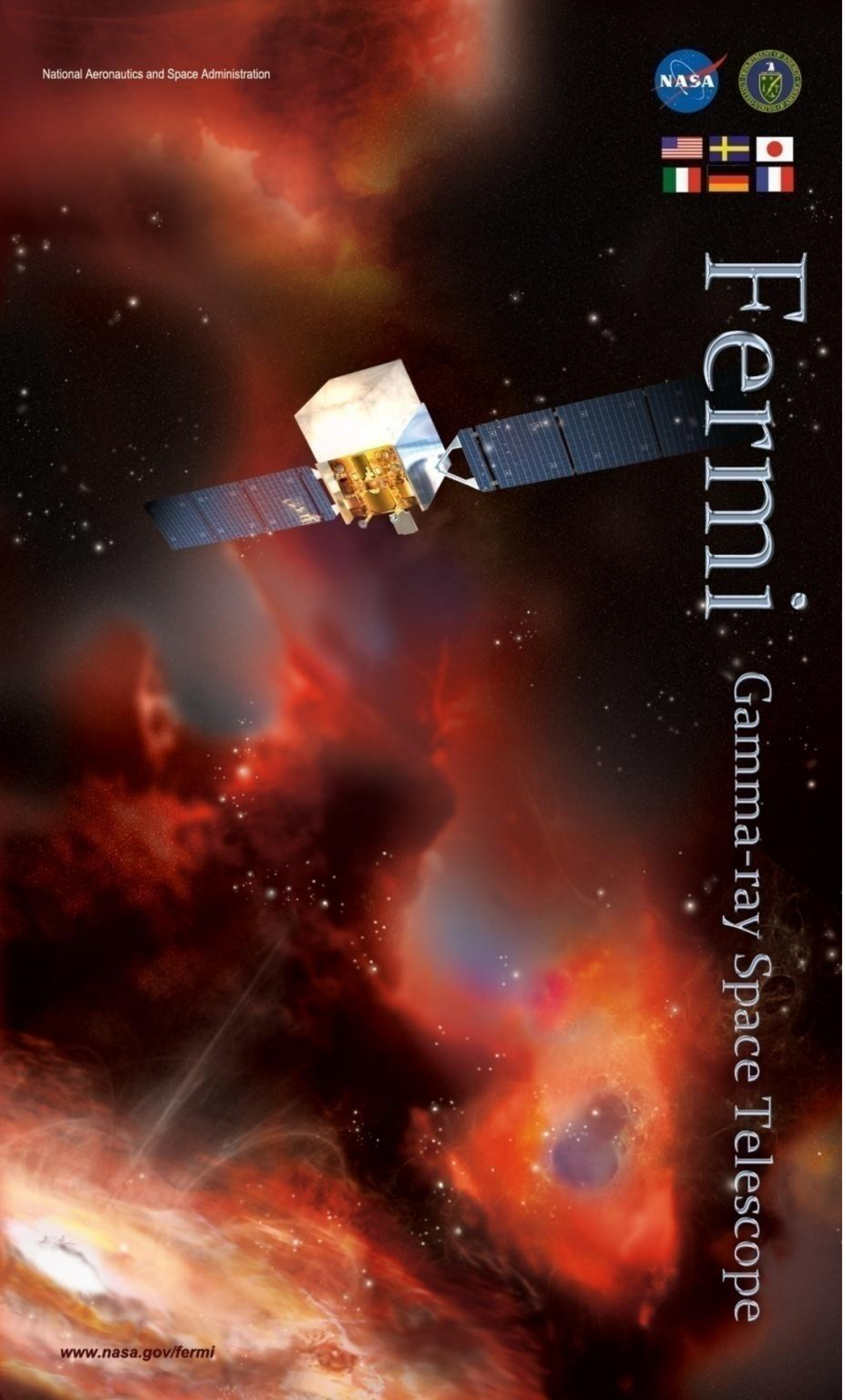


SLAC NATIONAL ACCELERATOR LABORATORY

KIPAC

Fermi Gamma-ray Space Telescope

Searching for Dark Matter with Gamma Rays

Andrea Albert
(SLAC)

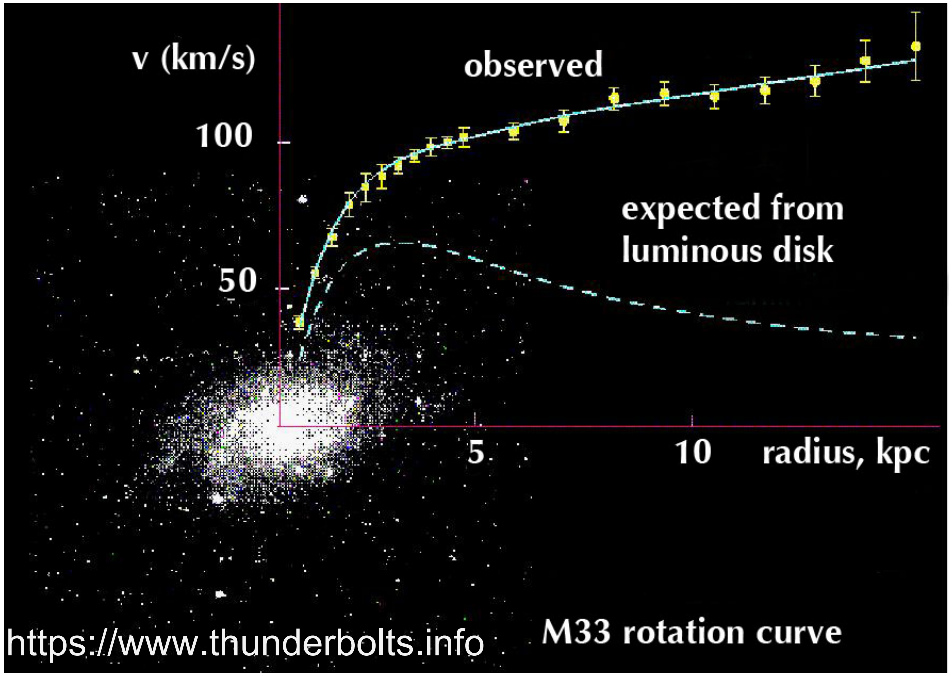
SLAC Summer Institute
Topical Conference
August 17, 2015

Outline

- Dark Matter Overview
  - DM evidence and candidates
  - Indirect DM detection

- Recent Dark Matter Results
  - Galactic Center
  - Dwarf Galaxies

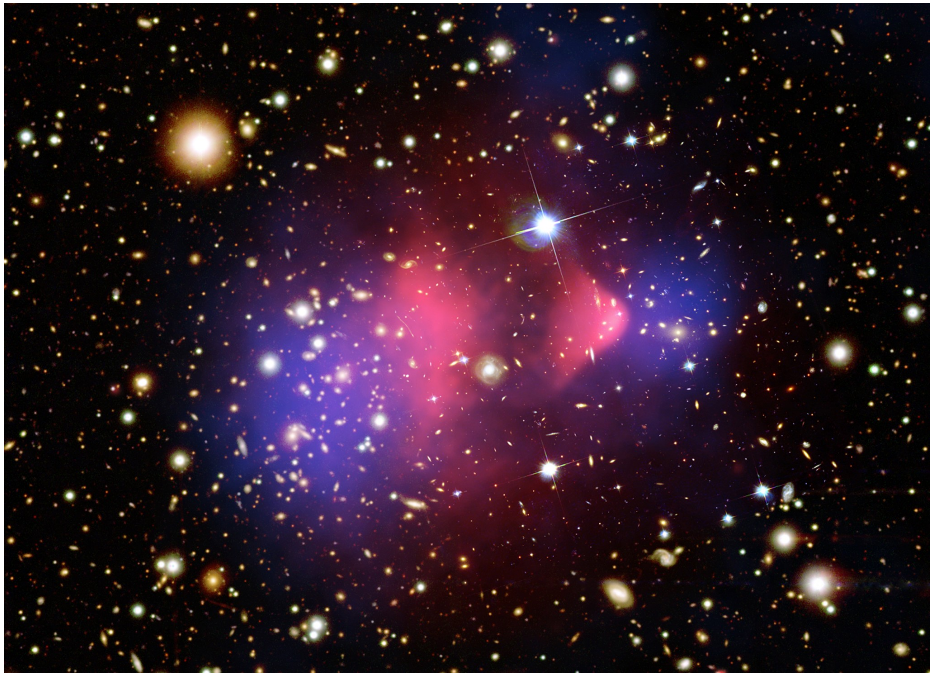
Cosmic Dark Matter Evidence



- **Galaxies reside in large dark matter halos that make up most of their mass**
  - **Coma Cluster + Virial Theorem, F. Zwicky (1937)**
  - **Galactic rotation curves, V. Rubin et al. (1980)**

All observational evidence for dark matter comes from space

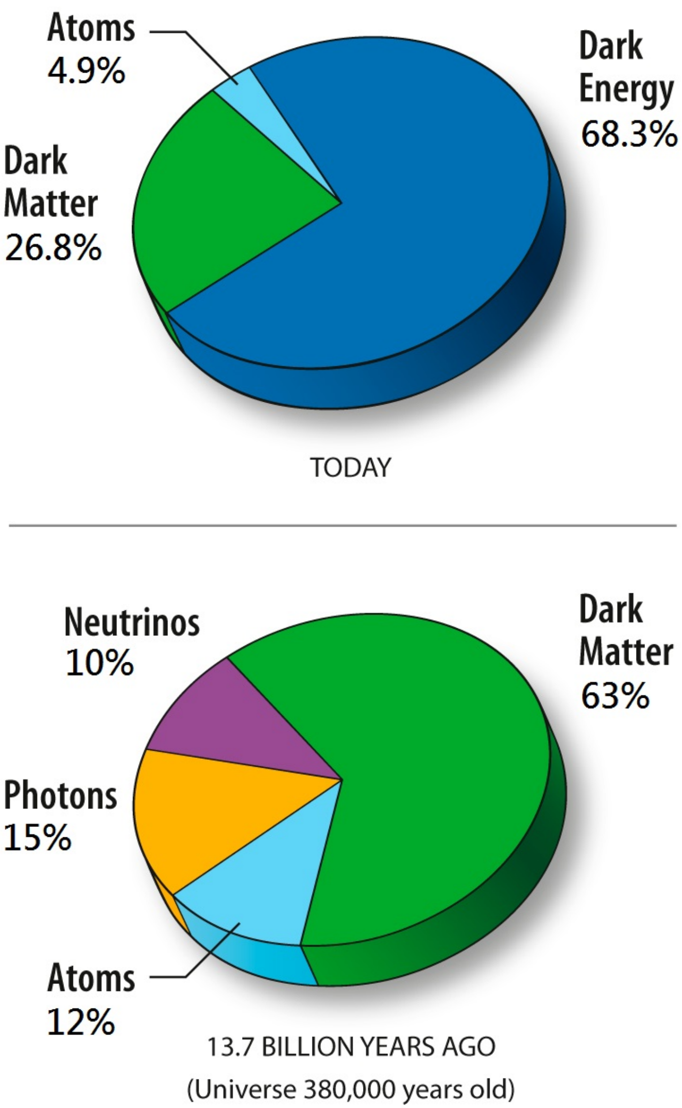
Cosmic Dark Matter Evidence



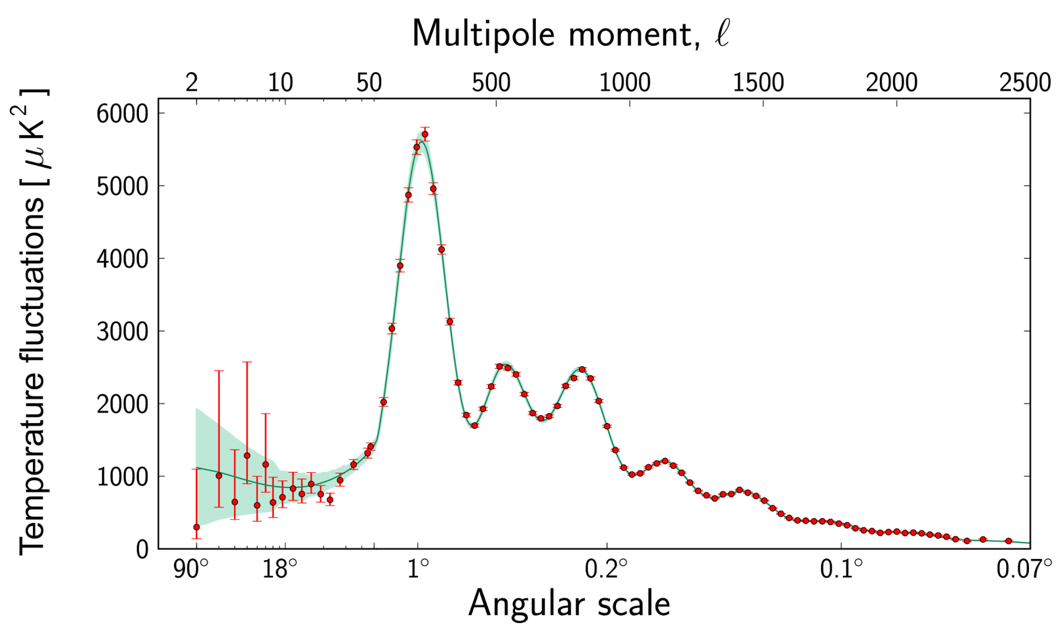
- Dark Matter is virtually **collisionless**
  - The Bullet Cluster, D. Clowe et al. (2006)

All observational evidence for dark matter comes from space

Cosmic Dark Matter Evidence



- **Dark Matter is non-baryonic**
  - **ΛCDM**
    - **CMB Acoustic Oscillations, Planck (2013)**
  - **BBN**



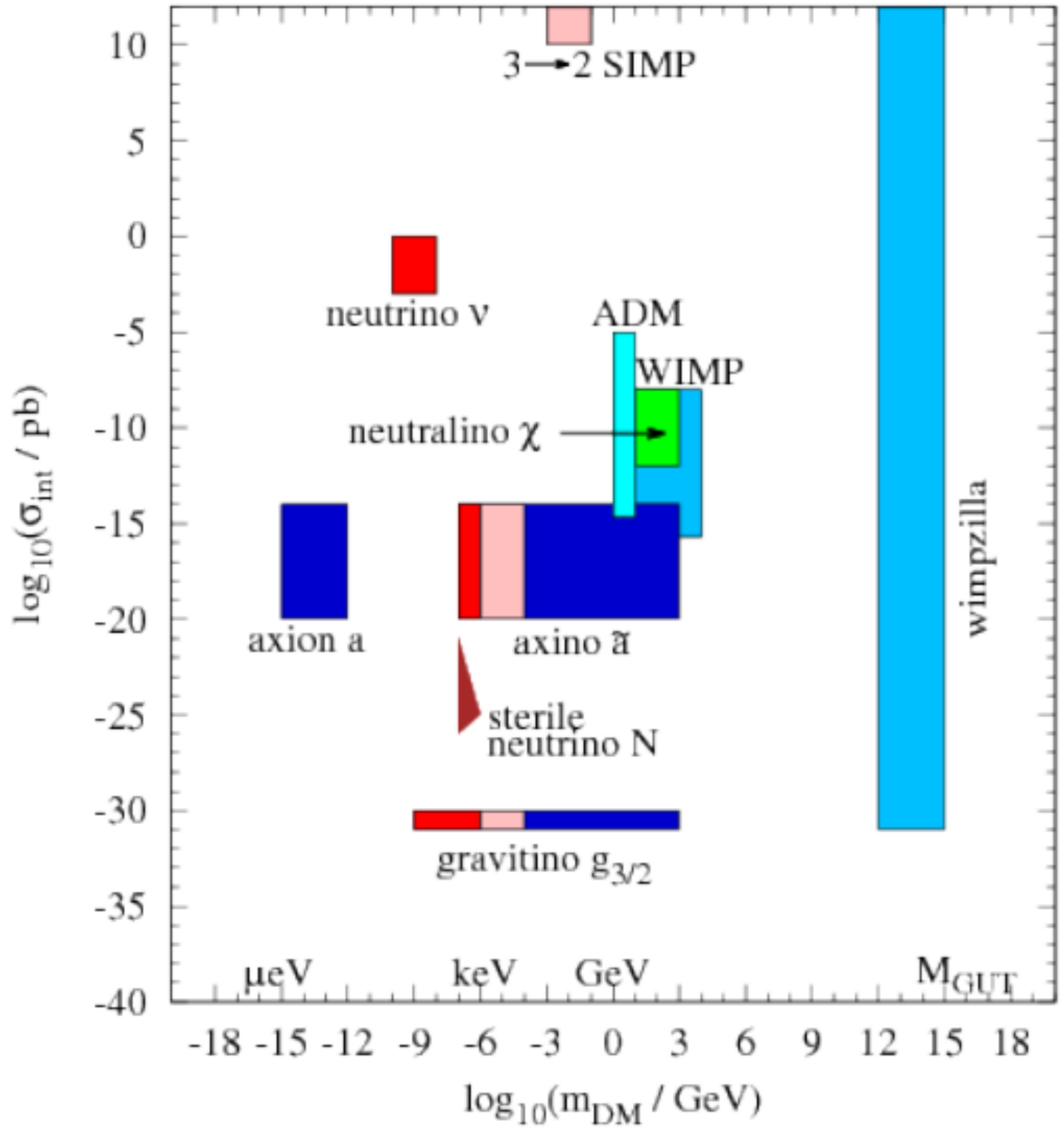
Planck A&A 571, A15 (2014)

