Challenges for Instrument Technologies for Indirect Dark Matter Searches

Eric Charles

on behalf of the Fermi-LAT Collaboration

CPAD Workshop

Arlington TX

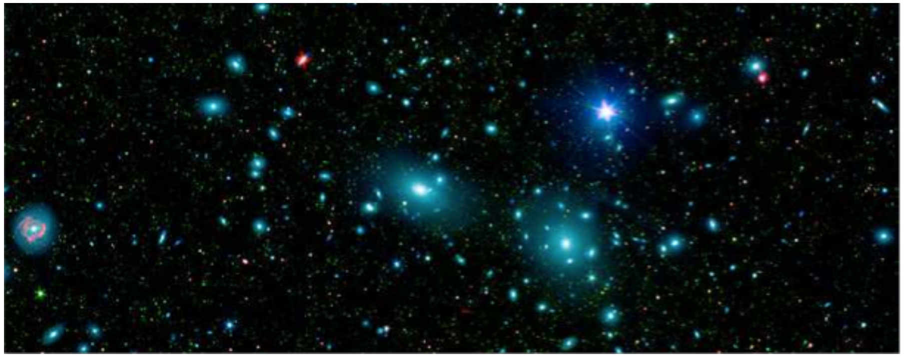
Oct. 5-7 2015

Outline

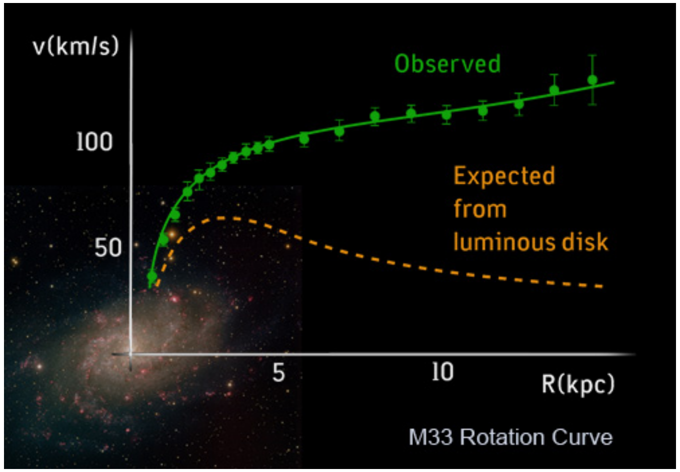
- Dark matter & dark matter candidates
  - Types of dark matter searches and complementarity
- Indirect searches for weakly-interacting massive particles (WIMPs)
  - Astrophysical backgrounds
  - Types of limiting factors for search sensitivity
- Current & planned instruments
- Selected WIMP search targets
  - Summary of search sensitivity and limiting factors
- Summary & Conclusions

DARK MATTER AND DARK MATTER CANDIDATES

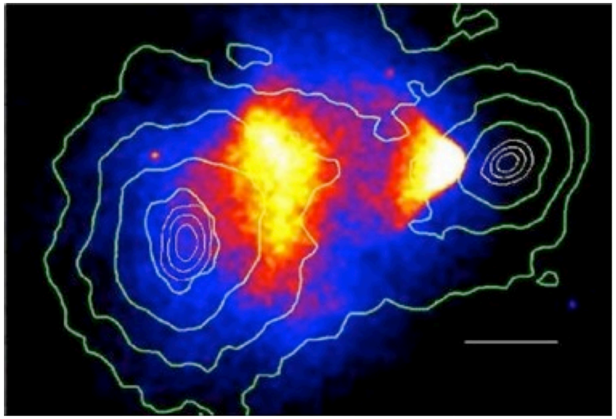
Evidence for / Salient Features of Dark Matter



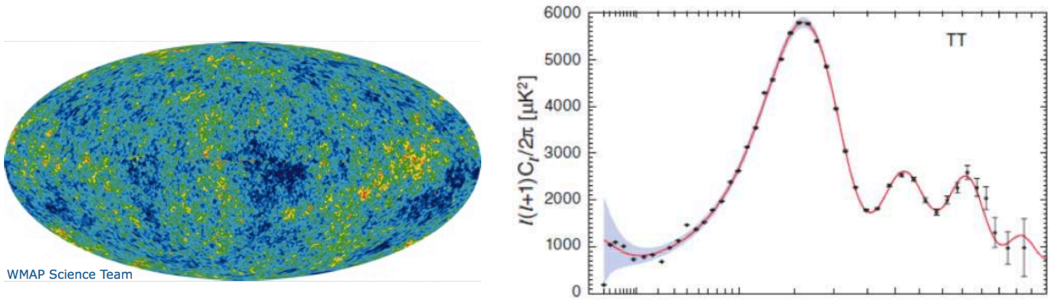
*Comprises **majority** of **mass** in Galaxies*
Missing mass on Galaxy Cluster scale
Zwicky (1937)



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

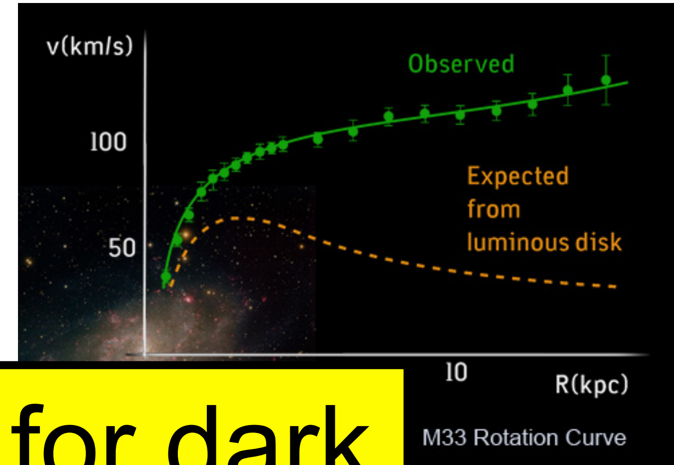


*Almost **collisionless***
Bullet Cluster
Clowe+(2006)



Non-Baryonic
CMB Acoustic Oscillations
WMAP(2010)

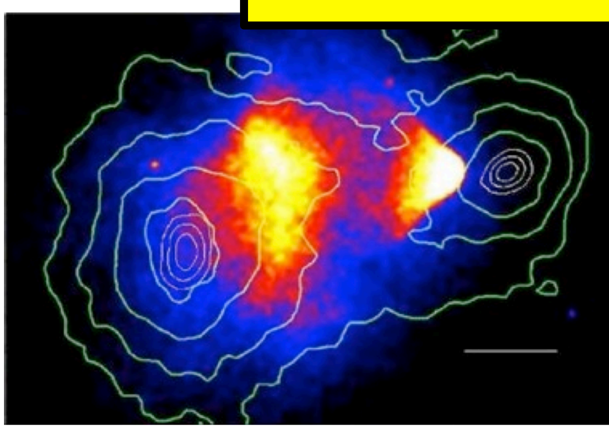
Evidence for / Salient Features of Dark Matter



Comprises
Missing ma
Zwicky (19

d Galaxies

All of the evidence for dark matter is astrophysical!



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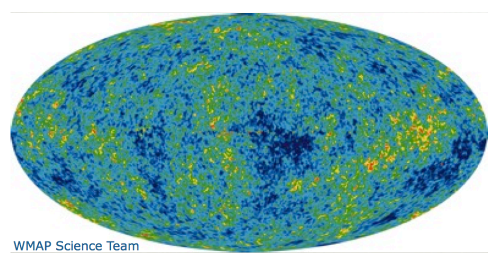

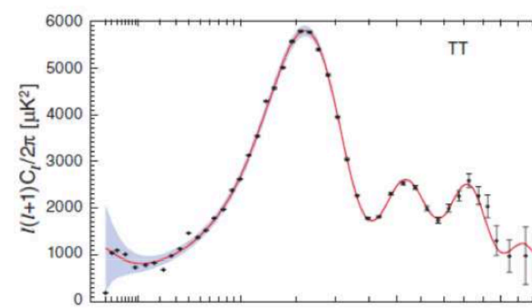

Non-Baryonic
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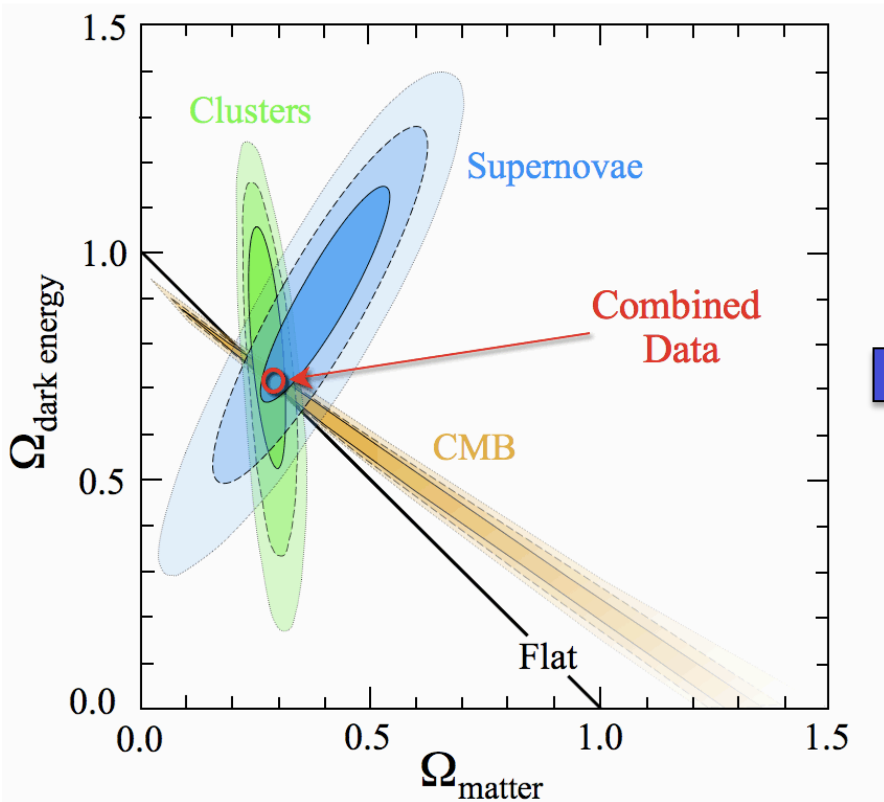
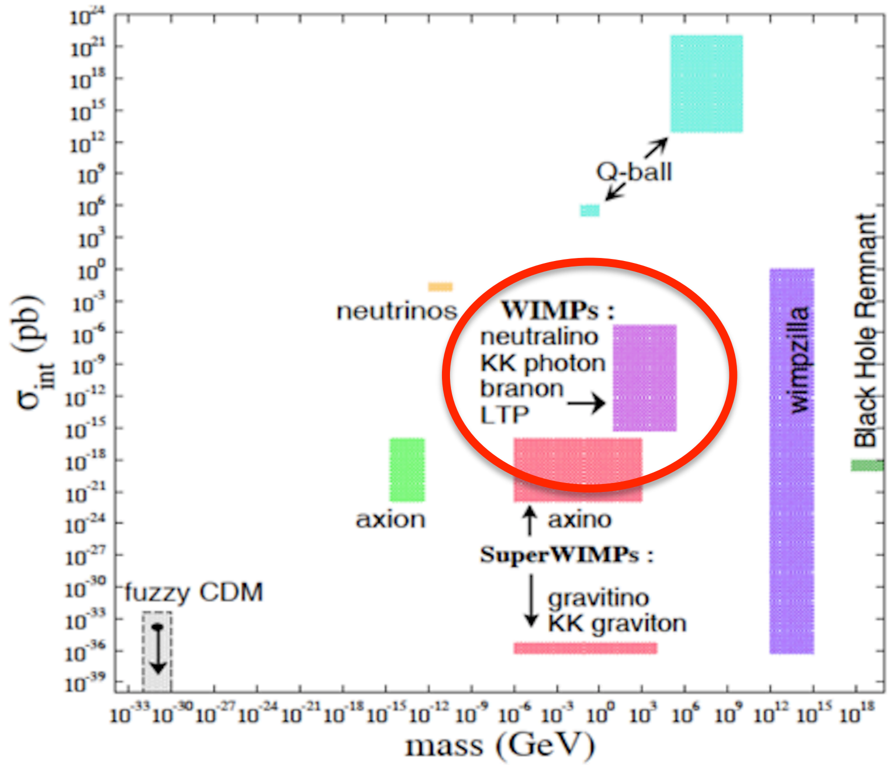
Cosmological Constraints on Dark Matter

Λ−CDM Concordance Fits

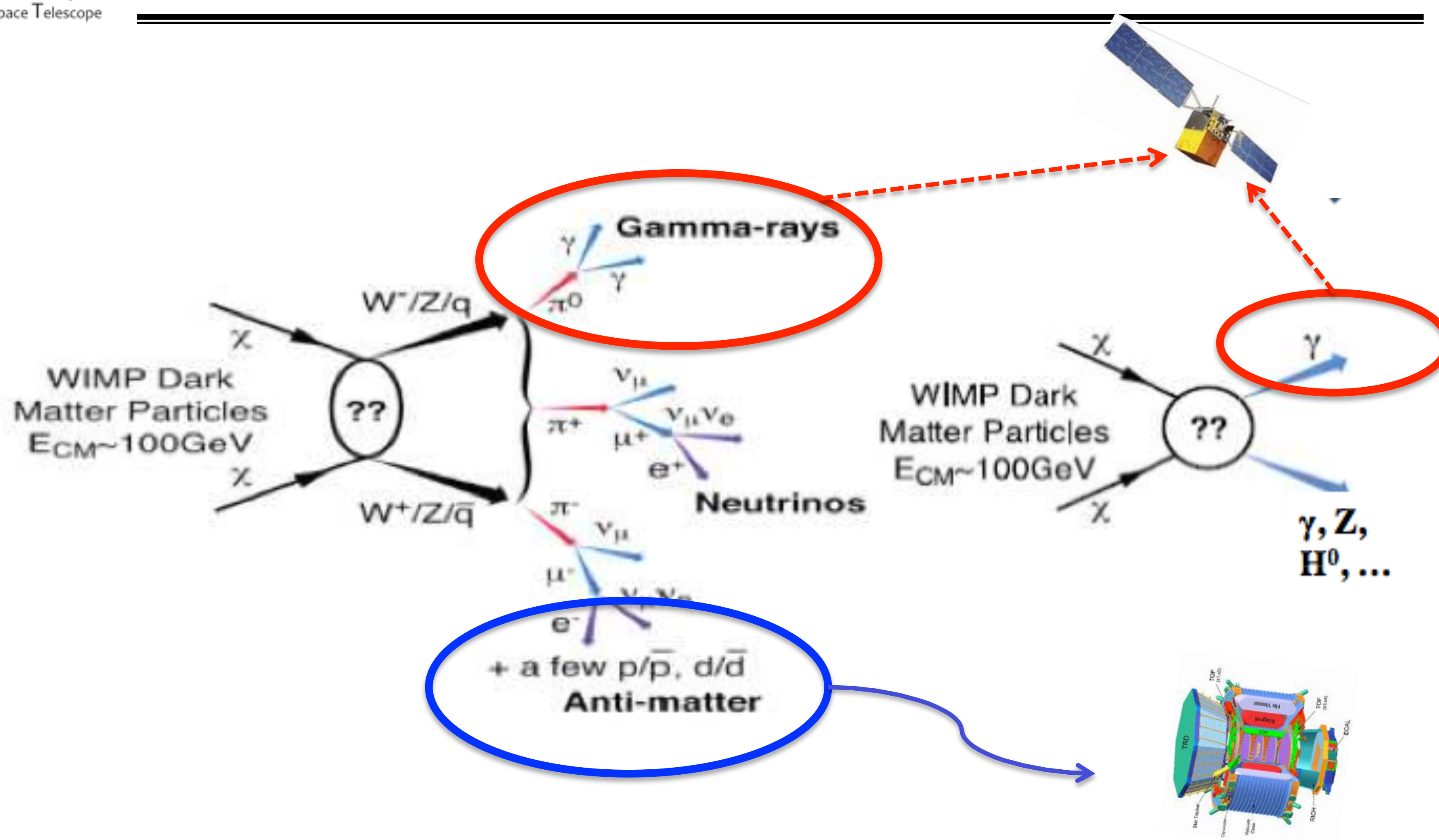


DM Candidates by Mass & Cross Section



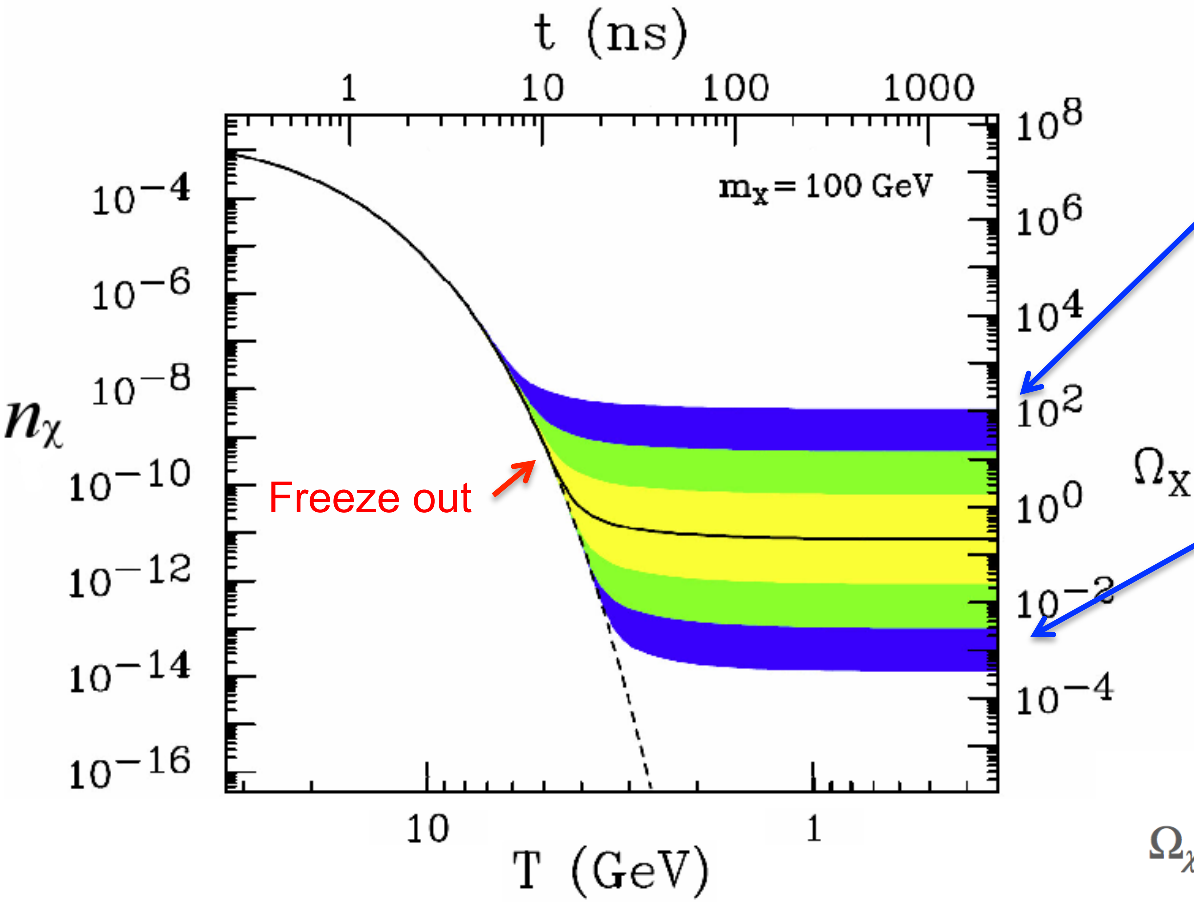
- No Standard Model particle matches the known properties of dark matter
- Many candidate particles have been proposed:
  - In this talk I will focus on WIMPs
  - Current instruments also sensitive to axion-like particles, primordial black holes, Q-balls

