A Compelling Case for Annihilating Dark Matter

Tim Linden

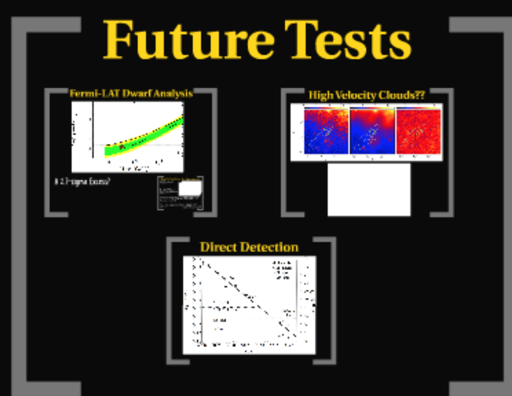
along with:

Tansu Daylan, Doug Finkbeiner, Dan Hooper, Stephan Portillo, Nick Rodd, Tracy Slatyer

arXiv: 1402.6703

Sungkyunkwan University Seminar - October 15, 2014

It's a compelling case -- but what is next?



Thank you for attending!

Any Questions?

A Compelling Case for Annihilating Dark Matter

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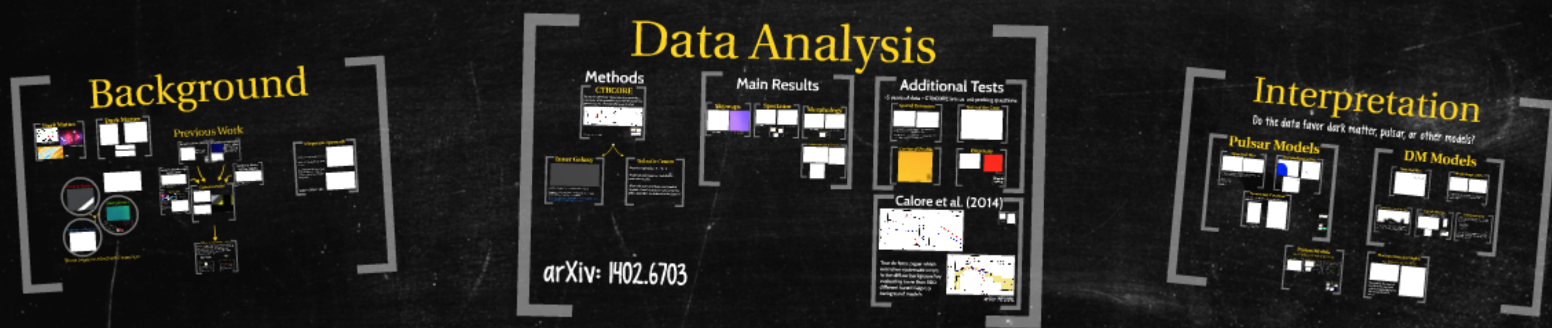

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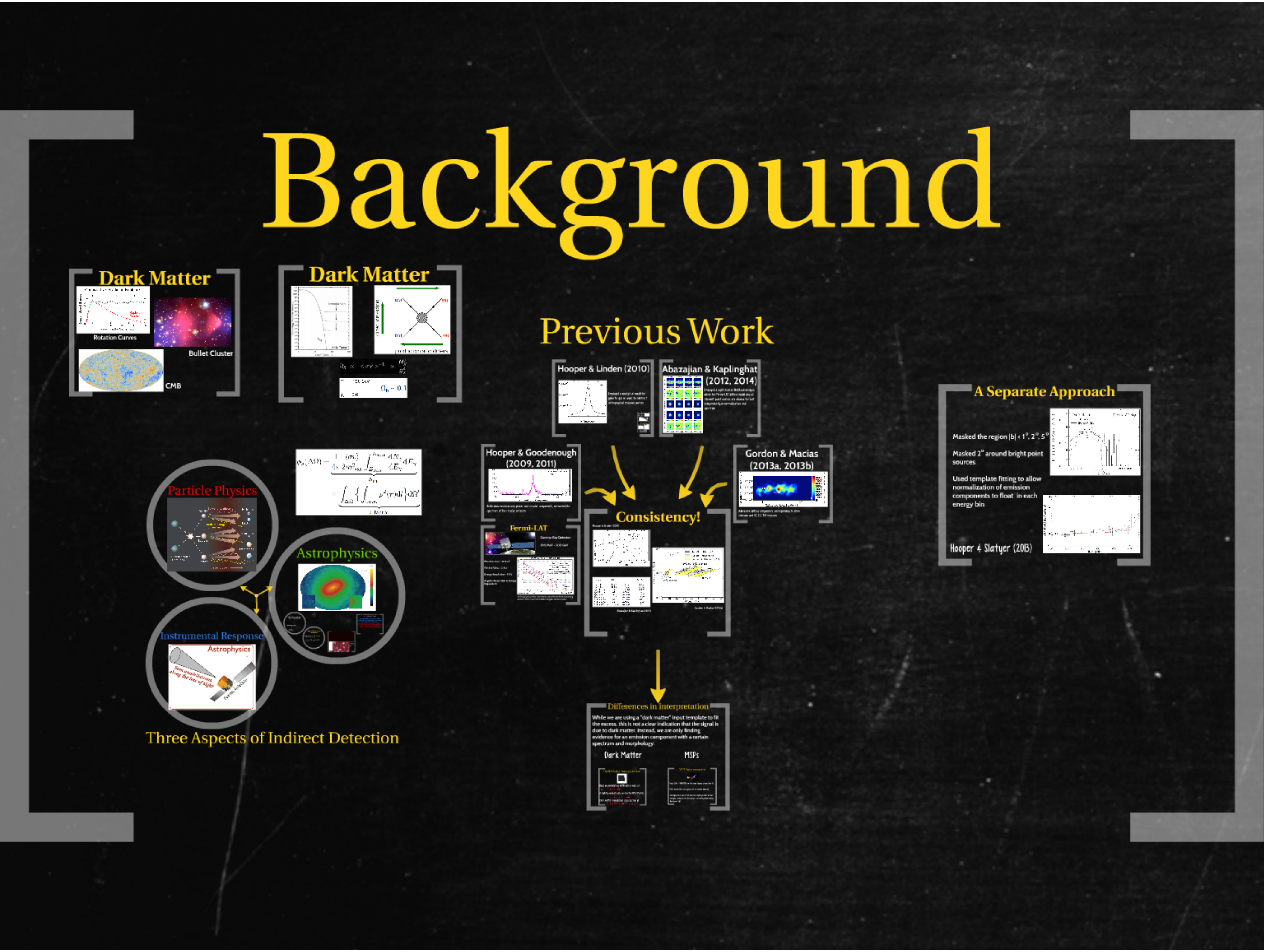

Background
Dark Matter
Rotation Curves
Bullet Cluster
CMB
Dark Matter
Previous Work
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Abazajian & Kaplinghat (2012, 2014)
Hooper & Goodenough (2009, 2011)
Gordon & Macias (2013a, 2013b)
Fermi-LAT
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A Separate Approach
Masked the region |b| < 1°, 2°, 5°
Masked 2° around bright point sources
Used template fitting to allow normalization of emission components to float in each energy bin
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Particle Physics
Astrophysics
Instrumental Response
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Three Aspects of Indirect Detection
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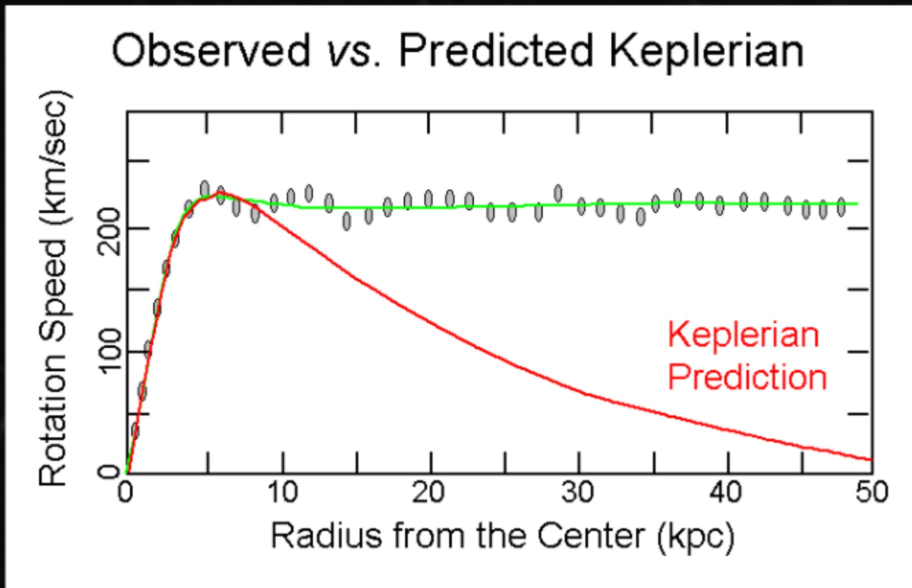
Dark Matter
MSPs

Dark Matter



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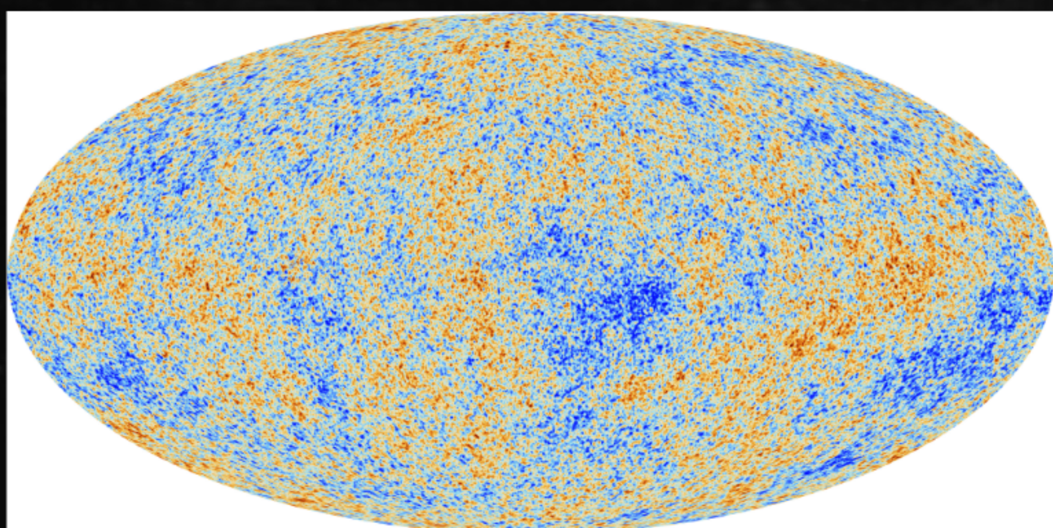

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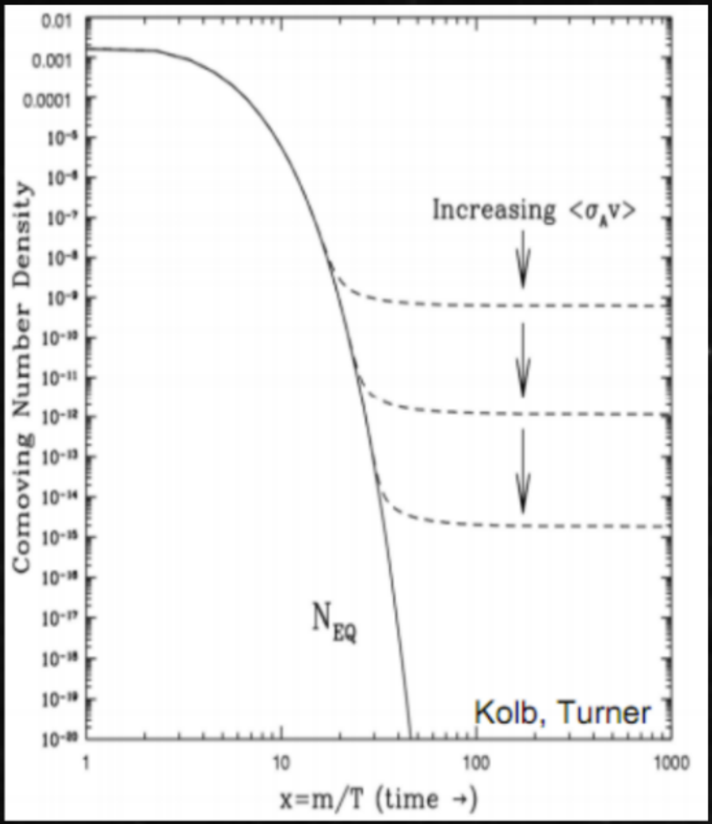
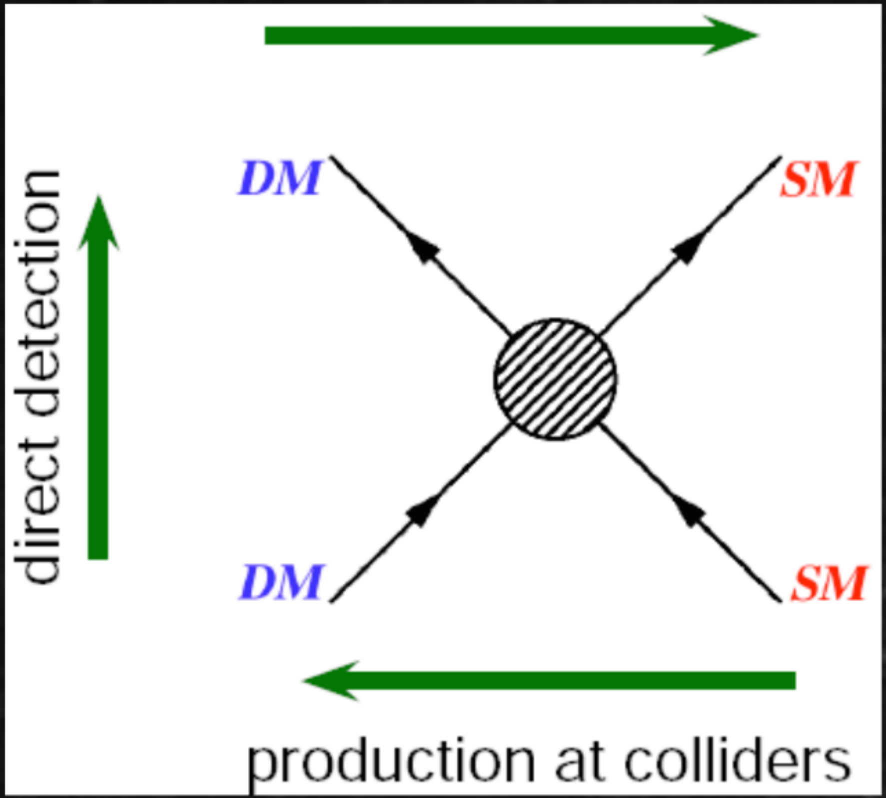




$$\Omega_h \propto \, <\sigma v>^{-1} \propto \frac{M_X^2}{g_X^4}$$

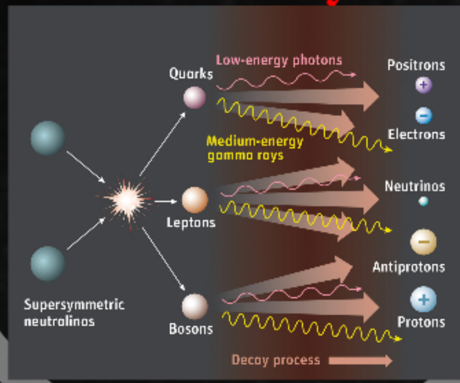
$M_X{}^2$ = 100 GeV

$g_X{}^4$ = 0.6

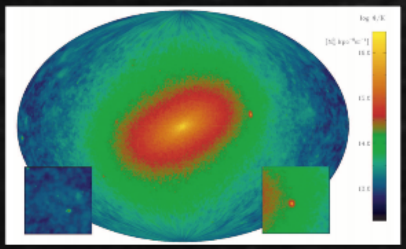
$\Omega_h \sim 0.1$

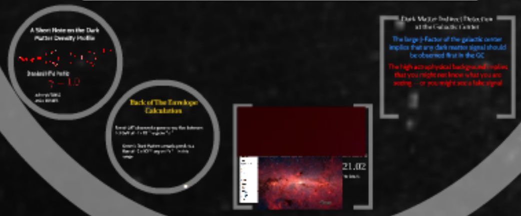
$$\phi_s(\Delta\Omega) = \underbrace{\frac{1}{4\pi}\frac{\langle\sigma v\rangle}{2m_{\mathrm{DM}}^2}\int_{E_{\mathrm{min}}}^{E_{\mathrm{max}}}\frac{\mathrm{d}N_\gamma}{\mathrm{d}E_\gamma}\mathrm{d}E_\gamma}_{\Phi_{\mathrm{PP}}} \times \underbrace{\int_{\Delta\Omega}\left\{\int_{\mathrm{l.o.s.}}\rho^2(\boldsymbol{r})\mathrm{d}l\right\}\mathrm{d}\Omega'}_{\text{J-factor}}$$

Particle Physics

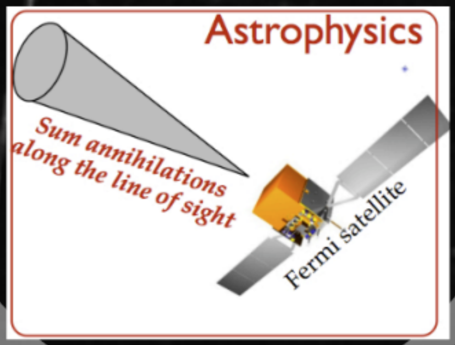


Astrophysics





Instrumental Response



Three Aspects of Indirect Detection

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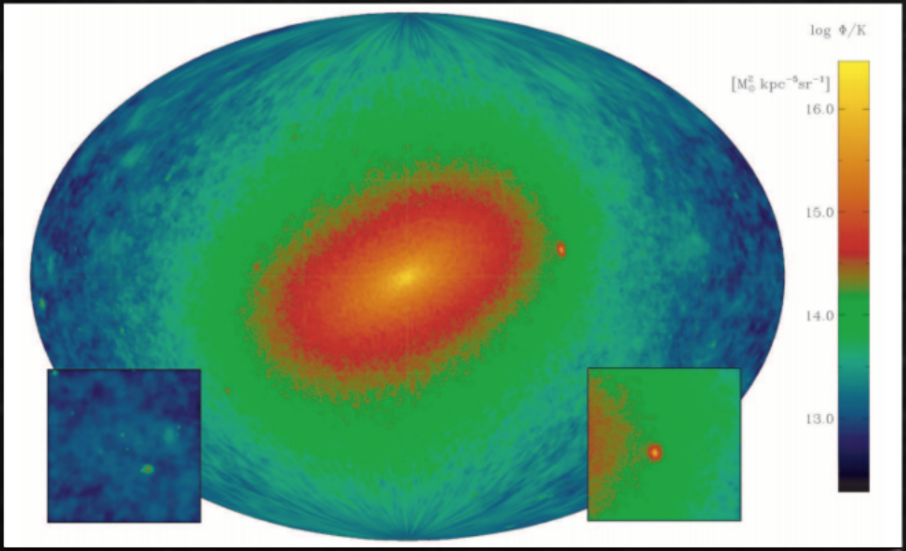
rotons

rotons

Astrophysics



A Short Note on the Dark Matter Density Profile

$$\rho_{NFW} = \left(\frac{r}{r_s}\right)^{-\gamma}\left(1+\frac{r}{r_s}\right)^{-3+\gamma}$$

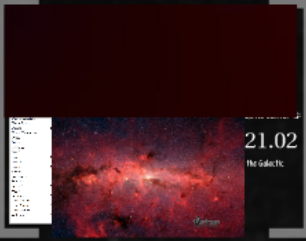
Standard NFW Profile:

$$\gamma = 1.0$$

Back of The Envelope Calculation

Fermi-LAT observed a gamma-ray flux between 1-3 GeV of ~1 x 10[illegible] erg cm^{-2} s^{-1}

Generic Dark Matter scenario predicts a flux of ~2 x 10^{-10} erg cm^{-2}s^{-1} in this range



Dark Matter Indirect Detection at the Galactic Center

The large J-Factor of the galactic center implies that any dark matter signal should be observed first in the GC

The high astrophysical background implies that you might not know what you are seeing -- or you might see a fake signal

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astro-ph/9508025
arXiv: 0809.0898

Bac

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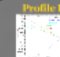
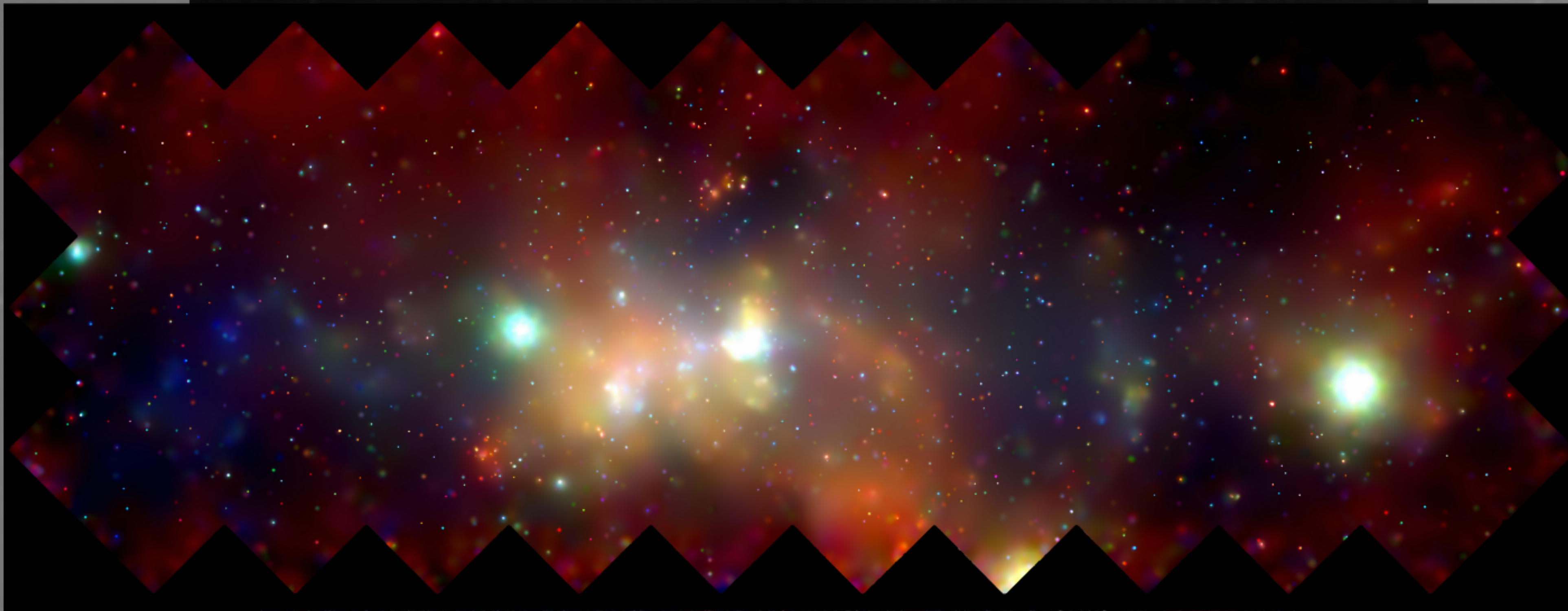
Profile Dependence





Canes Venatici II
Canis Major
Carina
Coma Berenices
Draco
Fornax
Hercules
Leo I
Leo II
Leo IV
Leo V
Pisces II
Sagittarius
Sculptor
Segue 1
Segue 2
Sextans
Ursa Major I
Ursa Major II
Ursa Minor
Willman 1

21.02

the Galactic

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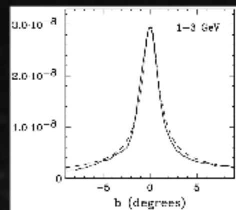

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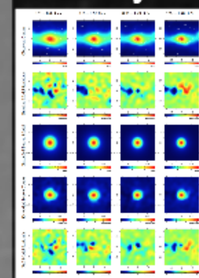

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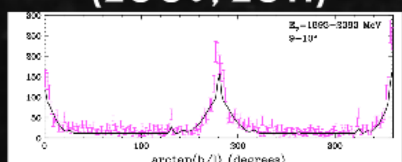

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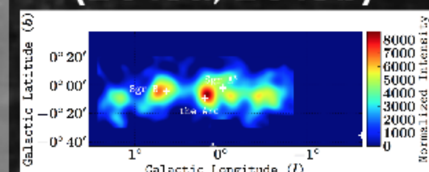


Added new diffuse components corresponding to 20cm emission and H.E.S.S. TeV emission

Fermi-LAT

Gamma-Ray Detector:

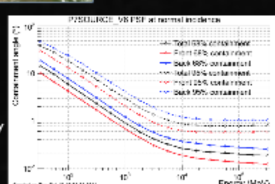
100 MeV - 300 GeV

Effective Area ≈ 0.8 m²

Field of View ≈ 2.4 sr

Energy Resolution ~ 10%

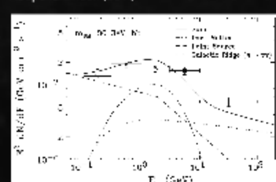
Angular Resolution is Energy Dependent



In the galactic center, we restrict ourselves to front converting events, which have much better angular reconstruction

Consistency!

