



Fermi

Gamma-ray Space Telescope



# Searching for Dark Matter with the Fermi-LAT

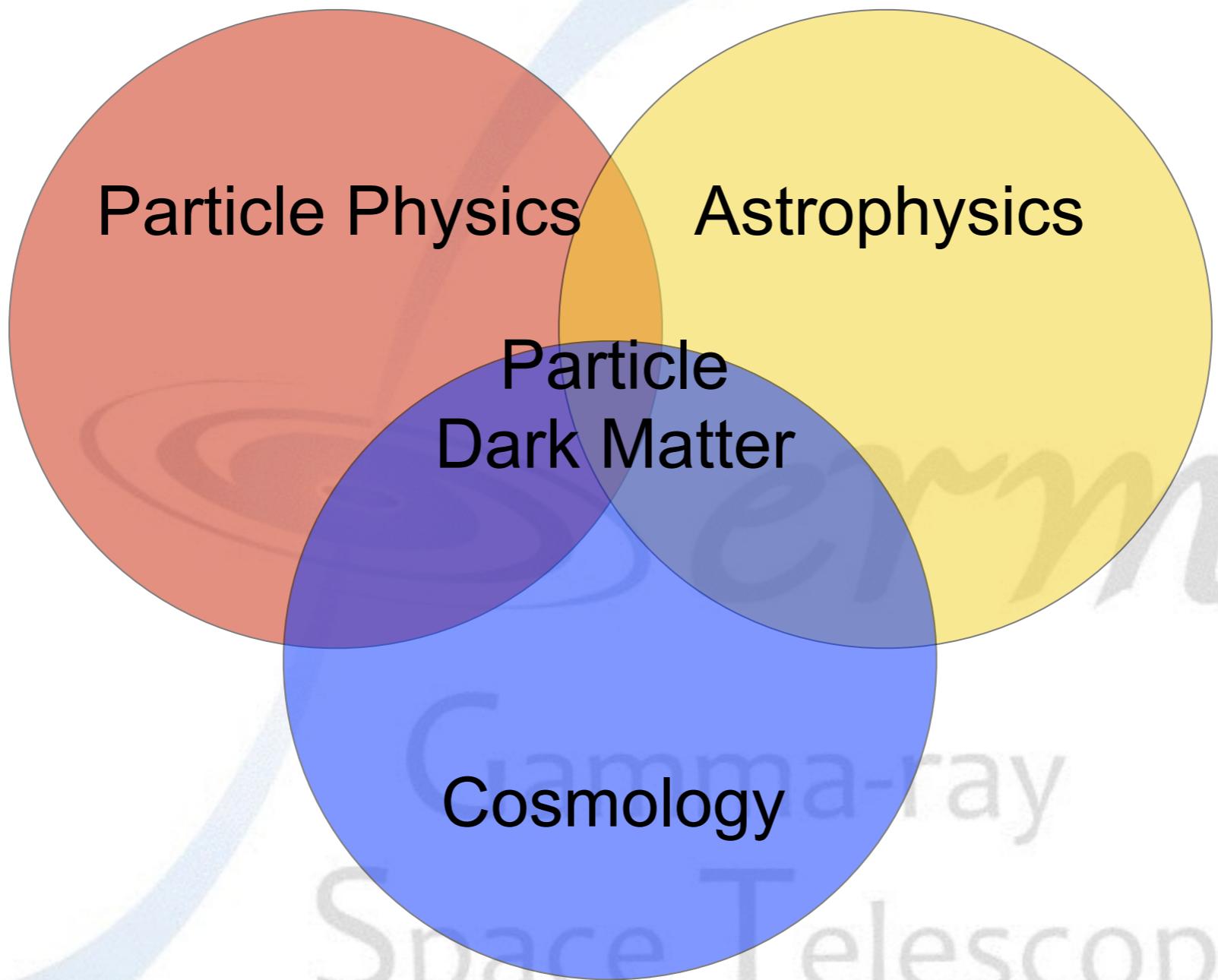
R. Caputo, UCSC  
Fermi Summer School  
Lewes, DE

9 June 2016



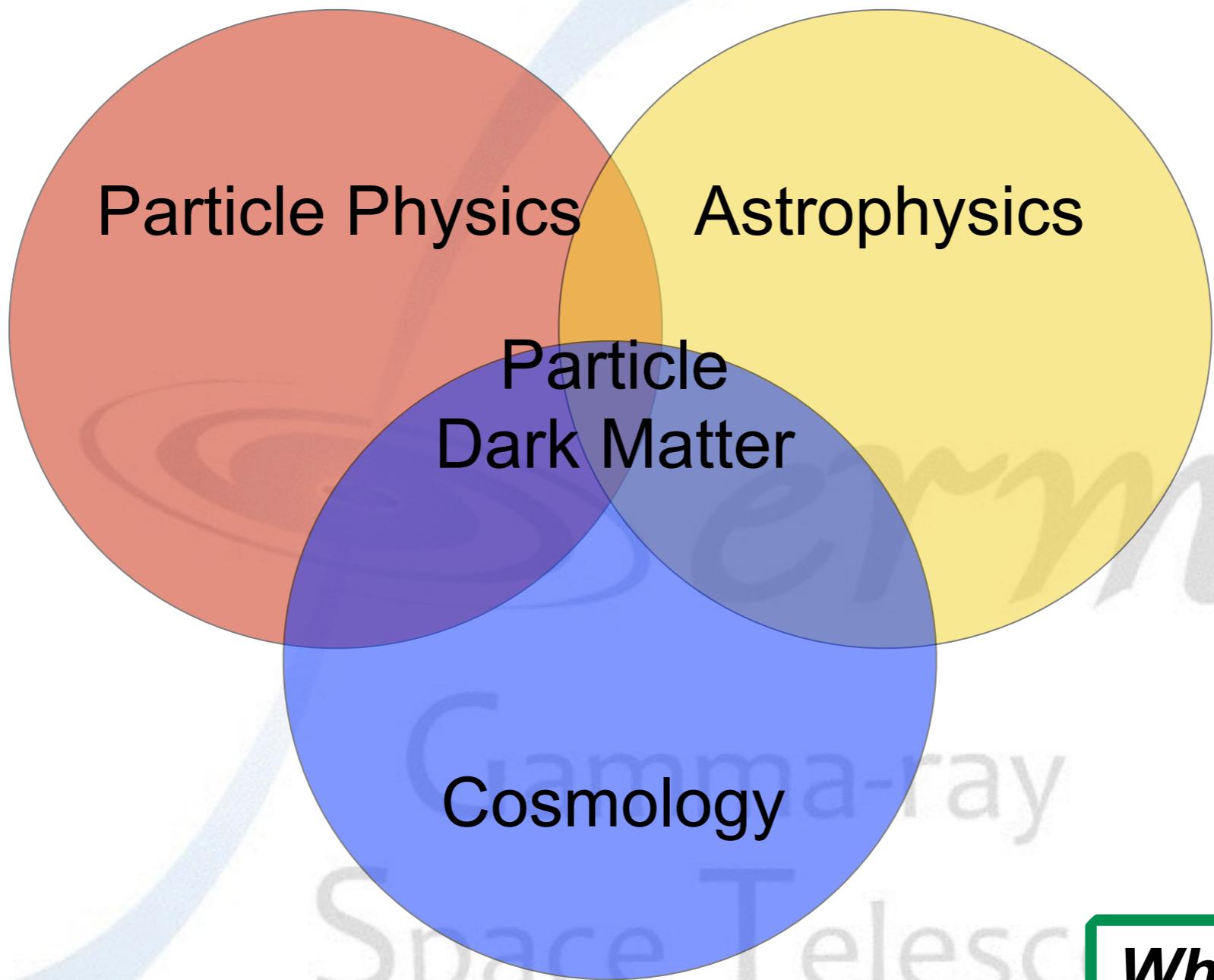


# A Brief History of Dark Matter



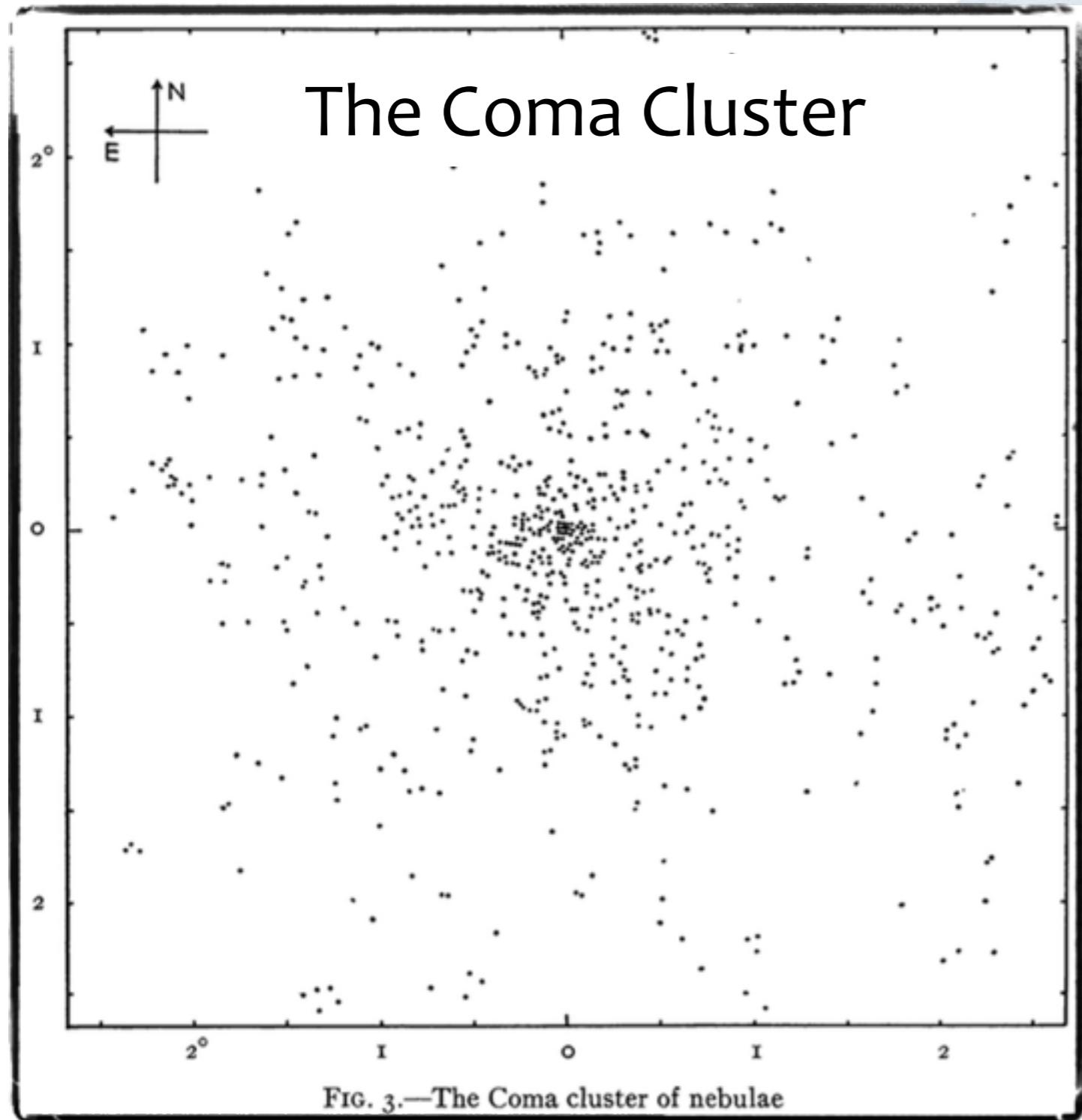


# A Brief History of Dark Matter



**Why...?**

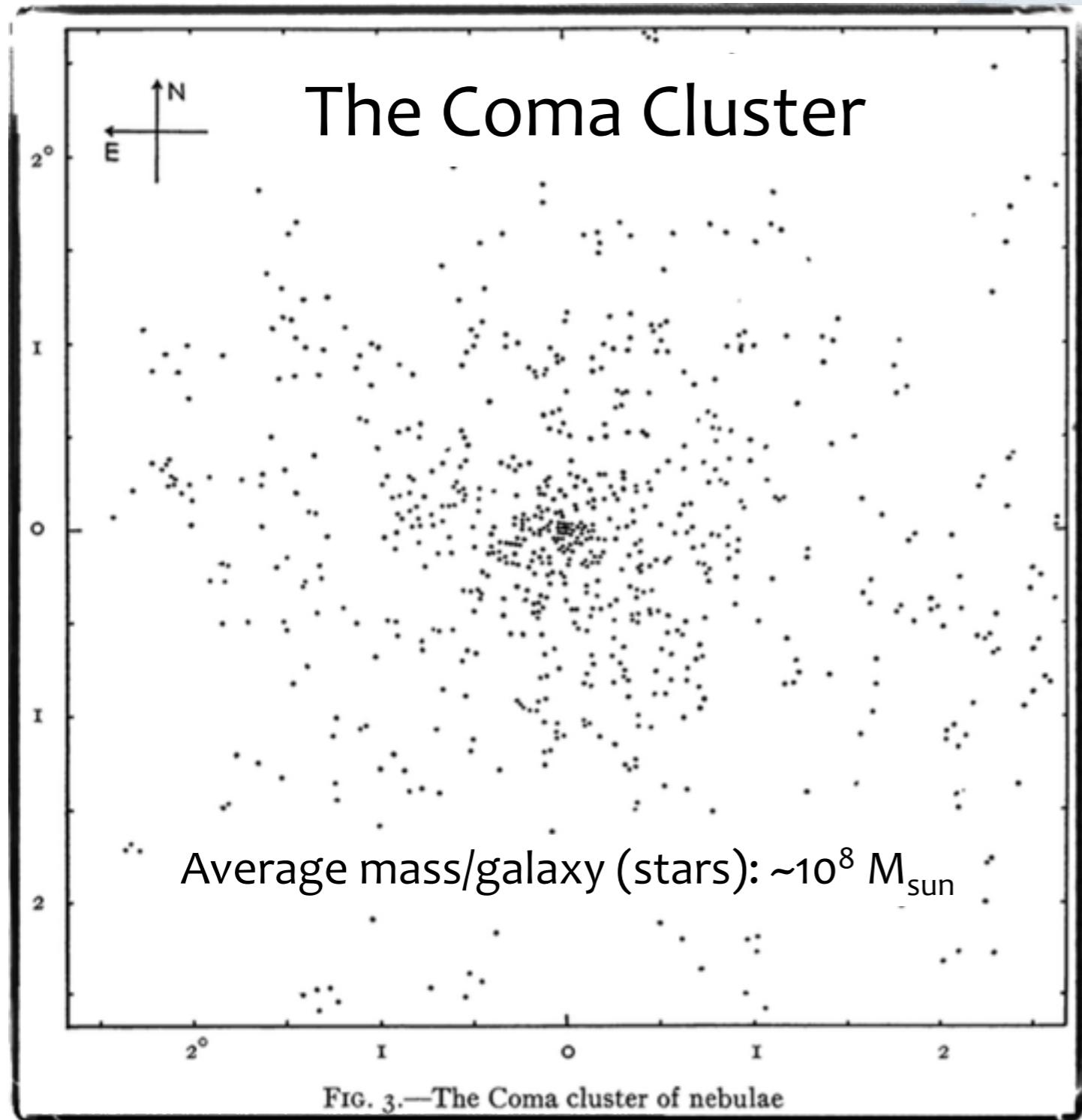
# The Mystery of Missing Mass



1930s- Zwicky, others

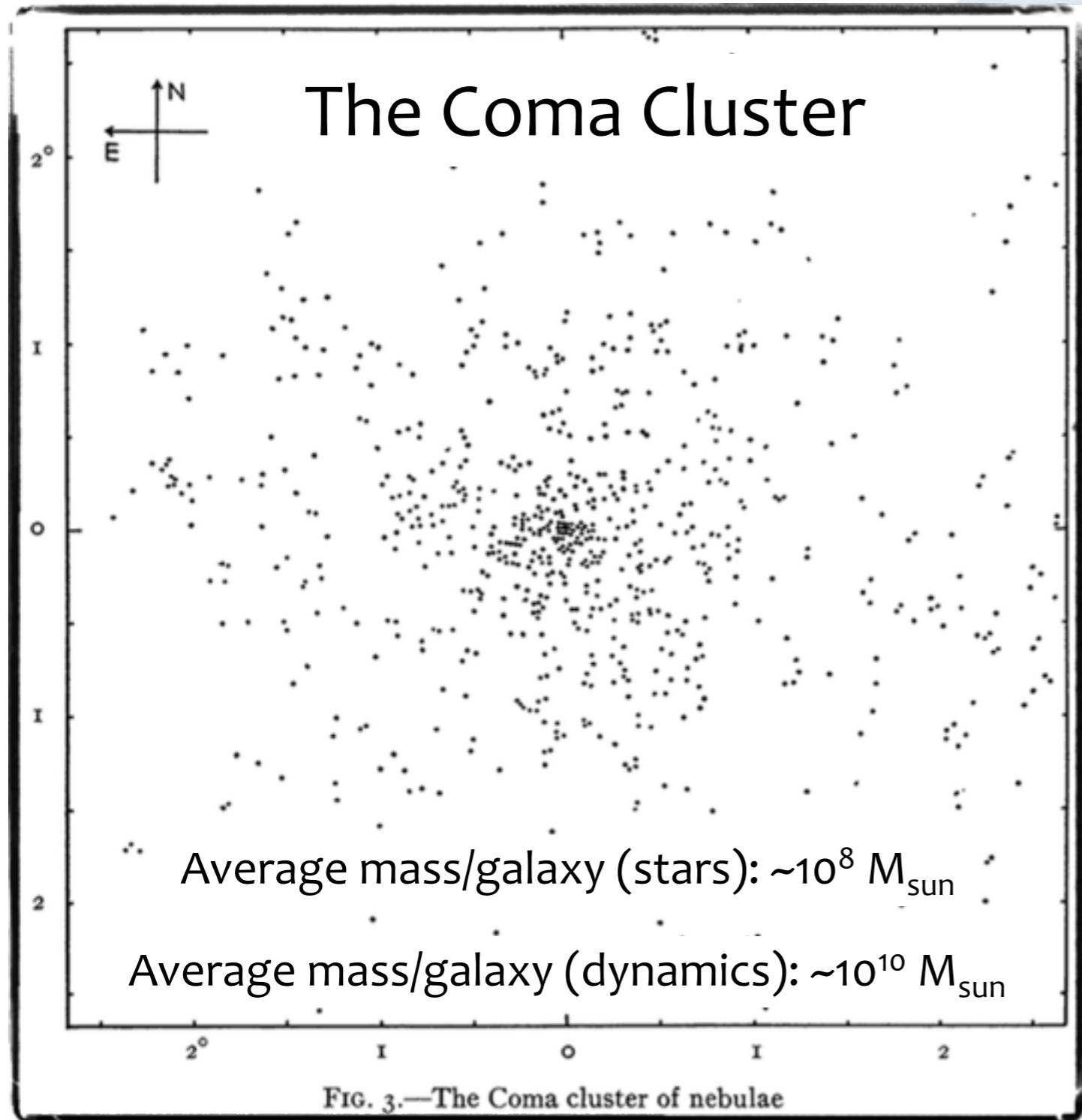
fermi  
gamma-ray  
telescope

# The Mystery of Missing Mass



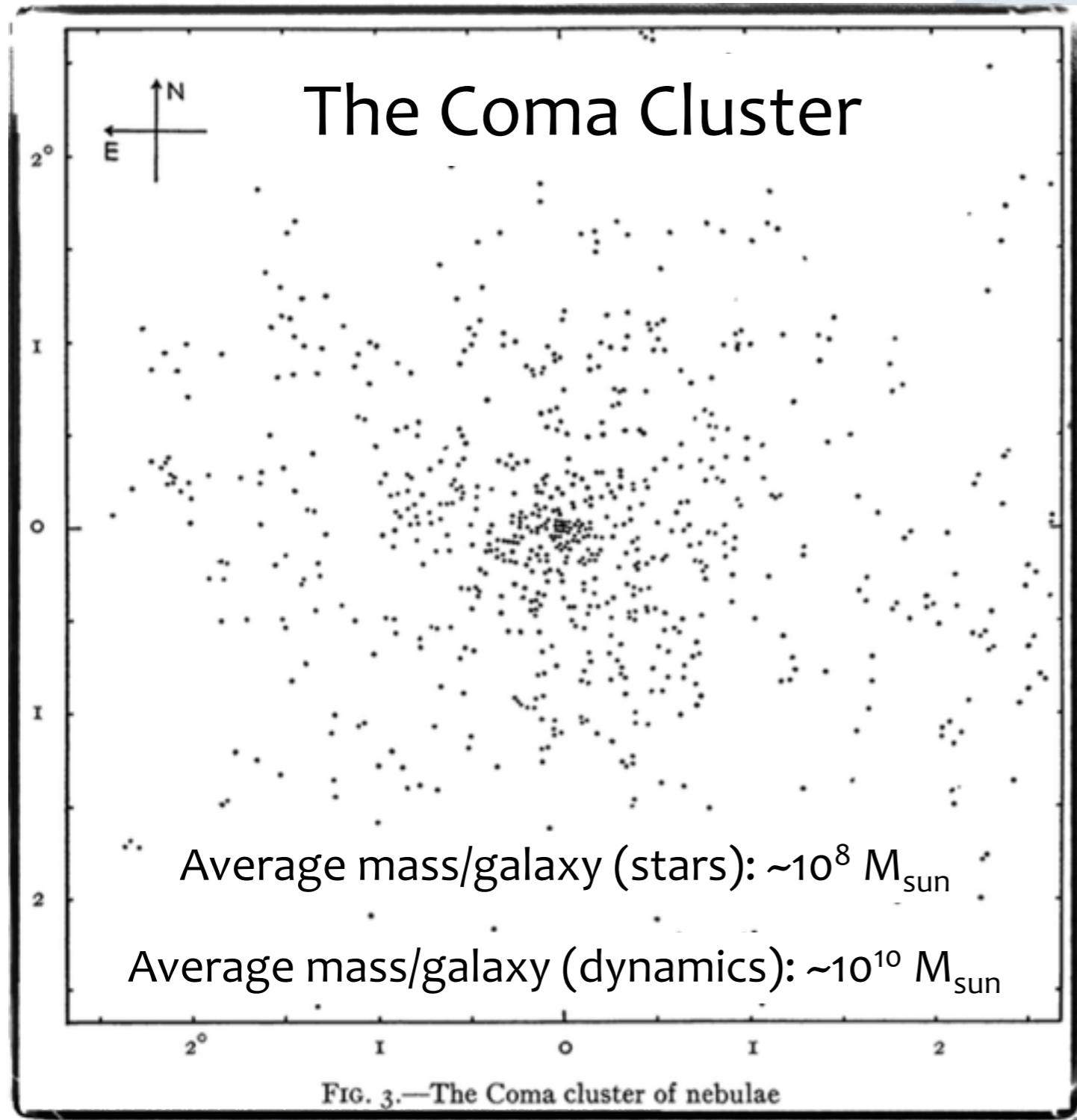
1930s- Zwicky, others

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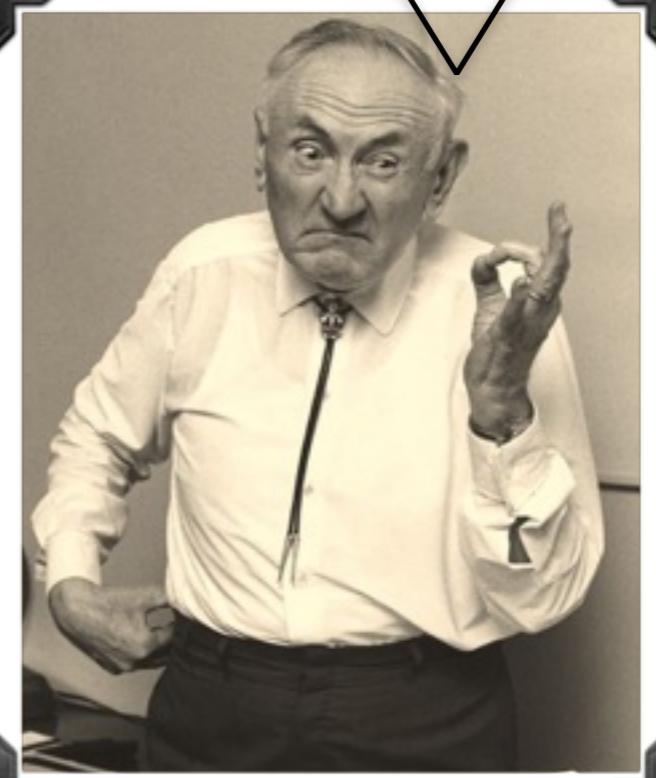
1930s- Zwicky, others

# The Mystery of Missing Mass



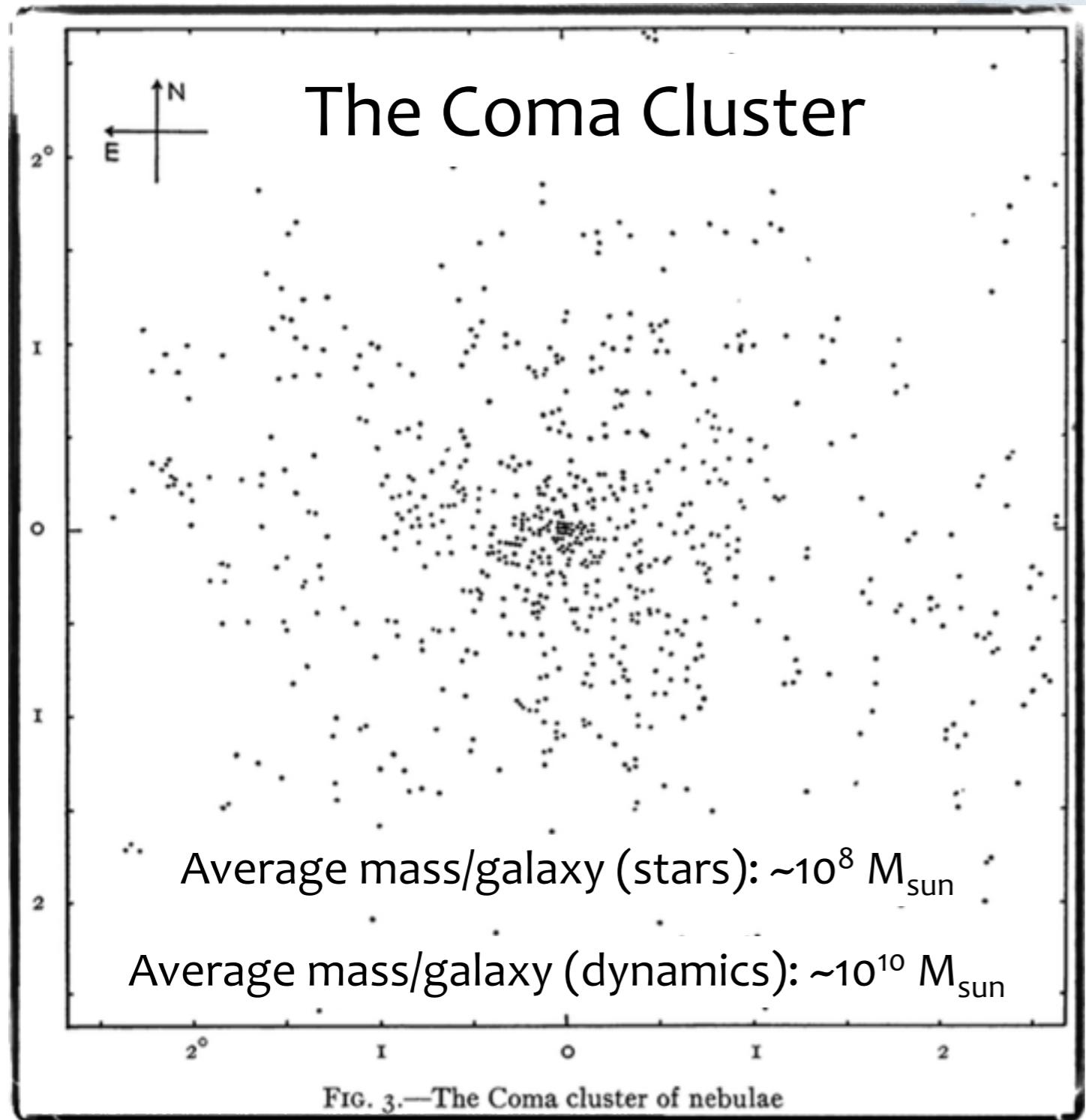
1930s- Zwicky, others

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



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!

# The Mystery of Missing Mass



1970s- Rubin, Ford,  
Thonnard  
Galactic Rotation Curves

Keplerian:  
 $v(r) \sim M(r)/\sqrt{r}$



YouTube: <https://www.youtube.com/watch?v=Omjx3OKAGDo>  
<http://cse.ssl.berkeley.edu/bmendez/ay10/2002/notes/lec18.html>

# The Mystery of Missing Mass



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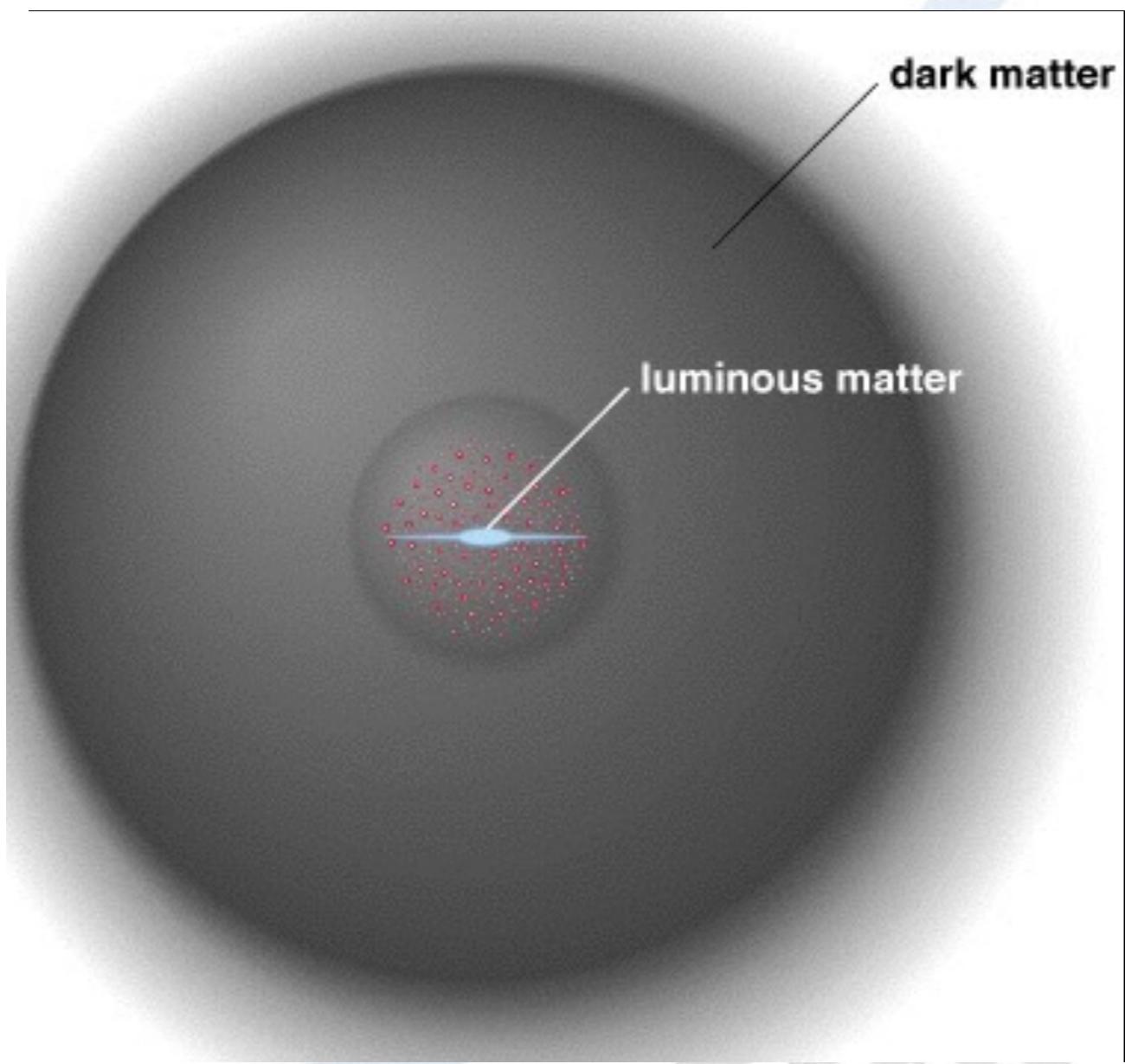
1970s- Rubin, Ford,  
Thonnard  
Galactic Rotation Curves

Keplerian:  
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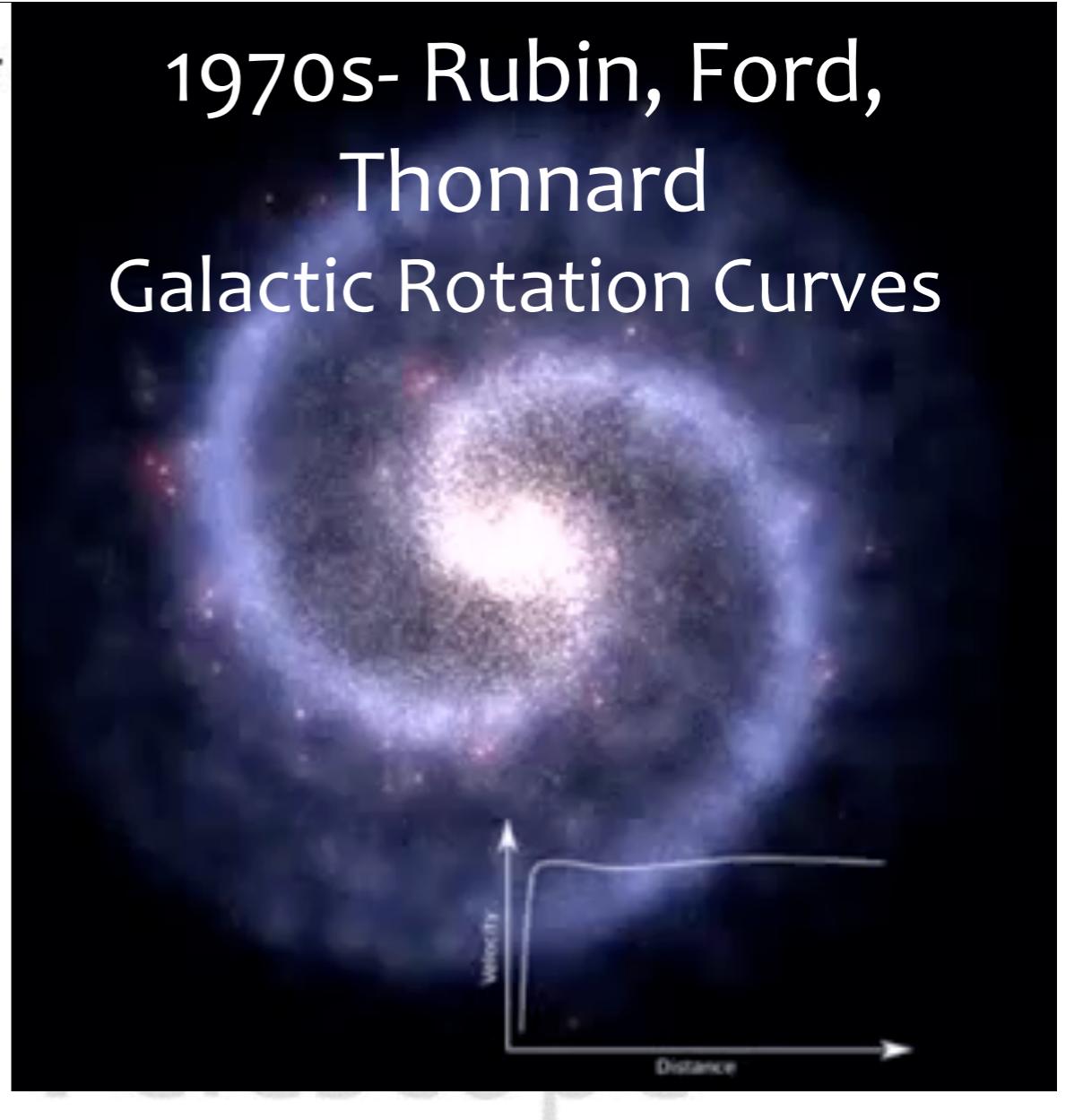


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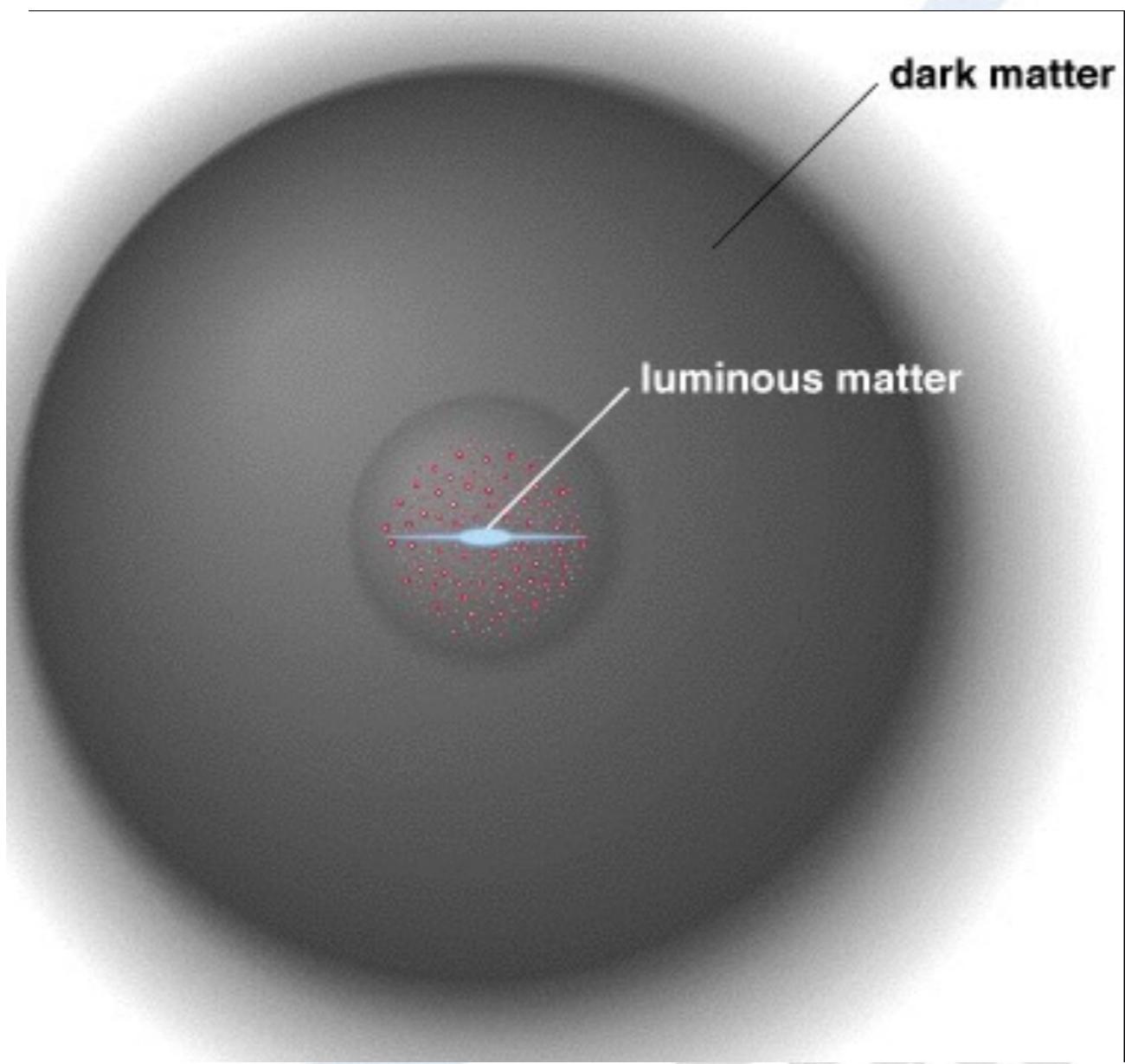


1970s- Rubin, Ford,  
Thonnard  
Galactic Rotation Curves

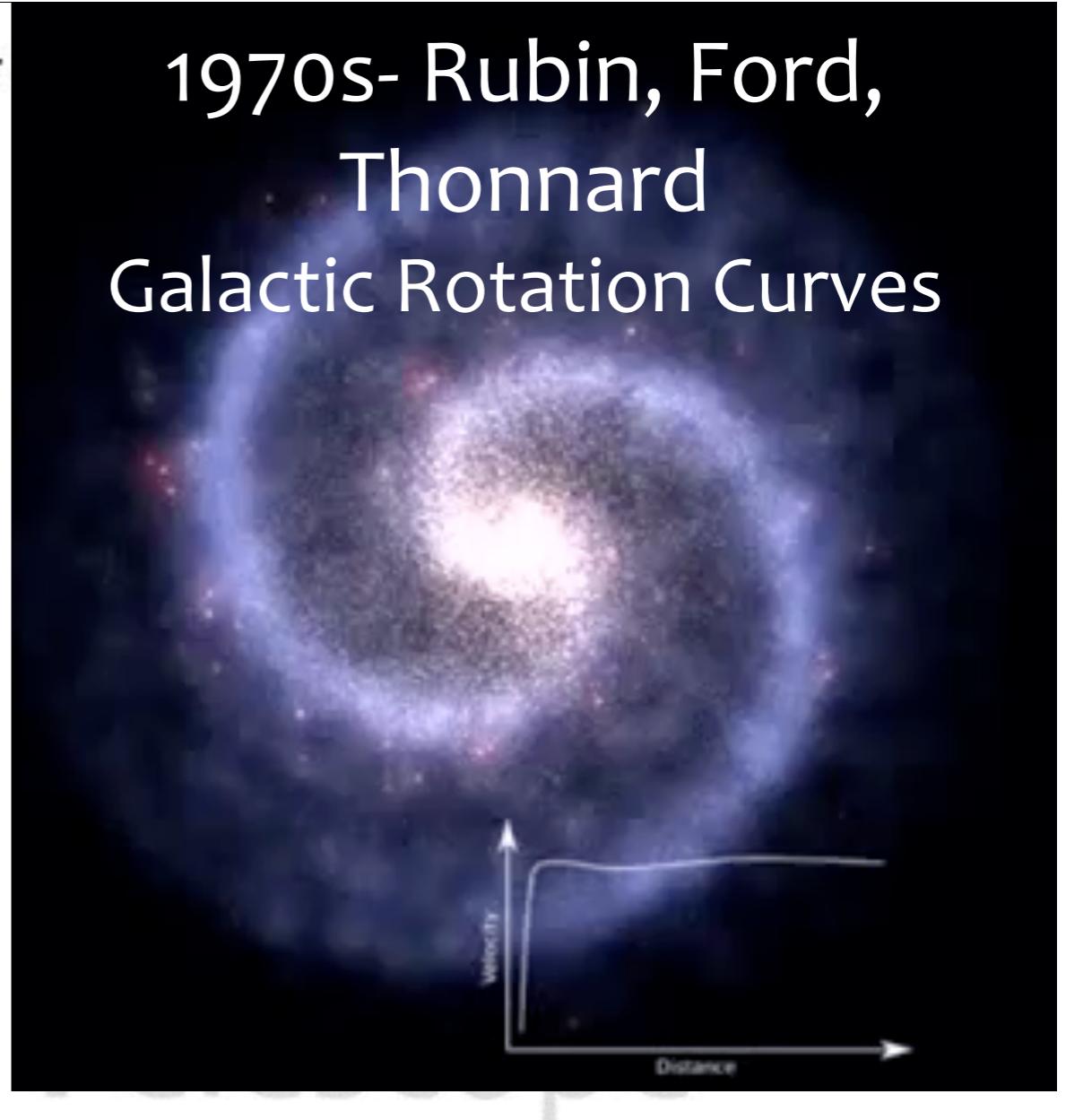


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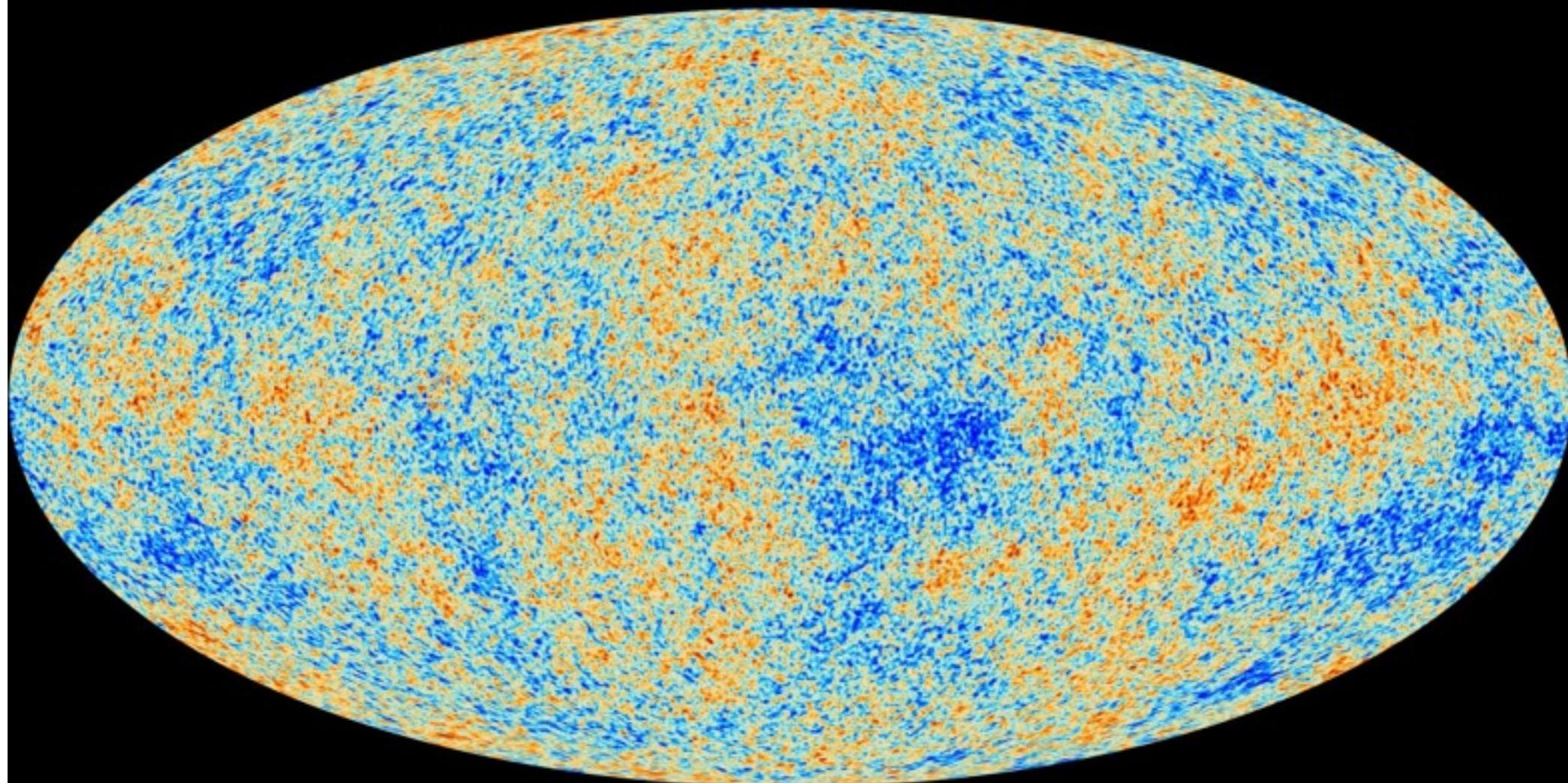