Dark Matter Candidates

- **Wide variety of particle DM candidates in beyond SM theories**

- **Large scale structure and galactic formation seem to require cold (non-relativistic) DM**

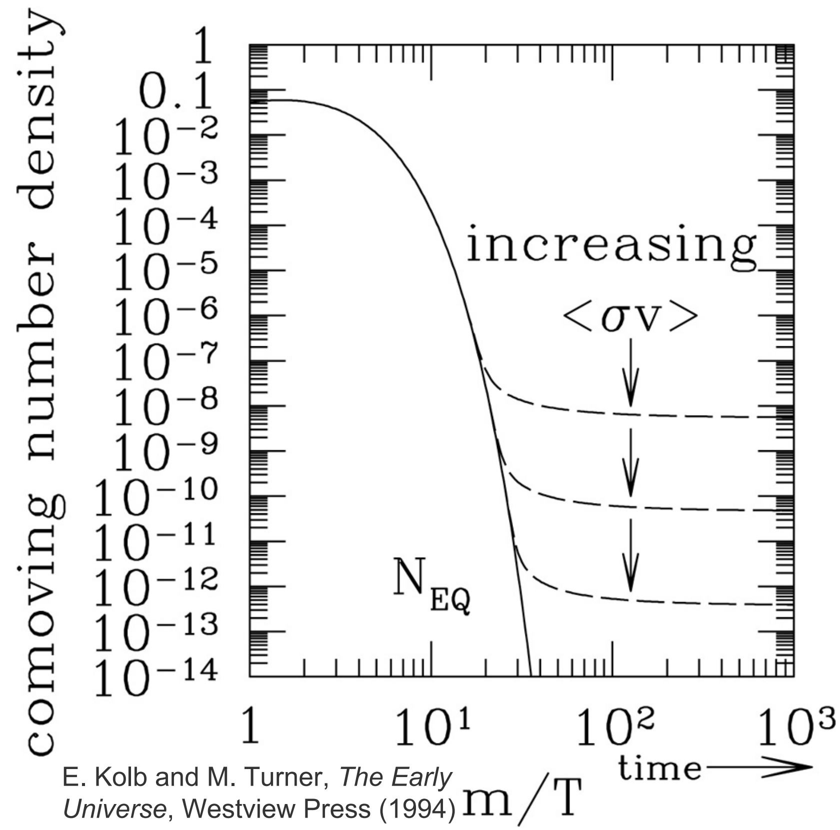
- **Focus on WIMPs**
  - **though Fermi can search for signatures from heavy axions, sterile neutrinos, and gravitinos too**



Baer et al (2015)
http://arxiv.org/abs/1407.0017

WIMPs

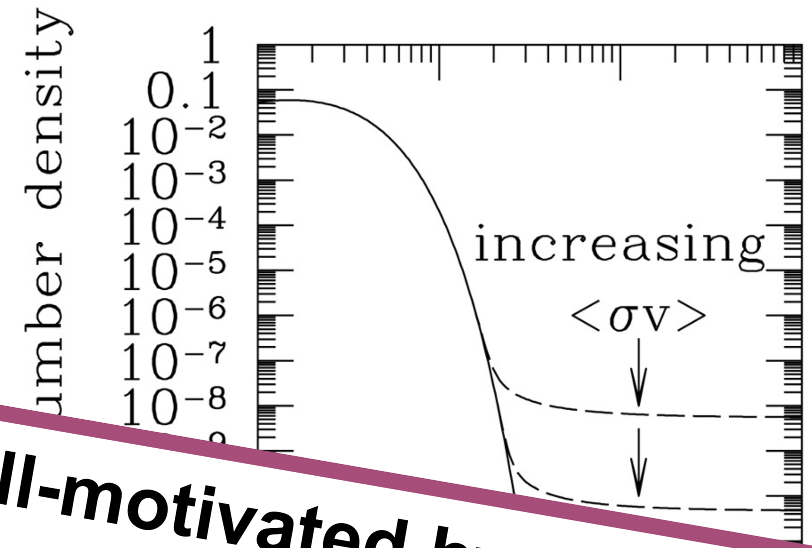
artist's concept



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

- **Weakly Interacting Massive Particle (WIMP, χ)**
  - **GeV - TeV mass scale**
  - **WIMPs may be thermal relics**
  - **e.g. neutralino (SUSY, electrically neutral, stable, motivated theoretically)**
- **Assuming a weak scale σ_{ann} yields observed relic abundance**
  - **$\langle \sigma v \rangle_{ann} \sim 3 \times 10^{-26}\ cm^3/s$ ($\sigma_{ann} \sim 3$ pb at time of decoupling)**
- **Particle DM annihilation may produce Standard Model particles**

WIMPs



Thermal Relic $<\sigma v>$ is a well-motivated hypothesis
Dan Hooper: "Not a fishing expedition"
Though e.g. SUSY gives other hypotheses too...

ned.ipac.caltec

- Weakly Interacting Massive
  (WIMP, χ)
  - GeV - TeV mass scale
  - WIMPs may be thermal relics
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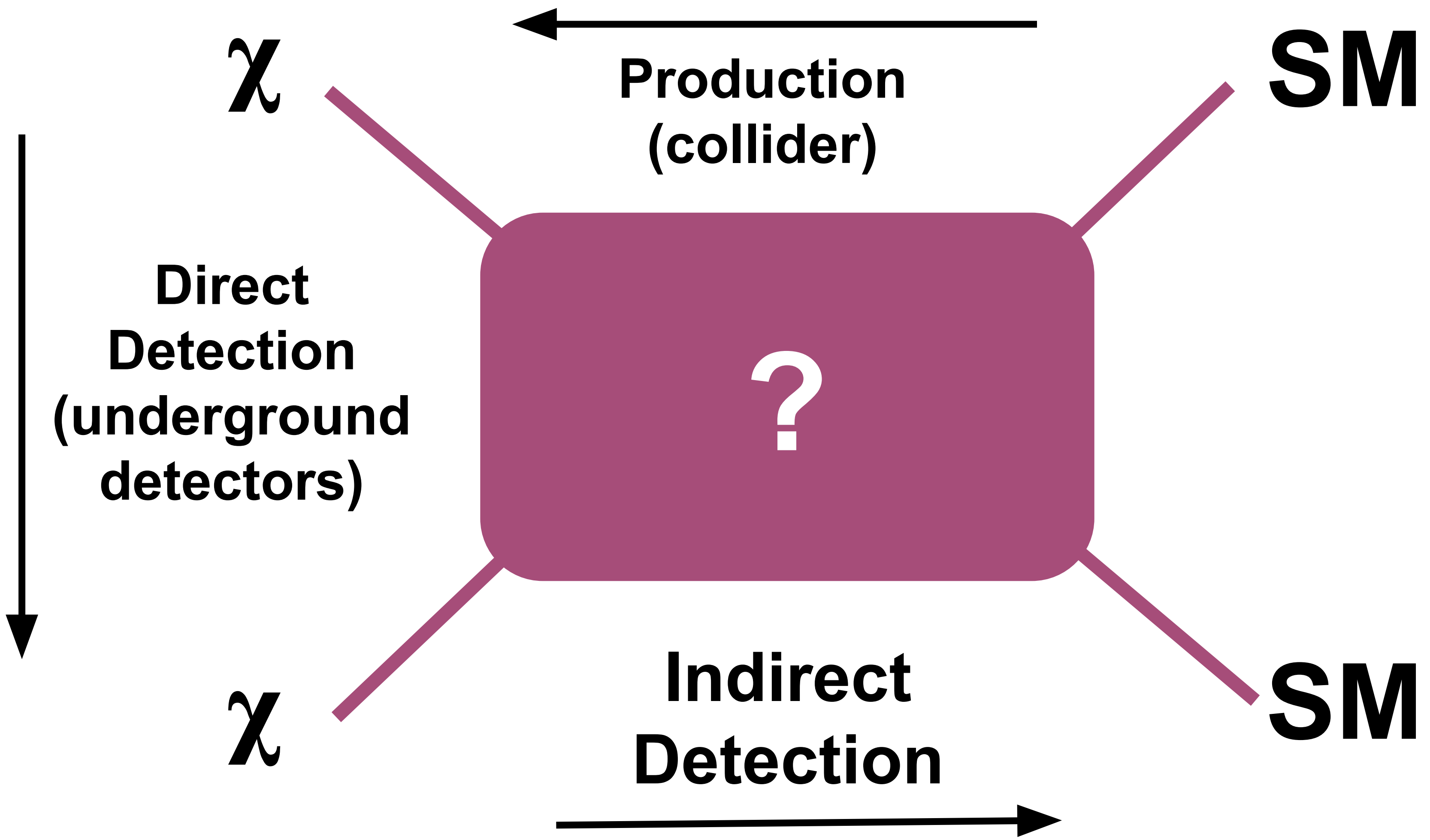
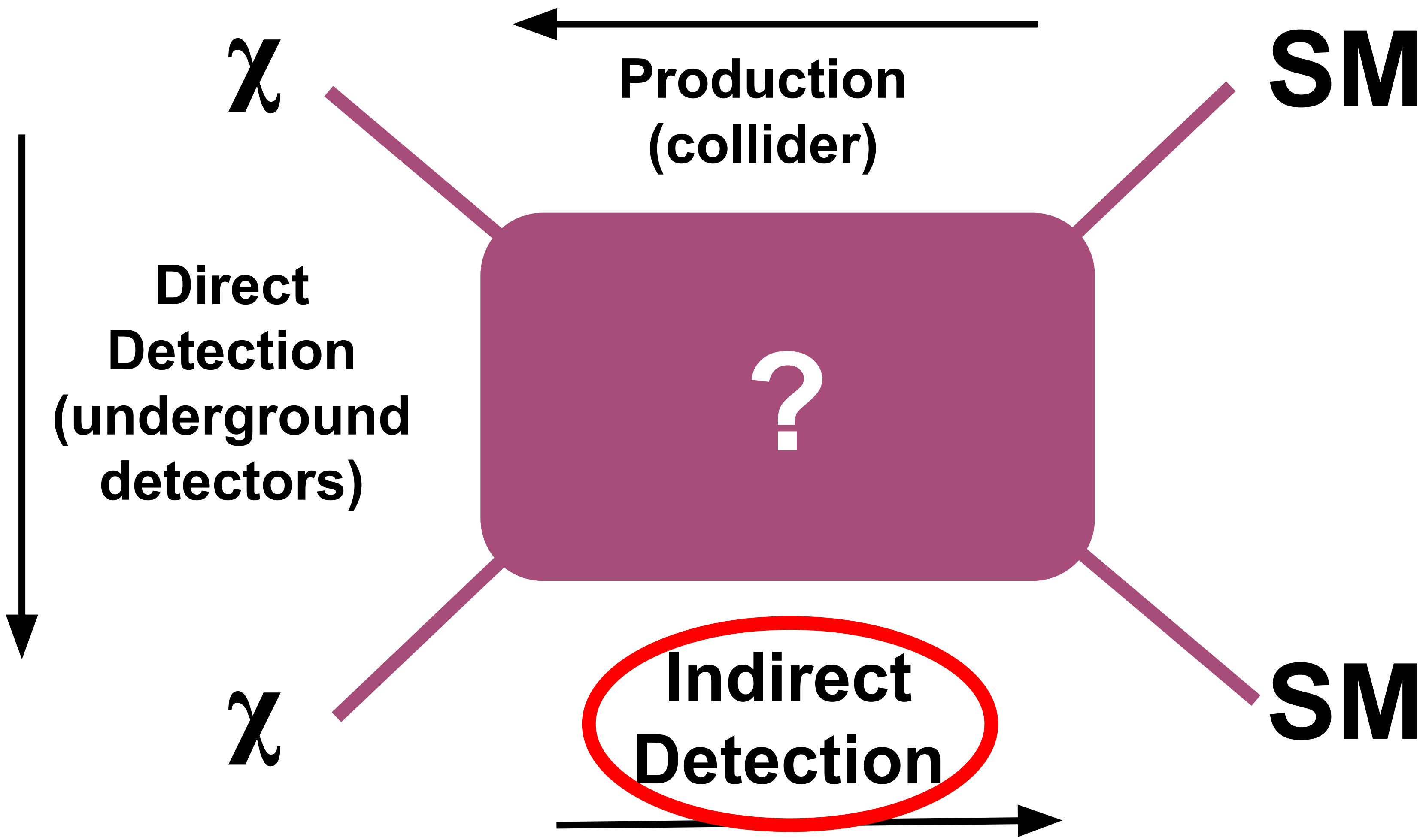
How to Investigate Dark Matter

