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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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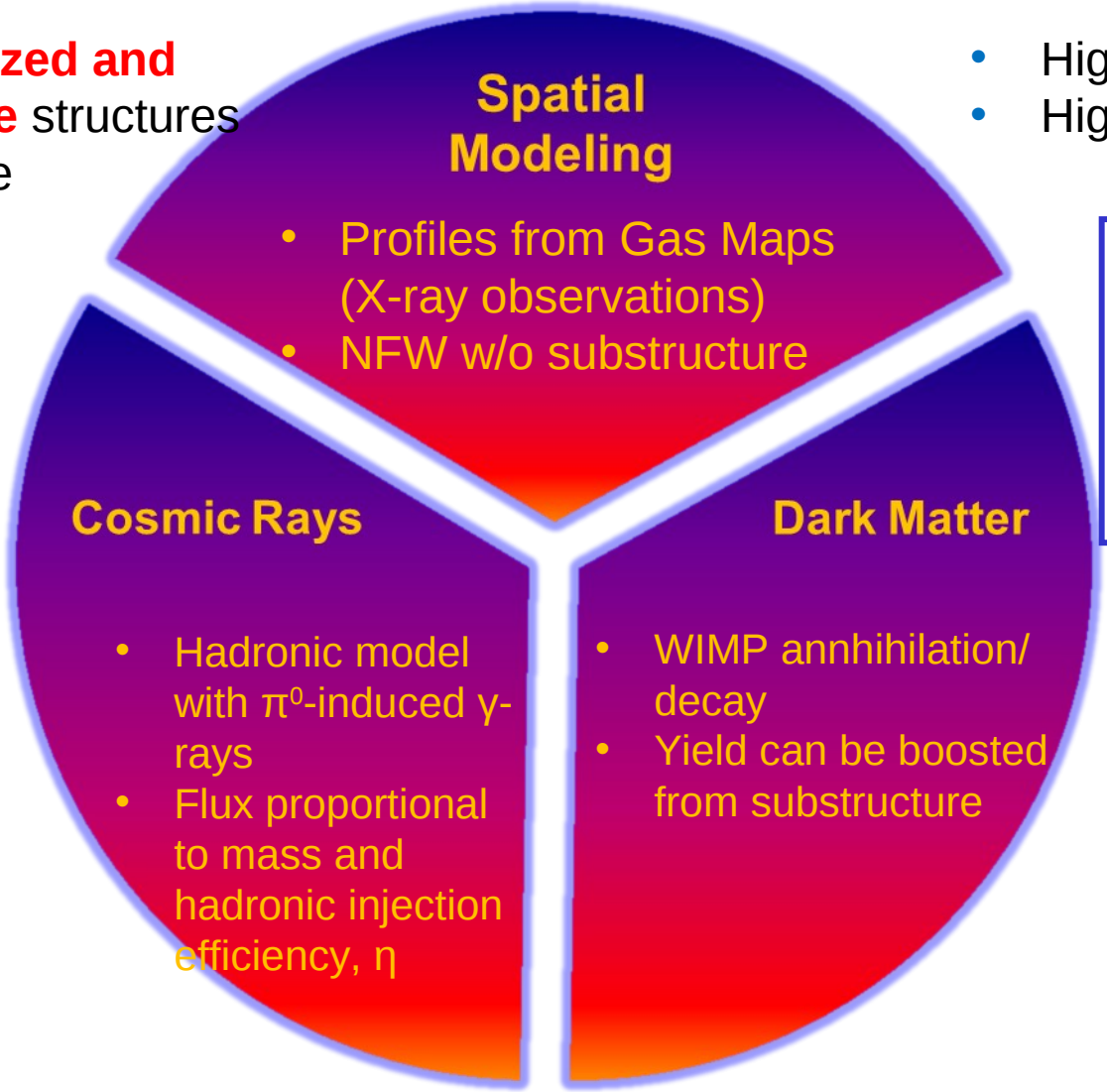
# Gamma Rays from Clusters of Galaxies

- Largest **virialized and most massive** structures in the universe

- High signal levels
- High Backgrounds

- **Radio emission** suggests rel. CR population

- **Lensing and X-Ray** observations indicate large dark matter (DM)



# Gamma Rays from Clusters of Galaxies

- Largest **virialized and most massive** structures in the universe

- High signal levels
- High Backgrounds

**Spatial Modeling**
- Profiles from Gas Maps (X-ray observations)
- NFW w/o substructure

**Cosmic Rays**
- Hadronic model with $\pi^0$-induced $\gamma$-

**Dark Matter**
- WIMP annhihilation/ decay

- **Radio emission** suggests rel. cosmic ray (CR) population

**Lensing and X-Ray** observations indicate large dark matter (DM) (e.g.*arXiv:astro-ph/0611496v1*)

*"Simulating the gamma-ray emission from galaxy clusters: a universal cosmic ray spectrum and spatial distribution"* (*Pinzke & Pfrommer, arXiv:1001.5035*)

