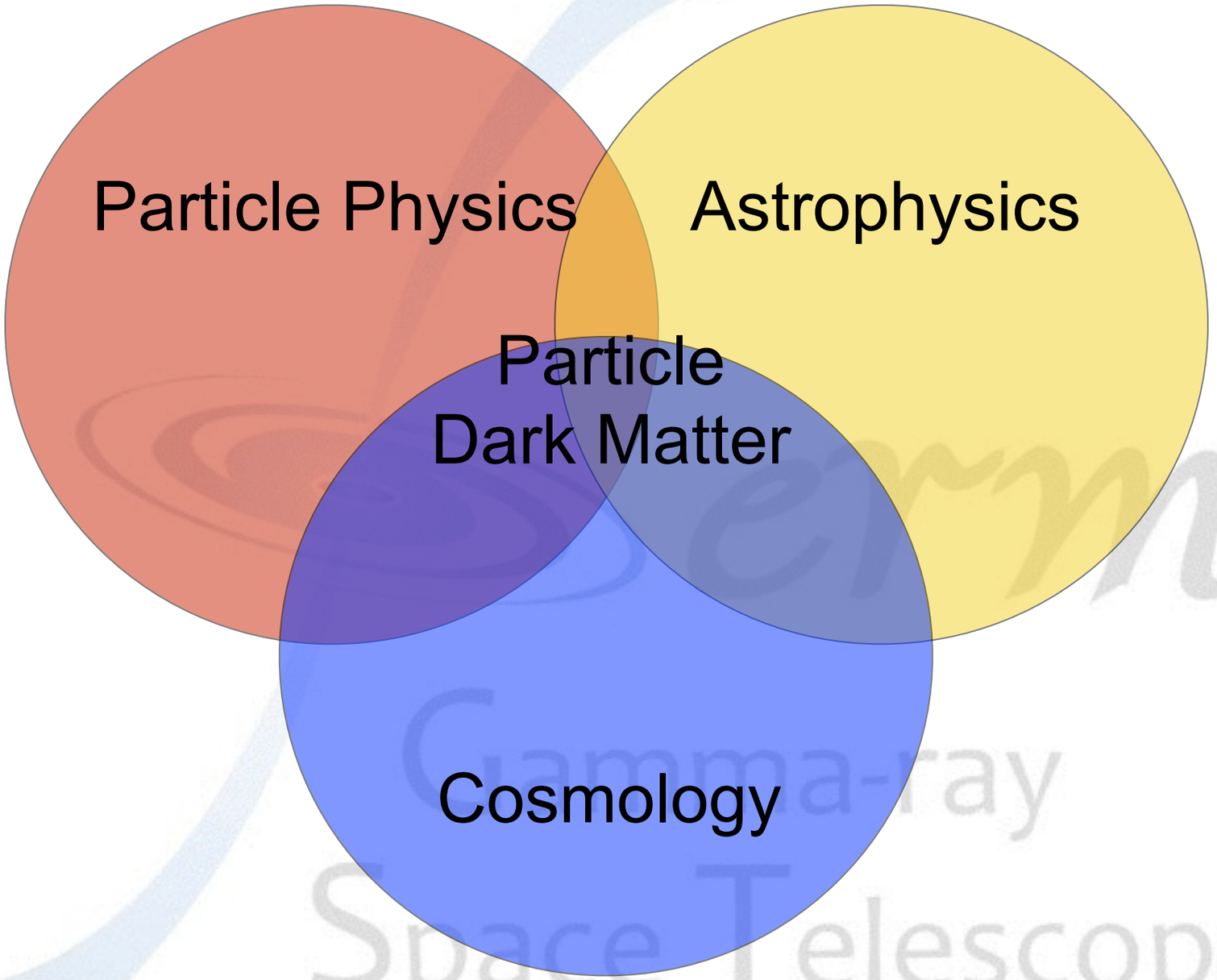
Searching for Dark Matter with the Fermi-LAT

R. Caputo, UCSC

Fermi Summer School
Lewes, DE

9 June 2016

A Brief History of Dark Matter



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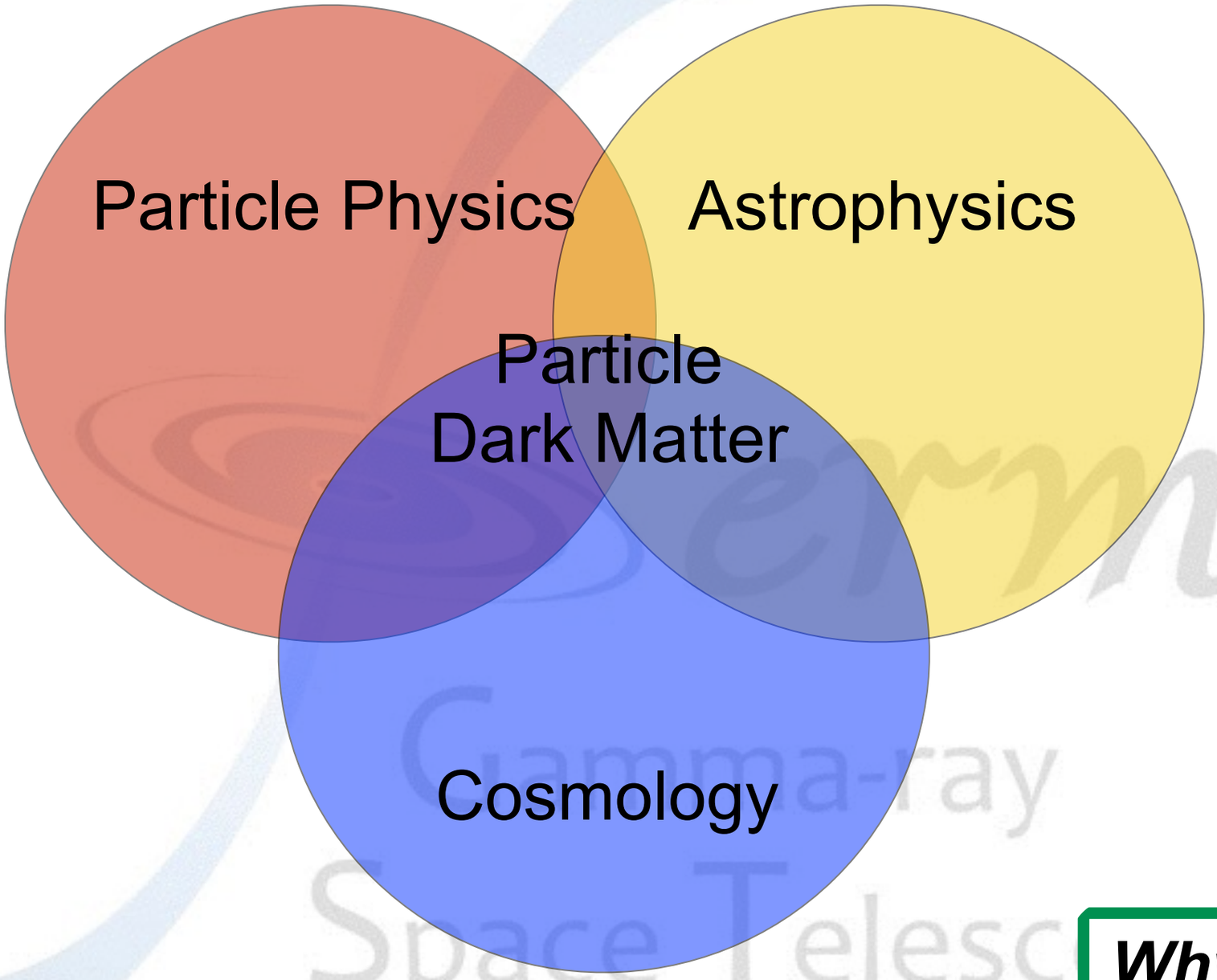


Why…?

The Mystery of Missing Mass

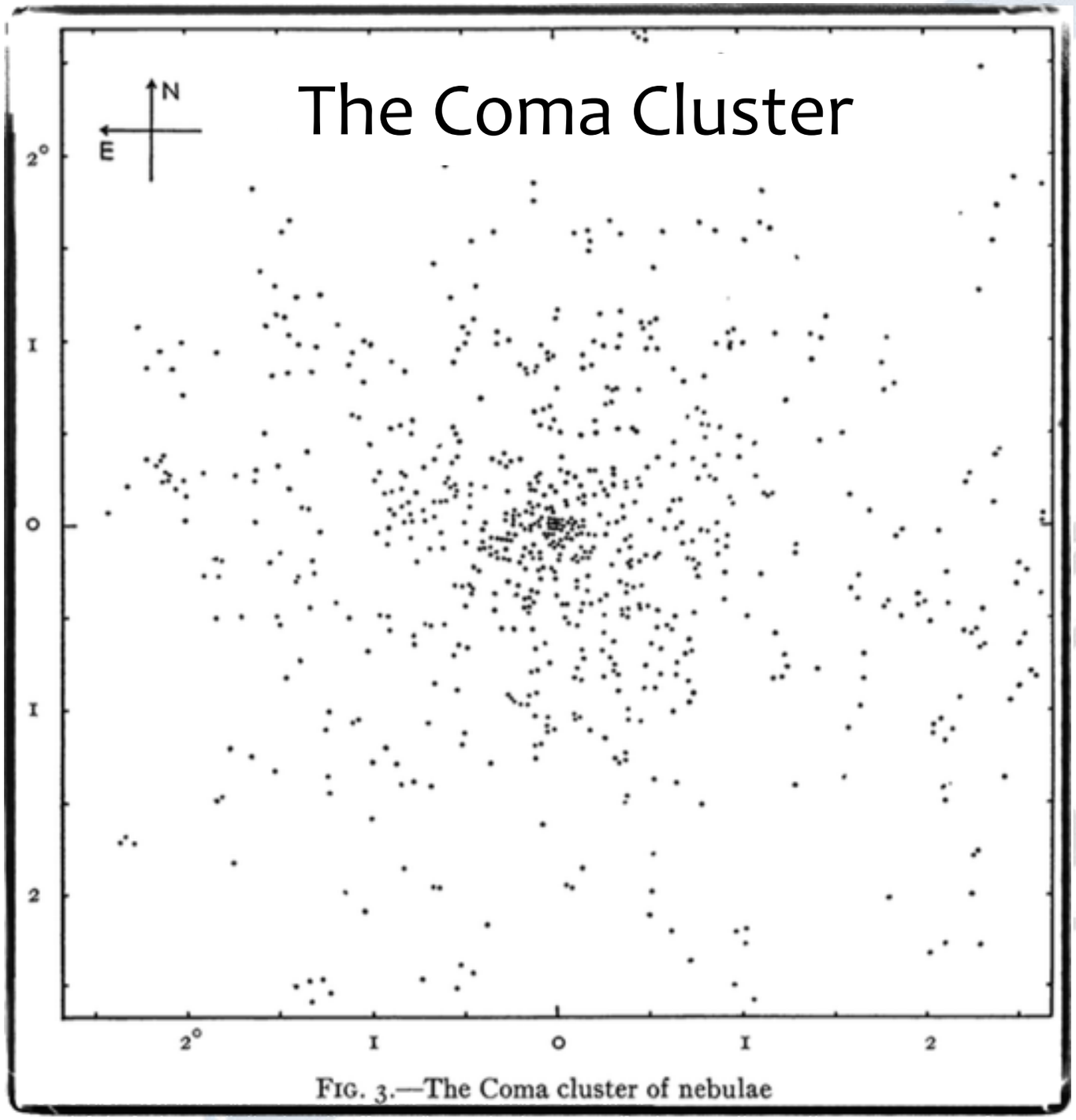
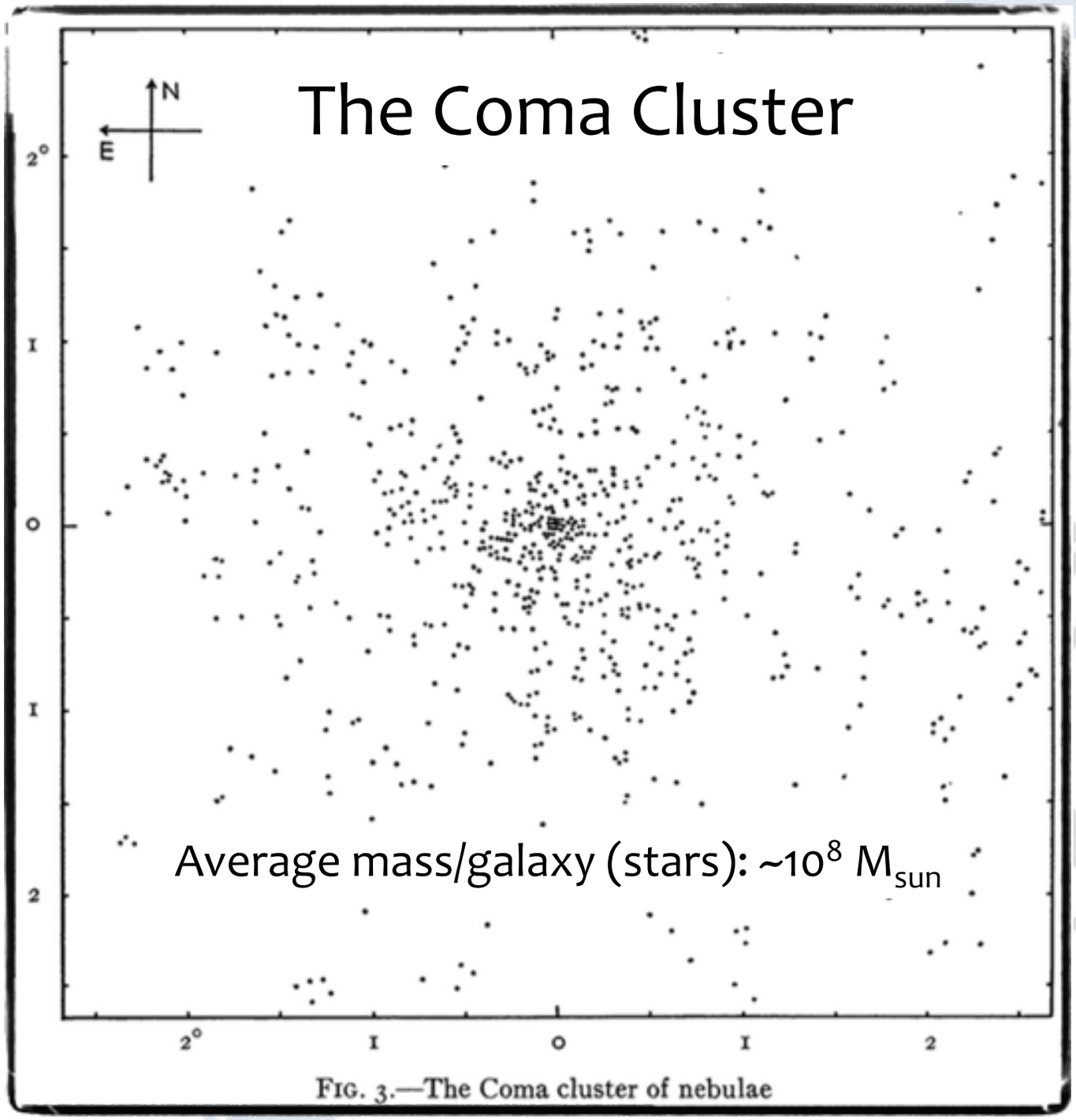


FIG. 3.—The Coma cluster of nebulae

1930s- Zwicky, others

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

The Mystery of Missing Mass



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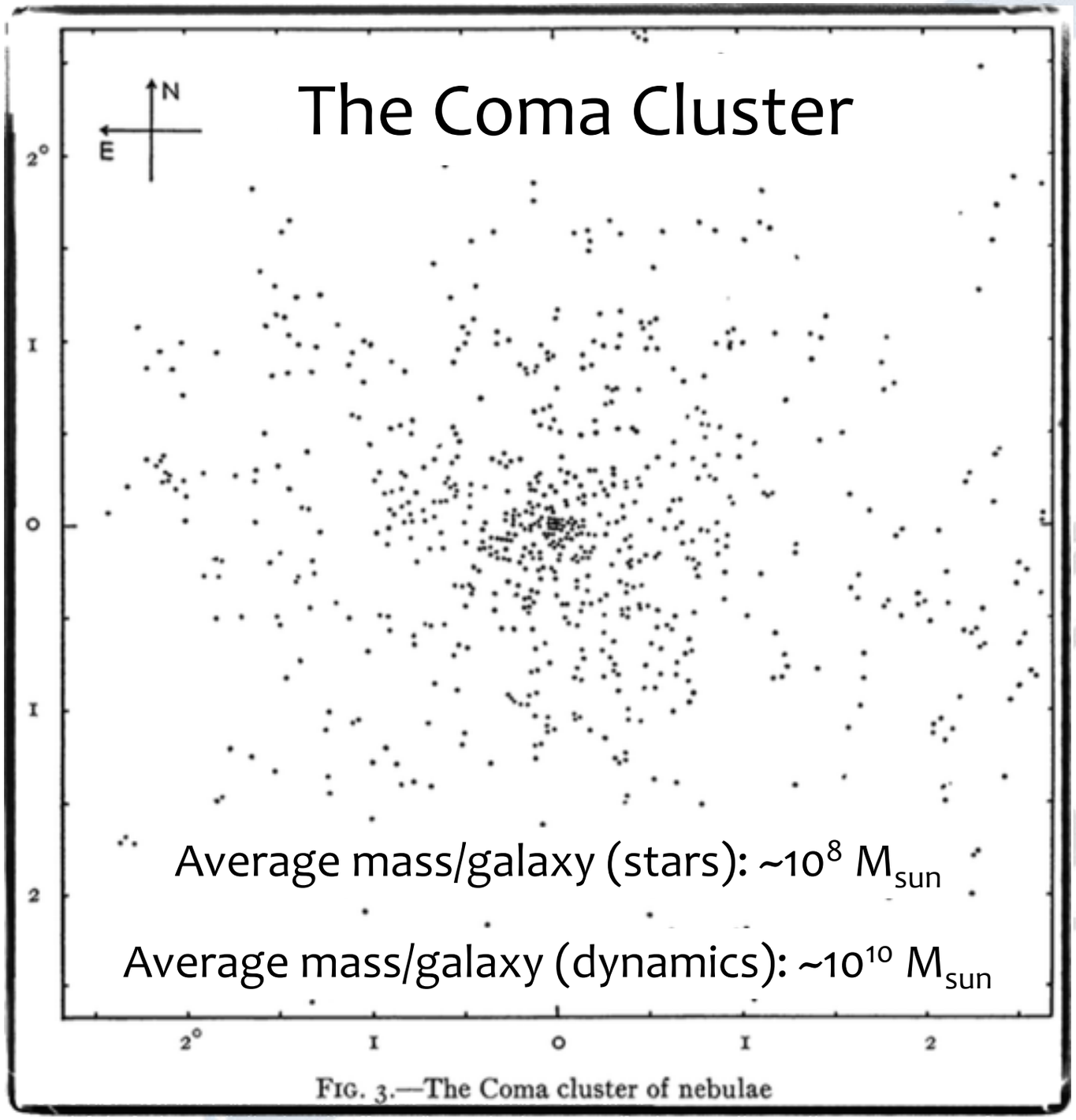

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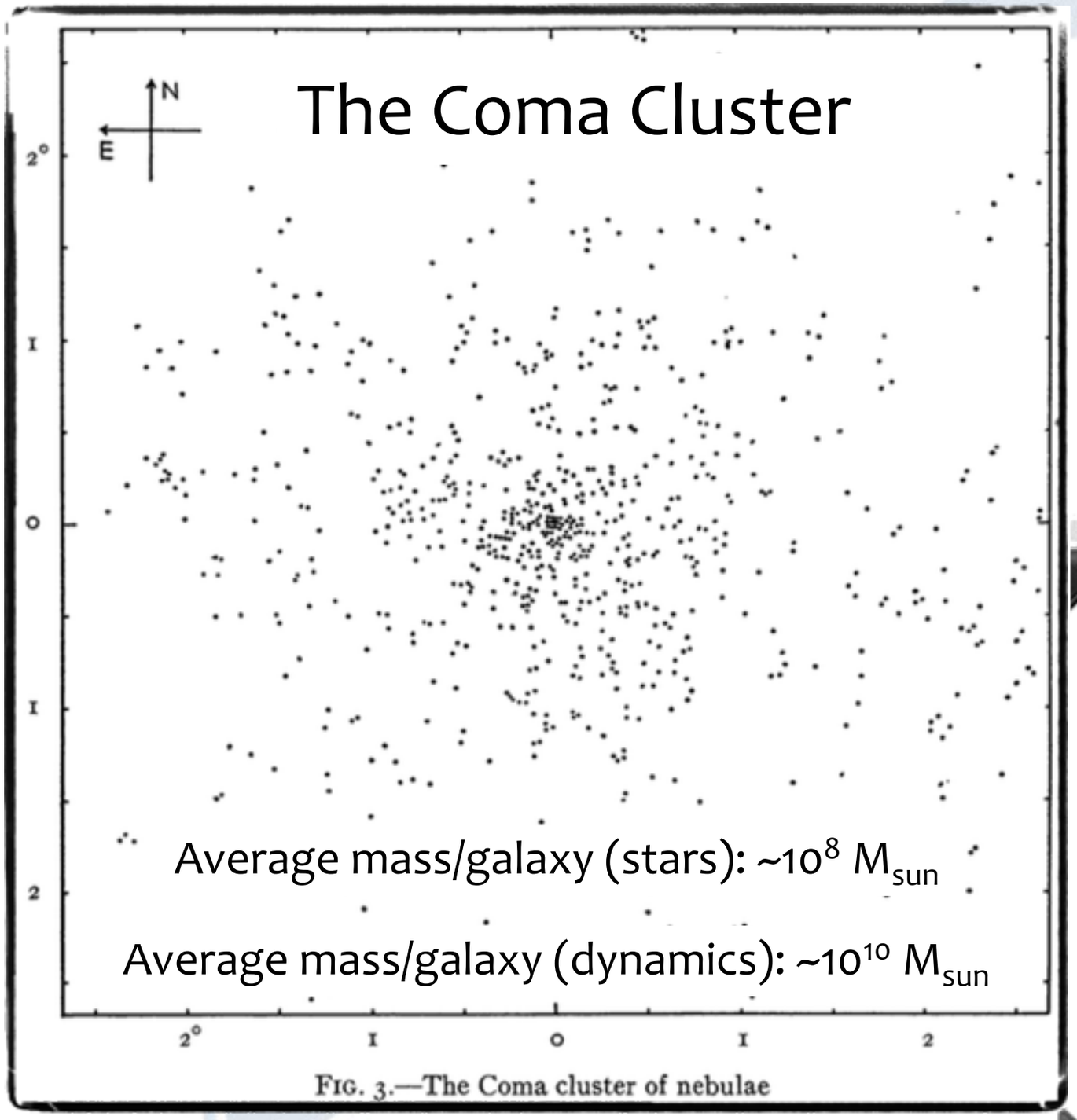

FIG. 3.—The Coma cluster of nebulae

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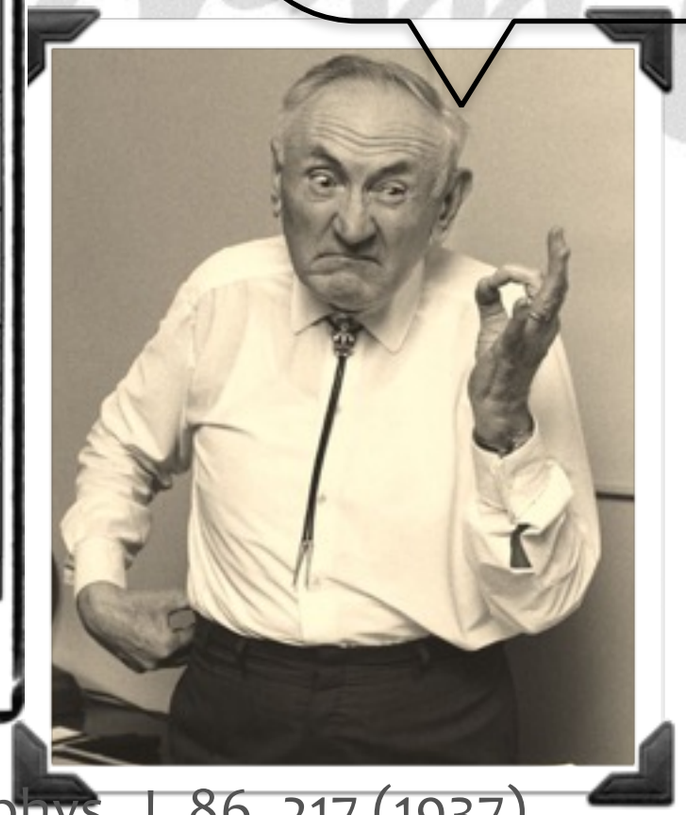
Coma cluster of galaxies: only small % mass from luminous matter



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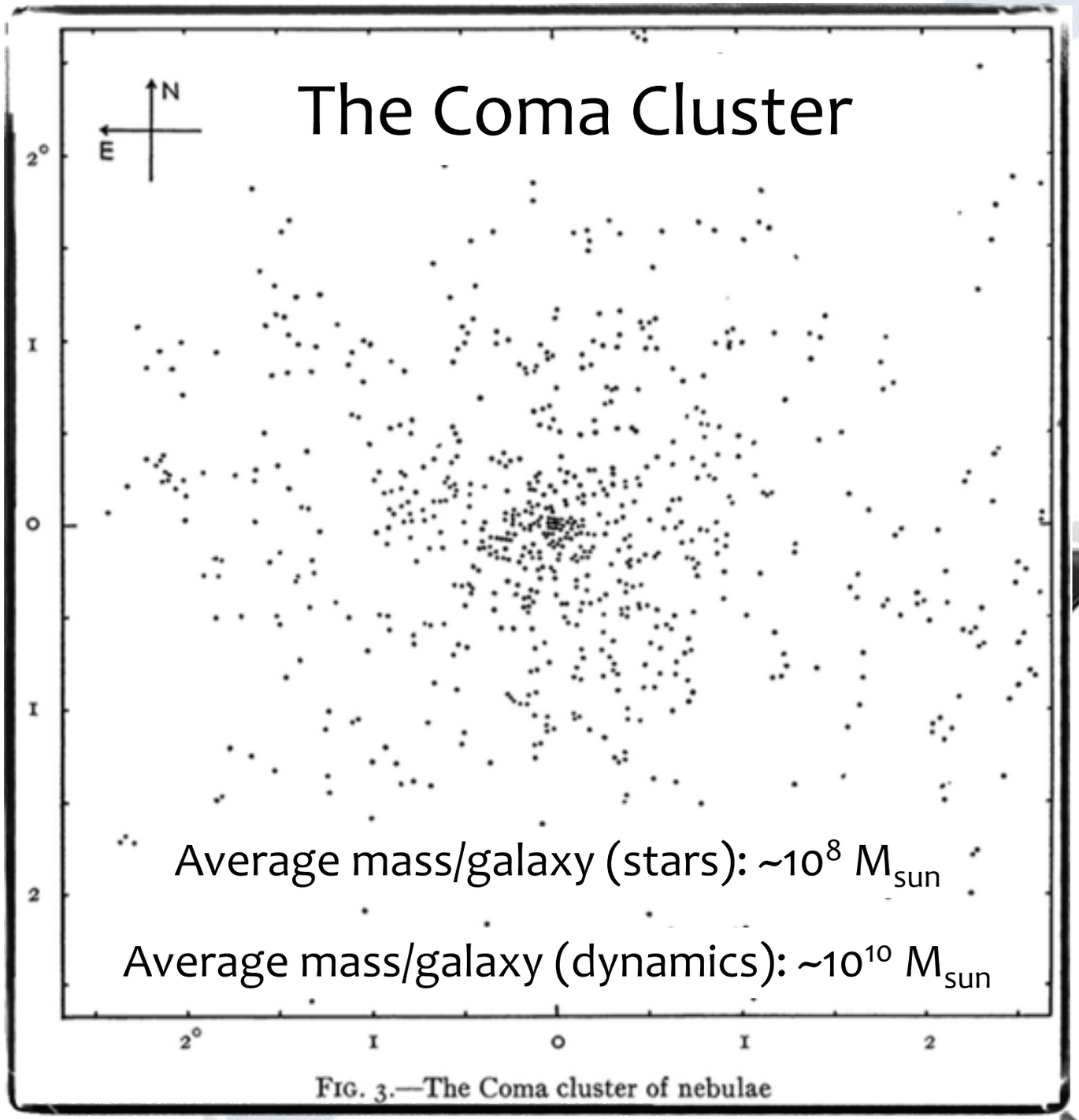

Average mass/galaxy (stars): ~10^8 M_{sun}

Average mass/galaxy (dynamics): ~10^{10} M_{sun}

FIG. 3.—The Coma cluster of nebulae

1930s- Zwicky, others

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

Dunkle Materie!

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

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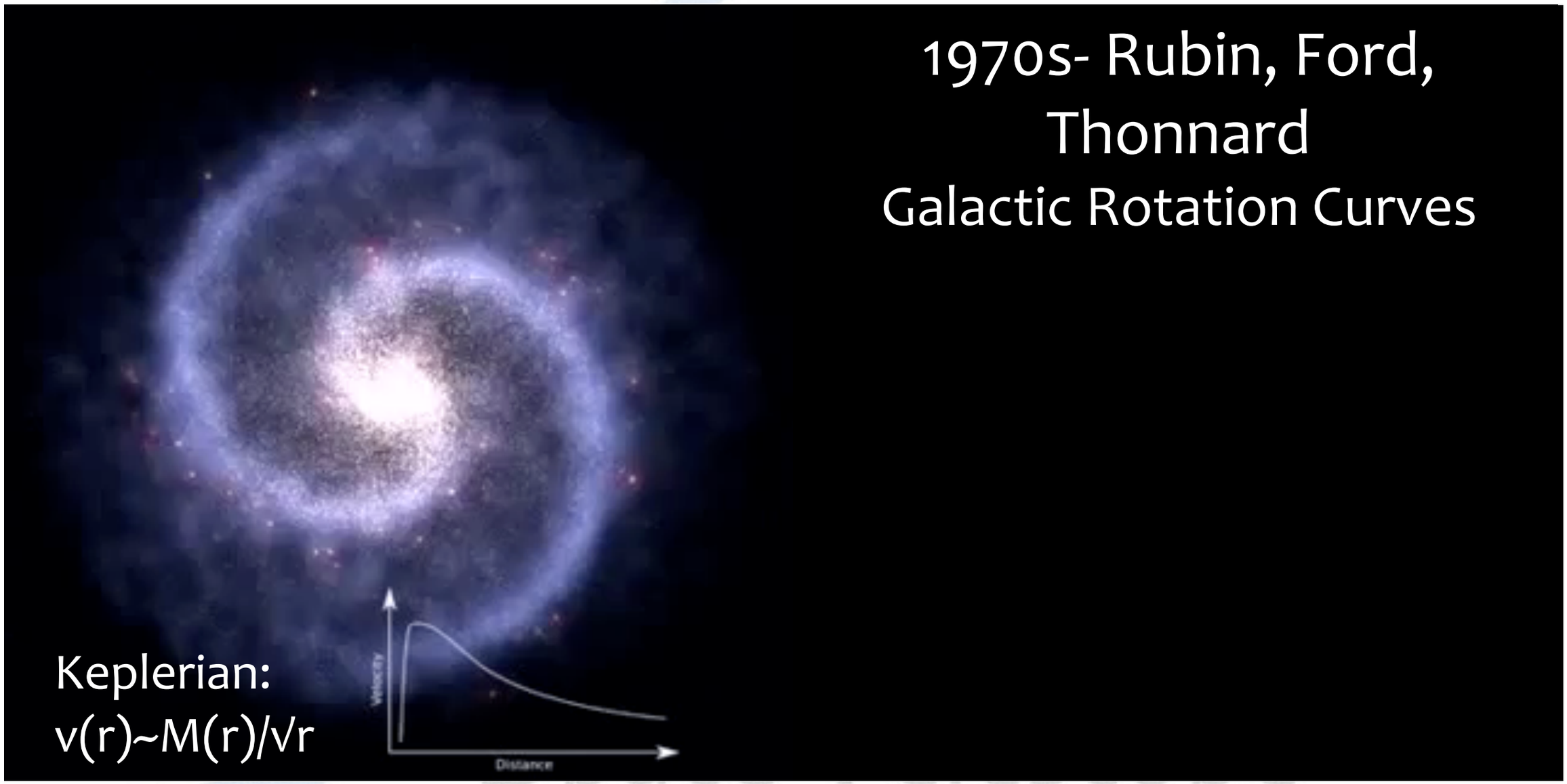

YouTube: https://www.youtube.com/watch?v=Omjx3OKAGDo
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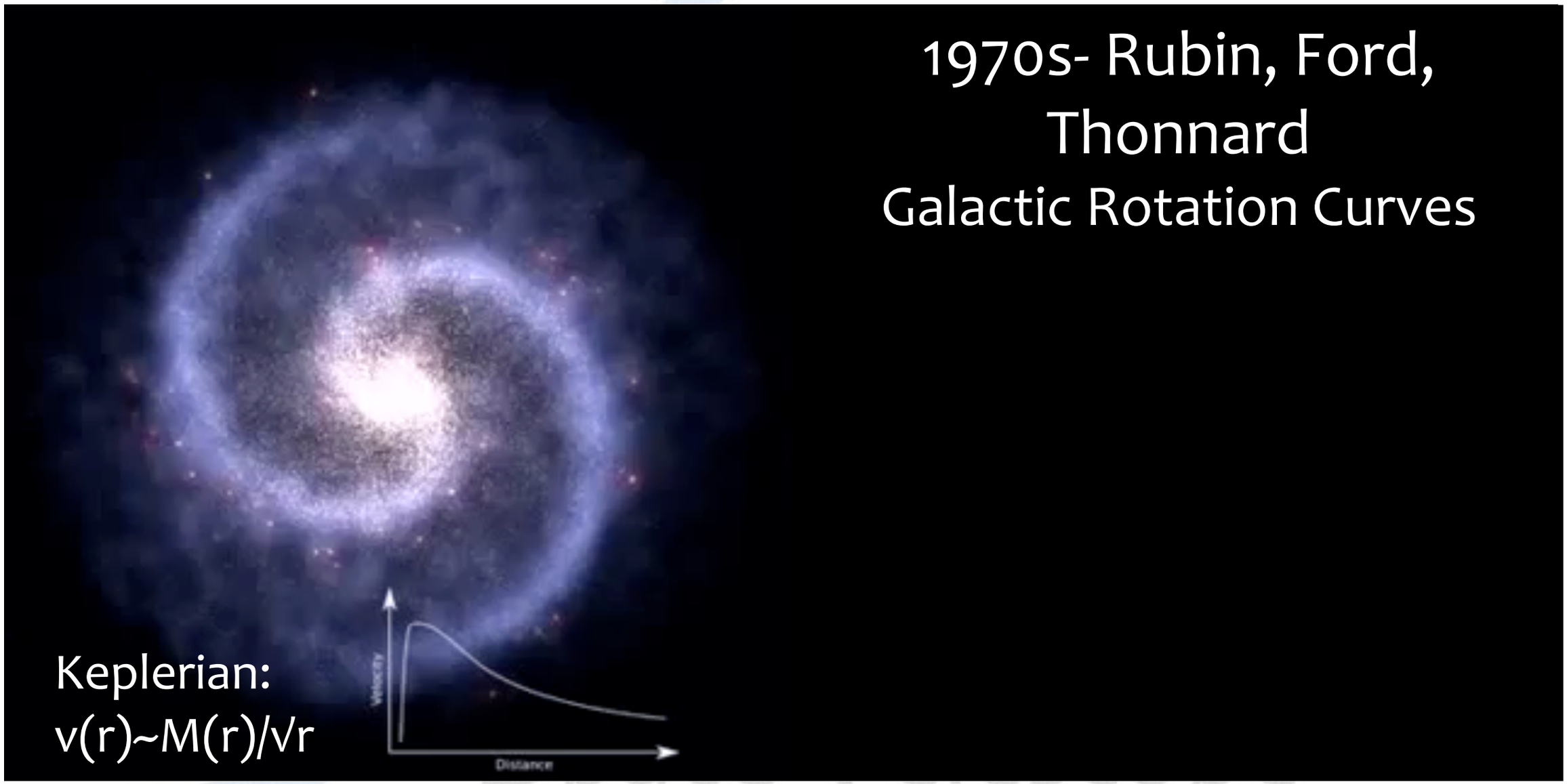

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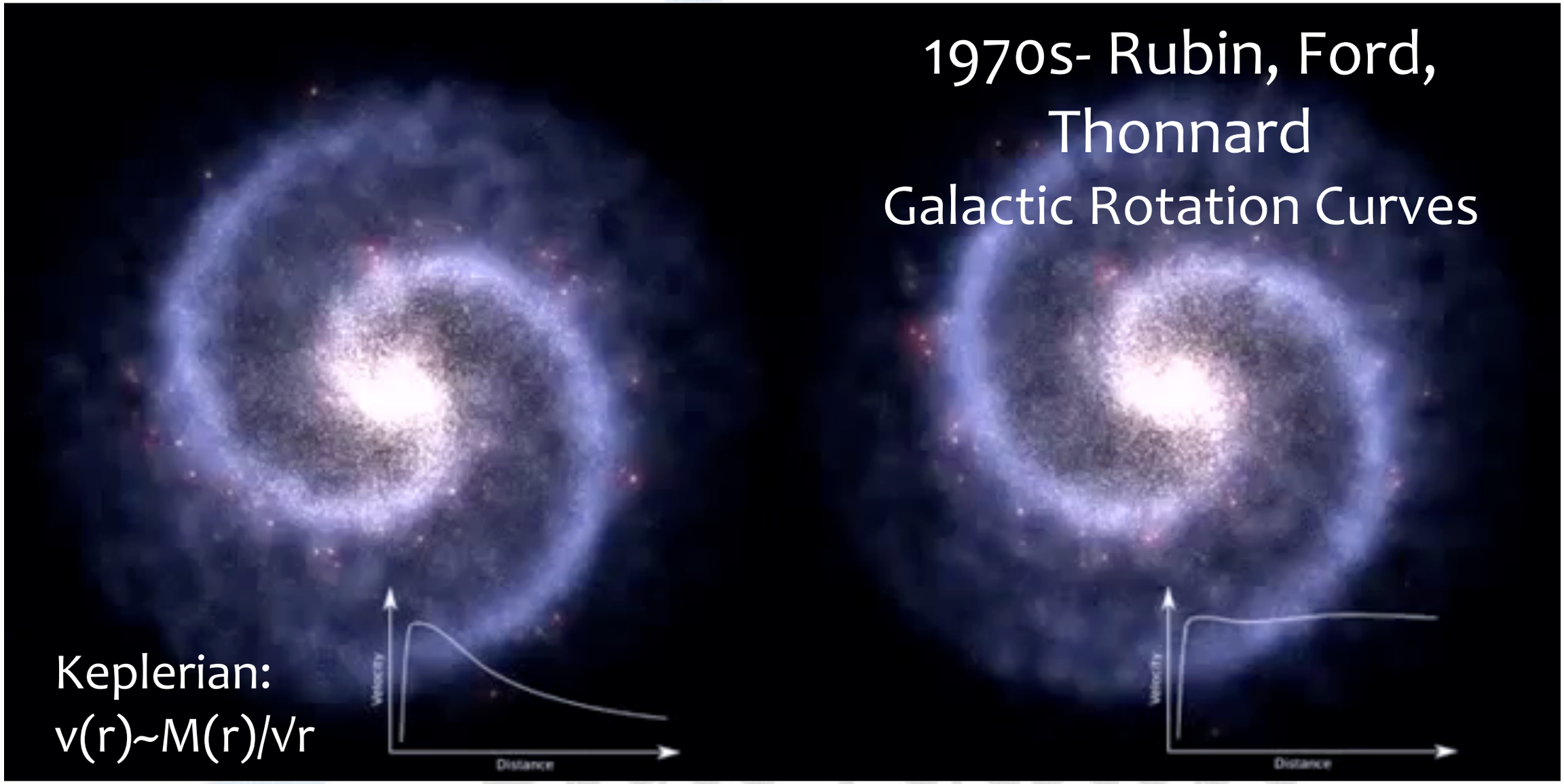

