

National Aeronautics and Space Administration



Fermi  
Gamma-ray Space Telescope

[www.nasa.gov/fermi/](http://www.nasa.gov/fermi/)

# Indirect Detection: Dark Matter in the Cosmos

R. Caputo, UCSC  
on behalf of the  
Fermi-LAT collaboration

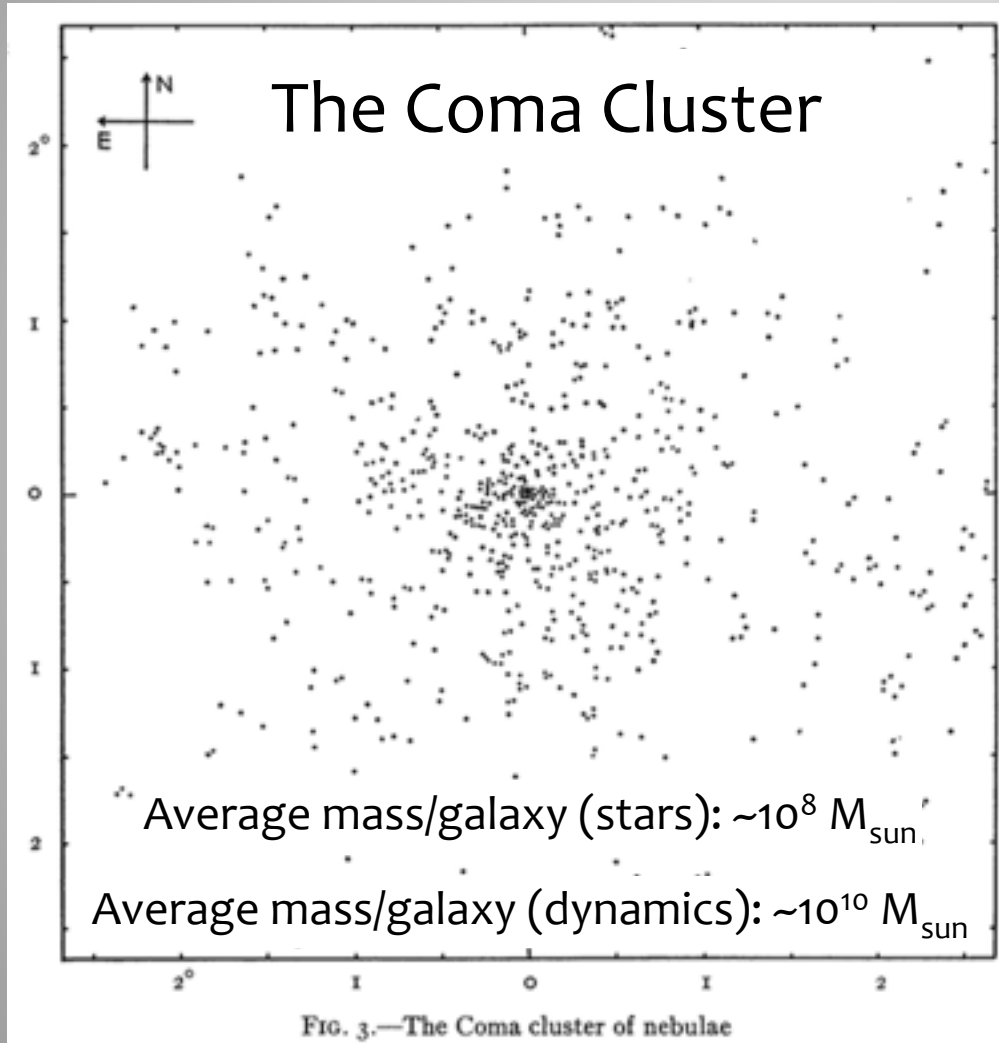
Mitchell Workshop on Collider  
and Dark Matter Physics

May 19, 2015





# The Mystery of Missing Mass



**1930s- Zwicky, others**

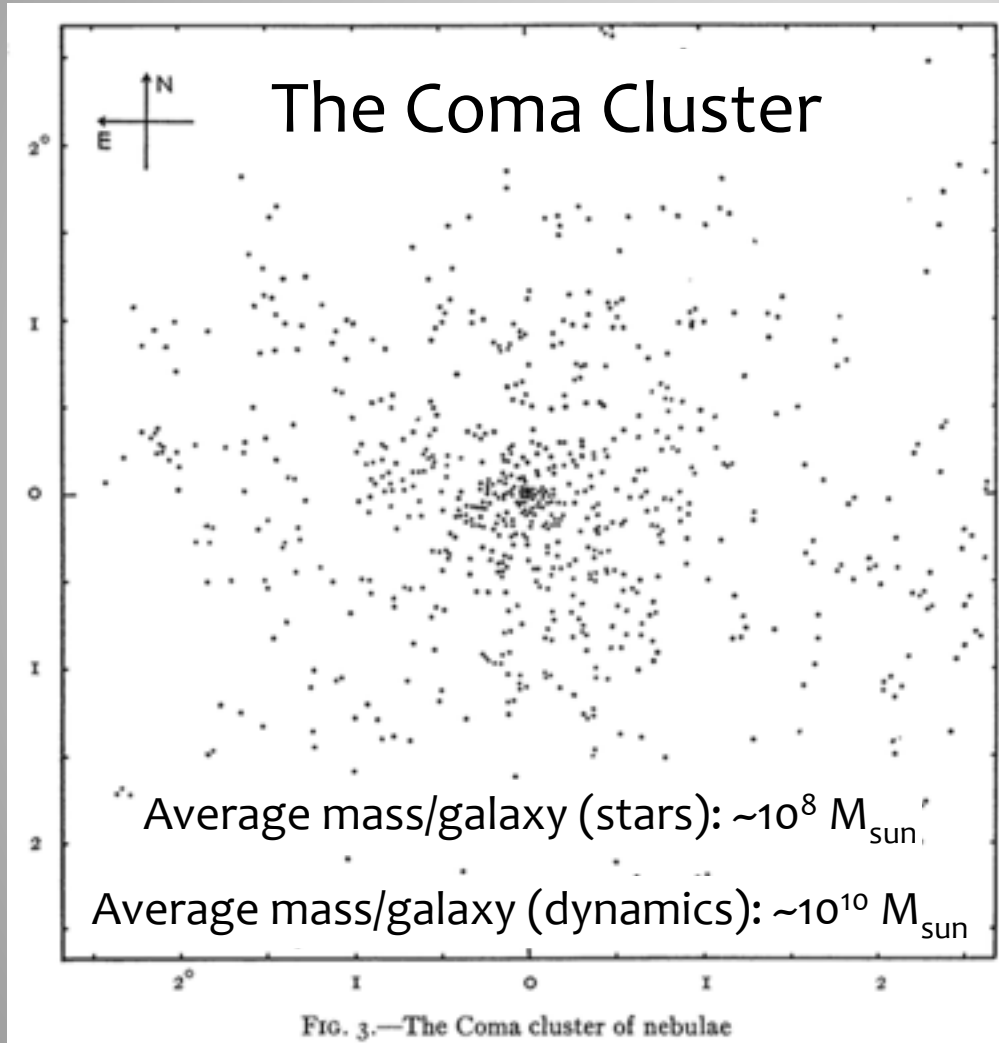
**1970s- V. Rubin, et al**

**1990s- Precision Cosmology**

F. Zwicky, *Astrophys. J.* 86, 217 (1937)



# The Mystery of Missing Mass



**1930s- Zwicky, others**

Coma cluster of galaxies:  
only small % mass from  
luminous matter

*dunkle Materie*

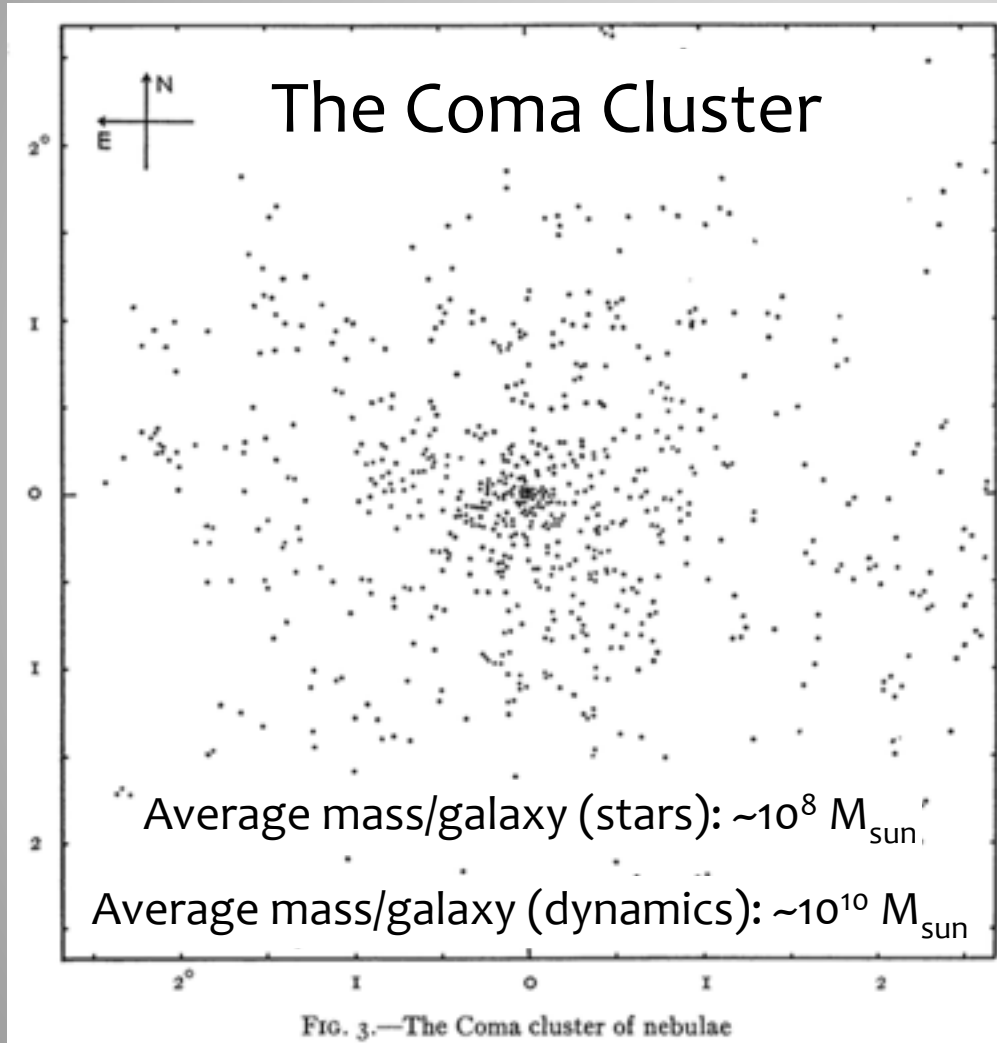
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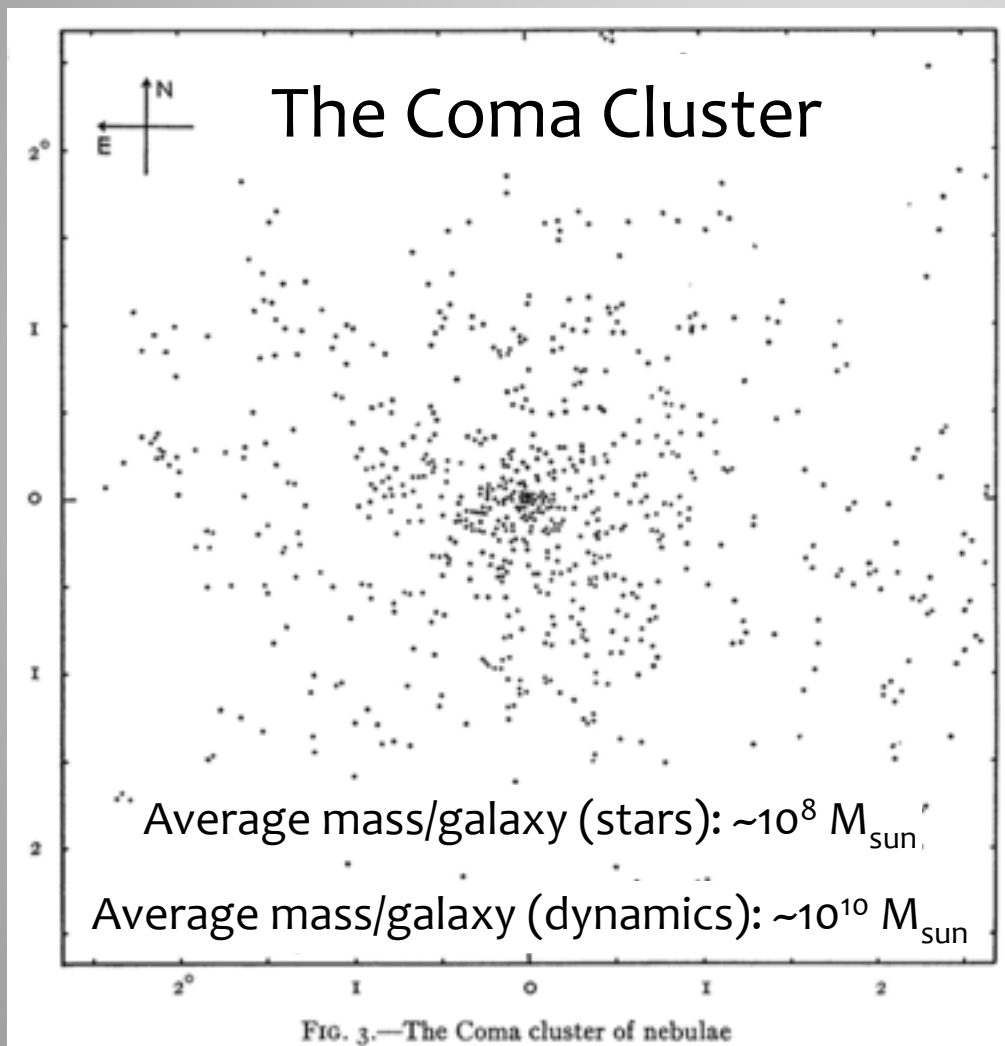
Galactic Rotation curves

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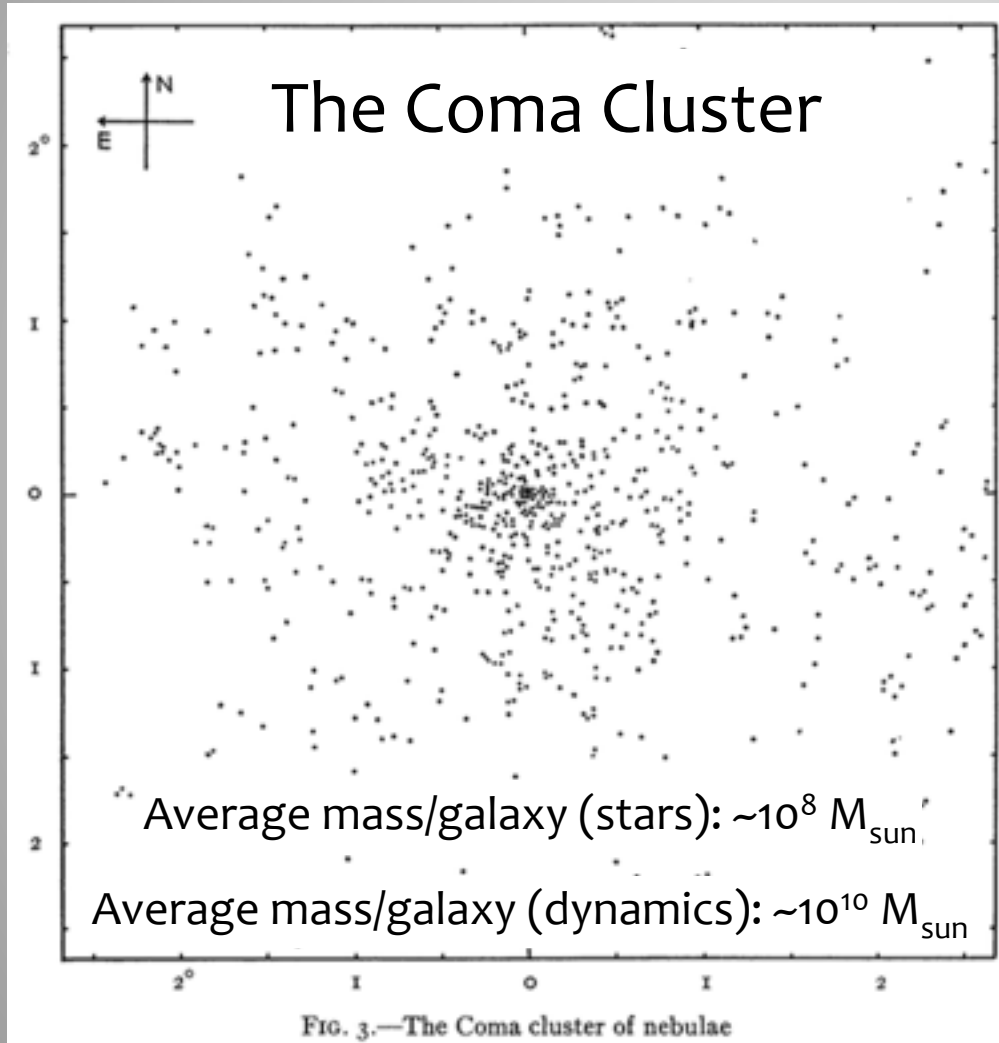
CMB, Large Scale Structure,  
BBN, BAO

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# The Mystery of Missing Mass



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*dunkle Materie*

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Galactic Rotation curves

## 1990s- Precision Cosmology

CMB, Large Scale Structure,  
BBN, BAO

*DM is there...*

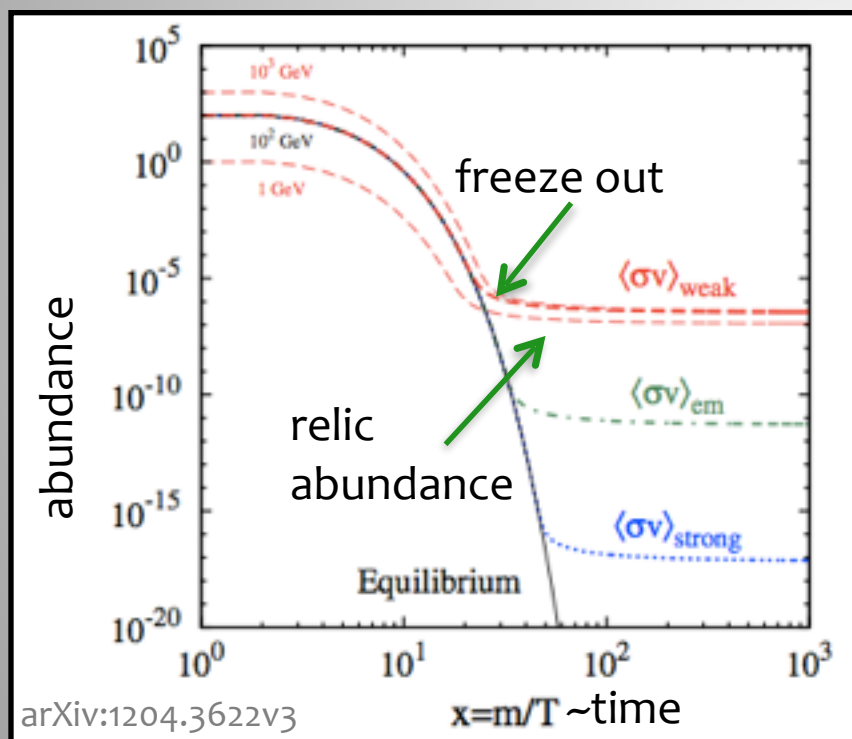
*and it's likely a particle*

F. Zwicky, Astrophys. J. 86, 217 (1937)



# Why WIMPS?

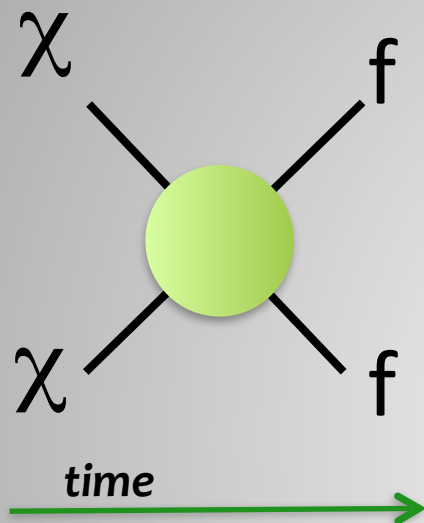
## Astrophysics/Cosmology/Particle Physics



- Thermal relic
  - $\chi$ 's no longer in creation/annihilation equilibrium
  - $\langle \sigma v_{\text{rel}} \rangle \approx \text{few} \times 10^{-26} \text{ cm}^3 / \text{s}$
- Weak-scale cross sections
  - assume  $m_{\chi} \approx 100 \text{ GeV}$
  - Right about where we can find them!
  - $\langle \sigma v_{\text{rel}} \rangle \approx \text{few} \times 10^{-26} \text{ cm}^3 / \text{s}$
- What's special about the weak scale?
  - expect new physics

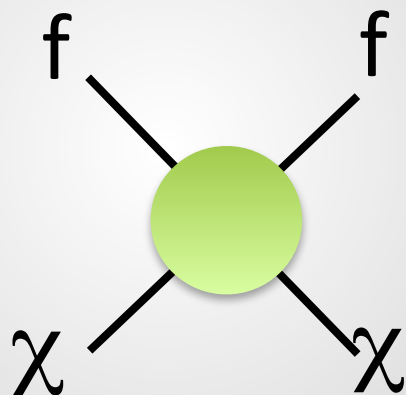


# Production/Detection Mechanism

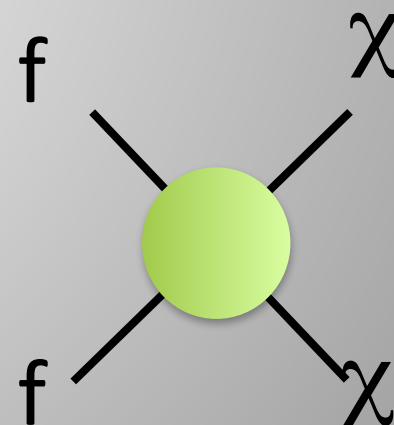


**Direct Detection**

**Indirect Detection**



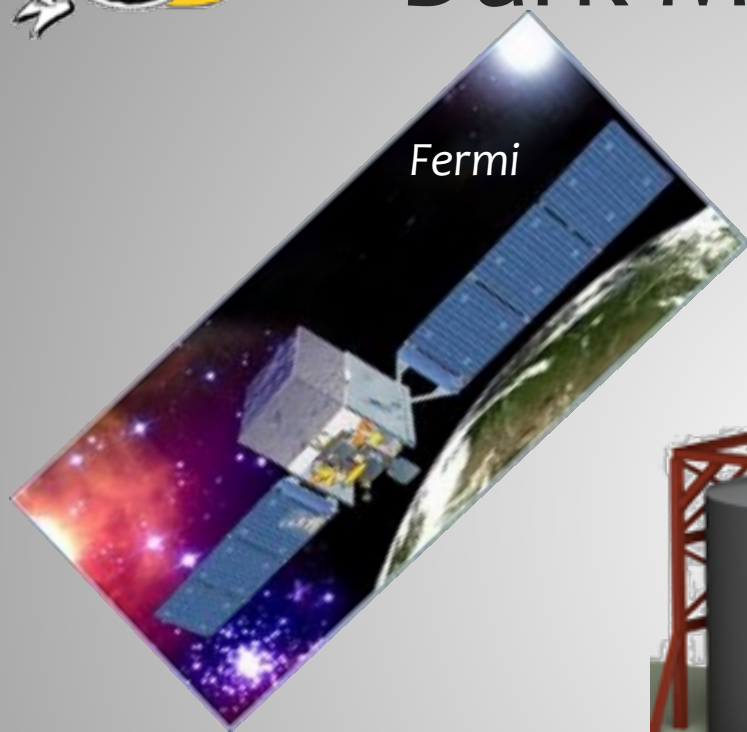
**Collider**





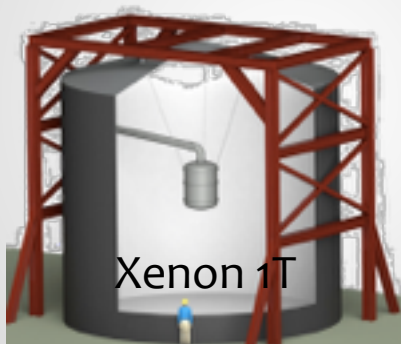


# Dark Matter Searches



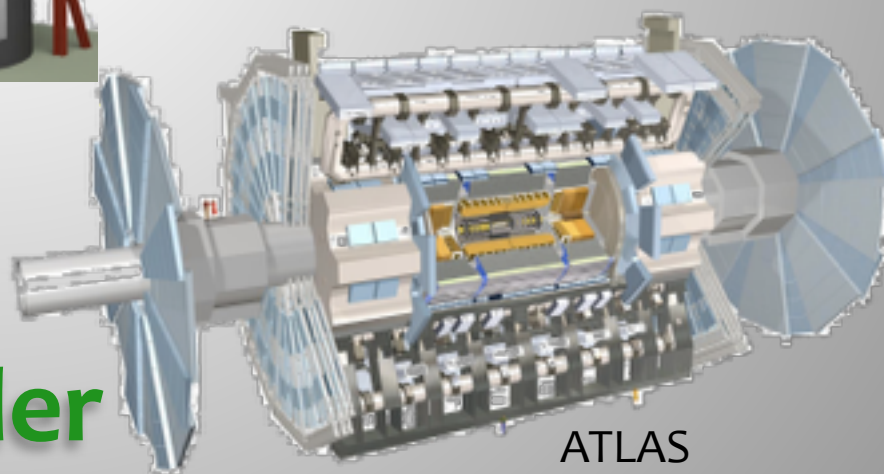
Fermi

## Indirect Detection



Xenon 1T

## Direct Detection



ATLAS

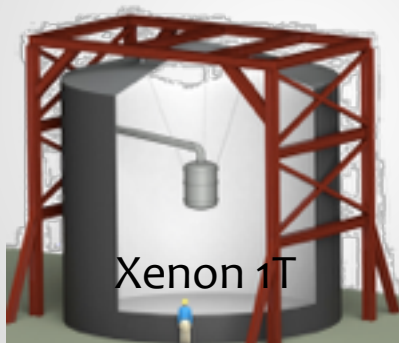
## Collider



# Dark Matter Searches

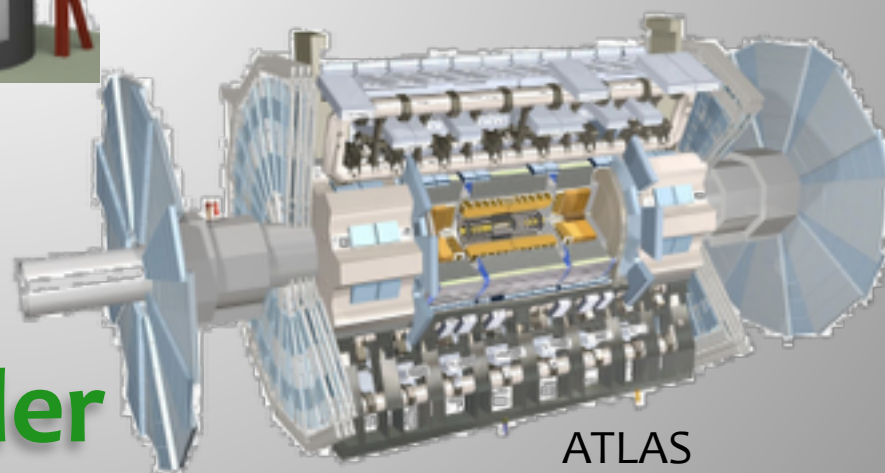


**Indirect Detection**



**Direct Detection**

**Collider**





# Indirect Searches



# Indirect Searches

*Observed* =



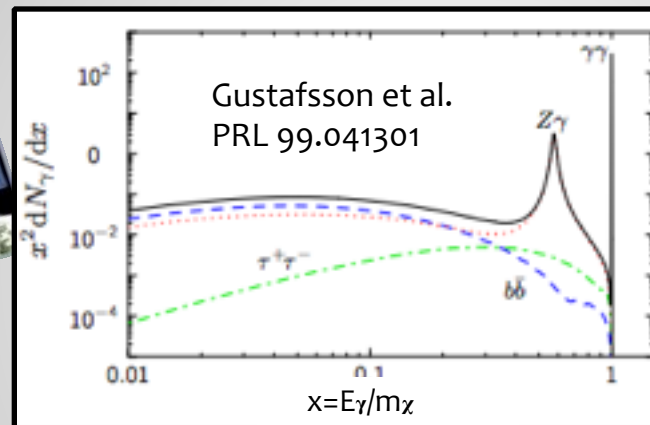
$$\Phi(E, \psi) =$$





# Indirect Searches

**Observed** = **Particle Properties**  $\times$



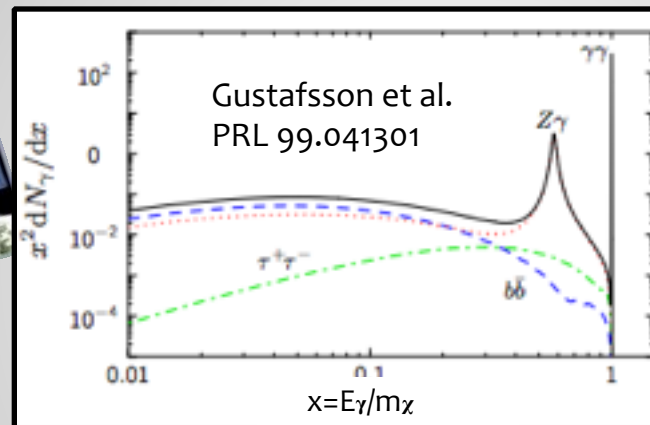
$$\Phi(E, \psi) = \frac{1}{4\pi} \frac{\langle \sigma_\chi v \rangle}{2m_\chi^2} N(E)$$





# Indirect Searches

**Observed** = **Particle Properties**  $\times$



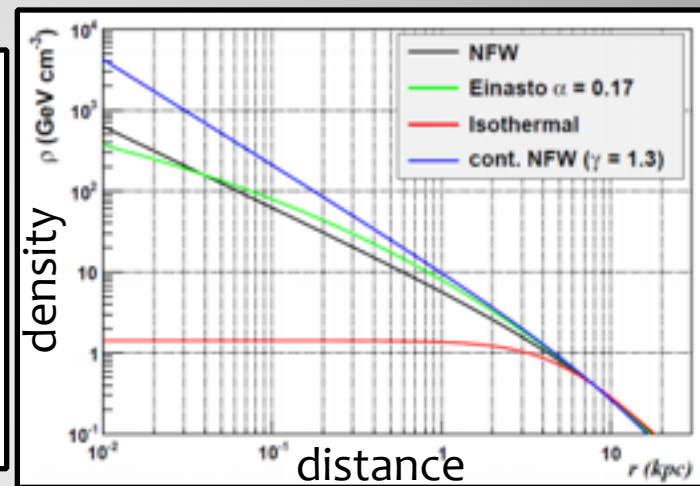
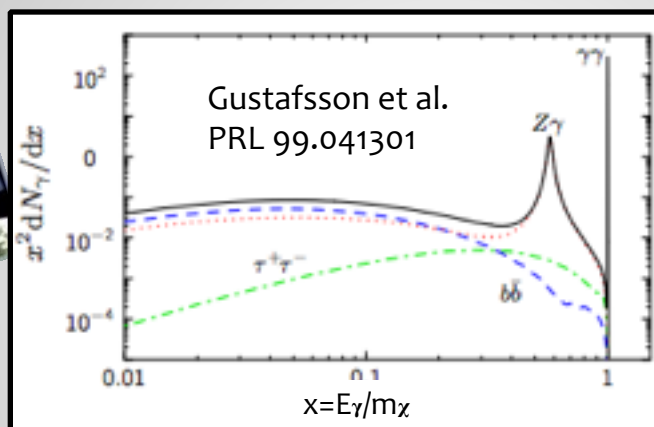
$$\Phi(E, \psi) = \frac{1}{4\pi} \frac{\langle \sigma_{\chi} v \rangle}{2m_{\chi}^2} N(E)$$

cross section
mass
detected particles



# Indirect Searches

**Observed** = **Particle Properties** x **Astrophysics Properties**



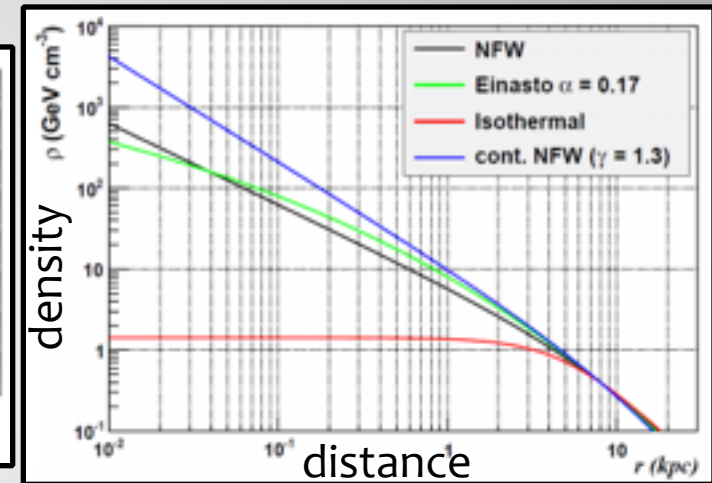
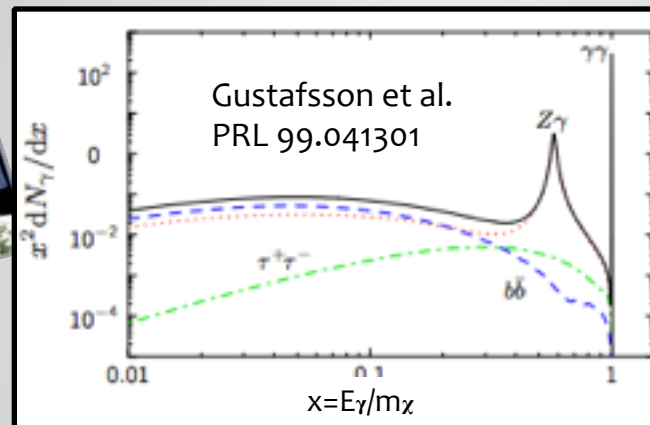
$$\Phi(E, \psi) = \frac{1}{4\pi} \frac{\langle \sigma_{\chi} v \rangle}{2m_{\chi}^2} N(E) \times J(\psi)$$

cross section
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# Indirect Searches

