The future of indirect dark matter searches

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WIN 2015

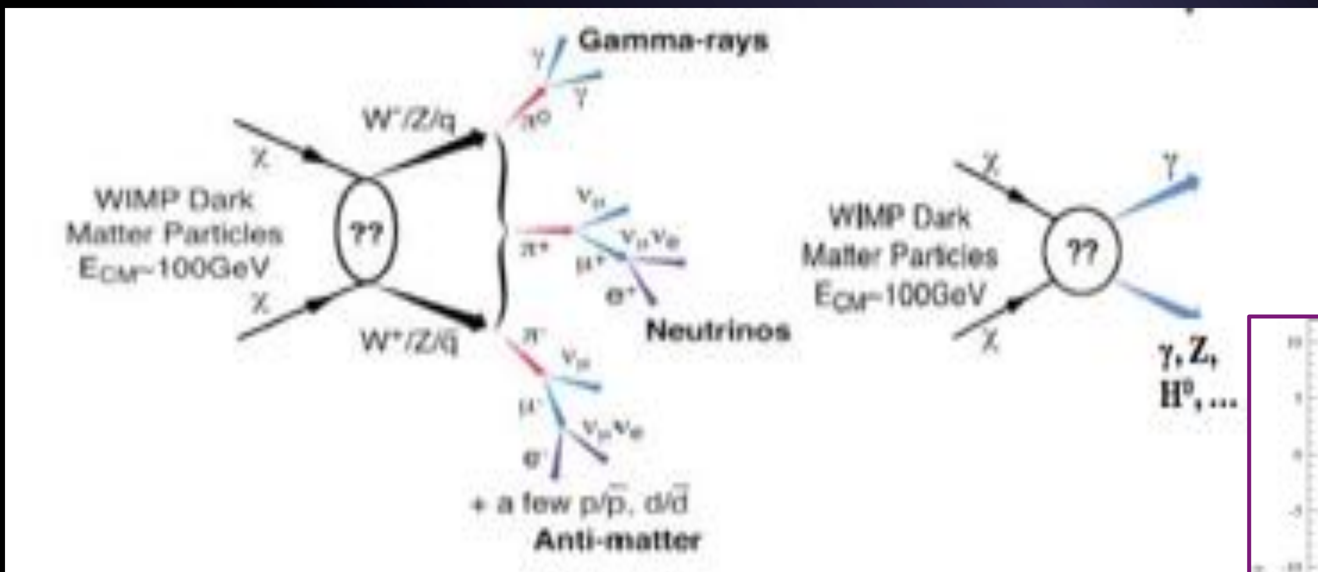
Heidelberg, June 12th 2015

Overview

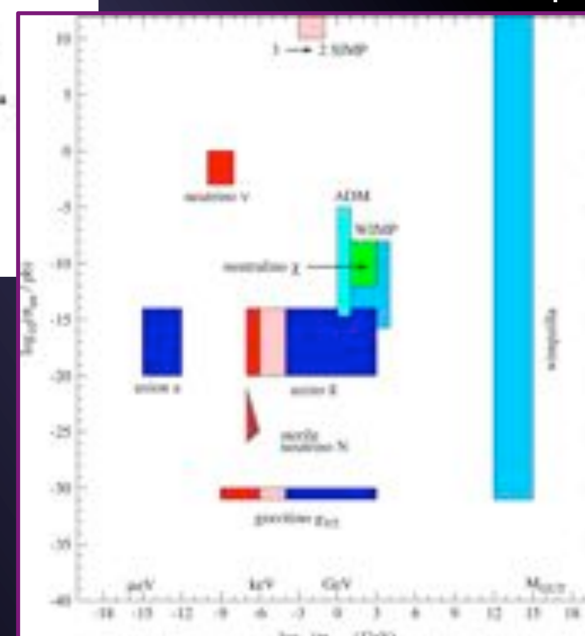
A. **Direct detection:** scattering of DM particles on target nuclei (nuclei recoil expected).

B. **Indirect detection:** DM annihilation products (neutrinos, positrons, gammas…)

C. **Direct production** of DM particles at the lab.



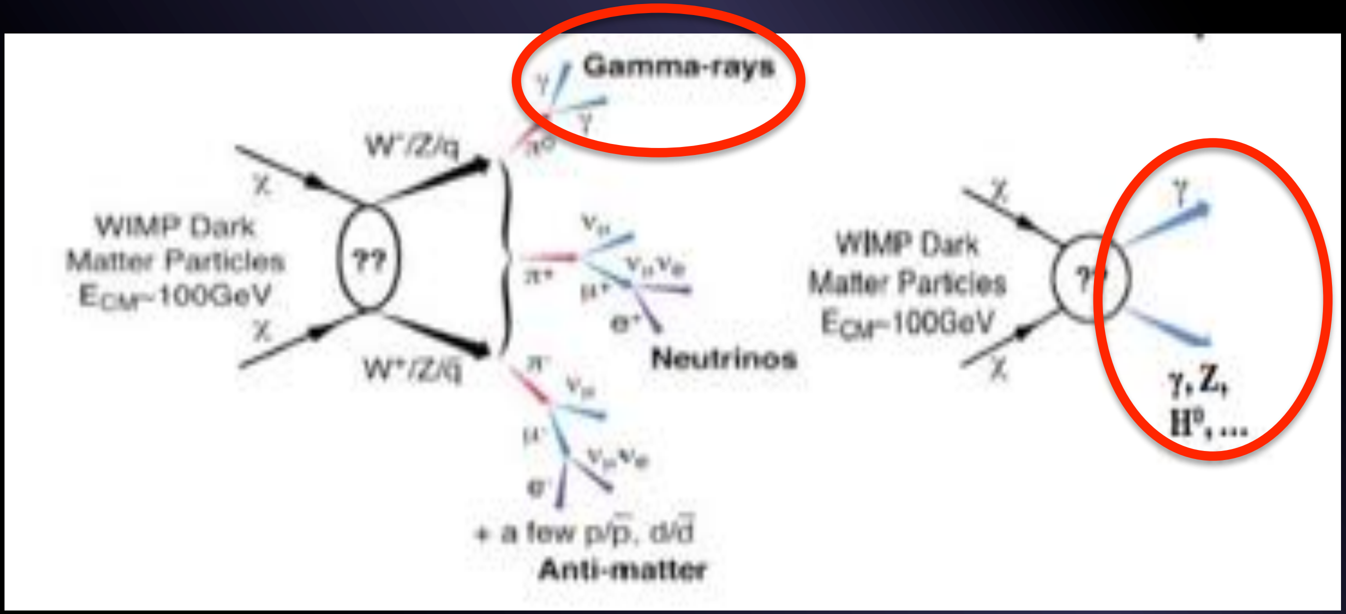
Baer+14



This talk:

WIMP annihilations.
Special attention to gammas.

The 'golden channel': GAMMAS



Why gammas?

✓Energy scale of annihilation products set by DM particle mass

→ favored models ~GeV-TeV

✓Gamma-rays travel following straight lines

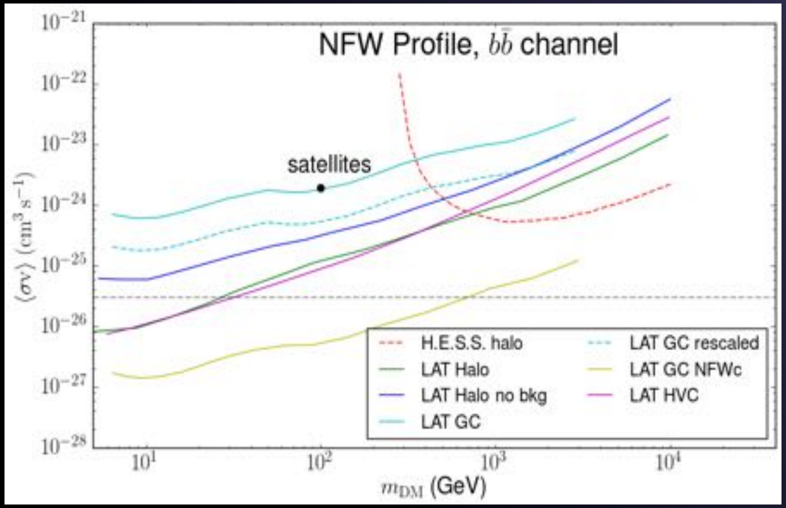
→ source can be known

✓[In the local Universe] Gamma-rays do not suffer from attenuation

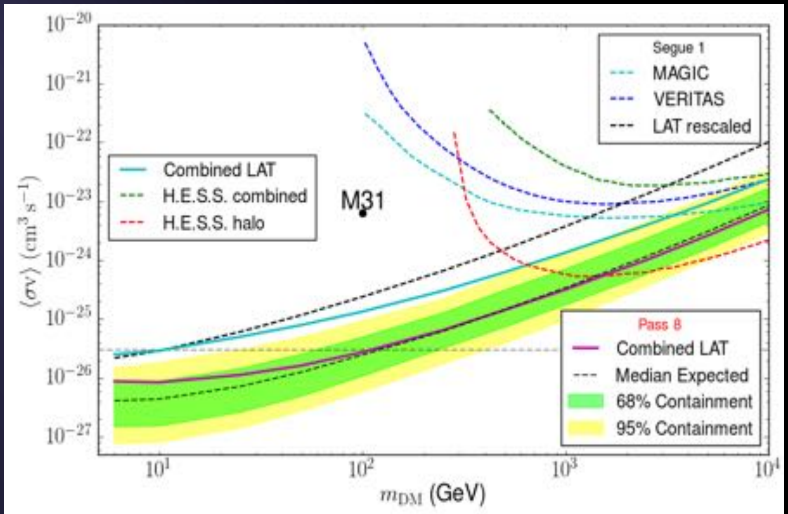
→ spectral information retained.

DM limits: current status

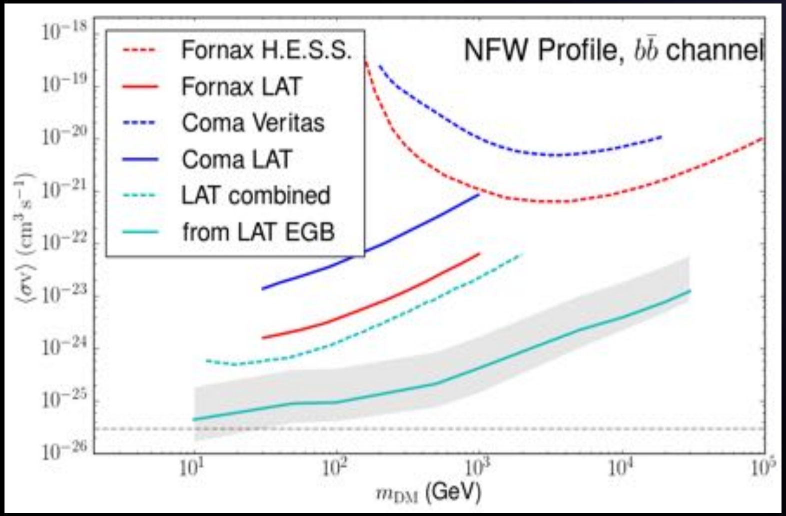
[Conrad 14]



Galactic Center and Halo



Dwarf galaxies and GC halo

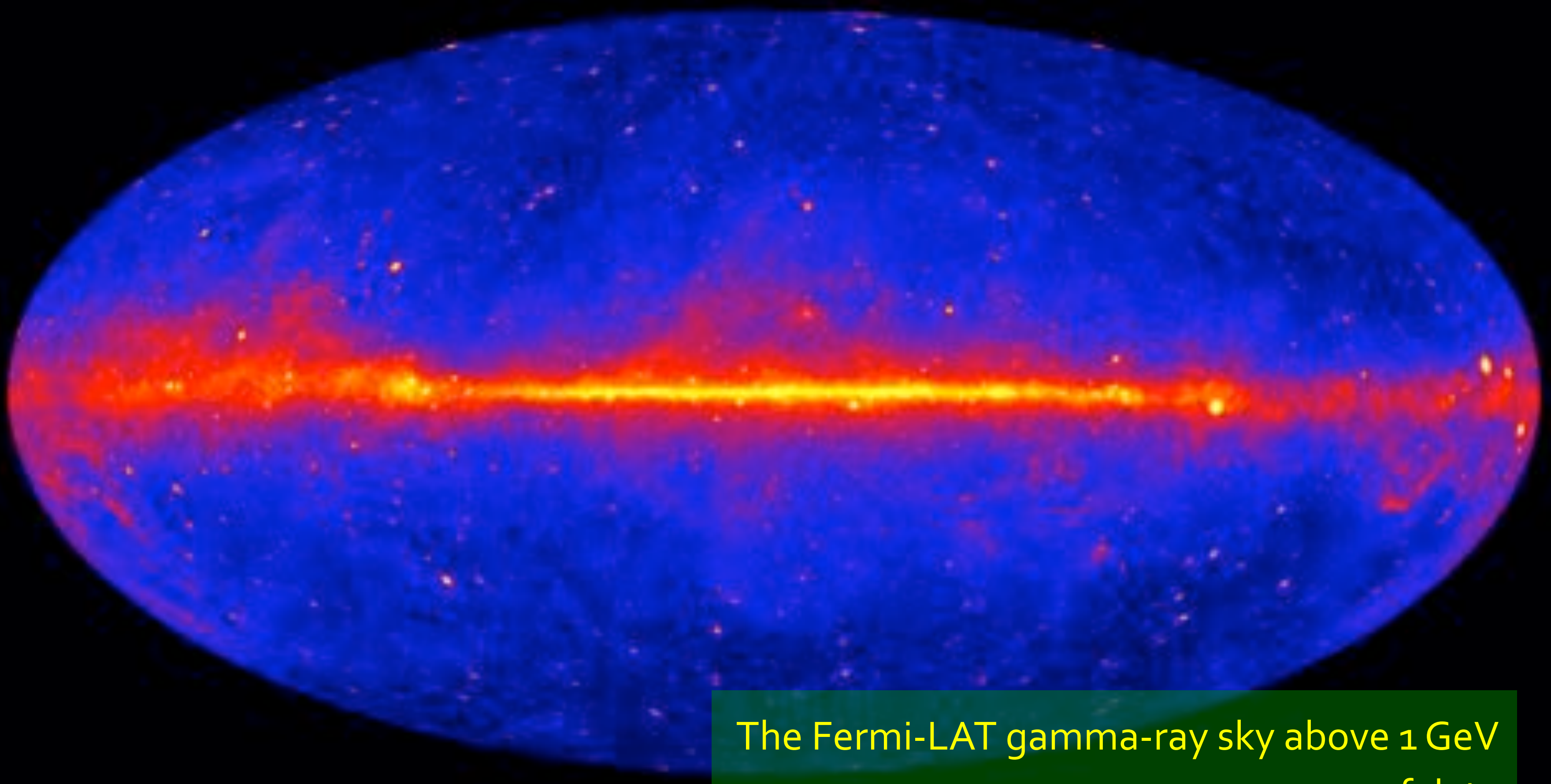


Galaxy clusters and extragalactic background

- ✓ Many different astrophysical targets.
- ✓ Fermi-LAT leading the field.
- ✓ IACTs better in the TeV regime.
- ✓ Starting to touch the relevant part of the parameter space

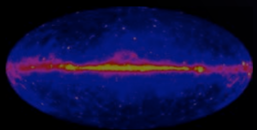
How to improve upon these results?