Indirect Detection of WIMPs



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

WIMP Dark Matter as a Thermal Relic



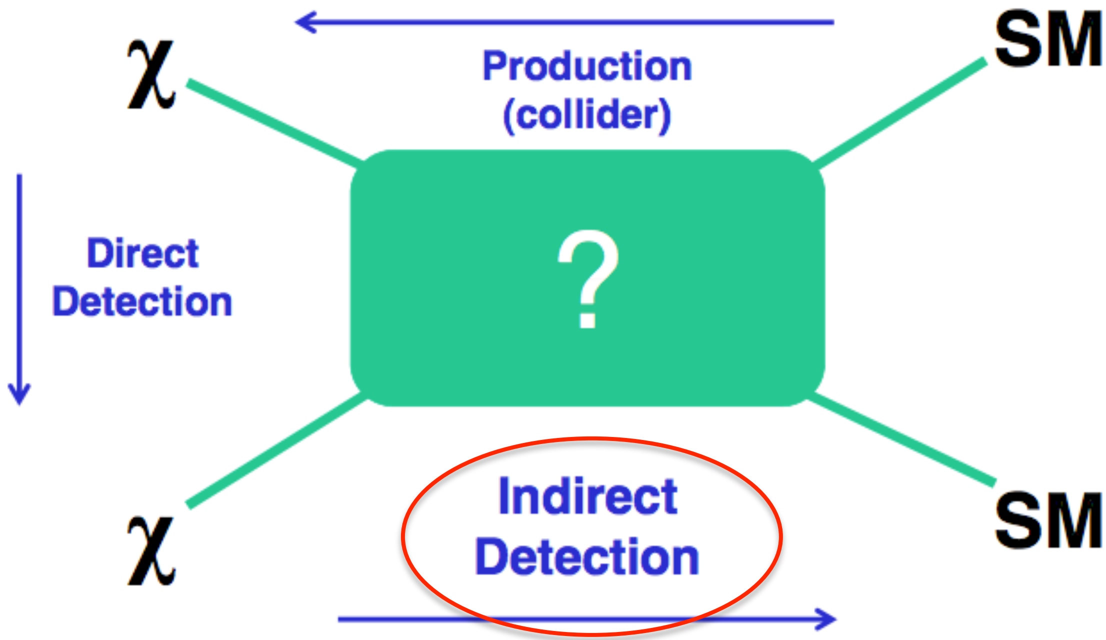
Small cross-section: freeze out too early, too many WIMPs

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 thermally 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 limits start to put constraints on model space

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)

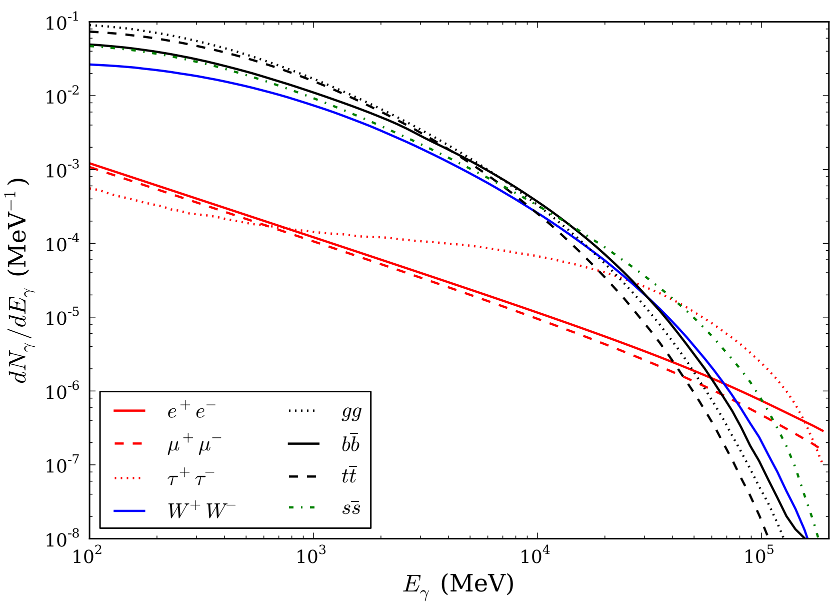
Indirect Searches for Weakly-Interacting Massive Particles

The Key Formula for WIMP Searches

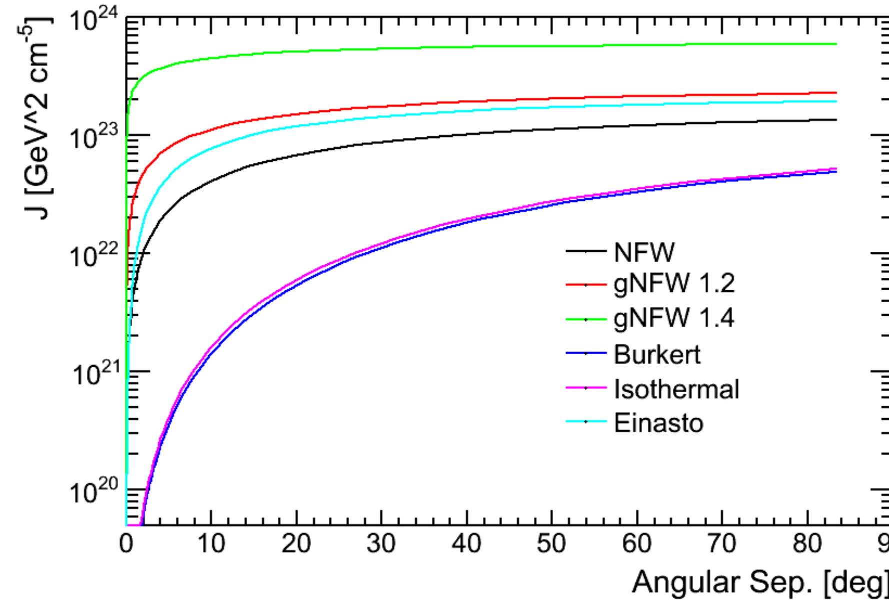
Particle Physics | Astrophysics (J-Factor)

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

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

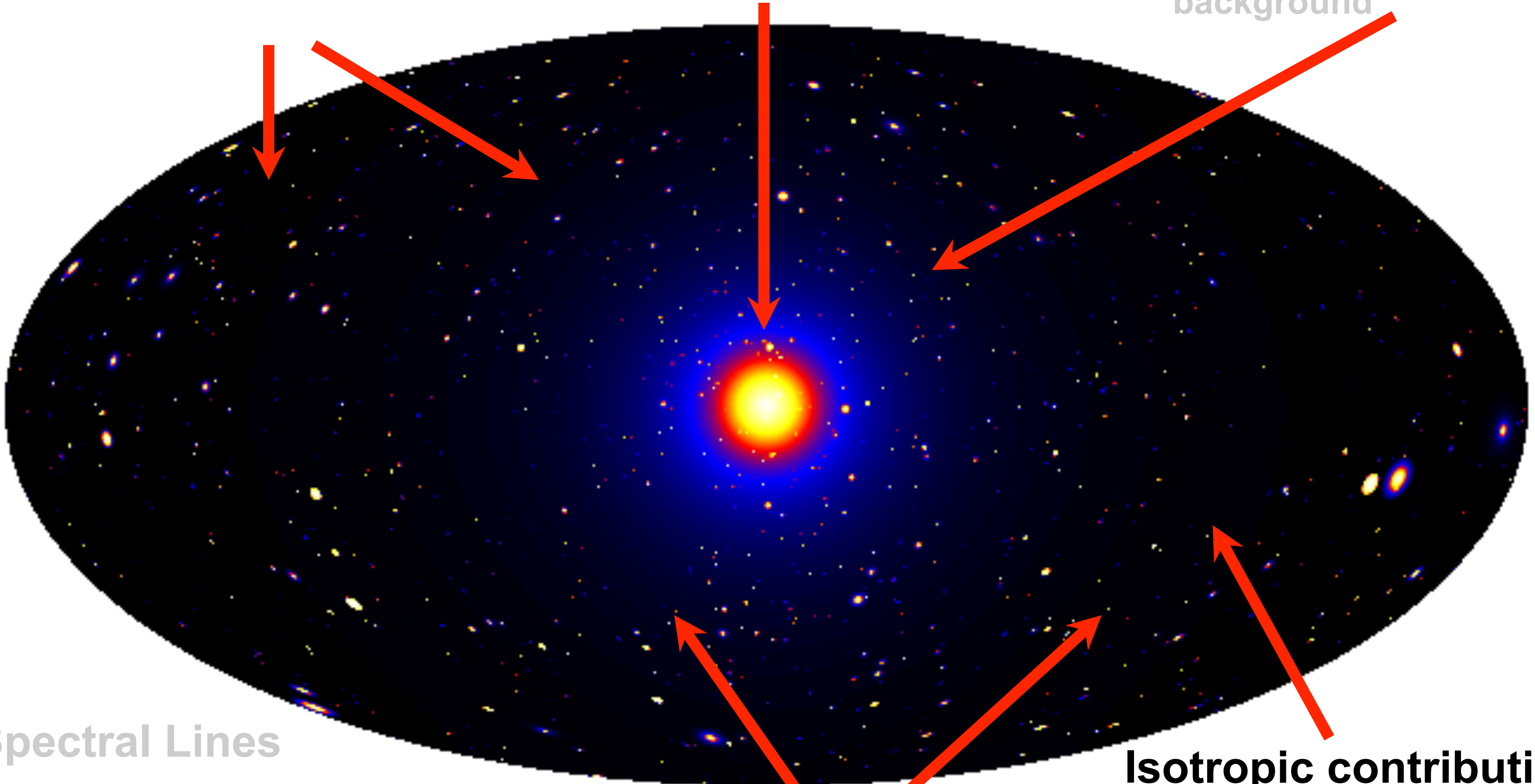
Low background and good source id, but low statistics

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

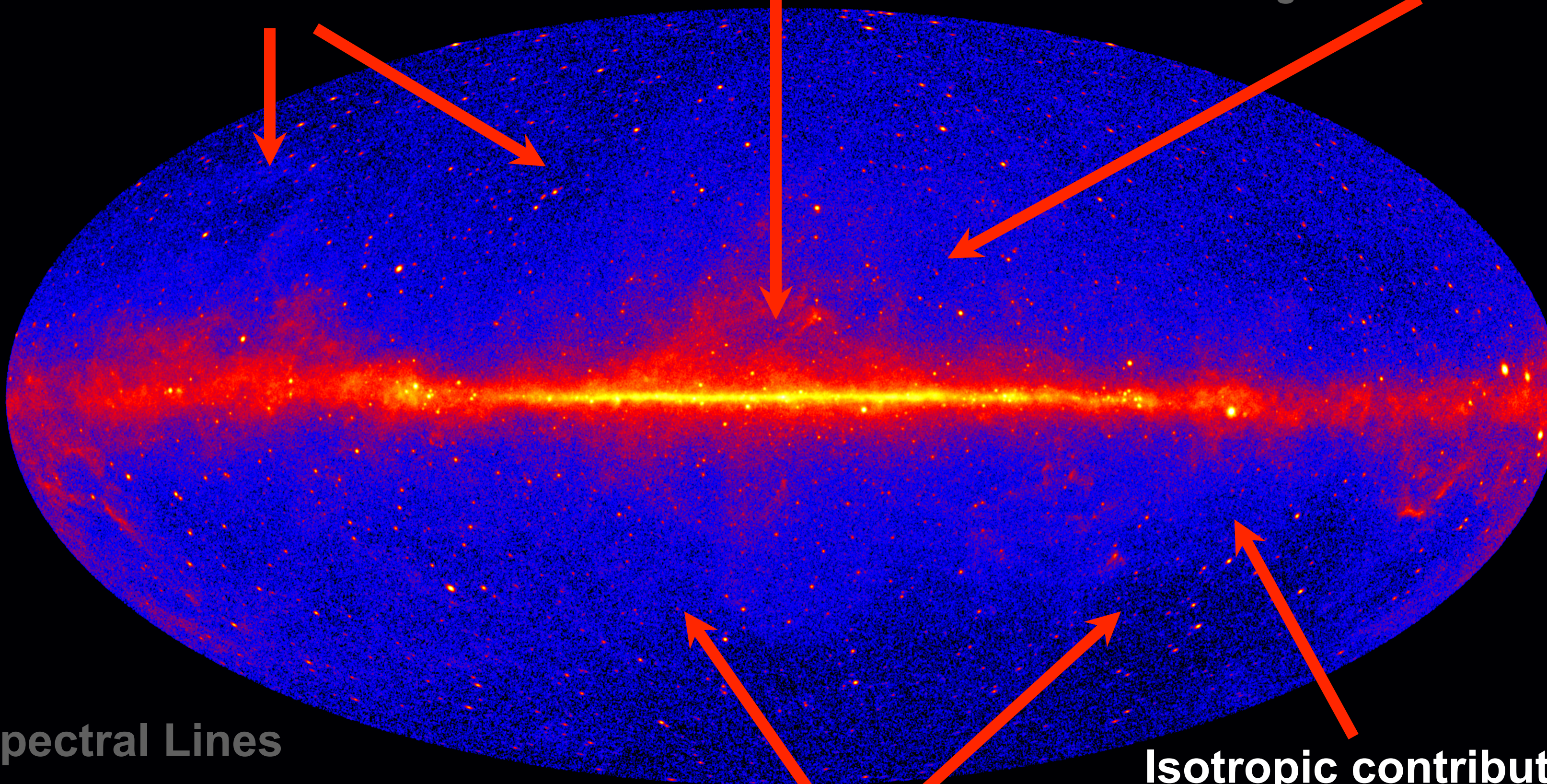
Low background and good source id, but low statistics

Galactic Center

Good statistics, but source confusion/diffuse background

Milky Way Halo

Large statistics, but diffuse background



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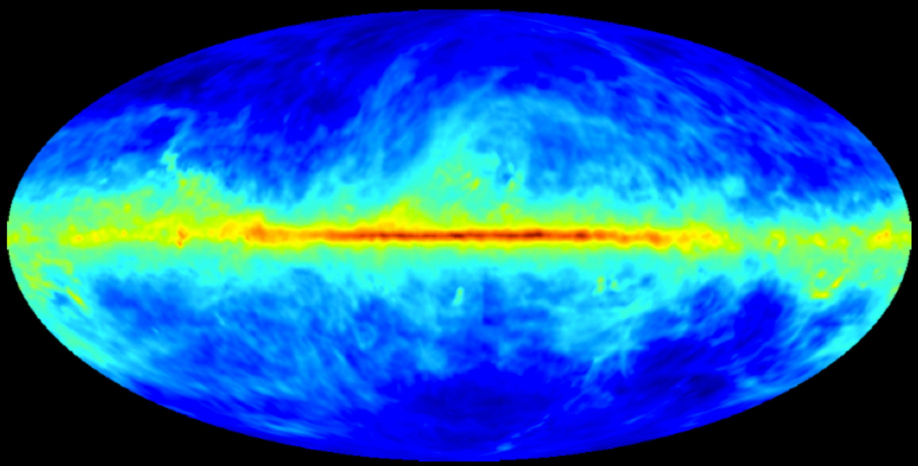
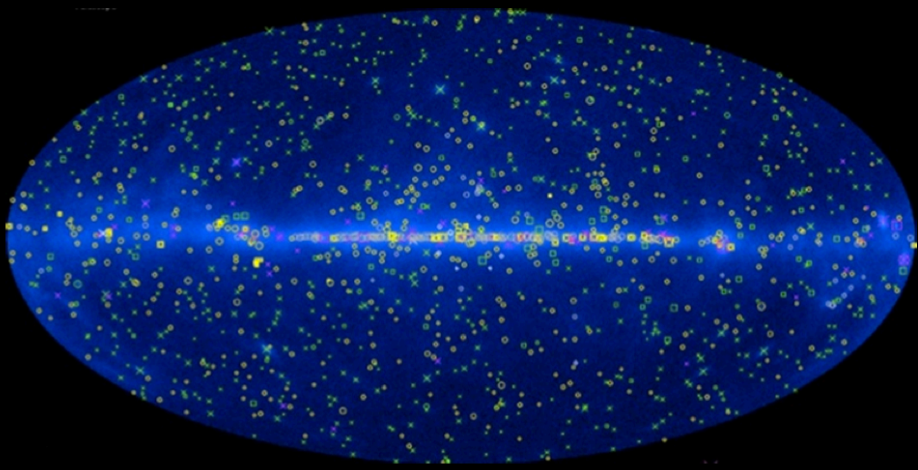
LAT 7 Years Sky > 1 GeV

