Towards the first gamma rays from Galaxy Clusters: Searches for Cosmic Rays and Dark Matter

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Special Thanks to: J. Conrad, O. Reimer, M. Gustafsson, M. Sánchez-Conde, A. Pinzke, C. Pfrommer (+ Fermi-LAT collaboration)

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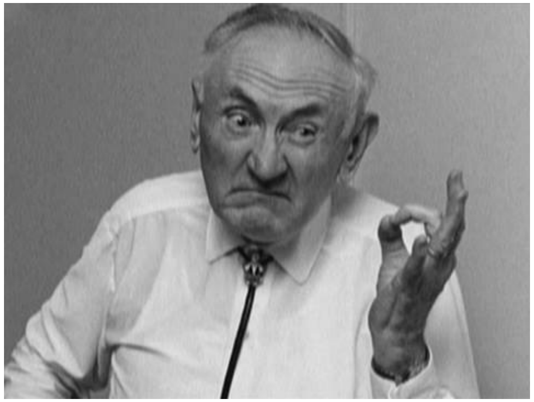
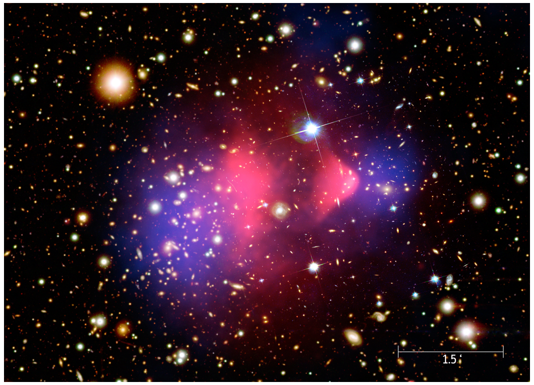
Outline

- Galaxy Clusters and Dark Matter
- Fermi-LAT & Gamma Ray Sky
- DM Searches in clusters
- CR-induced Gamma Rays in clusters and implications of non-detection

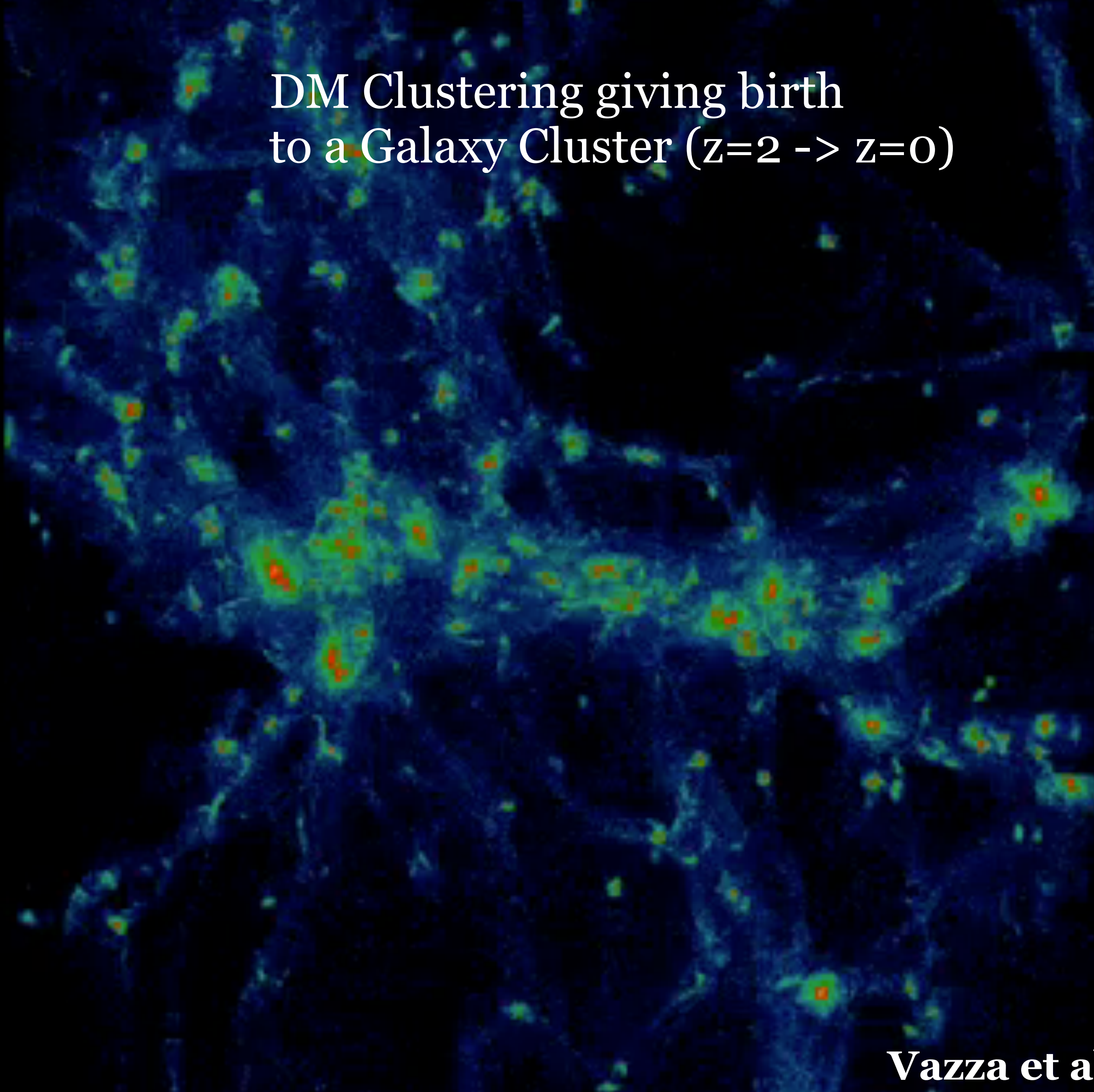
A Galaxy cluster primer

- largest and most massive gravitationally bound systems in the universe (r_{200}~Mpc, M~10^{14}-10^{18} M_{sun})
- DM dominated systems -> original discovery of Dark Matter by Fritz Zwicky (1933)
  - DM is directly observed through gravitational lensing
- believed to have form through hierarchical structure formation
  - accretion of baryonic matter onto gravitational wells of DM
  - merger events
- most baryonic matter is in form of hot gas (10^4 K)





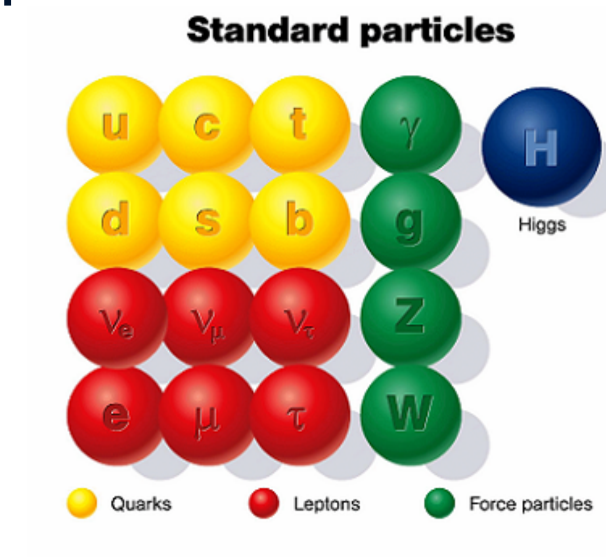
DM Clustering giving birth to a Galaxy Cluster (z=2 -> z=0)

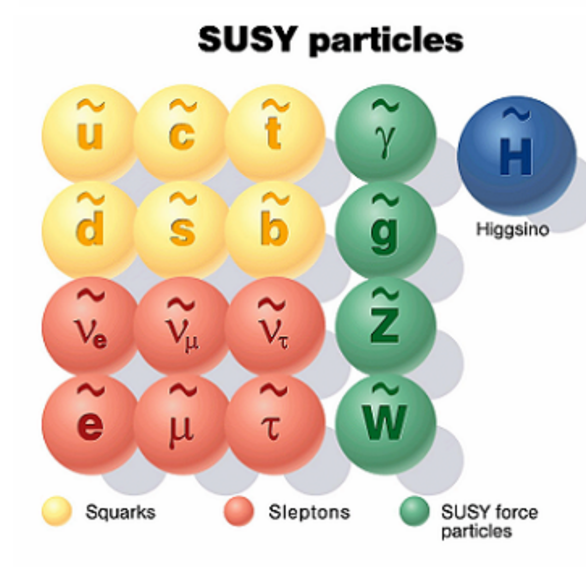


Vazza et al. (2010)

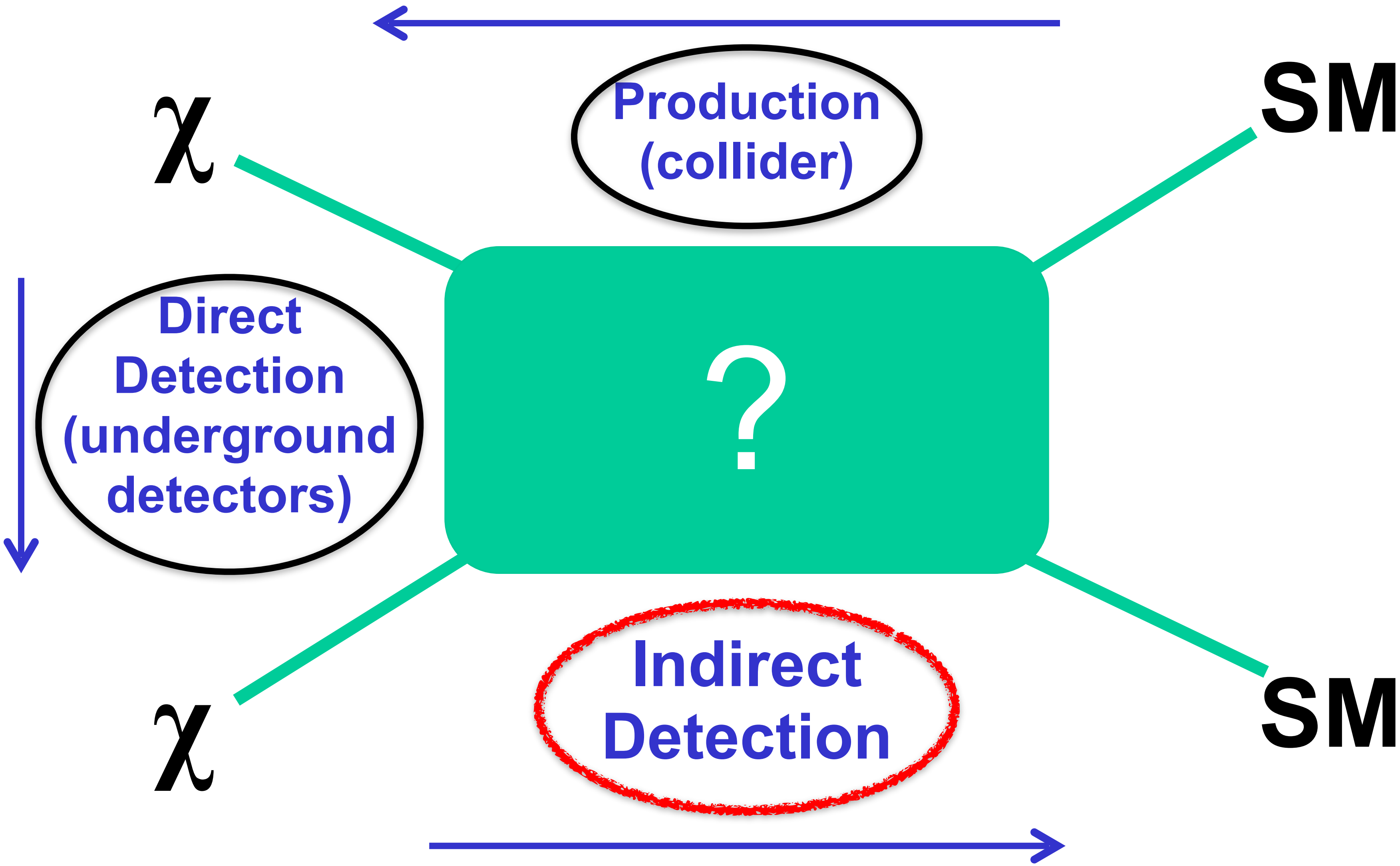
WIMP Dark Matter

- DM must be massive, cannot interact strongly/electromagnetically (with SM particles)
- neutrinos would be ideal candidates, but too light & not abundant enough
- SM extensions (e.g. SUSY) provide natural* WIMP candidates



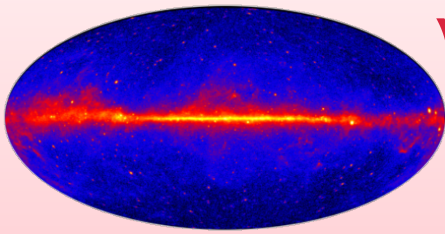


Detecting WIMPs

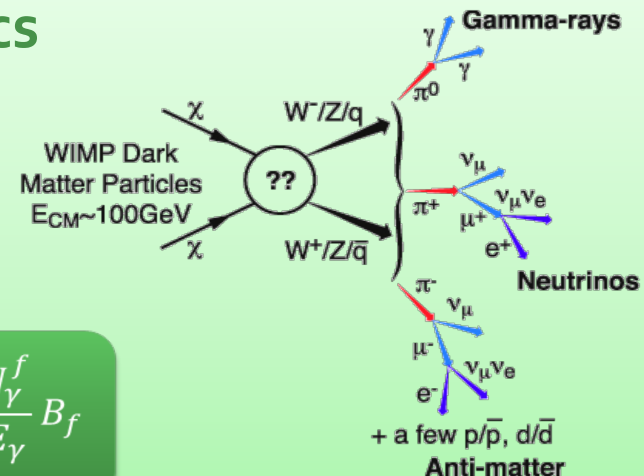


DM-induced γ Rays

γ-ray flux

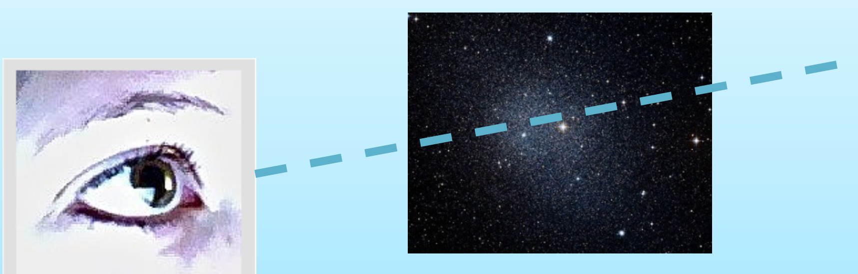


Particle Physics



$$\Phi_{WIMP}(E_\gamma,\psi) = \frac{1}{4\pi}\frac{\langle\sigma_{\text{ann}} v\rangle}{2m_{\text{WIMP}}^2}\sum_f \frac{\mathrm{d}N_\gamma^f}{\mathrm{d}E_\gamma}B_f$$

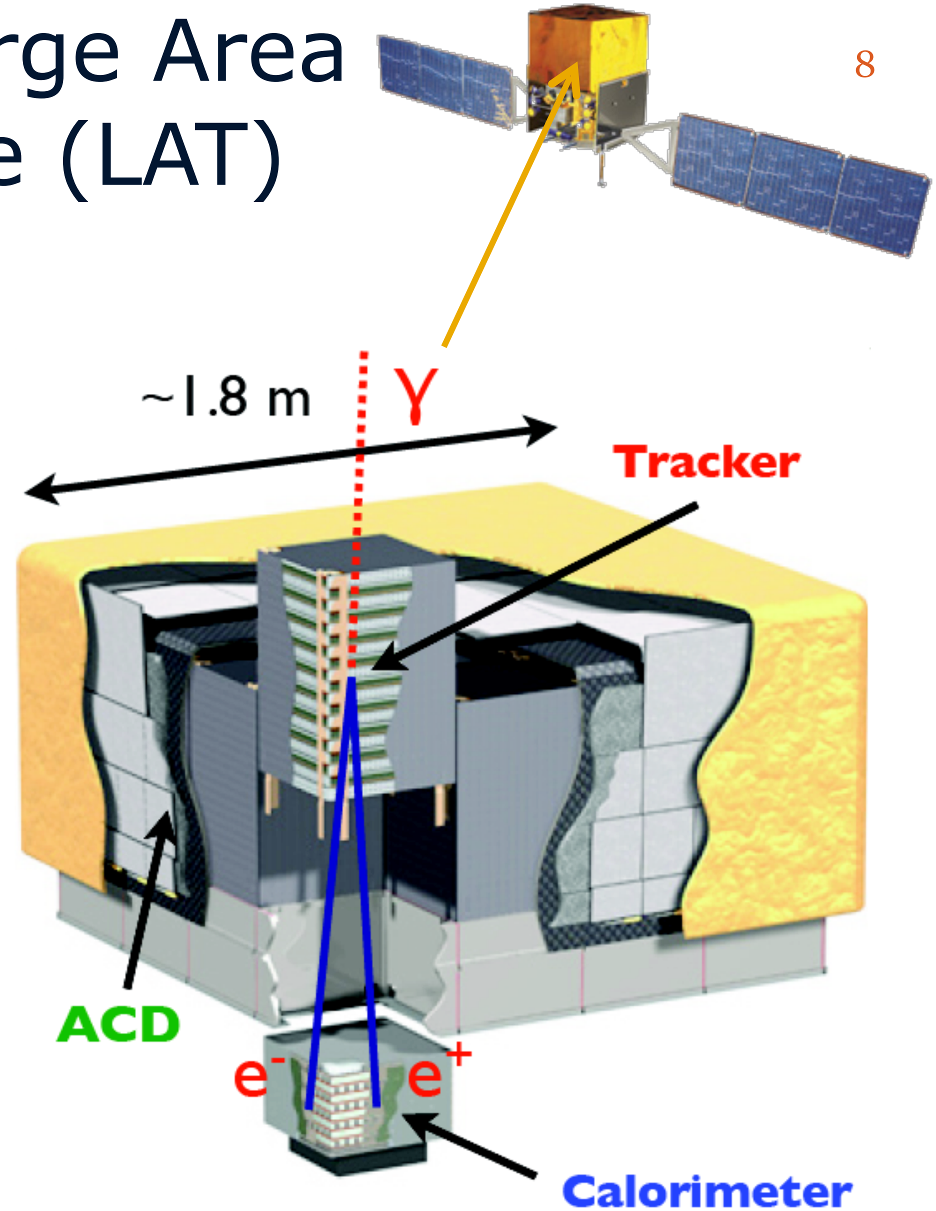
$$\times \int_{l.o.s.} dl(\psi)\rho^2(l(\psi))$$



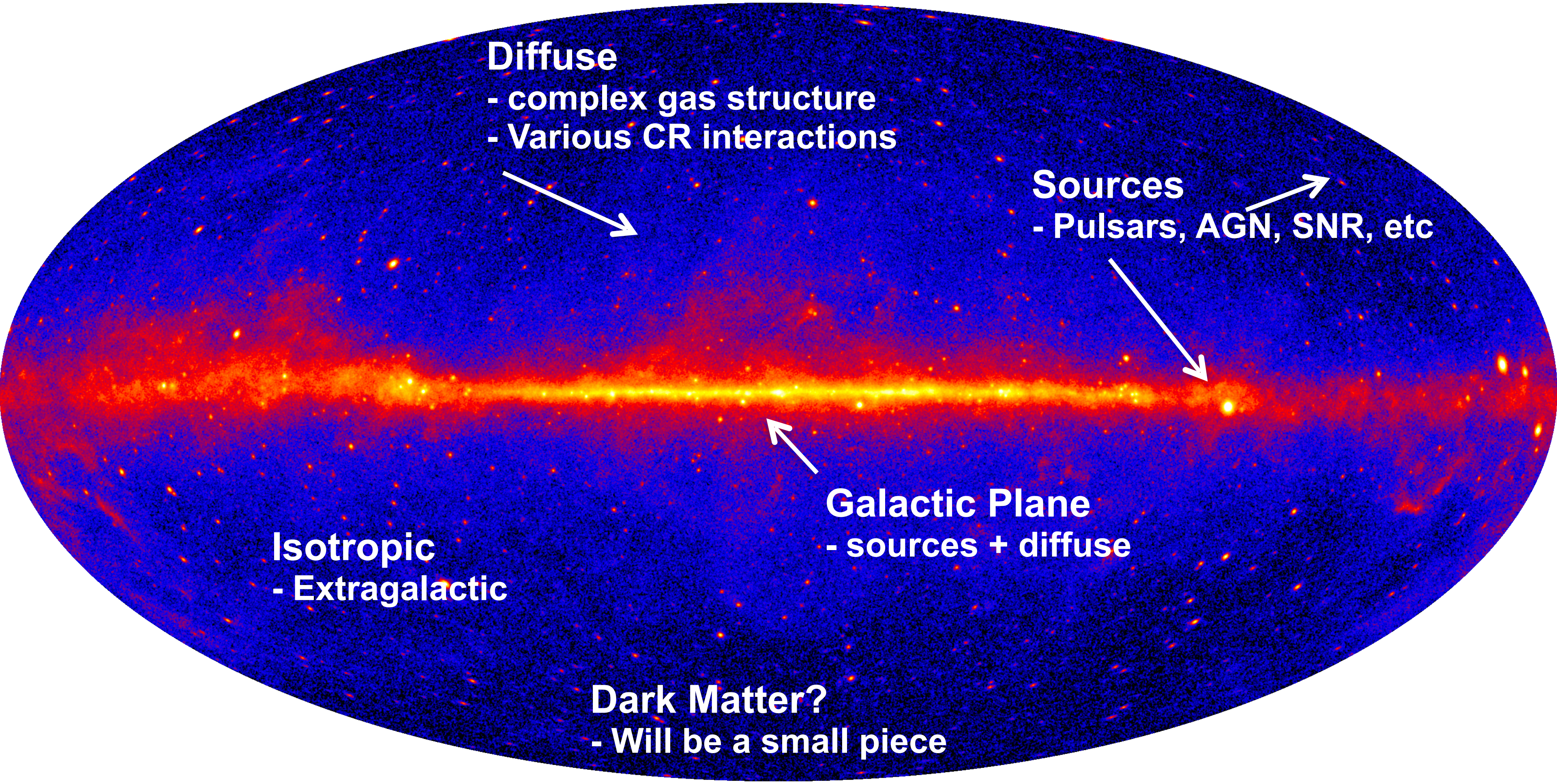
Dark Matter Distribution
"Astrophysical factor" or "J-factor"

Fermi Large Area Telescope (LAT)

- Launch: Jun 11, 2008
  - 5 years in orbit
- Pair conversion technique
  - 20 MeV to >300 GeV
- Principle Mode of Operation:
  - Survey (all-sky coverage every 2 orbits, 3hrs)
- Energy resolution ~10%
- PSF 1° @ 500 MeV
- PS sensitivity: $F > 3x10^{-9}$ $ph/cm^2/s$

