Indirect searches for dark matter with the Fermi LAT instrument

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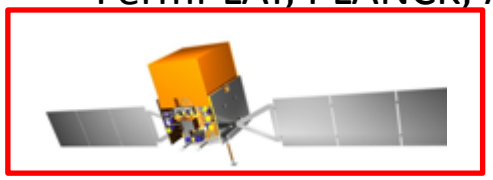
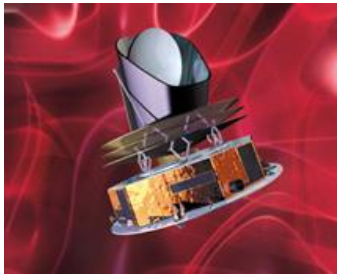
Indirect Dark Matter Search

γ

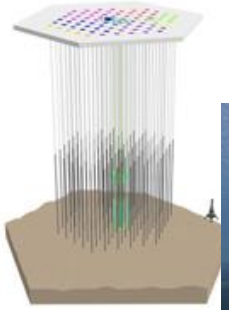
Ground-based instruments:
Cherenkov detector as HESS;
MAGIC, VERITAS, …
Space-based instruments:
Fermi-LAT, PLANCK, AMS-02,…

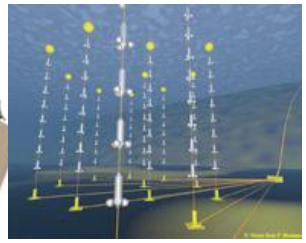




ν

IceCube
Antares
…



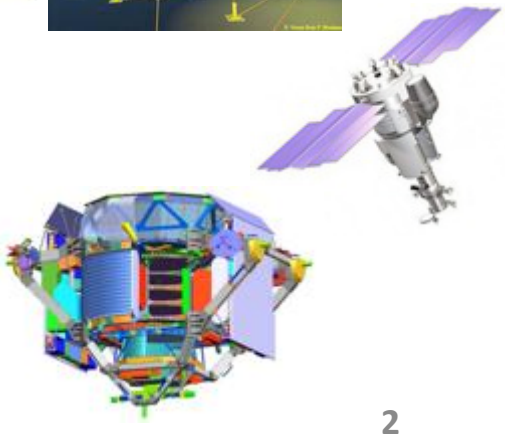


- Annihilation or decay of dark matter can produce a variety of potentially detectable Standard Model particles
  - Contribute to cosmic rays
- Spectrum of annihilation (or decay) products encodes info about intrinsic particle properties
- Variation in the intensity of the signal along different lines of sight is determined exclusively by the distribution of dark matter

B-field

PAMELA
AMS-02
Fermi-LAT

e+, anti-p, …

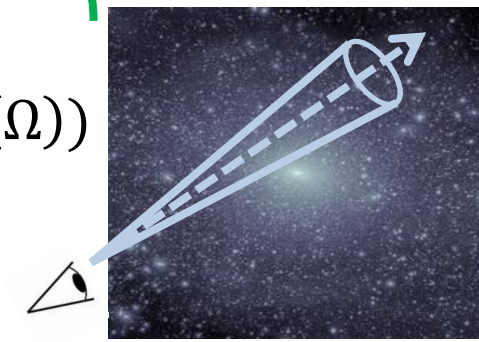


Indirect WIMP Signatures: gamma-rays

Observed flux | **Intrinsic Particle Properties** | **Astrophysics**

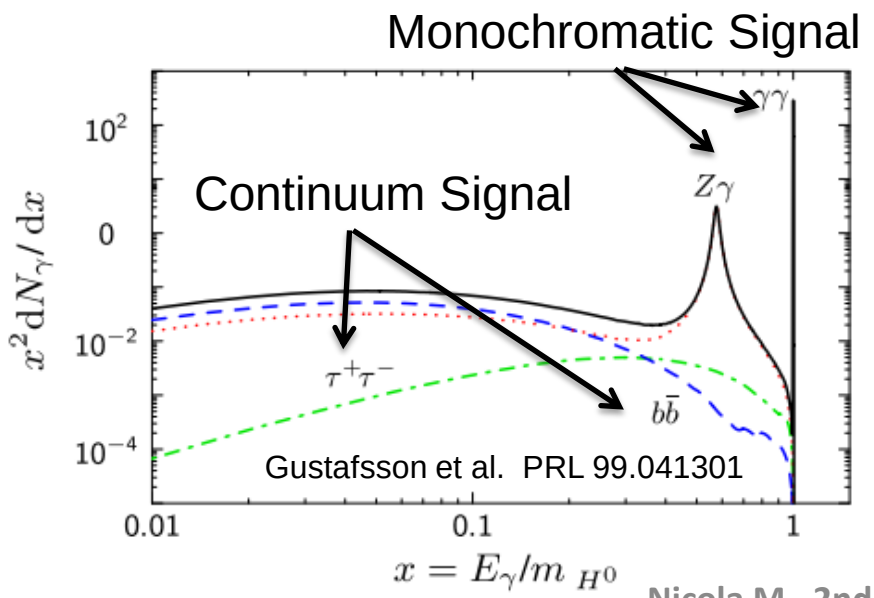
ann. $$\phi(E,\Delta\Omega) = \frac{1}{4\pi}\frac{\langle\sigma v\rangle}{2\,m_\chi^2}\sum_f \frac{dN_f}{dE} B_f \int_{\Delta\Omega} d\Omega \int_{l.o.s.} dl\, \rho^2(l(\Omega))$$

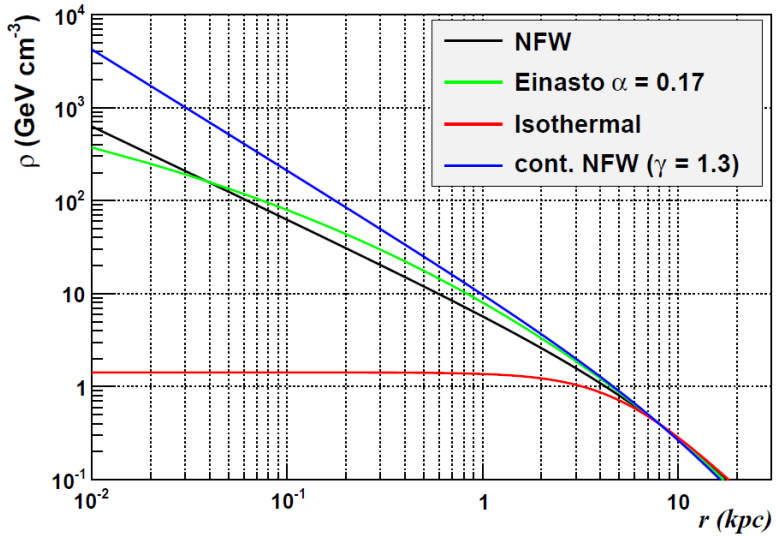
decay Γ_D/m_χ $\rho(l)$



$\langle\sigma v\rangle_{ann} \sim 3 \times 10^{-26}$ cm^3/s for thermal relic

J-factor – DM distribution (line-of-sight integral)

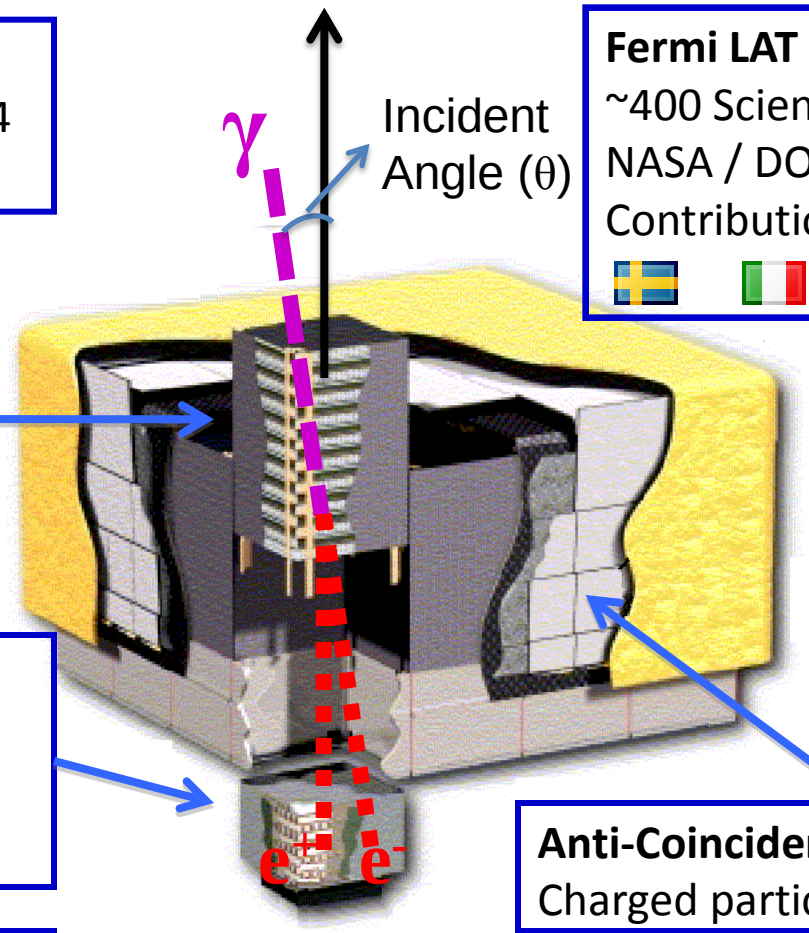




The Fermi Large Area Telescope

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

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



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

On orbit since June 11, 2008

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

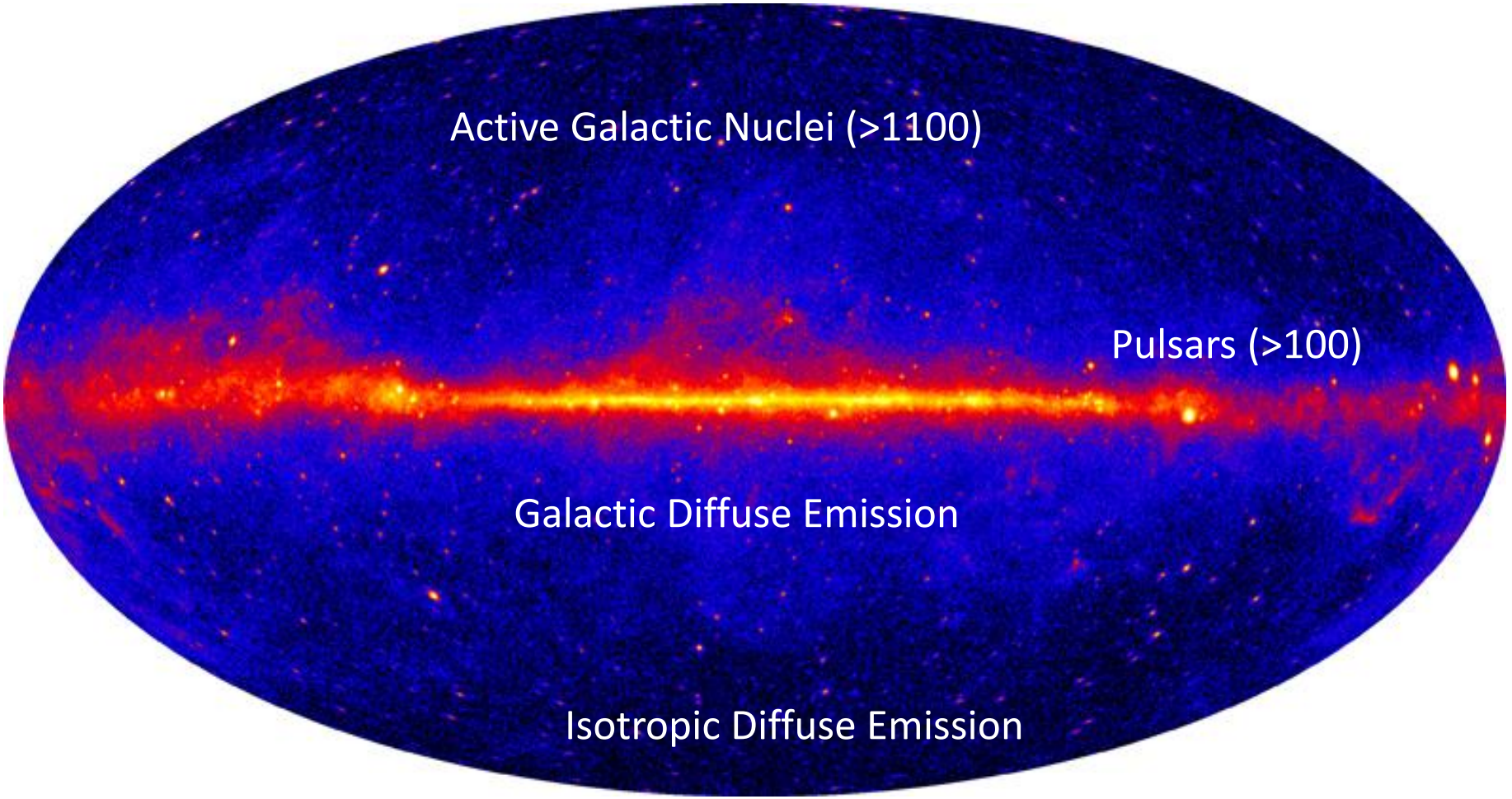
Anti-Coincidence Detector:
Charged particle separation

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

Atwood et al., ApJ 697, 1071 (2009)
Ackermann et al. ApJS 203, 4 (2012)

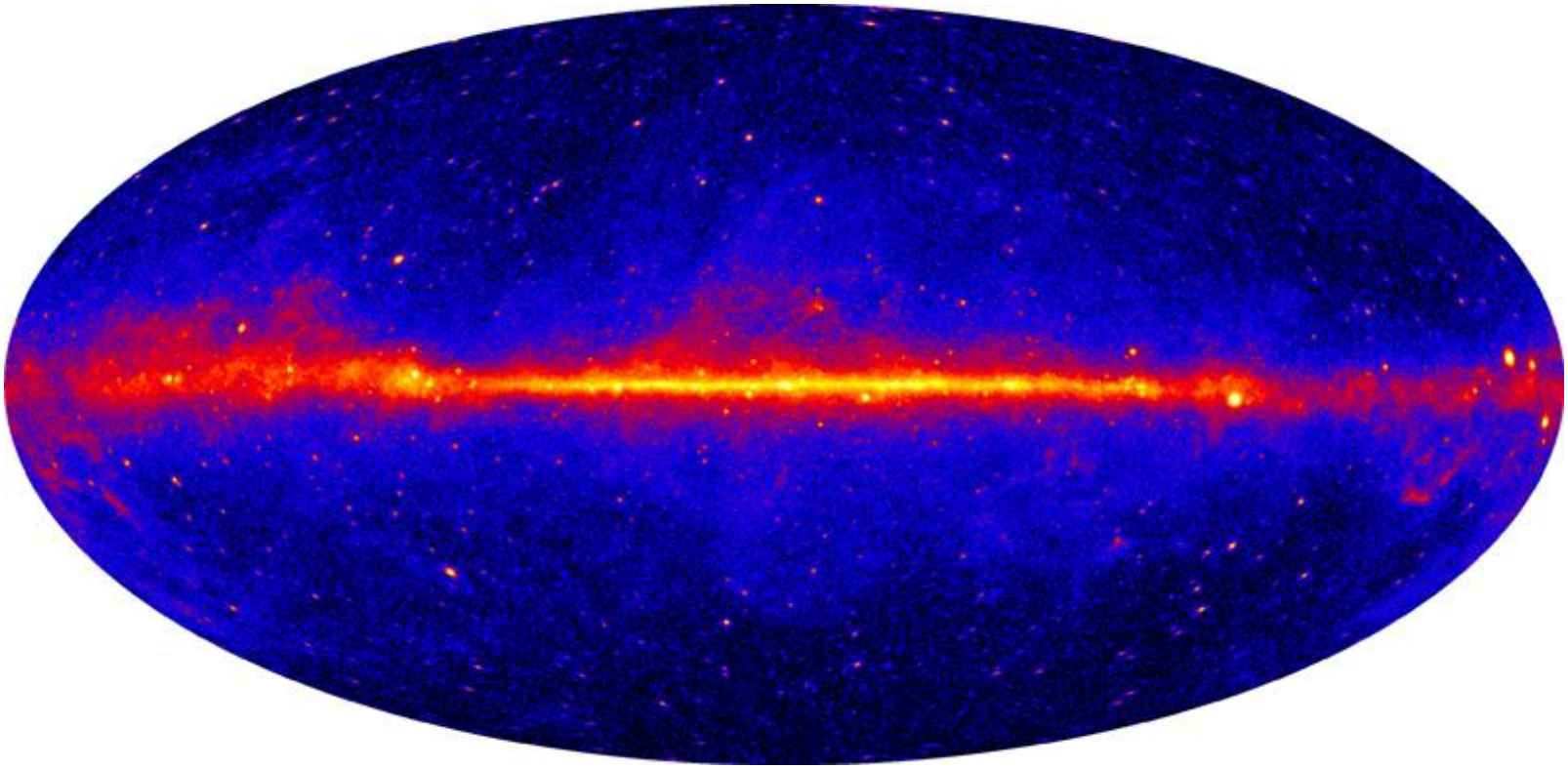
Fermi-LAT Gamma-Ray Sky Map (>1 GeV)

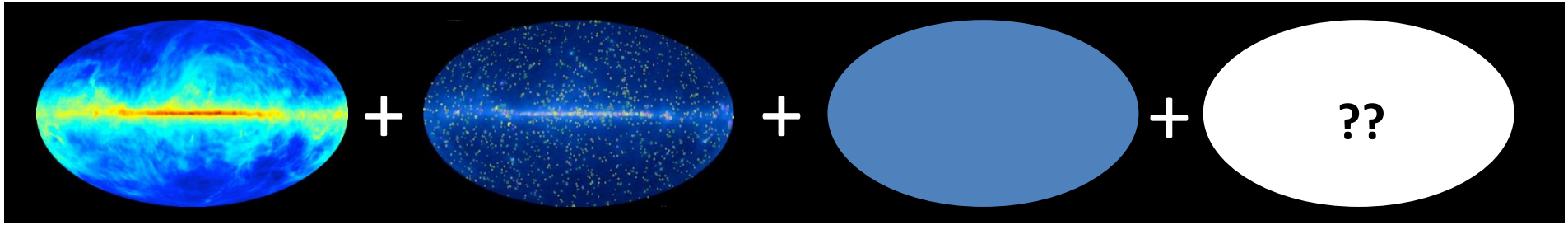
Credit: NASA/DOE/International LAT Team



+Pulsar Wind Nebulae + Supernova Remnants + Globular Clusters + Starburst Galaxies + Unassociated Sources+ …

Are there any hiding DM signals?





Galactic **Point Sources** **Isotropic** **.. DM signal**

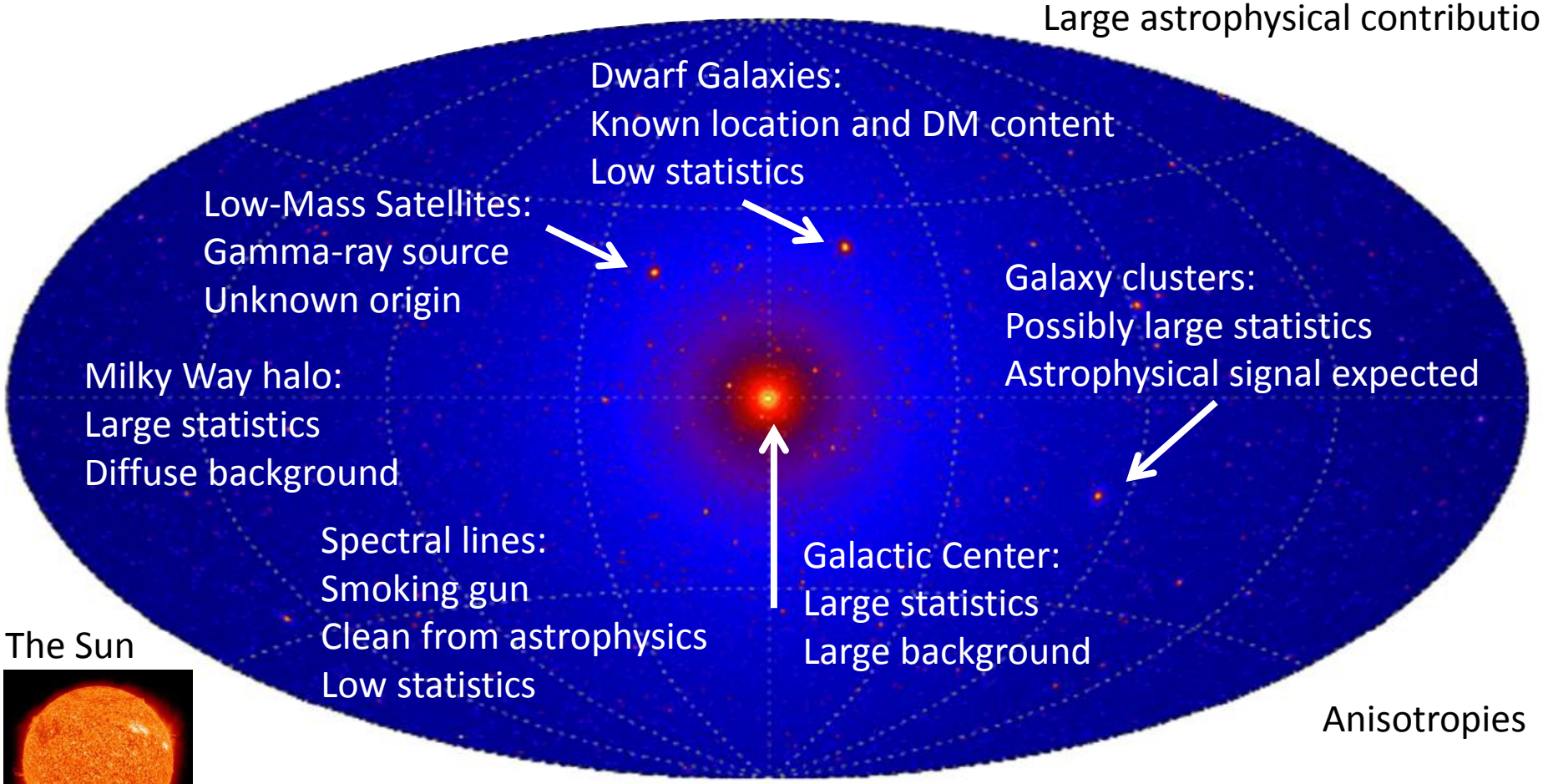
Dark Matter Distribution: search targets

$$\int_{\Delta\Omega} d\Omega \int_{l.o.s.} dl\ \rho^2(l(\Omega))$$

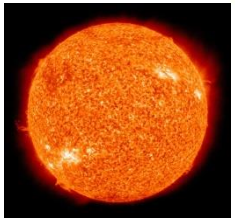
Boost factor = $\langle\rho^2\rangle/\langle\rho\rangle^2$ depends on position and on statistics (shape, mass) of subhalos