Needs and challengues



The Fermi-LAT gamma-ray sky above 1 GeV
5 years of data

The complexity of the γ-ray sky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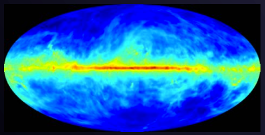
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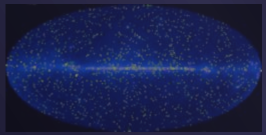
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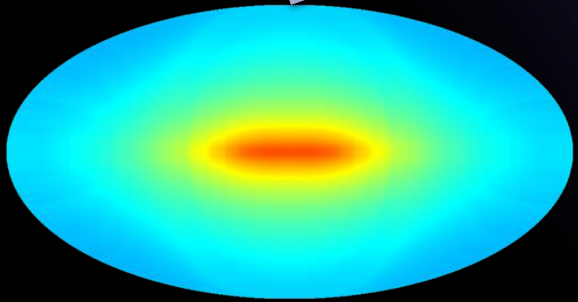
+ ???

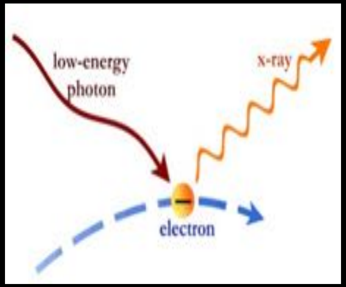
Galactic

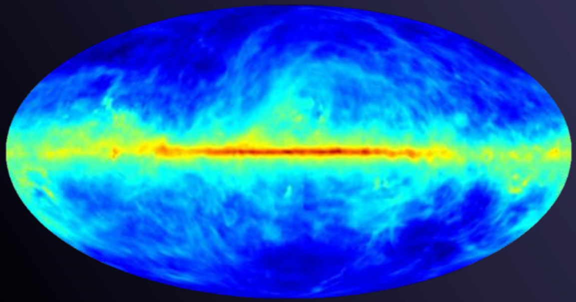
Point Sources

Isotropic

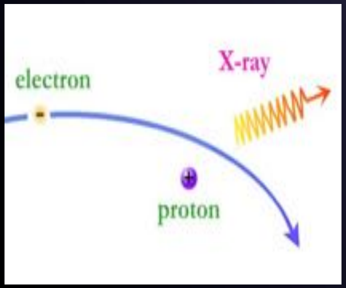


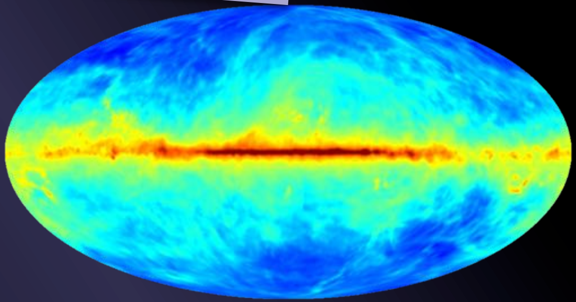
Inverse Compton



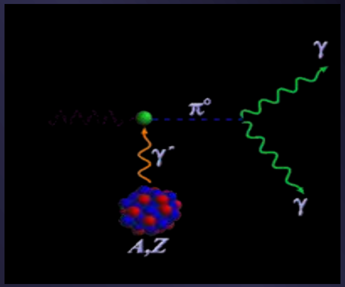


Bremsstrahlung

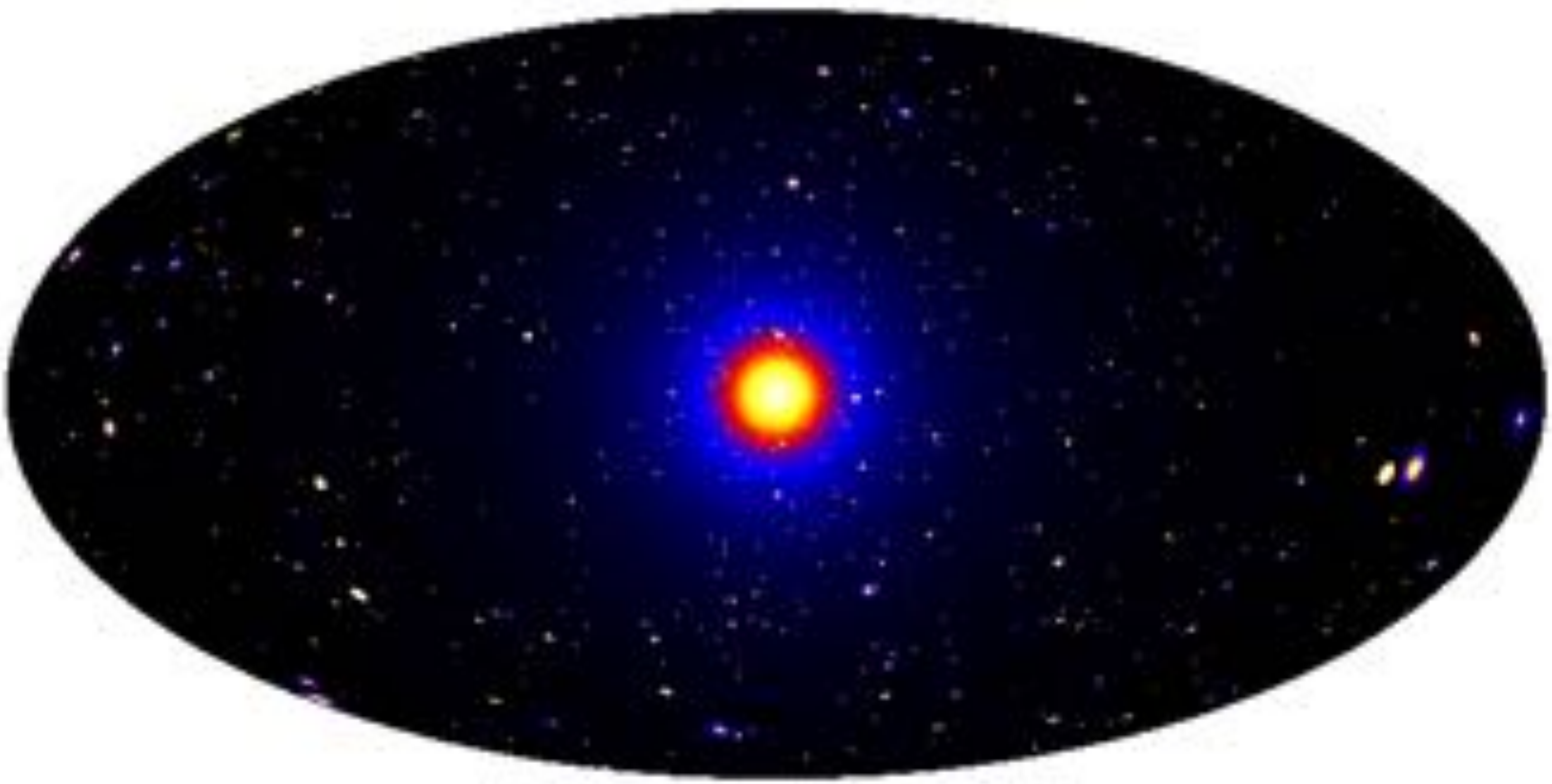




π^o decay

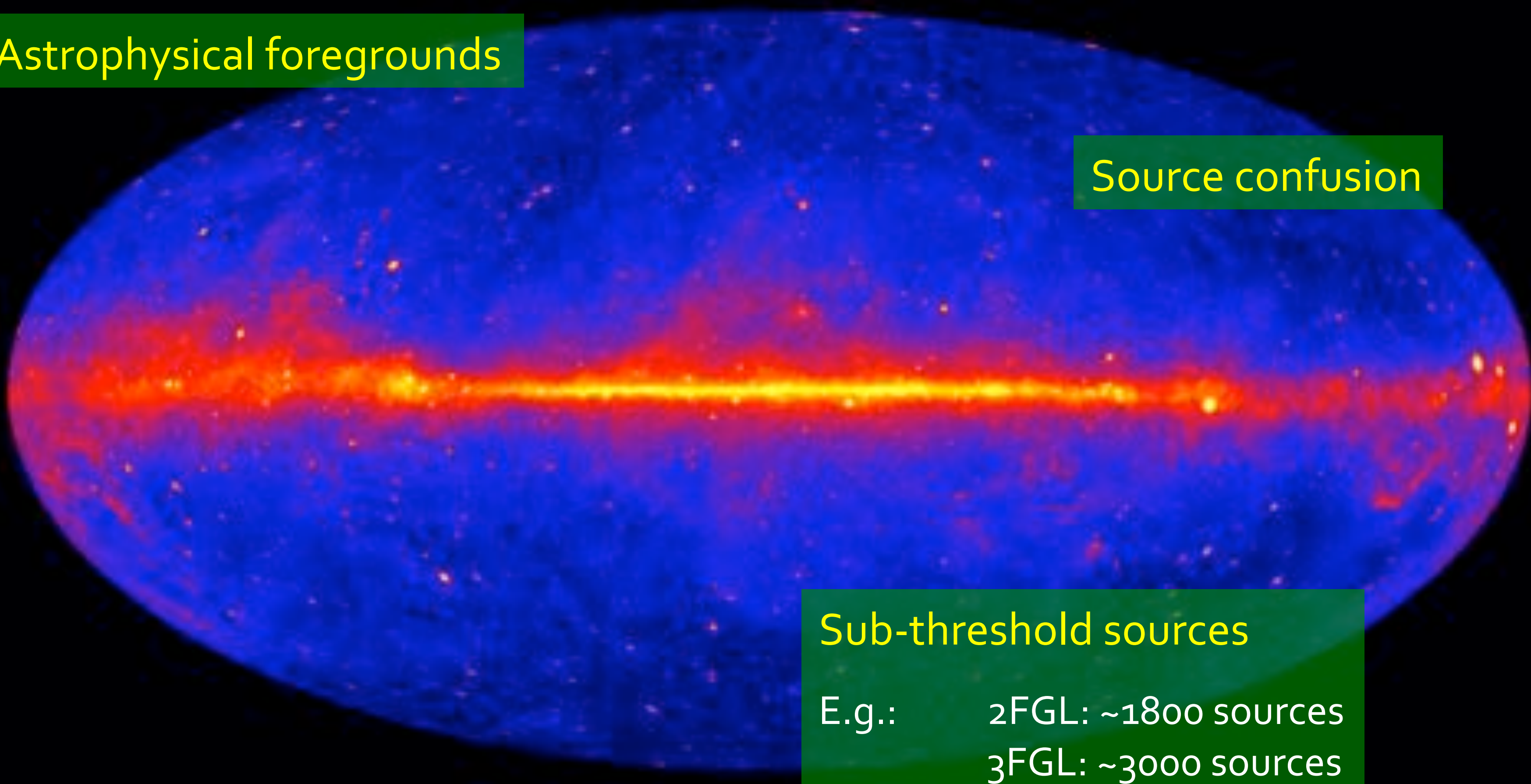


The DM-induced γ-ray sky



Dark Matter simulation:
Pieri+(2009) arXiv:0908.0195

Needs and challengues



Astrophysical foregrounds

Source confusion

Sub-threshold sources

E.g.: 2FGL: ~1800 sources
3FGL: ~3000 sources

Need to disentangle dark matter annihilations from 'conventional' astrophysics.

Crucial to understand the astrophysical processes in great detail.

Needs and challengues

- **A better knowledge/control on astrophysical systematics,** e.g.:
  - Galactic diffuse foregrounds.
  - DM content in the best targets (dwarfs, GC…).
  - Local DM density.

Experiments need better:

- ✓ **Spectral** resolution
- ✓ **Angular** resolution
- ✓ **Background** rejection

DM Search Strategies

Satellites

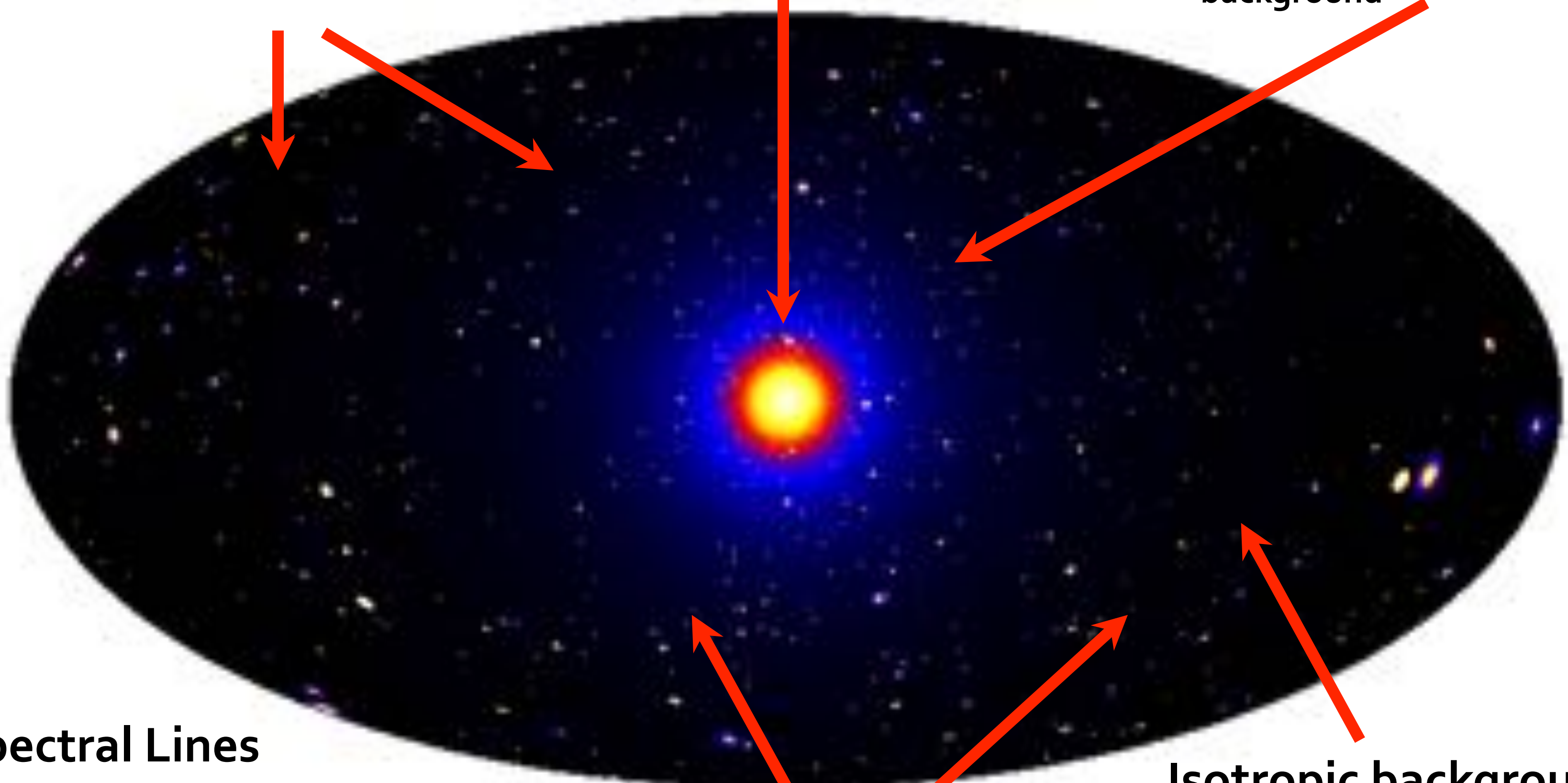
Low background and good source id, but low statistics