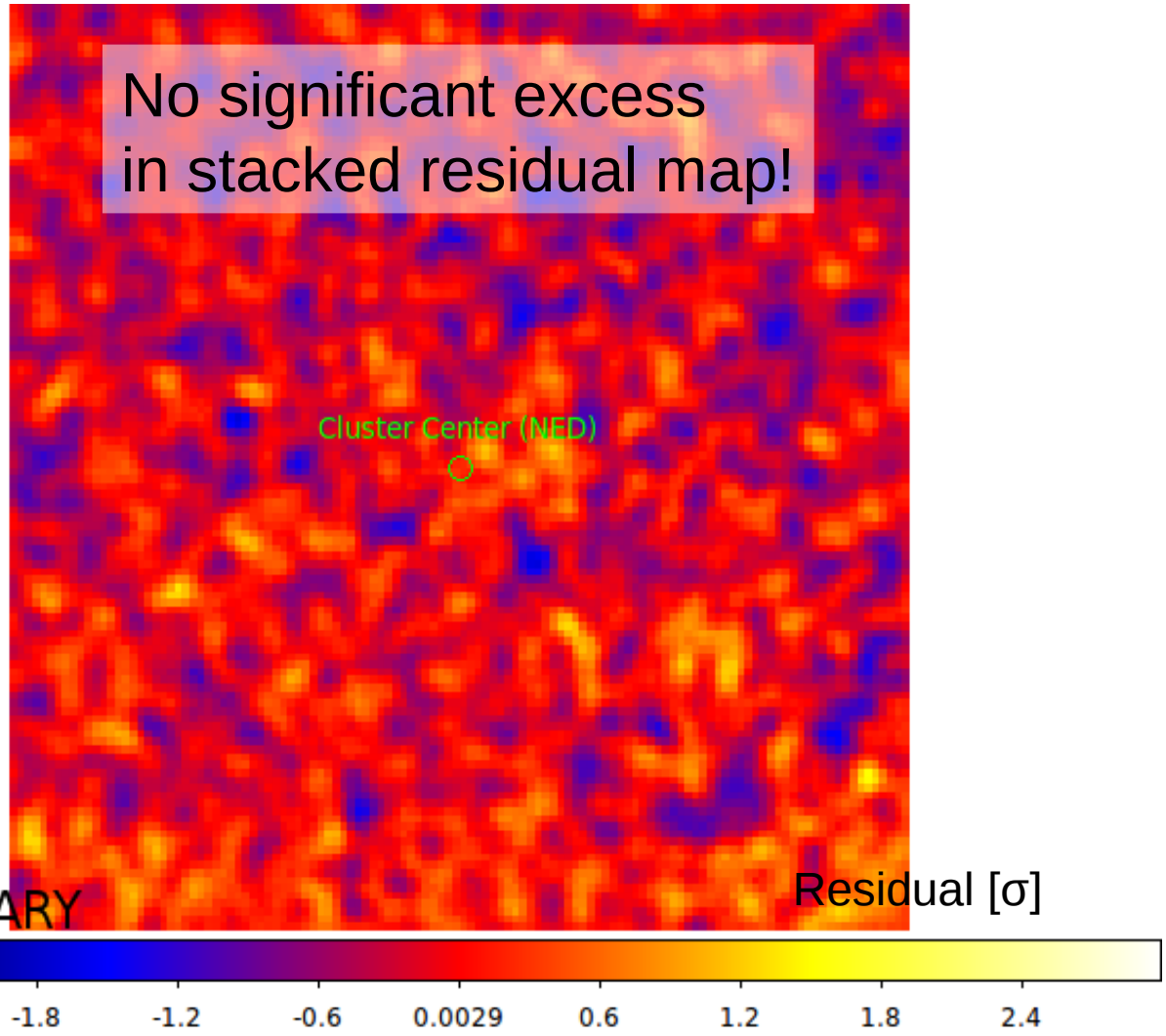
$$\Phi_{WIMP}(E,\Psi) = J(\Psi) \times \Phi^{PP}(E)$$

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

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

# Looking at the 'Stacked Residual Map‘
*(results from previous analysis iteration)*

- 24 Months of Fermi-LAT data, **p6v11 Diffuse** class Events
- Binned analysis, **10 deg ROI**, 20 Energy Bins from 200 MeV – 100 GeV
- Clusters modeled as **point sources**!