Hooper & Linden (2011)



channel, m_χ	TS_α	$-\ln\mathcal{L}$	$\Delta\ln\mathcal{L}$
$b\bar{b}$, 10 GeV	2065.5	139913.6	156.5
$b\bar{b}$, 30 GeV	3400.3	139658.4	411.8
$b\bar{b}$, 100 GeV	1305.1	139581.1	159.0
$b\bar{b}$, 300 GeV	229.4	140053.6	13.5
$b\bar{b}$, 1 TeV	27.6	140108.2	48.0
$b\bar{b}$, 2.5 TeV	7.8	140114.2	−44.0
$\tau^+\tau^-$, 10 GeV	1628.7	139787.7	292.5
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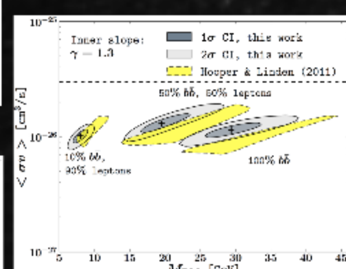
Abazajian & Kaplinghat (2012)



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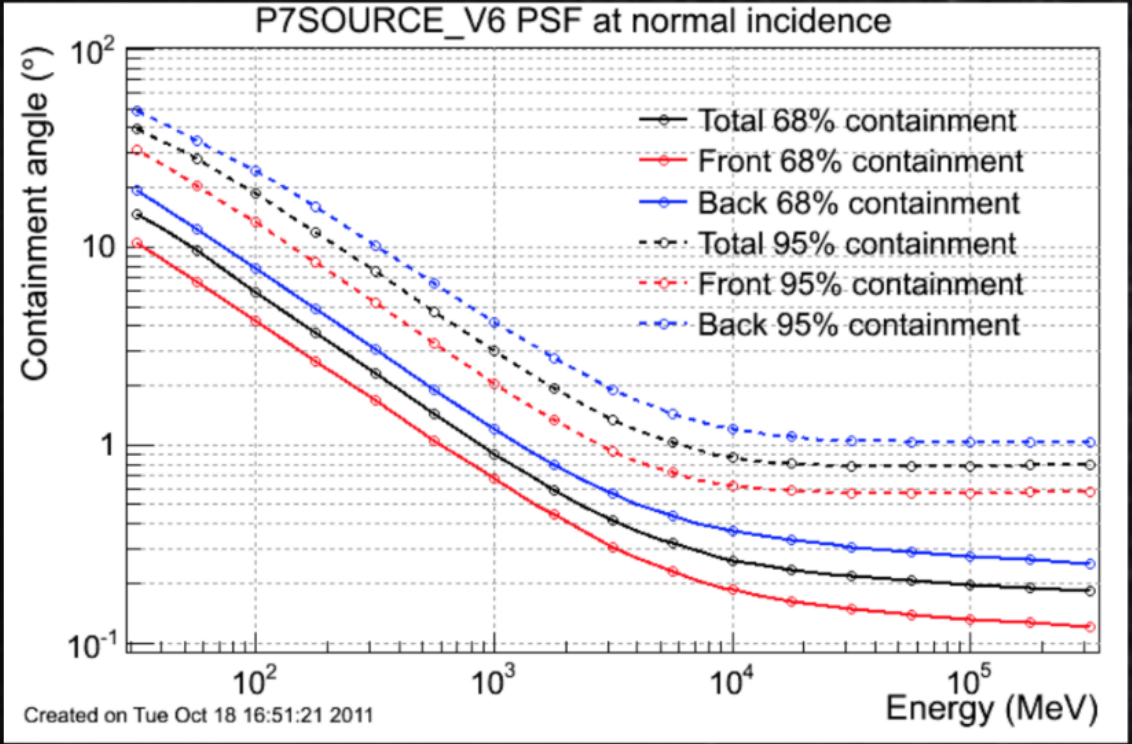

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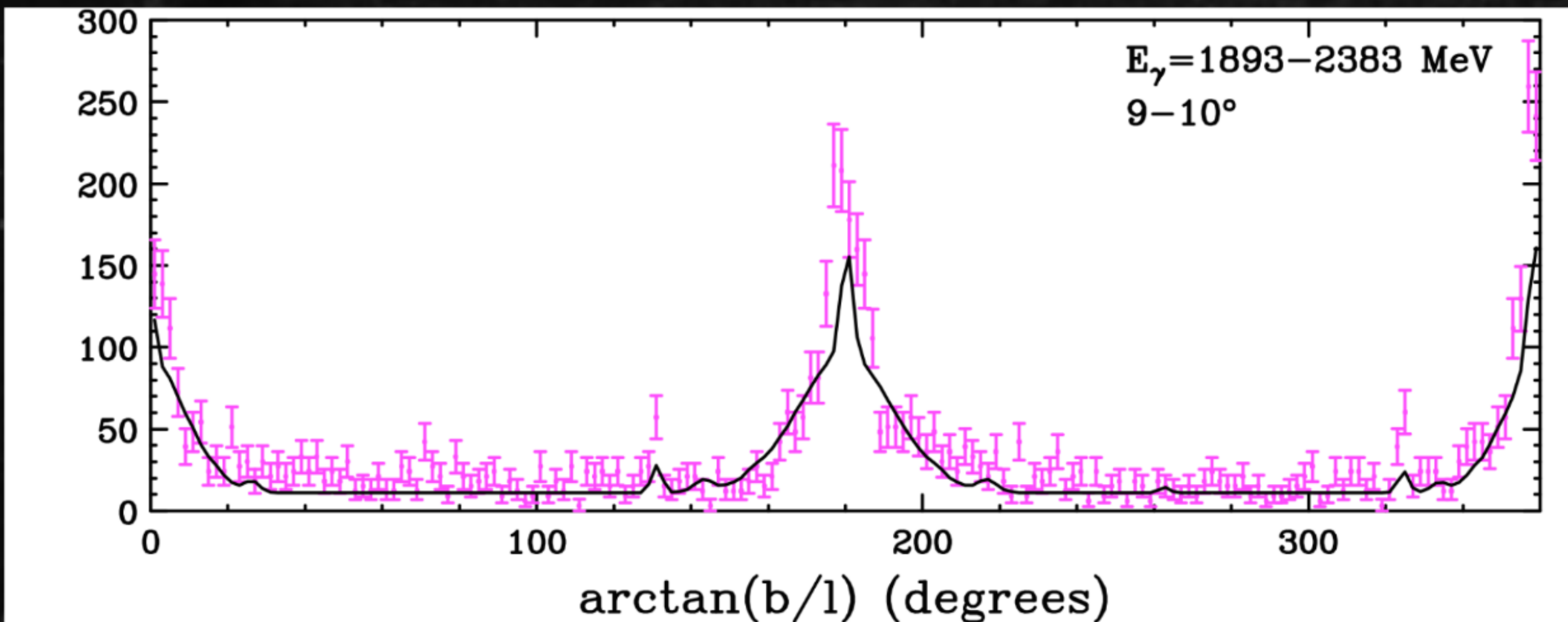

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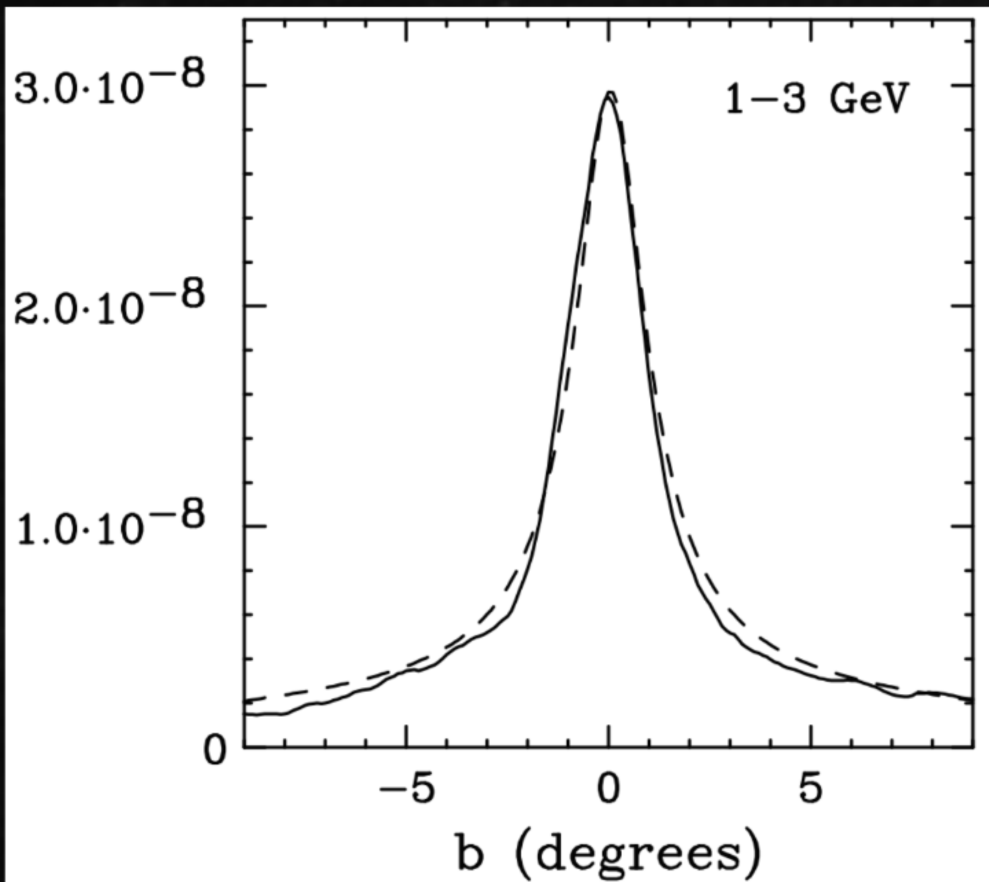

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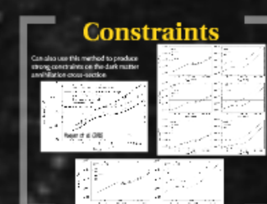

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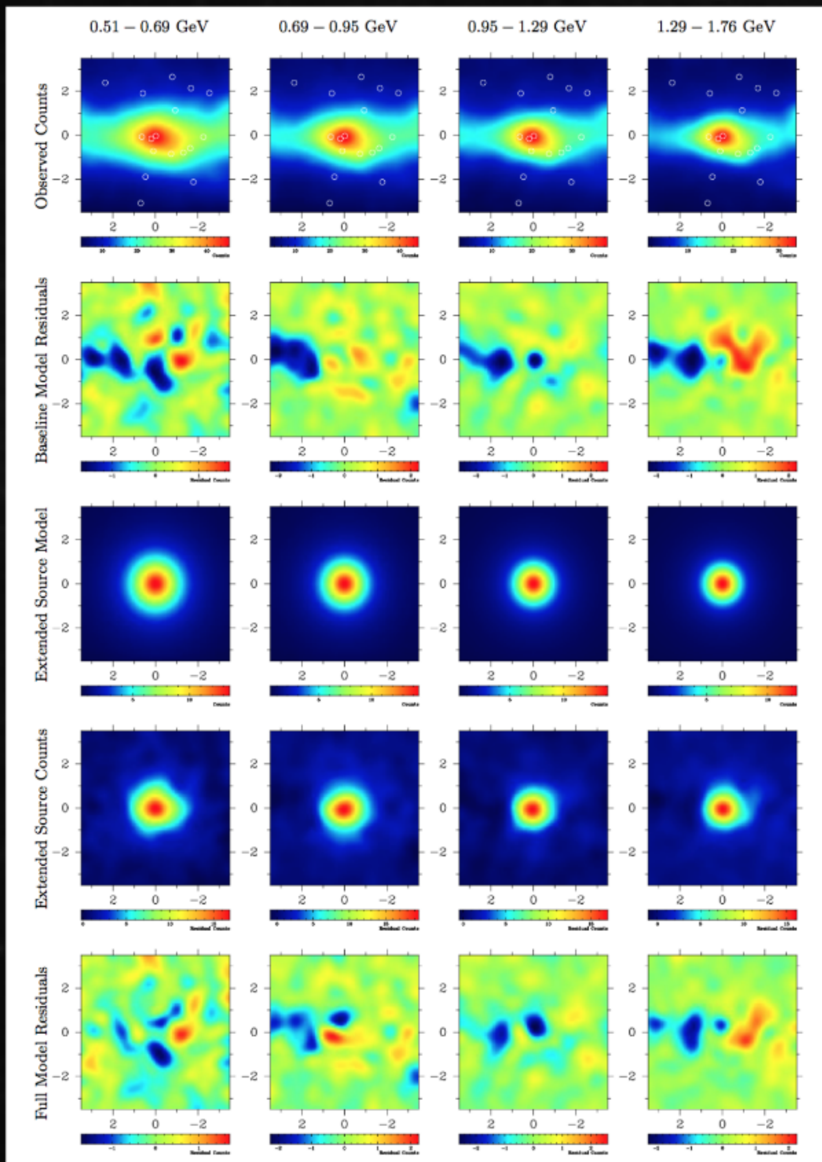

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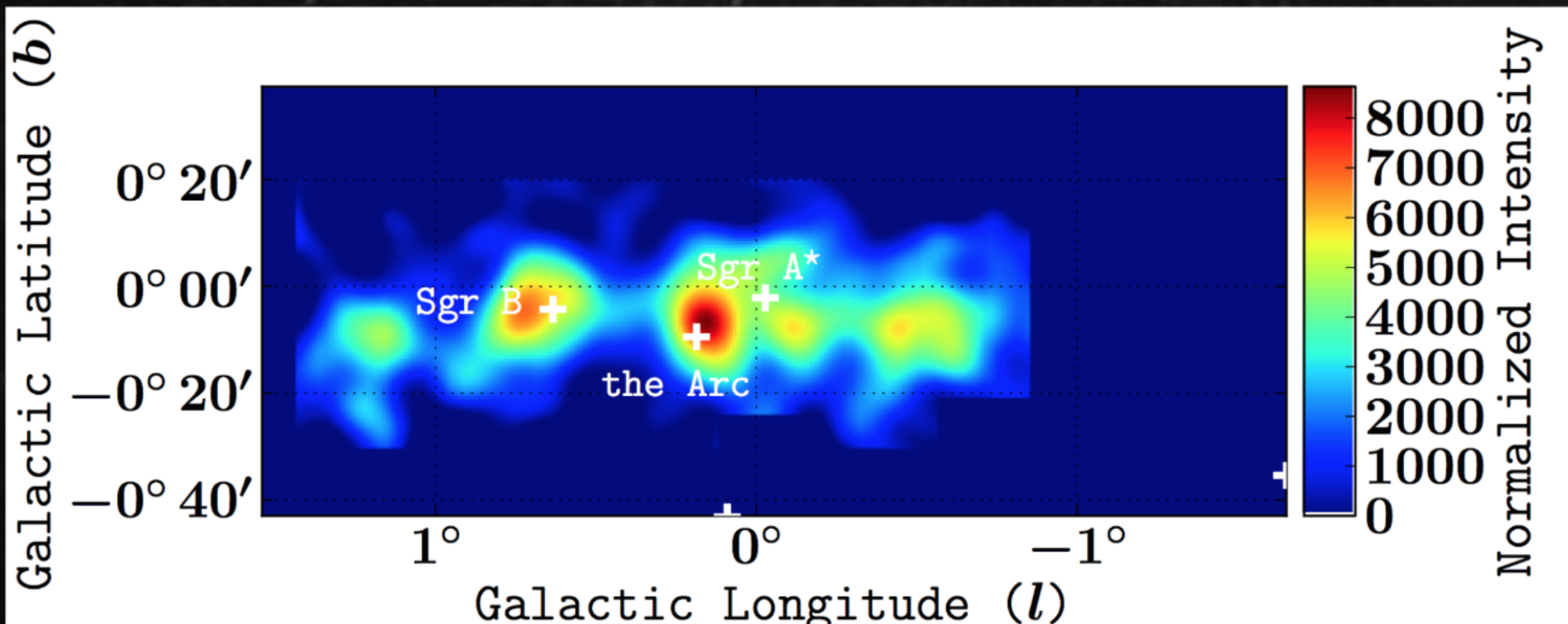

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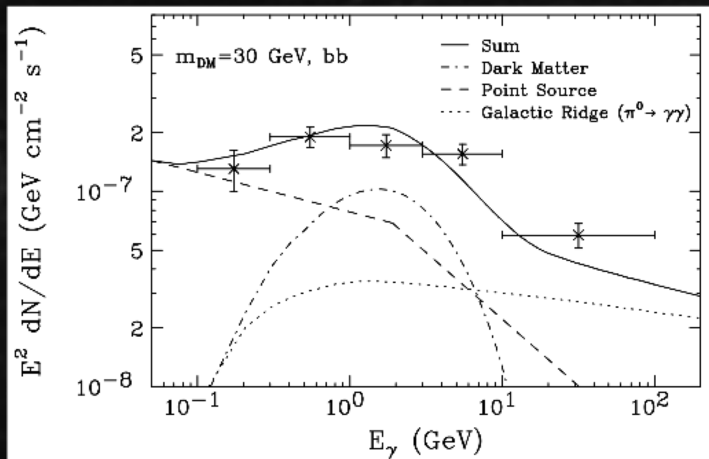

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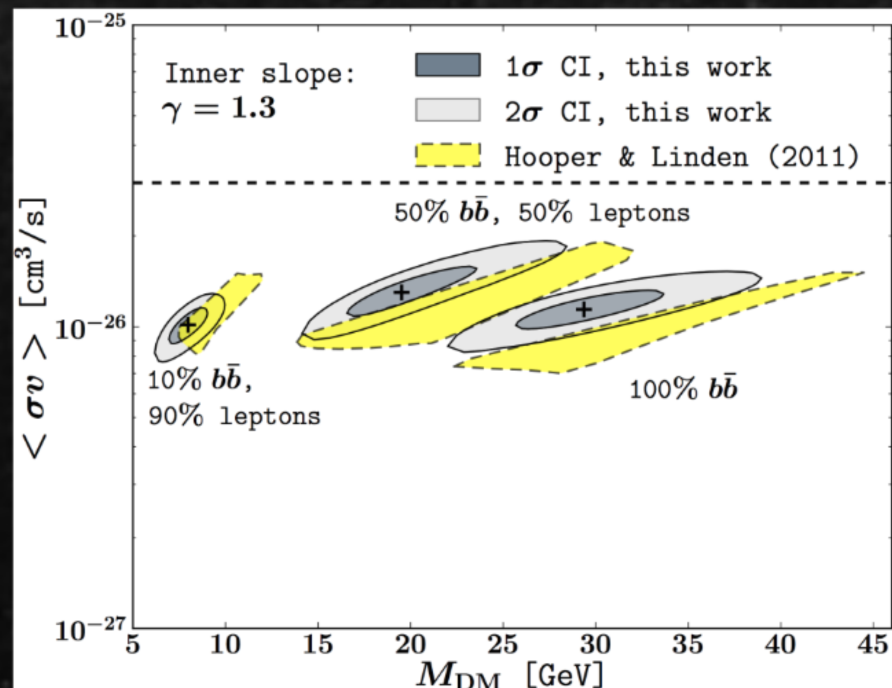

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Differences in Interpretation

While we are using a "dark matter" input template to fit the excess, this is not a clear indication that the signal is due to dark matter. Instead, we are only finding evidence for an emission component with a certain spectrum and morphology.

Dark Matter

Dark Matter Interpretation

Need an annihilating WIMP with a mass of:

$25 - 50\ \mathrm{GeV};\ b\bar{b}$ $8 - 12\ \mathrm{GeV};\ \tau^+\tau^-$

A slightly adiabatically contracted NFW Profile:

$\gamma = 1.1 - 1.3$

Dark matter annihilation cross-section of

$1.5 - 2.5 \times 10^{-26}\ \mathrm{cm^3 s^{-1}}$

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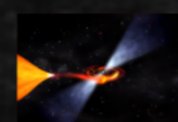

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MSPs must follow the square of the stellar density

Average pulsar spectrum must be slightly harder at low-energies, compared to the pulsars currently observed by the Fermi-LAT

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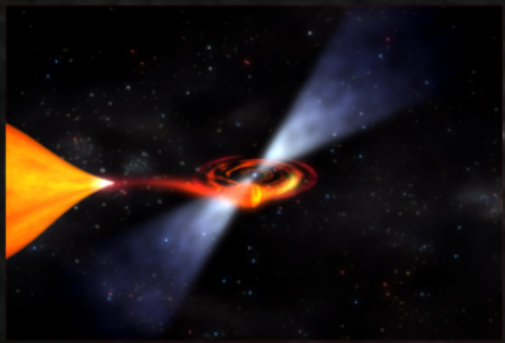

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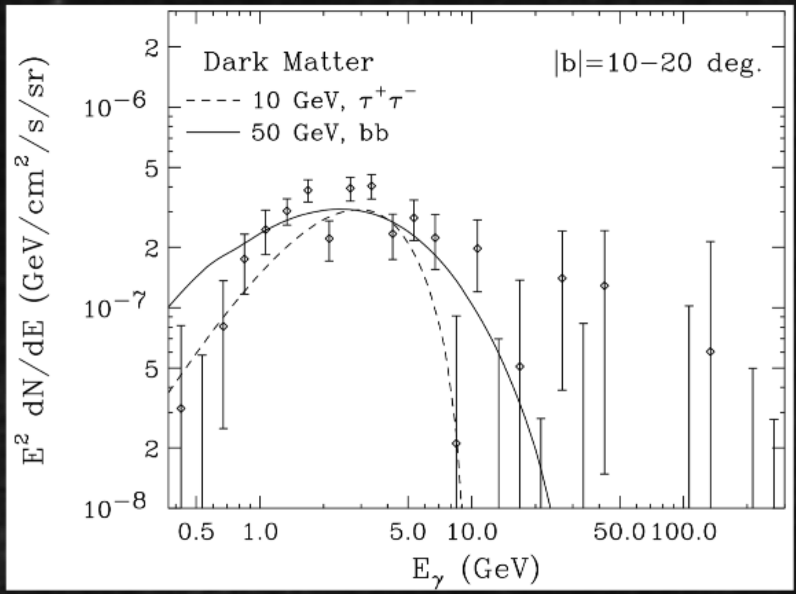

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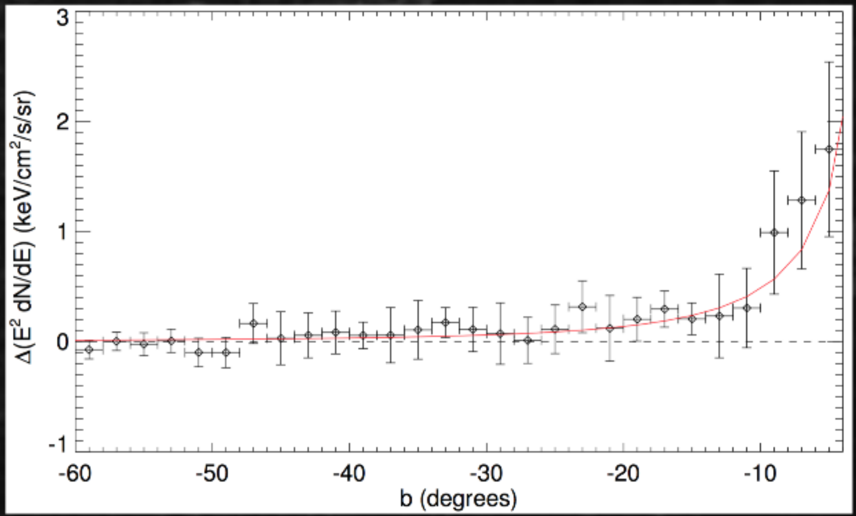