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# Precision Cosmology



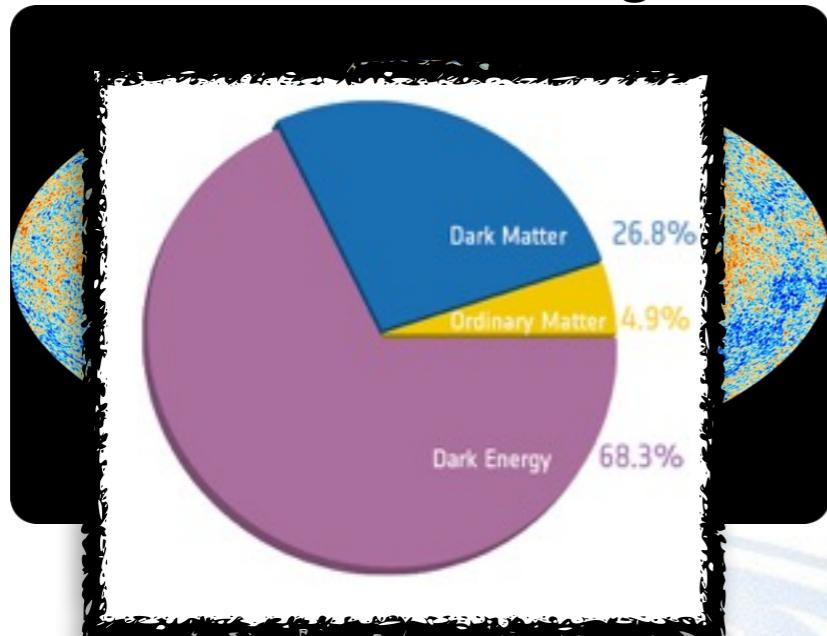
Cosmic Microwave Background



# Precision Cosmology



## Cosmic Microwave Background

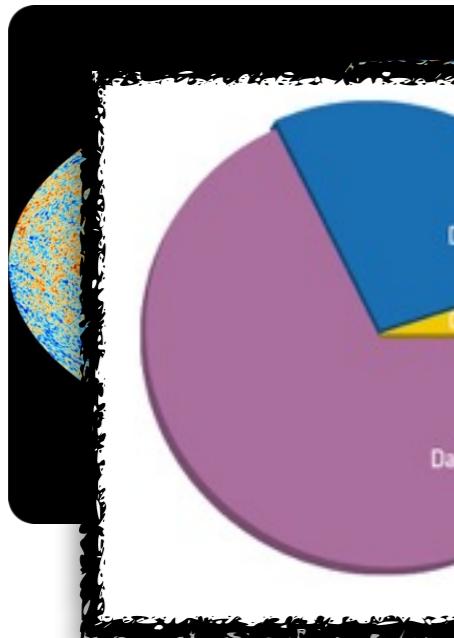


ermi  
Gamma-ray  
Space Telescope

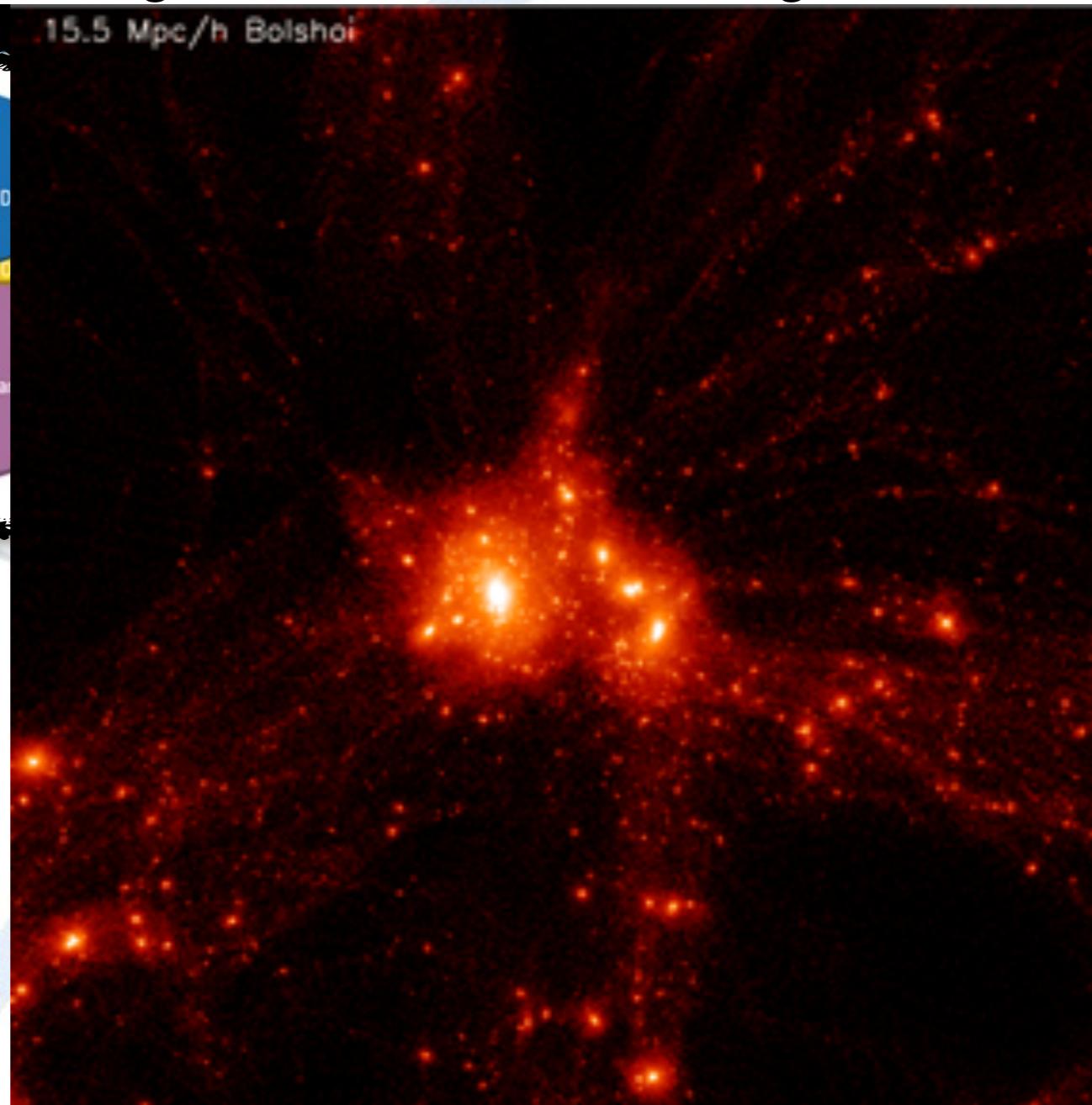
# Precision Cosmology



Cosmic Microwave Background



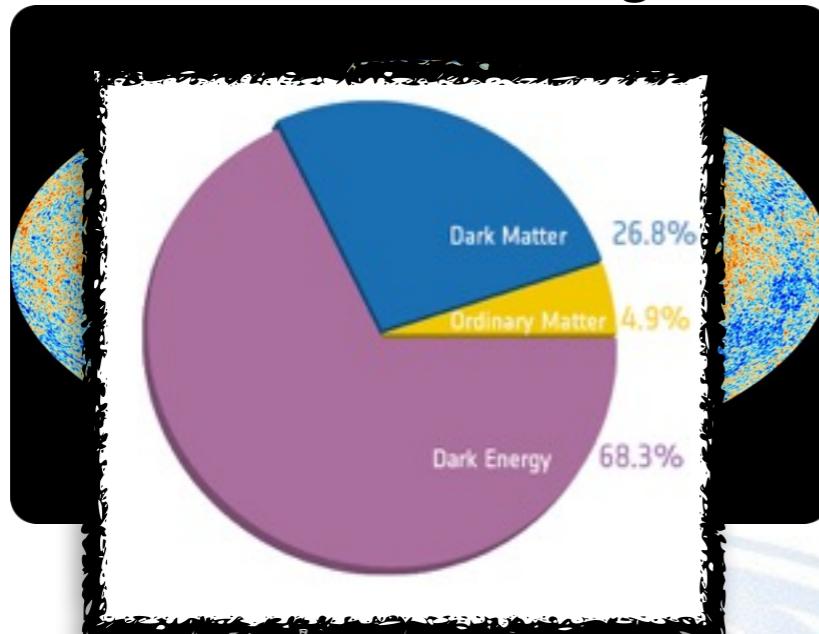
Large Scale Structure



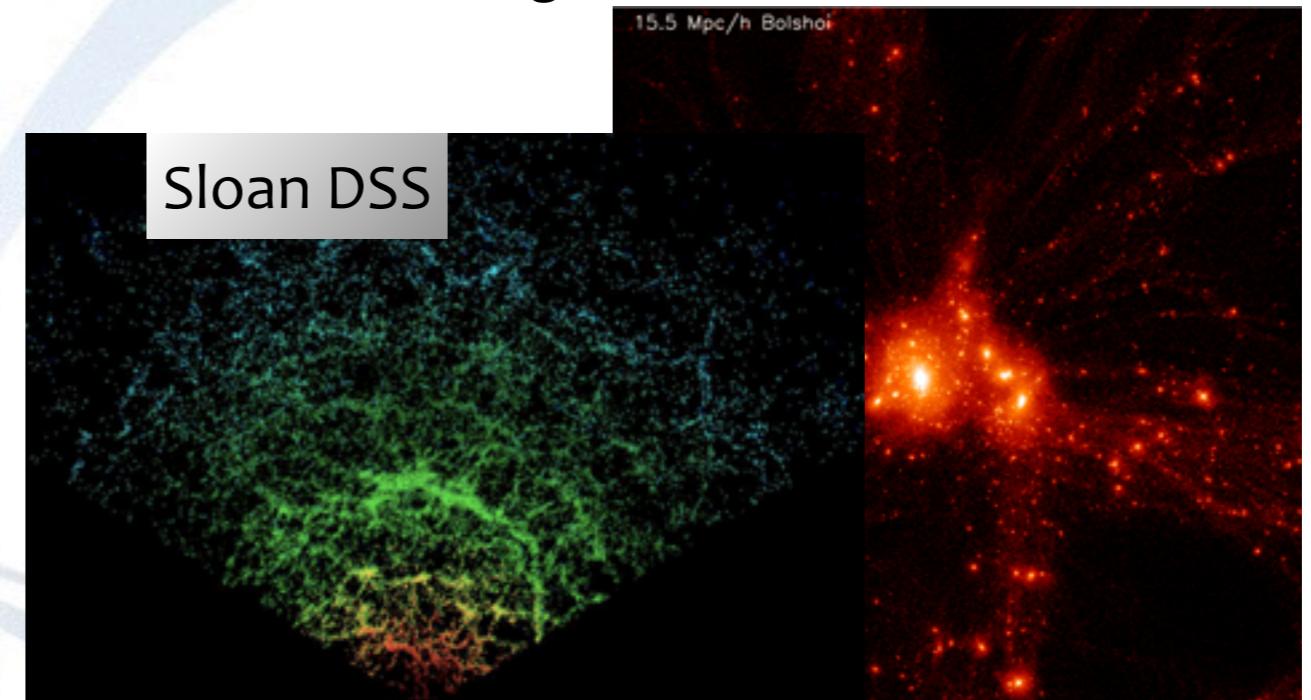
# Precision Cosmology



Cosmic Microwave Background



Large Scale Structure

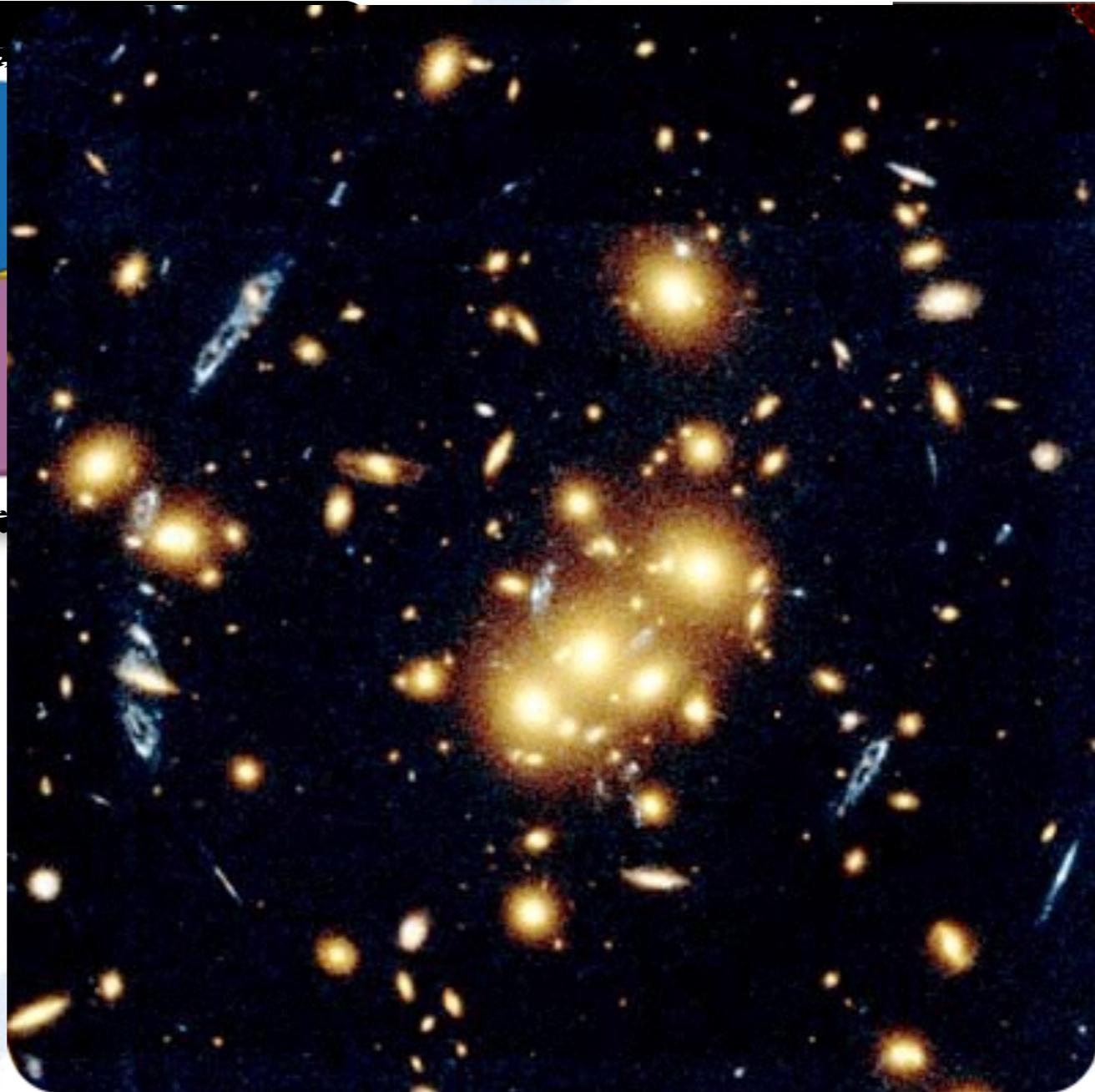
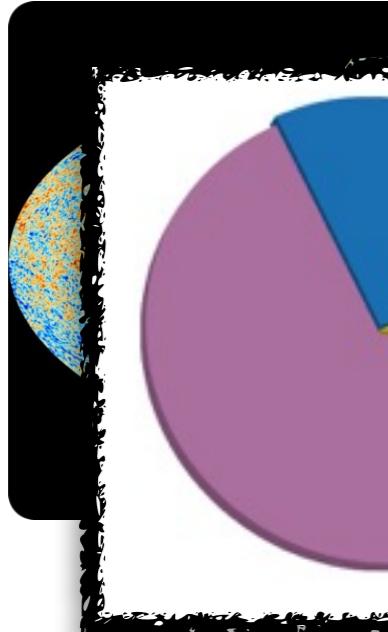


Gamma-ray  
Space Telescope

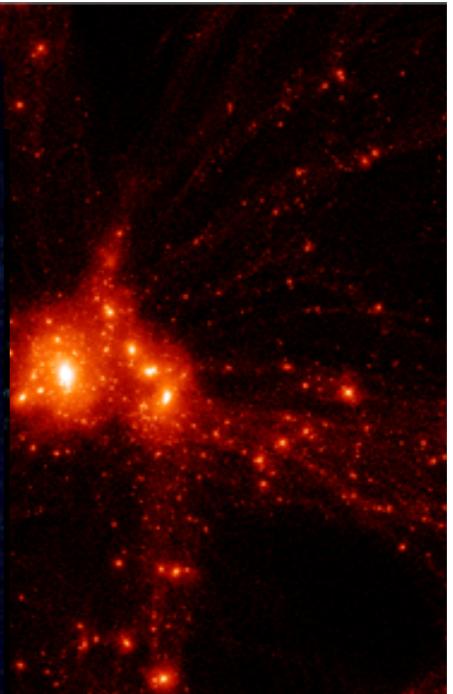
# Precision Cosmology



Cosmic Microwave Background



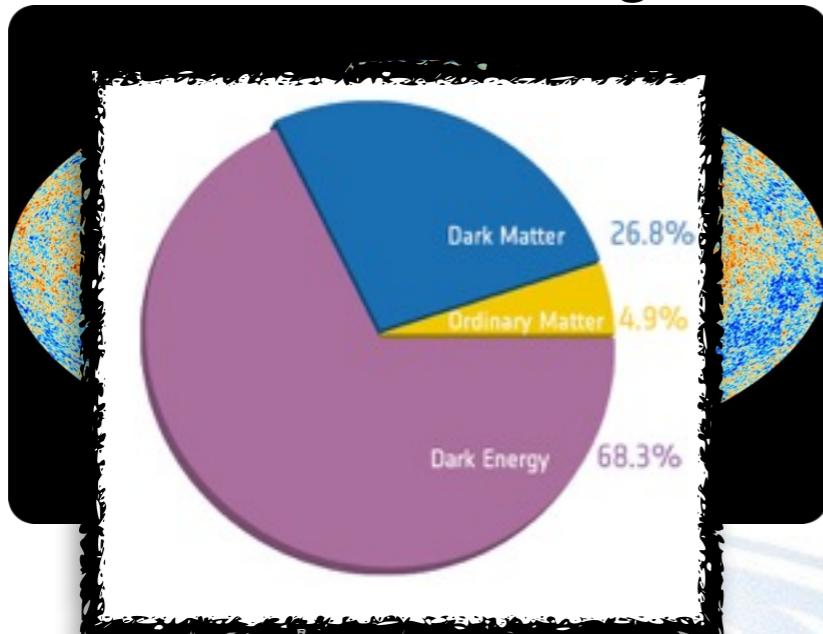
Large Scale Structure



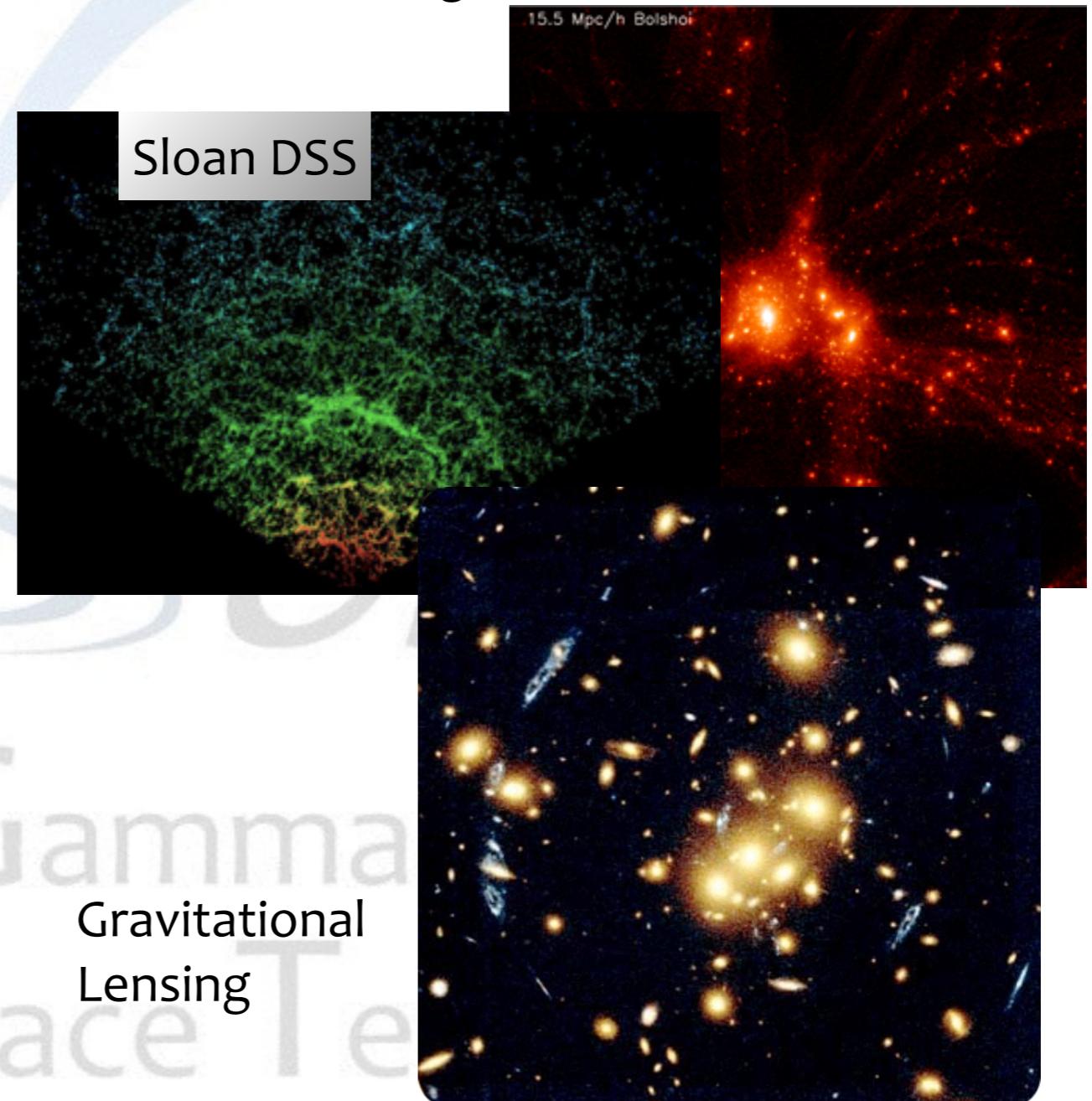
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Cosmic Microwave Background



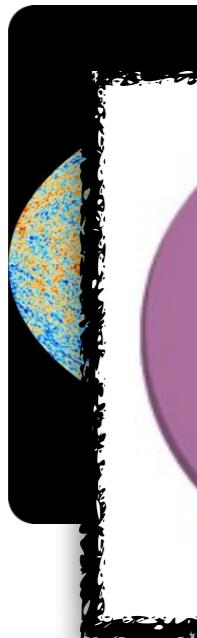
Large Scale Structure



# Precision Cosmology



Cosmic Microwave Background



Large Scale Structure

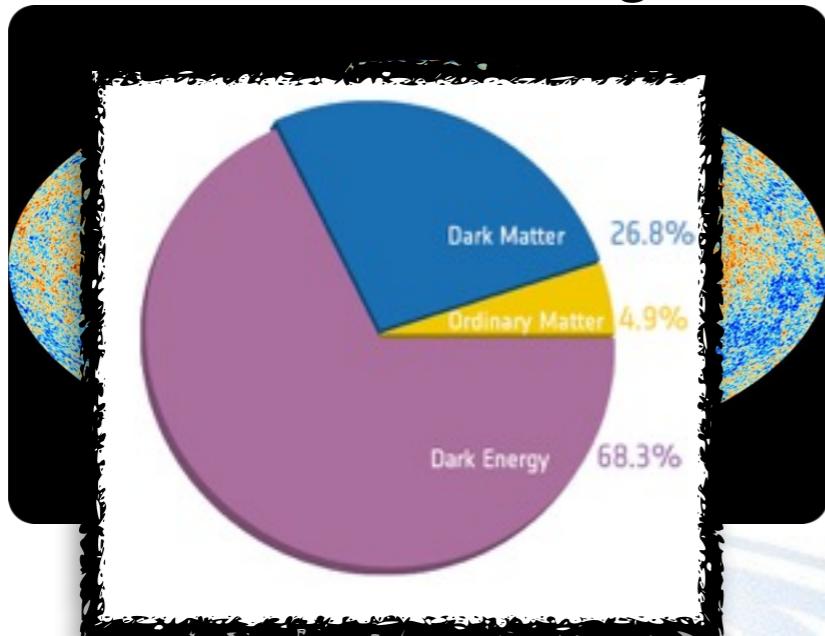
Blue: mass from lensing

Planck Collaboration, 2013; SubbaRao et al. (2008); Bolshoi Simulation, J. Primack et al., 2011;  
NASA, APOD, 2006 August 24, J. A. Tyson et al., Astrophys.J.498:L107,1998

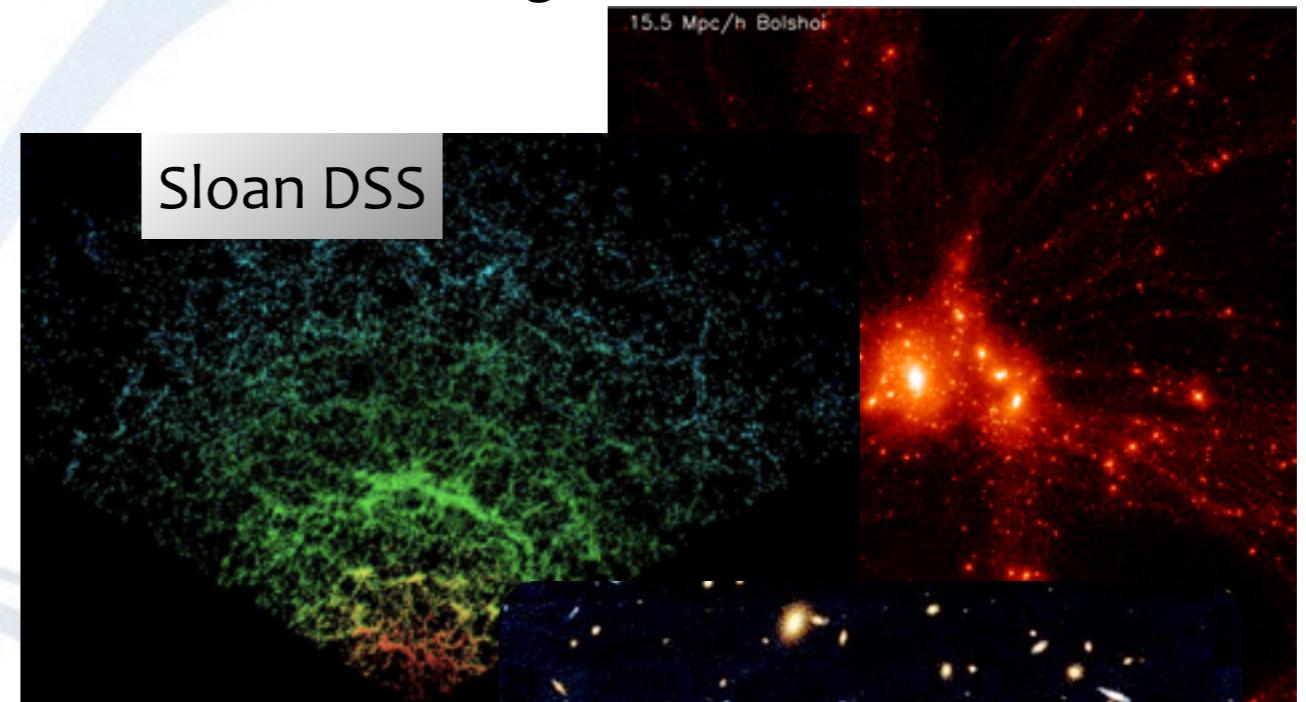
# Precision Cosmology



Cosmic Microwave Background



Large Scale Structure



Lensing/  
The Bullet  
Cluster



Gravitational  
Lensing

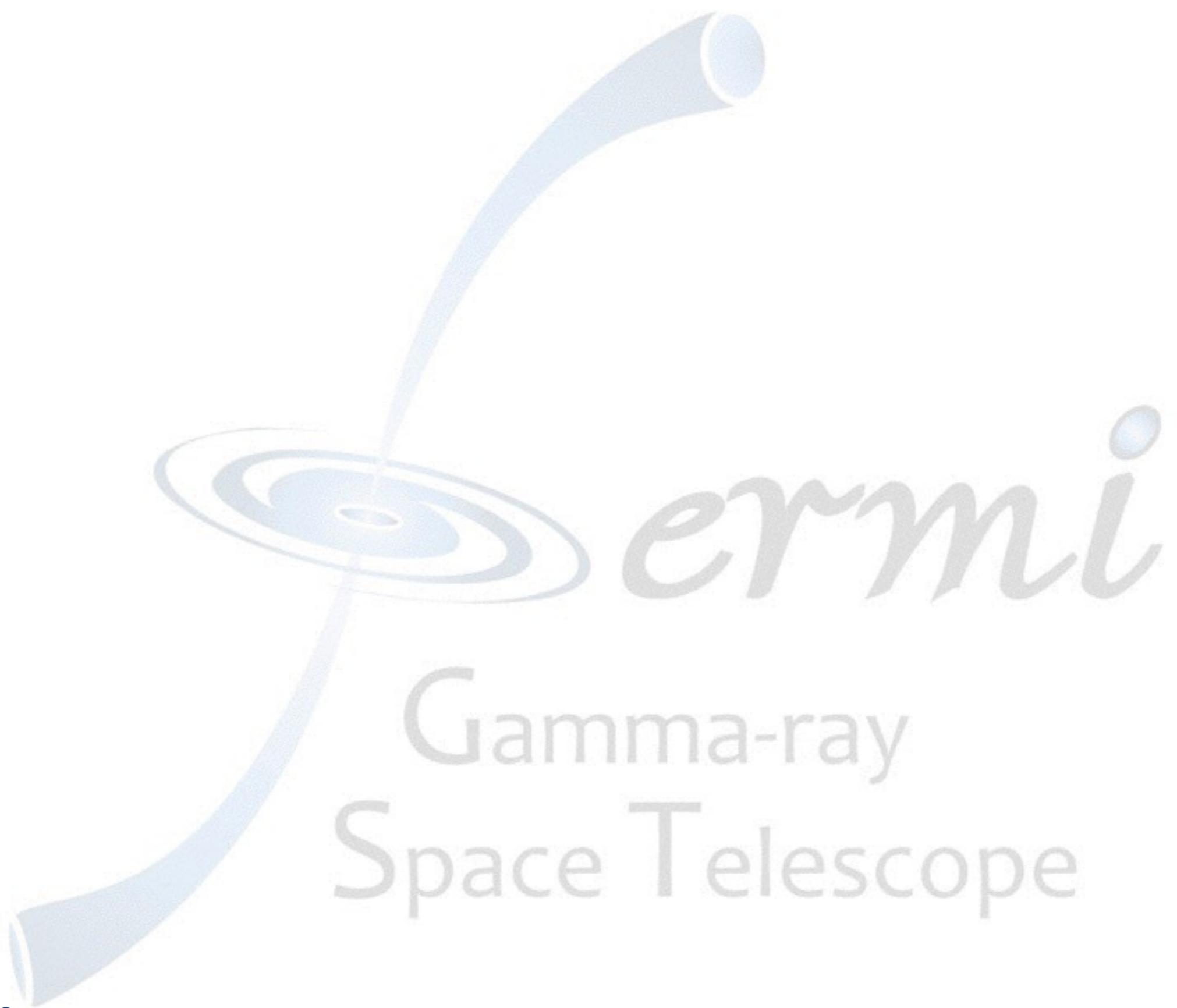


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# What do we know?

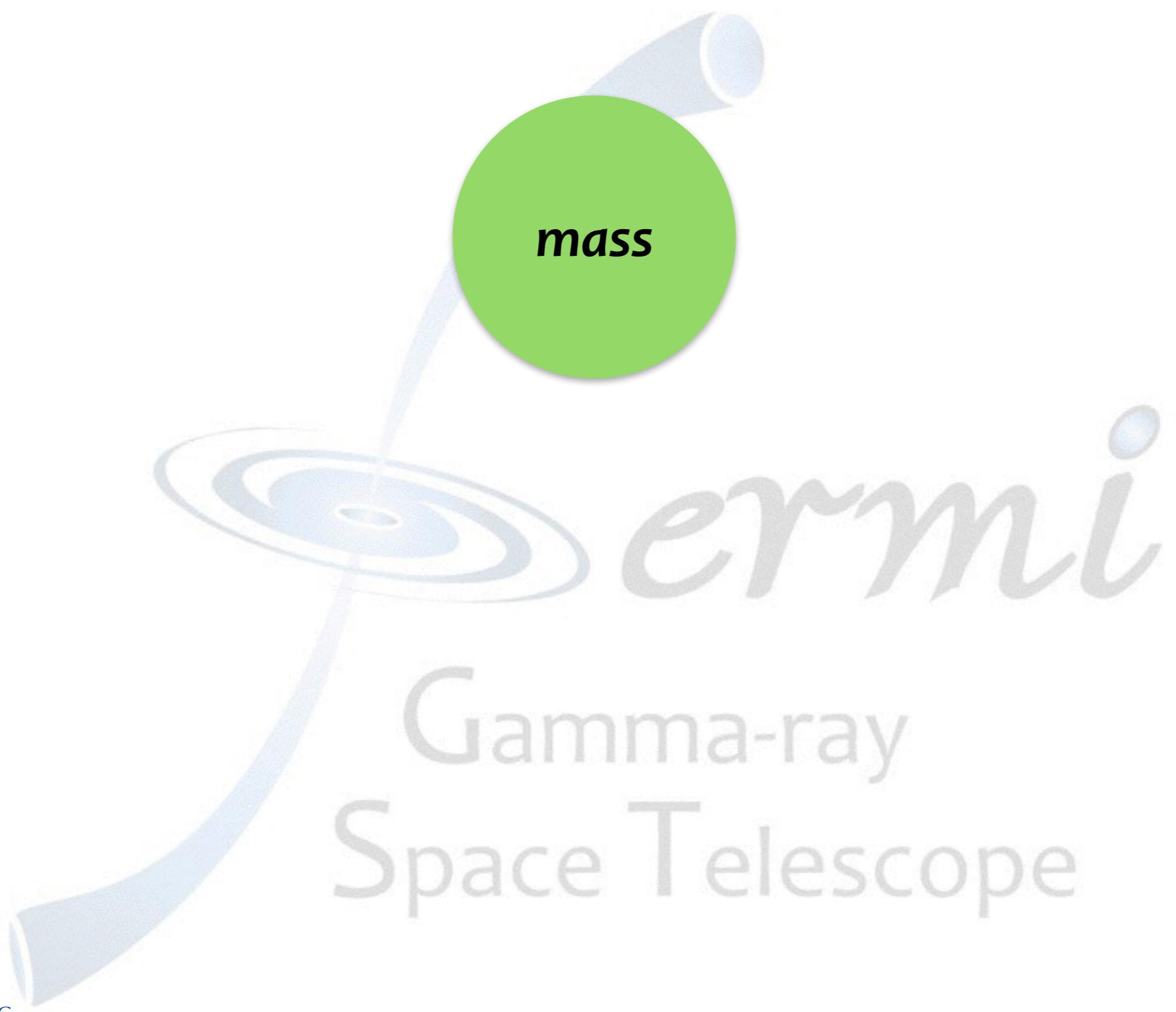




# What do we know?



**mass**





# What do we know?



**mass**

***not p/n  
(baryons)***

constraints from  
CMB, primordial  
nucleosynthesis

Gamma-ray  
Space Telescope

# What do we know?



**mass**

***not p/n  
(baryons)***

***neutral***

constraints from  
CMB, primordial  
nucleosynthesis

# What do we know?



**mass**

***not p/n  
(baryons)***

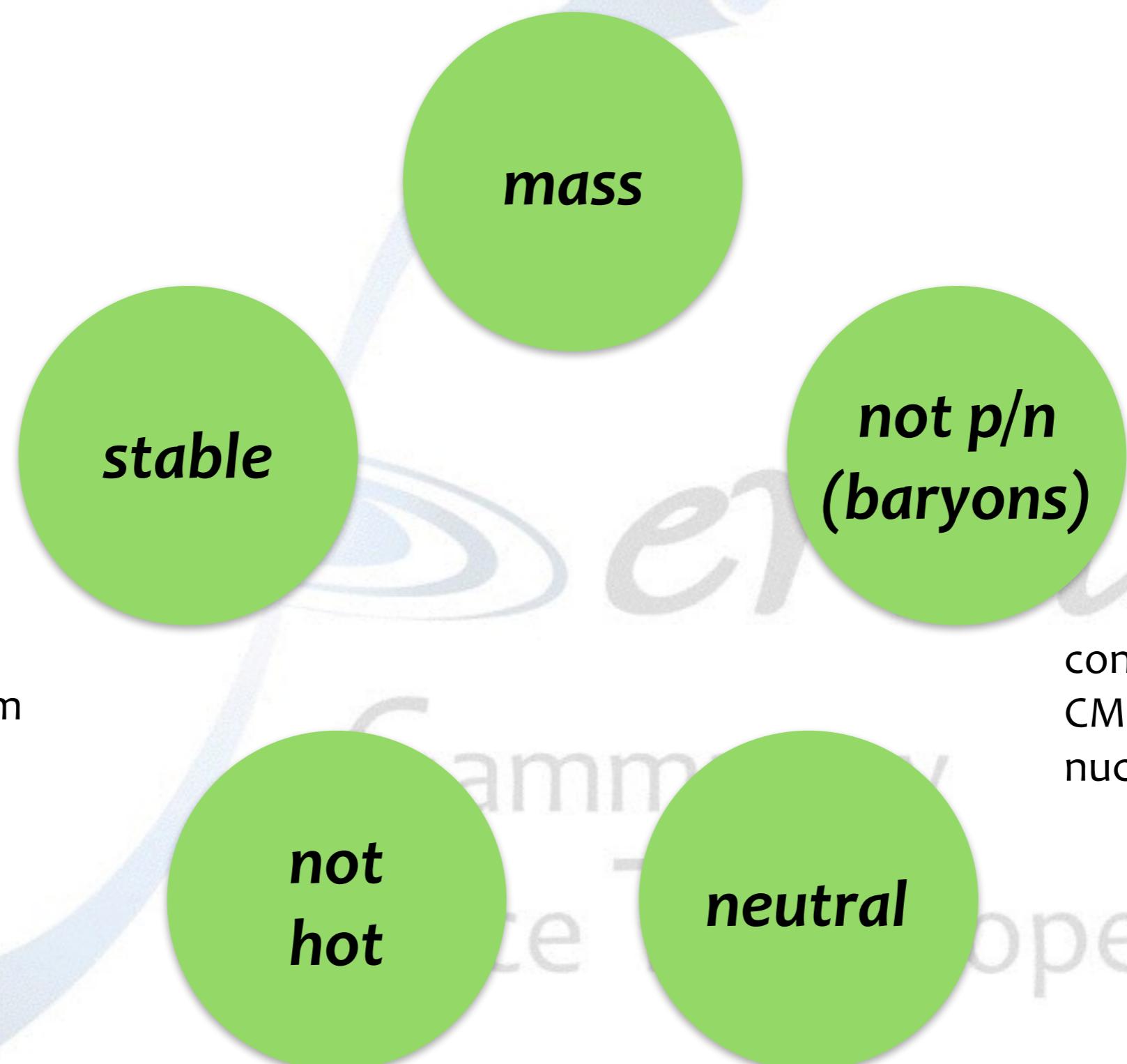
***not  
hot***

***neutral***

constraints from  
CMB, N-body  
simulations

constraints from  
CMB, primordial  
nucleosynthesis

# What do we know?



# What do we know?

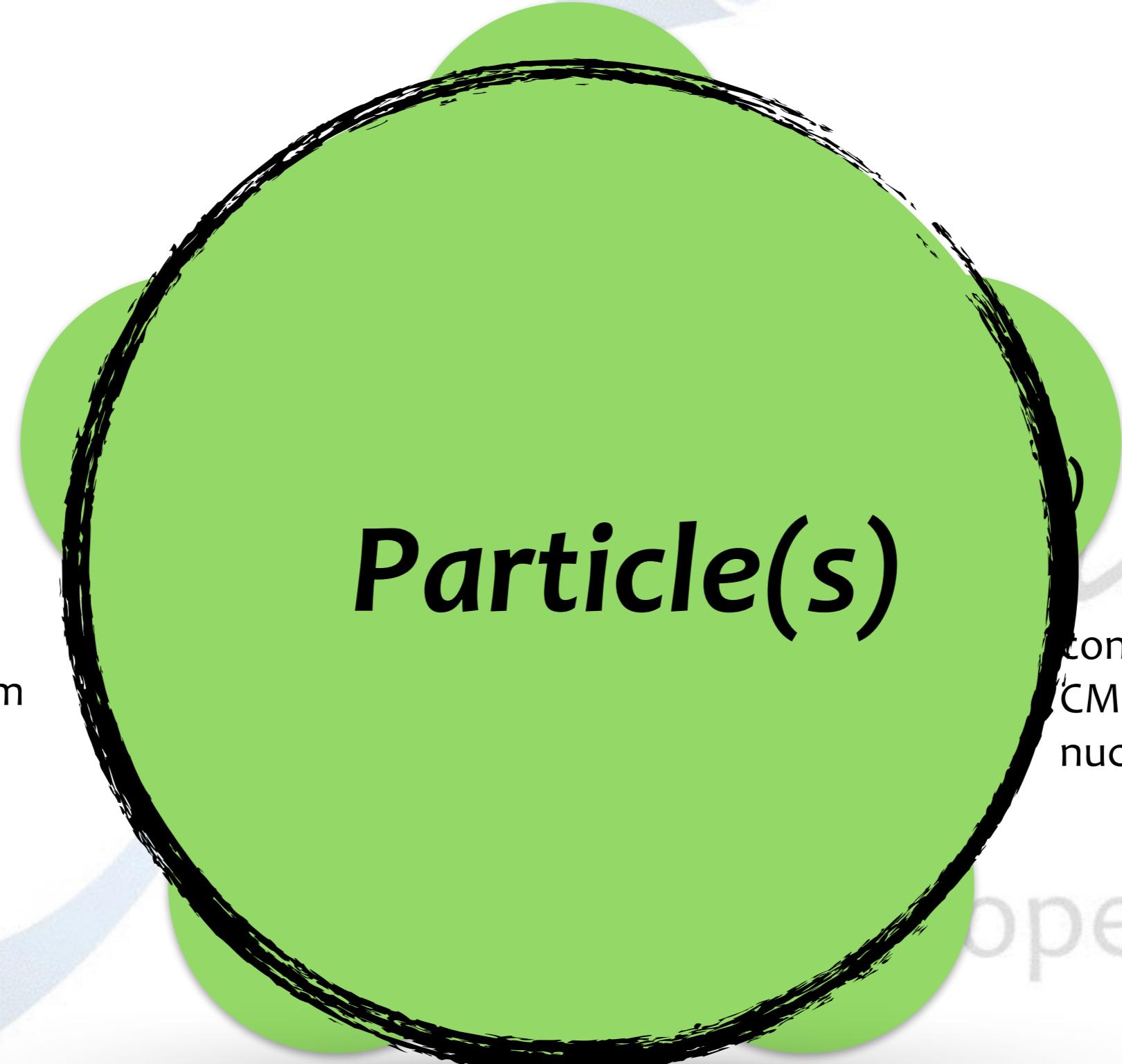


constraints from  
CMB, N-body  
simulations

## Particle

constraints from  
CMB, primordial  
nucleosynthesis

# What do we know?



constraints from  
CMB, N-body  
simulations

constraints from  
CMB, primordial  
nucleosynthesis

# Potential Candidates



	mass → ≈2.3 MeV/c <sup>2</sup> charge → 2/3 spin → 1/2	u	c	t	g	H
QUARKS		up	charm	top	gluon	Higgs boson
	≈4.8 MeV/c <sup>2</sup> -1/3 1/2	d	s	b	γ	
		down	strange	bottom	photon	
LEPTONS	0.511 MeV/c <sup>2</sup> -1 1/2	e	μ	τ	Z	GAUGE BOSONS
		electron	muon	tau	Z boson	
	<2.2 eV/c <sup>2</sup> 0 1/2	ν <sub>e</sub>	ν <sub>μ</sub>	ν <sub>τ</sub>	W	
		electron neutrino	muon neutrino	tau neutrino	W boson	

# Potential Candidates



mass → $\approx 2.3 \text{ MeV}/c^2$	charge → $2/3$	spin → $1/2$	mass → $\approx 1.275 \text{ GeV}/c^2$	charge → $2/3$	spin → $1/2$	mass → $\approx 173.07 \text{ GeV}/c^2$	charge → $2/3$	spin → $1/2$	mass → $0$	charge → $0$	spin → $1$	mass → $\approx 126 \text{ GeV}/c^2$	charge → $0$	spin → $0$
up	<del>✗</del>		d quark	<del>✗</del>		s quark	<del>✗</del>		gluon	<del>✗</del>		Higgs boson		
down	<del>✗</del>		strange	<del>✗</del>		bottom	<del>✗</del>		photon					
electron	$0.511 \text{ MeV}/c^2$	-1	$\mu$	$105.7 \text{ MeV}/c^2$	-1	$\tau$	$1.777 \text{ GeV}/c^2$	-1	Z boson	$91.2 \text{ GeV}/c^2$	$\pm 1$			
electron neutrino	$<2.2 \text{ eV}/c^2$	0	$\nu_e$	$<0.17 \text{ MeV}/c^2$	0	$\nu_\mu$	$<15.5 \text{ MeV}/c^2$	0	W boson	$80.4 \text{ GeV}/c^2$	1			
muon neutrino		1/2		muon neutrino			tau neutrino							

# Potential Candidates



mass → $\approx 2.3 \text{ MeV}/c^2$	charge → $2/3$	spin → $1/2$	mass → $\approx 1.275 \text{ GeV}/c^2$	charge → $2/3$	spin → $1/2$	mass → $\approx 173.07 \text{ GeV}/c^2$	charge → $2/3$	spin → $1/2$	mass → $0$	charge → $0$	spin → $1$	mass → $\approx 126 \text{ GeV}/c^2$	charge → $0$	spin → $0$
up			d quark			s quark			gluon			Higgs boson		
down			strange			bottom			photon					
electron			muon			tau			Z boson					
electron neutrino			muon neutrino			tau neutrino			W boson					

