fermi
Gamma-ray
Space Telescope

Indirect Dark Matter Searches: Status and Prospects

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2nd World Summit on Exploring the Dark Side of the Universe

26 June 2017,

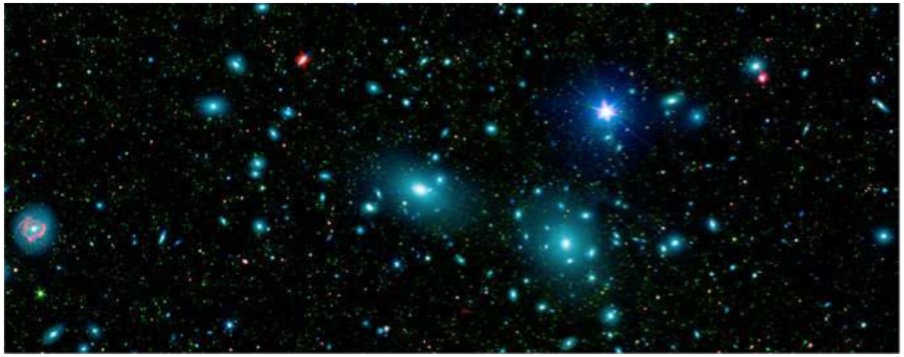
Fouillole, Pointe-à-Pitre, Guadeloupe

Outline

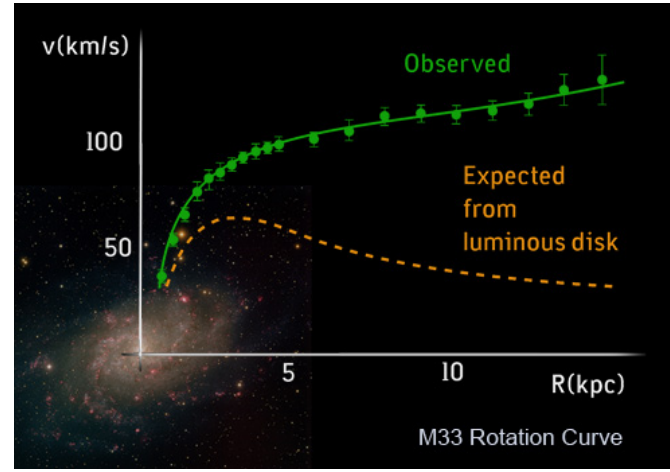
I. Review / context: indirect detection of dark matter
II. Understanding the astrophysical nature of dark matter
III. Weakly interacting massive particle (WIMP) searches
   A. Astrophysical dark matter signals
   B. Astrophysical backgrounds
   C. Summary of current search status
IV. Axion and axion-like Particle (ALP) searches
V. Summary and prospects

I. Review / Context: Indirect Detection of Dark Matter

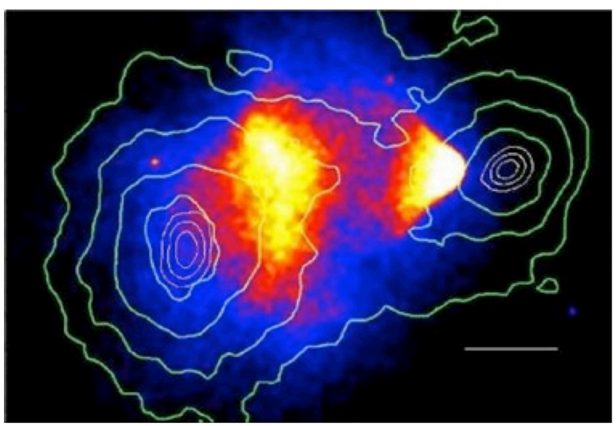
Evidence for / Salient Features of Dark Matter



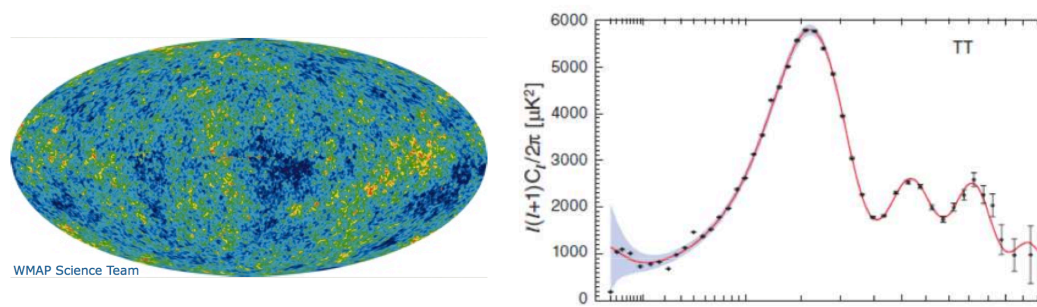
*Comprises **majority** of **mass** in Galaxies*
Missing mass on Galaxy Cluster scale
Zwicky (1937)



*Large **halos** around Galaxies*
Rotation Curves
Rubin+(1980)



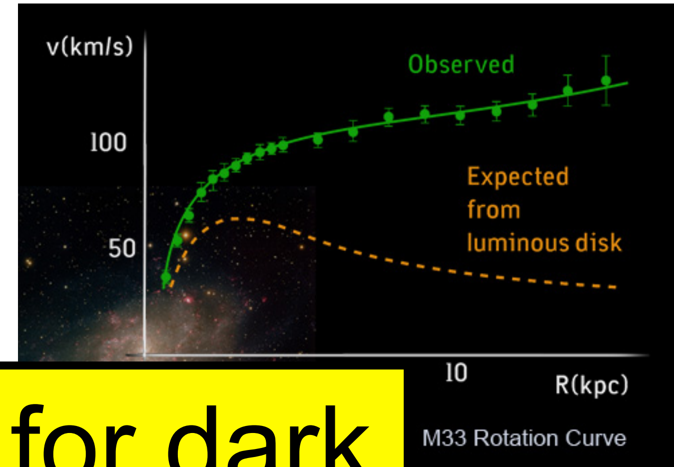
*Almost **collisionless***
Bullet Cluster
Clowe+(2006)



Non-Baryonic
Big-Bang Nucleosynthesis,
CMB Acoustic Oscillations
WMAP (2010), *Planck* (2015)

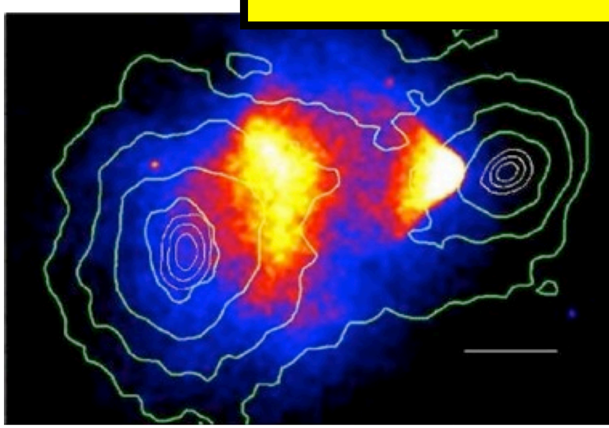
Evidence for / Salient Features of Dark Matter

Comprises
Missing ma
Zwicky (19



nd Galaxies

All of the evidence for dark matter is astrophysical!



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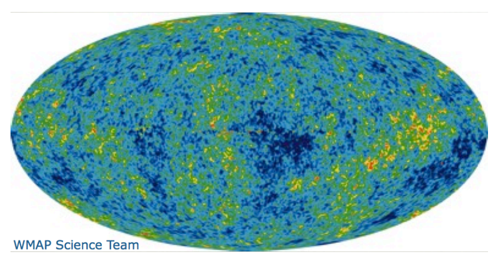
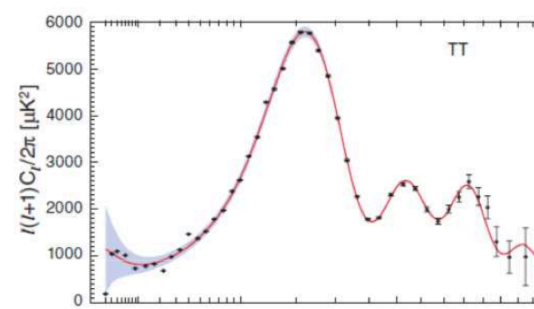


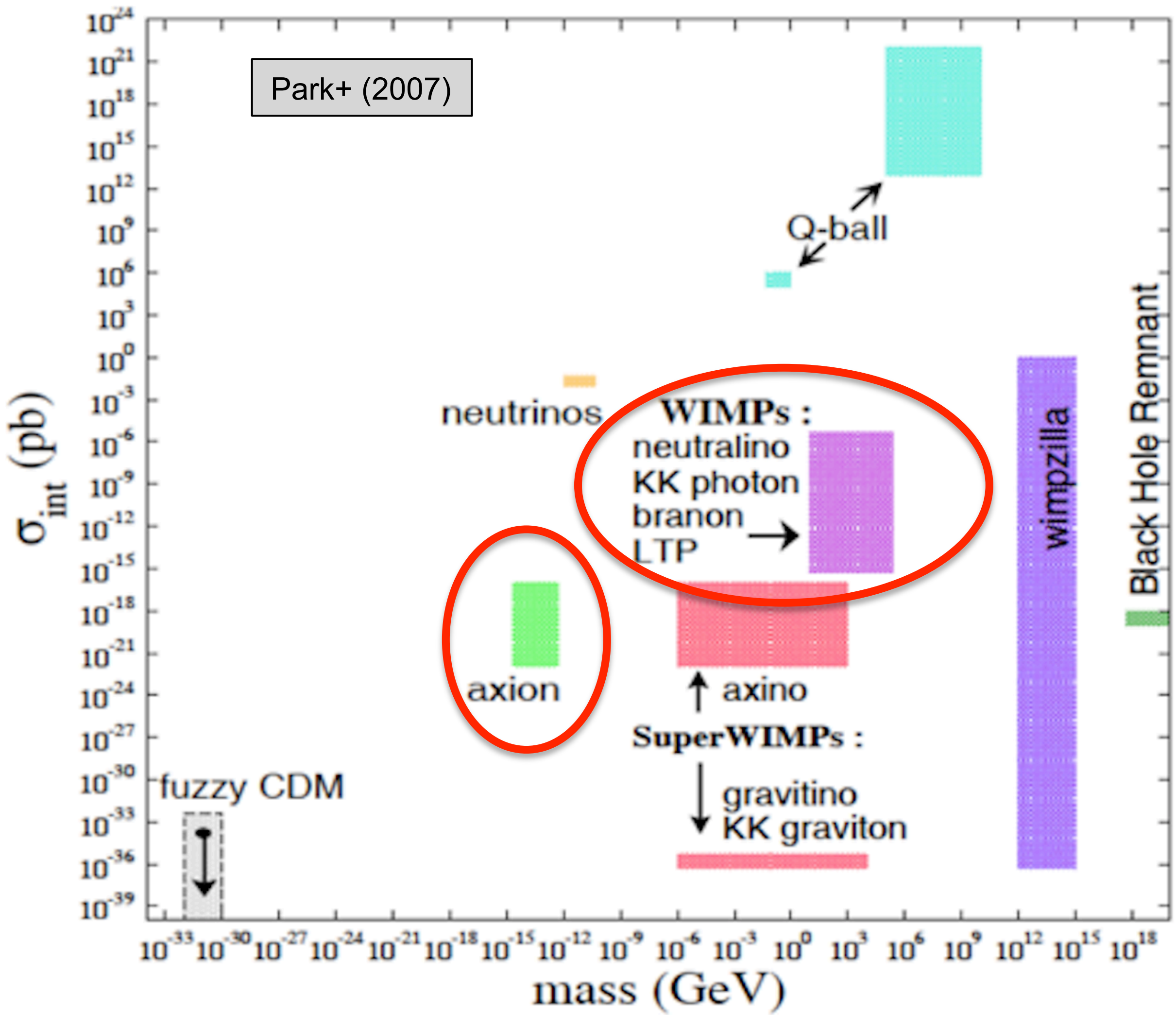


Non-Baryonic
Big-Bang Nucleosynthesis,
CMB Acoustic Oscillations
WMAP (2010), *Planck* (2015)

Dark Matter Particle Candidates

- No Standard Model particle matches the known properties of dark matter
- Many candidate particles have been proposed:
  - In this talk I will focus on WIMPs and axions / ALPs
  - Current experiments are also sensitive to signals from primordial black holes and gravitinos & other exotica