# Looking at the 'Stacked Residual Map‘
*(results from previous analysis iteration)*

**We don't see anything!**

# The Combined Likelihood Approach

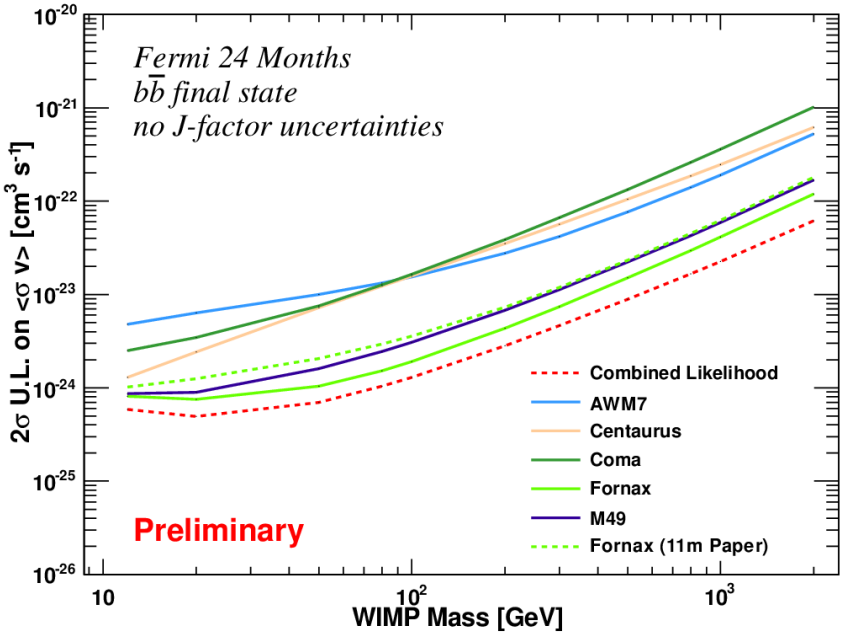
- In both cases, CR and DM have **common parameter** in all clusters:
  - Annihihilation cross section or decay time (**<σv>** or **τ**)
  - Maximum Injection Efficiency, **η**
- Powerful tool that puts tight constraints on a parameter of interest, **profiling over nuisance parameters**
- Implemented 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)

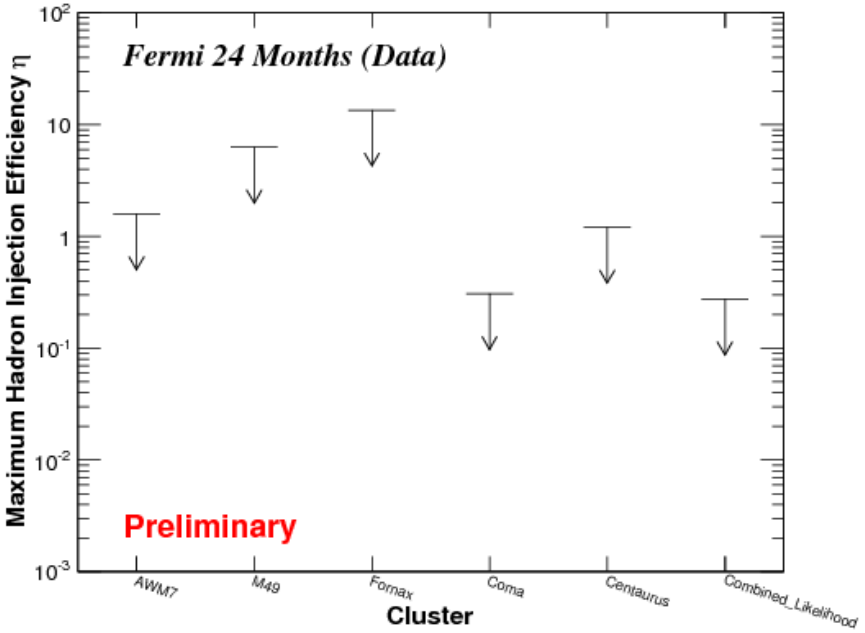
$$L\left(\langle\sigma v\rangle, m_{WIMP} \middle| obs\right) = \prod_i L_i\left(\langle\sigma v\rangle, m_{WIMP}, c, b_i \middle| obs_i\right)$$

- For more details on technique see *Ackermann et al. Phys. Rev. Lett. 107, 241302 (2011)*

# Combined Upper Limits on <σv> and η

*(from previous iteration of the analysis)*




- Combined DM Limits ~ **factor 2 better than individual** ones (varying for cluster and mass points)
- Initial CR results favor **η ≤ 0.5**
- **Coma only constraining** cluster in CR analysis (limits below 0.5); S/N tests indicates **several more within reach** of Fermi-LAT

