Searching for Dark Matter with Fermi (and beyond)

“So sind wohl manche Sachen, die wir getrost verlachen,
weil unsere Augen sie nicht sehen.”

Mattias Claudius (†Hamburg, 1815)

Jan Conrad, OKC, Stockholm

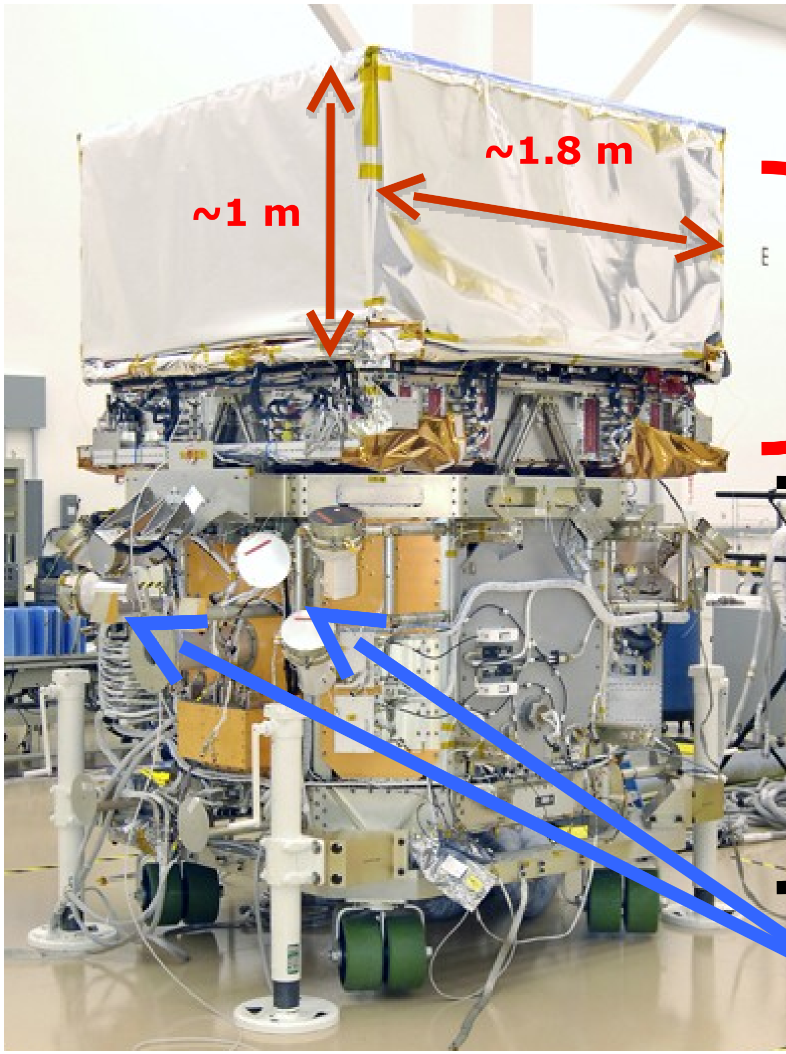
(On behalf of Fermi-LAT)

IDMS 2011

Oskar Klein centre

Stockholms universitet

Fermi Observatory



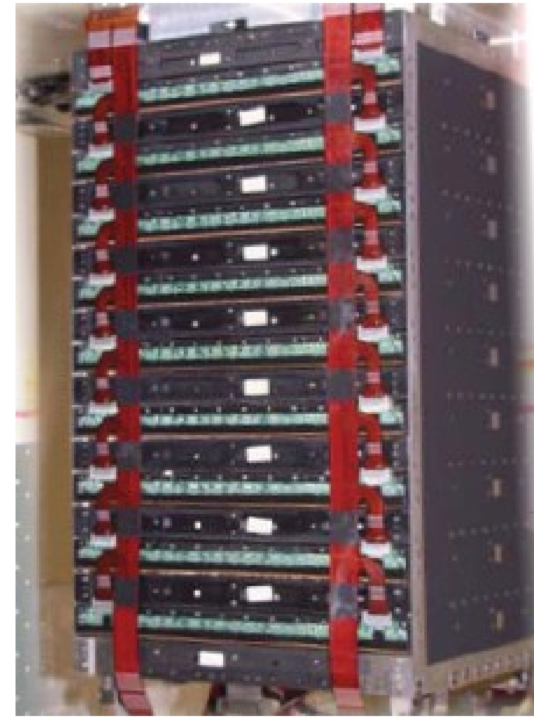
Large Area Telescope (LAT)
* High Energy Gamma Rays
* 20 MeV > E > ~300 GeV

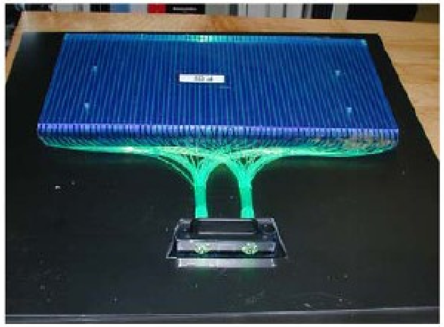
Spacecraft

Gamma-Ray Burst Monitor
* GRB Detection.
* 10 KeV < E < 40 MeV

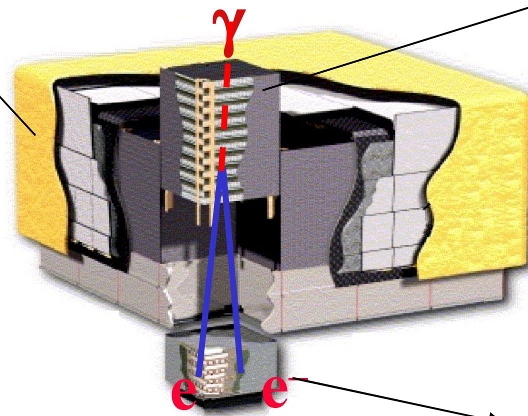
Fermi-LAT

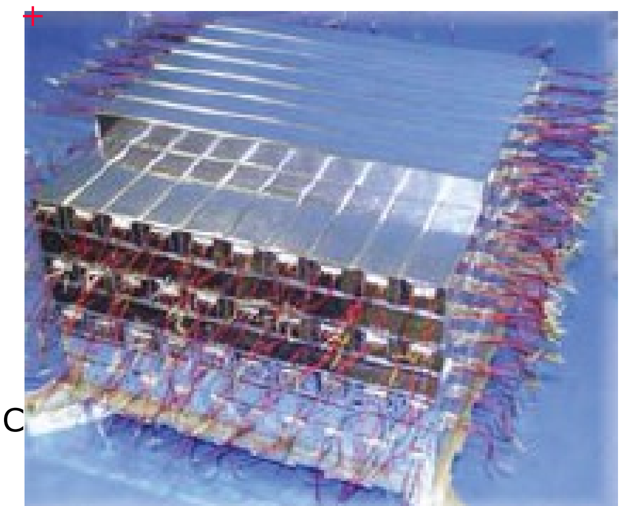
- Tracker
  - Single sided SSD (400 um, 228 um)
  - W foil interleaved (12x3%RL,4x18RL)
  - 18 xy planes





- ACD
  - 4% RL
  - Segmented (89 plastic scintillator tiles)
  - 0.9997 efficiency





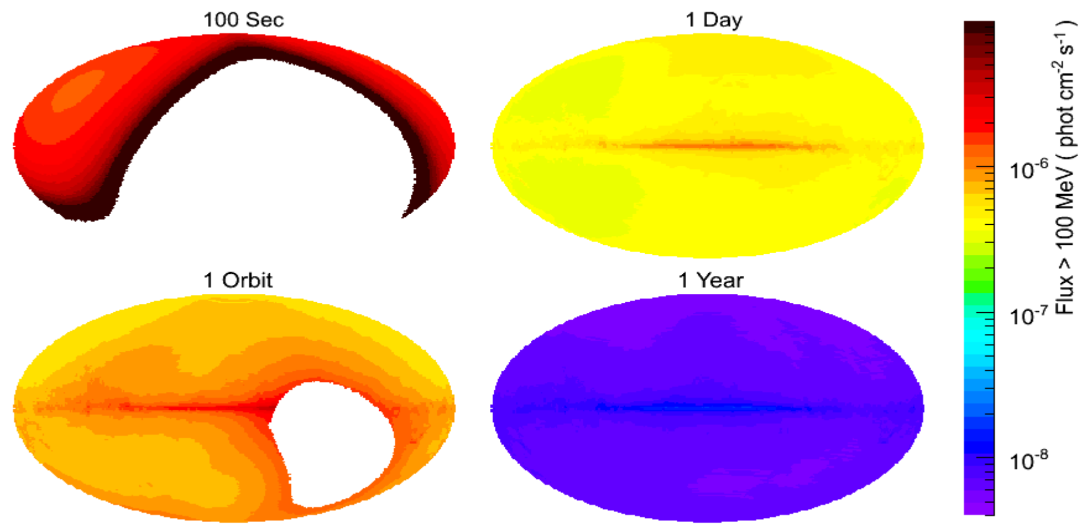
- Calorimeter
  - 8.5 R.L.
  - 1536 CsI(Tl) crystals (1200 kg)
  - Hodoscopic (8 layers)

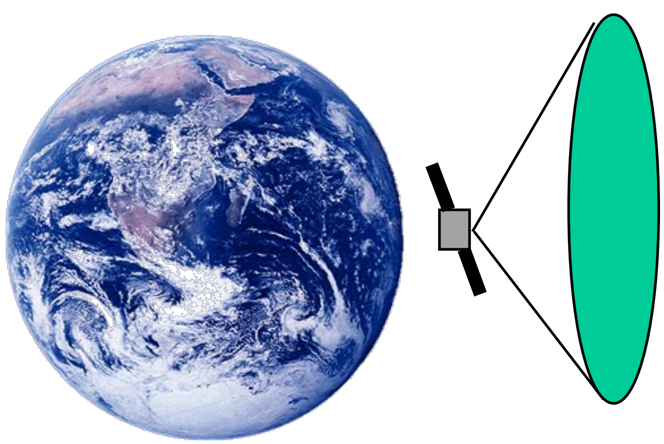
Launch 11. juni 2008

Nominal operations: Aug 4 2008

Operational Modes

- Sky survey mode
  - Standard operation mode
  - View full sky every 2 orbits
- Targets of opportunity (ToO)
  - Autonomous repoint (GRBs)
  - Slew to keep ToO in FOV
  - Later: ToO proposals

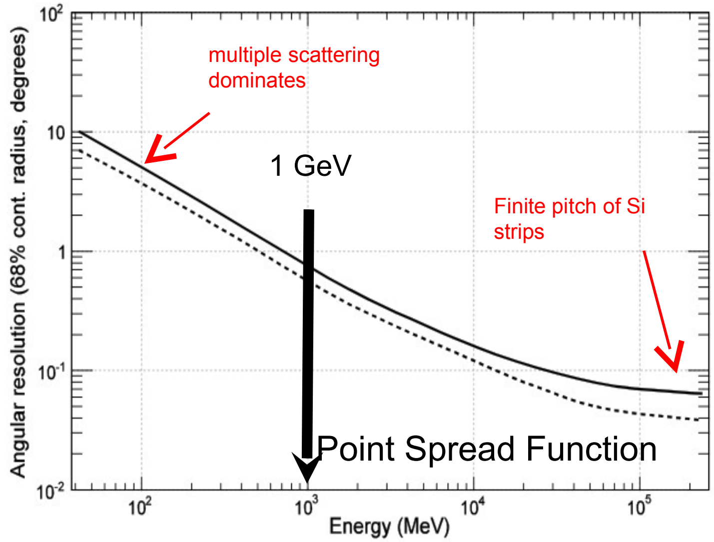


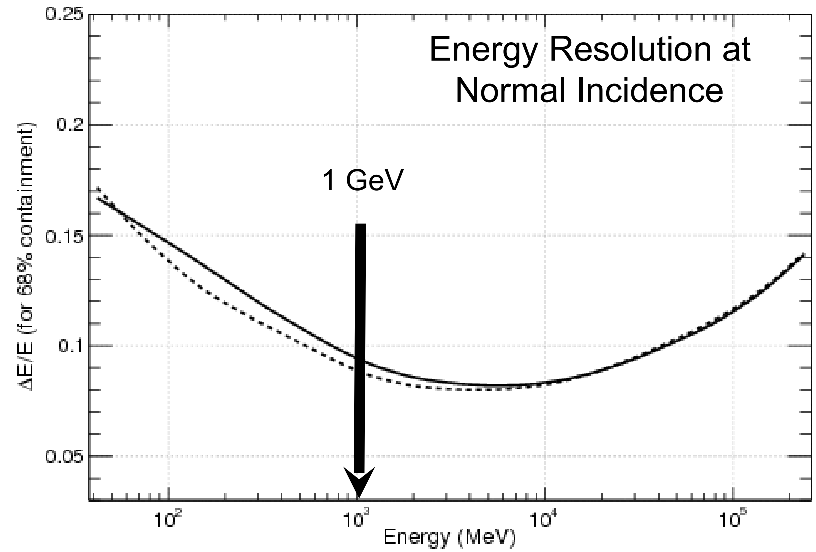


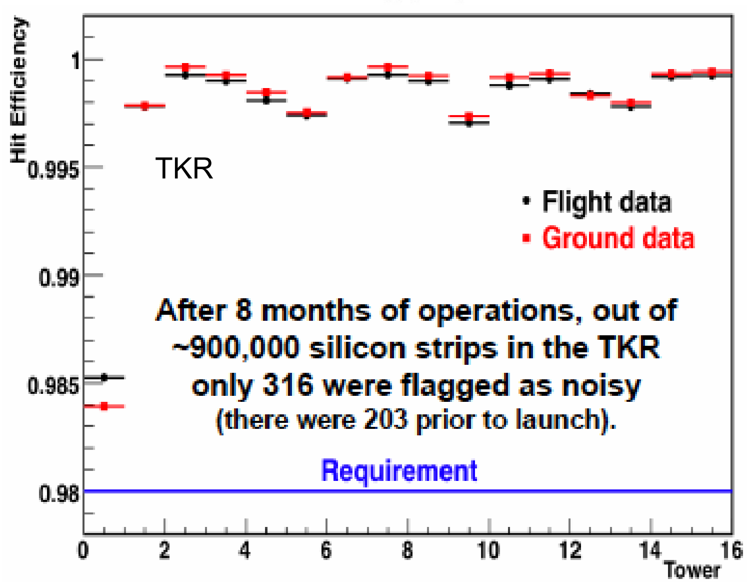
LAT: Wide Field of View ~2.4 sr

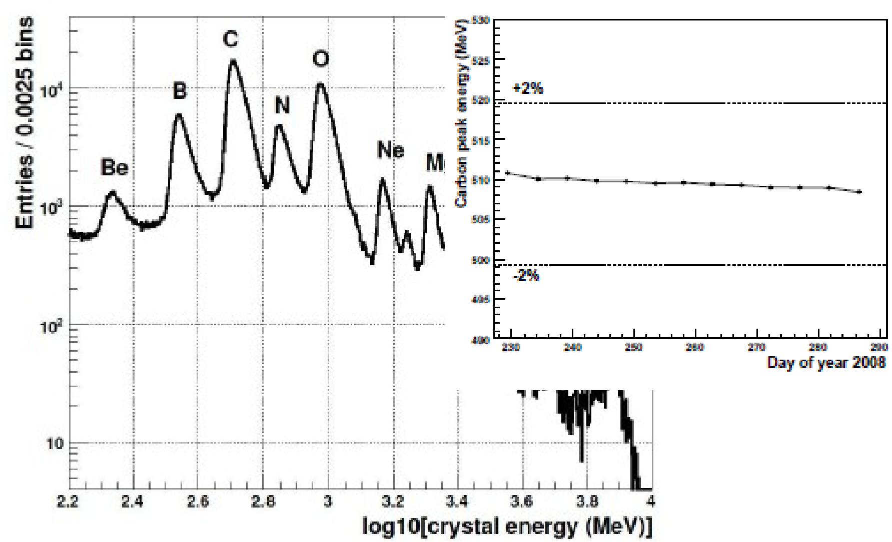
GBM: See almost all of the sky not occulted by the earth