# Potential Candidates



mass → ≈2.3 MeV/c <sup>2</sup>	≈1.275 GeV/c <sup>2</sup>	≈173.07 GeV/c <sup>2</sup>	0	≈126 GeV/c <sup>2</sup>
charge → 2/3	2/3	2/3	0	0
spin → 1/2	1/2	1/2	1	0
up	d charm	s top	gluon	Wiggs boson
mass → ≈4.8 MeV/c <sup>2</sup>	≈95 MeV/c <sup>2</sup>	≈4.18 GeV/c <sup>2</sup>	0	0
-1/3	-1/3	-1/3	0	0
1/2	1/2	1/2	1	1
down	s Strange	b Bottom	photon	Z boson
mass → 0.511 MeV/c <sup>2</sup>	105.7 MeV/c <sup>2</sup>	1.777 GeV/c <sup>2</sup>	91.2 GeV/c <sup>2</sup>	80.4 GeV/c <sup>2</sup>
-1	-1	-1	0	±1
1/2	1/2	1/2	1	1
electron	muon	tau	Z boson	W boson
mass → <2.2 eV/c <sup>2</sup>	<0.17 MeV/c <sup>2</sup>	<15.5 MeV/c <sup>2</sup>	0	0
0	0	0	1	1
1/2	1/2	1/2	1	1
ν <sub>e</sub>	ν <sub>μ</sub>	ν <sub>τ</sub>		
electron neutrino	muon neutrino	tau neutrino		

# Potential Candidates



mass → $\approx 2.3 \text{ MeV}/c^2$ charge → $2/3$ spin → $1/2$ <b>up</b>	mass → $\approx 1.275 \text{ GeV}/c^2$ charge → $2/3$ spin → $1/2$ <b>s quark</b>	mass → $\approx 173.07 \text{ GeV}/c^2$ charge → $2/3$ spin → $1/2$ <b>t quark</b>	mass → $0$ charge → $0$ spin → $1$ <b>gluon</b>	mass → $\approx 126 \text{ GeV}/c^2$ charge → $0$ spin → $0$ <b>Higgs boson</b>
mass → $\approx 4.8 \text{ MeV}/c^2$ charge → $-1/3$ spin → $1/2$ <b>down</b>	mass → $\approx 95 \text{ MeV}/c^2$ charge → $-1/3$ spin → $1/2$ <b>s quark</b>	mass → $\approx 4.18 \text{ GeV}/c^2$ charge → $-1/3$ spin → $1/2$ <b>b quark</b>	mass → $0$ charge → $0$ spin → $1$ <b>photon</b>	
mass → $0.511 \text{ MeV}/c^2$ charge → $-1$ spin → $1/2$ <b>electron</b>	mass → $105.7 \text{ MeV}/c^2$ charge → $-1$ spin → $1/2$ <b>muon</b>	mass → $1.777 \text{ GeV}/c^2$ charge → $-1$ spin → $1/2$ <b>tau</b>	mass → $91.2 \text{ GeV}/c^2$ charge → $0$ spin → $1$ <b>Z boson</b>	
mass → $< 2.2 \text{ eV}/c^2$ charge → $0$ spin → $1/2$ <b>electron neutrino</b>	mass → $< 0.17 \text{ MeV}/c^2$ charge → $0$ spin → $1/2$ <b>muon neutrino</b>	mass → $< 15.5 \text{ MeV}/c^2$ charge → $0$ spin → $1/2$ <b>tau neutrino</b>	mass → $80.4 \text{ GeV}/c^2$ charge → $\pm 1$ spin → $1$ <b>W boson</b>	

# Potential Candidates



# Potential Candidates



# Potential Candidates



# Potential Candidates





# Portrait of a Candidate



G. Steigman, et al., Phys.Rev. D86 (2012) 023506

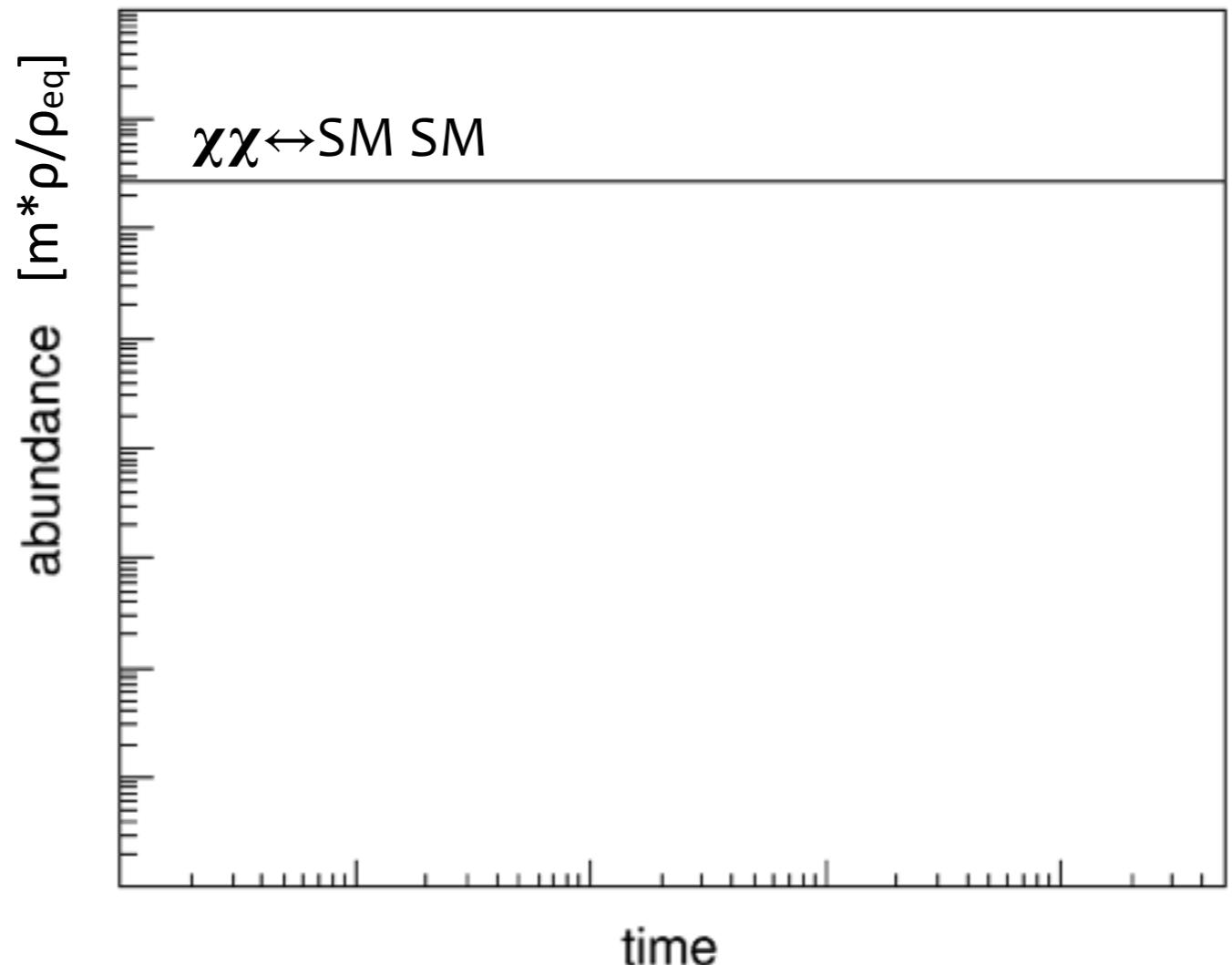


# Portrait of a Candidate



**Cosmology and Thermodynamics**

$DM = \chi$



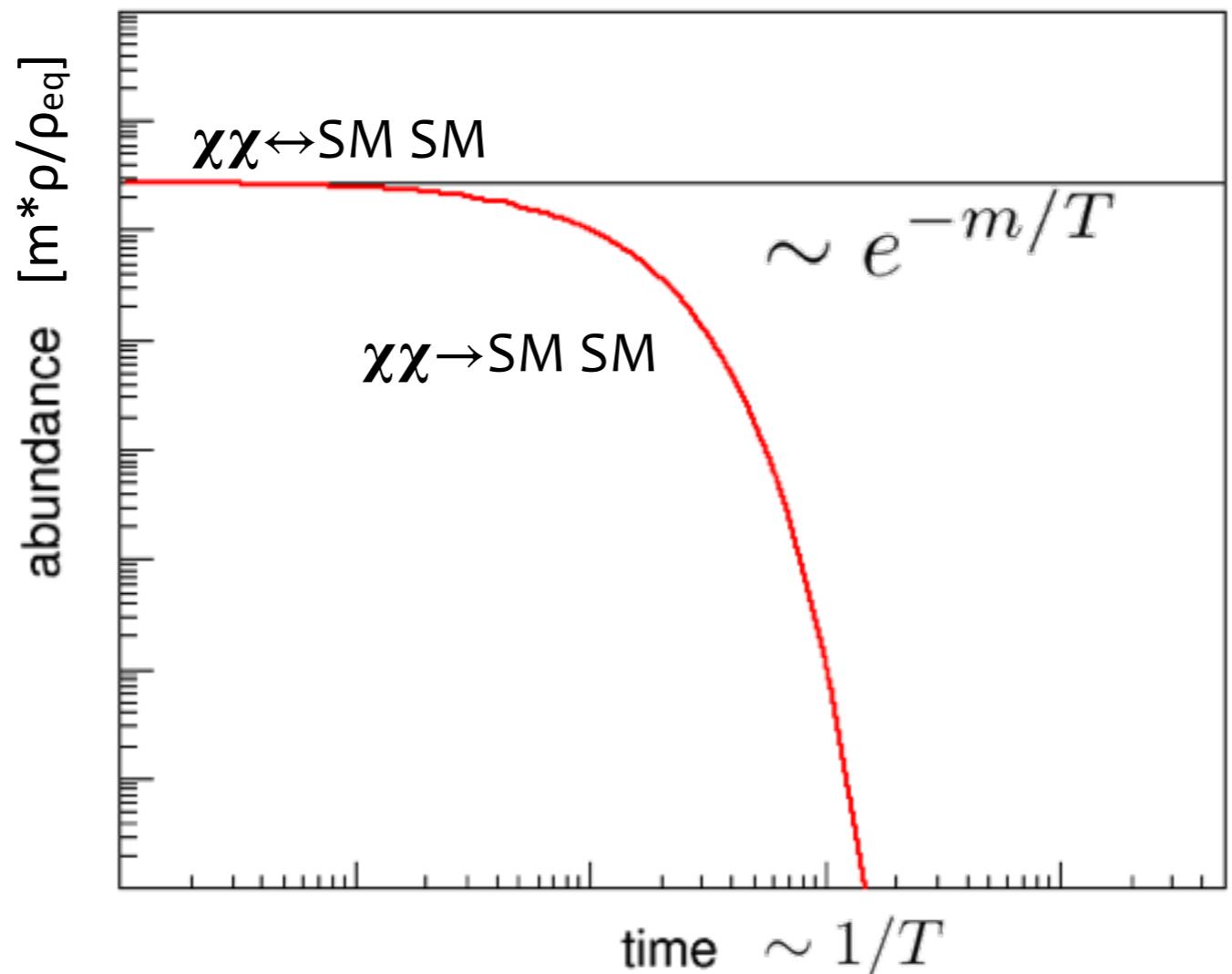
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# Portrait of a Candidate



## Cosmology and Thermodynamics

$$DM = \chi$$



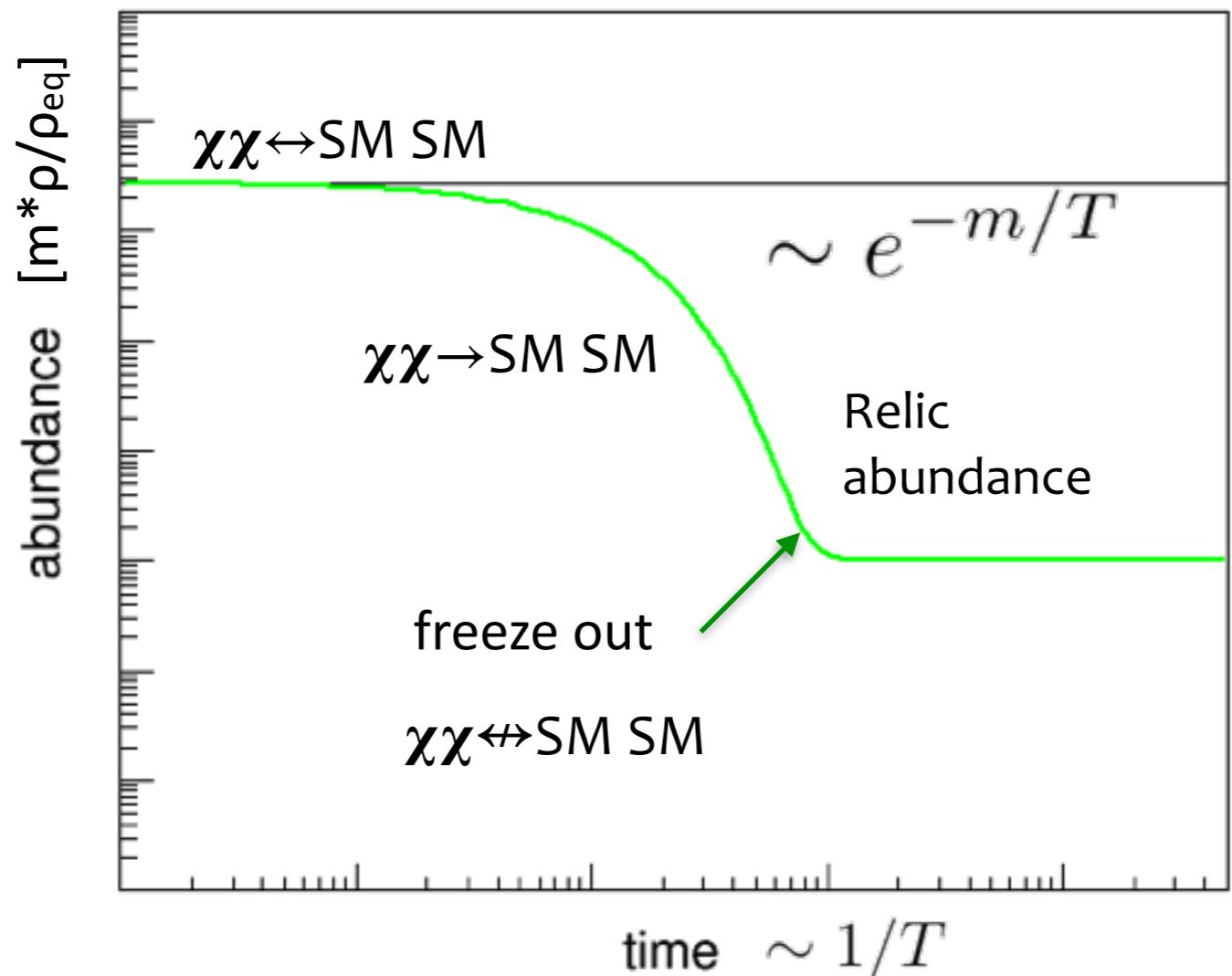
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# Portrait of a Candidate



## Cosmology and Thermodynamics

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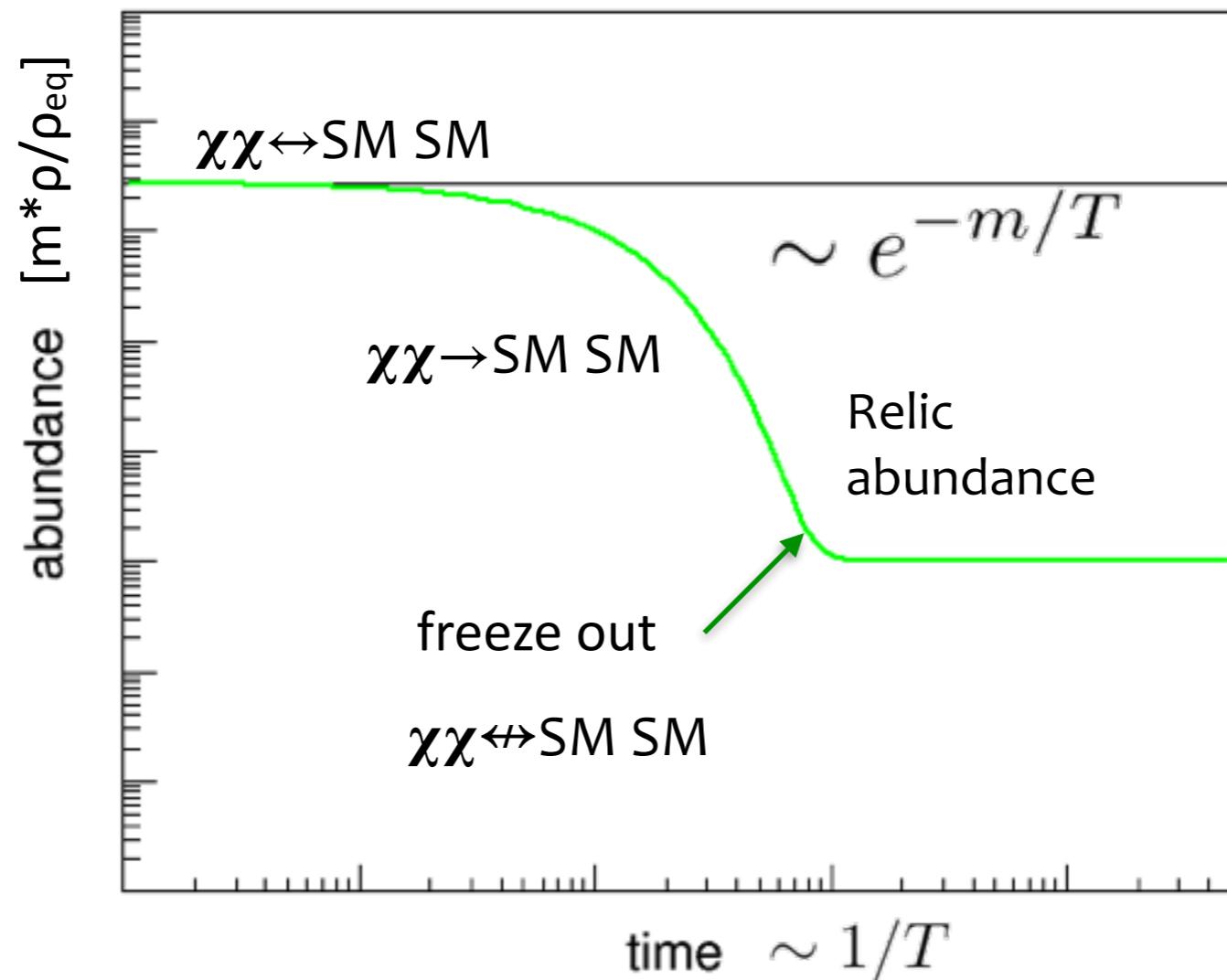
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# Portrait of a Candidate



## Cosmology and Thermodynamics

$$DM = \chi$$



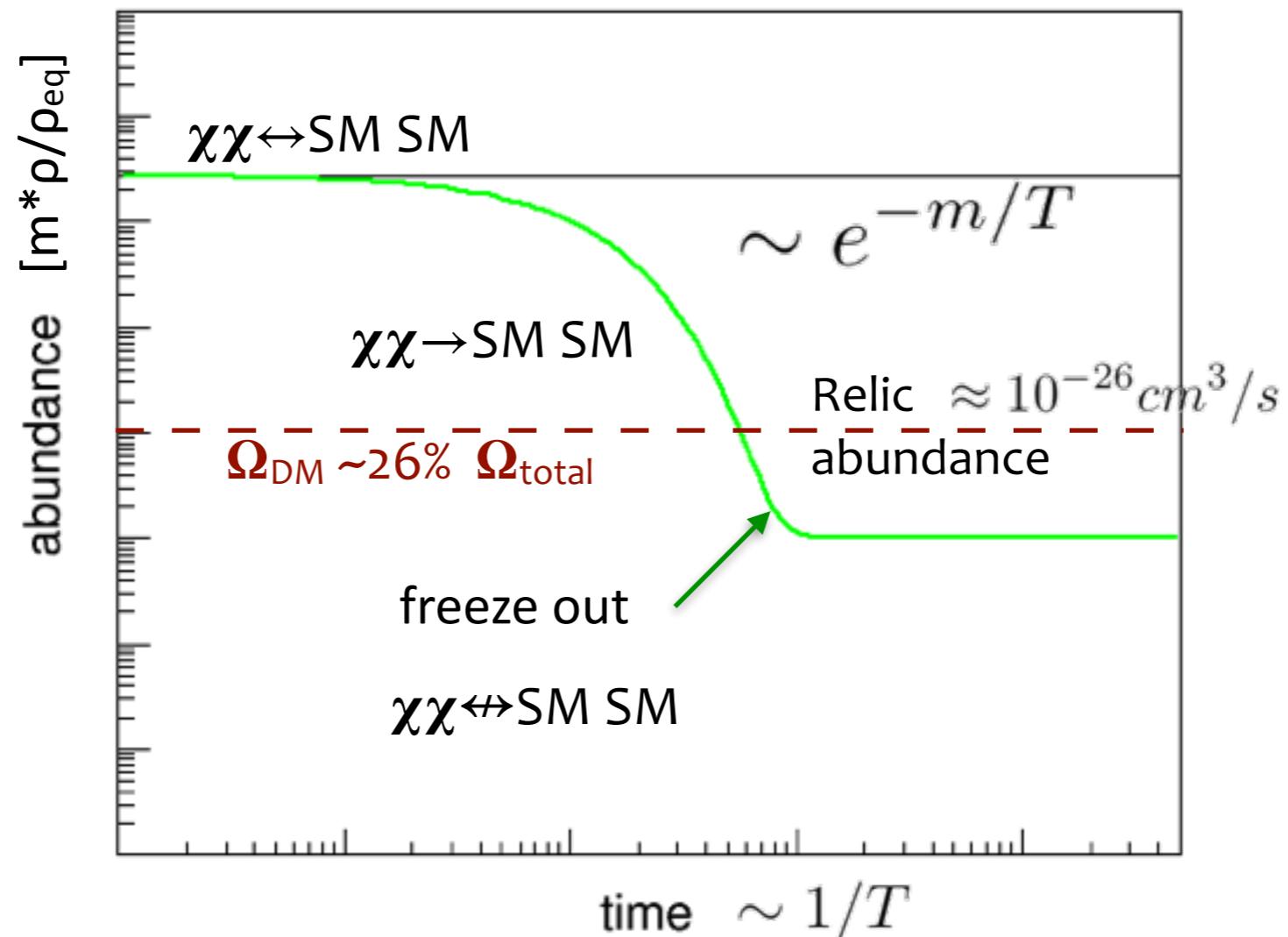
Abundance  
 $\langle \sigma v \rangle n_{eq} \sim H$   
 $\langle \sigma v \rangle \sim 10^{-26} \text{ cm}^3/\text{s}$

# Portrait of a Candidate



## Cosmology and Thermodynamics

$$DM = \chi$$



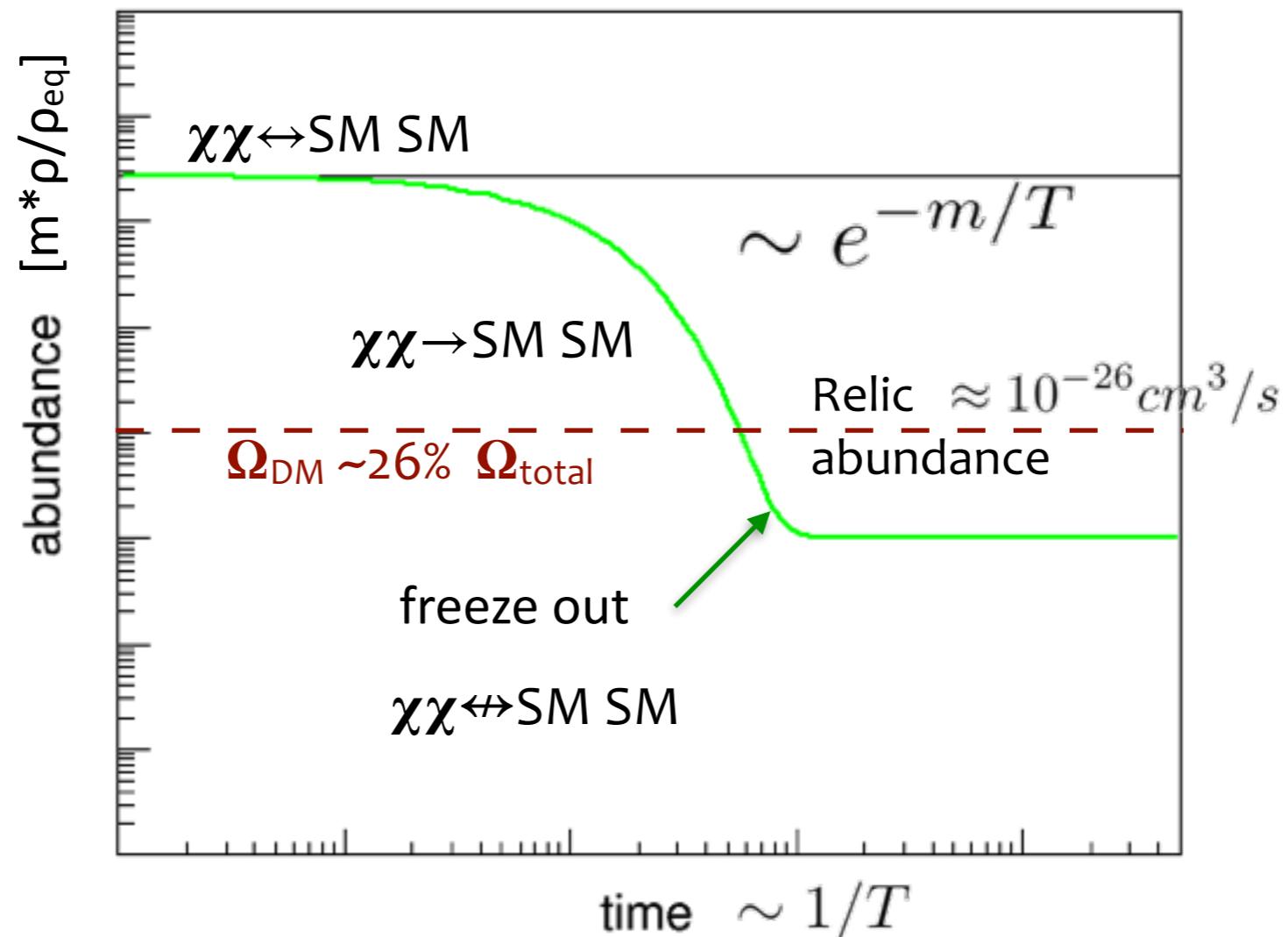
Abundance  
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# Portrait of a Candidate



**Particle Physics**

$\text{DM} = \chi$



Abundance  
 $\langle \sigma v \rangle n_{\text{eq}} \sim H$   
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# Portrait of a Candidate

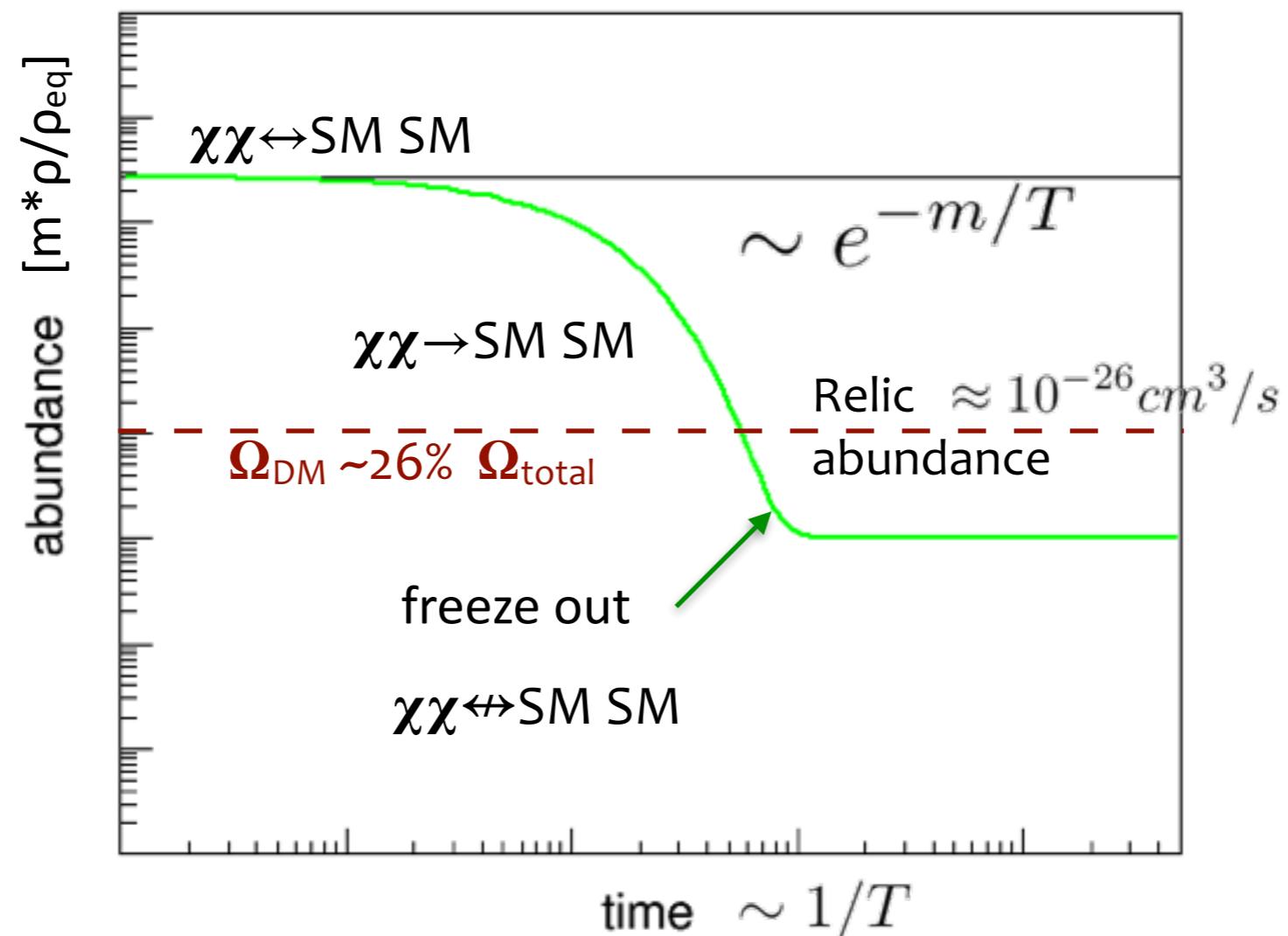


## Particle Physics

$DM = \chi$

Weak ( $\sigma$ ):  $10^{-36} \text{ cm}^2$

velocity ( $v$ ) @  
freeze out:  
 $10^5 \text{ km/s}$



Abundance  
 $\langle \sigma v \rangle n_{\text{eq}} \sim H$   
 $\langle \sigma v \rangle \sim 10^{-26} \text{ cm}^3/\text{s}$

# Portrait of a Candidate



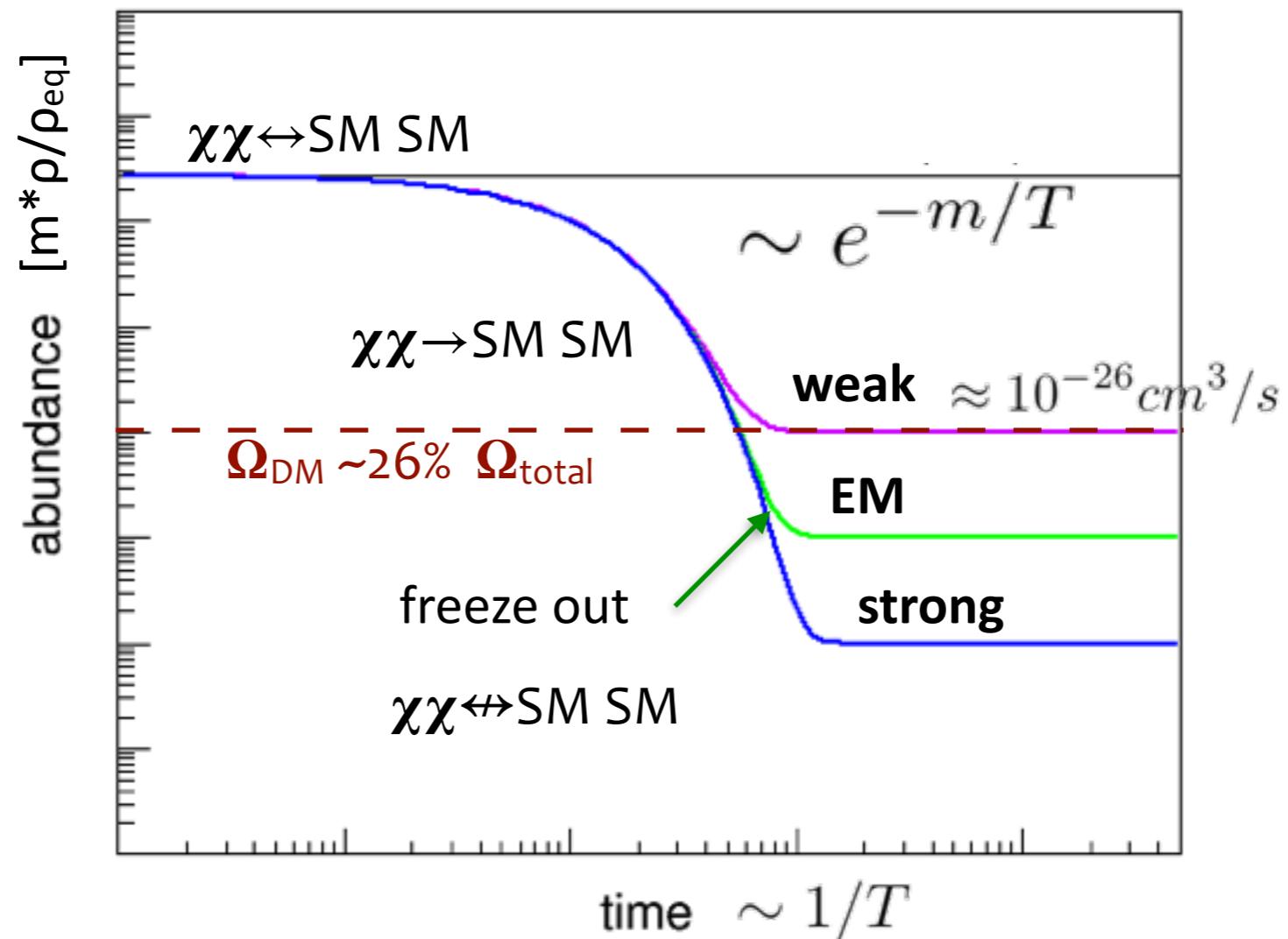
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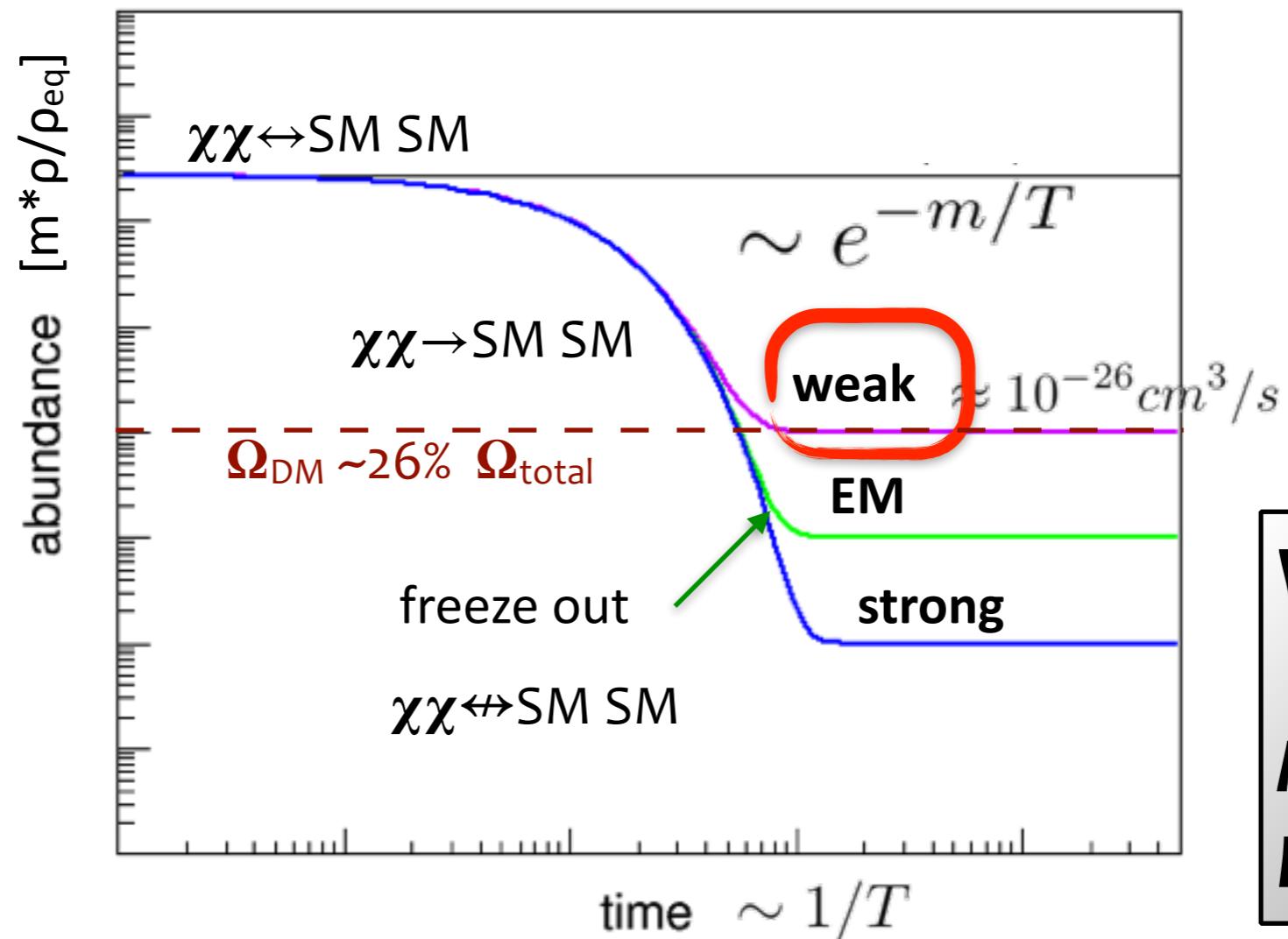
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**Weakly  
Interacting  
Massive  
Particles**

# Portrait of a Candidate



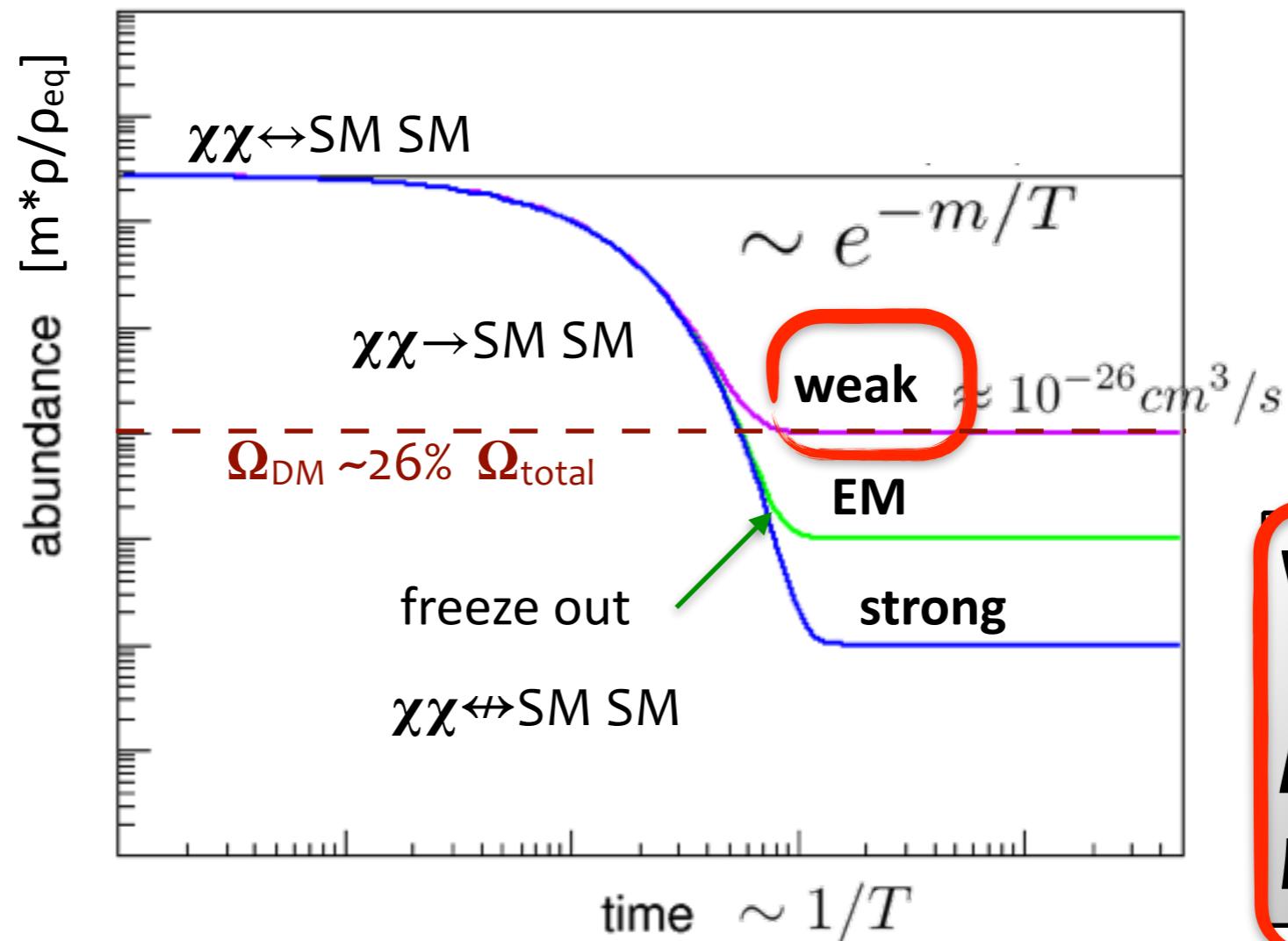
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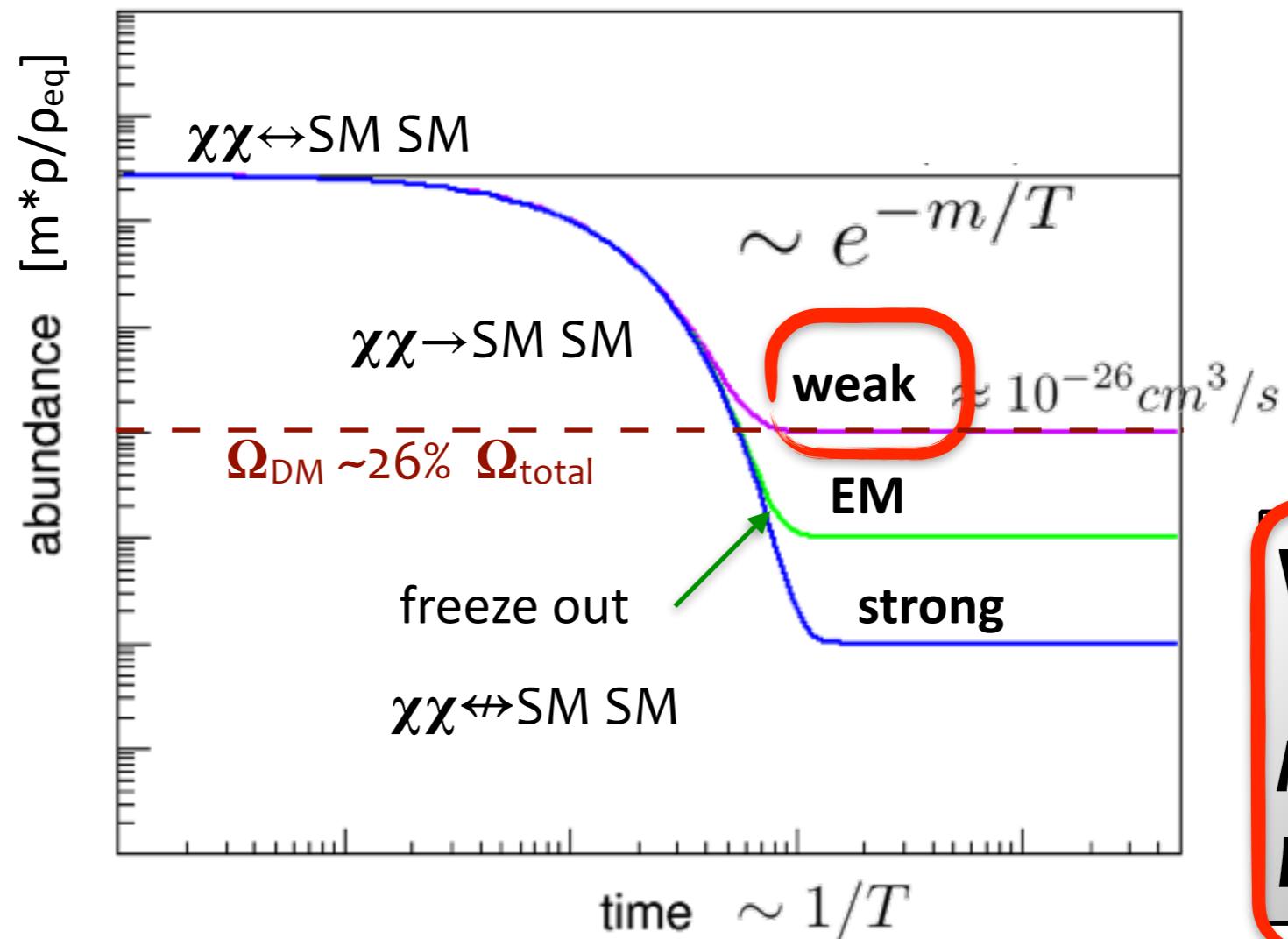
**The WIMP Miracle...**

$DM = \chi$

Weak ( $\sigma$ ):  $10^{-36} \text{ cm}^2$

velocity ( $v$ ) @  
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 $10^5 \text{ km/s}$

