Indirect Searches for Dark Matter with the Fermi Large Area Telescope

Eric Charles

on behalf of the Fermi-LAT Collaboration

Brookhaven Forum 2015

BNL, Oct. 7-9

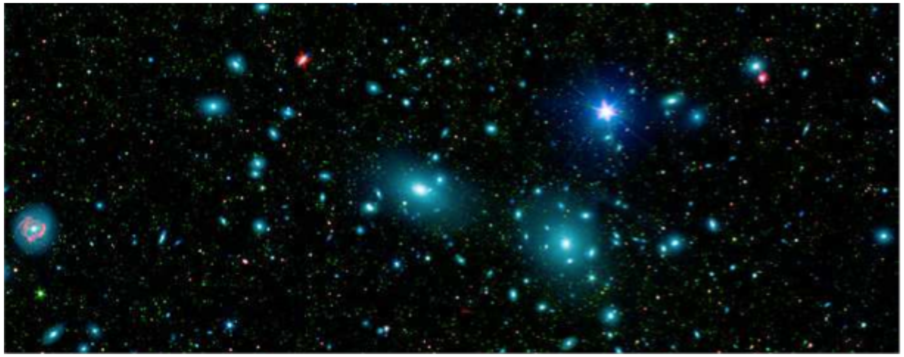
Fermi-LAT Searches for Dark Matter

- Indirect Searches for Dark Matter
- Fermi-LAT Search Strategies and Results
- Status and Summary

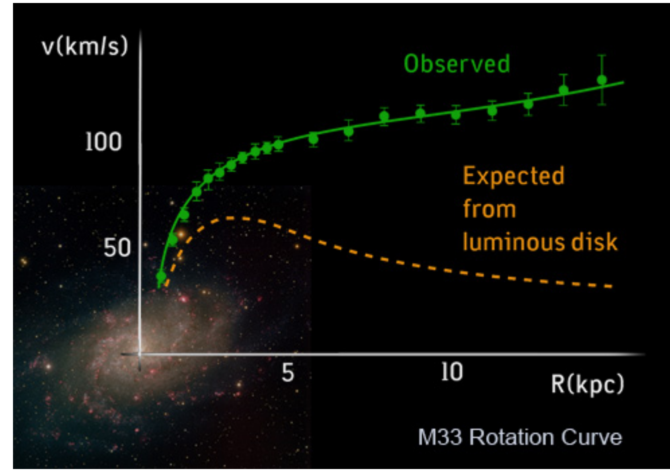
- Lots of Bonus Slides:
  - Gamma-ray Astrophysics and Astronomy
  - Modeling Galactic Diffuse γ-ray Emission
  - Gamma-ray Pulsars
  - J-factors for Dwarf Galaxies
  - Unresolved Sources, Luminosity Functions, log N – log S

Indirect Searches for Dark Matter

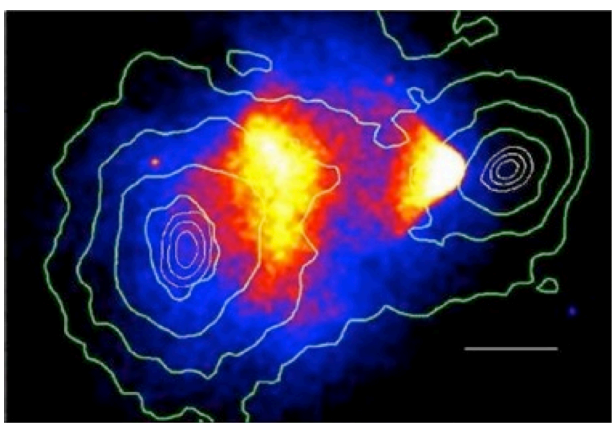
Evidence for / Salient Features of Dark Matter



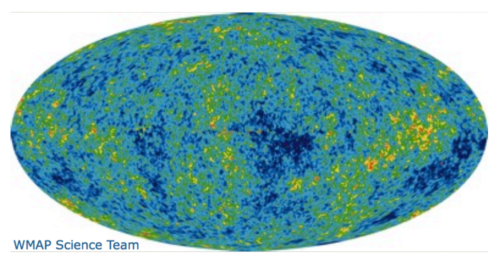
*Comprises **majority** of **mass** in Galaxies*
Missing mass on Galaxy Cluster scale
Zwicky (1937)

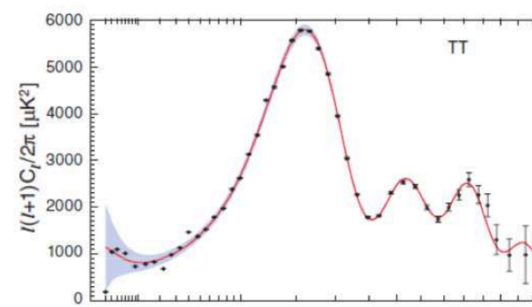


*Large **halos** around Galaxies*
Rotation Curves
Rubin+(1980)



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

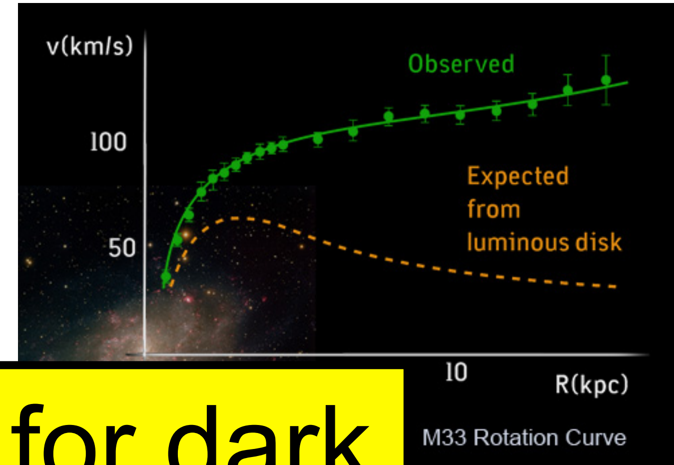




Non-Baryonic
Big-bang Nucleosynthesis,
CMB Acoustic Oscillations
WMAP(2010)

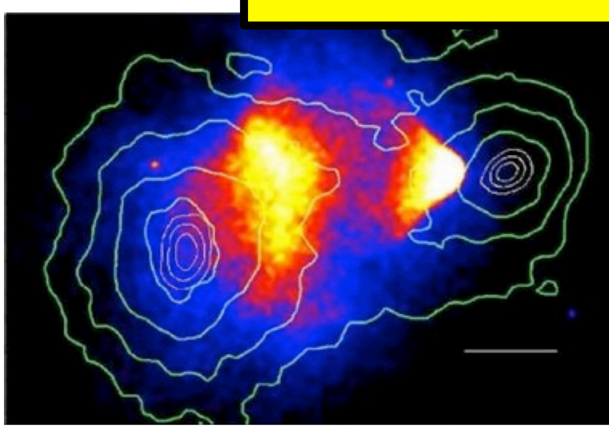
Evidence for / Salient Features of Dark Matter

Comprises
Missing ma
Zwicky (19



d Galaxies

All of the evidence for dark matter is astrophysical!



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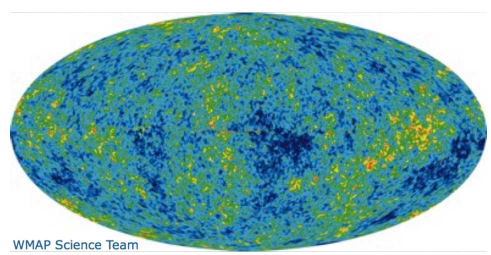
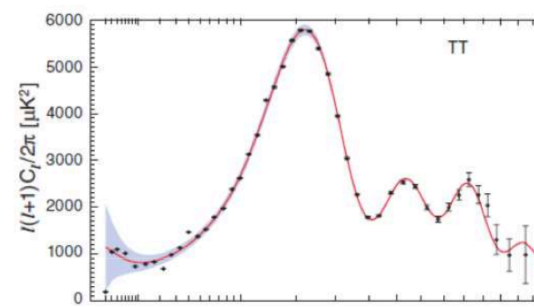
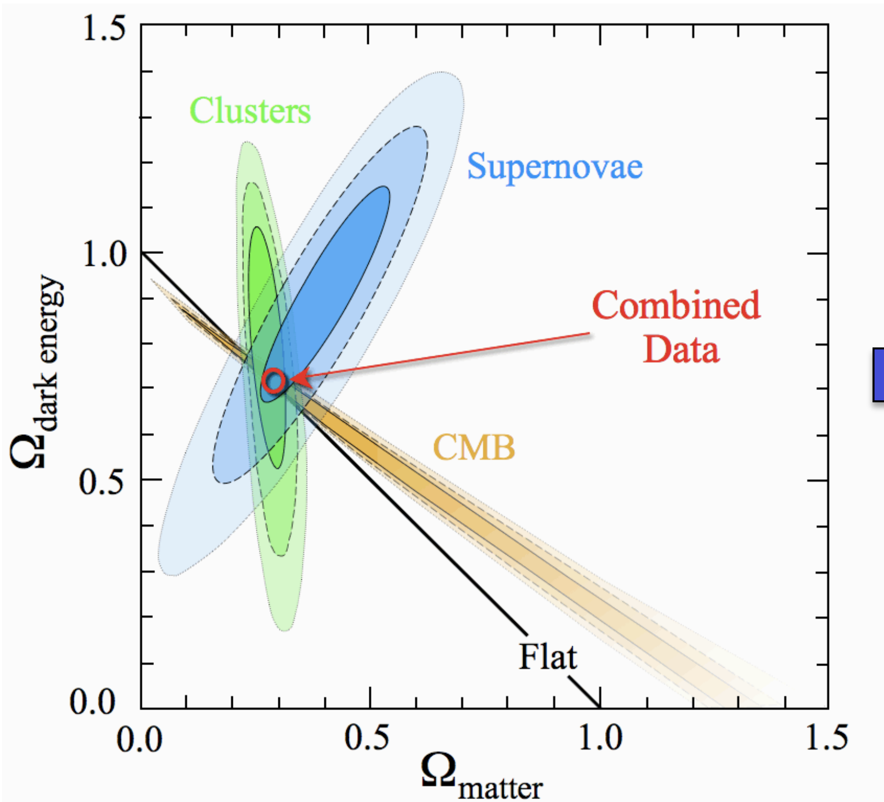




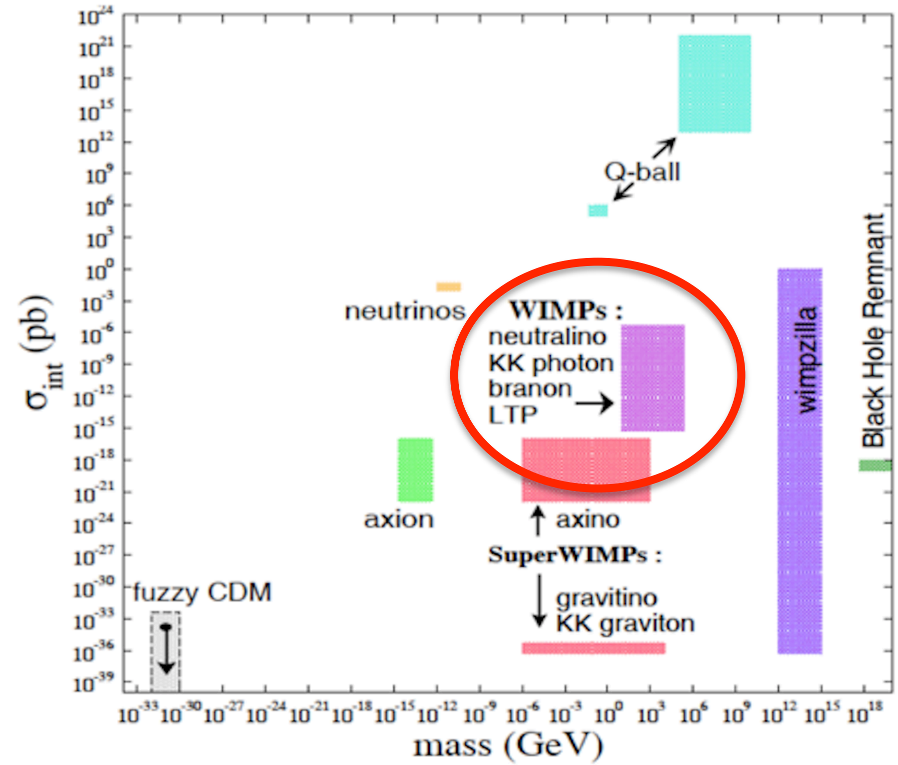
Non-Baryonic
Big-bang Nucleosynthesis,
CMB Acoustic Oscillations
WMAP(2010)

Cosmological Constraints on Dark Matter

Λ−CDM Concordance Fits

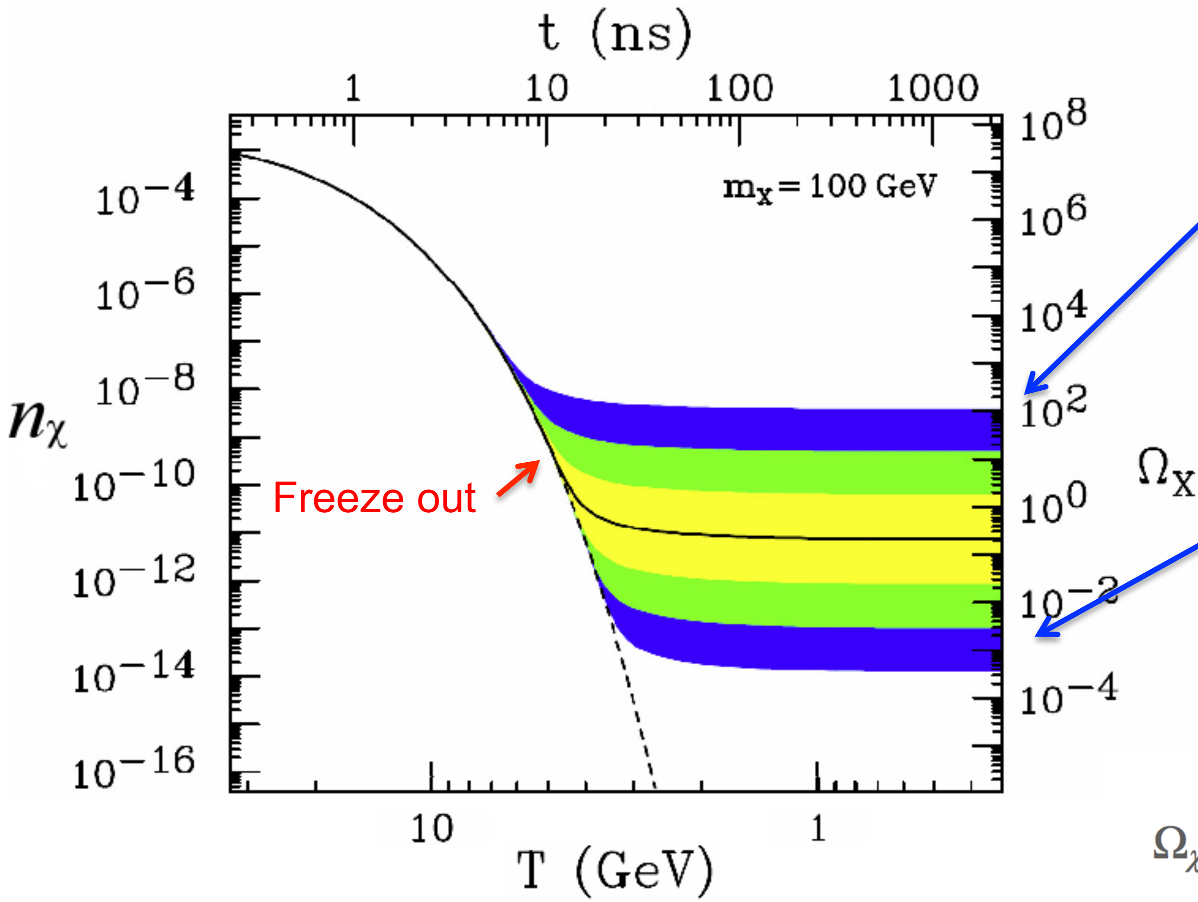


DM Candidates by Mass & Cross Section



- 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
  - Current instruments are also sensitive to axion-like particles, primordial black holes, gravitinos

WIMP Dark Matter as a Thermal Relic



Small cross-section:
freeze out too early,
too many WIMPs

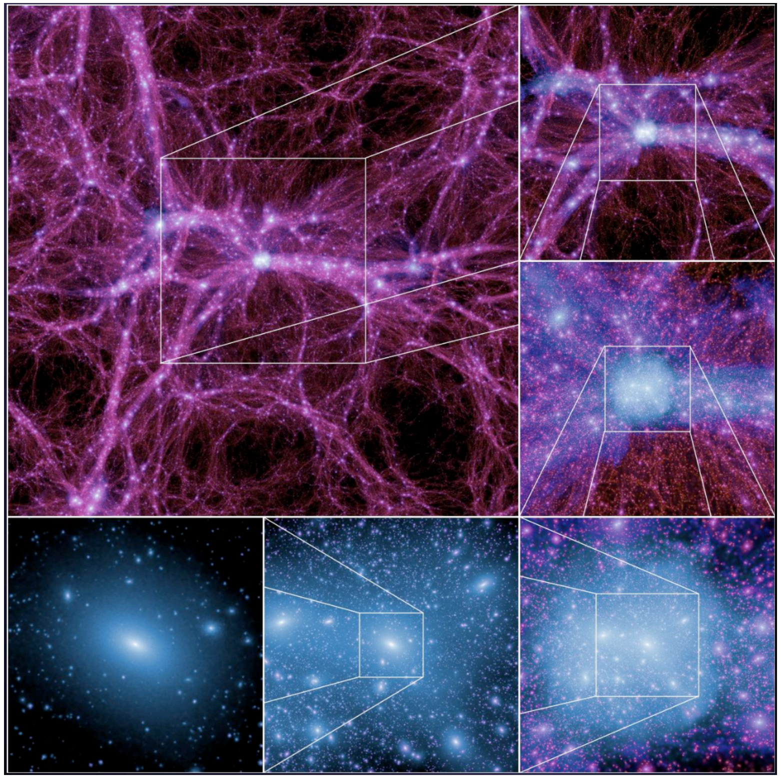
Large cross-section:
freeze out too late,
too few WIMPs

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

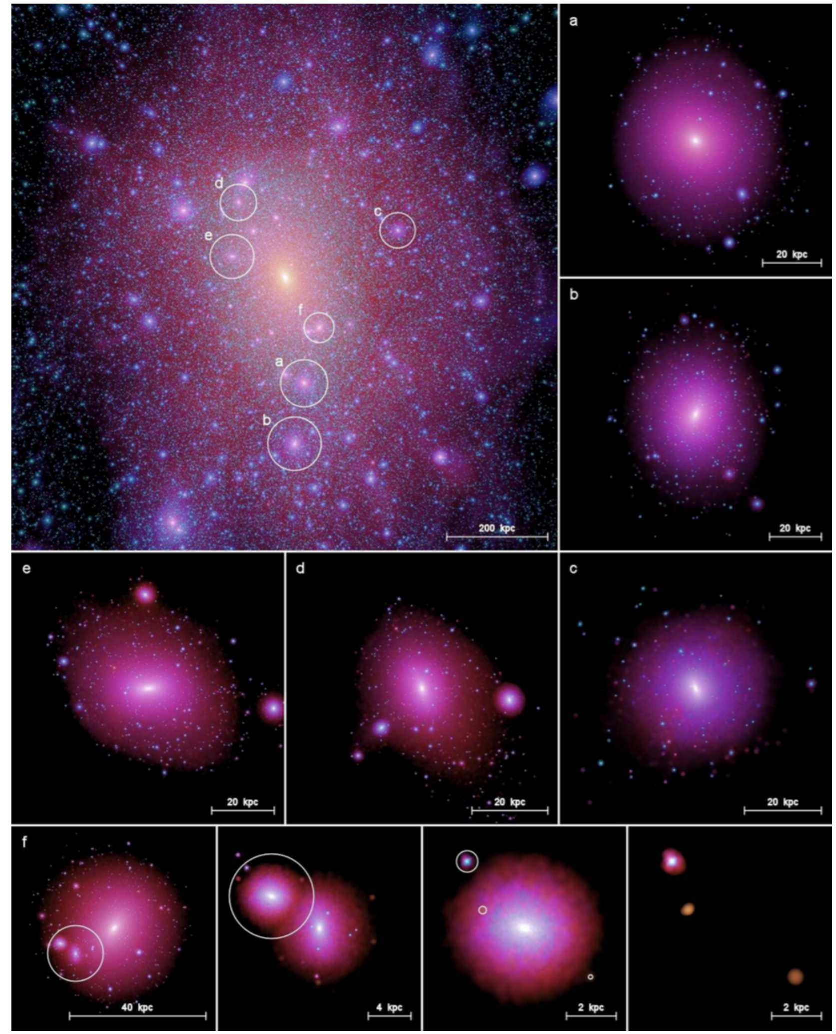
- The calculation of the thermal-averaged cross-section $\langle\sigma v\rangle$ needed to obtain the relic density is robust and gives $\langle\sigma v\rangle \sim 3\ 10^{-26}\ \mathrm{cm}^3\mathrm{s}^{-1}$
- At that cross-section limits start to put constraints on model space

DM Structures are Present on All Scales

Zoom Sequence of DM Structure on 100Mpc Scales



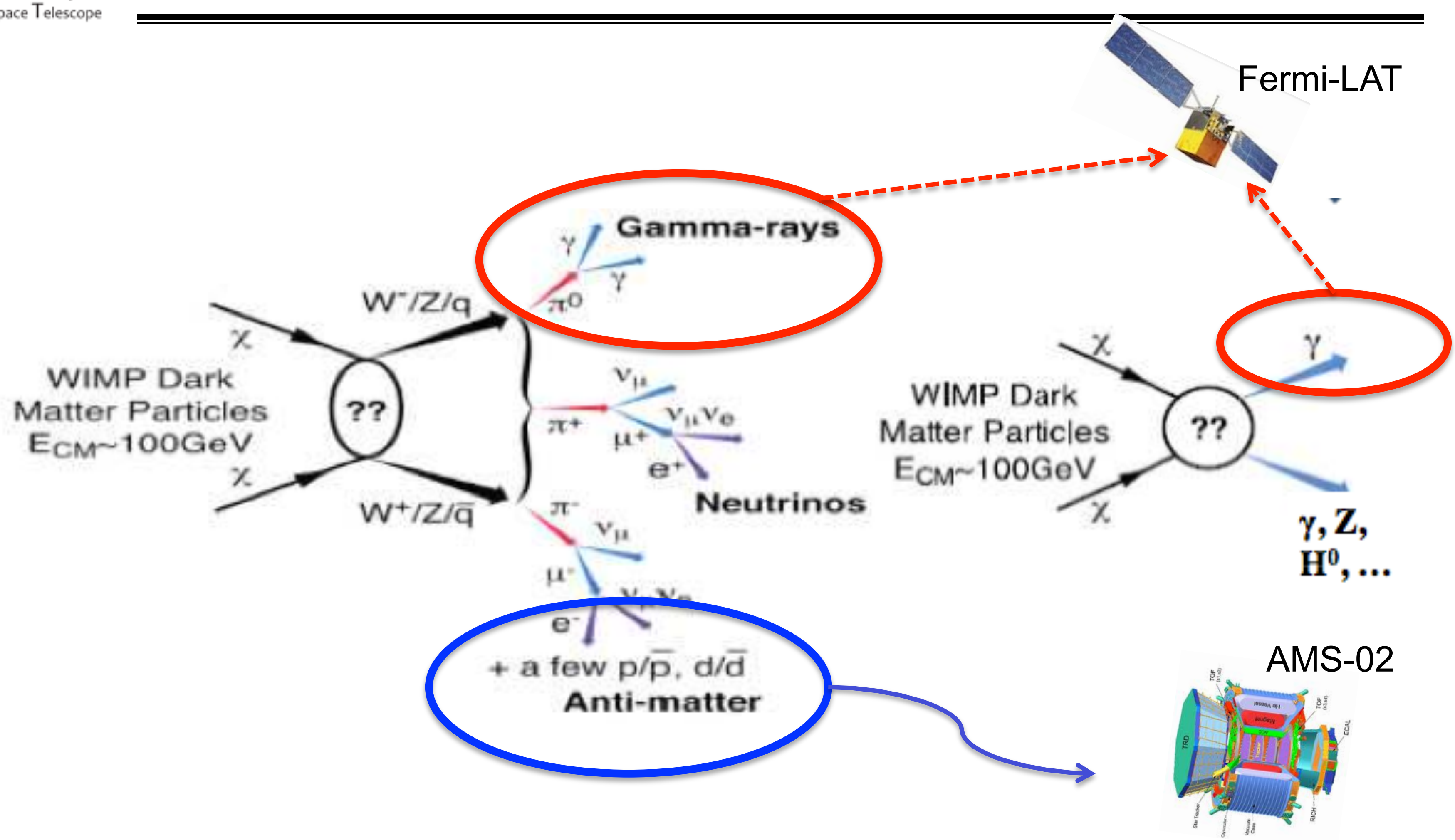
Milky Way-like Halo and Several Sub-Halos



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

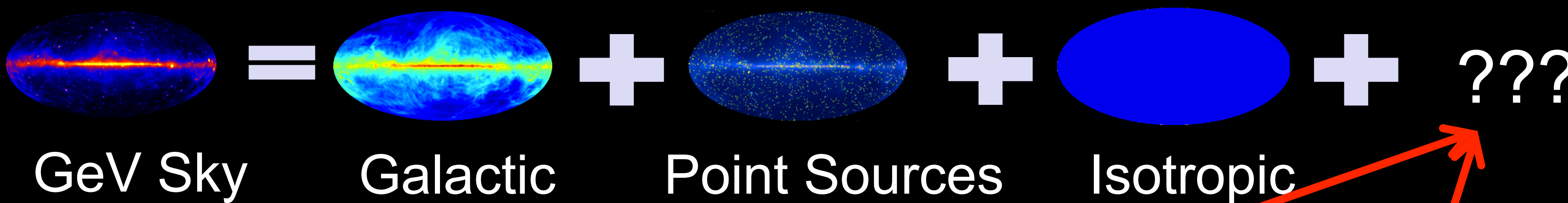
Left: Boylan-Kolchin+ (2009)
Right: Springel+ (2012)

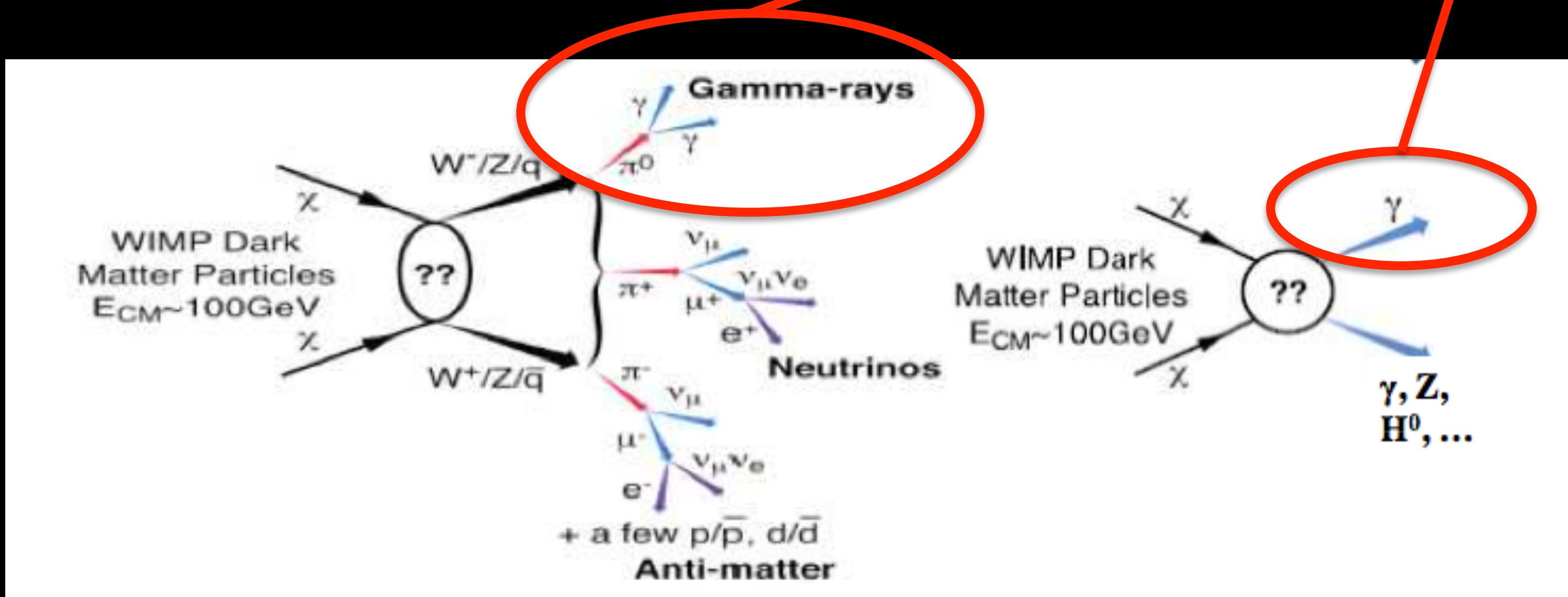
Indirect Detection of WIMPs



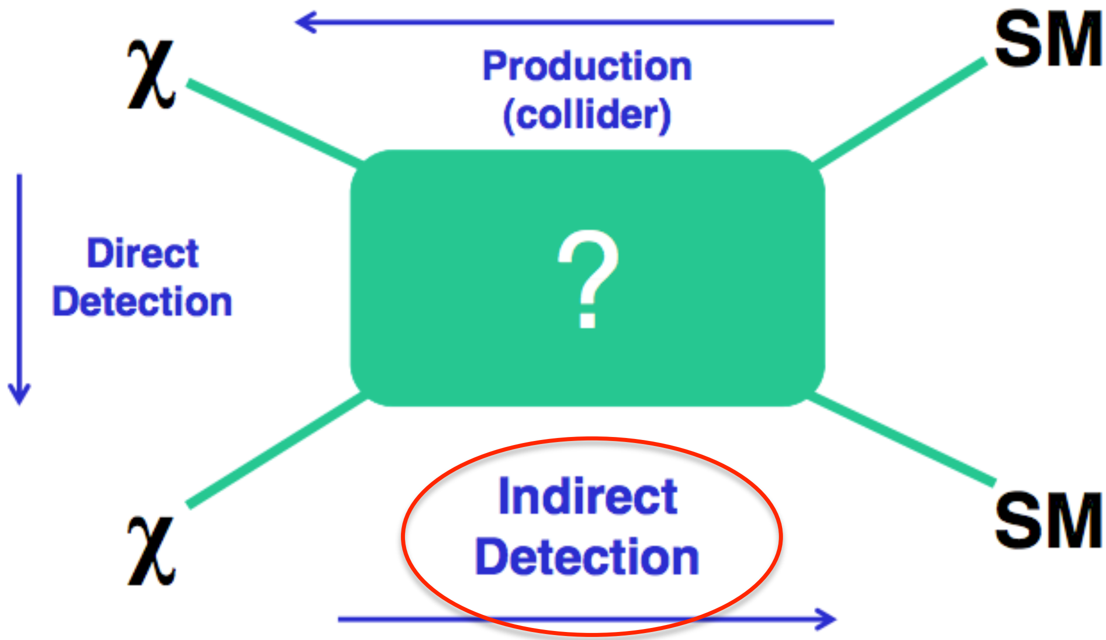
- What we observe are stable final-state annihilation products
  - Charged particles (e^+,e^-,p,anti-p) diffuse in Galactic magnetic fields
  - Neutral particles (γ; ν, observed by IceCube) travel directly to us