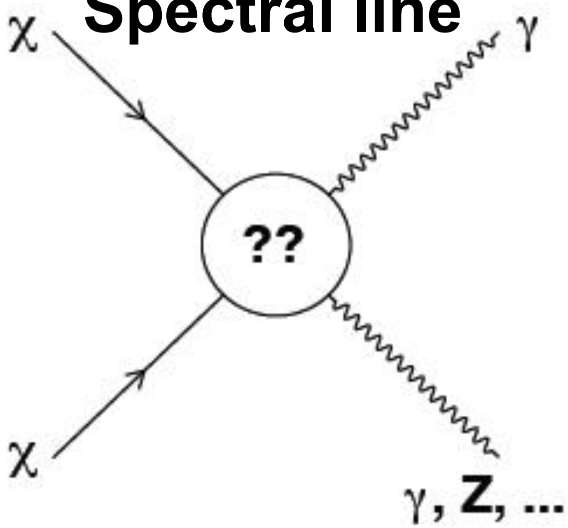


How to Investigate Dark Matter

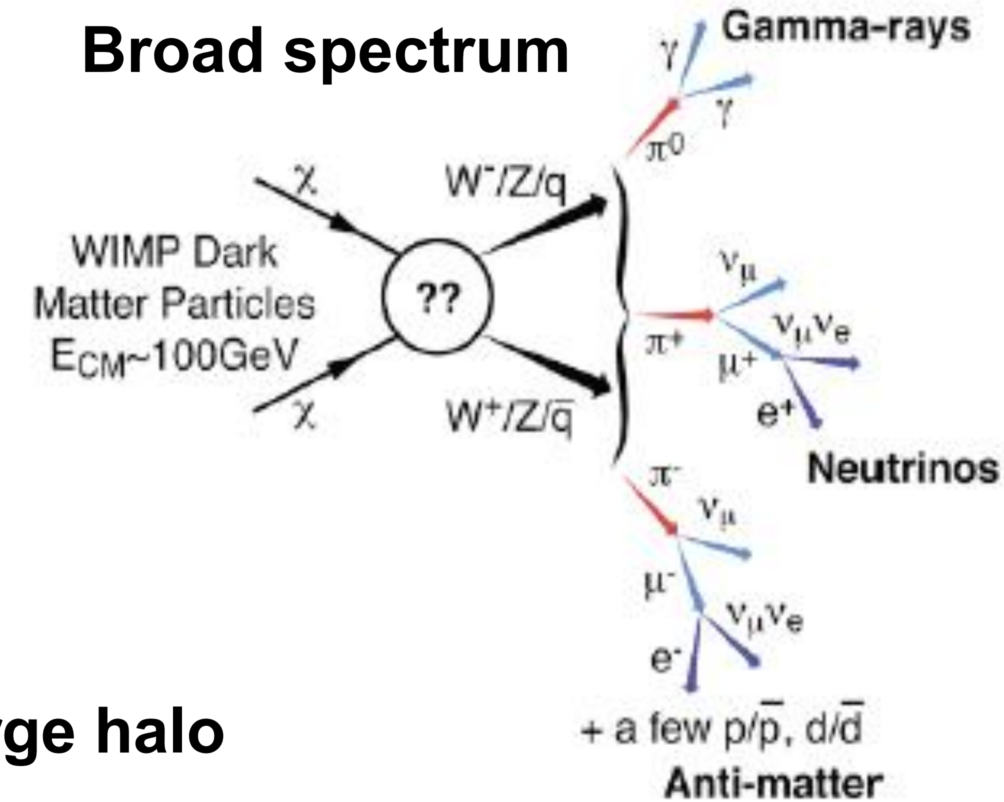


Indirect Dark Matter Detection

Spectral line



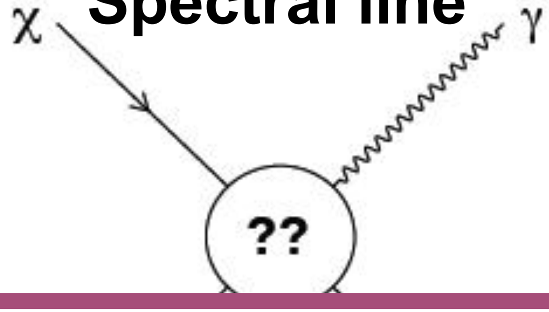
Broad spectrum



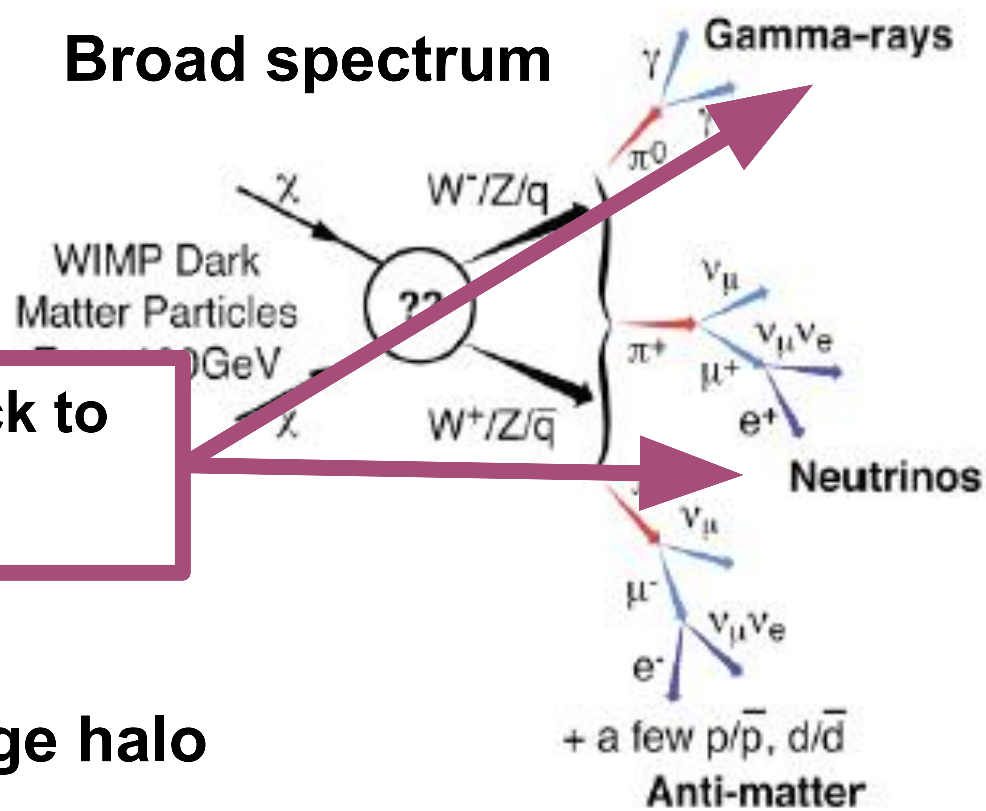
- **The Milky Way sits in a large halo of cold DM (v_{DM} << c)**
  - **Expect additional DM overdensities (halos / subhalos)**
    - **e.g. Milky Way dwarf galaxies**
    - **e.g. Galaxy Clusters**
- **WIMP annihilations (decays) may produce gamma rays**

Indirect Dark Matter Detection

Spectral line



Broad spectrum



Neutral particles point back to where they came from

- **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**

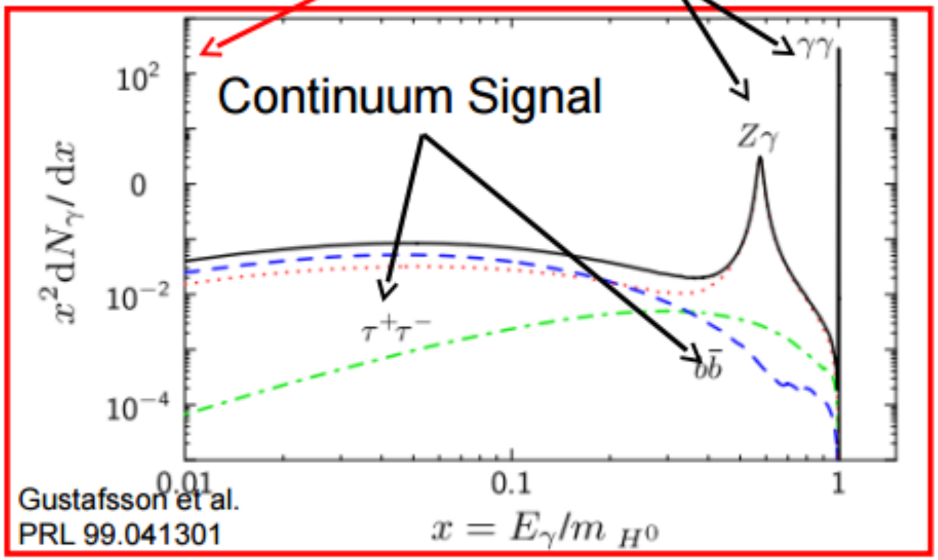
Gamma rays from DM Annihilation

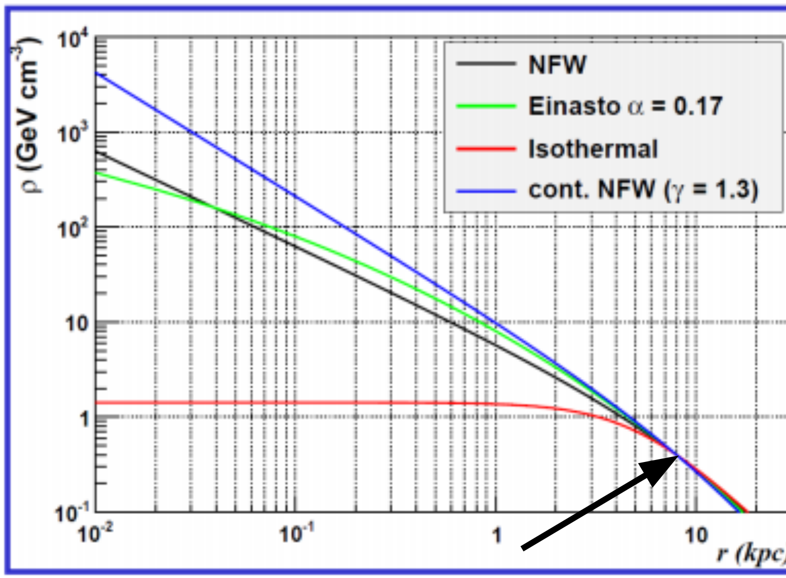
What we observe	Intrinsic Particle Properties	Astrophysics

$$\Phi_\chi(E,\Psi) = \frac{\langle\sigma_\chi v\rangle}{2} \sum \frac{dN_f}{dE} B_f \int_{LOS} dl(\Psi) \frac{1}{4\pi} \frac{\rho(l)^2}{m_\chi^2}$$

J-factor – Line of sight integral over a ROI

Monochromatic Signal

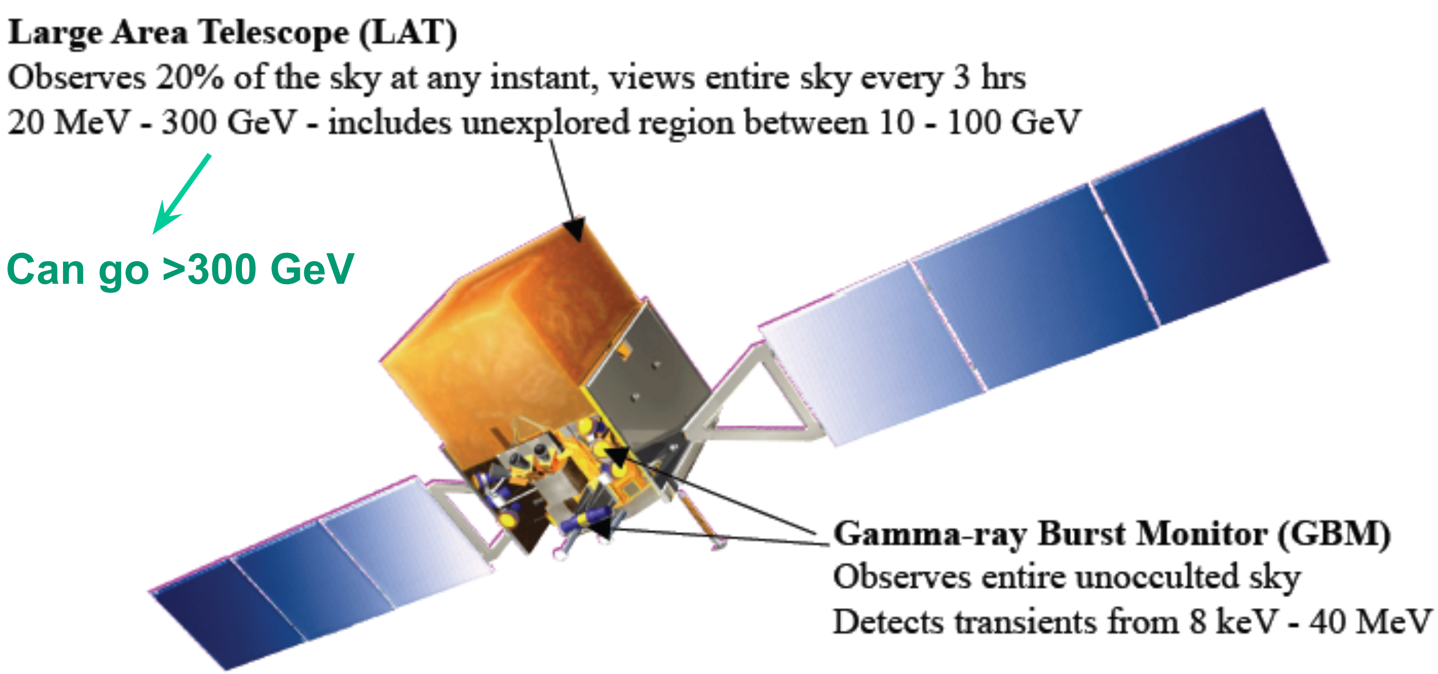




r_{sun} = 8.5 kpc

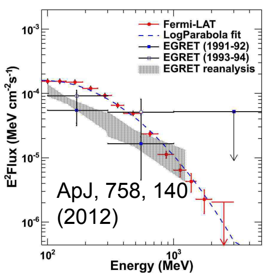
Fermi Large Area Telescope (LAT)

- **On board the Fermi Gamma-ray Space Telescope**
  - **Launched June 11, 2008 (science mission started Aug. 2008)**
    - **Mission extended at least through 2016**
    - **No consumables**
      - **Orbit re-entry expected ~2026-2044 (depending on solar activity)**
  - **LAT has triggered on >380 billion events**
    - **Processed >73 billion events (>1 Petabyte!)**

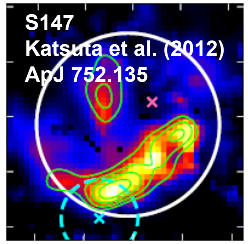


Fermi Gamma-ray Space Telescope Science

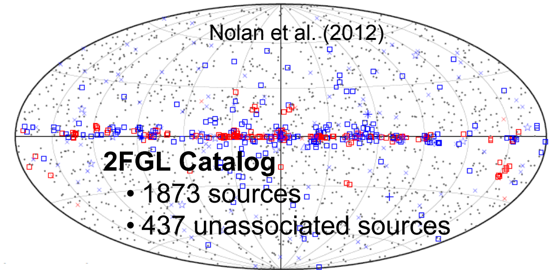
One person's background is another's source!



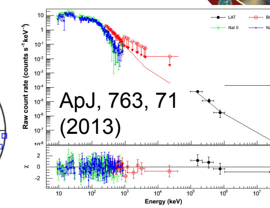
Lunar Gamma rays
CR hitting surface
Correlated w/ solar activity



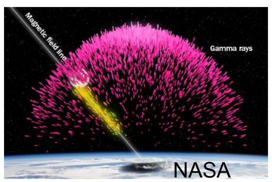
Supernova Remnants
25 published SNR + 30 cands in 2FGL
Multiwavelength objects
Require good diffuse emission modeling



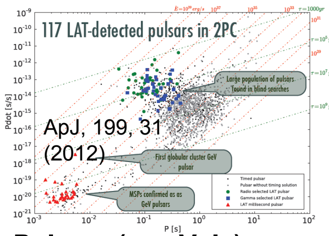
2FGL Catalog
- 1873 sources
- 437 unassociated sources



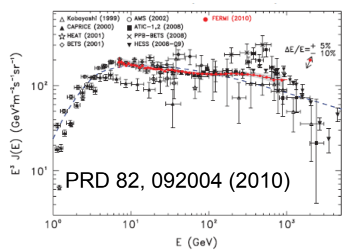
Gamma-ray Bursts
35 LAT, 1000+ GBM
GBM + LAT spectra



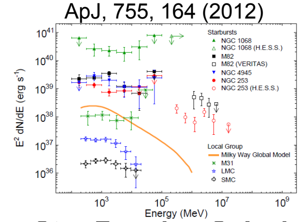
Terrestrial Gamma-ray Flashes
Associated w/ thunderstorms
Observed by GBM & LAT



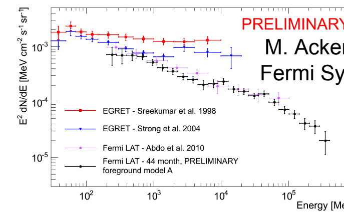
Pulsars (e.g. Vela)
117 Fermi-LAT det. pulsars
Multiwavelength objects
PSR J2021+4026 shows variablilty



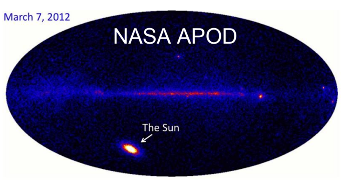
e^-e^+ Energy Spectrum
LAT can measure e's too board high-energy excess



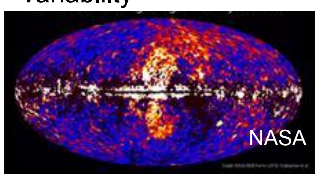
Star-Forming Galaxies
LAT has seen 7
Potential LAT-CTA synergy



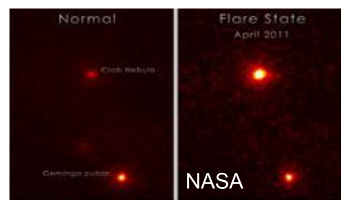
Extragalactic bkg
Spectrum from 0.2-410 GeV
Ainsotropy →population info



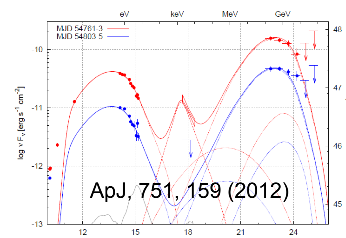
Solar Flares
Observed by GBM & LAT
X-class Flare on March 7^{th}, 2012



Fermi Bubbles
Unexpected high-energy excess lobes



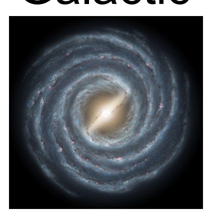
Pulsar Wind Nebula (e.g. Crab)
15 candidates found by LAT
Multiwavelength objects



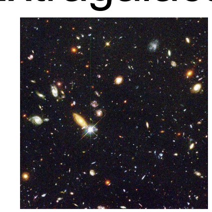
Blazars
Largest population of LAT known sources
PKS 1424+240 is harder than expected
Multiwavelength objects

Solar System

Galactic



Extragalactic



Andrea Albert (SLAC)