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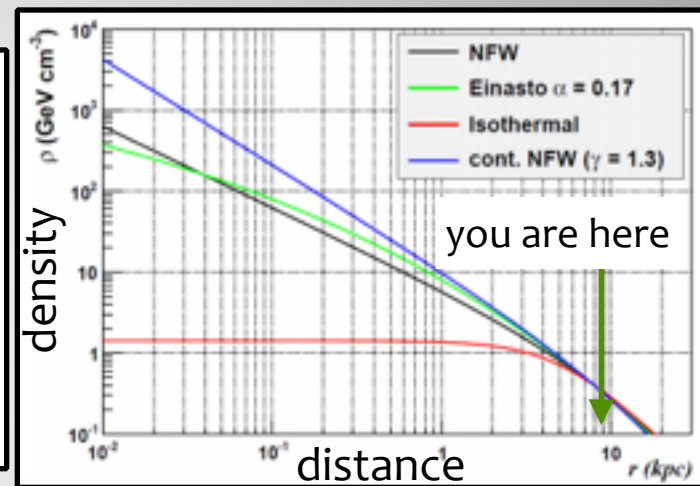
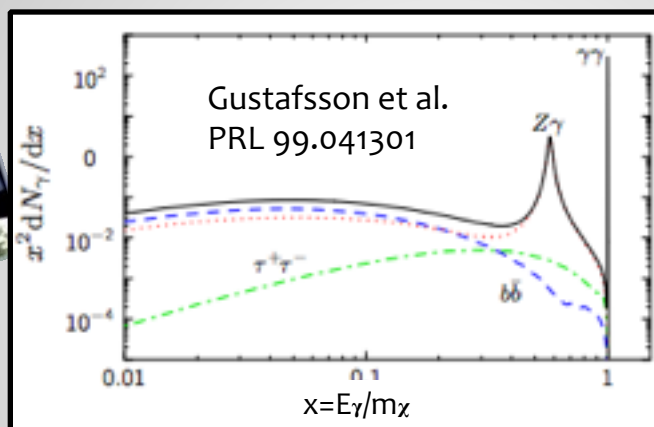
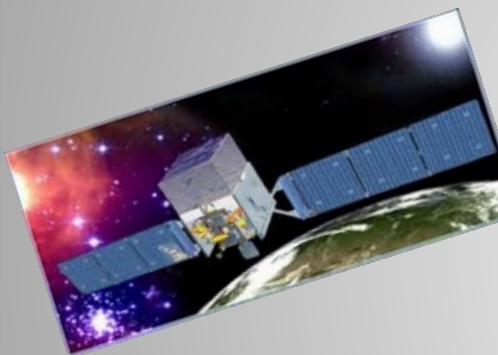
$$\Phi(E, \psi) = \frac{1}{4\pi} \frac{\langle \sigma_{\chi} v \rangle}{2m_{\chi}^2} N(E) \times J(\psi)$$

cross section (pointing to  $\langle \sigma_{\chi} v \rangle$ )  
 mass (pointing to  $m_{\chi}$ )  
 detected particles (pointing to  $N(E)$ )  
 J-Factor:  $\sim \int \rho^2$  (solid angle, line of sight) (pointing to  $J(\psi)$ )



# Indirect Searches

**Observed** = **Particle Properties** x **Astrophysics Properties**

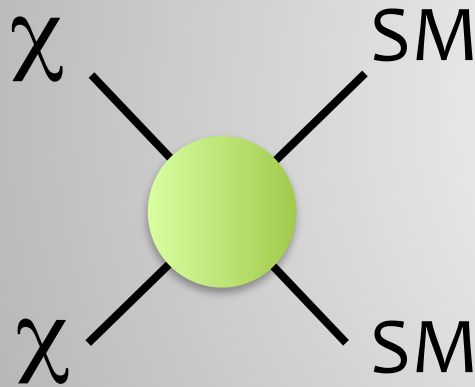


$$\Phi(E, \psi) = \frac{1}{4\pi} \frac{\langle \sigma_{\chi} v \rangle}{2m_{\chi}^2} N(E) \times J(\psi)$$

cross section  $\rightarrow \langle \sigma_{\chi} v \rangle$   
 mass  $\rightarrow m_{\chi}$   
 detected particles  $\rightarrow N(E)$   
 J-Factor:  $\sim \int \rho^2$  (solid angle, line of sight)  $\rightarrow J(\psi)$



# Indirect Searches

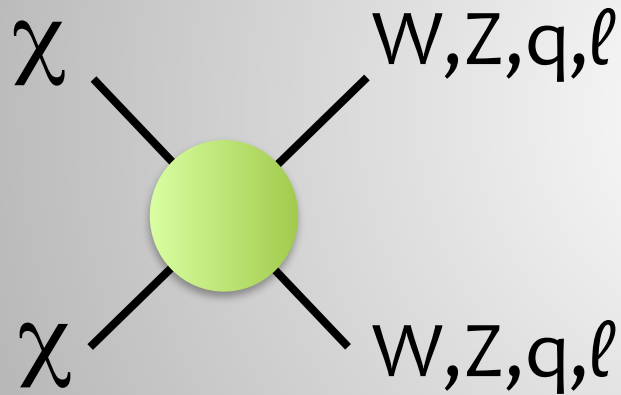






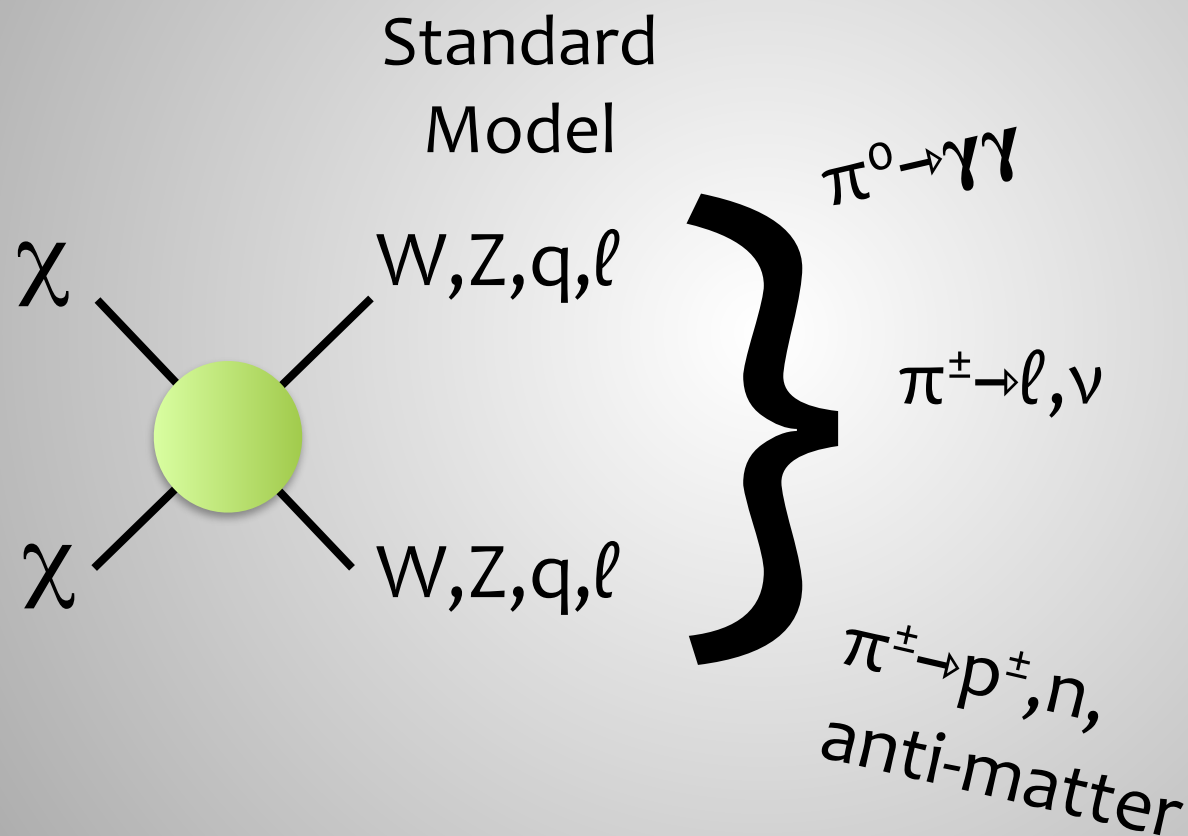
# Indirect Searches

Standard  
Model



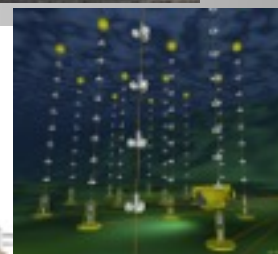
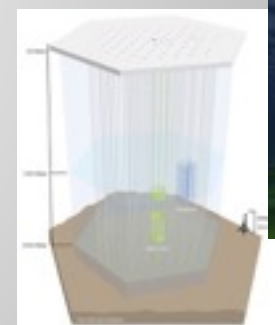
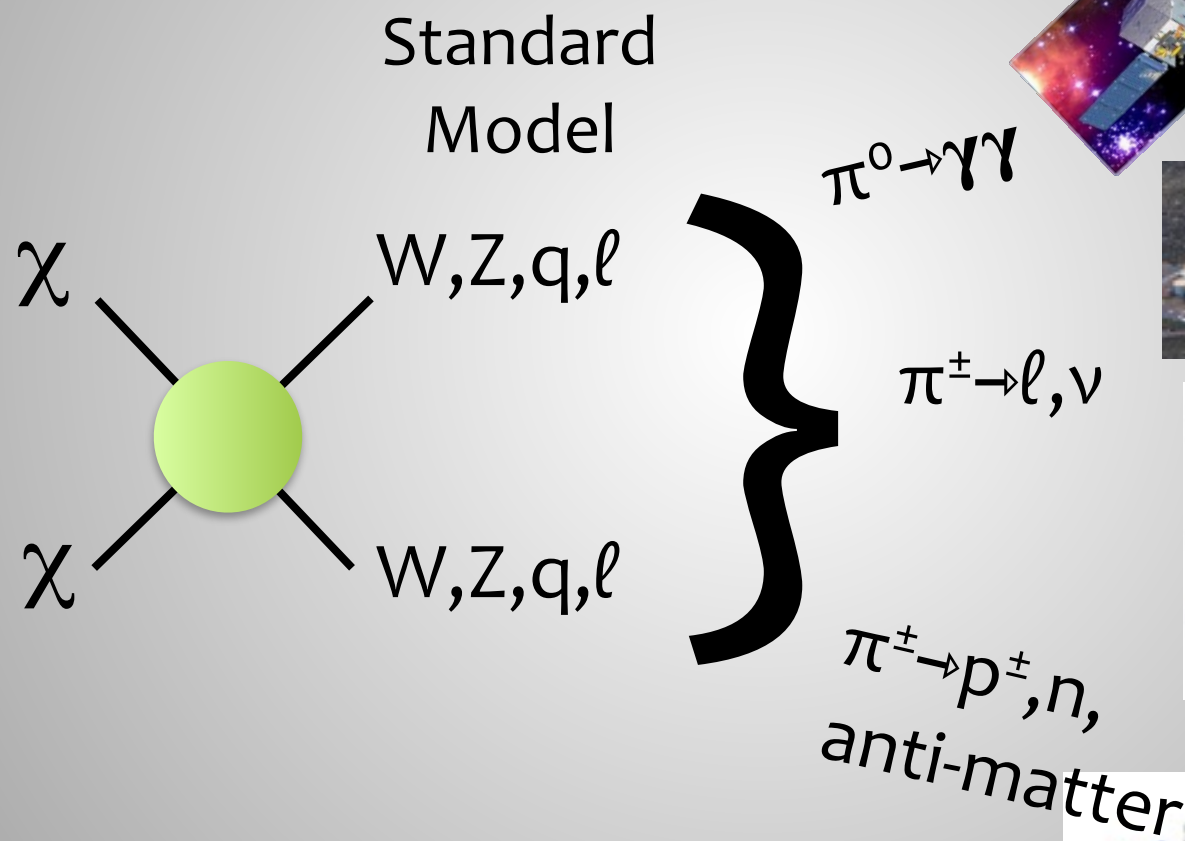


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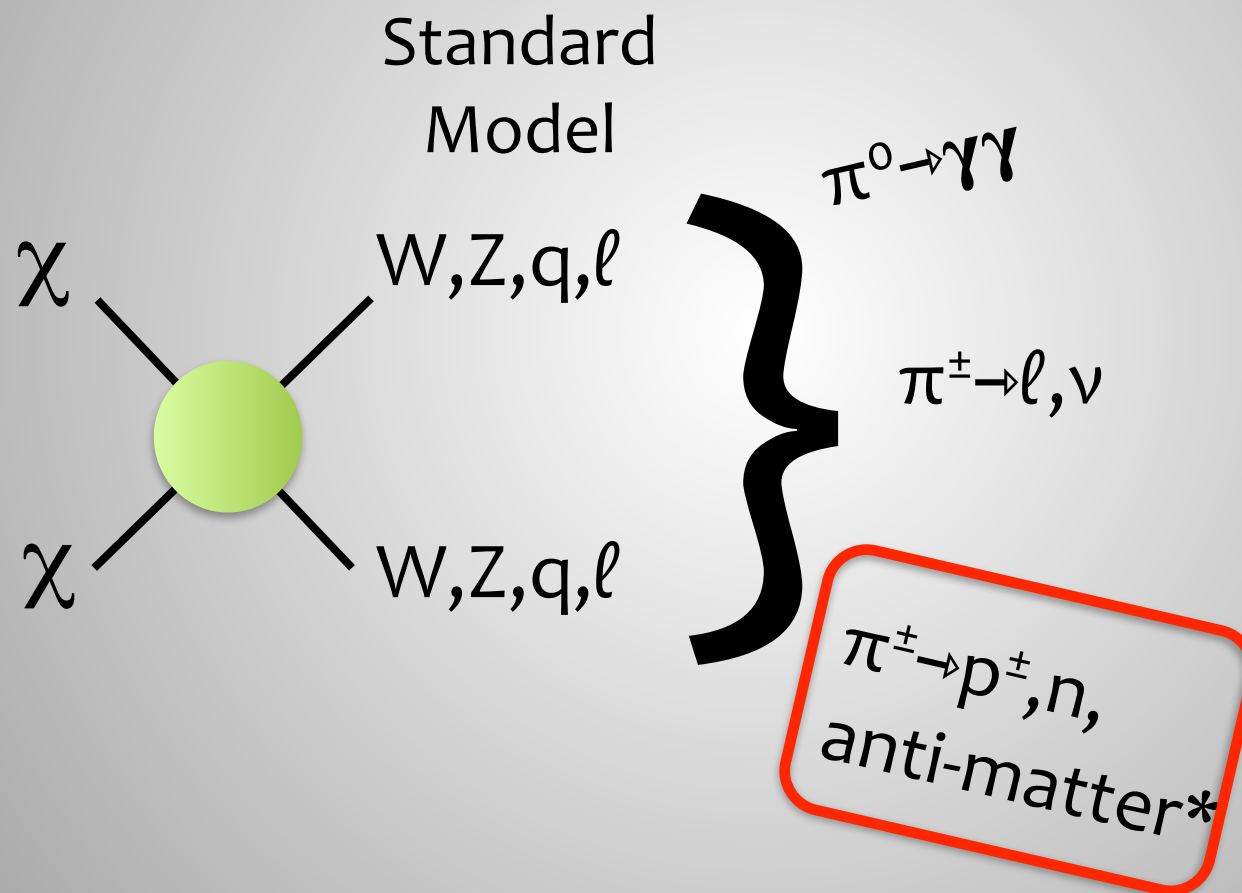


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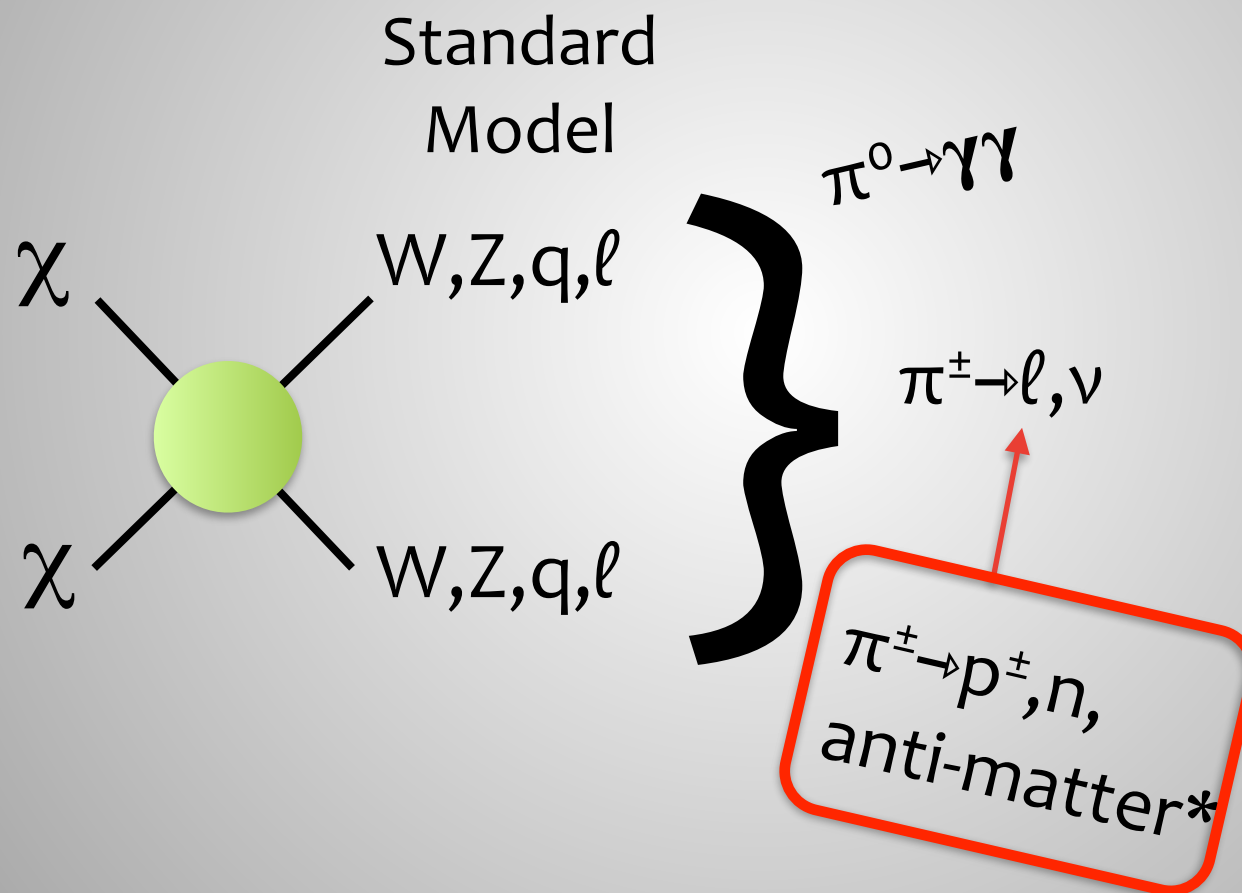


# Indirect Searches: cosmic rays





# Indirect Searches: cosmic rays



\*charged



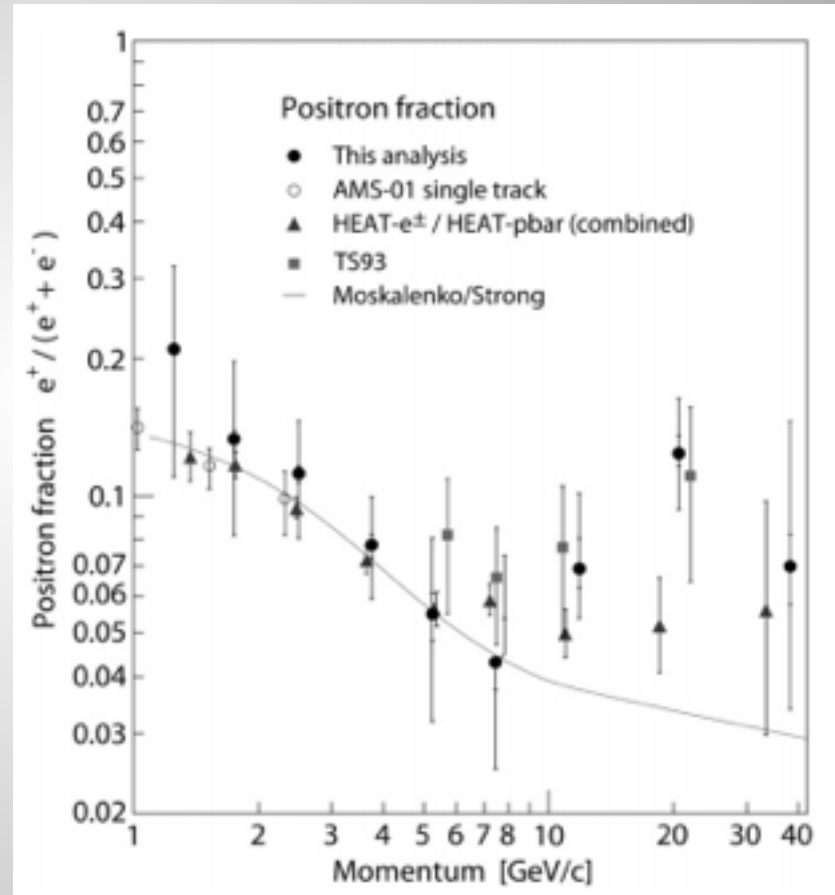


# Indirect Searches: $e^+/e^-$ spectrum

TS93 (1996)  
CAPRICE (2001)

HEAT (2004)

AMS-01 (2007)



Phys Let B, 2007, 01, 024



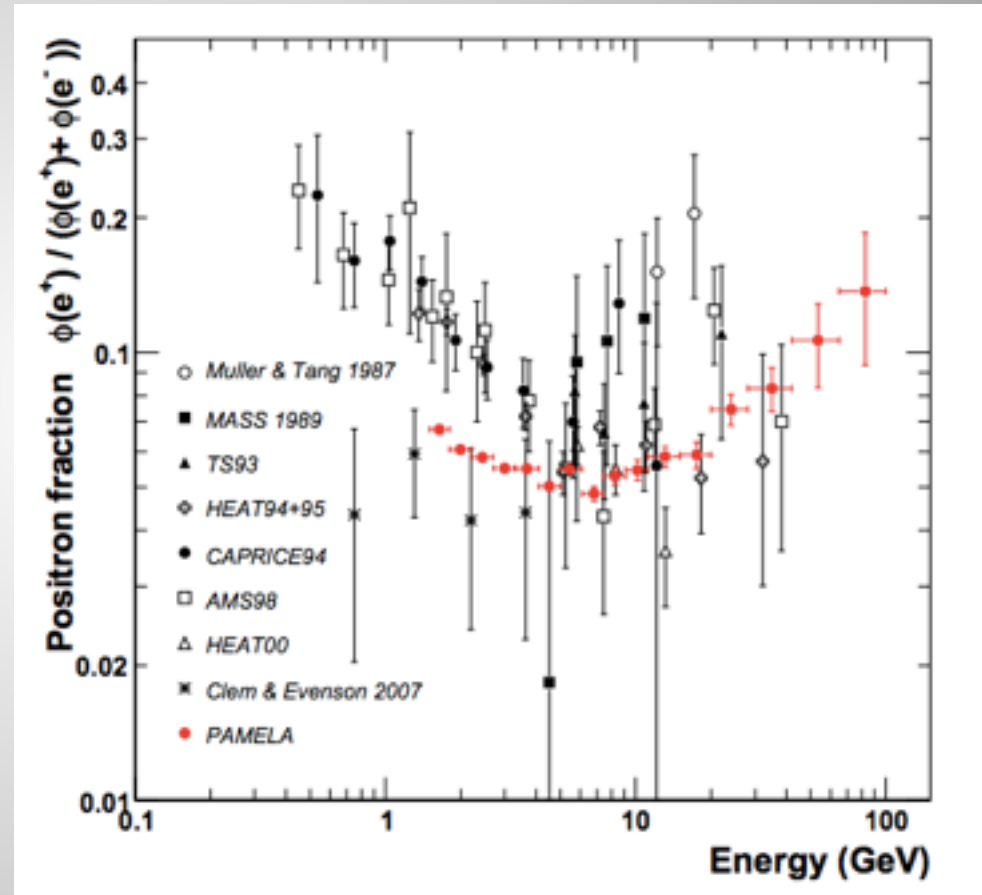
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Nature 458:607-609,2009



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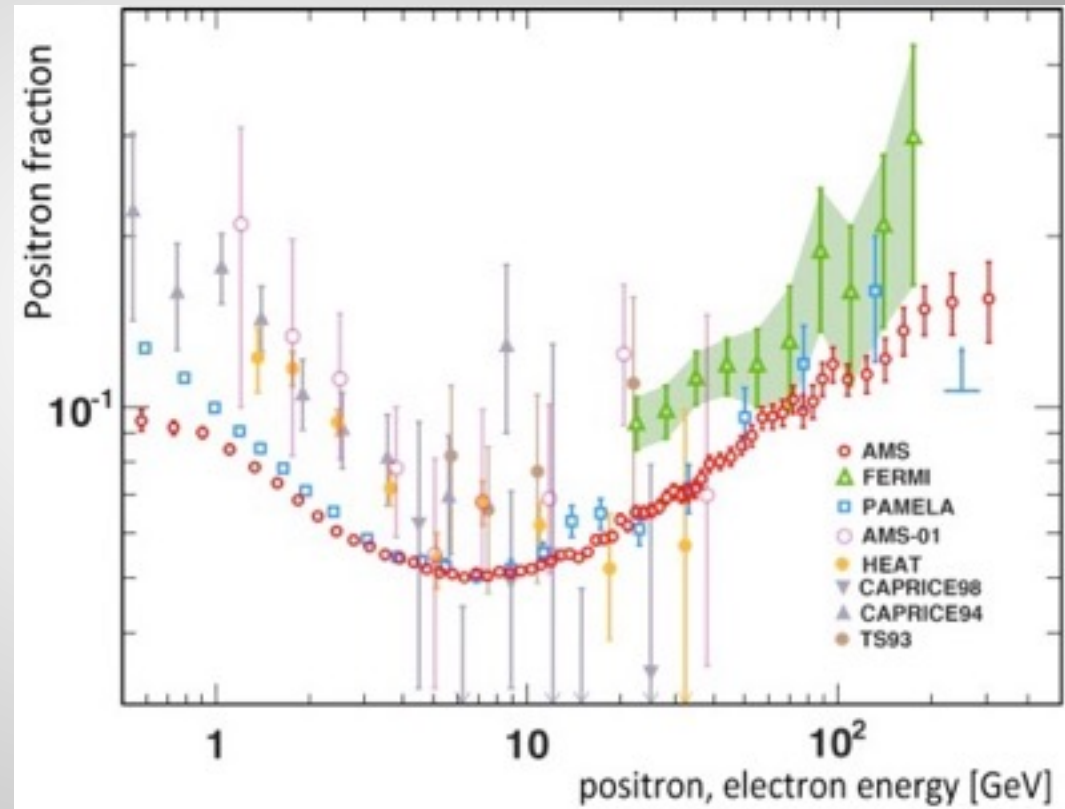
HEAT (2004)

AMS-01 (2007)

PAMELA (2008)

FERMI (2012)

AMS-2 (2013/14)





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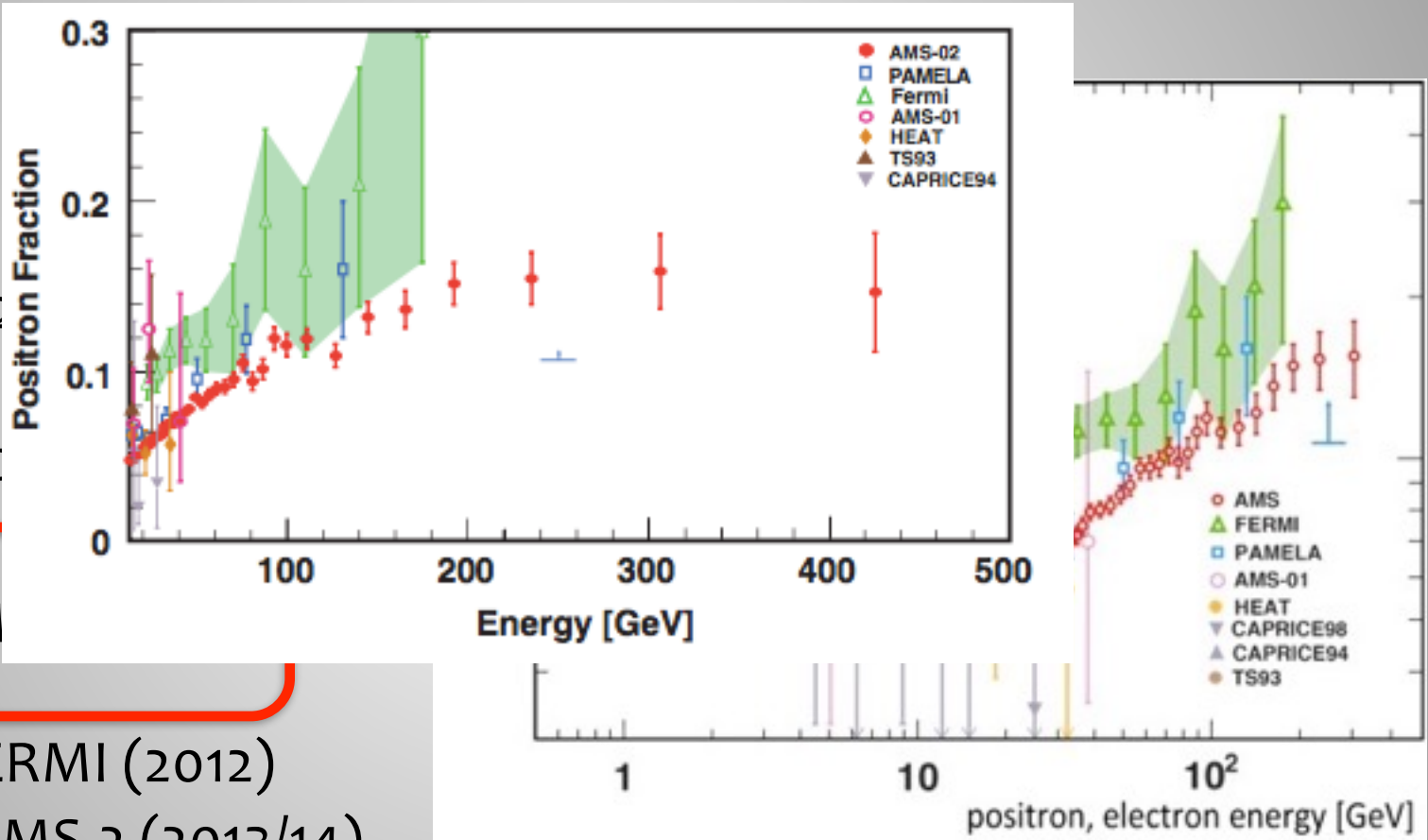
TS93 (1993)  
CAPRICE

HEAT (2003)

AMS-C

PAMELA

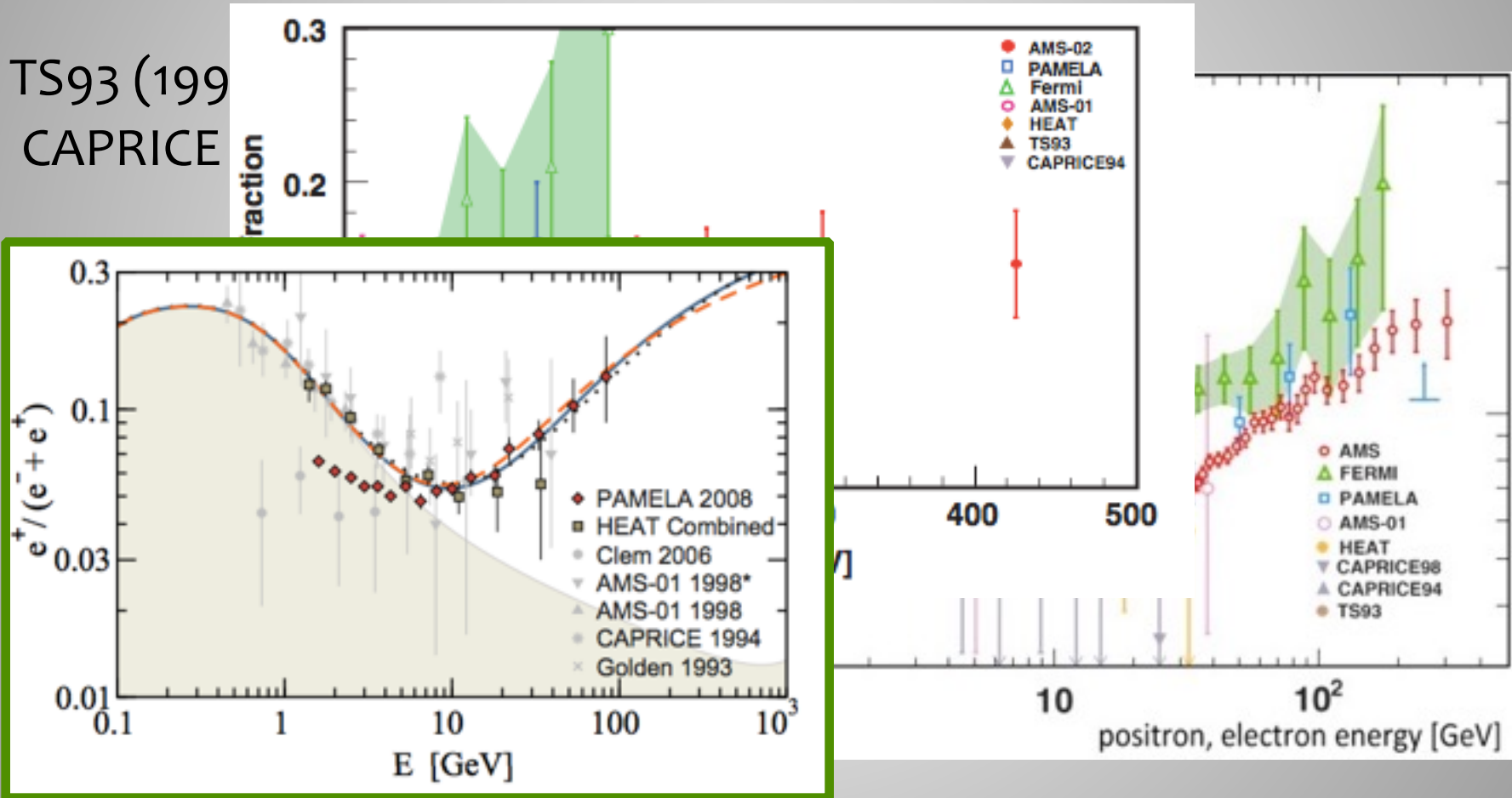
FERMI (2012)  
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Phys.Rev.Lett.103:051101,2009

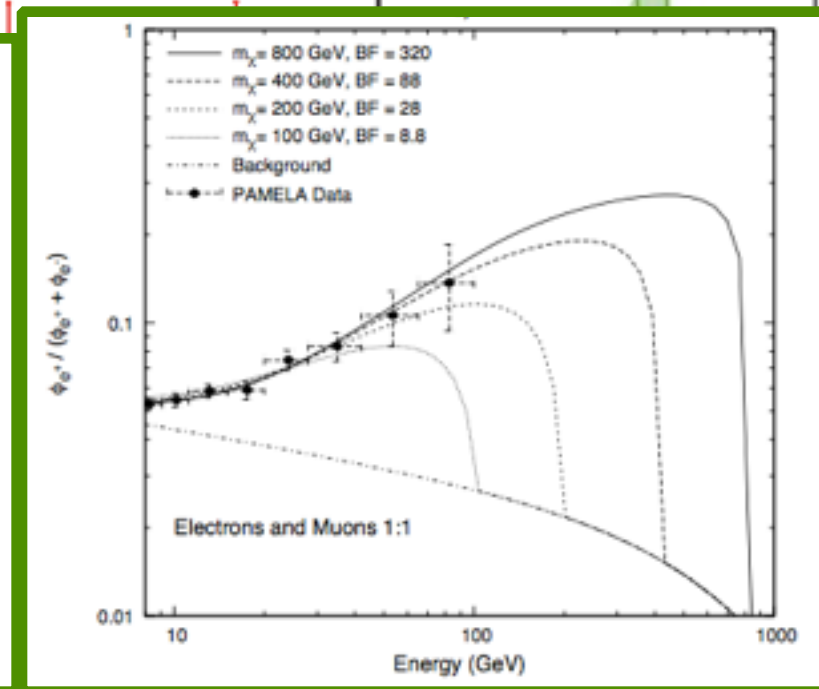
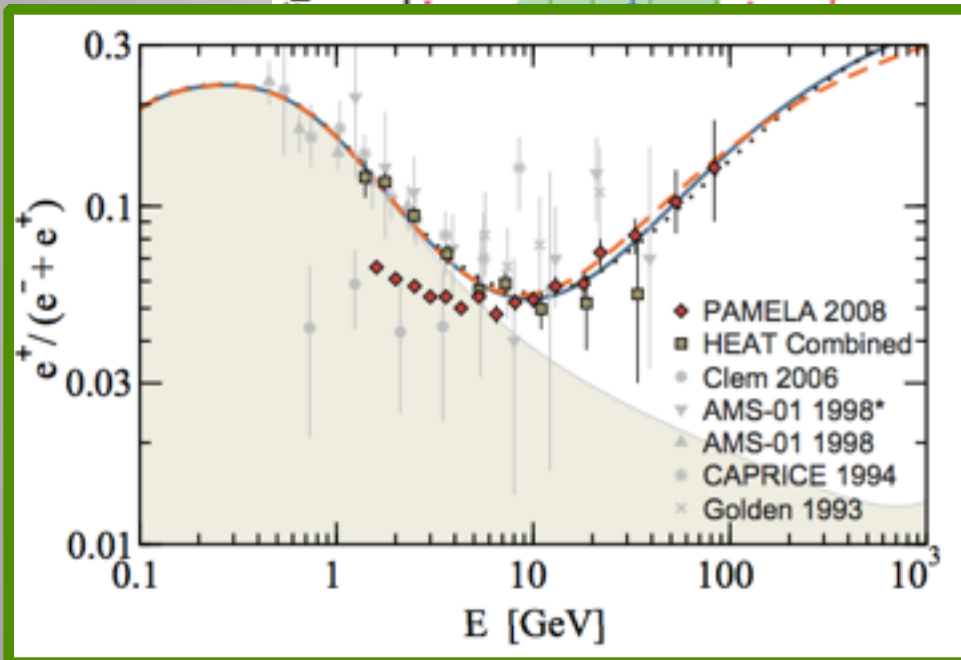
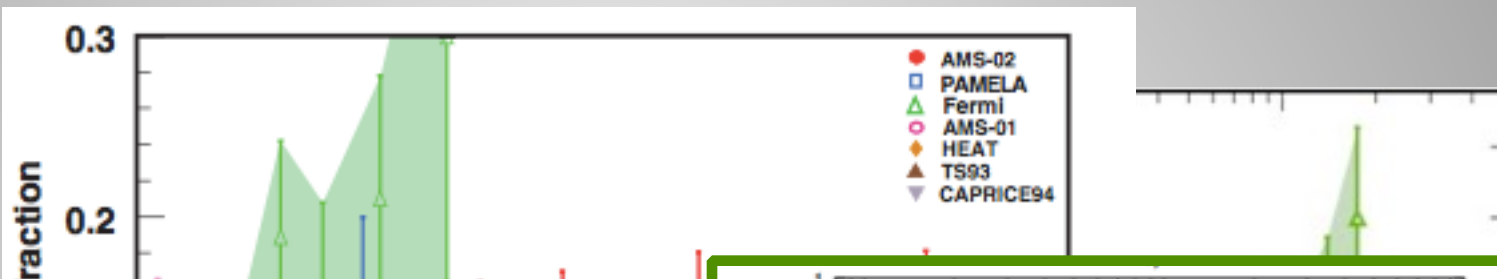
Could be pulsars...