Indirect Searches for DM in the GeV Sky





Role of Indirect Detection Dark Matter Searches

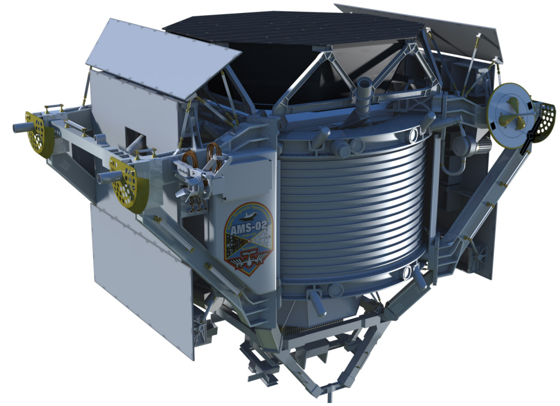


- ***Compared to collider searches***: indirect detection is sensitive to high mass scales (particles already exist, stable final state particle spectrum peaks at ~10% of m_χ)
- ***Compared to direct detection***: indirect detection is sensitive to annihilation rather than scattering off of nuclei (i.e., more sensitive when χ couples more to heavy quarks and vector bosons than to light quarks and gluons)

Fermi-LAT Search Strategies and Results

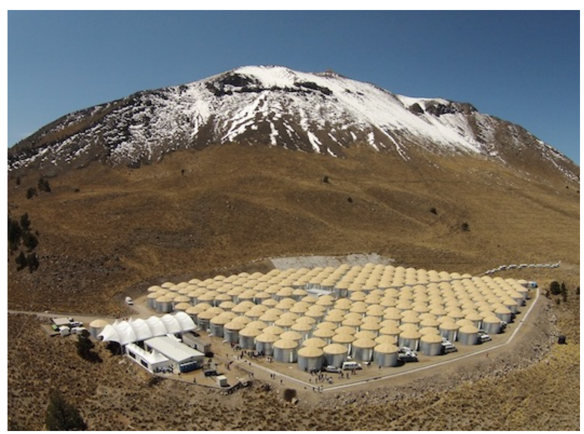
High Energy Astrophysics Instruments

Pair-conversion telescopes:
Fermi, *AGILE*, *DAMPE*, *Gamma-400*

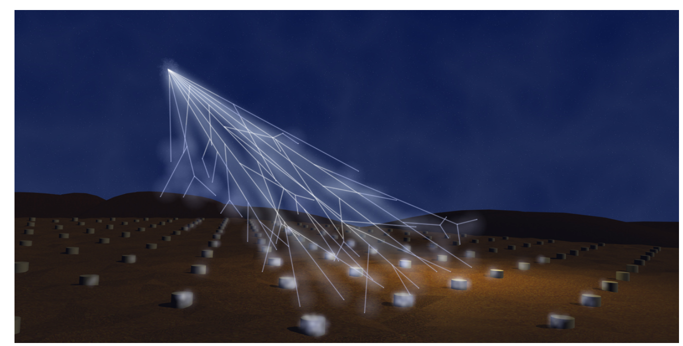


Cosmic-ray detectors:
PAMELA, *AMS-02*, *HERD*

Imaging Atmospheric Cherenkov Telescopes:
HESS, *MAGIC*, *VERITAS*, *CTA*



Water Cherenkov Telescopes:
HAWC, *ICE-Cube*



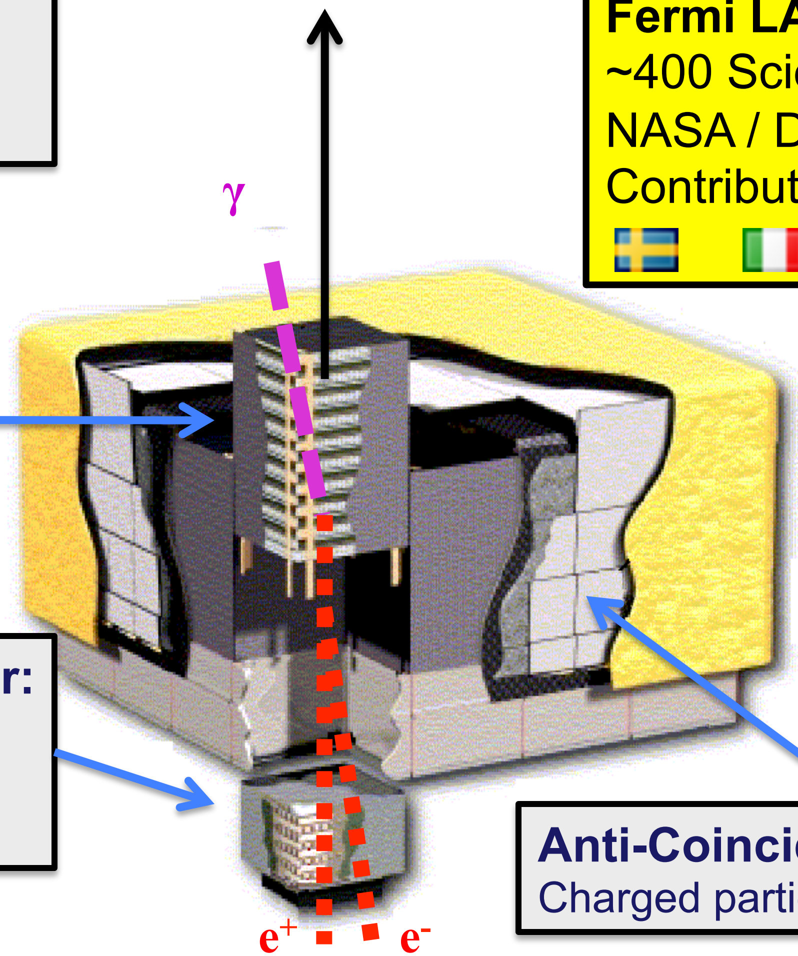
Hybrid cosmic-ray detectors:
Auger

The Fermi Large Area Telescope

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

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

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



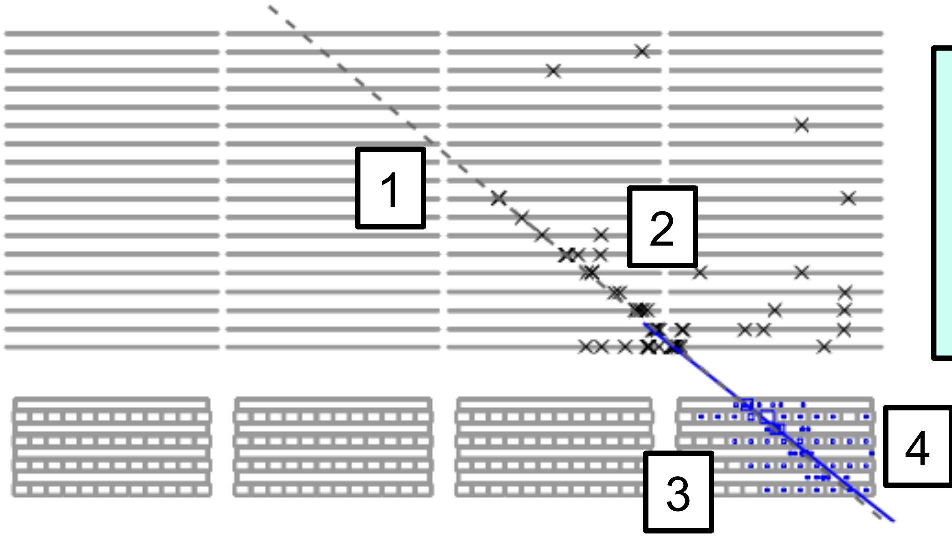
Hodoscopic CsI Calorimeter:
measure γ energy
image EM shower
EM v. hadron separation

Anti-Coincidence Detector:
Charged particle separation

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

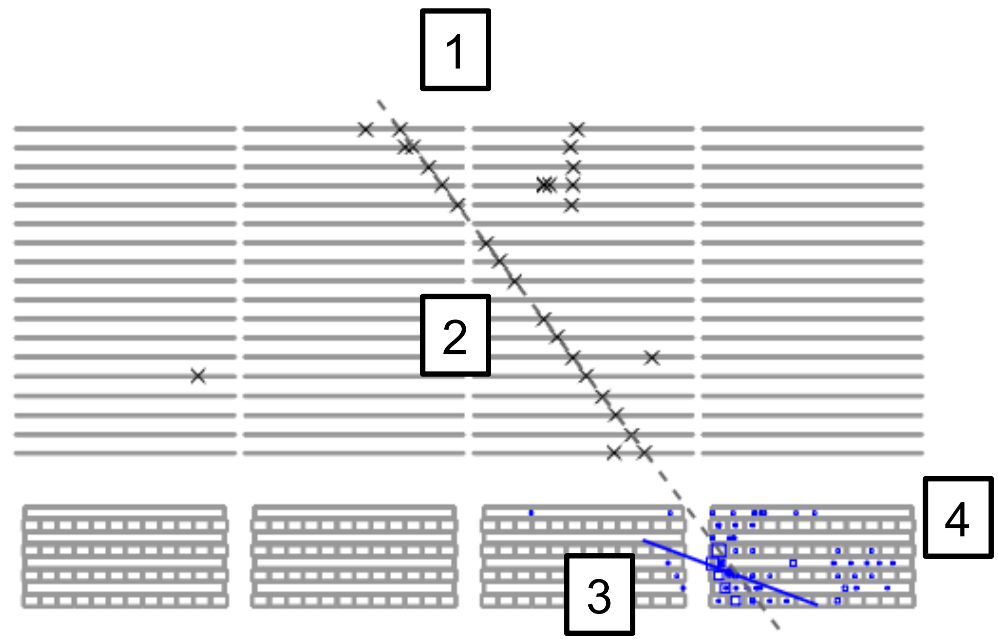
Trigger and Filter:
Reduce data rate from ~10kHz to 300-500 HZ

LAT Detects Individual γ rays (and Cosmic Rays)



Nearly ideal γ-ray candidate:

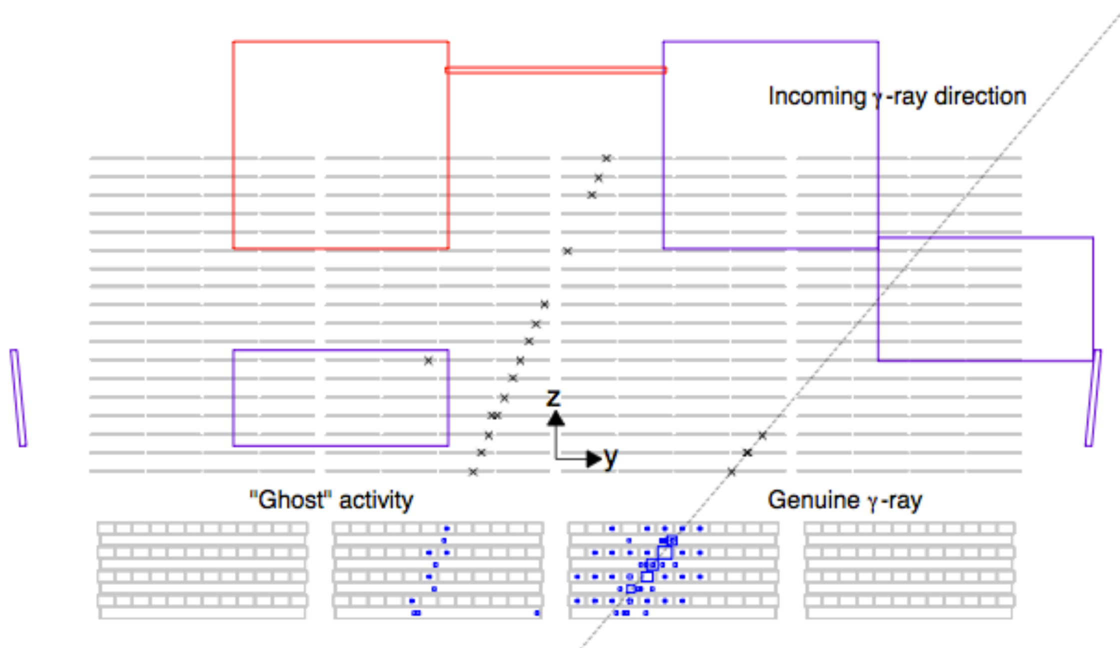
1. Converts in middle of TKR
2. Extra hits near track
3. CAL axis aligned with track
4. CAL energy confined near axis



Nearly ideal proton candidate:

1. Starts at top of TKR
2. Few extra hits near track
3. CAL axis not-aligned with track
4. CAL energy “lumpier”
5. Signal in the ACD (not shown)

"Pass 8" of the Event Analysis



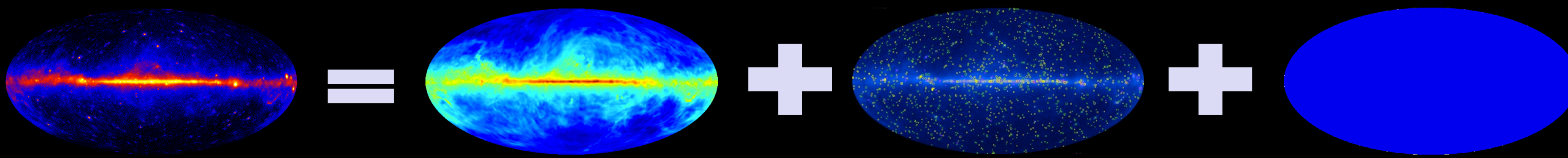
Pile-up affects up to 30% of events in certain parts of Fermi orbit.

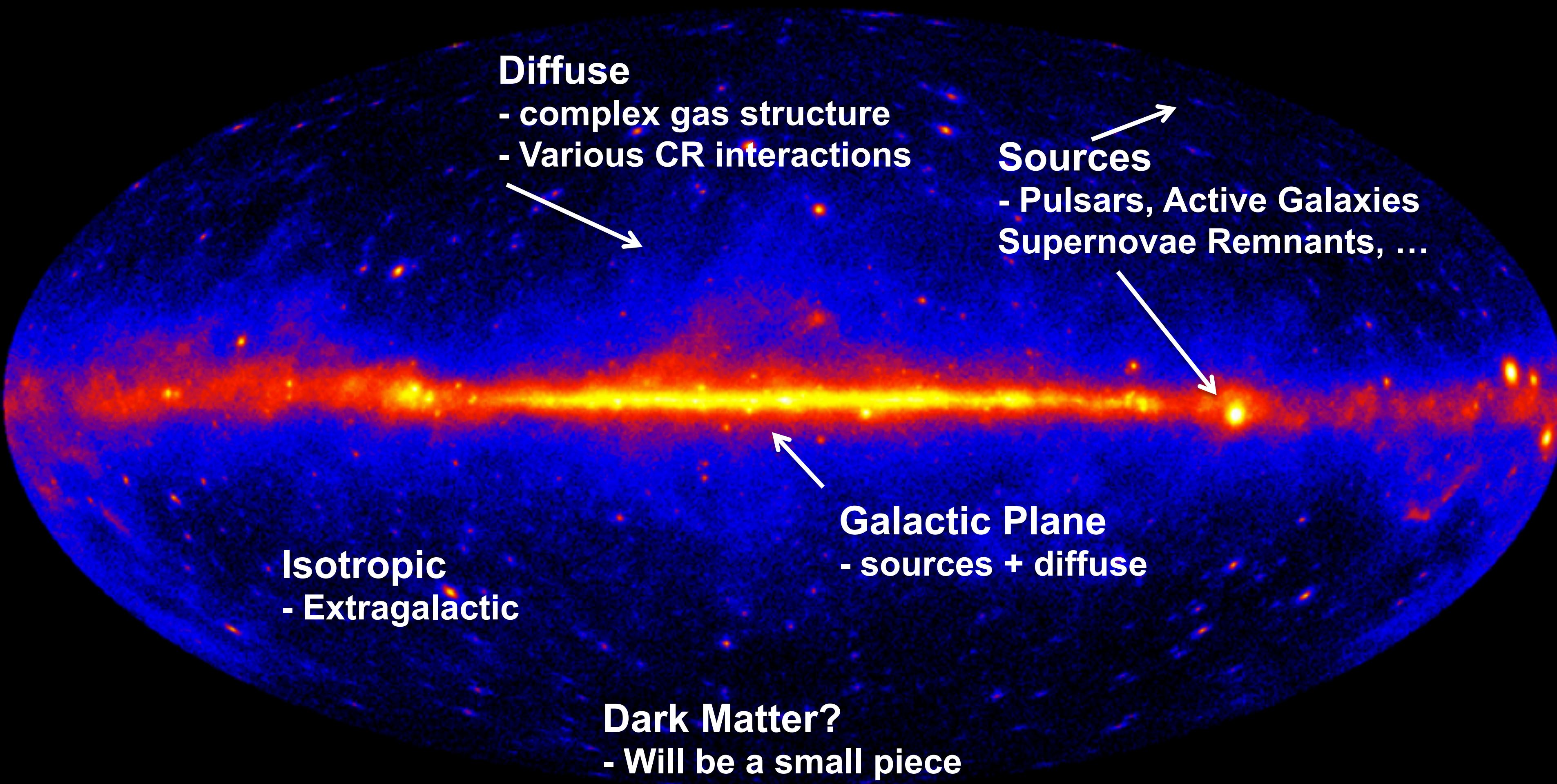
Low energy events are more severely affected

- The LAT is particle physics detector optimized for γ-ray astronomy
- LAT event-level analysis was largely developed before launch (Aug. 2008)
  - We now have improved knowledge of the instrument and backgrounds
    - E.g., we found that many events are accompanied by pile-up signals…
- Pass 8 uses this knowledge to improve data for science

First Pass 8 Science Results Presented at 5th Fermi Symposium, October 2014

Fermi-LAT Gamma-ray Sky



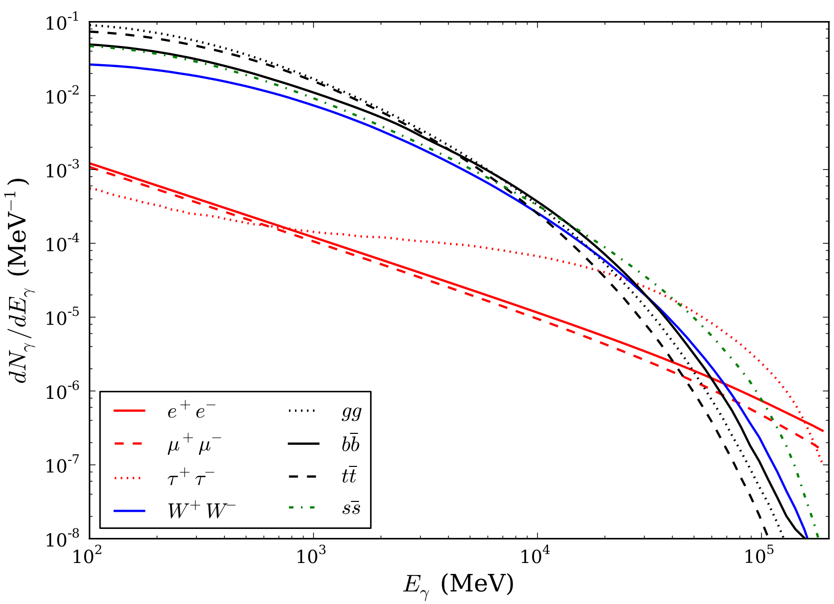


The Key Formula for WIMP Searches

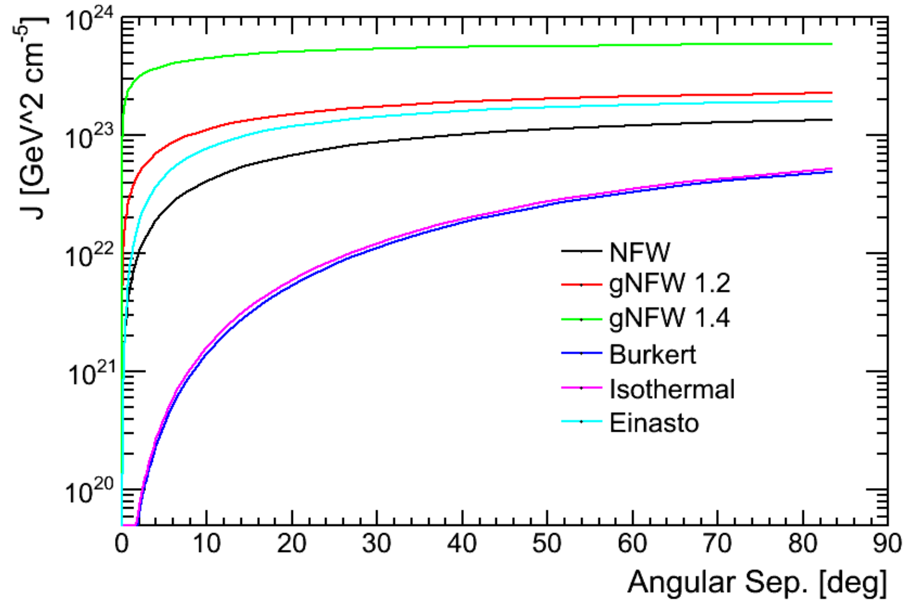
Particle Physics / Astrophysics (J-Factor)

$$\frac{d\Phi_\gamma}{dE_\gamma}(E_\gamma,\phi,\theta) = \boxed{\frac{1}{4\pi}\frac{<\sigma_{ann}v>}{2m^2_{WIMP}}\sum_f \frac{dN^f_\gamma}{dE_\gamma}B_f} \boxed{\int_{\Delta\Omega(\phi,\theta)} d\Omega' \int_{los} \rho^2(r(l,\phi'))dl(r,\phi')}$$

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 Search Strategies

Satellites

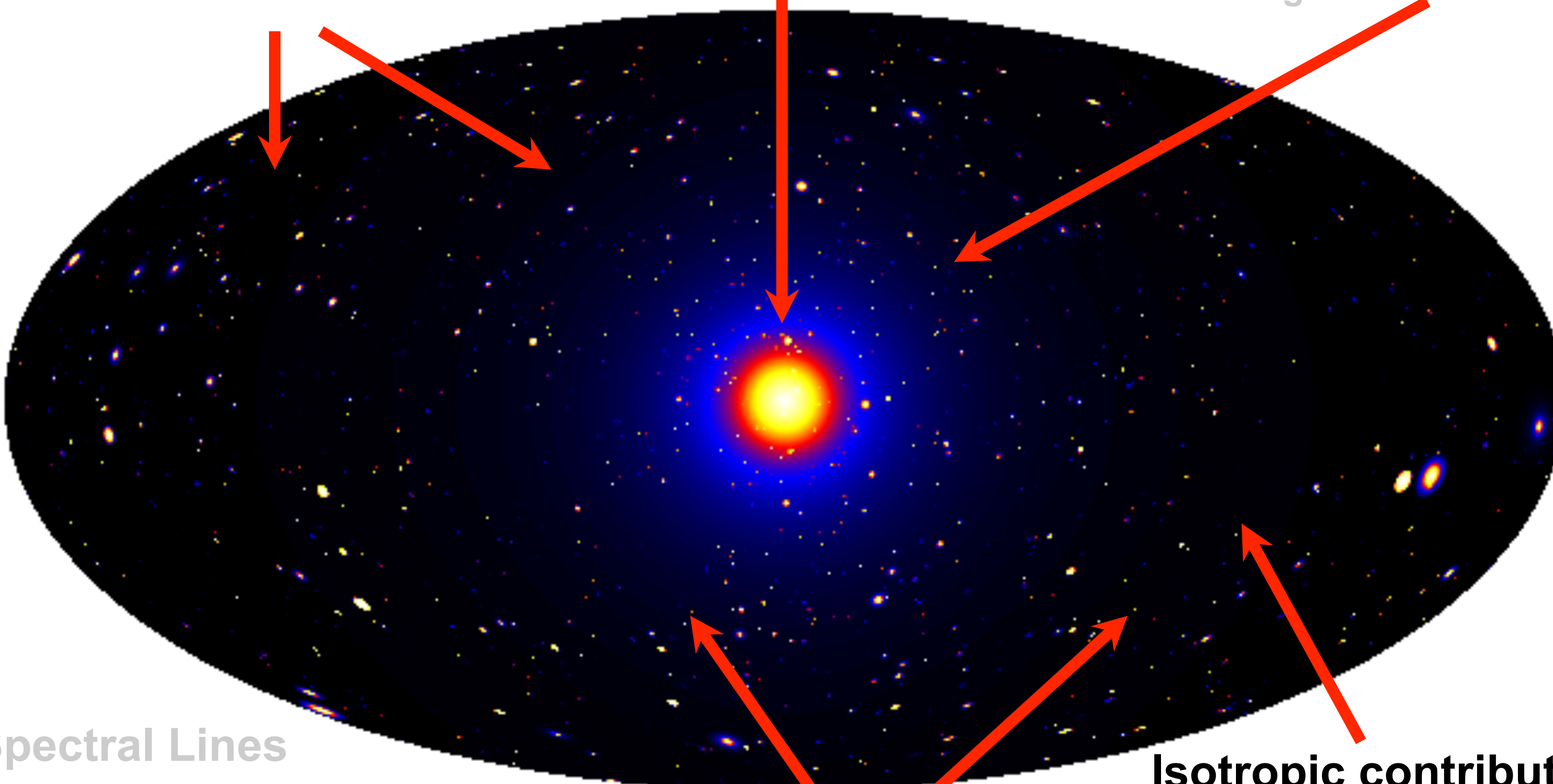
Low background and good source id, but low statistics

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+(2009) arXiv:0908.0195

Search Strategies (against the γ-ray Sky)

Satellites

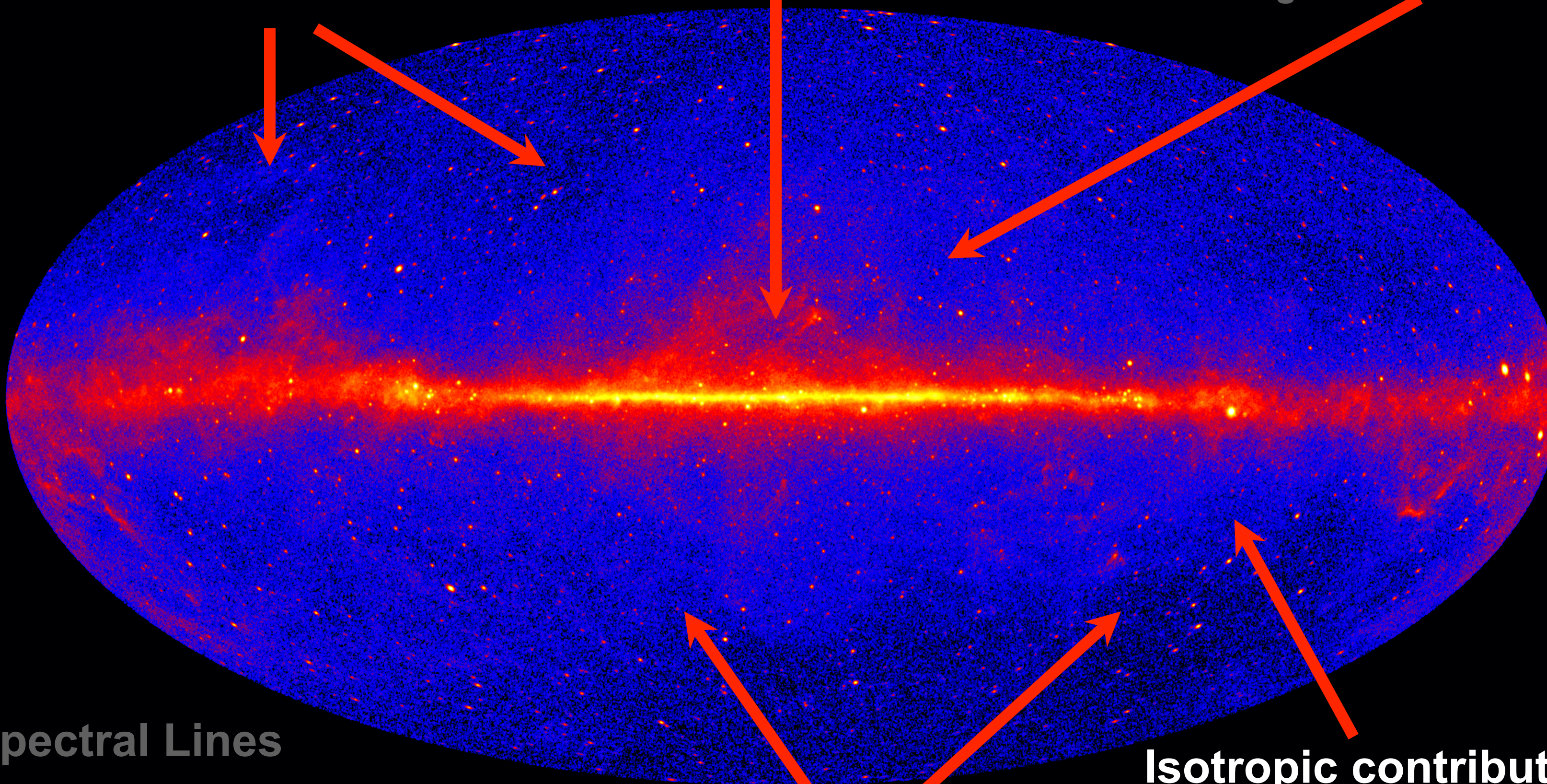
Low background and good source id, but low statistics