Electrons/Positrons

Extragalactic background:
Large statistics
Large astrophysical contribution



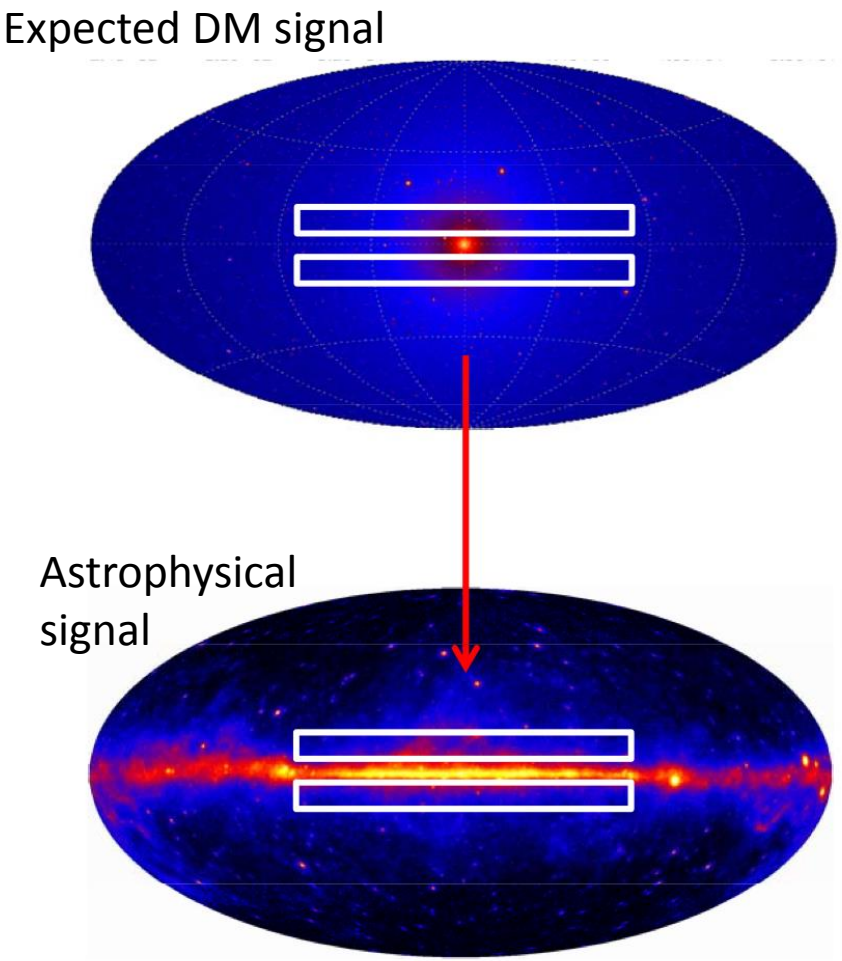
The Sun



Anisotropies

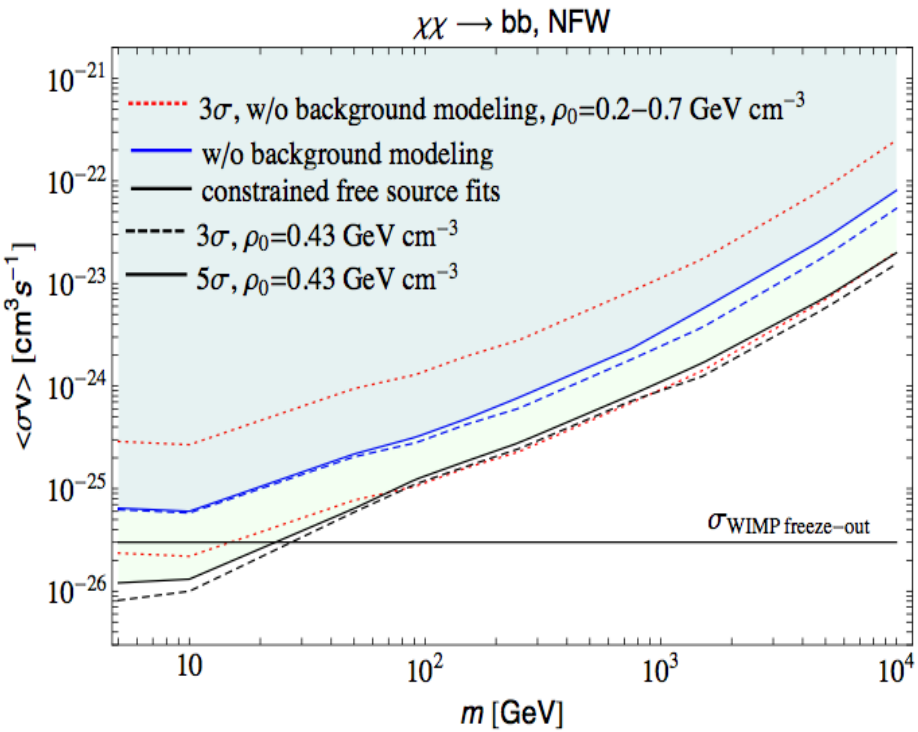
Milky Way Dark Matter Halo

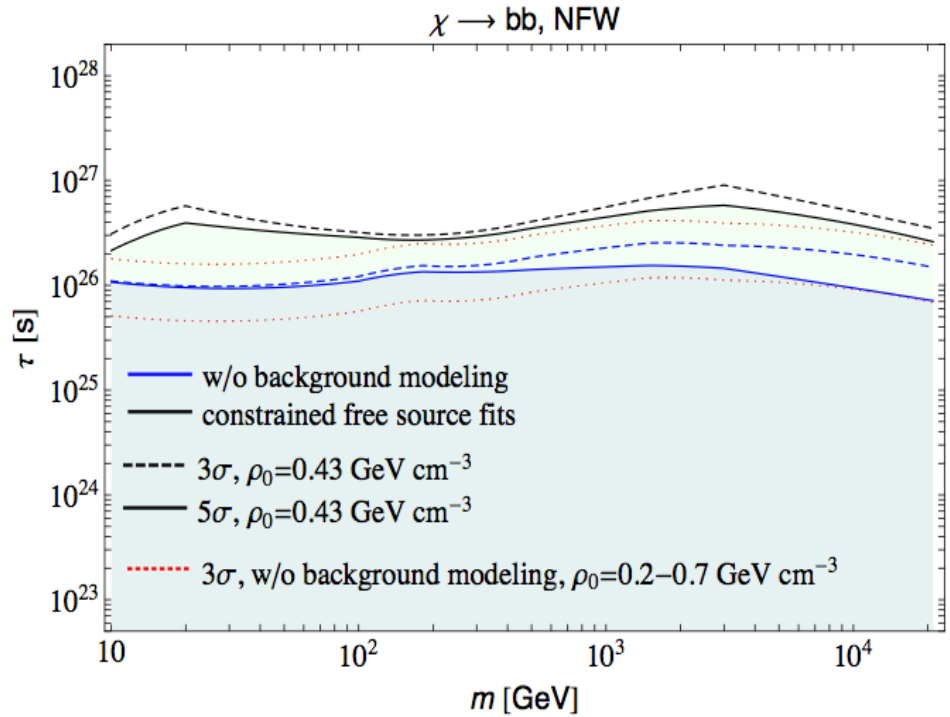
Search for emission from annihilating or decaying DM from the inner extended Milky Way DM halo [Ackermann+ ApJ 761 (2012) 91]



- Analyze two 10 degree bands 5 degrees off the plane
  - to decrease astrophysical background
  - to mitigate uncertainties from inner DM density profile
- Two approaches to set limits:
  1. more conservative: assume emission only from DM
  2. more accurate: fit the DM and astrophysical emission simultaneously

Constraints from Milky Way Halo

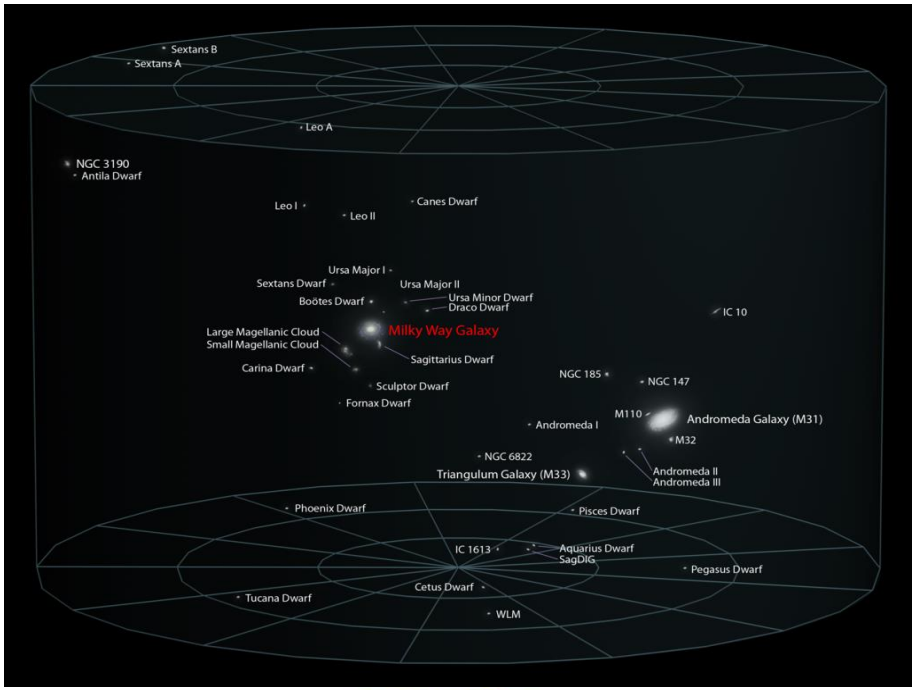


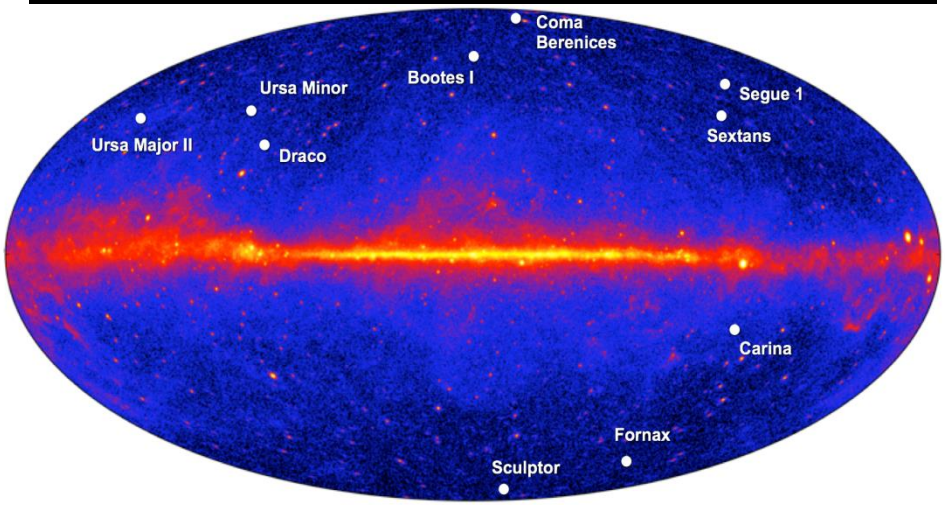


- Including modeling of the astrophysical emission improves the DM constraints by as much as factor of 5
- With inclusion of astrophysical backgrounds, the limit constrains a canonical thermal annihilation cross section into b-quarks to a WIMP mass $\gtrsim$ 30 GeV

Dwarf Spheroidal Galaxies

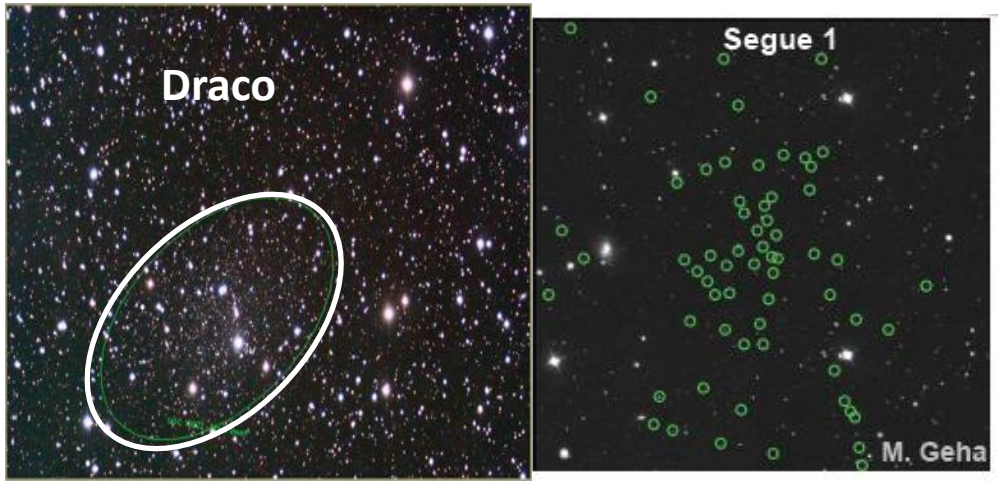
- Most dark-matter dominated objects in the universe (100 - 1000 times more dark matter than visible matter)
- Relatively close (25 - 150 kpc)
- High Galactic latitudes (minimize astrophysical foregrounds)
- Multi-wavelength observations show no mechanism for astrophysical gamma-ray production
  - No active star formation (no energy injection)
  - No appreciable magnetic fields (no acceleration)
  - No gas or dust (no target material)

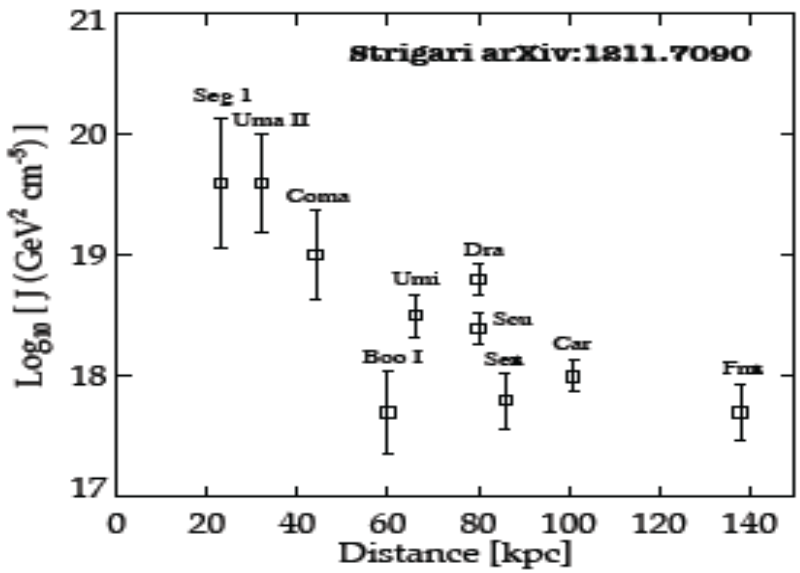




dSph Dark Matter Content

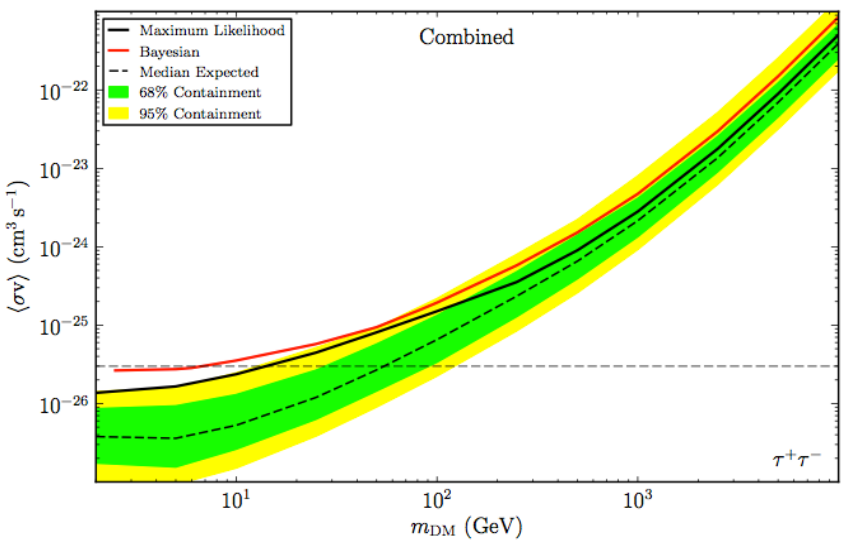
- Dark matter content determined from stellar velocity dispersion
  - Classical dwarfs: spectra for several thousand stars
  - Ultra-faint dwarfs: spectra for fewer than 100 stars
- Fit dark matter profile from the stellar velocity distribution of each dwarf
- Estimate the dark matter content and uncertainty
- Combine observations of multiple dwarf galaxies to improve search sensitivity, including the DM uncertainty

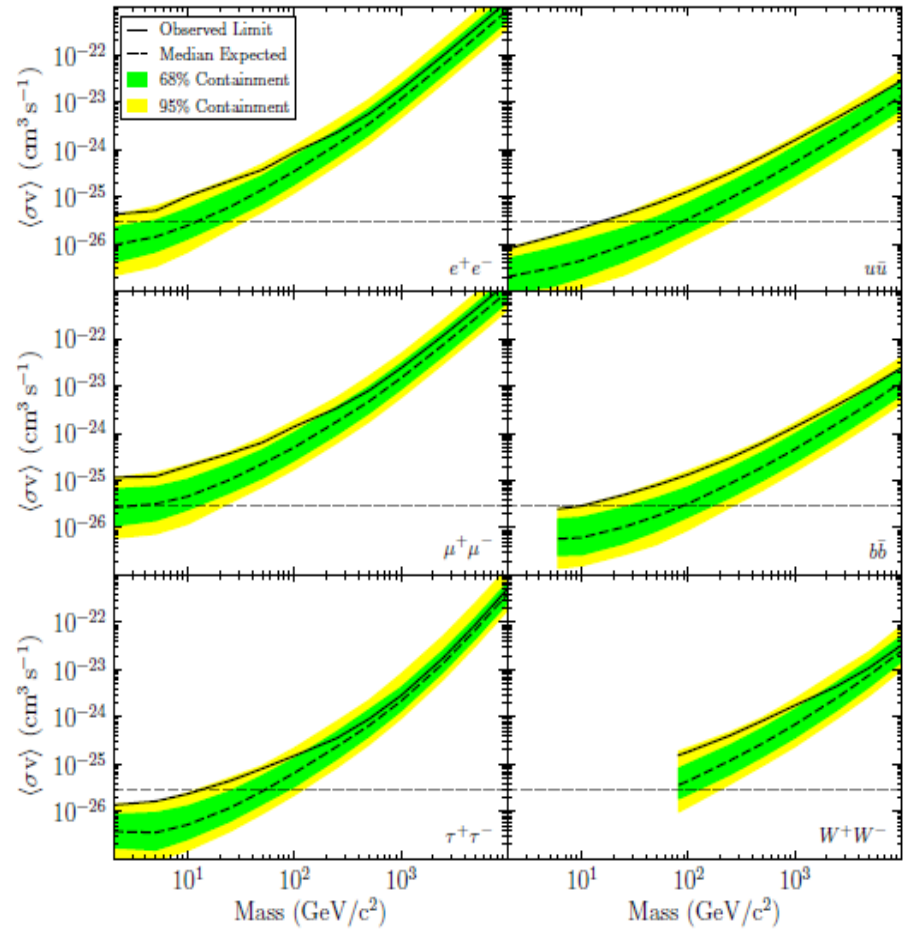




Combined analysis of 15 dwarf spheroidal galaxies arXiv:1310.0828

- Current limit close to thermal relic X-section <~ 30 GeV
  - Different analysis techniques
  - Updated J factors and 4 years of data
  - Extended studies of sensitivity and systematics
- Prospects from upcoming surveys
  - deeper, larger sky coverage