Astrophysical Backgrounds (GeV)

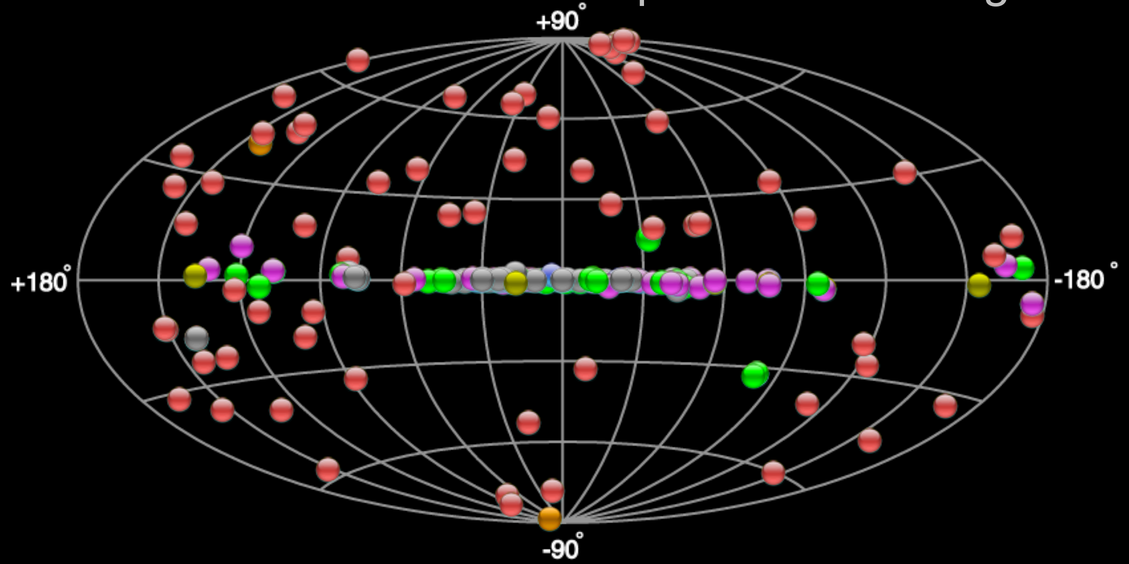




- Diffuse Backgrounds:
  - Cosmic-ray interactions with dust, gas and radiation fields
- Source Backgrounds:
  - Blazars and Active Galactic Nuclei
  - Pulsars
  - Supernova Remnants
  - Galaxies (starburst galaxies)
- Unresolved Sources

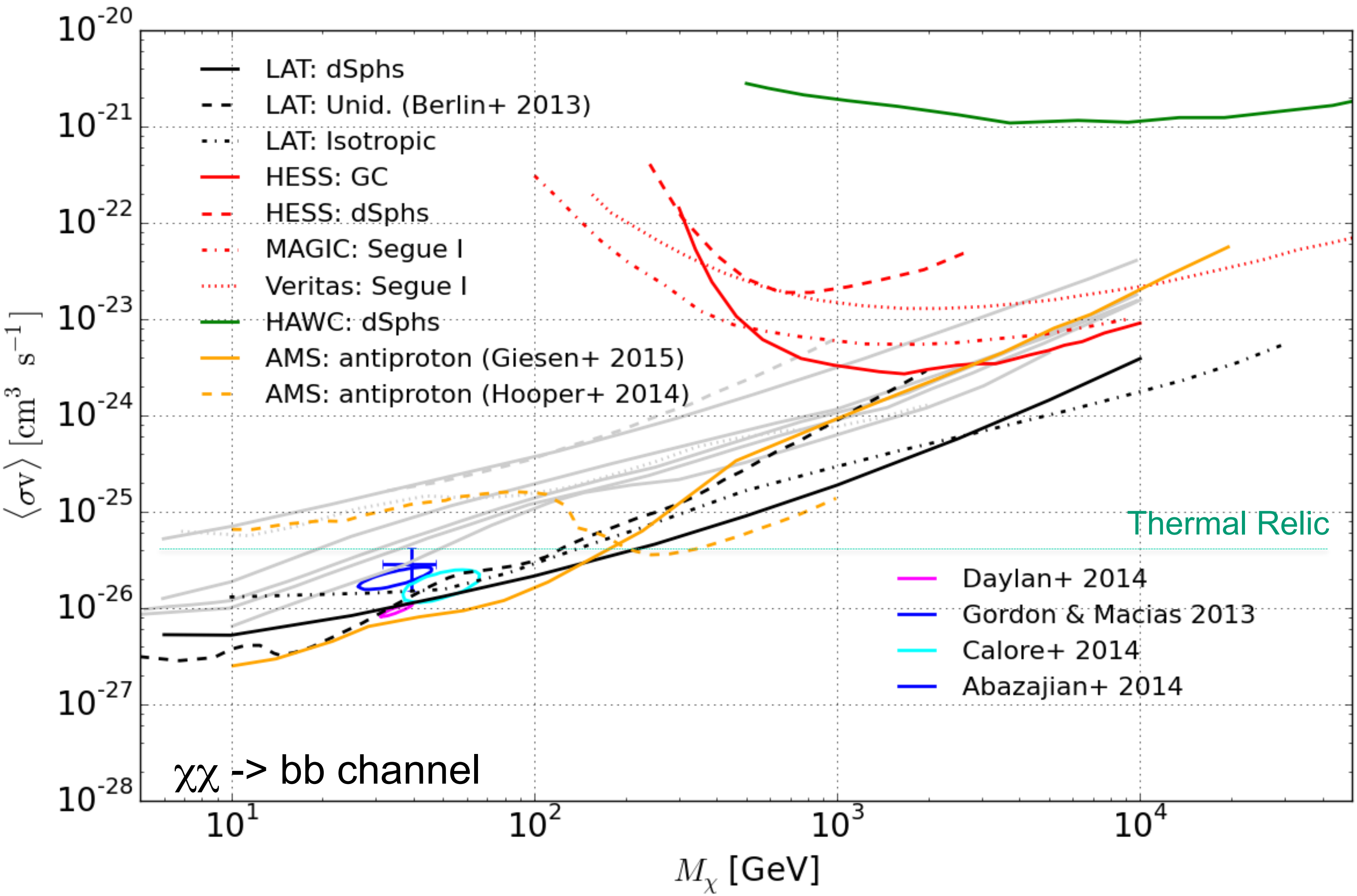
Astrophysical Backgrounds (TeV)

TeV sources from TeVCAT: http://tevcat.uchicago.edu/



- Diffuse Backgrounds:
  - Cosmic-ray interactions with dust, gas and radiation fields
    - Diffuse spectra softer than typical source spectra
- Source Backgrounds:
  - Blazars and Active Galactic Nuclei (z < ~0.5)
  - Pulsars
  - Supernova Remnants
  - Galaxies (starburst galaxies)
- Unresolved Sources

Some Published Results from Indirect DM Searches



Aside: Limiting Factors for Search Sensitivity

1. *Systematics-limited*: limited by uncertainties of modeling either the background or the dark matter target. Additional data will help to the extent that it improves the modeling uncertainties.
2. *Background-limited*: limited by the noise-fluctuations of the background. Additional data will improve sensitivity as sqrt(N)
3. *Signal-limited*: limited by the magnitude of the expected signal. Additional data will improve sensitivity linearly

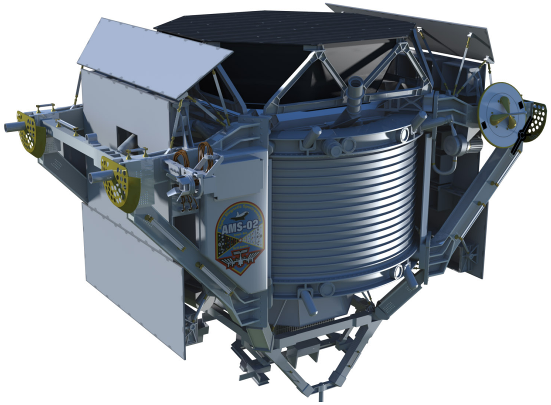
Limiting Factors Feed into Instrument Design

- For *systematics-limited* and *background-limited* searches we probably want to focus first on the background
  - Reduce background:
    - Better particle type identification (e.g., reduce cosmic-ray contamination of gamma-ray data)
    - Improve point-spread function, reducing area of sky within the signal target
  - Improve understanding / modeling of background
    - Reduce modeling uncertainties, constrain intensity of background
- For *signal-limited* searches we want more data:
  - Increase size, efficiency, duty cycle of detector, find more search targets

Current & Next Generation Instrumentation

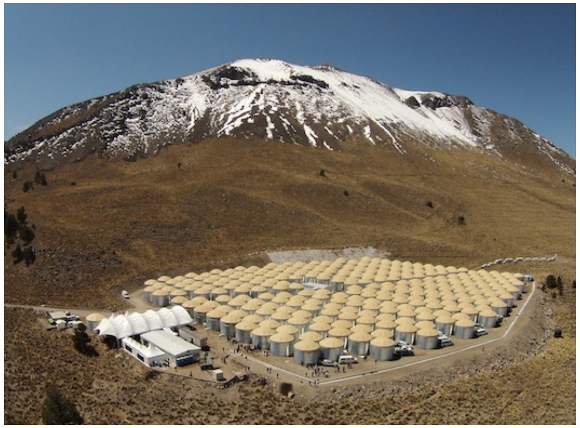
High Energy Astrophysics Instruments

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

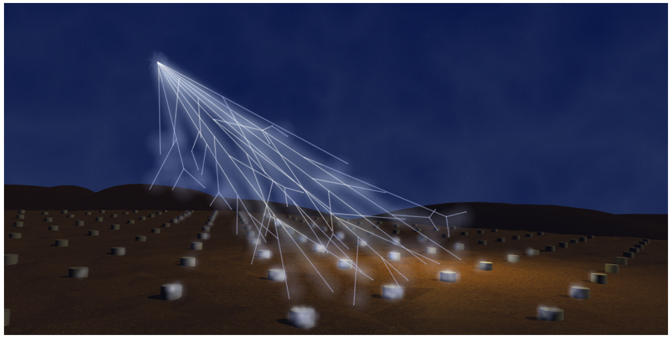


Cosmic-ray detectors:
PAMELA, *AMS-02*, *HERD*

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

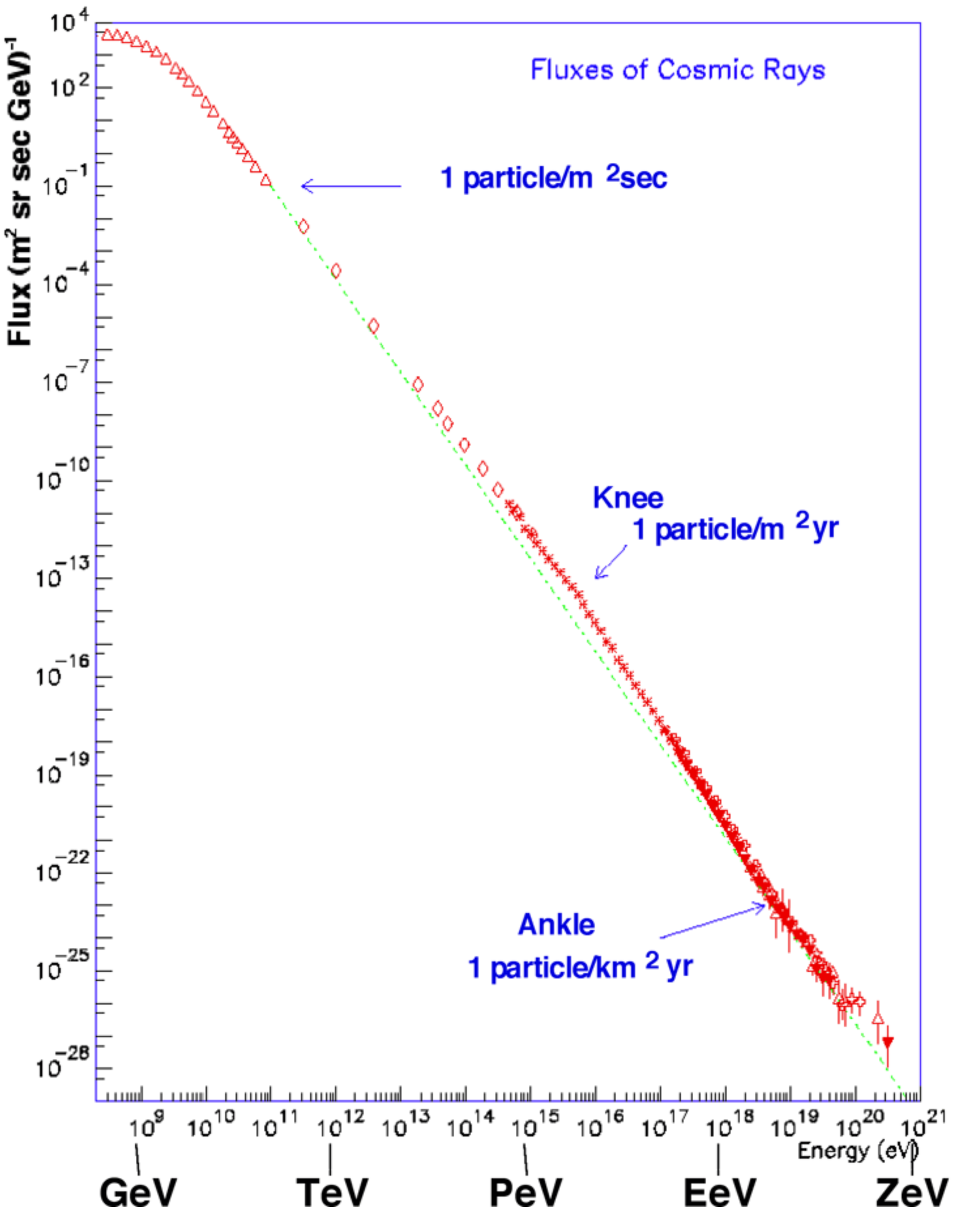


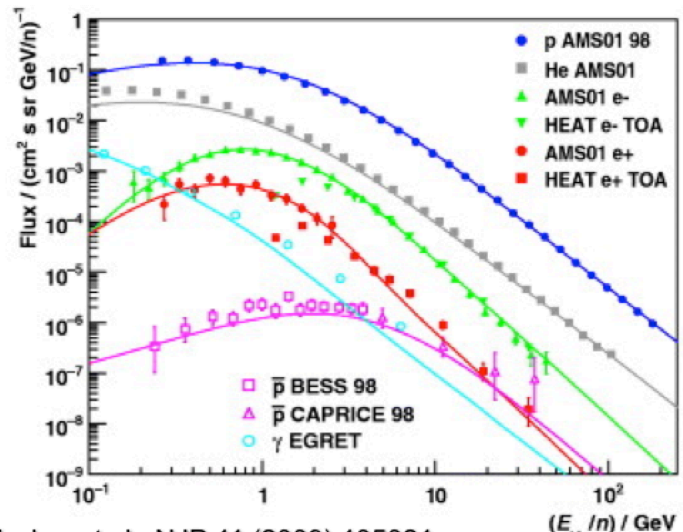
Water Cherenkov Telescopes:
HAWC, *ICE-Cube*



Hybrid cosmic-ray detectors:
Auger

Sensitivity to Cosmic Rays (and γ Rays) Depends on Instrument Area

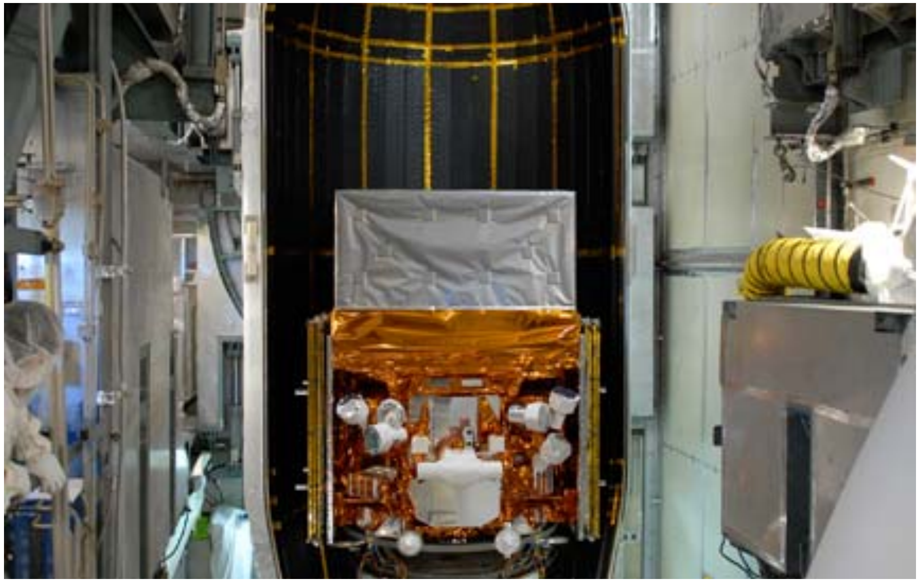


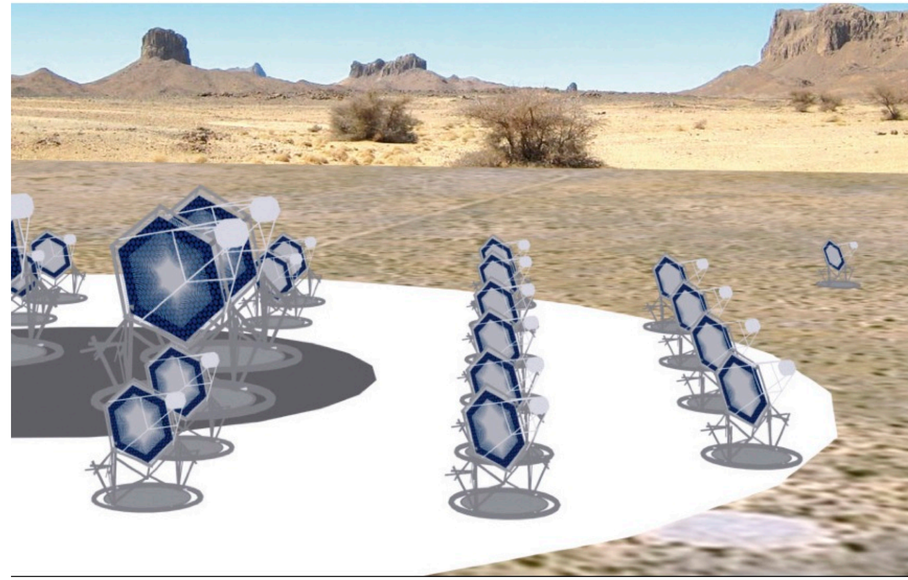


Beischer et al., NJP 11 (2009) 105021

- Fluxes fall like power laws, typically by three orders of magnitude per decade in energy, 87% p, 9% He, few % heavy ions, even fewer $e^{\pm}$ and γ
- Acceptance in $m^2 sr$ determines energy reach