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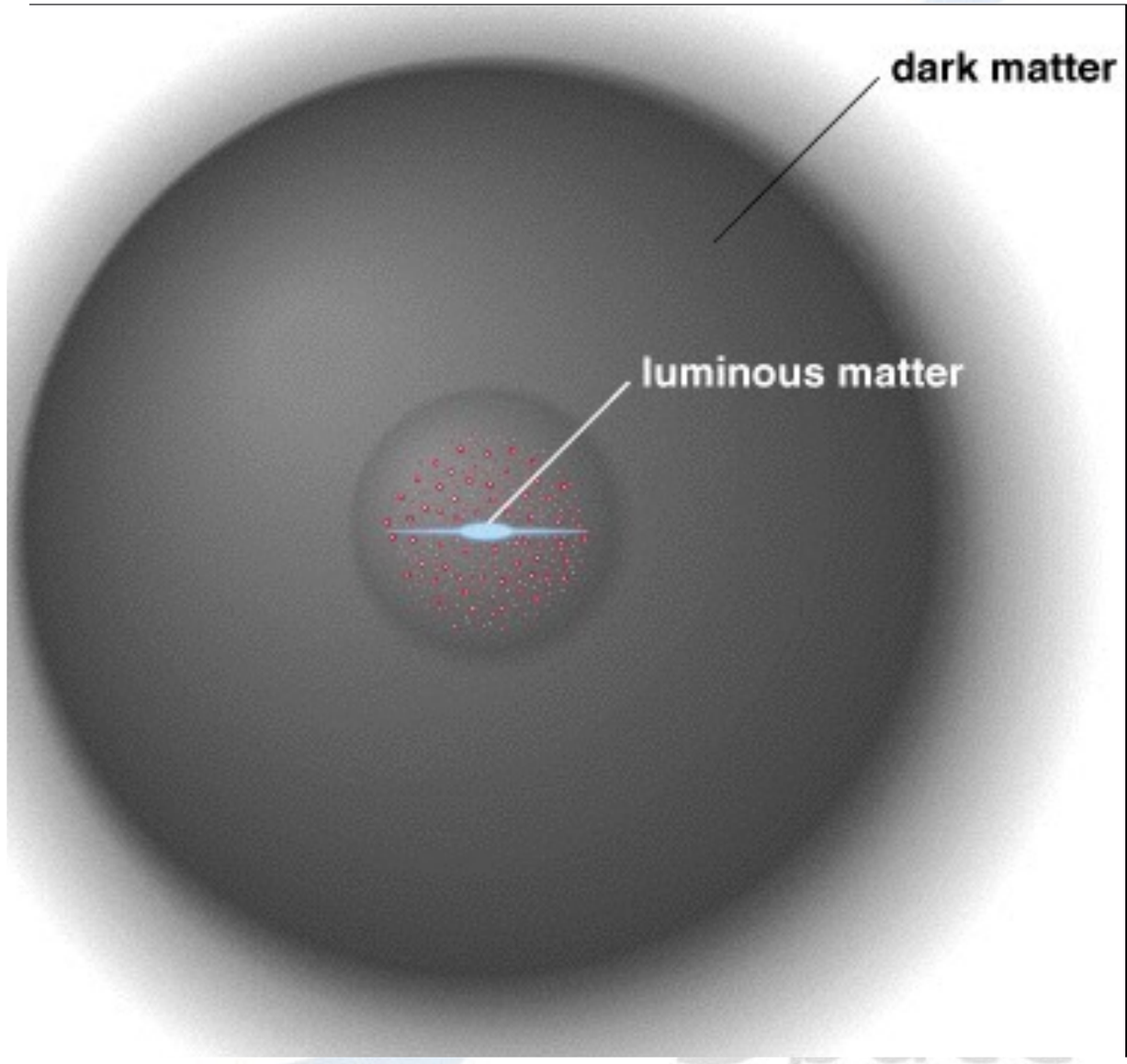

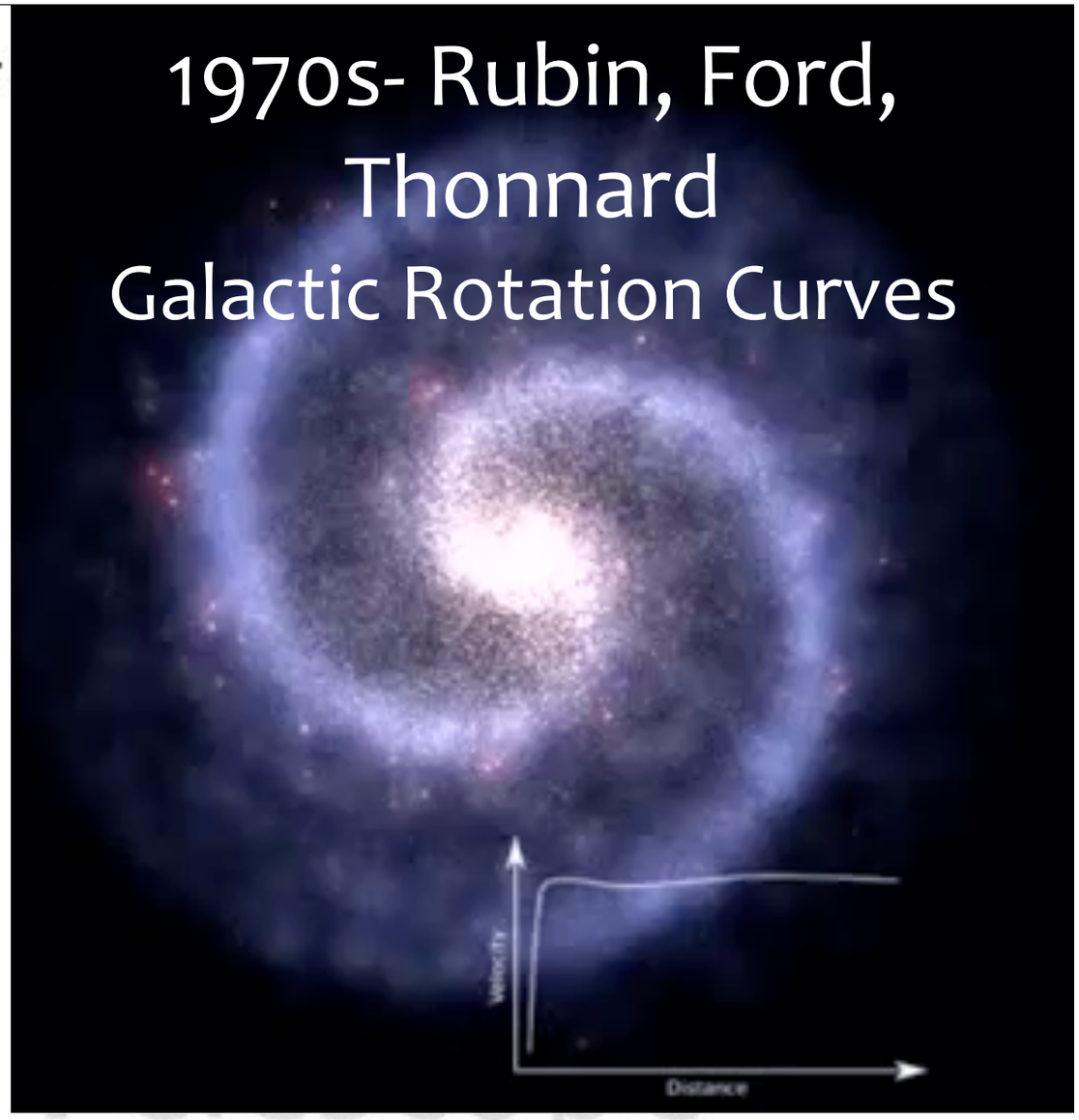

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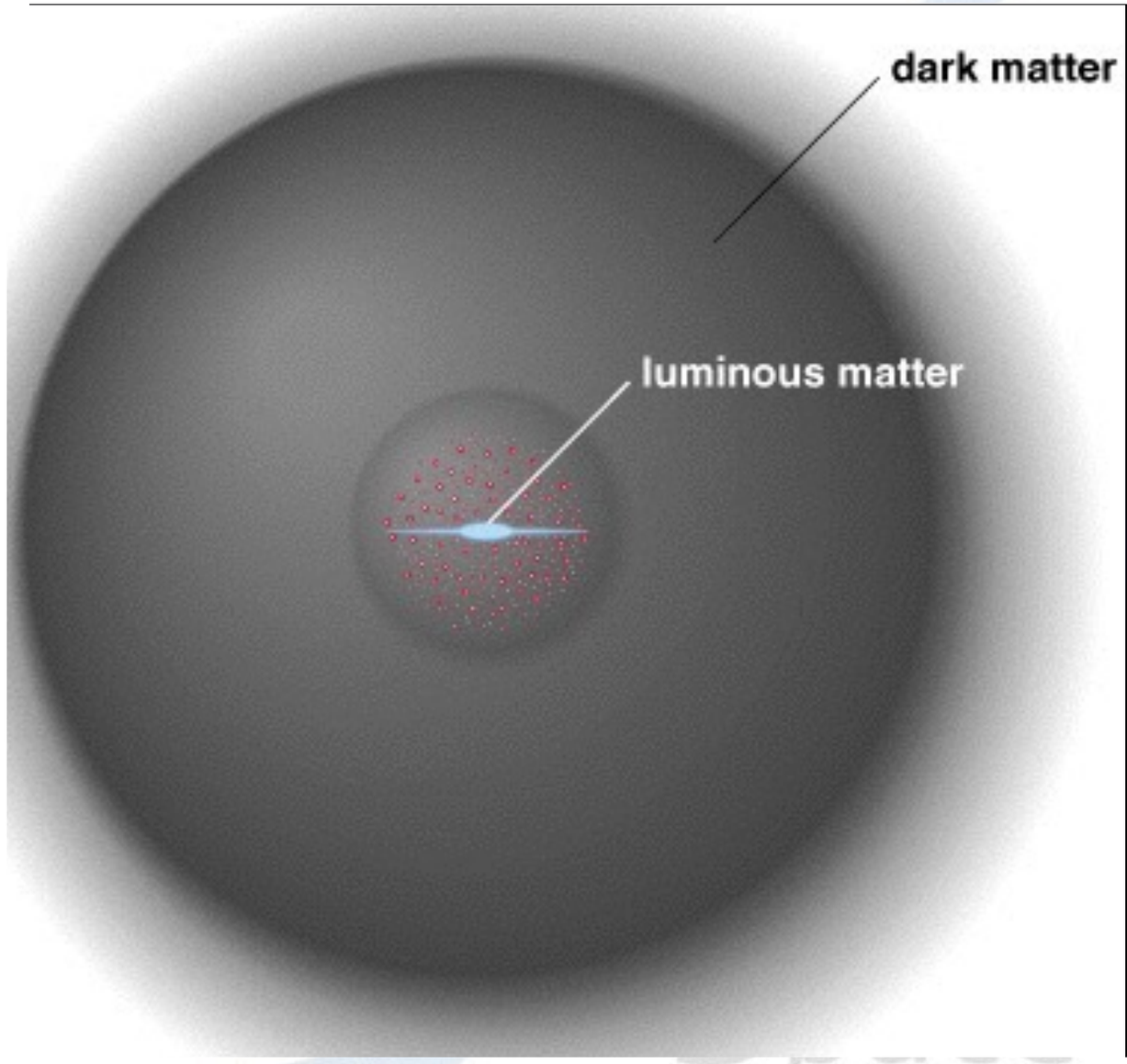

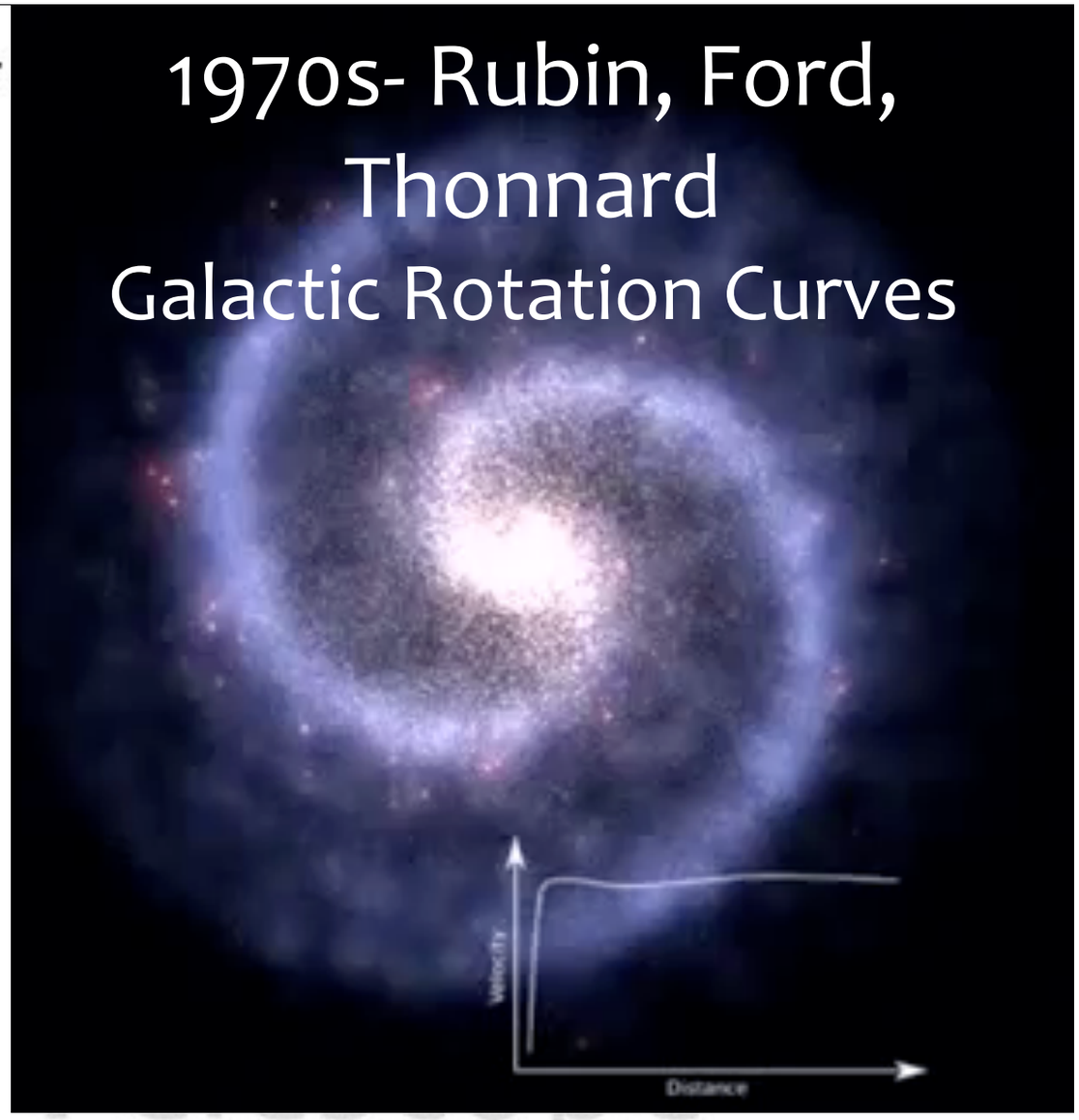

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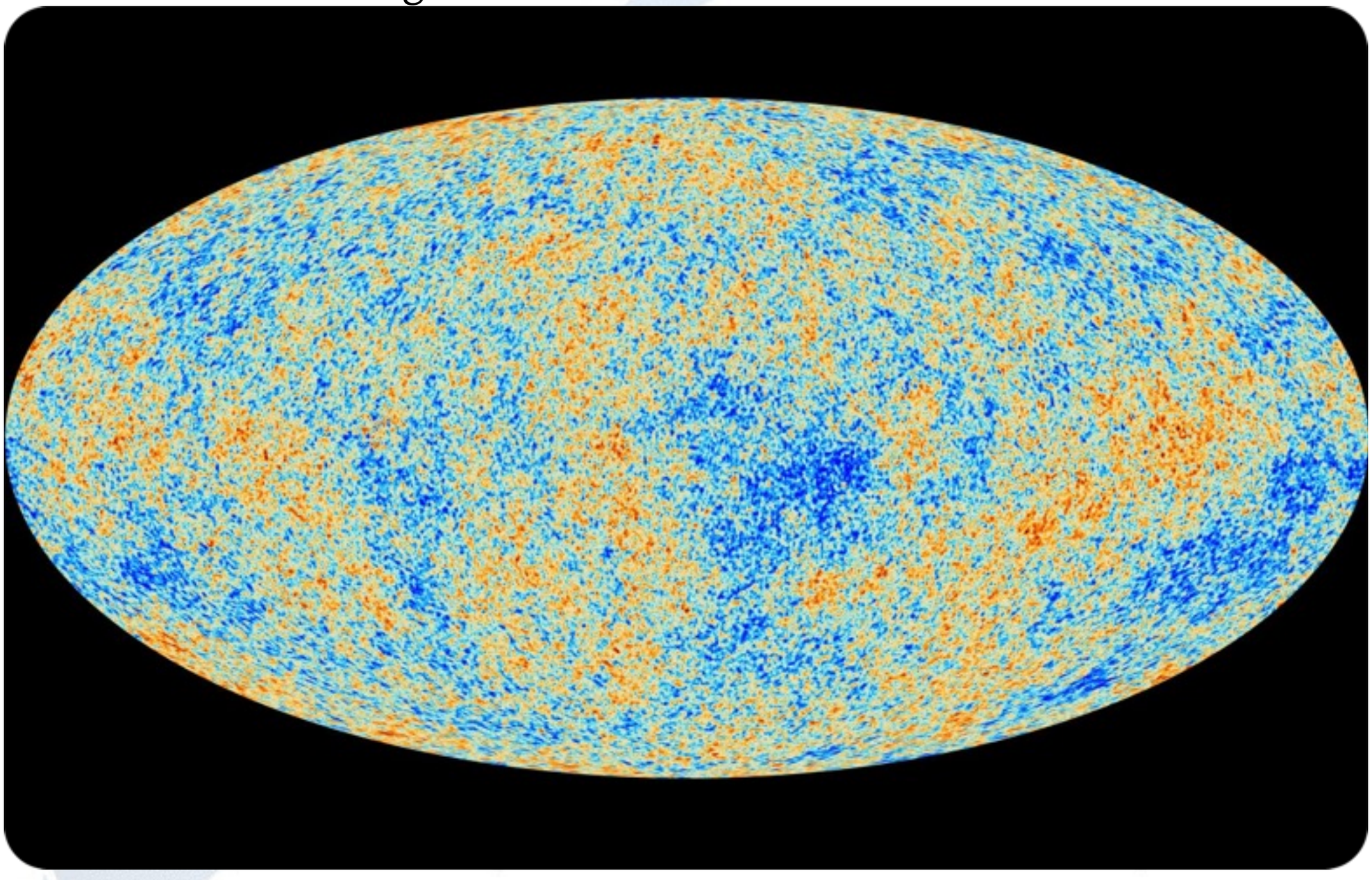
Precision Cosmology

Cosmic Microwave Background



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

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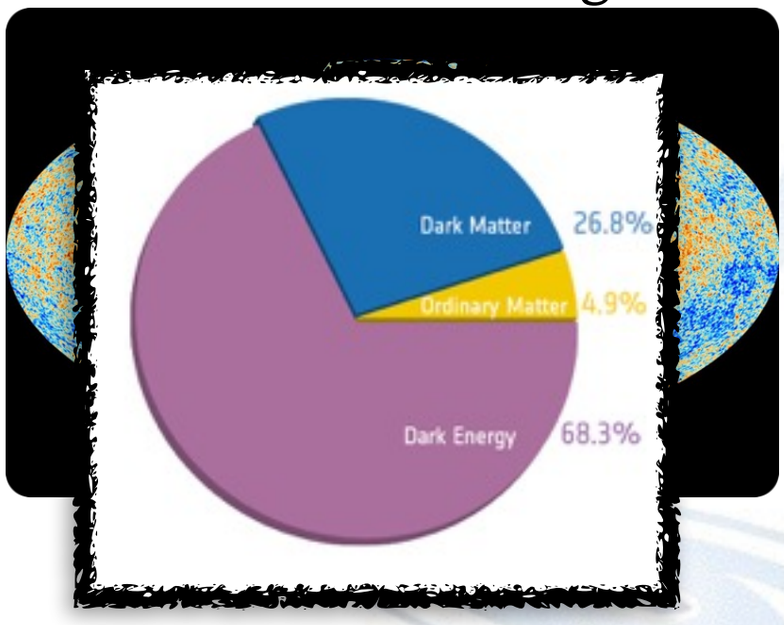

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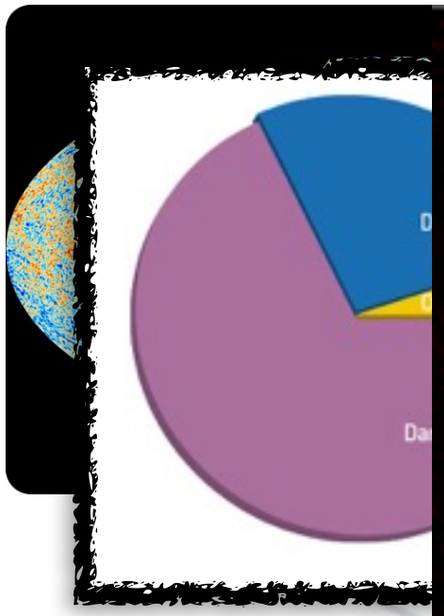
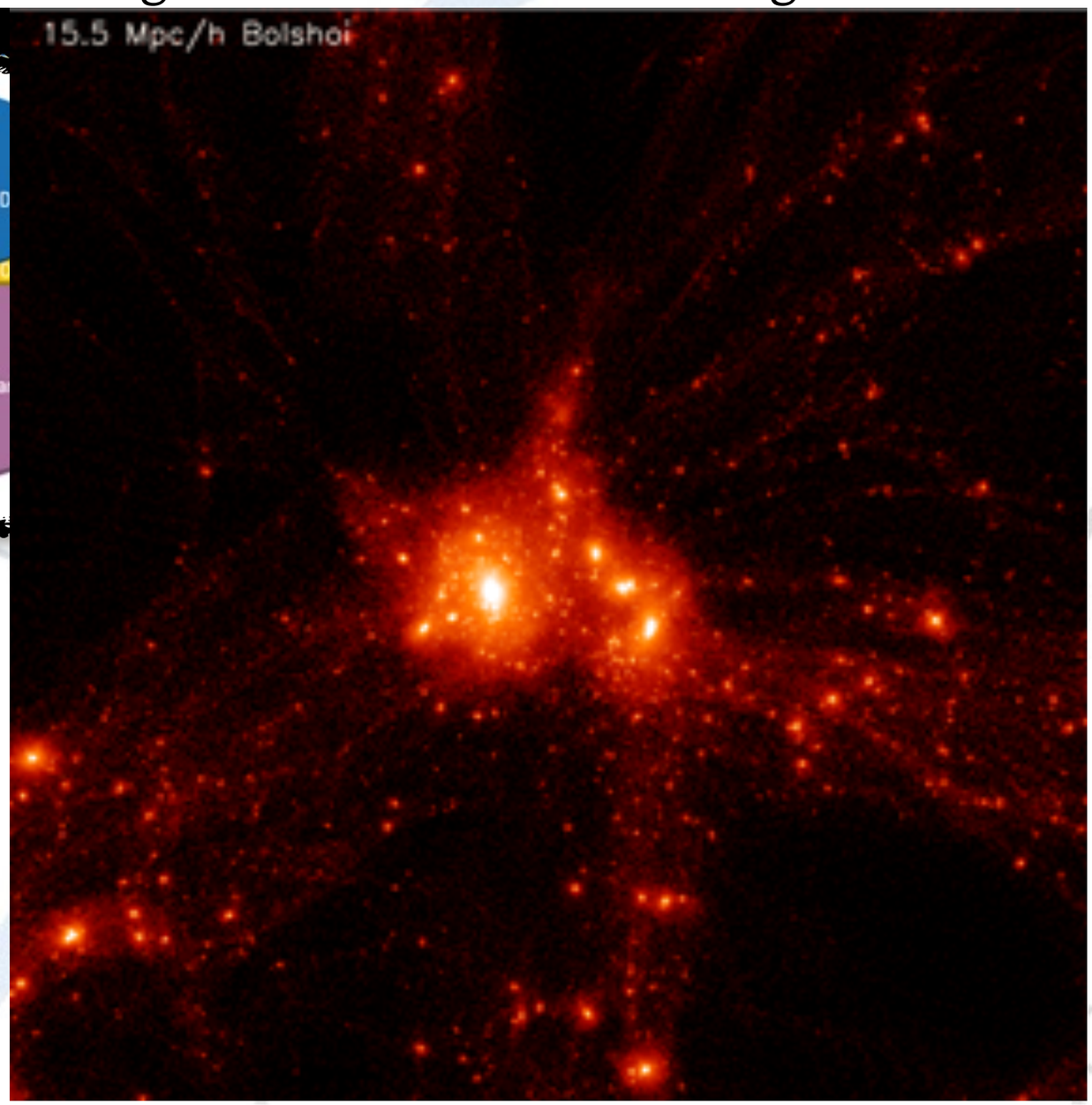


Large Scale Structure



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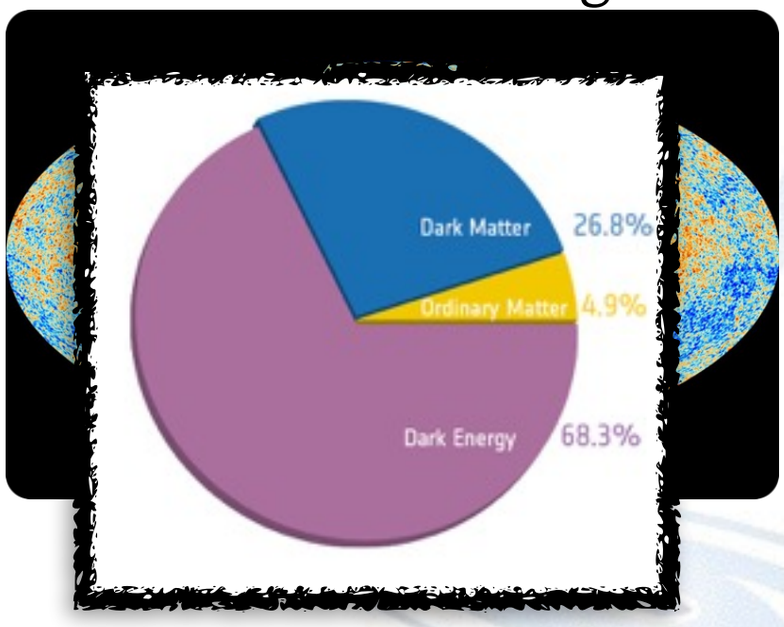

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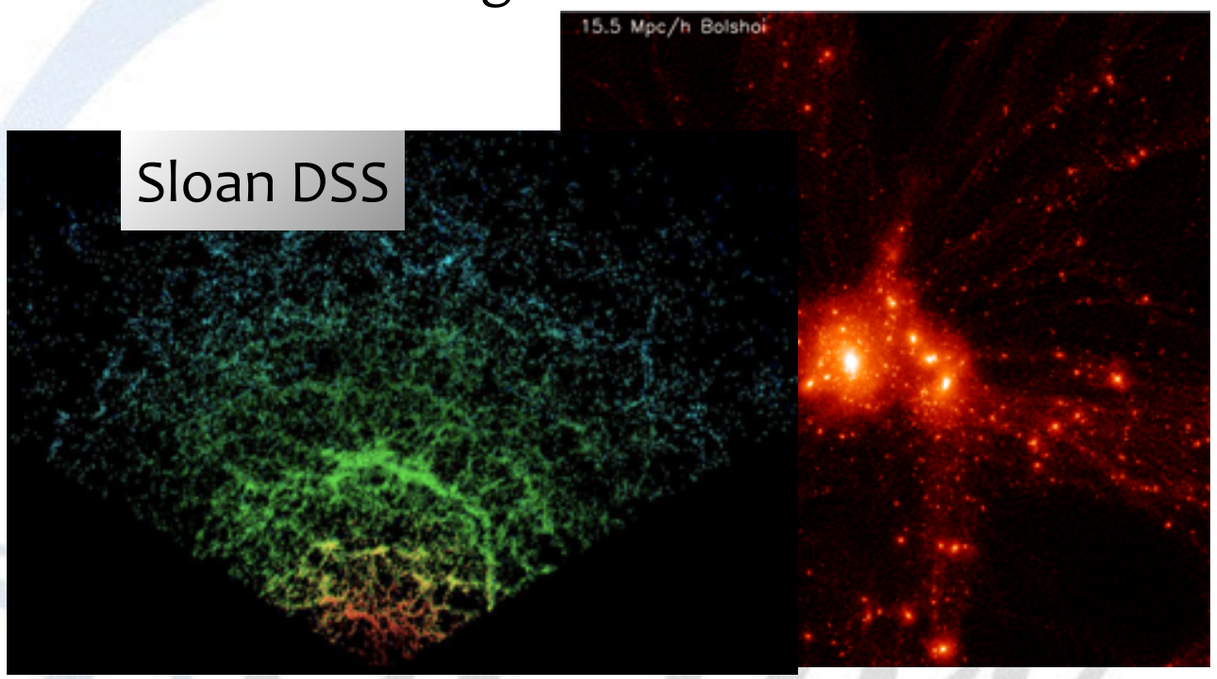

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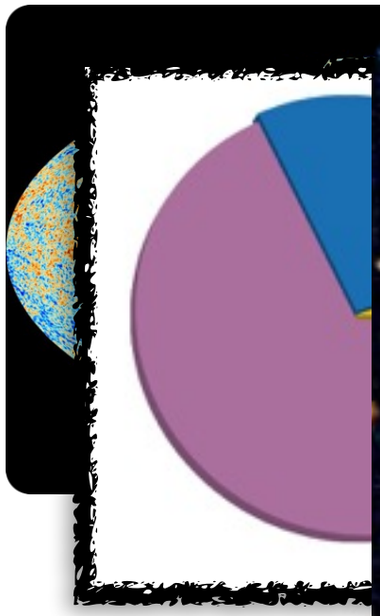

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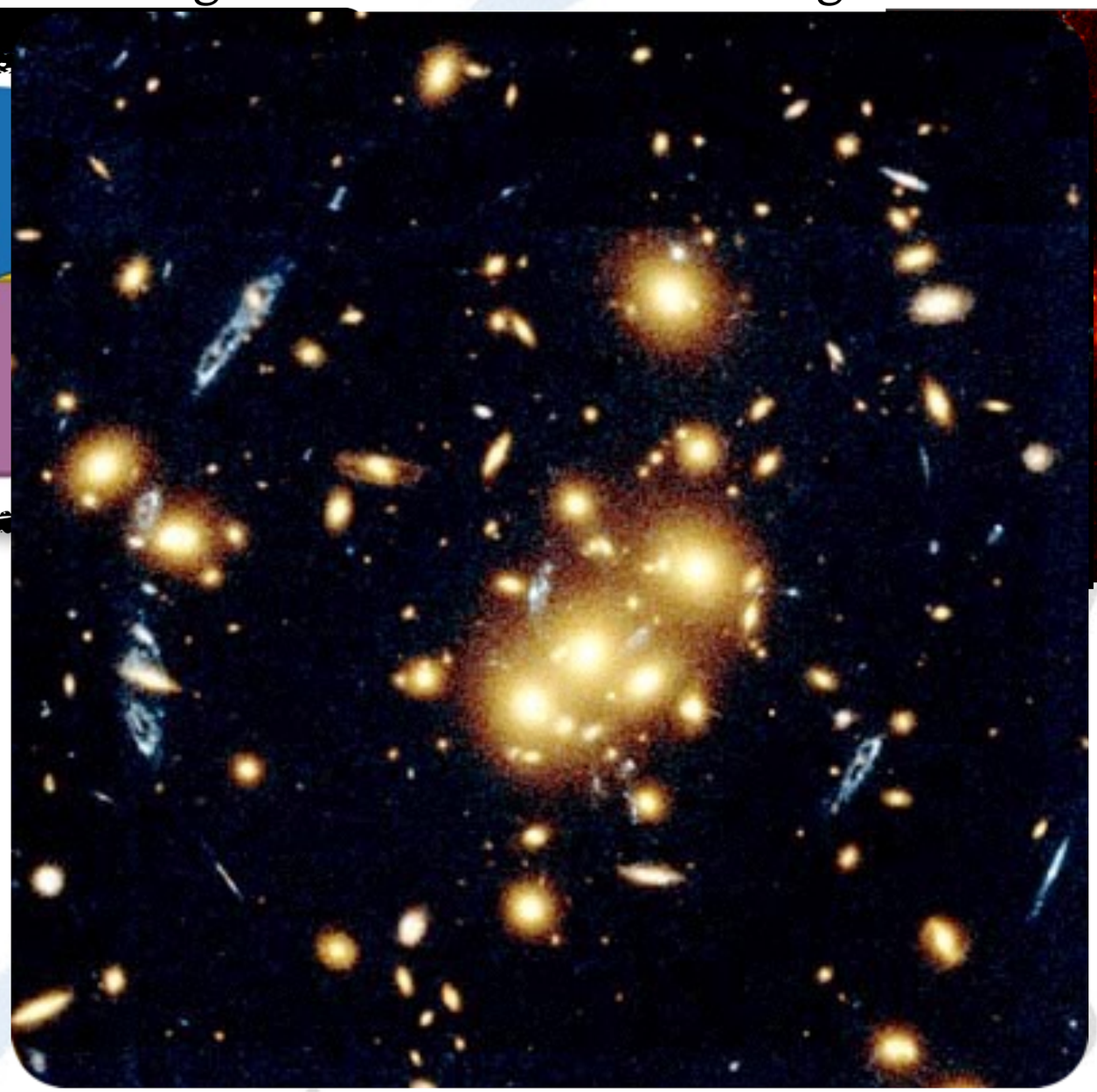

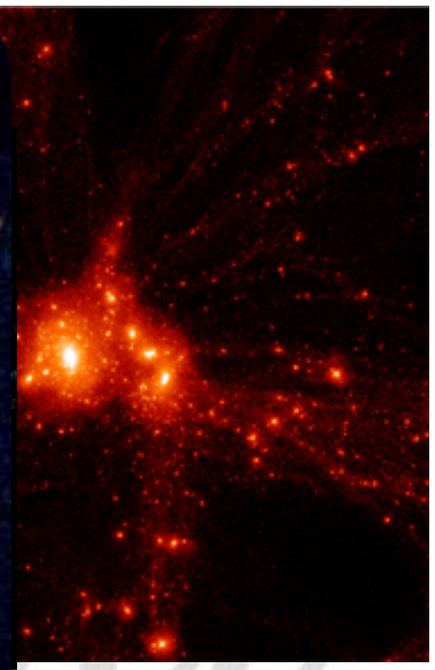

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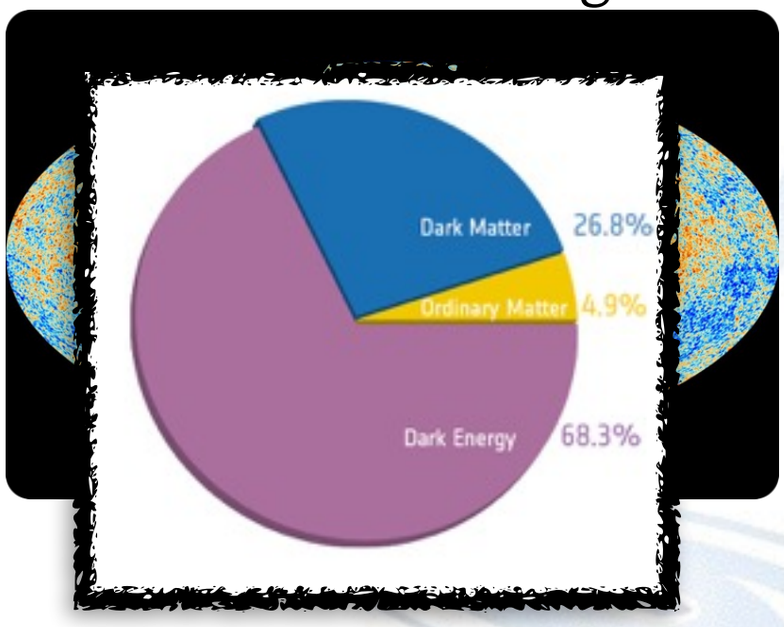

