Dark Matter Searches with Gamma Rays

Indirect Detection of Dark Matter

Robert Johnson
U.C. Santa Cruz
Department of Physics and
Santa Cruz Institute for Particle Physics
(Fermi-LAT collaboration member)

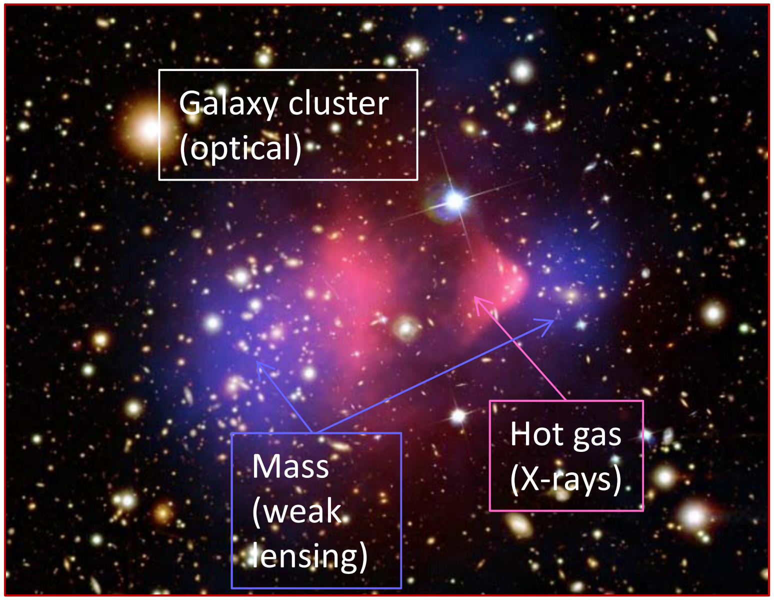
Outline

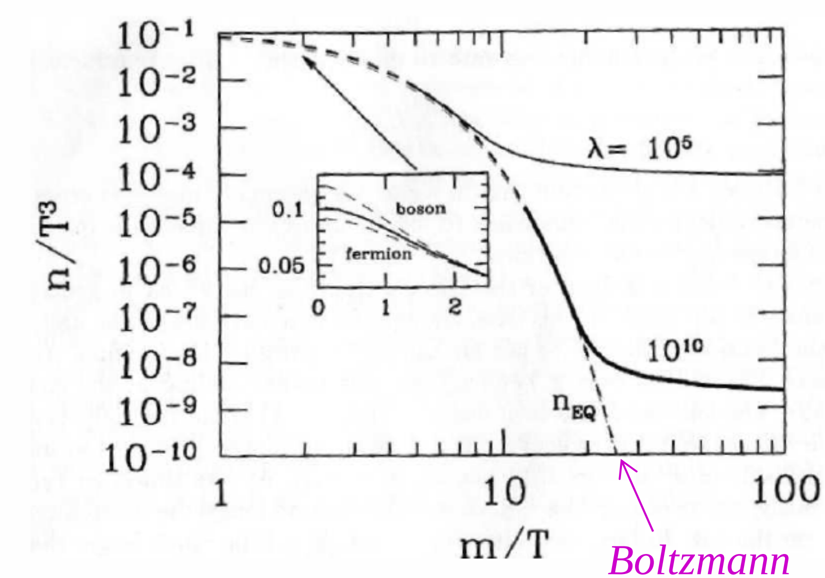
- Introduction to the science
- Detection methods
- Experiments: orbiting and ACT
- Local dwarfs
- Galaxy clusters
- Galactic center
- Lines
- Conclusions

More by Savvas Koushiappas in the next talk.

Introduction

Bullet Cluster (APOD, 2006 August 24)





Boltzmann

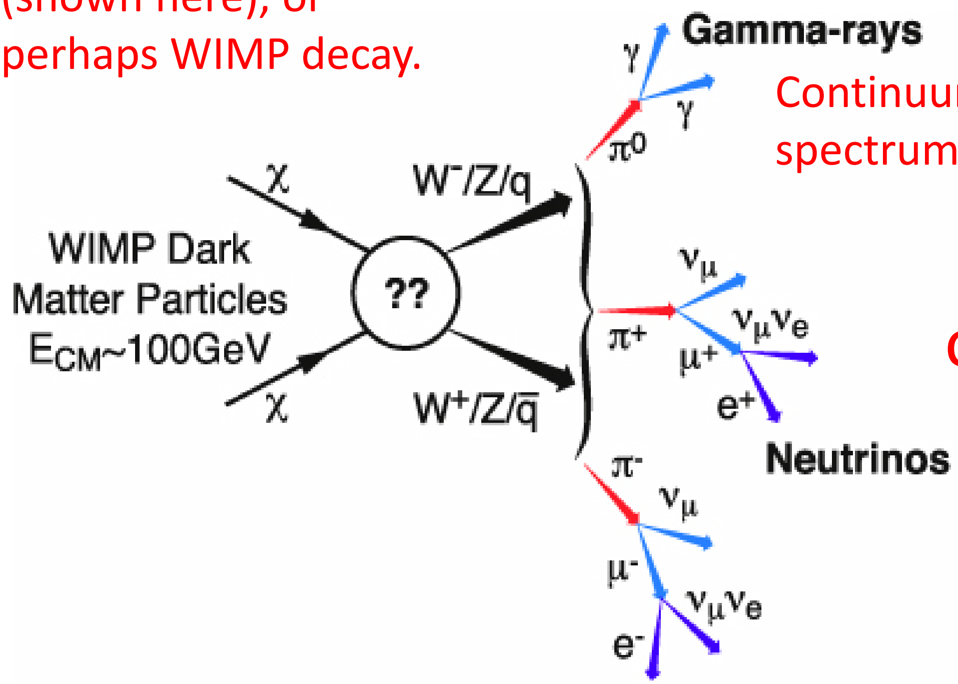
- Dark matter has been detected in many differing observations by its gravitational signature.
- Observations such as the Bullet Cluster suggest that it cannot be gas, or modified gravity. Insufficient MACHOs have been detected by gravitational microlensing.
- Structure formation demands that it be cold.
- The most viable hypothesis is a weakly interacting massive particle (WIMP) that is a thermal relic of the Big Bang.
- As the temperature became too low for them to remain in equilibrium, they froze out at a relic density inversely proportional to the annihilation cross section.

$$\Omega_{\rm WIMP} \approx 0.2 \times \left(\frac{3\times10^{-26}\ {\rm cm^3 s^{-1}}}{\langle \sigma v \rangle} \right)$$

Approximate known DM density, relative to the critical density.

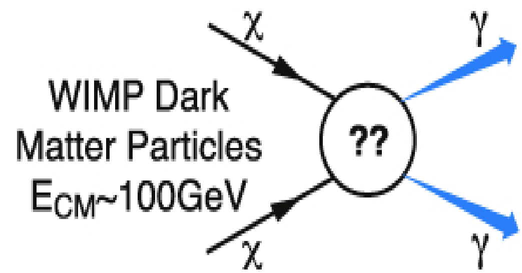
Indirect Detection of Dark Matter

WIMP annihilation
(shown here), or
perhaps WIMP decay.



Continuum
spectrum

or



Line
spectrum

(or Z^0)

$$\frac{d\Phi_\gamma}{dE_\gamma} = \frac{1}{4\pi} \times \boxed{\frac{\langle\sigma v\rangle}{2m_\chi^2} \sum_f \frac{dN_\gamma^f}{dE_\gamma} B_f} \times \int_{\Delta\Omega} d\Omega \int_{los} \rho^2(\ell)\, d\ell(\psi)$$

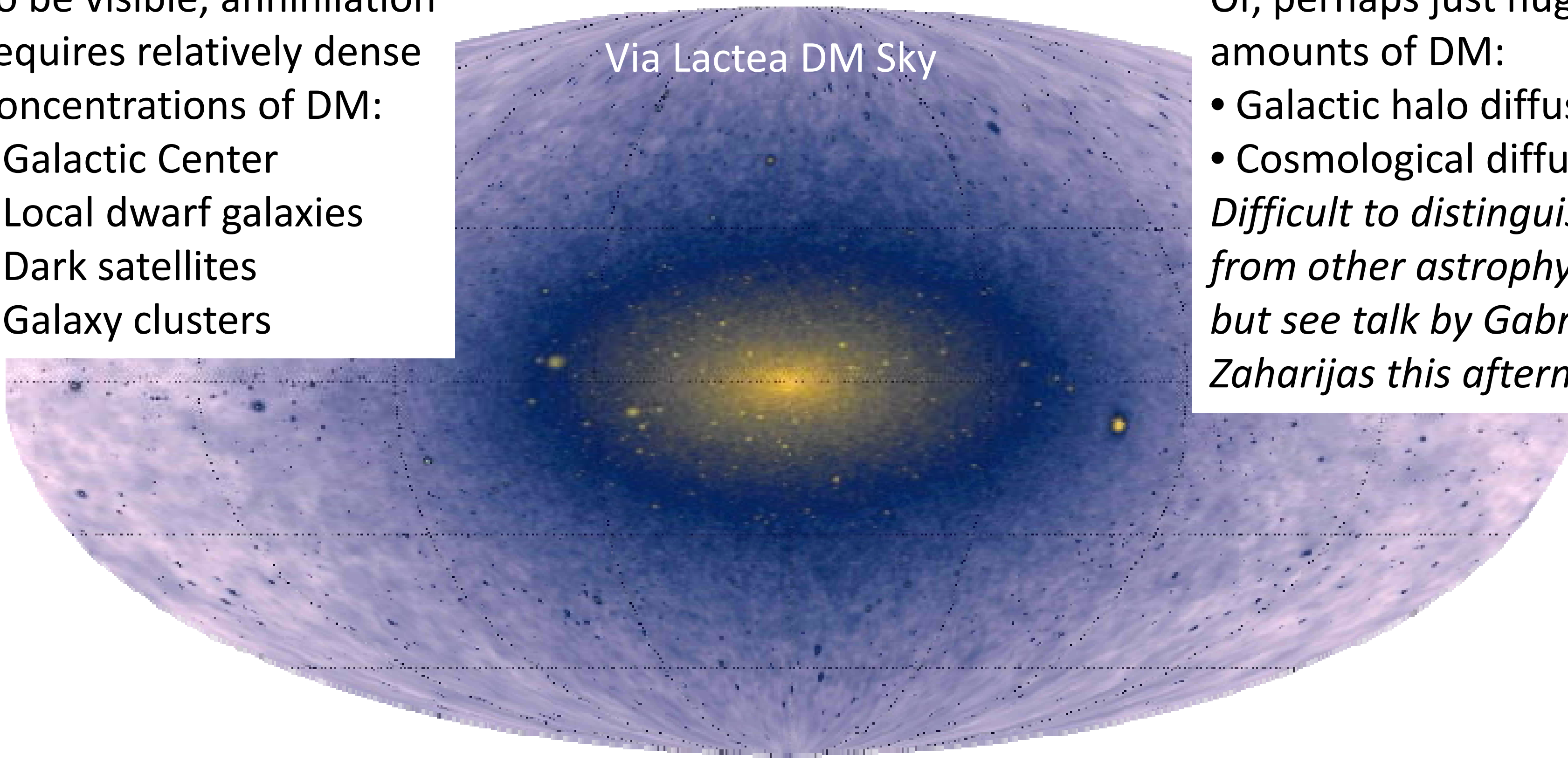
Particle Physics

Astrophysics

Indirect Detection of Dark Matter

To be visible, annihilation requires relatively dense concentrations of DM:

- Galactic Center
- Local dwarf galaxies
- Dark satellites
- Galaxy clusters



Or, perhaps just huge amounts of DM:

- Galactic halo diffuse
- Cosmological diffuse

Difficult to distinguish from other astrophysics, but see talk by Gabrijela Zaharijas this afternoon.

$$\frac{d\Phi_\gamma}{dE_\gamma} = \frac{1}{4\pi} \times \frac{\langle \sigma v \rangle}{2 m_\chi^2} \sum_f \frac{dN_\gamma^f}{dE_\gamma} B_f \times \boxed{\int_{\Delta\Omega} d\Omega \int_{los} \rho^2(\ell)\, d\ell(\psi)}$$

Particle Physics Astrophysics

The Observatories

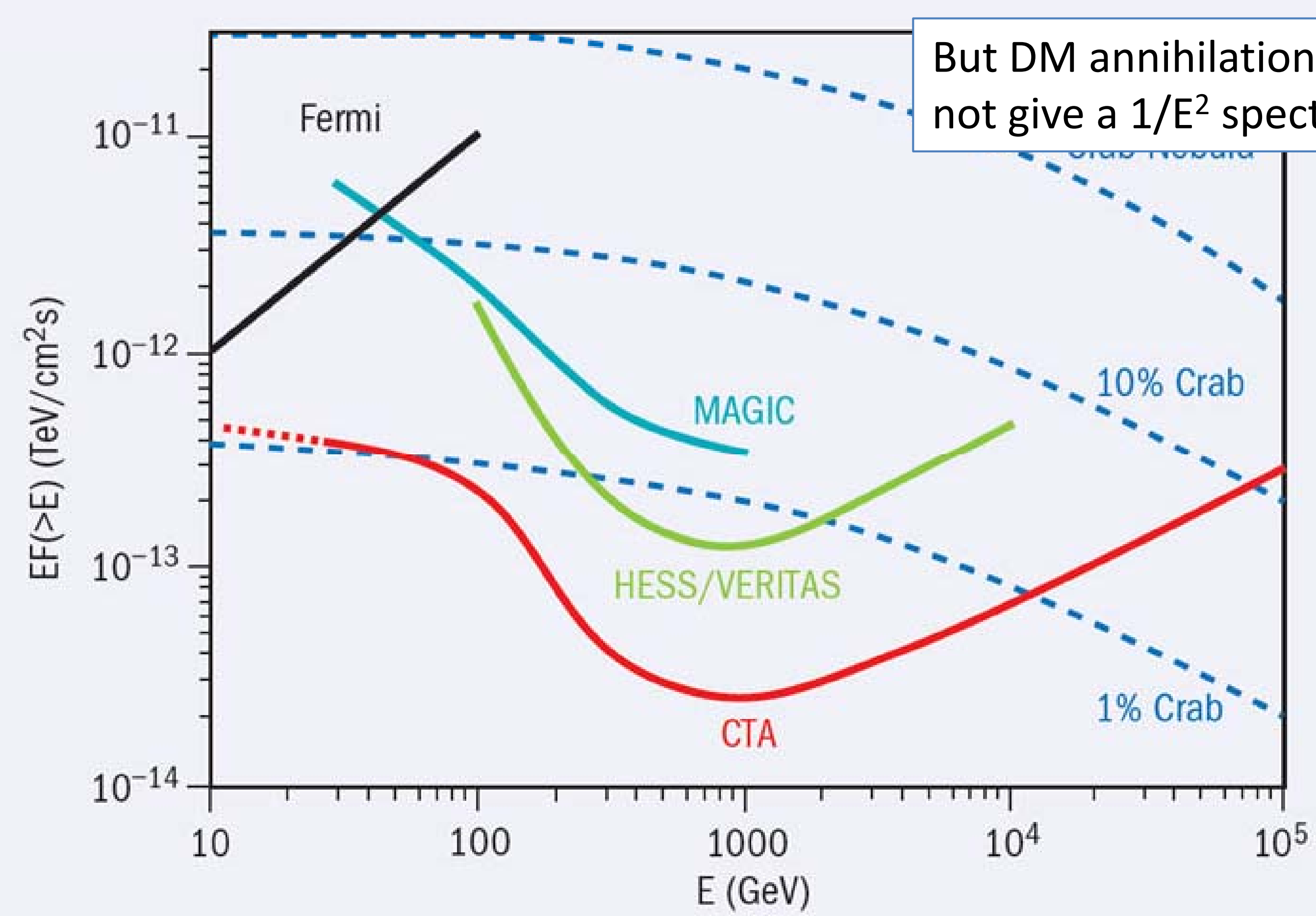
Ground based (ACT):
- Large effective area (>100,000 m^2).
- High energy threshold (≈ 100 GeV).
- Small field of view.
- Short observations (≈ 0.1 yr).
- Good angular resolution.

The Fermi data are public, and many or most of the dark matter papers from LAT data have come from outside the collaboration.

Atmospheric Cherenkov Telescopes

Orbiting:
- Small effective area (≈ 1 m^2)
- Low energy threshold (≈ 100 MeV); sensitive to DM well below 100 GeV.
- Wide field of view and long observations (≈ 1 year now on every source in the sky).
- Good energy resolution for lines.
- Very low CR background.

Integral Sensitivities

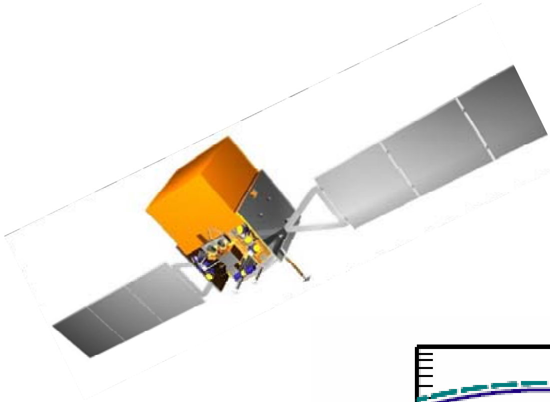


But DM annihilation does not give a $1/E^2$ spectrum!

From CERN Courier, July 18, 2012, Paula Chadwick.

