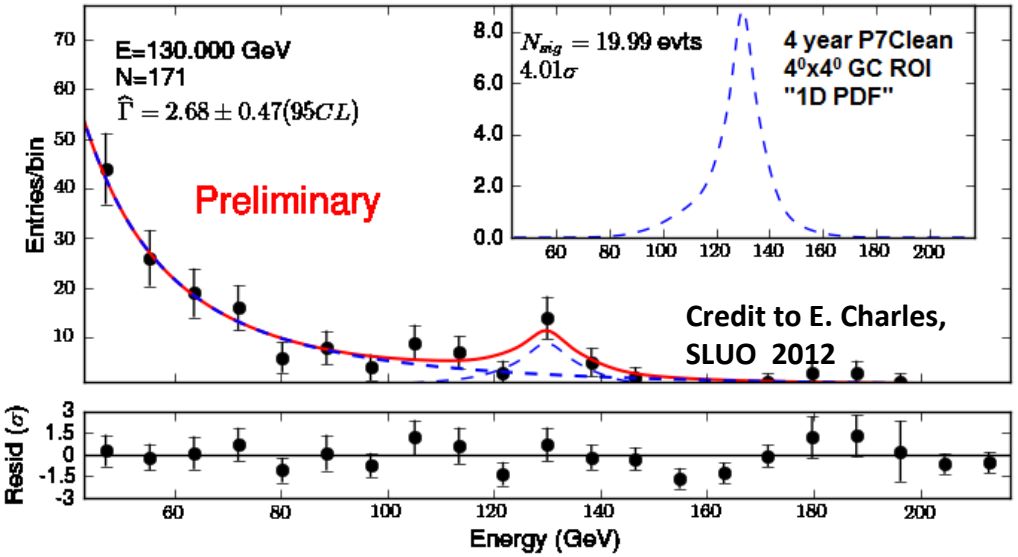
Dark matter search perspectives with GAMMA-400

Alexander Moiseev

CRESST/NASA/GSFC and University of Maryland, College Park

on behalf of the GAMMA-400 team

Probably the most exciting result in the search for Dark matter: Fermi LAT 135 GeV line



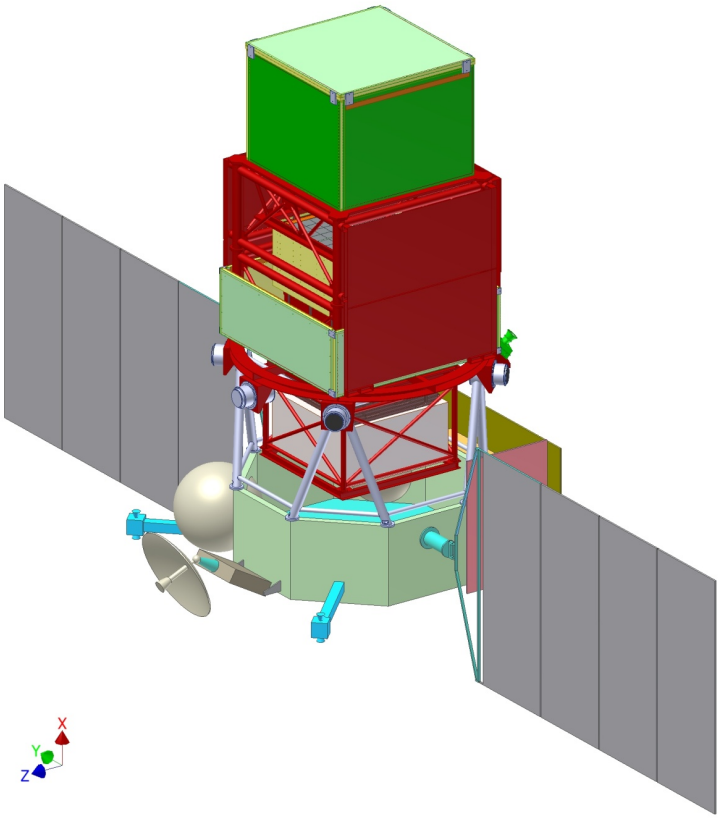
Bringmann et al. , Weniger, Eric Charles in this meeting and many other Fermi LAT presentations

However the significance of the line detection is not enough to state it with 100% confidence, and it is unlikely that Fermi LAT will be able to claim it as a globally significant result by the end of the mission

New experiments are needed !

What is GAMMA-400?

- ✓ **GAMMA-400 goals:** follow and deepen the findings of Fermi LAT (similar energy range and instrument overall capabilities)
- ✓ Very suitable for the search for WIMPs. Enhanced performance at high energy (> 10 GeV): PSF and energy resolution
- ✓ **Search for dark matter is the main goal for GAMMA-400 set by V. Ginzburg in mid-1980s**



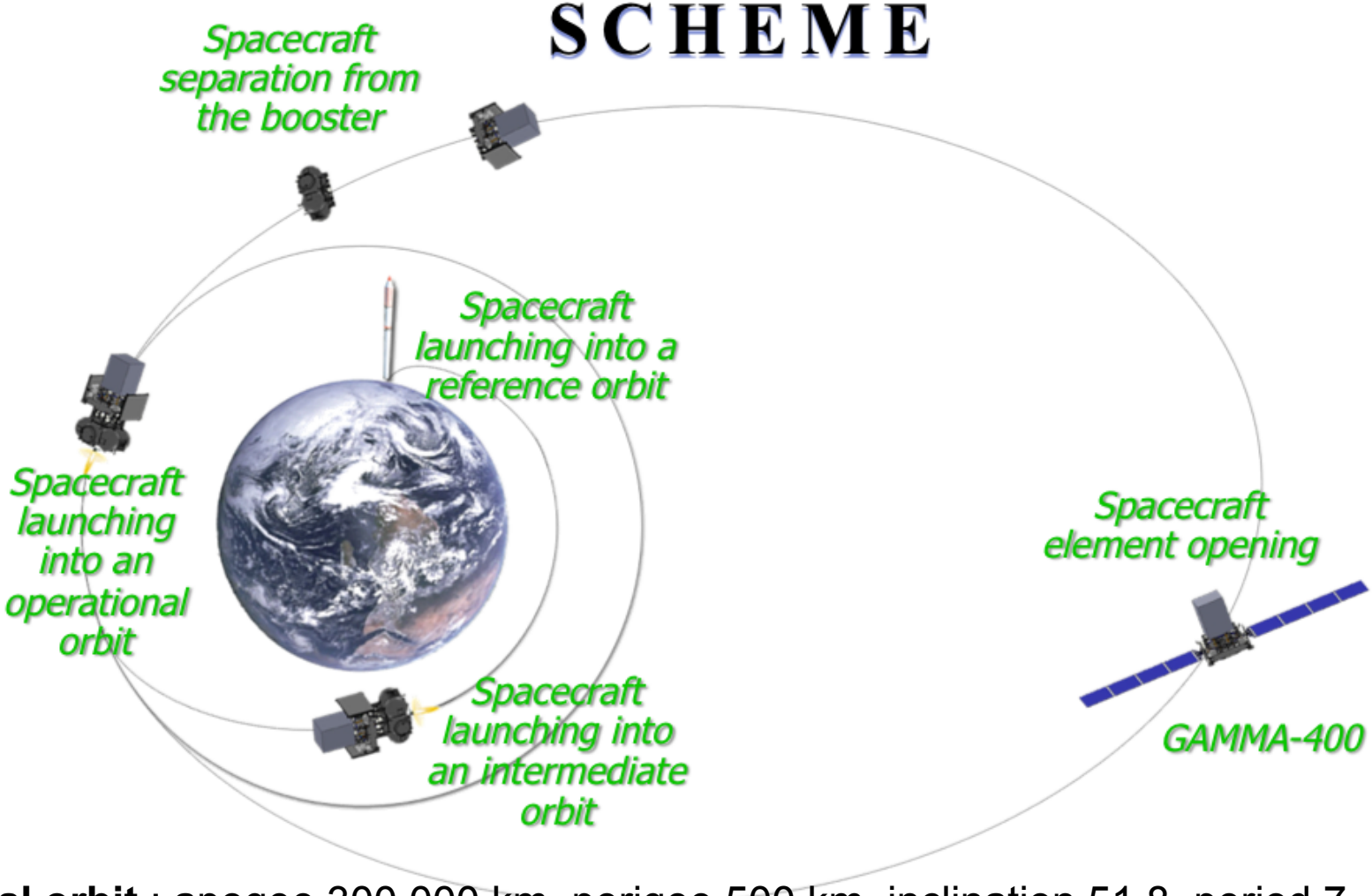
- **A new high-energy space *γ*-ray telescope**
- **Approved and fully funded by Russian Space Agency Russian, included in Federal Space Program**
- **Uses the Navigator service module made by Lavochkin Association, recently used for the RadioAstron mission, planned for other missions**
- **Uses technology similar to Fermi Large Area Telescope (tracker/converter, energy measurement system, anticoincidence detector)**
- **Launch is planned for 2018-2019**