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Phys.Rev.Lett.103:051101,2009

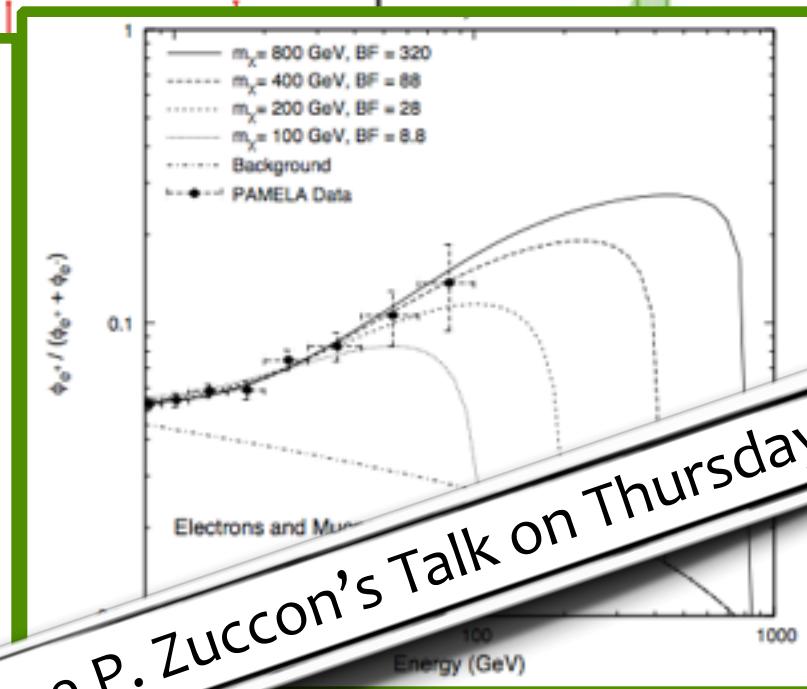
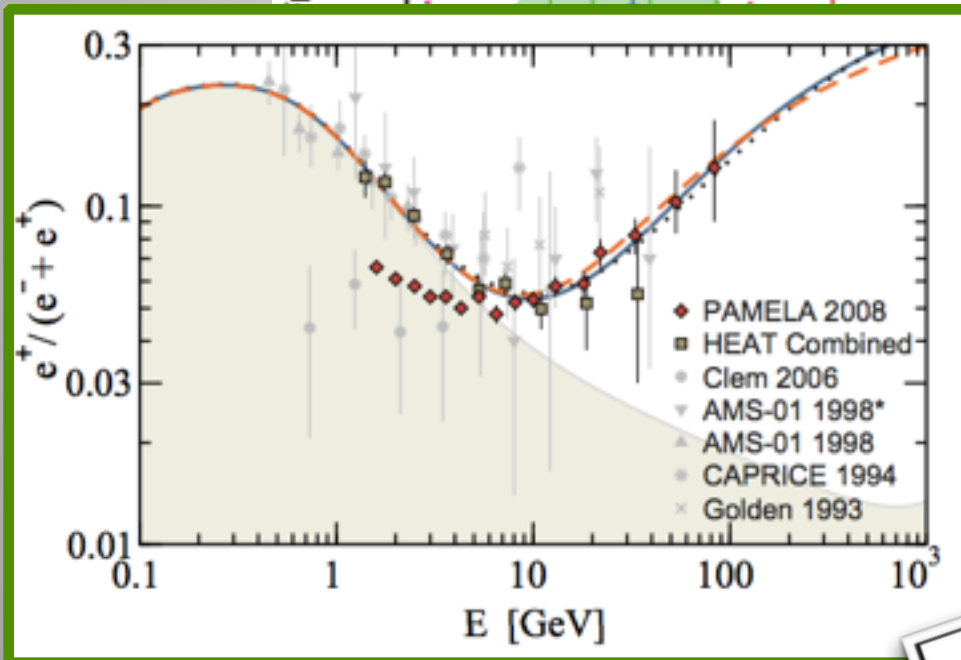
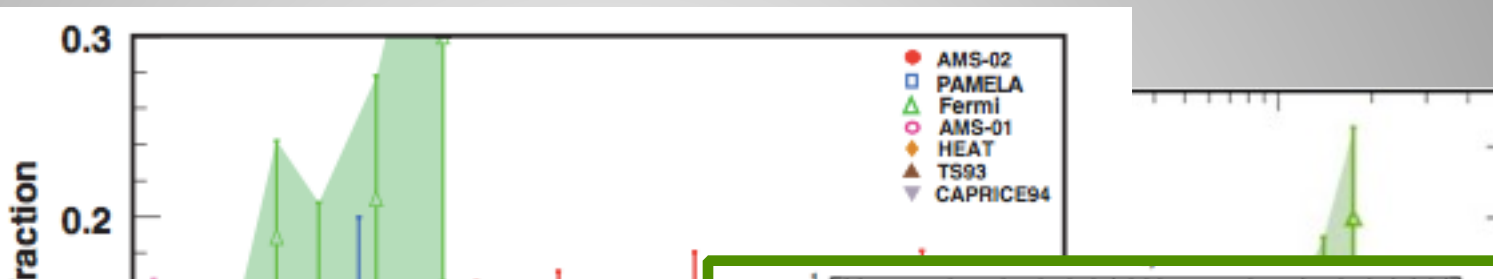
JCAP 0912:007,2009

Could be pulsars... Could be DM...



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Phys.Rev.Lett.103:051101,2009

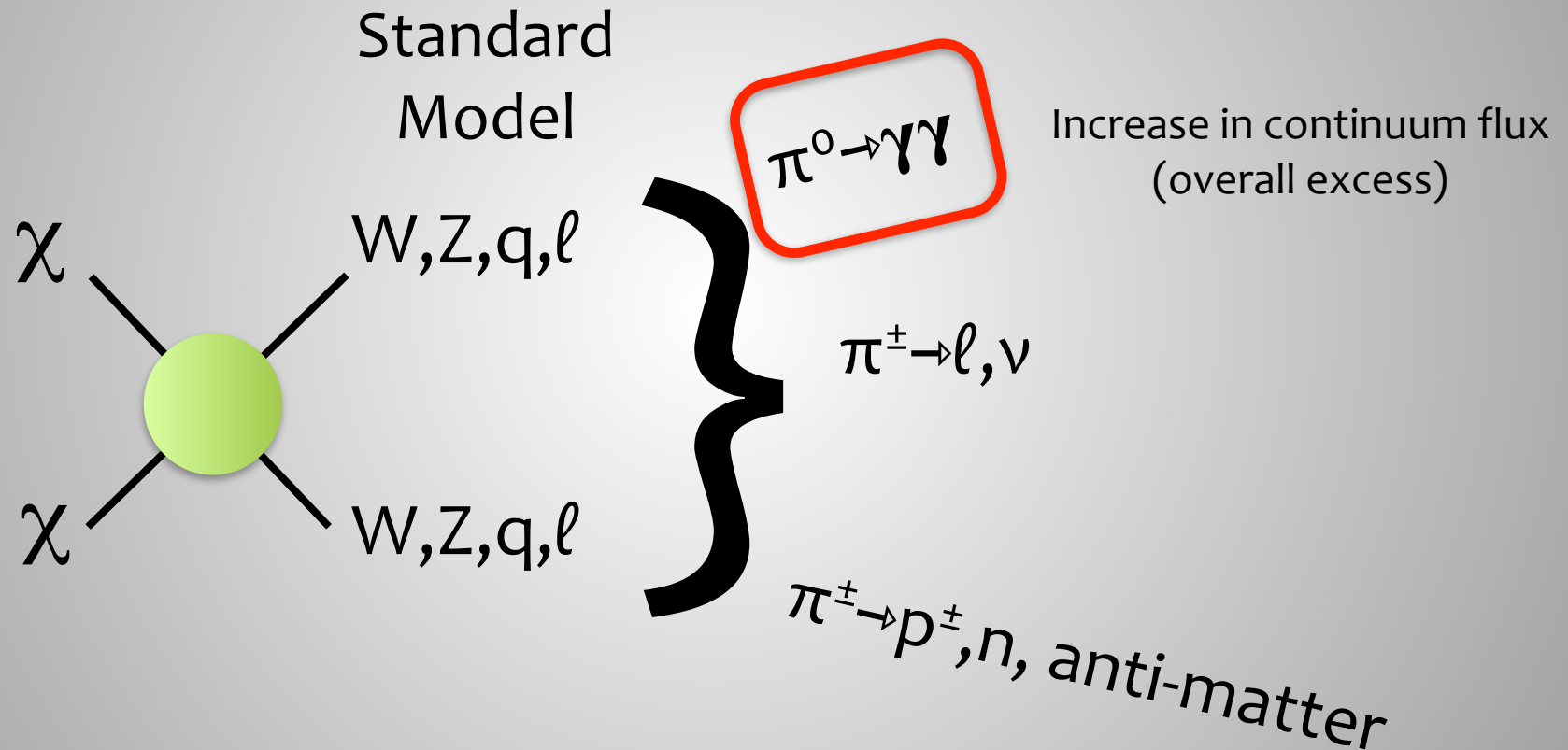
JCAP 0912:007,2009

See P. Zuccon's Talk on Thursday

Could be pulsars... Could be DM...

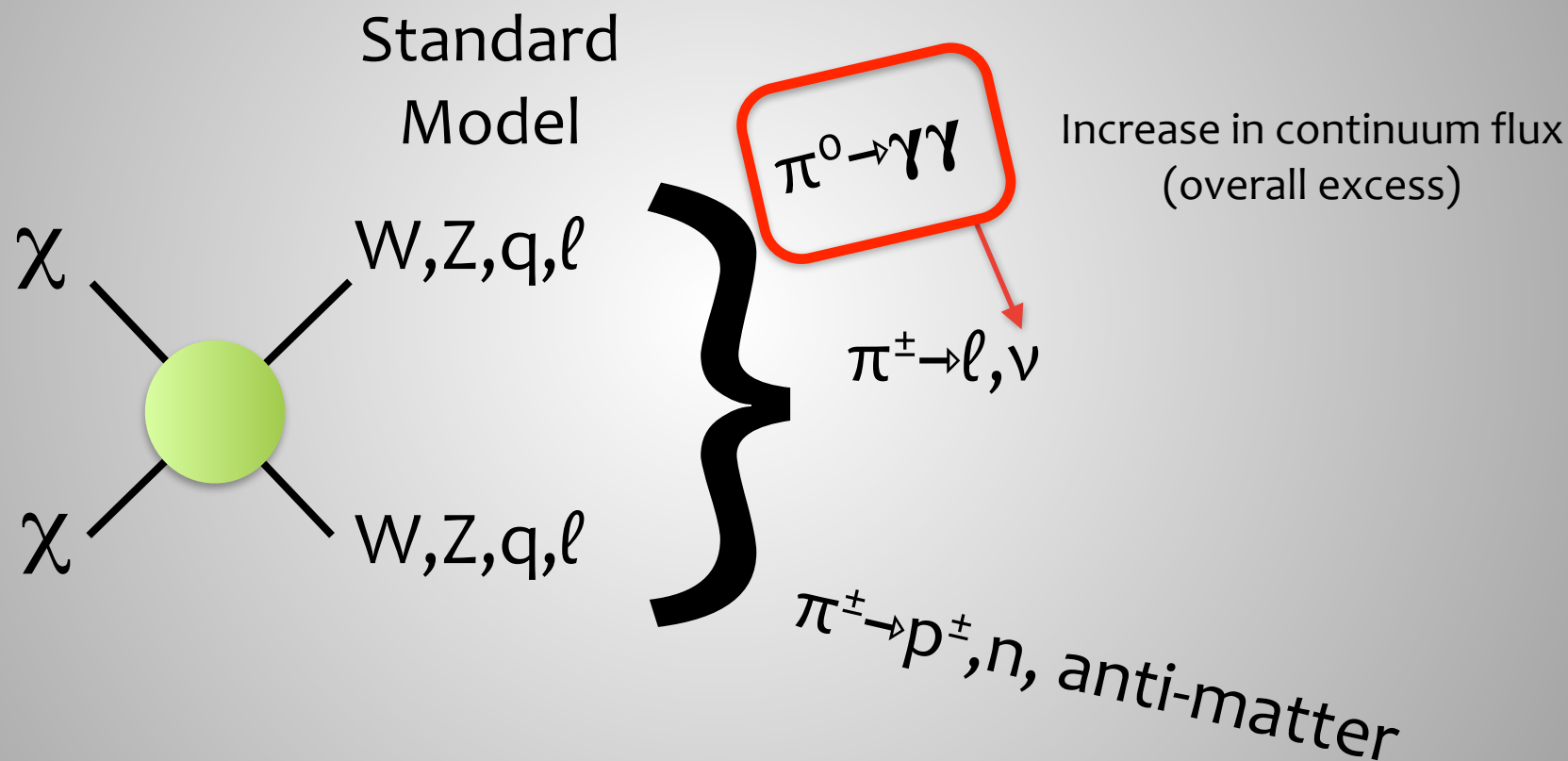


# Indirect Searches: neutral particles





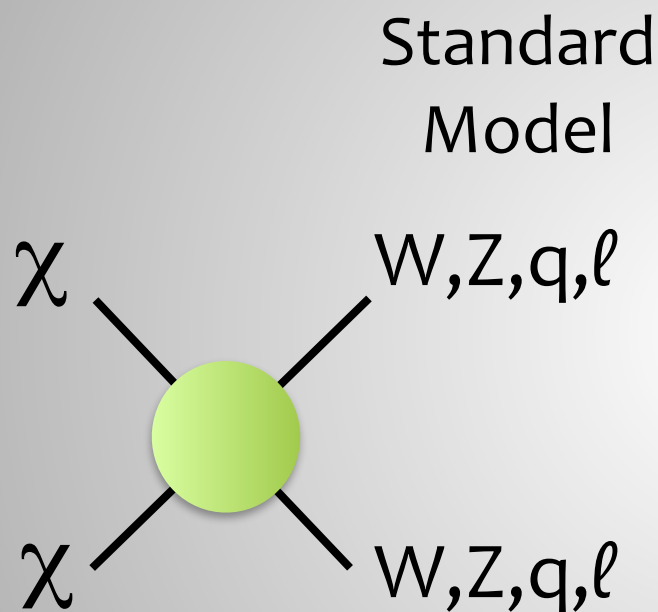
# Indirect Searches: neutral particles



**\*\* Point back to Source \*\***

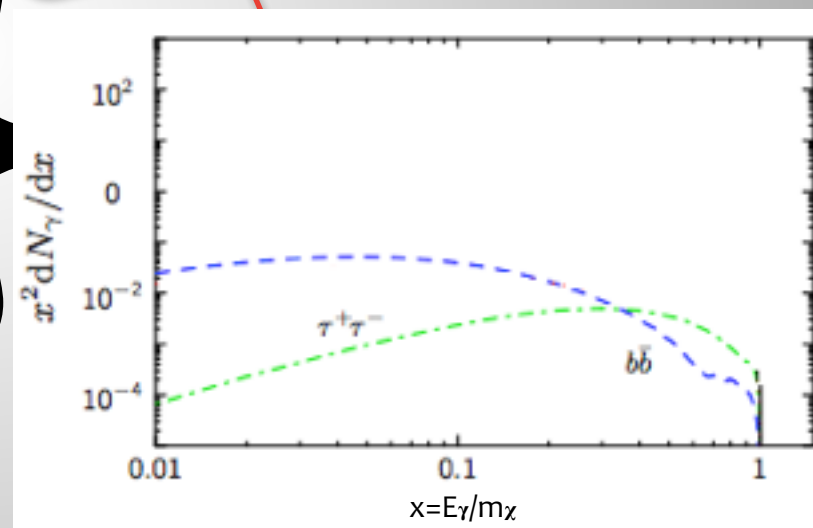


# Indirect Searches: neutral particles



$$\pi^0 \rightarrow \gamma\gamma$$

Increase in continuum flux  
(overall excess)



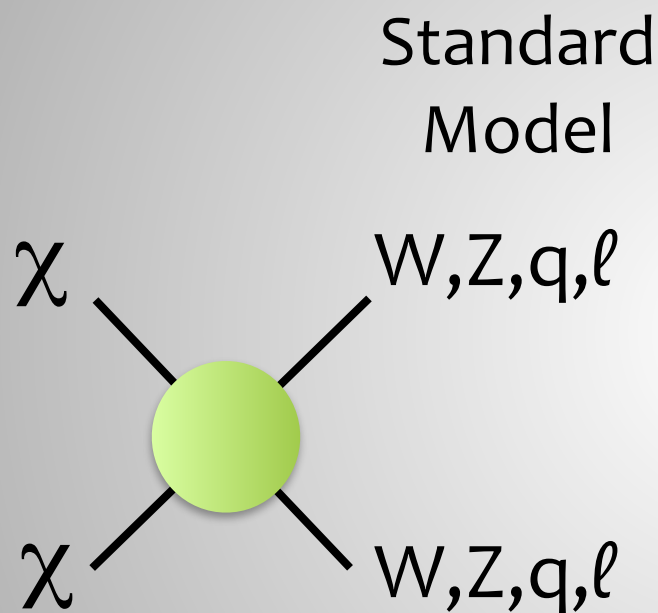
Gustafsson et al.  
PRL 99.041301

**\*\* Point back to Source \*\***



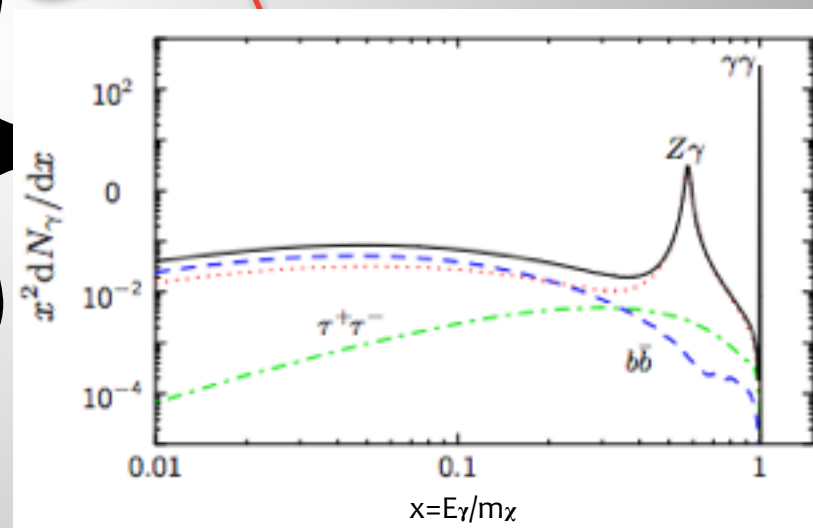


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$$\pi^0 \rightarrow \gamma\gamma$$

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(overall excess)



Gustafsson et al.  
PRL 99.041301

**\*\* Point back to Source \*\***



# $\gamma$ -ray Observatories



## Space Based Telescopes

Fermi  $\gamma$ -ray space  
telescope  
20 MeV to  $>300$  GeV



## Air Cherenkov Telescopes

VERITAS Array, H.E.S.S., Magic  
85 GeV - 50 TeV      30 GeV - 30 TeV  
30 GeV - 100 TeV