Detector Performance



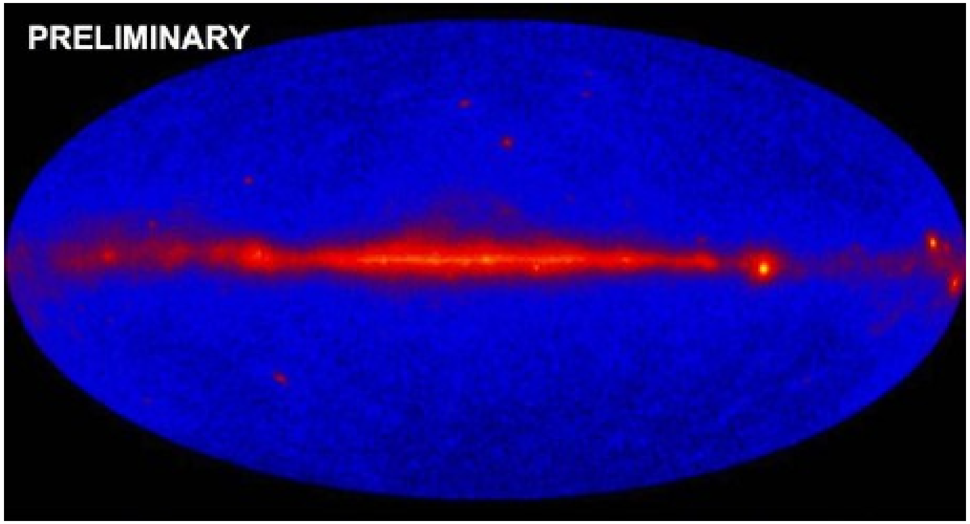




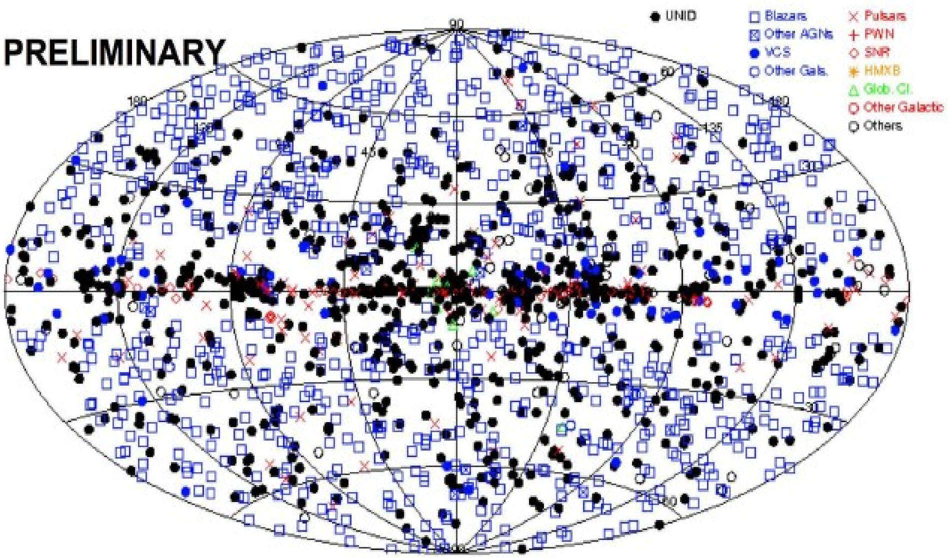


The Fermi-LAT sky (2nd catalogue)

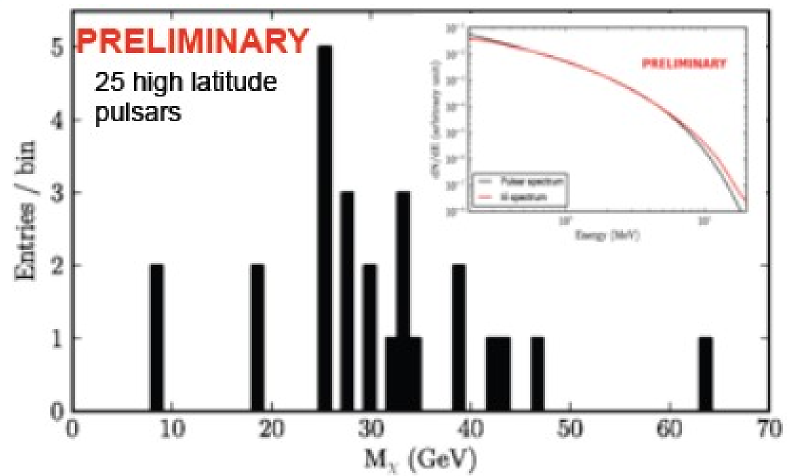
Released by end of Juli, Pass7v6



Type	Number	Percentage of total
Active Galactic Nuclei	832	44%
Candidate Active Galactic Nuclei	268	14%
Unassociated	594	32%
Pulsars (pulsed emission)	86	5%
Pulsars (no pulsations yet)	26	1%
Supernova Remnants/Pulsar Wind Nebulae	60	3%
Globular Clusters	11	< 1%
Other Galaxies	7	< 1%
Binary systems	4	< 1%
TOTAL	1888	100%



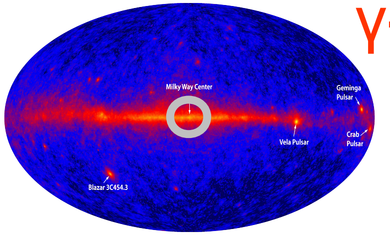
Very Preliminary - Work Still In Progress



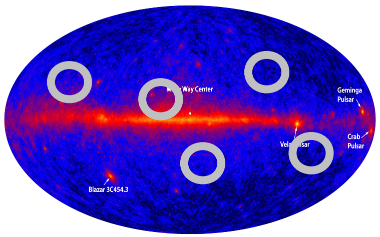
385 unassociated sources tested, no DM

Fermi-LAT results on DM

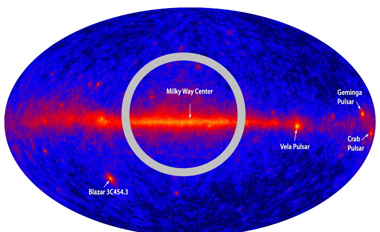
γ-ray spectral



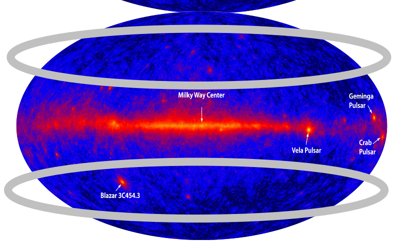
Fermi-LAT: TeVPA 2009, RICAP 2010,
Fermi Symposium 2011,
Goodenough & Hooper, arXiv:0910.2998
Dobler et al., arXiv:0910.4583



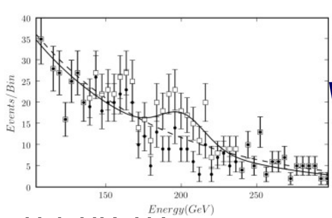
Fermi-LAT: Astrophys.J.712:147-158,2010
Fermi-LAT: JCAP 1005:025,2010
Scott et al.: JCAP 1001:031,2010
Buckley & Hooper, arXiv:1004.1644



Fermi-LAT: IDM 2010
Cirelli et. al. arXIv: 0912.0663

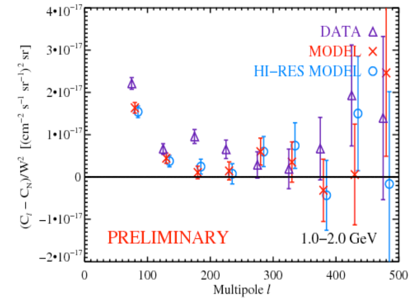


Fermi-LAT: JCAP 1004:014,2010
Akorvazian et. al. arXiv:1002.3820
Huetsi et. al. arXiv:1004.2036



Fermi-LAT: Phys.Rev.Lett.104:091302,2010
Vertongen et al, arXiv:1106.2201

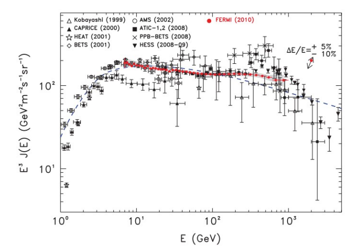
anisotropies



Fermi-LAT: Fermi Symposium 2011, I DM 2010

electrons

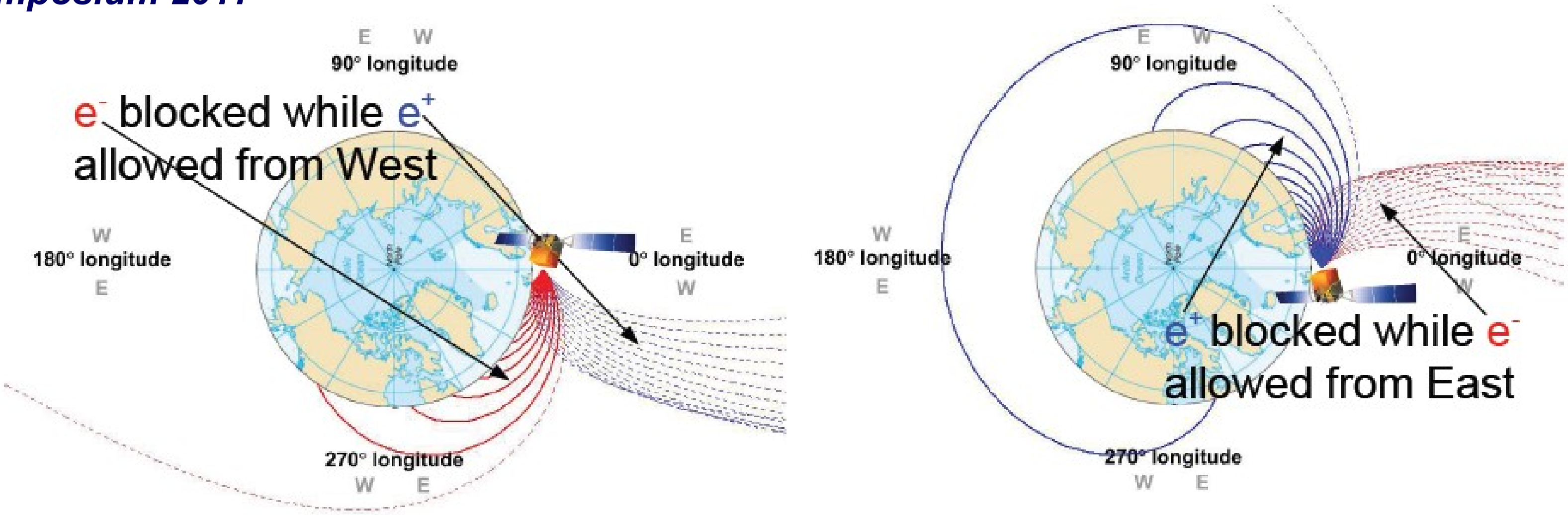
Fermi-LAT: **Phys. Rev. D., 82, 092004**