Overview of GAMMA-400 Science Goals

- **Main topics**
  - **Nature of Dark Matter**
  - **The origin of cosmic rays**
- **Extend high-energy *γ*-ray observations after the end of the Fermi LAT mission for multiwavelength analysis in synergy with:**
  - **Radio, optical, X-ray and TeV *γ*-ray observations (CTA)**
  - **Neutrino observations (IceCube, KM3NeT)**
  - **Gravitational radiation observations (ALIGO)**
- **Focus on high-energy gamma-ray tasks which GAMMA-400 will perform better than Fermi-LAT due to its better energy and angular resolution**
  - **Source localization and identification (puzzle of non-ID Fermi LAT sources)**
  - **Discovery of new sources in crowded regions (e.g. Galactic Center, Cygnus)**
  - **Study of spectral structure of diffuse radiation (addresses Dark Matter)**
  - **Study of gamma radiation from Supernova Remnants at low energy (addresses origin of cosmic rays)**

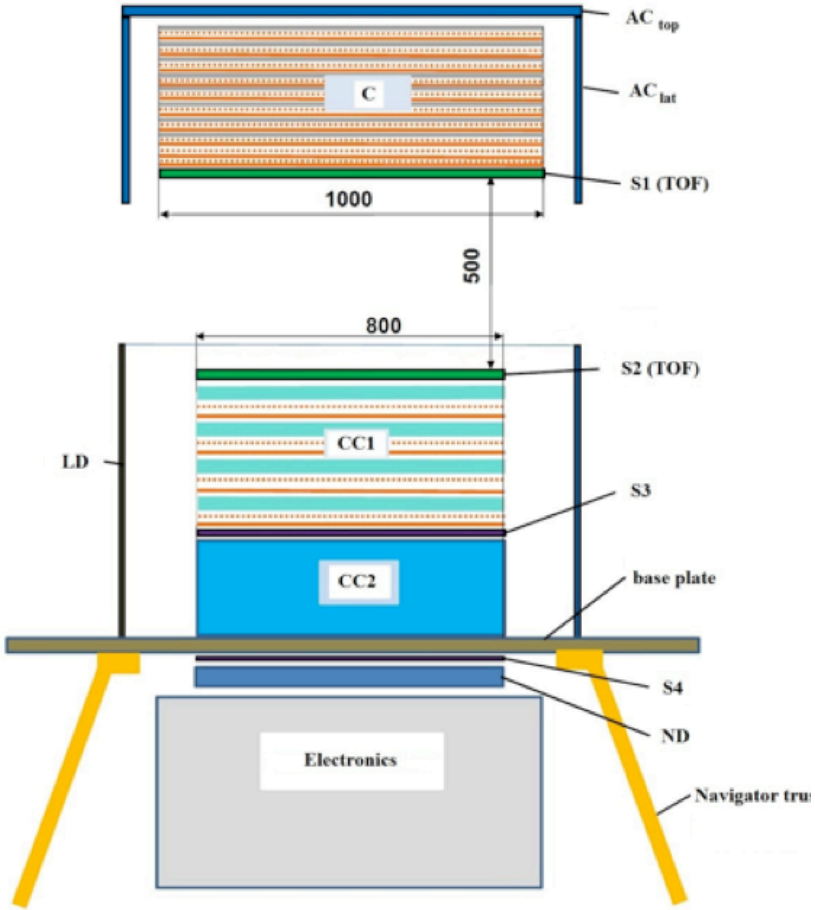
Currently no space-borne high-energy *γ*-ray observations are planned after Fermi LAT observations end (~ 2018)

GAMMA-400 LAUNCHING SCHEME



Initial orbit : apogee 300,000 km, perigee 500 km, inclination 51.8, period 7 days**. After ~ 230 days** the orbit will change to ~ circular with radius 150,000 km