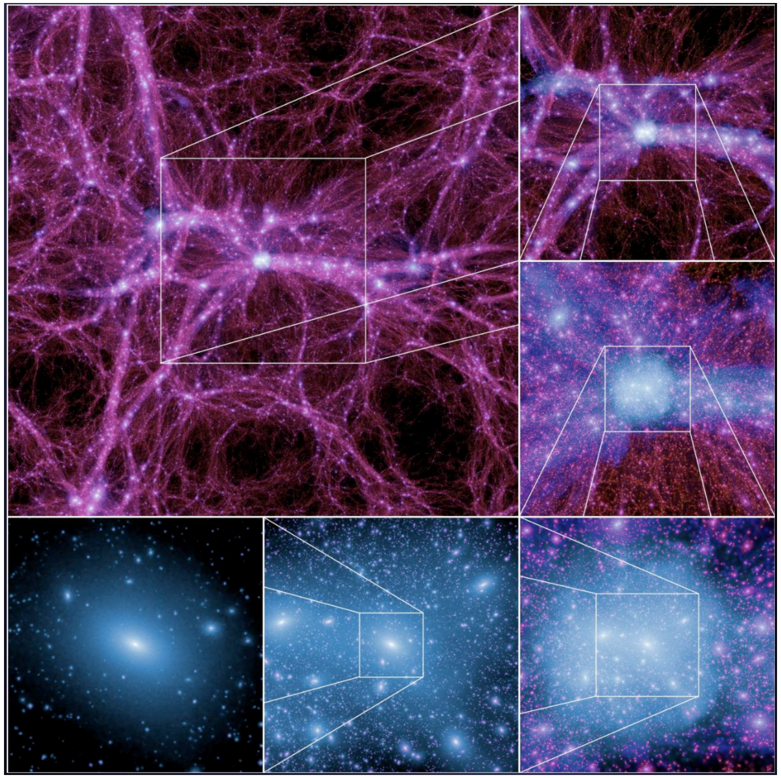
DM Candidates by Mass & Cross Section



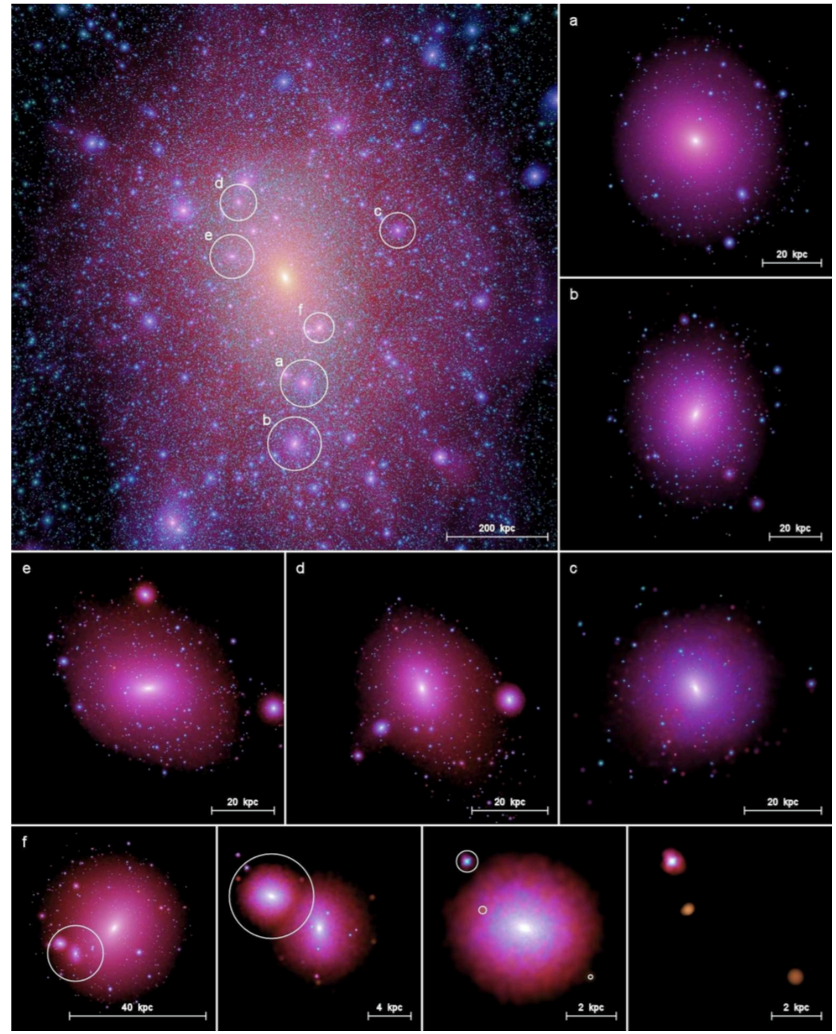
II. Understanding the Astrophysical Nature of Dark Matter

DM Structures are Present on Many Scales

Zoom Sequence of DM Structure from 100 Mpc Scale



Milky Way-like Halo and Several Sub-Halos



- We can probe DM by looking for signal contributions from halos:
  - On cosmological scales (left)
  - In the Milky Way virial radius (~300 kpc = ~1 MLY, right) (Visible size of MW = ~ 20 kpc)

Left: Boylan-Kolchin+ (2009) Right: Springel+ (2008)

Understanding the Astrophysical Nature of DM

https://lsstdarkmatter.github.io/

cold dark matter warm dark matter

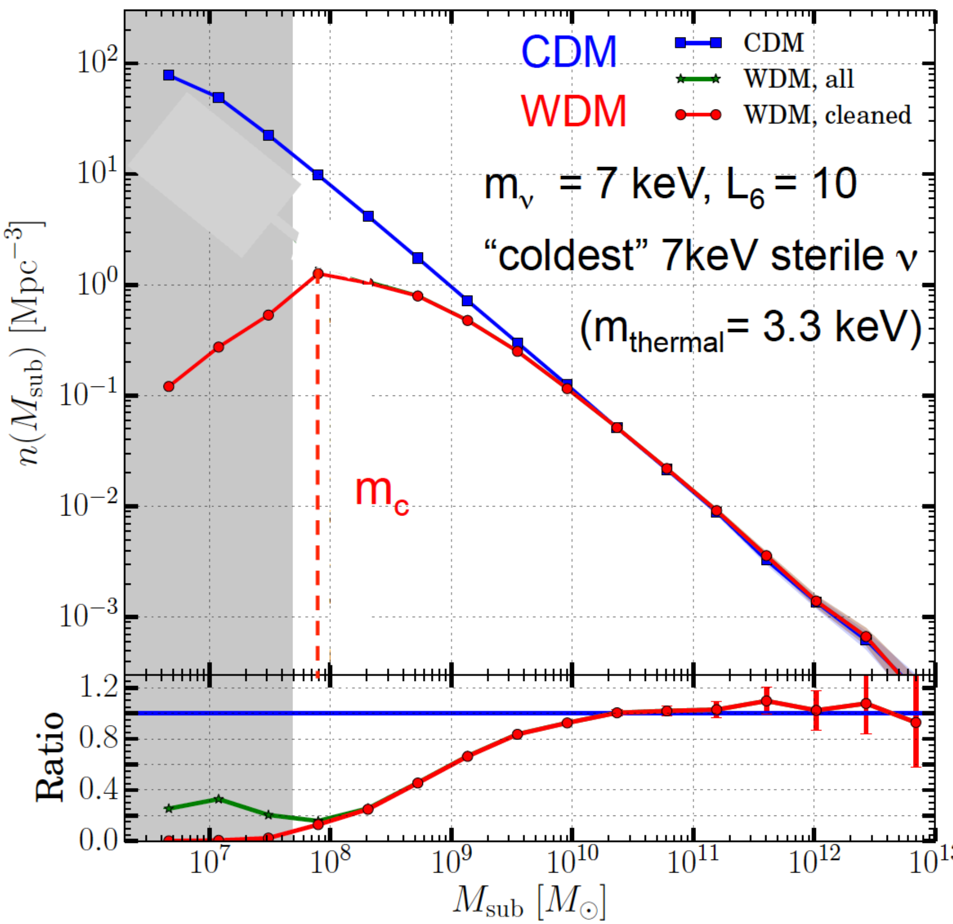
Lovell+ (2012)

- Wide-area surveys (DES, Pan-STARRS, Gaia, LSST) identify and characterize DM-dominated structures
- Modern numerical simulations improve our understanding of the dependence on cosmology, DM particle properties, “baryonic” effects in structure formation

Strong Lensing as a DM Probe

- "Warm" DM, e.g., from a ~keV sterile ν, would wash out structures smaller than about 10^8 $M_\odot$
- However, < 10^8 $M_\odot$ sub-halos are very unlikely to form stars
- Sub-structure searches in strong gravitational lenses will be sensitive down to 10^6 to 10^7 $M_\odot$

Simulated Dark Matter Halo Mass Function

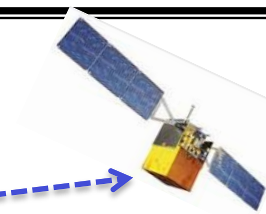


Bose+ (2016)

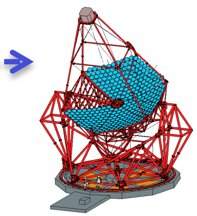
See also, e.g., Hezevah+ (2016)

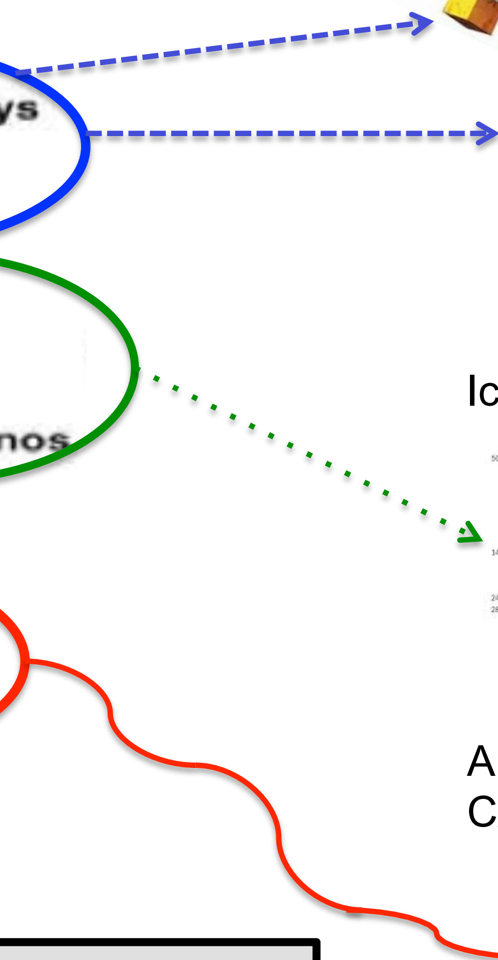
III. WIMP Dark Matter Searches

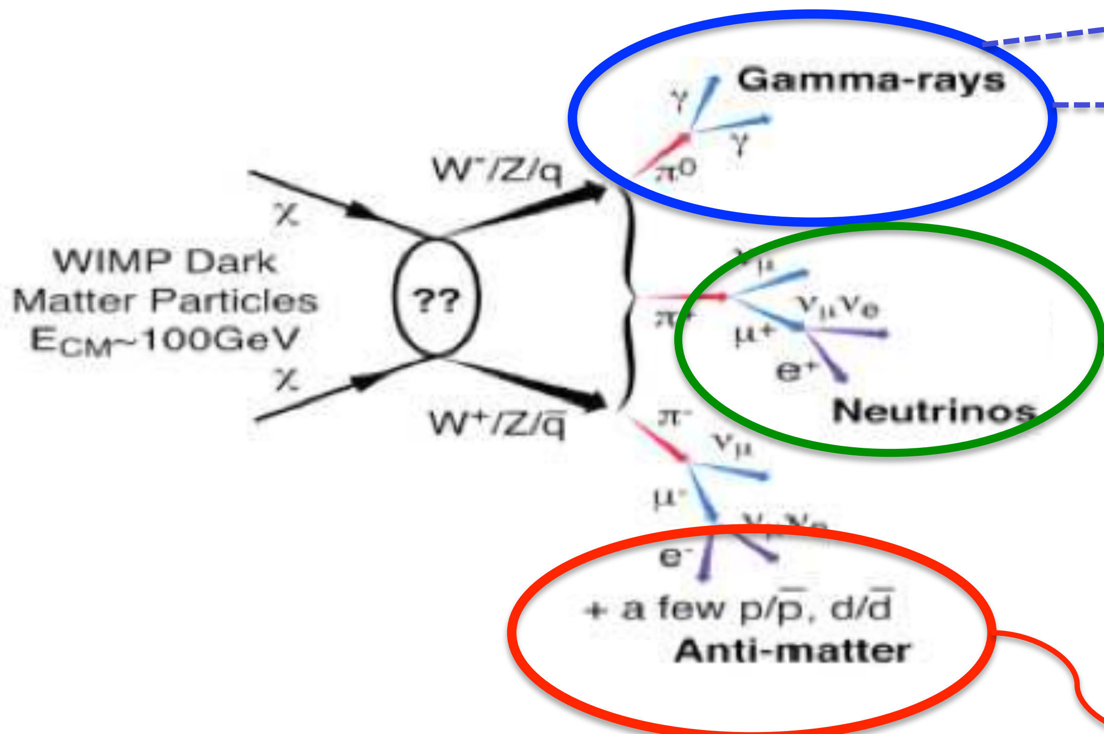
Indirect Detection of WIMPs



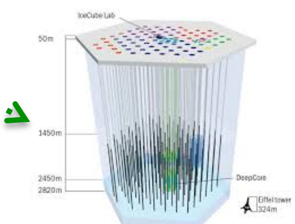
Fermi-LAT, IACTs, HAWC



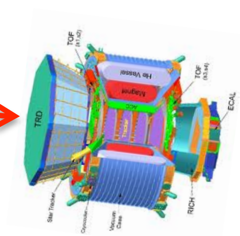




IceCube, Antares...



AMS-02, DAMPE, CALET...