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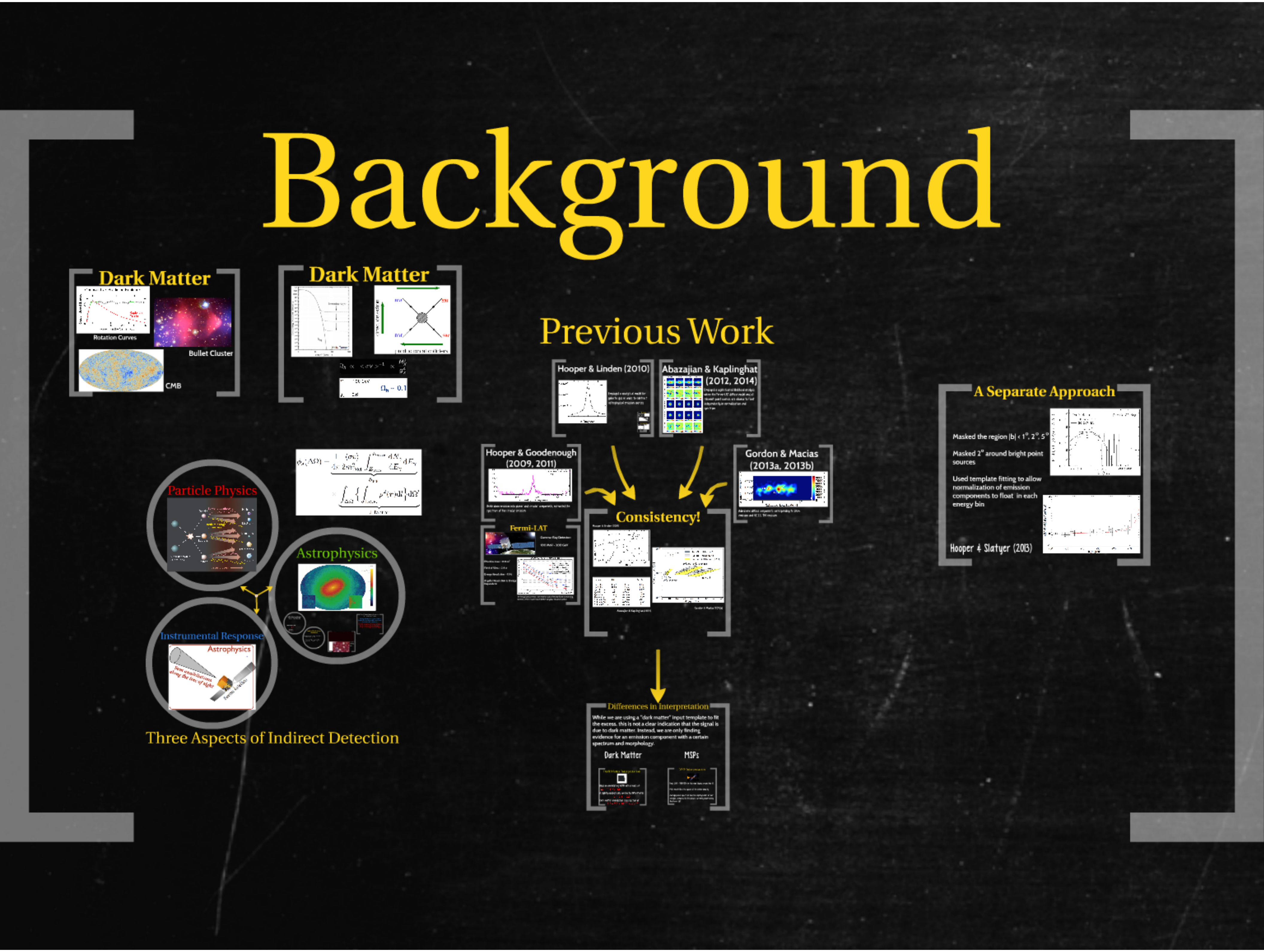
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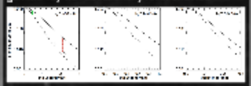
Data Analysis

Methods

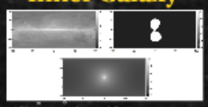
CTBCORE

The Fermi-LAT PASS 7 Data Selection provides a parameter which quantifies how well the incoming gamma-ray was directionally reconstructed



Portillo & Finkbeiner (2014)

Inner Galaxy



Mask $|b| < 1^\circ$ and a 2° radius around all 1FGL Sources

Employ models for the diffuse emission, isotropic emission, Fermi bubbles and a dark matter template

Allow the normalization of each component to float independently in 25 energy bins from 300 MeV to 100 GeV

Galactic Center

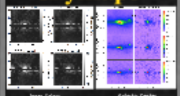
Examine region $|b| < 5^\circ$, $|l| < 5^\circ$

Model all point sources and diffuse emission models

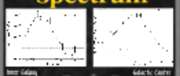
Allow the normalizations and spectral models of each source to vary using the *gtlike* algorithm to determine the best fit

Main Results

Skymaps



Spectrum



Morphology

Additional Tests

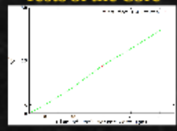
>5 years of data + CTBCORE lets us ask probing questions

Spatial Extension

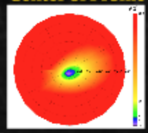
Inner Galaxy - Spatial Extension out to at least 11°, maybe as far as 15° depending on binning

Galactic Center - Spatial Extension out to at least 5°, cutoff due to region exceeding ROI

Tests of the Core

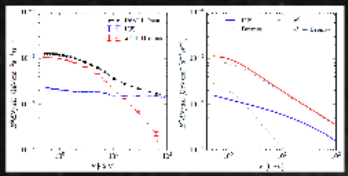


Center of Profile

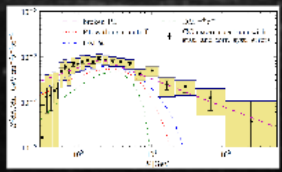


Ellipticity

Calore et al. (2014)



Tour de force paper which examines systematic errors in the diffuse background by evaluating more than 300 different tuned Galprop background models



arXiv: 1409.0042

arXiv: 1402.6703

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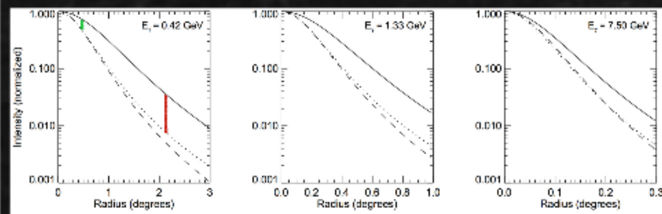
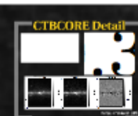
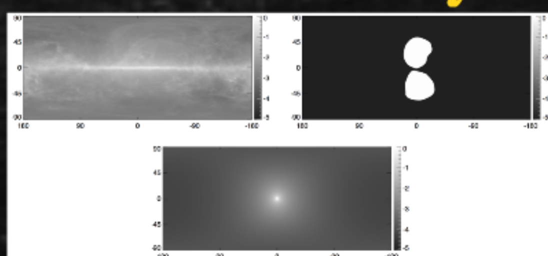




Portillo & Finkbeiner (2014)

Inner Galaxy



Mask |b| < 1° and a 2° radius around all 1FGL Sources

Employ models for the diffuse emission, isotropic emission, Fermi bubbles and a dark matter template

Allow the normalization of each component to float independently in 25 energy bins from 300 MeV to 100 GeV

Galactic Center

Examine region |b| < 5°, |l| < 5°

Model all point sources and diffuse emission models

Allow the normalizations and spectral models of each source to vary using the *gtlike* algorithm to determine the best fit

CTBCORE

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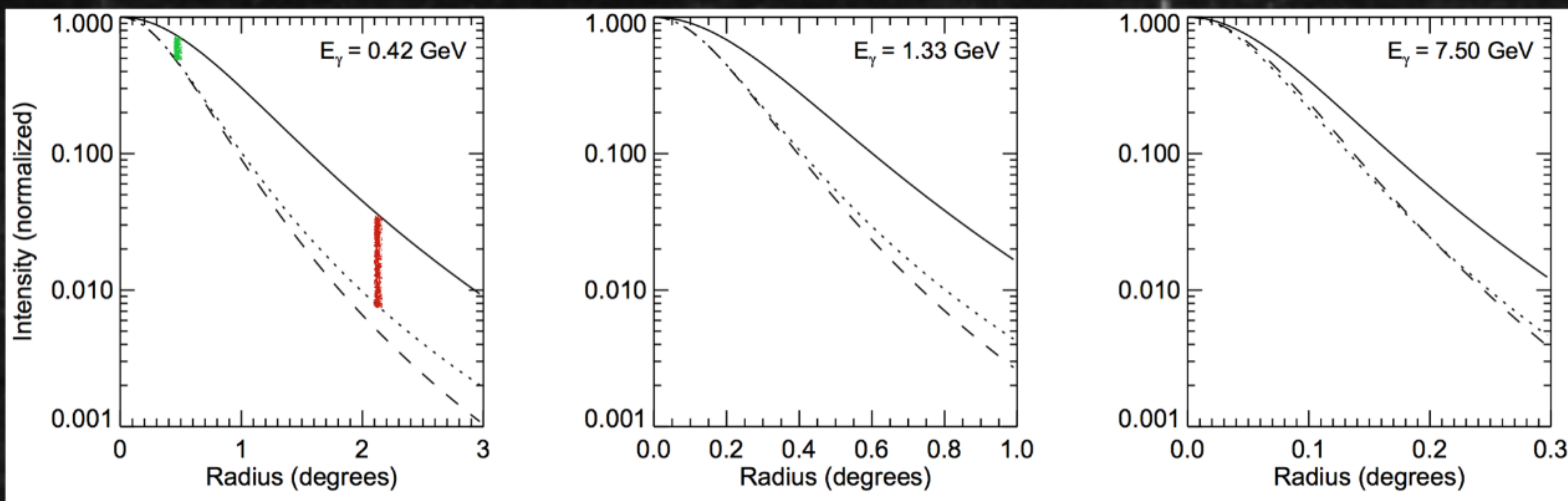

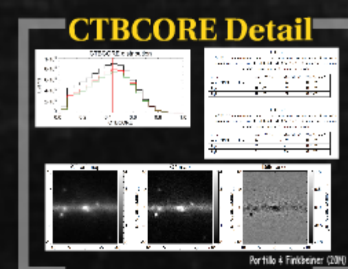

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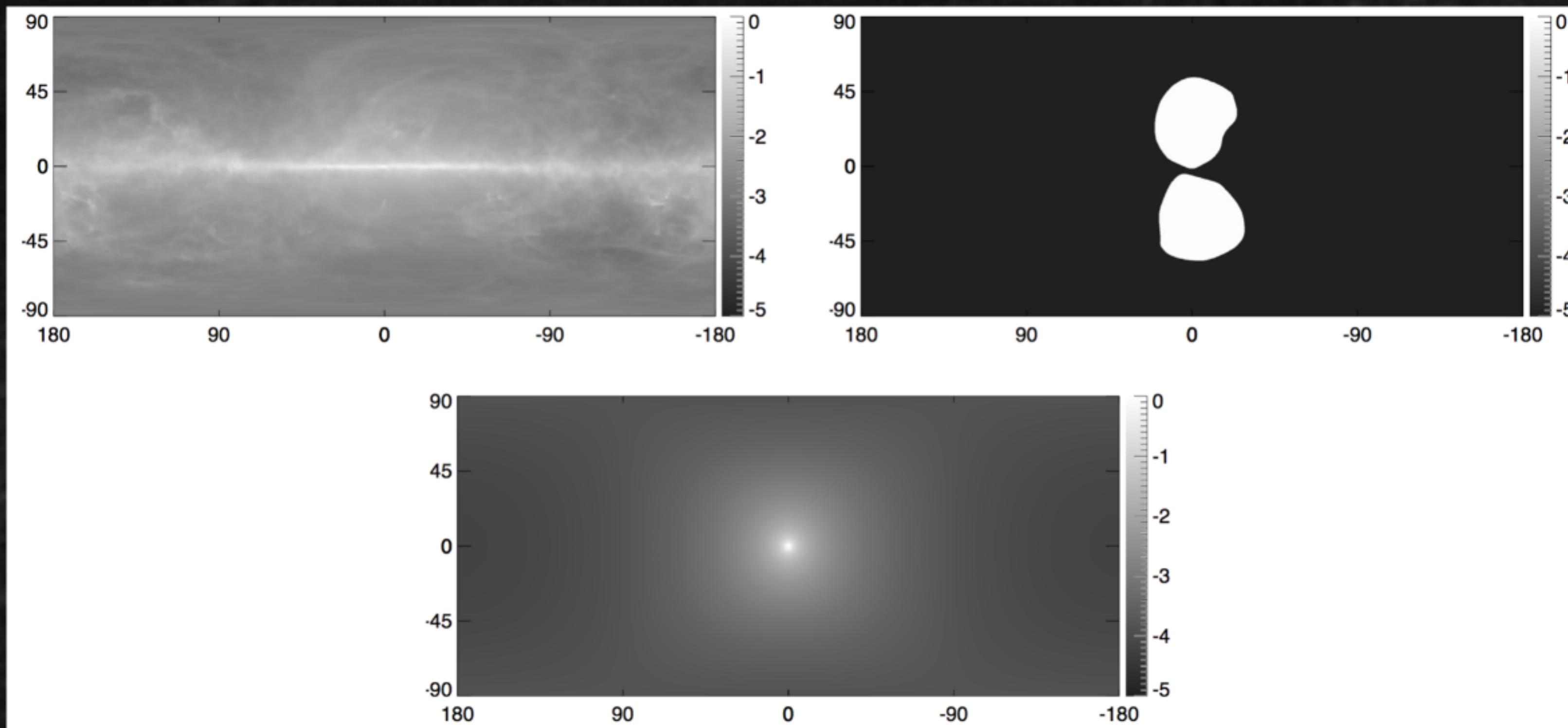

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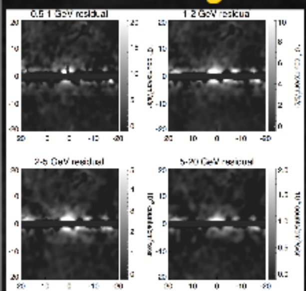
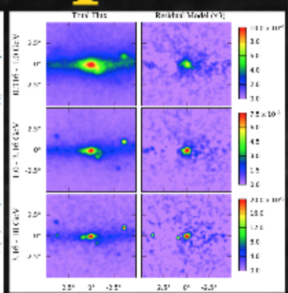
Main Results

Skymaps

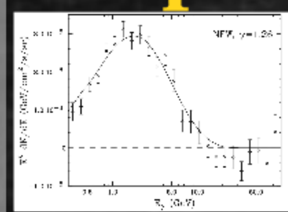


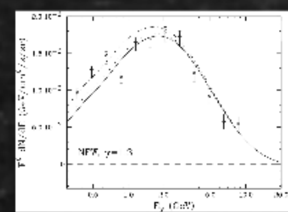


Inner Galaxy

Galactic Center

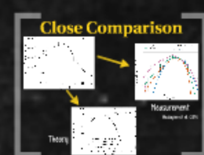
Spectrum



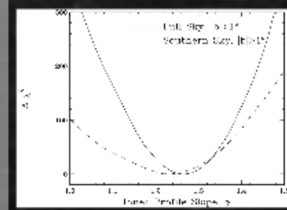


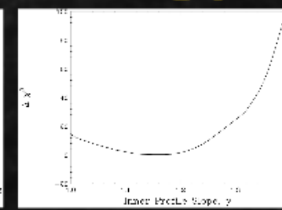
Inner Galaxy

Galactic Center



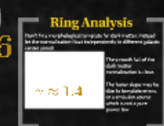
Morphology





Inner Galaxy

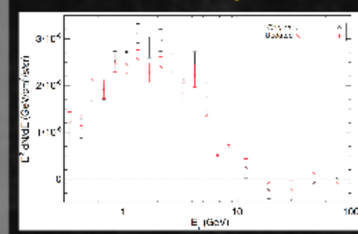
$\gamma \approx 1.26$

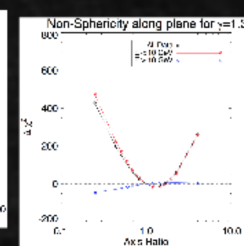


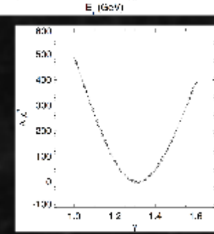
Galactic Center

$\gamma \approx 1.17$

Preliminary Results from Bug Fix







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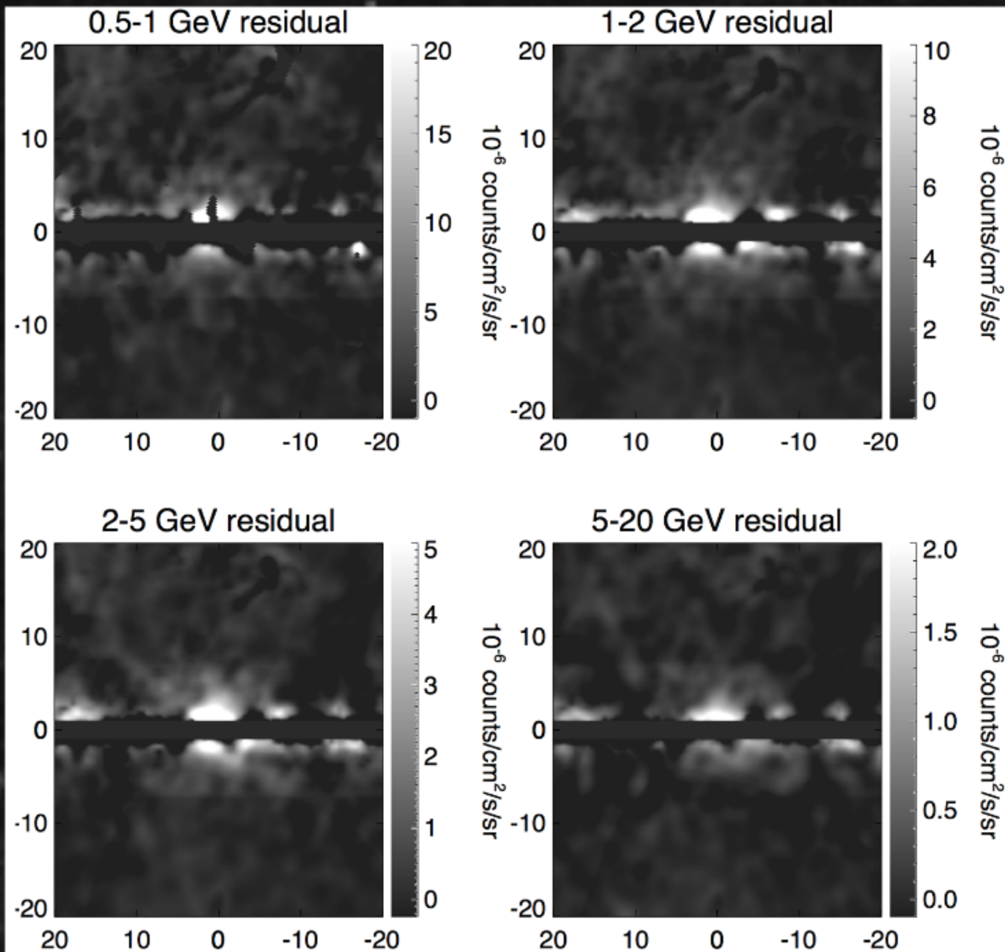
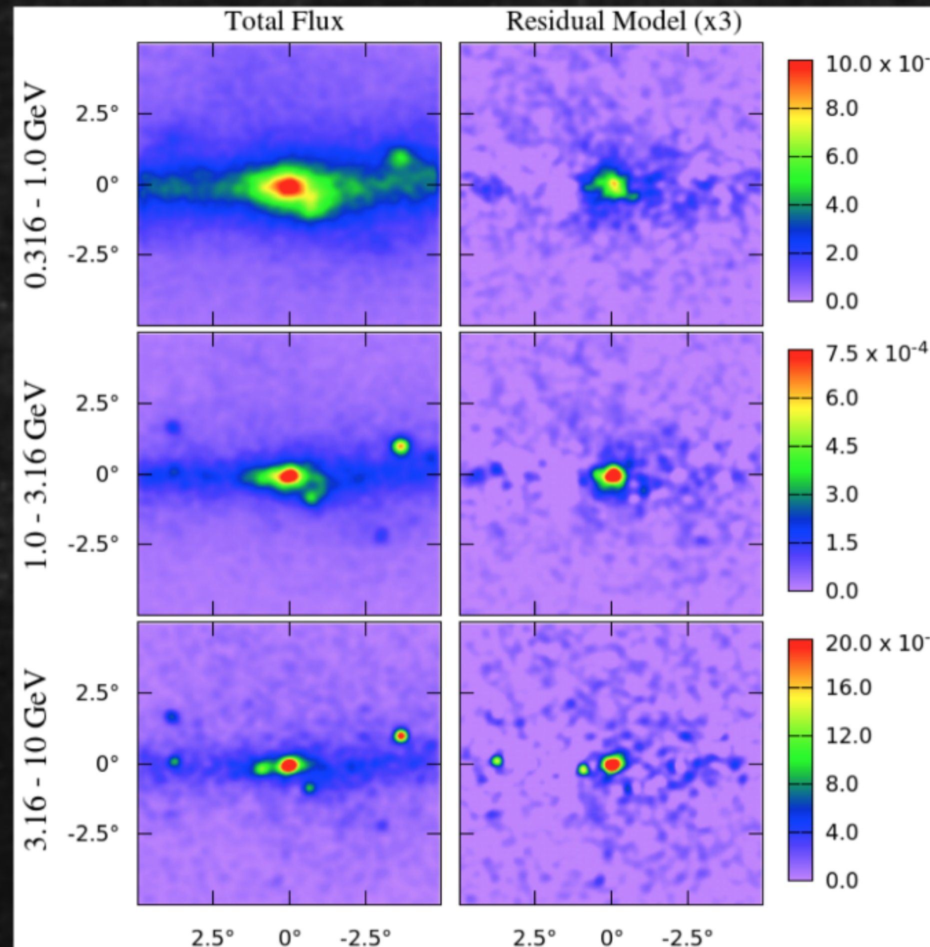
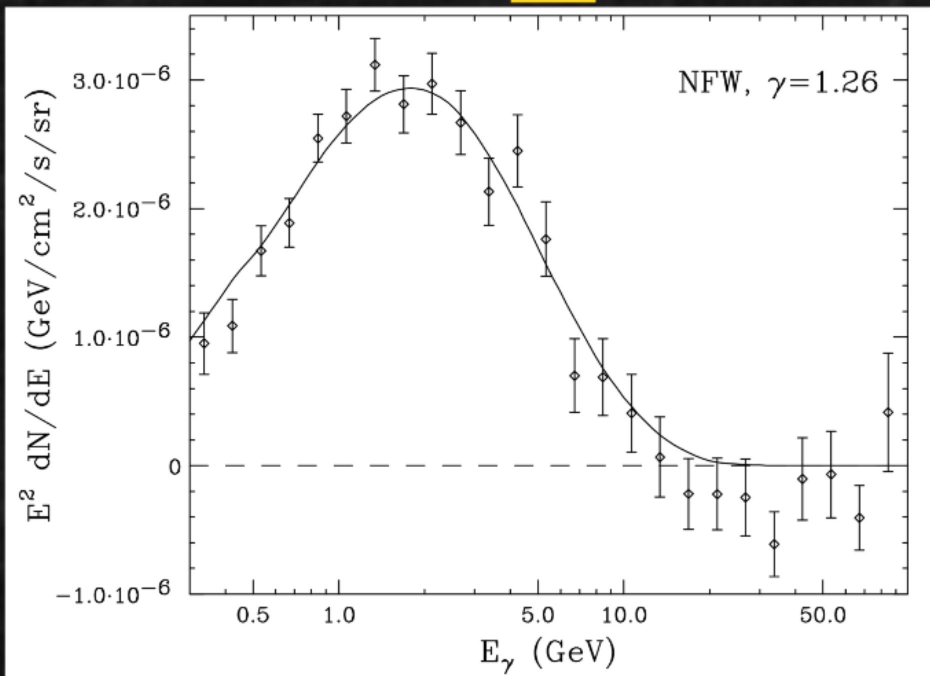




