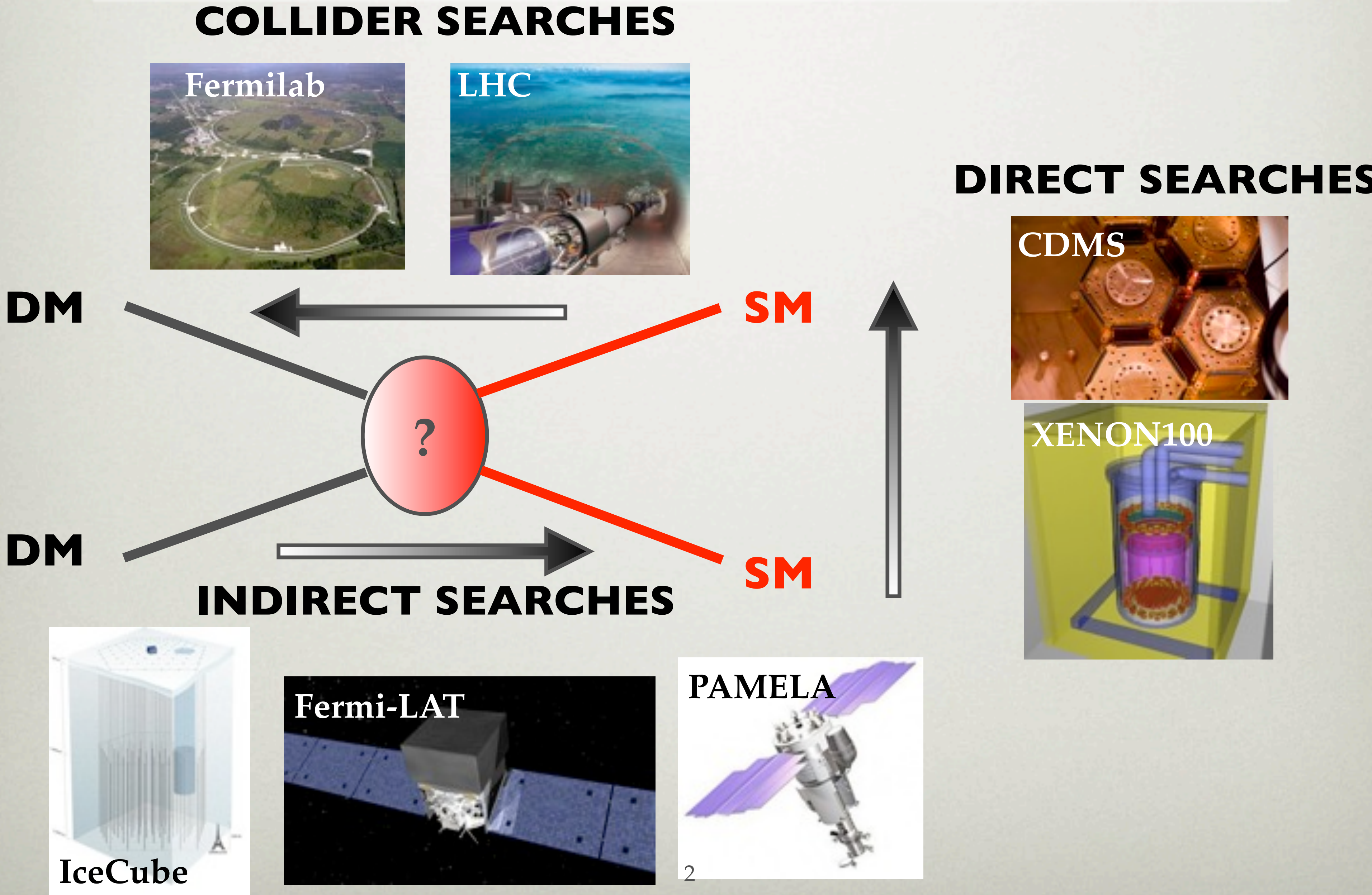
Indirect Detection of Dark Matter

Simona Murgia, SLAC-KIPAC

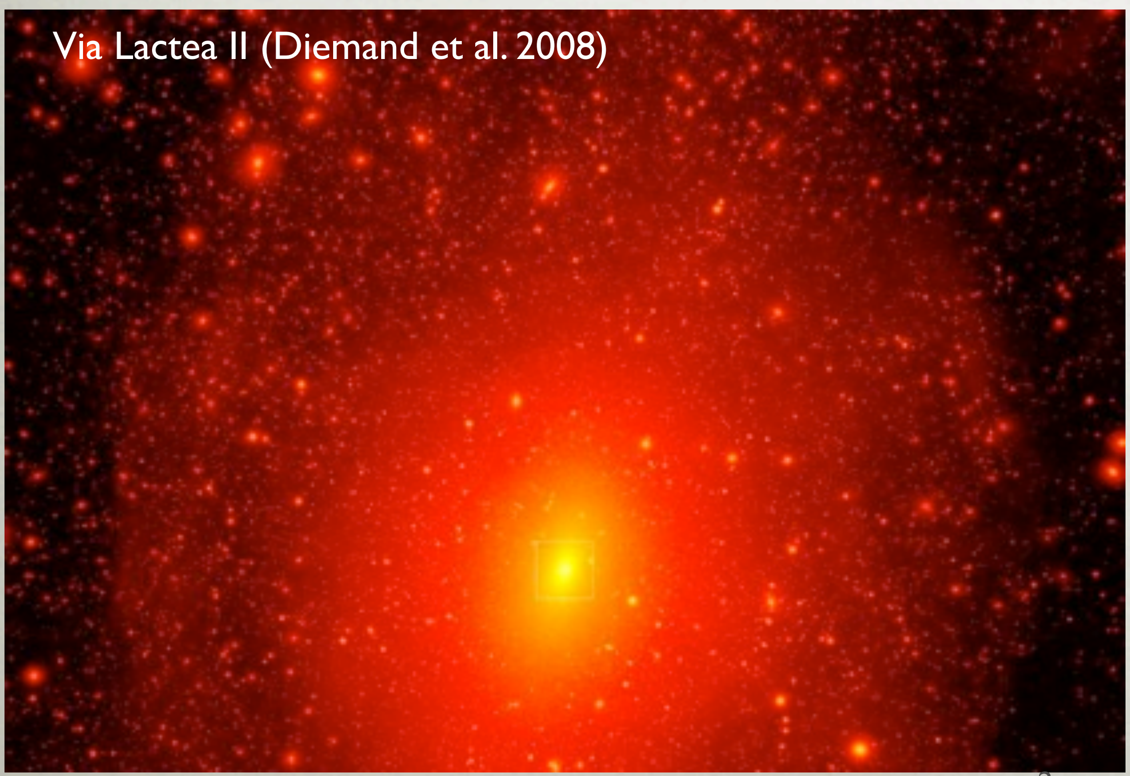
XXXIX SLAC Summer Institute
29 July 2011

WIMP Searches



Indirect Searches

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



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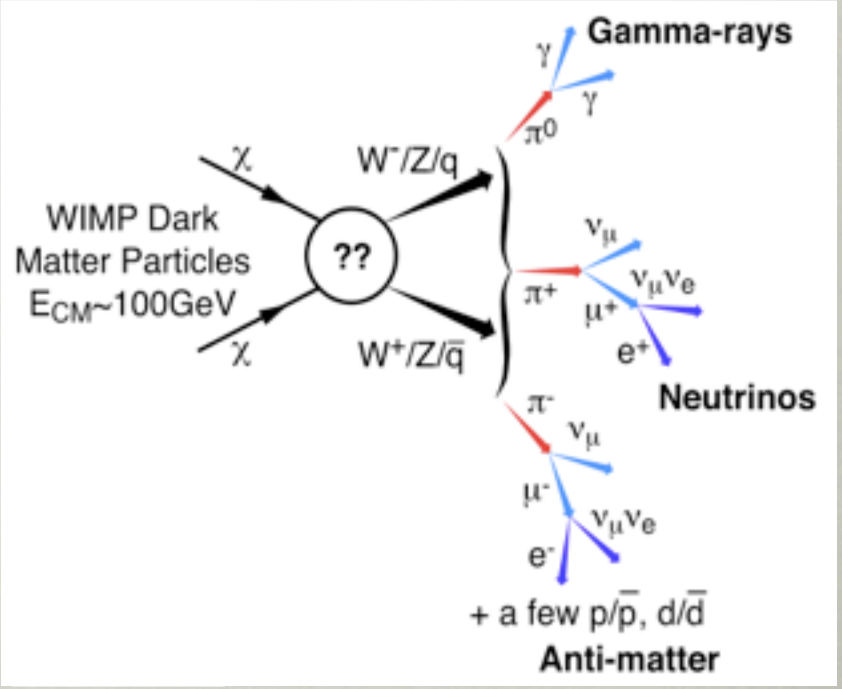
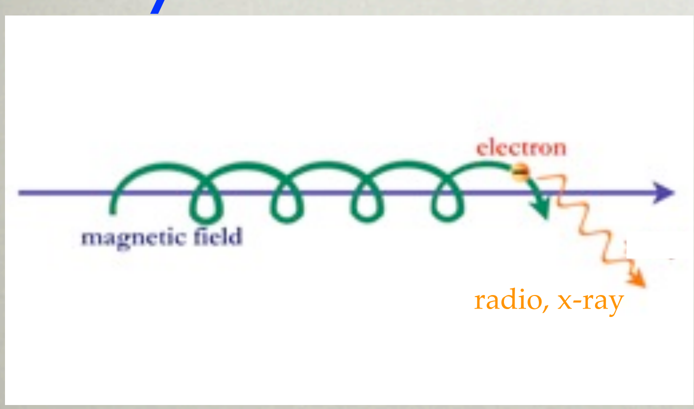


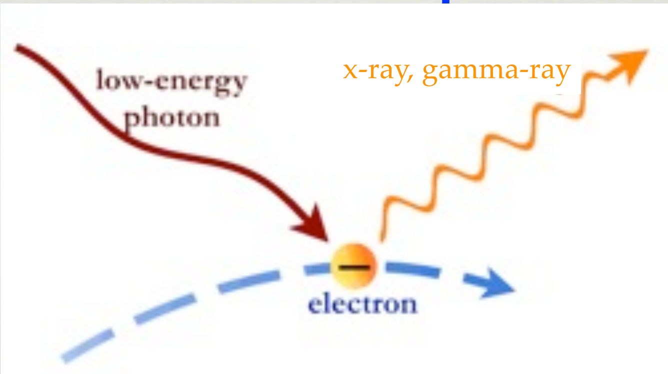
DM Messengers

- 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)

Synchrotron

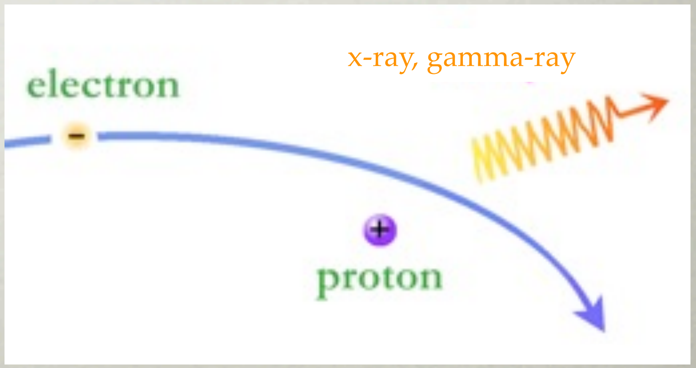


Inverse Compton



http://chandra.harvard.edu/resources/ppt/xray/index.html

Bremsstrahlung



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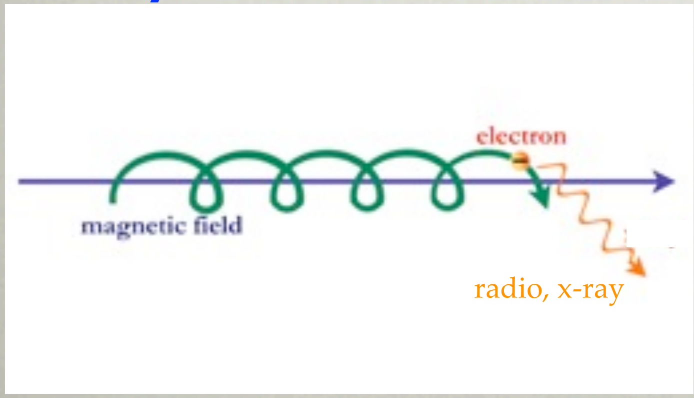
Neutral particles are more promising probes!
Among charged particles, antiparticles are favored

Synchrotron



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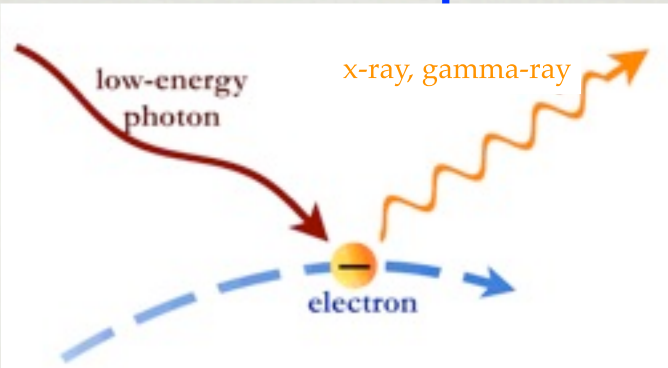

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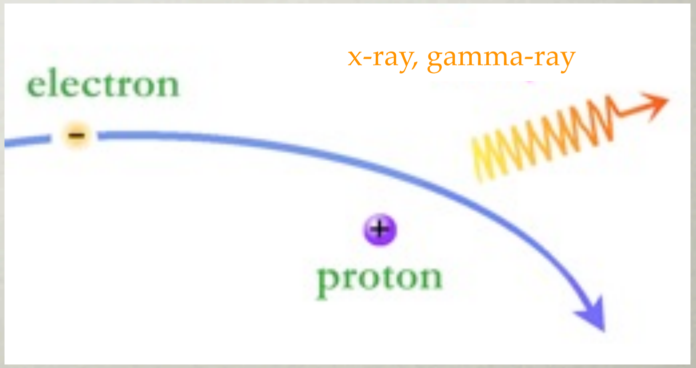
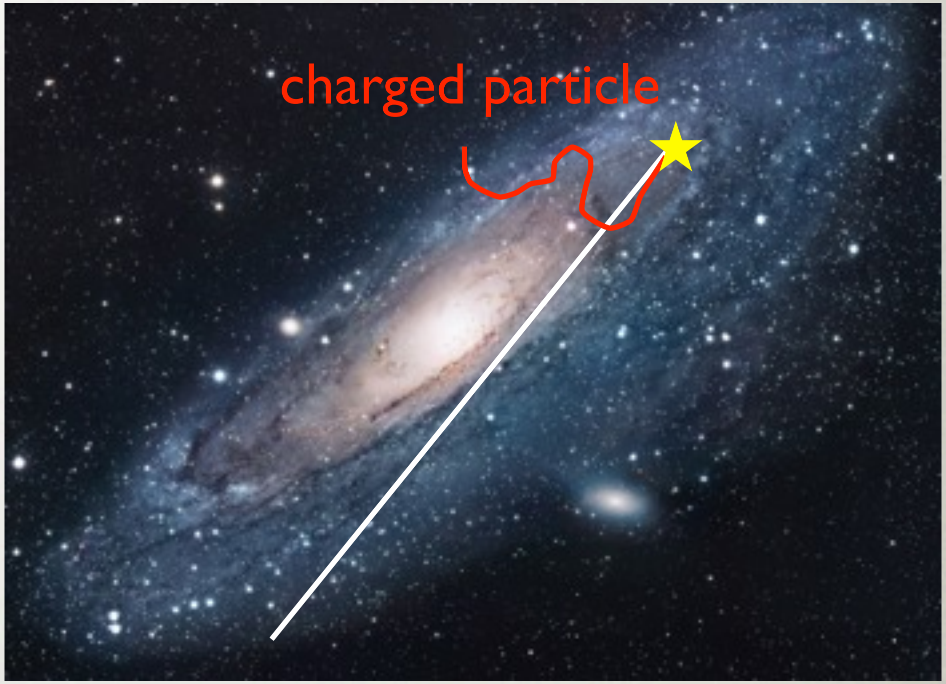


DM Messengers

- 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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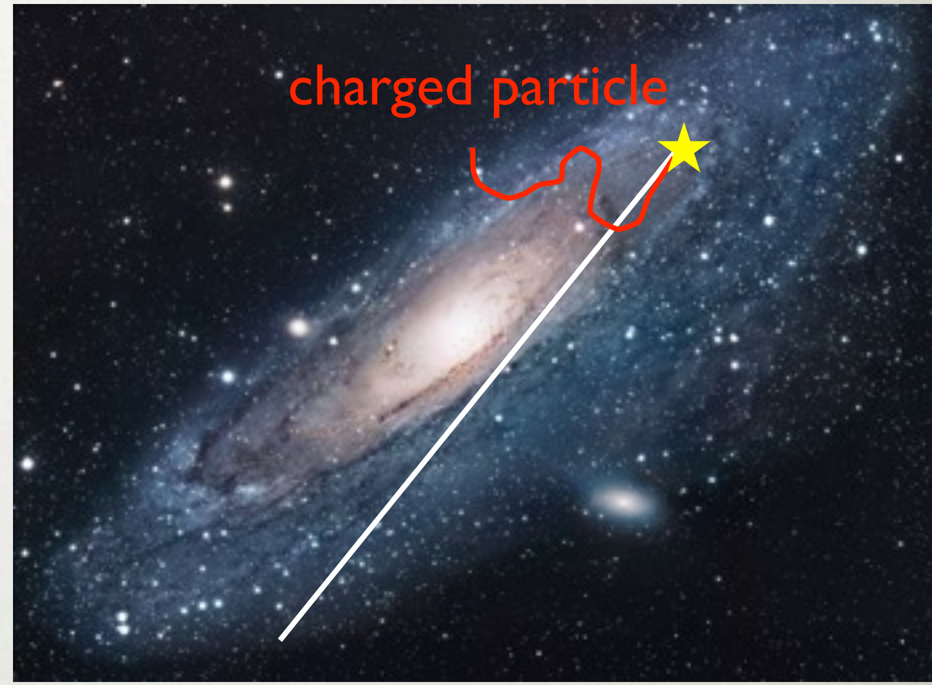
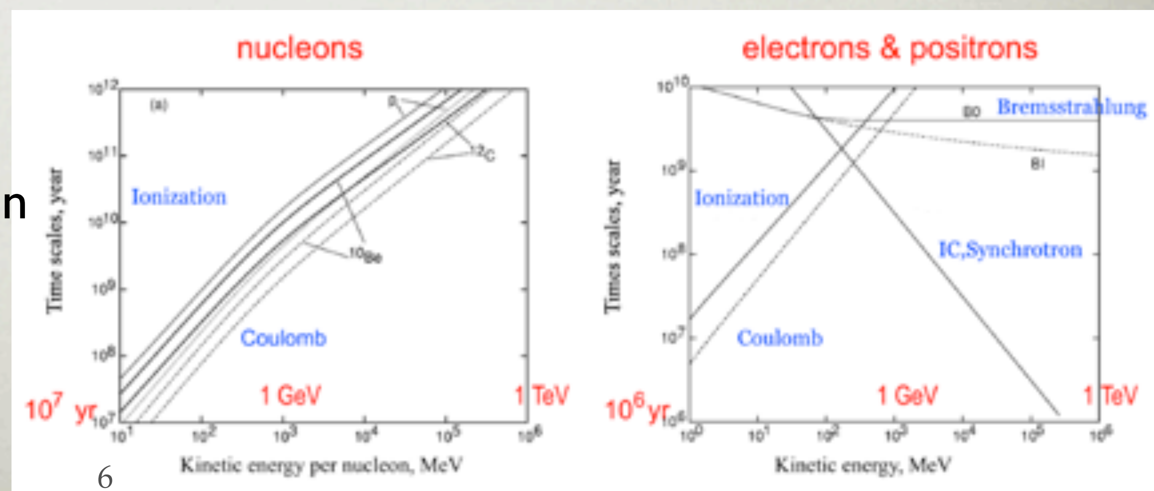
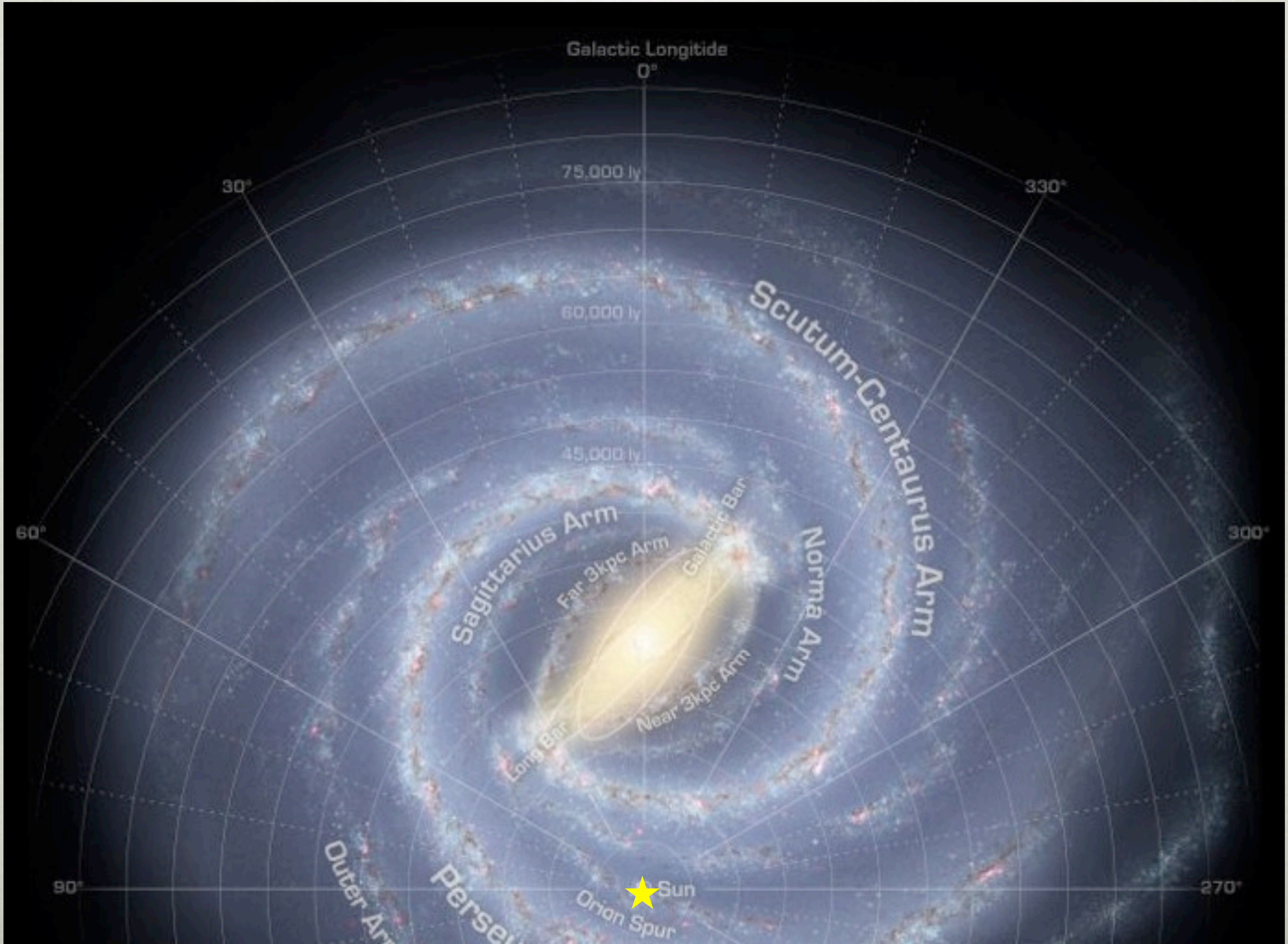


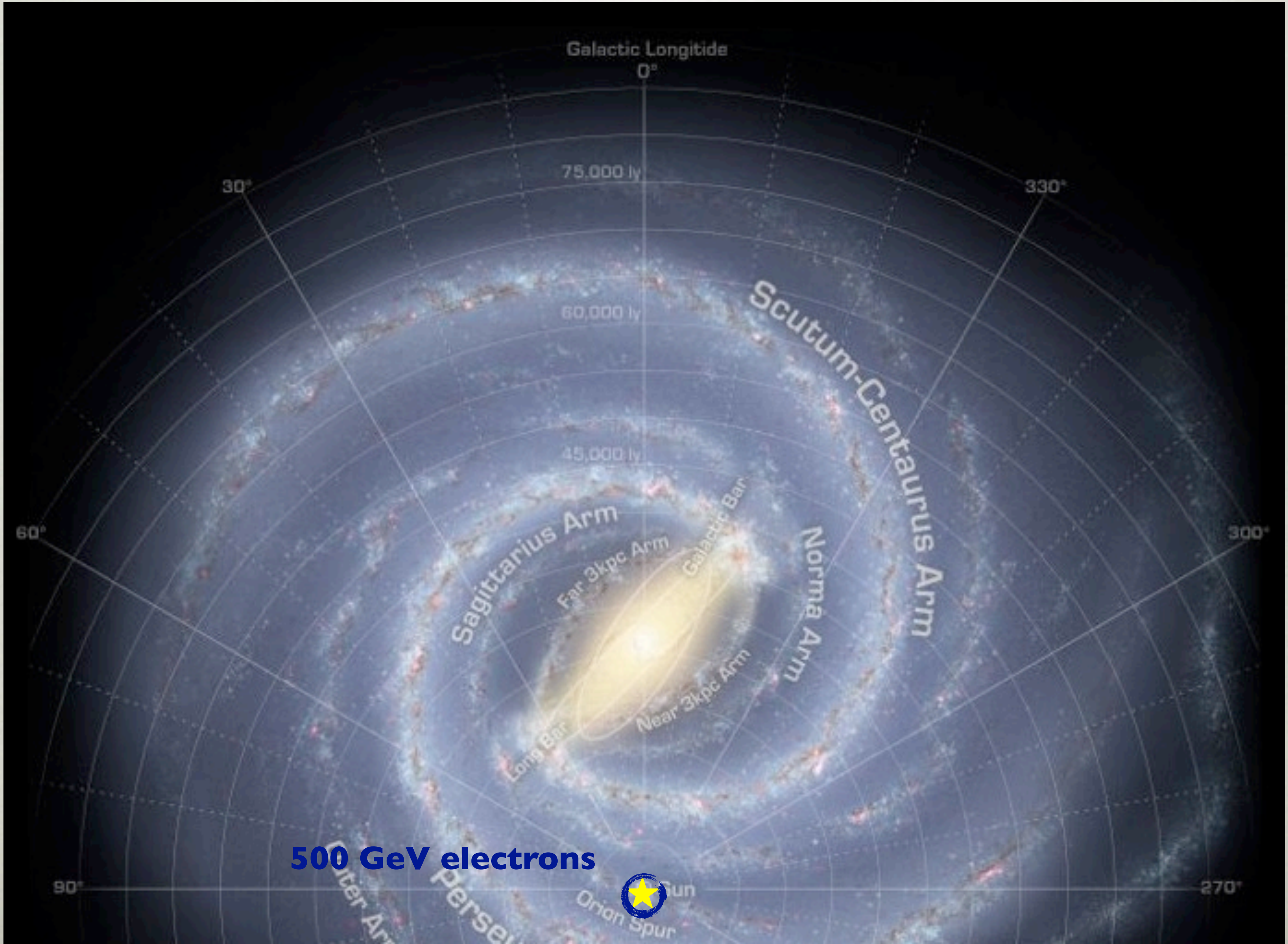
Electrons of > GeV energies primarily lose energy through synchrotron and IC emission

