

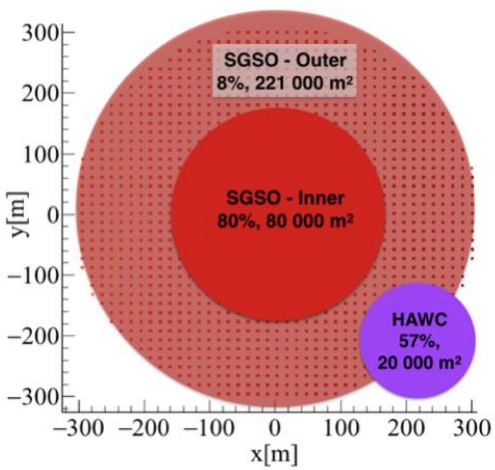

Current and Future WIMP Searches with the Fermi LAT, HAWC, and SWGO

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LA-UR-19-30966

Dark Matter searches in the 2020s

November 13, 2019

Images from the game Clue are used with permission by Hasbro Inc

Credit: SLAC Communications

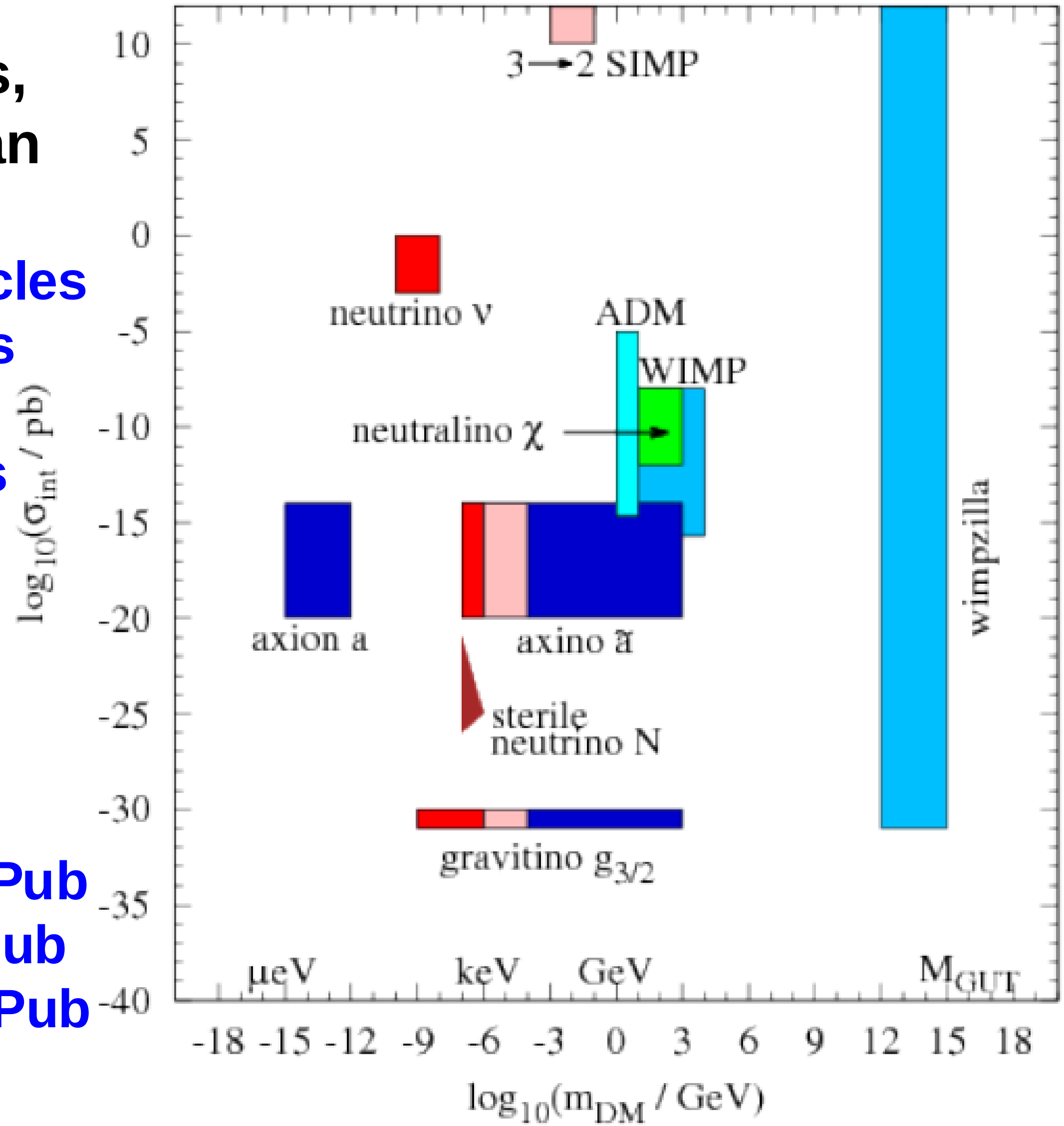
Who?
Where?
How?

Who?
Where?
How?

Dark Matter Candidates

- I will focus on WIMP results, but other DM candidates can leave cosmic signatures
  - axion and axion-like-particles couple to γ rays in B fields
  - x-ray lines from sterile ν
  - γ-ray lines from gravitinos
  - p-wave DM
  - Primordial black holes

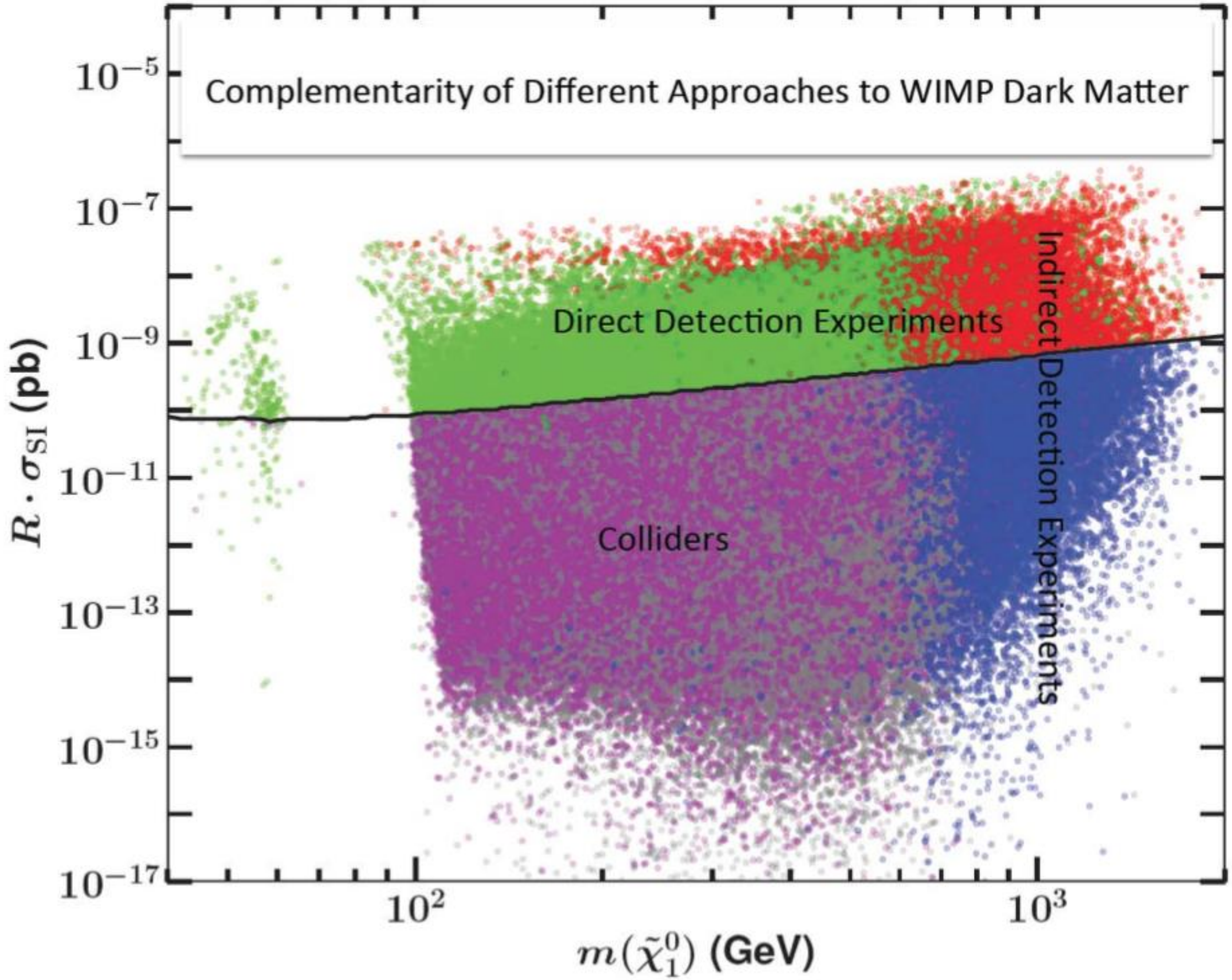
- Can find all DM and BSM searches online
  - https://tinyurl.com/HAWCPub
  - https://tinyurl.com/FermiPub
  - https://tinyurl.com/SWGOPub



Baer+ PR 555 (2015)

Dark Matter Search Complementarily

pMSSM 19-parameter scan of SUSY parameter space



Cahill-Rowley et al. (2013)

Dark Matter Search Complementarily

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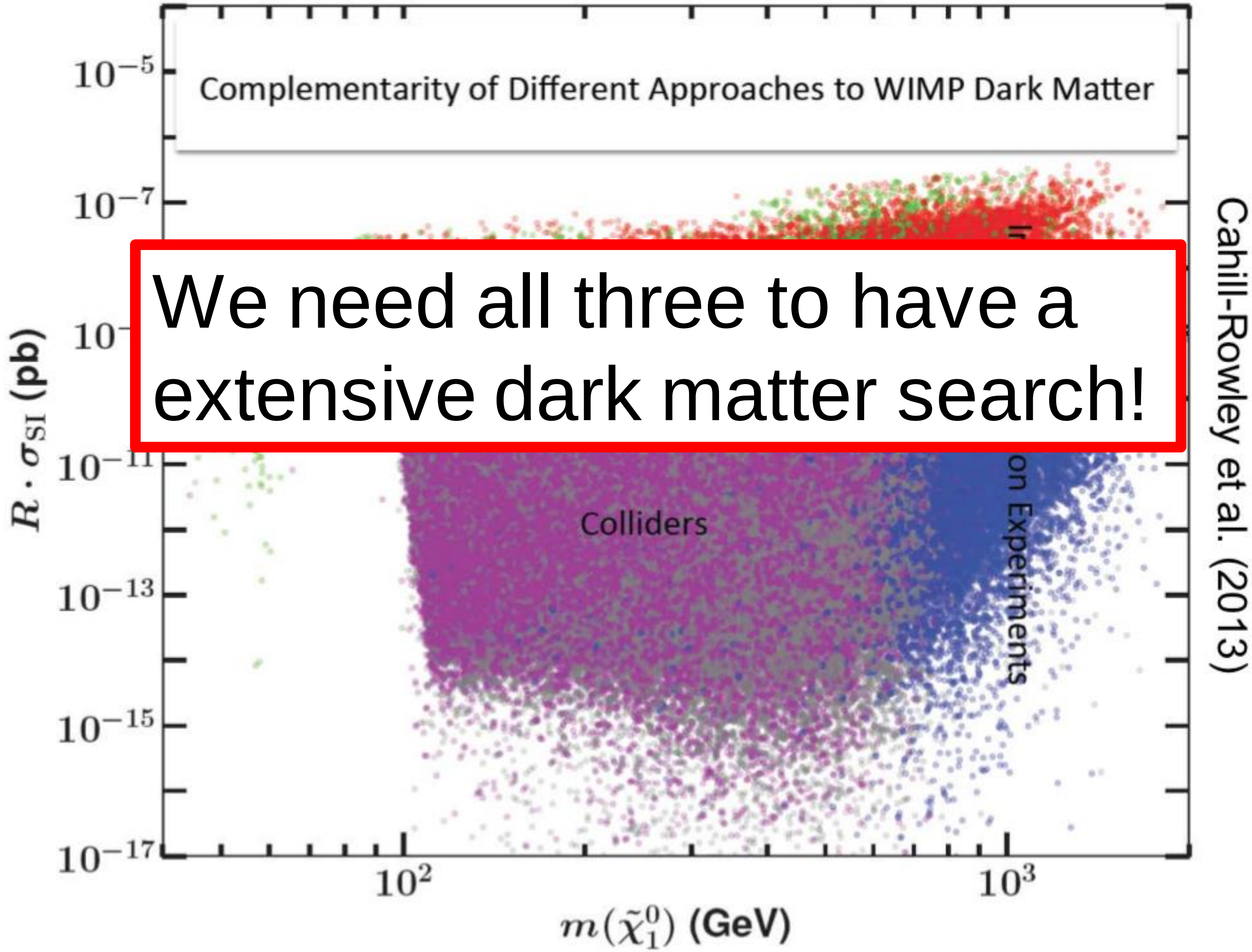
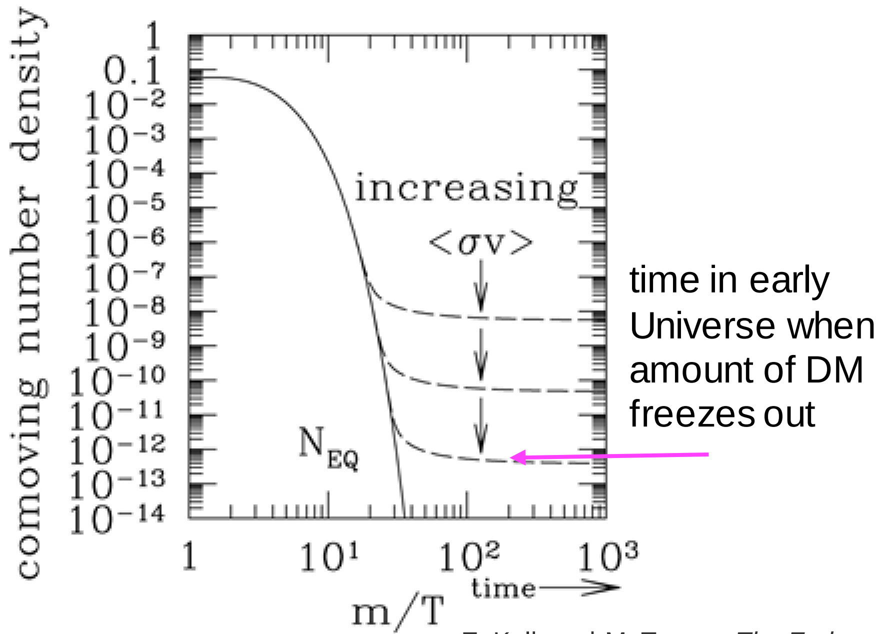


We need all three to have a extensive dark matter search!