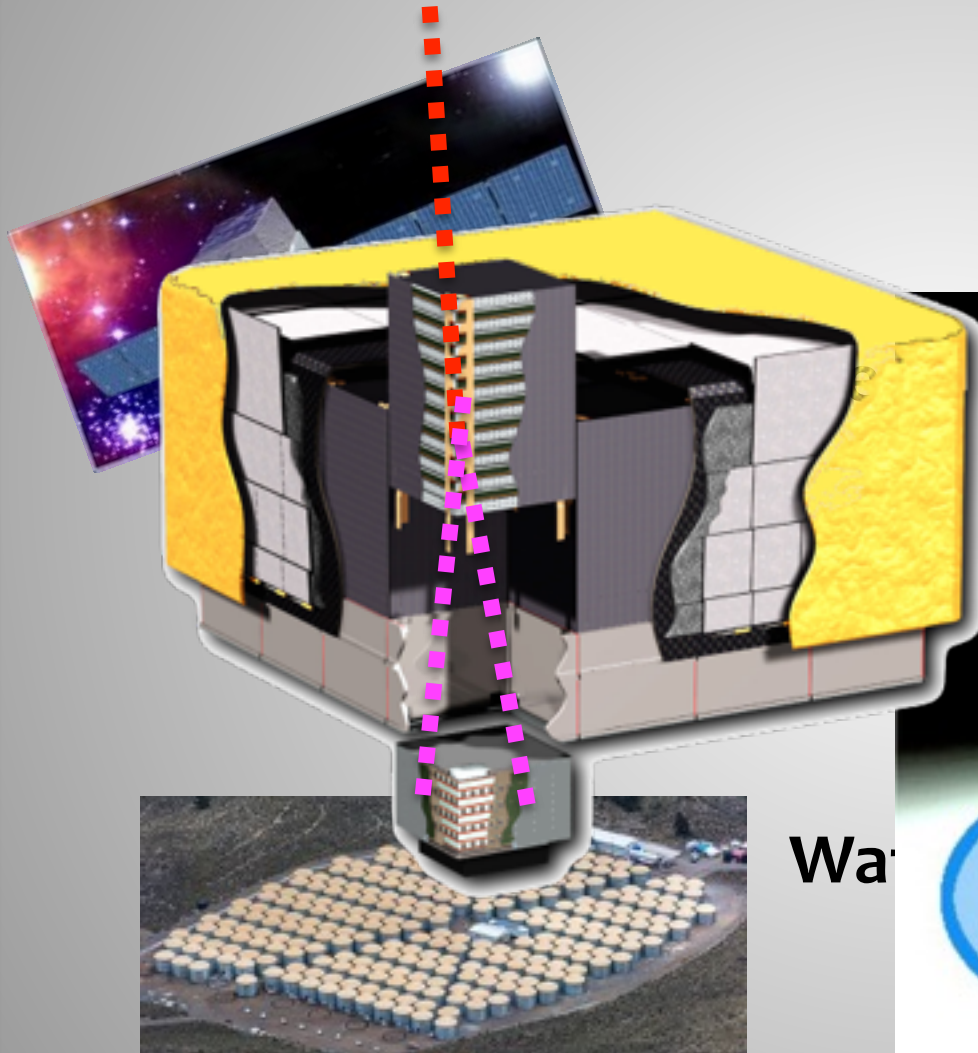


## Water Cherenkov Telescopes

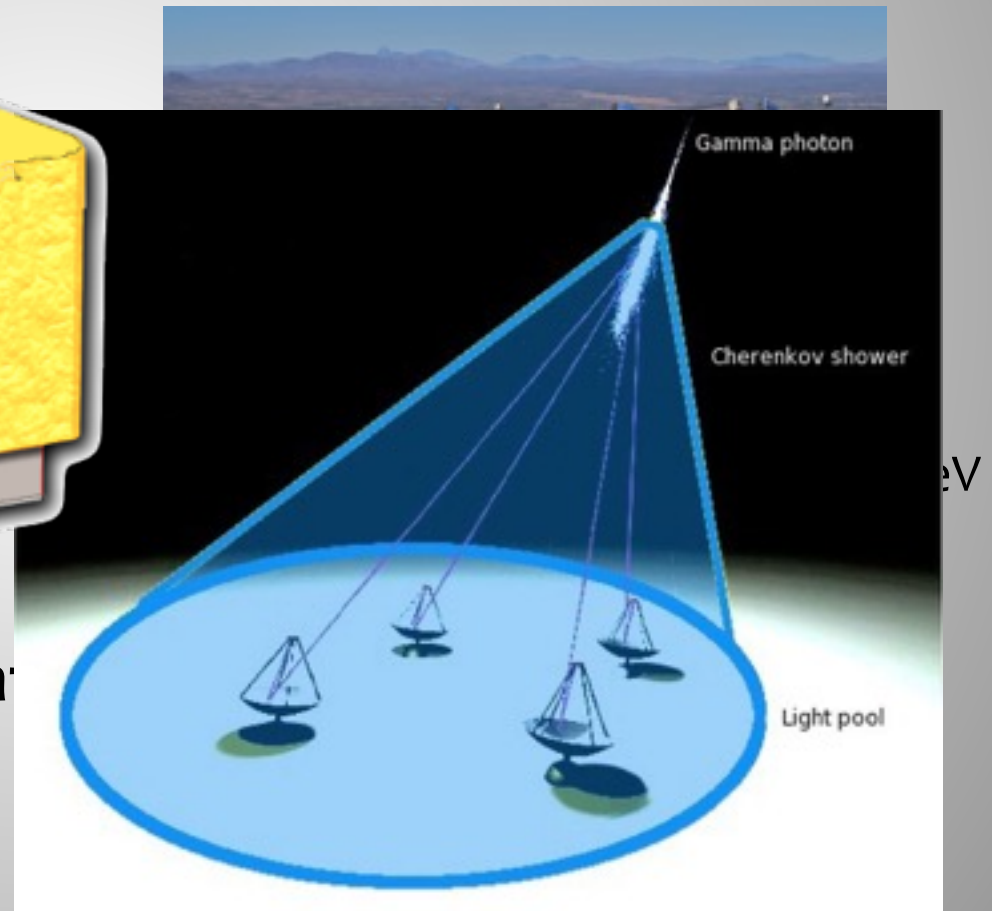
HAWC  
50 GeV -  $>100$  TeV



# $\gamma$ -ray Observatories



Water



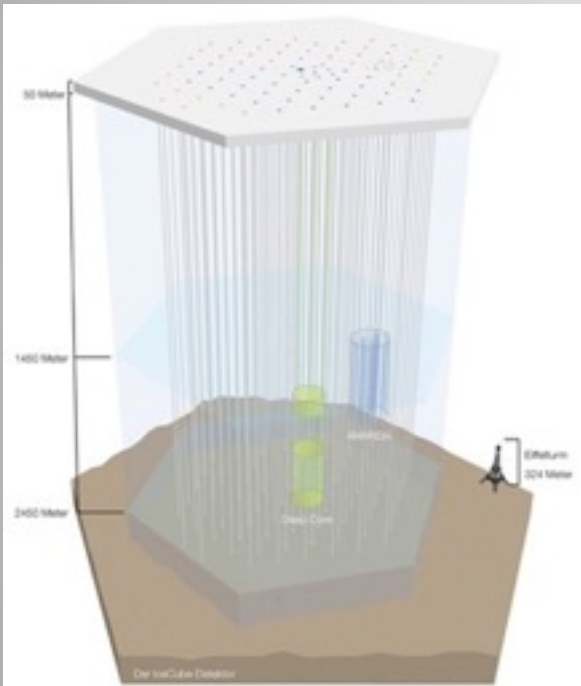
GeV



# Neutrino Observatories

## IceCube Neutrino Observatory

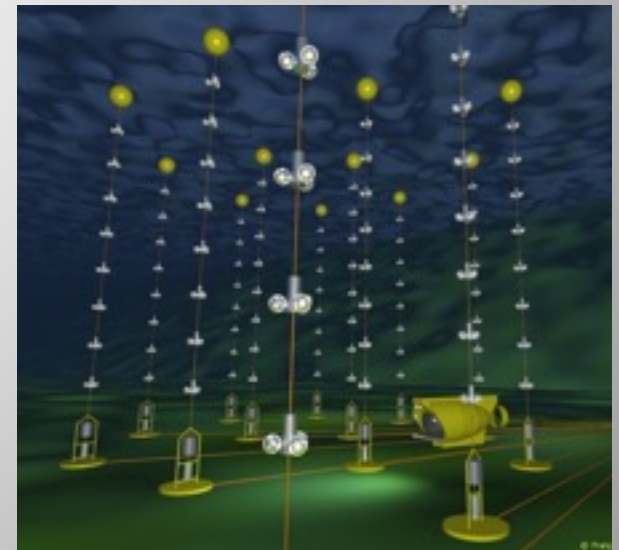
100 GeV - 1 EeV



## Antares

Neutrino Observatory

100 GeV - PeVs

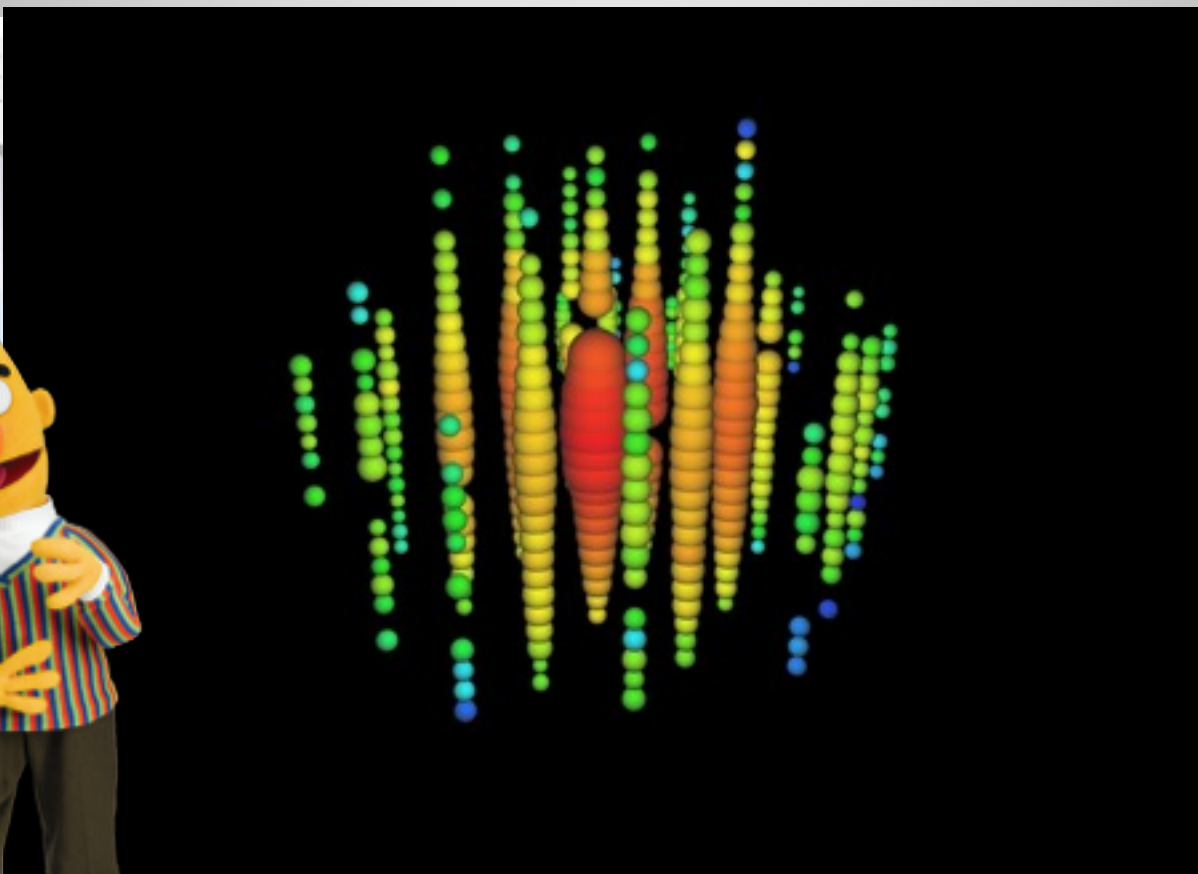






# Neutrino Observatories

## IceCube Neutrino



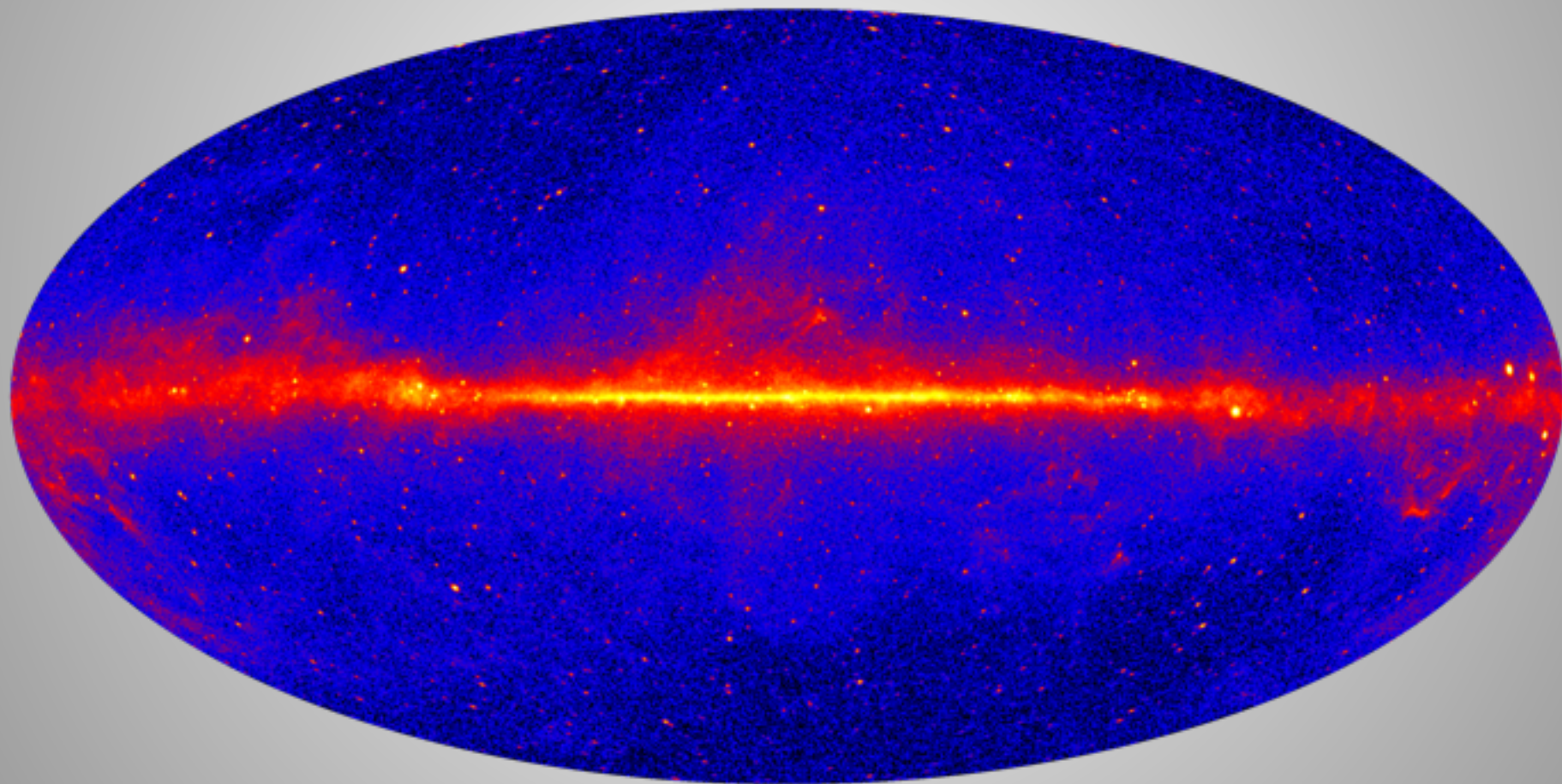
Neutrino Observatory

100 GeV - PeVs





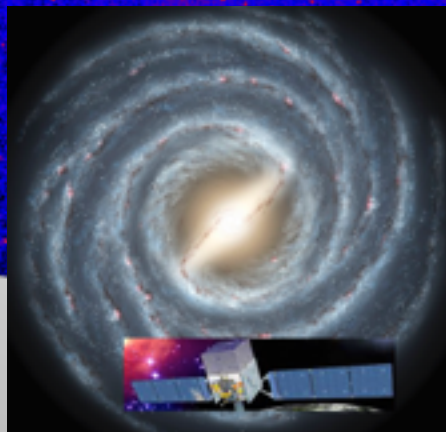
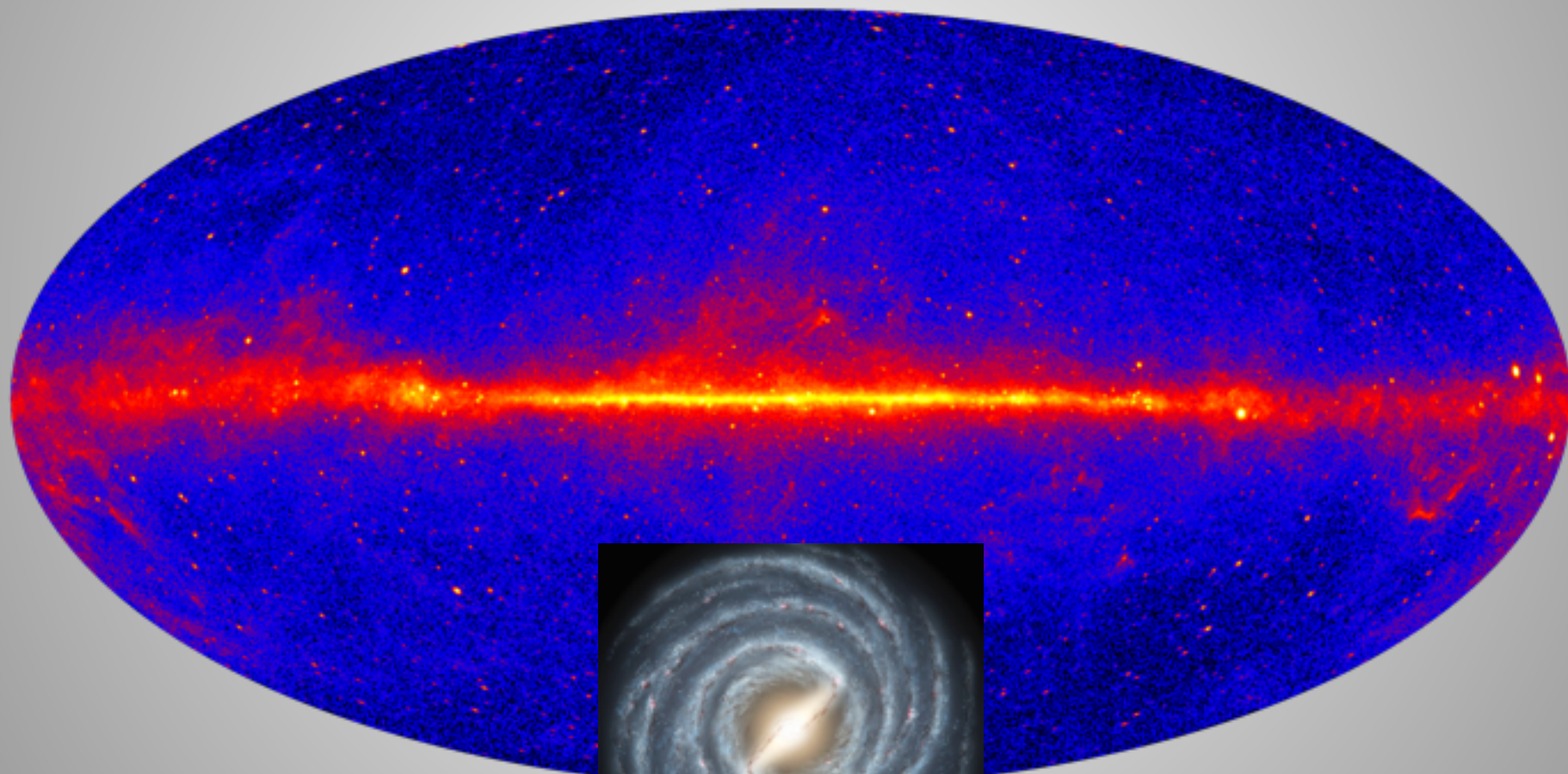
# Fermi-LAT $\gamma$ -ray sky



>1 GeV, 6 year map



# Fermi-LAT $\gamma$ -ray sky



>1 GeV, 6 year map





# Fermi-LAT $\gamma$ -ray sky

**Galactic Plane**

**Diffuse**

$\pi^0$  decay  
Bremsstrahlung  
Inverse Compton

**Point Sources**

**Dark Matter, Exotic Physics**

3FGL: Accepted ApJS



# Fermi-LAT $\gamma$ -ray sky

**Galactic Plane**

**Diffuse**

**Active Galactic Nuclei**

+ Supernova Remnants  
+ Globular Clusters  
+ Pulsar Wind Nebulae  
+ Starburst Galaxies + ...

**Pulsars**

**Point Sources**

**Dark Matter, Exotic Physics**

3FGL: Accepted ApJS

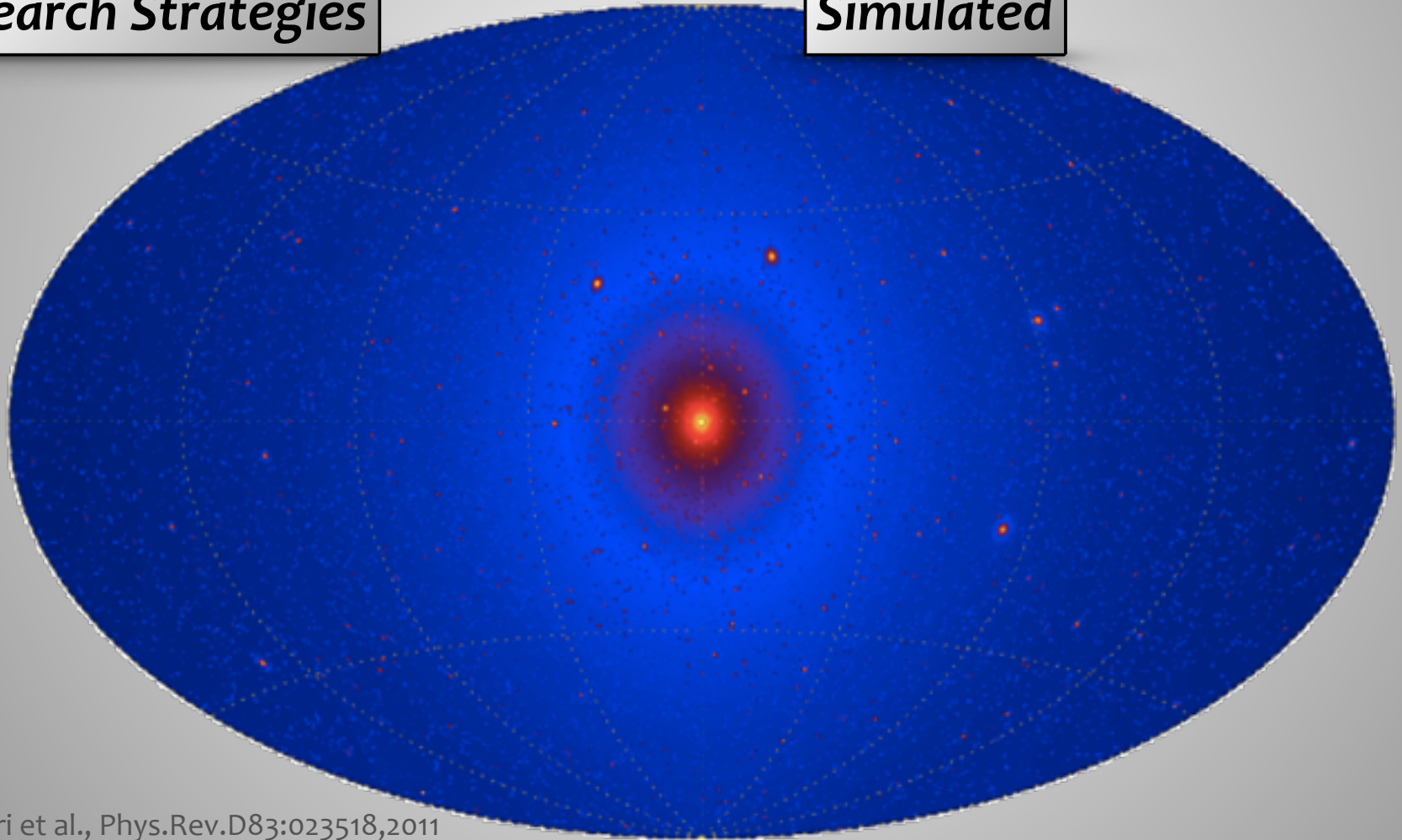




# Dark Matter Distribution

*Search Strategies*

*Simulated*



L. Pieri et al., Phys.Rev.D83:023518,2011

R. Caputo , UCSC | Mitchell Workshop 2015





# Dark Matter Distribution

**Search Strategies**

**Simulated**

**Dwarf Spheroidal  
Satellite Galaxies**

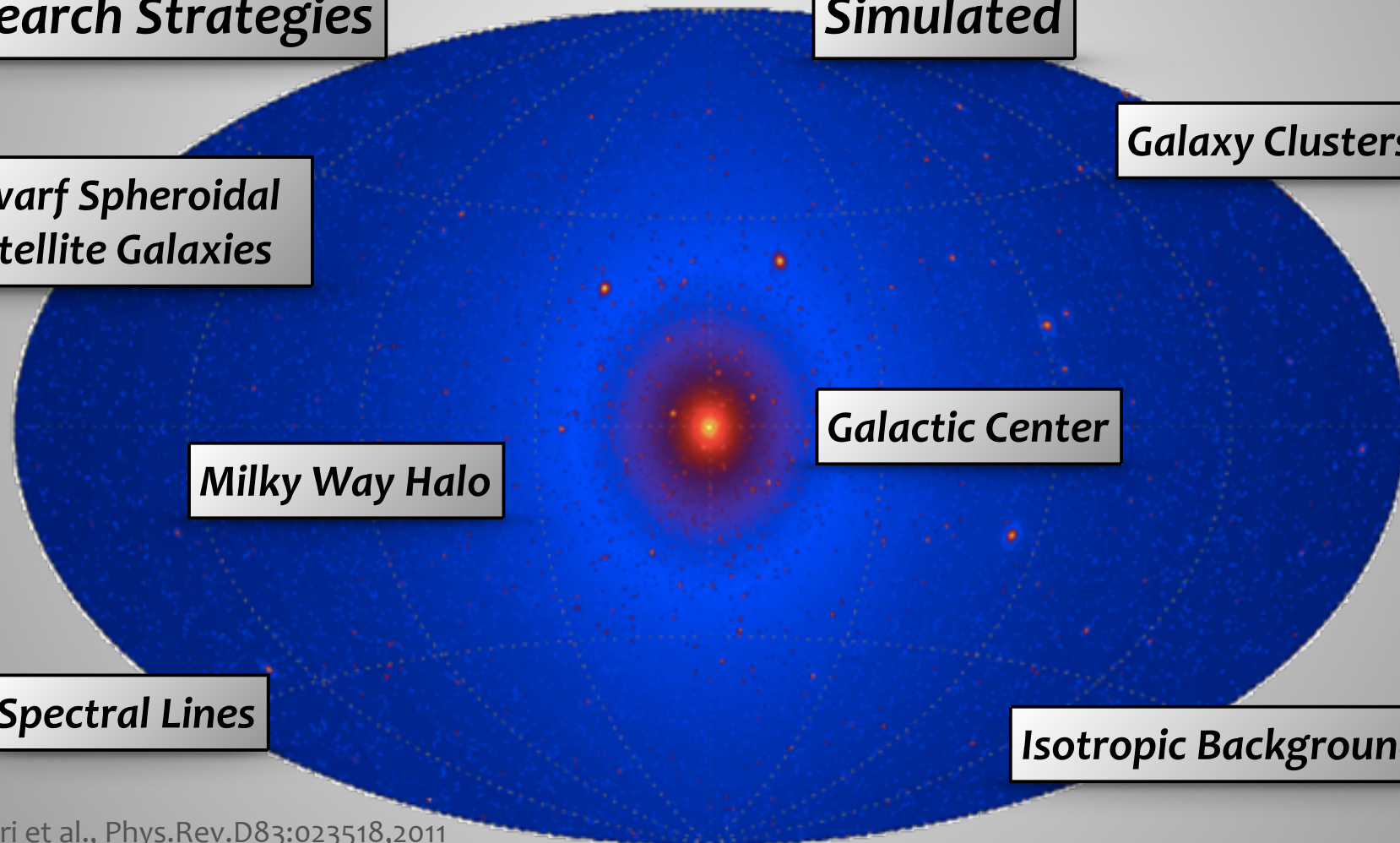
**Galaxy Clusters**

**Milky Way Halo**

**Galactic Center**

**Spectral Lines**

**Isotropic Background**



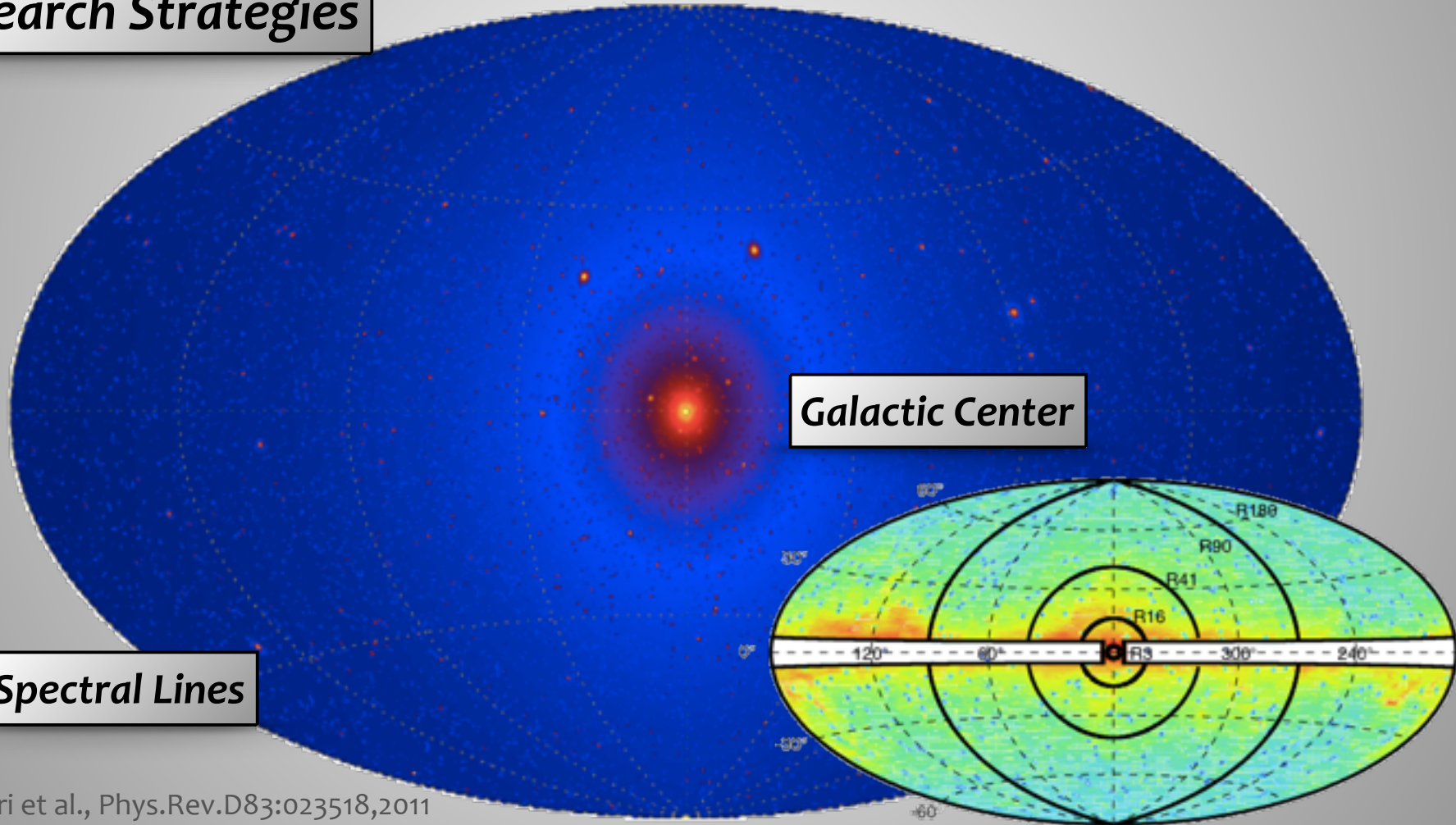


# Dark Matter Distribution

**Search Strategies**

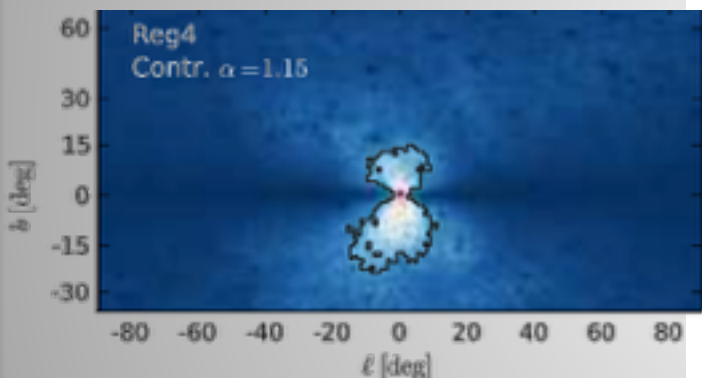
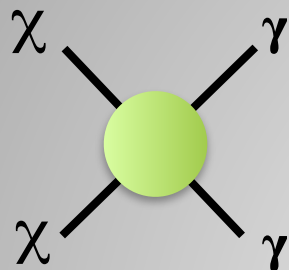
**Galactic Center**

**Spectral Lines**

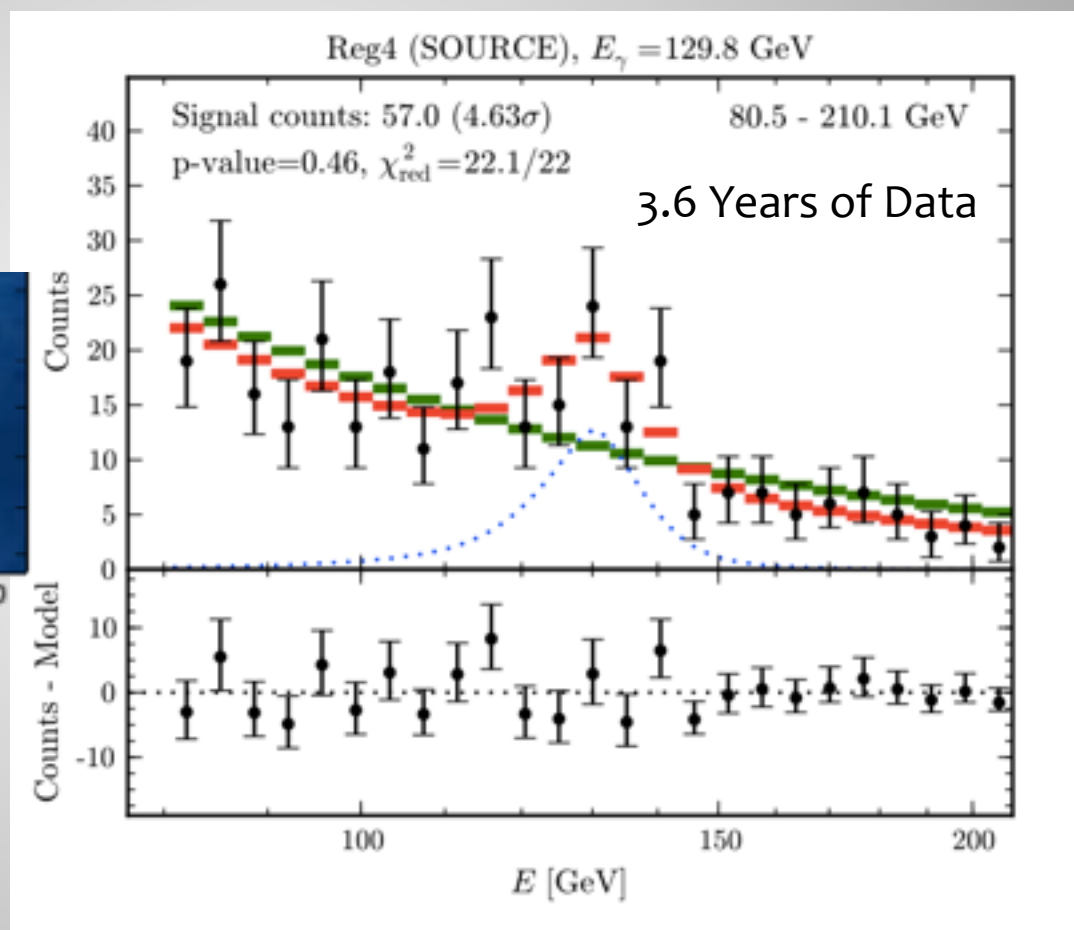




# $\gamma$ -ray Lines: 130 GeV Feature



- Cannot couple directly
  - loops required
- Lower branching fraction
  - $10^{-1} \sim 10^{-4}$

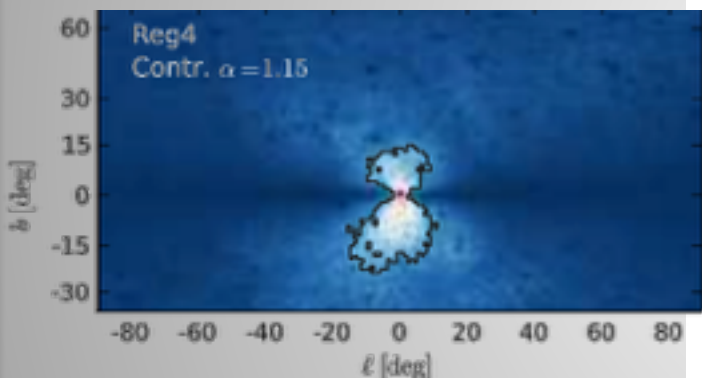
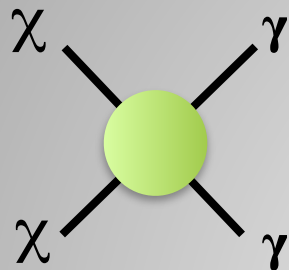


C. Weniger, Public Fermi-LAT data,  
 JCAP 1208 (2012) 007

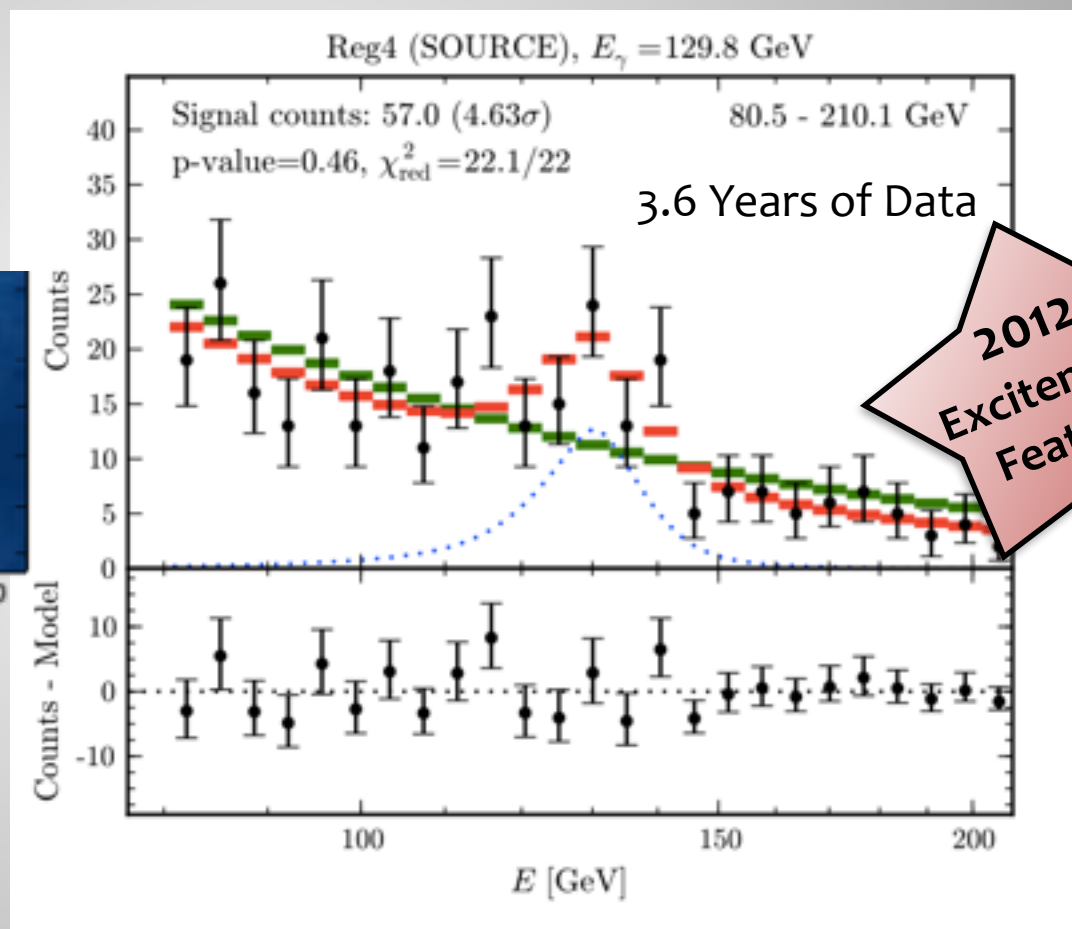




# $\gamma$ -ray Lines: 130 GeV Feature



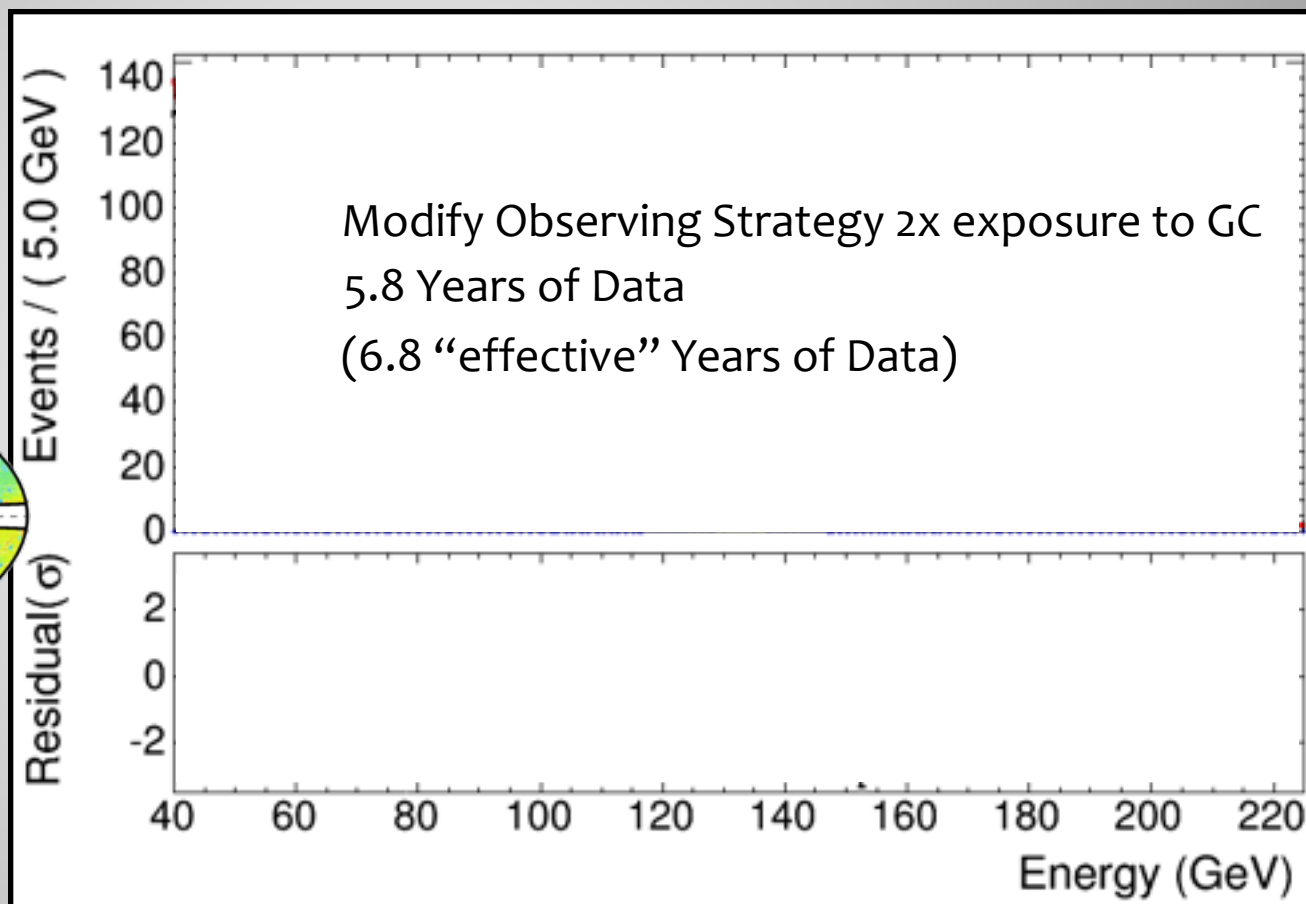
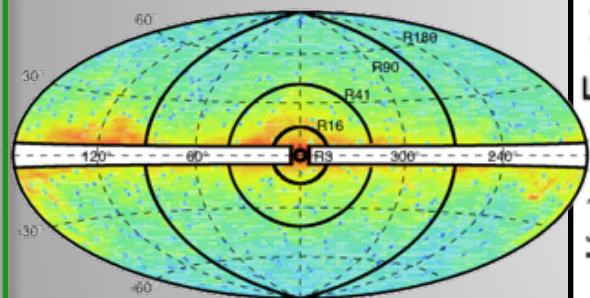
- Cannot couple directly
  - loops required
- Lower branching fraction
  - $10^{-1} \sim 10^{-4}$