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





Galactic Longitude
0°
75,000 ly
60,000 ly
45,000 ly
30°
330°
60°
300°
90°
270°
Scutum-Centaurus Arm
Sagittarius Arm
Far 3kpc Arm
Galactic Bar
Norma Arm
Near 3kpc Arm
Long Bar
Sun
Orion Spur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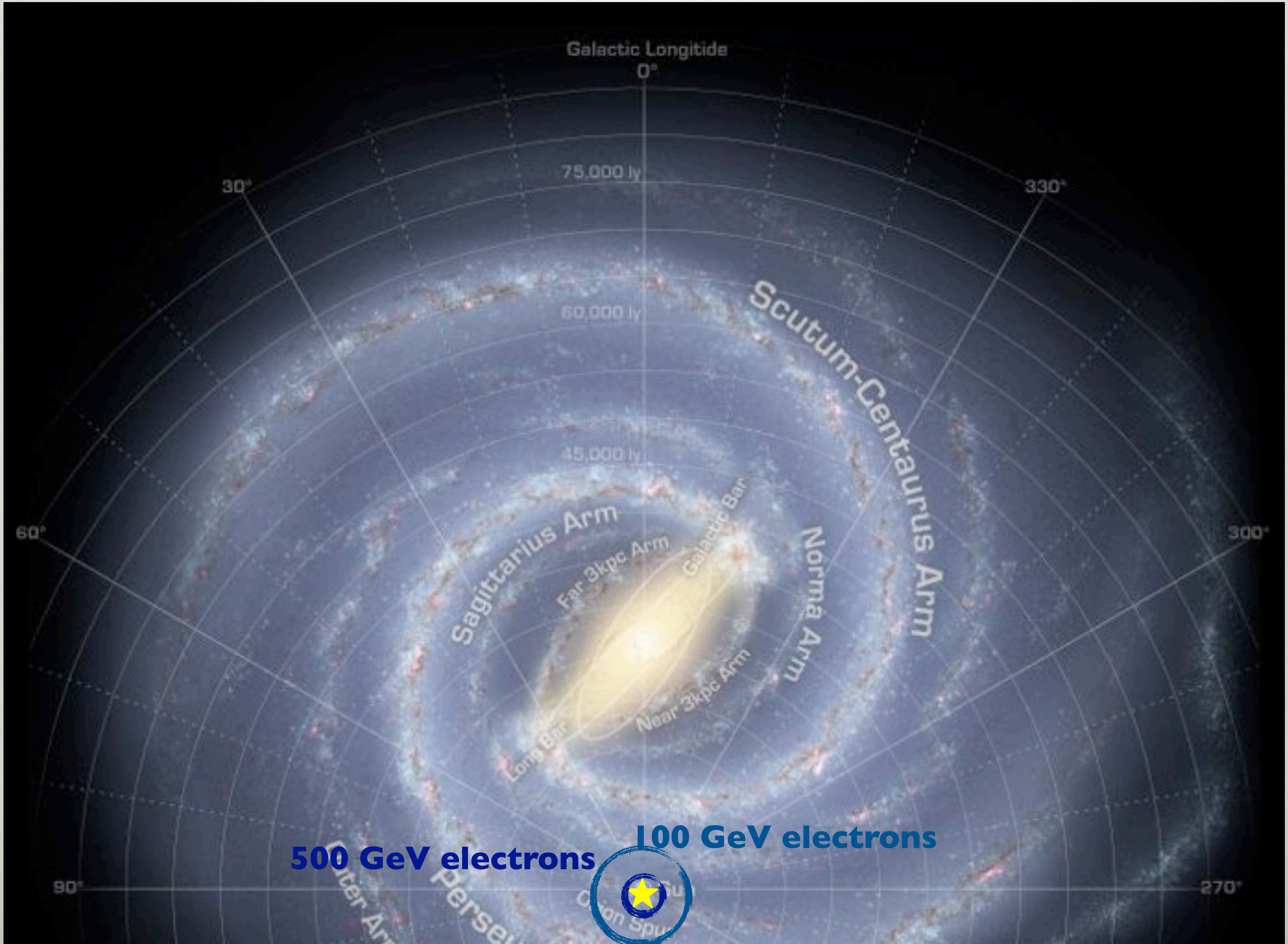
500 GeV electrons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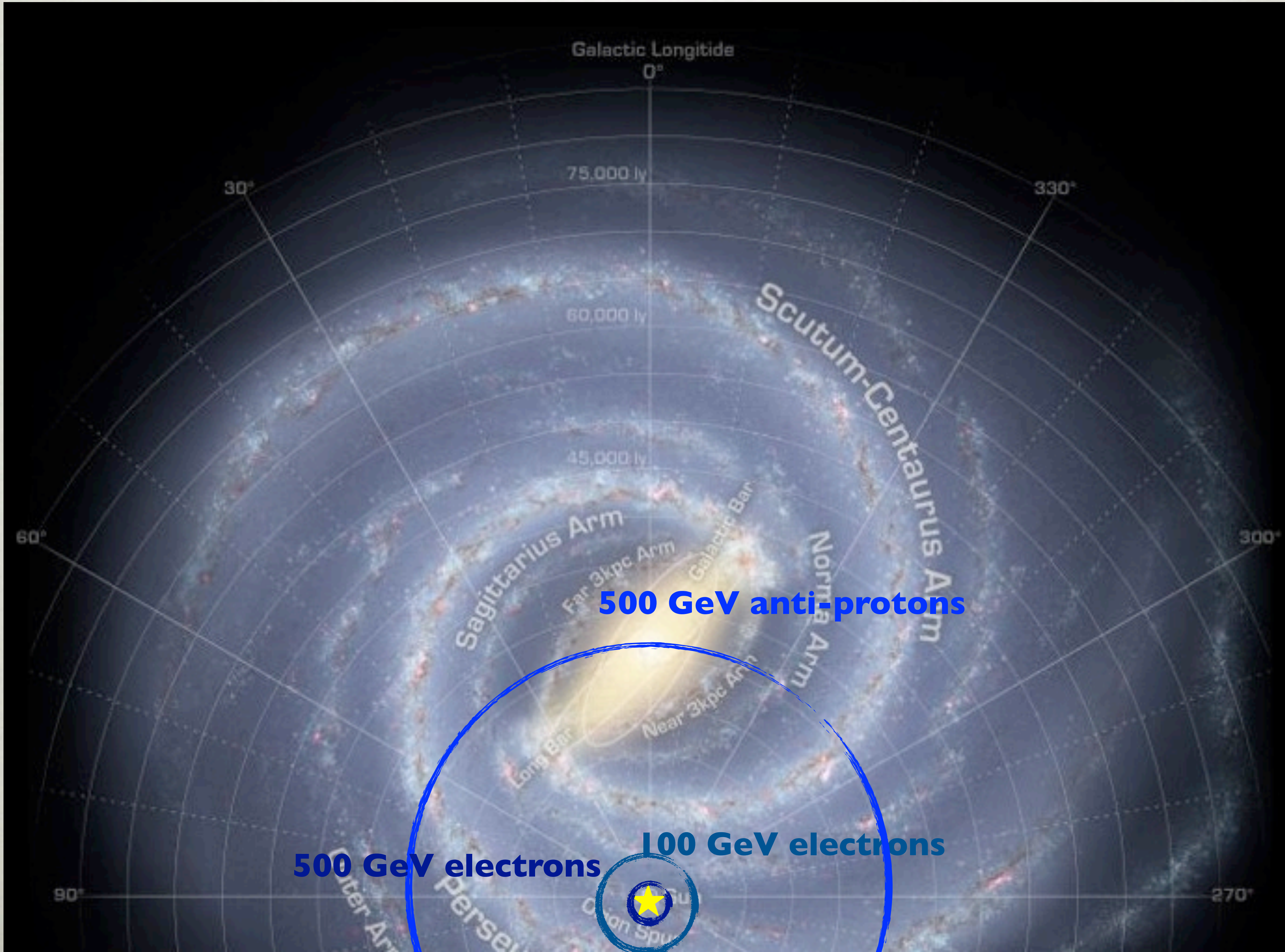
100 GeV electrons
500 GeV electrons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500 GeV anti-protons
100 GeV electrons
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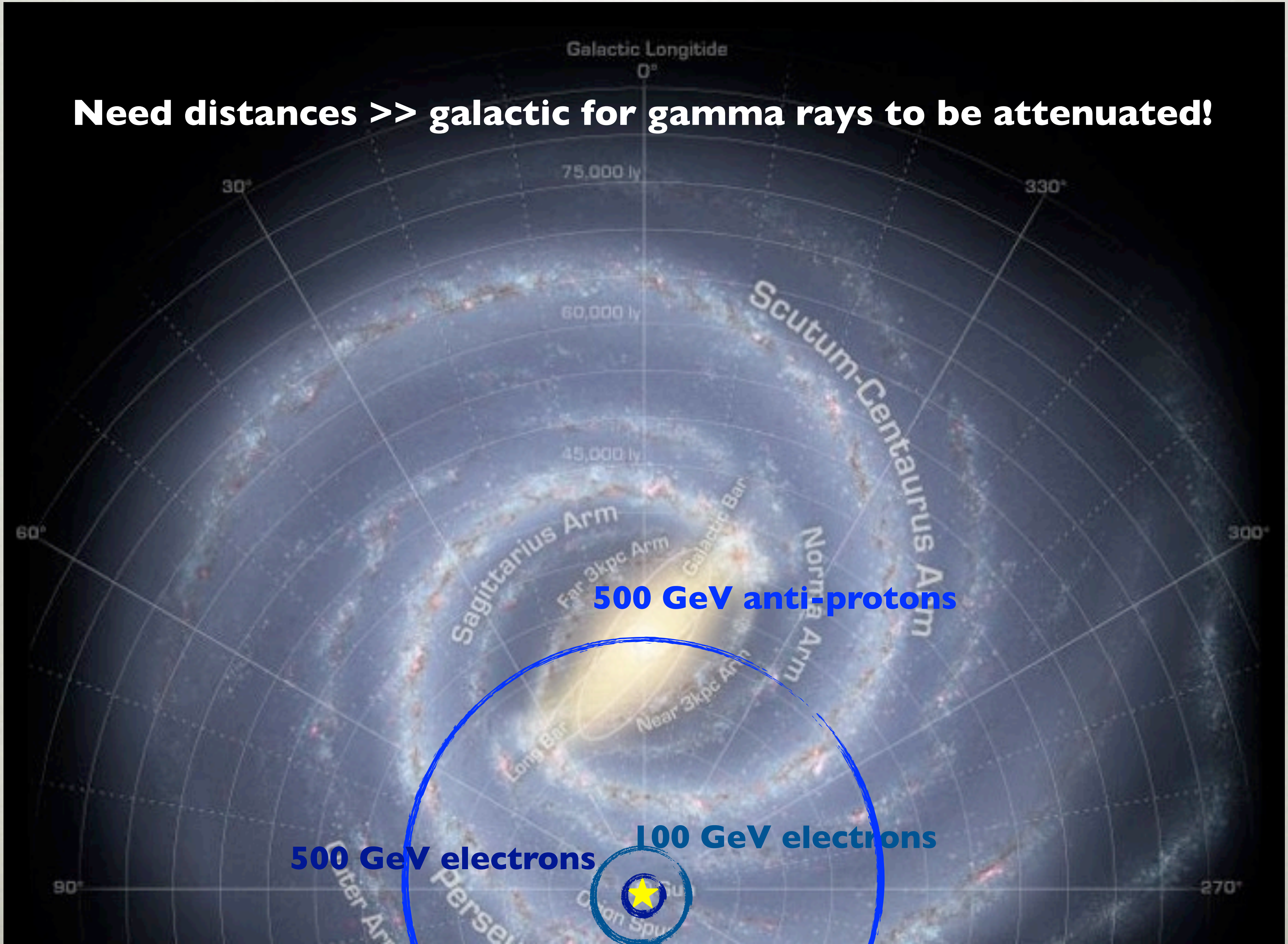
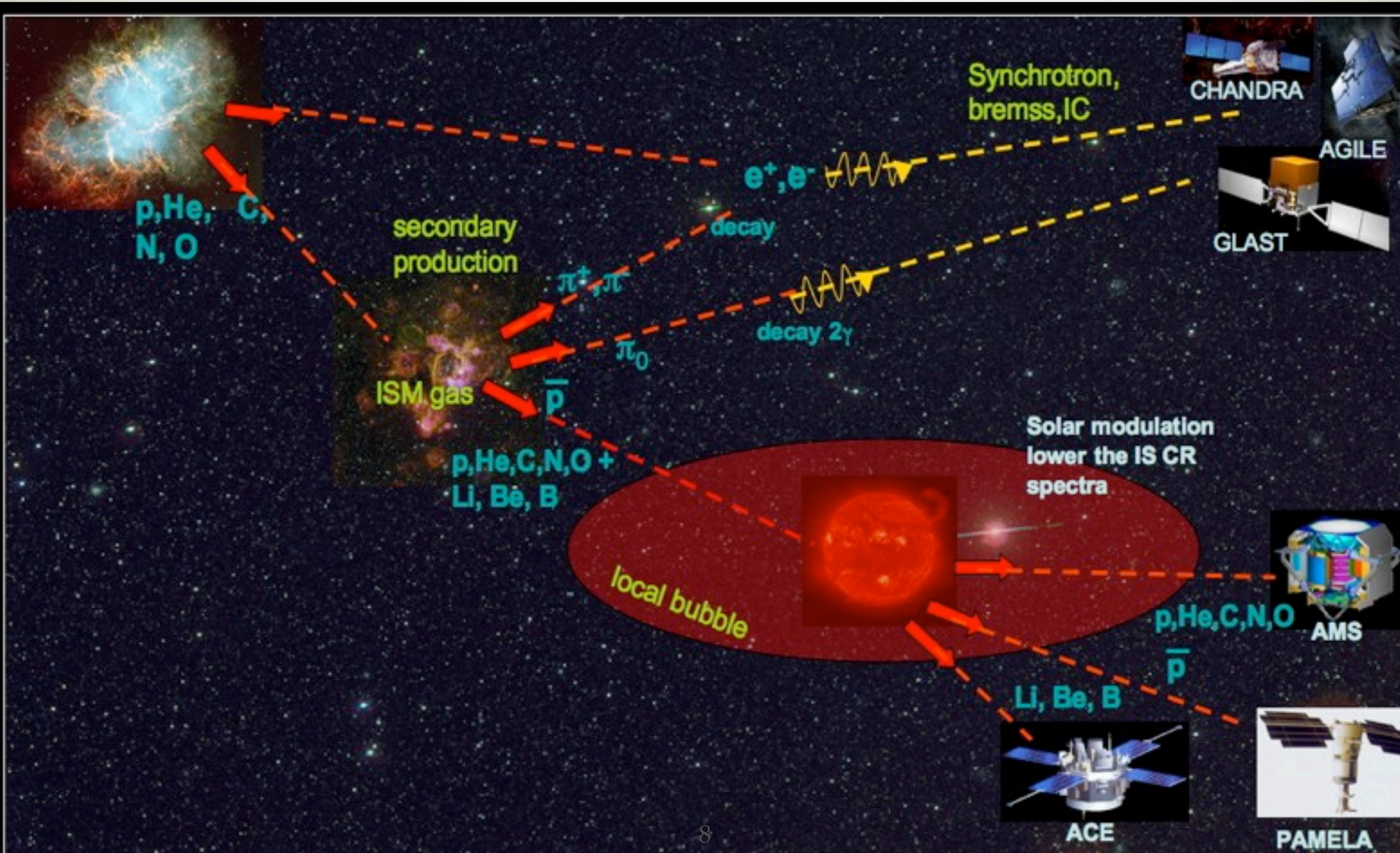
Need distances >> galactic for gamma rays to be attenuated!



And the Background...



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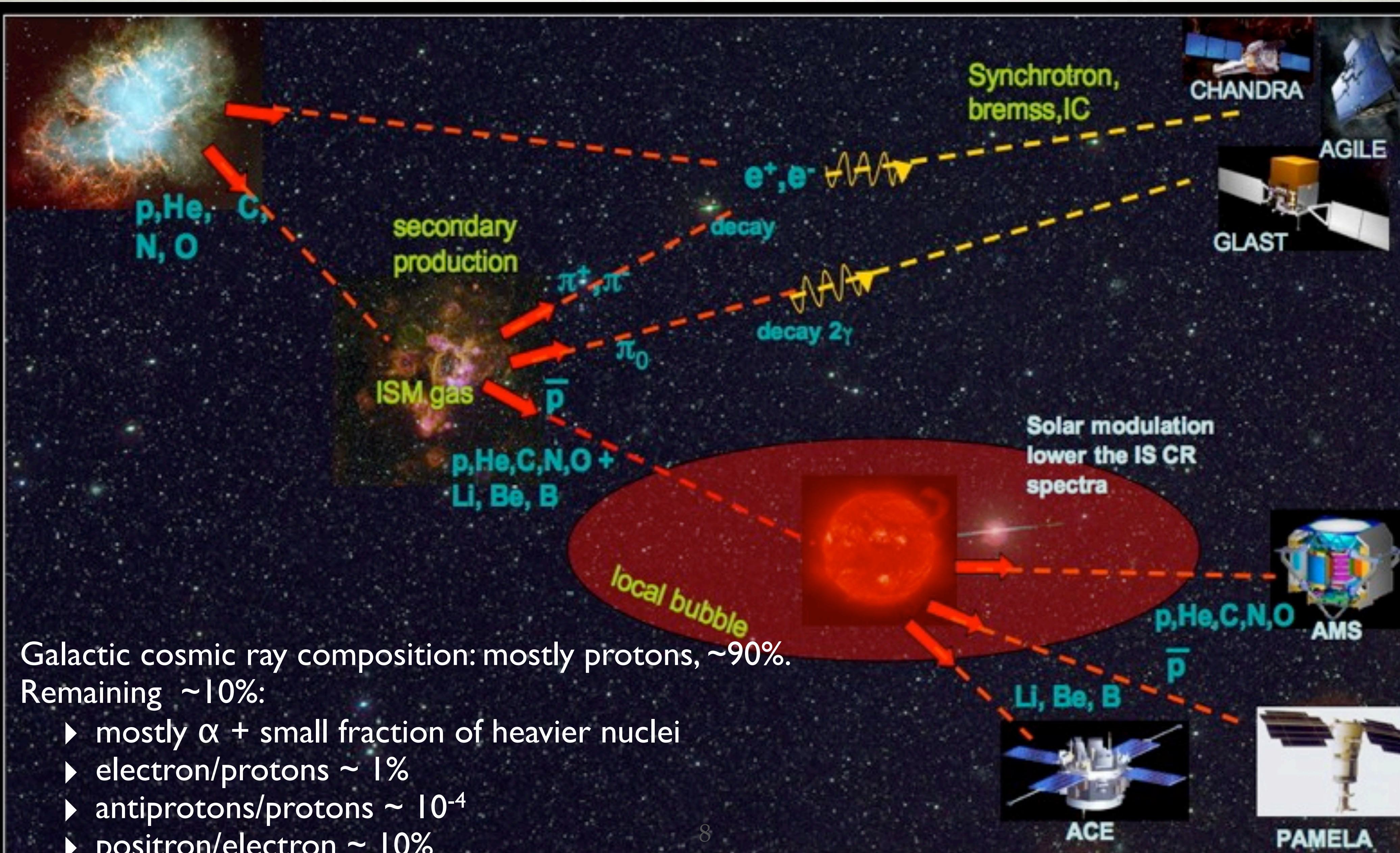

Galactic cosmic ray composition: mostly protons, ~90%.
Remaining ~10%:

- mostly α + small fraction of heavier nuclei
- electron/protons ~ 1%
- antiprotons/protons ~ 10^{-4}
- positron/electron ~ 10%

Components of realistic CR propagation model

- Detailed gas distributions (fragmentation, energy losses: π^0-decay, brem)
- Interstellar radiation field ($e^\pm$ energy losses: IC)
- Nuclear & particle production cross sections + reaction network
- Secondary particle production ($pX \rightarrow \pi^0 \pi^\pm \rightarrow \gamma, e^\pm, \nu$)
- Energy losses: ionisation, Coulomb, brem, IC, synchrotron $\rightarrow$ ISM heating, γ-rays and other diffuse emissions
- Spatial distribution of cosmic-ray sources, injection spectrum
- Solve propagation equations for all CR species
- Derive propagation parameters

Slide, plots from T. Porter's talk at Aspen Winter 2011

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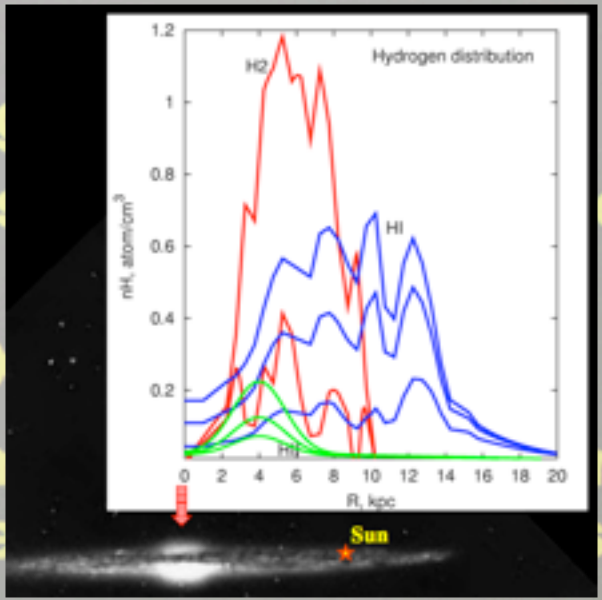

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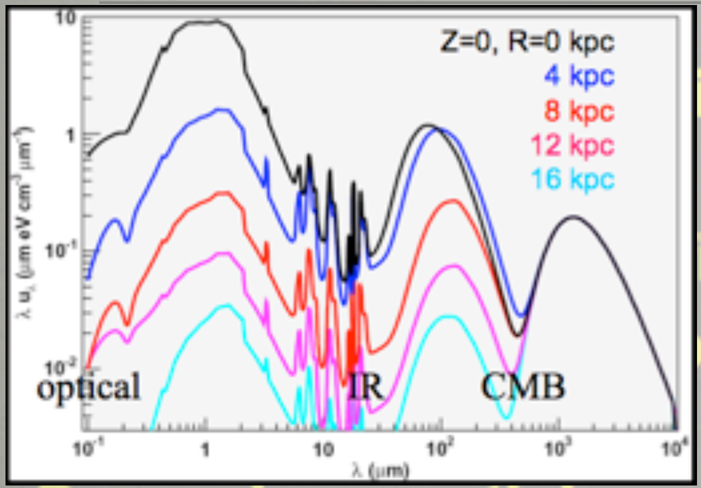

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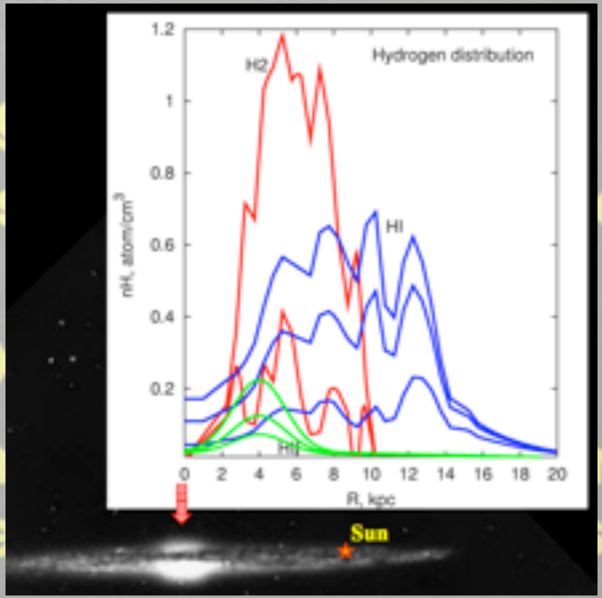

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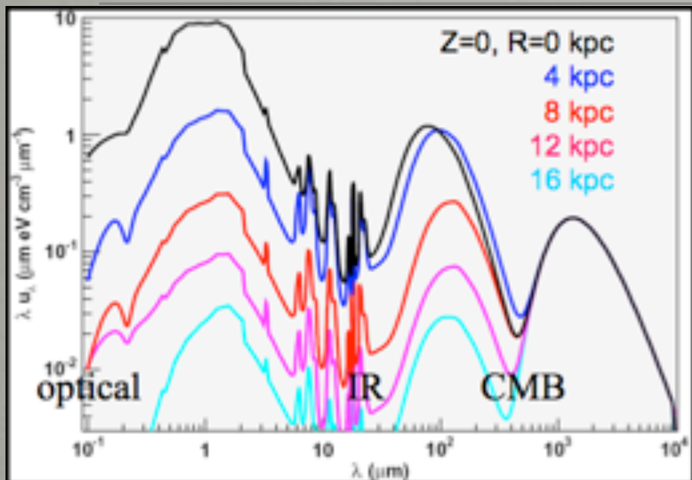

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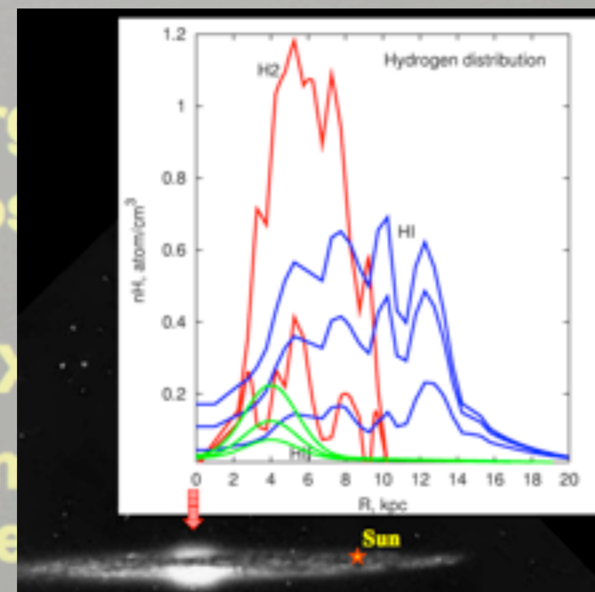
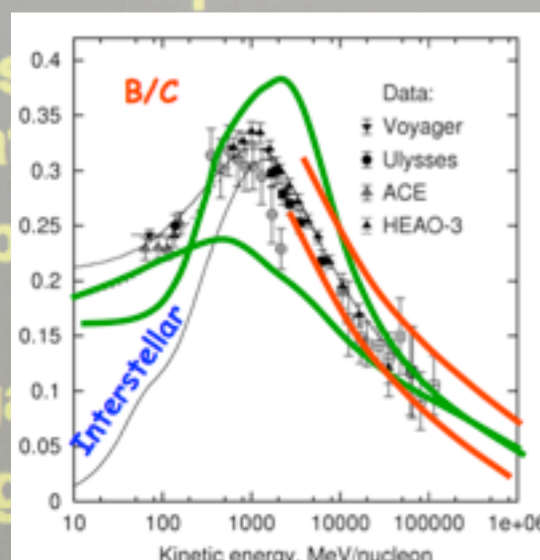


- Secondary particle production (p



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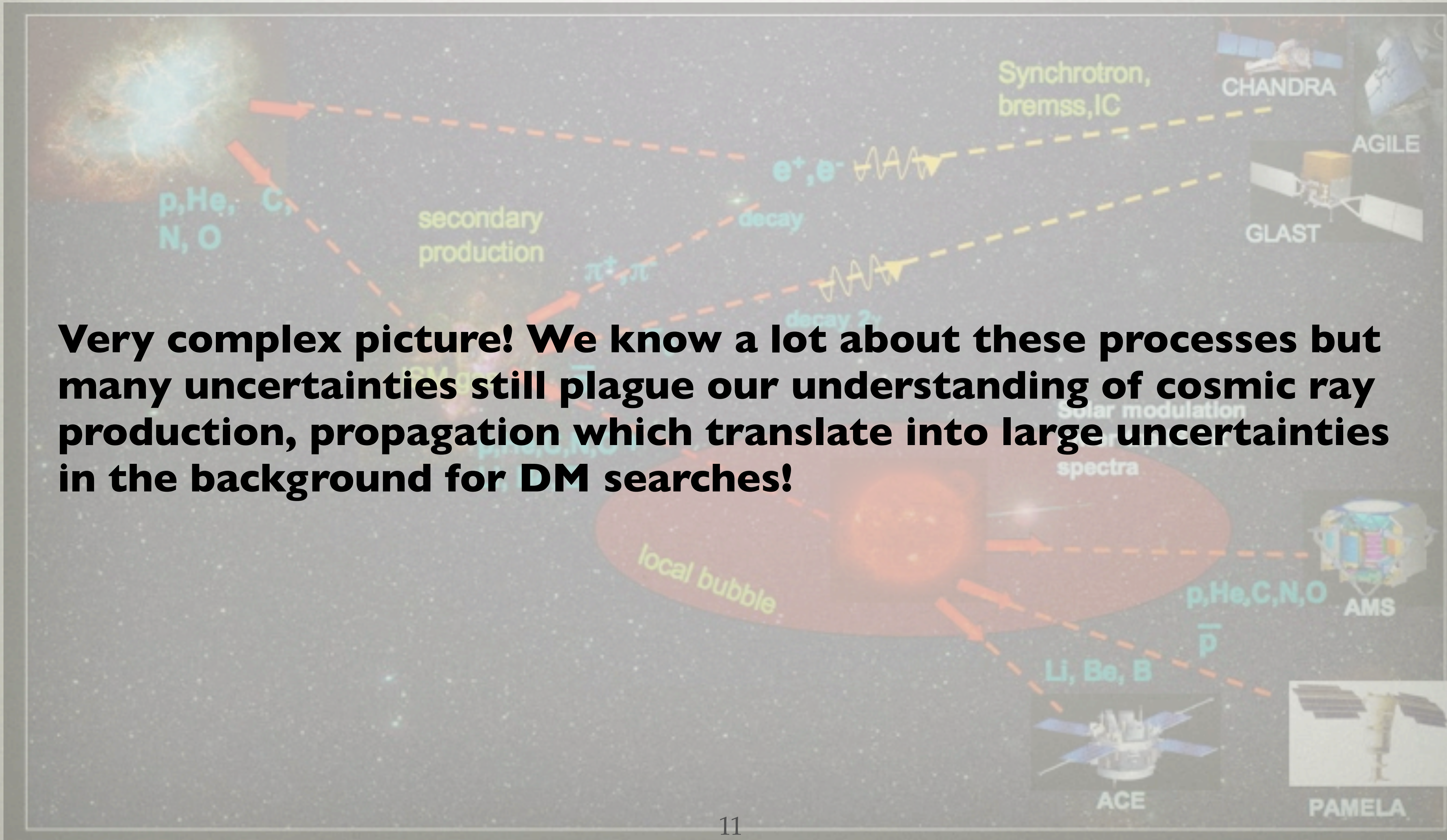


Very complex picture! We know a lot about these processes but many uncertainties still plague our understanding of cosmic ray production, propagation which translate into large uncertainties in the background for DM searches!

WIMP Annihilation(or Decay) Signal

- E.g. photons from DM annihilation:

particle physics

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

DM distribution

For DM decay:

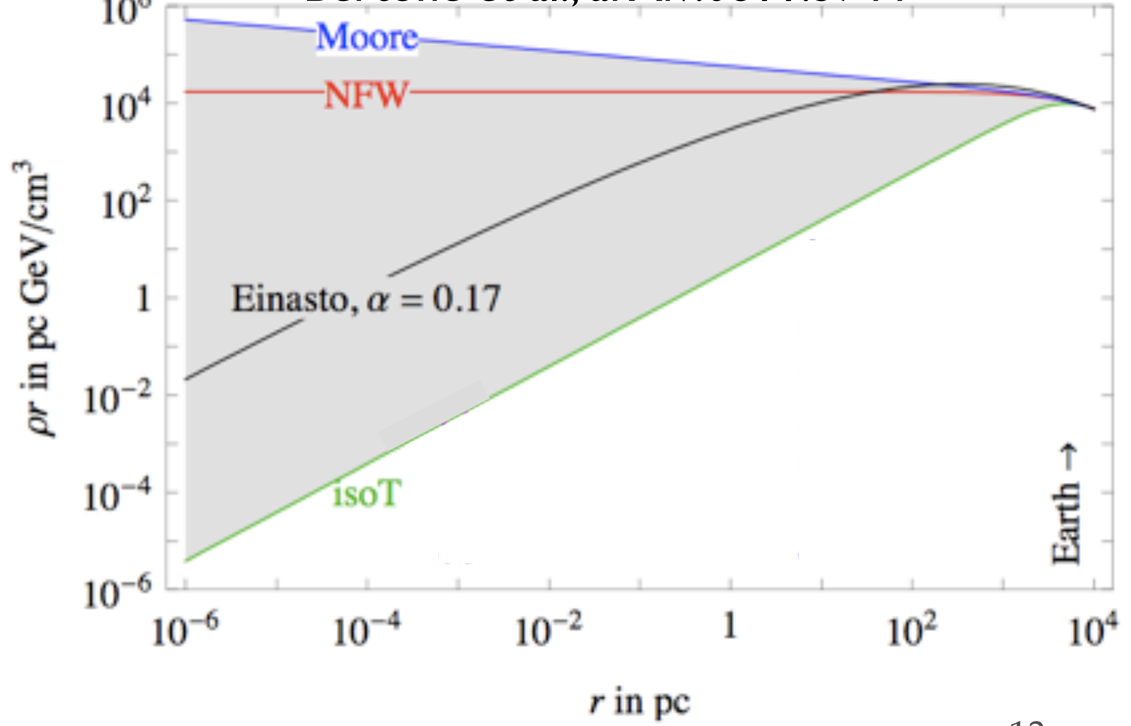
- $<\sigma_{ann}v>/2m^2_{WIMP} \to 1/\tau m_{WIMP}$
- $\varrho^2 \to \varrho$

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

Dark Matter Distribution

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

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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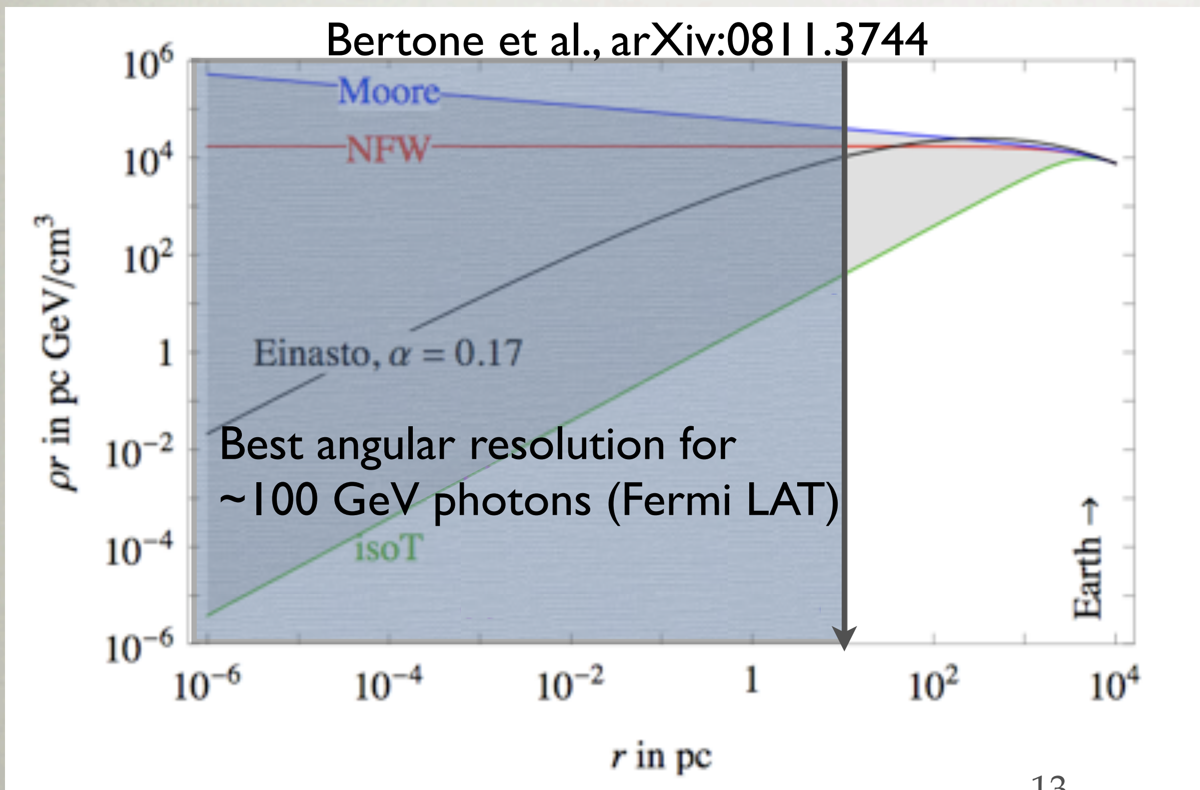

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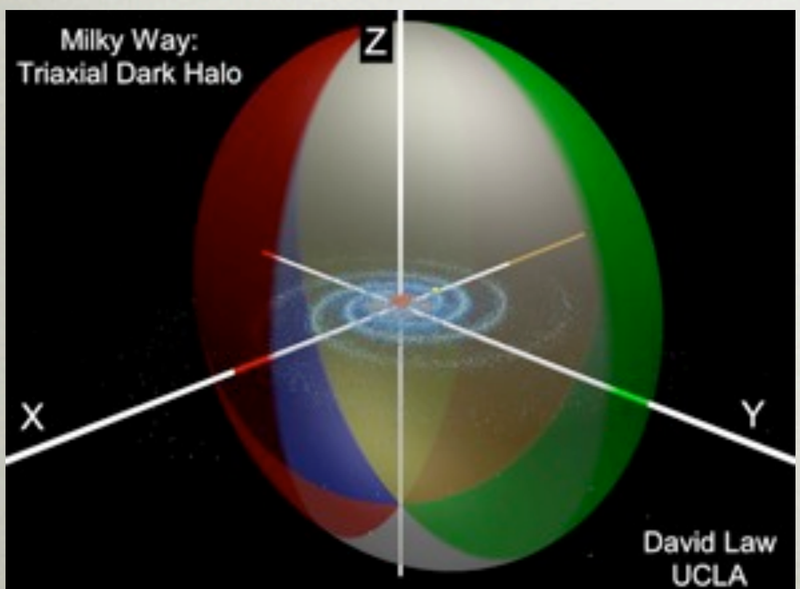
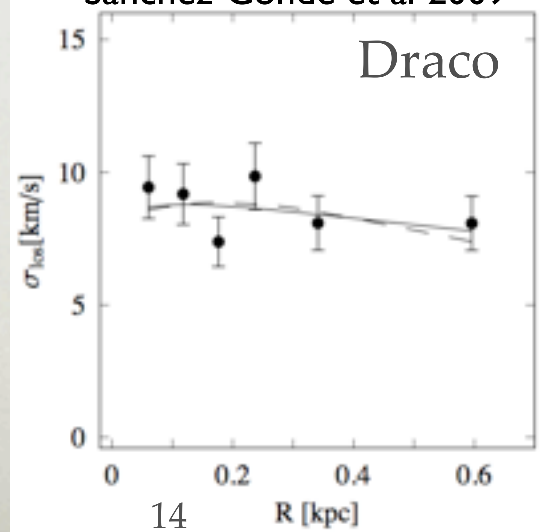
Dark Matter Distribution

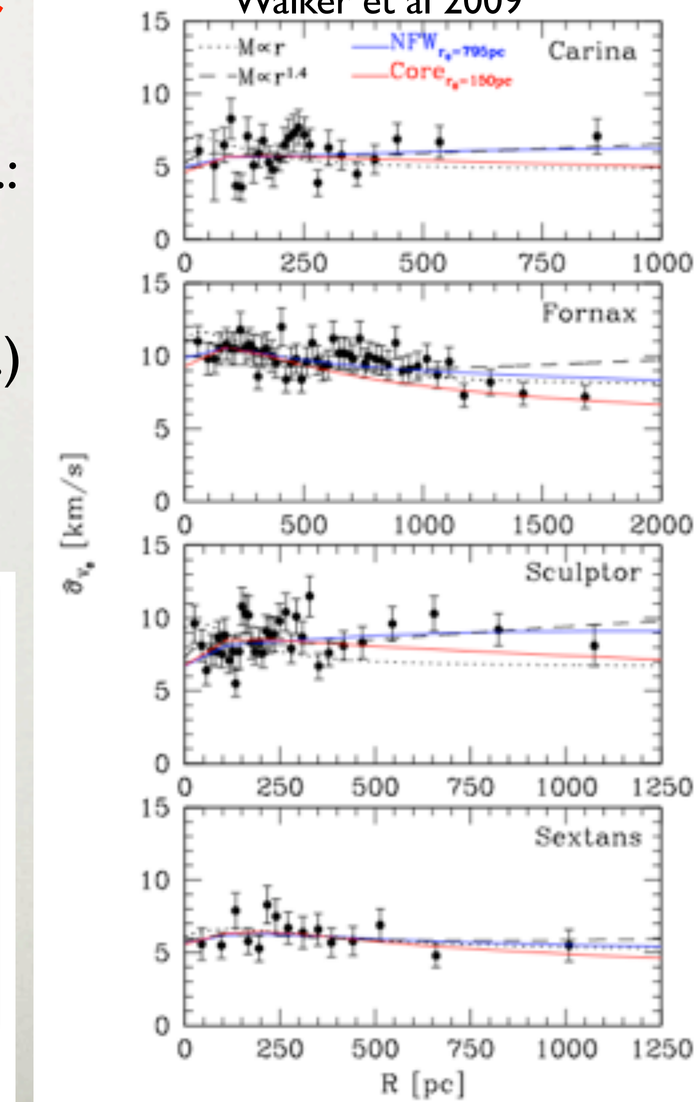
- We generally heavily rely on simulations of the dark matter distribution to make predictions for DM searches...
- ... but much is still unknown on how DM is distributed, e.g.:
  - cuspiness of the profile
  - halo shape (spherical, prolate, oblate, triaxial, dark disk, ...)
  - substructure