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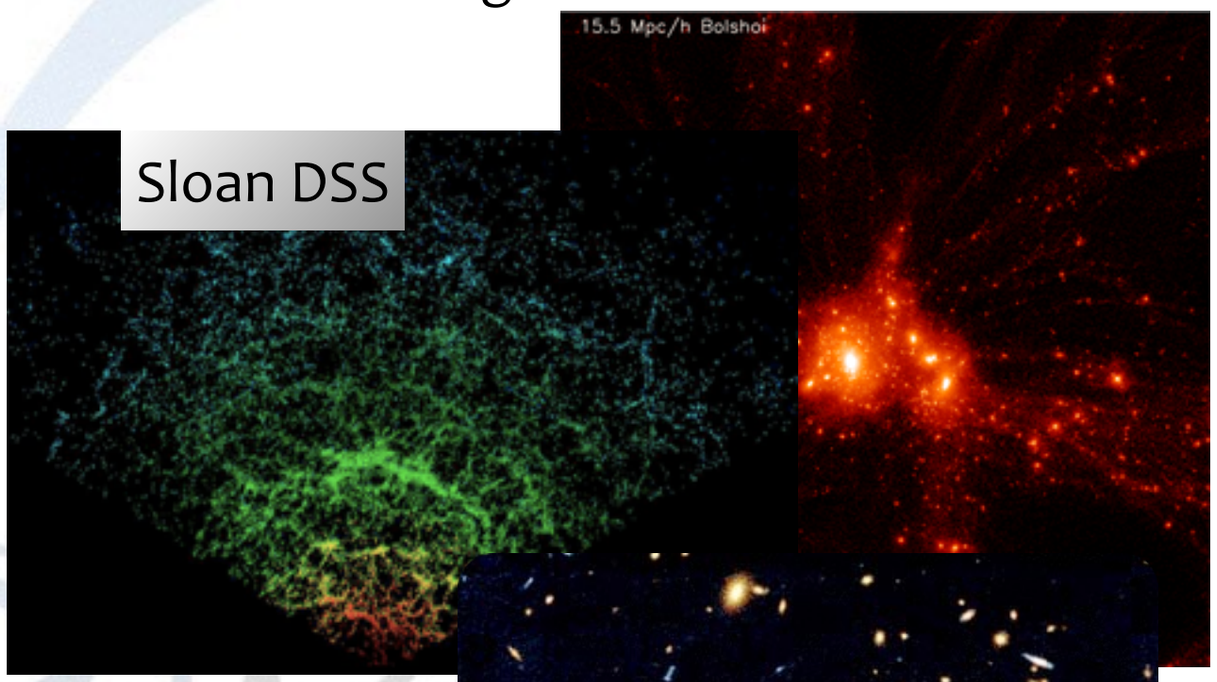

Gravitational Lensing

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

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

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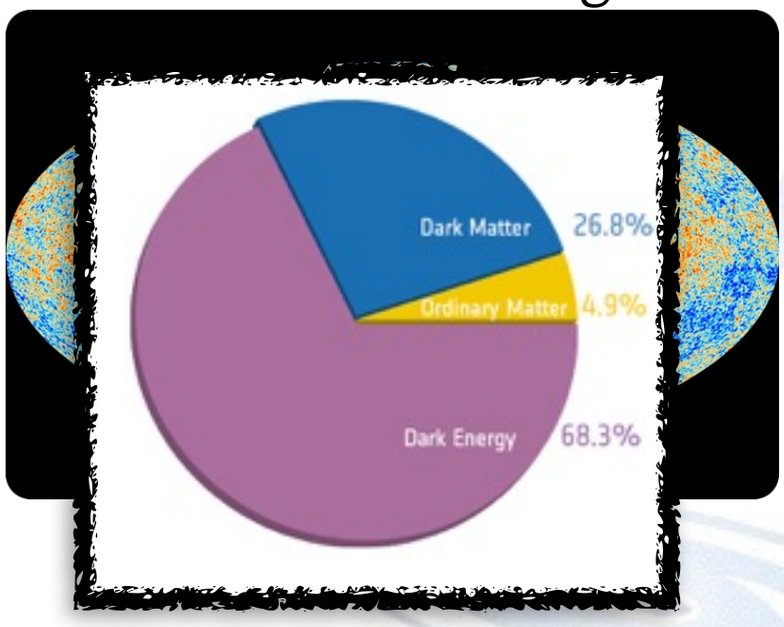

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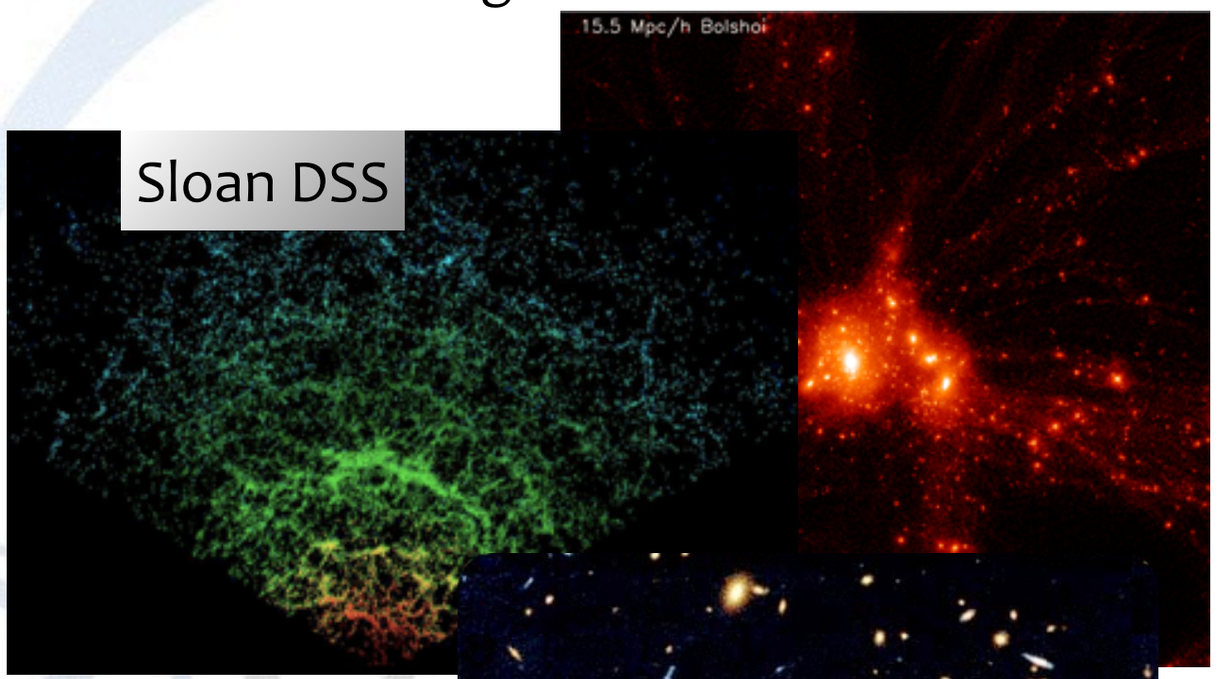


Lensing/
The Bullet
Cluster

Blue: mass from lensing

Gravitational
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

What do we know?

What do we know?

mass

What do we know?

mass

not p/n (baryons)

constraints from CMB, primordial nucleosynthesis

What do we know?

mass

not p/n (baryons)

constraints from CMB, primordial nucleosynthesis

neutral

What do we know?

mass

not p/n (baryons)

constraints from CMB, N-body simulations

not hot

neutral

constraints from CMB, primordial nucleosynthesis

What do we know?

mass

stable

not p/n (baryons)

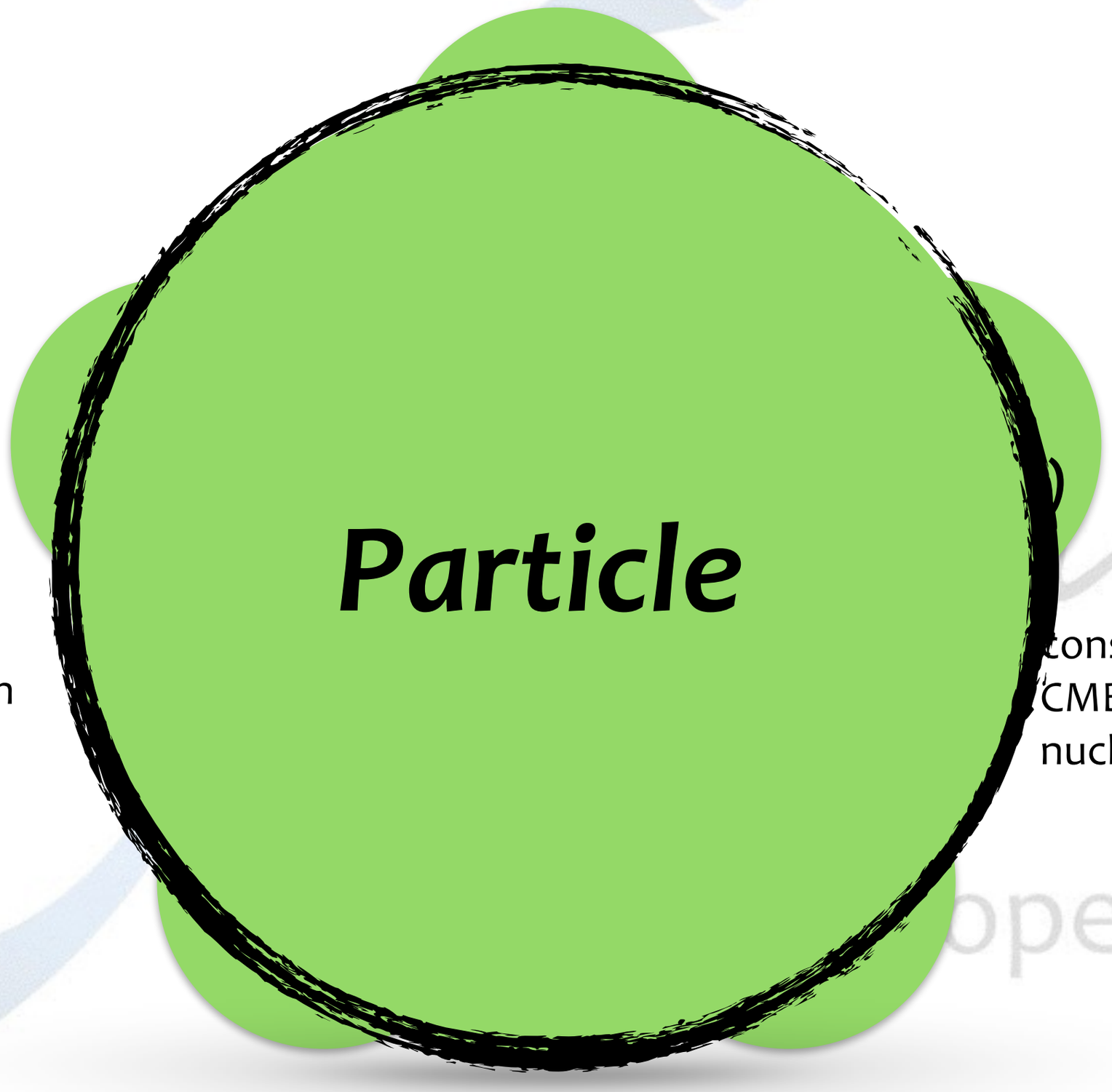
constraints from CMB, N-body simulations

constraints from CMB, primordial nucleosynthesis

not hot

neutral

What do we know?



constraints from CMB, N-body simulations

constraints from CMB, primordial nucleosynthesis

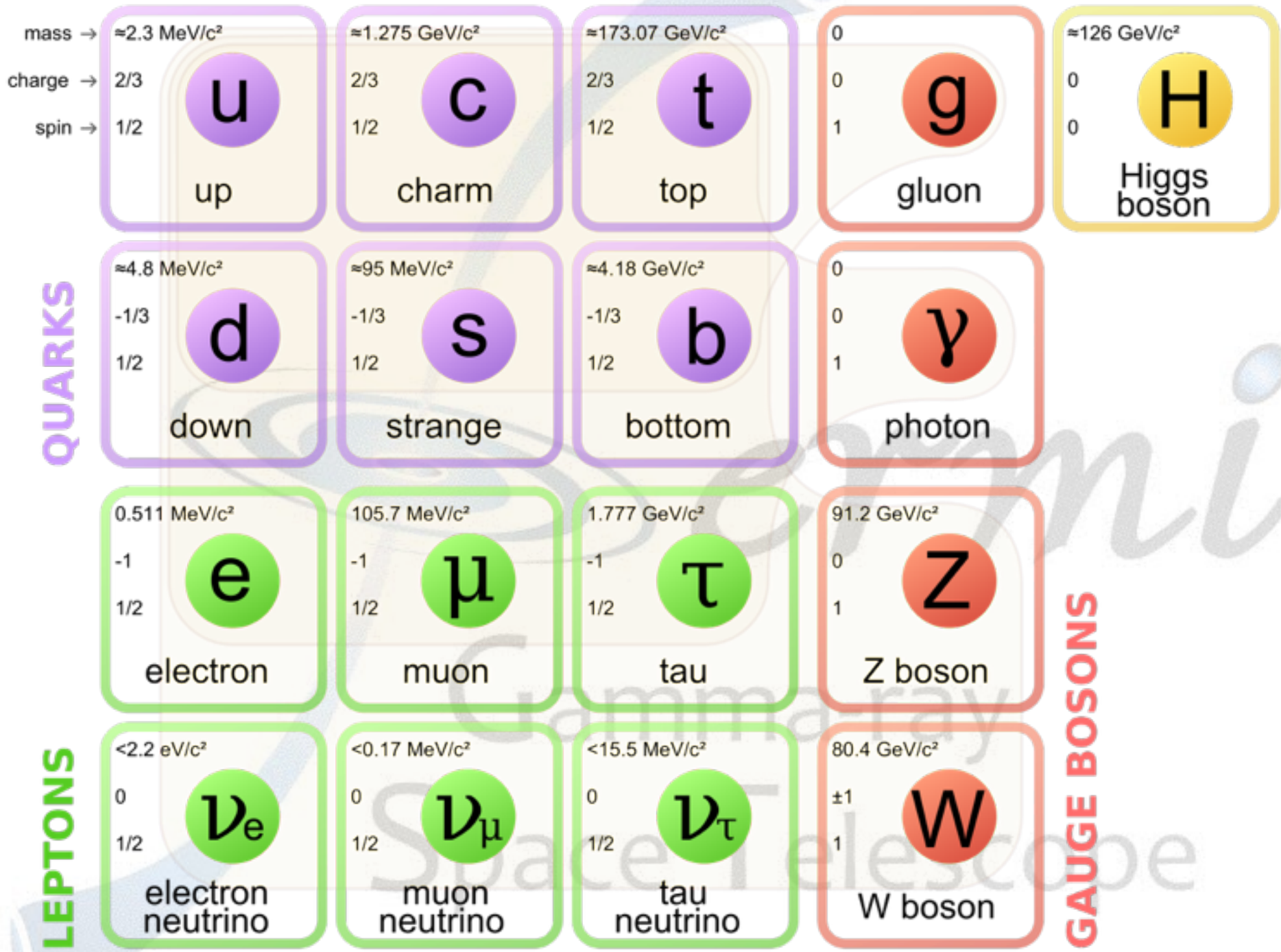
What do we know?

Particle(s)

constraints from CMB, N-body simulations

constraints from CMB, primordial nucleosynthesis

Potential Candidates



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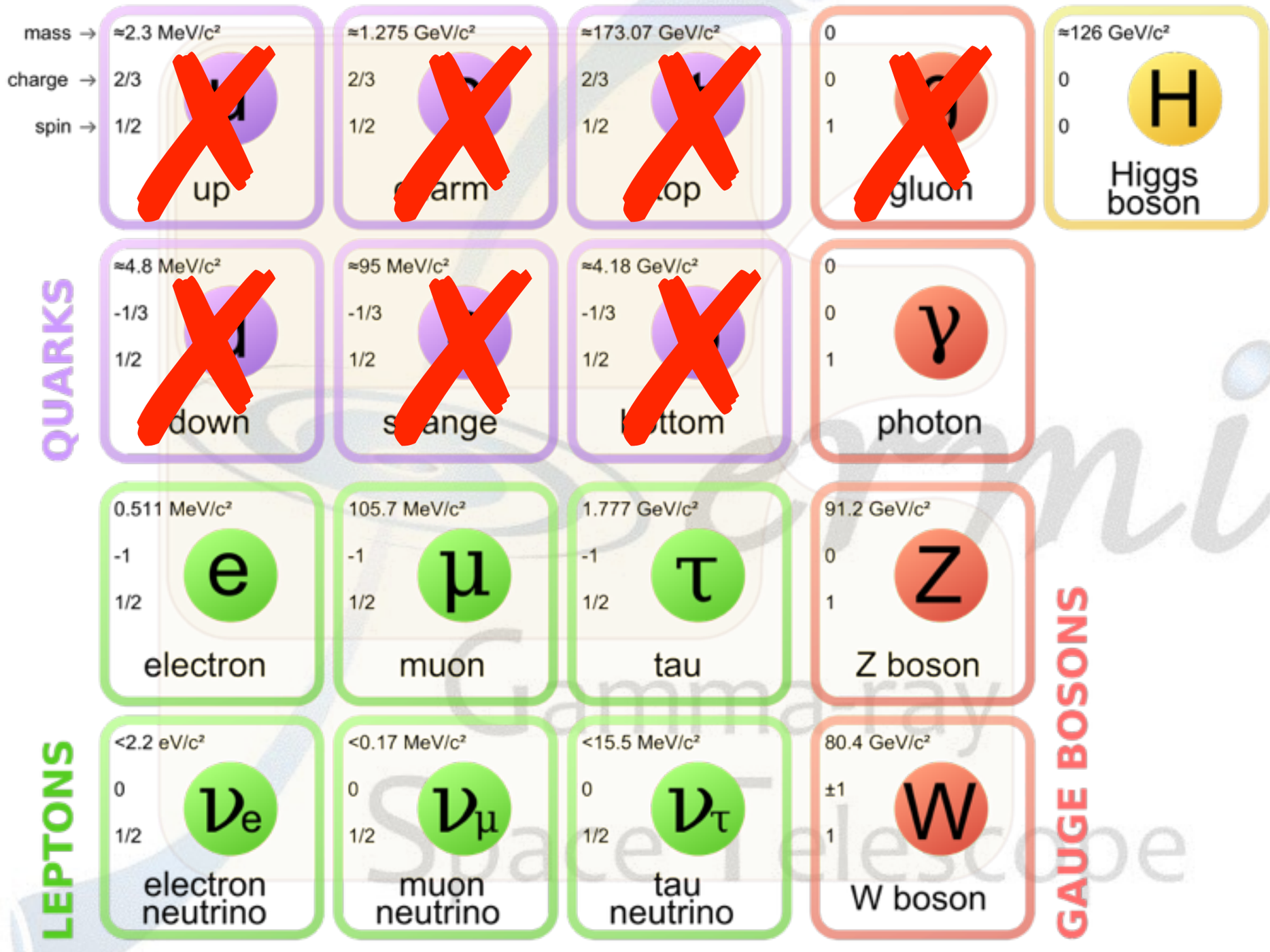

Potential Candidates

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Weak Scale

m~ 100 GeV
100× proton

Potential Candidates

Weak Scale

m~ 100 GeV
100× proton

~0.5 Caffeine molecule

Potential Candidates

Weak Scale

m~ 100 GeV
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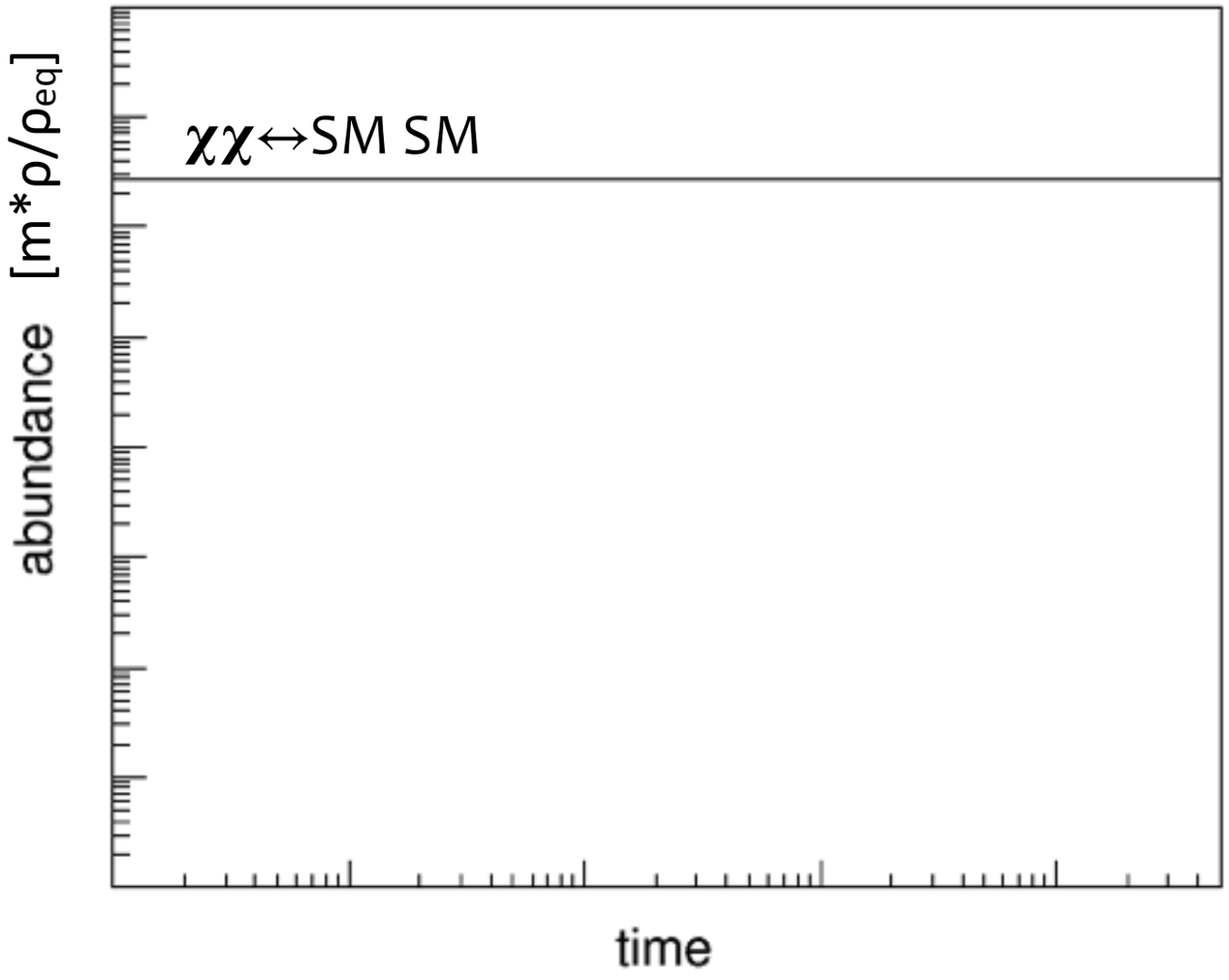
Portrait of a Candidate

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

Portrait of a Candidate

Cosmology and Thermodynamics

DM = χ



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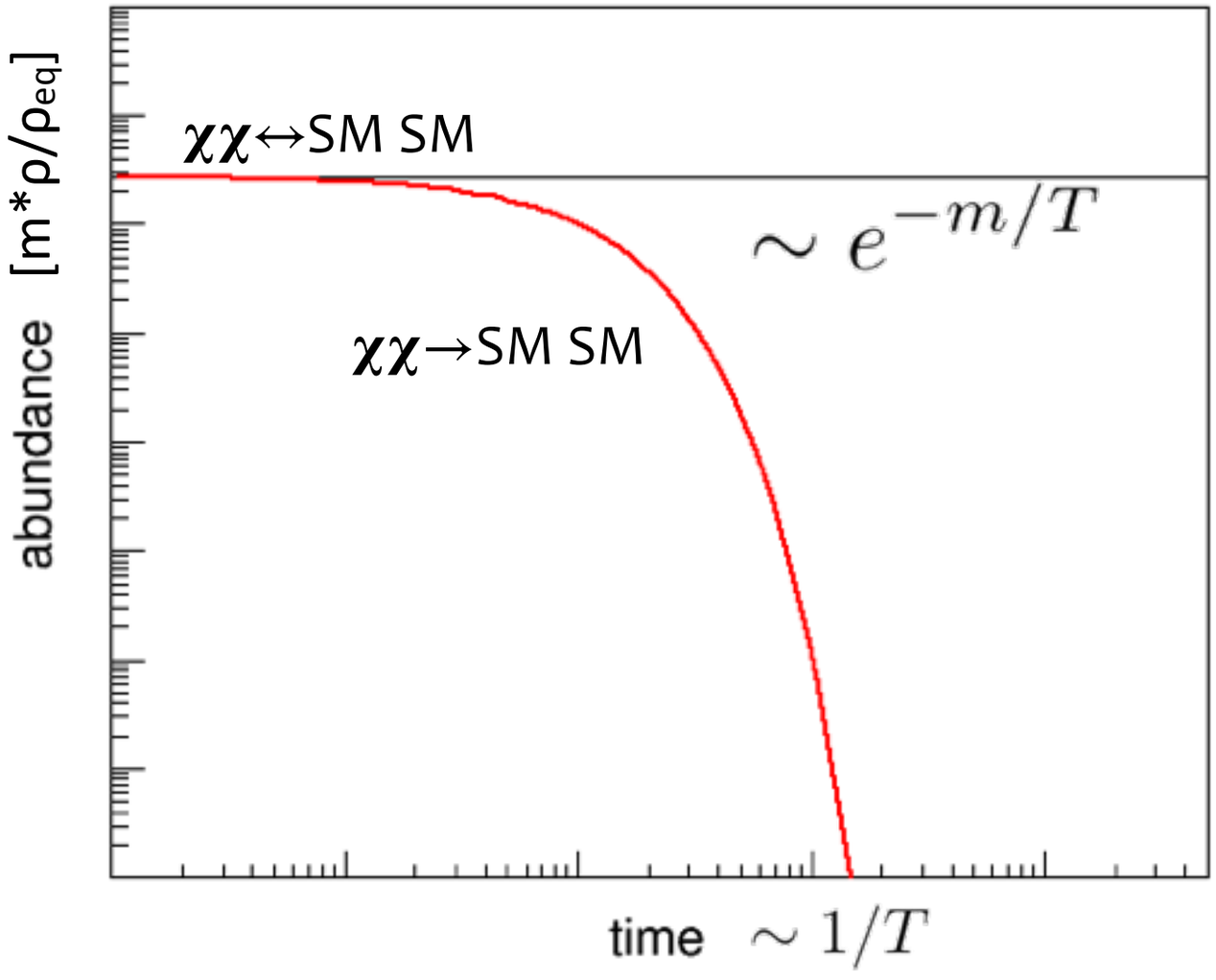

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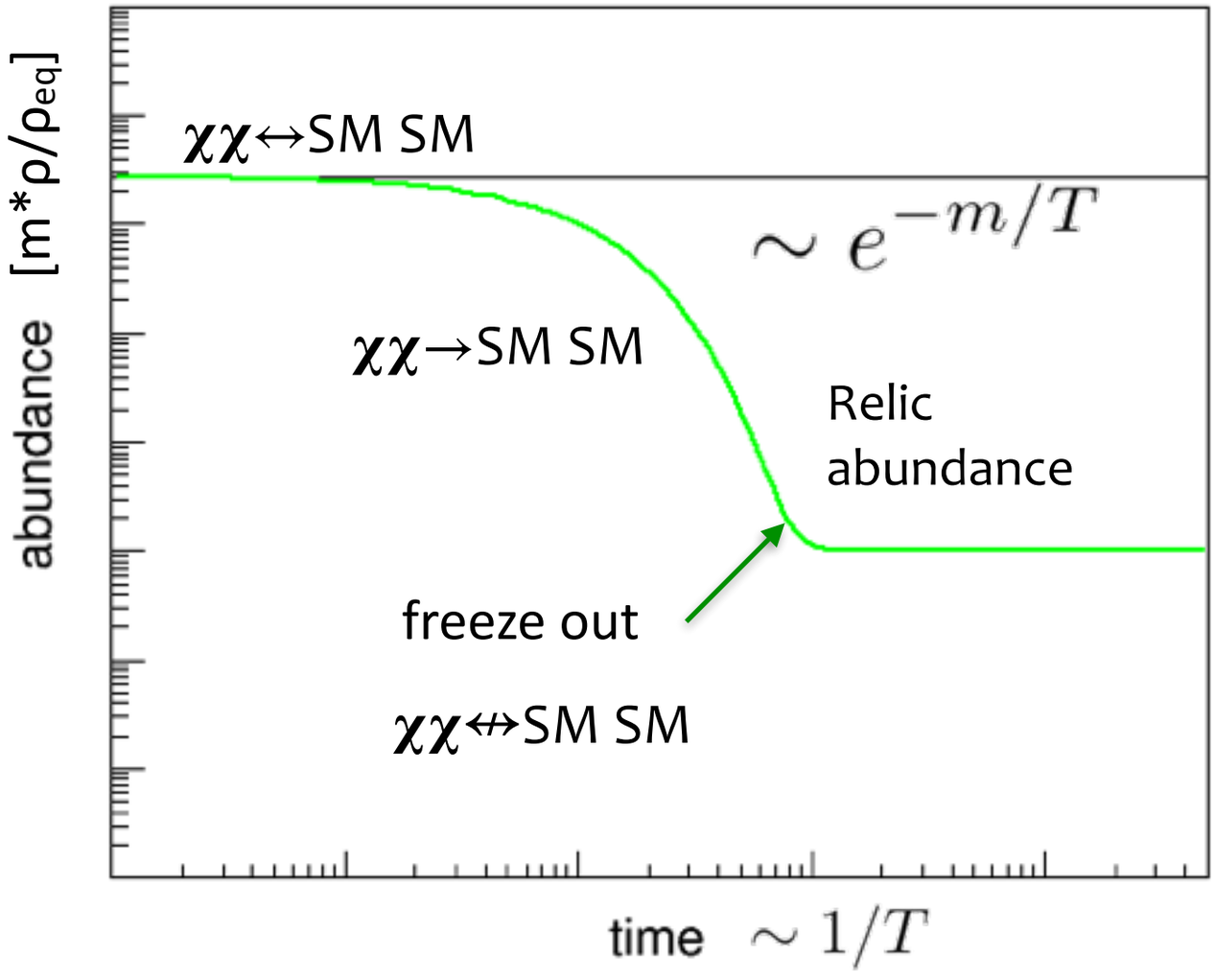

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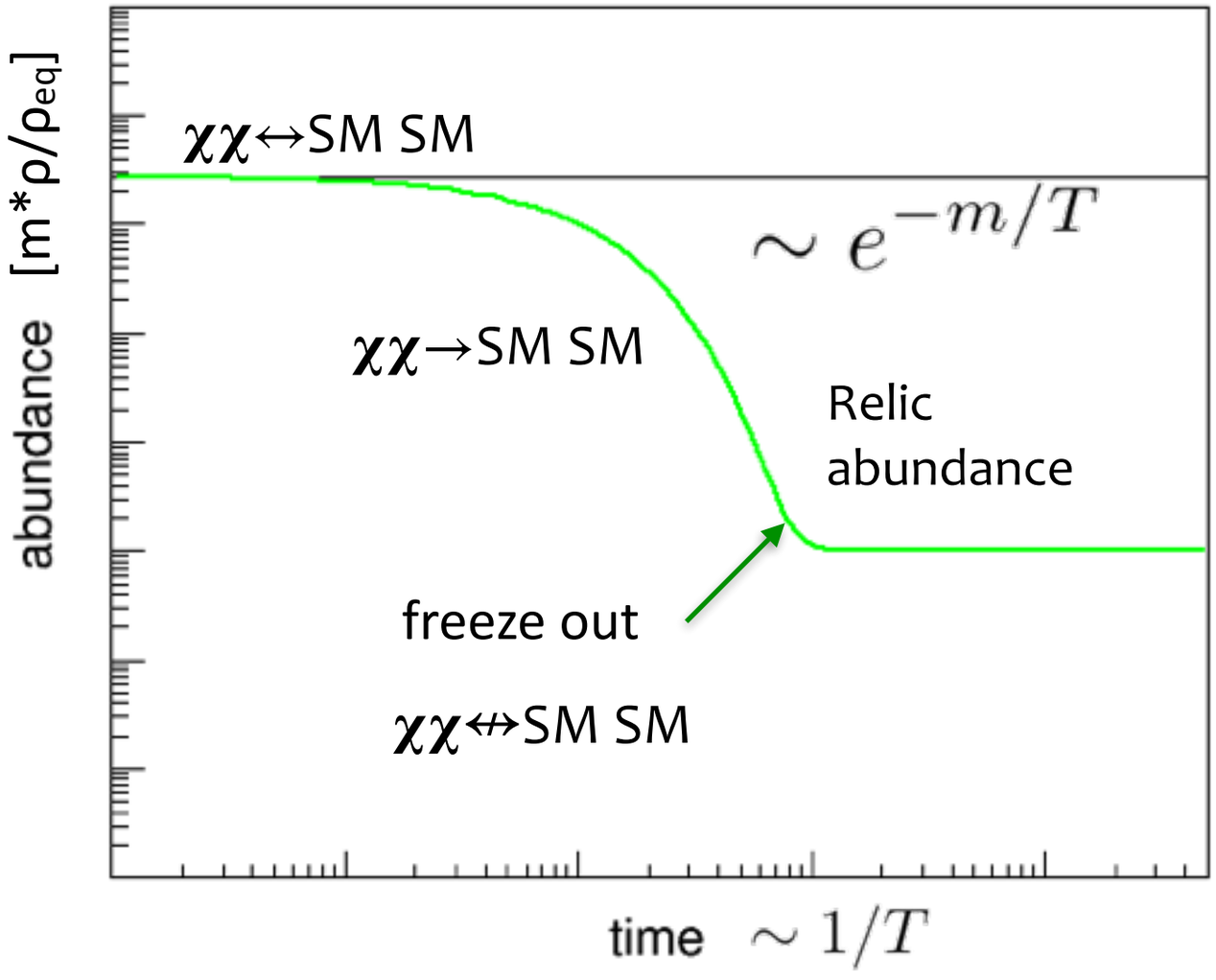

Abundance

$\langle\sigma v\rangle n_{eq} \sim H$

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

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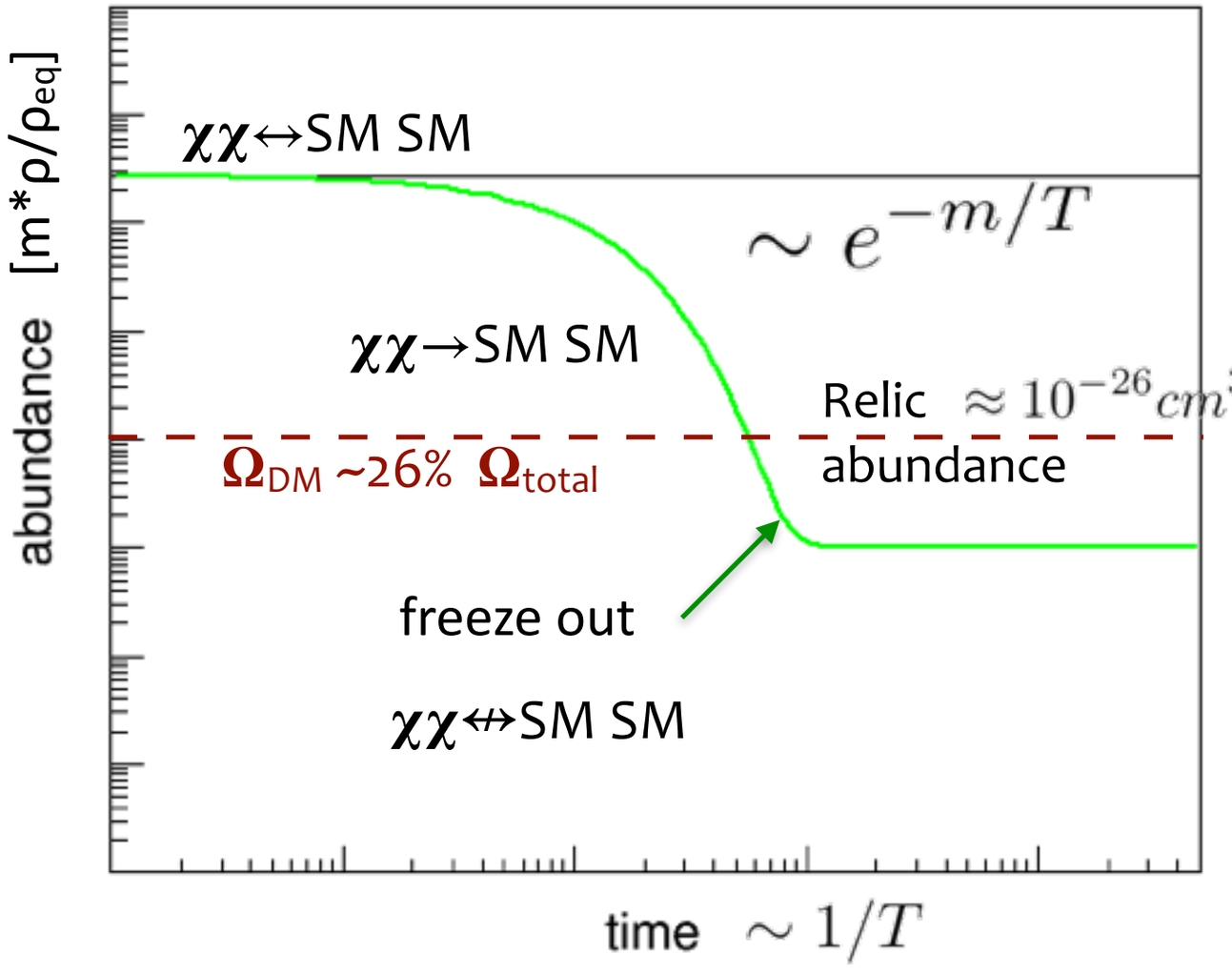