C. Weniger, Public Fermi-LAT data,  
JCAP 1208 (2012) 007



# $\gamma$ -ray Lines: 130 GeV Feature

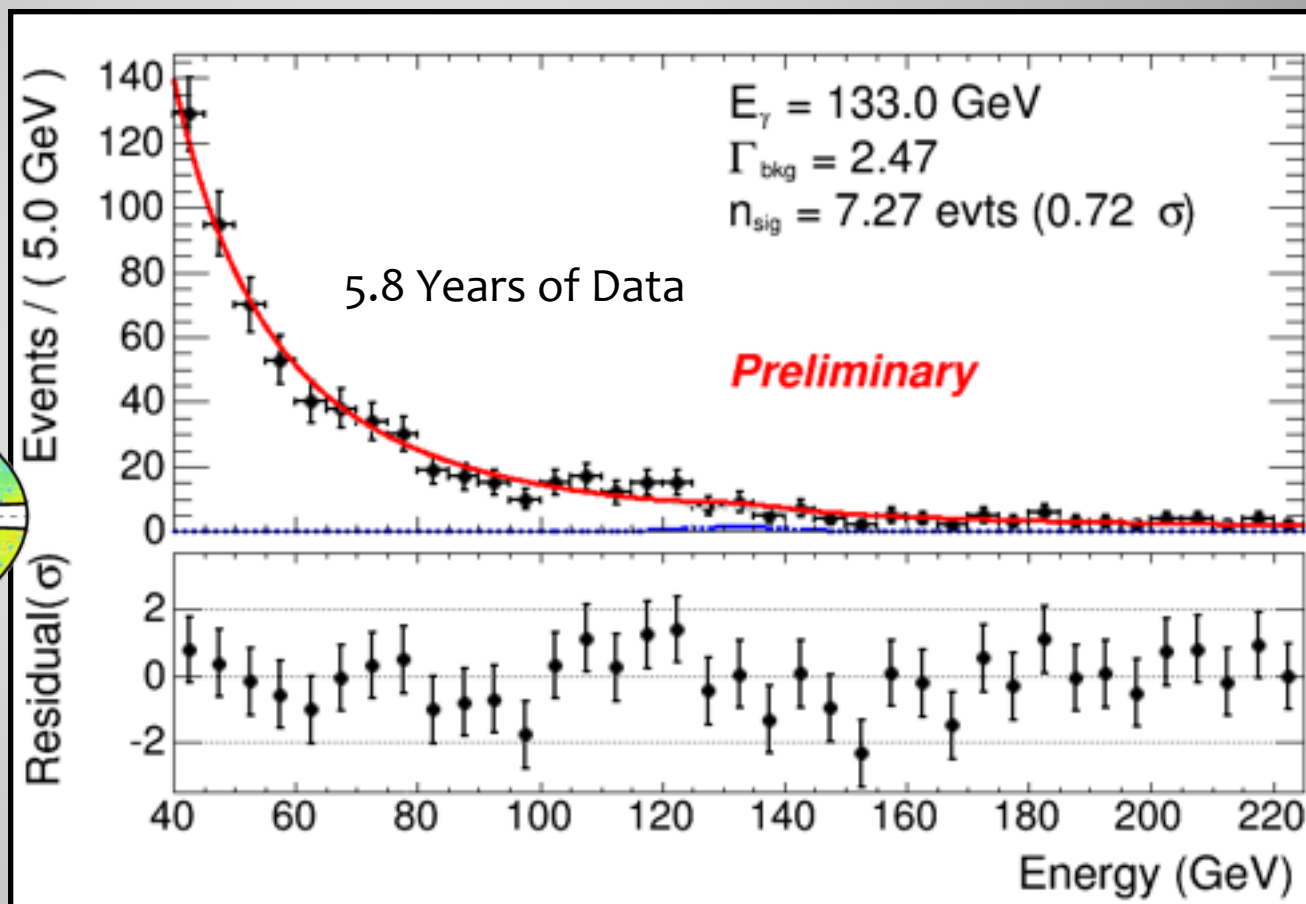
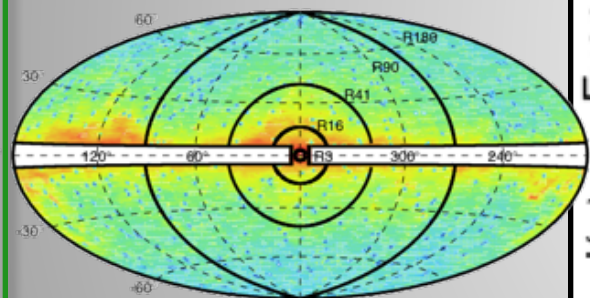


Fermi-LAT Collaboration  
Fermi Symposium 2014, Submitted  
PRD





# $\gamma$ -ray Lines: 130 GeV Feature

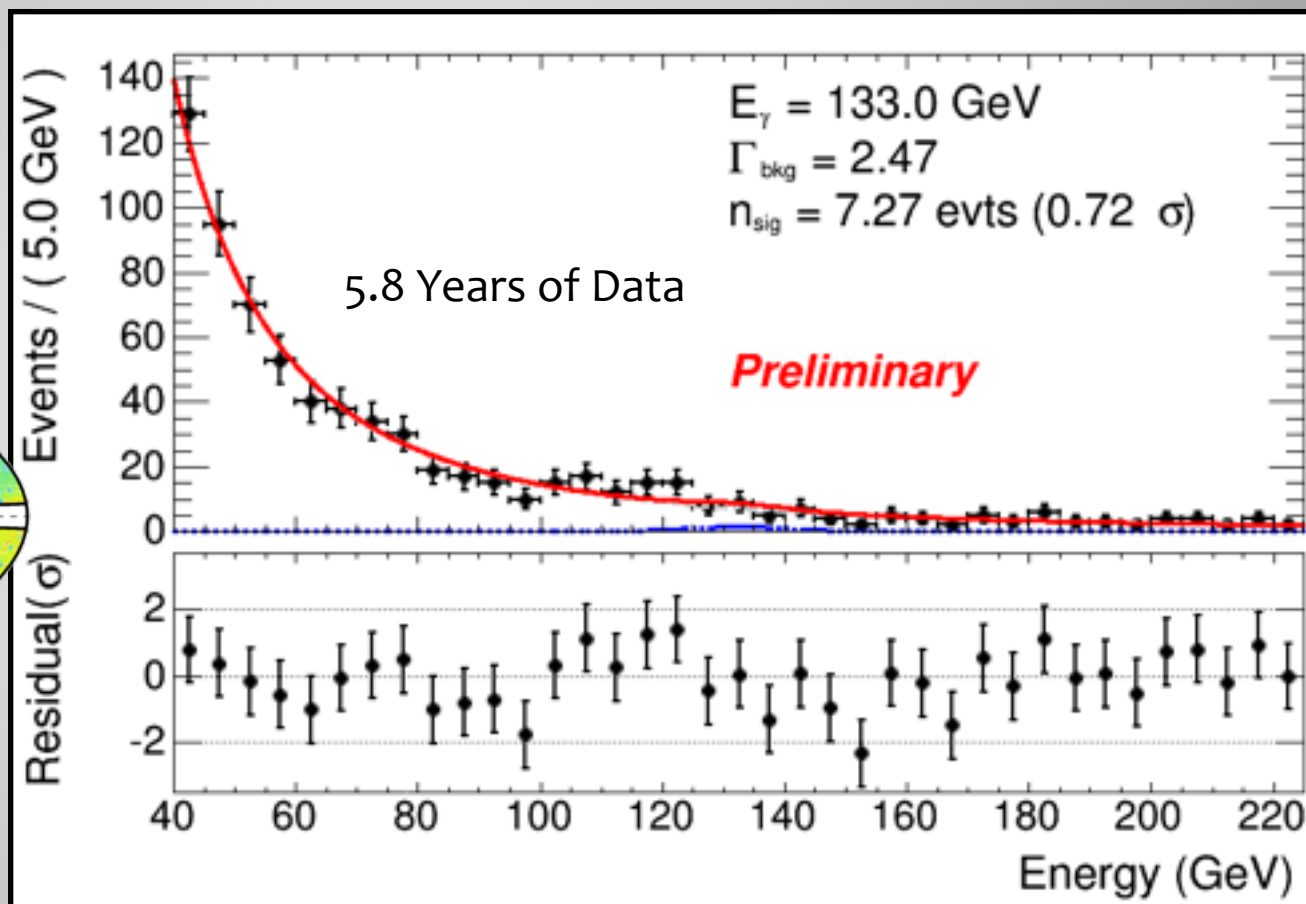
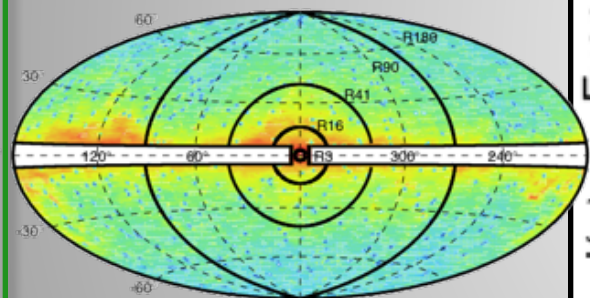


Fermi-LAT Collaboration  
Fermi Symposium 2014, Submitted  
PRD



# $\gamma$ -ray Lines: 130 GeV Feature

2014:  
No Feature

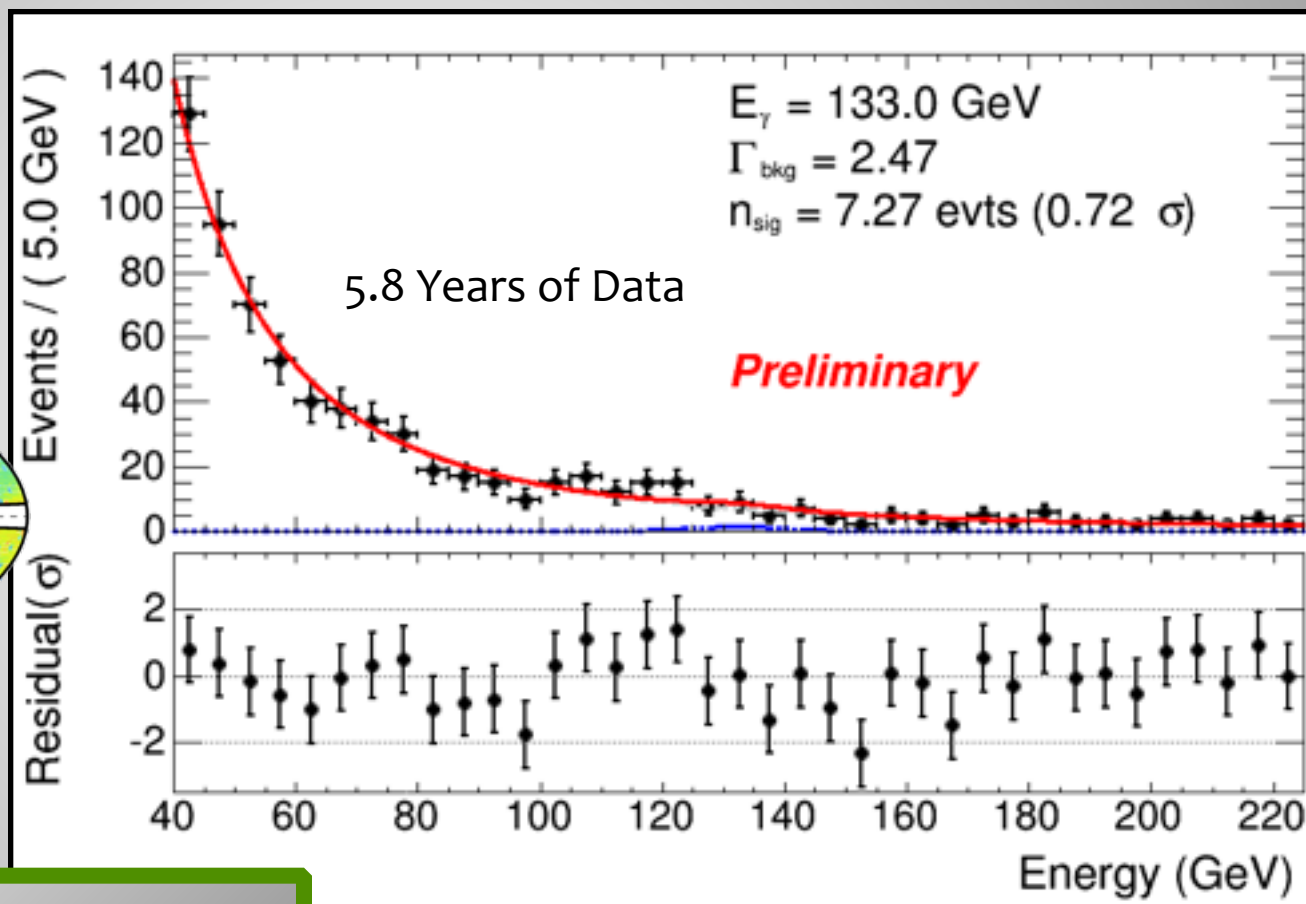
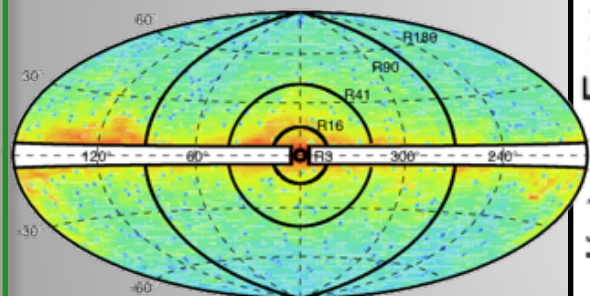


Fermi-LAT Collaboration  
Fermi Symposium 2014, Submitted  
PRD



# $\gamma$ -ray Lines: 130 GeV Feature

2014:  
No Feature 😞

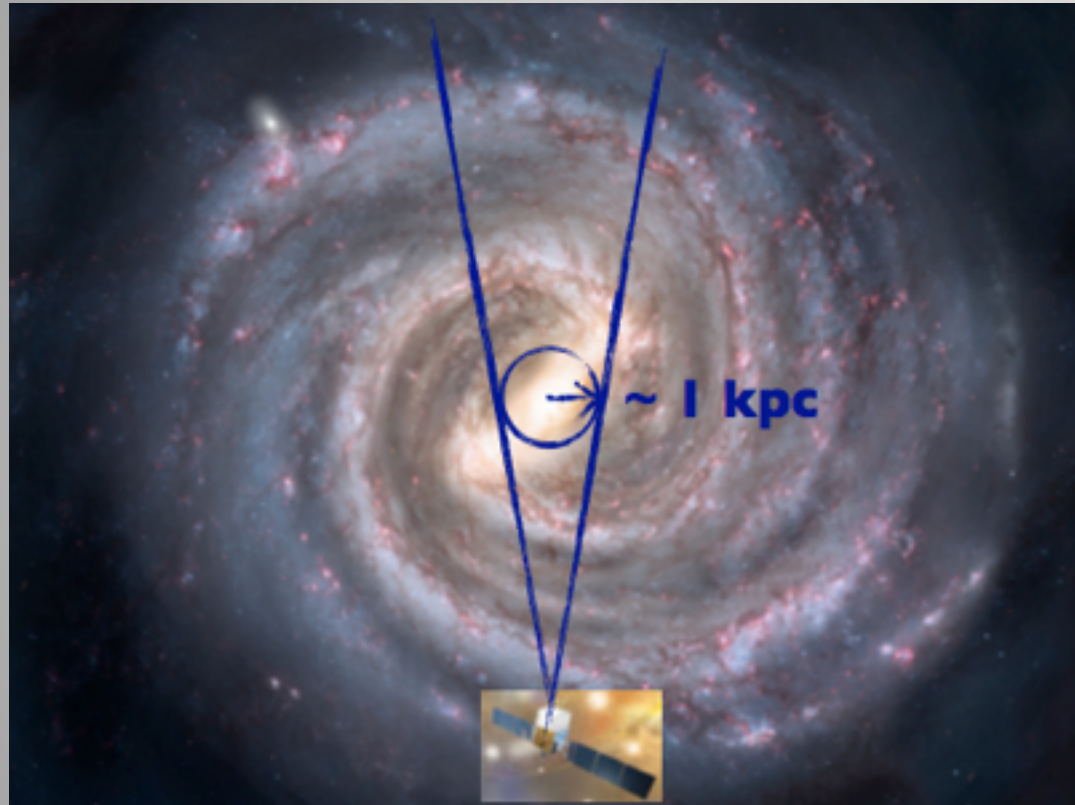


Continuum Spectrum...

Fermi-LAT Collaboration  
Fermi Symposium 2014, Submitted  
PRD



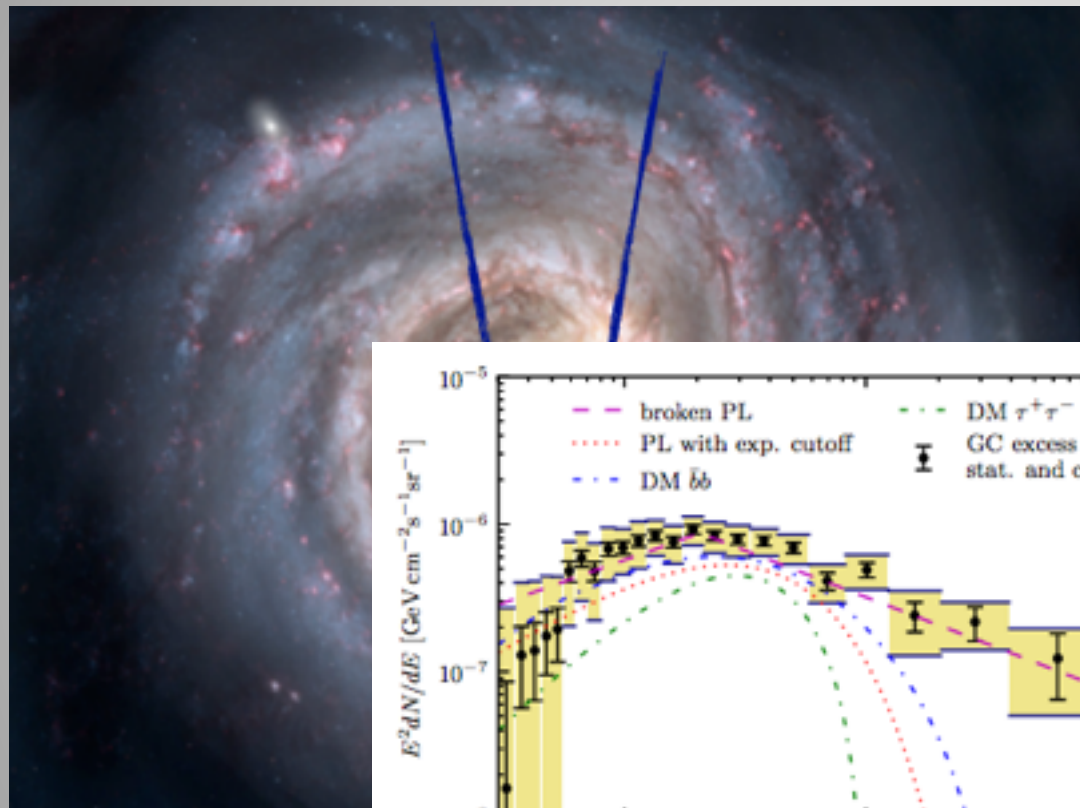
# $\gamma$ -ray Continuum in the Galactic Center



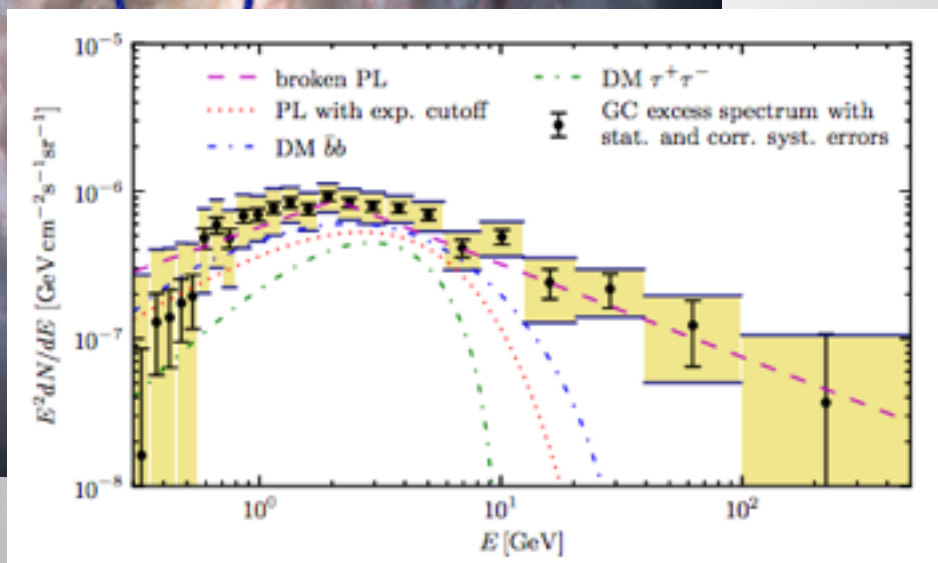




# $\gamma$ -ray Continuum in the Galactic Center



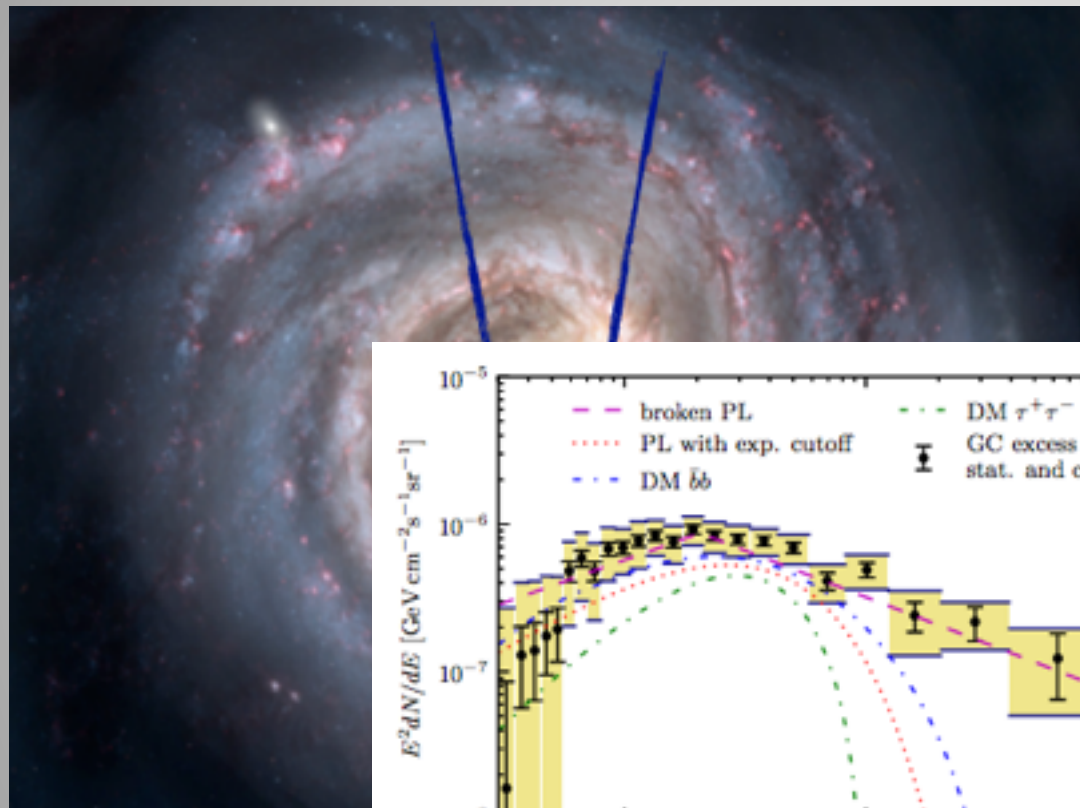
Calore et. al,  
arXiv:1409.0042



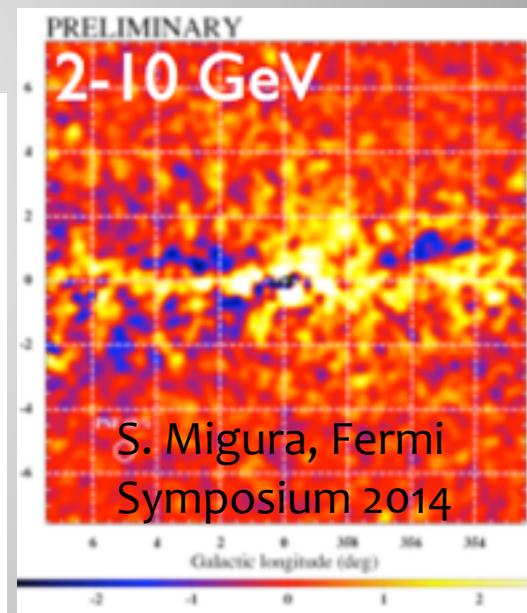
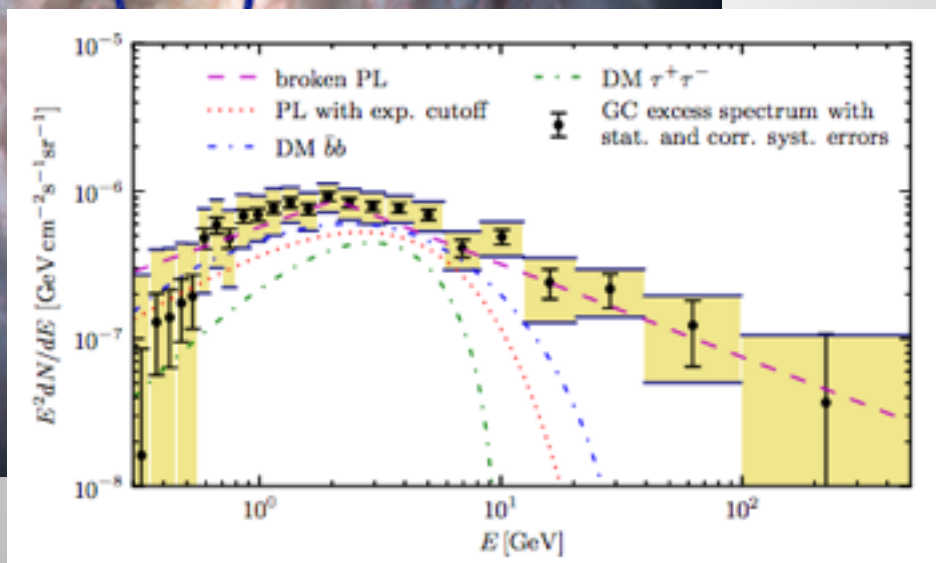




# $\gamma$ -ray Continuum in the Galactic Center



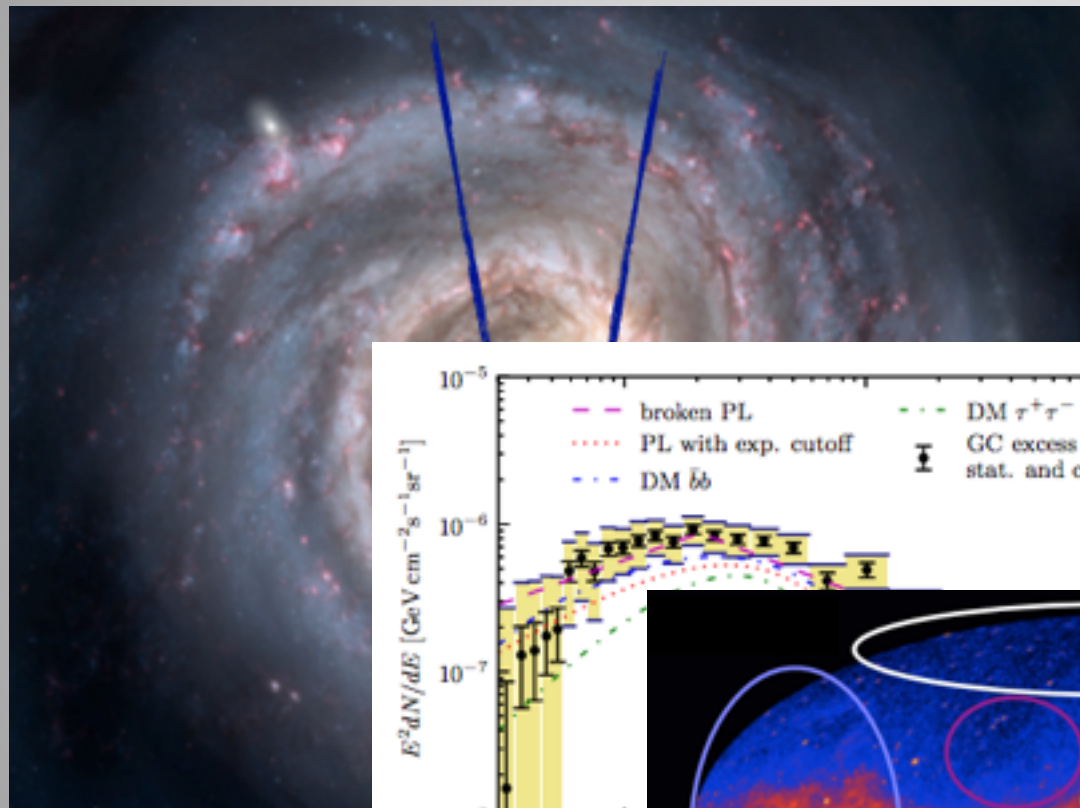
Calore et. al,  
arXiv:1409.0042



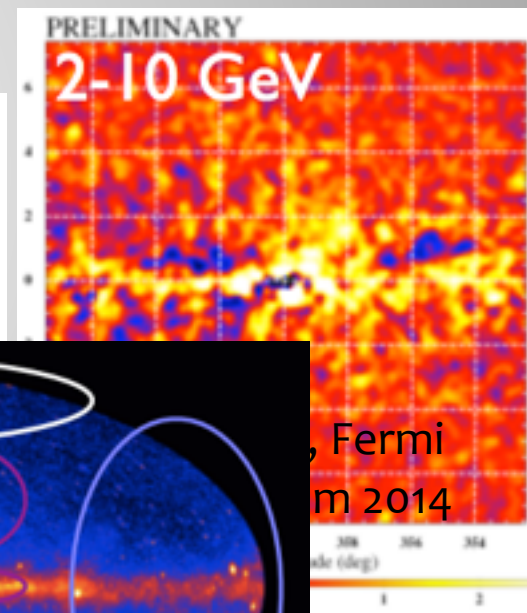
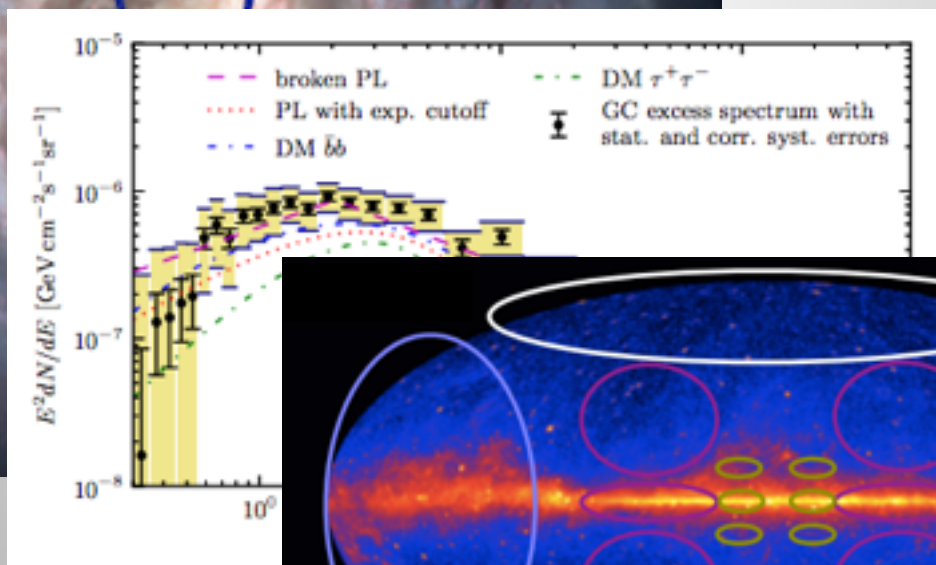
S. Migura, Fermi  
Symposium 2014



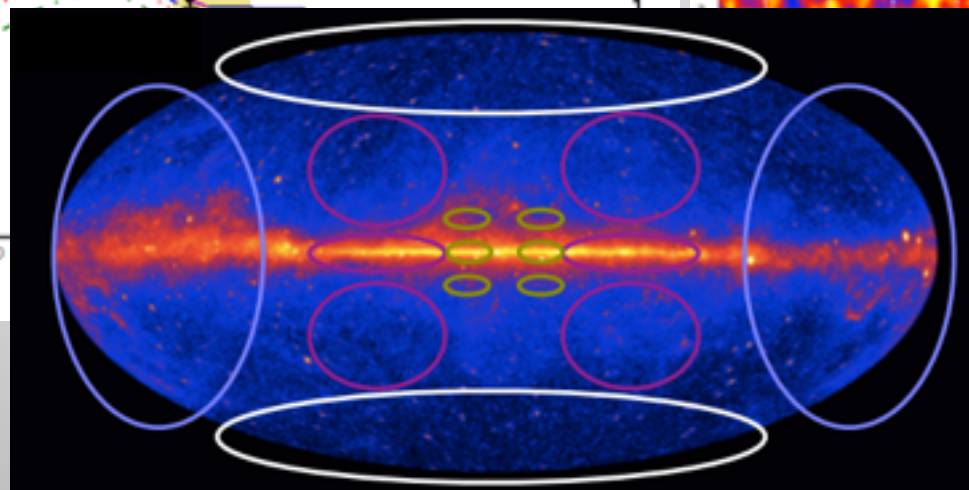
# $\gamma$ -ray Continuum in the Galactic Center



