observational evidence for γ-rays so far**
- **Individual Fits are compatible with the non-observation hypothesis, calculate upper limits on Dark Matter parameters (annihilating and decaying DM) and hadronic injection efficiency**
- **Combined Likelihood approach feasible as all clusters should reflect same physical properties**
- **Combined DM Limits ~ factor 2 better than individual ones (varying for cluster and mass points)**
- **Initial results from a first look at CR favor maximum hadronic injection efficiency below predictions ($\eta \leq 0.5$) assuming model characteristics provided by Pinzke & Pfrommer**

Outlook:

- **Increase the number of clusters (this was a proof-of-concept analysis)**
- **Explore CR scenarios more deeply**
- **Extend to extended sources, different final states, J-uncertainties...**
- **Coming Soon:** *Abdo et al. A Combined Analysis of Clusters of Galaxies*

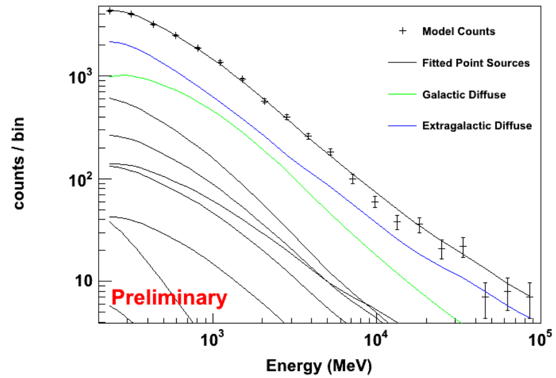
Thank you for your Attention!

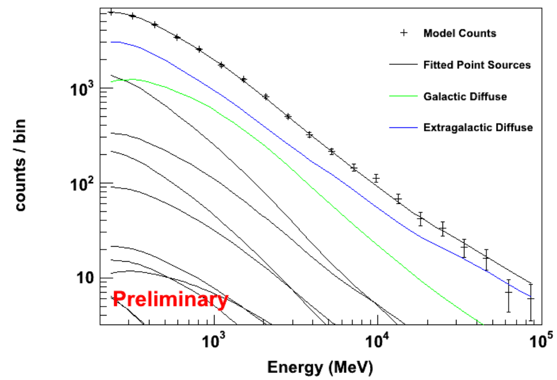


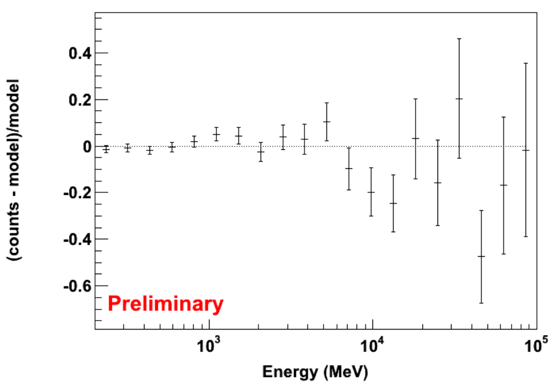
Individual Fits (500 GeV WIMP Mass)