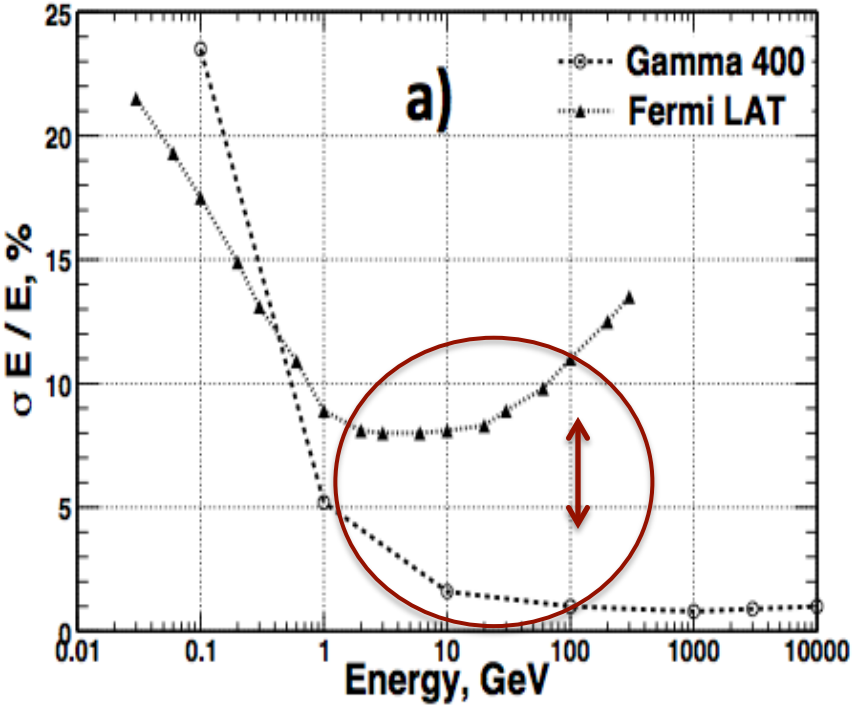
GAMMA-400 Concept



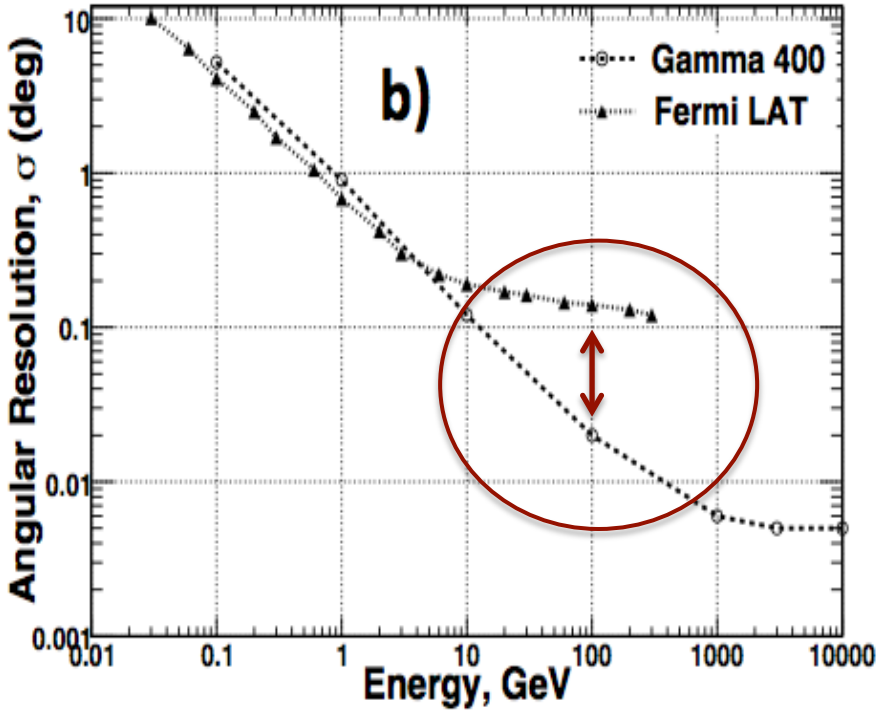
Energy range	100 MeV – 3000 GeV
Field-of-view, sr (E > 1 GeV)	~1.2
Effective area, cm^2 (E > 1 GeV)	~4,000
Energy resolution (E > 10 GeV)	~1%
Angular Resolution (E >100 GeV)	~0.01°
Converter-tracker thickness	~ $1X_0$
Calorimeter thickness	~ 25 X_0
Proton rejection factor	~ 10^6
Telemetry downlink volume, GB/ day	100
Total mass, kg	2,600
Maximum dimensions, m	2.0 x 2.0 x 3.0
Power consumption, W	2,000

GAMMA-400 Key Performance

Energy Resolution



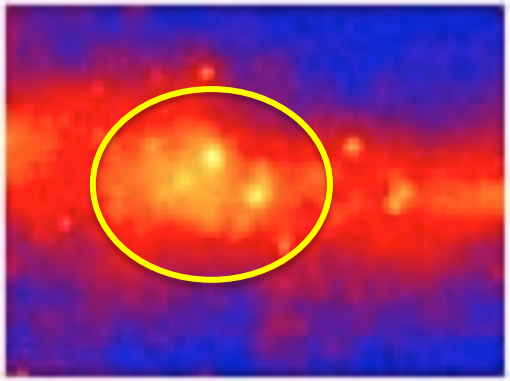
Angular Resolution



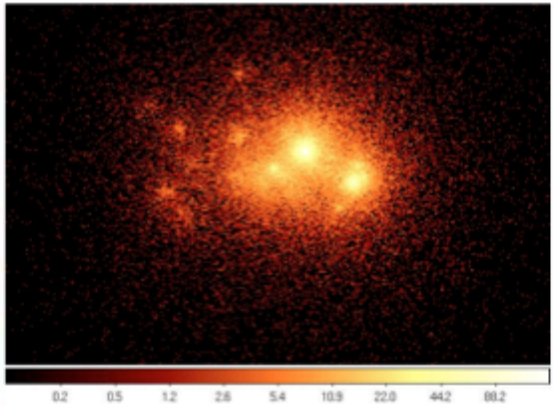
GAMMA-400 performance comparison

	Space-based instruments				Ground-based instruments		
	Fermi LAT	AMS-2	GAMMA-400	CALET	H.E.S.S. - II	MAGIC	CTA
Energy range, GeV	0.02-300	10-1000	0.1-3,000	10-10,000	>30	>50	>20
Field-of-view, sr	2.4	0.4	1.2		0.01	0.01	0.1
Effective area, m^2	0.8	0.2	~0.4	0.1-0.2	10^5	10^5	10^6
Angular resolution (E>100 GeV)	0.2°	1.0°	~0.01°	0.1°	0.07°	0.05°	0.06°
Energy resolution (E>100 GeV)	10%	2%	~1%	2%	15%	15%	10%

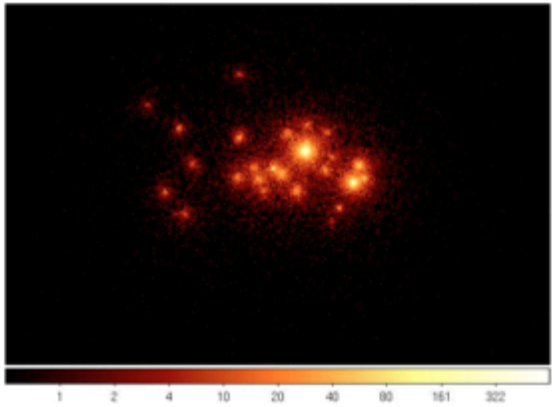
Cygnus region (above 30 MeV) as seen by Fermi LAT and simulated for Gamma-400



Fermi LAT 2-year flight data



Fermi LAT 2-year simulated data



Gamma-400 2-year simulated data

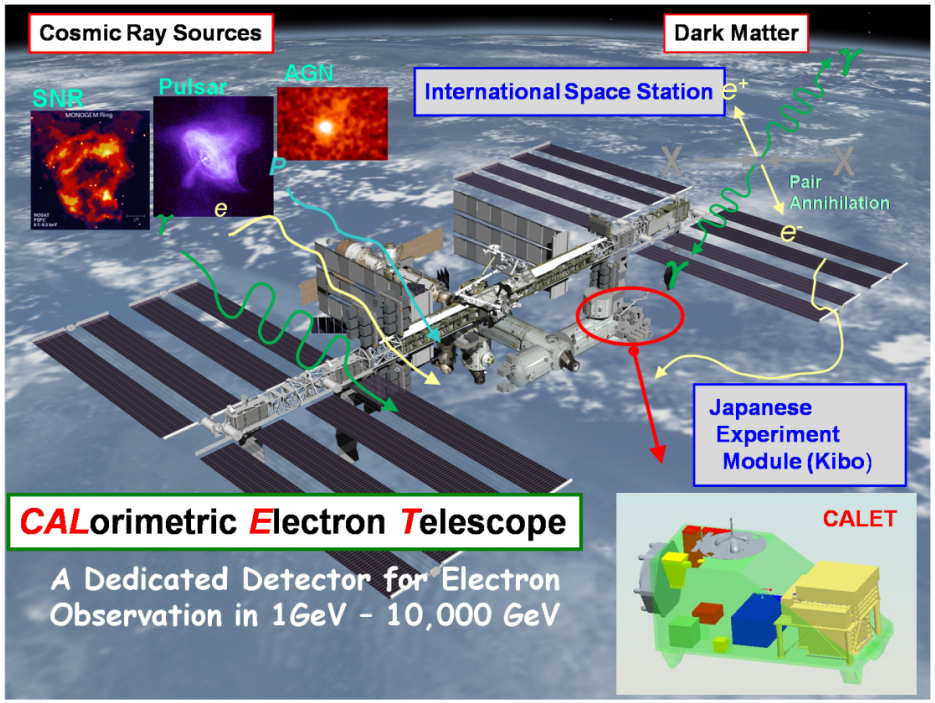
What else?