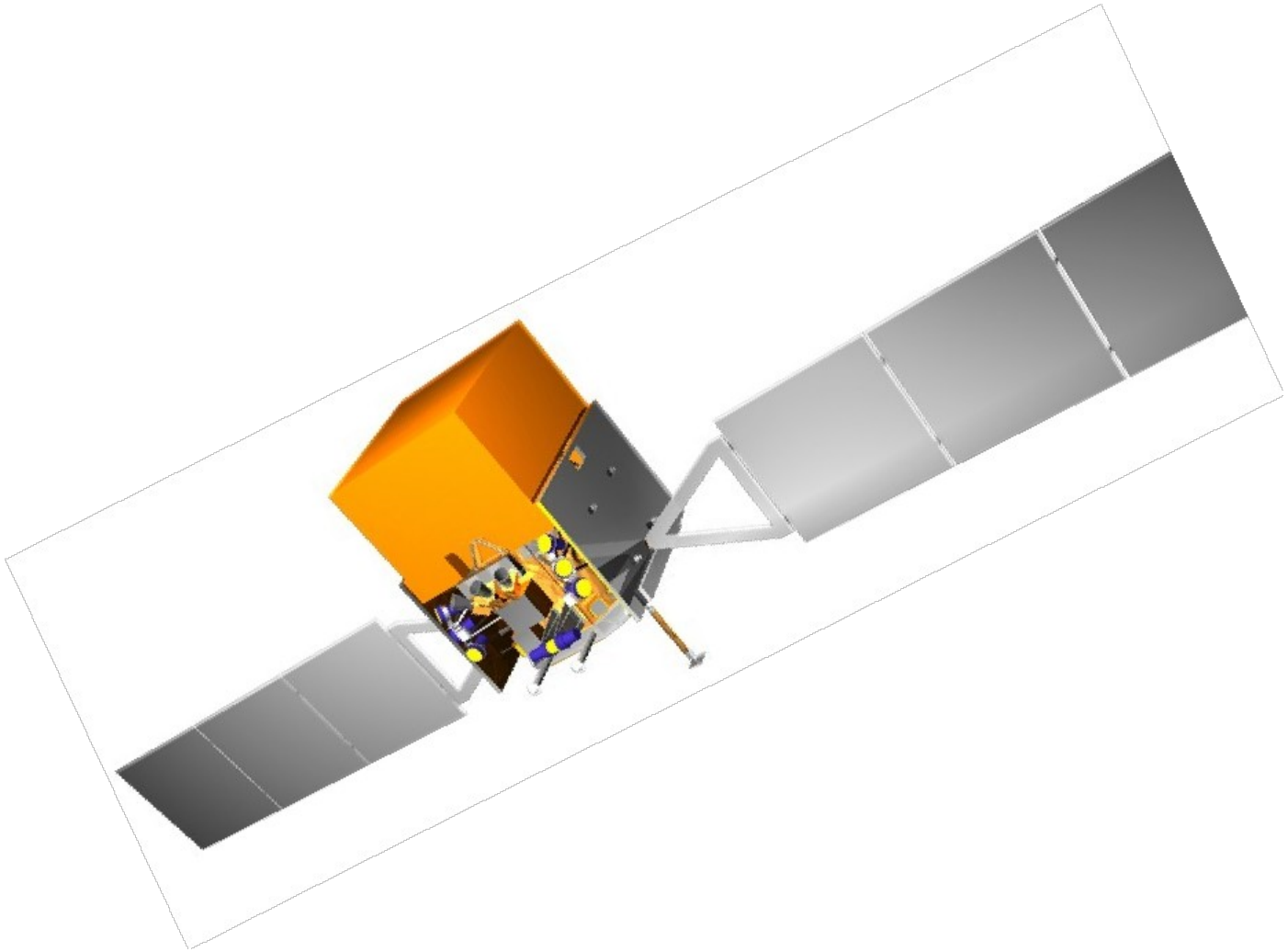
# Summary and Outlook

- Clusters of Galaxies **interesting targets both for CR and DM** searches but **no observational evidence** for $\gamma$-rays so far

  **UPDATE:** (*arXiv:1201.1003*) reporting evidence of extended $\gamma$-ray emission in Virgo, Fornax & Coma (but *arXiv:1201.0753* reports only upper limits)
- Individual fits are compatible with the **non-observation hypothesis**
- Combined Likelihood approach feasible as **all clusters should reflect same physical properties**
- Details on (optimistic) point-source analysis in **(***arXiv:1110.6863***)**
- A paper with details on careful modeling of clusters as **extended sources** considering both **CR- and DM-induced $\gamma$-ray** signals is in the works