Driving Factors in Instrument Development

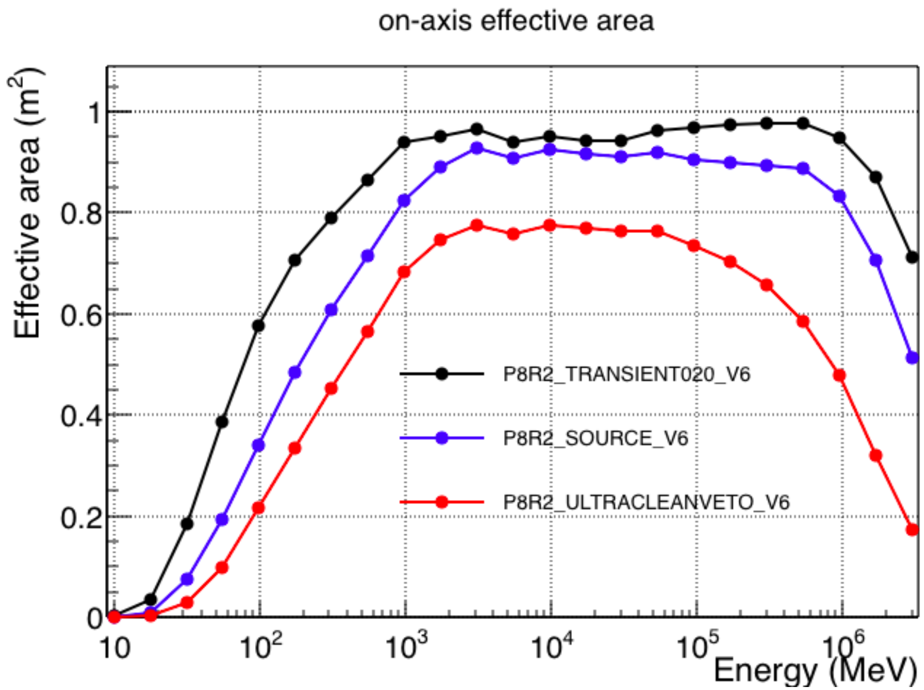




- *Space-based*: performance constrained by mass (~< 10000 kg), power budget (~< 3kW), bandwidth (~< 10 MHz averaged). Must survive launch (vibrational / acoustic noise), space radiation environment.
- *Ground-based*: performance constrained by light collection area, array size and in-fill factor, (air-showers arrays: night-sky brightness)

In both cases we are pushed toward modifying well-established technology to meet the instrument design challenges & optimize scientific return.

Key LAT Performance Limitation: Size



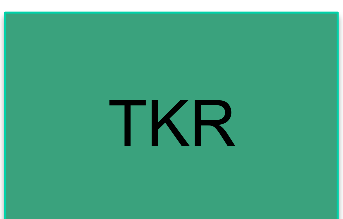
- The on-axis cross-sectional area of the LAT is ~2.25 m^2
- The tracker is 1.4 X_0 deep: roughly 2/3 of on-axis γ rays convert in the tracker, giving a maximum effective area of ~ 1.5 m^2
- Actual effective area is ~1m^2

Optimizing Pair-Conversion Telescopes

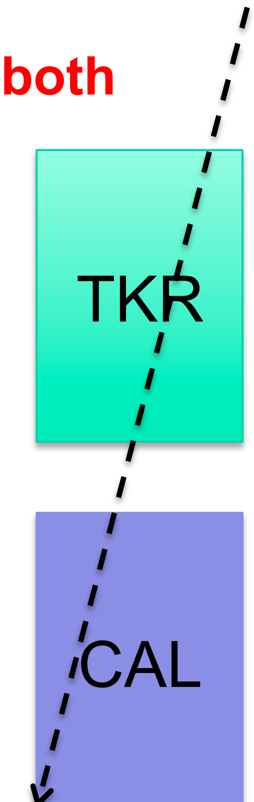
$$X_0 = \frac{716.4 \text{ g cm}^{-2} A}{Z(Z+1)\ln(287/\sqrt{Z})}$$

Radiation length sets scale for both scattering and pair conversion

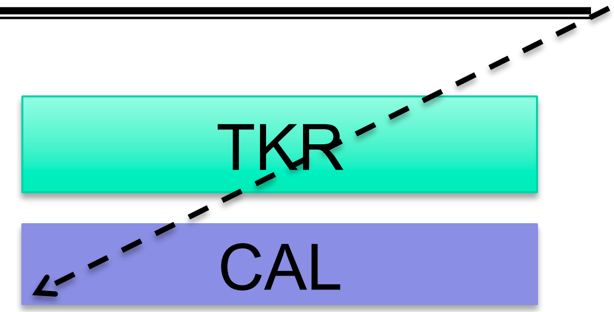
Low density:
Good PSF,
Poor A_{eff}



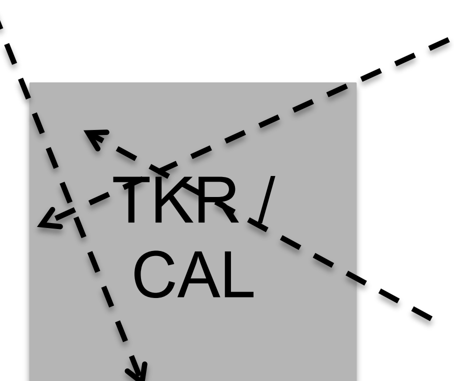
High density:
Poor PSF,
Good A_{eff}



Large Layer Spacing:
Good Resolution,
Poor FoV

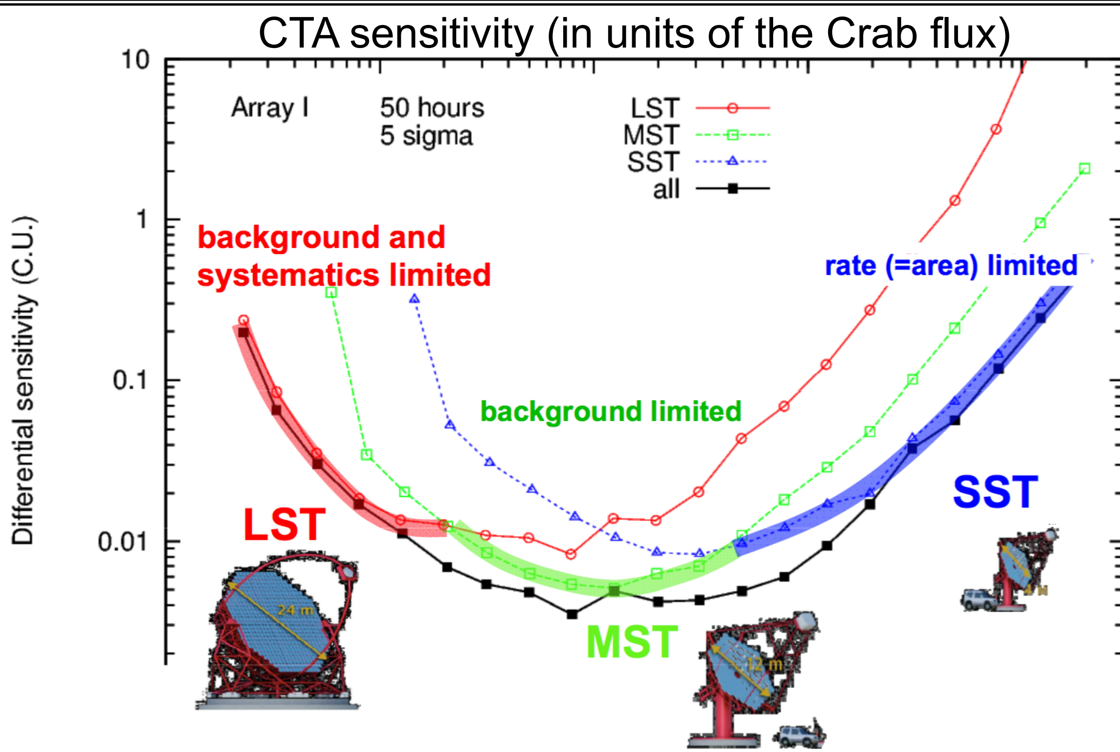


Small Layer Spacing:
Poor Resolution,
Good FoV



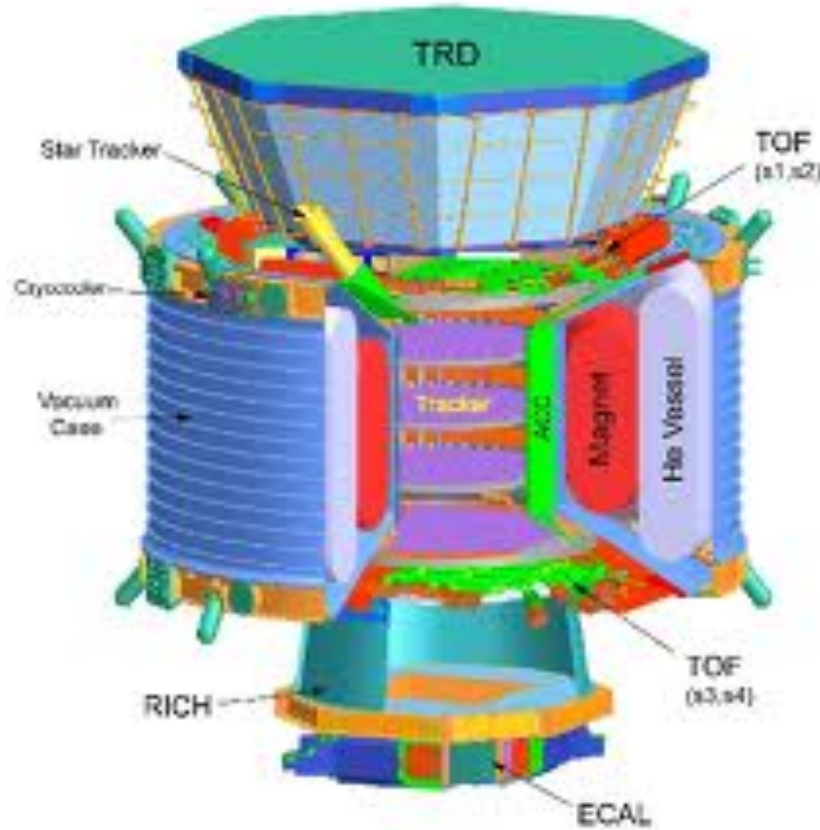
Is there a technology that allows monolithic design for > 2π field of view?

Optimizing Ground-based Telescopes



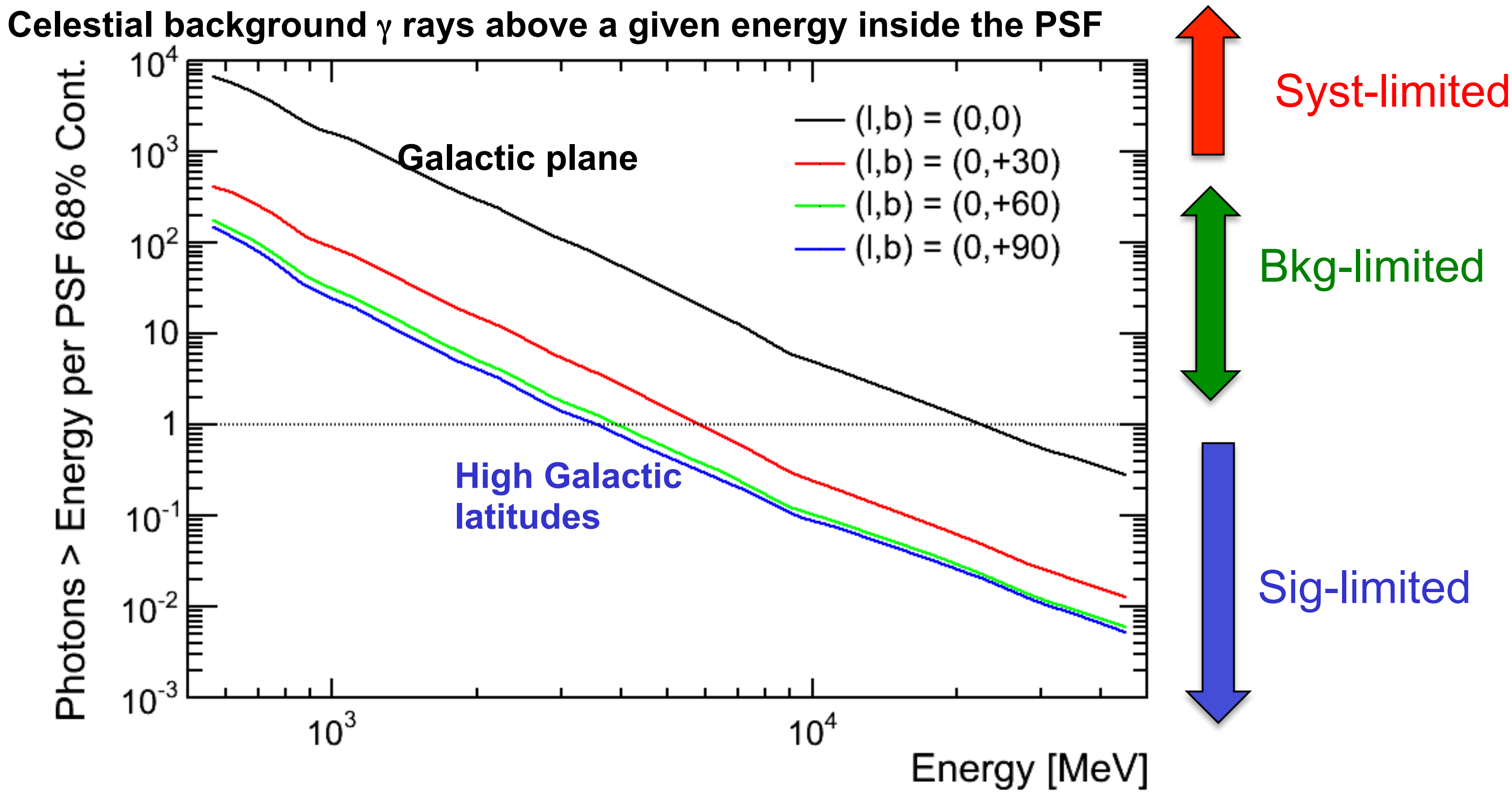
- CTA design extends energy band-pass by using different types of telescopes to cover different energy ranges
- *Low-energy*, need more sensitivity to detect Cerenkov light -> few large telescopes
- *High-energy*, need more area to compensate for falling rate -> lots of small telescopes

Optimizing Cosmic-Ray Detectors



- Large cosmic-ray fluxes, key is particle identification
  - Design multiple sub-systems to provide redundant information about particle charge, momentum, energy

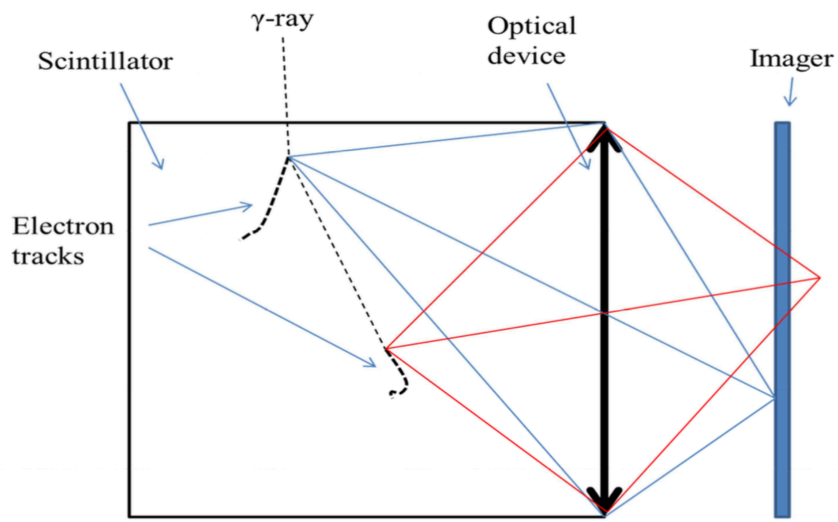
Optimizing PSF (Resolution) v. A_{eff} (Efficiency)



- Once we are signal limited, efficiency becomes more important than background rejection
  - Signal limited: expect < 1 background γ ray inside the PSF
  - Background limited: lots of background photons
    - we should favor spatial resolution over detection area to allow us to disentangle complex regions like the Galactic center