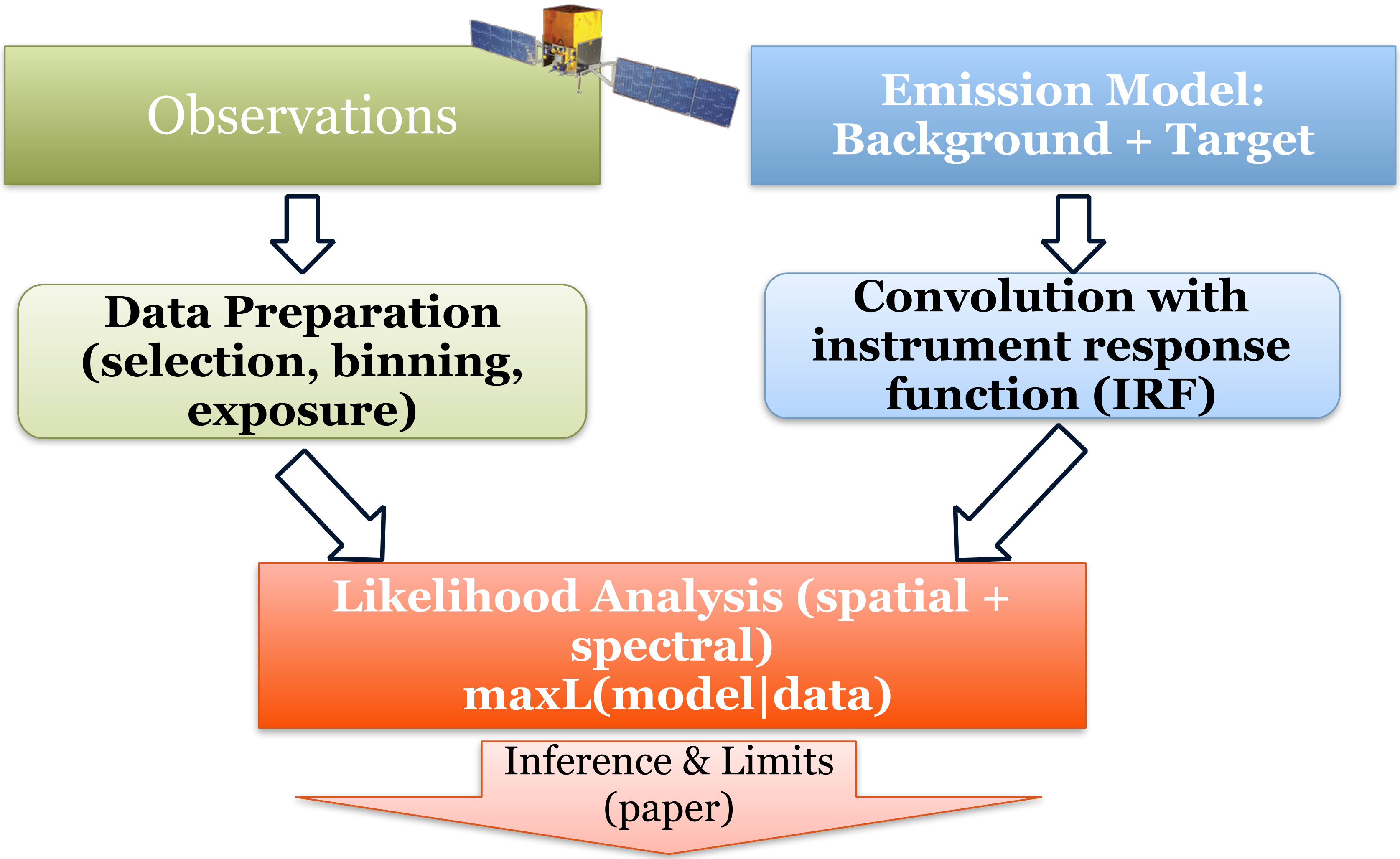


Fermi LAT Gamma-ray Sky

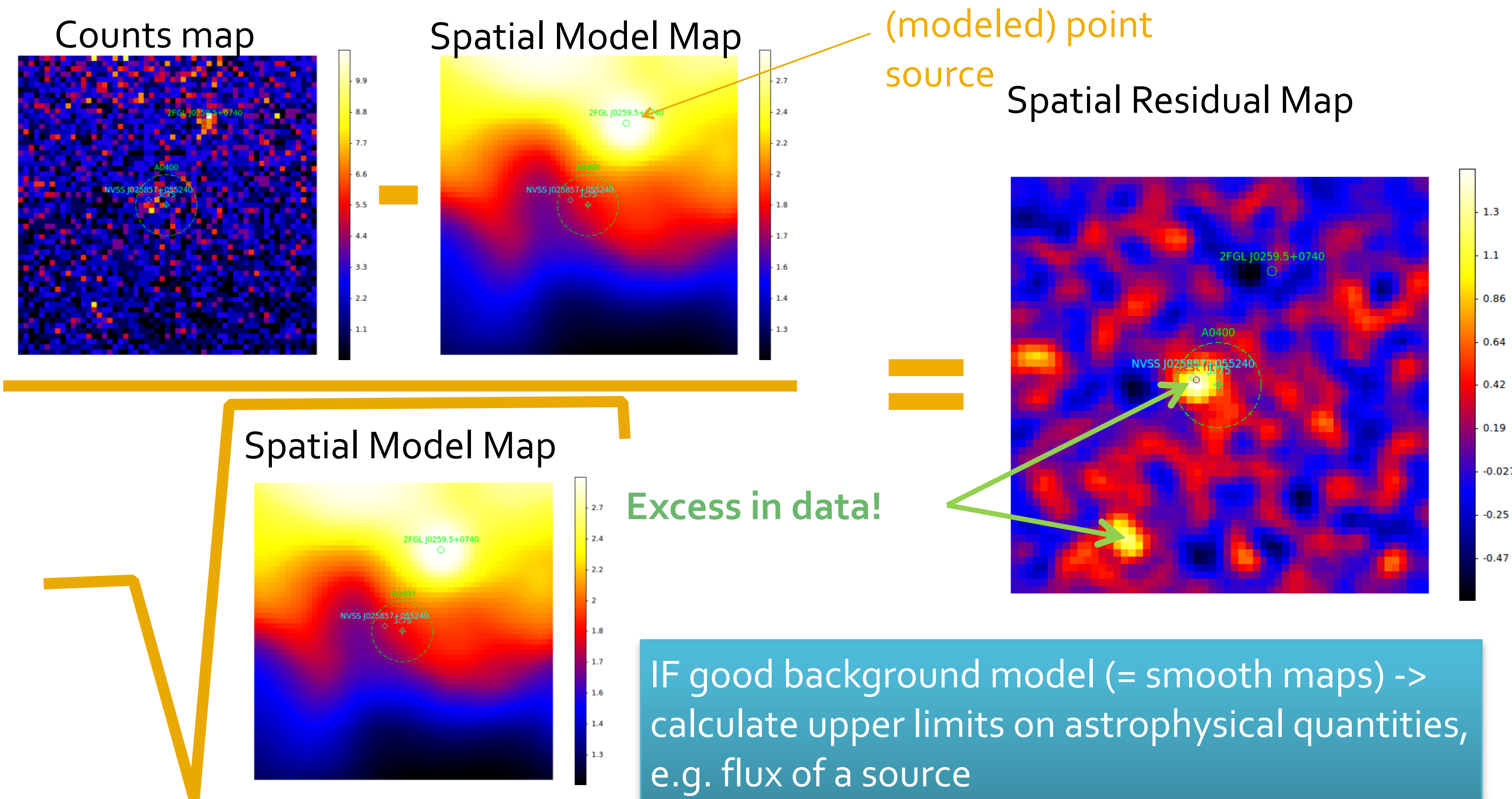


Nature has given us a rich and complicated gamma-ray sky!

Interlude: LAT analysis



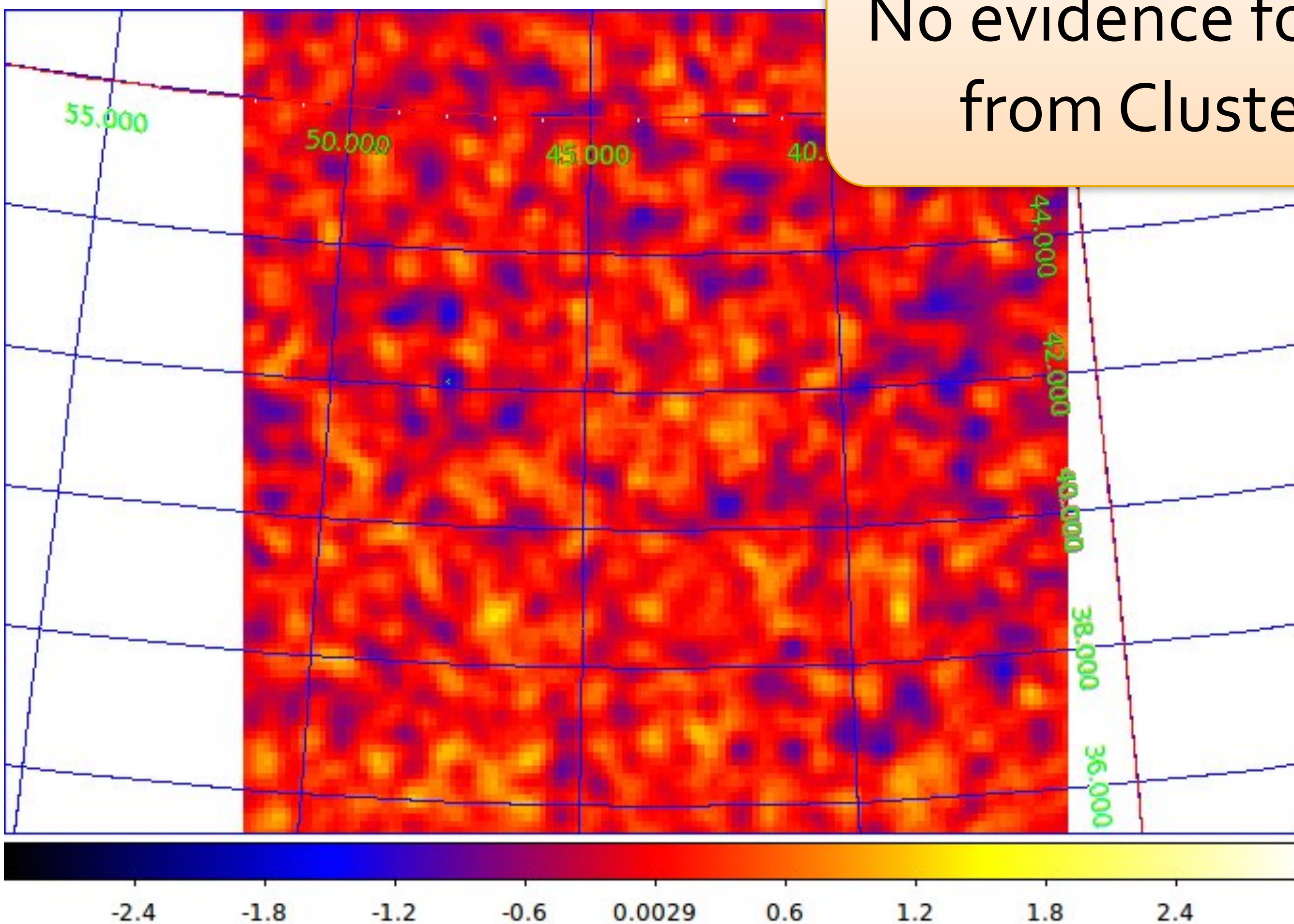
Interlude: LAT analysis (2)



IF good background model (= smooth maps) -> calculate upper limits on astrophysical quantities, e.g. flux of a source

STEP 1: Can simply stack many residual maps on top of each other

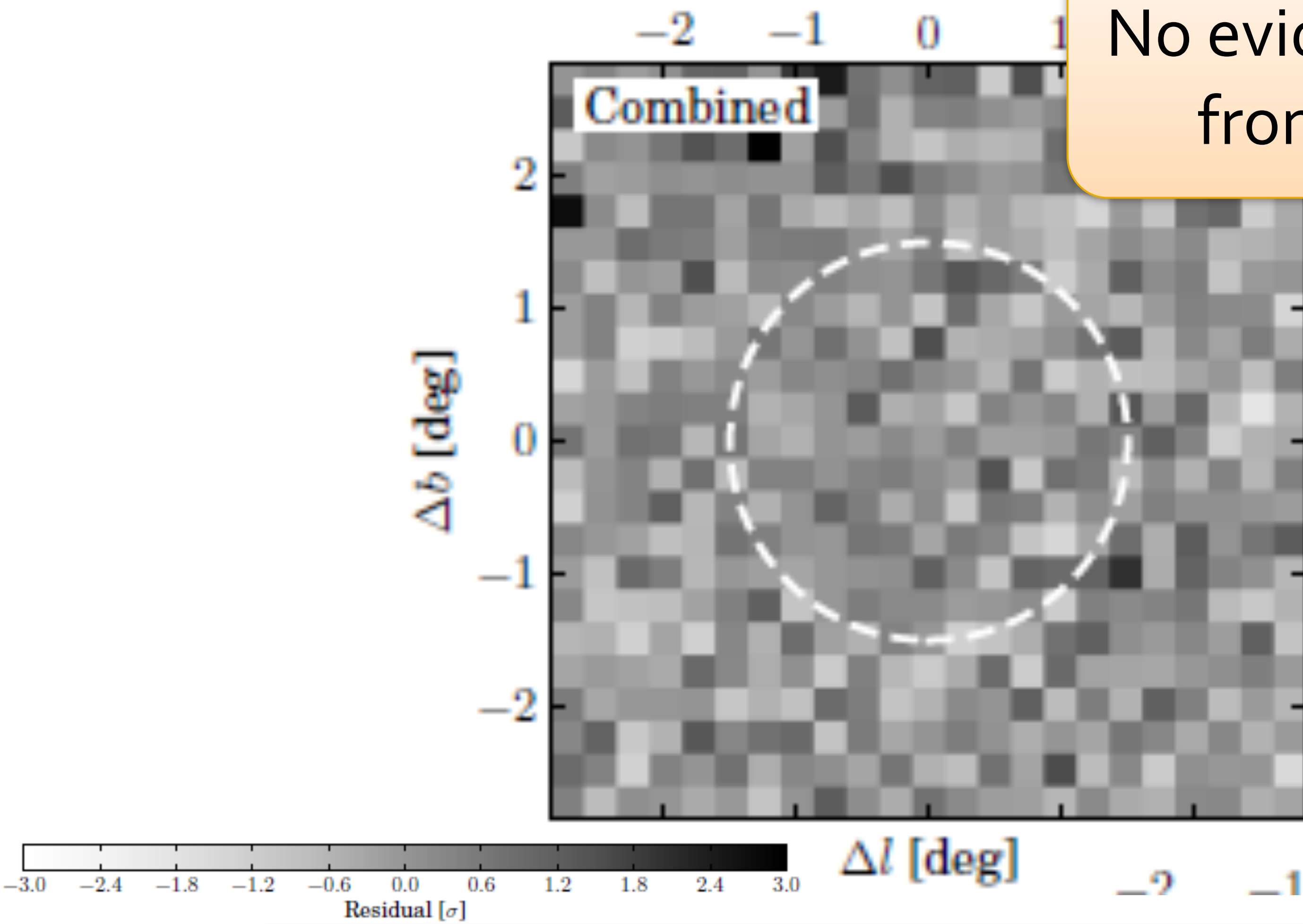
No evidence for γ rays from Clusters ☹



Stacked Residual Map from 5 clusters, 2 years of data SZ+ (for Fermi-LAT Coll., 1110.6863)

STEP 1: Can simply stack many residual maps on top of each other

No evidence for γ rays from Clusters ☹



Stacked Residual Map from 50 clusters, 4 years of data (Ackermann et al., Fermi-LAT Coll. ApJ 787, 18 2014)

Better than stacking: Joint Likelihood Analysis

- Basic assumption: class of sources can be described by one or more **common** parameters "x"

- Optimize each **individual likelihood** before combining them

$$L(x|D) = \prod_i L_i(x_i, b_i, c|D_i)$$

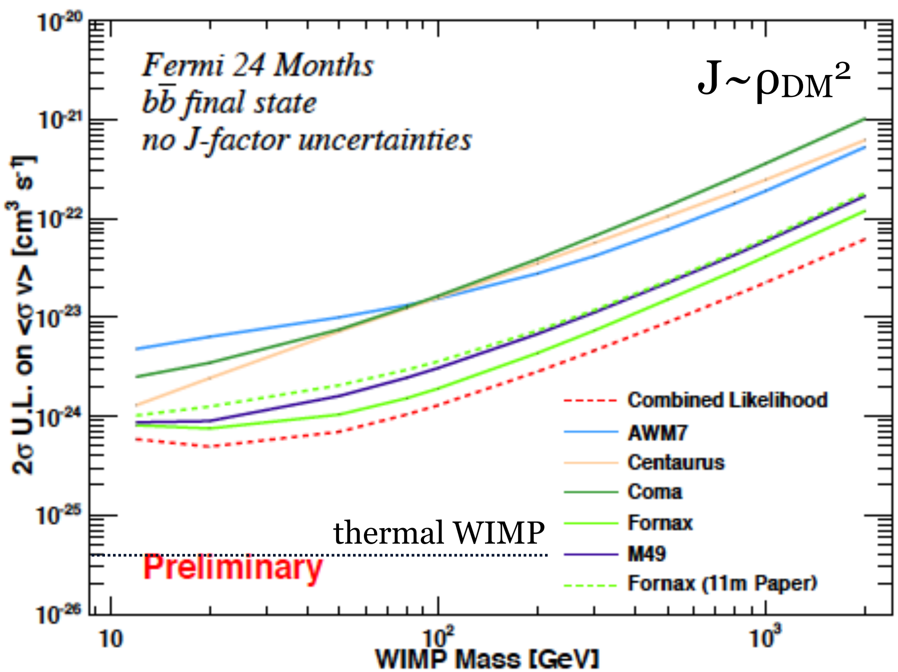
$$\log L(x|D) = \sum_i \log L_i(x_i, b_i, c|D_i)$$

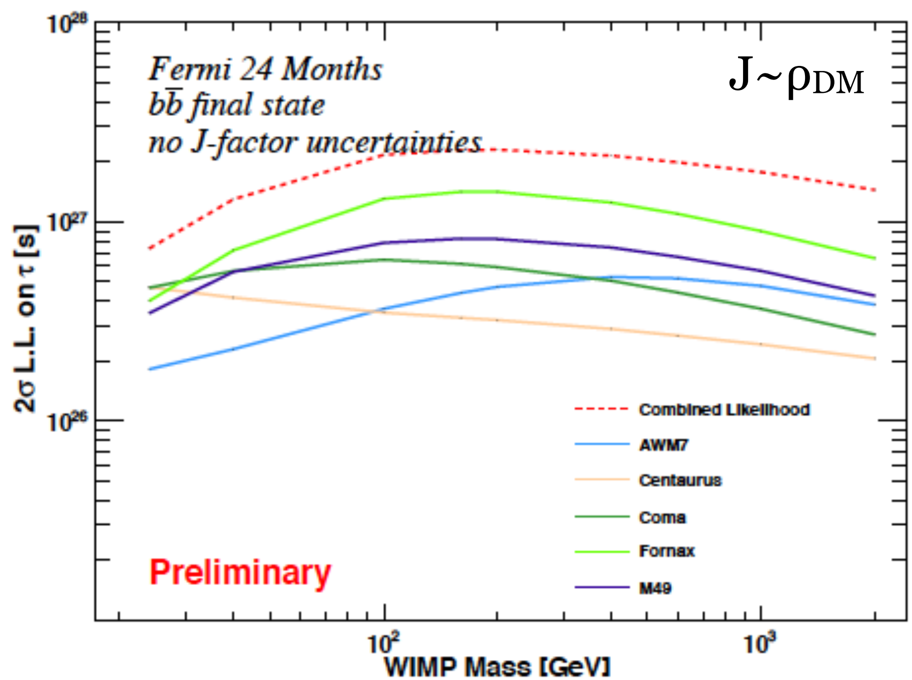
- Use **profile likelihood** method to treat nuisance parameters (e.g. normalization of diffuse emission, background sources)

- Initial analysis in Fermi: **joint dwarf constraints**, Ackermann et al. PRL 107 (2011)

First joint likelihood analysis Annihilation & Decay (2 years of data)

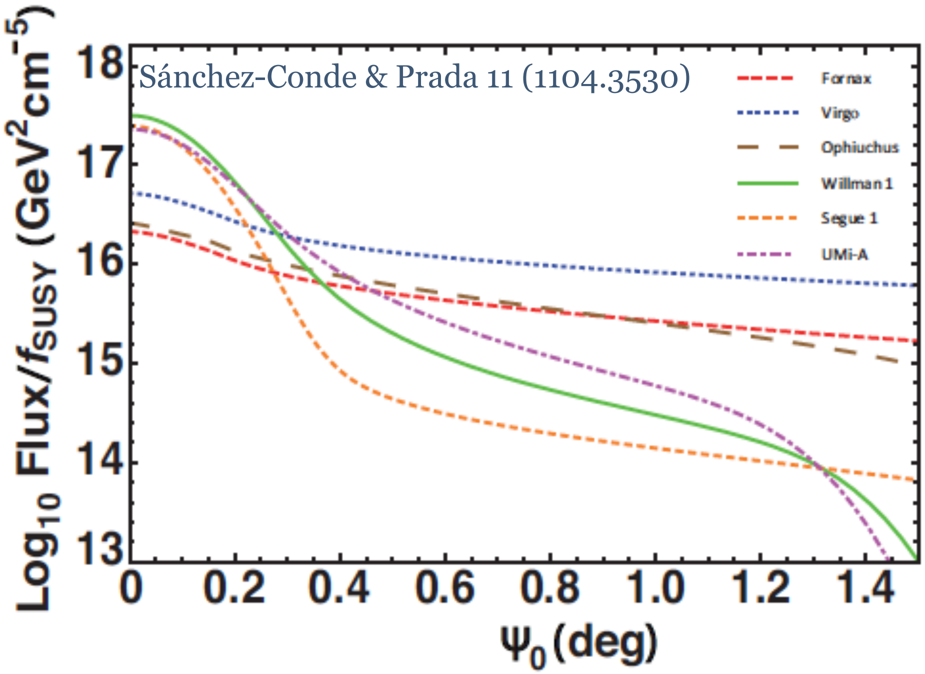
SZ+ (for Fermi-LAT Coll., 1110.6863)

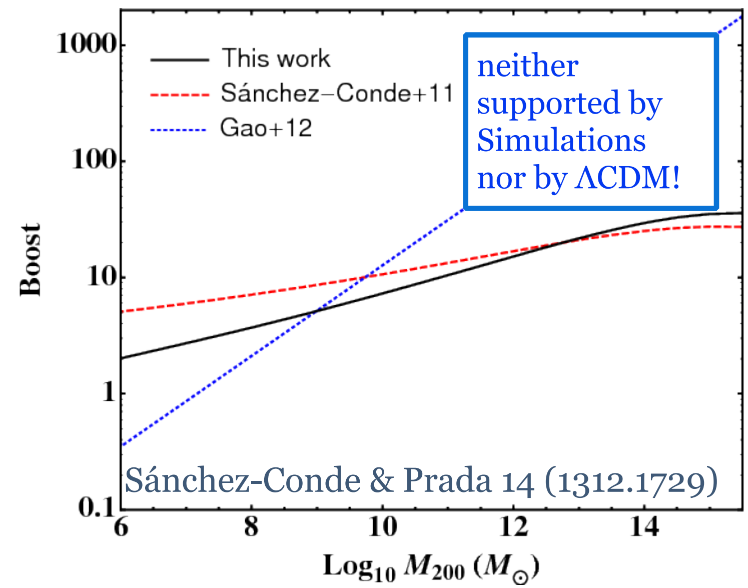




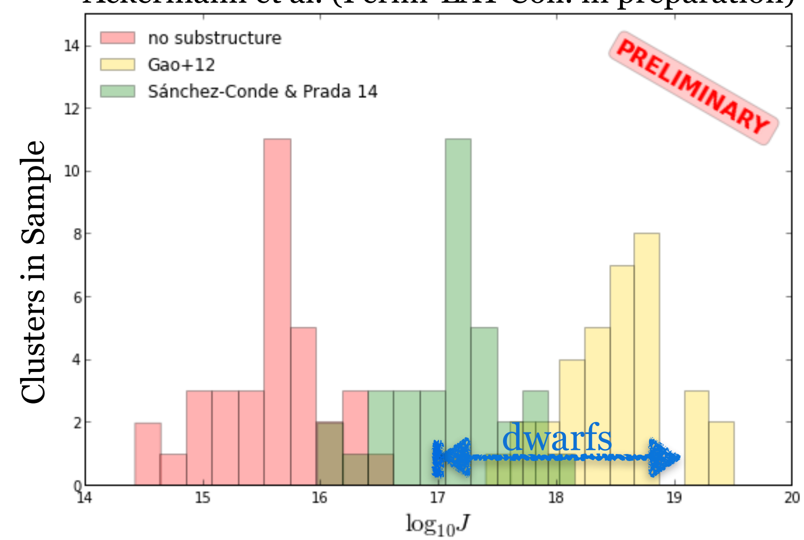
But: No J-factor uncertainties & clusters treated as point sources

