Searching for Dark Matter Gamma Rays from Dwarf Galaxies

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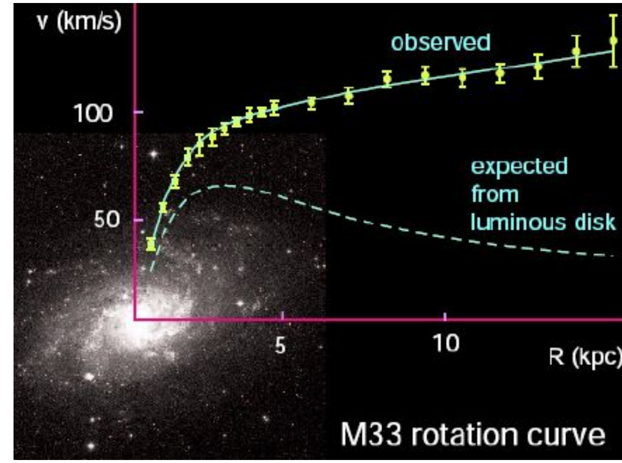
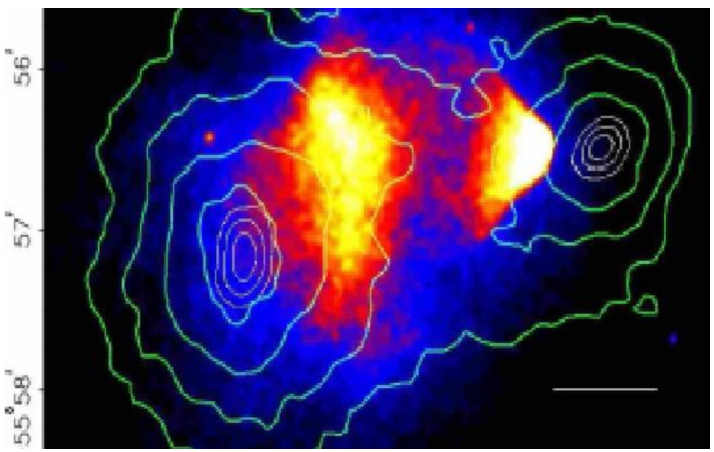
Dark Matter Primer

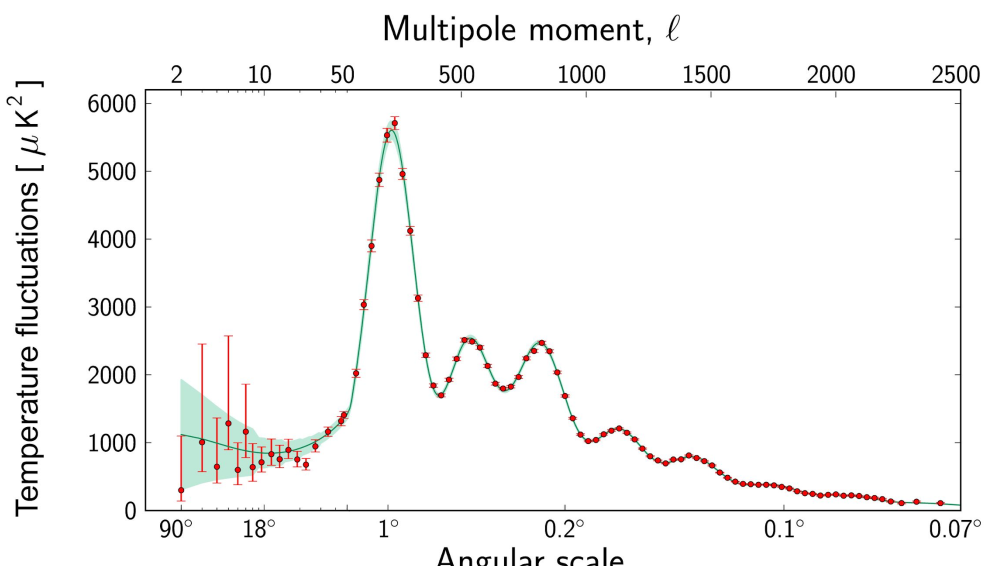
- Galaxies form in Dark Matter *halos* of various sizes, which make up most of their *mass*
  - Coma Cluster + Virial, F. Zwicky (1937)
  - Rotation Curves, V. Rubin et al 1980)





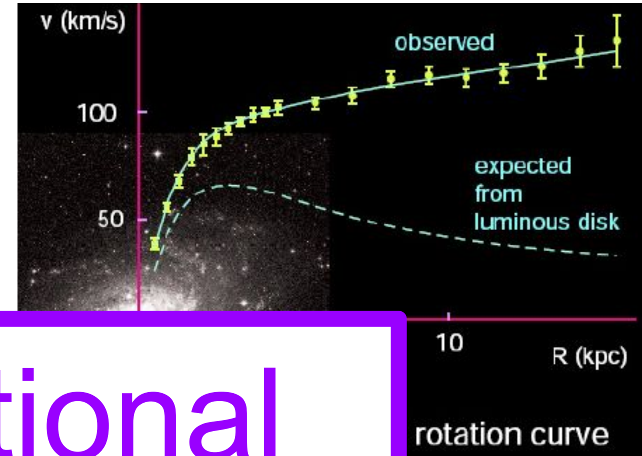
- Dark Matter is virtually *collisionless*
  - The Bullet Cluster, D. Clowe et al (2006)

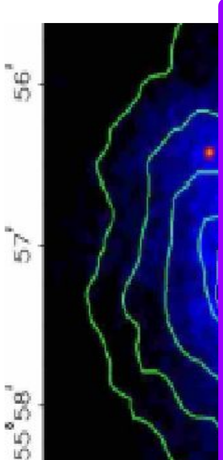
- Dark Matter is *non-baryonic*
  - CMB acoustic oscillations
  - Big Bang nucleosynthesis



Dark Matter Primer

- **Galaxies form in Dark Matter *halos* of various sizes, which make up most of their *mass***
  - **Coma Cluster + Virial, F. Zwicky (1937)**
  - **Rotation Curves, V. Rubin et al 1980)**





All of our observational evidence for dark matter comes from space

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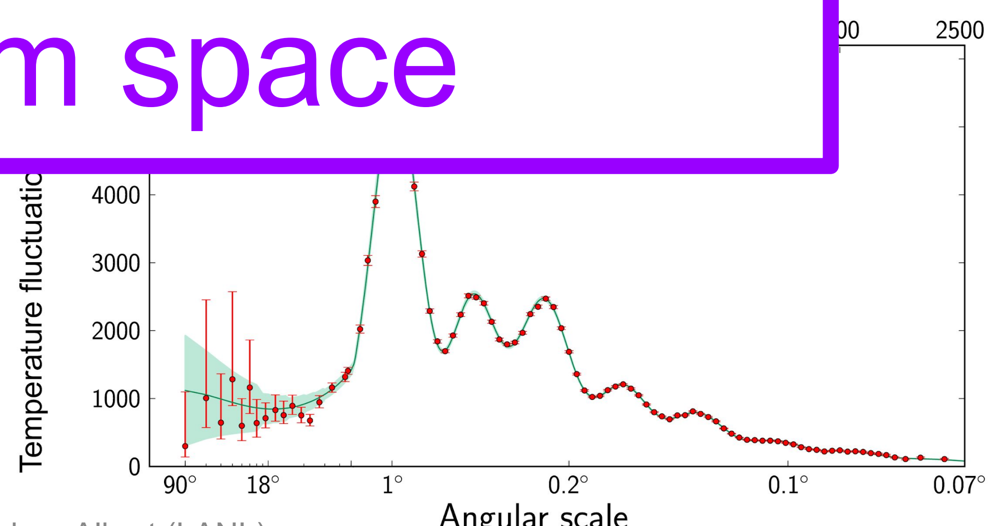
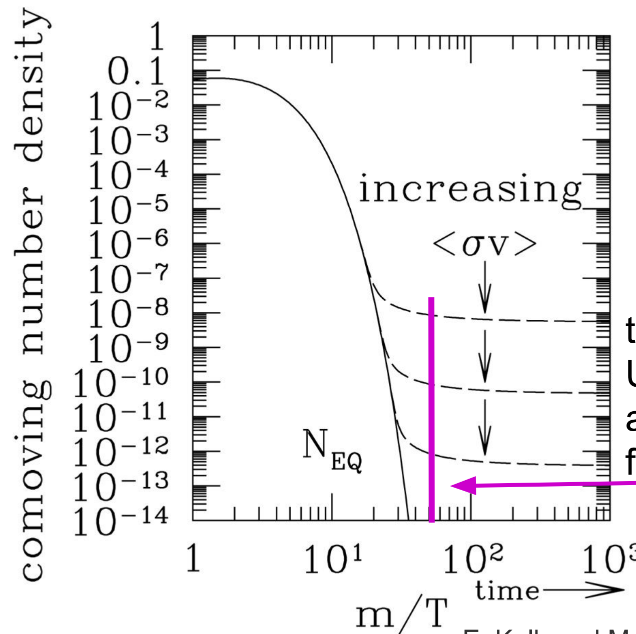


- **Dark Matter is *non-baryonic***
  - **CMB acoustic oscillations**
  - **Big Bang nucleosynthesis**