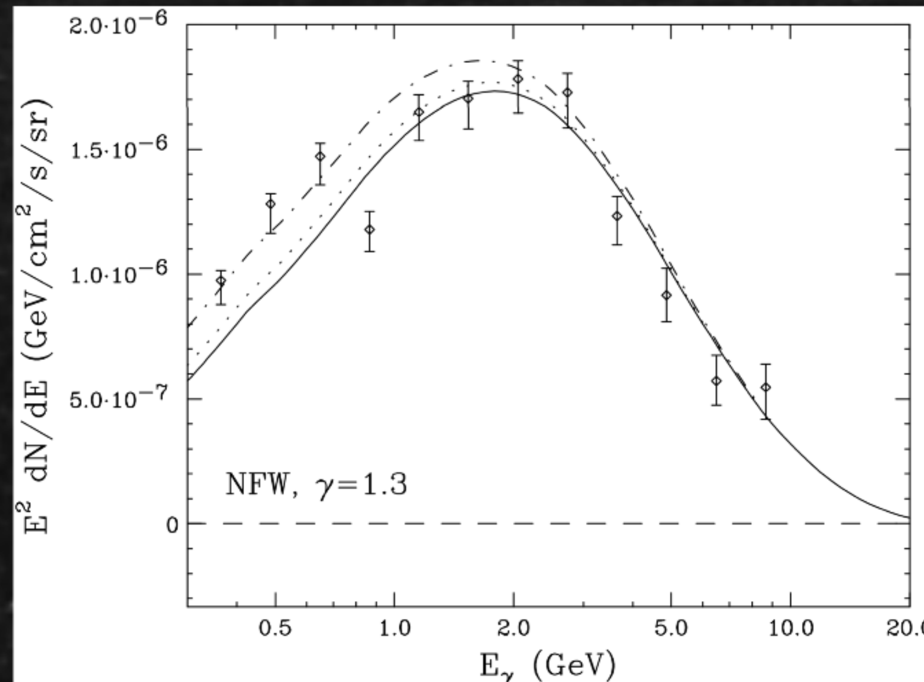
Inner Galaxy

Galactic Center

Spectrum

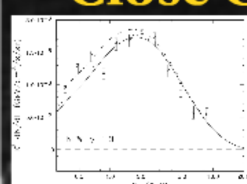


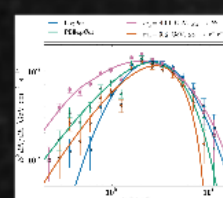
Inner Galaxy



Galactic Center

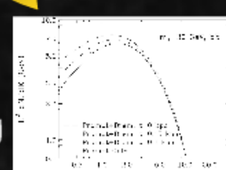
Close Comparison





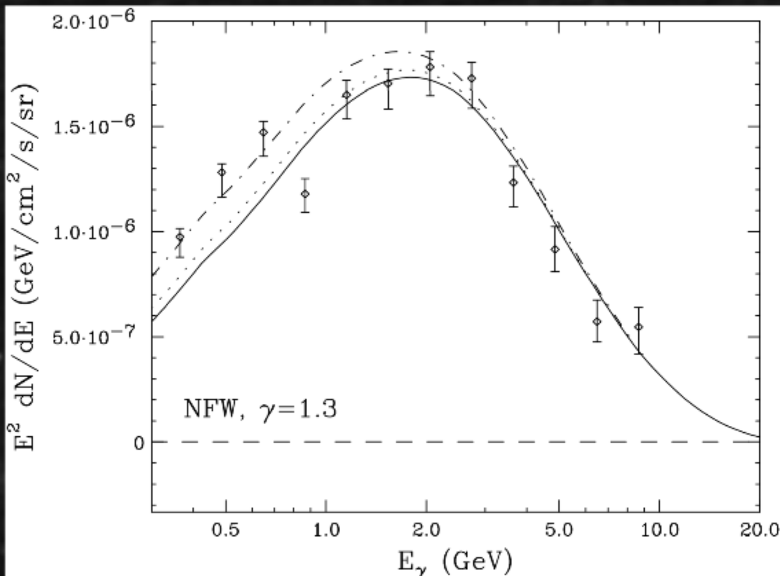
Measurement

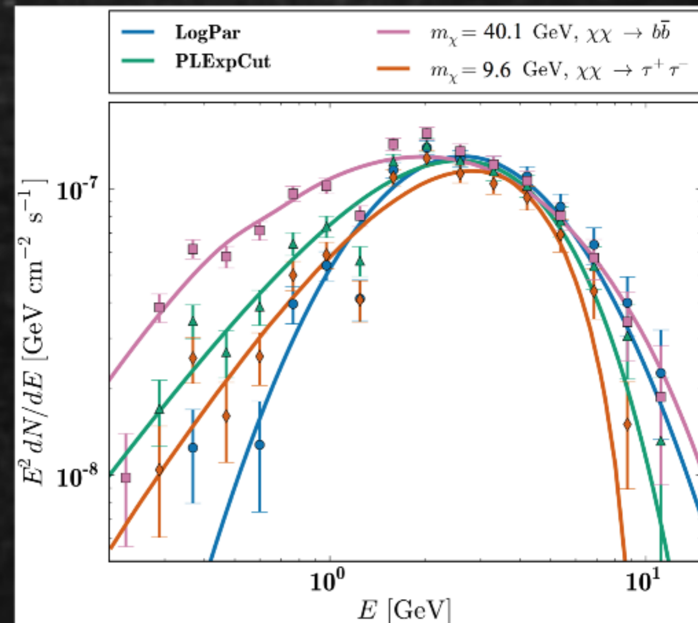
Abazajian et al. (2014)



Theory

Close Comparison





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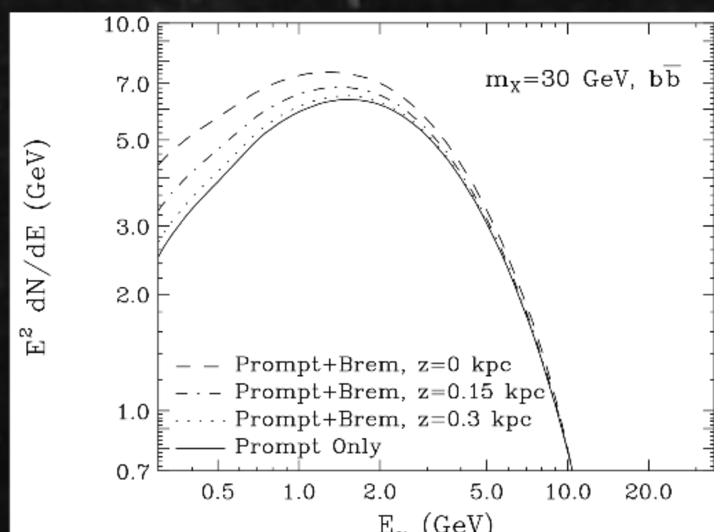
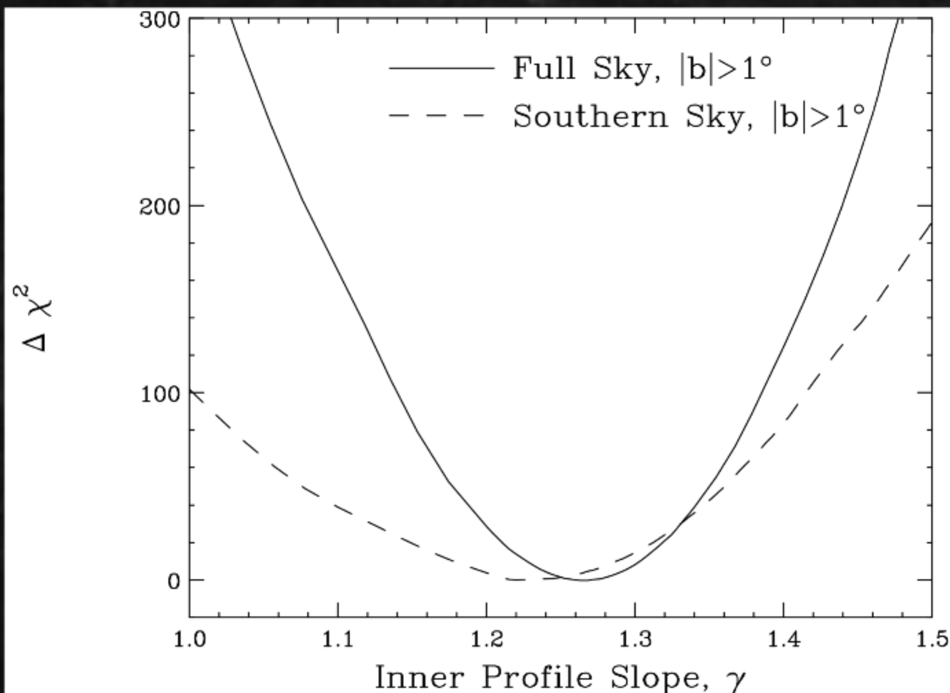
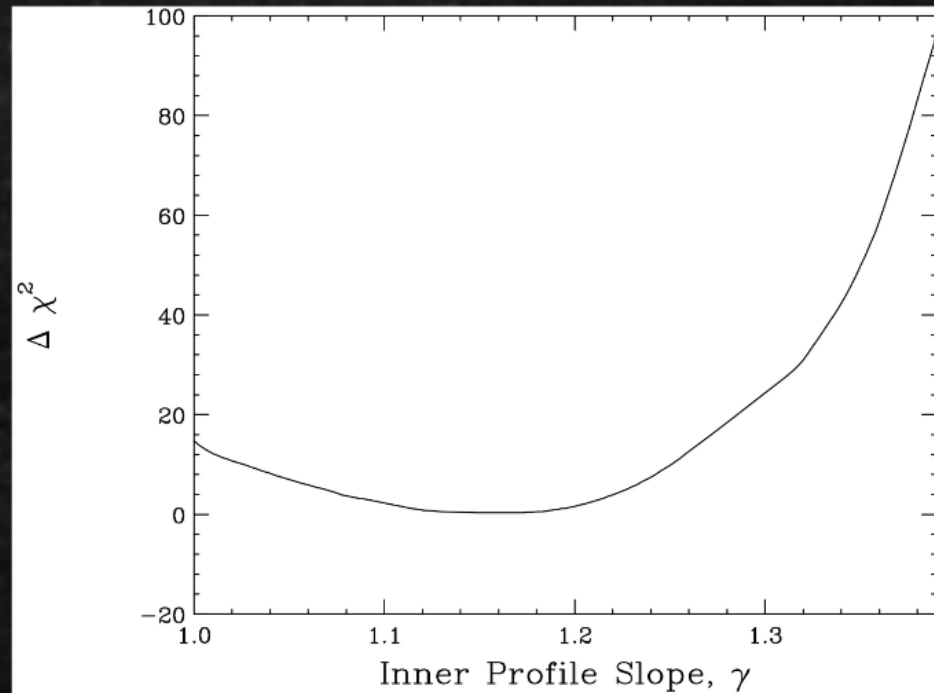


Theory

Morphology



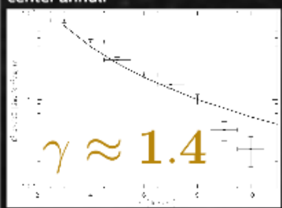


Inner Galaxy

$\gamma \approx 1.26$

Ring Analysis

Don't fix a morphological template for dark matter, instead let the normalization float independently in different galactic center annuli



The smooth fall of the dark matter normalization is clear.

The faster slope may be due to template errors, or a emission source which is not a pure power law

Galactic Center

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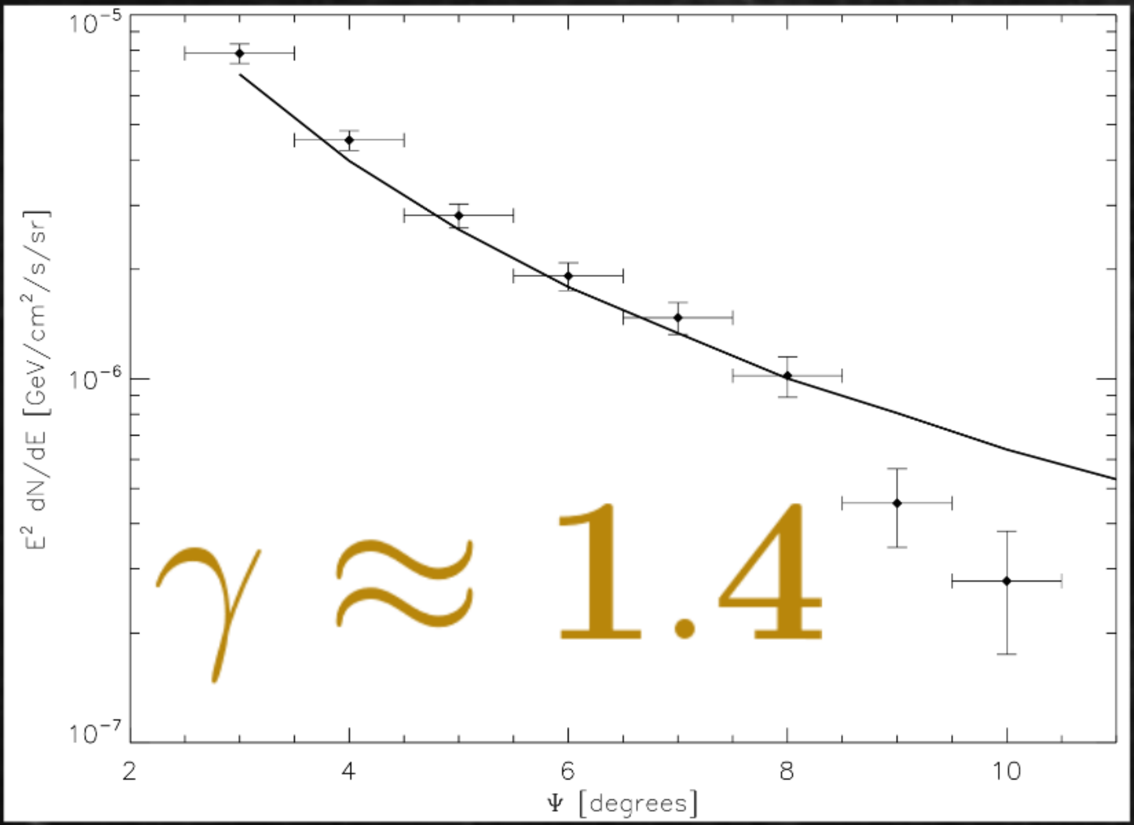

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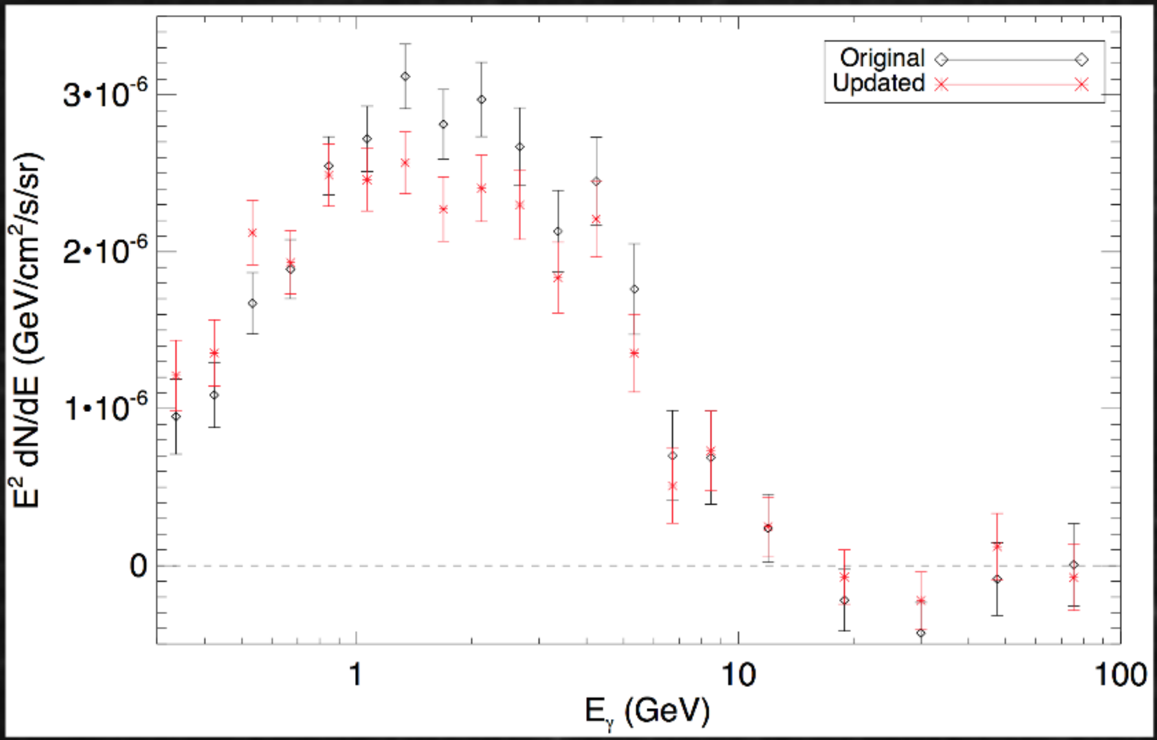
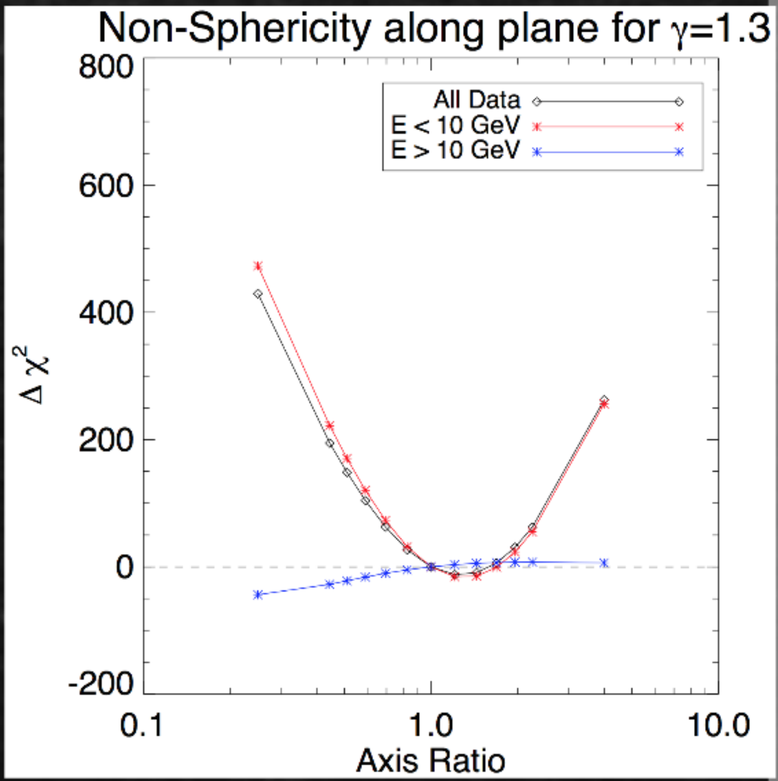
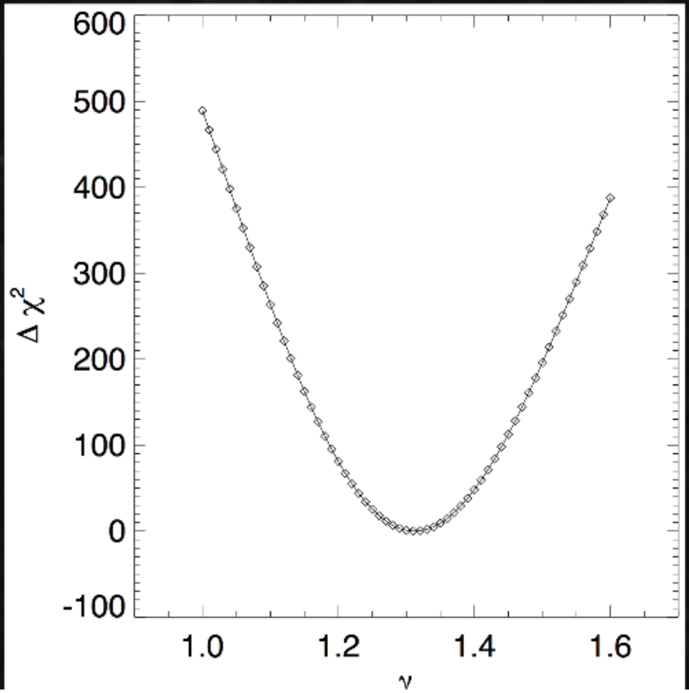


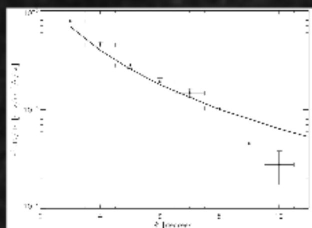


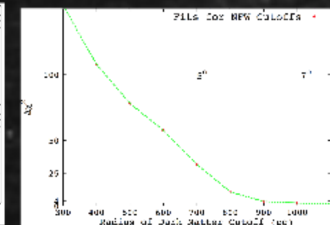


Additional Tests

>5 years of data + CTBCORE lets us ask probing questions

Spatial Extension

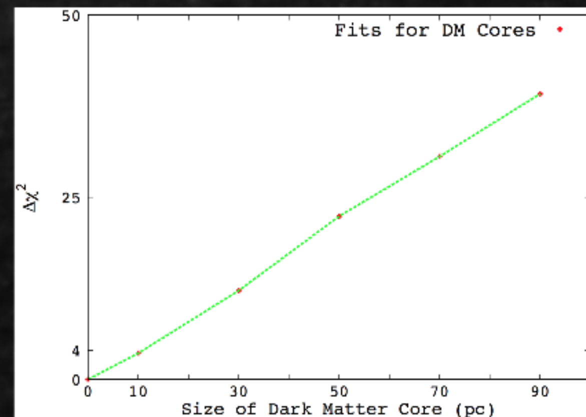




Inner Galaxy - Spatial Extension out to at least 11°, maybe as far as 15° depending on binning

Galactic Center - Spatial Extension out to at least 5°, cutoff due to region exceeding ROI

Tests of the Core



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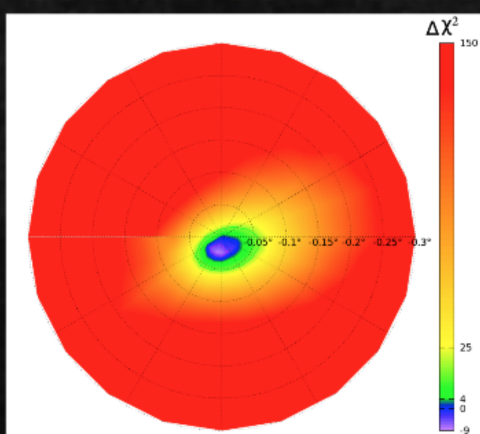
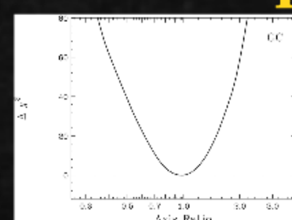
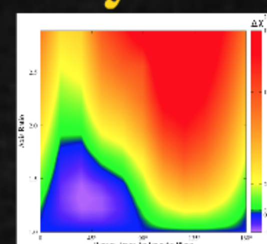