Challenge: Substructure





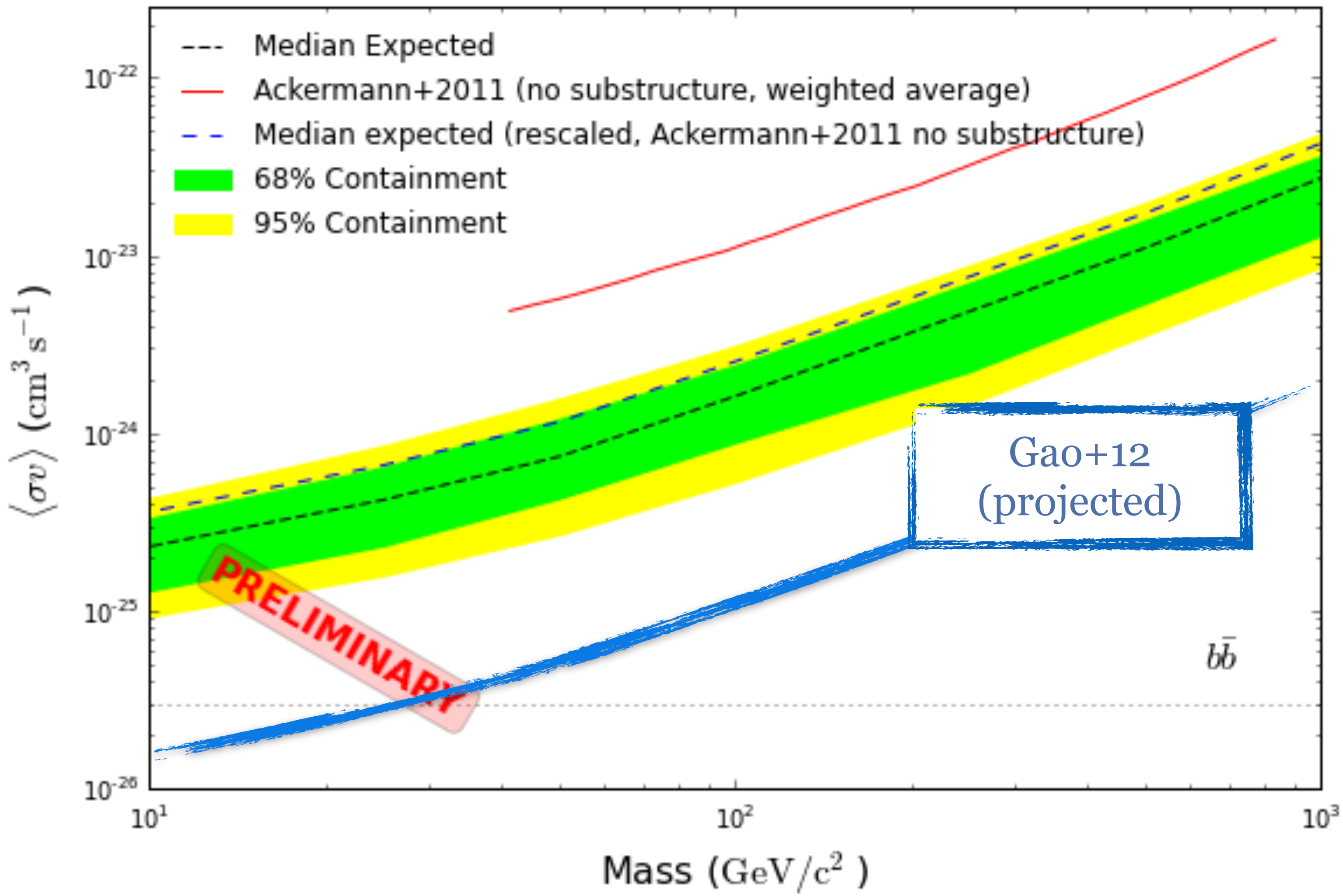
Ackermann et al. (Fermi-LAT Coll. in preparation)



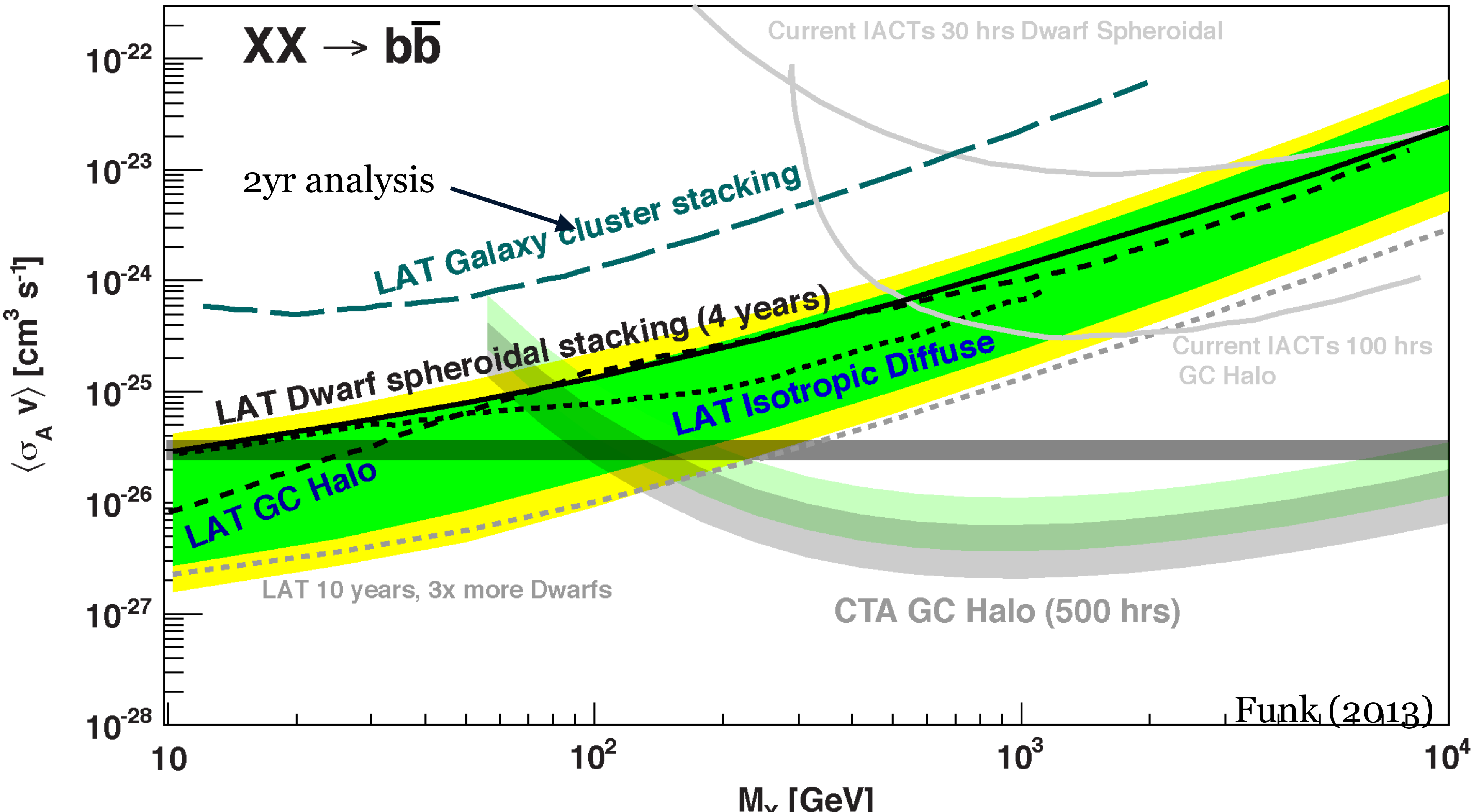
- largest uncertainty in cluster DM limits
- Extrapolation below mass resolution uncertain:
- powerlaw (Gao+12) vs. ΛCDM (Sánchez-Conde & Prada, 14)
- less important for decay!

Expected Sensitivity (5 yrs) (Annihilation case)

Ackermann et al. (Fermi-LAT Coll. in preparation)



Comparison w/ other targets



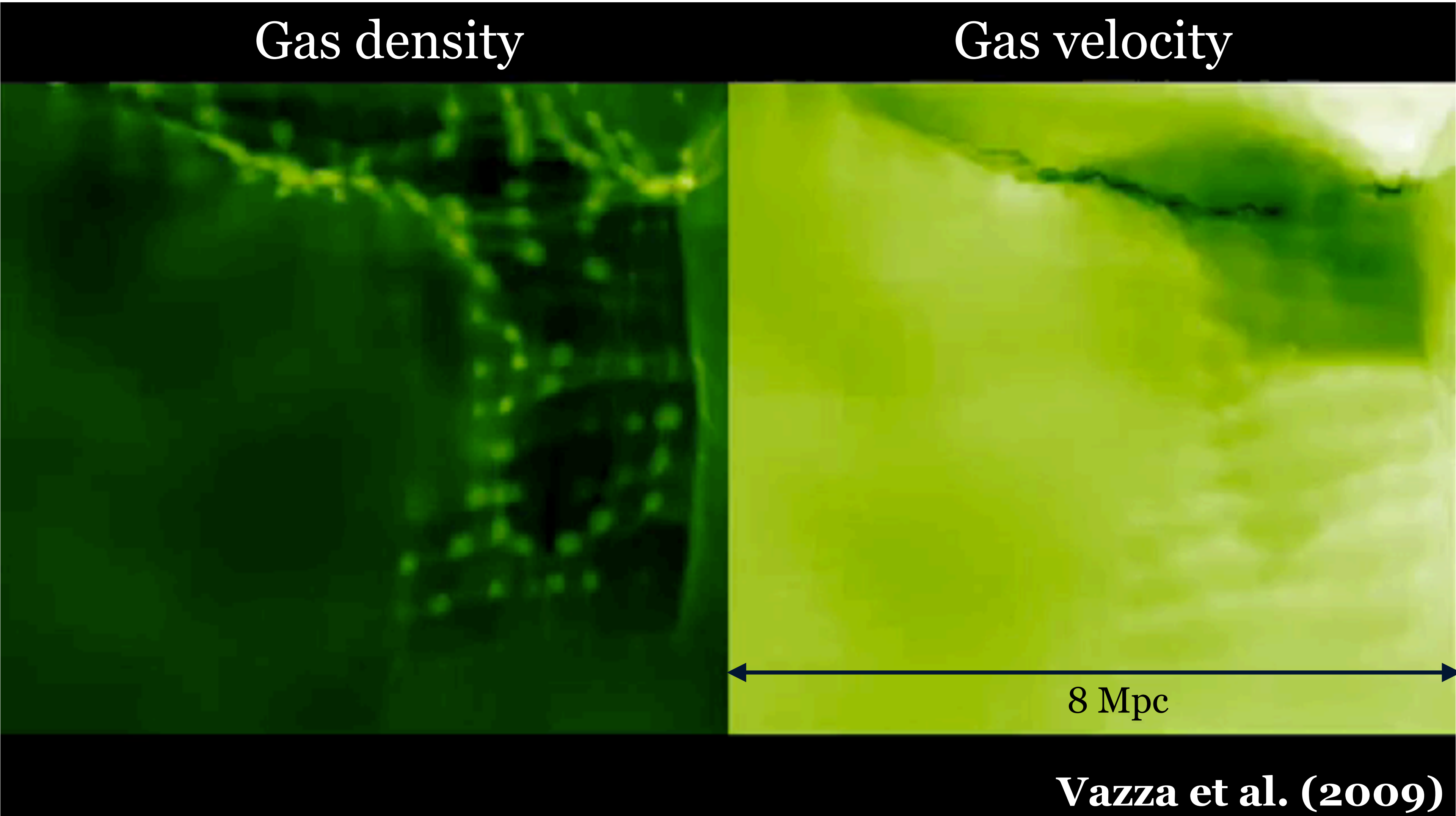
DM from clusters: summary

- NO DM-induced ɣ-rays has been found from clusters (yet)*
- level of substructure may enhance the predicted ɣ-ray flux by a factor of ~100
- generally less important for decay
- detection prospects are OK, but limits are not competitive with e.g. dwarfs - complementary targets

* no ɣ-rays have been found from clusters!

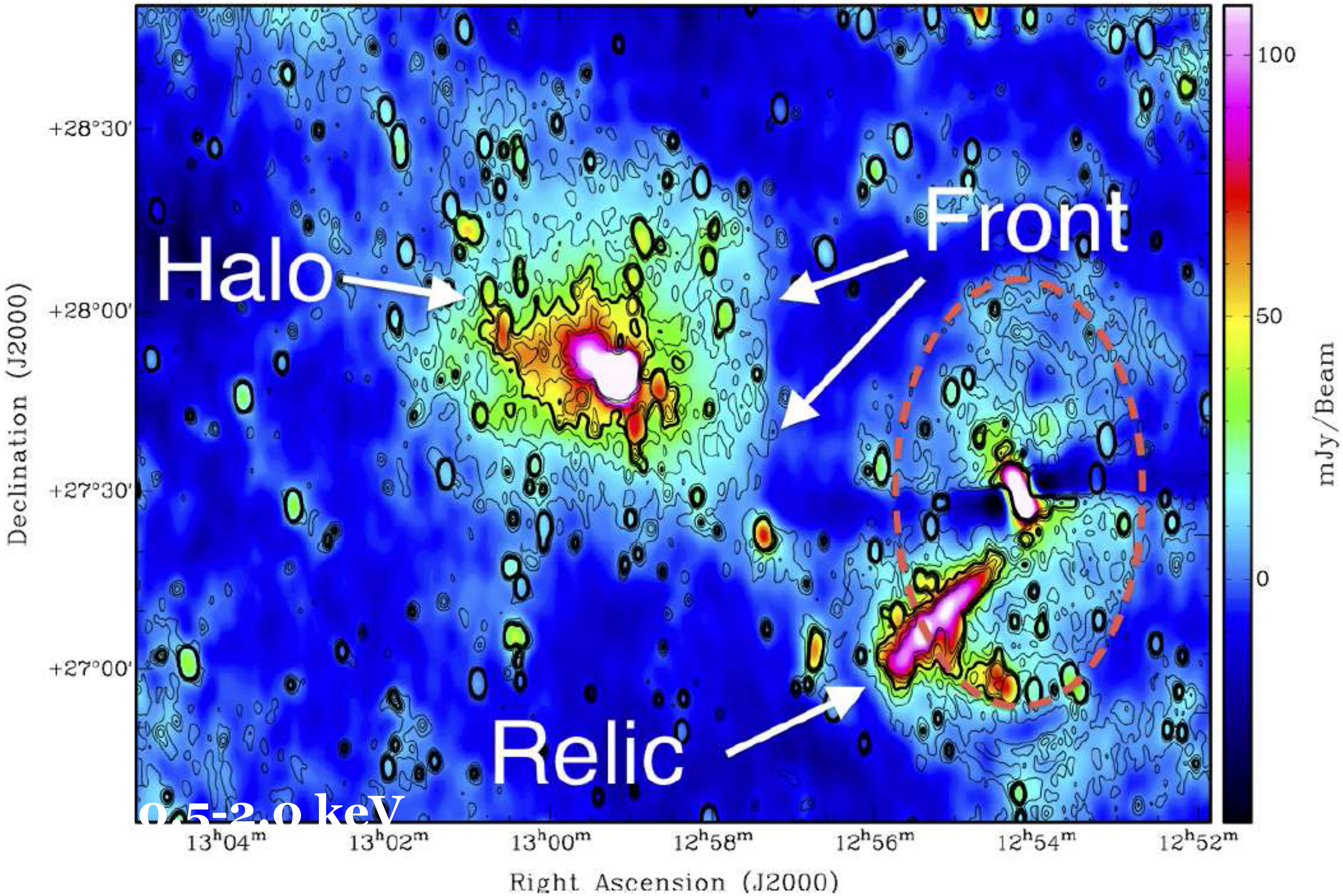
So what about baryonic matter in clusters?
(remember hot thermal gas)

Galaxy cluster evolution in a hydrodynamical simulation (z=10 -> z=0)



The puzzle: GHz radio features on top of thermal X-rays

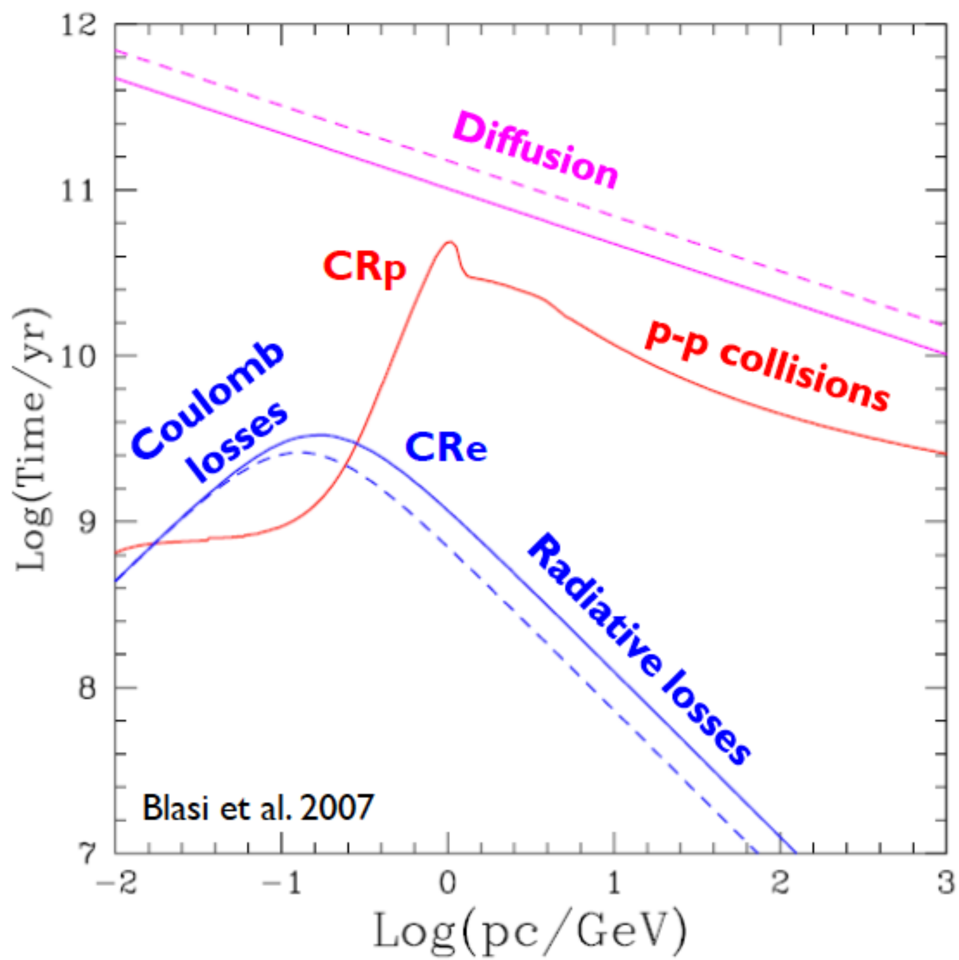
Brown & Rudnick (2010)



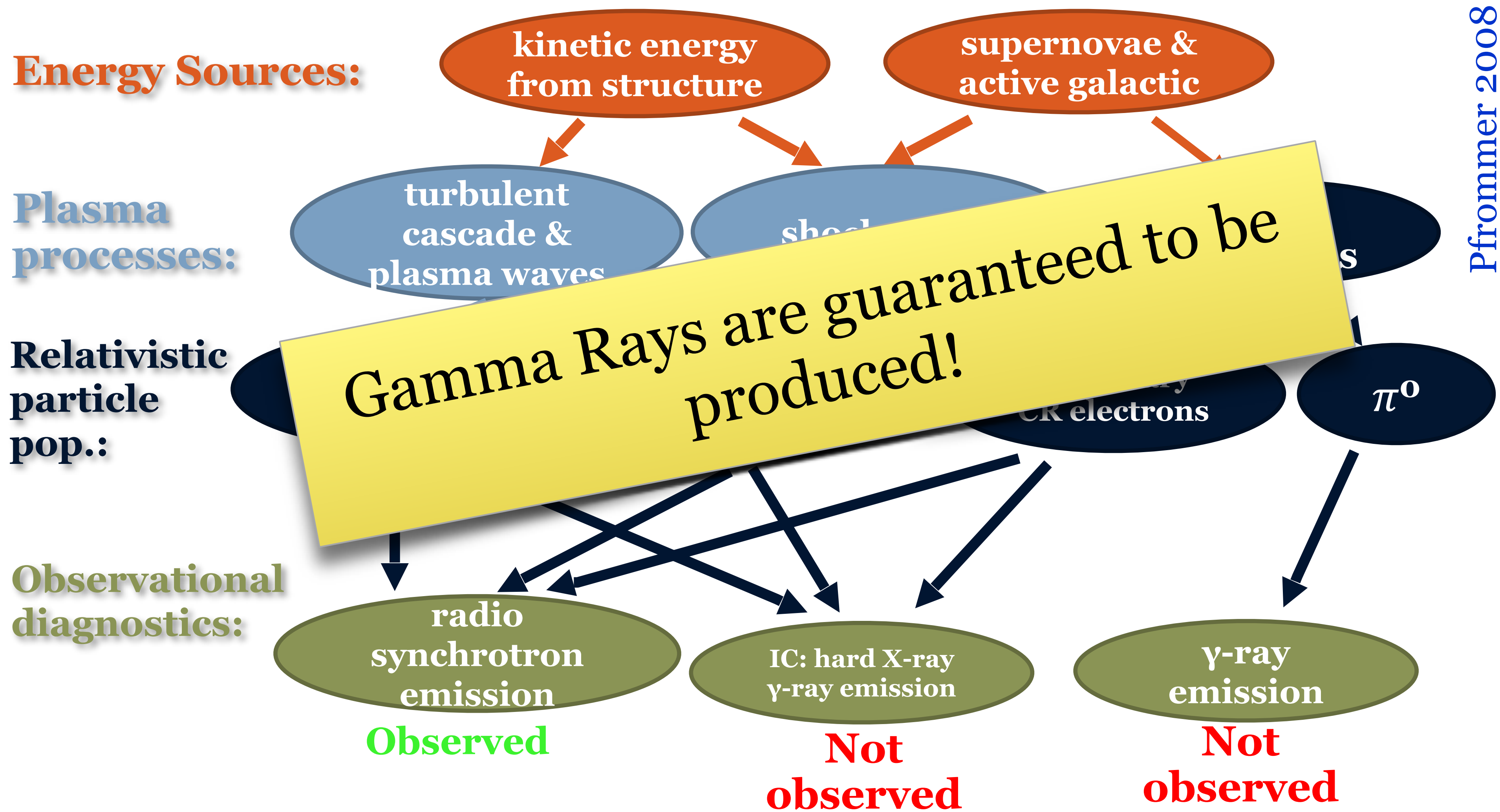
Clusters are unique CR reservoirs

CR electrons loose energy fast -> if they cause GHz emission, need to be constantly replenished

CR protons accumulate within cluster over Gyrs & carry integrated history of cluster formation