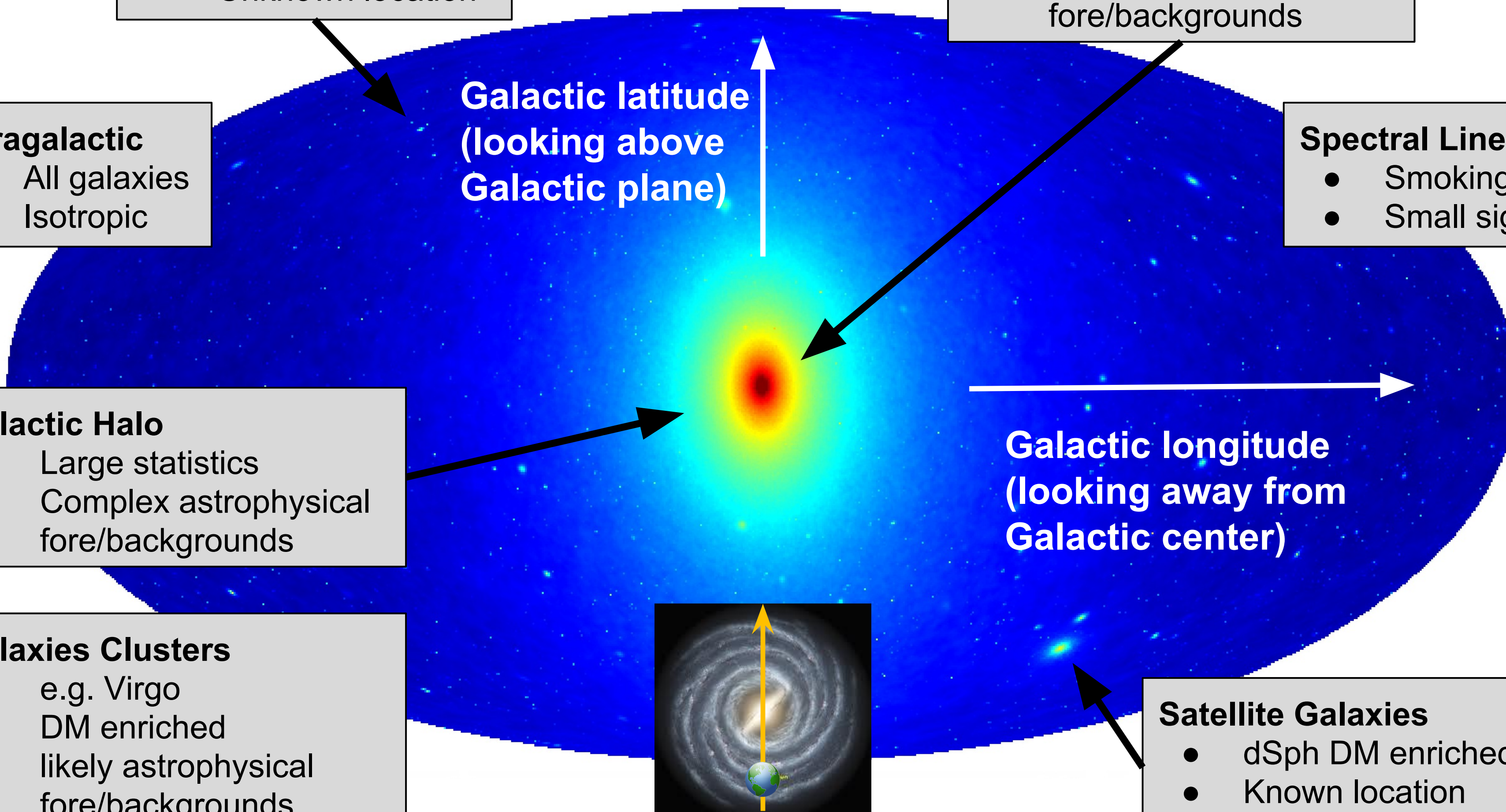
Galactic Distribution of Dark Matter

DM clumps in Halo
- Few backgrounds
- Unknown location

Galactic Center
- Large statistics
- Complex astrophysical fore/backgrounds

Extragalactic
- All galaxies
- Isotropic

Spectral Lines
- Smoking gun
- Small signal



Galactic Halo
- Large statistics
- Complex astrophysical fore/backgrounds

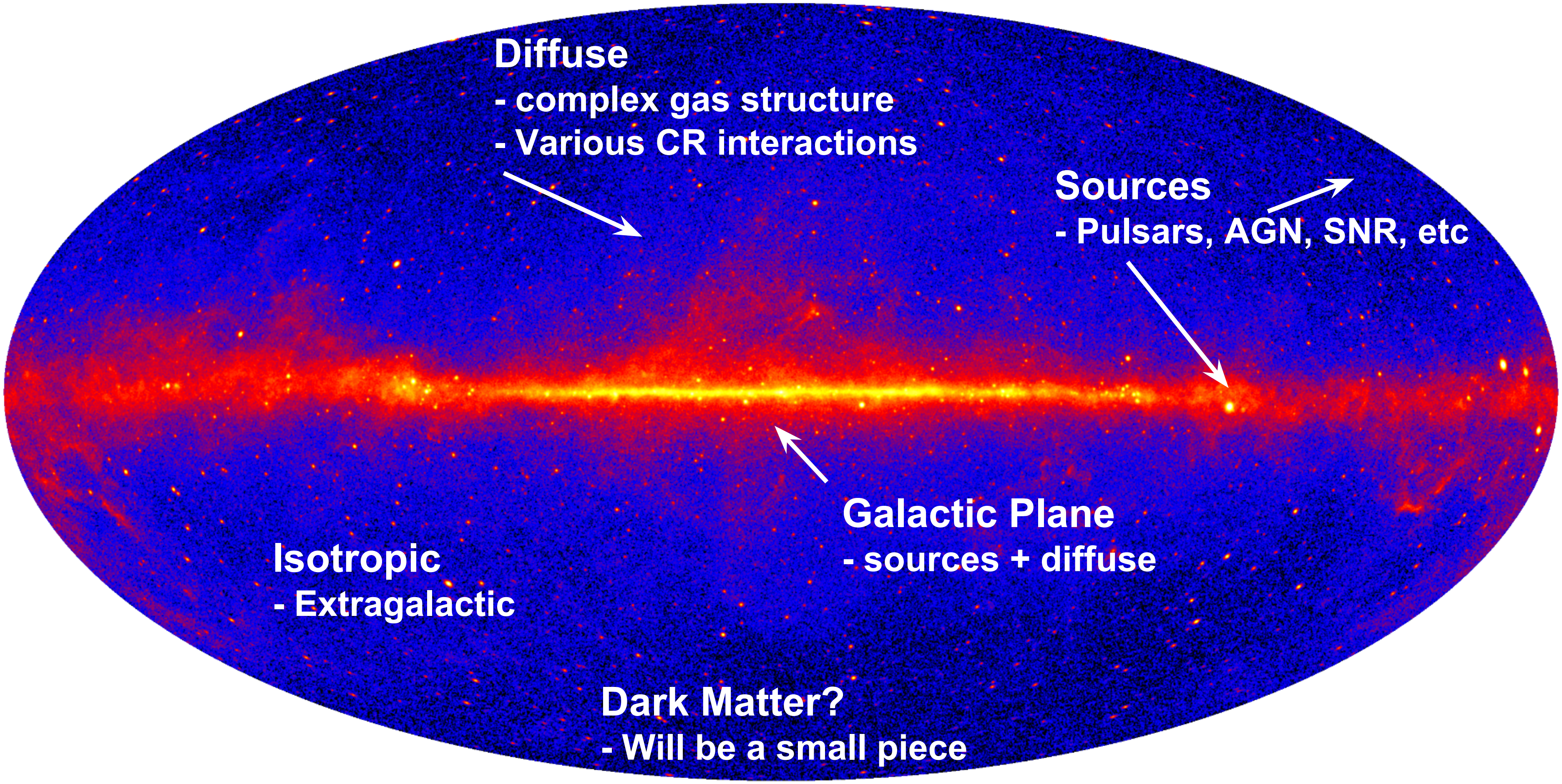
Galaxies Clusters
- e.g. Virgo
- DM enriched
- likely astrophysical fore/backgrounds

Satellite Galaxies
- dSph DM enriched
- Known location
- Smoking gun

Aquarius (A1) simulation

Fermi LAT Gamma-ray Sky

Nature has given us a rich and complicated gamma-ray sky!

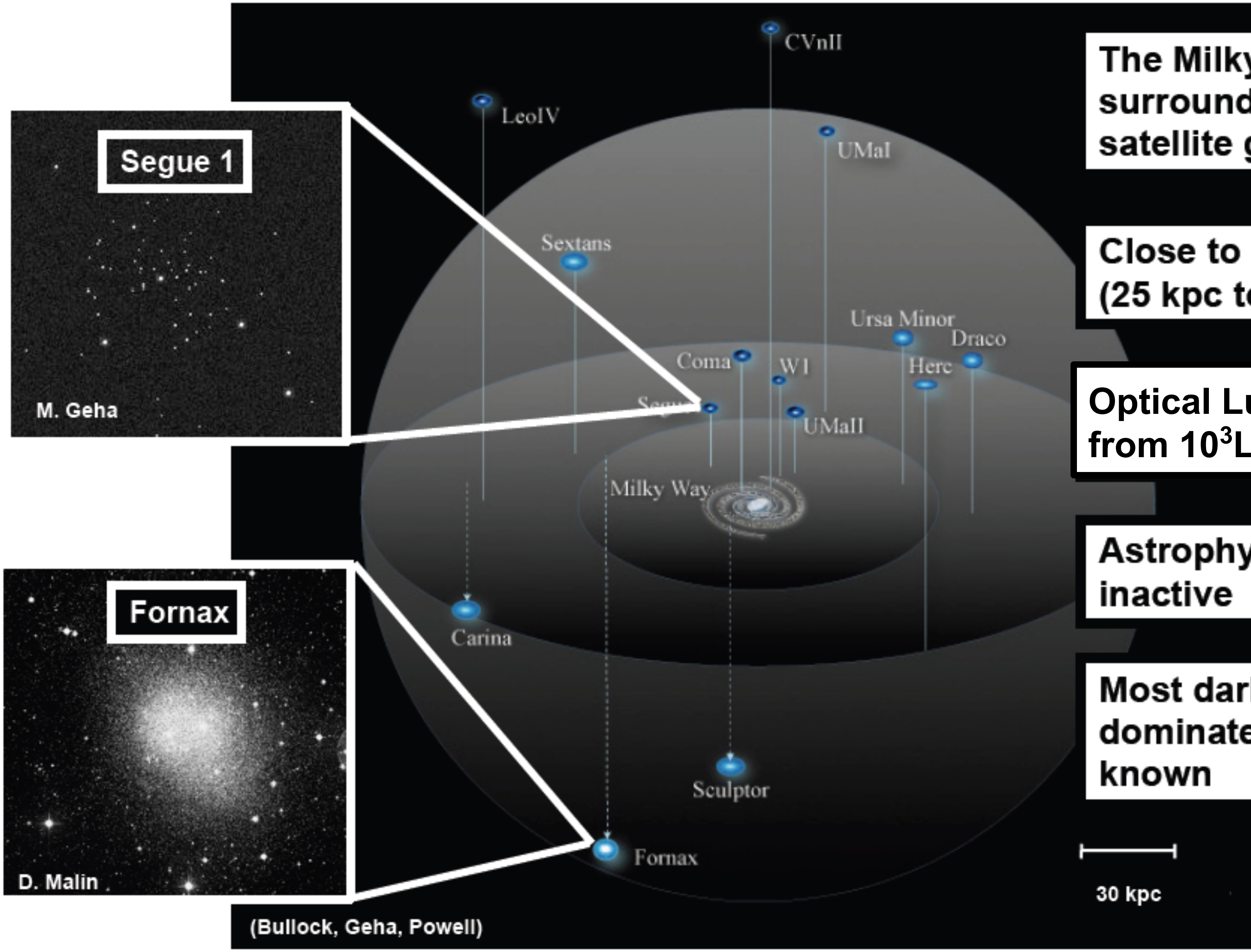


Outline

- Dark Matter Overview
  - DM evidence and candidates
  - Indirect DM detection

- Recent Dark Matter Results
  - Galactic Center
  - Dwarfs

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

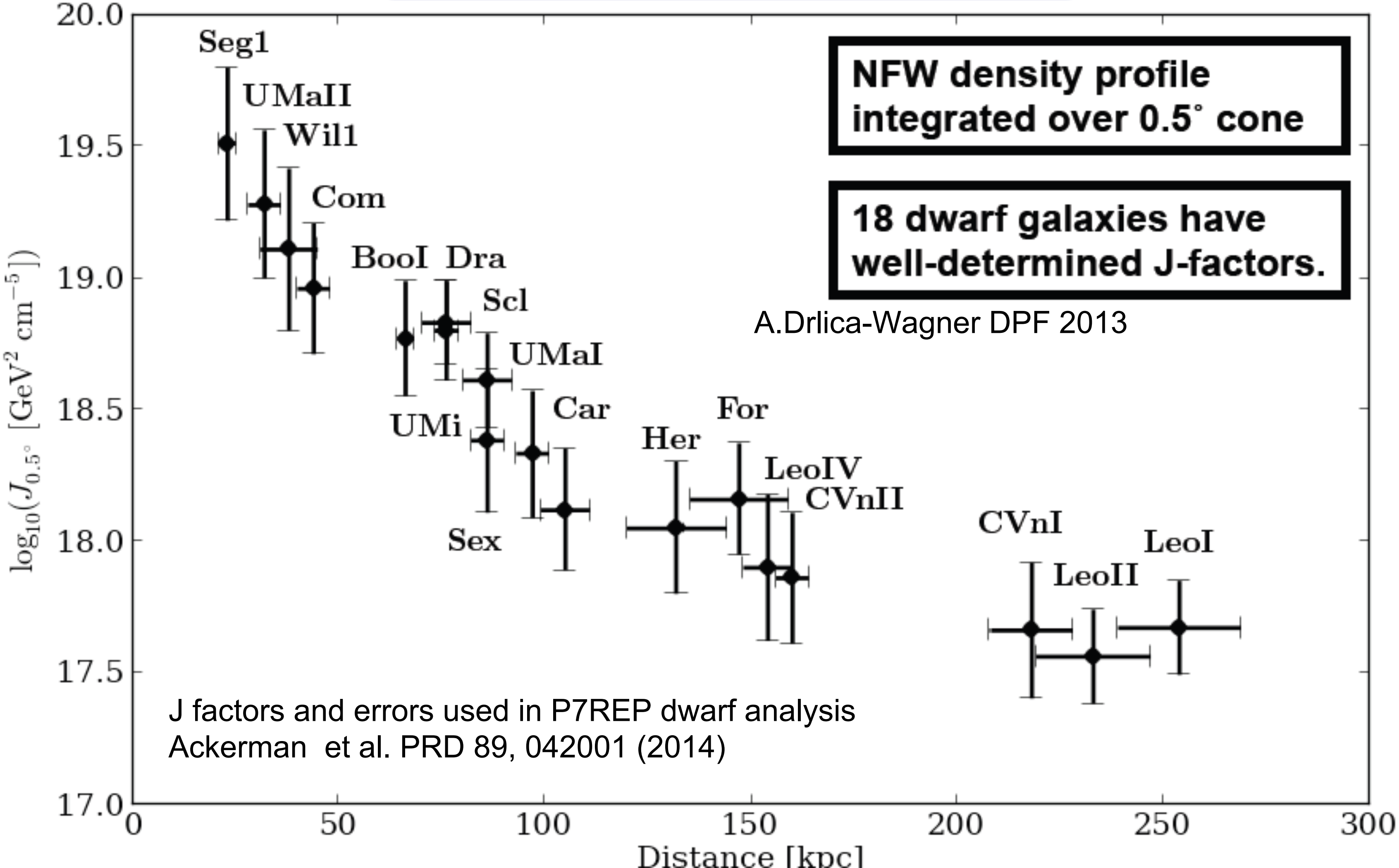
Most dark matter dominated objects known