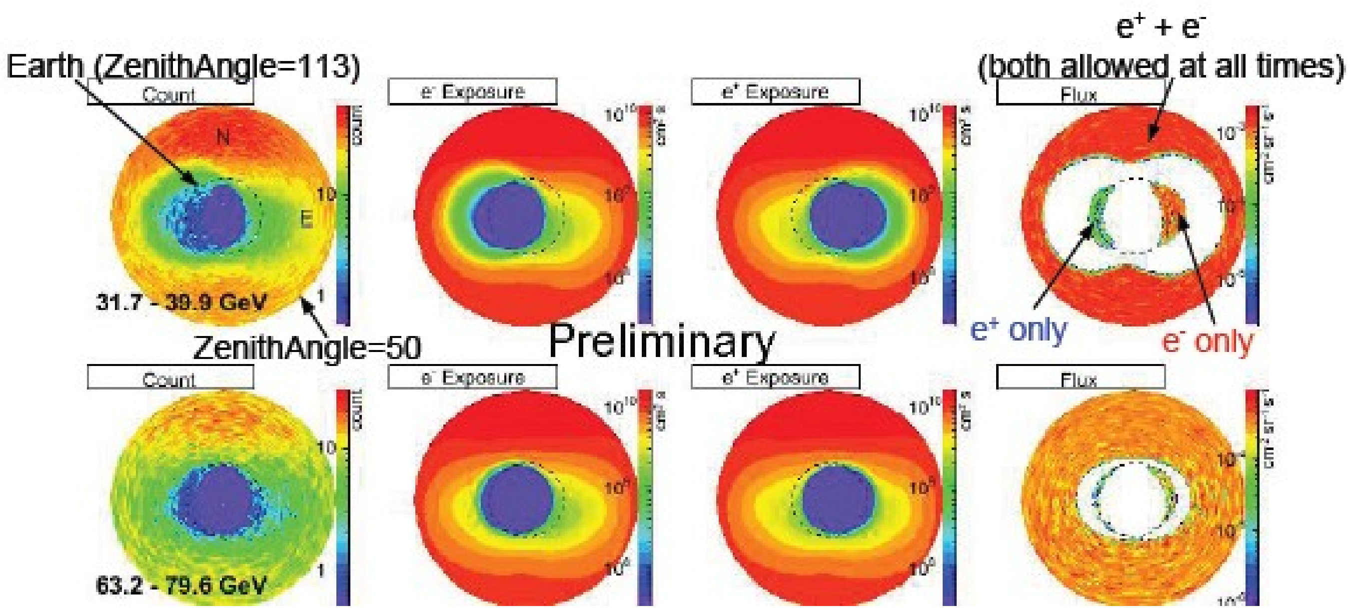


No Dark Matter detected so far, but some interesting constraints

Positron fraction measurement

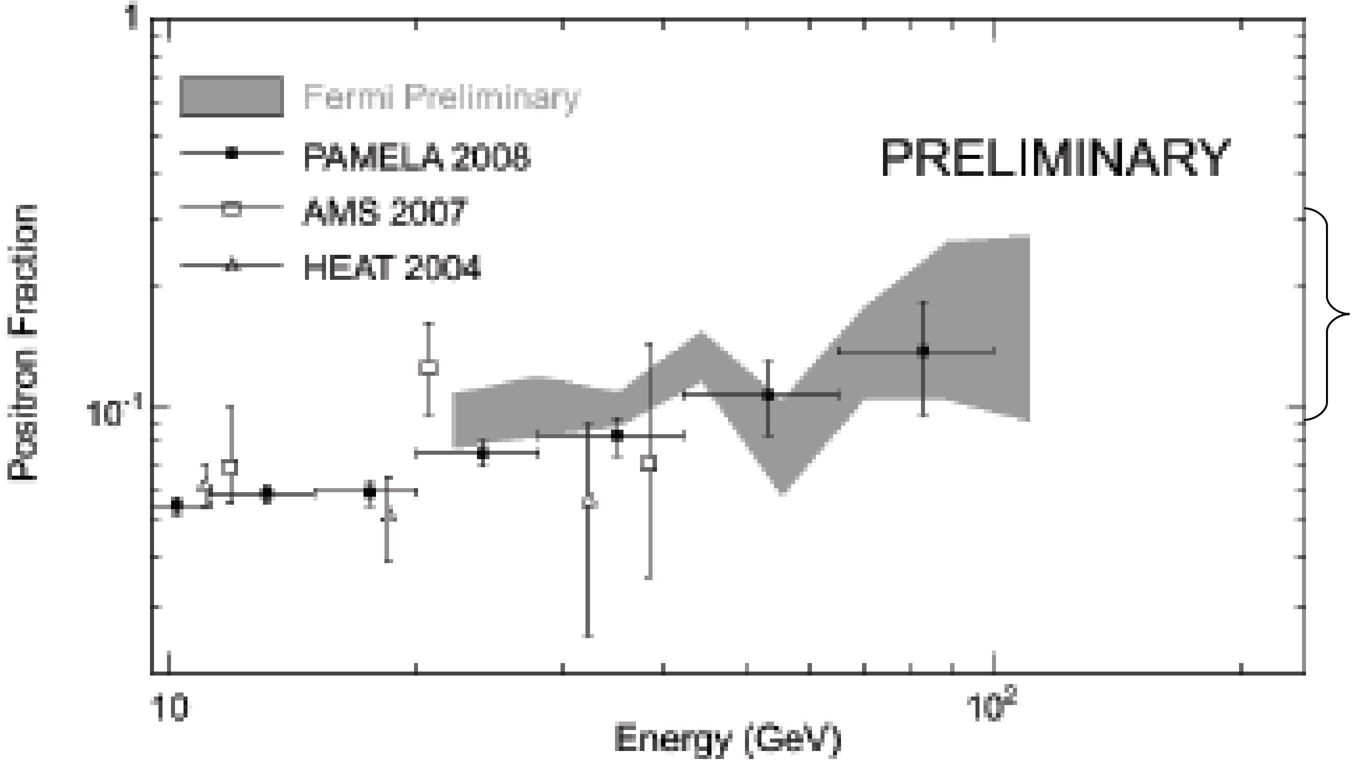
Fermi-LAT: 3rd Fermi Symposium 2011





09-08-07

Positron fraction measured by Fermi-LAT



Systematics due to background subtraction

	frac	error
7	0.128	0.0606
8	0.243	0.0625

Searches in gamma-rays covered in this talk

- **Stacked dwarfs**
  – or…..*"Yes we can"*

  Barack Obama

- **Stacked clusters**
  - or ….*"I do not seek, I find"*

  Pablo Picasso

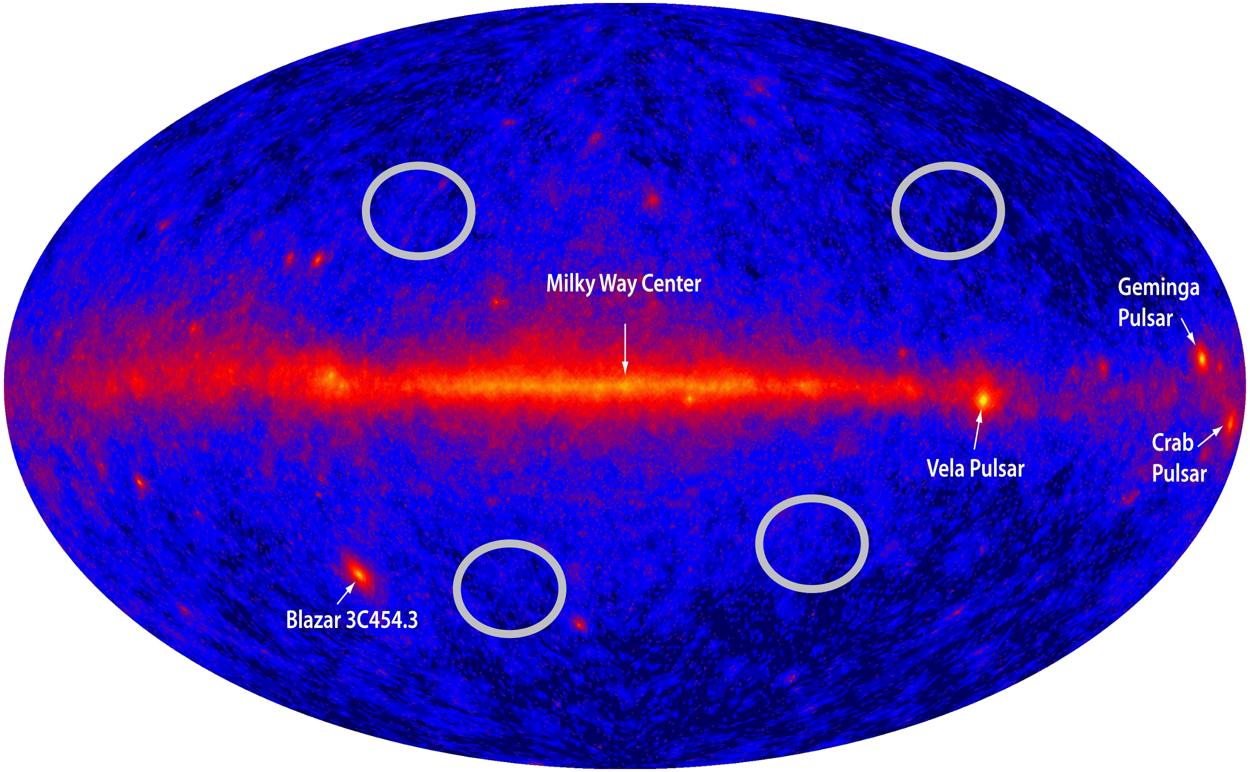
- **Galactic halo**
  – or ….. *"Much of your pain is self-chosen"*

  Khalil Gibran

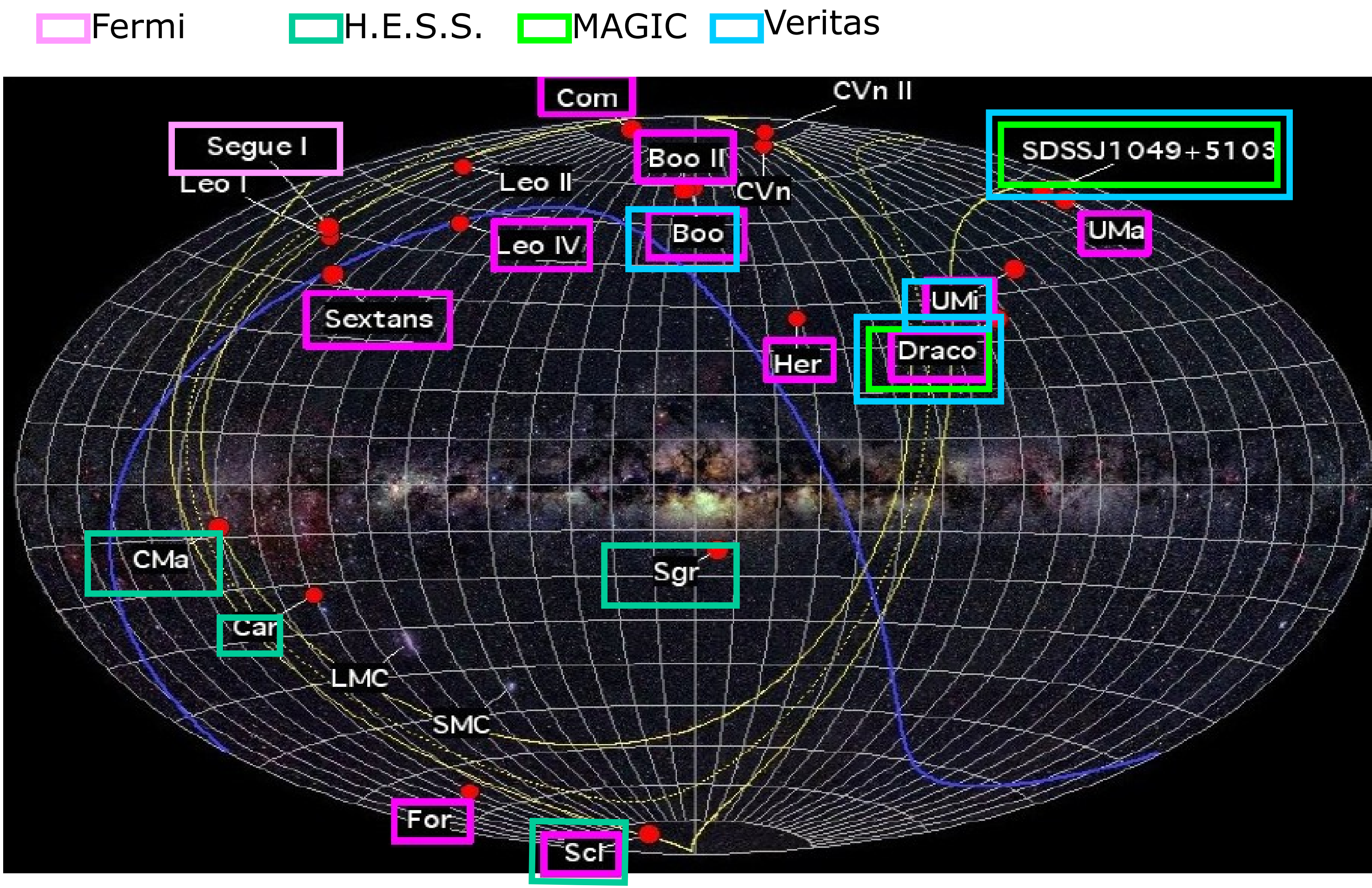
- **Lines**
  – or ….. *"All work and no play makes us dull?"*

  English proverb

Dwarfs and Galaxy Clusters.



Dwarfs probed in gamma-rays



	Exposure (hours)	Background	DM distribution
Fermi	**24** month (~ 3000 h)	Diffuse/ Point sources	Empirical NFW
H.E.S.S.	**18** (SgrD) **15** (Carina) **10** (Canis M.) **12** (Sculptor)	wobble	Empirical NFW Theo. NFW
VERITAS	**~15** (Willman, Bootes) **~19** (Draco, Ursa Min)	wobble	Empirical NFW
MAGIC	**16** (Willman I) 8 (Draco) **30** Segue	wobble	Empir. NFW Empir. core/cusp Kazantzidis

A novel approach: likelihood stacking

$$L(\langle \sigma_{ann} v \rangle, m_{WIMP}; \vec{\Theta}) = \prod_{i=1}^{N} L_i(\langle \sigma_{ann} v \rangle, m_{WIMP}, C, b_i; \vec{\Theta}_i)$$

Constants (e.g. branching fraction in our case)

DM properties Same for all dSphs

Individual parameters (e.g. galactic diffuse normalisation..)

- Decreased statistical uncertainies
- Less sensitive to individual DM distribution uncertainties
- Analysis can be optimized on individual sources

What about dark matter distribution uncertainties?

- So far: uncertainties due to DM distribution have either been ignored, or only considered for benchmarks.
- Profile likelihood:

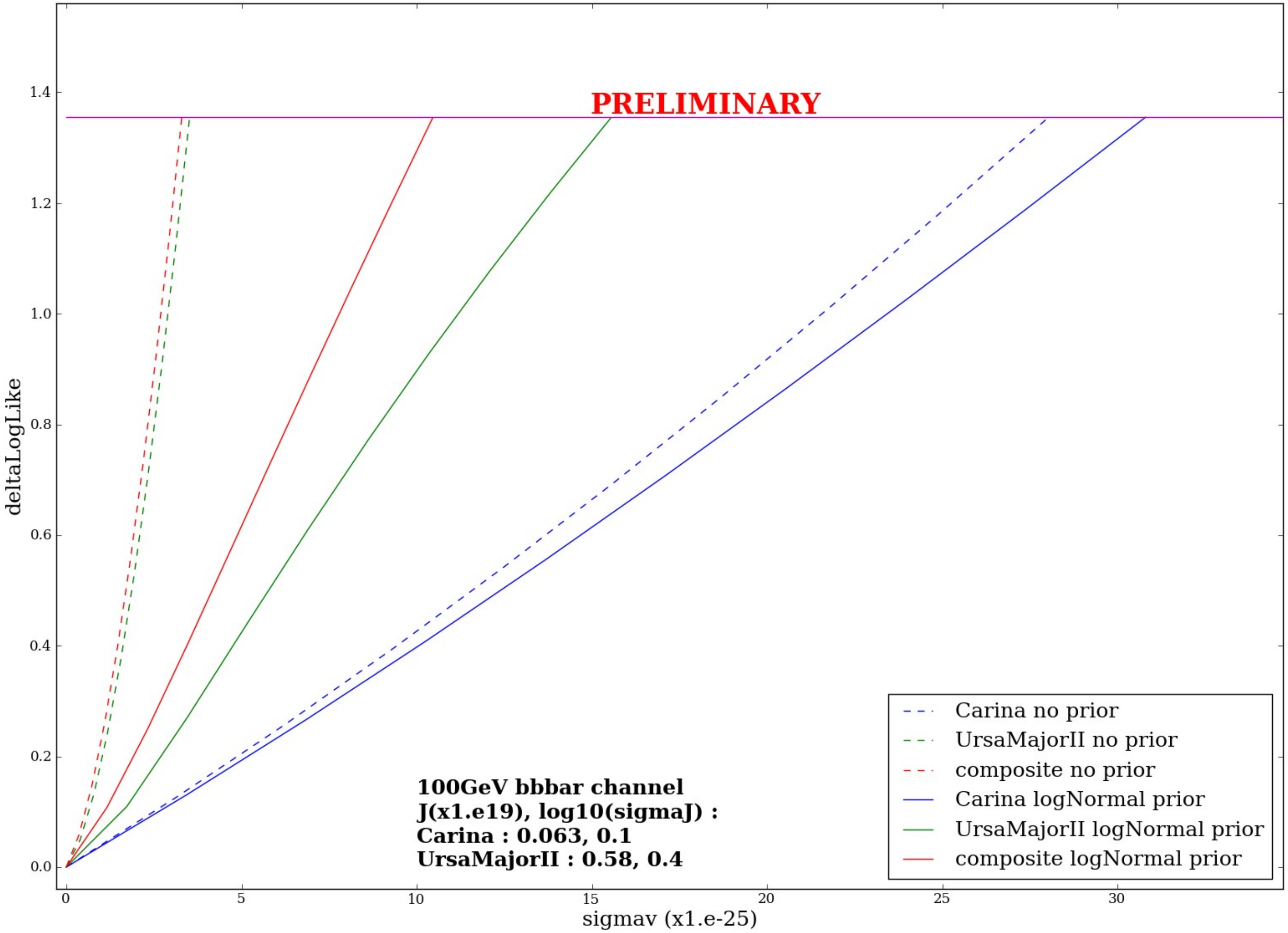
$$L(<\sigma_{ann}v>, m_{WIMP}; \vec{\Theta}) =$$

$$\prod_i^N L_i(<\sigma_{ann}v>, m_{WIMP}, J_i^m, C, b_i; \vec{\Theta}_i) \frac{1}{J_i^m \sigma_{J,i}\sqrt{2\pi}} e^{\frac{-(\ln(J_i^m) - J_i^{true})^2}{2\sigma_{J,i}^2}}$$

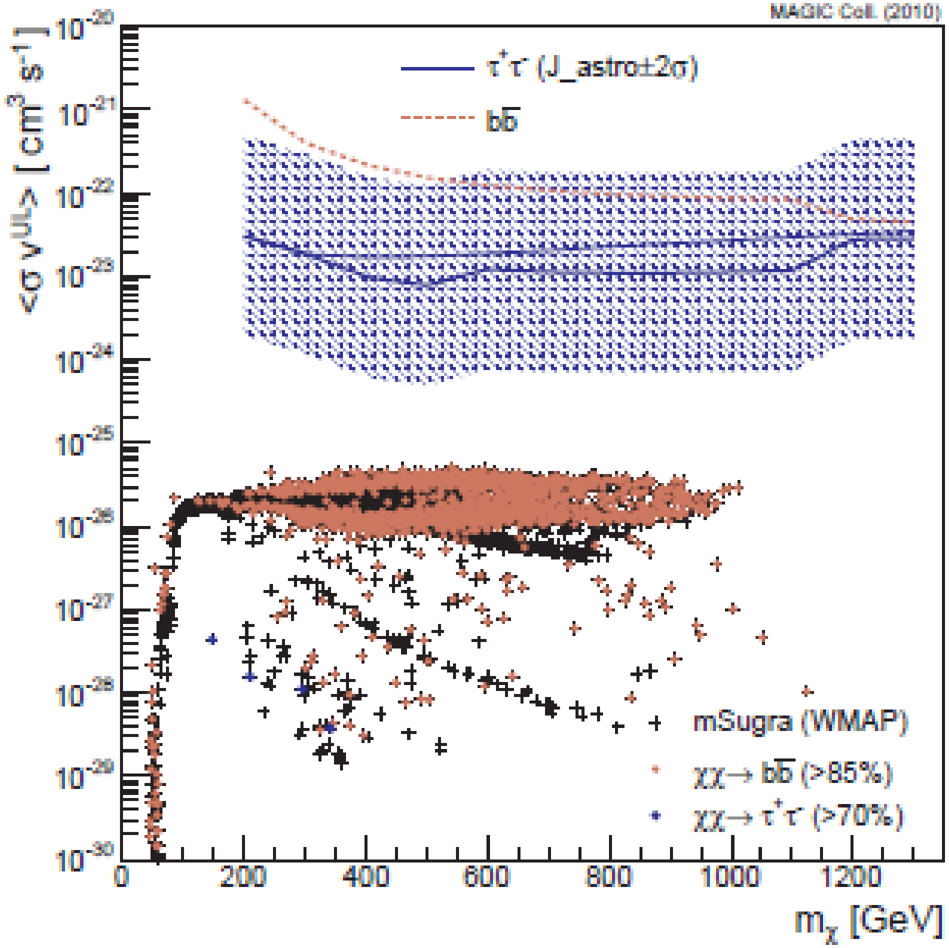
PRELIMINARY

Dwarf	J [10^19 GeV^2 cm^-5]	Error +	Error -	σ_J logNormal
Bootes I	0.16	0.35	0.13	0.73
Carina	0.06	0.02	0.01	0.10
Coma Berenices	0.16	0.22	0.08	0.30
Draco	1.20	0.31	0.25	0.10
Fornax	0.06	0.03	0.03	0.30
Sculptor	0.24	0.06	0.06	0.12
Seguel	2.00	5.95	1.49	0.59
Sextans	0.06	0.03	0.02	0.18
Ursa Major II	0.58	0.91	0.35	0.40
Ursa Minor	0.64	0.25	0.18	0.14