- **H.E.S.S. II ?**
- **AMS – 2 ?**
- **CALET ?**

CALET Overview

Observation

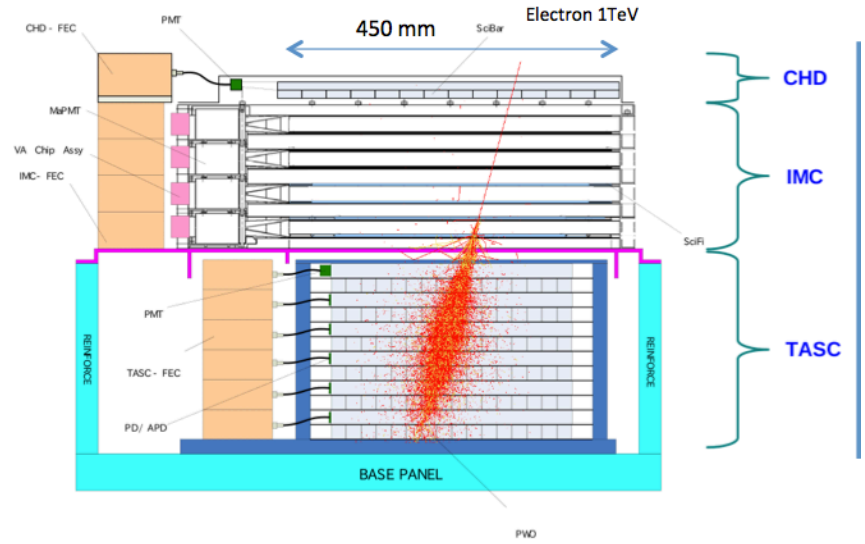
- **Electrons** : 1 GeV -10,000 GeV
- **Gamma-rays** : 10 GeV -10,000 GeV (GRB > 1 GeV)
  + Gamma-ray Bursts : 7 keV-20 MeV
- **Protons, Heavy Nuclei:**
  several 10 GeV- 1000TeV (per particle)
- **Solar Particles and Modulated Particles in Solar System**: 1 GeV-10 GeV (Electrons)



Instrument

High Energy Electron and Gamma- Ray Telescope Consisted of :

- **Imaging Calorimeter (Particle ID, Direction)**
  Total Thickness of Tungsten (W) : 3 X_0
  Layer Number of Scifi Belts: 8 Layers ×2(X,Y)
- **Total Absorption Calorimeter (Energy Measurement, Particle ID)**
  PWO 20mmx20mmx320mm
  Total Depth of PWO: 27 X_0 (24cm)
- **Silicon Pixel Array (by Italy) (or a substitute) (Charge Measurement in Z=1-35)**
  Silicon Pixel 11.25mmx11.25mmx0.5mm
  2 Layers with a coverage of 54 x54 cm^2



Indirect search for dark matter in γ-ray and cosmic ray radiations

Approach: Search for disagreement / difference between observed and predicted by "classical" model CR / γ-ray flux / spectra / spatial distribution

Dark matter signature	=	Observed spectrum / spatial features	-	γ-ray sources	-	Diffuse radiation (galactic and isotropic)

The sensitivities to a DM signal depend critically on accurate estimates of the backgrounds: diffuse Galactic and isotropic γ-rays, γ- rays from astrophysical sources, and charged particles detected as γ-rays