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Particle Physics

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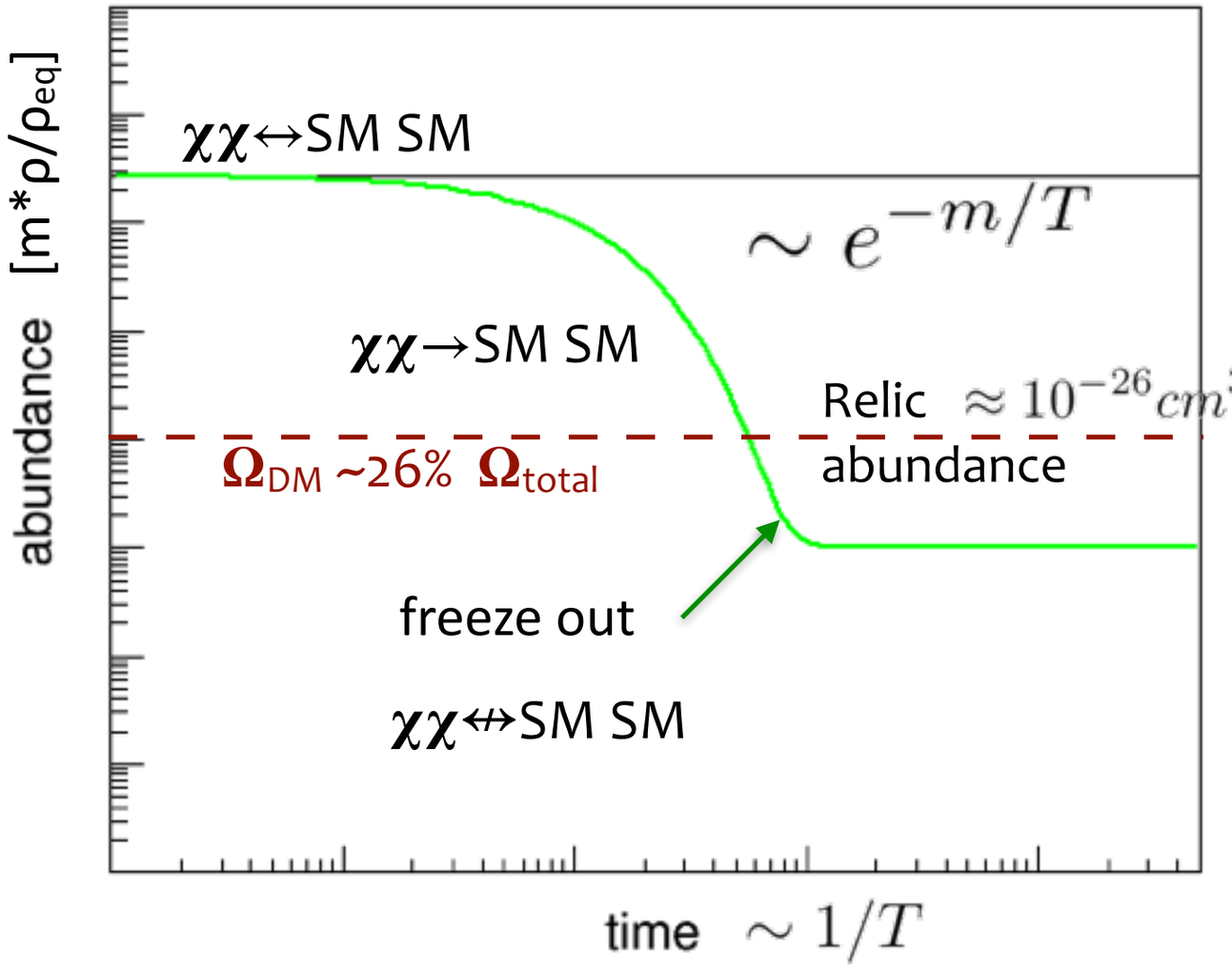

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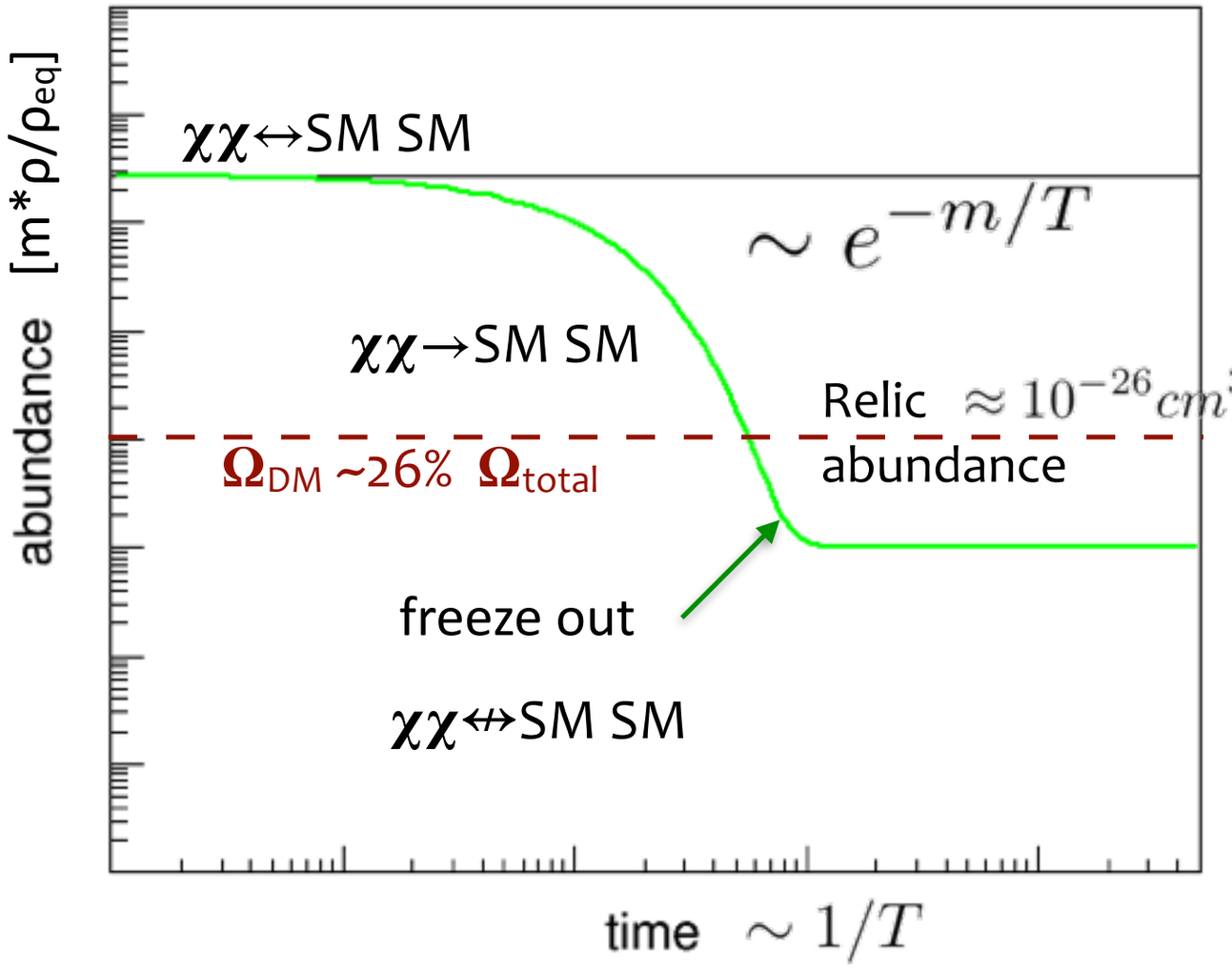
Weak (σ): 10^{-36} cm^2

velocity (v) @ freeze out: 10^5 km/s



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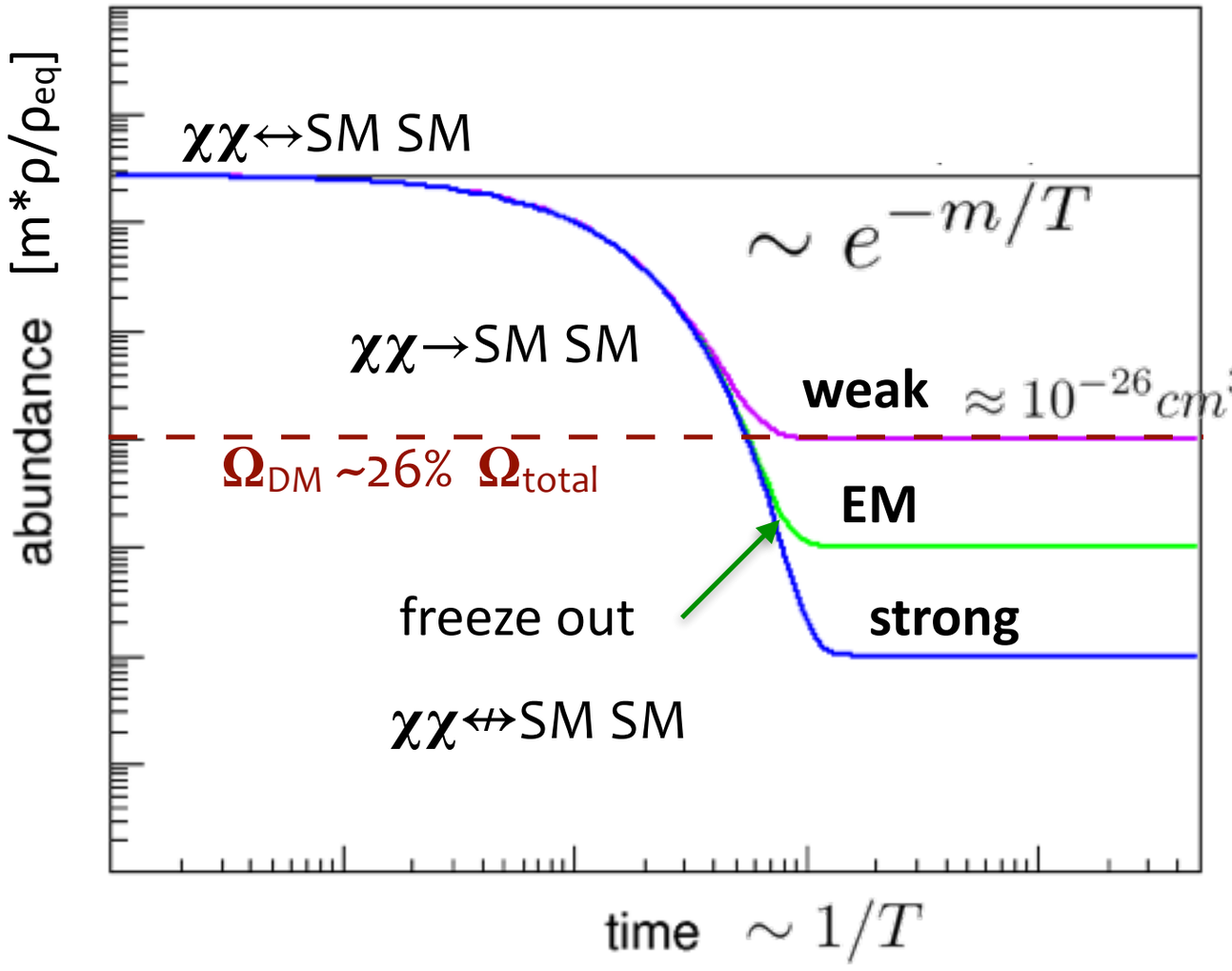

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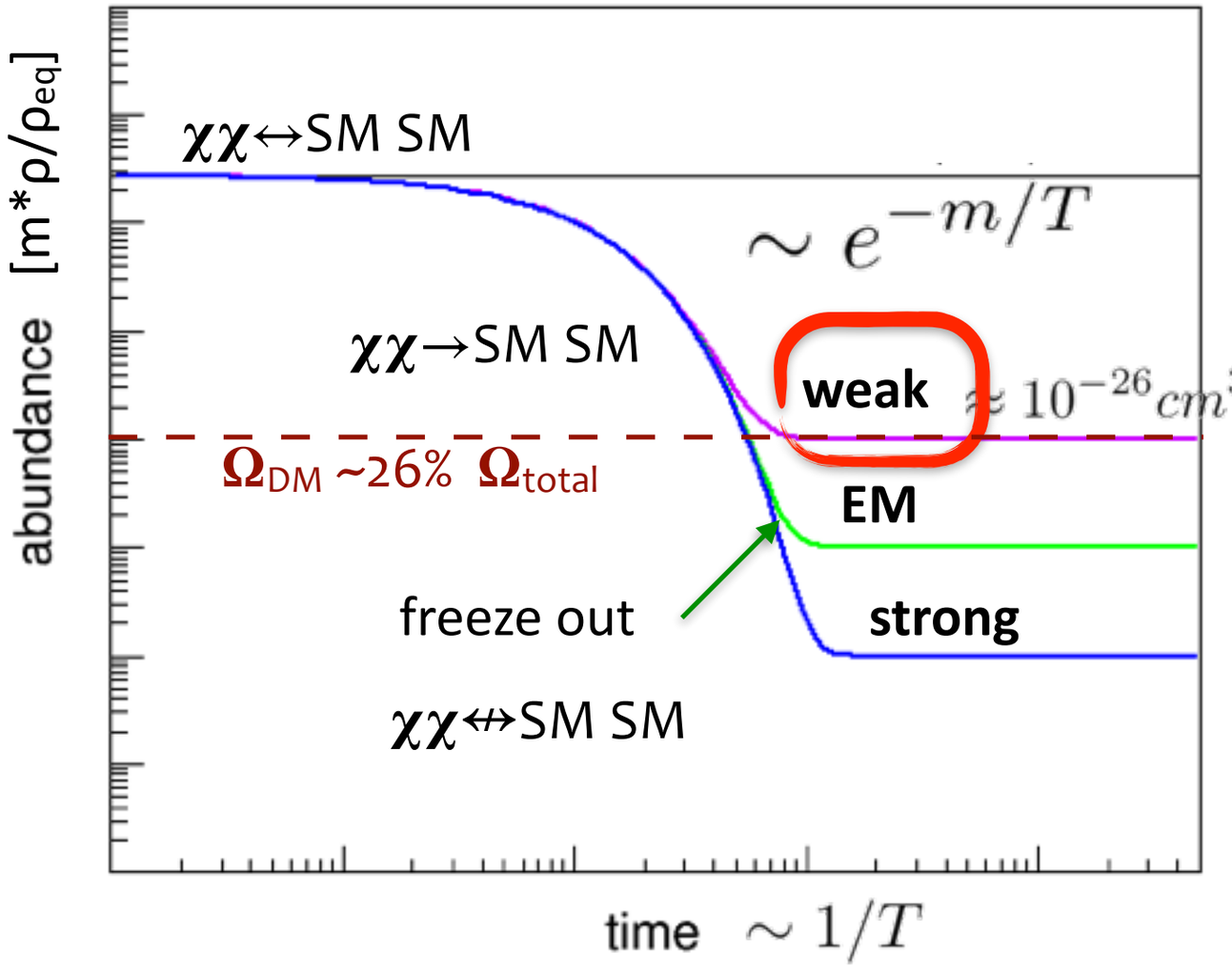

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Weakly Interacting Massive Particles

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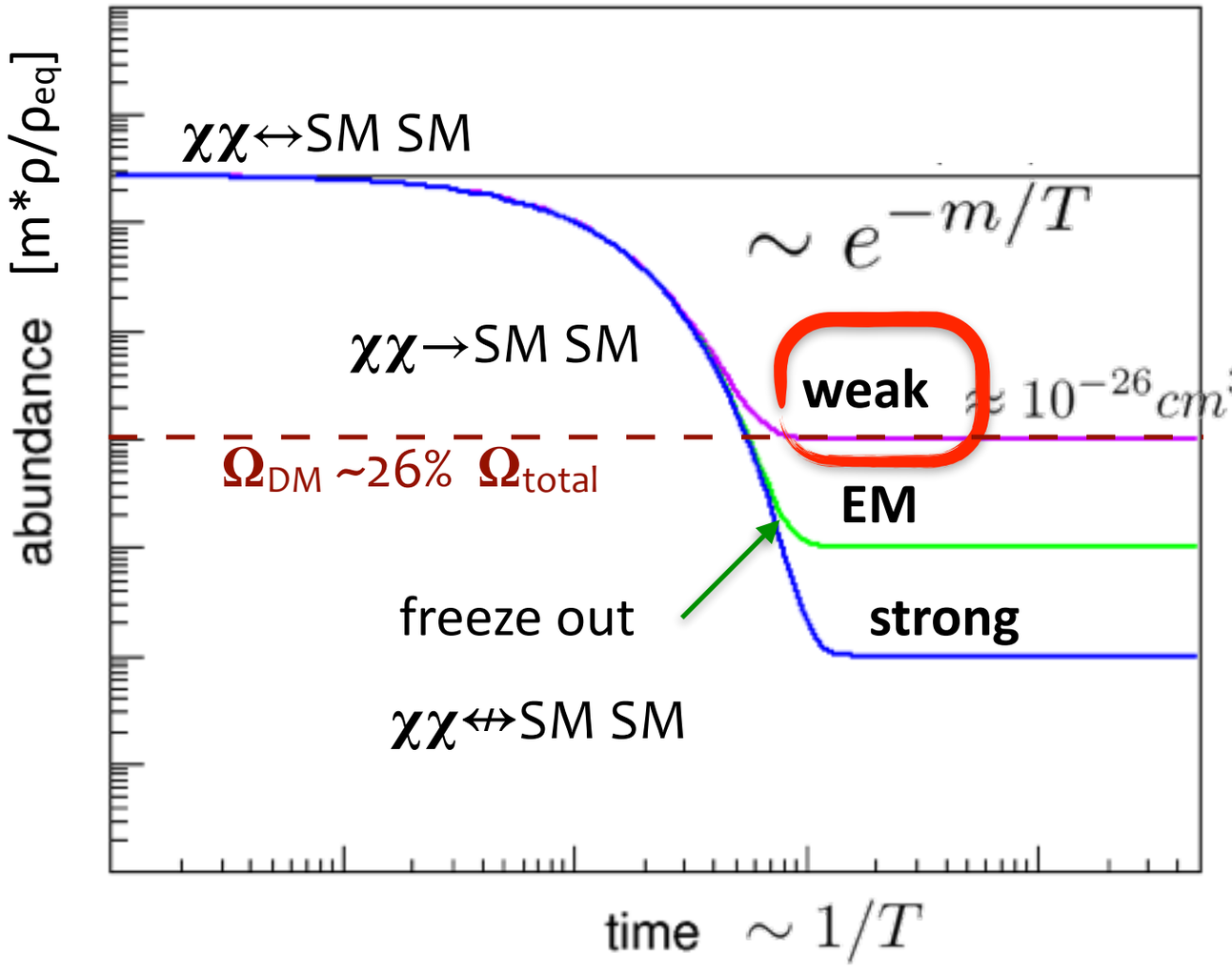

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The WIMP Miracle…

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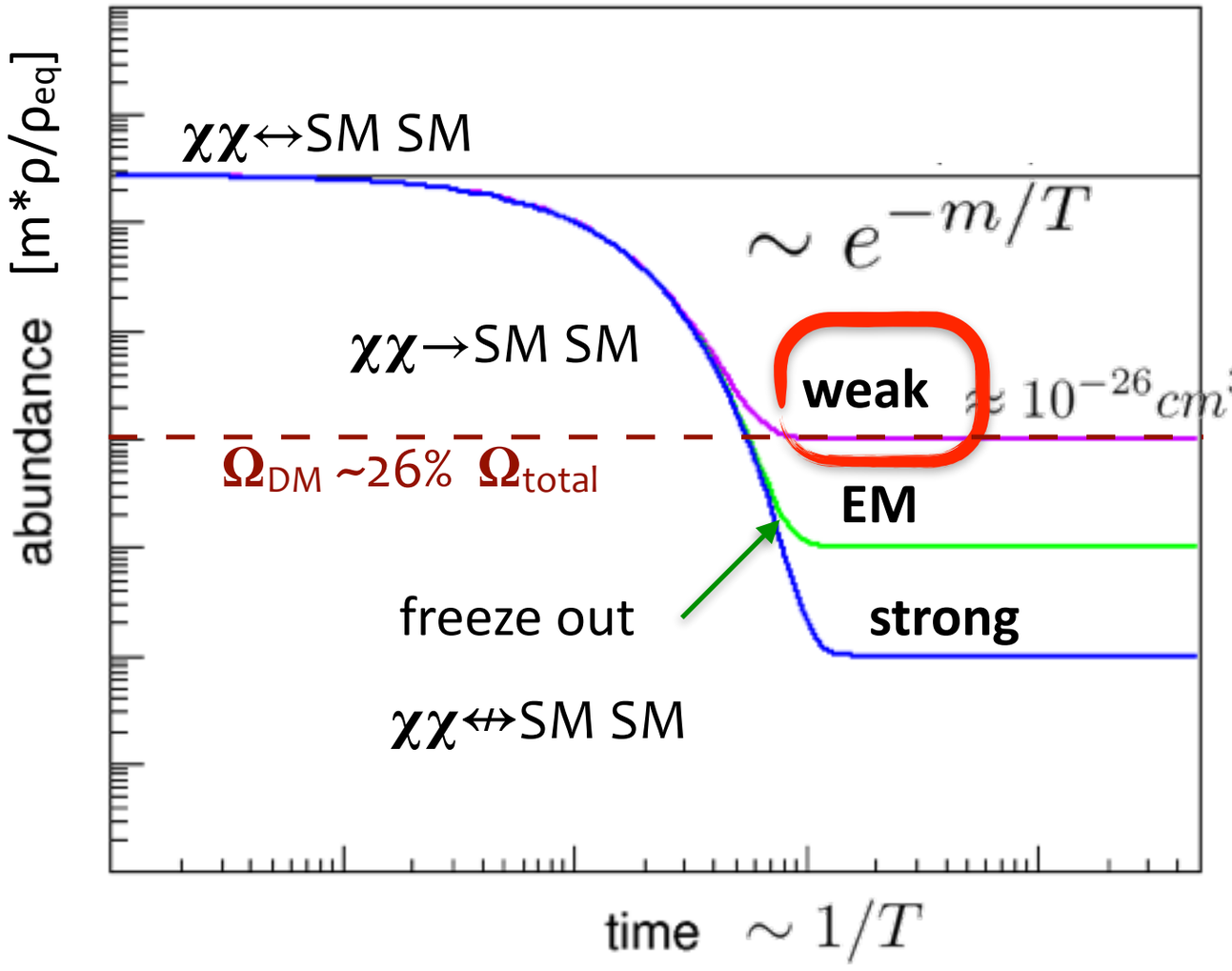

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G. Steigman, et al., Phys.Rev. D86 (2012) 023506

Portrait of a Candidate

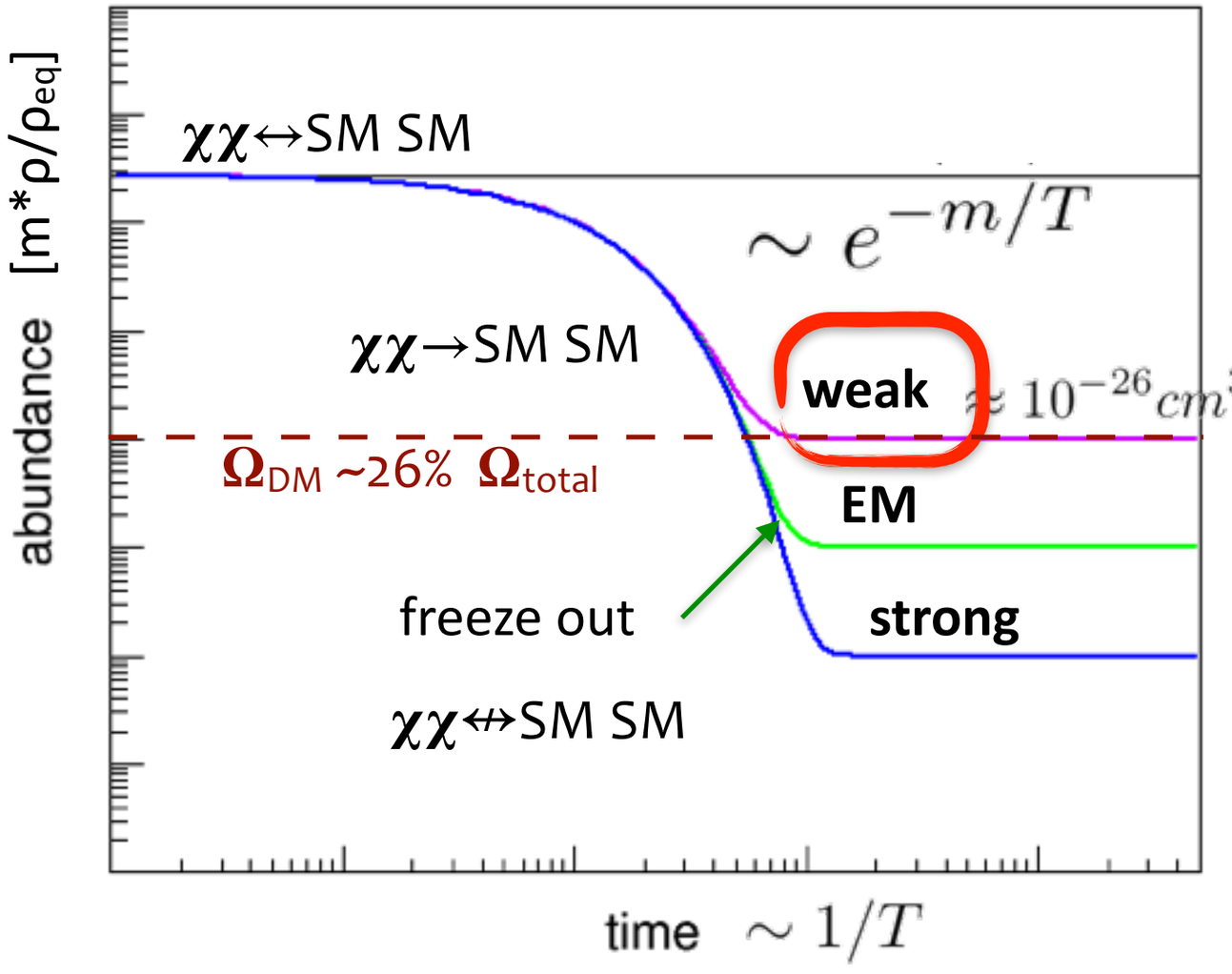
The WIMP Coincidence

DM = χ

Weak (σ): 10^{-36} cm^2

velocity (v) @ freeze out: 10^5 km/s

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



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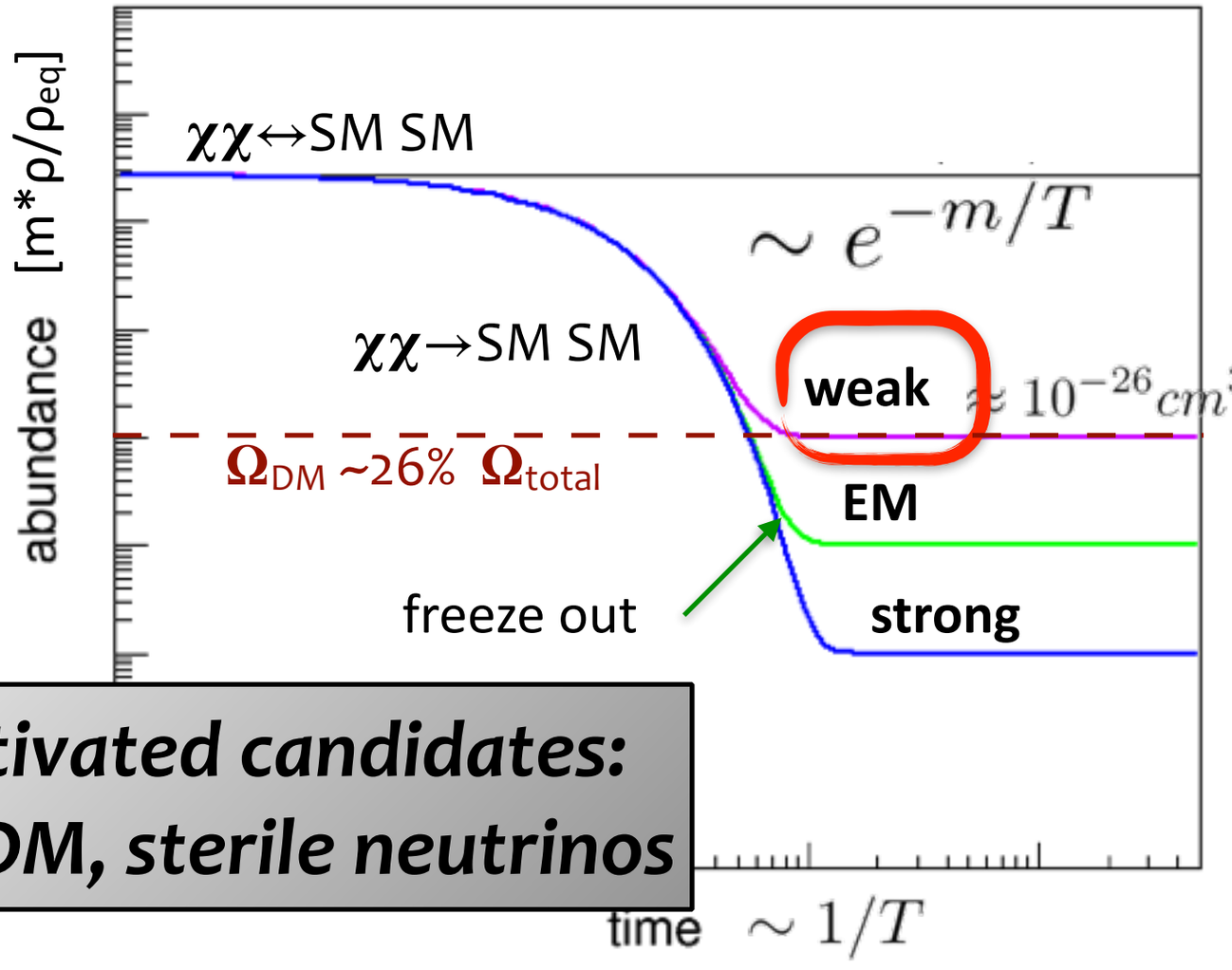

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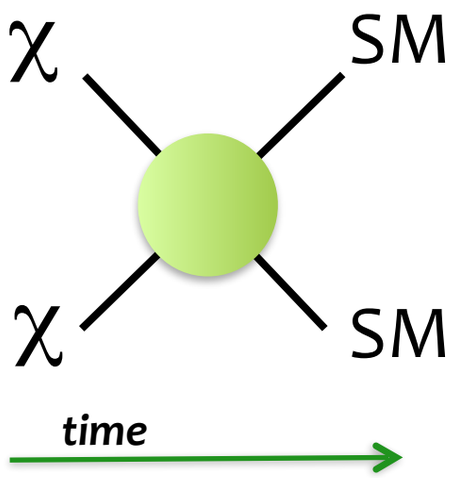
Weakly Interacting Massive Particles

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

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

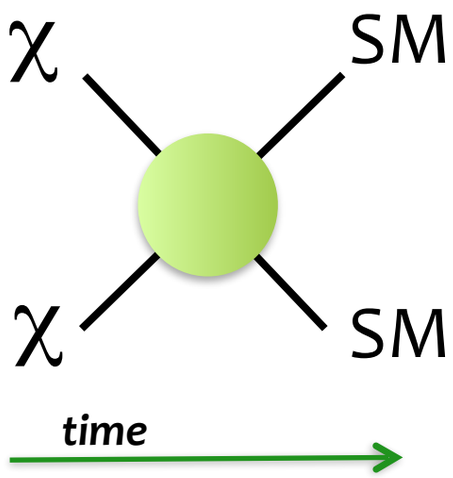
Detecting WIMP Dark Matter

Detecting WIMP Dark Matter



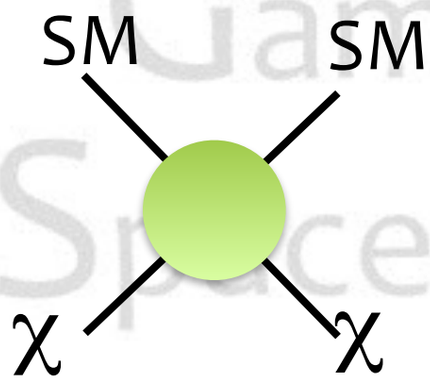
Indirect Detection

Detecting WIMP Dark Matter



Indirect Detection

Direct Detection



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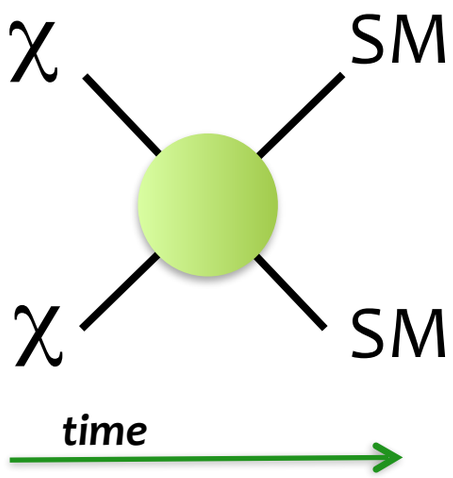

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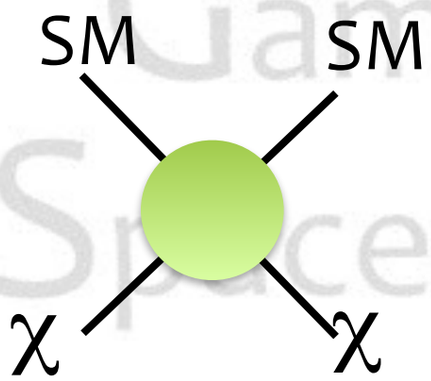
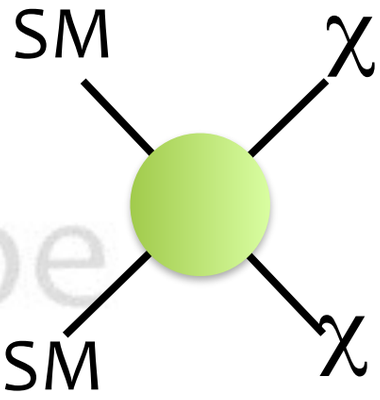


Collider



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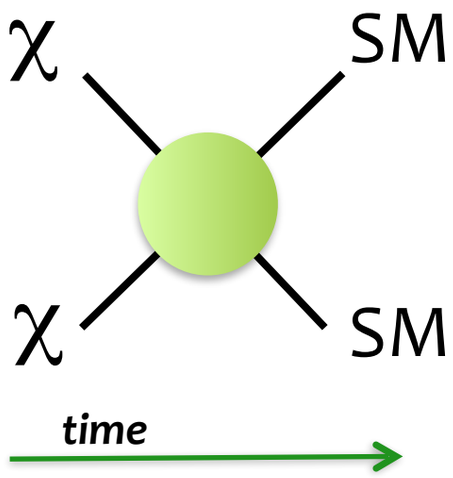
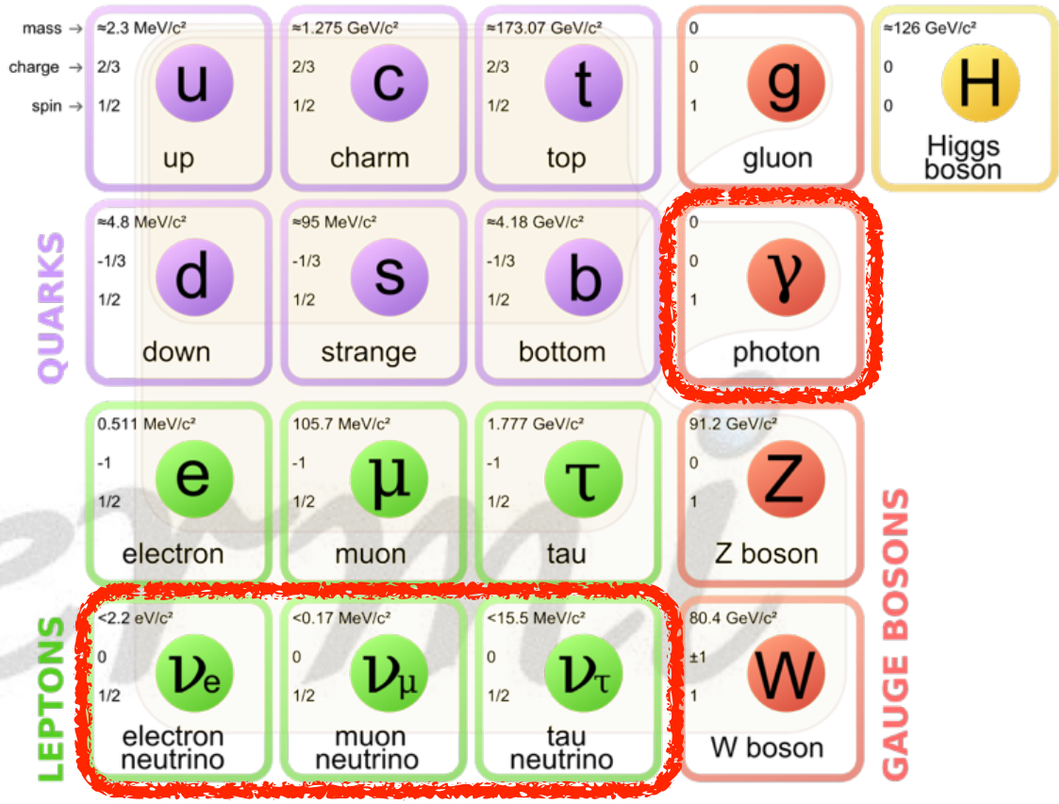


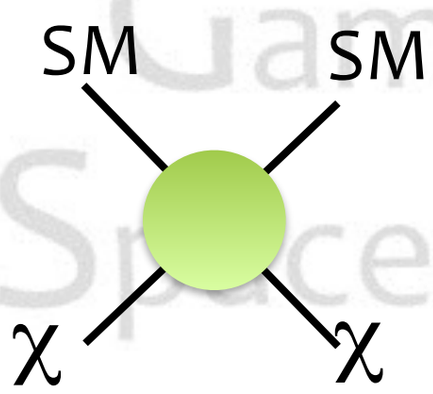
Indirect Detection

information about mass, point back to source

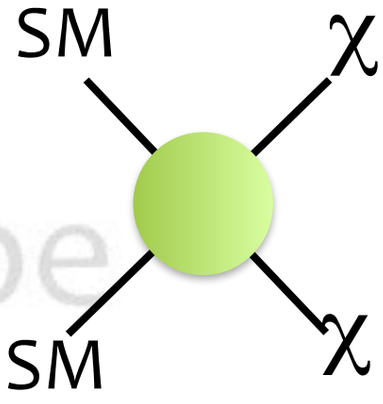
SM:



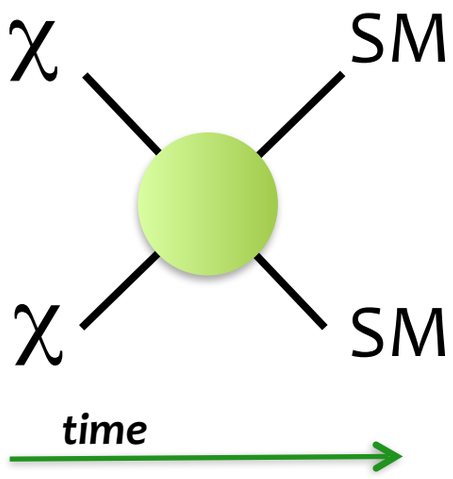
Direct Detection



Collider



Detecting WIMP Dark Matter



Indirect Detection

information about mass, point back to source

eventually can get to photons

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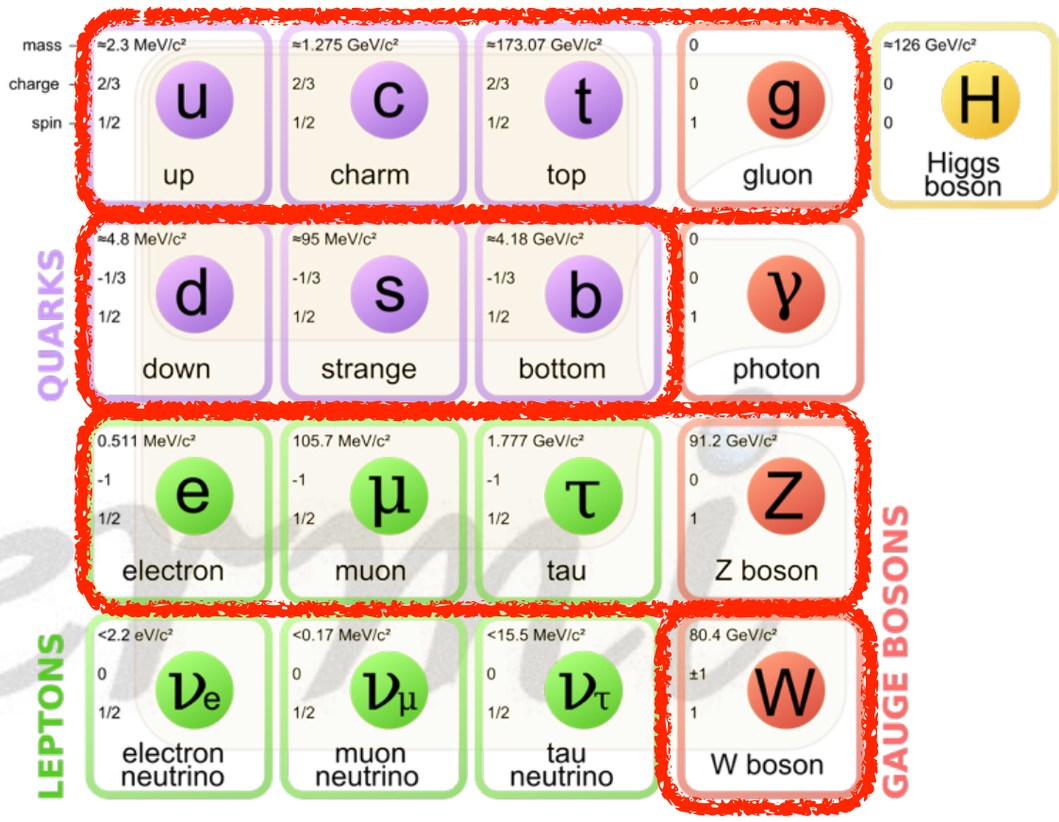

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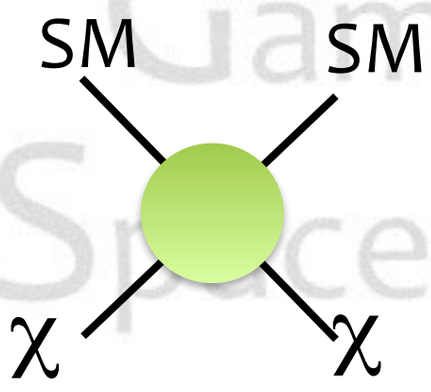
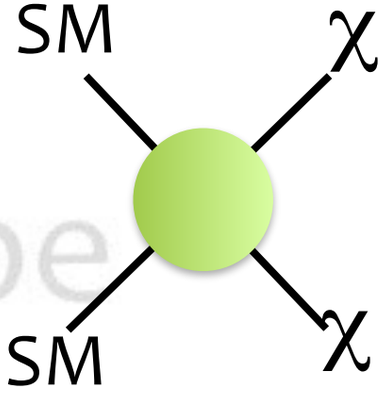


Collider



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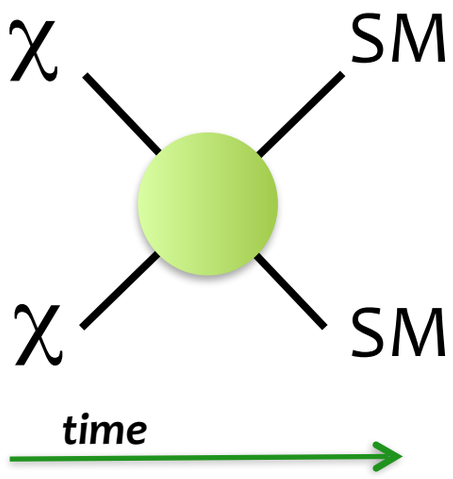

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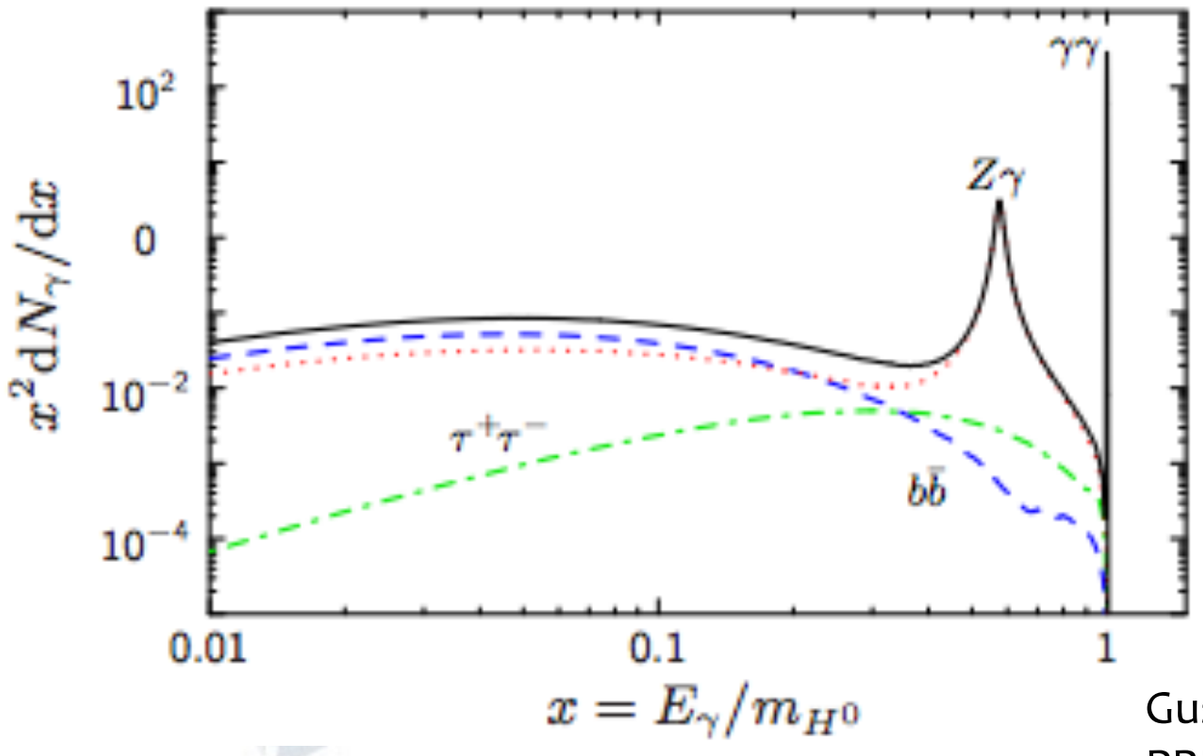

Gustafsson et al.
PRL 99.041301

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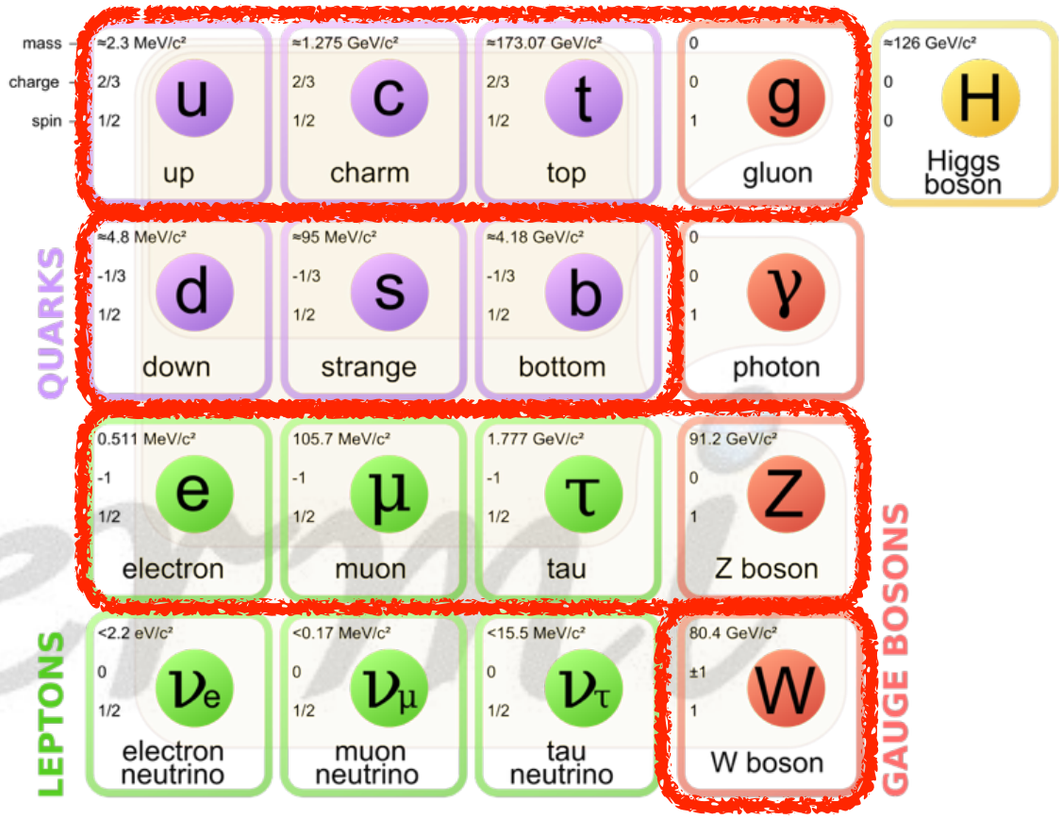

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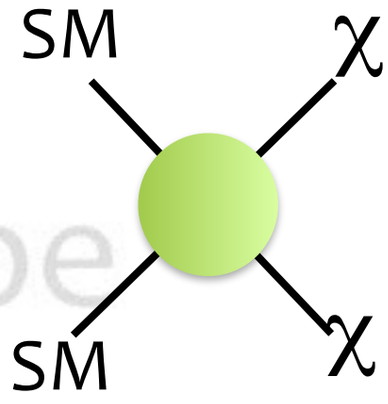
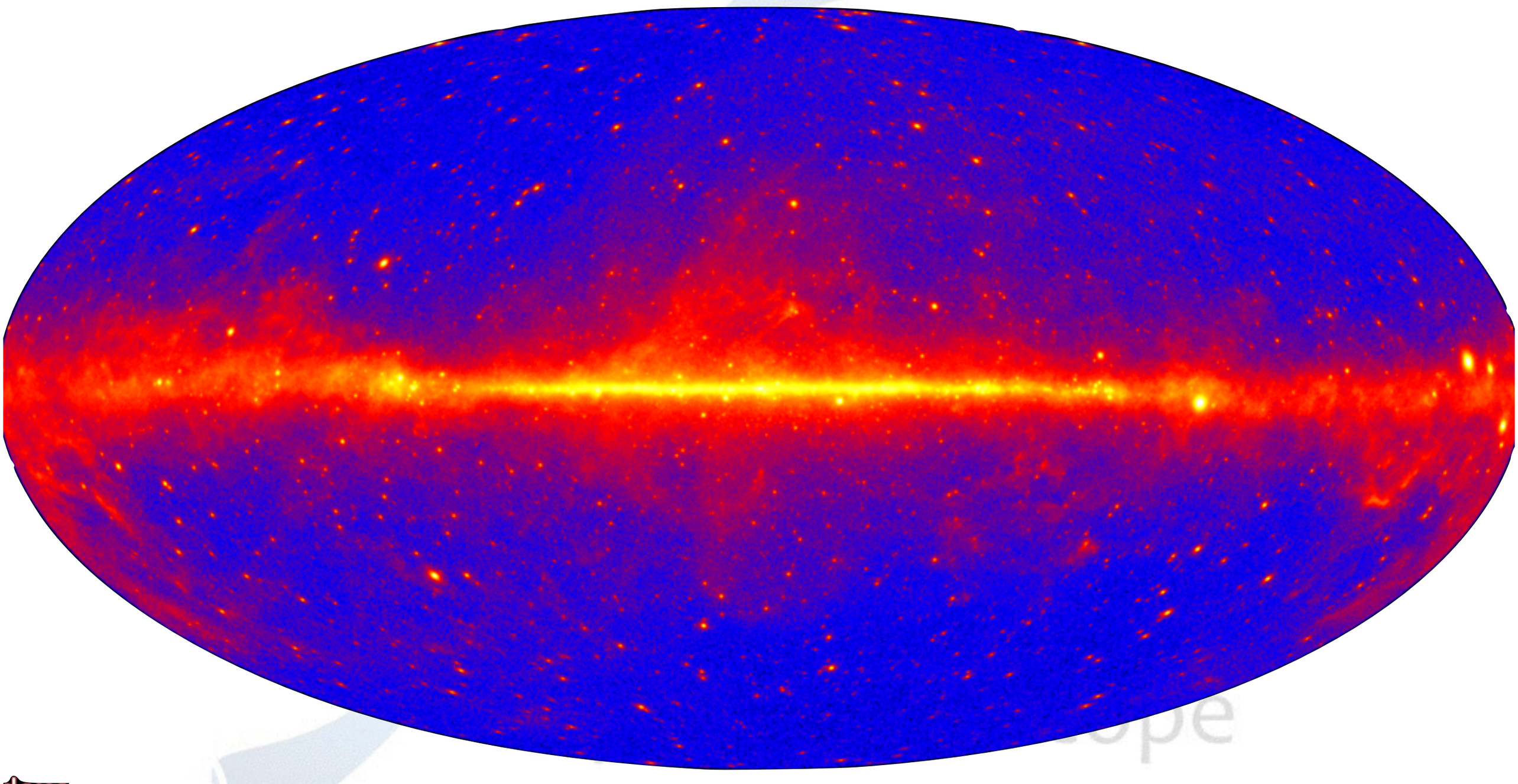
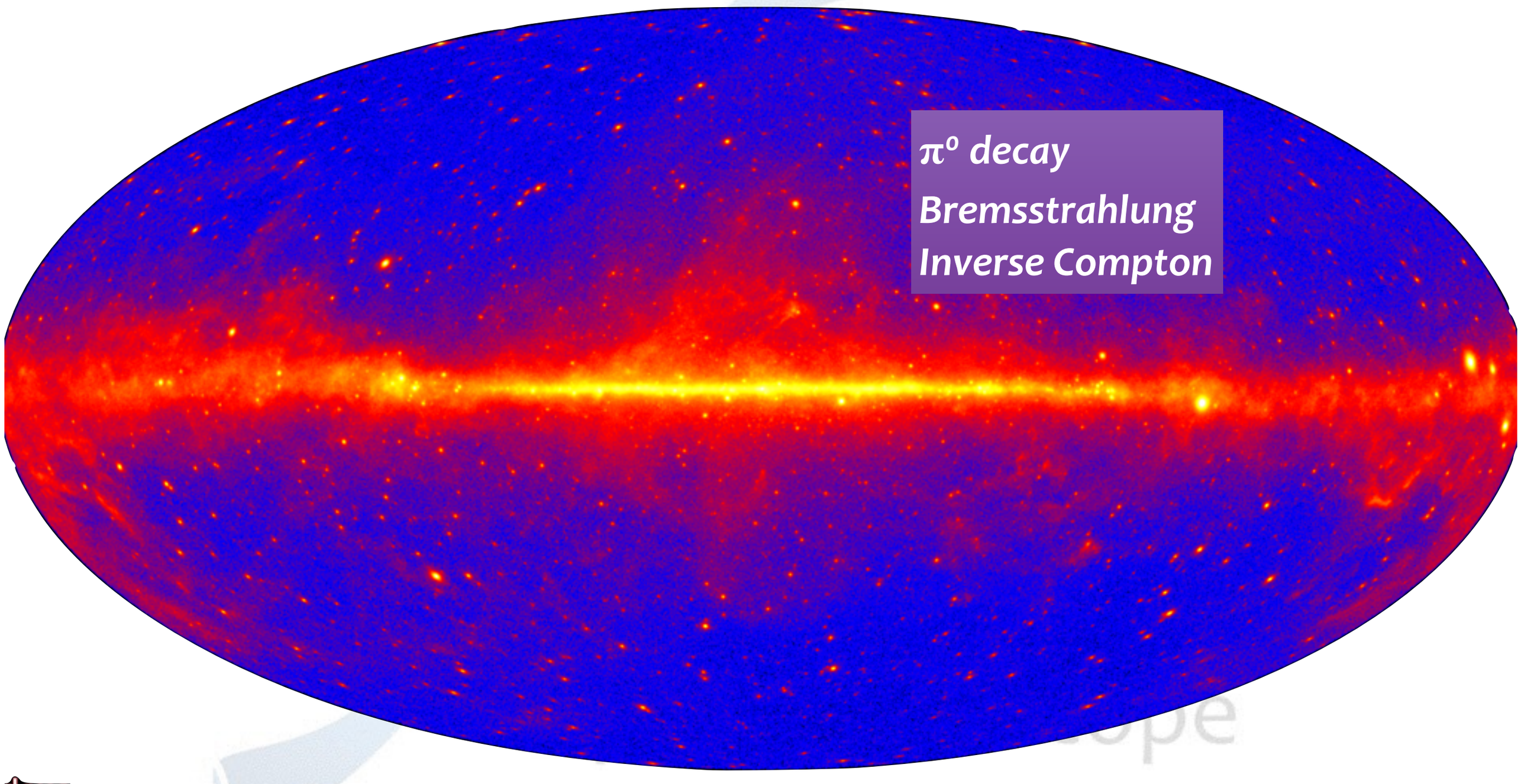


Fermi-LAT γ-ray sky



days

Fermi-LAT γ-ray sky



days

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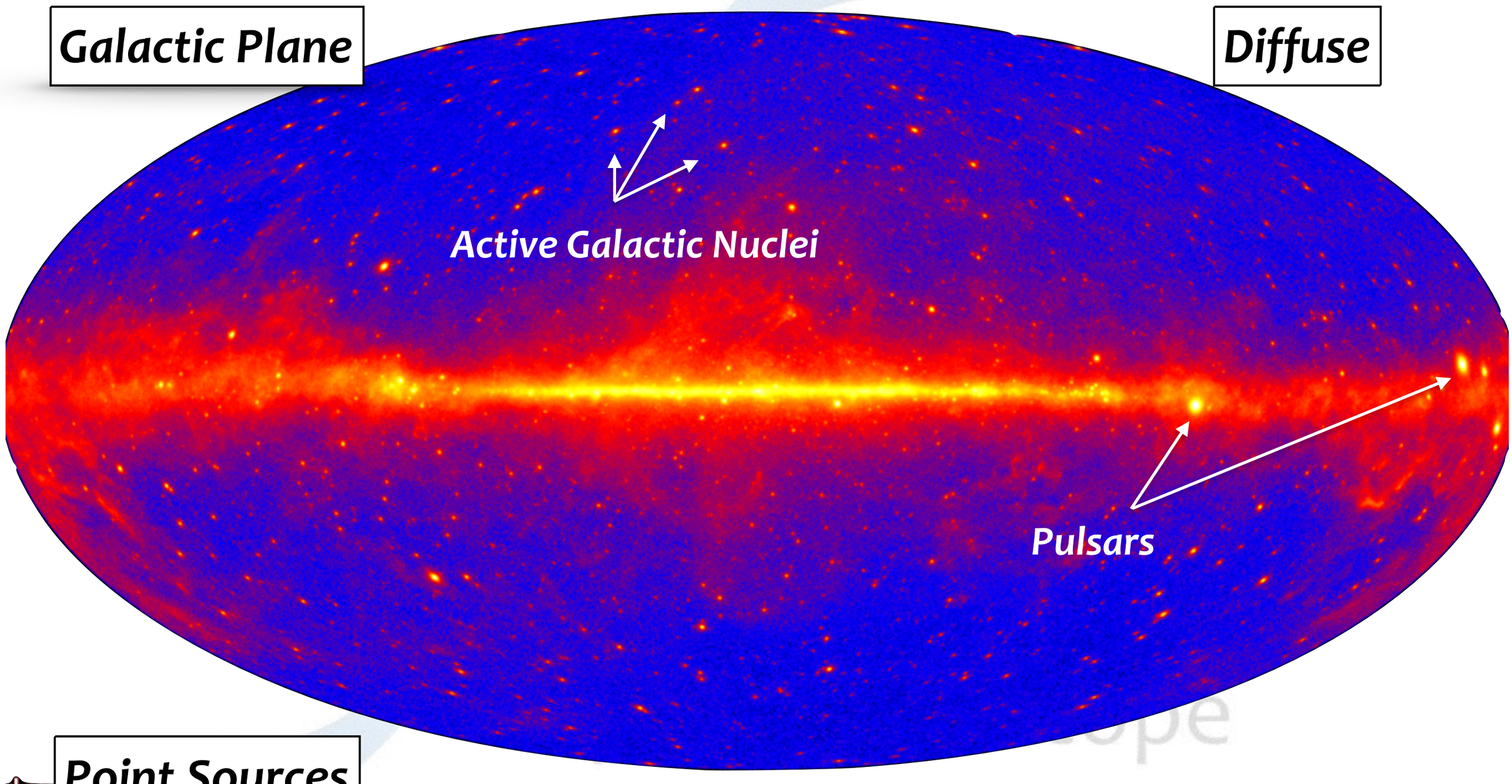

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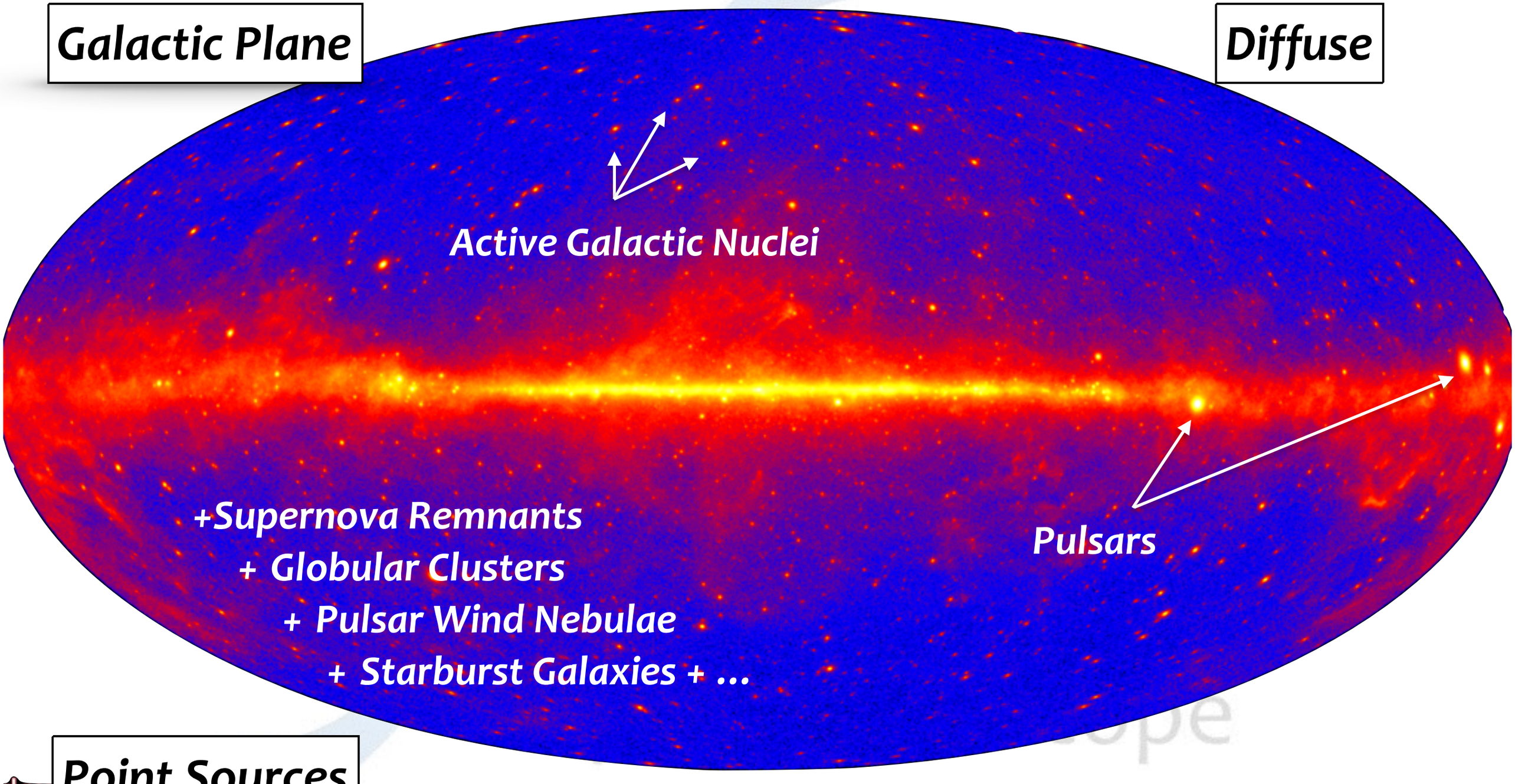
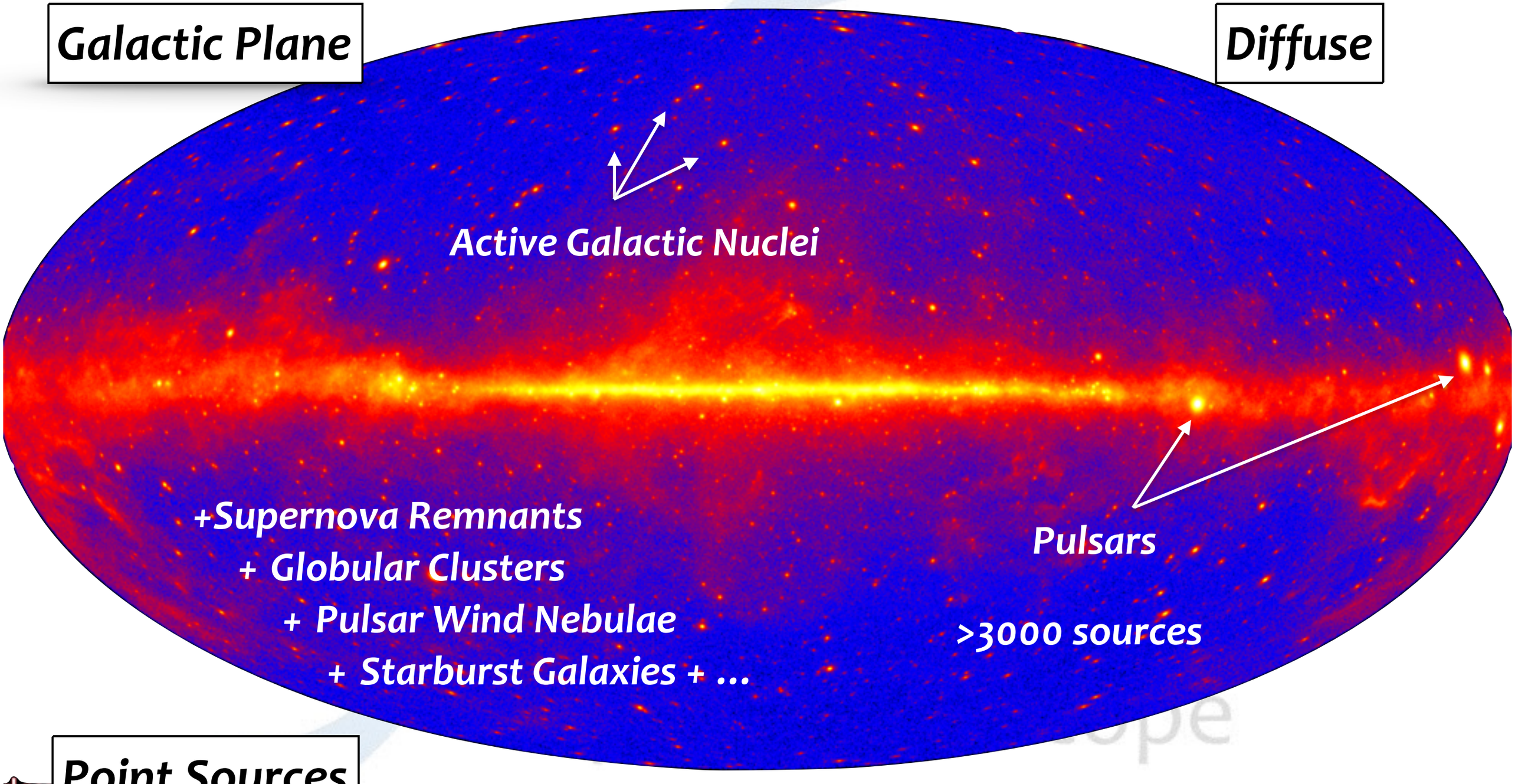


Point Sources

Fermi-LAT γ-ray sky



Point Sources

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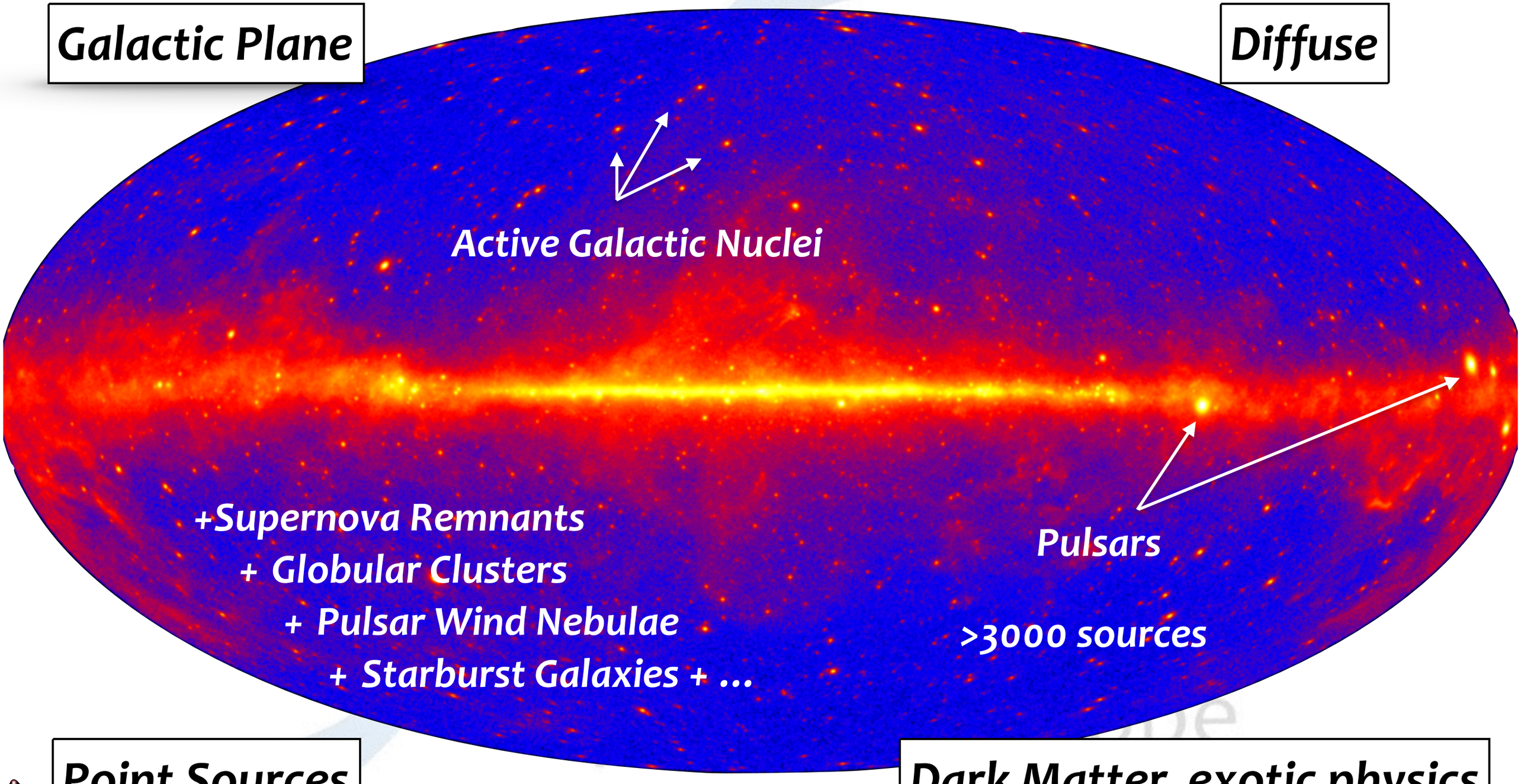
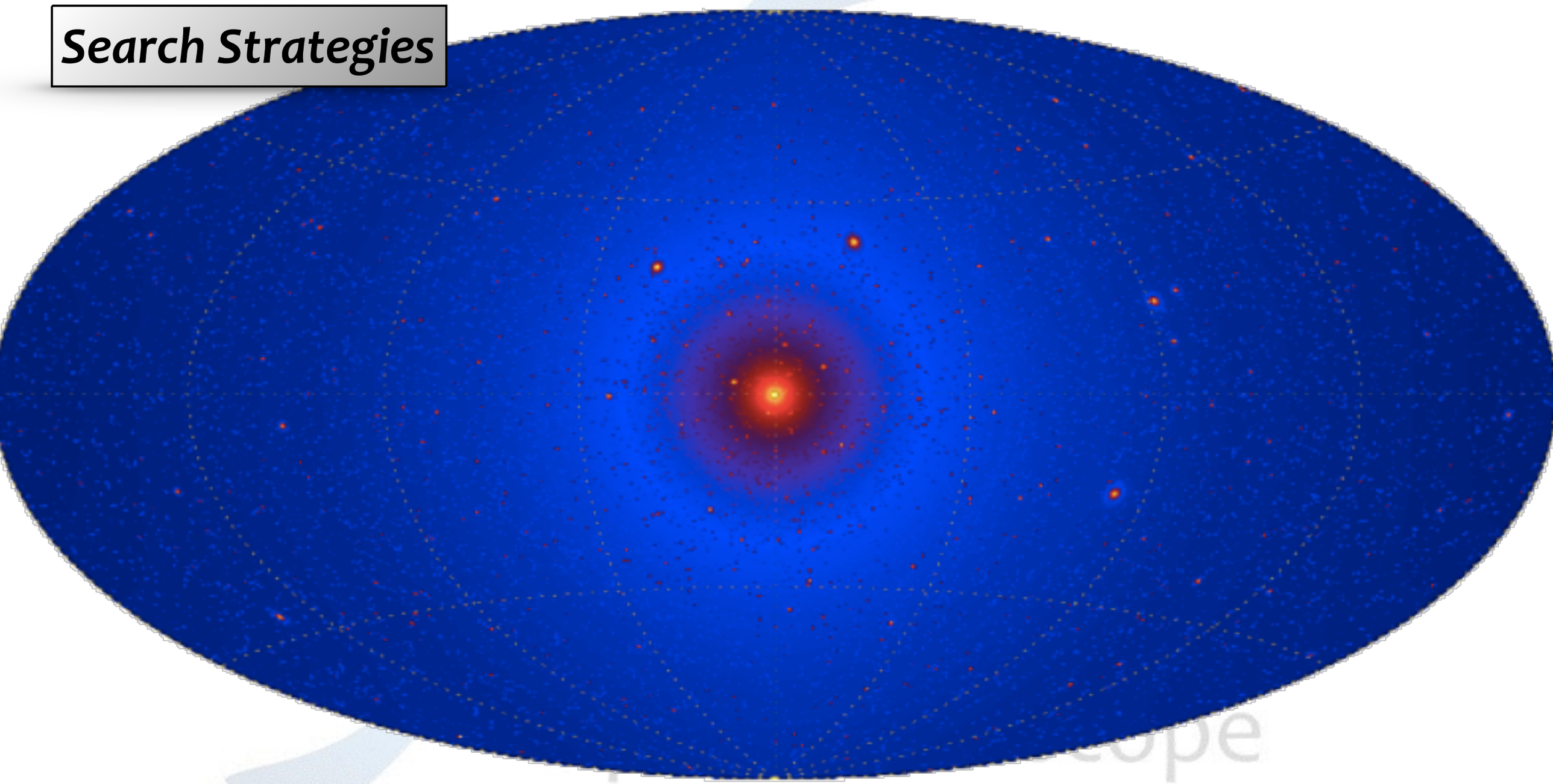