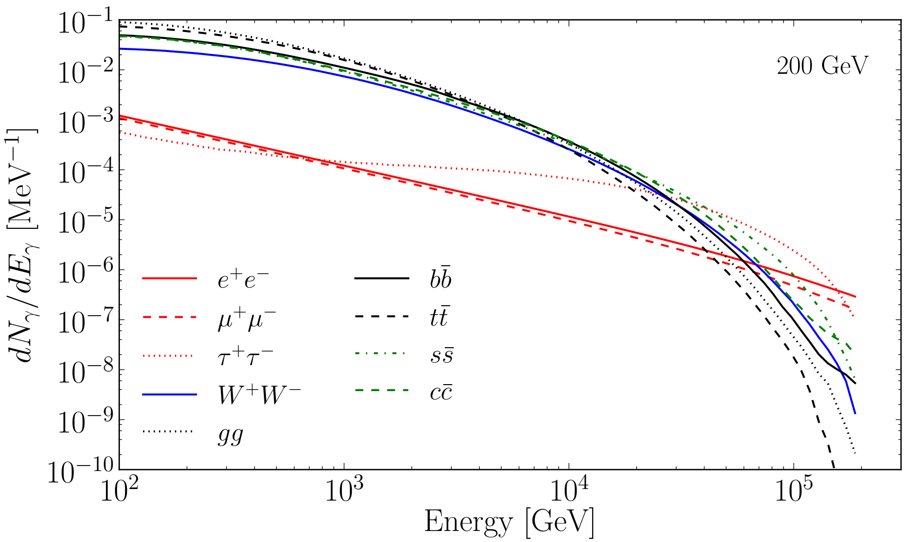
Also, consider cosmological effects of annihilation/ decay products on environment: e.g., Shirasaki+ (2016), Slatyer+ (2017)

The Key Formula for WIMP Searches

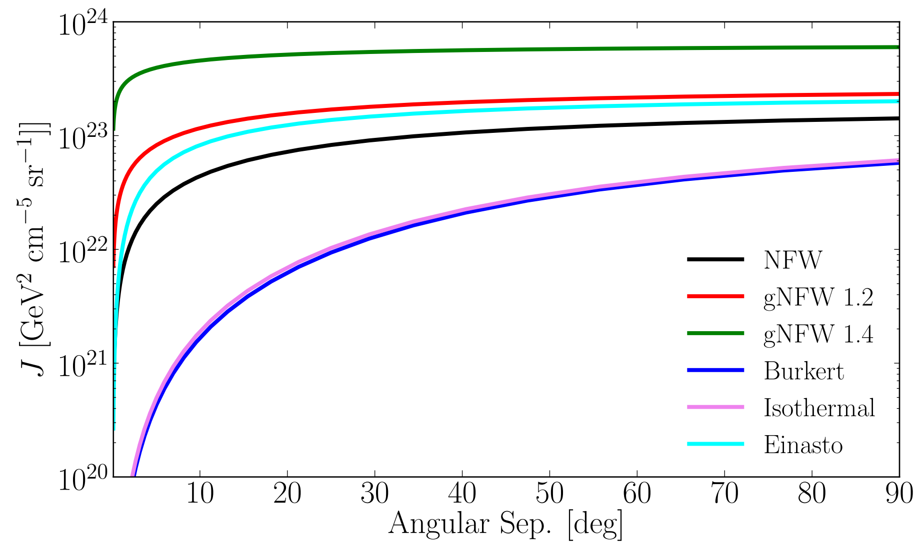
Particle Physics | Astrophysics (*J*-Factor)

$$\frac{d\Phi_\gamma}{dE_\gamma}(E_\gamma,\phi,\theta) = \underbrace{\frac{1}{4\pi}\frac{<\sigma_{ann}v>}{2m_{WIMP}^2}\sum_f \frac{dN_\gamma^f}{dE_\gamma}B_f}_{\text{Particle Physics}} \; \underbrace{\int_{\Delta\Omega(\phi,\theta)} d\Omega' \int_{los} \rho^2(r(l,\phi'))dl(r,\phi')}_{\text{Astrophysics (J-Factor)}}$$

dN/dE for 200 GeV DM

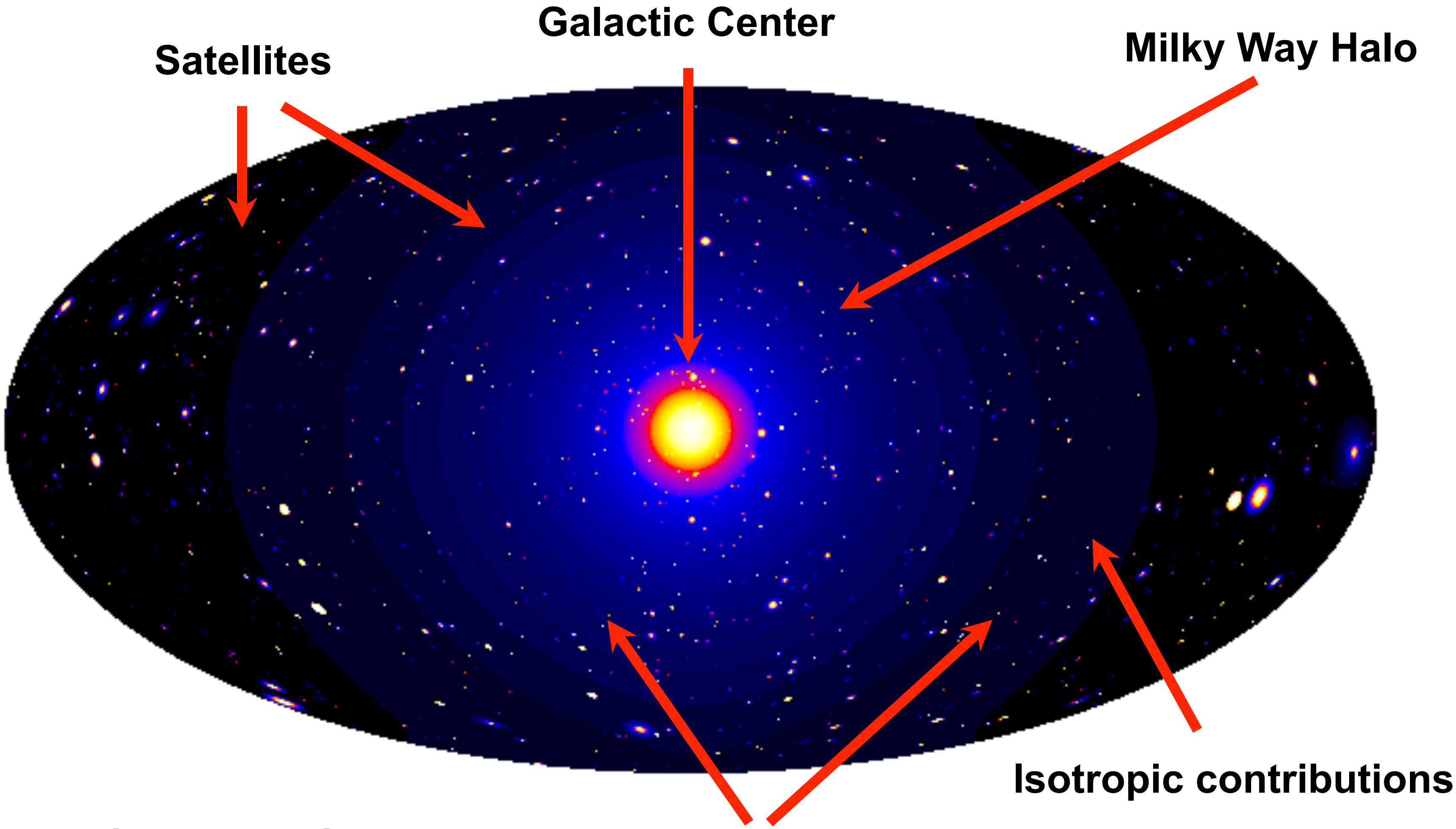


J-factor for the Galactic Center



- *Note*: *J*-factor includes distance, i.e., *J*-factor would decrease by four if a point-like source were twice as far away
- *Note*: the key factor of $1/m_\chi^2$ is b/c we express the *J*-factor as a function of mass density (which we can measure), not number density

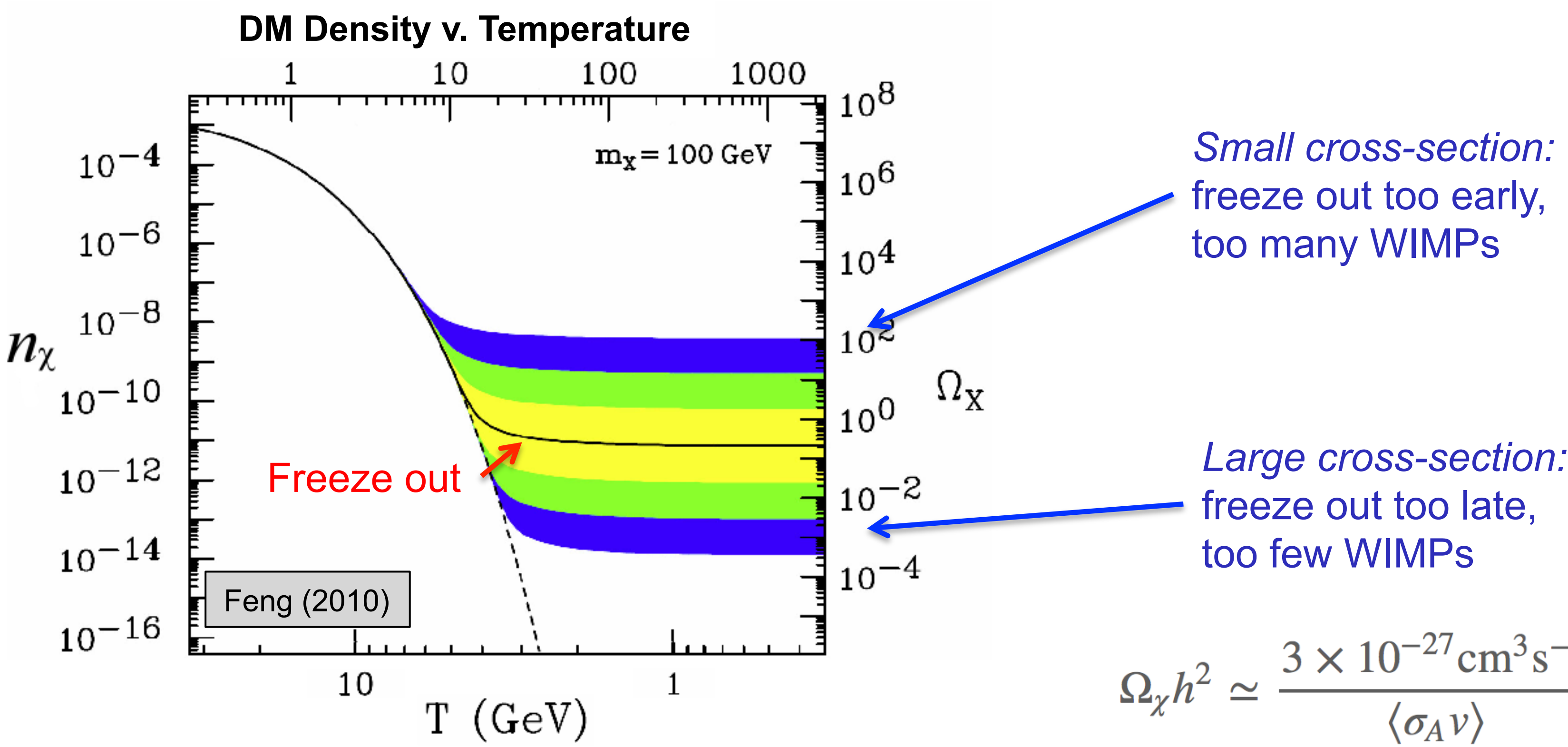
Dark Matter as Seen From Earth



Features in γ-ray and cosmic-ray spectra

Dark Matter simulation: Pieri+ (2011)

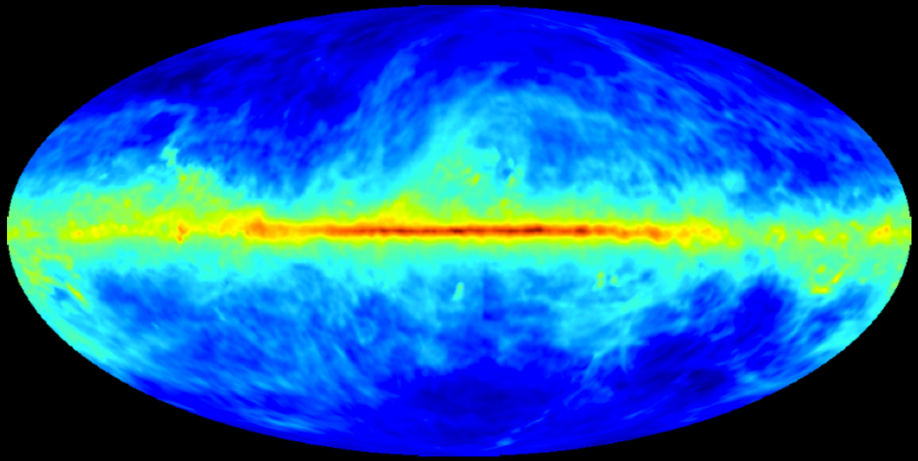
WIMP Dark Matter as a Thermal Relic

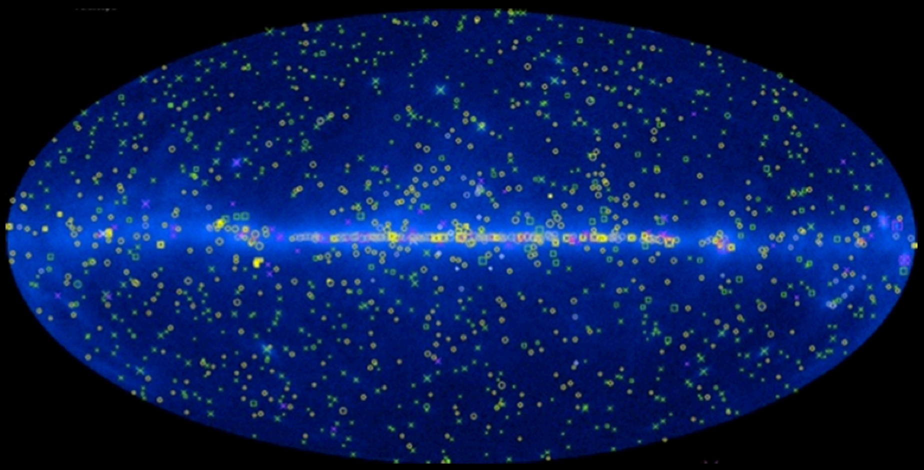


$$\Omega_\chi h^2 \simeq \frac{3 \times 10^{-27}\,\mathrm{cm}^3\mathrm{s}^{-1}}{\langle \sigma_A v \rangle}$$

- The calculation of the thermal-averaged cross-section $<\sigma v>$ needed to obtain the relic density is robust and gives $<\sigma v> \sim 3\ 10^{-26}\ \mathrm{cm}^3\mathrm{s}^{-1}$
- At that cross-section we are probing the entire class of particle models that would generate GeV-to-TeV dark matter

Astrophysical Backgrounds (GeV)





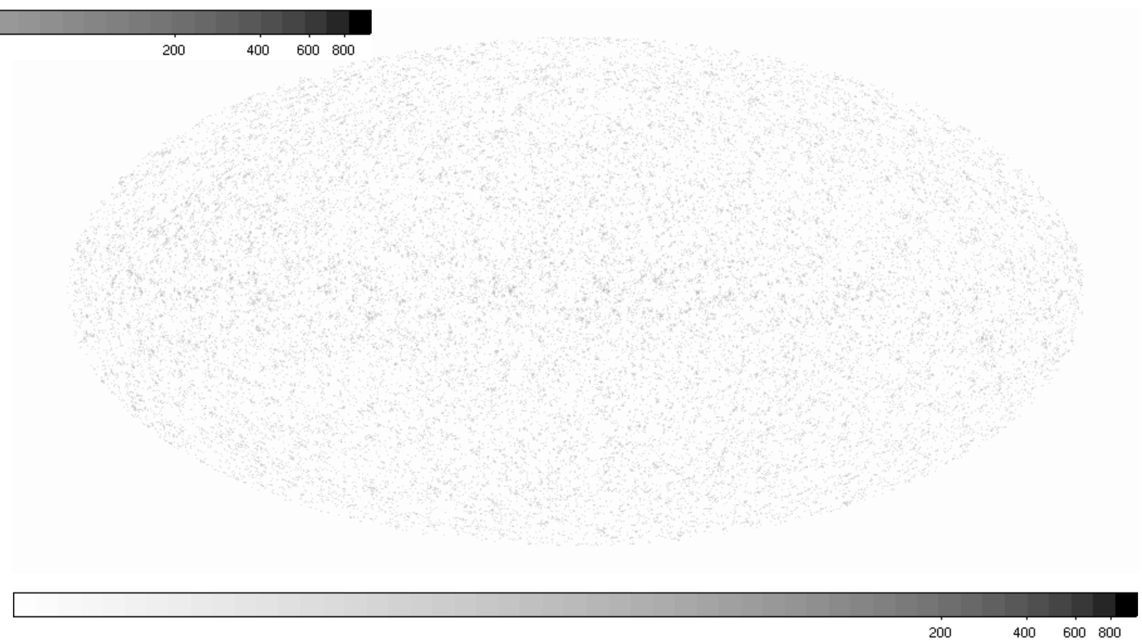
- Diffuse Backgrounds:
  - Cosmic-ray interactions with interstellar matter and radiation fields

- Source Backgrounds:
  - ***Pulsars***
  - Blazars and Active Galactic Nuclei
  - Supernova Remnants
  - Galaxies (starburst galaxies)

- Unresolved Sources

Unresolved Sources

These two images contain roughly the same number of γ rays, but in the top left they are truly randomly distributed, in the bottom right they are produced by individual sources that we can not resolve.