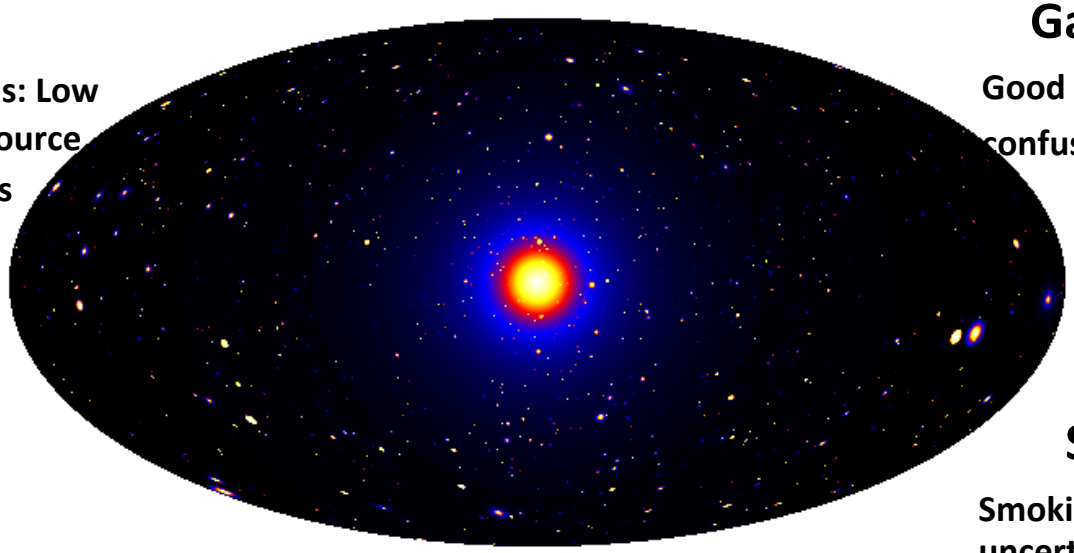
Dark Matter predicted in γ-ray sky

Satellites

Non-Id sources and dSphs: Low background and good source id, but low statistics

Galactic Center

Good Statistics, but source confusion/diffuse background

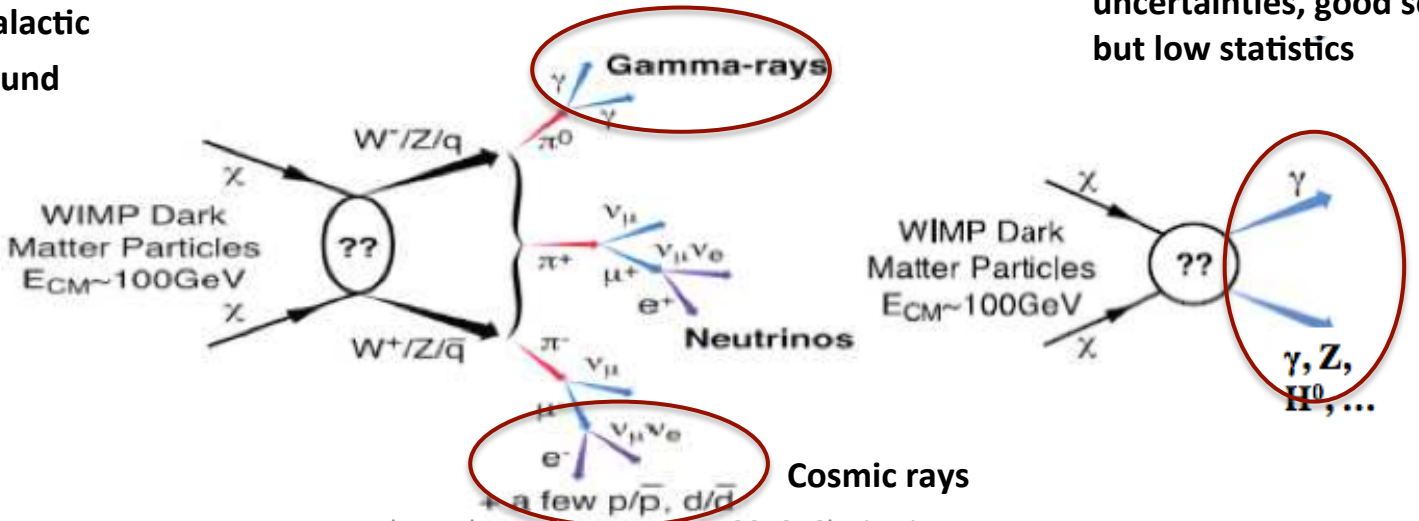


Isotropic contributions

Large statistics, but astrophysics, galactic diffuse background

Spectral Lines

Smoking gun: no astrophysical uncertainties, good source id, but low statistics



Galactic Center

- **Expected to be the strongest source of γ-rays from DM annihilation. "EGRET GeV excess" has been in the center of DM discussion for years, until it was closed by Fermi LAT results**
- **Intense background from unresolved sources remains the main problem, assuming that the part of background created by CR interactions with the matter, is much better known and can be accounted for**
- **Potential perspectives for GAMMA-400: having >10 times better angular resolution at high energy, faint sources in dense GC area can be localized and their radiation can be removed as a background, and better model of diffuse radiation can be built. Concern: smaller effective area can make this analysis more difficult and not efficient**

Clumps (or Satellites)

Features to search for:

- Hard (Not power-law) energy spectrum
- Extended spatial dimensions
- Lack of counterparts in other wavelengths

Approach:

- Check among non-ID Fermi LAT *γ*-sources to meet the above criteria

Fermi LAT (Ackermann et al., ApJ 747, 121, 2012):

- 2 DM satellite candidates were found out of 385 un-ID high latitude sources, 1FGL J1302.3-3255 and 1FGL J2325.8-4043
- 1FGL J1302.3-3255 was later associated with a millisecond pulsar (by radio observations)
- 1FGL J2325.8-4043 was found to have a high probability association with two AGN: 1ES 2322-409 and PKS 2322-411
- Conclusion: no viable DM satellite candidate was found so far
- Upper limit for $\langle \sigma v \rangle$ is set to 1.95×10^{-24} cm^3 s^{-1} for a 100 GeV WIMP annihilation through bb channel

Clumps : Perspectives for GAMMA-400

Features to search for:

- Hard (Not power-law) energy spectrum
- Extended spatial dimensions
- Lack of counterparts in other wavelengths

Approach:

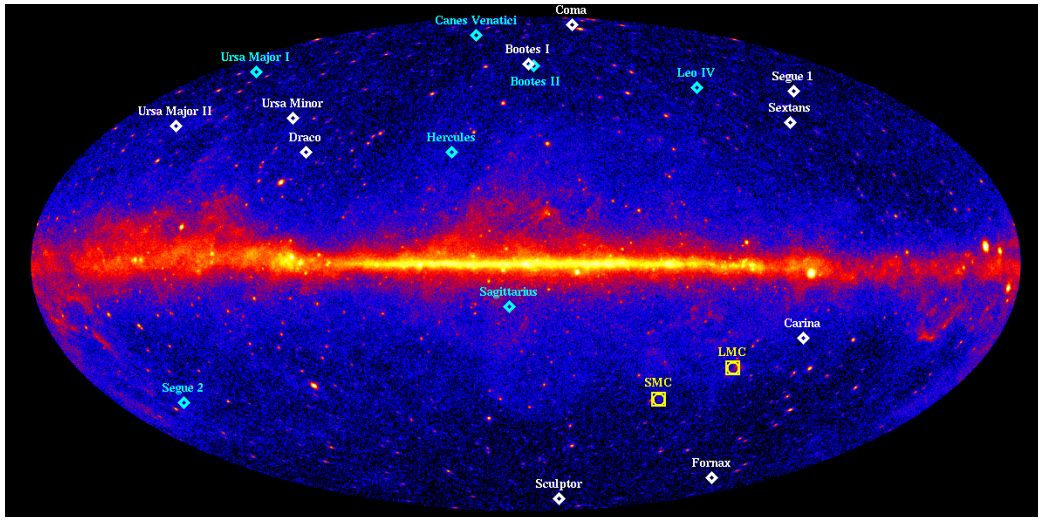
- Check among available by that time non-ID Fermi LAT and GAMMA-400 (if found) *γ*-sources to meet the above criteria

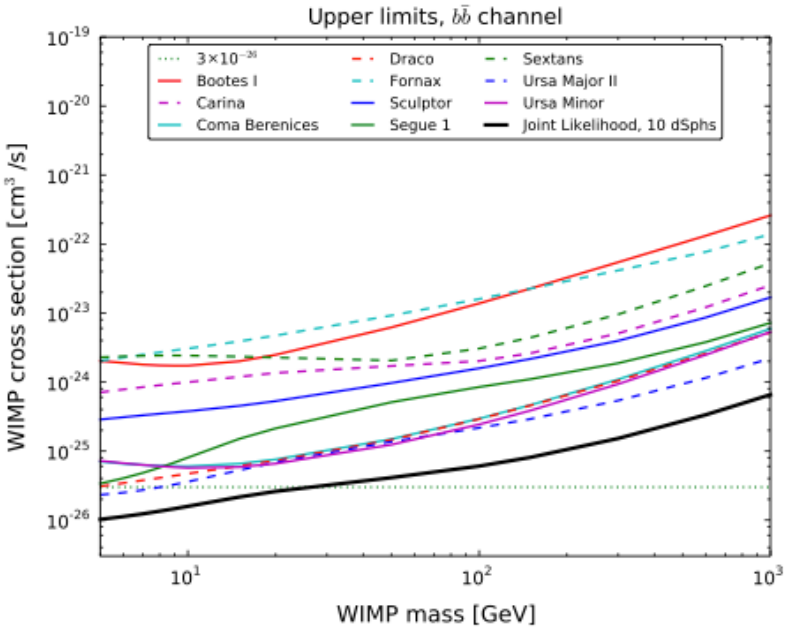
Perspectives:

- Better energy resolution will allow to better distinguish between power-law "normal source" and hard DM spectra, potentially increasing the number of satellite candidates
- Better angular resolution will allow to better distinguish between point and extended sources, also potentially increasing the number of satellite candidates
- Larger number of available by that time non-ID Fermi LAT sources shall also increase the number of satellite candidates

Dwarf Spheroidal Galaxies: prominent DM candidates

- Search for γ–ray emission from Dwarf Spheroidal Galaxies (satellite galaxies) with large J-factor (line-of-sight integral of the squared DM density)
- Fermi LAT applied a joint likelihood analysis to 10 satellite galaxies: no dark matter signal was detected. Upper limit for $\langle \sigma v \rangle$ is set to ~10^{-26} cm^3 s^{-1} at 5 GeV and 5 x 10^{-23} cm^3 s^{-1} at 1 TeV (Ackermann et al. PRL 107, 241302, 2011)





