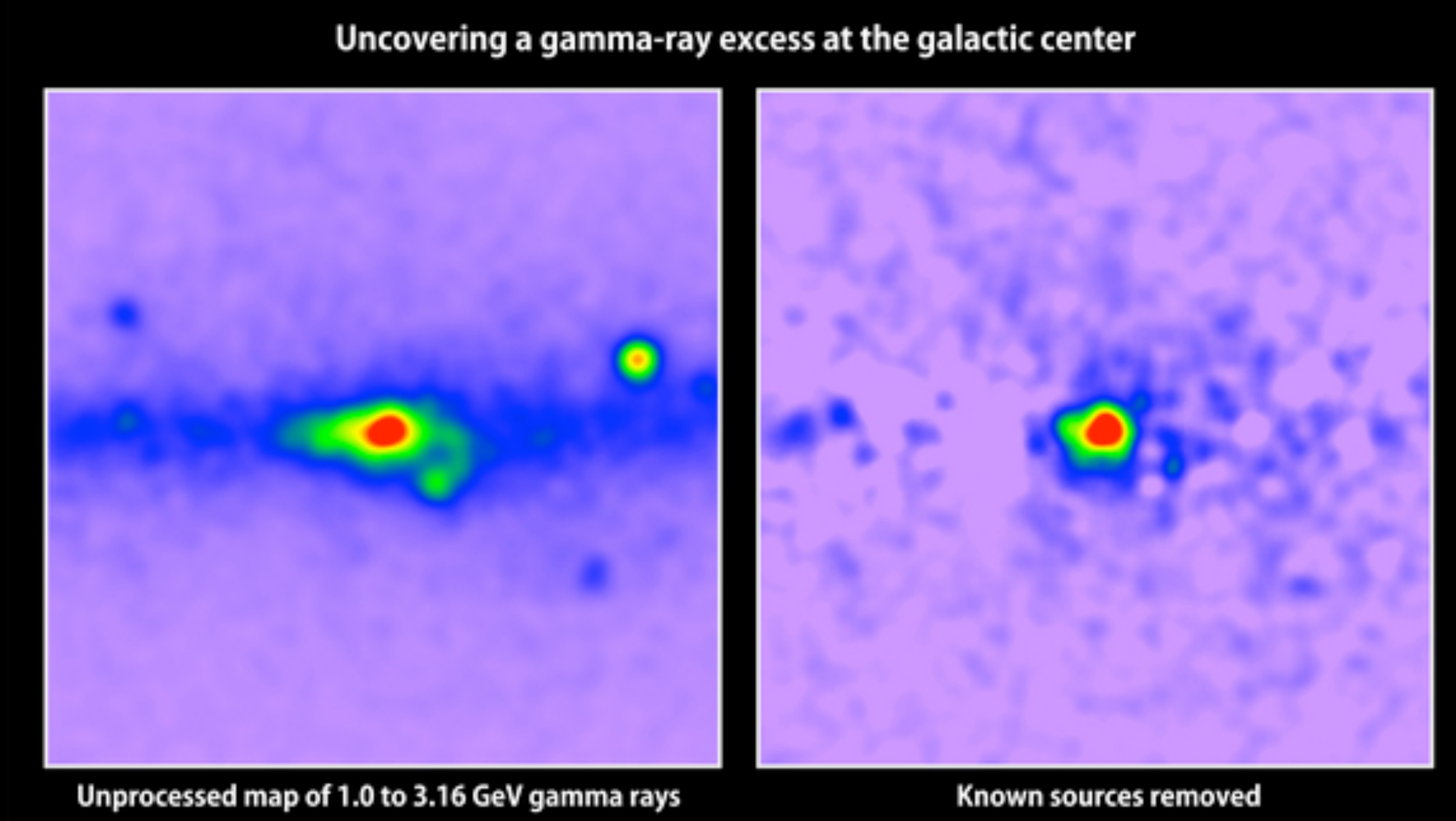
The Hunt for Dark Matter

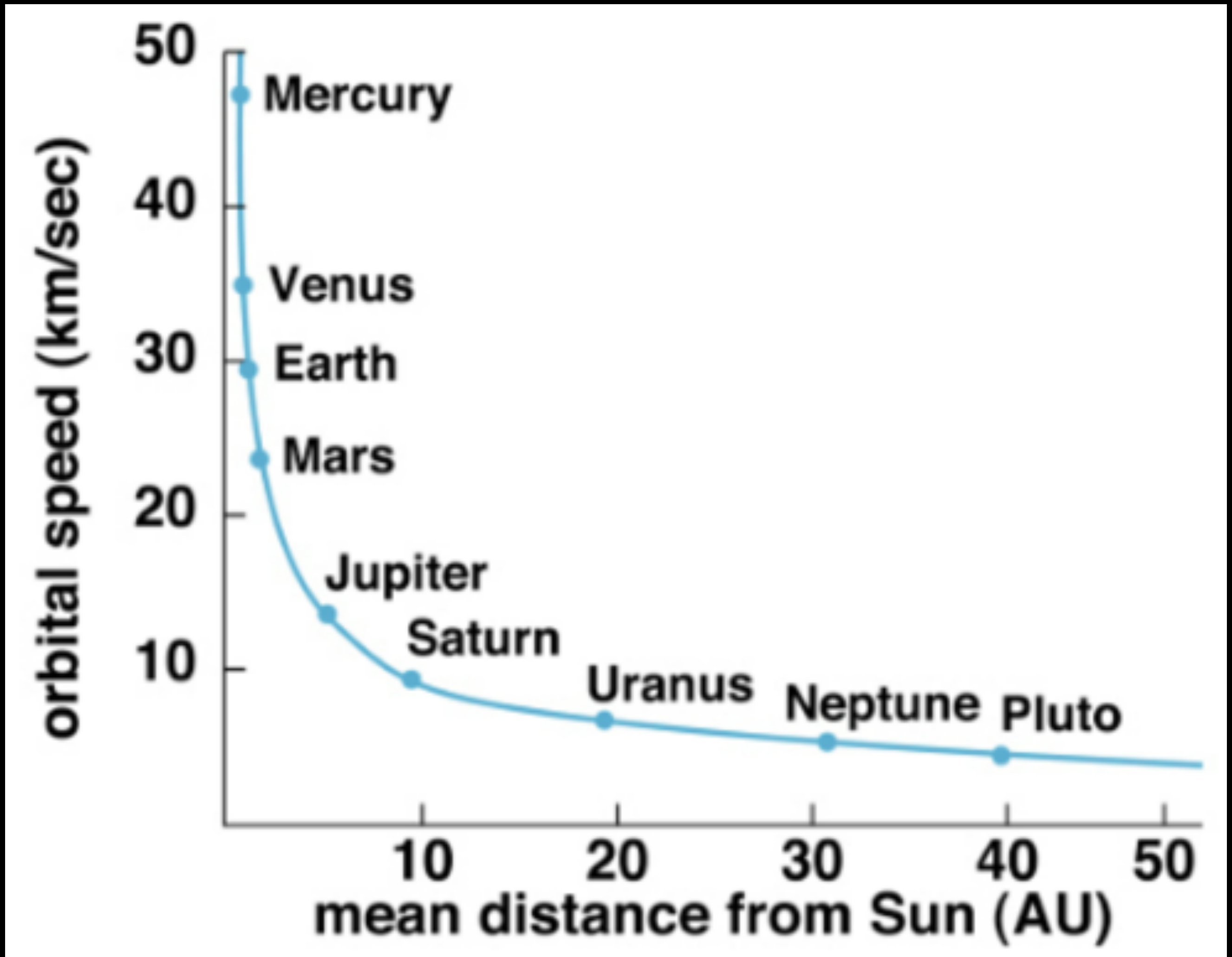


Tim Linden
Einstein/KICP Fellow
University of Chicago

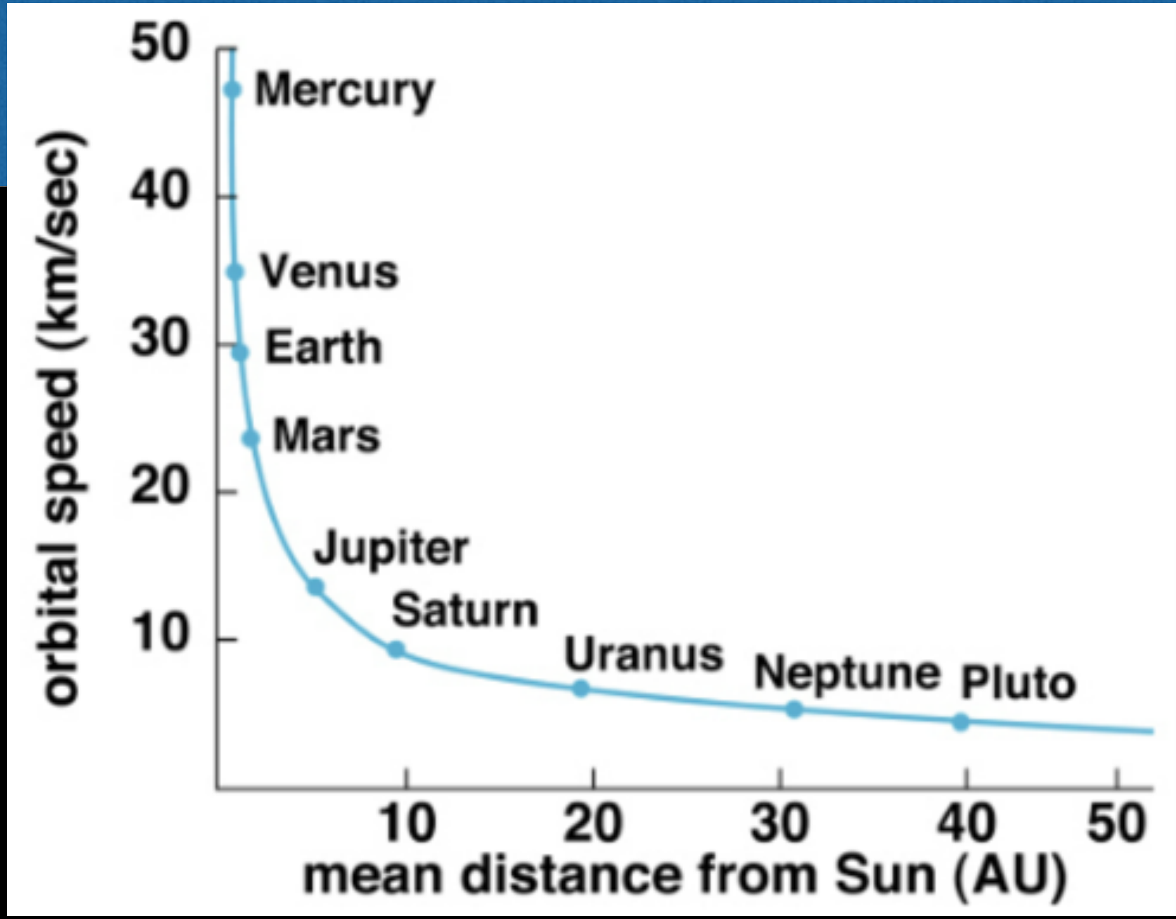
Hubble Circle Immersion Weekend - April 26, 2014

What is Dark Matter?

When things move faster and faster around a circle, it requires more force to prevent them from flying off of their orbit.

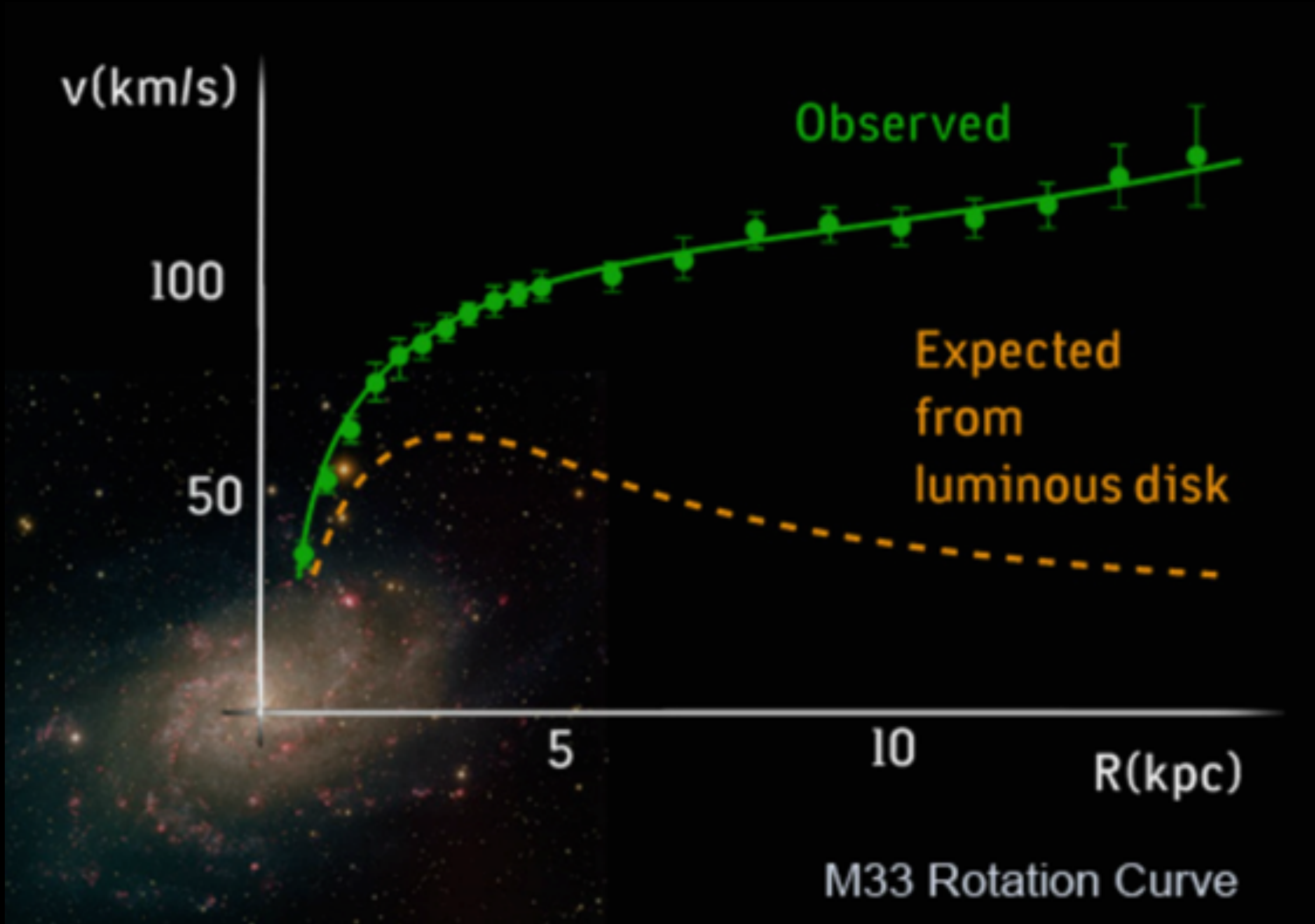


What is Dark Matter?



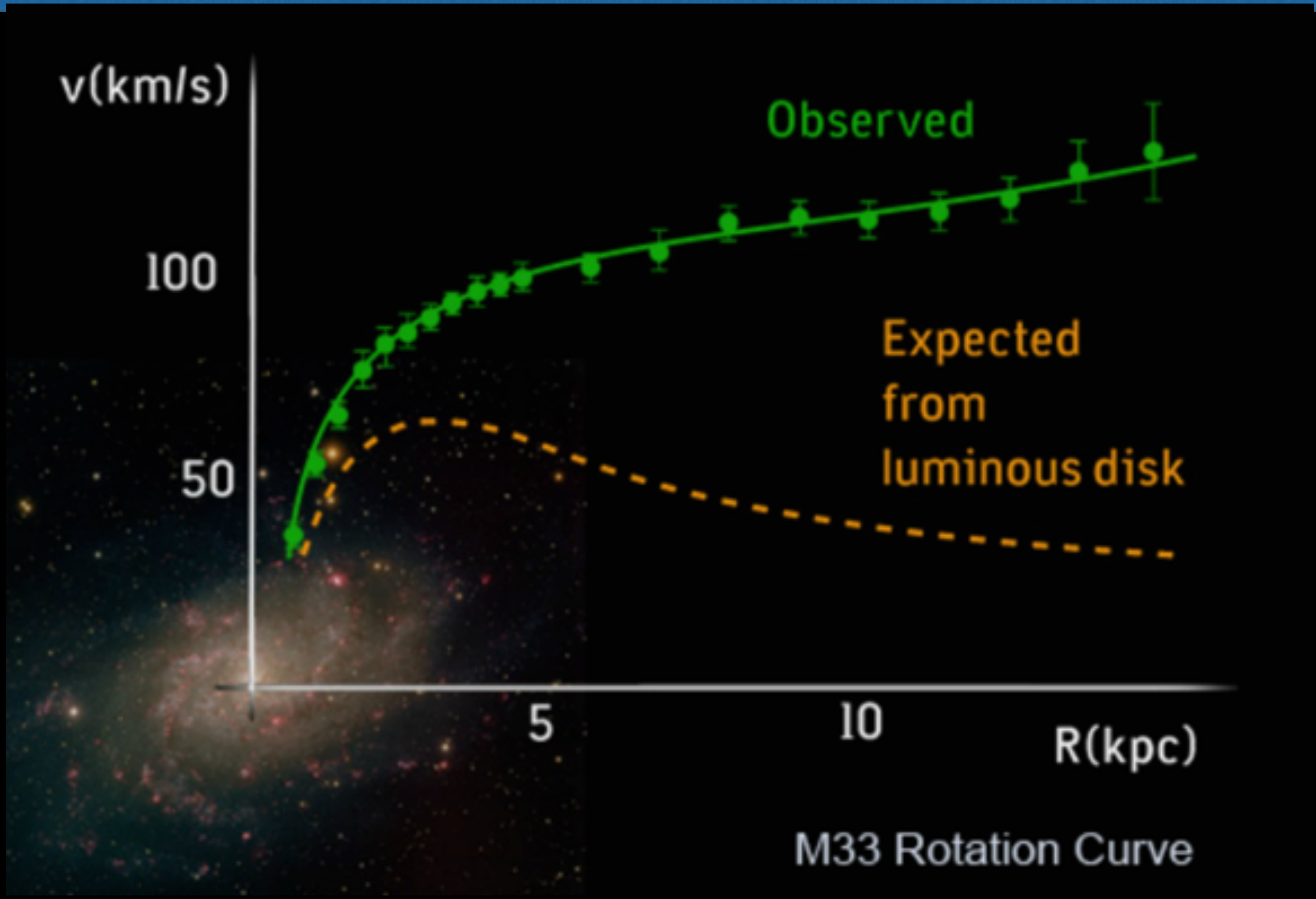
For our solar system we can measure the orbital speed of each planet and very accurately obtain the Sun's mass

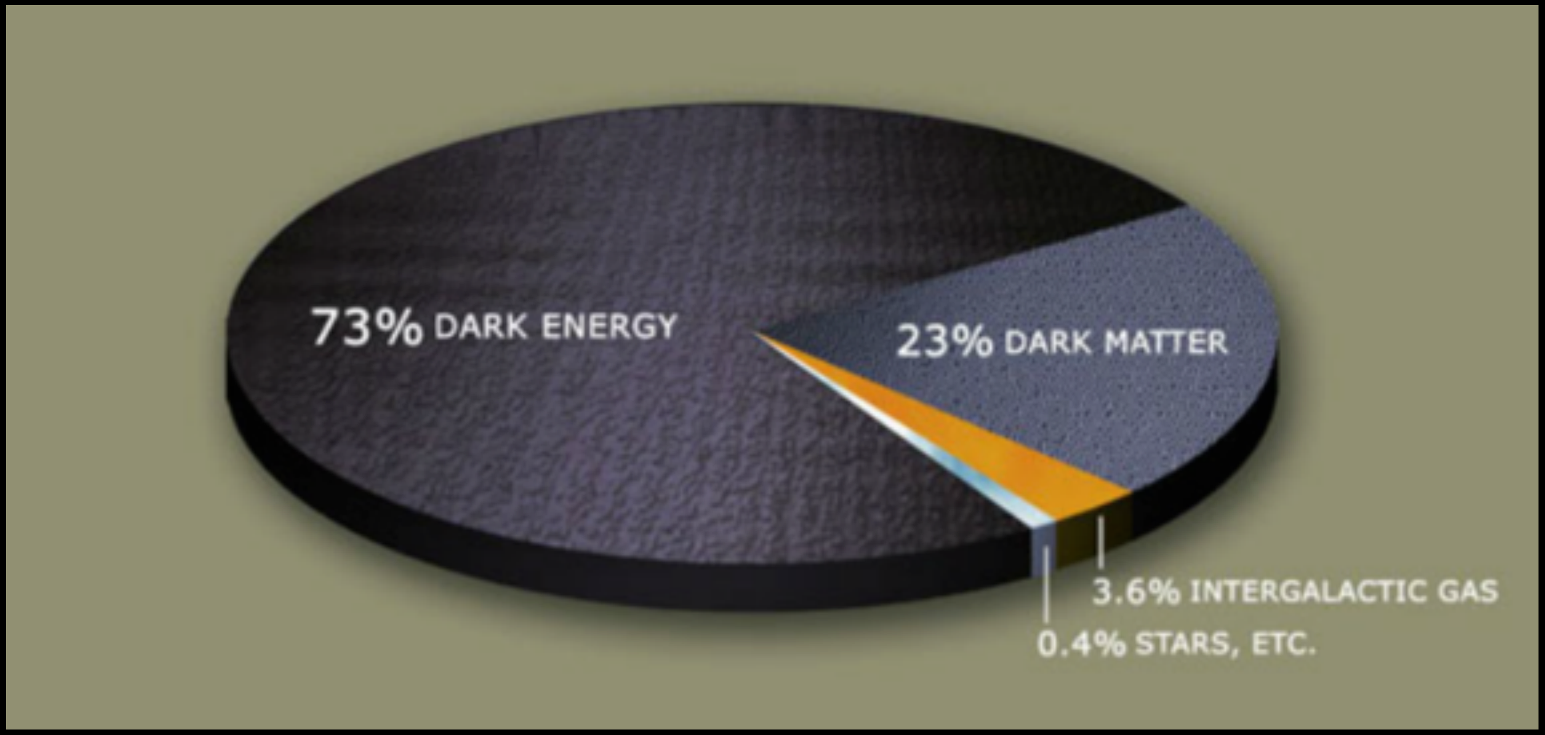
However, when applied to galaxies, this relation no longer holds. When we calculate the orbital speed of each star, we get a larger mass than we can see



What is Dark Matter?

How much dark matter?
In our galaxy there is about 5-10x as much dark matter as normal matter (stars and gas)

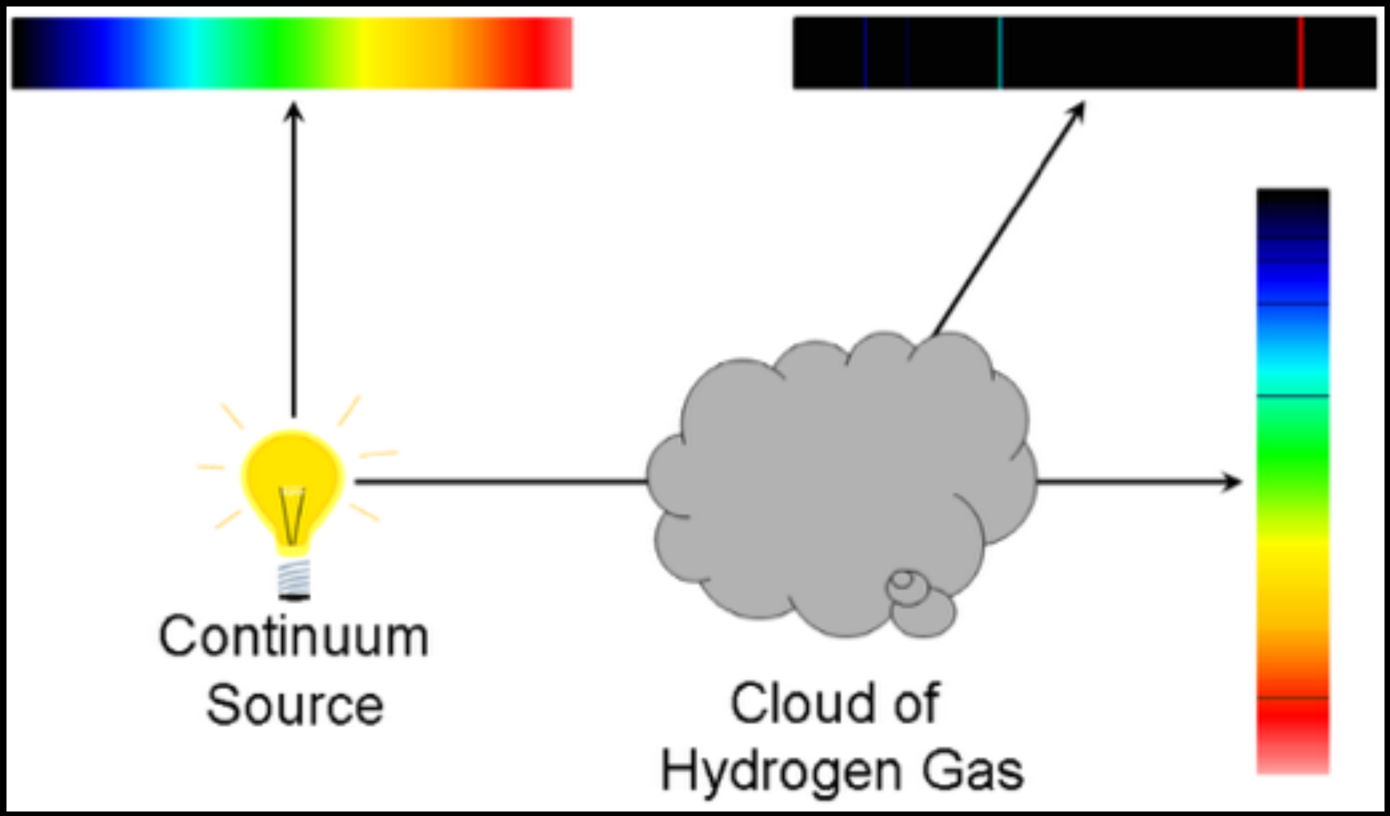


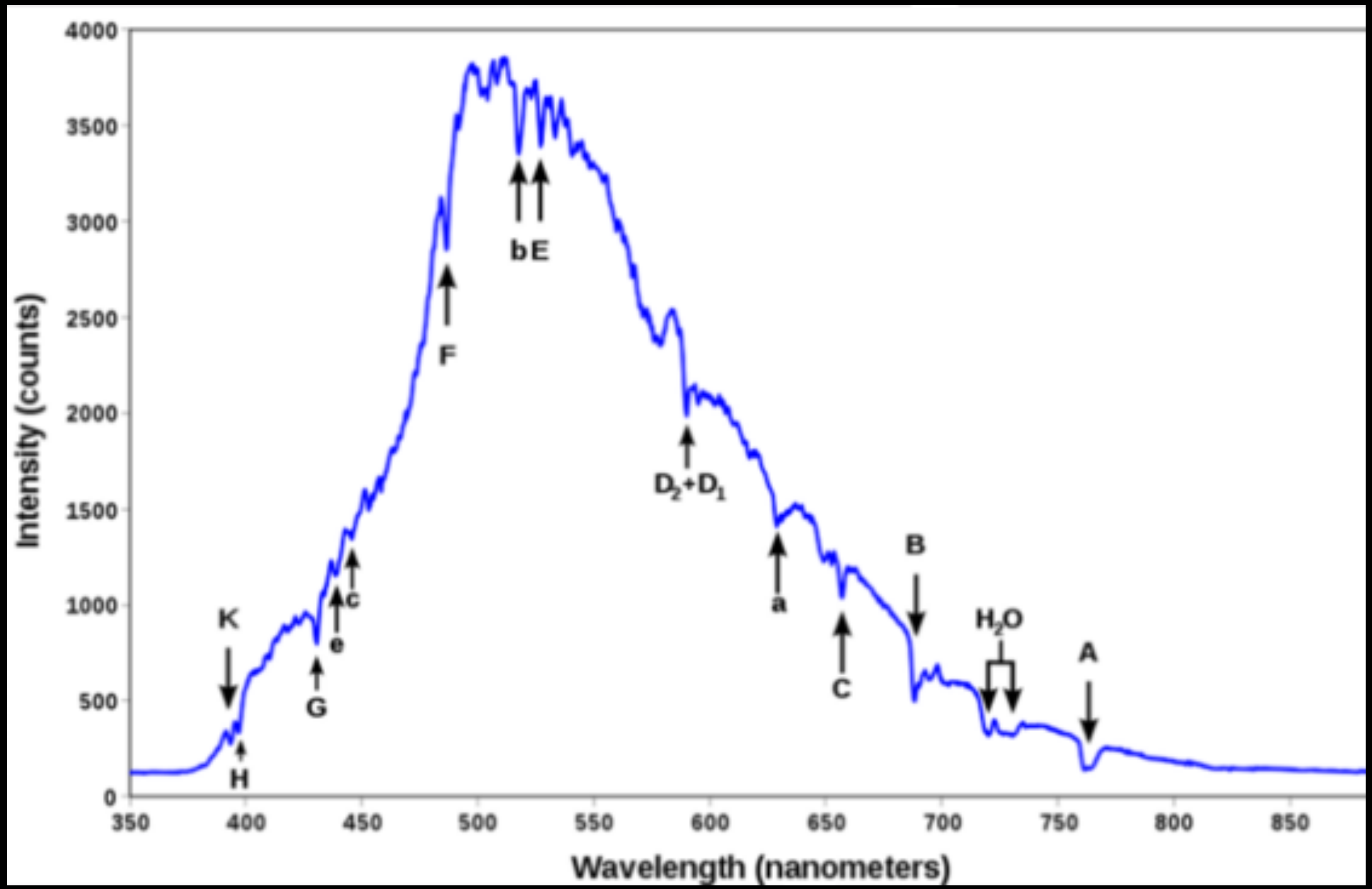


In the universe overall, there is about 6x as much dark matter as normal matter

What is not Dark Matter?

Maybe the dark matter is just extra gas and dust that we can't see?



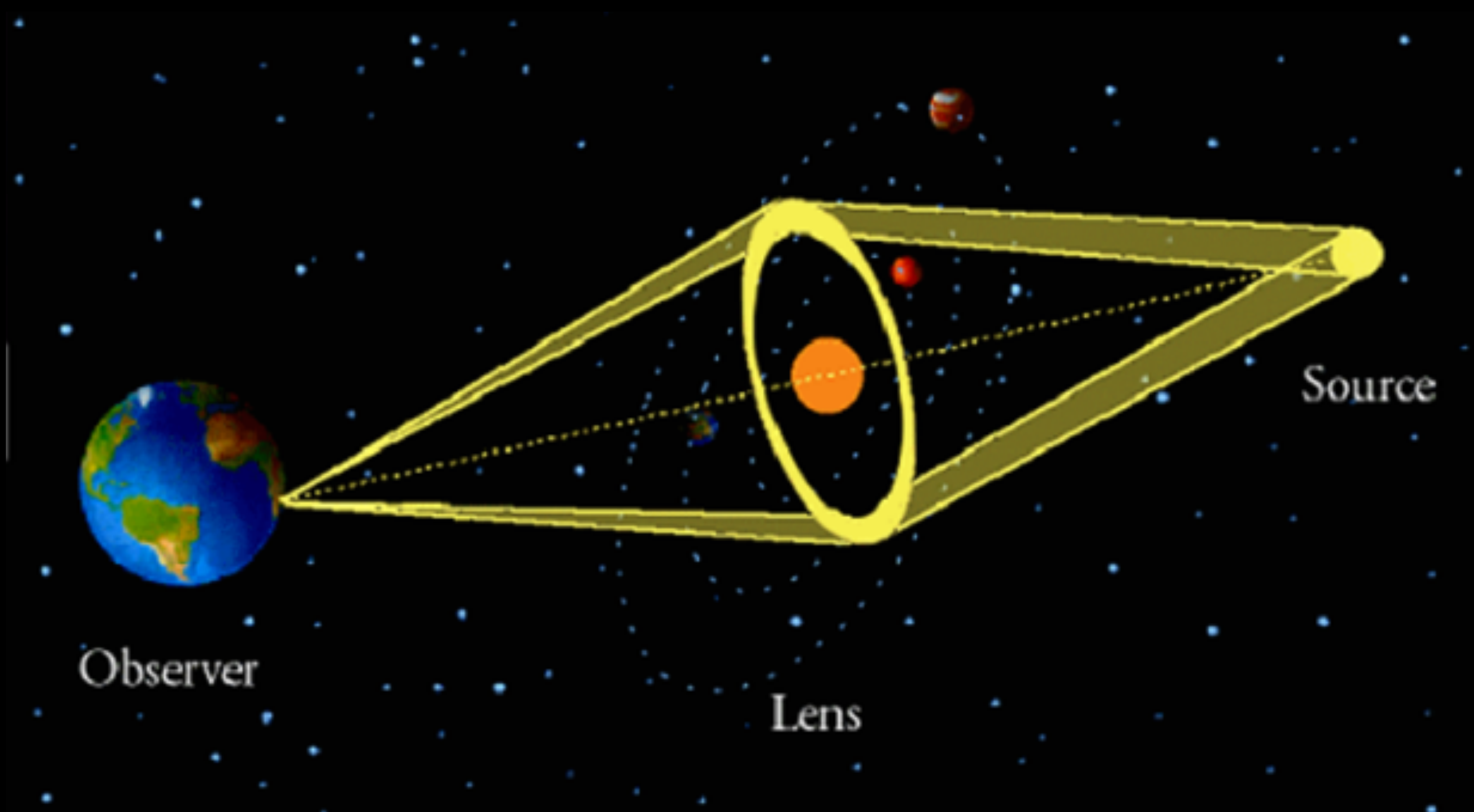


Observations of stars throughout our galaxy rule out this hypothesis

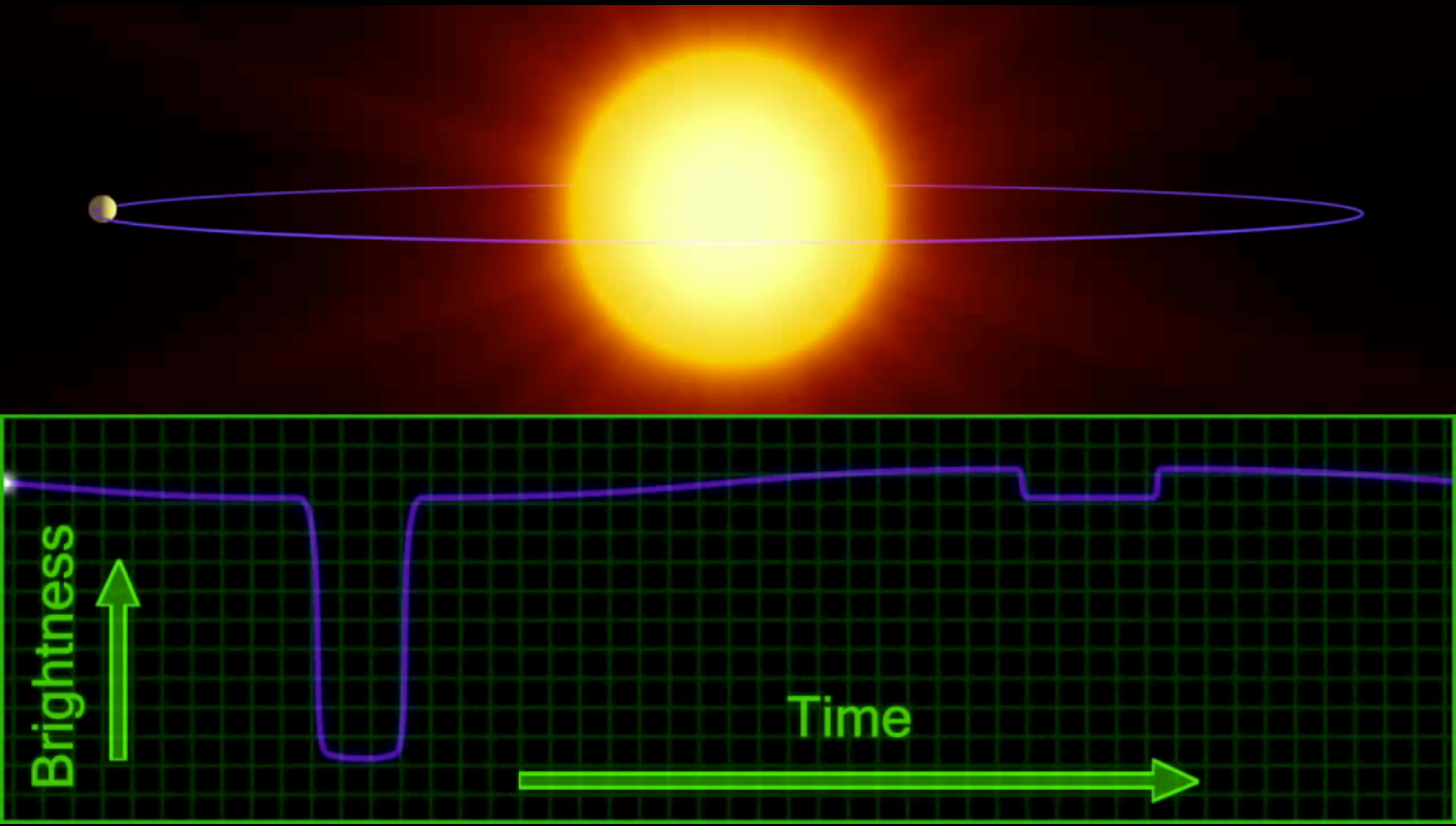
What is not Dark Matter?