$\langle\sigma v\rangle \sim 10^{-26} \text{ cm}^3/\text{s}$



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**Weakly  
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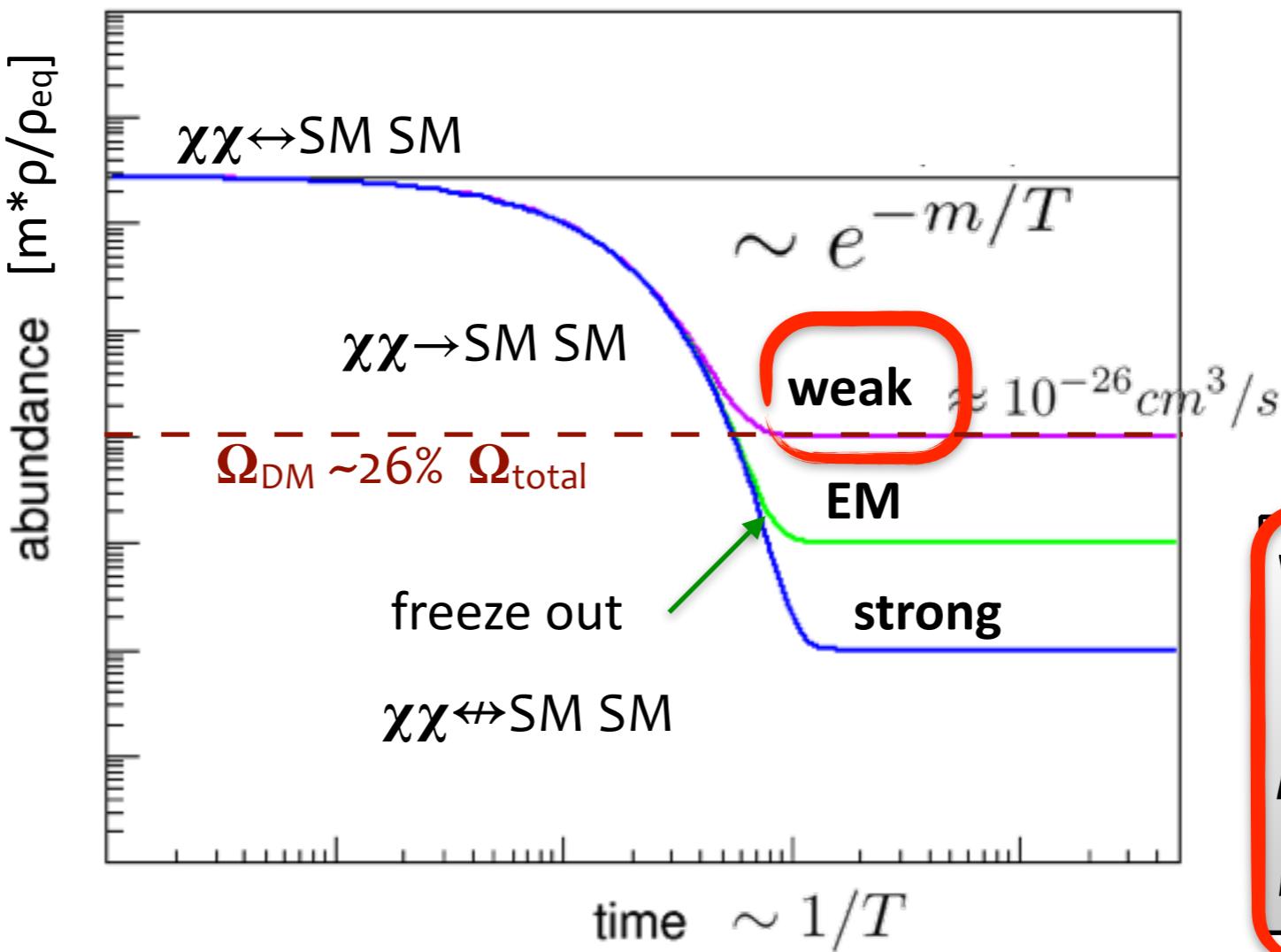
# Portrait of a Candidate



Weak ( $\sigma$ ):  $10^{-36} \text{ cm}^2$

velocity ( $v$ ) @  
freeze out:  
 $10^5 \text{ km/s}$

$\langle\sigma v\rangle \sim 10^{-26} \text{ cm}^3/\text{s}$



$DM = \chi$

Abundance  
 $\langle\sigma v\rangle n_{eq} \sim H$   
 $\langle\sigma v\rangle \sim 10^{-26} \text{ cm}^3/\text{s}$

**Weakly  
Interacting  
Massive  
Particles**

# Portrait of a Candidate



## The WIMP Coincidence

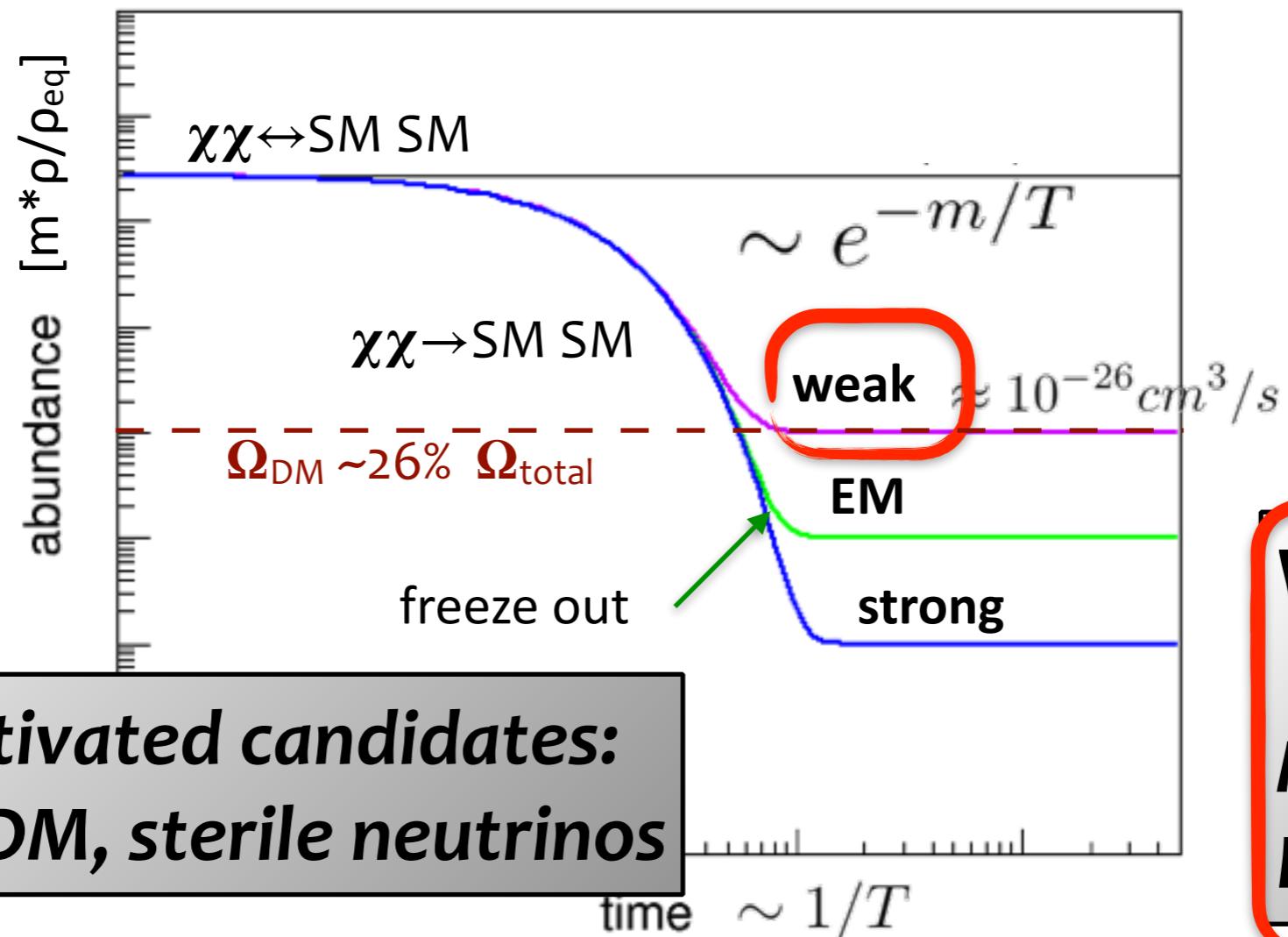
$DM = \chi$

Weak ( $\sigma$ ):  $10^{-36} \text{ cm}^2$

velocity ( $v$ ) @  
freeze out:  
 $10^5 \text{ km/s}$

$\langle\sigma v\rangle \sim 10^{-26} \text{ cm}^3/\text{s}$

**Other well motivated candidates:**  
**axions, asym. DM, sterile neutrinos**

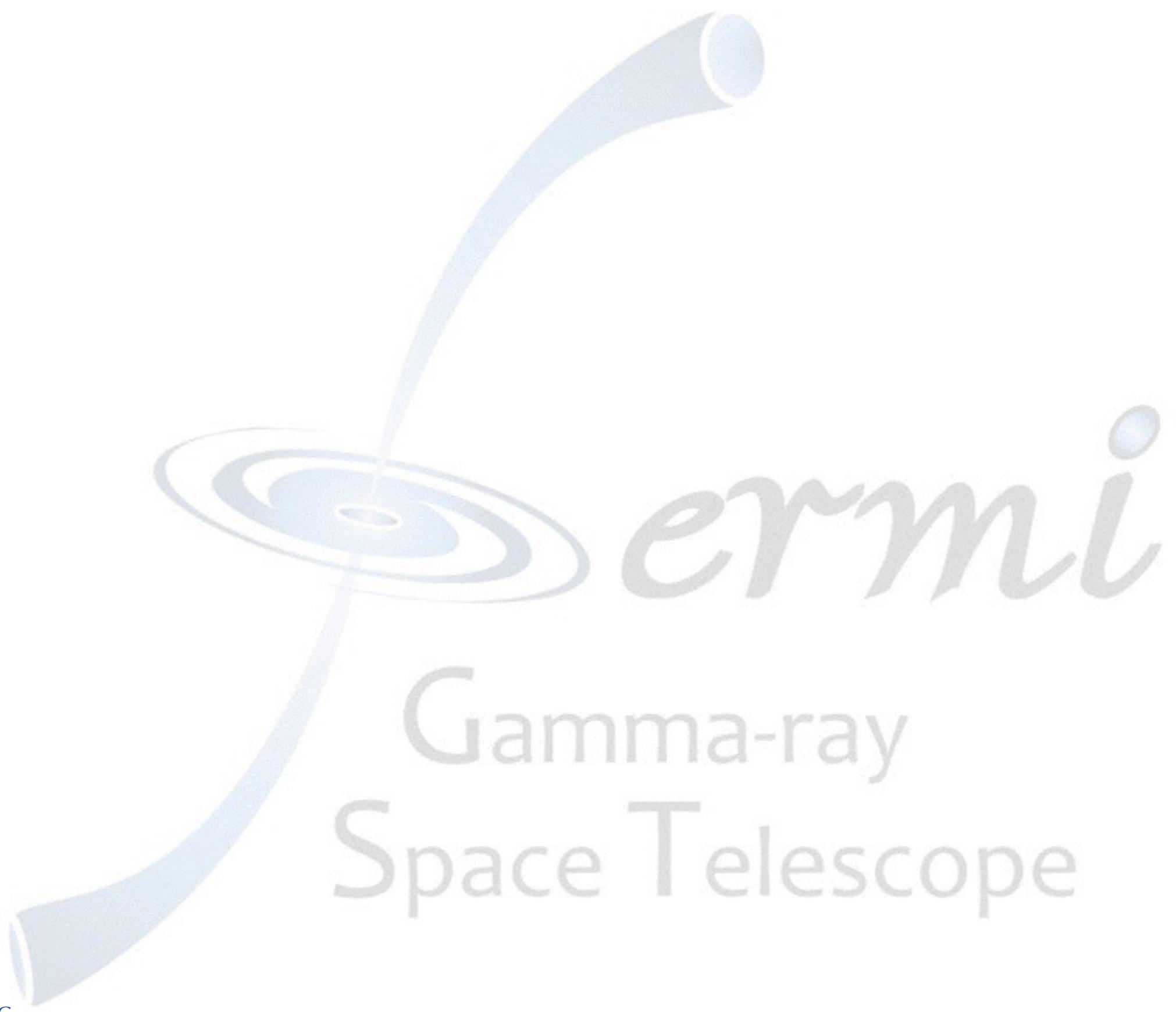


Abundance  
 $\langle\sigma v\rangle n_{\text{eq}} \sim H$   
 $\langle\sigma v\rangle \sim 10^{-26} \text{ cm}^3/\text{s}$

**Weakly  
Interacting  
Massive  
Particles**

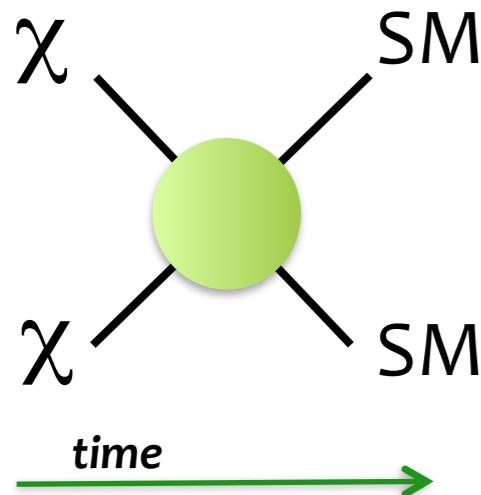


# Detecting WIMP Dark Matter





# Detecting WIMP Dark Matter

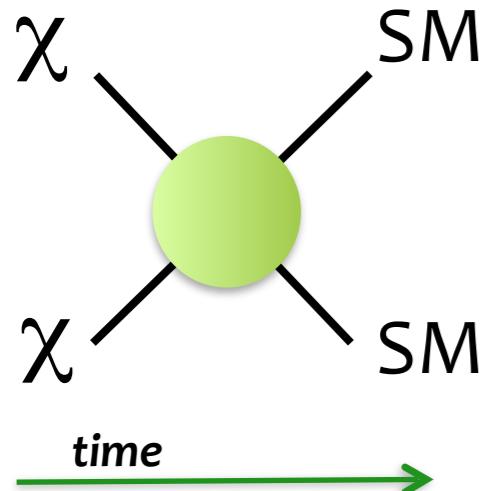


**Indirect Detection**

*fermi*  
Gamma-ray  
Space Telescope

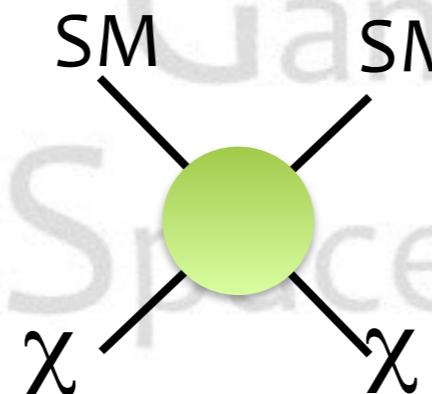
A large, semi-transparent watermark of the "fermi" logo is positioned in the lower right area of the slide. It features the word "fermi" in a stylized, italicized font above the words "Gamma-ray Space Telescope".

# Detecting WIMP Dark Matter



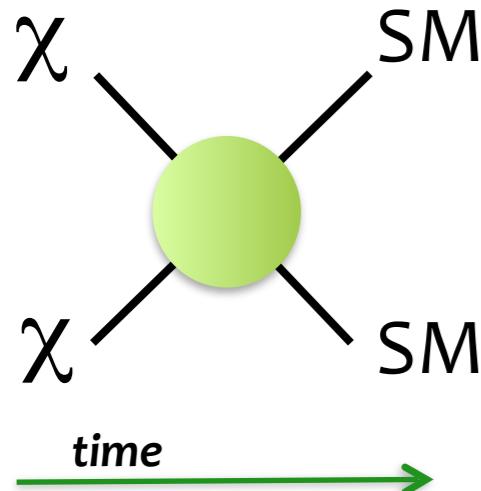
**Indirect Detection**

**Direct Detection**



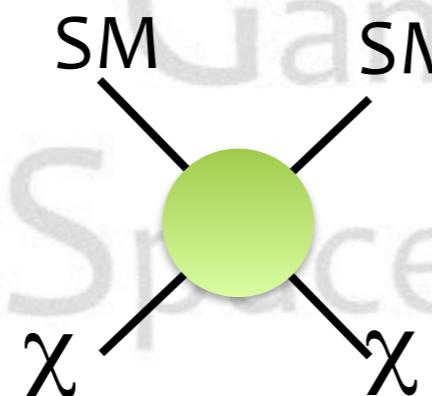
fermi  
Gamma-ray  
Space Telescope

# Detecting WIMP Dark Matter

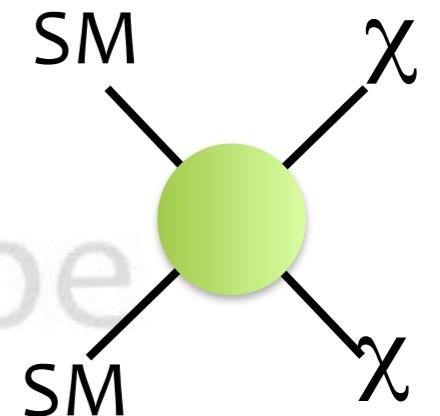


**Indirect Detection**

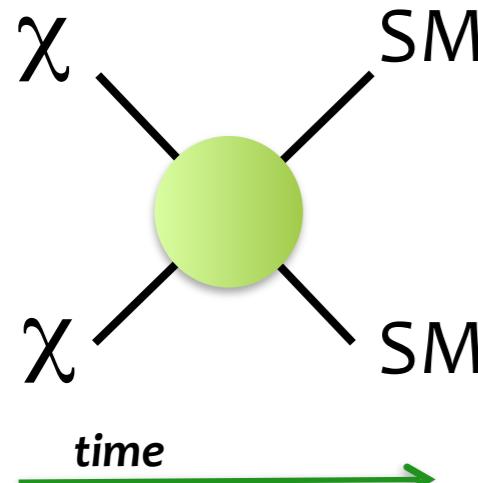
**Direct Detection**



**Collider**



# Detecting WIMP Dark Matter

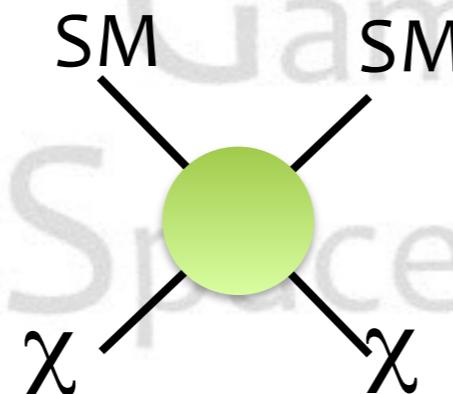


## Indirect Detection

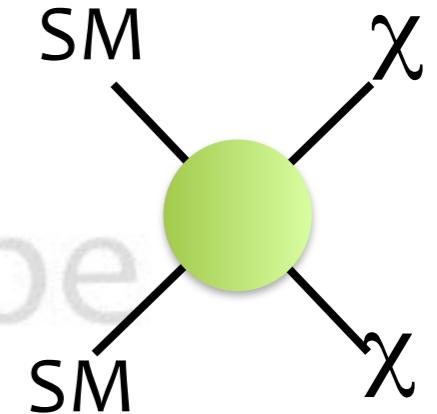
information about mass,  
point back to source

SM:					
QUARKS	LEPTONS	GAUGE BOSONS			
mass → $\approx 2.3 \text{ MeV}/c^2$ charge → $2/3$ spin → $1/2$	$u$ up	$\approx 1.275 \text{ GeV}/c^2$ $2/3$ $1/2$	$c$ charm	$\approx 173.07 \text{ GeV}/c^2$ $2/3$ $1/2$	$t$ top
$\approx 4.8 \text{ MeV}/c^2$ $-1/3$ $1/2$	$d$ down	$\approx 95 \text{ MeV}/c^2$ $-1/3$ $1/2$	$s$ strange	$\approx 4.18 \text{ GeV}/c^2$ $-1/3$ $1/2$	$b$ bottom
$0.511 \text{ MeV}/c^2$ $-1$ $1/2$	$e$ electron	$105.7 \text{ MeV}/c^2$ $-1$ $1/2$	$\mu$ muon	$1.777 \text{ GeV}/c^2$ $-1$ $1/2$	$\tau$ tau
$<2.2 \text{ eV}/c^2$ $0$ $1/2$	$\nu_e$ electron neutrino	$<0.17 \text{ MeV}/c^2$ $0$ $1/2$	$\nu_\mu$ muon neutrino	$<15.5 \text{ MeV}/c^2$ $0$ $1/2$	$\nu_\tau$ tau neutrino
				$91.2 \text{ GeV}/c^2$ $0$ $1$	$Z$ Z boson
				$80.4 \text{ GeV}/c^2$ $\pm 1$ $1$	$W$ W boson

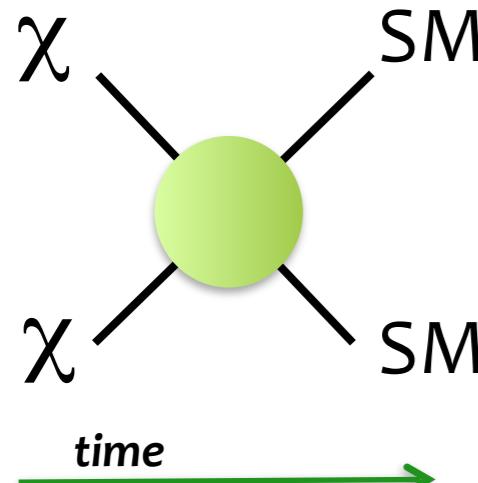
## Direct Detection



## Collider



# Detecting WIMP Dark Matter



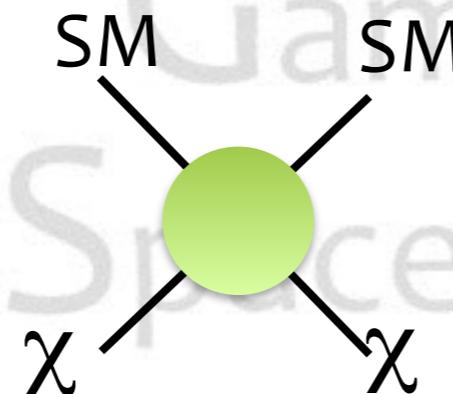
## Indirect Detection

information about mass,  
point back to source  
eventually can get  
to photons

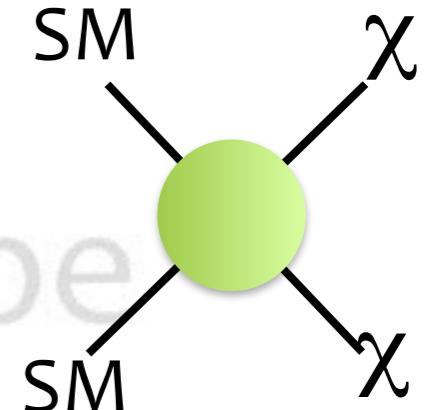
SM:

mass: $\approx 2.3 \text{ MeV}/c^2$	charge: $2/3$	spin: $1/2$	u	$\approx 1.275 \text{ GeV}/c^2$	charge: $2/3$	spin: $1/2$	c	$\approx 173.07 \text{ GeV}/c^2$	charge: $2/3$	spin: $1/2$	t	$\approx 126 \text{ GeV}/c^2$	charge: $0$	spin: $1$	g	Higgs boson
mass: $\approx 4.8 \text{ MeV}/c^2$	charge: $-1/3$	spin: $1/2$	d	$\approx 95 \text{ MeV}/c^2$	charge: $-1/3$	spin: $1/2$	s	$\approx 4.18 \text{ GeV}/c^2$	charge: $-1/3$	spin: $1/2$	b	$\approx 91.2 \text{ GeV}/c^2$	charge: $0$	spin: $1$	$\gamma$	photon
mass: $0.511 \text{ MeV}/c^2$	charge: $-1$	spin: $1/2$	e	mass: $105.7 \text{ MeV}/c^2$	charge: $-1$	spin: $1/2$	$\mu$	mass: $1.777 \text{ GeV}/c^2$	charge: $-1$	spin: $1/2$	$\tau$	mass: $91.2 \text{ GeV}/c^2$	charge: $0$	spin: $1$	Z	Z boson
mass: $<2.2 \text{ eV}/c^2$	charge: $0$	spin: $1/2$	$\nu_e$	mass: $<0.17 \text{ MeV}/c^2$	charge: $0$	spin: $1/2$	$\nu_\mu$	mass: $<15.5 \text{ MeV}/c^2$	charge: $0$	spin: $1/2$	$\nu_\tau$	mass: $80.4 \text{ GeV}/c^2$	charge: $\pm 1$	spin: $1$	W	W boson
LEPTONS				GAUGE BOSONS												

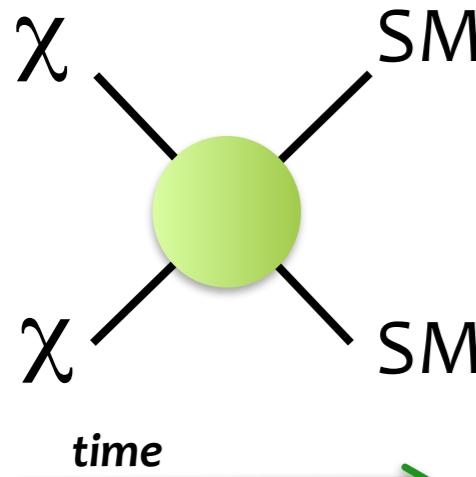
## Direct Detection



## Collider

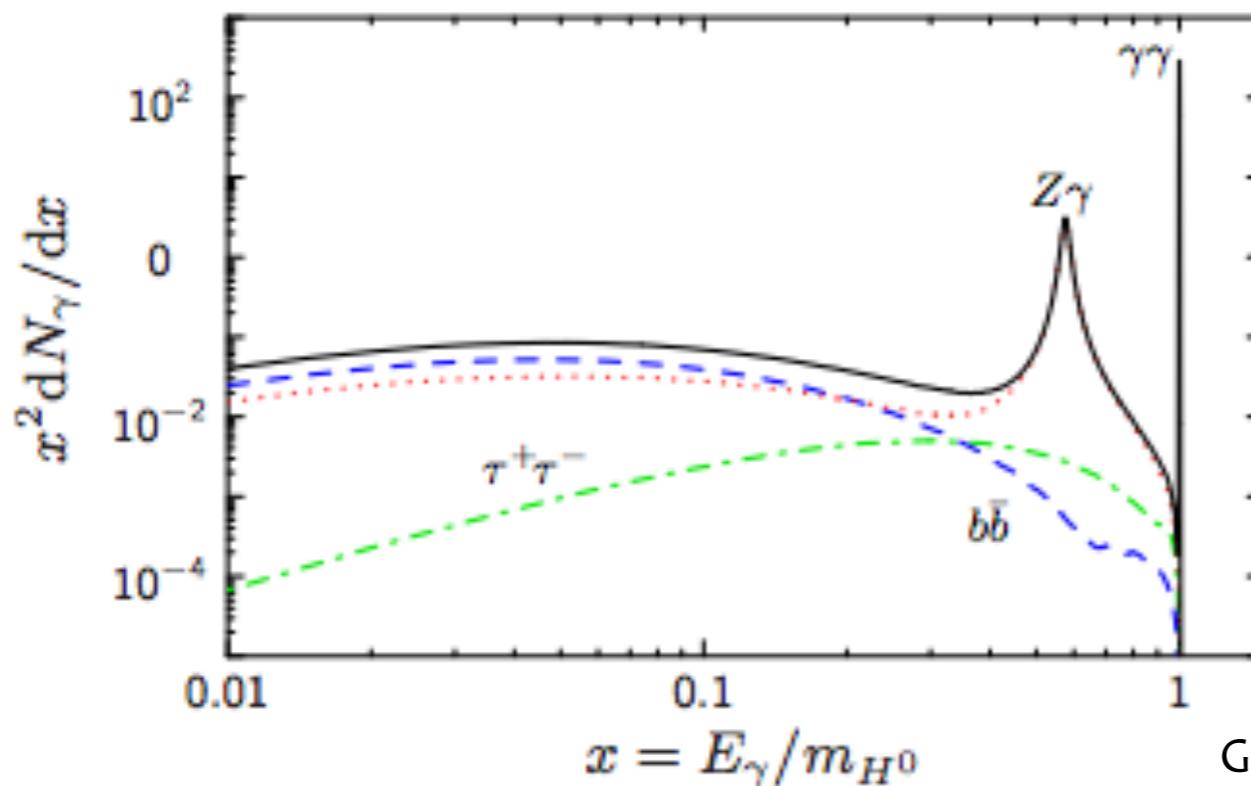


# Detecting WIMP Dark Matter



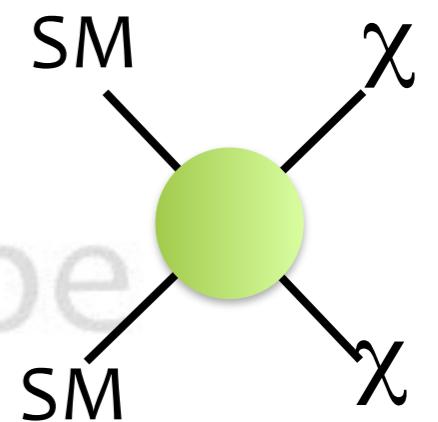
## Indirect Detection

information about mass,  
point back to source  
eventually can get  
to photons



SM:				
mass	$\approx 2.3 \text{ MeV}/c^2$	$\approx 1.275 \text{ GeV}/c^2$	$\approx 173.07 \text{ GeV}/c^2$	$\approx 126 \text{ GeV}/c^2$
charge	2/3	2/3	2/3	0
spin	1/2	1/2	1/2	1
	u	c	t	g
	up	charm	top	gluon
QUARKS				Higgs boson
mass	$\approx 4.8 \text{ MeV}/c^2$	$\approx 95 \text{ MeV}/c^2$	$\approx 4.18 \text{ GeV}/c^2$	
charge	-1/3	-1/3	-1/3	
spin	1/2	1/2	1/2	1
	d	s	b	γ
	down	strange	bottom	photon
LEPTONS				
mass	$0.511 \text{ MeV}/c^2$	$105.7 \text{ MeV}/c^2$	$1.777 \text{ GeV}/c^2$	$91.2 \text{ GeV}/c^2$
charge	-1	-1	-1	0
spin	1/2	1/2	1/2	1
	e	μ	τ	Z
	electron	muon	tau	Z boson
GAUGE BOSONS				
mass	$<2.2 \text{ eV}/c^2$	$<0.17 \text{ MeV}/c^2$	$<15.5 \text{ MeV}/c^2$	$80.4 \text{ GeV}/c^2$
charge	0	0	0	±1
spin	1/2	1/2	1/2	1
	ν <sub>e</sub>	ν <sub>μ</sub>	ν <sub>τ</sub>	W
	electron neutrino	muon neutrino	tau neutrino	W boson