Dwarf Spheroidal Galaxies: Perspectives for GAMMA-400

Joint likelihood (for 10 dSphs) of agreement between observed *γ*-radiation and that predicted by DM model:

Energy-binned *γ*-ray data; should be better for Gamma-400

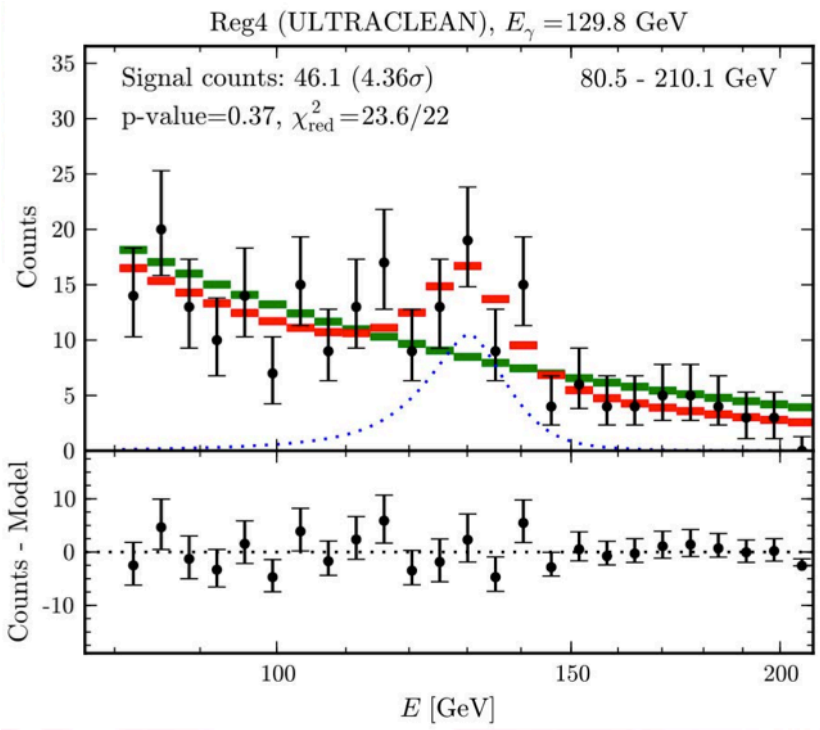
$$L(D|\mathbf{p}_W, \{\mathbf{p}\}_i) = \prod_i L_i^{\mathrm{LAT}}(D|\mathbf{p}_W, \mathbf{p}_i) \times \frac{1}{\ln(10) J_i \sqrt{2\pi}\sigma_i} e^{-[\log_{10}(J_i) - \overline{\log_{10}(J_i)}]^2/2\sigma_i^2},$$

Binned Poisson likelihood fully accounting of the PSF (E); should be better for Gamma-400

Improved dE/E and PSF for GAMMA-400 should provide better sensitivity for this analysis

Search for γ-ray lines

- Smoking gun if found
- Search for the line in isotropic radiation; also from Galactic Center, Galactic Halo



Bringmann et al. (arXiv:1203.1312) and **Weniger** (arXiv:1203.2797) showed evidence for a narrow spectral feature near 130 GeV near the Galactic center (GC) from the Fermi LAT data

- Over 4σ local significance with S/N > 30%, up to ~60% in optimized ROI.
- Some indication of double line (111 &130 GeV).

Fermi LAT team:

- Feature is also seen in Earth Limb control sample, but not large enough to explain all of Galactic Center signal
- Significance of feature decreases with analysis improvements
- The LAT team does see a ~2σ (global) excess.
- We can not rule out earlier claims, but also can not claim globally significant signal

All the details in Eric Charles talk at this meeting

γ-ray lines in diffuse radiation : Perspectives for GAMMA-400

Sensitivity to the γ-ray line (flux) in the diffuse radiation can be expressed in simplified form as: $I_\gamma = \frac{n_\sigma}{0.68}\sqrt{\frac{2F_{bck}\eta E_\gamma}{GT}}$

where n is a number of σ , F_{bck} is a (diffuse) background, ηEγ is an energy bin width, which depends on η (energy resolution), G is a geometric factor, T is an observation time

Comparison of Fermi LAT and GAMMA-400 sensitivity:

- **ηEγ for GAMMA-400 is 10X less than that for Fermi LAT at E>100 GeV,**
- **G for GAMMA-400 is ~ 0.5 of that for Fermi LAT,**
- **the sensitivity for GAMMA-400 for the same observation time is expected to be ~ 2 better than for Fermi LAT.**

γ-ray line from source : Perspectives for GAMMA-400

Assumption: the line is a δ-function in energy spectrrum

Confidence estimate: Confidence of the line detection can be taken similarly to the confidence in detection of point source (probability for the background to fluctuate to create a "feature")

$$C = \frac{N_{sig}}{\sqrt{N_{bkg}}}$$

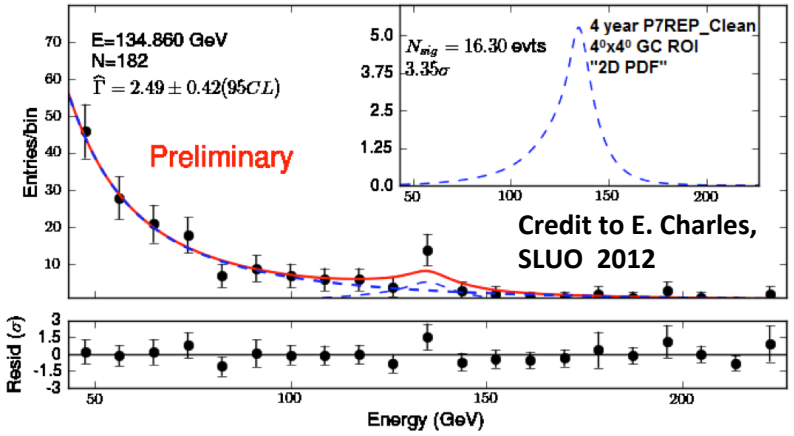
where N_{sig} is a number of events from the "line" (source), and N_{bkg} is a number of background (diffuse) events

With 10X better PSF for Gamma-400:

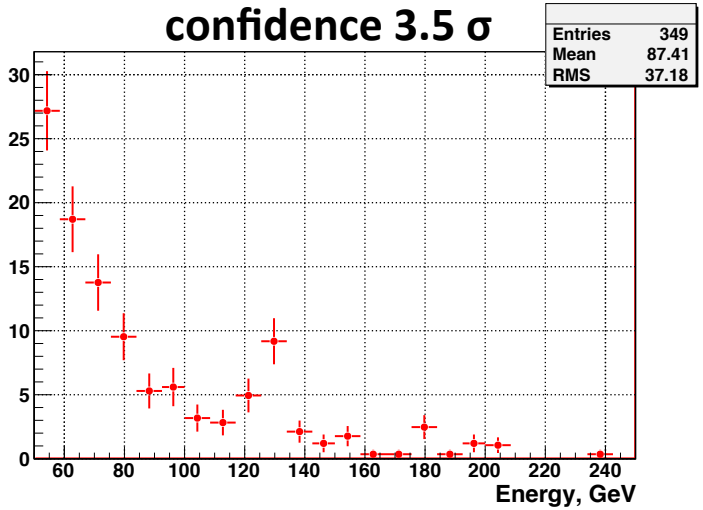
- N_{bkg} can be 100X less,
- detection confidence C will be ~5X larger, assuming twice less events from the "line" N_{sig} detected (due to smaller A_{eff})