Effect of including the uncertainties on the likelihood function



Recent MAGIC result on Segue 1



Results

10 dwarfs:

24 Month,

Pass 6 v3, diffuse,

point source, binned likelihood

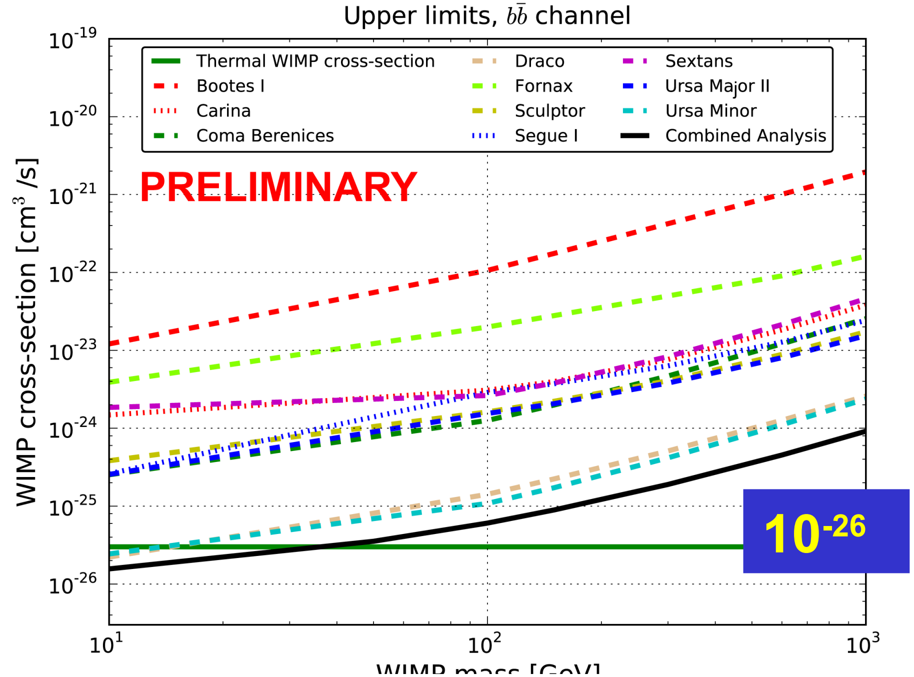
200 MeV – 100 GeV

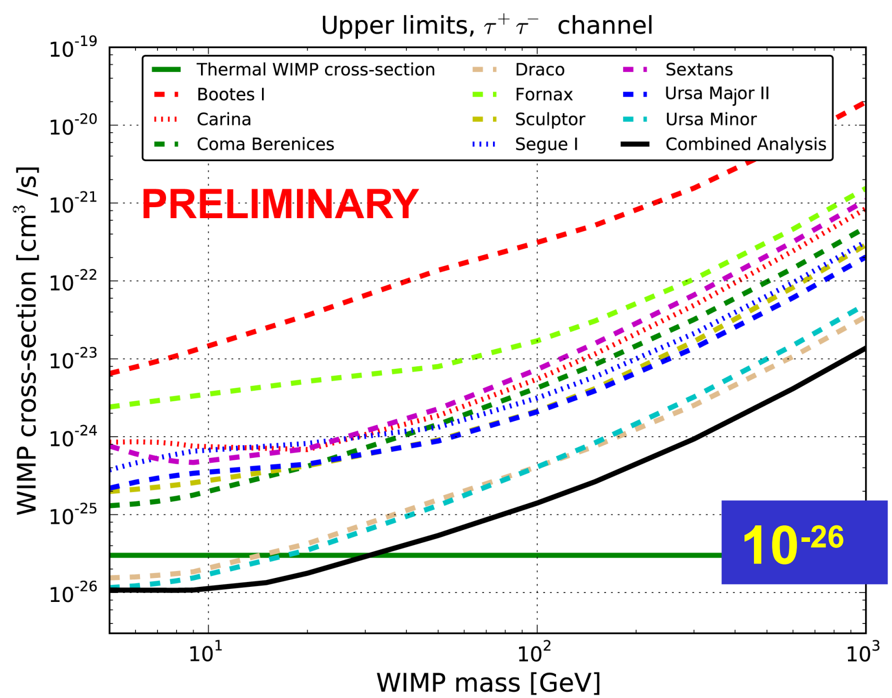
Diffuse/isotropic background

1FGL Point sources

J factors from stellar kinematics (NFW)

Fermi-LAT, Fermi symposium 2011

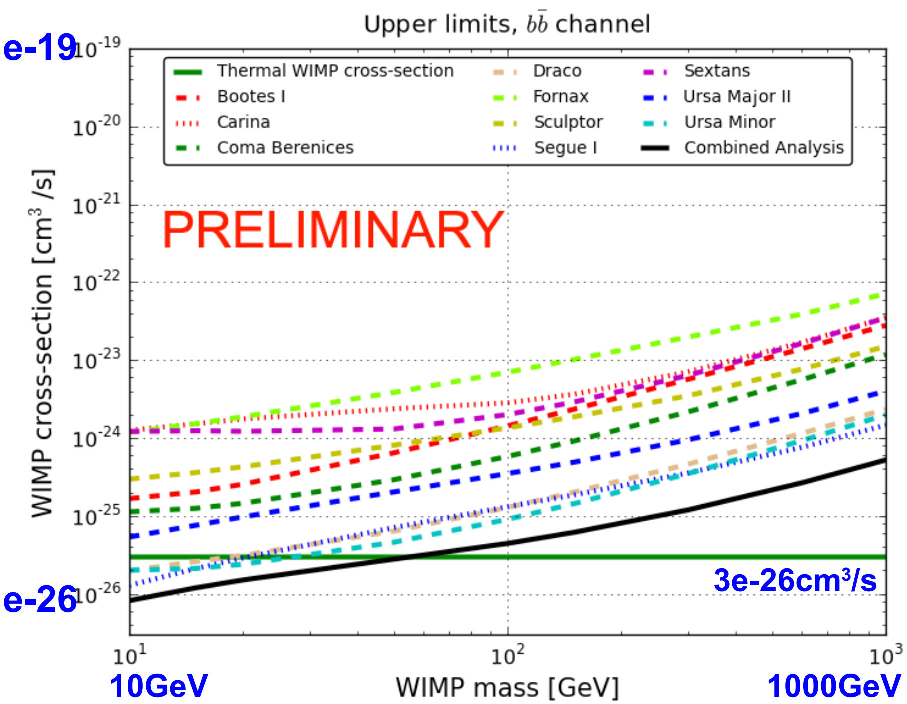


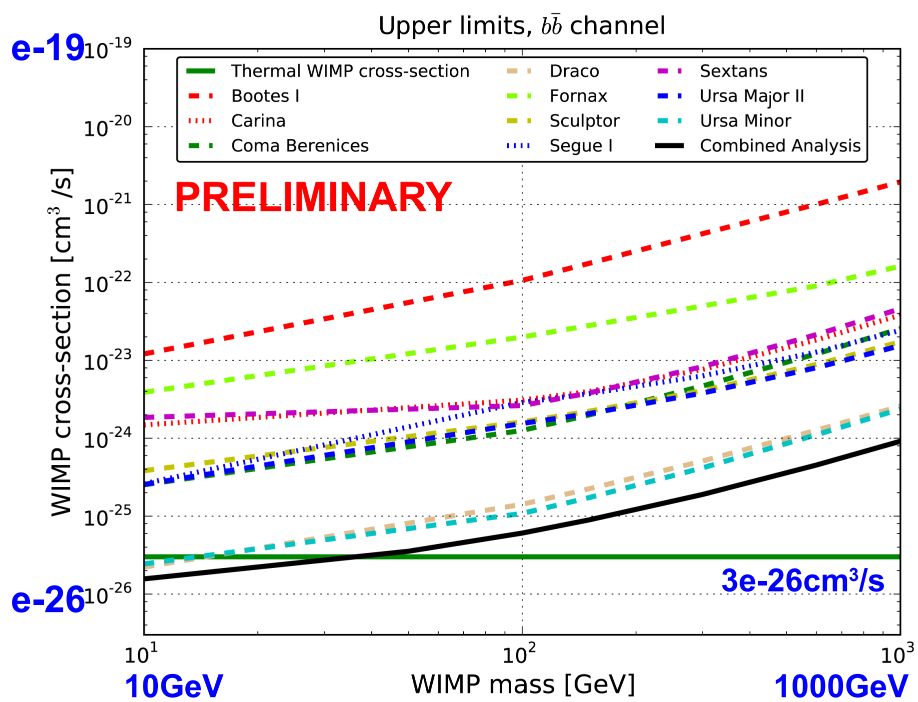


Including J-factor uncertainties

- Nominal J-factor used,
- no uncertainties included

- J-factor uncertainties included





Including the J-factor uncertainties changes the constraint by roughly 40 %.