Dark Matter Search Strategies

Satellites

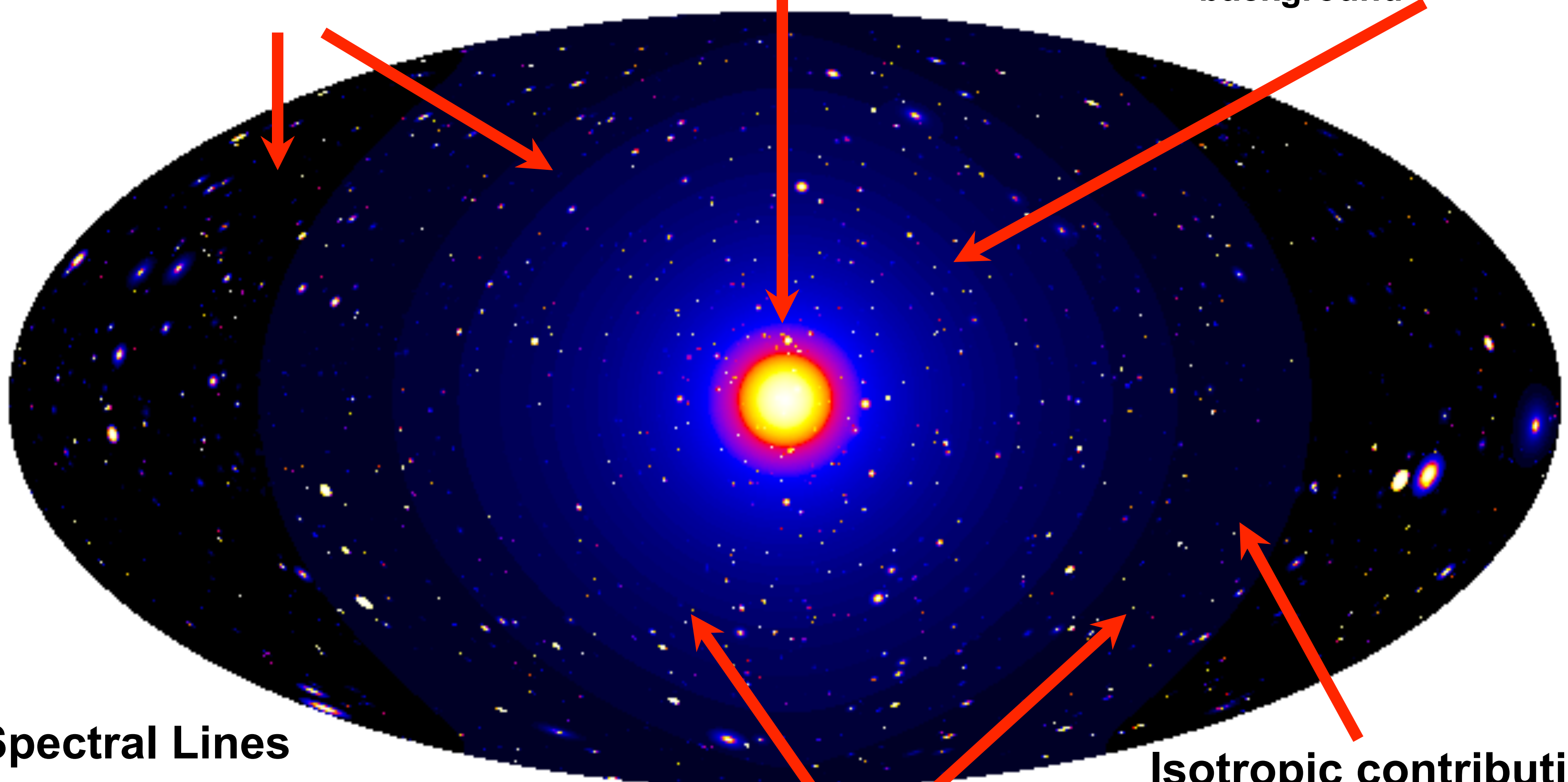
Low background and good source id, but low statistics

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

Isotropic contributions

Large statistics, but astrophysics, Galactic diffuse background

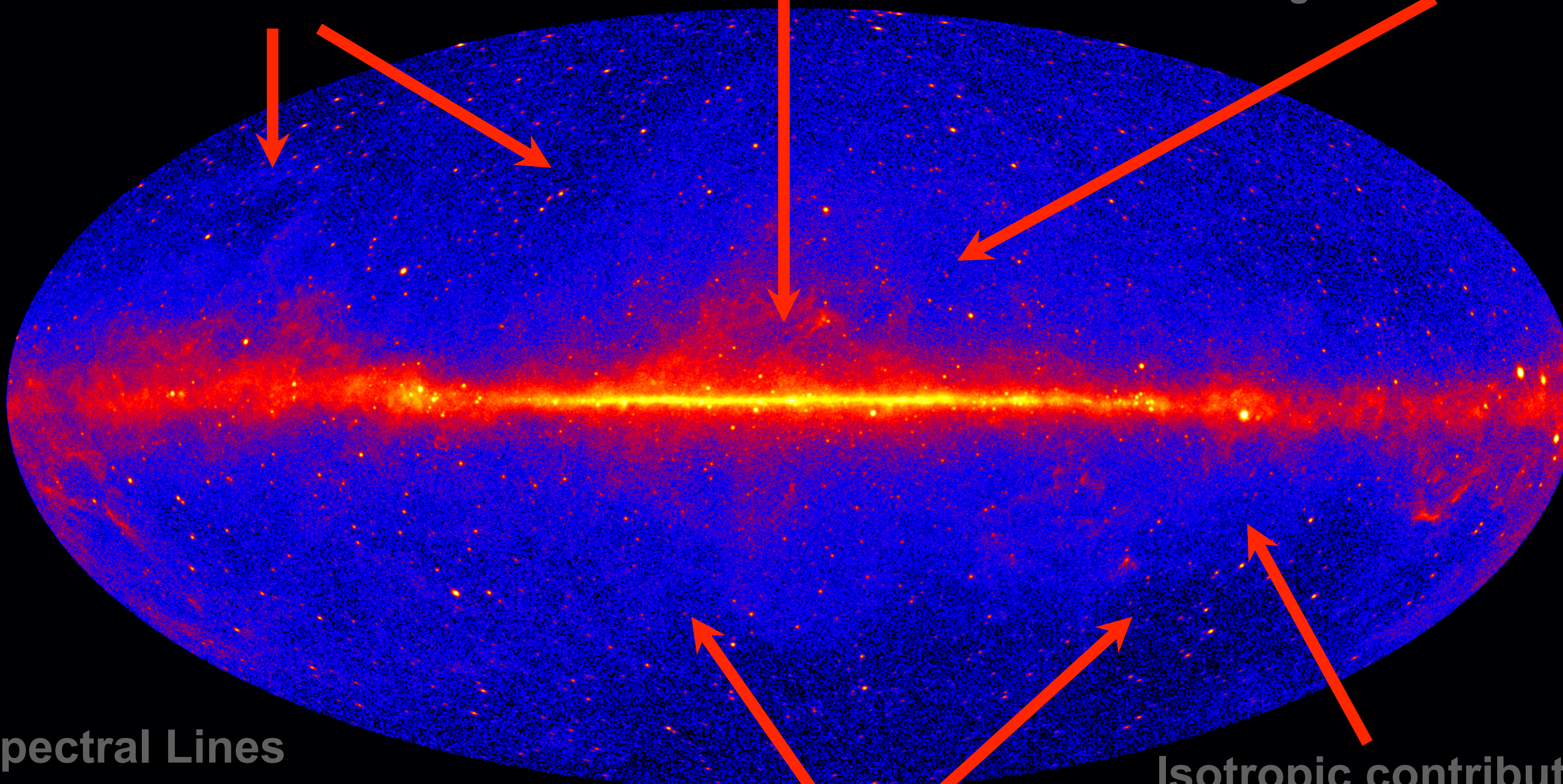
Dark Matter simulation: Pieri+ 2011PhRvD..83b3518P

Search Strategies (against the γ-ray Sky)

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



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Galaxy Clusters
Low background, but low statistics

Isotropic contributions
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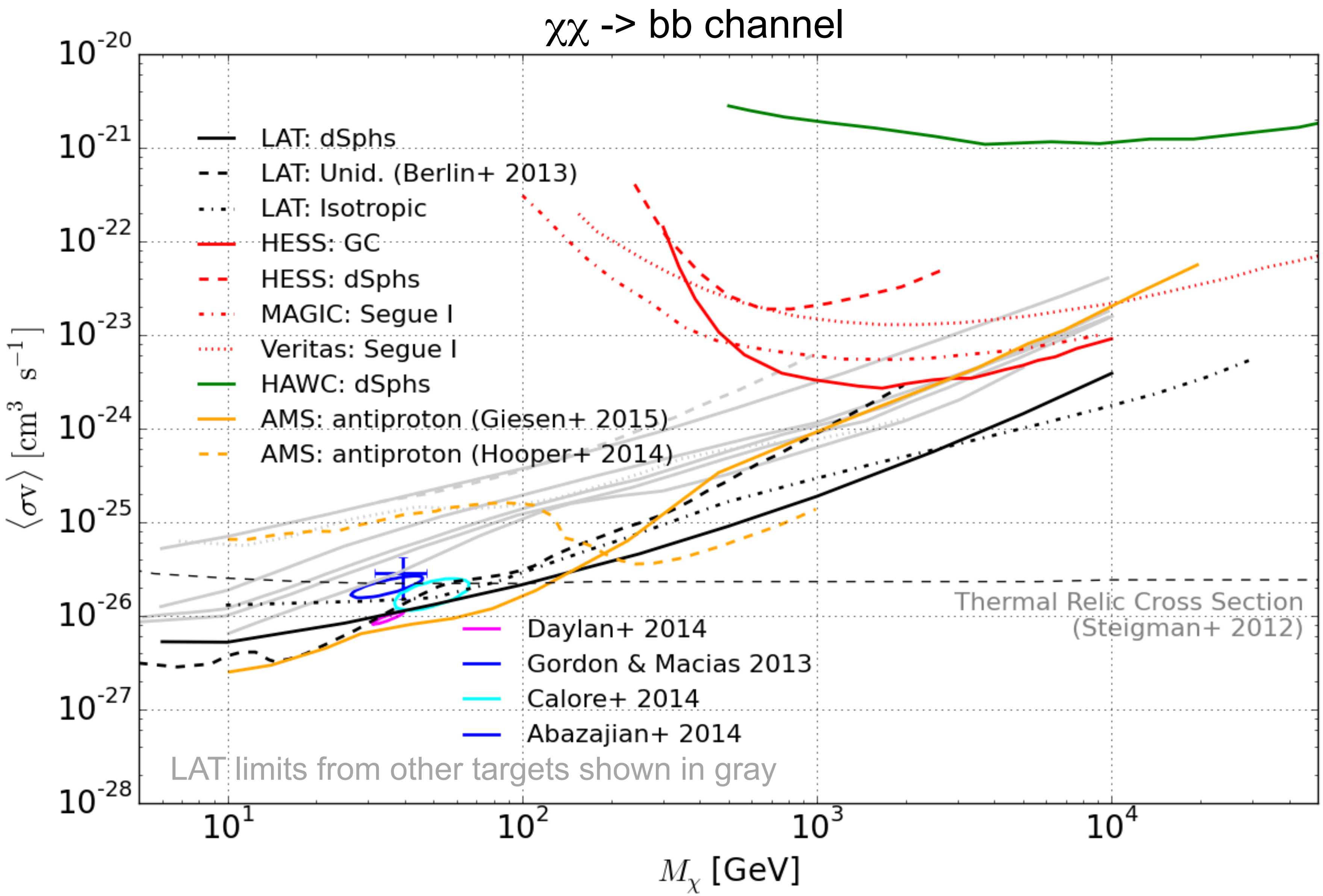
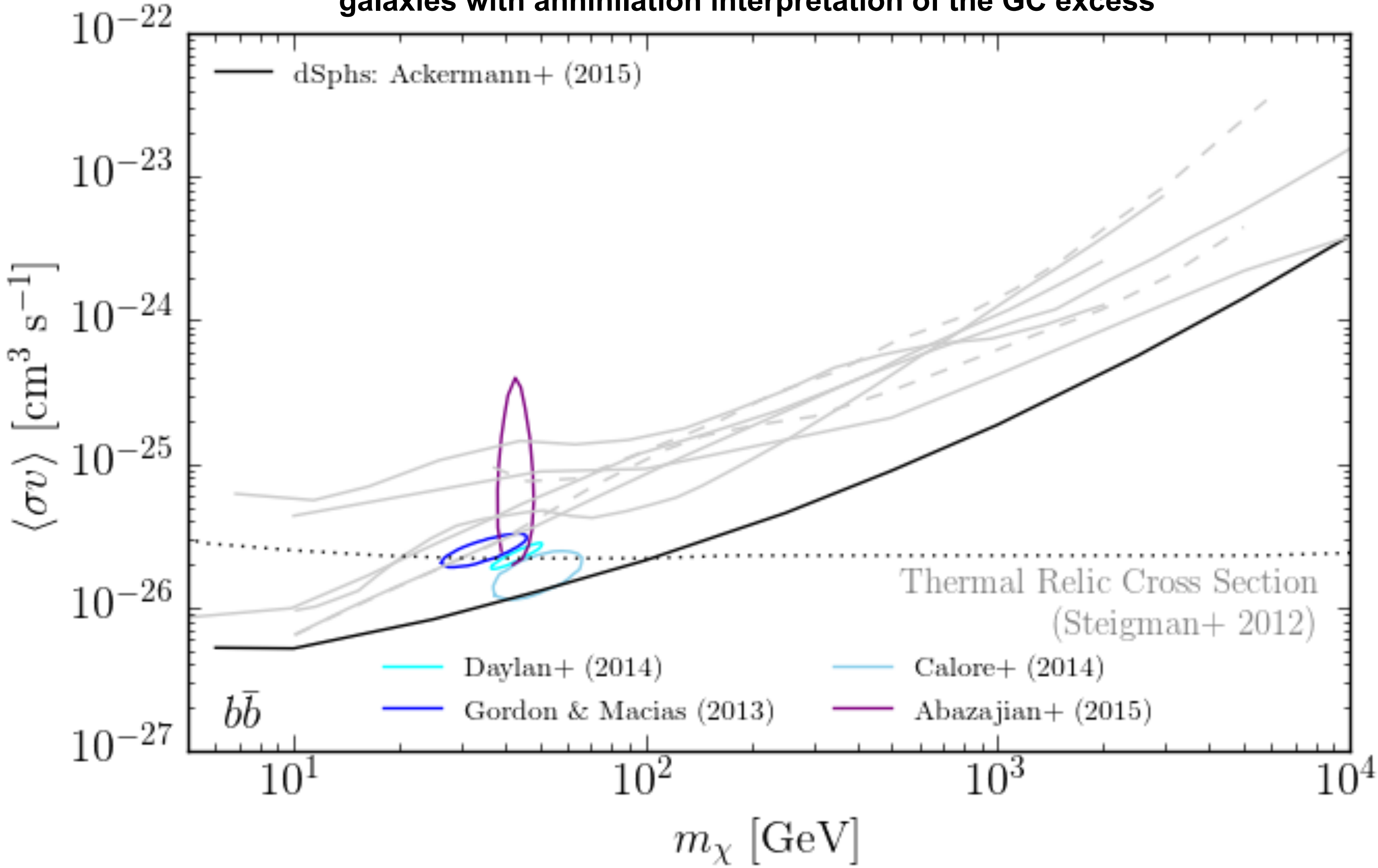
LAT 7 Year Sky > 1 GeV