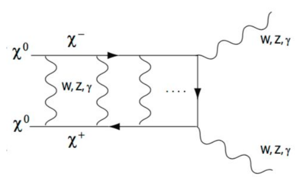
WIMP Dark Matter

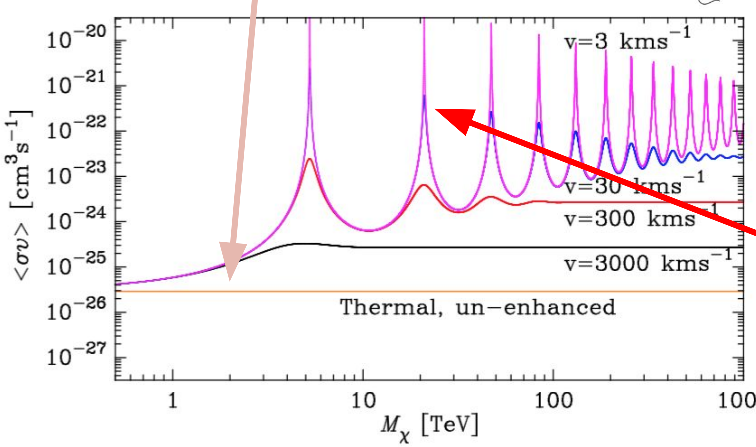
- **Weakly Interacting Massive Particle (WIMP, χ)**
  - **GeV - TeV mass scale**
  - **WIMPs may be thermal relics**
  - **e.g. neutralino (SUSY, electrically neutral, stable)**
- **Assuming a weak scale σ_{ann} at freeze yields observed relic abundance**
  - **$\langle\sigma v\rangle_{ann}$ ~ 3×10^{-26} cm^3/s**



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

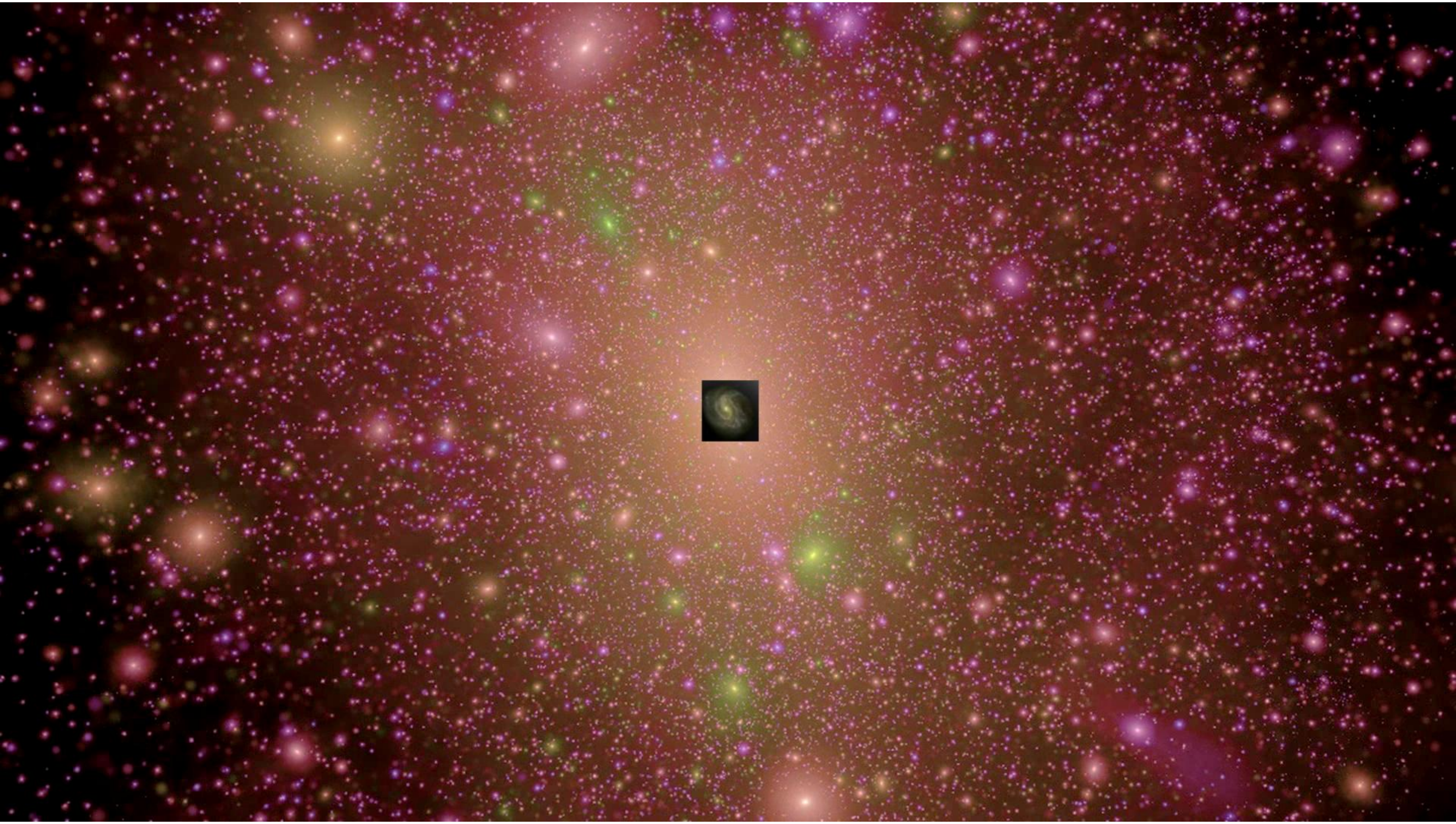
arXiv:1202.1170
arXiv:1405.1730





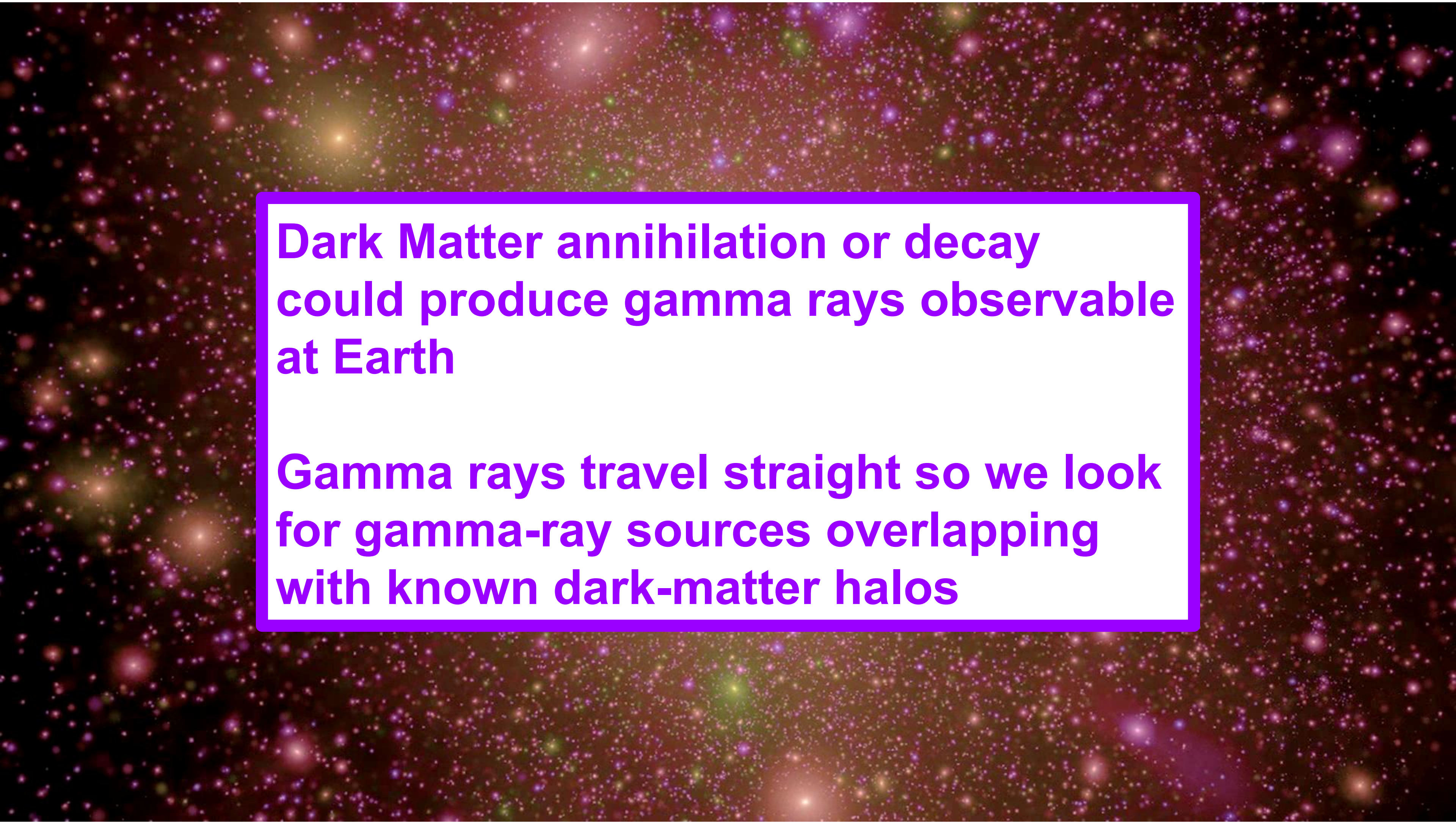
- **Sommerfeld enhancement**
  - **relevant for high DM masses (>~1 TeV)**
  - **enhanced at low WIMP velocities**
    - **this effect was suppressed at time of freeze out**
  - **high mass thermal relics have present $\langle\sigma v\rangle_{ann}$ larger than 3×10^{-26} cm^3/s in some models**