Alternate Technologies for Pair-conversion Telescopes

Gamma Cube design concept

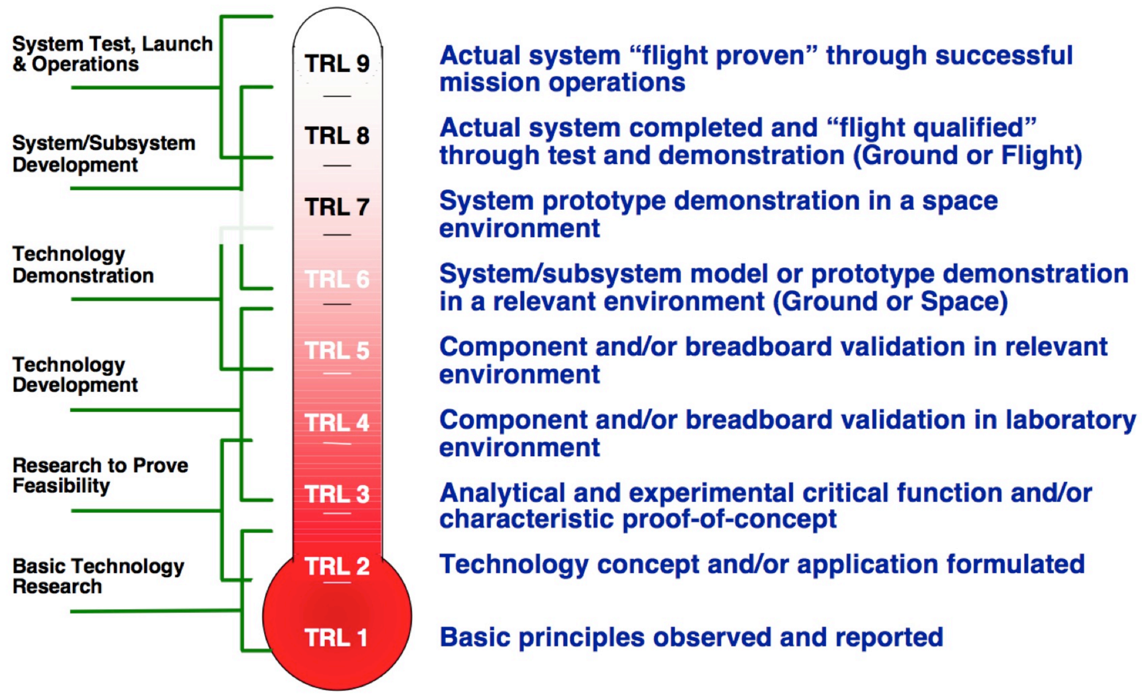


- *3D tracking:* use gas drift chambers or noble liquid TPCs: increase the density of spatial measurement; e.g., LaRGO, AdEPT.
- *Tracking Calorimeters*: highly segmented scintillator, e.g., HERD.
  - Fiber Tracker: scintillating fibers as sensor material, e.g., APT
- *Active masks / collimators*: like coded mask, but rather than try to shield the sensors against γ rays, use an active veto
- *Solid State Bubble Chamber*: imaging the scintillation light from a solid plastic scintillator, e.g., Gamma Cube

Aside: NASA Instrument development

NASA/DOD Technology Readiness Level

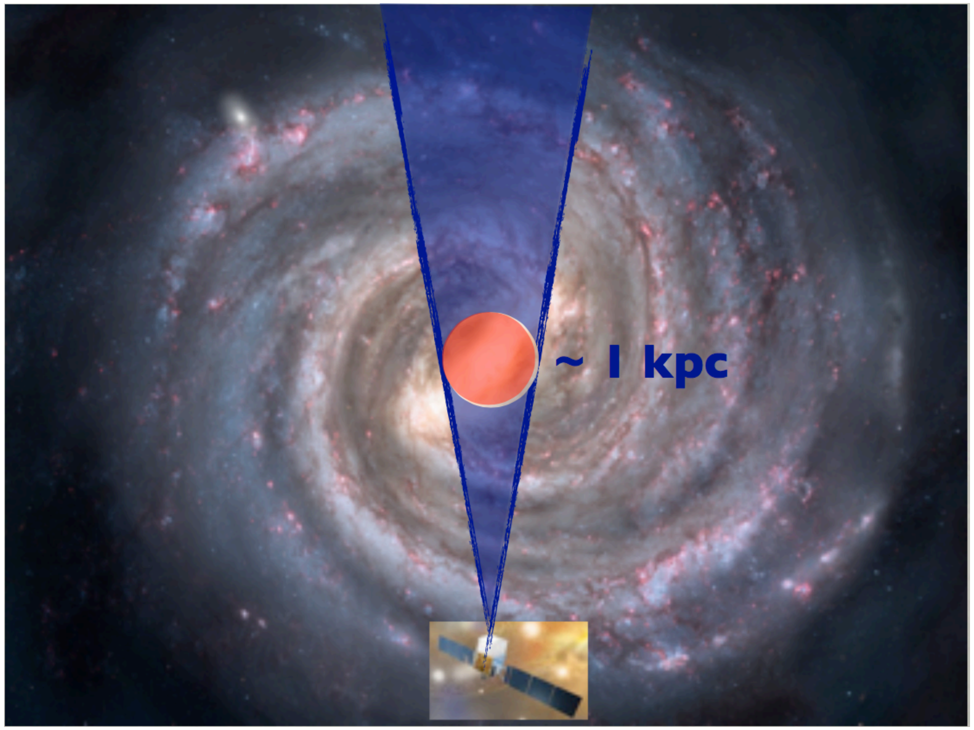
Technology adopted from Other HEP applications comes in here



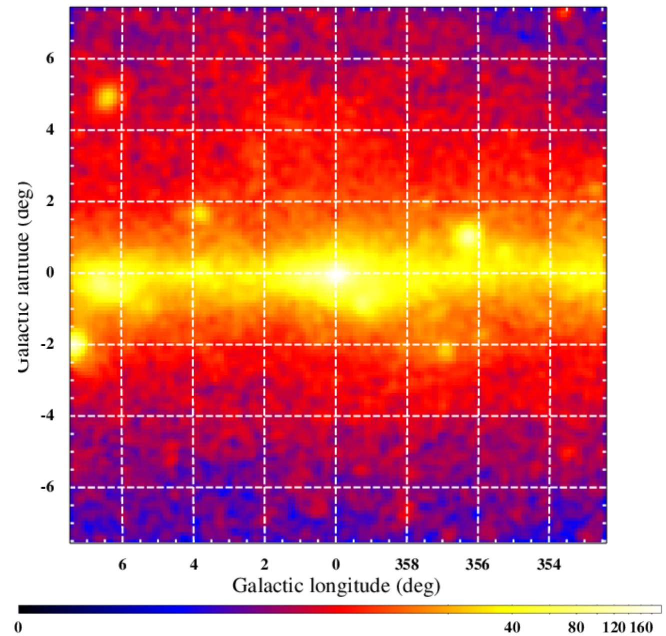
- NASA has a well-defined R&D program designed to adapt suitable technologies for space missions
  - NASA accepts proposals for technologies at all TRLs
- What is missing is LDRD-type funding to survey existing technologies and prepare competitive NASA R&D proposals.

WIMP Searches Targeting the Galactic Center

Observing the Galactic Center



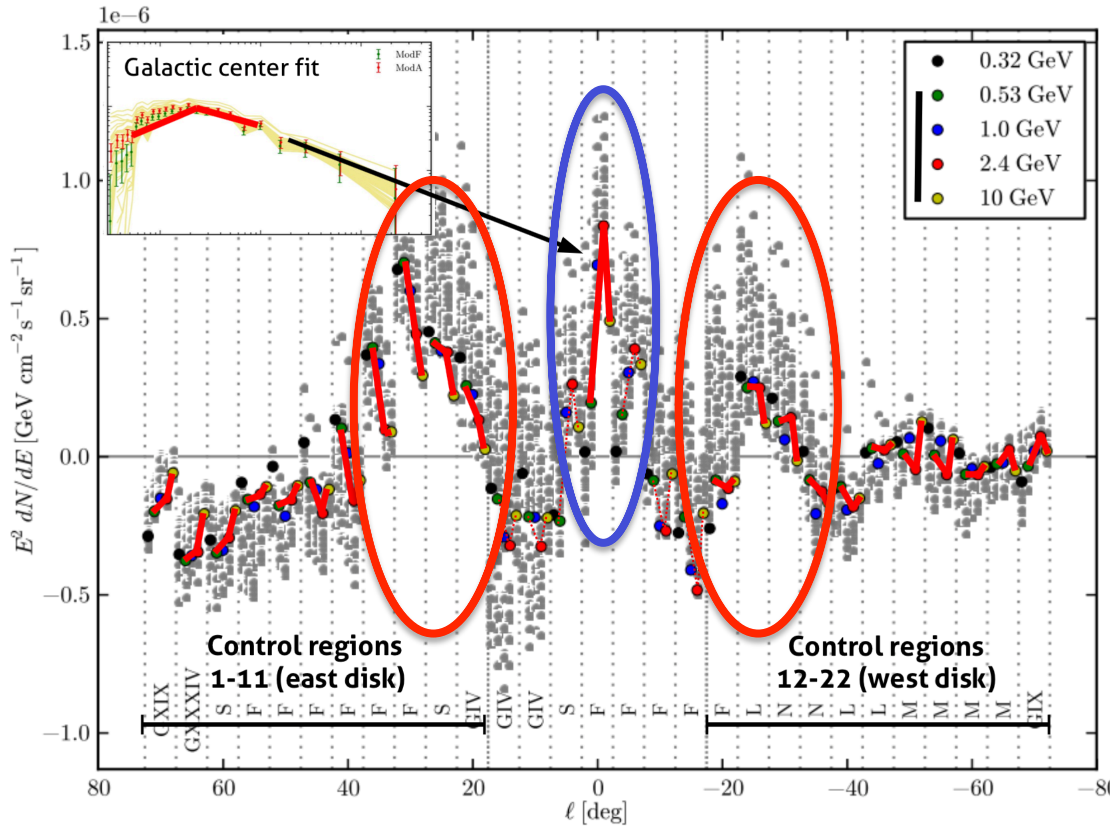
LAT Counts: 4 years, 1-100 GeV



- 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

Estimating the astrophysical modeling uncertainties

Spectral Excesses w.r.t. diffuse emission model in as a function of Galactic longitude

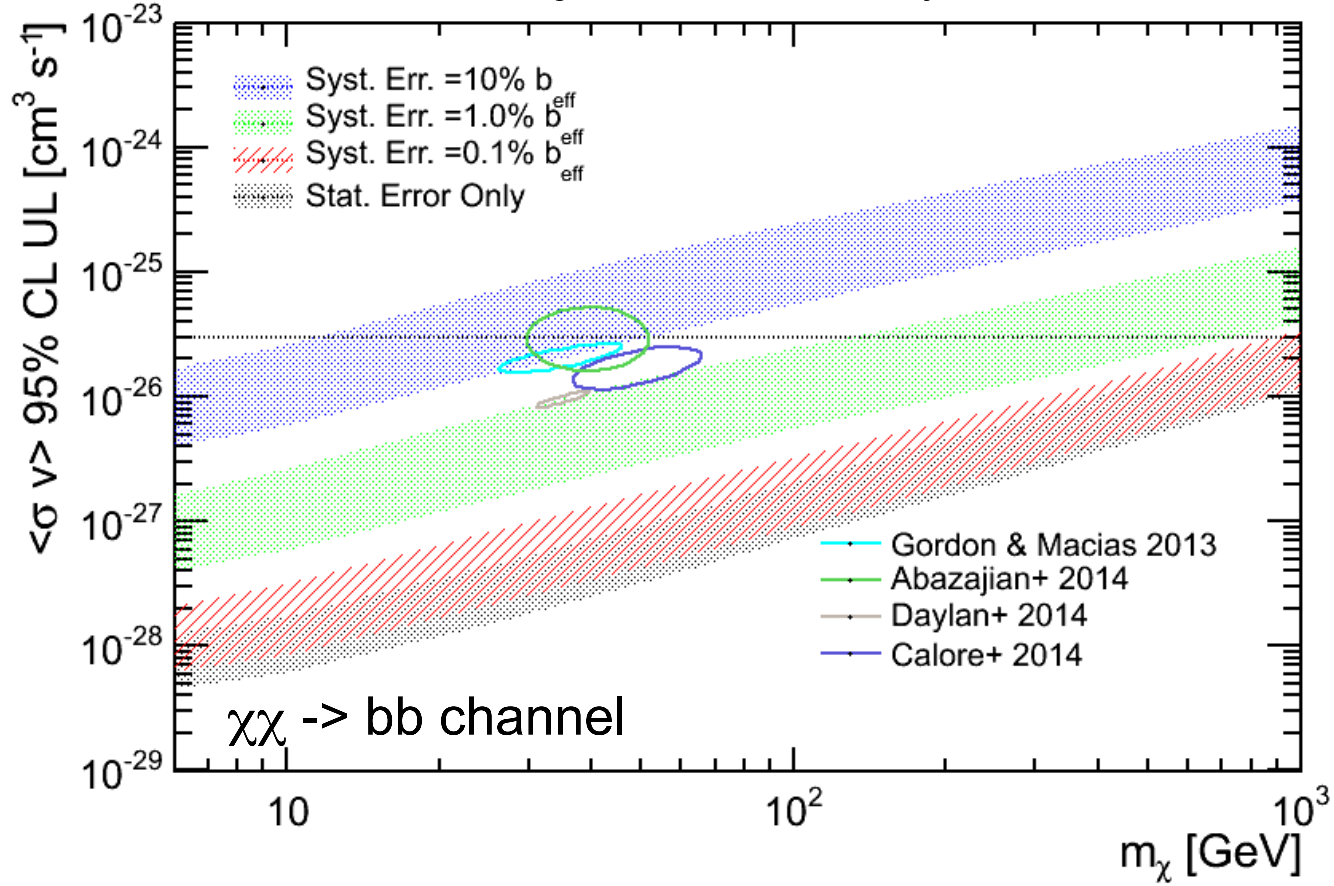


Calore+(2015)
arXiv:1409.0042

- 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 not-clear (similar size excesses attributed to local sources of cosmic rays are present elsewhere)

DM Search targeting GC is systematics-limited

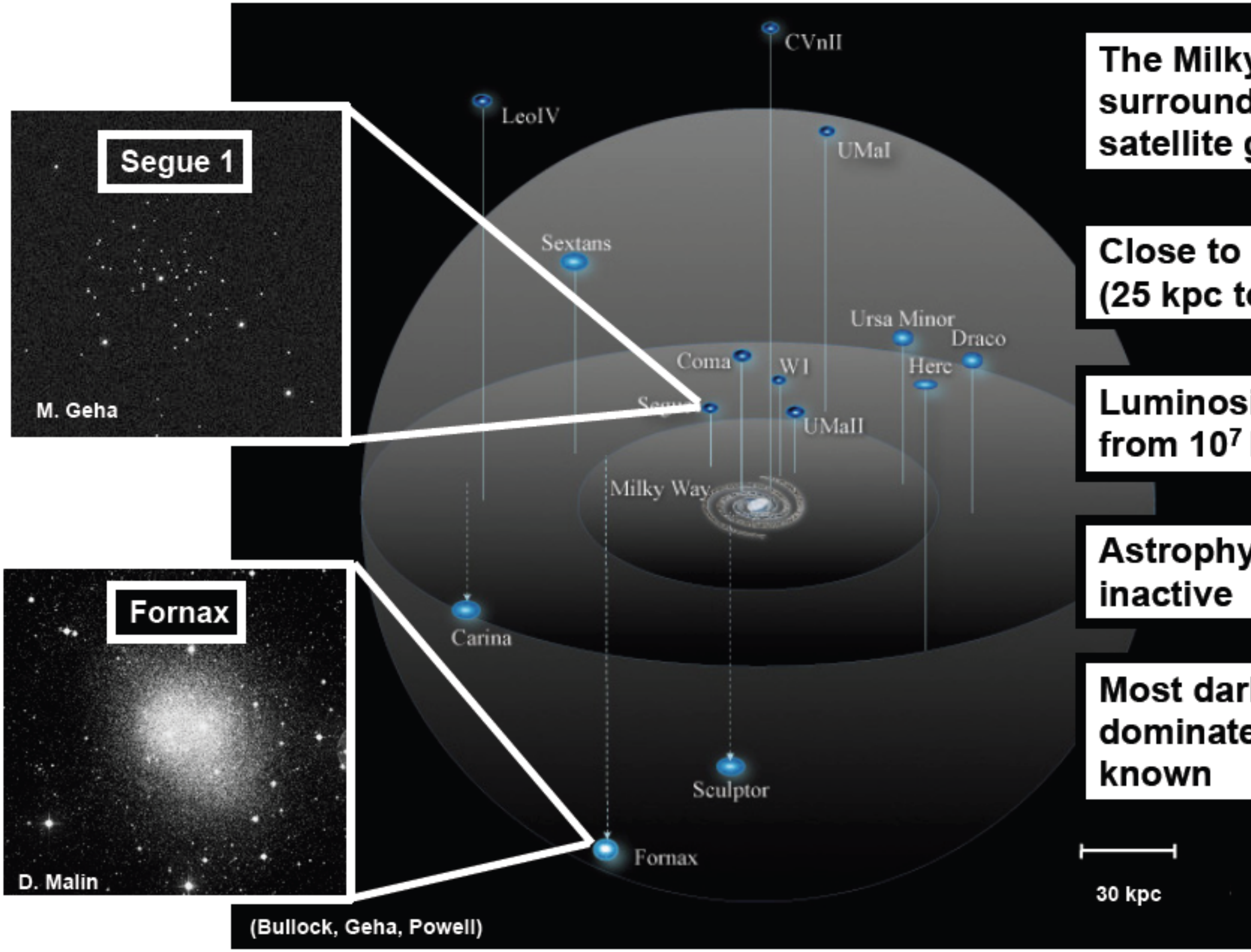
Expected ULs on DM from the GC assuming different levels of systematic uncertainties (LAT: 6 years)



- Express the expected uncertainties as a function of the "effective background", i.e., the background that overlaps with the dark matter profile
- Testing current signal claims require understanding the background at the few percent level (studies of control regions suggest we are at the ~10-20% level)