Galactic Center

Good Statistics, but source confusion/diffuse background

Milky Way Halo

Large statistics, but diffuse background



Spectral Lines

Little or no astrophysical uncertainties, good source id, but low sensitivity because of expected small branching ratio

Galaxy Clusters

Low background, but low statistics. Astrophysical contamination

Isotropic background

Large statistics, but astrophysics, galactic diffuse background

Dark Matter simulation:
Pieri+(2009) arXiv:0908.0195

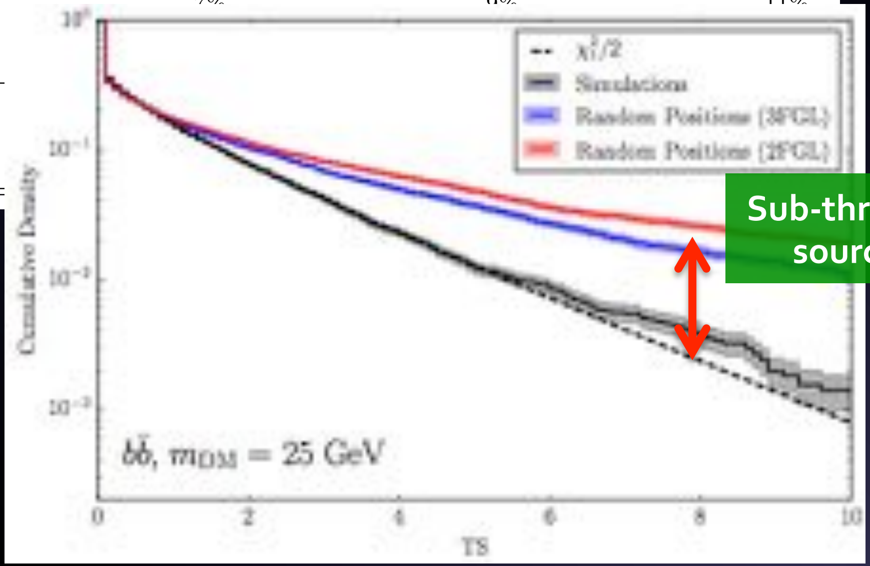
Anderson's talk

Example of systematic uncertainties: dwarfs in Pass 8

TABLE II. Effect of systematic uncertainties for various WIMP masses and channels reported as a symmetrical relative deviation from the combined 95% CL upper limits.

		10 GeV	100 GeV	1 TeV	10 TeV
e^+e^-	IRFs	6%	10%	11%	11%
	Diffuse	12%	6%	3%	2%
	J-factor	29%	31%	17%	16%
$\mu^+\mu^-$	IRFs	6%	10%	11%	11%
	Diffuse	13%	6%	3%	2%
	J-factor	28%	32%	18%	16%
$\tau^+\tau^-$	IRFs	7%	9%	11%	11%
	Diffuse	15%	6%	1%	1%
	J-factor	24%	35%	15%	14%
$u\bar{u}$	IRFs	6%	7%	9%	10%
	Diffuse	23%	12%	7%	4%
	J-factor	16%	34%	31%	24%
$b\bar{b}$	IRFs	6%	7%	9%	11%
	Diffuse	23%			
	J-factor	13%			
W^+W^-	IRFs				
	Diffuse				
	J-factor				

Instrument response functions
Diffuse modeling
J-factor values



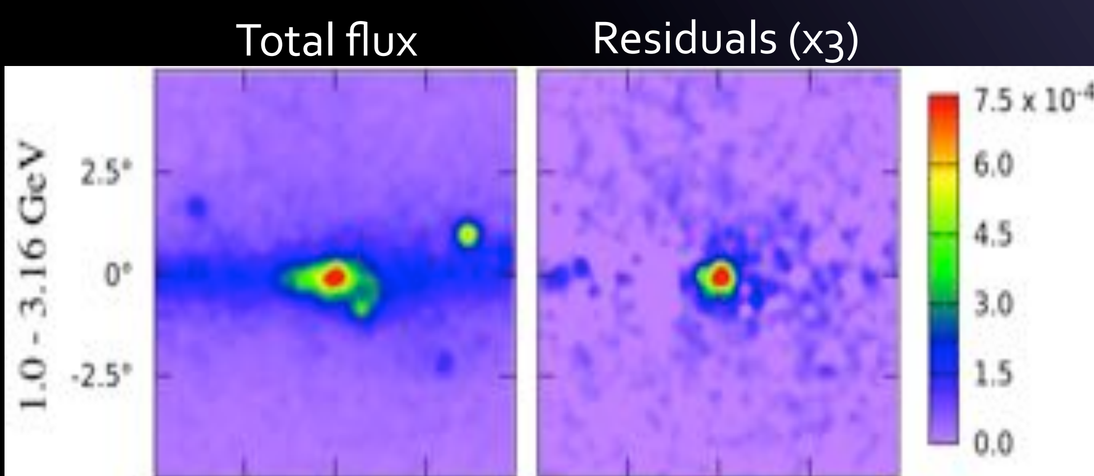
Sub-threshold sources?

Another example:
‘GeV excess’ in the Galactic Center

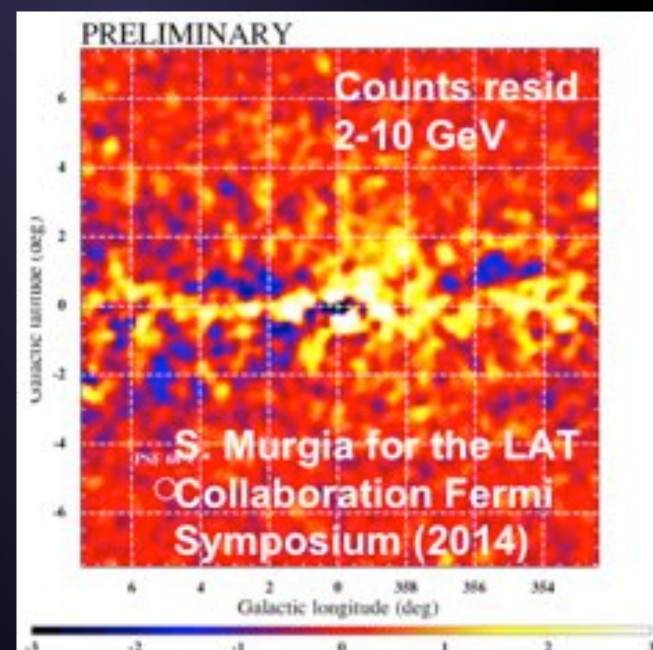
- Several groups have reported an excess of GeV photons from the GC region

(e.g., Goodenough & Hooper 09, 11; Hooper & Slatyer 13; Daylan+14, Abazajian+14, Calore+14; Gordon & Macías 14)

- General agreement on the excess peaking at 1-2 GeV above the standard diffuse emission models.
- Interpretation difficult due to complicated foreground/background modeling.
- DM annihilation is a plausible and exciting possibility!



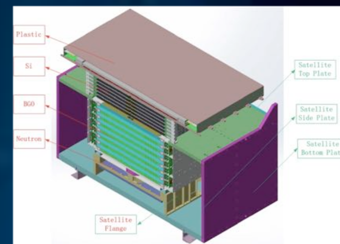
Daylan+14



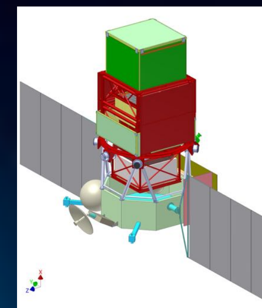
Gammas: the future ahead

Fermi
[<2018?]

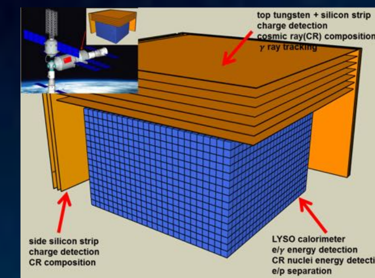
CALET
[> 2015?]



DAMPE
[> 2016]



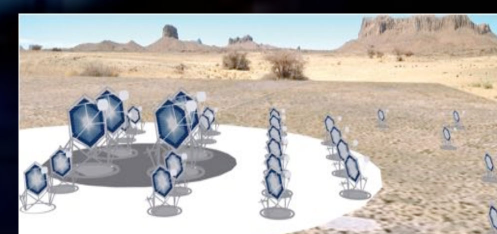
GAMMA-400
[> 2018]



HERD
[> 2019]

HESS-II
[already doing science]

HAWC
[just started]



CTA
[>2016?]

DESY/Milde Science Comm./Exozet

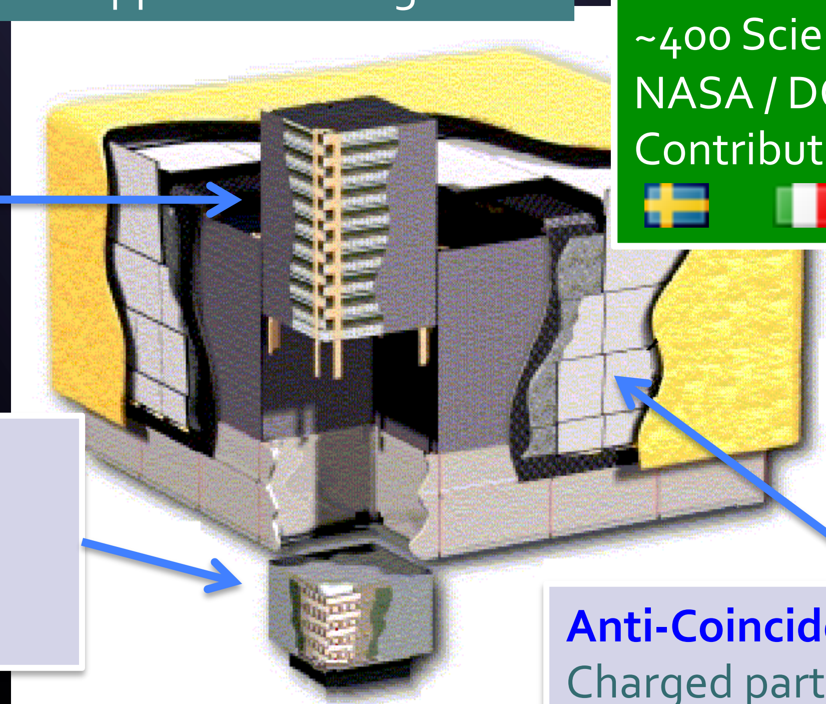
he Fermi Large Area Telescope

Anderson's talk

LAUNCHED IN JUNE 2008
Mission approved through 2016

Fermi LAT Collaboration:
~400 Scientific Members,
NASA / DOE & International
Contributions

Si-Strip Tracker:
convert $\gamma \rightarrow e^+e^-$
reconstruct γ direction
EM v. hadron separation



[1.8 m x 1.8 m x 0.7 m]

Hodoscopic CsI Calorimeter:
measure γ energy
image EM shower
EM v. hadron separation

Anti-Coincidence Detector:
Charged particle separation

Sky Survey:
2.5 sr field-of-view
whole sky every 3 hours

Trigger and Filter:
Reduce data rate from ~10kHz to 300-500 HZ

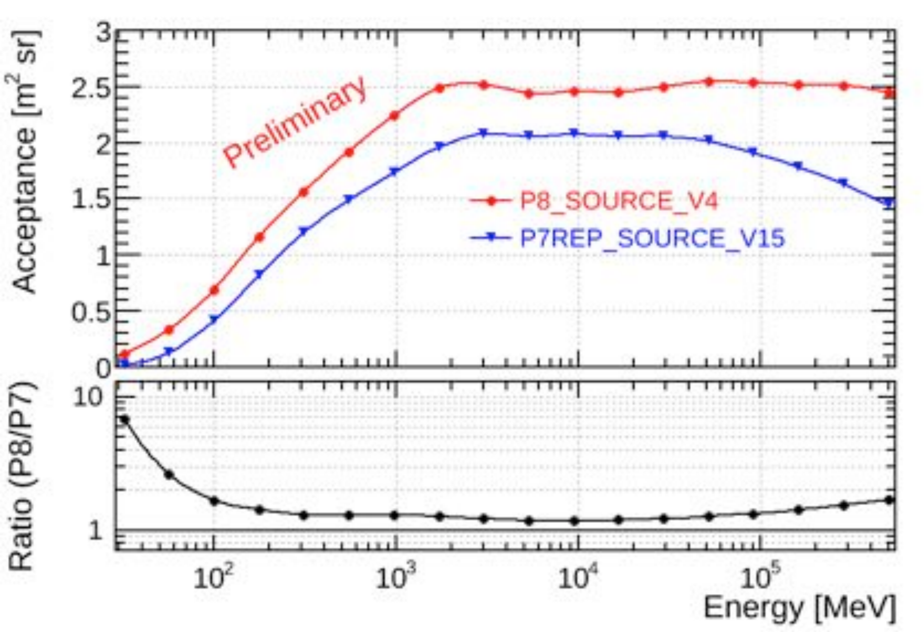
Public Data Release:
All γ-ray data made public within 24 hours (usually less)

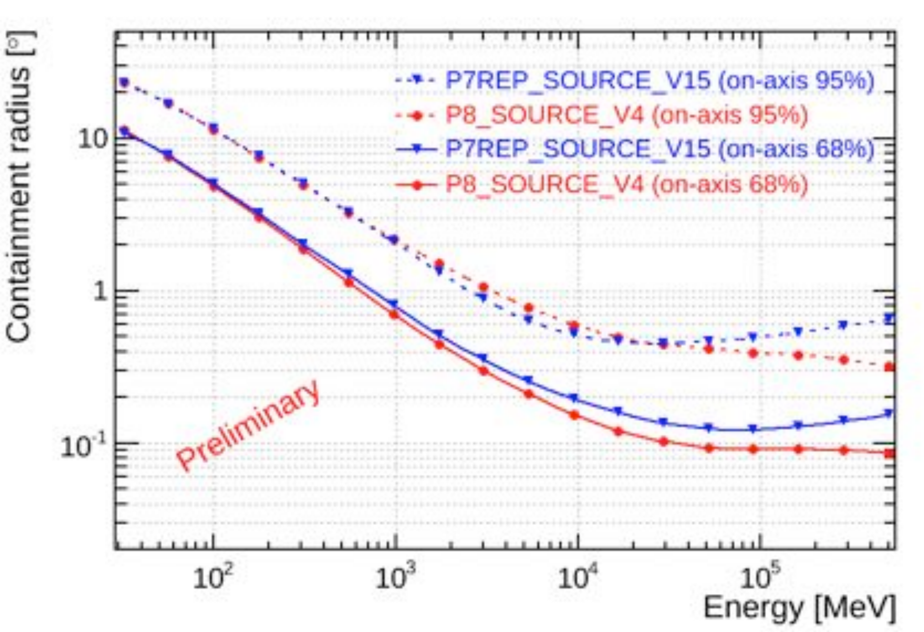
Fermi LAT

- Formally approved till 2016.
  - Very likely 2018. Probably beyond?
- With more data:
  - A better knowledge of foregrounds possible.
  - More sub-threshold sources detected.