Simulation of Milky Way Like Halo



Aquarius Simulation (Springel et al 2008)

Simulation of Milky Way Like Halo



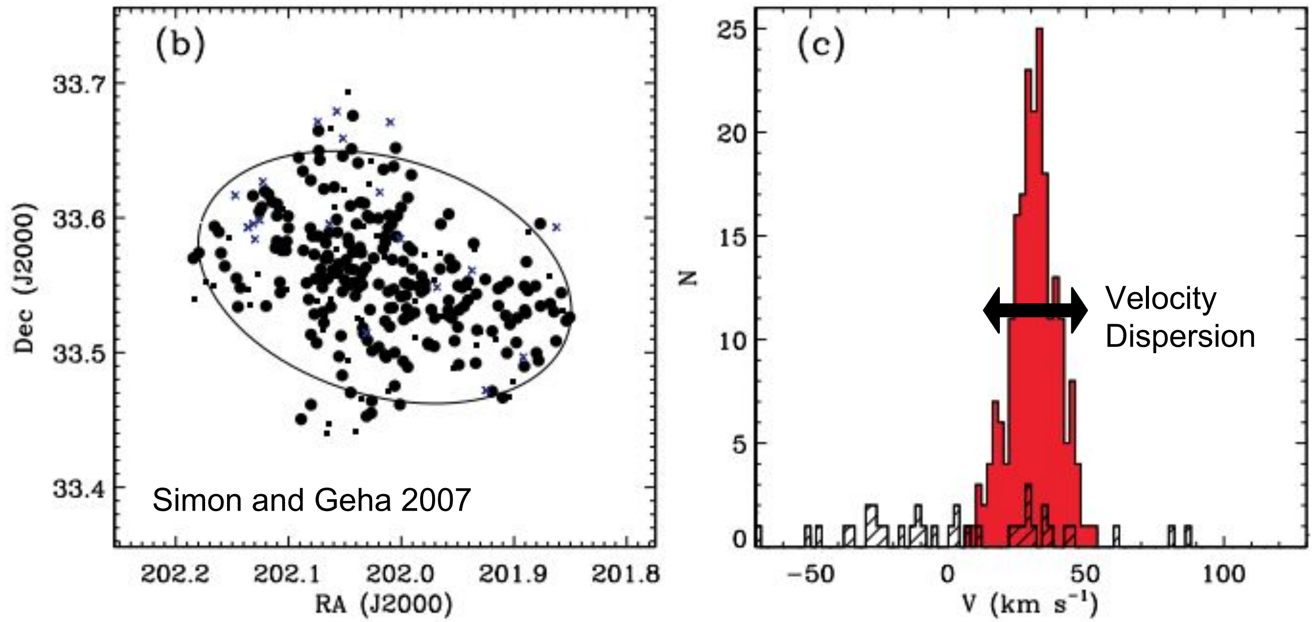
Dark Matter annihilation or decay could produce gamma rays observable at Earth

Gamma rays travel straight so we look for gamma-ray sources overlapping with known dark-matter halos

Aquarius Simulation (Springel et al 2008)

Dwarf Galaxies

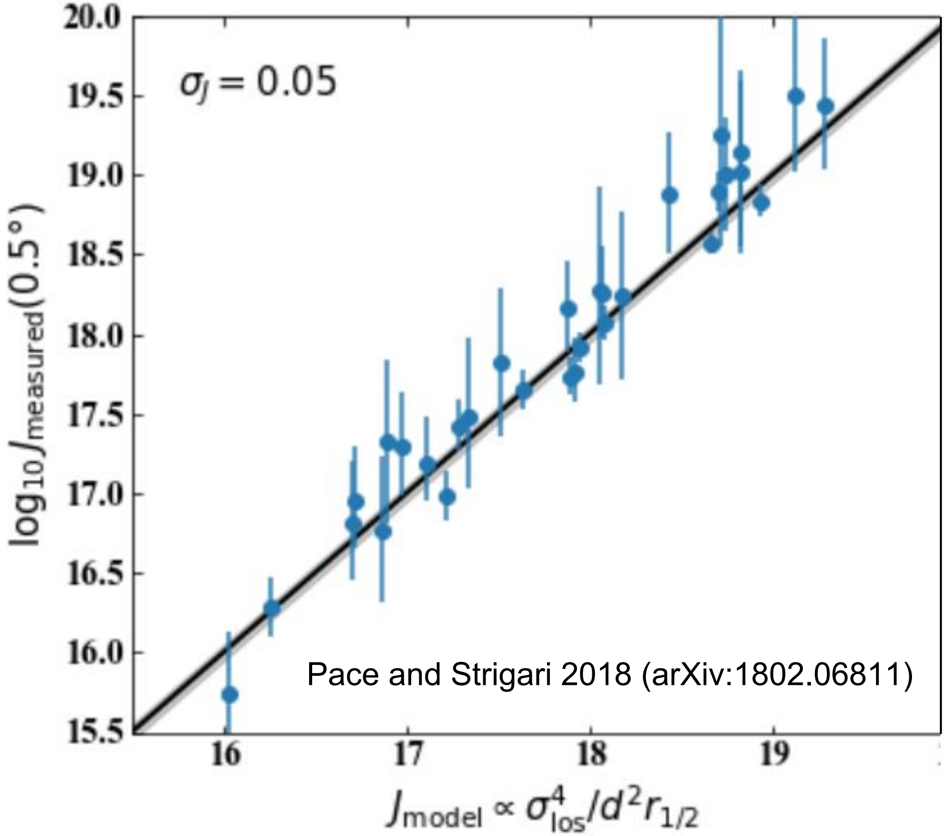
Hercules



- "A galaxy is a gravitationally bound collection of stars whose properties cannot be explained by a combination of baryons and Newton's laws of gravity" -- Willman & Strader (2012)
  - Dwarf galaxies typically have mass to light ratios ($M_\odot / L_\odot$) of >> 1
- There are dozens of known dwarf galaxies that are satellites of the Milky Way
  - ~ 20 to 250 kpc away (LMC is 50 kpc away)
- Dwarf galaxies exist around other larger galaxies (like M31) too, but for dark matter searches the nearby ones are most sensitive

Dwarf Galaxies "J-factors"

Los Alamos NATIONAL LABORATORY EST. 1943



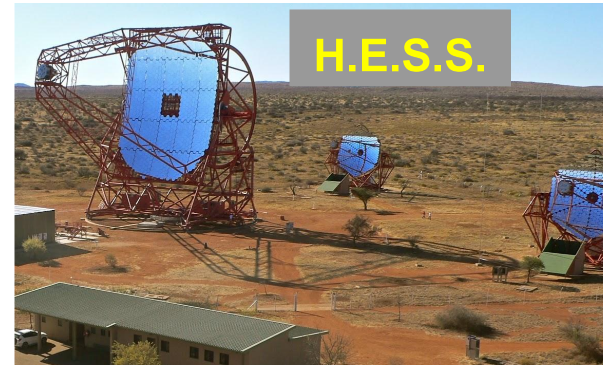
$$\int_{\Delta\Omega(\phi,\theta)} d\Omega' \int_{los} \rho^2(r(l,\phi'))dl(r,\phi')$$

- **J-factor is proportional to expected gamma-ray intensity**
  - **Dwarfs with larger J-factors are more sensitive targets**
- **$J(0.5^\circ) = 10^{17.72}\,(\sigma_{los}/5\ \mathrm{km\ s^{-1}})^4\,(d/100\ \mathrm{kpc})^{-2}\,(r_{1/2}/100\ \mathrm{pc})^{-1}$**

Current Gamma-ray Observatories

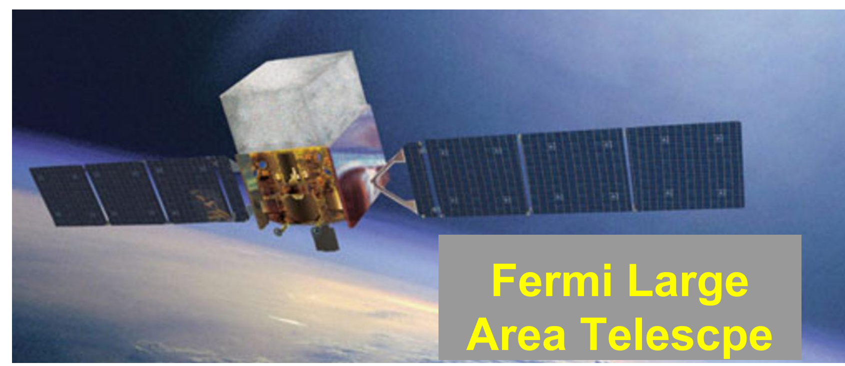
Tucson, Arizona
31° North Latitude, ~5° f.o.v.
~85 GeV -- ~50 TeV