Galactic Center

Good statistics, but source confusion/diffuse background

Milky Way Halo

Large statistics, but diffuse background



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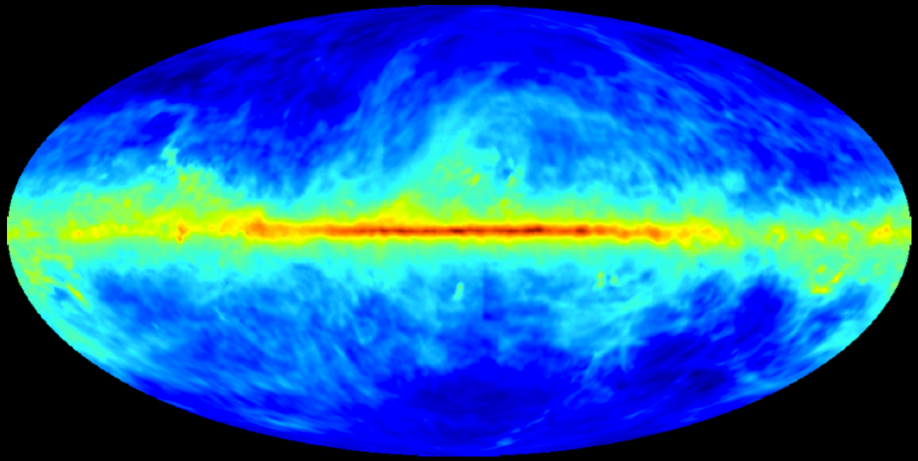
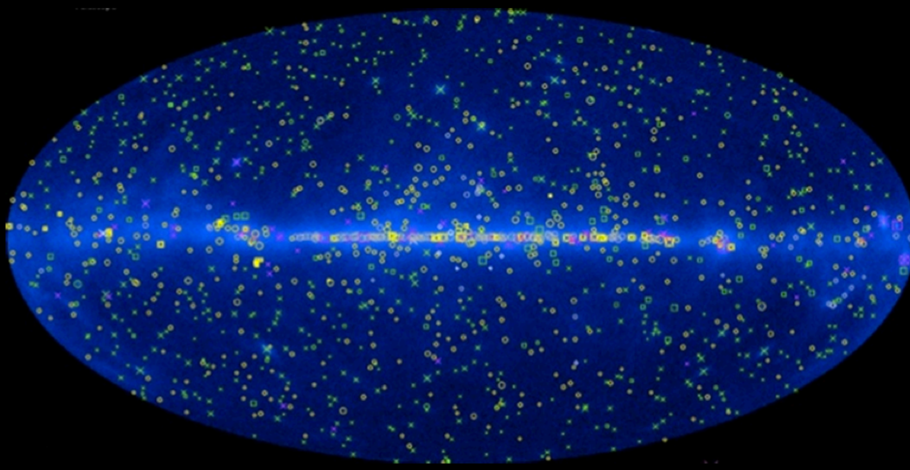
LAT 7 Years Sky > 1 GeV

Astrophysical Backgrounds (GeV)



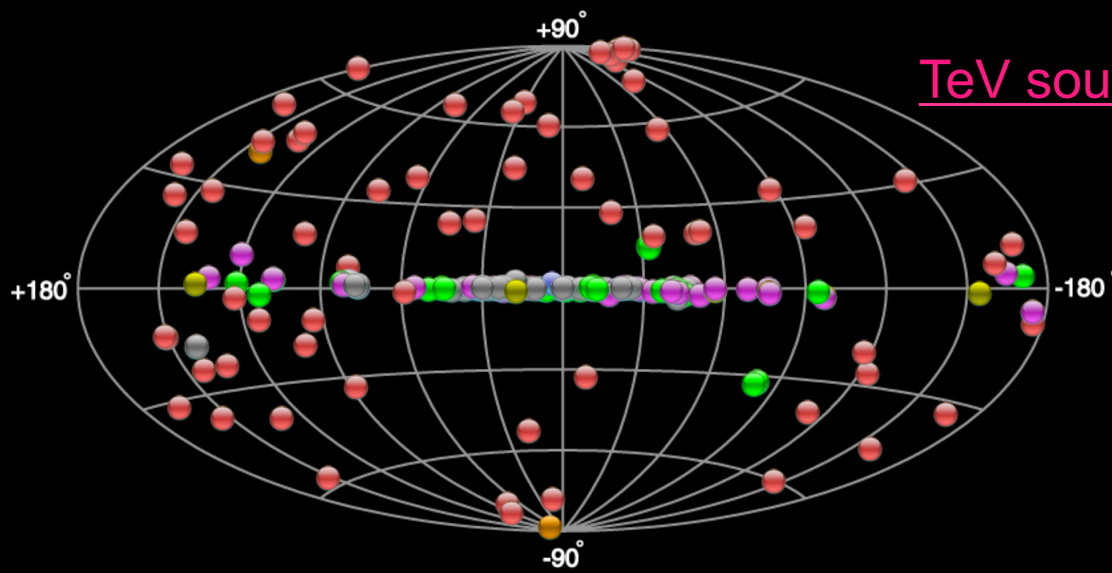


- Diffuse Backgrounds:
  - Cosmic-ray interactions with dust, gas and radiation fields

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

- Unresolved Sources

Astrophysical Backgrounds (TeV)



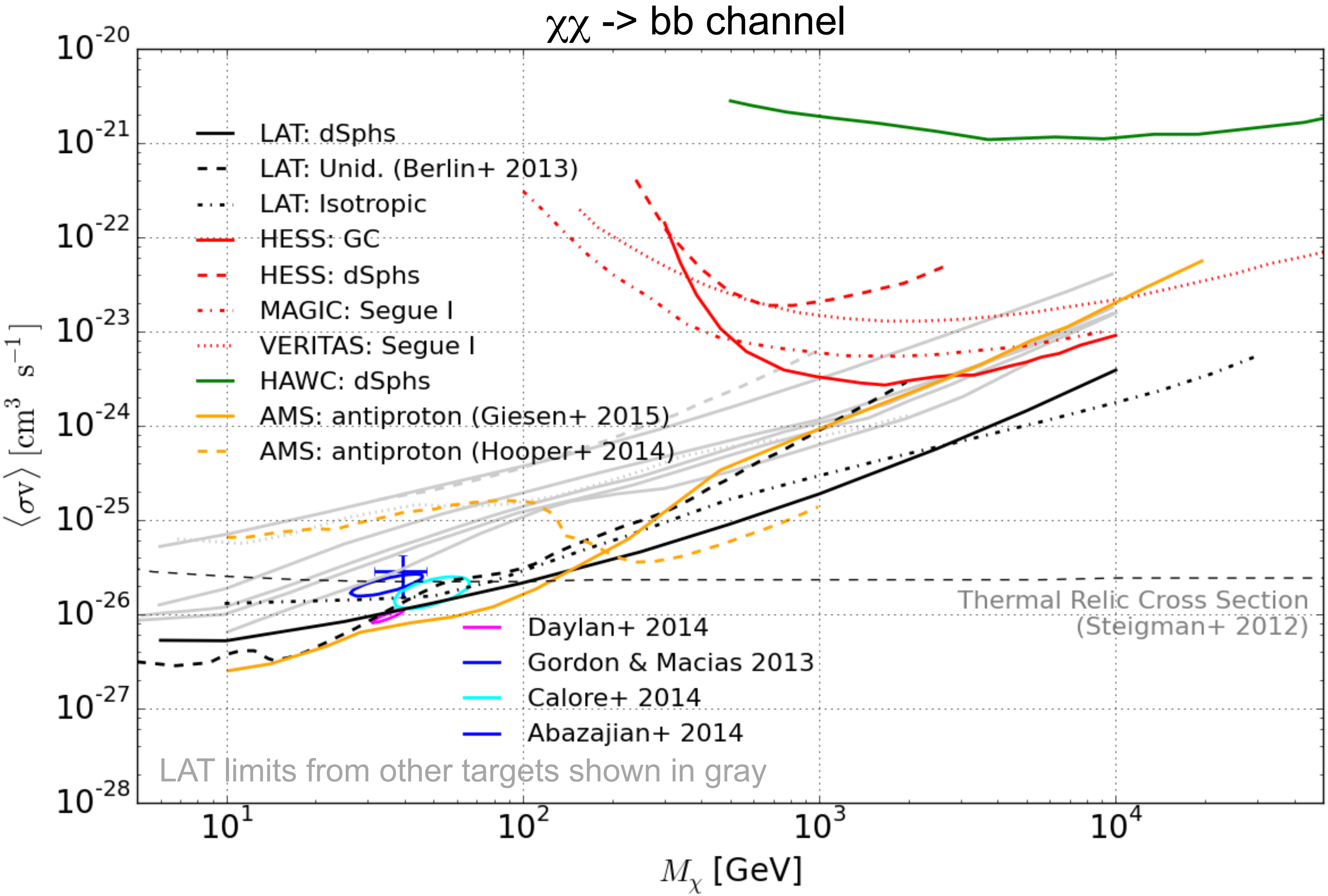
[TeV source catalog]

- Diffuse Backgrounds:
  - Cosmic-ray interactions with dust, gas and radiation fields
    - Diffuse spectra softer than typical source spectra

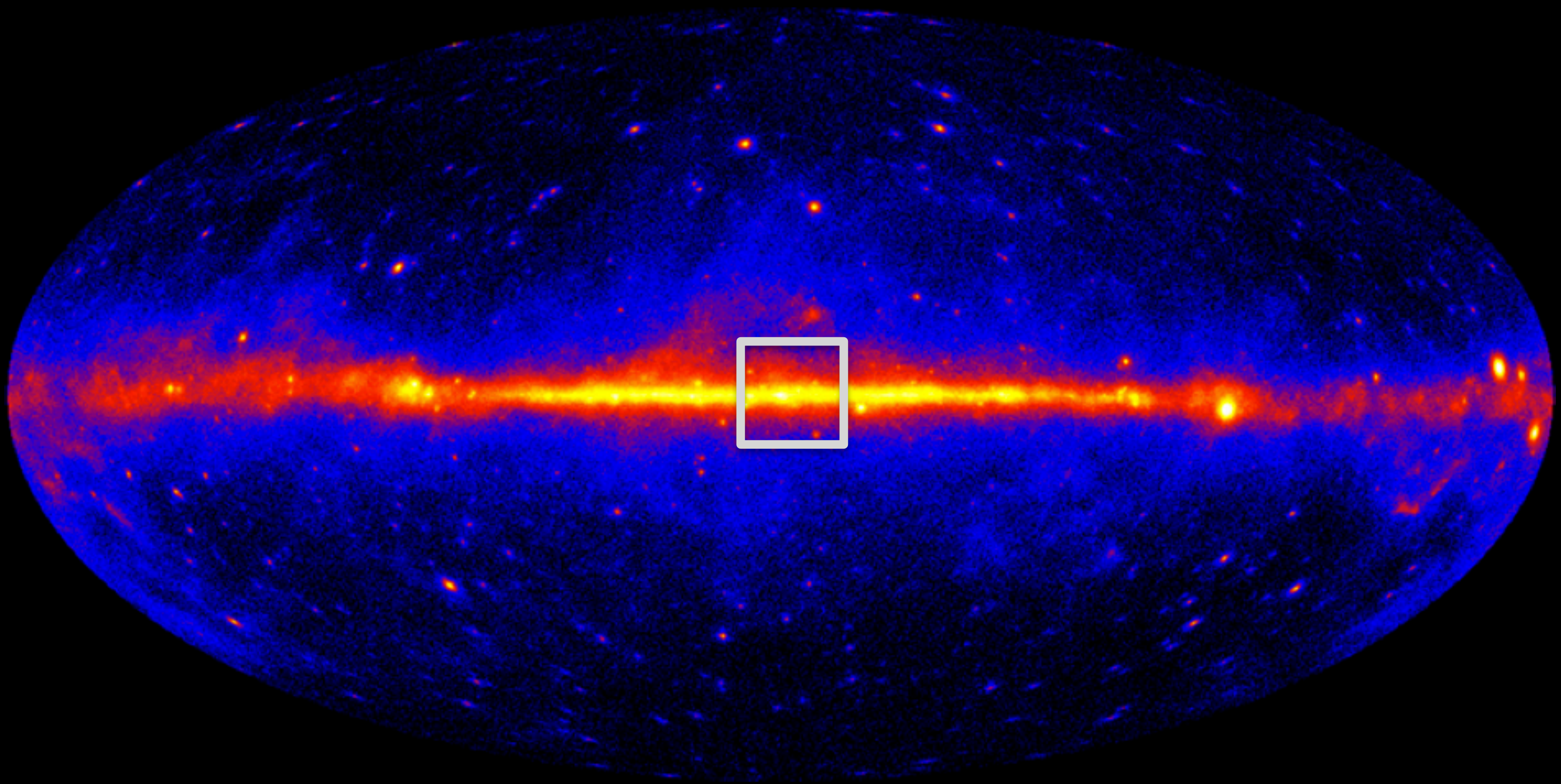
- Source Backgrounds:
  - Pulsars
  - Blazars and Active Galactic Nuclei (z < ~0.5)
  - Supernova Remnants
  - Galaxies (starburst galaxies)

- Unresolved Sources

A Sample of Published Results from Indirect DM Searches

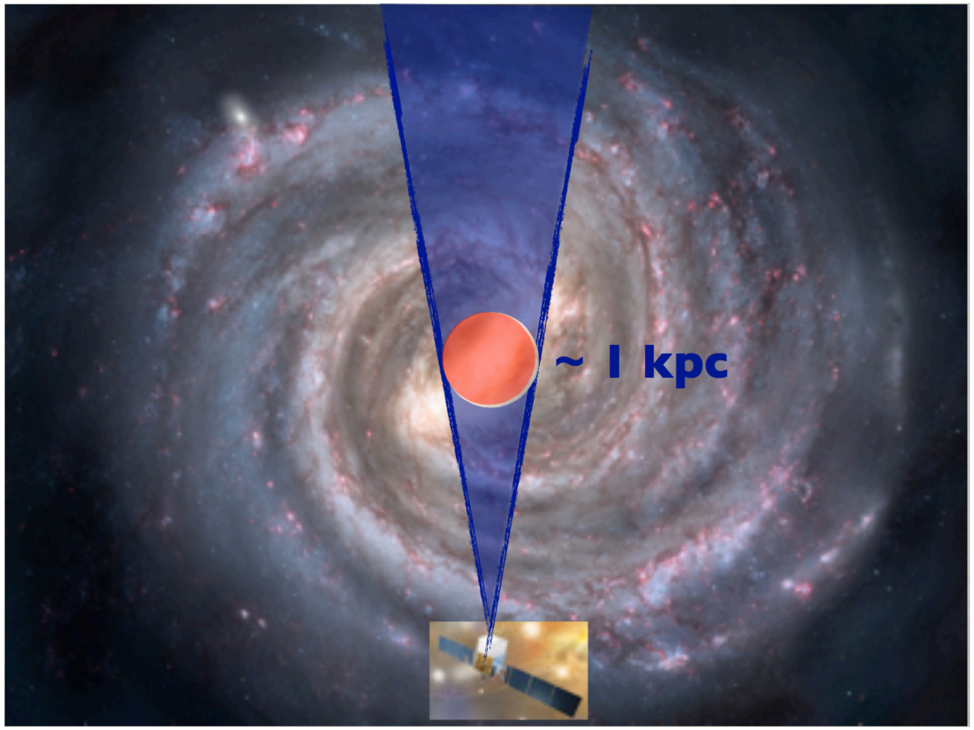


Search for DM in the Inner Galaxy

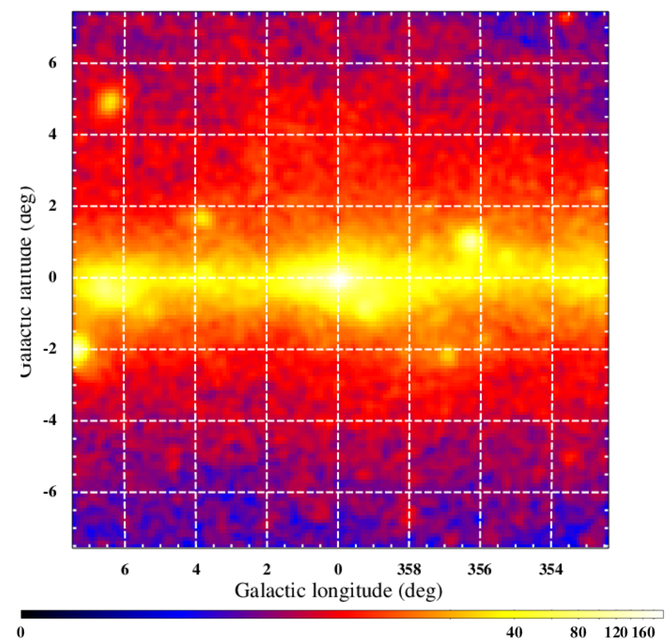


- The goal is to look for DM in the inner Galaxy
- Because of the large astrophysical foregrounds, we must first understand the γ-ray emission from the Galaxy and from known source classes

Observing the Galactic Center

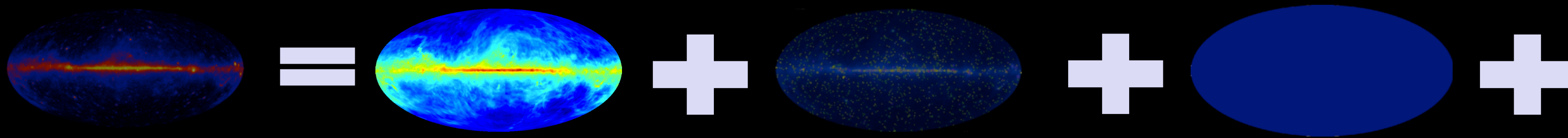


LAT Counts: 4 years, 1-100 GeV



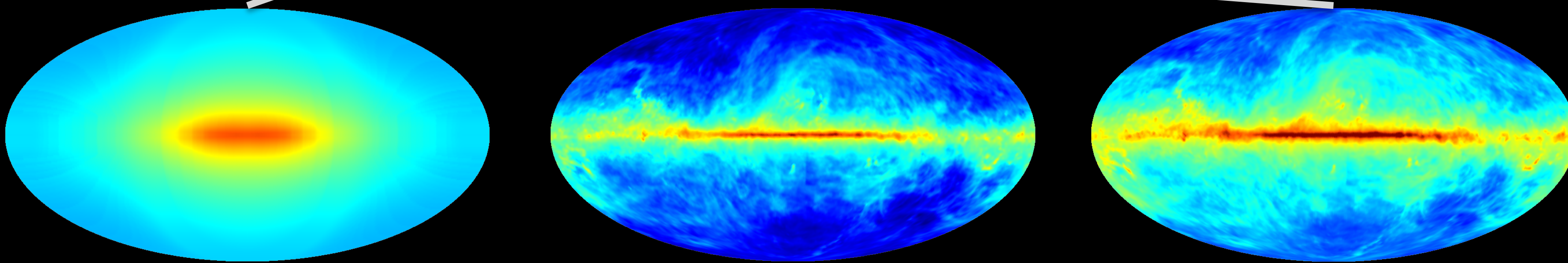
- Observations of the Galactic center include strong astrophysical foreground and backgrounds along the line-of-sight
  - In the 1-100 GeV energy band these account ~85% of the γ-rays in a 15°x15° box around the Galactic center

Analysis: Fitting the Astrophysical Diffuse Emission

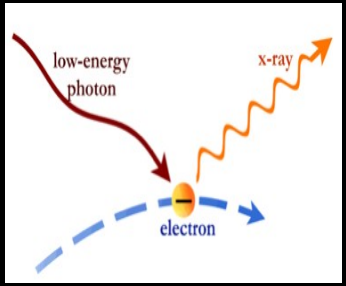


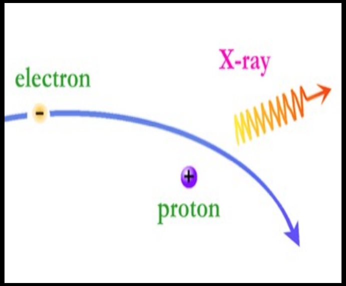
???

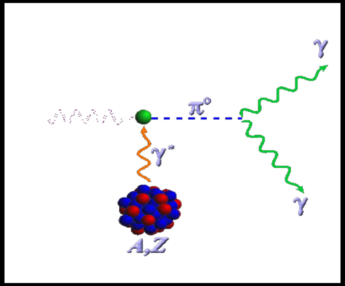
Galactic Point Sources Isotropic



Inverse Compton Bremsstrahlung π^0 decay

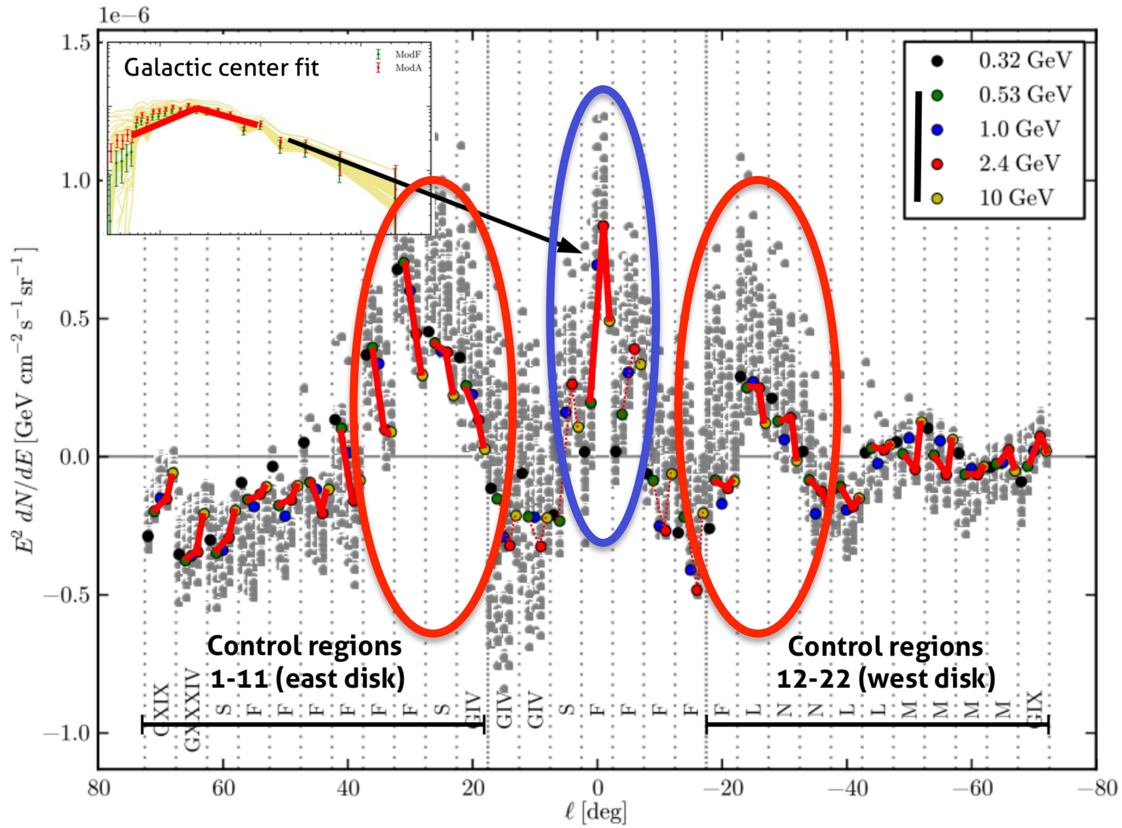






Estimating the astrophysical modeling uncertainties

Spectral Excesses w.r.t. Diffuse Emission Model in as a Function of Galactic Longitude

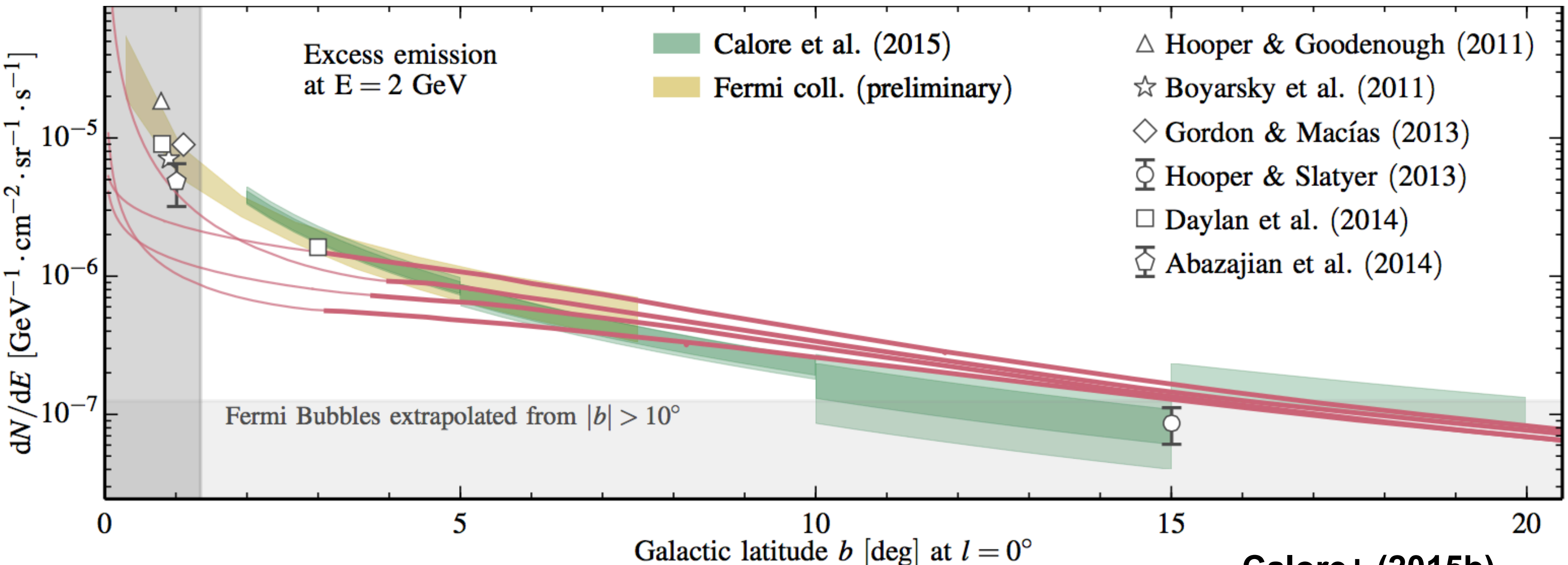


Calore+ (2015)
arXiv:1409.0042

- Excess emission w.r.t. standard diffuse emission models peaking around a few GeV near the Galactic center is well-established
- The interpretation of the excess is unclear (similar size excesses attributed to local sources of cosmic rays are present elsewhere)

Radial Profile of Galactic Center Excess

Radial profile of GC Excess (at 2 GeV) Compared to Predictions From N-Body Simulations

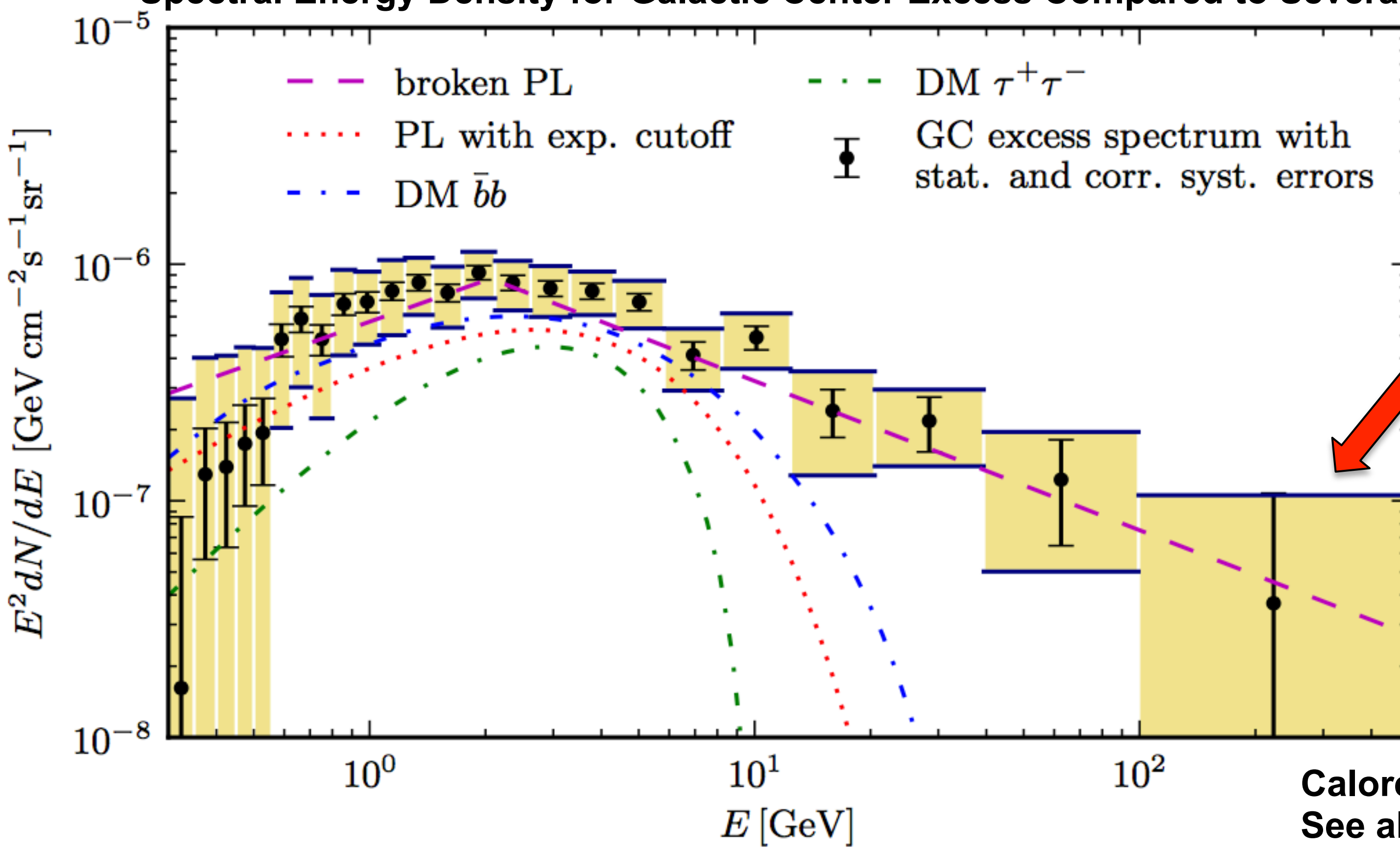


Calore+ (2015b)

- Many authors have noted that the radial profile is broadly consisted with dark matter expectations (red lines above)
- N-body simulations of Milky-Way like galaxies tend to show less DM signal in the inner few degrees than observations of the Galactic center (shaded regions)

Spectrum of the Galactic Center Excess

Spectral Energy Density for Galactic Center Excess Compared to Several Models



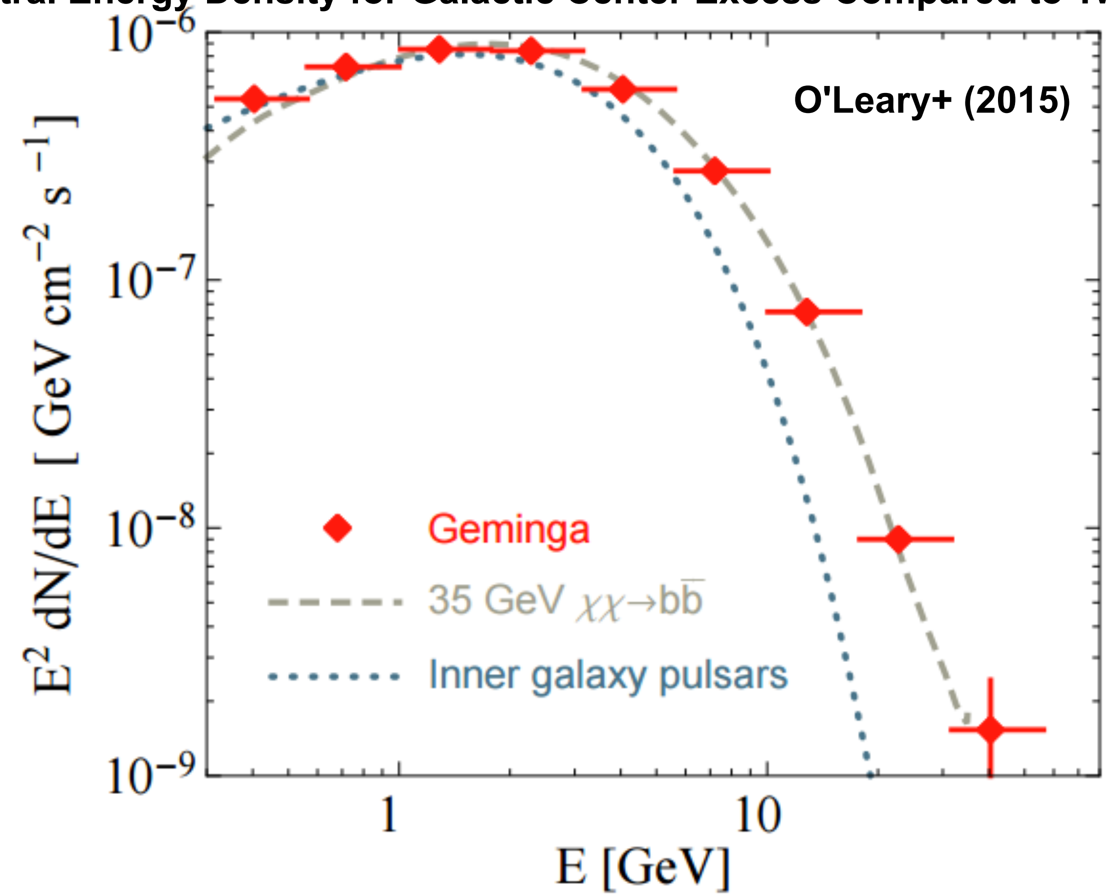
Emission above 50 GeV not from 50 GeV dark matter