Calore et. al,  
arXiv:1409.0042



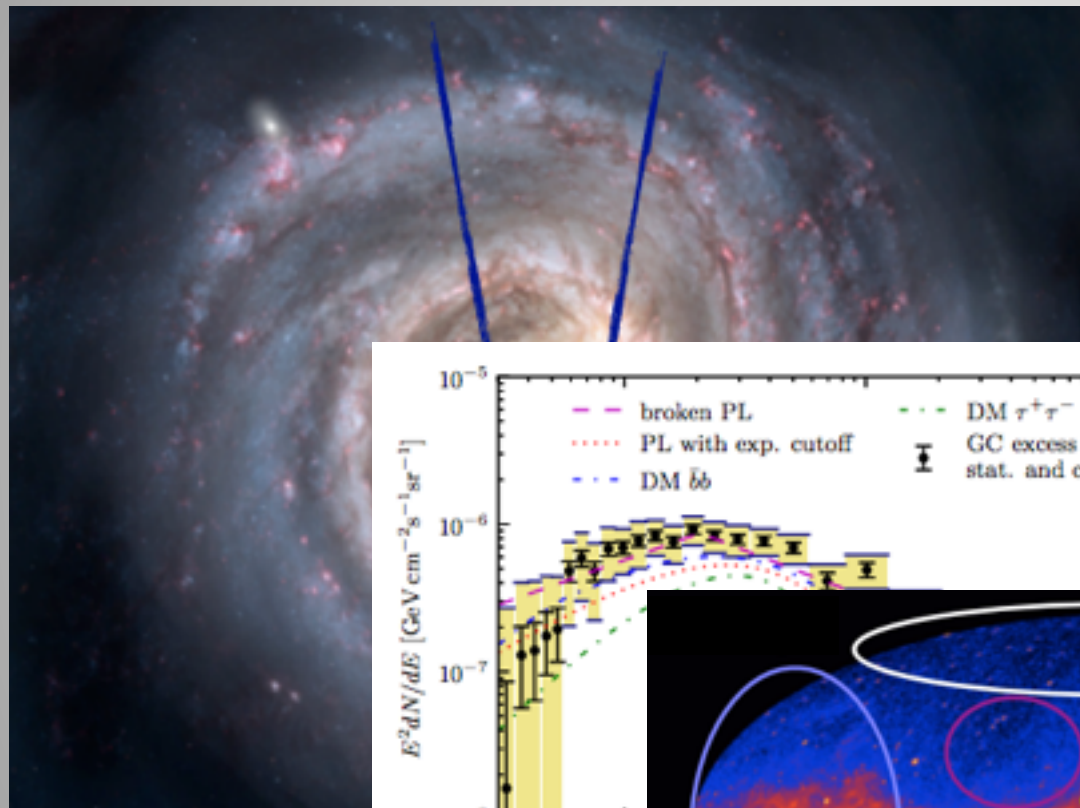
, Fermi  
m 2014



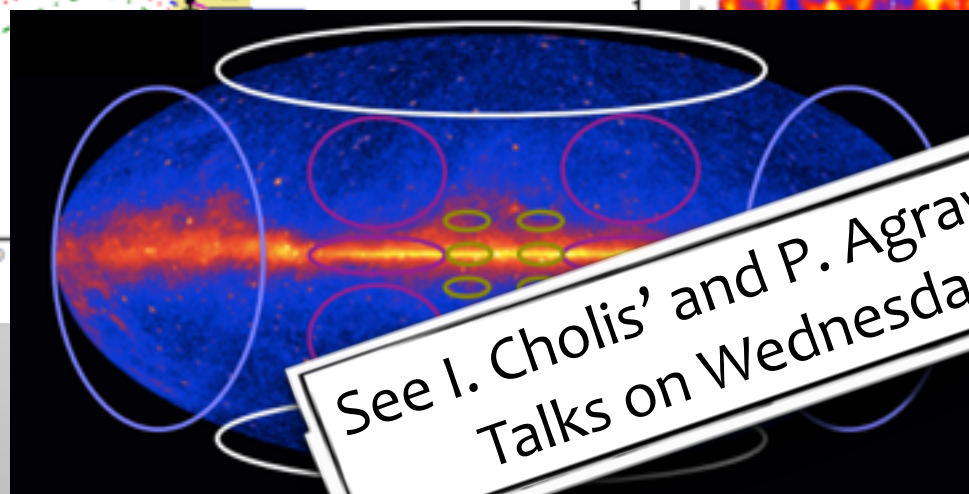
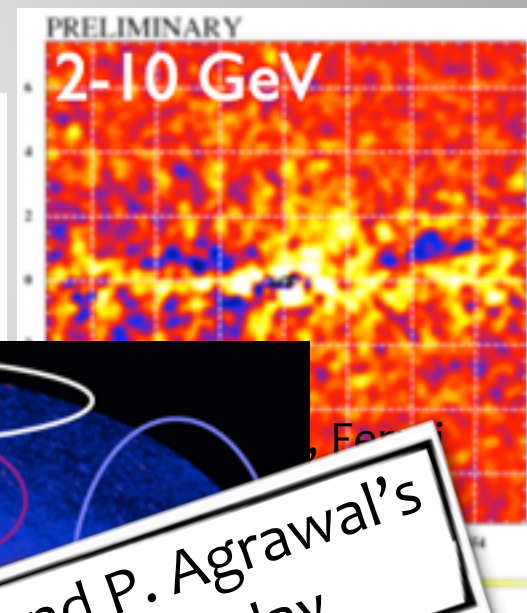
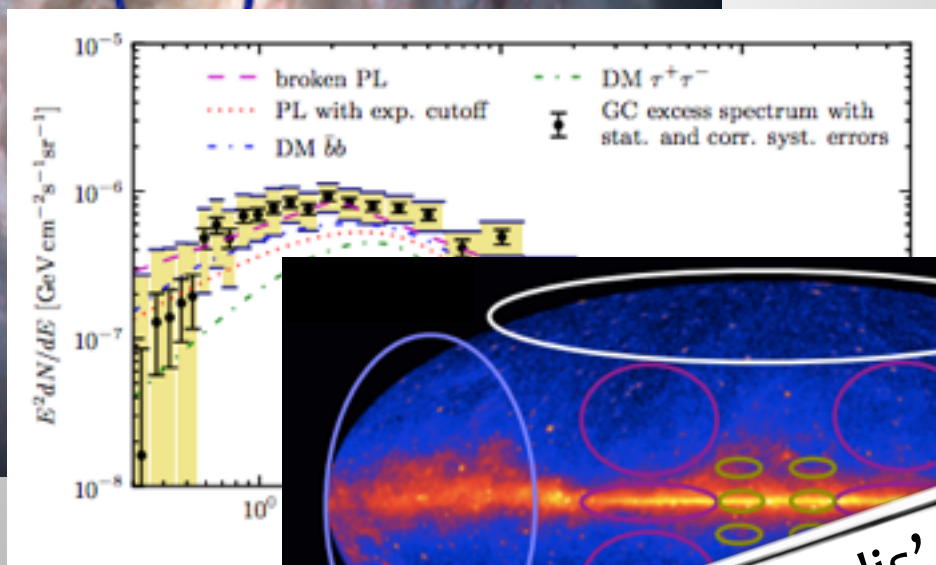




# $\gamma$ -ray Continuum in the Galactic Center



Calore et. al,  
arXiv:1409.0042

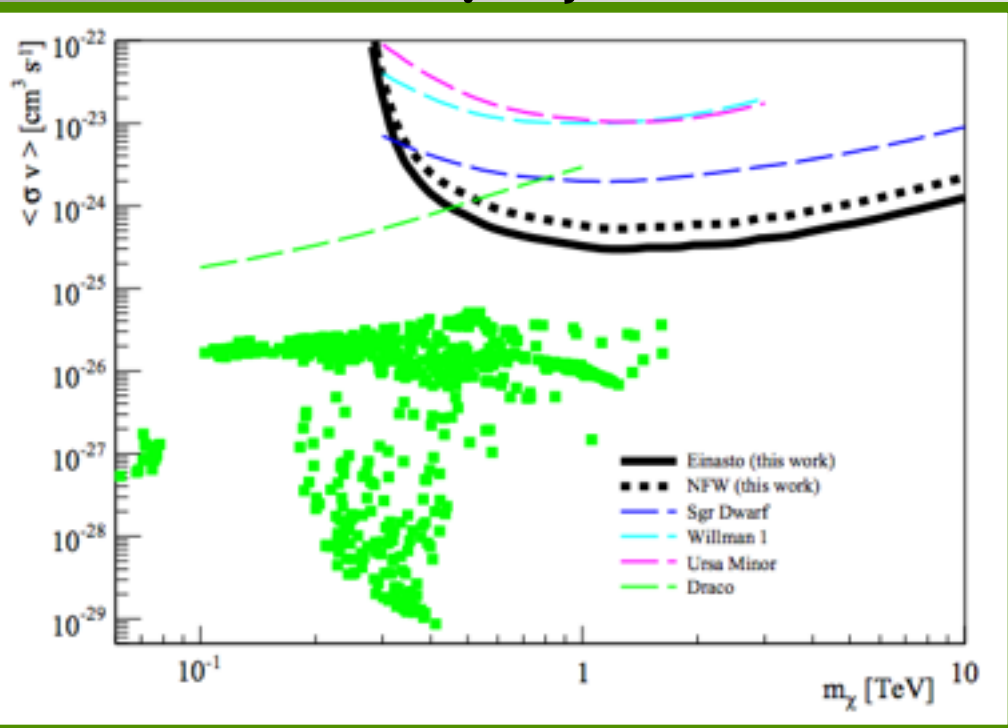


See I. Cholis' and P. Agrawal's  
Talks on Wednesday



# $\gamma$ -rays and neutrinos

The GC with  $\gamma$ -rays  $> 100$  GeV

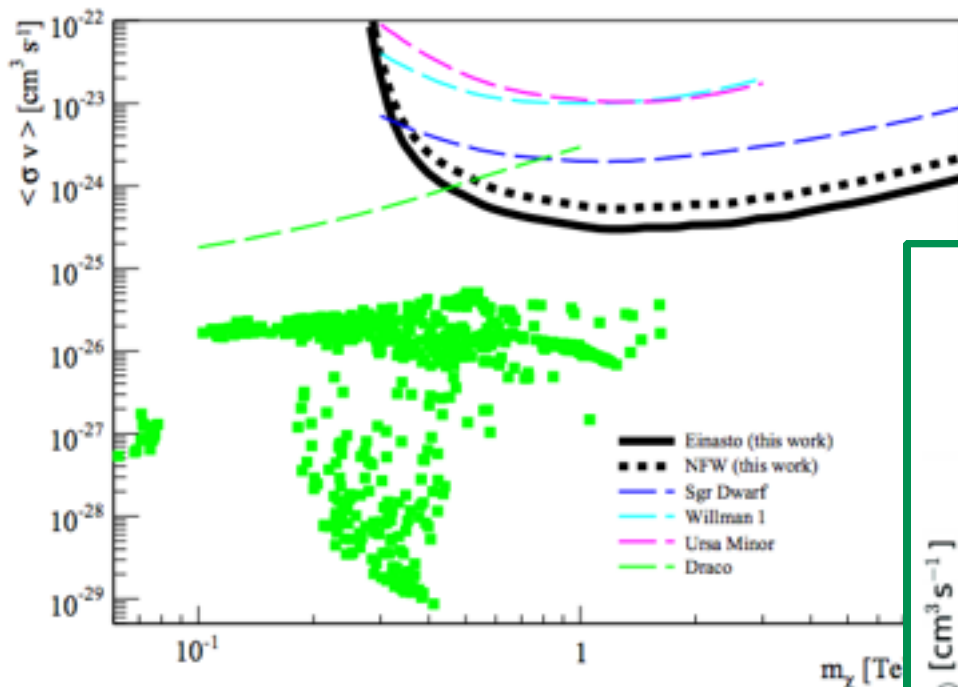


H.E.S.S Collaboration  
Phys.Rev.Lett.  
106:161301,2011



# $\gamma$ -rays and neutrinos

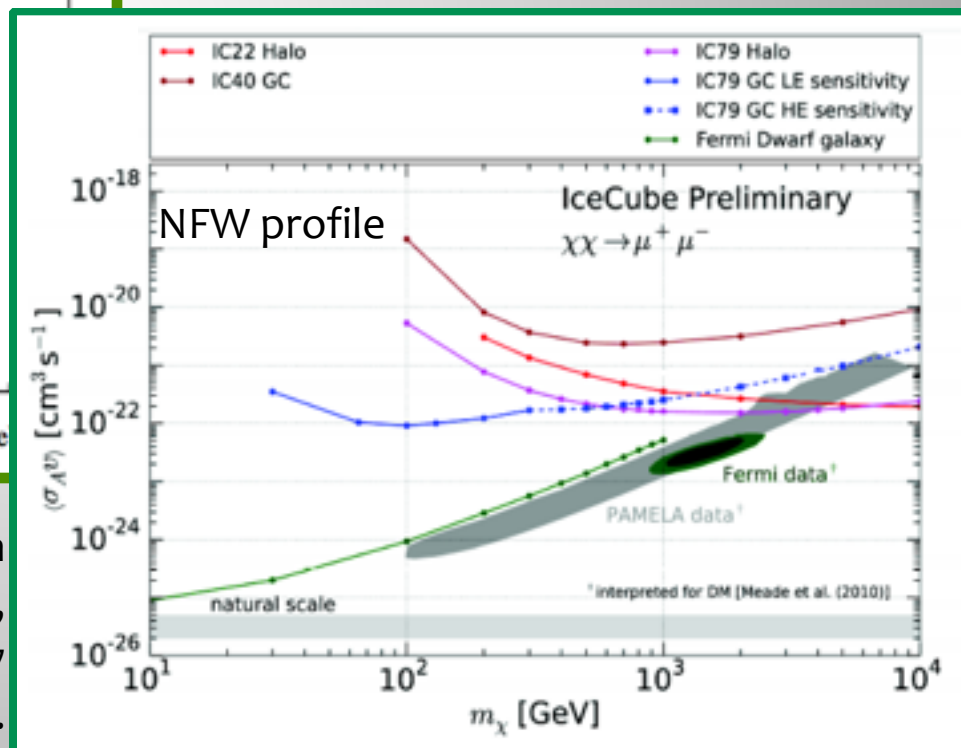
The GC with  $\gamma$ -rays  $>100$  GeV



H.E.S.S Collaboration  
Phys.Rev.Lett.  
106:161301,2011

IceCube Collaboration  
40 string,  
arXiv: 1210.3557  
79 string, in prep.

The GC with neutrinos







# Dark Matter Distribution

**Fermi-LAT**  
**Search Strategies**

**Dwarf Spheroidal  
Satellite Galaxies**

arXiv: 1310.0828

arXiv: 1503.02641

arXiv: 1503.02632

**From the Fermi-LAT  
Collaboration**

**DES candidates**

**Milky Way Halo**

arXiv: 1205.6474

**Spectral Lines**

arXiv: 1305.5597

Fermi Symposium 2014

**Galaxy Clusters**

arXiv: 1002.2239

**Galactic Center**

Fermi Symposium 2014

**Isotropic Background**

arXiv:1501.05464

Submitted to JCAP



# Dark Matter Distribution

**Fermi-LAT  
Search Strategies**

**Dwarf Spheroidal  
Satellite Galaxies**

arXiv: 1503.02320  
arXiv: 1503.06209

**Galaxy Clusters**  
arXiv: 1002.2239

**Dwarf Spheroidal  
Satellite Galaxies**

arXiv: 1310.0828  
arXiv: 1503.02641  
arXiv: 1503.02632

**External Analyses  
on DES candidates**  
**From the Fermi-LAT  
Collaboration**

**DES candidates**

**Milky Way Halo**  
arXiv: 1205.6474

**Galactic Center**  
Fermi Symposium 2014

**Spectral Lines**  
arXiv: 1305.5597  
Fermi Symposium 2014

**Isotropic Background**  
arXiv:1501.05464  
Submitted to JCAP



# What is a Dwarf Spheroidal Galaxy?

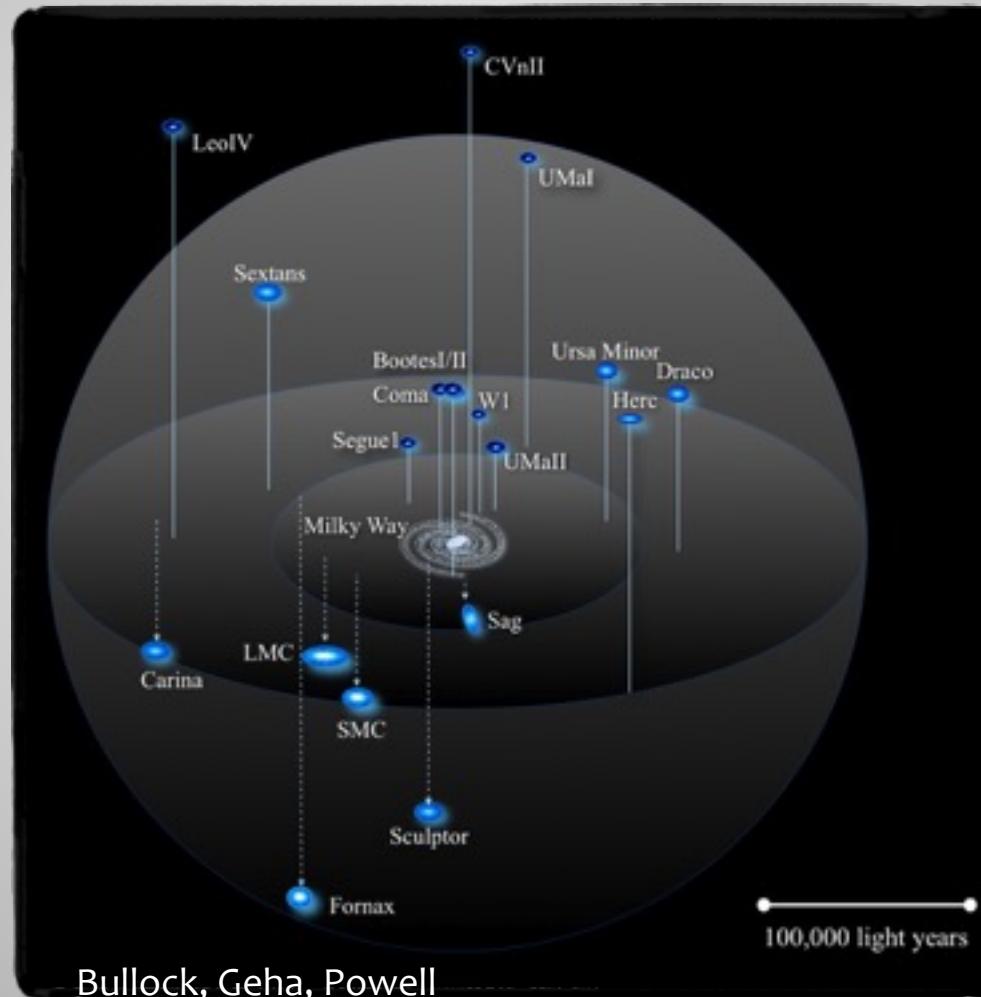
The Milky Way has many companion galaxies!

Little gas/dust/  
star formation

old: >13b years

Low Luminosity

Found around  
Milky Way  
and Andromeda



25 known dSphs

9 classical dSphs  
(pre-SDSS)

Bullock, Geha, Powell



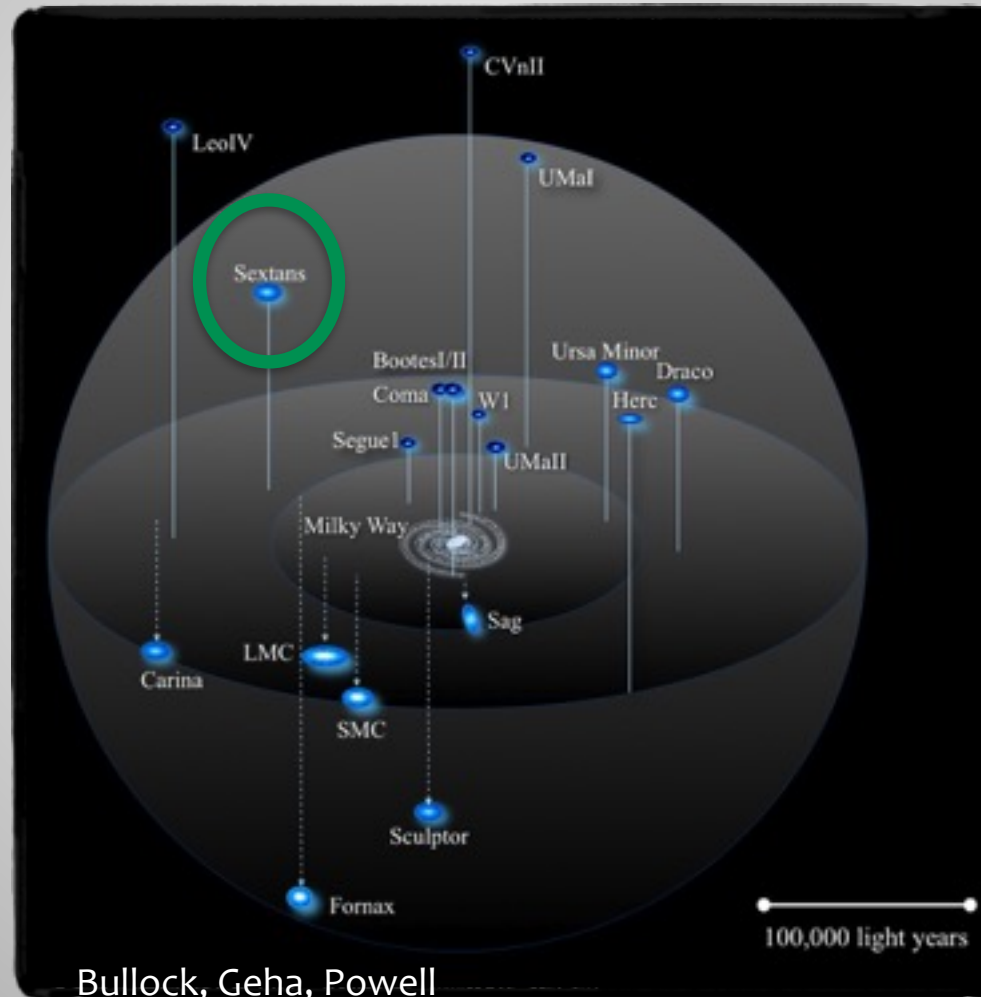


The Milky Way has many companion galaxies!

old: >13b years

## Low Luminosity

Found around  
Milky Way  
and Andromeda

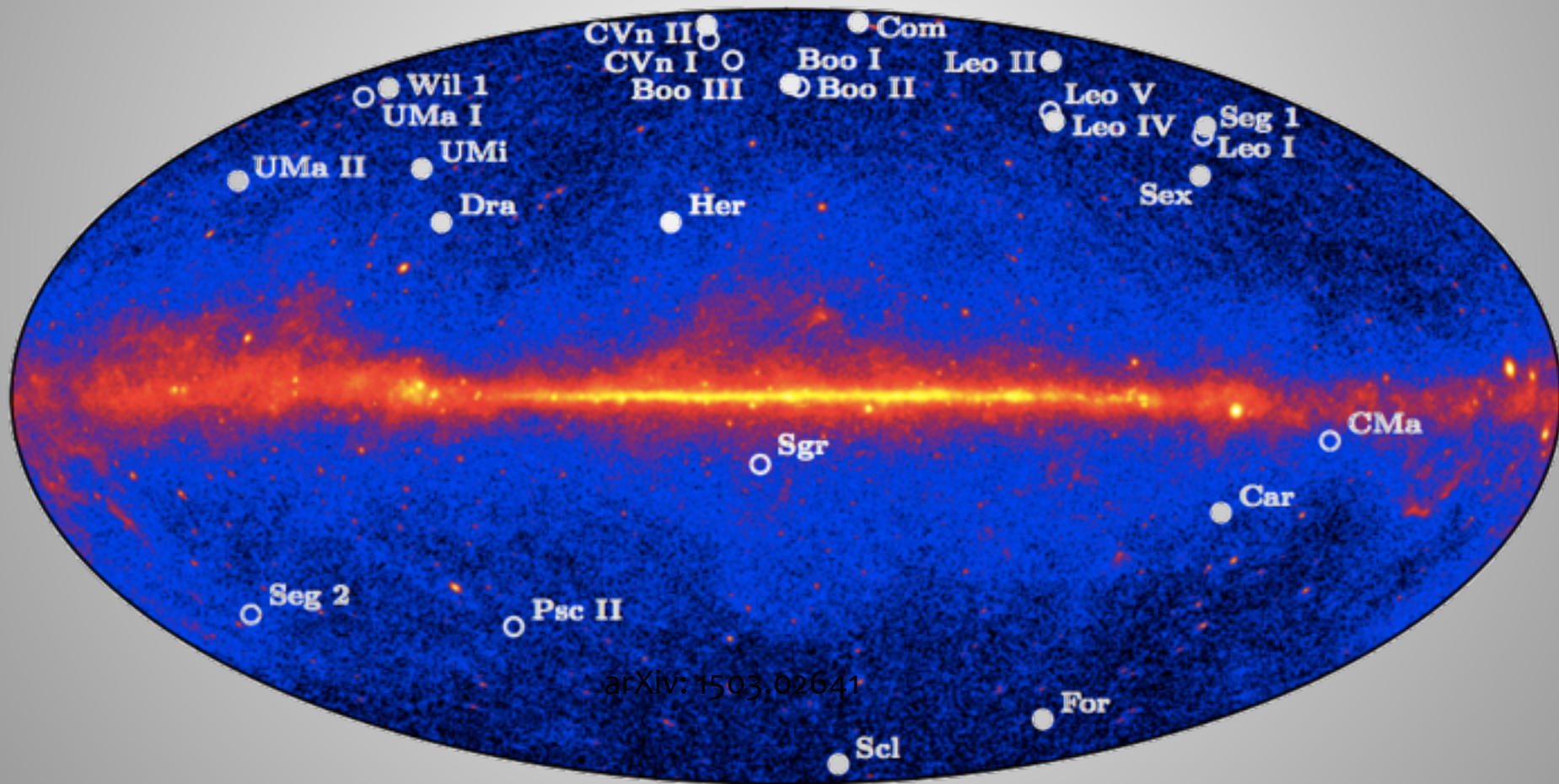


9 classical dSphs  
(pre-SDSS)



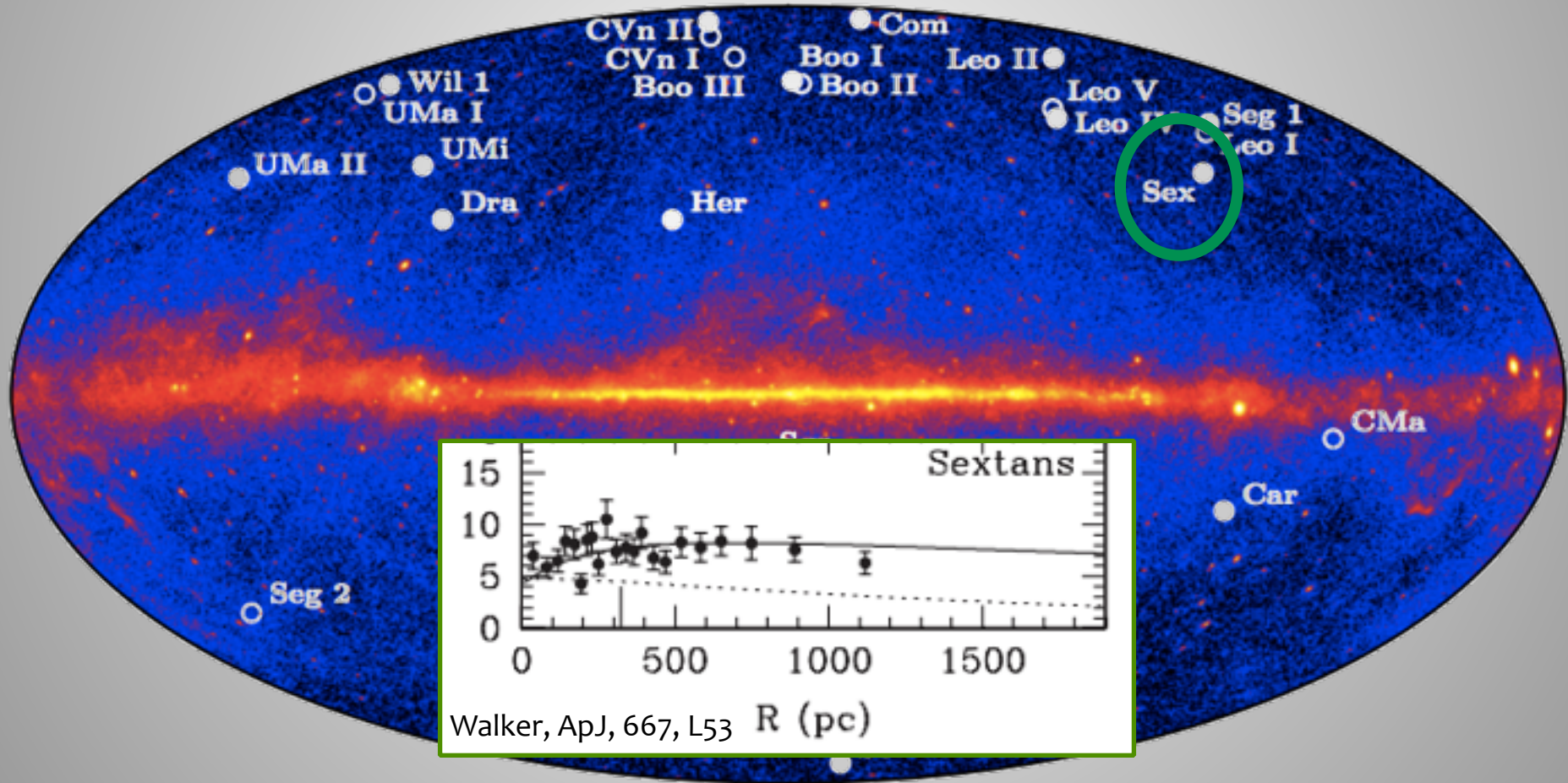


# Confirmed Dwarf Spheroidal Satellite Galaxies





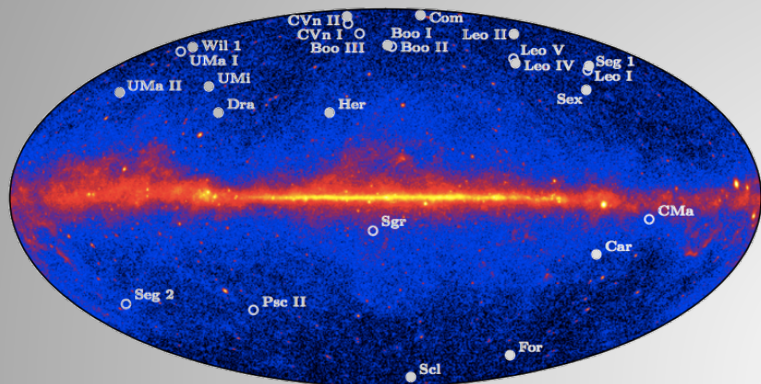
# Confirmed Dwarf Spheroidal Satellite Galaxies



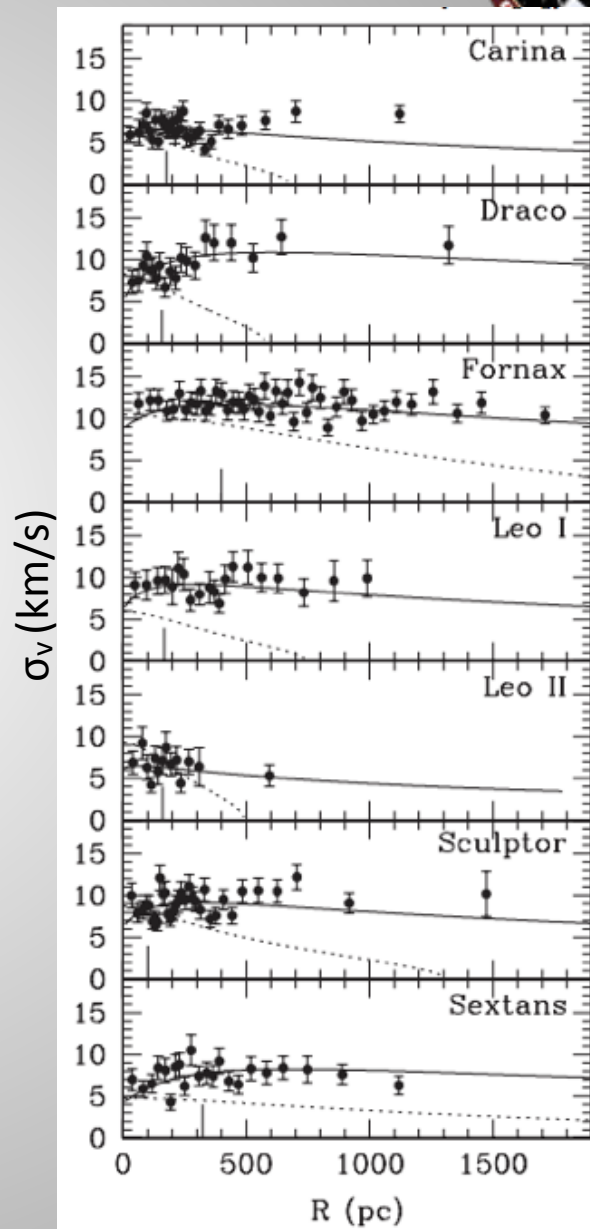




# Dwarf Spheroidal Satellite Galaxies

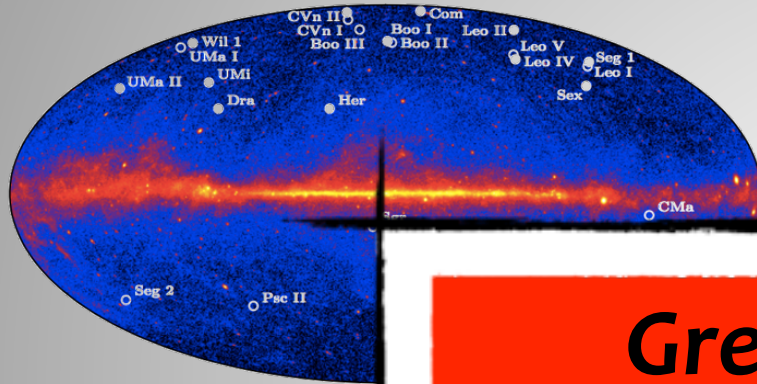
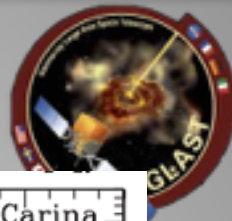


- DM content:  $v$  dispersion
  - dwarf  $v$  fit to NFW profile
- J-Factor calculated to  $R=0.5^\circ$ 
  - encloses half-light radii
  - insensitive to inner profile behavior