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



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

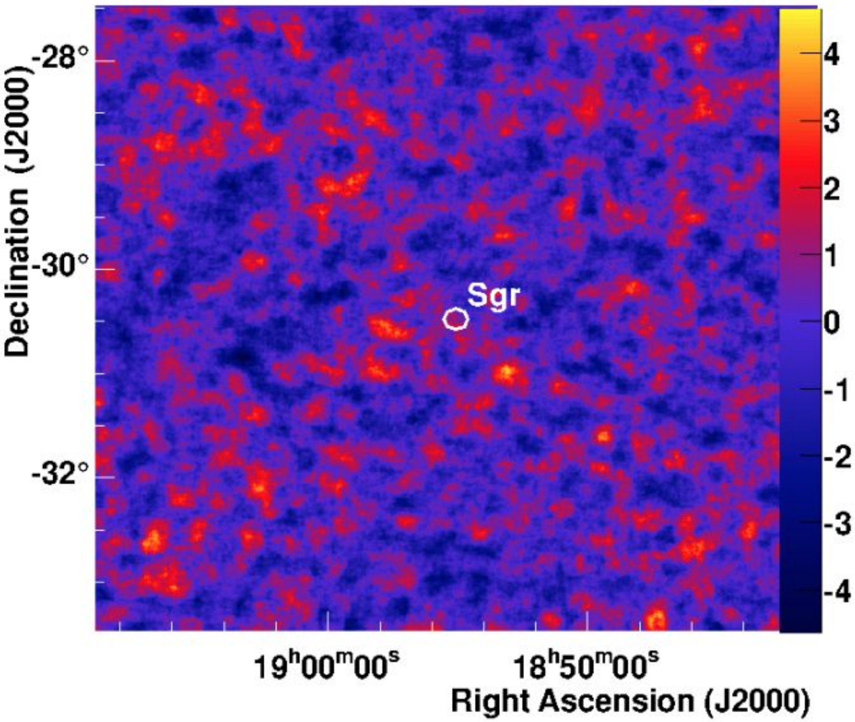
Parque Nacional Pico de Orizaba, México
19° North Latitude, ~2 sr f.o.v.
~50 GeV -- ~100 TeV, 100% Duty Cycle

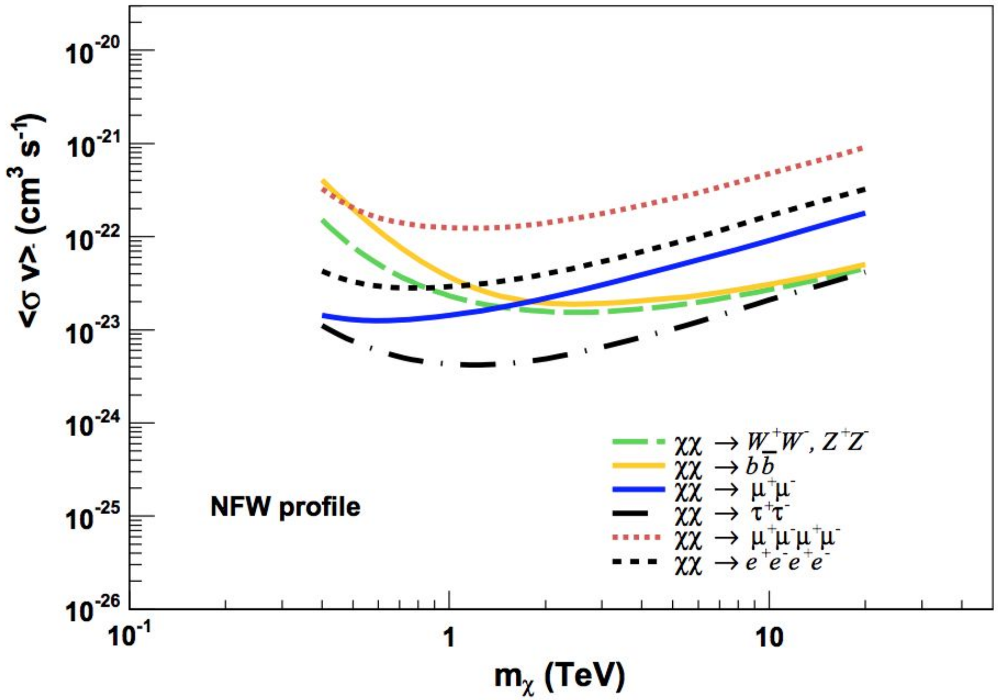


Low earth orbit (565 km)
28.5° orbital inclination, ~2 sr f.o.v.
20 MeV -- > 300 GeV, 100% Duty Cycle
(AGILE has similar technology, but has limited energy resolution)

Results from H.E.S.S.

Abramoski et al Phys.Rev. D90 (2014)

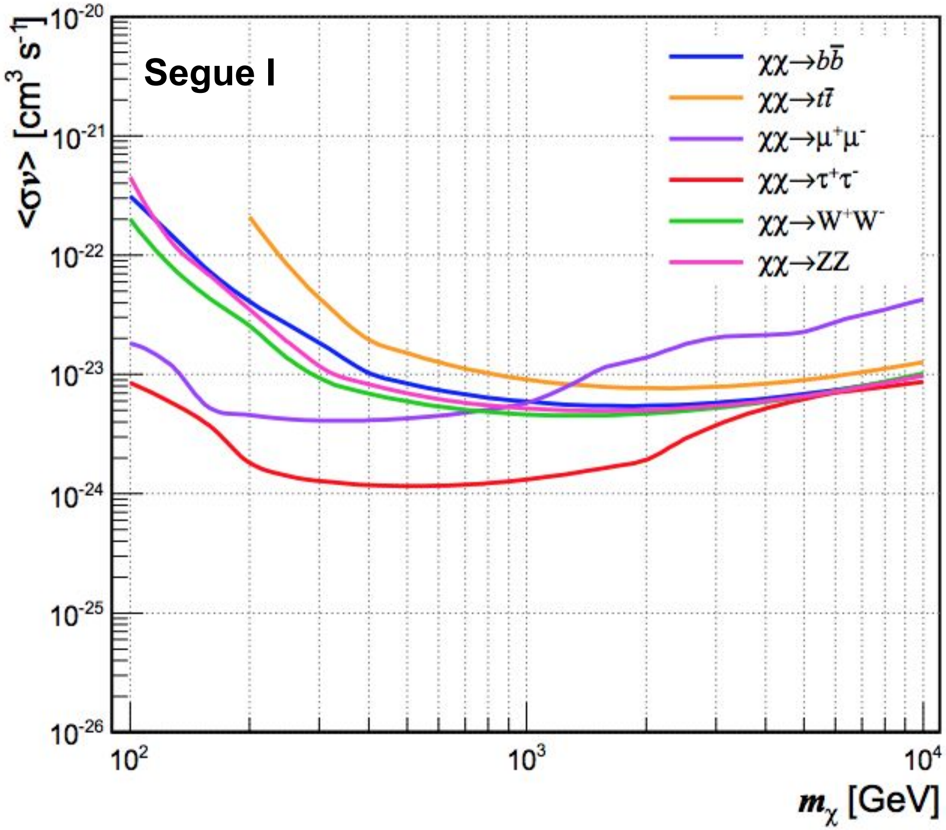




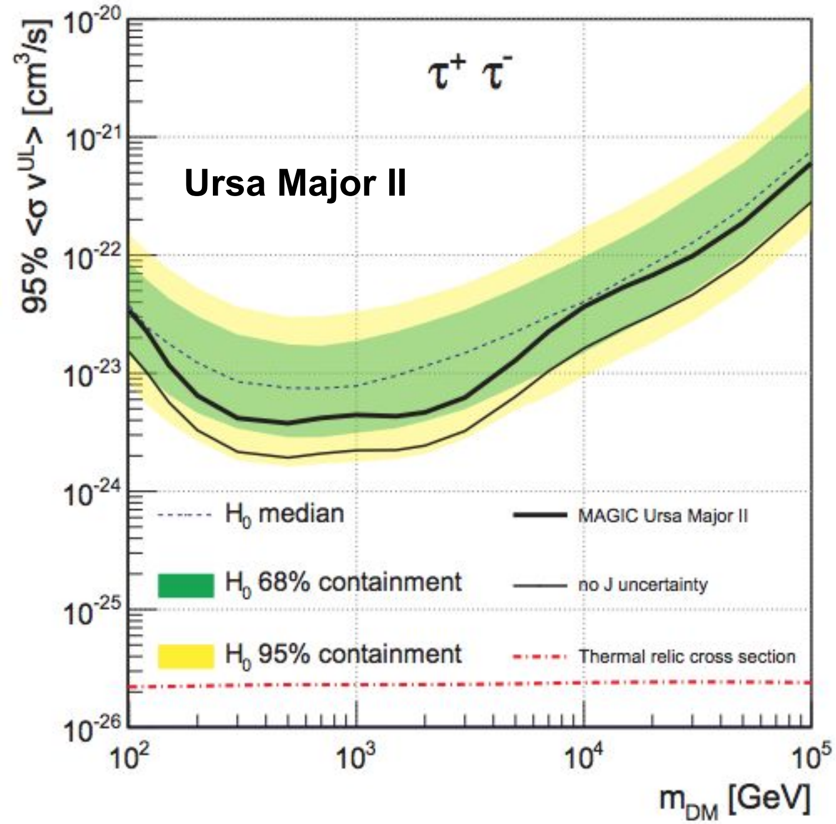
- Joint analysis of 5 dwarf galaxies
    - Sagittarius (log(J) = 19.1), Coma Berenices (log(J) = 18.8), Fornax (log(J) = 18.1), Carina (log(J) = 18.0), and Sculptor (log(J) = 18.5
- >140 hours of observation time