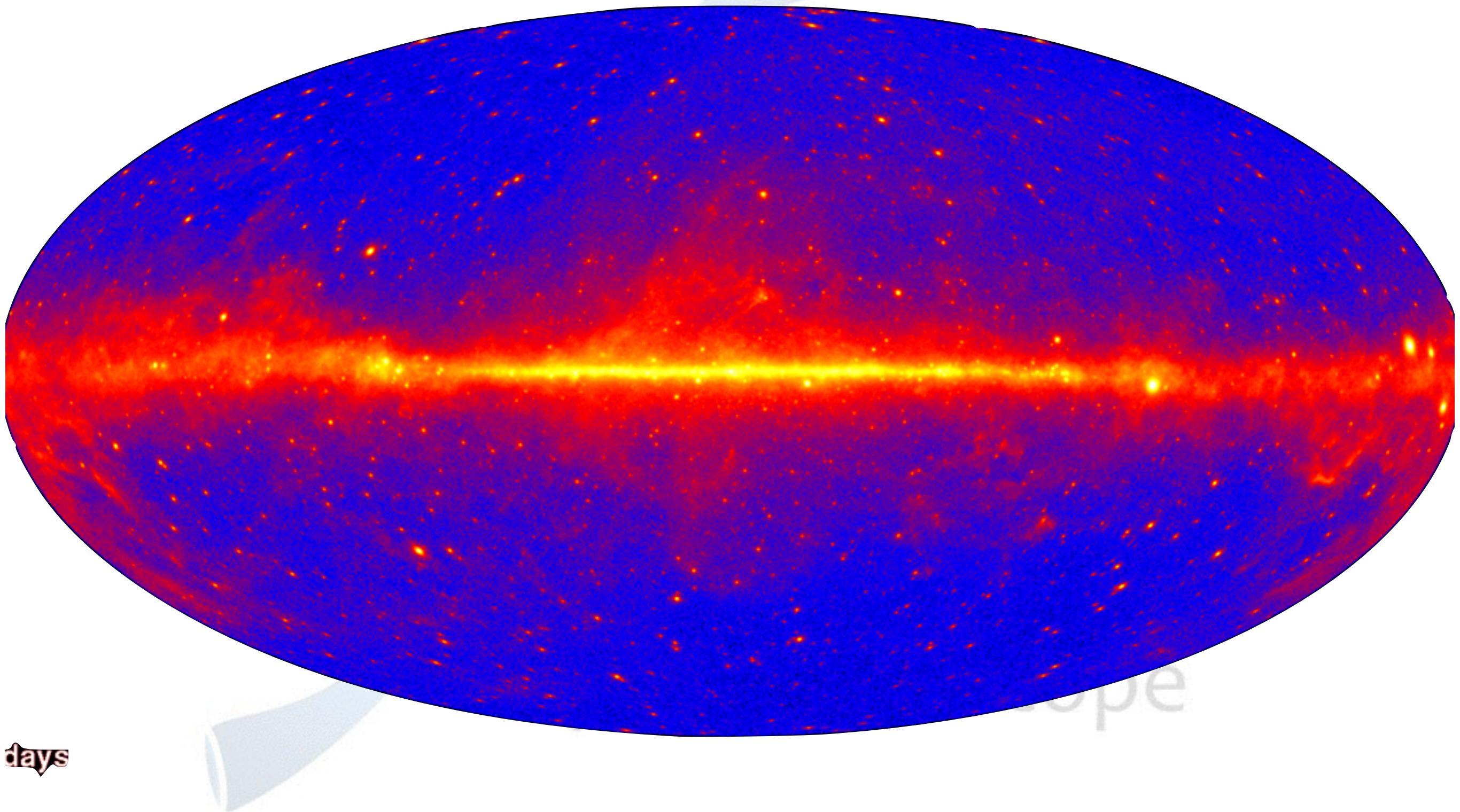
## Collider



Gustafsson et al.  
PRL 99.041301

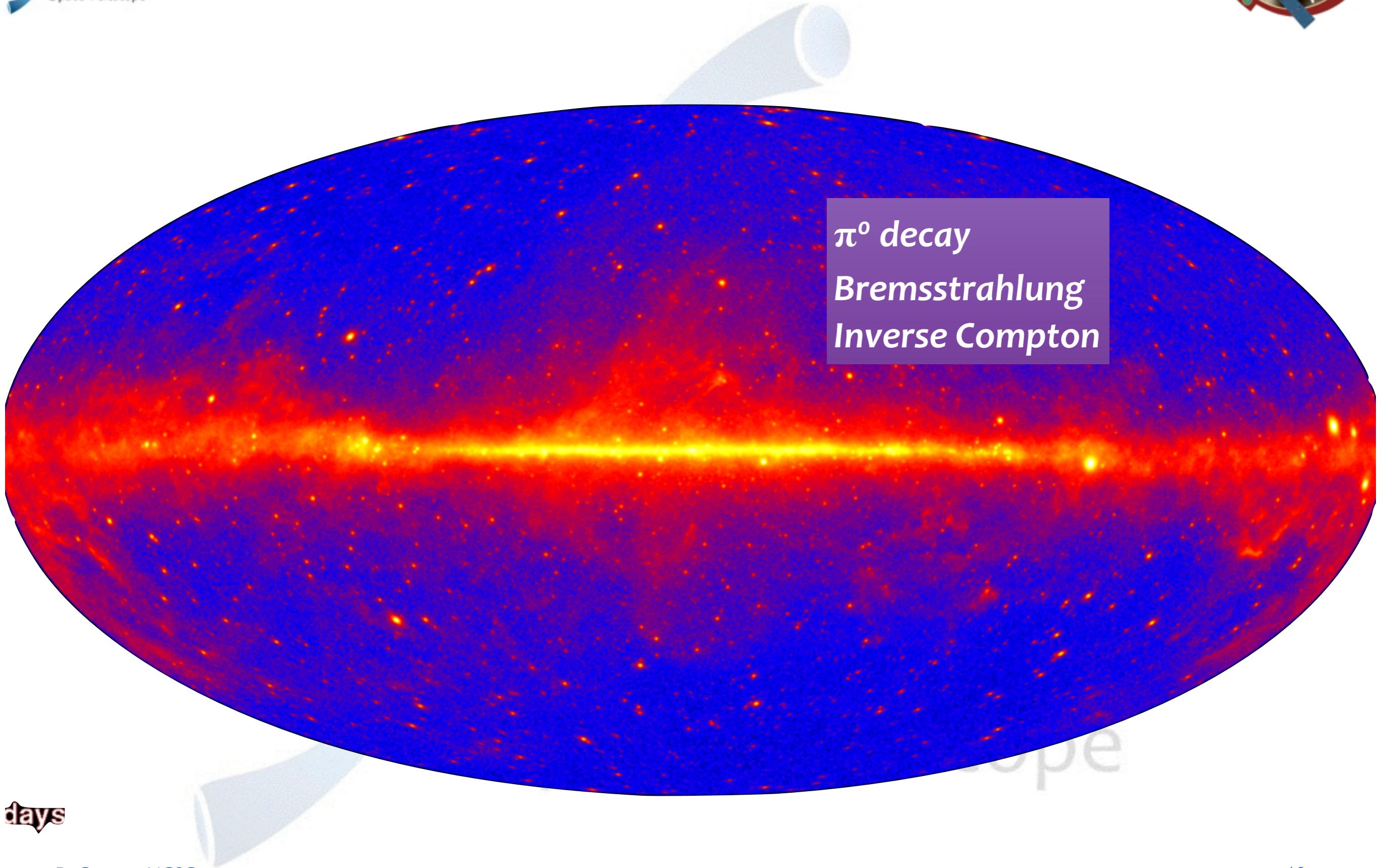


# Fermi-LAT $\gamma$ -ray sky

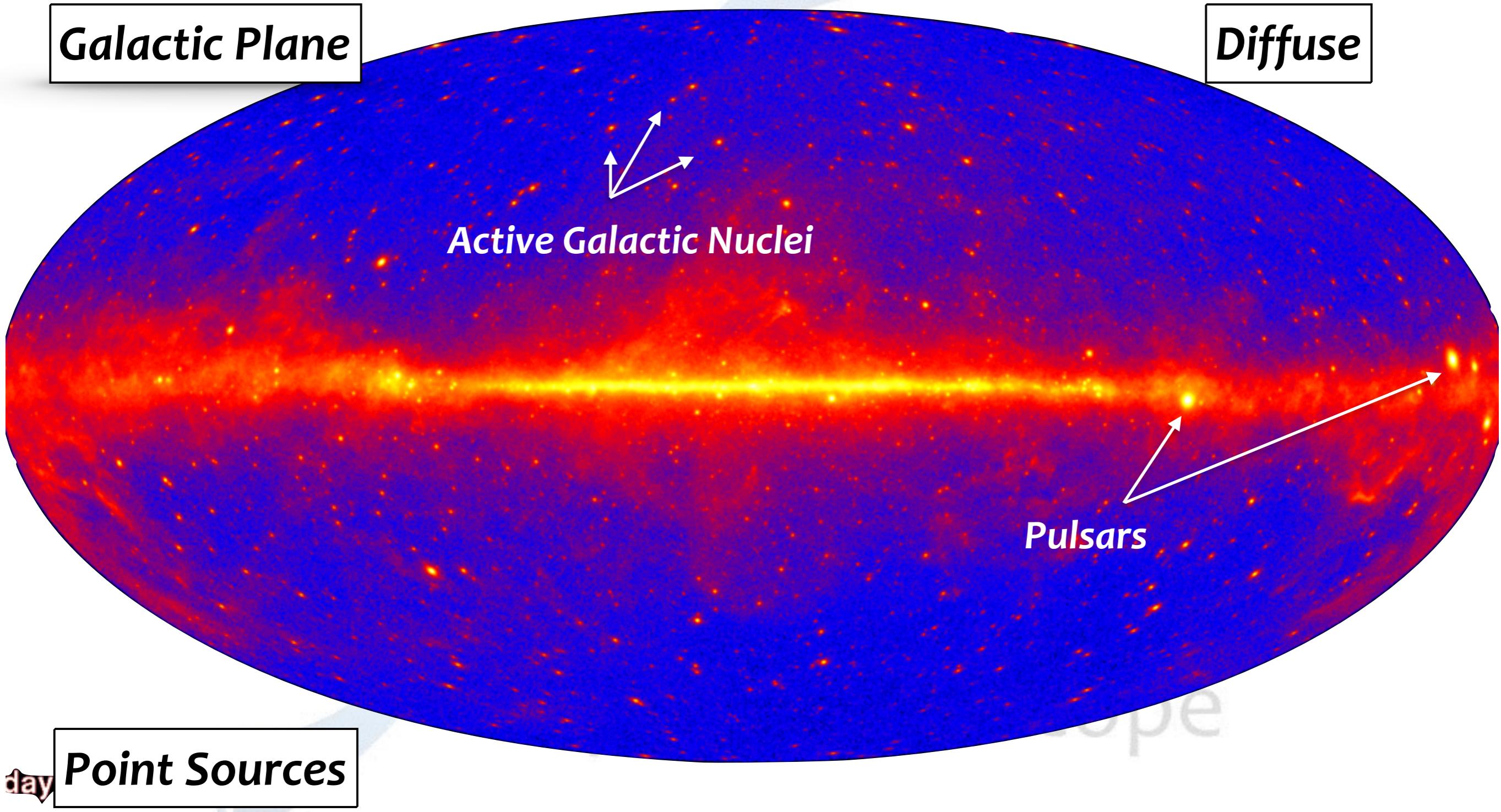


days

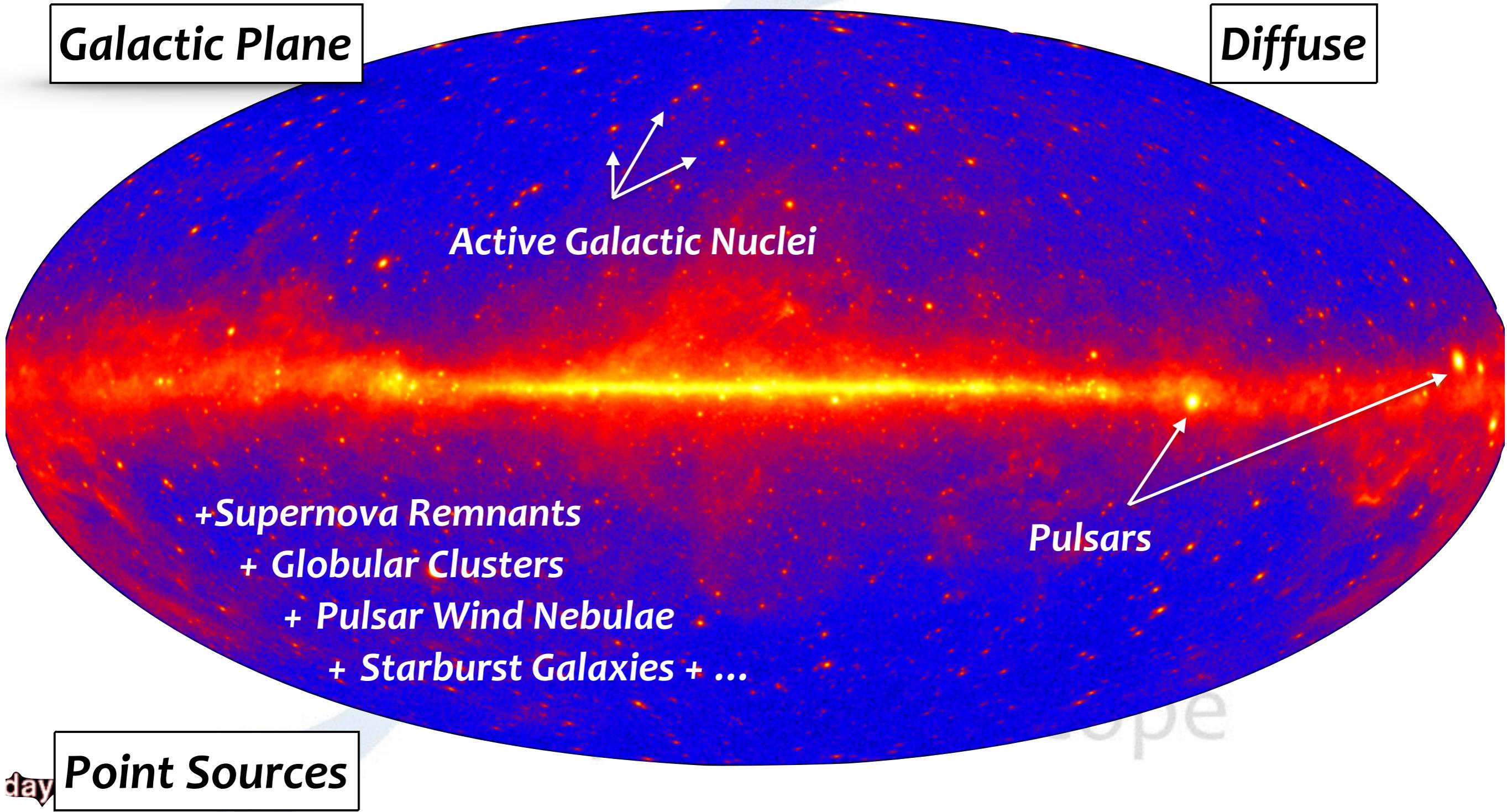
# Fermi-LAT $\gamma$ -ray sky



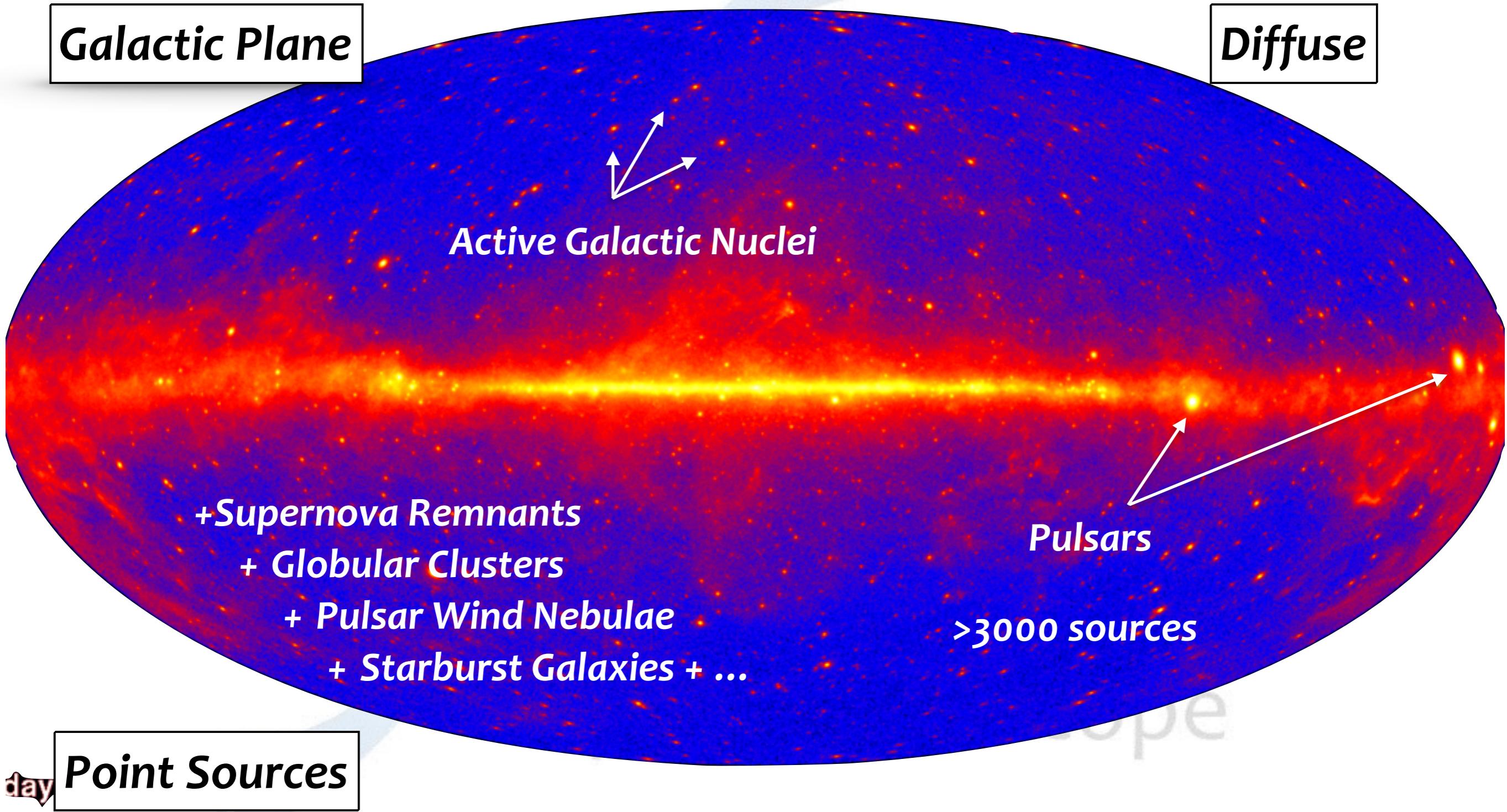
# Fermi-LAT $\gamma$ -ray sky



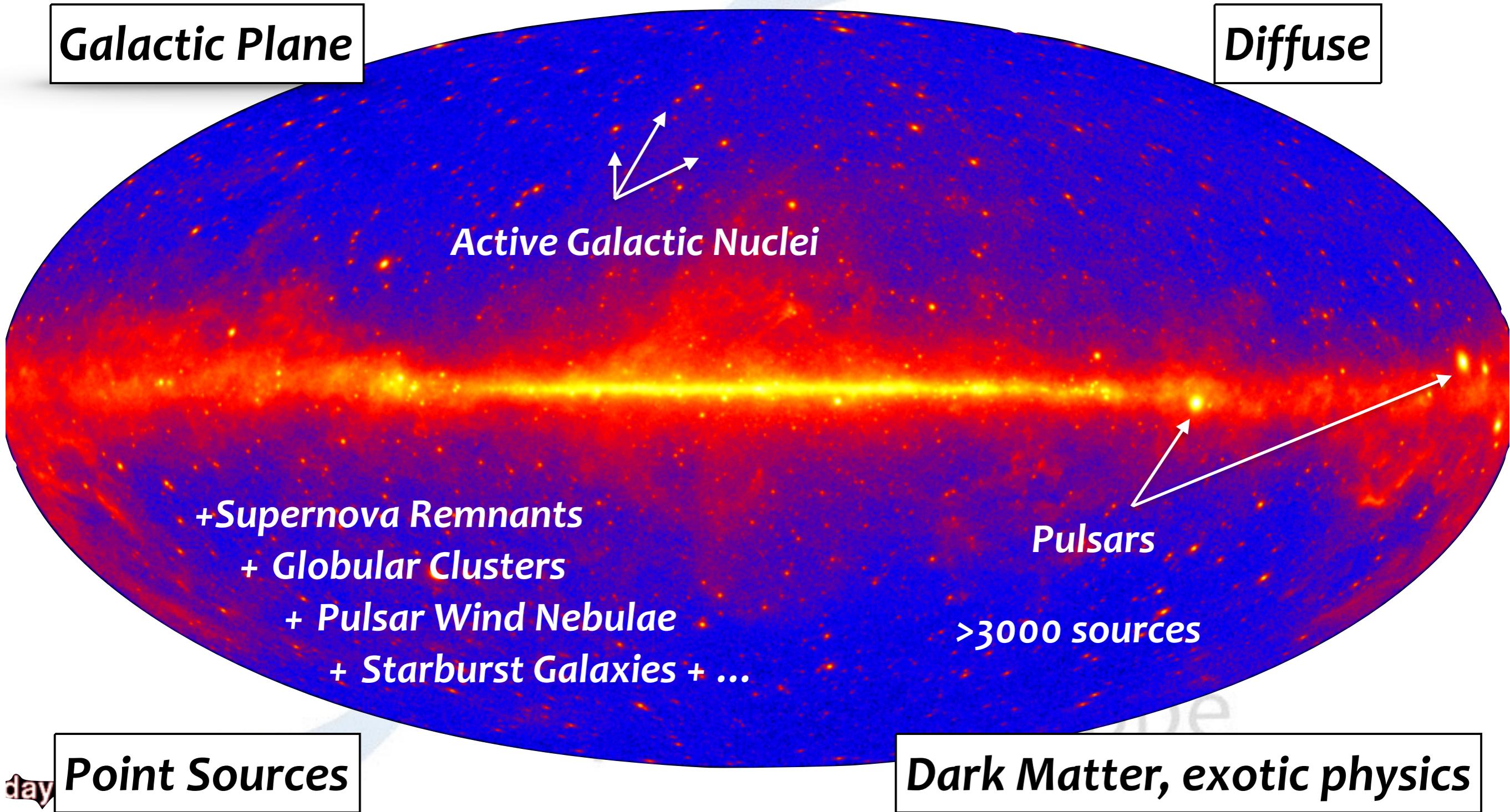
# Fermi-LAT $\gamma$ -ray sky



# Fermi-LAT $\gamma$ -ray sky



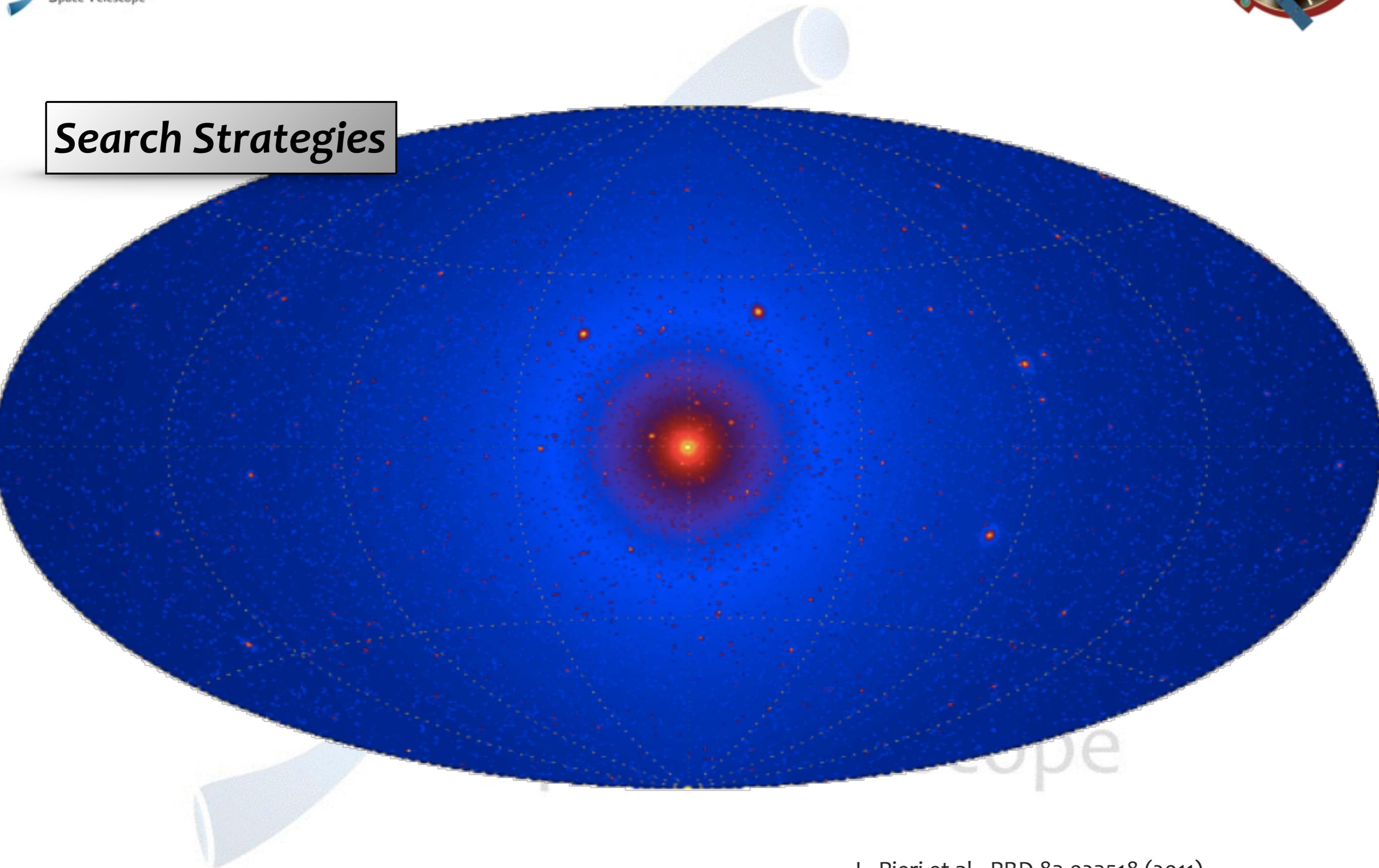
# Fermi-LAT $\gamma$ -ray sky



# Dark Matter Distribution



## Search Strategies



# Dark Matter Distribution



## Search Strategies

Dwarf Spheroidal  
Satellite Galaxies

Milky Way Halo

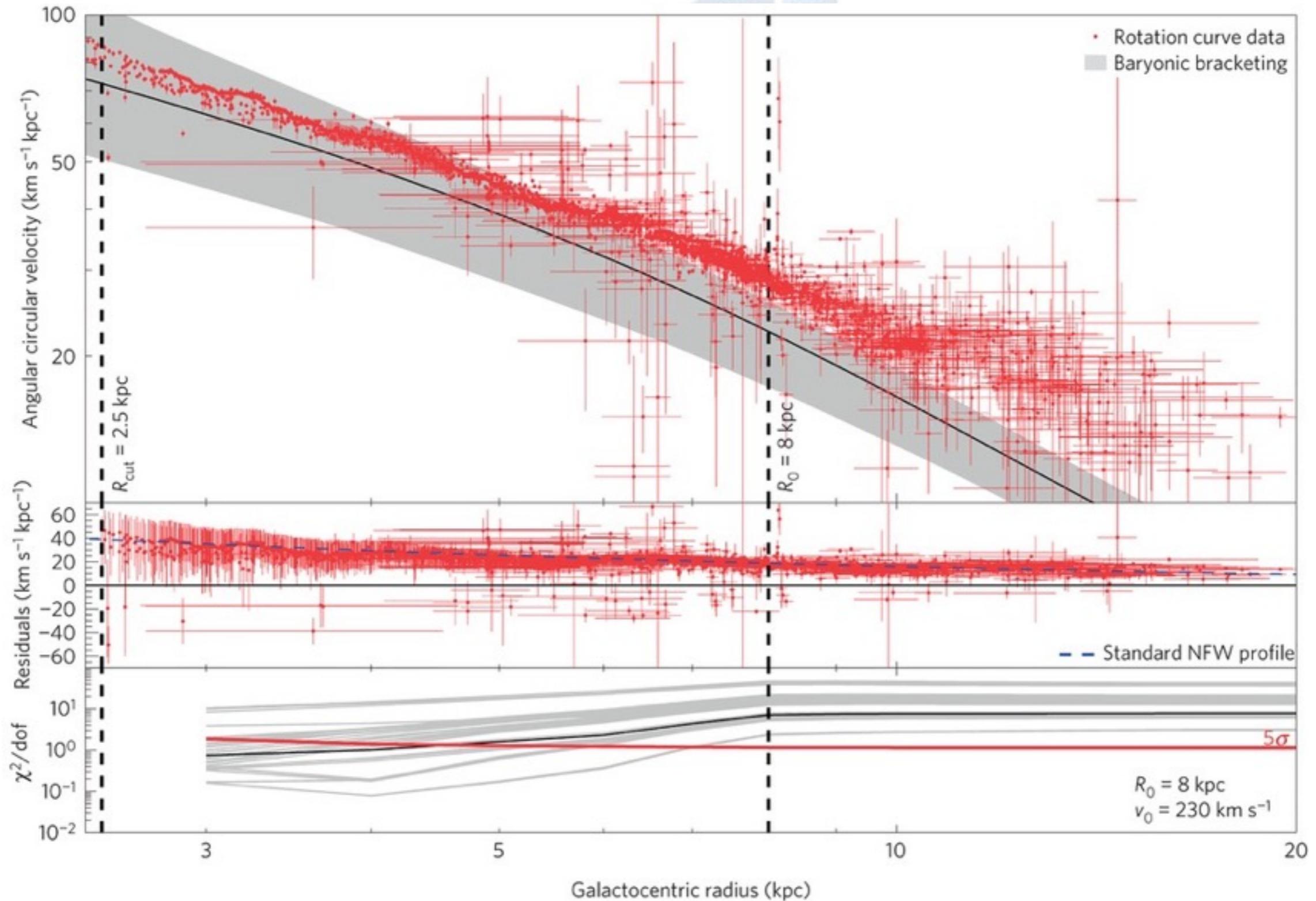
Spectral Lines

Galactic Center

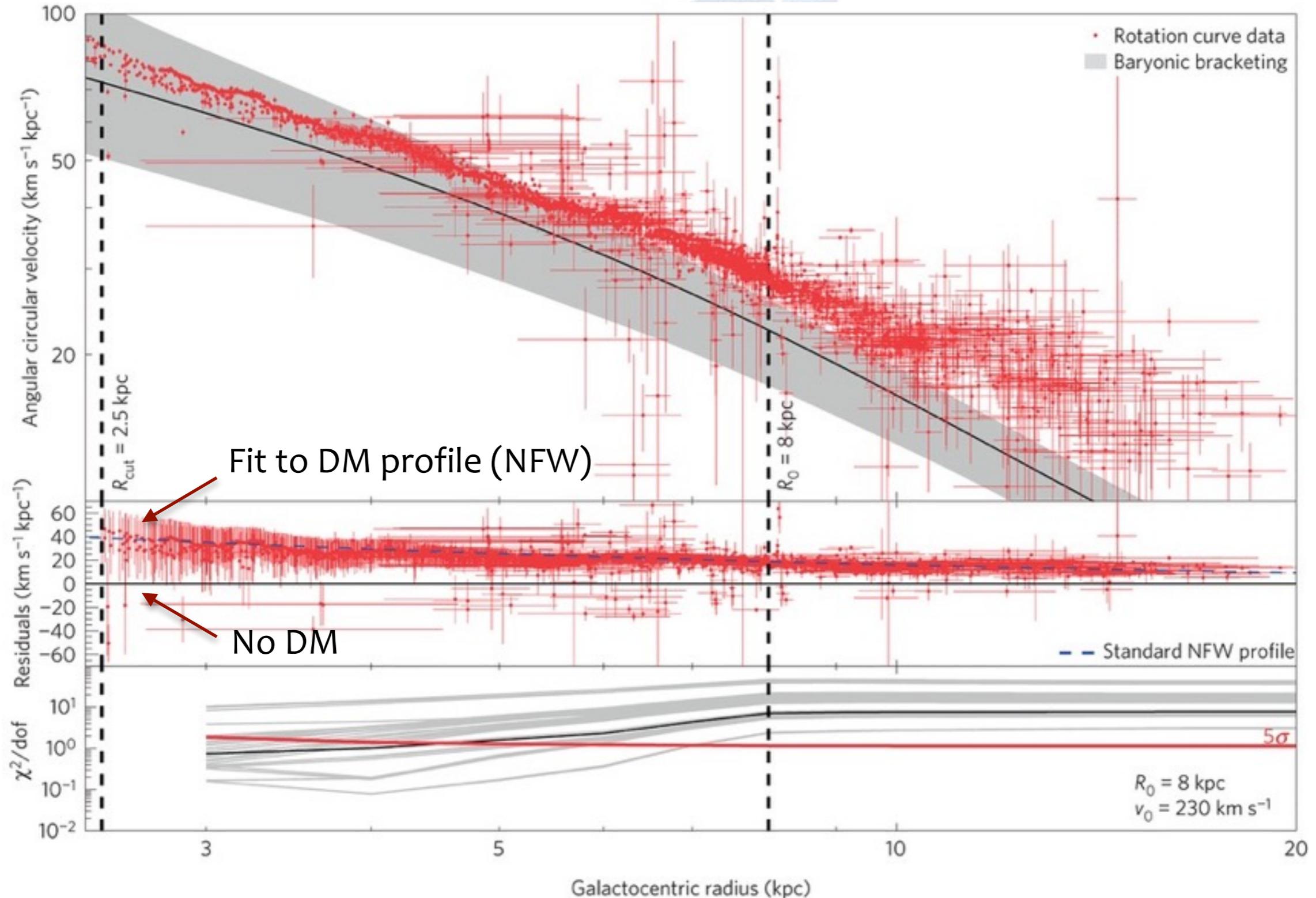
Galaxy Clusters

Isotropic Background

# Galactic Center



# Galactic Center





# Galactic Center



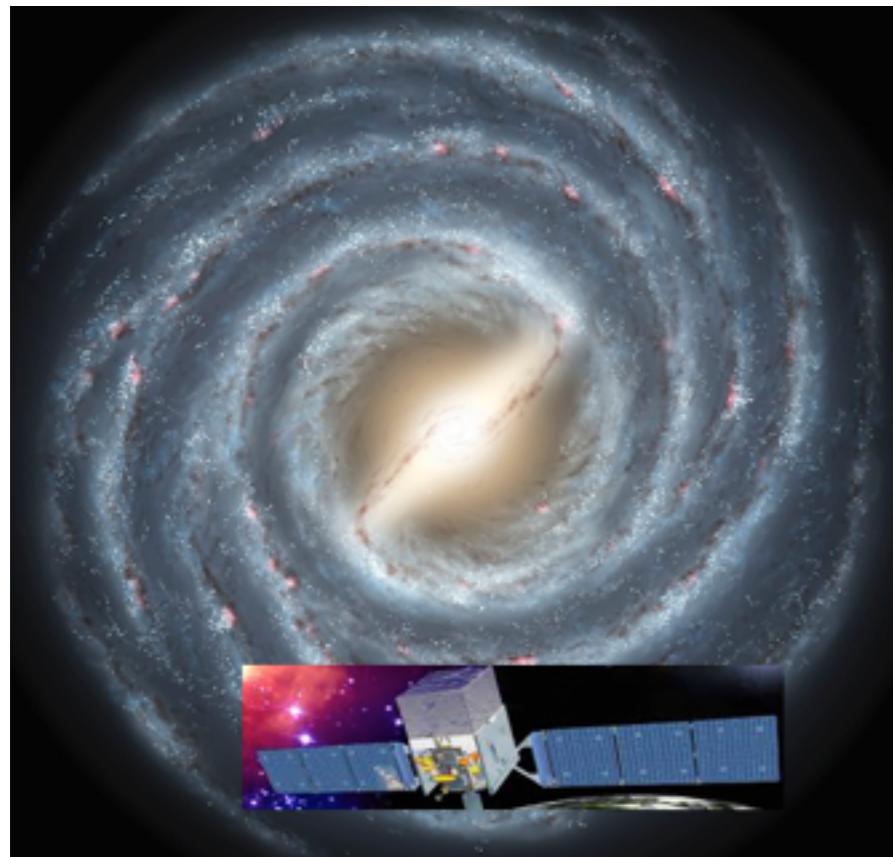
**Why is the Galactic Center so hard to observe?**  
**Follow up: With which wavelengths can we observe the GC?**



# Galactic Center



**Why is the Galactic Center so hard to observe?**  
**Follow up: With which wavelengths can we observe the GC?**



*fermi*  
Gamma-ray  
Space Telescope

# Galactic Center



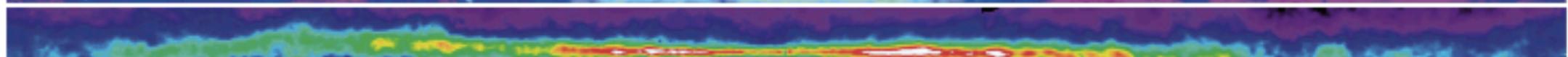
Why is the Galactic Center so hard to observe?

Follow up: With which wavelengths can we observe the GC?

Radio (0.4 GHz)



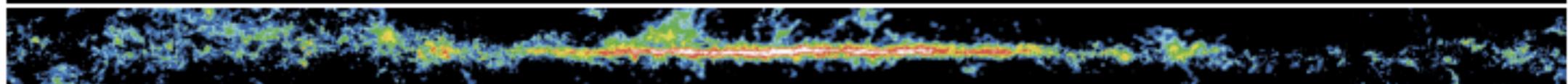
Atomic Hydrogen



Radio (2.7 GHz)



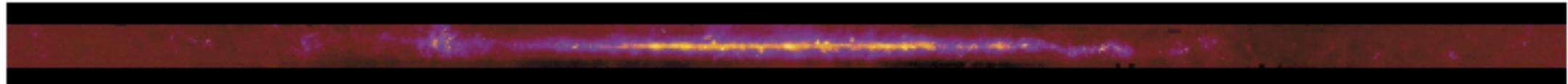
Molecular Hydrogen



Infrared



Mid Infrared



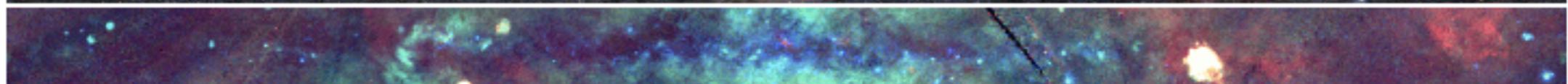
Near Infrared



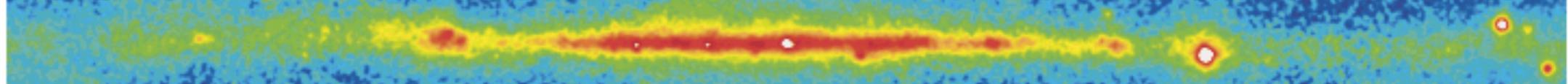
Optical



X-Ray



Gamma Ray

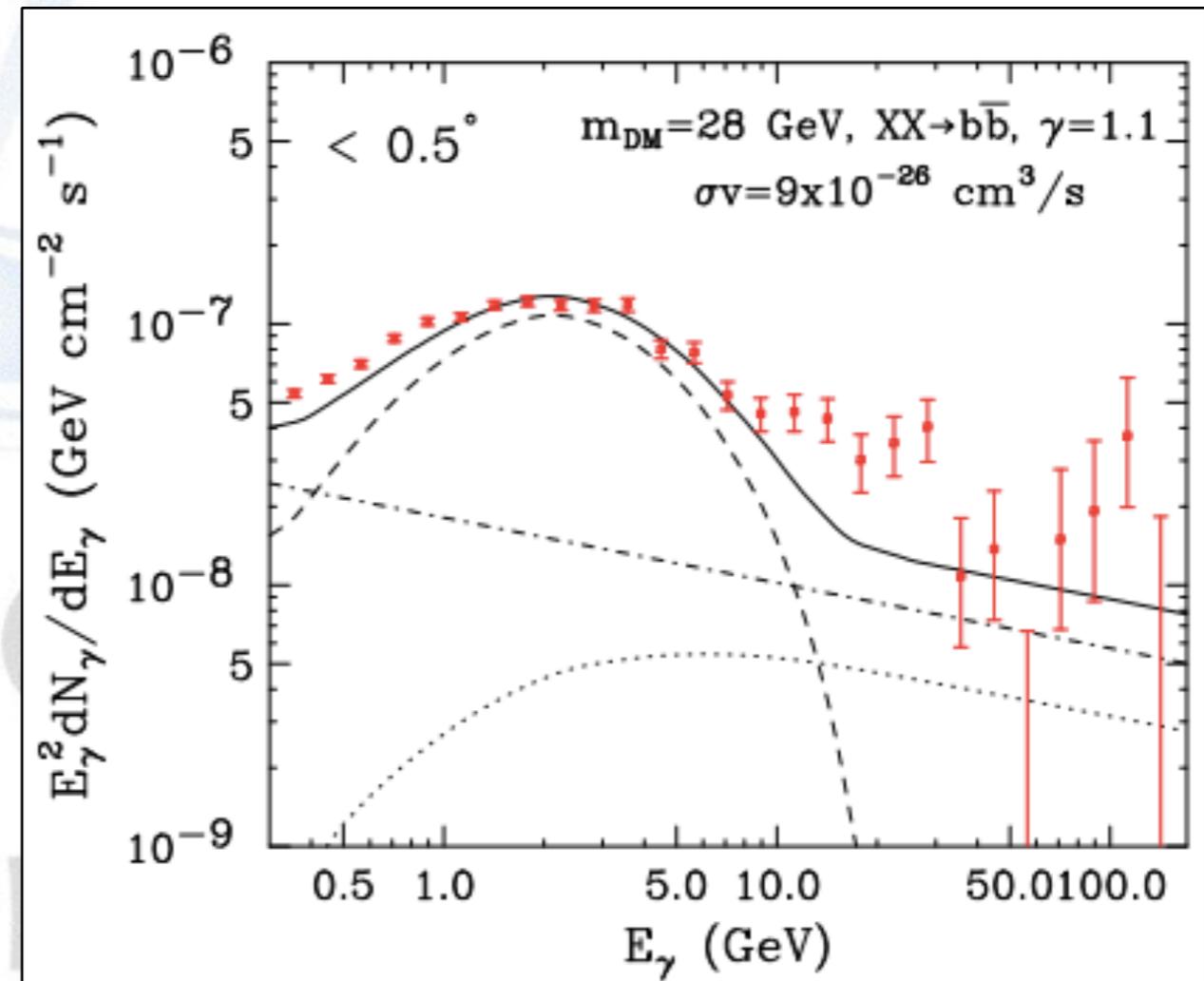


# What's Going On in the Galactic Center?



2009

Excess in gamma-ray flux from GC





# What's Going On in the Galactic Center?



**2009**

Excess in gamma-ray flux from GC

**2009 — now**

Many papers confirming the excess  
Speculation as to its origin

**Not exhaustive:**

- L. Goodenough, D. Hooper, arXiv:0910.2998
- D. Hooper, L. Goodenough, PLB, arXiv:1010.2752
- D. Hooper, T. Linden, PRD, arXiv:1110.0006
- K. Abazajian, M. Kaplinghat, PRD, arXiv:1207.6047
- D. Hooper, T. Slatyer, PDU, arXiv:1302.6589
- C. Gordon, O. Macias, PRD, arXiv:1306.5725
- W. Huang, A. Urbano, W. Xue, arXiv:1307.6862
- K. Abazajian, N. Canac, S. Horiuchi, M. Kaplinghat, arXiv:1402.4090
- T. Daylan, et al., PDU 12 1 (2016), arXiv: 1402.6703

**Dark Matter**

Gamma-ray  
Space Telescope



# What's Going On in the Galactic Center?



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- K. Abazajian, N. Canac, S. Horiuchi, M. Kaplinghat, arXiv:1402.4090
- T. Daylan, et al., PDU 12 1 (2016), arXiv: 1402.6703

**Unresolved populations\*\***

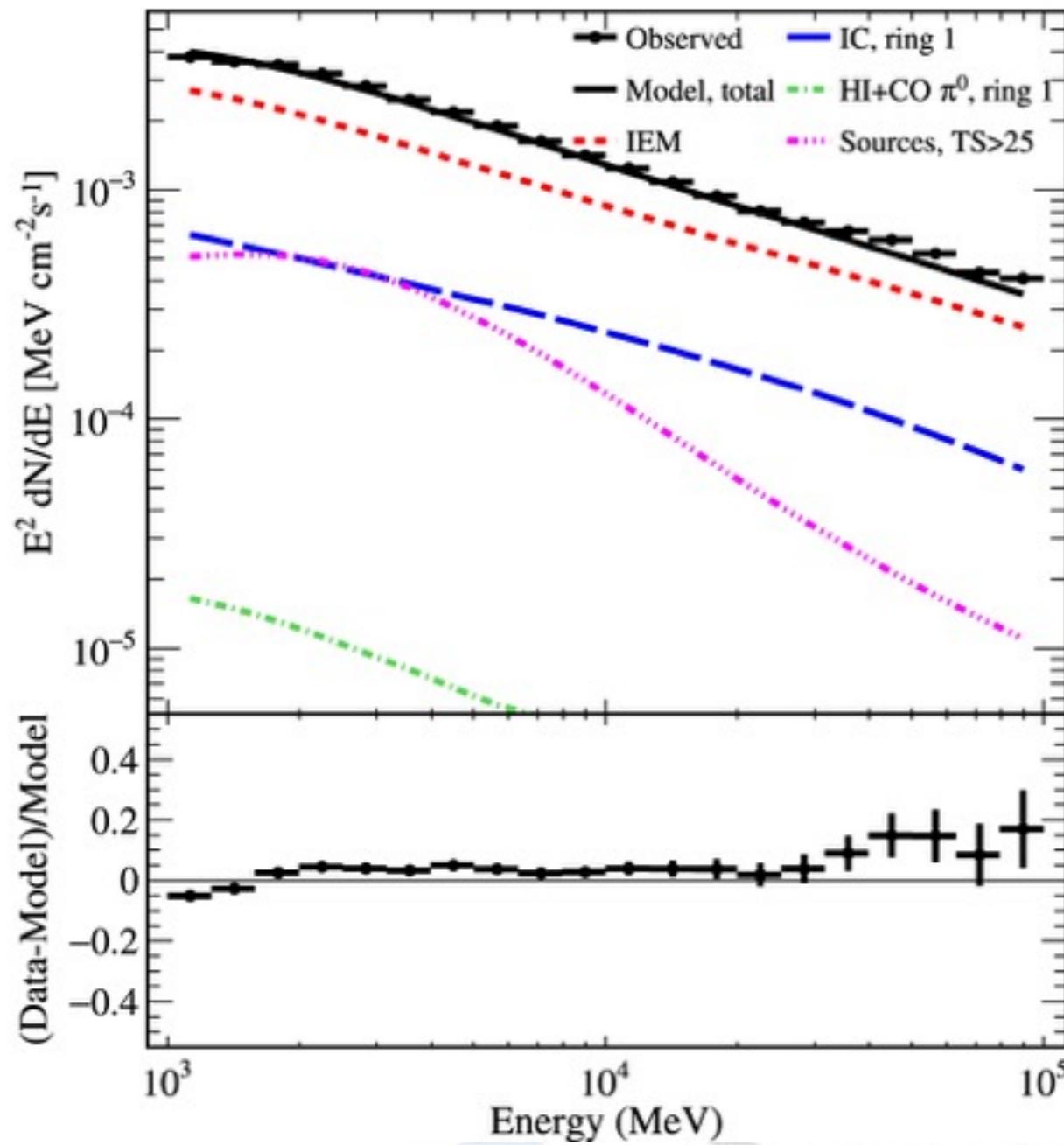
**Dark Matter**

**\*\*Massive star formation (OB type stars)**

**Unresolved point sources**

**Pulsars...**

# Dividing the Galaxy



## Constituents of the Model

Templates to define different background regions  
 Gamma-ray sources (pulsars, OB stars)  
 Intensity/Index scaled

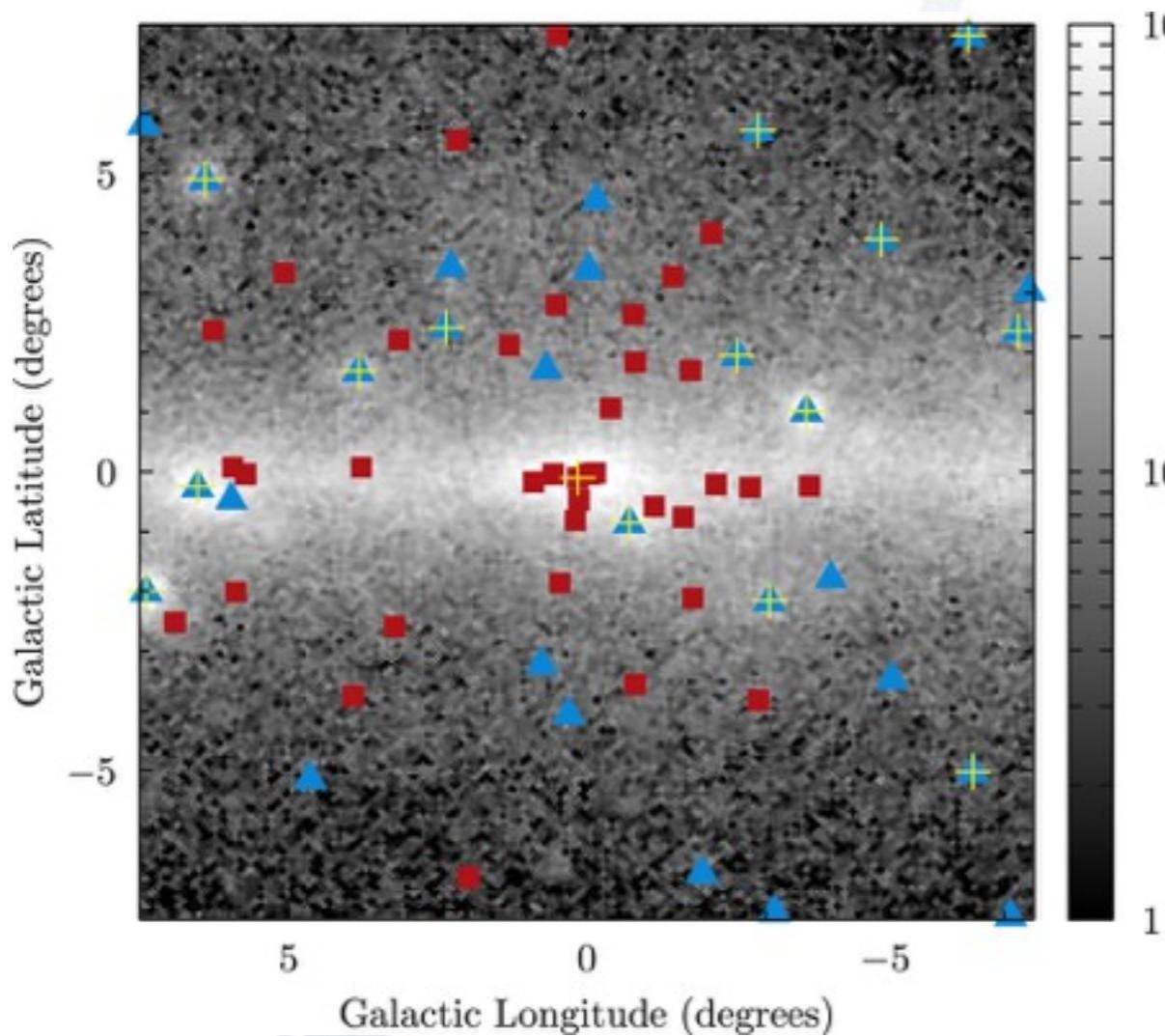
fermi

gamma-ray  
Space Telescope

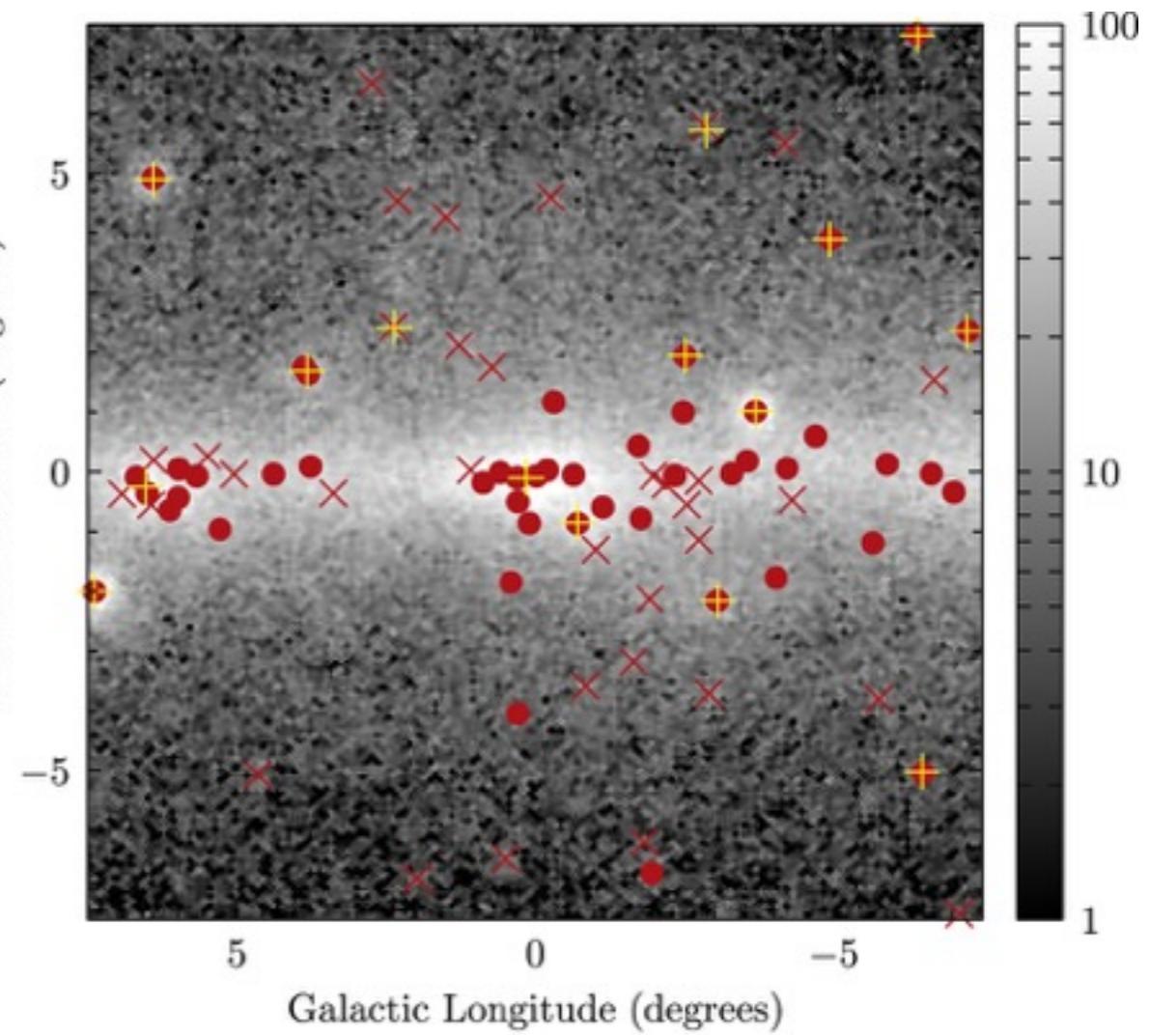
# Dividing the Galaxy



The 3FGL Catalog

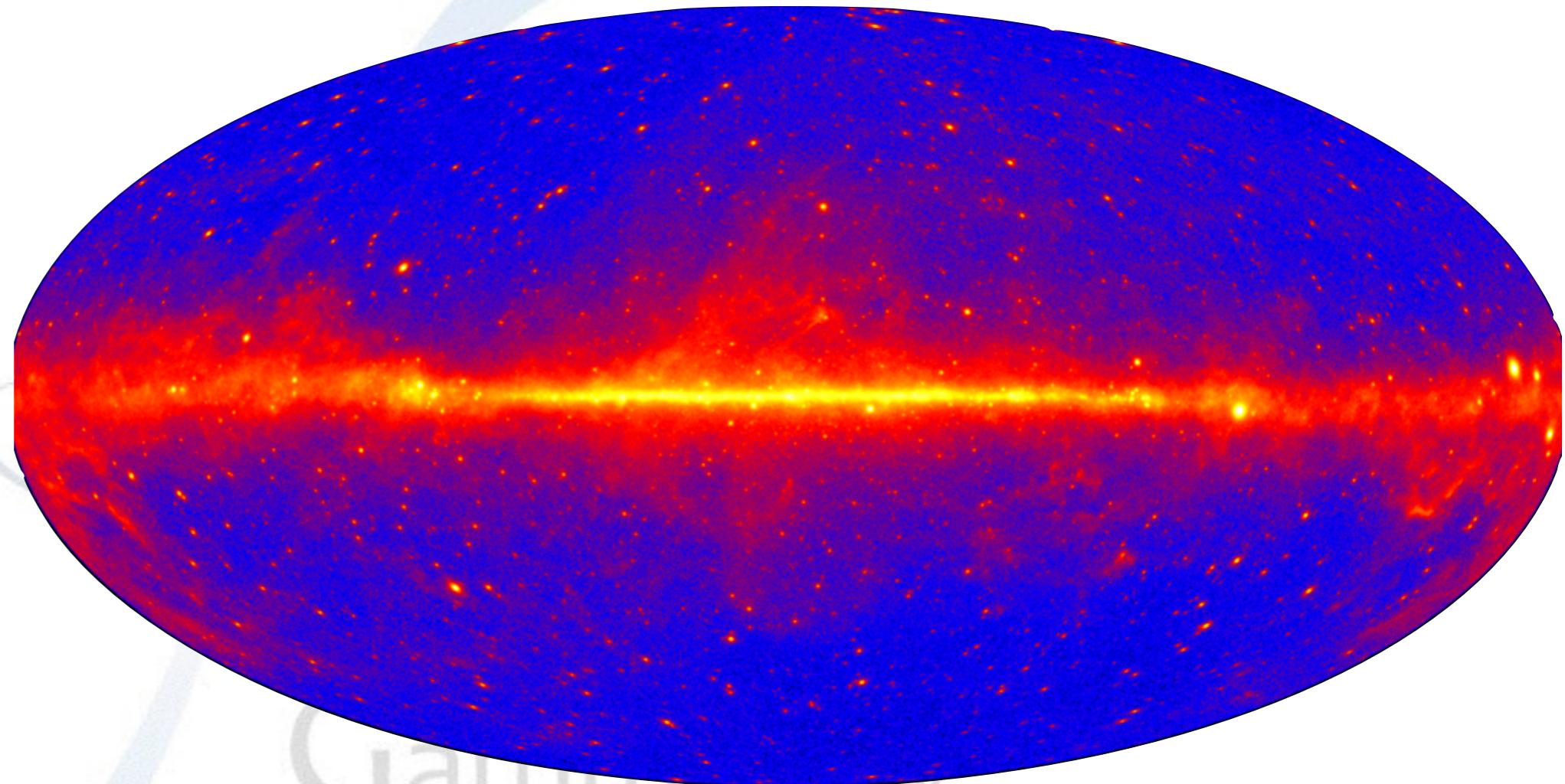


The 1FIG Catalog





# Upgrading to Pass 8

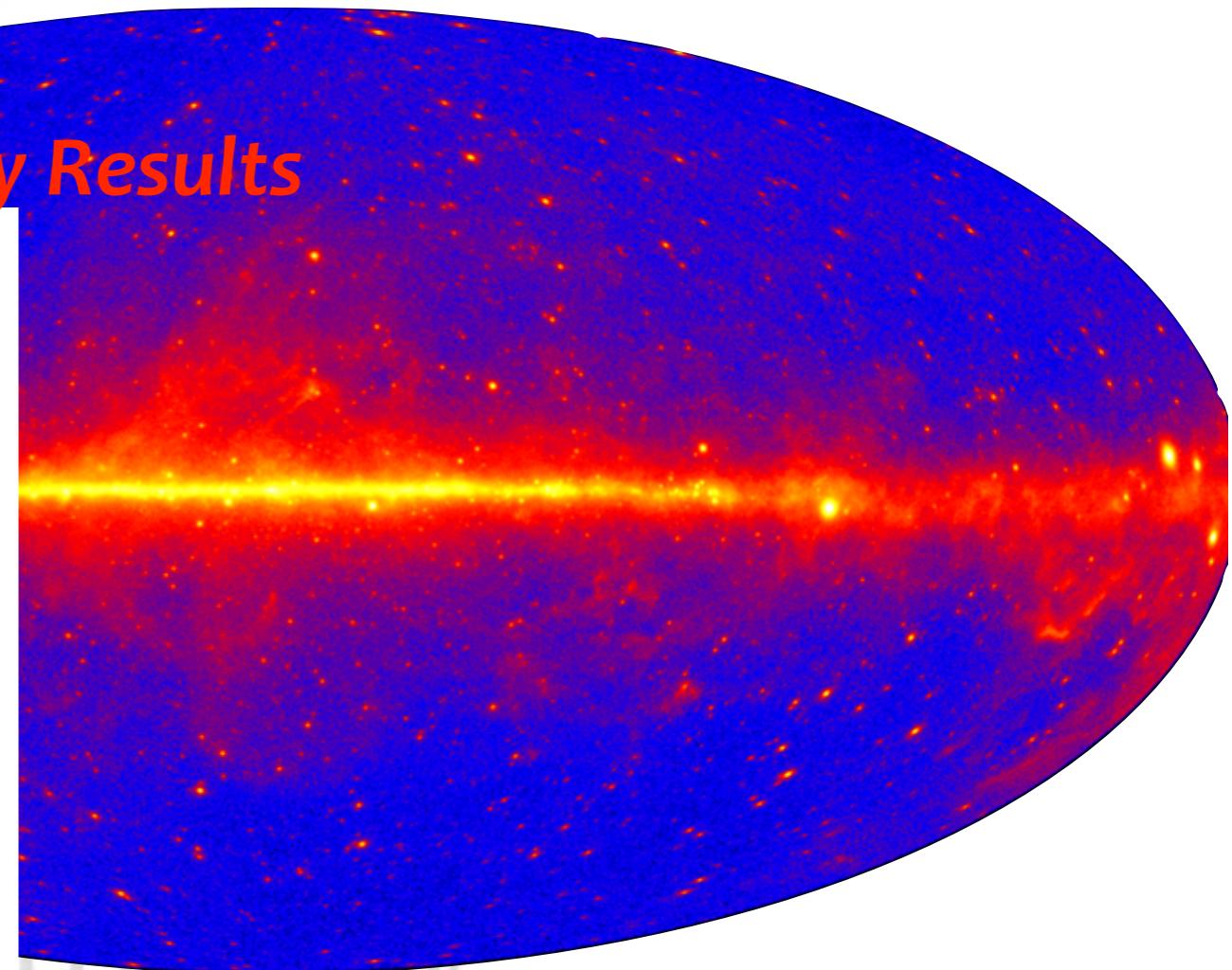
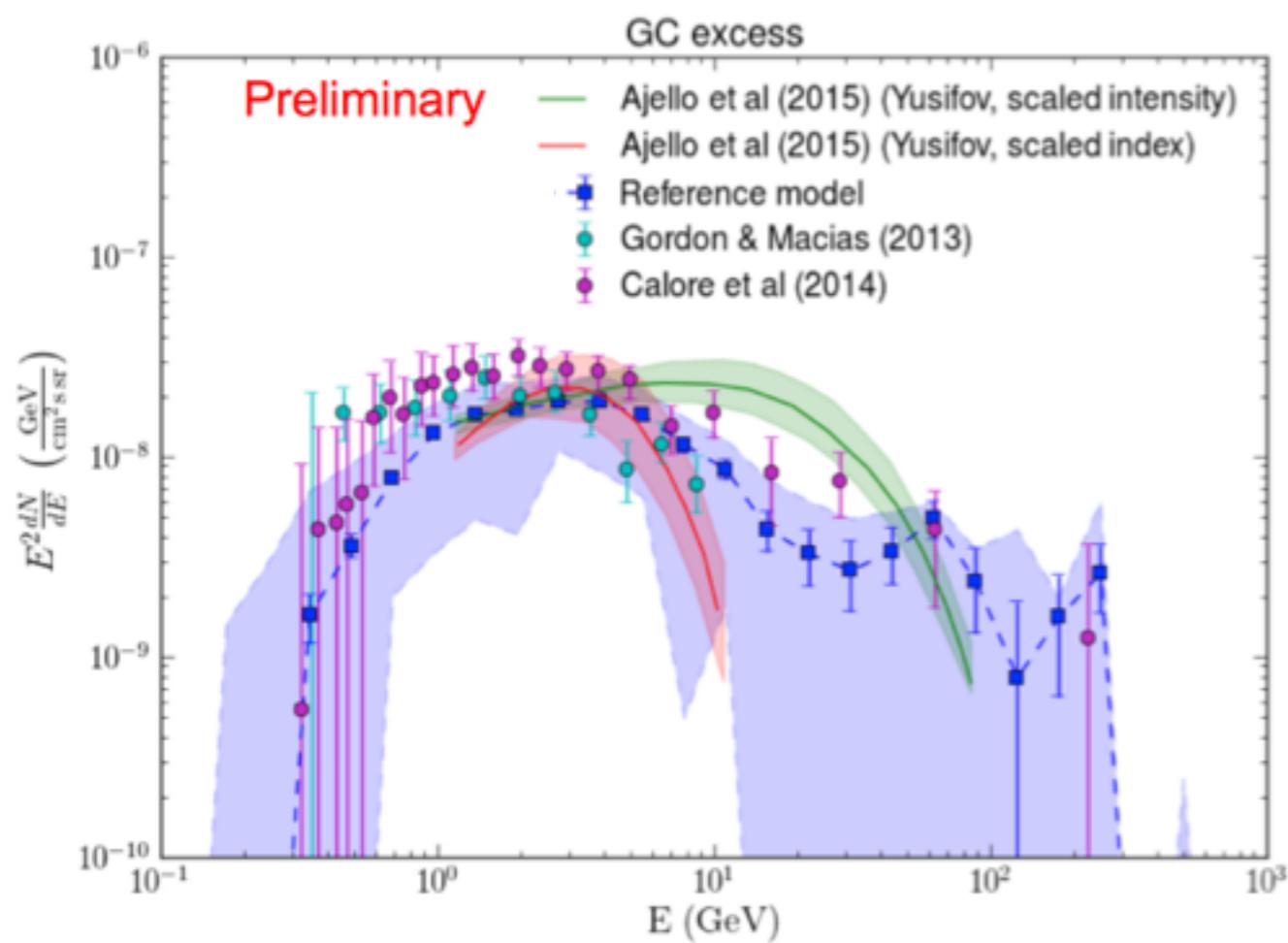