Perhaps the dark matter is large objects (like planets) that don't make their own light — and are difficult to see?

If the dark matter were planets the size of Jupiter, then we would need about 100,000 for every star in the galaxy



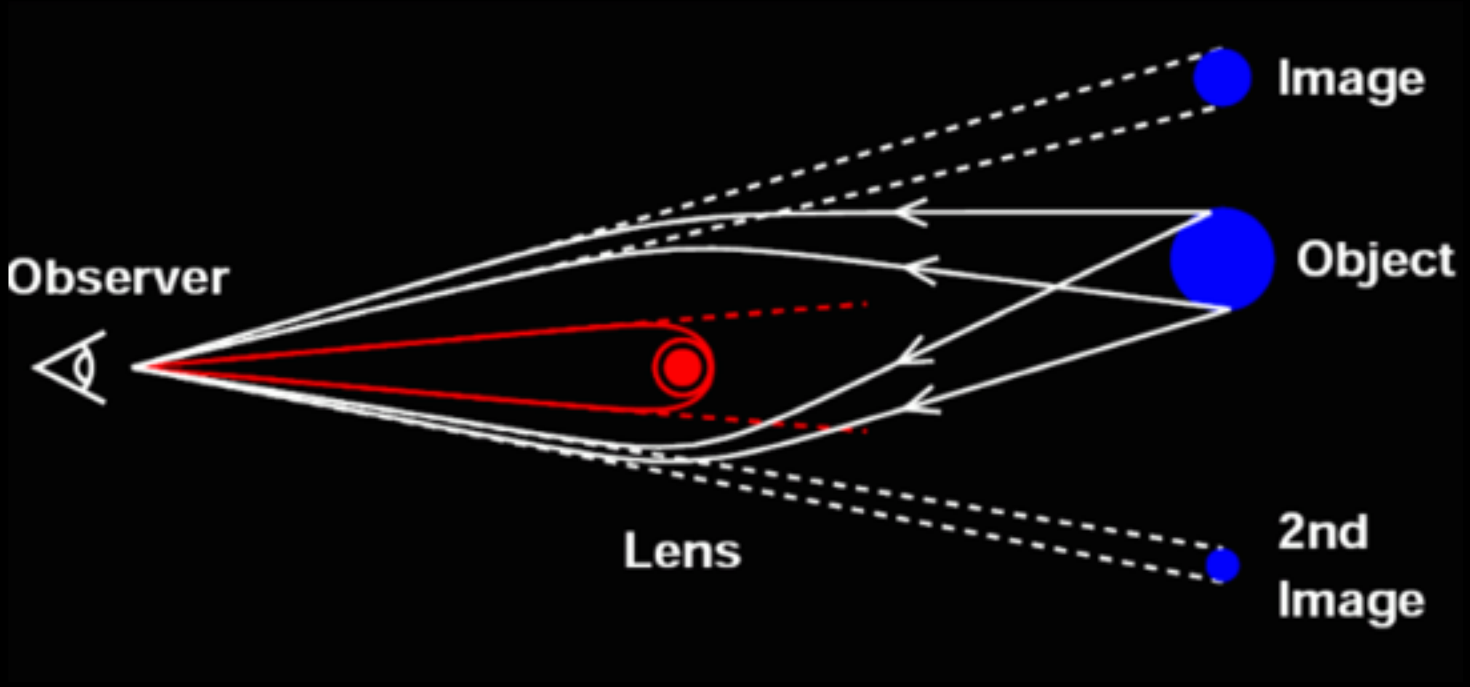
What is not Dark Matter?



What is not Dark Matter?

Maybe the dark matter is composed of even larger objects (like black holes) - then we would need less

But black holes would deflect light passing nearby



What is not Dark Matter?

What is not Dark Matter?

Well - we’ve rounded up all the usual suspects!

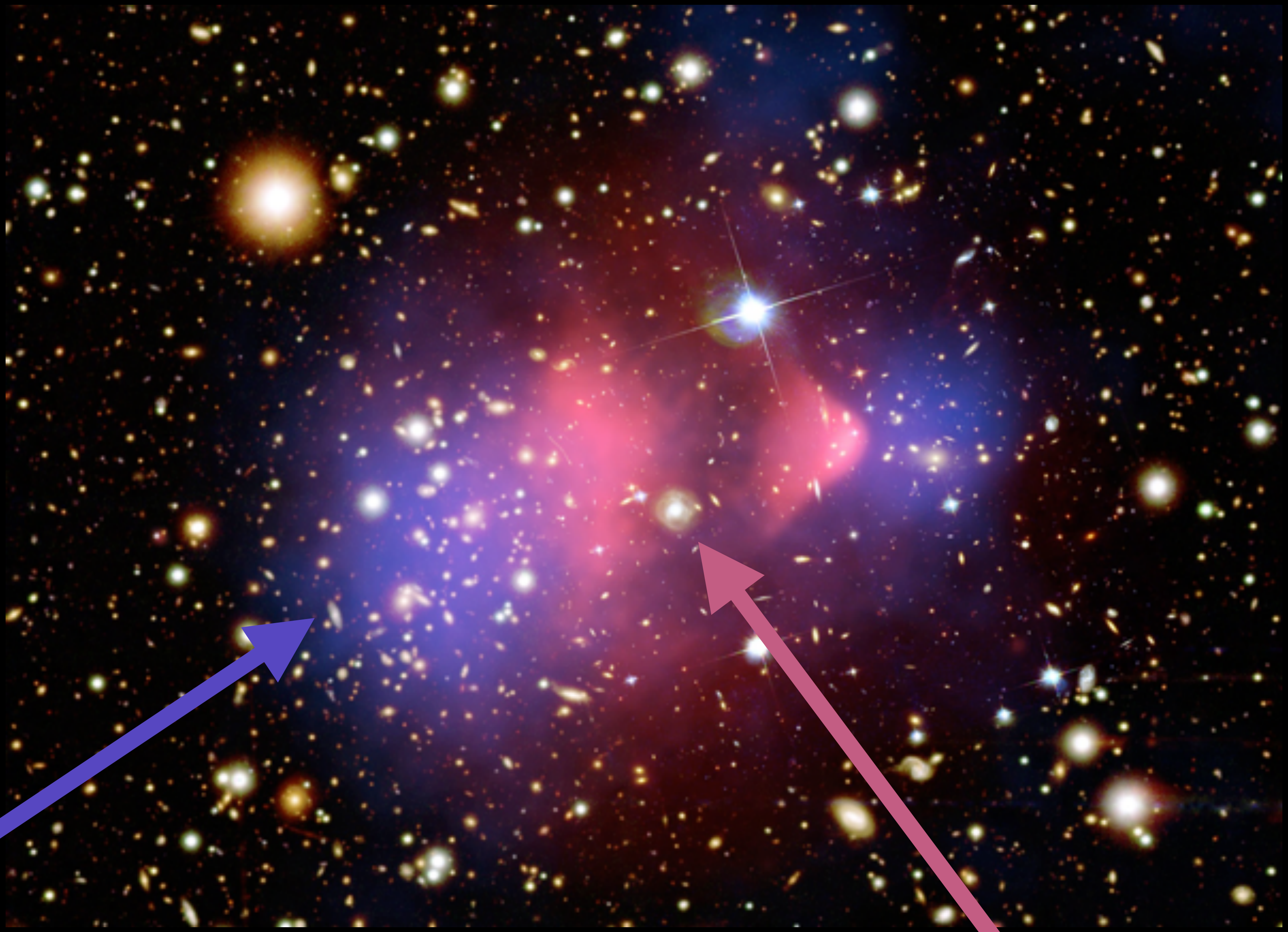
But it’s not them…..

So what is it?

More Evidence for Dark Matter

First - Is Dark Matter real?

Bullet Cluster!

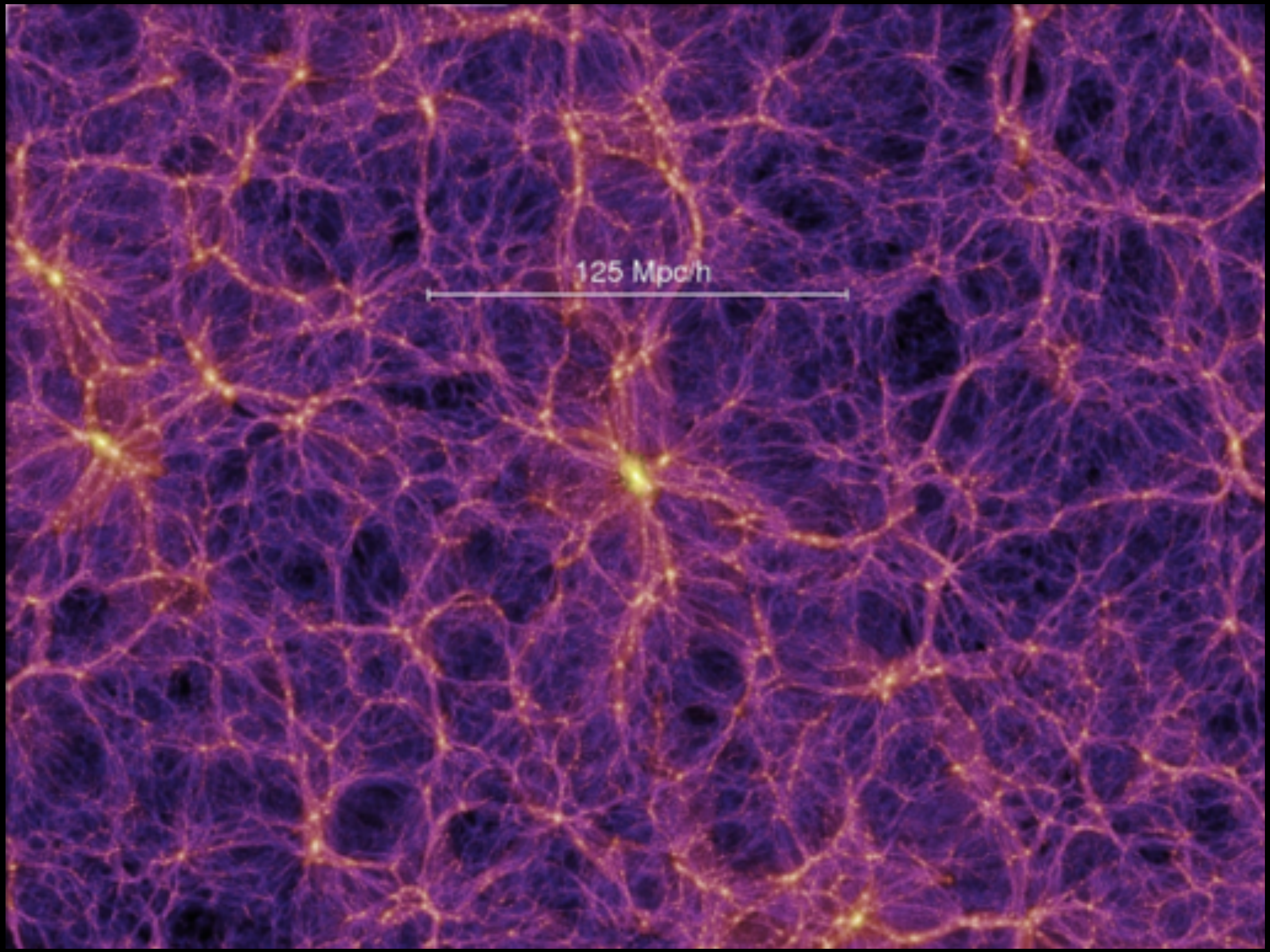


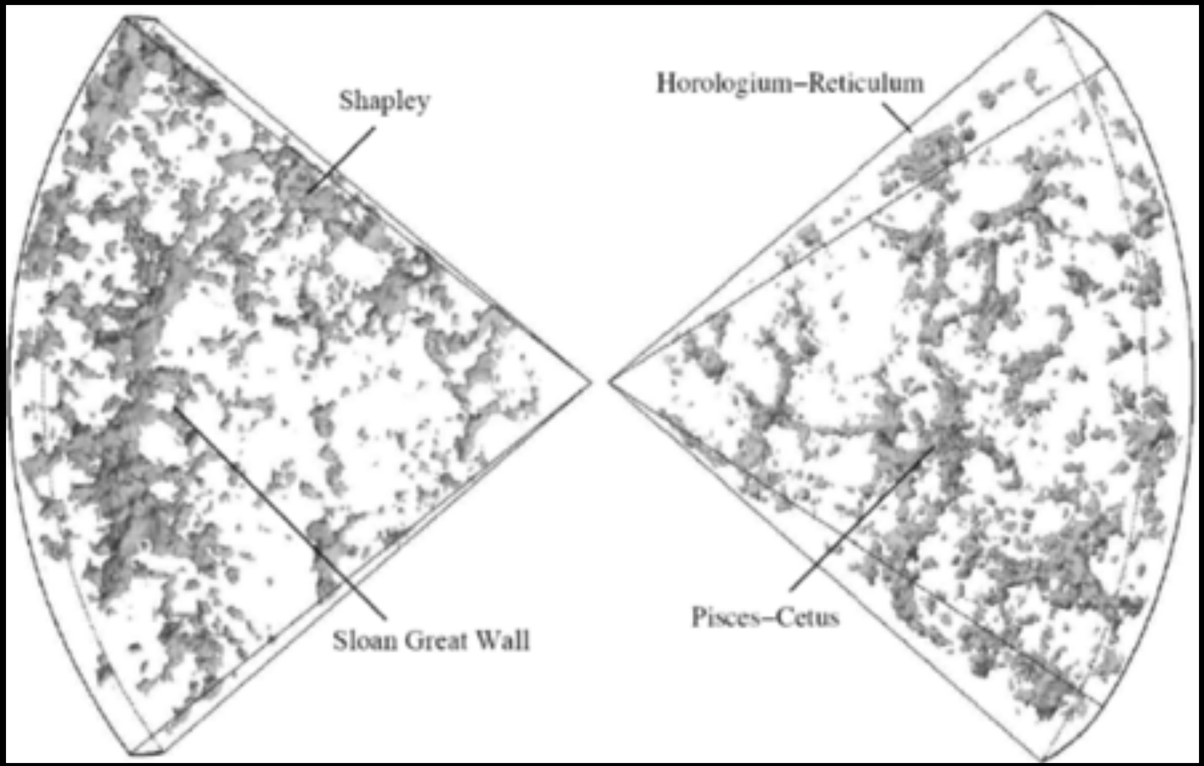
Mass and Stars

Gas

More Evidence for Dark Matter

Dark matter controls how mass "clumps" in the universe



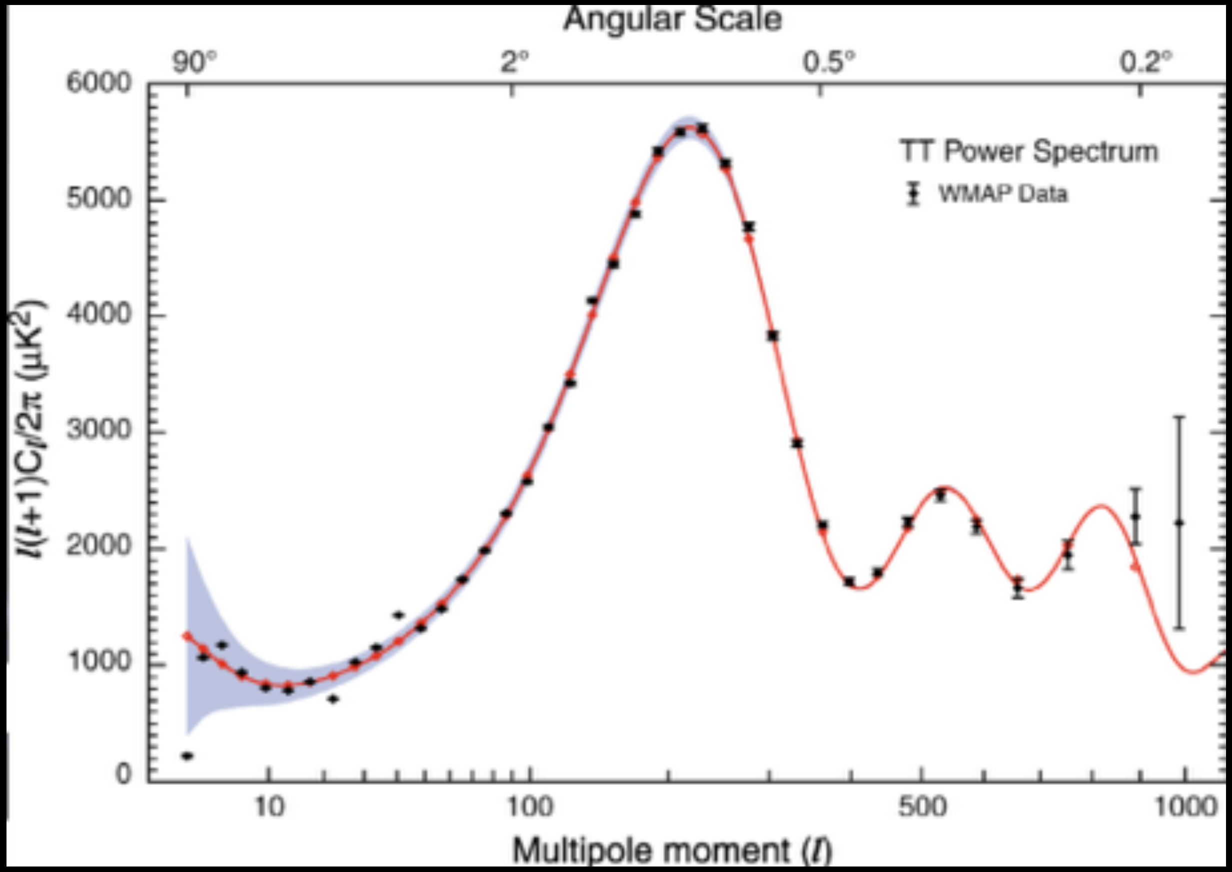


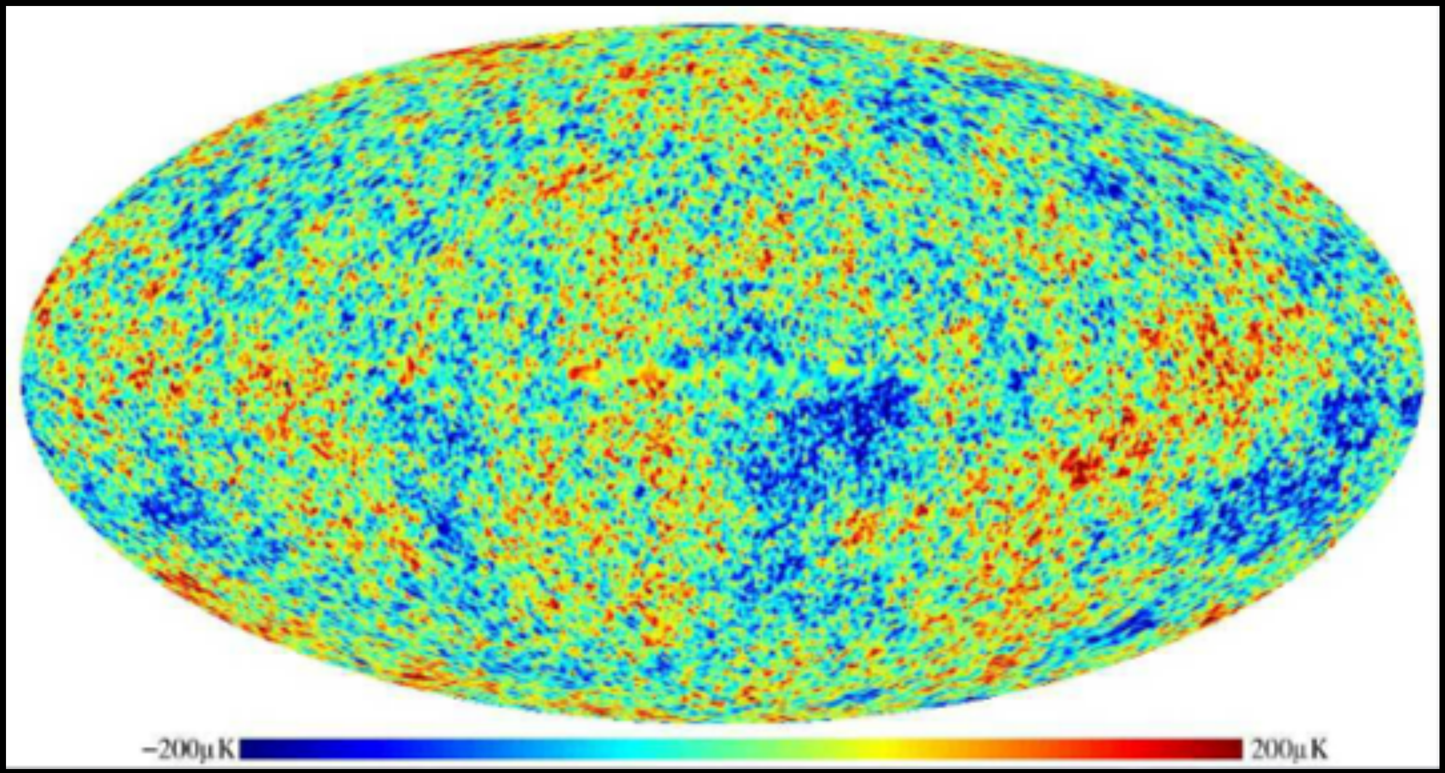
Visible galaxies fall into dark matter "clumps" - and trace the dark matter density

More Evidence for Dark Matter

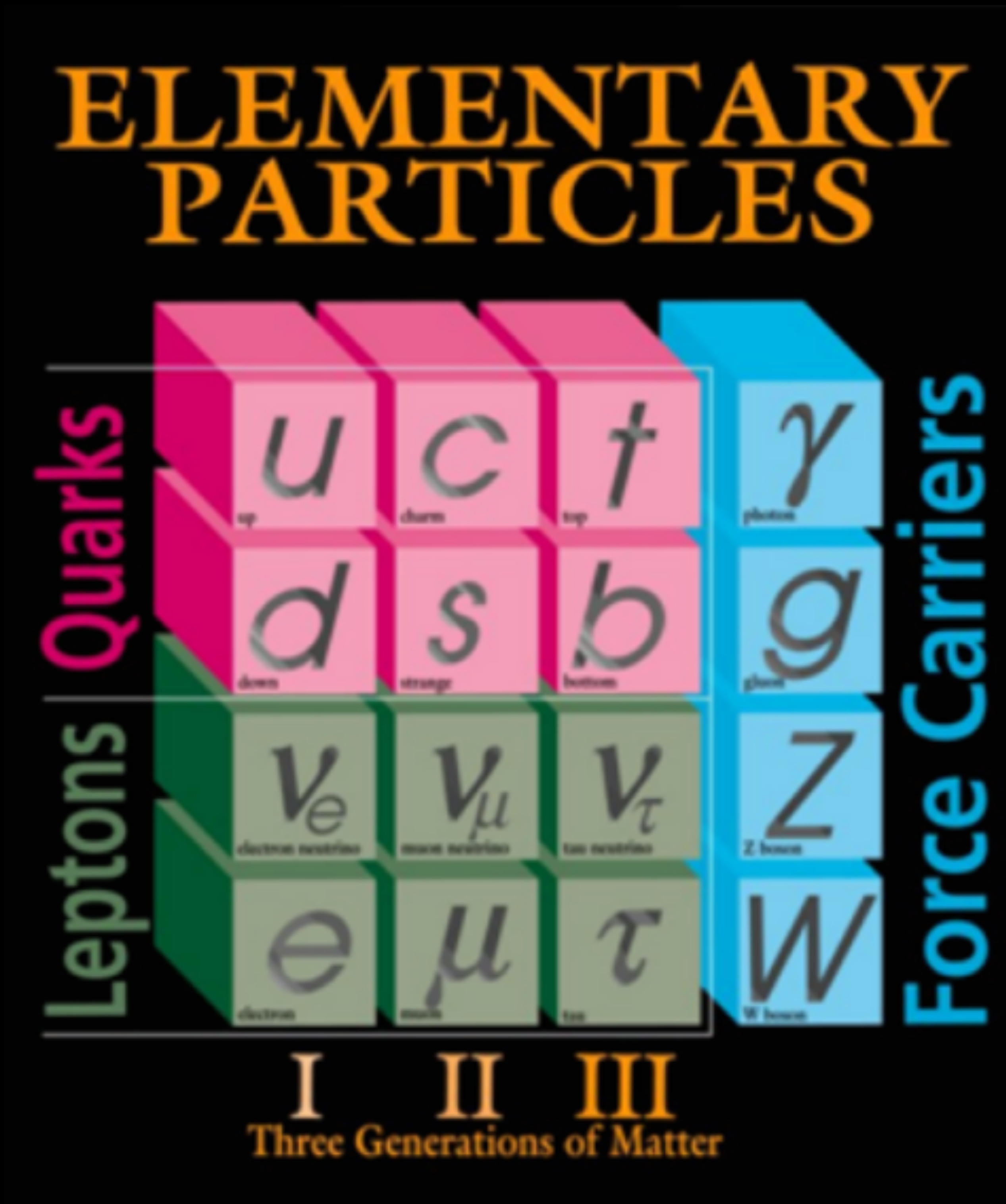
More Evidence for Dark Matter

Dark Matter also affects the earliest visible light - from the Cosmic Microwave Background



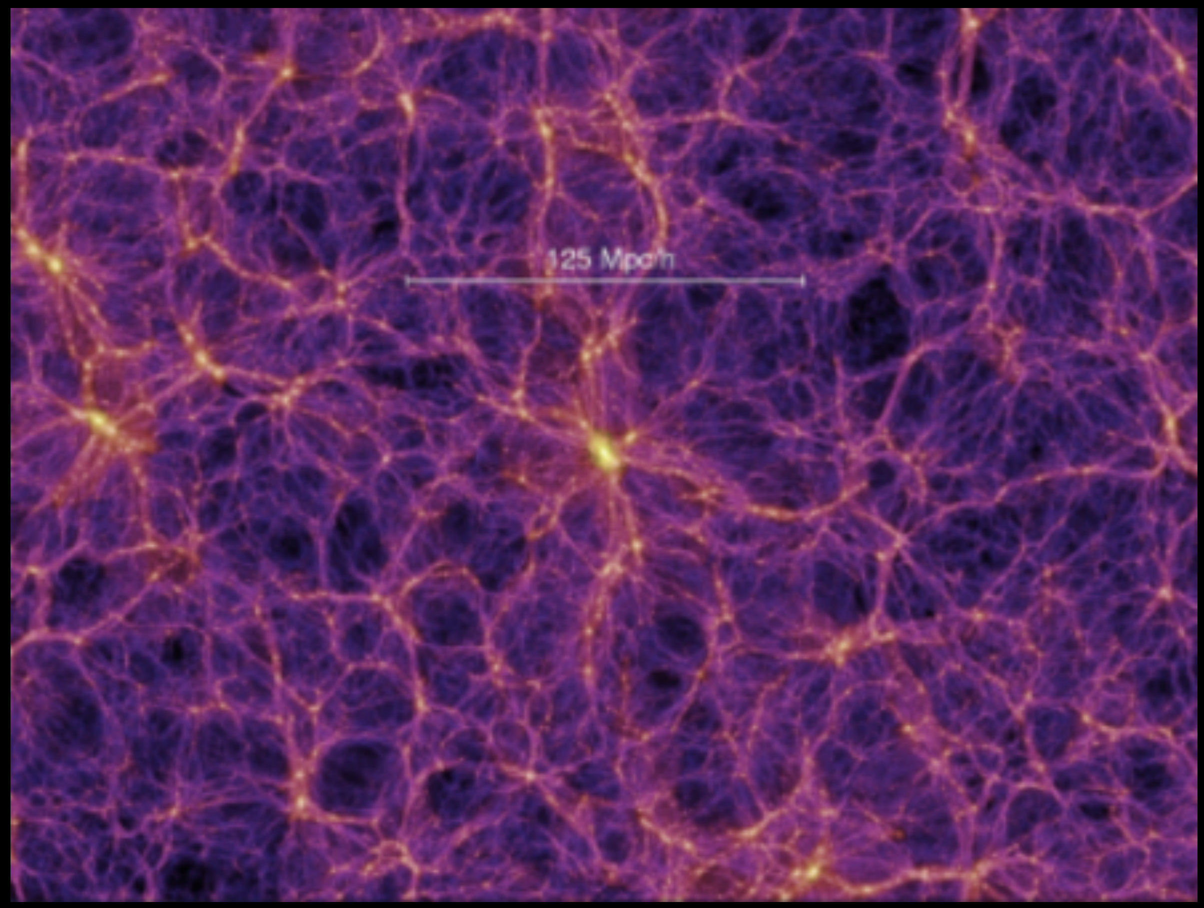


Dark Matter as a New Particle

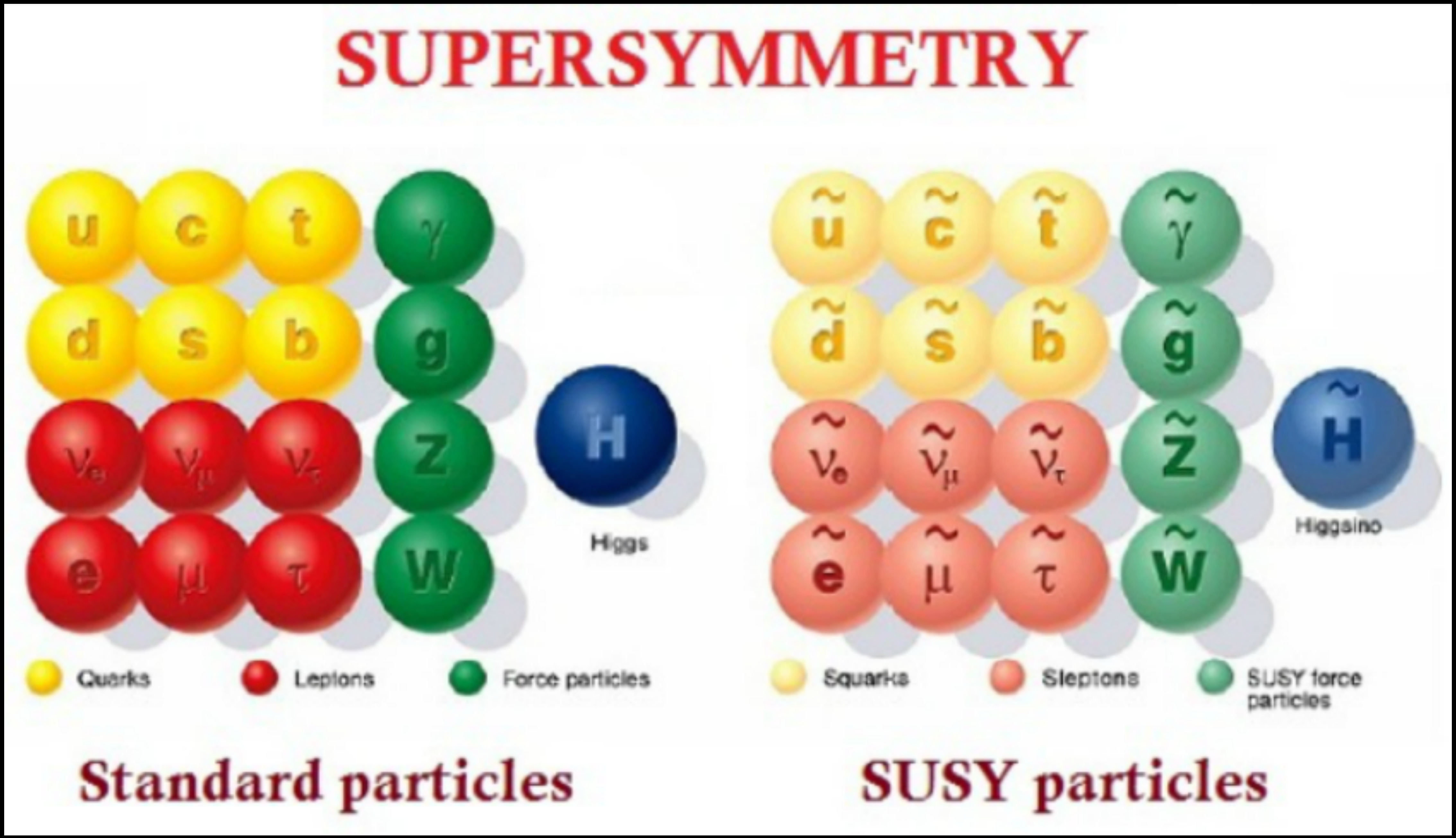


Properties of the Dark Matter Particle:

1.) Dark
2.) Stable
3.) Cold



Dark Matter as a New Particle

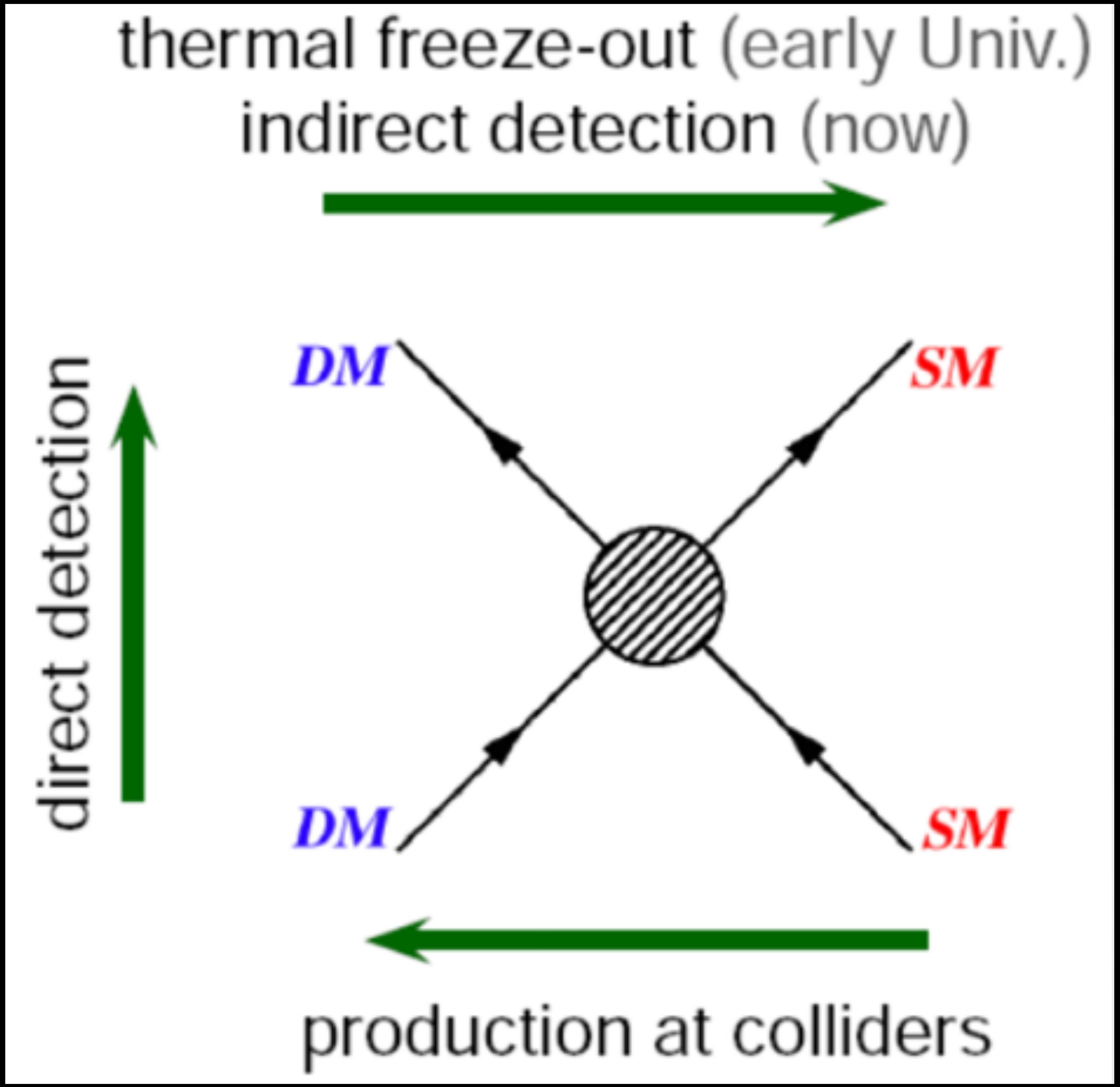


An extension of the standard model - motivated by particle physics - may solve the puzzle

WIMP Miracle

One question remains - why 6x as much dark matter?