Results from MAGIC

Aleksic et al JCAP 1402 (2014)

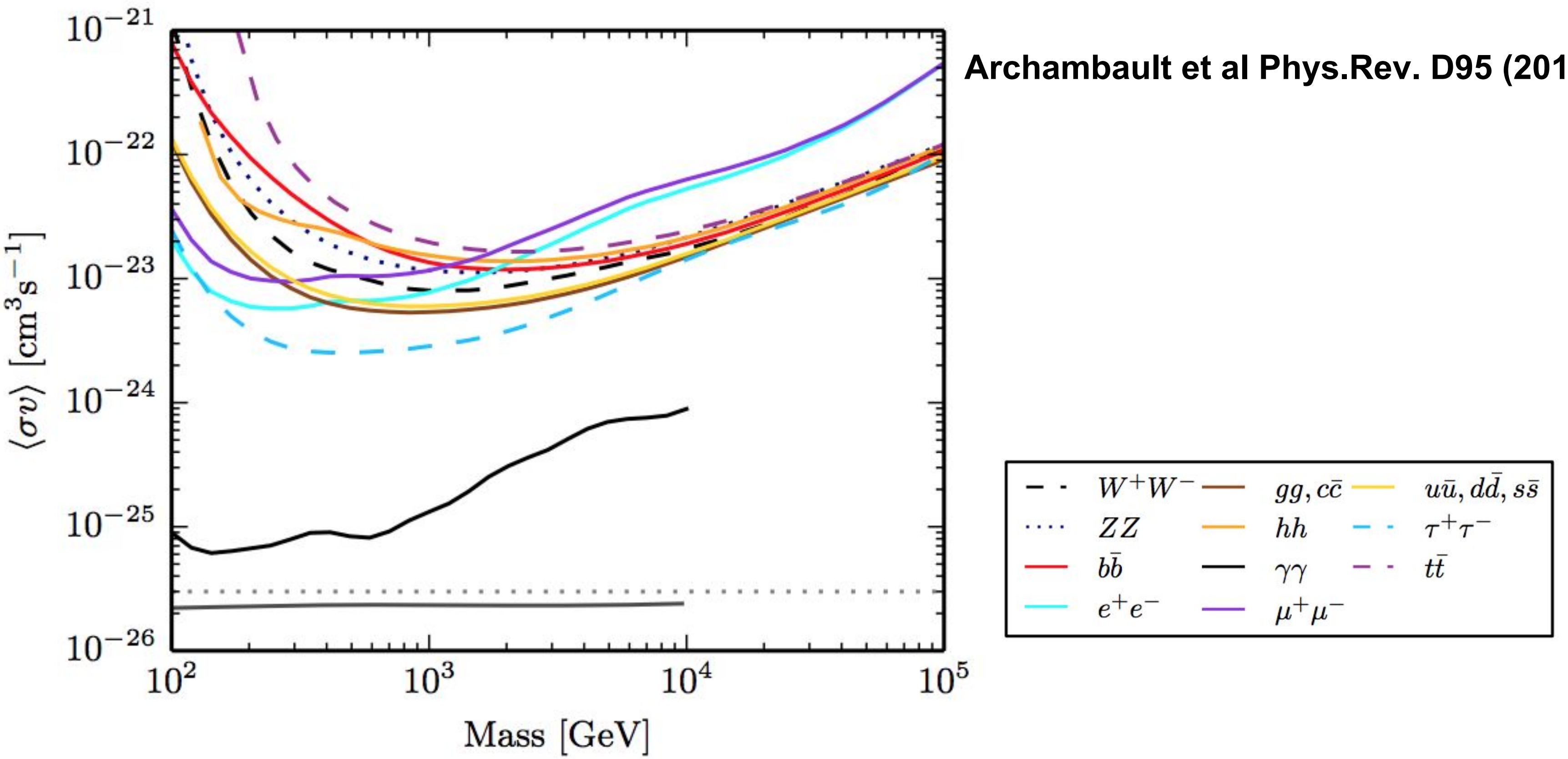


Ahnen et al JCAP 1803 (2018)



- **>160 hours observing Segue I (log(J) = 19.0)**
- **~100 hours observing Ursa Major II (log(J) = 19.4)**

Results from VERITAS

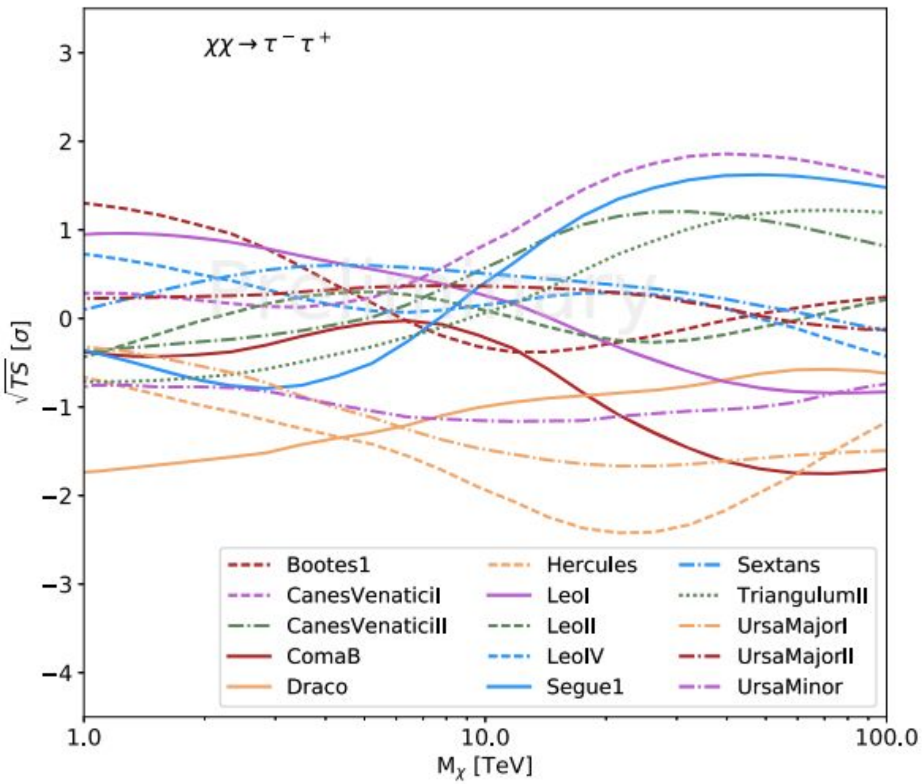


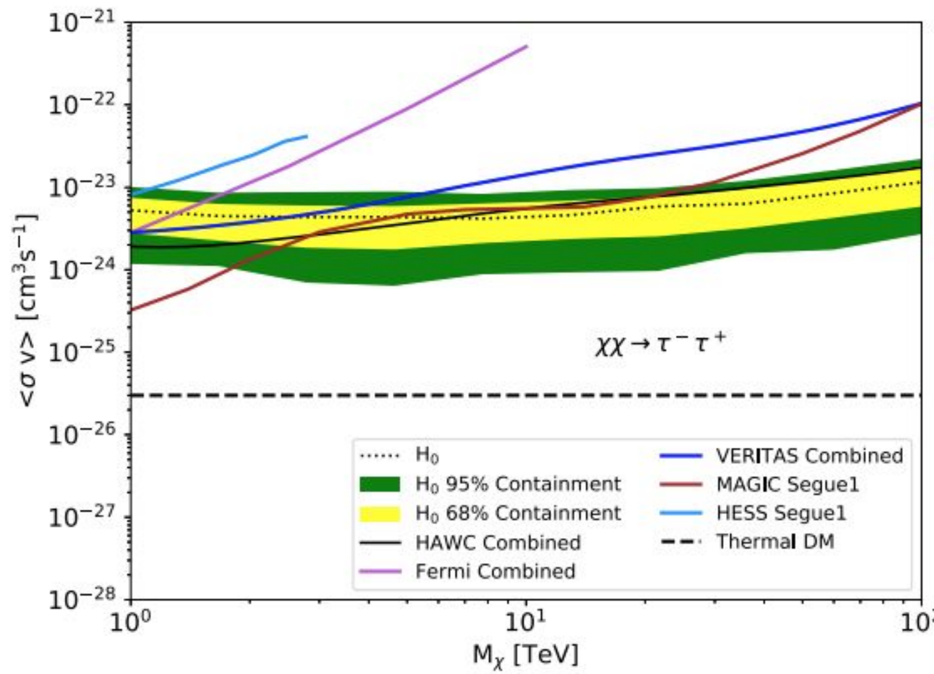
Archambault et al Phys.Rev. D95 (2017)

- **Joint analysis of 4 dwarf galaxies**
  - **Segue 1 (log(J) = 19.2), Ursa Minor (log(J) = 18.9), Draco (log(J) = 18.3), and Bootes (log(J) = 18.3)**
- **~230 hours of observations**

