Title: Astroparticle Physics â€“ Observations: Gamma rays and neutrinos

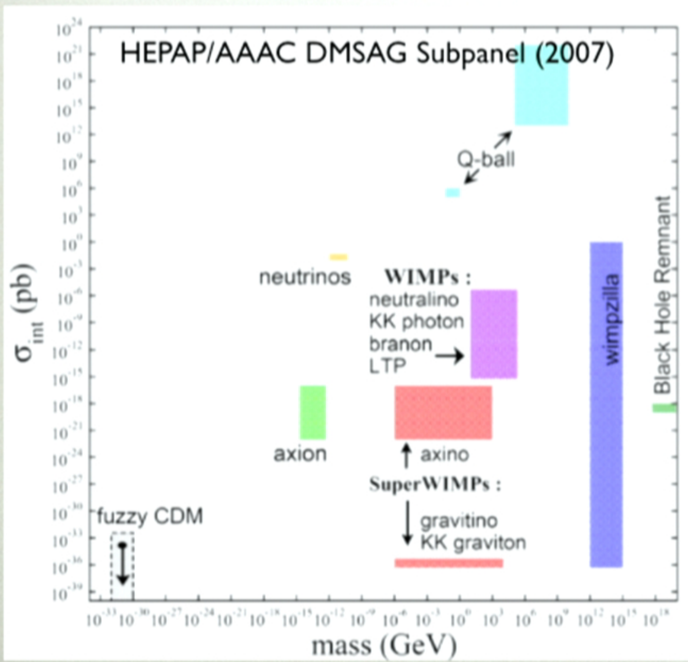
Date: Jul 14, 2015 10:15 AM

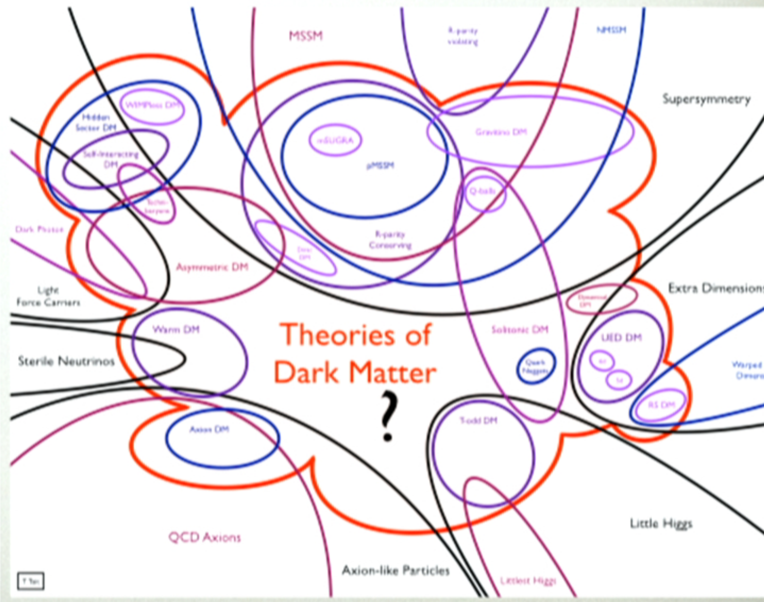
URL: http://pirsa.org/15070043

Abstract:

Dark Matter Candidates

- Several beyond the Standard Model of particle physics scenarios have been proposed that naturally predict the existence of new particles that are excellent dark matter candidates





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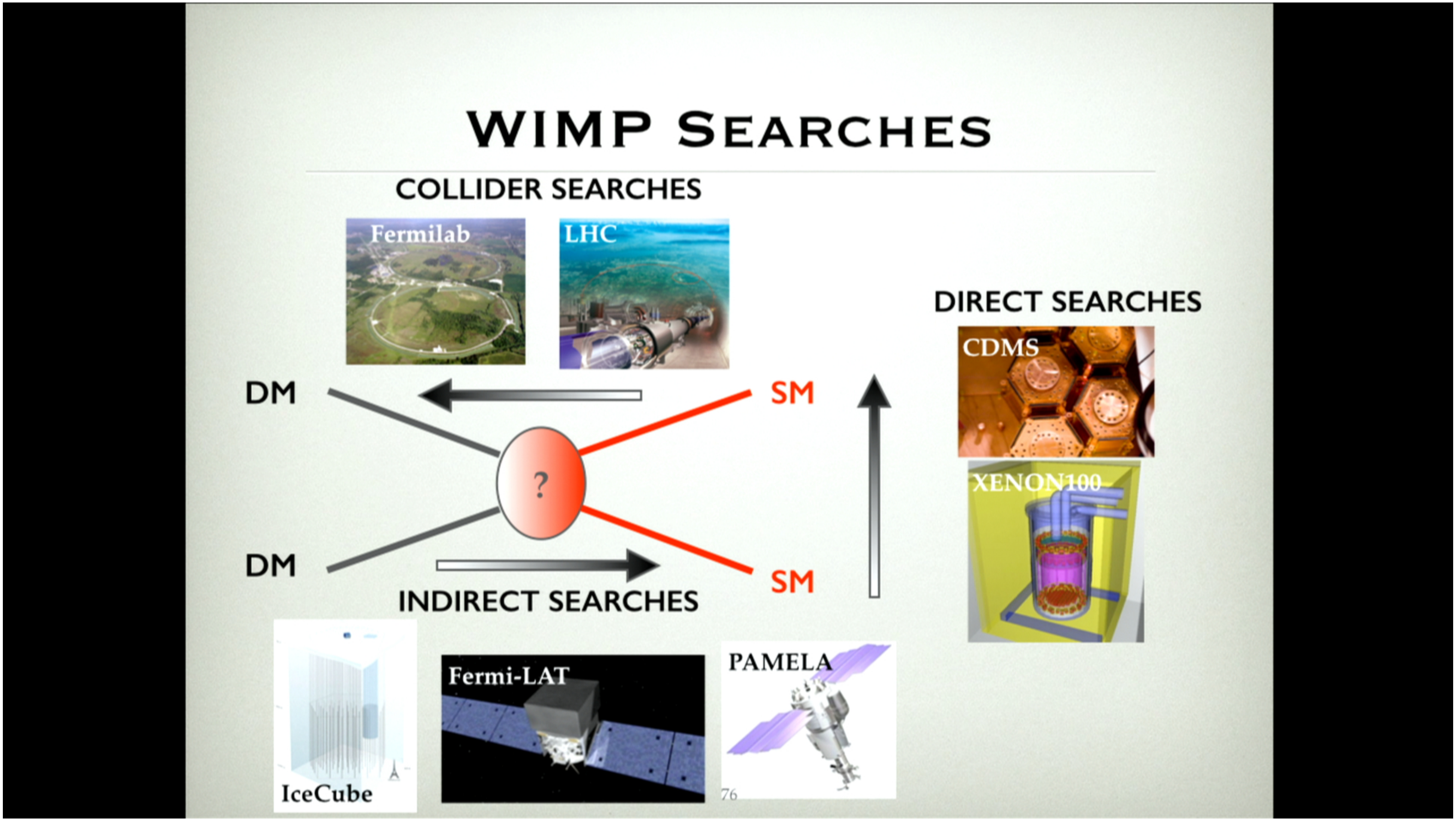
WIMP Searches
COLLIDER SEARCHES
Fermilab
LHC
DIRECT SEARCHES
CDMS
XENON100
DM
SM
?
DM
SM
INDIRECT SEARCHES
IceCube
Fermi-LAT
PAMELA
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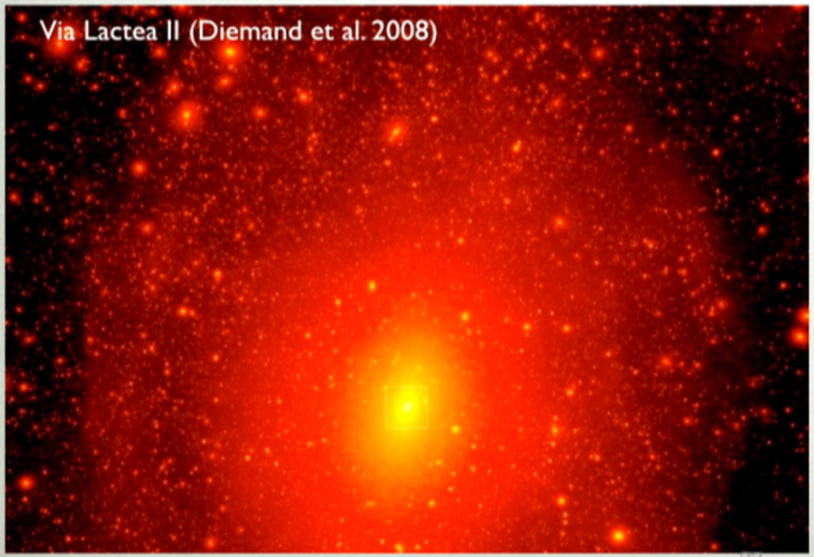
Indirect Searches

- Search for the byproducts of dark matter annihilation/decay
- Very rich search strategy, multi-messenger and multi-wavelength



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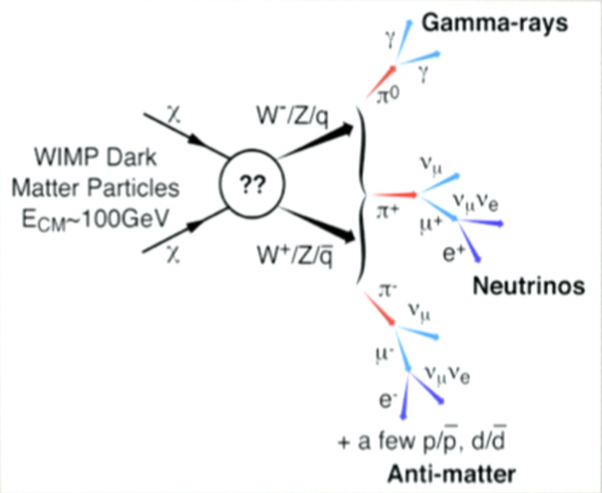
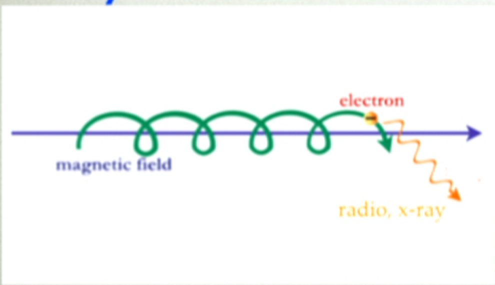


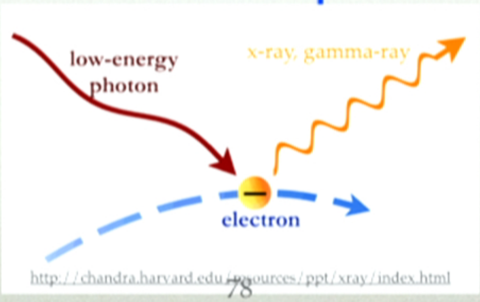
DM Messengers

- DM messengers:
  - neutral: photons, neutrinos
  - charged: electrons, antimatter (positrons, antiprotons, antideuteron, ...)
- Multi-wavelengths:
  - gamma rays from DM annihilation/decay products
  - but also emission from the interaction with the surrounding medium (interstellar gas, radiation and magnetic fields), from radio to gamma-ray (and other secondaries as well)
  - For electrons:

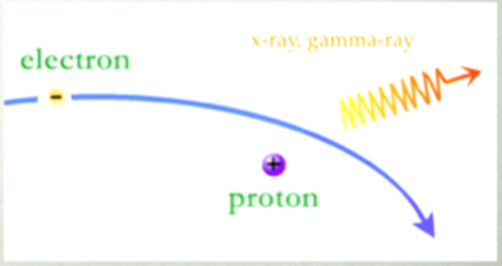
Synchrotron



Inverse Compton

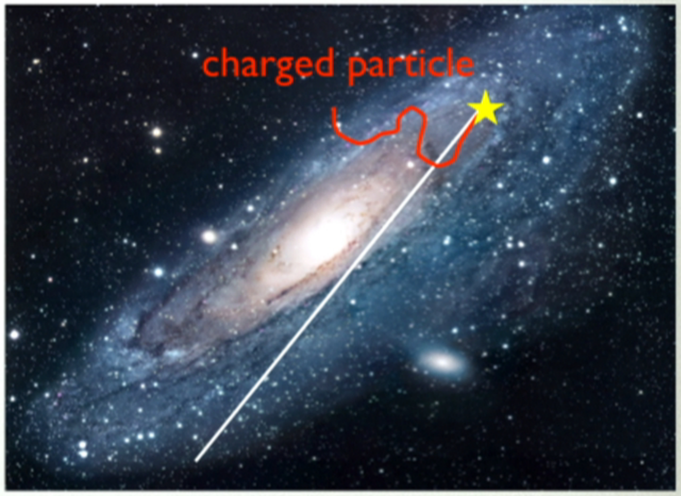


Bremsstrahlung



DM Messengers

- Generally, neutral particles are more promising probes
  - No loss of energy, directionality for neutrinos, gamma-rays ⇒ point back to source and preserve spectral information (on galactic scales)
  - Charged particles lose energy, directionality on their way to us ⇒ important information on their origin is lost



$$R \approx 10^{-6} pc \frac{1}{Z} \frac{E}{(1GeV)} \frac{(1\mu G)}{B}$$

In ~μG magnetic fields, the gyroradius for a 100 GeV electron or proton is ~ 10^{-4} pc, i.e. much shorter than the distance to a typical nearby source, which is of order of 100s pc (1 pc=3.26 light years)

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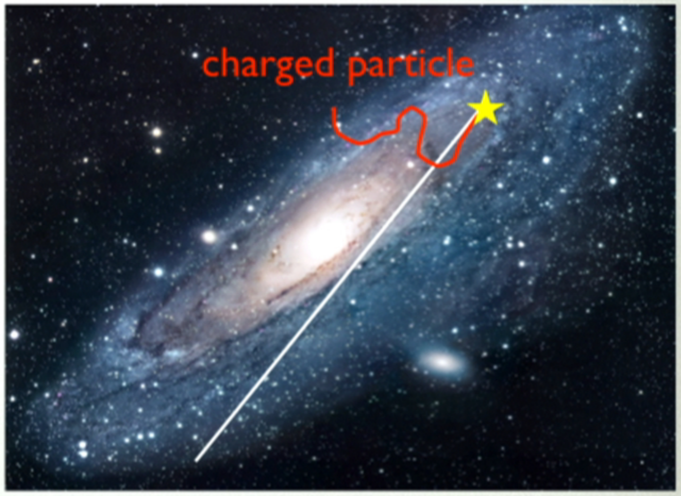

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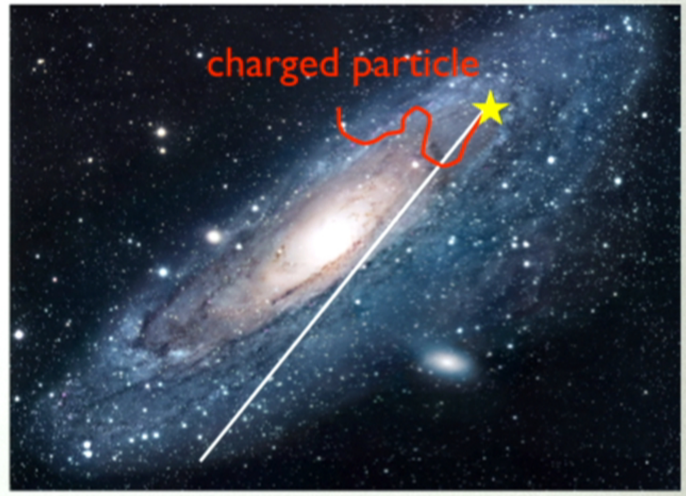
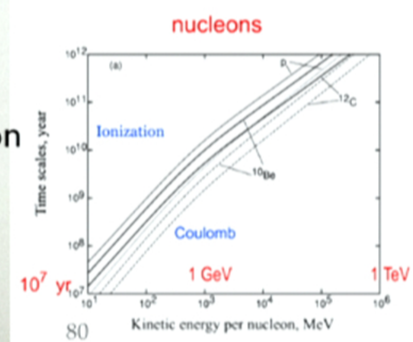
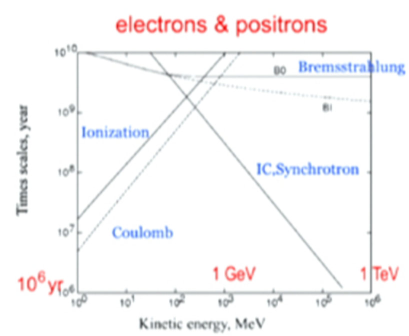
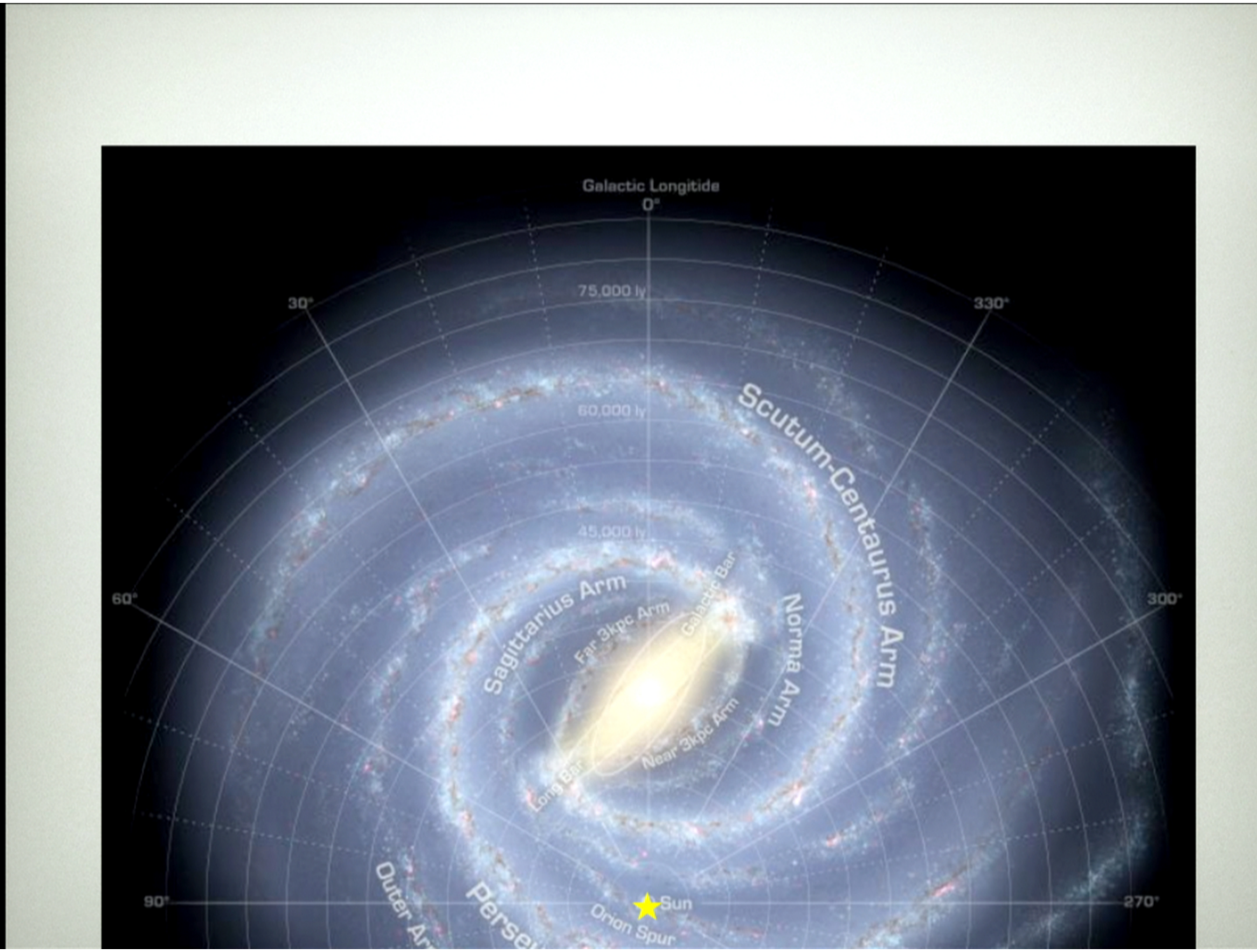


Electrons of > GeV energies primarily lose energy through synchrotron and IC emission

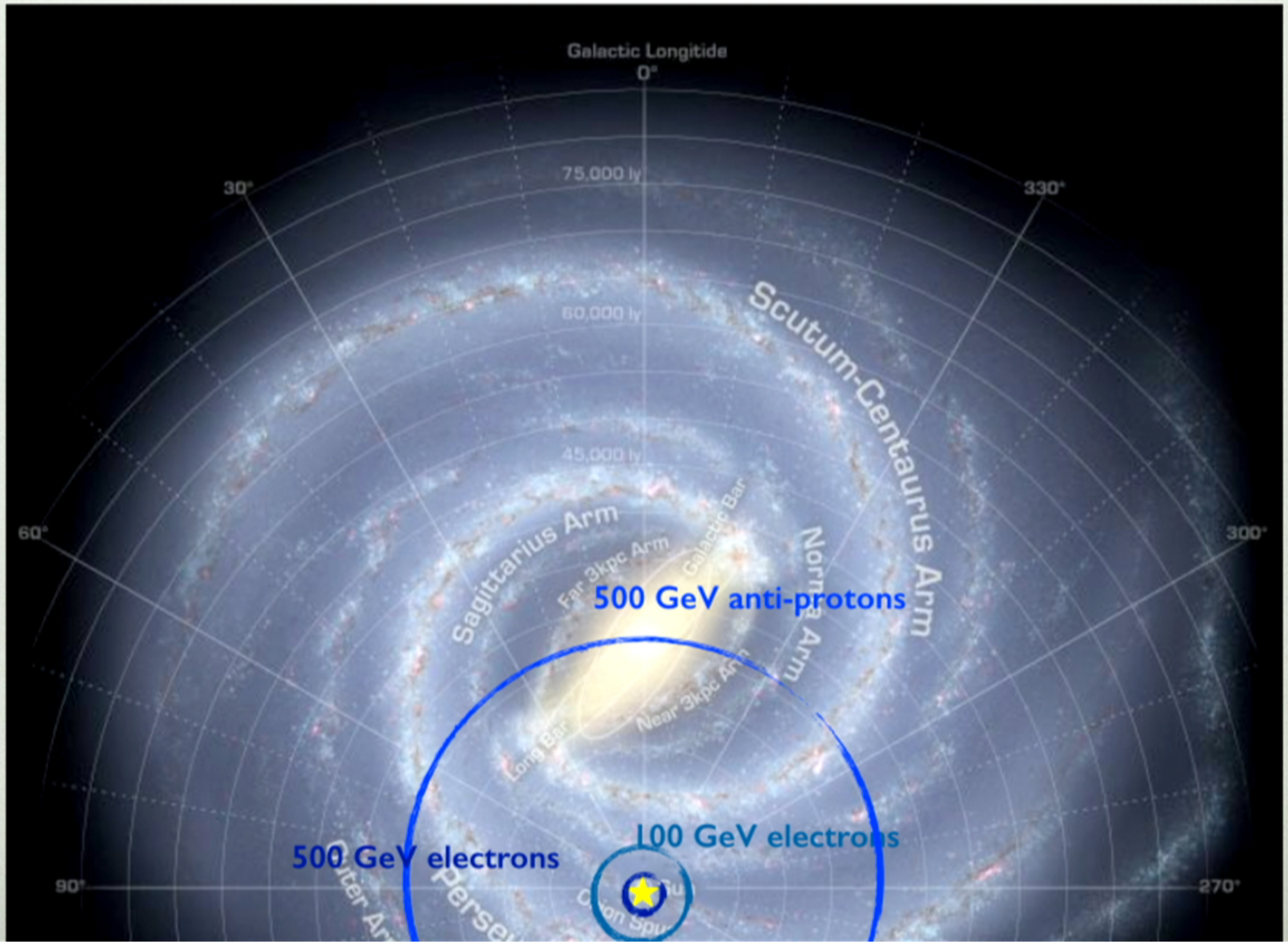
Protons primarily lose energy by scattering off of the interstellar medium (mainly hydrogen gas)