Solvable — *if* there is a way for dark matter to interact with standard model particles



Interestingly (Miraculously?) if this interaction happens via a force similar to the weak nuclear force, then the universe produces the correct density of dark matter

WIMP Miracle

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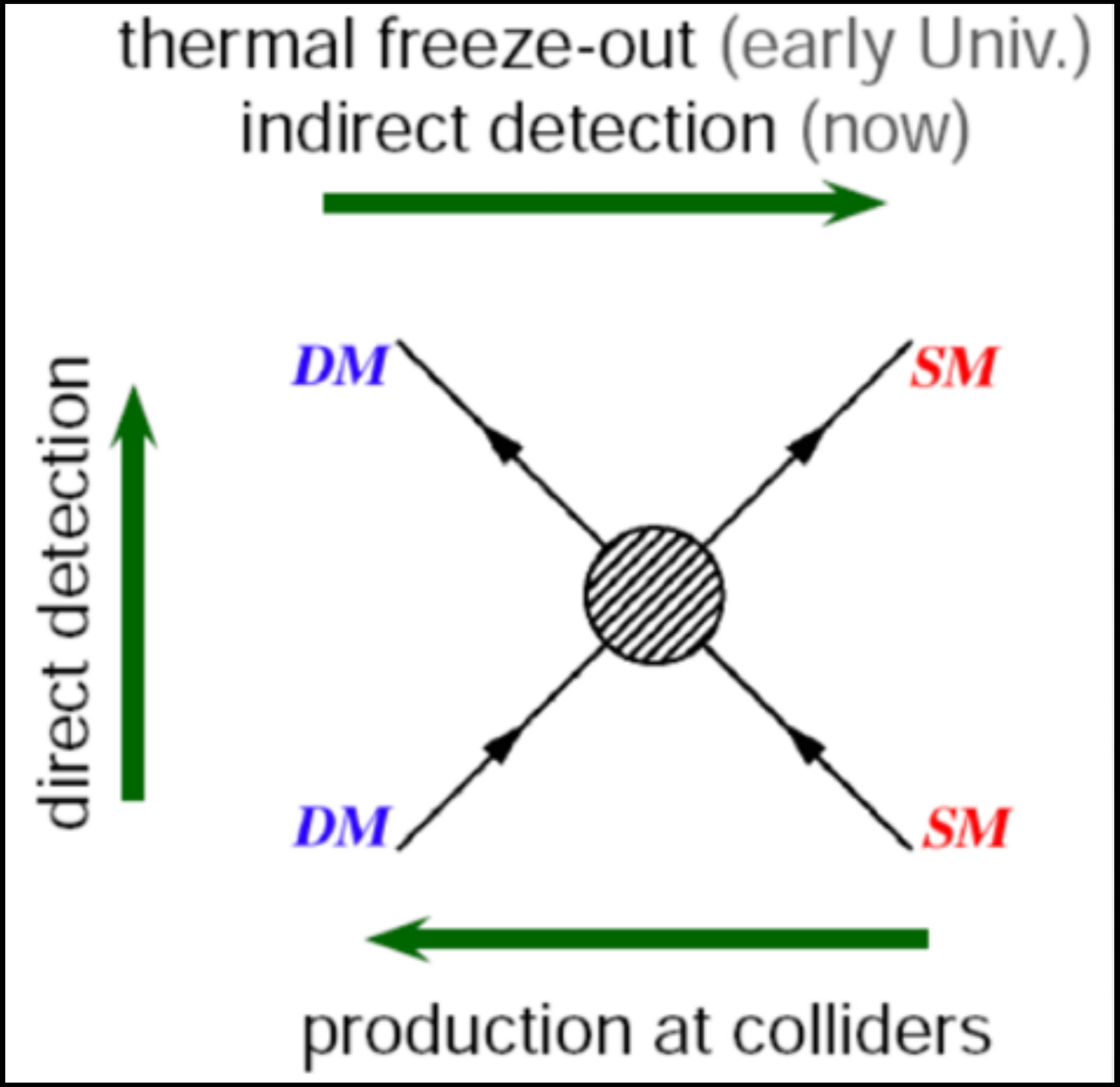
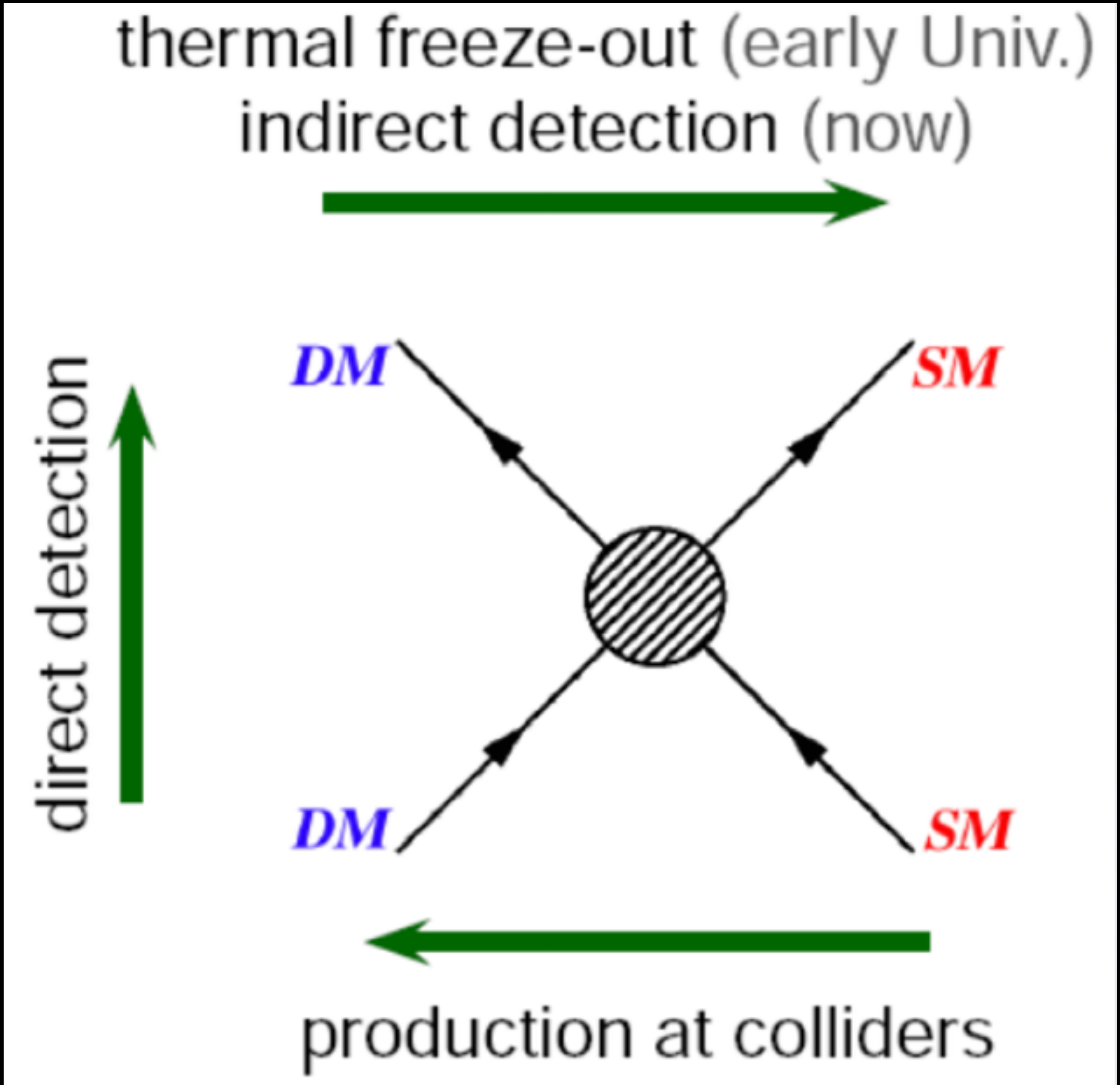


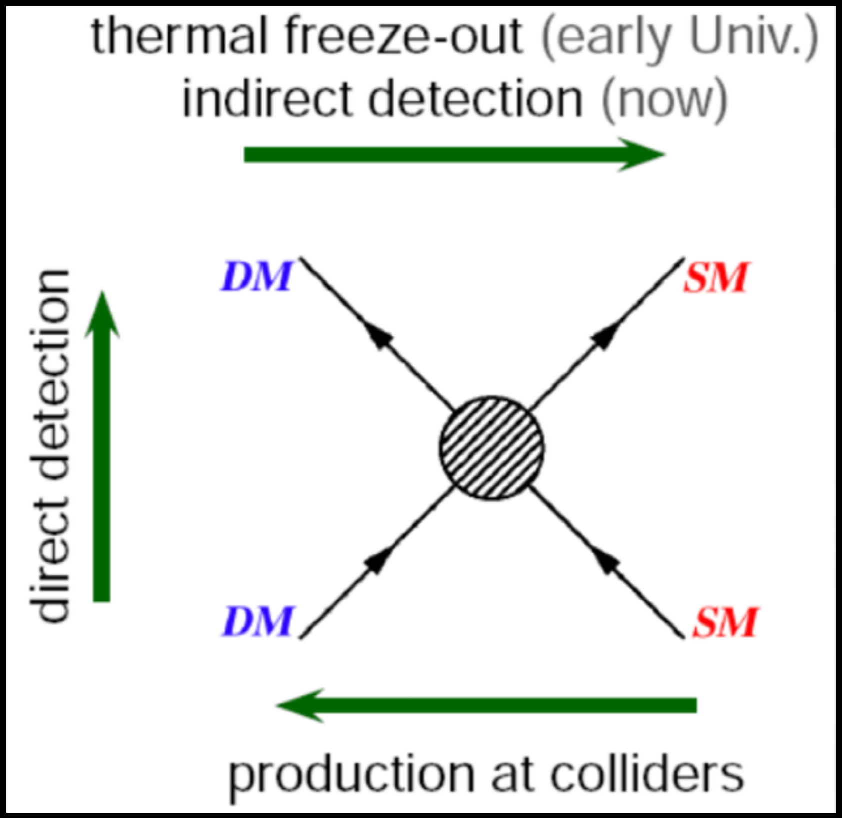
Magic Number! - The velocity multiplied by the dark matter annihilation cross-section should be $3 \times 10^{-26}\ cm^3 s^{-1}$

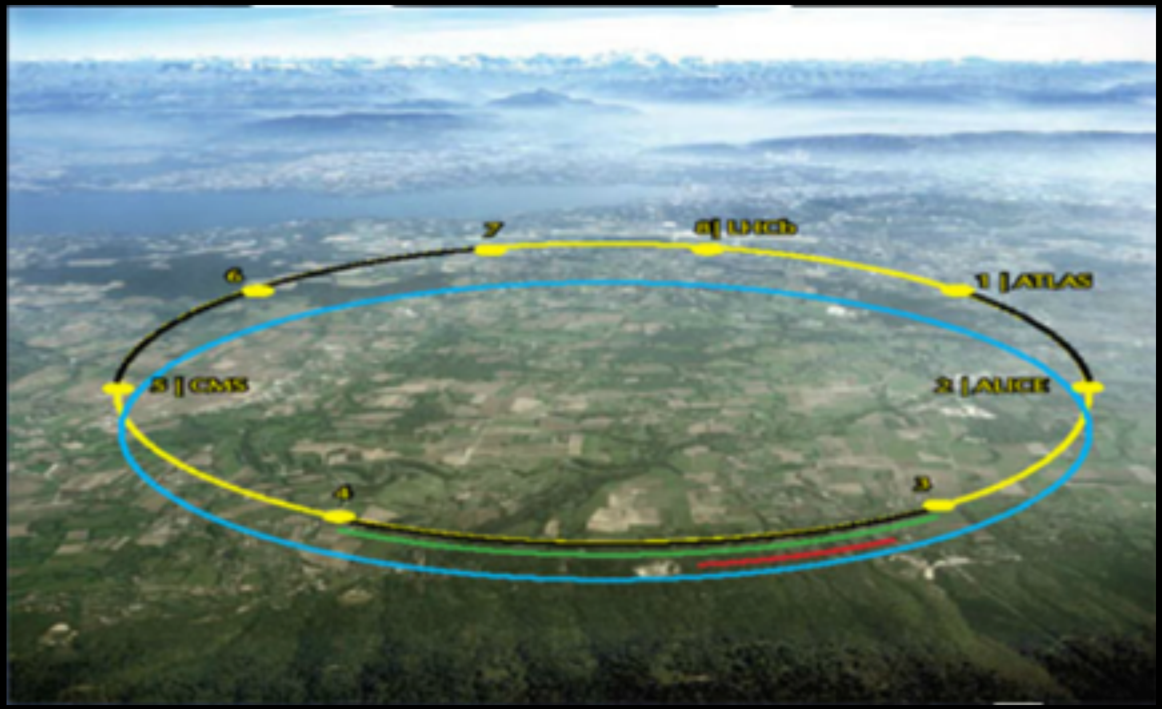
How Can We Detect this New Particle?

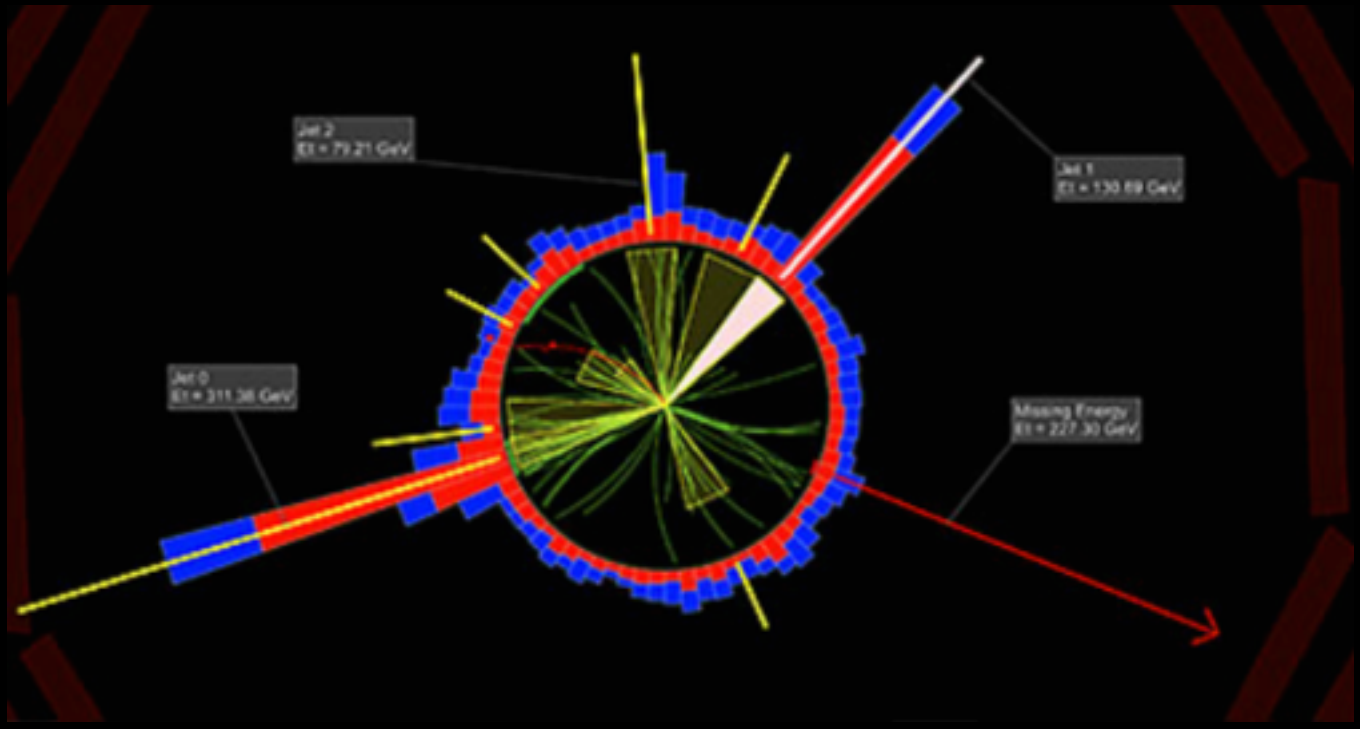


How Can We Detect this New Particle?

Crashing protons together may create a pair of dark matter particles

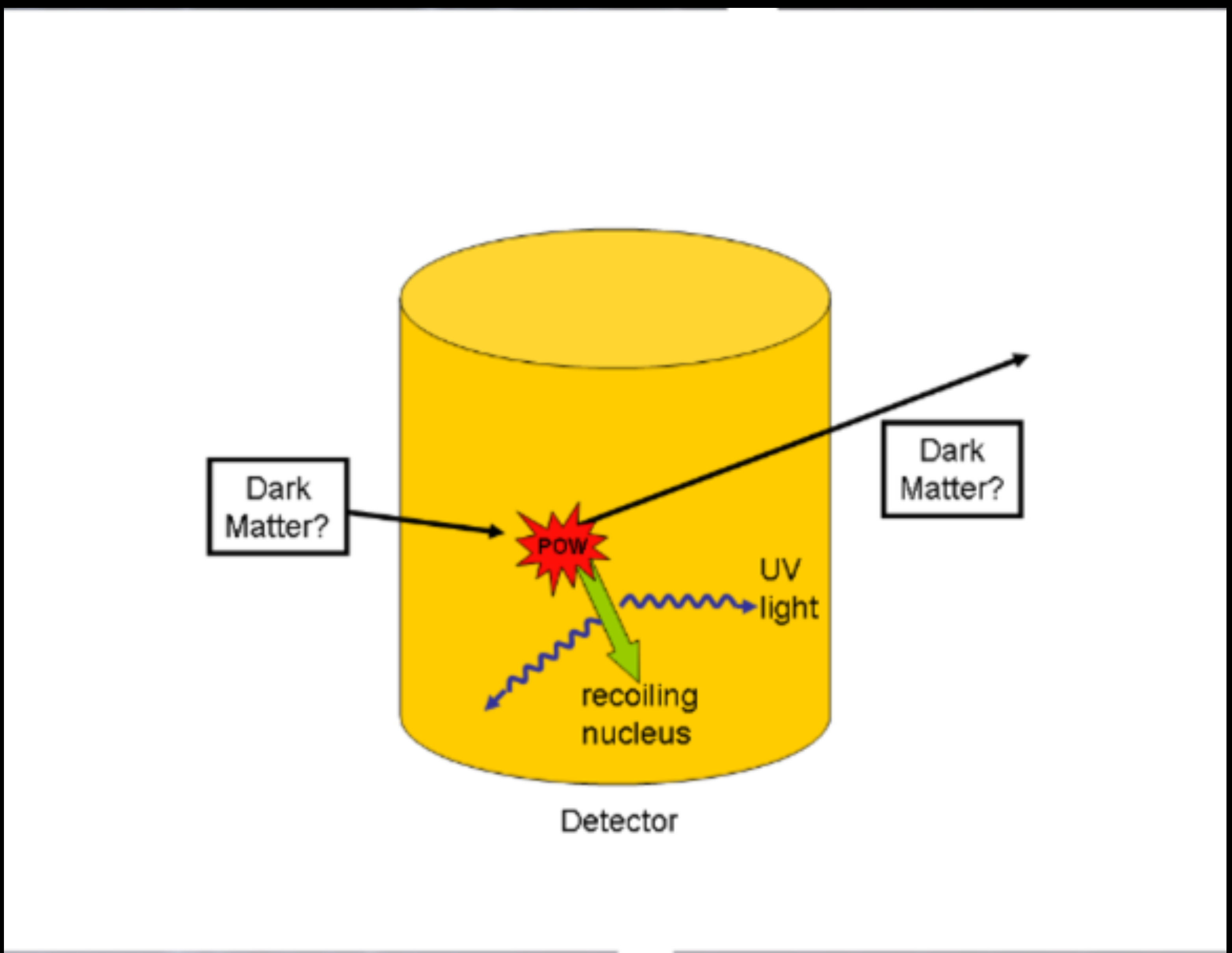


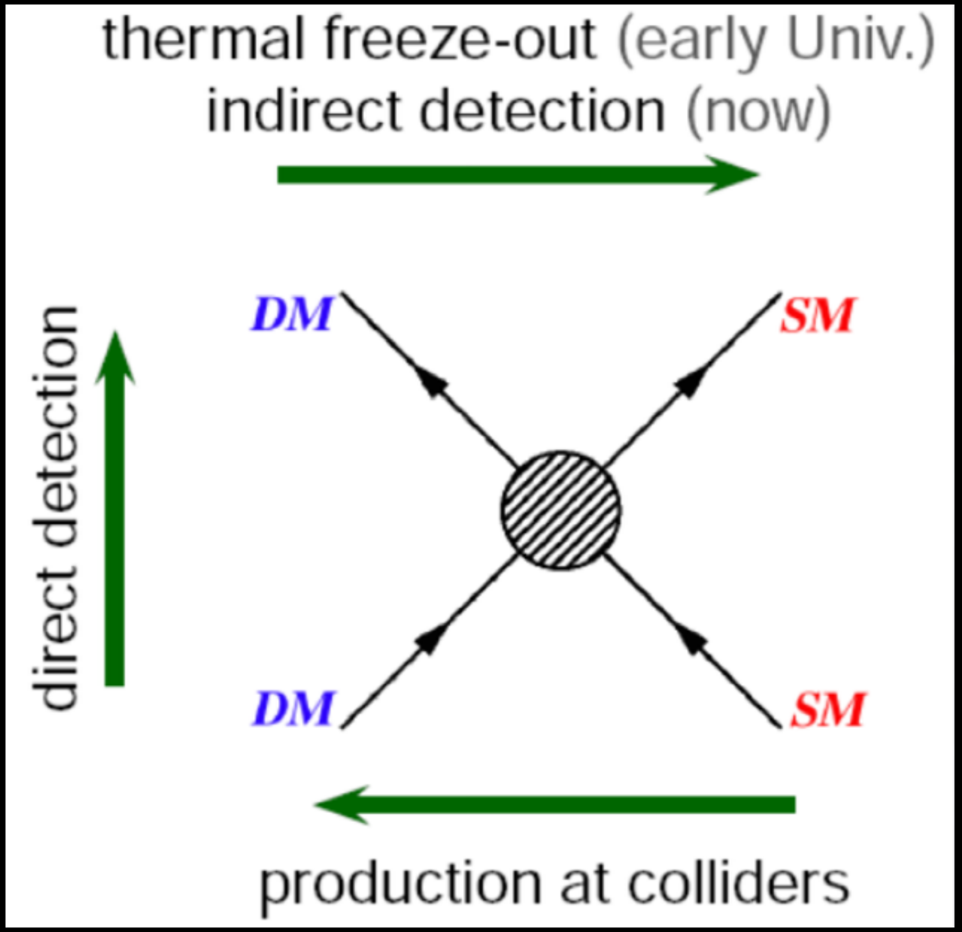


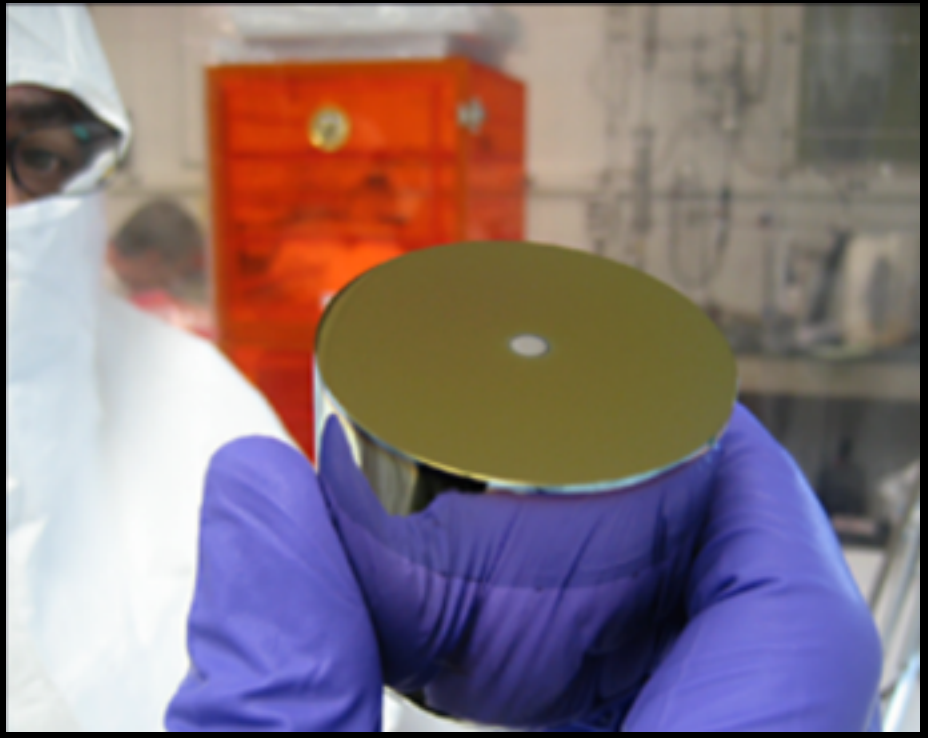


How Can We Detect this New Particle?

Dark matter moving through the Earth may bump into standard model particles - causing them to recoil







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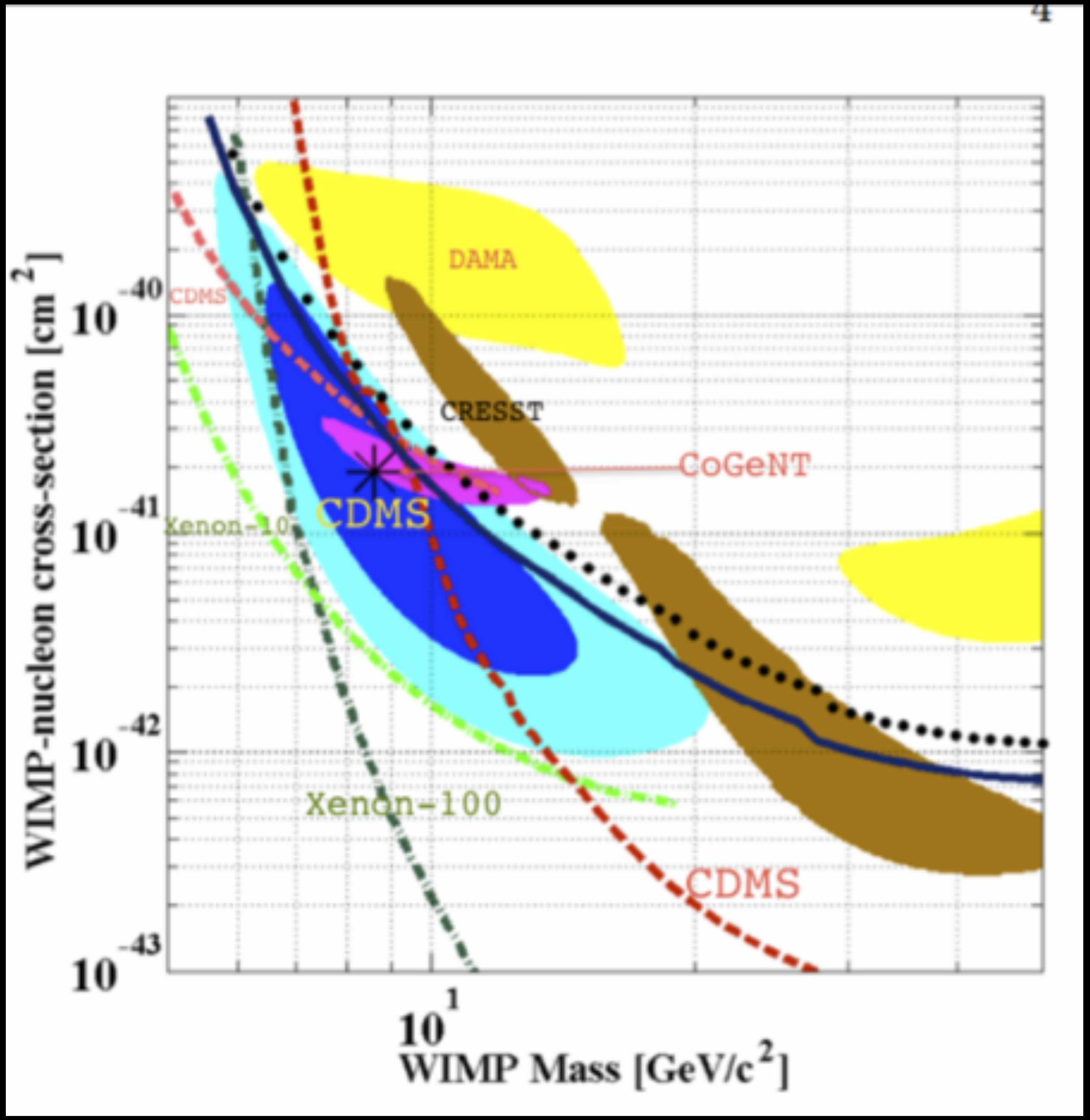