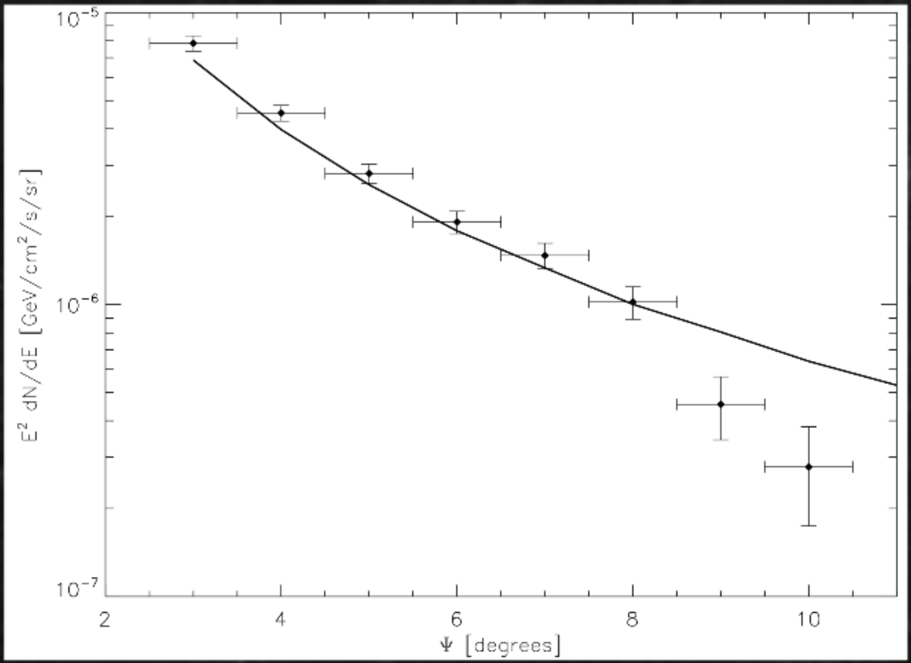
Ellipticity

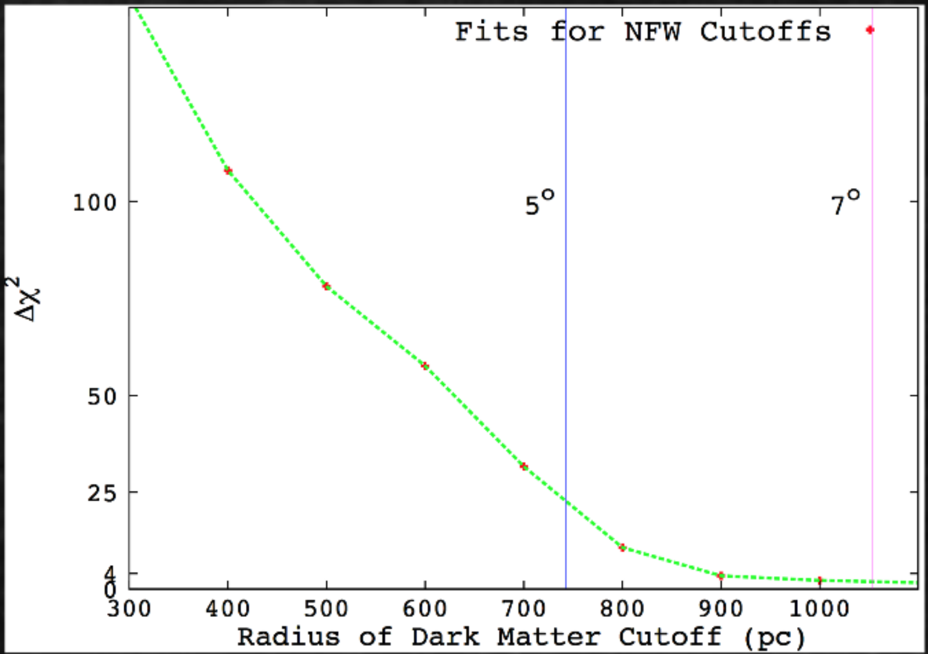




Galactic Center

Spatial Extension





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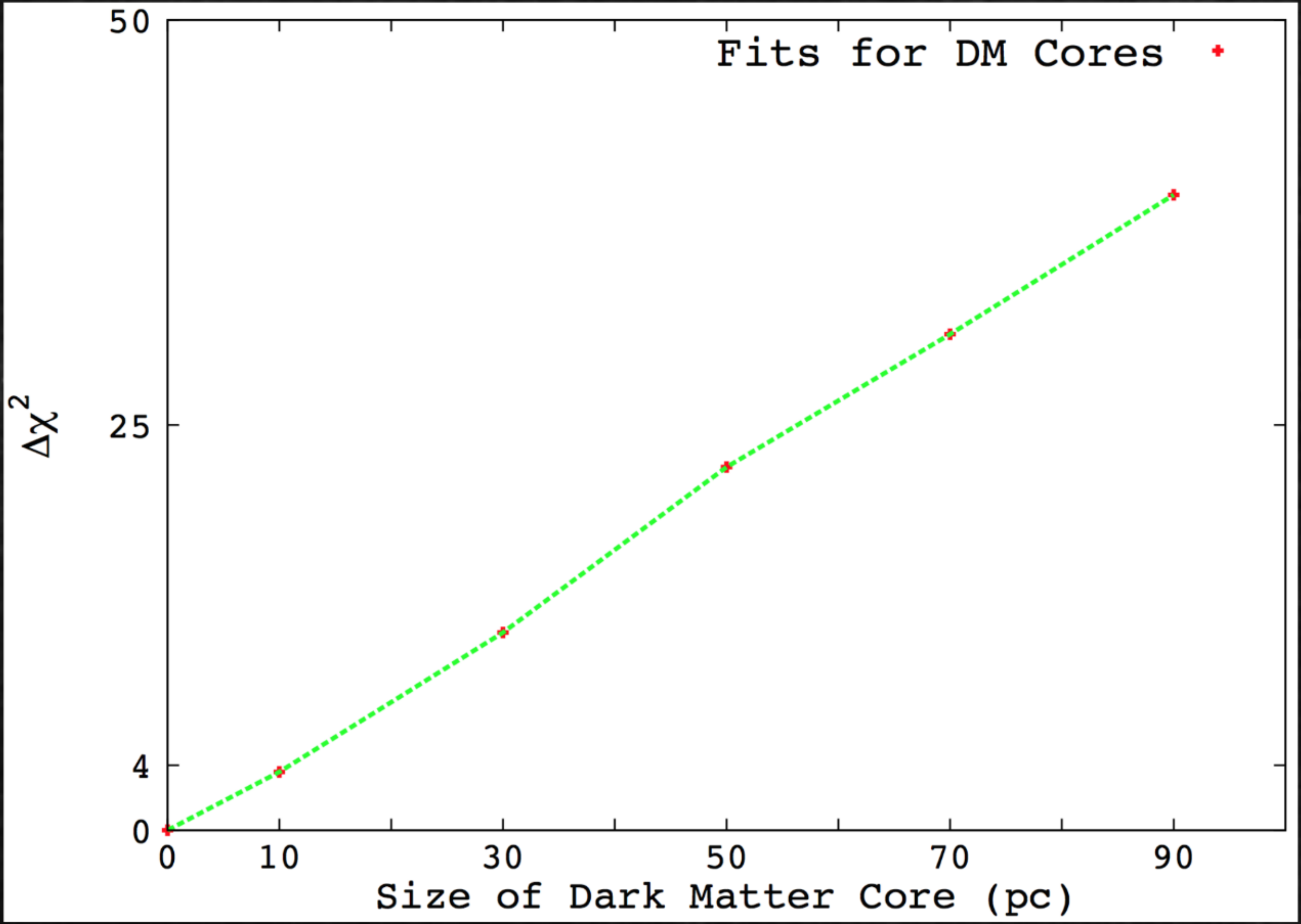

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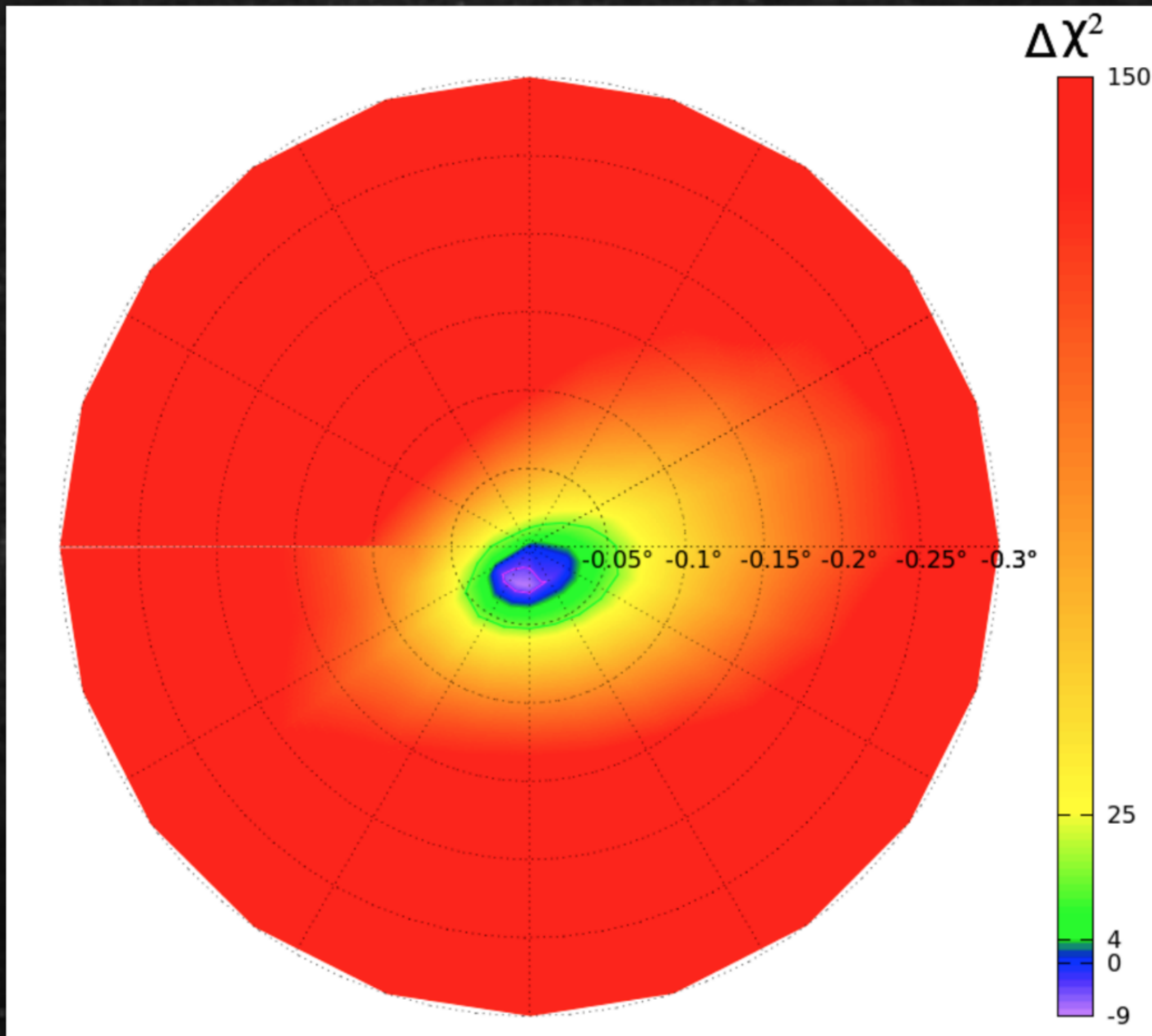

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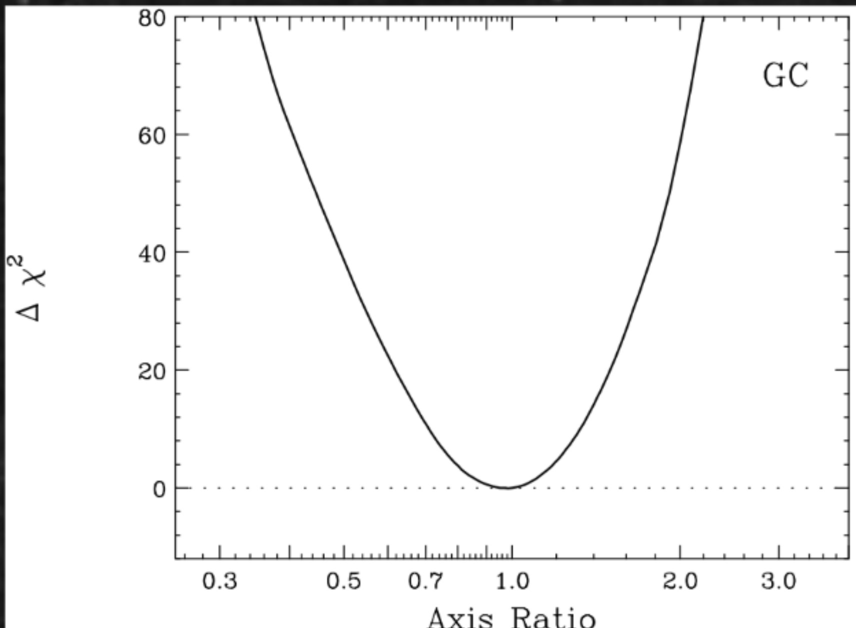
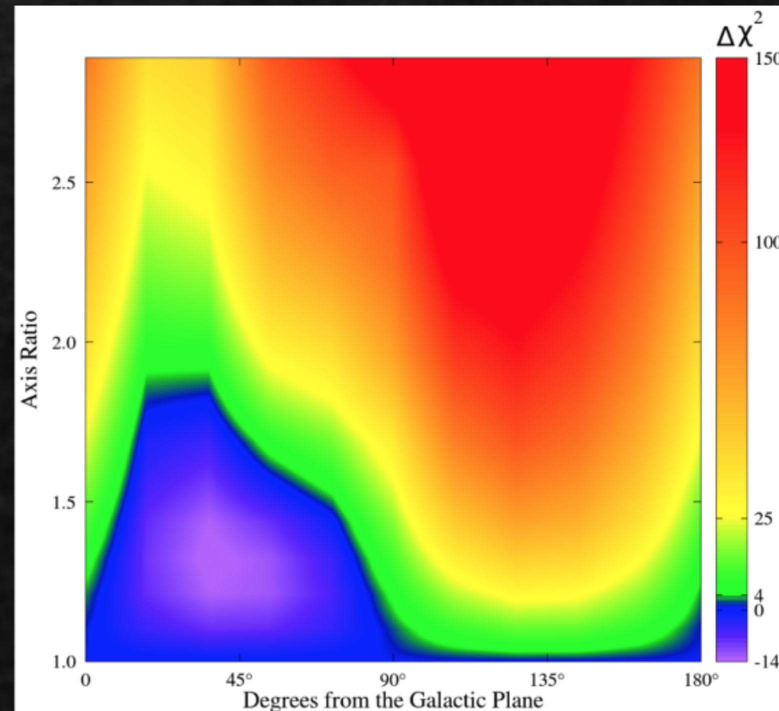
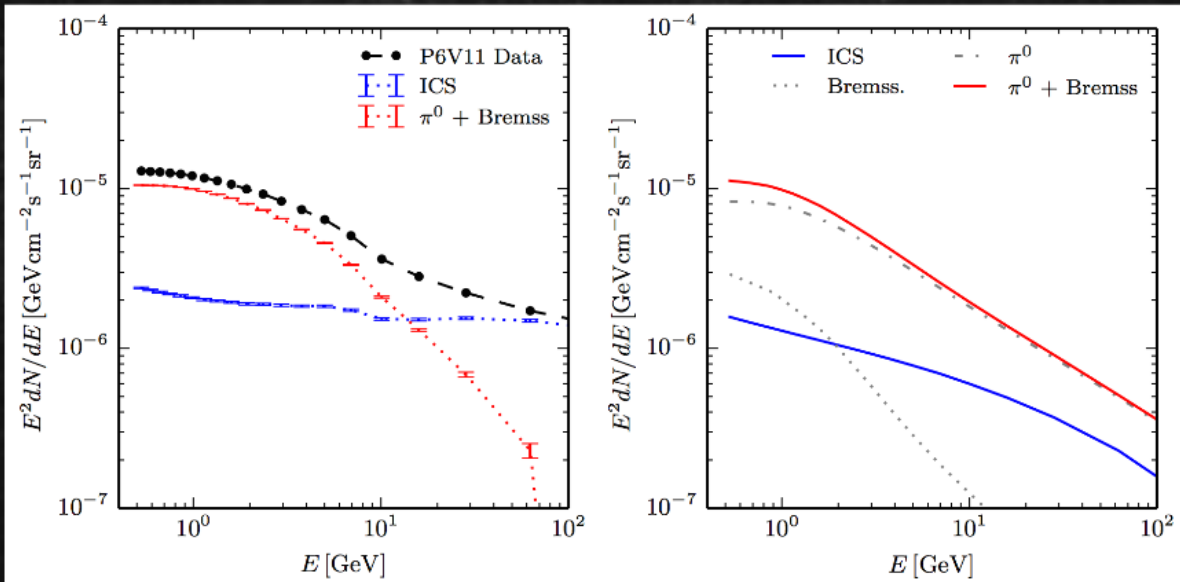
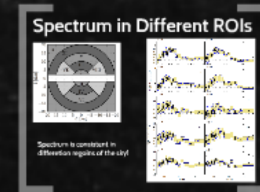


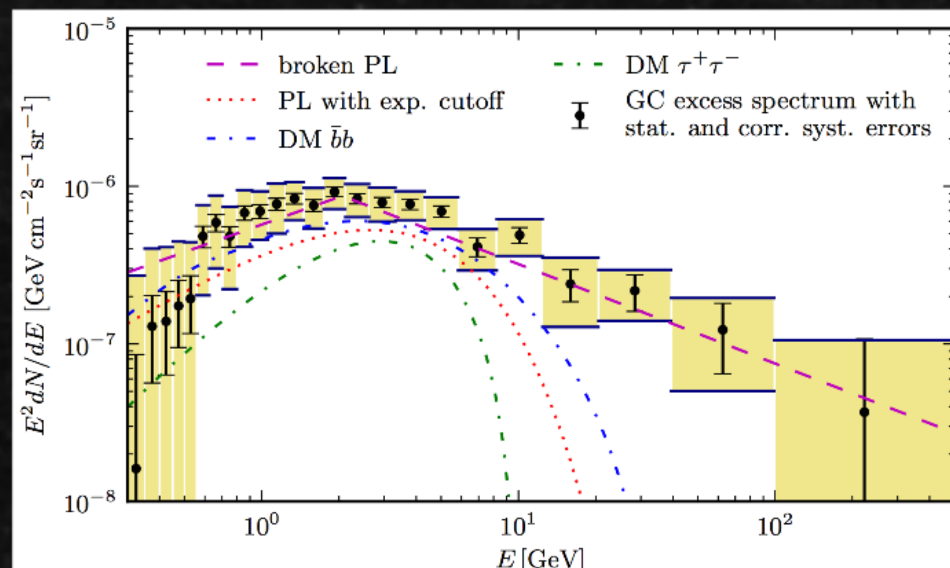


Galactic Center

Calore et al. (2014)







Tour de force paper which examines systematic errors in the diffuse background by evaluating more than 300 different tuned Galprop background models

arXiv: 1409.0042

Data Analysis

Methods

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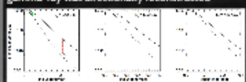

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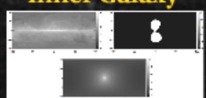

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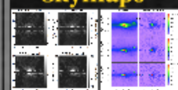
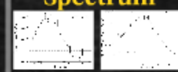


Spectrum



Morphology

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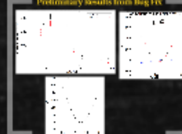

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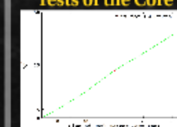

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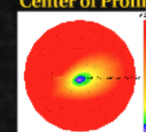

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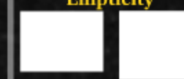

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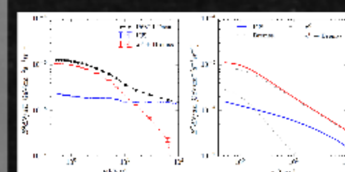

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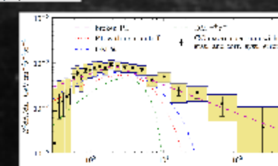
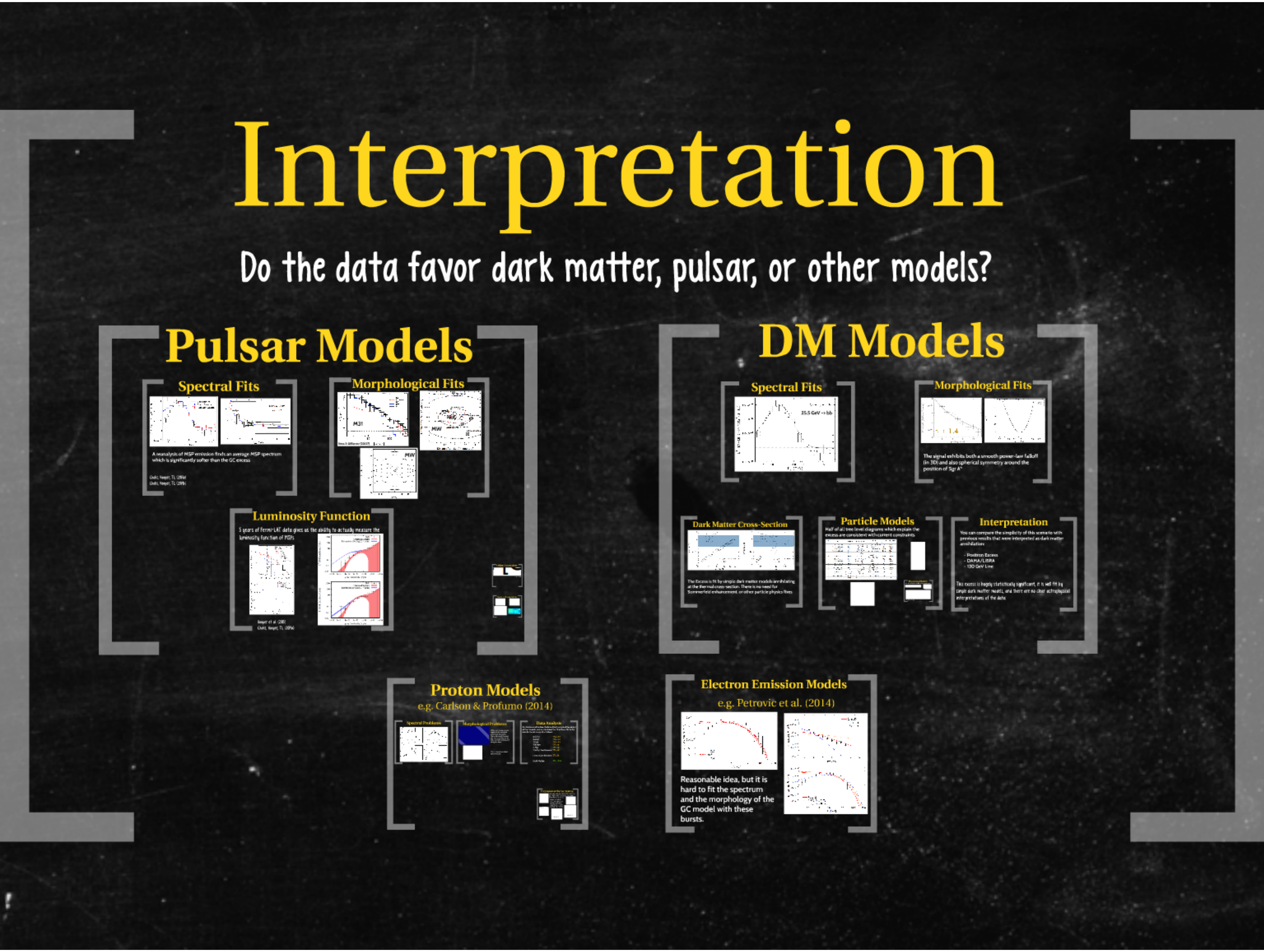


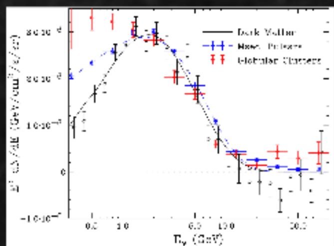
arXiv: 1409.0042

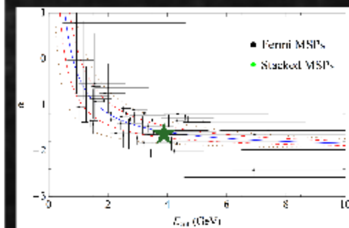
arXiv: 1402.6703


Interpretation
Do the data favor dark matter, pulsar, or other models?
Pulsar Models
Spectral Fits
A reanalysis of MSP emission finds an average MSP spectrum which is significantly softer than the GC excess
Morphological Fits
M31
MW
MW
Luminosity Function
5 years of Fermi-LAT data gives us the ability to actually measure the luminosity function of MSPs
DM Models
Spectral Fits
35.5 GeV -> bb
Morphological Fits
1.4
The signal exhibits both a smooth power-law falloff (in 3D) and also spherical symmetry around the position of Sgr A*
Dark Matter Cross-Section
The Excess is fit by simple dark matter models annihilating at the thermal cross-section. There is no need for Sommerfeld enhancement, or other particle physics fixes
Particle Models
Half of all tree level diagrams which explain the excess are consistent with current constraints
Interpretation
You can compare the simplicity of this scenario with previous results that were interpreted as dark matter annihilation
- Positron Excess
- DAMA/LIBRA
- 130 GeV Line
This excess is hugely statistically significant, it is well fit by simple dark matter models, and there are no clear astrophysical interpretations of the data
Proton Models
e.g. Carlson & Profumo (2014)
Spectral Problems
Morphological Problems
Data Analysis
Electron Emission Models
e.g. Petrovic et al. (2014)
Reasonable idea, but it is hard to fit the spectrum and the morphology of the GC model with these bursts.