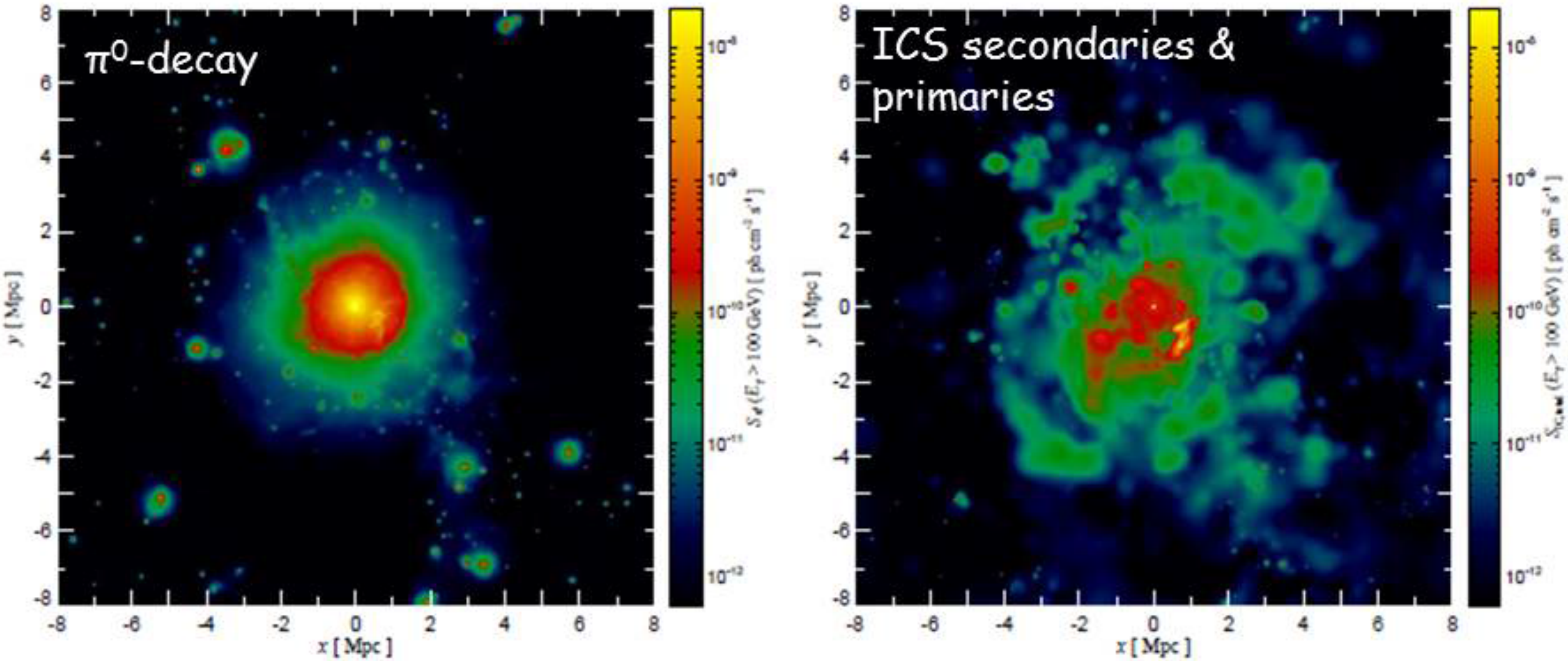


CR Population & Processes in Clusters



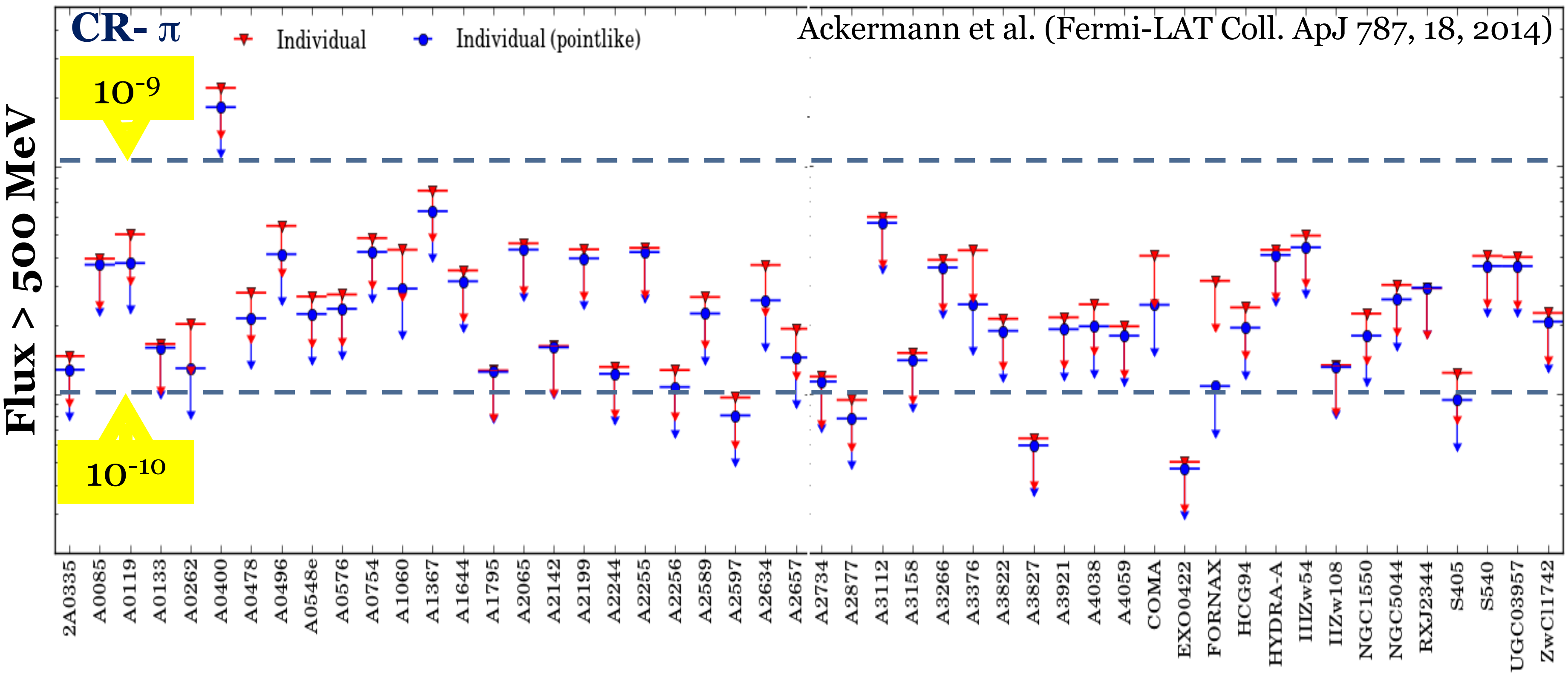
Predicted Gamma-Ray emission (universal model)

Pinzke & Pfrommer (2010)



<u>take-away point:</u>
neutral pion decay should dominate ɣ-ray spectrum, emission signature is **universal** wrt. mass or age

However - No Gamma Rays seen (50 clusters, 4 years)*



* we may have detected ɣ-rays from individual (radio) galaxies

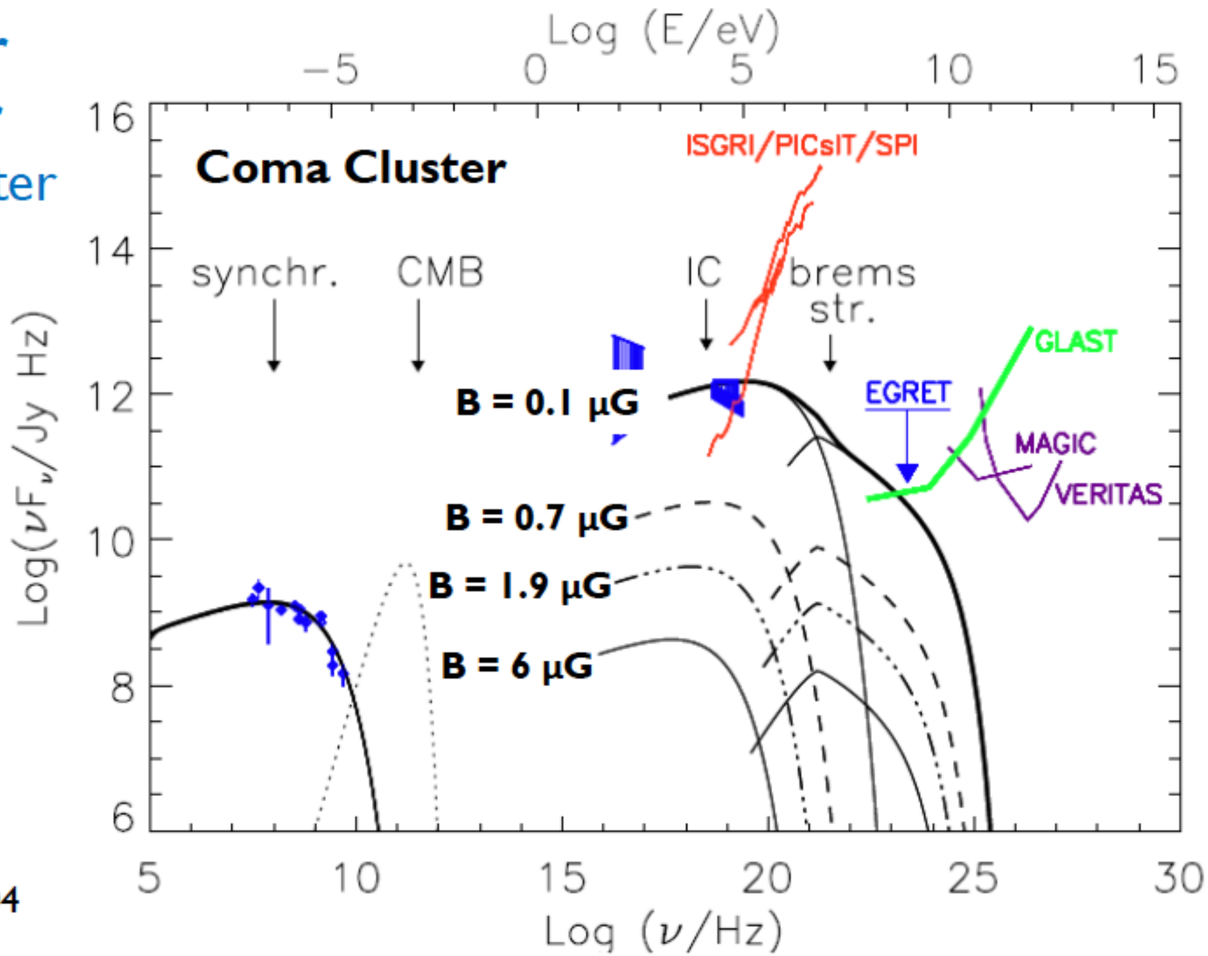
Implications of Non-detections

- Recall universality of CR spectrum from simulations -> use joint likelihood technique
- assuming bulk of gamma-rays come from CRp interactions, efficiencies must be significantly lower than e.g. SNR (<20%)
- CR / thermal pressure < 1% (for CR protons)
- accretion shocks don't play any effective role
- hadronic models severely challenged to explain radio emission!

Full details:
Ackermann et al. 2014, ApJ, 787, 18

Implications of Non-detection

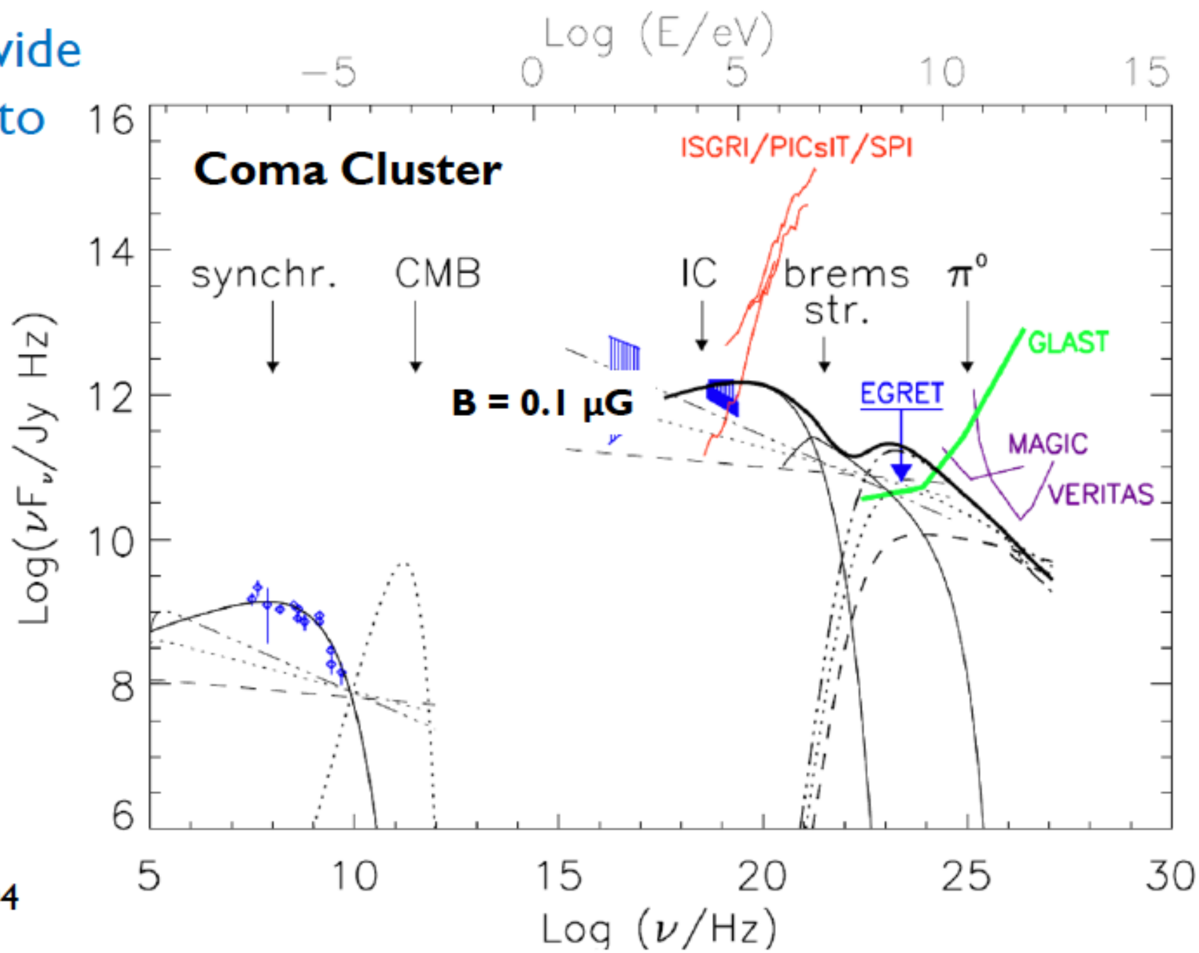
High-energy **upper limits** imply **lower limits** on intracluster magnetic field



Reimer et al. 2004

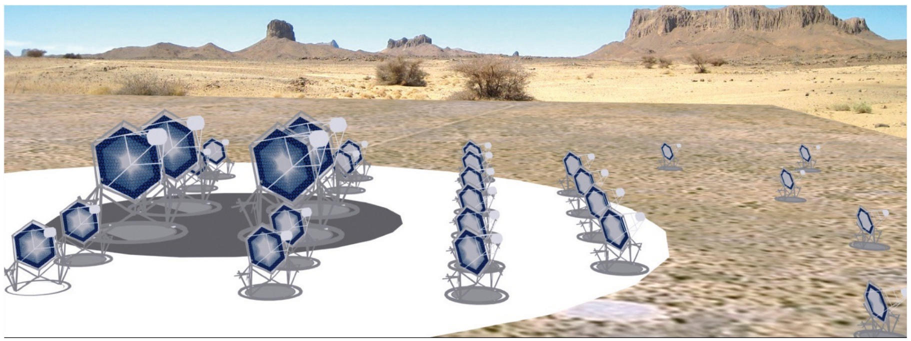
Implications of Non-detection

Gamma rays provide most direct access to **CR protons**



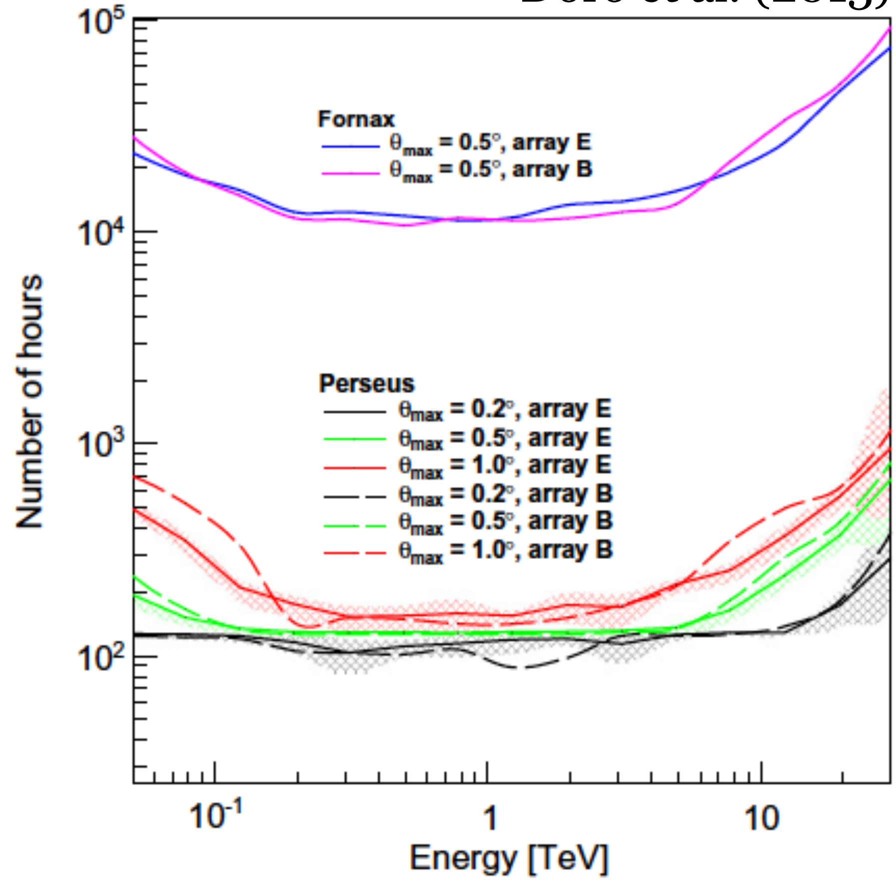
Reimer et al. 2004

Prospects for CTA?



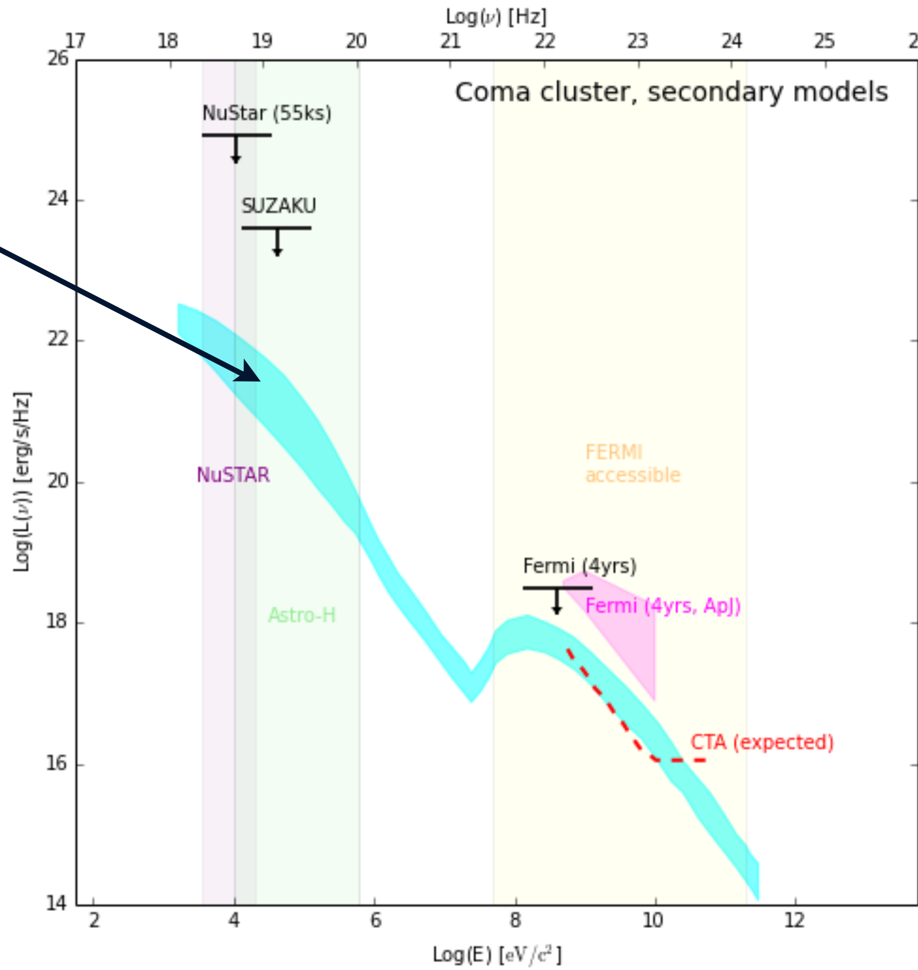
could detect gamma-rays from Perseus if focused on single cluster for O(100-200) hours?

Doro et al. (2013)



What if radio emission comes from secondaries?

Allowed secondary models which don't conflict with radio (B_{core}~4-5μG)



adapted from Brunetti & Jones (2014)

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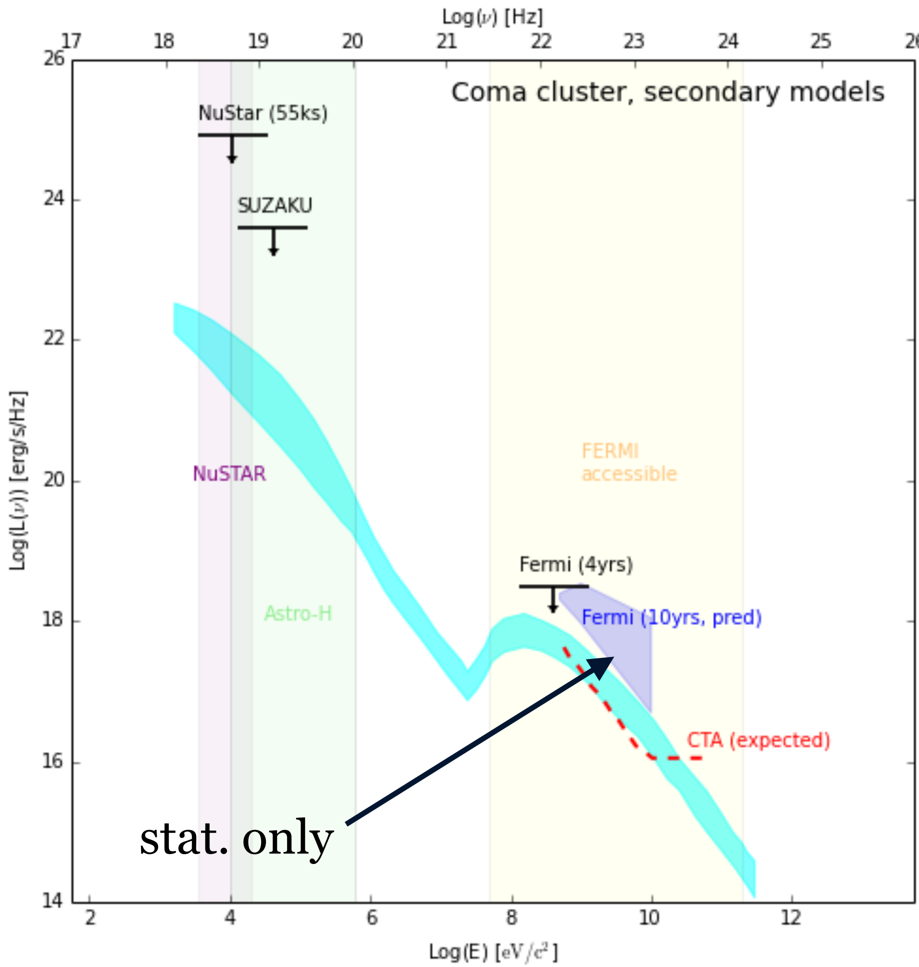


adapted from Brunetti & Jones (2014)

Beyond Coma

LOFAR will (hopefully) detect many more relics & halos!

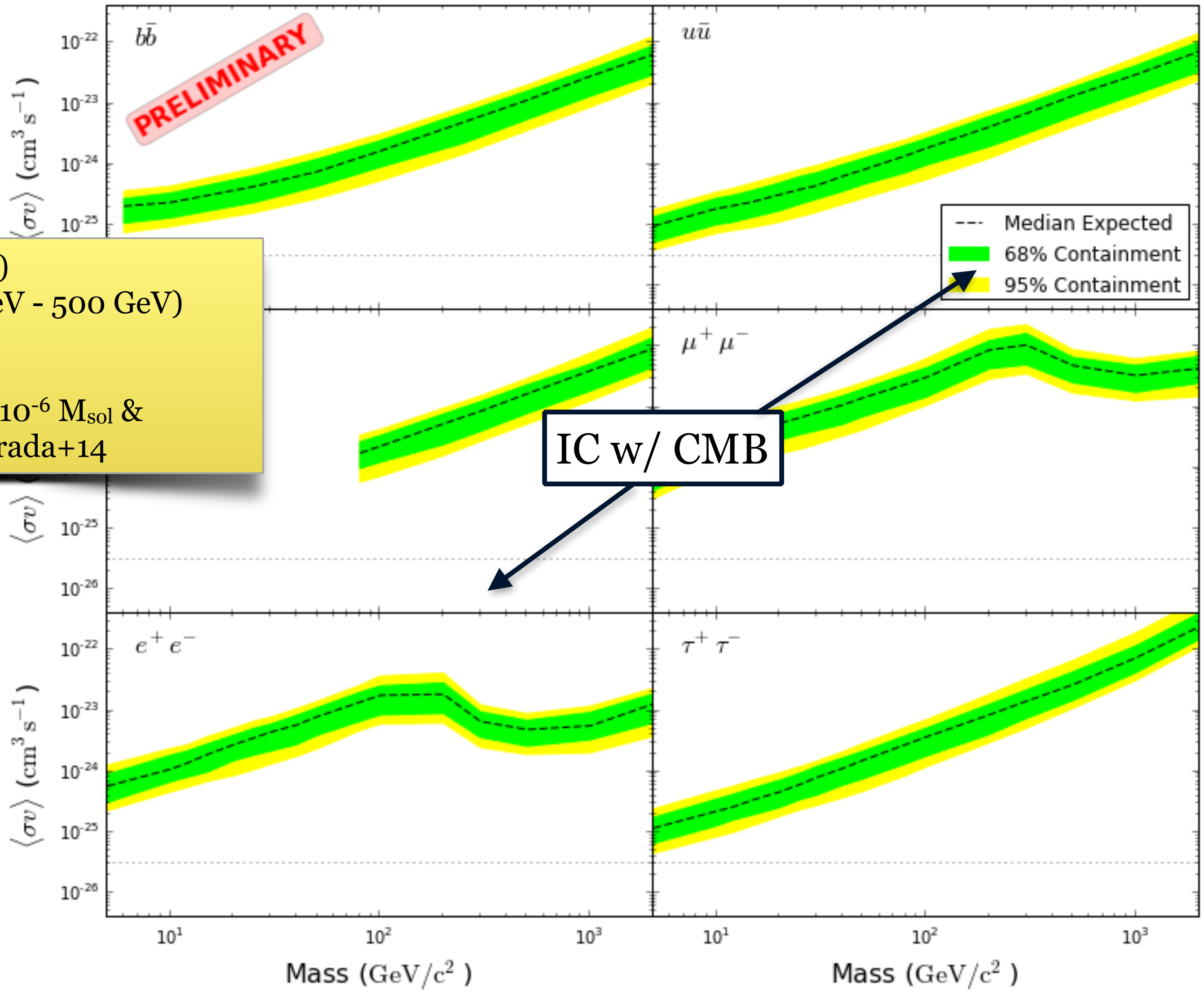
Summary & Conclusions

- Gamma rays are predicted from clusters both for DM scenarios as well as from conventional astrophysics
  - DM limits not terribly competitive, but provide complementarity
  - become competitive for DM-decay J~ρ
- Radio features in clusters observed but origin unclear
- Gamma-ray non-detection severely constrains hadronic models
  - acceleration in accretion shocks less efficient (<21%)
  - CR/thermal pressure ratio < 1%
- Future experiments?
  - CTA could have potential to detect gamma-rays from Perseus if accumulating O(100-200) hrs of observations $$
  - LOFAR may help by detecting more radio features

Thanks for Listening!