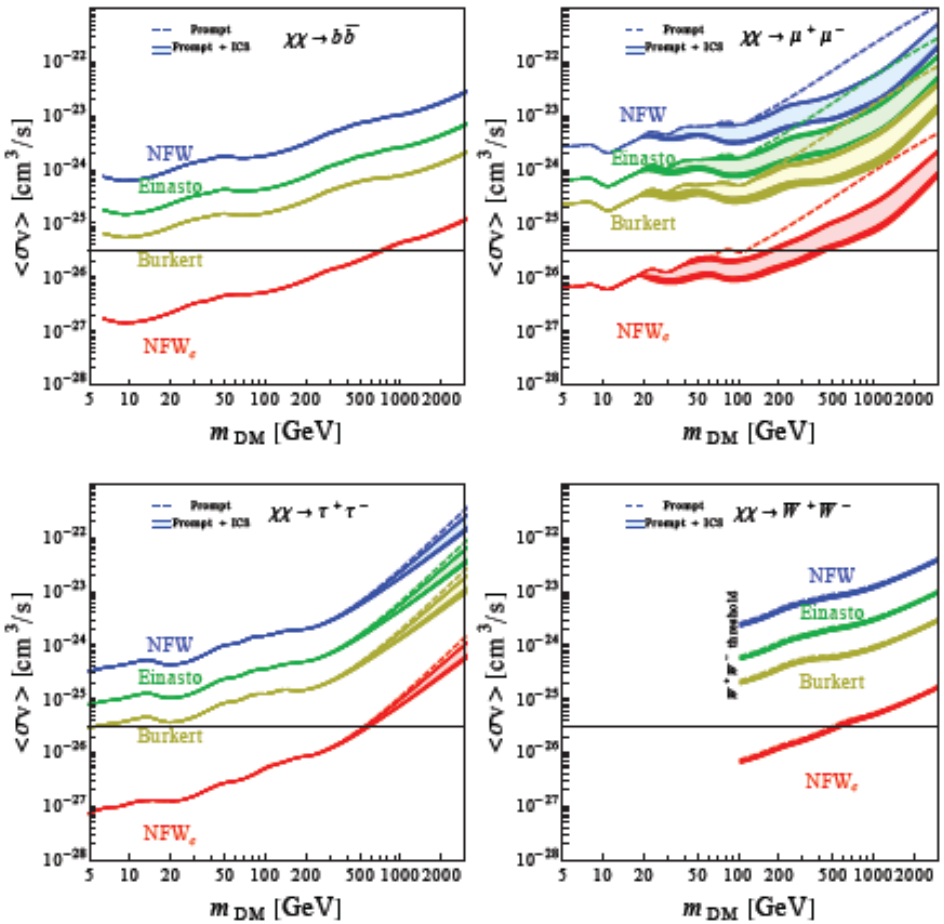




Ackermann et al., arXiv:1108.3546
Geringer-Sameth et al., arXiv:1108.2914
MNM et al., arXiv:1203.6731
…

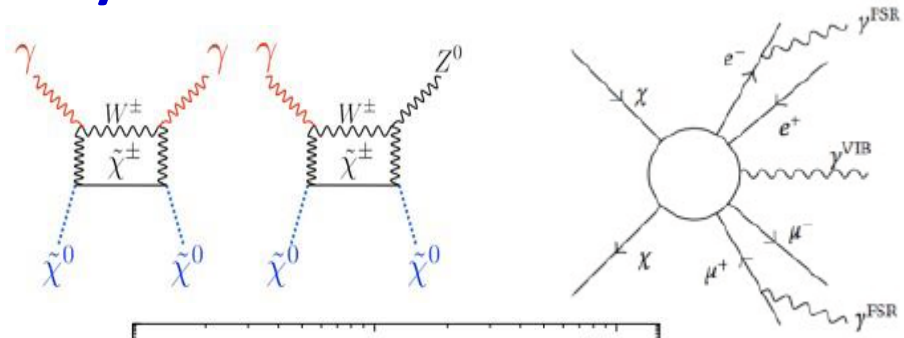
Dark matter constraint in the Inner Galaxy JCAP 10 (2013) 29

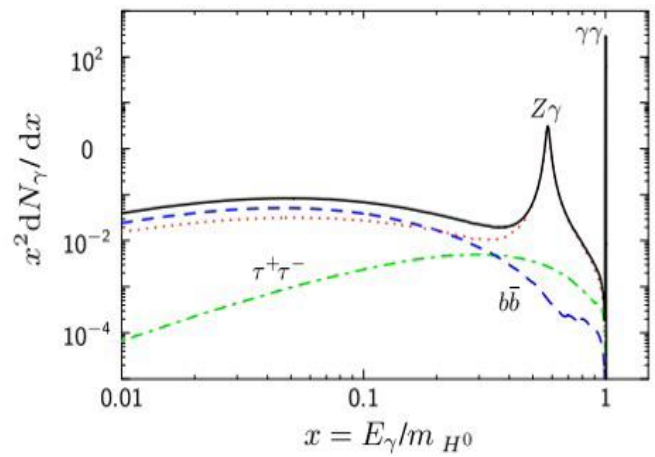
- Conservative limits
  - Does not subtract diffuse emission and sources
- Optimized Region of interest
  - For standard DM profiles
- Strong constraints for very cored profiles
  - Close or below thermal limit

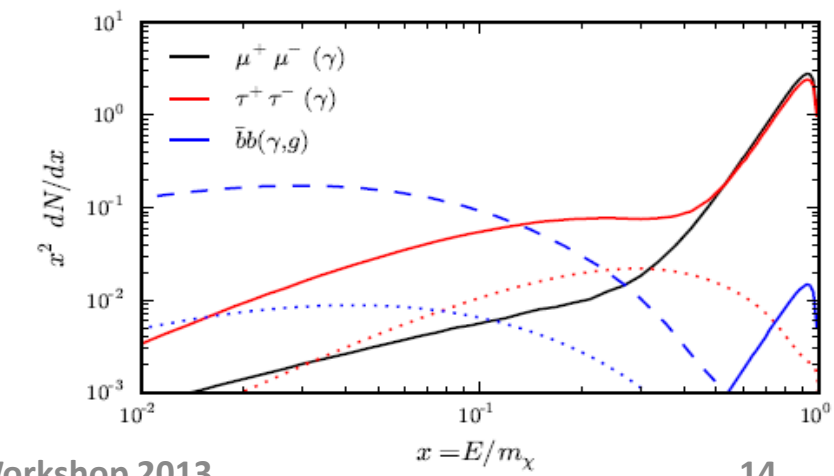


Gamma-ray lines

- Annihilation into $\gamma\gamma$ or γX ($X = Z^0, H^0, \ldots$) at loop level $O(\alpha^2)$ or Virtual internal bremsstrahlung (VIB) at loop level $O(\alpha)$ will produce a distinct spectral feature
  - Clean signal (hard to mimic with astrophysics) → Smoking gun signal!
  - Low statistics (suppressed by a factor of 10^2 to 10^3 in many models), $\langle\sigma v\rangle_{\gamma\gamma} \sim 10^{-30}$ cm^3/s
  - Optimal target regions depends on the DM profile



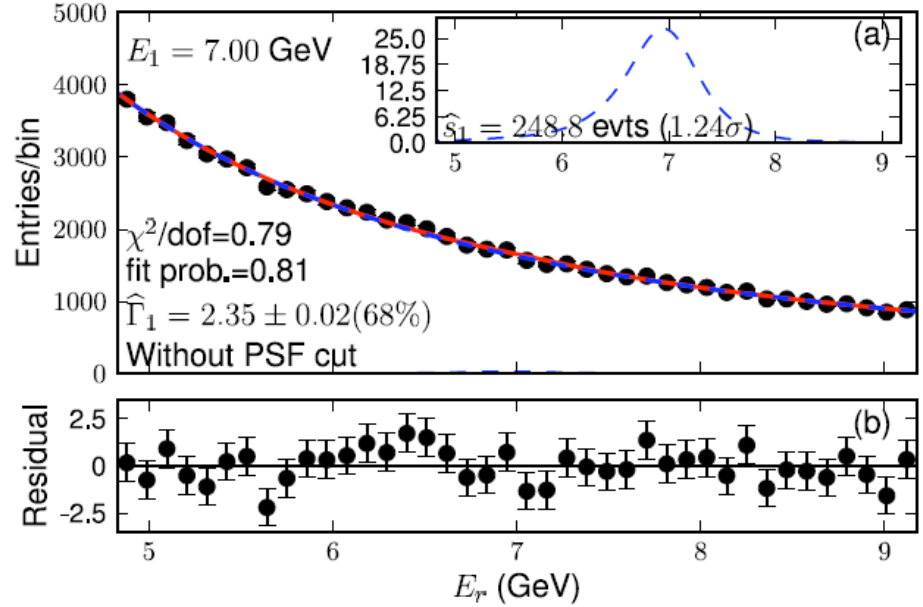


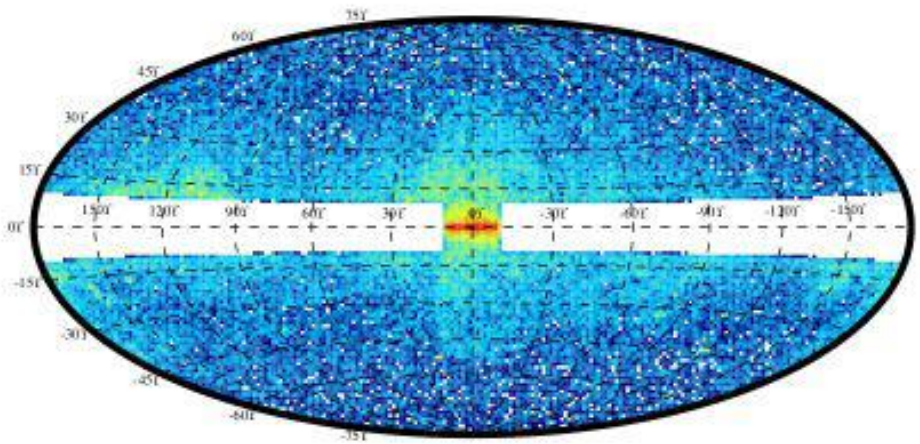


Bergstrom et al. Nucl. Phys. B504, 27 (1997)
Ferrer et al., Phys. Rev D74, 115007 (2006)
Gustafsson et al. PRL 99, 041301 (2007)
Profumo, Phys. Rev. D78, 023507 (2008)
Bringmann et al., arxiv::1203.1312 (2012)
...

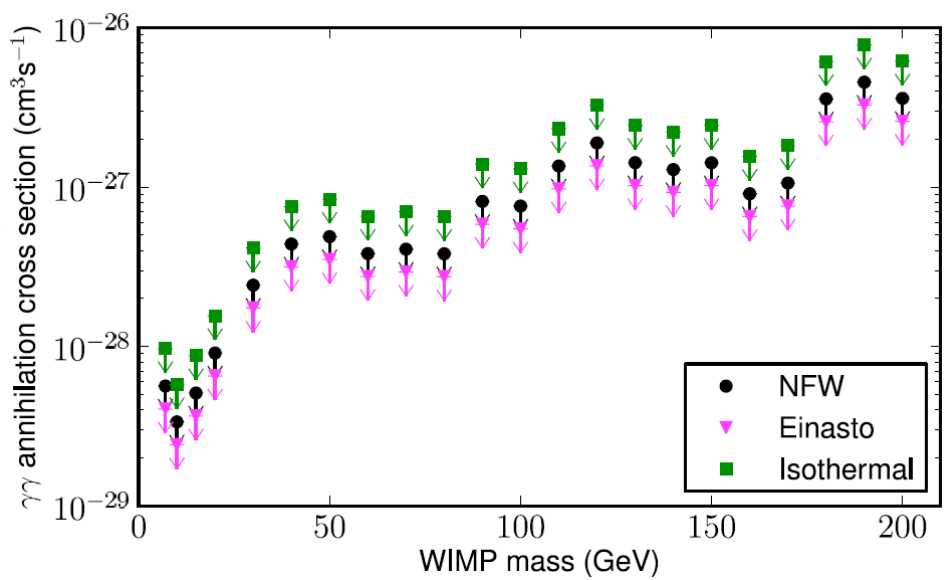
Spectral line search

- Sliding window technique: model bkg as single power law and model energy dispersion from simulation ('line like' excess).
- 2 yr analysis Fermi LAT looked at the whole sky data and found no evidence of a line



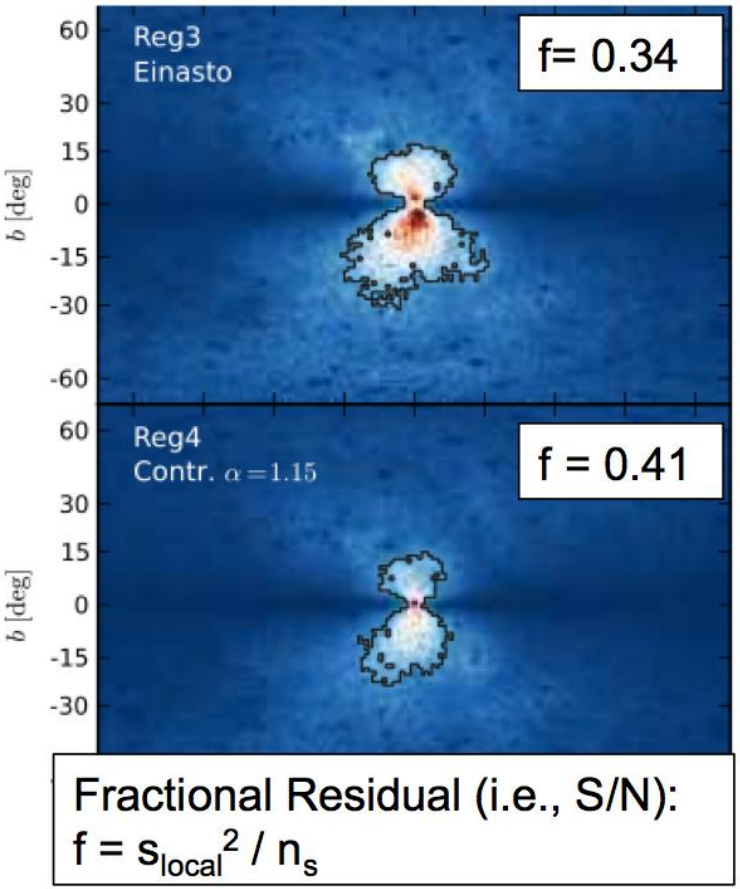


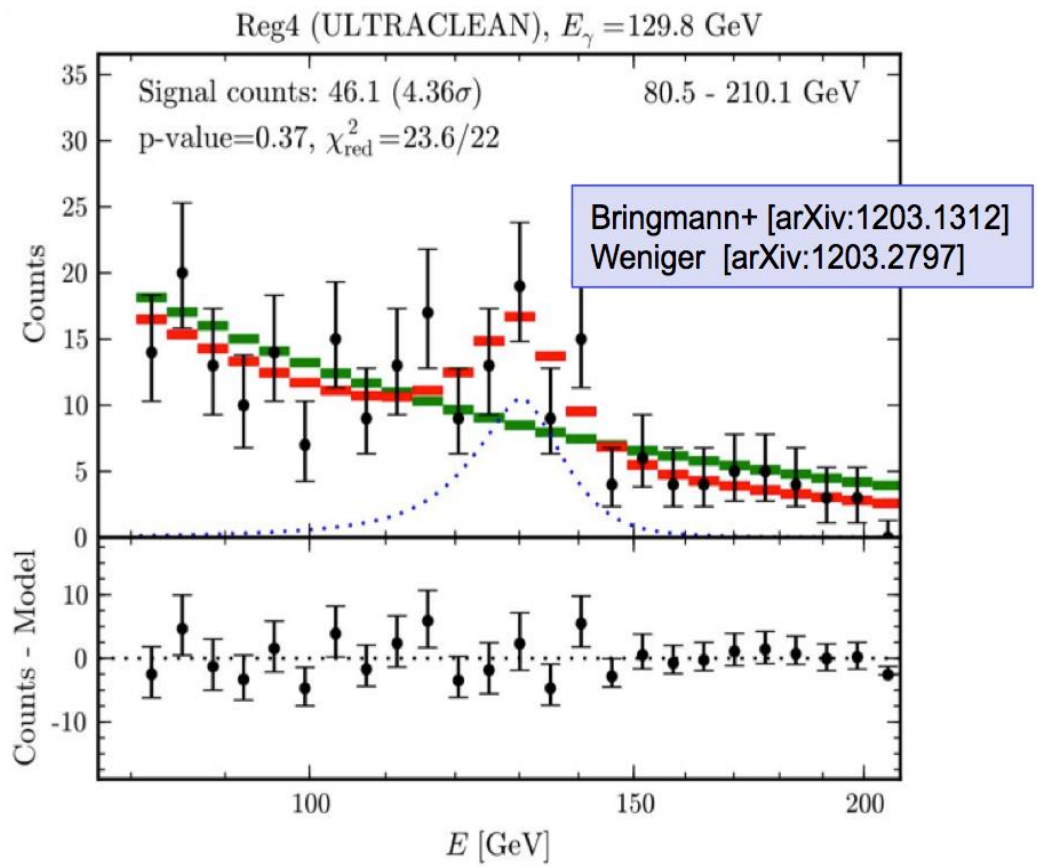
$|b| > 10^\circ$ plus $|\ell|, |b| < 10^\circ$



M. Ackermann el all. (FERMI-LAT)
PRD 86, 022002 (2012)
arXiv:1205.2739

Evidence for 130 GeV gamma-ray line?

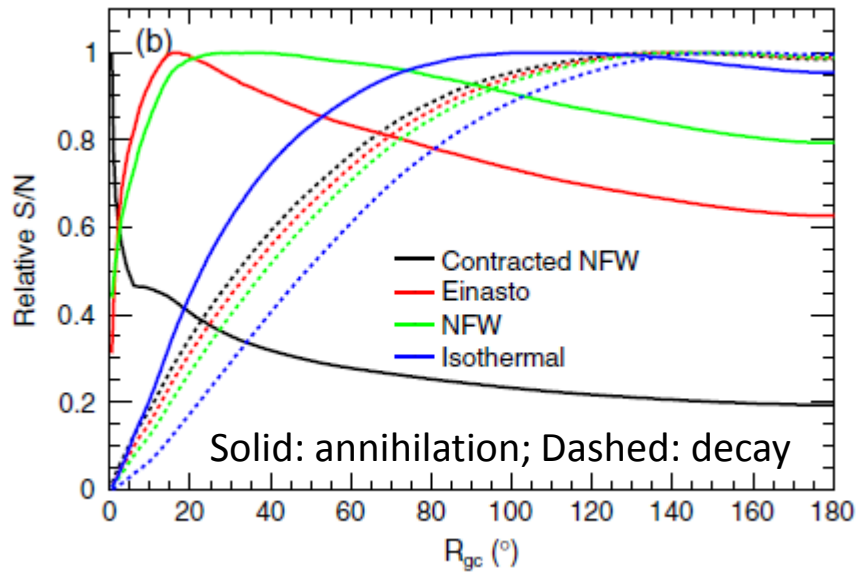


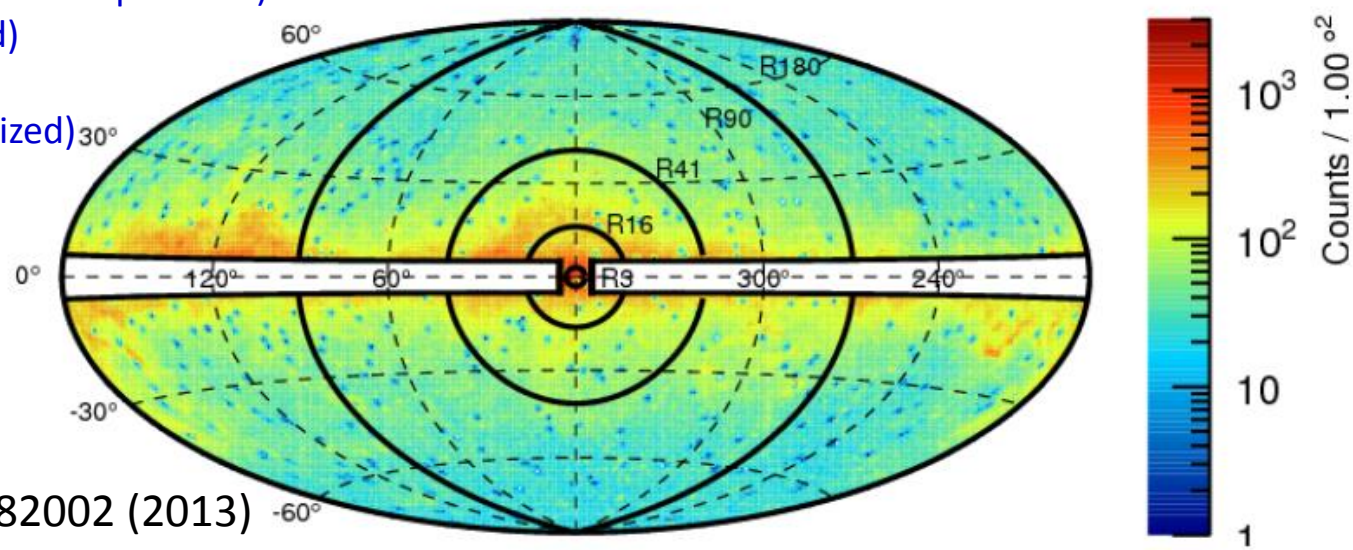


- Bringmann et al. and Weniger claimed evidence for a narrow spectral feature near 130 GeV and near the Galactic centre:
  - Signal is particularly strong in 2 out of their 5 test sky regions, shown above.
  - 4-5σ(local), with S/N ≈30-60% in optimized regions of interest (ROI).