Point Sources

Dark Matter, exotic physics

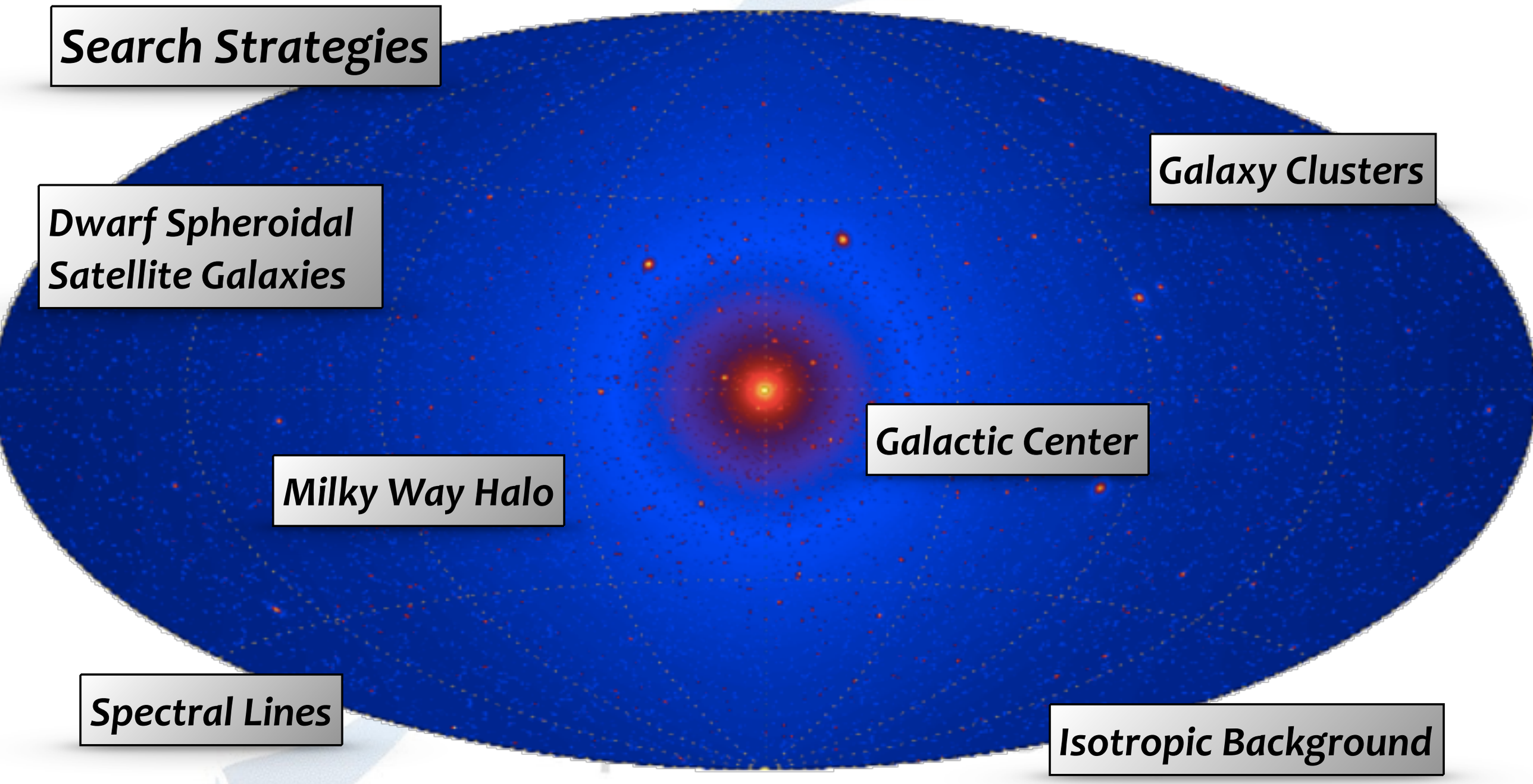
Dark Matter Distribution

Search Strategies



L. Pieri et al., PRD 83 023518 (2011)

Dark Matter Distribution



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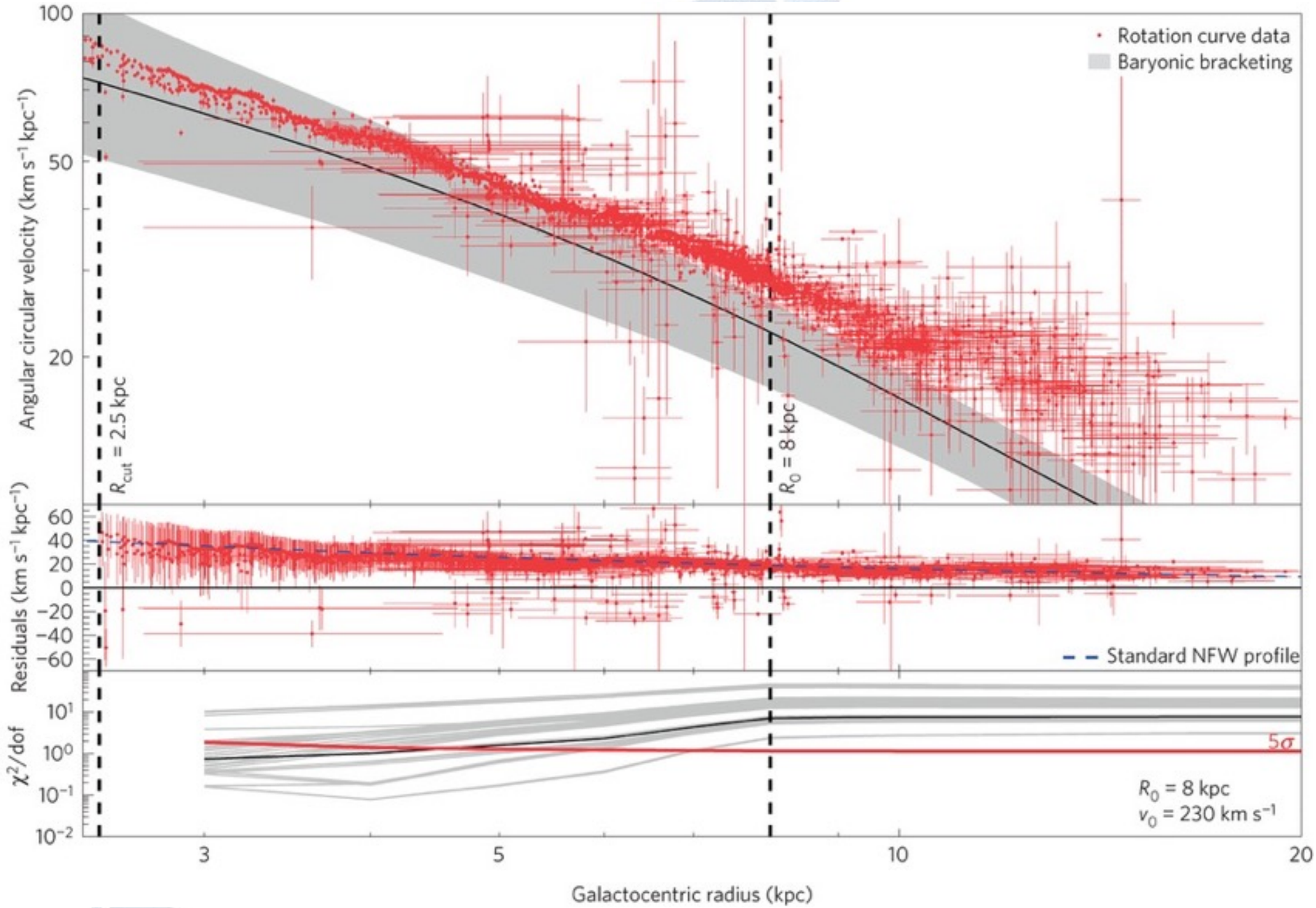
Galactic Center



F. Iocco, Pato, Bertone, Nature Physics 11, 245–248 (2015)

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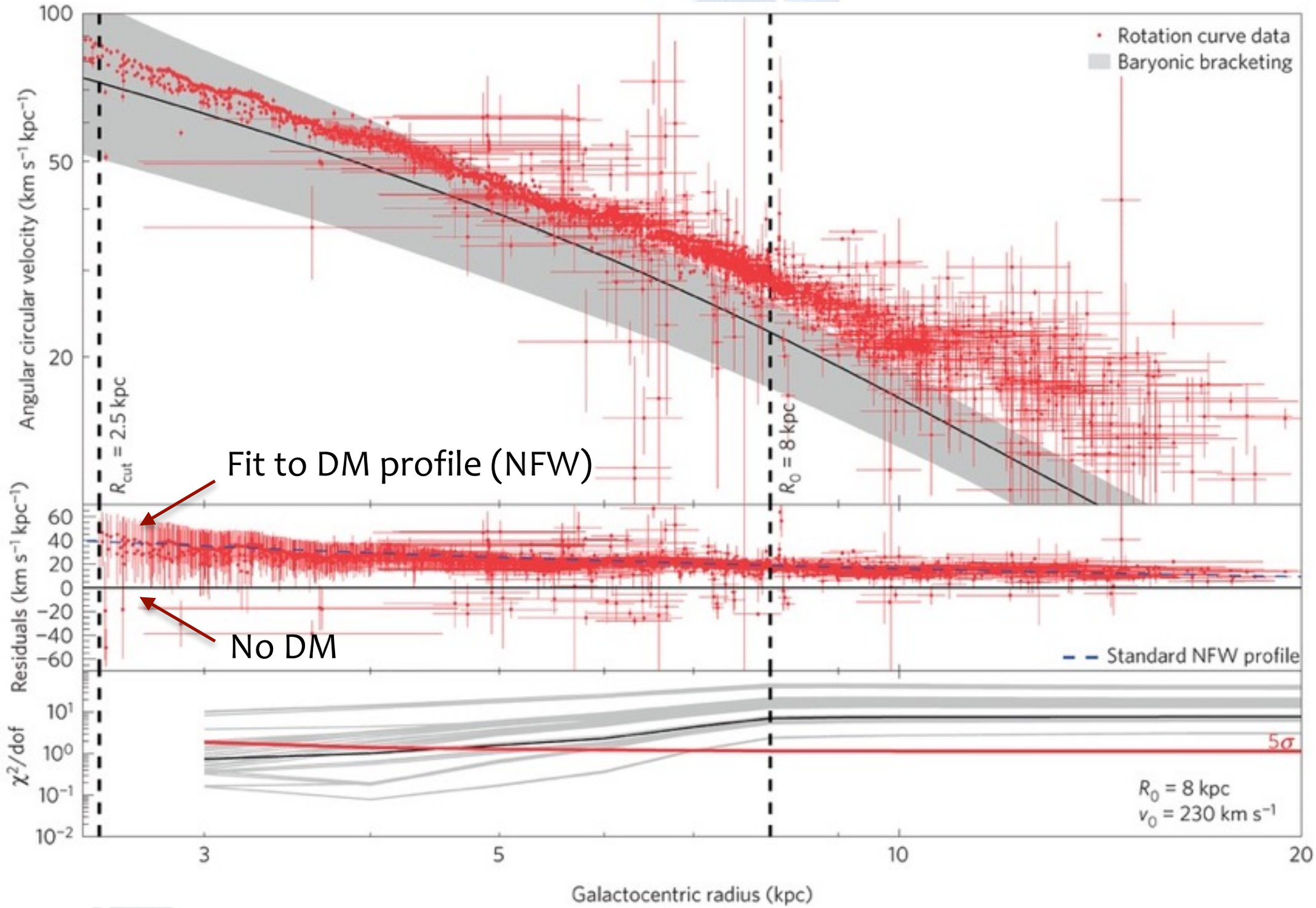

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Galactic Center

Why is the Galactic Center so hard to observe?

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

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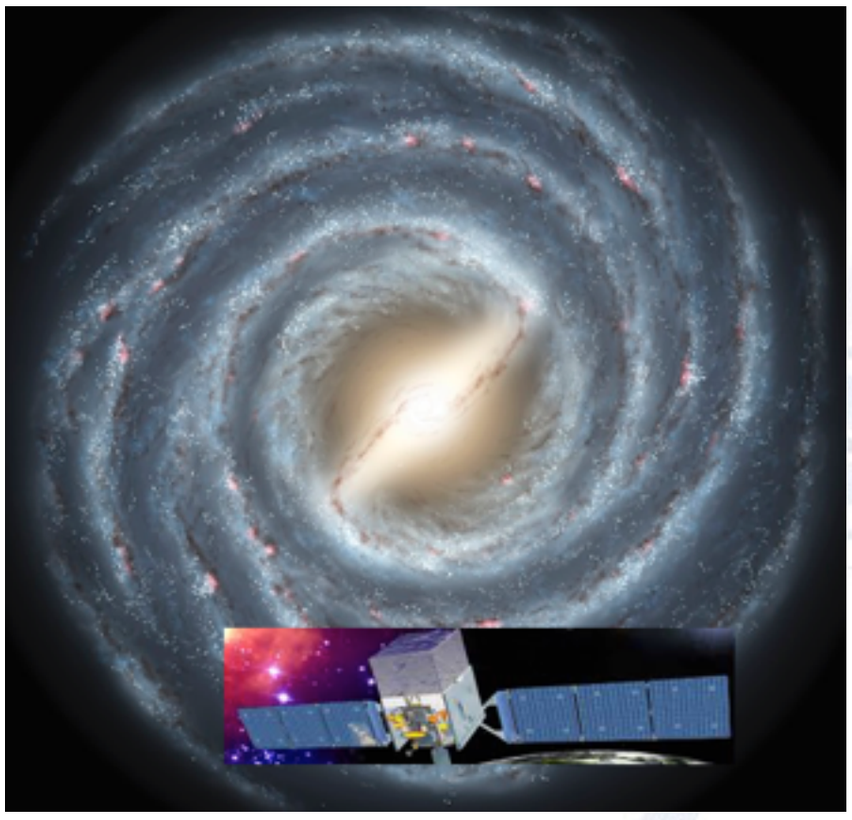

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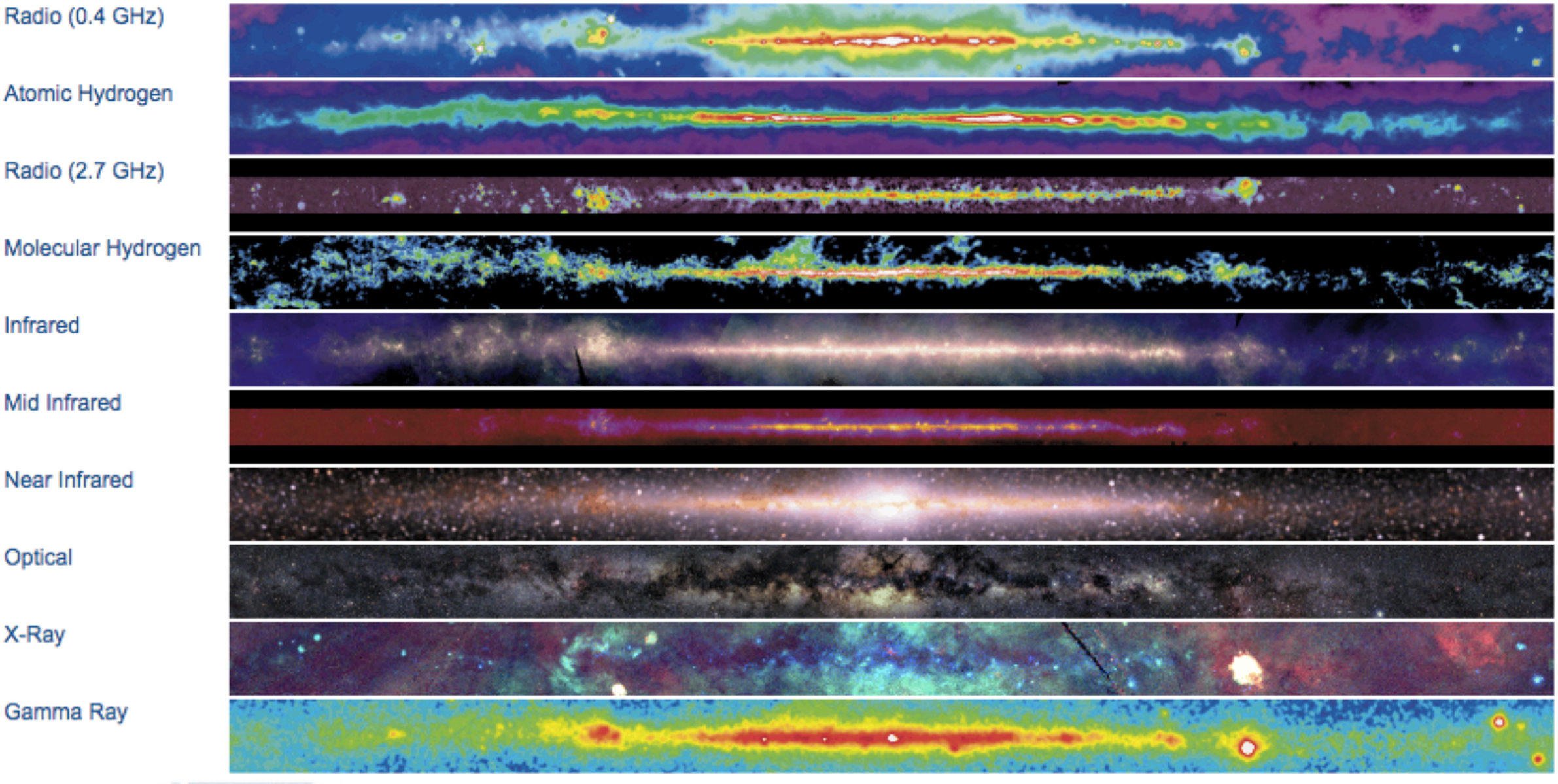
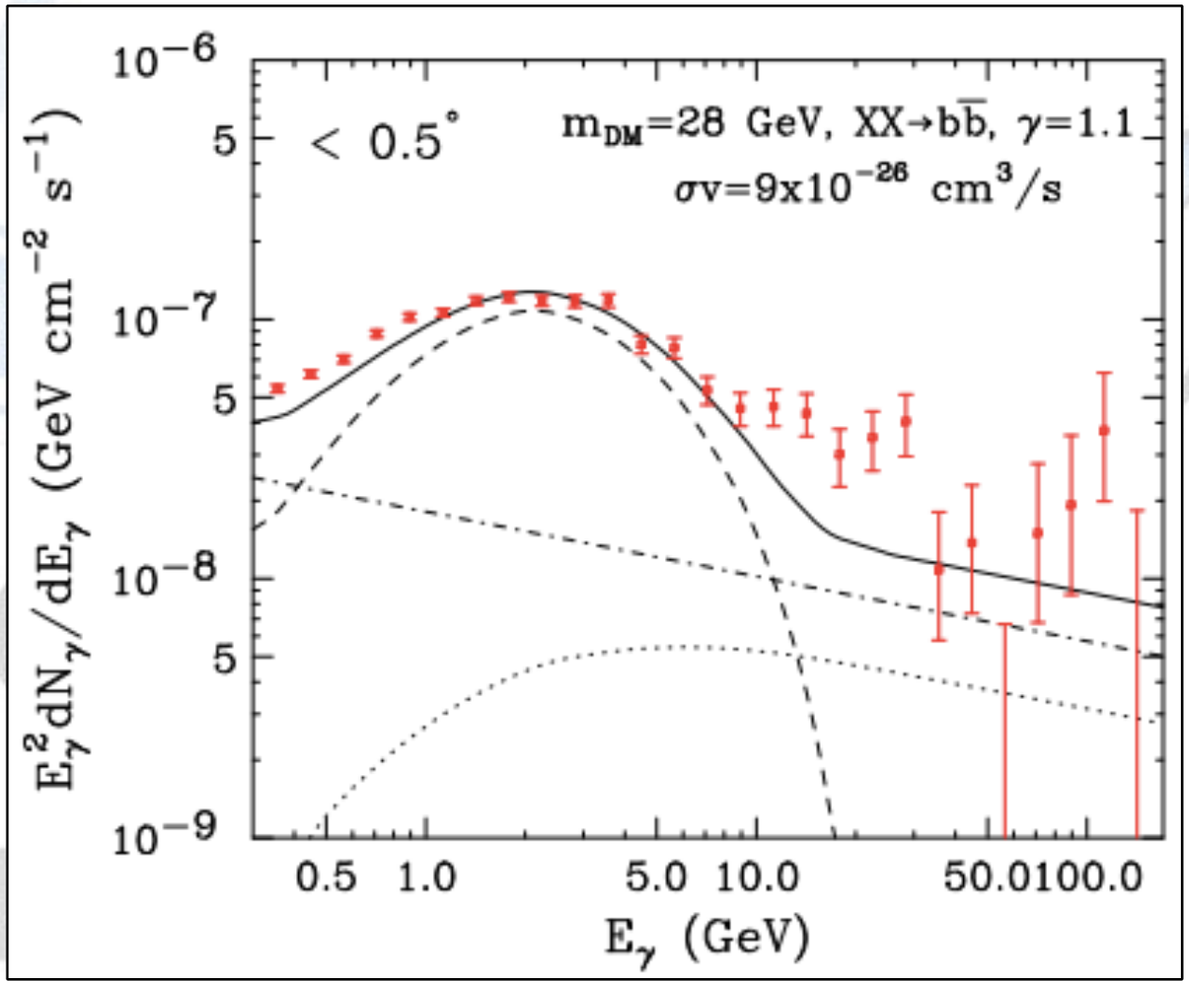


What's Going On in the Galactic Center?

2009

Excess in gamma-ray flux from GC



L. Goodenough, arXiv:0910.2998

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Speculation as to its origin

Not exhaustive:
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Dark Matter

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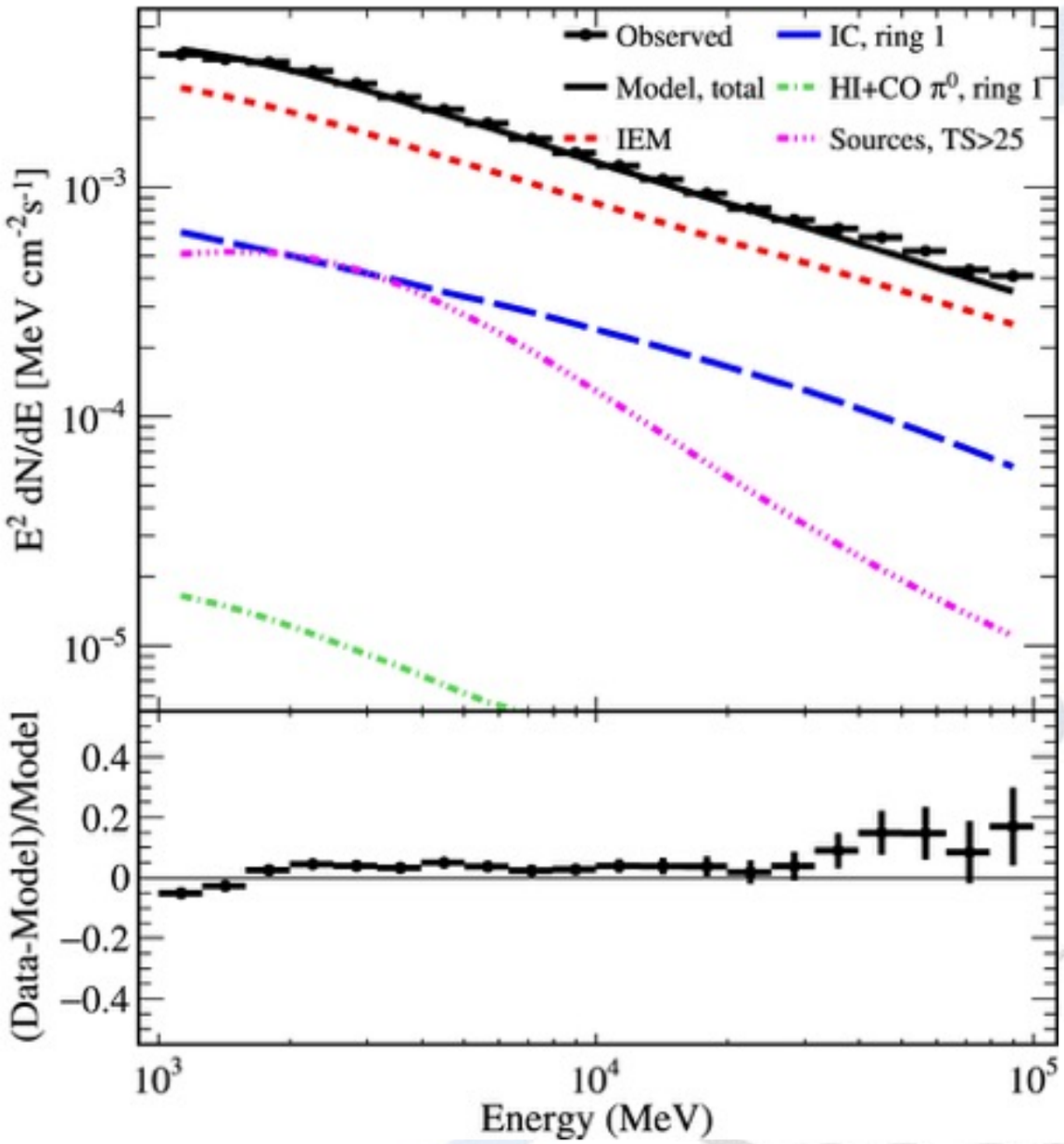
Unresolved populations**

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

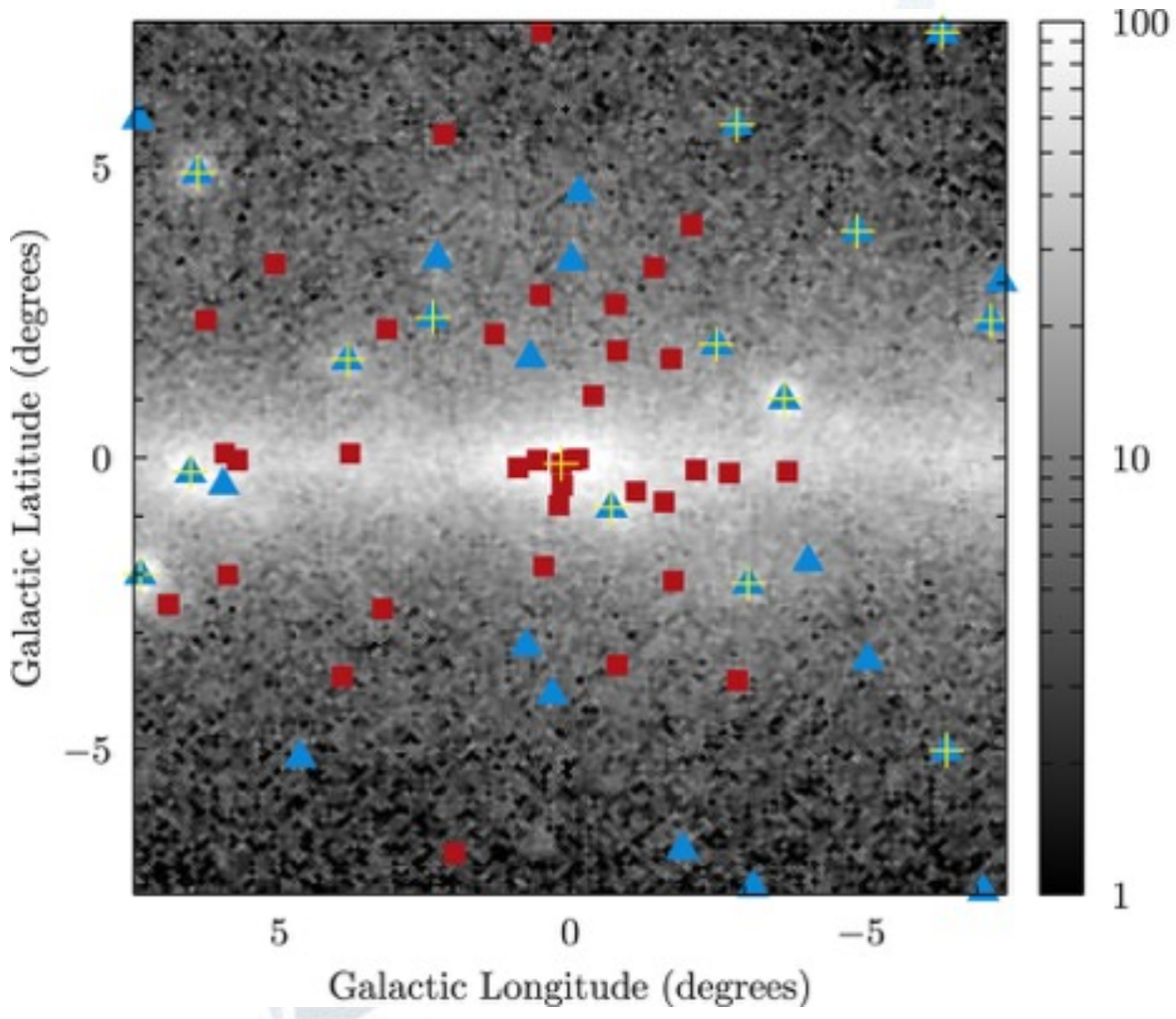
Gamma-ray sources (pulsars, OB stars)

Intensity/Index scaled

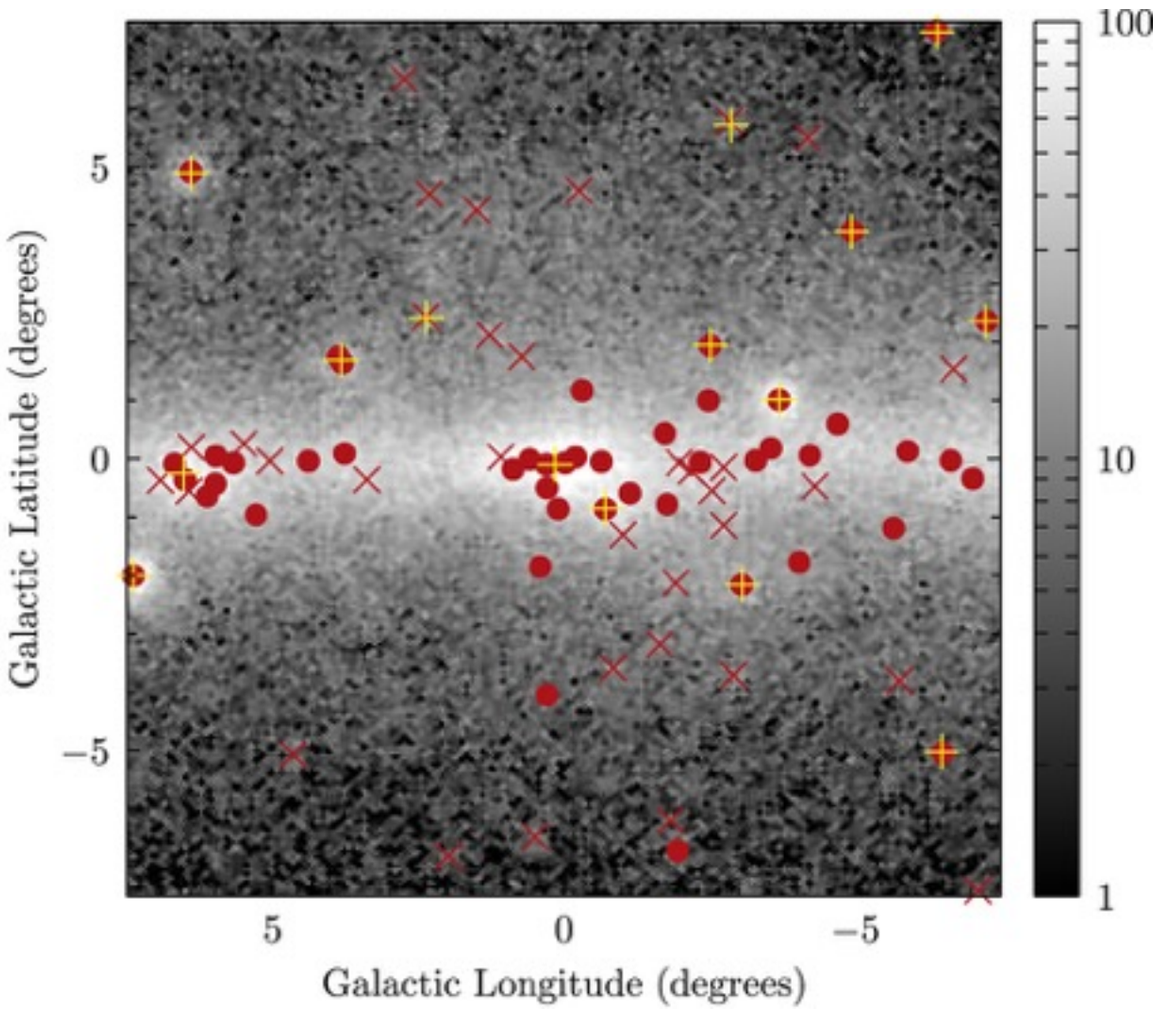
M. Ajello et al., Astrophys. J. 819, 44 (2016)

Dividing the Galaxy

The 3FGL Catalog



The 1FIG Catalog



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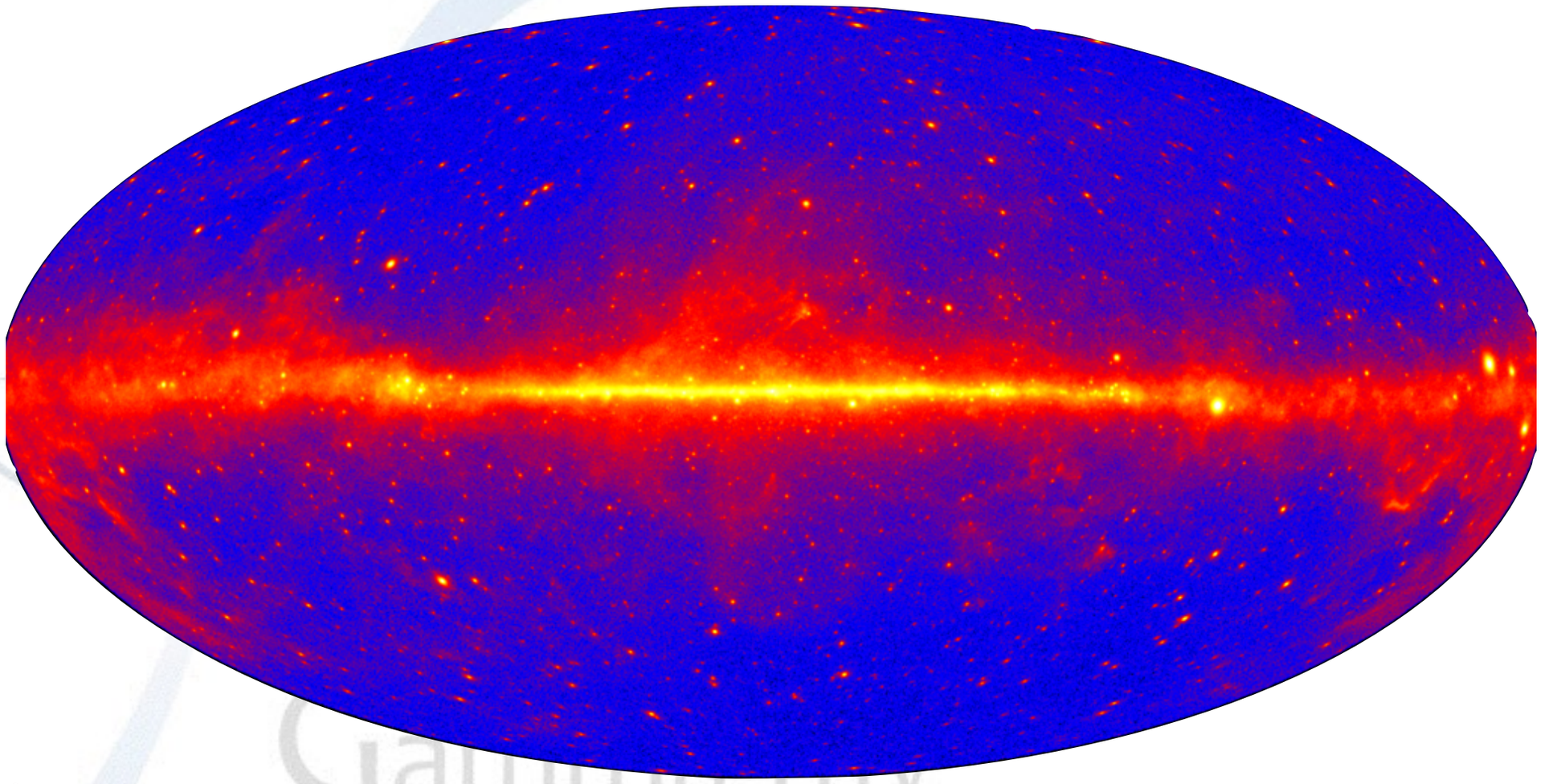
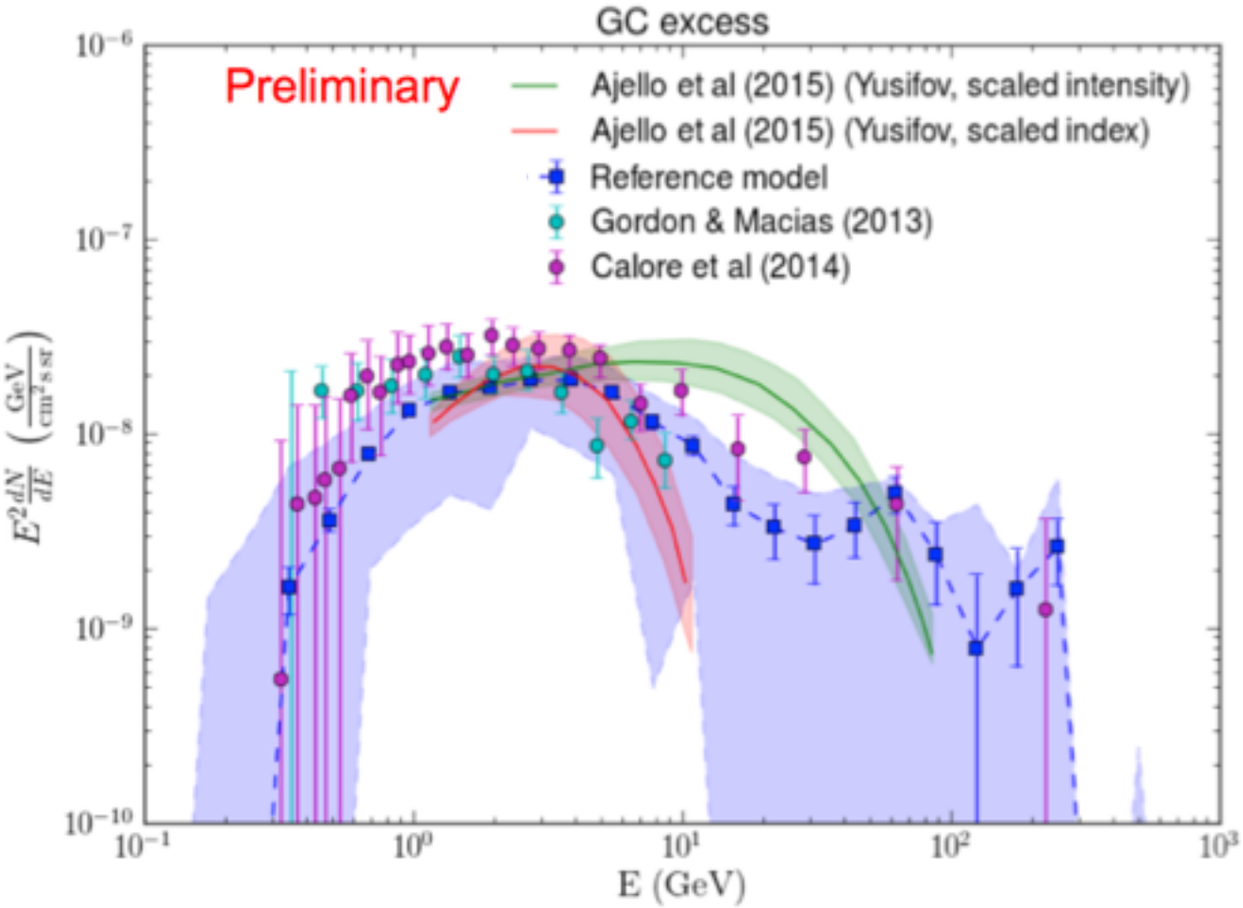
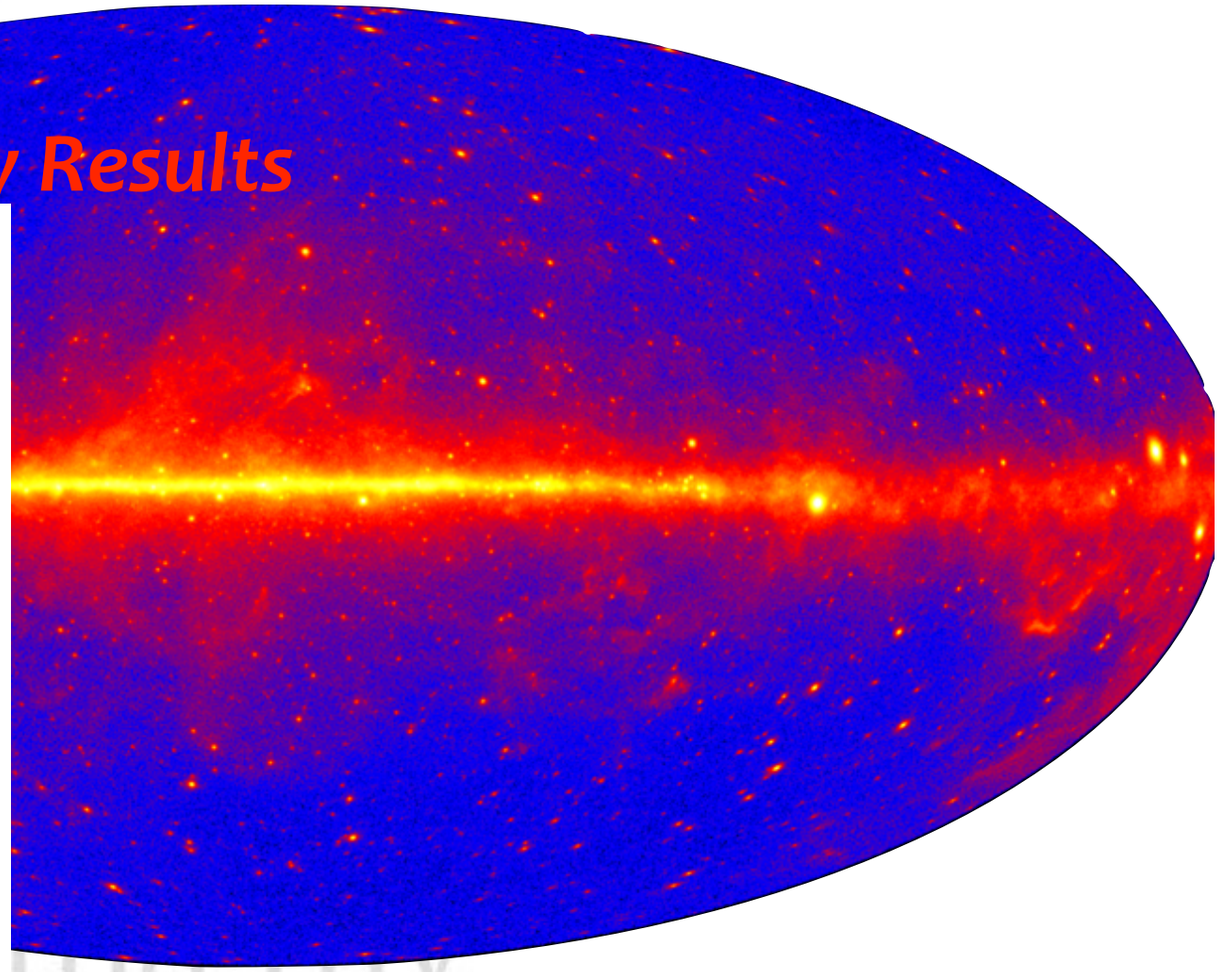
Upgrading to Pass 8