Results from HAWC

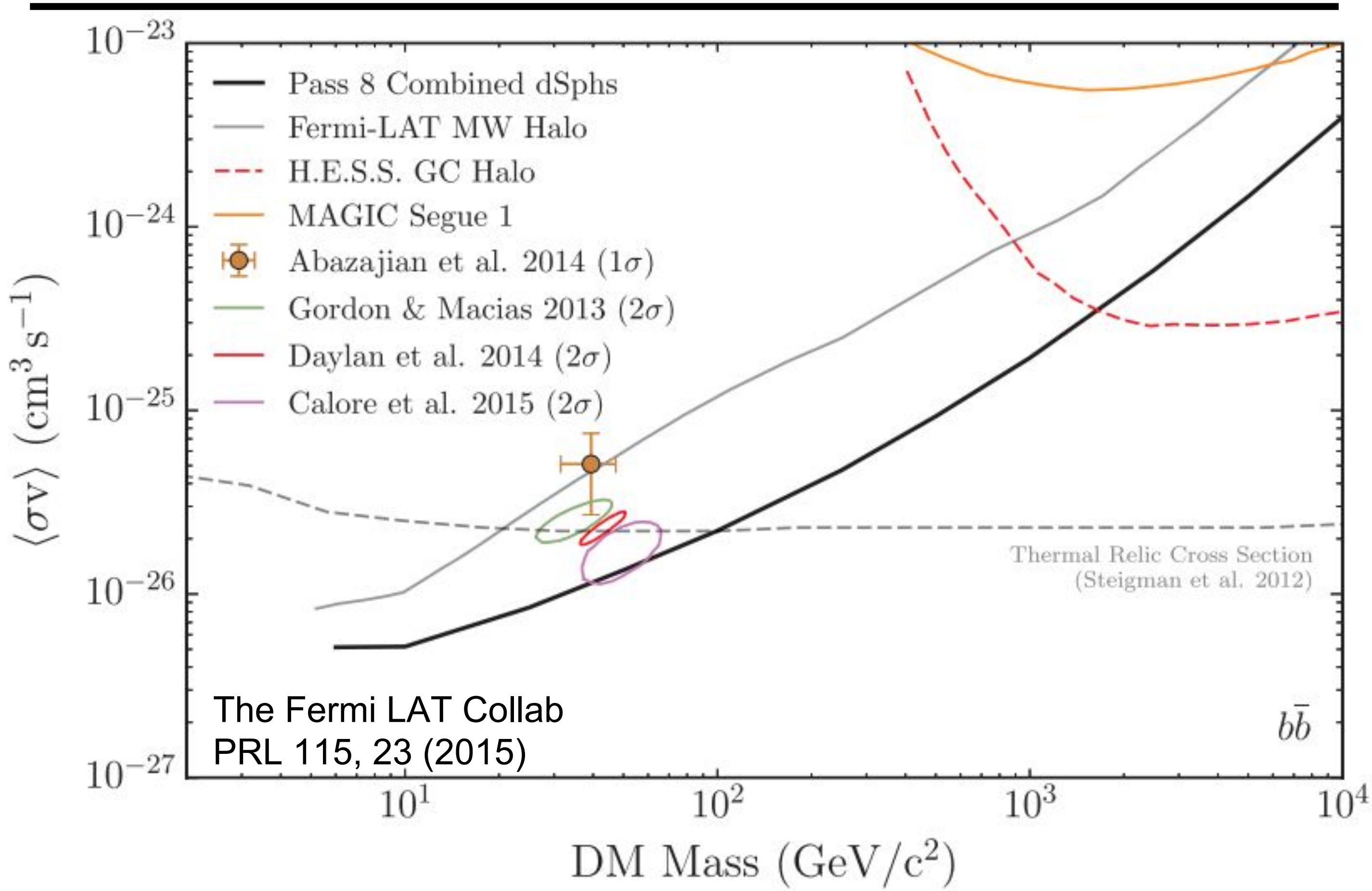
Albert et al Astrophys.J. 853 (2018)





- **Joint analysis of 15 dwarf galaxies**
  - **507 days of data**
- **Most constraining limits from dwarf galaxies above 20 TeV**

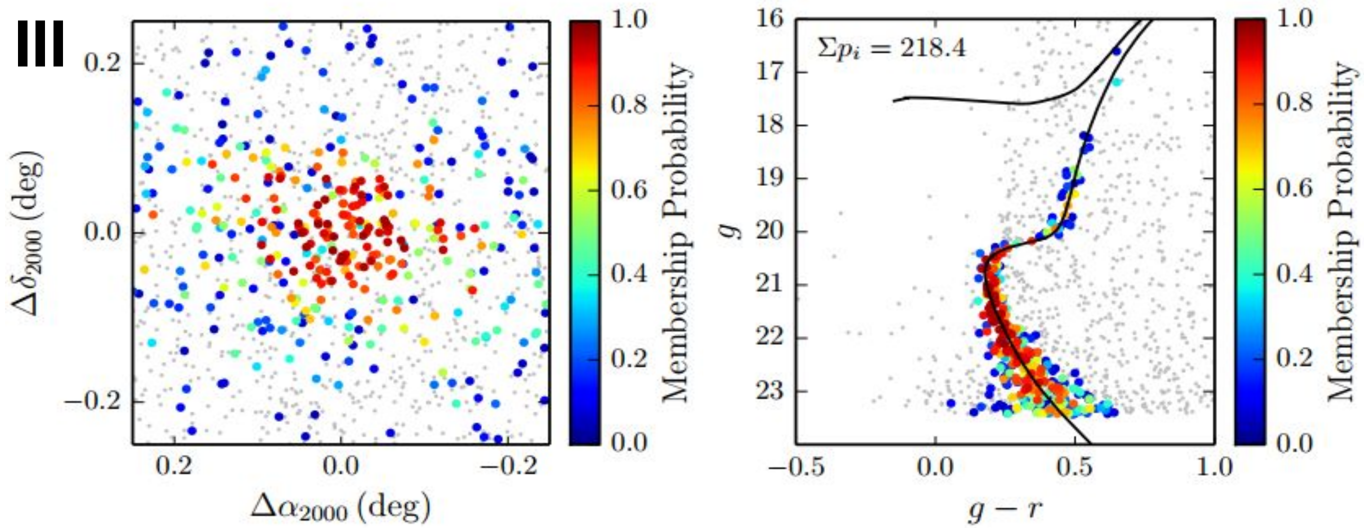
Results from the Fermi LAT



- **Joint likelihood analysis of 15 well characterized dwarf galaxies**
  - **6 years of data**
- **Limits exclude thermal relic $<\sigma v>_{ann}$ in $b\bar{b}$ channel for 5 GeV < m_χ < 100 GeV**

How to Find Ultra-faint Milky Way Satellites

Tucana III



Spatial component modeled with elliptical Plummer profile.

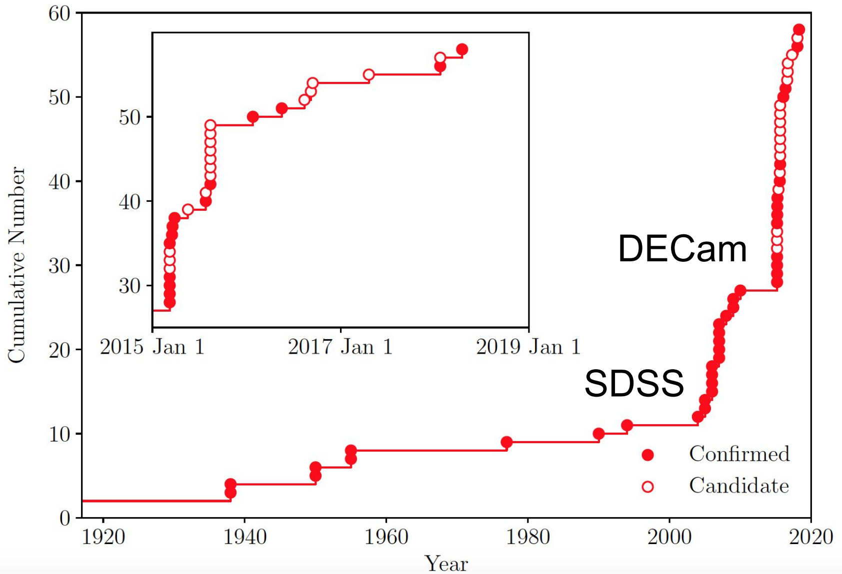
"Spectral" component modeled with color-magnitude distribution expected from old, metal-poor stellar population