WIMP Searches Targeting Dwarf Galaxies

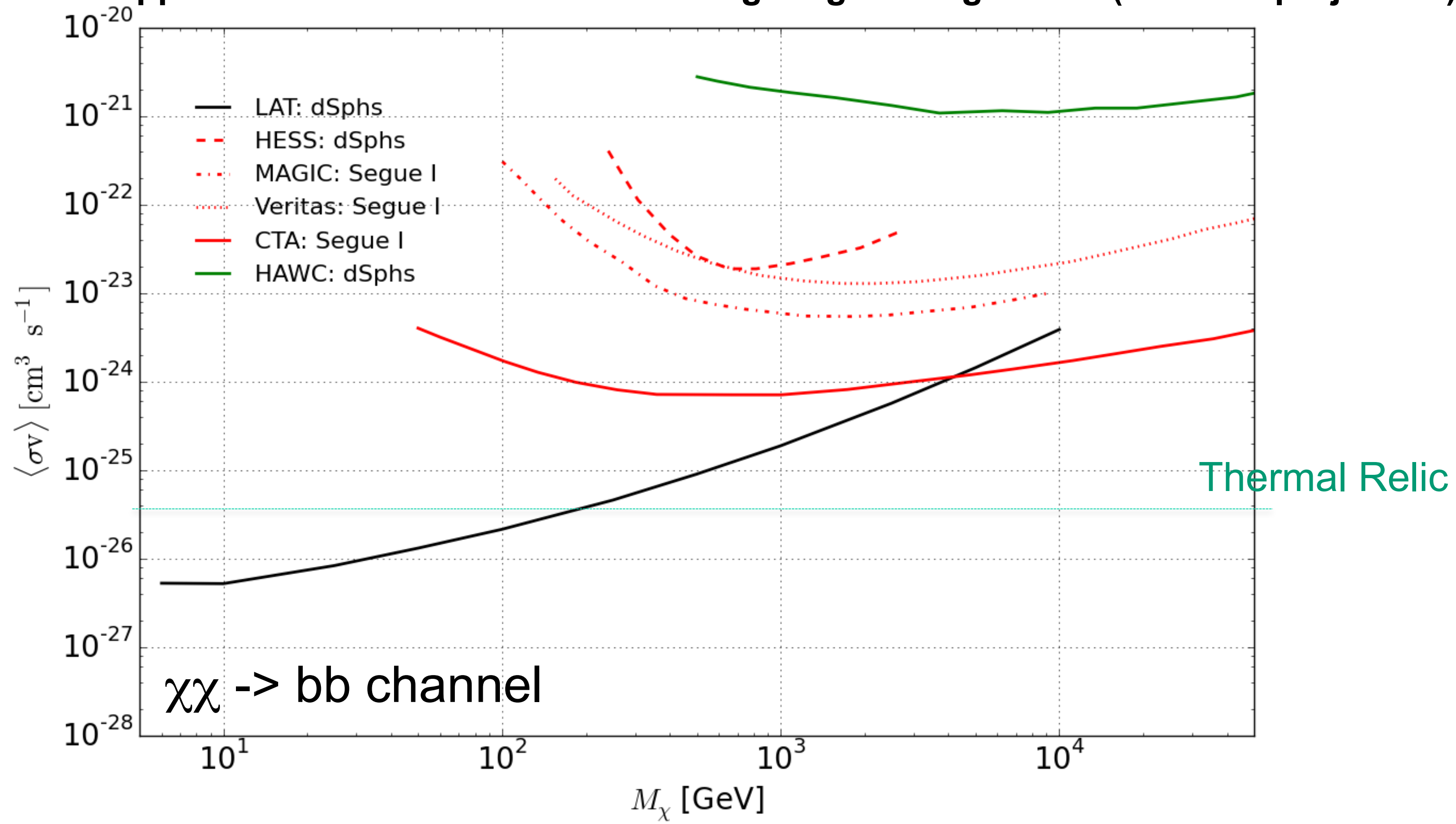
Dark Matter Searches in MW Dwarf Galaxies



- 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

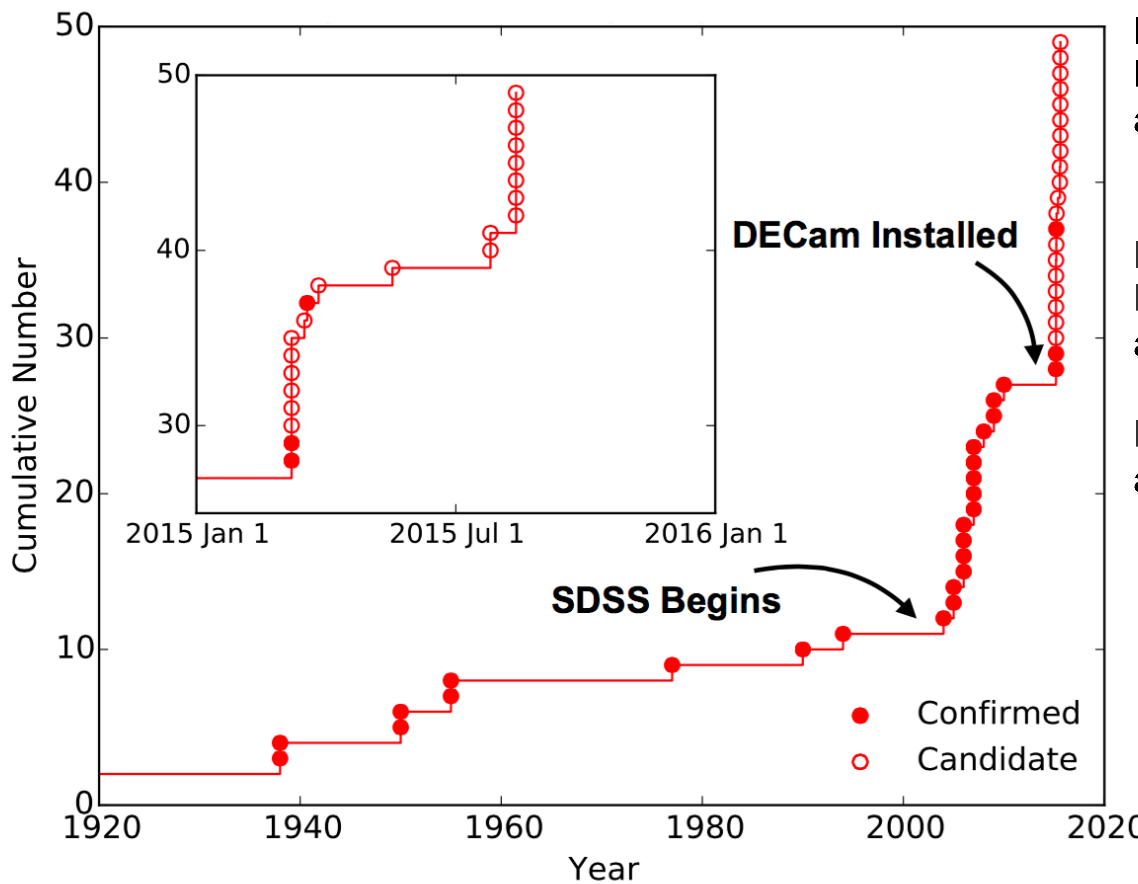
Limits from Dwarf Galaxy DM Searches

Published upper limits on DM from searches targeting dwarf galaxies (and CTA projection)



- Limits are dominated by LAT up to a few TeV
- LAT limits are background-limited up to ~100 GeV, signal-limited above

Rapidly Growing Dwarf Galaxy Population



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

DES Year 1 Data:
Bechtol+:
arXiv:1503.02584

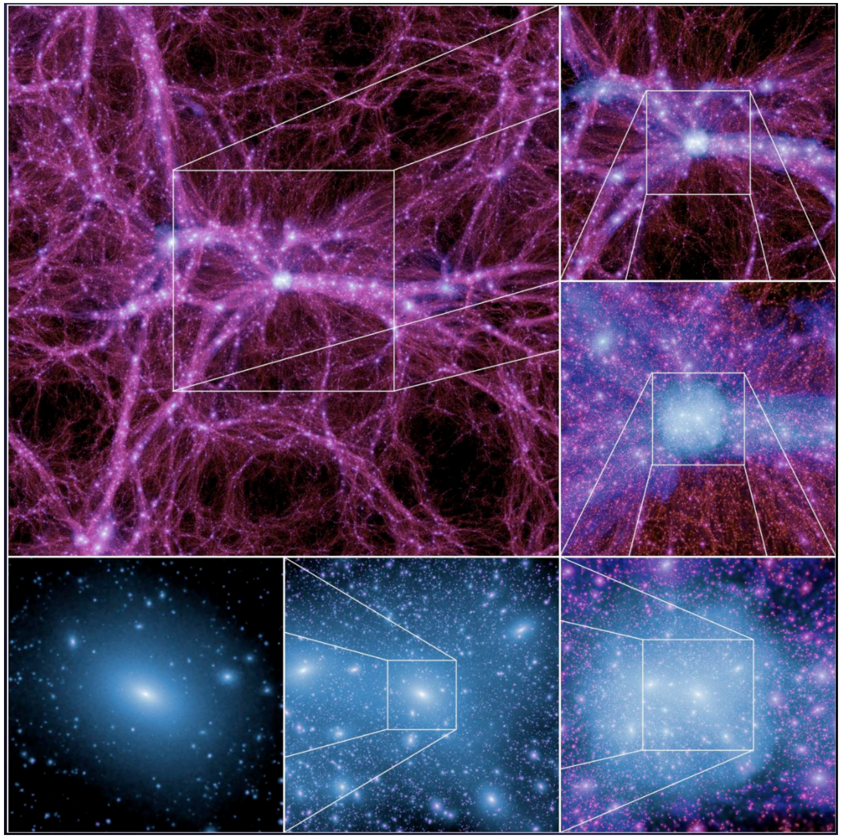
Koposov+:
arXiv:1503.02079

- Advent of 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 decomissioned (more on this later)

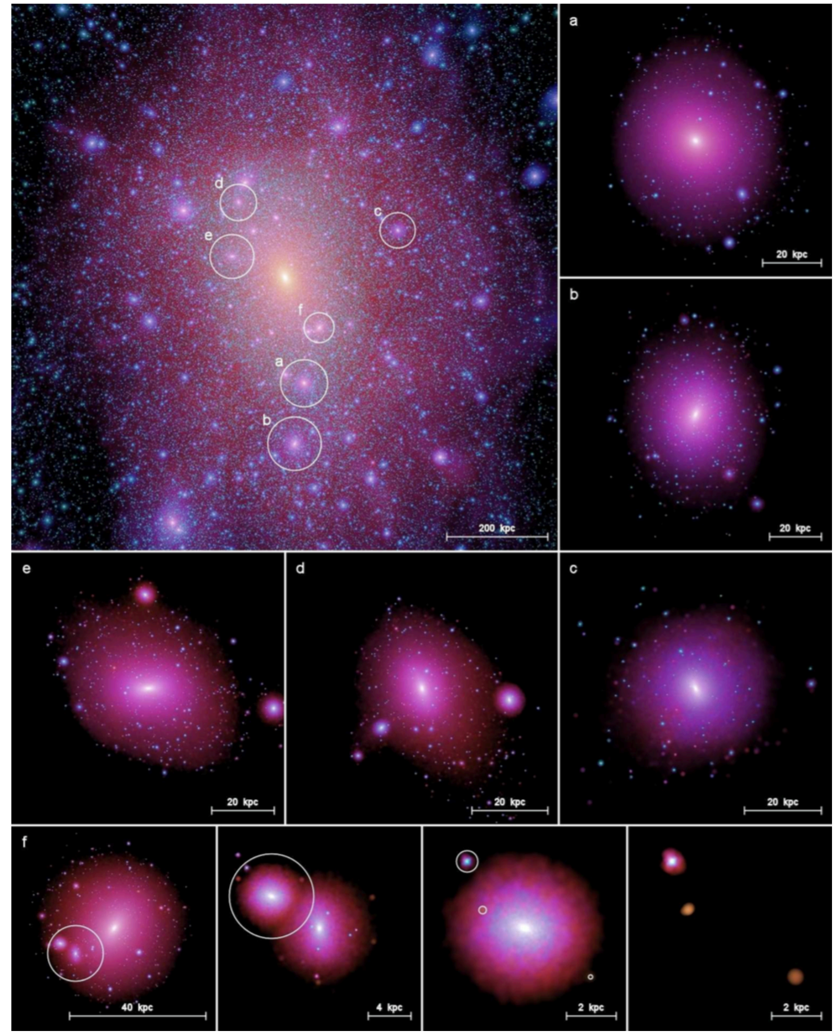
WIMP Searches Targeting Unresolved Dark Matter Structures

DM Structures are Present on Many Scales

Zoom sequence of DM structure on Cosmo. Scales



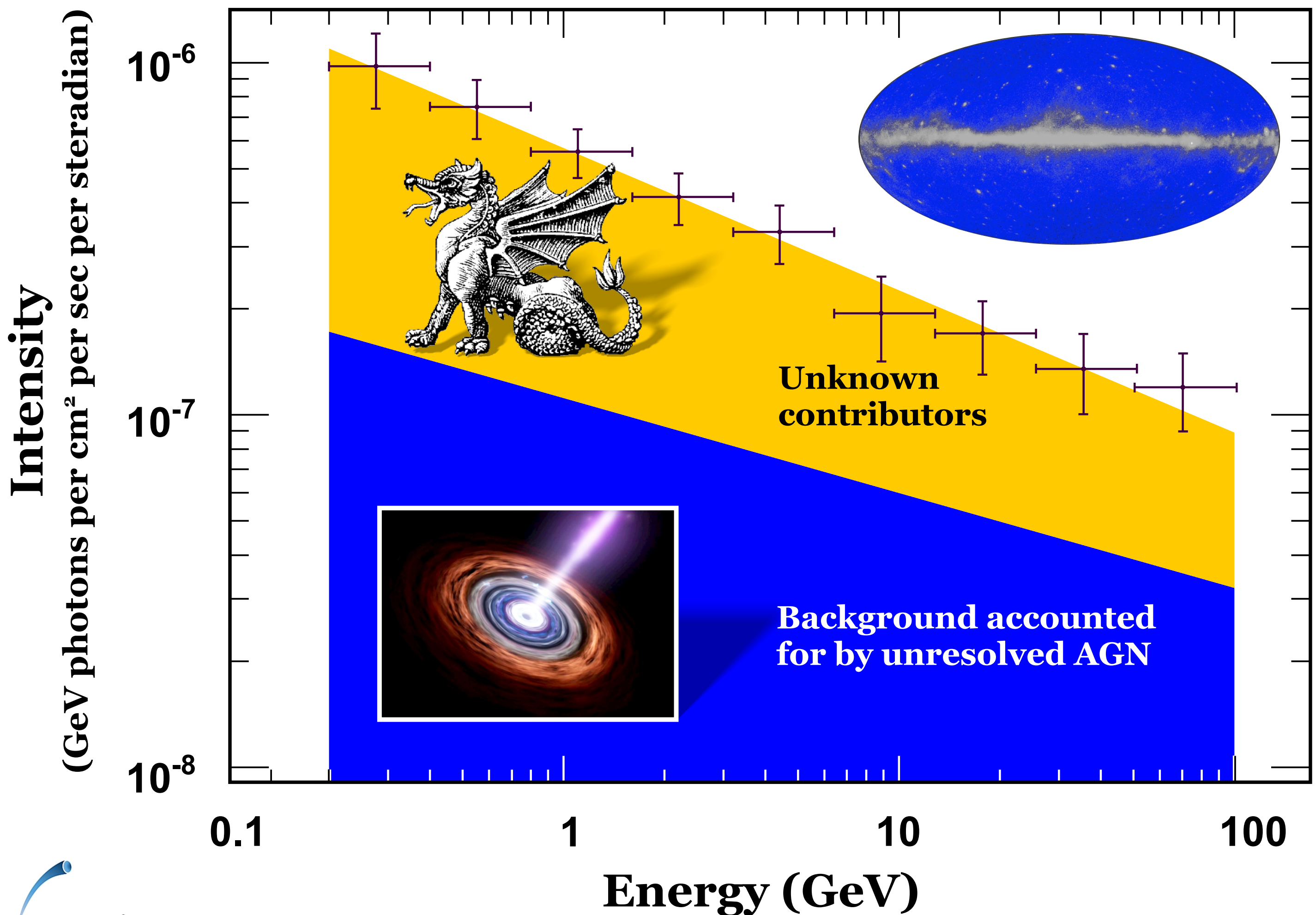
Milky Way like halo and several sub-halos



- We can probe DM by looking for signal contributions from halos:
  - On cosmological scales (left)
  - In the Milky Way virial radius (~300 kpc, right)

hic sunt dracones

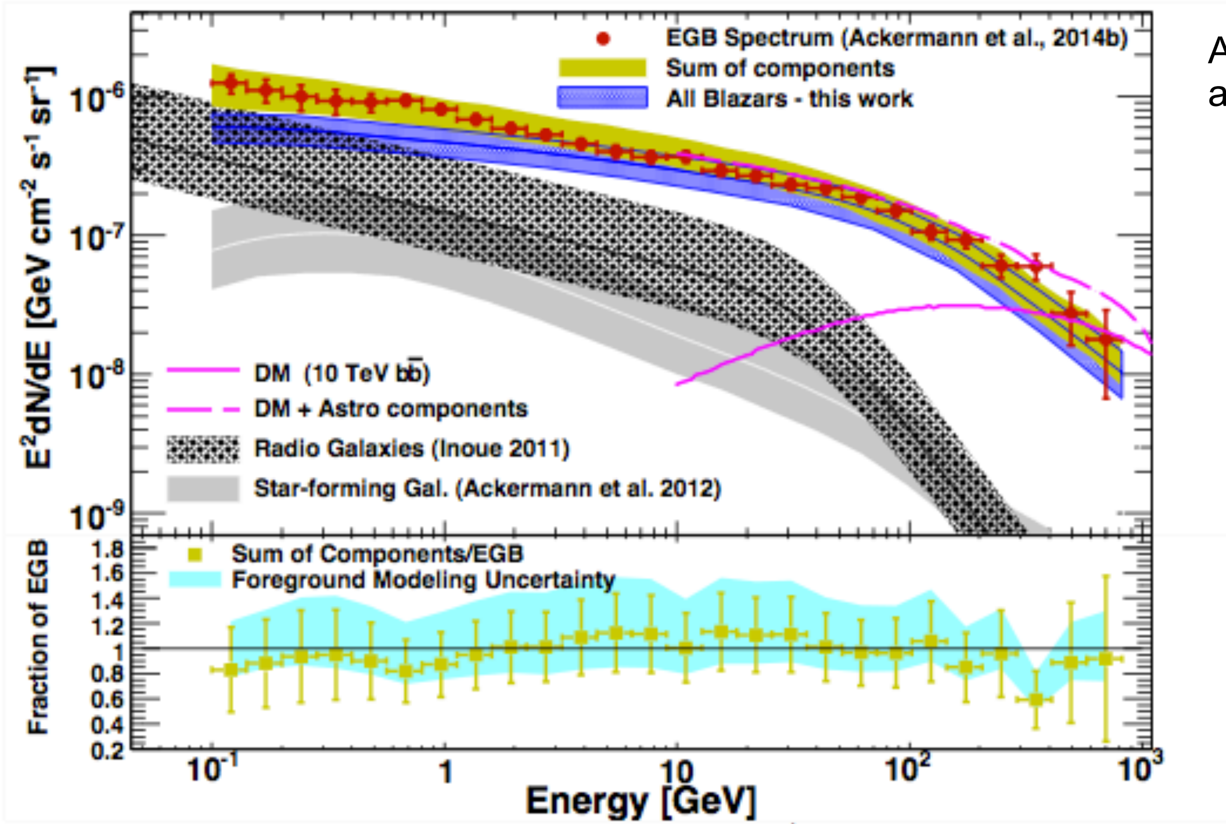
Fermi LAT Extragalactic Gamma-ray Background