Sanchez-Conde et al 2009

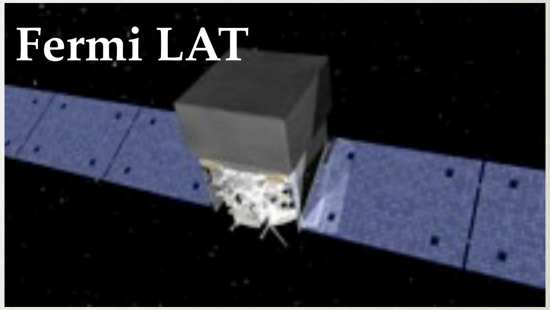


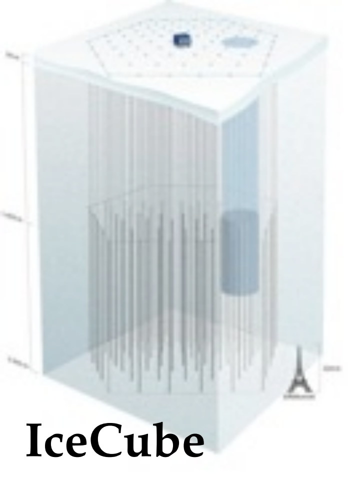
Walker et al 2009



EXPERIMENTS

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



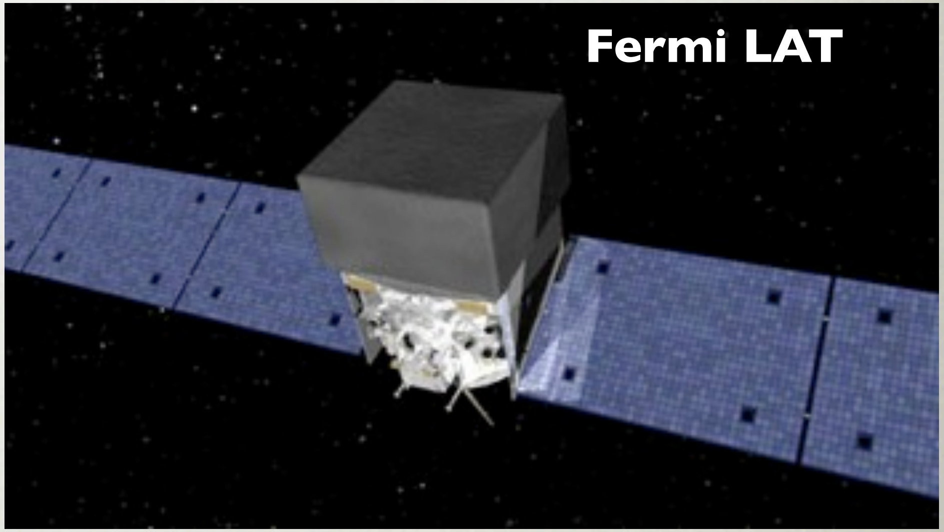


Gamma rays

ON THE GROUND

IN SPACE

Atmospheric Cherenkov Telescopes (ACTs)

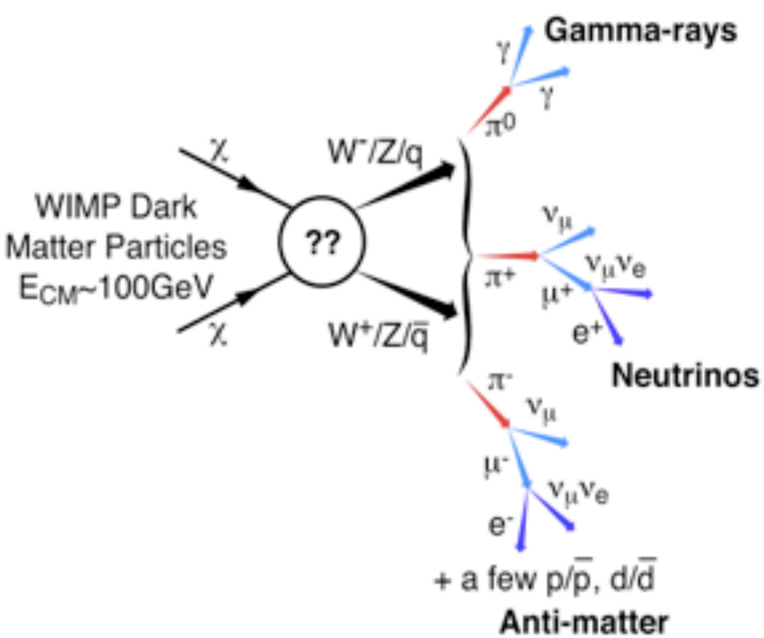


WIMP Dark Matter Spectrum

- Predicted gamma ray spectrum from WIMP annihilation

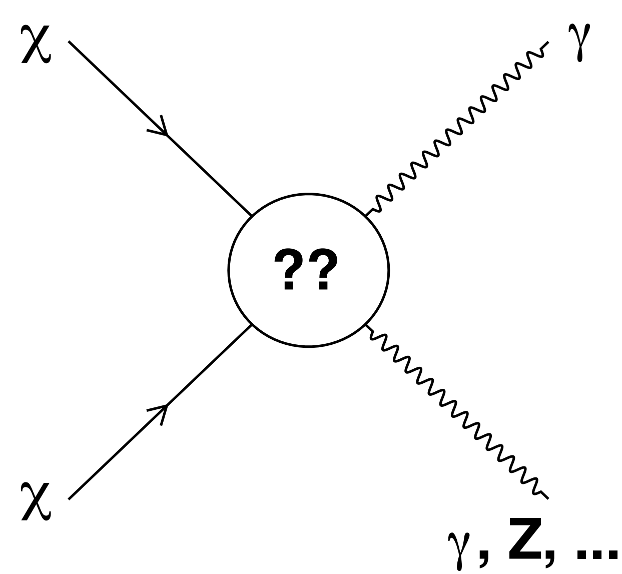
Continuum spectrum with cutoff at M_{DM}

Annihilation (or decay) into γ



Spectral line

Prompt annihilation into γγ, γZ, γH^0...
(also prompt decay into photons)



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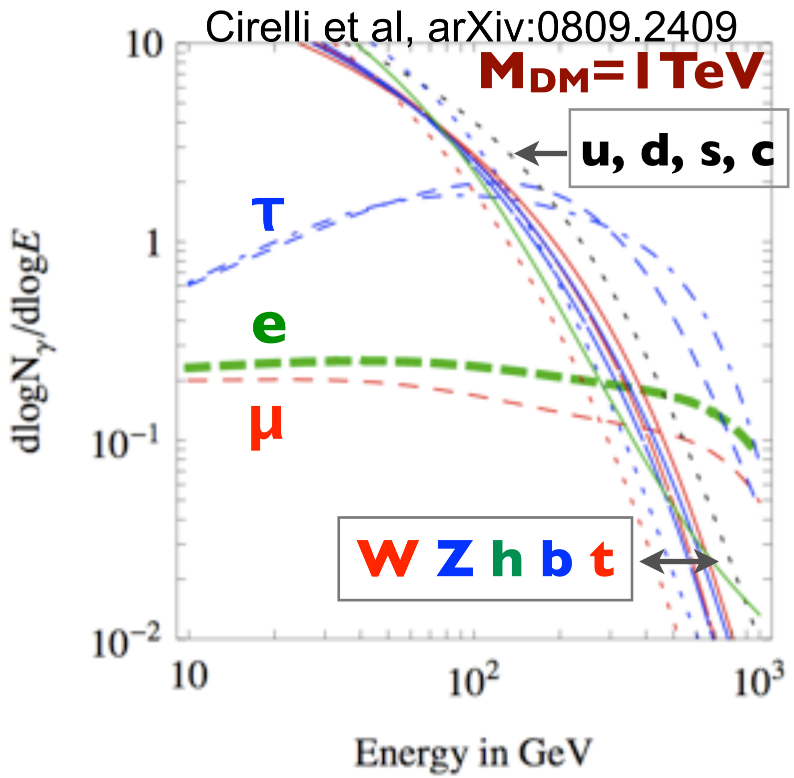

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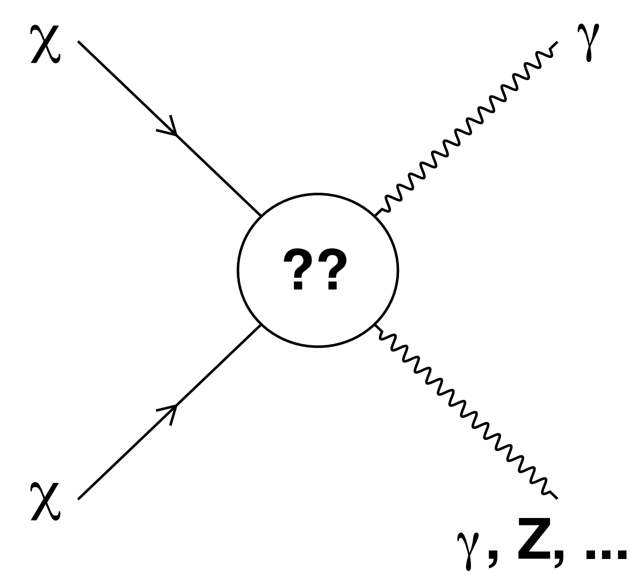

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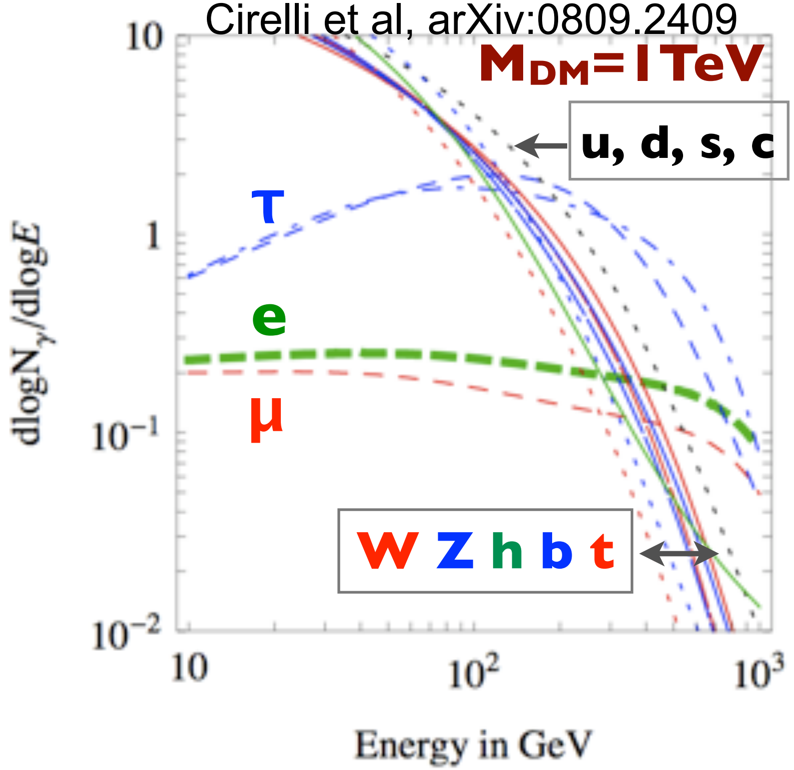

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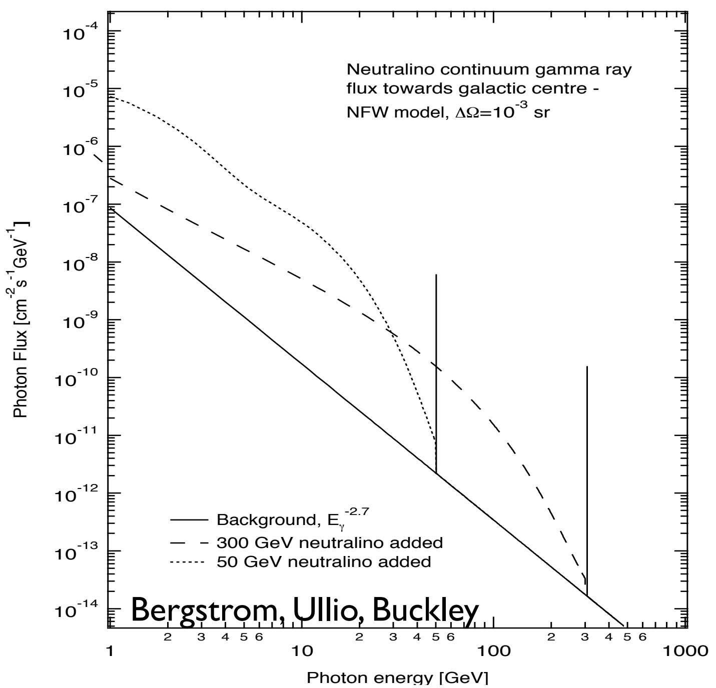

Indirect Detection Results - Gamma Ray

$$\frac{d\Phi_\gamma}{dE_\gamma}(E_\gamma,\phi,\theta) = \boxed{\frac{1}{4\pi}\frac{<\sigma_{ann}v>}{2m^2_{WIMP}}\sum_f \frac{dN^f_\gamma}{dE_\gamma}B_f}$$
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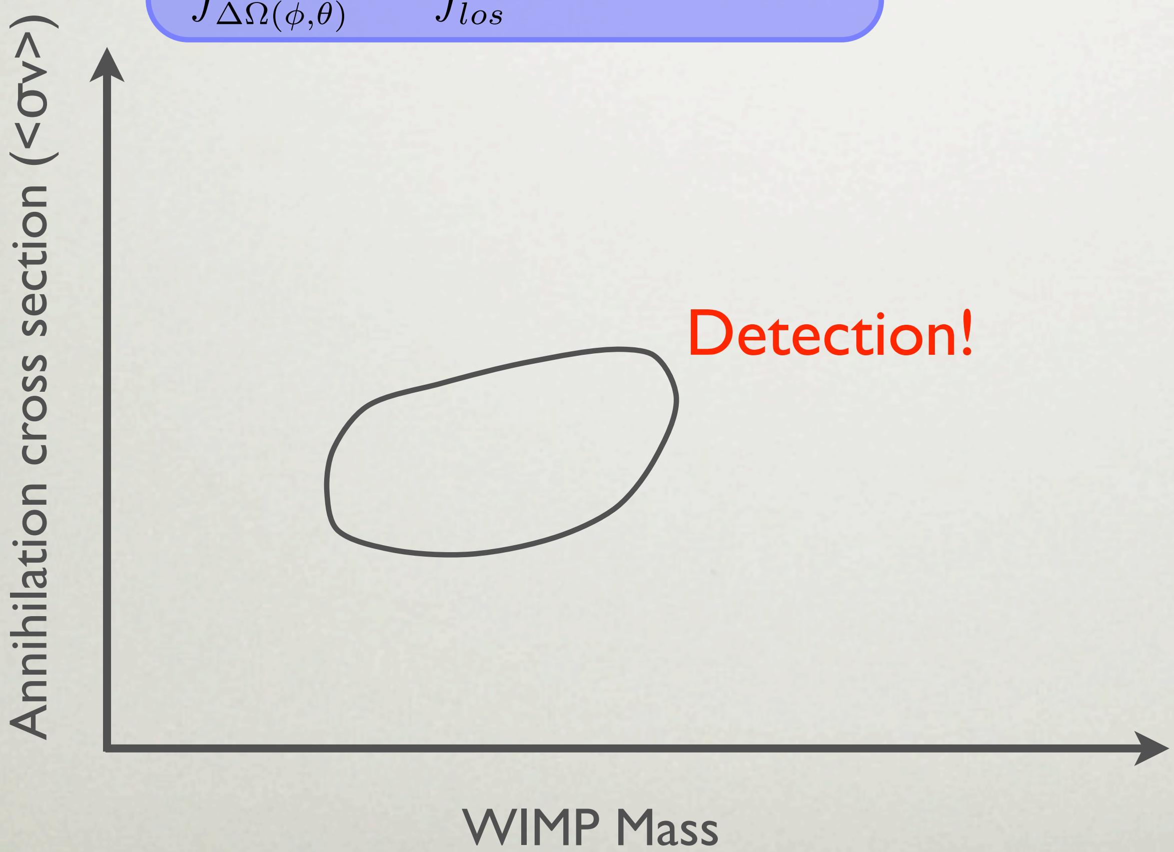

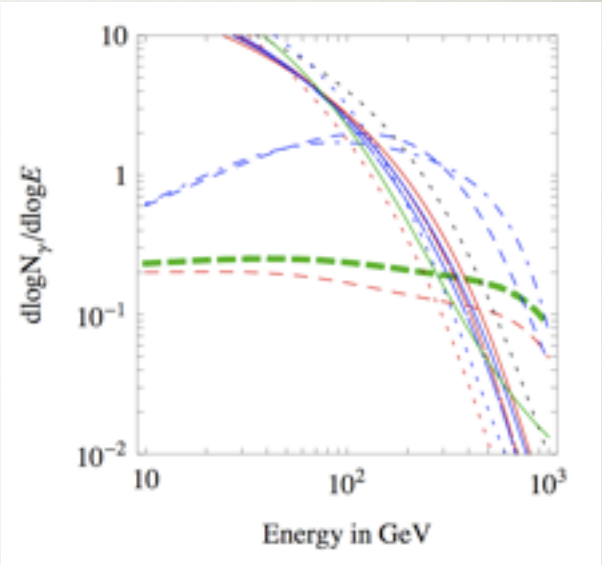

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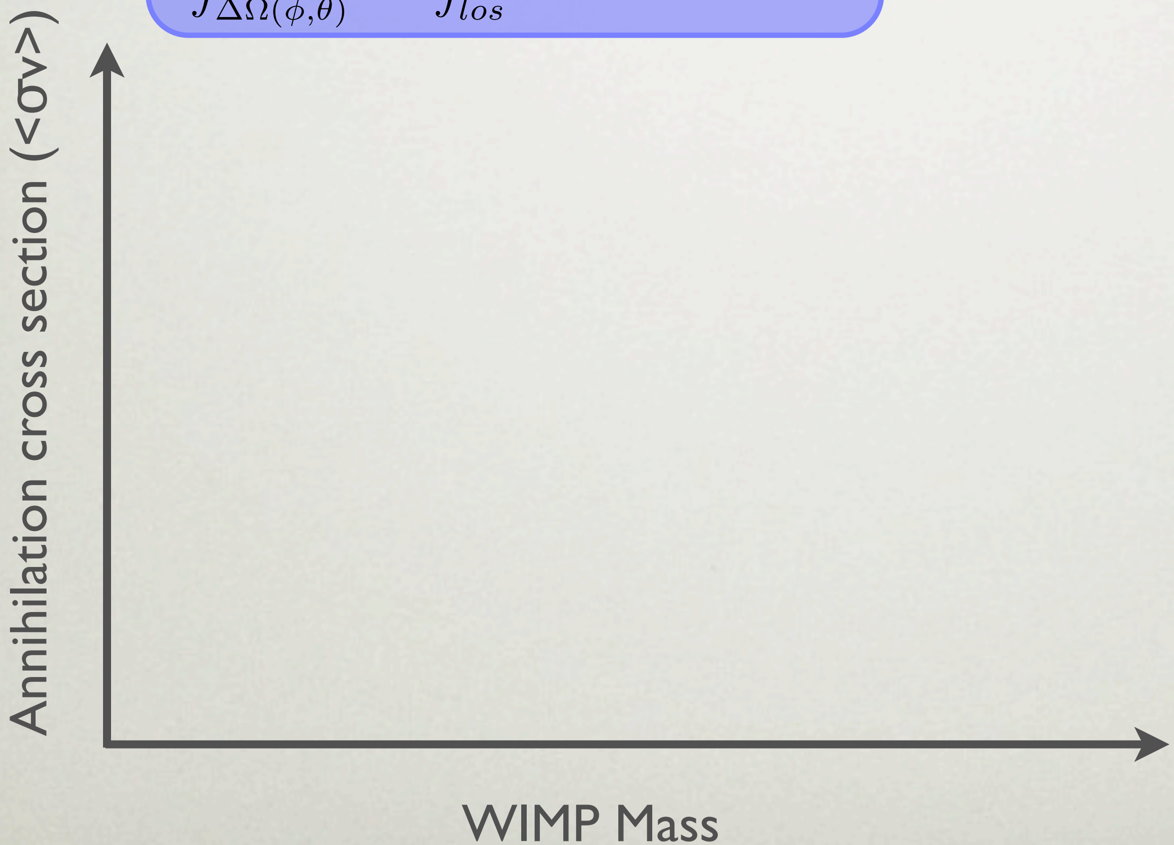

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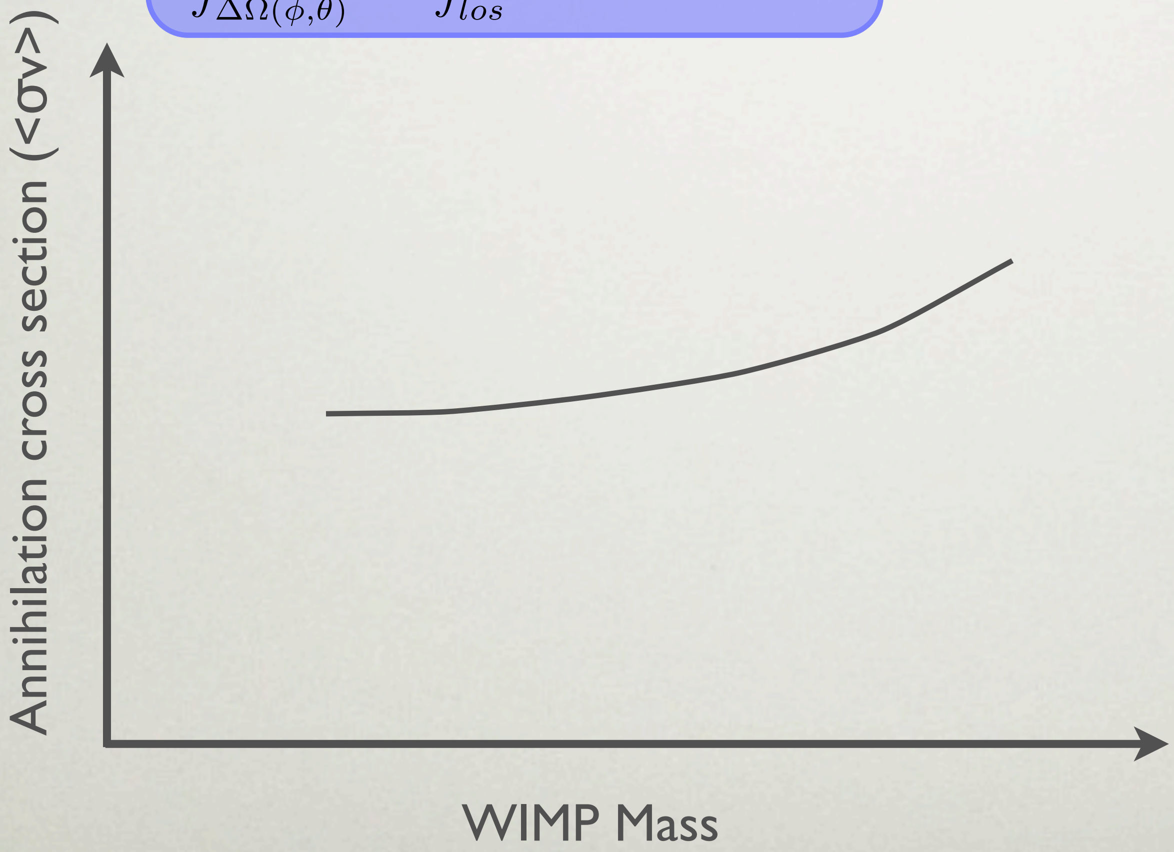

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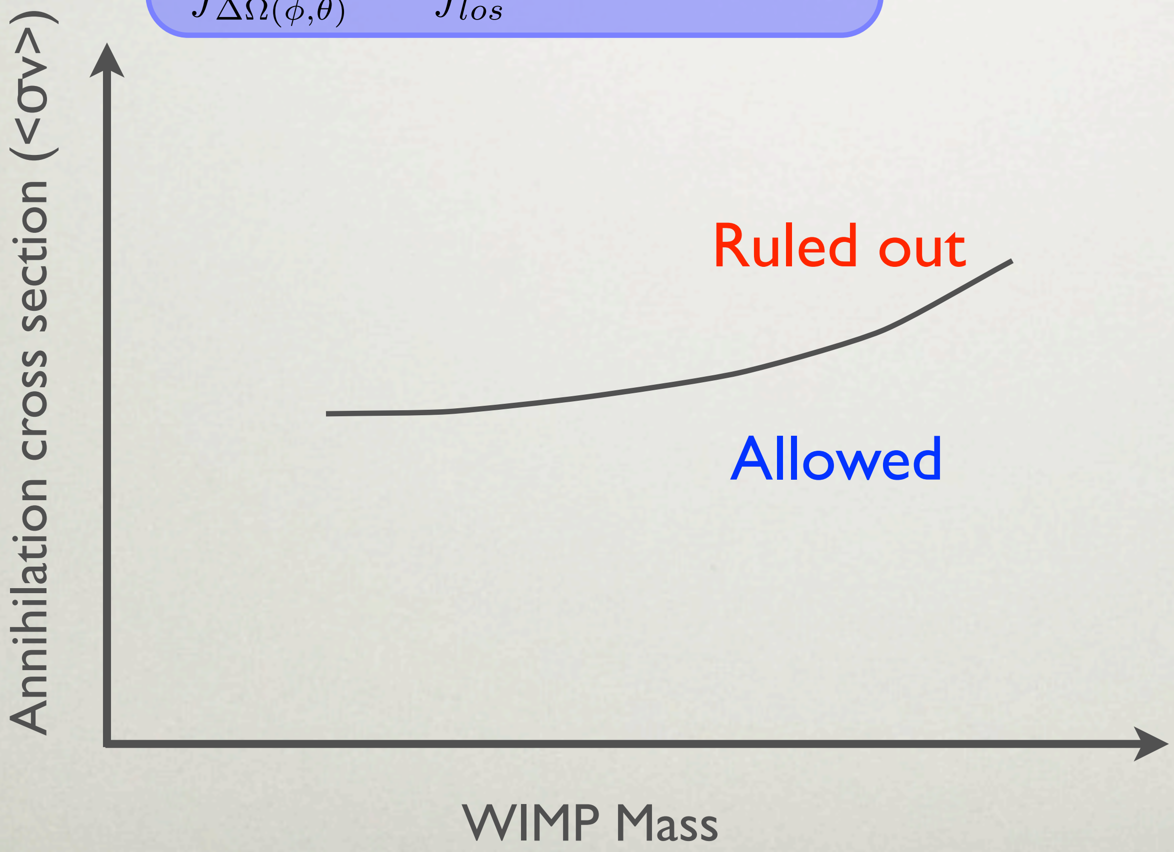

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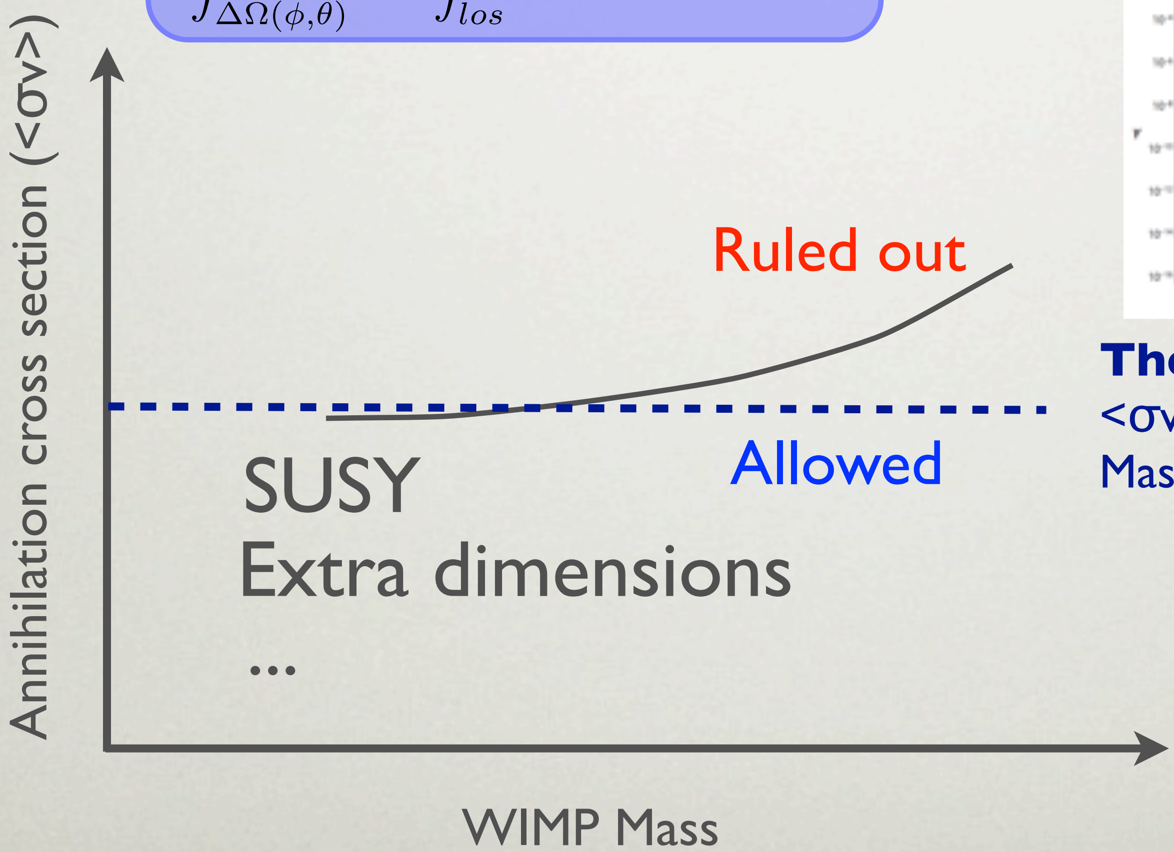
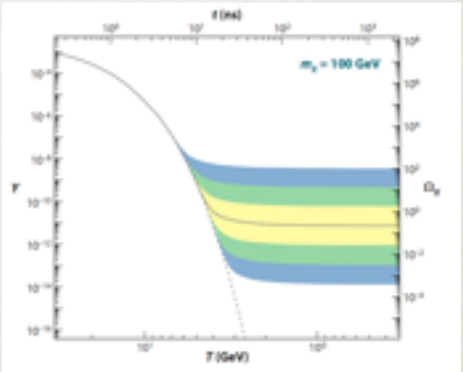
$$\frac{d\Phi_\gamma}{dE_\gamma}(E_\gamma,\phi,\theta) = \frac{1}{4\pi}\frac{<\sigma_{ann}v>}{2m^2_{WIMP}}\sum_f \frac{dN^f_\gamma}{dE_\gamma}B_f \times \int_{\Delta\Omega(\phi,\theta)} d\Omega' \int_{los}\rho^2(r(l,\phi'))dl(r,\phi')$$