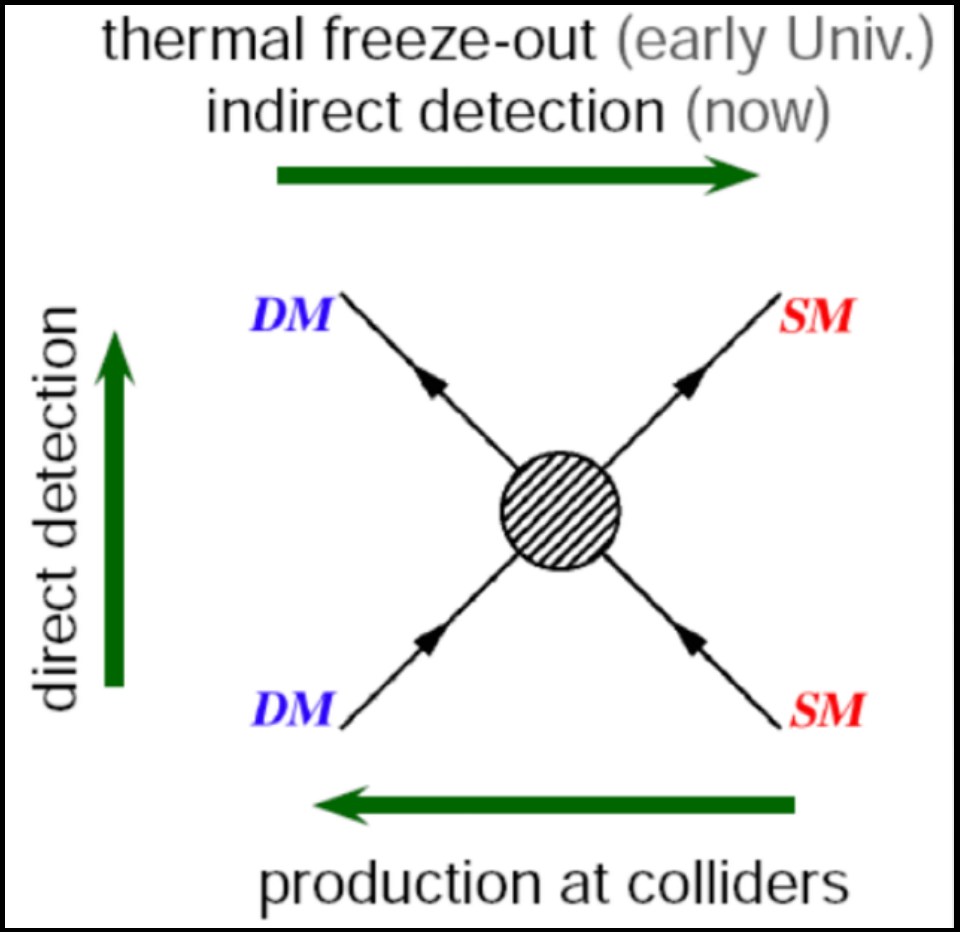

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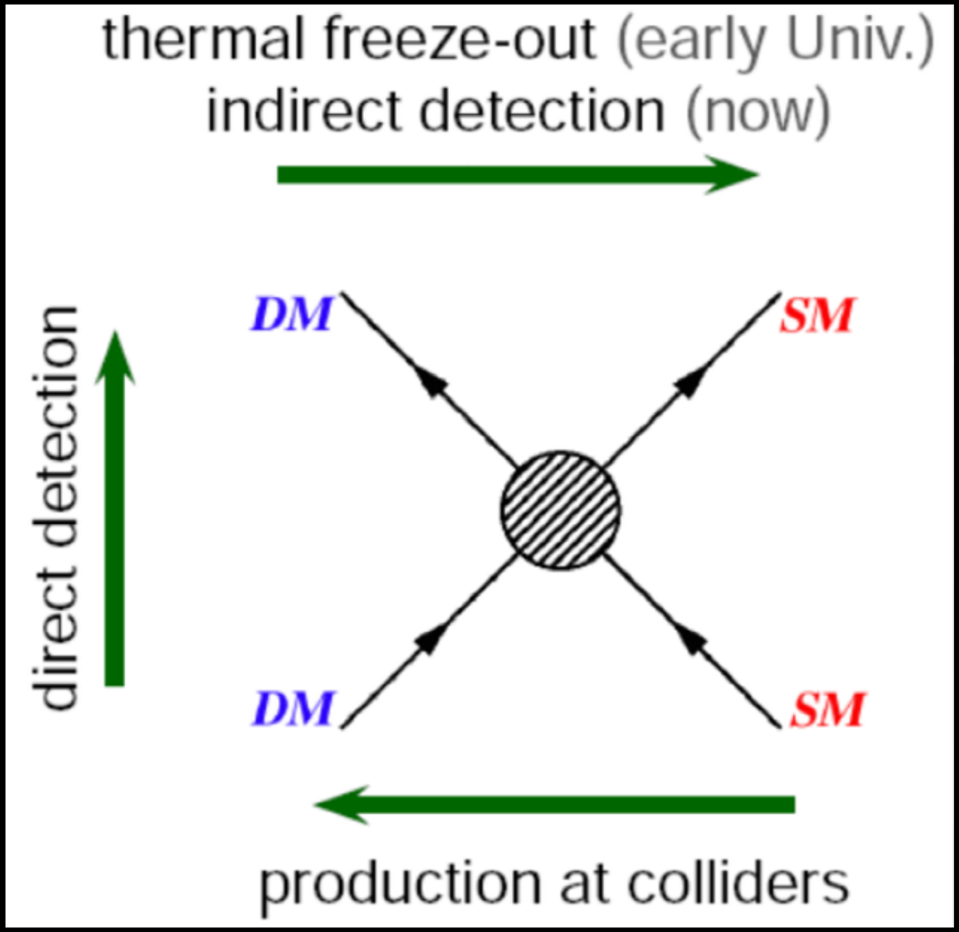
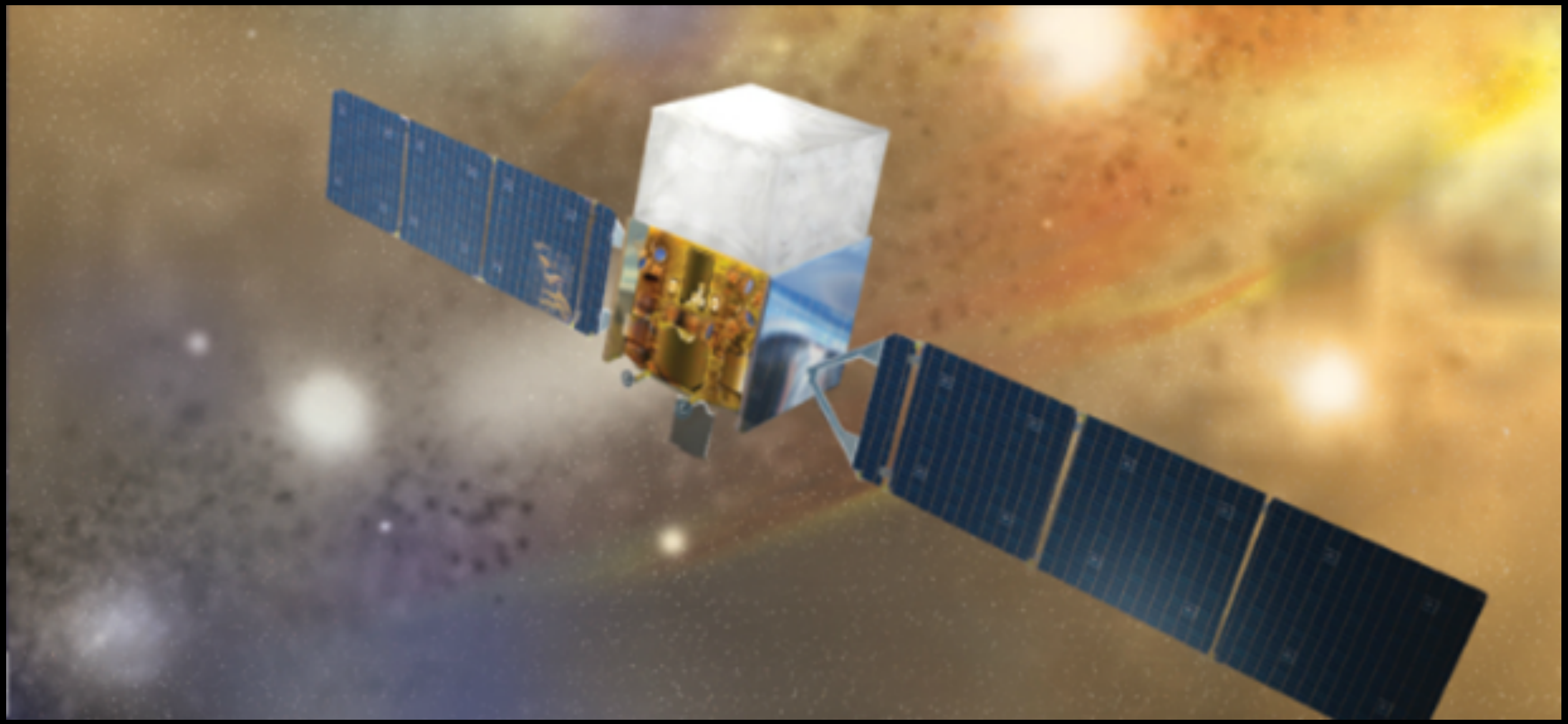
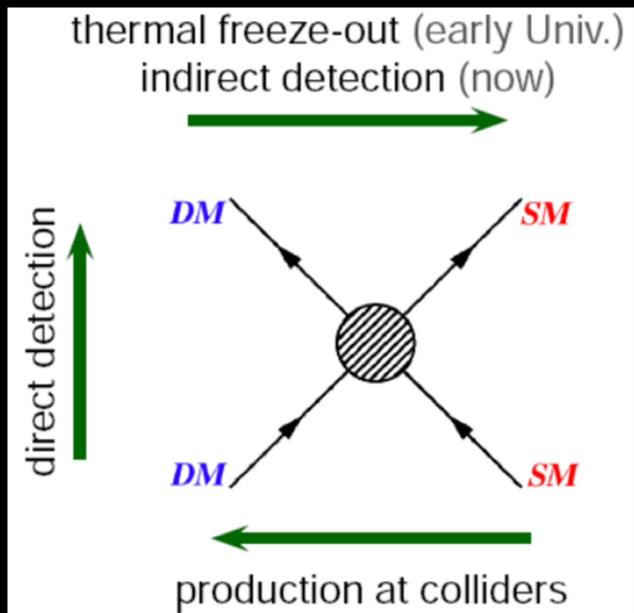


Two dark matter particles in space can collide and produce standard model particles that we **can** see



Fermi Gamma-Ray Space Telescope

How Can We Detect this New Particle?



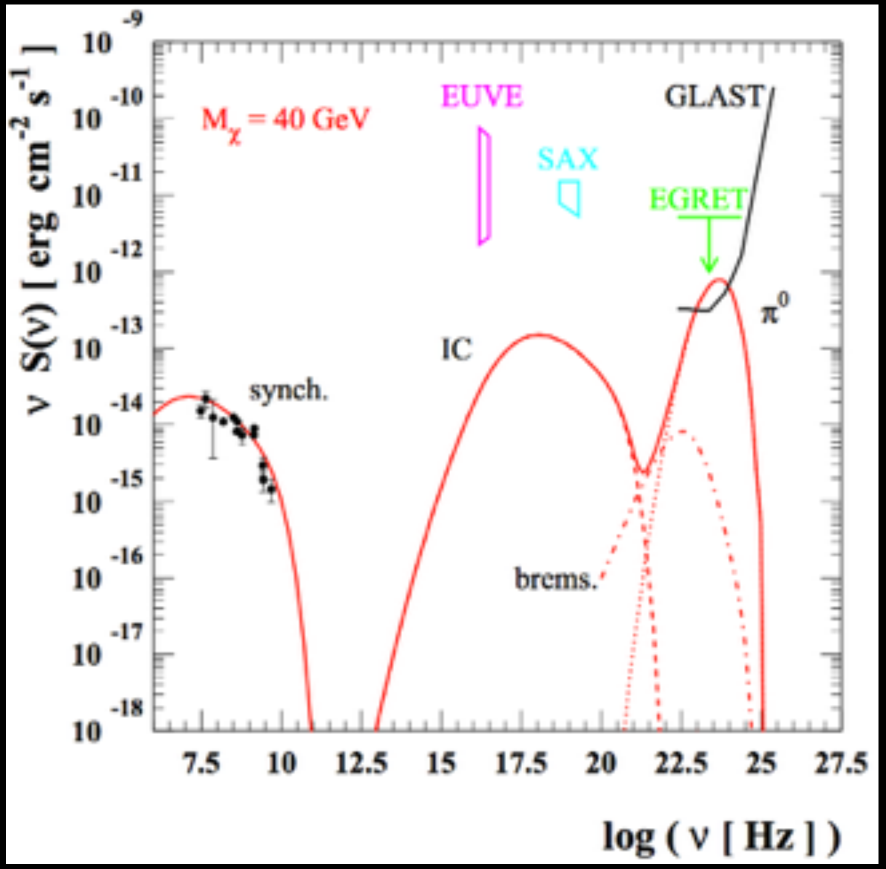
light

Advantage - This is the only way to tell that the particle is found throughout the universe

Indirect Detection with Gamma-Rays

- Fermi-LAT is a space based gamma-ray detector with an effective energy range of 20 MeV-300 GeV

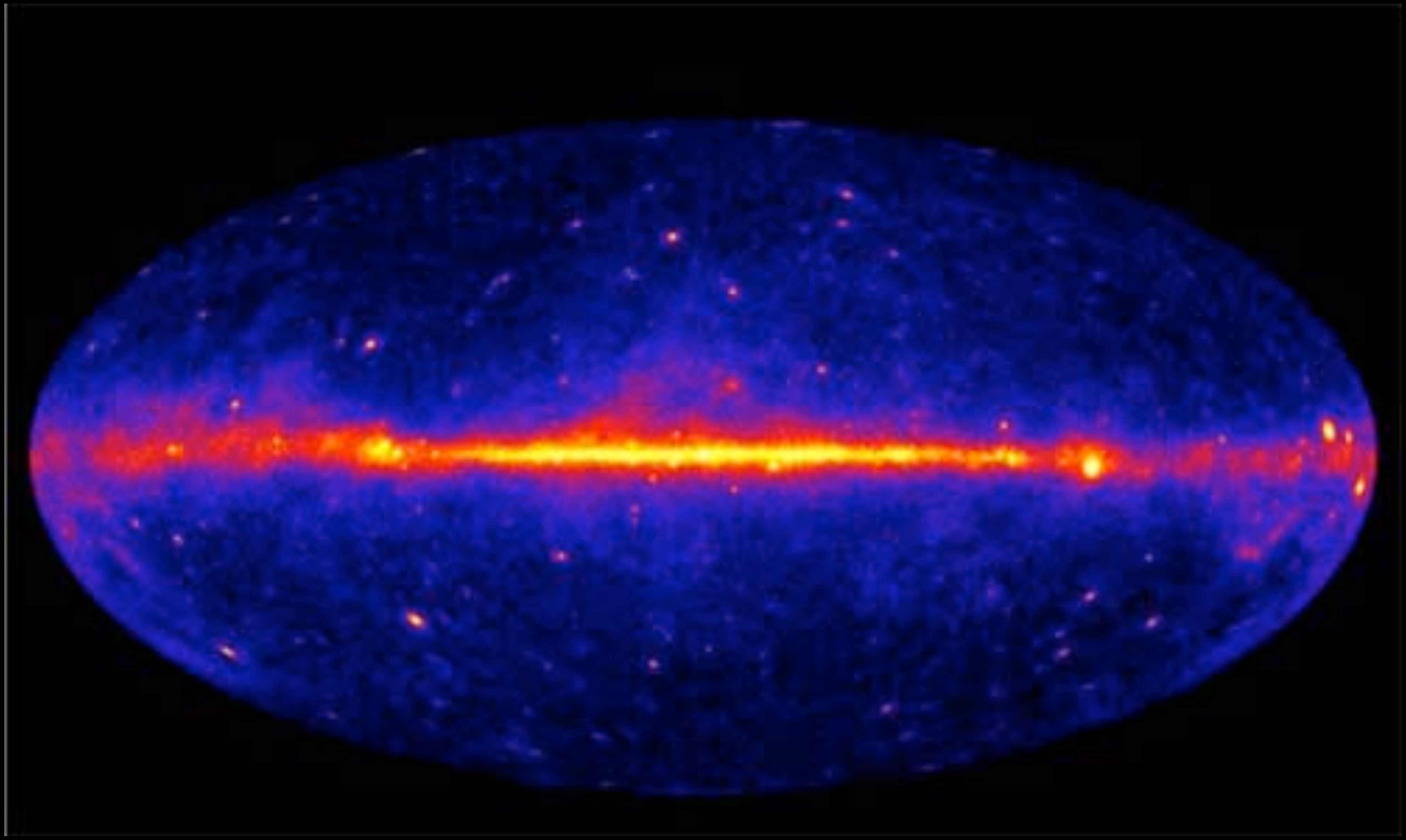
- Effective Area ~ 0.8 m^2
- Field of View ~ 10000 deg^2
- Energy Resolution ~ 10%
- Angular Resolution: Energy Dependent



How Can We Detect this New Particle?

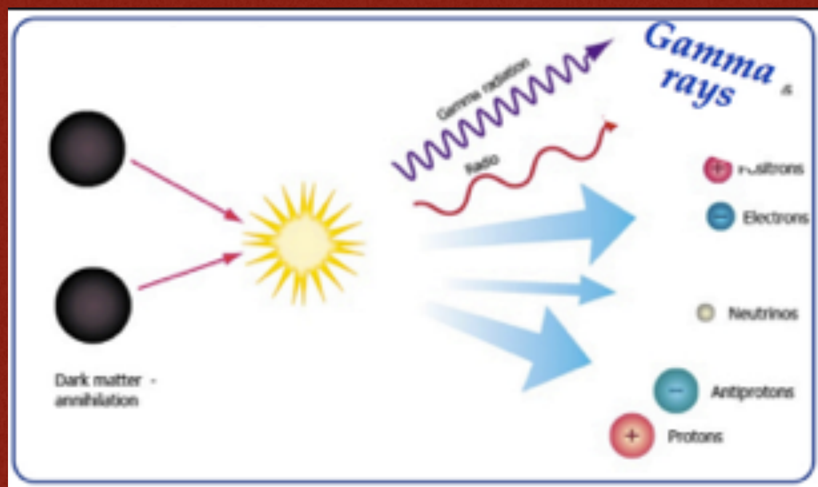
Visible Light: 1 eV

Gamma Rays: above 10,000,000 eV

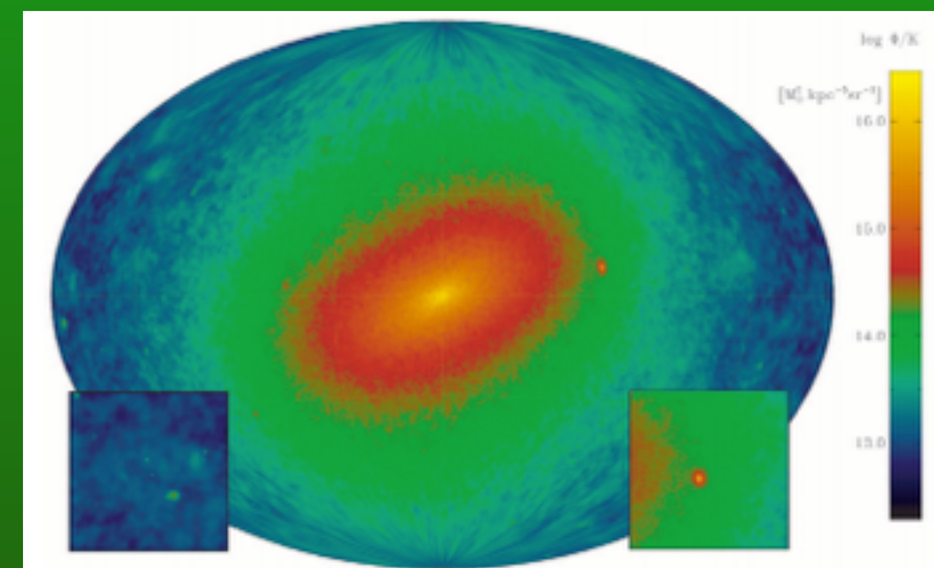


Dark Matter Indirect Detection

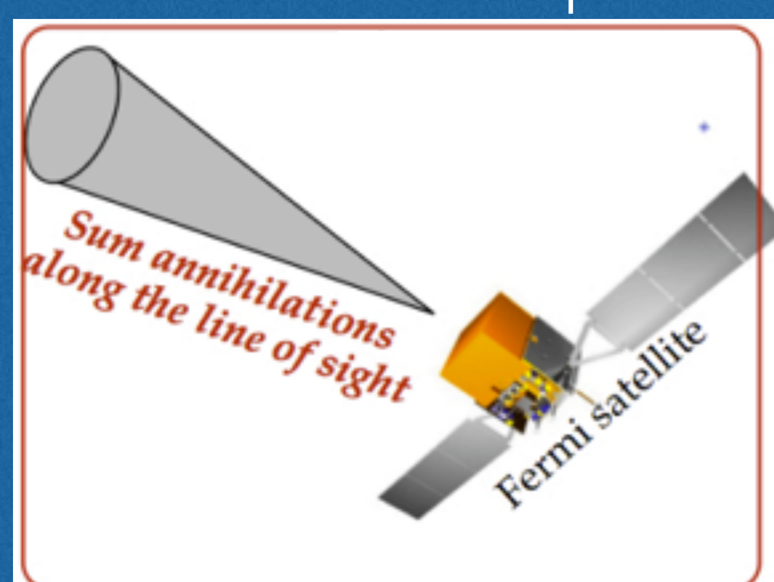
Particle Physics



Astrophysics

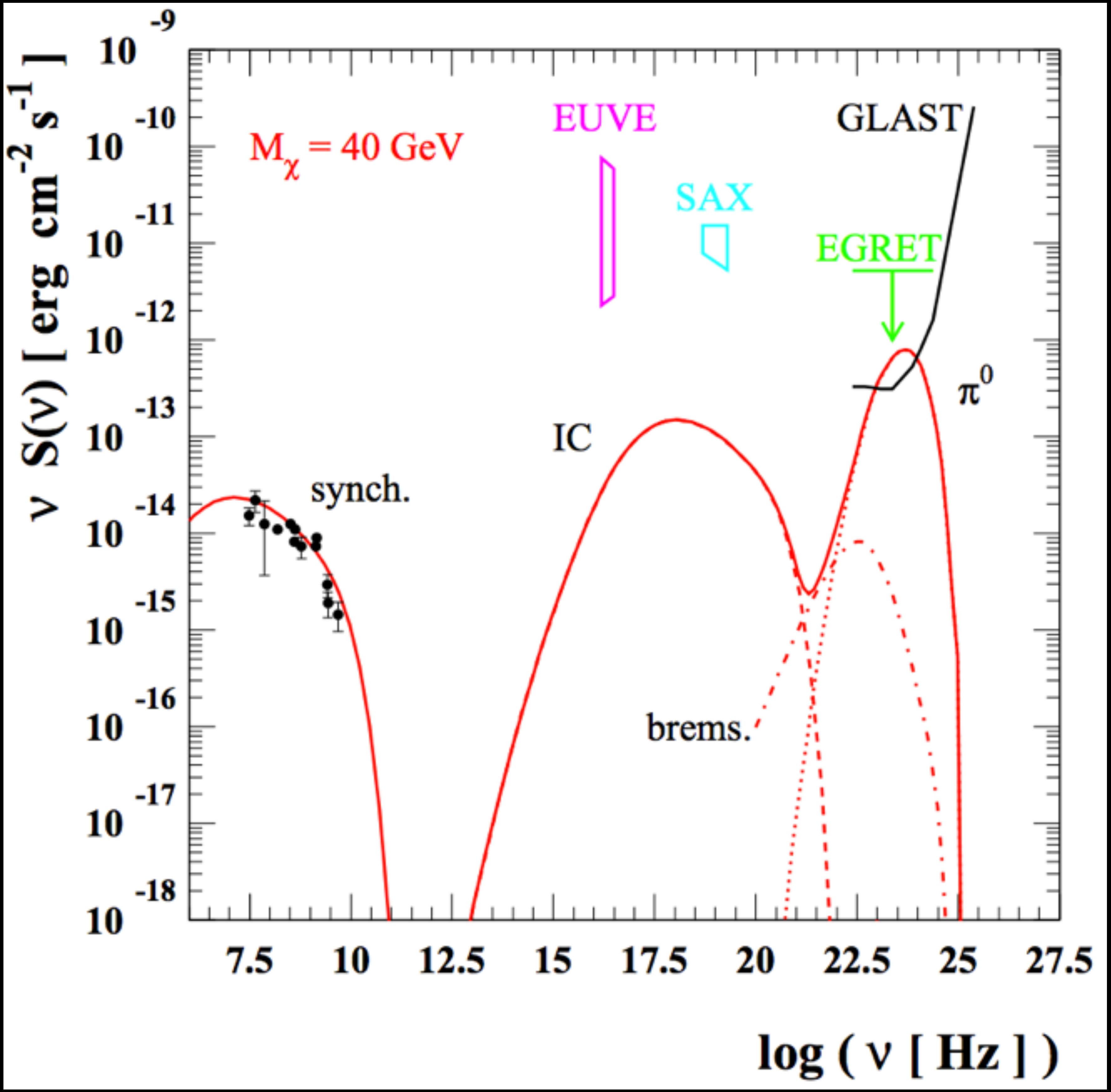


Instrumental Response

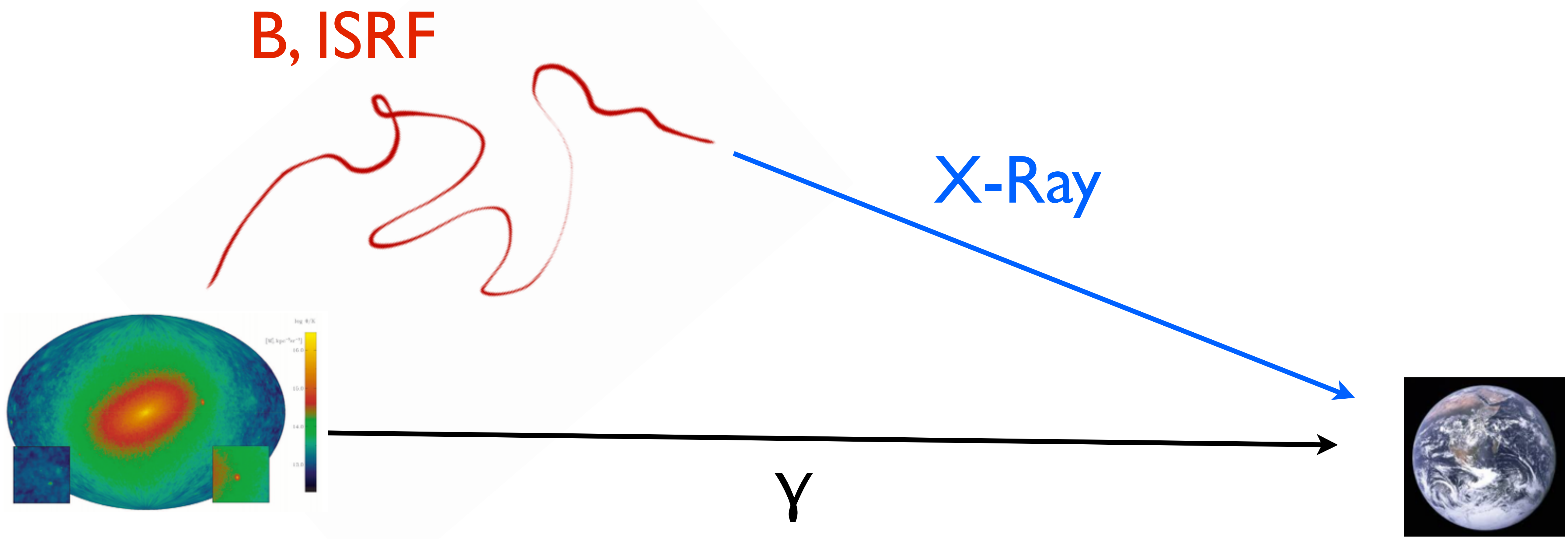


Slide Concept Courtesy of Gabrijela Zaharijas

Indirect Detection with Gamma-Rays



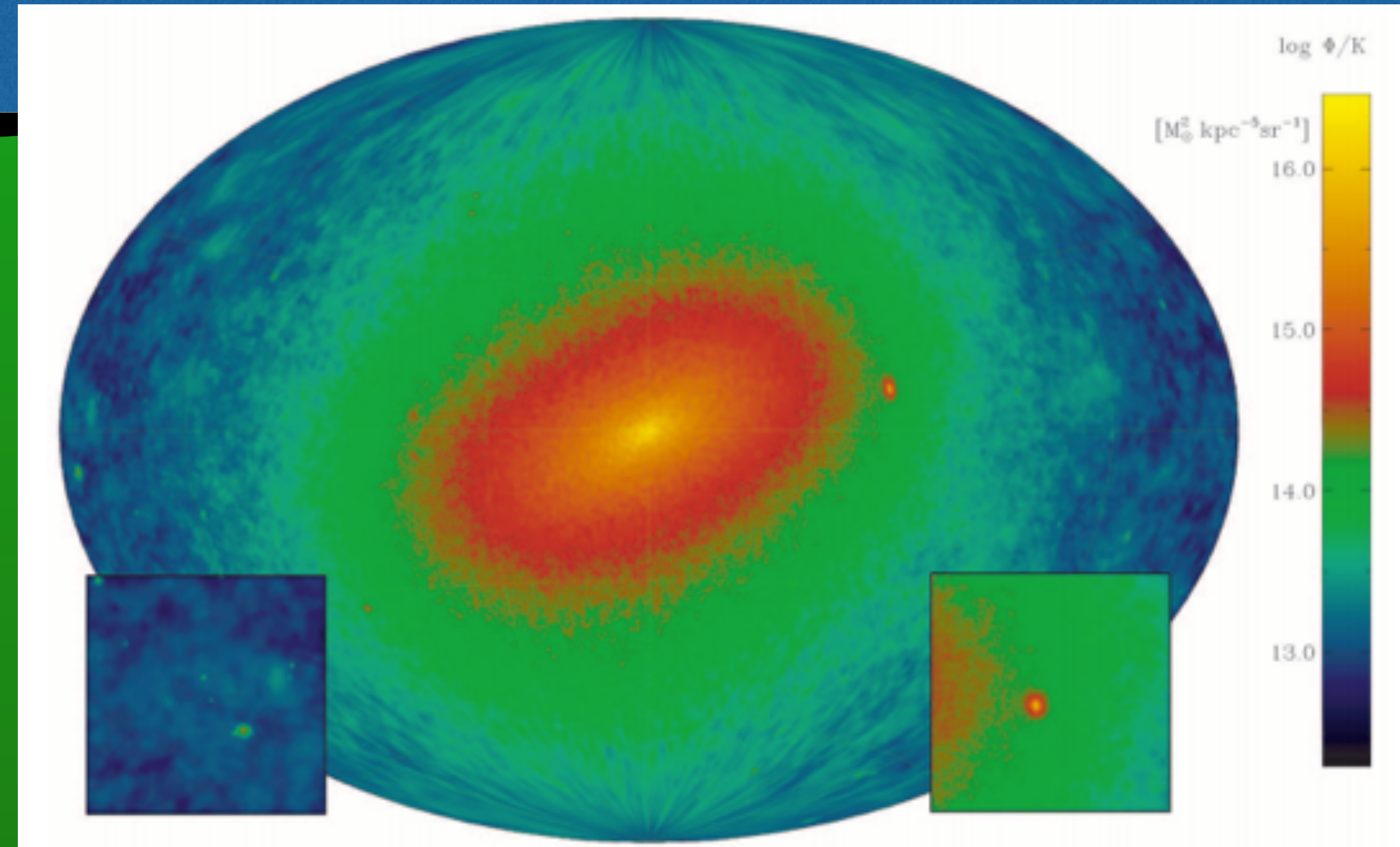
Indirect Detection with Gamma-Rays



- At low energy, propagation can carry the particles which create the observed signal far from the annihilation event, before they produce anything that is seen at the Earth

Early Observations of an Anomalous Signal at the GC

Astrophysics



The J-Factor of the Galactic center is:

$$\log_{10}(J) = 21.02$$

for a region within 100 pc of the Galactic center and an NFW profile

Name	GLON (deg)	GLAT (deg)	Distance (kpc)	$\overline{\log_{10}(J^{NFW})}^{a}$ ($\log_{10}$[GeV^2 cm^{-5} sr])
Bootes I	358.1	69.6	66	18.8 ± 0.22
Bootes II	353.7	68.9	42	–
Bootes III	35.4	75.4	47	–
Canes Venatici I	74.3	79.8	218	17.7 ± 0.26
Canes Venatici II	113.6	82.7	160	17.9 ± 0.25
Canis Major	240.0	-8.0	7	–
Carina	260.1	-22.2	105	18.1 ± 0.23
Coma Berenices	241.9	83.6	44	19.0 ± 0.25

oration (2013)

The Galactic Center "Zoo"

However - lots of other things in the center of the galaxy produce gamma-rays:

+ **Neutron Stars and Black Holes**
+ **High Energy Particles**
+ **Supernovae**

We need to be able to differentiate dark matter gamma-rays from other sources

The Galactic Center as an Indirect Detection Target

Positive: Any indirect signal from dark matter annihilation is likely to first be detected at the center of the Milky Way Galaxy

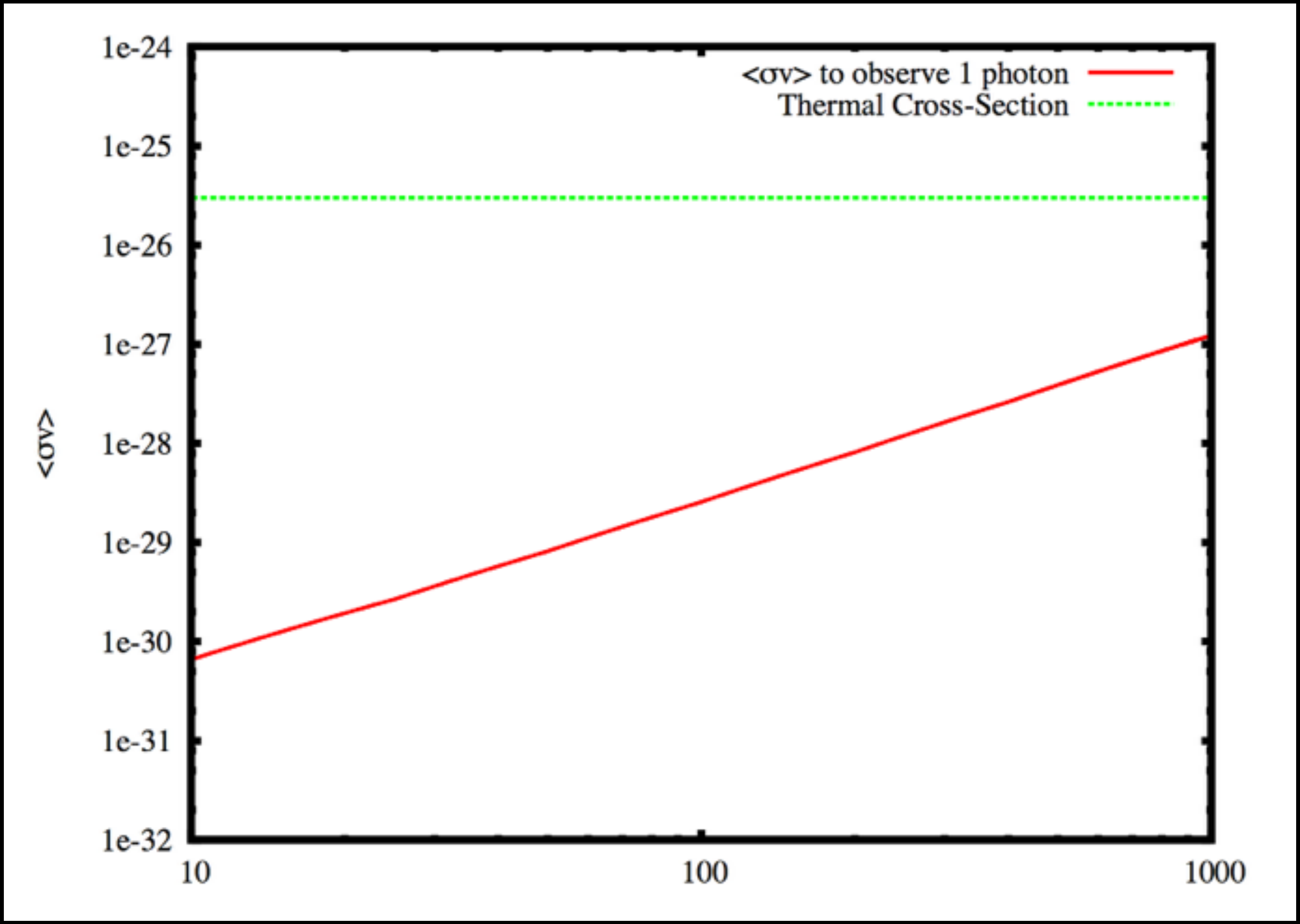
Corollary: Any signal observed elsewhere in the Galaxy should be consistent (or also seen in) the GC

Negative: Astrophysics may make it difficult to conclusively determine that an excess in the galactic center is due to dark matter