Summary of Results from Indirect-Detection DM Searches as of Fall 2015



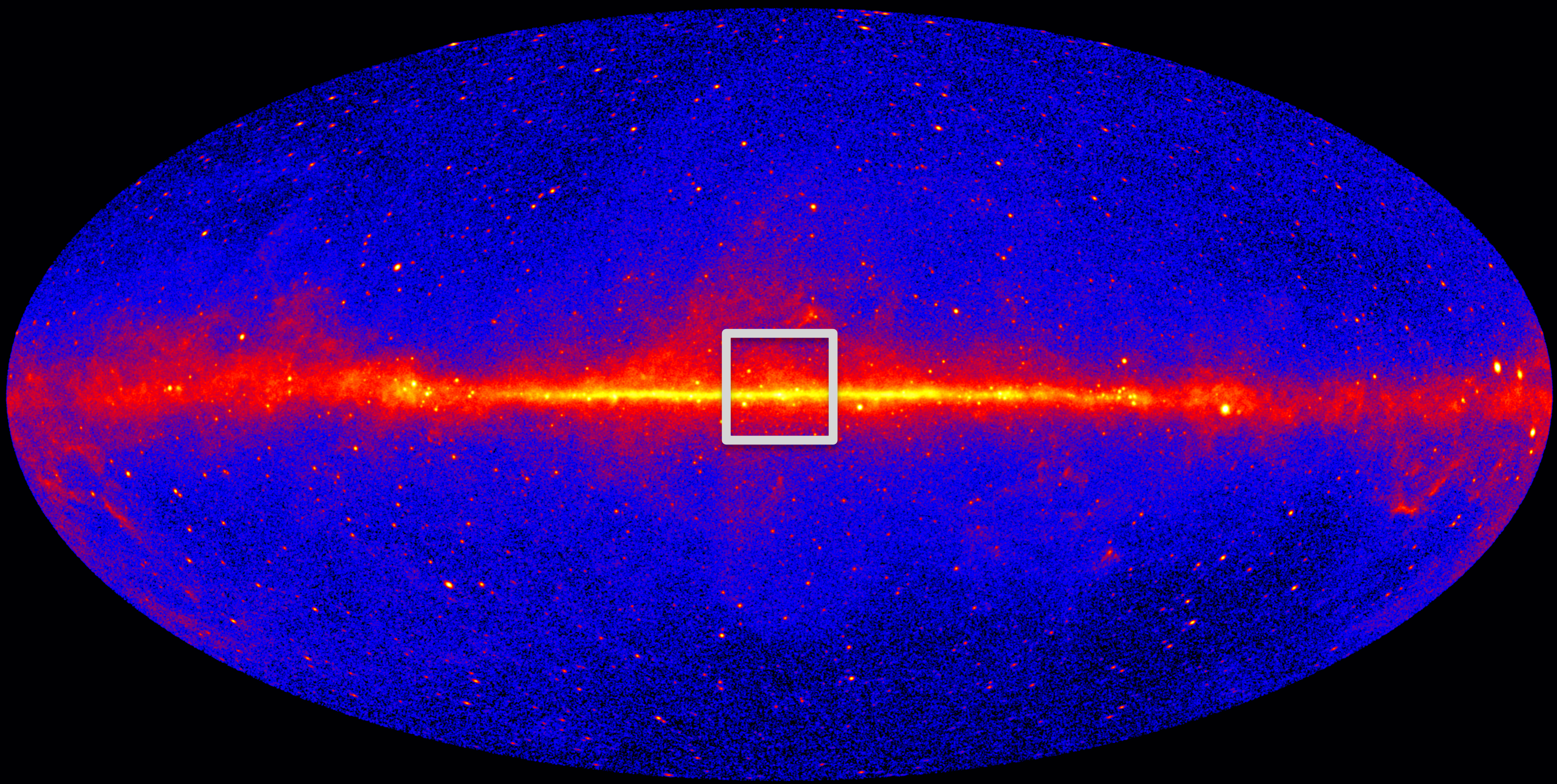
Summary of Dark Matter Searches with *Fermi*

Comparison of measured upper limits on annihilation of dark matter in dwarf satellite galaxies with annihilation interpretation of the GC excess



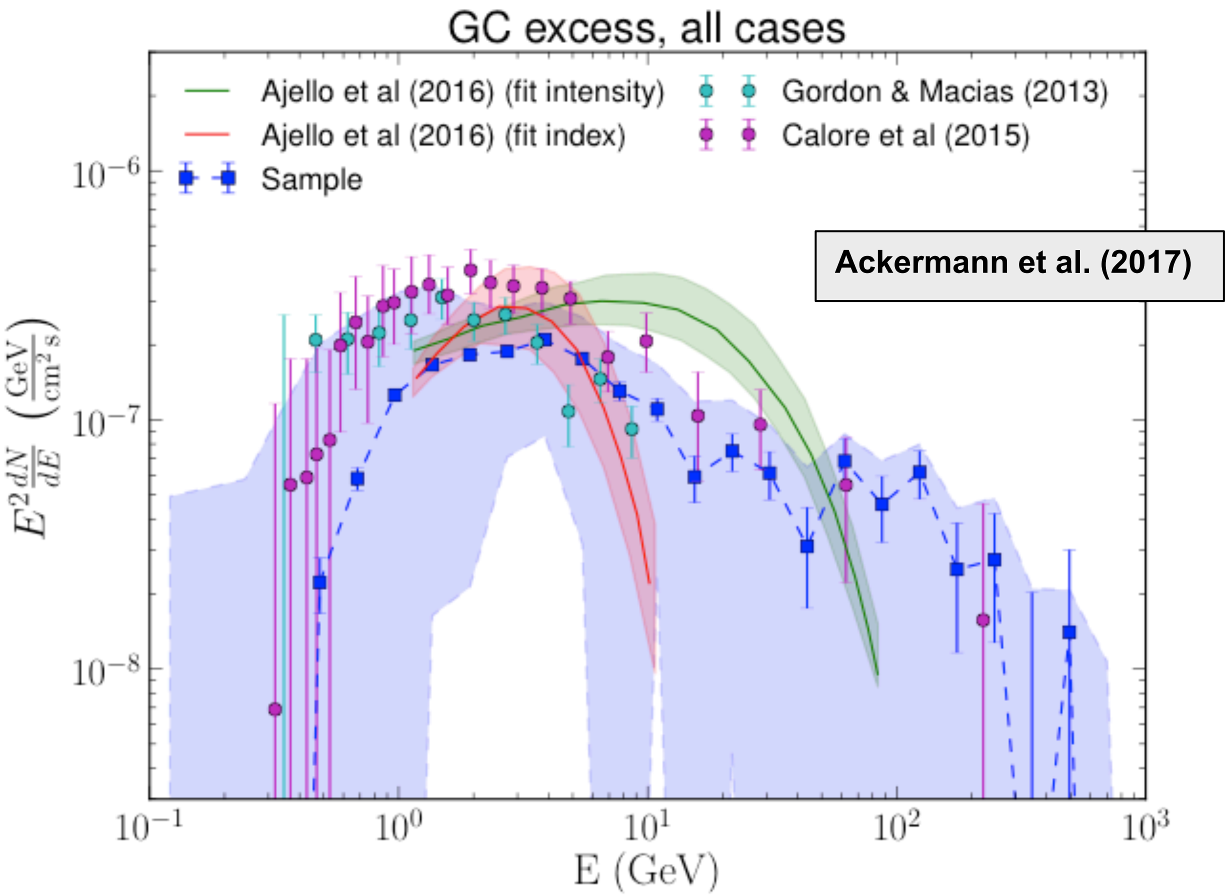
The Milky Way Galactic Center GeV "Excess"

Recent papers: Gordon & Macias (2013) , Abazajian+ (2014), Calore+ (2015), Daylan+ (2016), Ajello+ [LAT Clb] (2016)



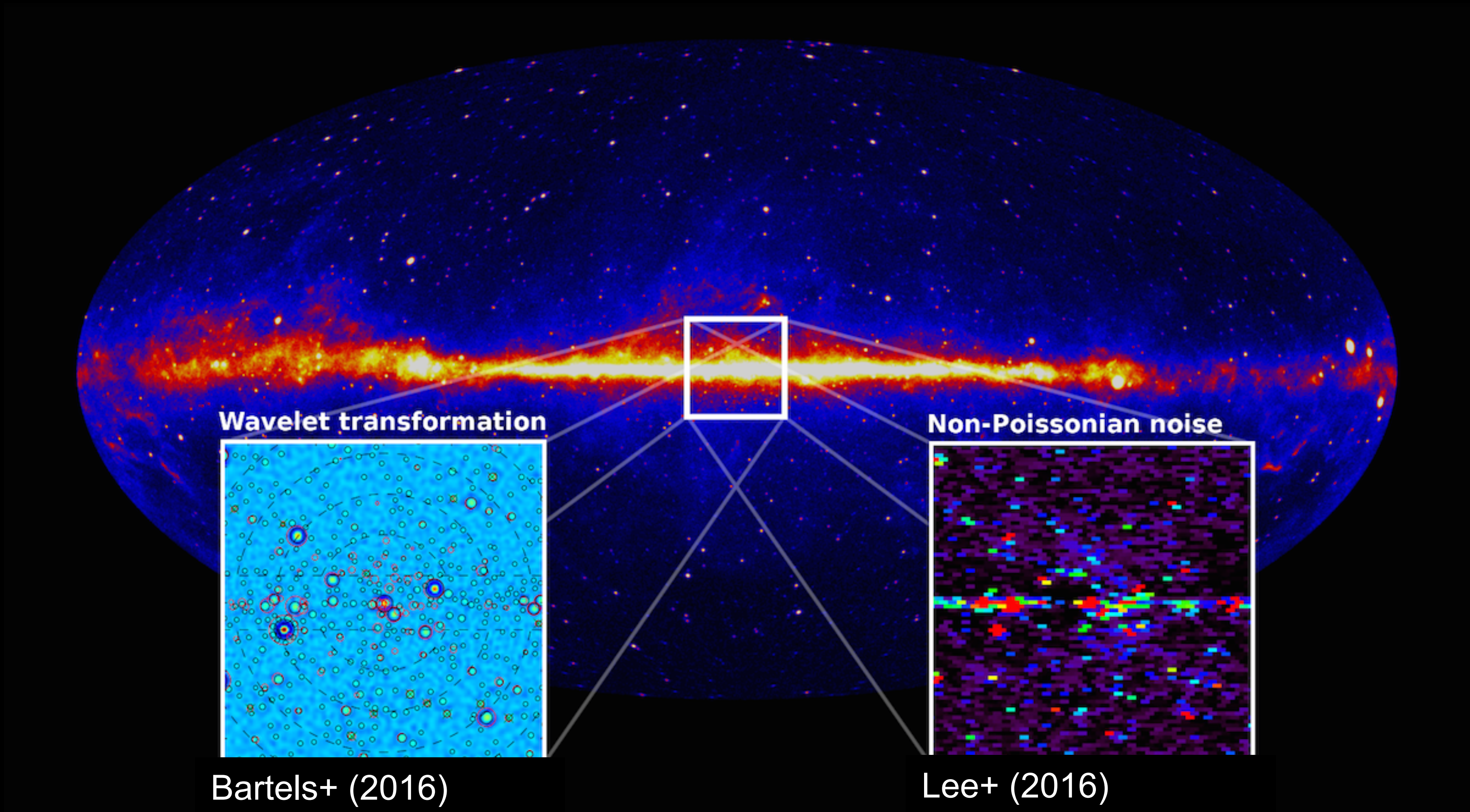
- The goal is to look for DM in the inner Galaxy
- Because of the large astrophysical foregrounds, we must first understand the γ-ray emission from the Galaxy and from known source classes