Who?

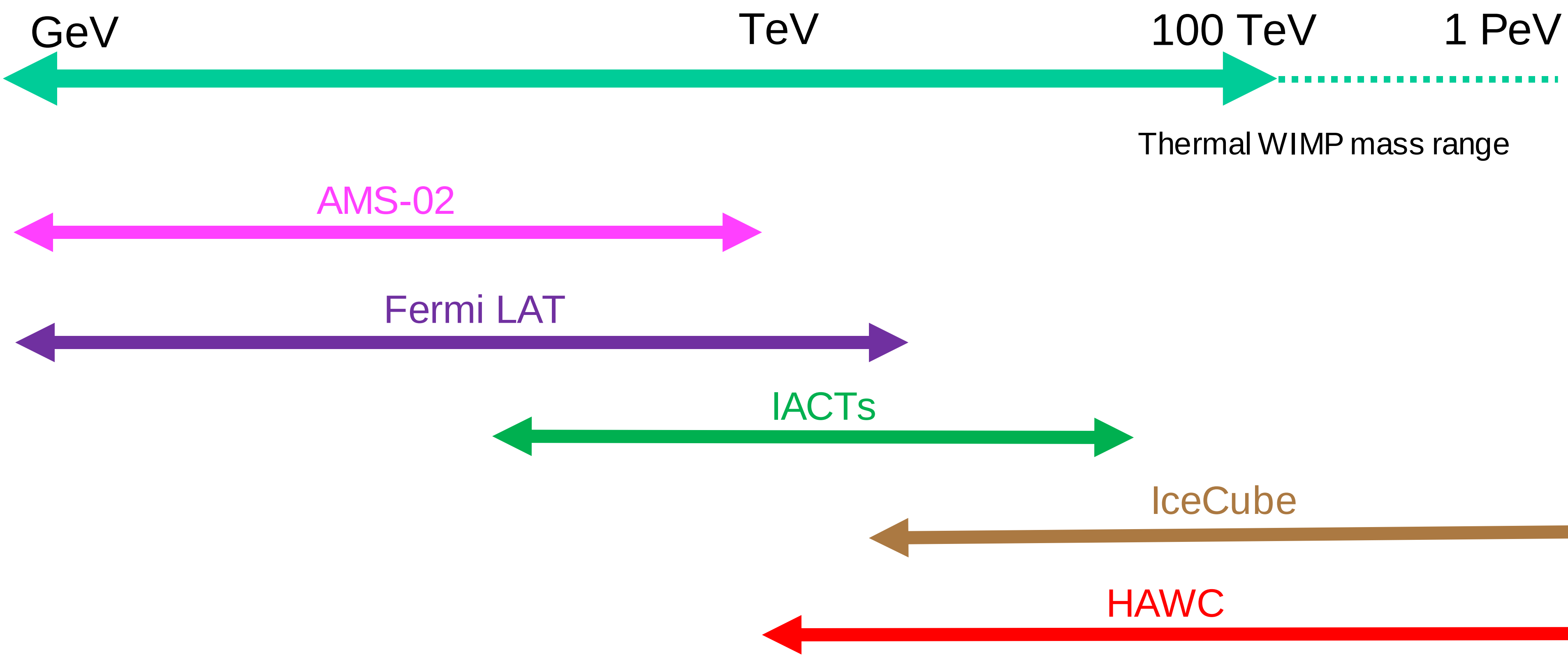
A Benchmark for Indirect Detection: Thermal WIMP Dark Matter



E. Kolb and M. Turner, *The Early Universe*, Westview Press (1994)

- **A particle in thermal equilibrium in early Universe with weak scale σ_{ann} independently predicts the observed DM relic abundance**
  - **$<\sigma v>_{ann} \sim 3\times10^{-26}$ cm^3/s**

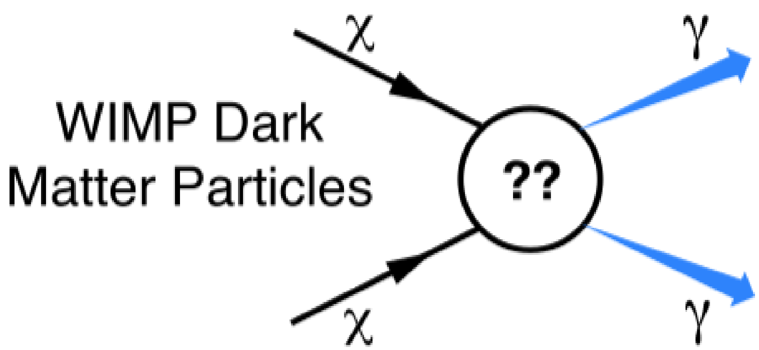
What's the mass?



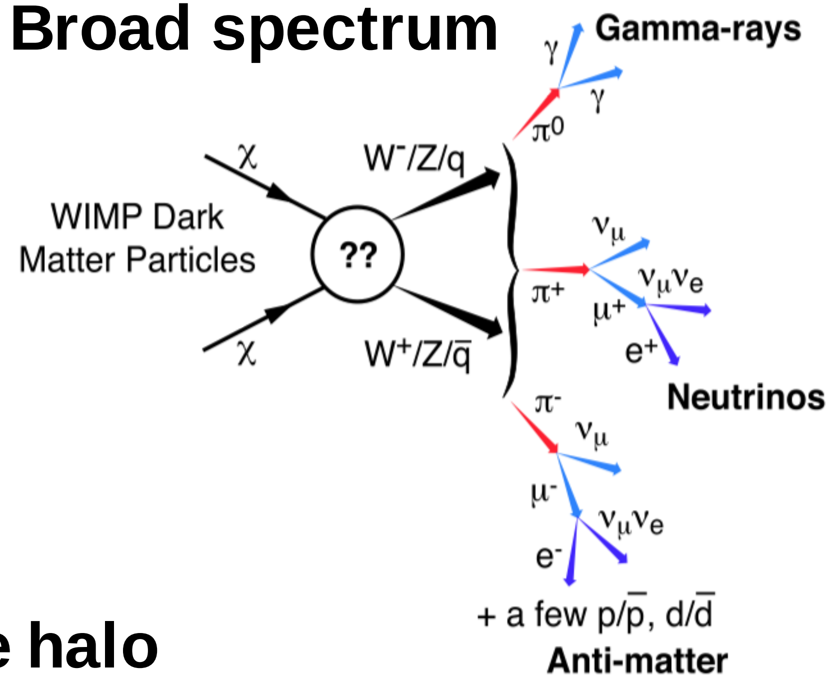
~100 TeV is the thermal WIMP unitarity bound (Smirnov and Beacom PRD 100, 043029 (2019))

Indirect Dark Matter Detection

Spectral line



Broad spectrum



- **The Milky Way sits in a large halo of cold DM (v_{DM} << c)**
  - **Expect additional DM overdensities (halos / subhalos)**
    - **e.g. Milky Way dwarf galaxies**
    - **e.g. Galaxy Clusters**
- **WIMP annihilations (decays) may produce gamma rays**

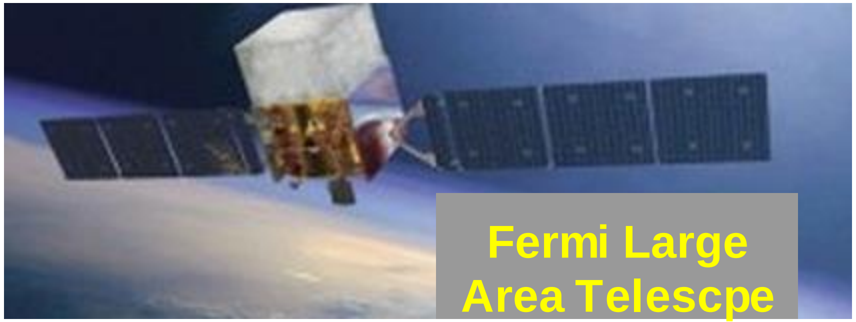
Current Gamma-ray Observatories

Tucson, Arizona
31° North Latitude, ~5° f.o.v.
~85 GeV to ~50 TeV

La Palma, Canary Islands
29° North Latitude, ~5° f.o.v.
~30 GeV to ~30 TeV

Khomas Highland of Namibia
23° South Latitude, ~5° f.o.v.
~30 GeV to ~100 TeV

Parque Nacional Pico de Orizaba, Mexico
19° North Latitude, ~2 sr f.o.v.
~50 GeV to >100 TeV, ~100% Duty Cycle



Low earth orbit (565 km)
28.5° orbital inclination, ~2 sr f.o.v.
20 MeV to > 300 GeV, ~100% Duty Cycle
(AGILE has similar technology, but has limited energy resolution)

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Imaging Air Cherenkov Telescopes (IACTs) have deeper exposure, good angular resolution, but a small field of view (~3% of the sky) and only operate at night in during good weather

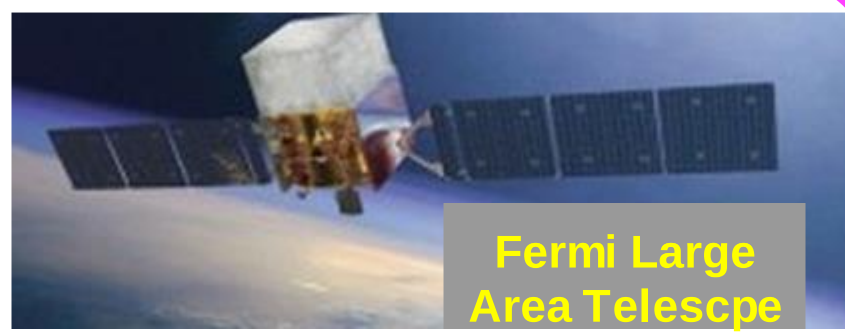
Pa
19
~50 GeV -- ~100 TeV, ~100% Duty Cycle

limited energy resolution)

Survey telescopes have a large field of view (~15% of the sky instantaneously), continuous monitoring, but some have lower effective area and poorer angular resolution than IACTs

Together, we can observe the gamma-ray sky across 7 decades of energy (20 MeV to >100 TeV)

Parque Nacional Pico de Orizaba, Mexico
19° North Latitude, ~2 sr f.o.v.
~50 GeV -- ~100 TeV, ~100% Duty Cycle



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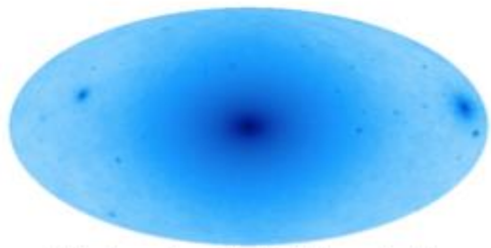
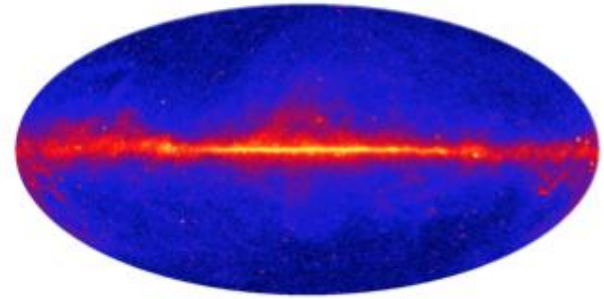
Overview of Results from Fermi LAT and HAWC

“GeV Excess” in the Galactic Center



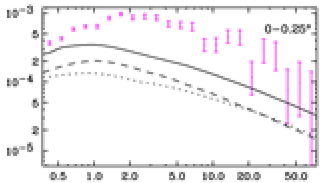
Via Lactea II, Kuhlen et al.,
Science 325:970-973,2009

?