Slide credit: A. Drlica-Wagner

dSph Galaxy J-Factors

J-factor is proportional to expected gamma-ray intensity

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



dSph Galaxy J-Factors

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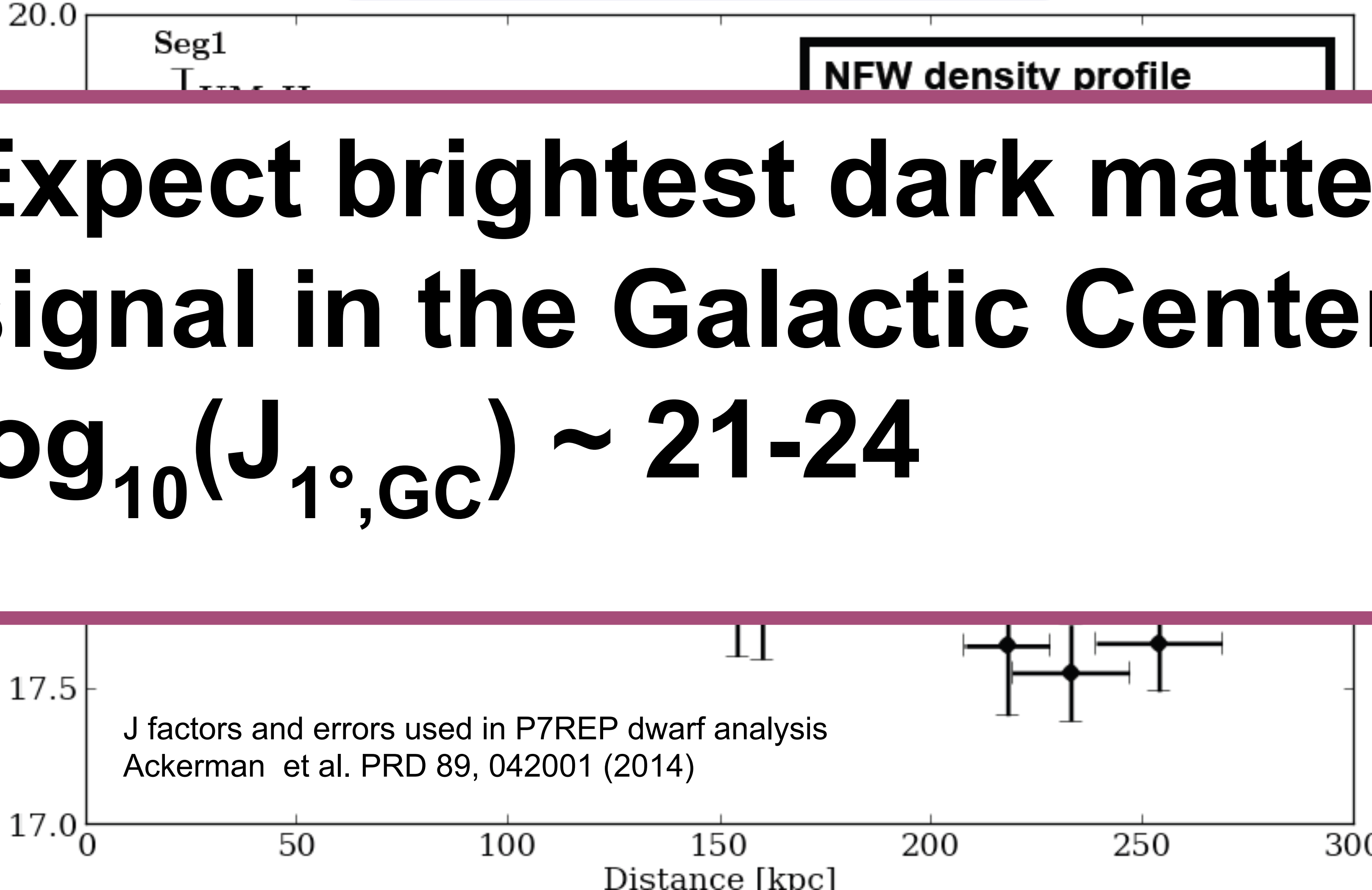
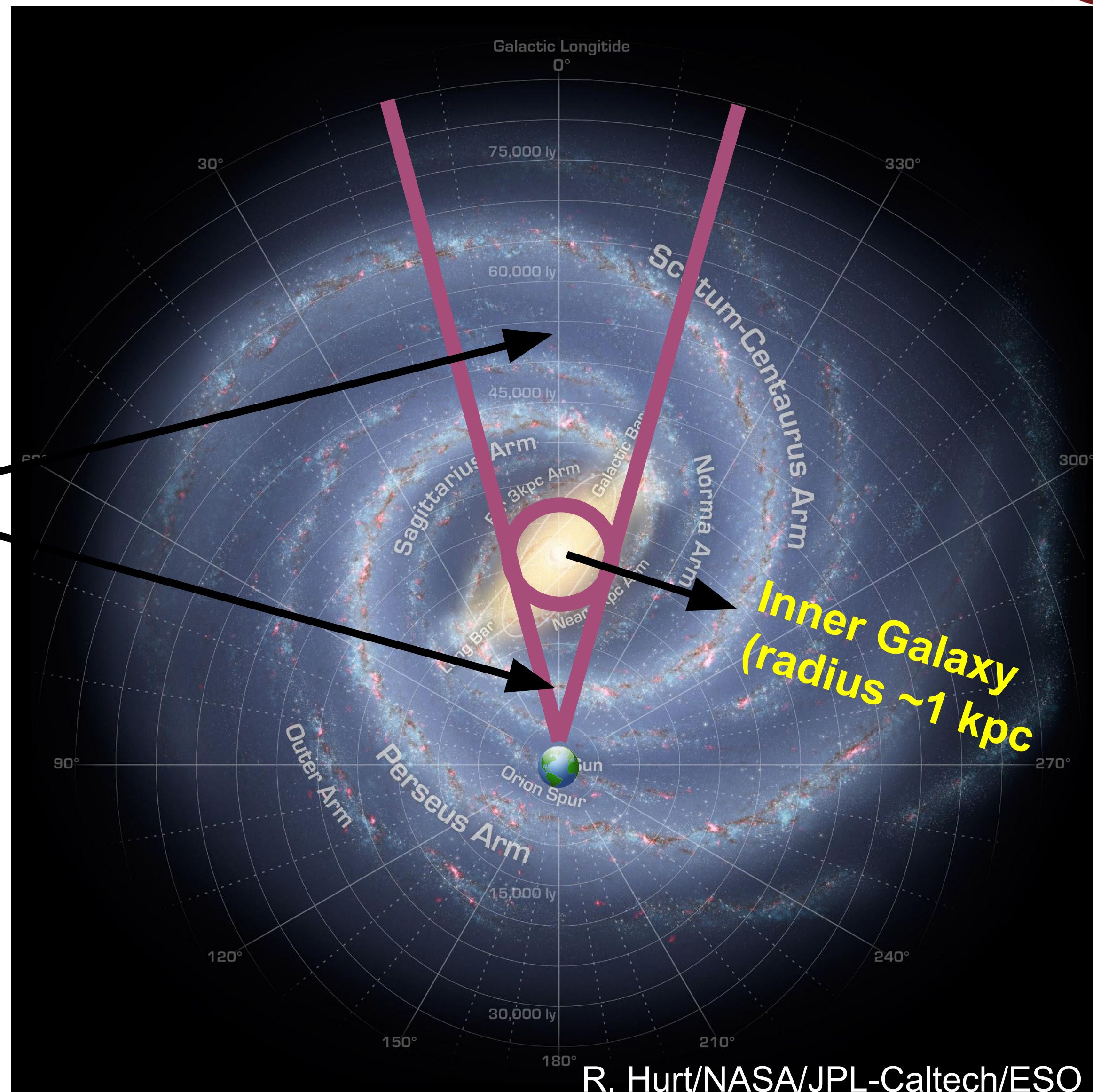


Expect brightest dark matter signal in the Galactic Center

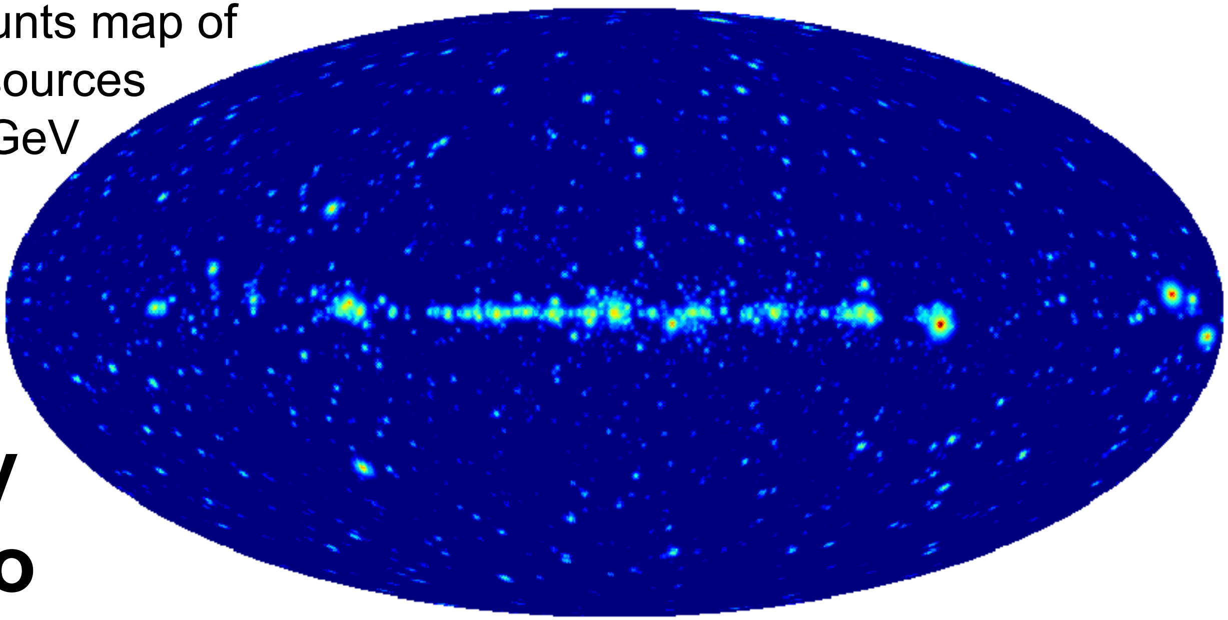
$\log_{10}(J_{1°,GC}) \sim 21\text{-}24$

The Galactic Center is Very Complicated

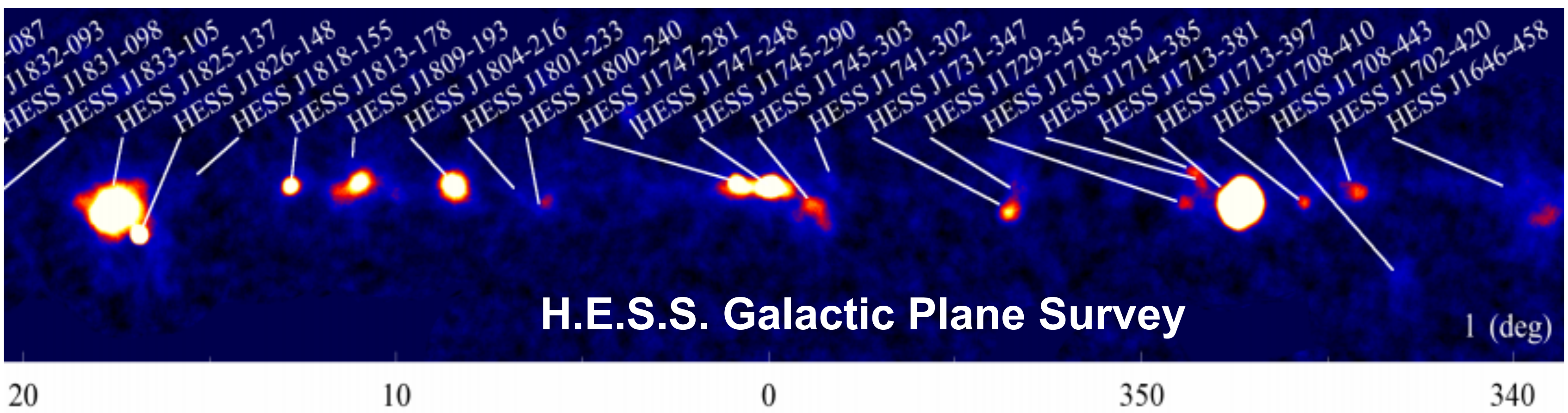
Significant foreground and background emission in Galactic Center line of sight



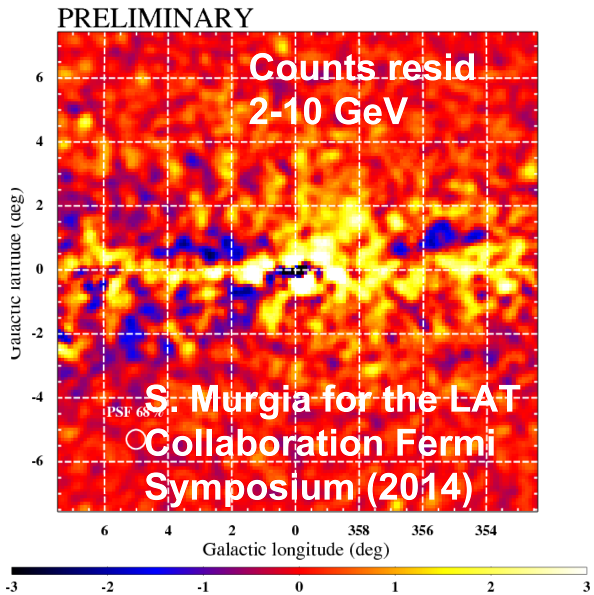
Simulated counts map of
Fermi 3FGL sources
800 MeV - 1 GeV



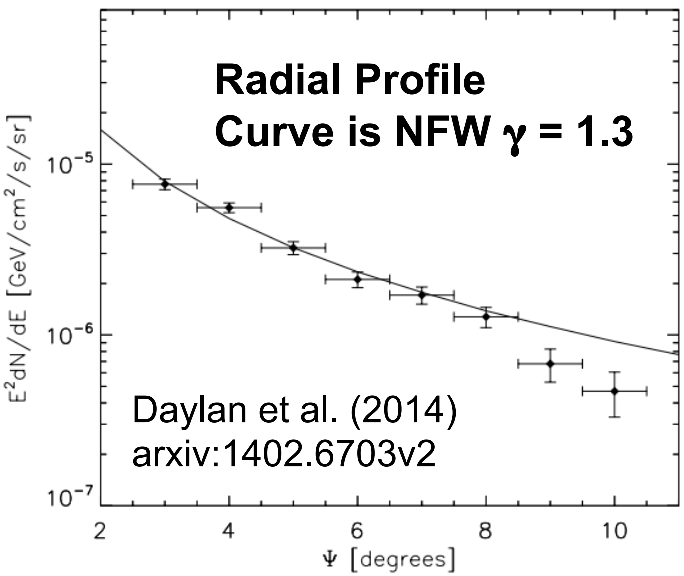
Many gamma-ray point sources too

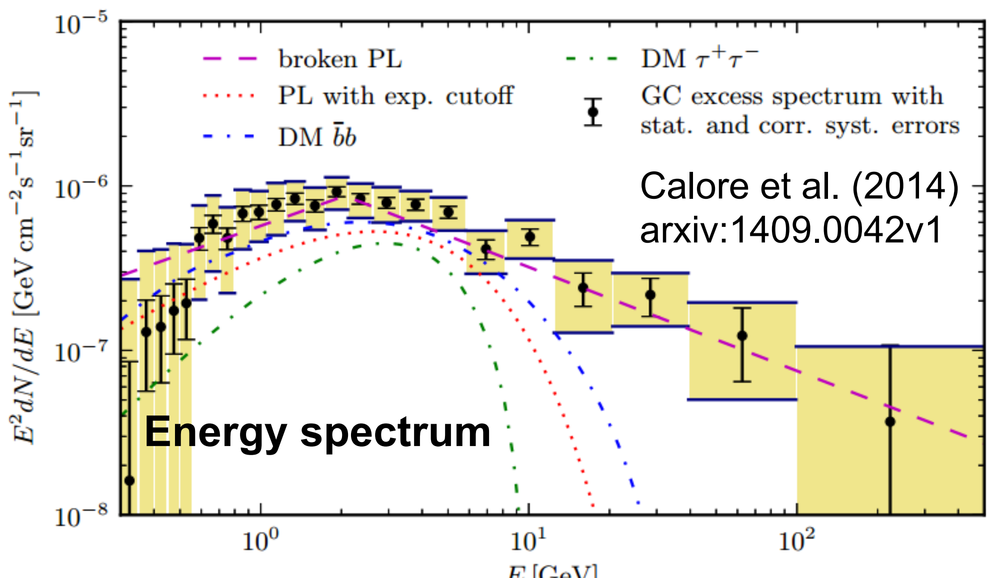


Galactic Center GeV Excess

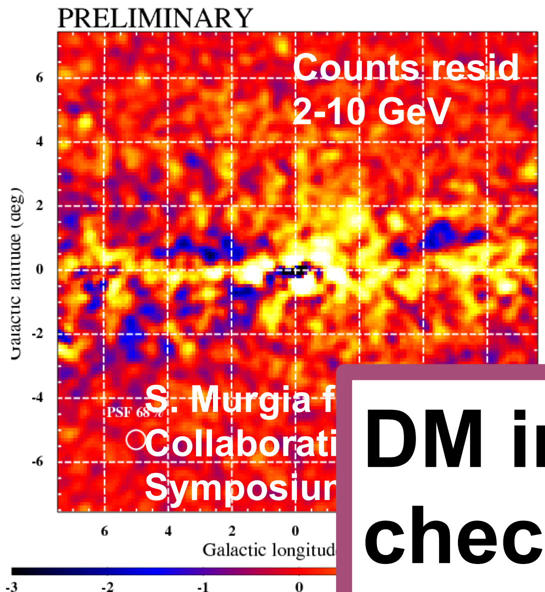


- **Many have reported a gamma-ray excess in the GC using Fermi-LAT data**
  - Goodenough & Hooper (2009, 2001), Hooper & Slatyer (2013), Abrazajian et al (2014), Calore et al (2014), Daylan et al (2014), Gordon & Macias (2014)
- **All groups generally agree there is an excess above standard astro. models peaking ~1-2 GeV**
- **Interpretation is complicated by foreground and background modeling uncertainties**
- **Regardless, any new excess is exciting!**