Fermi-LAT Line Search - 4 years data

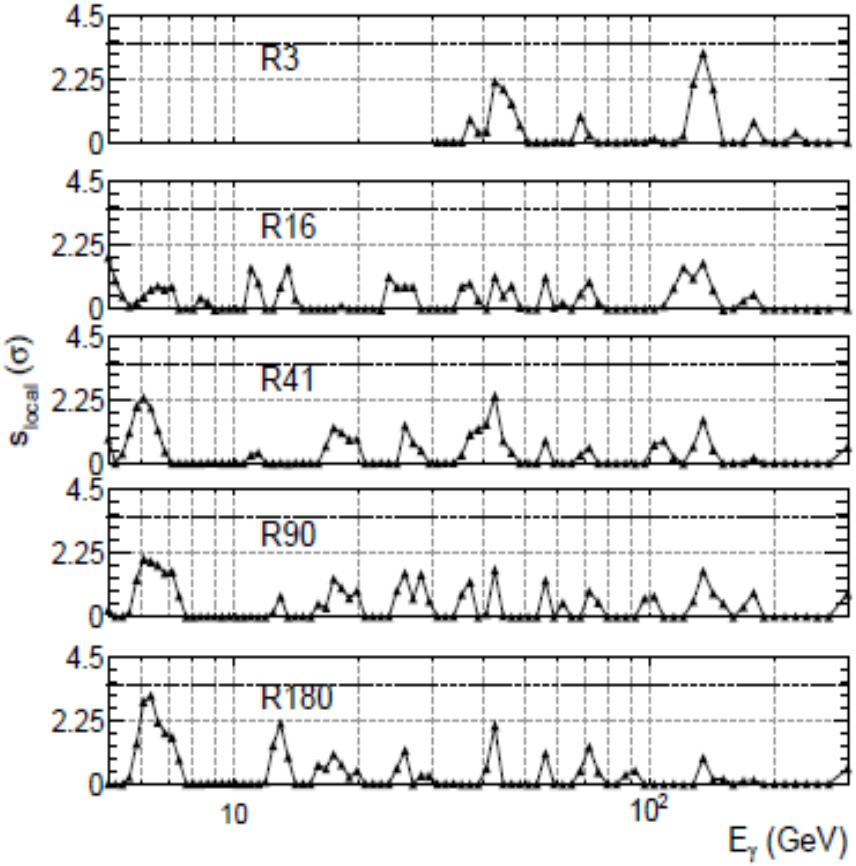
- Search for lines from 5 – 300 GeV using 3.7 years of data
- Use P7REP_CLEAN (REP = "reprocessed")
  - P7 data with updated instrument calibrations
- Mask bright (>10σ for E > 1 GeV) 2FGL sources
- Optimize ROI for a variety of DM profiles
  - Find RGC that optimizes S/sqrt(B)
- Search in 5 ROIs
  - R3 (3 ° GC Circle, cont. NFW Optimized)
  - R16 (Einasto Optimized)
  - R41 (NFW Optimized),
  - R90 (Isothermal Optimized)
  - R180 (DM Decay)

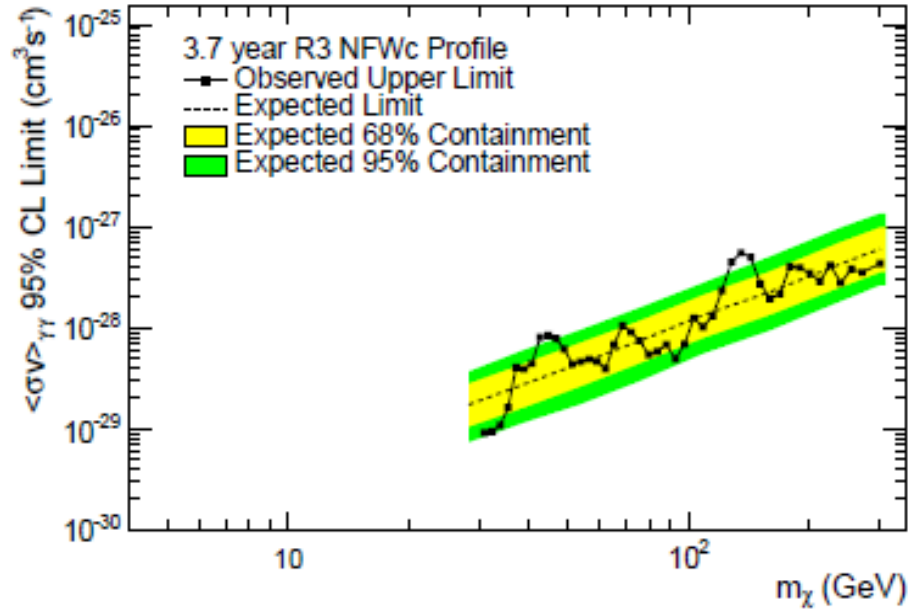


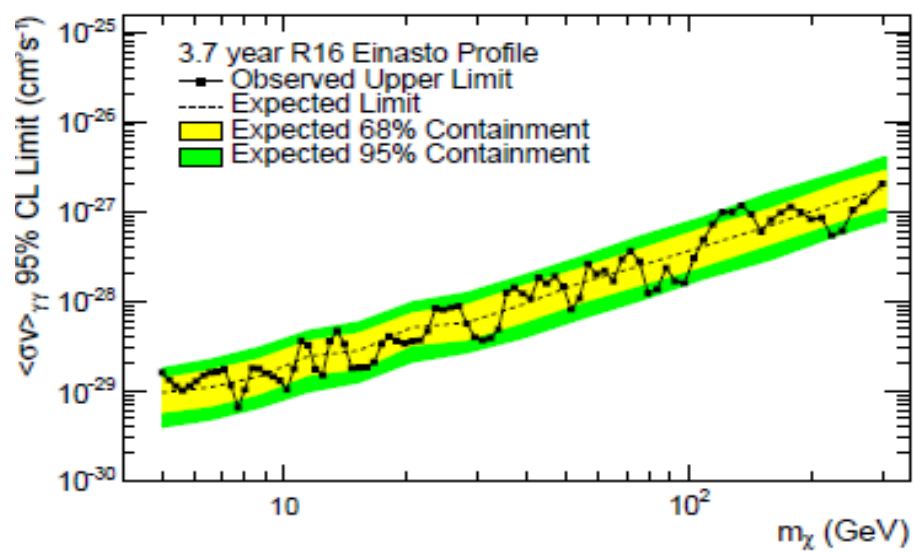


PHYSICAL REVIEW D 88, 082002 (2013)
arXiv:1305.5597

95% CL $<\sigma v>_{\gamma\gamma}$ Upper Limit R3-R16



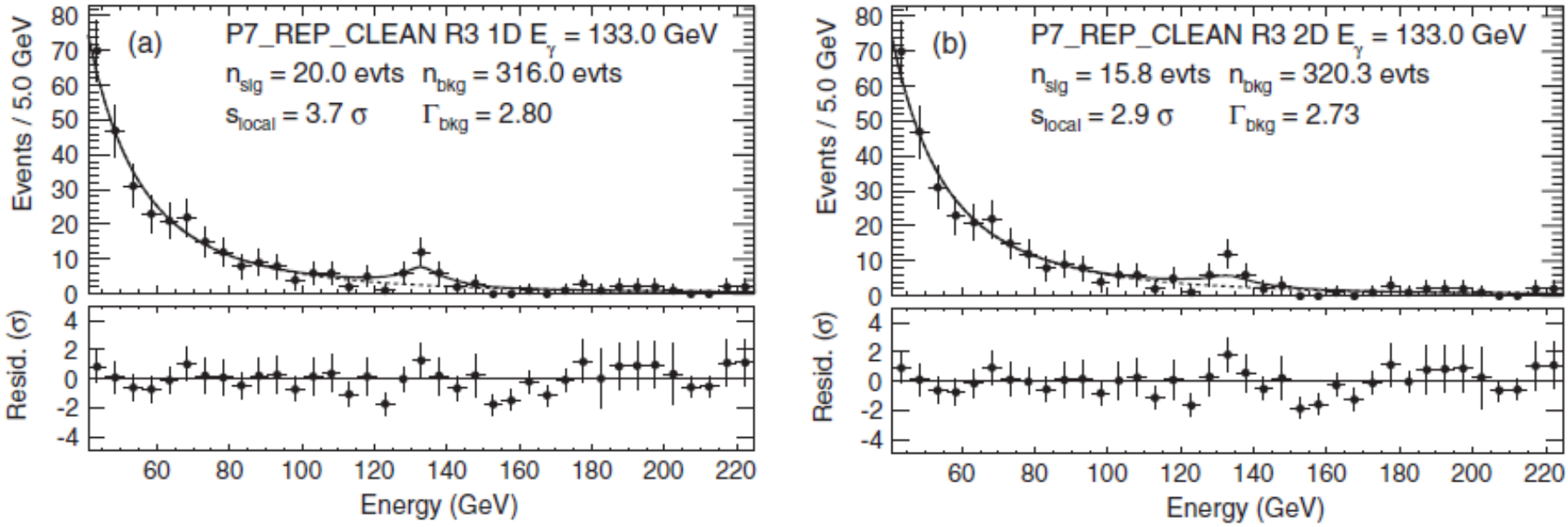




- No globally significant lines detected
  - All fits have global significance < 2σ

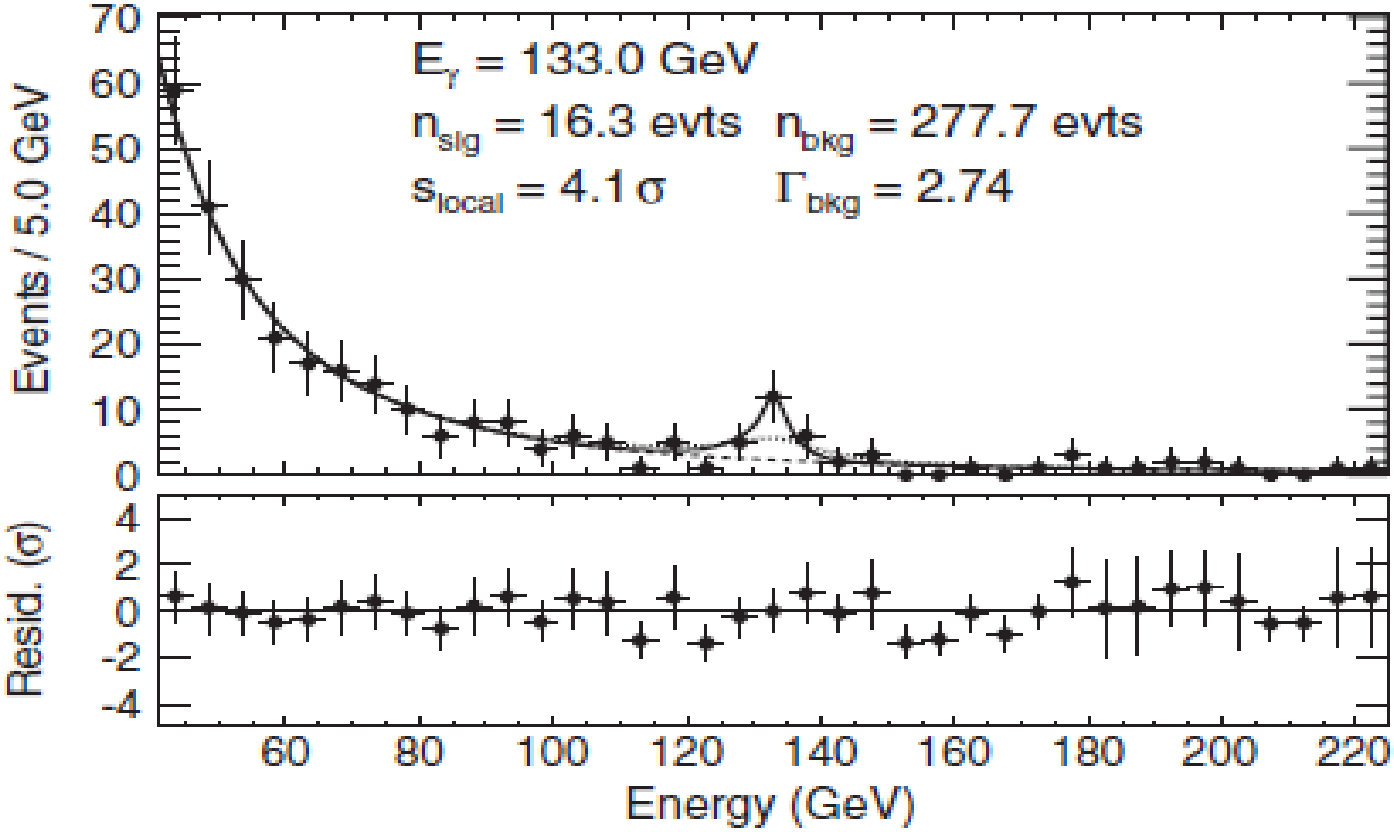
arXiv:1305.5597

Fermi-LAT Team Line Search at 133 GeV with 4.4 year of data in R3



- 3.7σ (local) 1D fit at 133 GeV with 4.4 year reprocessed data in R3
  - 1D PDF does not include of the energy reconstruction quality estimator, P_E
- 2.9σ (local) 2D fit at 133 GeV with 4.4 year reprocessed data in R3
  - 2D PDF includes of the energy reconstruction quality estimator, P_E
- <2σ global significance after trials factor

Width of Feature near 133 GeV

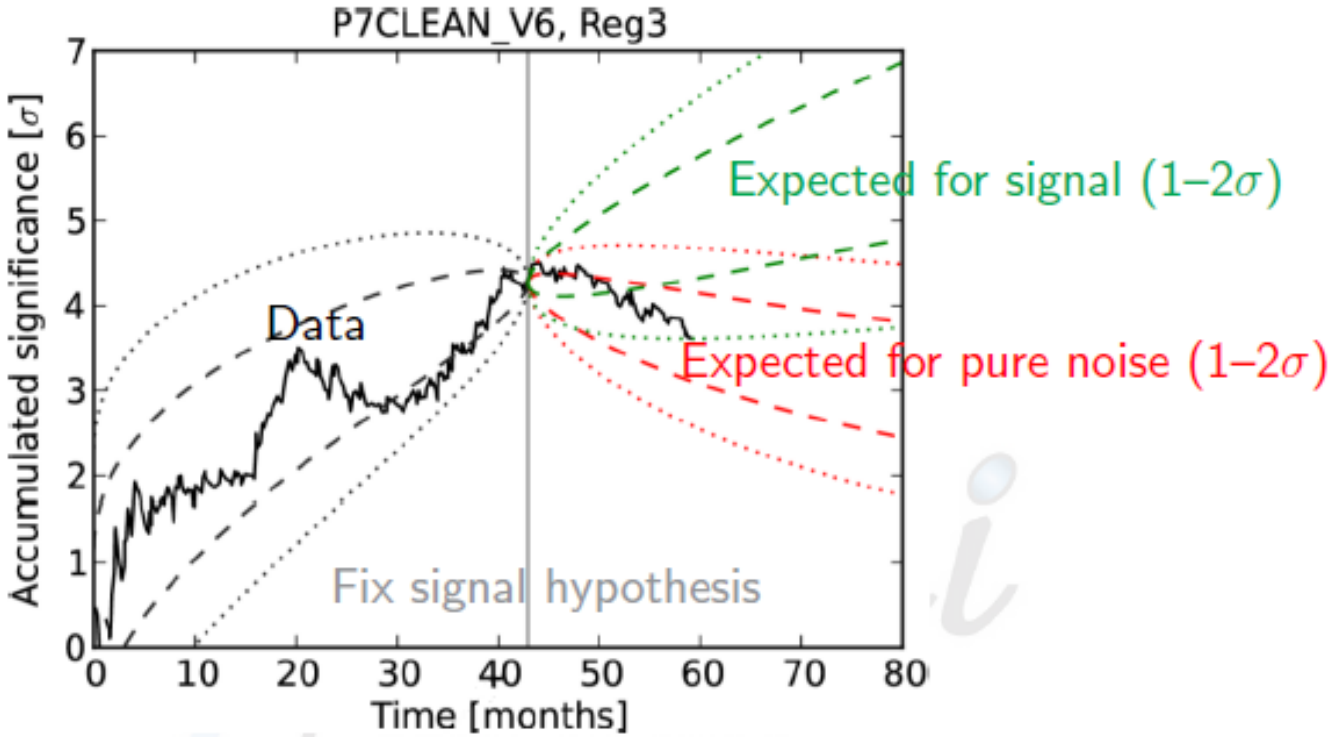


- Let width scale factor float in fit (while preserving shape)

$$s_\sigma = 0.32^{+0.30}_{-0.13}(95\%CL)$$

  - Feature in data is narrower than expected energy resolution measured in beam tests and detector simulations

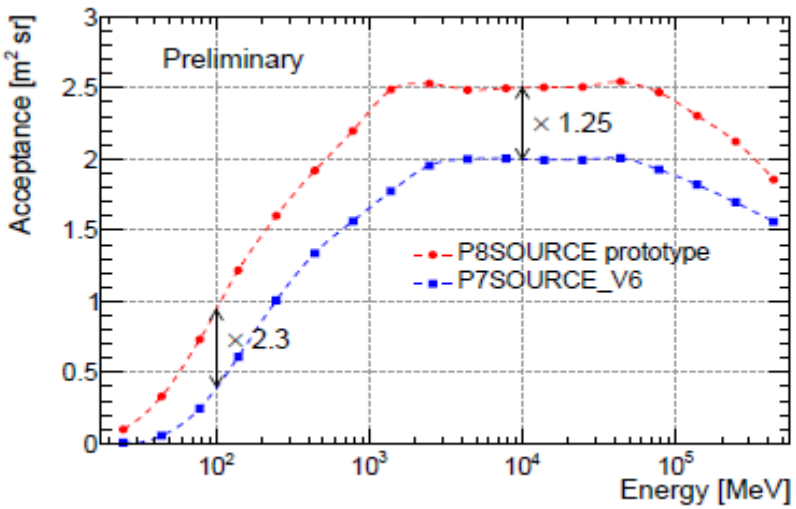
A gamma-ray line in the galactic center?
Time evolution of the signal, see arXiv:1303.1798



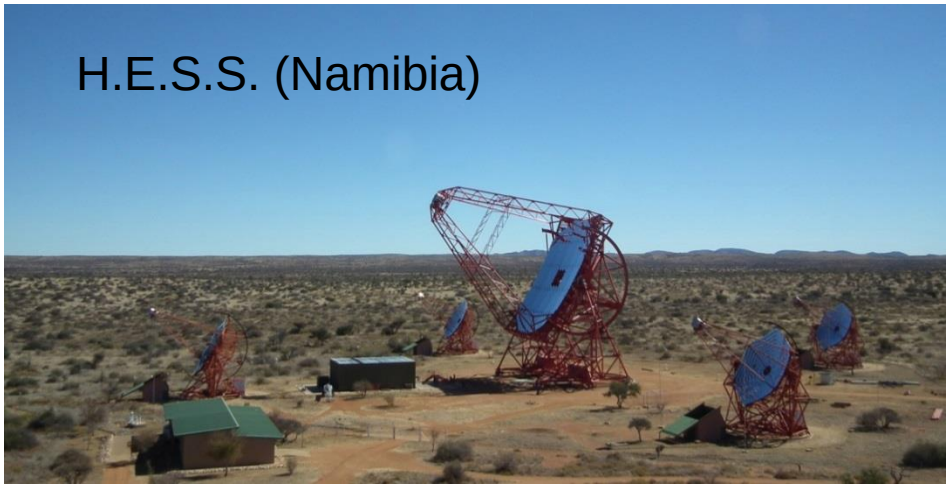
- Weniger's updated results are consistent with the results from the recent LAT line-search paper.
  - Likely that the original putative line signal was a statistical fluctuation.

Spectral line search: near terms prospects

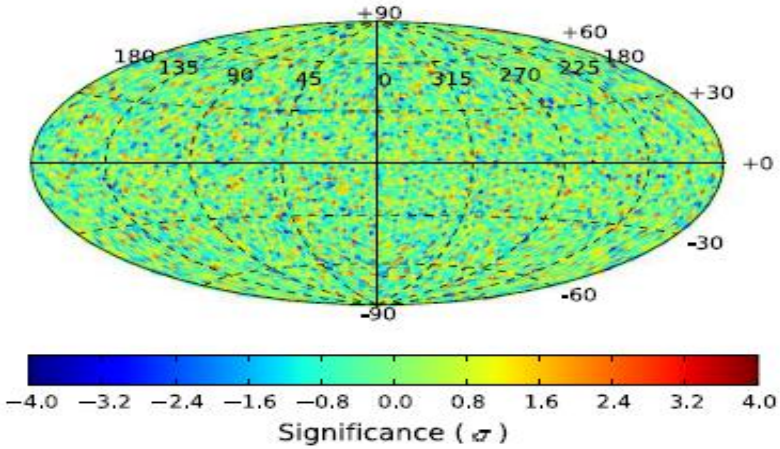
- Fermi LAT:
  - Improved event analysis with Pass 8
  - Possible modifications to the observing strategy
- H.E.S.S.-2 Cerenkov telescope:
  - 50 hours of GC observation could be enough to rule out signature or confirm it at 5 sigma



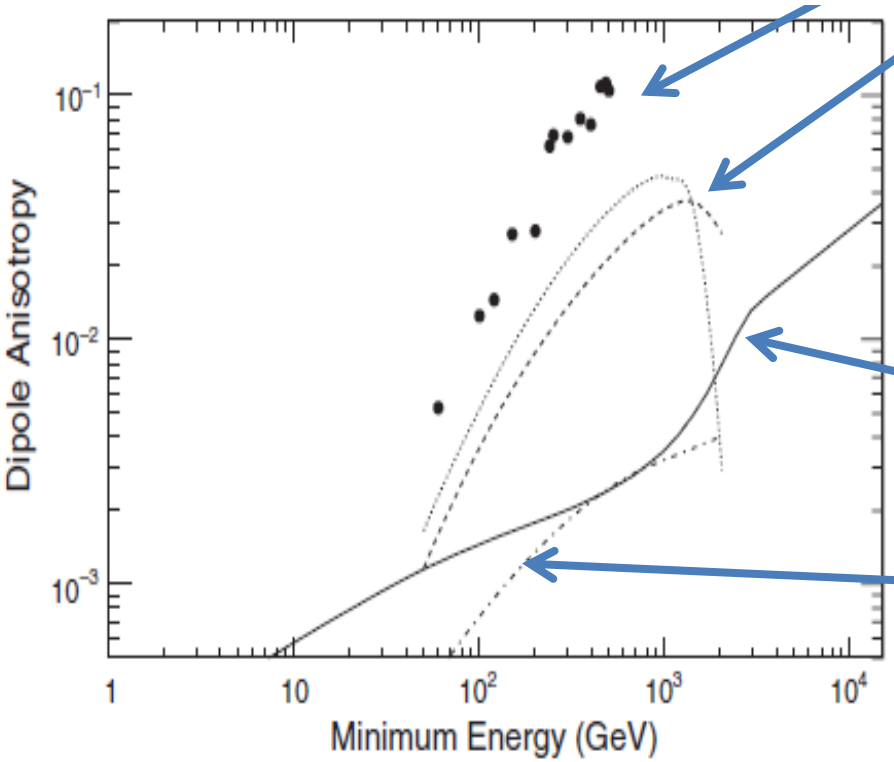
Fermi-LAT Upcoming Developments Pass 8



CRE anisotropies (PRD 82, 092003 (2010))