Back of the Envelope Calculation

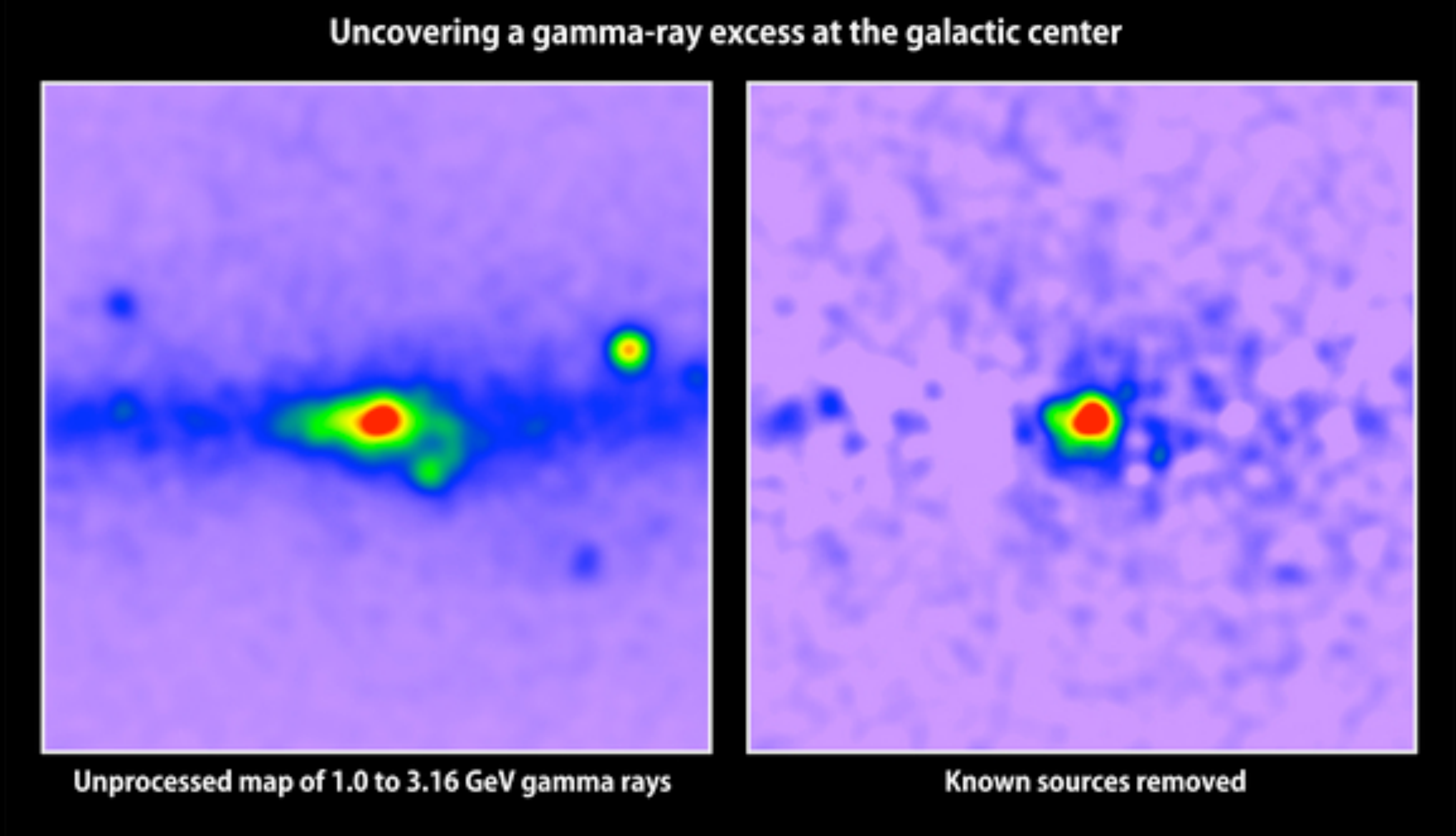
- Total Gamma-Ray Flux from within 1° of the GC is ~1×10^{-7} photons cm^{-2} s^{-1}
- The flux expected from a normal dark matter model is ~2×10^{-8} photons cm^{-2} s^{-1}
- There's no reason this needs to be true -- the total gamma-ray emission from the Galactic center happens to fall within an order of magnitude of the **most naive** prediction from dark matter simulations

The Galactic Center in Gamma-Rays



If you were able to somehow "tag" each **γ**-ray from the GC as "dark matter" or "astrophysics", these are the limits you could place on dark matter annihilation

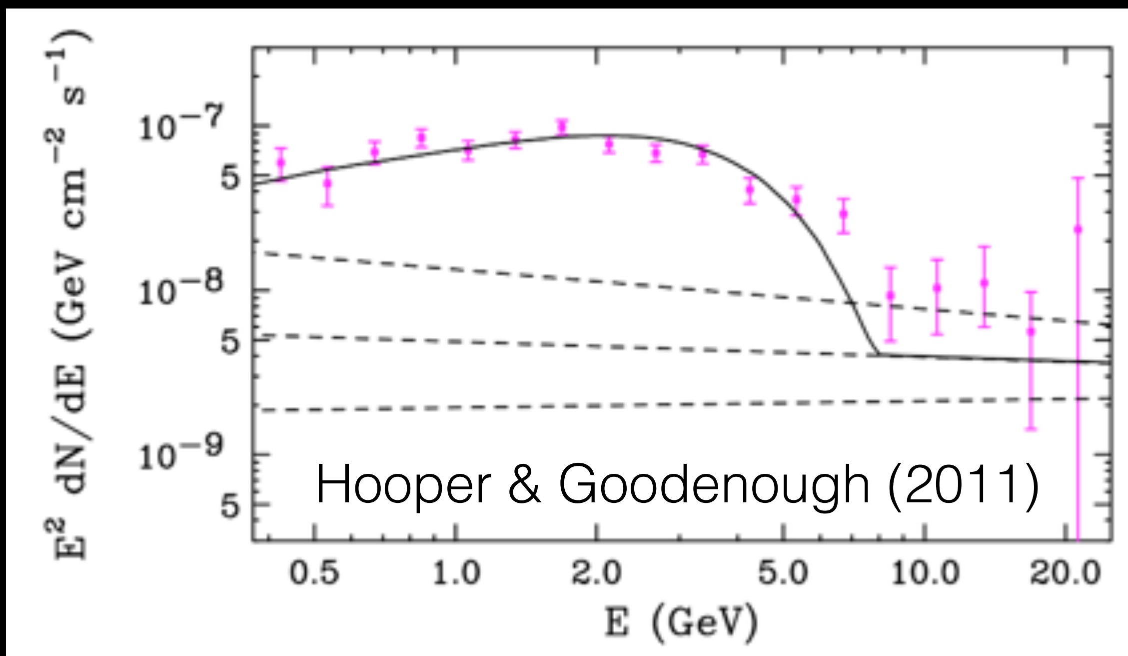
The Galactic Center in Gamma-Rays

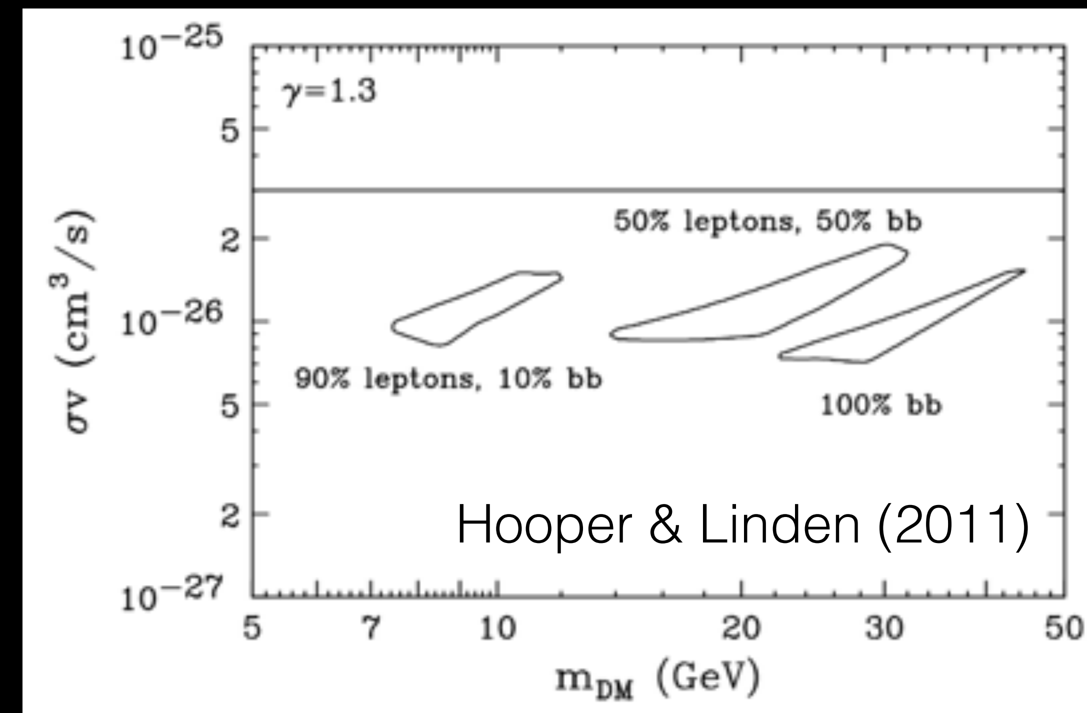


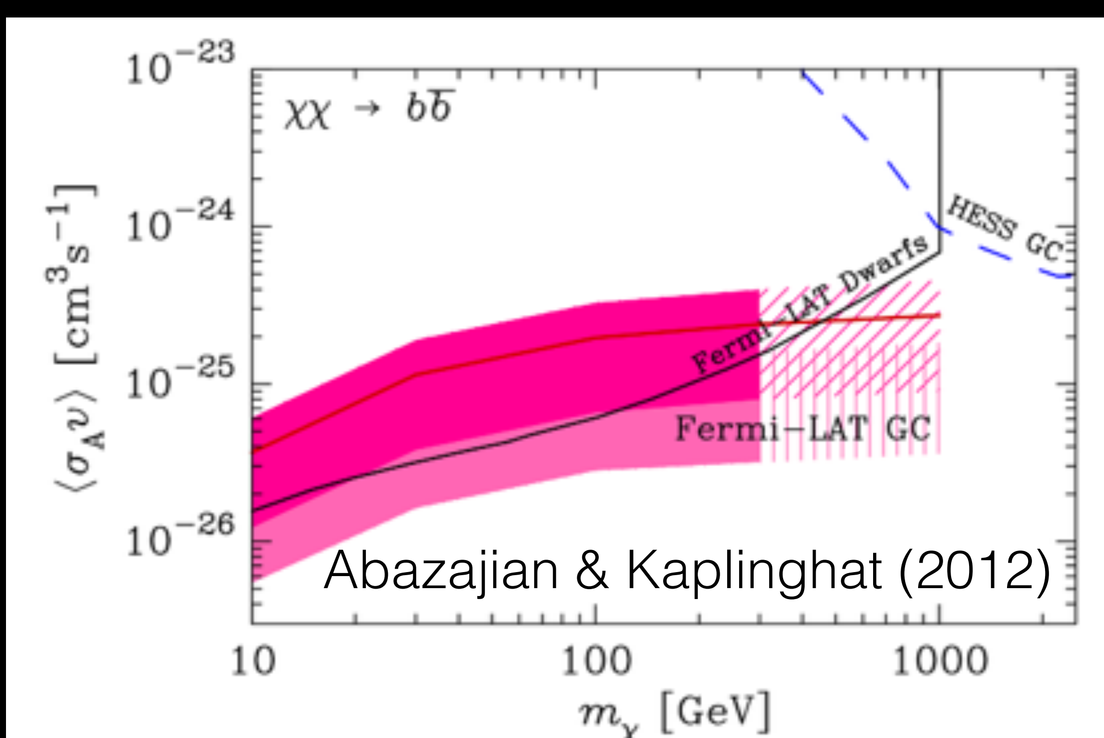
And maybe we are seeing something!

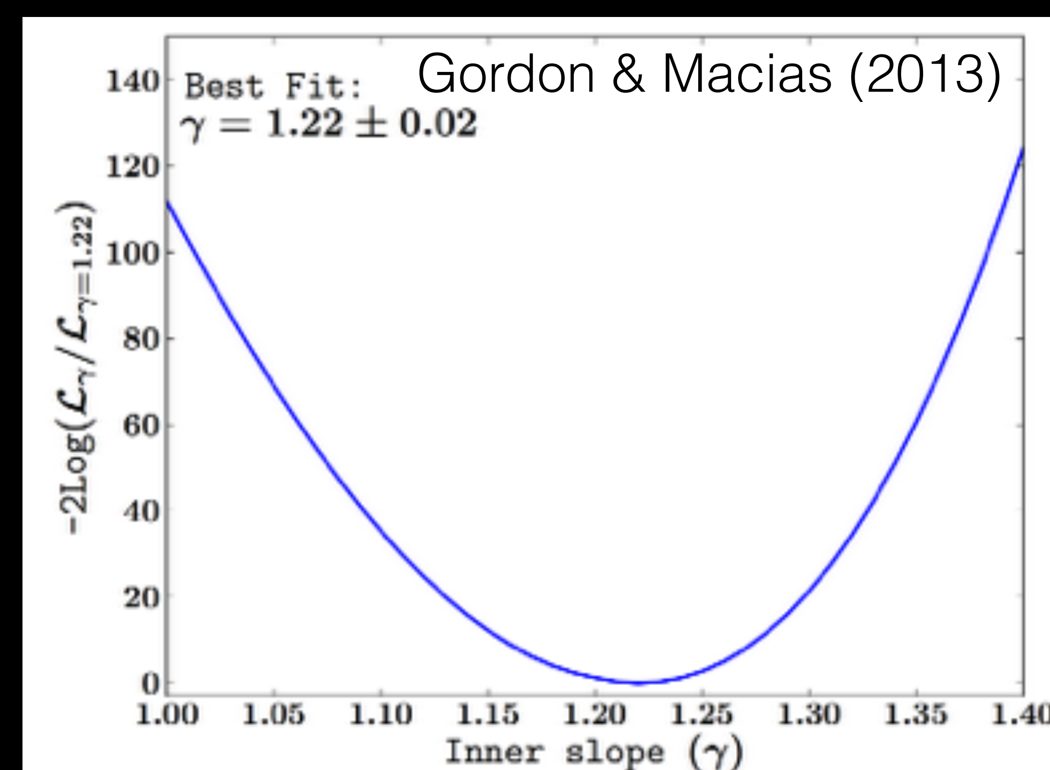
Early Observations of an Anomalous Signal at the GC

First noted as a feature in the Galactic Center region by Goodenough & Hooper (2009)

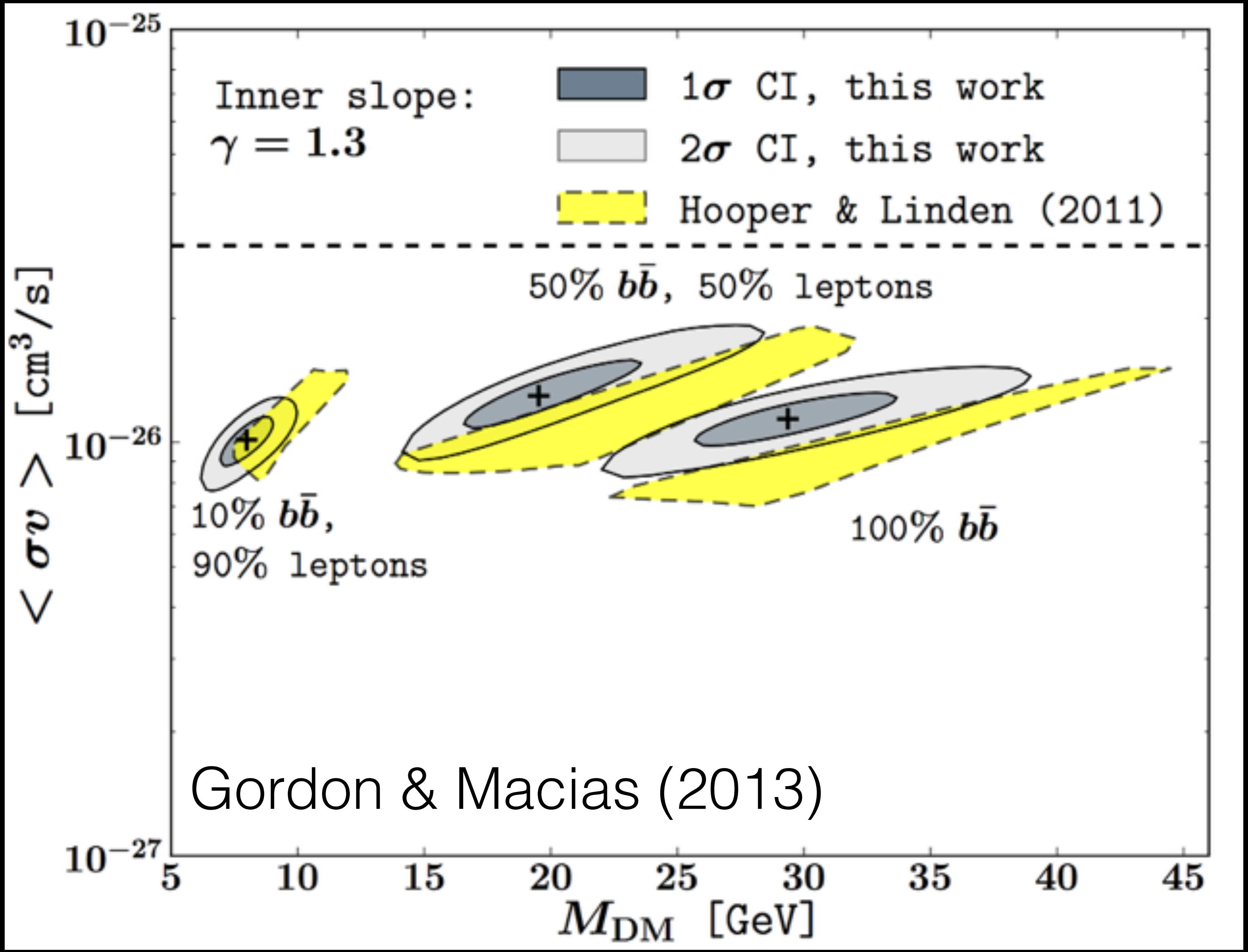








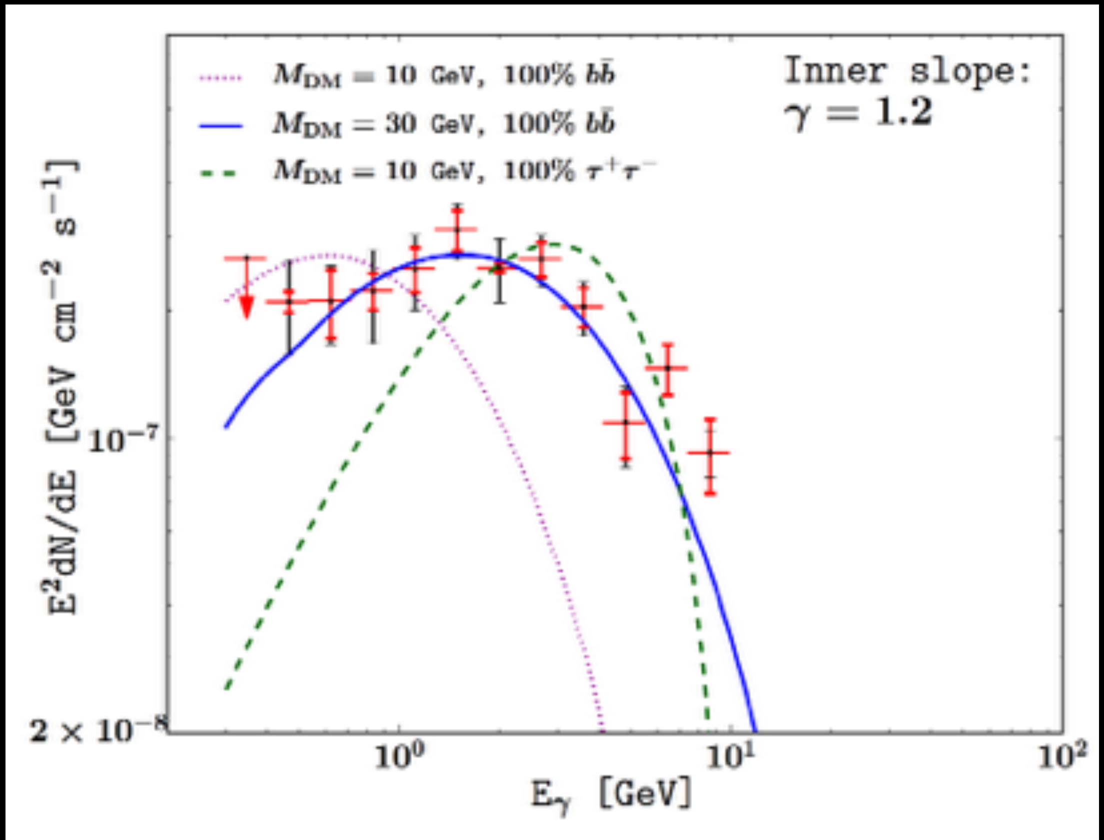
A Broad Consensus



At this point, there are 7 studies by three independent groups, which both qualitatively and quantitatively agree on the major features of the γ-ray excess.

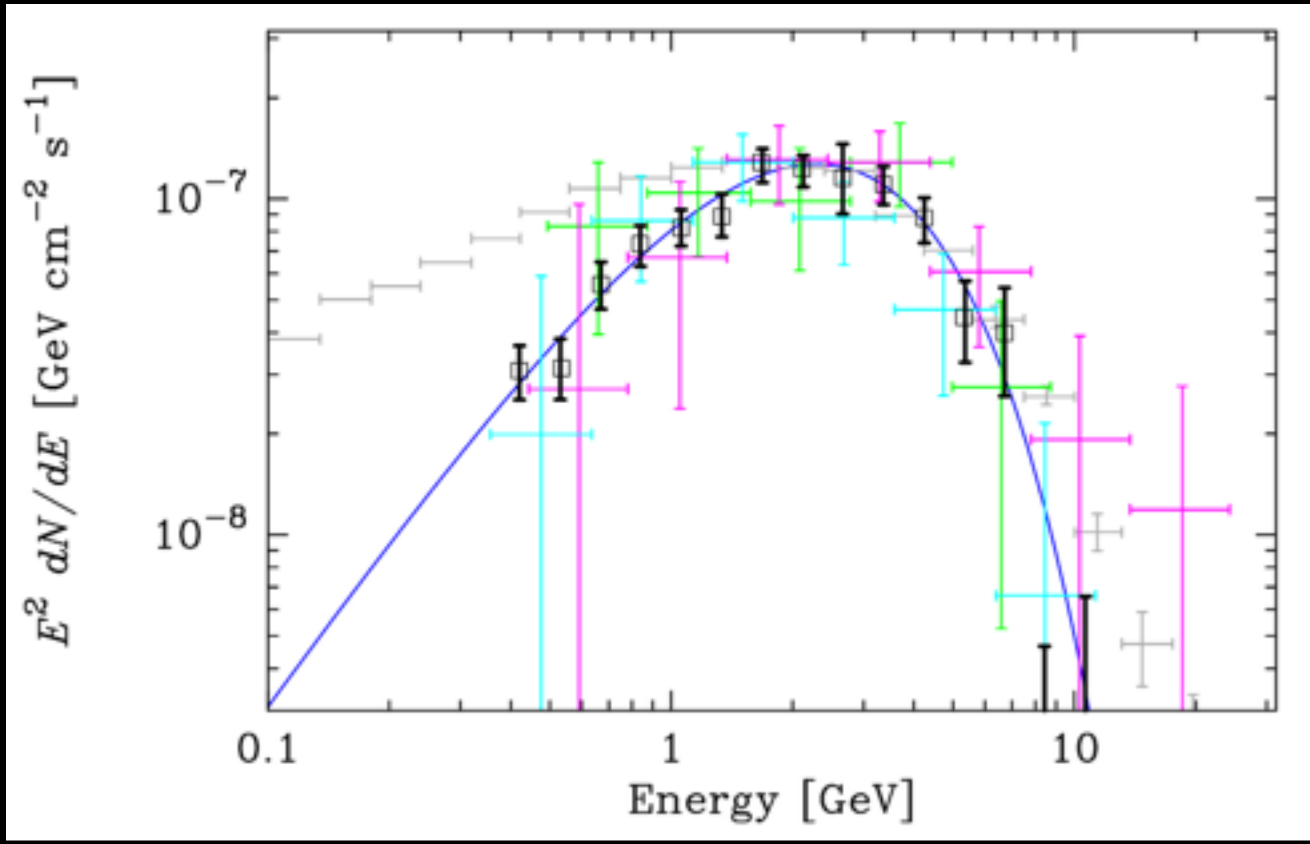
Two Interpretations of the Old Data

Dark Matter



Gordon & Macias (2013)

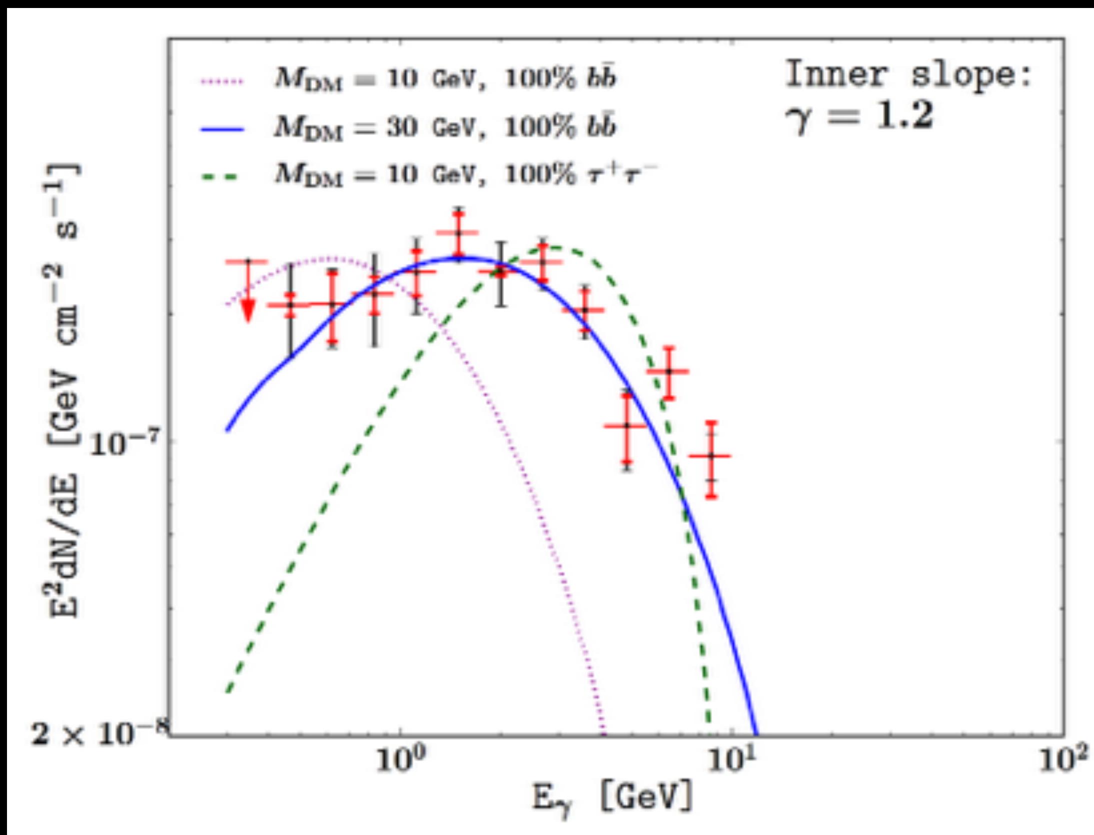
Millisecond Pulsars



Abazajian (2011)

Two Interpretations of the Old Data

Dark Matter



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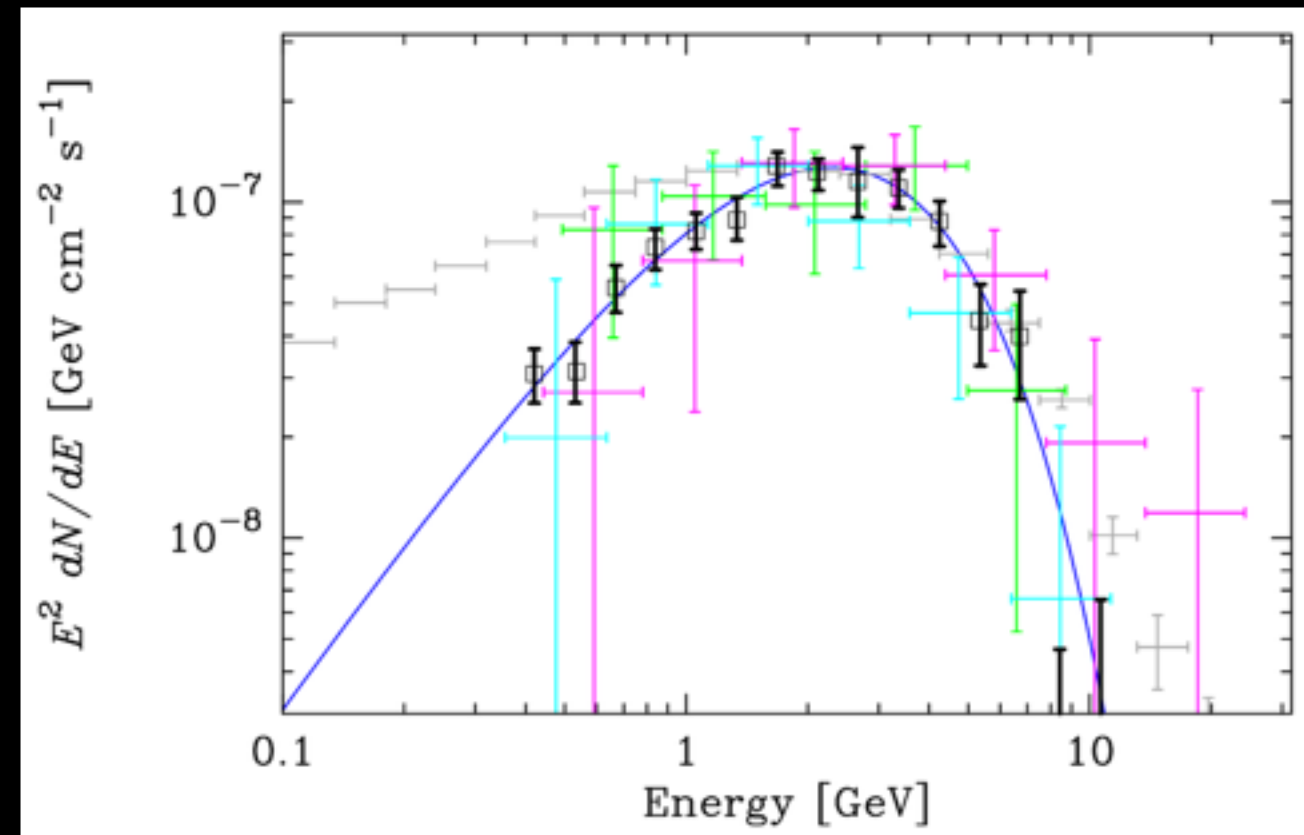
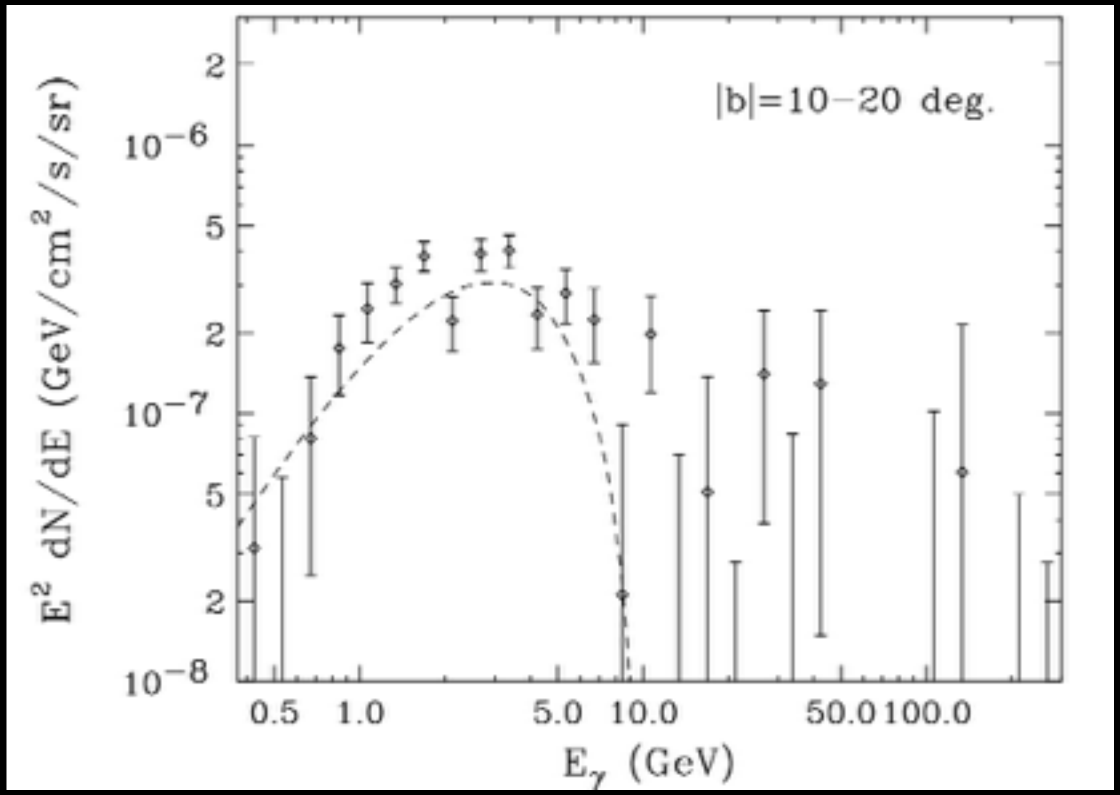


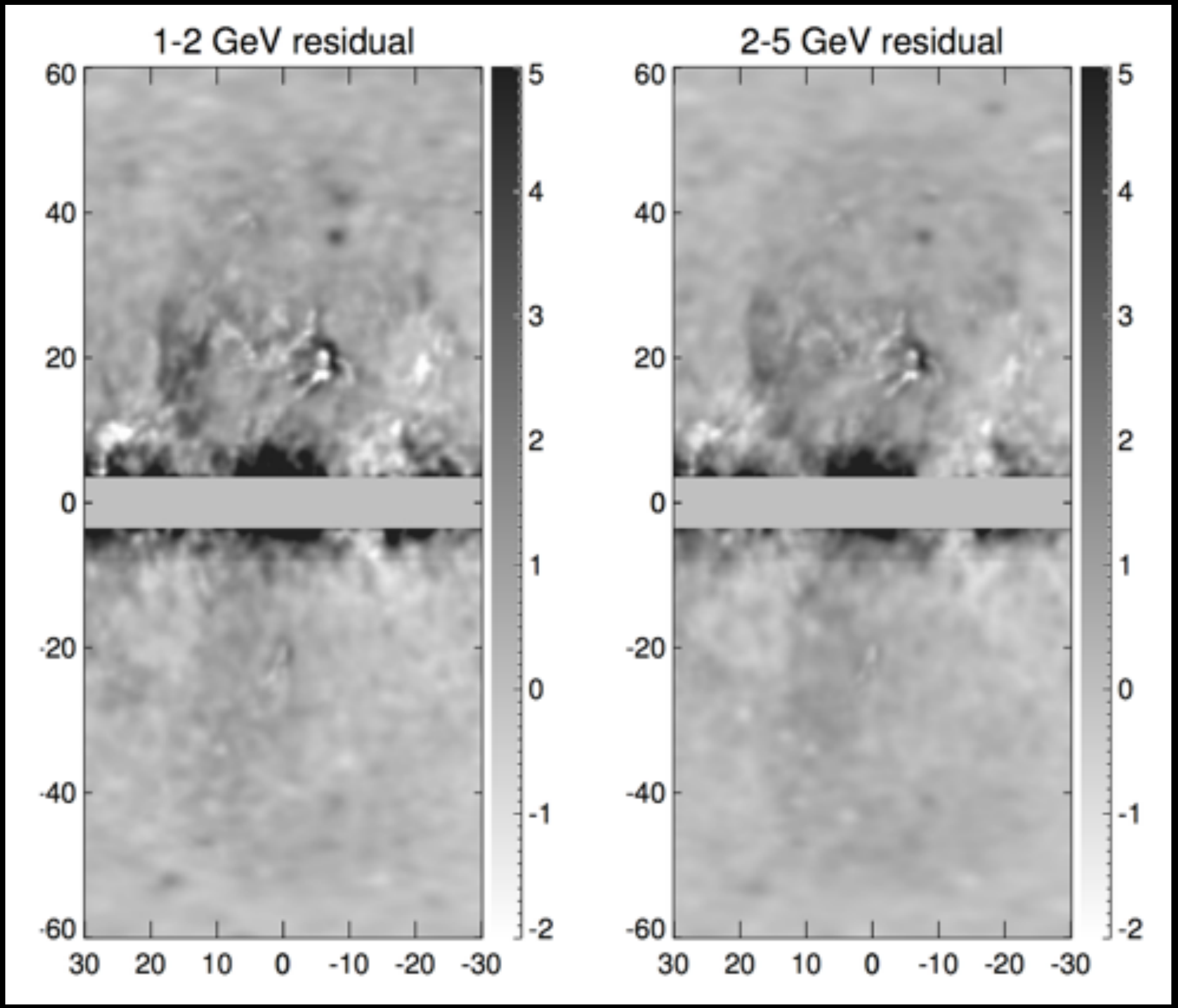
Abazajian (2011)

Prior to the current work, it was easy to debate the relative merits of both models - because the data did not strongly favor either.