Thermal WIMP

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

Mass of order100 GeV

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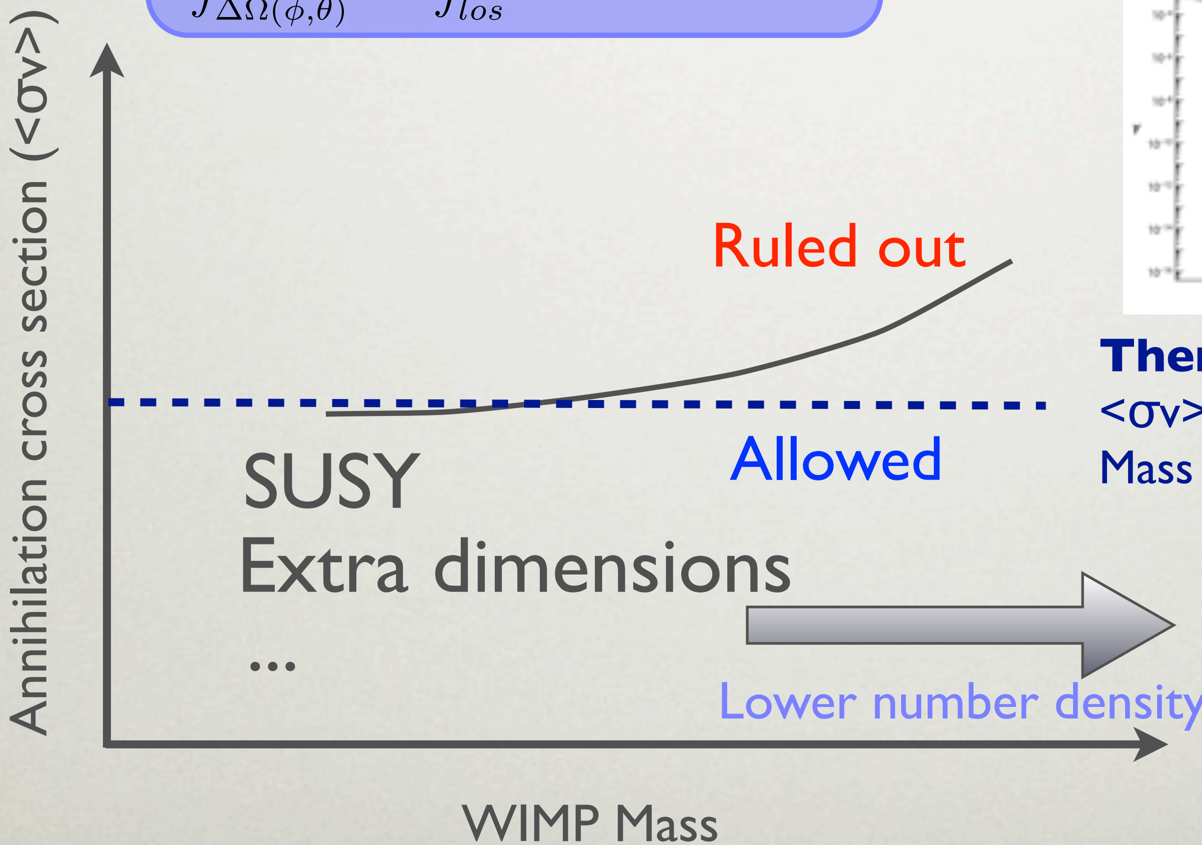
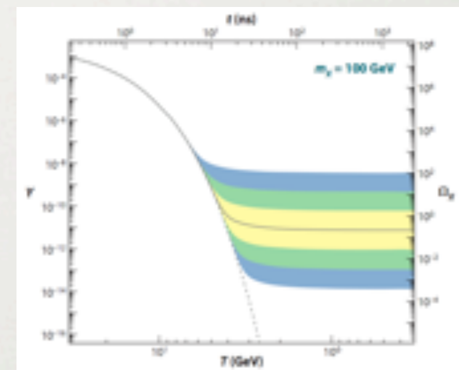


$$n = \frac{\rho}{M_{WIMP}}$$



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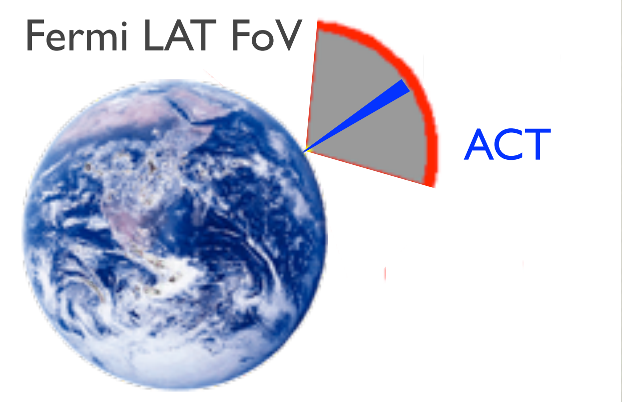
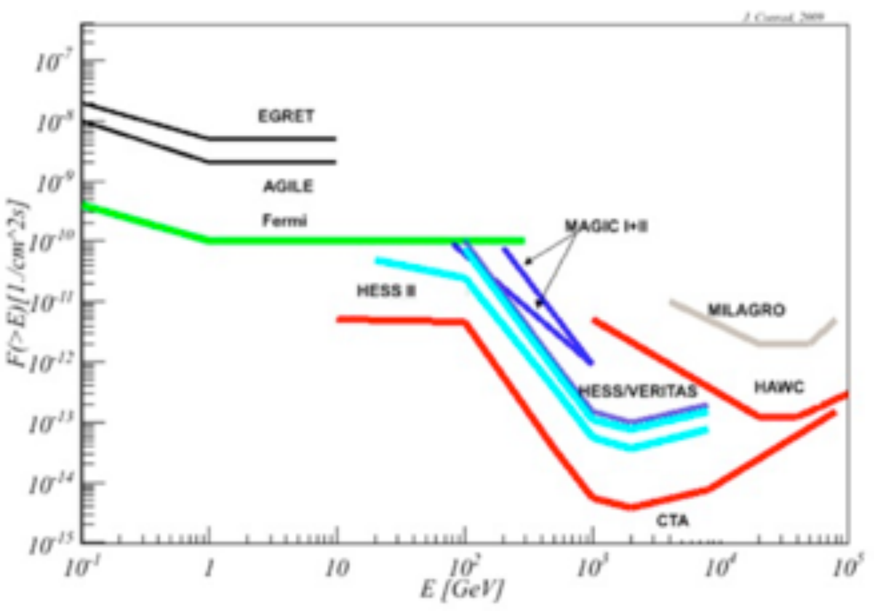
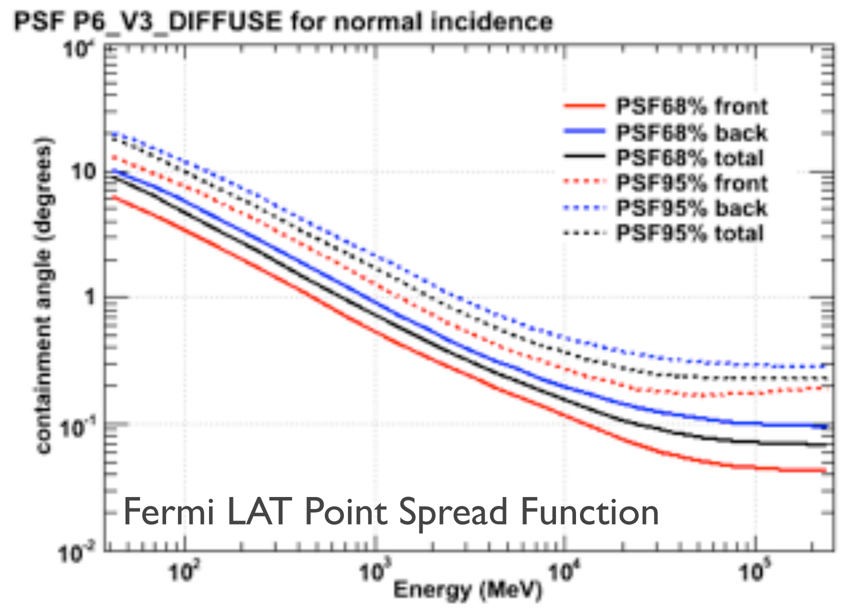
GROUND VS SPACE GAMMA RAY EXPERIMENTS

- Lower energy thresholds accessible in space, and up to ~100 TeV energies with experiments 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)







Very High Energy γ-rays

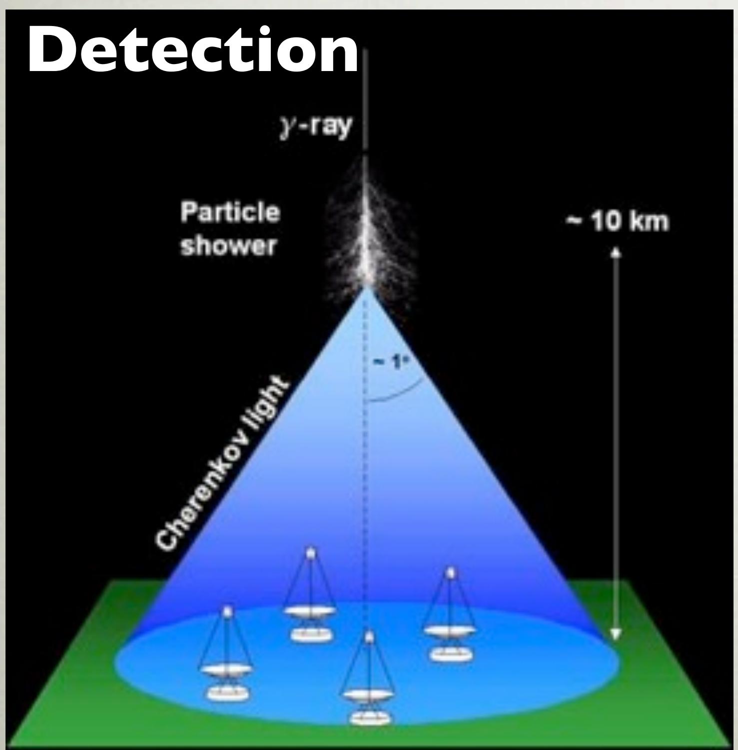
Imaging Atmospheric Cherenkov Telescopes (IACTs)

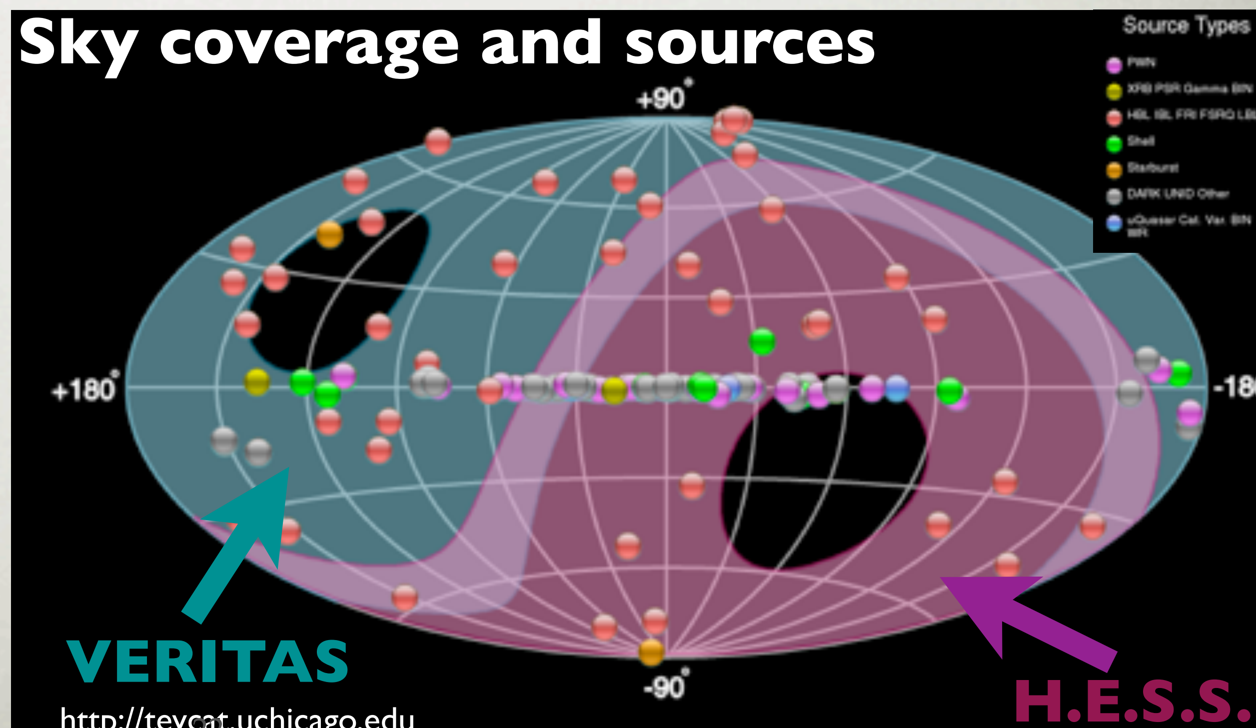
ACTs: Performance

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: 0.1 - 100 TeV
Angular resolution: ~ 0.1°
Energy resolution: ~15-20%
Field of view: ~5°
Sensitivity: 1% Crab flux in 25h

MAGIC
Energy range: 25 GeV - 10s TeV
Angular resolution: ~0.1 °
Energy resolution: ~15%
Field of view: ~3.5°
Sensitivity: 1% Crab flux in 50h



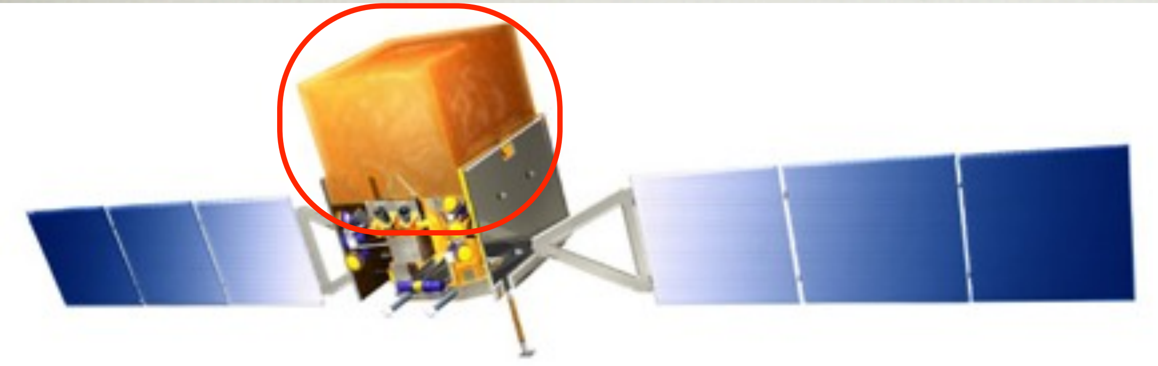


Fermi LAT

- 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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Launch (June 2008)

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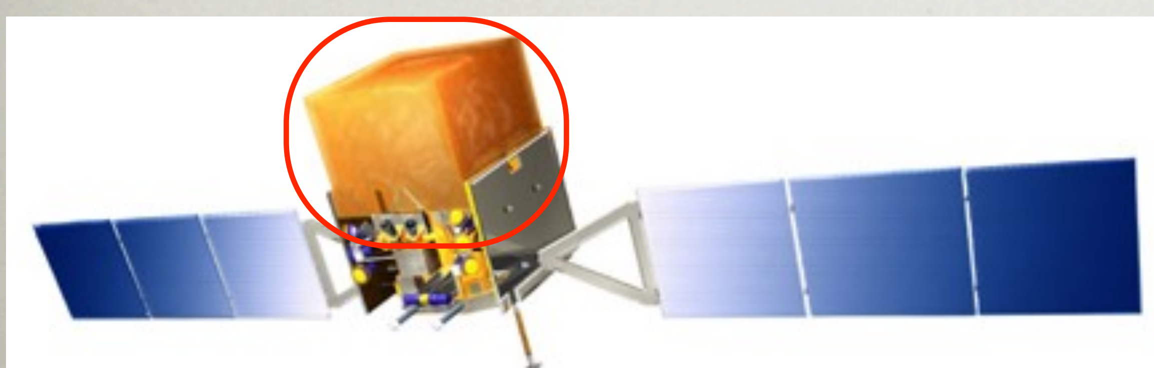
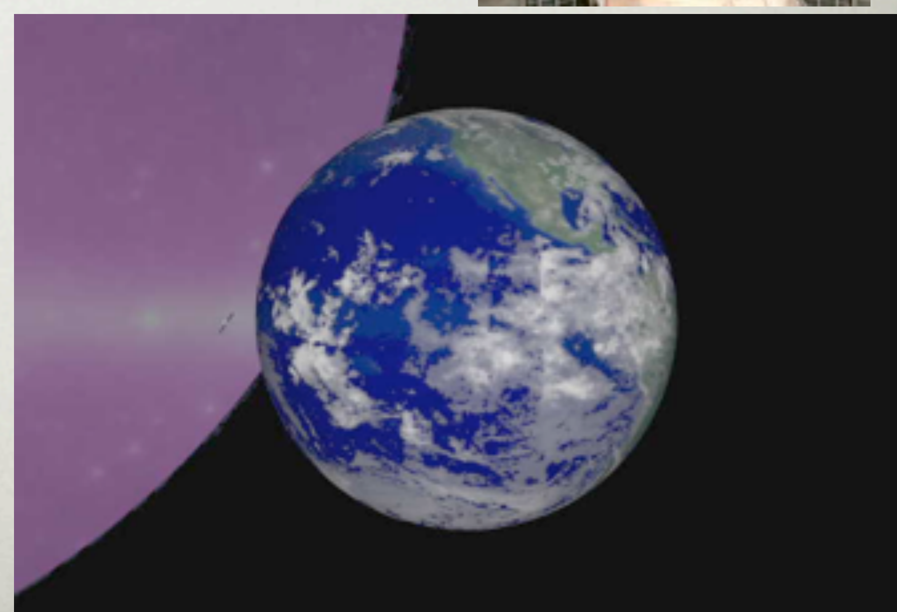
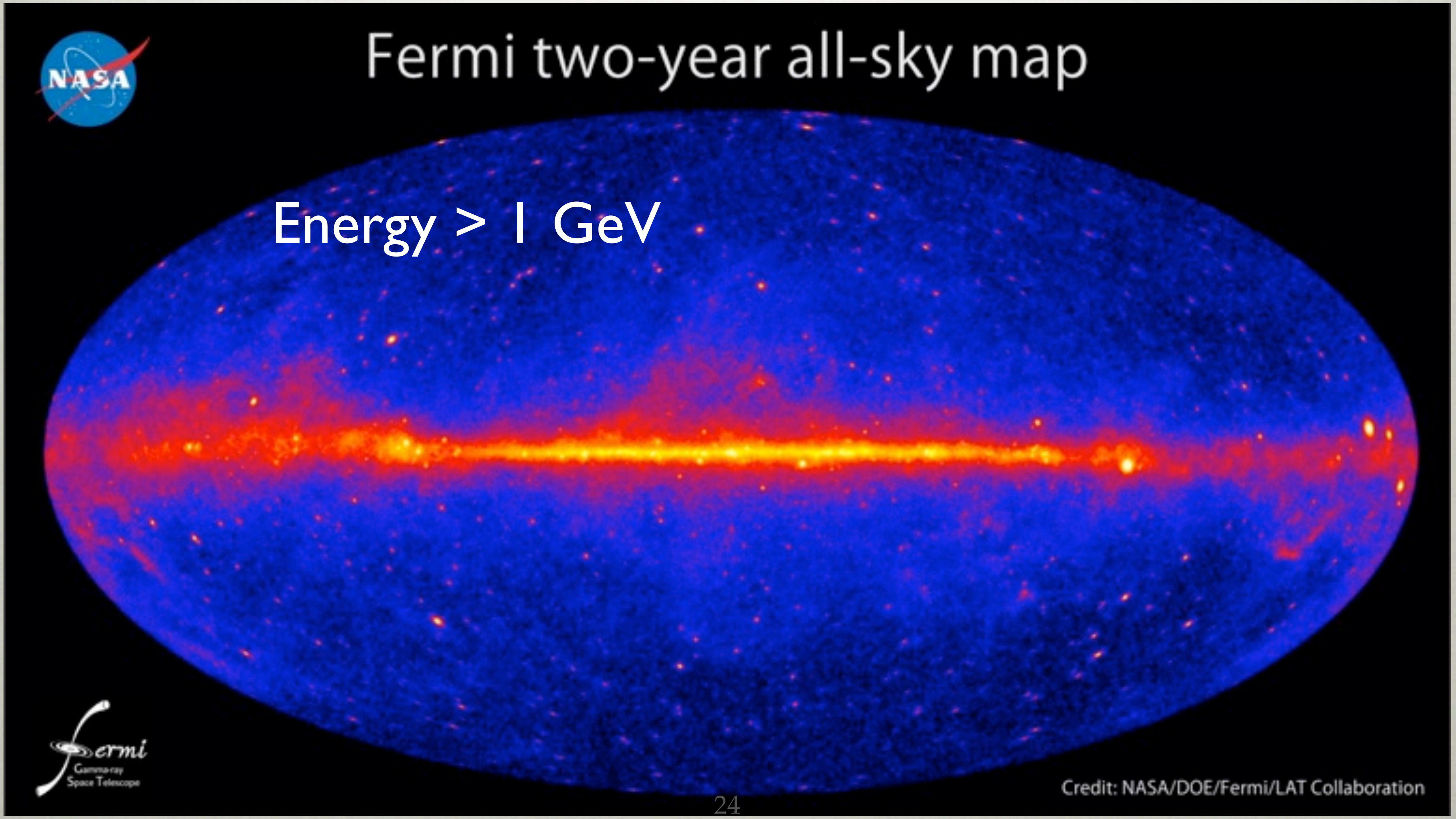
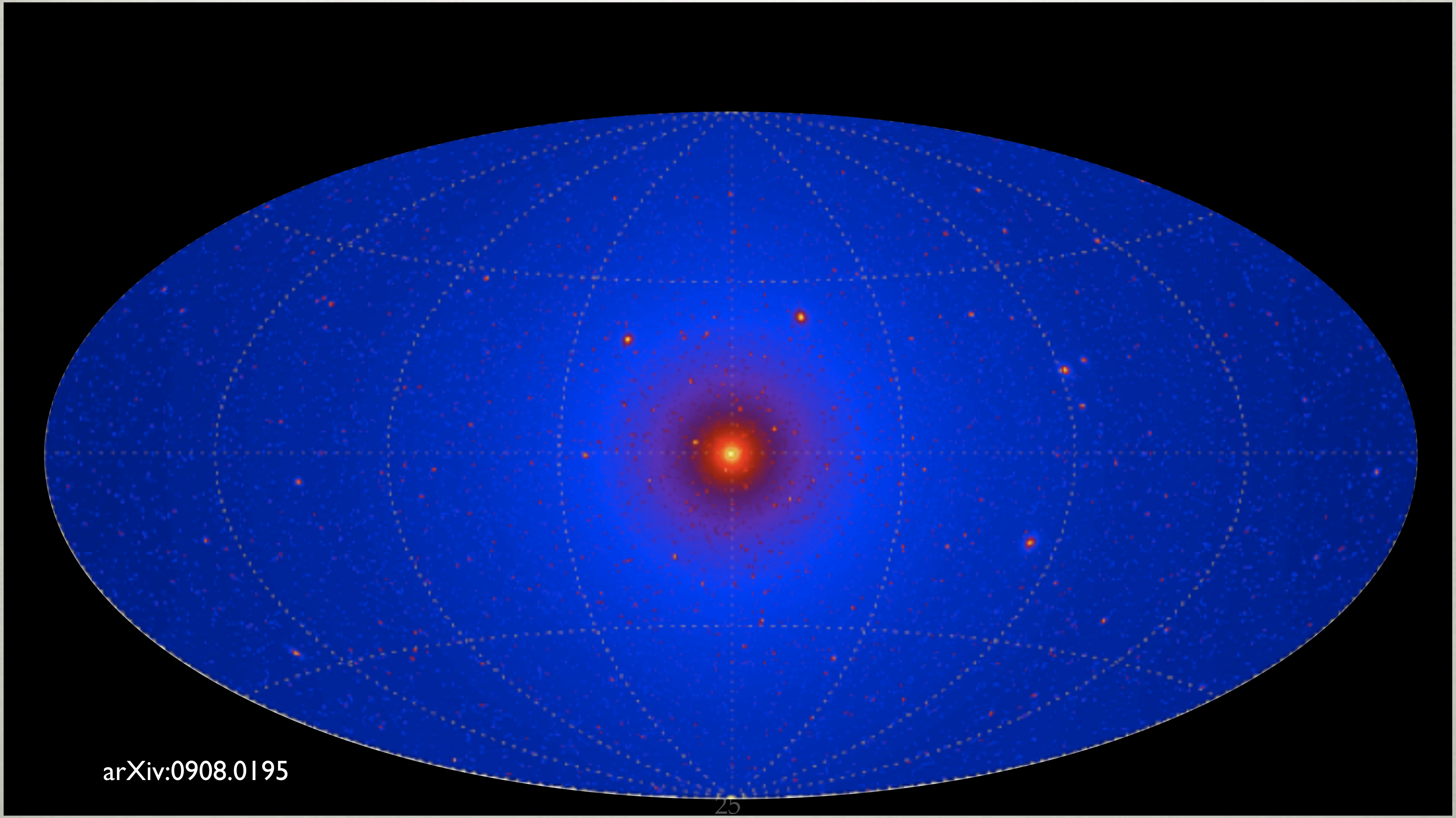




The Fermi Sky



Gamma rays from DM Annihilation



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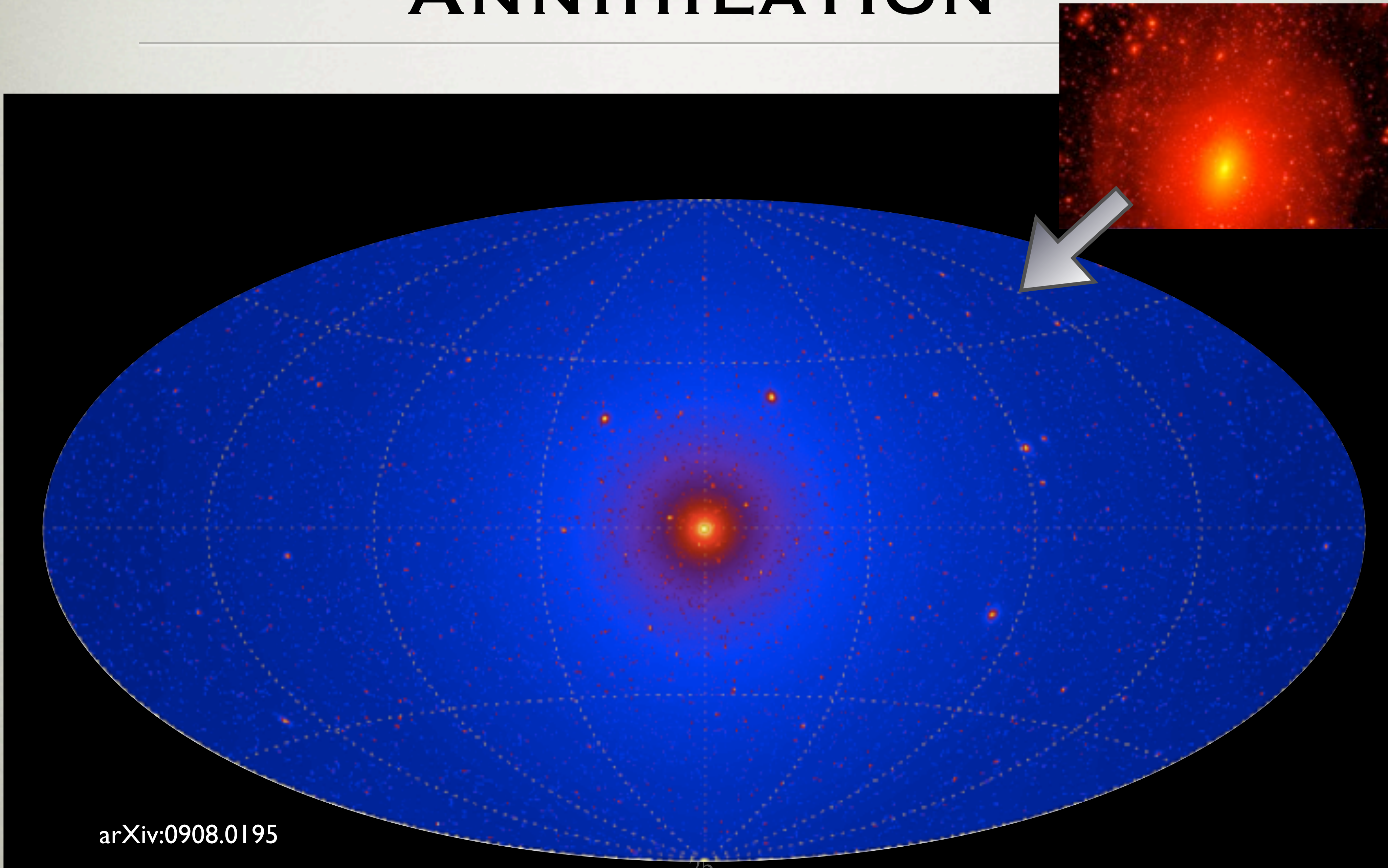
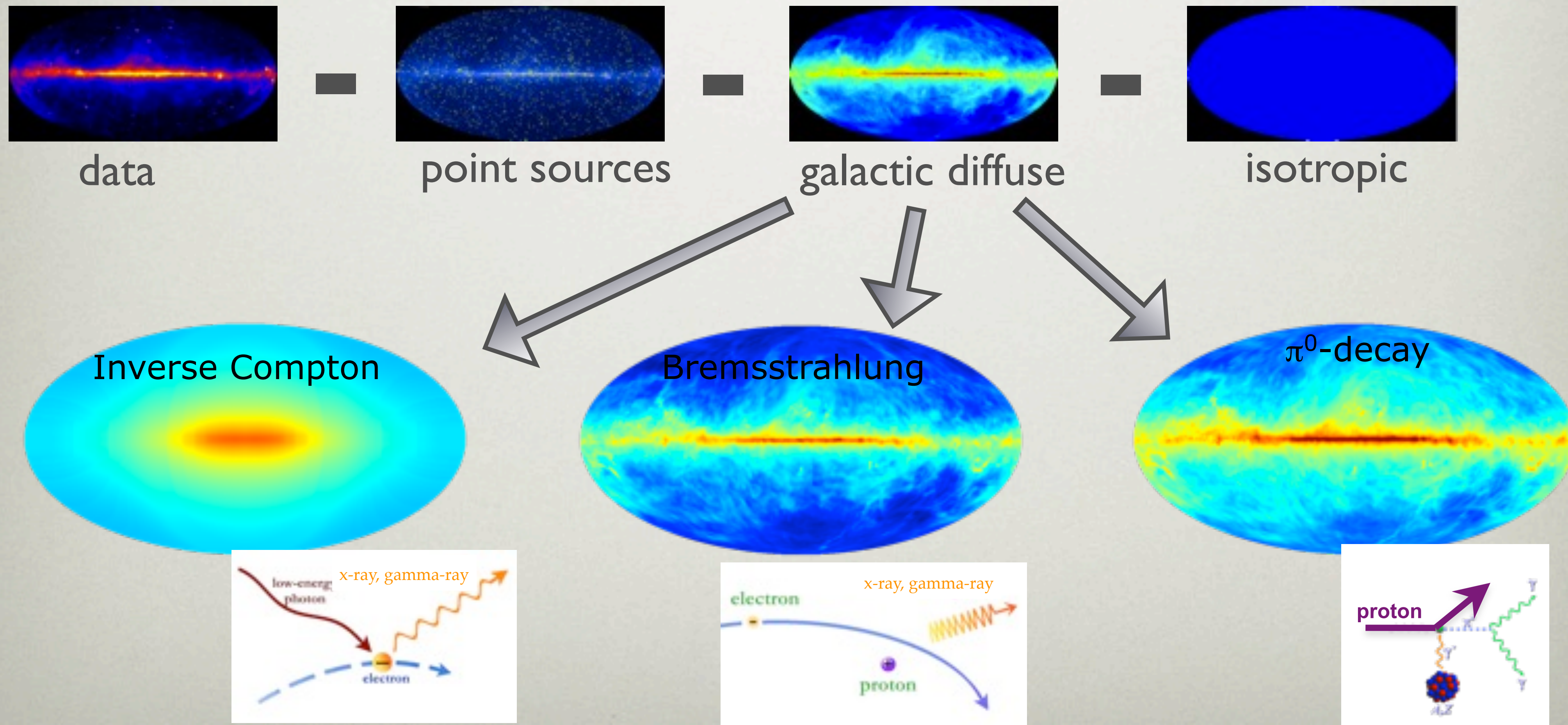


Understanding Fermi's Gamma-ray Sky

- 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.
- Cosmic ray propagation parameters and properties of the interstellar medium can be constrained by comparing the data to predictions.