Calore+ (2015)
See also Daylan+ (2014)

- The bin-to-bin error bars are highly correlated b/c of the modeling of the diffuse Galactic foregrounds
  - For example, the broken PL fit is only favored over DM $\tau^+\tau^-$ by 2-3σ

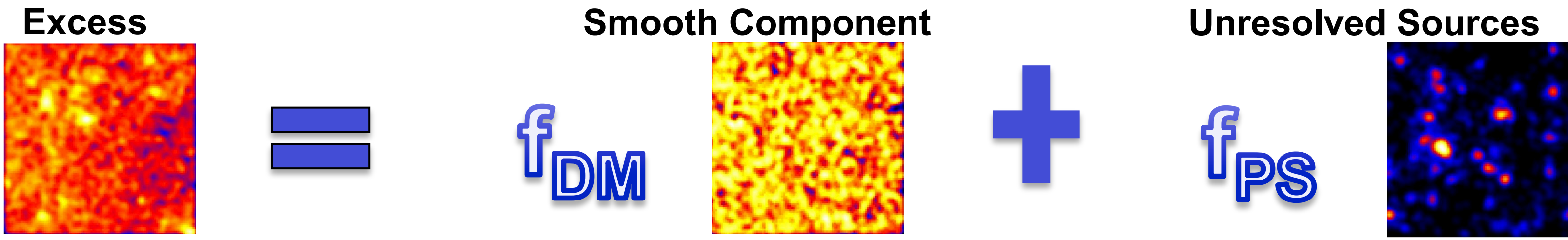
Signal Degeneracy with Pulsars

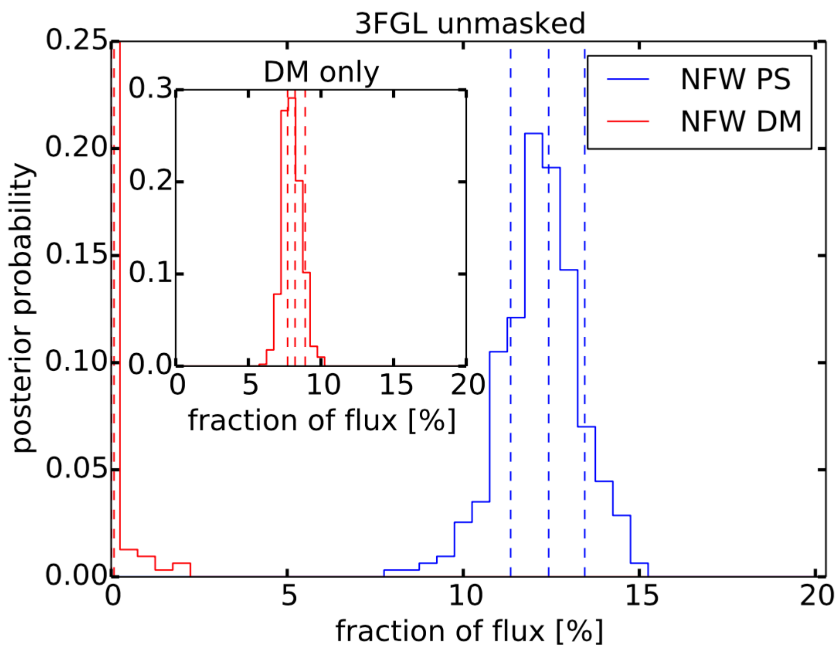
Spectral Energy Density for Galactic Center Excess Compared to Two Pulsar Models



- Many authors have pointed out that the γ-ray spectra for pulsars are very similar to the spectra for low-mass dark matter
- GC excess may be attributable to population of unresolved pulsars

Resolving the Pulsar / Dark Matter Degeneracy

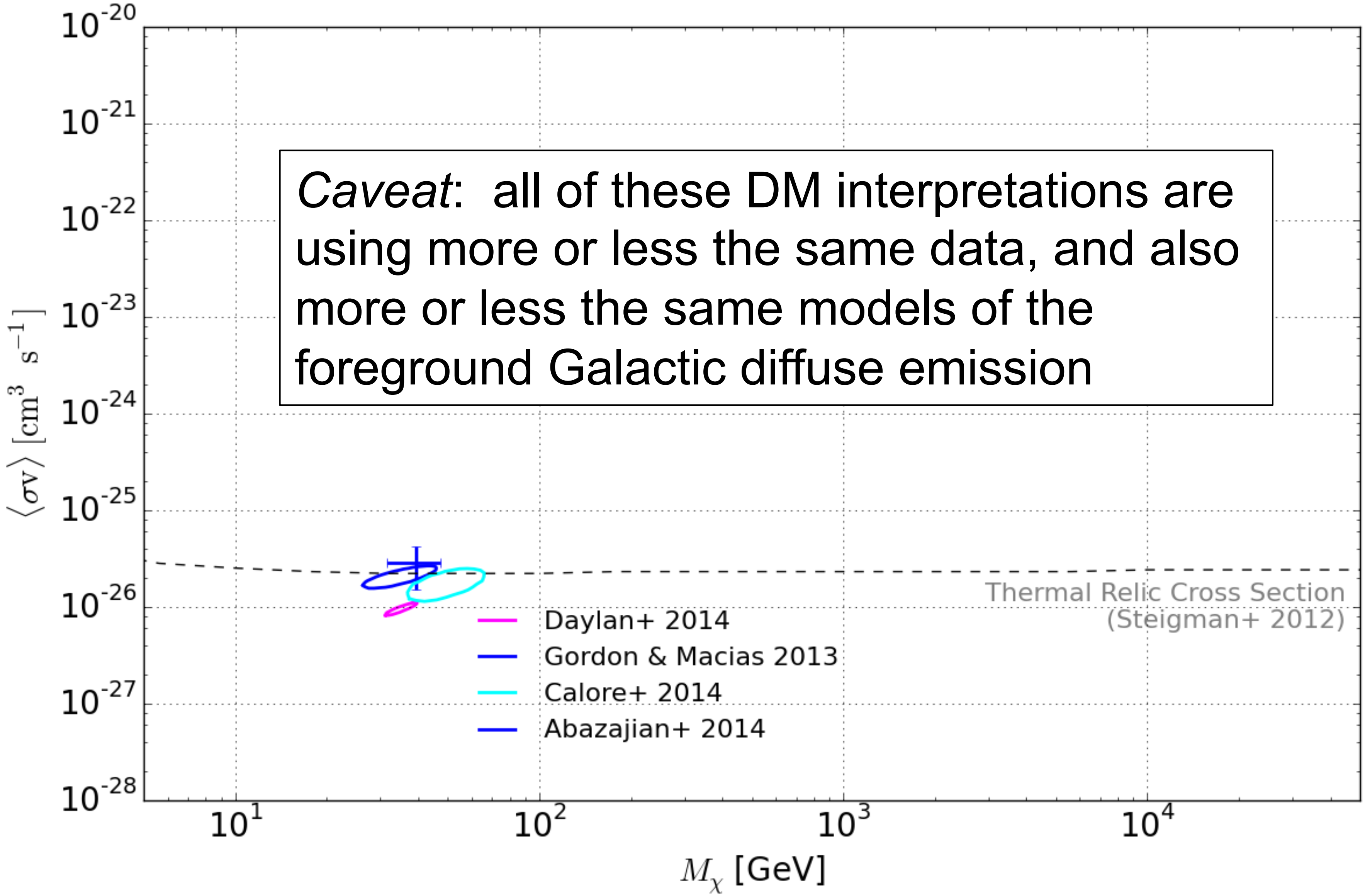




Lee+ (2015)
See also
Cholis+ (2015)
Bartels+ (2015) & others

- Several authors have performed statistical analyses of fluctuations near the Galactic center to disentangle the pulsar / DM degeneracy
- Claim that data favor population of unresolved point sources

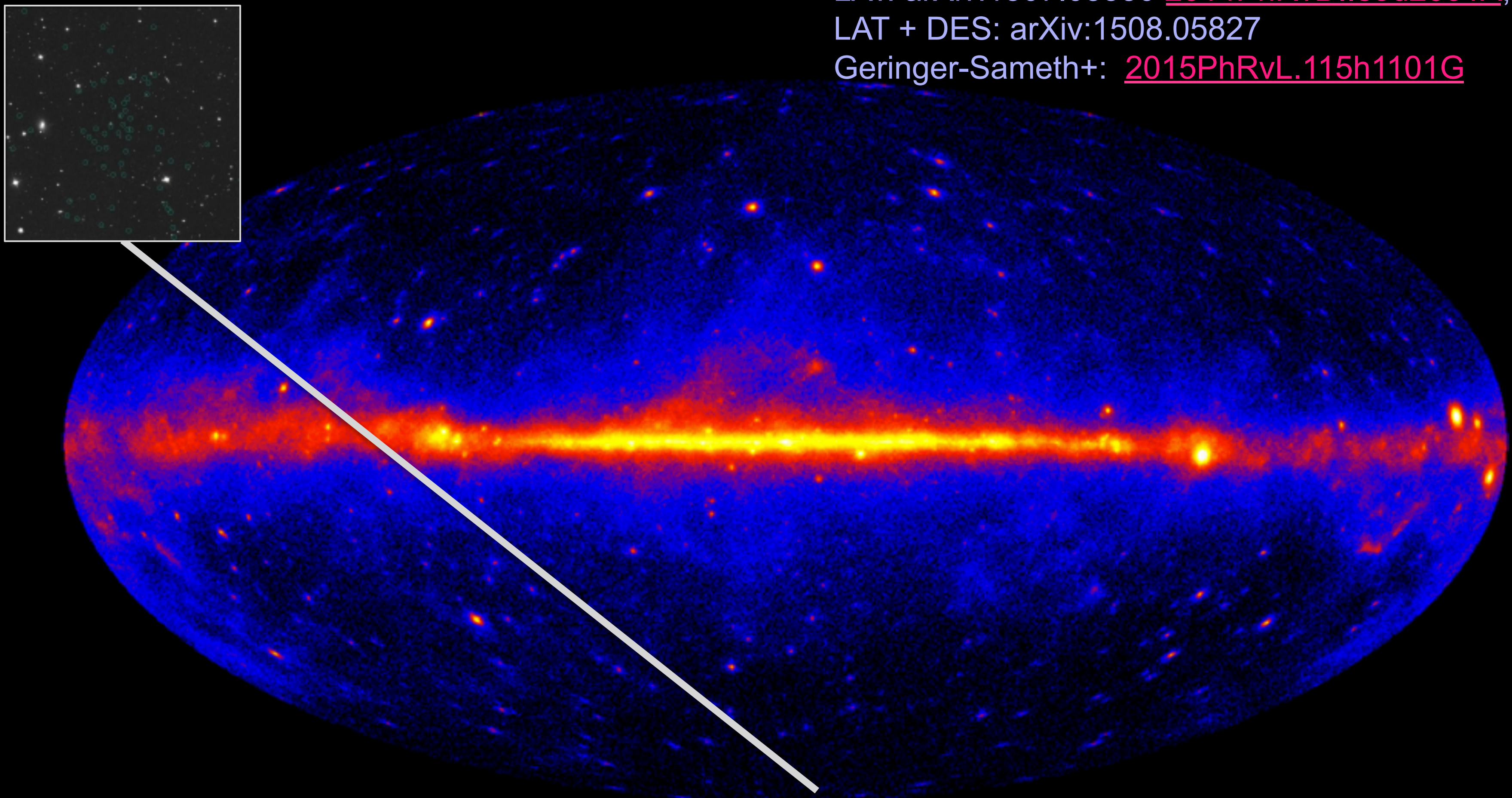
Dark Matter Interpretations of GC Excess



Searches for DM in Dwarf Spheroidal Galaxies

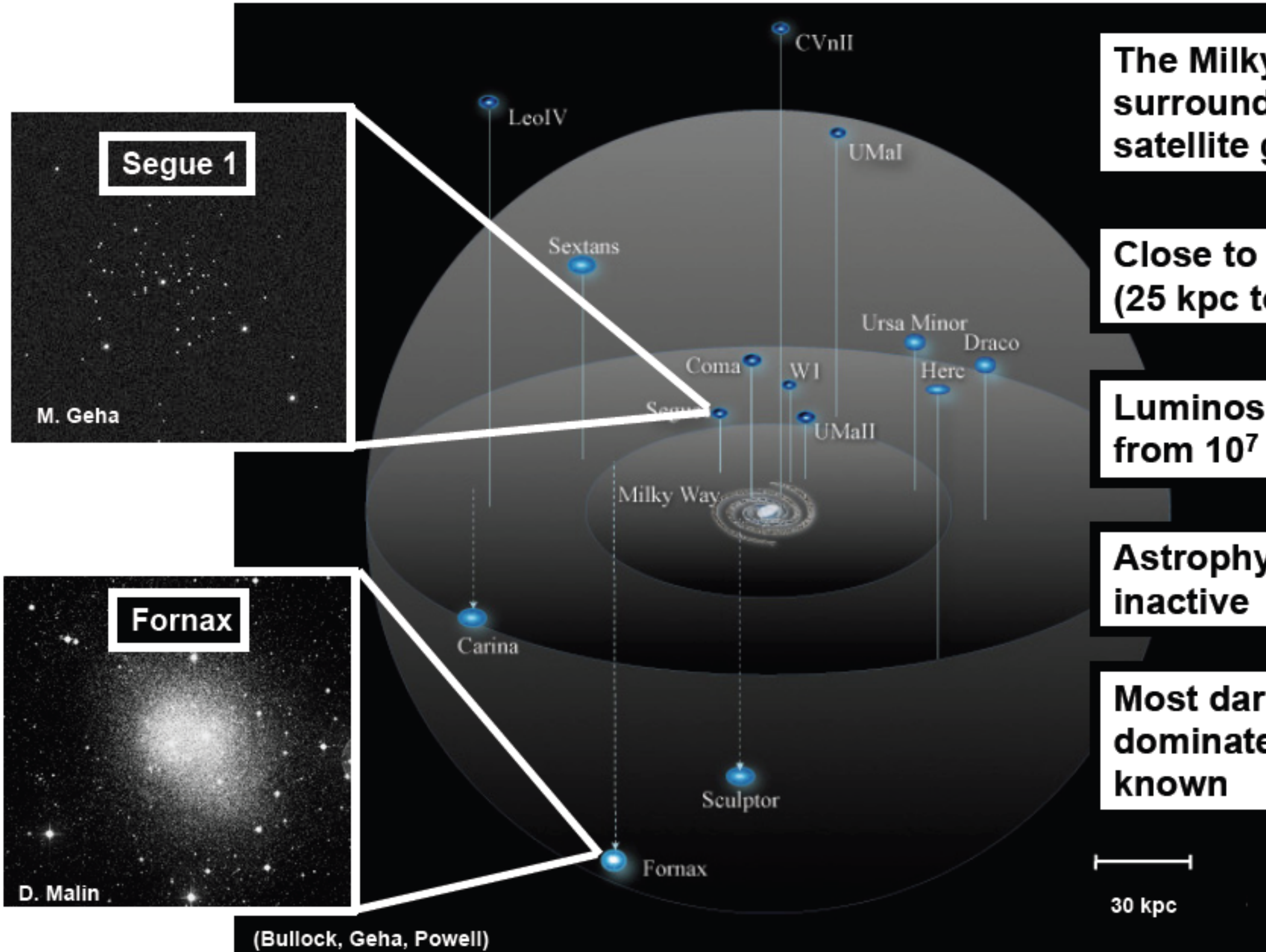
Segue 1
Keck Observatory

Recent papers
LAT: arXiv:1507.03530 2014PhRvD..89d2001A,
LAT + DES: arXiv:1508.05827
Geringer-Sameth+: 2015PhRvL.115h1101G



- Look for γ-ray emission from Dwarf spheroidal galaxies with large, well measured, J-factors at high Galactic latitudes
- This is a low-signal, low-background search strategy

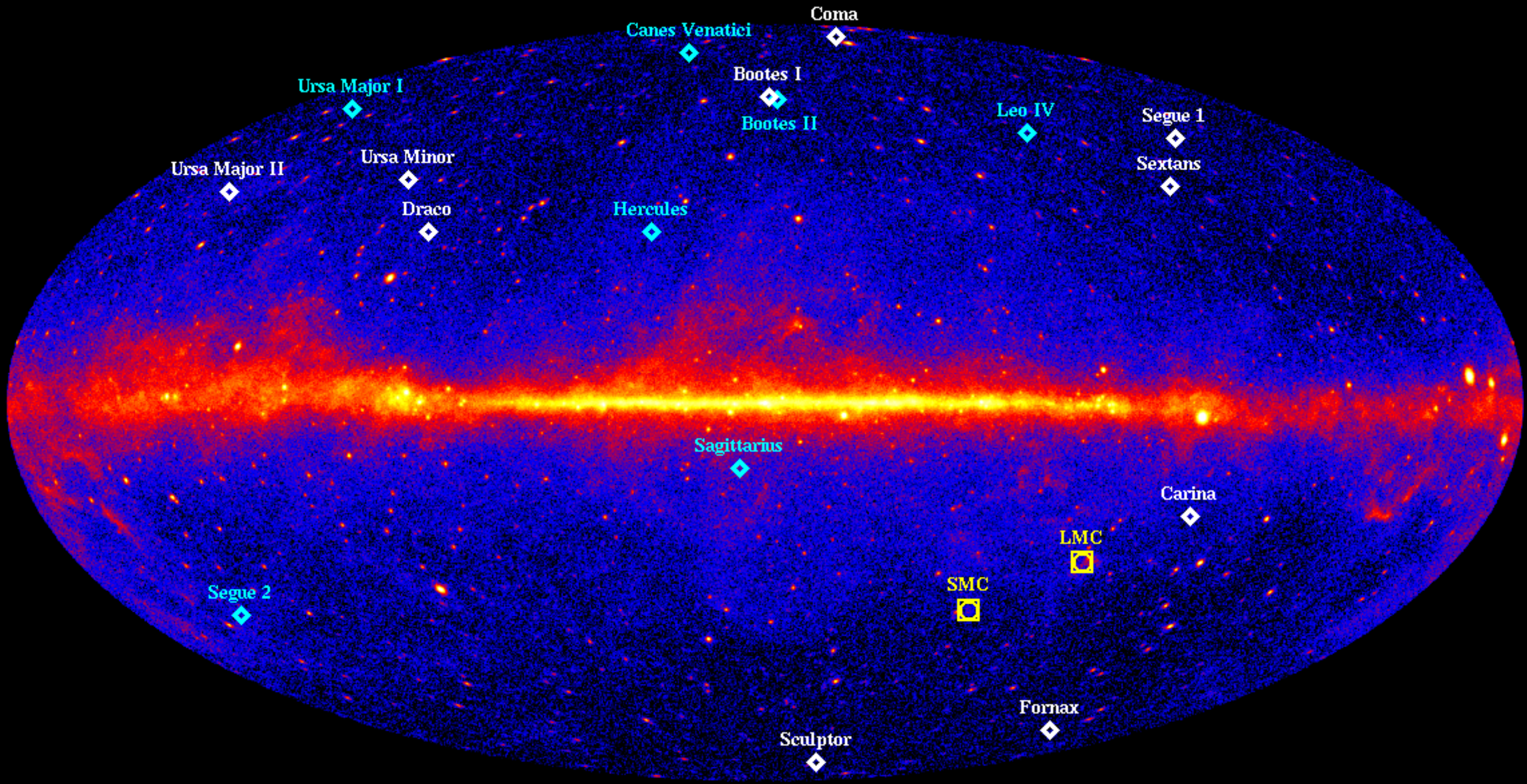
Searches for DM in Dwarf Spheroidal Galaxies



(Bullock, Geha, Powell)

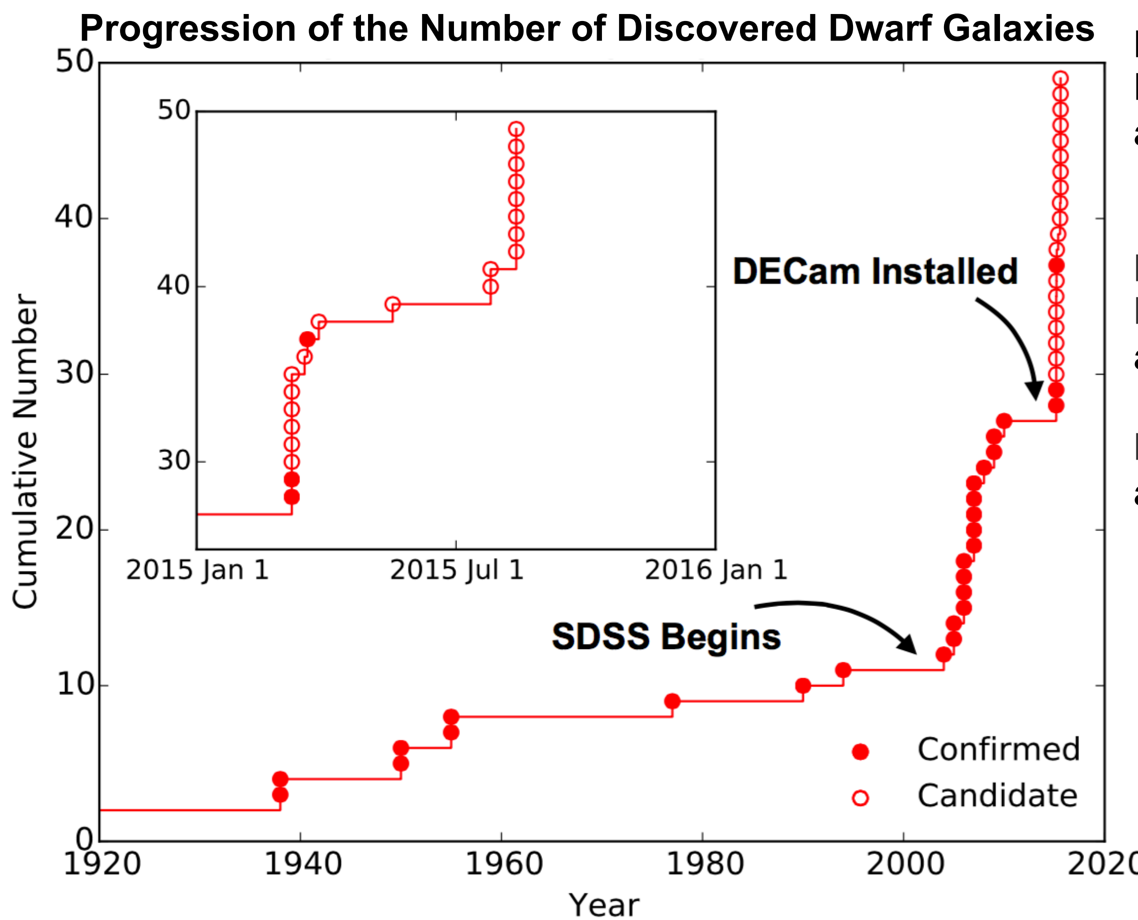
- The Milky Way is surrounded by small satellite galaxies
- Close to Earth (25 kpc to 250 kpc)
- Luminosities range from $10^7\ L_\odot$ to $10^3\ L_\odot$
- Astrophysically inactive
- Most dark matter dominated objects known

Searches for DM in Dwarf Spheroidal Galaxies



- Roughly two dozen Dwarf spheroidal satellite galaxies of the Milky Way
- Some of the most dark matter dominated objects in the Universe
- Negligable astrophysical γ-ray production expected

Growing Number of Known Dwarf Galaxies



DES Year 2 Data: Drlica-Wagner+, arXiv:1508.03622

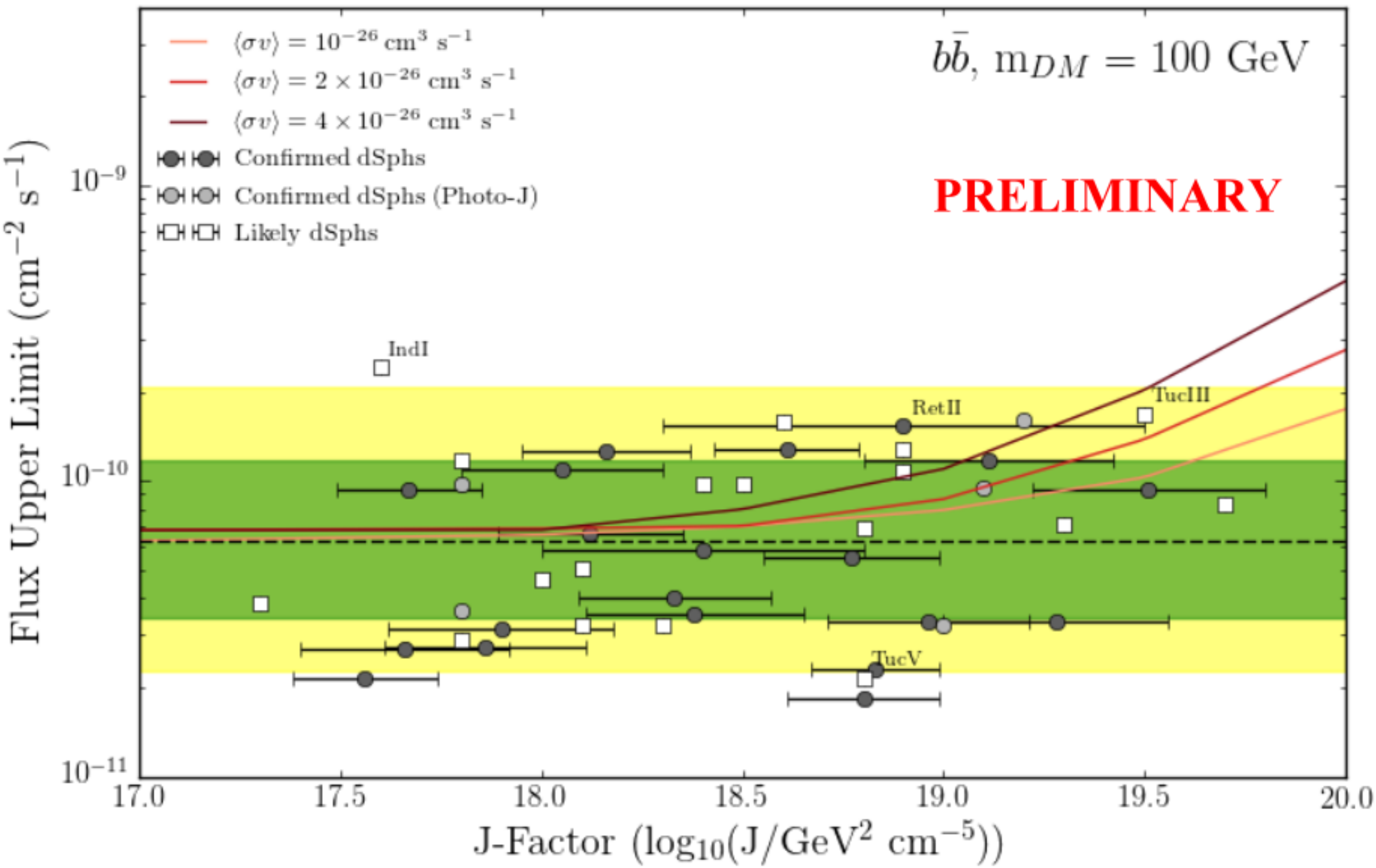
DES Year 1 Data: Bechtol+: arXiv:1503.02584