    → greater chances for detection!
  - General improvement on DM limits:
    - linearly with time at high energies (better statistics)
    - sqrt(time) at low energies.
- **Pass 8**: improved performance!

The inminent future: Pass 8 (a.k.a. improved LAT performance)





Impacts for dark matter:

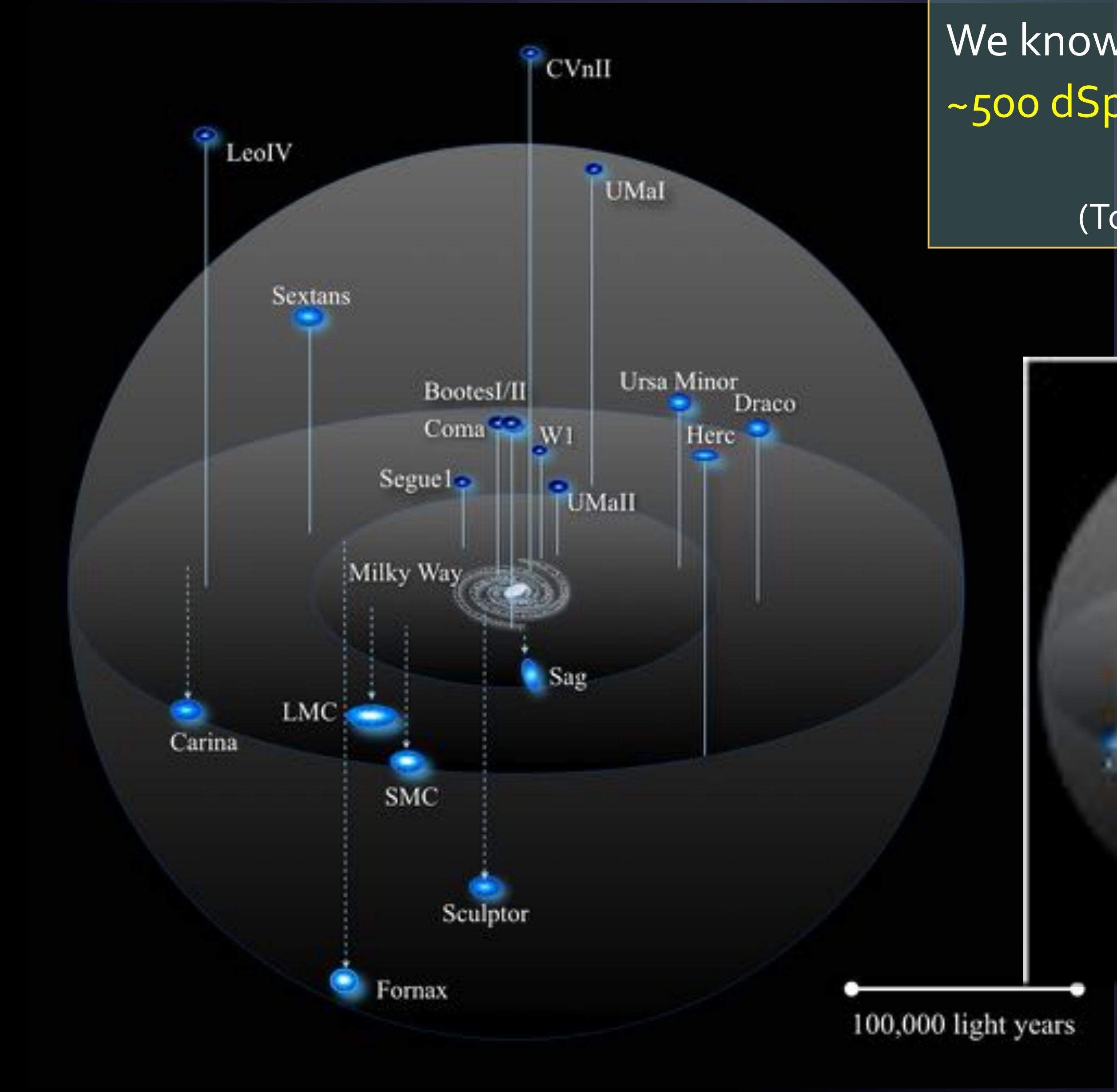
- Increased energy range <==> explore new mass parameter space
- Increased effective area <==> increased flux sensitivity
- Improved angular resolution <==> greater sensitivity to spatially extended sources
- Better background rejection
- New event classes <==> check systematic effects in event selection

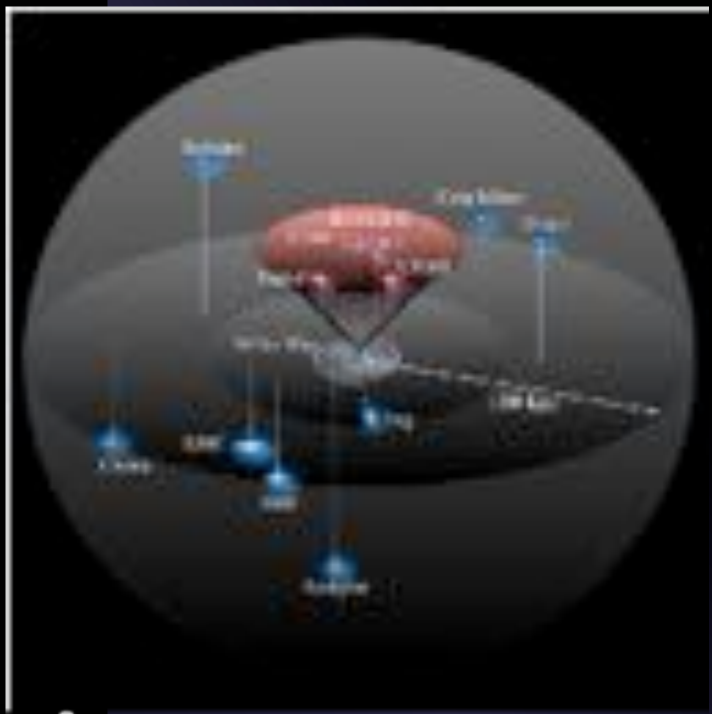
A particular case for the future: DWARFS

We know 2 dozens of dwarfs, but…

~500 dSphs inside the virial radius?

(Tollerud+08; Walsh+09; Hargis+14)



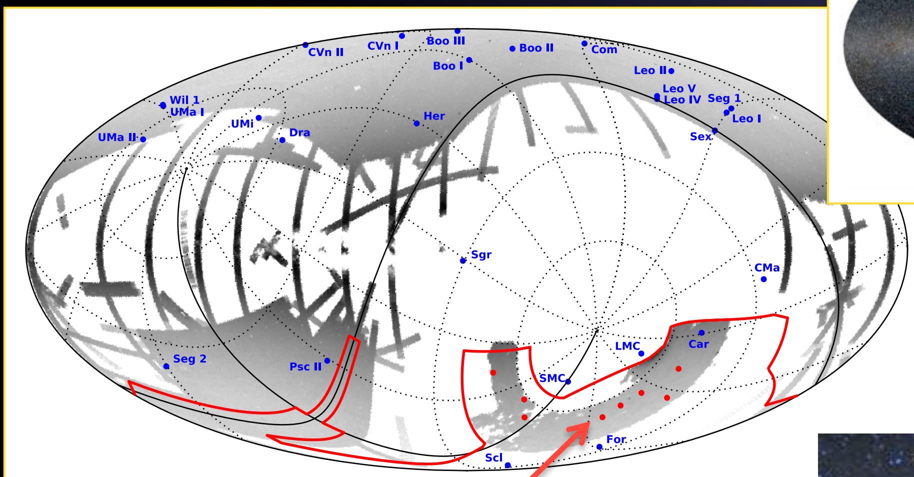


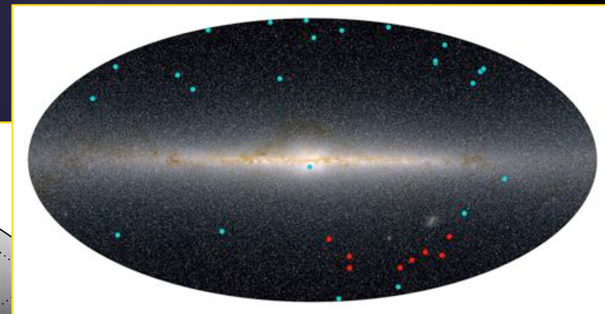
(Bullock et al. 2009)

Anderson's talk

The discovery of 8-9 new satellites with DES data

[Full DES footprint in red]





Credit: Y. Mao, R. Kaehler, R. Wechsler (KIPAC/SLAC)

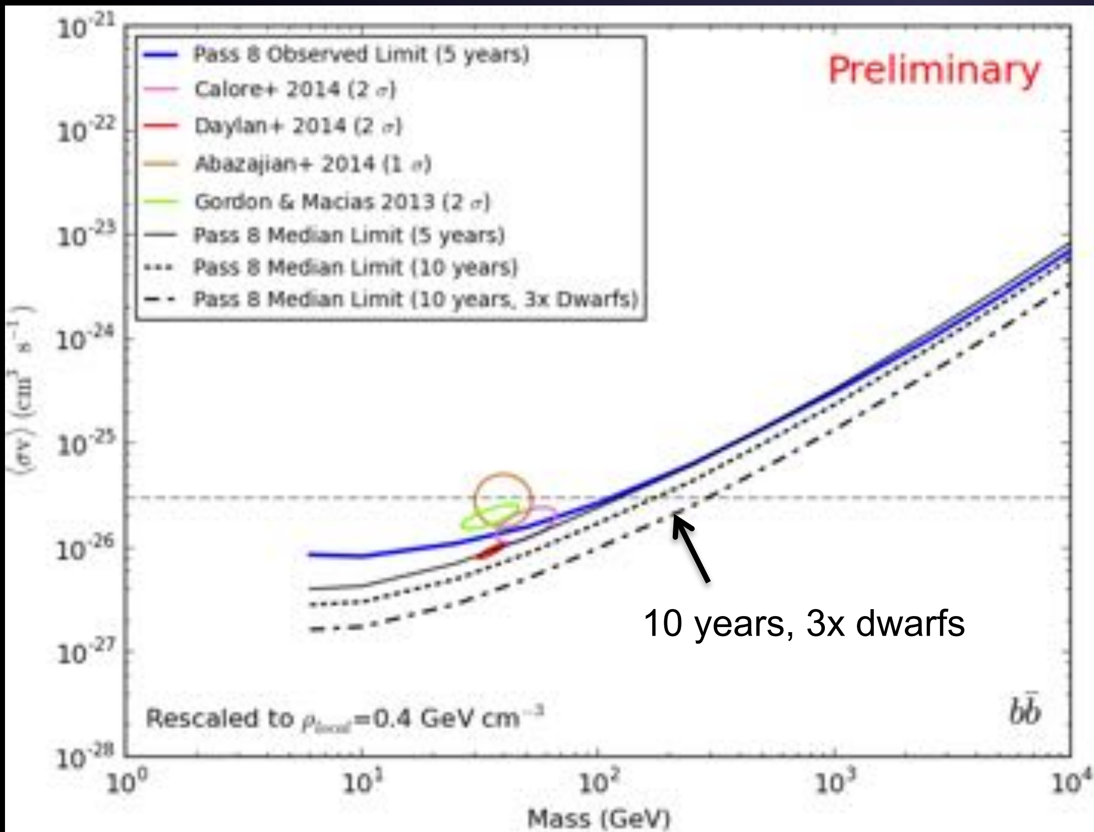
Koposov+15, 1503.02079
DES collab., 1503.02584

New dwarf candidates

Credit: Belokurov & Koposov; Beletsky

Satellites resolved as extremely weak over-densities of stars…

Projected Fermi dwarf stacking limits

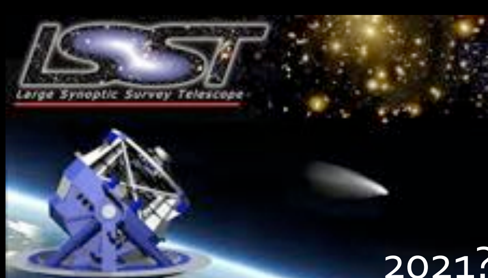


Ongoing or planned surveys should find many more dwarfs.

More precise DM distributions (also thanks **to 30m telescopes**)

GAIA will lower the uncertainties in the local DM density.

Powerful test of the GC excess!!



DARK ENERGY SURVEY

>2013

Southern Sky Survey

>2007

>2010

The inminent future for current generation IACTs

HESS-II

- first light in 2012
- push the threshold to lower energies ~50 GeV
- Expected to lead the IACT limits using the GC.