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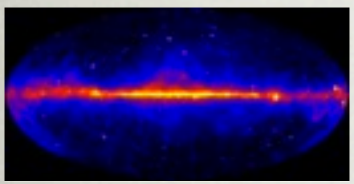
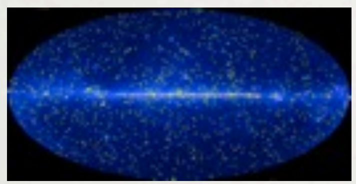


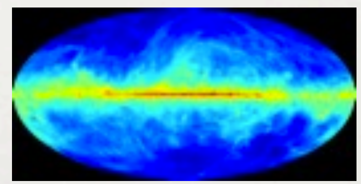
data

-



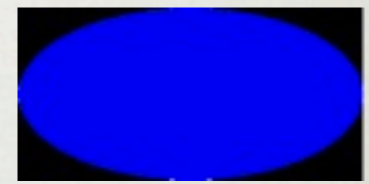
point sources

-



galactic diffuse

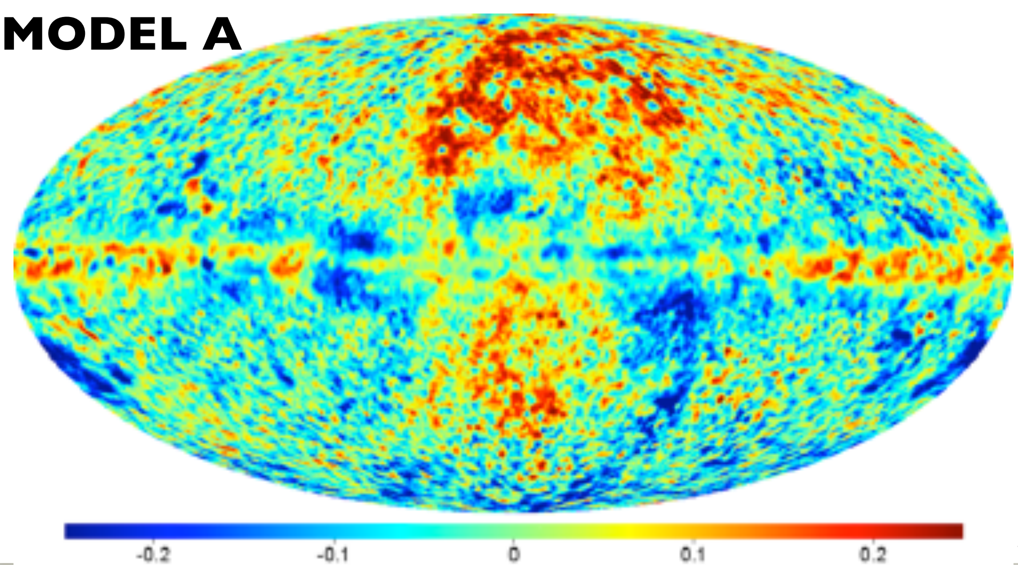
-



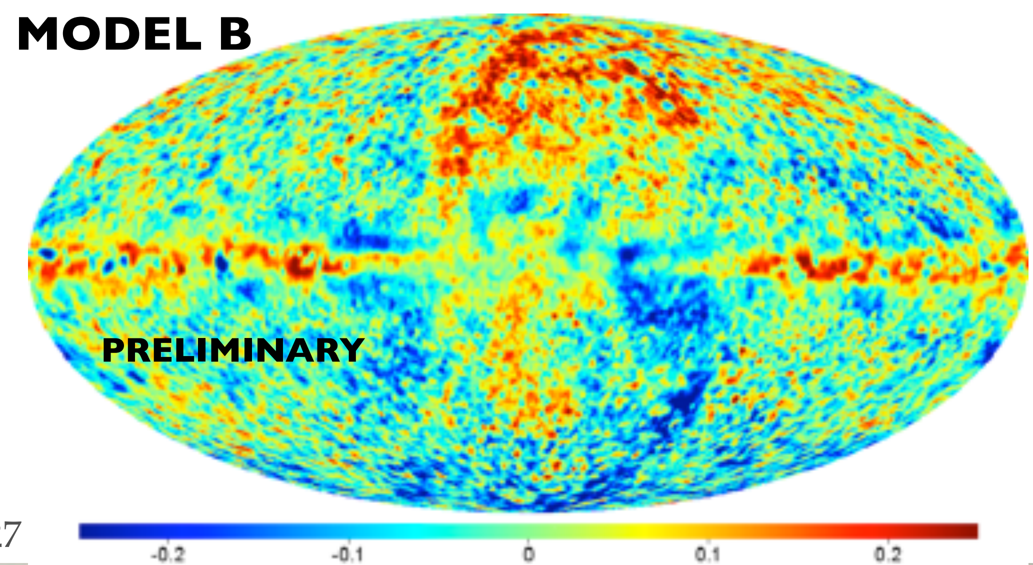
isotropic

Residual maps ((Fermi data - prediction)/prediction) for 2 example models

MODEL A



MODEL B



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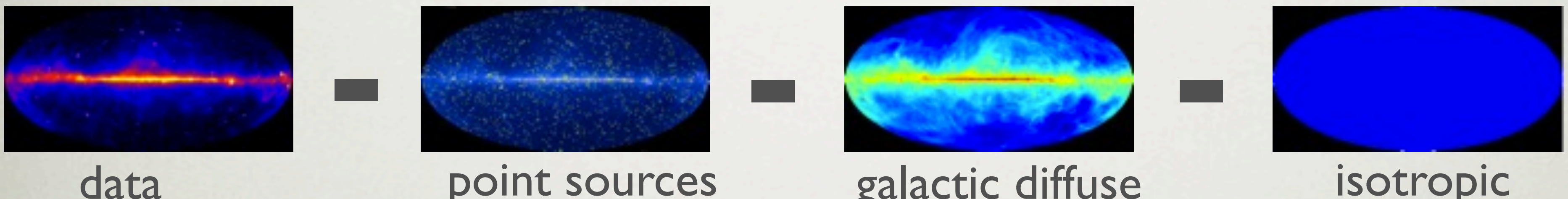
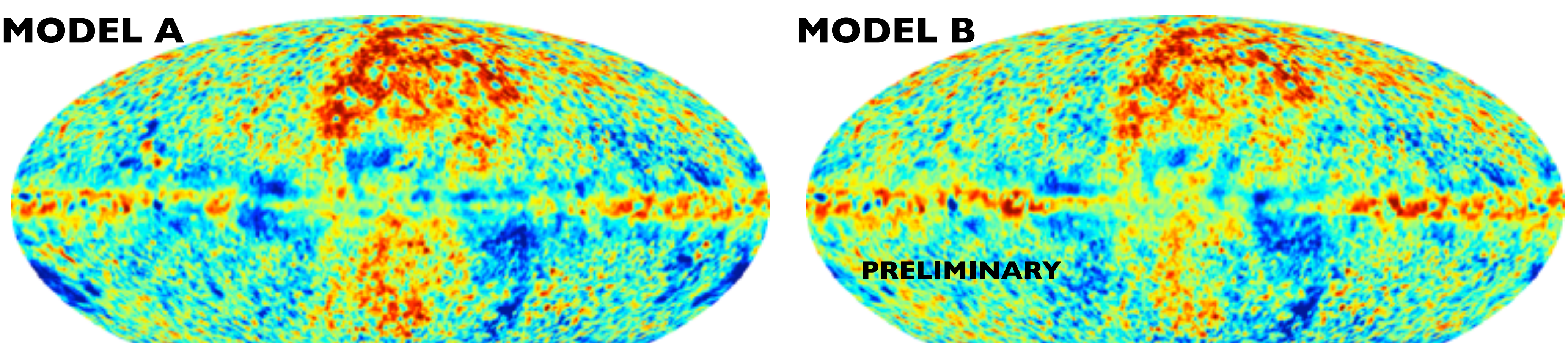


Residual maps ((Fermi data - prediction)/prediction) for 2 example models



➡ **On a large scale the agreement between data and predictions is overall good, however some extended excesses (and deficits) stand out. Under investigation!**

Understanding Fermi's Gamma-ray Sky

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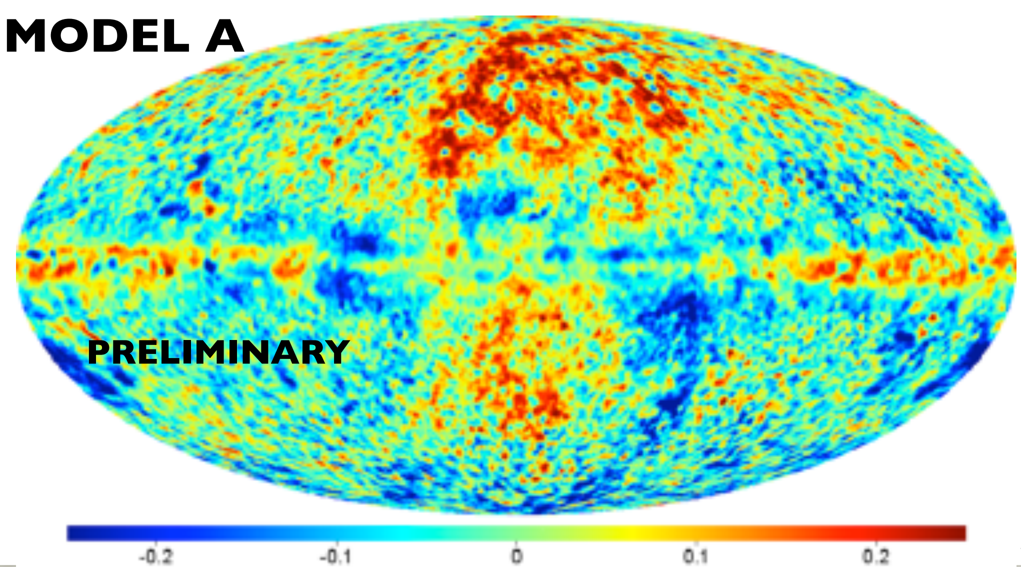
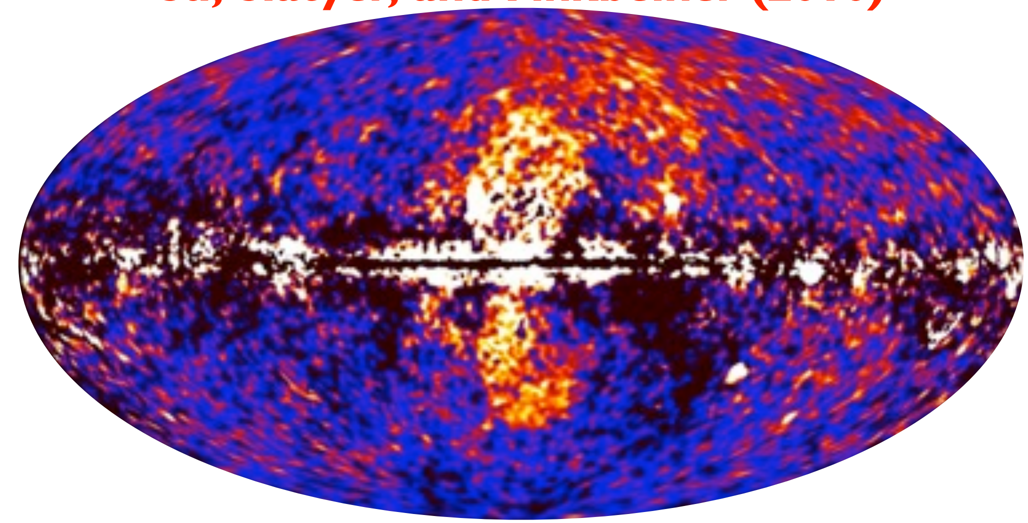
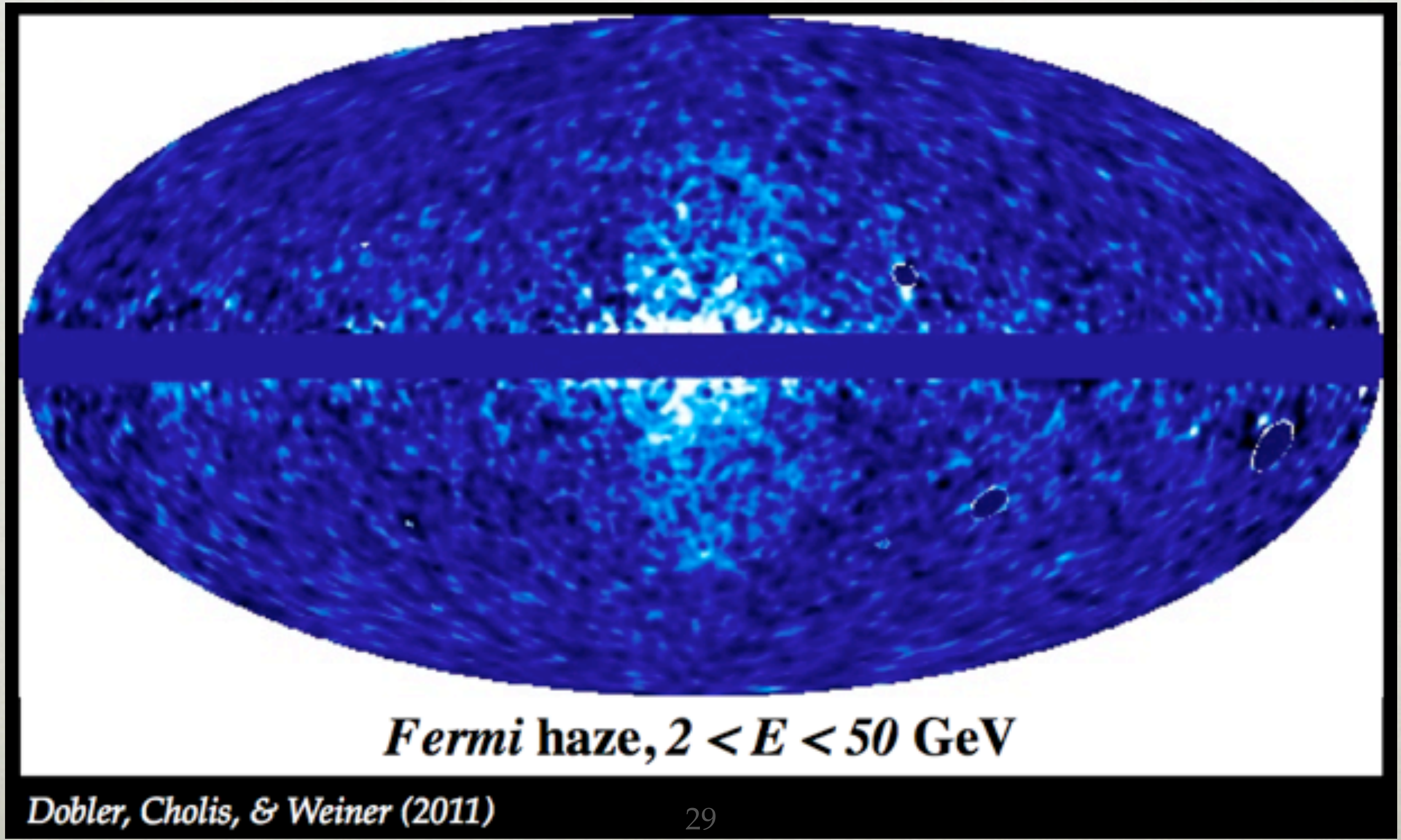




"Gamma-ray Lobes"
Su, Slatyer, and Finkbeiner (2010)

Could it be Dark Matter?



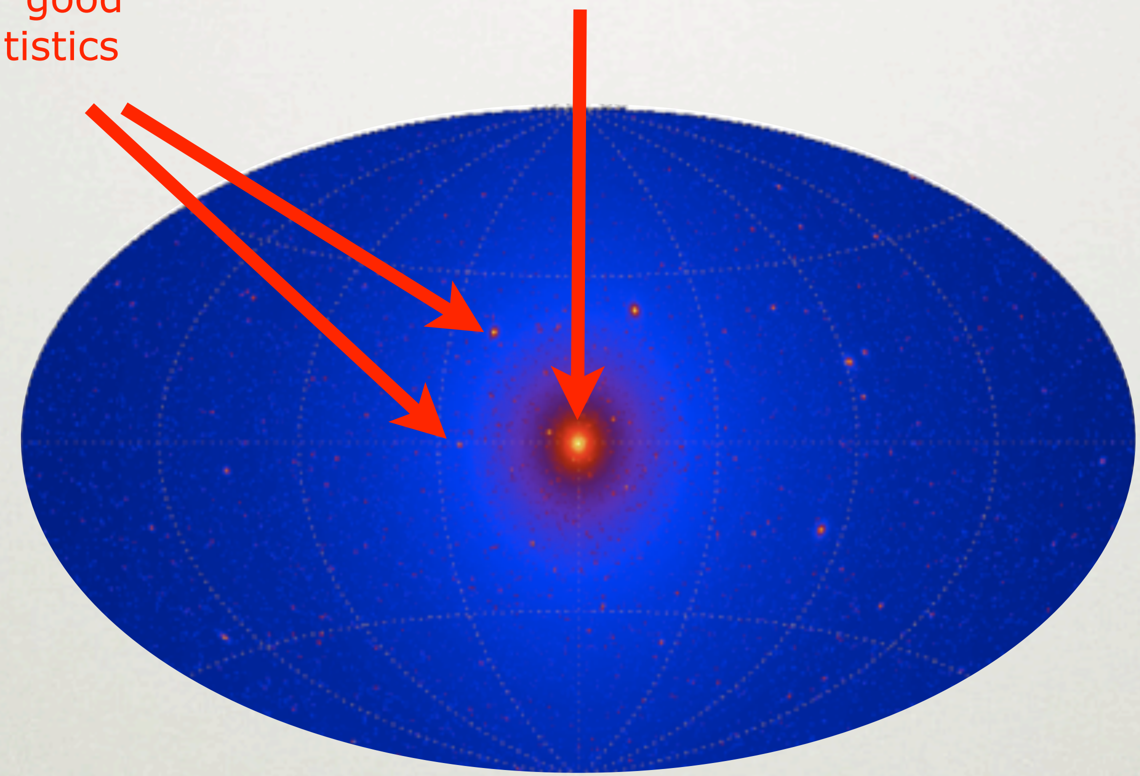
More on Fermi DM searches on monday
(Alex Drlica-Wagner's talk)

Search Strategies

Galactic center:
Good statistics but source confusion/diffuse background

Satellites:
Low background and good source ID, but low statistics

Milky Way halo:
Large statistics but diffuse background



All-sky map of gamma rays from DM annihilation arXiv:0908.0195 (based on Via Lactea II simulation)

+Electrons!

Anisotropies

Spectral lines:
No astrophysical uncertainties, good source ID, but low statistics

Galaxy clusters:
Low background but low statistics

Extragalactic:
Large statistics, but astrophysics, Galactic diffuse background

Pre-launch sensitivities published in Baltz et al., 2008, JCAP 0807:013 [astro-ph/0806.2911]

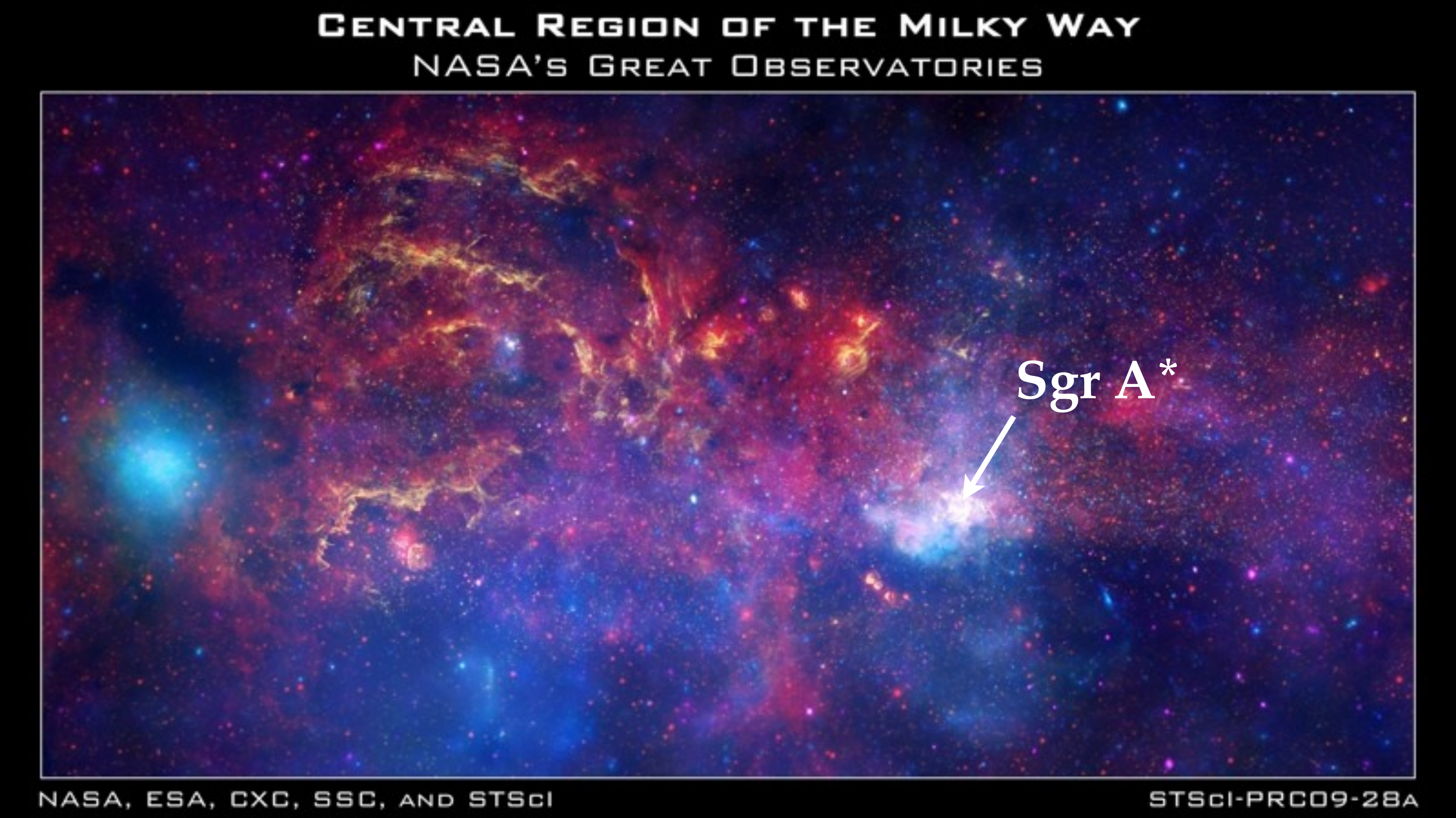


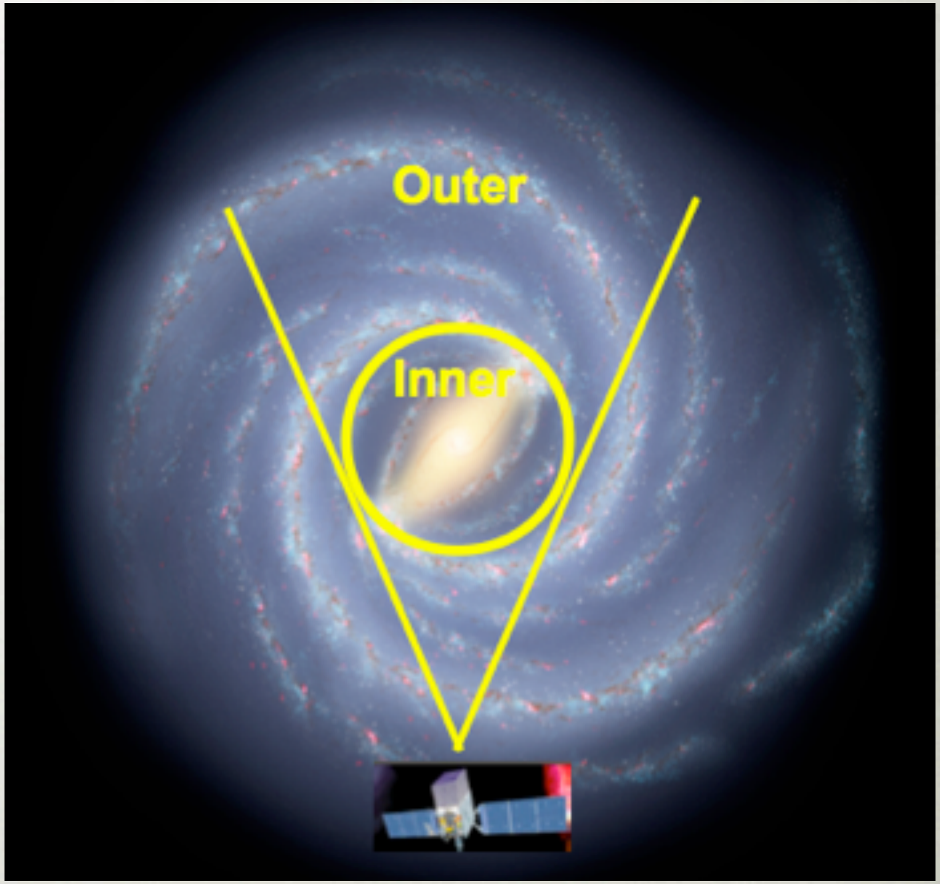
Image (width~0.5°) combines a near-infrared view from the Hubble Space Telescope (yellow), an infrared view from the Spitzer Space Telescope (red) and an X-ray view from the Chandra X-ray Observatory blue and violet) into one multi-wavelength picture.

Search for DM in the GC

☺ Steep DM profiles ⇒ Expect large DM annihilation/decay signal from the GC!

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

- source confusion: energetic sources near to or in the line of sight of the GC
- diffuse emission modeling: uncertainties in the integration over the line of sight in the direction of the GC, very difficult to model

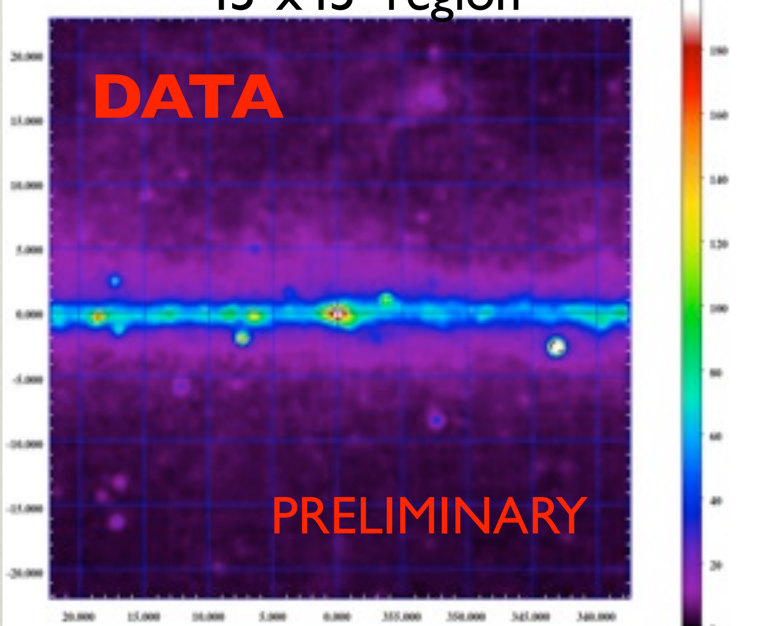


Fermi's View of the Inner Galaxy

Preliminary results with 32 months of data, E>1 GeV:

45°x45° region

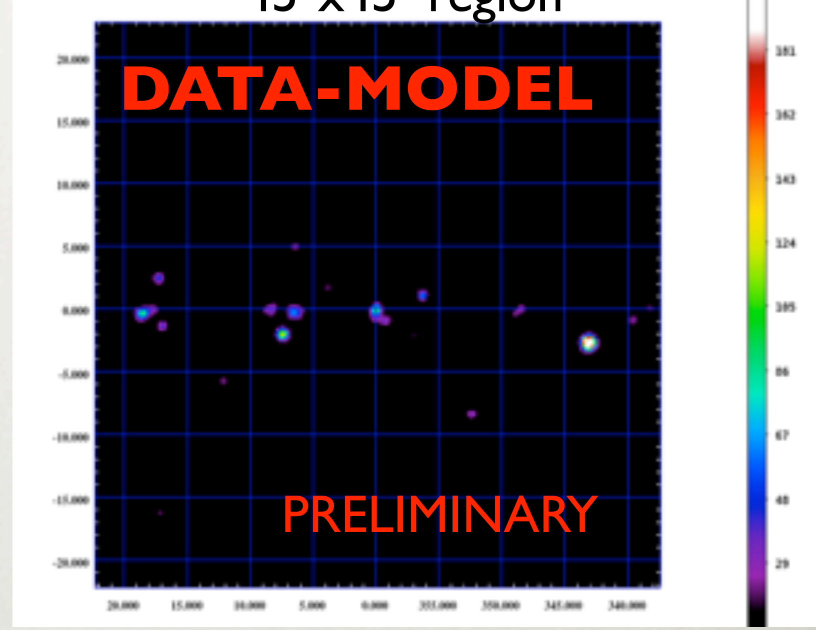
Galactic latitude



Galactic longitude

45°x45° region

Galactic latitude



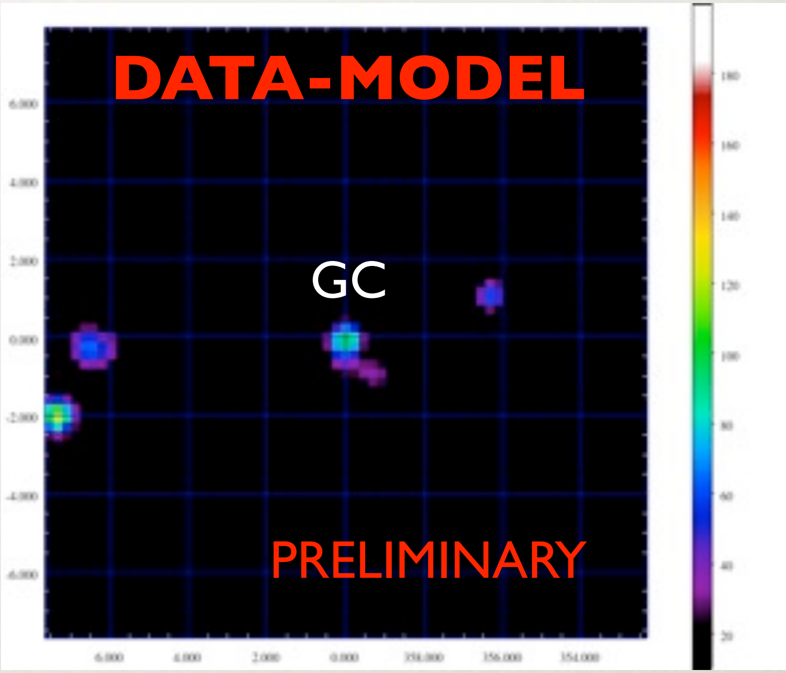
Galactic longitude

- ➡ Physically motivated diffuse emission model (GALPROP based) accounts for most of the emission observed in the region. Peaks in residuals are consistent with known point sources
- ➡ Work is ongoing to characterize the low scale residual structures and point sources.

Fermi's View of the Inner Galaxy

Preliminary results with 32 months of data, E>1 GeV:

Residuals in inner 15°x15° region
(residuals below 10 counts/pixels not shown)



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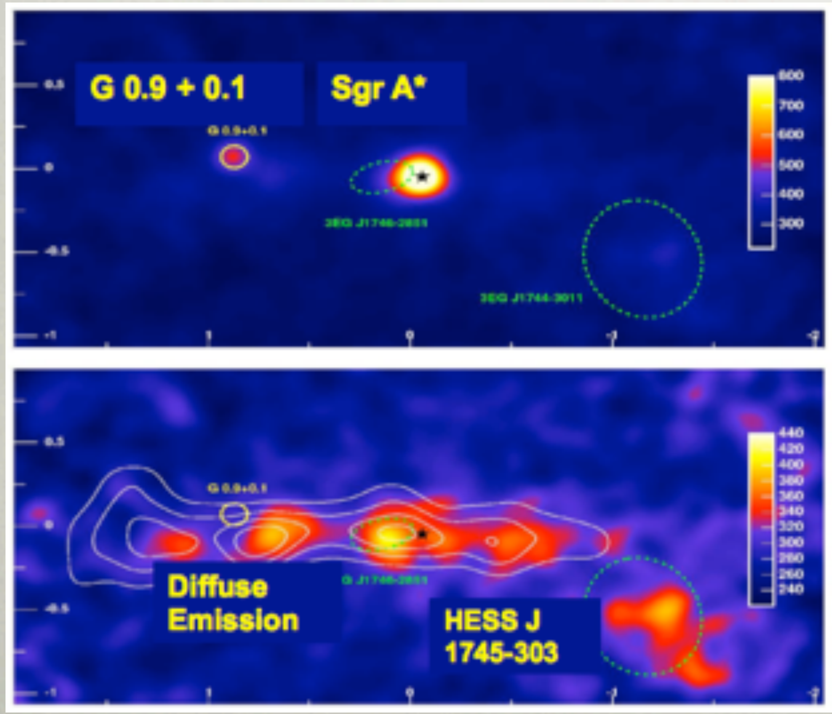
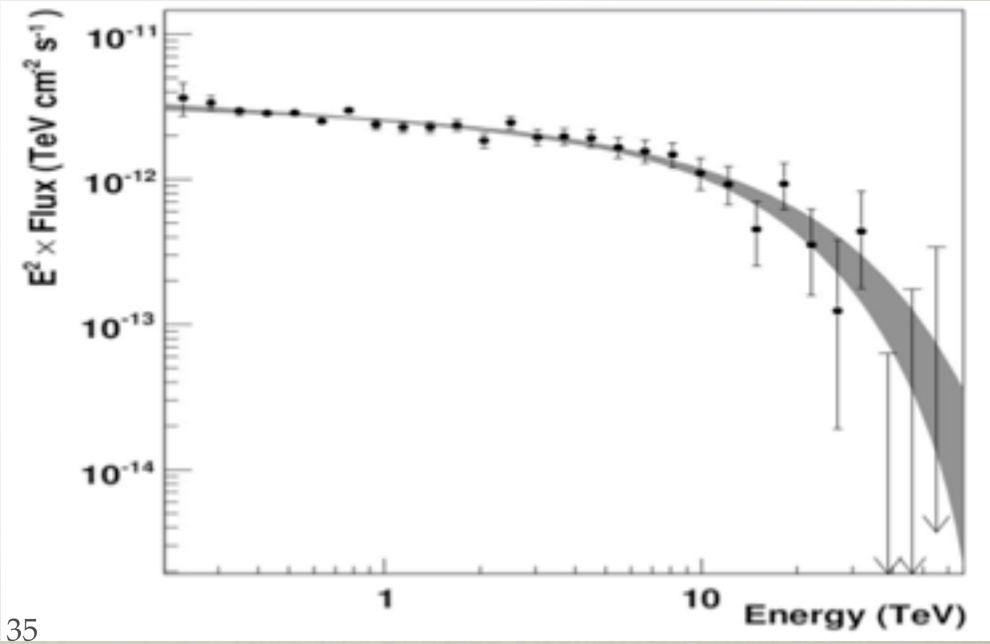
H.E.S.S.: Galactic Center Region

- Large dataset (> 100 hours)
- All found sources are either identified or have a plausible astrophysical interpretation
- GC source spectrum consistent with astrophysical particle accelerators