Pulsar Models

Spectral Fits

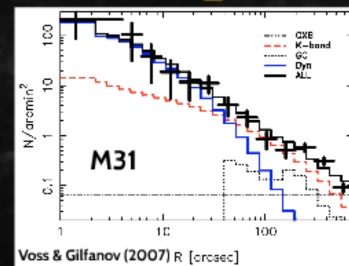


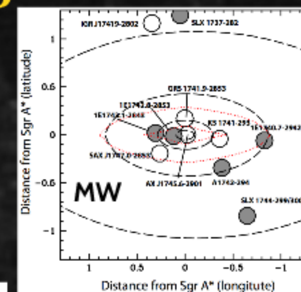


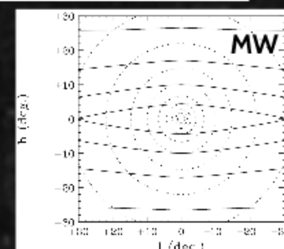
A reanalysis of MSP emission finds an average MSP spectrum which is significantly softer than the GC excess

Cholis, Hooper, TL (2014a)
Cholis, Hooper, TL (2014b)

Morphological Fits

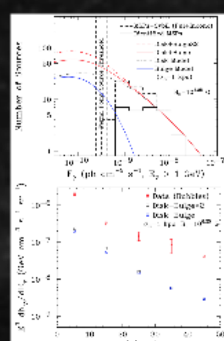


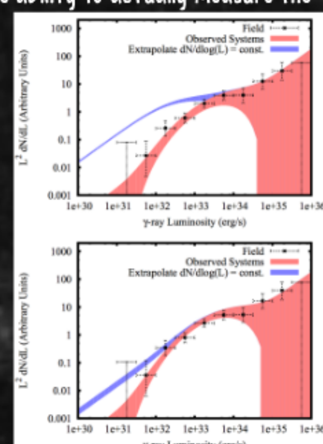




Luminosity Function

5 years of Fermi-LAT data gives us the ability to actually measure the luminosity function of MSPs



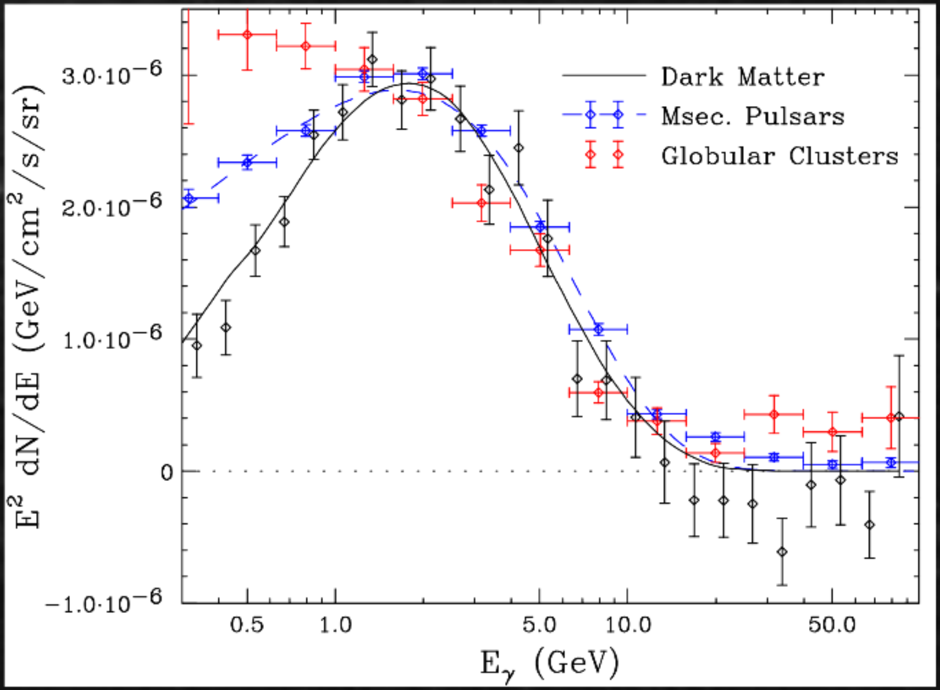


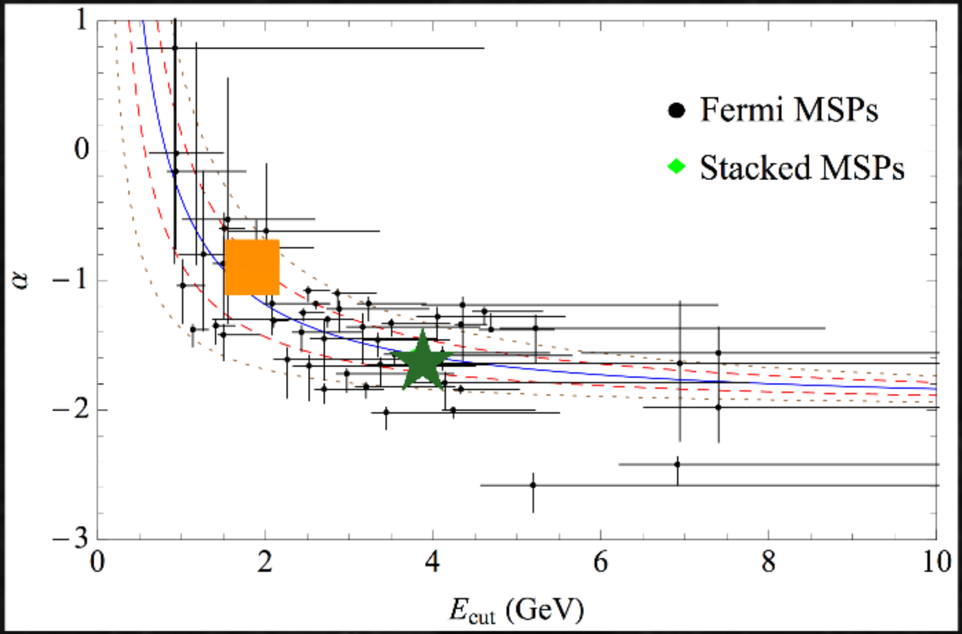
Hooper et al. (2013)
Cholis, Hooper, TL (2014a)

Other Constraints

Yuan & Zhang (2014)

Spectral Fits





A reanalysis of MSP emission finds an average MSP spectrum which is significantly softer than the GC excess

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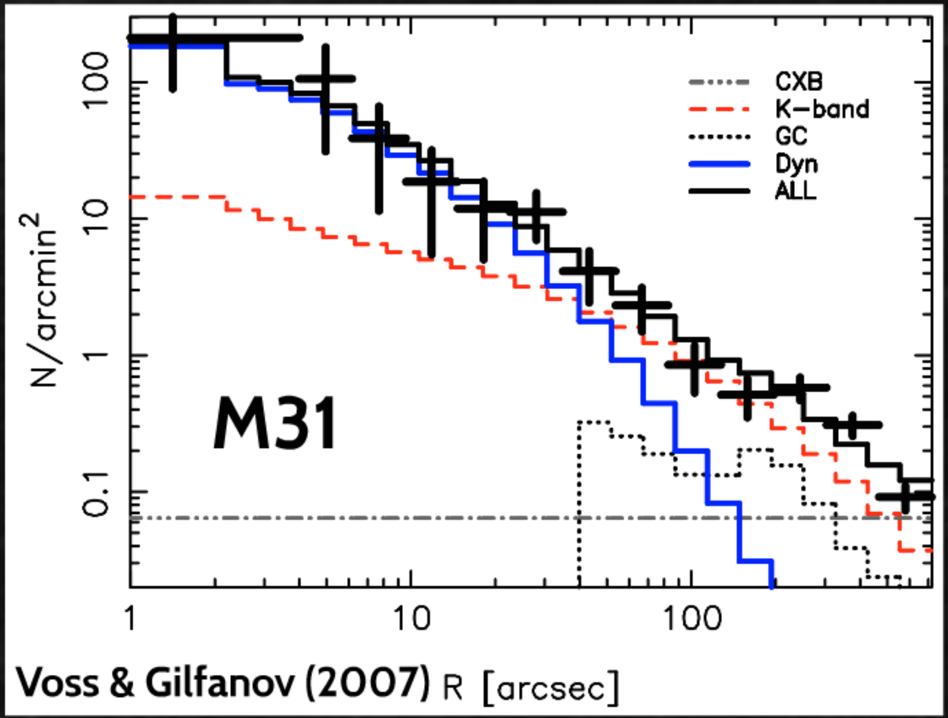

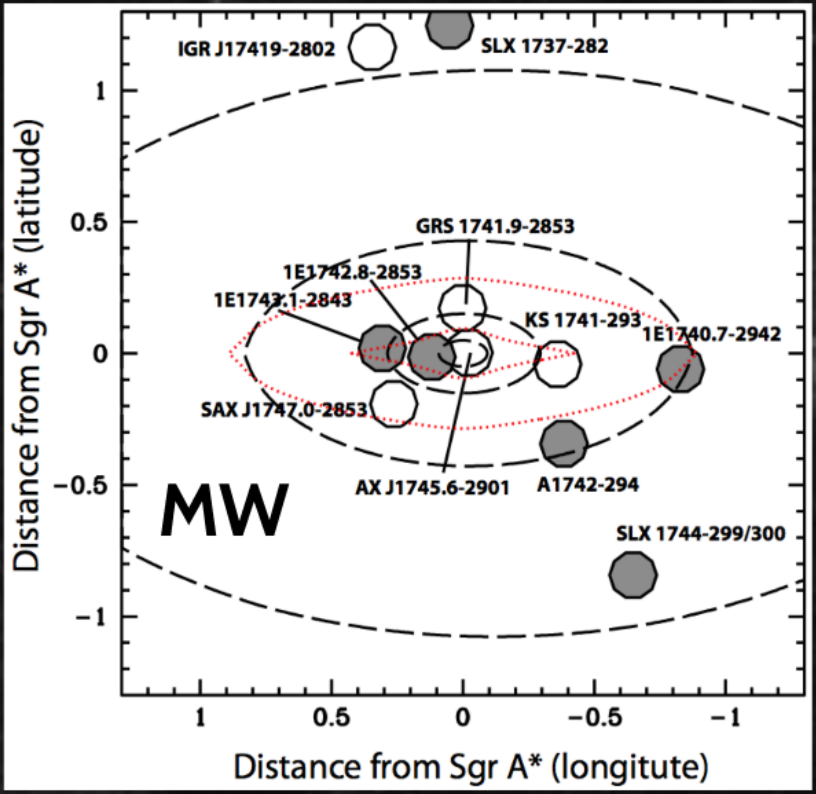

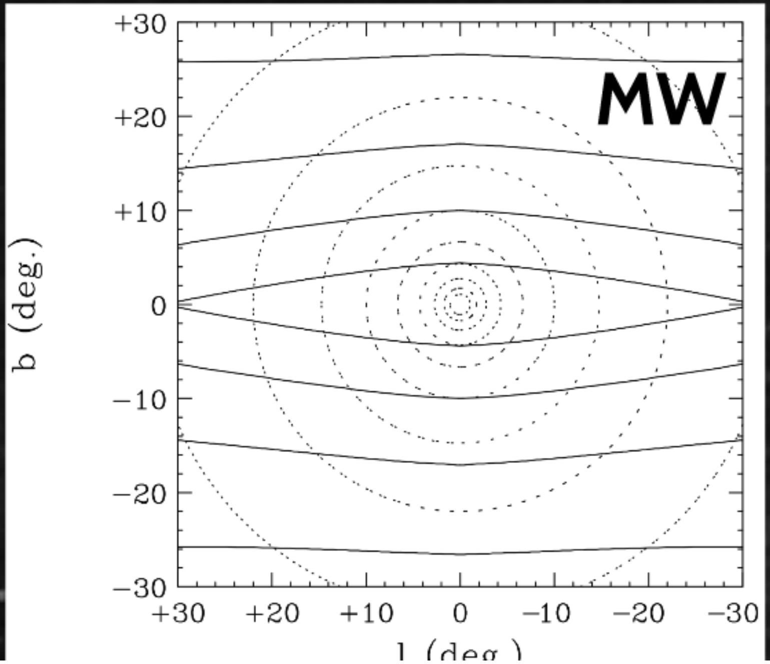

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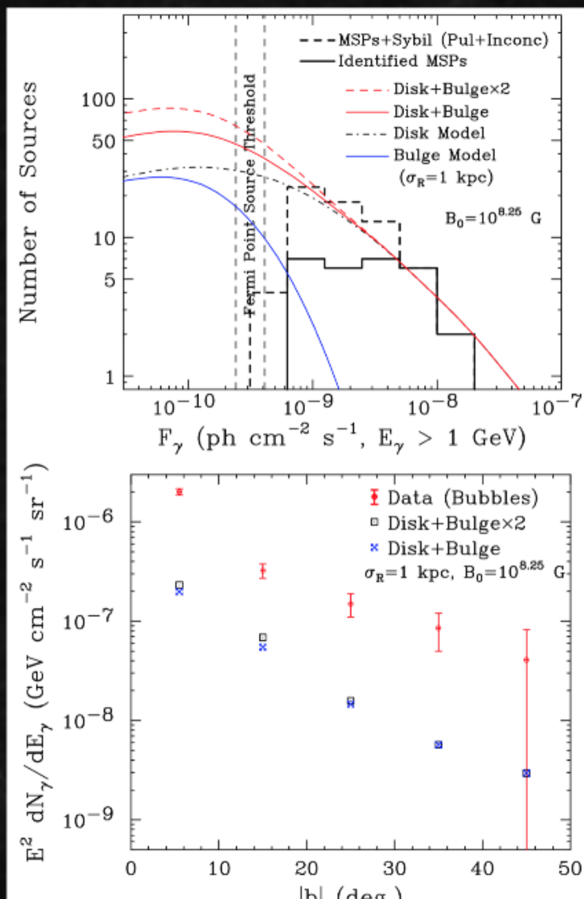
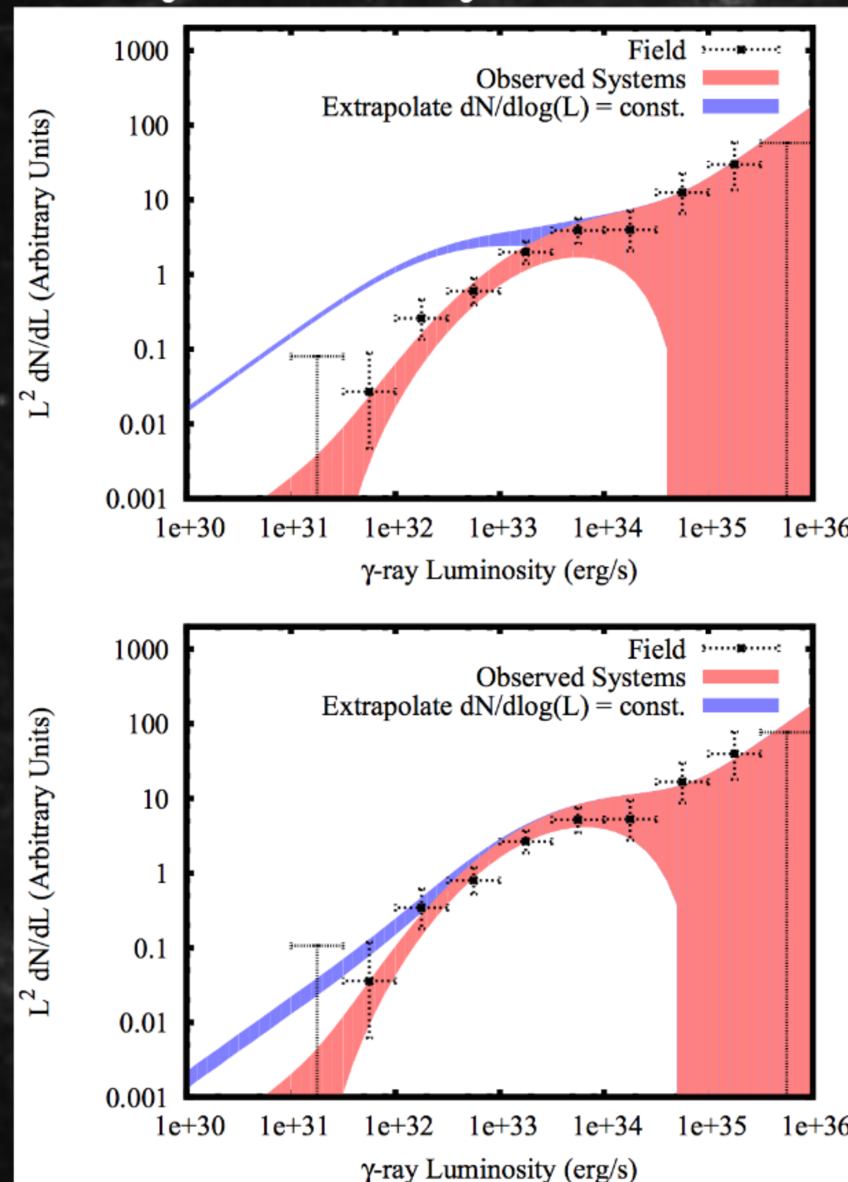


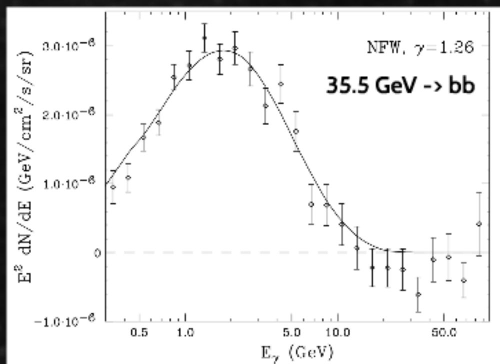


Hooper et al. (2013)

Cholis, Hooper, TL (2014a)

DM Models

Spectral Fits



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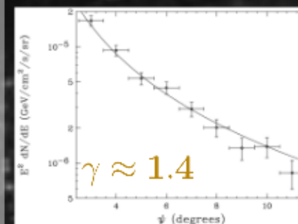
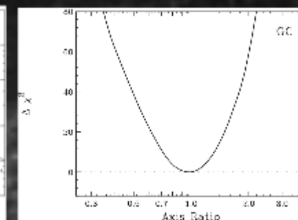
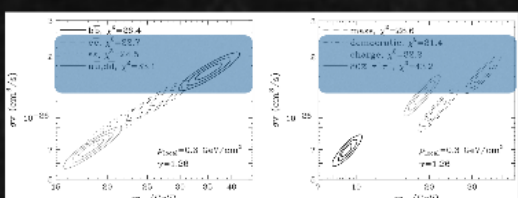




The signal exhibits both a smooth power-law falloff (in 3D) and also spherical symmetry around the position of Sgr A*

Dark Matter Cross-Section



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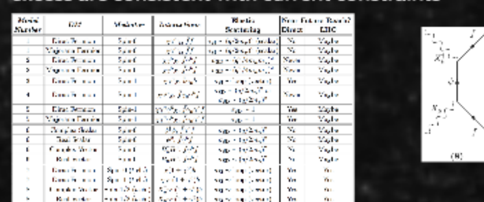
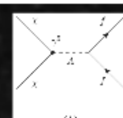
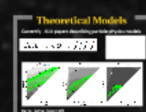
Particle Models

Half of all tree level diagrams which explain the excess are consistent with current constraints







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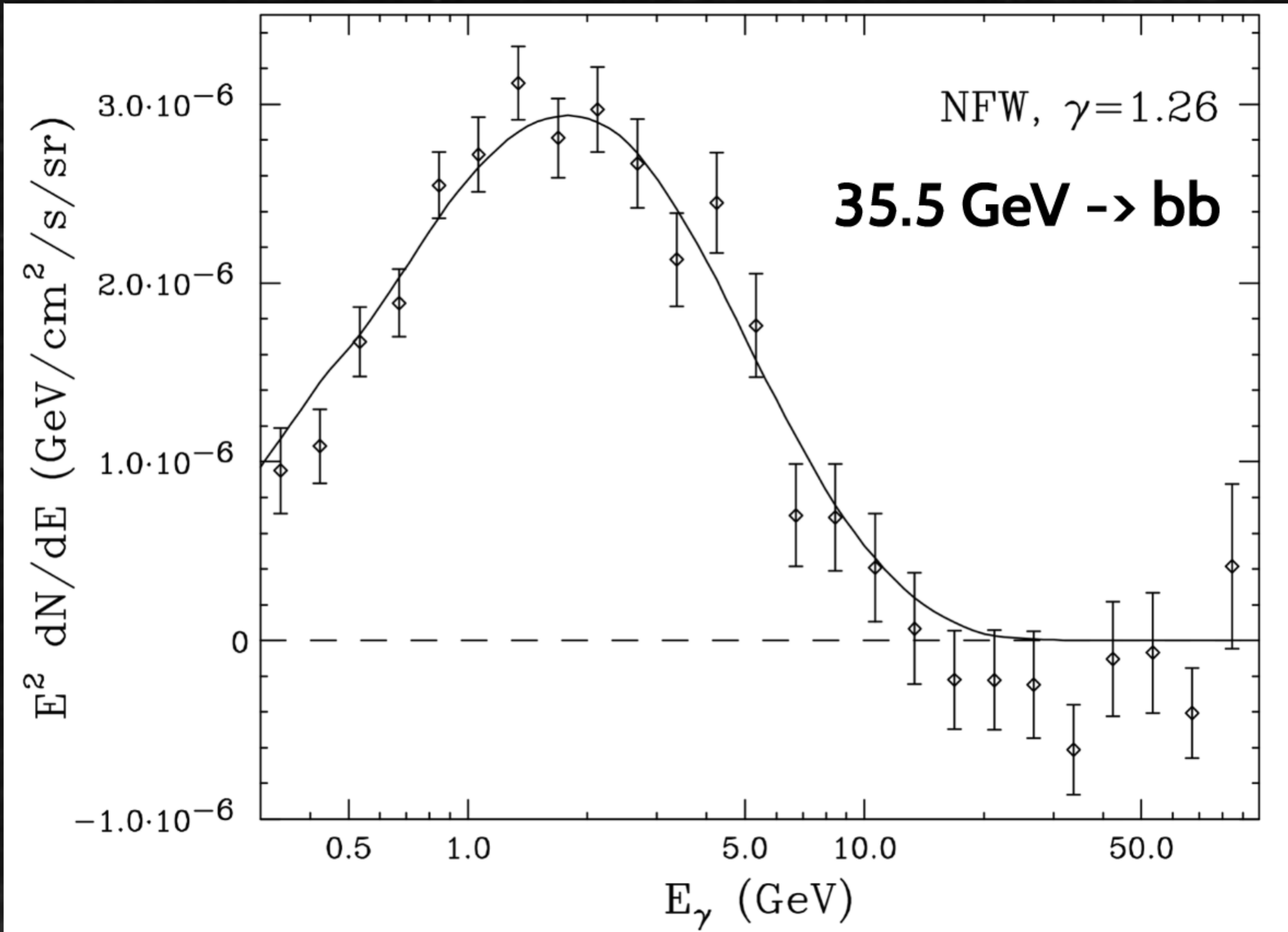
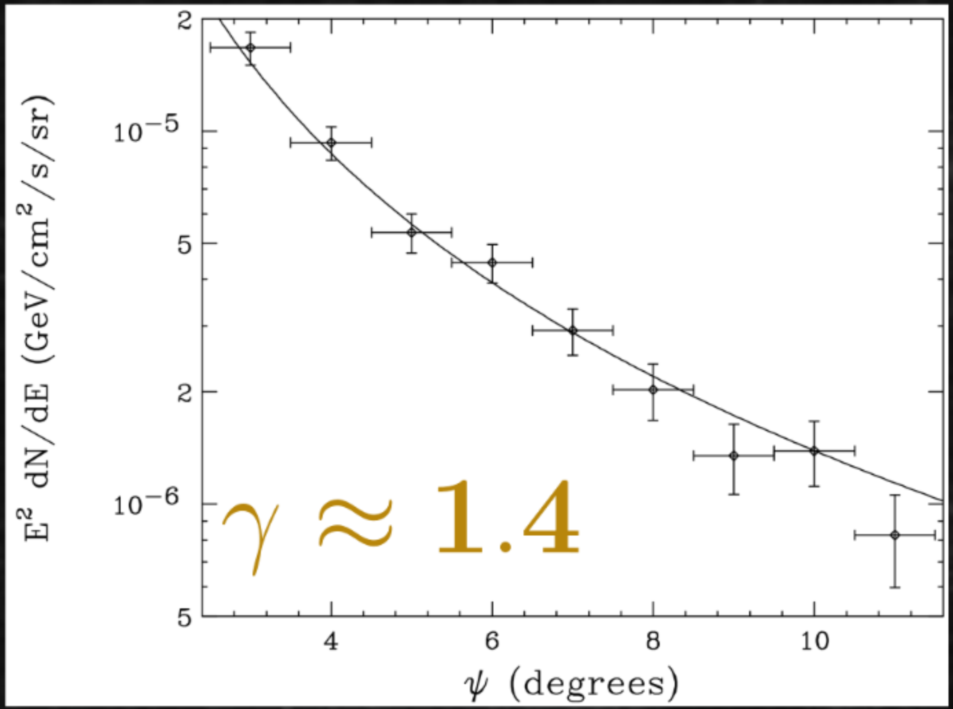
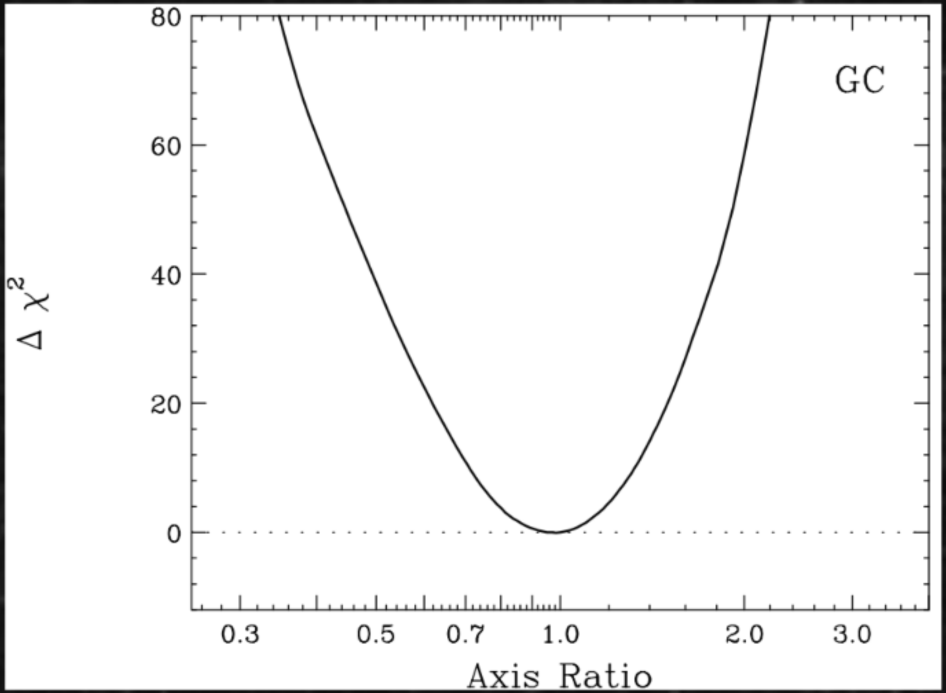