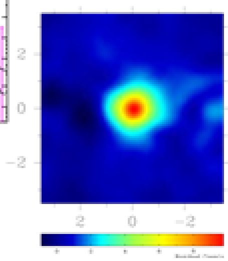


Fermi LAT >1 GeV, 6 years, Pass 8 data

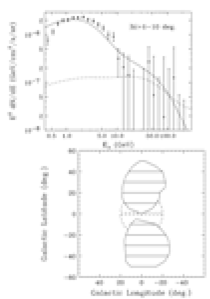
Excess emission spectrum peaks around 3 GeV



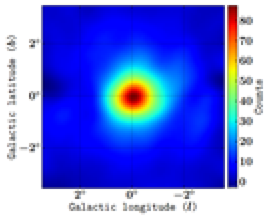
Goodenough & Hooper Phys.Lett. B697 (2011)



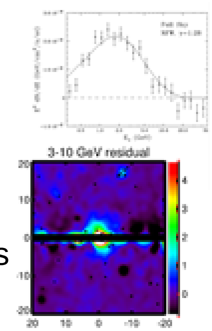
Abazajian & Kaplinghat PRD 87 129902 (2012)



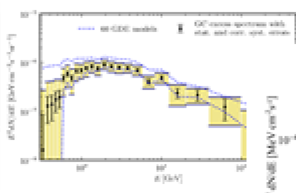
Hooper & Slatyer Phys.Dark Univ. 2 (2013)



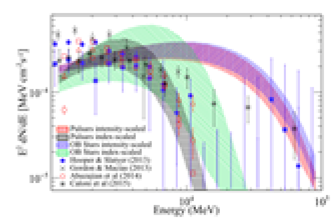
Gordon & Macias PRD 88, 083521 (2013)



Daylan et al. Phys. Dark Univ. 12 (2016)



Calore et al. JCAP 1503 (2015)

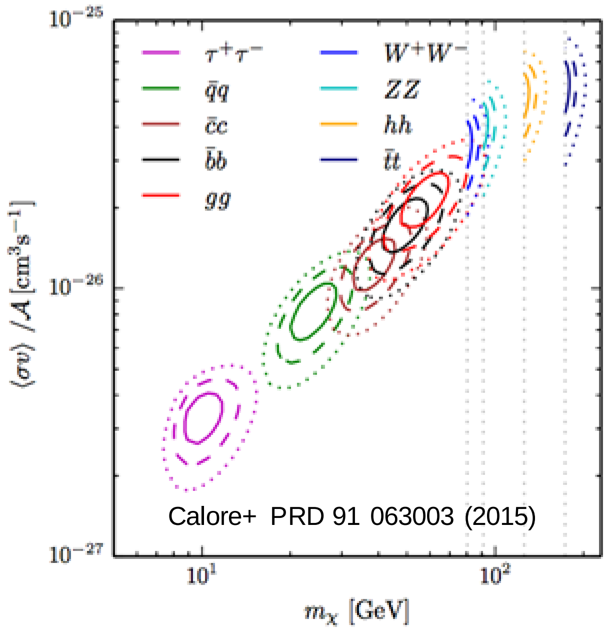


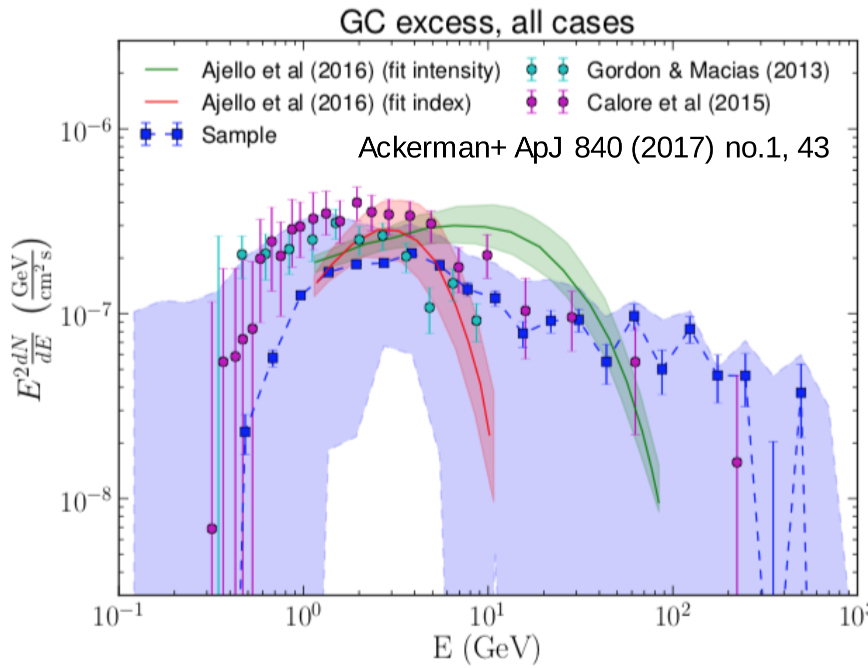
Ajello et al. (The Fermi-LAT Collaboration) ApJ 819 1 44 (2016)

Dark matter annihilation, unresolved sources, CR electrons?

- **Mirabal** (MNRAS 436 (2013) 2461), **Petrovic et al.** (JCAP 1502 (2015) 02,023), **Cholis et al.** (JCAP 1512 (2015) 12, 005), **Lee et al.** (PRL 116 051103 (2016)), **Bartels et al.** (PRL 116 051102 (2016)), **Brandt & Kocsis** (ApJ 812 (2015) 1, 15), **Carlson et al.** (arXiv:1510.04698) **etc.**

"GeV Excess" in the Galactic Center

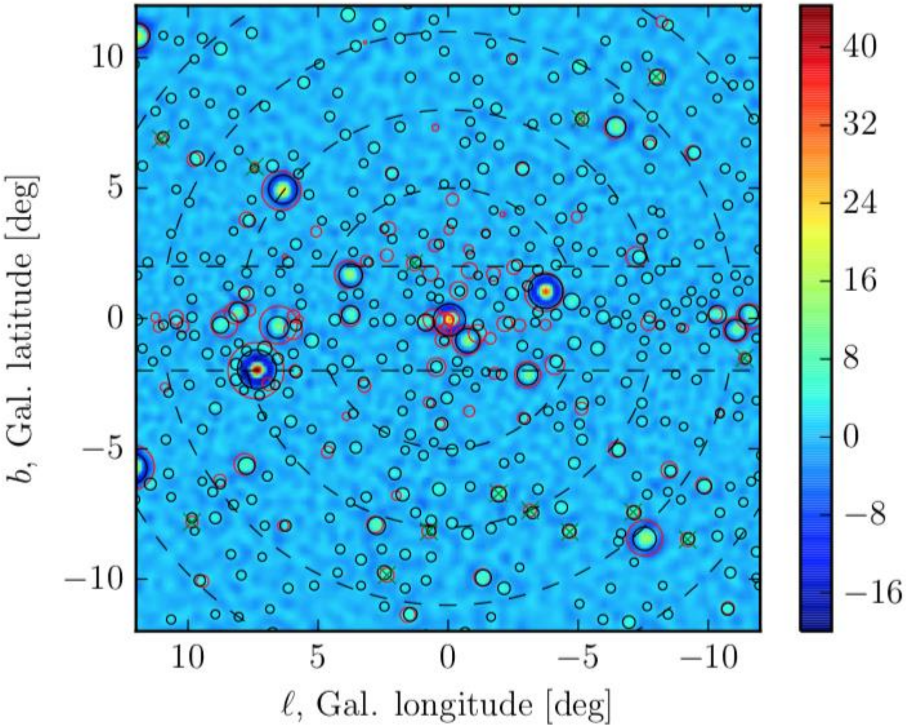




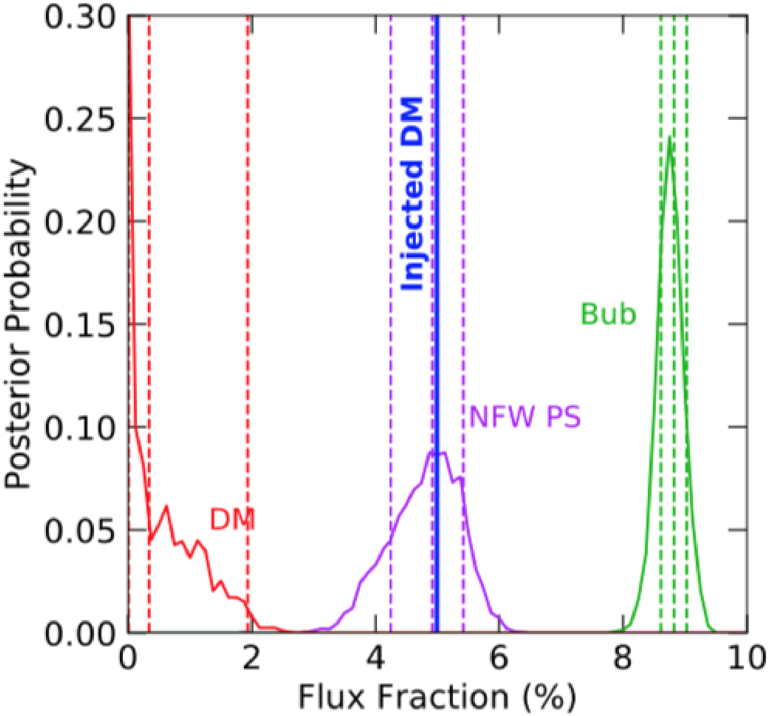
- **Excess of GeV gamma rays from the GC above standard models first detected by Goodenough & Hooper in 2009 in the Fermi Large Area Telescope data**
  - **If interpreted as DM annihilation, m_{DM} ~ 50 GeV with 'WIMP miracle' cross section**
- **Even when you use different GALPROP parameters, IC and gas models, and include low latitude Fermi bubbles, excess does *not* go away**
  - **Spectrum can change, but always peaks around 2 GeV**
- **Excess is correlated with the Galactic bulge**
  - **e.g. Macias+ Nature Astronomy 2 (2018) no.5, 387-392; Bartels+ Nature Astronomy 2 (2018) no.10, 819-828; Macias+ JCAP 1909 (2019) no.09, 042**

Point Sources or Smooth Distribution?

Bartels+ PRL 116, 051102 (2016)

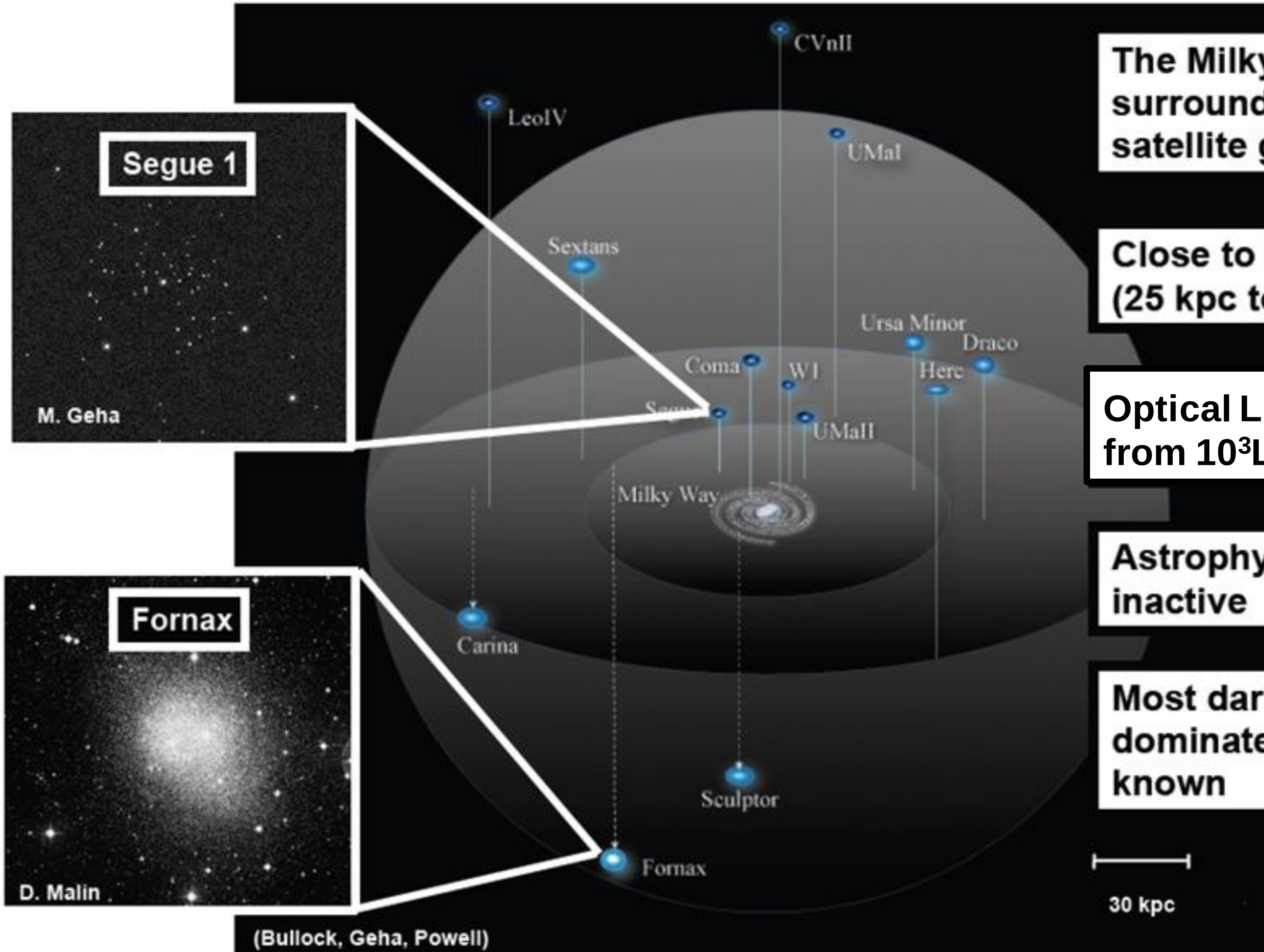


Leane+ MIT-CTP/5104 (2019)