H.E.S.S.: Galactic Center Region

- Large dataset (> 100 hours)
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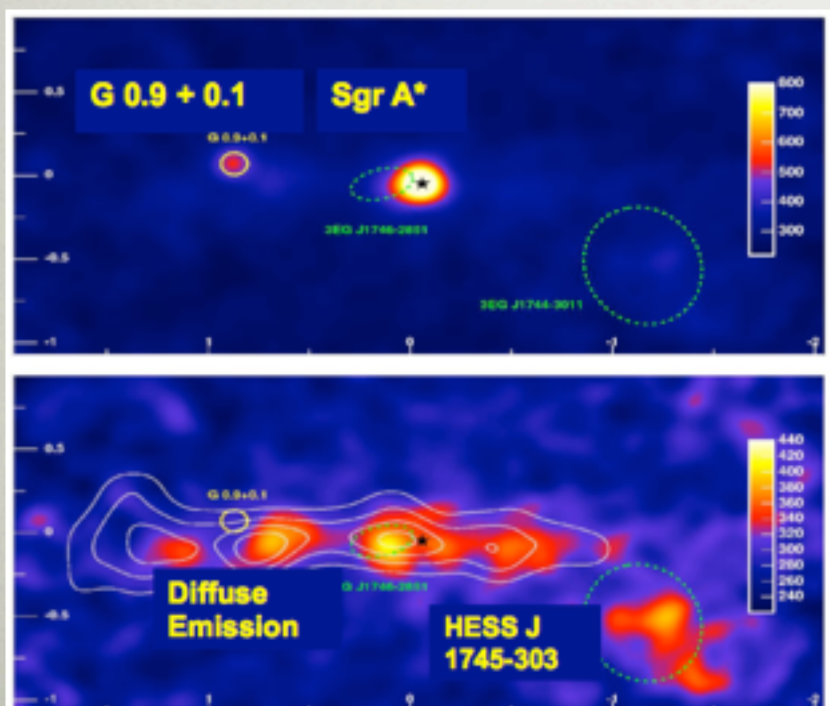
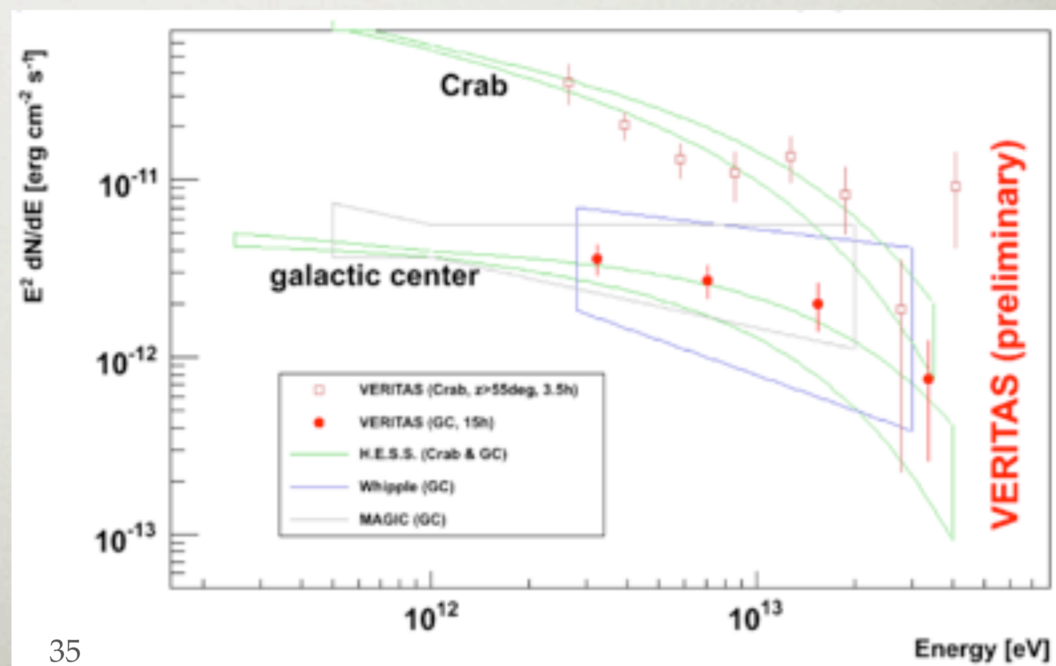
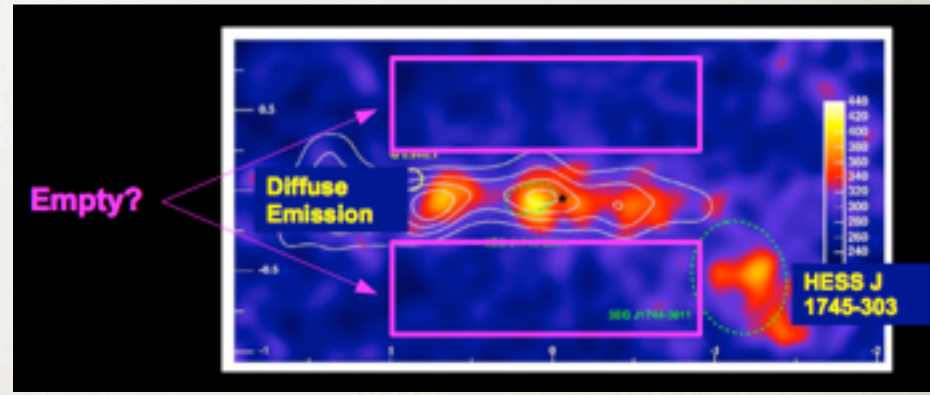
- GC source spectrum consistent with astrophysical particle accelerators
- Consistent spectrum observed by VERITAS/MAGIC

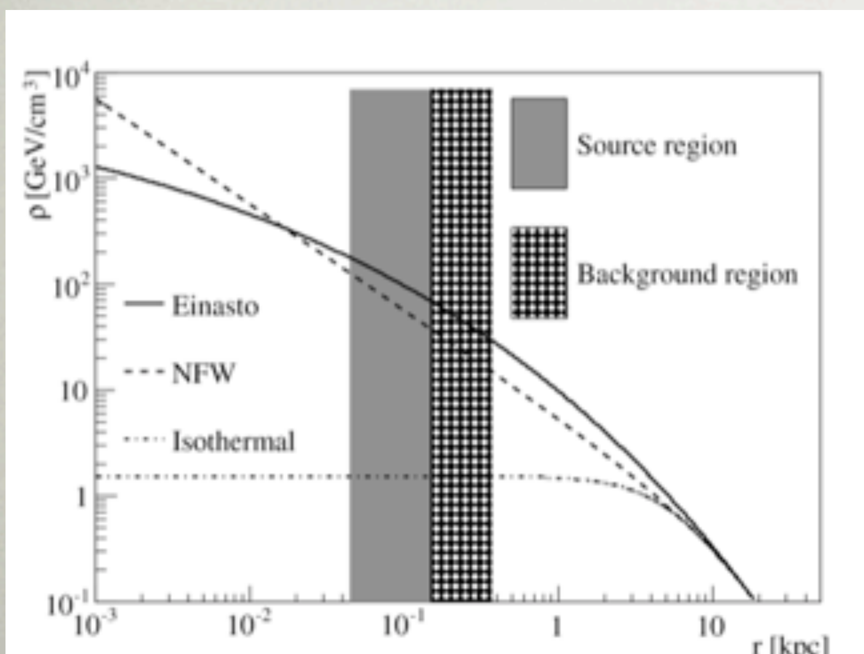




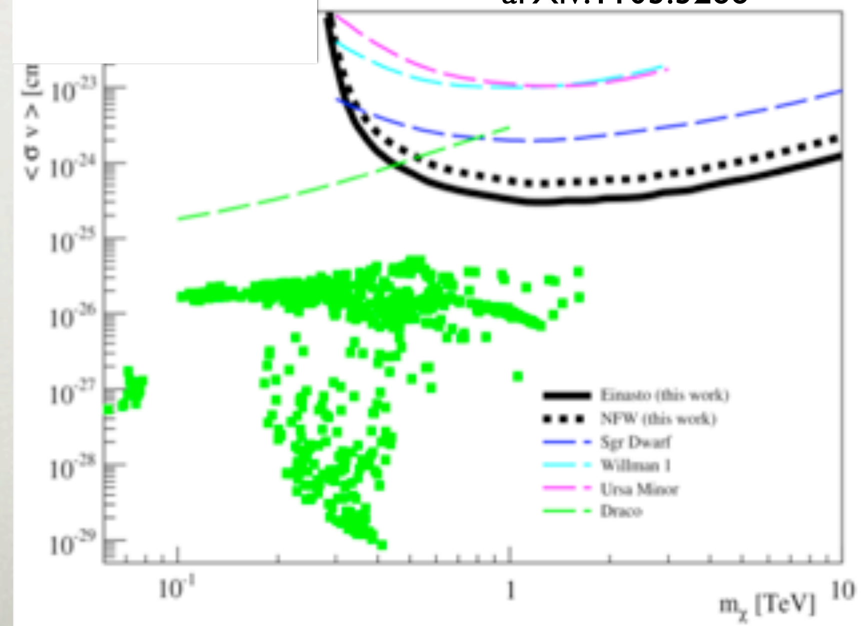
H.E.S.S.: Galactic Halo

- GC is complicated by astrophysics, look away from it!
- Signal region: relatively close to GC but “free” from astrophysical background
- Select a region where the contribution from DM is smaller for background subtraction (background region)
- Small dependence on DM profile





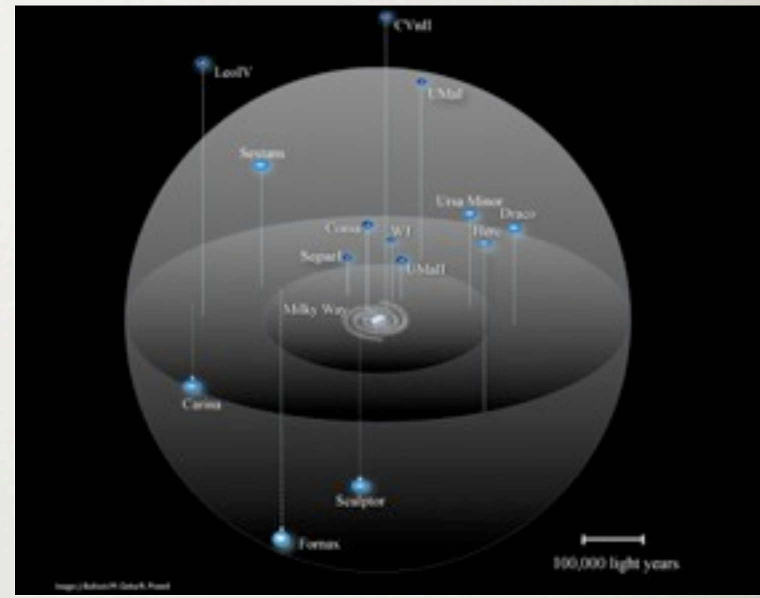
arXiv:1103.3266

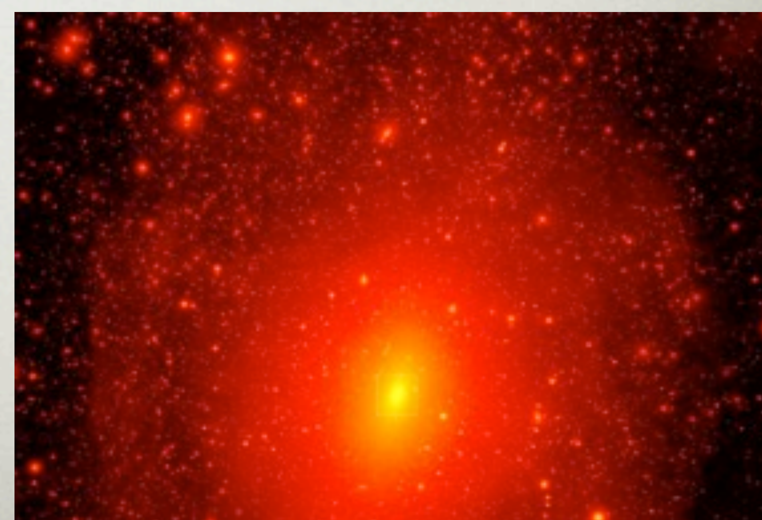


DM Substructures

➡ DM substructures: excellent targets for DM searches!

- Optically observed dwarf spheroidal galaxies (dSph): largest clumps predicted by N-body simulation.
  - Very large M/L ratio: 10 to ~> 1000 (M/L ~10 for Milky Way)
  - More promising targets could be discovered by current and upcoming experiments! (SDSS, DES, PanSTARRS, ...)
  - Great targets for gamma ray observations as most are expected to be free from other gamma ray sources and have low content in dust/gas, very few stars
  - Select promising dSph (based on proximity, stellar kinematic data, DM content, away from galactic plane)





➡ <u>DM density inferred from the stellar data!</u>

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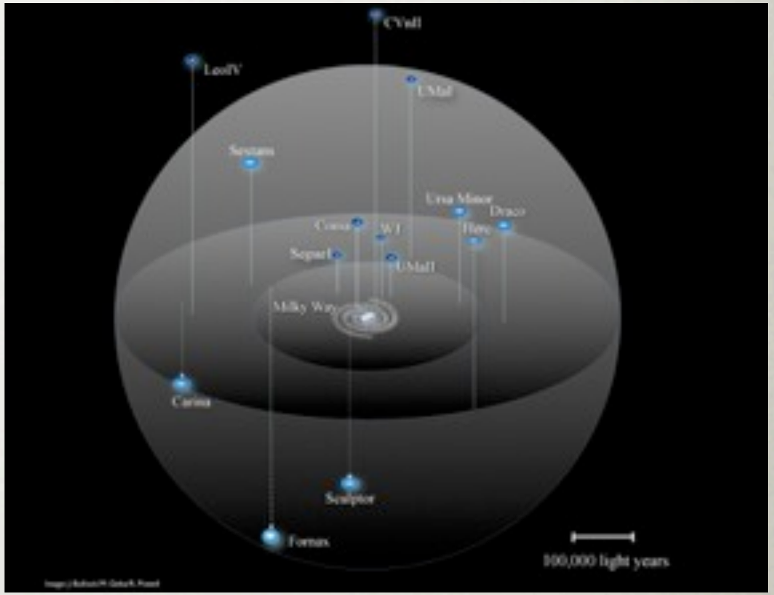


- Never before observed DM substructures:
  - Would significantly shine only in radiation produced by DM annihilation/decay
  - But we don't know where they are!
  - All sky search for promising candidates with the LAT

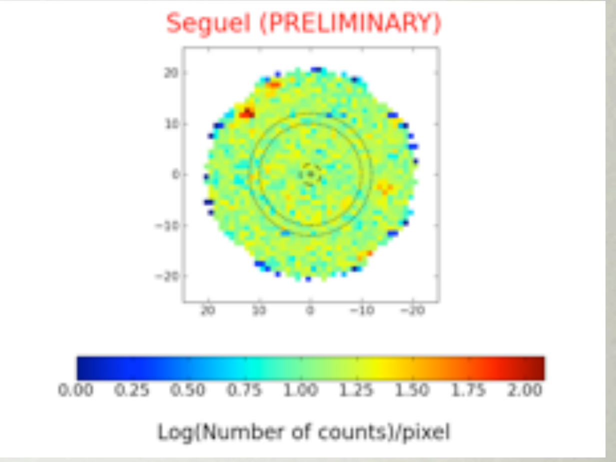
Fermi: Dwarf Spheroidals

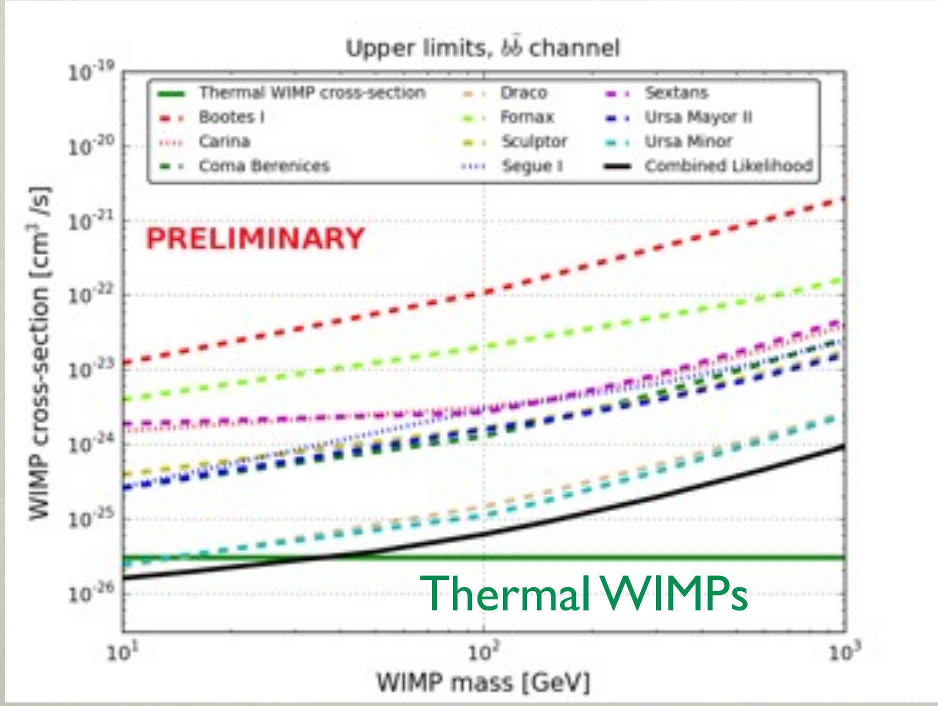
- Bootes I, Carina, Coma Berenices, Draco, Fornax, Sculptor, Segue I, Sextans, Ursa Mayor II, Ursa Minor

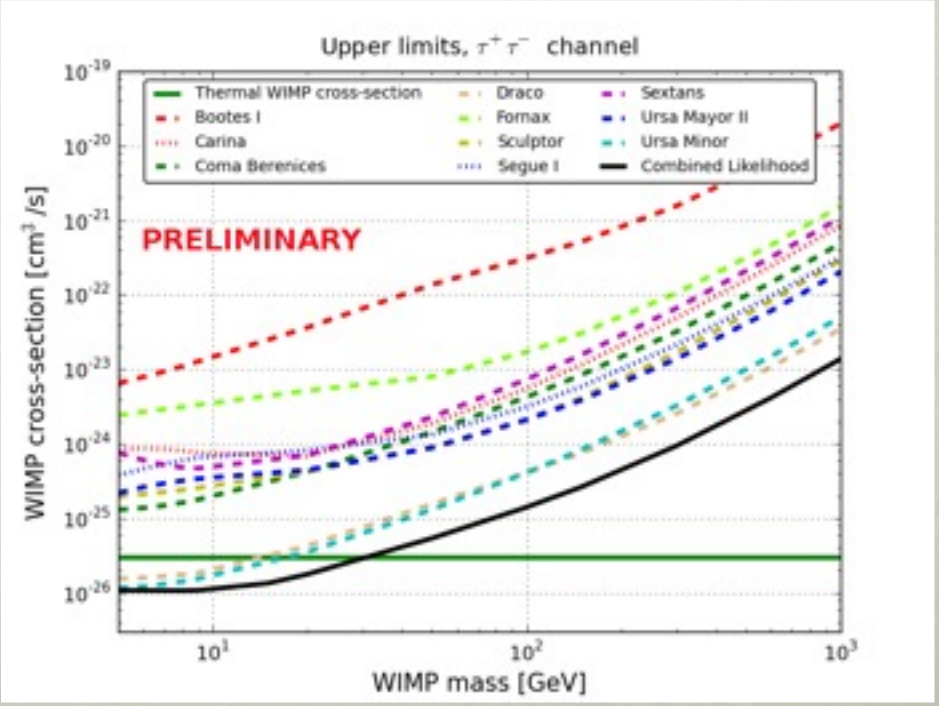
➡ No detection of dSph by Fermi with 2 years of data

- Determine 95% flux upper limits for several possible annihilation final states

- Combine with the <u>DM density inferred from the stellar data</u> to set constraints on the annihilation cross section.







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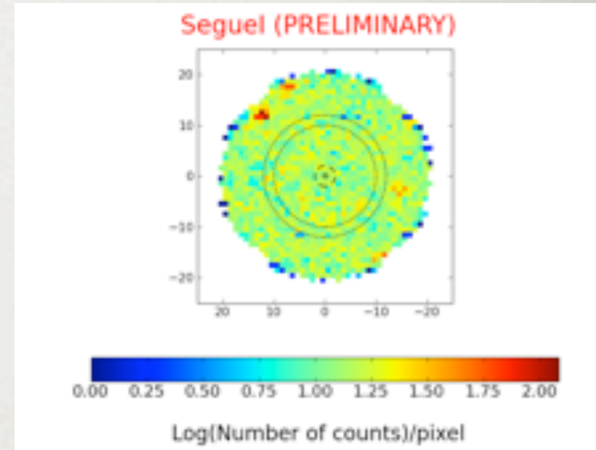
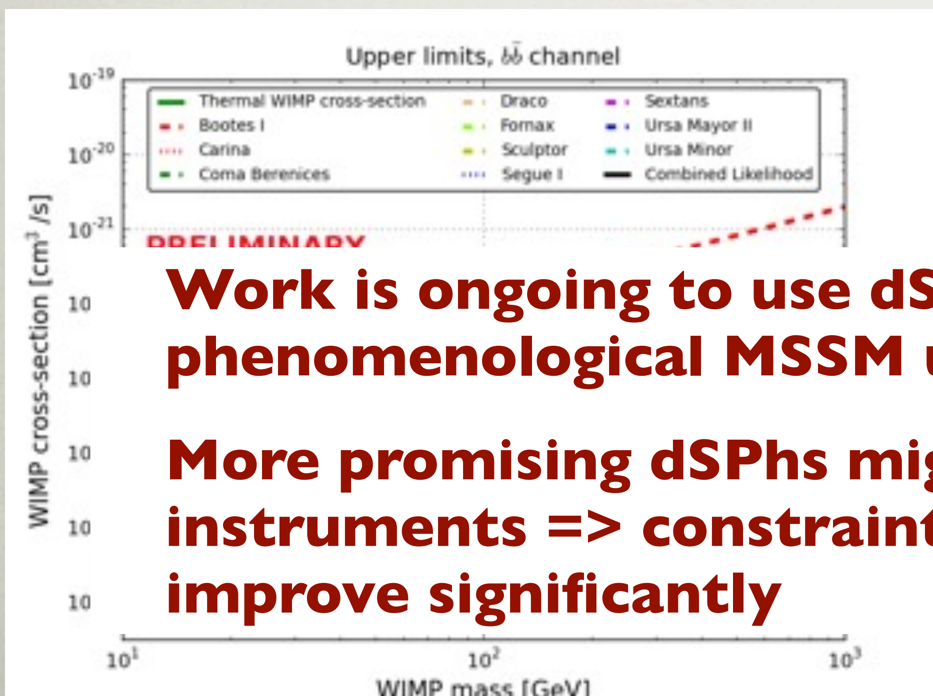
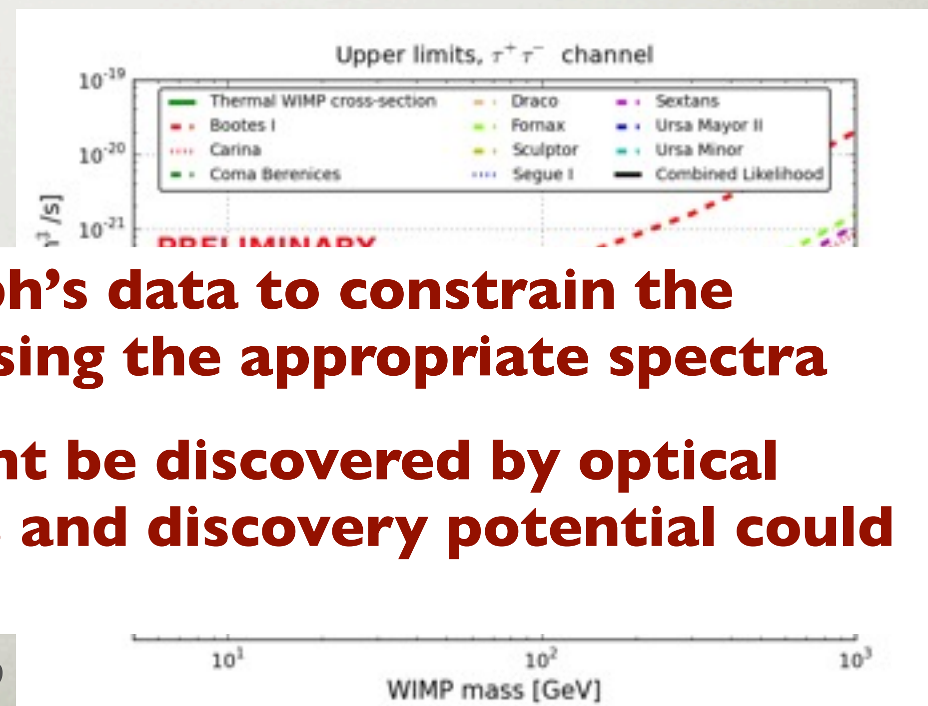




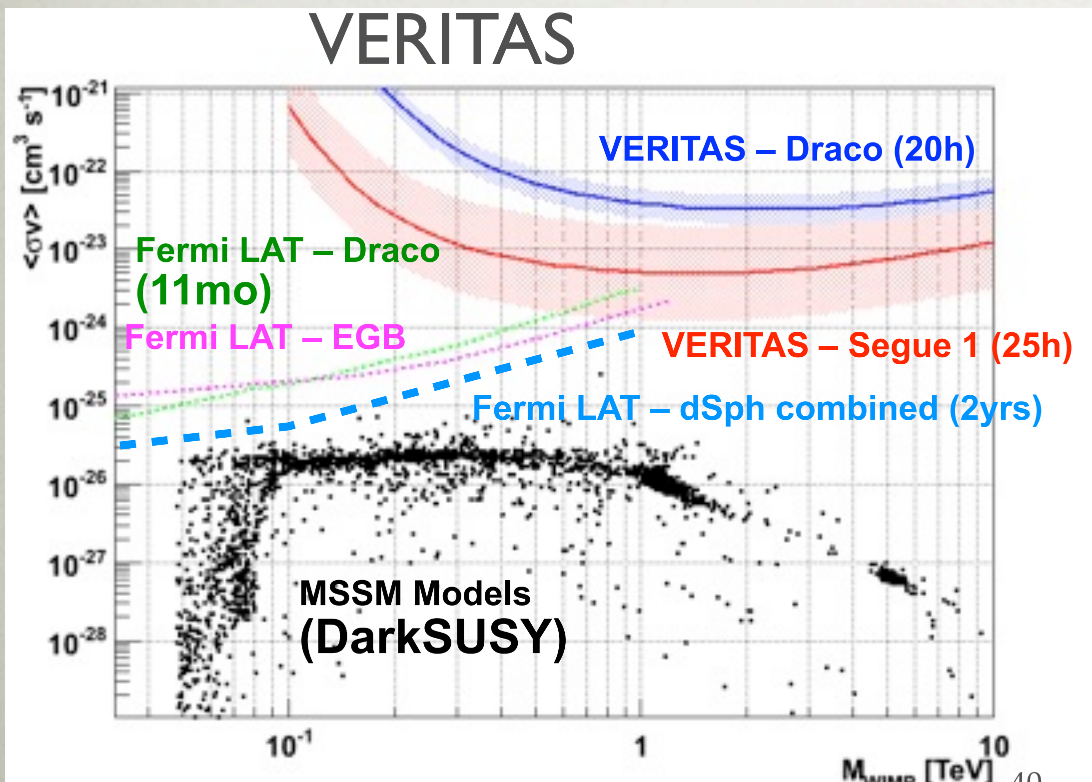


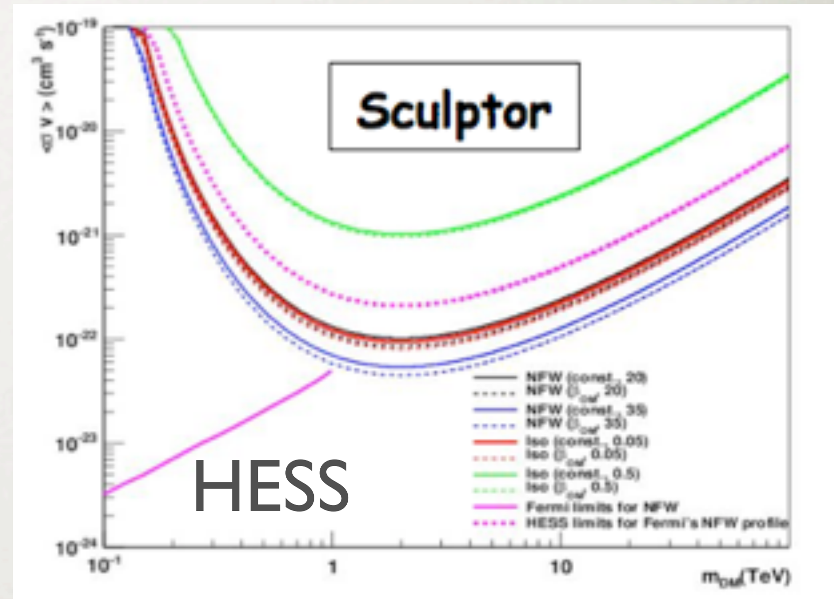
Work is ongoing to use dSph's data to constrain the phenomenological MSSM using the appropriate spectra

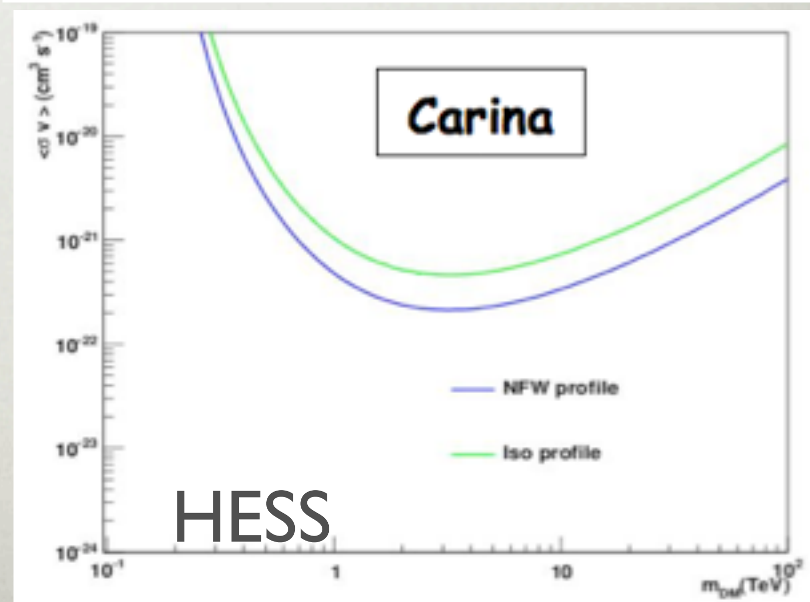
More promising dSPhs might be discovered by optical instruments => constraints and discovery potential could improve significantly

VERITAS and HESS: Dwarf Spheroidals

- Dedicated observations of a number of dark matter targets
- No significant excess in any of the observations
- Set constraints on the annihilation cross section (assume annihilation into b-bbar)

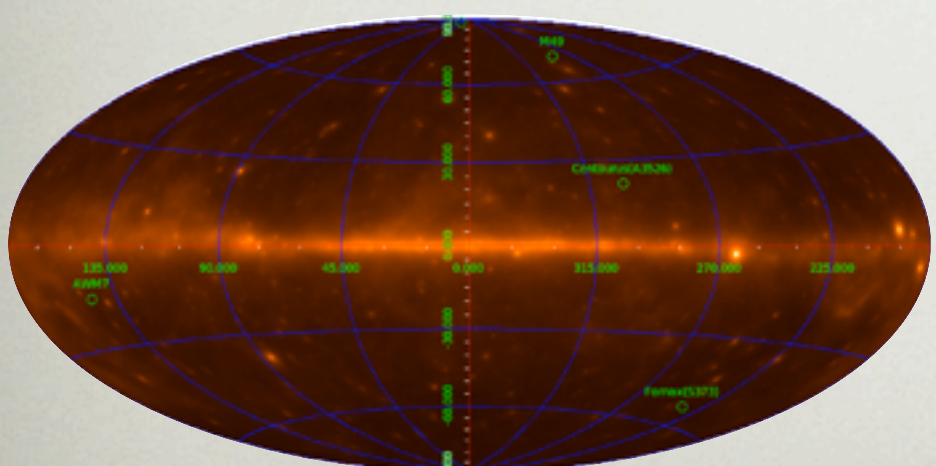


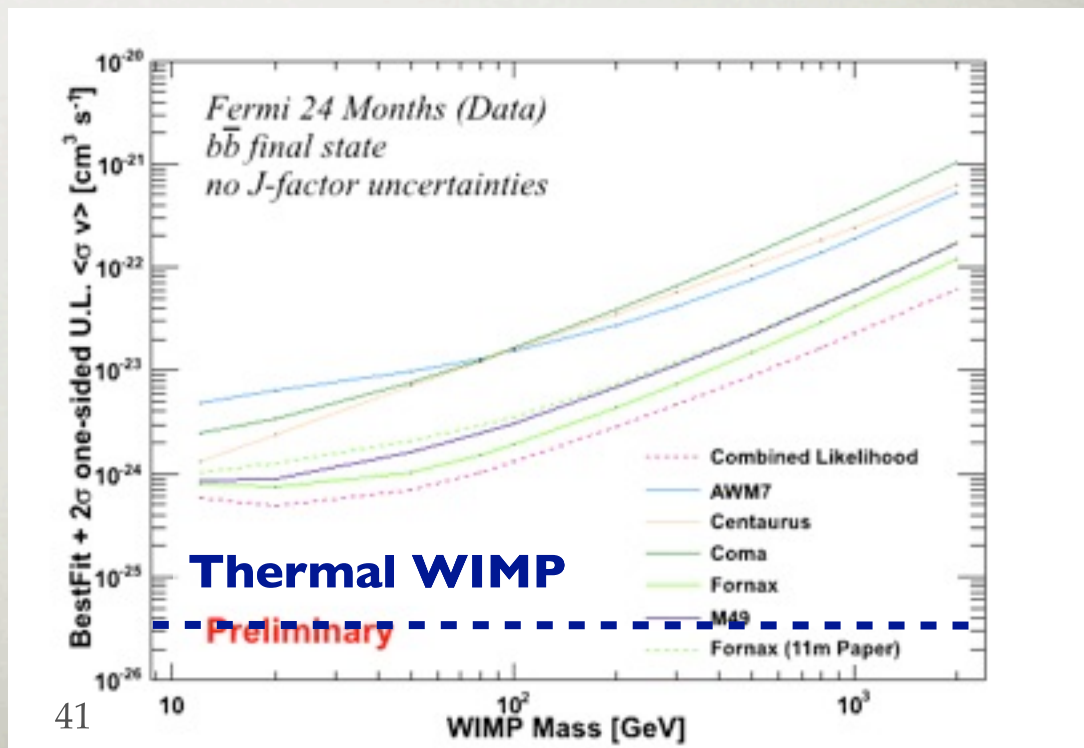




Fermi: Search for DM in Galaxy Clusters

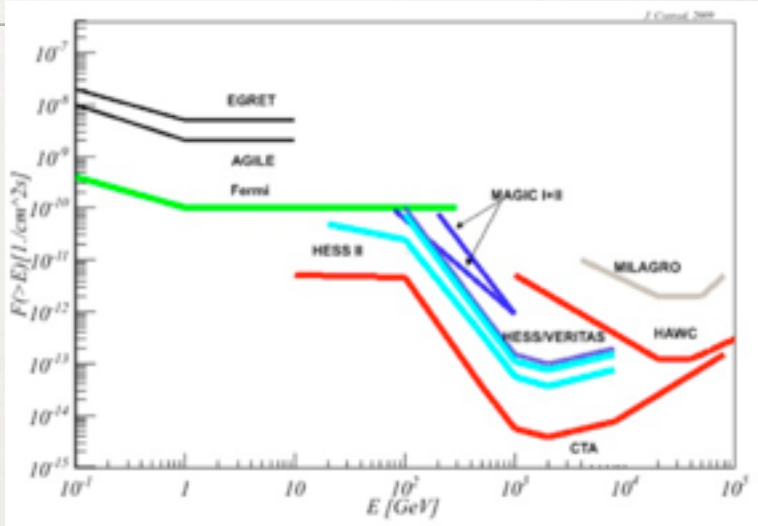
- Most massive structures observed in the Universe, very large dark matter content.
- Predicted to emit gamma rays from conventional astrophysical processes.
- Non-detection of galaxy clusters by Fermi is used to set constraint on DM annihilation

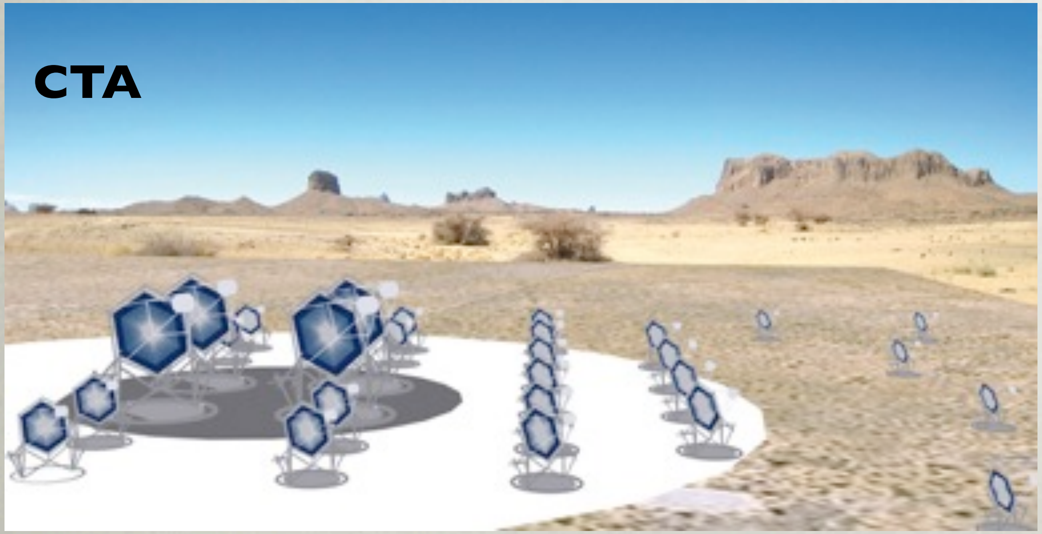




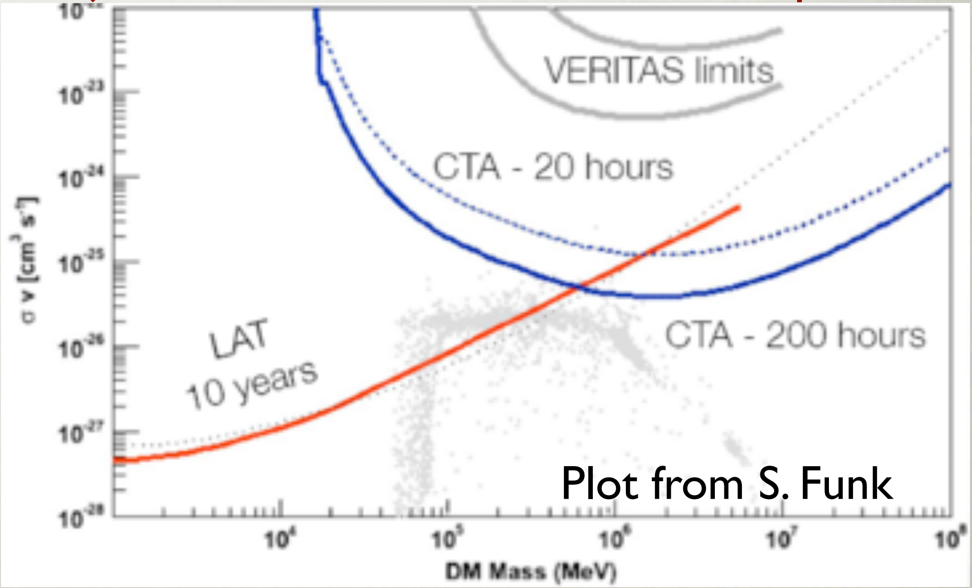
DM Searches with Gamma rays: Future Prospects

- Next generation gamma ray observatory
- Basic design: small core of large telescopes, surrounded by mid size telescopes and an outer ring of small telescopes
- Improve sensitivity of current ATCs (~10x), extend to lower and higher energies (~ 10s GeV to >100 TeV).