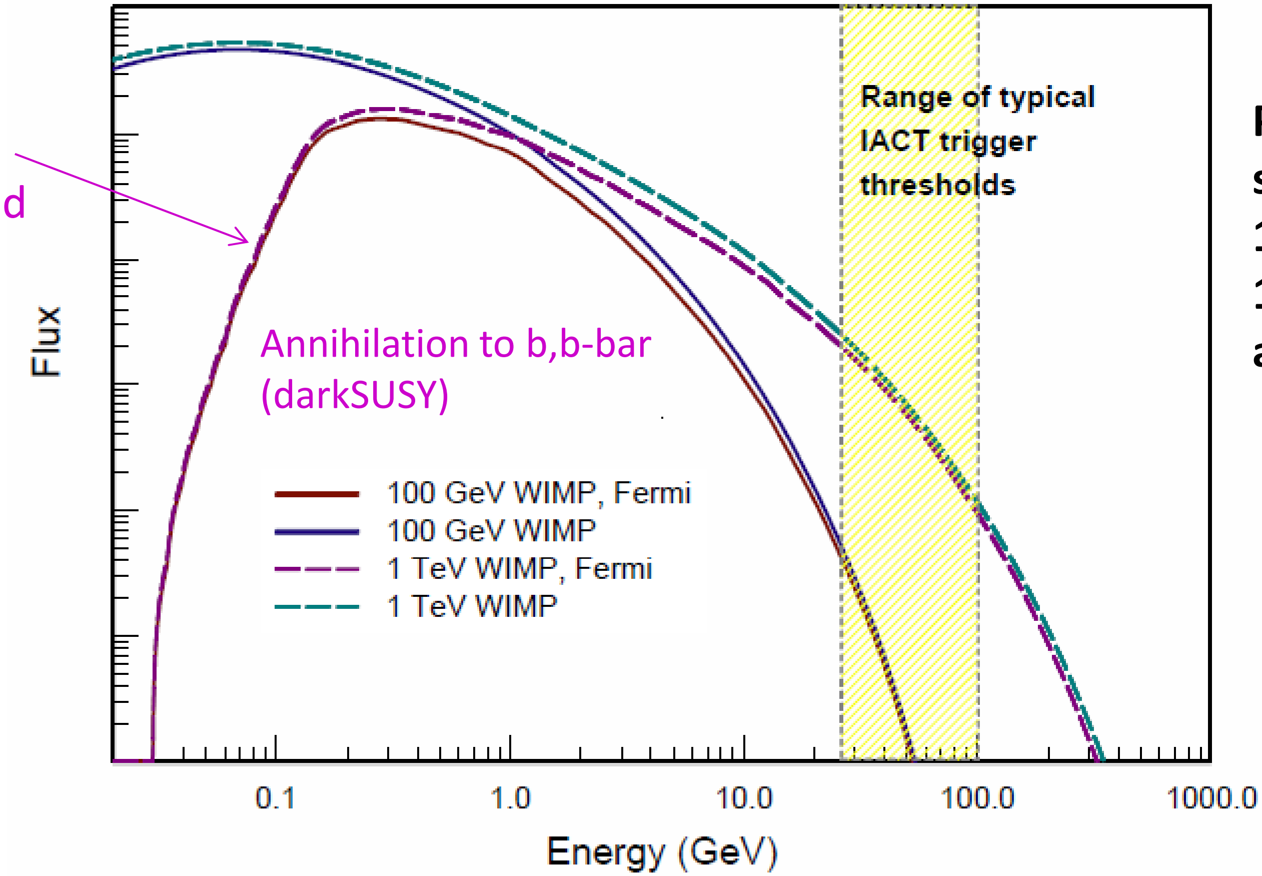
The advertised Fermi-LAT sensitivity (http://fermi.gsfc.nasa.gov) is for a 5-sigma detection of a high latitude (i.e. low background) point source with a $1/E^2$ spectrum in a 1-year all-sky survey.

Photon Spectra from DM Annihilation or Decay



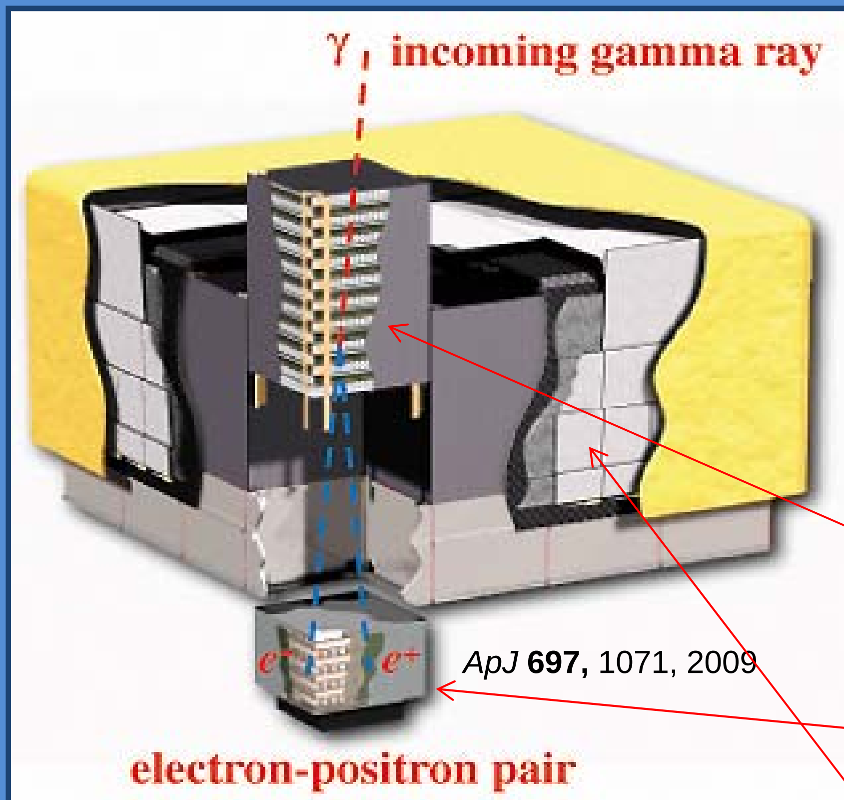
For inclusive, continuum signals, most of the photons have energy far below the WIMP mass. Therefore, ground-based detectors must look for very massive WIMPs, at the TeV scale.

Fermi threshold



Photon spectra from 100 GeV and 1 TeV WIMP annihilation

Fermi-LAT Instrument



D.o.E.

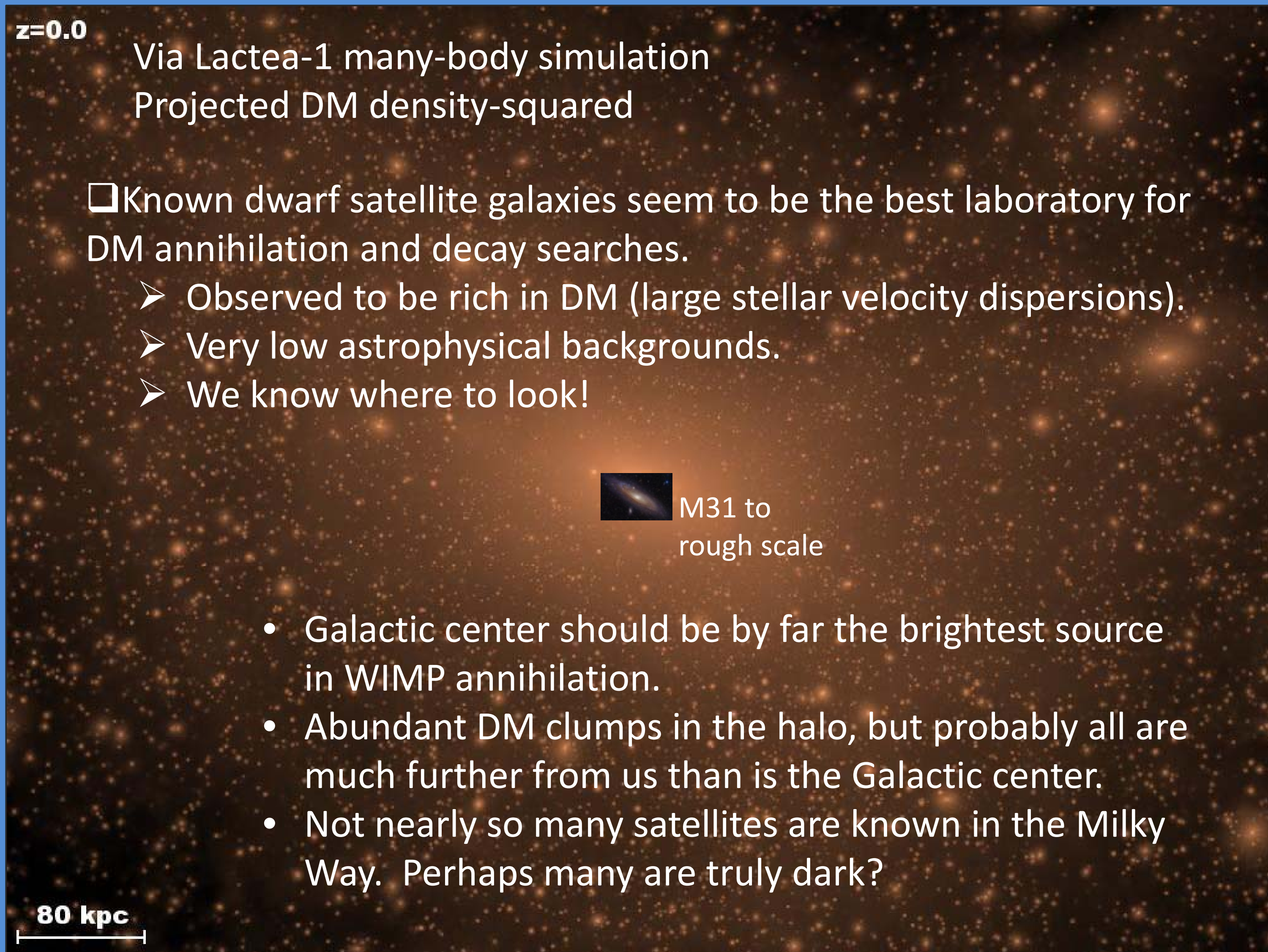
Large Area Telescope (LAT)

- 3 ton particle detector “telescope”.
- ≈million amplifiers; 5 computers.
- Successful collaboration of particle physicists and astrophysicists.

- We are celebrating this month conclusion of the initial 5-year mission on orbit!
- The instrument can continue operating for many more years (no consumables) subject to continued NASA funding.
- Pair-conversion telescope:
  - Silicon-strip tracking interleaved with tungsten converter foils.
  - CsI calorimeter for energy measurement.
  - Scintillator cosmic-ray veto.

  By including detailed tracking and calorimeter information, background rejection better than 10^5:1 is obtained.

Predicted Local Dark Matter Clumps



Via Lactea-1 many-body simulation
Projected DM density-squared

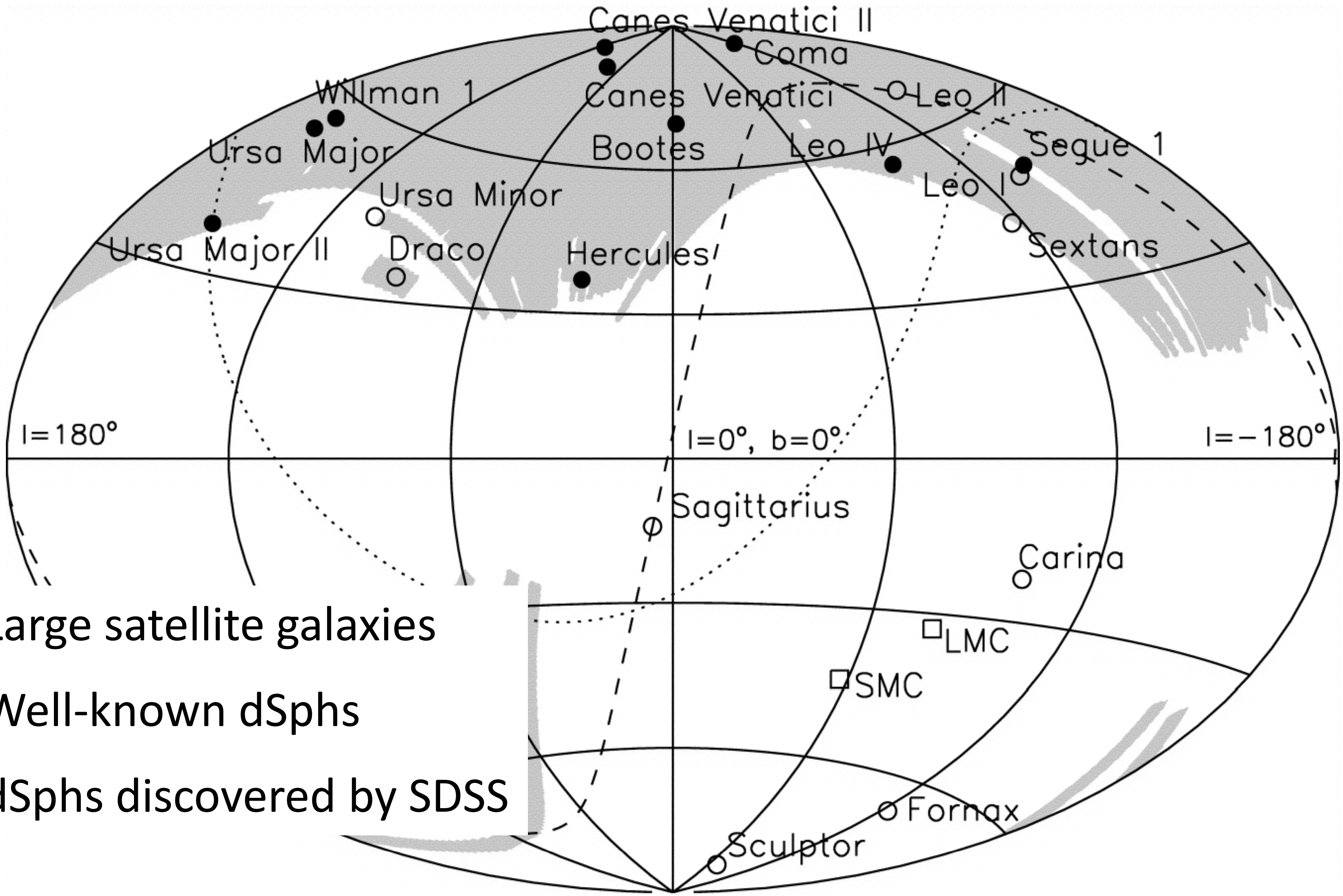
- ❑Known dwarf satellite galaxies seem to be the best laboratory for DM annihilation and decay searches.
  - ➢ Observed to be rich in DM (large stellar velocity dispersions).
  - ➢ Very low astrophysical backgrounds.
  - ➢ We know where to look!

M31 to rough scale

- Galactic center should be by far the brightest source in WIMP annihilation.
- Abundant DM clumps in the halo, but probably all are much further from us than is the Galactic center.
- Not nearly so many satellites are known in the Milky Way. Perhaps many are truly dark?