The somewhat Fermi-centric view

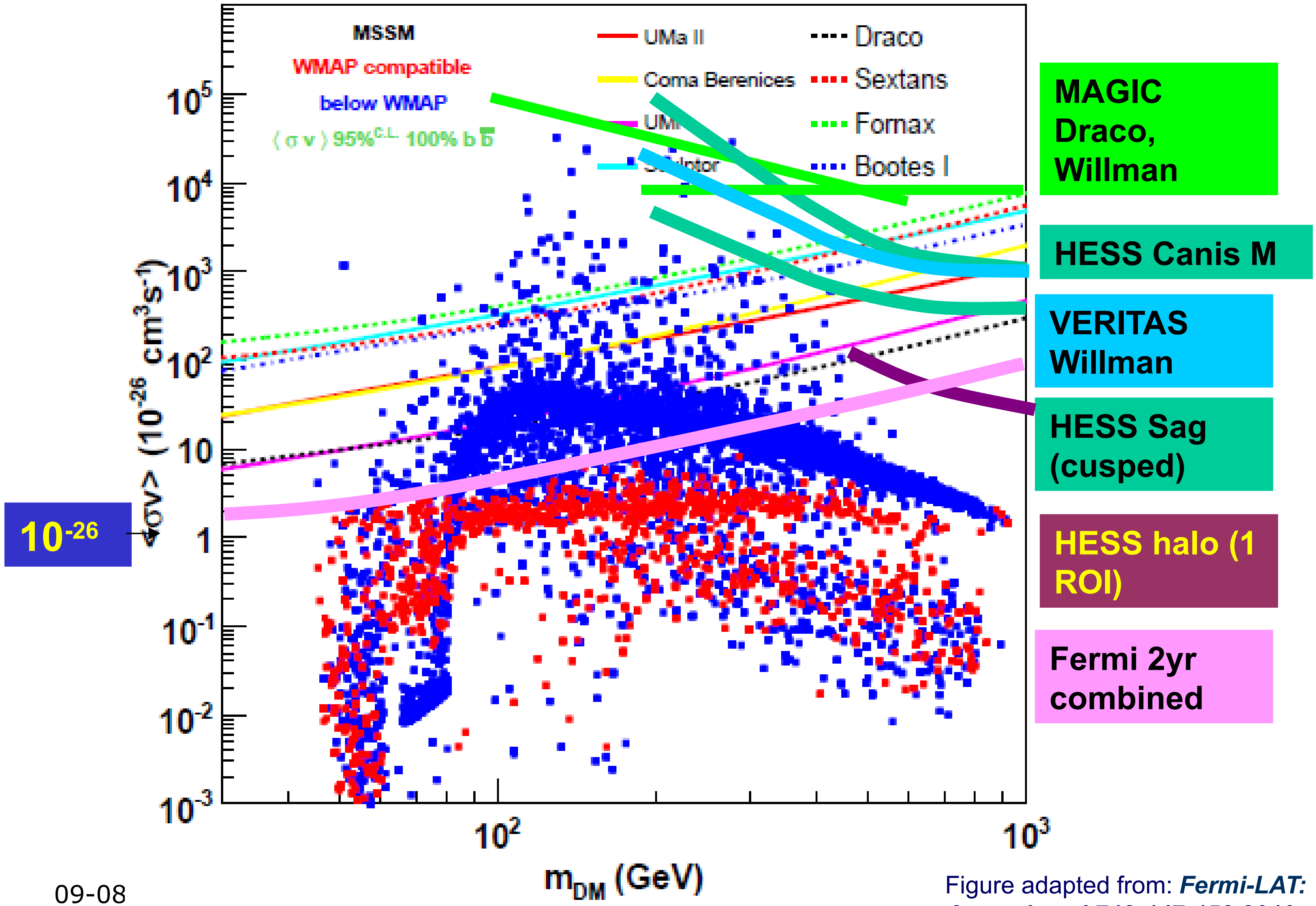


Figure adapted from: ***Fermi-LAT: Astrophys.J.712:147-158,2010***

… not so Fermi centric

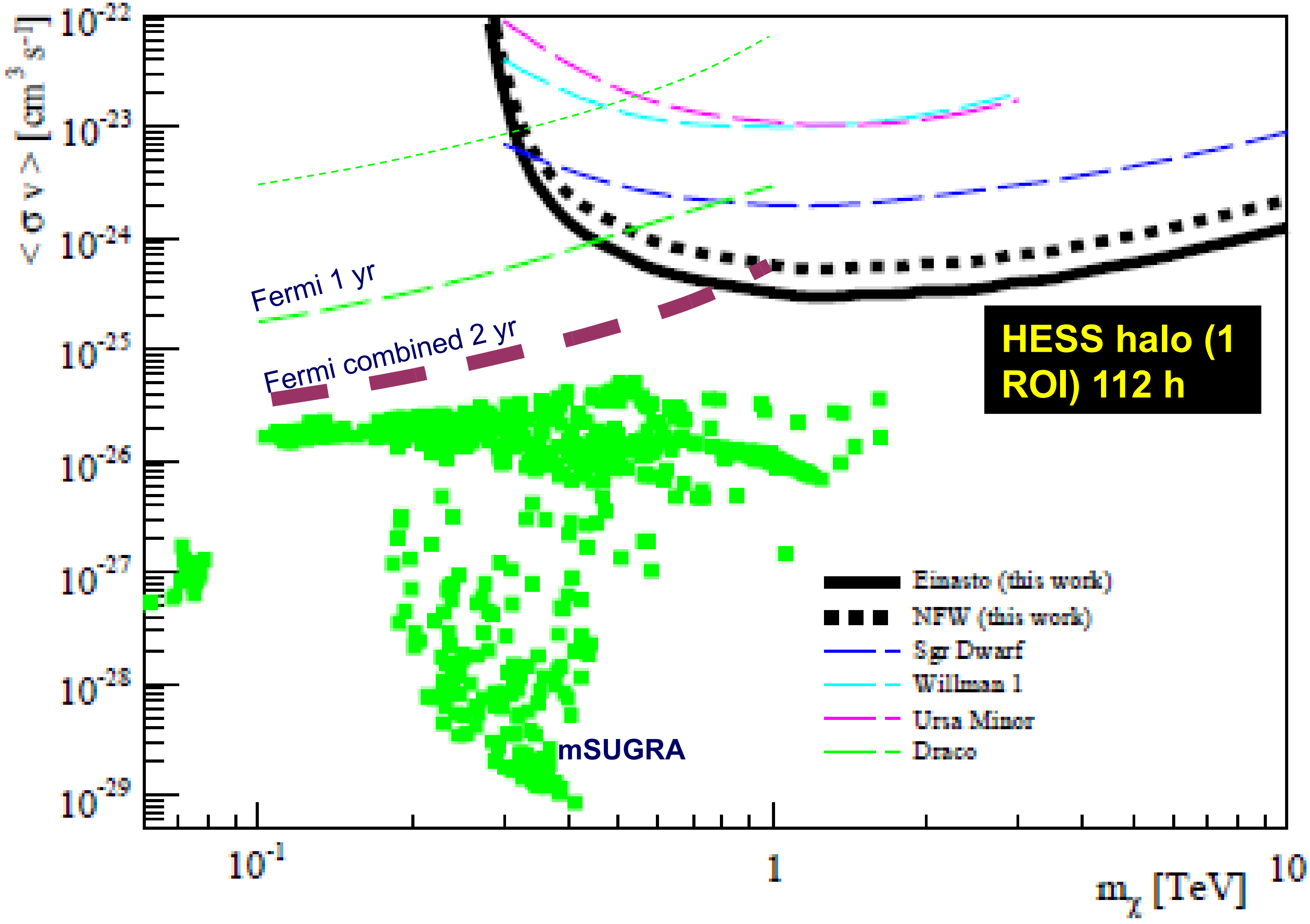


Figure adapted from: ***H.E.S.S: Phys.Rev.Lett. 106 (2011) 161301***

Remarks

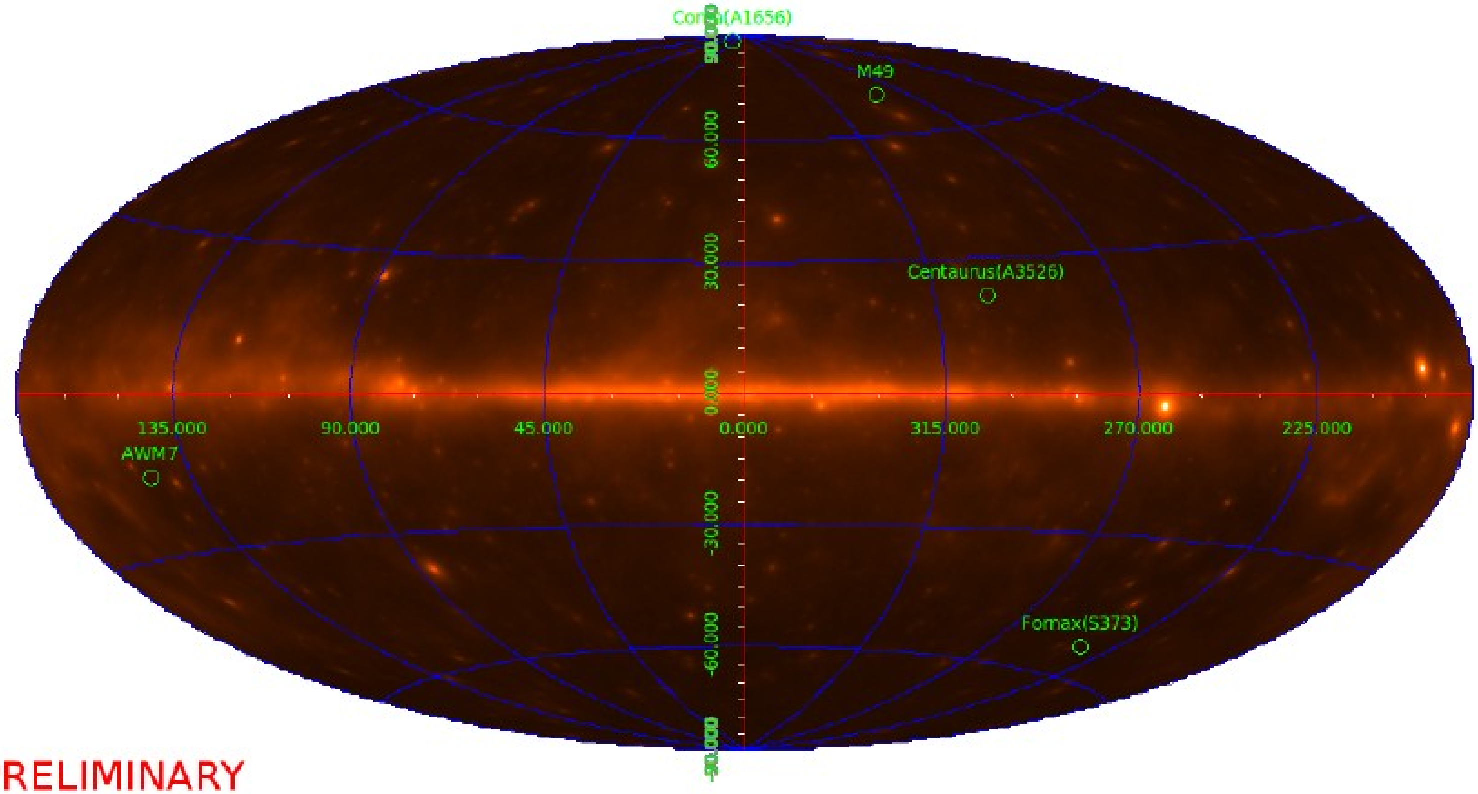
- Improvements by adding dwarfs to the stack, more data, event selection, smarter way of modeling the background ….

- Further progress on J factor uncertainties: no King model, no NFW …..? → can go in both directions.

- Yes, we can ….. go below 10^{-26} (10 year)

- Dwarfs are good for constraints, but not necessarily for discovery.

From small to large: Galaxy Clusters



PRELIMINARY

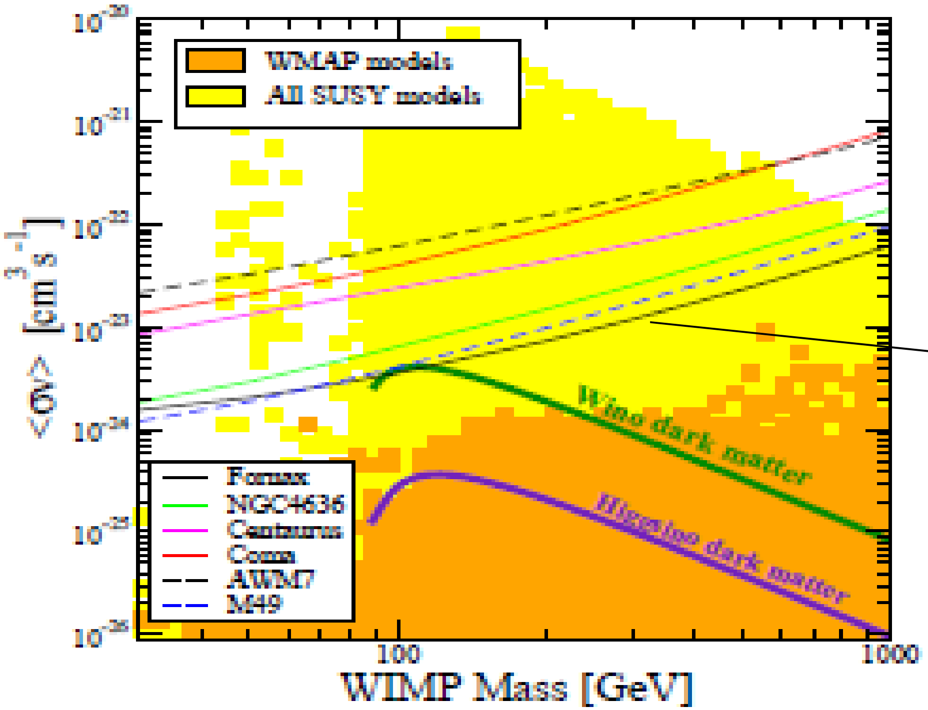
Cluster	Mean Distance (Mpc)	Mass Estimate M_{500} (10^{14}) $M_{\odot}$	CR Ranking*	DM Ranking**
M49	16.1	0.41	1	2
Coma	99.0	11.99	2	4
Centaurus	51.2	2.39	3	3
AWM7	69.2	3.79	4	5
Fornax	19.0	0.87	5	1

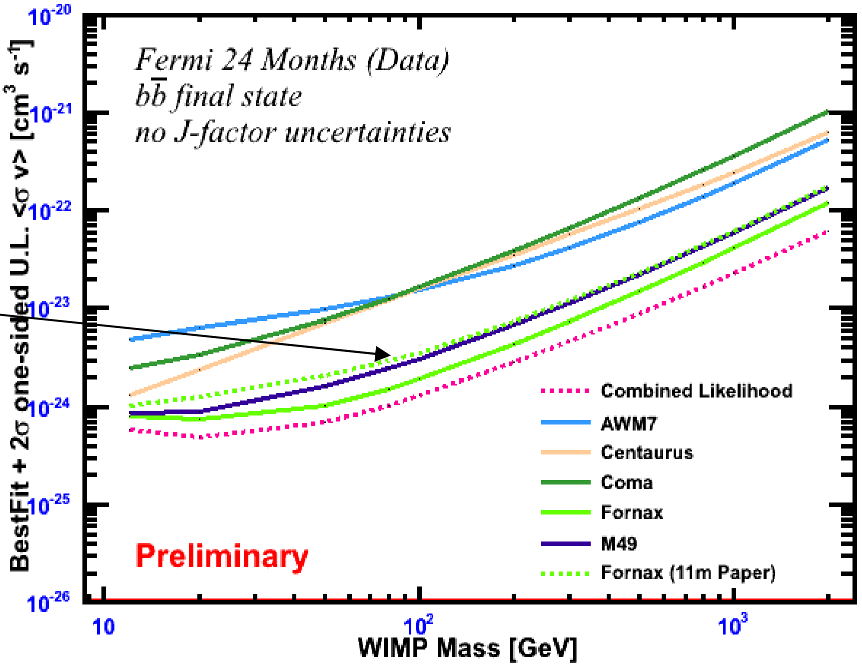
DM limits

Factor 2.5 improvement
w.r.t 11 month Fornax

Fermi-LAT: Fermi Symp. 2011

Analysis details the same as In dwarf analysis

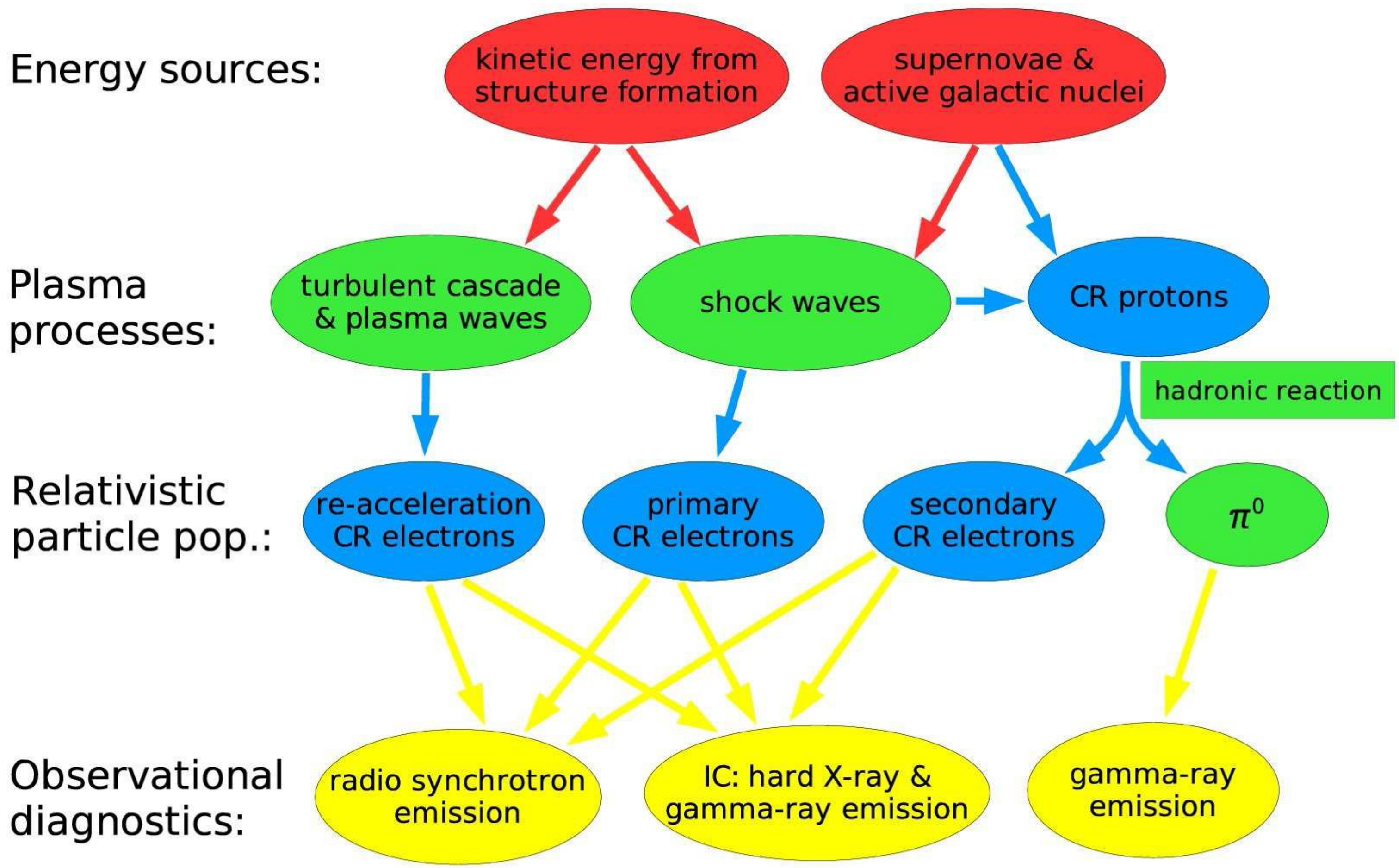




No boost: J factor of the "best" cluster comparable to the "worst" dwarf

I apologize .....

Relativistic populations and radiative processes in clusters:

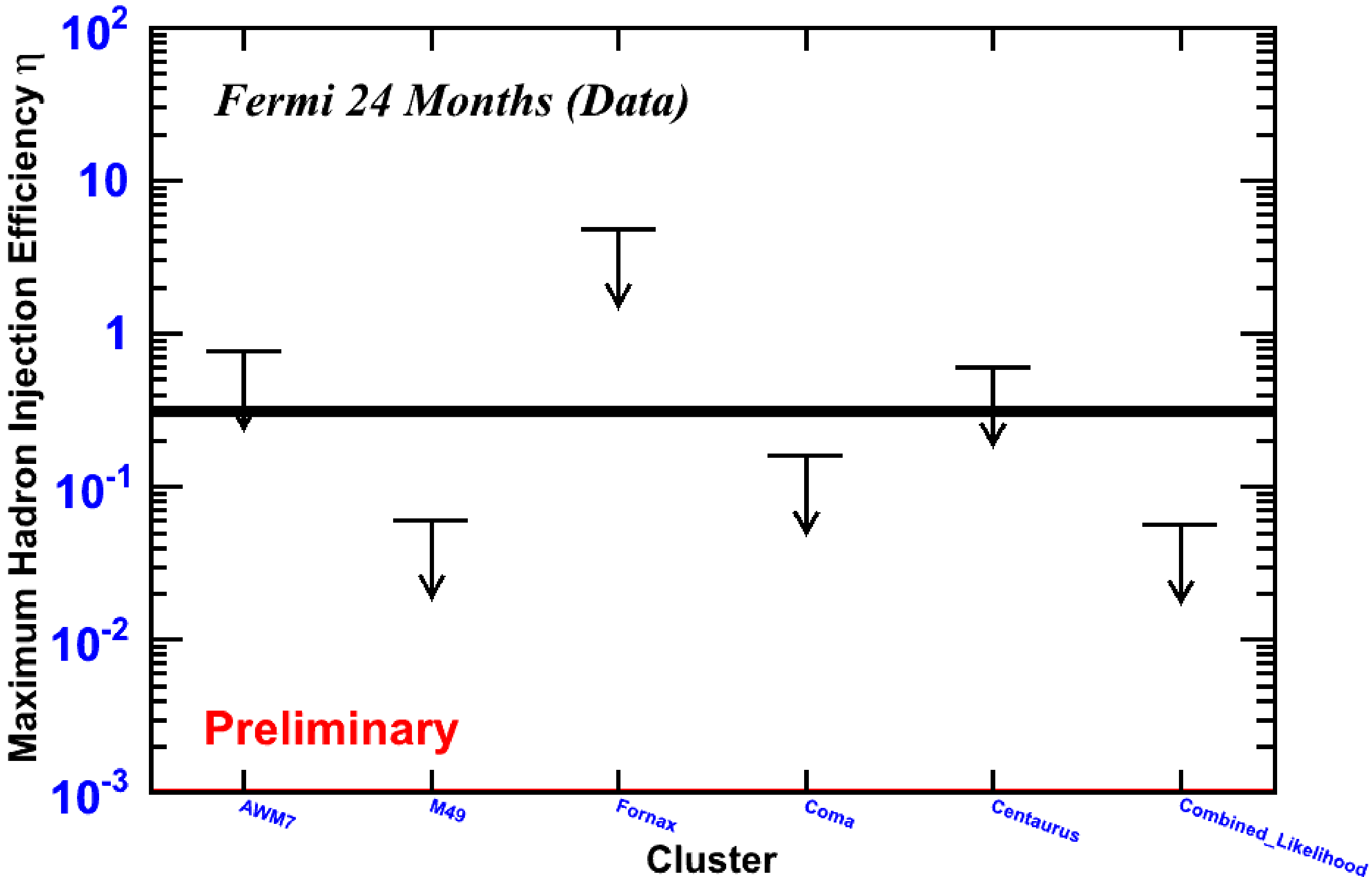


Hadron injection efficiency η

$$\Phi_\gamma = \int d^3 r \underbrace{A(R)}_{\text{Individual}} \underbrace{\lambda_{\pi^0-\gamma}(E)\eta}_{\text{Universal}}$$