Results are schematic only

Dark Matter Contributions to the Extragalactic Background

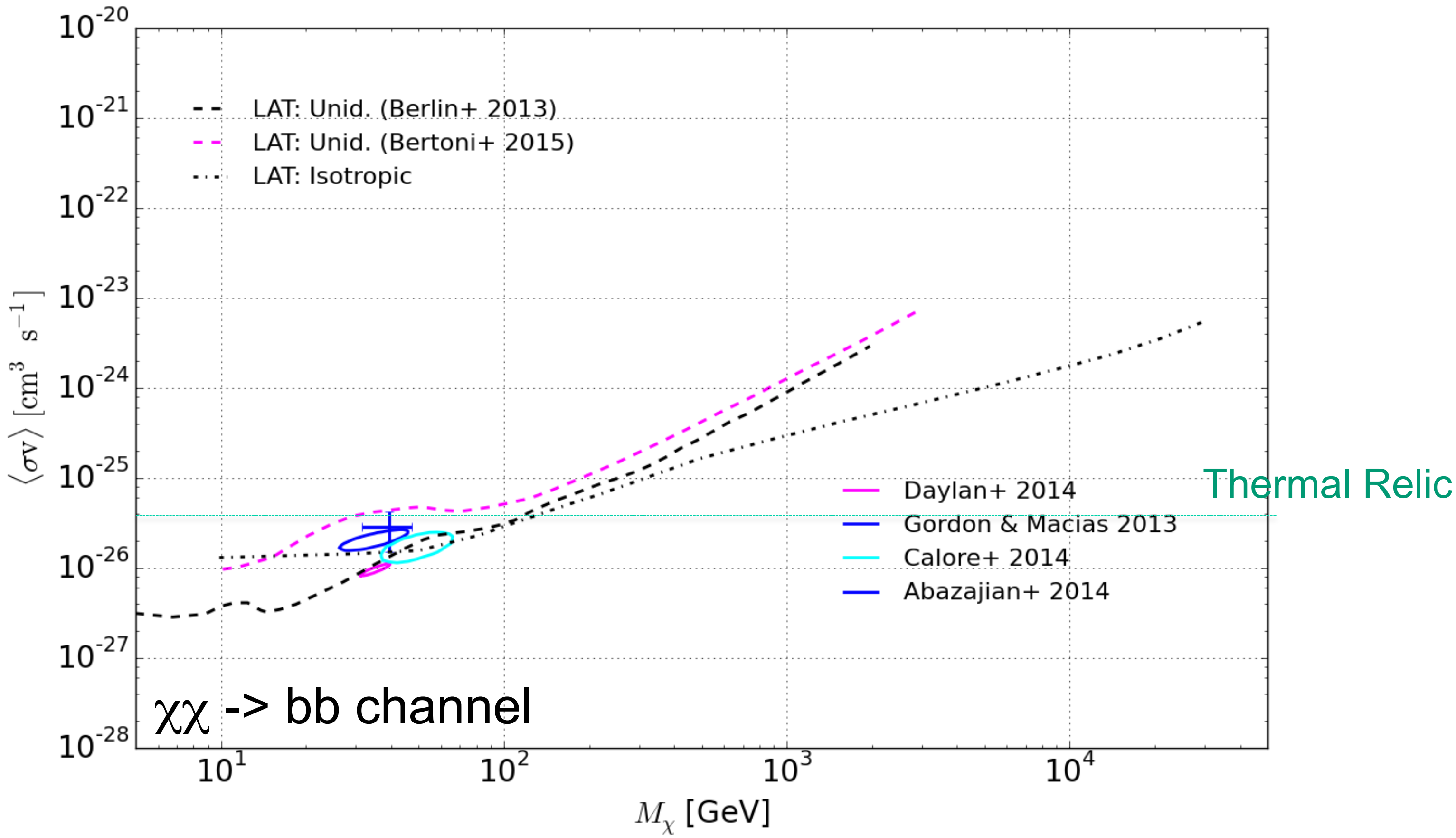
Comparison of extragalactic gamma-ray background to contributions from sources



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

Published Limits from Cosmological Halos & Local Sub-Halos

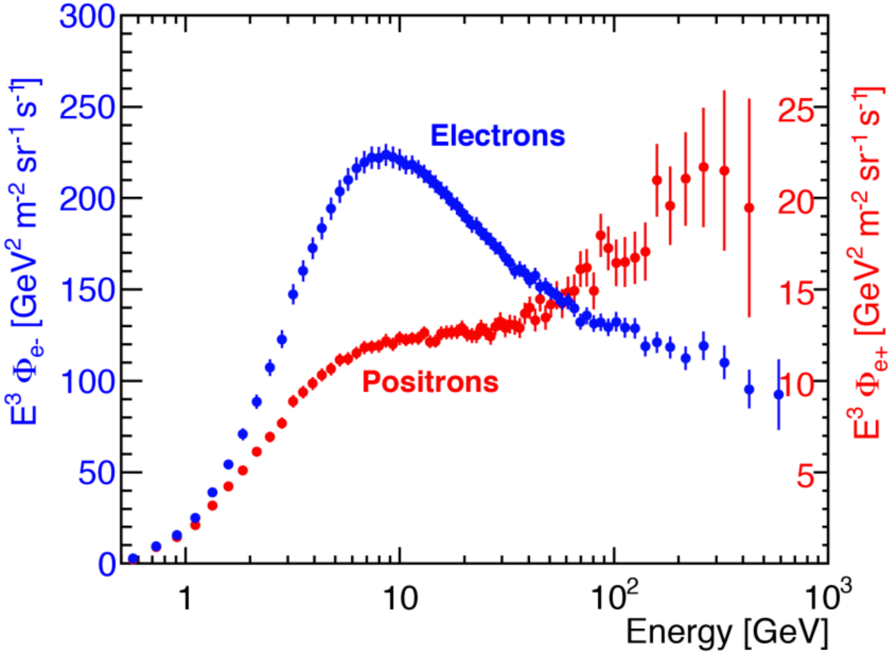


- These methods only work for sky-survey instruments (i.e., Fermi and HAWC)
- Sensitivity is set by the point-source detection threshold

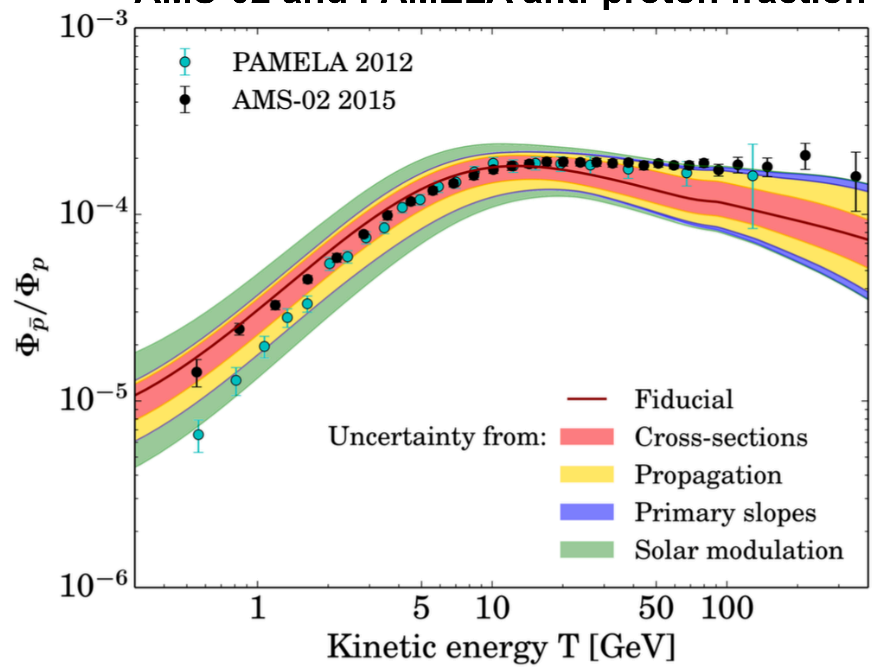
WIMP Searches Targeting Cosmic Rays

DM constraints from anti-matter fluxes

AMS-02 electron and positron fluxes



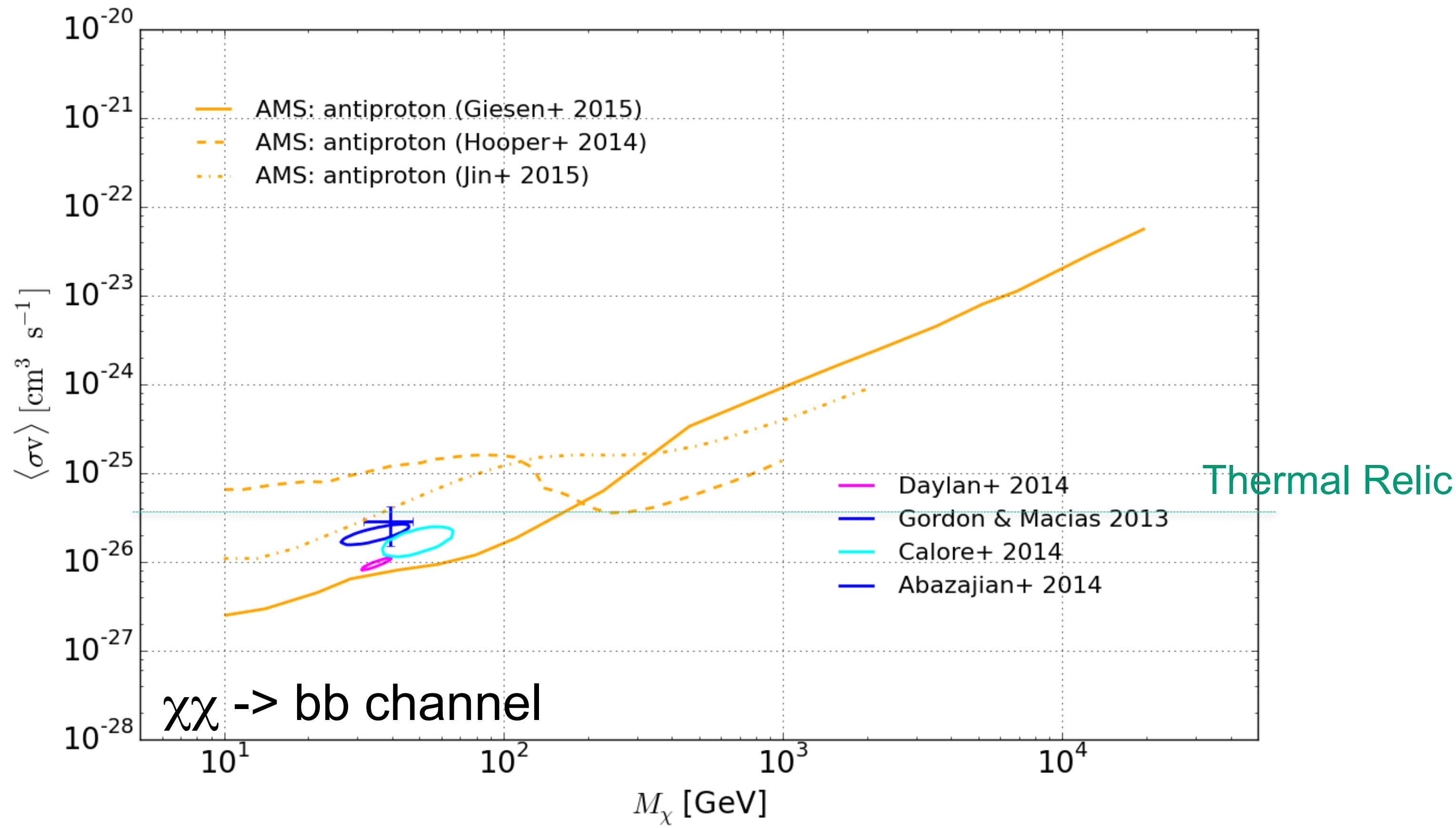
AMS-02 and PAMELA anti-proton fraction



Geisen+ arXiv:1504.04276

- Extracting constraints on DM cross section from anti-particle fluxes requires detailed modeling (see sources of uncertainty on right figure).

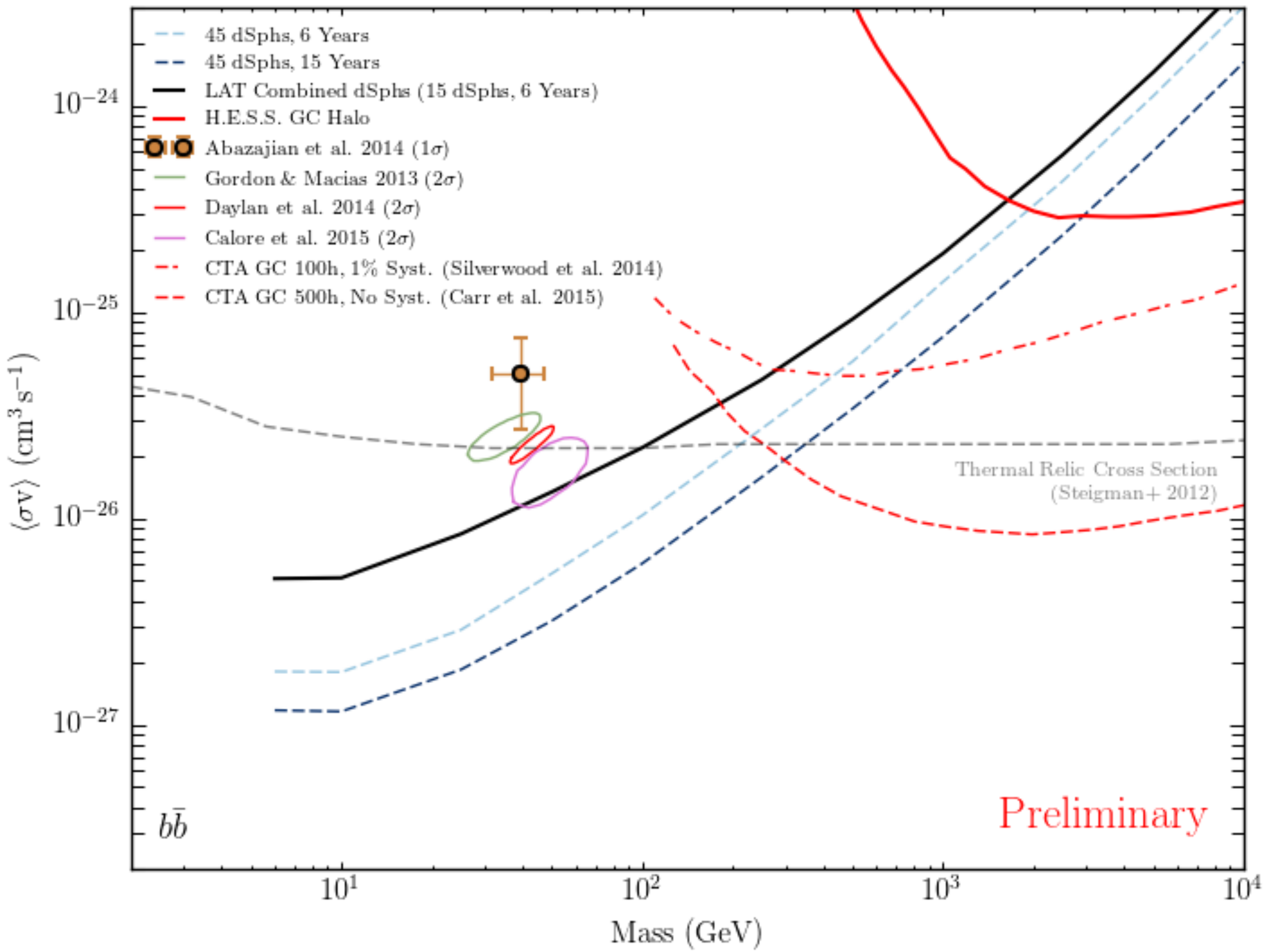
Published Limits from anti-proton Spectra



- All of these limit curves were derived from the same anti-proton spectrum (and similar cosmic-ray propagation models)
- Large variation in the limits suggests large systematic uncertainties from input source and propagation modeling

SUMMARY OF WIMP SEARCHES

Projected Limits from Best Targets



Summary of Best Projected DM Limits

- It is likely that the DM sensitivity from the current crop of instruments and CTA will largely be set by two types of searches
  - Fermi-LAT searches targeting dwarf galaxies
    - This search is background-limited at lower energies (m_χ < 100 GeV) and signal-limited at higher energies
    - Searches targeting halos both on cosmological scales and Galactic scales are competitive with dwarfs and are limited by the LAT point-source sensitivity
  - CTA searches targeting the Galactic center
    - This search is systematics limited, possibly by both instrumental systematics and uncertainties of the TeV diffuse Galactic emission