Upgrading to Pass 8

Preliminary Results





Fermi-LAT Collaboration, Fermi Symposium 2015

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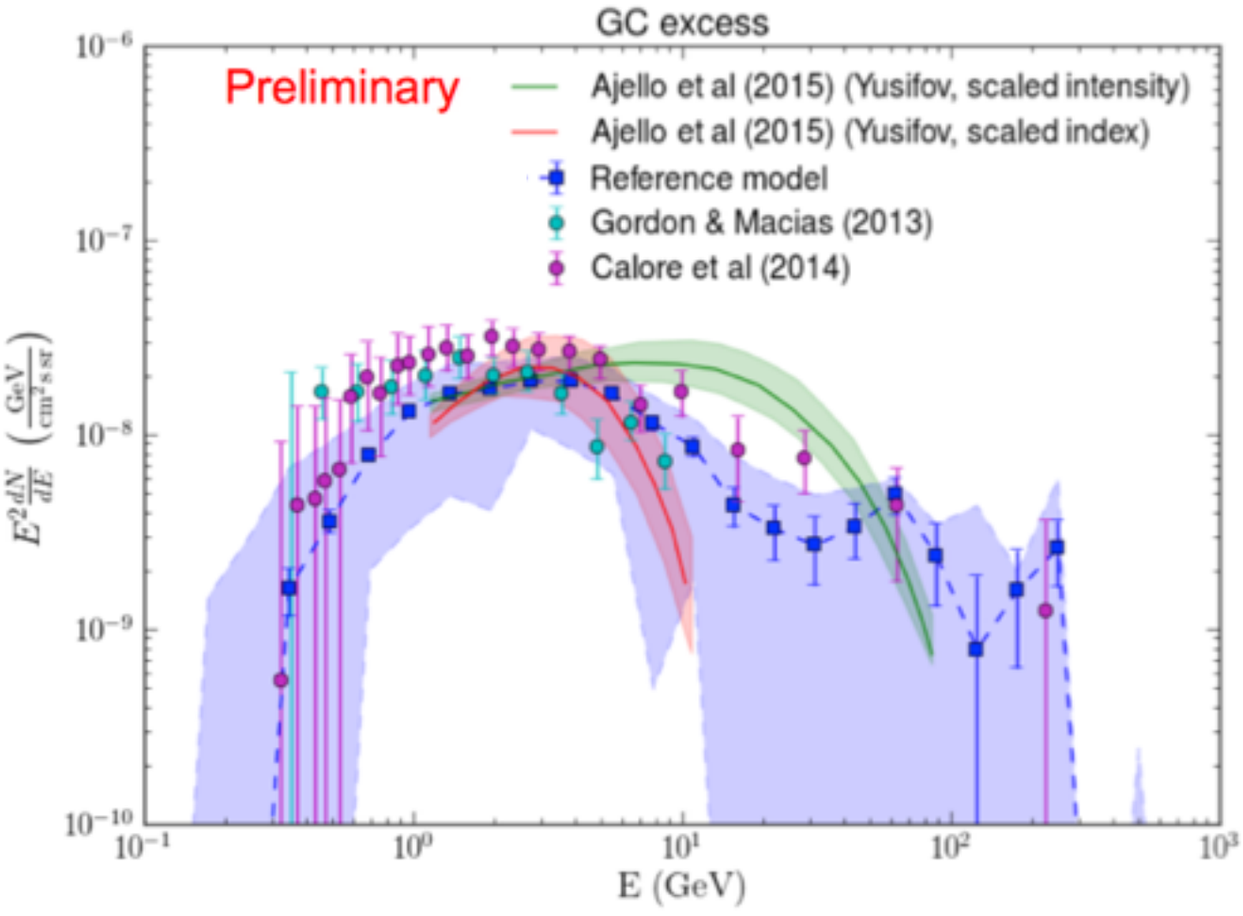

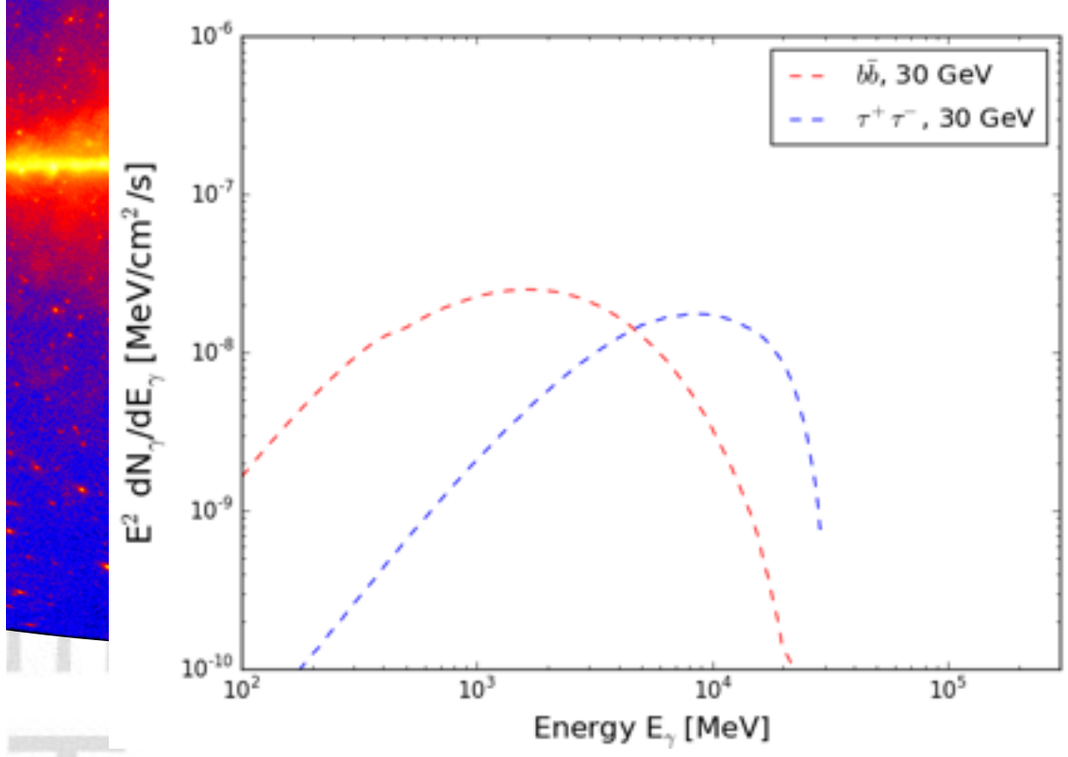

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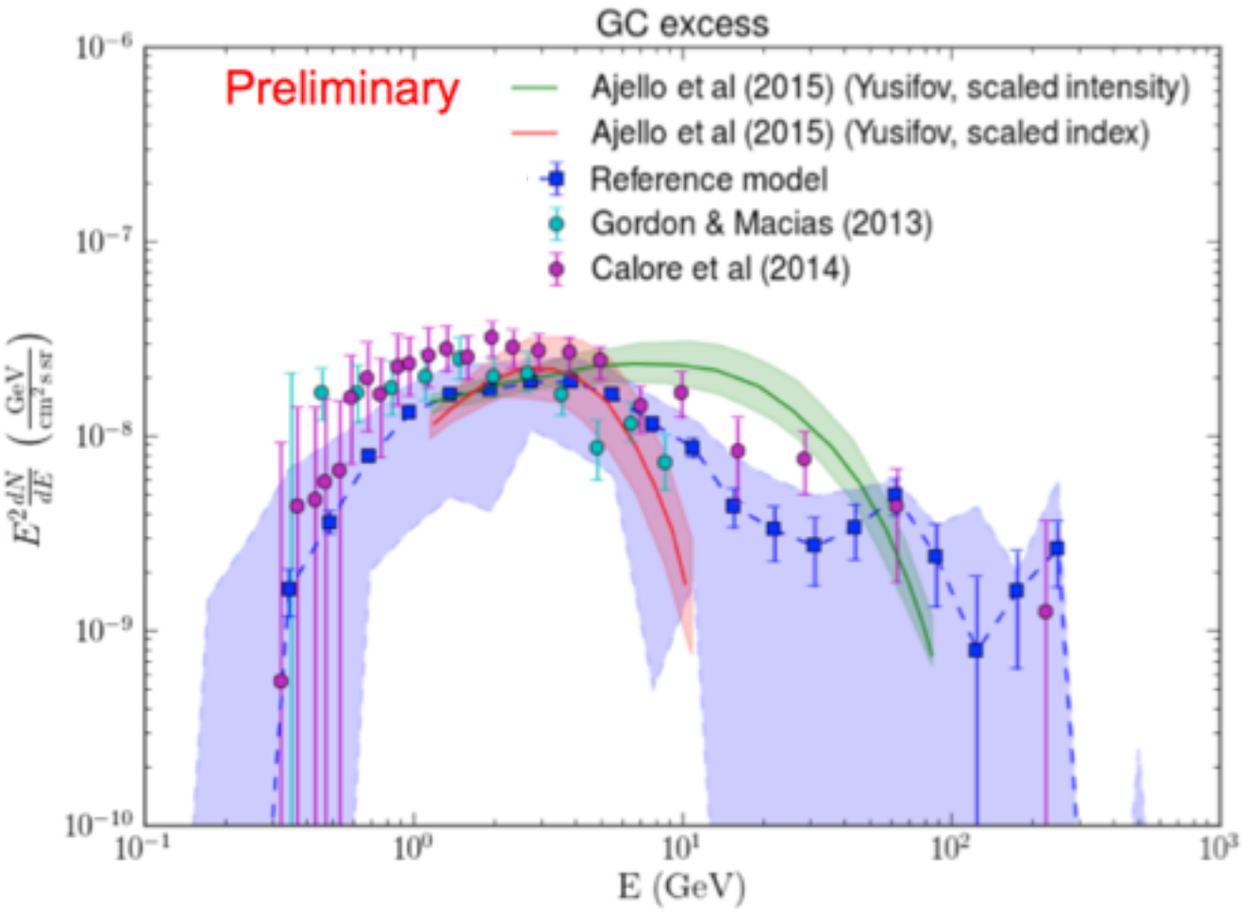

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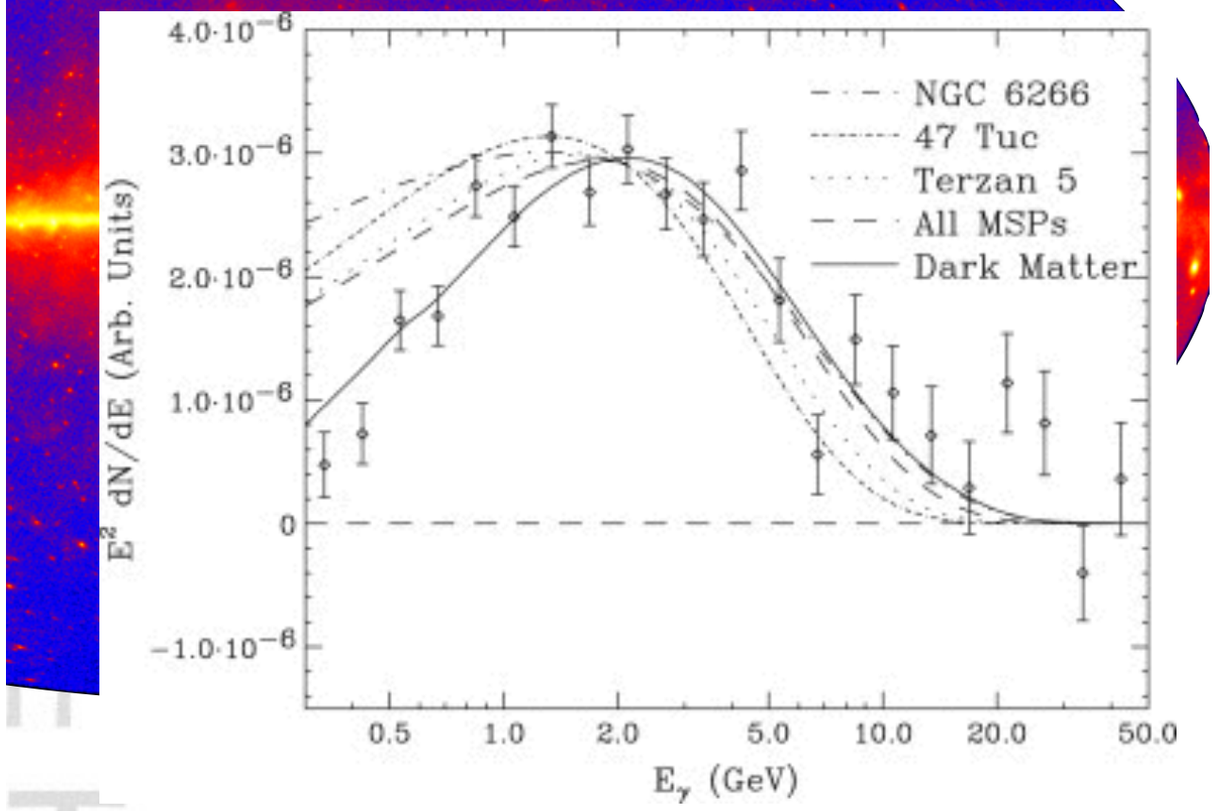

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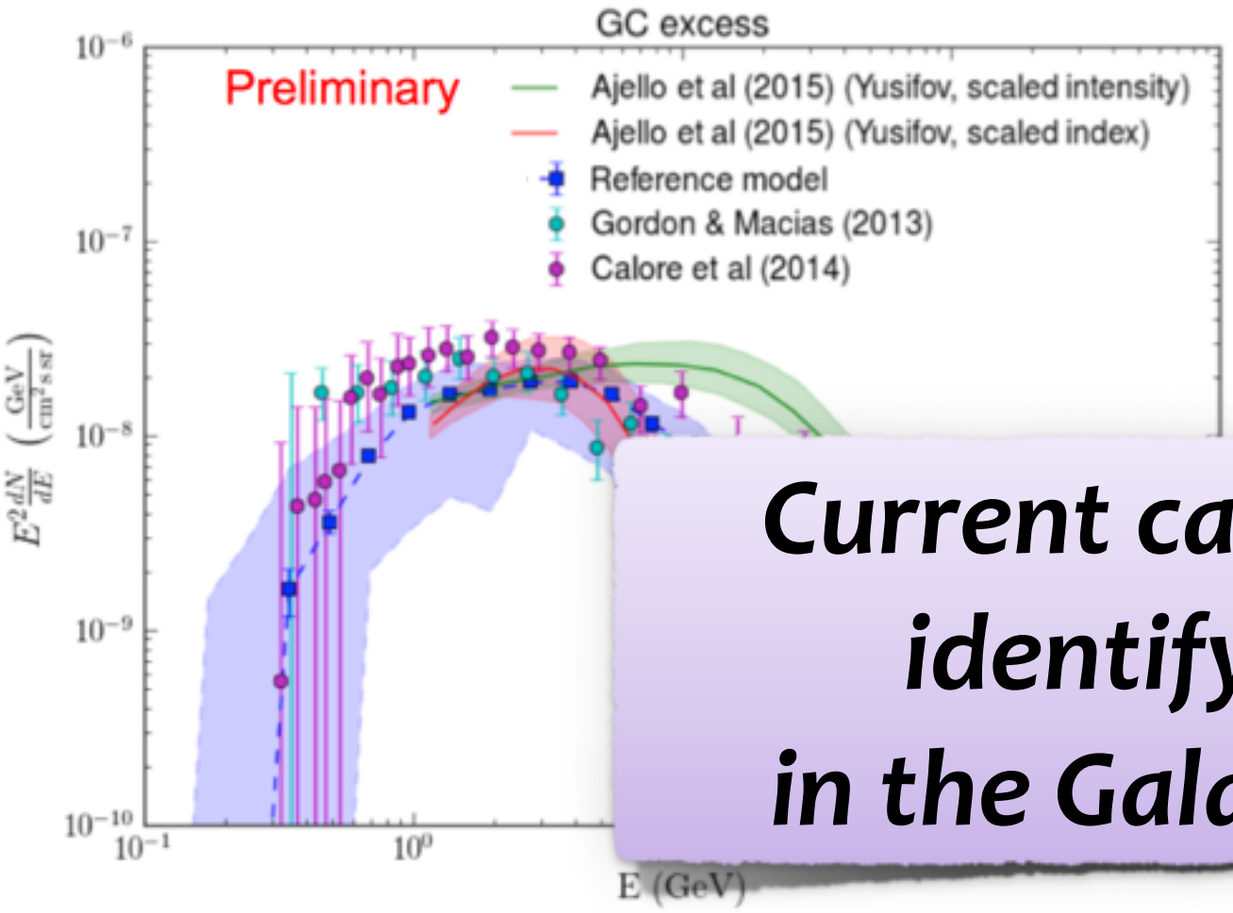
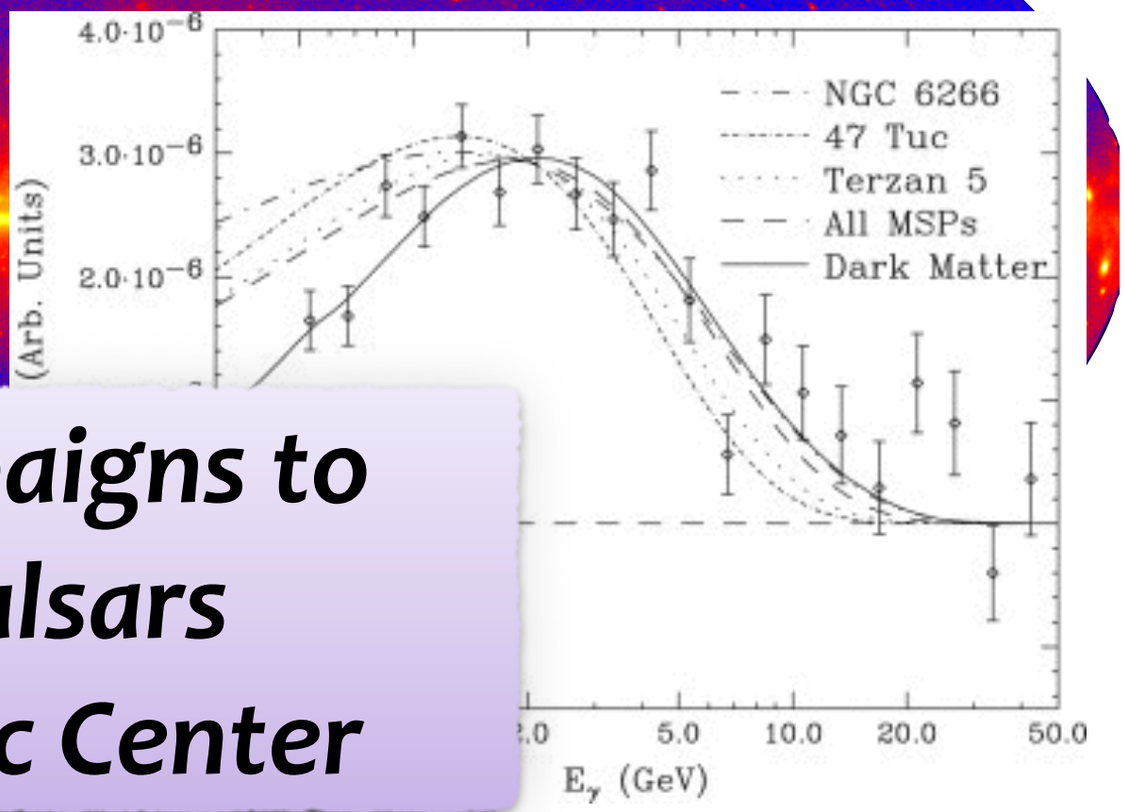




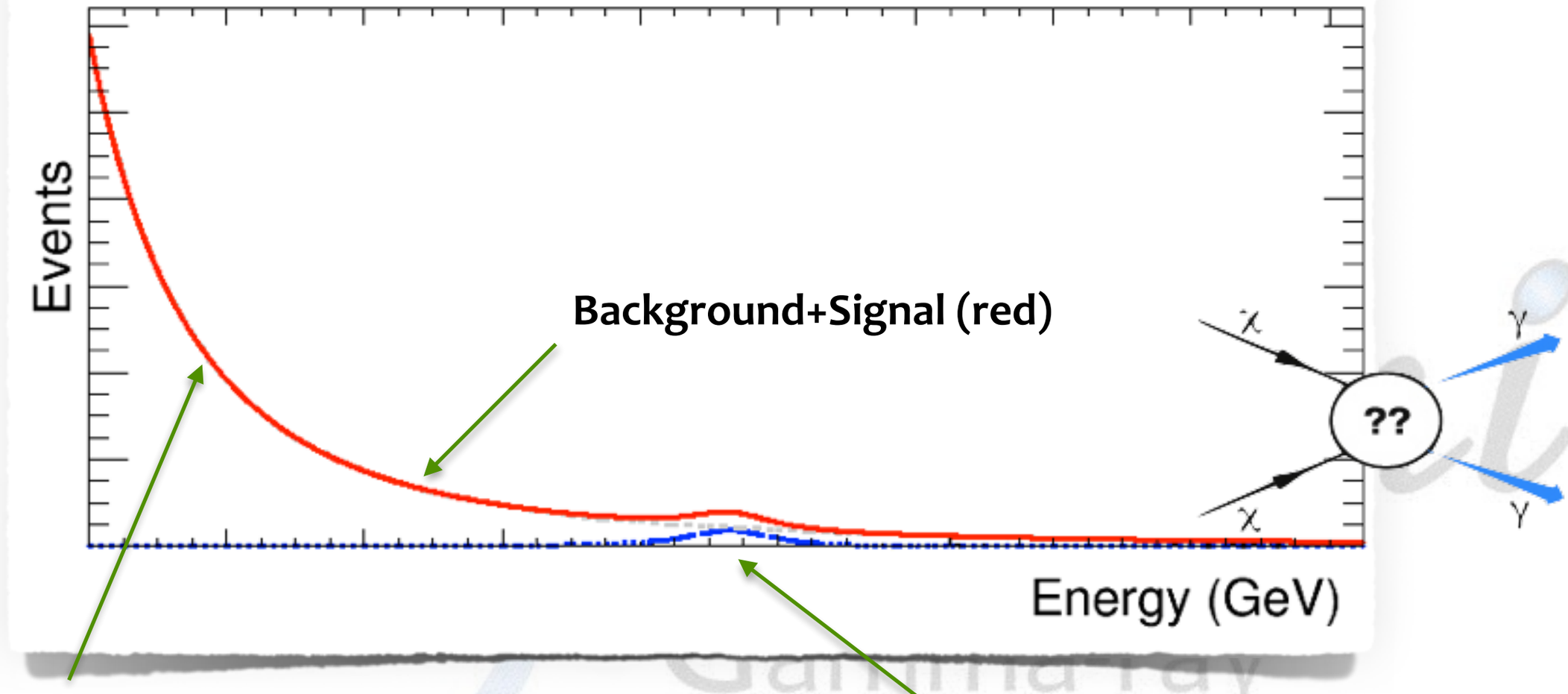
Current campaigns to identify pulsars in the Galactic Center

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):

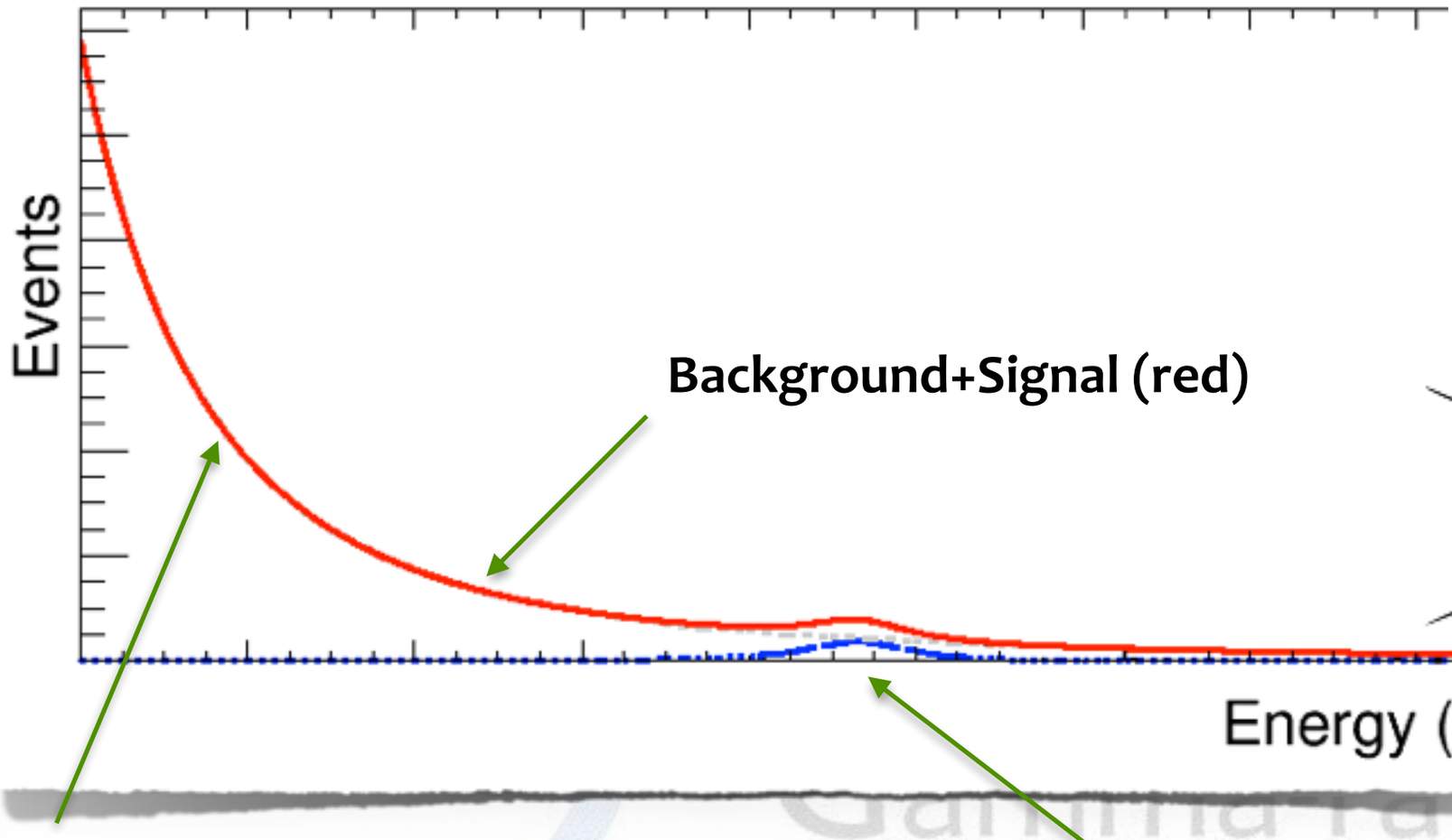
- Single power law with index Γ_{bkg} allowed to float
- Energy dependent exposure correction

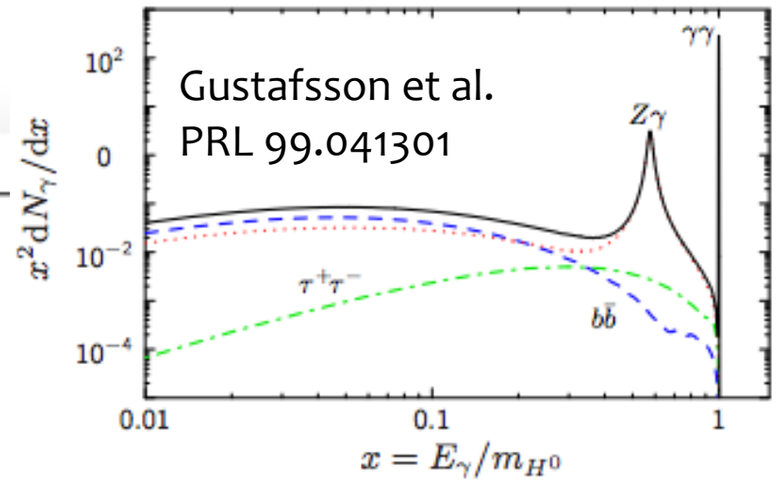
Signal model (blue):

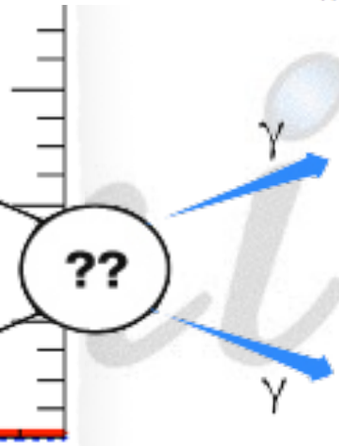
- E dispersion (Gaussian)
- n_{sig} fit model independent

Spectral Lines

Unbinned Maximum Likelihood Fits







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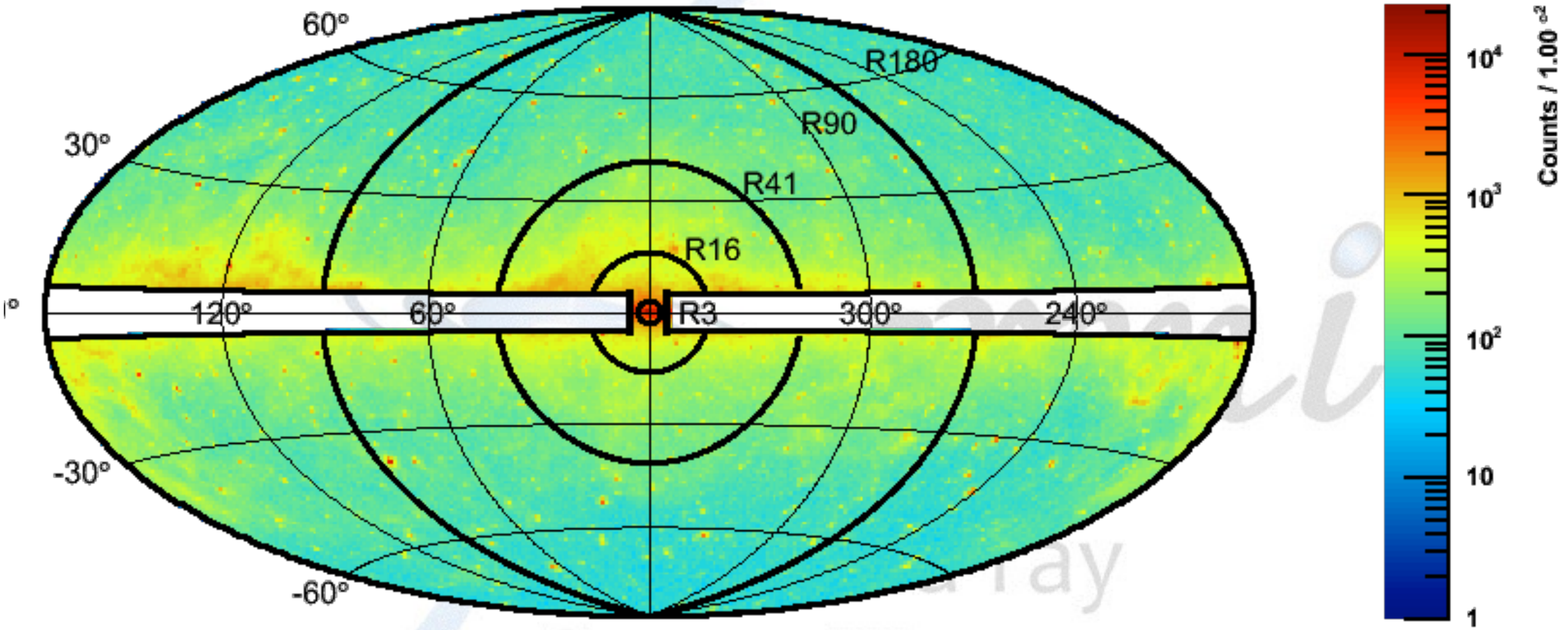
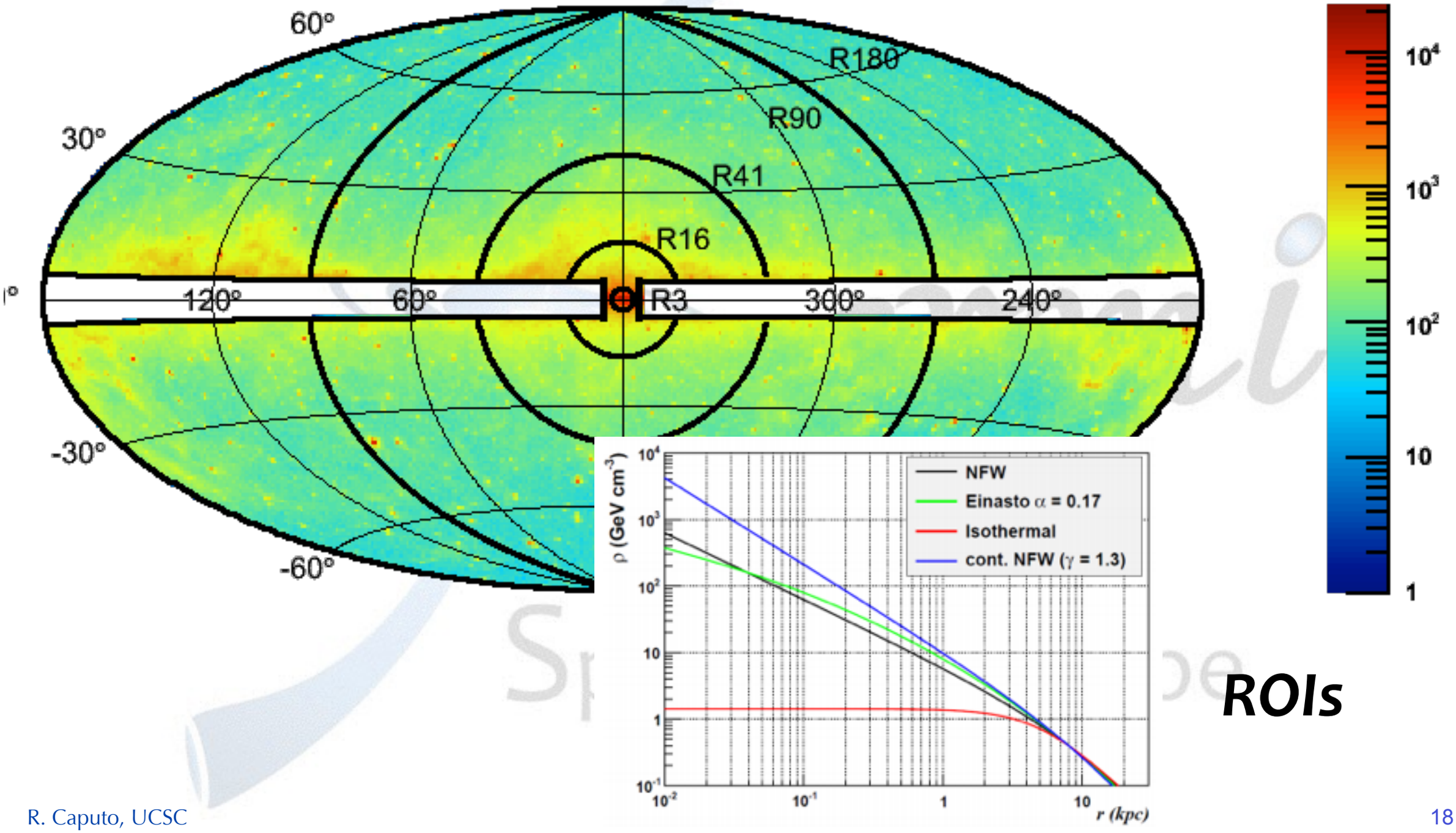
- n_{sig} fit model independent