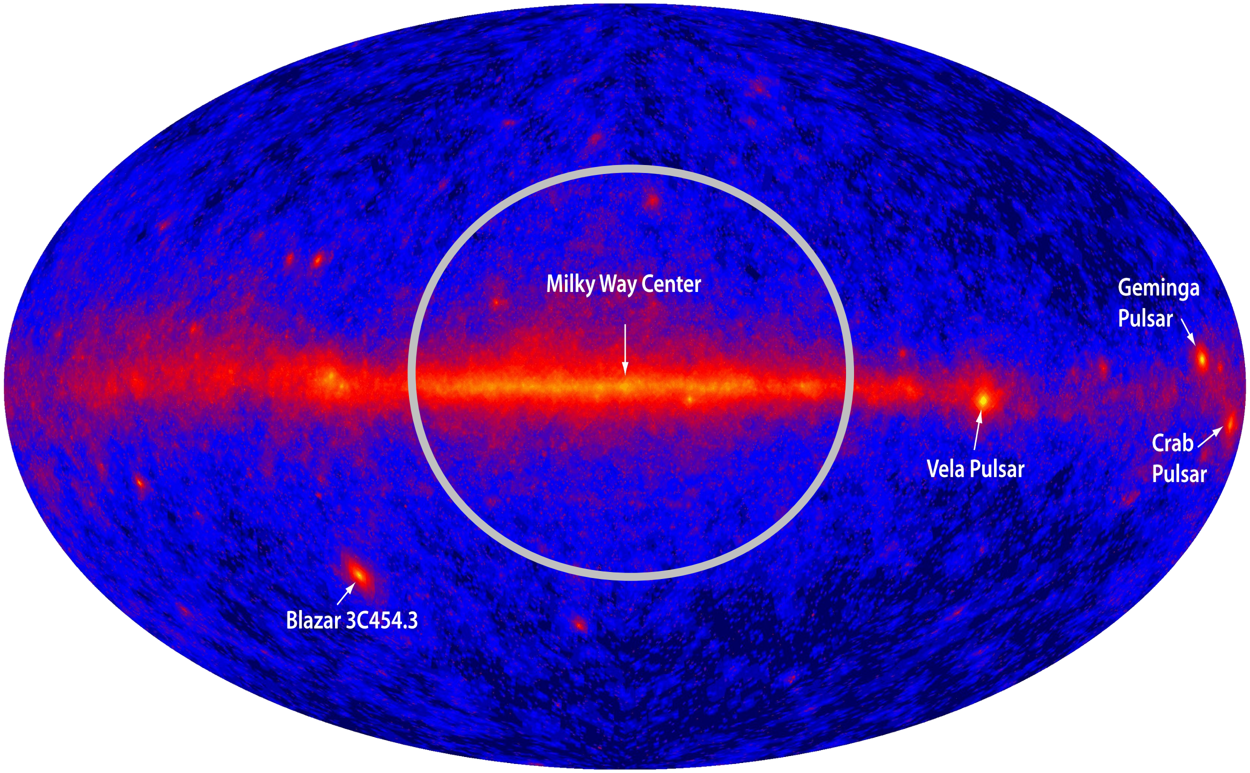
Pinzke & Pfrommer, 2010

Individual Universal

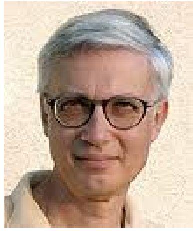


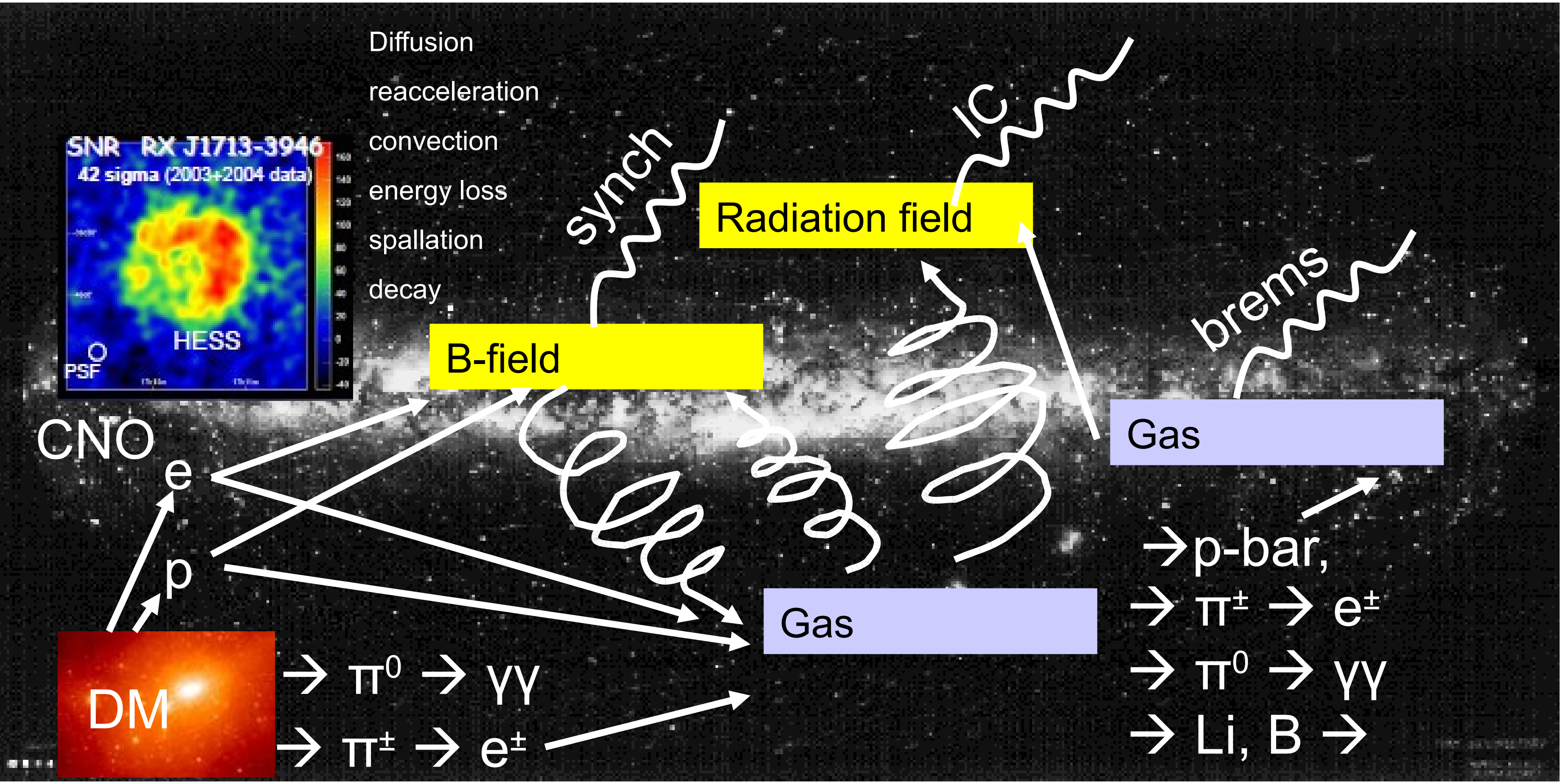
Remarks Galaxy clusters

- Proof of concept: updates on CR model and DM models are in the making (e.g. so far only assumed point source DM).
- Selection and source modelling more difficult (AGN feedback …)
- Clusters are a place to look (potential large boost), but rather bad for constraints.
- ”I do not seek. I find …”   a cosmic ray induced gamma-ray signal?

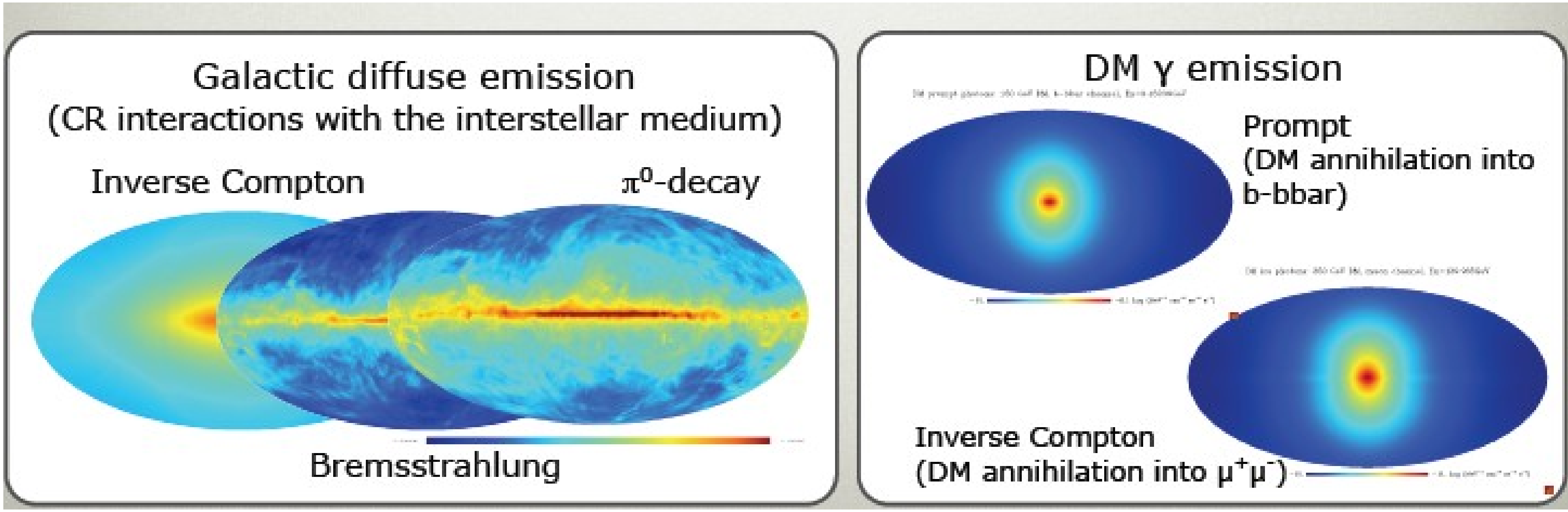

Milky Way Center
Geminga
Pulsar
Vela Pulsar
Crab
Pulsar
Blazar 3C454.3

Galactic diffuse emission

To him:  =  To me: 



Fermi halo – ongoing work.



- For the first time: try to incorporate uncertainties in the Galactic diffuse emission into the dark matter constraint
  - → profile likelihood over a grid of galprop models,
  - → Include goodness of fit to local CR data
  - → Challenge: sampling of the likelihood

Parameter	Range
Diffusion Coefficient	$1\times10^{27} \to 4\times10^{29}$
Halo Height	$1 \to 11$ kpc
Diffusion Index	0.33, 0.50
Alfven Velocity	$0 \to 50$ km s^{-1}
Electron Injection Index	$1.8 \to 2.5$
Nucleon Injection Index (Low)	$1.7 \to 2.6$
Nucleon Injection Index (High)	2.26, 2.43
Source Distribution	Parameterized, SNR, Pulsars

Stay tuned!

e.g. B. Anderson (Fermi-LAT), IDM 2010

Remarks

- The approach is ambitious but will probably not be able to encompass the complete freedom (anisotropic diffusion, assumptions on the local CR spectrum)

From my 2007 talk in HH:

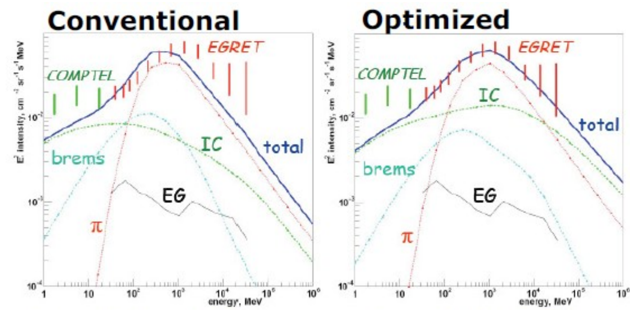
Regarding EGRET GeV excess:

Stecker, Hunter, Kniffen
e-Print: arXiv:0705.4311 [astro-ph]

EGRET excess instrumental, i.e. disappears with correct calibration

Porter, Atwood, Baughman, Johnson
ICRC 2007
e-Print: arXiv:0706.0220 [astro-ph]

EGRET excess becomes larger if cp bg taken into account

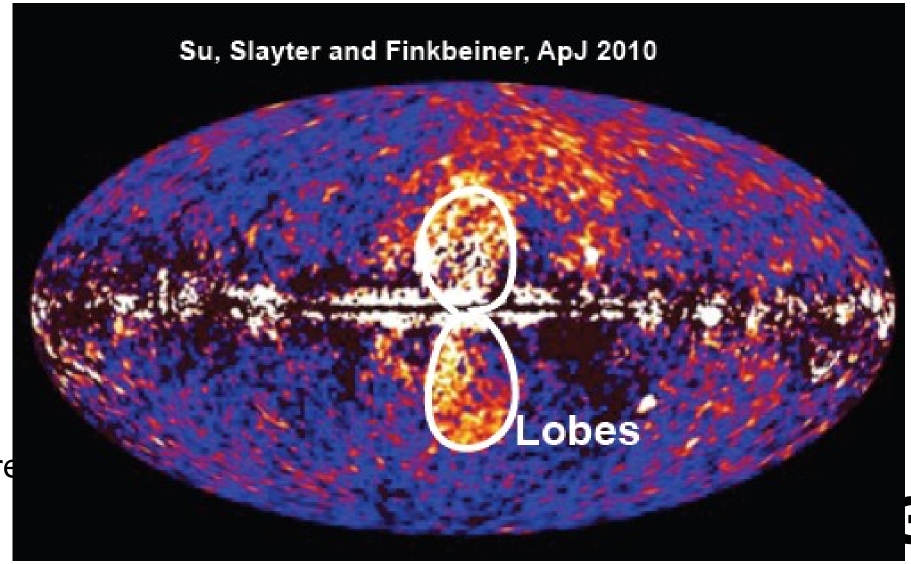


Strong, Moskalenko, Reimer, *ApJ* **537**, 736, 2000

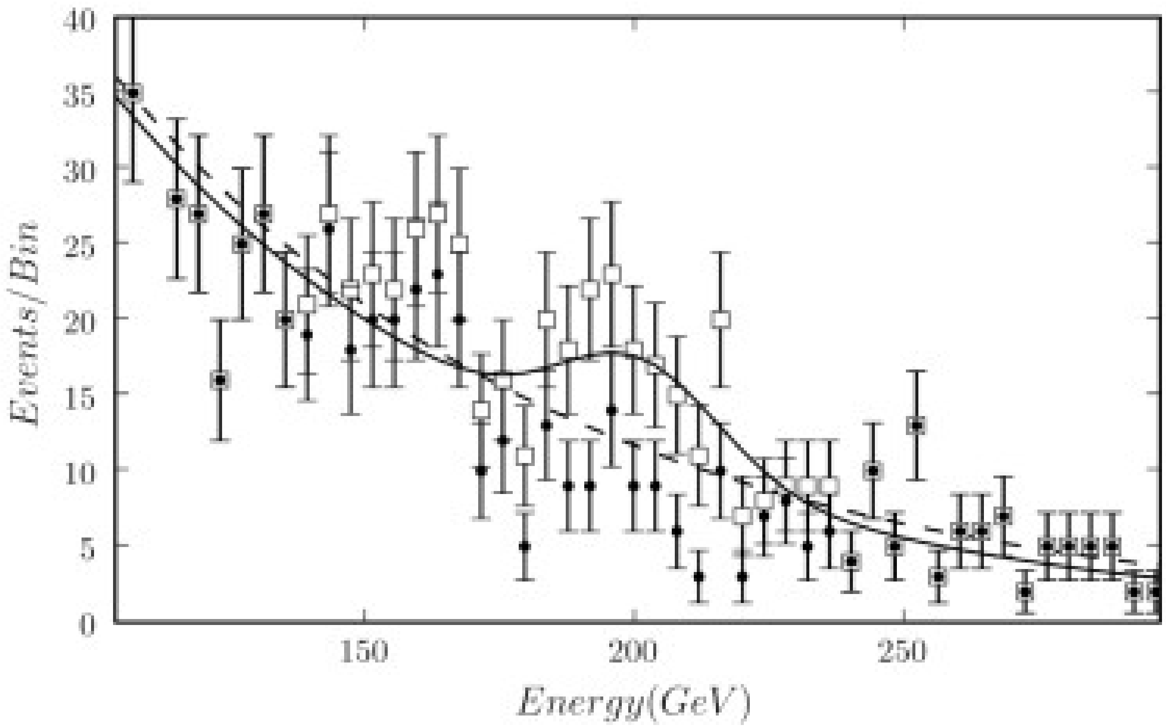
Strong, Moskalenko, Reimer, *ApJ* **613**, 962-976, 2004

- The Galactic halos is hard for constraints (except for line search, next topic).