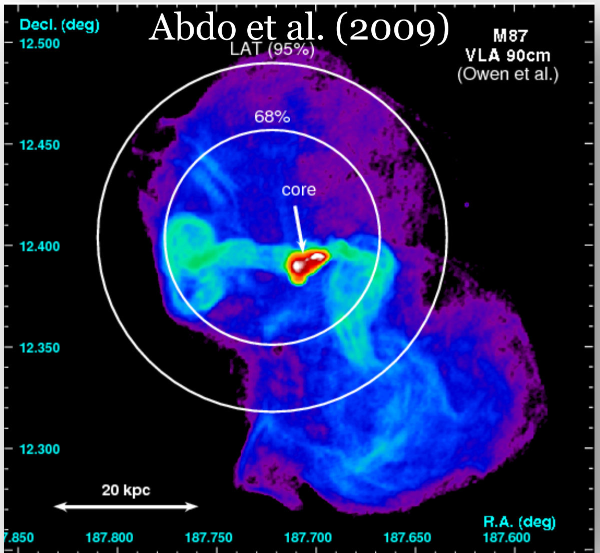
Backup Slides

Expected Sensitivity

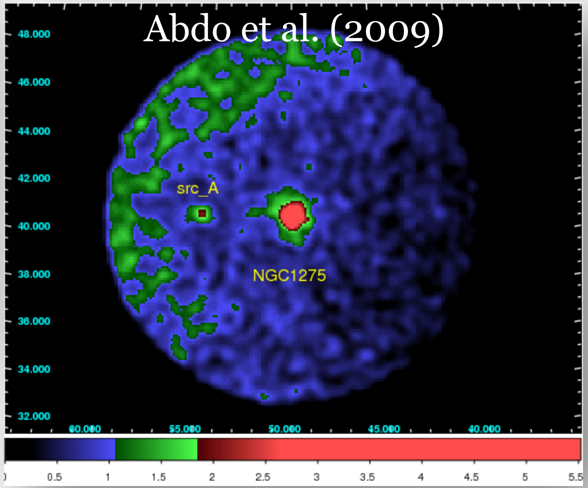


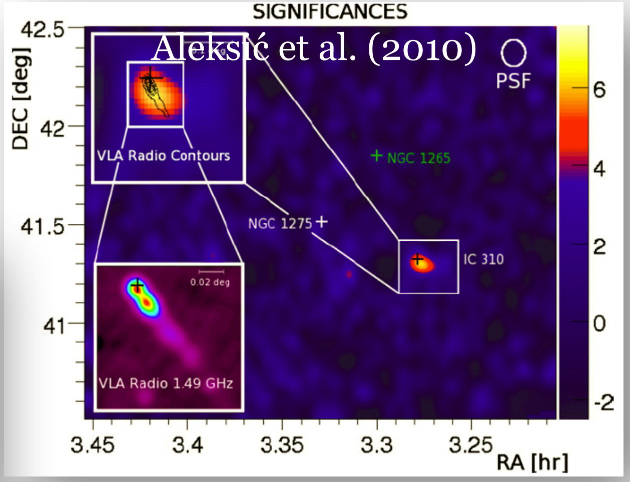
P7REP v15 (CLEAN)
5 years MC (500 MeV - 500 GeV)
Diffuse + 3FGL
34 Galaxy Clusters
Substructure: $M_{cut}=10^{-6}$ M_{sol} &
Sánchez-Conde & Prada+14

Observed Gamma Rays from Galaxy Clusters?



M87 (Virgo)

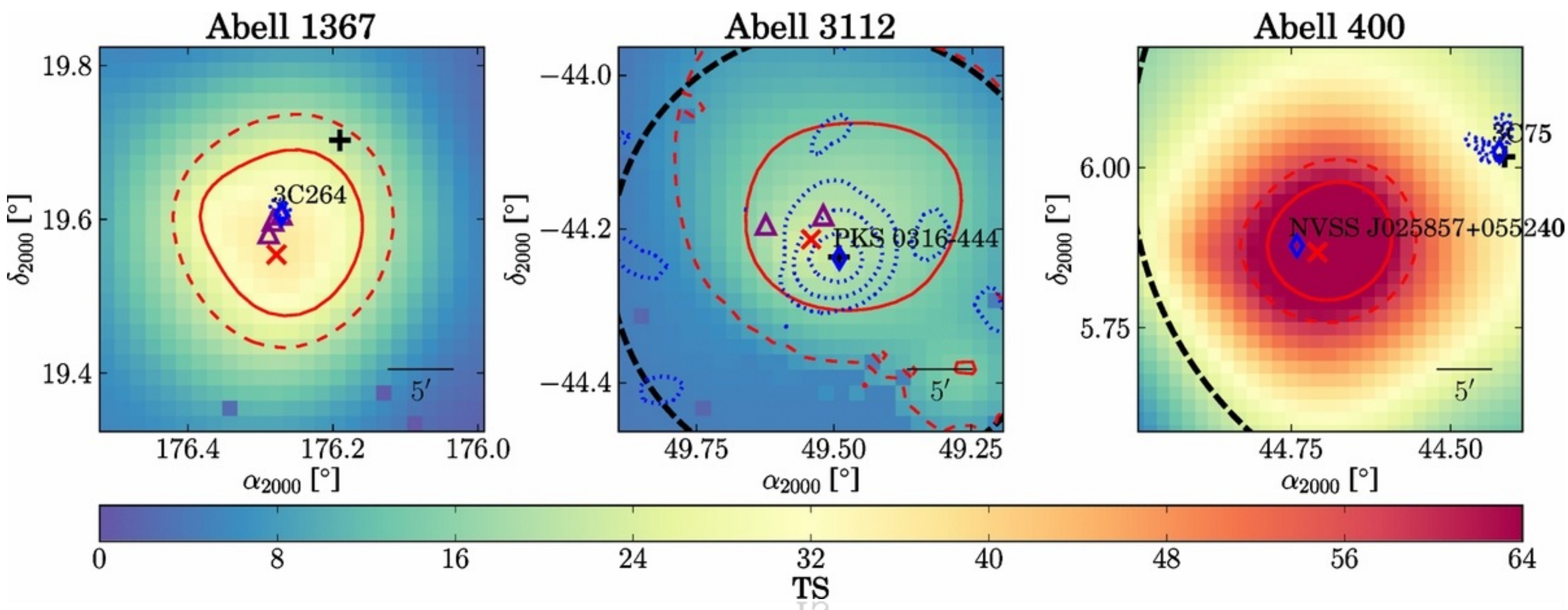




IC310/NGC1275 (Perseus)

Numerous observations of individual (radio) galaxies in galaxy clusters
-> but: any excess would first manifest itself as **point likae emission**
NO sign of diffuse emission

Zoom-In to TS-maps



-- γ-ray centroid (68% containment radius) — Radio contours

x Best fit from γ-ray data Δ Chandra X-ray sources ♦ NVSS radio sources

\+ Cluster Center (NED coordinates)

Ackermann et al. (Fermi-LAT Coll. ApJ 787, 18, 2014)

Oskar Klein centre

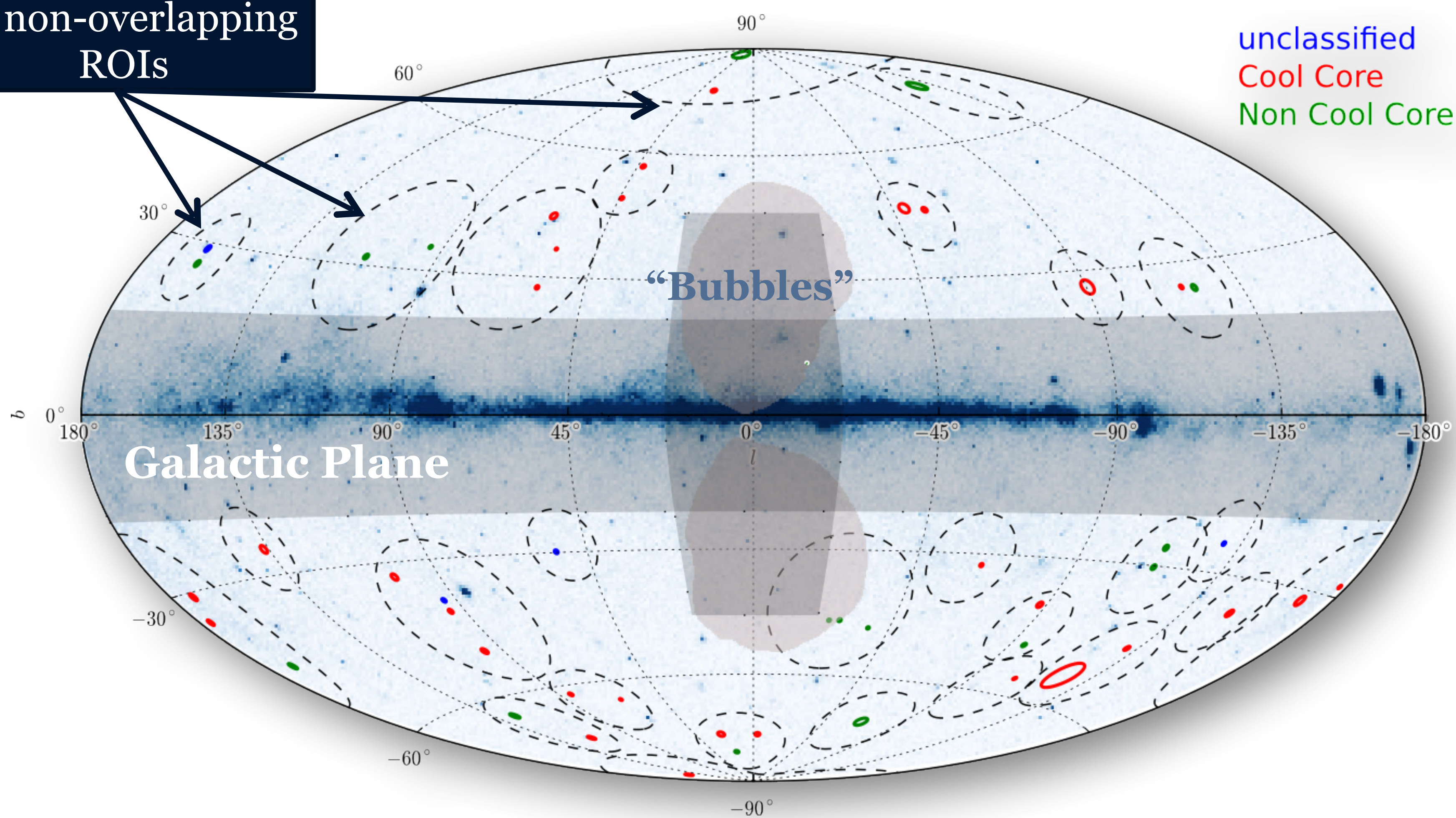
Is the Emission coming from the Cluster?

Pro	Con	Maybe Con
No indication for **source variability** (aperture photometry) A400 fits well with **soft spectrum (Γ~2.3)** with comparable TS values	**Emission offset from Cluster center** (0.1 – 0.3 °) → **point-source emission** offset is preferred! A3112 & A1367 fit well with **hard spectrum (Γ~1.7)**	Scale factors O(3-30) → **higher than expected** from model (expect O(1)) **AGN/radio sources** in all 3 clusters

Emission **unlikely to come from ICM**
-> leave **unmodeled**
-> contributes to overall TS value (**~2.7σ excess**)
-> likely: newly detected **radio galaxies** in FoV (cf. M87, IC310…)

Cluster positions & ROIs

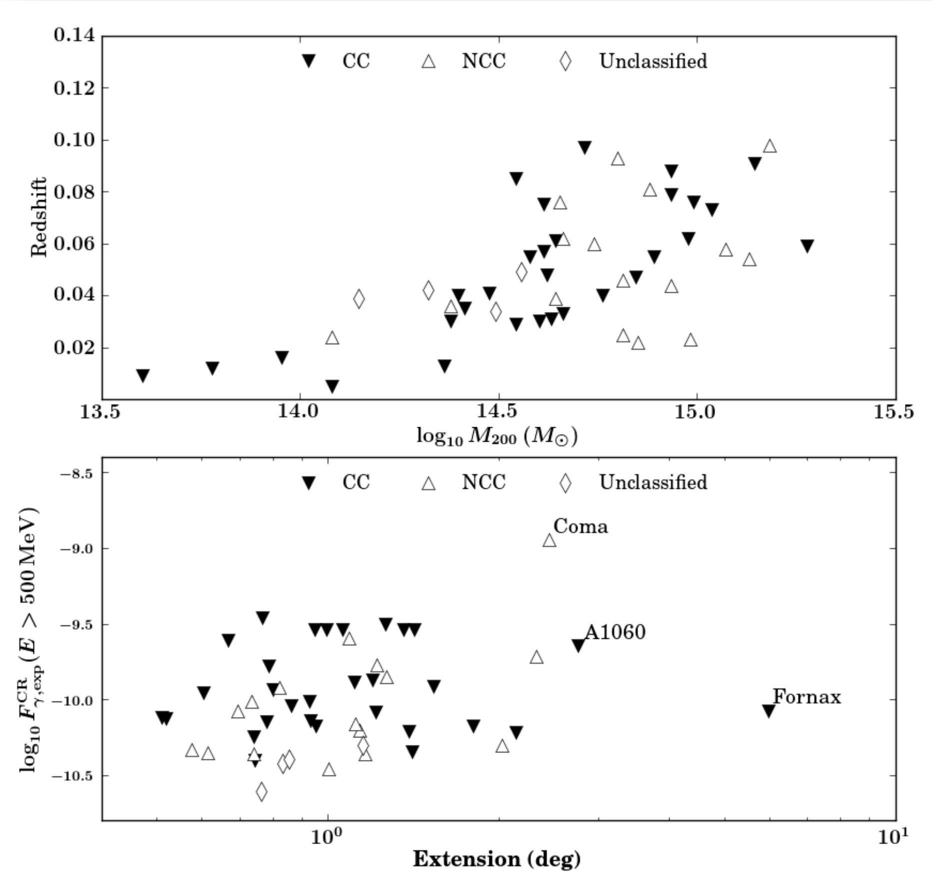
26 non-overlapping ROIs



Ackermann et al. (Fermi-LAT Coll. ApJ 787, 18, 2014)

Cluster Sample & Selection

- Start from Extended HIFLUGCS sample (Chen et al. 2007)
- Selection & Analysis cuts
  - remove z>0.1 (almost no contribution to overall expected flux)
  - geometric cuts: Galactic plane, "bubbles"
  - remove complicated diffuse regions (Virgo, Centaurus)
  - remove overlapping Clusters
- Remaining set of 50 clusters used for analysis, classify by morphology (X-ray, ACCEPT, Hudson et al. 2010):
  - Cool core if K_0<30 keV cm², else NCC
  - If no X-ray data available leave unclassified (remove clusters)



Ackermann et al. (Fermi-LAT Coll. ApJ 787, 18, 2014)

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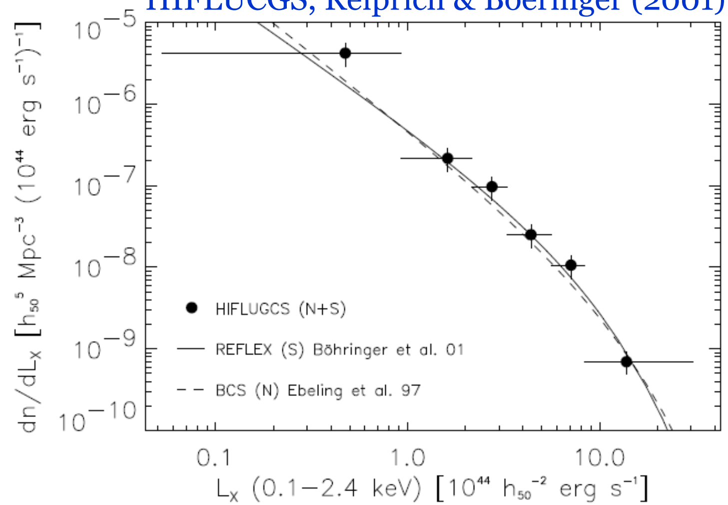
Analysis Details

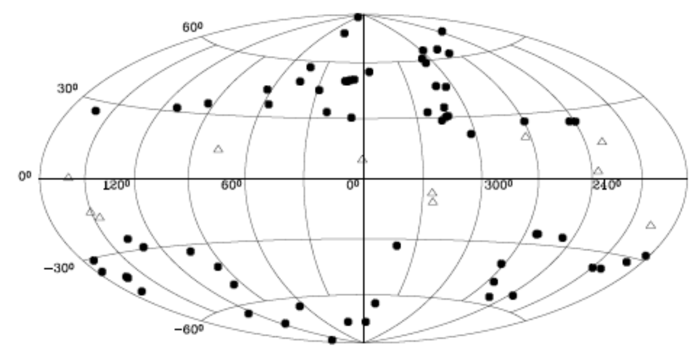
- 4 years of data (2008-08-04 – 2012-08-04)
  - **P7 reprocessed data**, CLEAN events (500 MeV – 200 GeV, 18 bins)
- 26 non-overlapping ROIs with varying size (8-16°)
  - **2FGL & std. diffuse templates** as background model
  - Include all PS within **10° from cluster & ROI-size+5°**
  - Leave normalization of **sources within 4° free**, refit bright residuals of 2FGL sources
- **Freeze all free** source parameters before joint likelihood fit
  - Limitation by MINUIT (<100 parameter), ensures convergence

Extended HIFLUCGS catalog

- **Strong correlation** between X-ray flux & γ-rays
- **X-ray flux limited complete sample** of brightest X-ray clusters (no additional clusters at z~0.1)
- Based on number of X-ray catalog surveys
- Initial HIFLUCGS
  - |b|>20° & outside Virgo
- Extended HIFLUCGS:
  - Include Virgo & other clusters
- Benchmark catalog for clusters

HIFLUCGS, Reiprich & Boeringer (2001)

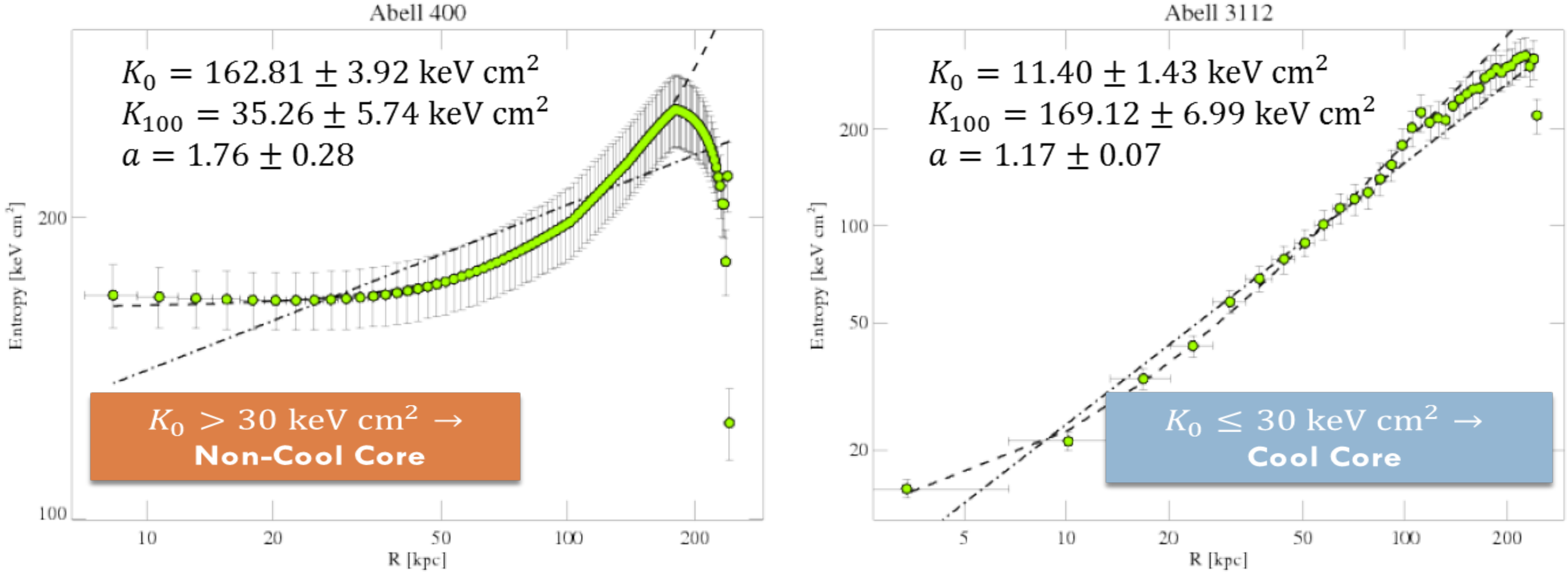




HIFLUCGS, Reiprich & Boeringer (2001)

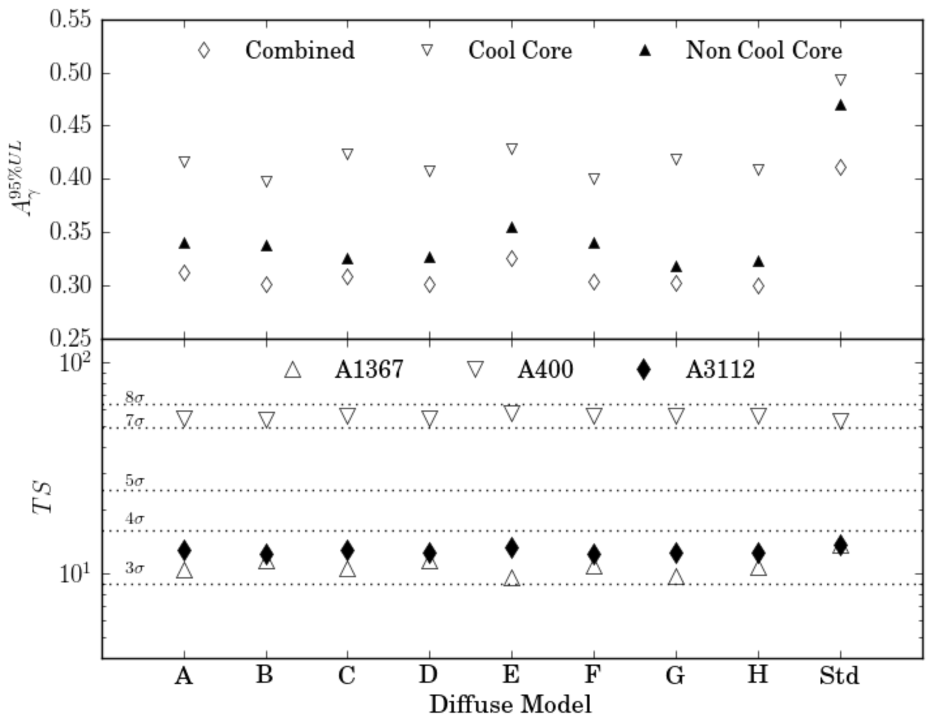
X-Ray Morphology Classification (Hudson et al. 2010)

- **Entropy profile** ($S = kT/n_e^{2/3}$) determines structure of ICM & thermodynamic history
- Entropy profile **fit to** $\boldsymbol{K(r) = K_0 + K_{100}\left(\frac{r}{100kpc}\right)^a}$
- Hudson et al. 2010 uses **17 different X-ray diagnostics** for **full morphological characterization**, K_0 only for simplicity shown



Systematic Uncertainties

Ackermann et al. (Fermi-LAT Coll. ApJ 787, 18, 2014)



- Most critical for extended source analysis: diffuse Galactic foreground model
  - Templates optimized for PS analysis
  - Large uncertainties -> CR propagation details, source distribution, B-fields, etc.
  - Checked analysis against alternative models (GALPROP) -> more stringent limits on scale factor

Systematic Uncertainties (Ctd.)