Instead, arguments normally were reduced to biases about how reasonable each model is.

Early Observations of an Anomalous Signal at the GC





Hooper & Slatyer (2013) found the same spectrum more than 10º from the galactic center

This is evidence against the pulsar interpretation. A large population of pulsars 10º from the galactic center should be observable by Fermi telescope

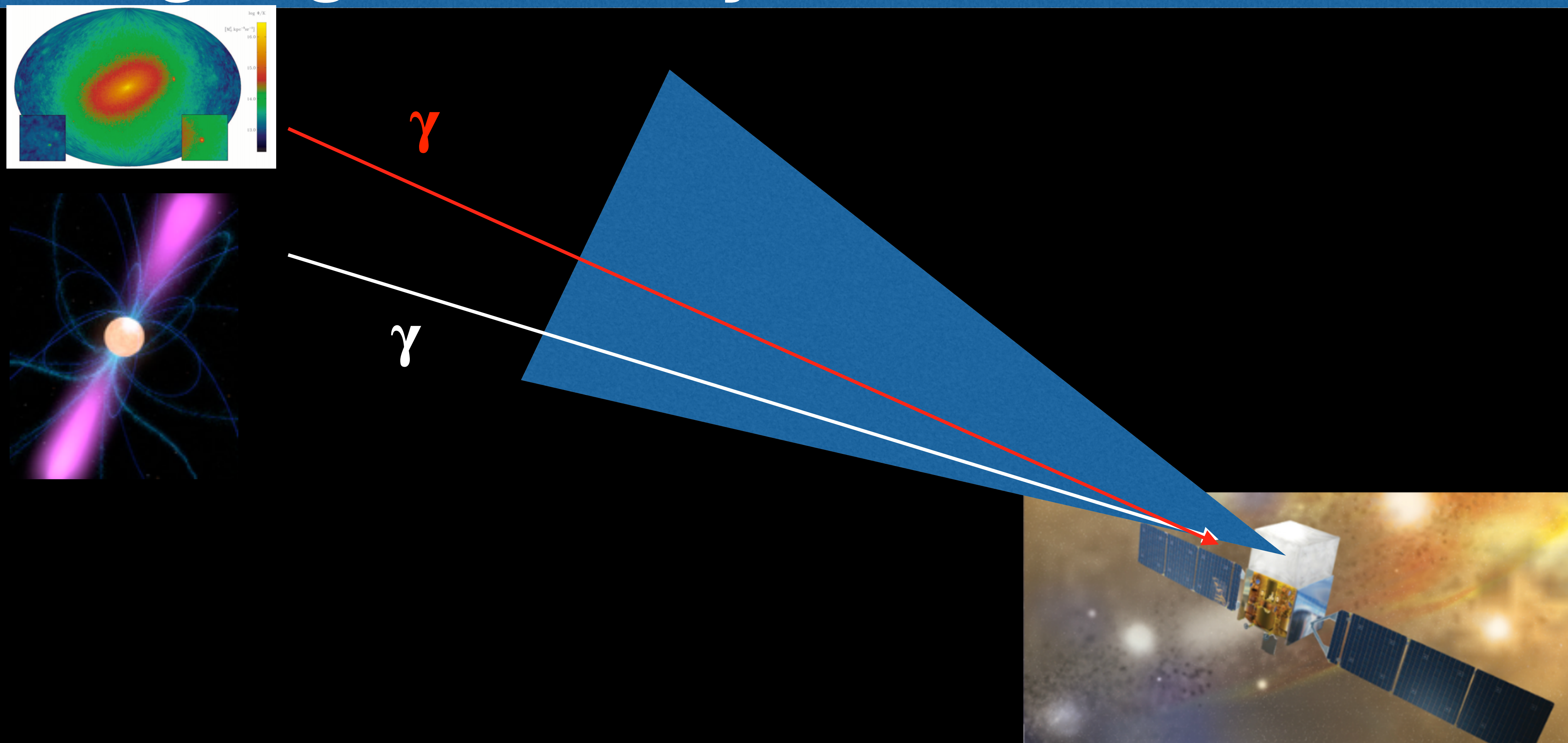
The Current Analysis - Three Objectives

1.) Produce a significantly enhanced version of the Fermi dataset, using only photons with the best directional reconstruction

2.) Test the compatibility of the excess in the Galactic Center and Inner Galaxy

3.) Produce multiple tests of the dark matter interpretation of the data - concentrating on tests which can differentiate a dark matter or pulsar signal

Getting Higher Quality Data

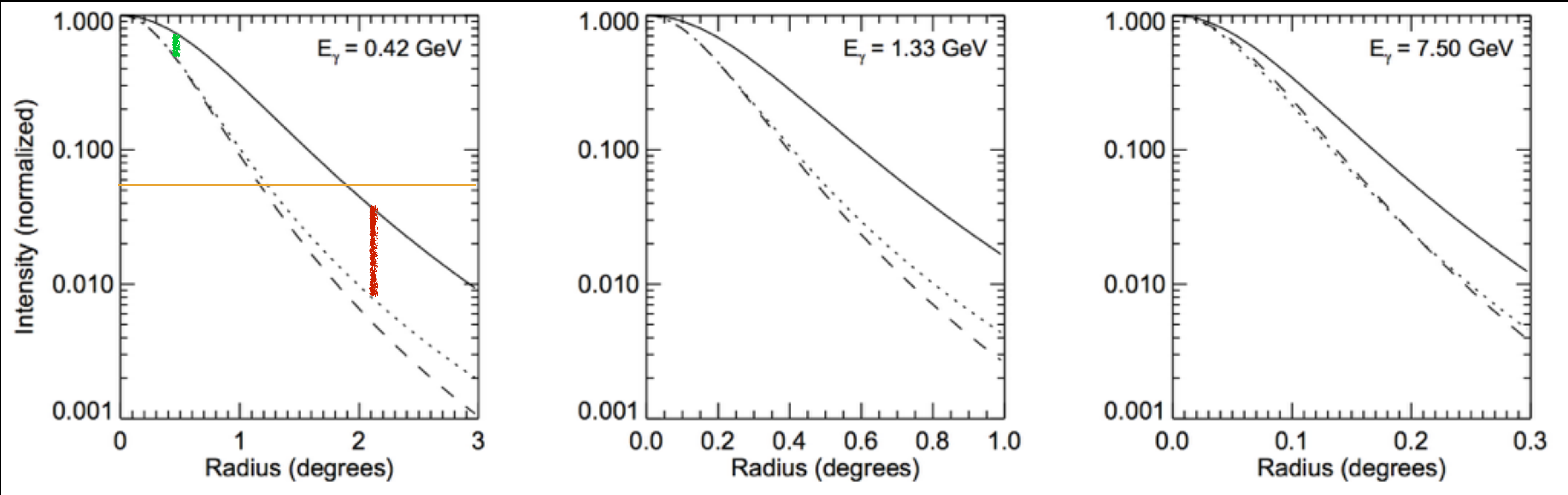


1.) Each photon observed by the Fermi-LAT has a different uncertainty in the directional reconstruction

2.) We select only the 50% of photons with the best directional information, which greatly improves the point-spread function of the instrument

Portillo & Finkbeiner (2014, TBS)

Getting Higher Quality Data



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Portillo & Finkbeiner (2014, TBS)

Data Selection

The new data cut is applied to two different selections of the Fermi-LAT data

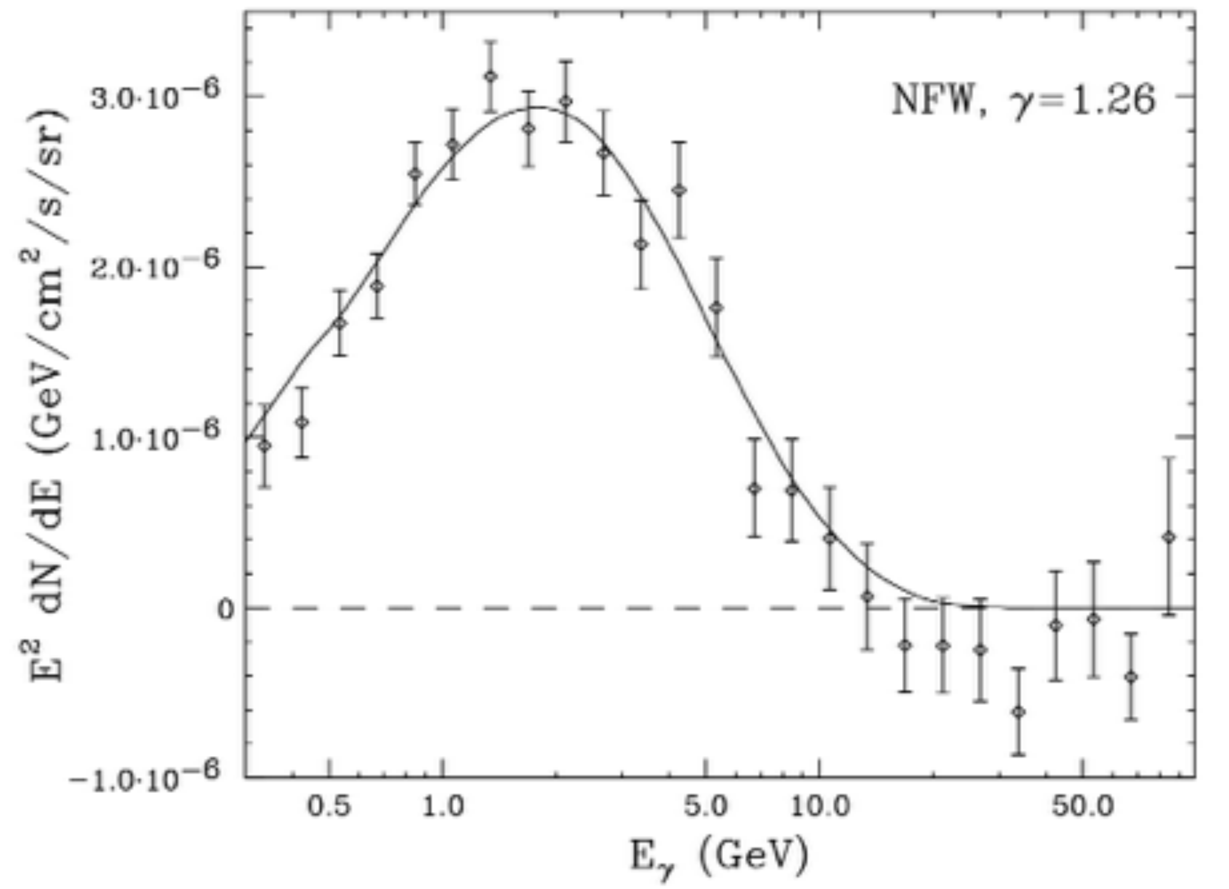
Inner Galaxy - $|b| > 1^o$

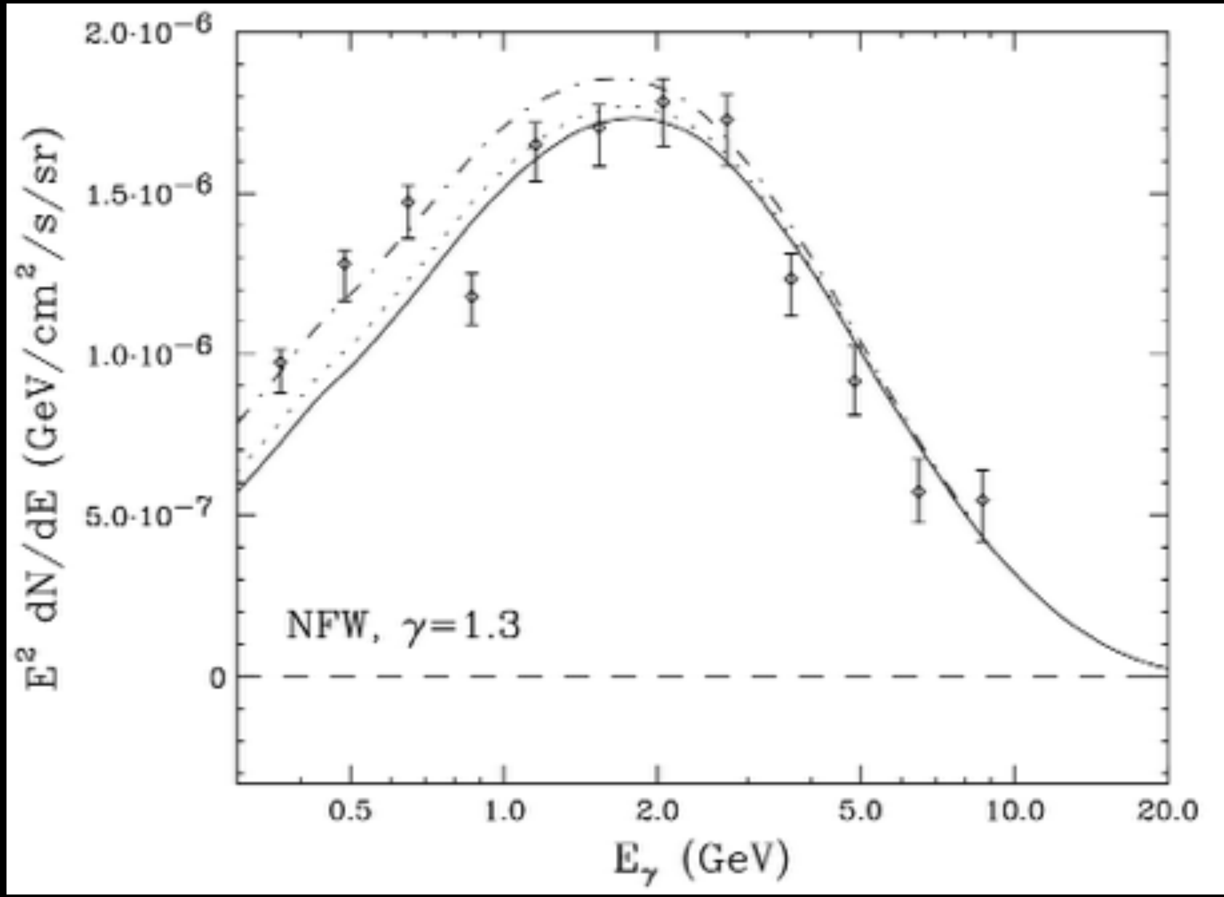
- Mask bright point sources at 2^o

Galactic Center - $| l | < 5^o$ $|b| < 5^o$

- Allow the spectrum of point sources to vary

Spectrum of the Residuals

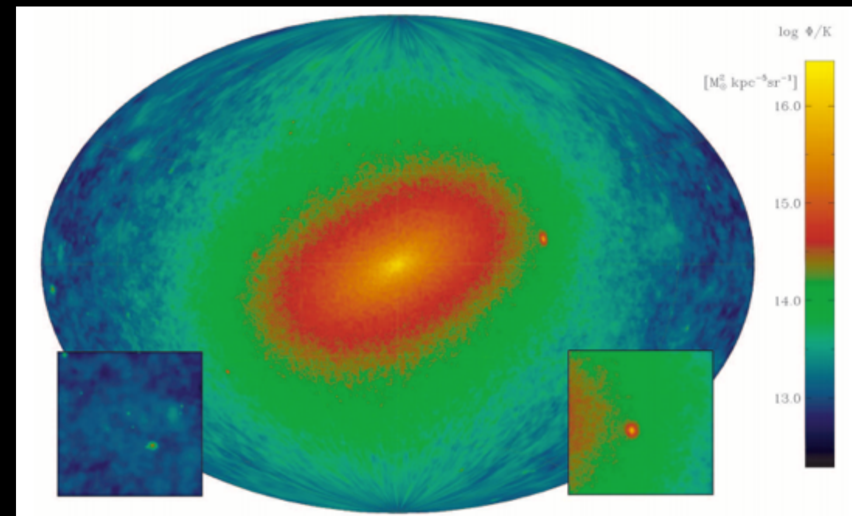


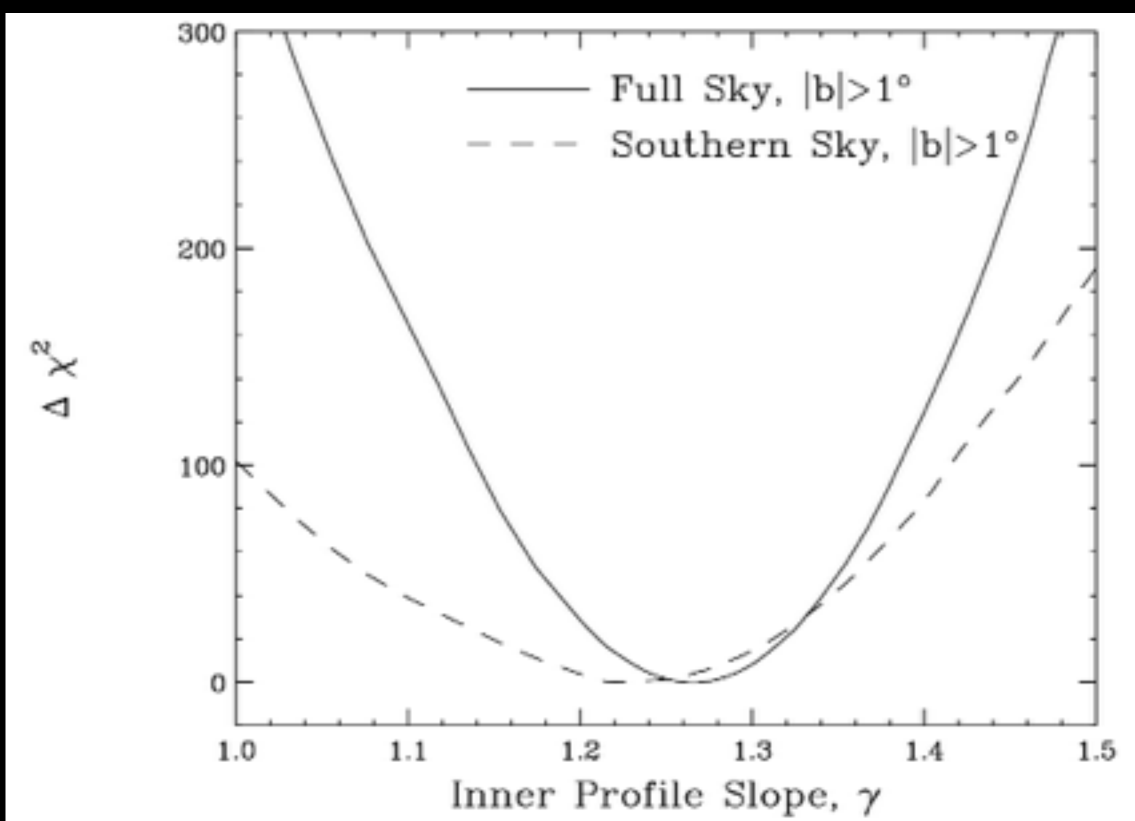


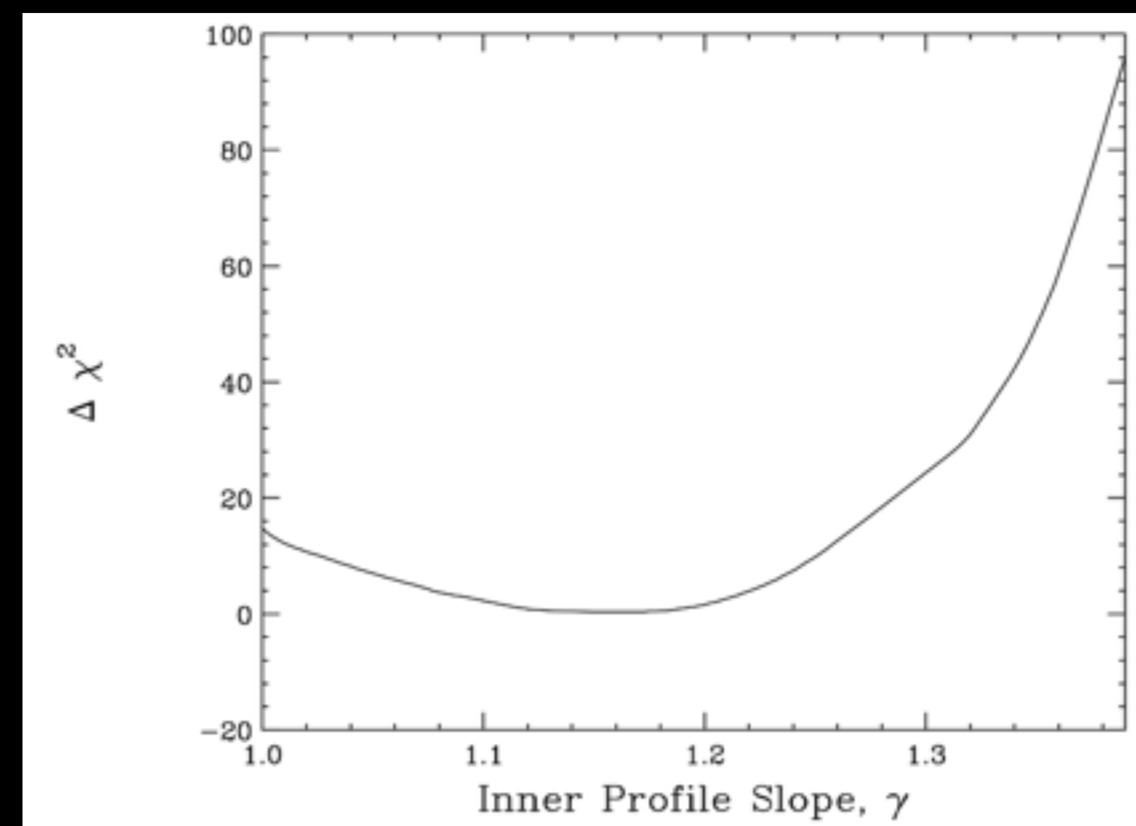
Inner Galaxy - The DM template naturally picks up the following spectral shape - the normalization of the NFW template is allowed to float independently in every energy bin

Galactic Center - Various initial seeds for the dark matter spectrum, the best fit spectrum is then calculated and fed back into the fitting algorithm, the process is repeated iteratively until a best fit solution is reached. We find the final spectrum to be independent of the initial seed.

The Morphology of the Gamma-Ray Excess



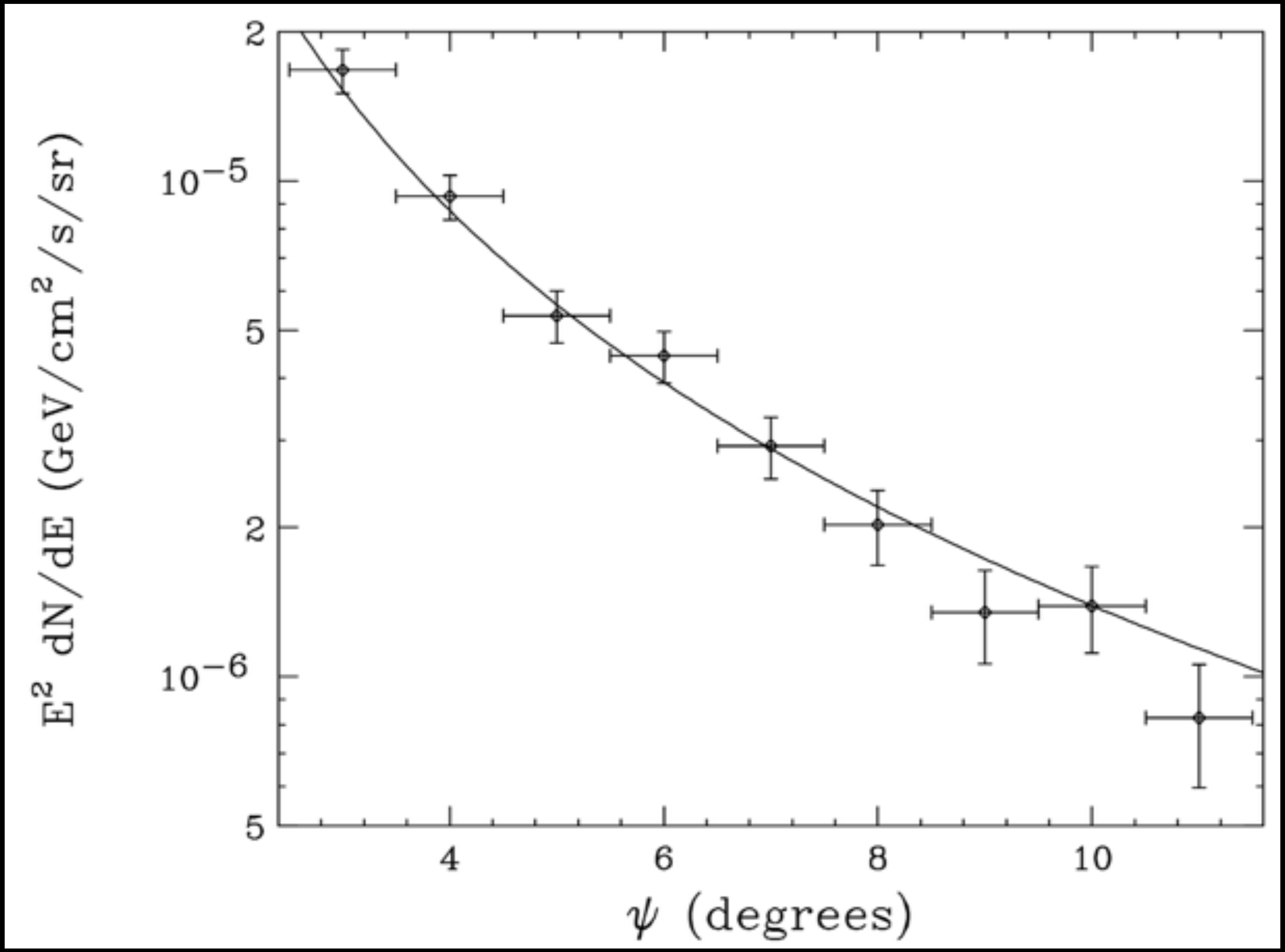




Inner Galaxy - The best fit is given by a dark matter profile with γ=1.26.

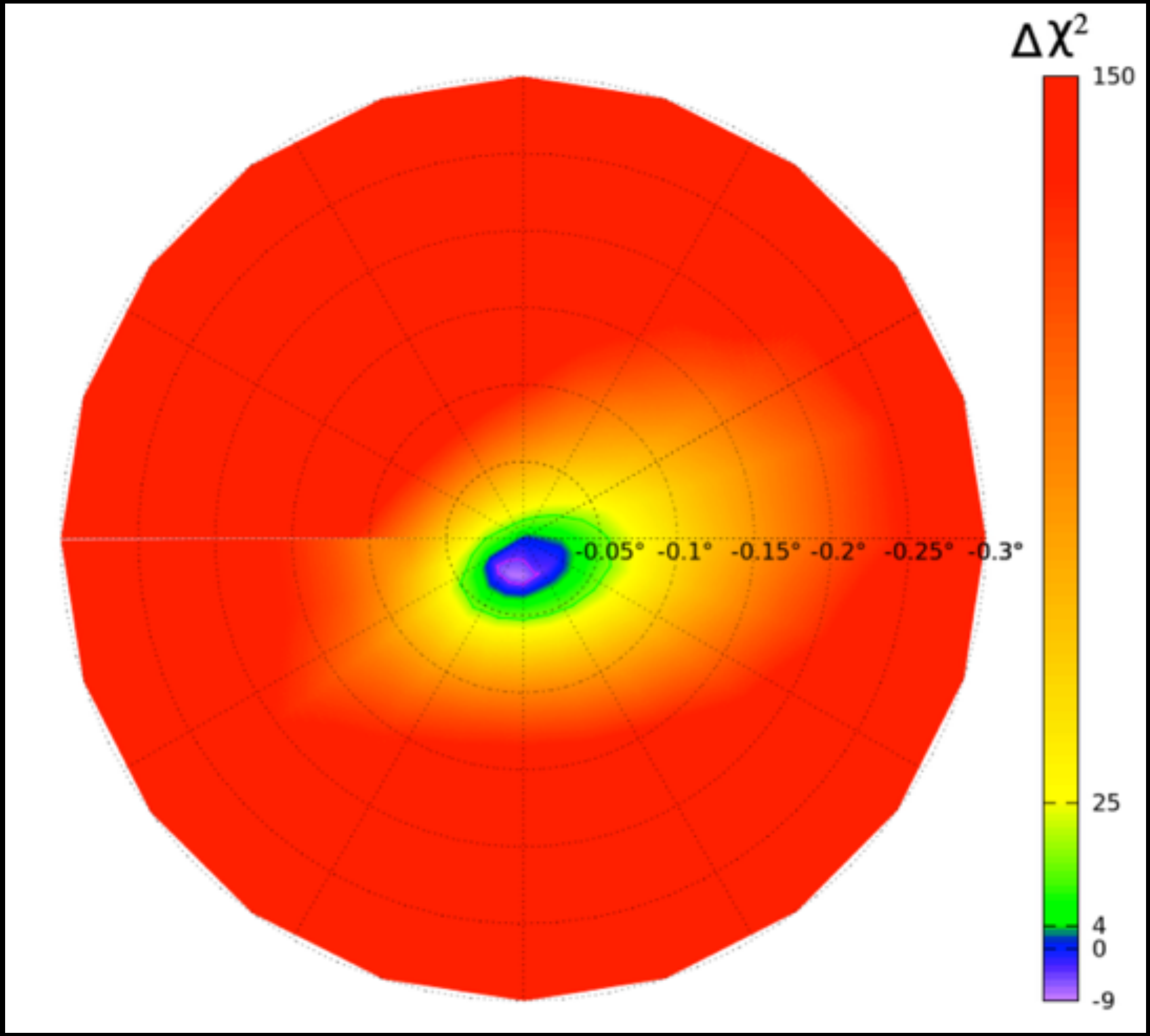
Galactic Center - The best fit is given by γ=1.17.

The Morphology of the Gamma-Ray Excess



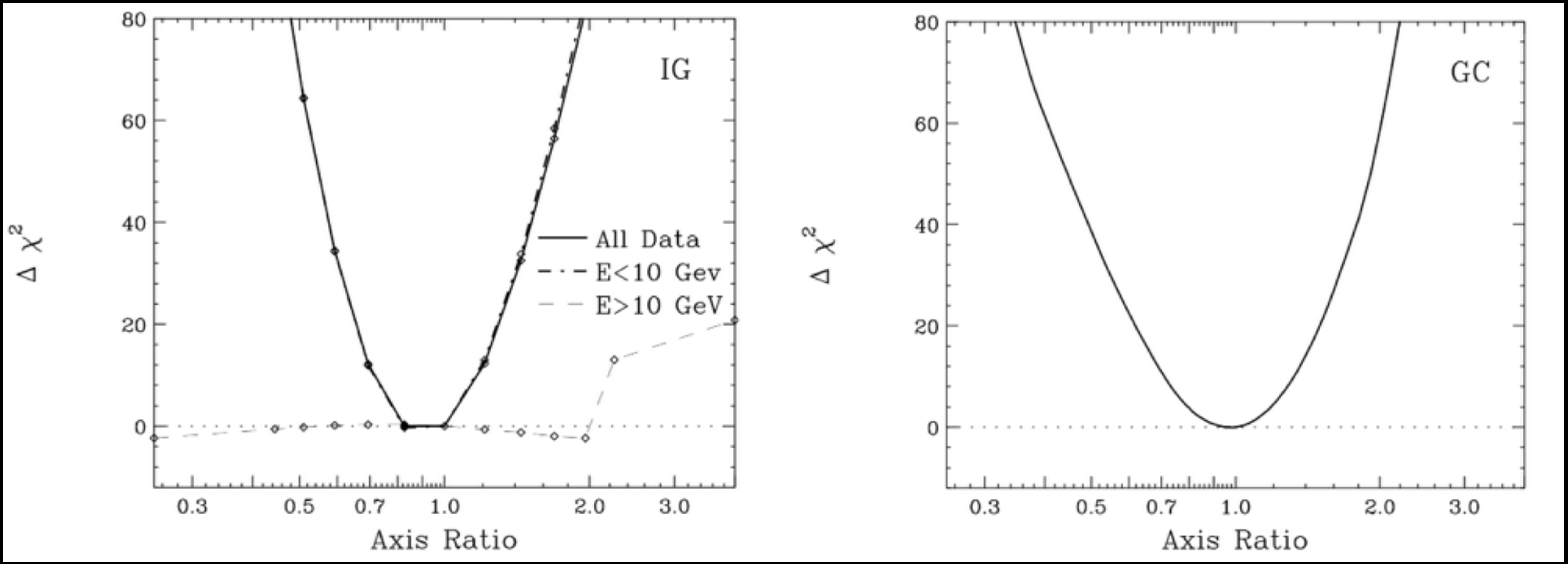
The new gamma-ray signal is detected at least 11° from the galactic center - this favors dark matter interpretations, over pulsar interpretations

The Morphology of the Gamma-Ray Excess



Galactic Center Model: We can test models where the DM profile is spatially offset from the true position of the Galactic Center. We find the data to prefer a NFW profile centered on the position of Sgr A* to within 0.05°

The Morphology of the Gamma-Ray Excess



Ellipticity: We can also ask if the data prefer a spherical profile

Axis ratios of greater than 20% either along or perpendicular to the galactic plane.