- And of course →

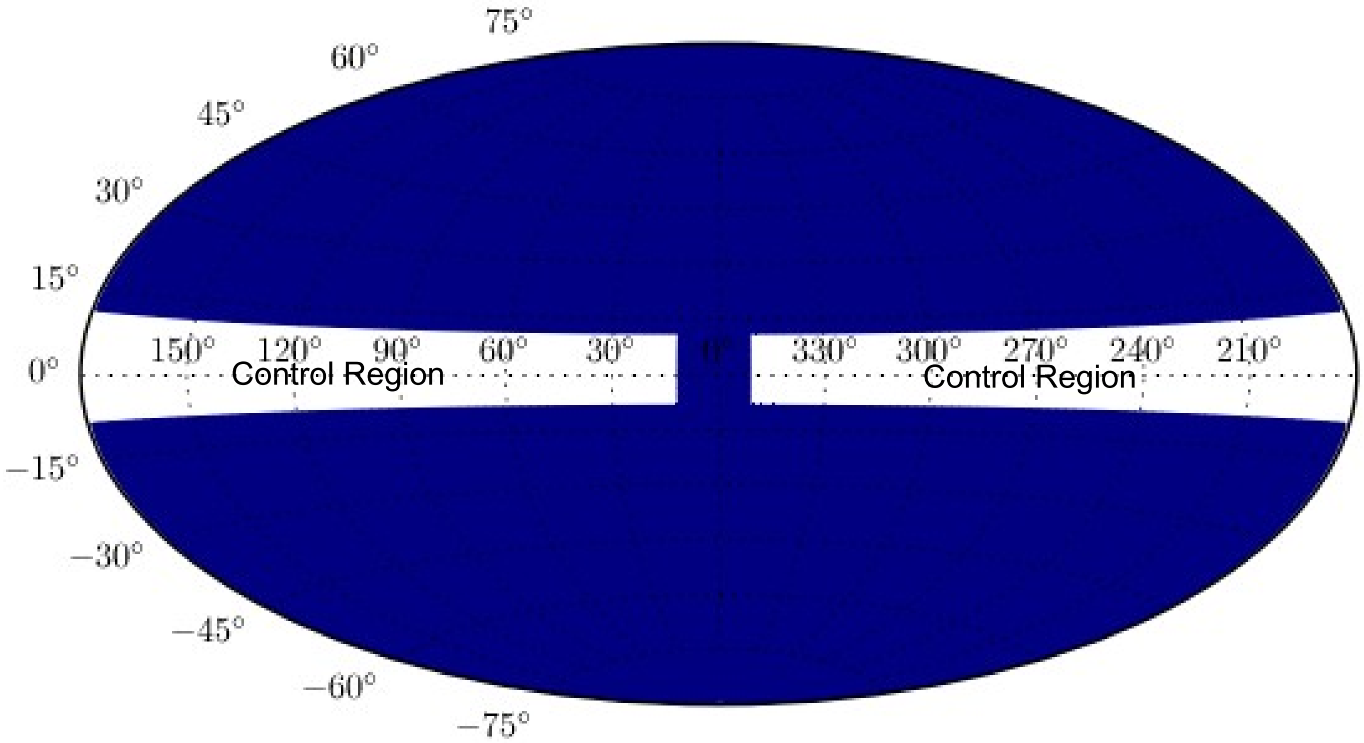


Spectral features



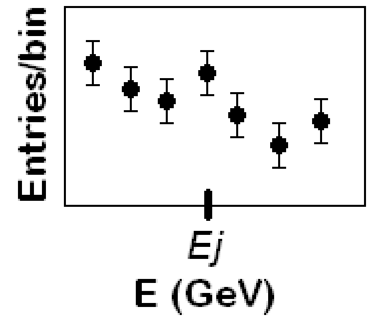
- No astrophysical source confusion
- Background determined from data.
- Maybe the only way to convince people of a positive ”indirect” detection

Region of Interest



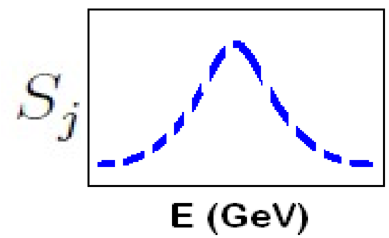
Line search methodology.

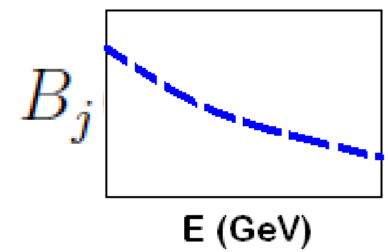
- Sliding window (E_j *(7-200 GeV)*



Fitting ranges in search are ± 4σ_E wide. Unbinned fit over this range.

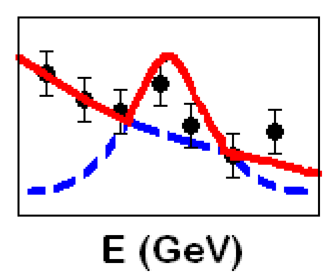
- Counts spectrum
  - Signal distribution
  - Background distribution





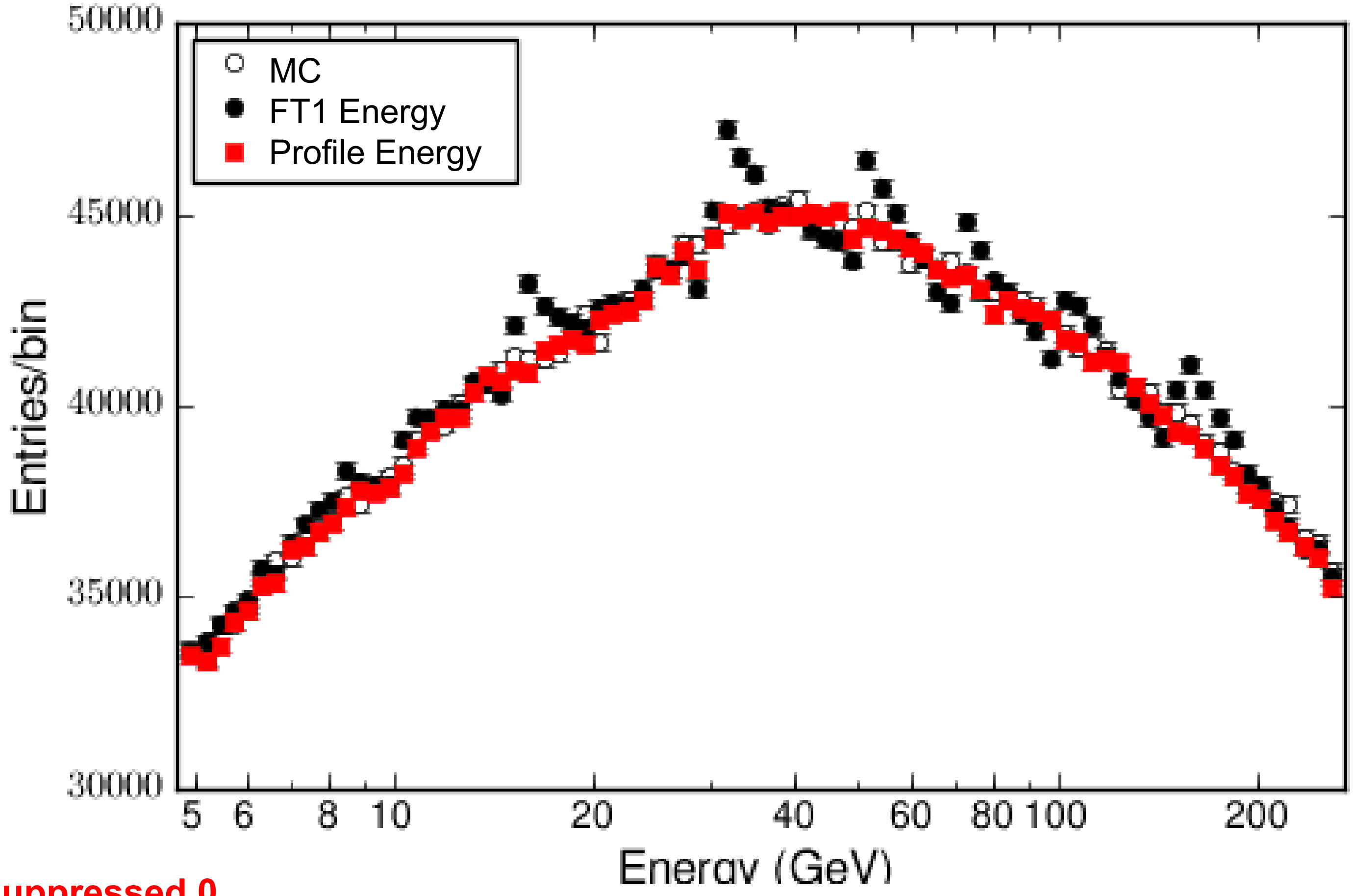
- Composite unbinned likelihood fit for fraction of events from signal PDF, f_i $\quad -1 < f_j < 1$

$$\mathscr{L}_j\left(f_j,\Gamma_j\right)=\prod_{i=1}^{N_j} f_j S_j(E_i)+(1-f_j)B(E_i,\Gamma_j),$$



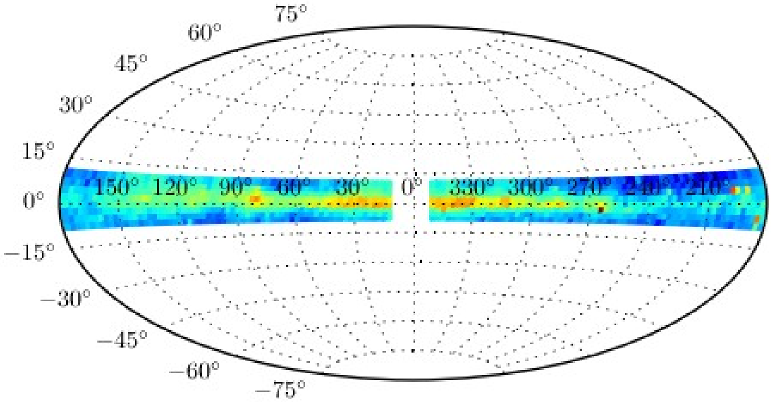
Free parameters:
- Signal fraction
- Spectral index

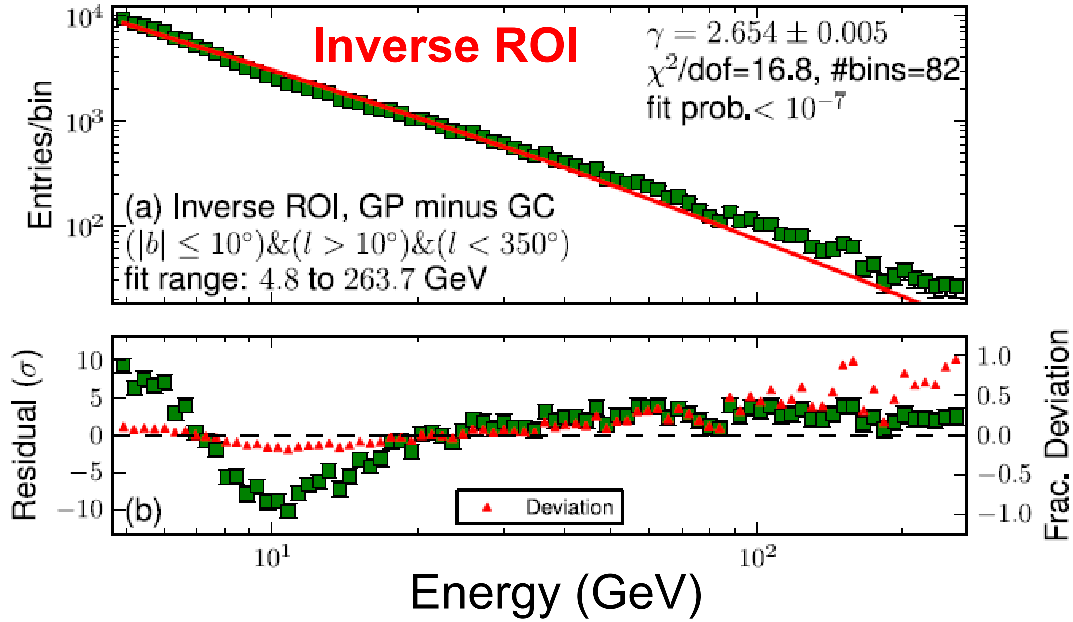
Line search: issue 1: FT1 energy

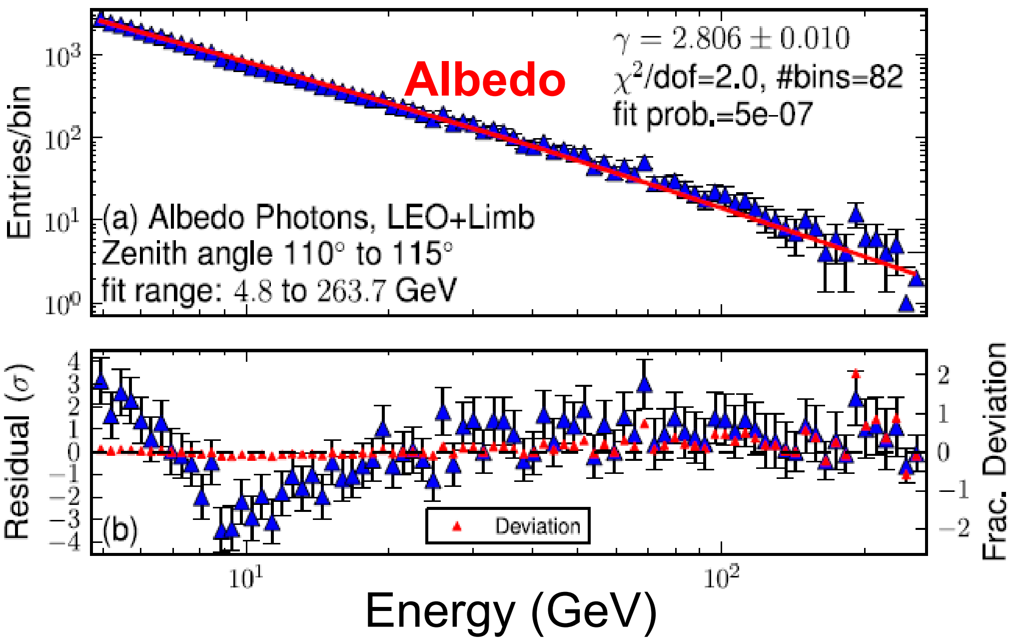


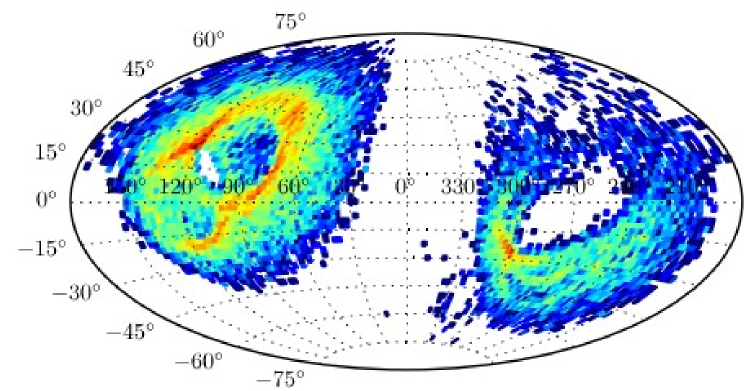
Suppressed 0

Control data sets









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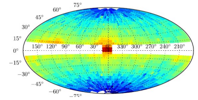
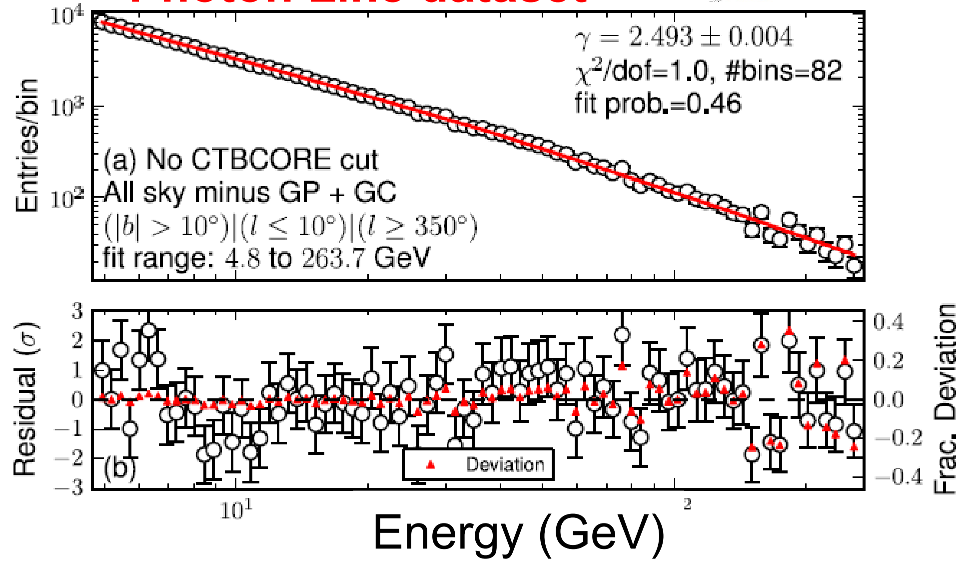
Event selection matters ....