Galactic Center GeV Excess



- The presence of an γ-ray excess with respect to the modeled diffuse emission at the Galactic center at a few GeV is well established
- However, the characteristics (and the interpretation) of the excess depend on the modeling of the astrophysical fore/background

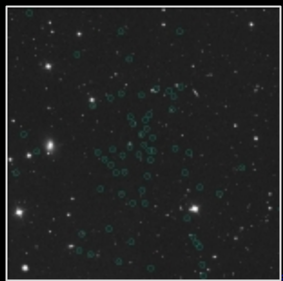
Galactic Center Excess as Unresolved Sources



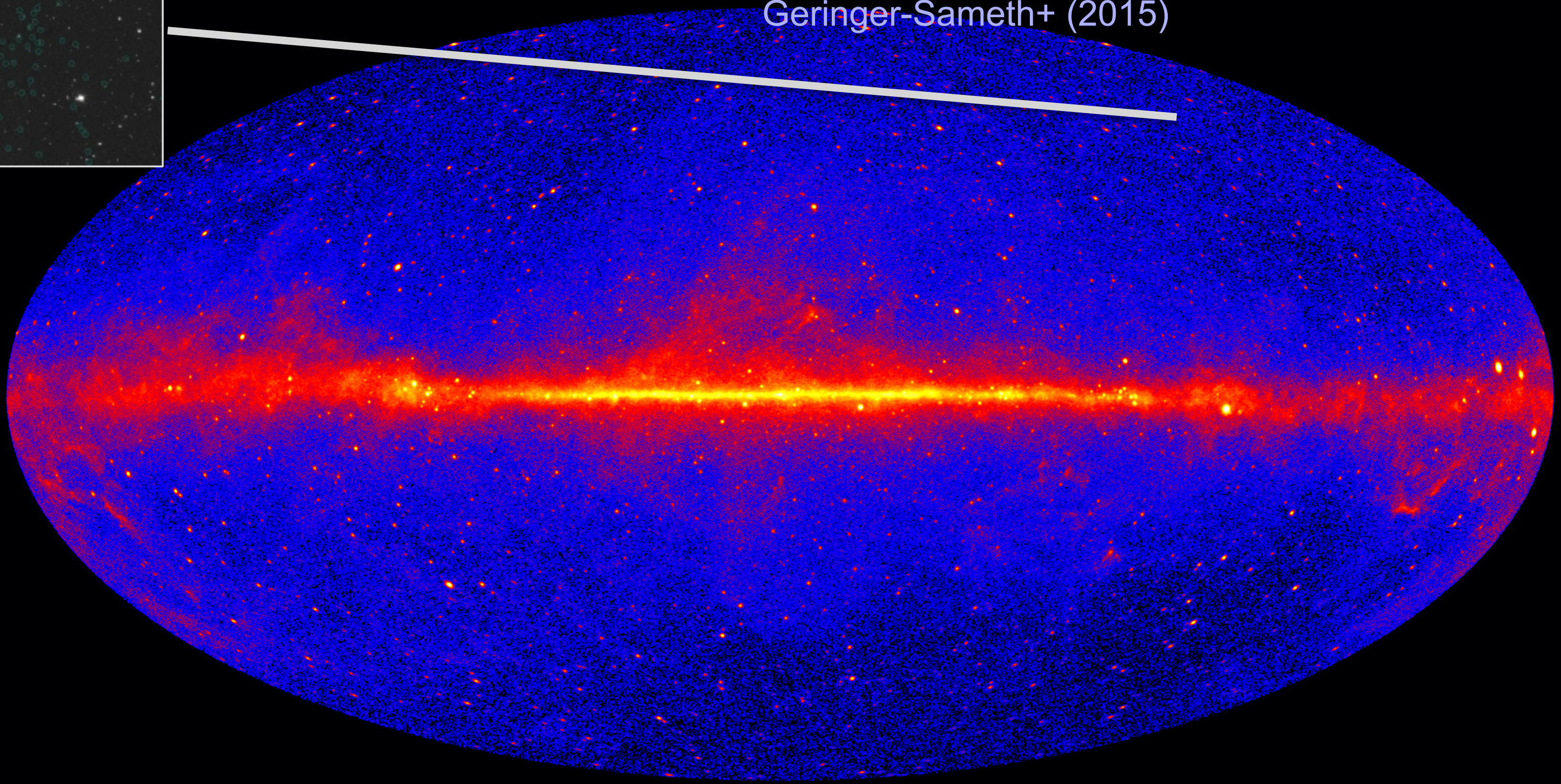
In 2016, two groups analyzed statistical fluctuations in the Galactic center excess and found that it appears to consist of numerous unresolved point sources, not the sort of smooth halo we would expect from a dark matter signal

Known Satellites of the Milky Way

Segue 1
Keck Observatory



Recent papers:
Ackermann+ [LAT Clb] (2015)
Drlica-Wagner+ [LAT + DES Clbs] (2015)
Albert+ [LAT Clb] (2017)
Geringer-Sameth+ (2015)



- Look for γ-ray emission from Dwarf spheroidal galaxies (dSphs), which are the most dark matter dominated objects known
- This is a moderate-signal, low-background search strategy

Dwarf Spheroidal Satellites of the Milky Way

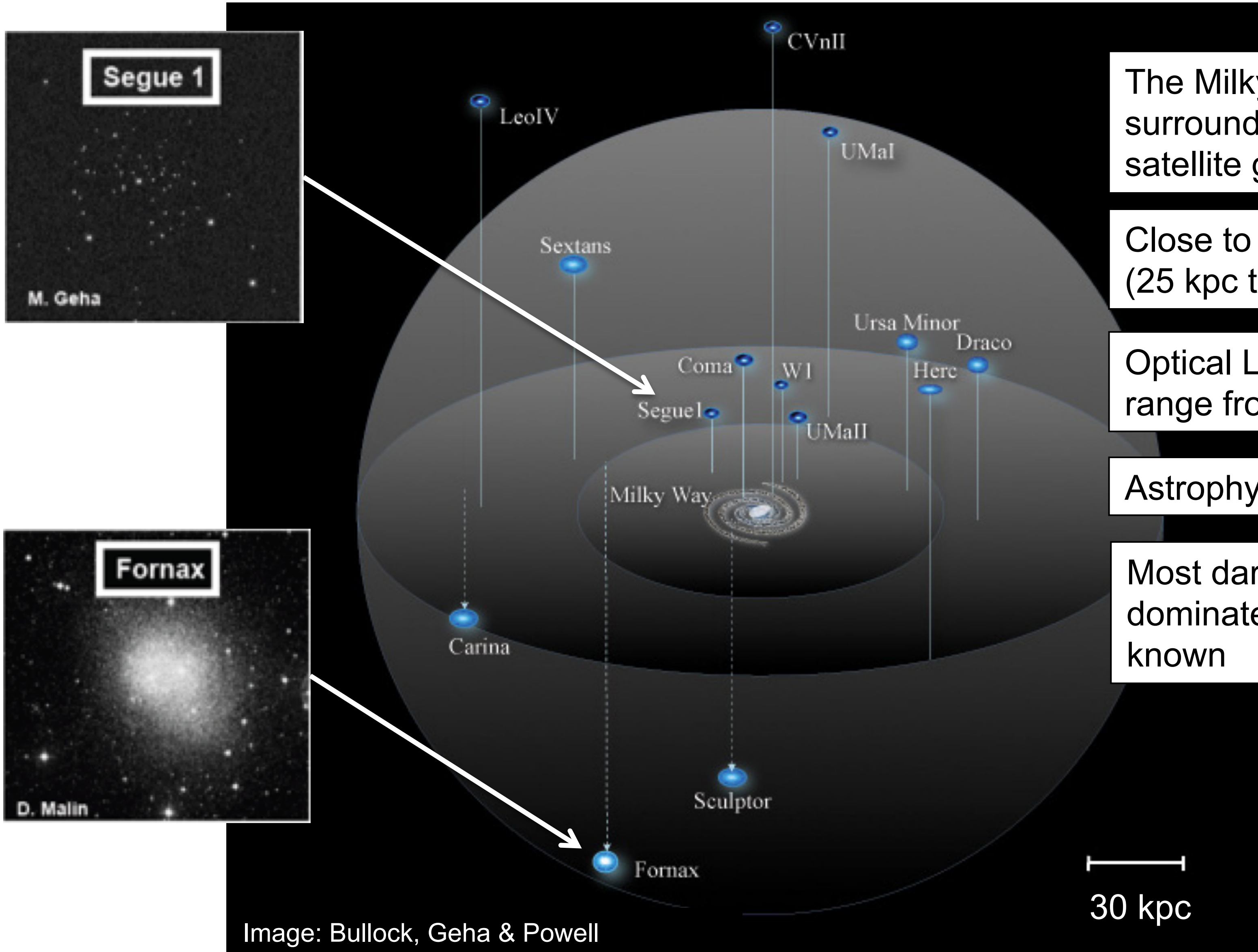
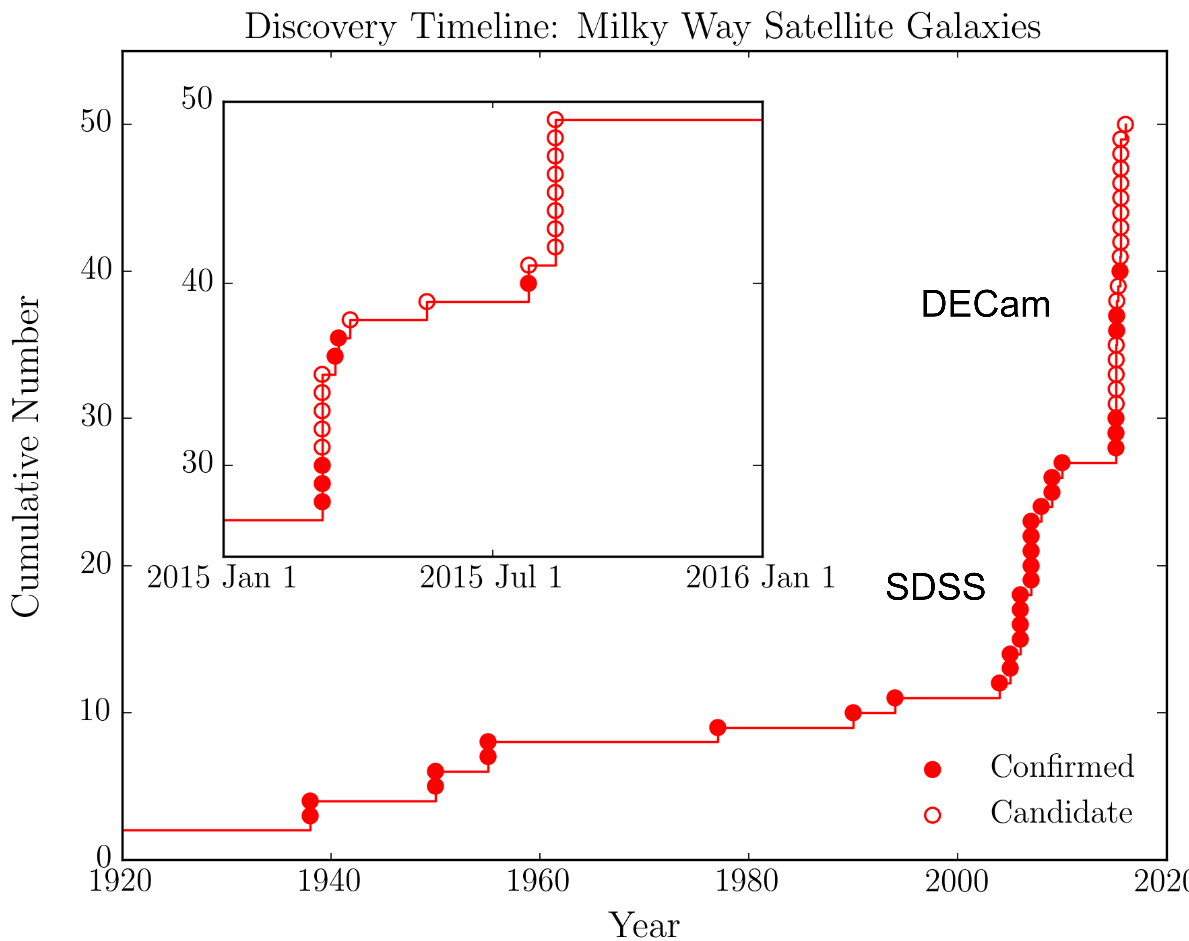


Image: Bullock, Geha & Powell

- The Milky Way is surrounded by small satellite galaxies
- Close to Earth (25 kpc to 250 kpc)
- Optical Luminosities range from 10^3 to 10^7 $L_\odot$
- Astrophysically inactive
- Most dark matter dominated objects known

Rapidly Growing Number of Known Dwarf Galaxies



DES Year 2 Data: Drlica-Wagner+(2015)

DES Year 1 Data: Bechtol+ (2015)