Morphological Fits





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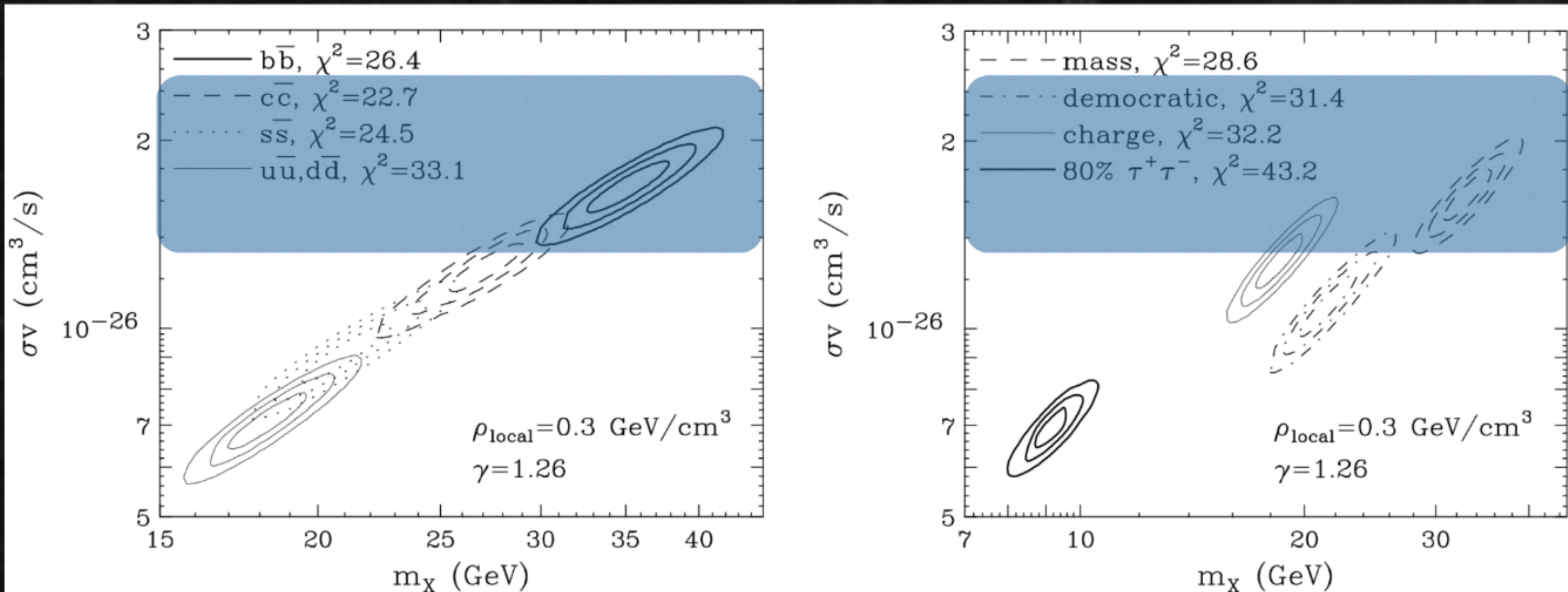

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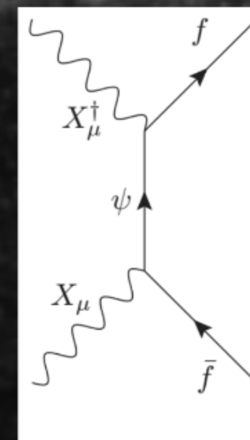
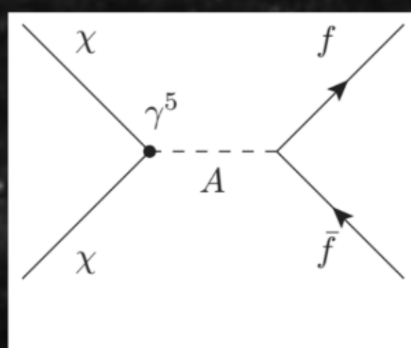
Model Number	*DM*	*Mediator*	*Interactions*	Elastic Scattering	Near Future Reach?	
					Direct	LHC
1	Dirac Fermion	Spin-0	$\bar\chi\gamma^5\chi,\ \bar f f$	$\sigma_{\rm SI}\sim(q/2m_\chi)^2$ (scalar)	No	Maybe
1	Majorana Fermion	Spin-0	$\bar\chi\gamma^5\chi,\ \bar f f$	$\sigma_{\rm SI}\sim(q/2m_\chi)^2$ (scalar)	No	Maybe
2	Dirac Fermion	Spin-0	$\bar\chi\gamma^5\chi,\ \bar f\gamma^5 f$	$\sigma_{\rm SD}\sim(q^2/4m_n m_\chi)^2$	Never	Maybe
2	Majorana Fermion	Spin-0	$\bar\chi\gamma^5\chi,\ \bar f\gamma^5 f$	$\sigma_{\rm SD}\sim(q^2/4m_n m_\chi)^2$	Never	Maybe
3	Dirac Fermion	Spin-1	$\bar\chi\gamma^\mu\chi,\ \bar b\gamma_\mu b$	$\sigma_{\rm SI}\sim$ loop (vector)	Yes	Maybe
4	Dirac Fermion	Spin-1	$\bar\chi\gamma^\mu\chi,\ \bar f\gamma_\mu\gamma^5 f$	$\sigma_{\rm SD}\sim(q/2m_n)^2$ or $\sigma_{\rm SD}\sim(q/2m_\chi)^2$	Never	Maybe
5	Dirac Fermion	Spin-1	$\bar\chi\gamma^\mu\gamma^5\chi,\ \bar f\gamma_\mu\gamma^5 f$	$\sigma_{\rm SD}\sim 1$	Yes	Maybe
5	Majorana Fermion	Spin-1	$\bar\chi\gamma^\mu\gamma^5\chi,\ \bar f\gamma_\mu\gamma^5 f$	$\sigma_{\rm SD}\sim 1$	Yes	Maybe
6	Complex Scalar	Spin-0	$\phi^\dagger\phi,\ \bar f\gamma^5 f$	$\sigma_{\rm SD}\sim(q/2m_n)^2$	No	Maybe
6	Real Scalar	Spin-0	$\phi^2,\ \bar f\gamma^5 f$	$\sigma_{\rm SD}\sim(q/2m_n)^2$	No	Maybe
6	Complex Vector	Spin-0	$B^\dagger_\mu B^\mu,\ \bar f\gamma^5 f$	$\sigma_{\rm SD}\sim(q/2m_n)^2$	No	Maybe
6	Real Vector	Spin-0	$B_\mu B^\mu,\ \bar f\gamma^5 f$	$\sigma_{\rm SD}\sim(q/2m_n)^2$	No	Maybe
7	Dirac Fermion	Spin-0 (*t*-ch.)	$\bar\chi(1\pm\gamma^5)b$	$\sigma_{\rm SI}\sim$ loop (vector)	Yes	Yes
7	Dirac Fermion	Spin-1 (*t*-ch.)	$\bar\chi\gamma^\mu(1\pm\gamma^5)b$	$\sigma_{\rm SI}\sim$ loop (vector)	Yes	Yes
8	Complex Vector	Spin-1/2 (*t*-ch.)	$X^\dagger_\mu\gamma^\mu(1\pm\gamma^5)b$	$\sigma_{\rm SI}\sim$ loop (vector)	Yes	Yes
8	Real Vector	Spin-1/2 (*t*-ch.)	$X_\mu\gamma^\mu(1\pm\gamma^5)b$	$\sigma_{\rm SI}\sim$ loop (vector)	Yes	Yes



(8)



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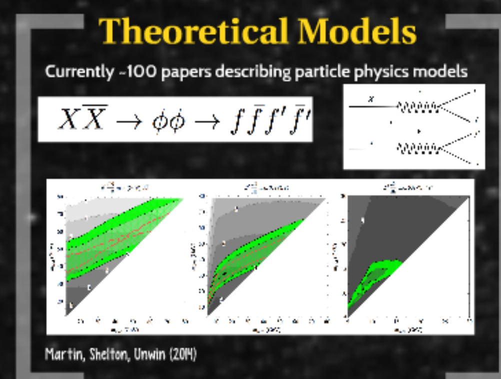
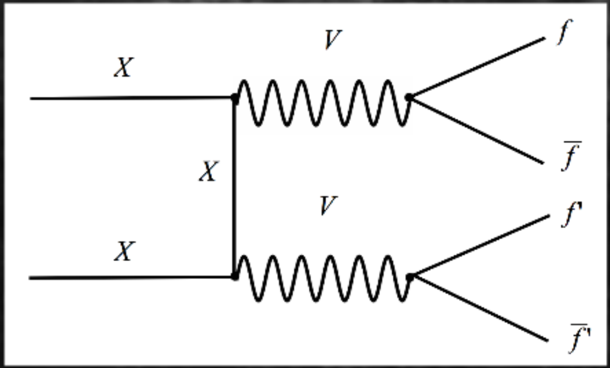
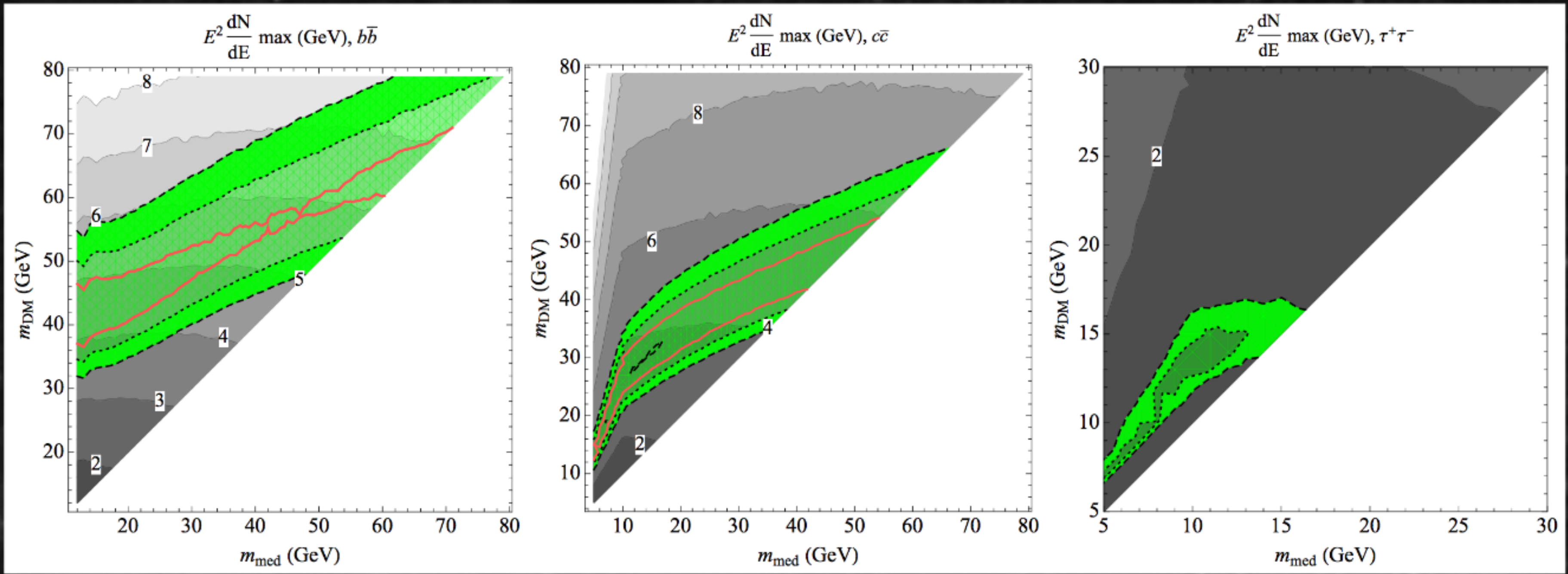


Theoretical Models

Currently ~100 papers describing particle physics models

$$X\overline{X} \to \phi\phi \to f\bar{f}f'\bar{f}'$$





Martin, Shelton, Unwin (2014)

Interpretation

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- 130 GeV Line

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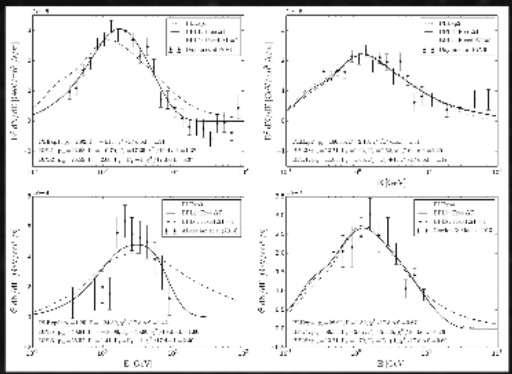
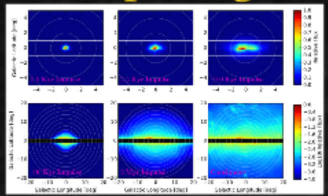
Proton Models

e.g. Carlson & Profumo (2014)

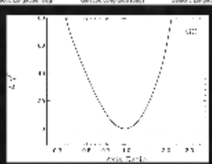
Spectral Problems



Morphological Problems



While very young systems appear to be somewhat spherically symmetric, those old enough to cover the ~10° extentsion of the data are highly enlongated along the plane



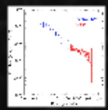
This is strongly excluded by our models

Data Analysis

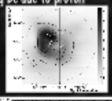
Eric Carlson and Stefano Profumo kindly provided the output of their models, and we calculated the TS of these fits to the data (in the GC analysis) as follows:

0.5 kyr	TS = 33
2.5 kyr	TS = 43
19 kyr	TS = 14
100 kyr	TS = 0
2 Myr	TS = 0
7.5 Myr Continuous:	TS = 0
Linear Combination	TS=51
Dark Matter:	TS = 315

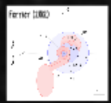
Extension of the GC Source

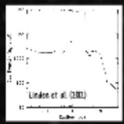


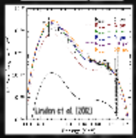
Has long been posited that the Fermi-LAT and H.E.S.S. GC source might be connected, and may be due to proton emission from the central source



One problem is that the H.E.S.S. source appears to be point-like, and the H.E.S.S. angular resolution is better than that of the Fermi-LAT







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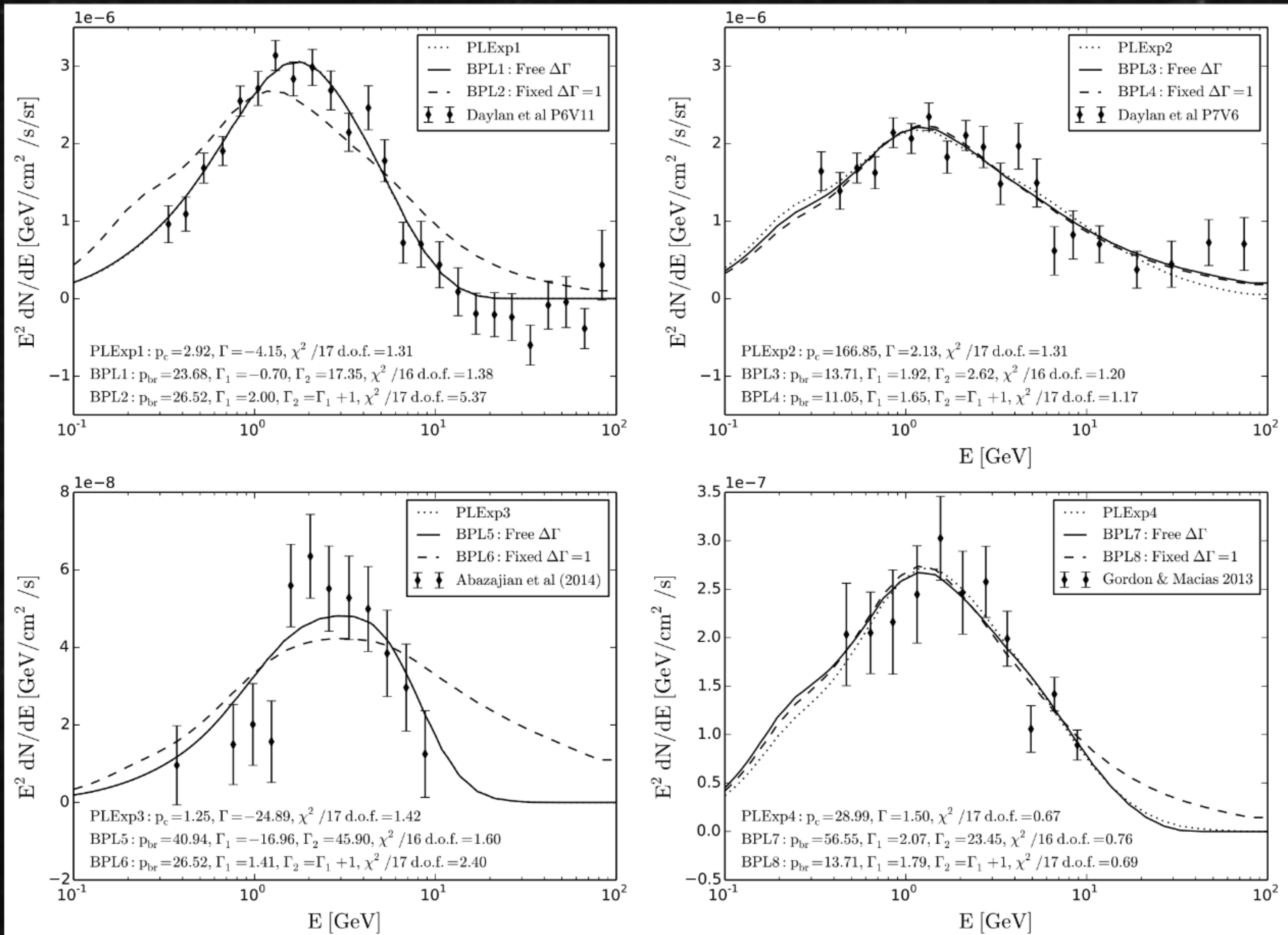

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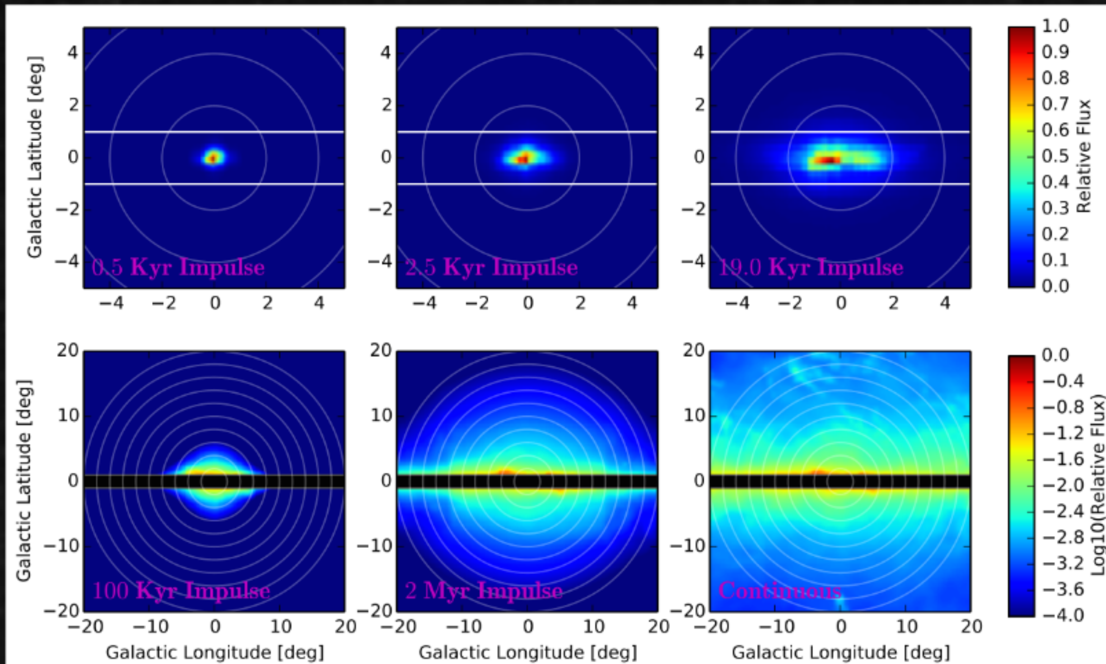

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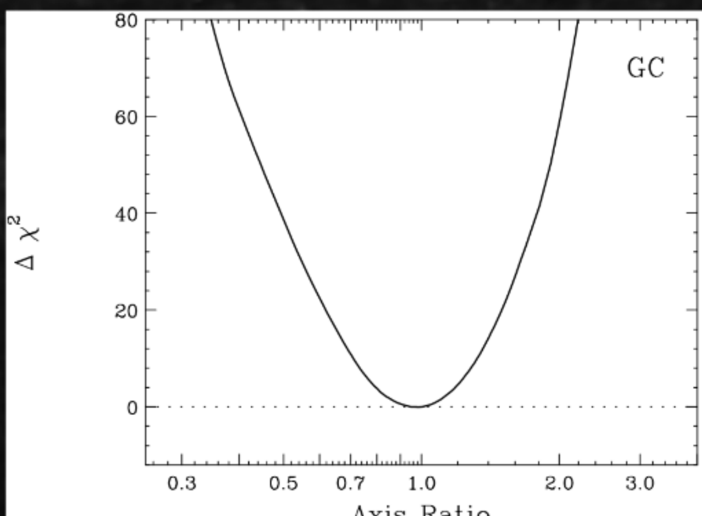

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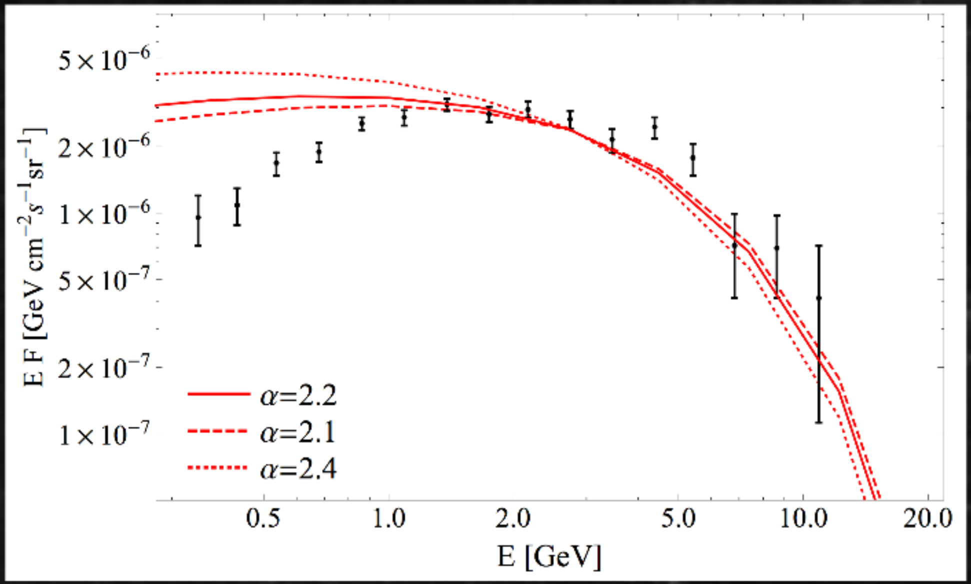
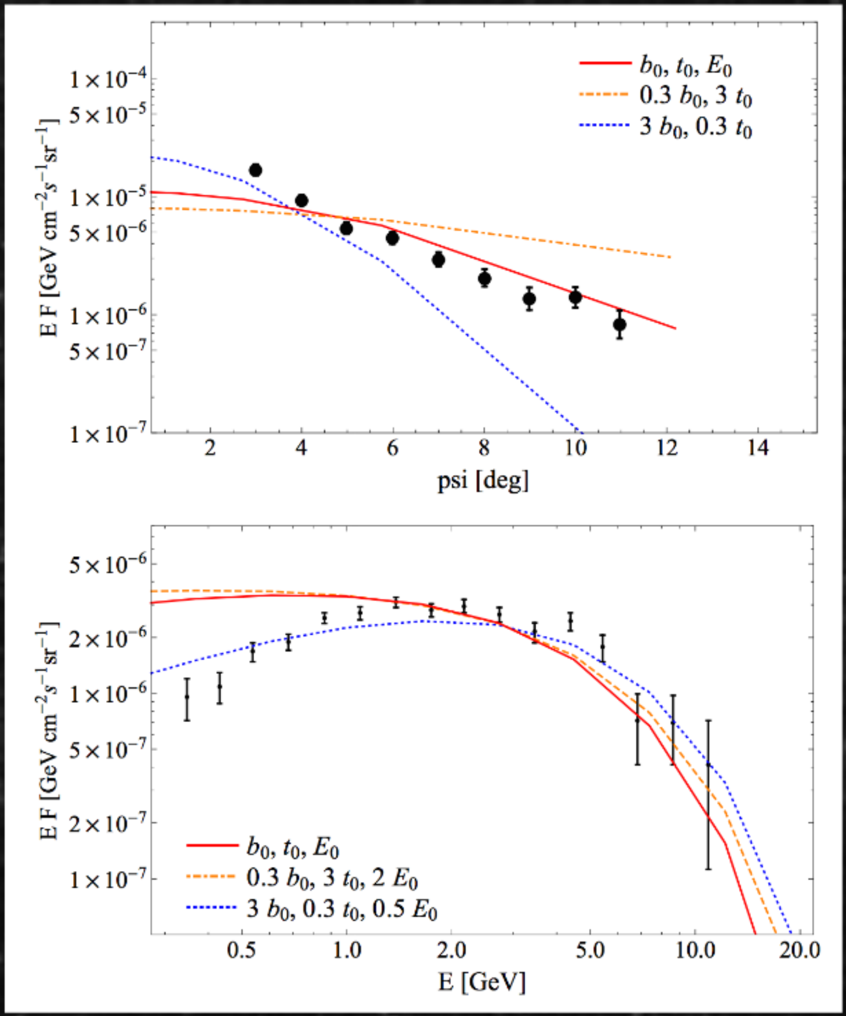
Electron Emission Models

e.g. Petrovic et al. (2014)





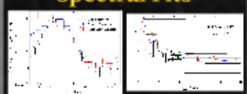
Reasonable idea, but it is hard to fit the spectrum and the morphology of the GC model with these bursts.