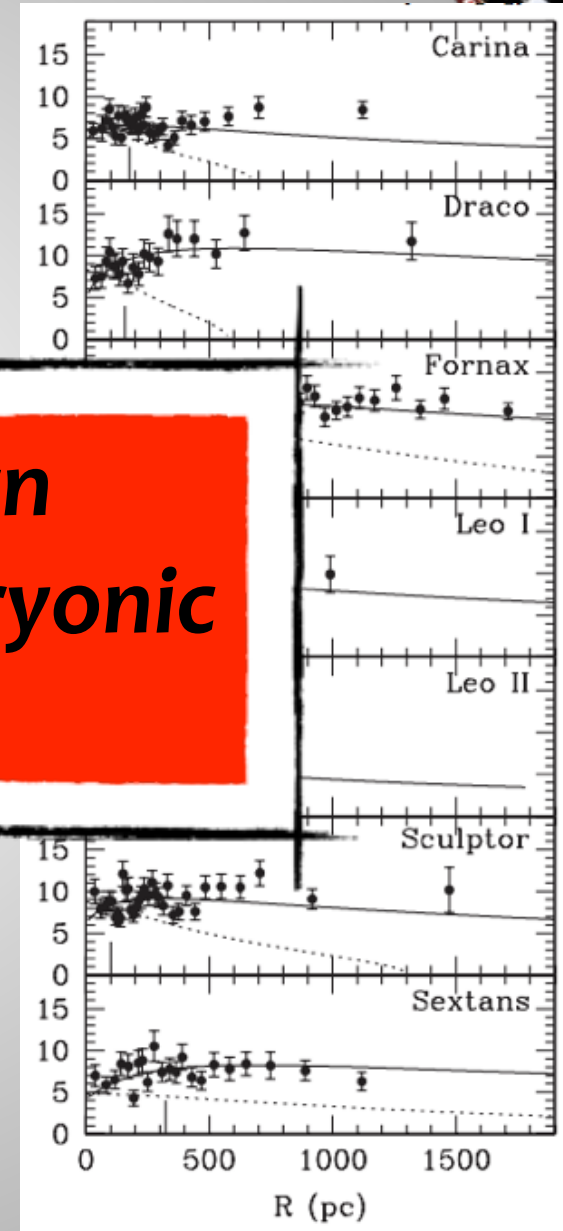


# Dwarf Spheroidal Satellite Galaxies



***Greatest known  
dark matter-to-baryonic  
matter ratio***

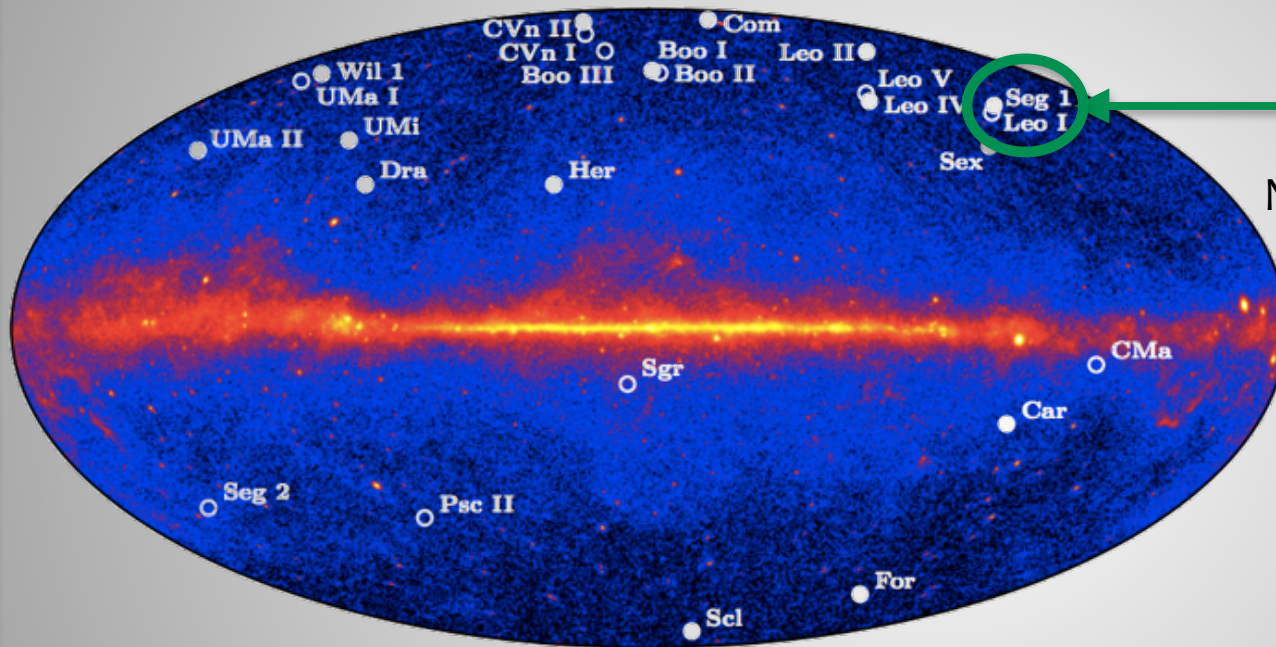
- DM content of dwarf galaxies
- J-Factor calculated to  $R=0.5$ 
  - encloses half-light radii
  - insensitive to inner profile behavior







# Dwarf Spheroidal Satellite Galaxies: Segue 1

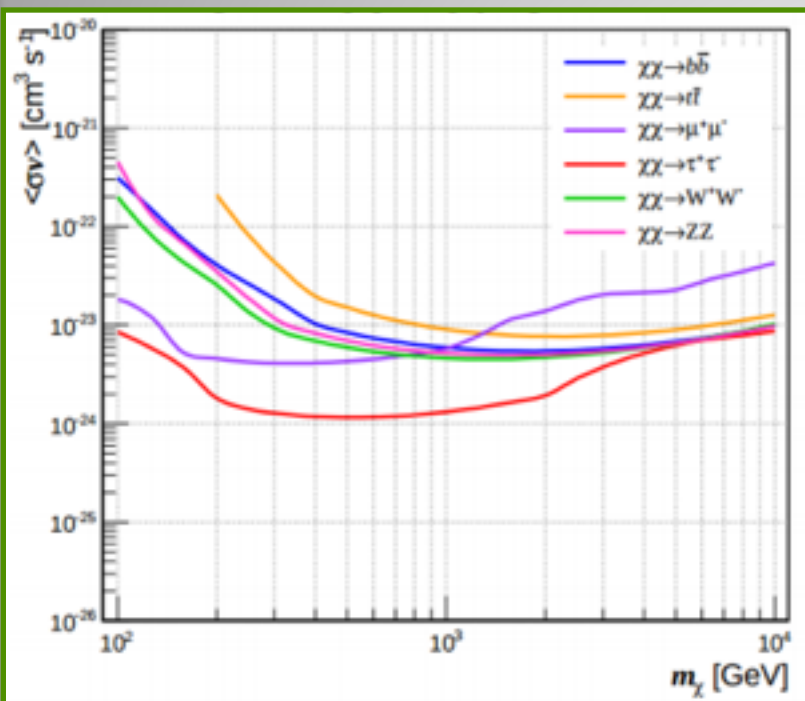


## **Segue 1:**

Closest dwarf  
No detection by Fermi-LAT,  
MAGIC, VERITAS



# Dwarf Spheroidal Satellite Galaxies: Segue 1

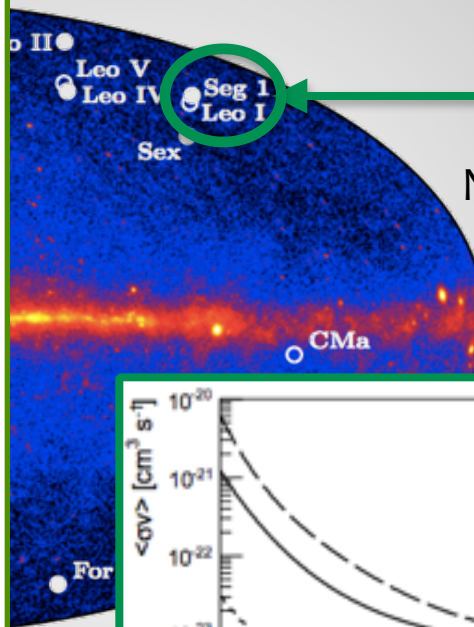


**MAGIC 158h** ↑

JCAP 02 (2014) 008

**VERITAS 48h** →

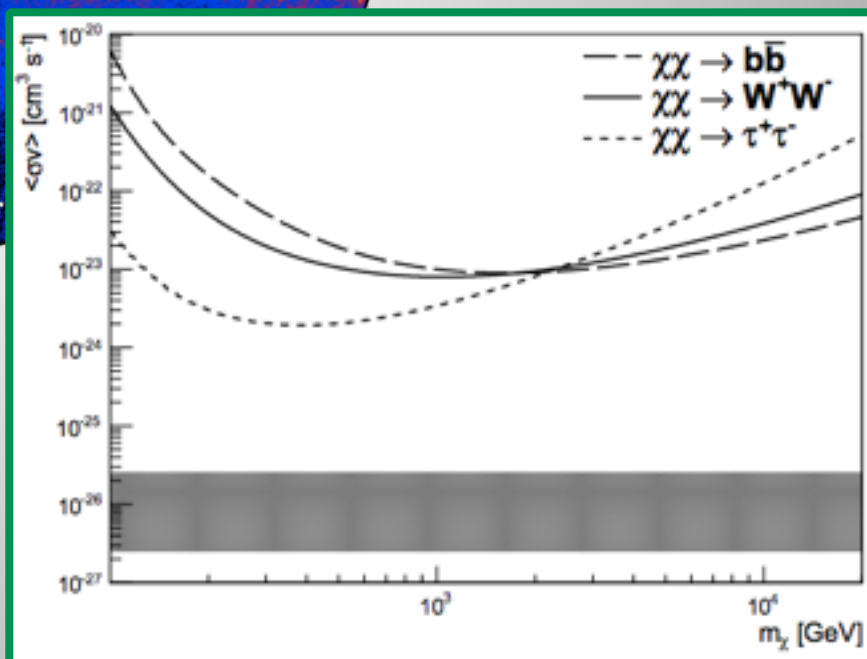
Phys. Rev. D 85, 062001 (2012)



**Segue 1:**

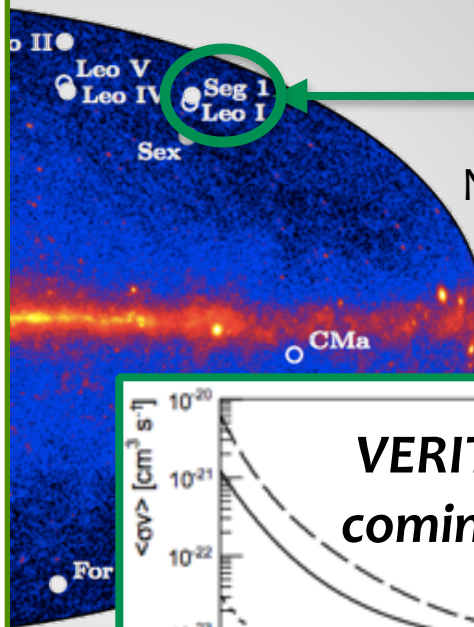
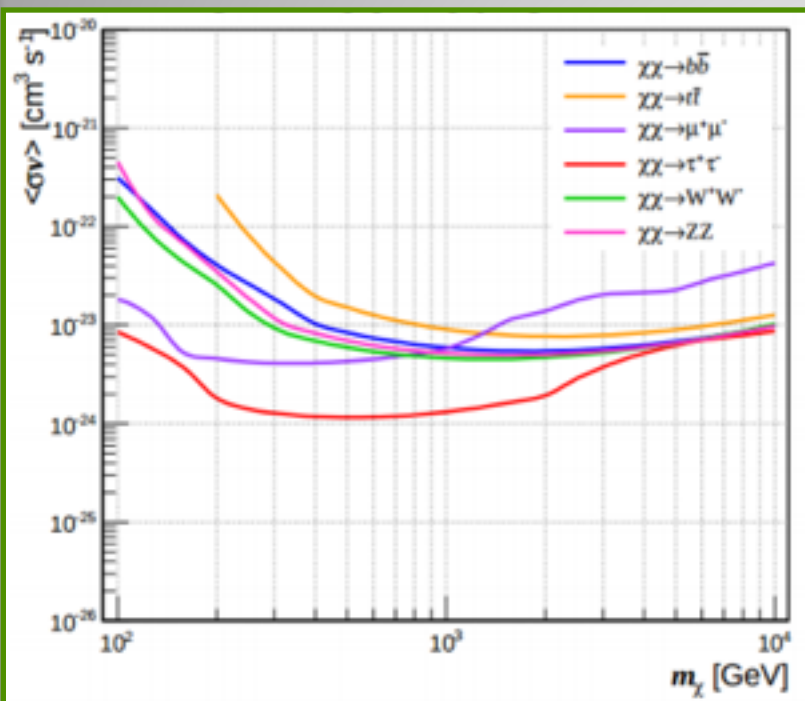
Closest dwarf

No detection by Fermi-LAT,  
MAGIC, VERITAS





# Dwarf Spheroidal Satellite Galaxies: Segue 1



## Segue 1:

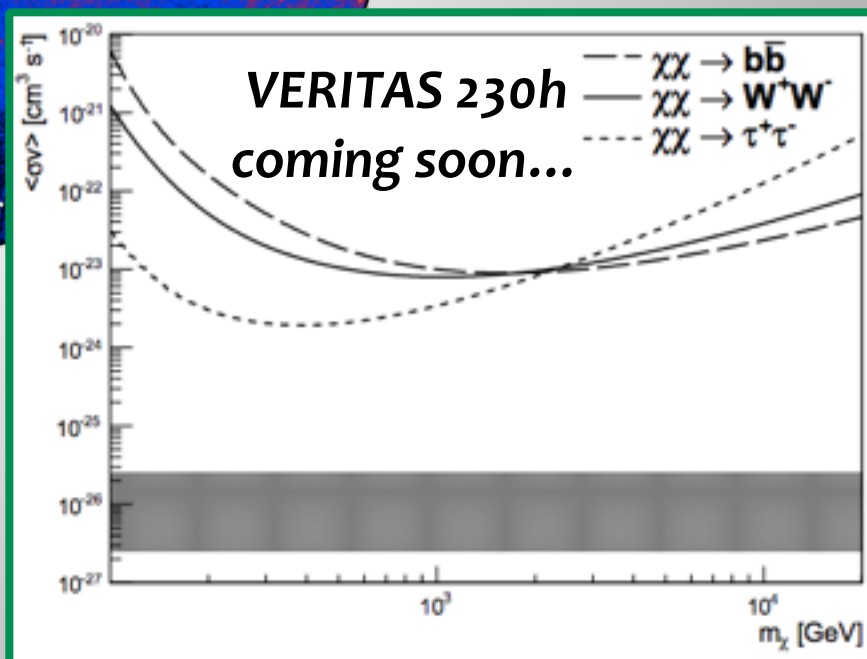
Closest dwarf  
No detection by Fermi-LAT,  
MAGIC, VERITAS

**MAGIC 158h** ↑

JCAP 02 (2014) 008

**VERITAS 48h** →

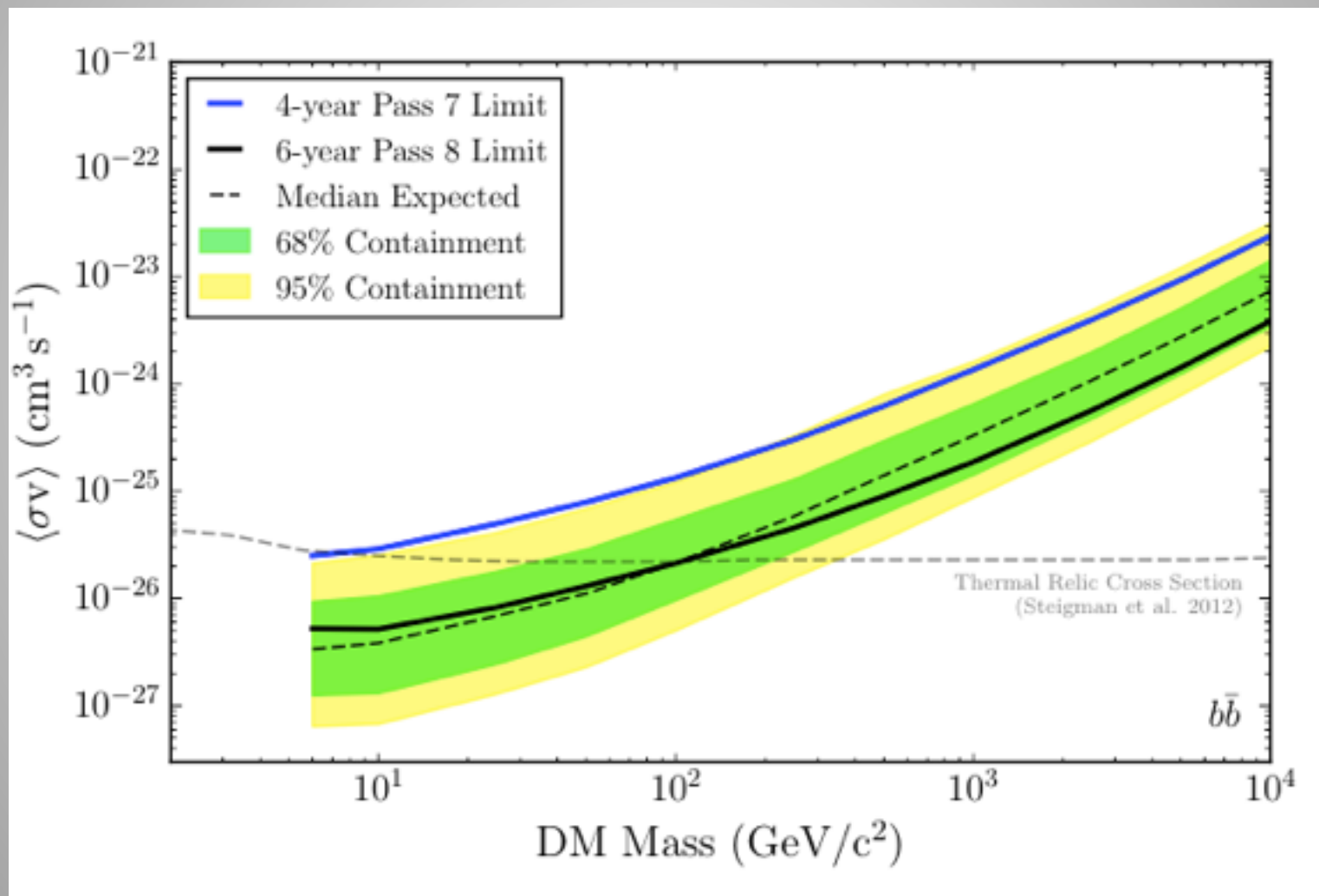
Phys. Rev. D 85, 062001 (2012)







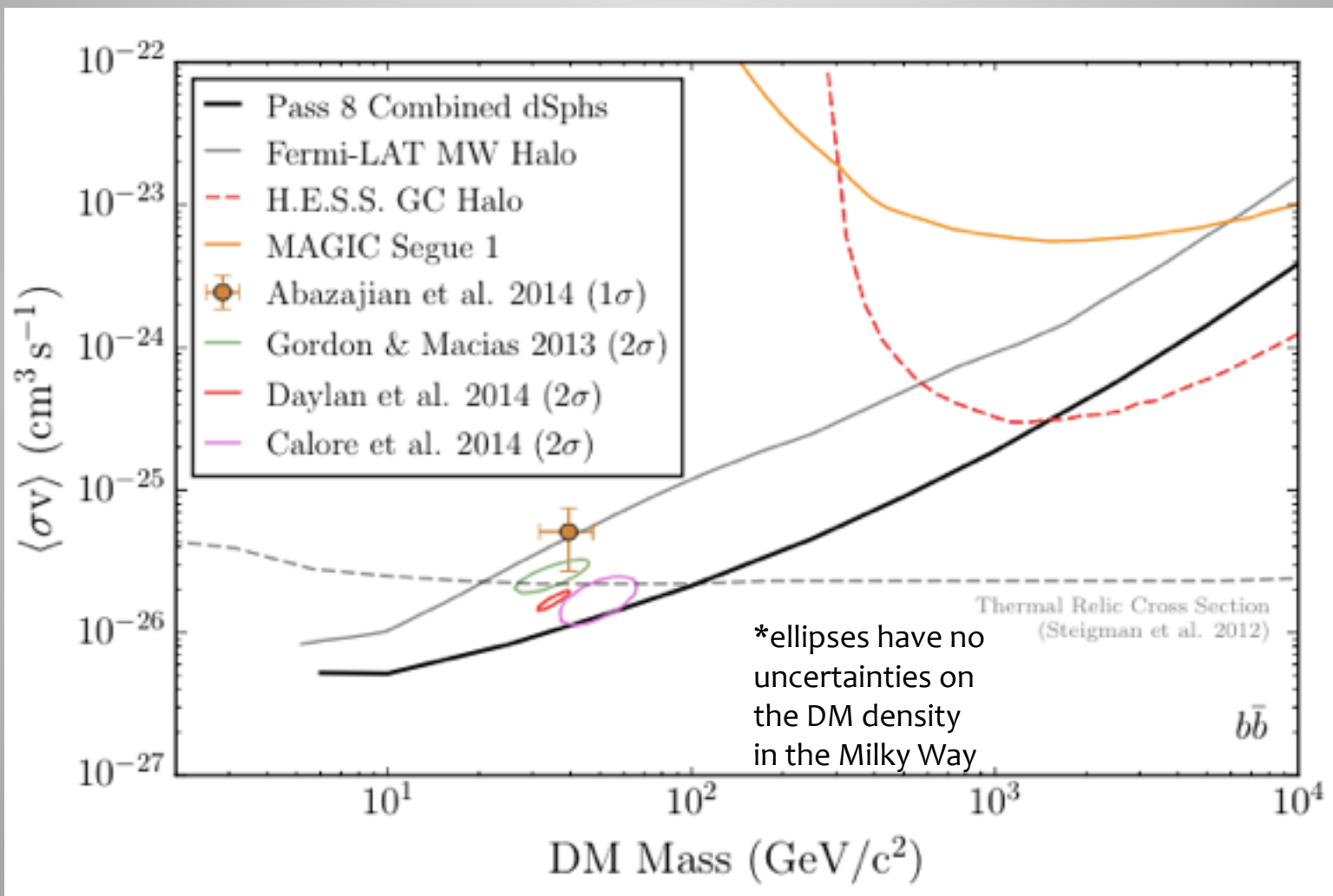
# Dwarf Spheroidal Satellite Galaxies: Combined





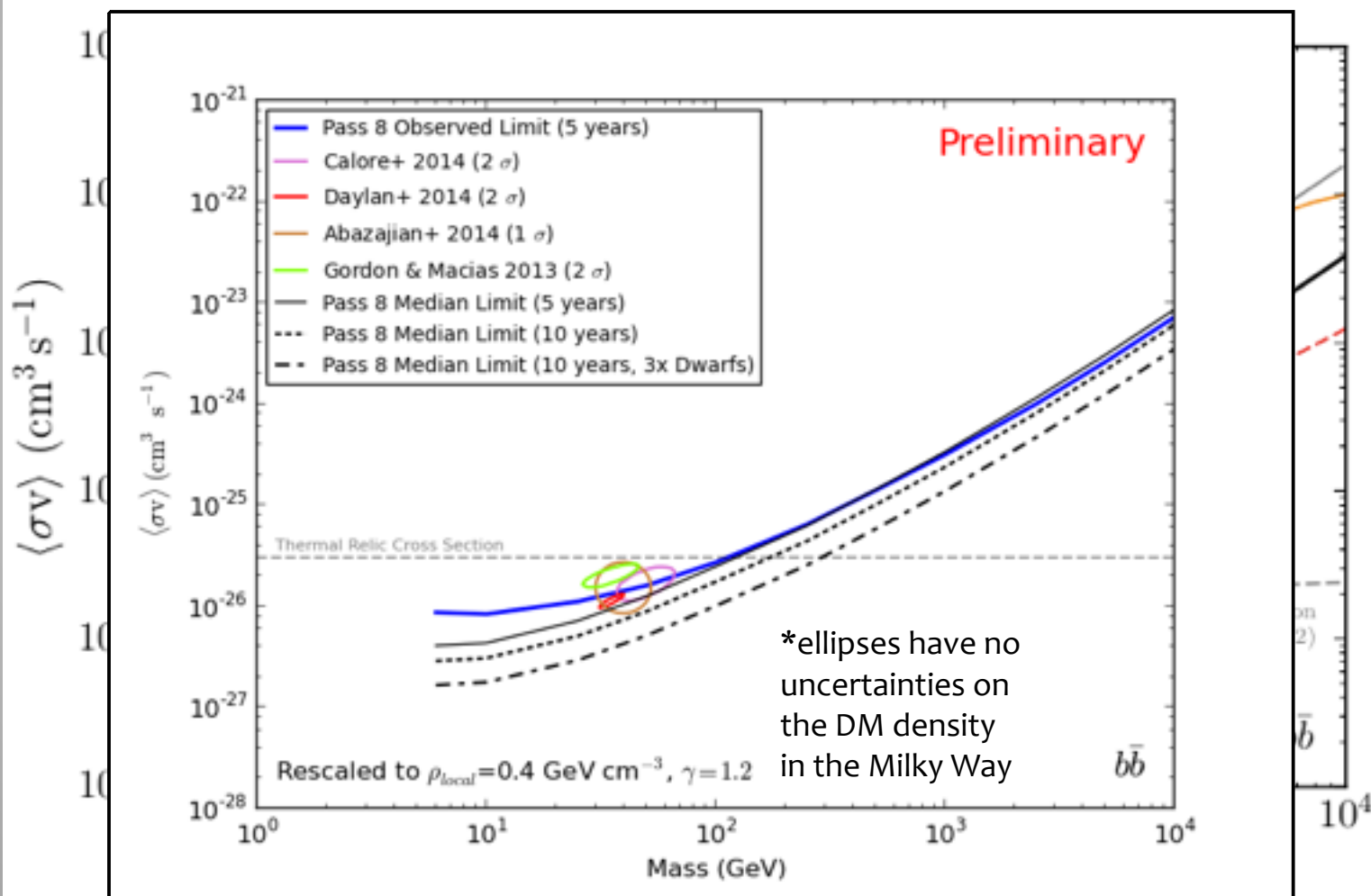


# Dwarf Spheroidal Satellite Galaxies: Combined



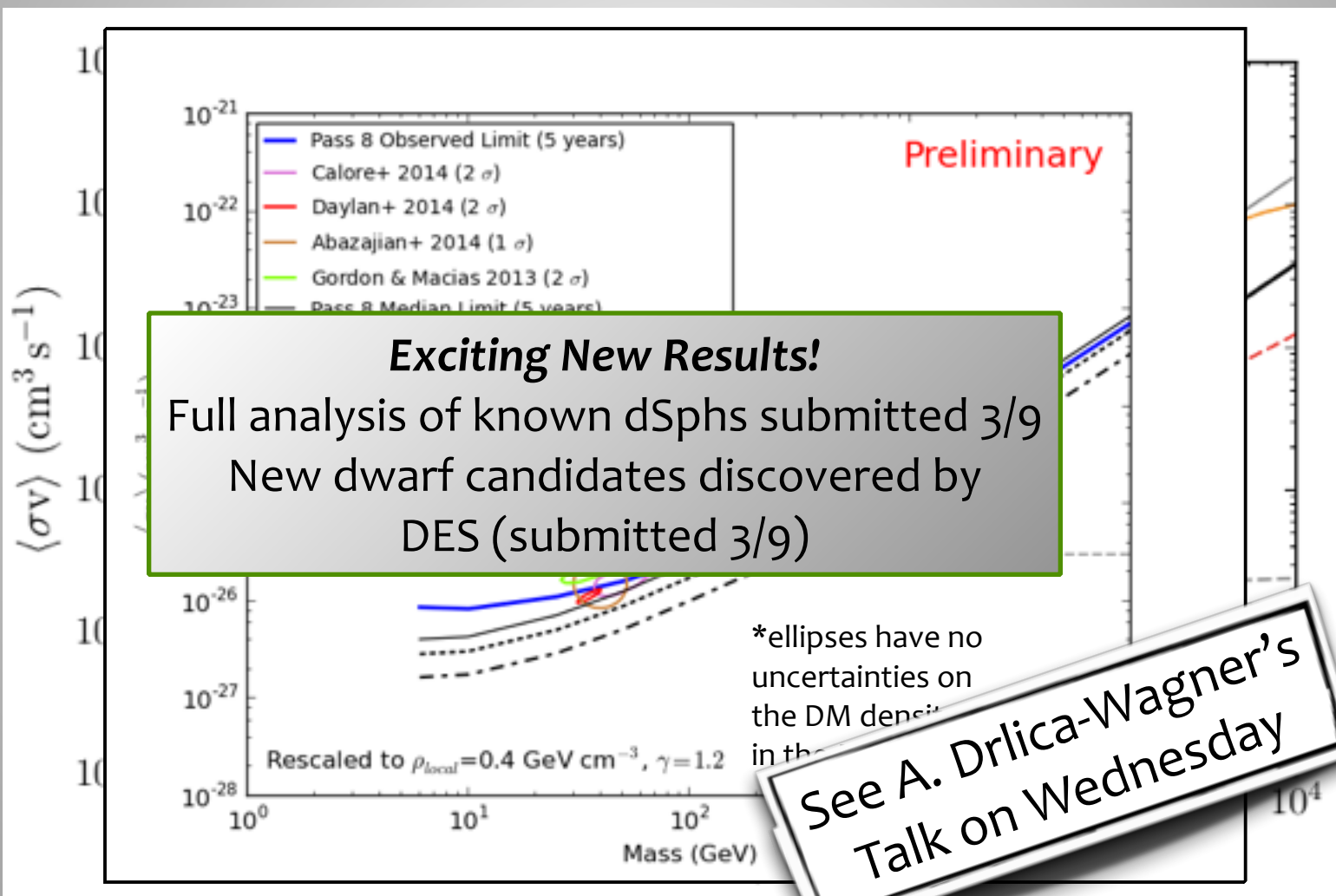


# Dwarf Spheroidal Satellite Galaxies: Combined



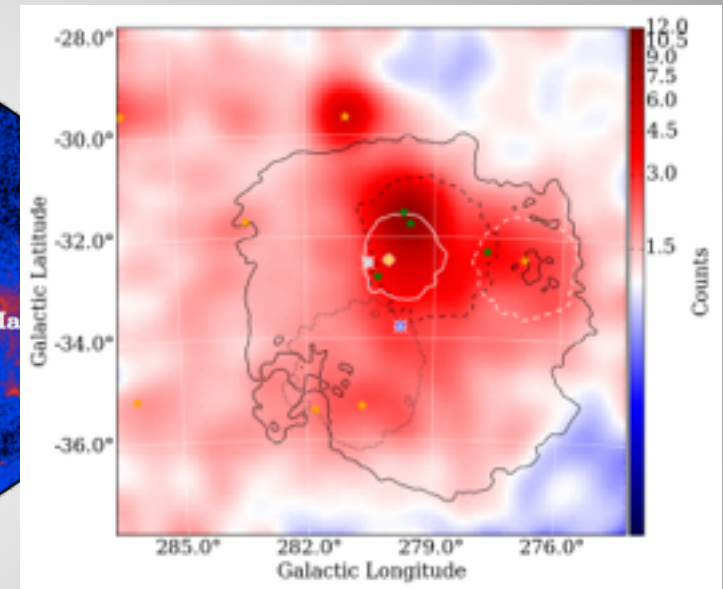
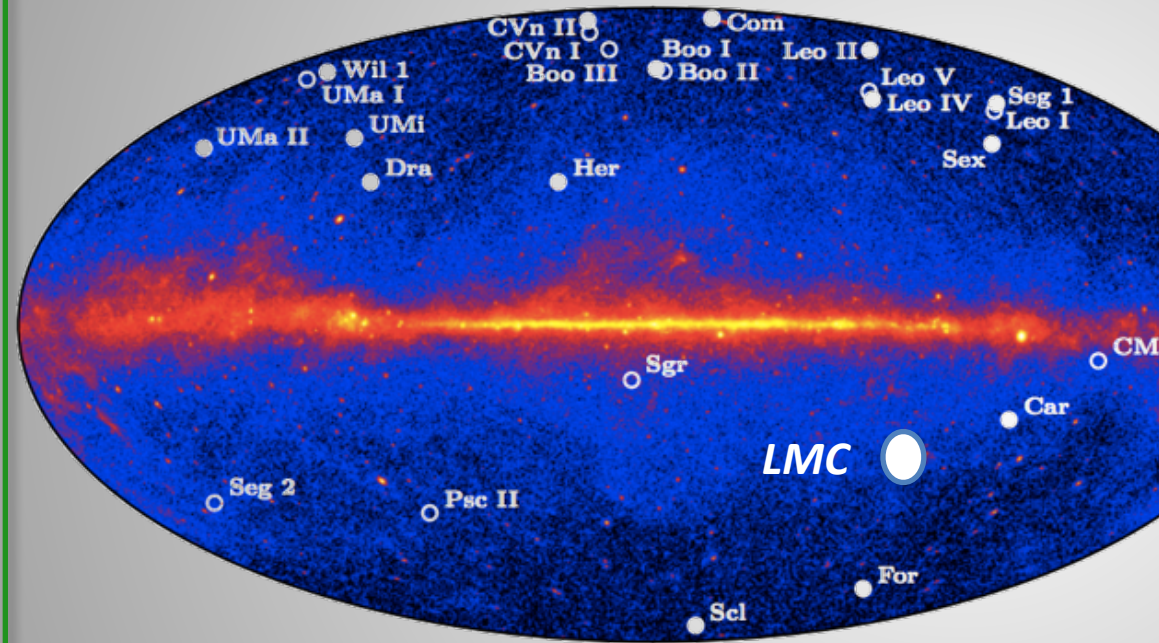


# Dwarf Spheroidal Satellite Galaxies: Combined





# Large Magellanic Cloud

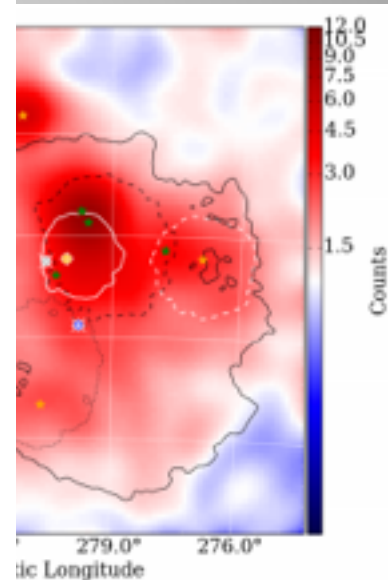
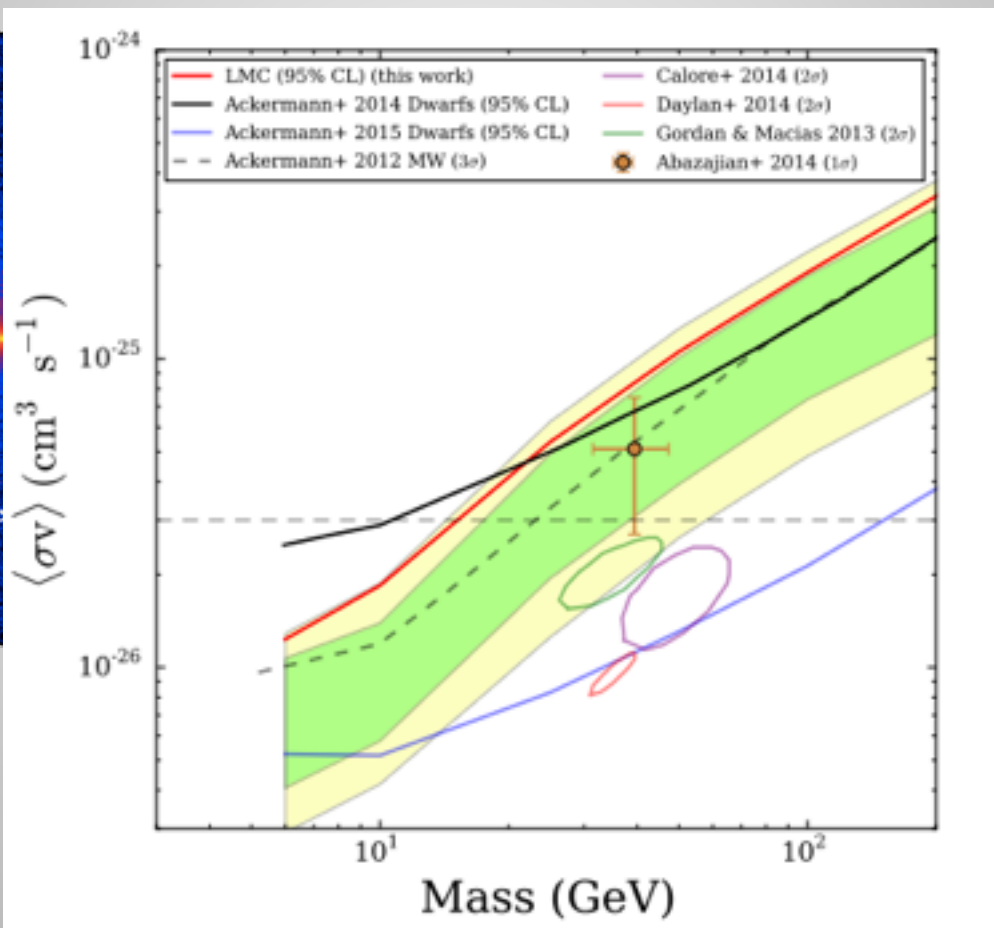
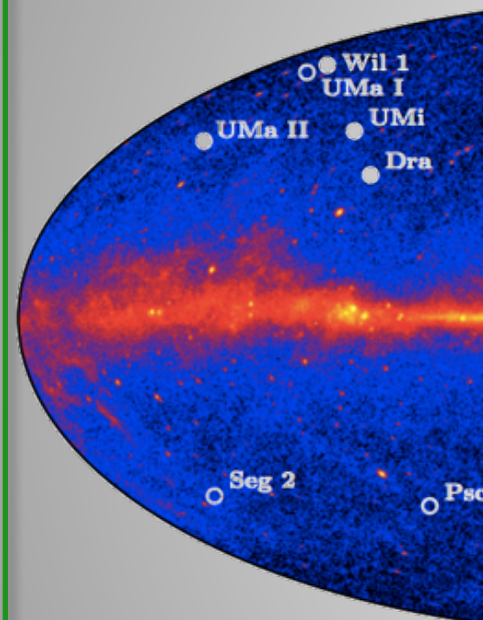