VERITAS

- 1000h observation of Segue 1 by 2018 (Smith +13)

MAGIC

- Will be running too!
- Expected to produce new DM limits from dwarfs

High Altitude Water Cherenkov Observatory (HAWC)

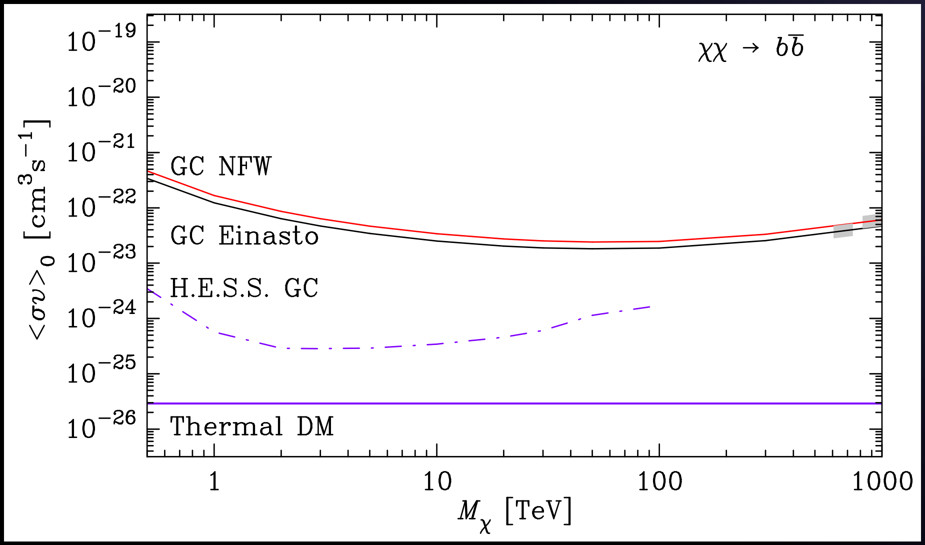
- 2nd generation water Cherenkov, MILAGRO-like array.
  - 300 tanks, 180,000 l each, 7x5 m.
  - Wide field of view (~2 sr)
  - High duty cycle (~90%)
  - Large collecting area (~22,000 m^2)
- Joint US-Mexico effort. Officially inaugurated last March 2015.
- Will survey the entire sky over 10 years between 100 GeV and ~100 TeV.
  - 50 mCrab sensitivity at 5σ in a 1yr survey

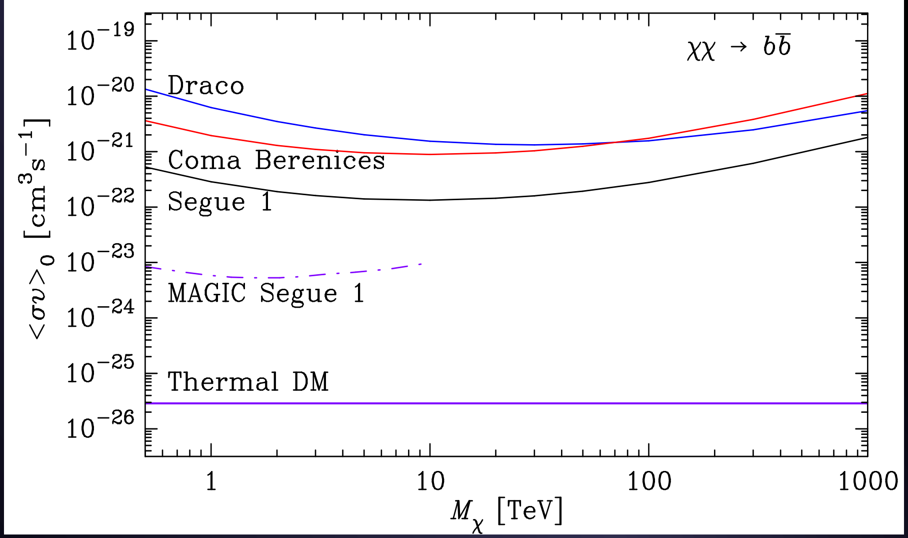
Sierra Negra, Mexico, 4100 m a.s.l.

HAWC and DM

- Fundamental physics studies possible, but not the main science.
  - Competitive for DM searches probably above ~1 TeV.
  - Particularly valuable for DM subhalos' searches! (large FoV)

Abeysekara+14

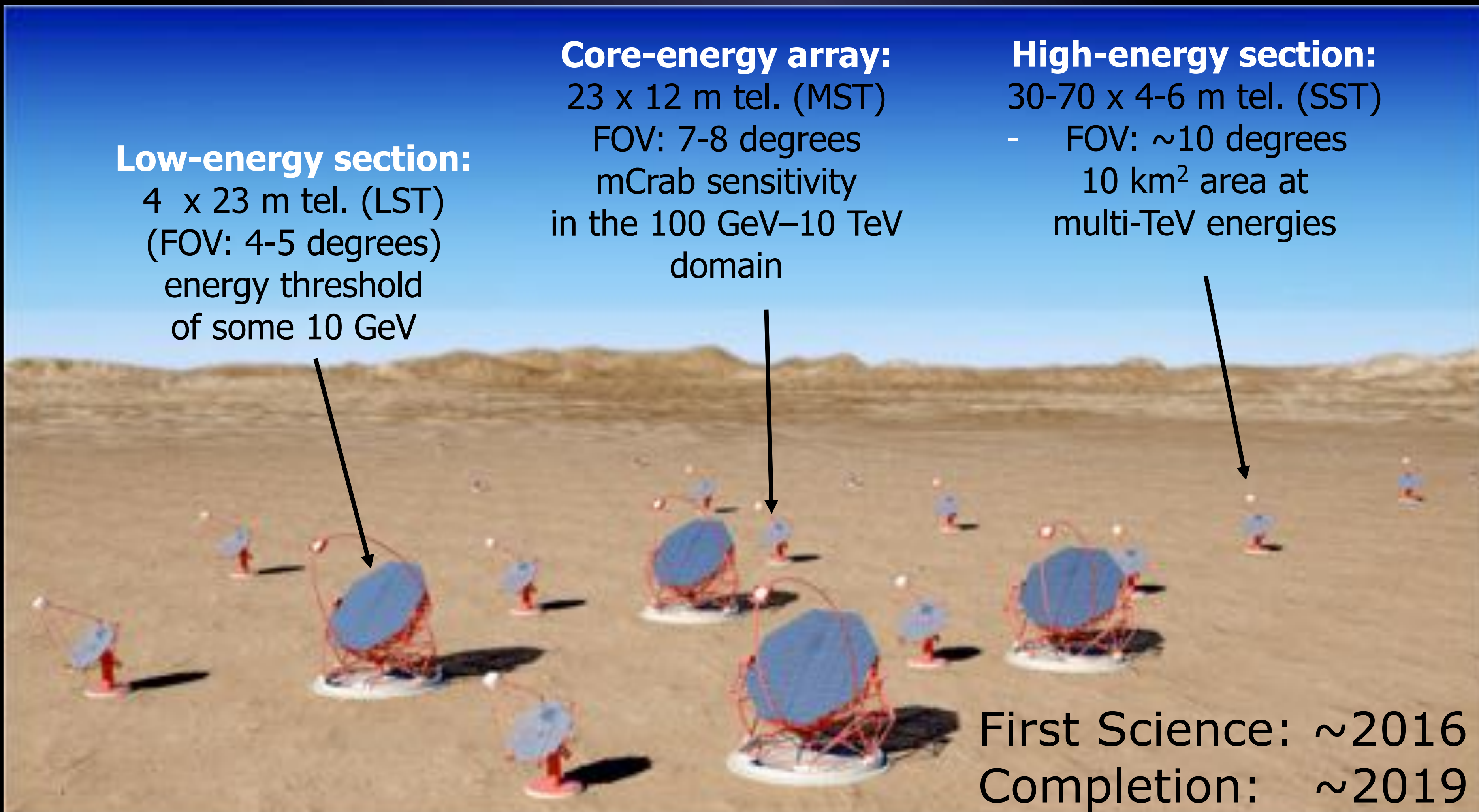




Projected DM limits for the GC and dwarfs, 5 years

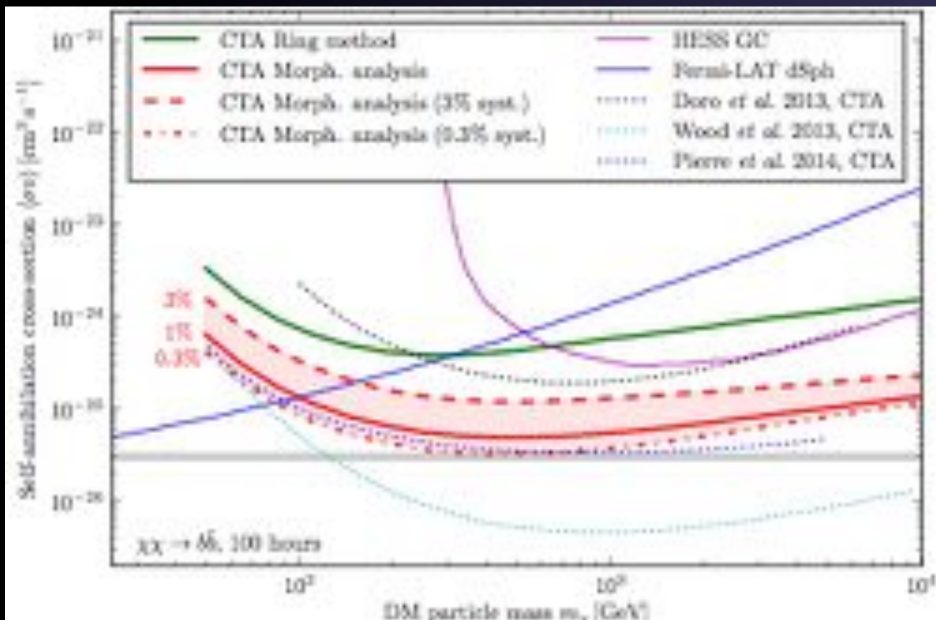
Fornasa's talk

IACT future:
Cherenkov Telescope Array (CTA)

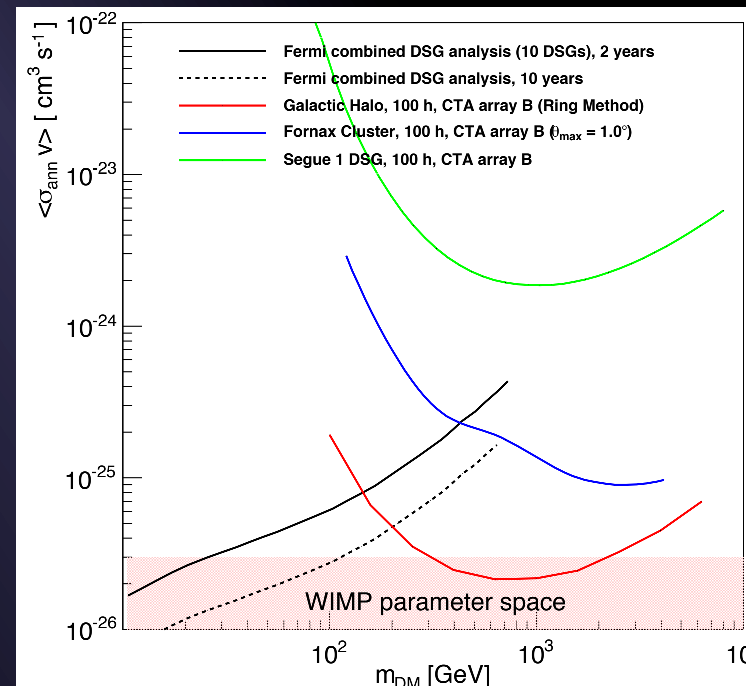


Fornasa's talk

A glimpse of what CTA can do



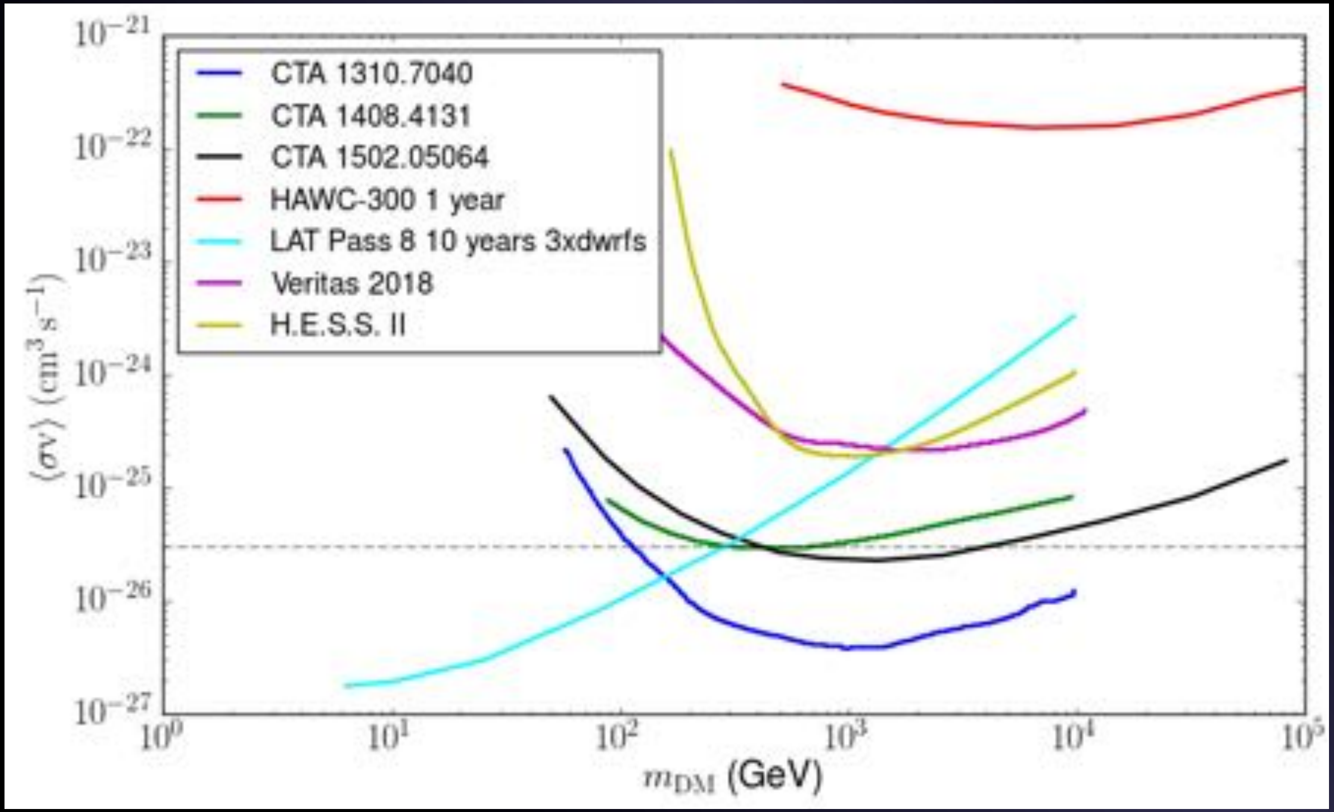
Silverwood+14



Doro+13

- Best target expected to be the Galactic Center
- Control of systematics crucial to reach the thermal cross section value…

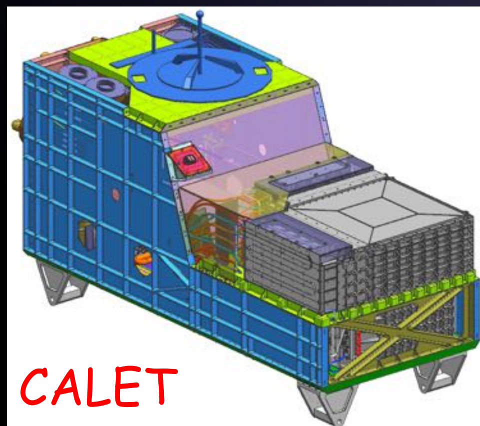
DM limits circa 2020?