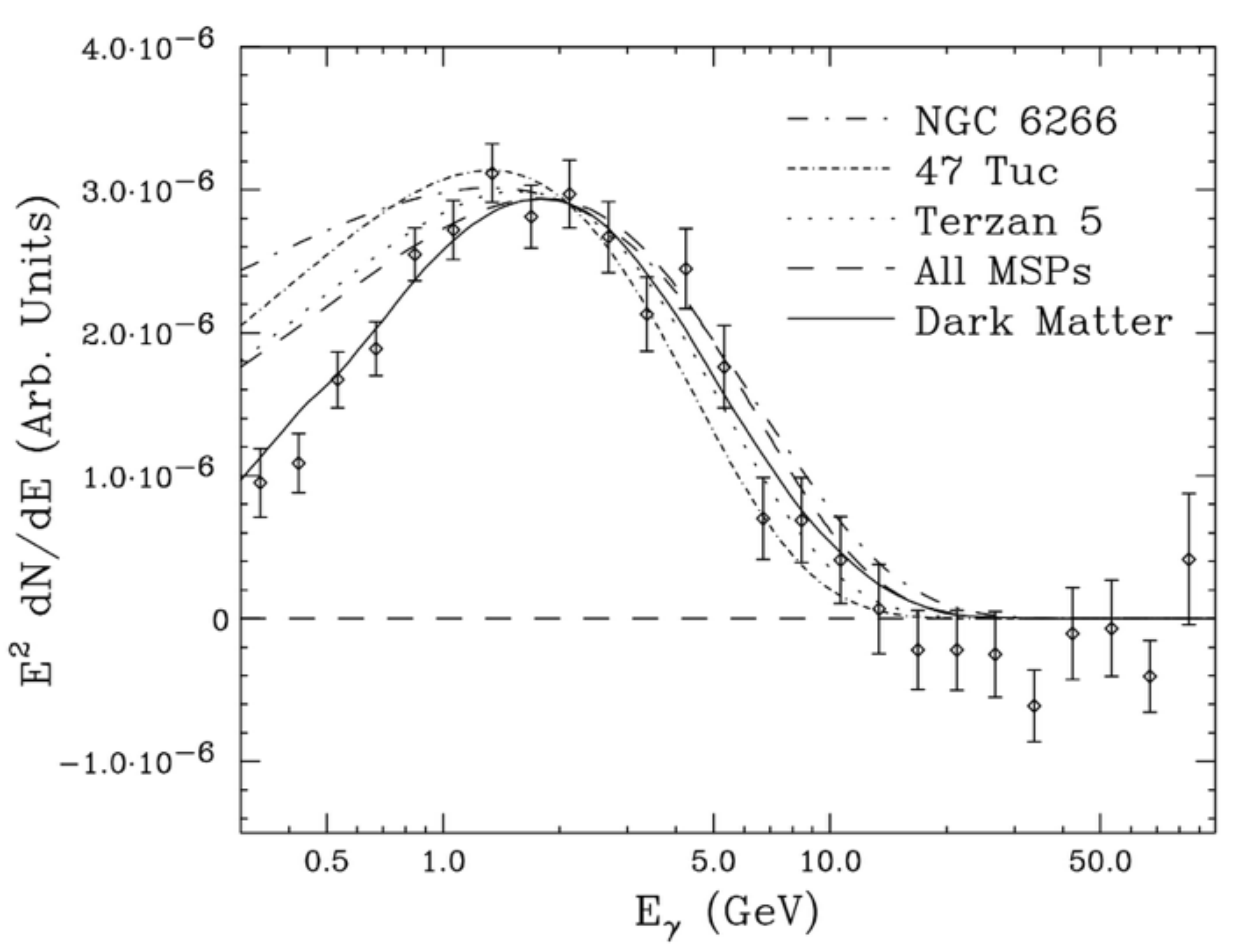
Interpretations of the Excess

1.) Do the data prefer millisecond pulsars or dark matter annihilation?

2.) How do the data compare to theoretically predicted dark matter models?

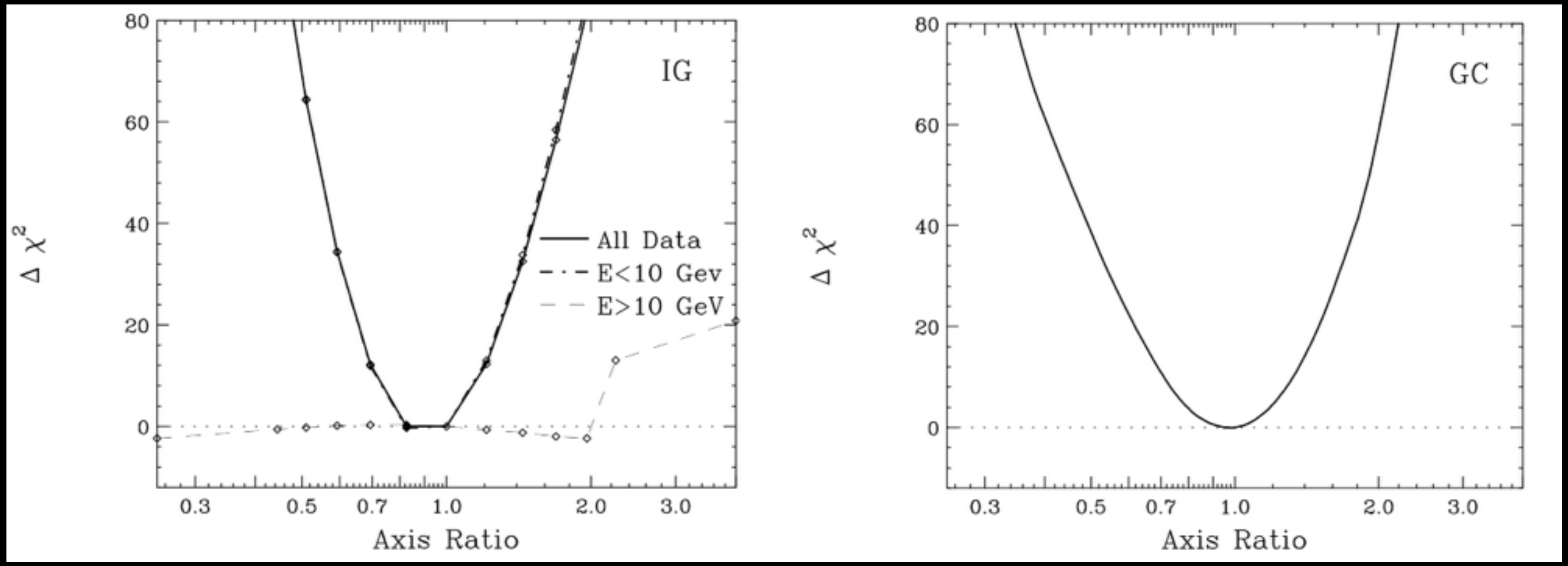
Interpretations of the Excess

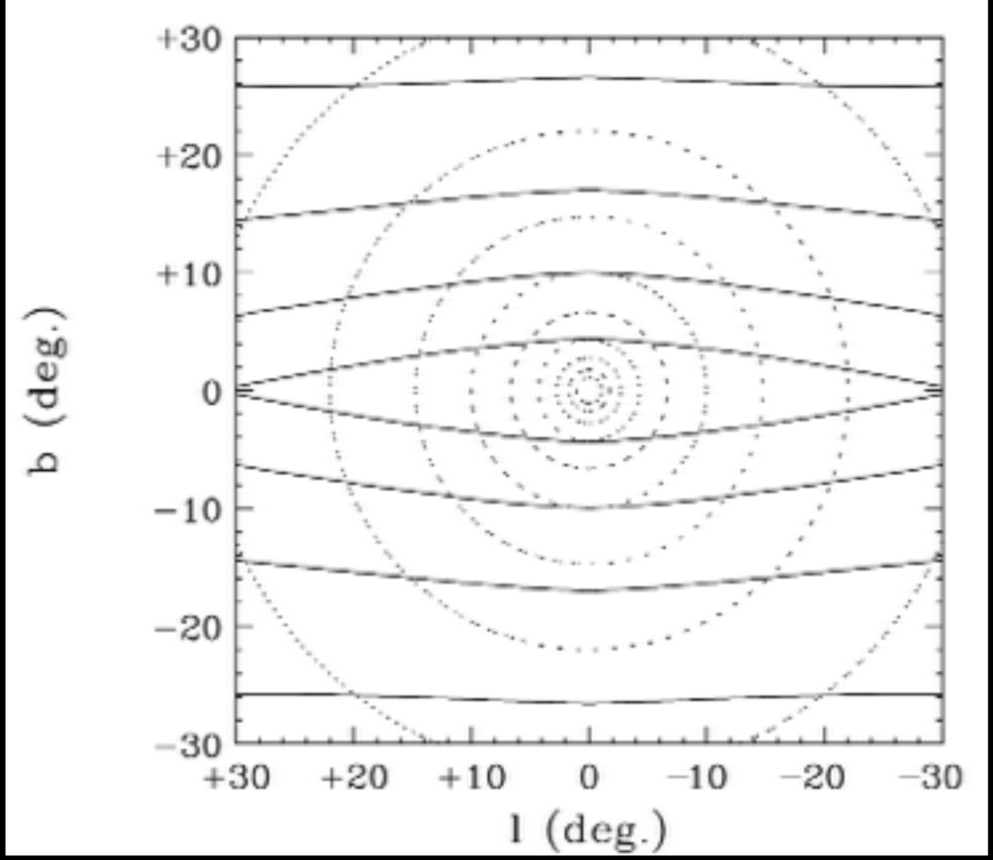
The spectrum of the signal does not look like MSPs



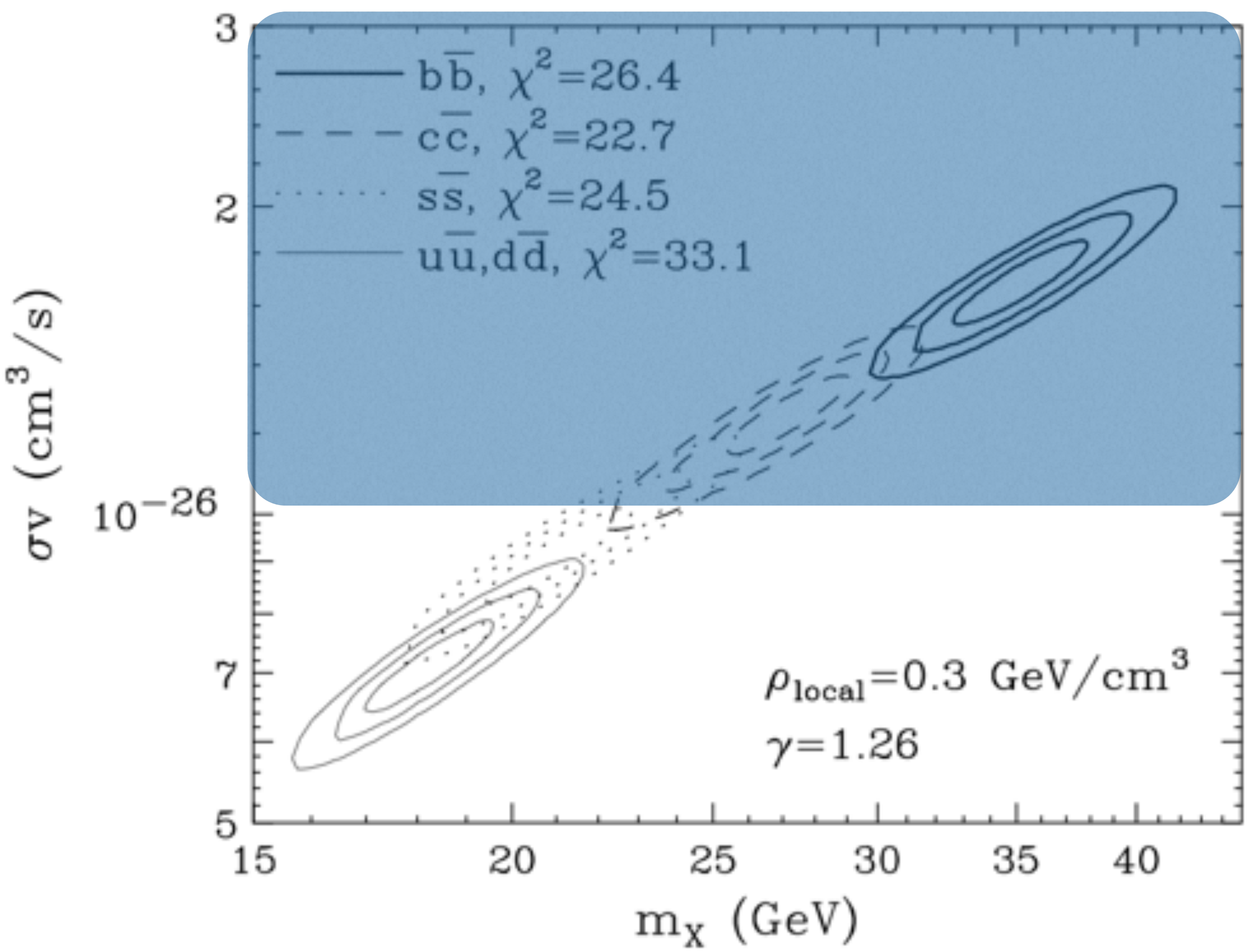
Interpretations of the Excess

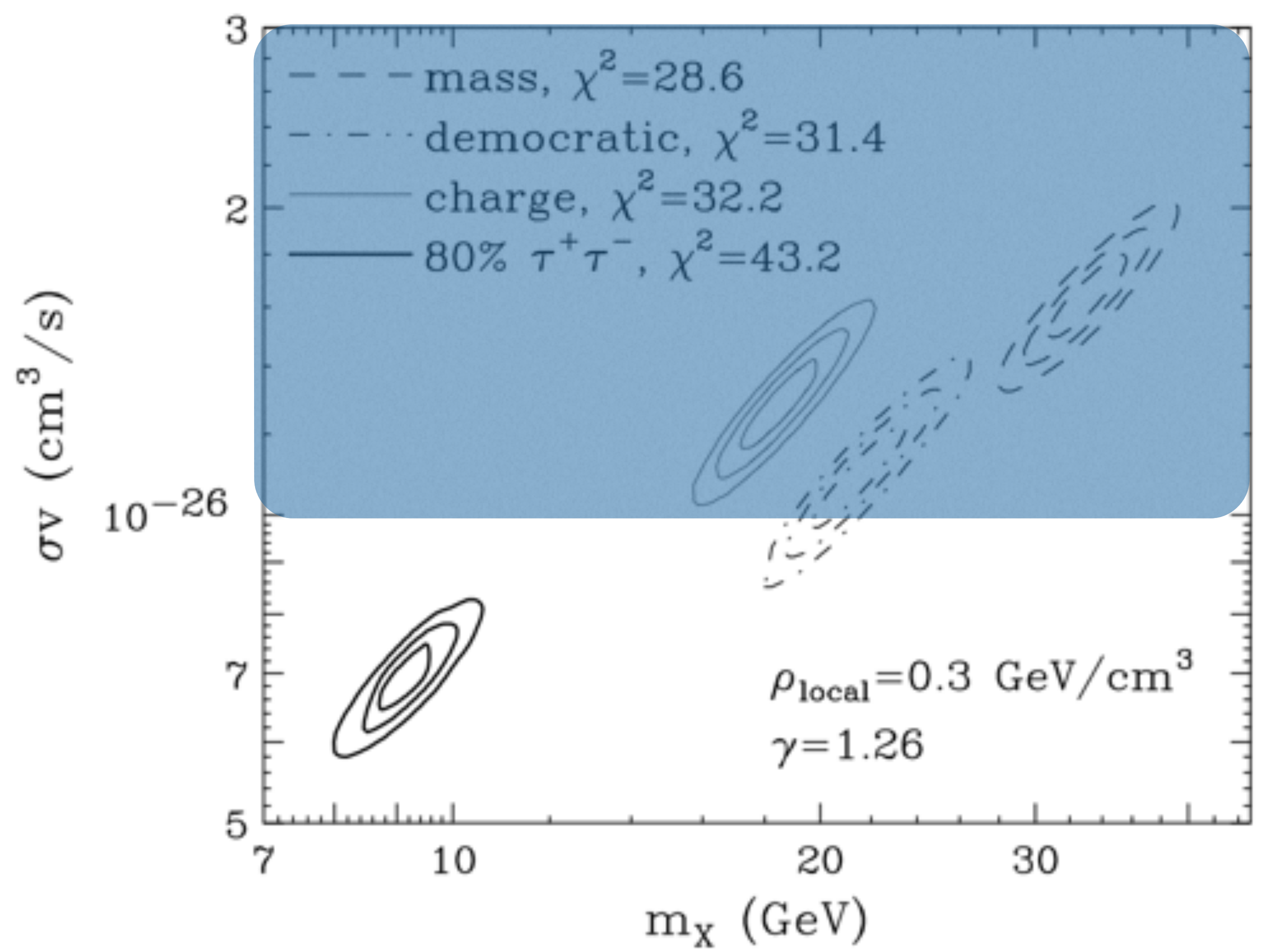
The spherical symmetry of the fit is hard to reconcile with pulsar models





Dark Matter Fits to the Data





The gamma-ray excess is very well fit by simple, theoretically motivated dark matter models.

We tune only:

1.) The dark matter mass and annihilation pathway
2.) The dark matter profile slope
3.) The dark matter annihilation cross-section

Dark Matter Fits to the Data

This is in stark contrast to nearly every other excess which has claimed to fit a dark matter signal

The dark matter models that explain the galactic center signal look like the textbook models we learned in graduate school

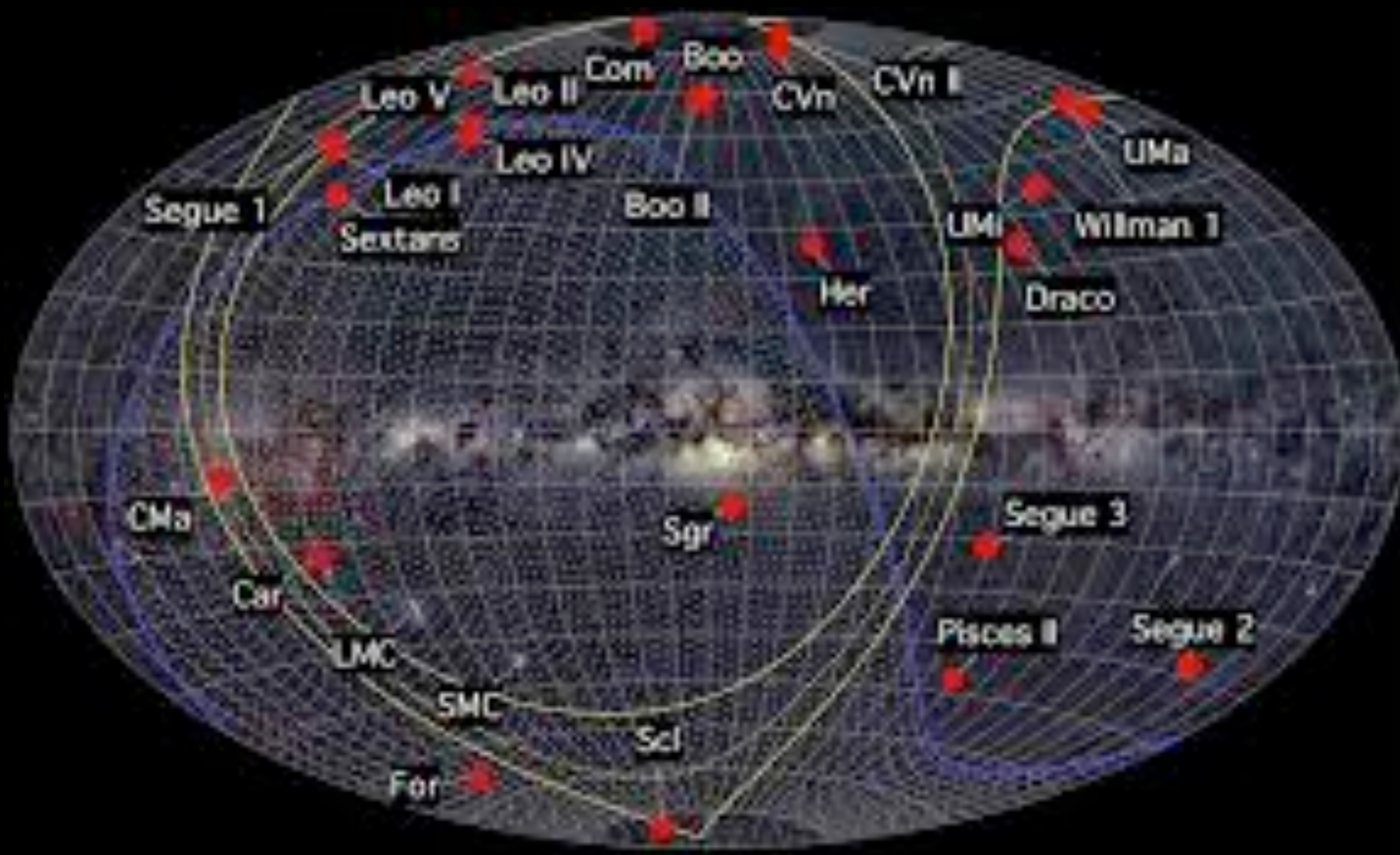
The Current State of the Excess

1.) The excess is hugely statistically robust (40σ for the Inner Galaxy, 17σ for the Galactic Center). This gives us ~30,000 photons in the dark matter signal, which we can use to scan the morphology and spectrum of the excess.

2.) The excess is extremely well fit by very standard dark matter models. No strange theoretical tricks are necessary.

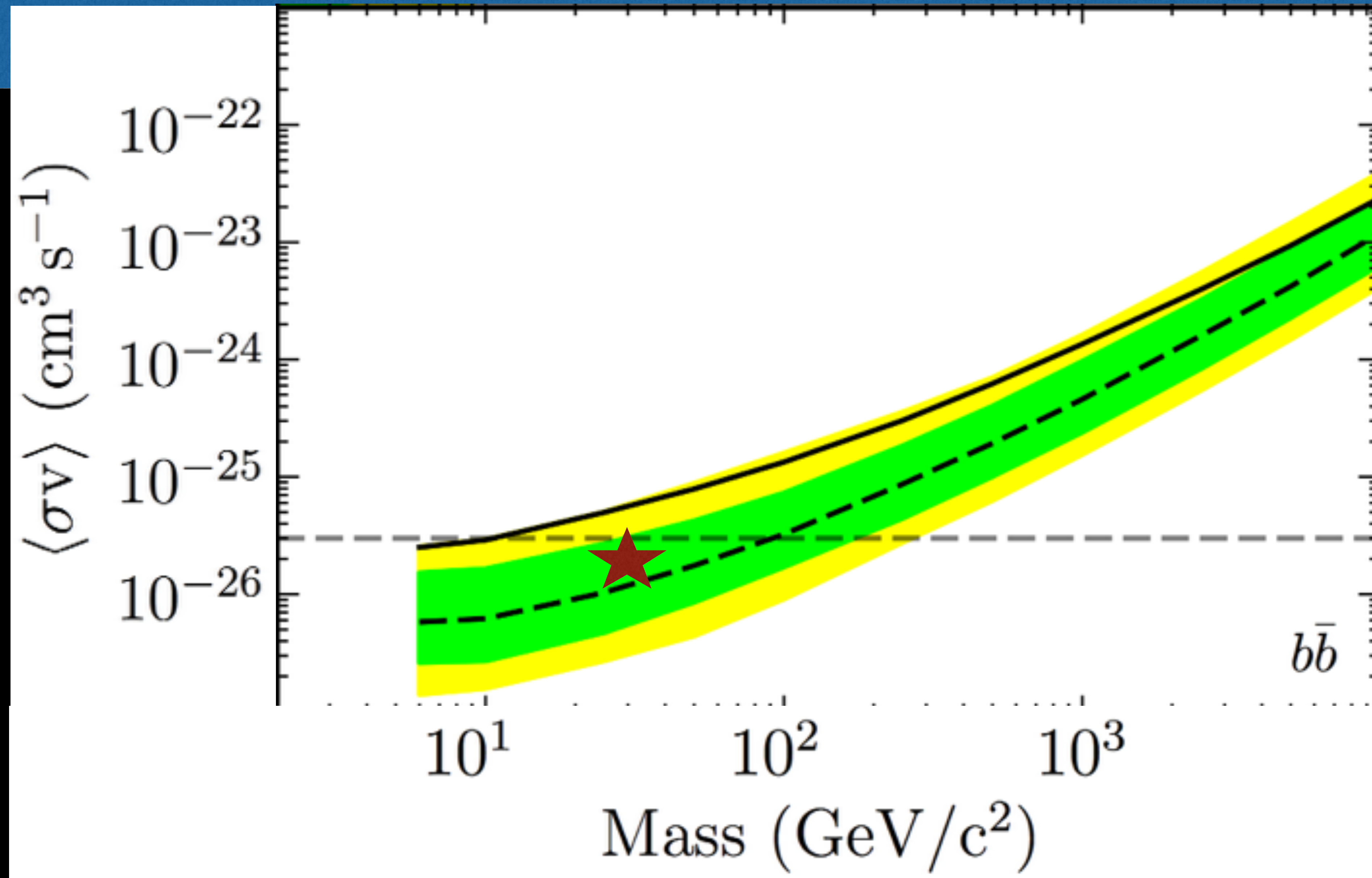
3.) There is no other reasonable model which has been put forward to explain the excess.

Future Tests



How would we test this excess? - Dwarf galaxies are another natural target for dark matter indirect detection. Interestingly, the Fermi-LAT finds an excess with a local significance of 2.7σ at the mass most favored by our dark matter model.

Future Tests



How would we test this excess? - Dwarf galaxies are another natural target for dark matter indirect detection. Interestingly, the Fermi-LAT finds an excess with a local significance of 2.7σ at the mass most favored by our dark matter model.

Is this how the story should unfold?

$$\Phi_\gamma \propto J = \frac{1}{\Delta\Omega}\int d\Omega \int_{l.o.s} \rho^2 dl(\phi)$$

Name	GLON (deg)	GLAT (deg)	Distance (kpc)	$\overline{\log_{10}(J^{NFW})}$[a] ($\log_{10}$[$GeV^2\,cm^{-5}\,sr$])
Bootes I	358.1	69.6	66	18.8 ± 0.22
Bootes II	353.7	68.9	42	–
Bootes III	35.4	75.4	47	–
Canes Venatici I	74.3	79.8	218	17.7 ± 0.26
Canes Venatici II	113.6	82.7	160	17.9 ± 0.25
Canis Major	240.0	-8.0	7	–
Carina	260.1	-22.2	105	18.1 ± 0.23
Coma Berenices	241.9	83.6	44	19.0 ± 0.25
Draco	86.4	34.7	76	18.8 ± 0.16
Fornax	237.1	-65.7	147	18.2 ± 0.21
Hercules	28.7	36.9	132	18.1 ± 0.25
Leo I	226.0	49.1	254	17.7 ± 0.18
Leo II	220.2	67.2	233	17.6 ± 0.18
Leo IV	265.4	56.5	154	17.9 ± 0.28
Leo V	261.9	58.5	178	–
Pisces II	79.2	-47.1	182	–
Sagittarius	5.6	-14.2	26	–
Sculptor	287.5	-83.2	86	18.6 ± 0.18
Segue 1	220.5	50.4	23	19.5 ± 0.29
Segue 2	149.4	-38.1	35	–
Sextans	243.5	42.3	86	18.4 ± 0.27
Ursa Major I	159.4	54.4	97	18.3 ± 0.24
Ursa Major II	152.5	37.4	32	19.3 ± 0.28
Ursa Minor	105.0	44.8	76	18.8 ± 0.19
Willman 1	158.6	56.8	38	19.1 ± 0.31

The Fermi-LAT Collaboration (2013)

The J-Factor of the Galactic center is:

$\log_{10}(J) = 21.02$

for a region within 100 pc of the Galactic center and an NFW profile

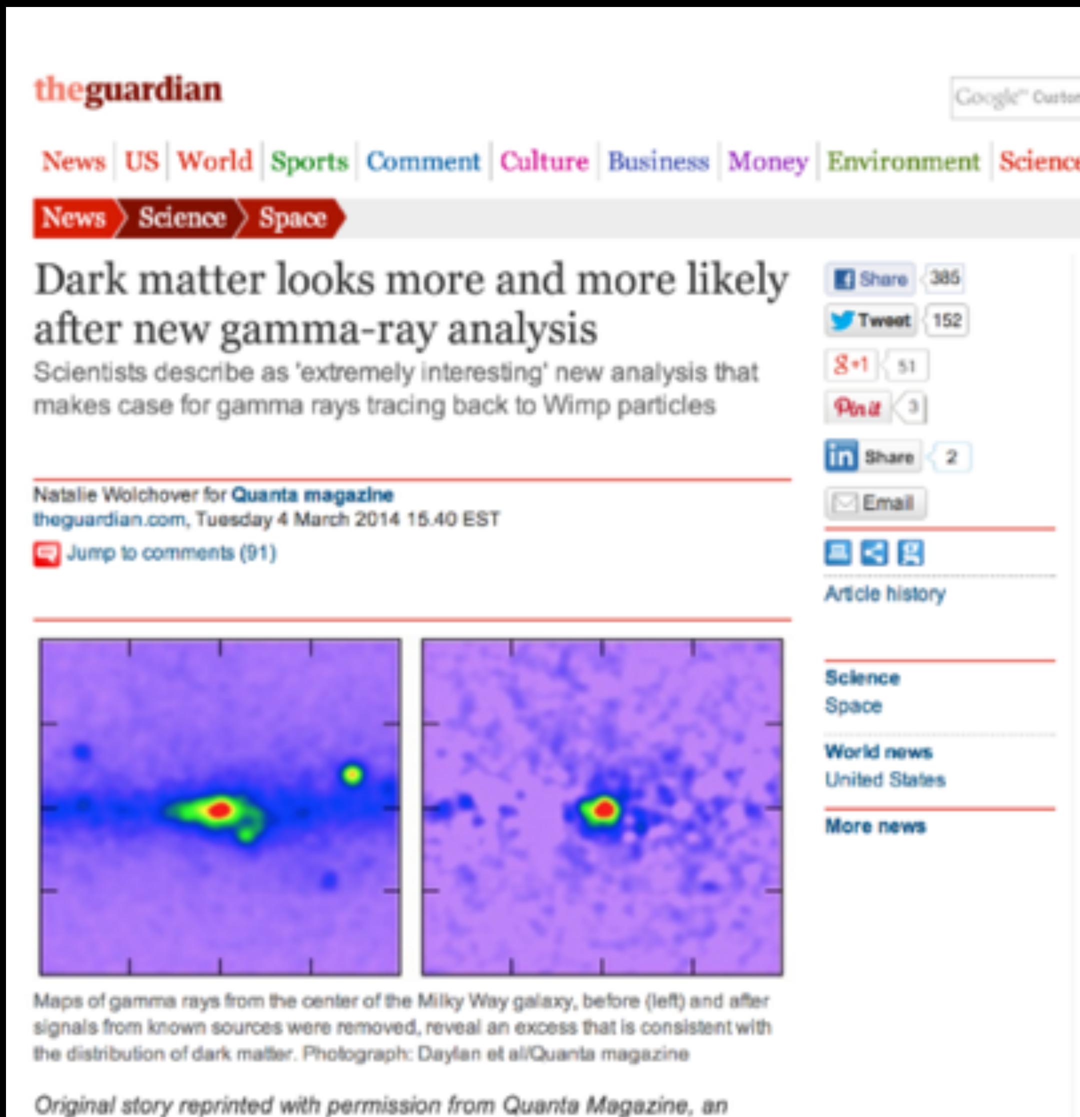
Conclusion

1.) The discovery of fast moving stars around the edges of nearby galaxies has taken us in surprising (and exciting!) directions

2.) By doing good science, the most obvious culprits for extra matter in our universe were ruled out — leaving us with strong evidence that there is a new particle which makes up more than 6x as much mass as everything we can see in the universe

3.) This new particle may be detectable in a number of ways, most interestingly by observations of the center of our galaxy

Conclusion



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Dark matter looks more and more likely after new gamma-ray analysis

Scientists describe as 'extremely interesting' new analysis that makes case for gamma rays tracing back to Wimp particles

Natalie Wolchover for Quanta magazine
theguardian.com, Tuesday 4 March 2014 15.40 EST

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Maps of gamma rays from the center of the Milky Way galaxy, before (left) and after signals from known sources were removed, reveal an excess that is consistent with the distribution of dark matter. Photograph: Daylan et al/Quanta magazine

Original story reprinted with permission from Quanta Magazine, an

SCIENCE PHYSICS

The Mystery of Dark Matter: WIMPS May Have the Answer

Michael D. Lemonick @MLemonick | April 8, 2014

Eighty percent of the universe is utterly invisible, but an exotic dance of mutually annihilating particles may explain it all

It's a mystery that has haunted astronomers for nearly 80 years now: what is the mysterious dark matter that outweighs ordinary matter—all of the atoms that make up stars, galaxies and clouds in the cosmos—by a factor of four to one? We know with near-certainty

At the heart of our galaxy, the WIMPS are at war

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Fermi Data Tantalize With New Clues To Dark Matter

A new study of gamma-ray light from the center of our galaxy makes the strongest case to date that some of this emission may arise from dark matter, an unknown substance making up most of the material universe. Scientists have developed new maps showing that the galactic center produces more high-energy gamma rays than can be explained by known sources and that this excess emission is consistent with some forms of dark matter.