Koposov+: arXiv:1503.02079

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

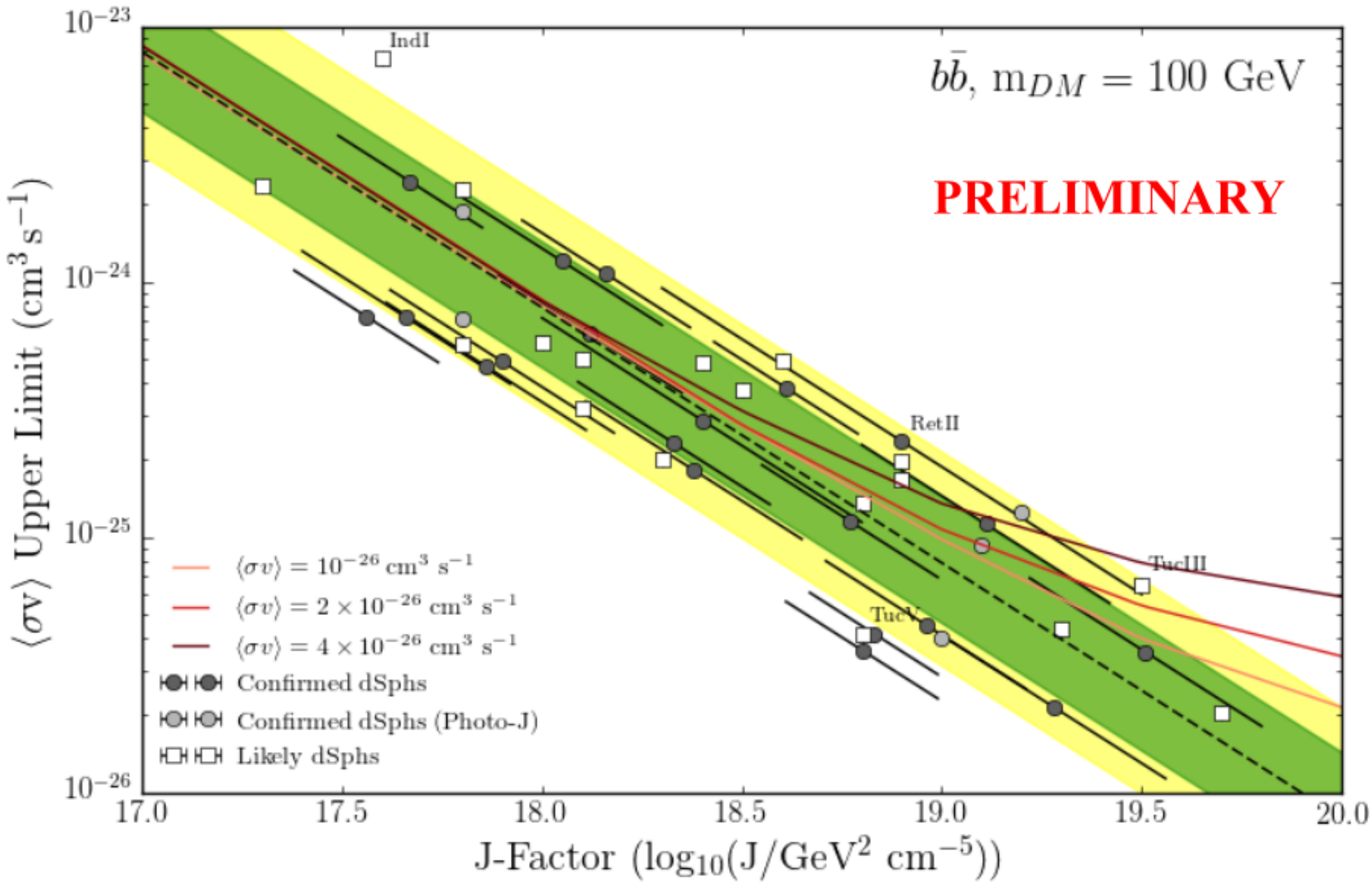
Flux Upper Limits From Dwarf Galaxies

Flux Upper Limit v. J-Factor for several Dwarf Galaxies

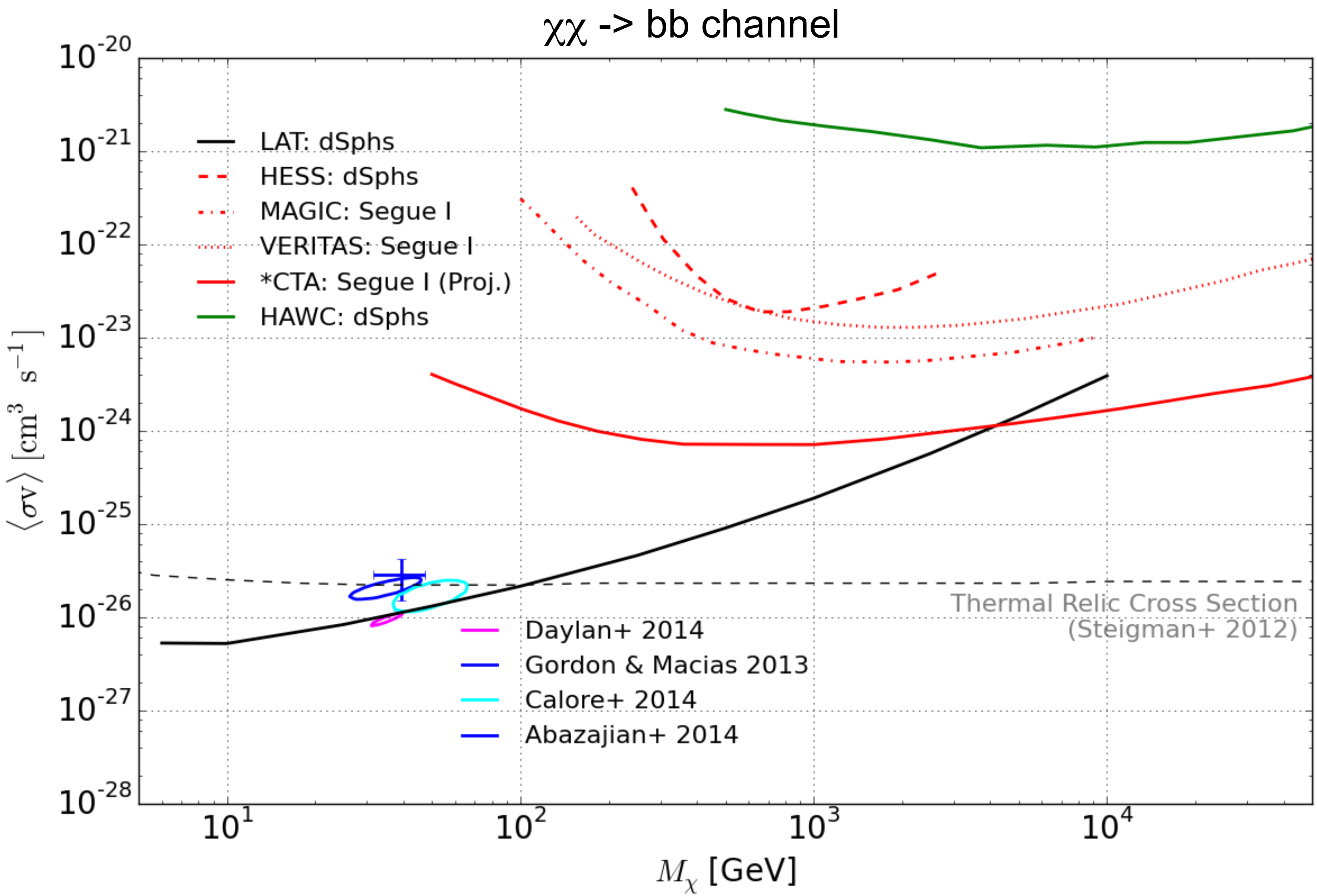


<σv> Upper Limits From Dwarf Galaxies

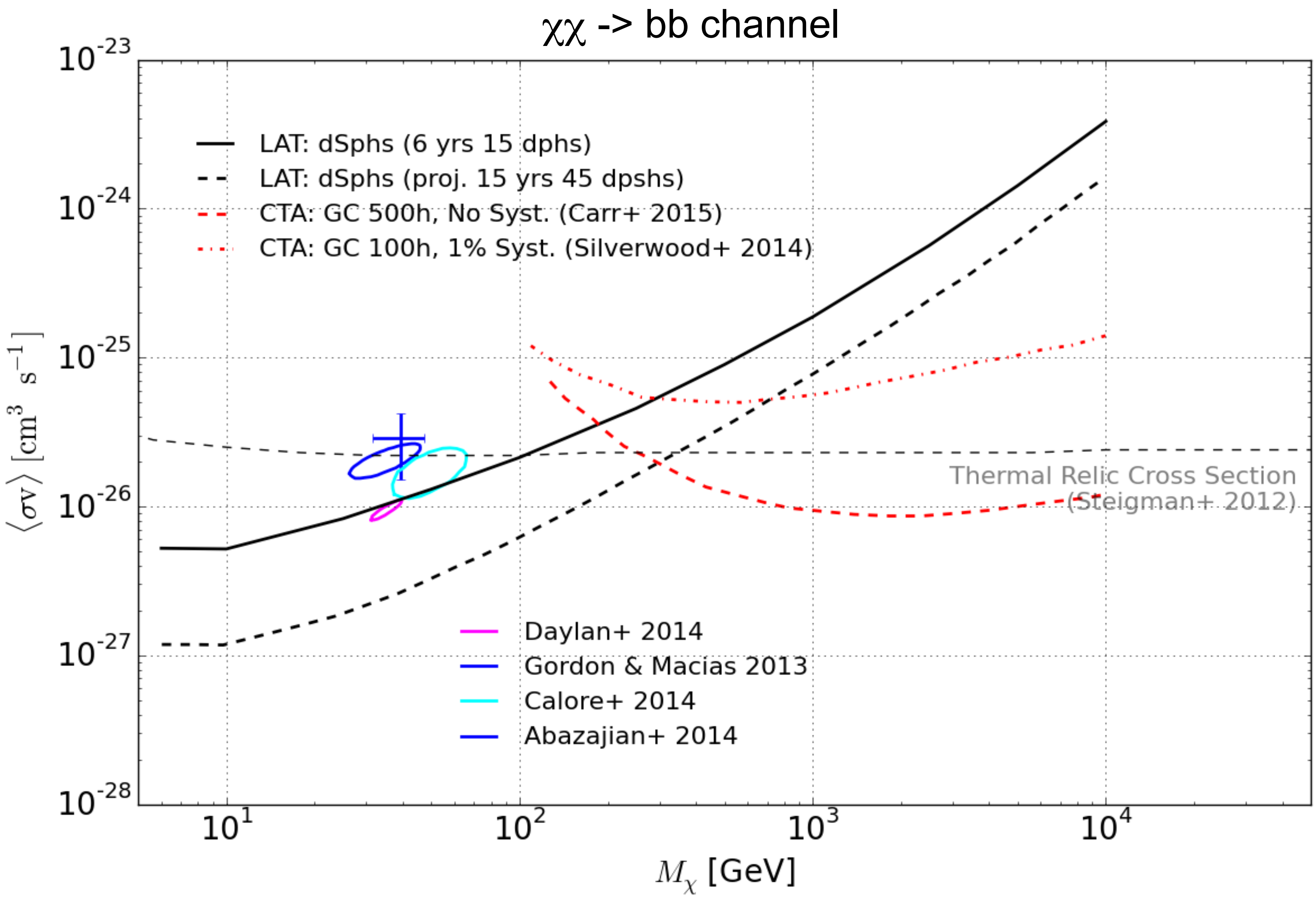
<σv> Upper Limit v. J-Factor for Several Dwarf Galaxies



Published* Upper Limits from Dwarf Galaxies

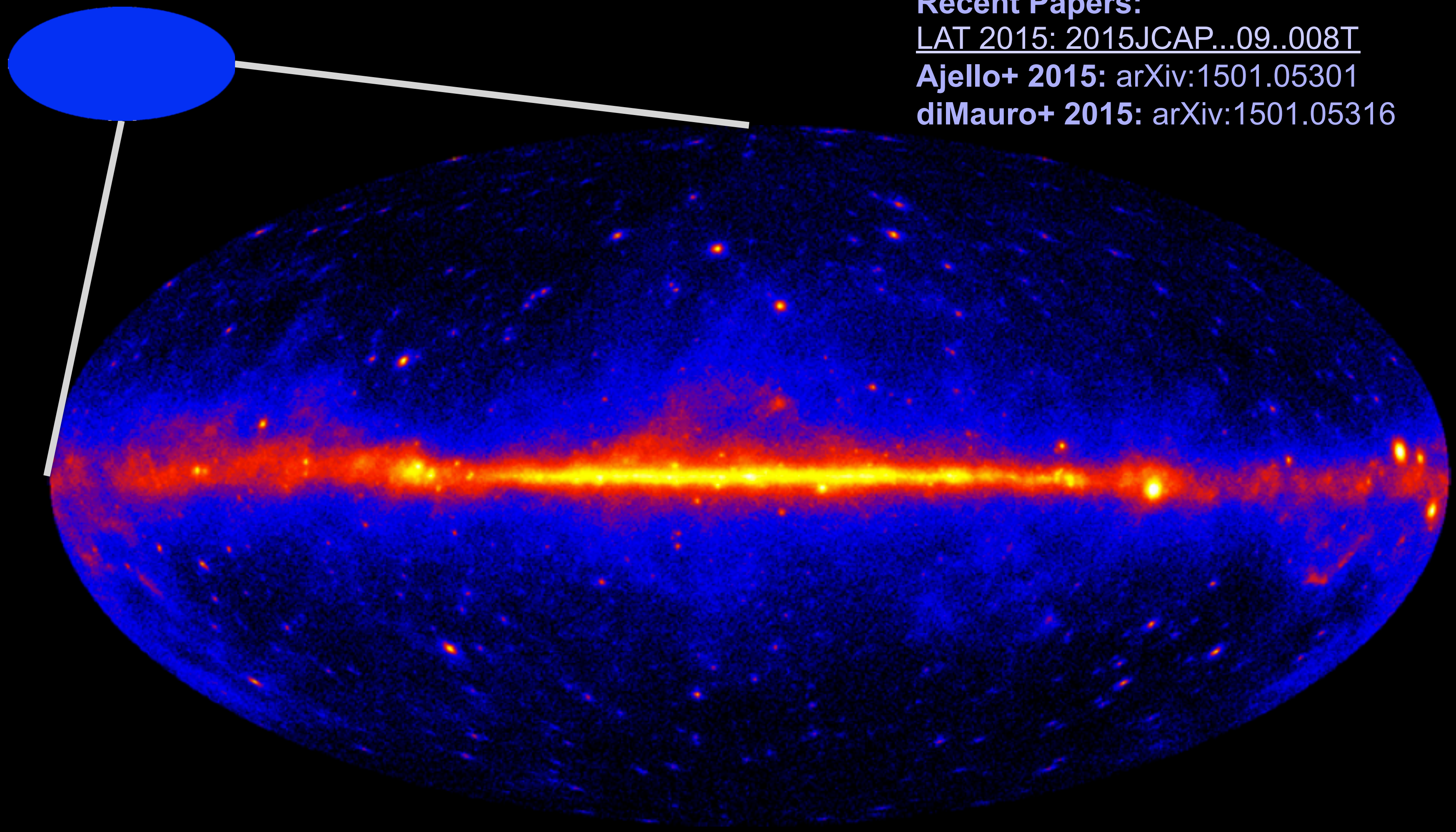


Projected Upper Limits From LAT + CTA



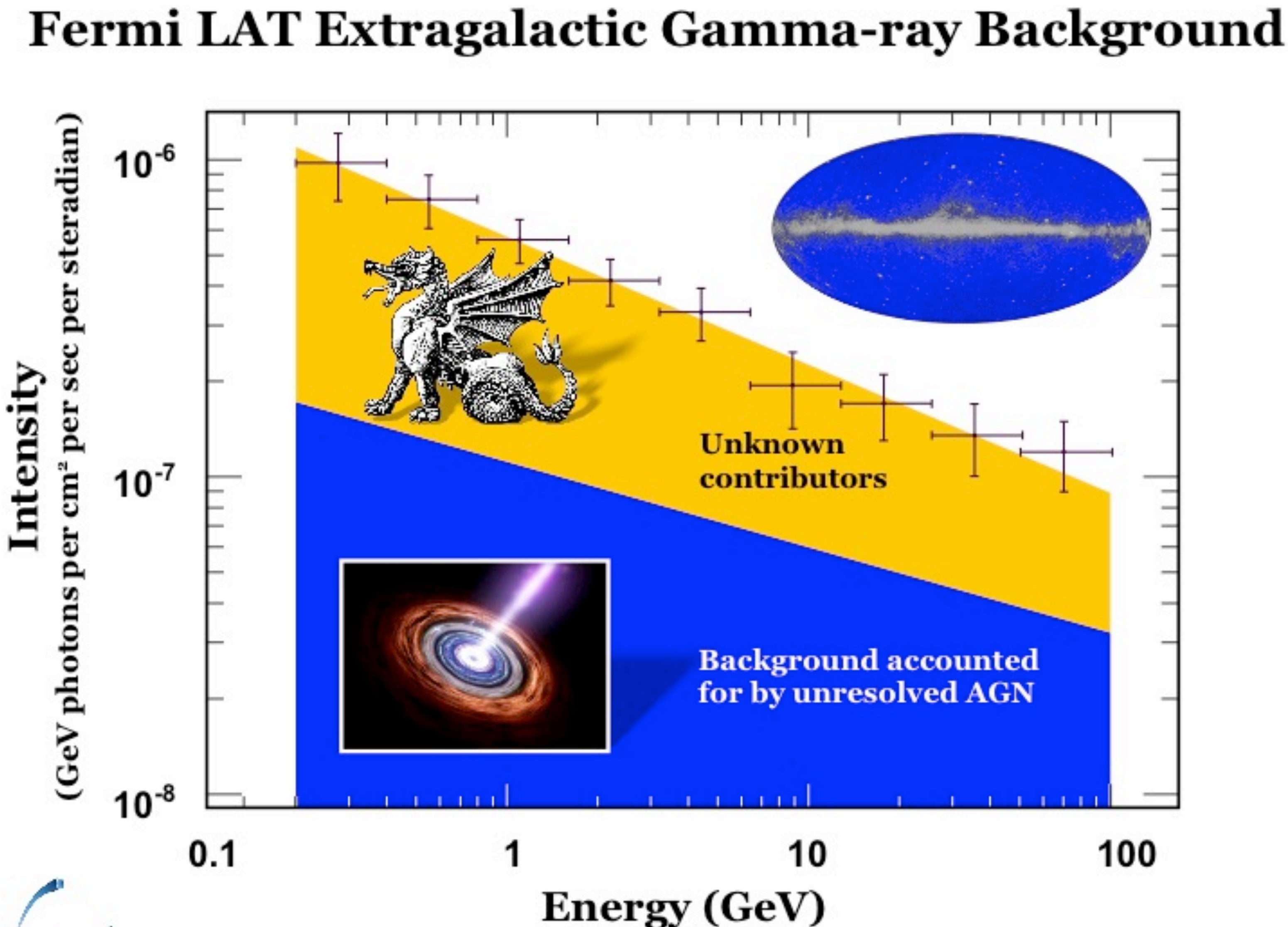
DM Contributions to the "Isotropic" Background

Recent Papers:
LAT 2015: 2015JCAP...09..008T
Ajello+ 2015: arXiv:1501.05301
diMauro+ 2015: arXiv:1501.05316



- Look for signatures of dark matter in the Isotropic background
- This requires good knowledge of all the astrophysical foregrounds

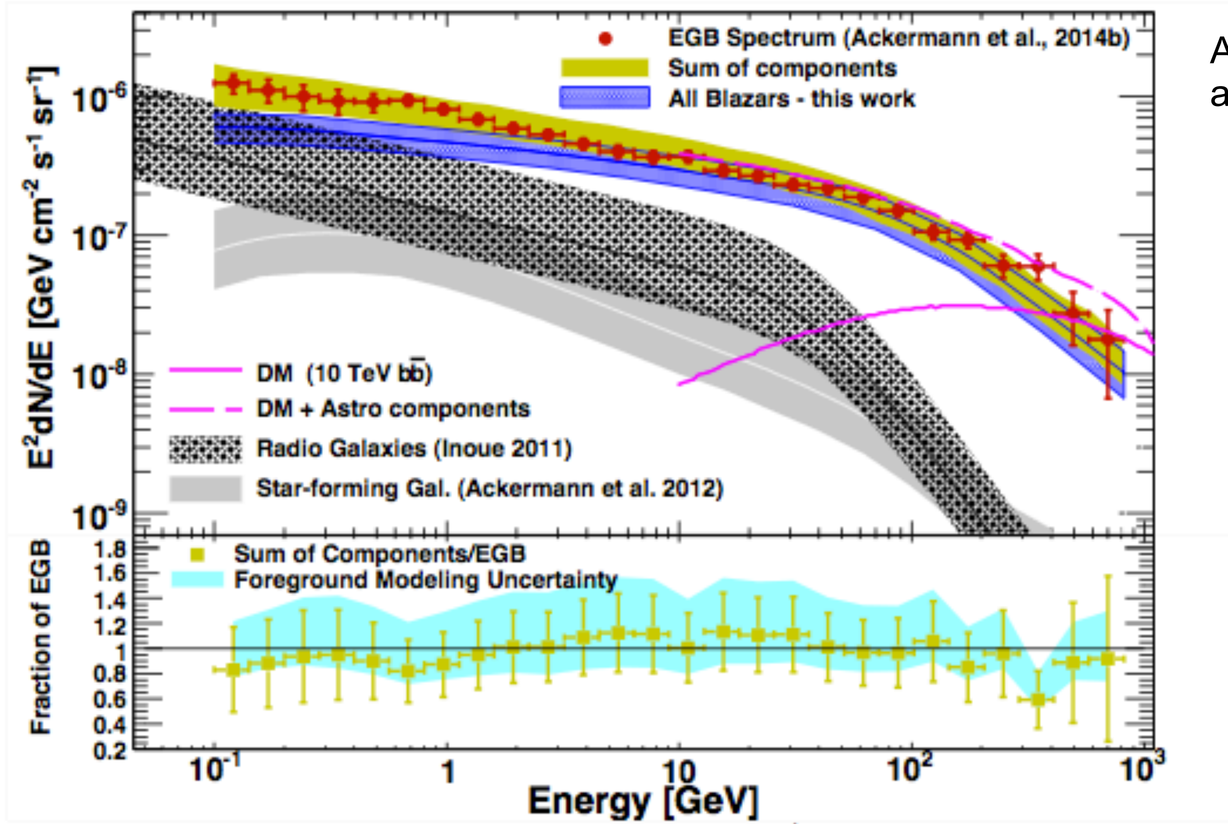
hic sunt dracones



Results are schematic only

Dark Matter Contributions to the Extragalactic Background

Comparison of Extragalactic Gamma-ray Background to Contributions from Sources

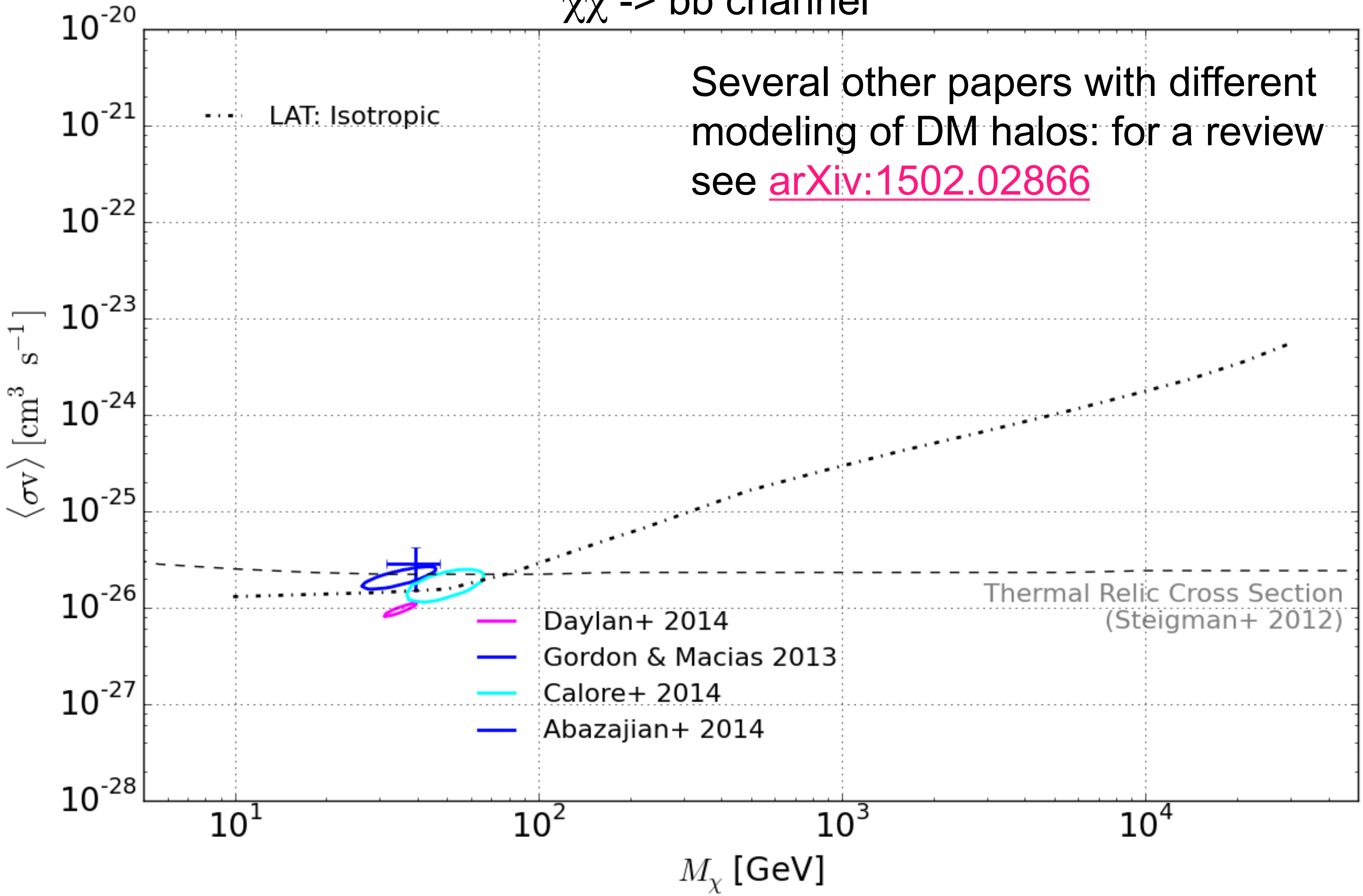


Ajello+
arXiv:1501.05301

- Estimating the contribution from unresolved sources requires fitting the cumulative luminosity function N(Flux > Threshold) as a function of the threshold (log N – log S in astronomy parlance)
- Good knowledge of the log N –log S can also constrain the DM emission from local DM halos

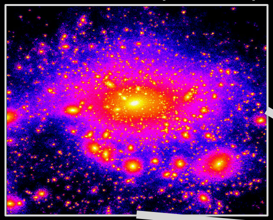
Typical Limit from Cosmological Halos and Galactic Sub-Halos

χχ -> bb channel

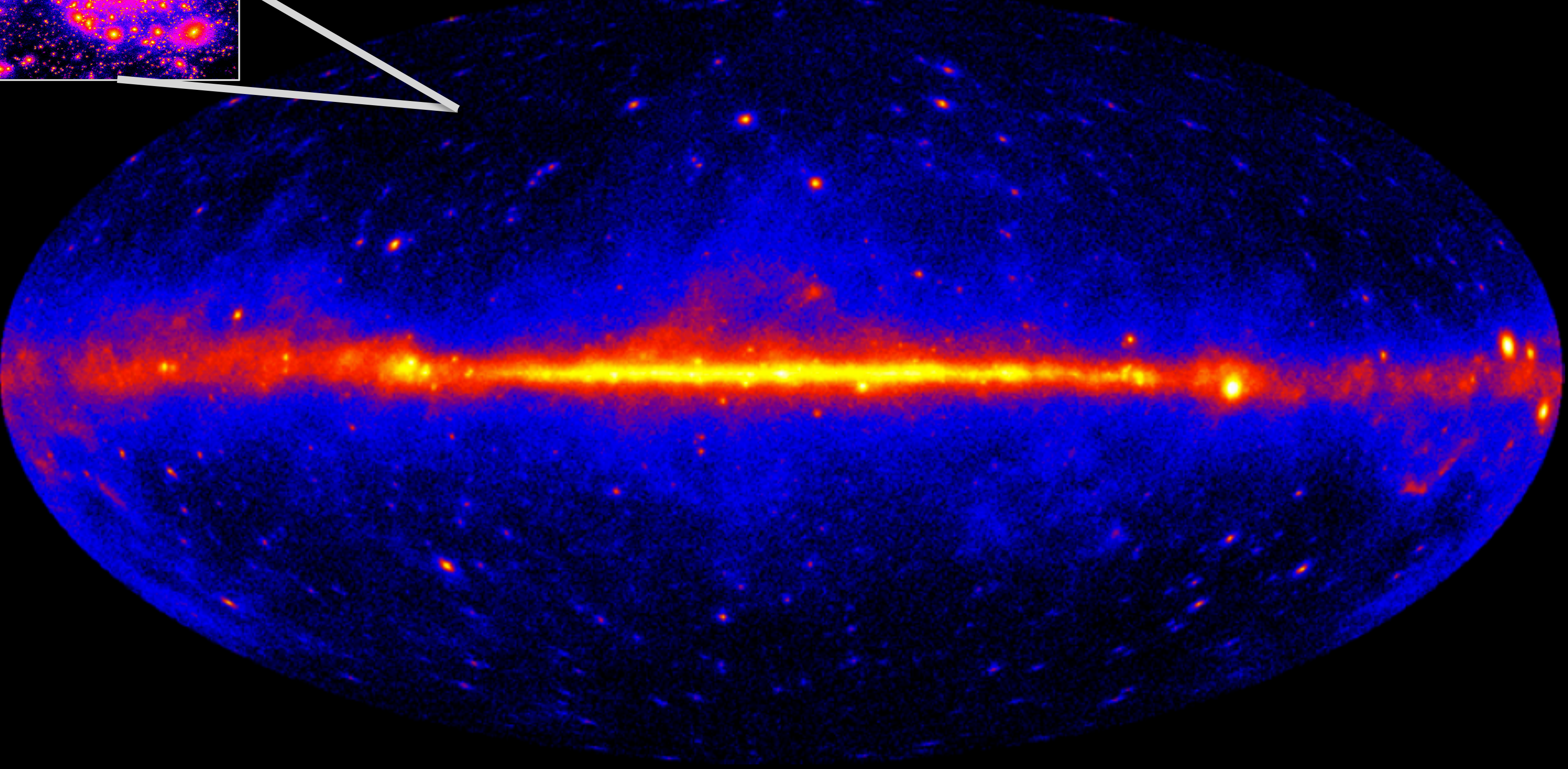


Searches for DM Satellites in Unid. LAT Sources

Simulated DM Satellite
Kazantzidis (2007)

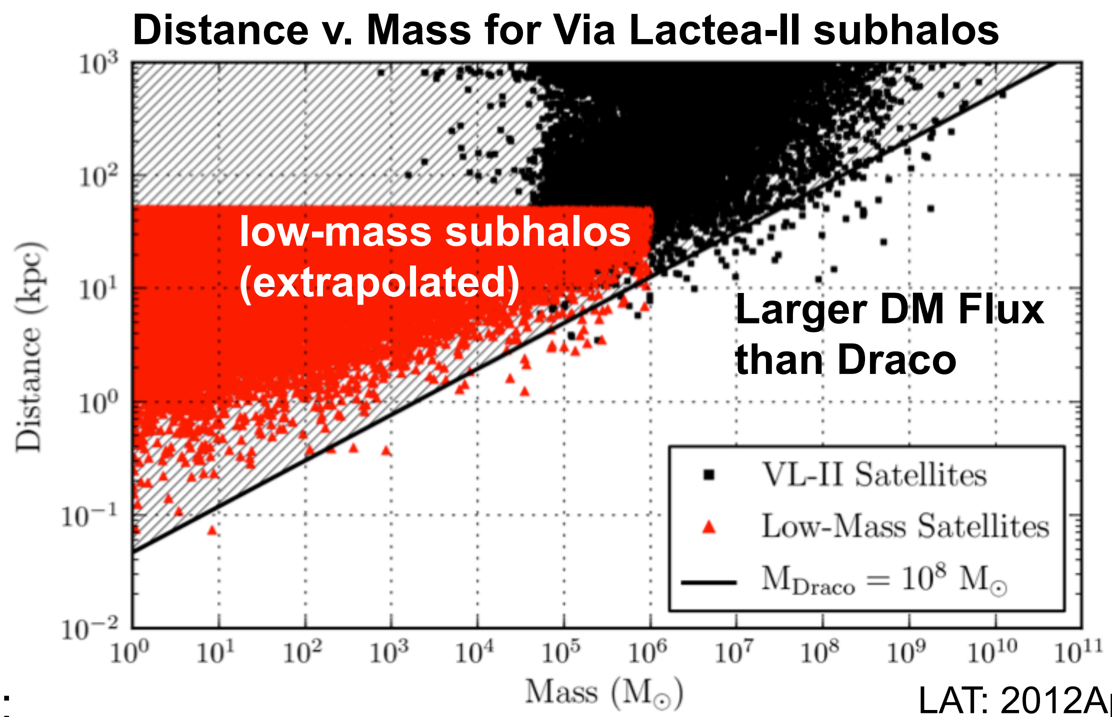


Recent Papers:
Berlin+ 2013 arXiv:1508.05390
Bertoni+ 2015 arXiv:1504.02087



- Look for population of LAT catalog sources that are consistent with DM signatures and inconsistent with known astrophysical source classes