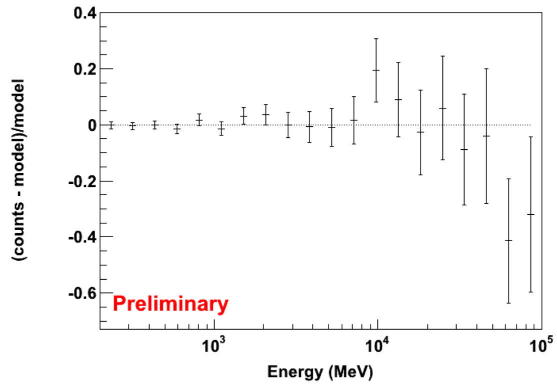
Fornax

M49

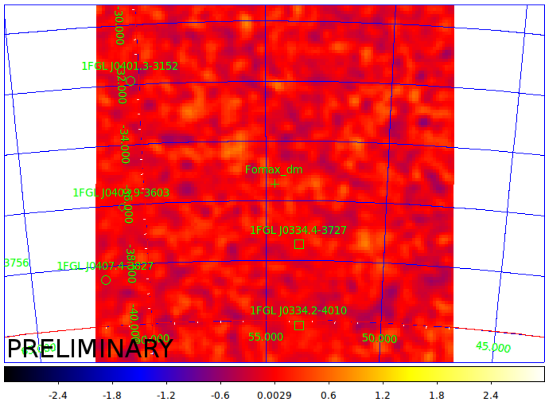


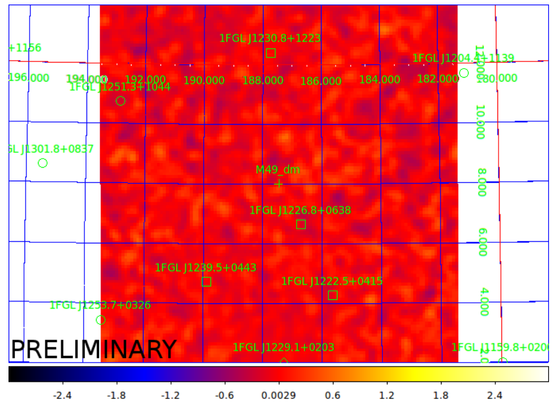


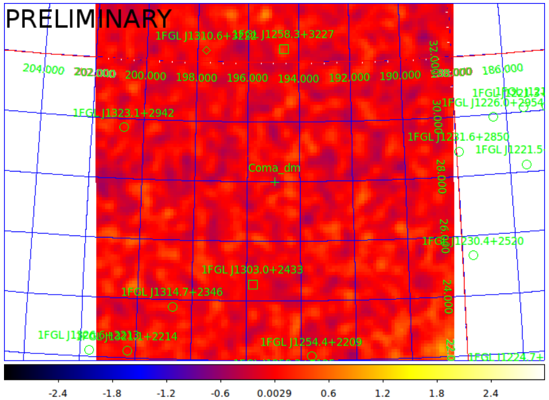


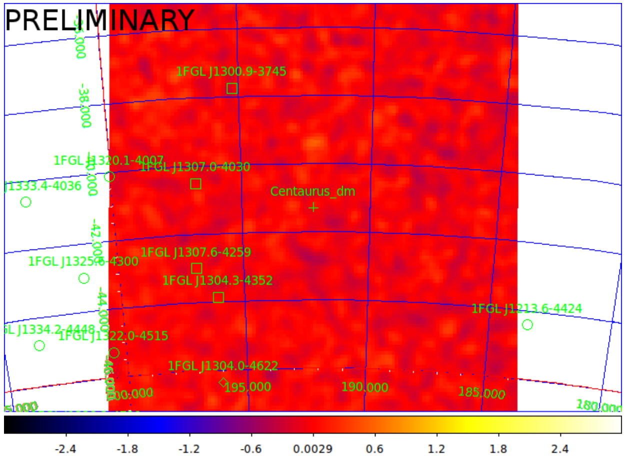


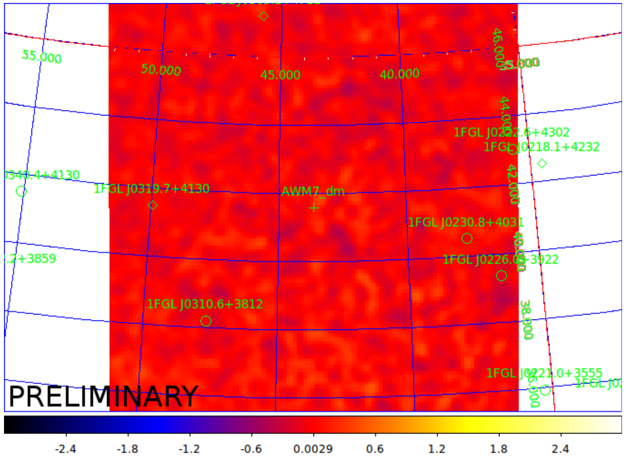
Individual Residual Maps in Sigma



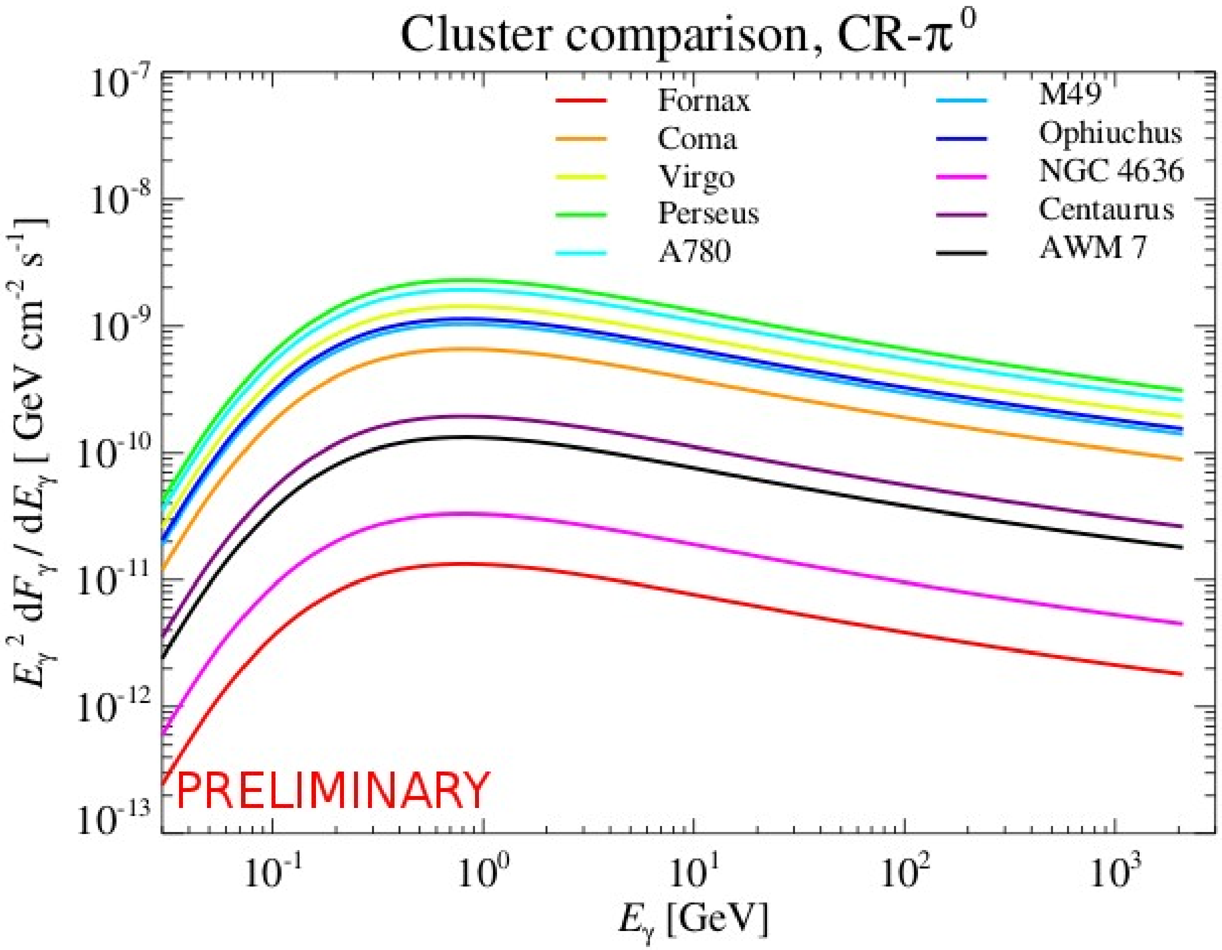








Flux Predictions from CR Model



Motivating η≤0.5

- Injection efficiency depends on mach number of shockwave, higher efficiencies only realized at strong shockwaves outside supercluster regions

- Not excluded by radio data: for FRM can explain morphology, bulk of flux, and some of power law spectra (Miniati et al. 2001, Profumo & Jeltema 2011)

- Radio halos too extended for plain hadronic model, need some CR transport and additional components in violent outer parts, but CR flux bulk comes from center

Spatial Model of Pinzke & Pfrommer (2010)