- **Unresolved millisecond pulsars have been proposed to explain the GeV excess**
  - **Actual distribution would be point sources for MSP and smooth for DM**
- **Evidence, like a wavelet analysis and non-poissonian fitting, has suggested its unresolved point sources**
- **However, recent study (Leane+ MIT-CTP/5104 2019) shows the non-poissonian technique would incorrectly identify DM as point sources**

Milky Way Dwarf Spheroidal Galaxies



The Milky Way is surrounded by small satellite galaxies

Close to Earth (25 kpc to 250 kpc)

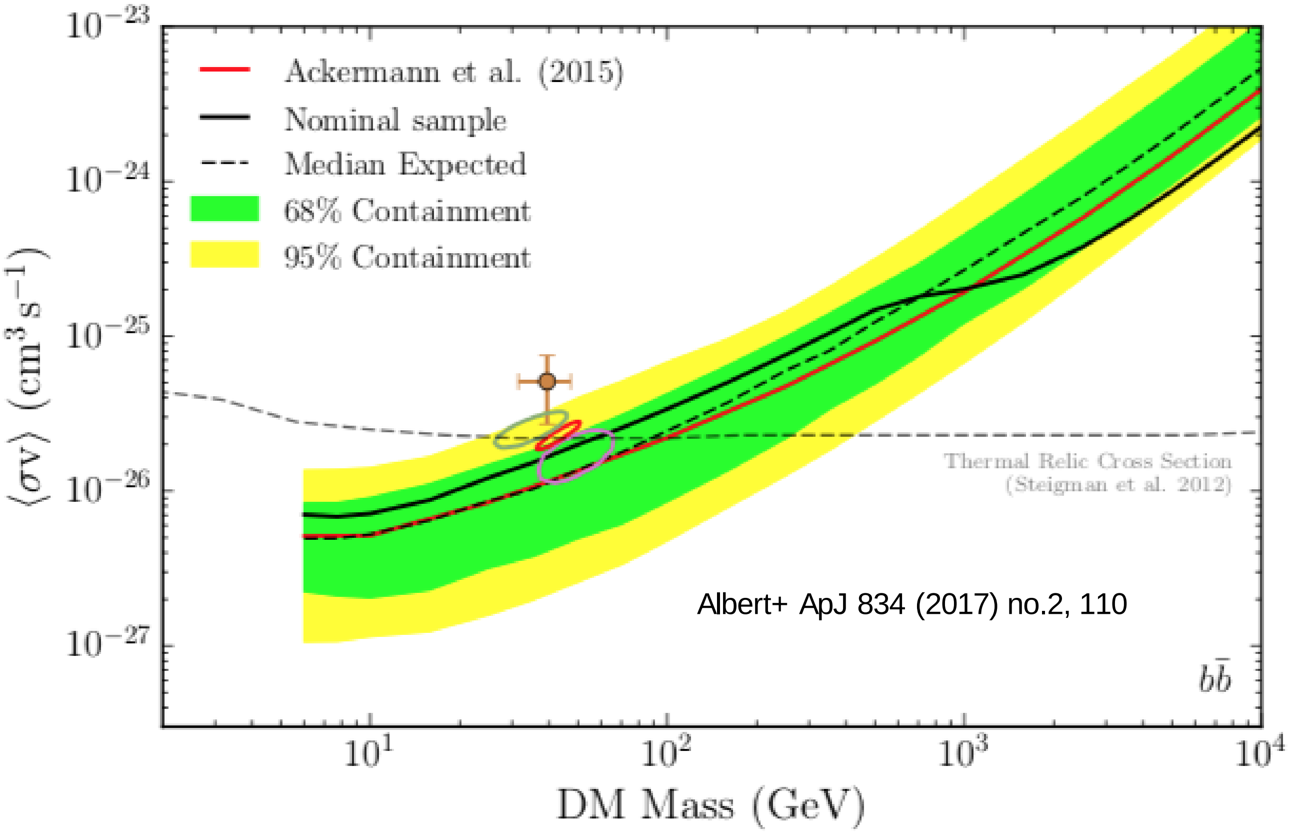
Optical Luminosities from $10^3 L_\odot$ to $10^7 L_\odot$

Astrophysically inactive

Most dark matter dominated objects known

A.Drlica-Wagner
DPF 2013

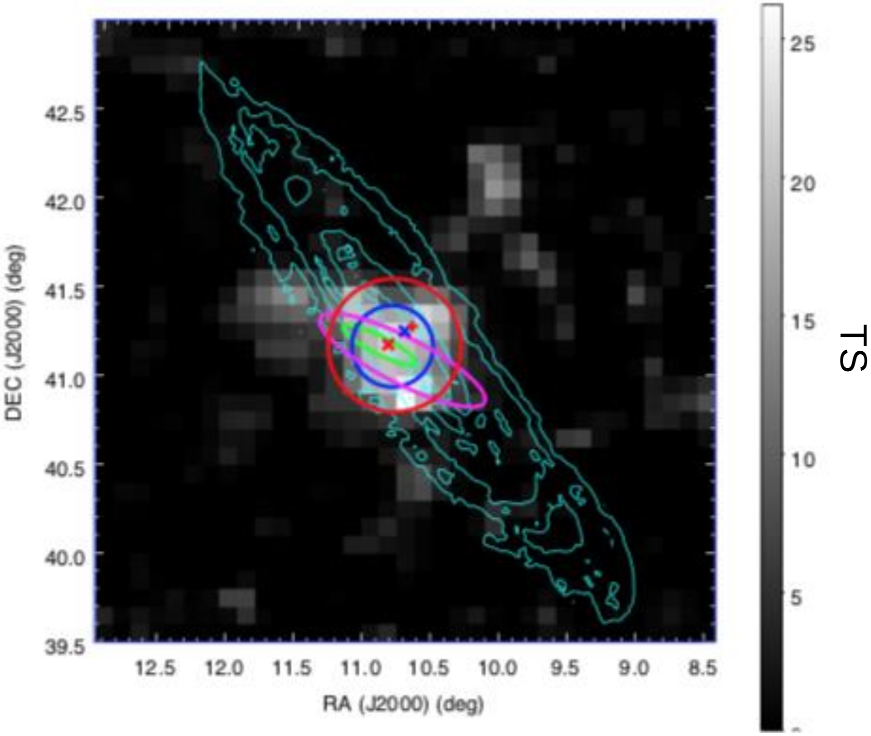
6 year Fermi LAT dSphs Results

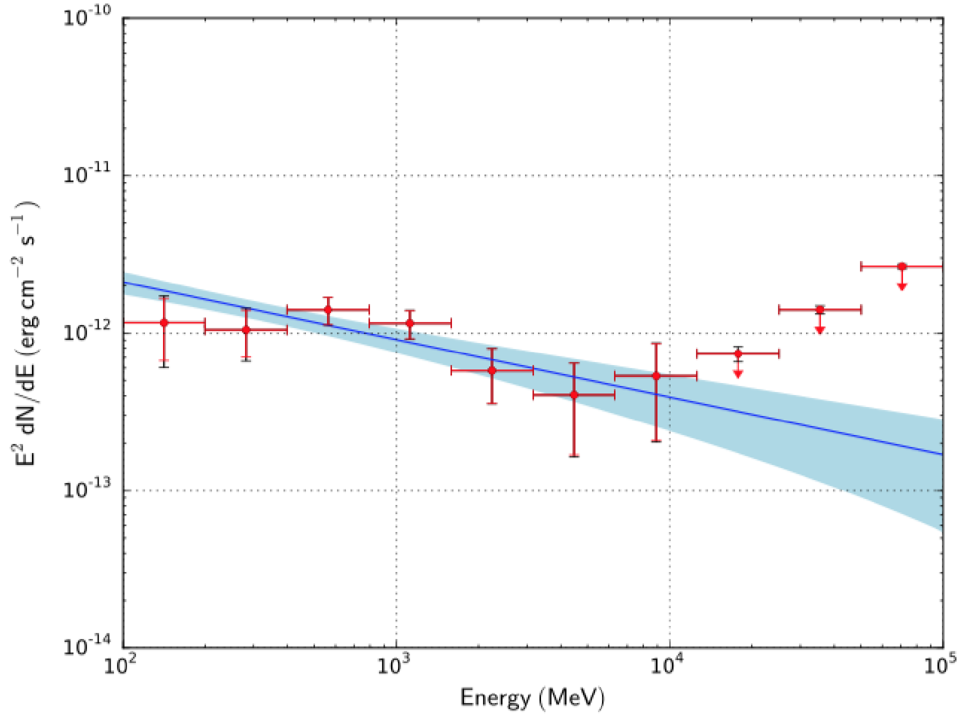


- **Red -- Joint likelihood limit of 15 well characterized dwarf galaxies**
- **Black -- Joint likelihood limit of 40 dwarfs including those with unknown or unconstrained J-factors**
  - **Includes 24 newly discovered dSphs**
- **dSph limits are starting to constrain the DM interpretation of the GC excess**

GeV Emission from M31

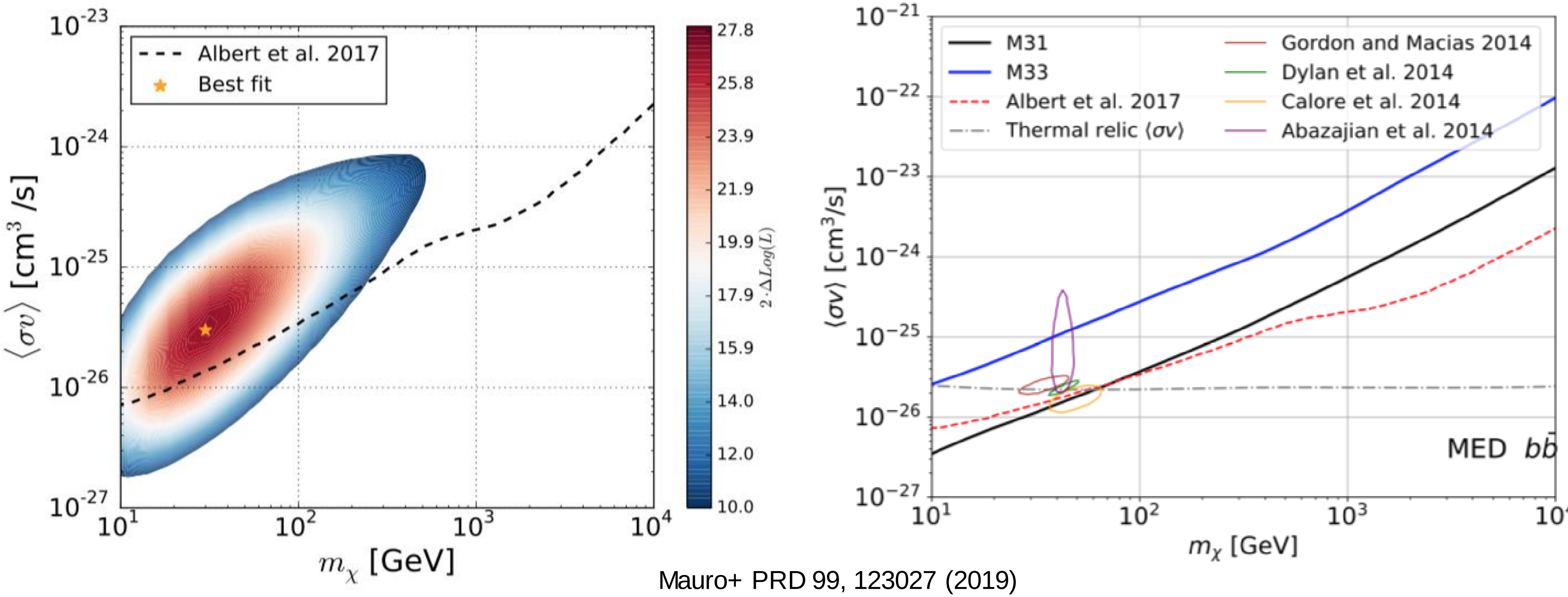
Ackerman+ ApJ 836 (2017) no.2, 208





- **M31 detected by Fermi-LAT at 10σ with evidence of extension (0.4 degrees) at 4σ**
- **Emission is correlated with central bulge, not atomic gas**
- **Spectrum is consistent with a power law index = 2.4**