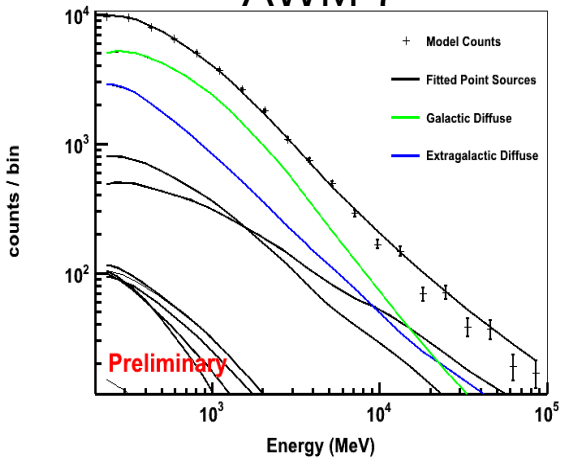
**Thank you for your Attention!**

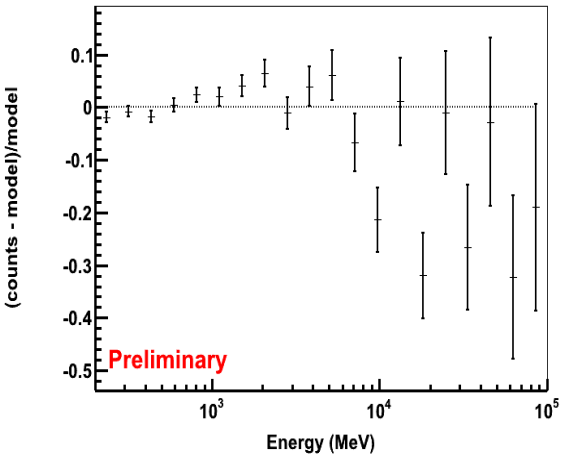
# Backup Slides



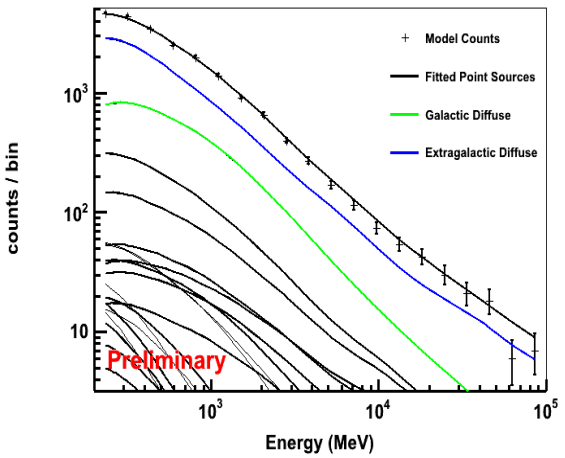
# Individual Fit Results (500 GeV DM Mass)