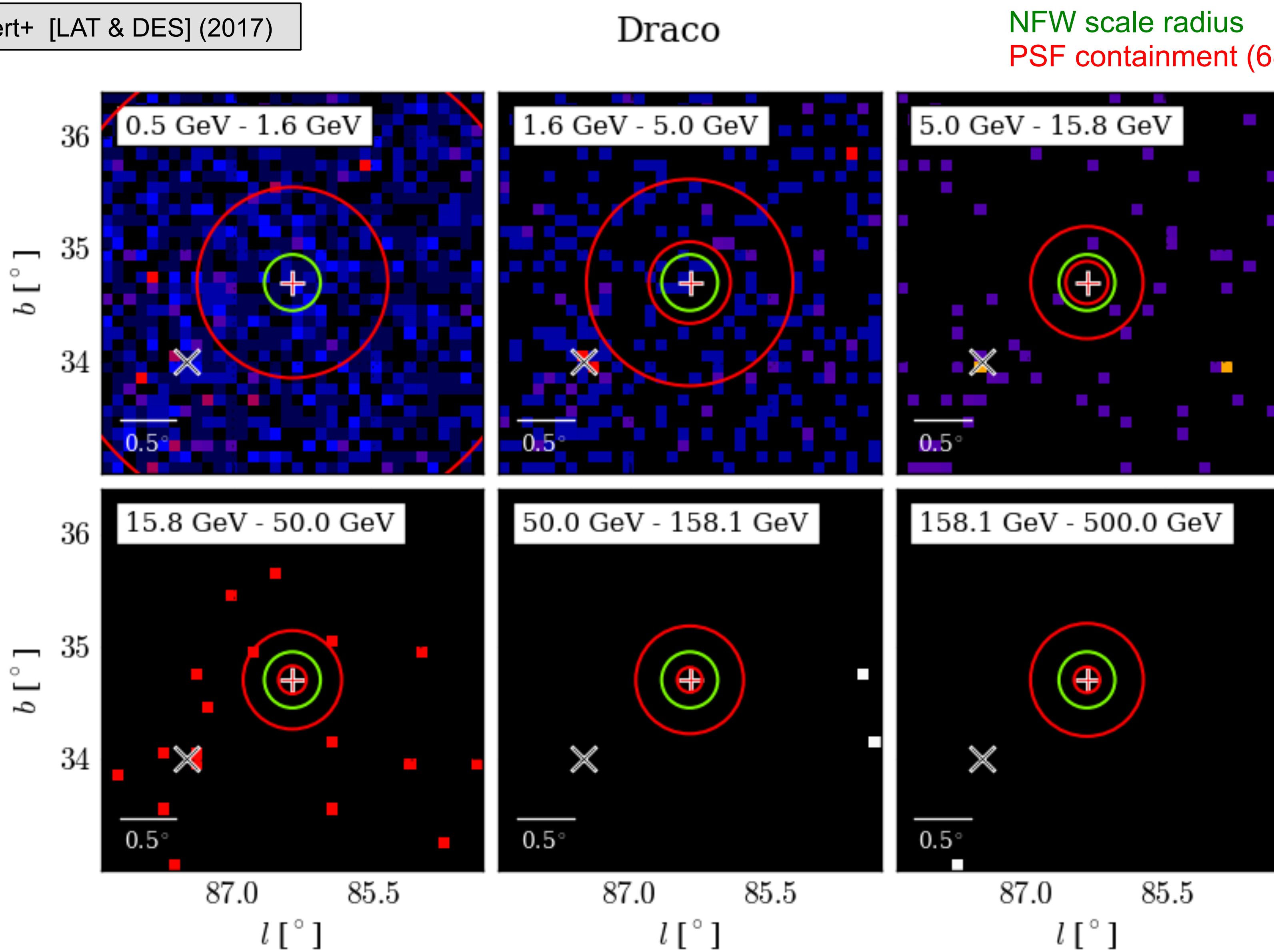
Koposov+ (2015)

- Advent of deep, digital survey era in optical astronomy has led to the discovery of numerous new Milky Way-satellite dwarf galaxies
- LSST & other surveys will continue to find new dwarf galaxies after the *Fermi* mission

Example γ-ray Count Maps for a dSph Galaxy

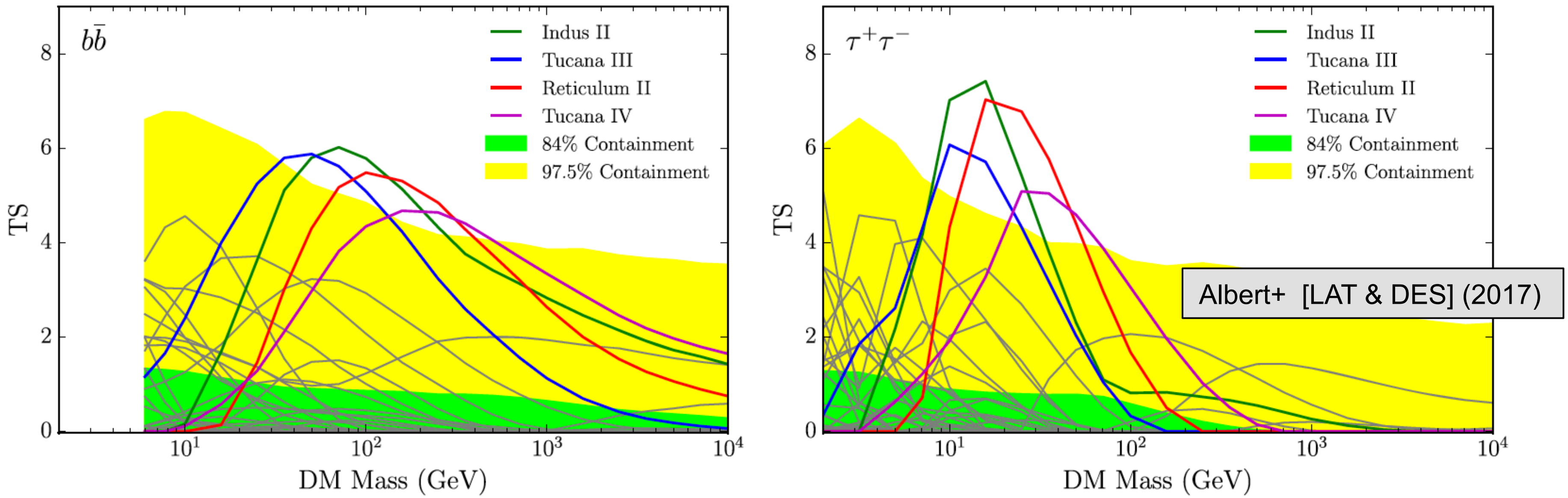
Albert+ [LAT & DES] (2017)

NFW scale radius
PSF containment (68%,98%)



Trials Effect: Most dSphs Lie Inside Expectation Bands

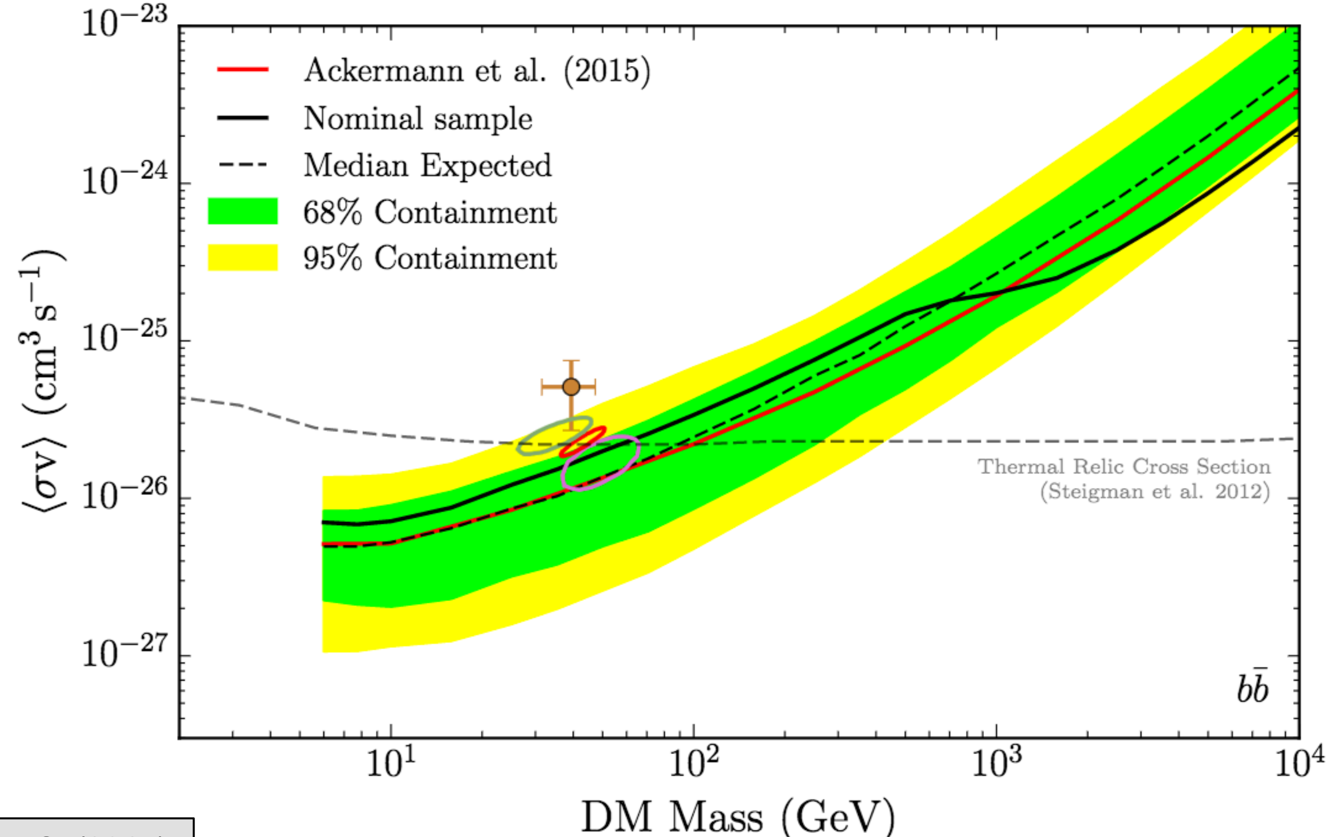
Significance v. DM mass for dSph targets for the bb and ττ annihilation channels



- Here we have highlighted the 4 dSphs that fall outside the 95% containment band for any DM particle mass
- Note: these are NOT the 4 dSphs with the highest J-factors
  - Caveat: for the faintest dSphs the J-factors can be quite uncertain (> 0.4 dex)

Joint Fitting Results from dSphs

Upper limits from joint analysis of all dSphs



Albert+ [LAT & DES] (2017)

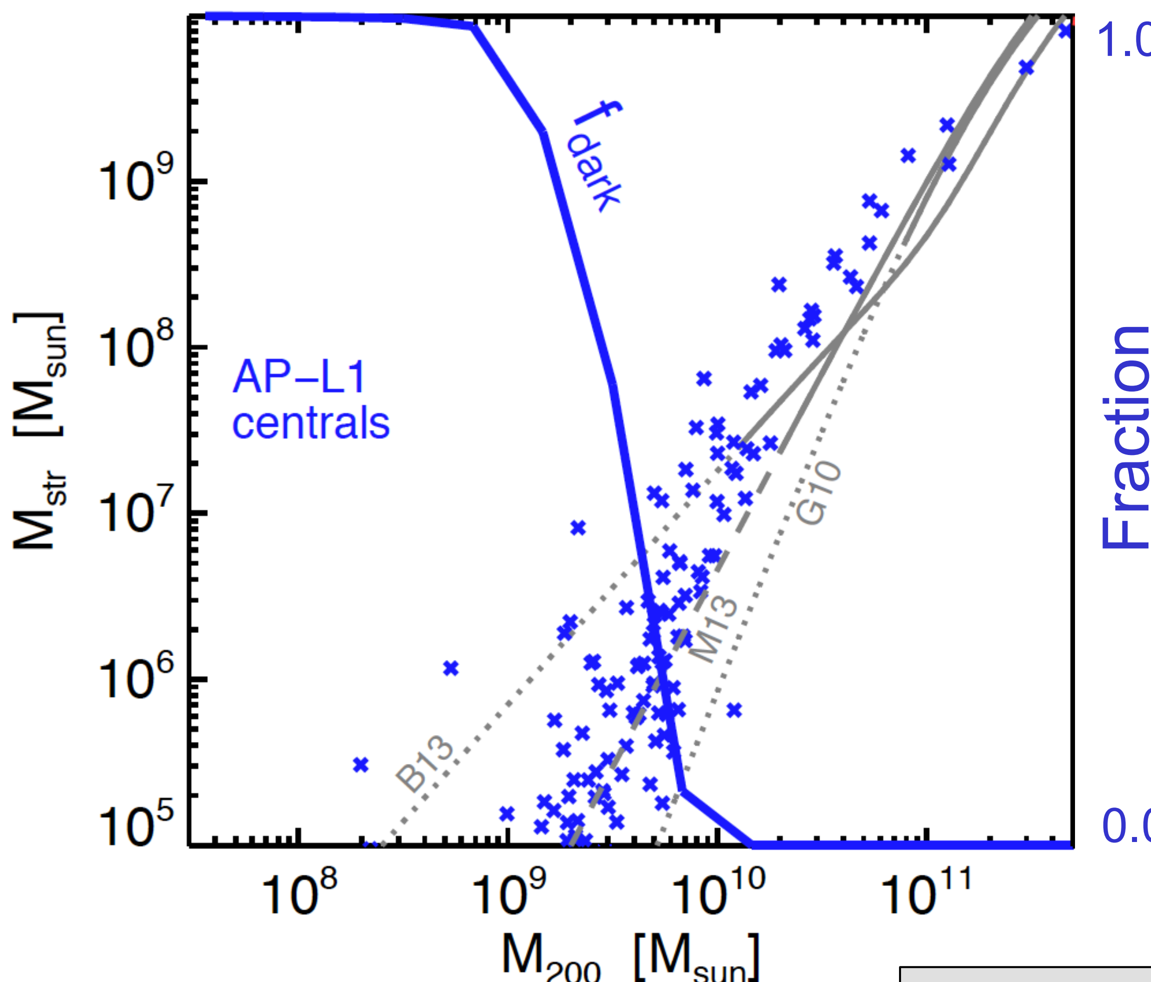
- Stacked analysis of a “nominal sample” of confirmed dSphs is well within the expectation band for null hypothesis and is in mild tension with DM interpretations of GC excess

Searches for Dark Satellites

- Approximately 1/3 of Fermi-LAT catalog sources are "Unassociated"
  - This means that we cannot clearly identify a multi-wavelength counterpart.
- Searches for "dark" satellites requiring:
  - No counterpart
  - DM-like spectra
  - No variability
  - Spatial extension (optional)

Searches: Berlin+ (2014), Bertoni+ (2015), Ciuca+ (2018)