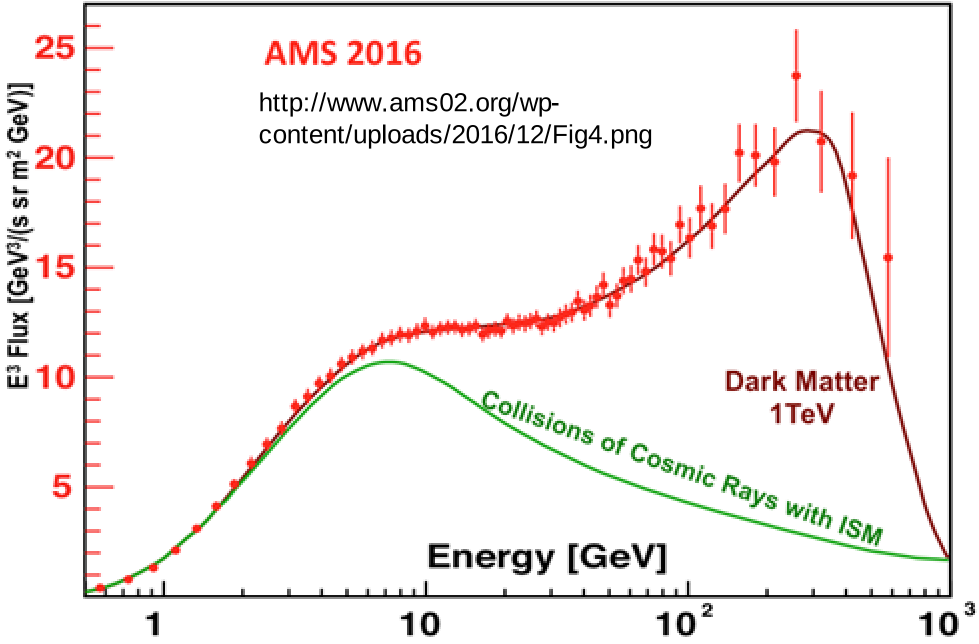
Is the M31 Emission from DM?

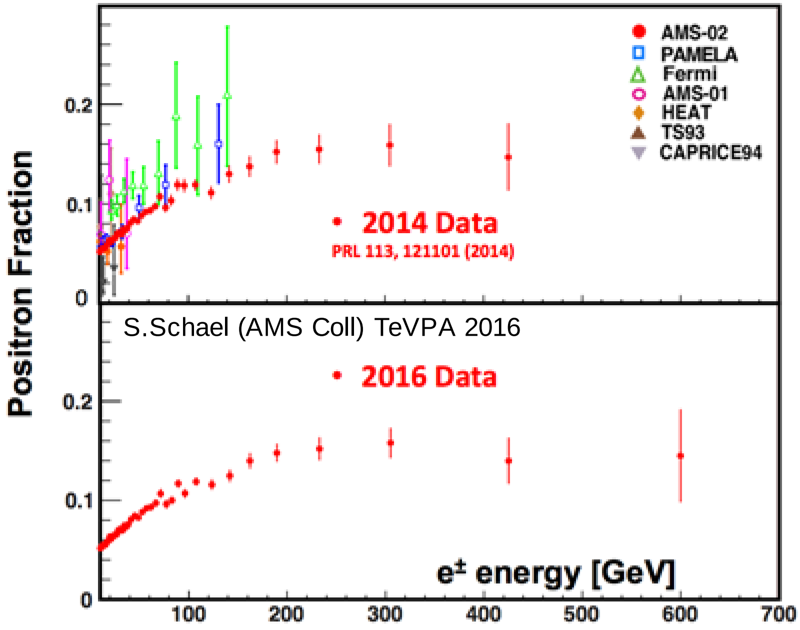


Mauro+ PRD 99, 123027 (2019)

- **DM only interpretation of M31 emission is mostly excluded by dSph limits**
- **When accounting for additional non-DM astrophysical sources, no significant DM excess is seen**
  - **ISM gamma-ray models tuned on data from other wavelengths**
    - **Herschel/PACS map at 160 μm, the Spitzer/IRAC map at 3.6μm, and the atomic gas column density NH map**

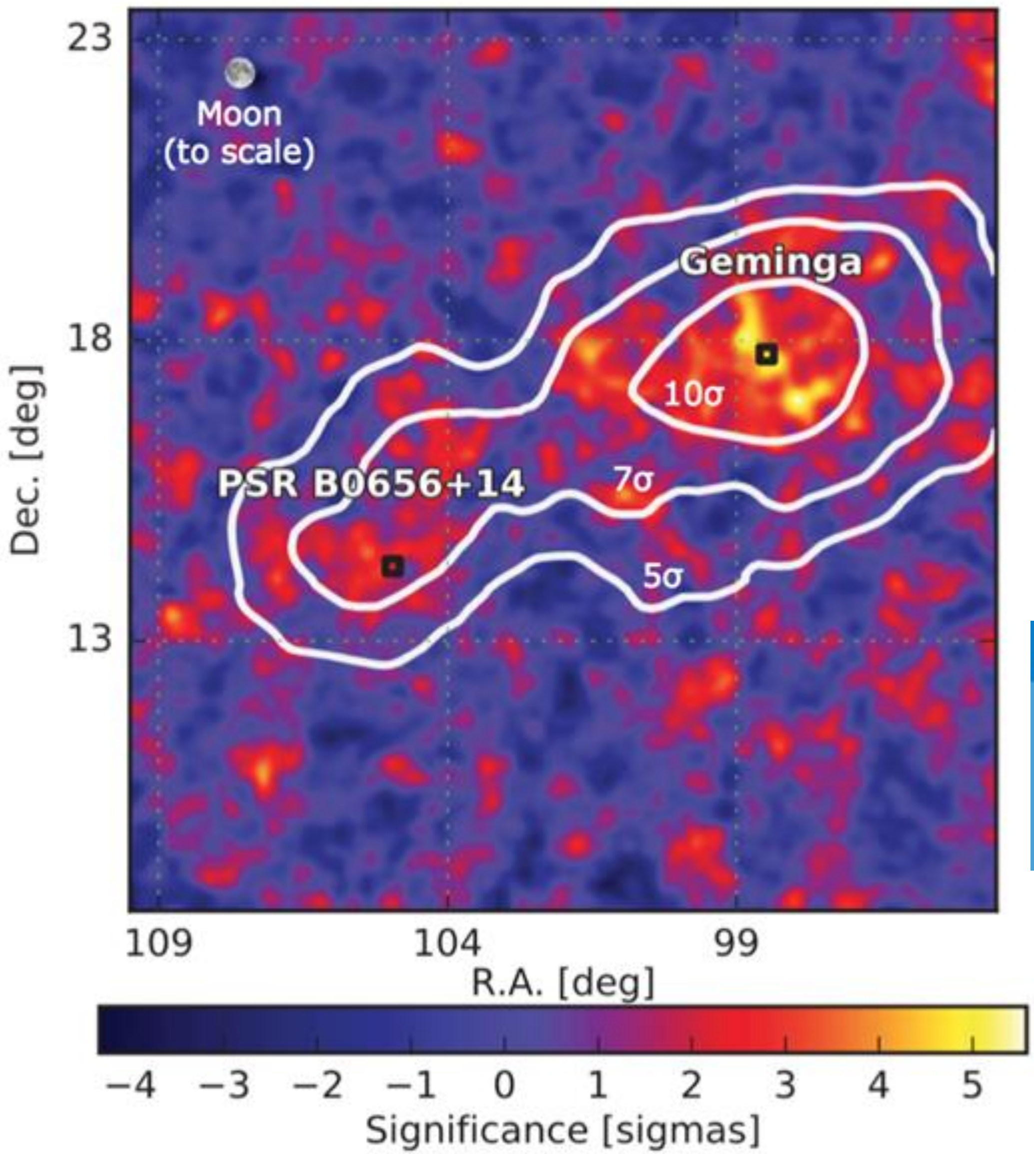
Local Positron Fraction Mystery





- AMS-02 on board the International Space Station observes local cosmic rays since 2011
- TeV e^-e^+ lose energy quickly and therefore must be produced locally (d < ~100 pc)
  - *secondaries* produced by cosmic ray interactions with ISM (spallation)
  - *primaries* produced by local source (Geminga? Dark matter?)
- Larger positron flux observed above ~10 GeV than expected from secondaries
  - First observed by Pamela in 2009, since confirmed by Fermi LAT and AMS-02
  - Are they from a local cosmic accelerator or dark matter?

HAWC Observations of Geminga and Monogem

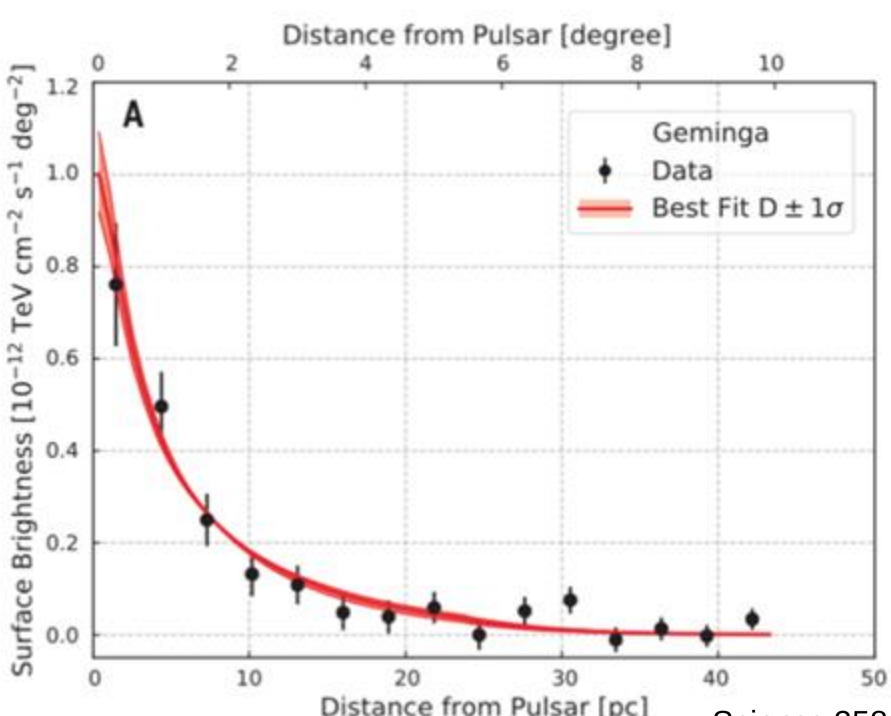


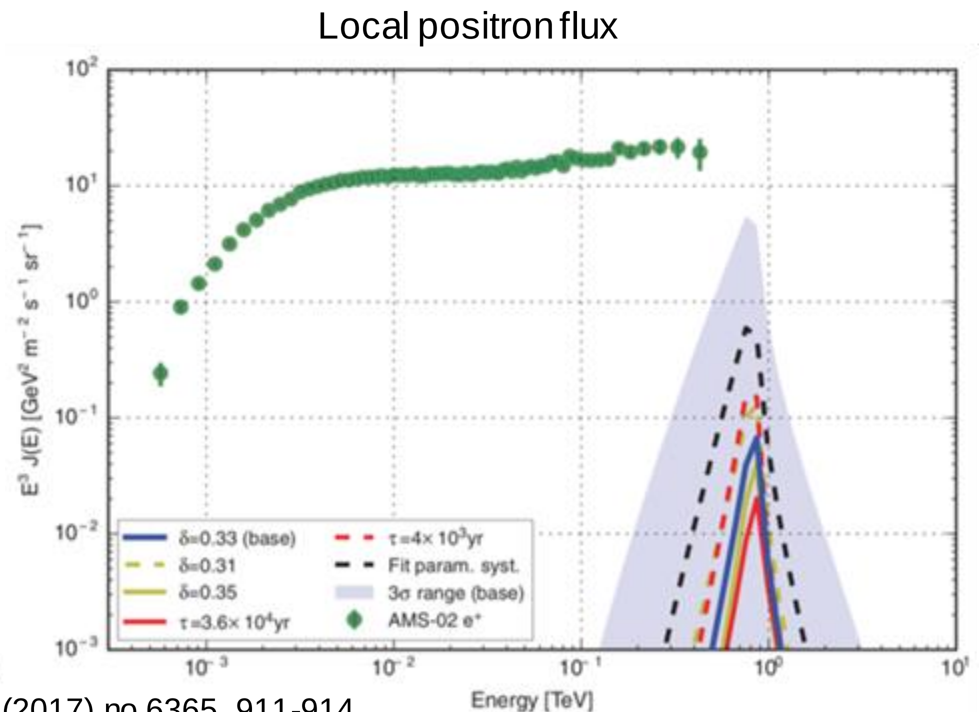
- **HAWC observes extended emission from both the Geminga and Monogem (PSR B0656+14) pulsars**
- **These are both nearby, middle-aged pulsars that could be producing the observed local positrons**