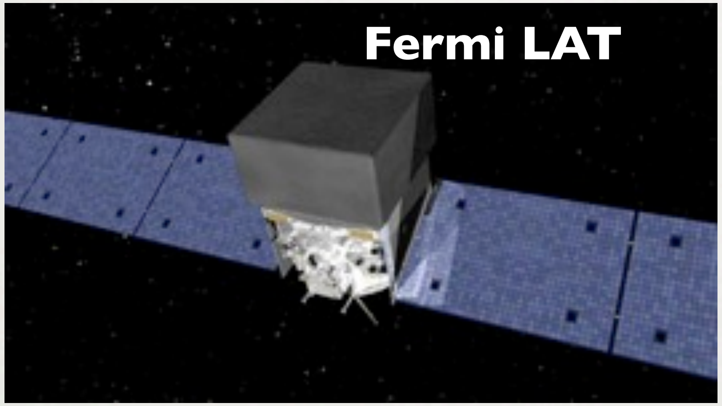


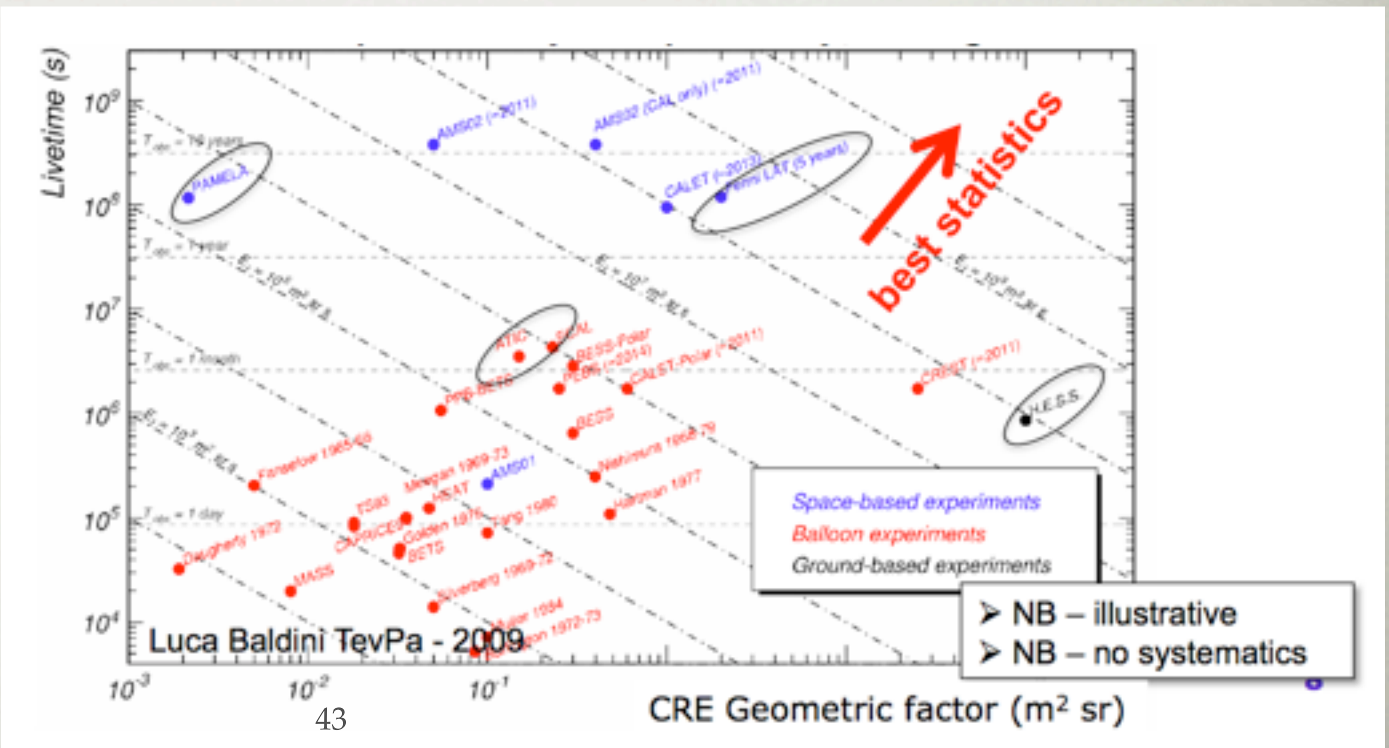
Projected CTA constraints - dwarf spheroidals



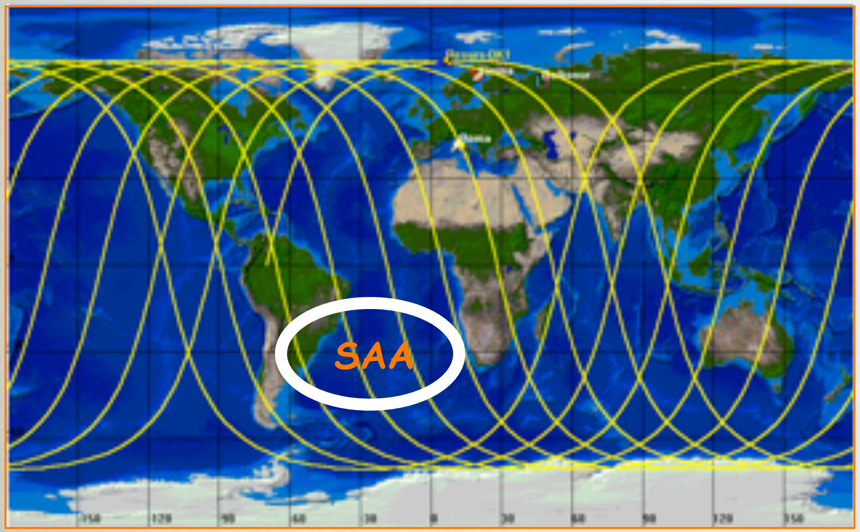
Cosmic rays


PAMELA


Fermi LAT


Livetime (s)
CRE Geometric factor (m² sr)
best statistics
Space-based experiments
Balloon experiments
Ground-based experiments
➢ NB – illustrative
➢ NB – no systematics
Luca Baldini TevPa - 2009

PAMELA



Low-earth elliptical orbit

350 – 610 km

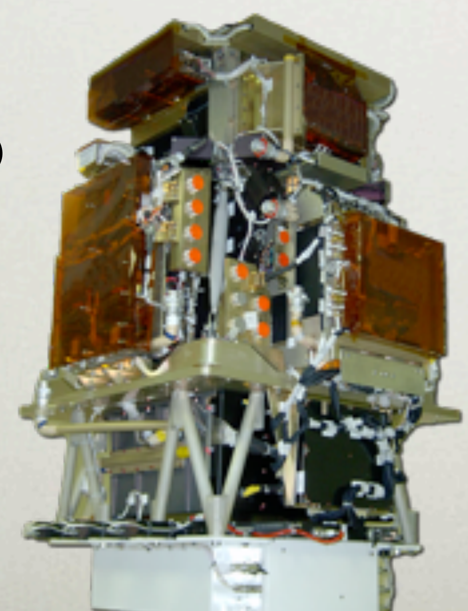
Quasi-polar (70° inclination)

SAA crossed

GF ~21.5 $cm^2 sr$

Mass: 470 kg

Size: 130x70x70 cm^3



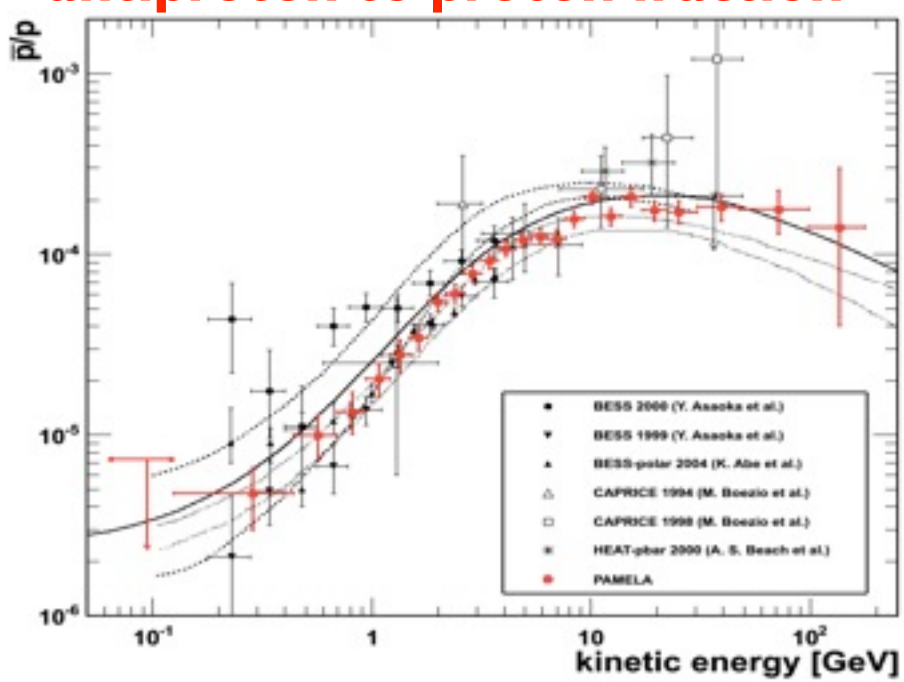
Design Performance

	Energy range
Antiprotons	80 MeV - 190 GeV
Positrons	50 MeV - 300 GeV
Electrons	up to 800 GeV
Protons	up to 1 TeV
Helium	up to 400 GeV/n
Electrons+positrons	up to 2 TeV (by calorimeter)
Light Nuclei (Li/Be/B/C)	up to 200 GeV/n
AntiNuclei search	sensitivity of 3×10^{-8} in He/He

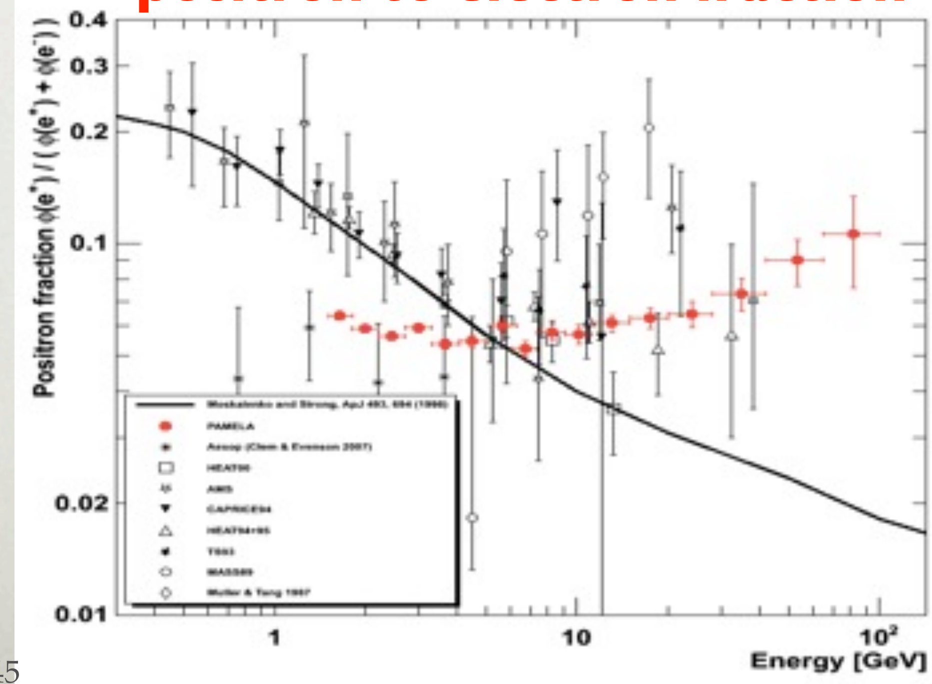
PAMELA Results

- Measurement of the antiproton fraction in cosmic rays by PAMELA is in agreement with secondary production predictions
- Positron fraction unexpectedly raises at high energy!
- Many plausible explanations (production of secondaries at source, nearby source, dark matter, ...)

antiproton to proton fraction

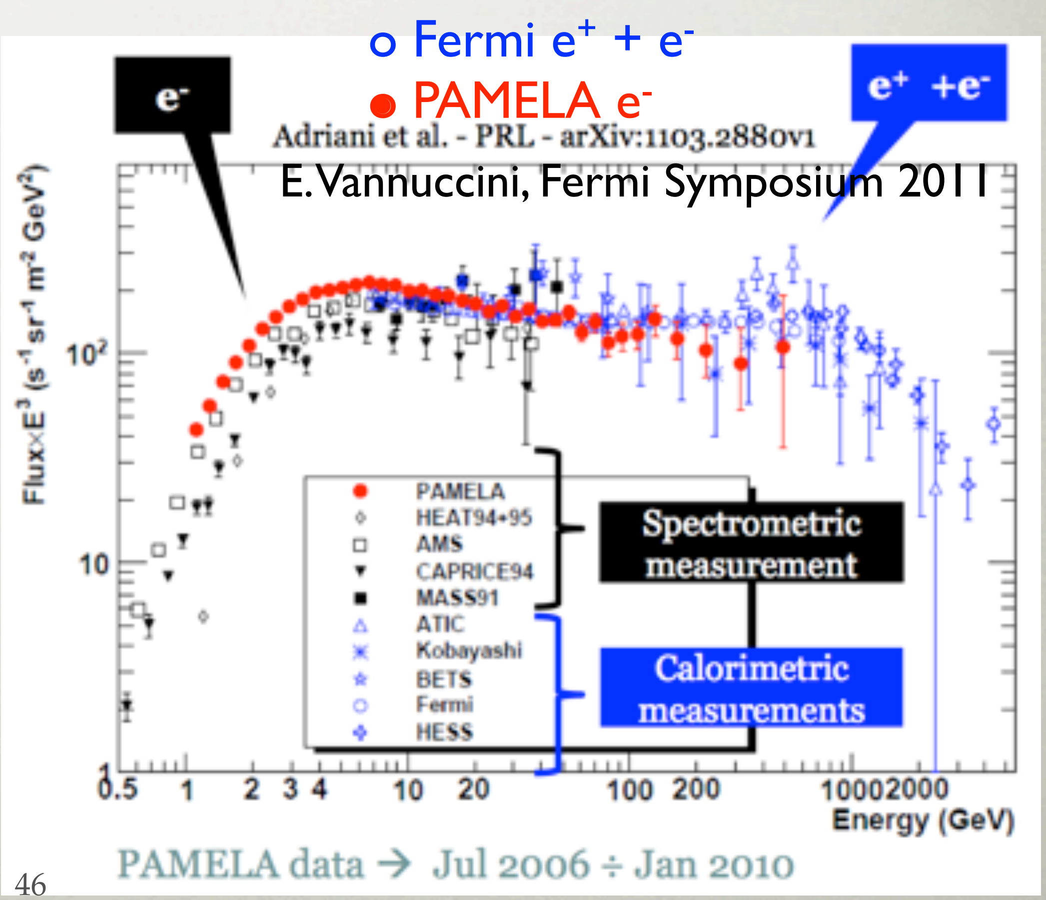


positron to electron fraction



PAMELA and Fermi Electrons

- A softer electron spectrum could cause the raise in the positron to electron fraction
- However the electron spectrum measured by PAMELA (spectral index = -3.18±0.05) is not compatible with this explanation (not soft enough)
- Fermi LAT is an excellent electrons (and positrons) detector and measured the combined $e^+ + e^-$ spectrum
- PAMELA electron spectrum is consistent, within uncertainties, both with Fermi (and ATIC) measurement and with a raising positron contribution



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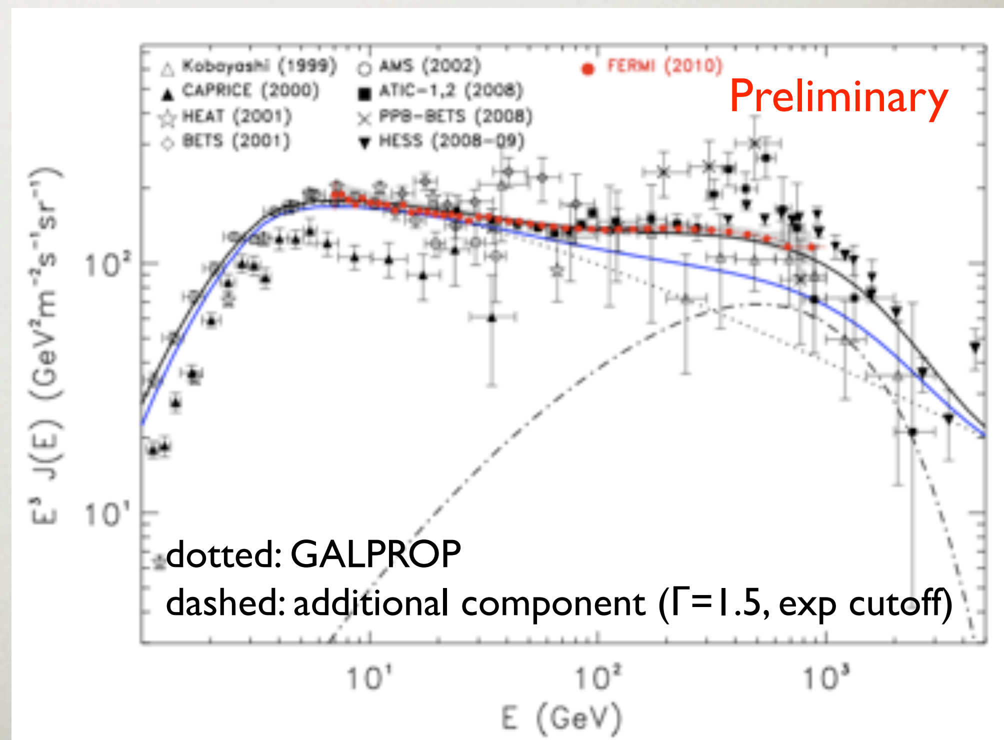
➡ Adding a new component (nearby source of e^+e^-) fits the PAMELA (electron and positron fraction) and Fermi ($e^+ + e^-$) data well.

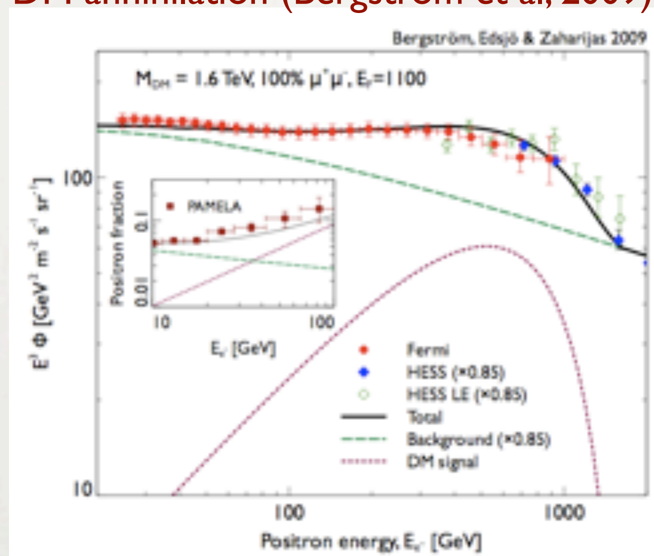
➡ Can test this hypothesis looking for anisotropies in the $e^+ + e^-$ sky with Fermi



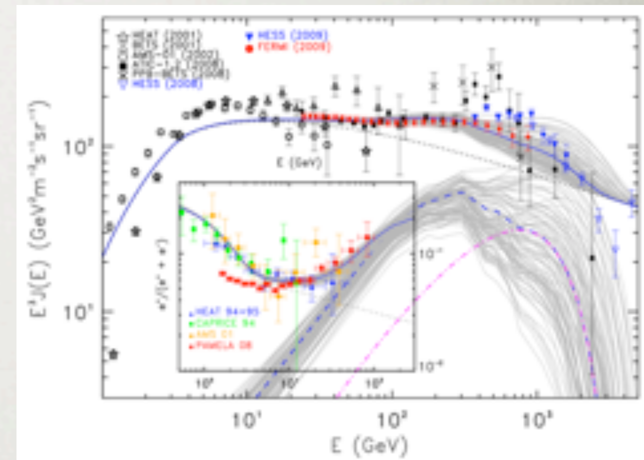
Could it Be Dark Matter?

Dark matter can reproduce the raise in the positron fraction, but several other explanations exists!

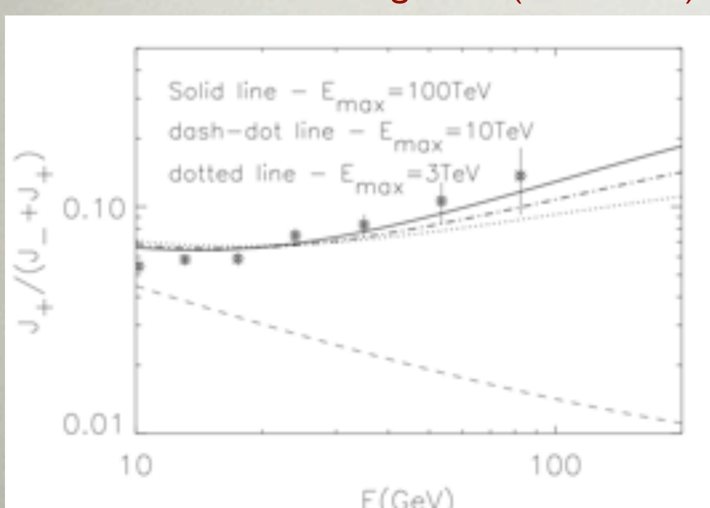
DM annihilation (Bergstrom et al, 2009)



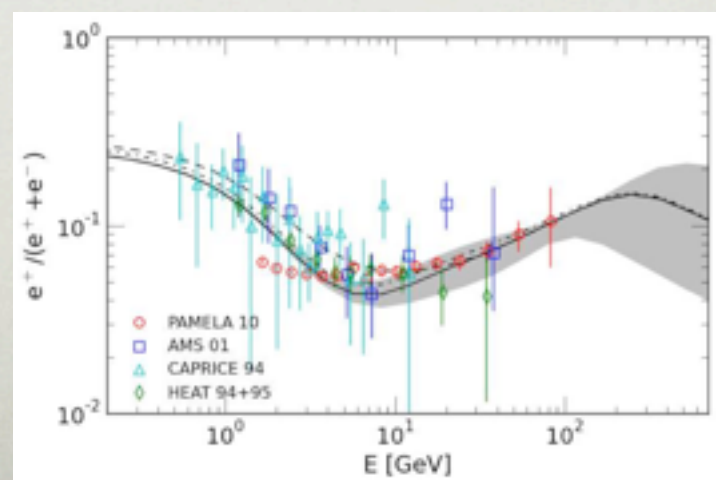
Pulsars (Grasso et al, 2011)



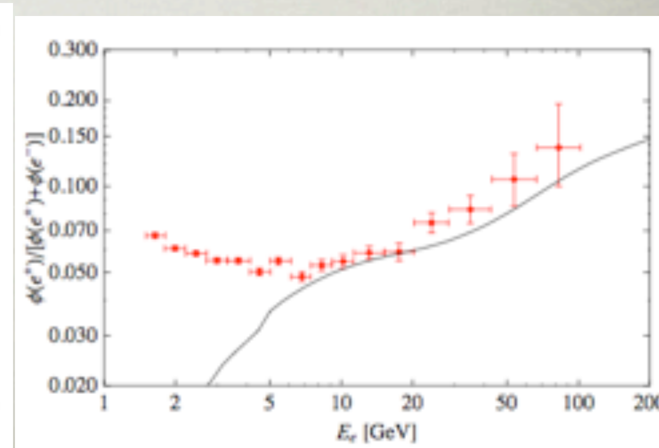
Production of secondary positrons at CR acceleration site, e.g. SNR (Blasi 2009)



Injection model based on gamma ray observations (Kamae et al, 2010)



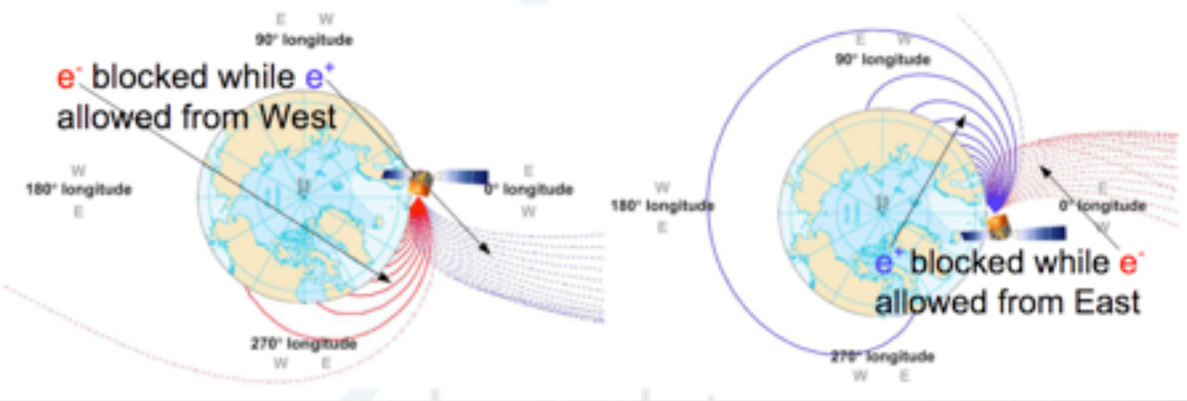
Klein-Nishina suppression of the IC cooling rate (Stawarz et al, 2009)

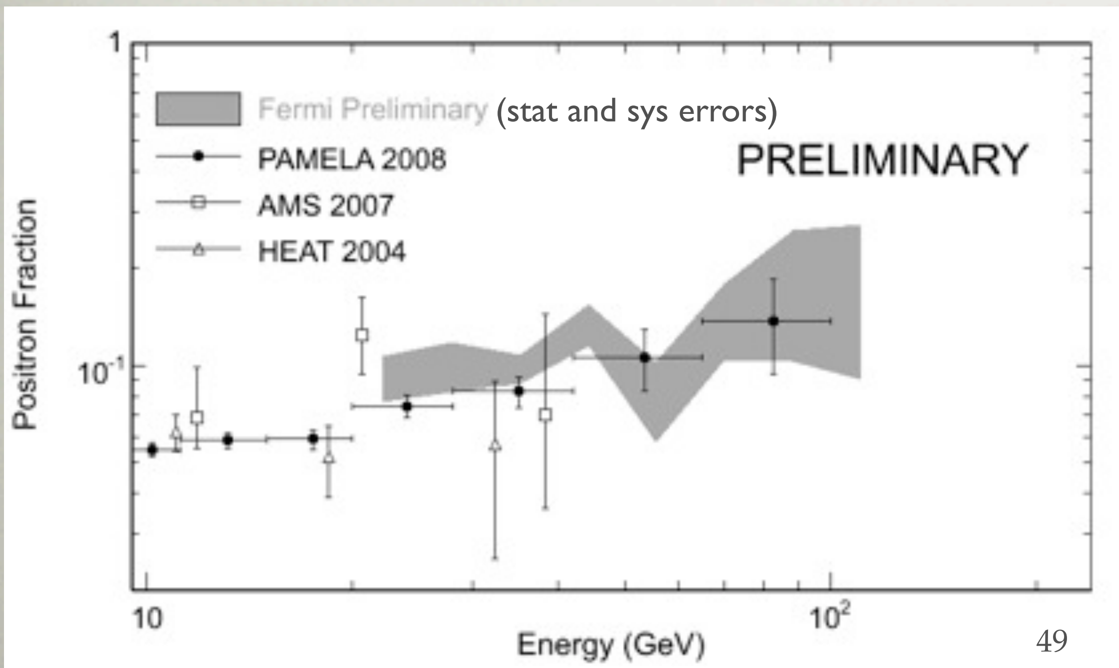


Fermi Positrons

➡ Use the Earth magnetic field to separate electrons and positrons!