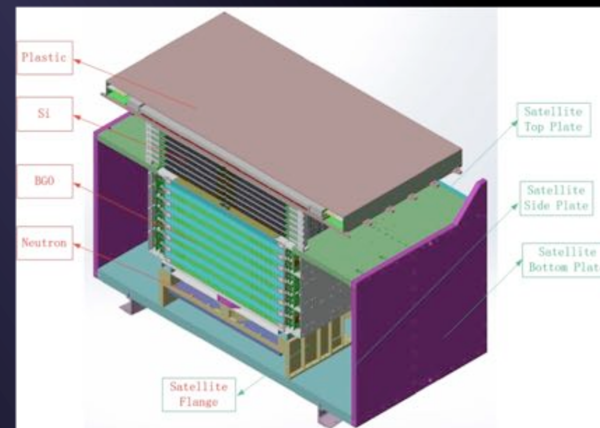


Conrad 15

Fermi + CTA will be able to exclude the thermal cross section up to ~20 TeV

The inminent future for satellite-based experiments





CALET

- Japanese-led.
- For launch this year!
- Placed at the ISS

DAMPE

- Chinese
- Lauch ~2015/16

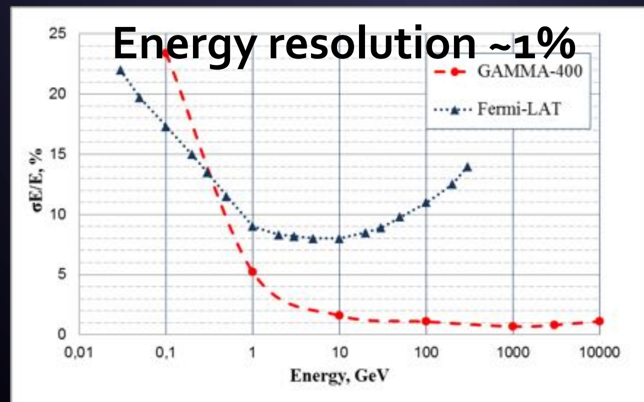
Both:

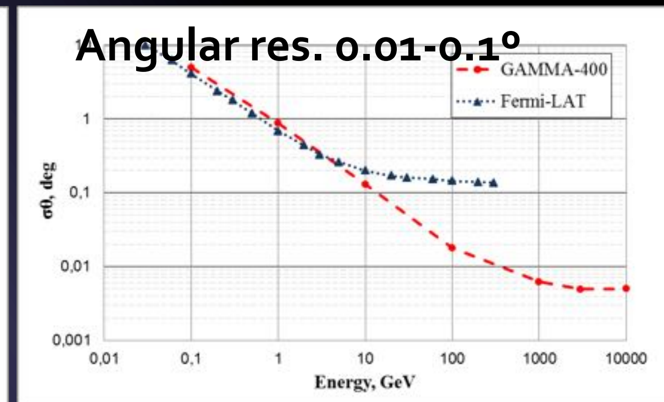
- ✓ deep calorimeter, 1 GeV – 10 TeV
- ✓ superb energy resolution ~2% @ 100 GeV
- ✓ 0.3º angular resolution @ 100 GeV
- ✓ Very good background rejection power
- ✓ Small collecting area of ~0.15 and ~0.5 m^2

The future beyond

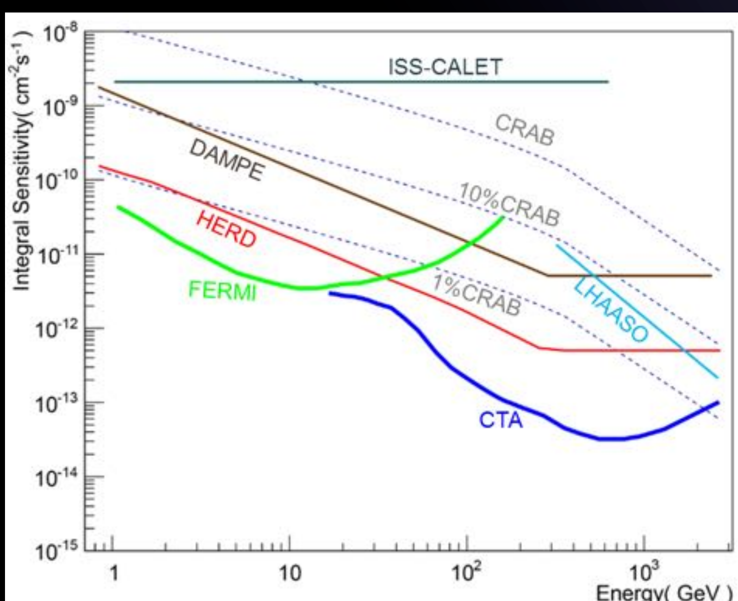
GAMMA-400

- Russian-led.
- Launch by 2018/19.
- 100 MeV – 3TeV
- Efective area ~0.4 m^2
- FoV: ~1.2 sr





Big improvement w.r.t. Fermi, but smaller ollection area.



HERD

- Chinese
- Launch by 2018/19.
- 100 MeV – 10 TeV
- Efective area ~3.7 m^{2}sr
- $\Delta E/E$ ~1% > 100 GeV
- 0.1º @ 200 GeV angular resolution.

The future beyond?

PANGU (Wu+14)

- ESA/CAS joint small mission.
- Spectro-imaging, timing and polarization.
- 10 MeV – few GeV
- $\Delta E/E \sim 1\% > 100$ GeV
- 0.1^{o} @ 1 GeV angular res.

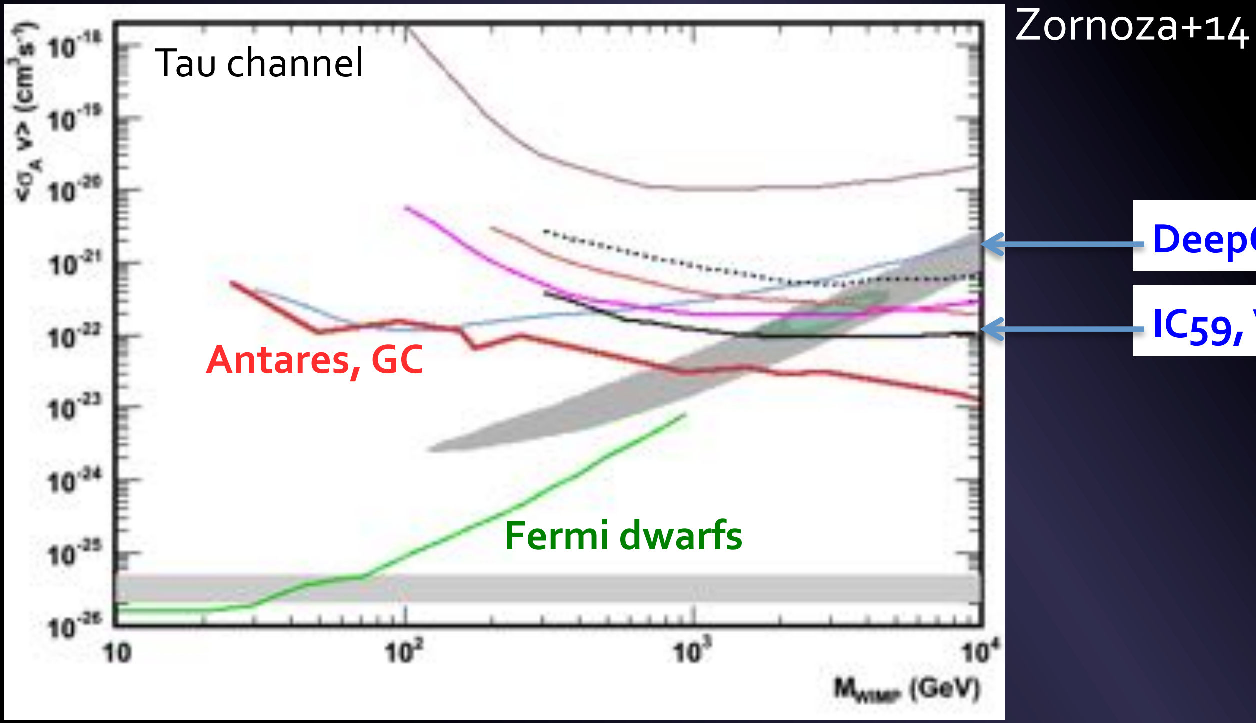
AstroMeV

- Space mission by ~2025.
- 0.1 – 100 MeV
- Consortium formed to respond to AO of space agencies.
- http://astromev.in2p3.fr/

Full list of Future High-Energy Astrophysics missions:
https://heasarc.gsfc.nasa.gov/docs/heasarc/missions/concepts.html

Wolf's talk

Neutrinos vs Gammas
(WIMP annihilations)



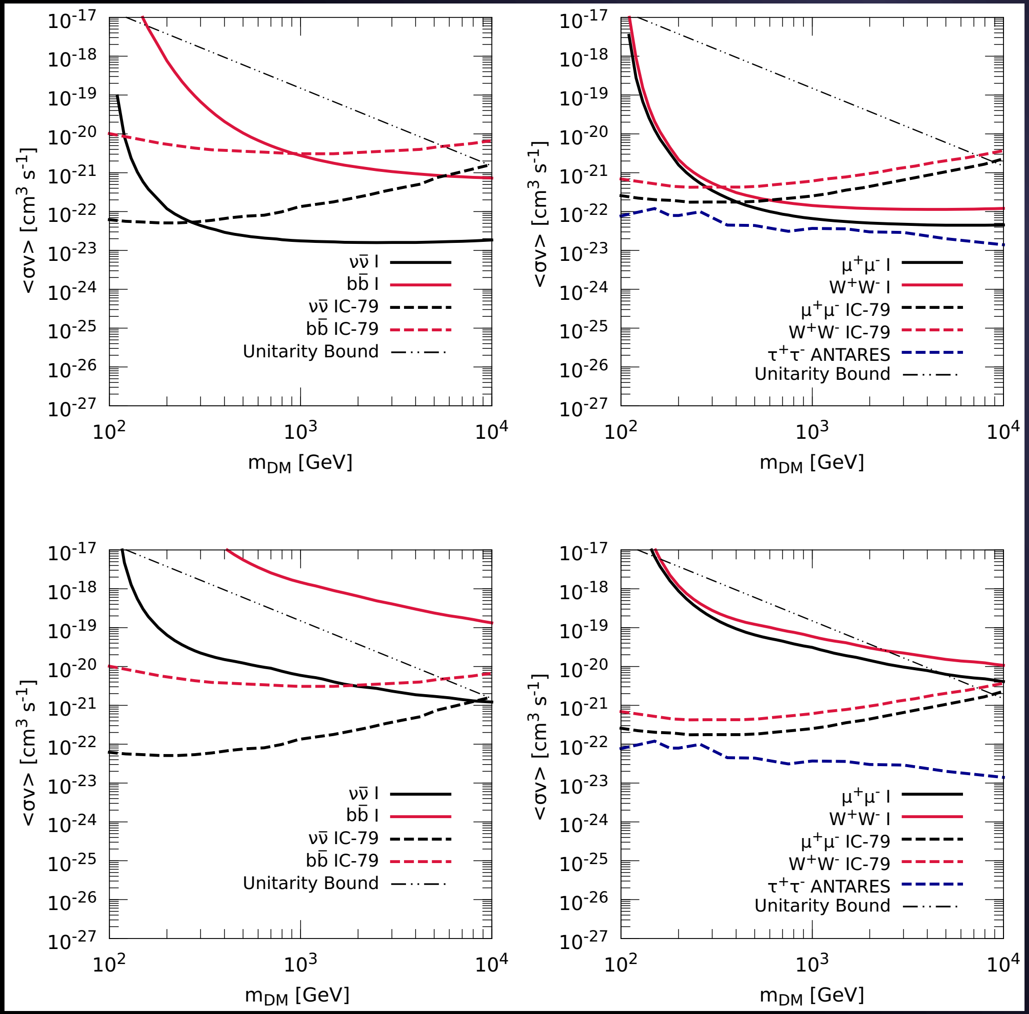
Neutrinos not as competitive as the gamma-ray channel for this game.
(though they provide the best limits on SD cross sections)

IceCube extensions:

→ PINGU at low WIMP masses ~5 GeV

→ High energy extension: specially interesting for DM decay scenarios

Future prospects from cosmological DM annihilations



Thru-going muon events

10 years of data of a 1 km³ detector

Realistic/conservative DM annihilation flux

Moliné+15

ANTI-MATTER

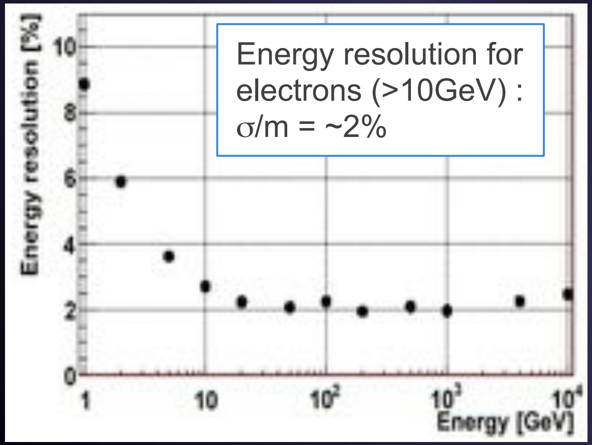
Main signature for DM probably in the anti-proton and positron channel.