	Geminga	Monogem
Ė [erg/s]	3.2×10^{34}	3.8×10^{34}
Age [yr]	3.42×10^{5}	1.1×10^{5}
Dist. [pc]	250	288

Science 358 (2017) no.6365, 911-914

Electron/Positron Diffusion Coefficient

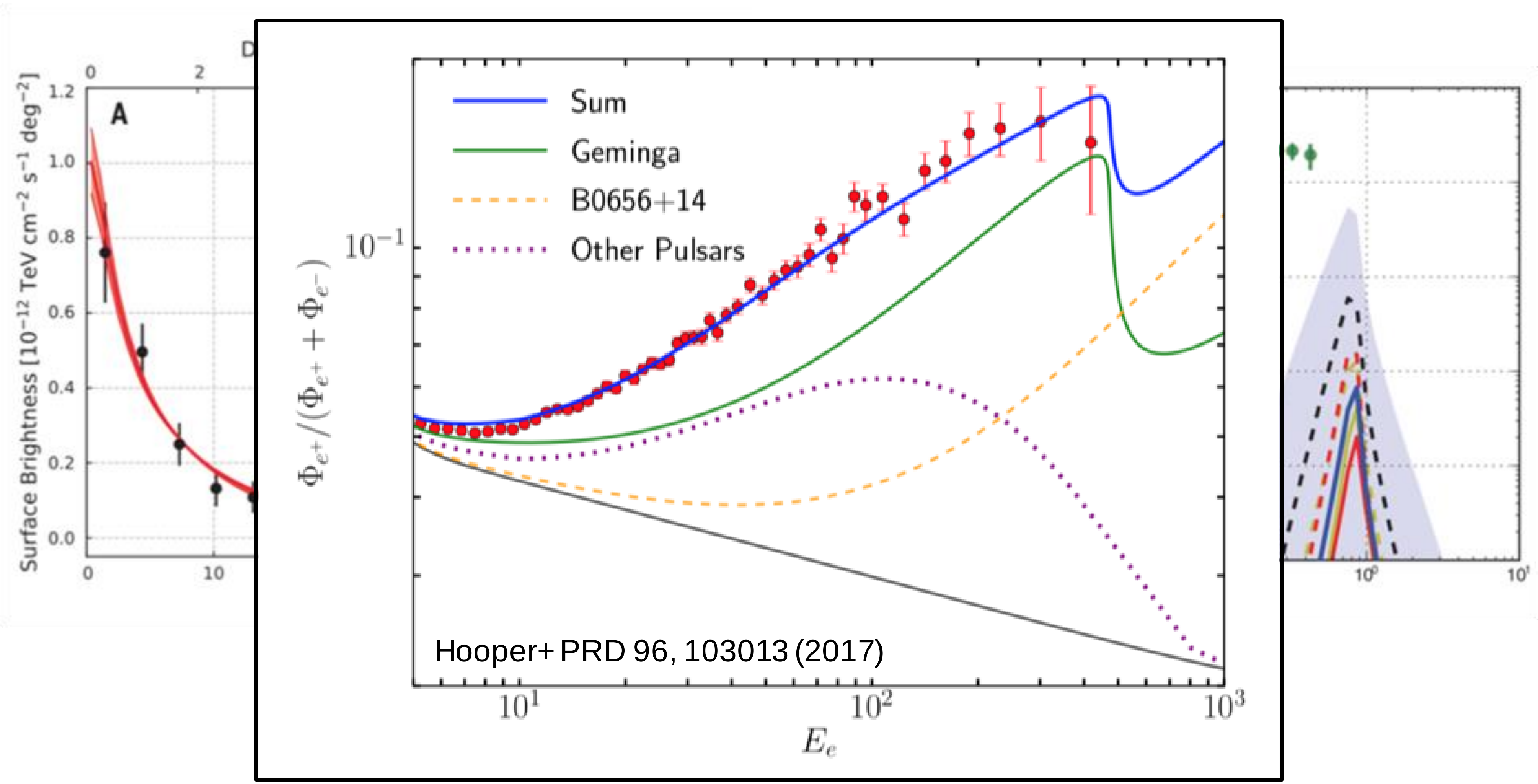




Science 358 (2017) no.6365, 911-914

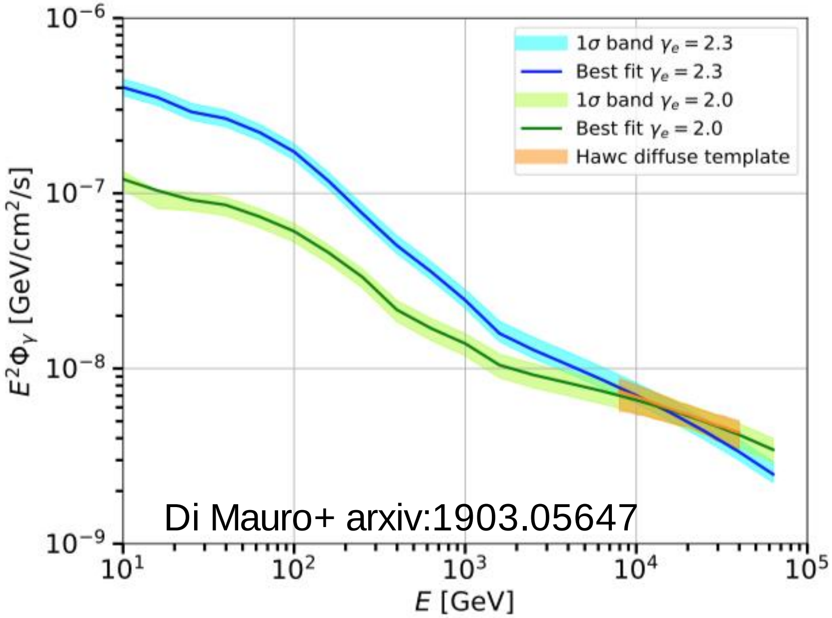
- **TeV radial profile → measurement of e^+e^- diffusion at the source**
- **Measured diffusion at 100 TeV is ~100 times smaller than the ISM diffusion derived from the B/C ratio**
  - **$D_{100TeV} = 4.5 \pm 1.2 \times 10^{27}$ cm^2/s**
- **Using the measured diffusion coefficient , e^+/e^- cannot reach Earth and Geminga/Monogem do not explain the positron excess**
  - **Assume diffusion coeff is constant from source to Earth**

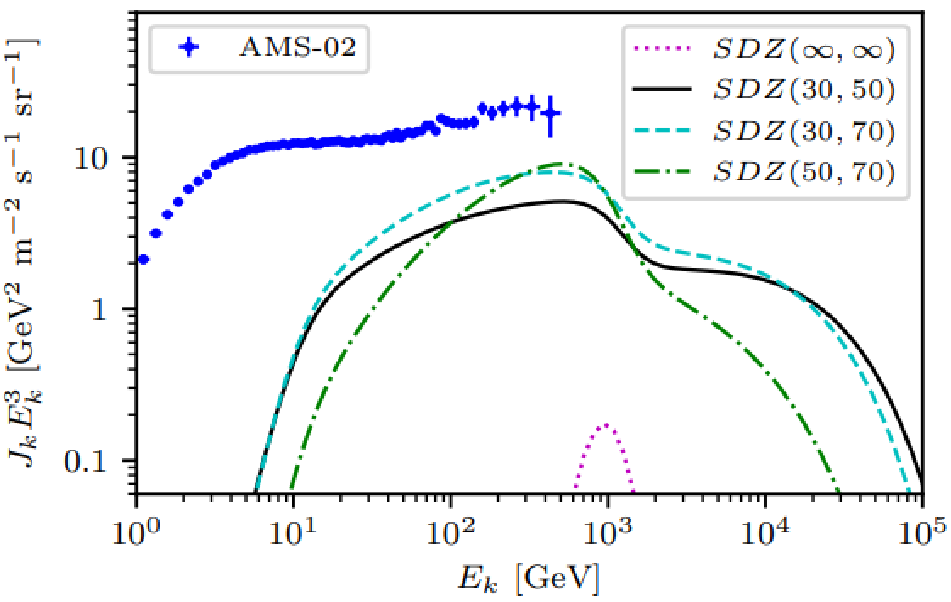
Electron/Positron Diffusion Coefficient



- **But, if you use a variable diffusion coefficient, the positrons can reach Earth and explain the positron excess**
  - **D. Hooper+ PRD 96, 103013 (2017); K. Fang+ ApJ 863 (2018) no.1, 30; S. Profumo+ PRD 97, 123008 (2018)**