http://www.ucolick.org/~diemand/vl/

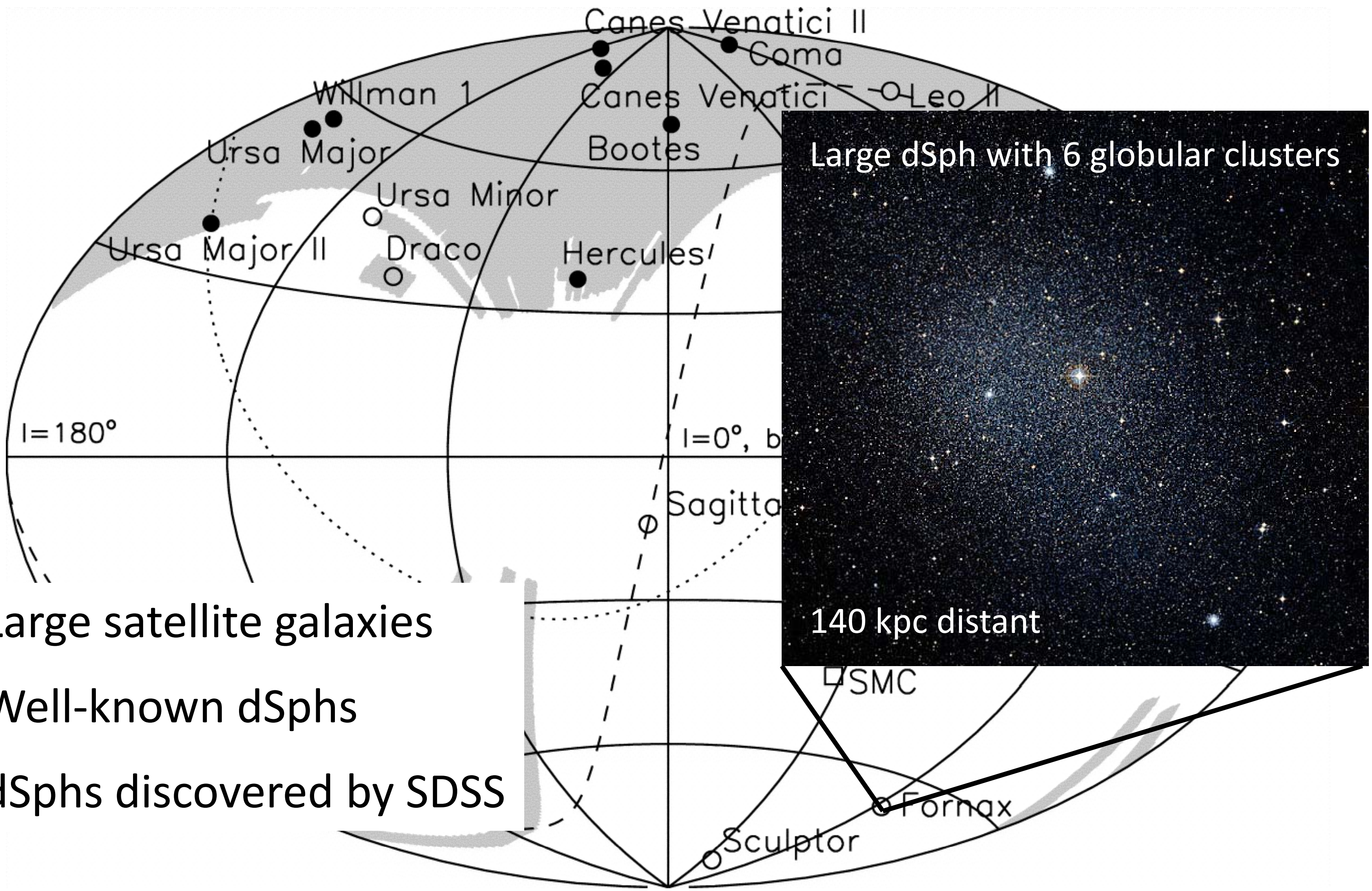
Local Dwarf Spheroidal Galaxies



- □ Large satellite galaxies
- ○ Well-known dSphs
- ● dSphs discovered by SDSS

Belokurov, V., et al. 2007, ApJ, 654, 897

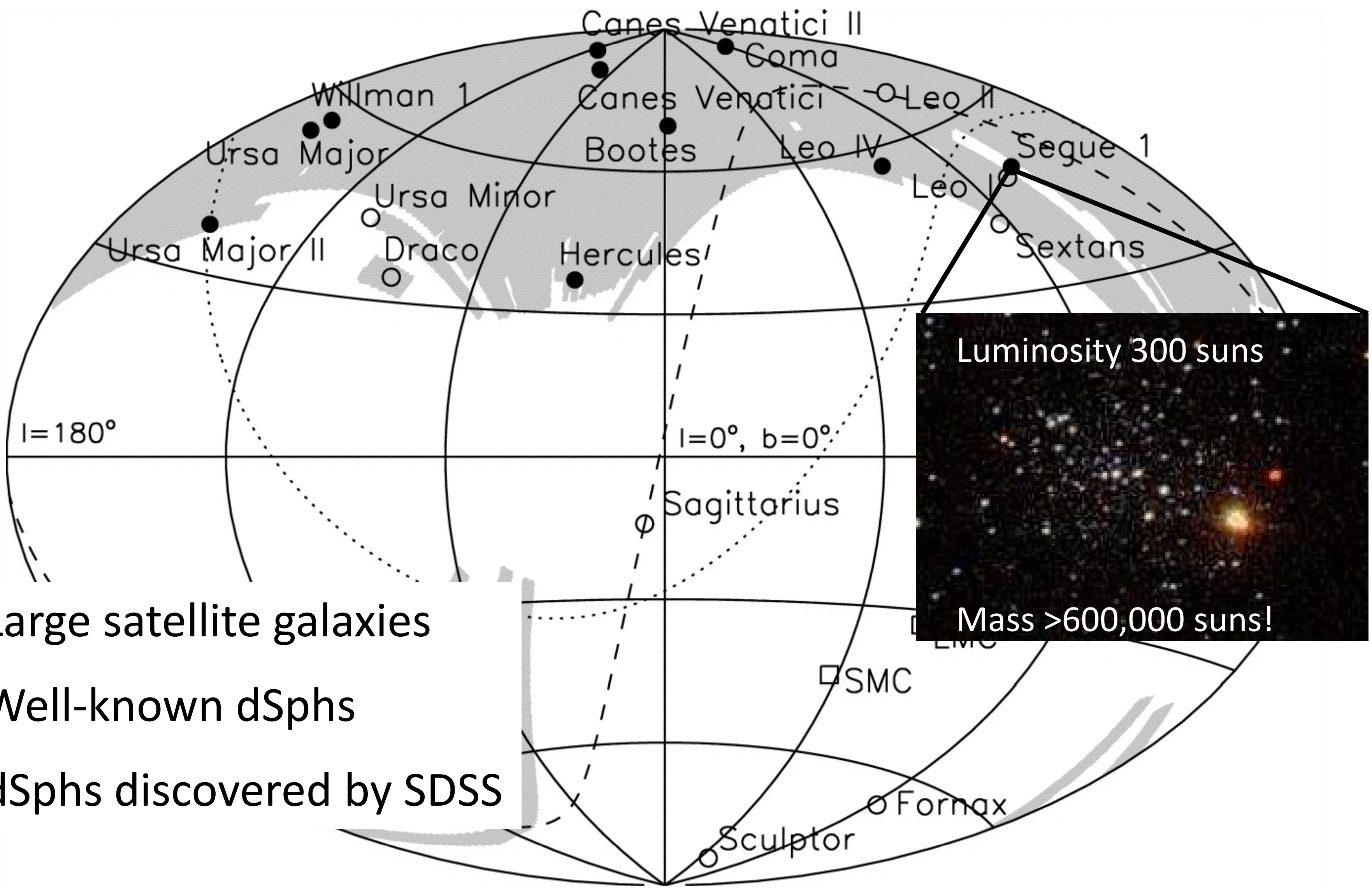
Local Dwarf Spheroidal Galaxies



- □ Large satellite galaxies
- ○ Well-known dSphs
- ● dSphs discovered by SDSS

Belokurov, V., et al. 2007, ApJ, 654, 897

Local Dwarf Spheroidal Galaxies



□ Large satellite galaxies

○ Well-known dSphs

● dSphs discovered by SDSS

Belokurov, V., et al. 2007, ApJ, 654, 897

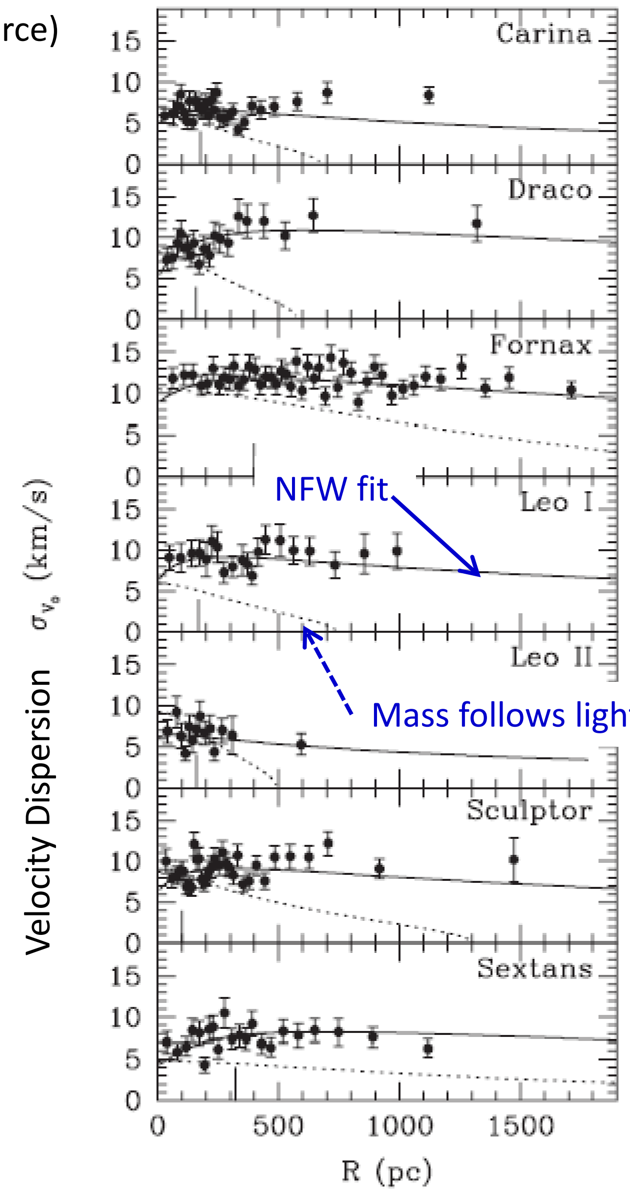
Dwarf Astrophysical "J" Factors

$$\int_{\Delta\Omega(\phi,\theta)} d\Omega \int_{los} \rho^2(r(\ell,\phi'))\, d\ell(r,\phi')$$

(Spherically symmetric source)

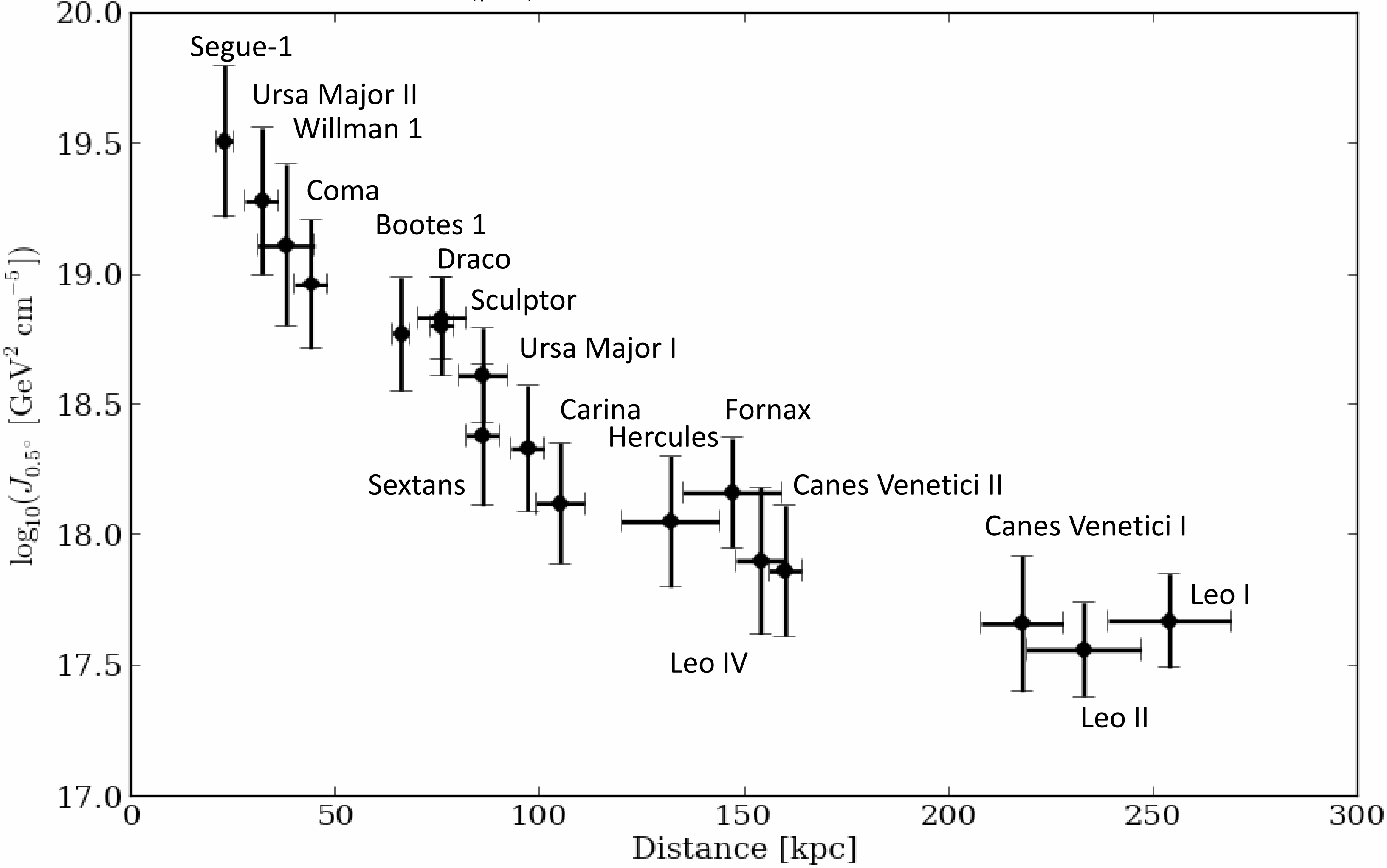
- Dark matter contents are inferred from stellar velocity dispersion.
  - Fewer than 100 stars up to thousands of stars.
- The velocity distribution is fitted for each dwarf, using a model with an NFW halo profile.
  - Two free parameters: virial mass and constant velocity anisotropy
- The J factor is calculated by integrating out to a radius of 0.5°.
  - Encloses the half-light radius of any of the dwarves.
  - Large enough to be insensitive to the inner profile shape (cored vs cusp).
  - A J-factor uncertainty is also calculated and used for each dwarf.

Walker et al., Ap.J. 667:L53 (2007)



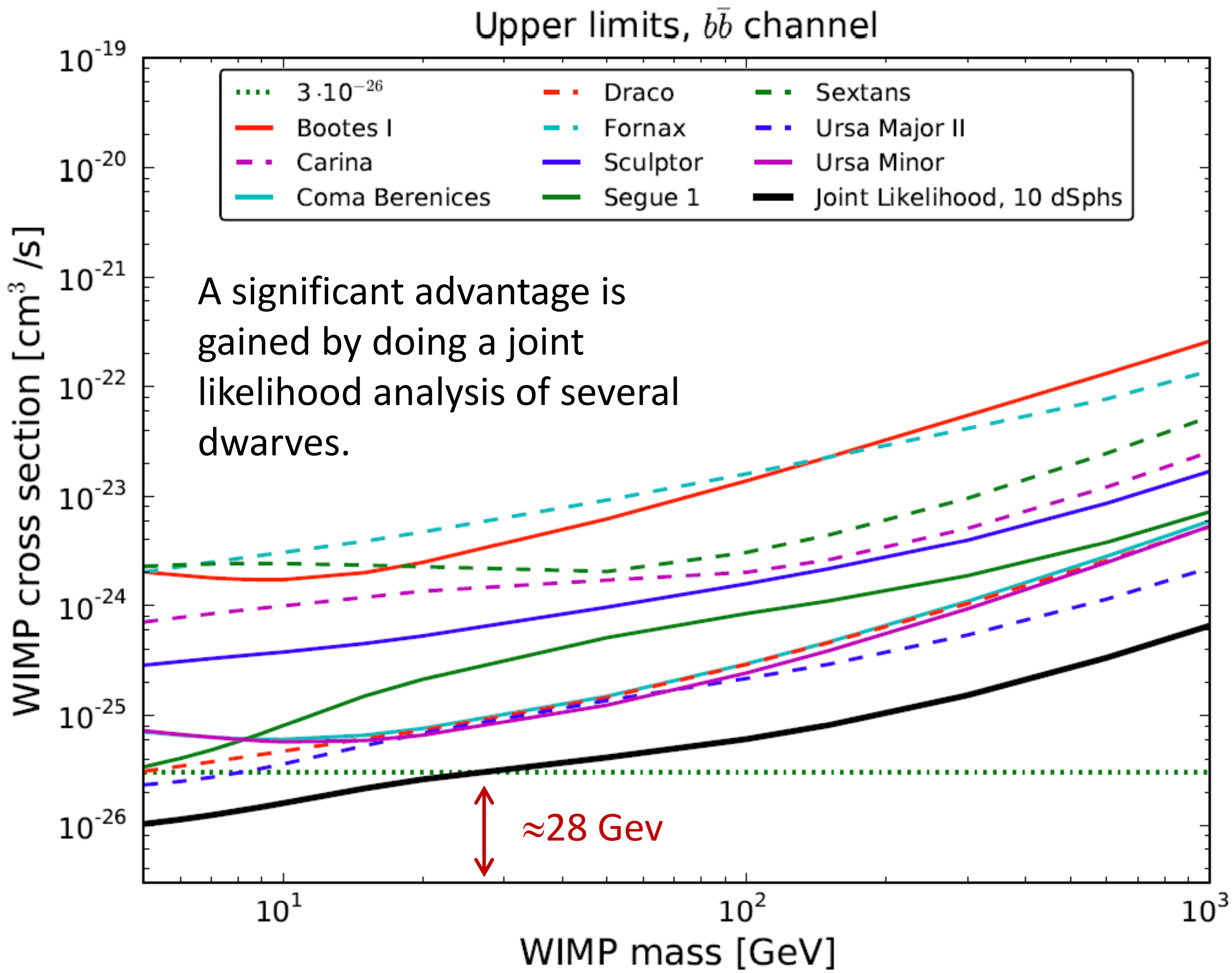
J Factors for 18 Dwarf Galaxies

$$\int_{\Delta\Omega(\phi,\theta)} d\Omega \int_{los} \rho^2(r(\ell,\phi'))\, d\ell(r,\phi')$$



Alex Drlica-Wagner, DPF 2013

Fermi-LAT Dwarf Limits from 24 Months of Data



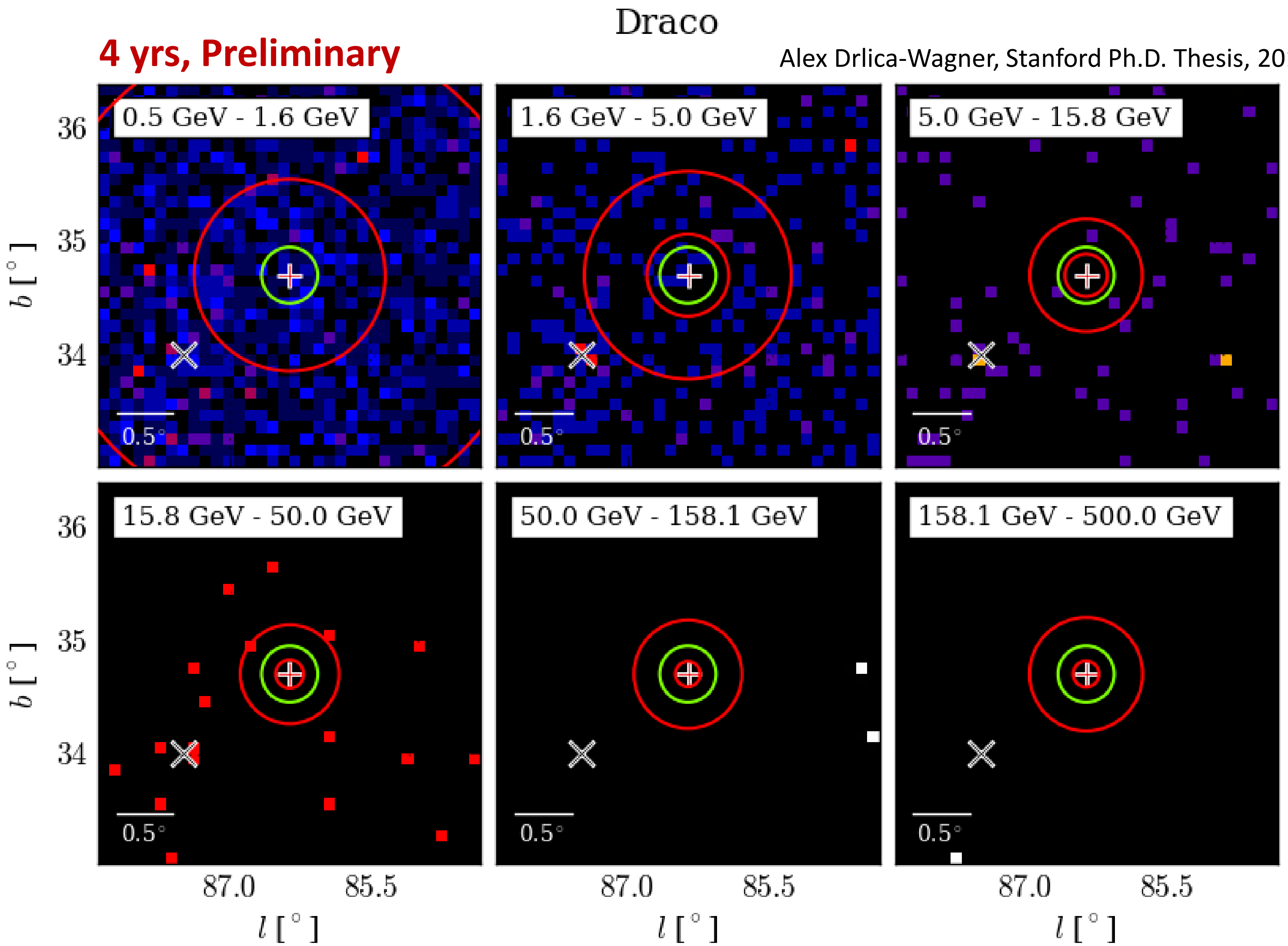
Phys. Rev. Lett. 107 (2011) 241302 and 241303.