Galactic Longitide
0°
30°
330°
75,000 ly
60,000 ly
45,000 ly
Scutum-Centaurus Arm
60°
300°
Sagittarius Arm
Far 3kpc Arm
Galactic Bar
Norma Arm
Near 3kpc Arm
Long Bar
Outer Arm
90°
Sun
270°
Orion Spur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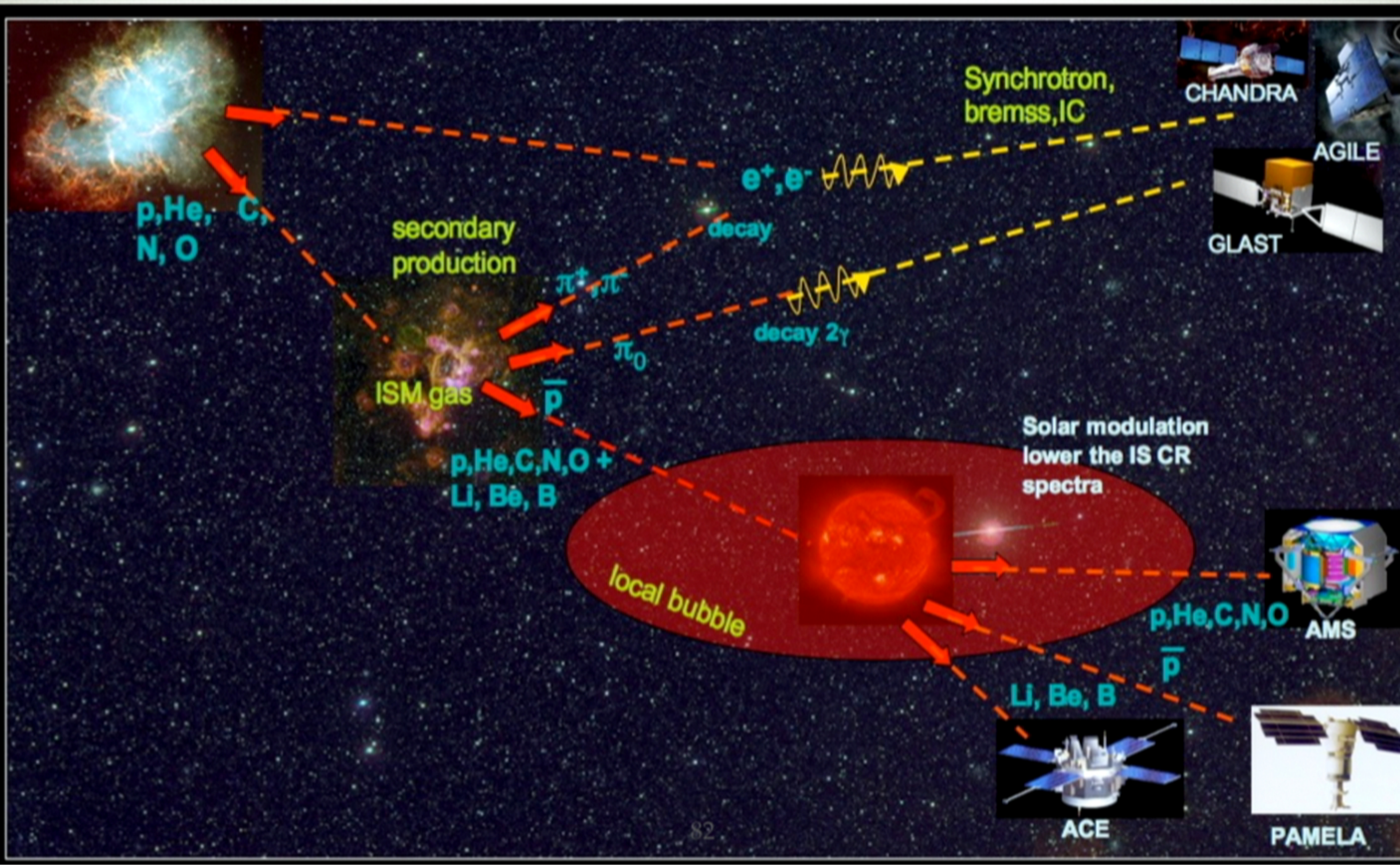
Scutum-Centaurus Arm
Sagittarius Arm
Far 3kpc Arm
Galactic Bar
Norma Arm
Near 3kpc Arm
Long Bar
500 GeV anti-protons
500 GeV electrons
100 GeV electrons

And the Background...



WIMP Signal

- Gamma rays from DM annihilation:

particle physics

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

J factor — DM distribution

For DM decay:

- $<\sigma_{ann}v>/2m^2_{WIMP} \rightarrow 1/\tau m_{WIMP}$
- $\rho^2 \rightarrow \rho$

➡ Charged particles are more complicated (need to include propagation)

WIMP Signal

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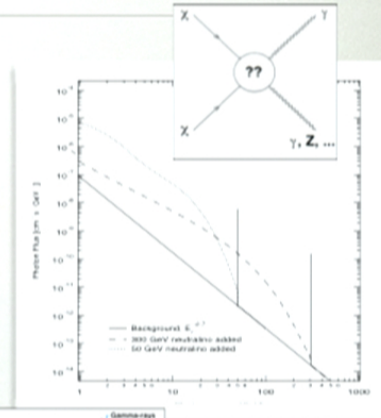
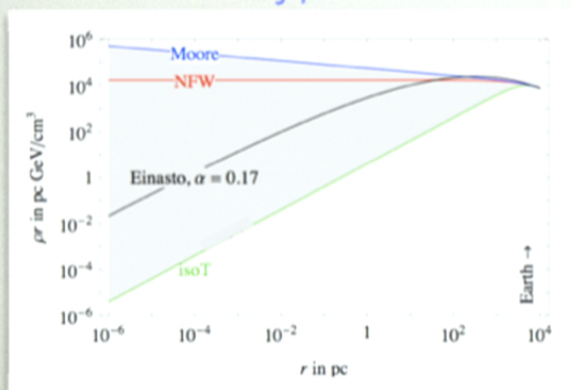
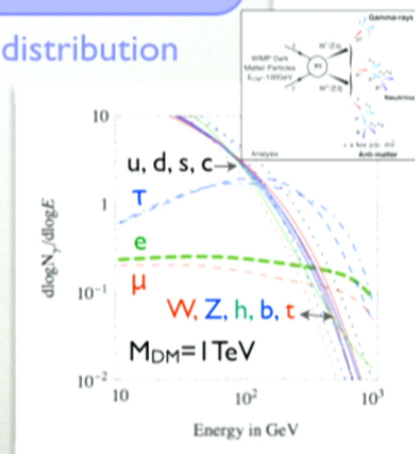
J factor DM distribution

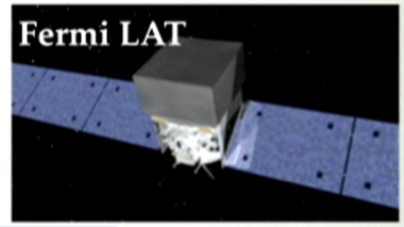


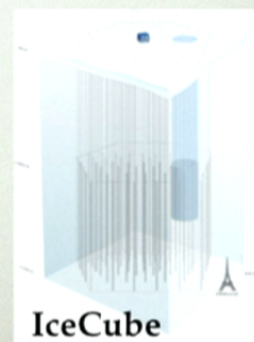




EXPERIMENTS

- Gamma rays
  - VERITAS
  - HESS
  - MAGIC
  - Fermi LAT
- Cosmic Rays
  - AMS-02
  - PAMELA
  - Fermi LAT
- Neutrinos
  - IceCube



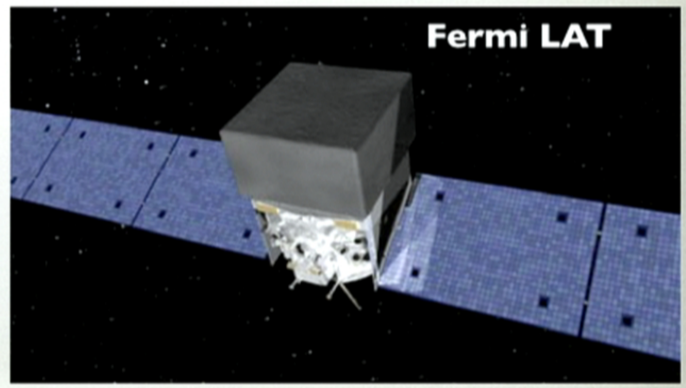


Gamma rays

ON THE GROUND

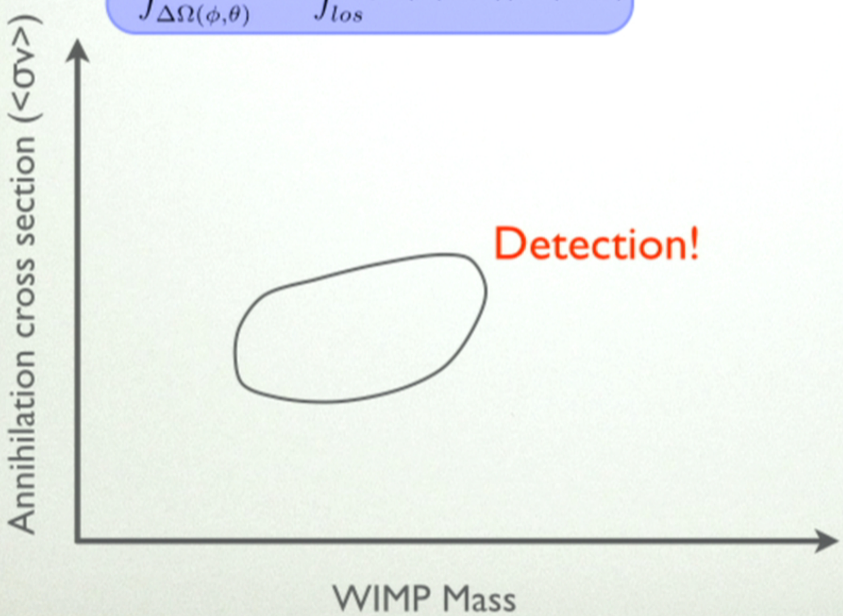
Atmospheric Cherenkov Telescopes (ACTs)

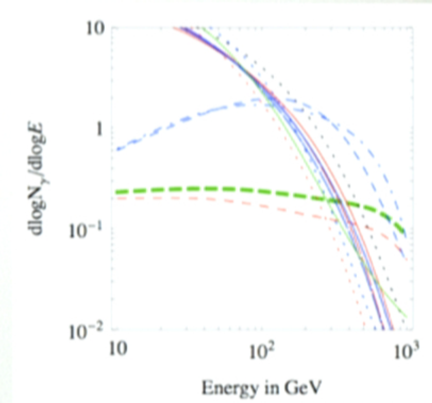
IN SPACE

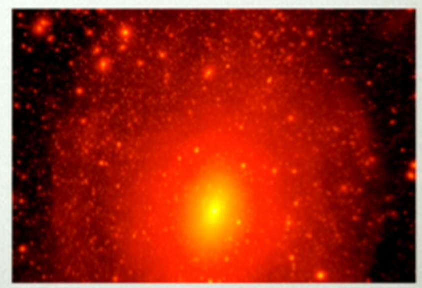


Indirect Detection Results - Gamma Ray

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







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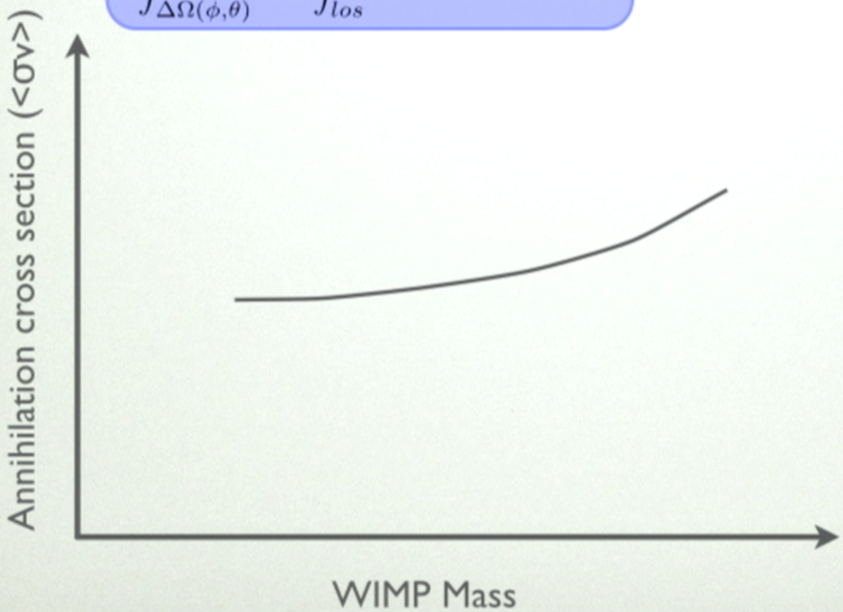