Illustration with “135 GeV line” Toy model simulation

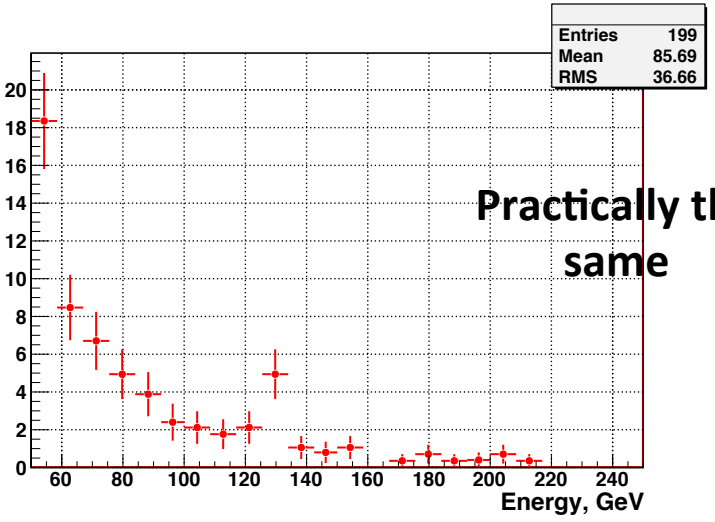
Toy model simulates the line to look like the Fermi LAT result, with “LAT-like” instrument parameters (A_{eff} and dE/E)



LAT-like instrument, 300 events total, line confidence 3.5 σ

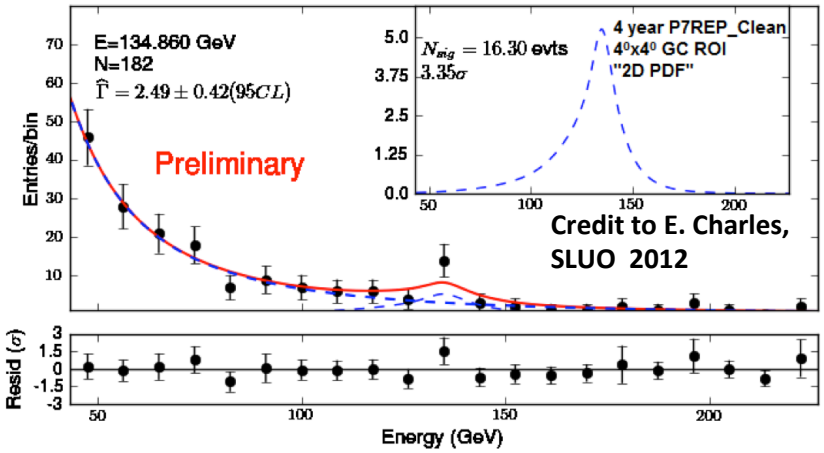


Gamma-400, 150 events, 10X better dE/E, line confidence 3.9 σ

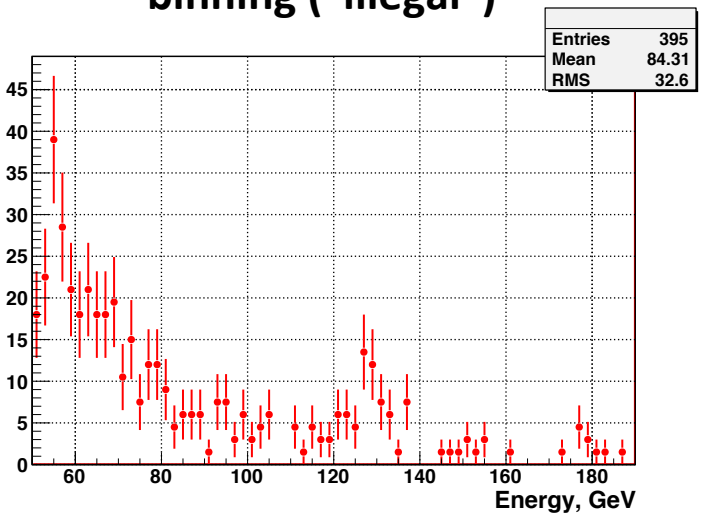


Practically the same

Illustration with “135 GeV line” Toy model simulation



LAT-like instrument, Fine binning (“illegal”)



Gamma-400, 10X better dE/E, Fine binning

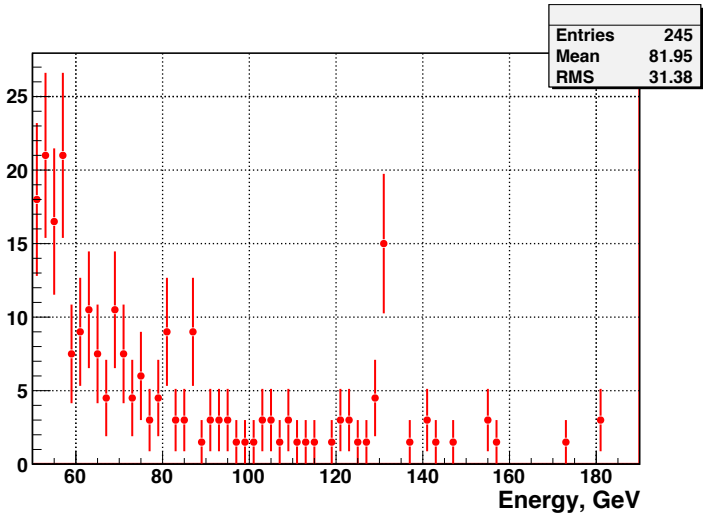
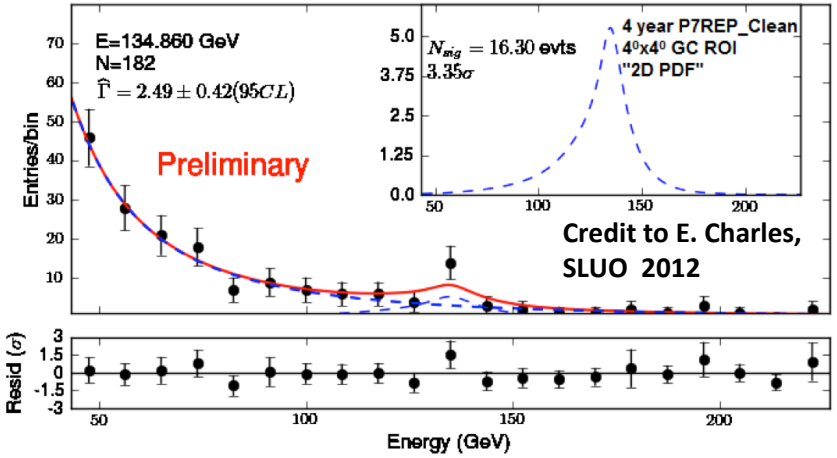
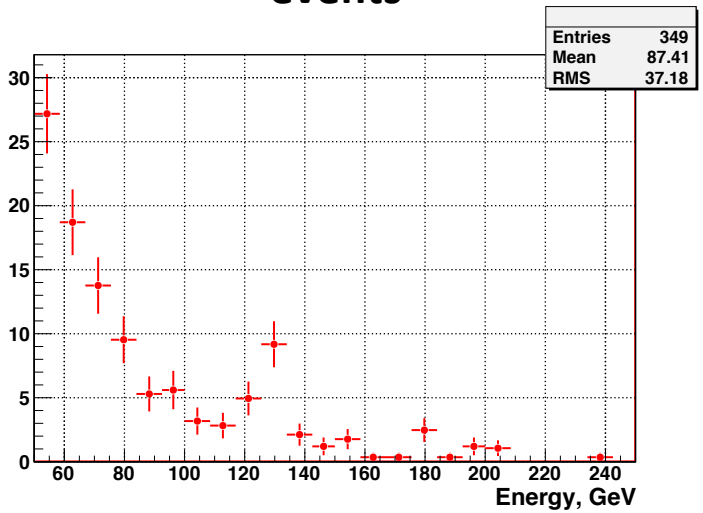