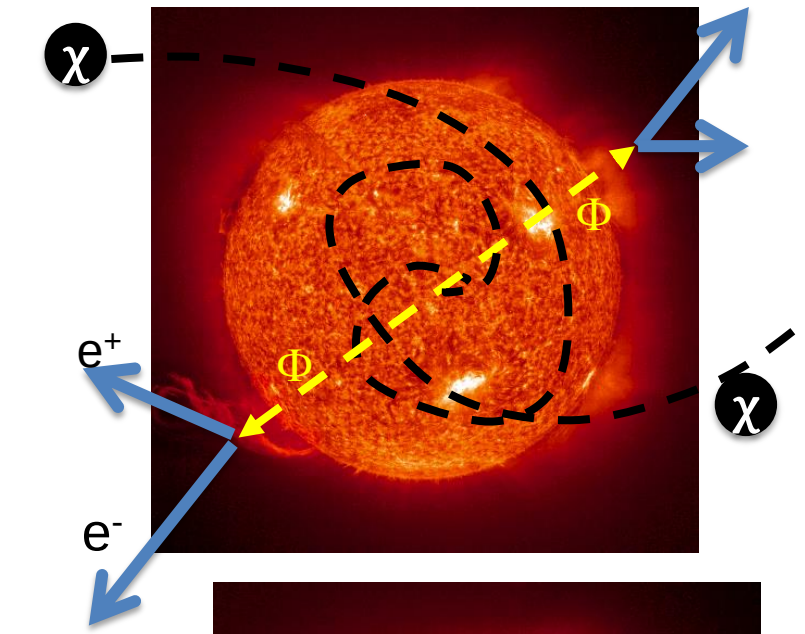
- Fermi offers a unique opportunity for the measurement of possible CRE anisotropies
  - Key factors: large exposure factor and large field of view
- Most stringent upper limits to date based on one year of data
  - More than 1.6 M CRE candidate above 60 GeV

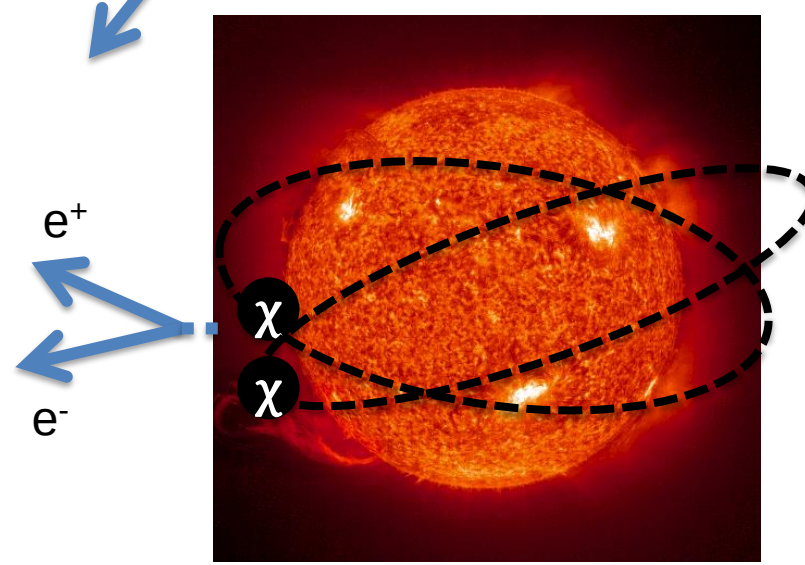


- Markers: 3 sigma ULs data
- Dashed (dotted) lines: single nearby dark matter clump with a speed of 300km s^{-1} perpendicular to the Galactic plane, with DM particle mass of 5 TeV that is departing at 1.54 kpc (mass of 5 TeV that is approaching at 1.43 kpc) (for more details see M. Regis and P. Ullio, arXiv:0907.5093)
- Solid line: DM distributed in the Milky Way Halo according to a Navarro, Frenk and White (NFW) profile, with a 3 TeV mass candidate that annihilates into $\tau^+\tau^-$
- Dot-dashed line: DM from the population of Galactic substructures of dark matter clumps in the halo following a NFW profile , with DM particle mass of 3.6 TeV that annihilates into τ leptons (for more details see I. Cernuda, arXiv:0905.1653)

Solar CREs from DM annihilation

- Combination of direct and indirect detection mechanisms
  - WIMP-nucleon scattering leads to WIMP capture by the Sun
  - WIMP-WIMP annihilation leads to the production of cosmic rays (e.g. neutrino)
- Charged particles (e.g. electrons and positrons) from DM capture and annihilation in the Sun core would not escape, but ….
- DM capture and annihilation through an intermediate state
  - WIMP accretion rate determined by scattering cross section
  - Annihilation through an intermediate particle Φ that can travel out of the Sun and decay into cosmic rays
- DM captured through inelastic scattering and forms a loosely bound halo around the Sun
  - WIMP accretion via inelastic scattering (maintain large orbits)
  - Annihilation directly into cosmic-ray electrons in the solar neighborhood
- See P. Schuster et al., PRD 82, 115012 (2010)

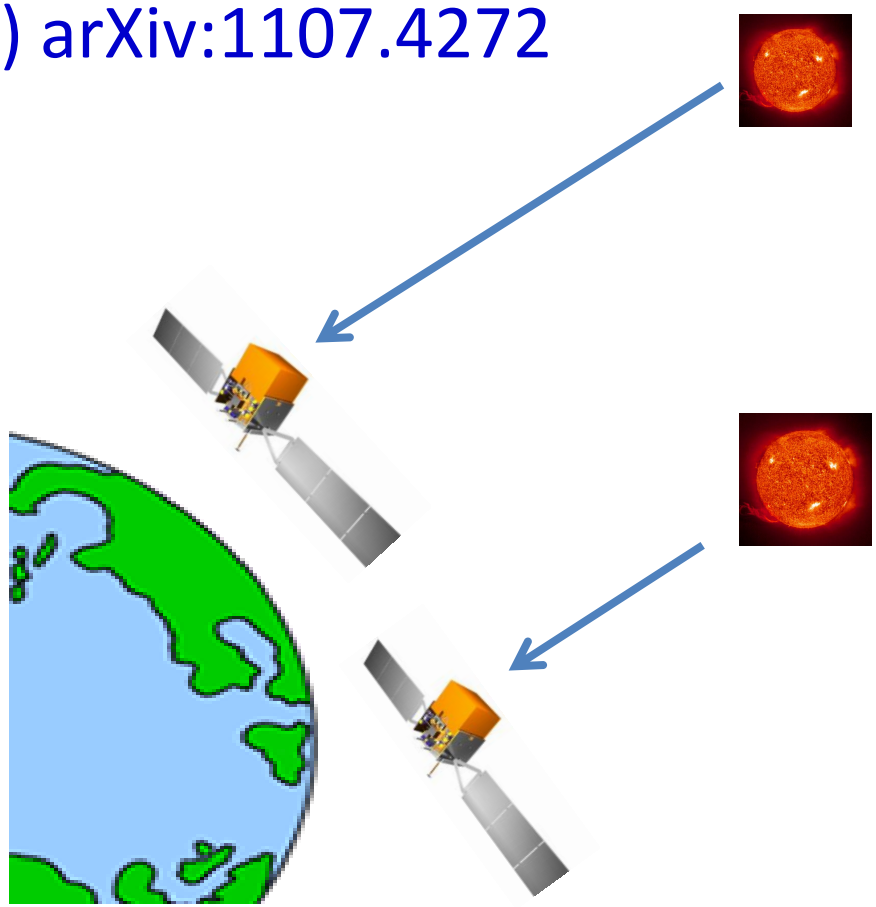




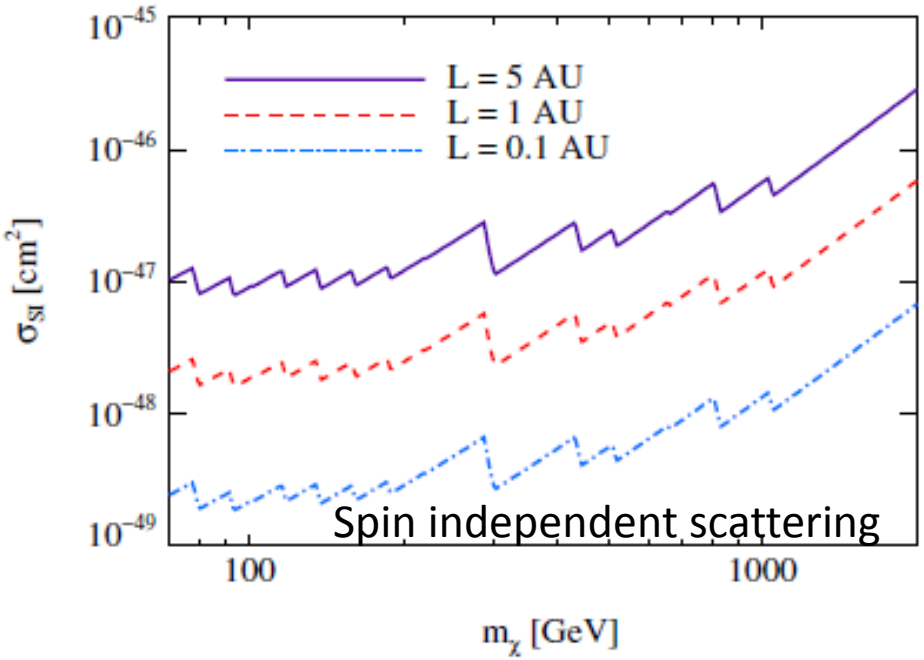
CRE from the Sun: Fermi LAT results

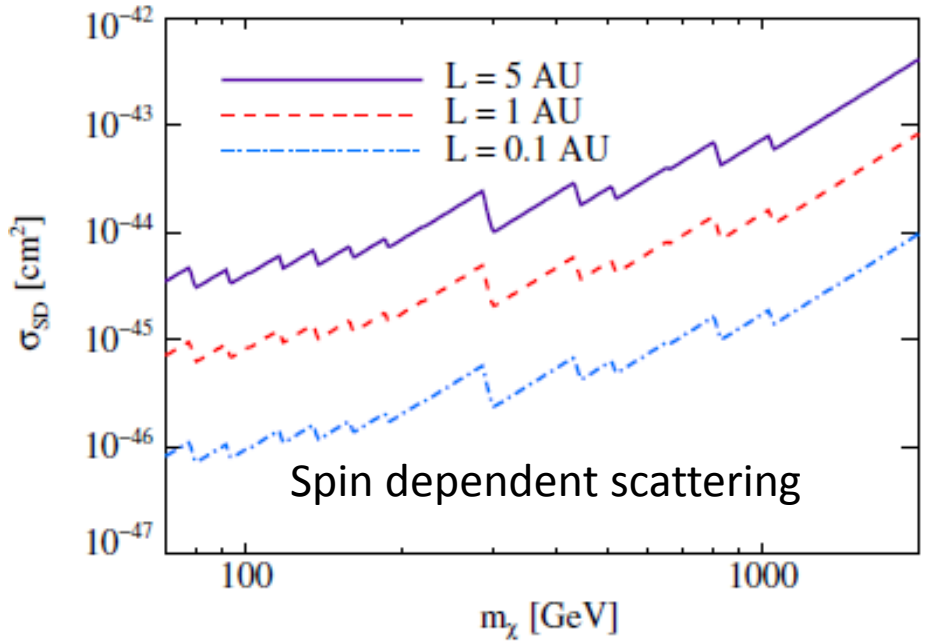
PRD 84, 032007 (2011) arXiv:1107.4272

- ~10^6 CRE events (E > 60 GeV), from 1st year of operation
- Analysis performed in ecliptic coordinates, in reference frame centered on the Sun
  - "Background" template centered in opposite direction or shuffling the arrival directions
  - Extended sky regions centered on the Sun with angular radii of 30°, 45°, 60° and 90° have been considered because the CRE trajectories could be affected by the geomagnetic and heliospheric magnetic field
- Search for a flux excess correlated with Sun's direction yielded no significant detection, flux upper limits placed



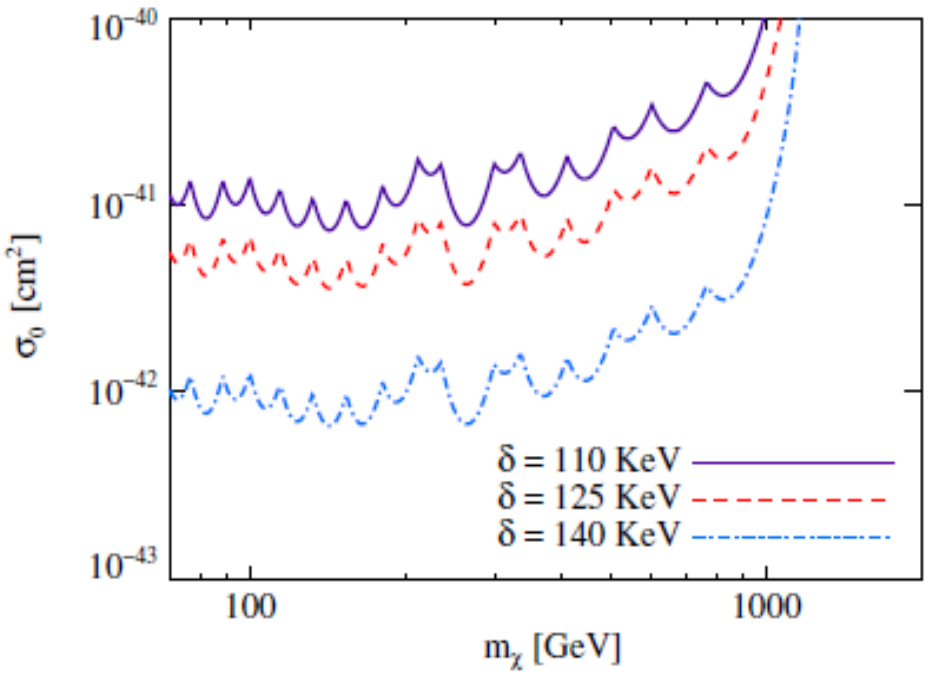
Limits on elastic scattering X-section via Φ

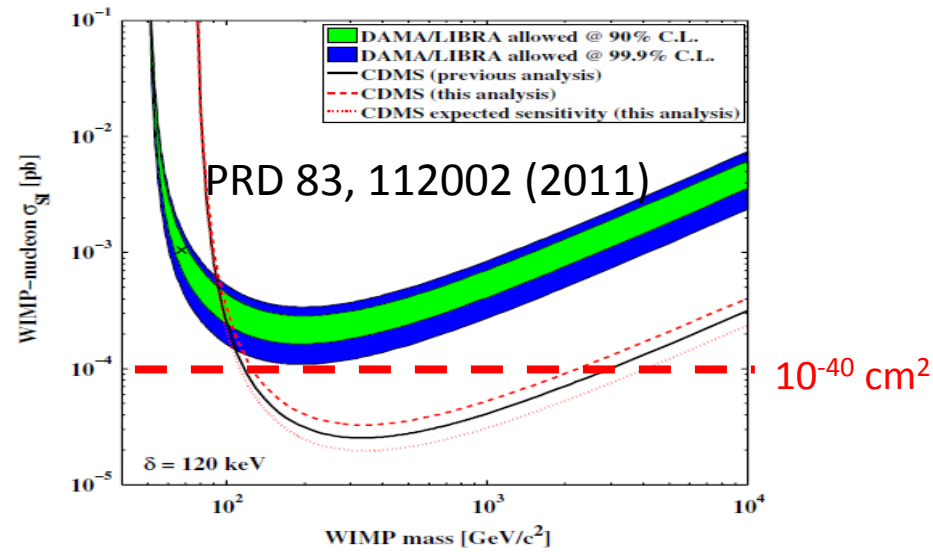


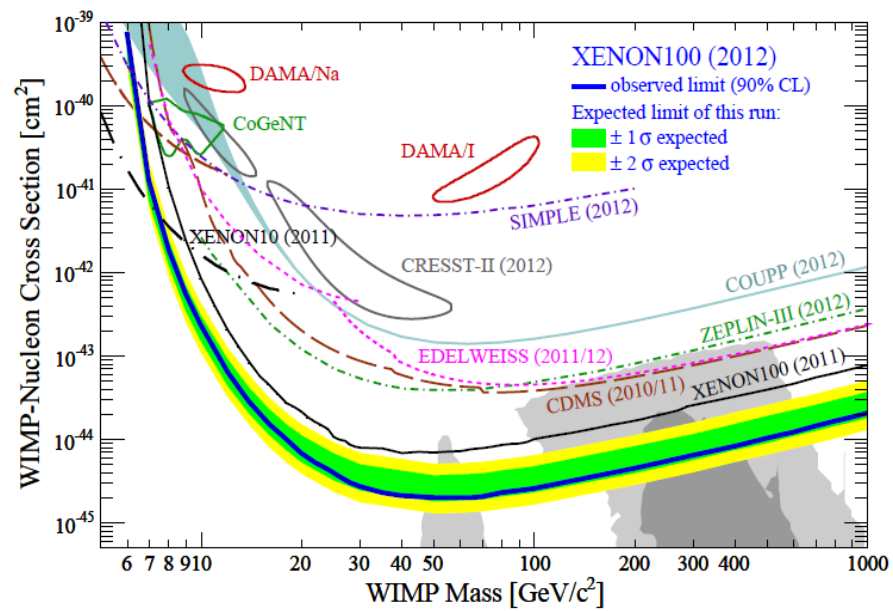


- The limits at 95%CL have been evaluated for three values of the decay length L=5 AU, 1 AU, and 0.1 AU
  - Decreasing L increases the observed CRE flux by condensing the region within which most decay
  - Even for as large a decay length as L = 5 AU, the signal in the energy range used in this analysis is strongly peaked in the direction of the Sun and extends only a few degrees at most
- "Solar" CRE flux limits correspond to constraints on the rate of decay to CREs outside the Sun that are ~ 2-4 orders of magnitude stronger than constraints on the associated FSR derived from solar gamma-ray data

Limits on inelastic scattering X-section



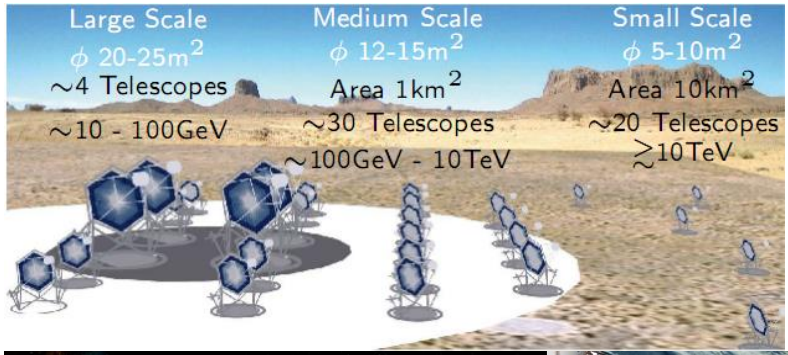


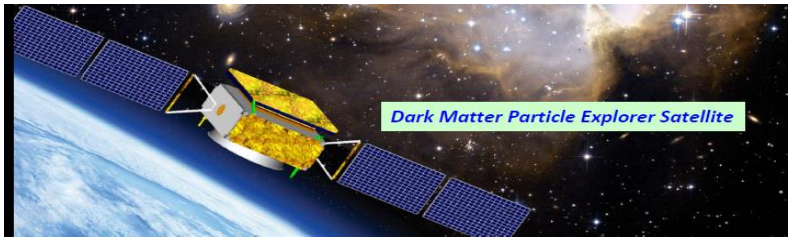


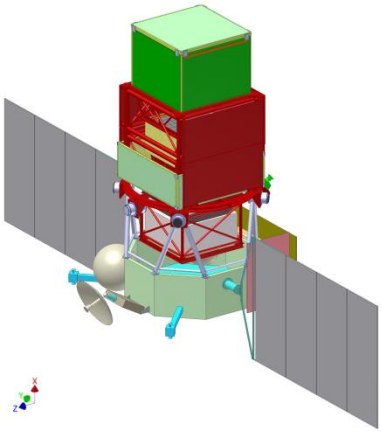
- For a DM particle to scatter inelastically off a nucleon N via the process χ+N → χ*+N, the DM must have energy E≥ δ (1+ m_χ/m_N), where $\delta = m_{\chi^*} - m_\chi$
- The limit at 95%CL have been evaluated with three different δ=110 keV, 125 keV and 140 keV

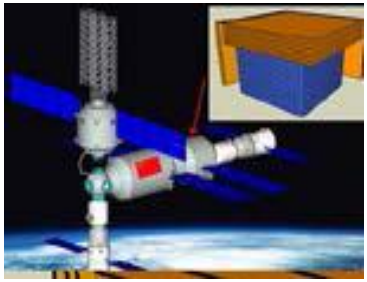
Next generation (gamma-ray) experiments

- CTA: a km^2 array of Atmospheric Cherenkov telescopes! Sensitivity about a factor 10 better than current ACTs; an energy coverage from a ~10 GeV -~10 TeV, field of view of up to 10°; angular resolution could be as low as 0.02°
- CALET on ISS : 30 X_0 few % of energy resolution, good angular resolution and high electron/proton separation
  - Launch planned in 2014
- DAMPE satellite: 31 X_0 depth calorimeter, few % of energy resolution, good angular resolution and high electron/proton separation
  - Launch planned in 2015-2016
- Gamma-400: satellite with better angular and energy resolution in gamma rays + high precision charged particles detector up to several TeV for e- and PeV for protons!
  - launch planned in 2018.
- HERD: The High Energy cosmic-Radiation Detection facility onboard China's Spacestation
  - planned for operation around 2020.