Example Fermi-LAT Dwarf Observation

- The LAT sees *no statistically significant* photon excess from any of the dwarfs.
- But these objects are not expected to contain significant other gamma-ray sources.

4 yrs, Preliminary

Alex Drlica-Wagner, Stanford Ph.D. Thesis, 2013



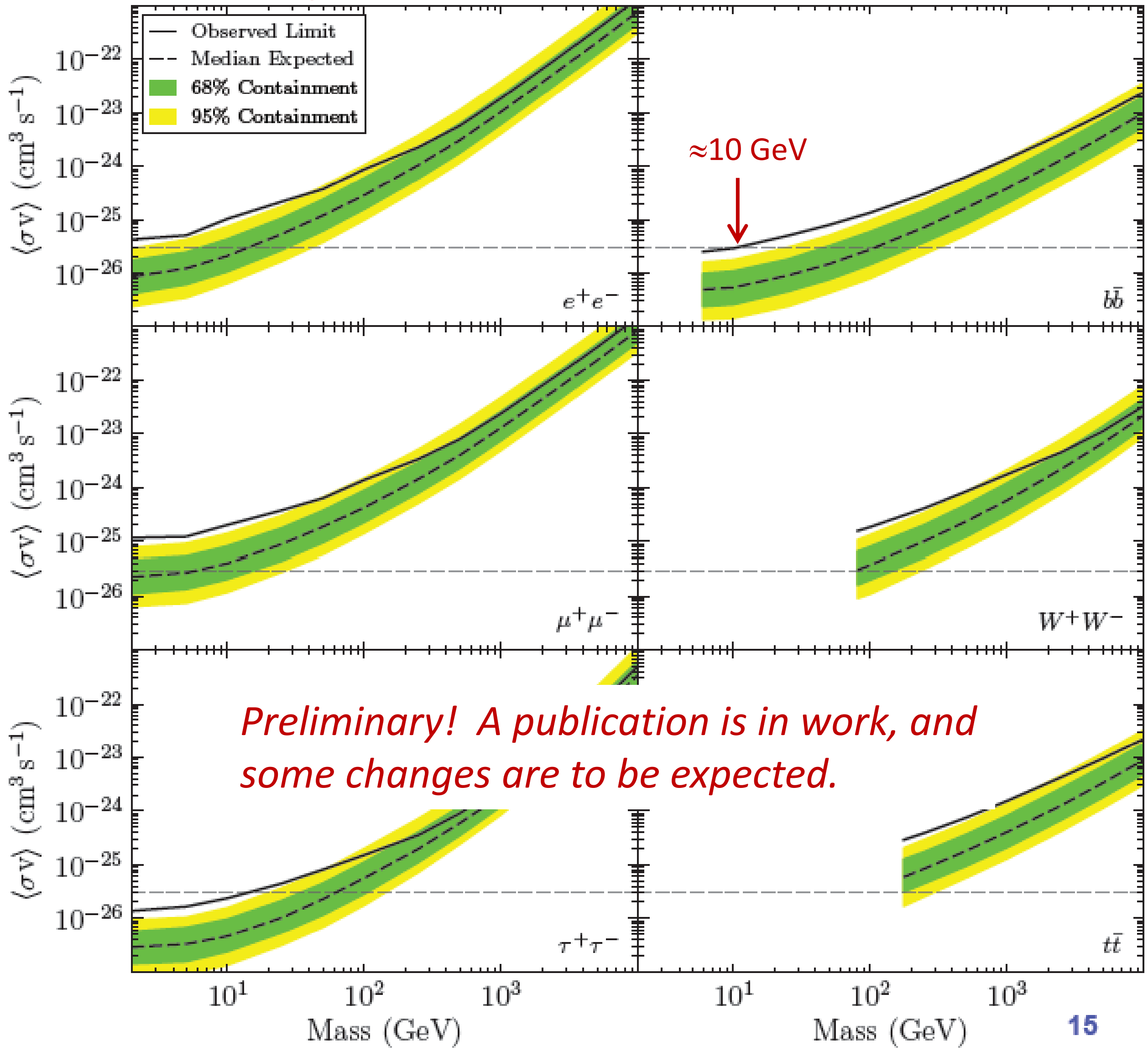
Dwarf Limits from 4 Years of Fermi-LAT Data

- Joint likelihood analysis of 15 dwarf galaxies
- Four years of Fermi-LAT data included
- Expected sensitivity was calculated from 2000 realistic simulations
- The green and yellow bands, plus the dashed curve, indicate the simulation results

Discrepancies from the MC expected limits come from a 1.4σ global excess in data, dominated by Segue 1, Ursa Major II, and Willman 1.

- *Unresolved background sources?*
- *Hint of a signal?*

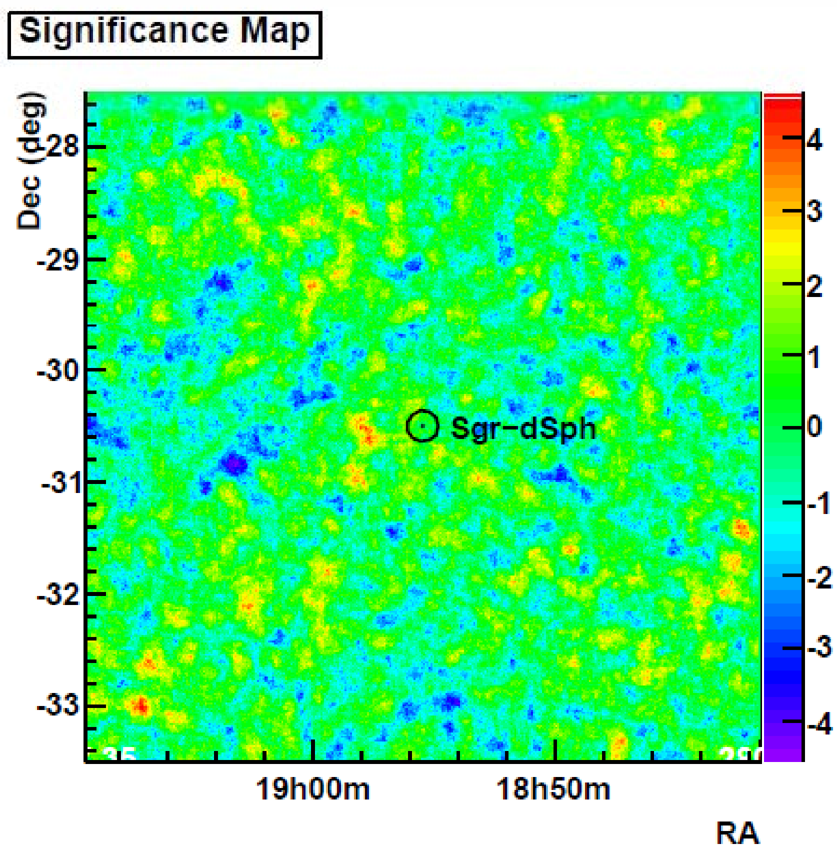
Preliminary Alex Drlica-Wagner, Stanford Ph.D. Thesis, 2013

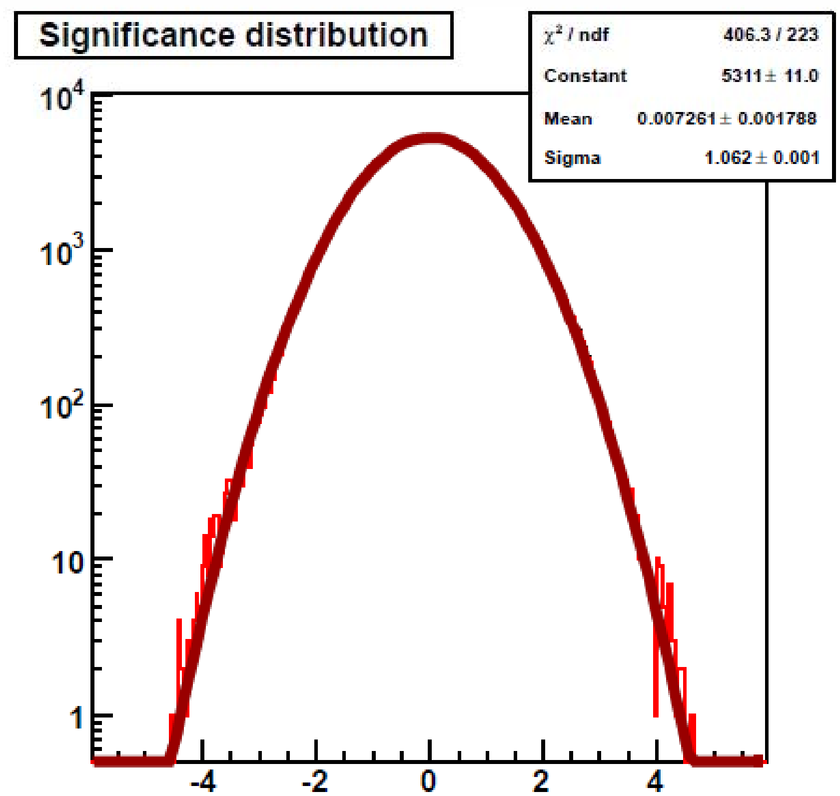


Preliminary! A publication is in work, and some changes are to be expected.

H.E.S.S. Limits from the Sagittarius Dwarf

Lamanna et al, ICRC 2013, arXiv:1307.4918v1



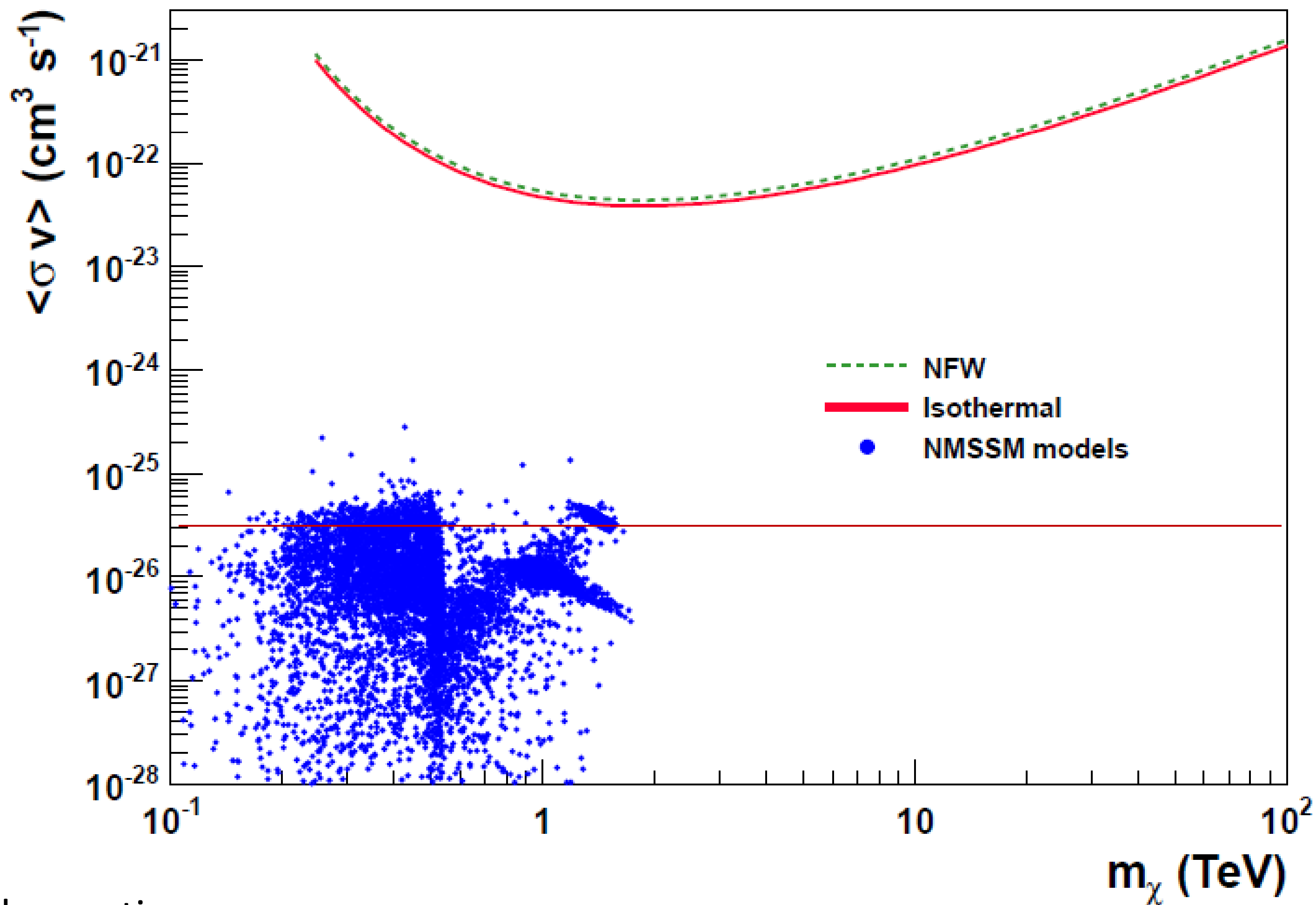


Nothing in the field but Gaussian noise.

91.5 hour observation.

H.E.S.S. Limits from Sagittarius Dwarf

Lamanna et al, ICRC 2013, arXiv:1307.4918v1



91.5 hour observation.

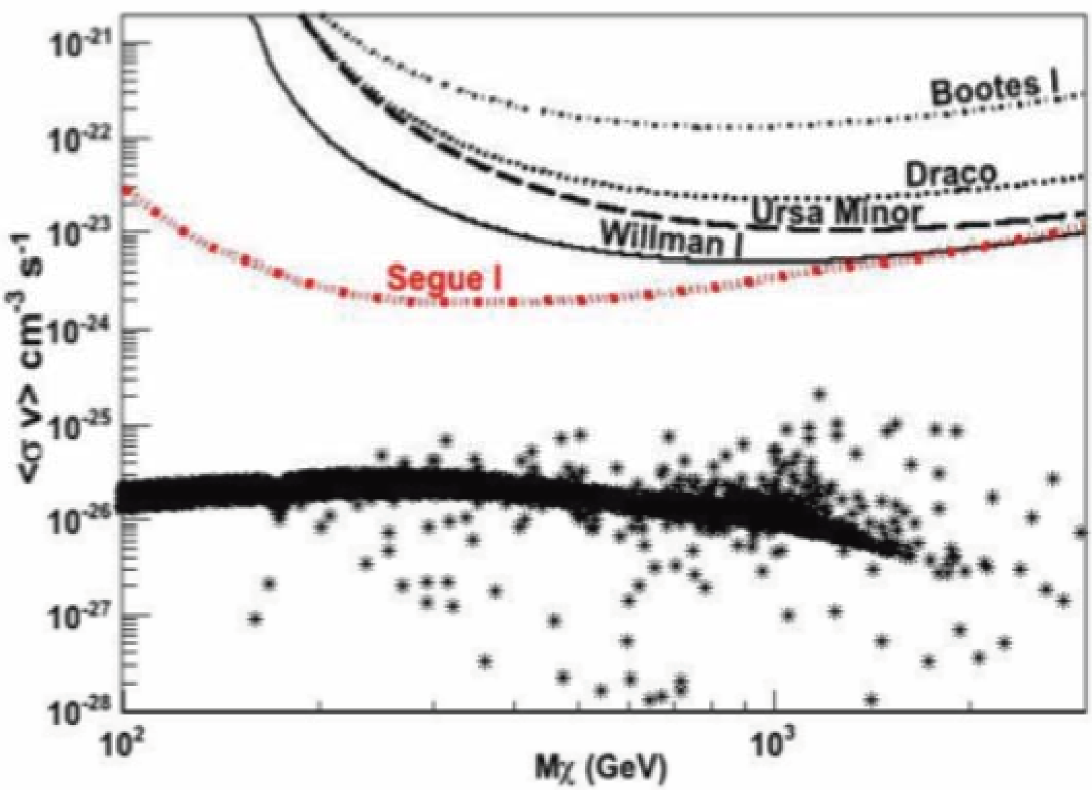
Conservative DM model that accounts for the large tidal disruption.

VERITAS Dwarf Limits

Dwarf	Distance (kpc)	Exposure (hrs)	Significance (σ, prelim.)	E_{th} (GeV, prelim.)	$F(E > E_{th})$ (CU, prelim.)
Segue 1	23	83	-1.34	150	0.15%
Draco	80	38	0.71	380	1.36%
Ursa Minor	66	39	-1.1	290	0.52%
Wilman 1	38	14	-0.15	200	1.62%
Bootes	62	14	-0.31	200	0.81%

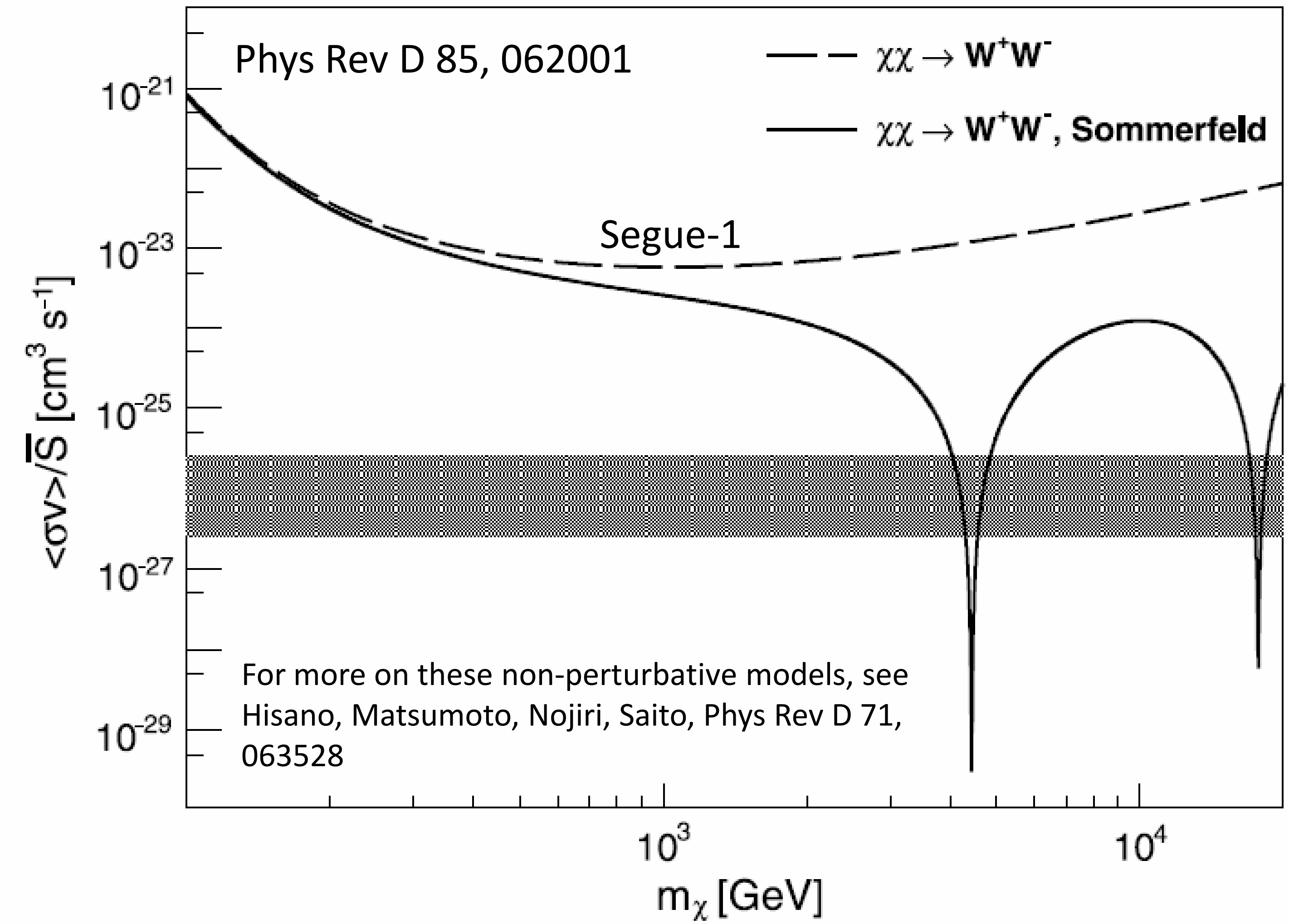
B. Zitzer, ICRC 2013, arXiv:1307.8367

See the talk by Benjamin Zitzer this afternoon.