Galactic Center GeV Excess



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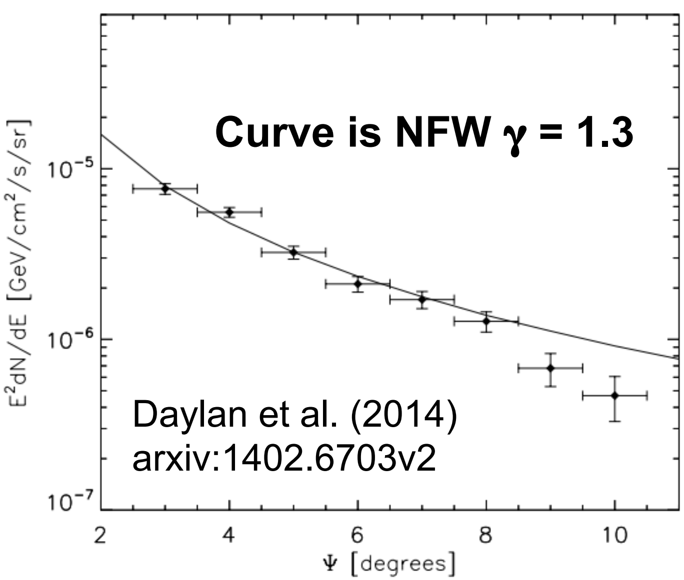
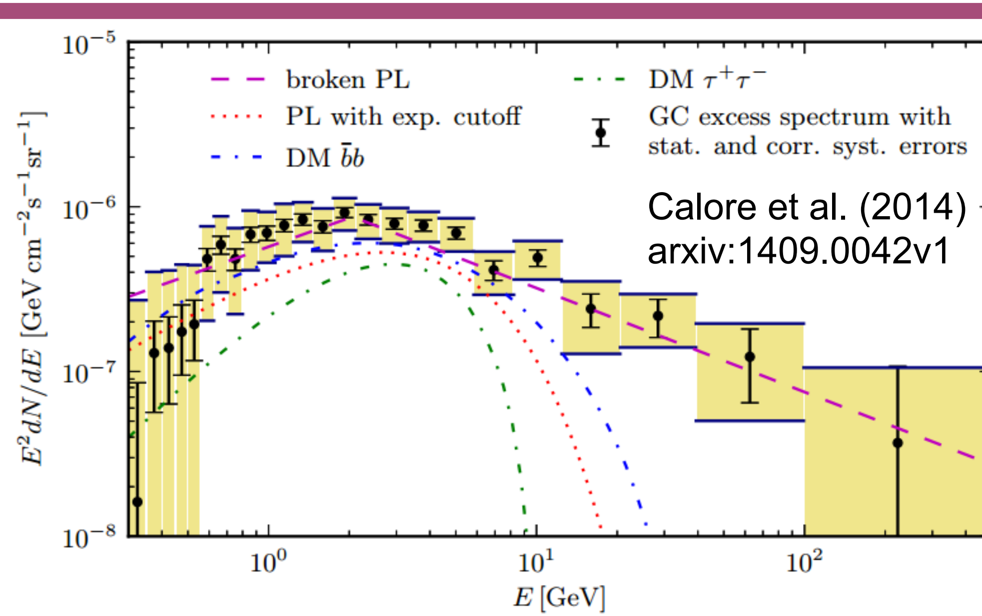
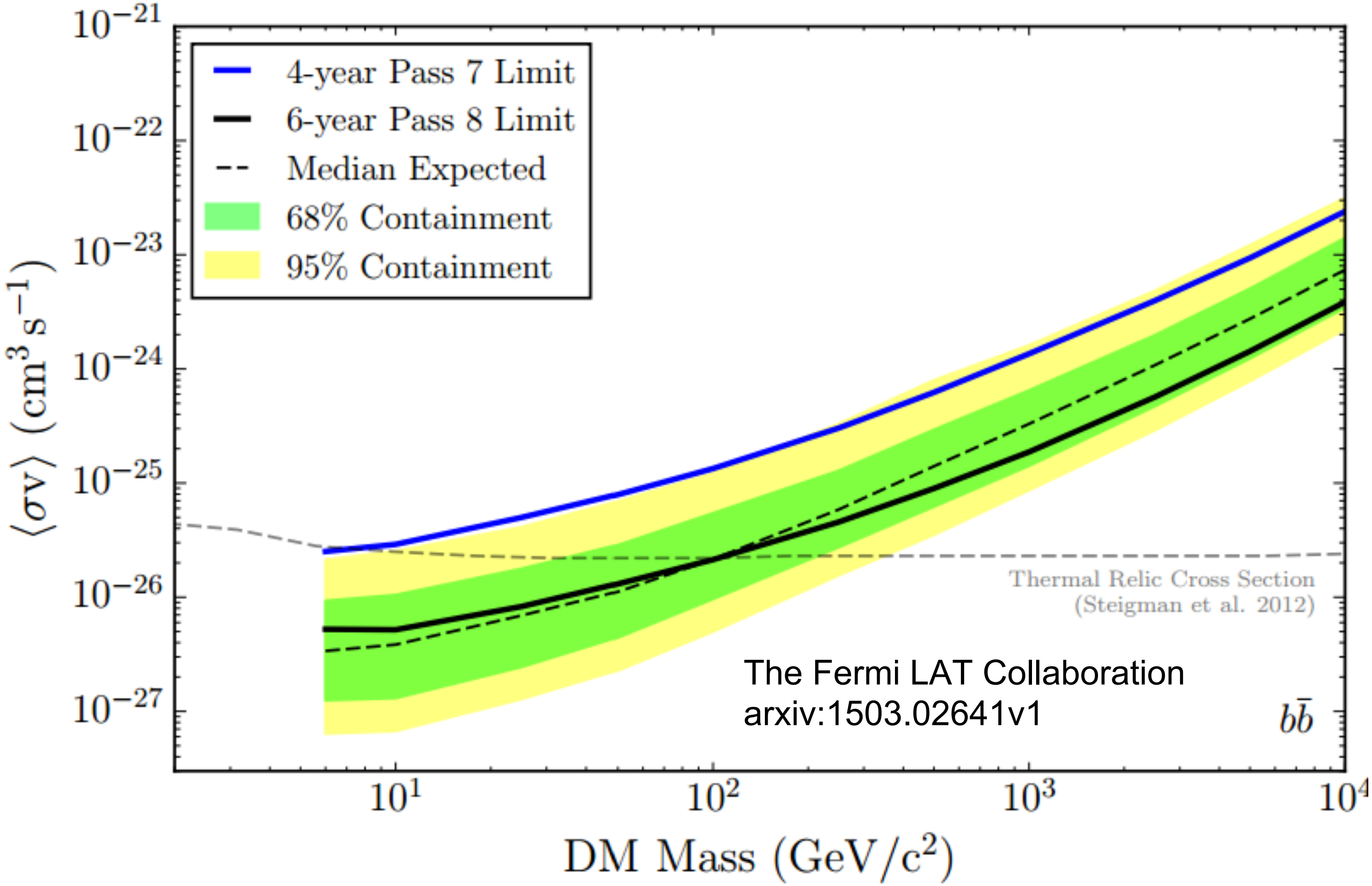
DM interpretation has independent check: dwarf galaxies





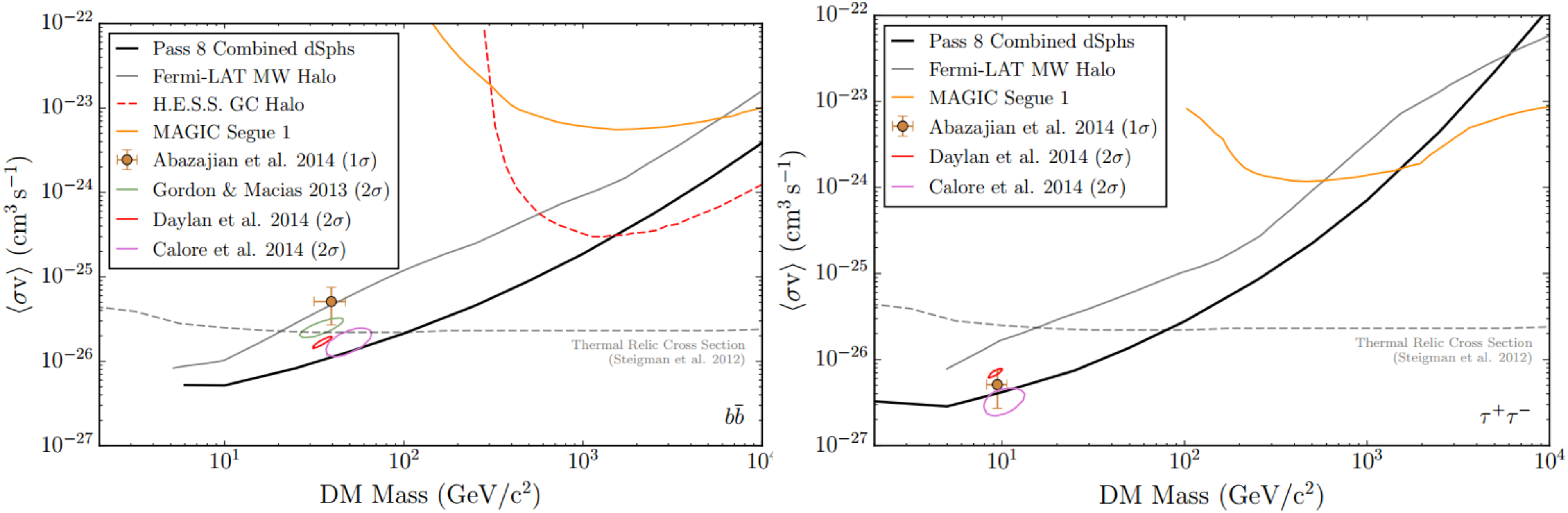
Fermi LAT dSphs Results



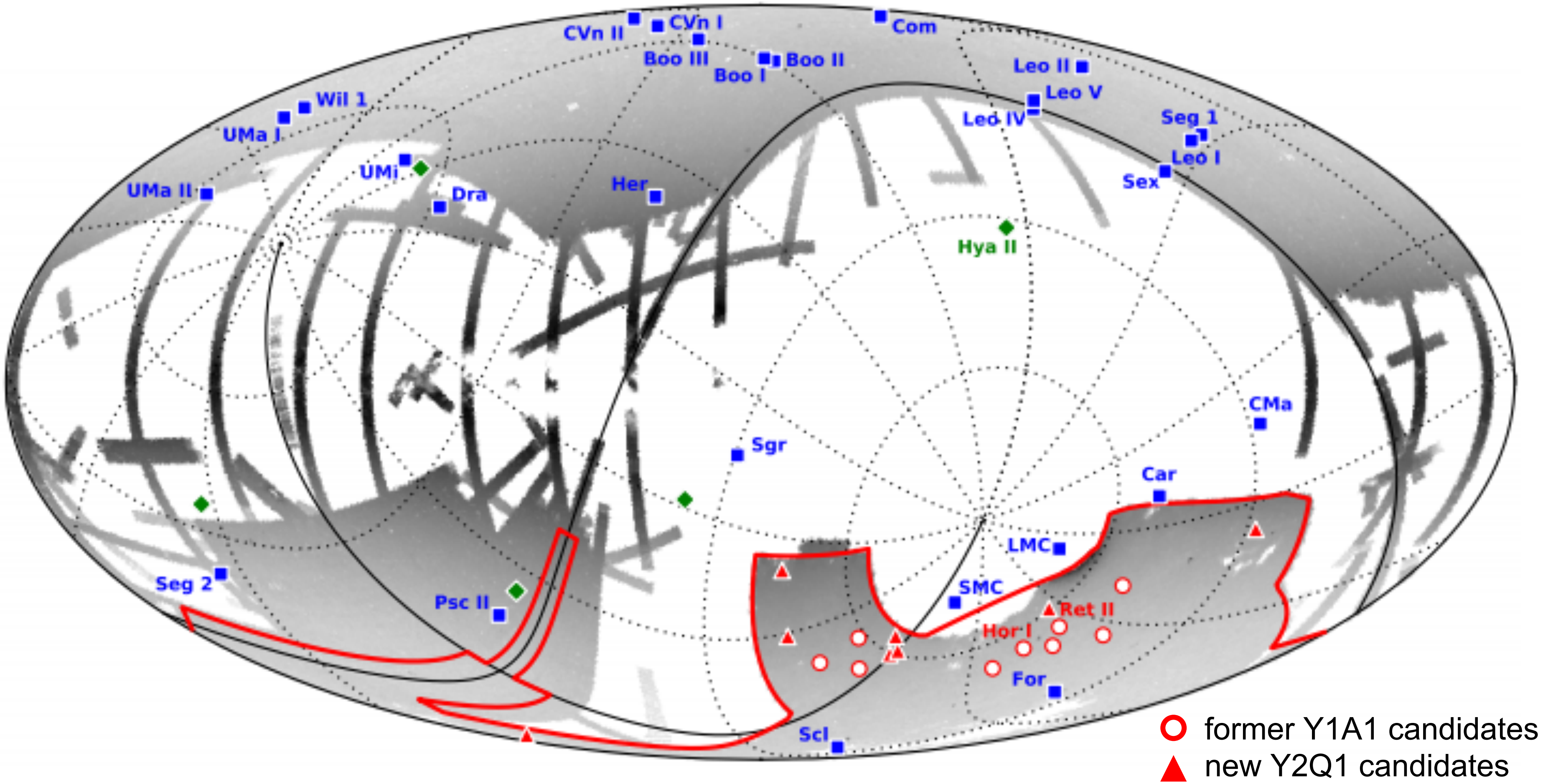
- **Joint likelihood analysis of 15 dwarf galaxies**
- **Limits exclude thermal relic $<\sigma v>_{ann}$ in $b\bar{b}$ channel for 5 GeV < m_χ < 100 GeV**

dSphs as Check of GeV Excess

The Fermi LAT Collaboration
arxiv:1503.02641v1



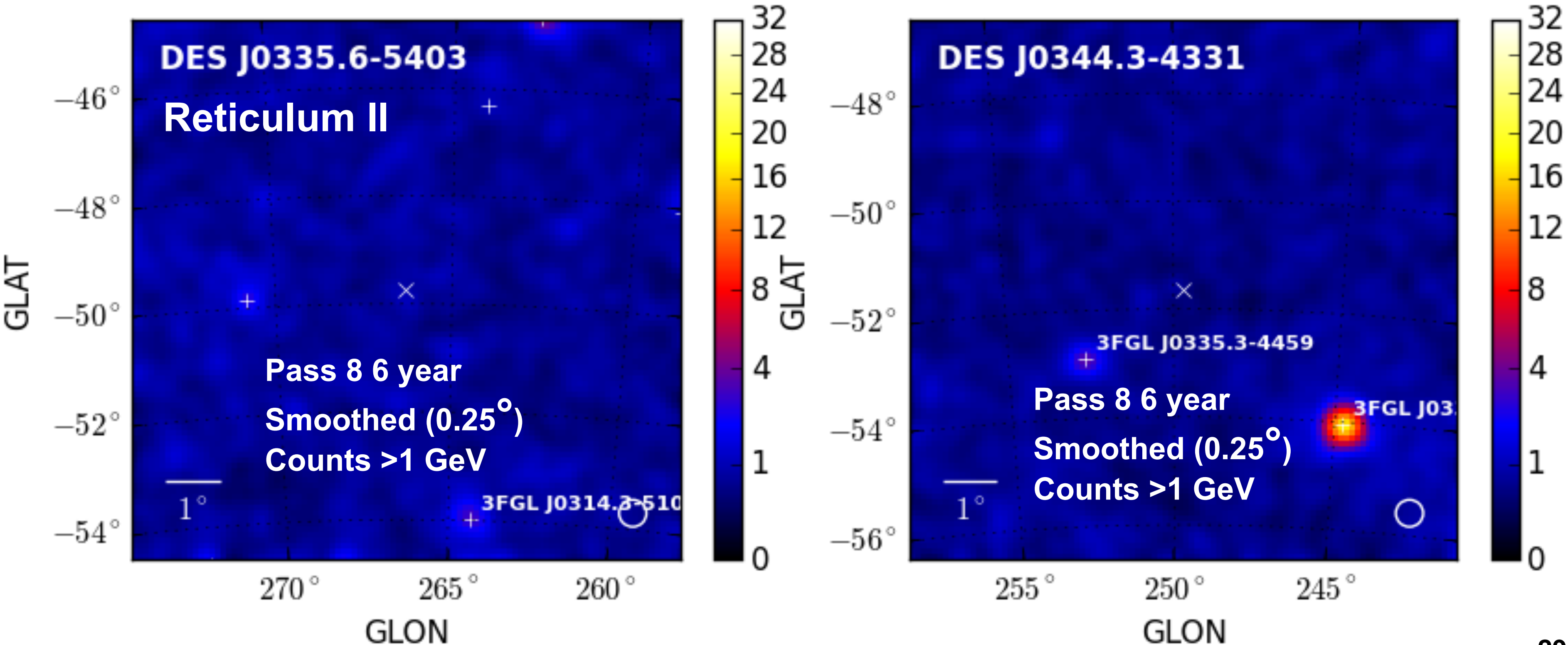
- **Expect same DM in dwarf galaxies as in the GC**
  - **Independent check of DM interpretation of GeV excess in the GC**
- **No excess seen in dwarfs, limits are starting to challenge some of the DM signal regions from the GeV excess**
  - **Increased exposure and finding new dwarf galaxies will improve limits and help clear up the situation**