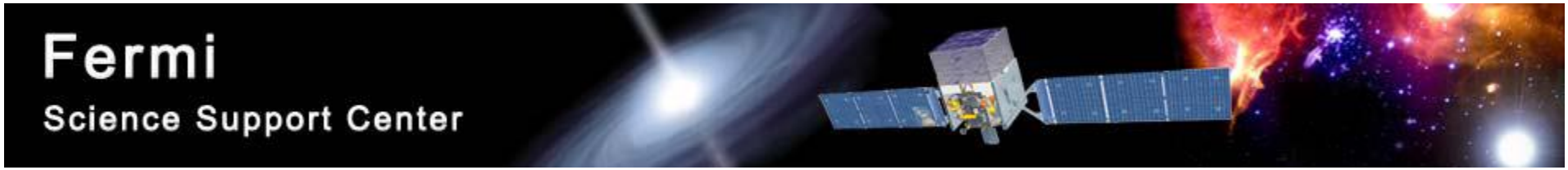




Summary

- The Fermi LAT team has looked for indirect DM signals using a wide variety of methods
  - So far no signal has been detected and strong constraints have been set
  - No global significant spectral lines from 5–300 GeV in 5 ROIs
    - Uncovered some aspects of the 135 GeV line that require more study
      - Much narrower than expected energy resolution
      - Similar feature seen in Limb
    - Larger than expected systematic uncertainty
    - Does not appear in the inverse ROI
- The next generation of instruments will provide many other exciting results!

Pass 7 Data Reprocessed at FSSC

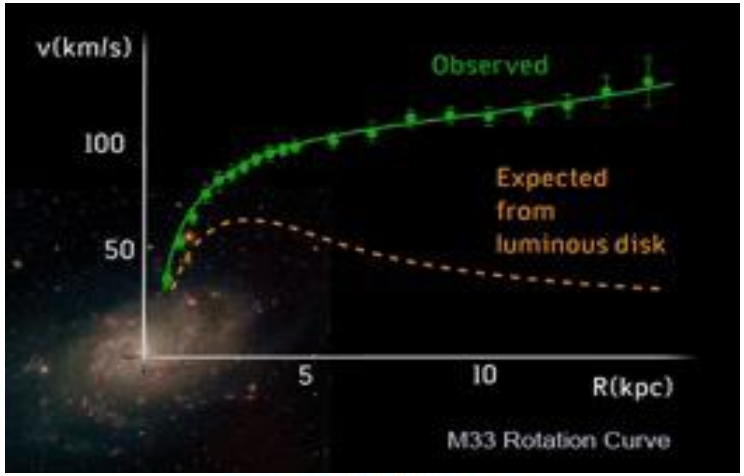


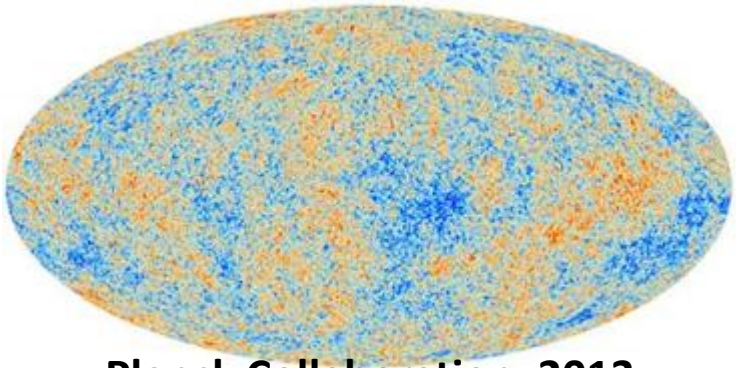
- The FSSC has released a new version of the pass 7 data that has been reprocessed (P7REP).
- The updated instrument calibrations used to produce the P7REP data improve the LAT PSF above 3 GeV and provide a new on-orbit PSF for P7REP data.
- The updated LAT data can be downloaded from the LAT LAT Data Server at the FSSC website.
- A description of the updates and links to new analysis products is available at the P7REP Usage page.

BACKUP

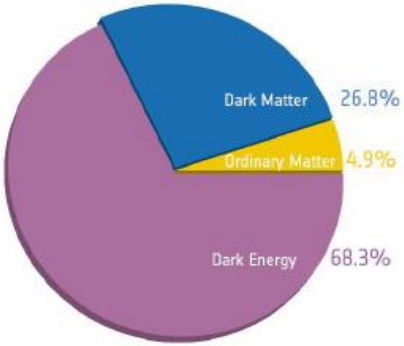
Dark Matter

- Astrophysical evidence for missing mass
  - Galaxy rotation curves
  - Colliding clusters
  - Cosmological probes ($\Omega_{dm}\, h^2 \approx 0.1$)
- Observational evidence indicates:
  - Non-baryonic
  - (Almost totally) neutral
  - (Almost totally) collisionless
- Theoretical candidates:
  - Axions, sterile neutrinos, etc.
  - Modifications to gravity
  - Weakly Interacting Massive Particles (WIMPS)

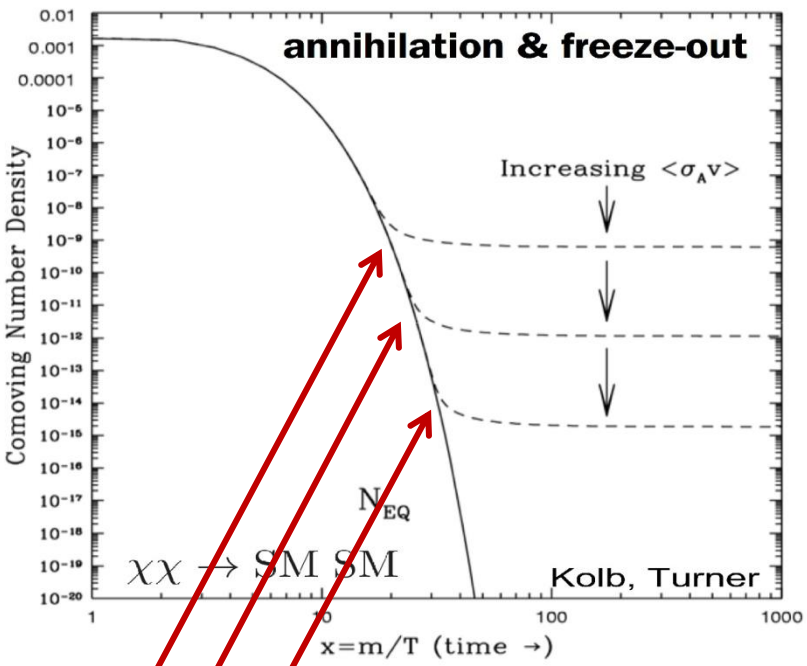




Planck Collaboration, 2013



WIMPs



Freeze-out:
$\Gamma_{ann} = n \langle\sigma v\rangle \sim H$
annihilation rate ~ expansion rate

$\langle\sigma v\rangle_{ann} \sim 3 \times 10^{-26}$ cm^3/s for thermal relic

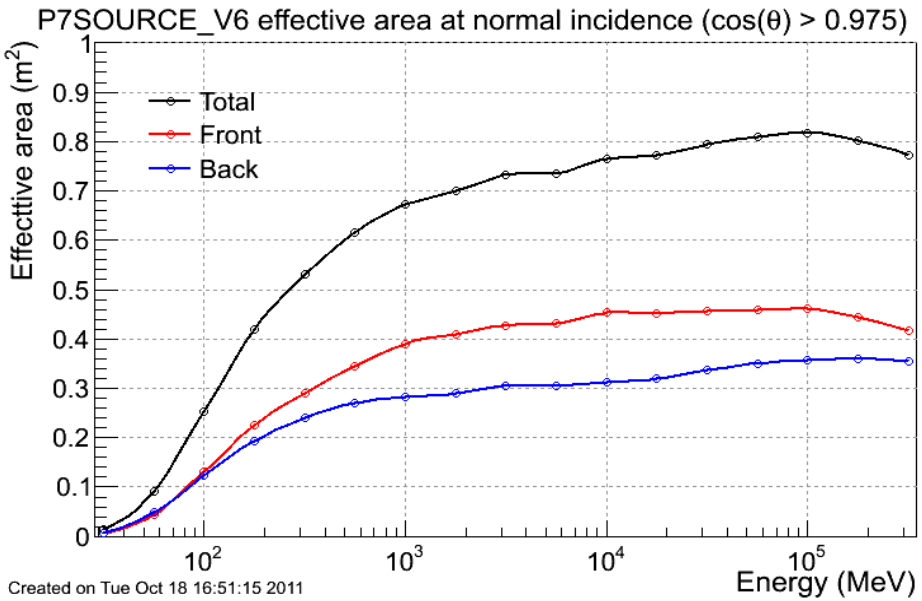
- A WIMP in chemical equilibrium in the early Universe naturally has the right density to be Cold Dark Matter
  - At early times, WIMPs are produced in l^+l^-, ... collisions in the hot primordial soup (*thermal production*)
  - WIMP production ceases when the production rate becomes smaller than the Hubble expansion rate (*freeze-out*)
  - After freeze-out, the number of WIMPs per photon is constant
- Standard relic density calculation yields for nonrelativistic relics

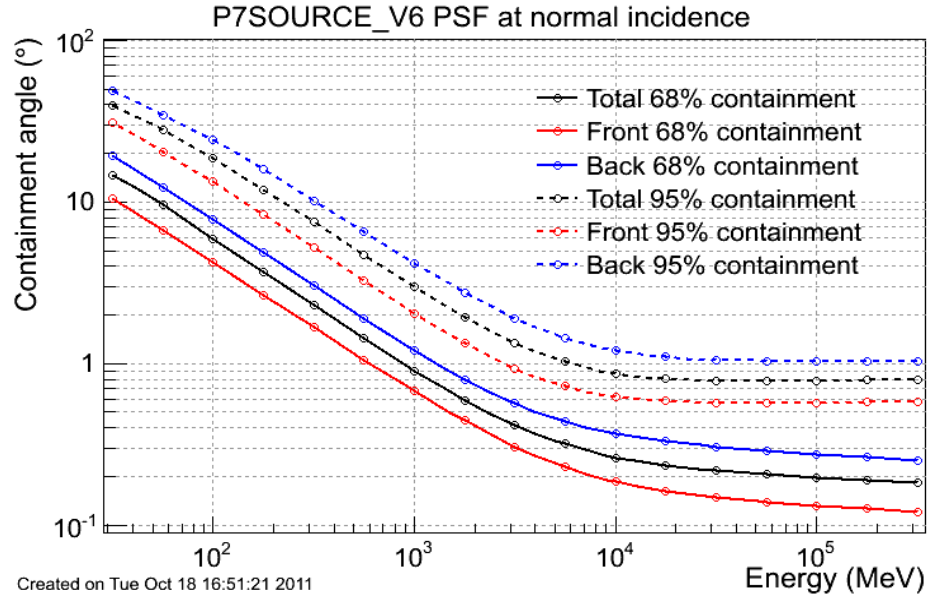
$$\Omega_{\rm dm} h^2 \approx \frac{3 \times 10^{-27} {\rm cm}^3 {\rm s}^{-1}}{\langle \sigma v \rangle} \simeq 0.1$$

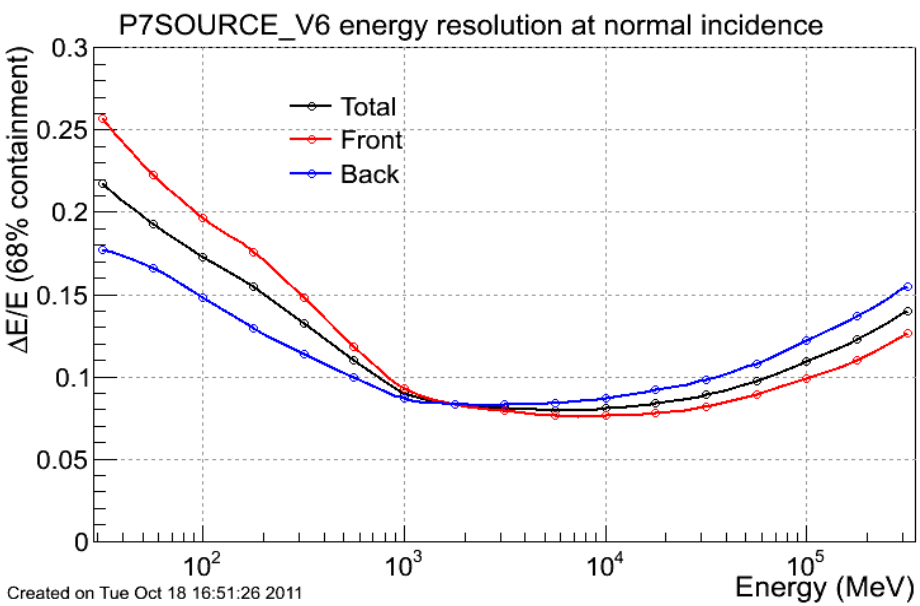
- Electroweak cross-sections are in correct range

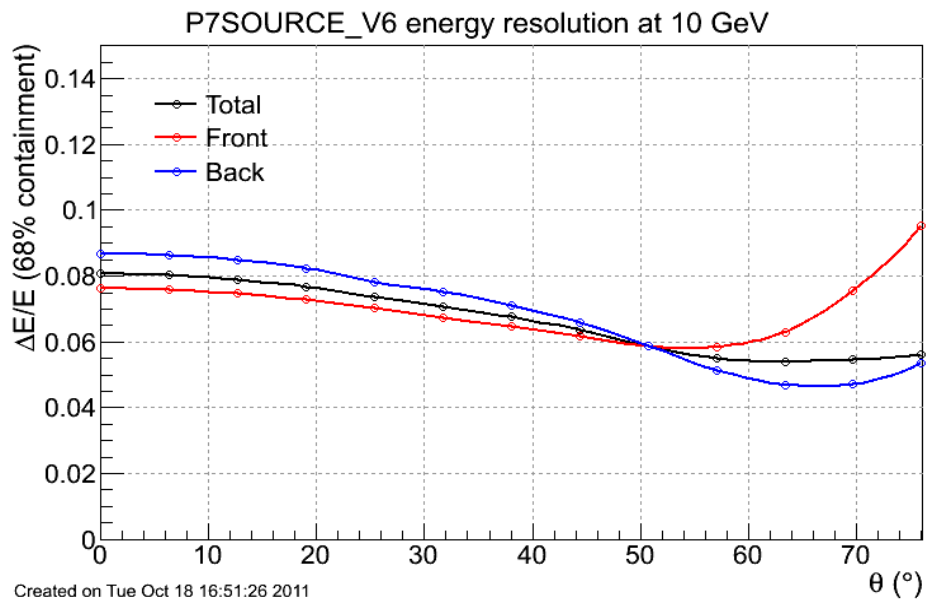
$$\langle \sigma v \rangle \sim \frac{\alpha^2}{(200{\rm GeV})^2} \sim 10^{-26} {\rm cm}^3 {\rm s}^{-1}$$

Fermi-LAT performance



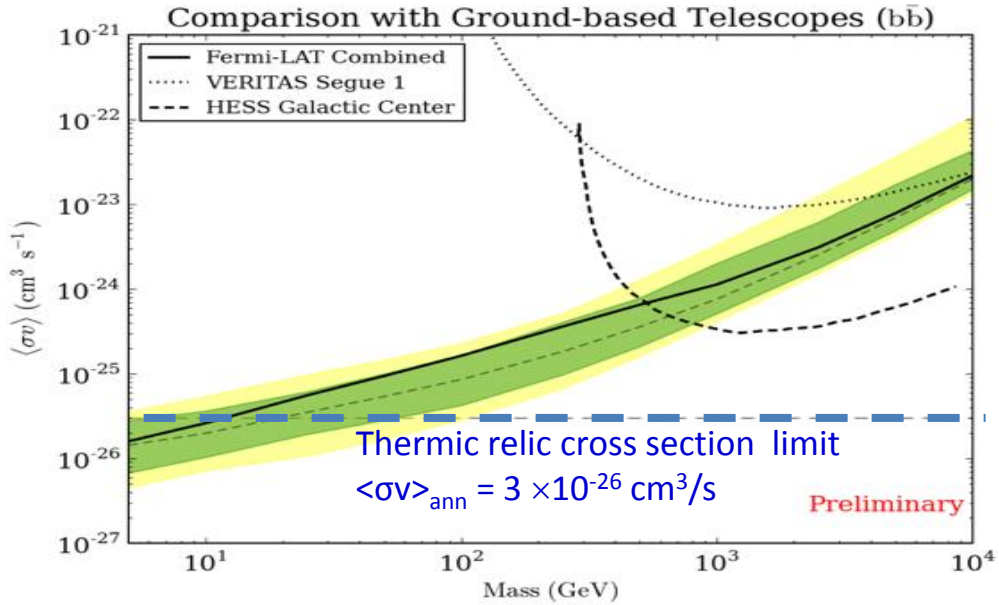


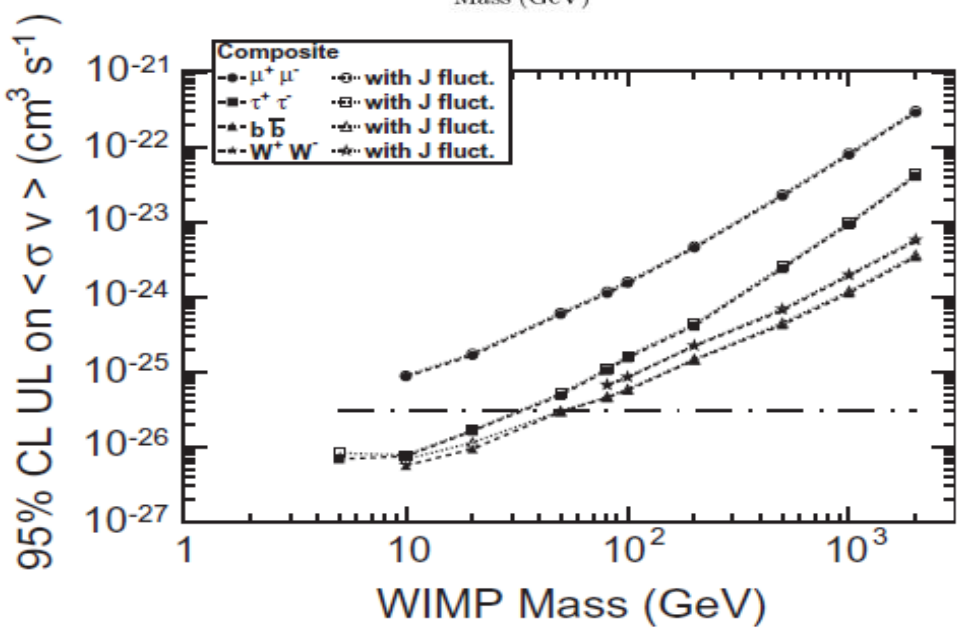




Dwarf Spheroidal Summary

- 3-4 years of Fermi-LAT data from 10 dwarf spheroidal galaxies constrain the thermal relic cross section for low mass dark matter
- Comparable to limits from ACT observations of dwarf galaxies for high-mass dark matter.
- Currently, statistically limited (especially at high masses).
- Many dwarf galaxies remain to be discovered in optical surveys of the southern hemisphere.





Ackermann et al., arXiv:1108.3546
Geringer-Sameth et al., arXiv:1108.2914
MNM et al., arXiv:1203.6731
…

Fermi-LAT Line Search (4 years) systematic

TABLE III. Summary of systematic effects. As stated in the text, we quote either the relative uncertainty of the exposure ($\delta\mathcal{E}/\mathcal{E}$), the relative uncertainty of the number of signal events ($\delta n_{\rm sig}/n_{\rm sig}$) or the uncertainty of the induced fractional signal (δf). We give representative values when the magnitude of the effect depends on energy, or varies between ROIs.

Systematic		Effect	Section
Effective area scale		$\delta\mathcal{E}/\mathcal{E} = \pm 0.1$	D 1
Averaging exposure over ROI	(R3)	$\lvert\delta\mathcal{E}/\mathcal{E}\rvert < 0.01$	D 1
	(R180, $E_\gamma = 300$ GeV)	$\delta\mathcal{E}/\mathcal{E} = \pm 0.13$	D 1
E_γ grid spacing		$\delta n_{\rm sig}/n_{\rm sig} = {}^{+0.0}_{-0.1}$	V A
Energy resolution		$\delta n_{\rm sig}/n_{\rm sig} = \pm 0.07$	D 2
Broadening from Z width	($E_\gamma = 68$ GeV)	$\delta n_{\rm sig}/n_{\rm sig} = -0.07$	D 3
$P_{\rm E}$ distribution variation		$\delta n_{\rm sig}/n_{\rm sig} = \pm 0.01$	D 4
Energy dispersion model θ-variation		$\delta n_{\rm sig}/n_{\rm sig} = \pm 0.02$	D 4
CR contamination	(R3)	$\lvert\delta f\rvert < 0.005$	D 5
	(R180)	$\delta f = \pm 0.014$	D 5
Point-source contamination		$\lvert\delta f\rvert < 0.005$	D 6
Effective area variations	($E_\gamma = 5$ GeV)	$\delta f = \pm 0.005$	D 7 a
	($E_\gamma > 100$ GeV)	$\delta f = \pm 0.025$	D 7 a
Astrophysical background modeling	(R180, $E_\gamma = 30$ GeV)	$\delta f = \pm 0.005$	D 7 b
	(R180, $E_\gamma > 100$ GeV)	$\delta f = \pm 0.011$	D 7 b
	(R3)	$\delta f = \pm 0.019$	D 7 c

TABLE IV. Total magnitude of systematic effects, by ROI and Energy. We obtained these estimates by adding in quadrature the magnitudes of all the potential uncertainties on $\delta\mathcal{E}/\mathcal{E}$, $\delta n_{\rm sig}/n_{\rm sig}$ and δf for each ROI.