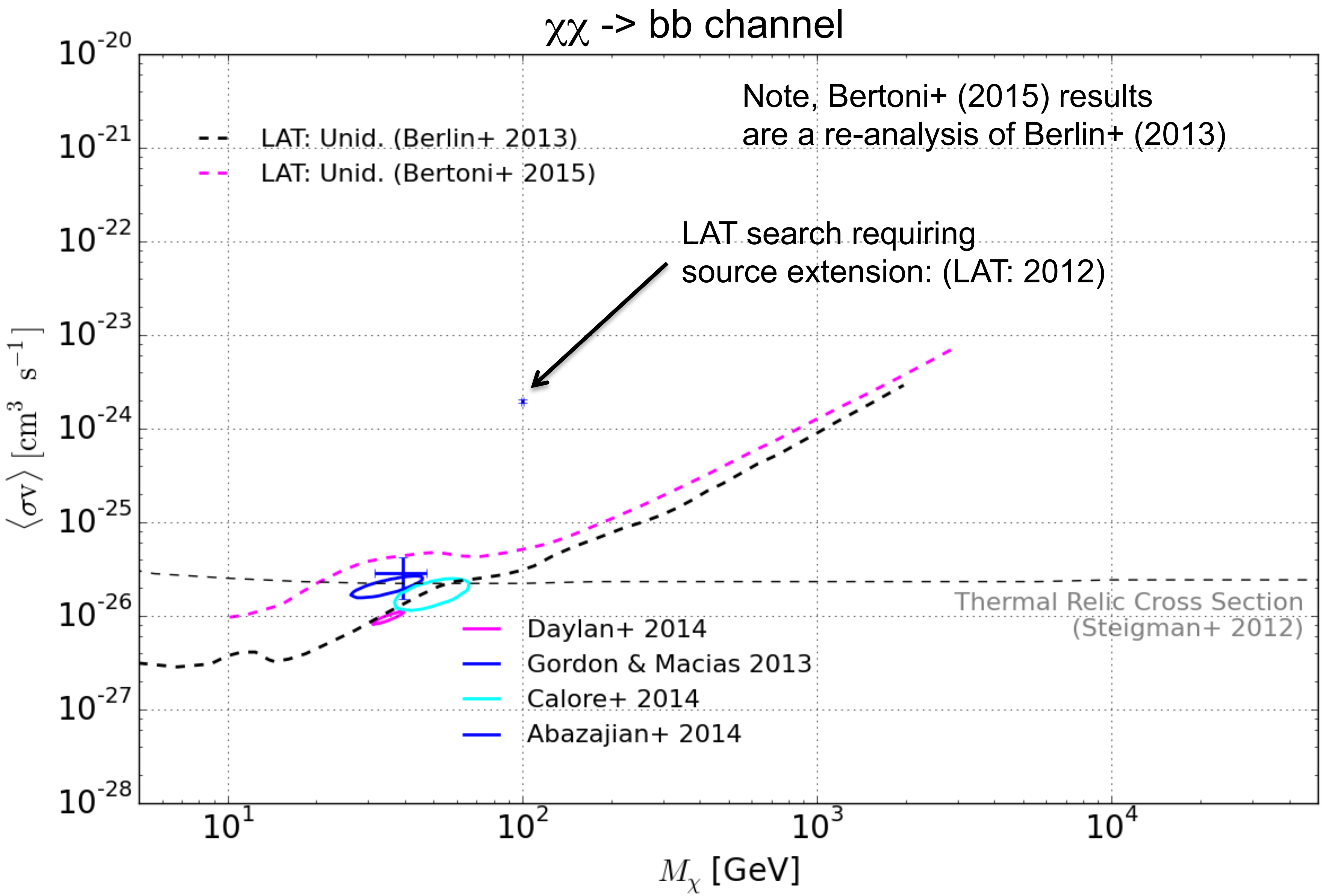
Searches for DM Satellites in Unid. LAT Sources



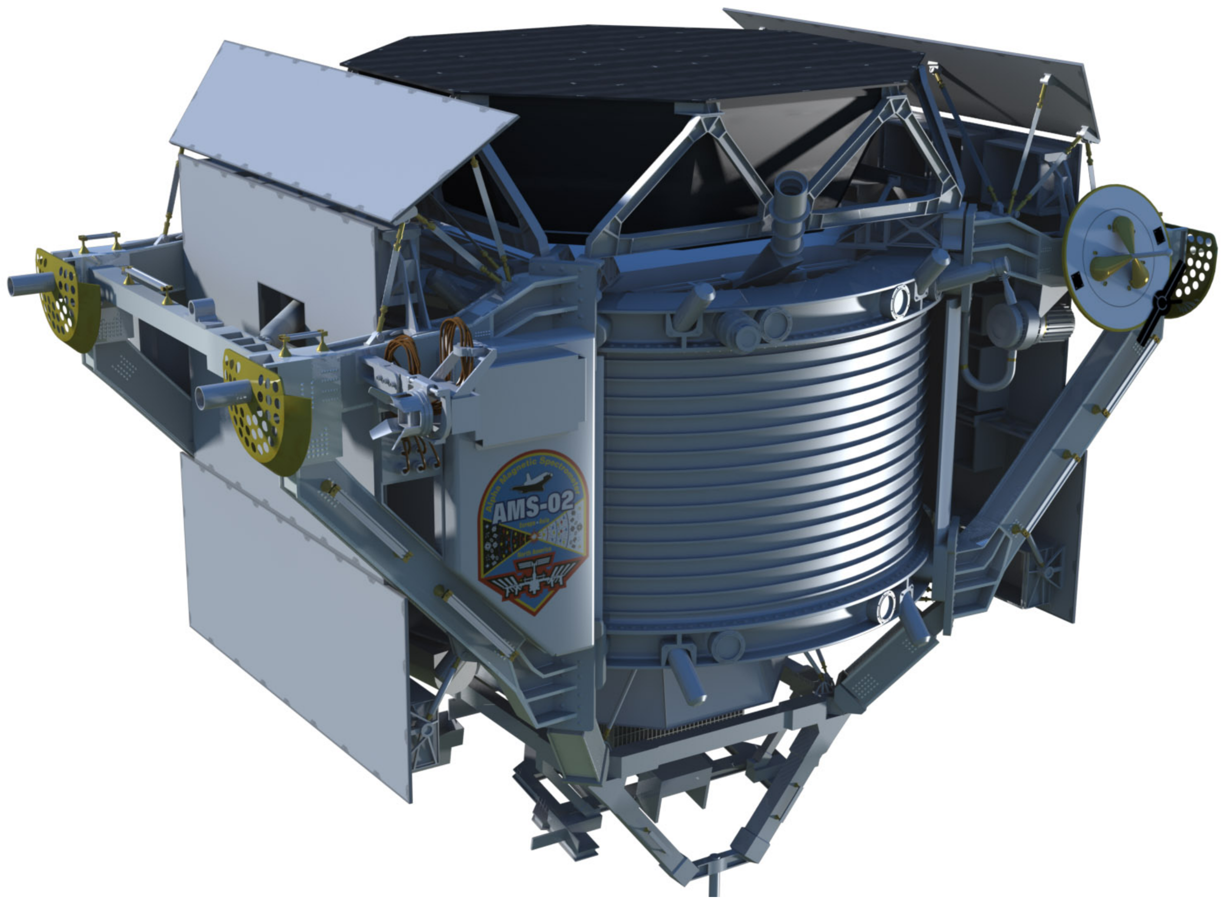
LAT: 2012ApJ.747..121A

- Search criteria:
  - catalog sources, off-plane: |b| > 10°
  - not associated with counterparts at other wavelengths
  - steady emission, spectrum consistent with DM spectra
  - spatially extended (>~ 0.25°)
- Results:
  - Few sources pass criteria
  - From N-body simulations we infer a constraints on annihilation cross-section

Published Limits from Searches for Galactic Sub-Halos in Un-associated Sources

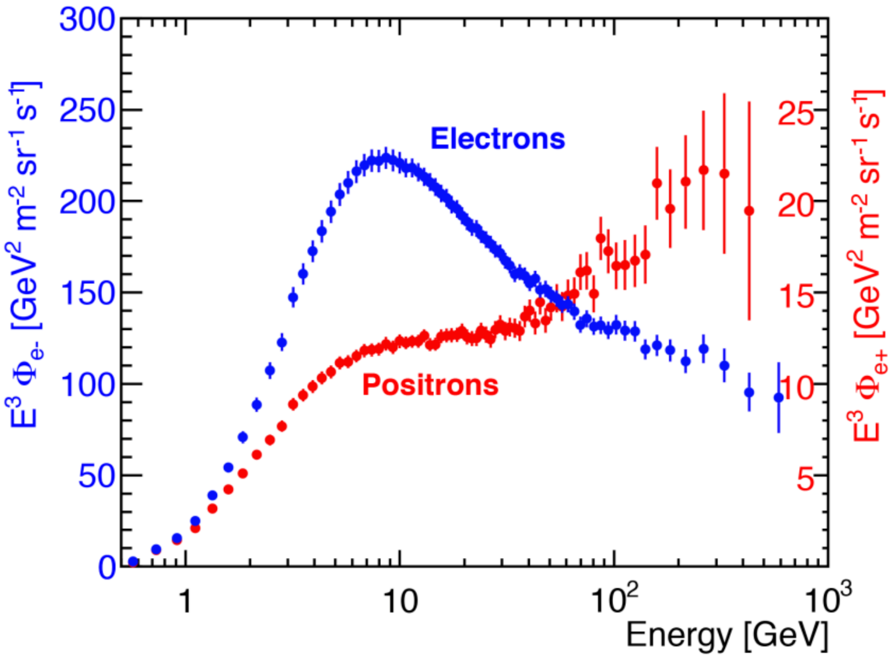


DM Limits from Cosmic-Ray Spectra

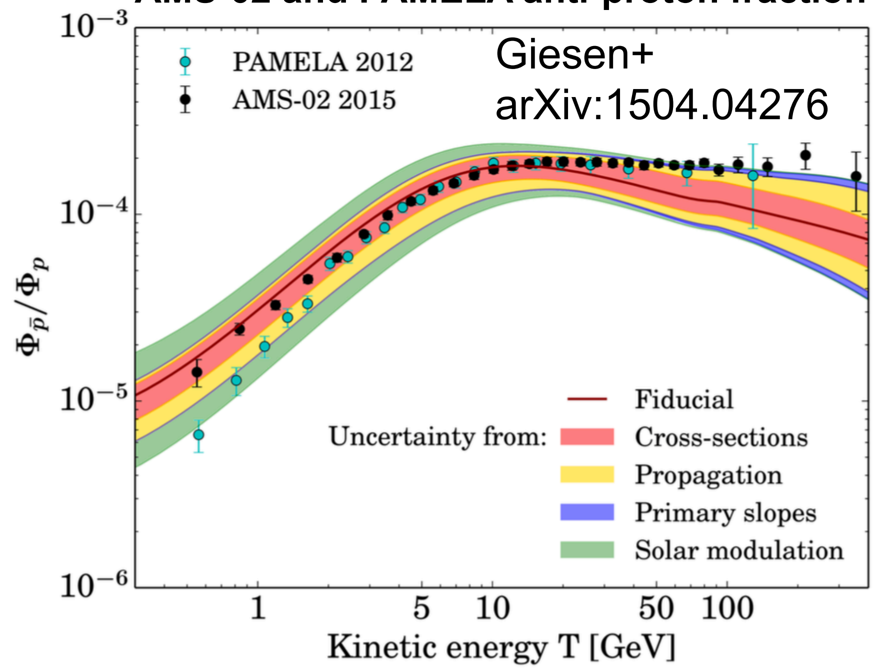


DM Limits from Cosmic-Ray Spectra

AMS-02 electron and positron fluxes

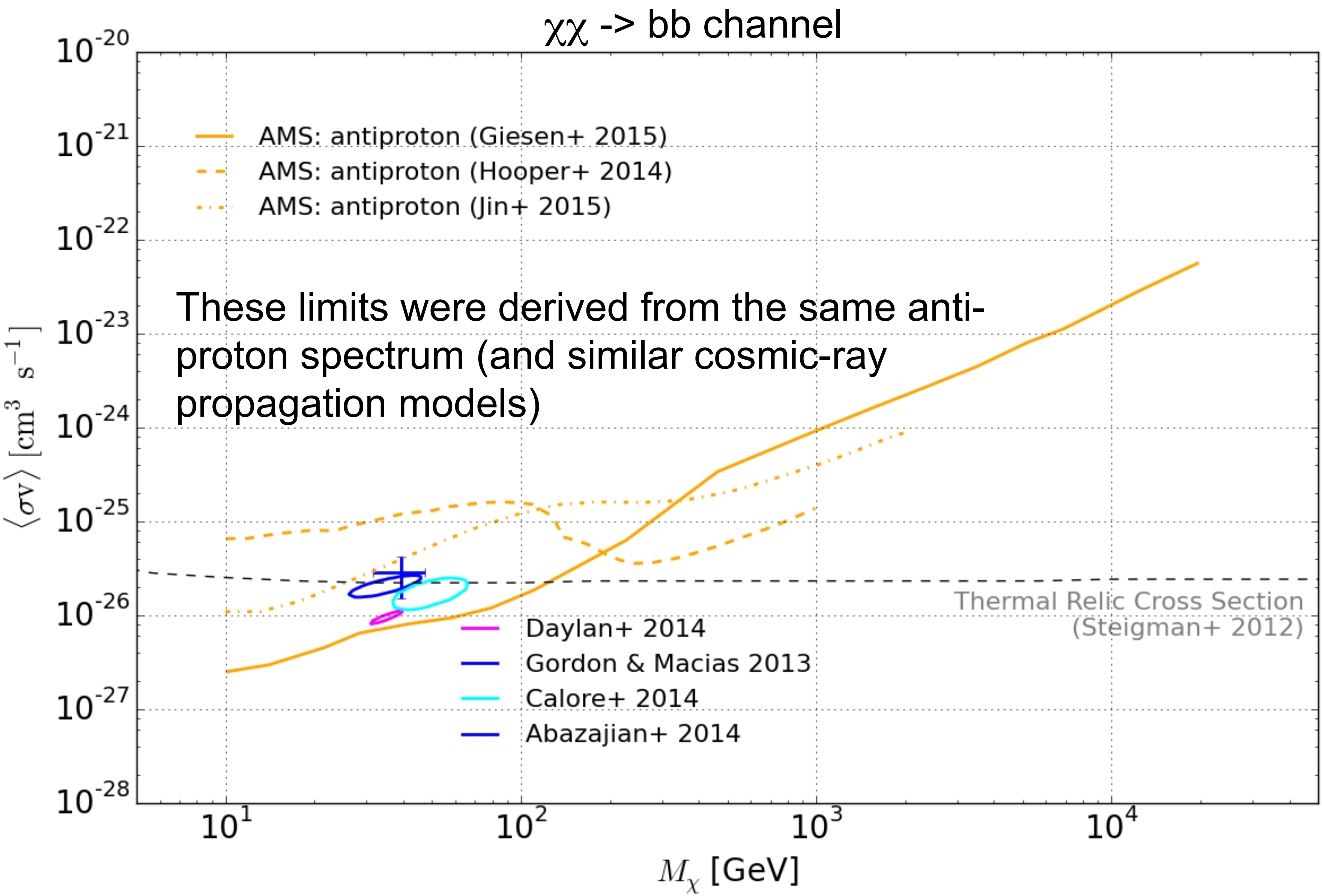


AMS-02 and PAMELA anti-proton fraction



- Extracting constraints on DM cross section from anti-particle fluxes requires detailed modeling of source populations, cosmic-ray propagation and other astrophysical effects (see sources of uncertainty on right figure).

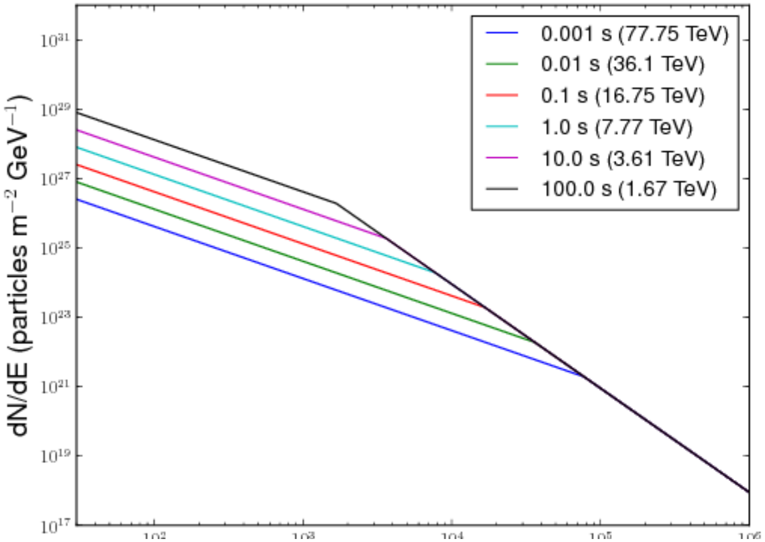
Published Limits from Anti-Proton Spectra



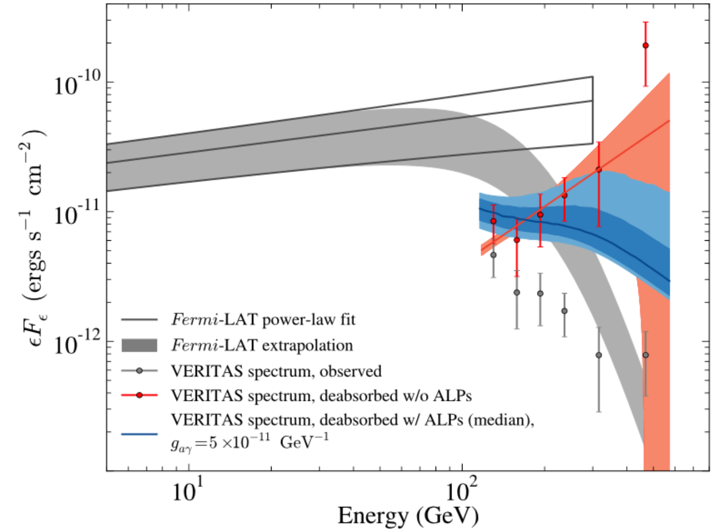
SEARCHES FOR NON-WIMP DARK MATTER

Searches for Primordial Black Holes and Axions

Spectra over remaining lifetime of PBH



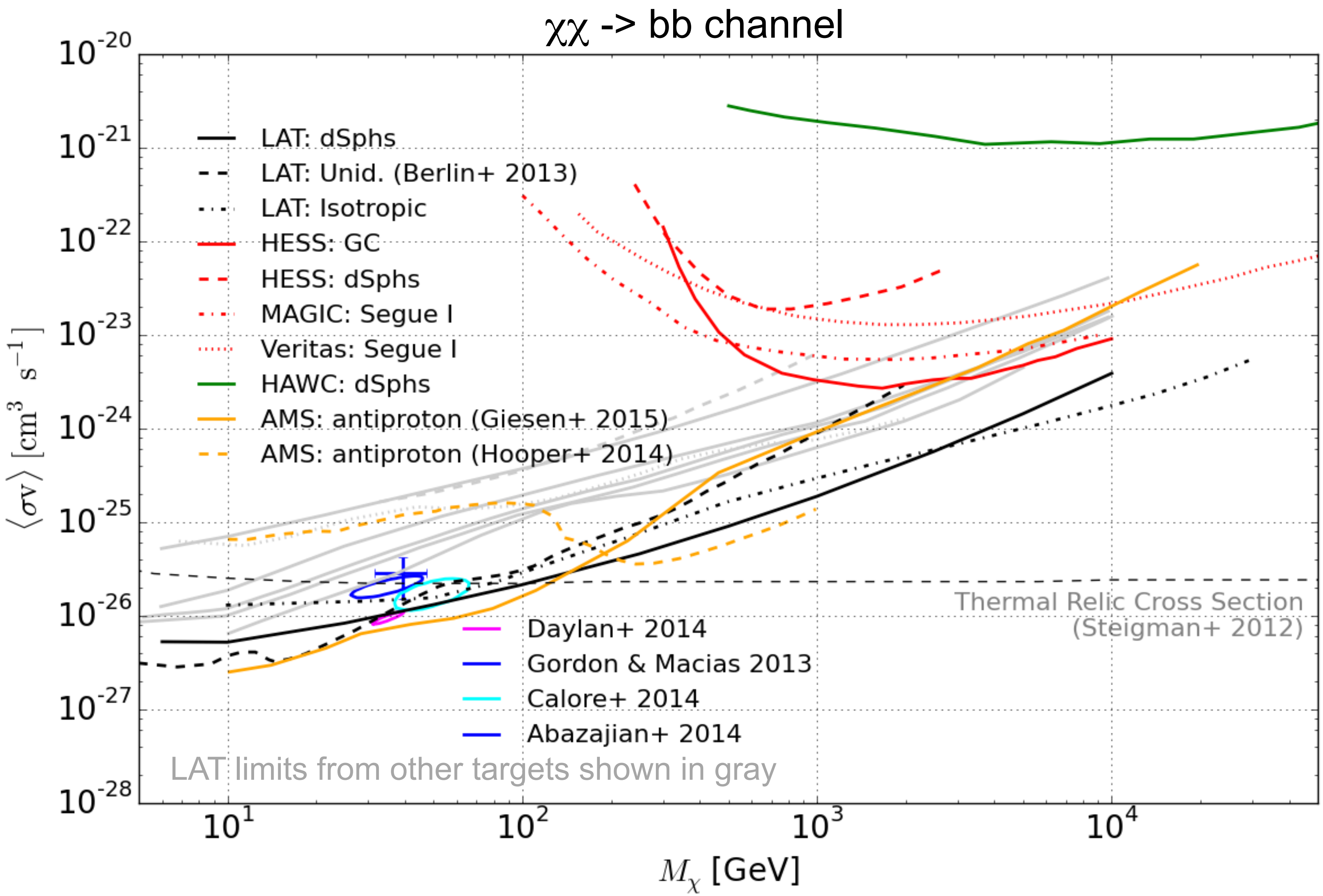
Spectrum from Blazar PKS 1424+240



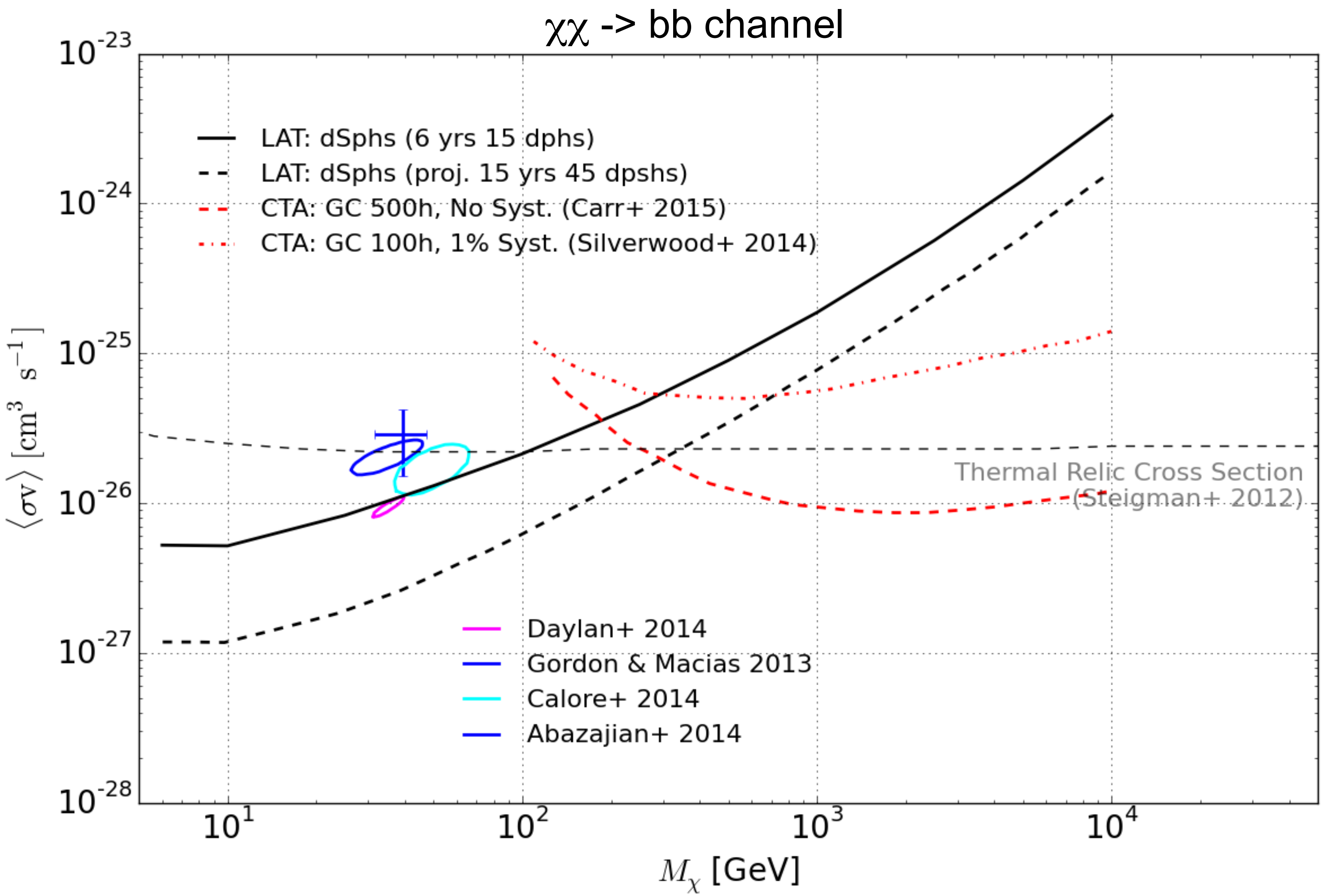
- *PBH Evaporation*: best limits come from considering the total contributions to the isotropic emission over the entire lifetime of the PBH
  - The “burst” at the end of the PBH life is dramatic, but for every dying PBH there are millions that are emitting MeV γ rays
- *Axion-like particles*: search for TeV gamma-rays that reach us from distant Blazars where the optical depth from attenuation from interactions with extra-galactic background light is large ($\tau >> 1$)
  - Other searches consider spectral distortions of nearby Blazars

SUMMARY

Summary of Current Results from Indirect-Detection DM Searches



Projected Results for Best Search Targets



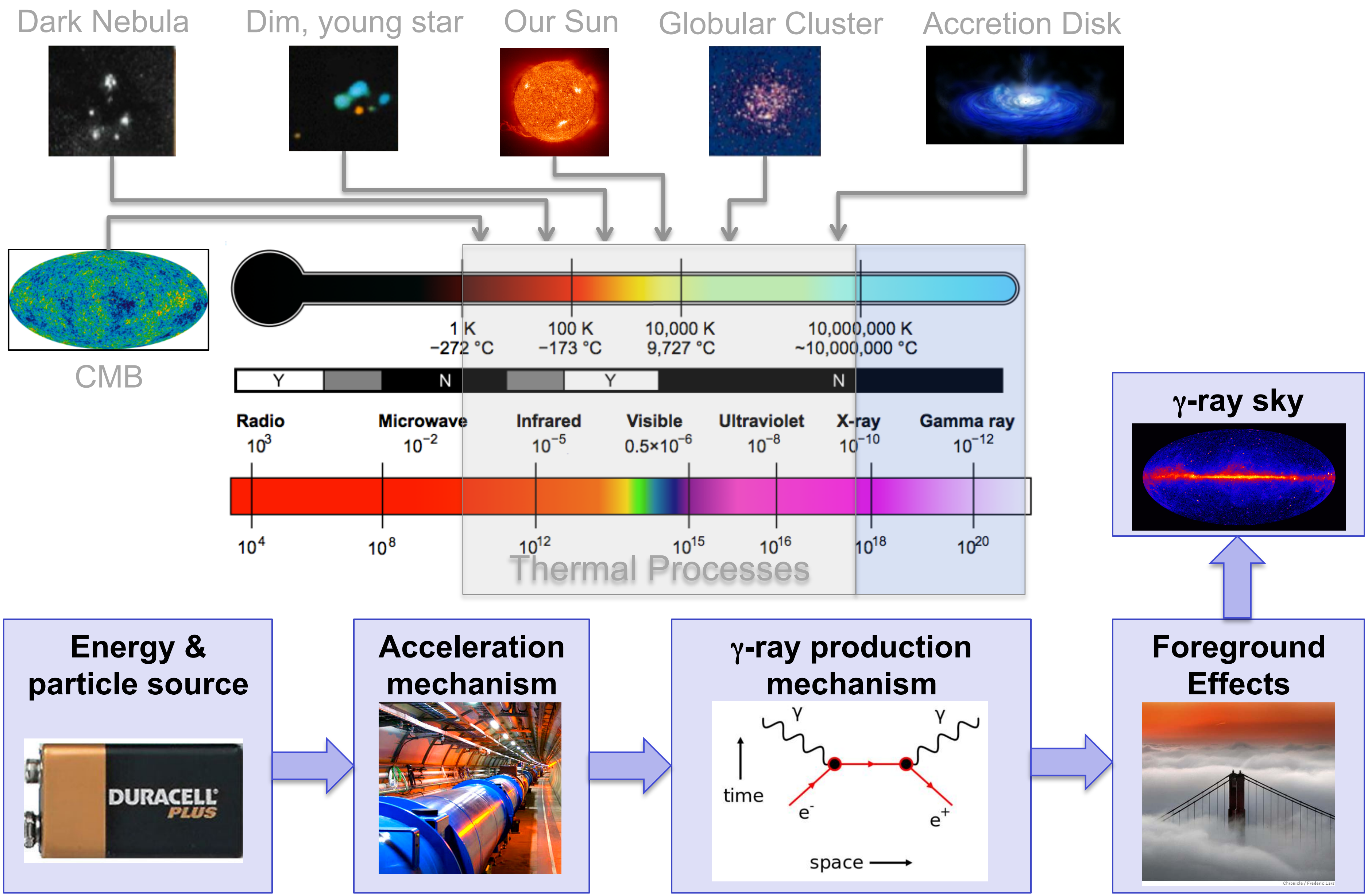
Summary

- All the evidence for dark matter comes from astronomical observations
- Many indirect-detection dark matter searches look for dark matter signals associated with specific astrophysical targets with large known dark matter content, such as dwarf galaxies
- Cosmology provides a robust prediction of the thermally averaged cross section for a thermal relic DM particle: $\langle\sigma v\rangle \sim 3 \times 10^{-26}\ \mathrm{cm}^3\ \mathrm{s}^{-1}$
- LAT data have been used to rule out WIMPs at the thermal relic cross-section up to ~150 GeV (for annihilation to b-quarks)
- The LAT sensitivity has reached the thermal relic level and thus is informing us about the DM production mechanism in the early Universe
- With the LAT and CTA we can hope to cover the thermal relic cross-section up to several TeV

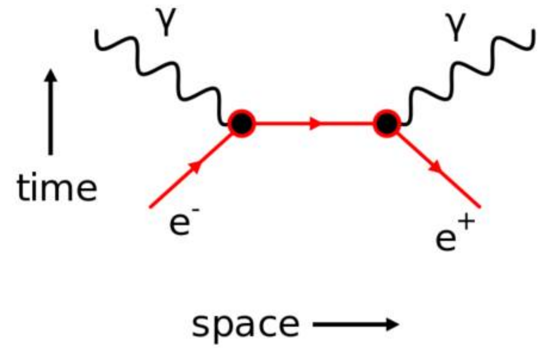
BONUS SLIDES

High-energy Astrophysics and astronomy

γ-rays Probe the Extreme, Non-Thermal, Universe



Non-thermal γ ray Emission

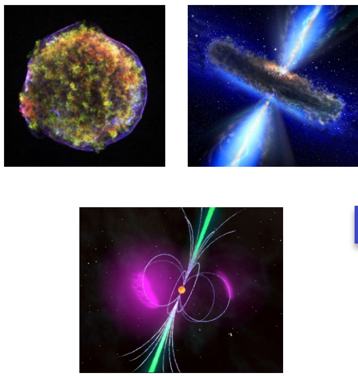


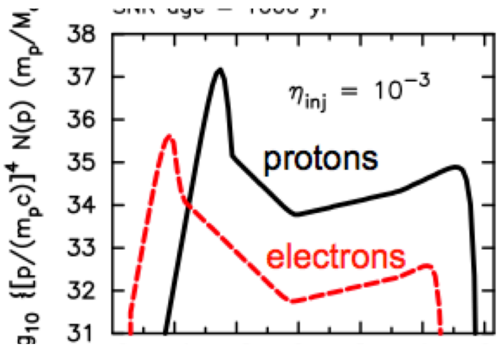
Energy source + **Acceleration mechanism** + **γ-ray production mechanism**

Chronicle / Frederic Larson

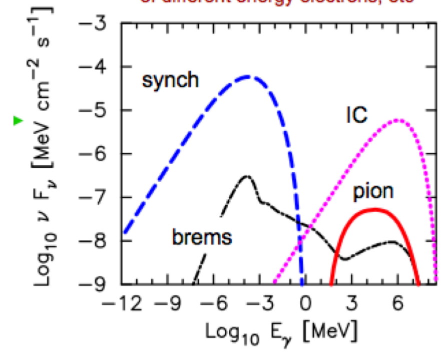
− **Foreground absorption** = **γ rays**

Non-thermal γ ray Emission





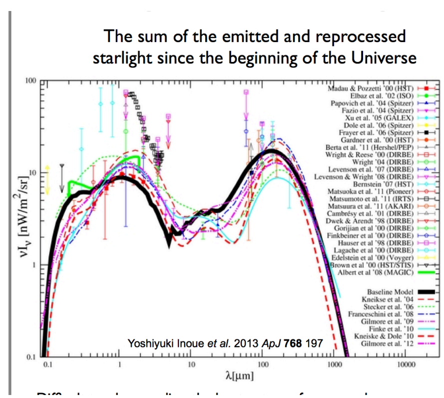
Must consider B-field, diffusion lengths of different energy electrons, etc

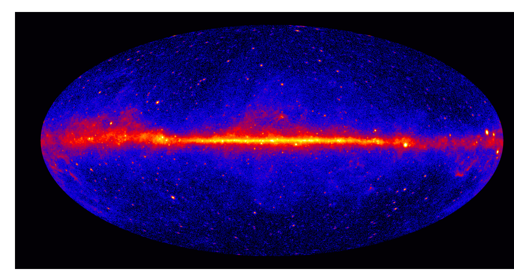


Energy source

Acceleration mechanism

γ-ray production mechanism



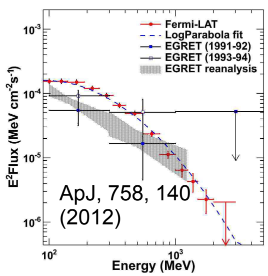


Foreground absorption

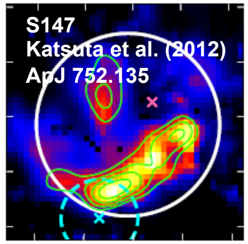
γ rays

Fermi Gamma-ray Space Telescope

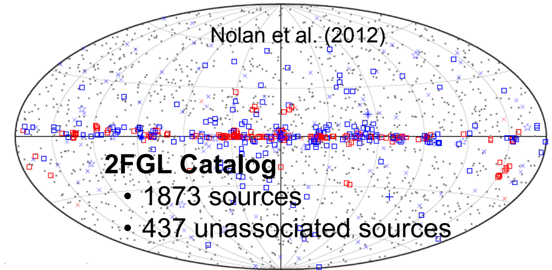
Fermi Gamma-ray Space Telescope Science
One person's background is another person's source!