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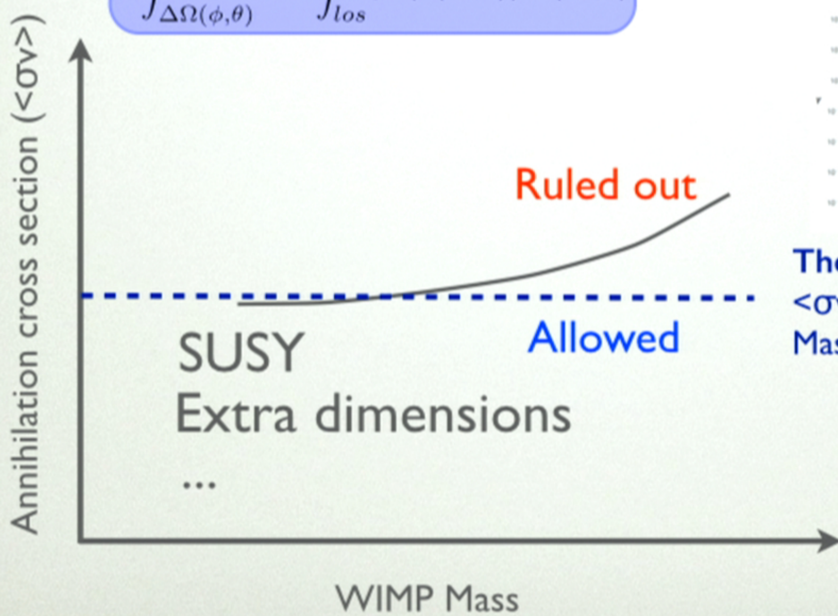
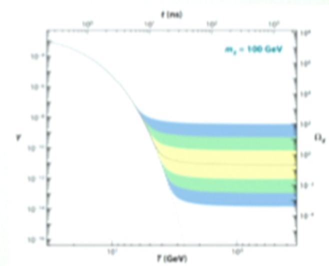




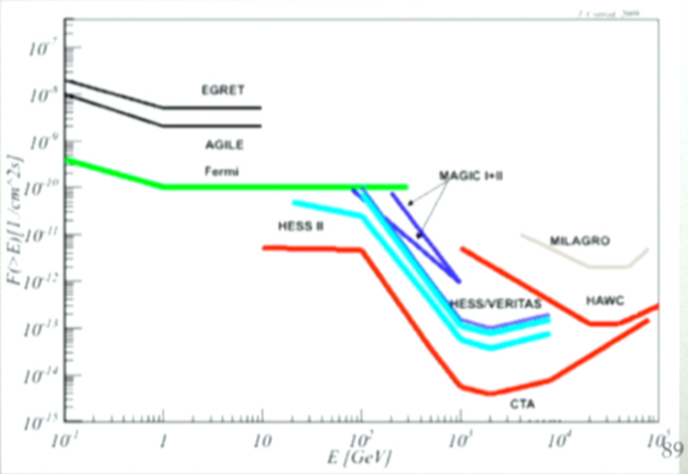
Thermal WIMP

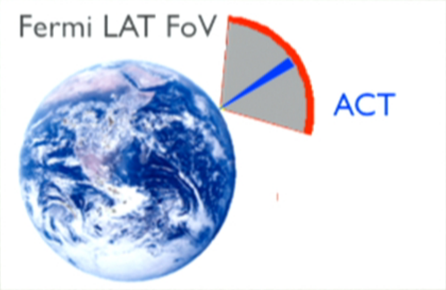
$<\sigma v>$ of order 3×10^{-26} cm^3/s

Mass of order 100 GeV

Ground vs Space Gamma ray experiments

- Lower energy thresholds accessible in space, and up to ~100 TeV energies with experiment on the ground. Overlap in the ~100 GeV region
- Larger field of view, great duty cycle, and all sky coverage in space
- Best single photon angular resolution: ~0.1° at 100 GeV, ~1° at 1 GeV (but position accuracy for bright sources is better (also depending on their spectrum)!)
- Large collecting area on the ground (high sensitivity)





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Very High Energy Γ-rays

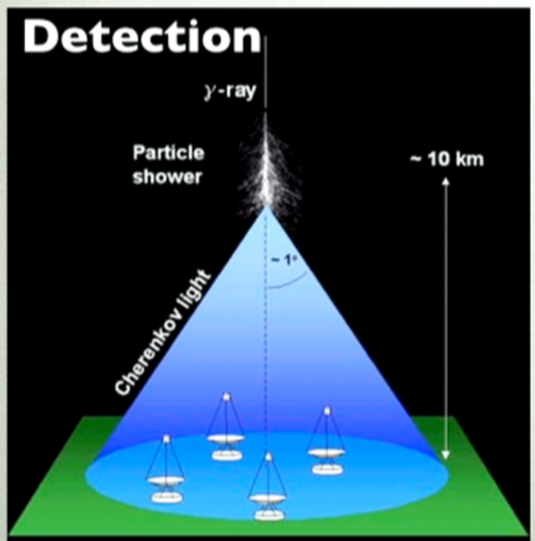
Imaging Atmospheric Cherenkov Telescopes (IACTs)

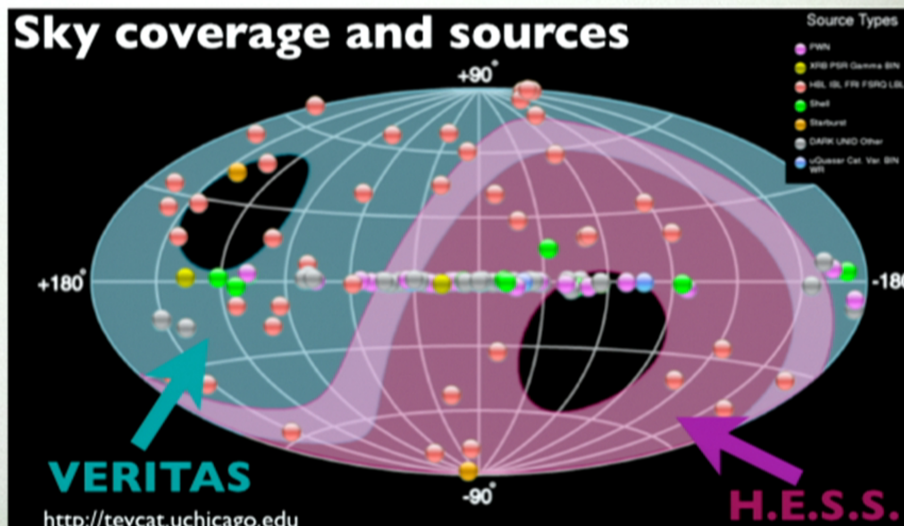
ACTs: Performance

VERITAS
Energy range: ~0.1 - 30 TeV
Angular resolution: r68< 0.1°
Energy resolution: ~15-25%
Field of view: ~3.5°
Sensitivity: 1% Crab flux in 30h

H.E.S.S.
Energy range: ~10s GeV - 10s TeV
Angular resolution: ~ 0.1°
Energy resolution: ~10-15%
Field of view: ~5°
Sensitivity: 1% Crab flux in 25h

MAGIC
Energy range: ~30 GeV - 10s TeV
Angular resolution: ~0.1 °
Energy resolution: ~15%
Field of view: ~3.5°
Sensitivity: 1% Crab flux in 50h

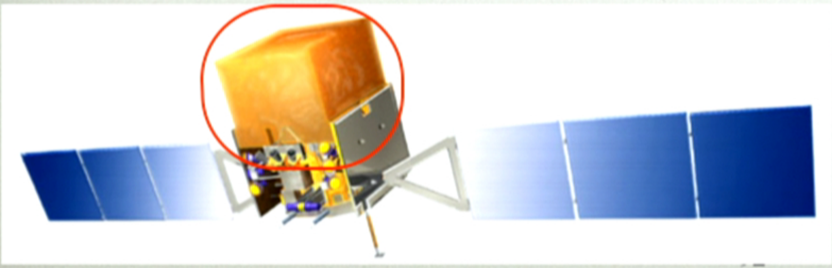




Fermi LAT

- Observe the gamma-ray sky in the 20 MeV to >300 GeV energy range with unprecedented sensitivity
- Orbit: 565 km, 25.6° inclination, circular. The LAT observes the entire sky every ~3 hrs (2 orbits)

Large Area Telescope (LAT)



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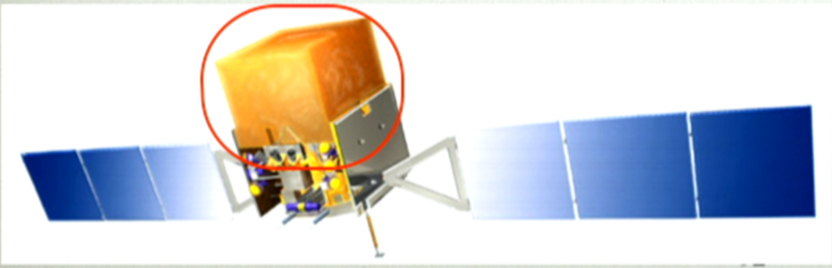