Interpretation of the VERITAS Segue-1 Observation

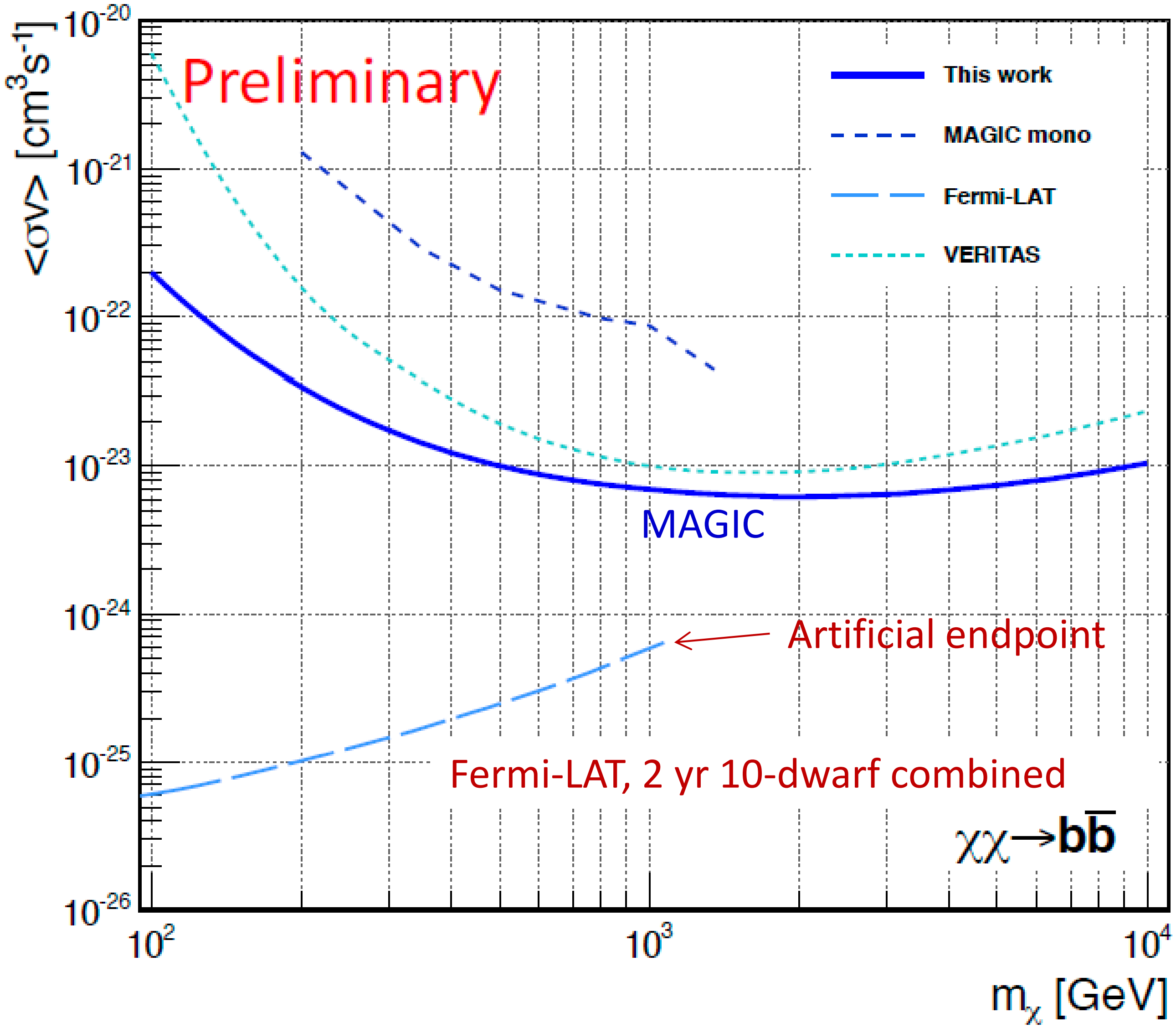
Including a "Sommerfeld" enhancement in the annihilation cross section can make a big difference above about a TeV. In this example model, the attractive potential between the neutralinos is mediated by a Z^0 exchange.



Latest MAGIC Limits on Segue-1

Jelena Aleksic, EPS HEP 2013

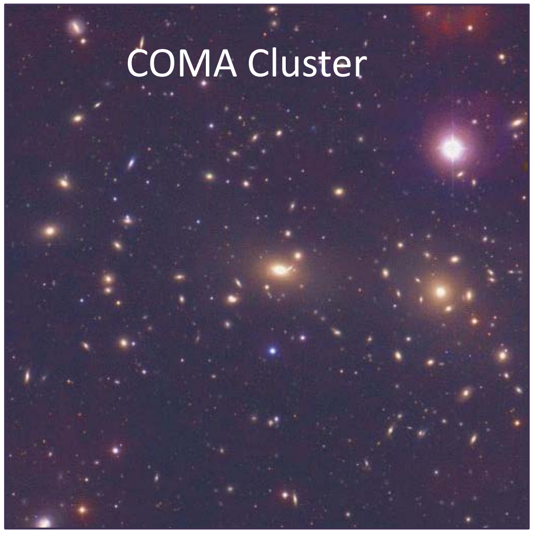
Deep 110 hour observation



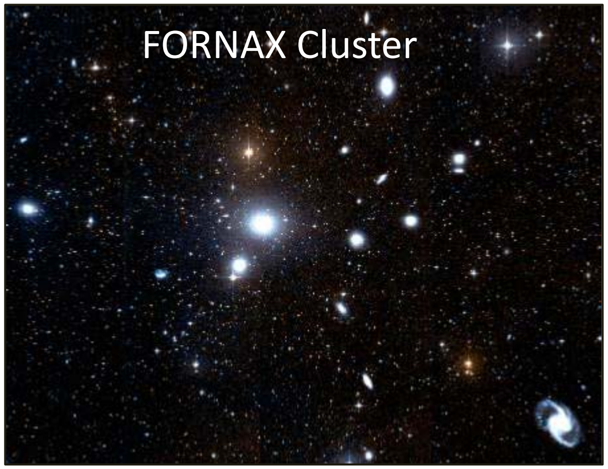
Galaxy Clusters

JCAP, doi:10.1088/1475-7516/2010/05/025

Cluster	RA	Dec.	z	J (10^{17} GeV^2 cm^{-5})
AWM 7	43.6229	41.5781	0.0172	$1.4^{+0.1}_{-0.1}$
Fornax	54.6686	-35.3103	0.0046	$6.8^{+1.0}_{-0.9}$
M49	187.4437	7.9956	0.0033	$4.4^{+0.2}_{-0.1}$
NGC 4636	190.7084	2.6880	0.0031	$4.1^{+0.3}_{-0.3}$
Centaurus (A3526)	192.1995	-41.3087	0.0114	$2.7^{+0.1}_{-0.1}$
Coma	194.9468	27.9388	0.0231	$1.7^{+0.1}_{-0.1}$



- These are the 6 nearby, quiet (no AGN) galaxy clusters used in the published Fermi-LAT analysis.
- For comparison, the dwarf J factors range on this scale from about 3 to 300.
  - However, the cluster J factors shown here assume no substructure, but a boost of about 5 from substructure down to dwarf galaxy scales is almost guaranteed. And larger boosts from smaller structure are possible.



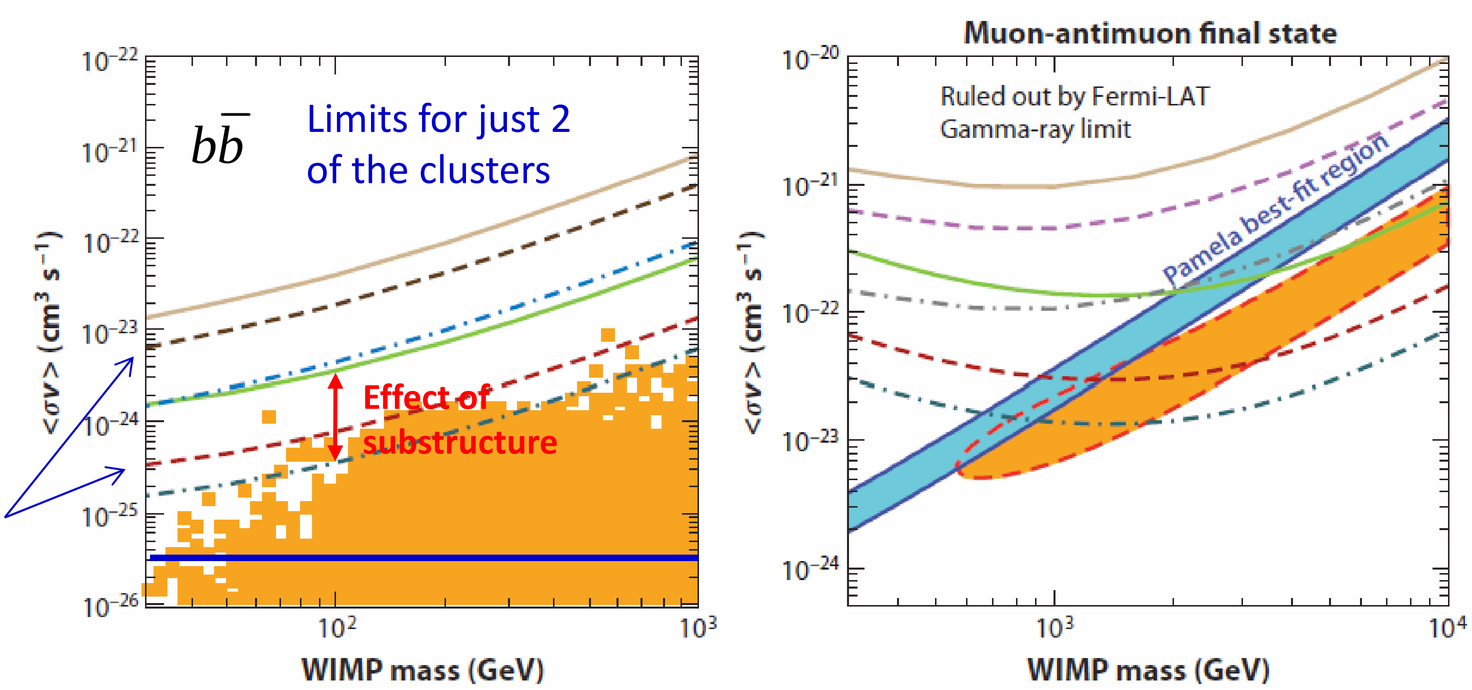
Note that for clusters, CR contributions have to be considered as a background!

Fermi-LAT Cluster Limits from 11 Months

- No observation of gamma rays from the observed galaxy clusters (whether originating from DM or CR).
- To obtain conservative limits, zero emission from cluster cosmic rays is assumed.

JCAP, doi:10.1088/1475-7516/2010/05/025

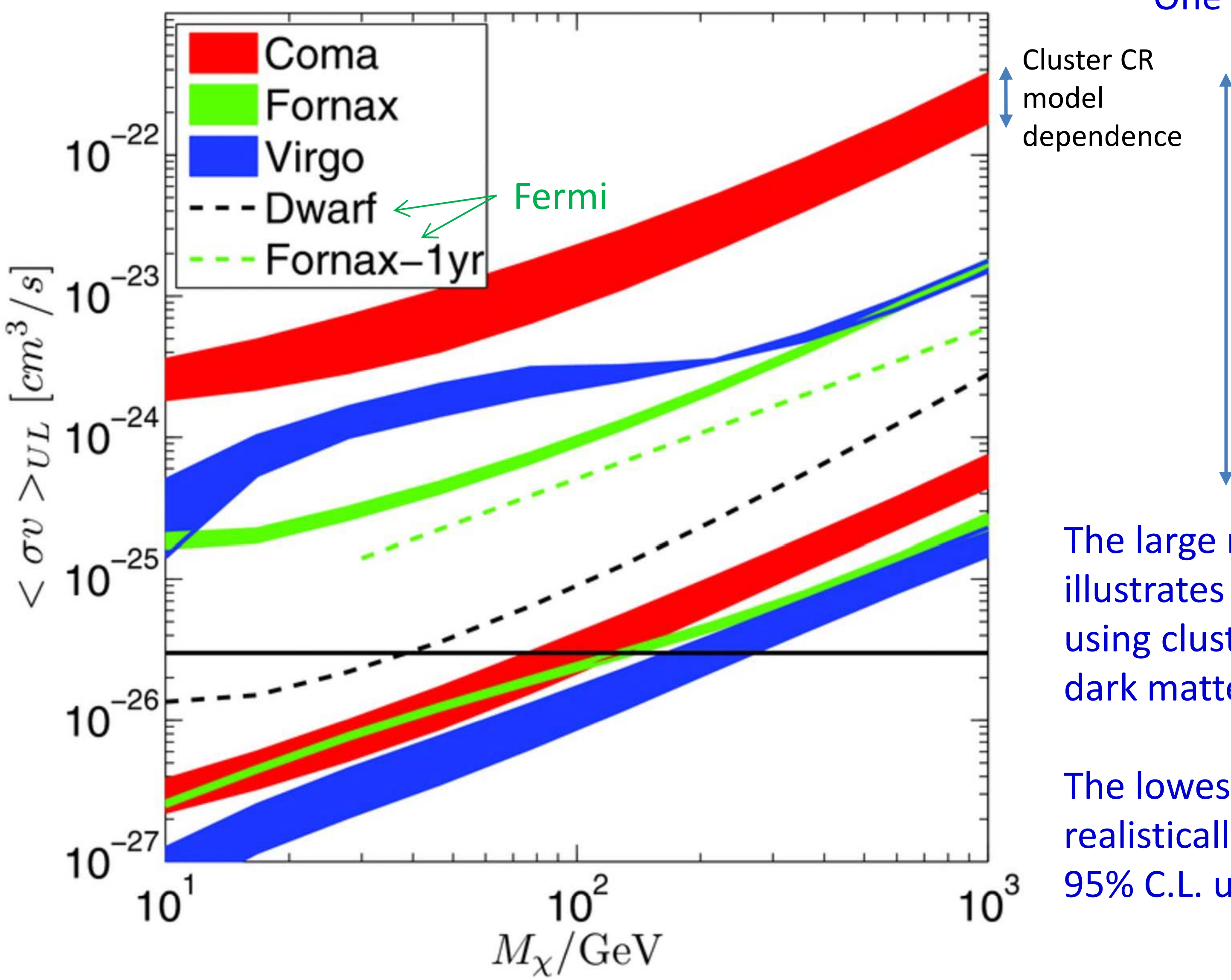
Based on a conservative estimate of substructure boost, assuming clumping only down to the dwarf galaxy level.



- The Fermi-LAT collaboration has not updated this analysis with more data.
- In fact, work in progress on clusters is primarily concerned with detecting signs of cosmic-ray induced gamma-ray production.
- But authors outside of that collaboration have continued this work.

Analysis of 3 Clusters in 45 Months of Data

Han J et al. MNRAS 2012;427:1651-1665



One recent example.