Gamma-ray  
Space Telescope

# Upgrading to Pass 8



## Preliminary Results

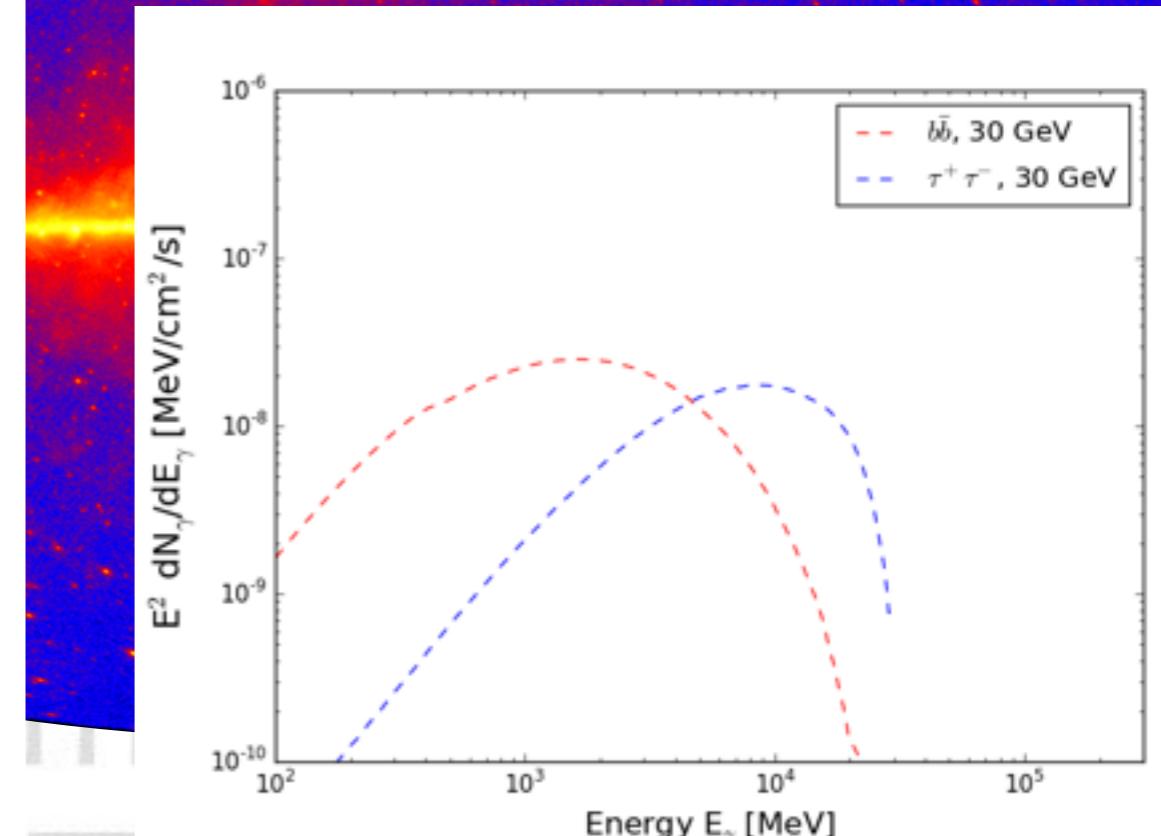
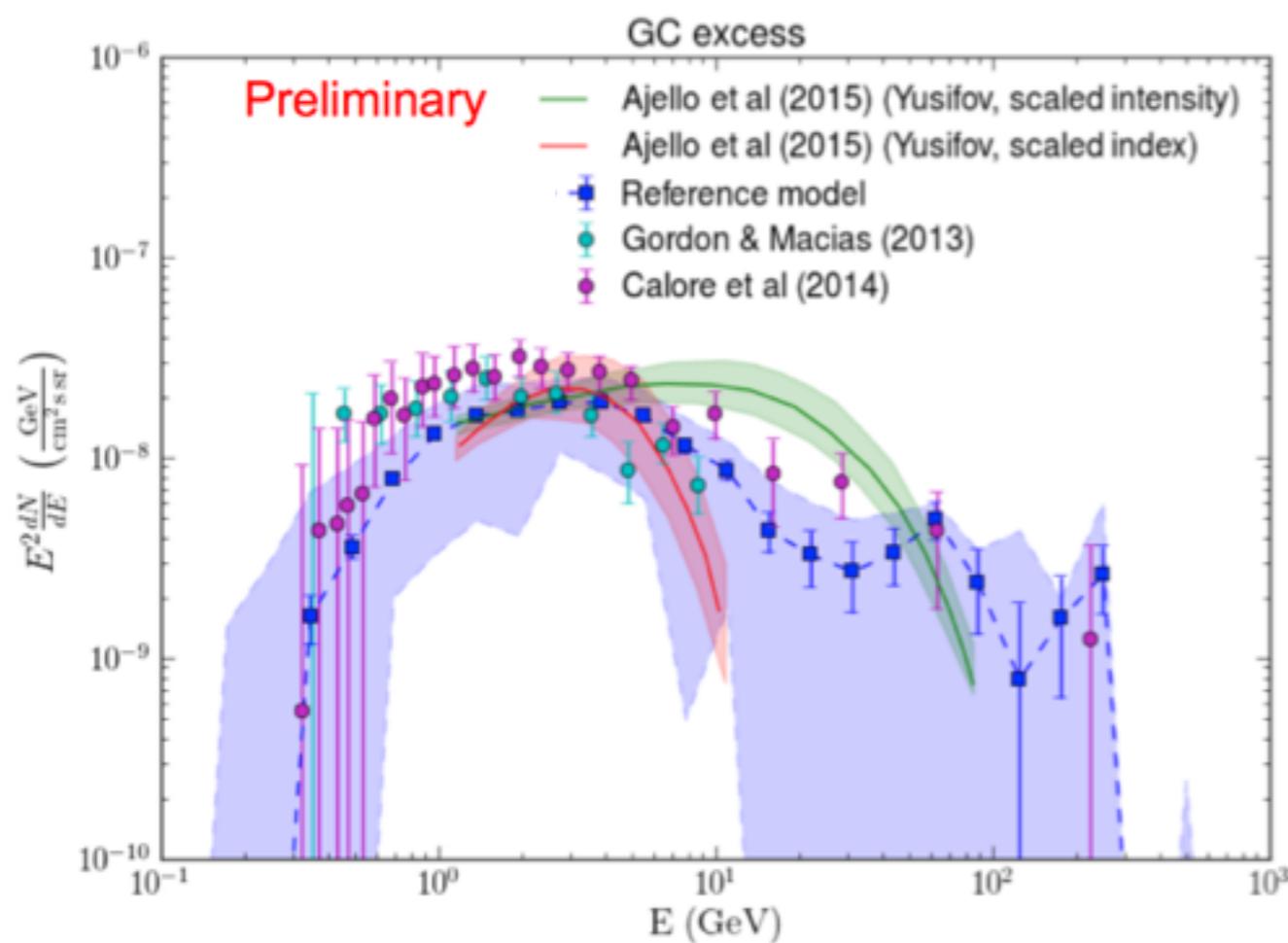


Fermi-LAT Collaboration, Fermi Symposium 2015

# Upgrading to Pass 8



## Preliminary Results



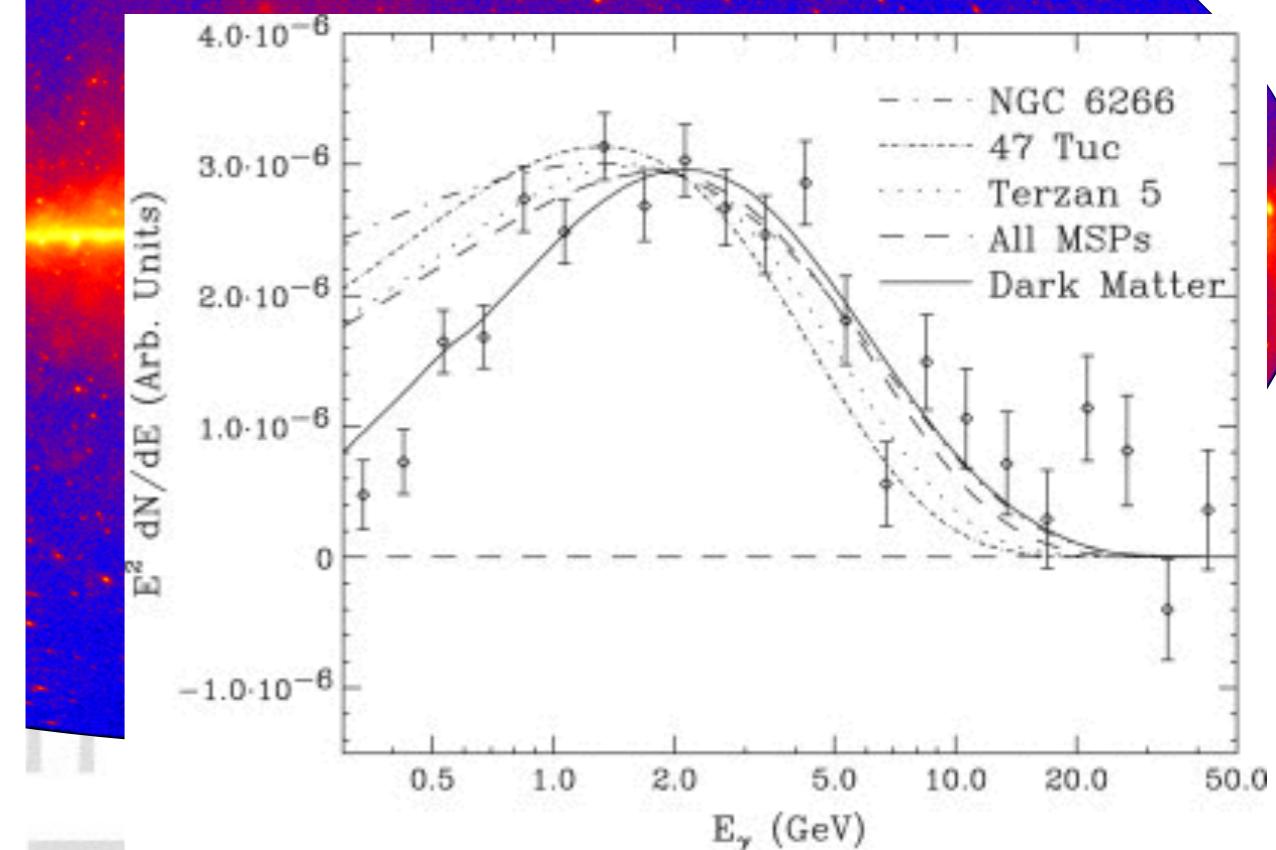
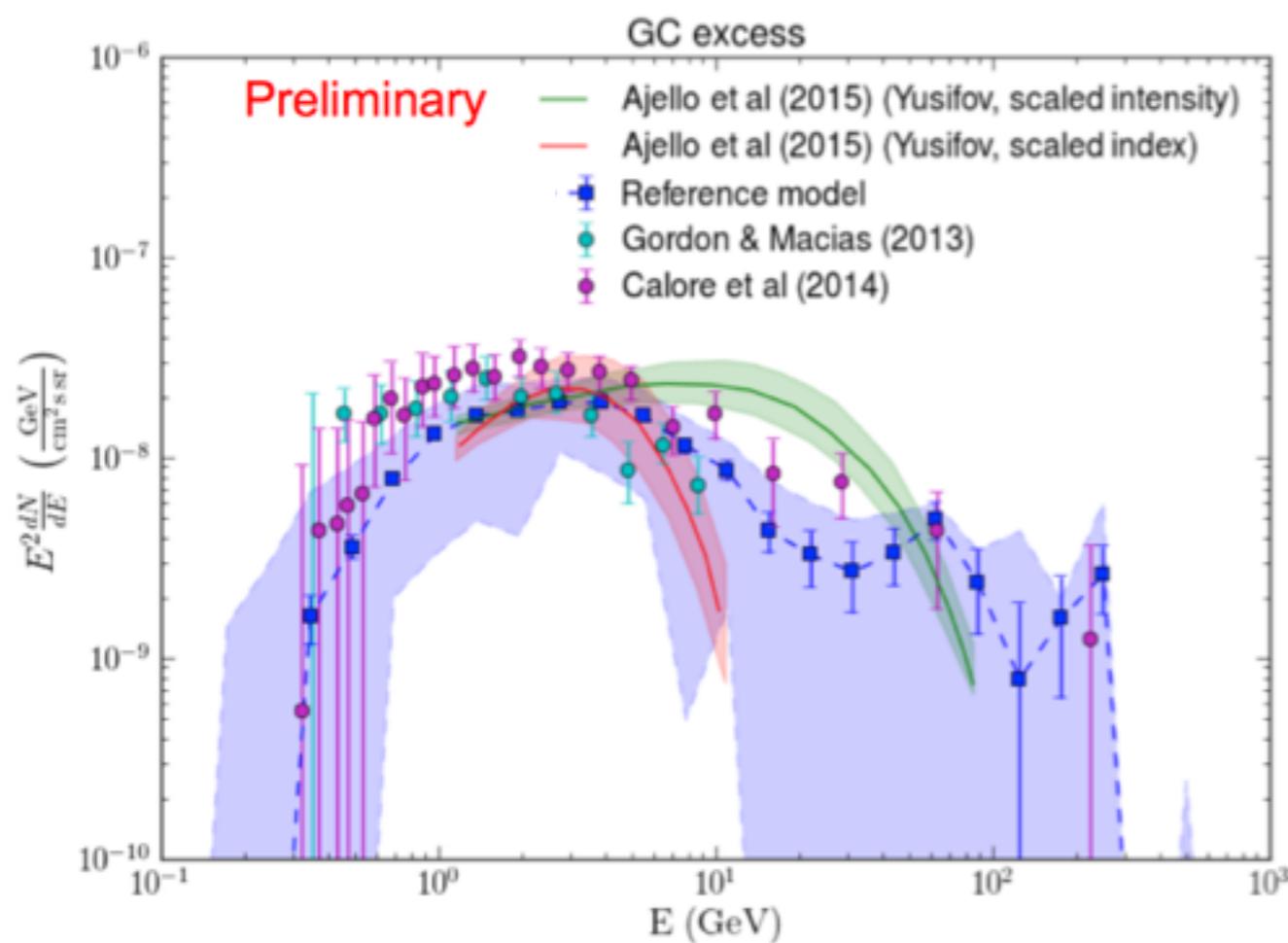
Fermi-LAT Collaboration, Fermi Symposium 2015

space Telescope

# Upgrading to Pass 8



## Preliminary Results



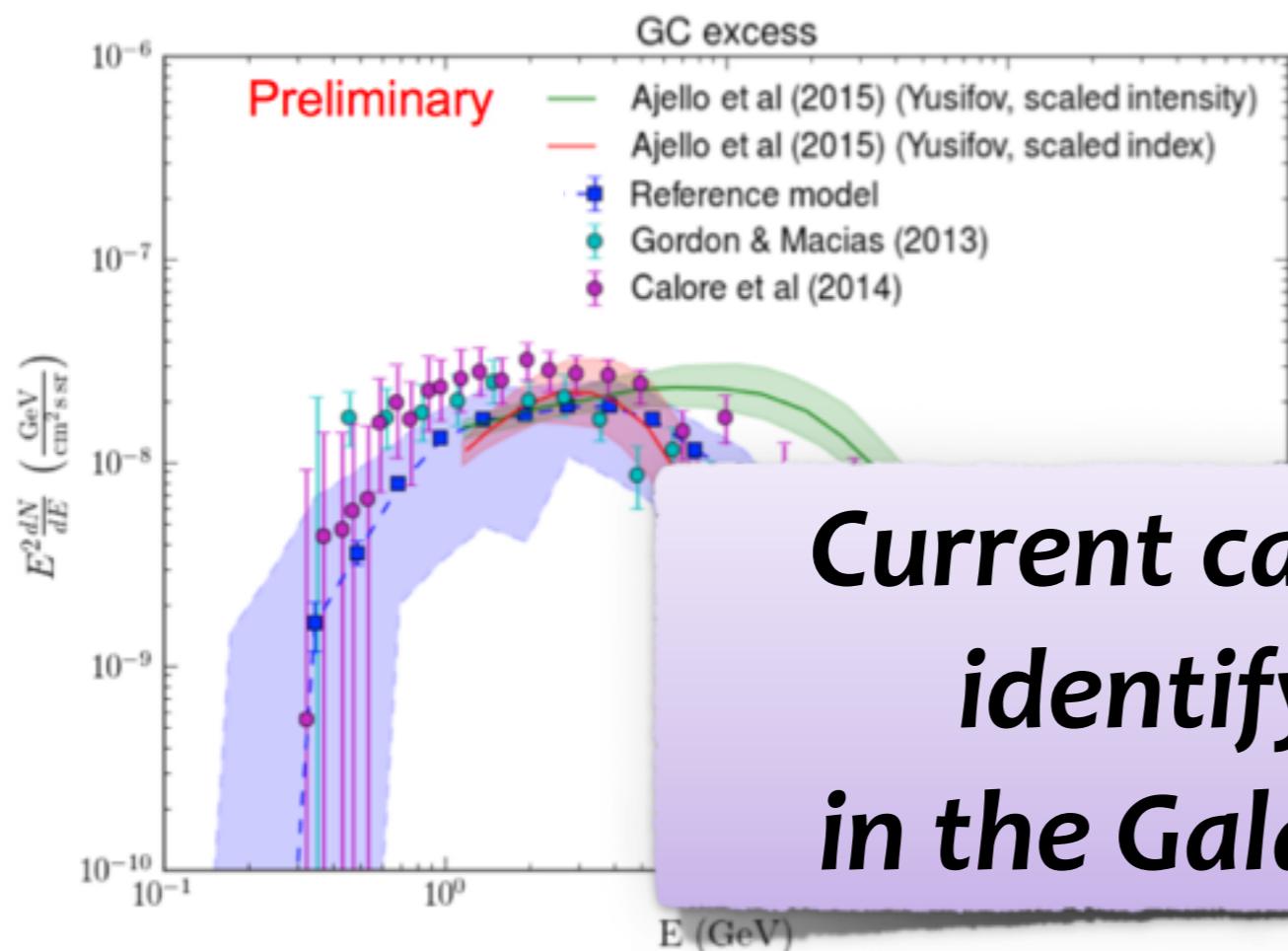
Fermi-LAT Collaboration, Fermi Symposium 2015

T. Daylan, et al., PDU 12 1 (2016), arXiv: 1402.6703

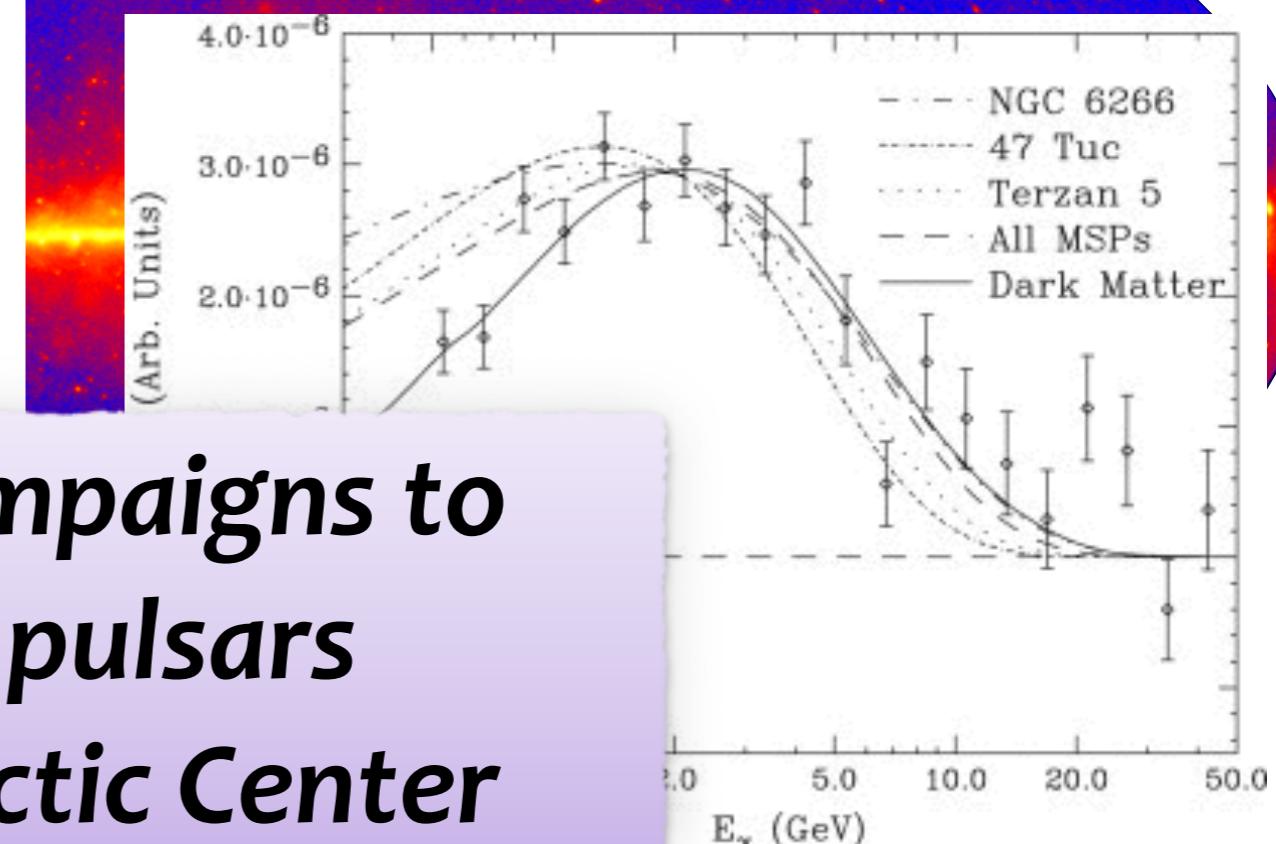
# Upgrading to Pass 8



## Preliminary Results



**Current campaigns to identify pulsars in the Galactic Center**



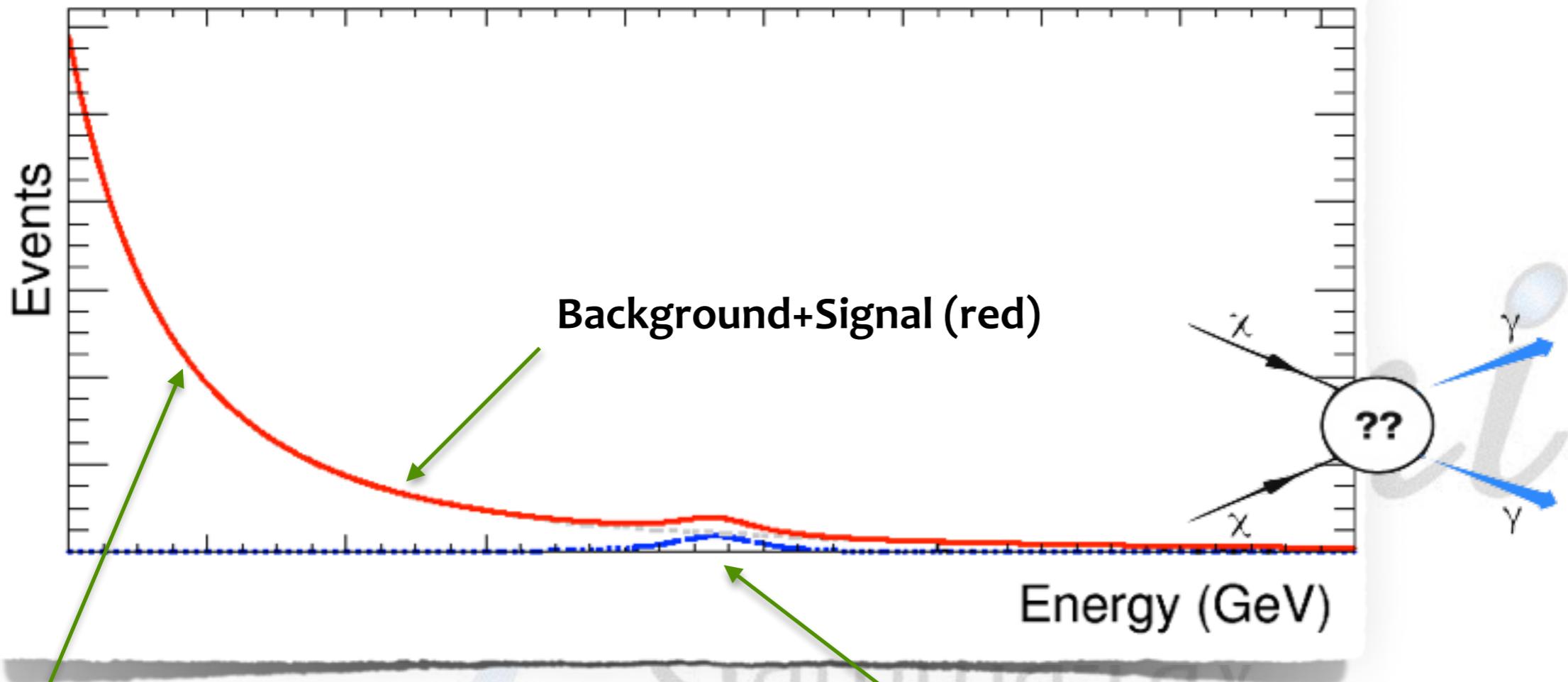
Fermi-LAT Collaboration, Fermi Symposium 2015

T. Daylan, et al., PDU 12 1 (2016), arXiv: 1402.6703

# Spectral Lines



Unbinned Maximum Likelihood Fits



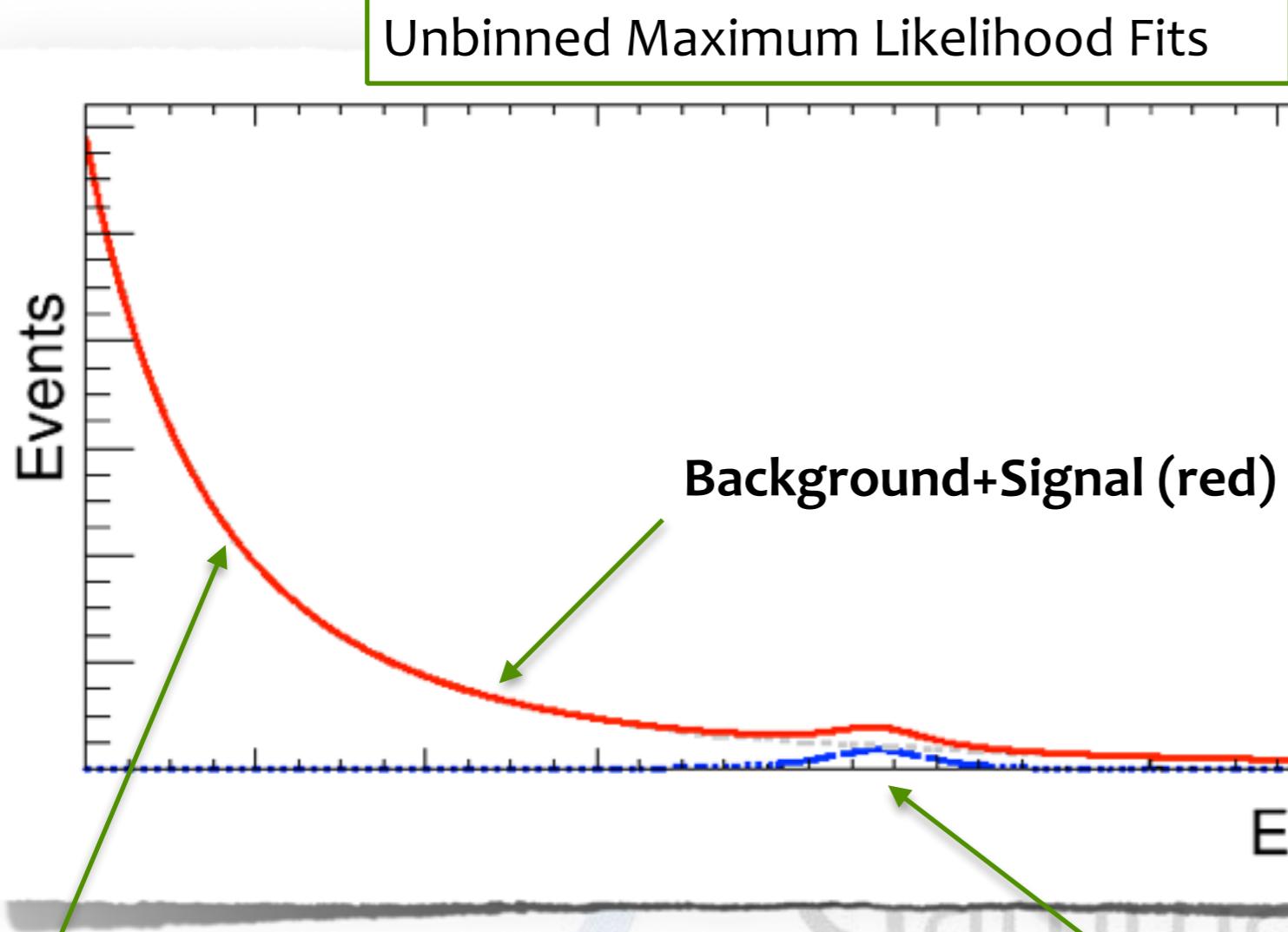
## Background model (grey dashed):

- Single power law with index  $\Gamma_{\text{bkg}}$  allowed to float
- Energy dependent exposure correction

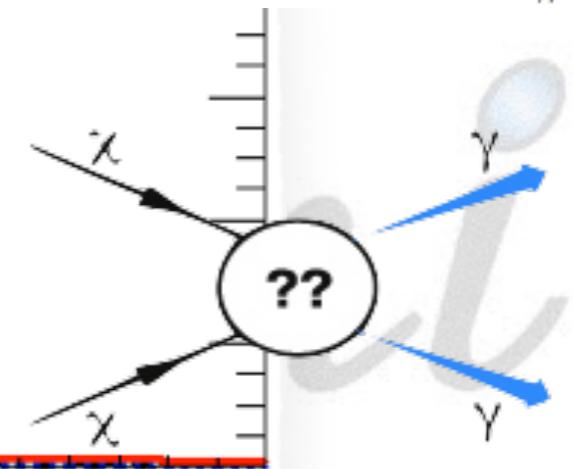
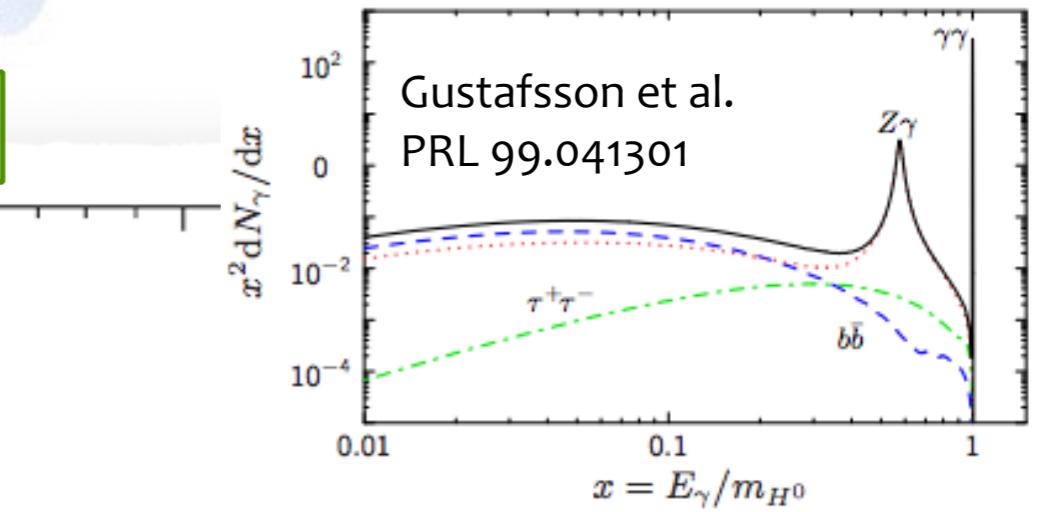
## Signal model (blue):

- E dispersion (Gaussian)
- $n_{\text{sig}}$  fit model independent

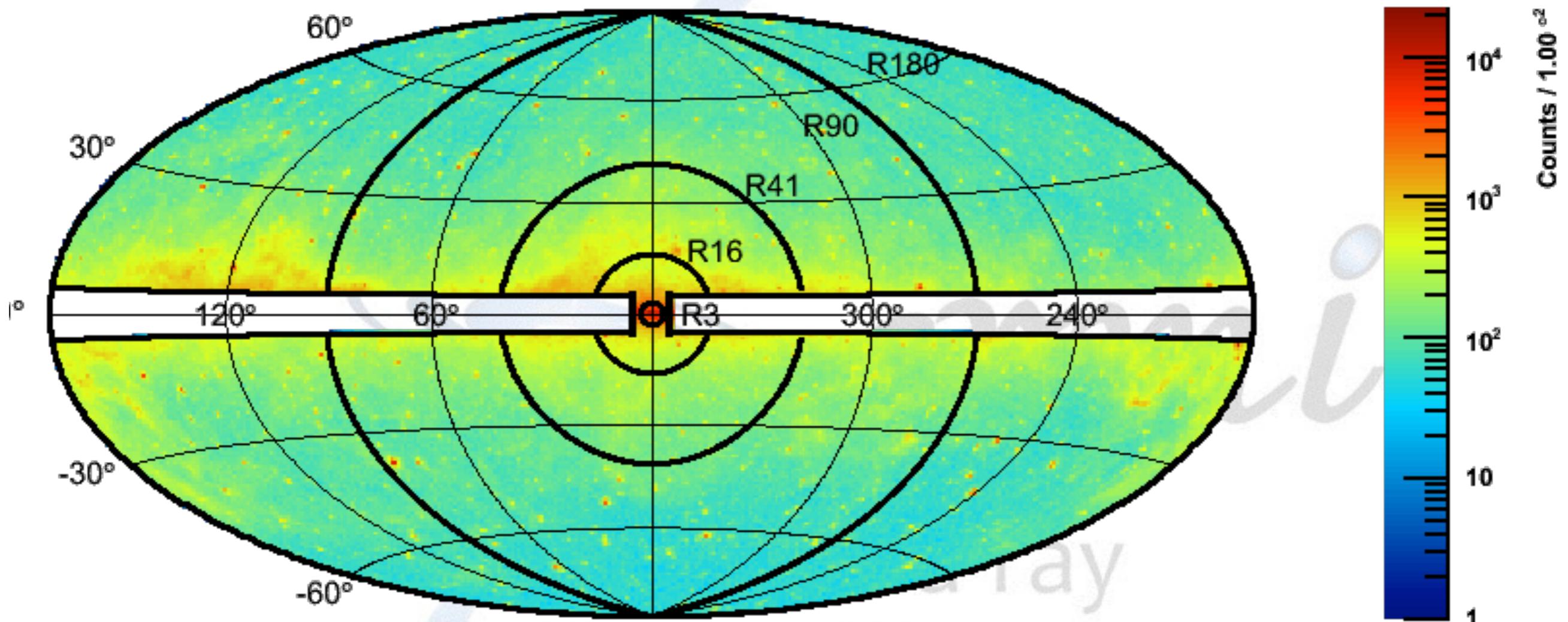
# Spectral Lines



- Single power law with index  $\Gamma_{\text{bkg}}$  allowed to float
- Energy dependent exposure correction

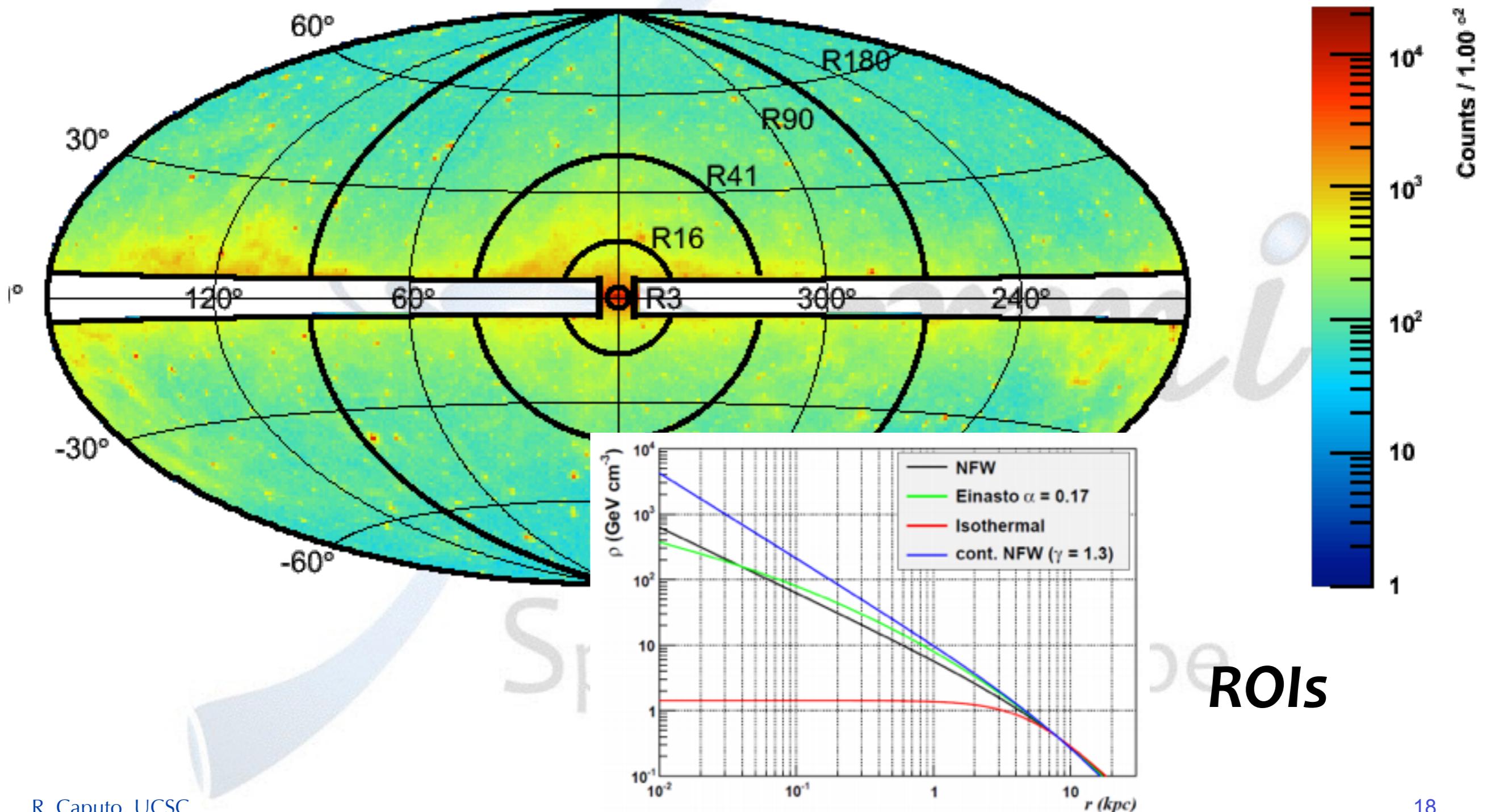


# Spectral Lines



Space Telescope ROIs

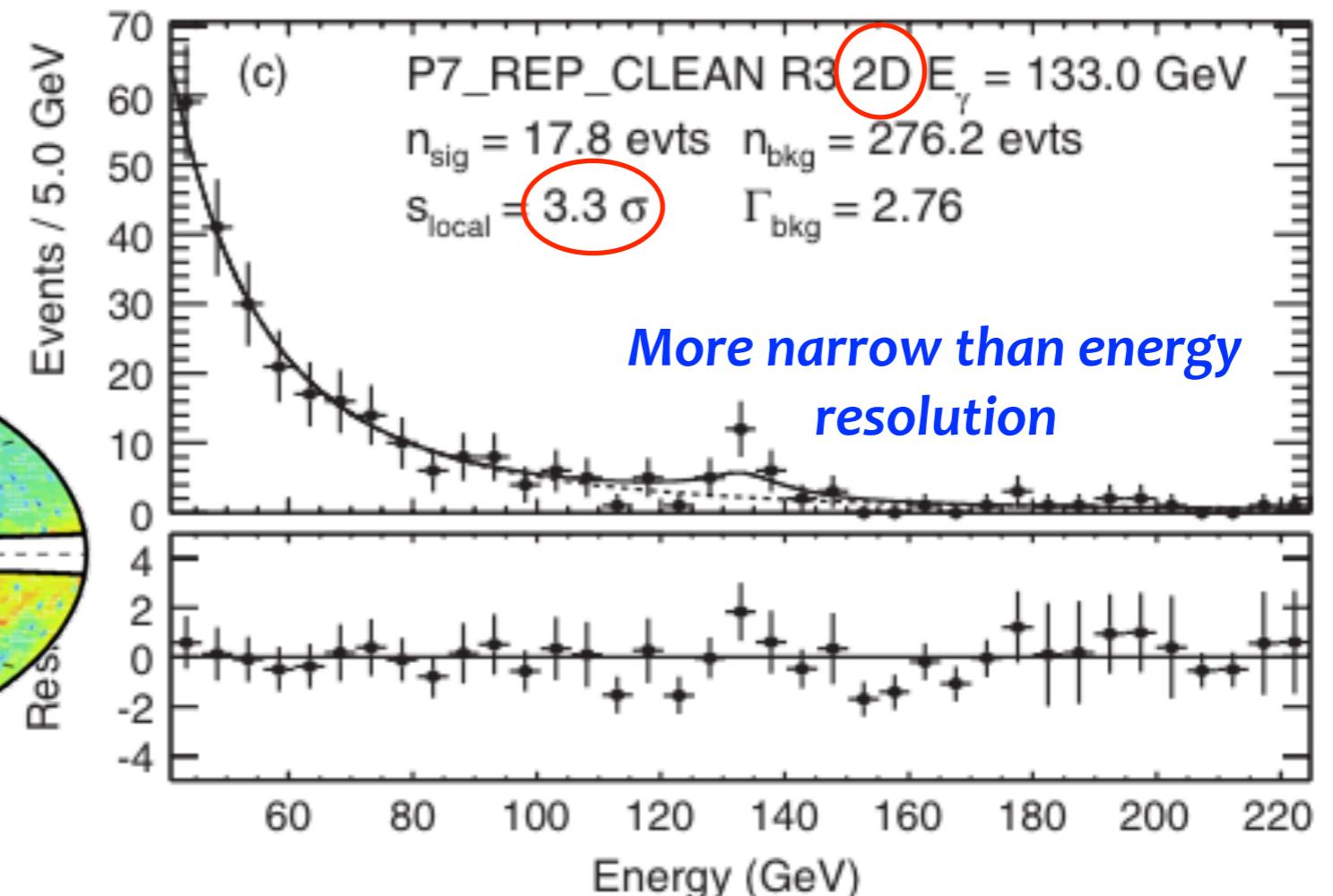
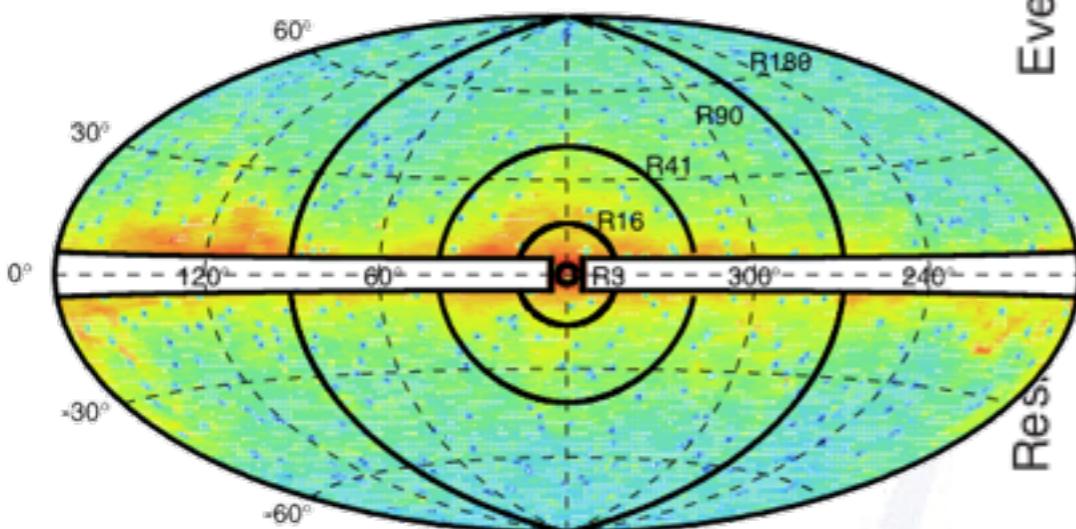
# Spectral Lines