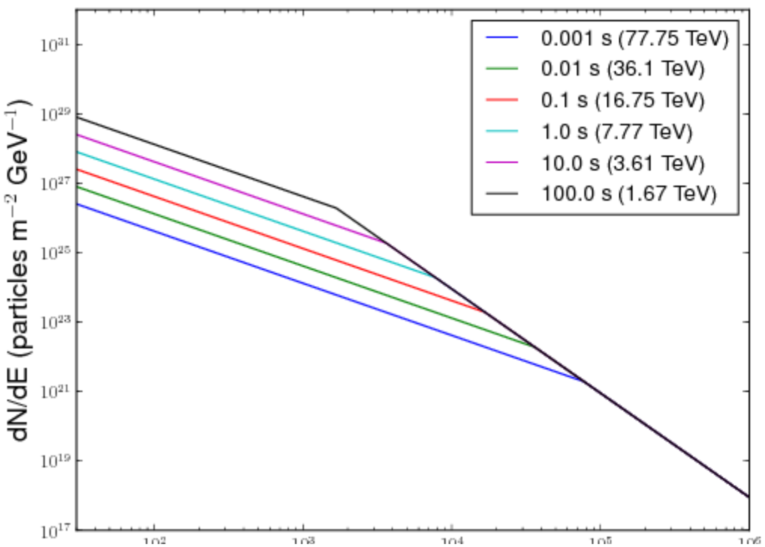
Room for Improvement

- Main room for improvement for pair-conversion telescopes:
  - More collecting area (bigger)
  - Larger field-of-view (monolithic technologies?)
  - More target dwarf galaxies (LSST…)
  - Reasonable target for next generation-telescope:
    - 10x LAT = 25 m^2sr acceptance
- Main room for improvement for IACTs:
  - Better γ-hadron separation (more telescopes, greater infill)

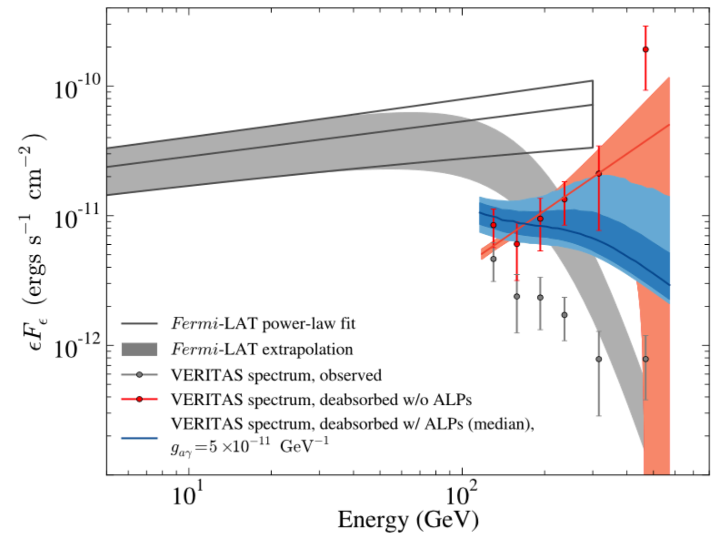
Searches for Non-WIMP Dark Matter

Searches for Primordial Black Holes and Axions

Spectra over remaining lifetime of PBH



Spectrum from Blazar PKS1424+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 search methods consider spectral distortions of nearby Blazars

SUMMARY

Summary

- The sensitivity of indirect DM searches from current instruments and CTA will likely be set by:
  - LAT searches targeting dwarf galaxies (below~ 500 GeV to 1TeV)
    - These will probe the thermal relic cross section up to ~400 GeV
    - Improving on these will require larger area (or more targets)
  - CTA searches targeting the Galactic center
    - Depending on control of systematic uncertainties these may probe the thermal relic up to 10 TeV
    - Keys to reducing systematic uncertainties are to improve hadron rejection and understanding of TeV galactic diffuse emission
- Design of next-generation instruments for indirect DM searches will focus on scalability issues such as:
  - Building a pair-telescope with 25 m^2sr acceptance
  - Infilling CTA to better image the entire air-shower

Comments for the CPAD Panelists

- Indirect DM detection is poorly represented in DOE portfolio
  - Little or no presence post Fermi, few or no ongoing R&D projects
- Instrumental R&D for indirect DM detection will likely focus primarily on scaling existing technologies for use in future instruments
  - Cost per channel, data volume and rate, and instrument infrastructure will be key factors
  - Space-based instruments have the additional constraints (in particular power budget)
  - Exceptions do exist; e.g., Gamma cube concept is extremely novel
- Adapting existing technologies for scalable, low-cost, applications takes time, effort and resources
  - NASA has a well established R & D program to adapt technologies for space missions
  - Missing LDRD-type funding to survey existing technologies and prepare competitive NASA R&D proposals (i.e., ~$100k grants)
  - Missing LDRD-type funding identify how to scale up existing technologies to mutli-km^2 scales for air shower arrays

EXTRA SLIDES

Radiation Length

$$X_0 = \frac{716.4 \text{ g cm}^{-2} A}{Z(Z+1)\ln(287/\sqrt{Z})}$$

The radiation length is the distance over which:

1. Electrons lose 1/e of their energy to Bremsstrahlung.
2. 54% of high-energy γ rays will pair convert.
3. An average 1 GeV particle will change direction by 1.1° due to multiple Coulomb scattering.

X_0 / ρ values:

Si: 9.5 cm

Ge: 2.4 cm

CsI: 1.7 cm

W: 0.4 cm

Multiple Coulomb Scattering

$$\theta_{\rm space}^{\rm rms} = \frac{\sqrt{2}\ 13.6\ {\rm MeV rad}}{E}\sqrt{x/X_0}[1 + 0.038\ln(x/X_0)].$$

For 100 MeV $e^{\pm}$: 0.006 X_0 => 1° of MCS

For 20 MeV $e^{\pm}$: 0.006 X_0 => 5° of MCS

Key design question:

How much information (positional accuracy * lever-arm * sqrt(N)) can we extract from the instrument before the particles are MCS dominated?

Electromagnetic Shower Development

Key longitudinal parameter, shower maximum:

$$x_{\max} = X_0(\log(E/E_c) + 0.5).$$

Energy resolution improves markedly if the shower maximum is contained in the detector.

Key transverse parameter, Moliere Radius:

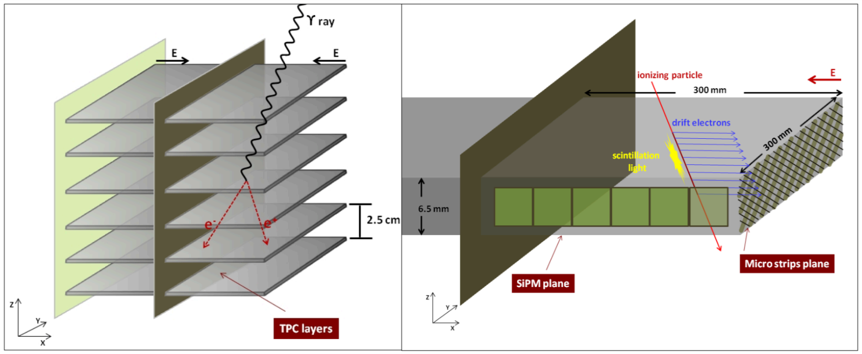
$$R_M = X_0 \frac{21.2\mathrm{MeV}}{E_c}.$$

> 99% of EM shower energy is < 3 R_m from shower axis.

Fermi Gamma-ray Space Telescope

Drift chamber-based concepts

LArGO

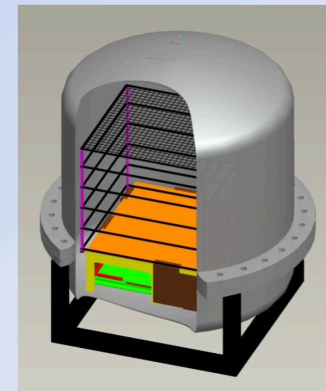


- LArGO design elements
  - a stack of 32 very thin (6.5 mm) LAr-TPCs (TPC-layers),
  - Inter-layer distance 2.5 cm
    - the e^+e^- tracks by 1 GeV photon converted in a TPC-layer are separated at the underlying layer by twice the TPC pitch.
  - 1 X_0 diluted in 1 m
  - Pitch of the drift charge readout plane p = 100 µm
  - Spatial resolution 25 µm
    - Current LAr-TPC have pitch and spatial resolution of ~1 mm,
  - LAr close to triple point (84 K, 70 kPa)
    - X_0 = 20 cm. Minimum multiple scattering

LArGO 4

AdEPT Instrument Development

- 2015-18 ROSES-APRA
  - 50 x 50 x 100 cm³ AdEPT prototype
    - Multi-core processor to discriminate gamma-rays from background
      - Determine gamma-ray direction, energy, polarization, and time of arrival
    - Large area MWD integration
    - FEE ASIC
  - Calibrate at accelerator with polarized gamma rays, 5 - ~90 MeV
    - Determine electron energy from Coulomb scattering
    - Measure angular resolution and Polarization sensitivity
- Future NASA mission!

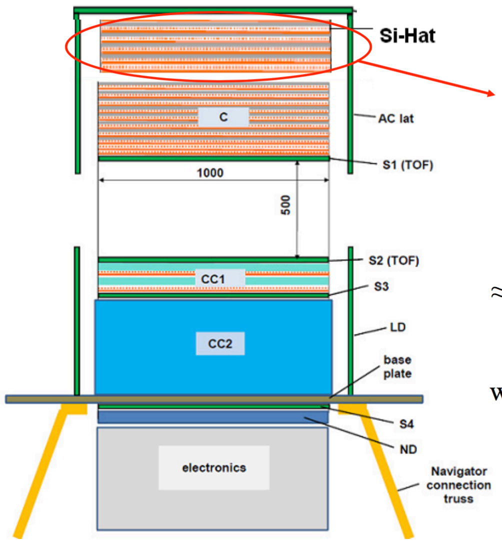


6 February 2015 AdEPT Gamma Ray Polarimeter 11

- These designs optimize the amount of active to passive sensor material in the detector fiducial volume by using drift chamber technologies
  - LArGO: Liquid Argon. AdEPT: gas, HARPO: high-pressure gas
- Expect excellent performance for polarization
- Challenges arise for operation in space, must reject large induced backgrounds from pressure vessel
- AdEPT approved for balloon flight for prototype

"Fermi-Lite" concepts

Gamma 400

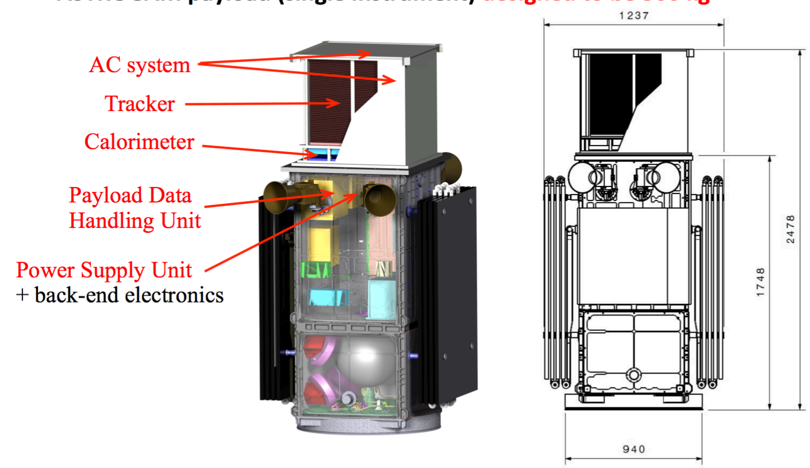


10-30 *x-y* Si-planes
(thickness: 0.5 mm)
+ electronics
no passive converter

≈ 10% X_0 of total conversion
additional ~400 cm^2 of A_{eff}
at E ~100 MeV
with ~1° of *PSF* at 100 MeV.

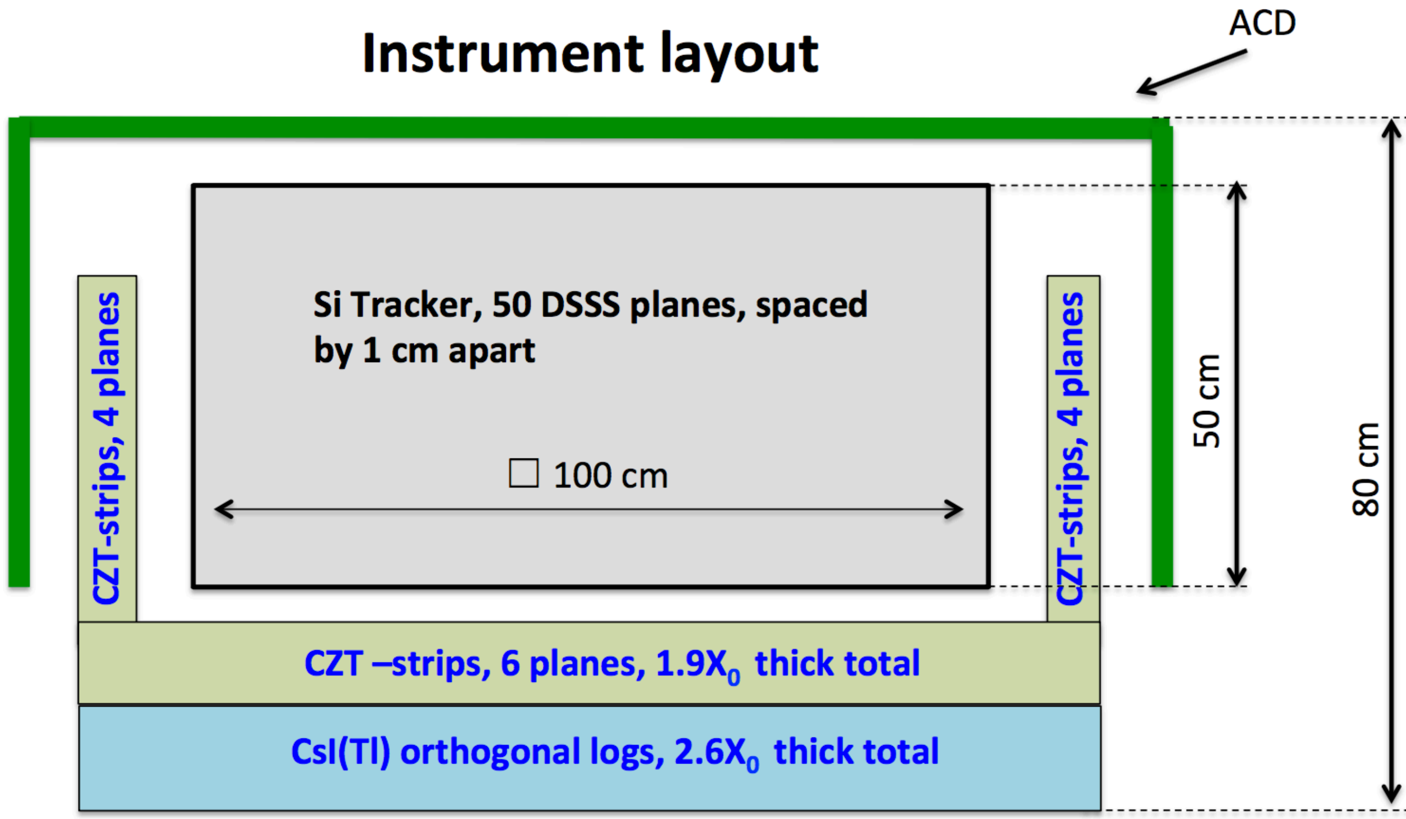
ASTROGAM Payload

- **ESA guidelines for the M4 Call interpreted at face value ⇒ ASTROGAM payload (single instrument) designed to be 300 kg**



- These concepts are similar to *Fermi* with the Tungsten convertors removed
- Good PSF at 100 MeV
  - not quite as good as AdEPT, but larger A_{eff}, and simpler design
- Proposals to European Space Agency, also PANGU (China)

Compton / Pair-production concept (ComPair)

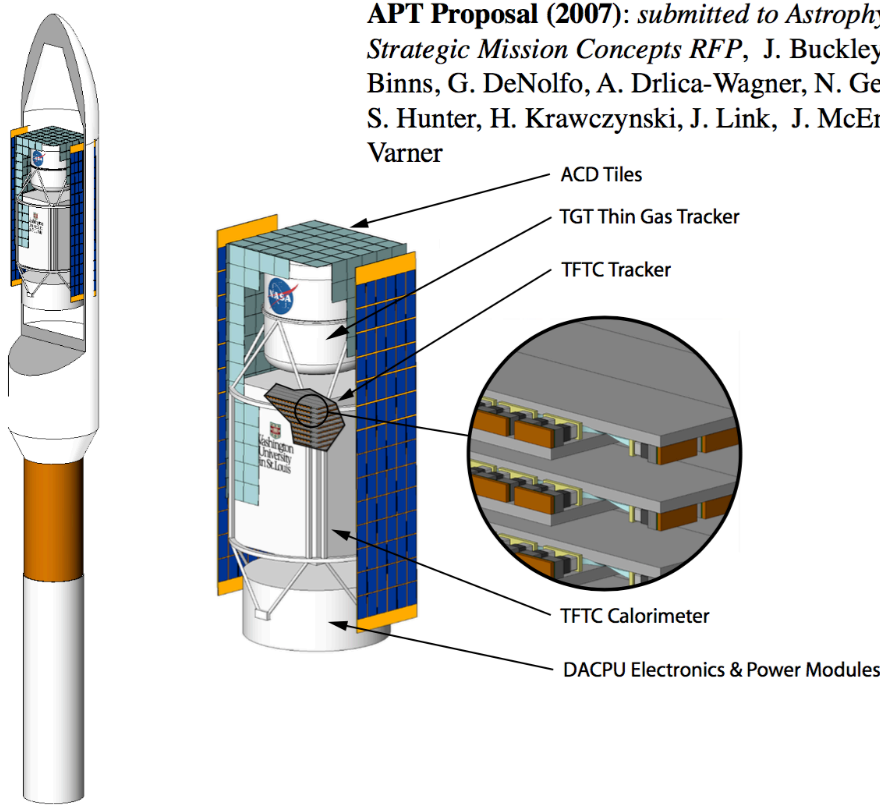


- Sensitivity to both Compton scattering and pair-conversions
- CZT strips surrounding Si Tracker to achieve full absorption of Compton scattered photon
- Approved for balloon-flight prototype development

Advanced pair telescope concept

APT Concept

APT Proposal (2007): *submitted to Astrophysics Strategic Mission Concepts RFP*, J. Buckley, W. R. Binns, G. DeNolfo, A. Drlica-Wagner, N. Gehrels, S. Hunter, H. Krawczynski, J. Link, J. McEnery, G. Varner



- Optimized for *Fermi*-LAT energy range, trades energy resolution for larger tracking volume and improved spatial resolution
- Aims for > 10x sensitivity improvement in GeV energy range

Segmented Calorimeter instrument concept