Type	Variation of Input Parameters	Impact on Results
Spectral bins	$\pm 50\%$	$< 5\%$
Spatial bins	$\pm 50\%$	$< 1\%$
Spatial template bins	$\pm 50\%$	$< 1\%$
Small ROIs	$+25\%$	$\sim 3\%$
Number of free sources	$4^\circ \rightarrow \theta_{200} + 1^{\circ\,a}$	$< 10\%$
IRF uncertainties: Effective Area	$\pm 10\%^{b}$	$< 7\%$
IRF uncertainties: PSF	$\pm 15\%^{b}$	$< 4\%$
Diffuse model uncertainties	alternative diffuse models[c]	15-25% more stringent limits

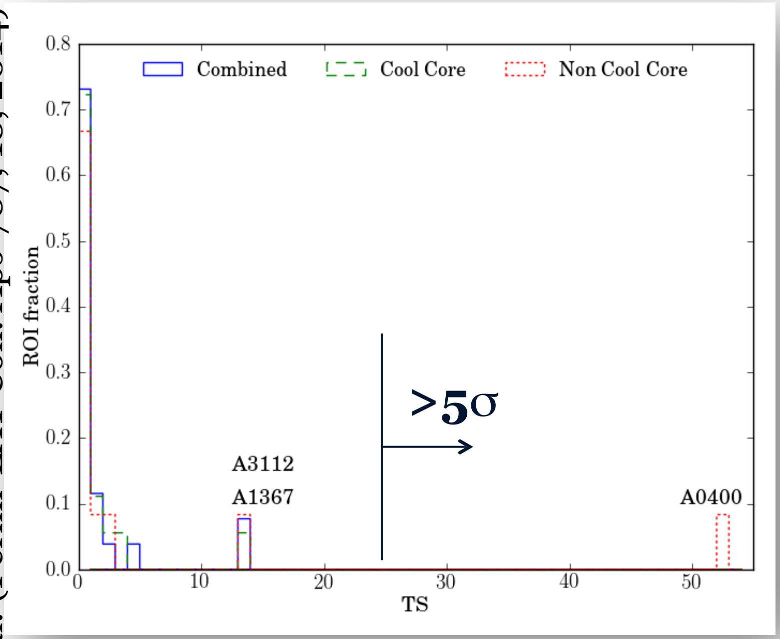
[a]We chose a radius of 4° around each cluster center to account for photon contamination due to the PSF at low energies. In this test we modify the radius in which we leave the normalization free to vary within $\theta_{200} + 1^\circ$.

[b]We employ the *bracketing IRF* approach as discussed in Ackermann et al. (2012a) and use the tabulated values to scale the relevant IRF components.

[c]We use a set of alternative diffuse emission models and replace the standard emission template used in the baseline analysis with these

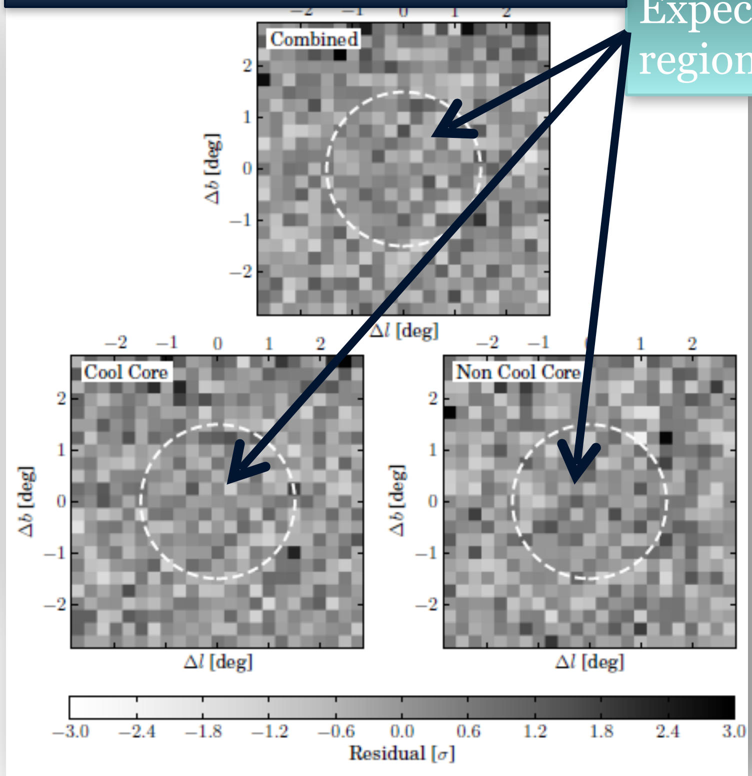
Results on the sample

Ackermann et al. (Fermi-LAT Coll. ApJ 787, 18, 2014)



With exception of 3 ROIs follows MC nullfit expectation

Stacked Residual Maps



Expected emission region (2.5°)

Constraints from Joint Analysis

	Combined Sample	Cool Core	Non Cool Core
# Clusters	50	30	16
95% U.L. on A_γ (model: $A_\gamma = 1$)	0.41 (0.29 without exceptions)	0.49	0.47
Global TS-value (significance)	7.3 (**2.7σ**) (<2σ without exceptions)	4.7 (2.1σ)	3.3 (1.8σ)
Exclude $A_\gamma = 1$ (σ)	5.5	4.3	4.4
95% U.L. on $\zeta_{\text{p,max}}$ ($\zeta_{\text{p,max}} = 0.5 \times A_\gamma^{UL}$)*	**21%** (15% without exceptions)	25%	24%

Strongest constraints on $\zeta_{\text{p,max}}$ so far!

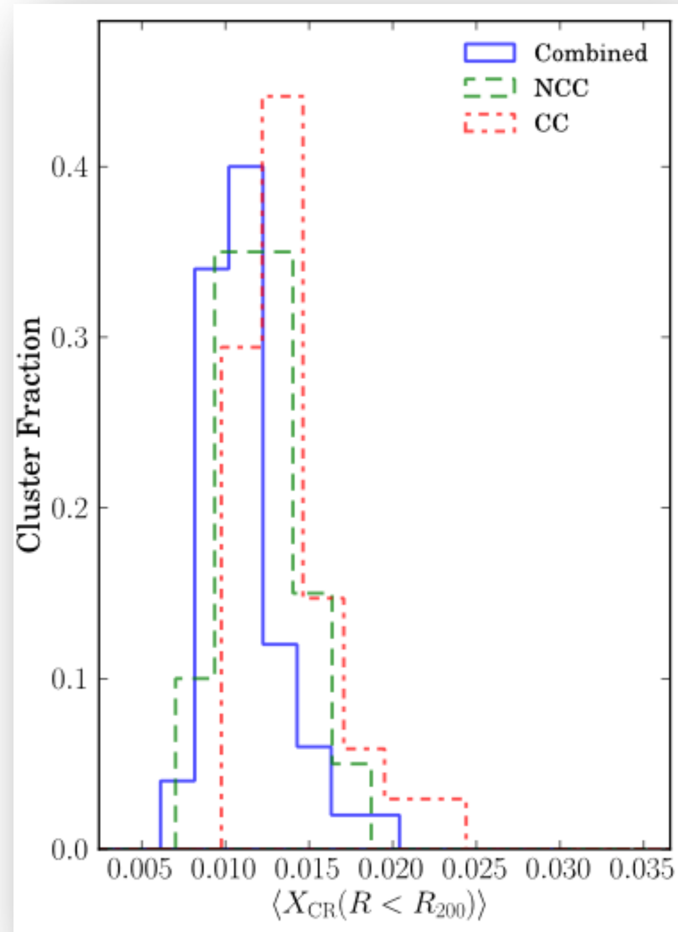
* Assumes $\zeta_{\text{p,max}} \propto \langle X_{\text{CR}} \rangle \propto A_\gamma$

Constraining CR content in Galaxy Clusters

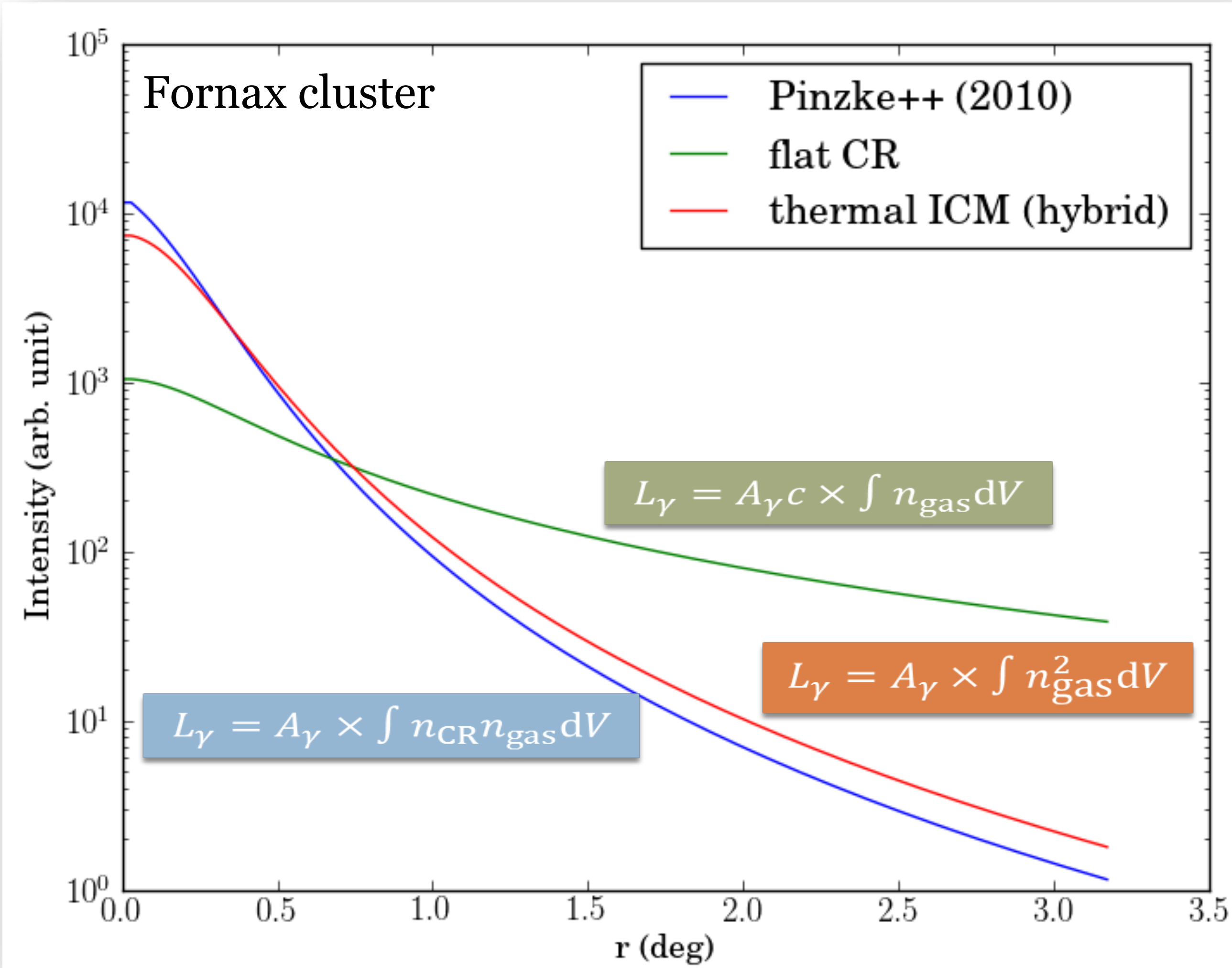
- Use **joint scale factors** to derive CR-to-thermal pressure ratio for each cluster **individually**:

$$\langle X_{CR}(< R)\rangle \propto A_\gamma$$

  - Assumes a) **universality** of model and b) **scaling relation** to hold
- Derive $\langle X_{CR}\rangle$ within **determined radius** (e.g. R_{200})
- Median **values** within R_{200}: $\langle X_{CR}\rangle$<1.0-1.5%



Spatial Modeling



Universal CR Model
(Pinzke & Pfrommer, 2010)

- Simulate clusters in **cosmological** environment
  - **CR proton (CRp)** transport & injection, acceleration from **structure formation shocks**
  - Find **universality** across their simulated sample
- Model input: **maximum hadronic injection efficiency, $\zeta_{\mathrm{p,max}}$**
  - Captured by **joint scale factor A_γ** (model prediction: $A_\gamma = 1$)
  - Assume linearity: $\zeta_{\mathrm{p,max}} = 0.5 \times A_\gamma$
- Prediction of **γ-rays from CRp interactions ($\pi^0 \rightarrow 2\gamma$)**
  - Dominates **IC** contribution
  - Can constrain **CR content** using **γ-rays** : $\zeta_{\mathrm{p,max}} \propto \langle X_{\mathrm{CR}} \rangle$

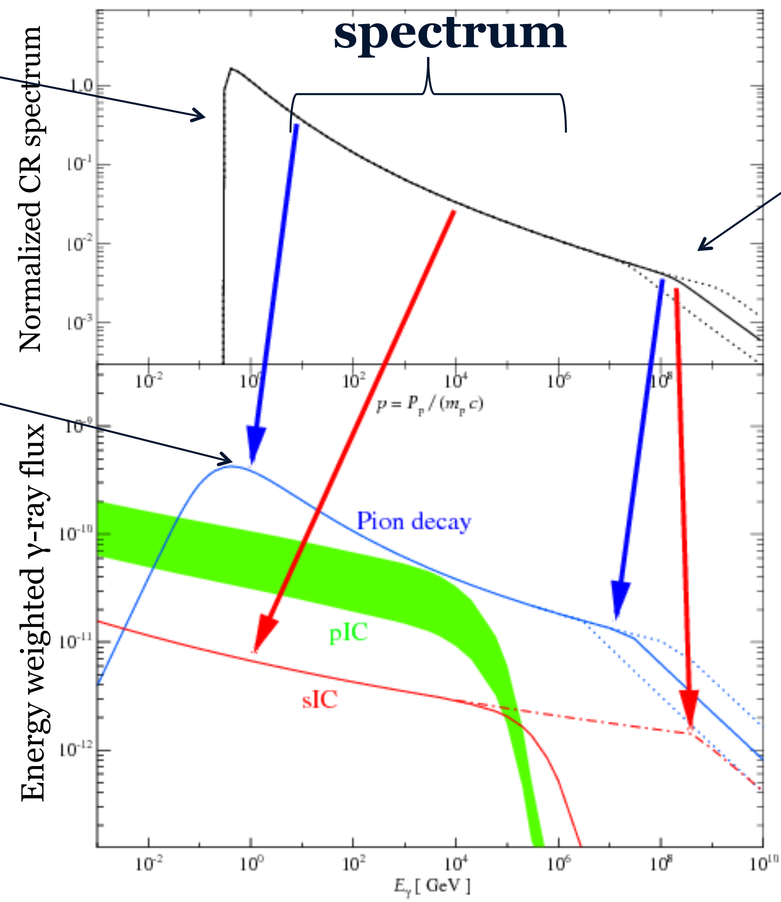
Result from simulations: CR Spectrum (Pinzke & Pfrommer 2010) acceleration of CRp from large scale shocks

Low momentum cut-off

Concave spectrum

Diffuse break

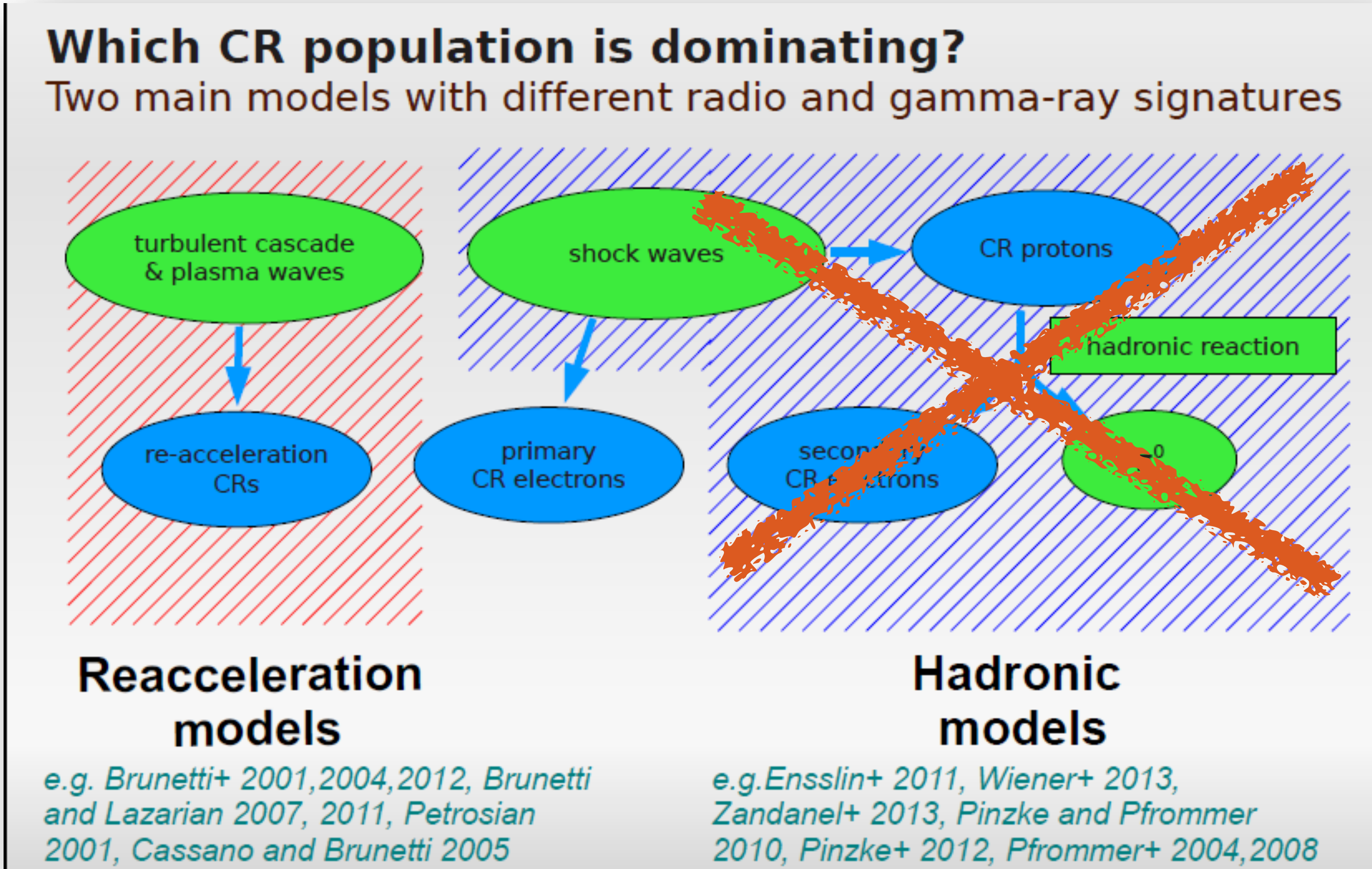
Pion-"bump"



Pinzke & Pfrommer (2010)

<u>Universal spectrum</u> for various simulated clusters!
-> universal physical processes?

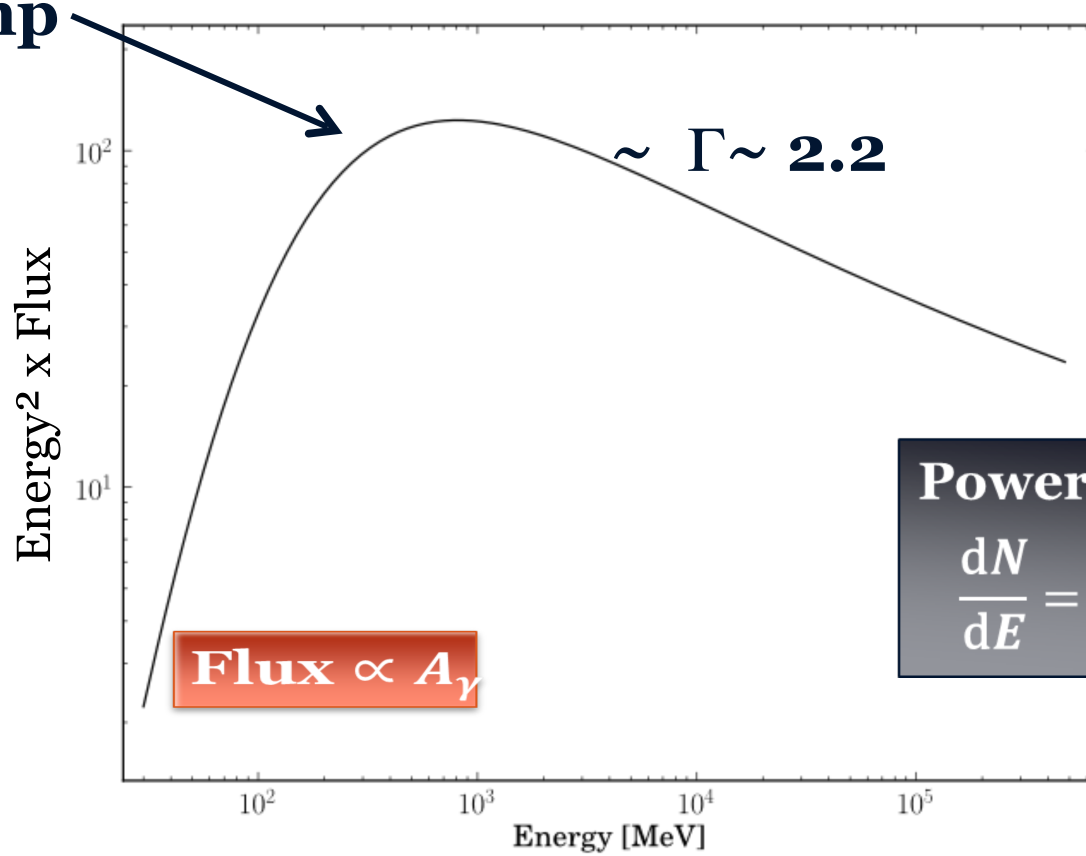
Different models for CR physics



A. Pinzke

Derived γ-Ray Spectrum

Pion-"bump"



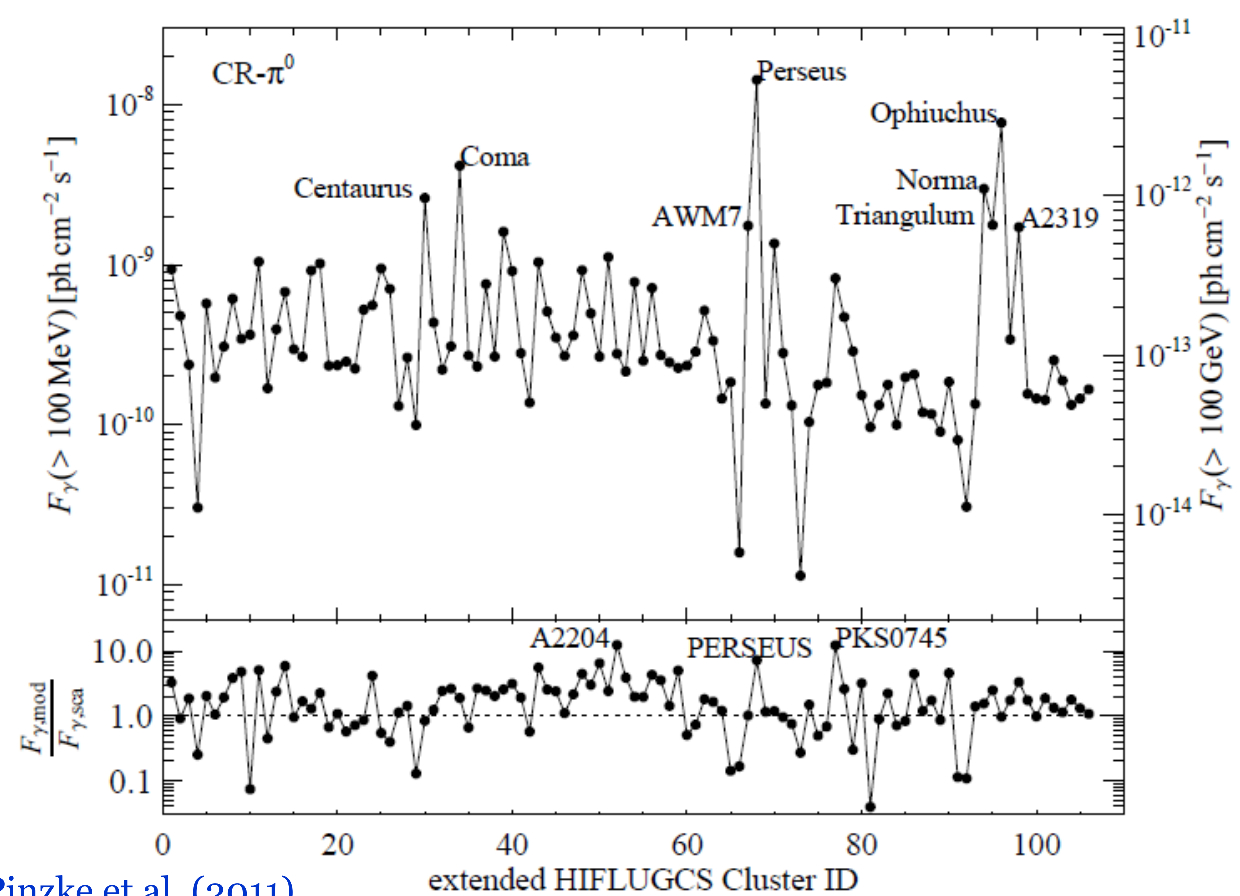
Powerlaw:

$$\frac{dN}{dE} = N_0 \times \left(\frac{E}{E_0}\right)^{-\Gamma}$$

Flux Predictions* by Pinzke et al. (2011)