Fraction of Halos without Stars as a Function of Mass

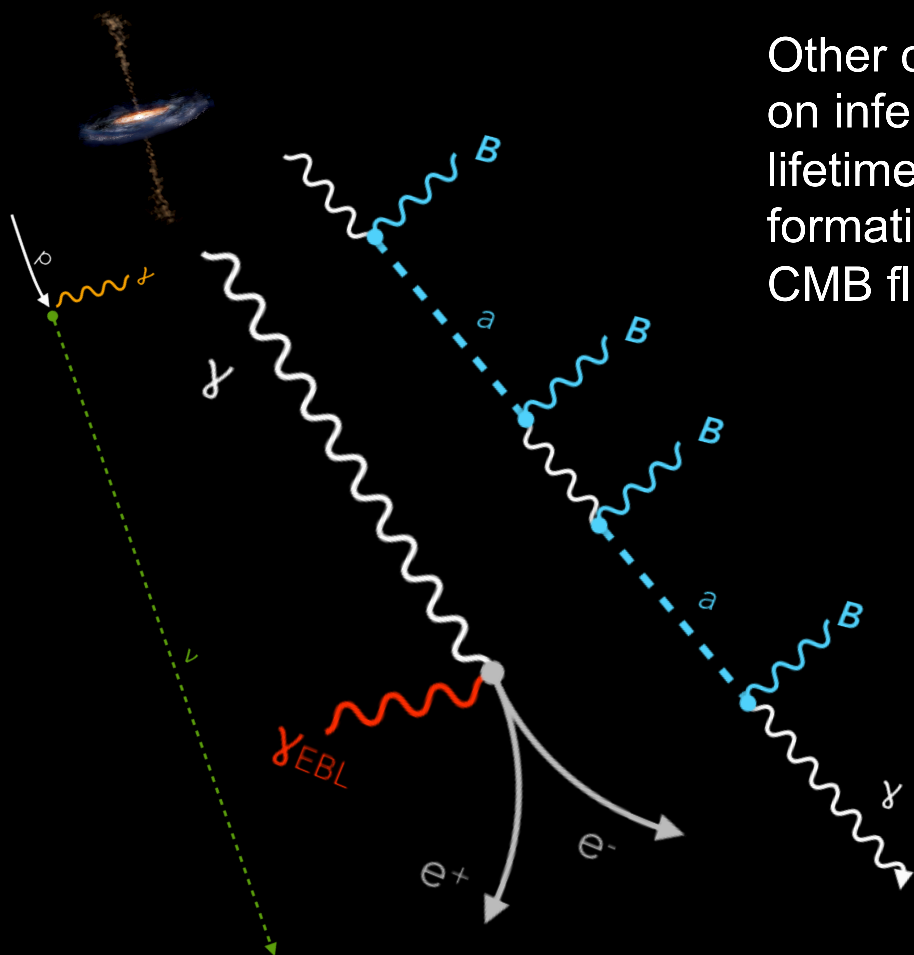


Fattahi+ (2016)

IV. Axion and Axion-Like Particle Searches

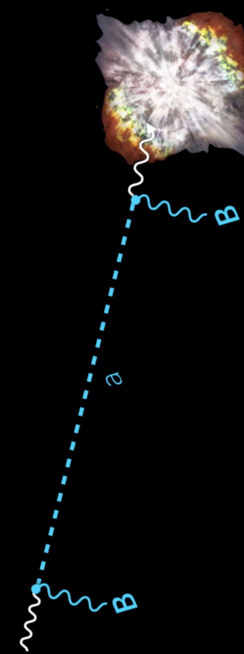
Indirect Detection of Axions and Axion-Like Particles

Blazar



Other constraints based on inferences from stellar lifetimes, structure formation,
CMB fluctuations, …

Supernova

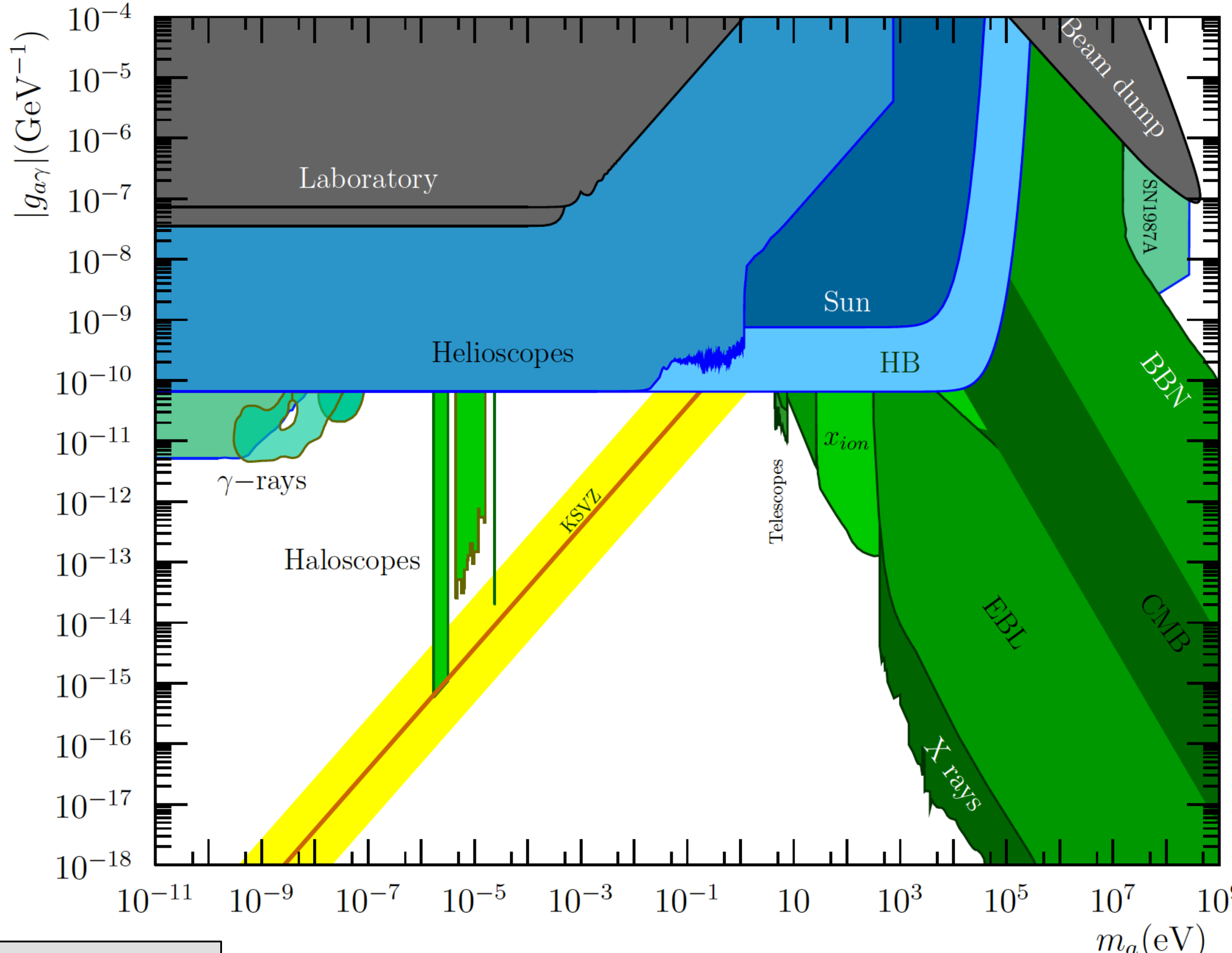


Search for prompt γ-rays from supernova core collapse

Search for reduced opacity, spectral features and correlation with high energy neutrinos from distance (z >~ 1) blazars

Axion/ALP Results

Excluded Regions in Axion/ALPs Mass-Coupling Constant Plane



Irastorza & Redondo (2018)

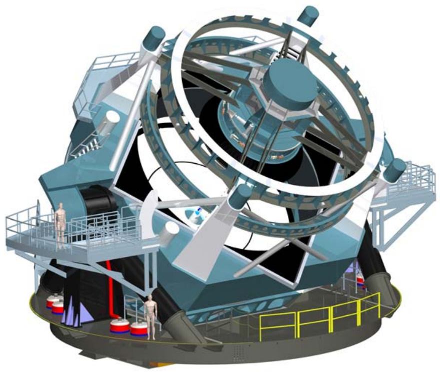
V. Summary

Summary of Current Status

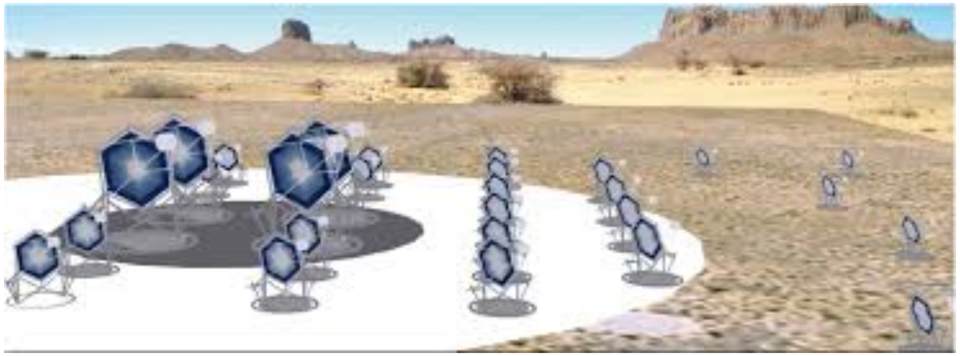
- Indirect detection searches of most promising DM targets have not found any compelling signals.
  - Galactic center excess can be explained as emission from unresolved pulsars, DM interpretation is not required.
  - Excesses from particular dwarf galaxies are consistent with sub-threshold unresolved sources.
- Current limits exclude the thermal relic cross section up to ~100GeV.
- Best astrophysical constraints on ALPs come from ALP-photon mixing
- Numerical simulations, large scale surveys have improved our understanding of structure formation, mass distribution and other properties of DM halos

Looking Forward

Large Synoptic Survey Telescope (LSST)



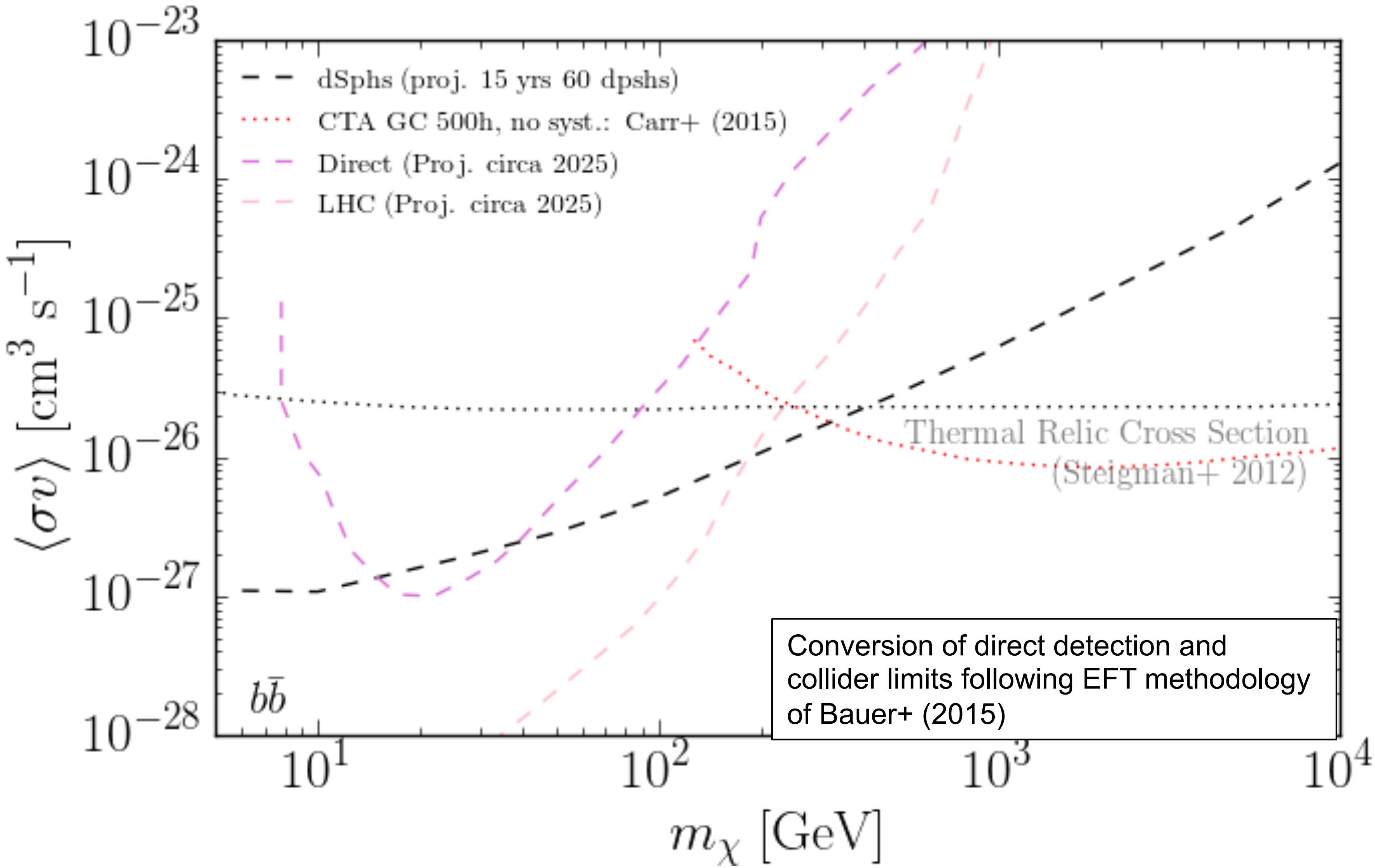
Cerenkov Telescope Array (CTA)



- Existing experiments (Fermi, IACTs, HAWC) will continue to push sensitivity at thermal relic cross section to higher masses
- New optical survey (e.g., LSST) telescopes are coming online that will find more dark matter targets and better quantify the dark matter in existing targets
  - In particular, strong lensing will improve our understand of halo mass function
- New ground-based high-energy γ-ray telescope array (CTA) that will search for γ rays from dark matter annihilation to much higher energies than Fermi. (See talk by Morselli).

Dark Matter Sensitivity, circa 2025

Comparison of Projected Limits with Direct-Detection and Collider Limits



Charles+ [Fermi-LAT Clb] (2016)