Interpretation

Do the data favor dark matter, pulsar, or other models?

Pulsar Models

Spectral Fits



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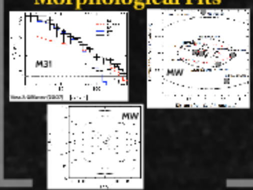

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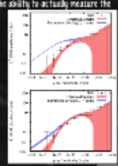

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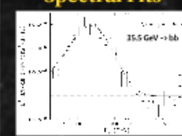

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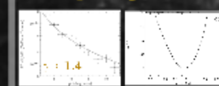

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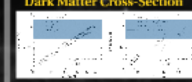

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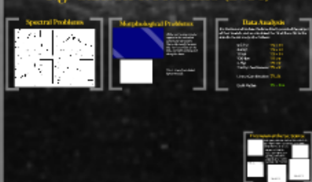

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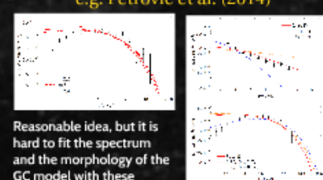

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A Compelling Case for Annihilating Dark Matter

Tim Linden

Background

Data Analysis

Methods

Main Results

Additional Tests

Calore et al. (2014)

arXiv: 1402.6703

Interpretation

Pulsar Models

DM Models

along with:
Tansu Daylan, Doug Finkbeiner, Dan Hooper, Stephan Portillo, Nick Rodd, Tracy Slatyer

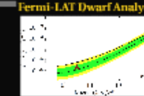
arXiv: 1402.6703

Sungkyunkwan University Seminar - October 15, 2014

It's a compelling case -- but what is next?

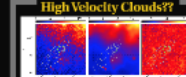
Future Tests

Fermi-LAT Dwarf Analysis



A 2.3-sigma Excess?

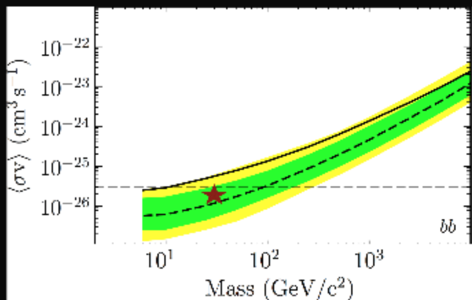
High Velocity Clouds??



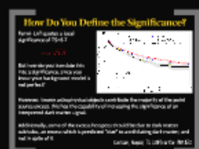
Direct Detection

Future Tests

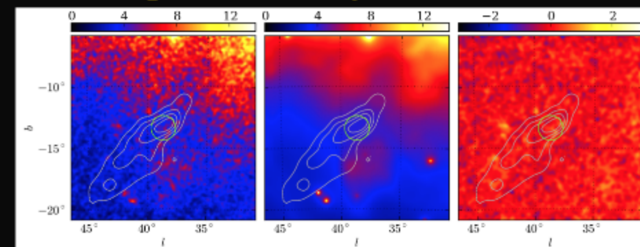
Fermi-LAT Dwarf Analysis

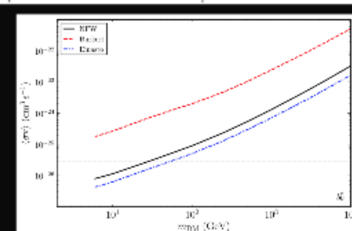


A 2.7-sigma Excess?

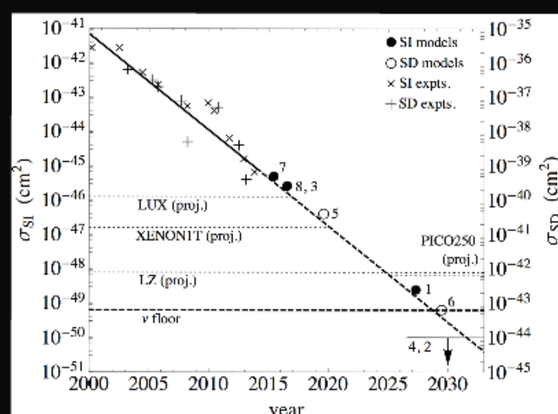


High Velocity Clouds??

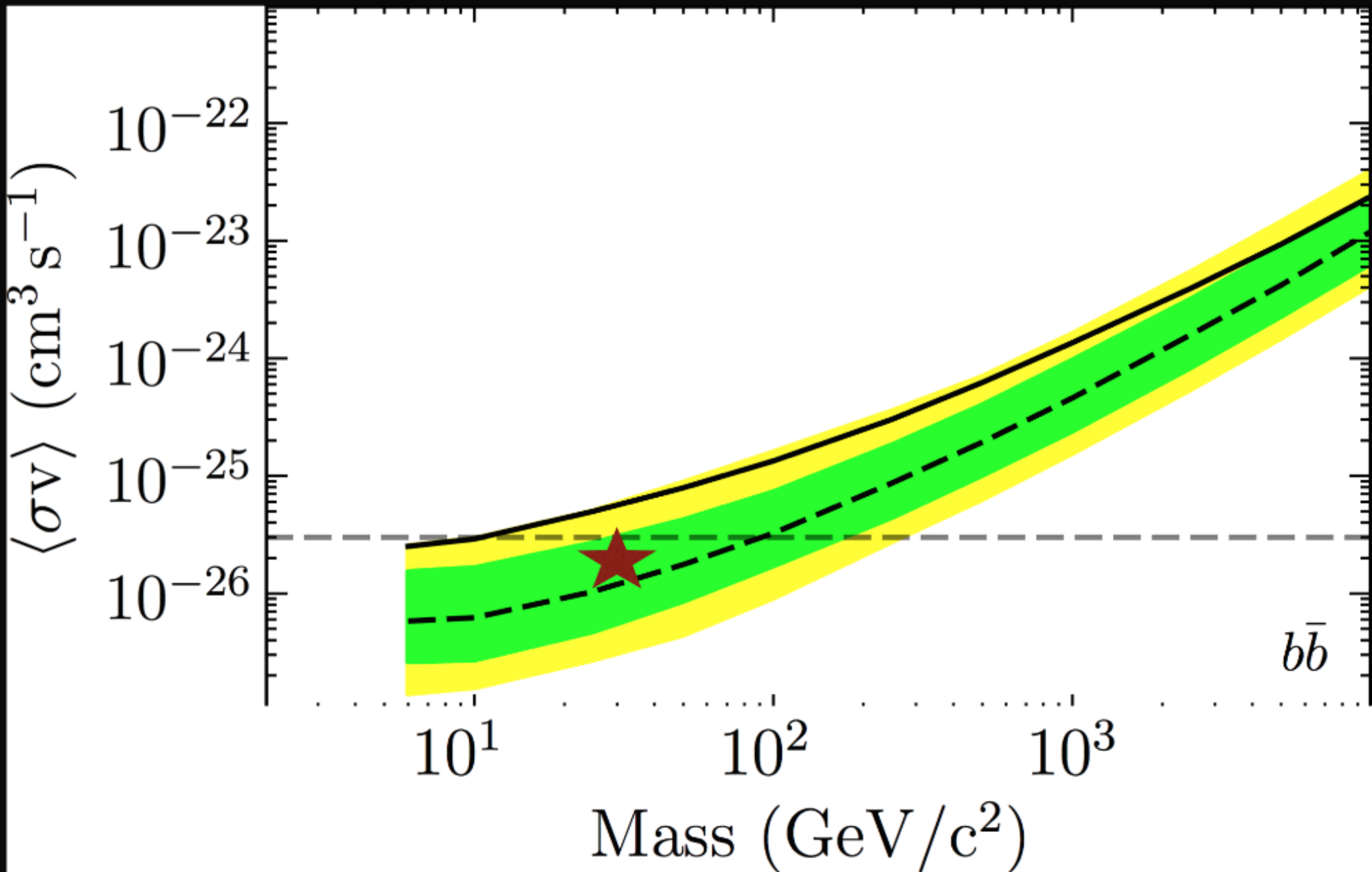




Direct Detection



Fermi-LAT Dwarf Analysis



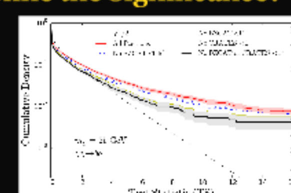
A 2.7-sigma Excess?

How Do You Define the Significance?

Fermi-LAT quotes a local significance of TS=8.7

$$\sigma \approx \sqrt{TS}$$

But how do you translate this into a significance, since you know your background model is not perfect?



However, known astrophysical objects contribute the majority of the point source excess, this has the capability of increasing the significance of an interpreted dark matter signal.

Additionally, some of the excess hotspots should be due to dark matter subhalos, an excess which is predicted "due" to annihilating dark matter, and not in spite of it

Carlson, Hooper, TL (2014) arXiv: 1409.1572

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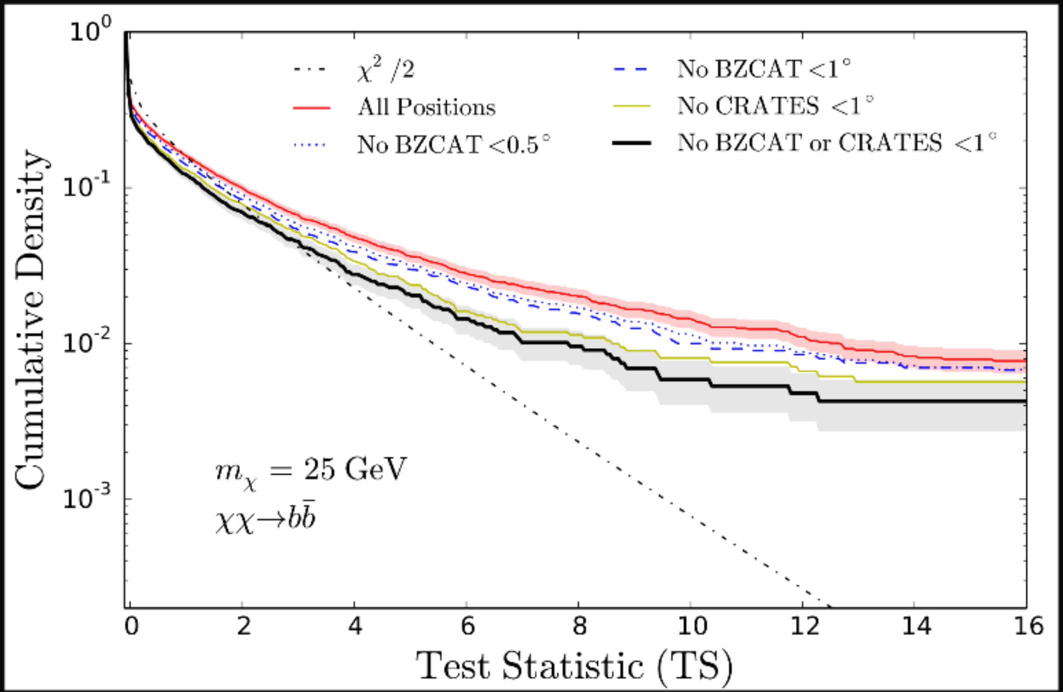

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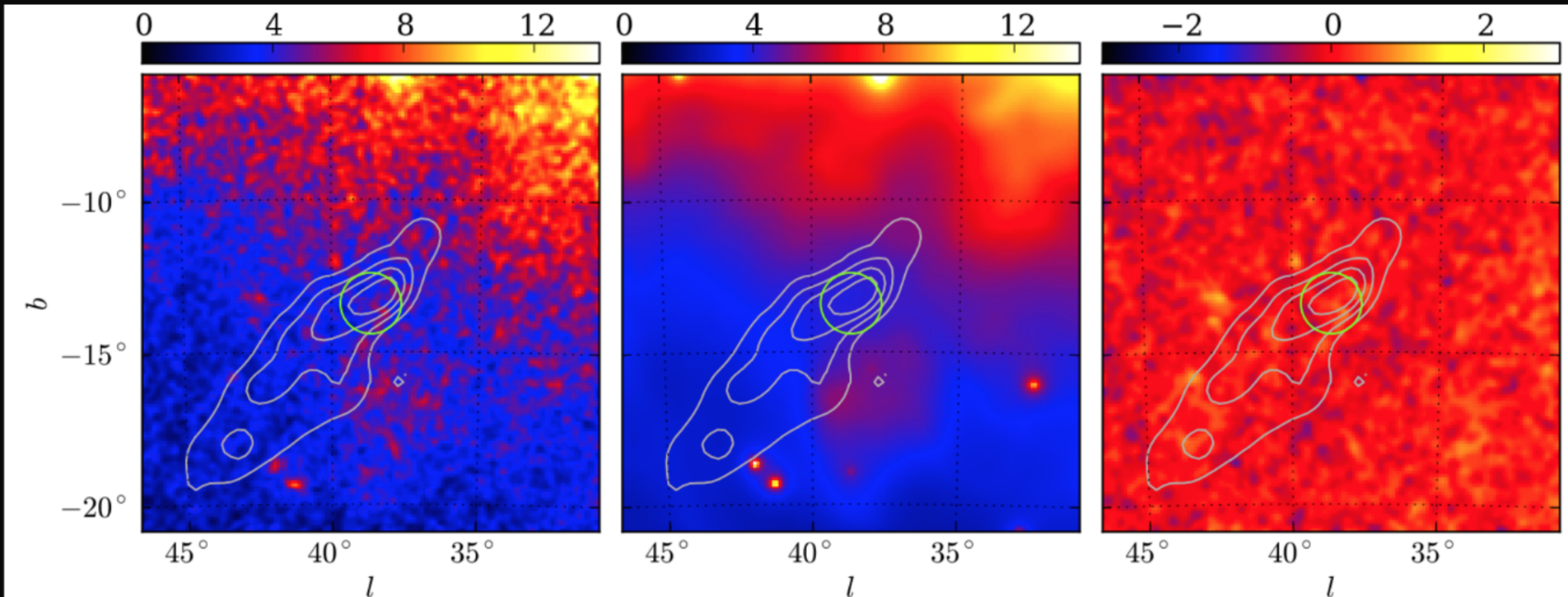
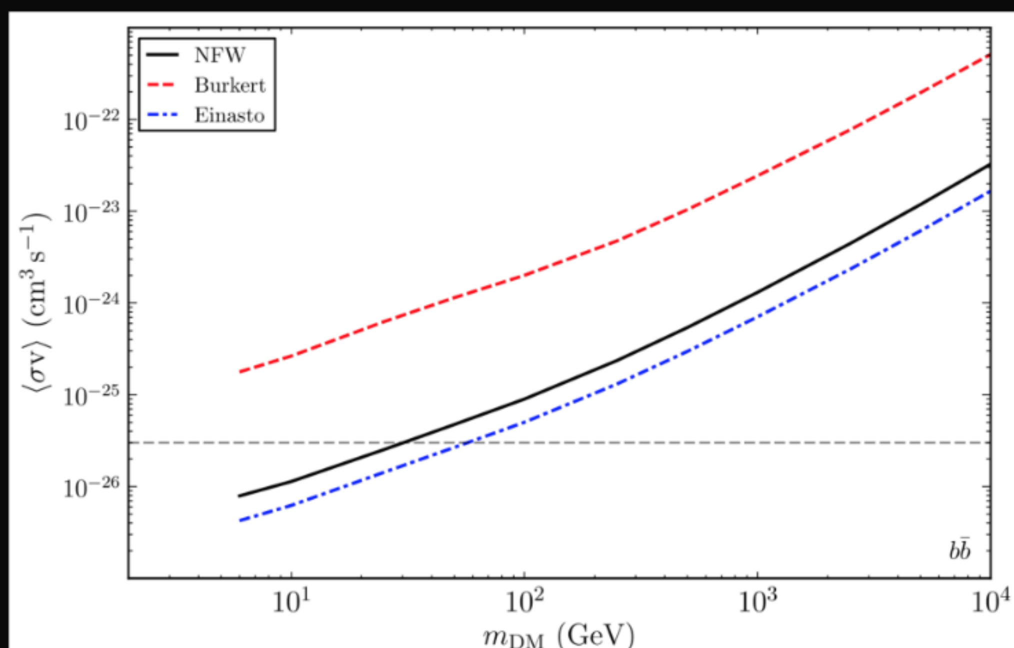
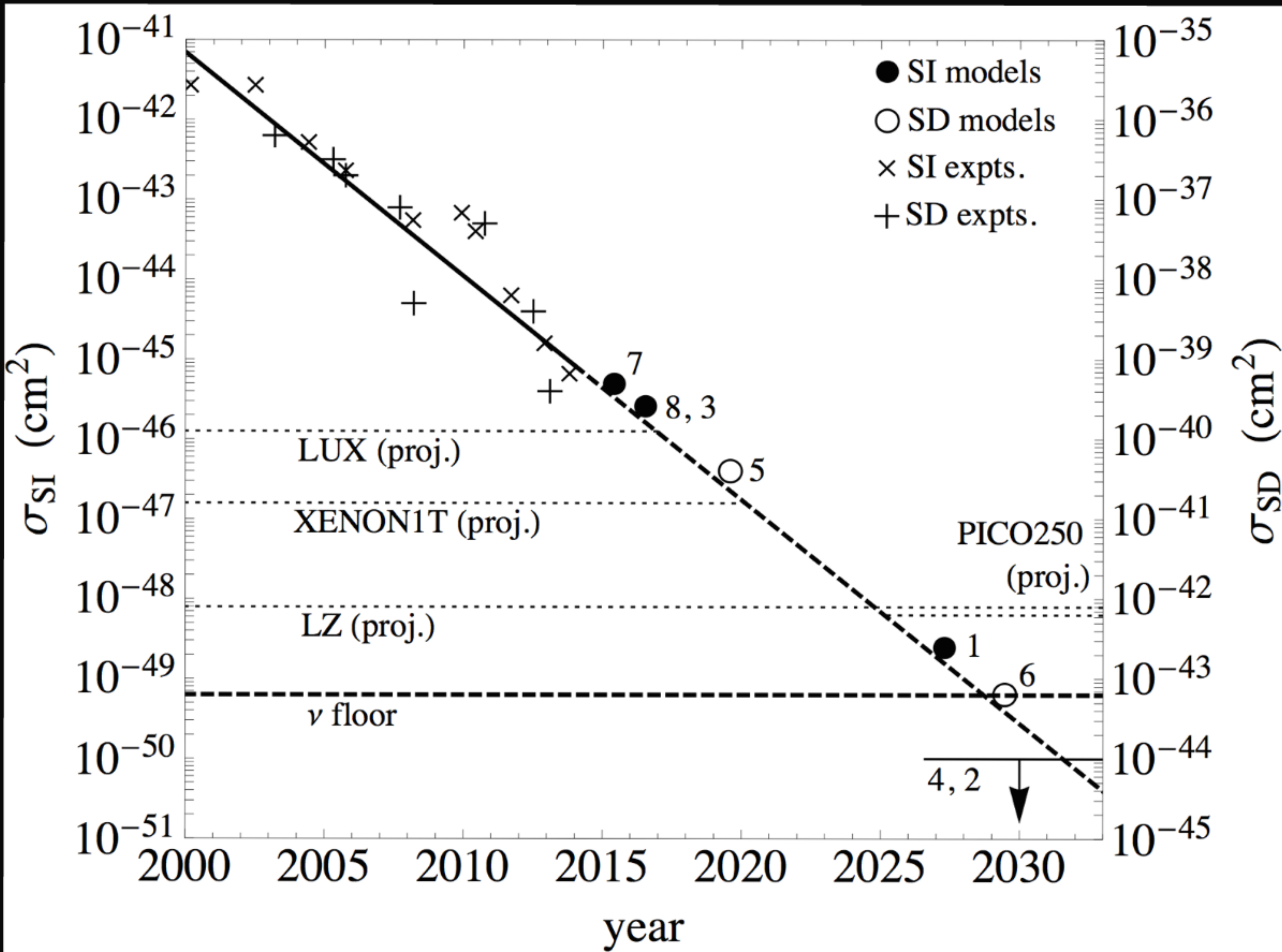




Direct Detection



A Compelling Case for Annihilating Dark Matter

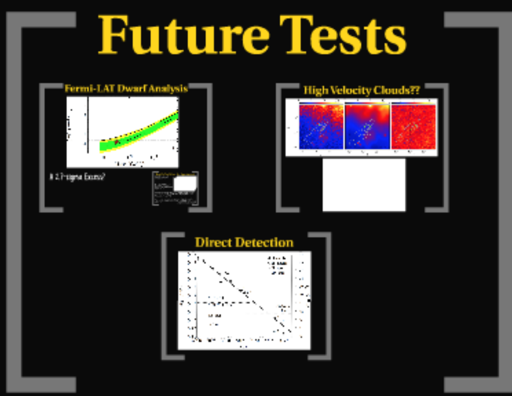
Tim Linden

along with:
Tansu Daylan, Doug Finkbeiner, Dan Hooper, Stephan Portillo, Nick Rodd, Tracy Slatyer

arXiv: 1402.6703

Sungkyunkwan University Seminar - October 15, 2014

It's a compelling case
-- but what is next?



Thank you for attending!

Any Questions?