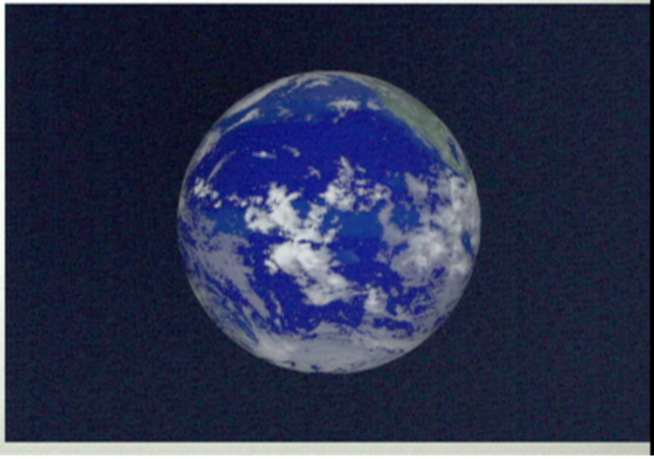

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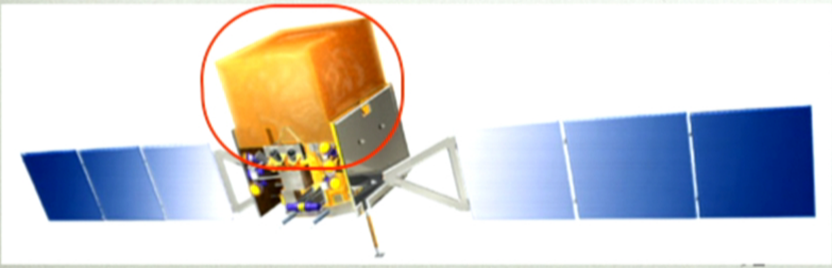
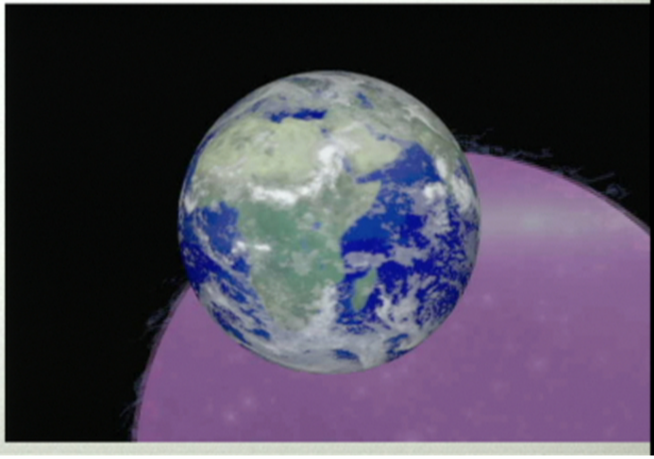
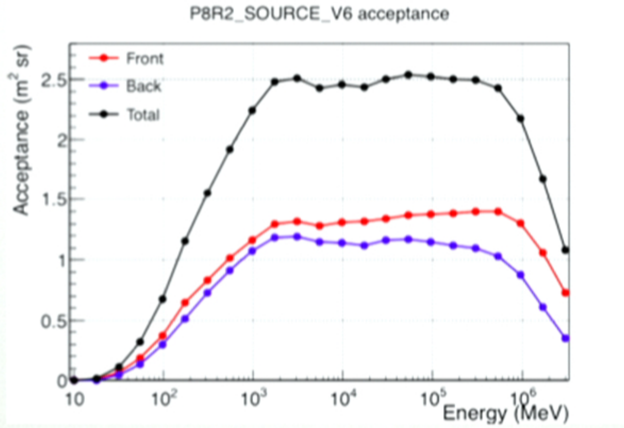
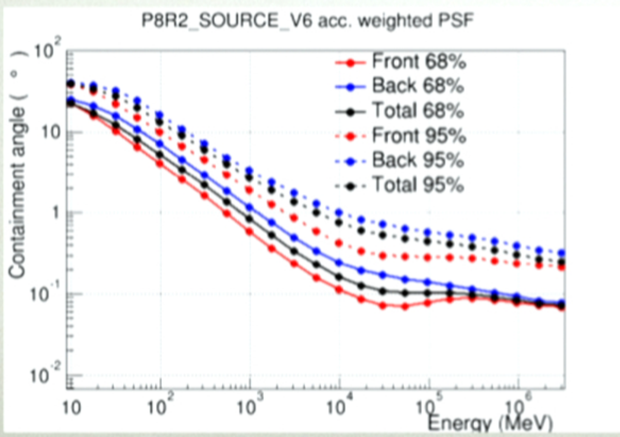
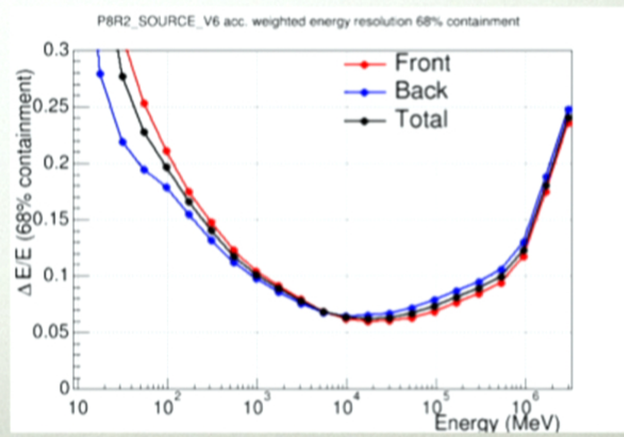




Fermi LAT Performance







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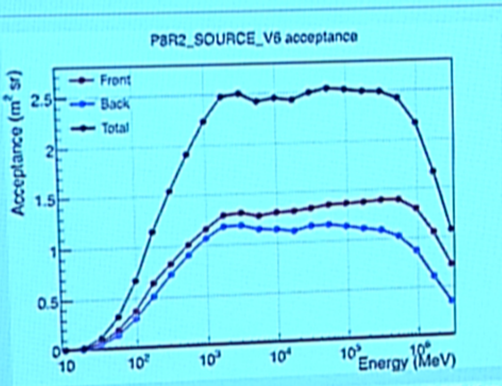
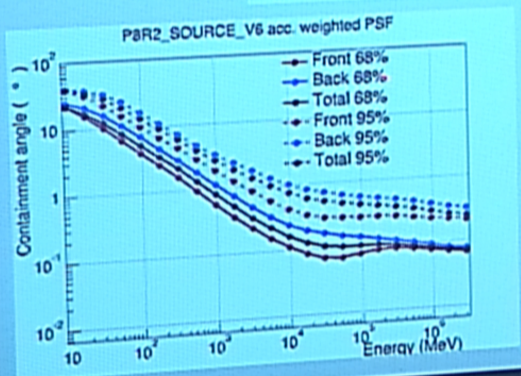
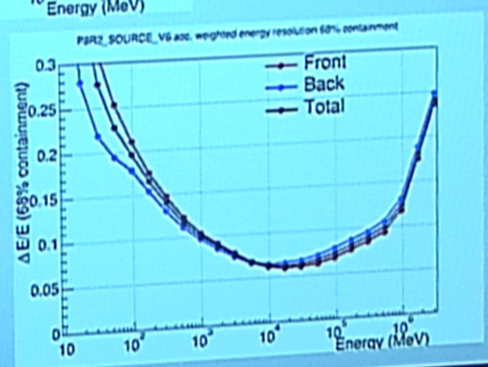
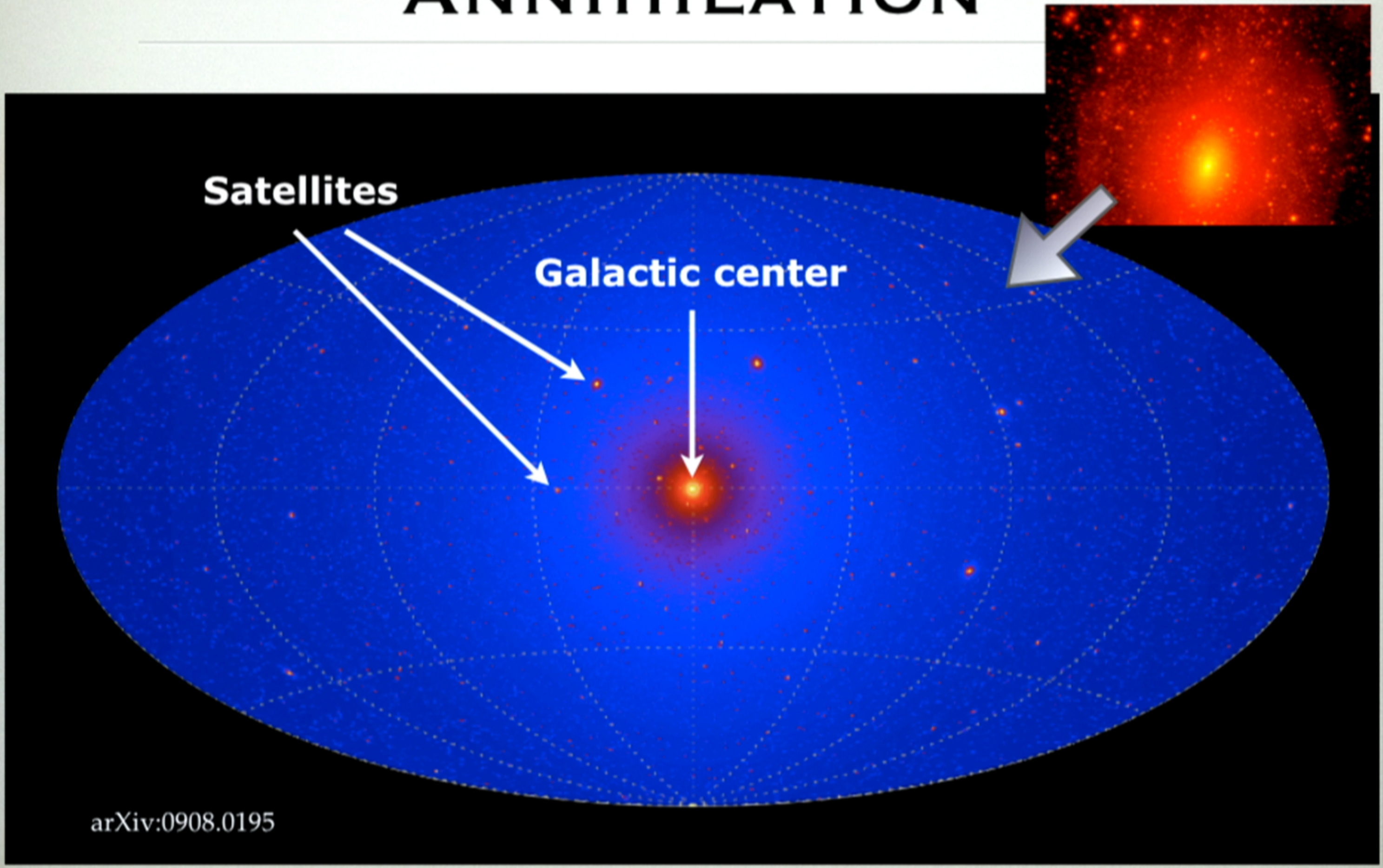