Predicted CR-induced γ-ray flux from π^0-decay; analysis input, equiv. to J-factor in DM searches

Directly derived flux vs. flux from scaling relation



Pinzke et al. (2011)

* predictions translate to $A_\gamma = 1$

Significance Estimate

- Neyman Pearson **likelihood ratio** (**T**est **S**tatistic):

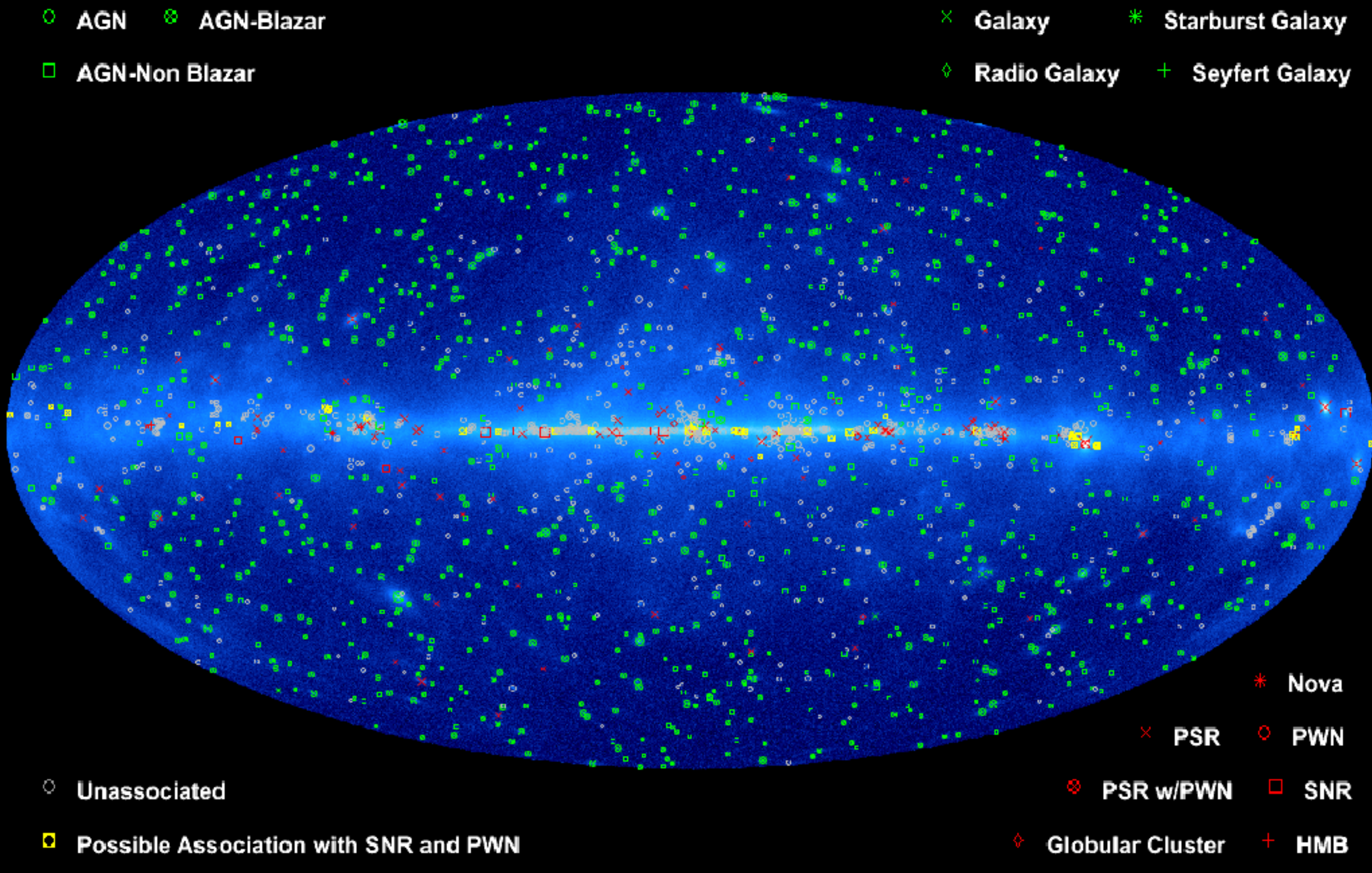
$$TS = -2\log\left(\frac{L\left(x=0,\hat{\hat{b}}\right)}{L(\hat{x},\hat{b})}\right)$$

LLH for Null hypothesis

LLH for Signal hypothesis

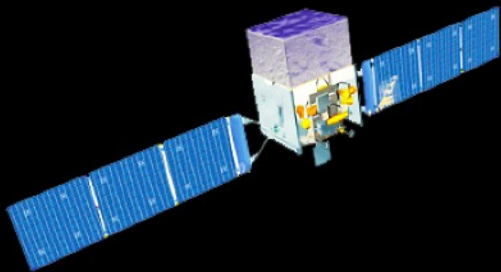
- Defined for each target, ROI or even **combined TS** (use **joint LLH** instead)
- Can be related to **significance:** $\sigma = \sqrt{TS}$

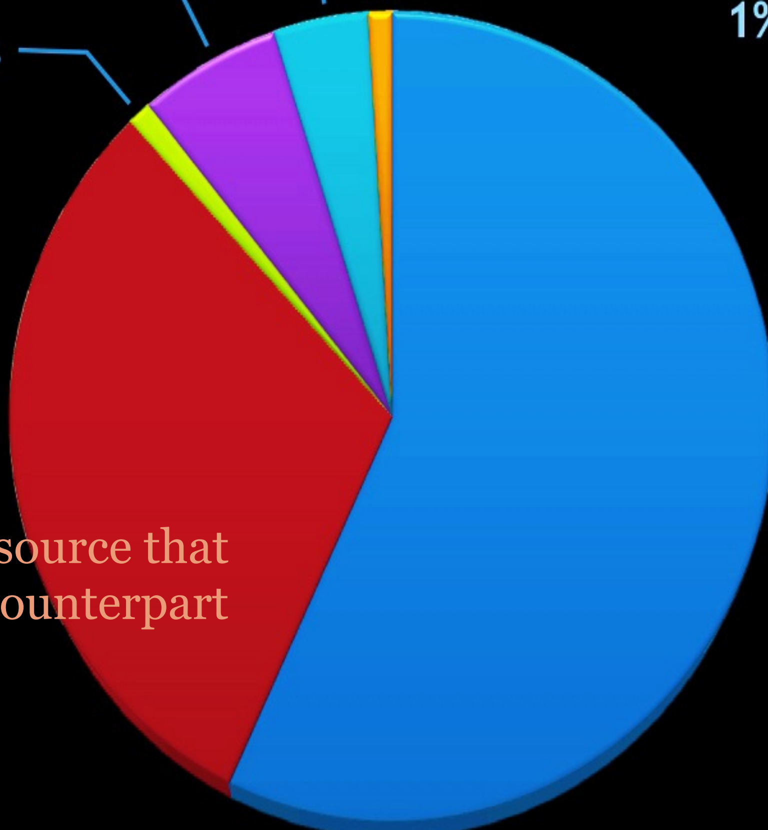
Fermi Large Area Telescope 2FGL catalog



Credit: Fermi Large Area Telescope Collaboration

What has Fermi found: The LAT two-year catalog

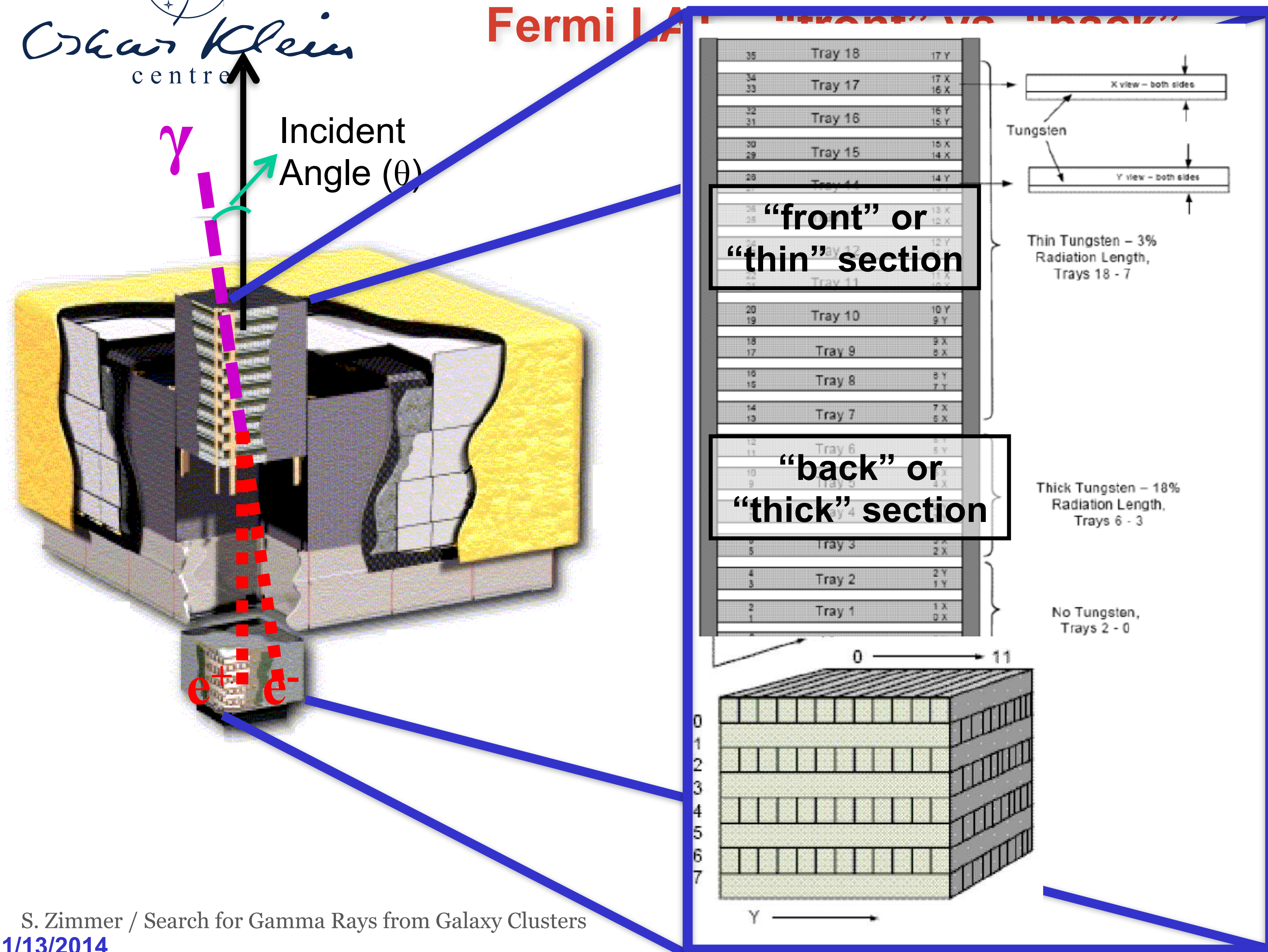




Pointlike source that
lacks MW counterpart

Credit: NASA/Goddard Space Flight Center

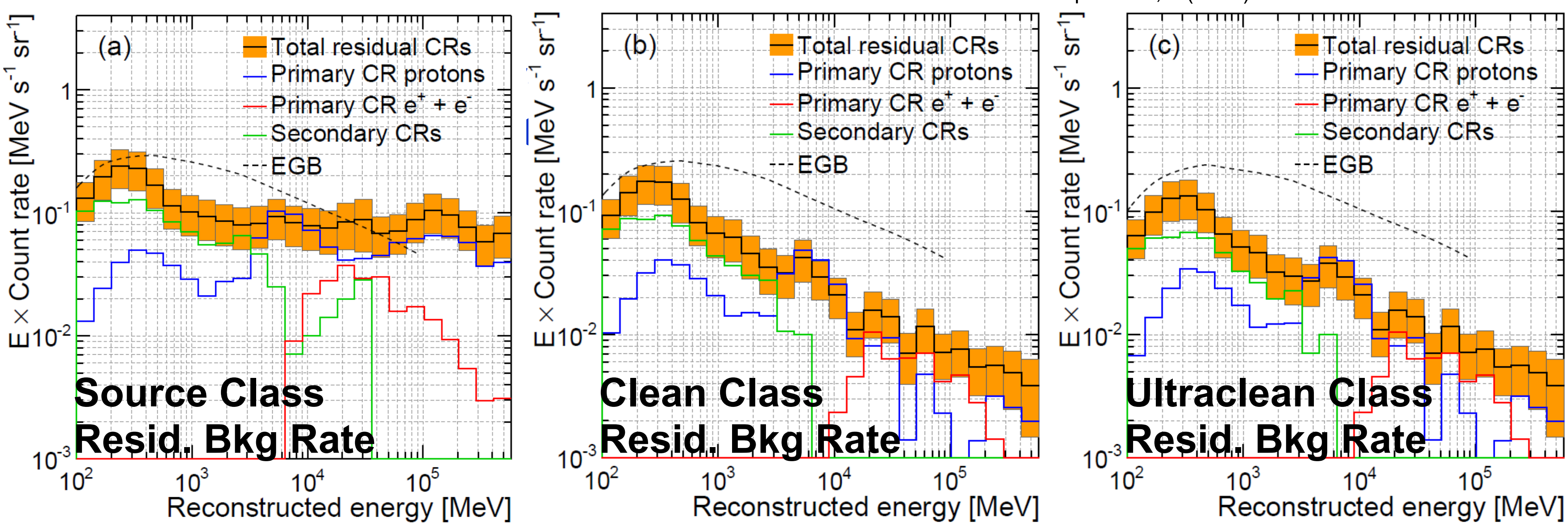
Fermi LA


γ
Incident
Angle (θ)
e+
e-
Tray 18
Tray 17
Tray 16
Tray 15
Tray 10
Tray 9
Tray 8
Tray 7
Tray 2
Tray 1
"front" or
"thin" section
"back" or
"thick" section
X view – both sides
Tungsten
Y view – both sides
Thin Tungsten – 3% Radiation Length, Trays 18 - 7
Thick Tungsten – 18% Radiation Length, Trays 6 - 3
No Tungsten, Trays 2 - 0
0
11
Y

Gamma-ray Event Classes

- **Triggered events are dominated by CR background events**
  - **Need to define additional cuts to get γ-ray rich dataset**
- **Nested "event classes" for various types of γ ray sources**
  - **Transient: loosest, for transient sources (< 200 s)**

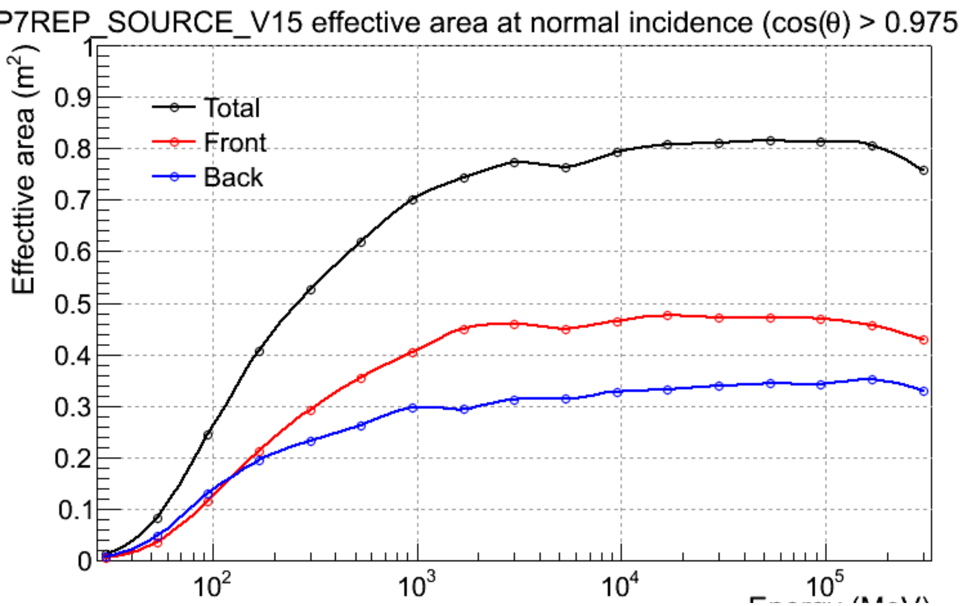
M. Ackermann et al (The Fermi LAT Collaboration) ApJS 203, 4 (2012) arXiv:1206.1896

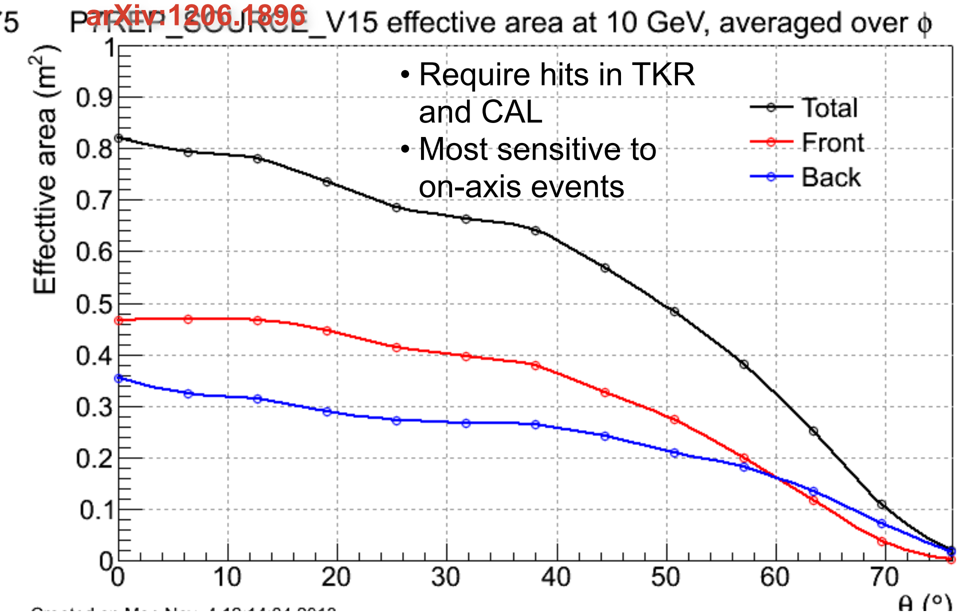


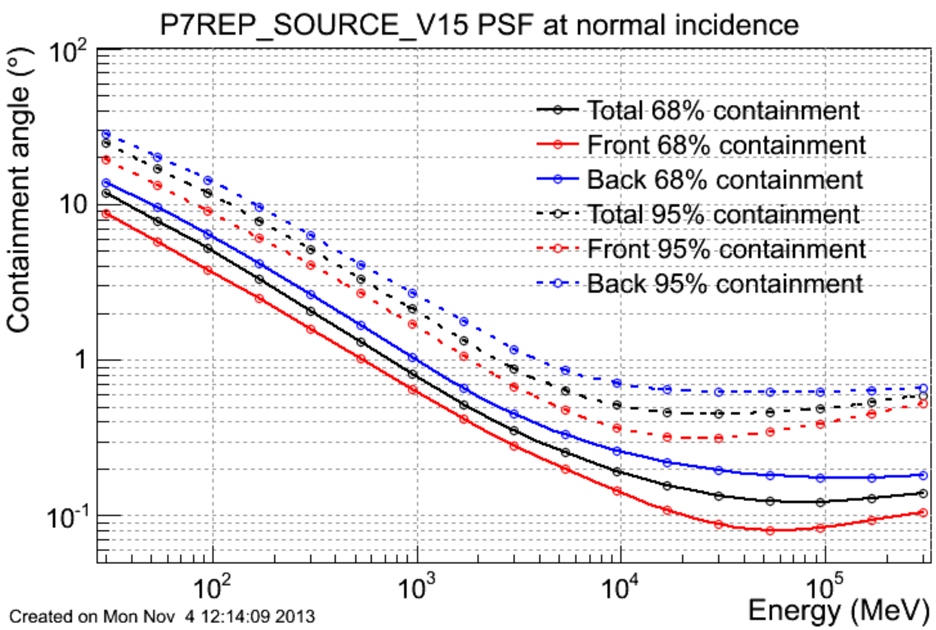
Fermi LAT Performance

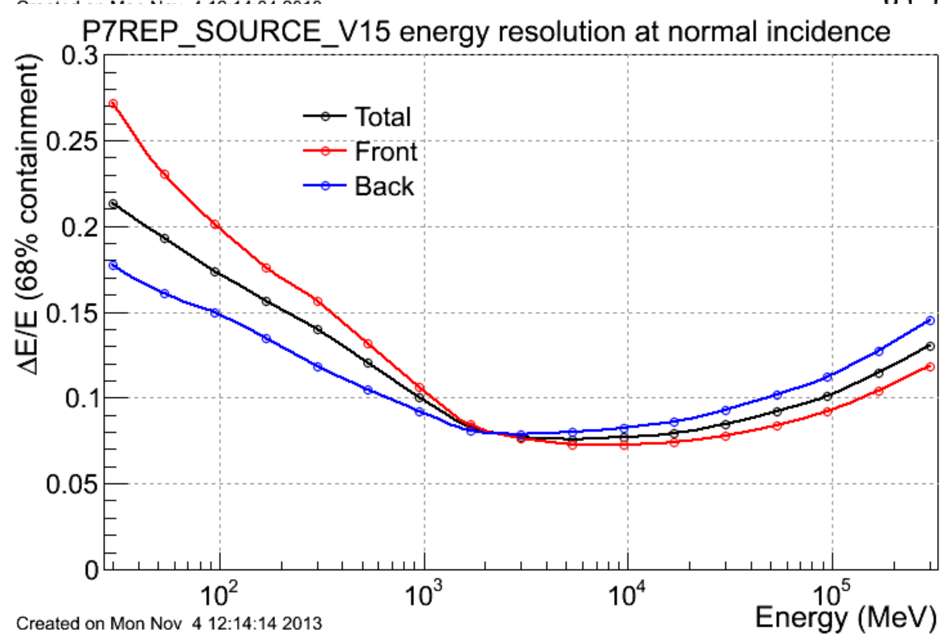
see also M. Ackermann et al (The Fermi LAT Collaboration) ApJS 203, 4 (2012)

arXiv:1206.1896







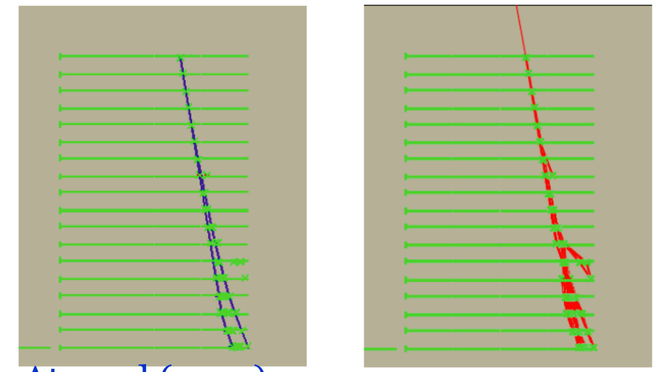


Pass 8

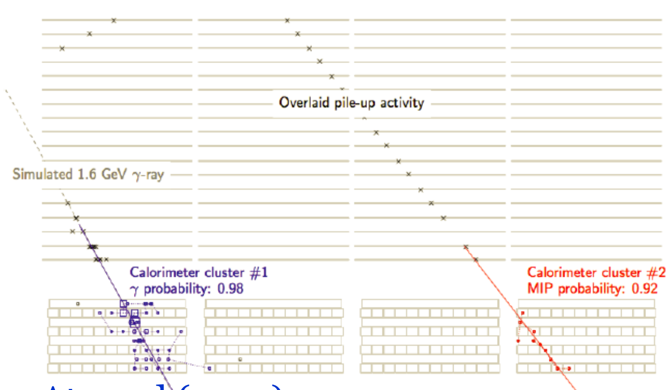
- Handle on **instrumental pile-up** & maximizing science potential
- **Rewrite** of core-recon parts
  - TKR: **tree based tracking** instead of combinatorial
  - CAL: introduce **calorimeter clustering**, 3D fit to shower profile
  - ACD: improved background rejection (from sims)
- Expected to roll out in **late 2014** (hopefully)