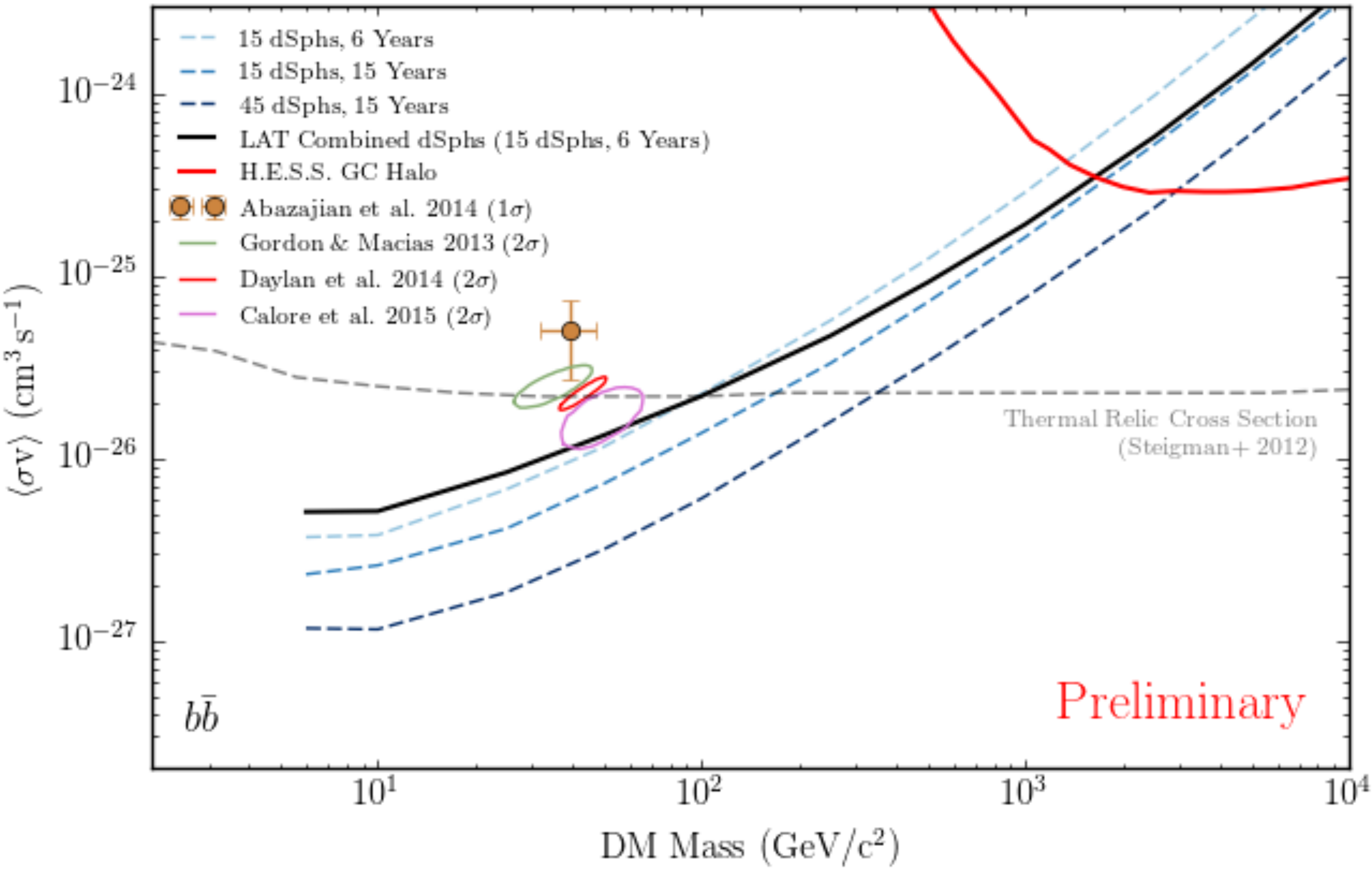
8 new dSph candidates discovered in Y1 Dark Energy Survey Data!
4 announced in PanSTARRs, 4 more discovered using public DES or DECam data, 8 more in Y2 DES Data (arXiv:1508.03622), and counting

Joint LAT-DES Follow up

- No Fermi-LAT emission seen from Y1 dwarf candidates
  - arXiv:1503.02632v2
- Largest TS = 6.7 seen in J0335.6-5403 (Ret II)
  - For m_{DM} = 25 GeV, $\chi\chi \rightarrow \tau^{+}\tau^{-}$
  - 1.5σ (with mass and channel scan trials factor)
  - 0.26σ (with mass, channel, 8 candidate scan trials factor)



Future Expected Limits

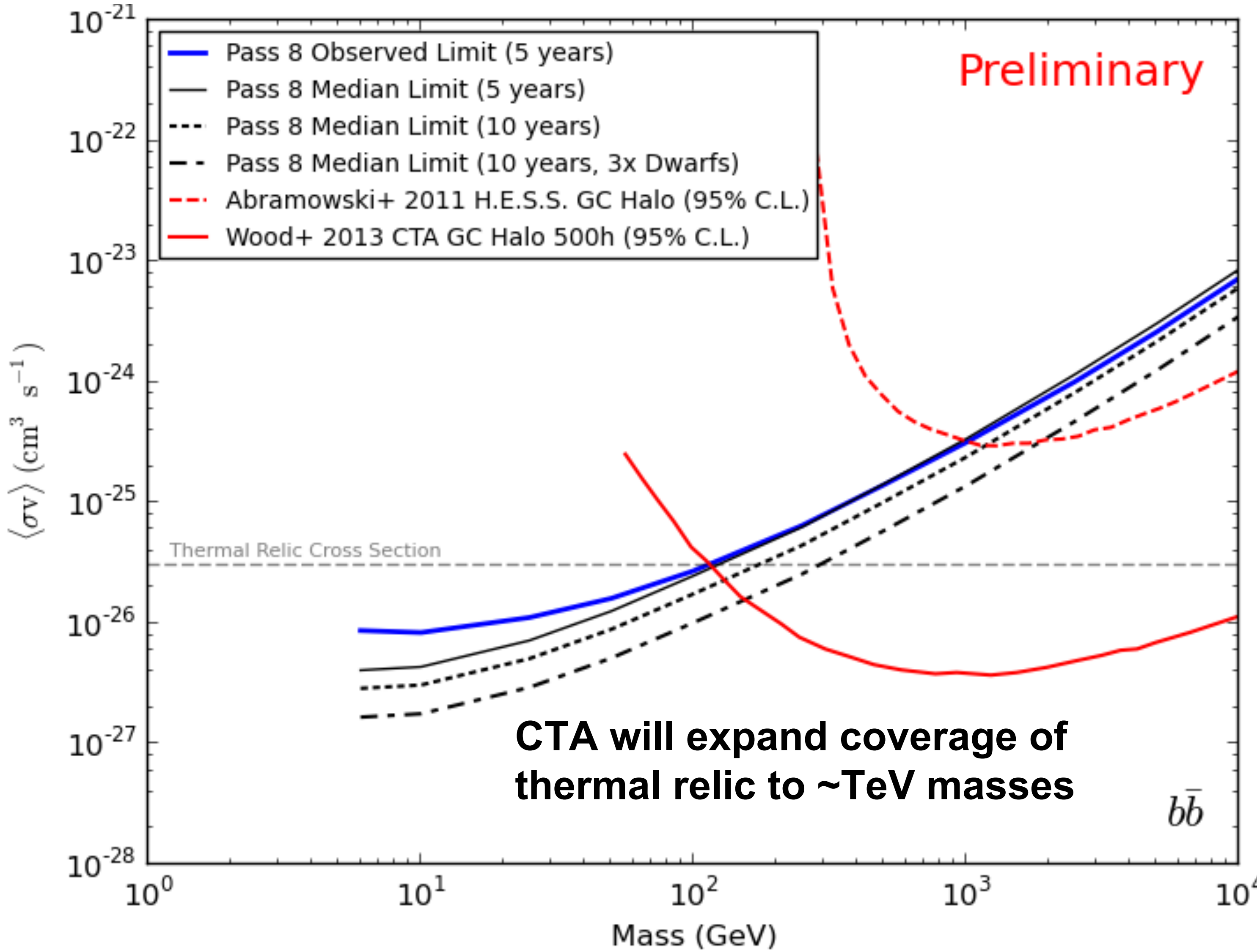


Summary

- Indirect detection searches for dark matter are a crucial complement to other dark matter searches
  - all observational evidence for dark matter comes from space; we must continue investigating dark matter in its cosmic setting
- Fermi-LAT limits have just started to probe the thermal relic annihilation cross section
  - First experiment to reach thermal relic
- No definitive gamma-ray signal from dark matter seen… but still lot's to investigate
  - spatially extended GeV excess in the GC is drawing attention
  - Things are getting very interesting and plans to increase sensitivity are underway. Look forward to more exciting results!

BACKUP SLIDES

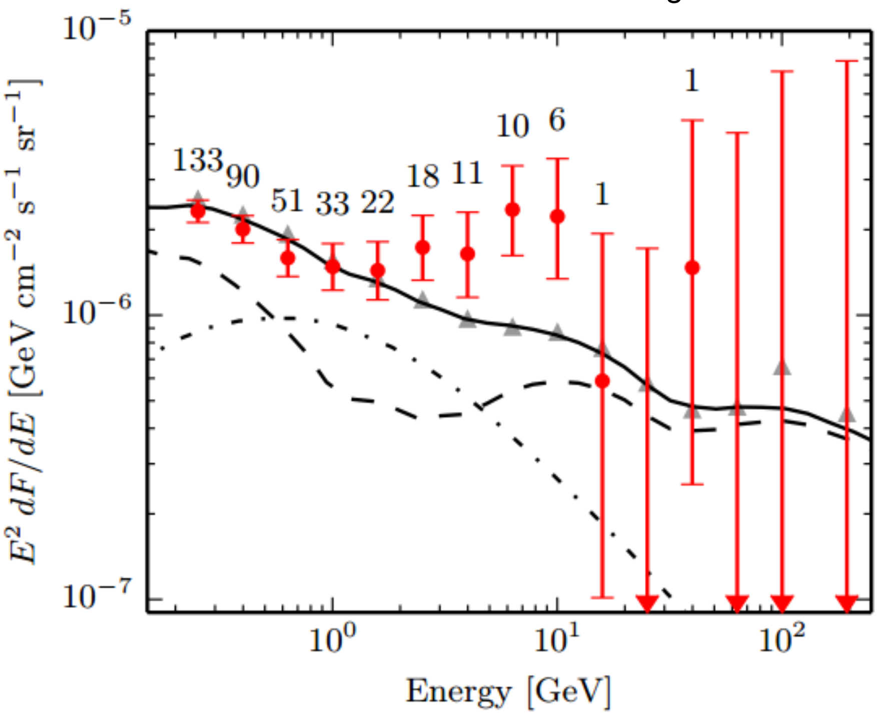
Future Dark Matter Sensitivity



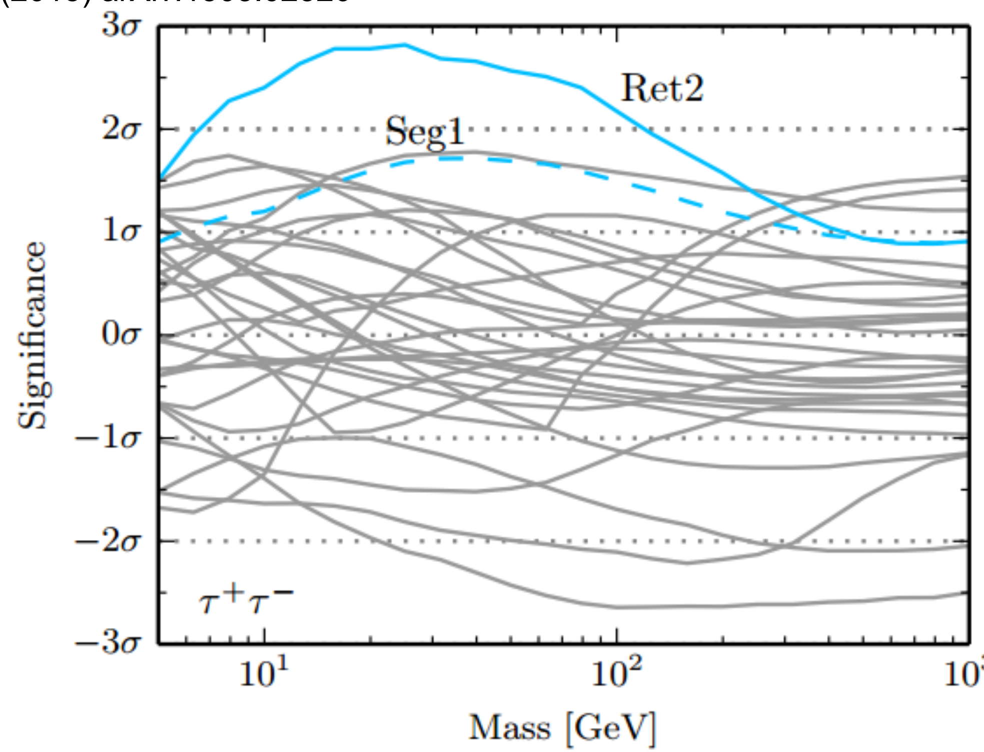
CTA will expand coverage of thermal relic to ~TeV masses

Independent Ret II Gamma-ray Analysis

Geringer-Sameth et al (2015) arXiv:1503.02320



Energy spectrum of events within 0.5° of Ret II
(dash = isotropic, dot dash = diffuse model



- **Independent analysis also found slight excess for m = 25 GeV, $\chi\chi \rightarrow \tau^+\tau^-$**
  - **significance (Pass 7 REP) = 2.3σ (after mass scan trials factor. Note 2.3σ does not account for scans in other dwarf candidates)**
    - **best compared to LAT-DES results of 1.5σ using Pass 8 data**
- **Also found approx -3σ fits, which suggests systematic uncertainty from modeling imperfections is around the 3σ level**

Dark Matter Candidates

- **Wide variety of particle DM candidates in BSM theories**
- **Large scale structure and galactic formation seem to require cold (non-relativistic) DM**
- **Focus on WIMPs**
  - **though Fermi can search for signatures from heavy axions, sterile neutrinos, and gravitinos too**