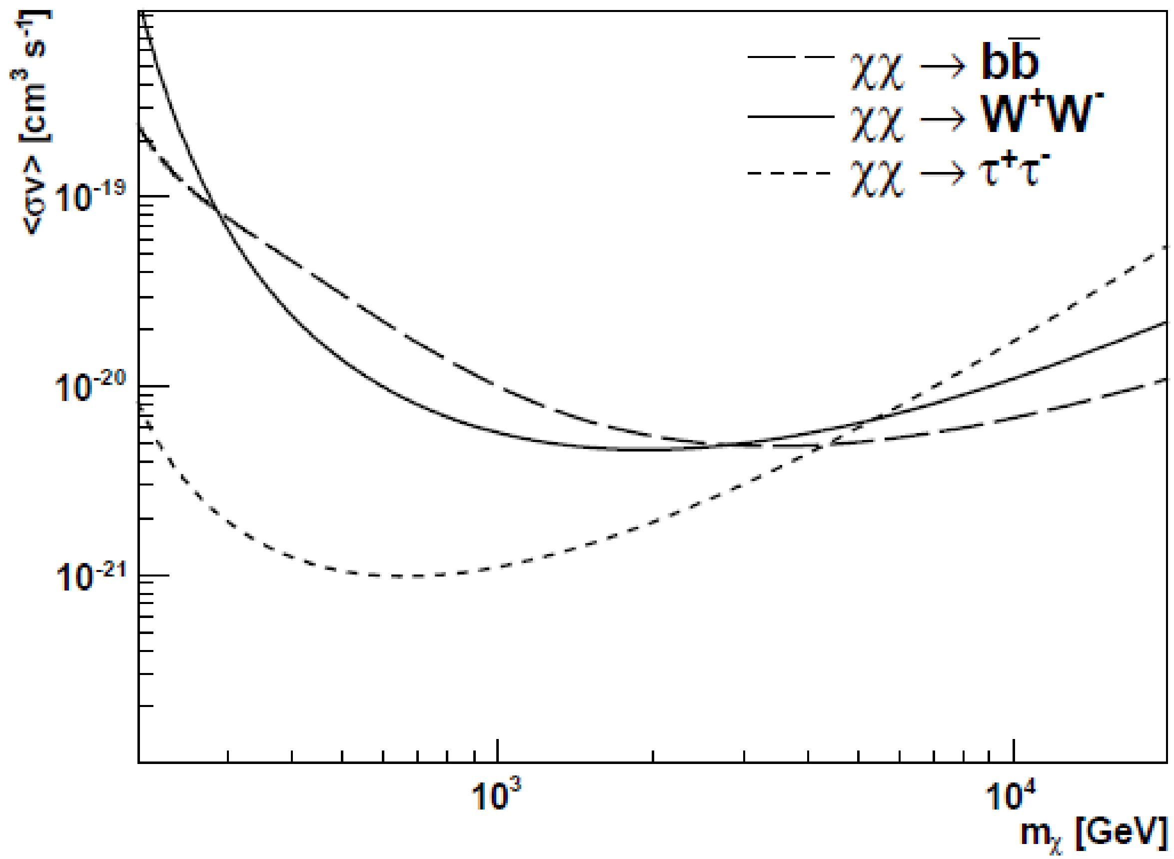
Cluster model dependence; boosts of up to ≈1000

The large model dependence illustrates problems with using clusters to constrain dark matter.

The lowest curves cannot realistically be considered 95% C.L. upper limits!

VERITAS DM Limits from the Coma Cluster

arXiv:1208.0676v1 (3 Aug 2012)



- 18.6 hour observation.
- Conservative limits assuming zero boost from substructure, no CR production, and no Sommerfeld enhancement.

Galactic Center

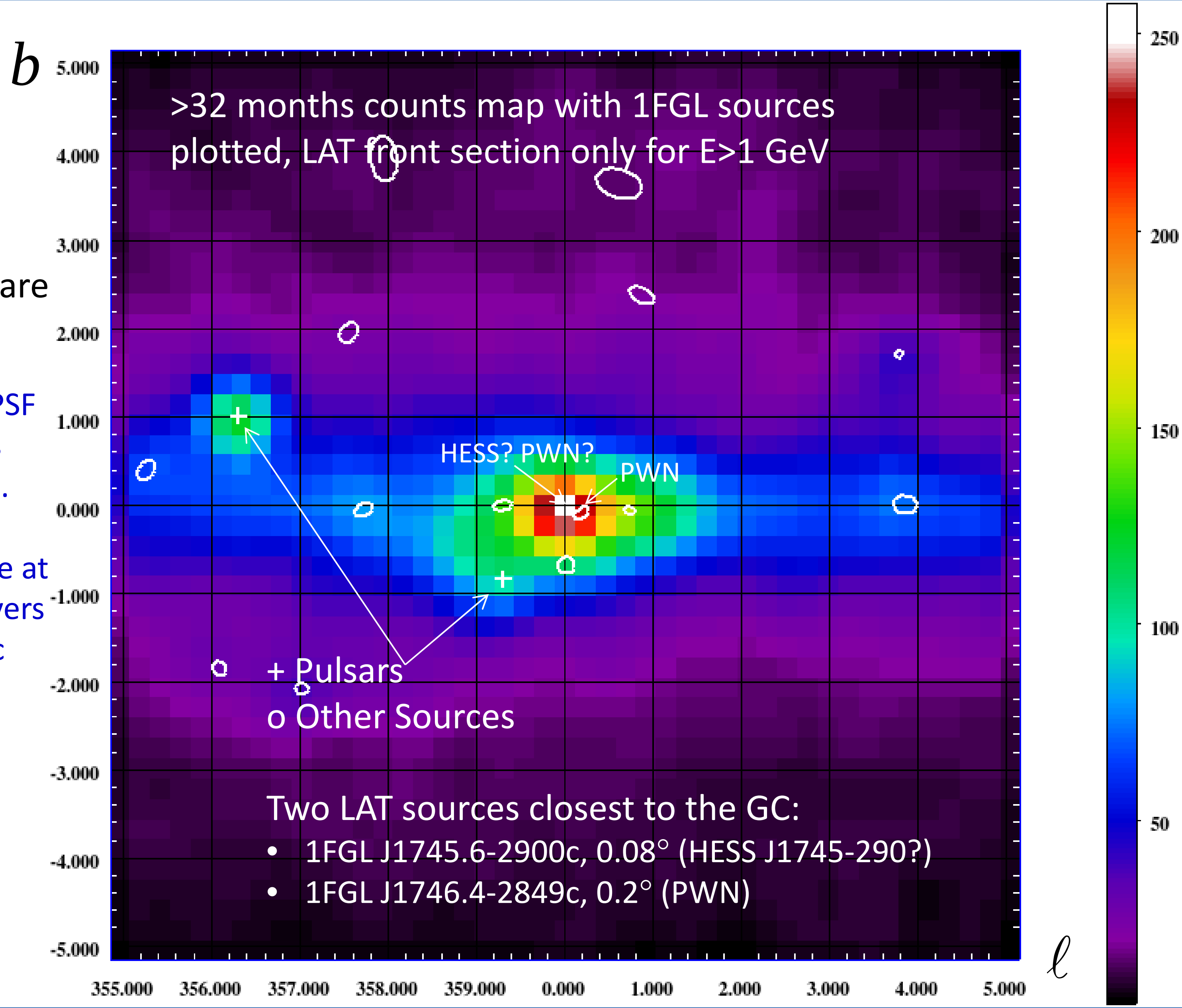
- This is the obvious place to look for dark matter annihilation, as it must have by far the greatest J factor
- But…
  - This region also has by far the greatest astrophysical background, especially in the Fermi-LAT energy range.
    - Searches in the continuum are very hard to interpret.
    - On the other hand, this is the perfect place for line searches.
  - The J factor has a lot of uncertainty, depending on the dark matter distribution.
    - A cusp profile, or a cored profile?
    - Dark-matter-only many-body simulations cannot tell the full story.
    - And baryon interactions could push it either way.

Fermi-LAT Galactic Center View

10° square

LAT front PSF at 1 GeV is about 0.5°.

A 0.5° cone at the GC covers 150 parsec diameter!

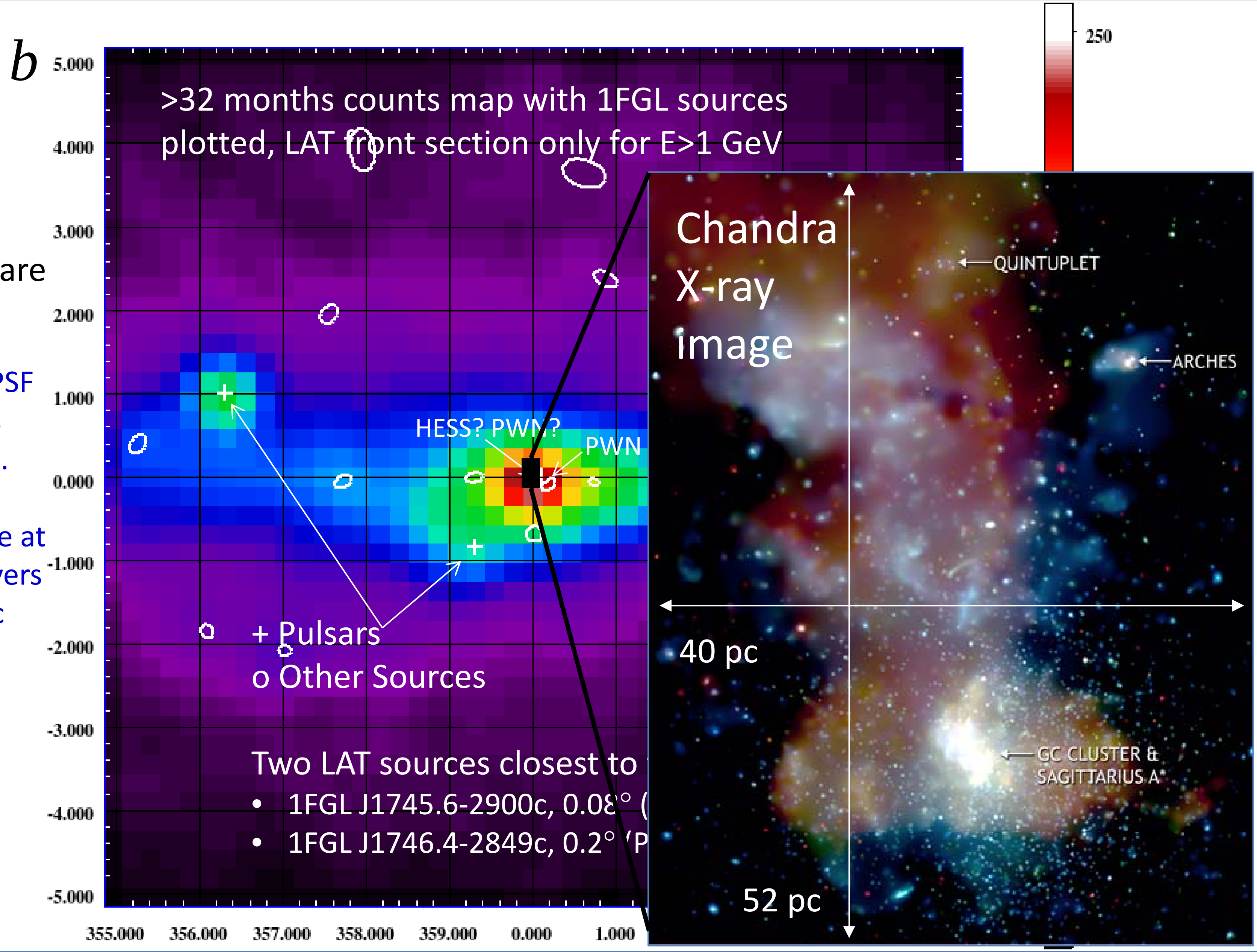


Fermi-LAT Galactic Center View

10° square

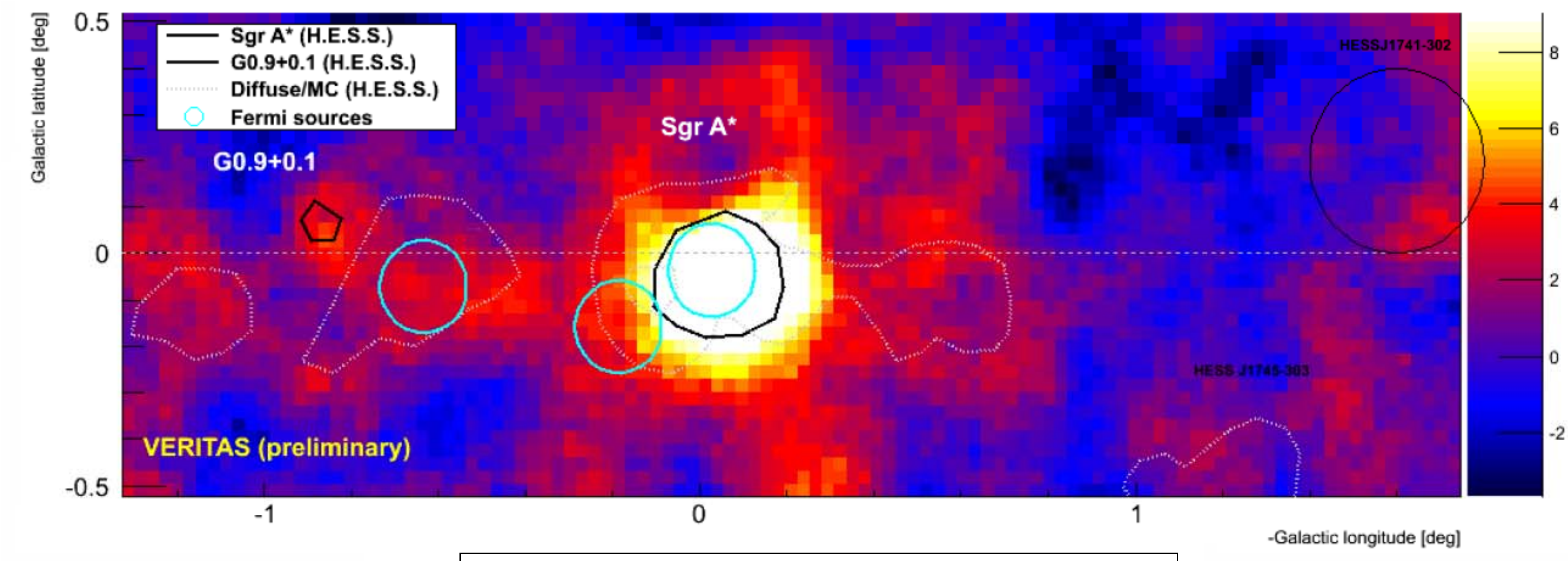
LAT front PSF at 1 GeV is about 0.5°.

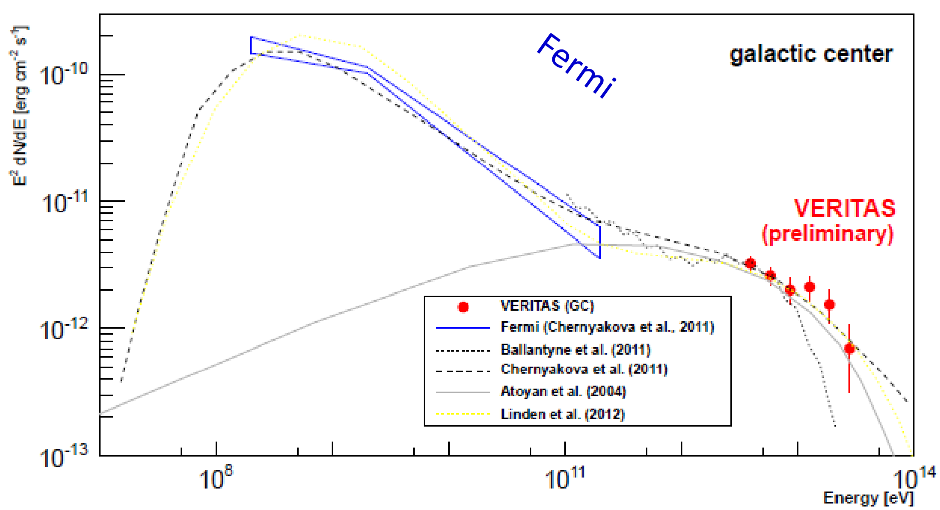
A 0.5° cone at the GC covers 150 parsec diameter!



VERITAS GC Observations

M. Beilicke, arXiv:1210.7832v1



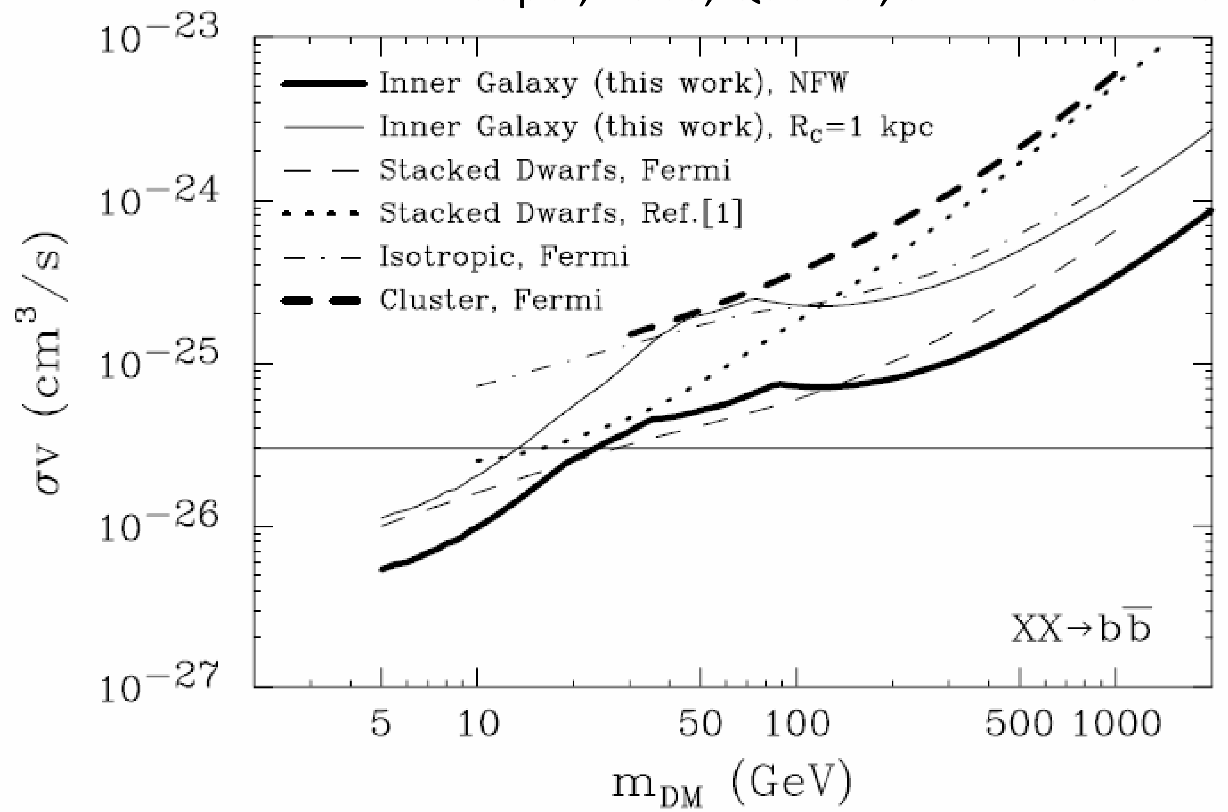


GC Limits from Fermi-LAT Data

- This analysis involves a large but conservative background subtraction (The GC catalog source is *not* subtracted.)
- The limit is similar to the dwarf limit, despite the very large J factor, mainly because there is a substantial unsubtracted excess.

See also the talk this afternoon by German Gomez Vargas.