Drlica-Wagner et al (DES Collaboration) 2015

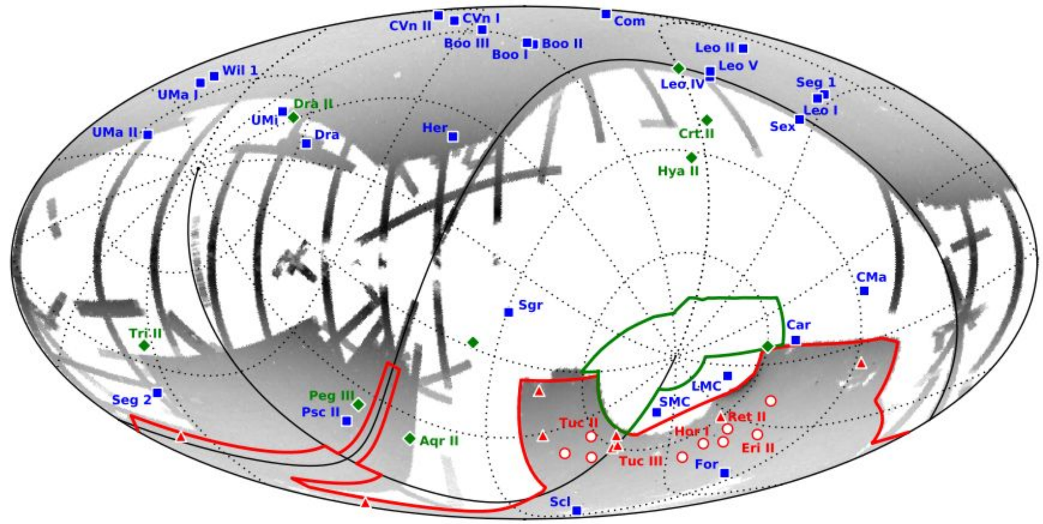
The likelihood analysis produces a probability of each star being a member of the satellite

- **Deep photometric surveys in optical astronomy have led to the discovery of numerous new dwarf galaxy candidates**
  - **Search for overdensities of old and metal-poor stars**
    - **Look for stars with similar properties of known ultra-faint dwarf galaxies**
  - **Spectroscopic follow up necessary to determine if they are DM-dominated dwarf galaxies.**

Growing Number of Known Dwarf Galaxies



Bechtol and Drlica-Wagner 2018



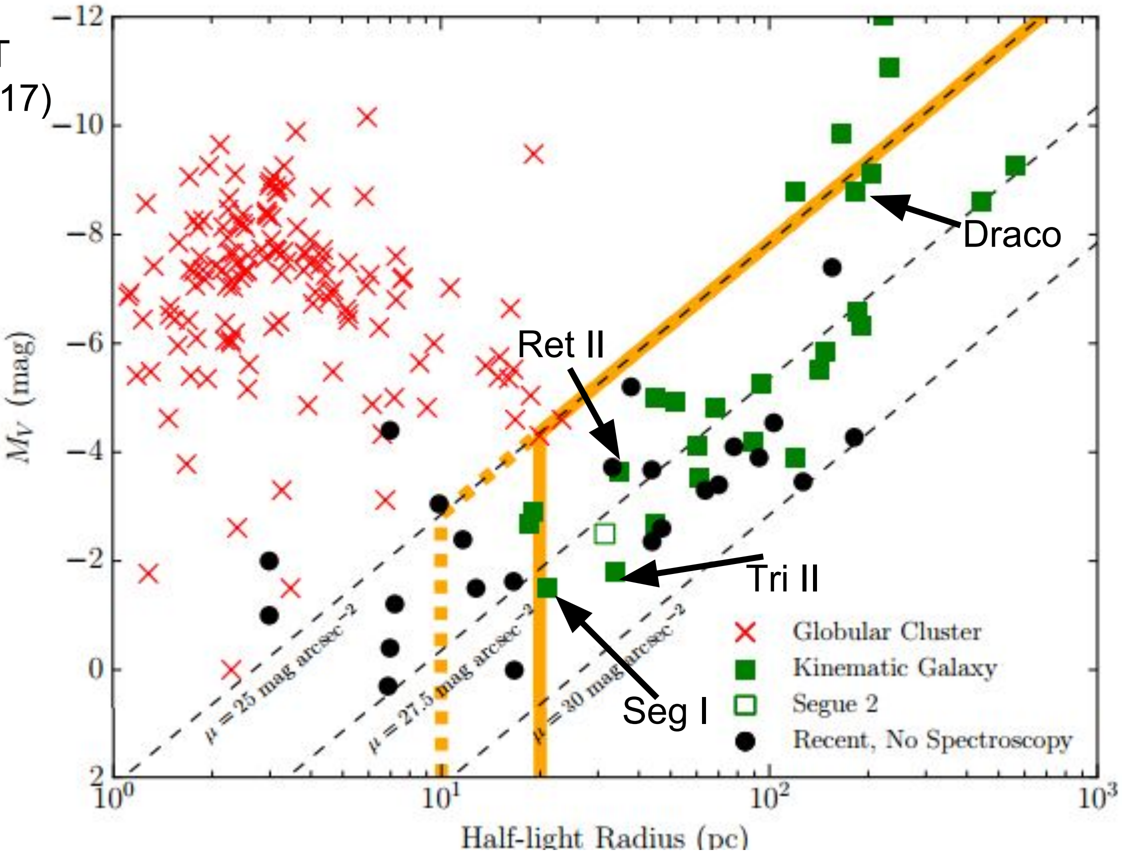
Bechtol and Drlica-Wagner 2016

- **31 new ultra-faint Milky Way satellites have been discovered since SDSS**
  - **e.g. Drlica-Wagner et al (DES Collaboration) 2015, Bechtol et al (DES Collaboration) 2015, Koposov et al 2015, Laevens et al 2015, Kim et al 2015, Martin et al 2015, Homma et al 2016, Drlica-Wagner et al 2016 (MagLiteS), Laevens et al 2016, Torrealba et al 2018 (MagLiteS)**

- **14 of the new satellites have been spectroscopically confirmed dwarf galaxies**
  - **e.g. Simon et al 2015, Walker et al 2015, Kim et al 2015, Simon et al 2016, Kirby et al 2017**

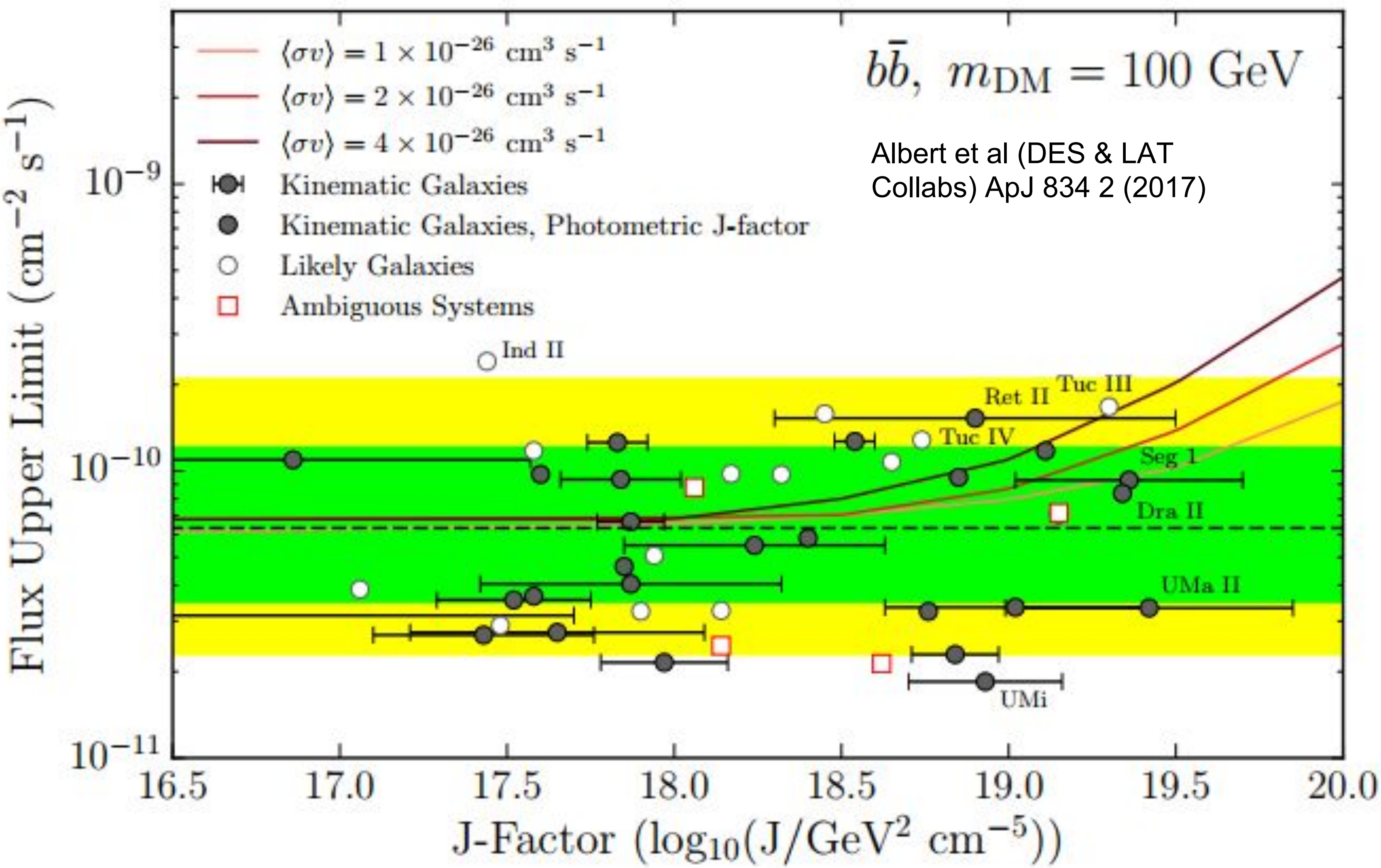
New Satellites Classification

Albert et al (DES & LAT Collabs) ApJ 834 2 (2017)