# Spectral Lines



2013:  
Tentative...  
Too Narrow



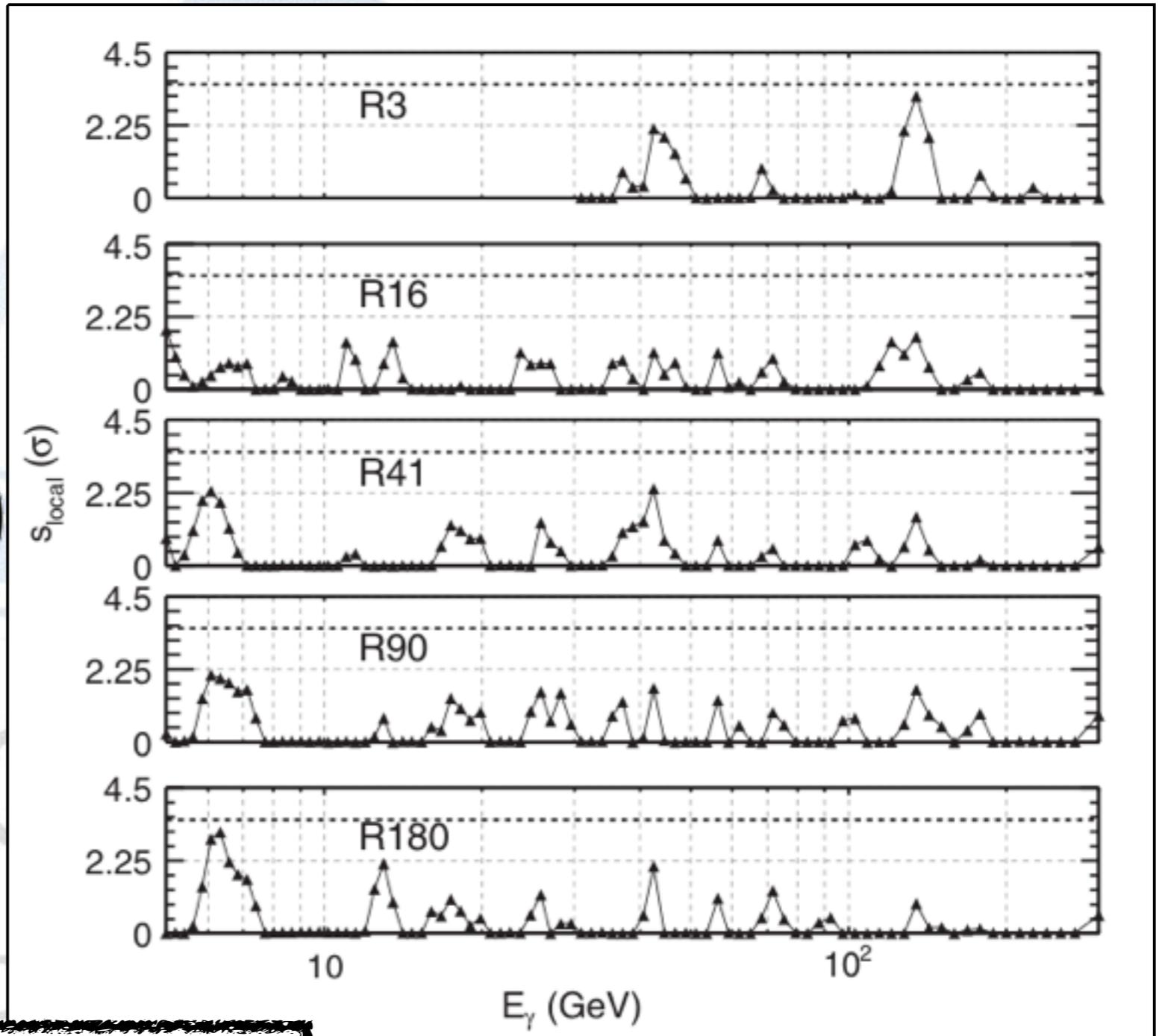
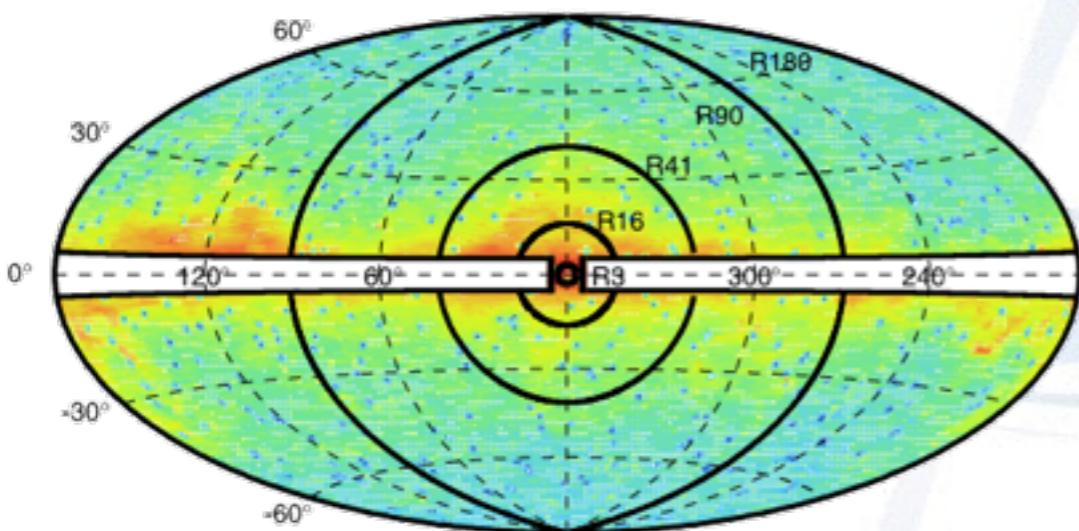
Fermi-LAT analysis with Pass 7  
Reprocessed data and 2D PDF fit

arXiv: 1305.5597

# Spectral Lines



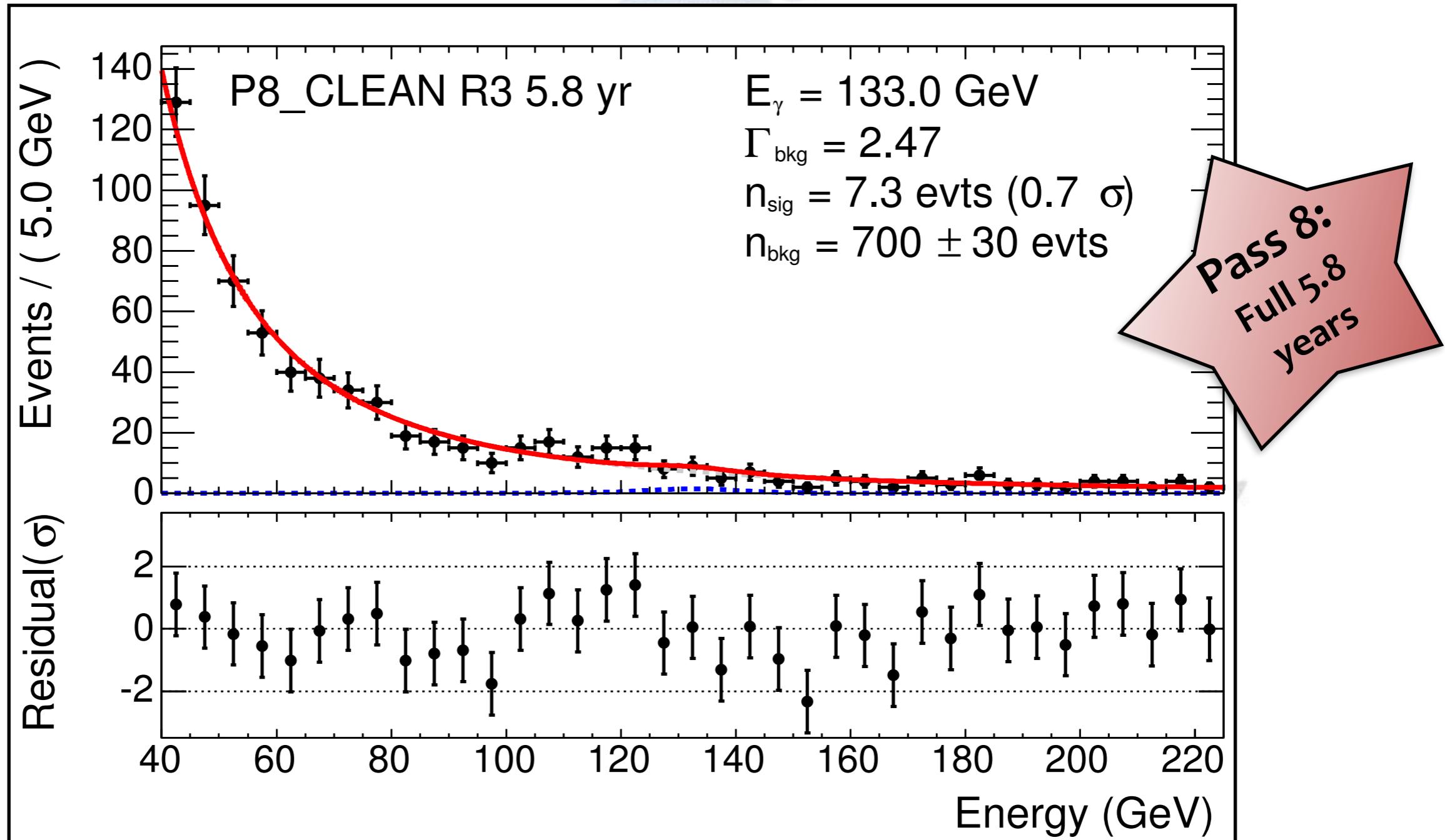
2013:  
All ROIs  
All  $\sigma$



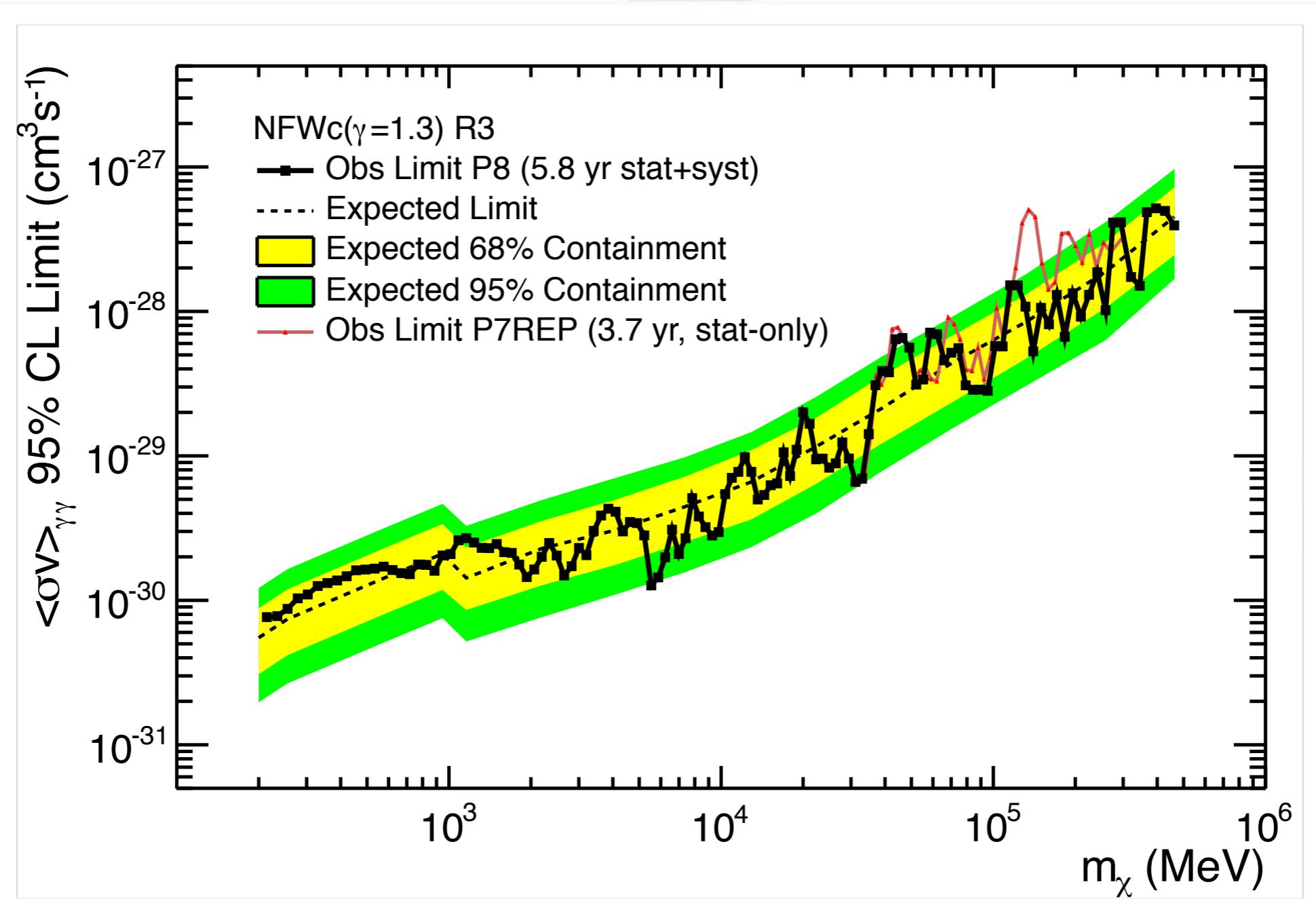
Wait and see what happens...

arXiv: 1305.5597

# 133 GeV Feature with Pass 8



# Spectral Lines: Full $E_\gamma$ range



# Dark Matter Distribution



## Search Strategies

**Dwarf Spheroidal Satellite Galaxies**  
arXiv: 1310.0828  
arXiv: 1503.02641  
arXiv: 1503.02632

**Dwarf Spheroidal Satellite Galaxies**  
arXiv: 1503.02320  
arXiv: 1503.06209

**Galaxy Clusters**  
arXiv: 1308.5654  
arXiv: 1002.2239

**Milky Way Halo**  
arXiv: 1205.6474

**External Analyses on DES candidates**

**Galactic Center**  
arXiv: 1511.02938  
(many external)

**Spectral Lines**  
arXiv: 1305.5597  
arXiv: 1506.00013

**Isotropic Background**  
arXiv: 1202.2856  
arXiv: 1501.05464

**From the Fermi-LAT Collaboration**

**DES candidates**

# What is a Dwarf Spheroidal Galaxy?



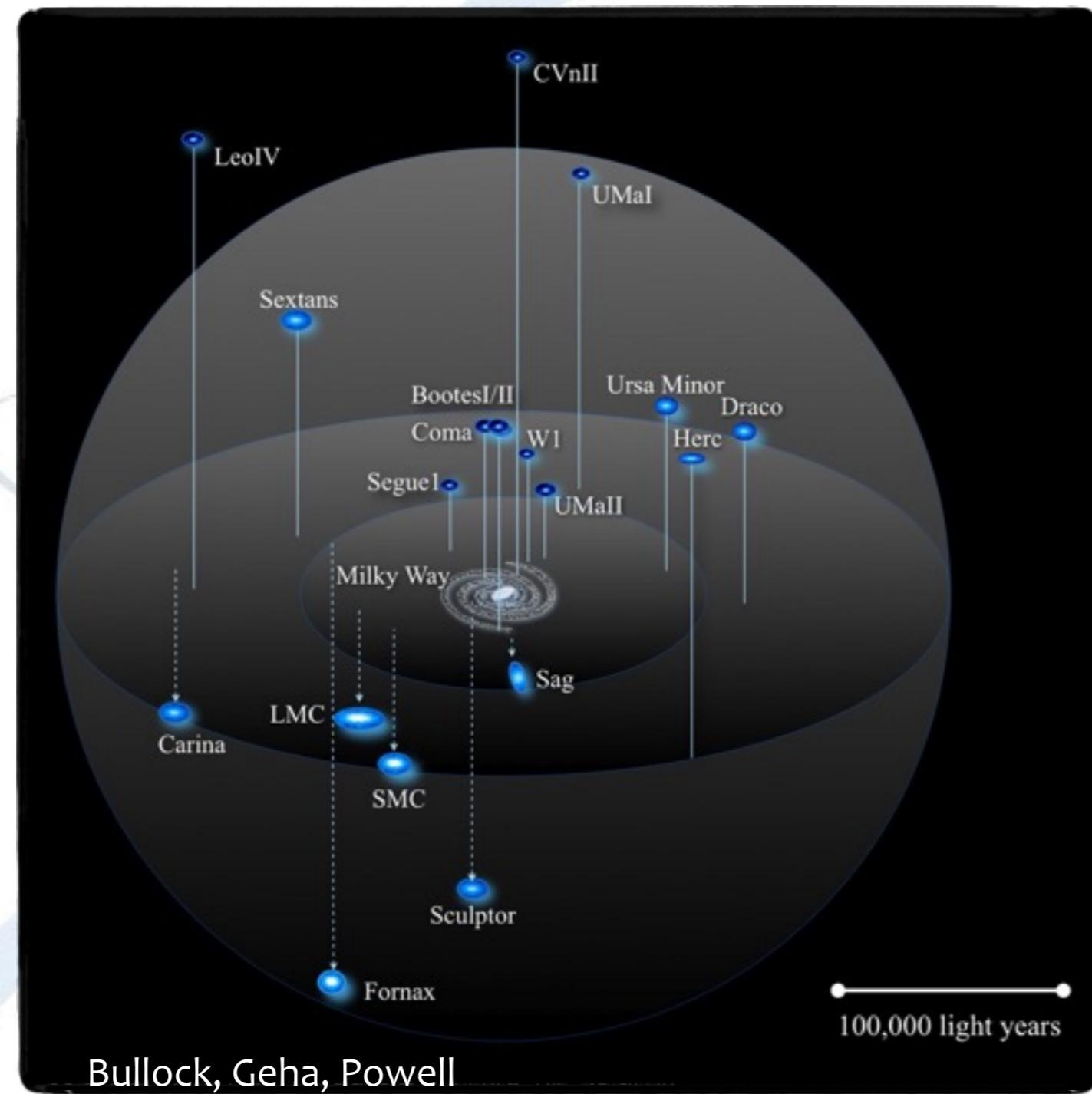
The Milky Way has many companion galaxies!

Little gas/dust/  
star formation

old: >13b years

Low Luminosity

Found around  
Milky Way  
and Andromeda



25 known dSphs

9 classical dSphs  
(pre-SDSS)

# What is a Dwarf Spheroidal Galaxy?



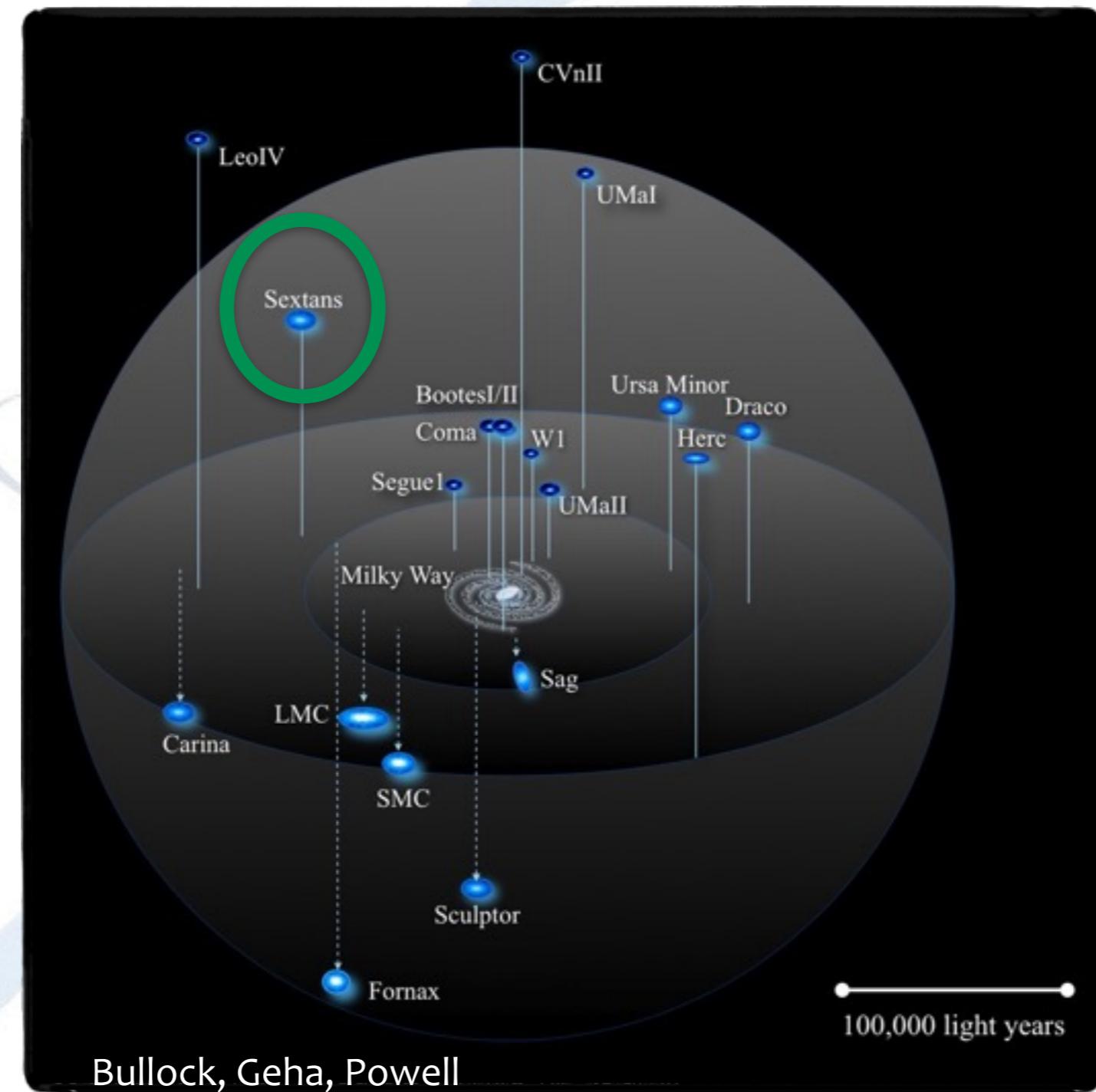
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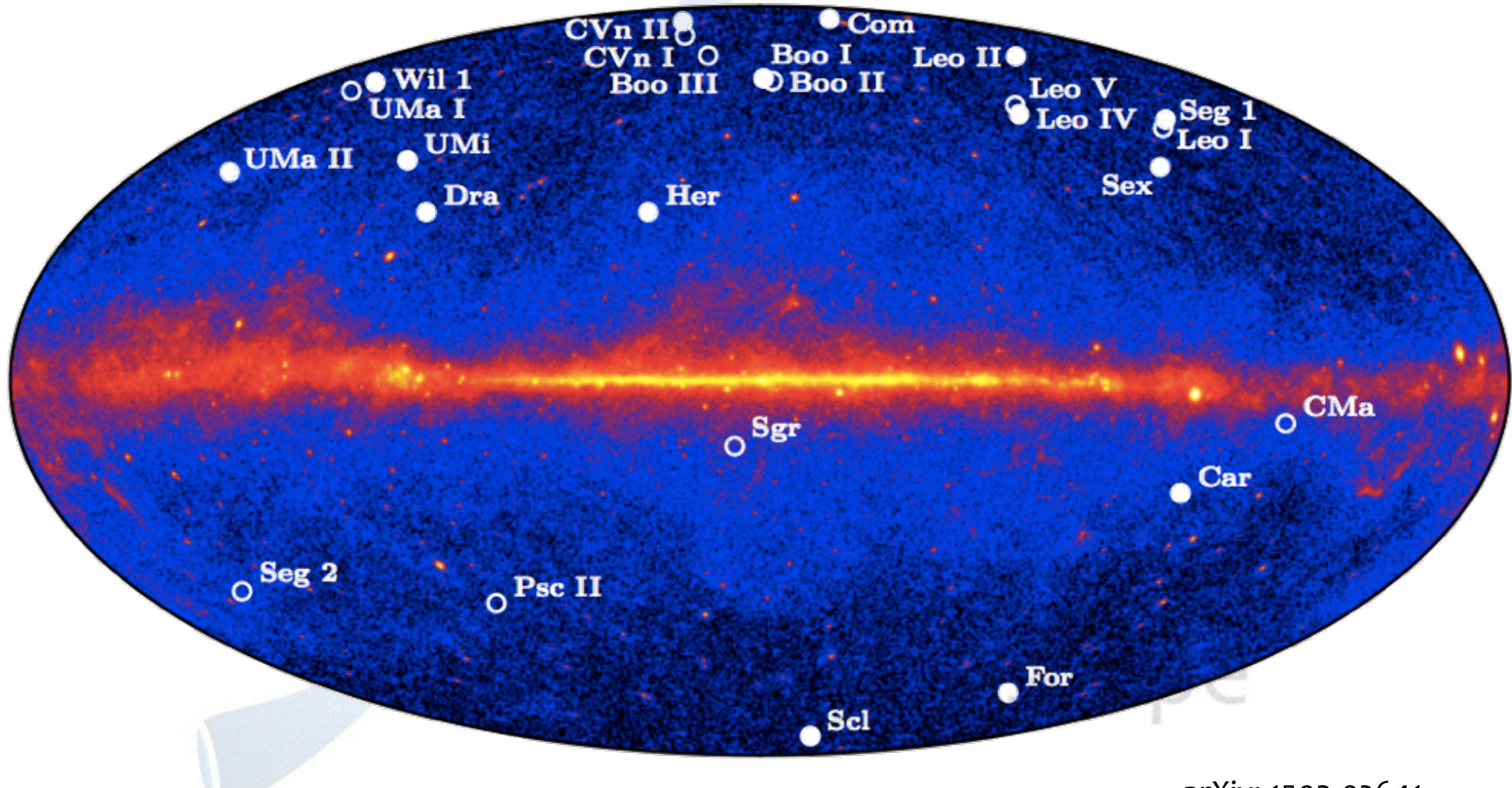
Found around  
Milky Way  
and Andromeda



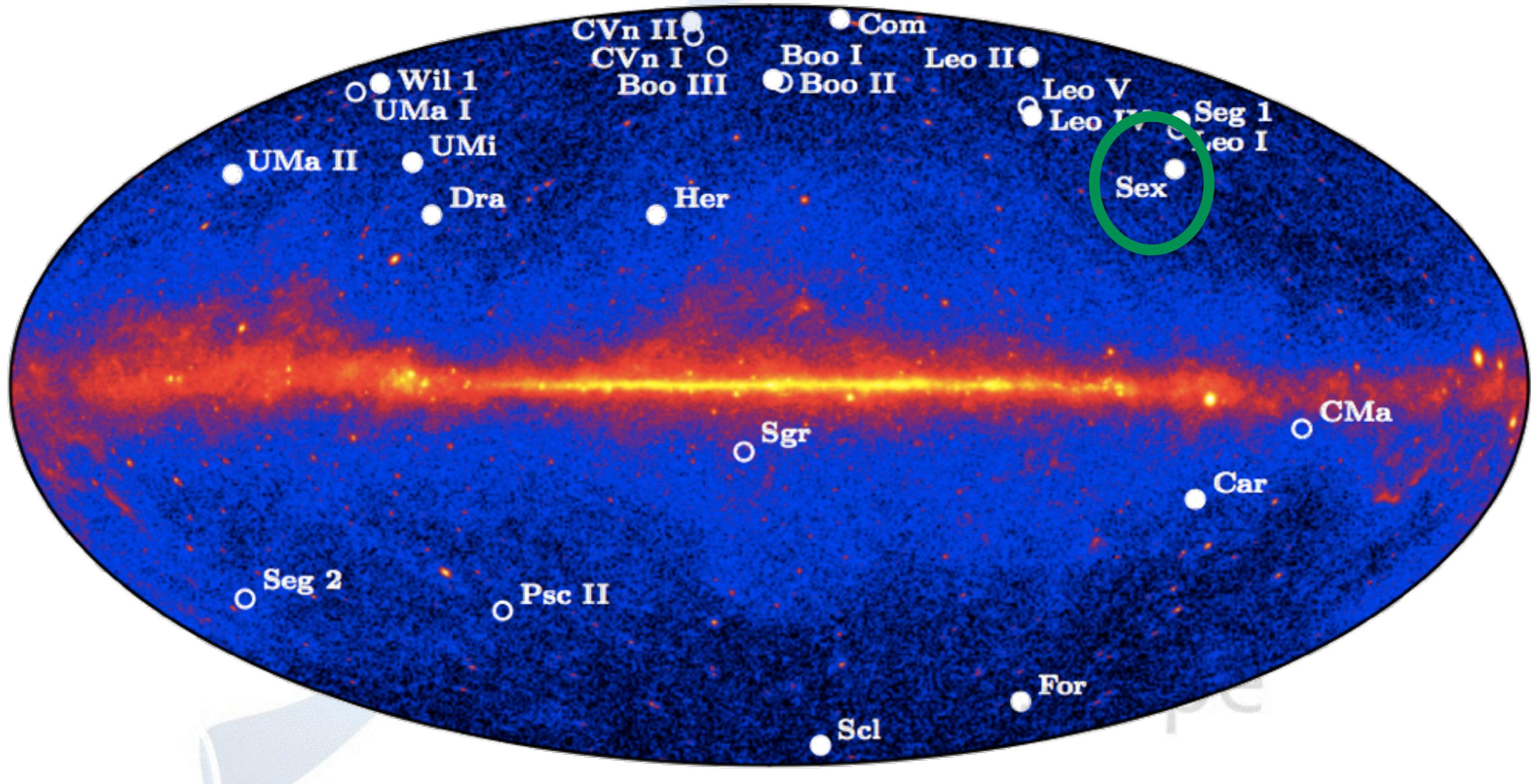
25 known dSphs

9 classical dSphs  
(pre-SDSS)

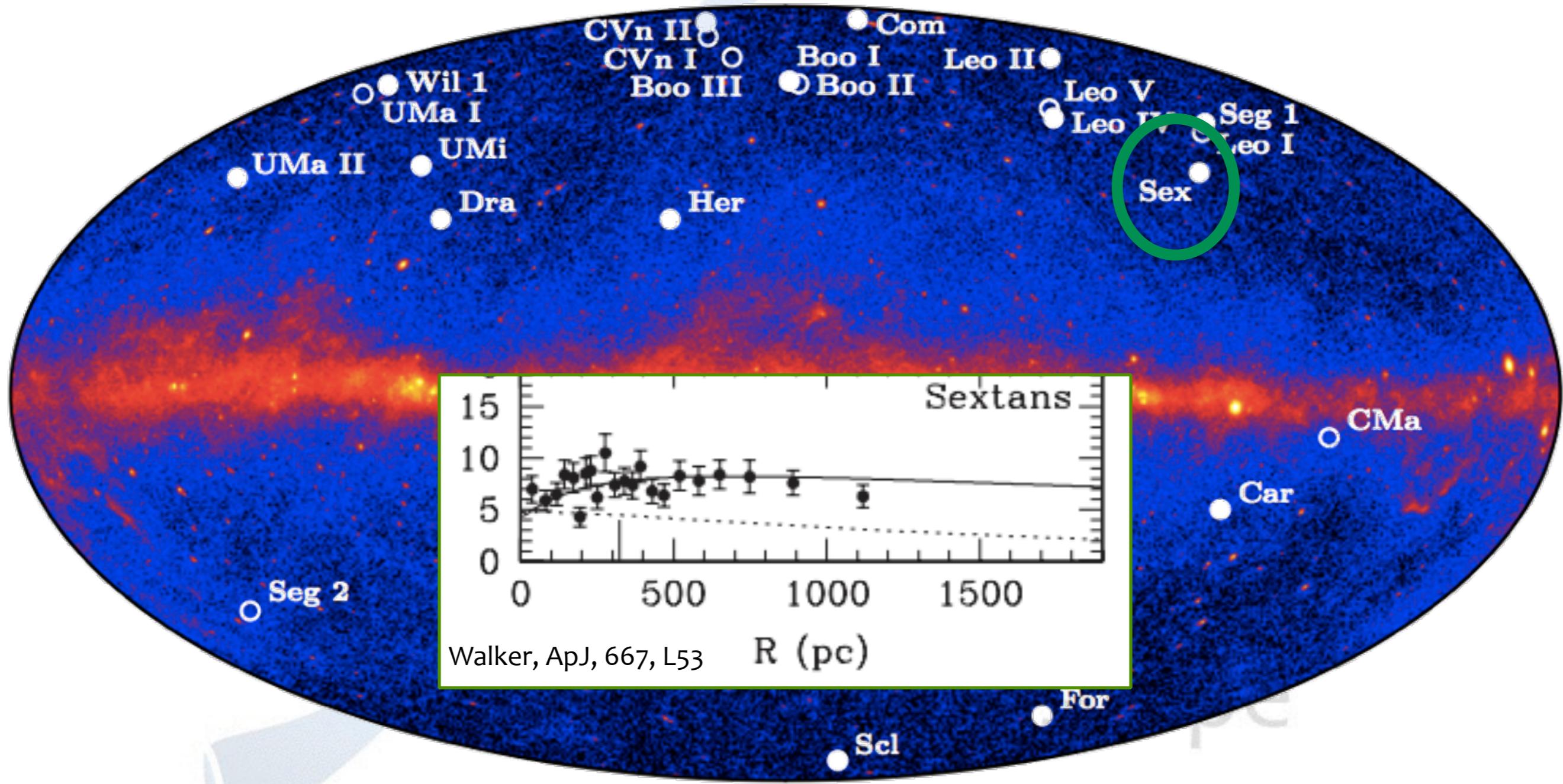
# Dwarf Spheroidal Satellite Galaxies



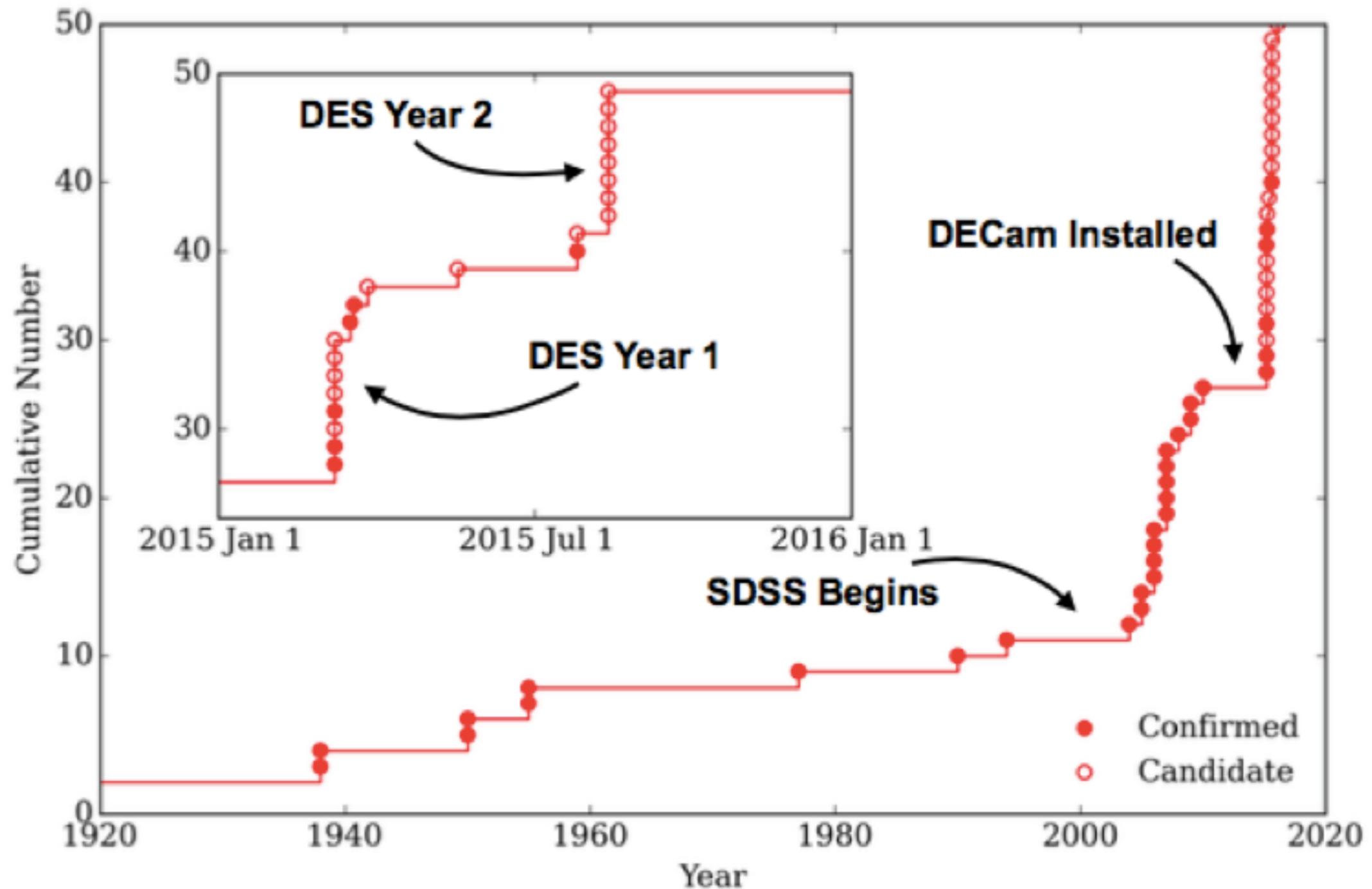
# Dwarf Spheroidal Satellite Galaxies



# Dwarf Spheroidal Satellite Galaxies



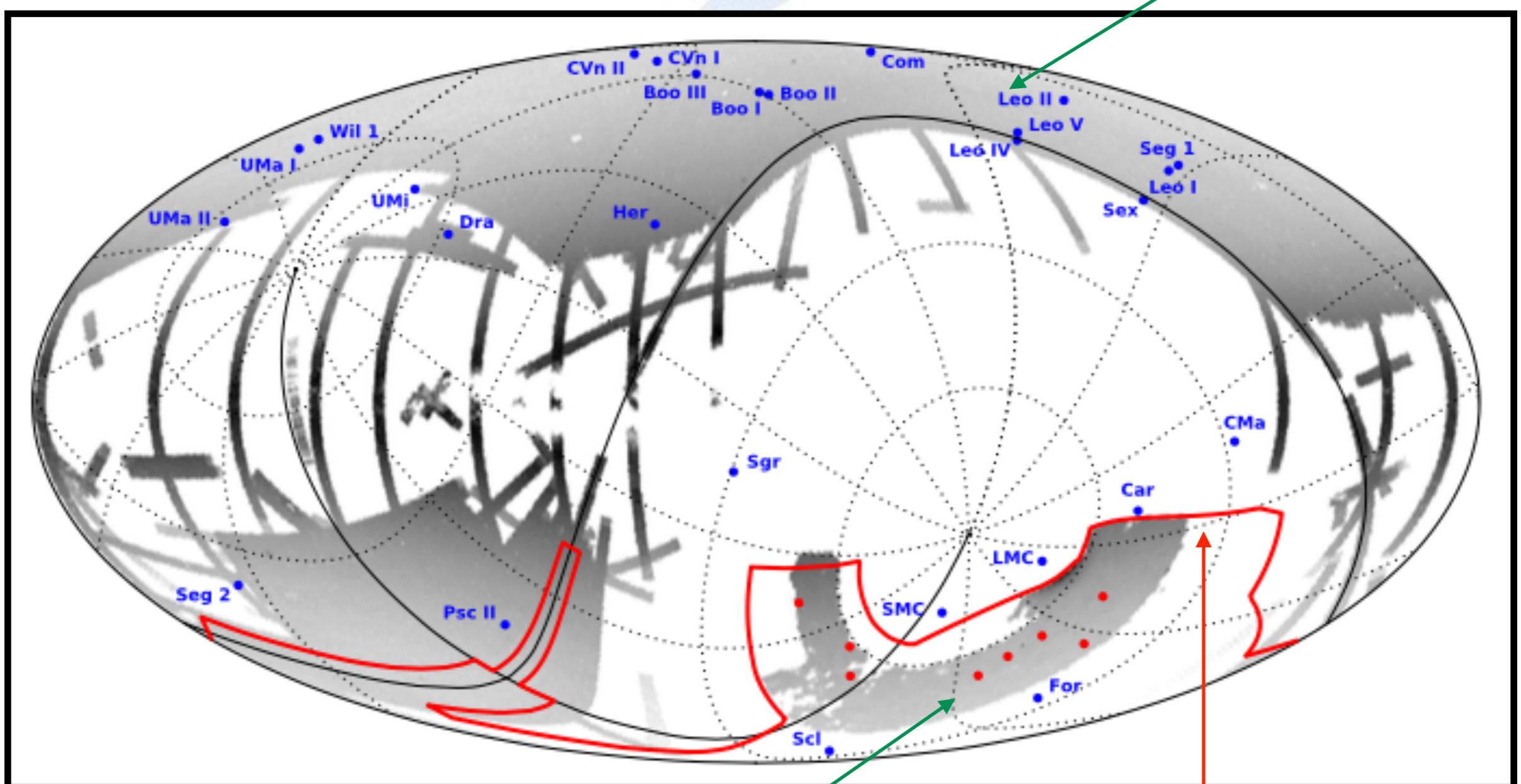
# Dwarf Spheroidal Satellite Galaxies



# DES Dwarf Candidates



SDSS sky coverage  $\sim 14\text{k deg}^2$



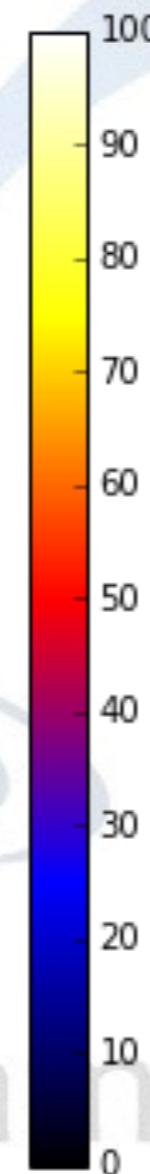
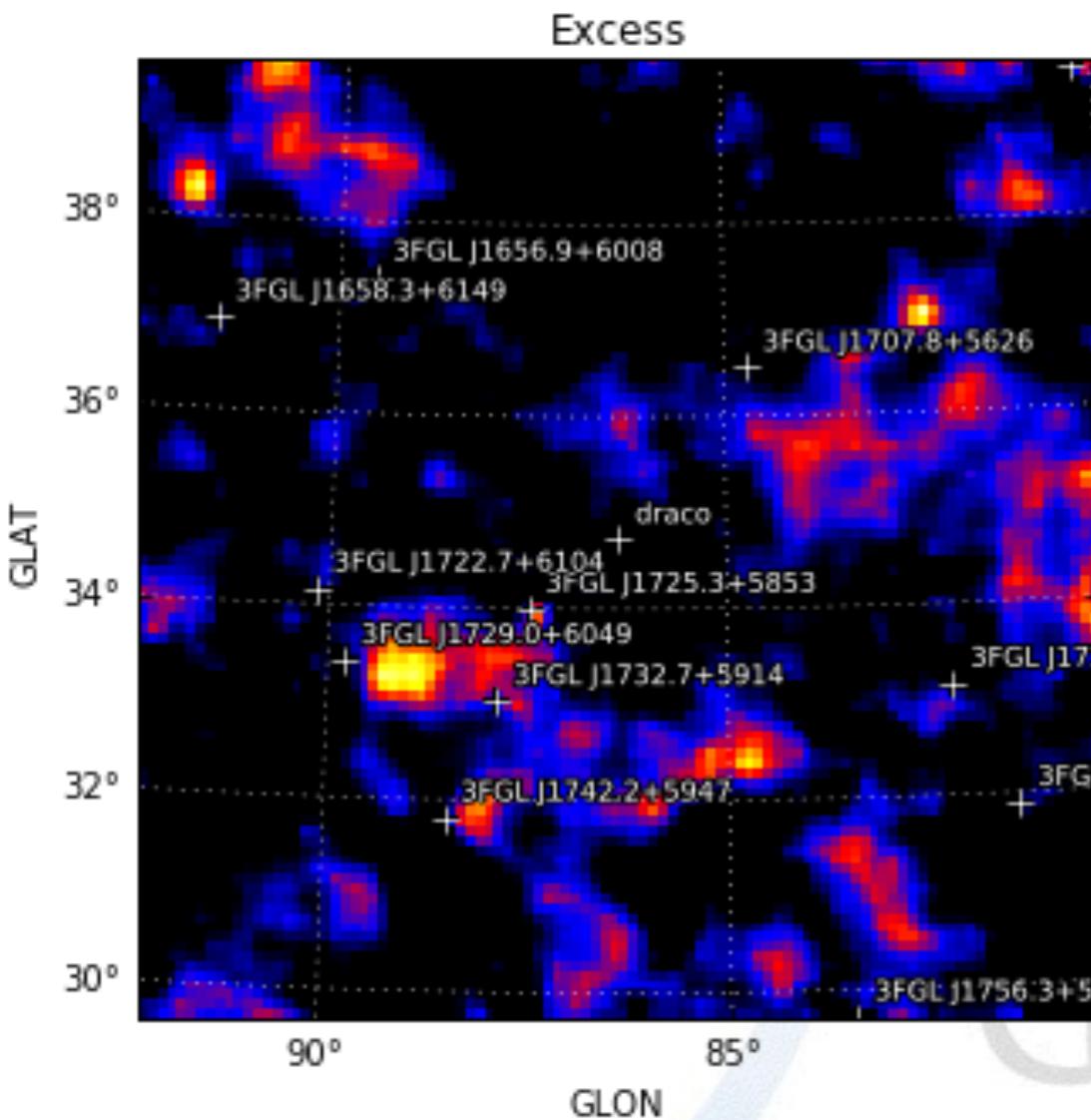
DES Year 1 Annual Release: new  $\sim 1.5\text{k deg}^2$