- Some regions of the sky (which depend on the energy of the particle and the Fermi position in the orbit) are be blind to electrons or positrons due to shadowing from the Earth





➡ Fermi measurement of the positron fraction is consistent with raise observed by PAMELA

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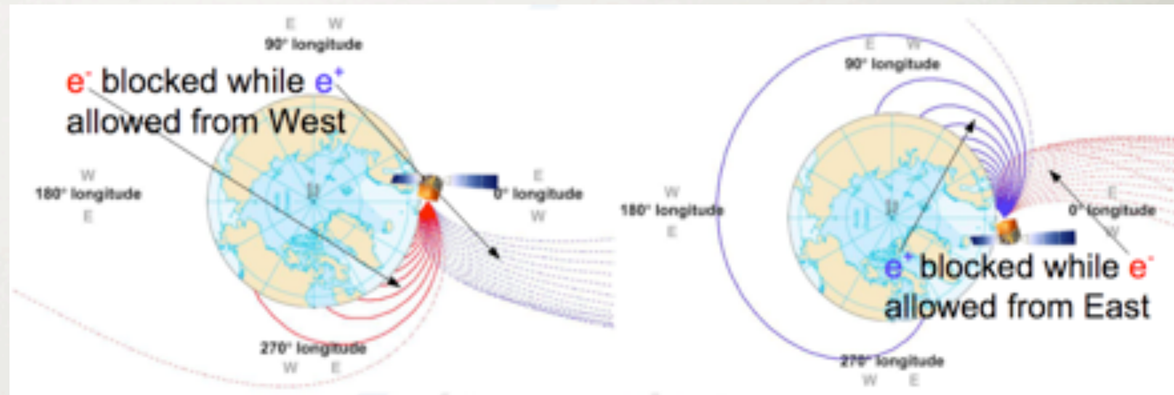

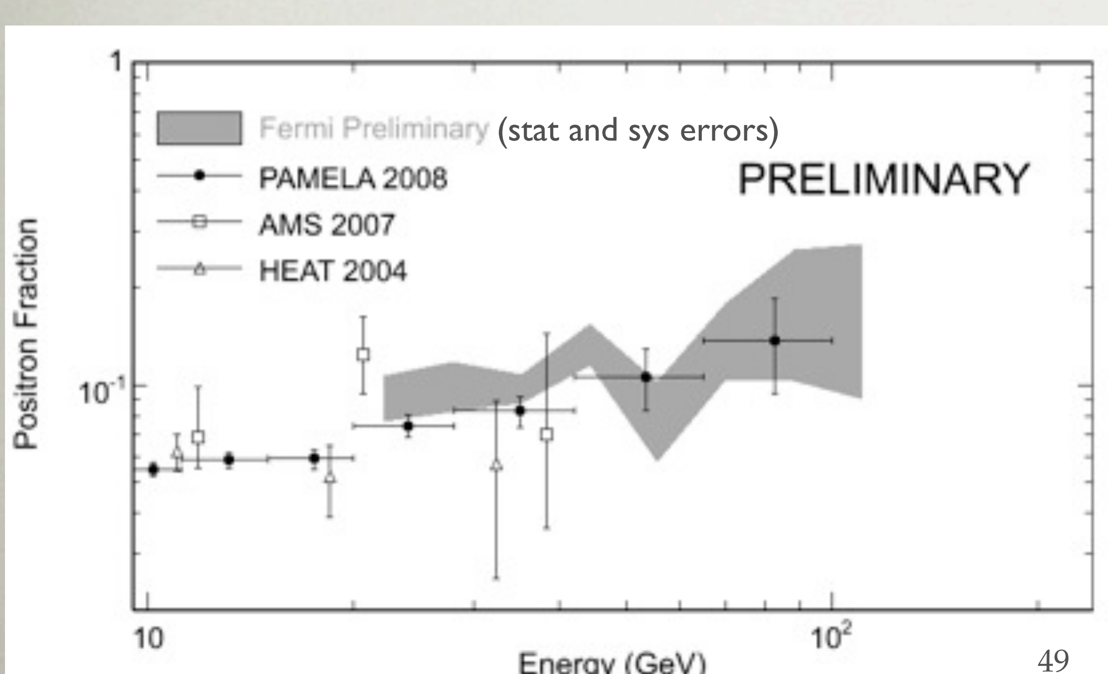

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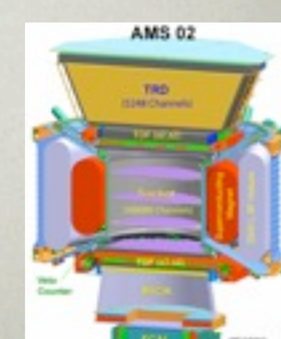
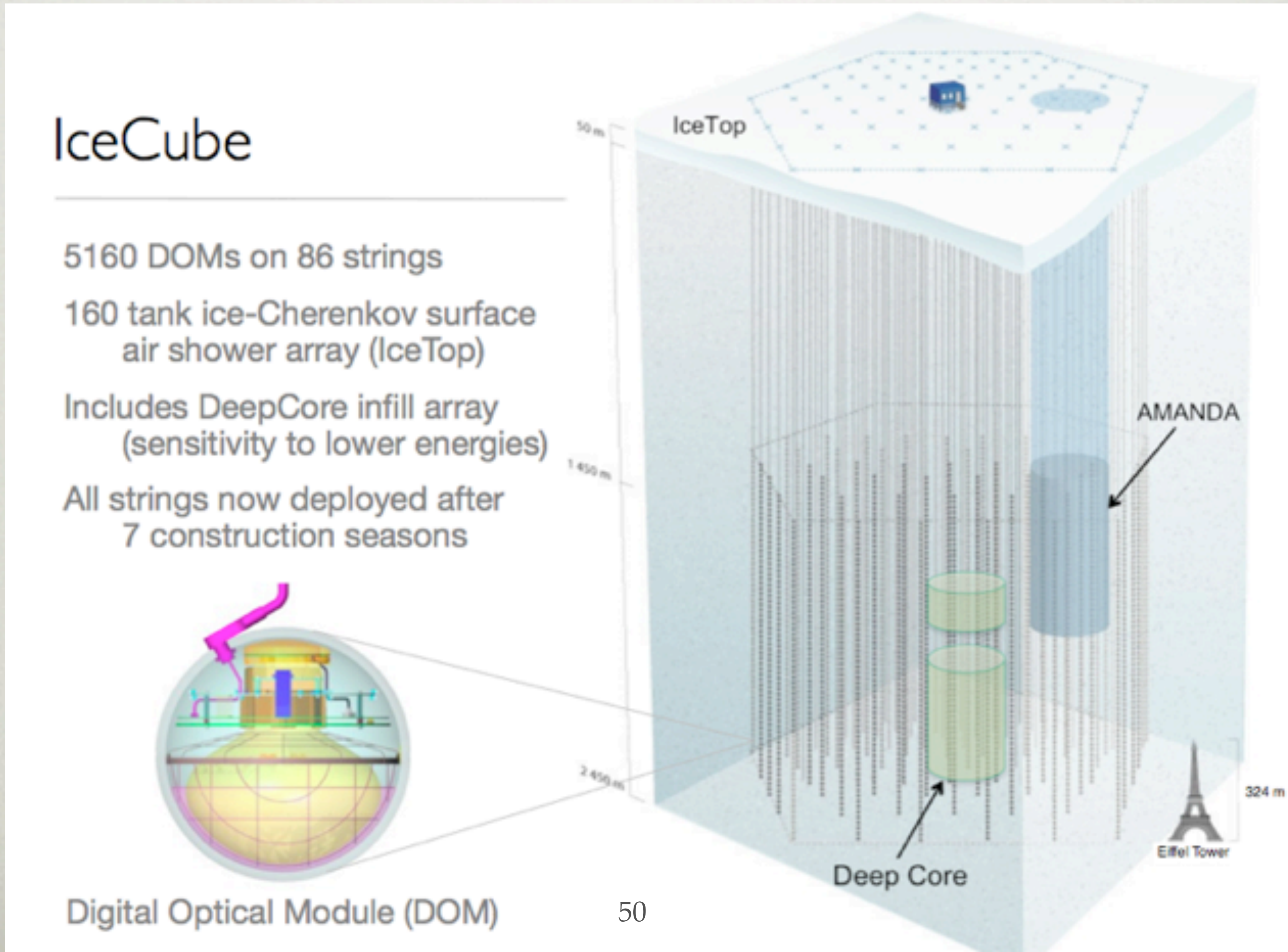
Waiting for AMS data!

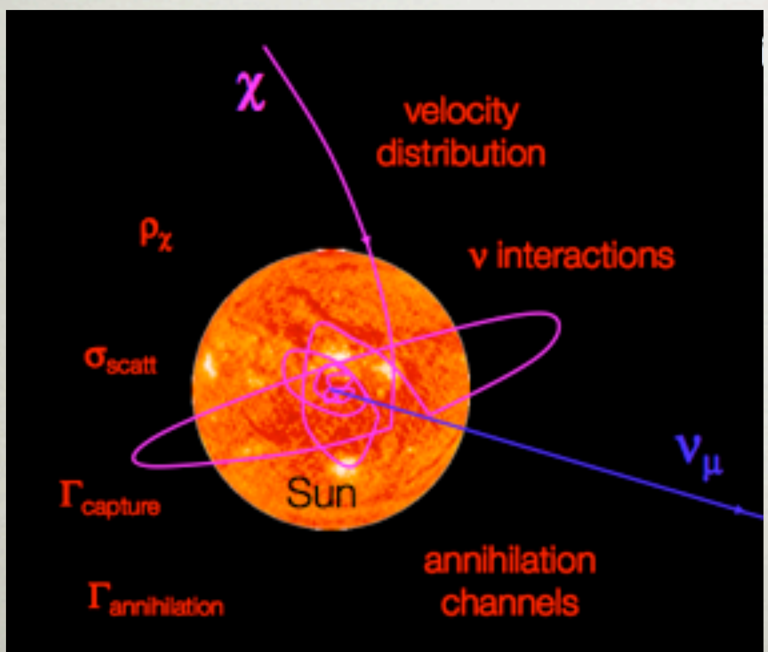


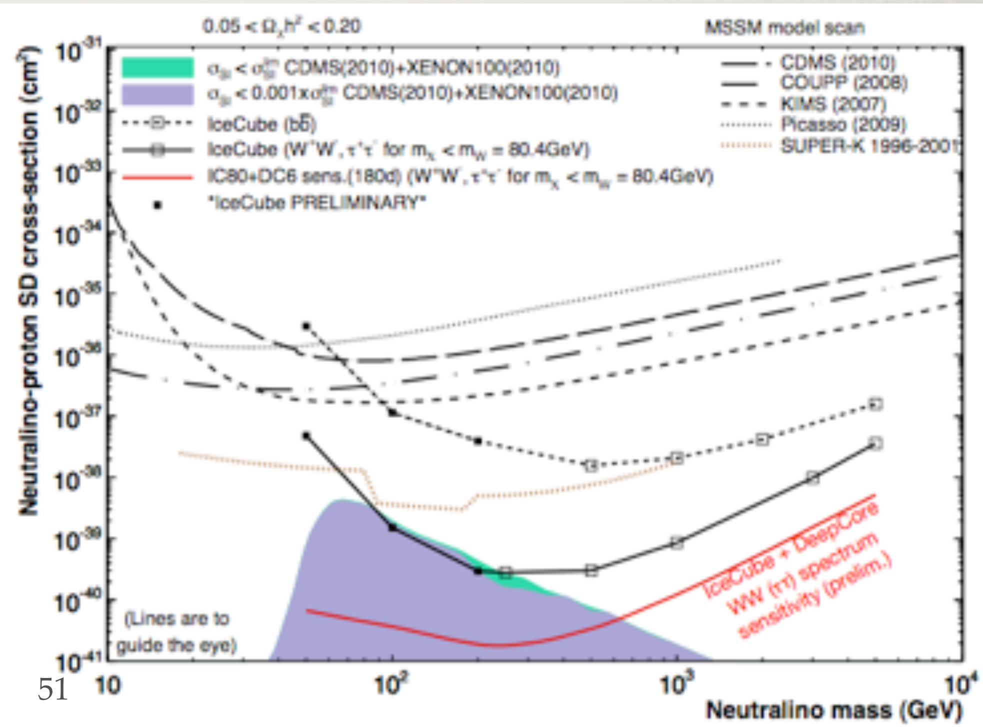
Neutrinos: IceCube



IceCube: Sun

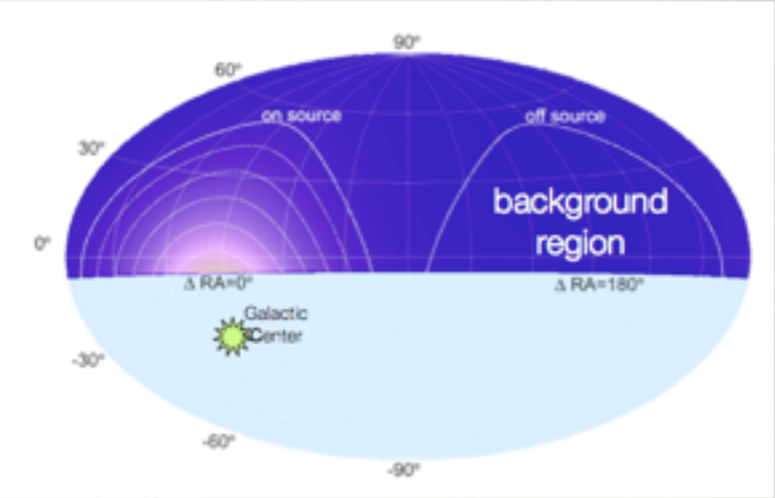
- Dark matter captured in the Sun
- Large model uncertainties (velocity distribution, density, capture rate, scattering cross-section, annihilation cross-section, annihilation channel, energy losses)
- Competitive limits compared to direct detection for spin-dependent interactions for heavy DM

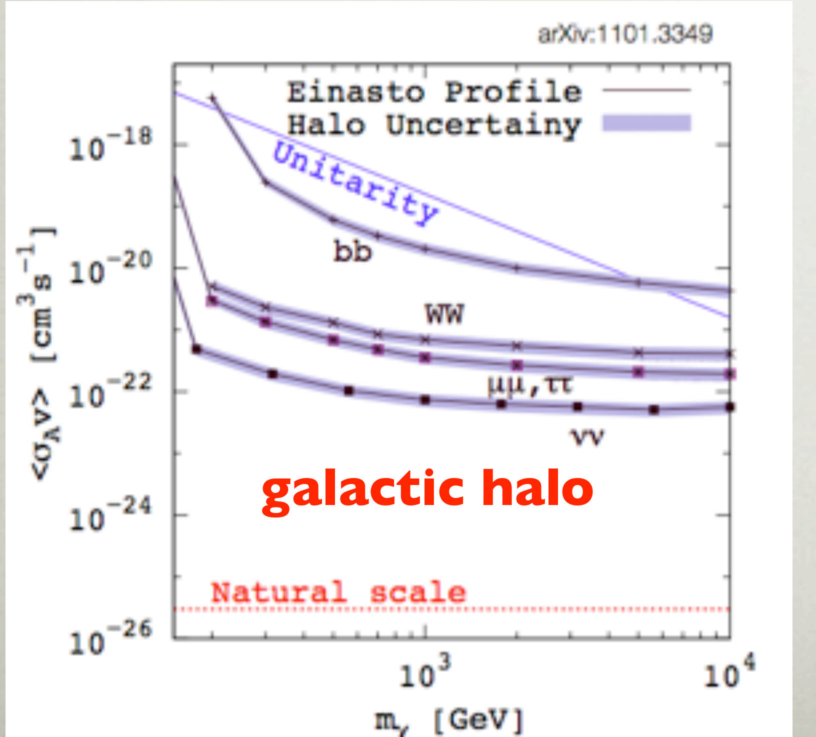


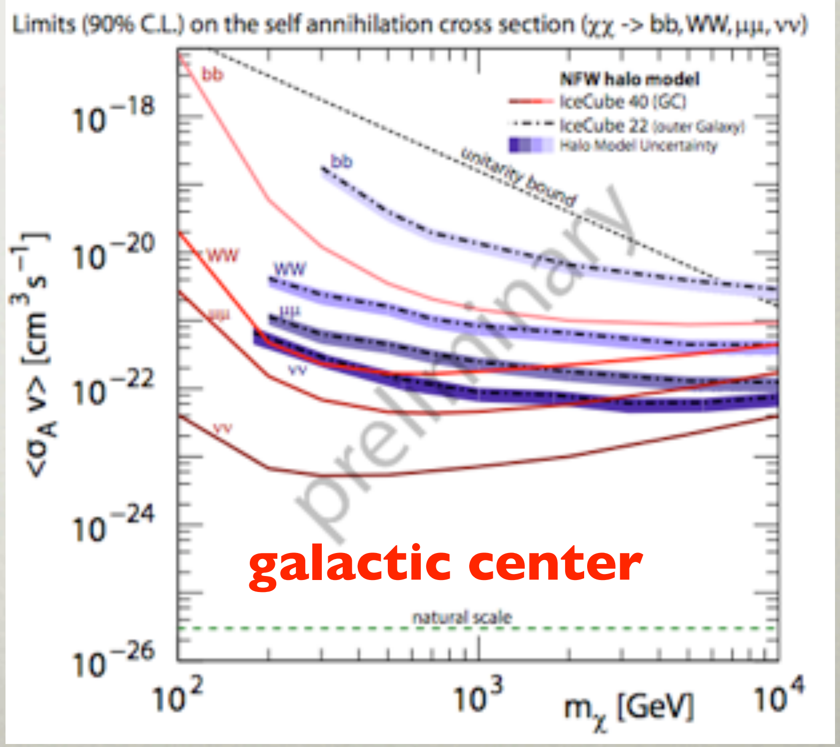


IceCube: Galactic Center and Halo

- Search for a signal from the galactic center or halo
- Cleaner analysis than for solar DM
- Limits complementary to gamma-rays searches for heavy dark matter

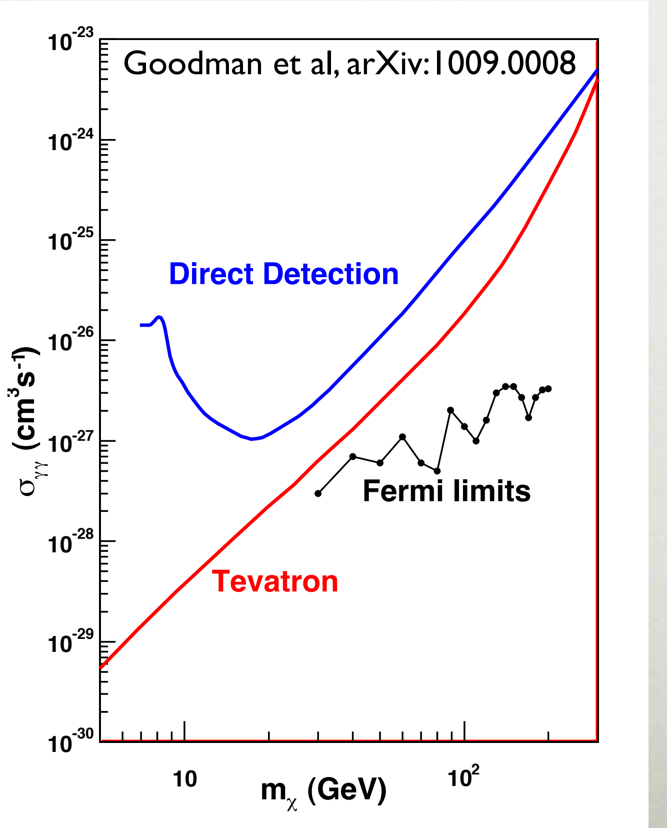


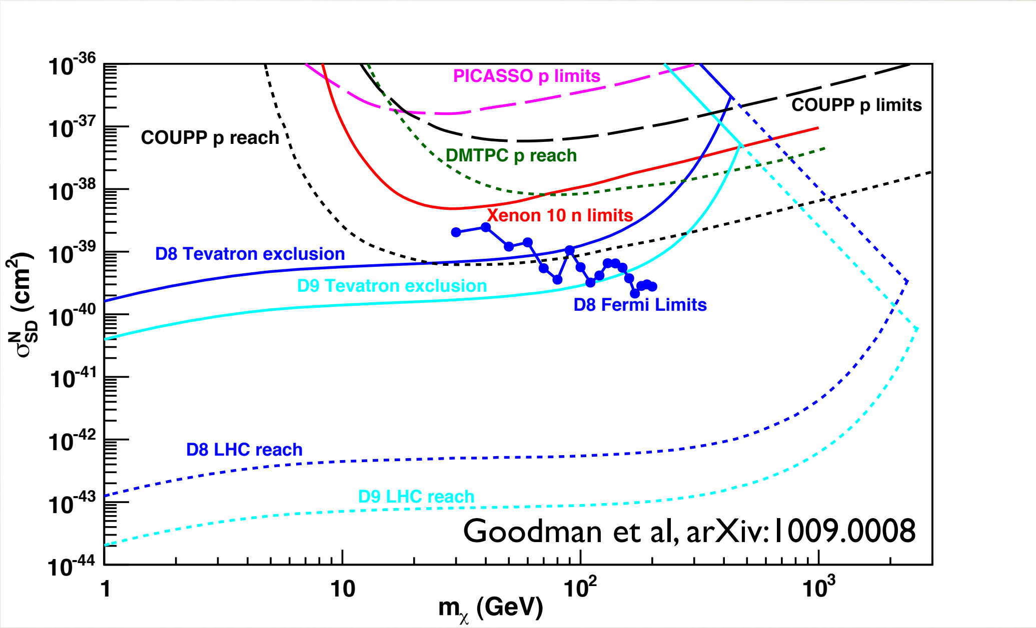




Model Independent Constraints

- Constraints on WIMPs are generally presented by assuming a specific underlying particle physics model (e.g. Supersymmetry, Extra Dimensions)
- If you don't have a favorite model, it is possible to express these constraints in a more model independent way by capturing all possible interactions in general categories. Most theories can be included in this type of formalism (effective theory)
- Fermi line constraints in the effective theory formalism compared to direct and collider searches:





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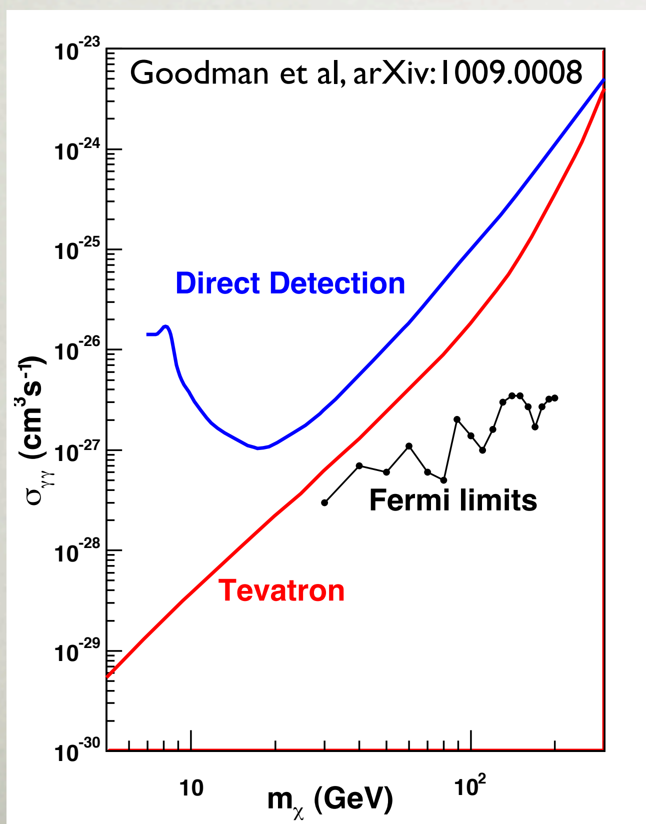
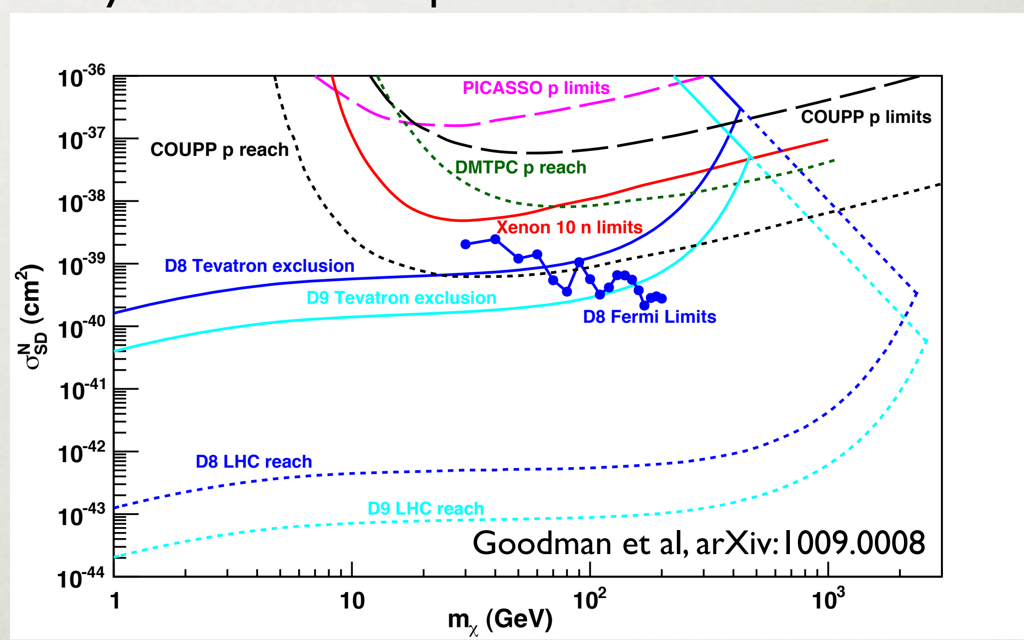




➡ **Constraints in this framework will be extended to other Fermi searches (e.g. dSph, GC, etc.)**

Have We Seen a Signal?

- Potential signals could be interpreted as dark matter annihilation/interaction:

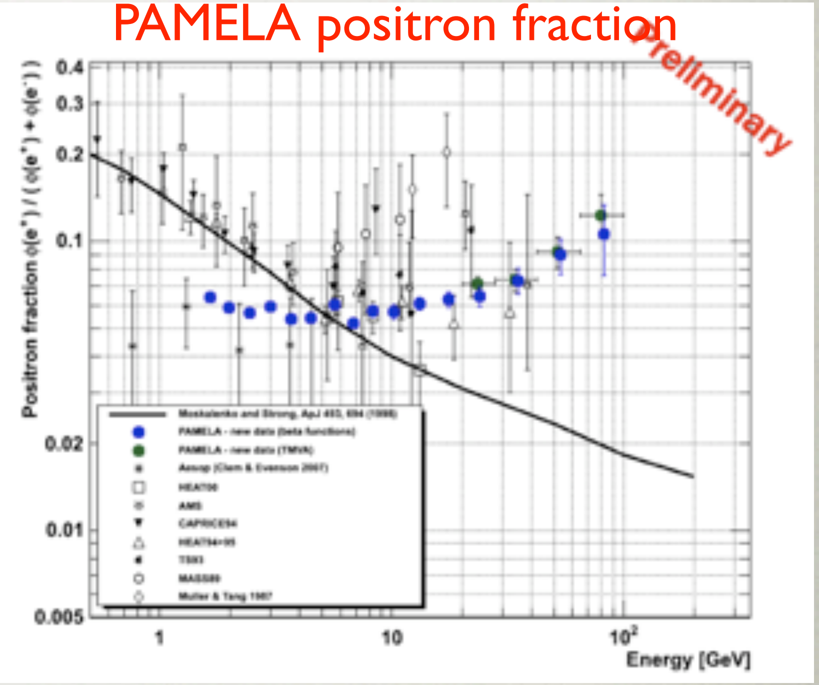
  PAMELA positron fraction

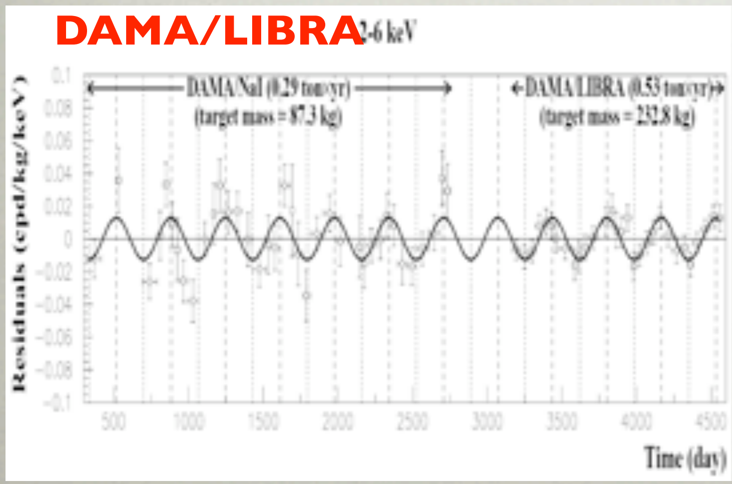
  WMAP haze and potentially related excesses in the Fermi data (Finkbeiner et al, Dobler et al)

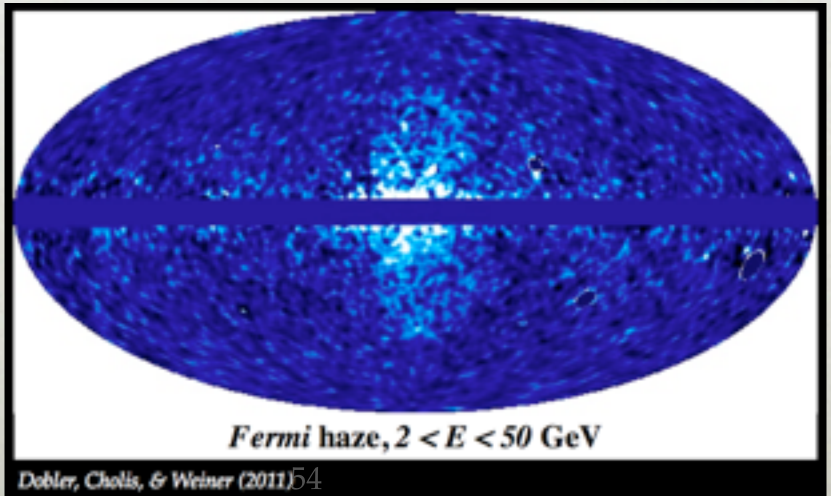
  Fermi Galactic center (Hooper et al)

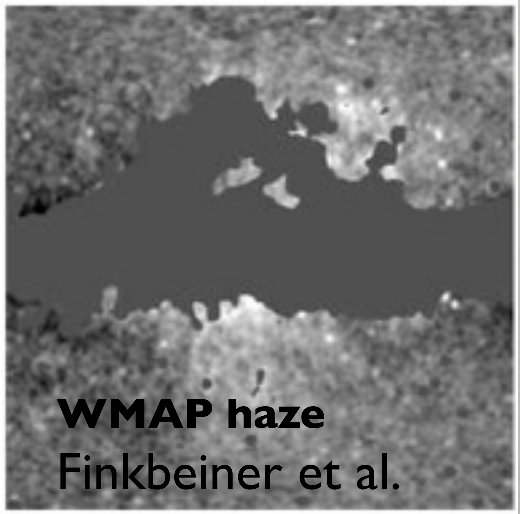
  DAMA/LIBRA, CoGeNT annual modulation

  (...)









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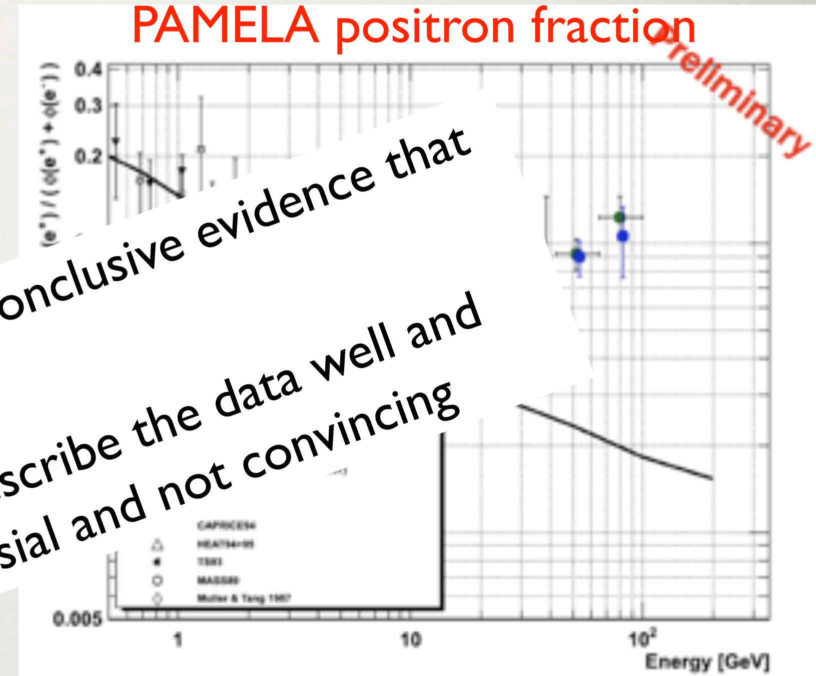
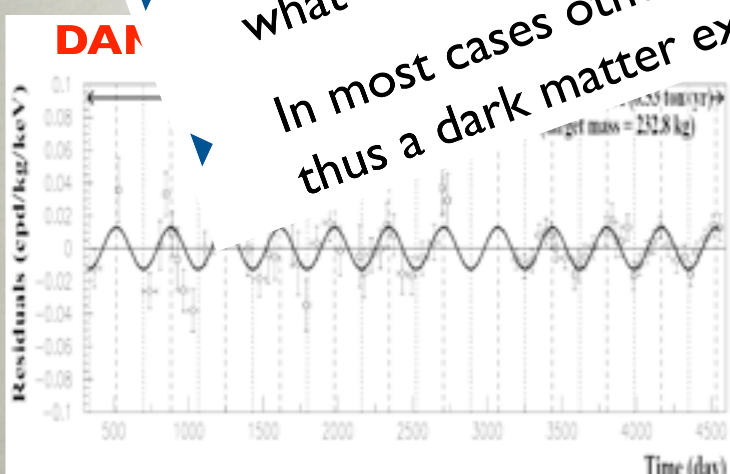
  DAMA/LIBRA, CoGeN

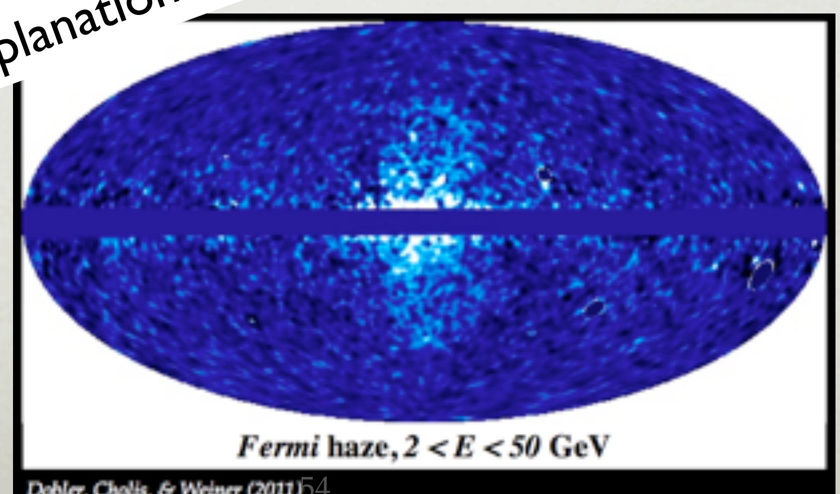
  (...)

Unfortunately NONE of these potential signals are conclusive evidence that what we are seeing is dark matter

In most cases other more prosaic explanations describe the data well and thus a dark matter explanation is very controversial and not convincing







Conclusions

- No discovery yet unfortunately... however promising constraints on the nature of DM have been placed.
- Our knowledge of the astrophysical background is uncertain. This is currently a big limitation in particular for the Galactic center and the Galactic halo which otherwise have huge potential in terms of discovery or setting constraints.
- Some analyses will further benefit from multi-wavelength observations (e.g. dSph and DM satellites.) And if a signal is observed elsewhere (e.g. LHC) it's likely to make our job easier!
- Upcoming and future experiments (e.g. CTA, AMS) will significantly improve the reach of indirect dark matter searches.
- In addition, better understanding of the dark matter density distribution is essential in interpreting observations.


Exciting Times Ahead!