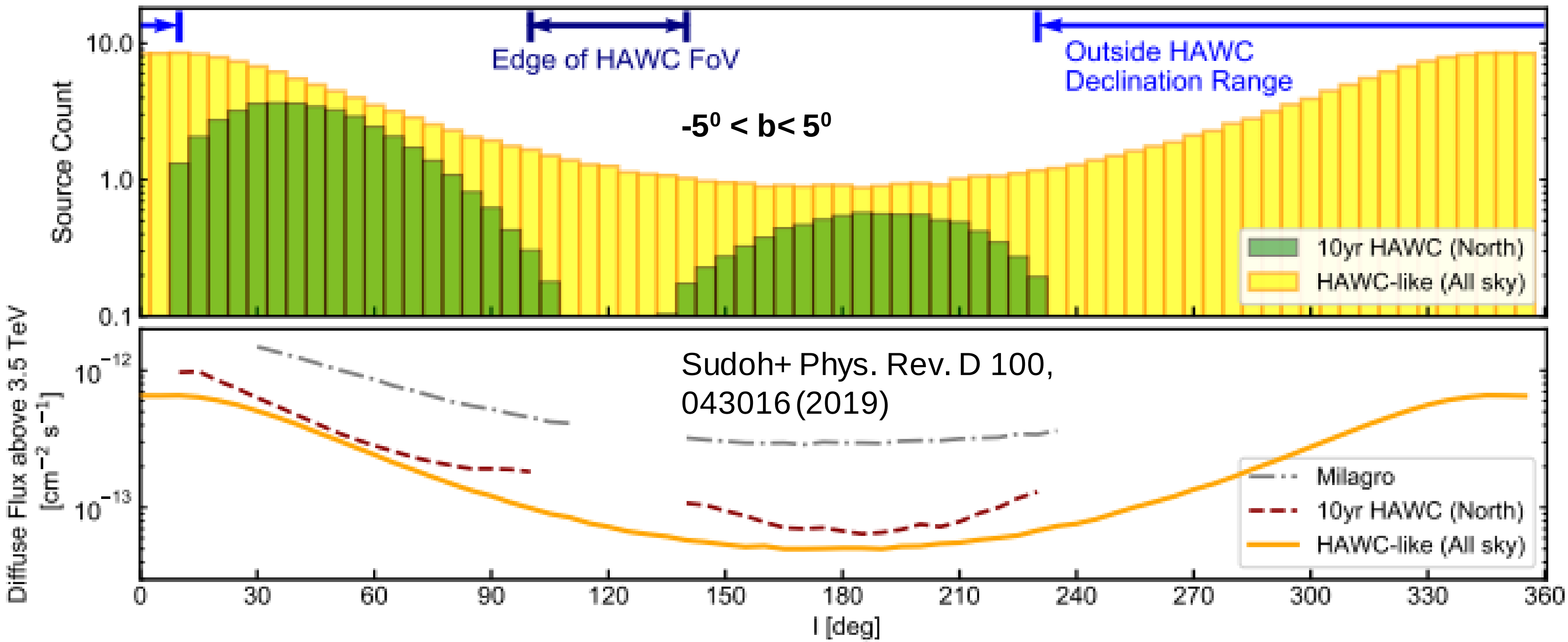
Fermi-LAT Observations of Geminga





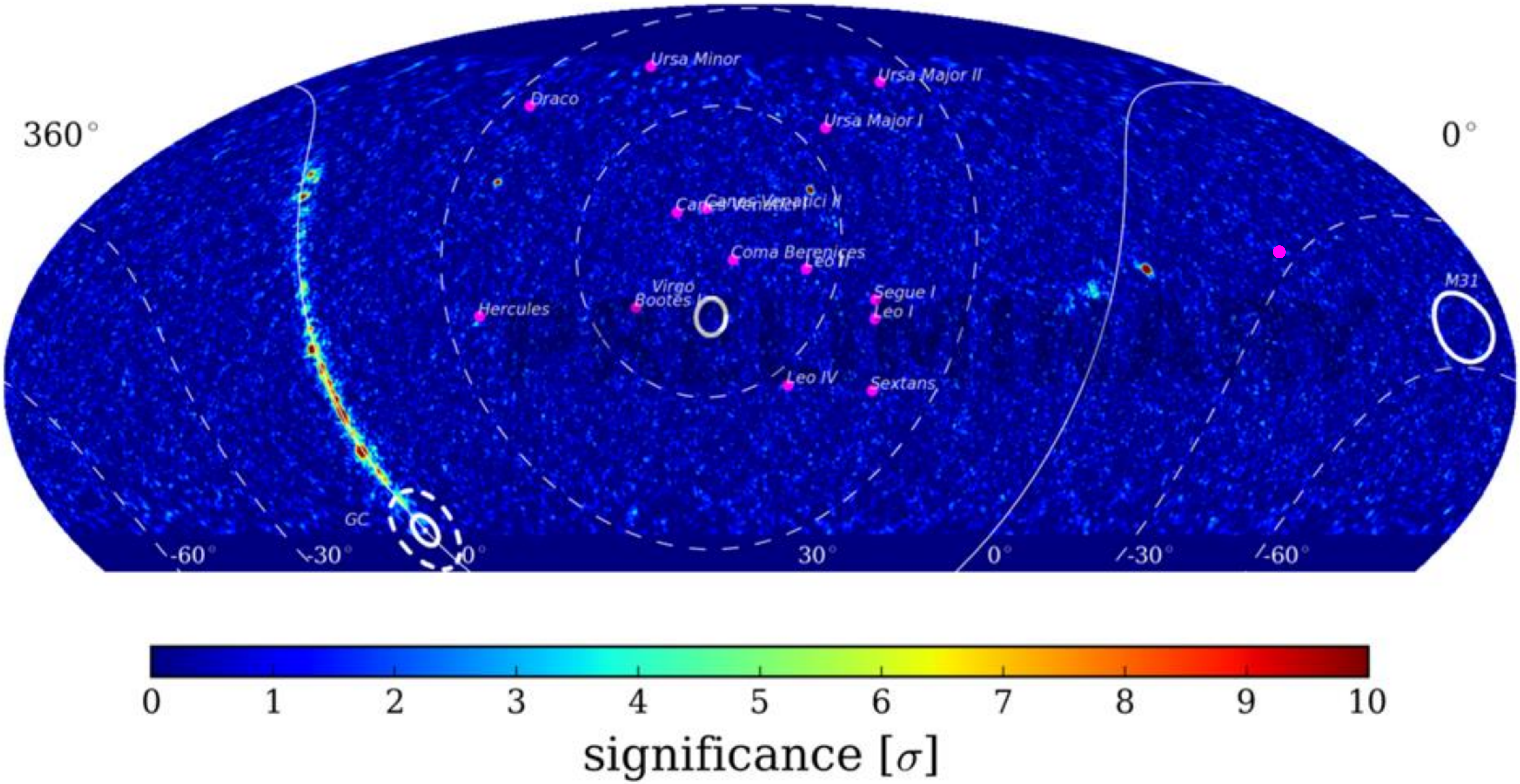
- **Geminga is detected at ~10σ as an extended object with Fermi LAT**
- **CR injection function is not well-constrained by HAWC data, but can be at GeV energies with Fermi LAT**
  - **CR injection is degenerate with size of diffusion zone**
- **Depending on propagation and injection models, Fermi data shows Geminga can produce up to 20% of the AMS-02 positron excess**

Predicted Future TeV Halo Detections



- **Extended TeV emission from pulsar wind nebula are a new class of objects: TeV Halos**
  - **Able to detect pulsars without radio pulses**
- **10 years of HAWC observations are predicted to find ~70 new TeV halos**
  - **Future discoveries will expand our knowledge about these sources**

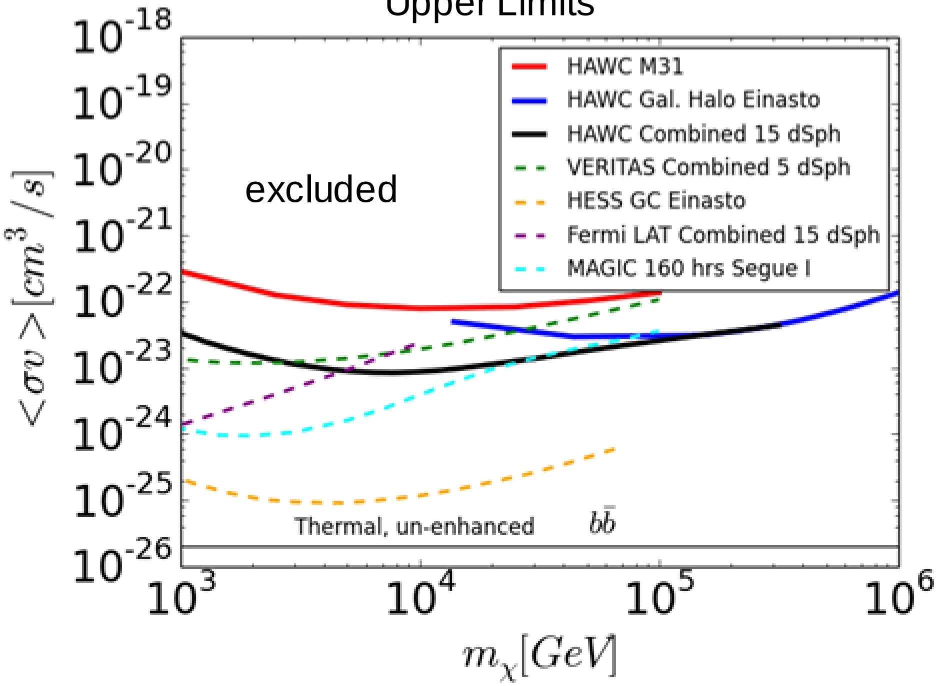
HAWC Dark Matter Targets



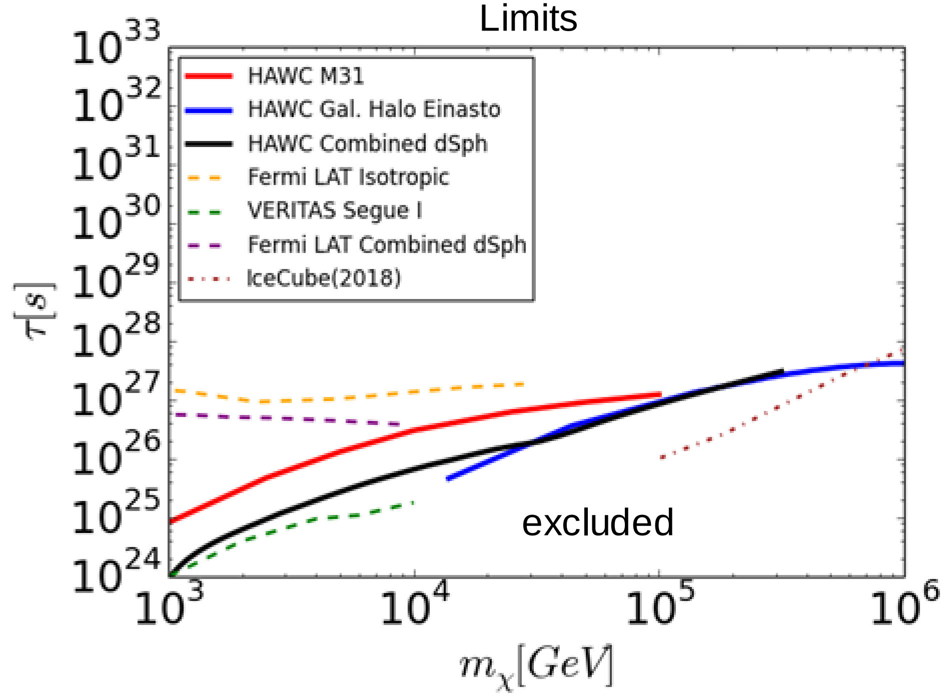
- **HAWC has a wide field of view making it sensitive to extended objects**
- **HAWC surveys ⅔ of the sky every day, including several DM targets**

Dark Matter Limits -- tau$^+$tau$^-$

DM Annihilation Cross Section Upper Limits



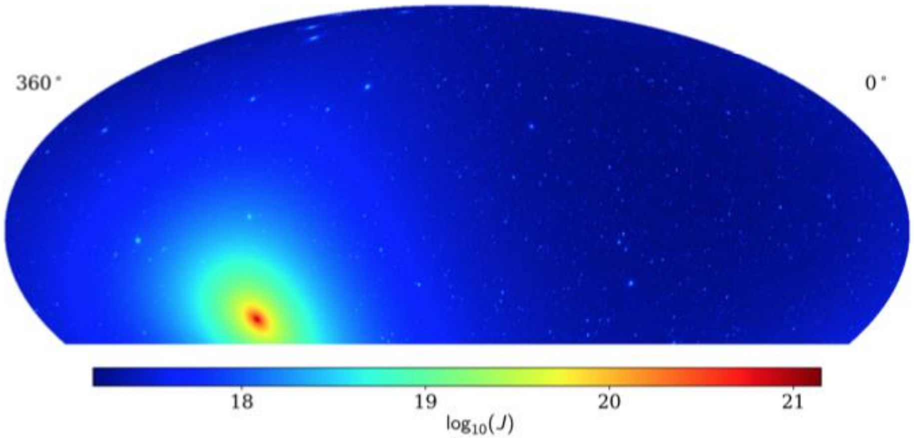
DM Decay Lifetime Lower Limits



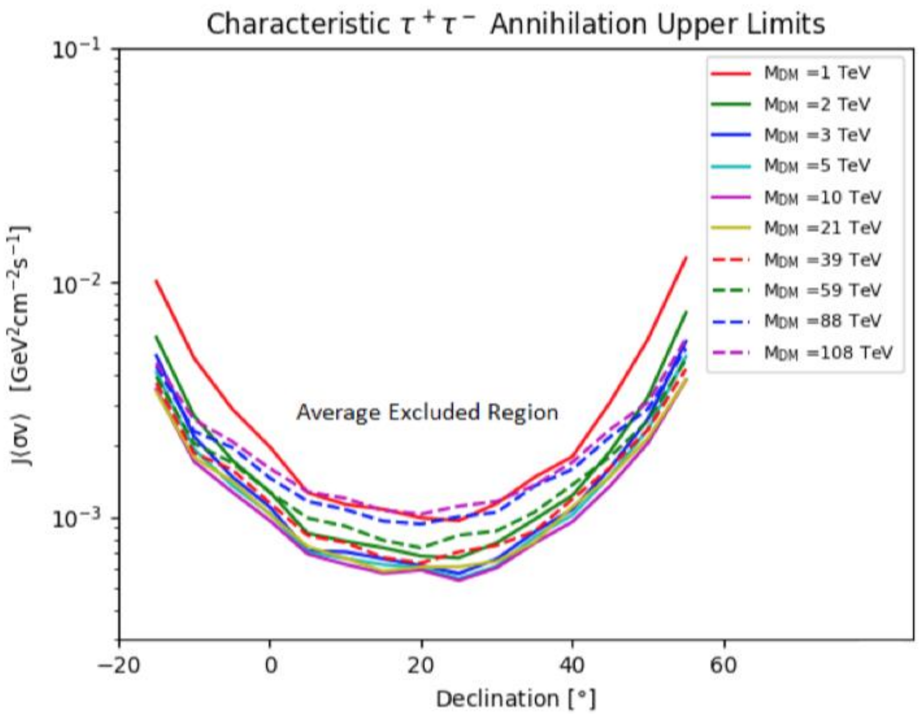
HAWC M31: Albert+ JCAP 1806 (2018) 043 , HAWC Gal Halo: Abeysekara+ JCAP 1802 (2018) 049
HAWC dSph: Albert+ ApJ 853 (2018) no.2, 154

- **No gamma-ray excess detected in any target**
- **Limits set on DM annihilation cross section and decay lifetime**
  - **Able to see extended objects (e.g. Galactic Halo)**
- **Only gamma-ray limits published from 100 TeV to 1 PeV**