→ Yet, would we get a signal clear enough?

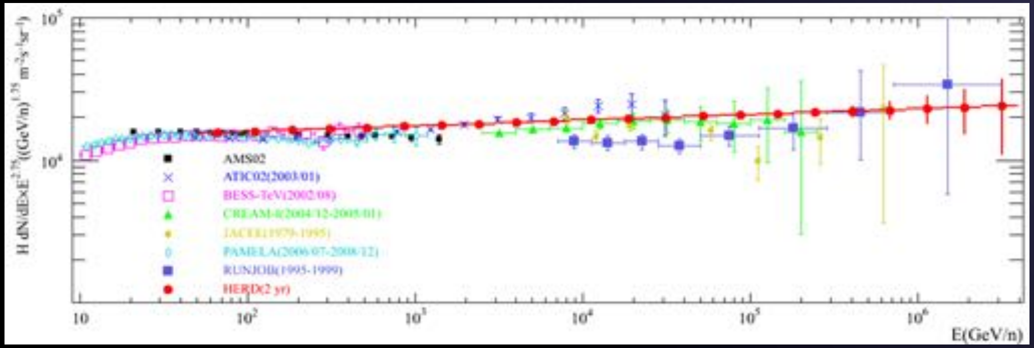
Anti-deuterons: smoking gun (but, is the background actually so low?)

CALET, DAMPE, HERD… also suitable for charged particles' studies.

Torii+13



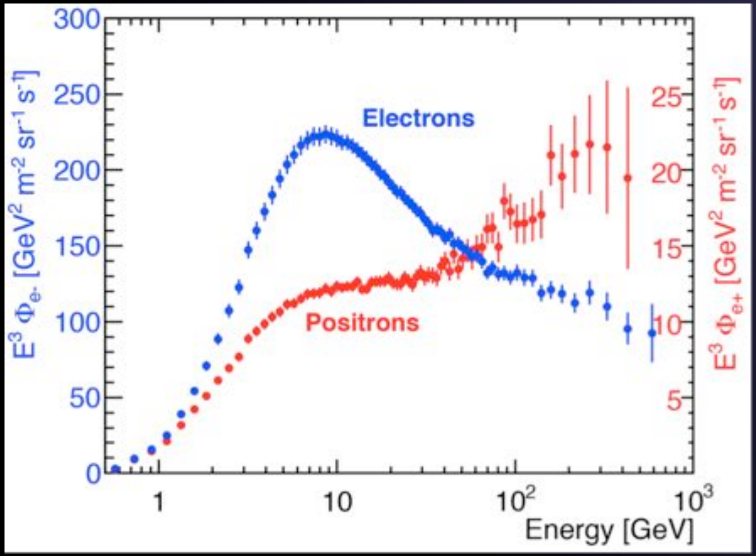
CALET



HERD
Protons

Zhang+14

AMS-02 and GAPS

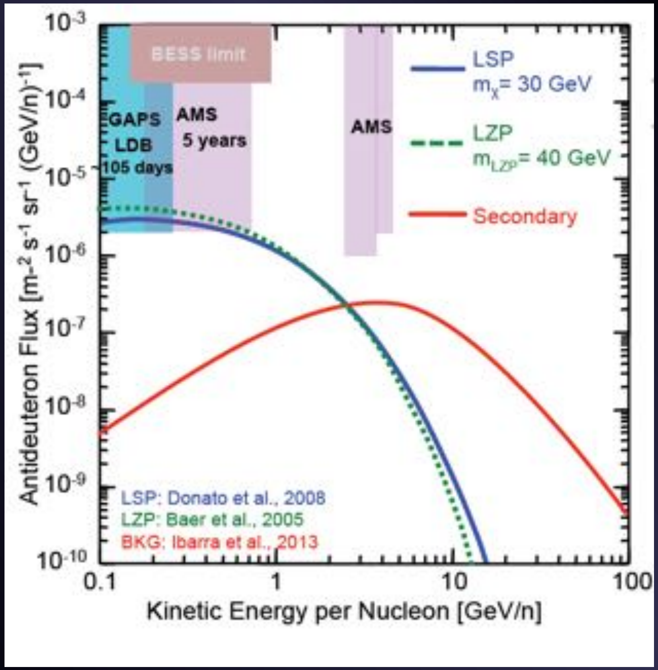


AMS-02:

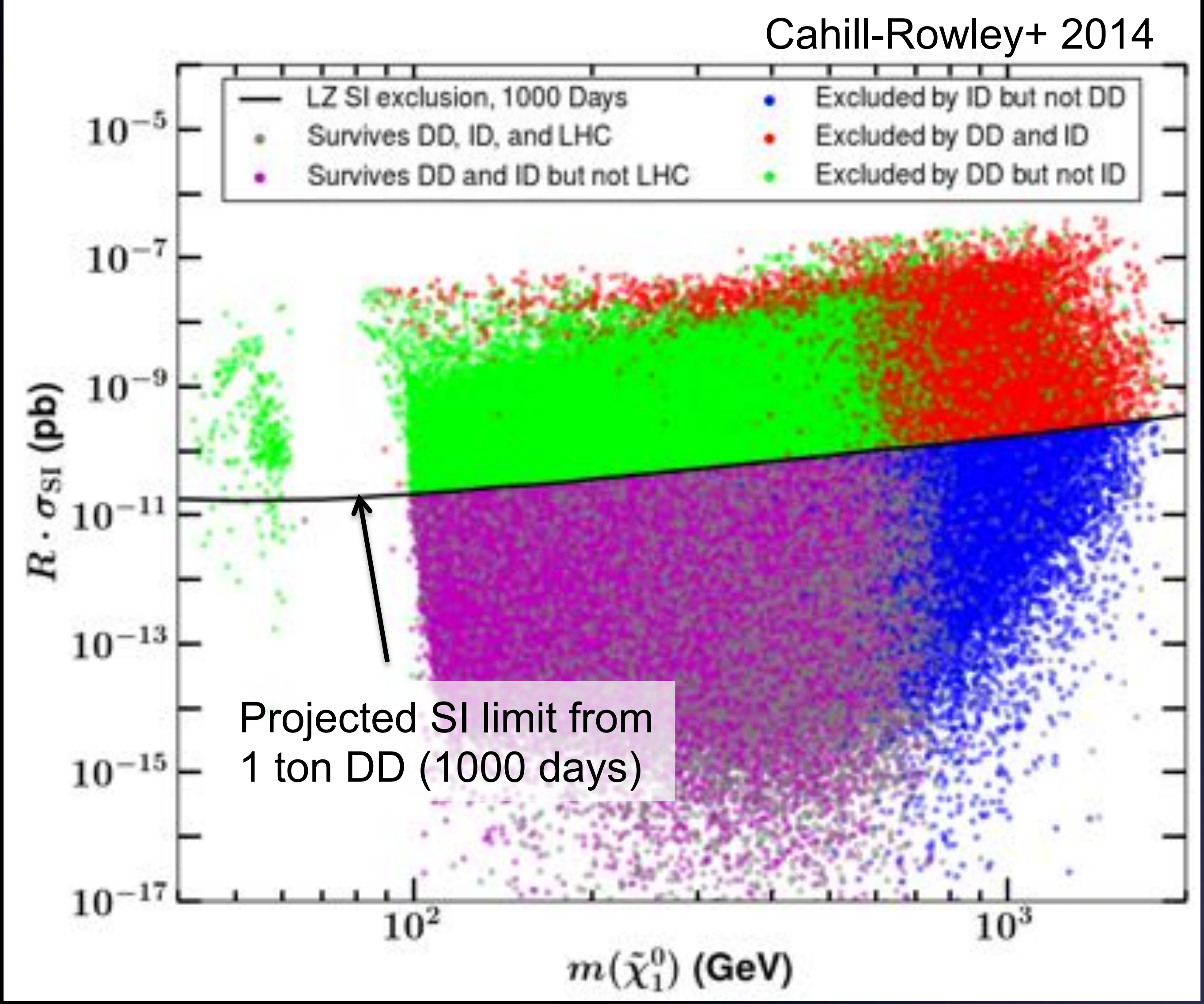
- Should be there at least till 2021 .
- Superb statistics
  - → Very detailed CR spectra.
  - → refinement of CR propagation models
- Will help for understanding the gamma-ray foregrounds too.

GAPS:

- Even the detection of a few low-energy antideuterons would be extremely interesting.
- No dedicated search exists.
- Will be ready by ~2018.
- Succesful prototype flight in 2012.



Complementarity needed!



Remarks on the future

- Gamma-rays will still be the most promising channel for indirect detection.
  - → Several new instruments expected in the near future, both from the ground and on space (CTA, HAWC, GAMMA-400, CALET, DAMPE
  - → Thermal value of the DM annihilation cross section fully tested up to a few TeV by ~2020.
  - → If no detection, end of the WIMP paradigm? When should we stop looking?
- Neutrinos not as competitive as gamma rays for DM annihiilations.
  - → GC with ANTARES probably the most promising target.
  - → Limits competitive only at the highest possible WIMP masses.
- Antimatter:
  - → AMS-02 critical for understanding CR propagation
  - → GAPS: exciting potential
- Complementarity with colliders and direct detection needed!
- Critical to keep the diversity of astrophysical targets, experiments, DM candidates….

THANKS

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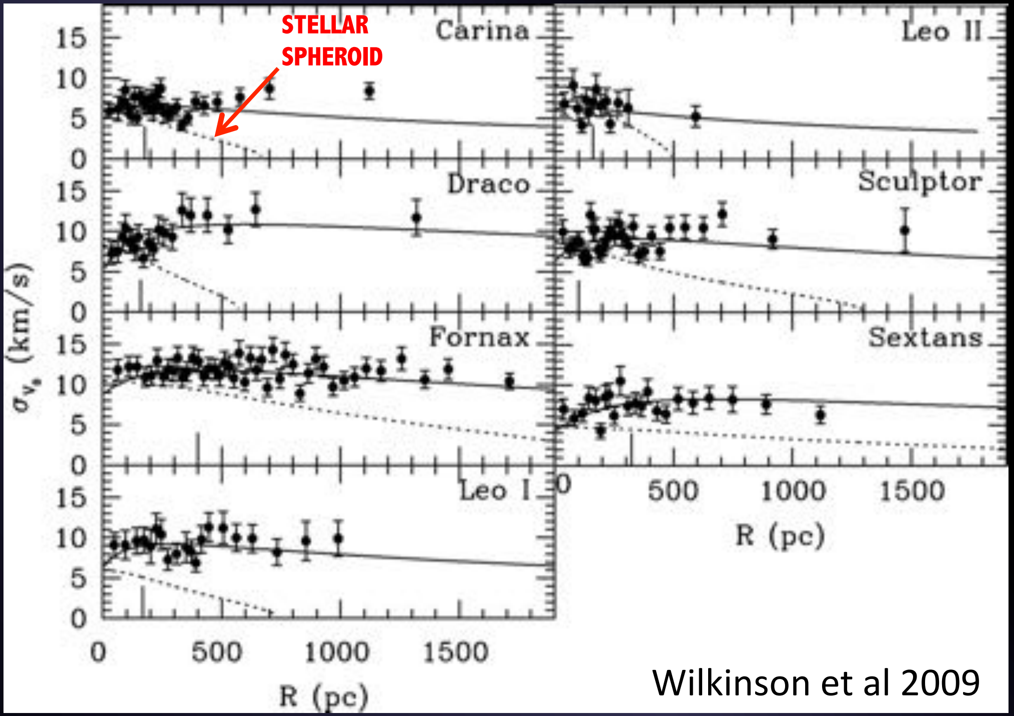
ADDITIONAL MATERIAL

Measuring the DM content in dwarfs

- Determined spectroscopically from stellar velocity dispersions:
  - In classical dwarfs, hundreds of stars.
  - Only few tens of stars in ultra-faint dwarfs.

- J-factor: l.o.s. velocity dispersion profiles + DM profile (e.g. NFW)



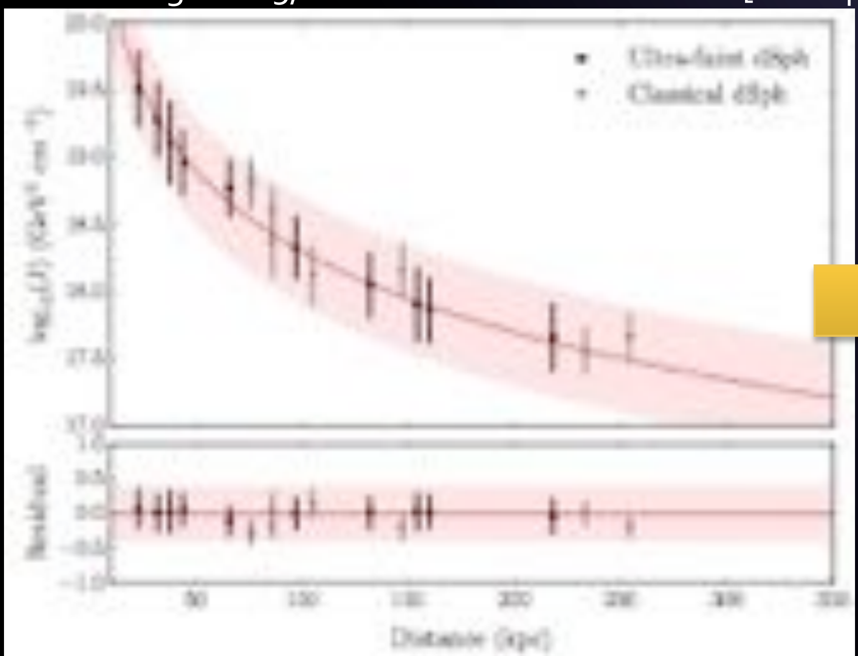
Wilkinson et al 2009

Dispersion profiles generally remain flat up to large radii

The DM case: J factor estimation

- New DES objects share many similarities with known ultra-faint dwarfs.
- Confirmation of their true nature (dwarf vs anything else) only possible with spectroscopy.
- We assume these new satellites to be dwarfs with similar properties to those we know.
- First order estimate of the J-factor. Spectroscopy needed.