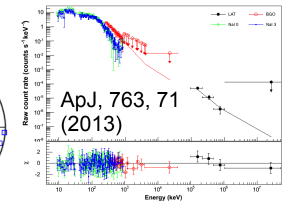
Lunar Gamma rays
- CR hitting surface
- Correlated w/ solar activity



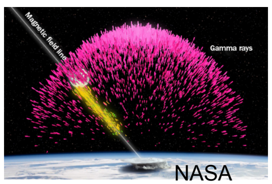
Supernova Remnants
- 25 published SNR + 30 cands in 2FGL
- Multiwavelength objects
- Require good diffuse emission modeling



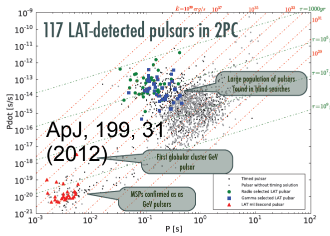
2FGL Catalog
- 1873 sources
- 437 unassociated sources



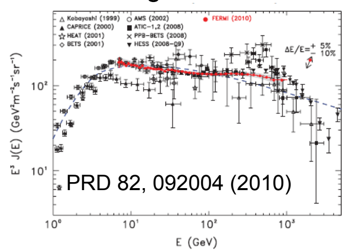
Gamma-ray Bursts
- 35 LAT, 1000+ GBM
- GBM + LAT spectra



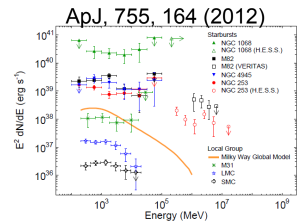
Terrestrial Gamma-ray Flashes
- Associated w/ thunderstorms
- Observed by GBM & LAT



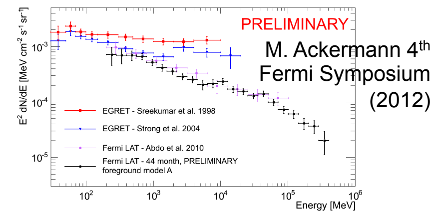
Pulsars (e.g. Vela)
- 117 Fermi-LAT det. pulsars
- Multiwavelength objects
- PSR J2021+4026 shows variablilty



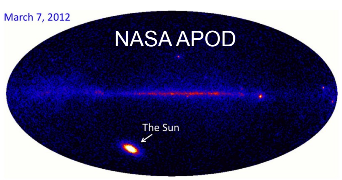
e^-e^+ Energy Spectrum
- LAT can measure e's too
- board high-energy excess



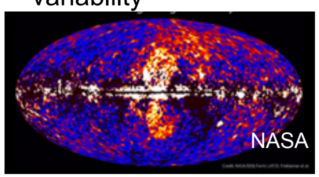
Star-Forming Galaxies
- LAT has seen 7
- Potential LAT-CTA synergy



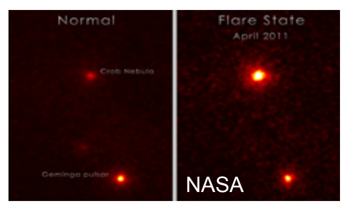
Extragalactic bkg
- Spectrum from 0.2-410 GeV
- Ainsotropy →population info



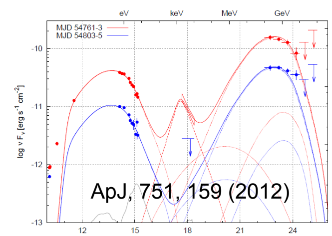
Solar Flares
- Observed by GBM & LAT
- X-class Flare on March 7th, 2012



Fermi Bubbles
- Unexpected high-energy excess lobes

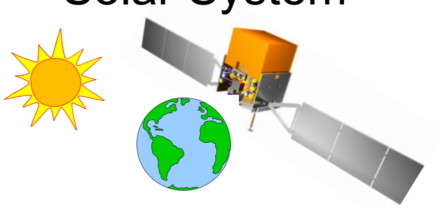


Pulsar Wind Nebula (e.g. Crab)
- 15 candidates found by LAT
- Multiwavelength objects



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

Solar System

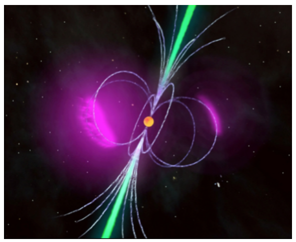


Galactic

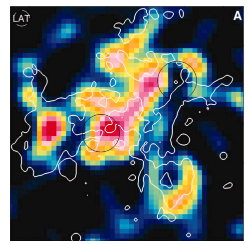
Extragalactic

Particle Acceleration

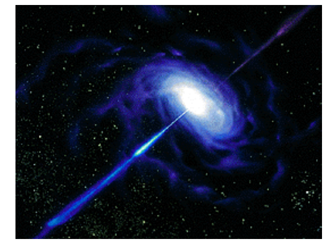
Fermi data have forced fundamental changes in our understanding of almost every source of high energy γ rays, and of particle acceleration processes that drive them



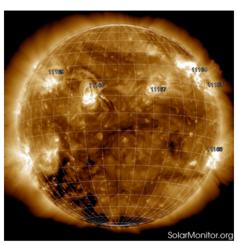
Pulsar γ-ray emission ***does not*** come from polar caps



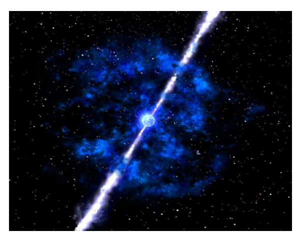
Cosmic rays ***are*** trapped in cocoons and bubbles



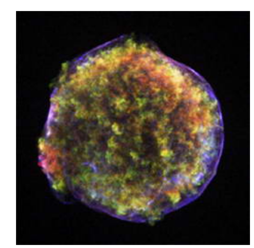
AGN γ-ray emission ***is not*** confined to region near the central black hole



Solar Flares high-energy γ rays **are associated** with mass ejections



GRBs ***are not*** adequately described by "Band" model



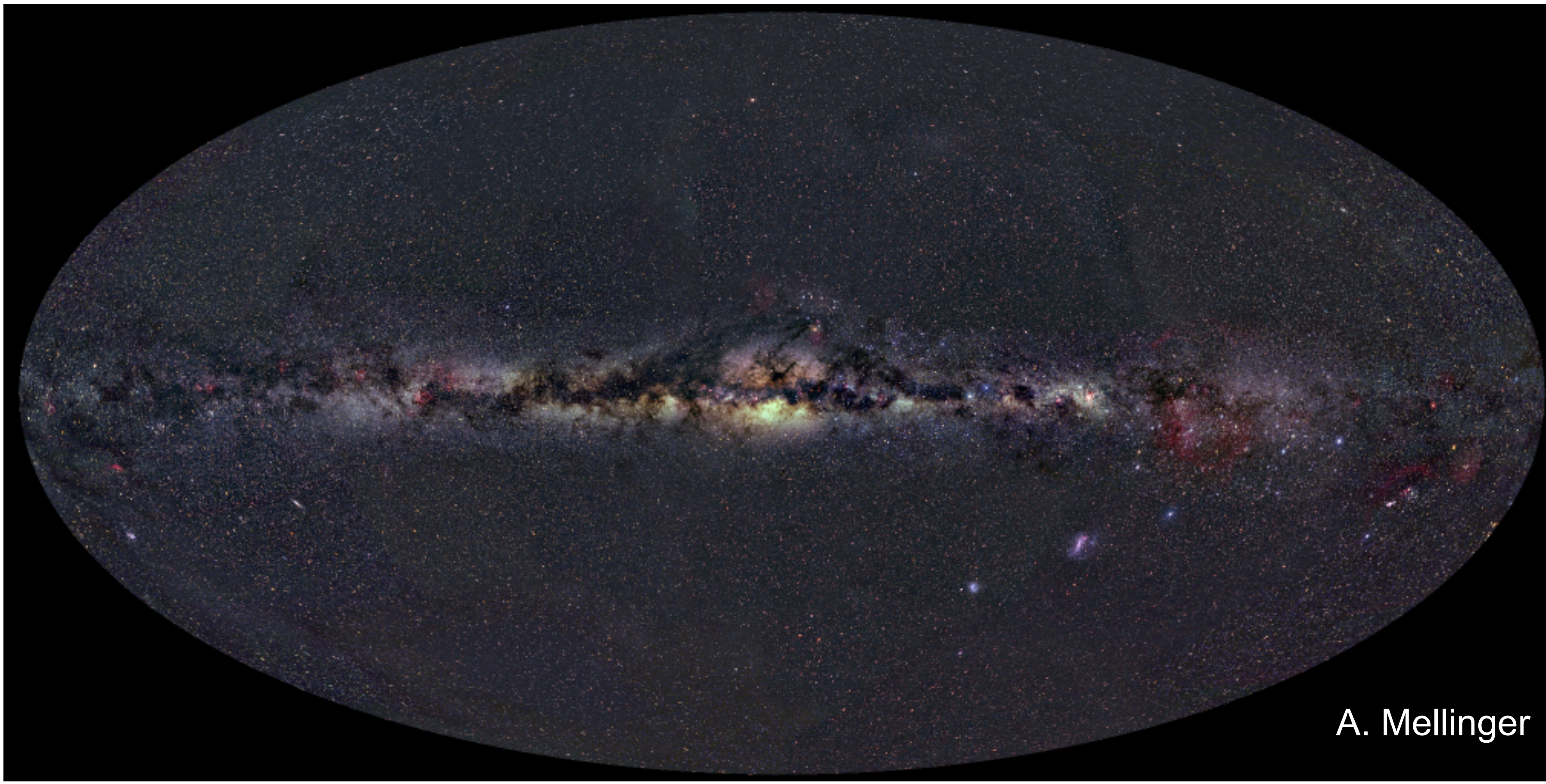
Supernova remnants ***are*** sites of hadronic acceleration

MODELING GALACTIC DIFFUSE EMISSION

Thanks to Seth Digel for the next slides. With apologies to Seth, I'm using these slides to impress the complexities on you, rather than to convey much information.

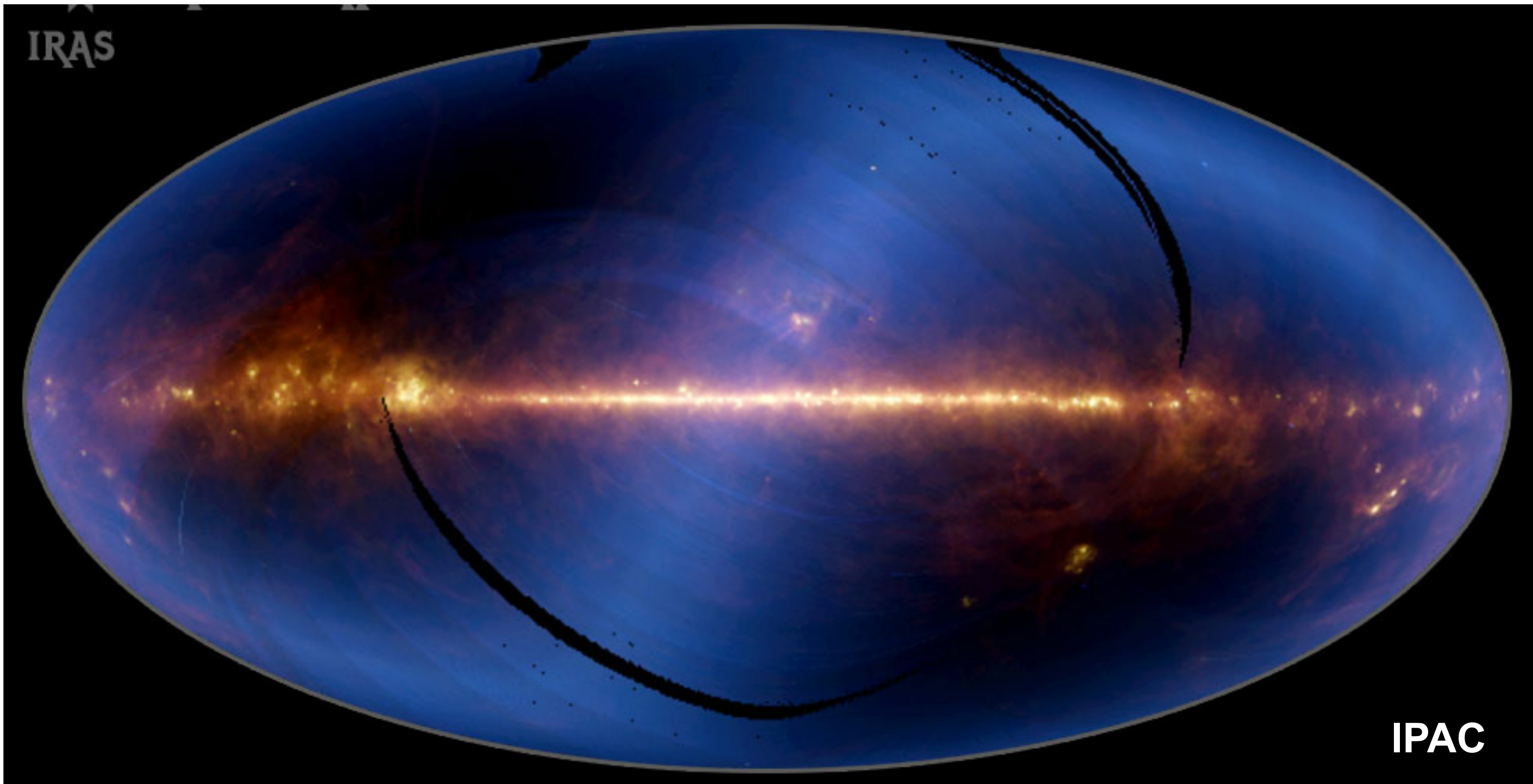
Interstellar gas as dark clouds

Interstellar clouds are not literally clouds but appear as dark nebulae or ‘clouds’ against the Milky Way



Why are the clouds dark?

What we see (in absorption) is the interstellar *dust*



25-60-100 μm

Neutral interstellar medium

The neutral interstellar medium is gas mixed with dust; associations of gas, especially dense ones, are referred to as clouds – which doesn't meaningfully help for understanding them

The gas very, very cold (few K to 10s of Kelvin) and very, very tenuous (10^3 cm^{-3} is a *high* density)

- 10^3 H_2 molecules cm^{-3} at 5 K corresponds to a pressure of 10^{-13} torr, much lower than can be achieved in the laboratory

They are quite unlike atmospheric clouds in other ways

- To the extent that they are stable, they are (sort of) self gravitating, with important magnetic support
- They are huge and massive – largest ~100 pc and ~10^6 Msun.

Overall, most of the mass of the interstellar medium is atomic hydrogen*

- The densest component of the neutral medium is primarily H_2
- This is where stars (OB assoc., SNR, pulsars, XRB, …) form

* He makes up 21% by mass of the ISM and is assumed to be in proportion to the H

Studying the neutral ISM

- H (or H I) is abundant, has 21-cm hyperfine transition
  - Detected in 1951 (Ewen & Purcell)
- H_2 has no dipole moment, and so no rotational spectrum. The lowest vibrational bands are a few 1000 K above ground. It can be detected directly when shock heated or in absorption in the UV, but is not directly detectable under ordinary interstellar conditions
  - CO is the 2nd most abundant molecule, down by a factor of ~10^5 from H_2
  - CO has a permanent dipole moment (0.1 Debye or so) and the lowest excited rotational level (J = 1) is only a ~5 K (115.271 GHz) above ground
  - Detected in 1970 (Wilson, Penzias & Jefferts)

CO as a tracer of molecular clouds

Dame/Mellinger

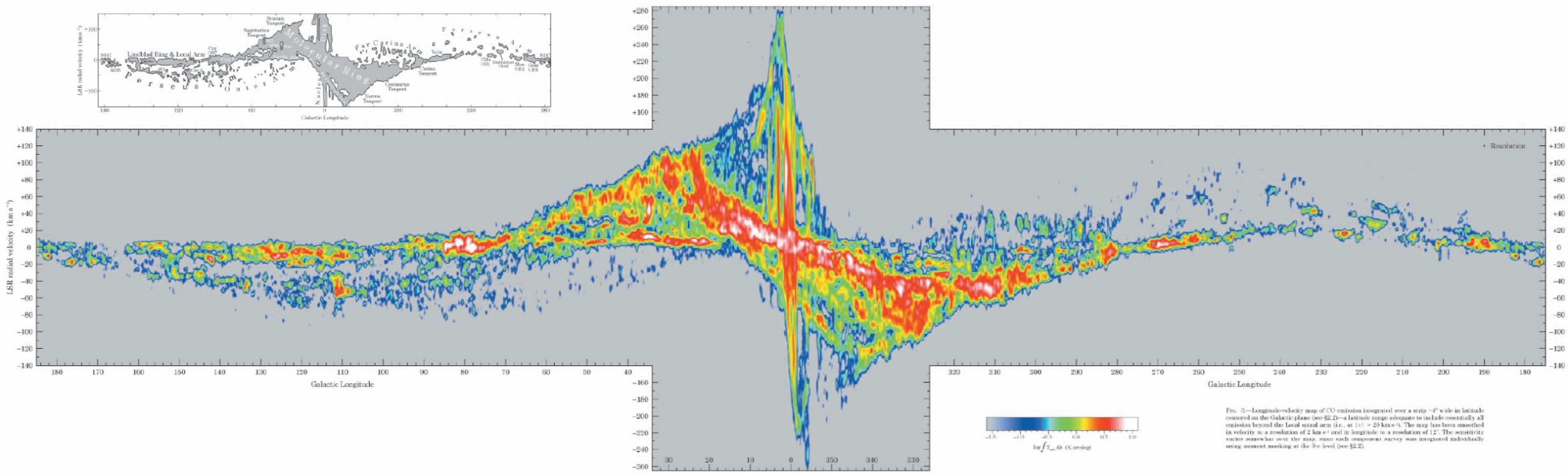
For various reasons, CO ought to be at least an ok tracer of molecular hydrogen

- Conditions for their formation and destruction are similar, and as mentioned collisional excitation is well matched to conditions of molecular clouds

However, CO is abundant enough that it is certainly optically thick (=*bad news for a mass tracer*; in principle you measure its temperature rather than its column density)

Distribution of CO in velocity

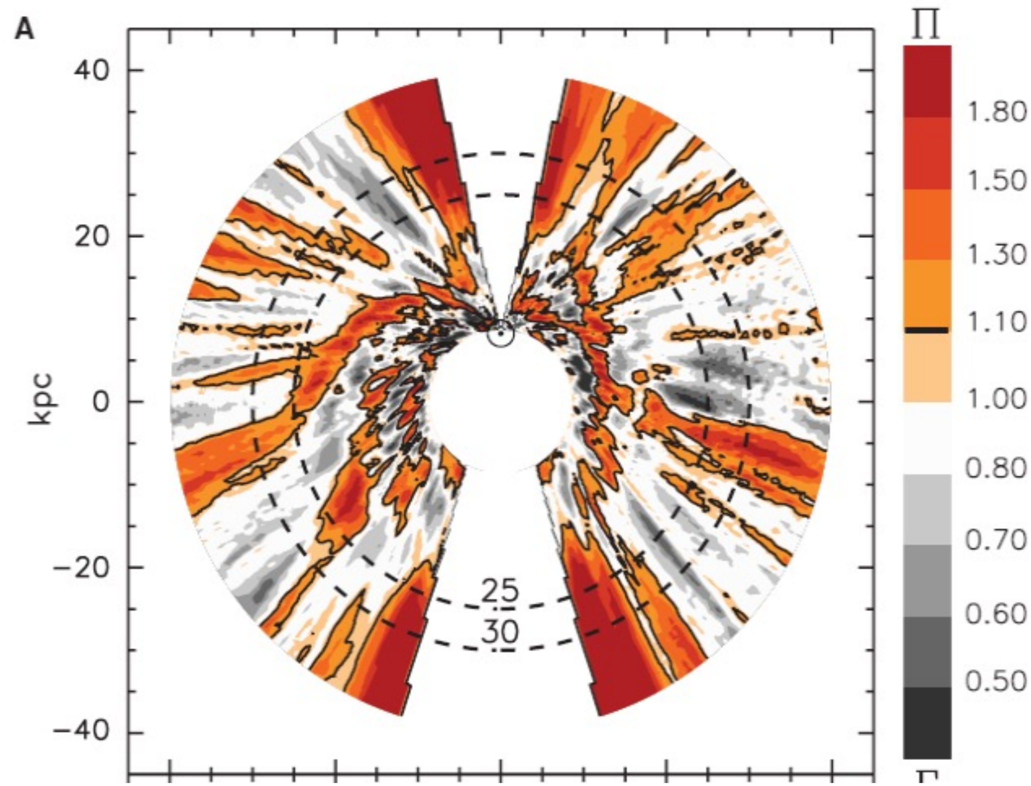
Dame, Hartmann, & Thaddeus (2001) composite survey



Notice that you can inferr the sense of Galactic rotation, you can see (some spiral arms), as well as the molecular ring (and the molecular hole), and clear evidence of non-circular motions

Putting together the pieces

- A velocity-to-distance algorithm together with a large-area H I or CO survey leads to an almost-irresistible urge to derive the distribution of gas across the Milky Way
- Automatic procedures don't work very well
- For example, systematic noncircular motions, especially in regions with poor kinematic distance resolution were early (late 1950s) recognized to produce 'fingers of God' pointing at us (Bok)
  - *They still do*



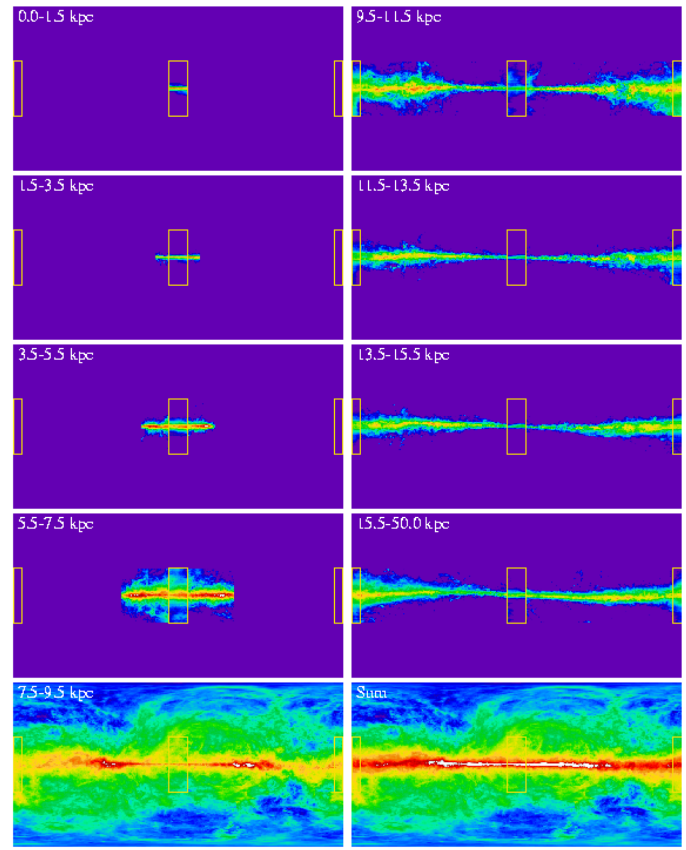
Levine, Blitz, & Heiles (2006)

For gamma-ray astronomy

Since the COS-B era, 'rings' of H I and CO gas (column density) have been used to study and model the Galactic diffuse emission. This eliminates the kinematic distance ambiguity in the inner Galaxy

The down sides:

- It builds in axisymmetry to underlying models for distributions of cosmic rays
- And *does not* map directly to the 3-dimensional distribution of gas density.
- And the Galactic center and anticenter longitude ranges need to be filled in

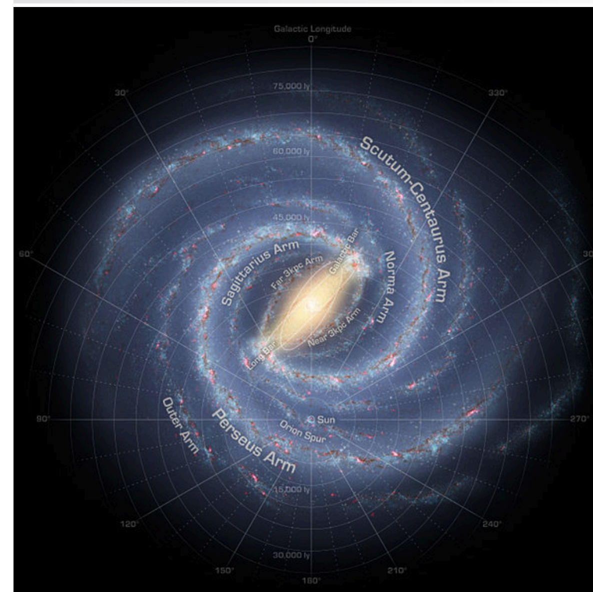


https://confluence.slac.stanford.edu/display/SCIGRPS/Interstellar+Medium+Rings+for+GALPROP

[1] Ackermann et al. 2012ApJ...750....3A. [2] Ackermann et al. 2011ApJ...726...81A. [3] Abdo et al. 2010PhRvL.104j1101A [5] Casandjian 2012AIPC.1505...37C. [6-8] Ackermann et al. 2011Sci...334.1103A, 2012A&A...538A..71A, 2012ApJ...756....4A

GALPROP

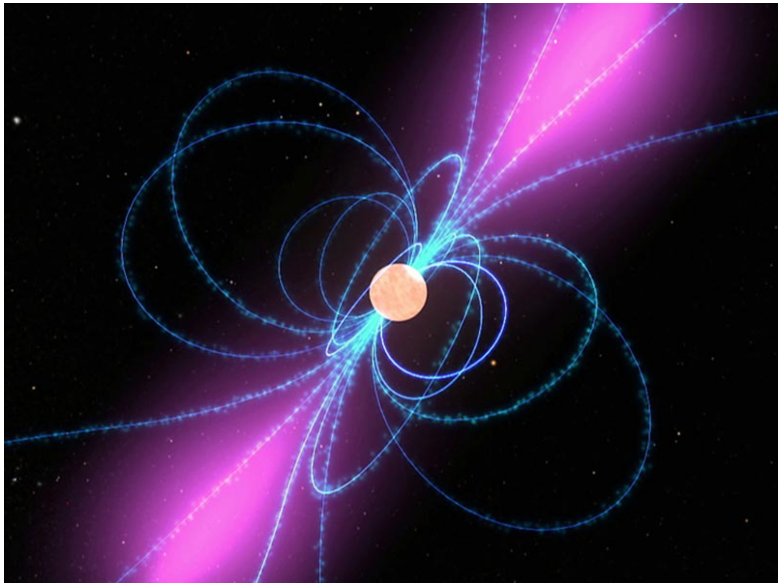
- Cosmic-ray propagation code that has been in development since the 90s
- Read all about it at http://galprop.stanford.edu
  - You can run it on servers at Stanford through webrun or download the code to run on your own machine
- Development still going strong
  - Latest release is version 54