Combinatoric Example

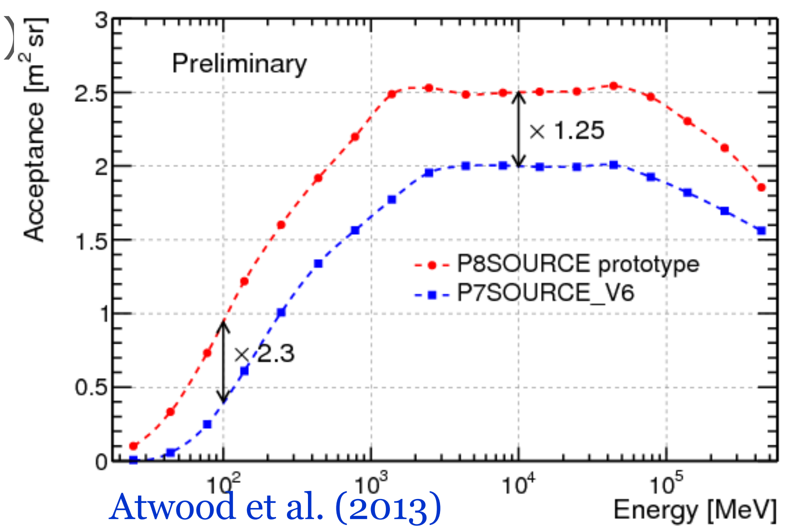
Tree-Based Example



Atwood (2012)

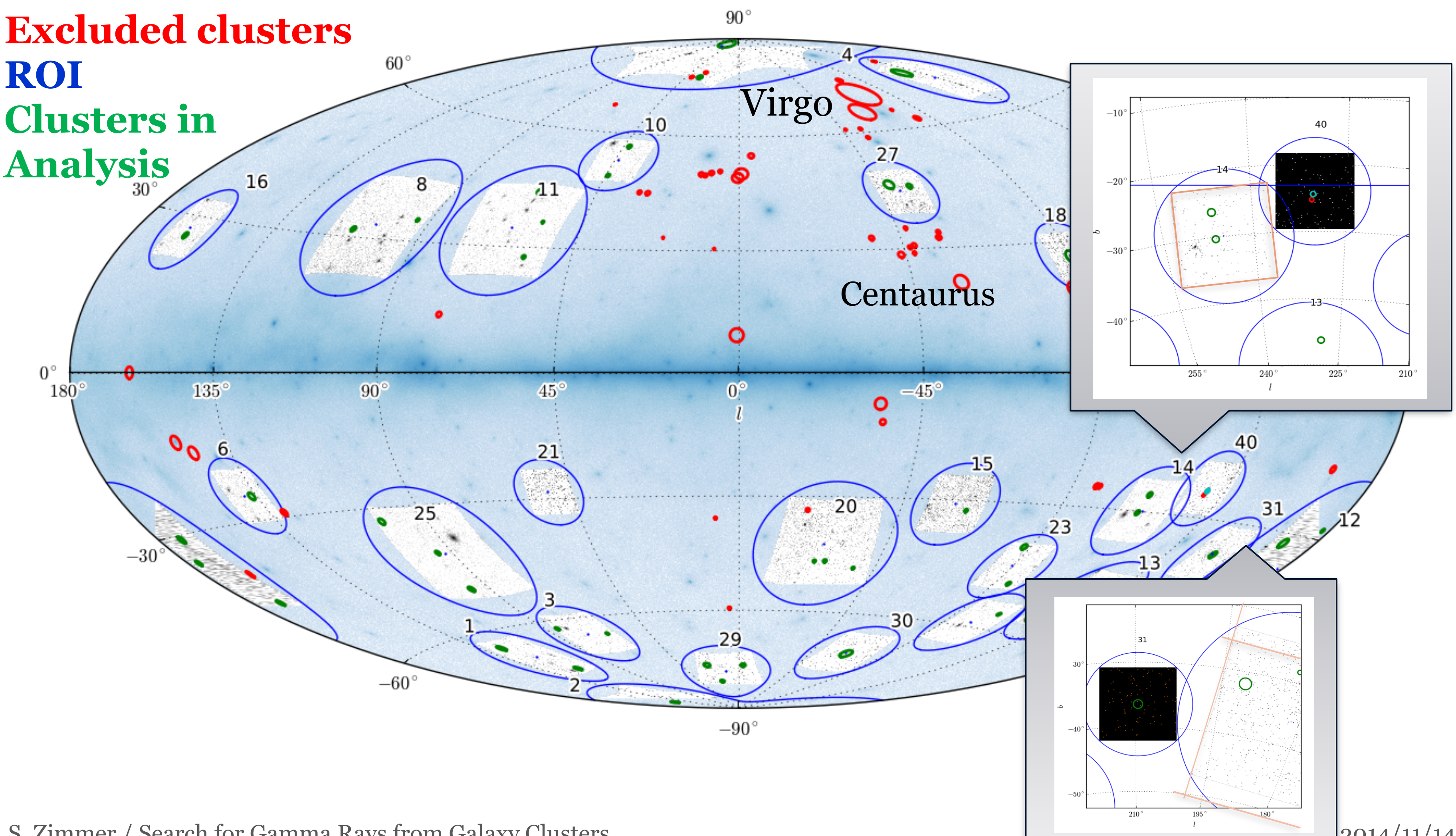


Atwood (2012)



Atwood et al. (2013)

Non-Overlapping ROIs



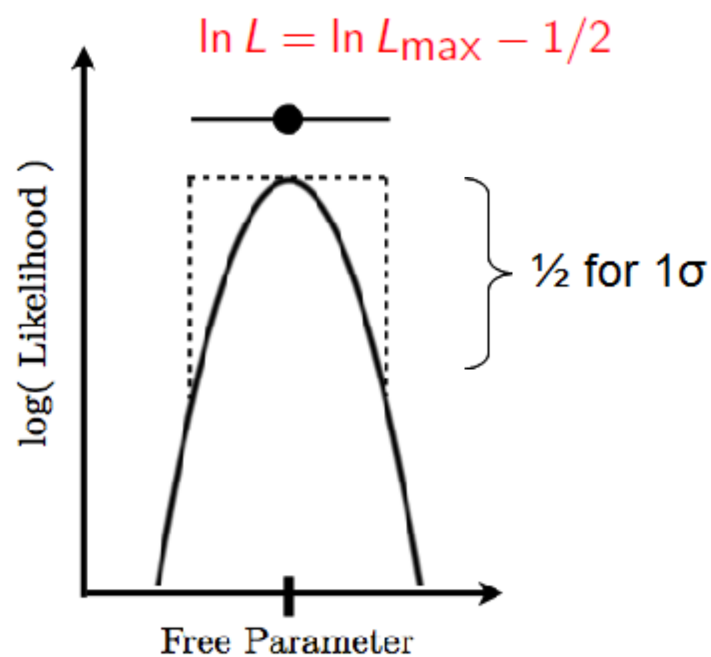
Oskar Klein centre

deltaLogLikelihood method

Number of Parameters	Confidence level (probability contents desired inside hypercontour of $\chi^2 = \chi^2_{min} + \mathrm{UP}$)				
	50%	70%	90%	95%	99%
1	0.46	1.07	2.70	3.84	6.63
2	1.39	2.41	4.61	5.99	9.21
3	2.37	3.67	6.25	7.82	11.36
4	3.36	4.88	7.78	9.49	13.28
5	4.35	6.06	9.24	11.07	15.09
6	5.35	7.23	10.65	12.59	16.81
7	6.35	8.38	12.02	14.07	18.49
8	7.34	9.52	13.36	15.51	20.09
9	8.34	10.66	14.68	16.92	21.67
10	9.34	11.78	15.99	18.31	23.21
11	10.34	12.88	17.29	19.68	24.71
	If FCN is $-\log(\text{likelihood})$ instead of χ^2, all values of UP should be divided by 2.				

Table 7.1: Table of UP for multi-parameter confidence regions

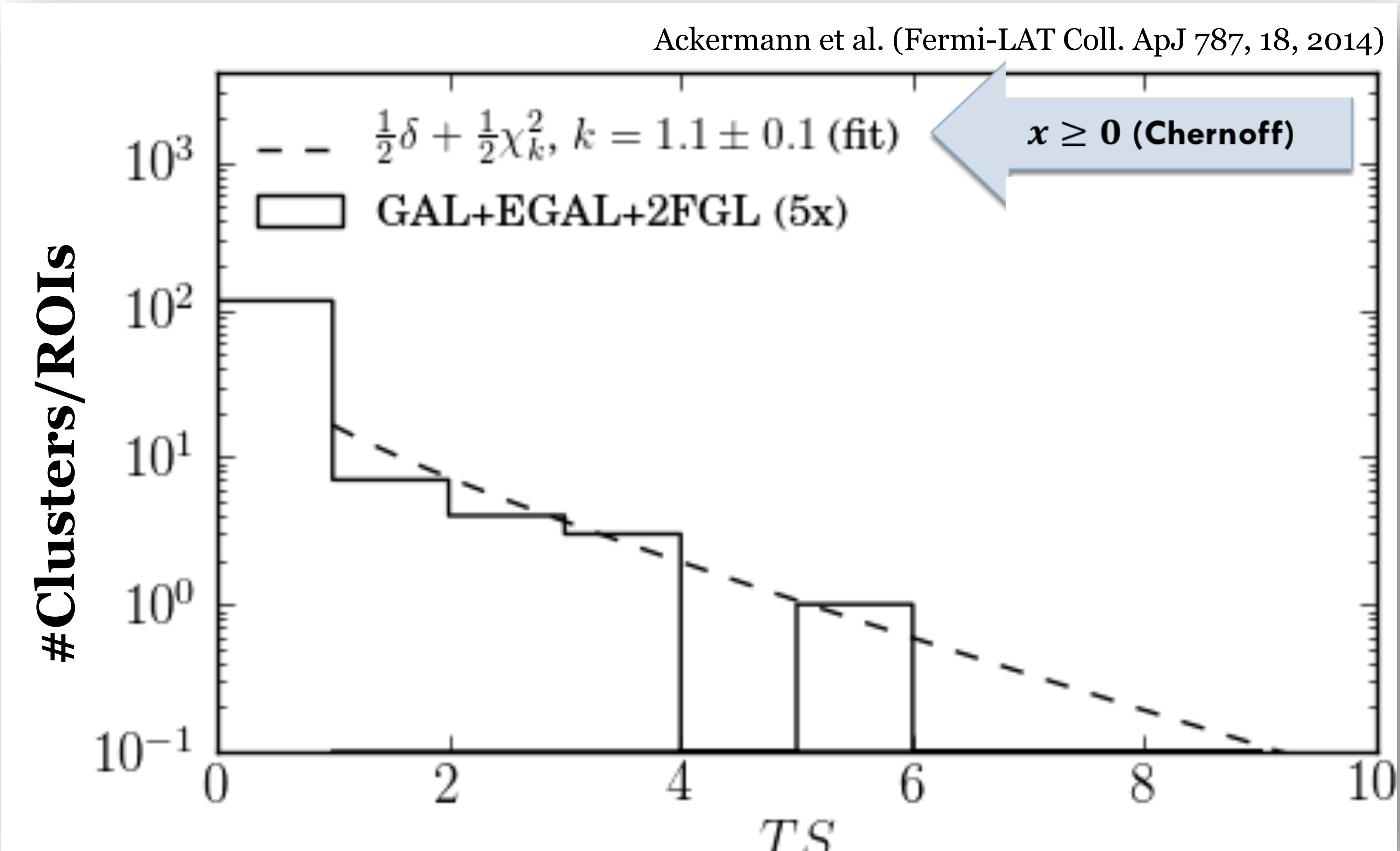
F. James, MINUIT reference manual



from Alex Drlica-Wagner

90% two-sided C.L. for deltaLogLikelihood step ~ 2.70 (1 free parameter) -> 95% U.L.

TS distribution for Null hypothesis

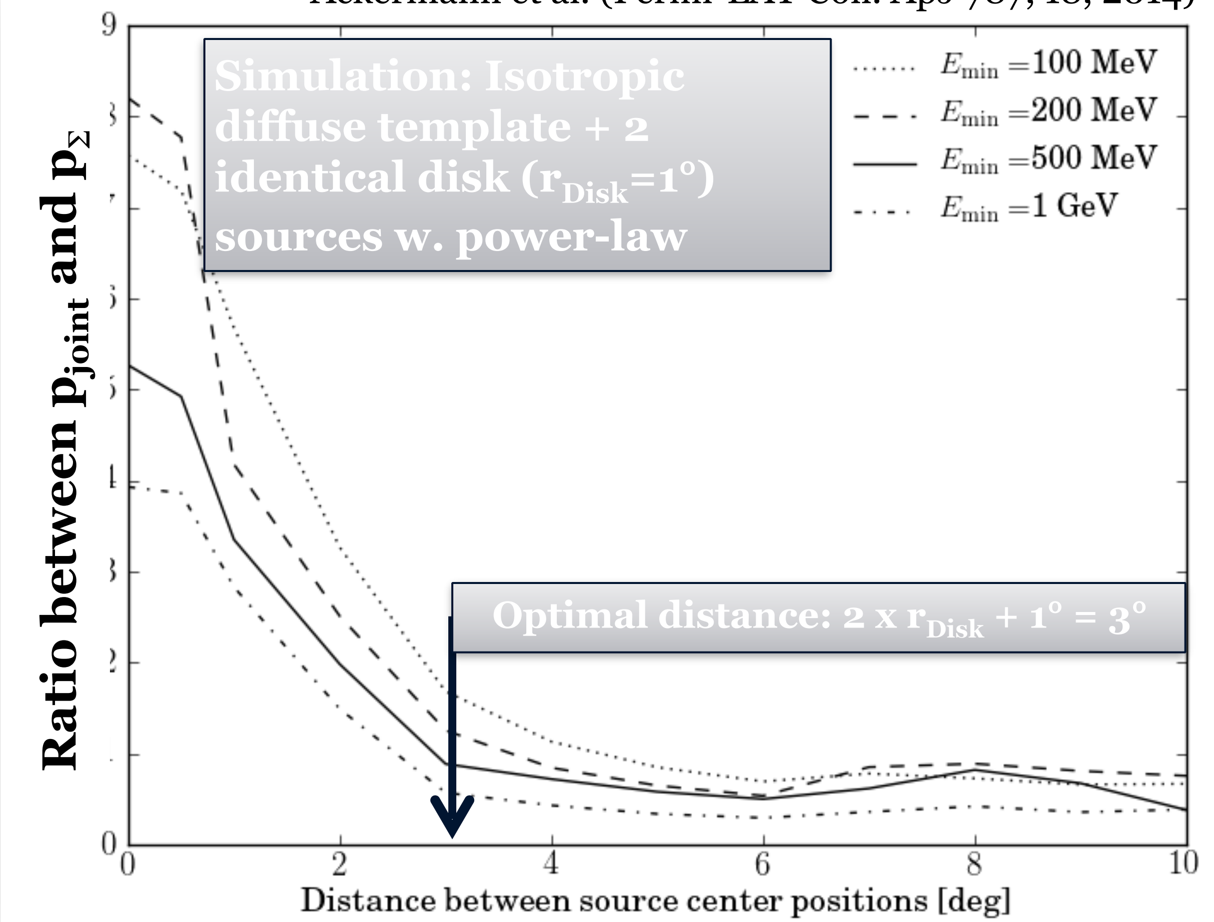


Photon Overlaps

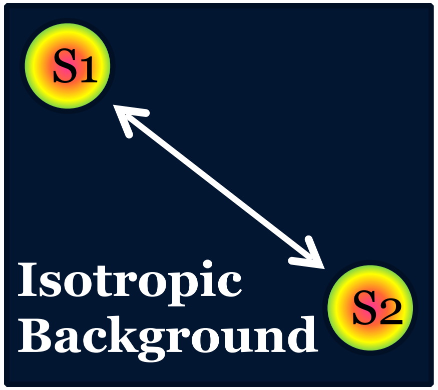
- **Joint LLH** does not include **correlation terms**
  - Need **independent analysis** regions "ROI"
    - "double counting of backgrounds"
  - **Targets should not overlap**
    - "photon sharing"
- Possible **bias** when deriving significance from **p-values**
  - $p = 1\text{-erf}(\sqrt{TS}/2)$ – connects p-value with TS
  - uncorrelated case $p_\Sigma = p_1 \times p_2$
  - Compare p_{joint} with p_Σ from **simulations**

Bias on p-values due to Overlaps

Ackermann et al. (Fermi-LAT Coll. ApJ 787, 18, 2014)

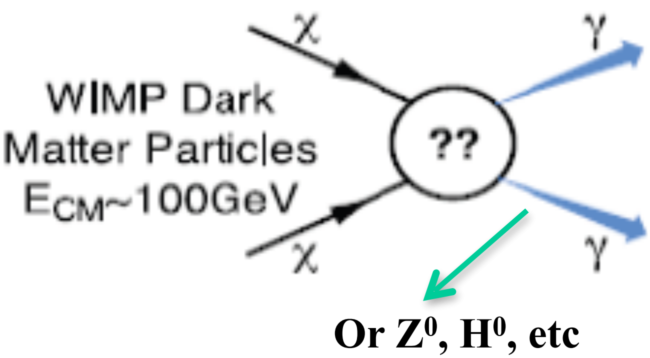


Toy MC

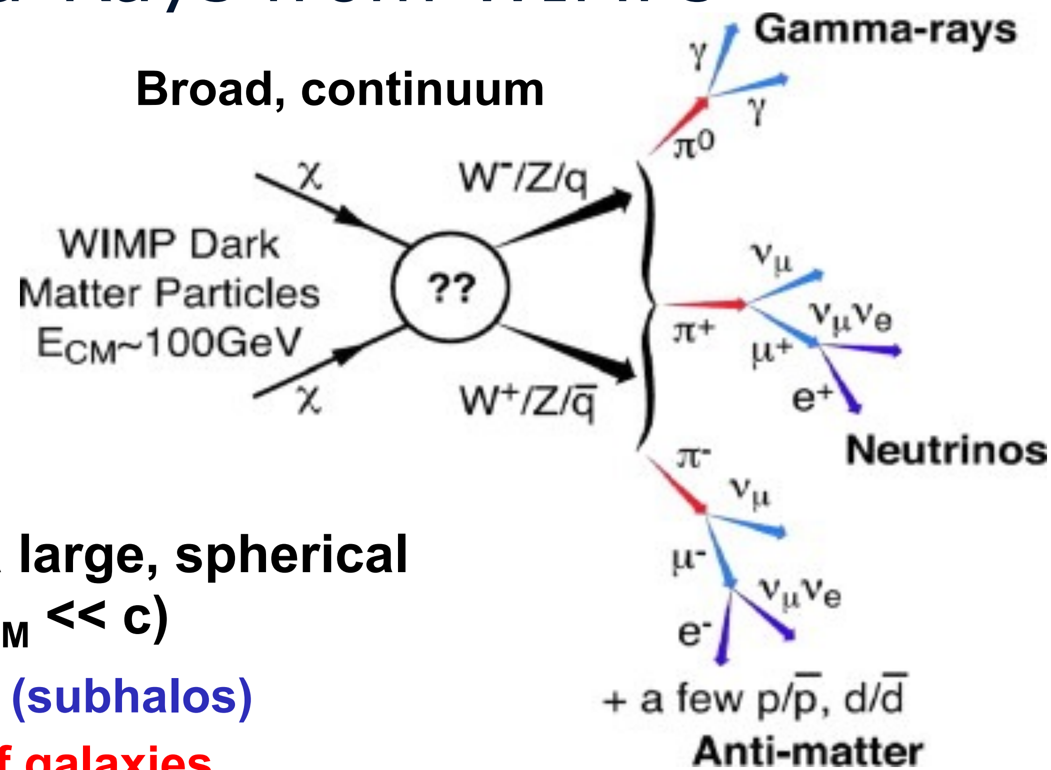


Gamma-Rays from WIMPs

Spectral Line

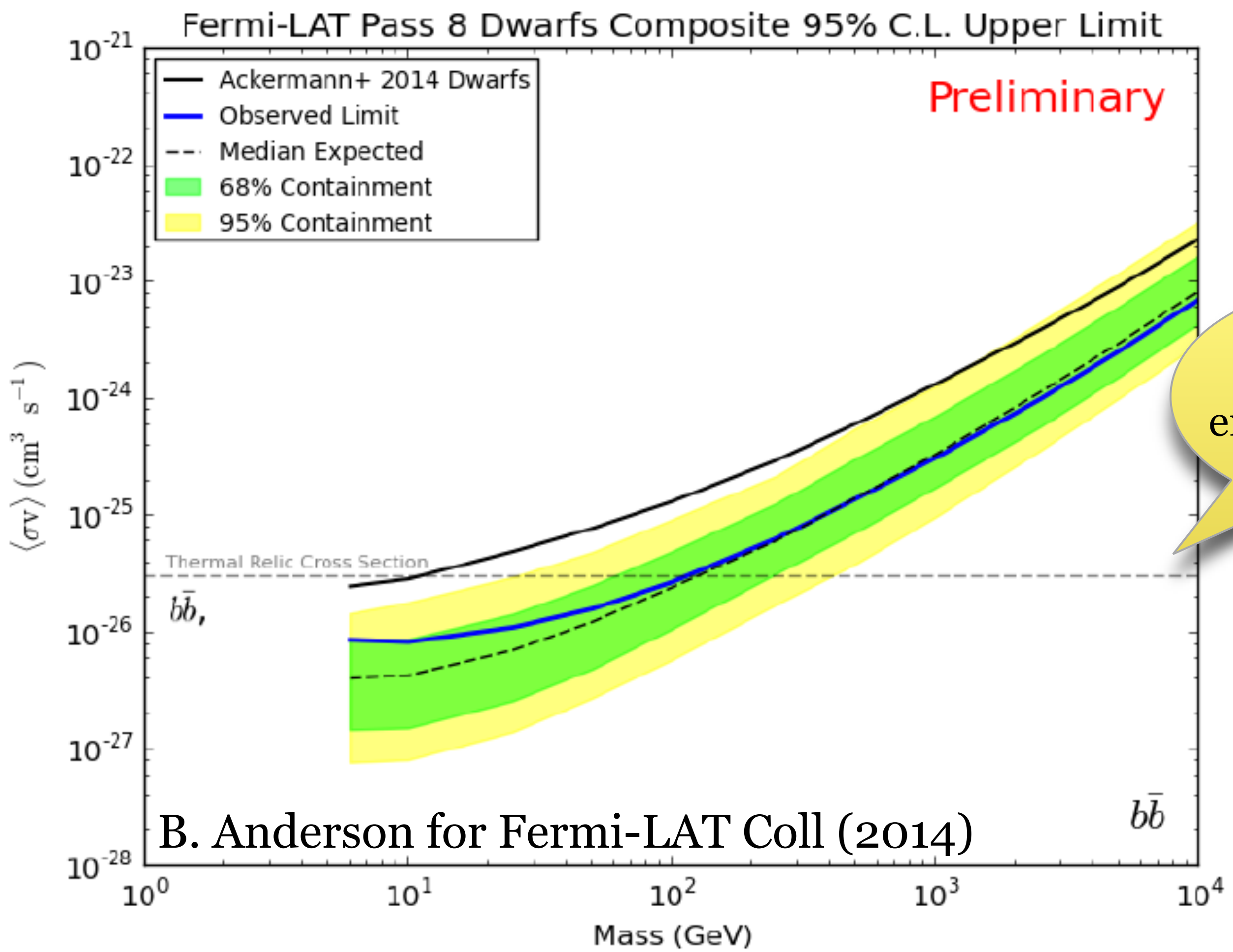


Broad, continuum



- **Believe the Milky Way sits in a large, spherical "halo" or cloud of cold DM (v_{DM} << c)**
  - **Expect DM overdensities (subhalos)**
    - **Largest are the dwarf galaxies**
  - **Other extra-galactic DM expected too (like clusters)**
- **WIMPs annihilations (decays) may produce gammas**
  - **Dominant channels -> broad continuum**
  - **Monochromatic channels expected to be rare (loop-suppressed)**

Latest results from dwarfs



no significant emission detected