Quantity	Energy	R3	R16	R41	R90	R180
$\delta\mathcal{E}/\mathcal{E}$	5 GeV	± 0.10	± 0.10	± 0.11	± 0.12	± 0.14
$\delta\mathcal{E}/\mathcal{E}$	300 GeV	± 0.10	± 0.10	± 0.12	± 0.13	± 0.16
$\delta n_{\rm sig}/n_{\rm sig}$	All	${}^{+0.07}_{-0.12}$	${}^{+0.07}_{-0.12}$	${}^{+0.07}_{-0.12}$	${}^{+0.07}_{-0.12}$	${}^{+0.07}_{-0.12}$
δf	5 GeV	± 0.020	± 0.020	± 0.008	± 0.008	± 0.008
δf	50 GeV	± 0.024	± 0.024	± 0.015	± 0.015	± 0.015
δf	300 GeV	± 0.032	± 0.032	± 0.035	± 0.035	± 0.035

arXiv:1305.5597

Fermi-LAT Line Search (4 years) - decay

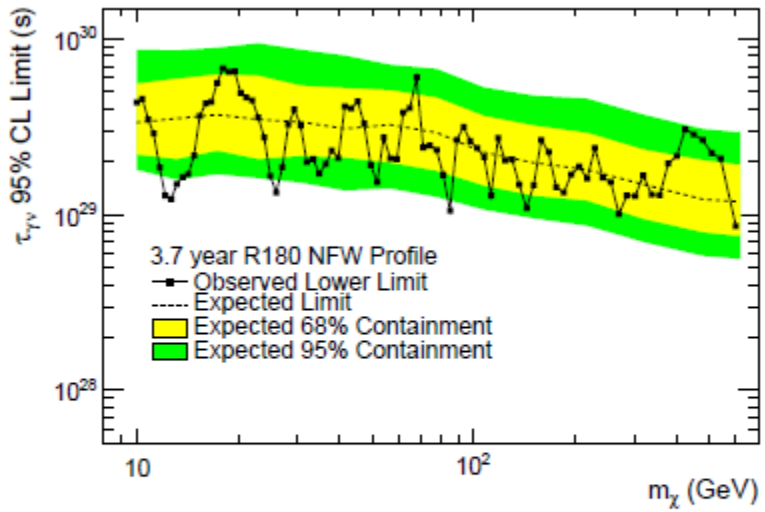
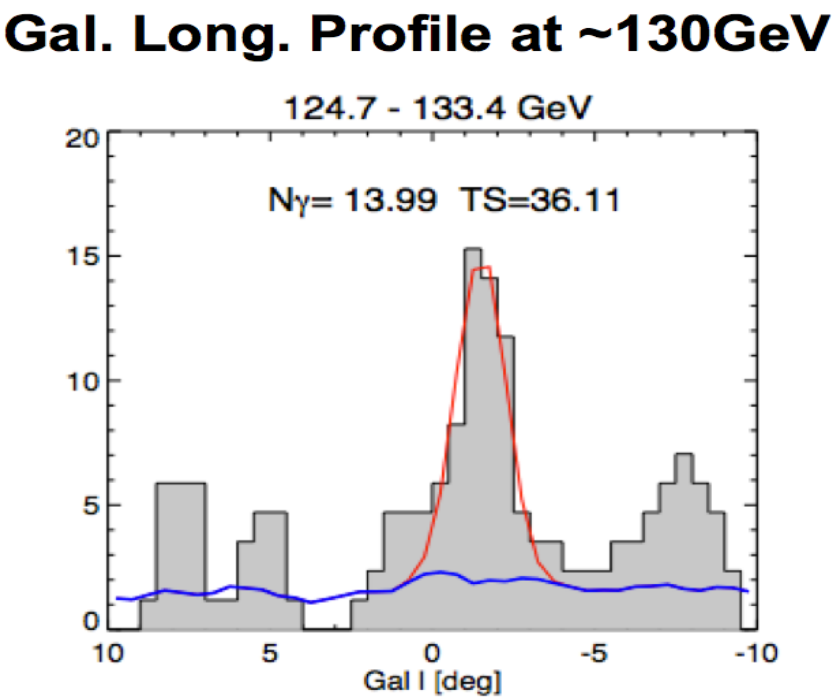
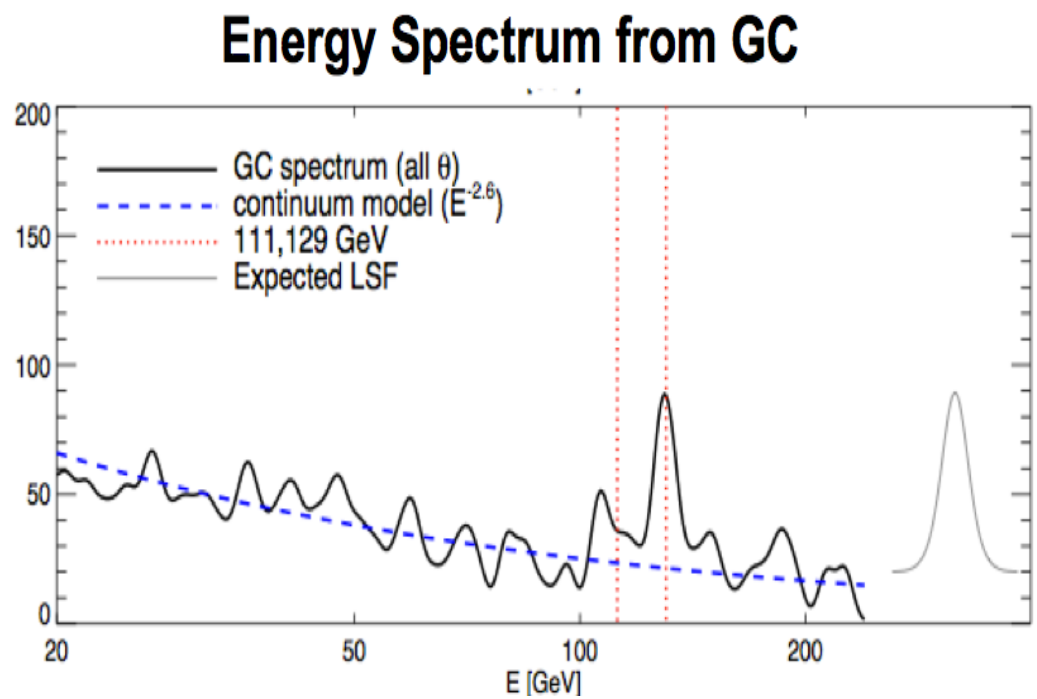


FIG. 10. 95% CL $\tau_{\gamma\nu}$ lower limits in R180 for an NFW profile. Yellow (green) bands show the 68% (95%) expected containment derived from 1000 single-power-law (no DM) MC simulations. The dashed lines show the median expected limits from those simulations.

arXiv:1305.5597

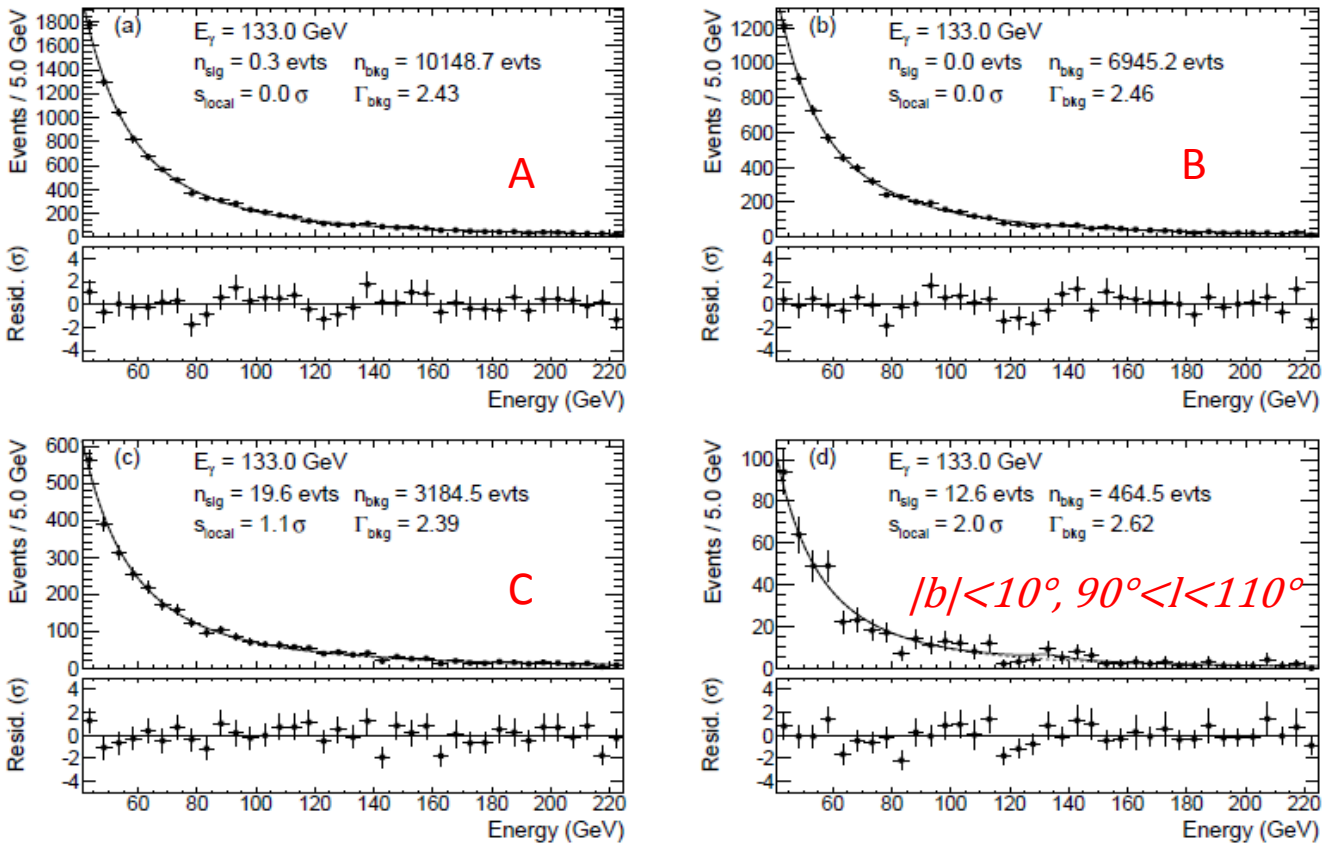
Evidence for 130 GeV gamma-ray line?

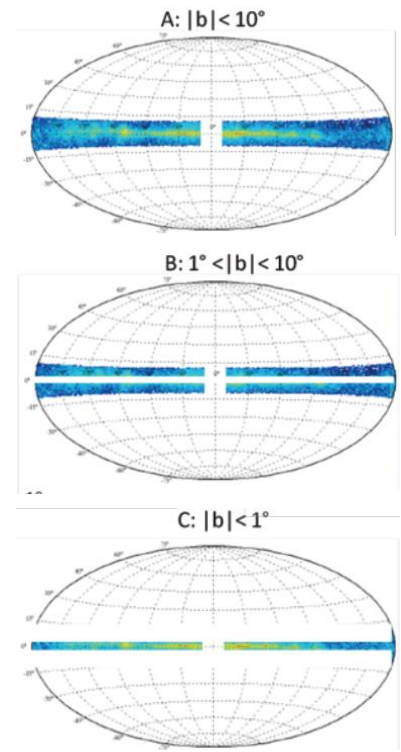




- Su & Finkbeiner showed that the spectral feature was close to, but slightly (~1.5 deg) offset from, the Galactic centre [arXiv:1206.1616].
- Their likelihood analysis included a spatial morphology of signal, and data-driven model of Galactic astrophysical backgrounds.
- Claimed 6σ statistical significance, after a trials factor of ~6000, but acknowledge uncertainties of modeling the Galactic astrophysical backgrounds.

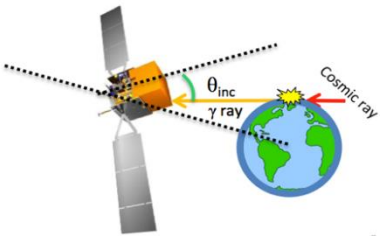
135 GeV in the inverse ROI spectrum

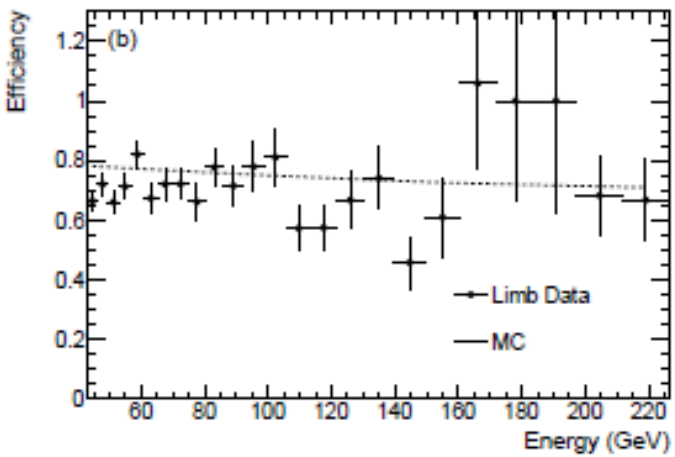


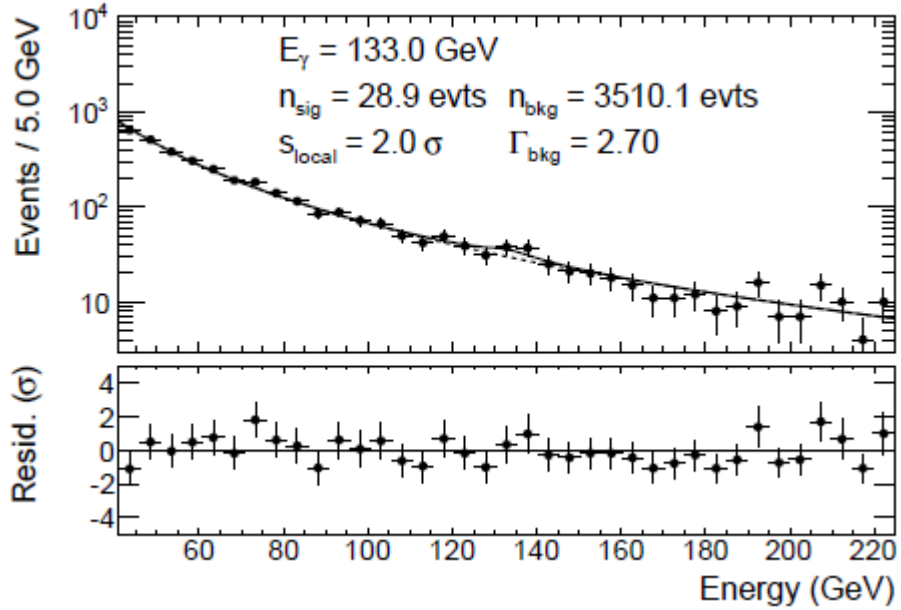


- No significant feature at 135 GeV seen in inverse ROI searches (2D fits)
- If instrumental cause, then why isn't it in the inverse ROI?
  - Distributions of cut variables in specific ROIs affect cut efficiencies
  - Possible multivariate explanation (might not just be one culprit)
- Investigations still on going

Earth limb control region

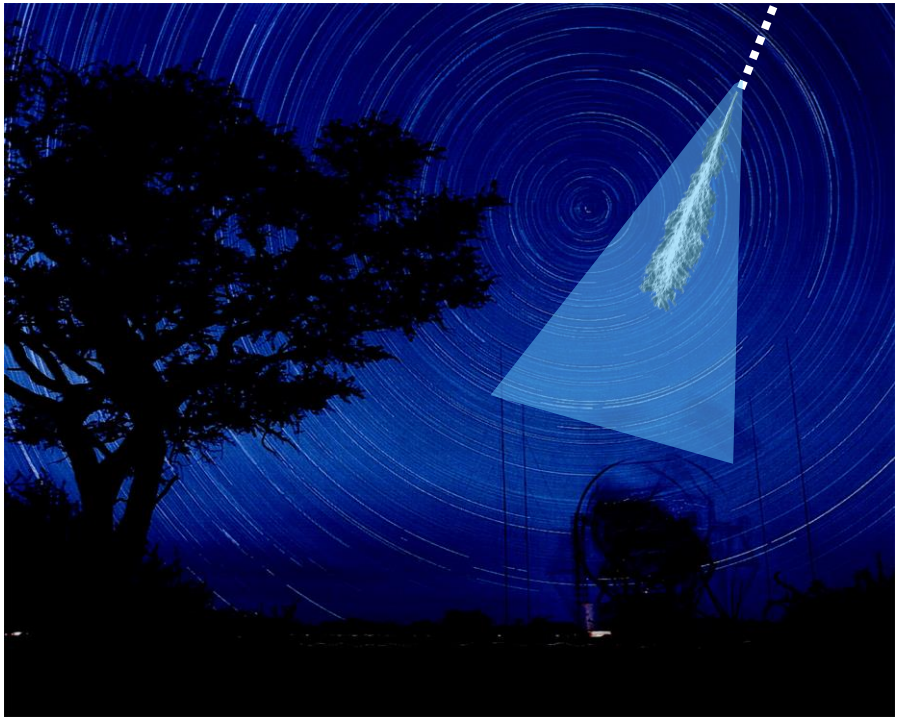






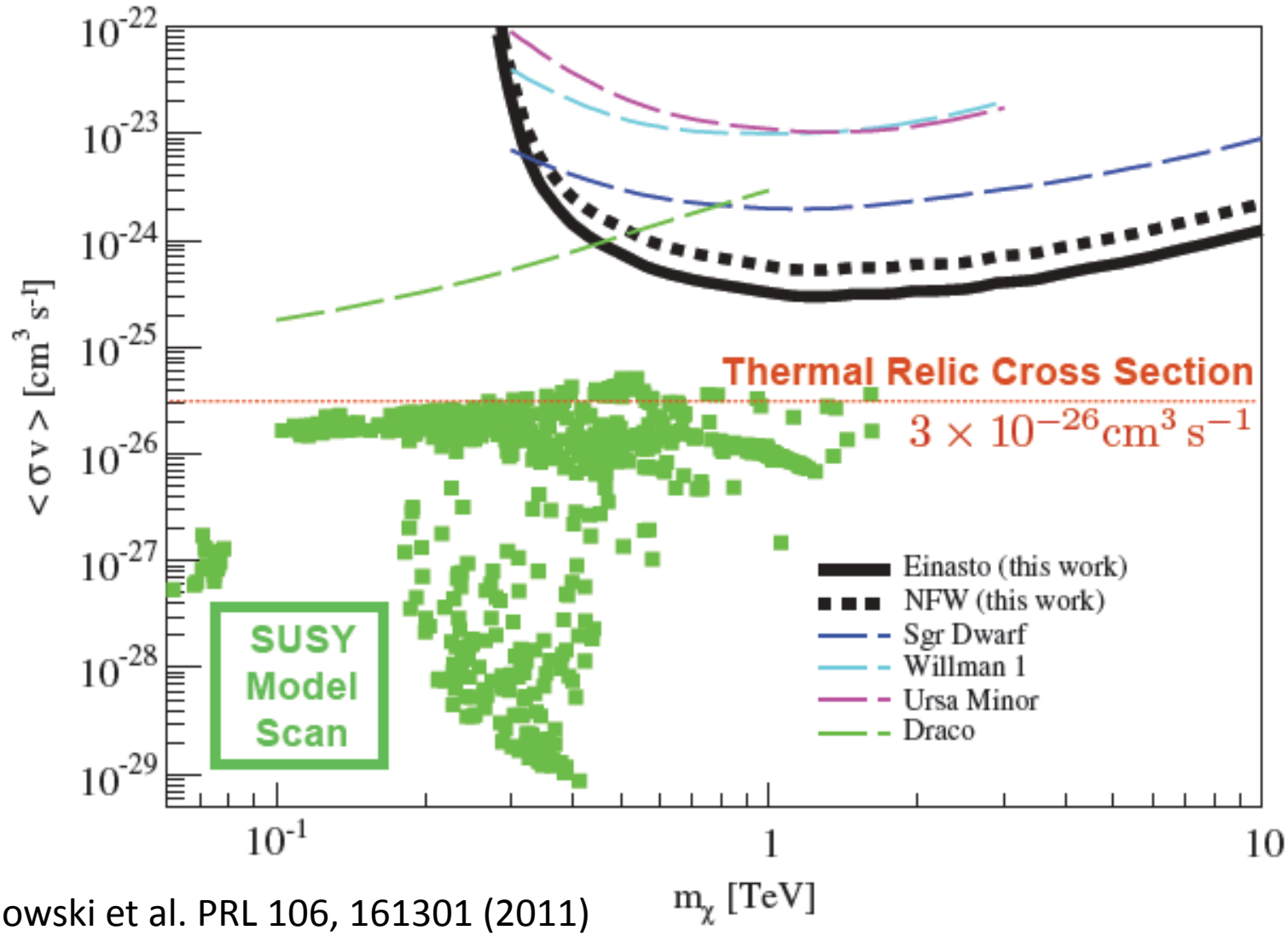
- Study Limb spectrum, which is expected to be a smooth power law
  - No line-like features expected in Limb → from stat. flucs and/or systematics
  - δf_{Aeff} ranges from 0.5% to 2.5% (larger at high energies)
- See a slightly larger than average feature at ~135 GeV (S/N_{limb} ~14%)
- Dips in efficiency below and above 135 GeV
  - Could be artificially sculpting the energy spectrum

Air Cherenkov Telescopes



- Use Cherenkov light from air showers produced from gamma rays interacting with the Earth's atmosphere.
- Use an array of telescopes for improved shower imaging (angular resolution and background rejection)
- Large collecting area (~10^5 m^2 at 100 GeV)
- "Excellent" angular resolution (<0.1 deg.)
- Threshold at low energy (pushing 100 GeV)
- Limited livetime (moon, zenith angle, etc.)