CTBCORE is used to improve γ PSF.

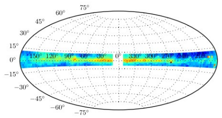
- Residual structure is highly muted if CTBCORE is not used
- Fit probability improved

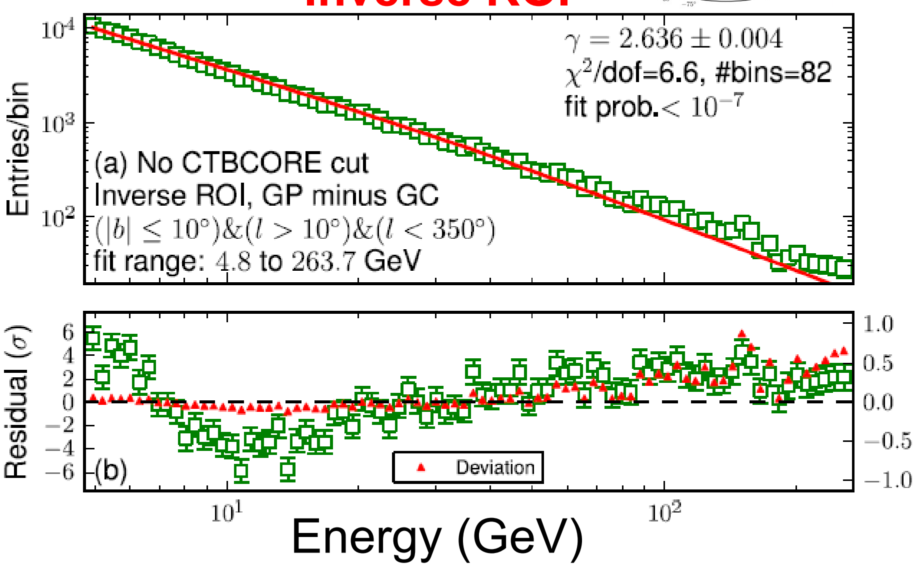


Photon Line dataset

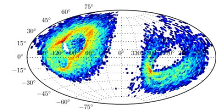


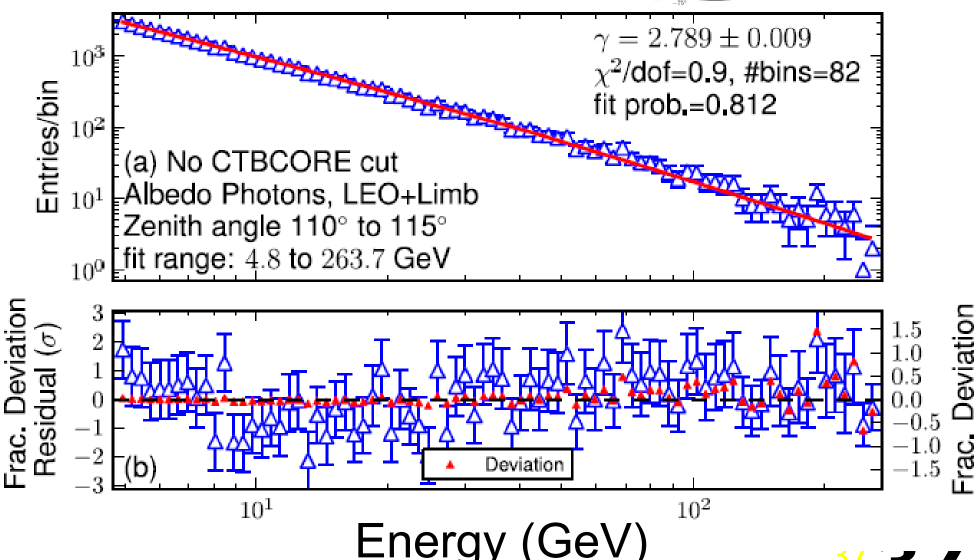
Inverse ROI



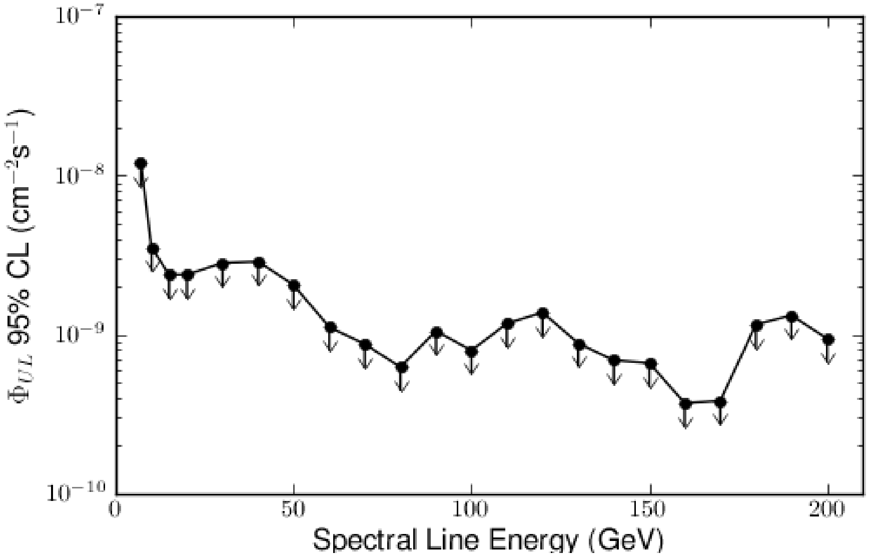


Albedo

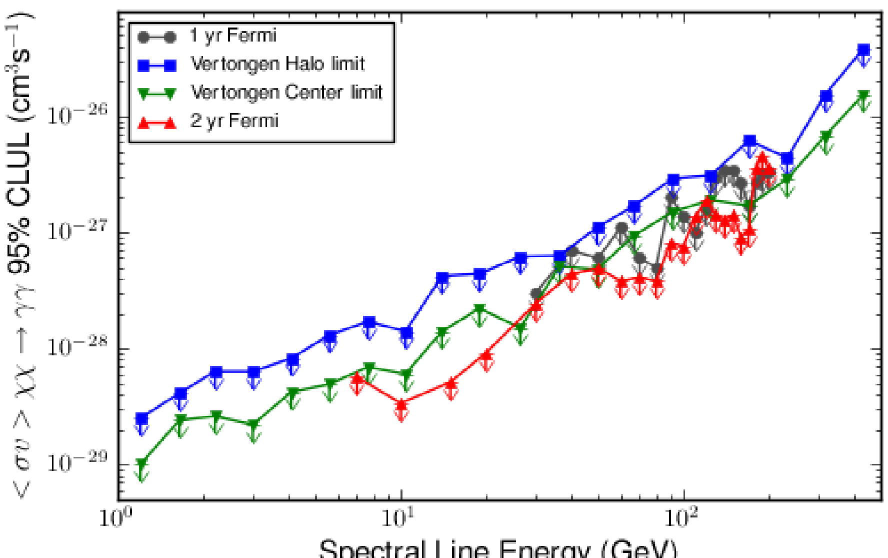




Line results



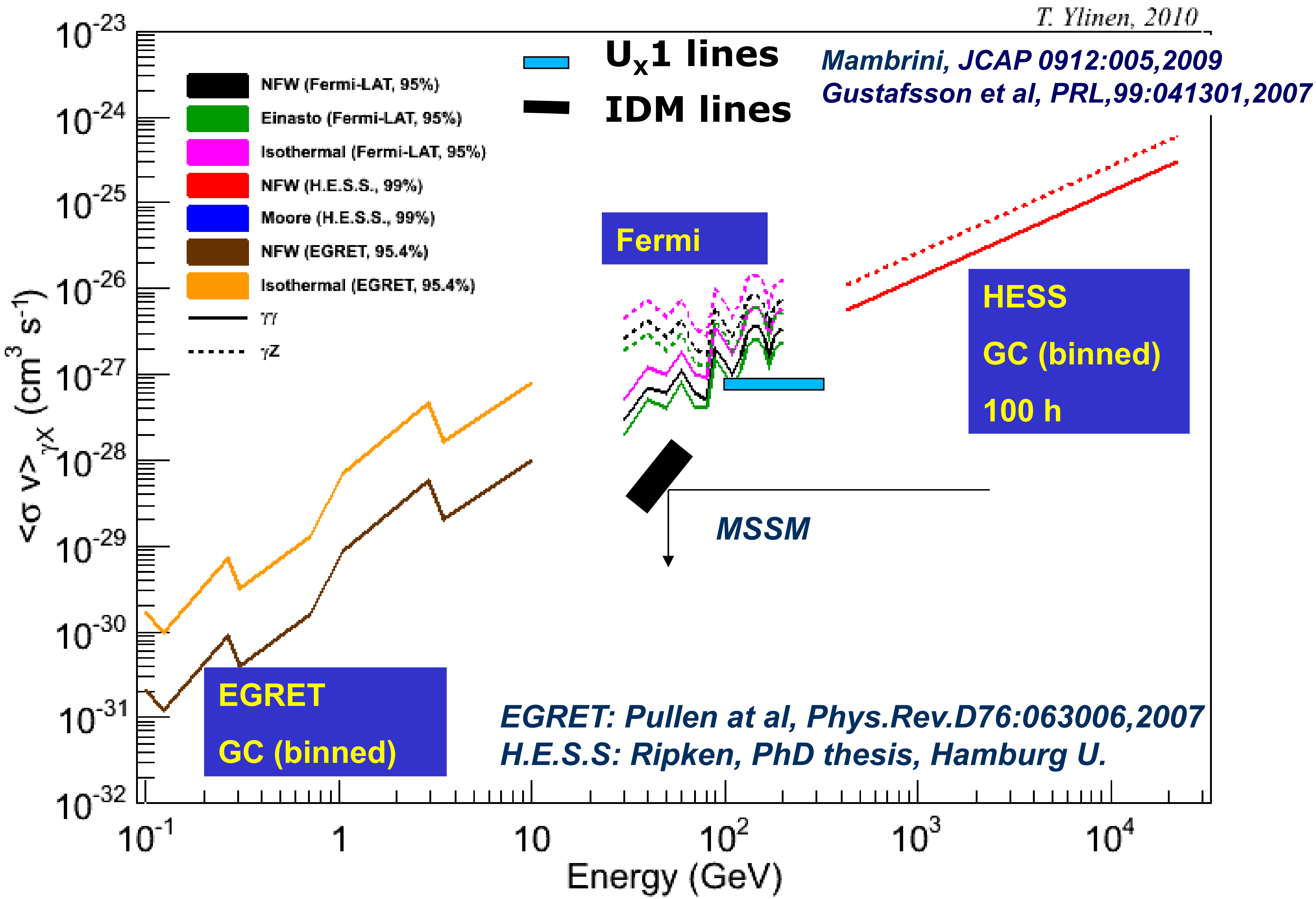
Flux constraints



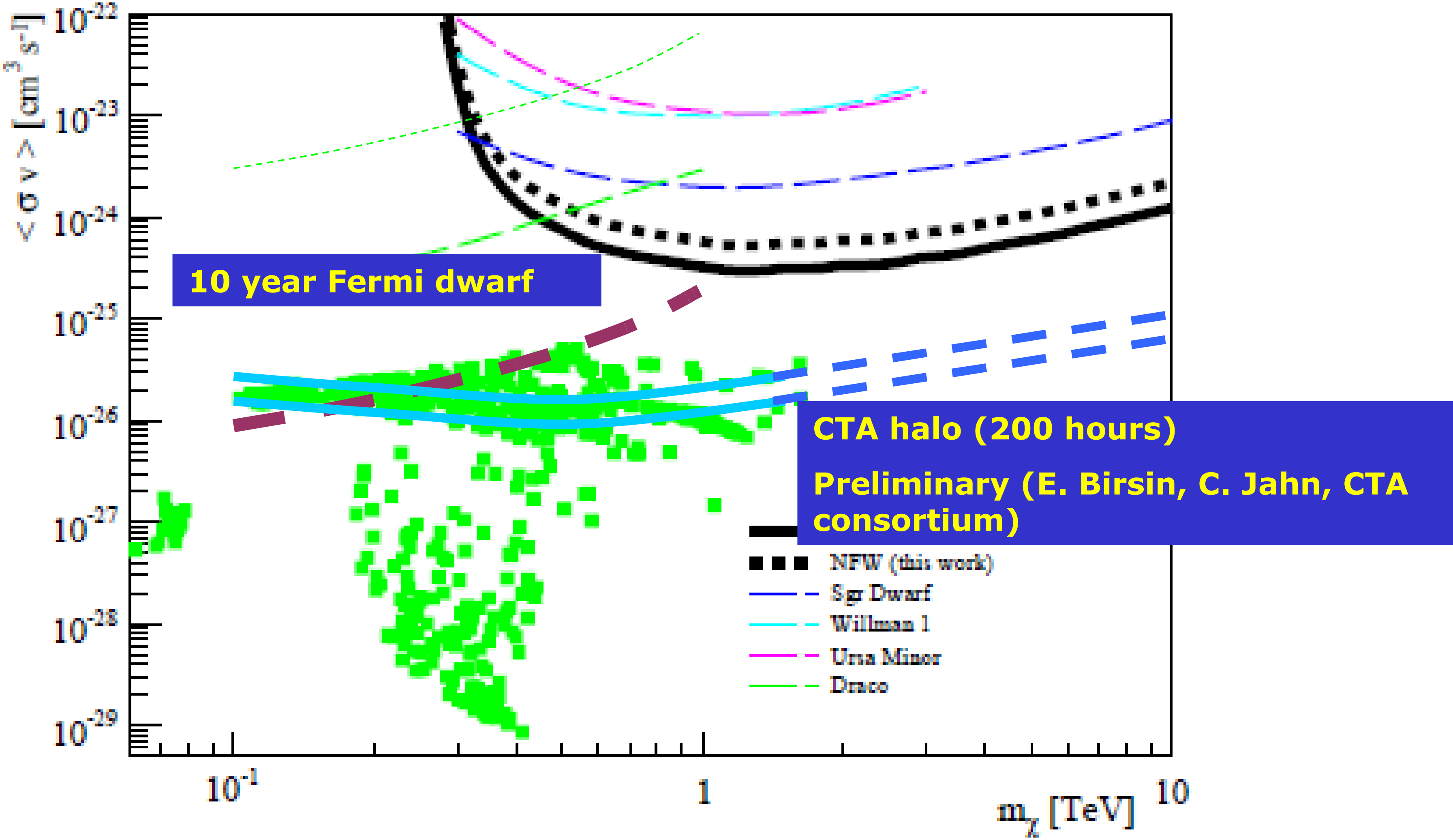
Cross section constraints

Yes, quite dull, but ....

Put in comparison (1 year results)



Some projection to the future.



Concluding remarks

- Essentially all bases covered.
- ”Stacking” methodology big step forward
  - We have reached the predicted 5yr sensitivity (optimistic) already now
  - currently constraining thermal WIMP cross-section for masses < 30 GeV (bbar, mumu+) *including J-factor uncertainties*
  - Improvement by around a factor 4-5 until the end of the Fermi-LAT mission (only with dwarfs).
- All-sky diffuse analyses: challenging.
- Line features: robust analysis, clear signature, but detector can fool
- *Close to submission/internal refereeing: Dwarf stacking, DM Satellites, update on line search, further down: clusters, anisotropies, halo.*
- Looking ahead: ”vanilla” CTA will be competitive above ~300 GeV.

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