M. Buckley, et al.,  
 Phys. Rev. D, 91.102001, (2015)  
 arXiv: 1502.01020





# Large Magellanic Cloud



J-factor:  
 $\log_{10} J \sim 20$   
 Distance: 50 kpc

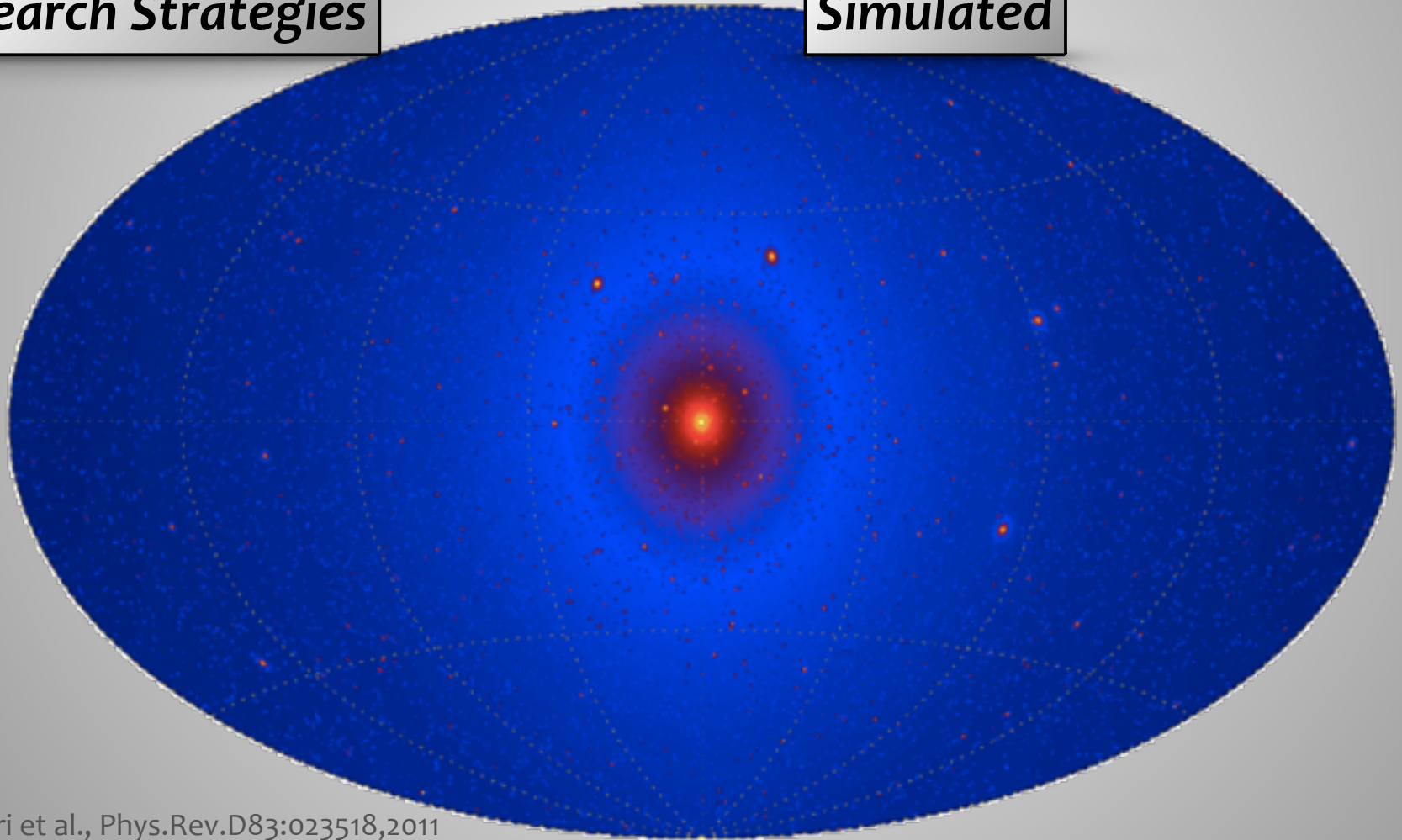
M. Buckley, et al.,  
 Phys. Rev. D, 91.102001, (2015)  
 arXiv: 1502.01020



# Dark Matter Distribution

*Search Strategies*

*Simulated*



L. Pieri et al., Phys.Rev.D83:023518,2011

R. Caputo , UCSC | Mitchell Workshop 2015



# Dark Matter Distribution

**Search Strategies**

**Simulated**

**Galaxy Clusters**

**Dwarf Spheroidal  
Satellite Galaxies**

**Galactic Center**

**Milky Way Halo**

**Spectral Lines**

**Isotropic Background**

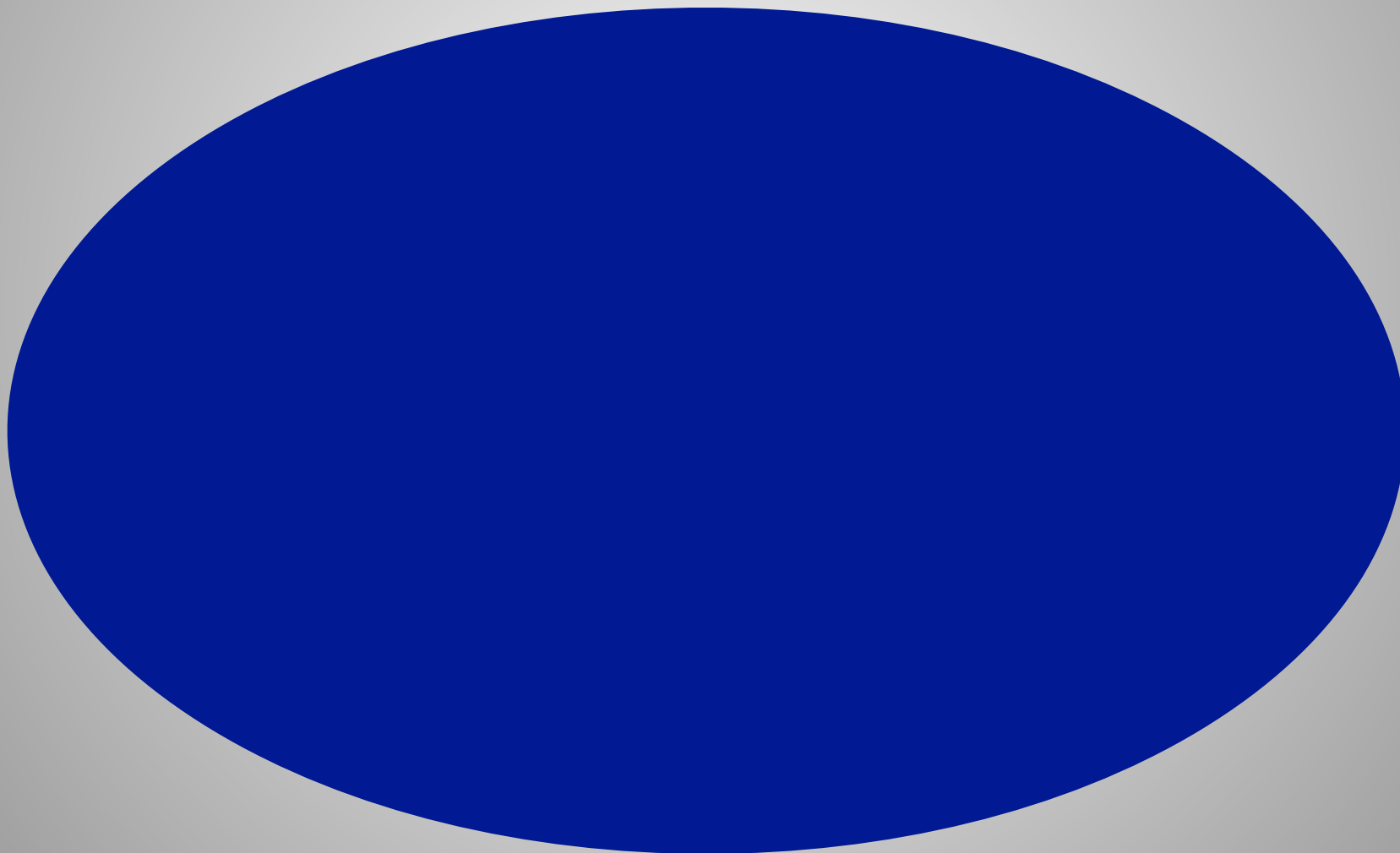
arXiv:1501.05464

Submitted to JCAP





# Isotropic $\gamma$ -ray Background







# Isotropic $\gamma$ -ray Background

Extragalactic  $\gamma$ -ray Background =  
Isotropic Diffuse  $\gamma$ -ray Background + resolved sources

- + **Blazars**
- + **Gamma Ray Bursts (GRBs)**
- + **Radio Galaxies**
- + **Star Forming Galaxies**
- + **Galaxy Clusters (ul)**
- + **Cascades (ul) + ...**



# Isotropic $\gamma$ -ray Background

Extragalactic  $\gamma$ -ray Background =  
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**+ Radio Galaxies**

**+ Star Forming Galaxies**

**+ Galaxy Clusters (ul)**

**+ Cascades (ul) + ...**

**Dark Matter  
Annihilation/Decay**



# Isotropic $\gamma$ -ray Background

Extragalactic  $\gamma$ -ray Background =  
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**+ Gamma Ray Bursts (GRBs)**

**+ Radio Galaxies**

**+ Star Forming Galaxies**

**+ Galaxy Clusters (ul)**

**+ Cascades (ul) + ...**

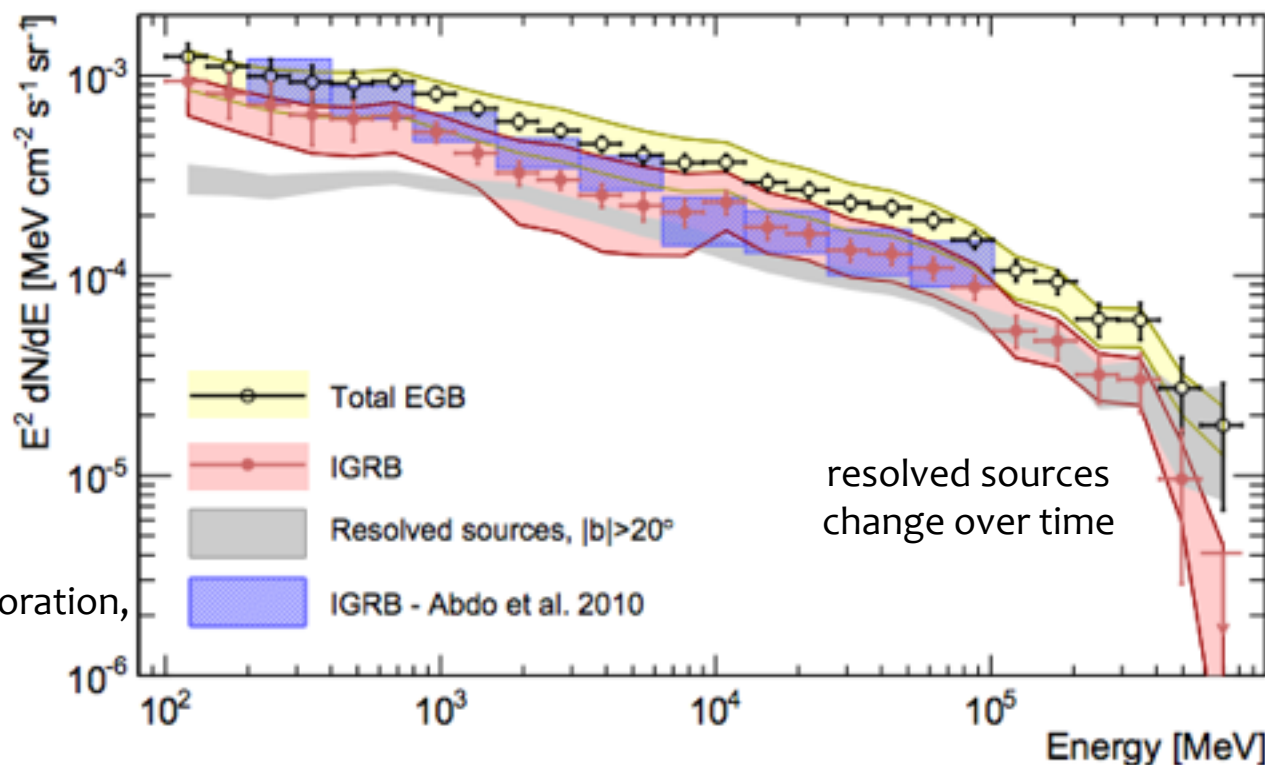
**Dark Matter  
Annihilation/Decay**

**Unknown  
Sources/Processes!**



# Isotropic $\gamma$ -ray Background

Extragalactic  $\gamma$ -ray Background =  
Isotropic Diffuse  $\gamma$ -ray Background + resolved sources



+Blaz  
+

atter  
decay

Fermi-LAT Collaboration,  
Accepted ApJ  
arXiv: 1410.3696





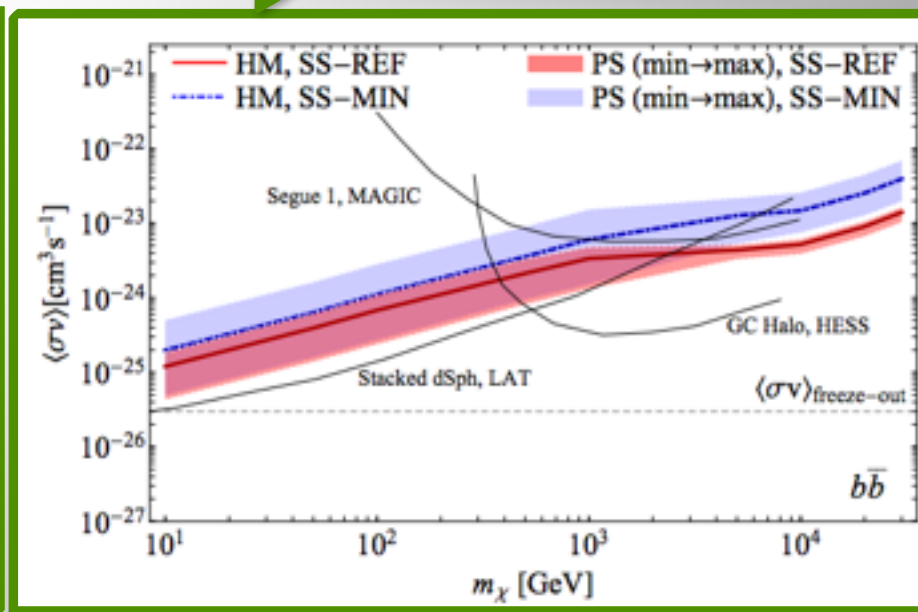
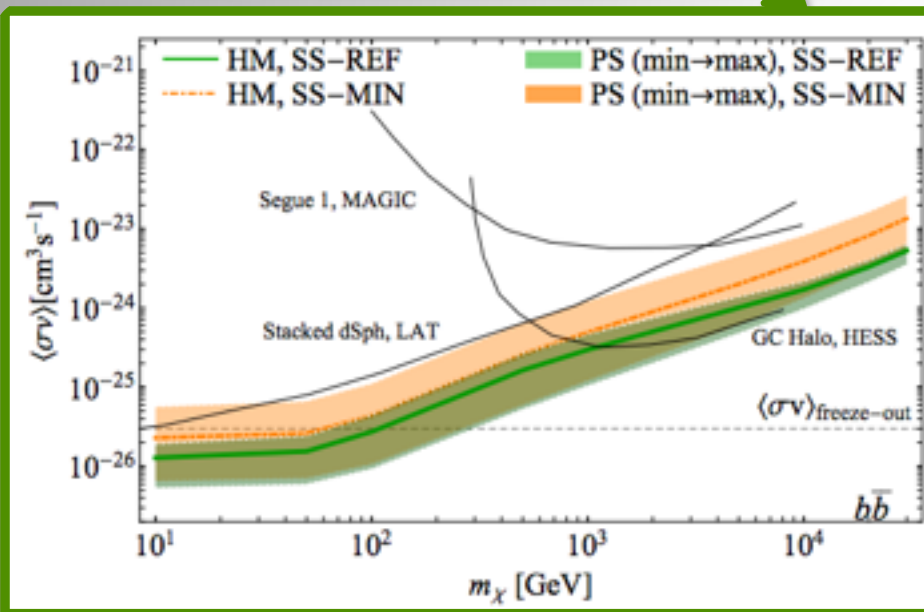
# Isotropic $\gamma$ -ray Background

## Two Models:

Halo Model (HM)  
Power Spectrum (PS)

## Two Scenarios:

All IGRB is DM  
None of IGRB is DM





# Indirect Dark Matter

Today      2015      2018      2020      2023      2025



# Indirect Dark Matter

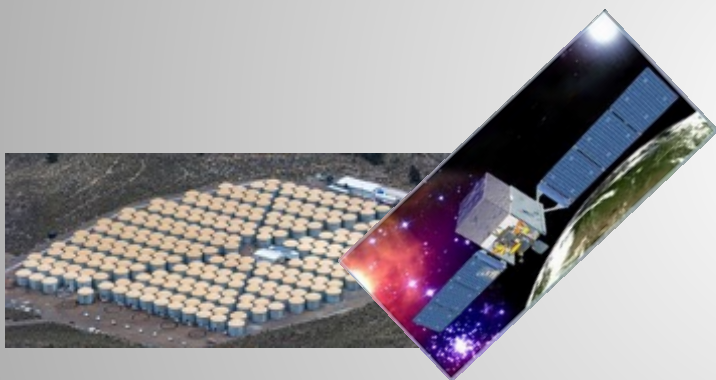
Just beginning to probe the  
most **theoretically motivated**  
regions of **dark matter**  
**parameter space**

Today      2015      2018      2020      2023      2025



# Indirect Dark Matter

Just beginning to probe the most **theoretically motivated** regions of **dark matter** parameter space



Fermi, ACT, WCT, AMS

Today	2015	2018	2020	2023	2025
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# Indirect Dark Matter

Just beginning to probe the most **theoretically motivated** regions of **dark matter** parameter space



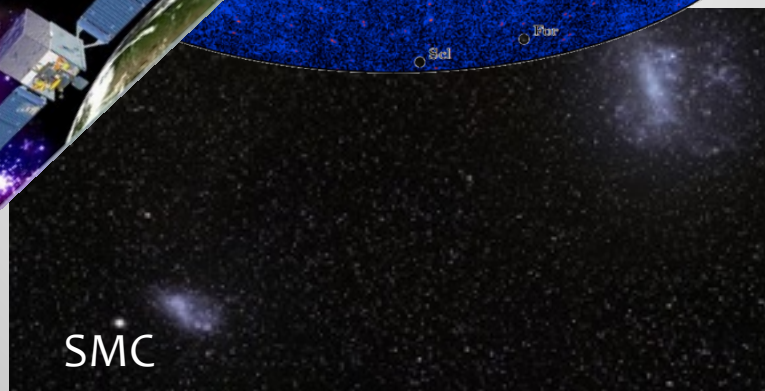
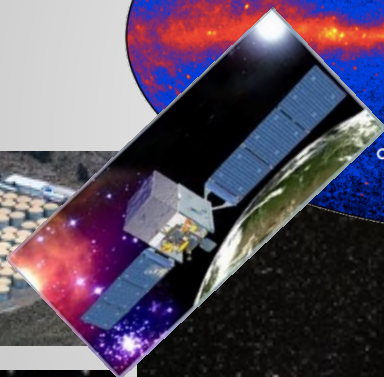
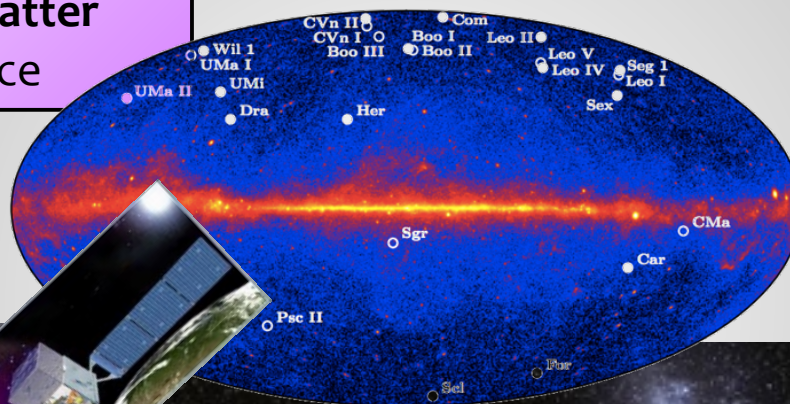
Fermi, ACT, WCT, AMS

Today      2015      2018      2020      2023      2025



# Indirect Dark Matter

Just beginning to probe the most **theoretically motivated** regions of **dark matter** parameter space



Fermi, ACT, WCT, AMS

LSST

Today

2015

2018

2020

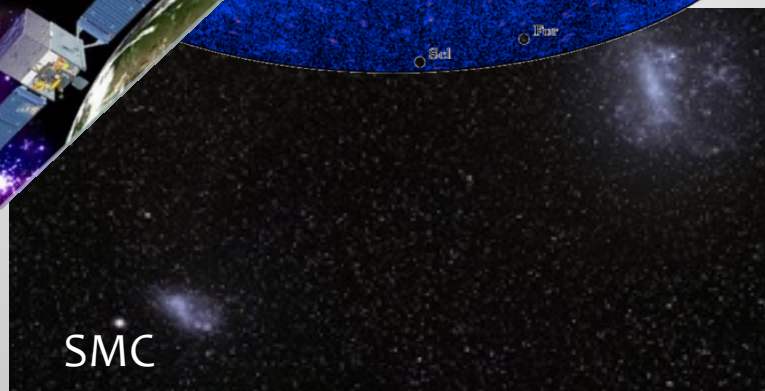
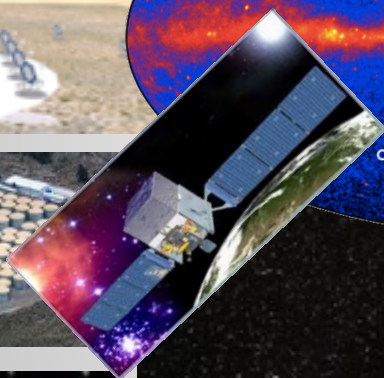
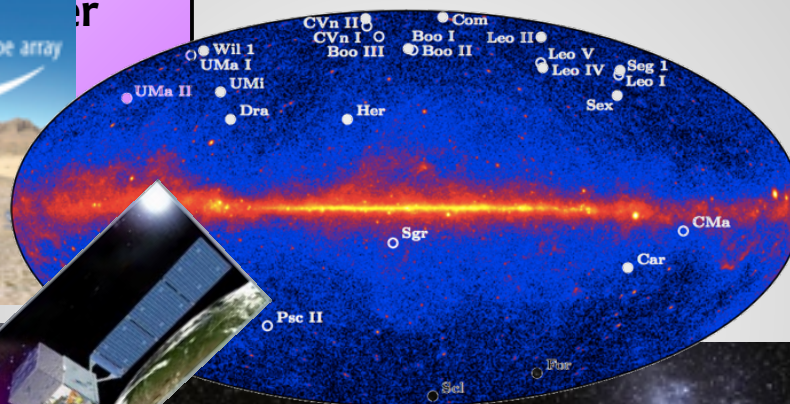
2023

2025



# Indirect Dark Matter

Just beginning to probe the



Fermi, ACT, WCT, AMS

LSST

CTA

Today

2015

2018

2020

2023

2025

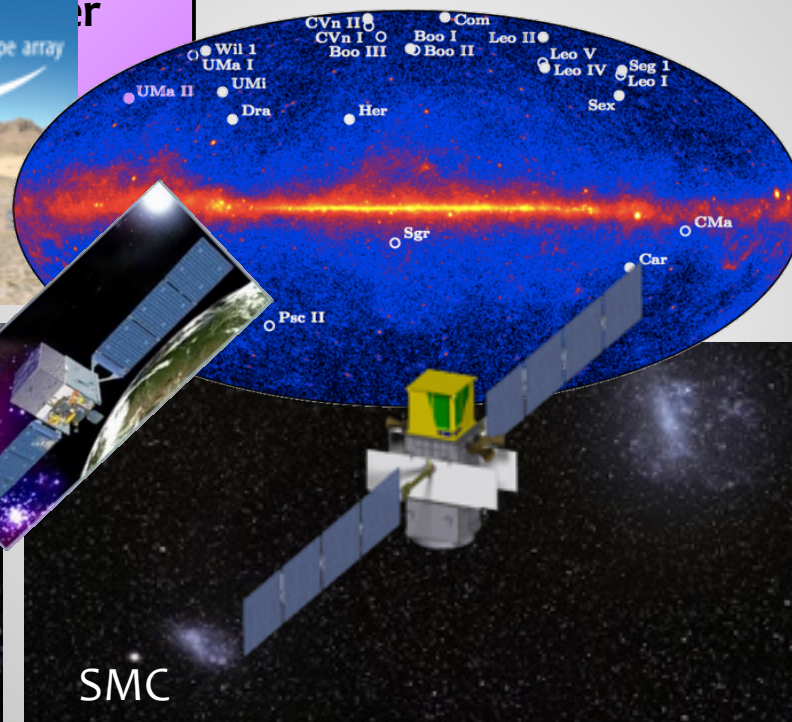
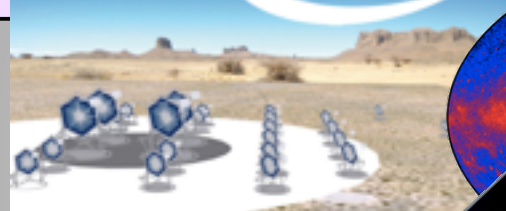
SMC





# Indirect Dark Matter

Just beginning to probe the



Fermi, ACT, WCT, AMS

Today

2015

2018

2020

LSST

CTA

2023

AstroGAM

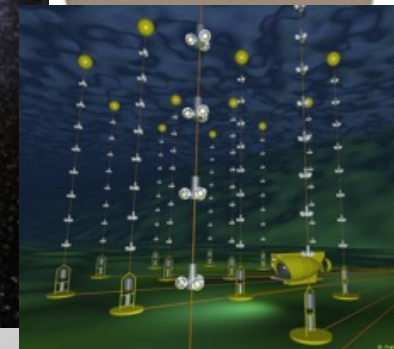
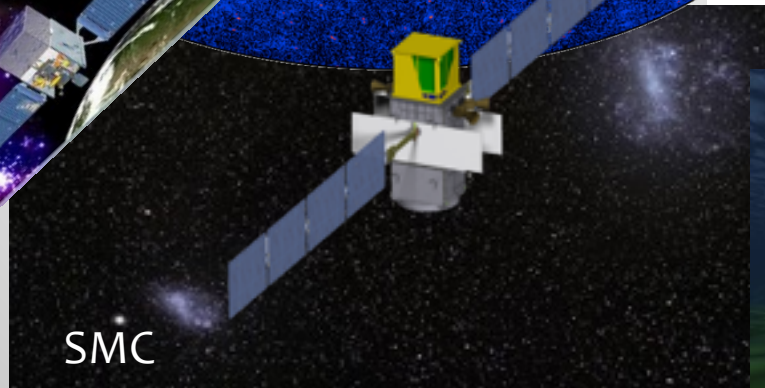
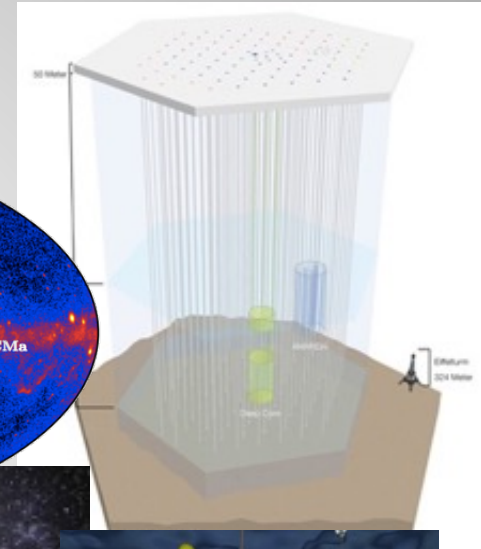
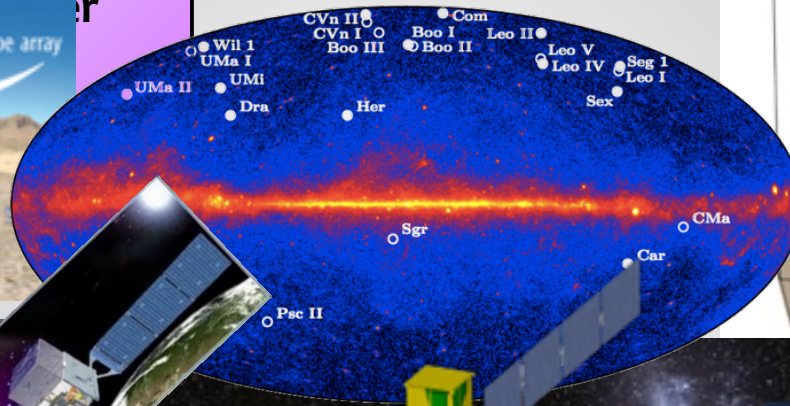
2025





# Indirect Dark Matter

Just beginning to probe the



Fermi, ACT, WCT, AMS

Today

2015

2018

2020

LSST

CTA

AstroGAM

2023

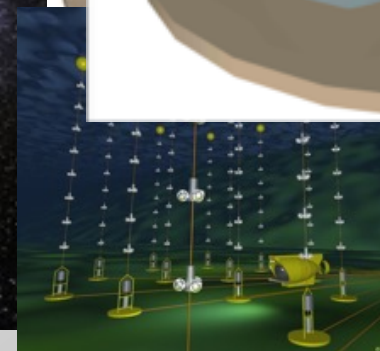
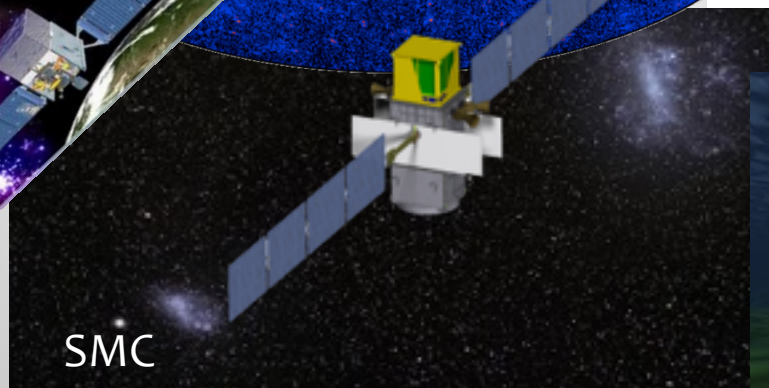
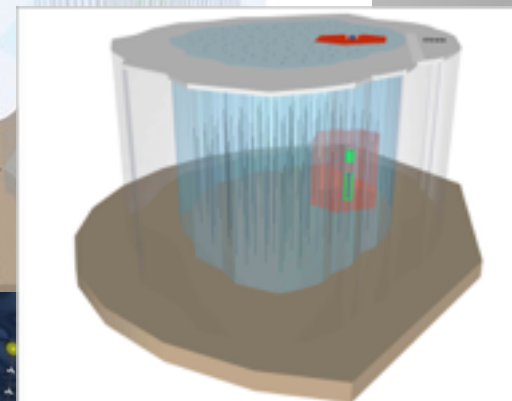
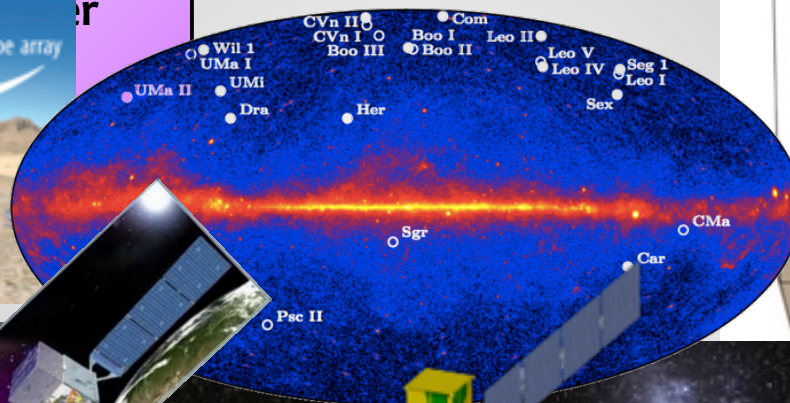
2025

IceCube/ANTARES



# Indirect Dark Matter

Just beginning to probe the



Fermi, ACT, WCT, AMS

LSST

CTA

AstroGAM

Today

2015

2018

2020

2023

2025

IceCube/ANTARES

IceCube-Gen 2

PINGU



*Thank you!*

**BACKUPS**