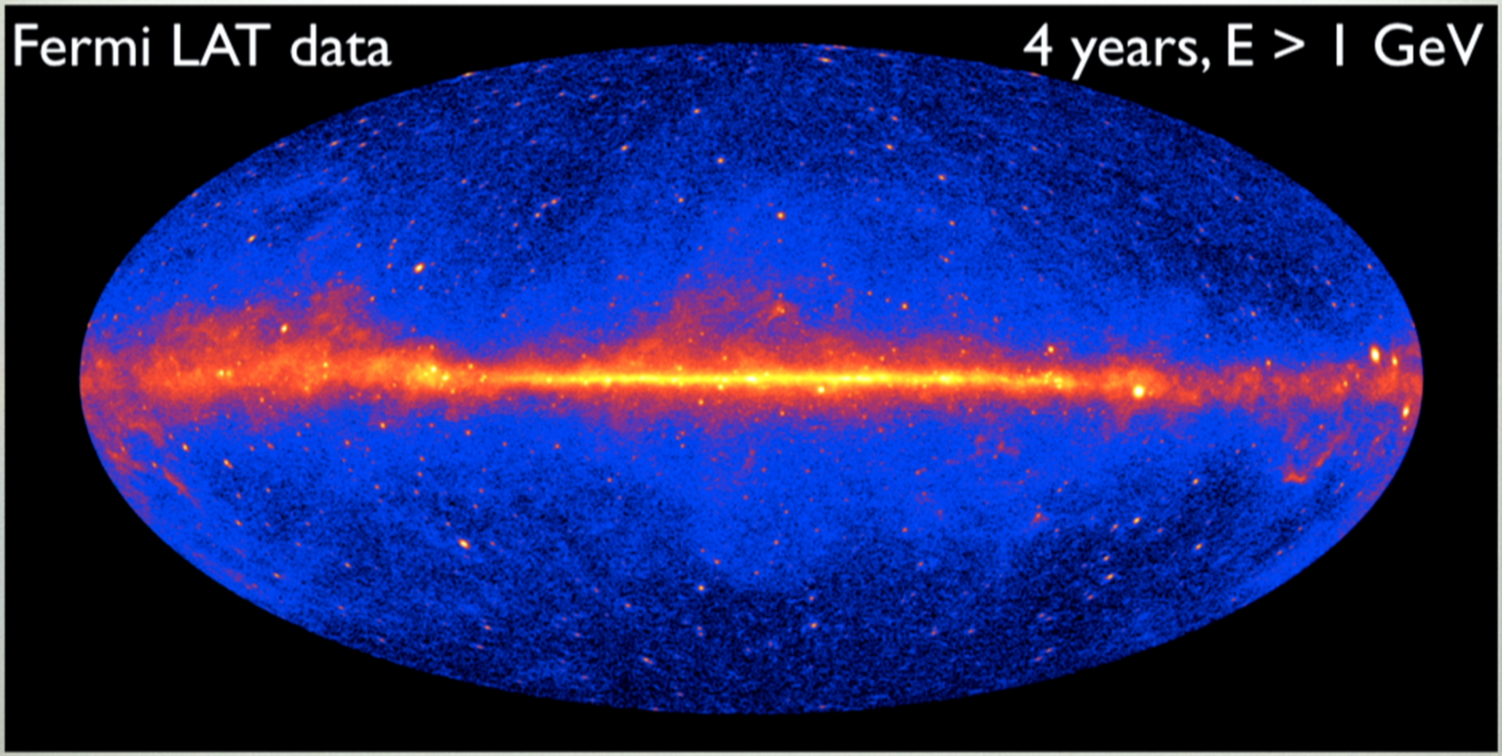




Gamma rays from DM Annihilation

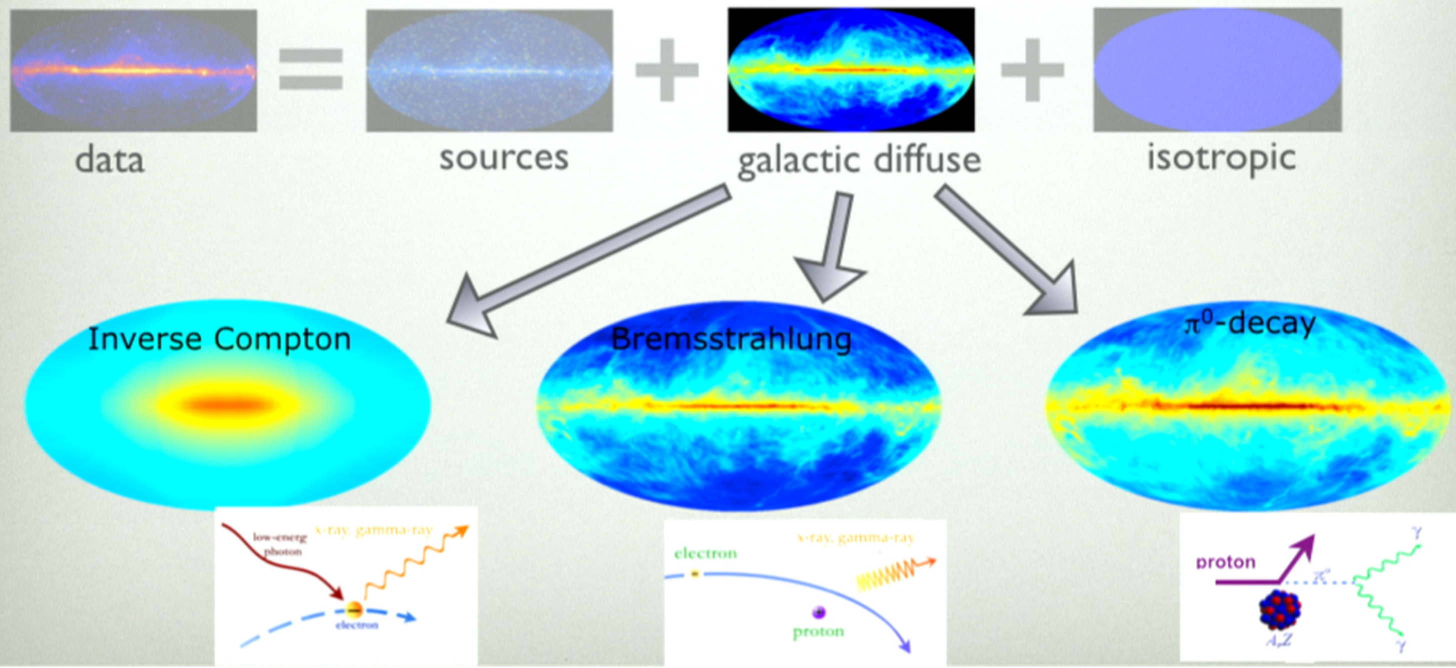


The Fermi Sky



Galactic Gamma-Ray Interstellar Emission

- The diffuse gamma-ray emission from the Milky Way is produced by cosmic rays interacting with the interstellar gas and radiation field and carries important information on the acceleration, distribution, and propagation of cosmic rays.



All Sky

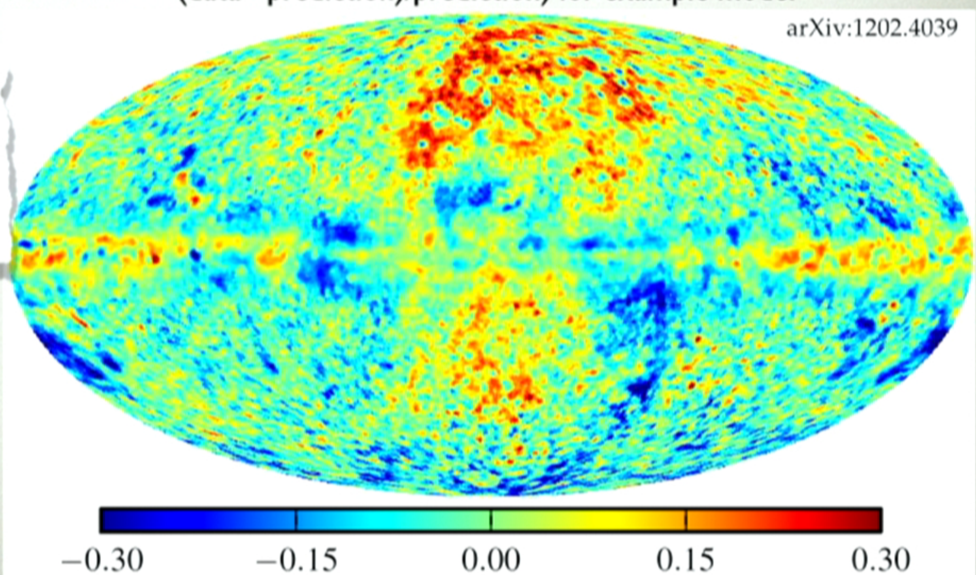
- Cosmic ray origin, propagation, and properties of the interstellar medium can be constrained by comparing the data to predictions.
- Generate models (in agreement with CR data) varying CR source distribution, CR halo size, gas distribution (GALPROP, http://galprop.stanford.edu) and compare the predictions for gamma rays with Fermi LAT data

Fermi LAT data
21 months, 200 MeV-100 GeV

On a large scale the agreement between data and prediction overall is good

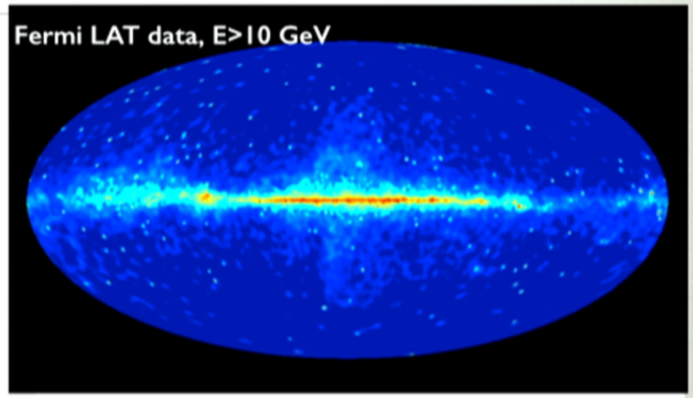
However some extended excesses and deficits stand out.

(data - prediction)/prediction) for example model

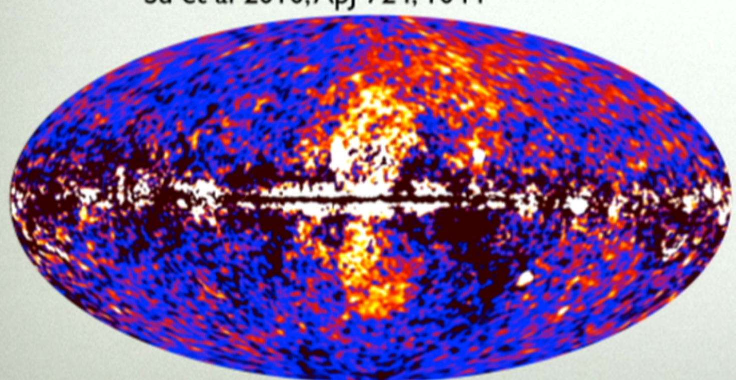


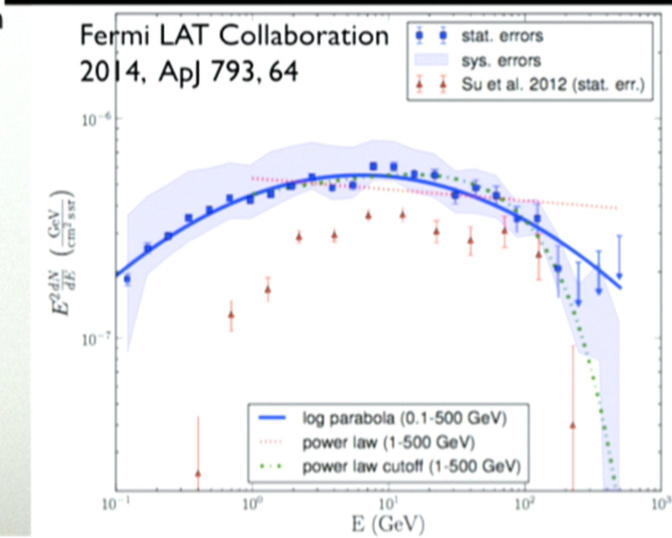
Fermi Bubbles

- Gamma-ray bubbles (Su et al 2010, ApJ 724, 1044):
  - very extended (~ 50° from plane)
  - hard spectrum (~E^{-2}, 1-100 GeV)
  - sharp edges
  - possible counterparts in other wavelengths (ROSAT, WMAP, and Planck)
- Outflow from the center of the Milky Way: jets from the supermassive black hole? starburst?



Su et al 2010, ApJ 724, 1044





INNER GALAXY

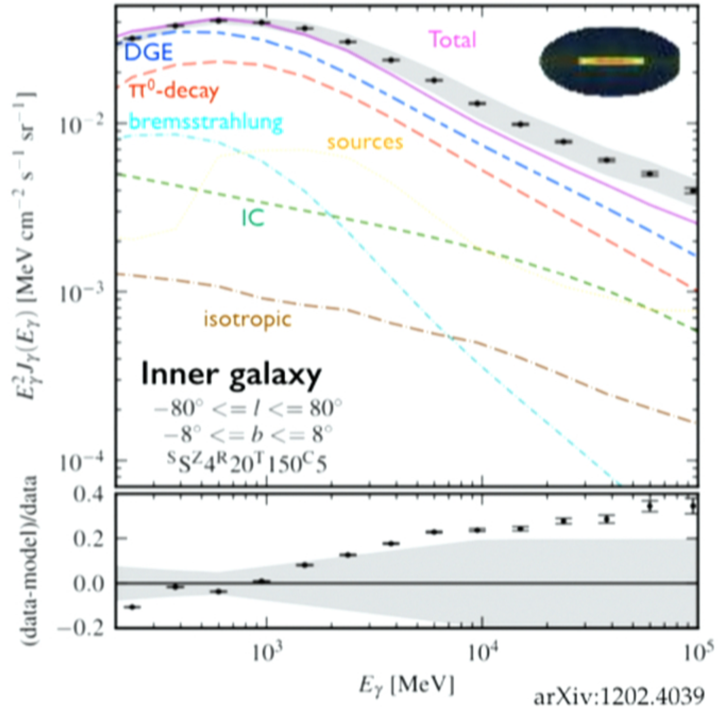
- Cosmic ray origin, propagation, and properties of the interstellar medium can be constrained by comparing the data to predictions.
- Generate models (in agreement with CR data) varying CR source distribution, CR halo size, gas distribution (GALPROP, http://galprop.stanford.edu) and compare the predictions for gamma rays with Fermi LAT data

Fermi LAT data
21 months, 200 MeV-100 GeV

Generally, models under-predict emission from inner Galaxy above ~1 GeV

Some plausible explanations:

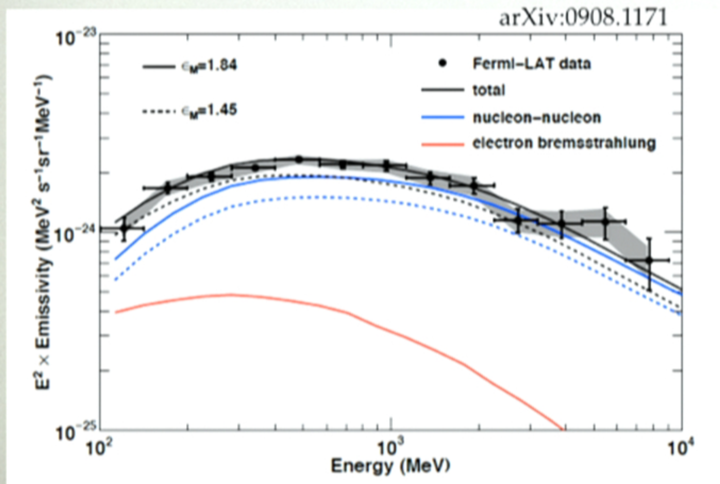
- unresolved point sources up to ~10 GeV
- failure of the locally measured CR spectra to represent the average for the Galaxy or, alternatively, to model a harder spectrum from freshly accelerated CR in the inner Galaxy

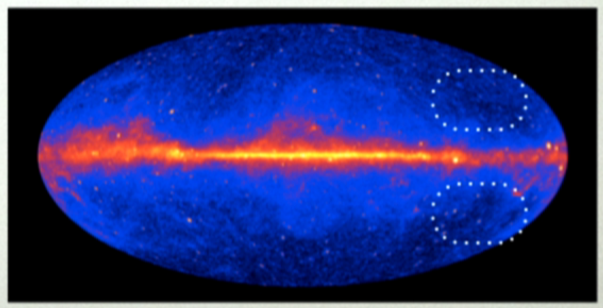


arXiv:1202.4039

Gamma Rays from Local HI

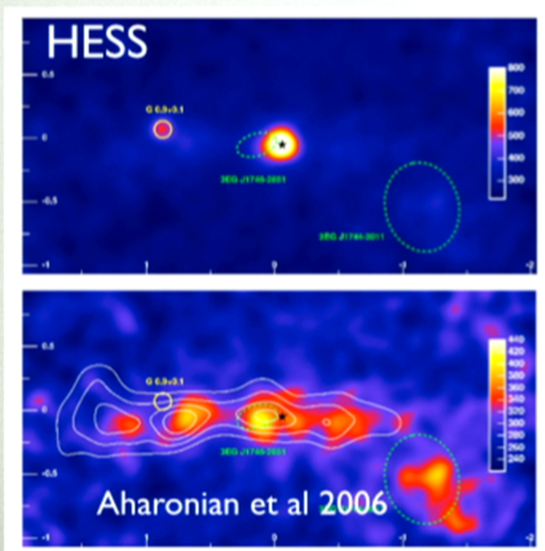
- Cosmic ray origin, propagation, and properties of the interstellar medium can be constrained by comparing the data to predictions.
- Generate models (in agreement with CR data) varying CR source distribution, CR halo size, gas distribution (GALPROP, http://galprop.stanford.edu) and compare the predictions for gamma rays with Fermi LAT data
- Assume locally measured CR spectra and intensities are representative of the Galaxy
- Gamma-ray emissivity of hydrogen gas from within ~ 1kpc from the Sun is in agreement with predictions ba
directly measured CR spectra

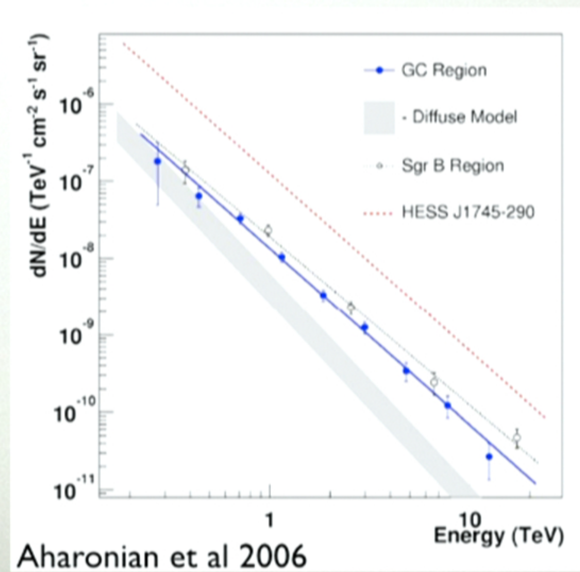




Diffuse TeV Emission

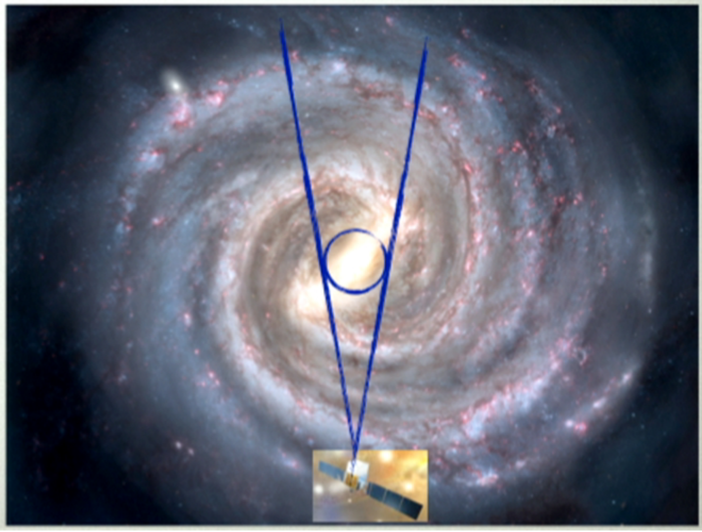
- The gamma rays of the Galactic center ridge at TeV energies observed by HESS is hard (spectral index~2.3), suggesting spectrum of CRs is harder than measured locally





Galactic Center Region

- Complex region: CR intensities, density of radiation fields and gas are highest; large uncertainties modeling the gamma-ray interstellar emission, significant foreground/background contribution with long integration path over the entire Galactic disc
- Large density of gamma-ray sources: many energetic sources near to or in the line of sight of the GC, difficult to disentangle from interstellar emission
- A signal of new physics (dark matter annihilation/decay) is also predicted to be largest here

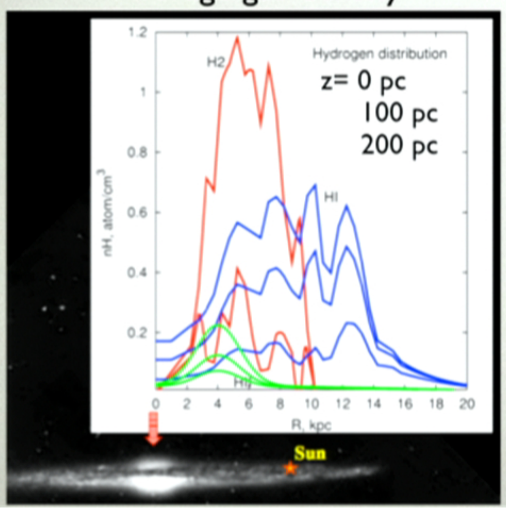


Interstellar Medium

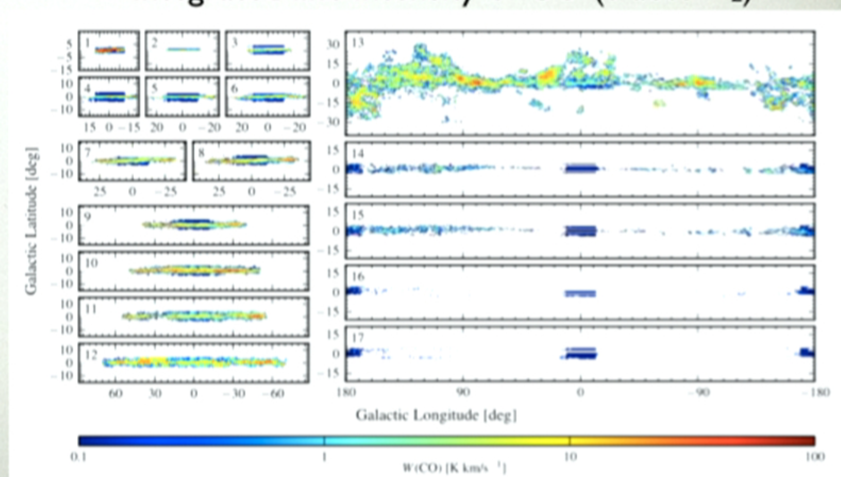
☺ Steep DM profiles predicted by CDM ⇒ Large DM annihilation/decay signal from GC!

☹ Good understanding of the conventional astrophysical background is crucial to extract a potential DM signal from this complex region of the sky

Average gas density



Integrated line intensity of CO (traces H_2)



Unresolved Sources

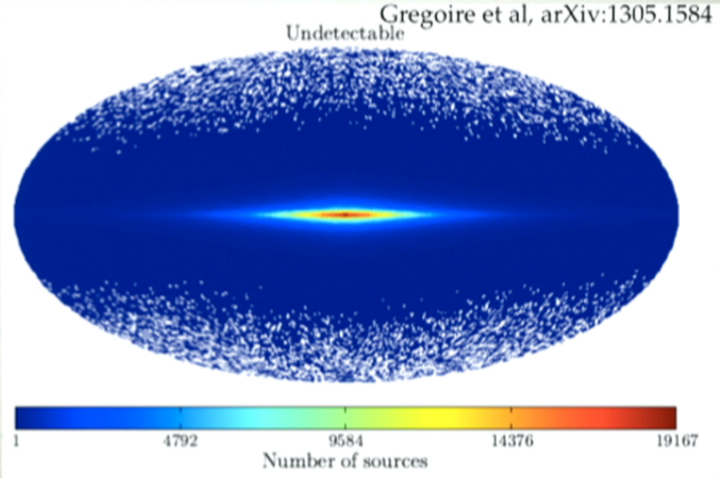
☺ Steep DM profiles predicted by CDM ⇒ Large DM annihilation/decay signal from GC!

☹ Good understanding of the conventional astrophysical background is crucial to extract a potential DM signal from this complex region of the sky

Predicted millisecond pulsar population undetectable by the LAT

Models based on Story et al 2007, Faucher-Giguere & Loeb 2010

Gregoire et al, arXiv:1305.1584



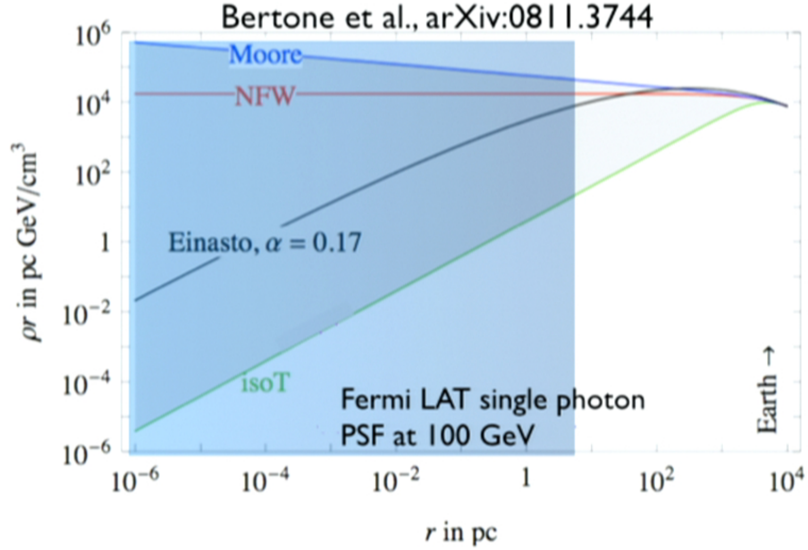
Dark Matter Distribution

- The dark matter annihilation (or decay) signal strongly depends on the dark matter distribution.
- Cuspier profiles can provide large boost factors

➡ For central DM density:

$\rho(r) \sim r^{-\gamma}$ γ=0 core, γ=1 NFW/cusp

Bertone et al., arXiv:0811.3744



NFW profile

Navarro, Frenk, and White 1997

$$\rho(r) = \rho_0 \frac{r_0}{r} \frac{(1 + r_0/a_0)^2}{(1 + r/a_0)^2}$$

$$\rho_0 = 0.3 \text{ GeV/cm}^3$$

$$a_0 = 20 \text{ kpc}, \; r_0 = 8.5 \text{ kpc}$$

✓ Via Lactea II (Diemand et al 2008) predicts a cuspier profile, $\rho(r) \propto r^{-1.2}$