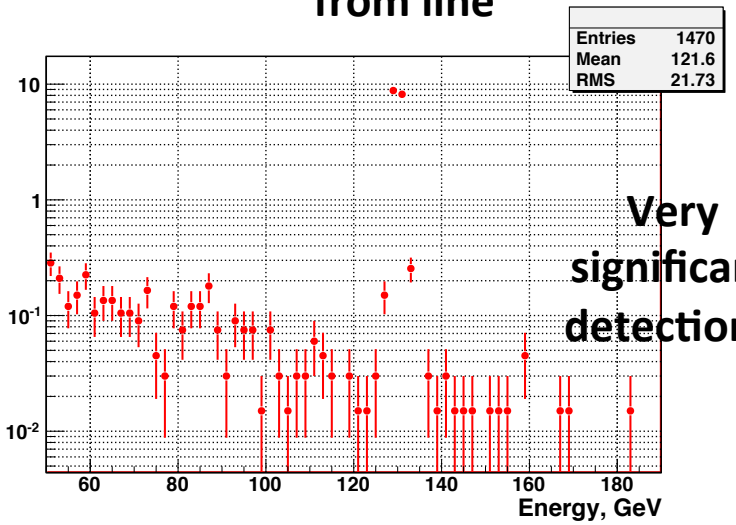
Illustration with “135 GeV line” Toy model simulation



LAT-like instrument, 300 events

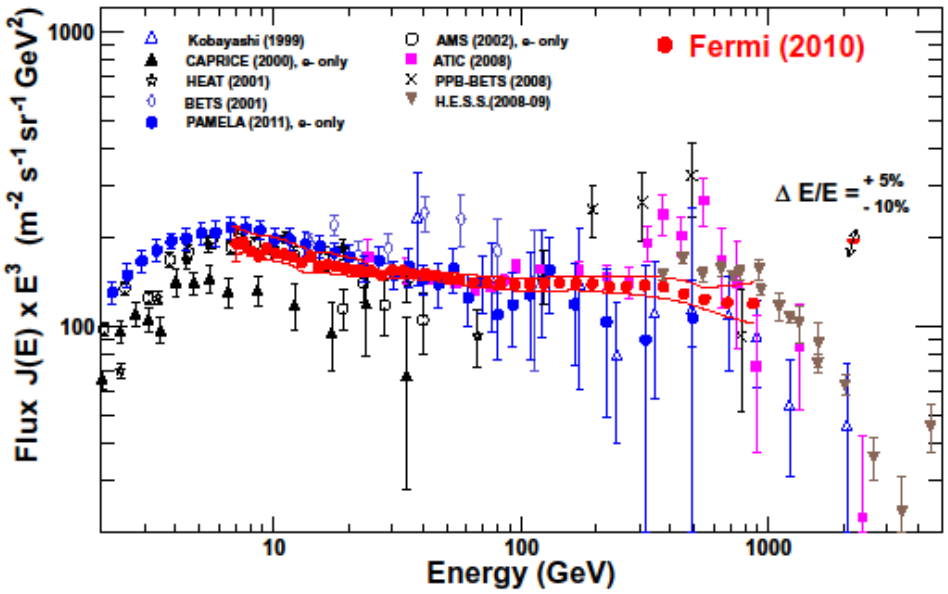


Gamma-400, 10X better dE/E, 10X better PSF (100X less background), same # of events from line



Very significant detection !

Electrons and Positrons inclusive spectrum

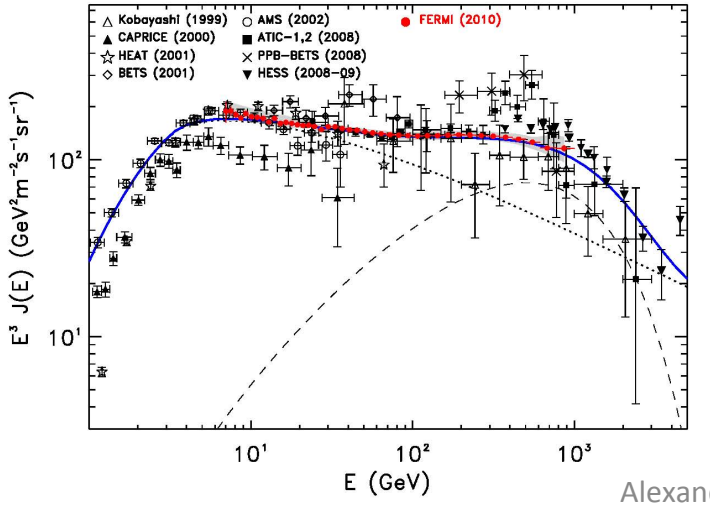


- **ATIC reported sharp spectral feature at around 600 GeV, possibly indicating dark matter involvement**
- **Fermi-LAT observes a small, wide spectral feature in the combined e^+e^- spectrum between 100 GeV and 1 TeV, but does not confirm sharp ATIC spectral feature**
- **H.E.S.S. and PAMELA also do not confirm this feature**

Cosmic rays: Electrons and Positrons

Fermi LAT electron spectrum cannot be explained within conventional single-component model,

- **but introduction of an additional component of the CRE flux with hard spectrum can resolve the problem,**
- **however it can be also explained by adjusting injection spectrum and propagation parameters)**
- **This component can be astrophysical (many different scenarios have been considered) or "exotic", such as dark matter clump**



GAMMA-400: with its superior energy range and resolution can provide critical information on the spectral structure and spectral index drop above ~1 TeV (as reported by H.E.S.S.)

SUMMARY

- **GAMMA-400 will be a very important successor of the Fermi LAT and will provide important observations of *γ*-rays and cosmic rays in synergy with ground-based *γ*-ray telescopes and other wavelength instruments. After the end of the Fermi LAT mission, GAMMA-400 will be the only flying *γ*-ray observatory**
- **GAMMA-400 main differences from Fermi LAT are ~10 times better angular and energy resolution at energy > 100 GeV**
- **The main objective for GAMMA-400 is to conduct an accurate measurement of the *γ*-radiation to search for the dark matter smoking gun: *γ*-ray lines. It will be at least twice more sensitive in this search compared to Fermi LAT**
- **Significant contributions to the dark matter constraints will be made with the study of *γ*-ray satellites (clumps), satellite galaxies (such as dwarf Spheroidal Galaxies), and Galactic Center. Also important results are expected with cosmic ray electrons and positrons**
- **Stay tune !**

THANK YOU !