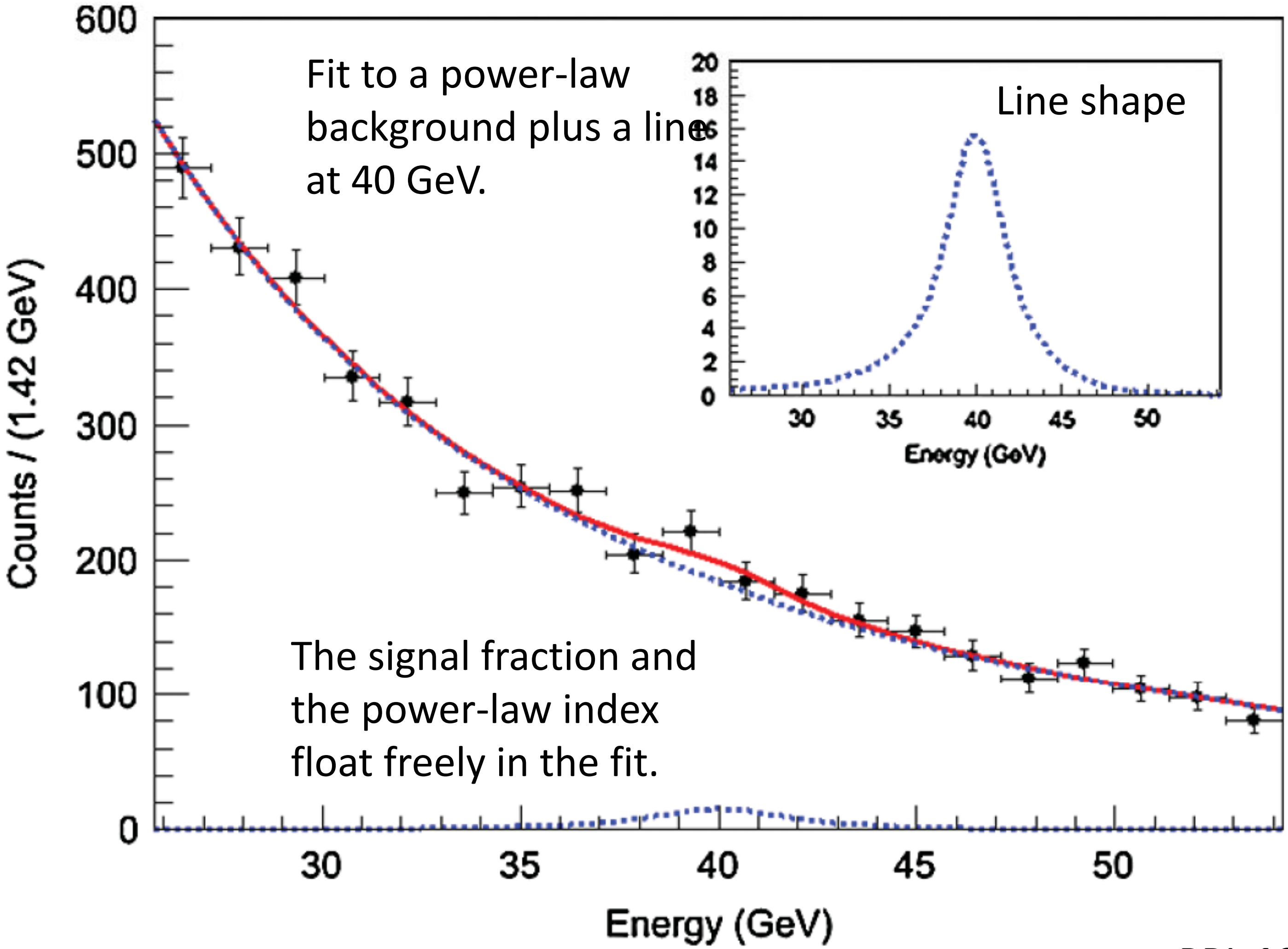
Hooper, Kelso, Queiroz, arXiv:1209.3015



- The same data have also been interpreted by the authors as DM signal!
- e.g. Hooper, Goodenough, Phys. Lett. B697, 412-428, 2011, where a 7 to 10 GeV WIMP is shown to give a good fit to GC data.
- Or Hooper and Linden, Phys Rev D 84, 123005, where the data are interpreted in terms of a 7-12 GeV WIMP annihilating to leptons or a 25-45 GeV WIMP annihilating to hadrons.
- Unfortunately, more mundane explanations can also be found.

Lines

Example LAT fit, at 40 GeV (the fit with the largest line "signal")



11 Months of data

Almost all sky:

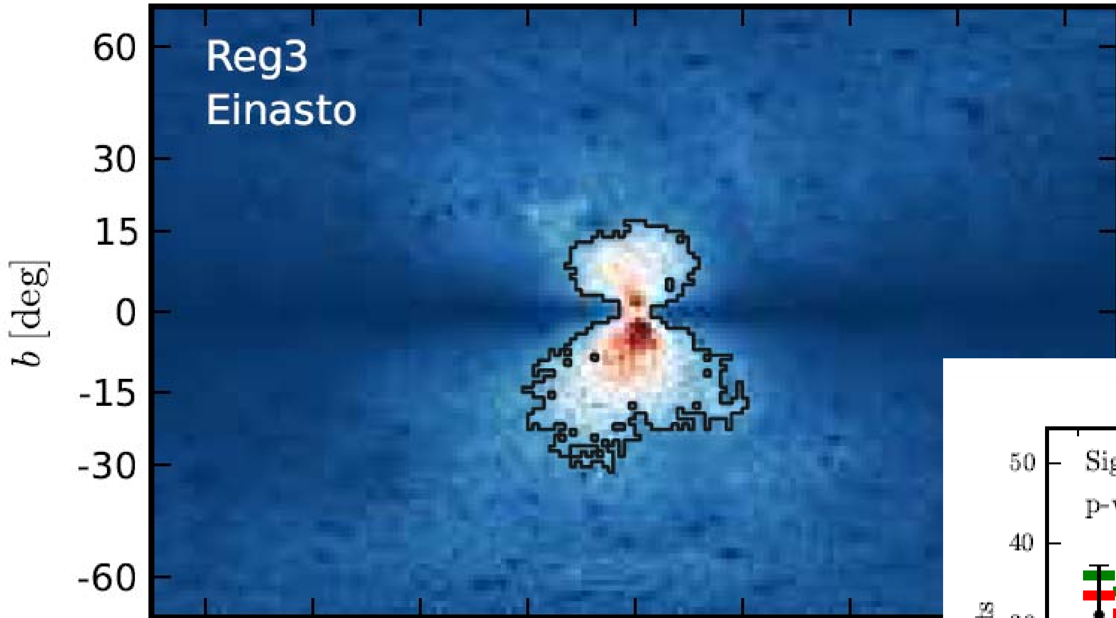
Galactic plane removed, except for Galactic center.

Sources removed by 0.2° cut.

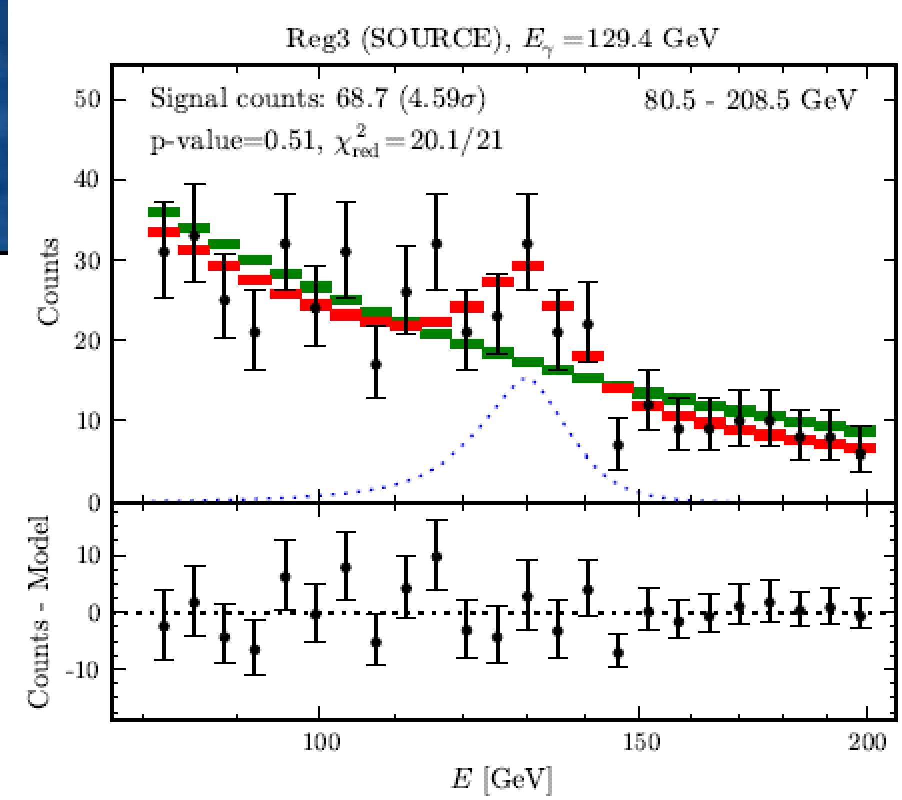
PRL **104**, 091302 (2010)

A Tantalizing Line Signal

C. Weniger, JCAP08 (2012) 007



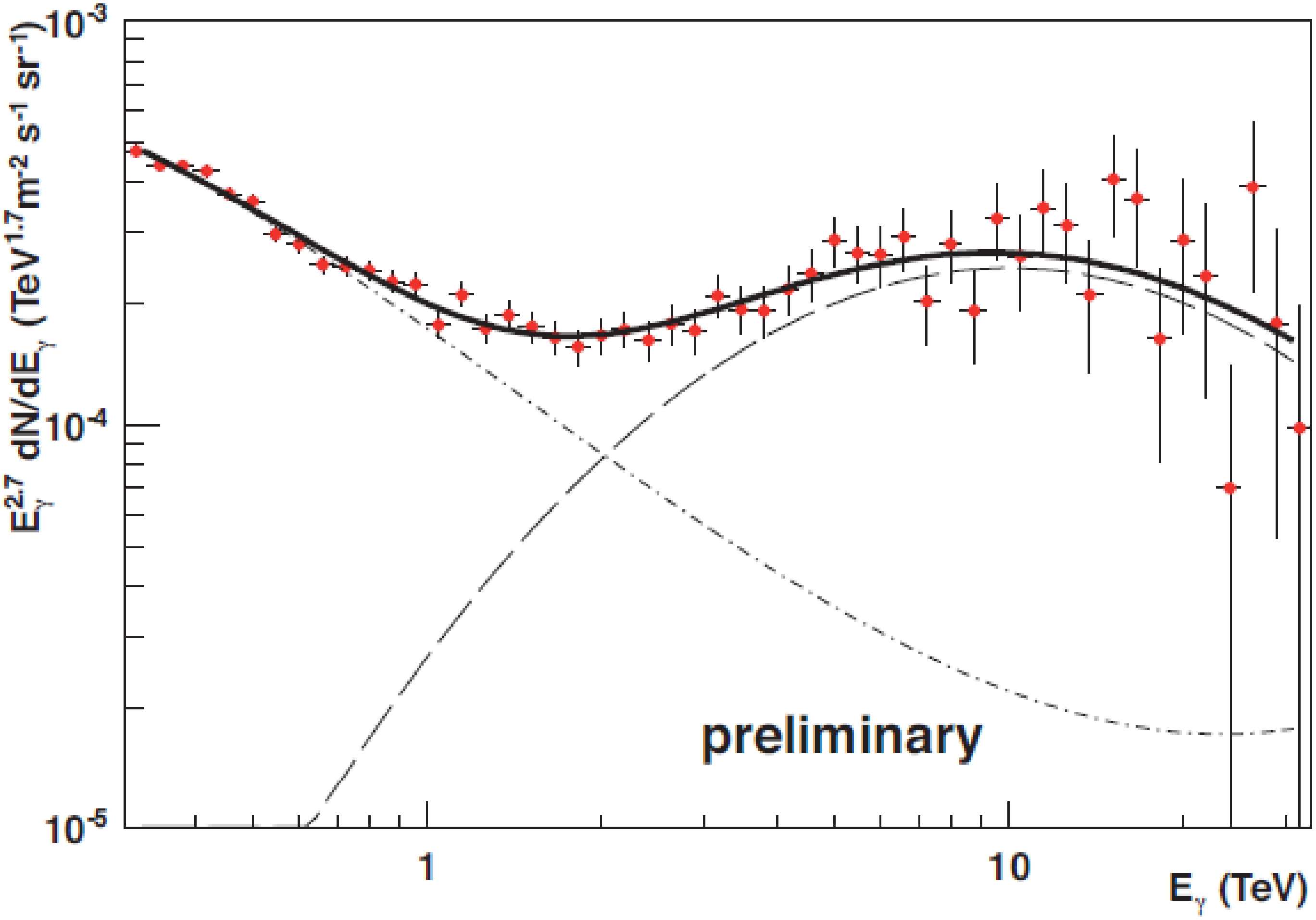
- One of five trial regions analyzed, in this case with an Einasto profile assumed for the DM.
- For each region, two photon selections were considered: “source” and “ultraclean”.



- In 2012 Weniger reminded us that we should concentrate on the GC for line searches, and he included 43 months of data.
- He defined regions that optimized the ratio of DM signal to background for several assumed DM profiles.
- A marginal signal (3.2σ with trials) showed up at around 130 GeV.

H.E.S.S. Line Search

van Eldik and Nekrassov, AIP Conf. Proc. 1505, pp. 474-477, Gamma 2012,

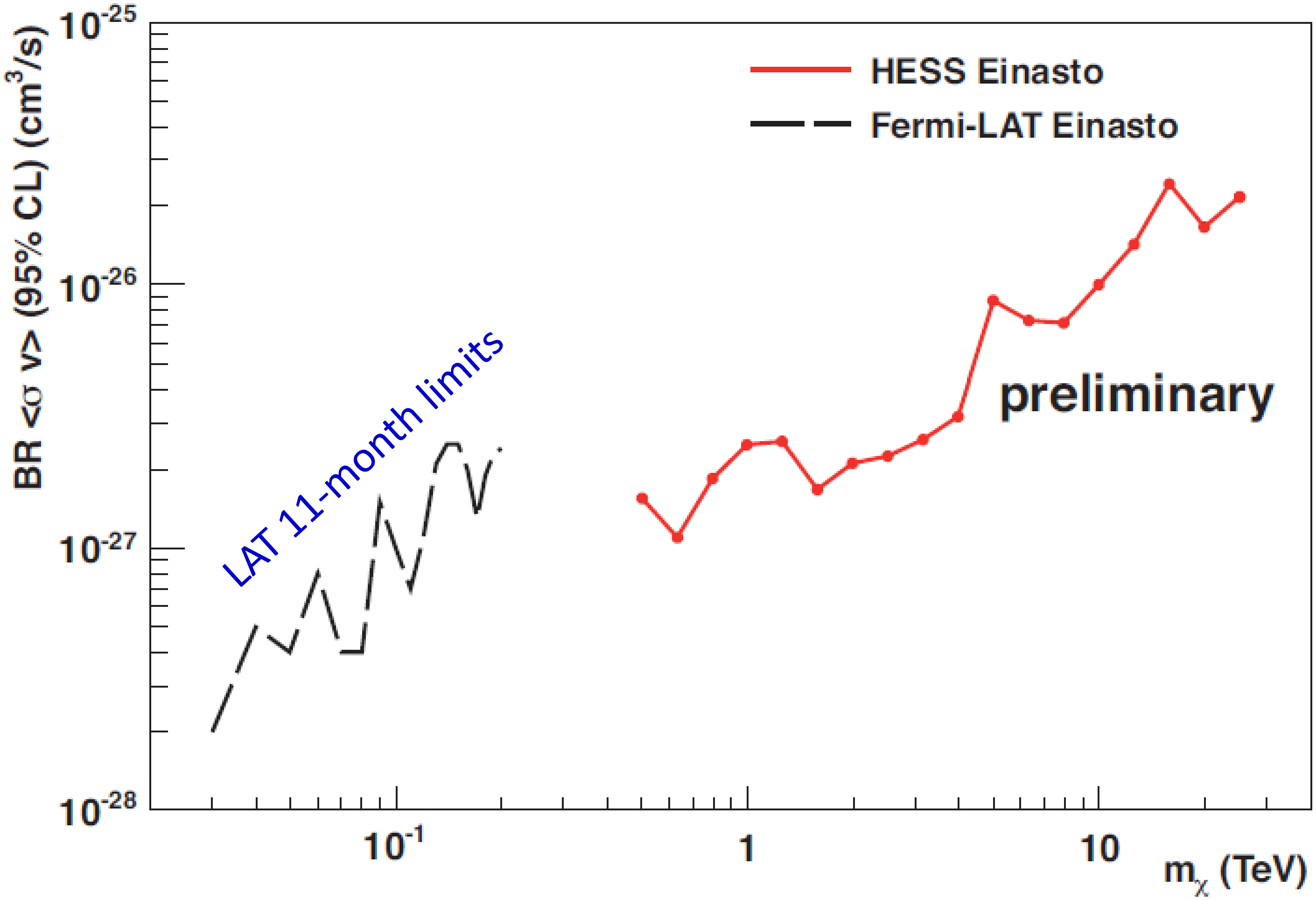


112 hours of H.E.S.S. I observations of a 1° radius circle about the Galactic center.

130 GeV is off the scale to the left.

H.E.S.S. Line Search

van Eldik and Nekrassov, AIP Conf. Proc. 1505, pp. 474-477, Gamma 2012,



112 hours of H.E.S.S. I observations of a 1° radius circle about the Galactic center.

Question: could the new big H.E.S.S. II telescope see a 130 GeV line?