✓ Aquarius (Springel et al 2008) predicts a shallower than r^{-1} innermost profile

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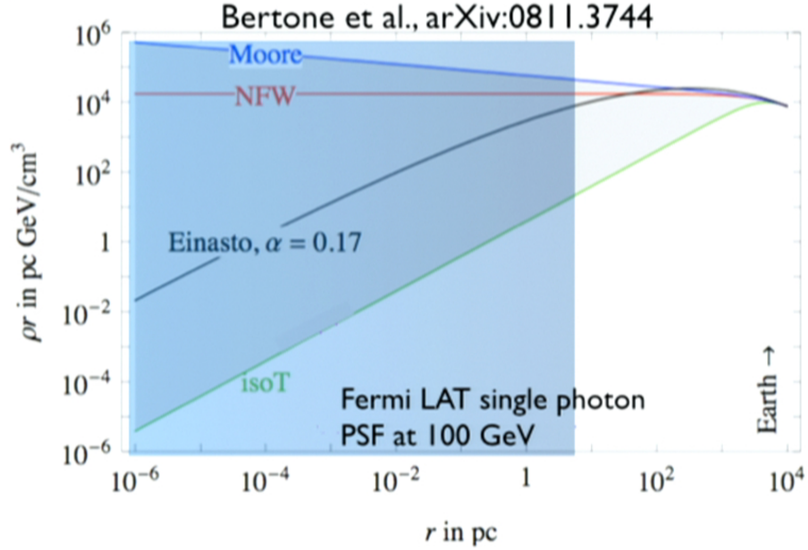

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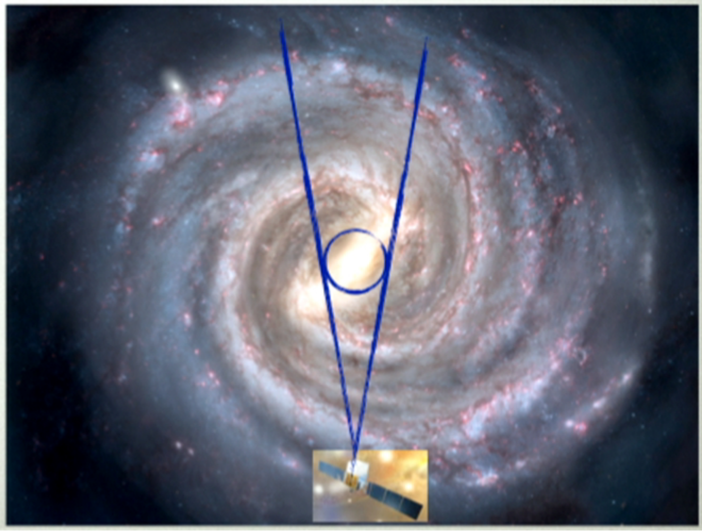
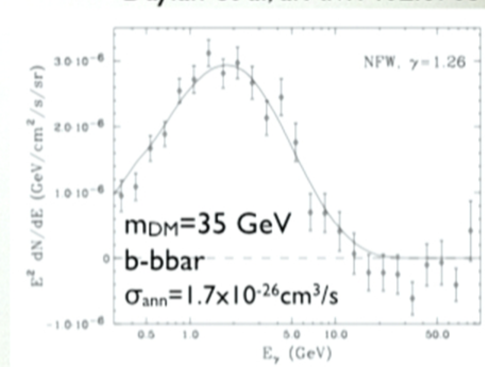
- Large density of gamma-ray sources: many energetic sources near to or in the line of sight of the GC, difficult to disentangle from interstellar emission
- A signal of new physics (dark matter annihilation/decay) is also predicted to be largest here
- An excess in the Fermi LAT GC data was first cautiously claimed by Goodenough and Hooper (arXiv:0910.2998) consistent with a 25-30 GeV WIMP annihilating into b-bbar with an annihilation cross-section a few times larger than expected from an s-wave thermal relic (9×10^{-26} cm^3/s)



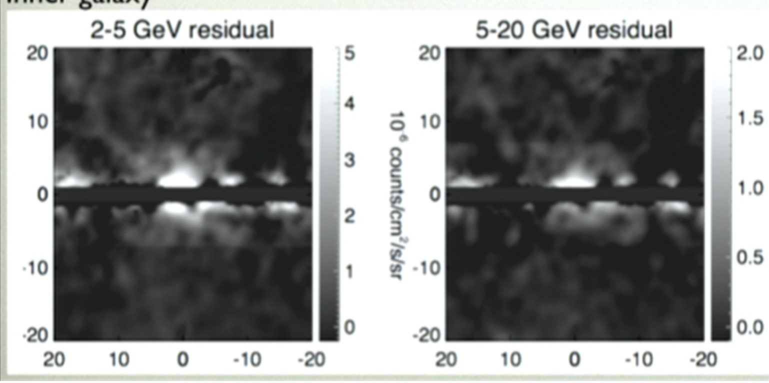
Galactic Center Dark Matter Searches

- A re-analysis of the Fermi LAT data by Daylan et al (with more statistics, over 5 years, and improved event selection aimed at reducing background leakage in the search region) confirms the presence of an excess on top of the adopted background models
- The addition of the DM component improves the data-model agreement very significantly
- The signal can be modeled by DM annihilating into b-bbar with a mass of 31-40 GeV and $\sigma_{ann}=(1.4\text{-}2)\times10^{-26}cm^3/s$

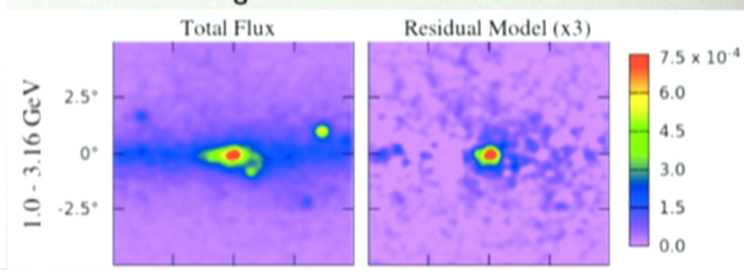
Daylan et al, arXiv:1402.6703



Inner galaxy



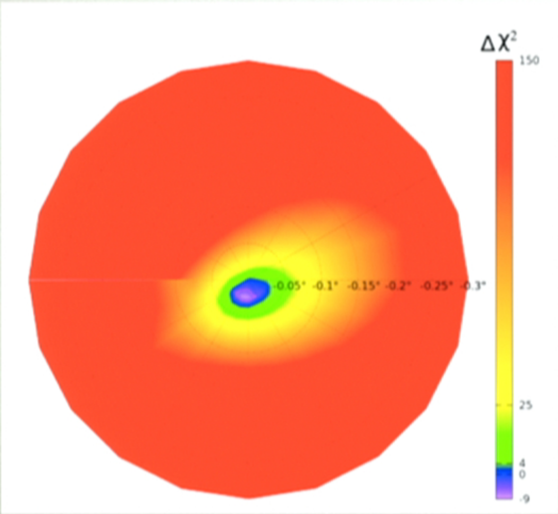
Galactic center region

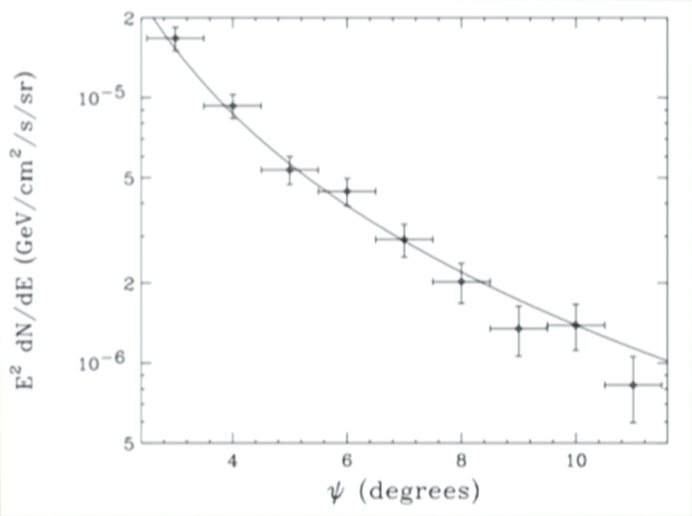


Galactic Center Dark Matter Searches

- The morphology of the excess in Daylan et al is consistent with an NFW profile with slope γ=1.1-1.3 centered within 0.05° of Sgr A*. Deviations from the spherically symmetric morphology are disfavored
- Independent fits in annuli about the direction of the GC confirm the excess up to at least 10° from the Galactic plane following a steep NFW profile

Daylan et al, arXiv:1402.6703

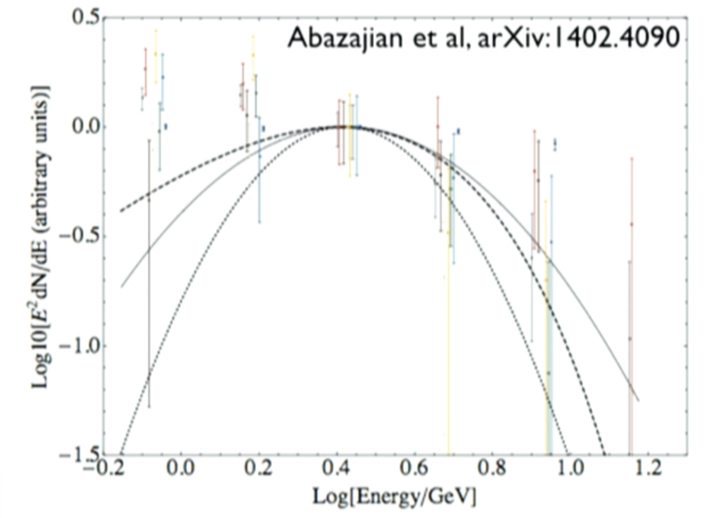




Galactic Center Dark Matter Searches

- A similar excess has been found by the work of Abazajian et al, focused on a 7°x7° region centered at the GC. In addition to DM, an unresolved pulsar interpretation is found plausible
- Based on globular clusters observations, observed signal is found to be consistent with 3000-5000 millisecond pulsars in a 1 kpc x 1 kpc region
- Morphology? Can MSPs extend out to 10°? Spherical symmetry?

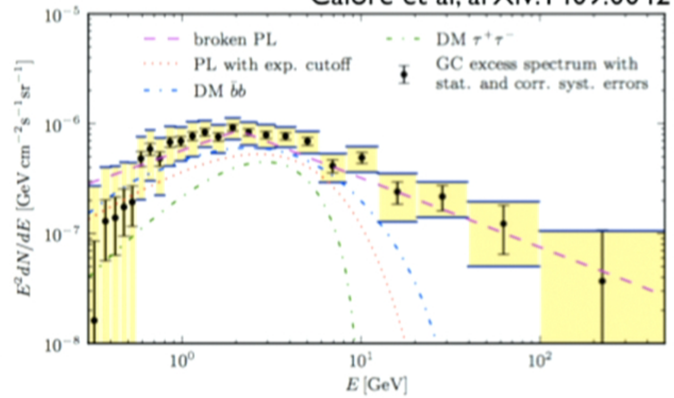
GC extended excess, lines
MSP predictions based on globular clusters, data points



Galactic Center Dark Matter Searches

- More extensive study of the background model systematics
- Broad range of interstellar emission models
- Results compatible with dark matter annihilation into b-bbar and a mass of ~50 GeV

Calore et al, arXiv:1409.0042



- Recently, Lee, Lisanti et al (arXiv:1506.05124) et al used template analysis that accounts for non-poissonian photon statistics to determine if the excess can be explained by unresolved point sources
- The result by Lee et al favors the excess originating from point sources at/below the Fermi LAT detection threshold
- Improved angular resolution has been recently be made available in the Fermi LAT data (*Pass 8*) and might be useful to test this claim

Galactic Center Region

Fermi LAT Collaboration

- Focus on a 15°x15° region (~ 1 kpc) around Galactic center