Galactic Center

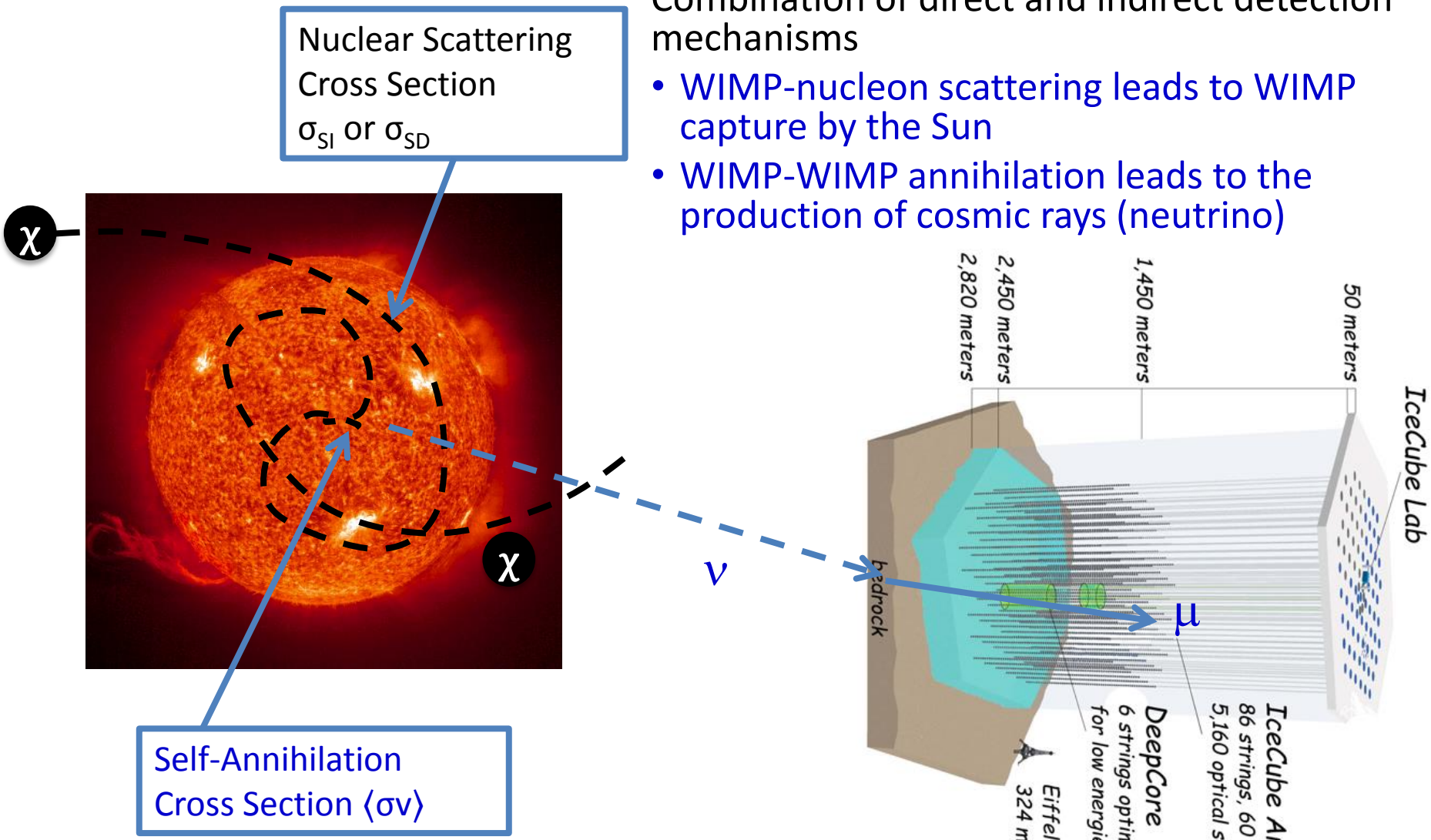


Abramowski et al. PRL 106, 161301 (2011)

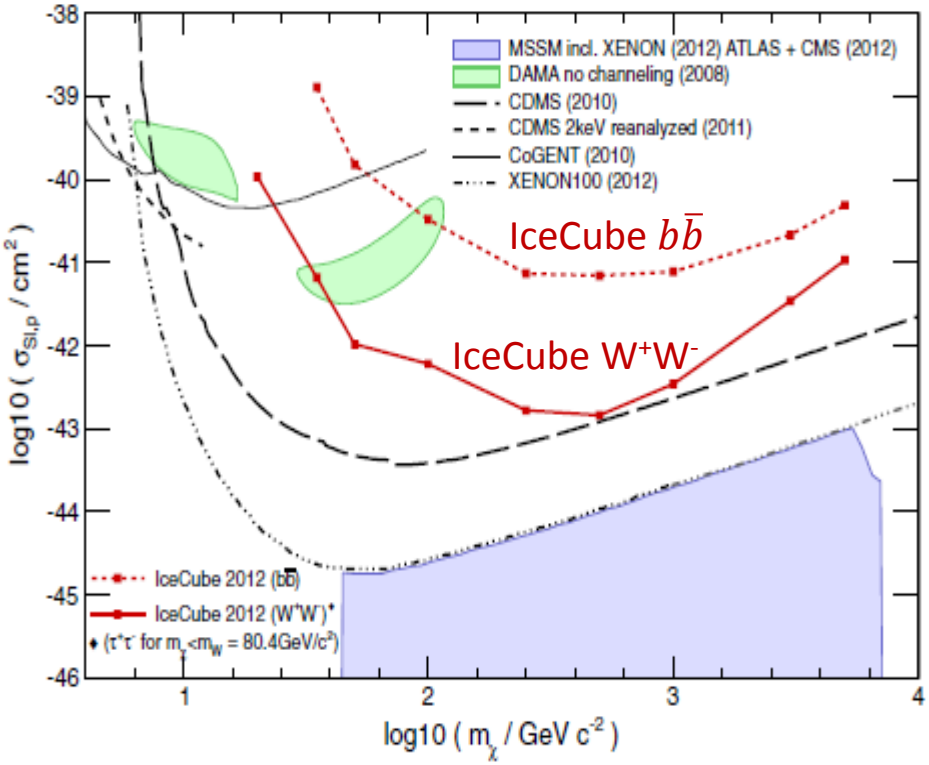
Neutrinos from the Sun

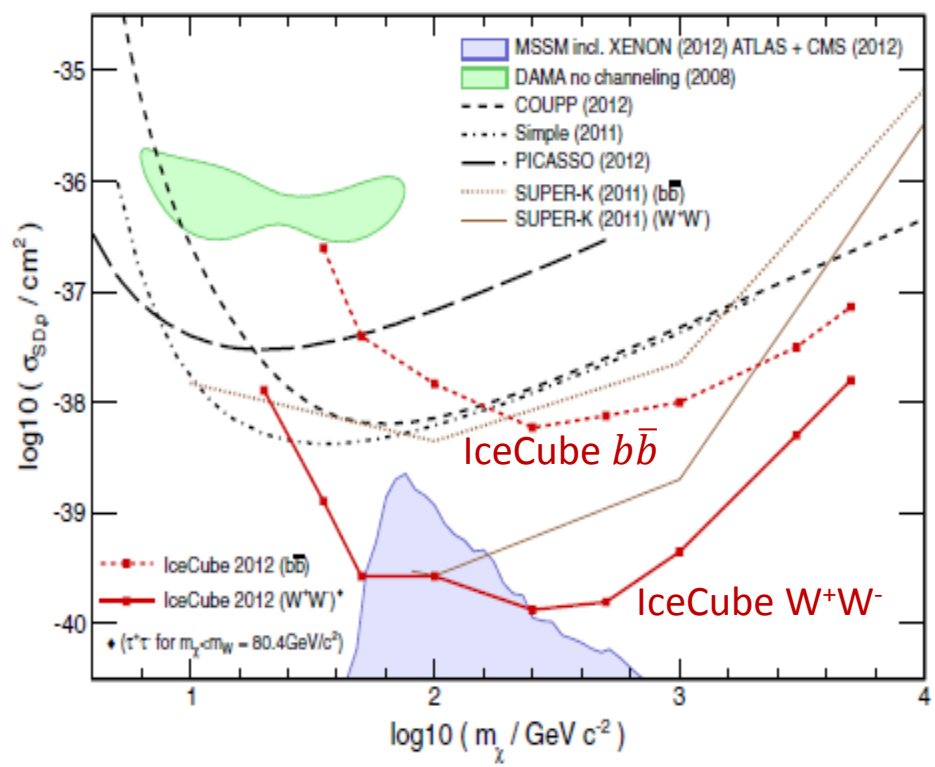
Combination of direct and indirect detection mechanisms

- WIMP-nucleon scattering leads to WIMP capture by the Sun
- WIMP-WIMP annihilation leads to the production of cosmic rays (neutrino)



Neutrinos from the Sun



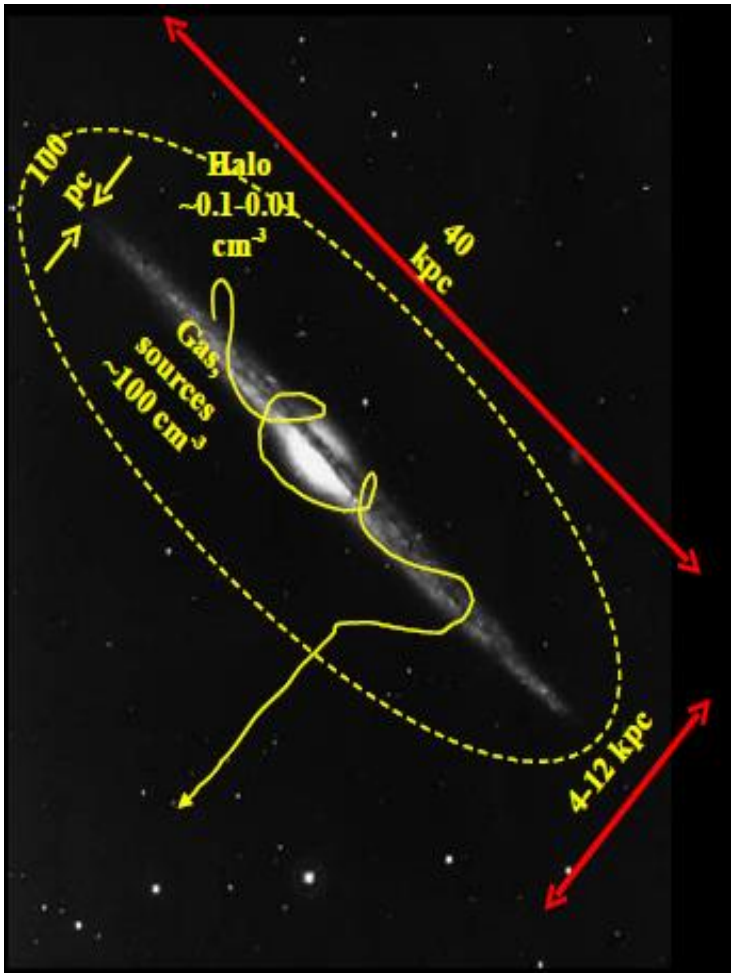


The plots show the 90% C.L. upper limits on Spin Independent (left figure) and Spin Dependent (right figure) for hard and soft annihilation channels over a range of WIMP masses

M. G. Aartsen et al., PRL 110, 131302 (2013)

Galactic cosmic rays

- High-energy (GeV–TeV) charged primary Cosmic Rays (CRs) are believed to be produced in our galaxy, most likely in Supernova Remnants (SNRs)
- CRs injected into ISM propagate for millions of years before escaping to intergalactic space
- Particle interactions with interstellar gas, radiation and magnetic fields produce EM radiation from radio to gamma rays, and other secondaries ($e^{\pm}$, nuclei, etc.)
- During the transport from their source of origin to our solar system, CRs scatter on random and irregular components of the μG Galactic Magnetic Field (GMF), which almost isotropize their directions.
- Contrary to hadronic CRs, high-energy (>GeV) Cosmic Ray Electrons and Positrons (CREs) propagating in the GMF lose their energy rapidly through synchrotron radiation and by inverse Compton collisions with low-energy photons of the interstellar radiation field.



CRE propagation equation

- For CREs the convection and reacceleration could be neglected above few GeV, so that the propagation of CREs can be expressed in terms of usual conservation equation:

$$\frac{\partial N}{\partial t} - \vec{\nabla}\cdot\left(D\vec{\nabla}N\right) - \frac{\partial}{\partial E}\left(bN\right) = q$$

  - b is the continuous energy loss rate, $b \approx 1.4 \times 10^{-16}$ GeV^{-1} s^{-1}
  - *D is the diffusion coefficient, $D = D_0 (E/E_0)^{\delta}$*
    - $D_0 \approx 5.8 \times 10^{28}$ cm^2 s^{-1}, $\delta = 1/3$ *and* $E_0 \approx 4$ GeV
- CREs lose almost all of their energy E after a time T:
  - $T = 1/bE \approx 2 \times 10^5$ *yr/E(TeV)*
- CREs can diffuse over a distance $R = (2DT)^{1/2}$ during the lifetime T
  - $R \approx 1.6\ (0.75)$ *kpc for E=100 GeV (1 TeV)*
- Such high-energy CREs might originate from a highly anisotropic collection of a few nearby sources

Anisotropy

- Degree of anisotropy: $$\delta = \frac{I_{\max} - I_{\min}}{I_{\max} + I_{\min}}$$

  where $I_{max(min)}$ is the maximum (minimum) intensity
- In case of the dipole anisotropy: $I(\theta) = I_0 + I_1 cos(\theta) \Rightarrow \delta = I_1/I_0$
- The anisotropy due to the pure diffusion term is given by: $$\delta = \frac{3D}{c}\frac{|\vec{\nabla} N|}{N}$$
- In case of a single source of age t_i at the position r_i (burst-like injection) the spectrum of CREs at the solar system is $\propto \exp\left(-\frac{r_i^2}{r_{diff}^2}\right)$ (Green's function)
- So that, its contribution to the anisotropy is given by:

$$\delta_i = \frac{3D}{c}\frac{2|\vec{r}_i|}{r_{diff}^2} \quad \Rightarrow \quad \delta_i = \frac{3|\vec{r}_i|}{2ct_i}$$

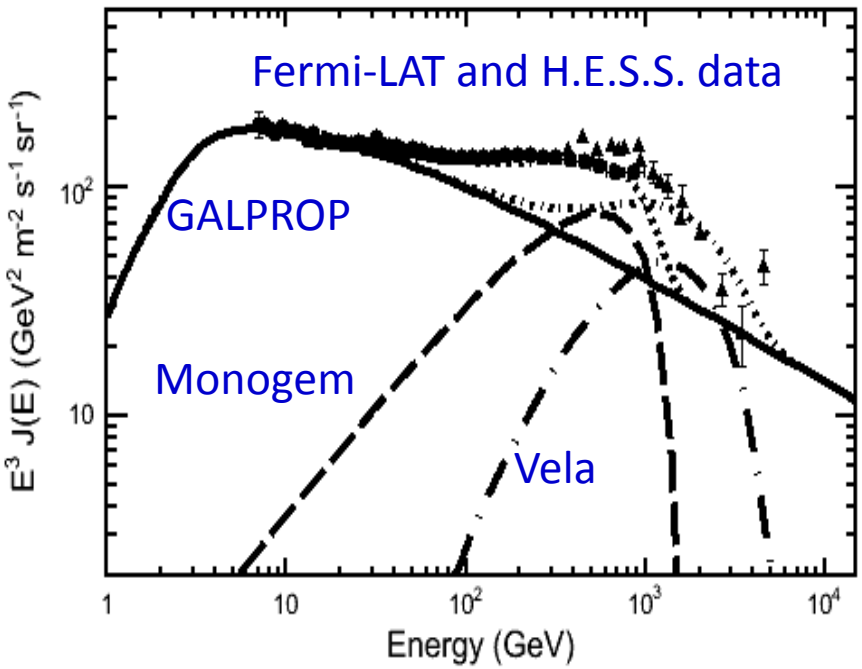
- The total anisotropy due to a distribution of point-like sources in the sky is then given by:

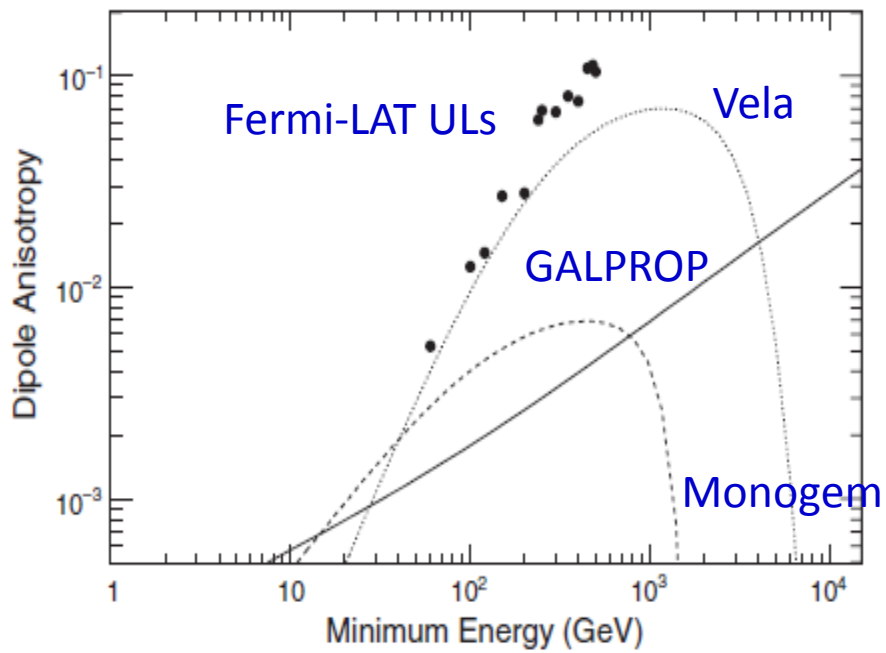
$$\delta = \frac{\sum_i N_i \, \delta_i \, \hat{r}_i \cdot \hat{n}_{max}}{\sum_i N_i}$$

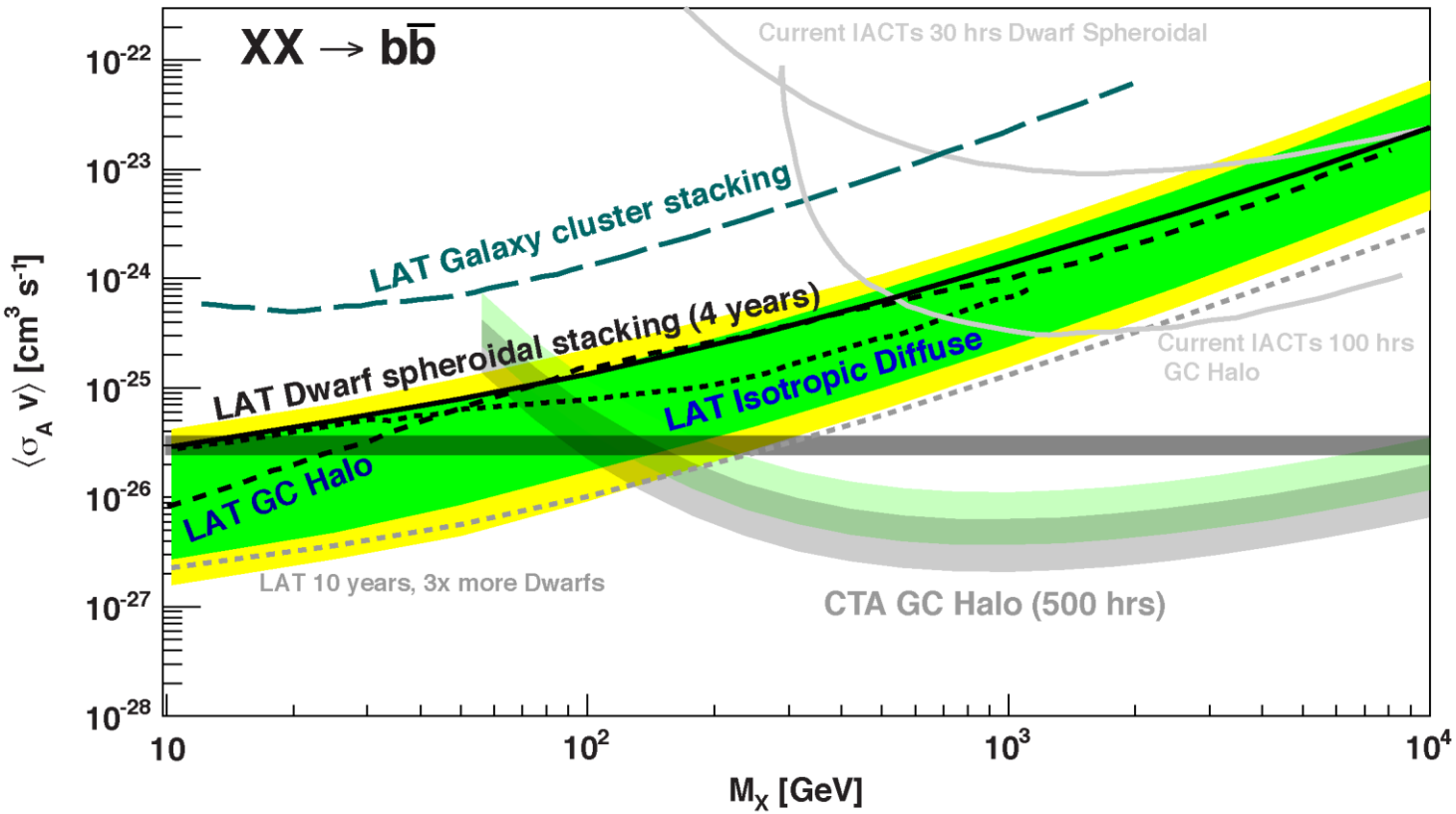
where n_{max} is the direction of maximum intensity

CRE Fermi-LAT spectrum

- Hard to fit the CRE spectrum with a single-component diffusive model
- Good fit possible with an additional high-energy component
  - If it's an e^+/e^- source (e. g. nearby pulsars or dark matter), the Fermi spectrum and Pamela positron fraction can be simultaneously fitted
- For single sources (e.g. Vela-like and Monogem-like) the value of the injected luminosity is such that the total flux is not higher than the one measured by the Fermi-LAT and H.E.S.S.
- For each source, the anisotropy has been evaluated assuming that the contributions to the anisotropy from all remaining sources are negligible






XX → bb̄
Current IACTs 30 hrs Dwarf Spheroidal
LAT Galaxy cluster stacking
LAT Dwarf spheroidal stacking (4 years)
LAT Isotropic Diffuse
LAT GC Halo
Current IACTs 100 hrs
GC Halo
LAT 10 years, 3x more Dwarfs
CTA GC Halo (500 hrs)
⟨σ_A v⟩ [cm³ s⁻¹]
M_X [GeV]
10⁻²²
10⁻²³
10⁻²⁴
10⁻²⁵
10⁻²⁶
10⁻²⁷
10⁻²⁸
10
10²
10³
10⁴