Line Follow-Up

- Weniger's observation was confirmed by many people.
  - Simpler, geometric ROI selections show the same bump.
  - Data are consistent with 2 lines ($\gamma\gamma$ and γZ).
- Claims of the same signal in 18 galaxy clusters (Hektor, Raidal, Tempel, arXiv:1207.4466), but I'm very skeptical of that one…
  - Would have to believe in boost factors of several thousand.
  - 5° ROI radius is much larger than most clusters, while the LAT psf at 130 GeV is $\approx 0.1^\circ$. Smaller ROI do not enhance the S/N.
- Null result from a line search in dwarfs (Geringer-Sameth & SMK, PRD 021302(R) (2012))
- Conflicting claims of a 130 GeV line in Earth limb data.
- Adding a fifth year of data does not increase the significance but also does not rule out a signal.
- A recently submitted paper by the LAT collaboration analyzes the Pass-7 reprocessed data
  - Smaller significance seen.
  - 2-D analysis to account for photon-by-photon energy reconstruction quality does not enhance the signal.
  - The peak appears to be a bit too narrow for the known PSF.
  - **See the talk by Andrea Albert tomorrow afternoon.**

Line Prospects

- The LAT may begin galactic-center biased observations toward the end of this year, which would significantly decrease the time needed to obtain an additional significant data sample.
- As we speak the LAT collaboration is reprocessing all of the data through “Pass-8”, a new reconstruction code that will enhance the effective area and performance.
- The Pass-8 reconstruction will enable analyses of photons that convert in the calorimeter, leaving no tracks.
  - Above 20 GeV the trigger is fully efficient for such photons.
  - For 100 GeV photons, the angular resolution for sky positions derived from the calorimeter cluster is not much worse than those derived from tracks and is certainly sufficient for Galactic-center observations.
  - Completion of background analysis cuts will immediately yield a ≈50% increase in statistics at 130 GeV.

Conclusions

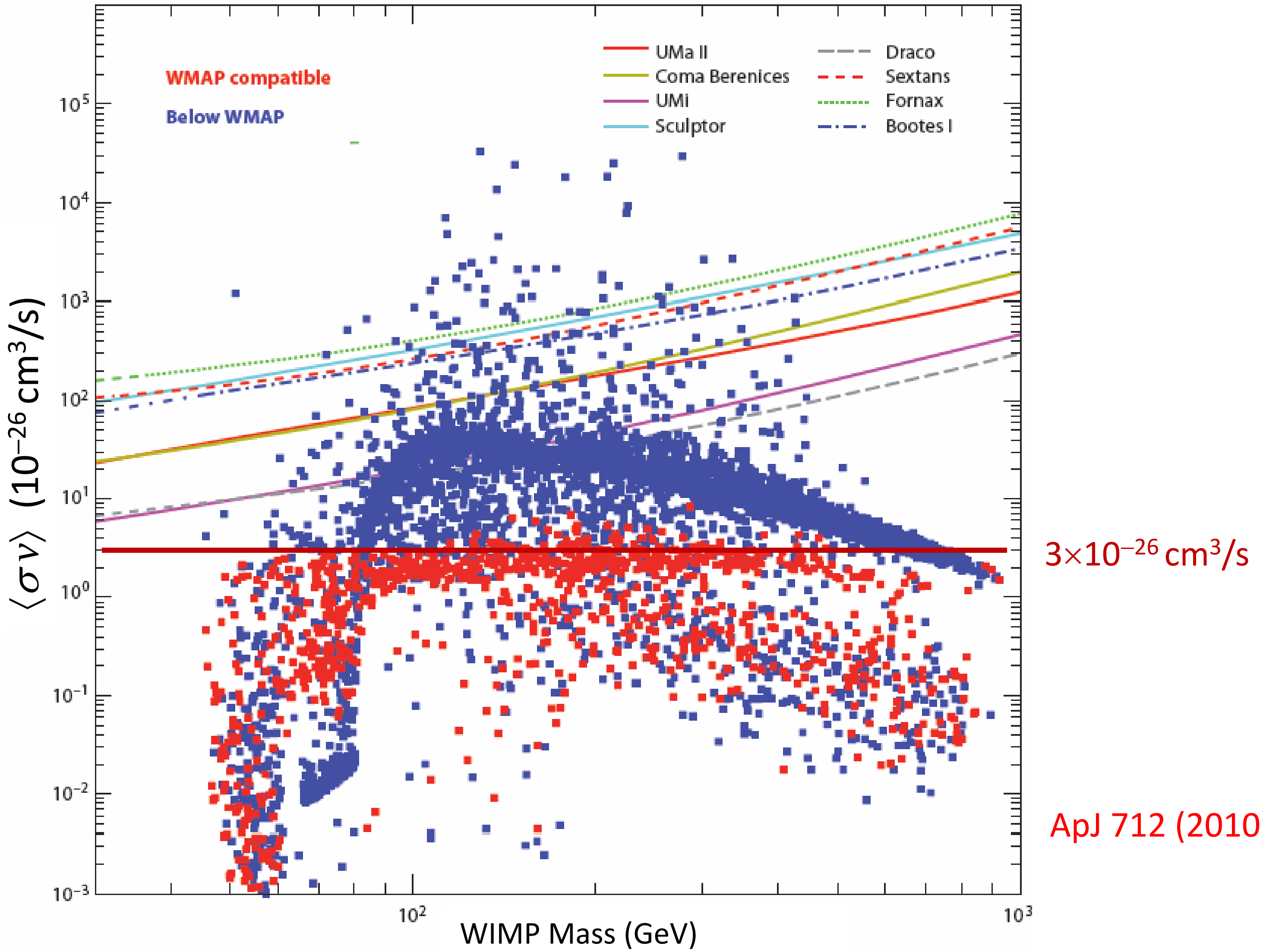
- We have a lot of published DM annihilation and decay limits from gamma-ray observations, but…
  - At the canonical thermal-relic cross section, only WIMP masses below 10 to 20 GeV are convincingly ruled out by these observations,
  - And still the theorists have a lot of wiggle room there in specific theories, such as MSSM.
- There have also been a number of claims of detection based on Fermi-LAT data, but…
  - More mundane explanations are easy to find in the continuum, especially in the confusing Galactic center region.
  - A confirmed line at 130 GeV would be spectacular, if Nature would only make us so lucky.
    - Some further observations and analyses since the original paper have bolstered the positions of the doubters, but a line is not ruled out.
    - A larger Fermi-LAT dataset will either confirm or rule this out over the next year.
- See the next talk for prospects of discovering particle dark matter in future gamma-ray observations.

Abstract

Indirect detection of particle dark matter through its annihilation or decay to gamma rays is complementary to direct searches by terrestrial experiments as well as to direct detection of dark-matter particle candidates at accelerator experiments. Many searches have been made using orbiting gamma-ray telescopes and ground-based atmospheric-Cherenkov telescopes. Experiments have looked for narrow lines from exclusive $\gamma\gamma$ or γZ production as well as for inclusive gamma production in quark or vector-boson final states. The searches have looked at the Galactic center, local dwarf galaxies, unassociated gamma-ray sources, nearby galaxy clusters, diffuse emission from our Galaxy, and extragalactic isotropic diffuse emission. The strongest limits have come from observations of dwarf spheroidal galaxies, while the most tantalizing hint of a signal has come from line searches around the Galactic center. This presentation will summarize the present experimental status and the outlook for further observations.

Fermi-LAT Dwarf Limits from 11 Months of Data

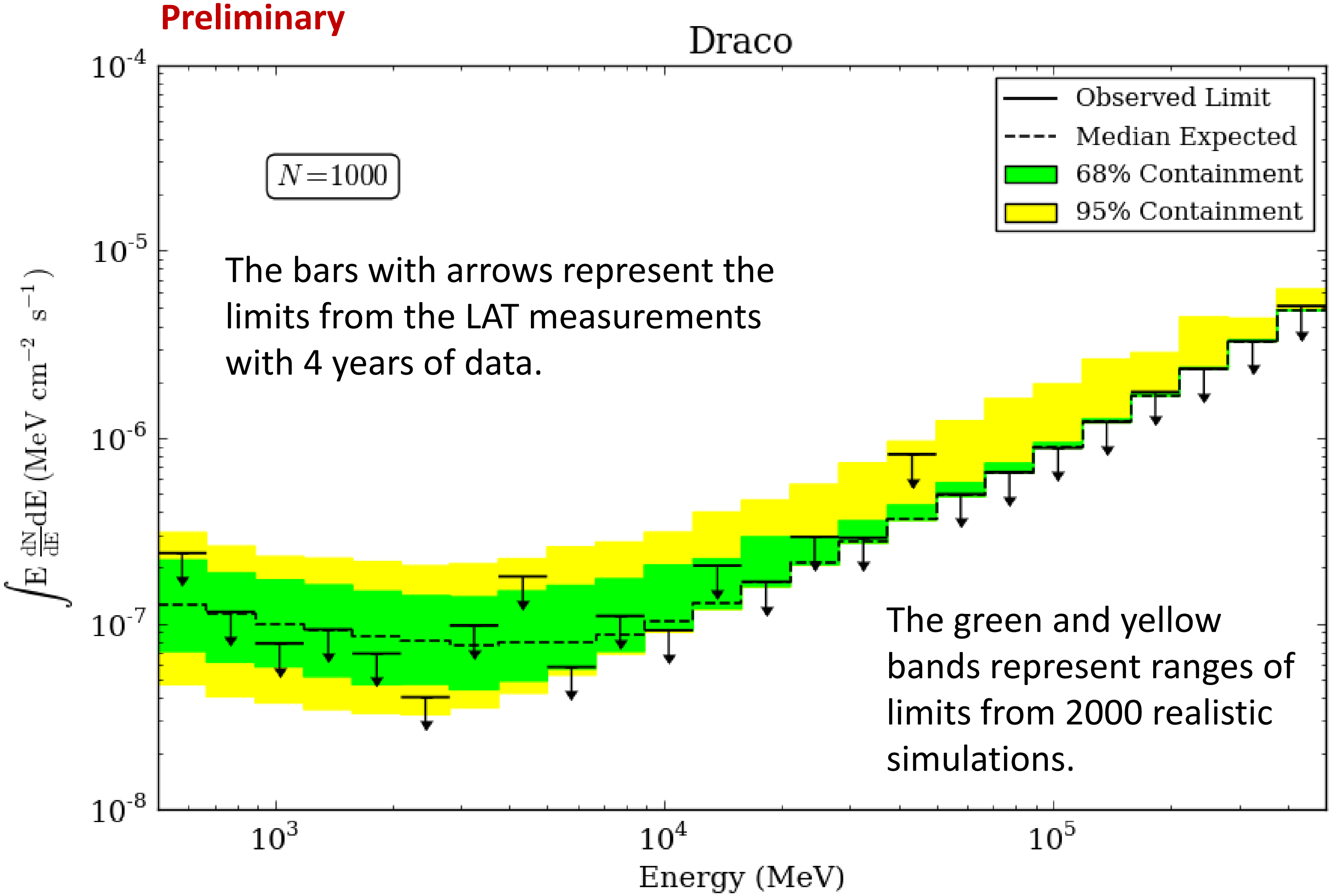
- Red points are MSSM models with a cosmological WIMP thermal relic density compatible with WMAP data.



ApJ 712 (2010) 147.

Fermi-LAT Example Flux Limit

Preliminary



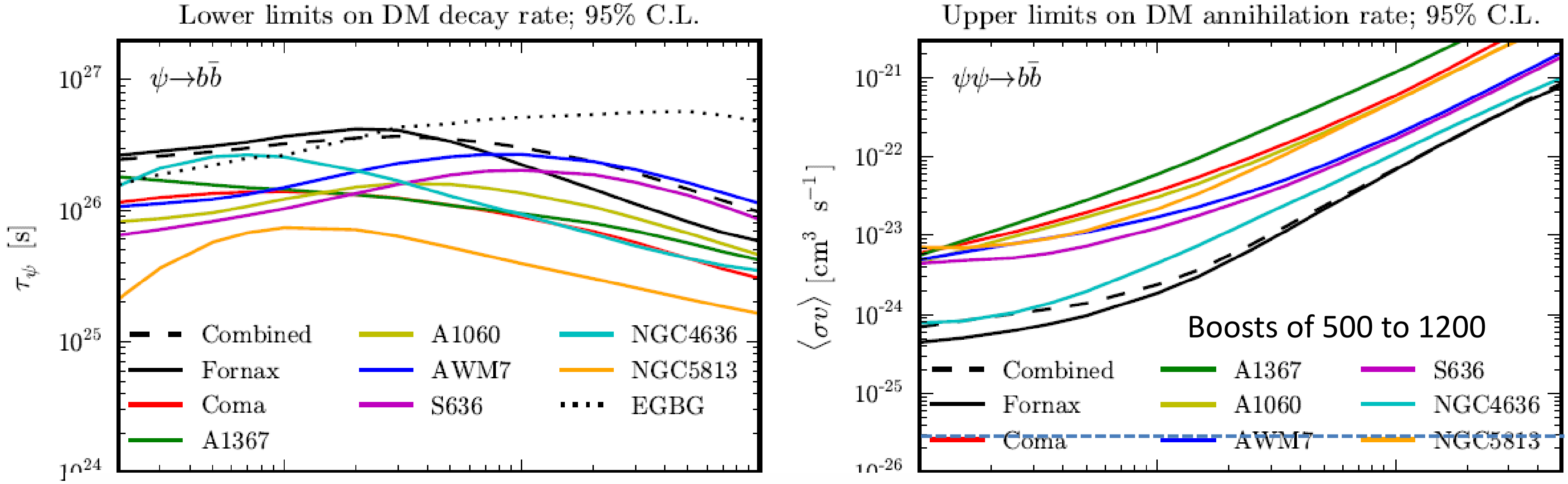
The bars with arrows represent the limits from the LAT measurements with 4 years of data.

The green and yellow bands represent ranges of limits from 2000 realistic simulations.

Alex Drlica-Wagner, Stanford Ph.D. Thesis, 2013

Cluster Analysis from 3 Years of LAT Data

Huang, Vertongen, Weniger, JCAP01 (2012) 042



Cluster	R.A.	Dec.	z	$J^{\rm dec.}_{\Delta\Omega}$ [10^{18} GeV cm^{-2}]	$J^{\rm ann.}_{\Delta\Omega}$ [10^{17} GeV^2 cm^{-5}]	θ_s [°]
Fornax	54.67	−35.31	0.0046	$20.3^{+4.6}_{-6.8}$	$8.8^{+2.0}_{-2.8}$	$0.44^{+0.07}_{-0.11}$
Coma	194.95	27.94	0.0232	$10.7^{+1.8}_{-2.7}$	$1.3^{+0.20}_{-0.31}$	$0.23^{+0.02}_{-0.04}$
A1367	176.19	19.70	0.0216	$10.6^{+1.3}_{-2.9}$	$1.4^{+0.15}_{-0.34}$	$0.23^{+0.02}_{-0.04}$
A1060	159.18	−27.52	0.0114	$10.2^{+2.0}_{-3.5}$	$2.2^{+0.38}_{-0.69}$	$0.24^{+0.03}_{-0.06}$
AWM7	43.62	41.58	0.0172	$9.9^{+1.9}_{-3.9}$	$1.6^{+0.27}_{-0.56}$	$0.22^{+0.03}_{-0.06}$
S636	157.52	−35.31	0.0116	$6.8^{+1.5}_{-1.7}$	$1.5^{+0.29}_{-0.34}$	$0.18^{+0.03}_{-0.03}$
NGC4636	190.71	2.69	0.0037	$6.1^{+0.80}_{-1.7}$	$3.5^{+0.39}_{-0.85}$	$0.19^{+0.02}_{-0.04}$
NGC5813	225.30	1.70	0.0064	$6.0^{+4.6}_{-4.2}$	$2.2^{+1.4}_{-1.4}$	$0.18^{+0.08}_{-0.10}$

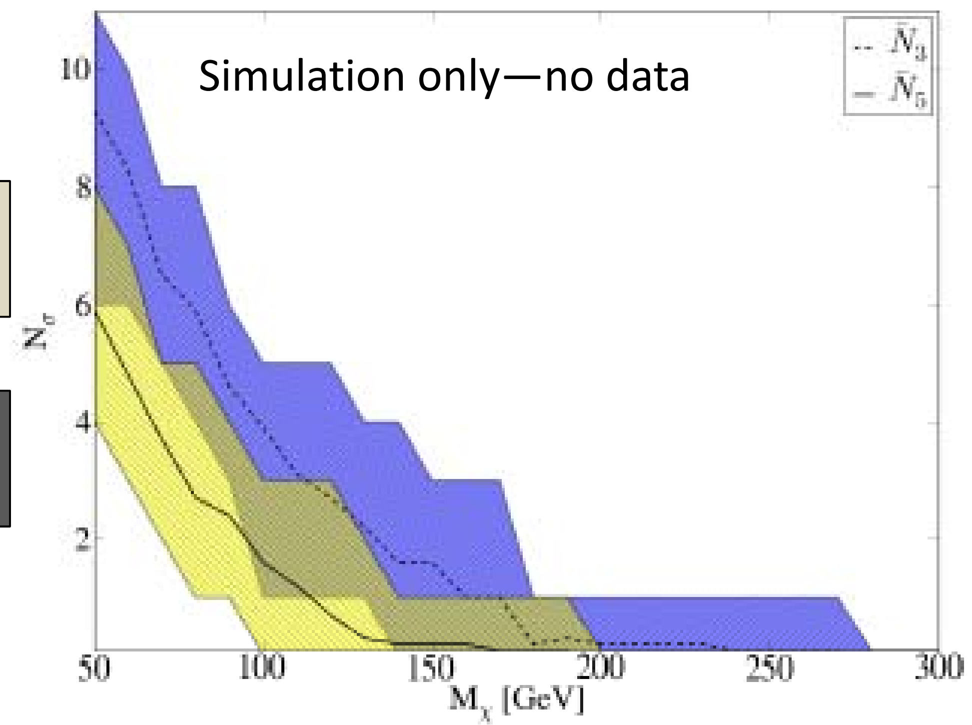
Dark Satellites

- Via Lactea-2 simulation of the DM galaxy (Nature 454, 735)
  - Including a boost for unresolved substructure
  - Sample 10 viewing points 8 kpc from the Galactic center
- WIMP annihilation to b,b-bar using Dark-SUSY (JCAP 0407, 008)
  - Nominal expected thermal WIMP cross section: 3×10^{-26} cm^3/s
- MC simulation of the Fermi-LAT instrument response
- *10 year* observation time

Expected number of DM halo objects visible at 3 std. dev. significance.

Expected number of DM halo objects visible at 5 std. dev. significance.

80 kpc



B. Anderson et al., Ap. J. 718 (2010) 899.

Fermi-LAT Dark Satellite Search

- Start with LAT catalog and non-catalog source candidates out of the Galactic plane.
  - Eliminate sources with identified counterparts, and transient sources.
  - Require a non-power-law spectrum.
    - *This alone still leaves a large pulsar & AGN background, especially MSP.*
  - Require some spatial extension.
- No sources passed this selection in the first year of data, yielded a limit of 2×10^{-24} cm^2/s for a 100 GeV WIMP.
- A more complete search with 3 or more years of data is in progress. *See the UCSC Ph.D. thesis of Sheridan Zalewski.*