- **Photometric data tells us half-light radius, mag, and distance**
- **Spectroscopic data is needed to determine mass to light ratio (i.e. if object is dark matter dominated)**
  - **'galaxy' mass to light ratio >> 1**
  - **'globular cluster' mass to light ratio ~ 1**

LAT-DES Analysis of dSphs and dSph Candidates



Albert et al (DES & LAT Collabs) ApJ 834 2 (2017)

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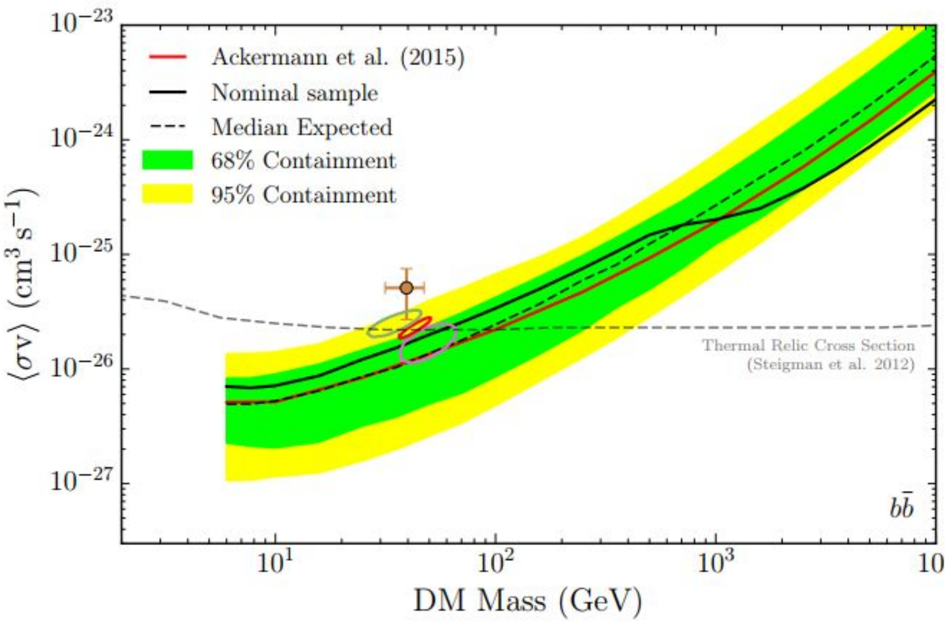
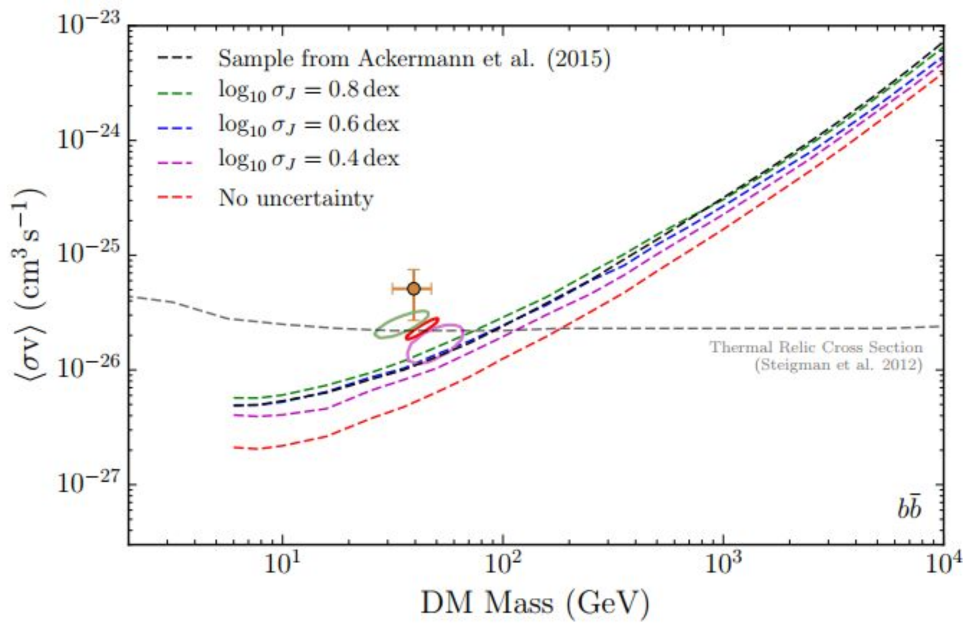
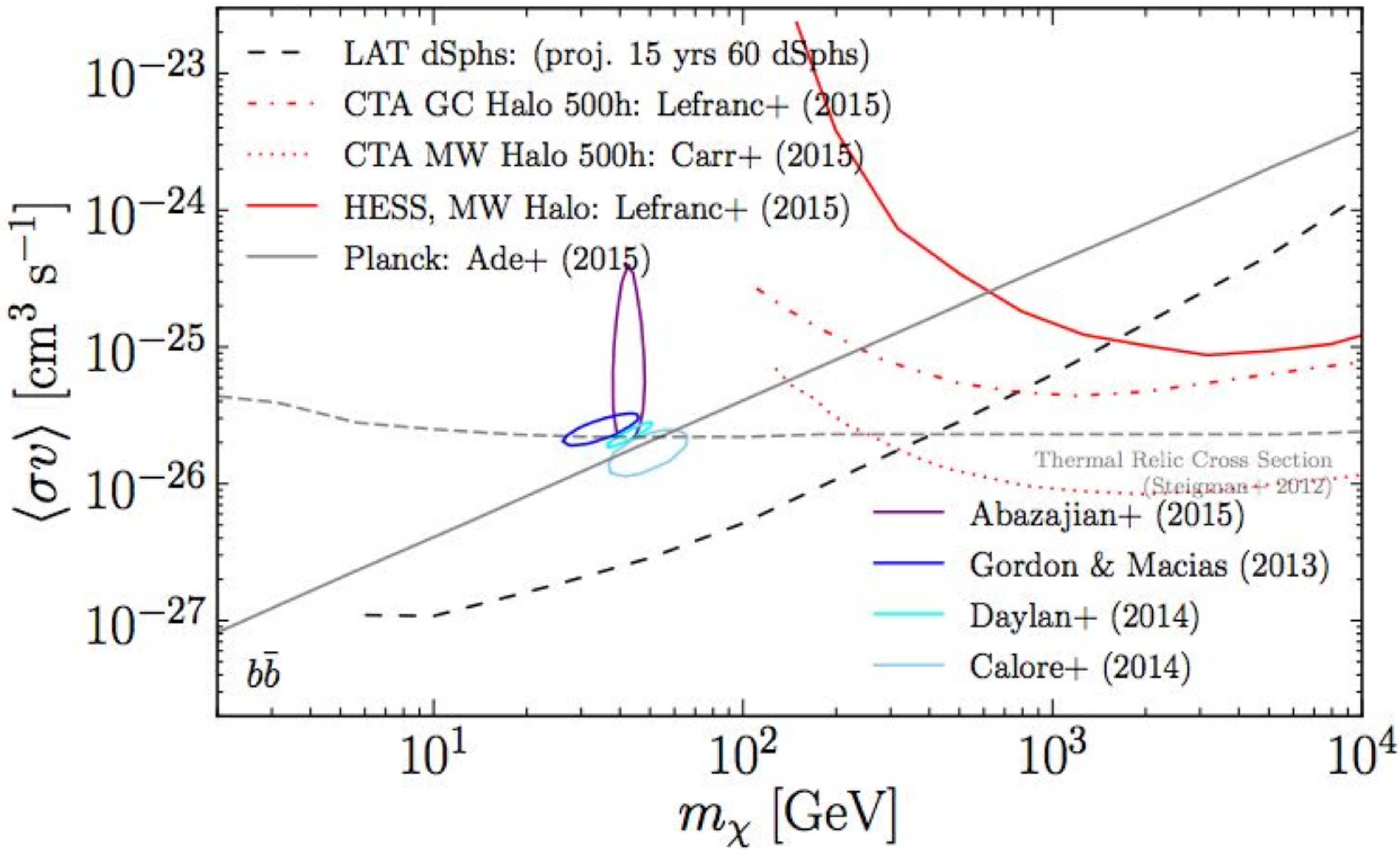




- **Combined limits including new DES dSph candidates are consistent within statistical uncertainties with LAT limits from 15 known dSphs**
- **Simply find new dSphs will not give maximum sensitivity...we need well measured J-factors too!**
  - **This is because the J-factor uncertainties are included as a nuisance parameter in the limit calculation**

Expected Future Sensitivity



Charles+ [LAT Clb] PR 636 (2016)

Summary

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- Milky Way dwarf galaxies are some of the best indirect dark matter search targets
  - Nearby and dark matter dominated
- Network of gamma-ray experiments have devoted both deep observations and wide field of view surveys of dwarf galaxies
  - No gamma rays from dark matter annihilation or decay have been detected
- Deep optical surveys have recently found >30 new ultra-faint Milky Way satellites that are potentially dark-matter dominated dwarf galaxies
  - >10 have been spectroscopically confirmed as dwarf galaxies
- Future indirect dark matter searches in dwarf galaxies will improve current limits as more are discovered and better characterized