Total DES Survey:  $5\text{k deg}^2$

# Dwarf Spheroidal Satellite Galaxies: Combined



*Draco*



\*ellipses have no uncertainties on the DM density in the Milky Way

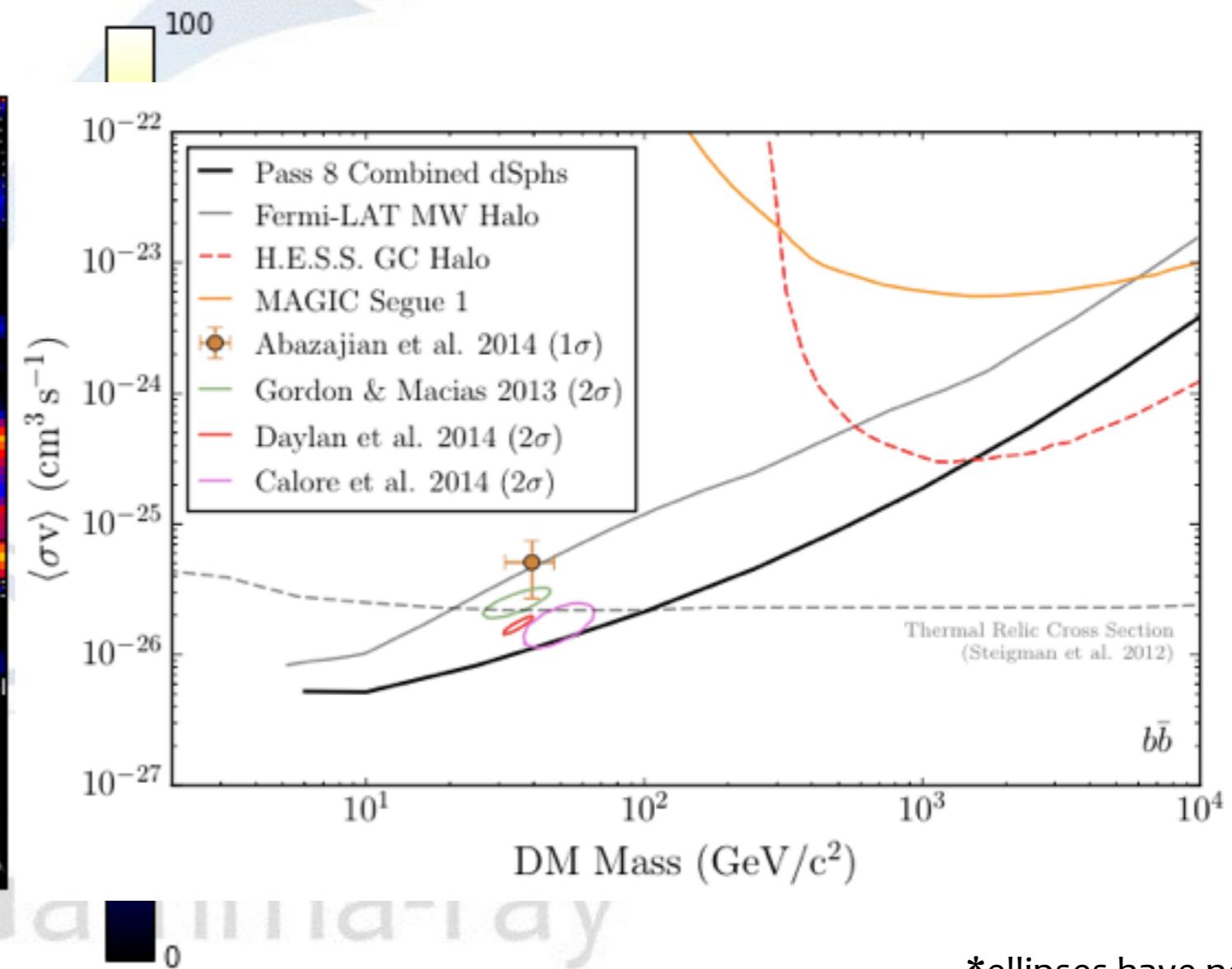
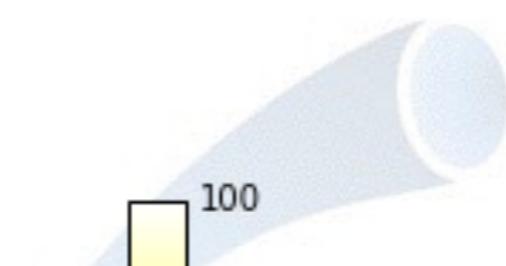
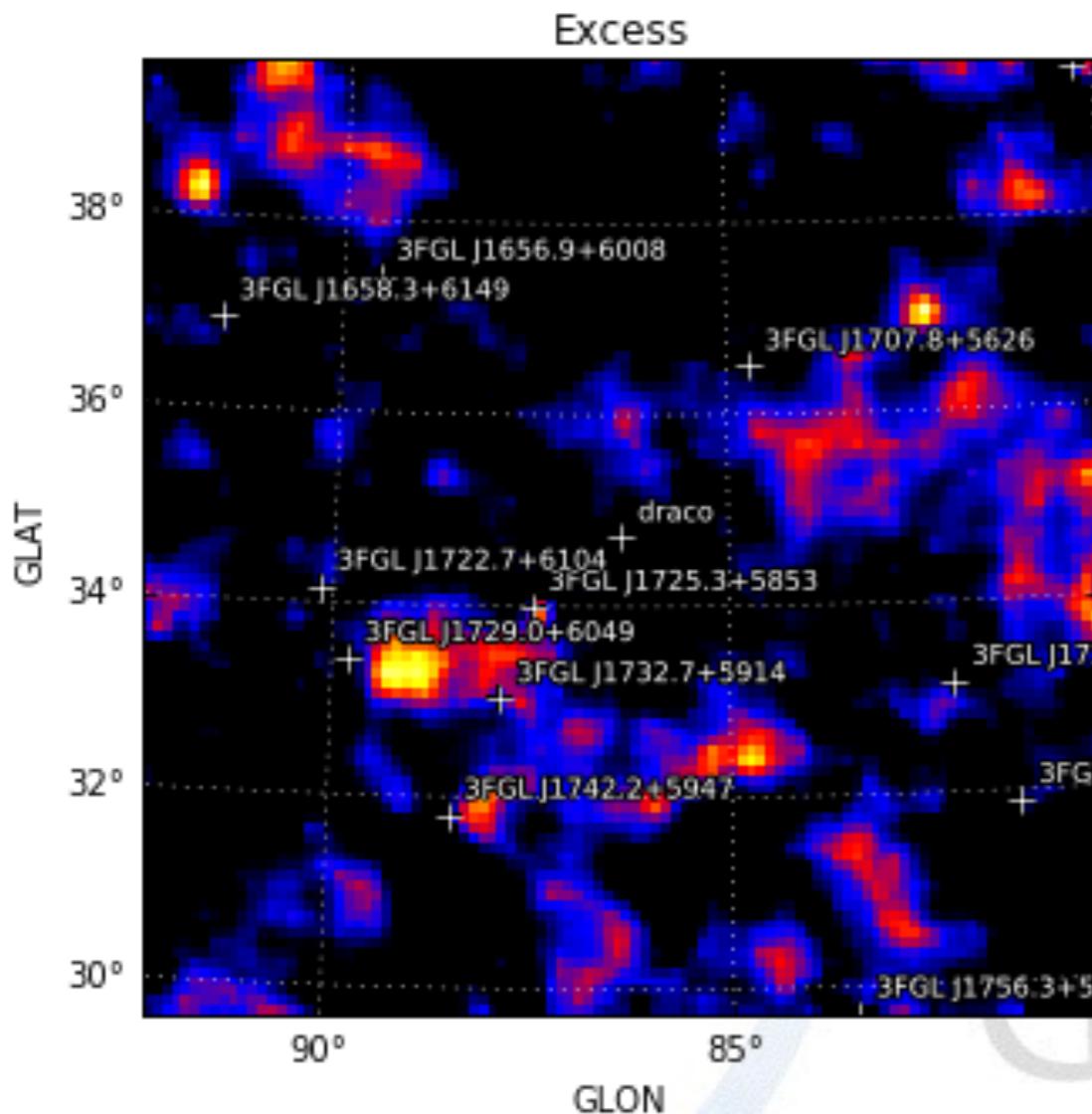
<https://github.com/fermiPy/fermipy-extra/blob/master/notebooks/draco.ipynb>

**We actually got this working more or less...**

# Dwarf Spheroidal Satellite Galaxies: Combined



## Draco

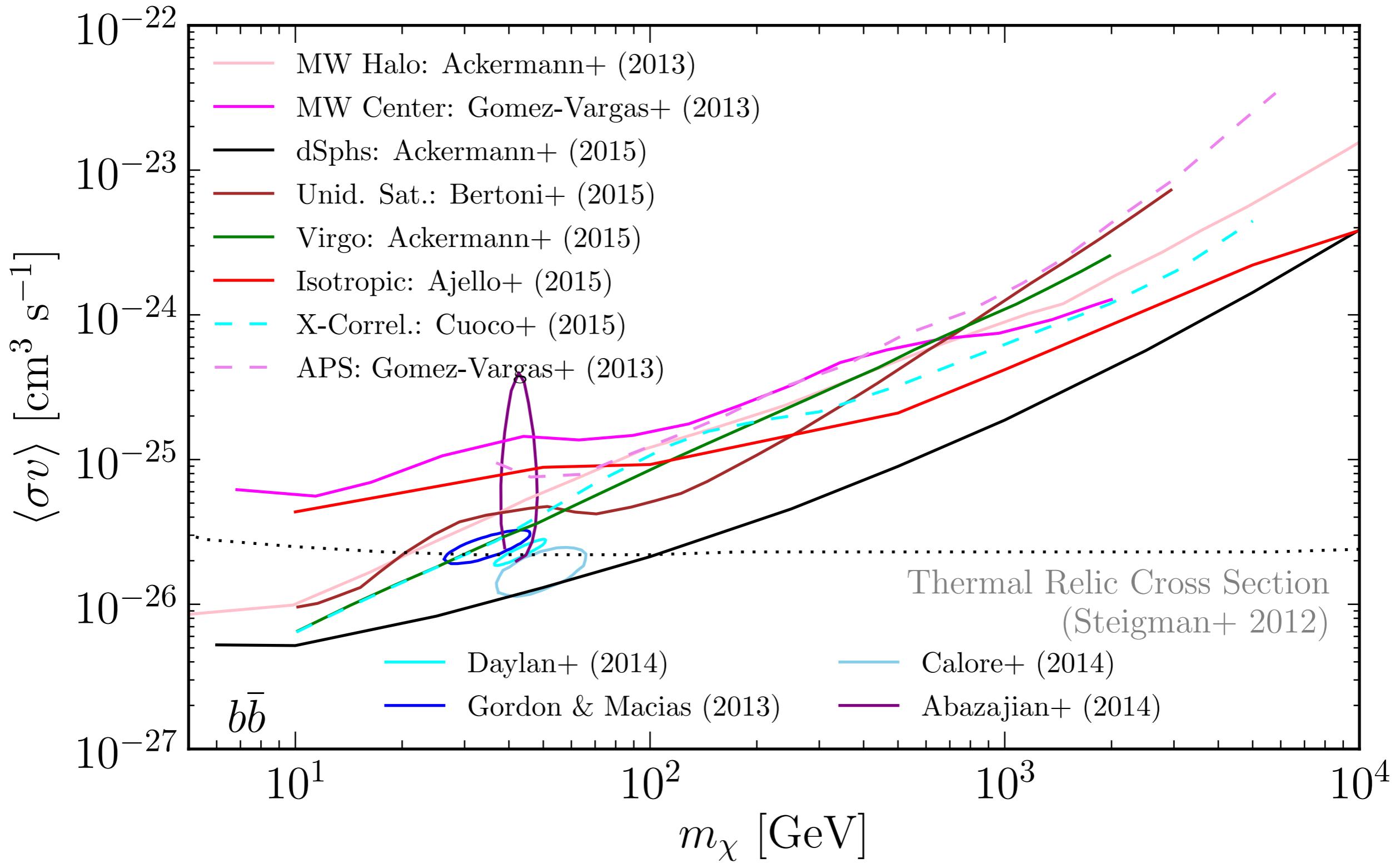


<https://github.com/fermiPy/fermipy-extra/blob/master/notebooks/draco.ipynb>

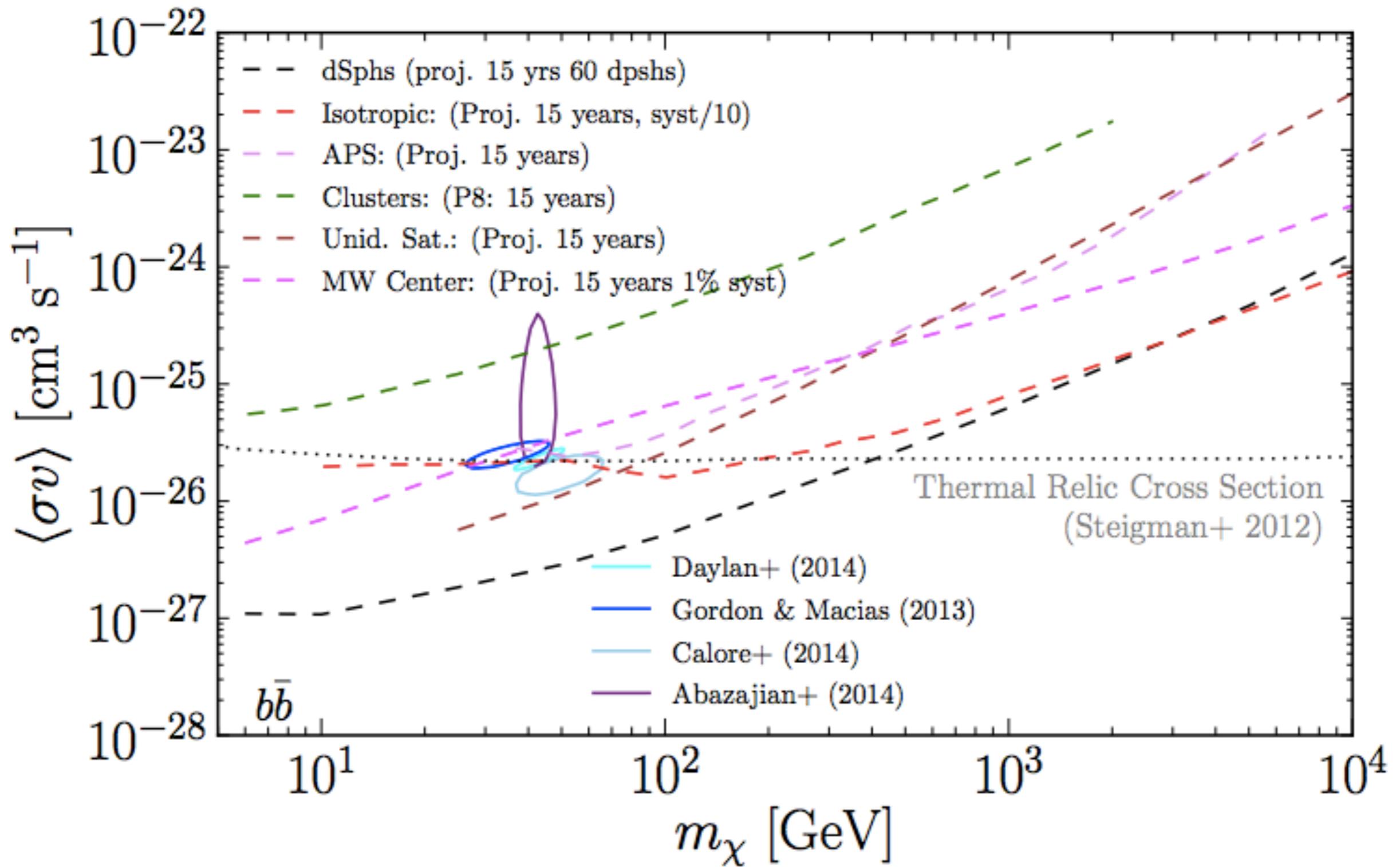
\*ellipses have no uncertainties on the DM density in the Milky Way

**We actually got this working more or less...**

# Summary of Fermi-LAT Dark Matter Searches



# Future WIMP Dark Matter Searches





**And now for something completely different...**

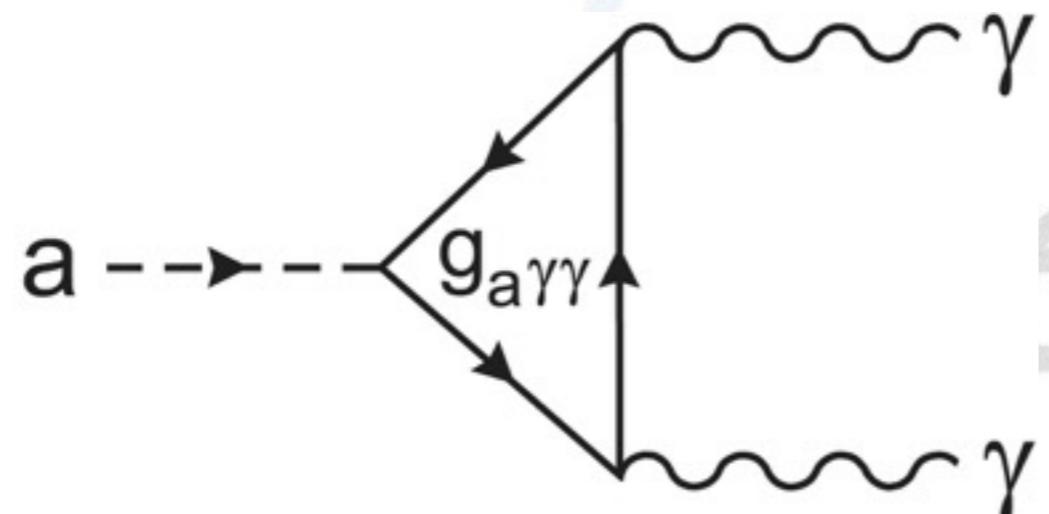
Gamma-ray  
Space Telesco



# Portrait of Another Candidate



- A solution to a different problem
  - Quantum chromodynamics (QCD)
  - Axions!  $10^{-5}$  to  $10^{-3}$  eV
  - Couple to photons in an external magnetic field
    - strong field = more coupling



We can make strong magnets...  
What else has a strong magnetic field?

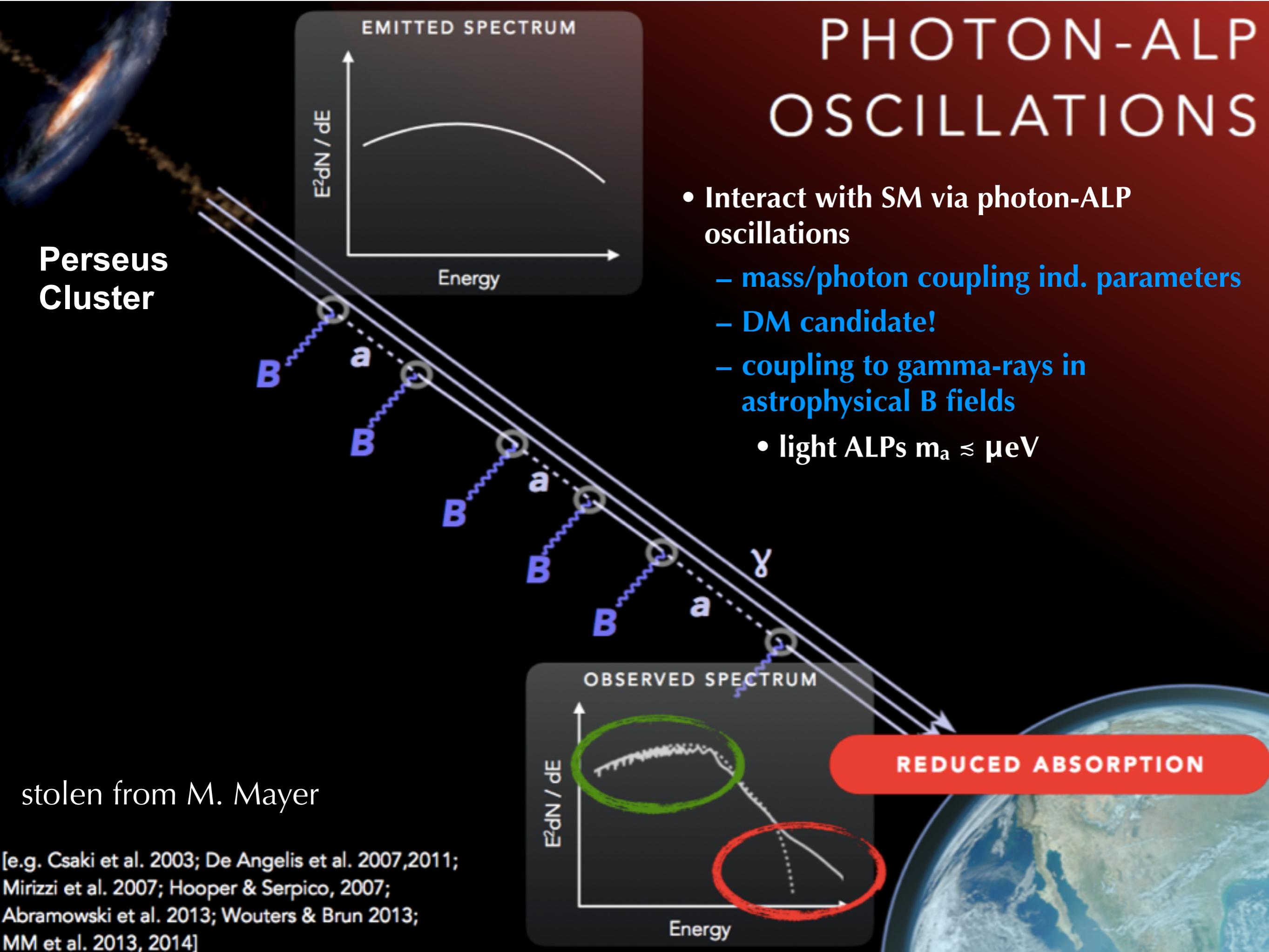
- Axion-Like Particles (ALPs) ← this one
  - not restricted to those masses... but still light

arXiv:1603.06978v1

<http://depts.washington.edu/admx/index.shtml>

# PHOTON-ALP OSCILLATIONS

# Perseus Cluster



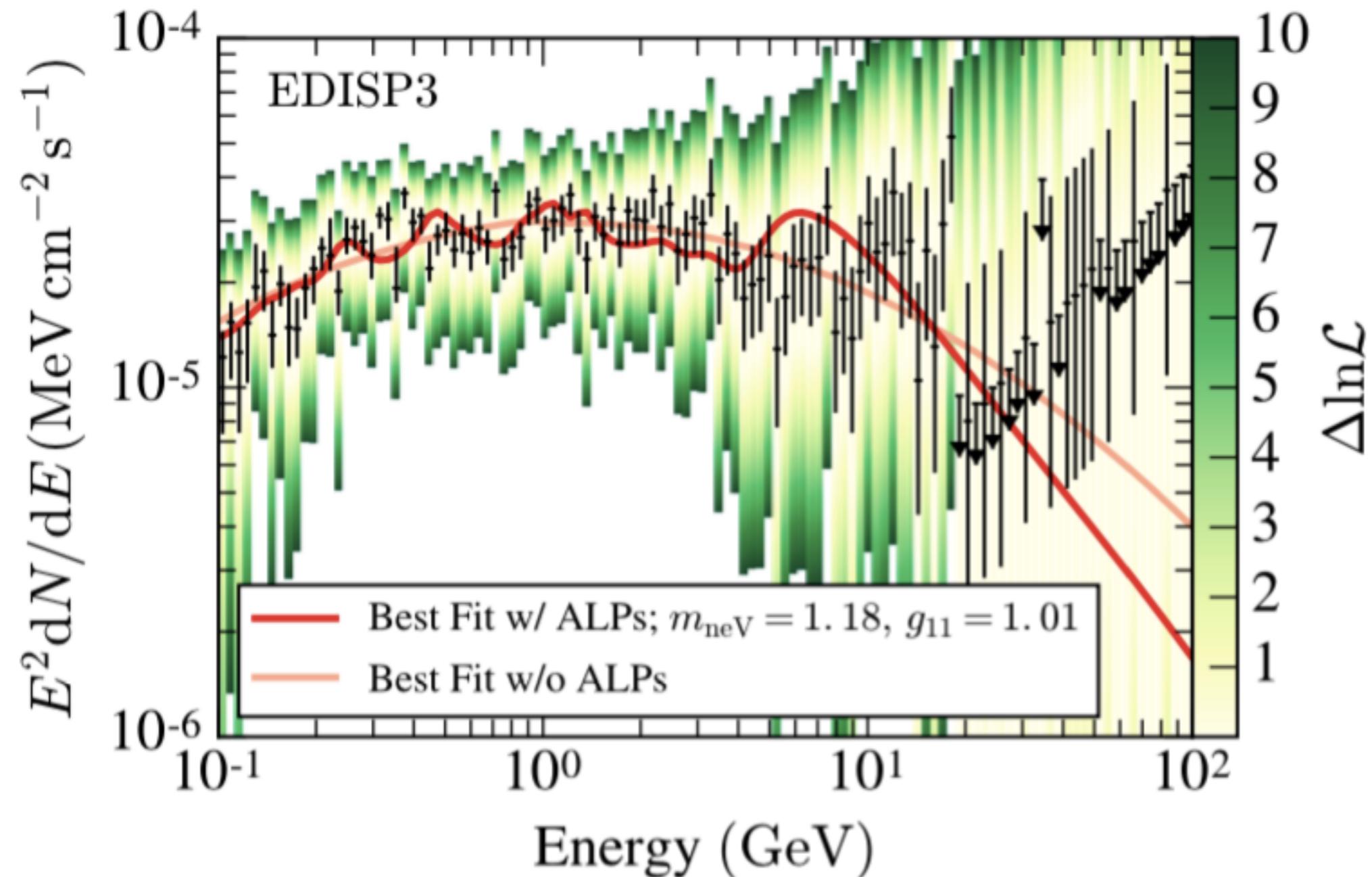
# stolen from M. Mayer

[e.g. Csaki et al. 2003; De Angelis et al. 2007, 2011; Mirizzi et al. 2007; Hooper & Serpico, 2007; Abramowski et al. 2013; Wouters & Brun 2013; MM et al. 2013, 2014]

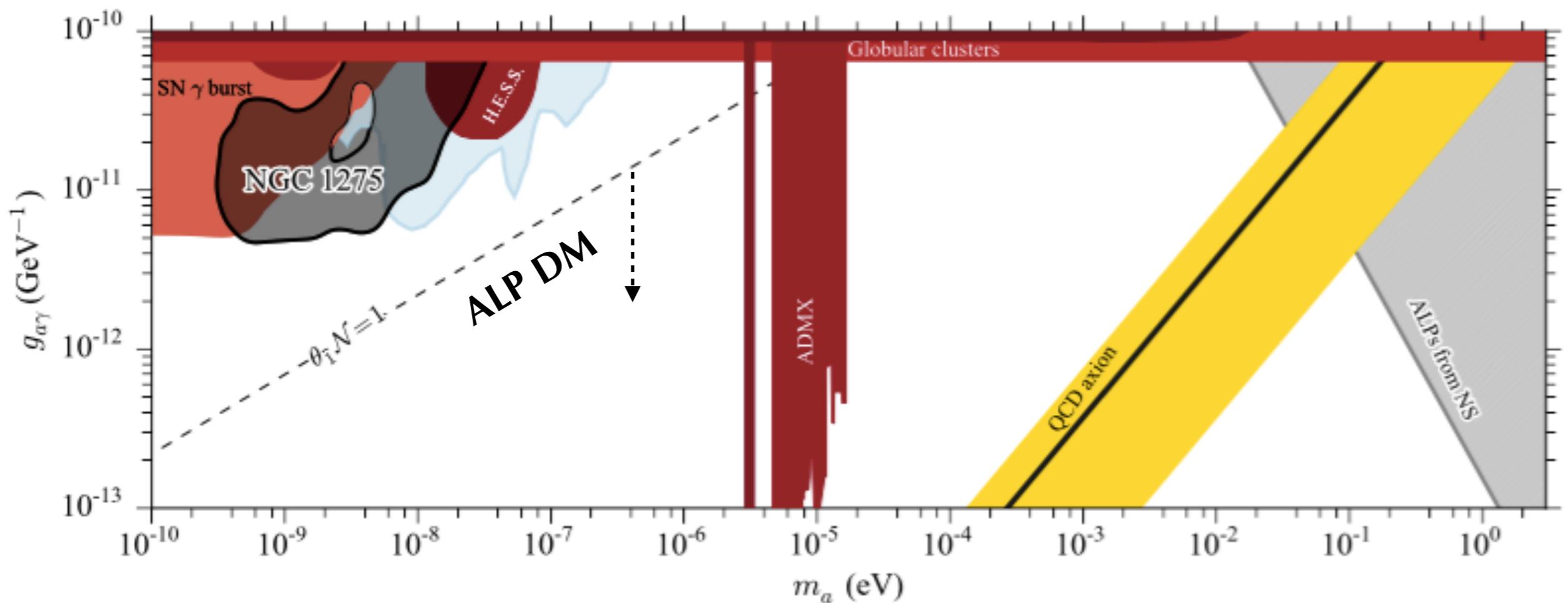
# Light Curves



NGC 1275



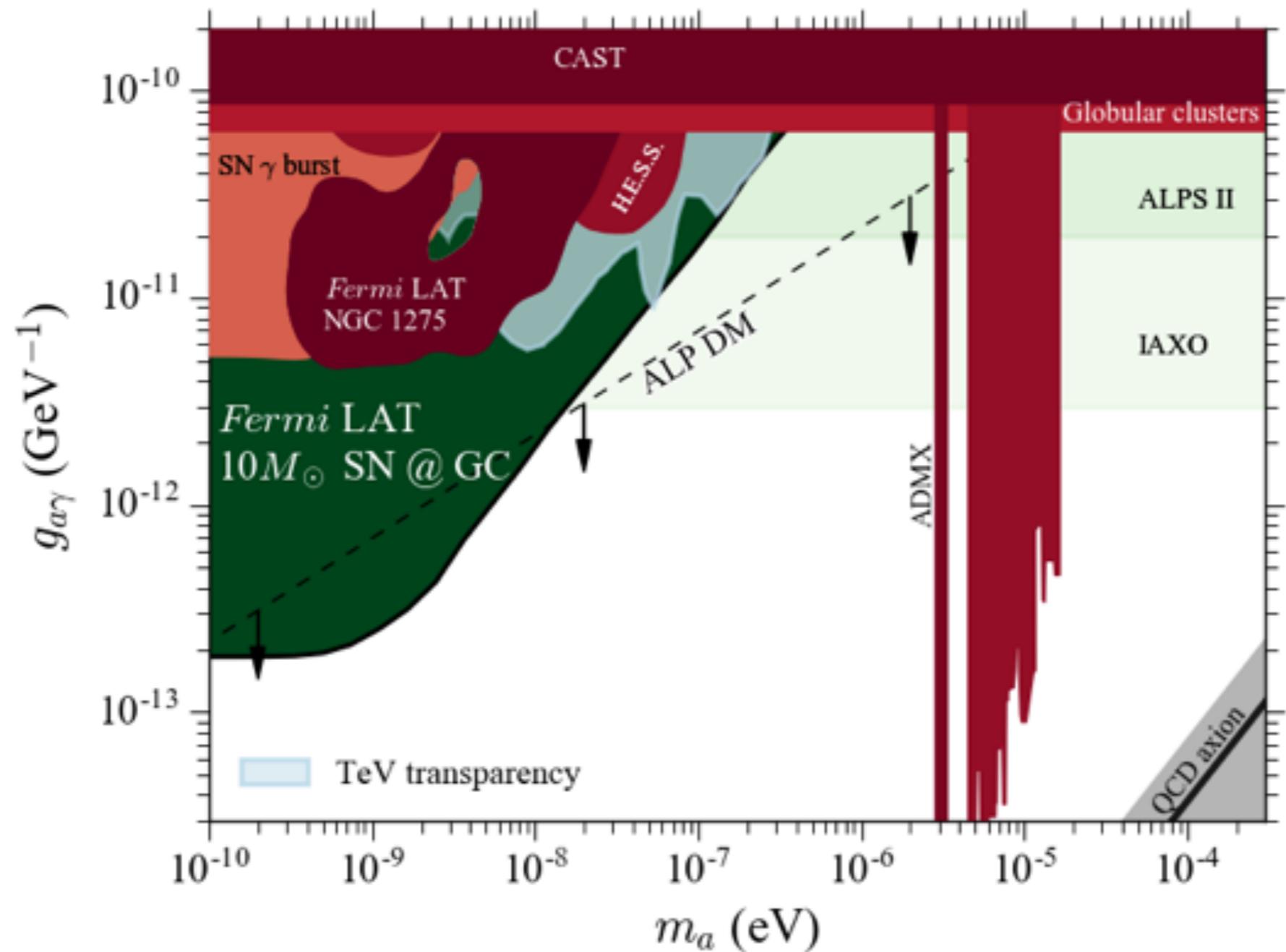
# Current Axion Limits



# MeV Dark Matter: Axions



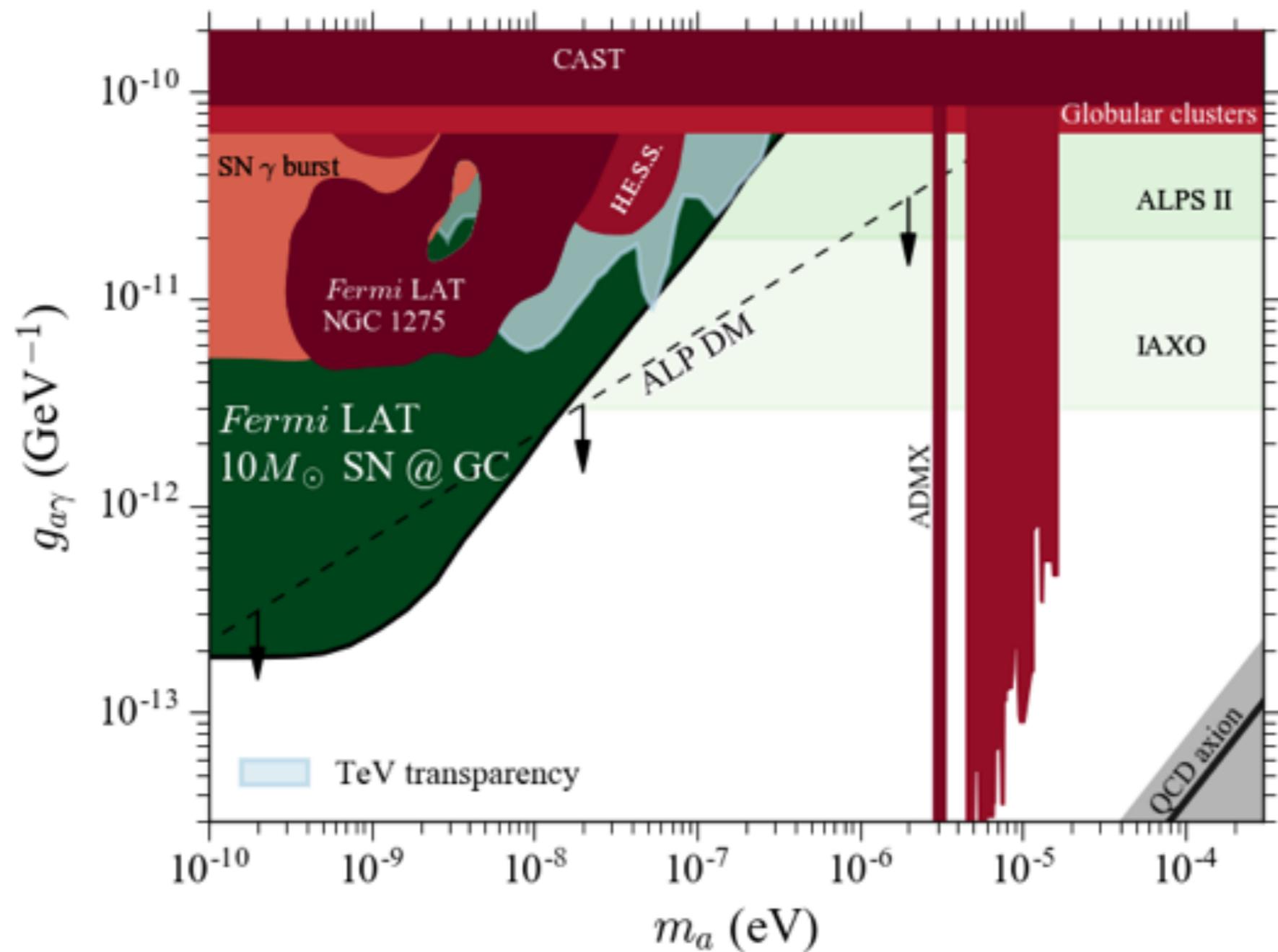
- Axions produced in supernovae (arXiv:1410.3747)
  - core collapse supernova (SN1987A)



# MeV Dark Matter: Axions

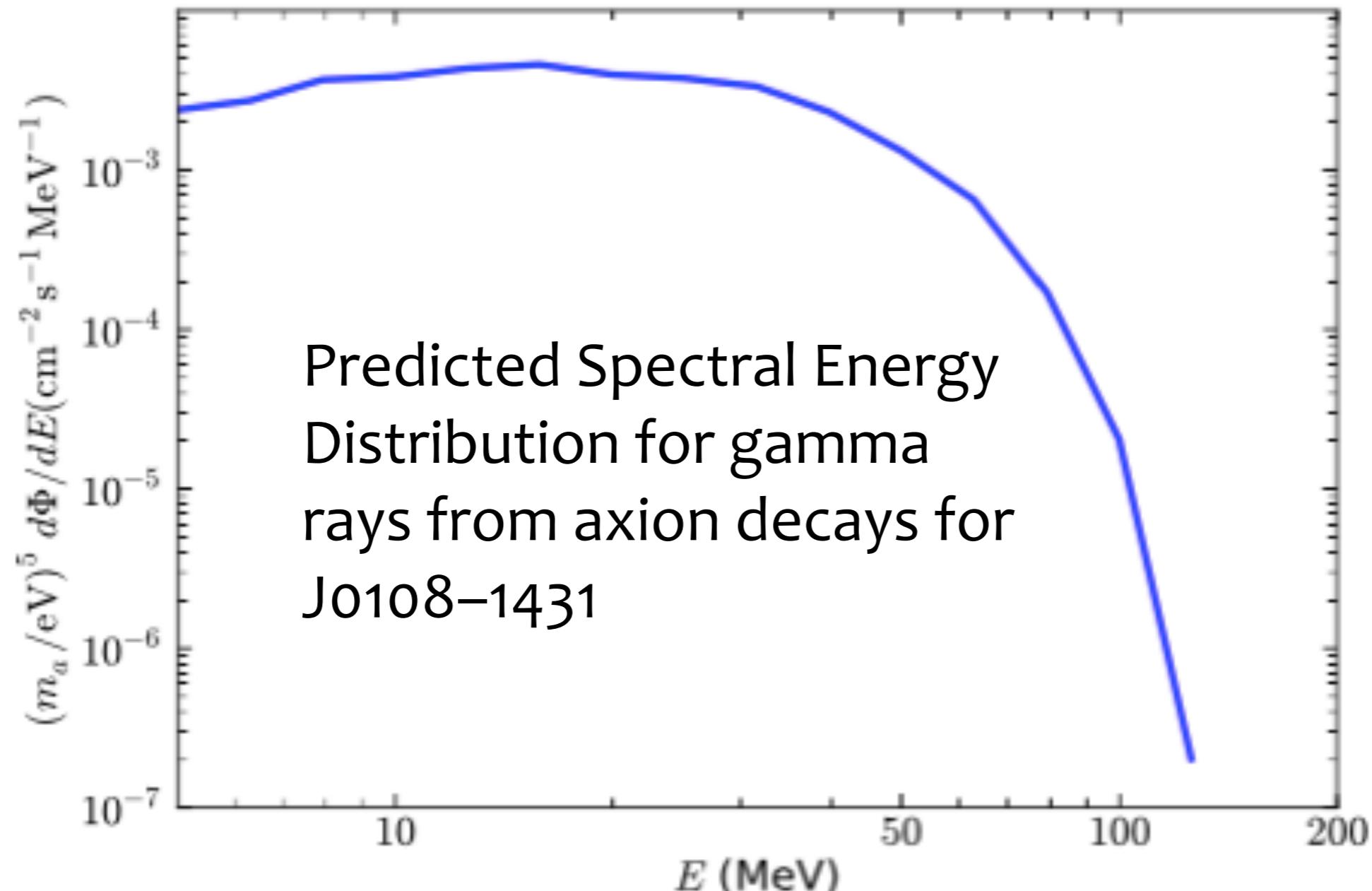


- Axions produced in supernovae (arXiv:1410.3747)
  - core collapse supernova (SN1987A)



Limited by PSF  
@<100 MeV

# Axions in Pulsars



arXiv:1602.00091

Space Telescope

# Pulsar Targets



**What characteristics are we looking for in a good target?**

Source Name	RA (°)	Dec.(°)	$\ell$ (°)	$b$ (°)	$d$ (kpc)	Age (Myr)	$B_{\text{surf}}$ (G)
J0108-1431	17.035	-14.351	140.93	-76.82	$0.240^{+0.124}_{-0.061}$	166	$2.52 \times 10^{11}$
J0953+0755	148.289	7.927	228.91	43.7	$0.262^{+0.005}_{-0.005}$	17.5	$2.44 \times 10^{11}$
J0630-2834	97.706	-28.579	236.95	-16.76	$0.332^{+0.052}_{-0.040}$	2.77	$3.01 \times 10^{12}$
J1136+1551	174.014	15.851	241.90	69.20	$0.360^{+0.019}_{-0.019}$	5.04	$2.13 \times 10^{12}$

Gamma-ray  
Space Telescope

# Pulsar Targets



**What characteristics are we looking for in a good target?**

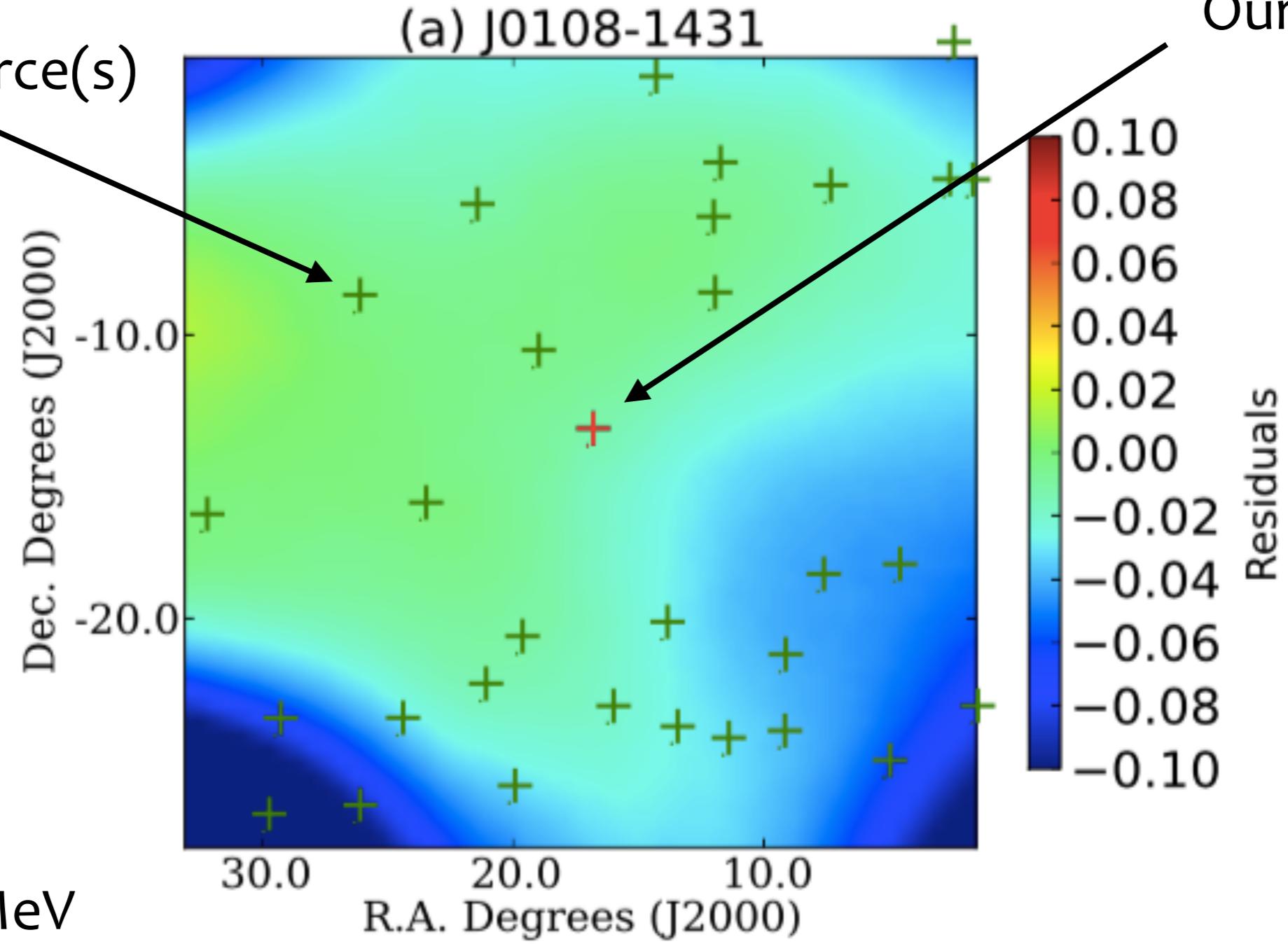
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*Away from  
galactic plane*      *Close*      *Measured*  
*B-Field*

# Pulsar Target!



Known Source(s)



**No excess, set a limit:  $7.9 \times 10^{-2}$  eV**



- **Summary**

- **We can learn a lot about “W”IMPs**
  - maybe at least what they aren’t
- **We can learn a lot about axions**
  - or also at least what they aren’t
- **We can learn a lot about other things? (Sterile neutrinos? from other complementary experiments?)**

- **Not finding DM in the obvious places**

- **Continue searching because we really need to figure this whole thing out...**



**Discussion!**

*fermi*  
Gamma-ray  
Space Telescope