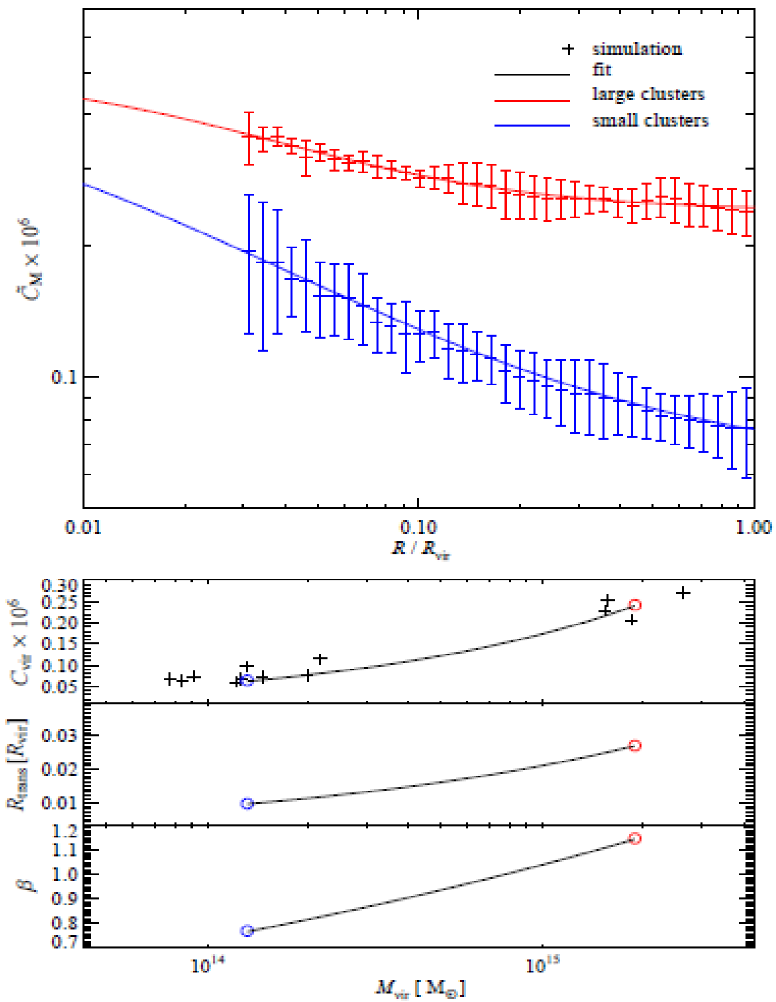


Figure 8. The top panel shows the profile of the dimensionless normalization of the CR spectrum, $\tilde{C}_M$. We show the mean $\tilde{C}_M$ and the standard deviation across our cluster sample which has been subdivided into two different mass intervals: large- (red), and low-mass clusters (blue) representing the mass range $1 \times 10^{15} < M_{vir}/M_\odot < 3 \times 10^{15}$, and $7 \times 10^{13} < M_{vir}/M_\odot < 4 \times 10^{14}$. The solid lines show the best fit to equation (22). The lower three panels show the mass dependence of the quantities which parametrize $\tilde{C}_M$ for low mass clusters (blue circles) and large mass clusters (red circles). The top small panel shows the asymptotic $\tilde{C}_M$ for large radii (C_{vir}), where each cross shows $\tilde{C}_M$ at R_{vir} for each cluster. The middle panel shows the transition radius R_{trans}, and the bottom panel shows the inverse transition width denoted by β.

$$\tilde{C}_M(R) = (C_{vir} - C_{center}) \left(1 + \left(\frac{R}{R_{trans}}\right)^{-\beta}\right)^{-1} + C_{center} \,. \qquad (22)$$

A. Pinzke, C. Pfrommer, Simulating the gamma-ray emission from galaxy clusters: a universal cosmic ray spectrum and spatial distribution, MNRAS 277 (2010), arXiv:1001.5023v2

J-Values for Clusters (no uncertainties included, no substructure assumed)

Cluster	Annhihilation [1)] $[10^{17}\,GeV^2\,cm^{-5}]$	Decay [2)] $[10^{18}\,GeV\,cm^{-2}]$
AWM7	1.4	10.2
Coma	1.7	16.6
Centaurus	2.7	13.7
Fornax	6.8	18.4
M49	4.4	11.1

1) Constraints on Dark Matter Annihilation in Clusters of Galaxies with the Fermi Large Area Telescope, arXiv:1002.2239v4, Ackermann et al. (2010)
2) Constraints on Decaying Dark Matter from Fermi Observations of Nearby Galaxies and Clusters, arXiv:1009.5988v2, Jeltema et al. (2010)