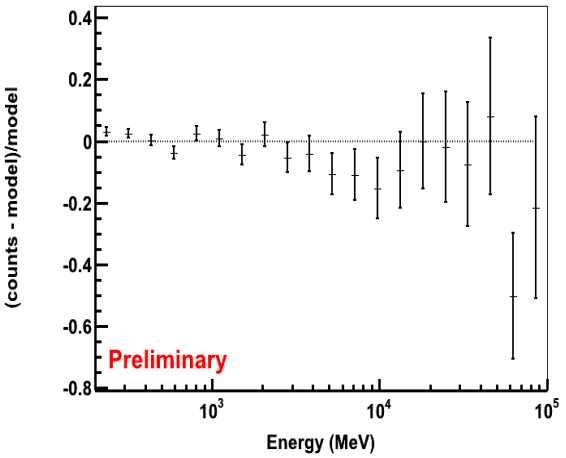
AWM 7



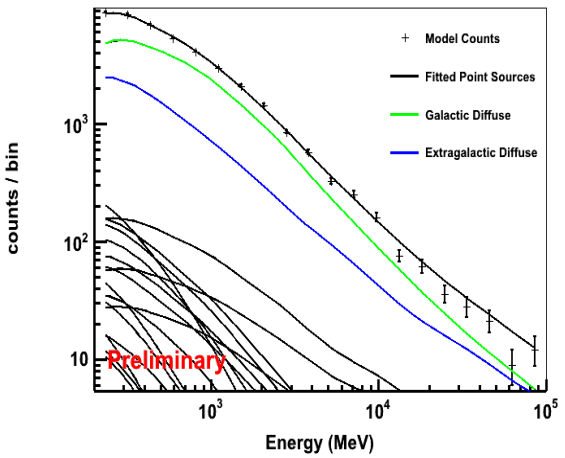



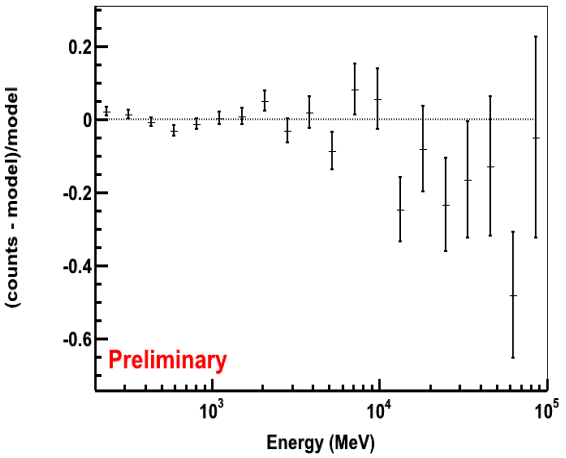

Coma



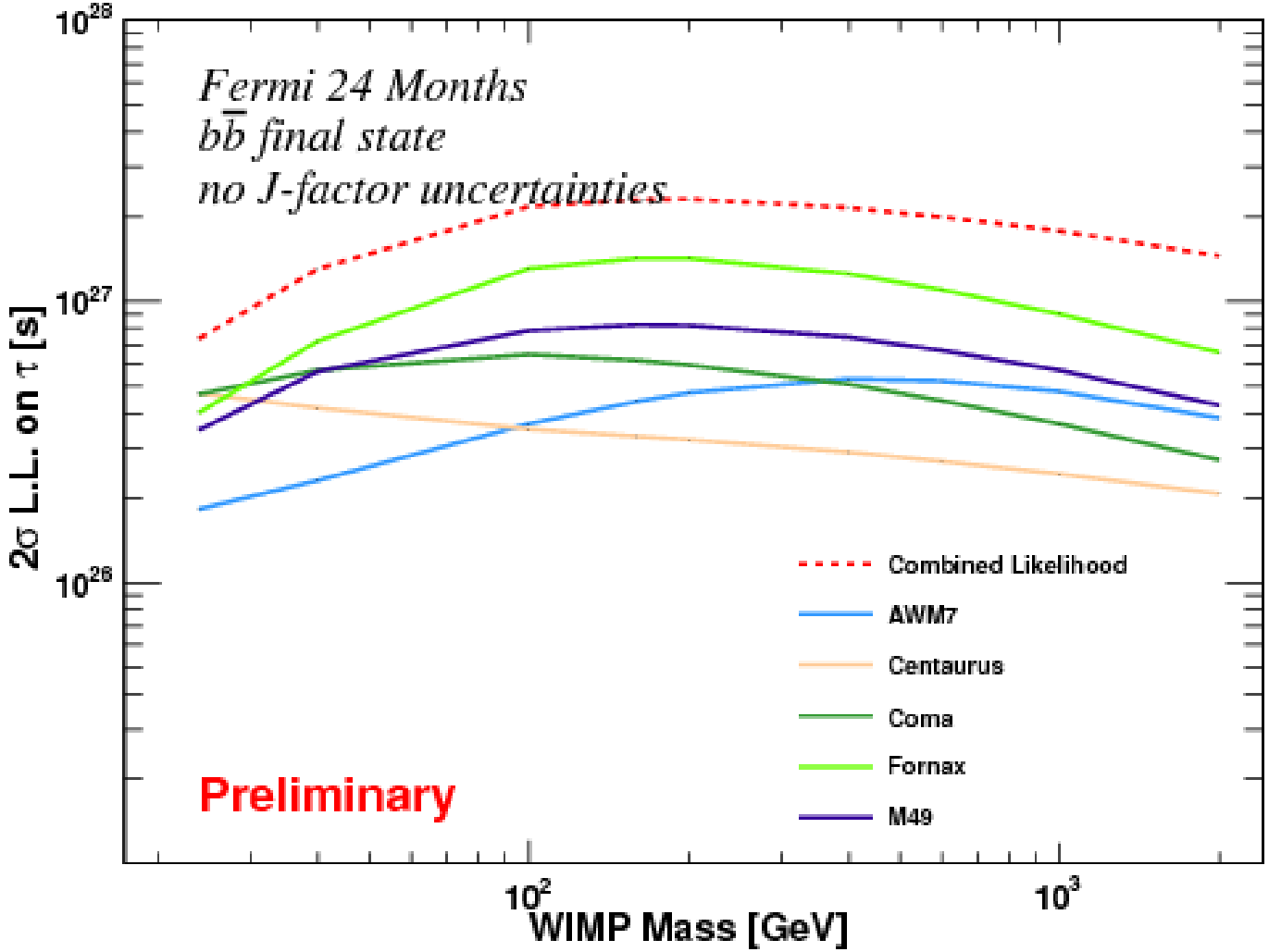




Centaurus

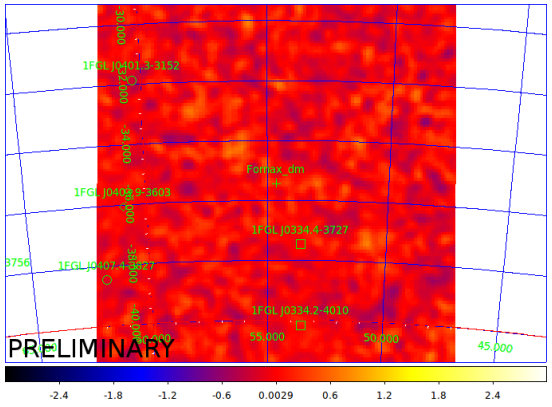


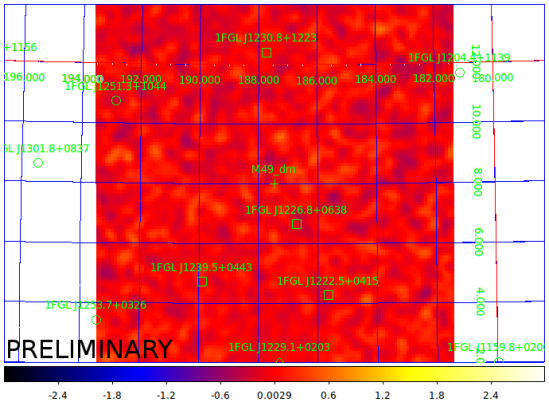



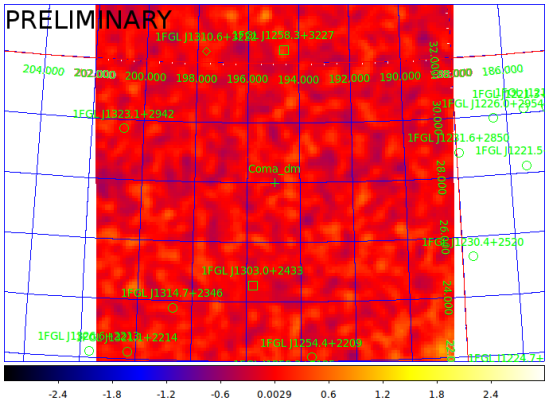
# Combined Lower Limits on τ (Decaying DM)