Events
Monday, April 7: NES Video Chat: Robotics at NASA, 1 p.m. EDT
View Events Calendar
Launch Schedule
NASA TV Schedule

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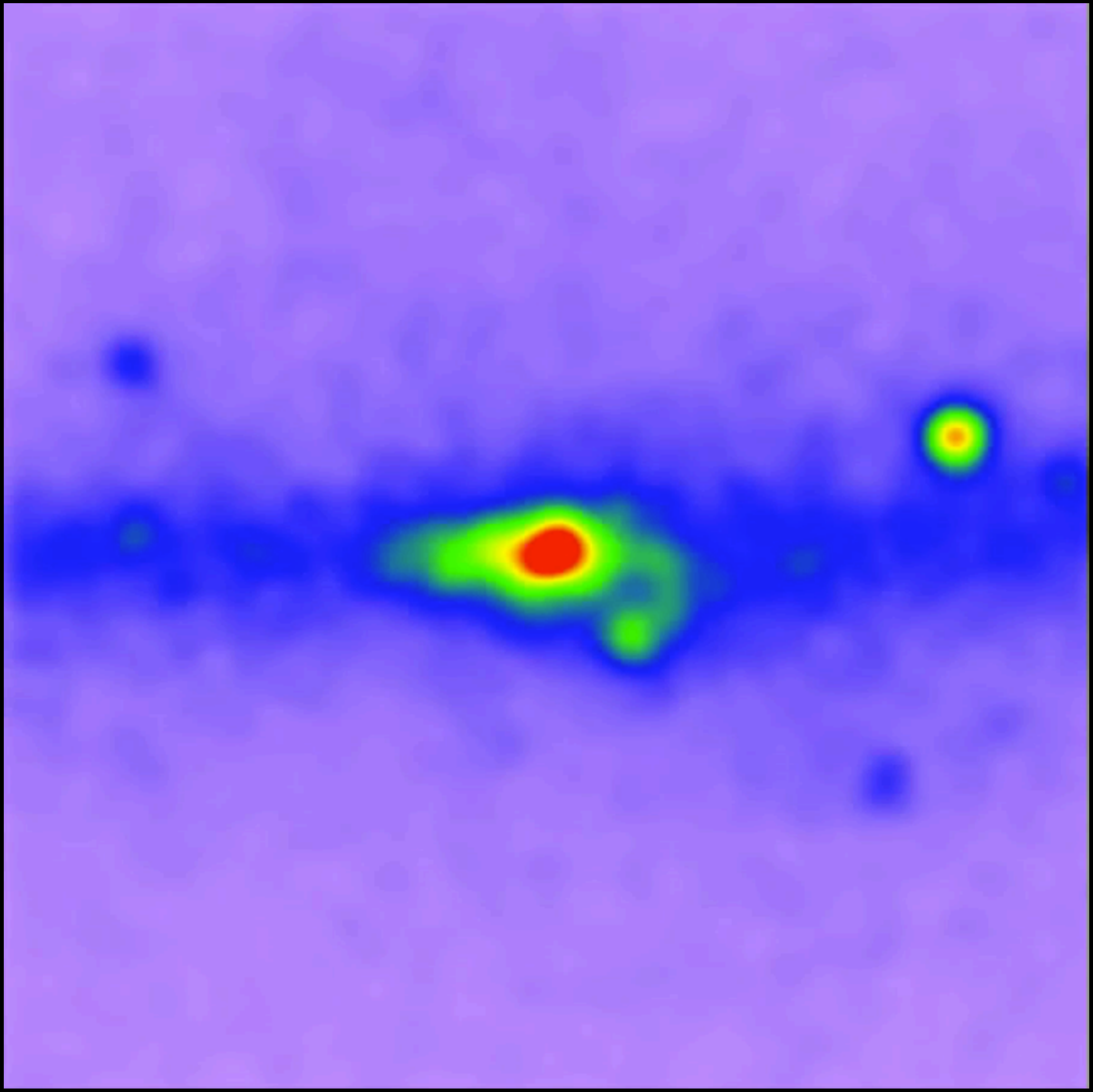
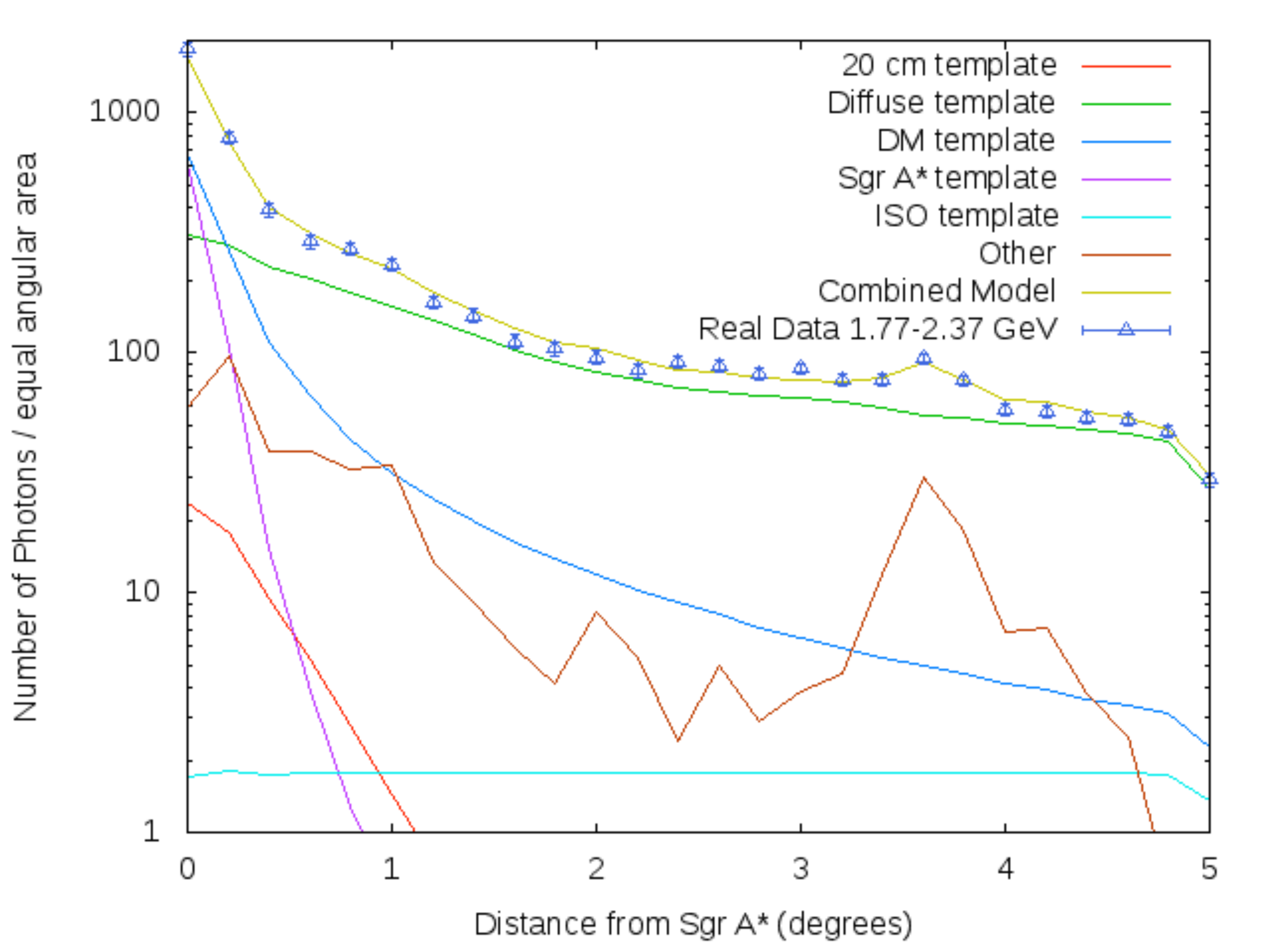
Conclusion

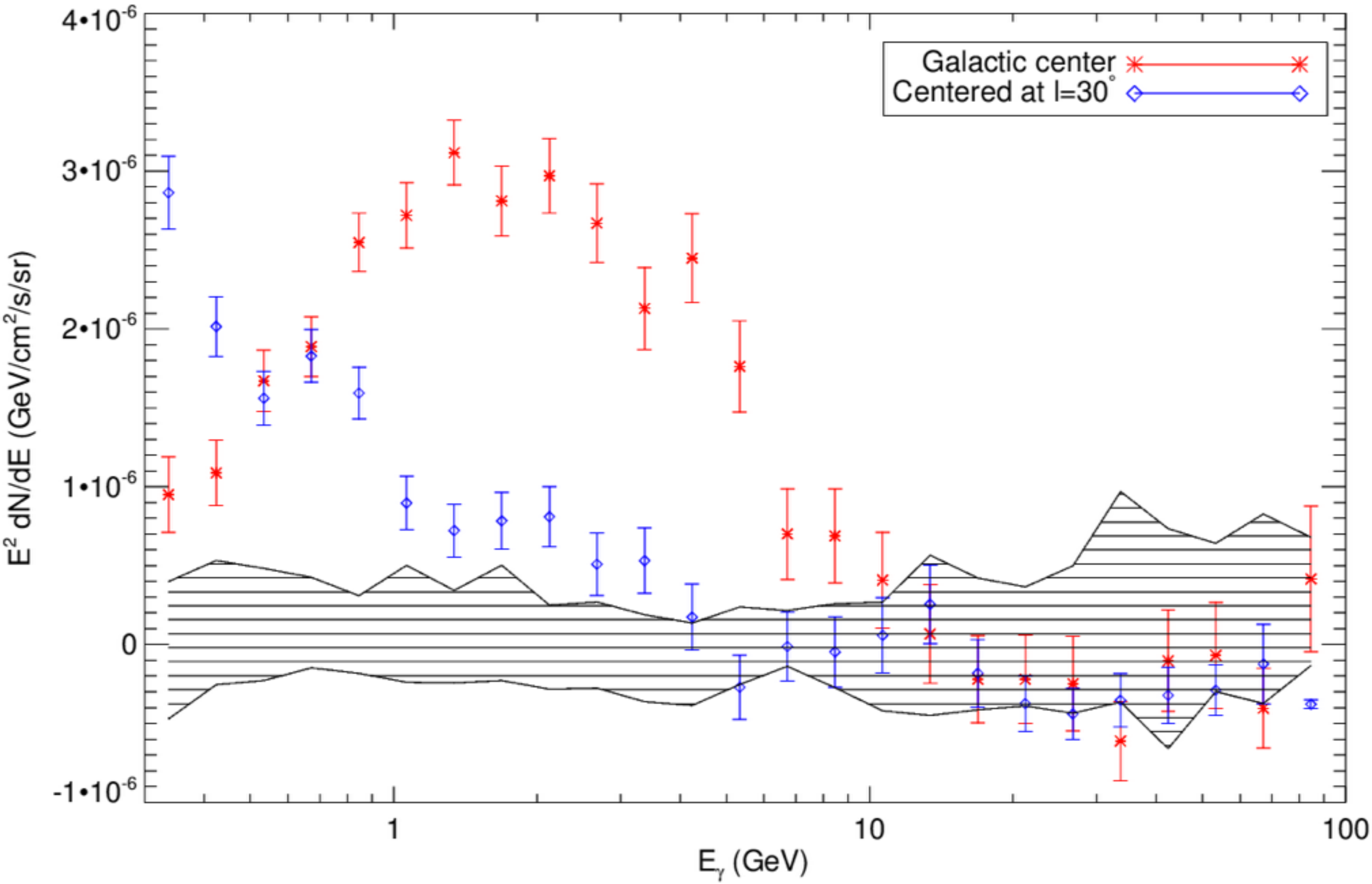


Extra Slides

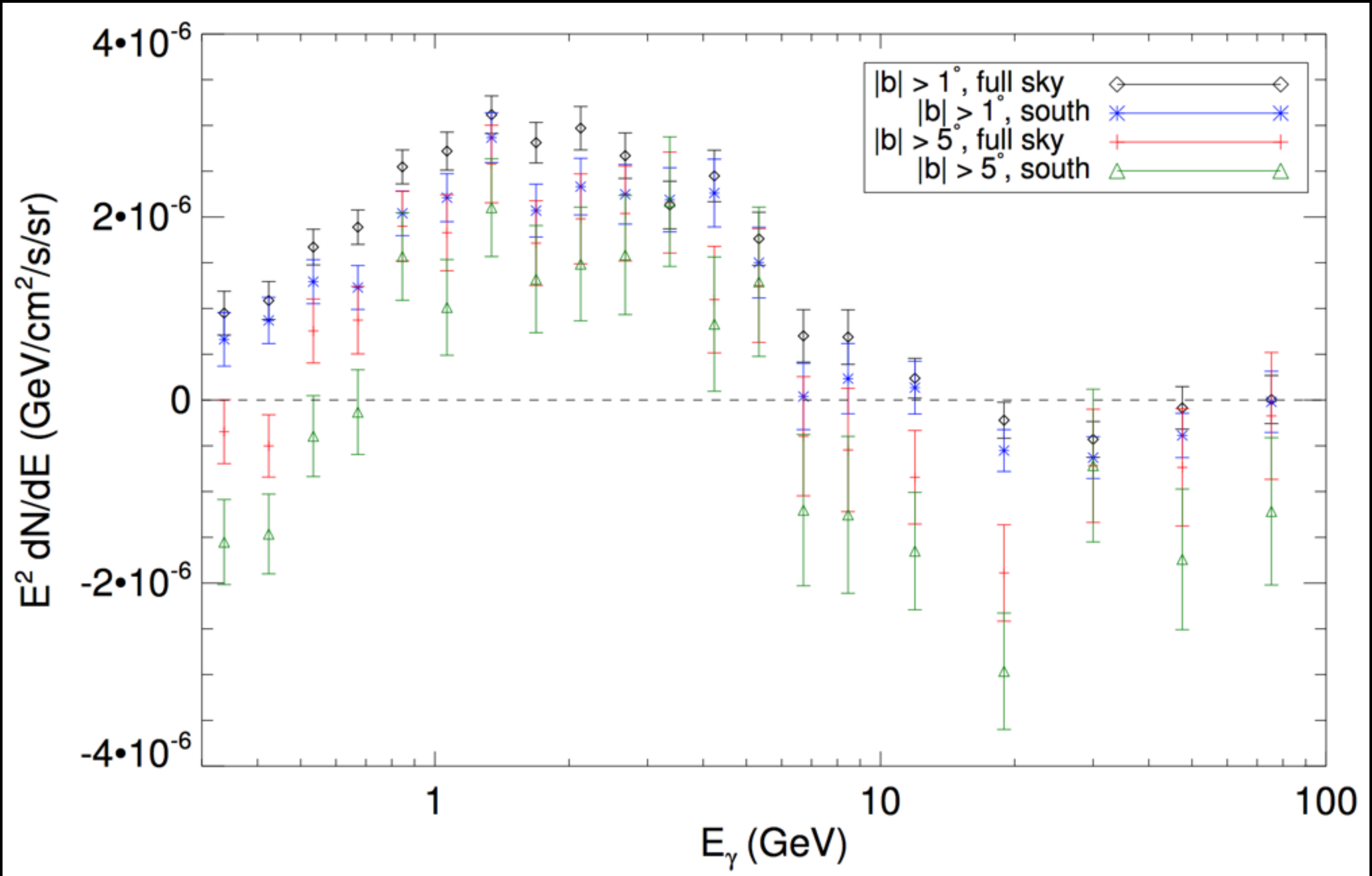
How Big Is This Excess?



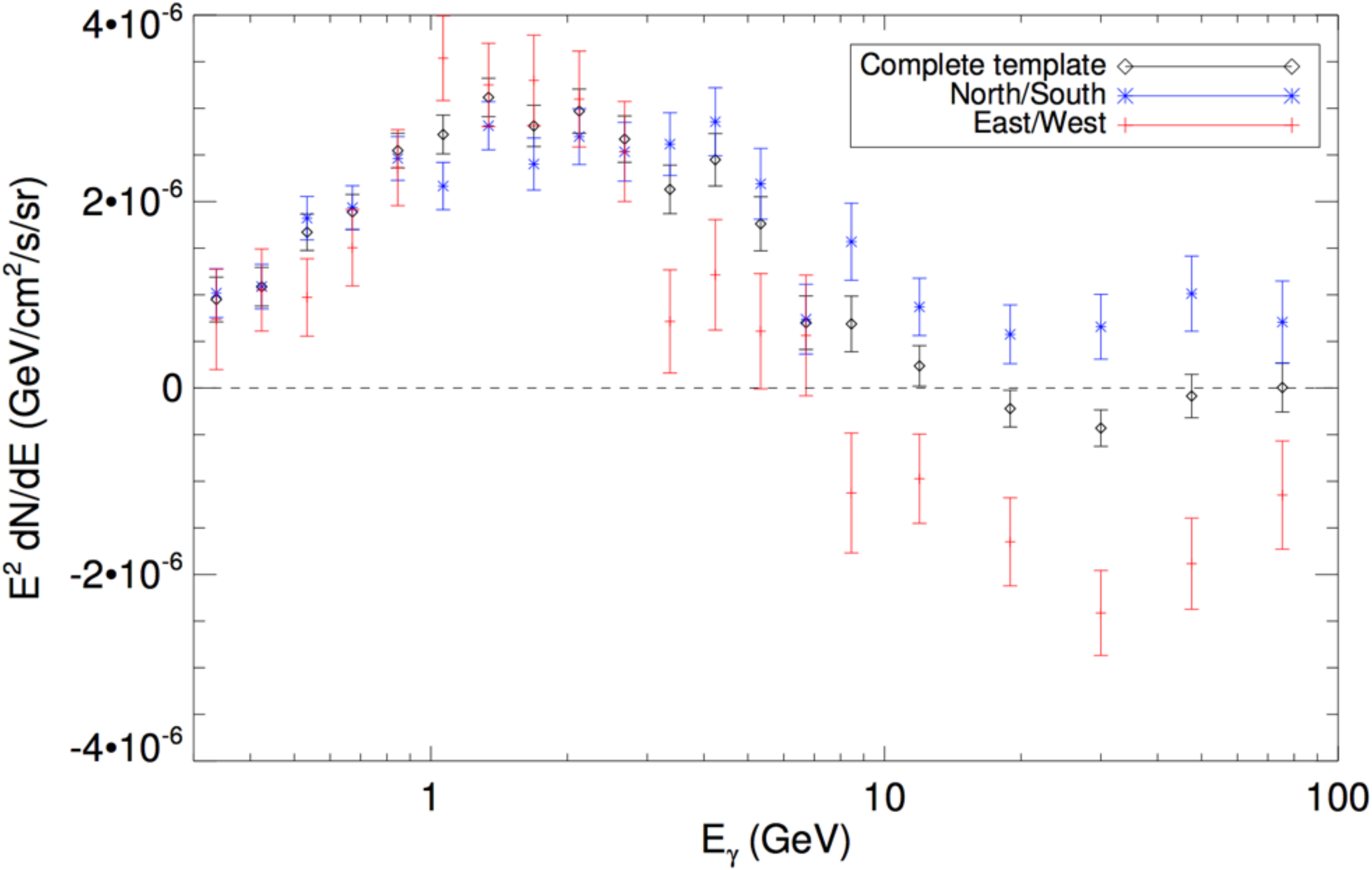
Do Other Residuals Have the Same Spectrum?



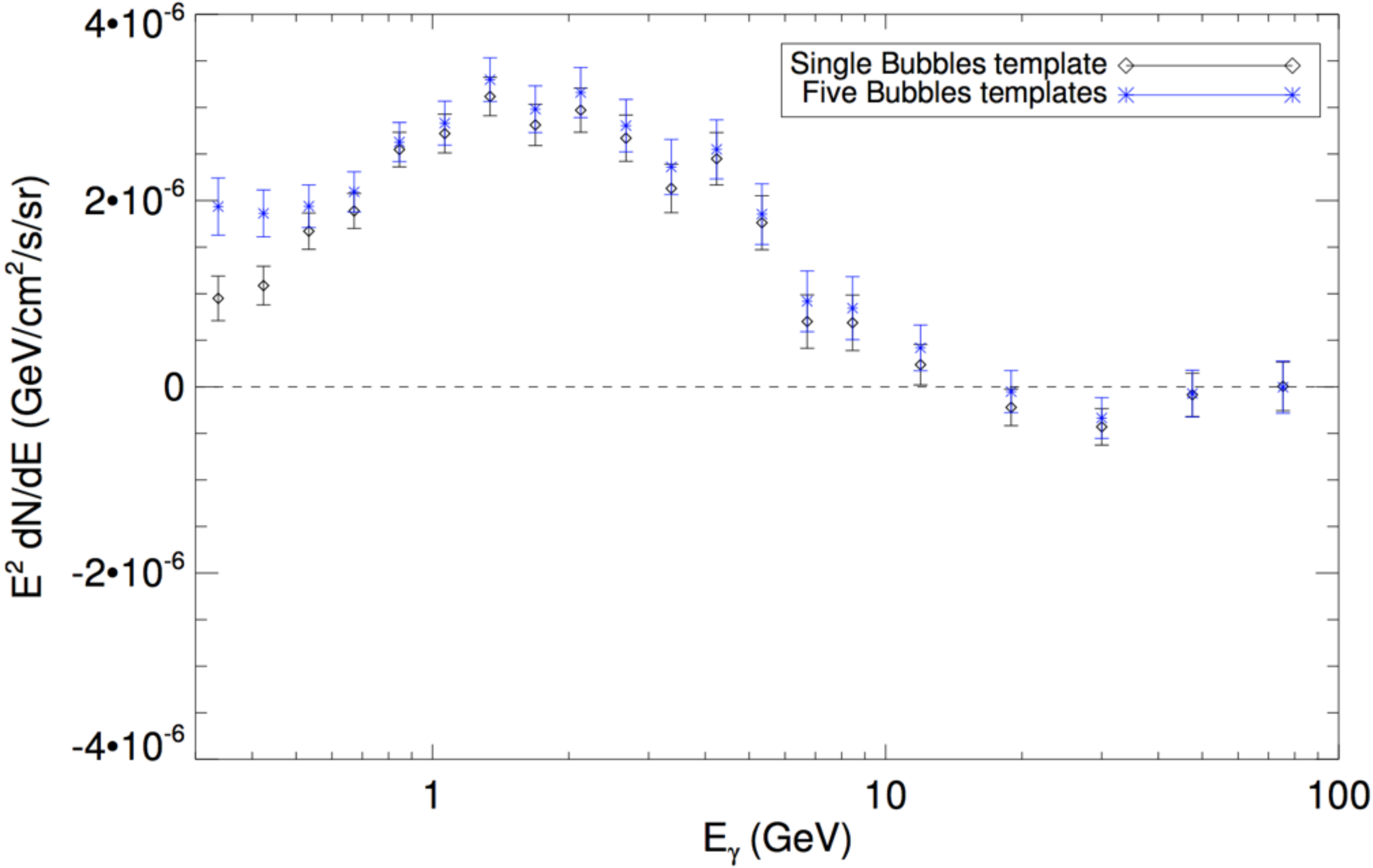
Wait, Some of the Same Photons are in Each Sample?



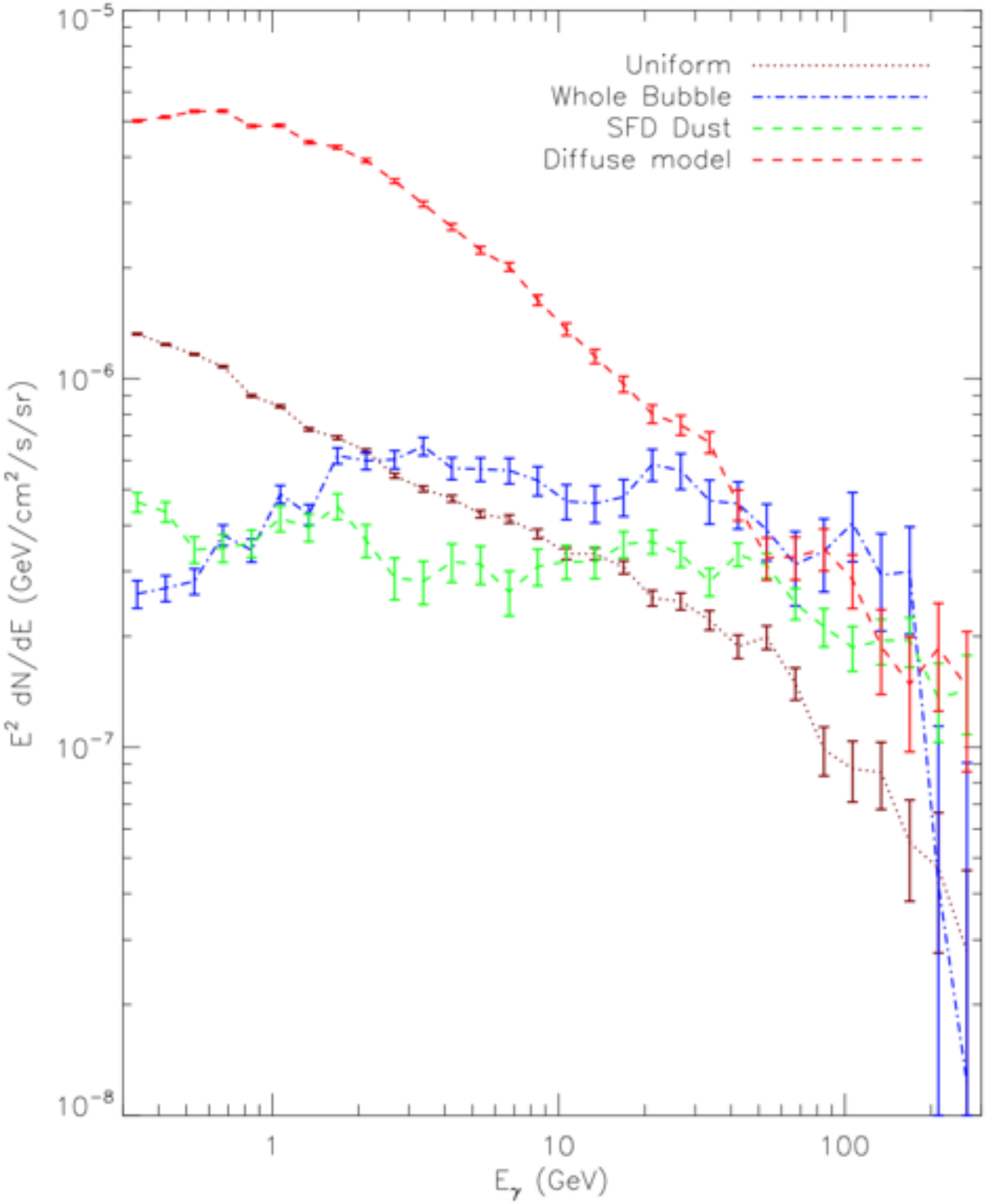
Maybe it's just part of the Bubbles?

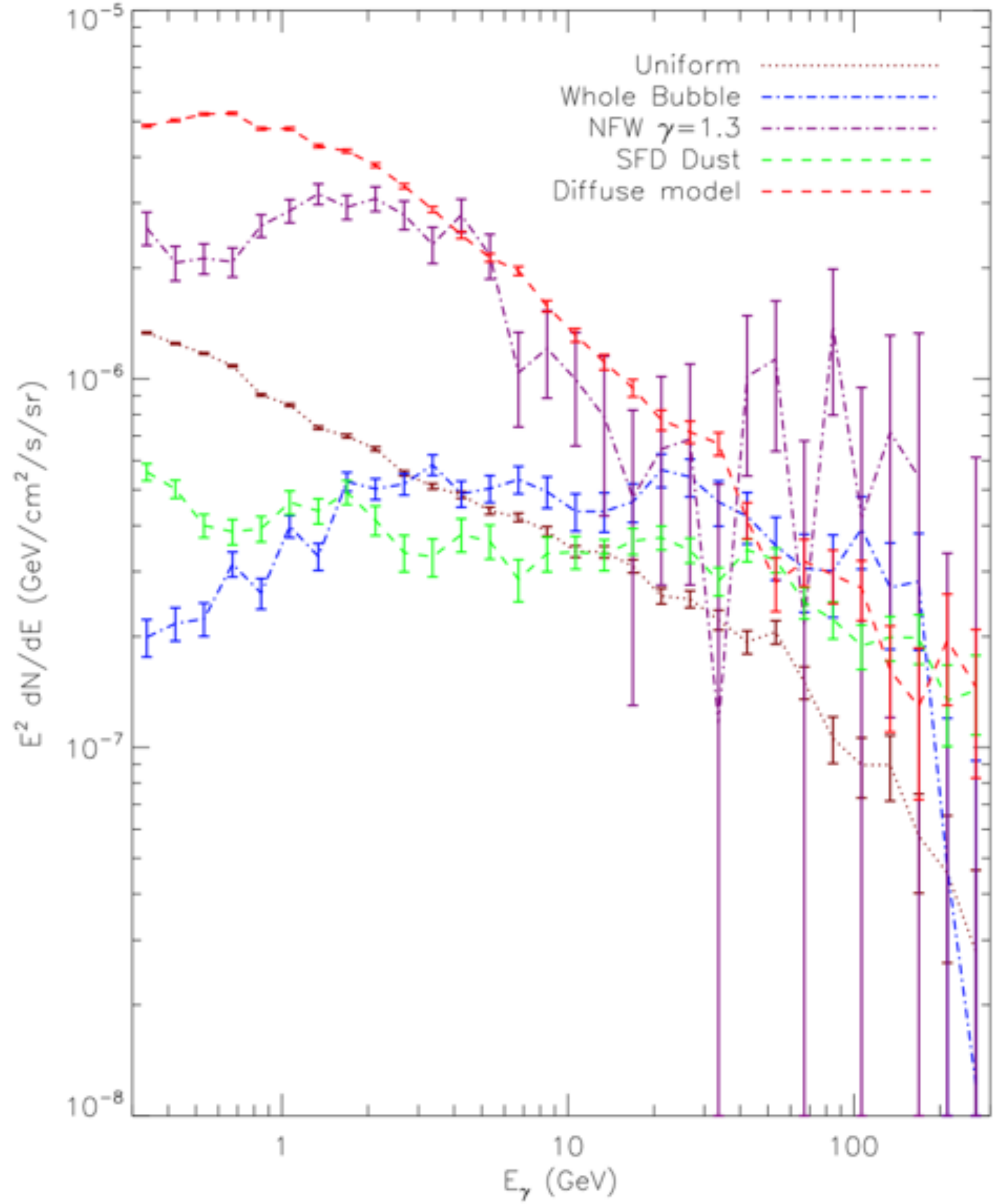


Maybe the Bubbles Have A Spectral Variation?



Does it Correlate with Gas?





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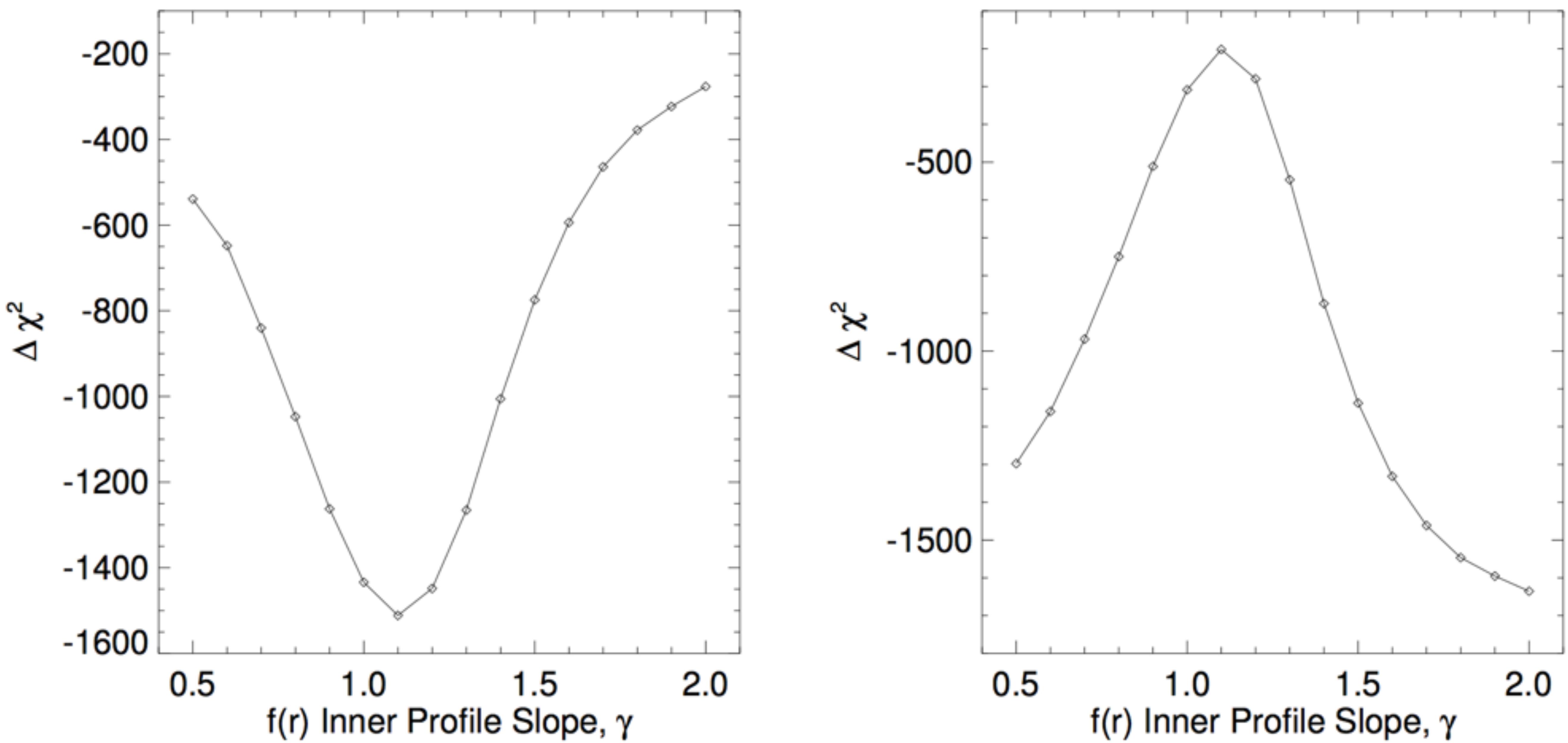
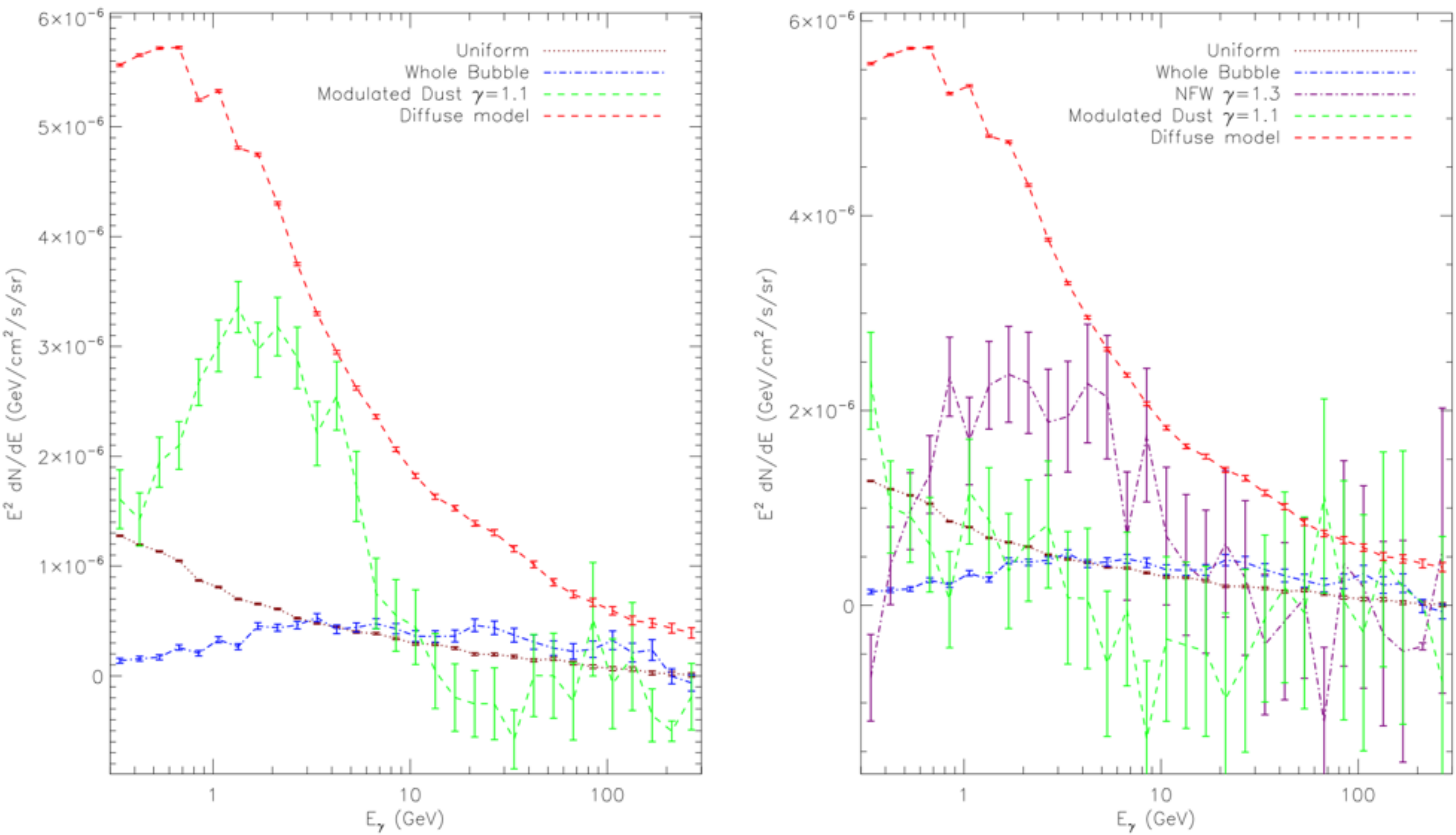


Even more generically, you can add an f(r) α r^(-gamma) profile for the SFD template, this is highly preferred in the model with no dark matter (left), but the dark matter template is still highly preferred even when gamma can float freely (right)

Does it Correlate with Gas?



With the best fit modulated SFD map, the dark matter fit is still highly preferred

Maybe the Models of the Diffuse Emission in the GC are Wrong