Search for DM substructure

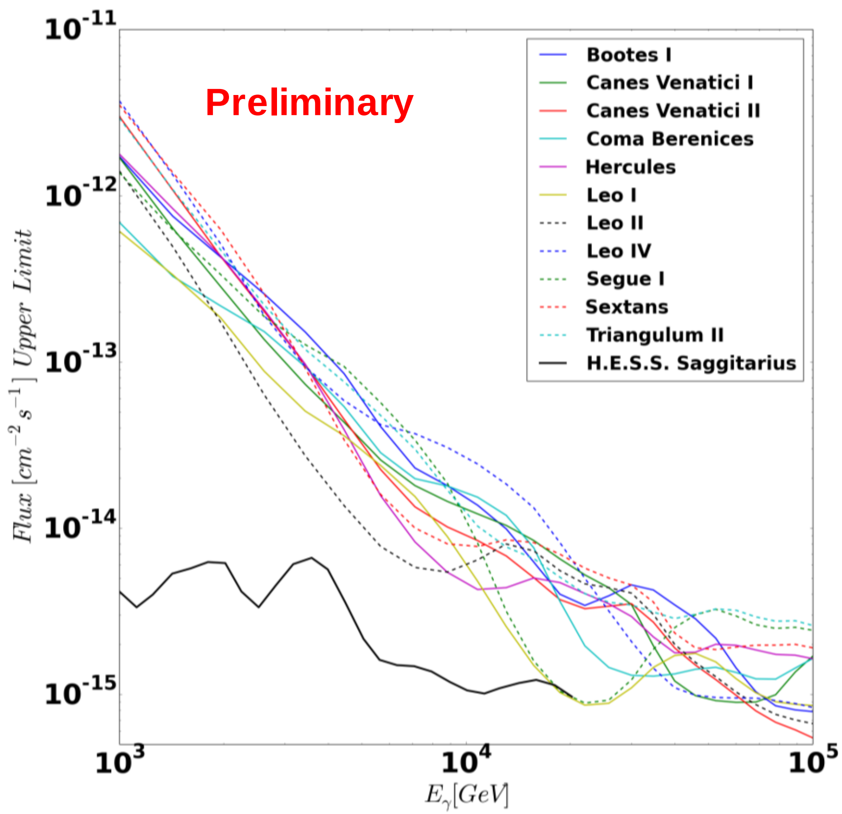


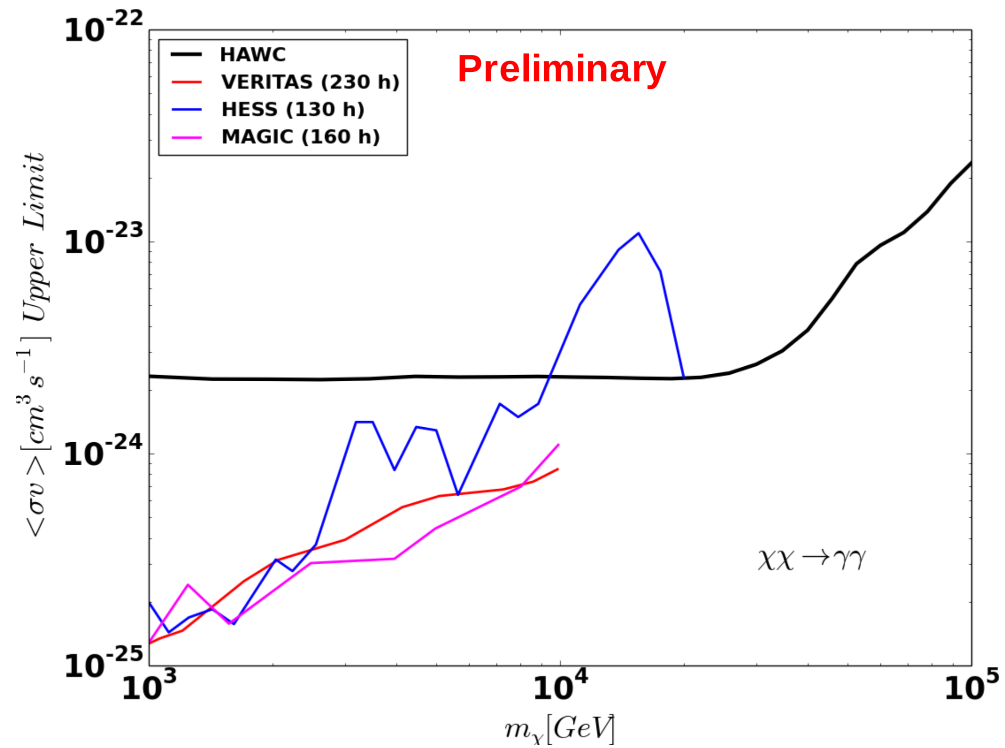
Abeysekara+ JCAP 1907 (2019) 022



- **Know the Milky Way halo contains substructure (dSphs)**
  - **Various simulations predict different amount of substructure**
- **No point sources detected significantly preferred DM models**
- **Calculate characteristic limits at all declinations**
  - **These can be used to calculate HAWC limits for any DM model**

HAWC Spectral Line Search



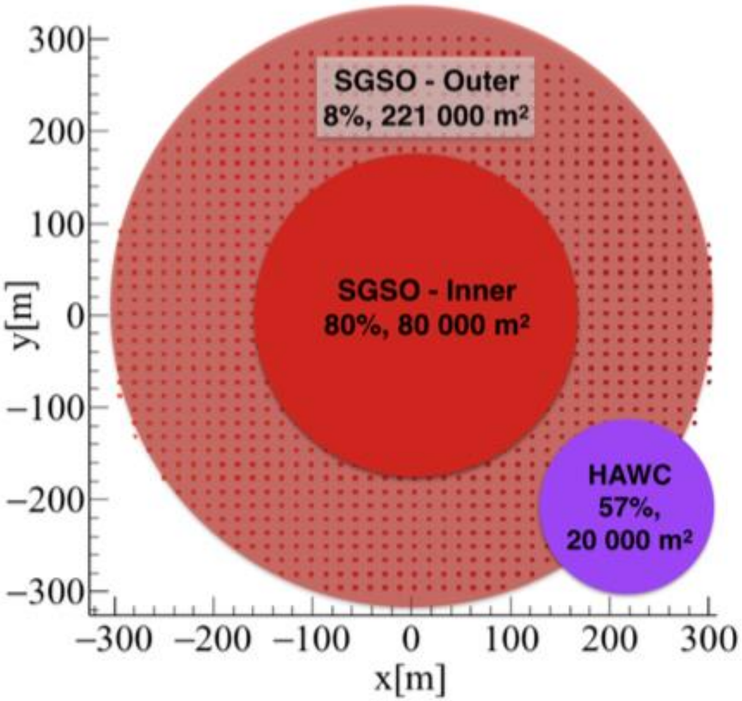


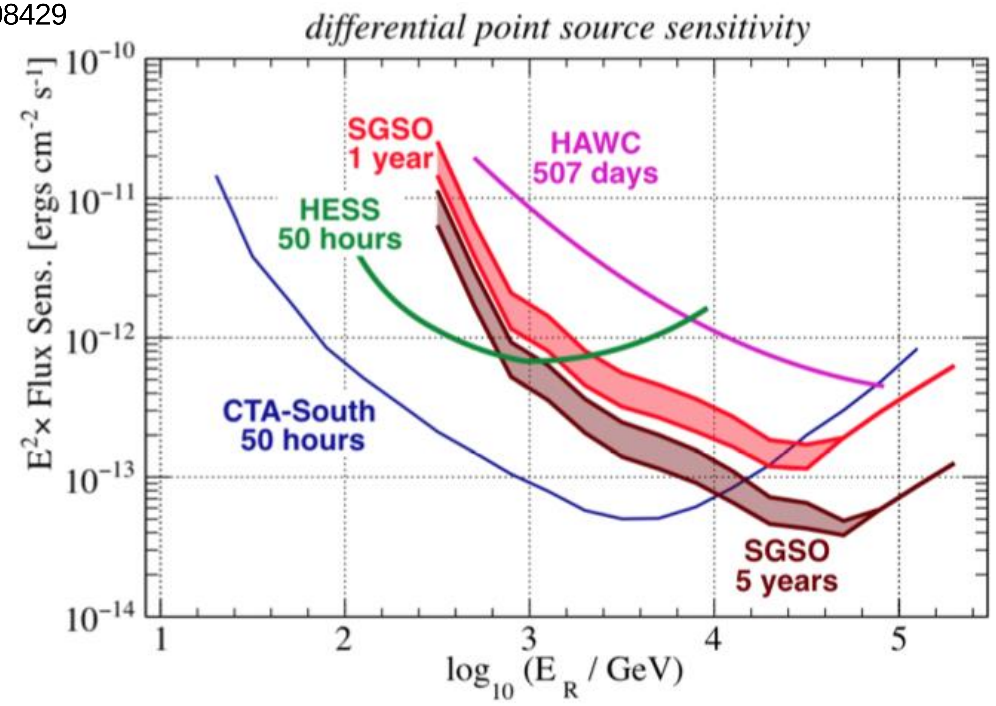
- DM annihilation directly to gamma rays produces a spectral line at the DM mass
- HAWC line search explores 20 -- 100 TeV for the first time
- HAWC DM line limits are the strongest from 10 – 100 TeV

Future Gamma Ray Prospects

SWGO

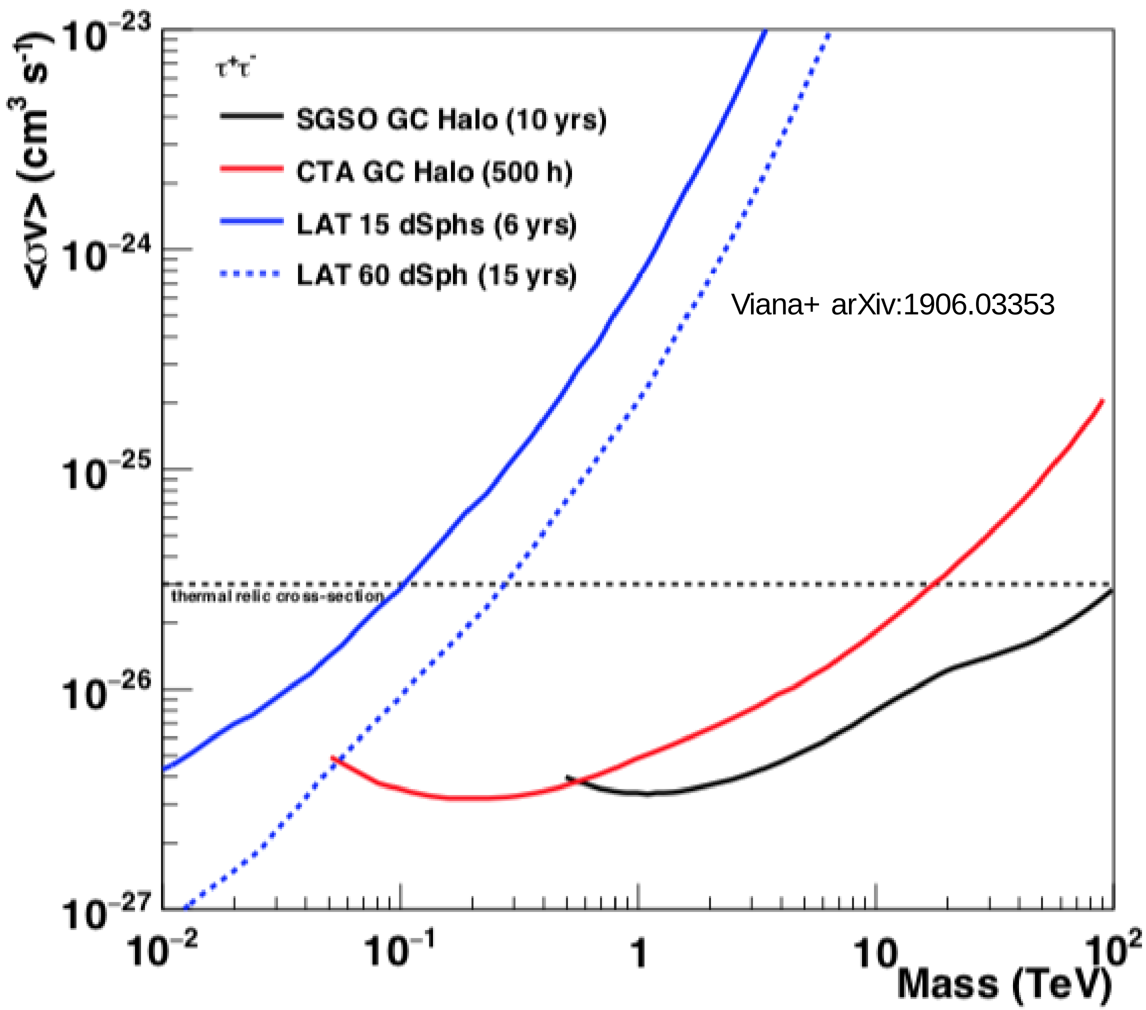
Albert+ arXiv:1902.08429





- Proposed HAWC-like water Cherenkov array in the Southern Hemisphere
  - Plan to have 10x HAWC's sensitivity
- Collaboration has formed
- Will complement CTA and be the most sensitive southern gamma-ray experiment above 10 TeV

SWGO WIMP Sensitivity



- **Fermi LAT + CTA + SWGO will explore thermal WIMPs from 5 GeV -- 100 TeV!**
- **There is overlap in mass between experiments which will allow for multiple potential detections**

Summary

- Dark matter annihilations (decay) are predicted to produce a cascade of secondary standard model particles, which produce gamma rays
  - We can search for these cosmic messengers with a network of ground-based and space-based observatories
- Current gamma-ray limits are probing thermal WIMP models
- Some intriguing anomalies exist that require extensive follow up work from all experiments to complete the picture
  - The fundamental particle properties of DM (e.g. mass) must be the same from all messengers and targets
- The future is bright and full of exciting questions!
  - With continued Fermi-LAT observations, CTA, and SWGO we can probe some thermal WIMP models from 5 GeV to 100 TeV