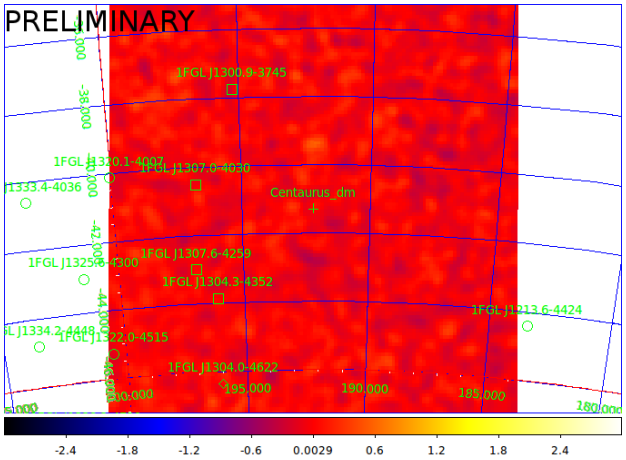


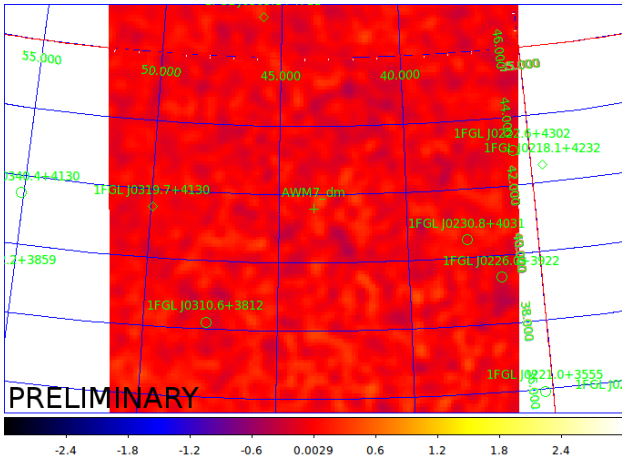
# Individual Residual Maps in Sigma



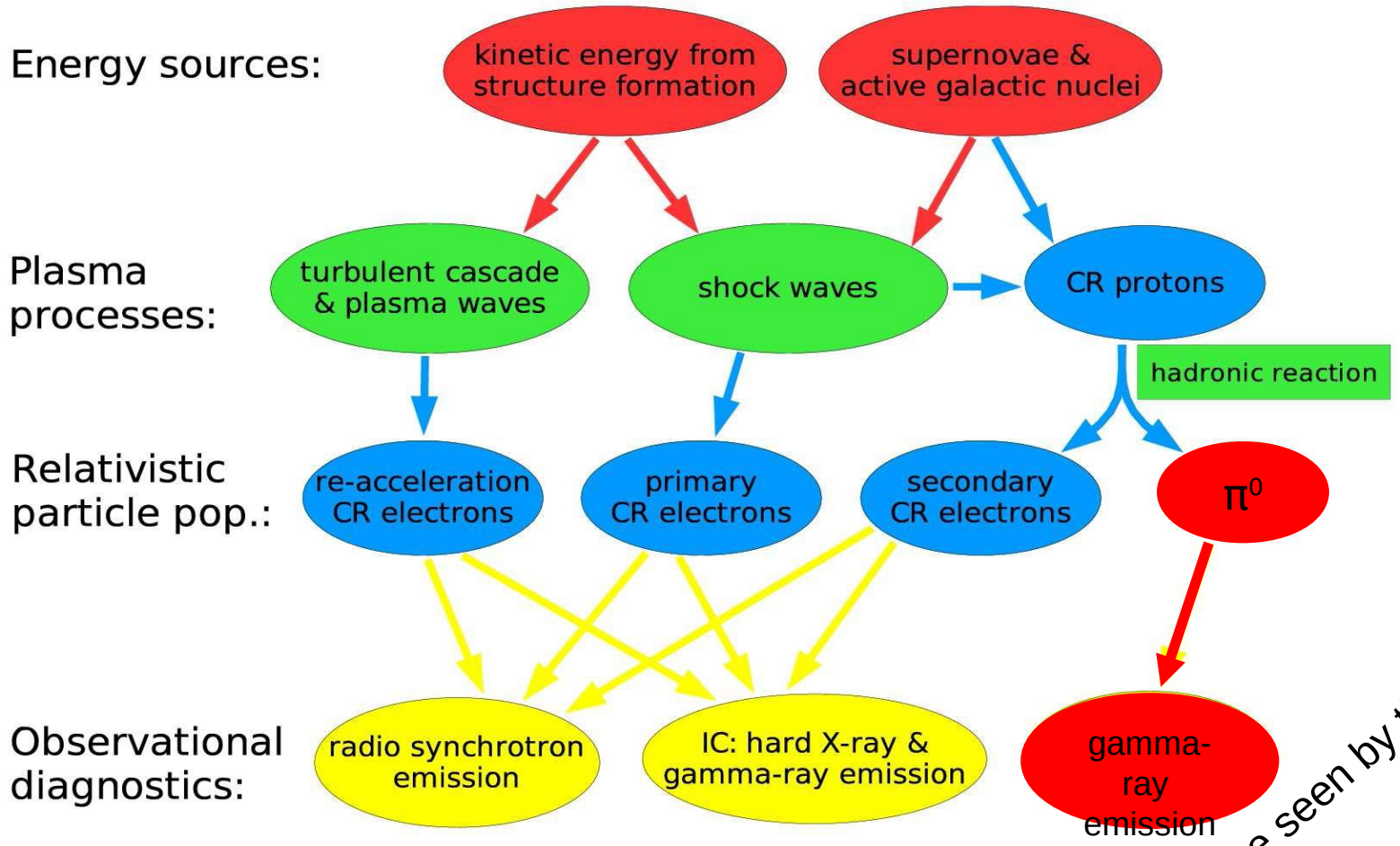



# γ-Ray Emission from Clusters of Galaxies

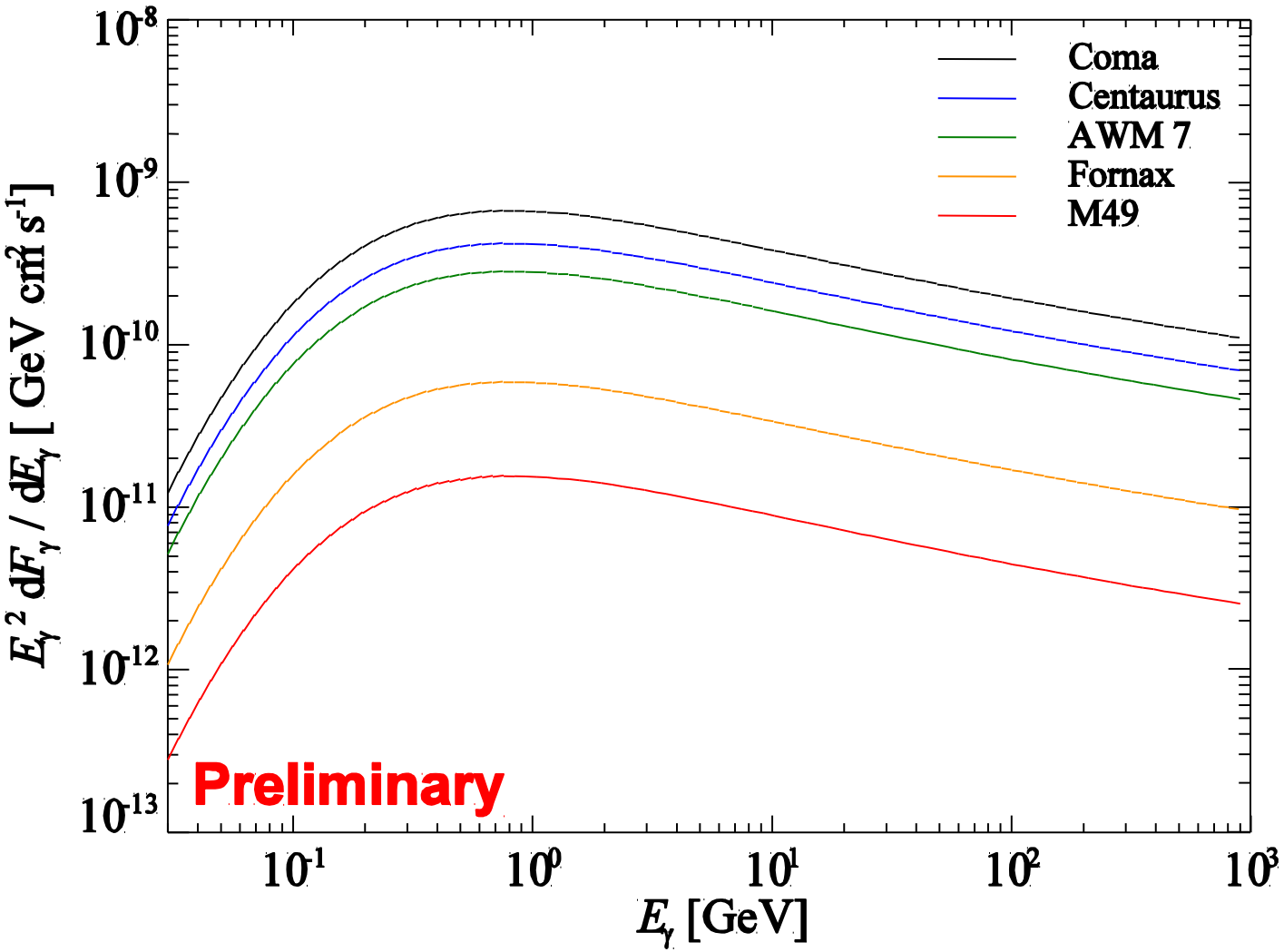
C. Pfrommer et al., MNRAS, 378:285-408 (2007) [modified]

Relativistic populations and radiative processes in clusters:




Could be seen by the LAT!

# 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**

# 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)