	WIMPs	SuperWIMPs	Light $\tilde{G}$	Hidden DM	Sterile ν	Axions
Motivation	GHP	GHP	GHP NPFP	GHP NPFP	ν Mass	Strong CP
Naturally Correct Ω	Yes	Yes	No	Possible	No	No
Production Mechanism	Freeze Out	Decay	Thermal	Various	Various	Various
Mass Range	GeV−TeV	GeV−TeV	eV−keV	GeV−TeV	keV	μeV − meV
Temperature	Cold	Cold/Warm	Cold/Warm	Cold/Warm	Warm	Cold
Collisional				√		
Early Universe	√√	√√		√		
Direct Detection	√√			√		√√
Indirect Detection	√√	√		√	√√	√
Particle Colliders	√√	√√	√√	√		

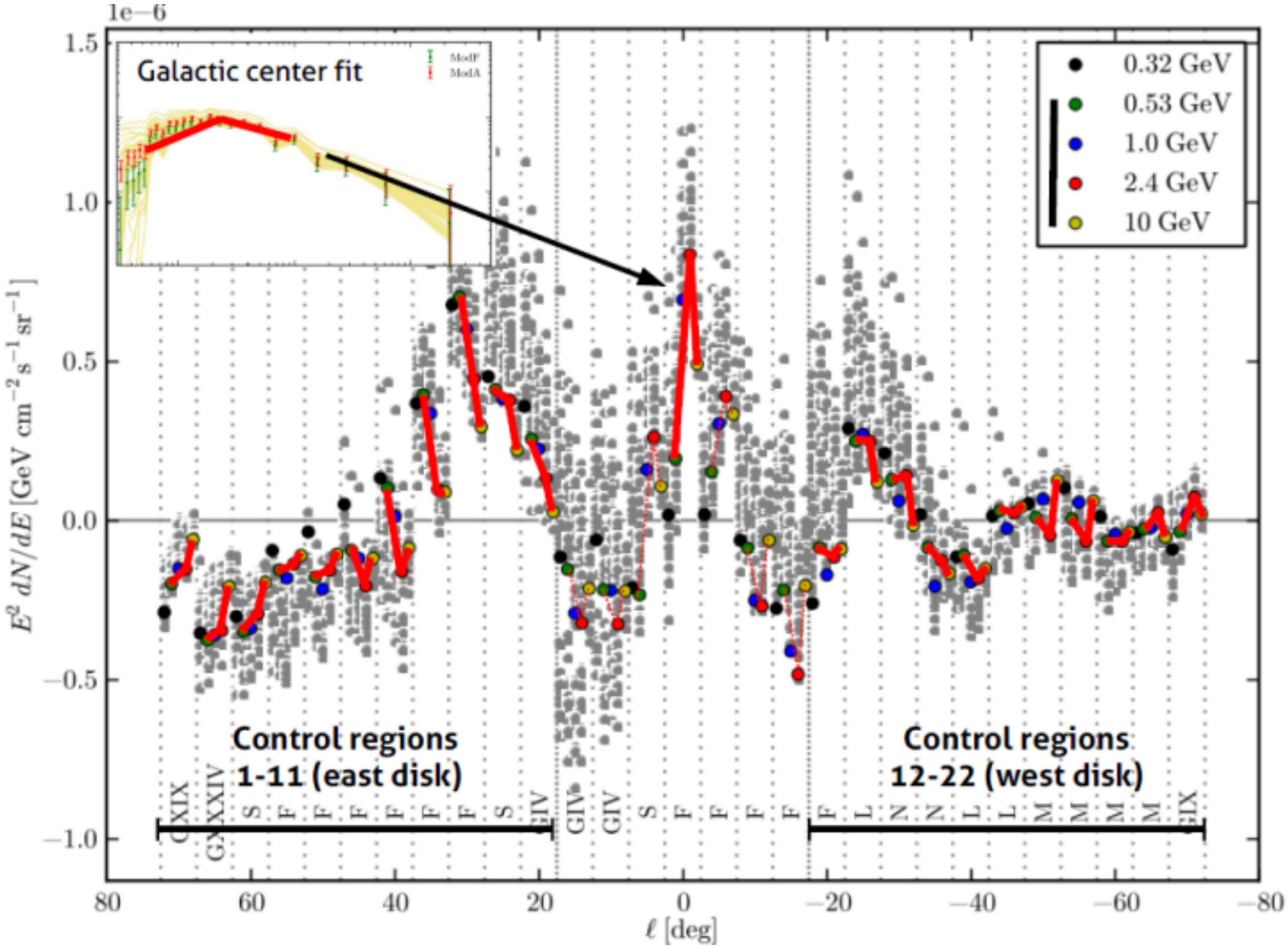
TABLE I Summary of dark matter particle candidates, their properties, and their potential methods of detection. The particle physics motivations are discussed in Sec. II.B; GHP and NPFP are abbreviations for the gauge hierarchy problem and new physics flavor problem, respectively. In the last five rows, √√ denotes detection signals that are generic for this class of dark matter candidate and √ denotes signals that are possible, but not generic. "Early Universe" includes phenomena such as BBN and the CMB; "Direct Detection" implies signatures from dark matter scattering off normal matter in the laboratory; "Indirect Detection" implies signatures of late time dark matter annihilation or decay; and "Particle Colliders" implies signatures of dark matter or its progenitors produced at colliders, such as the Large Hadron Collider (LHC). See the text for details.

Feng (2010)
http://arxiv.org/abs/1003.0904

What is causing the GeV Excess in the GC

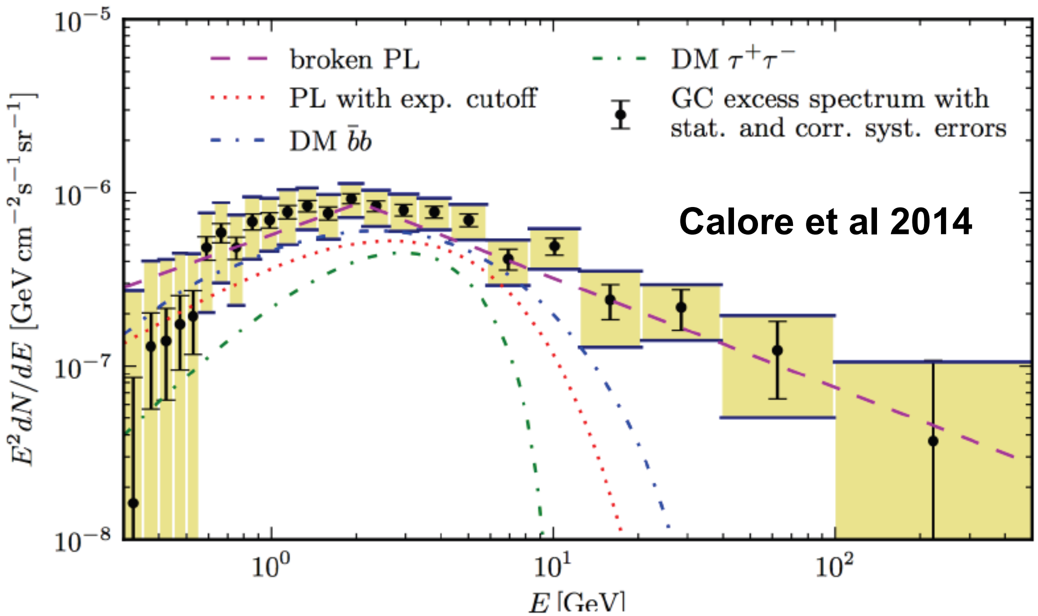
Pic credit: C. Weniger
5th Fermi Symposium

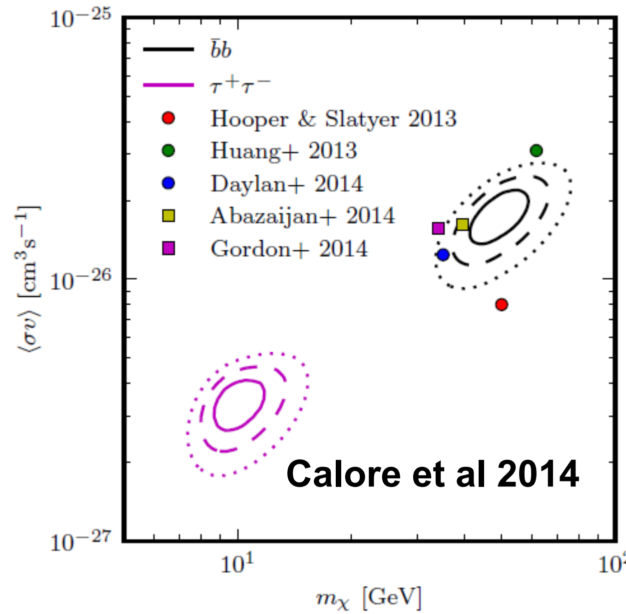
Calore et al 2014



- **Calore et al scanned DM template along Galactic Plane**
  - **found other excesses with similar intensity as GC excess, but different spectra**

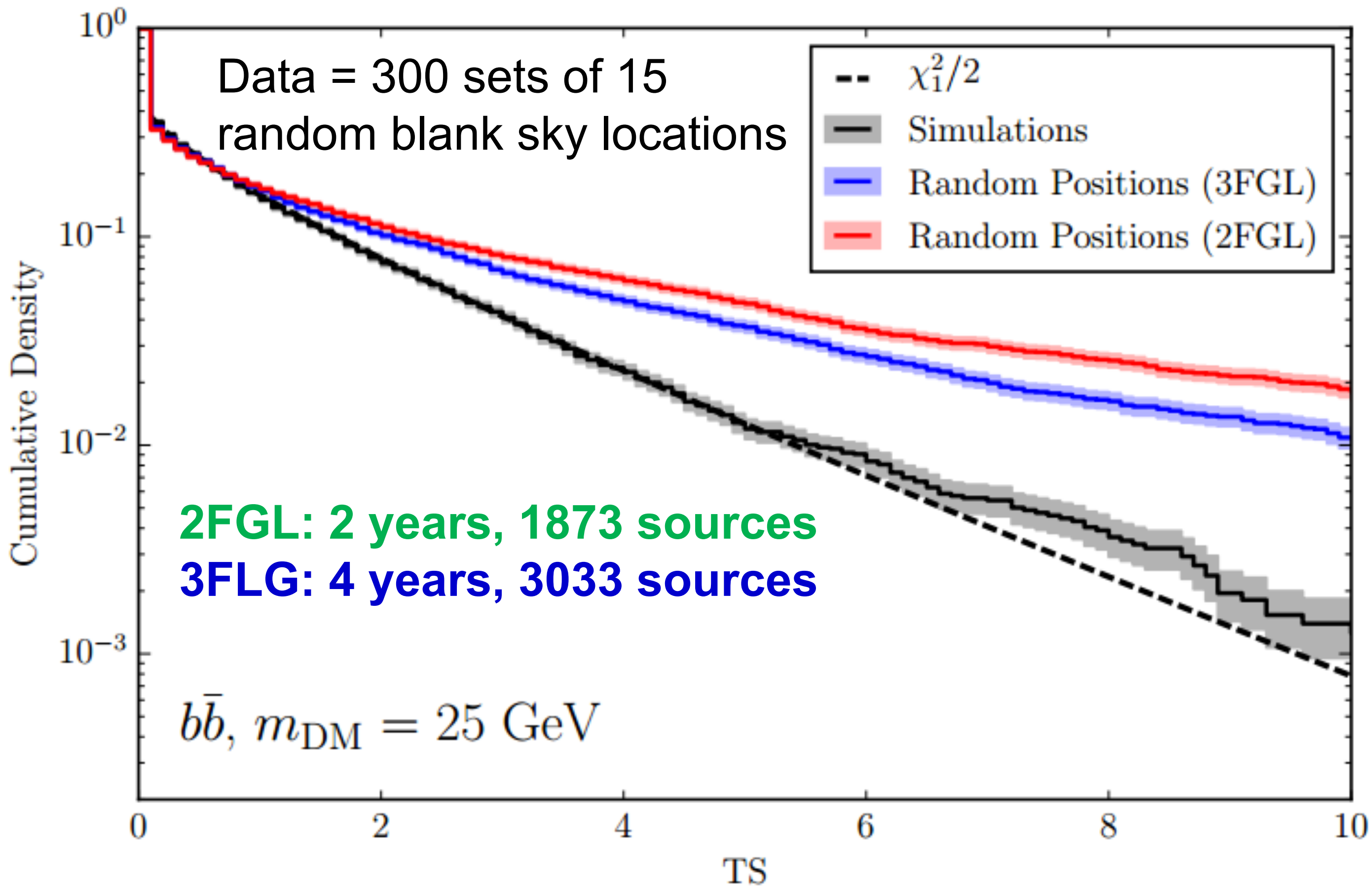
What is Causing this Extra High-energy Emission?





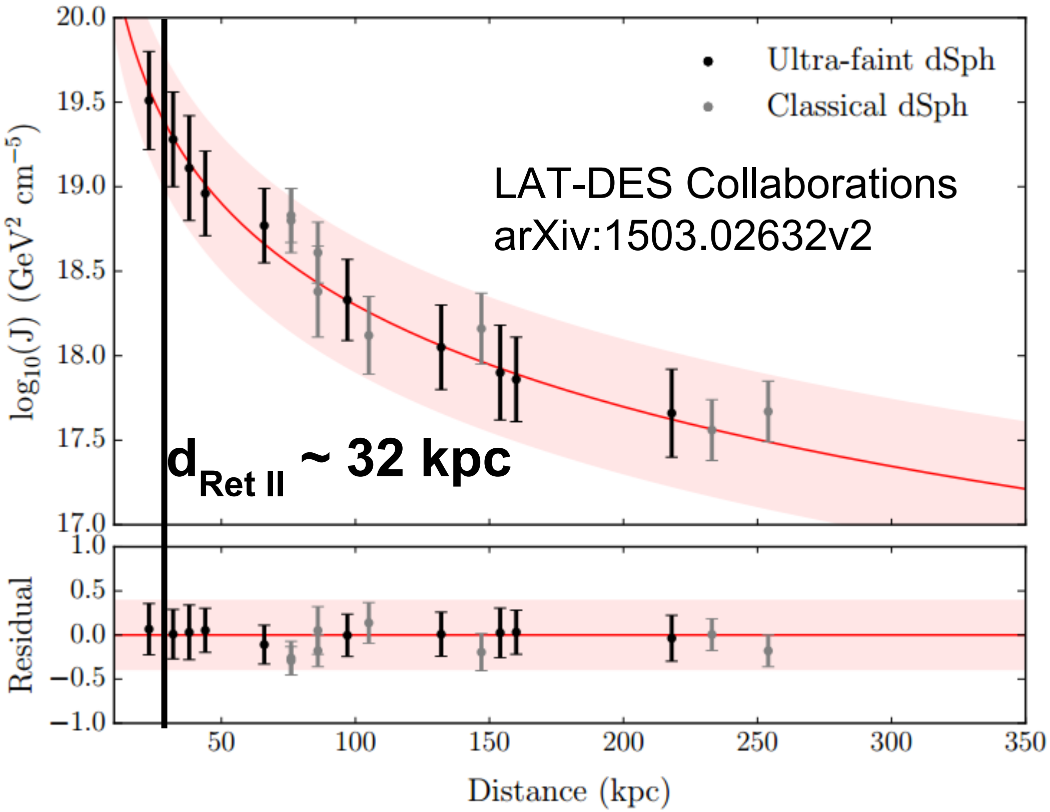
- **Many groups have found a similar excess in the GC and interpreted at gamma rays from DM annihilation**
  - **Expect brightest DM signal from the GC, but modeling other astrophysical components is tricky**
- **Regardless of what it is, any new high-energy gamma-ray source is exciting!**
  - **Much more study is needed to better understand the spectrum and morphology**
- **We do have another independent DM search that can test the DM interpretation of the GeV excess: dwarf spheroidal galaxies**

Results from Blank Field Control Regions



- **Using more extensive point-source catalog (3FGL) mitigates some of the MC-data discrepancy**
  - **Suggests discrepancy in TS distributions from MC and random sky data is due in part to unresolved point sources**

Dwarf Candidate J-factors



- **Hi-res spectroscopy from Magellan/M2FS for Ret II**
  - **1st confirmed DES dwarf galaxy!**
- **Bonnivard et al. log(J(0.5°)) = 19.5 +1.0 -0.6**
  - **arXiv:1504.03309v1**
- **Simon et al. (DES Col) log(J(0.5°)) = 18.9 +- 0.6**
  - **arXiv:1504.02889v1**

- **Optical spectra are needed to confirm if dwarf candidates are DM dominated and measure J-factors from stellar kinematics**
- **Dwarfs from Fermi-LAT analysis roughly follow $1/d^2$ relation**
  - **Those w/ complex kinematics excluded from joint analysis (e.g. Sag., Seg II)**
  - **in LAT-DES paper, derive limits under the assumption dwarf candidates are dwarfs and distance-estimated J-factors**