PULSARS

GAMMA-RAY PULSARS

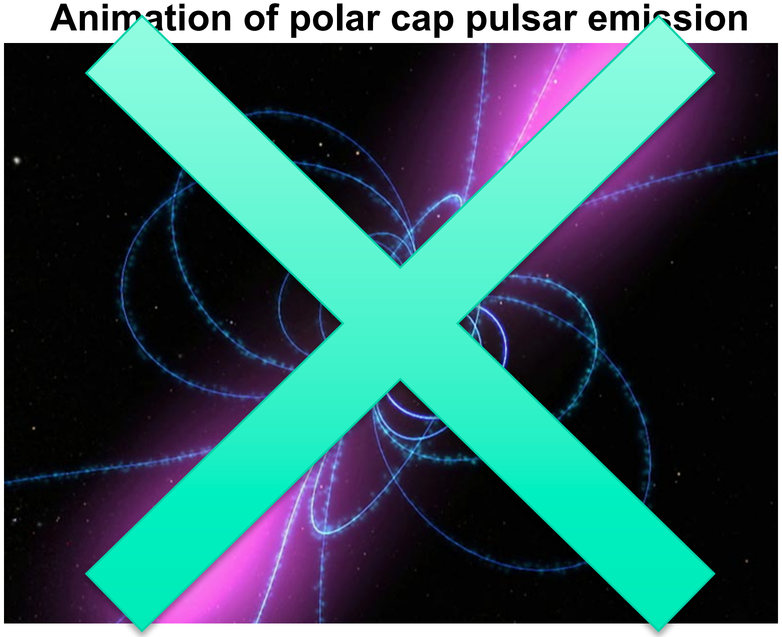
Animation of polar cap pulsar emission



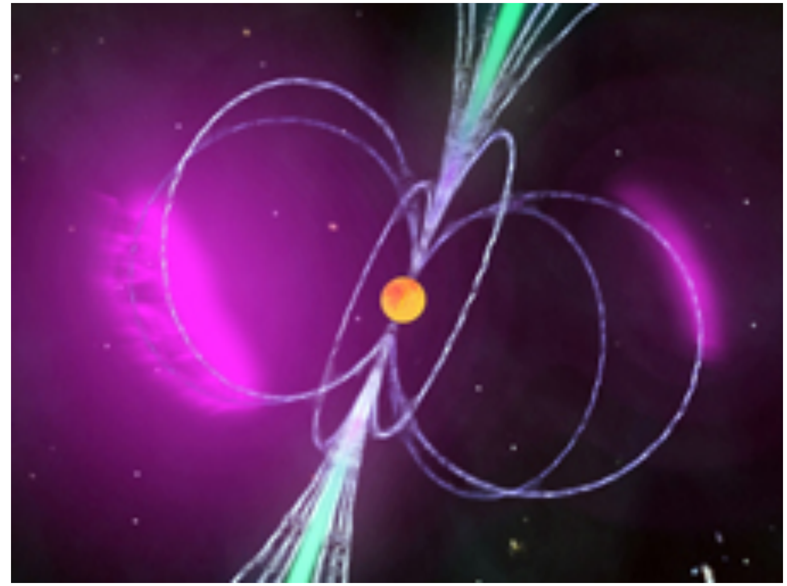
- Rotating neutron stars
- Rotation periods range from ms to seconds
- Emit strongly in radio and γ-ray bands

GAMMA-RAY PULSARS

Animation of polar cap pulsar emission



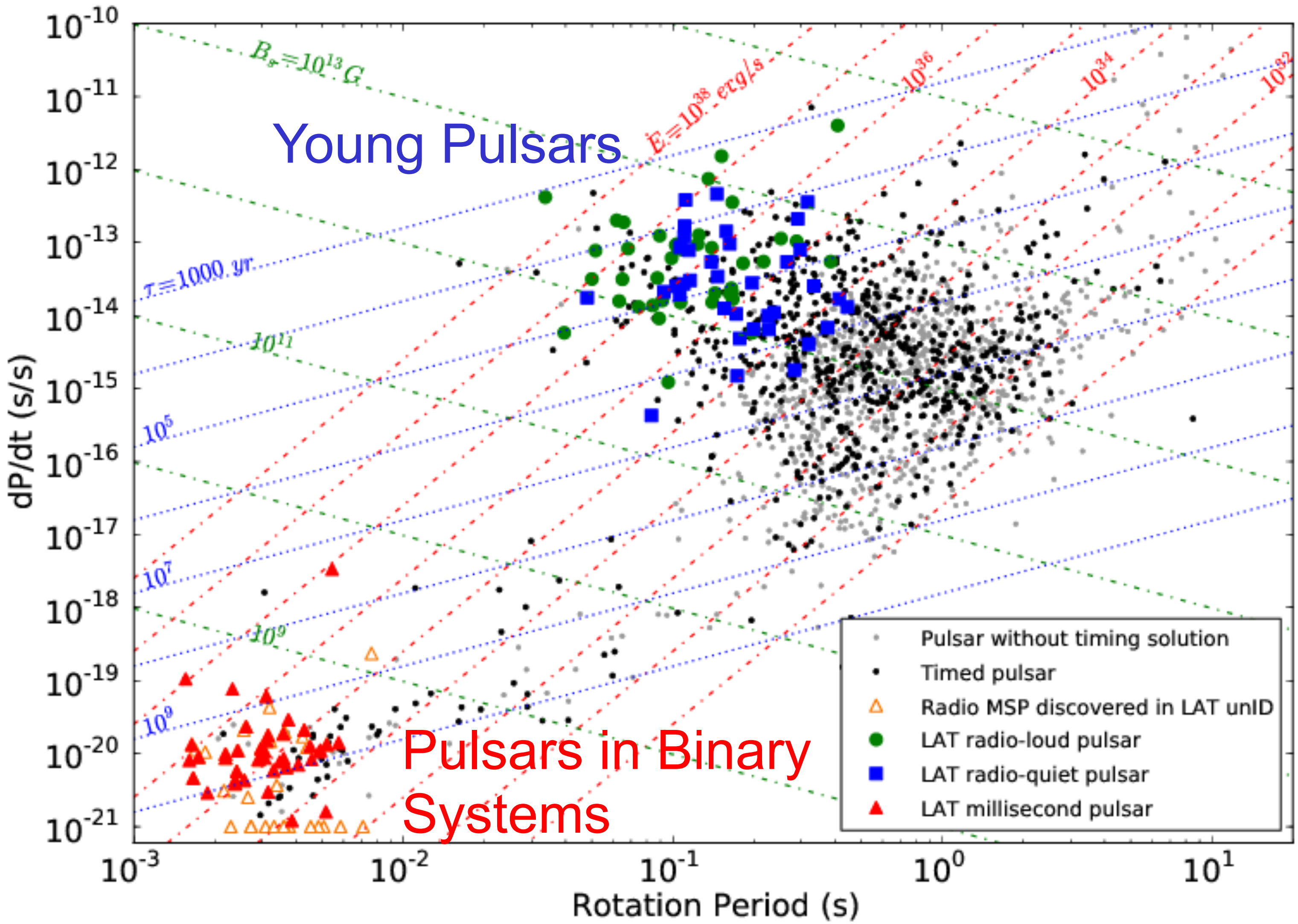
Animation of outer gap pulsar emission



- Rotating neutron stars
- Rotation periods range from ms to seconds
- Emit strongly in radio and γ-ray bands
  - LAT data show that radio and γ-ray emission coming from different regions of magnetosphere (i.e., depending on viewing angle radio & γ-ray pulse may or may not overlap)

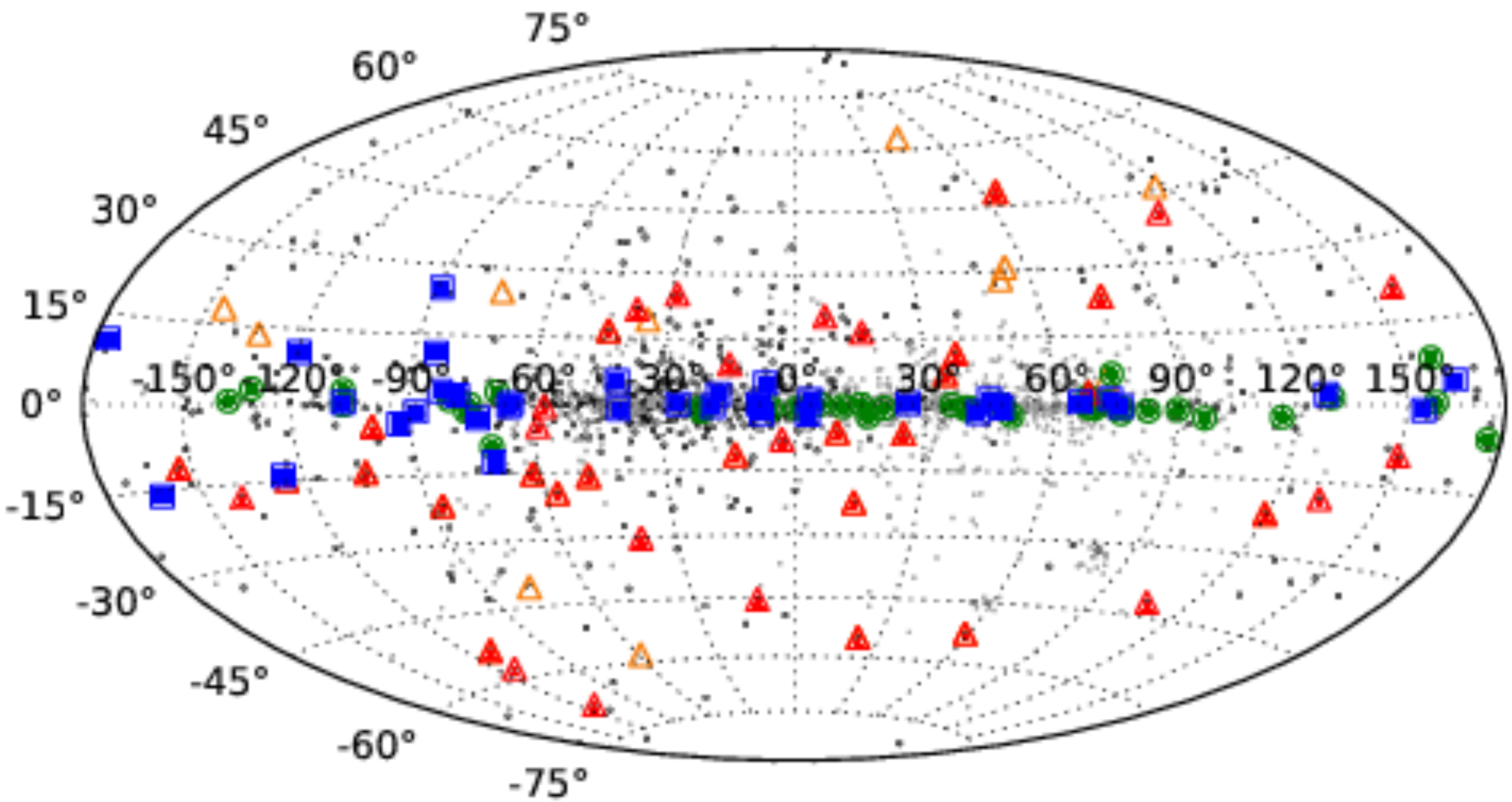
Two Pulsar populations

Rotation Period v. Rate of Change of Period for All Known Pulsars (LAT-detected pulsars highlighted)



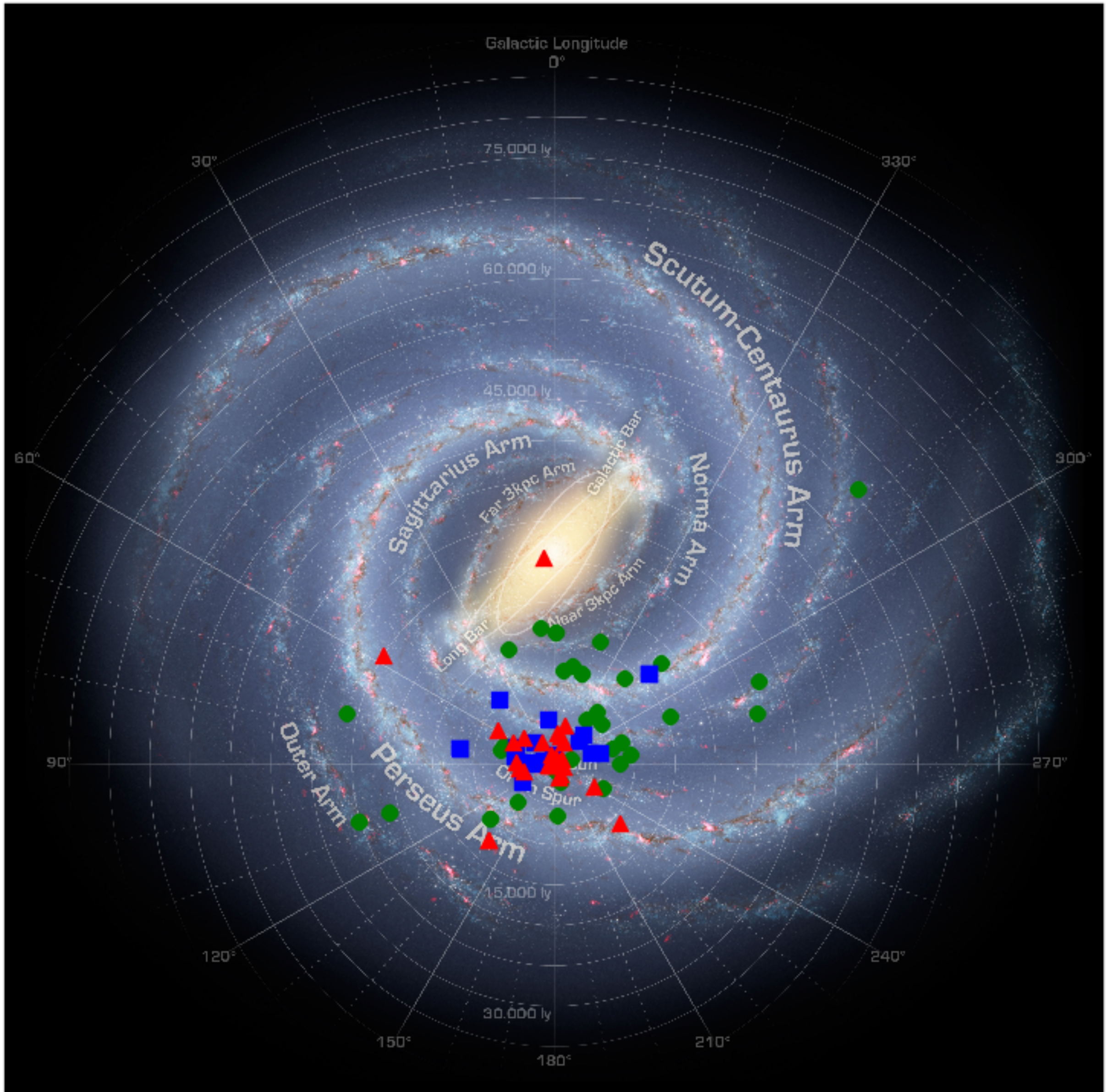
Two Pulsar populations

Position in Galactic Coordinates of All Known Pulsars (LAT-detected pulsars highlighted)



- Young pulsars are found closer to Galactic plane
- Millisecond pulsar are more isotropically distributed

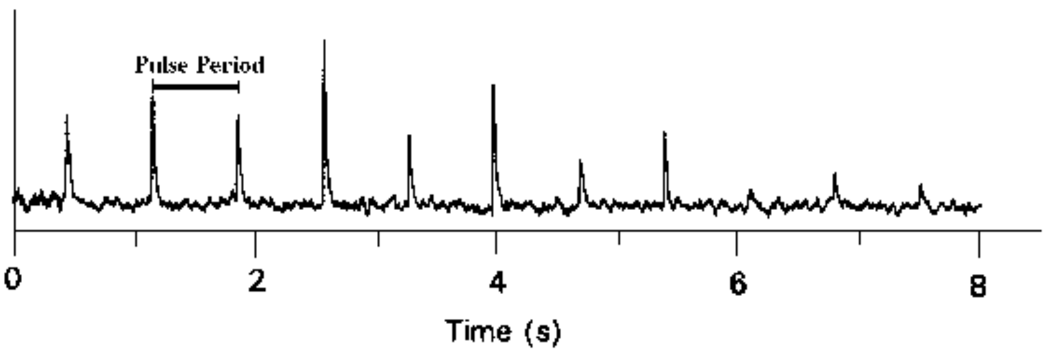
Observational Horizon for Pulsars



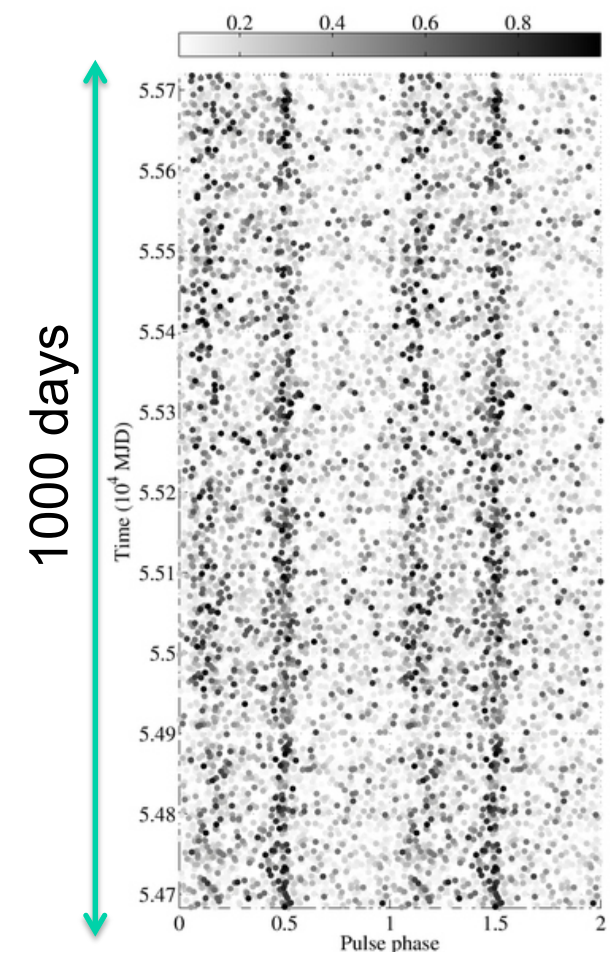
- Most γ-ray detected pulsars are within 2 kpc
  - Even less for ms pulsars
  - GC at 8.5 kpc

Detecting Pulsars

Radio Detection in Intensity Time Series



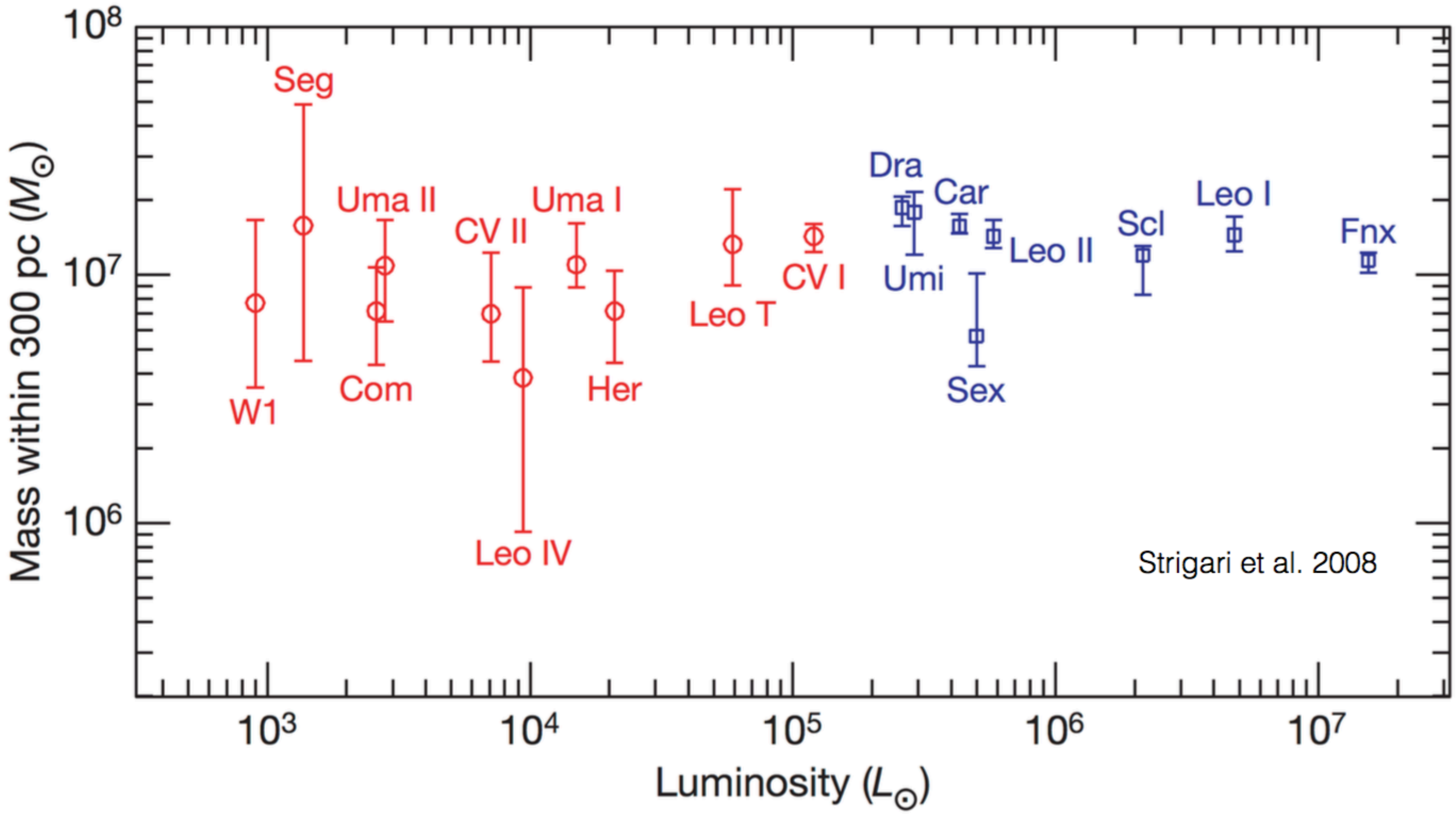
γ-ray Detection: 1000 days of weighted photons phase-folded against timing solution



- Pulsars are detected primarily in radio and γ-ray searches
- Radio searches: point radio array at pulsar, look for pulses
  - Weak towards galactic center where free electrons disperse pulse profile
- γ-ray searches:
  - Weak for binary searches where orbital motion modulates timing solultion

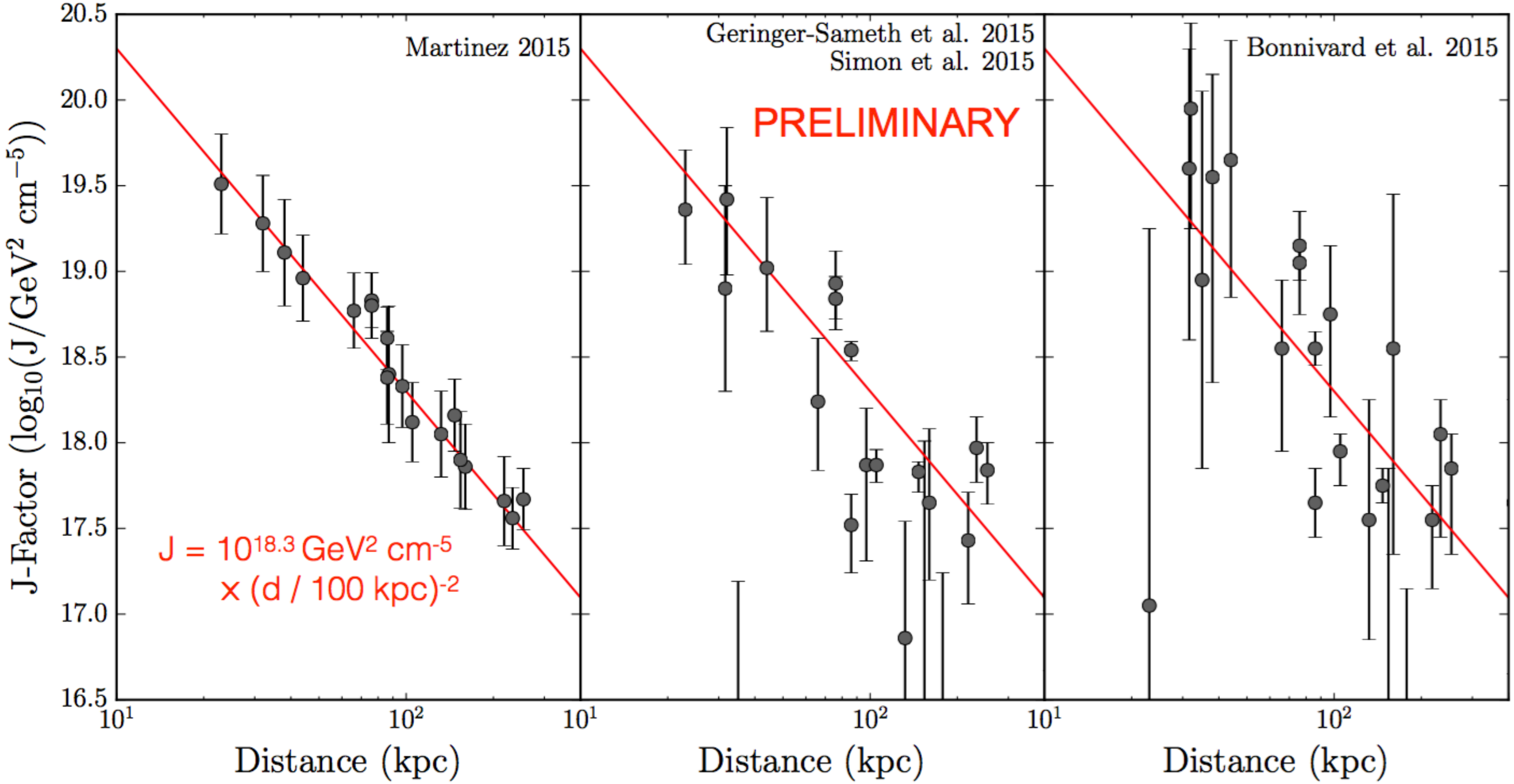
J-Factors of Dwarf Galaxies

Dwarf Galaxy Central Density



- Dwarf Galaxies seem to have comparable central densities over a broad range of luminosity

Current Published Limits from Dwarf Galaxies

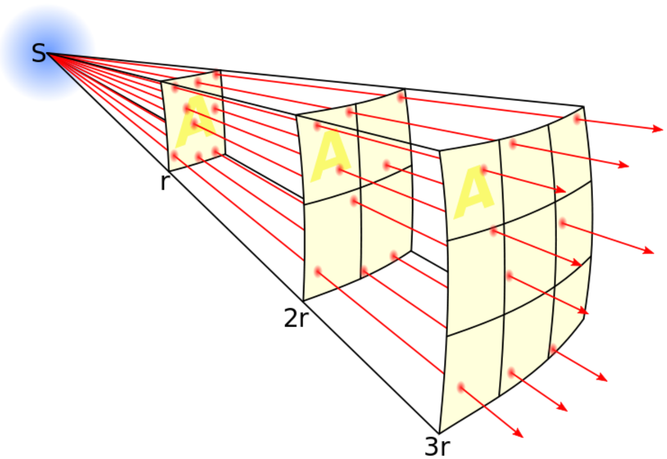


- If most Milky Way dSphs are hosted by DM halos with similar central densities, predicted DM annihilation flux is mainly determined by heliocentric distance

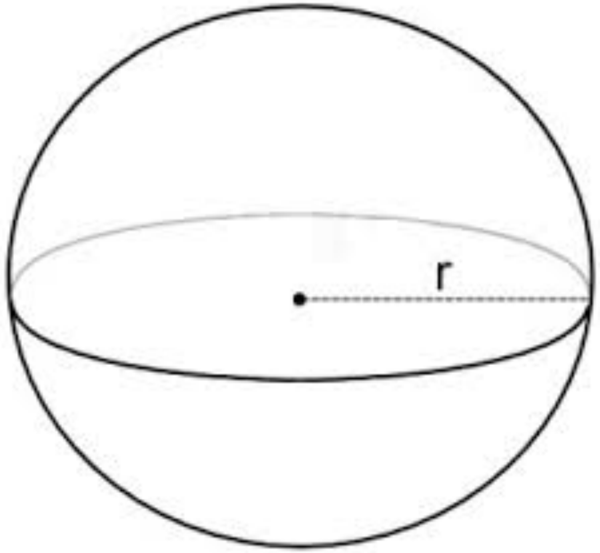
Unresolved Sources, Luminosity Functions, log N – log S

Number of Resolved Source as a Function of Instrument Senstivity (S)

Flux falls as 1 / d^2

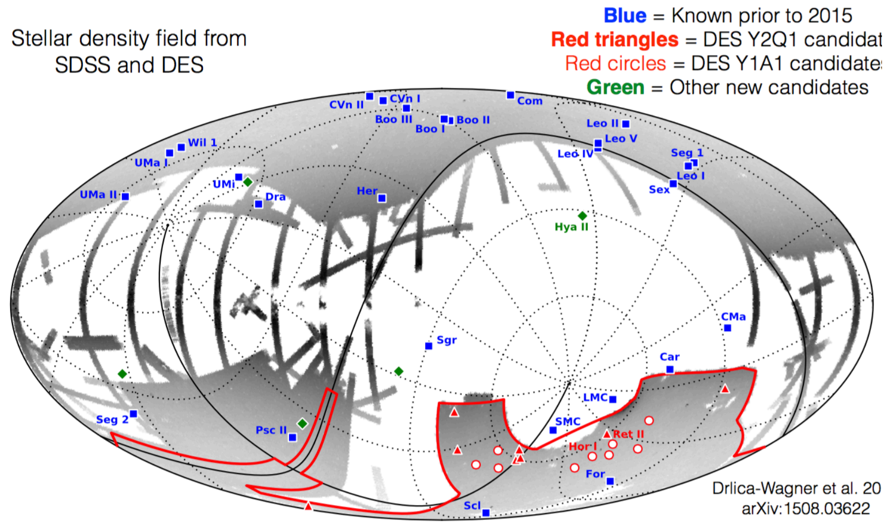


Volume grows as r^3



- For population of objects with the same intrinsic brightness uniformly distributed in space:
  - N (Flux > S) scales as $S^{1.5}$
  - The total unresolved flux scales as S
    - *Aside*: this leads to Olber's Paradox, a classical proof that the universe is not infinite and static

Discovery Volume for Dwarf Galaxies



DES footprint in Galactic coordinates (~5000 deg^2)

- Much of the sky is unsurveyed, and surveys depth is quickly increasing
- Following Dwarf J-factor scaling with distance we could expect a 5σ signal for 100 GeV DM -> b-quarks for any dwarf within 8 kpc (a volume of 2100 kpc^3)
- Doubling the data increases that to V > 3600 kpc^3; i.e., increases the discovery volume by a factor of > ***1.75***
- At higher masses, where the sensitivity is signal-limited, doubling the data increases the discovery volume by ***$2^{1.5}$ = 2.83***