Drlica-Wagner+15, LAT and DES collaborations [astro-ph/1503.02632]



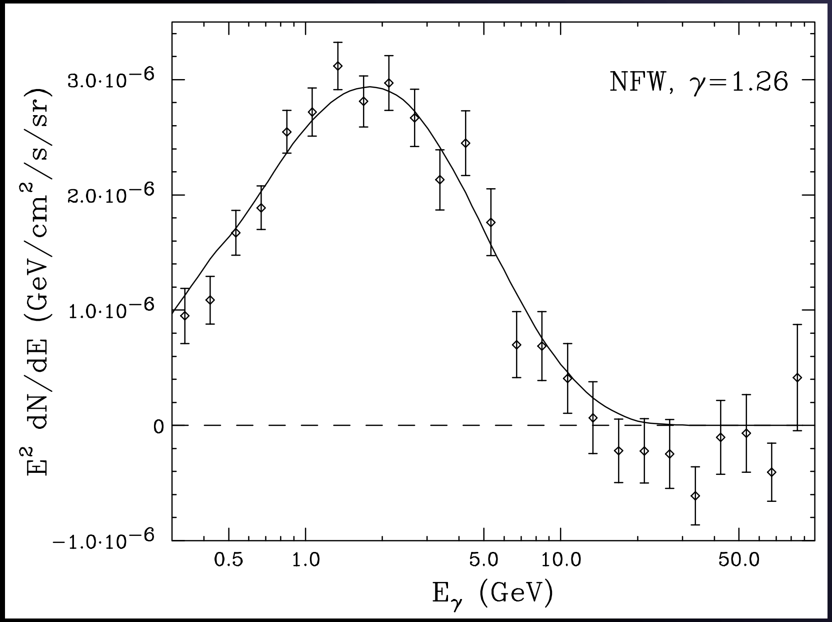
Name	$(\ell,\ b)^{a}$ deg	Distance[b] kpc	$\log_{10}(\mathrm{Est.J})^{c}$ $\log_{10}(\frac{\mathrm{GeV}^2}{\mathrm{cm}^5})$
DES J0222.7−5217	(275.0, −59.6)	95	18.3
DES J0255.4−5406	(271.4, −54.7)	87	18.4
DES J0335.6−5403	(266.3, −49.7)	32	19.3
DES J0344.3−4331	(249.8, −51.6)	330	17.3
DES J0443.8−5017	(257.3, −40.6)	126	18.1
DES J2108.8−5109	(347.2, −42.1)	69	18.3
DES J2251.2−5836	(328.0, −52.4)	58	18.8
DES J2339.9−5424	(323.7, −59.7)	95	18.4

(In comparison, $\log_{10}$J ~ 21.5 for the GC)

We use the 'observed' J-factor vs distance relation to estimate the J-factors of the new dwarf candidates (and assume an uncertainty of 0.4 dex).

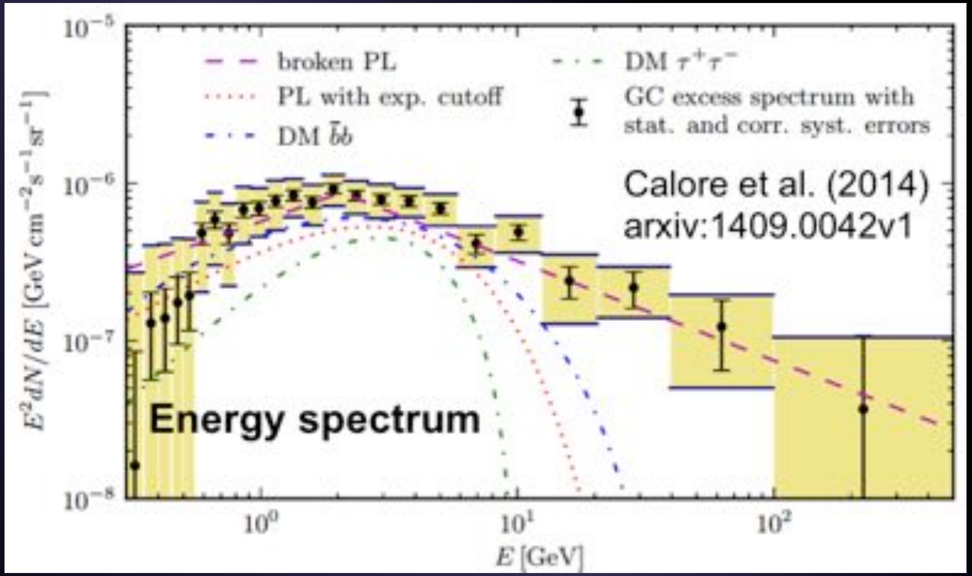
Properties of the GC excess

Daylan+14

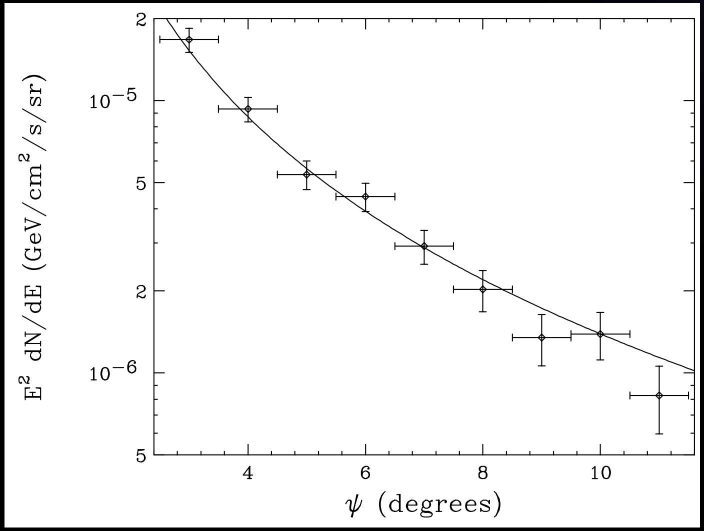


Spectrum consistent with gNFW
Half the thermal cross section value

Calore+14



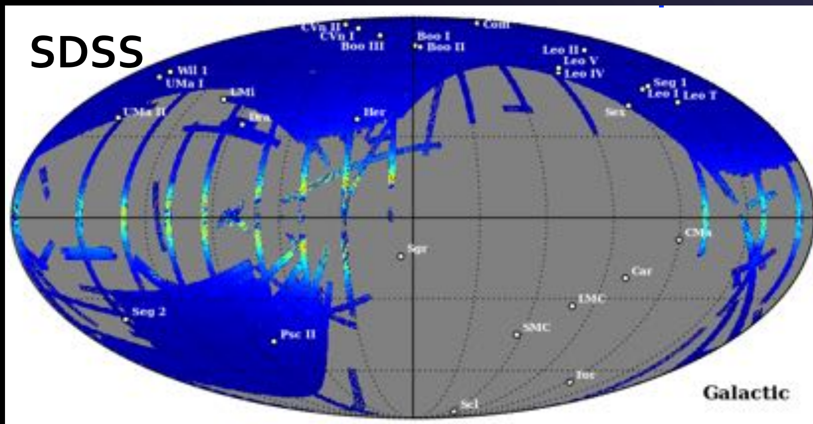
Robust to uncertainties in the diffuse modeling



Spatially extended

[Daylan+14]

The Dark Energy Survey (DES)



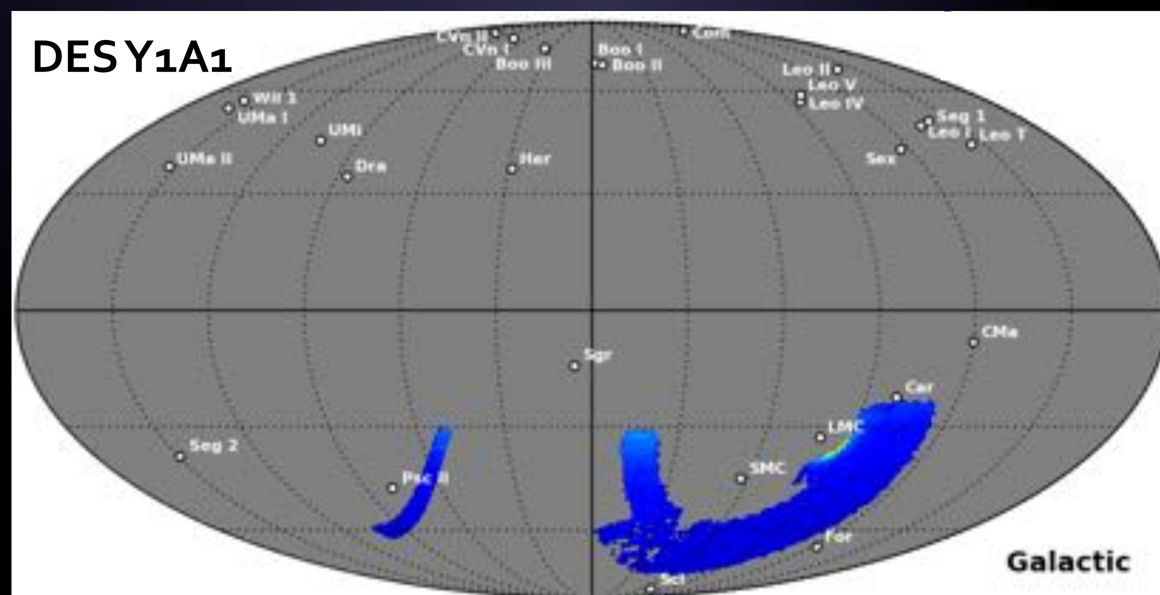
SDSS discovered 14 new satellites in 14,000 sq. deg. northern hemisphere.

Biased towards the Northern Hemisphere.

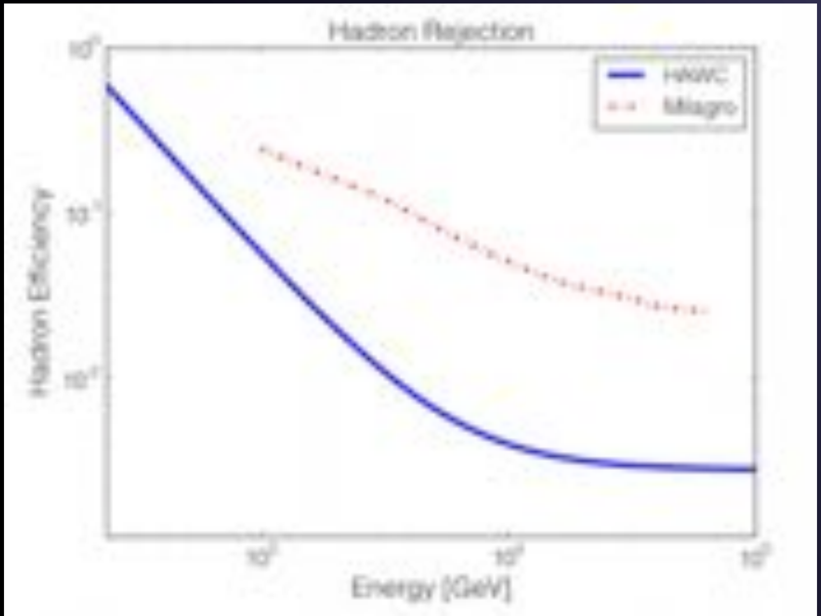
DES will cover 5,000 sq. deg. of the Southern Hemisphere in 5 years.

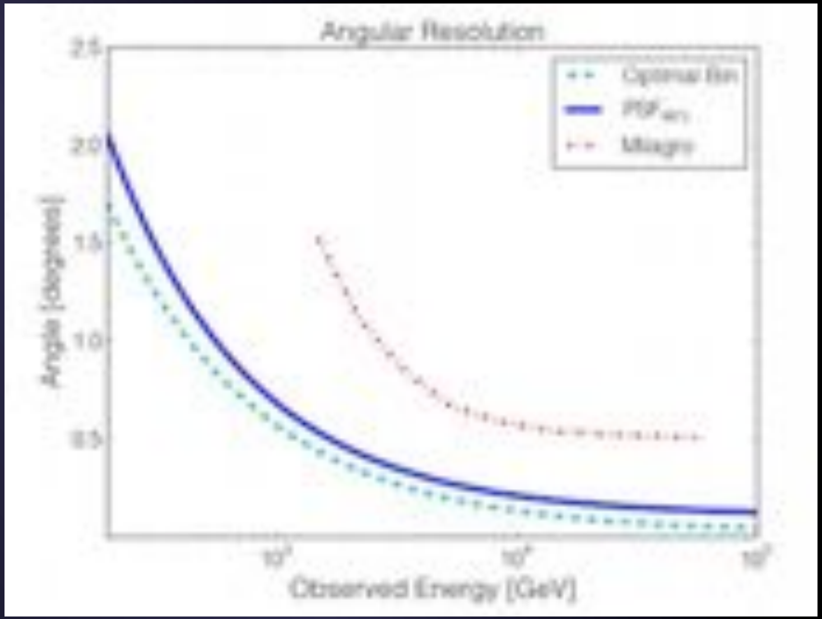
5-20 new dwarfs expected?

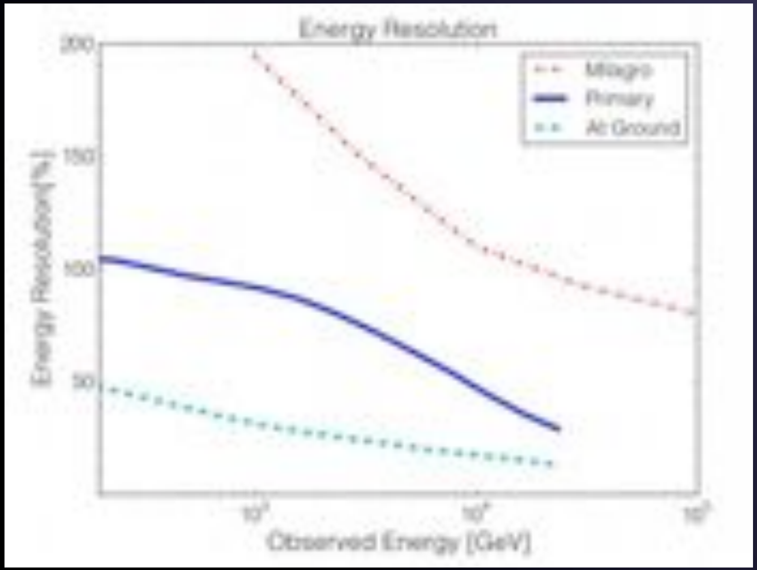
First release: DES Y1A1
→ 1,800 sq. deg.
→ 1,500 sq. deg. of new sky!



HAWC PERFORMANCE







	Space-based experiments			Ground-based experiments		
	Fermi	**AMS-2**	**GAMMA-400**	**H.E.S.S.-II**	**MAGIC**	**CTA**
Energy range, GeV	0.02-300	10-1000	**0.1-3000**	> 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**	10^5	10^5	10^6
Angular resolution (E_γ > 100 GeV)	0.2º	1.0º	**~0.01º**	0.07º	0.05º	0.06º
Energy resolution (E_γ > 100 GeV)	10%	2%	**~1%**	15%	15%	10%

Gasper+12