Spectral Lines



ROIs

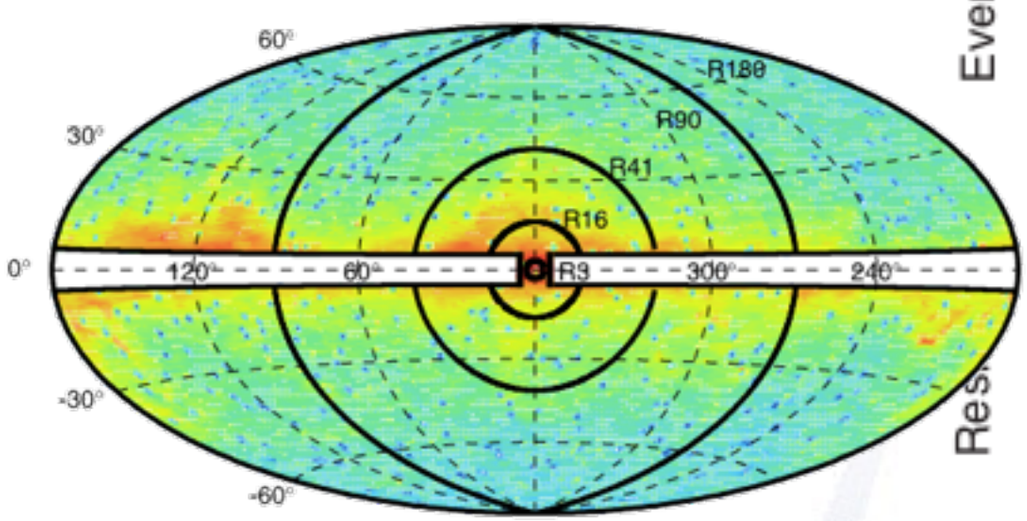
Spectral Lines

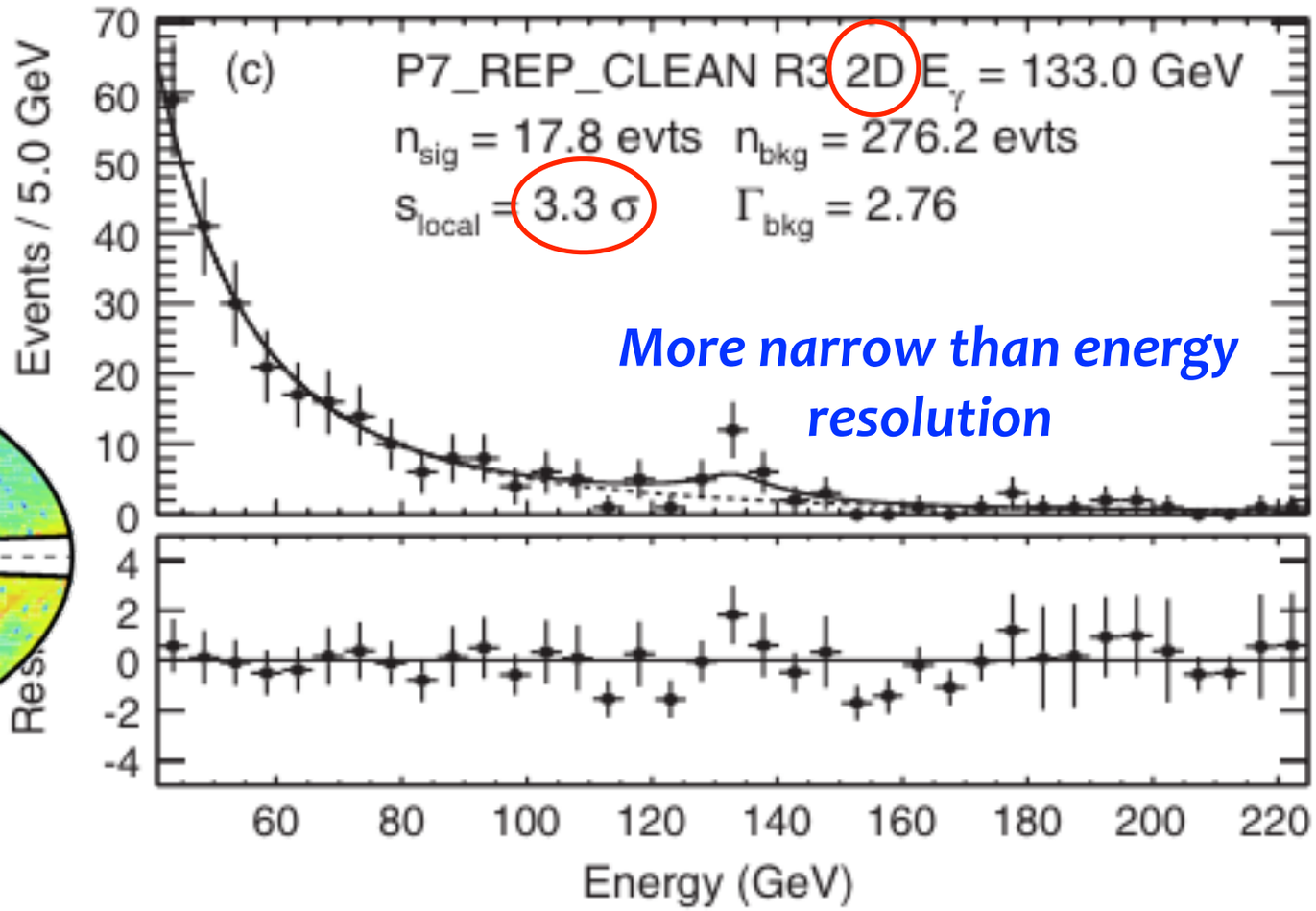


ROIs

Spectral Lines

2013: Tentative… Too Narrow





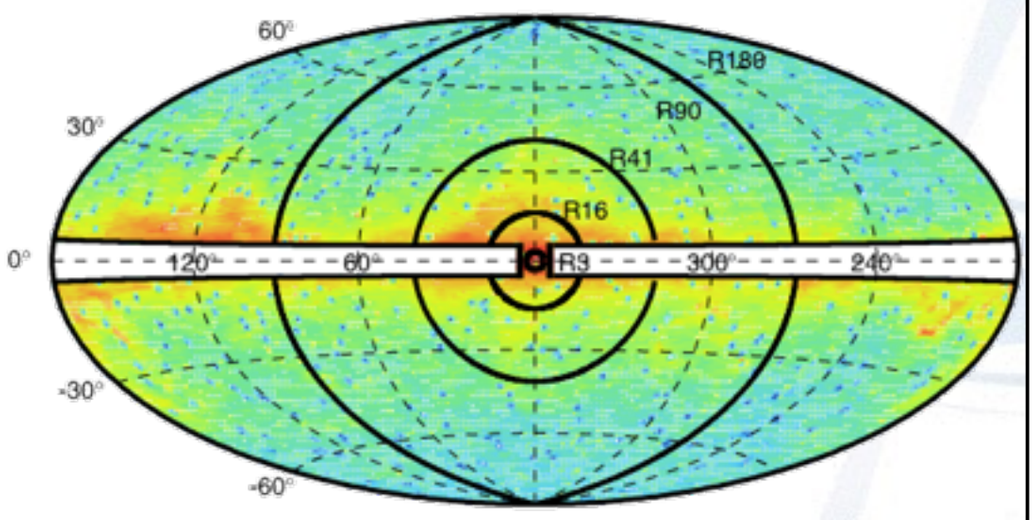
More narrow than energy resolution

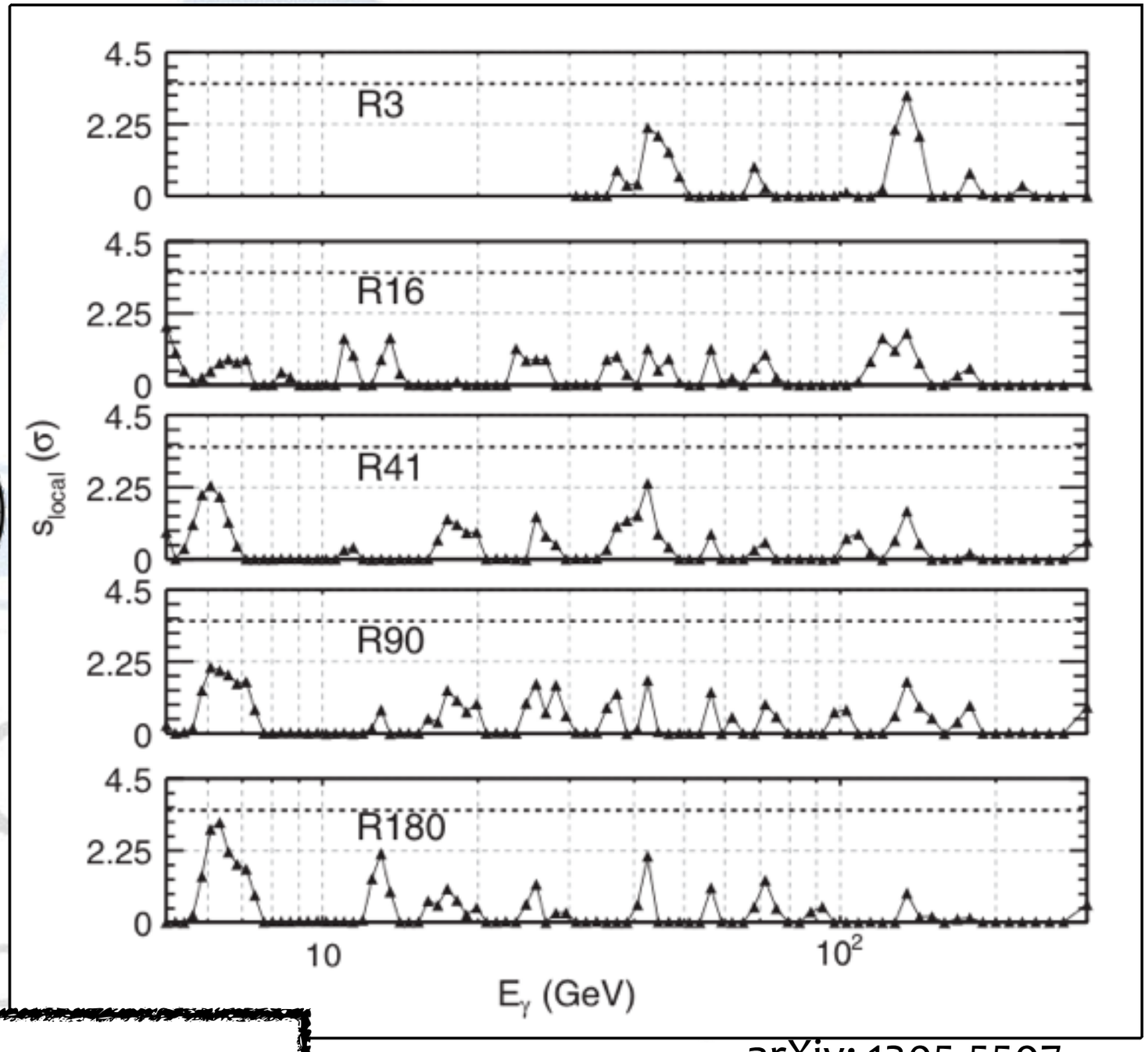
Fermi-LAT analysis with Pass 7 Reprocessed data and 2D PDF fit

arXiv: 1305.5597

Spectral Lines

2013:
All ROIs
All σ

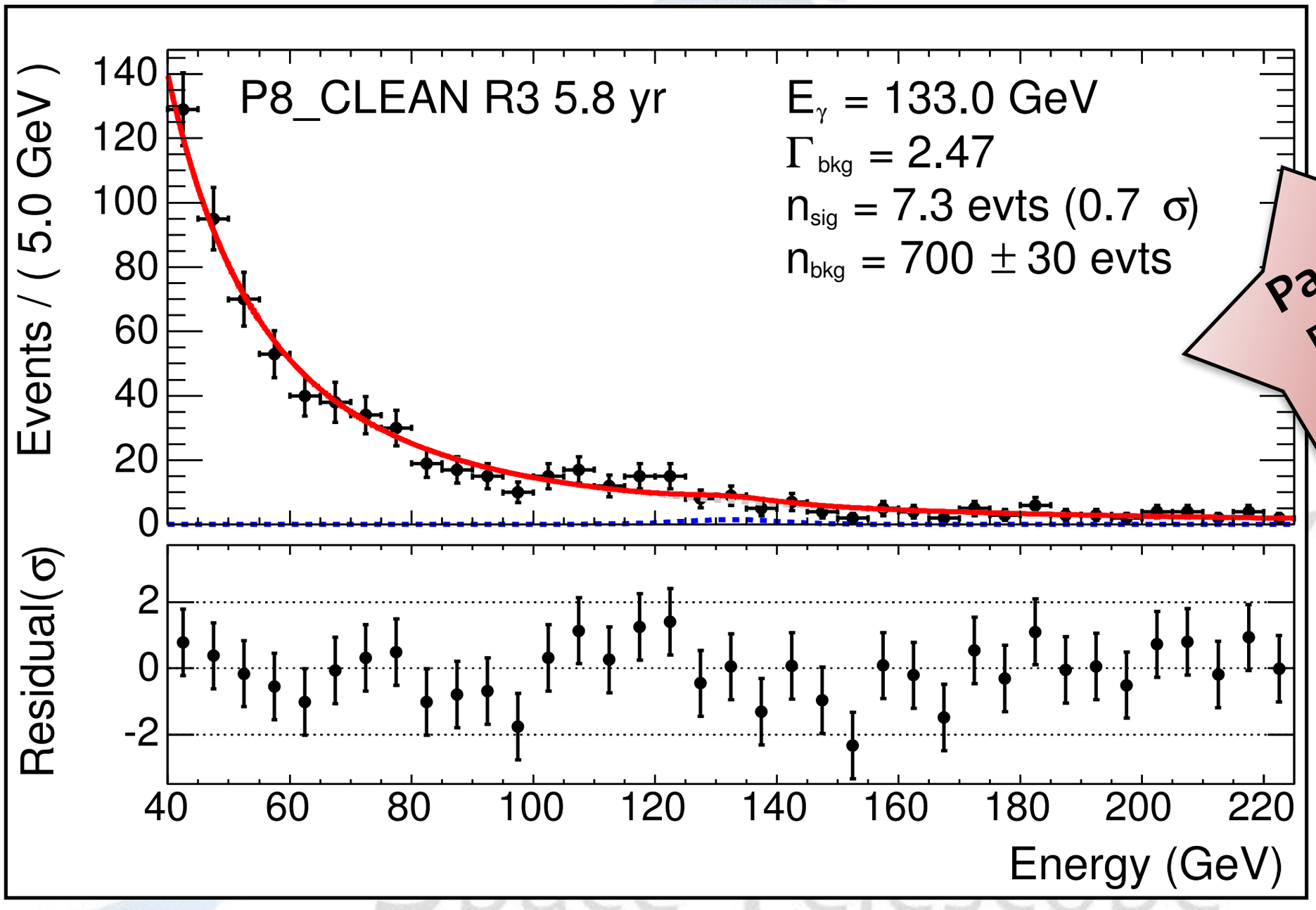




arXiv: 1305.5597

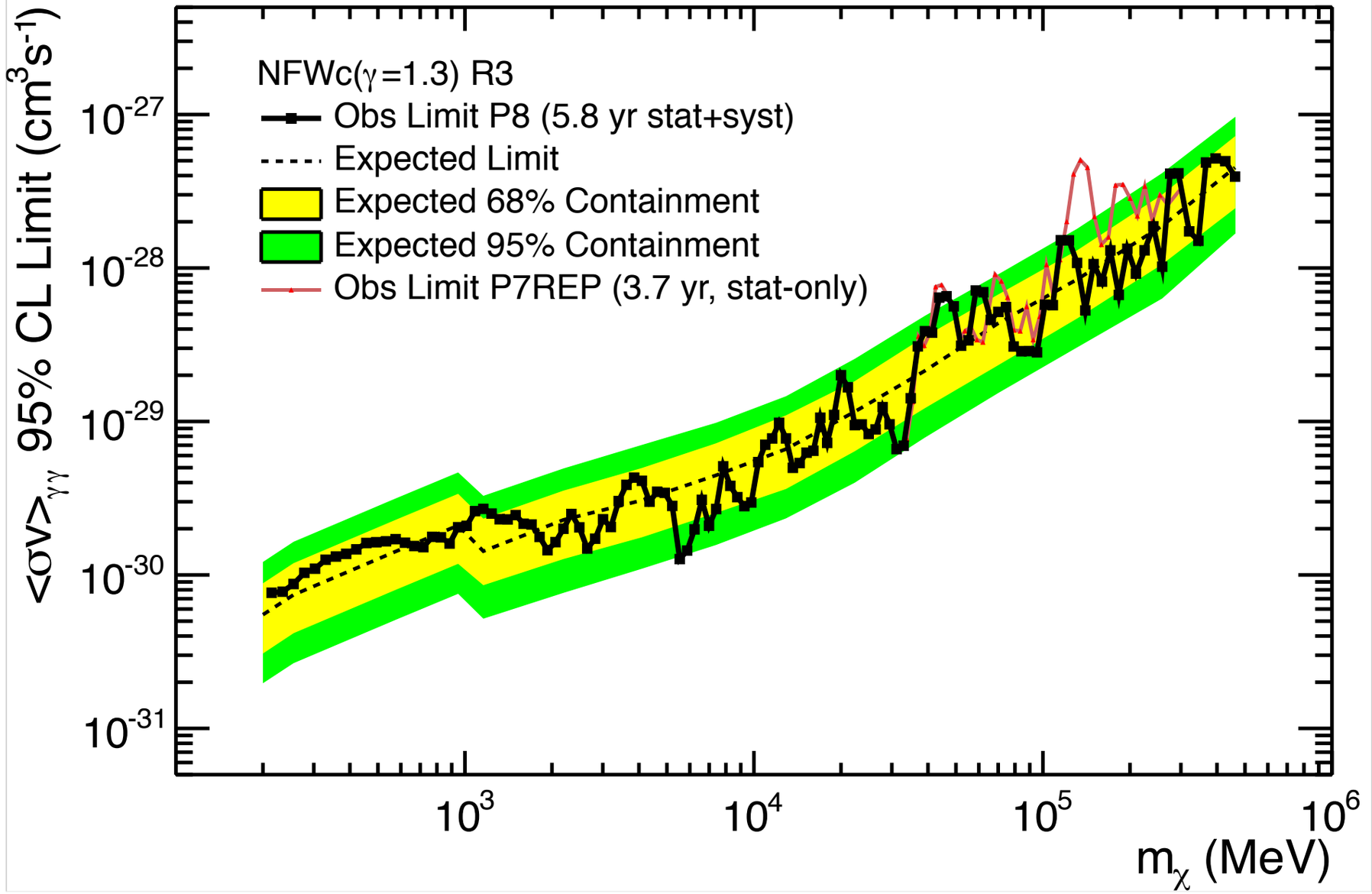
Wait and see what happens…

133 GeV Feature with Pass 8



Pass 8: Full 5.8 years

Spectral Lines: Full E_γ range



Dark Matter Distribution

Search Strategies

Dwarf Spheroidal Satellite Galaxies
arXiv: 1503.02320
arXiv: 1503.06209

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

From the Fermi-LAT Collaboration

DES candidates

External Analyses on DES candidates

Galaxy Clusters
arXiv: 1308.5654
arXiv: 1002.2239

Milky Way Halo
arXiv: 1205.6474

Galactic Center
arXiv:1511.02938
(many external)

Spectral Lines
arXiv: 1305.5597
arXiv: 1506.00013

Isotropic Background
arXiv: 1202.2856
arXiv: 1501.05464

What is a Dwarf Spheroidal Galaxy?

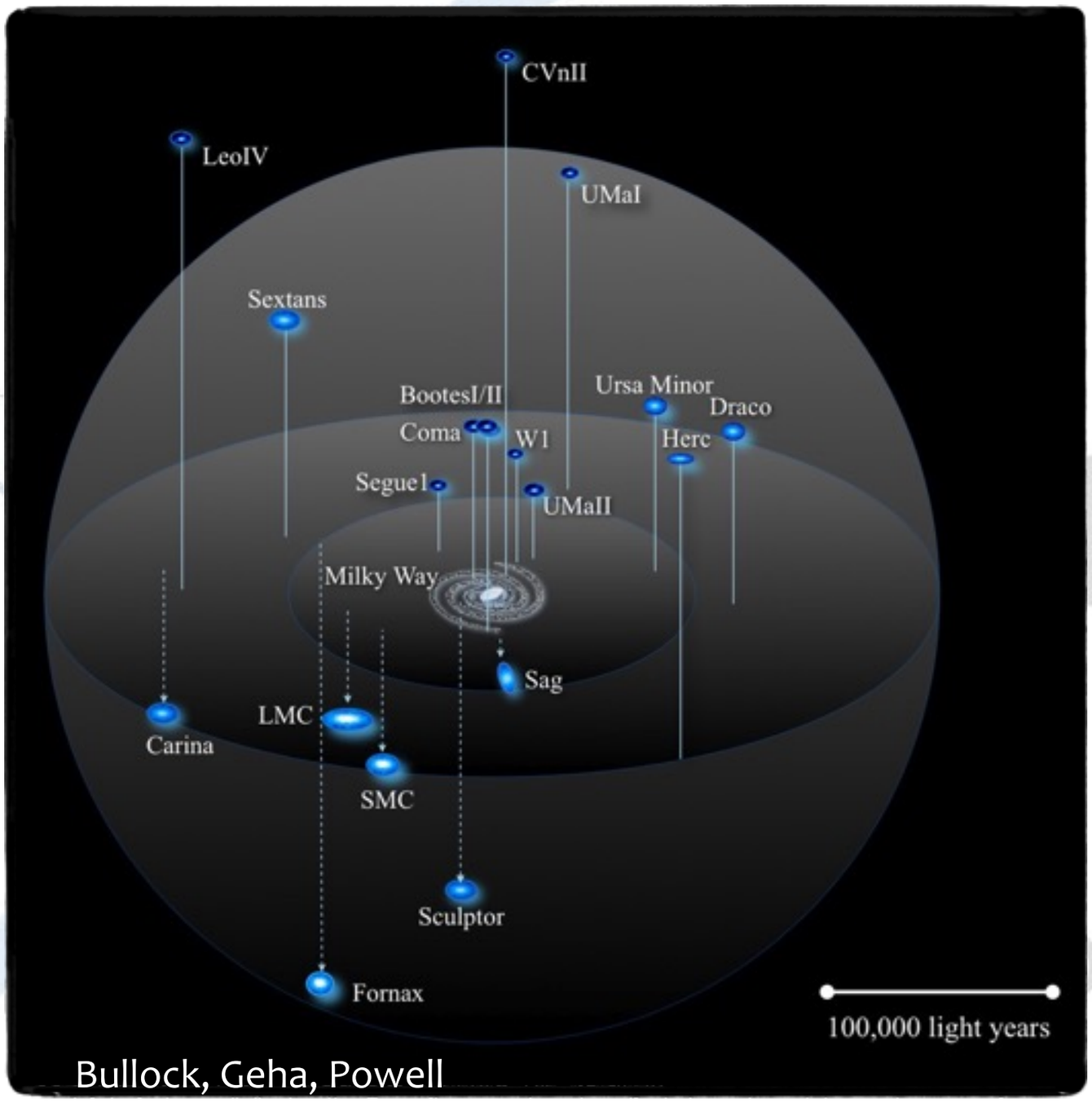
The Milky Way has many companion galaxies!

Little gas/dust/ star formation

old: >13b years

Low Luminosity

Found around Milky Way and Andromeda



Bullock, Geha, Powell

25 known dSphs

9 classical dSphs (pre-SDSS)

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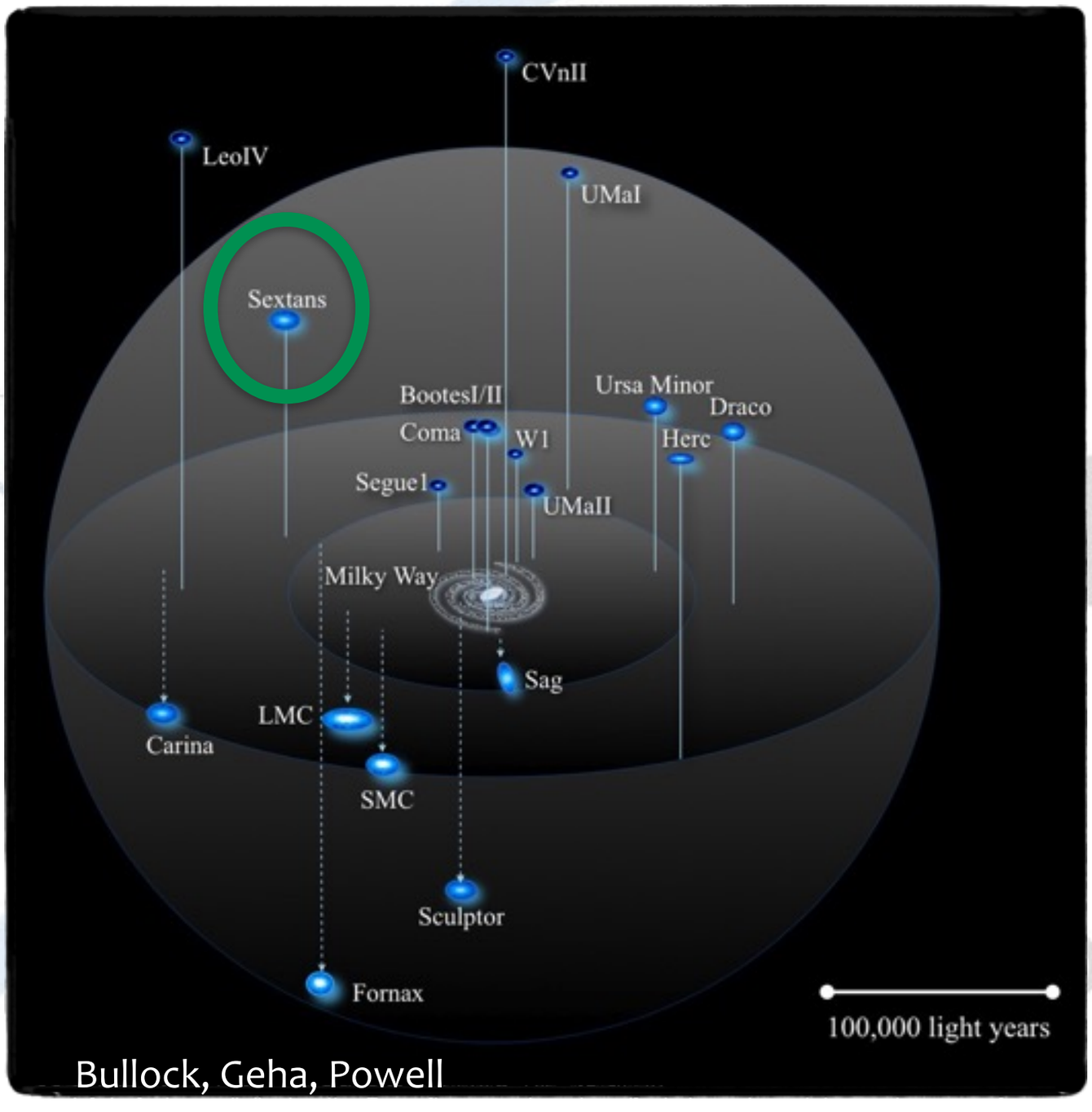

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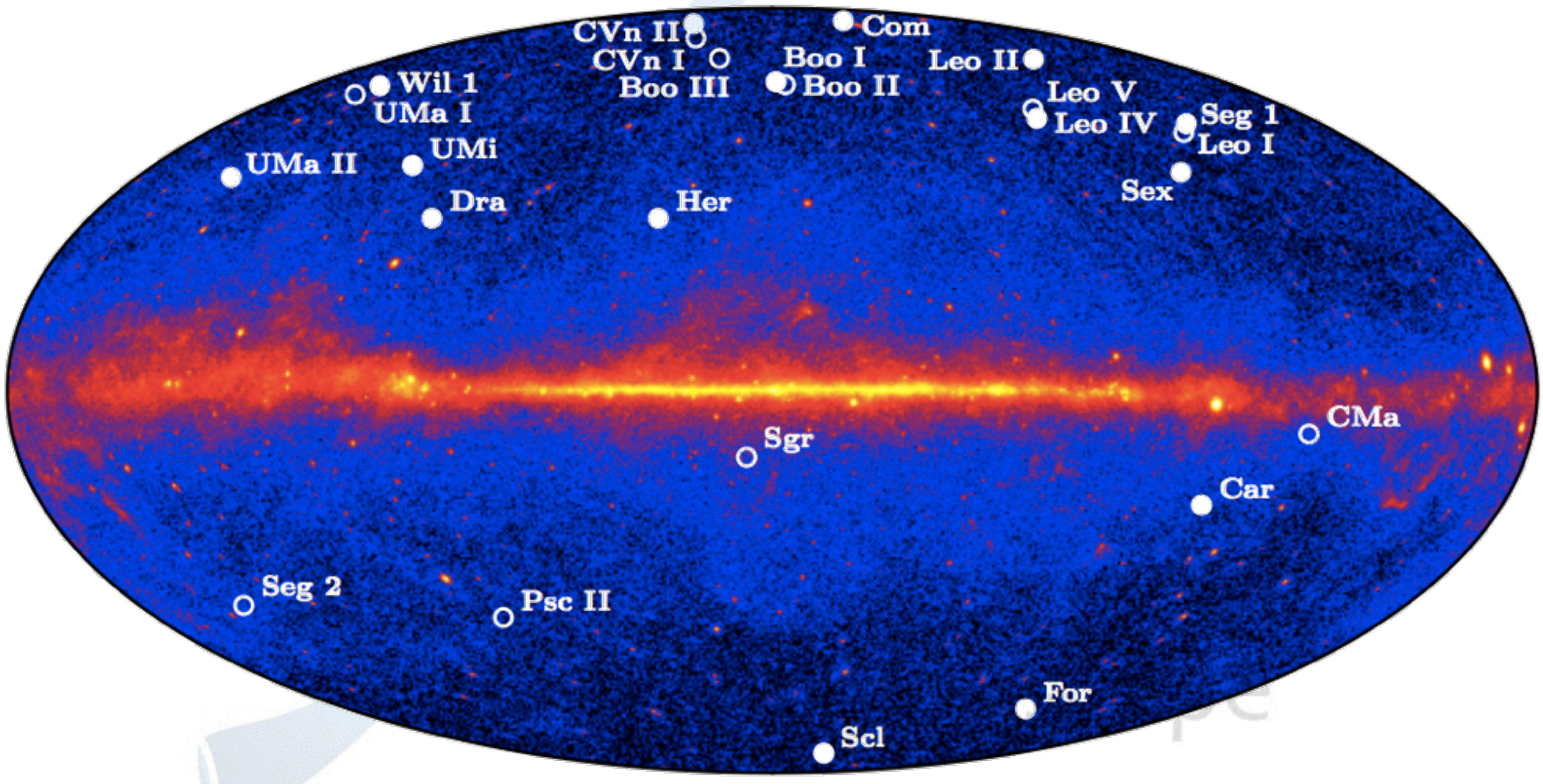
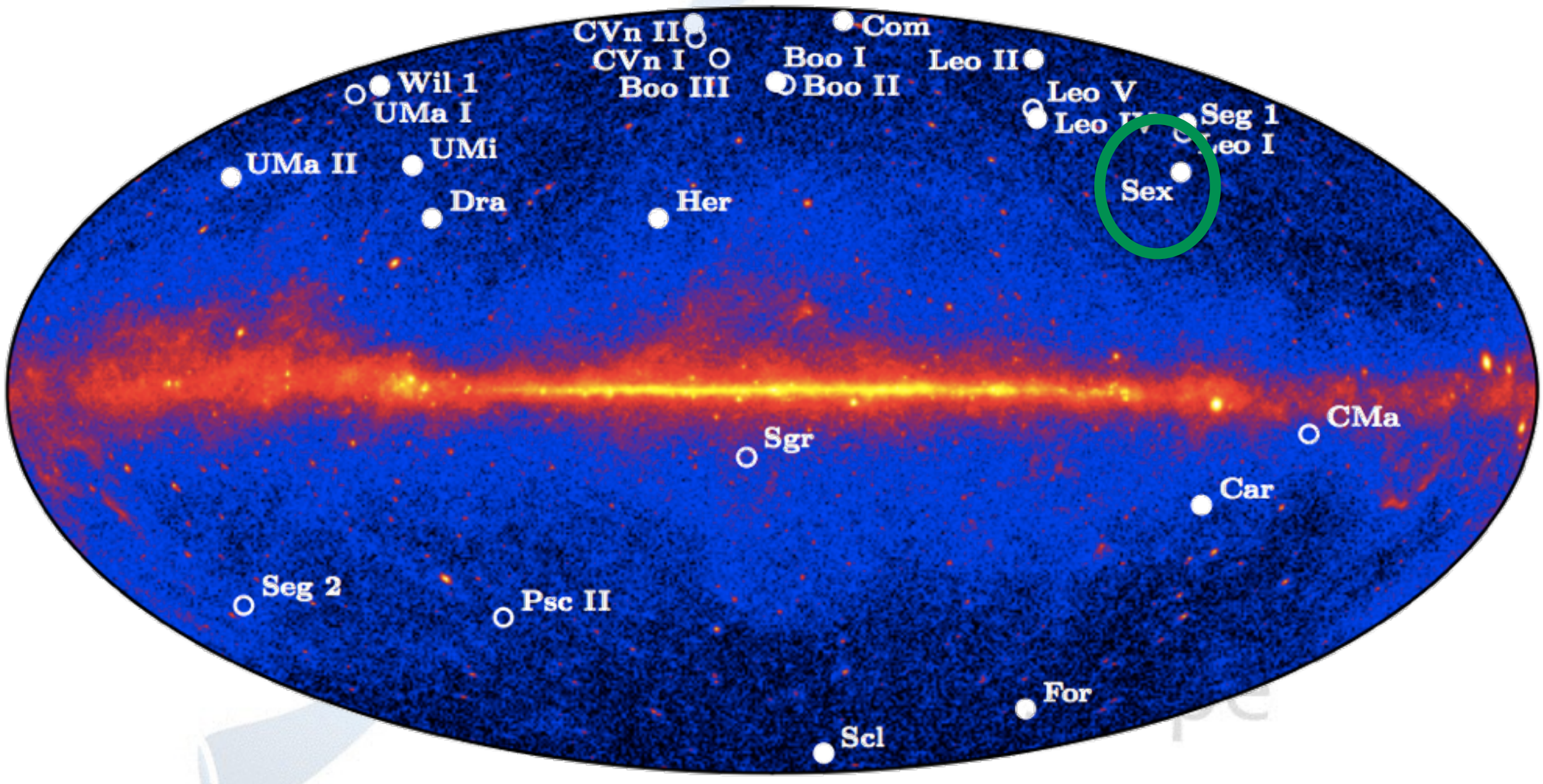
Dwarf Spheroidal Satellite Galaxies



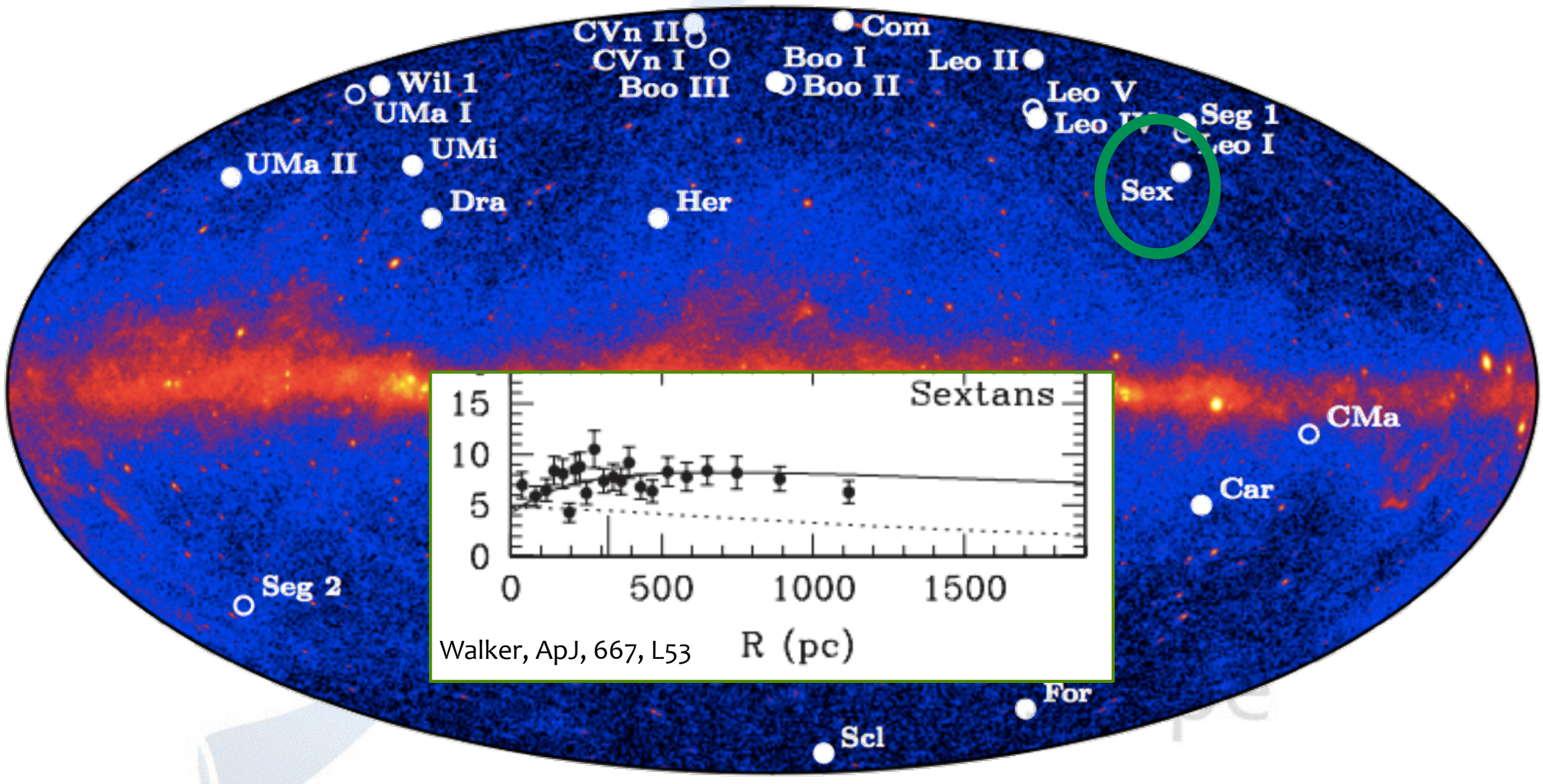
arXiv: 1503.02641

Dwarf Spheroidal Satellite Galaxies



arXiv: 1503.02641

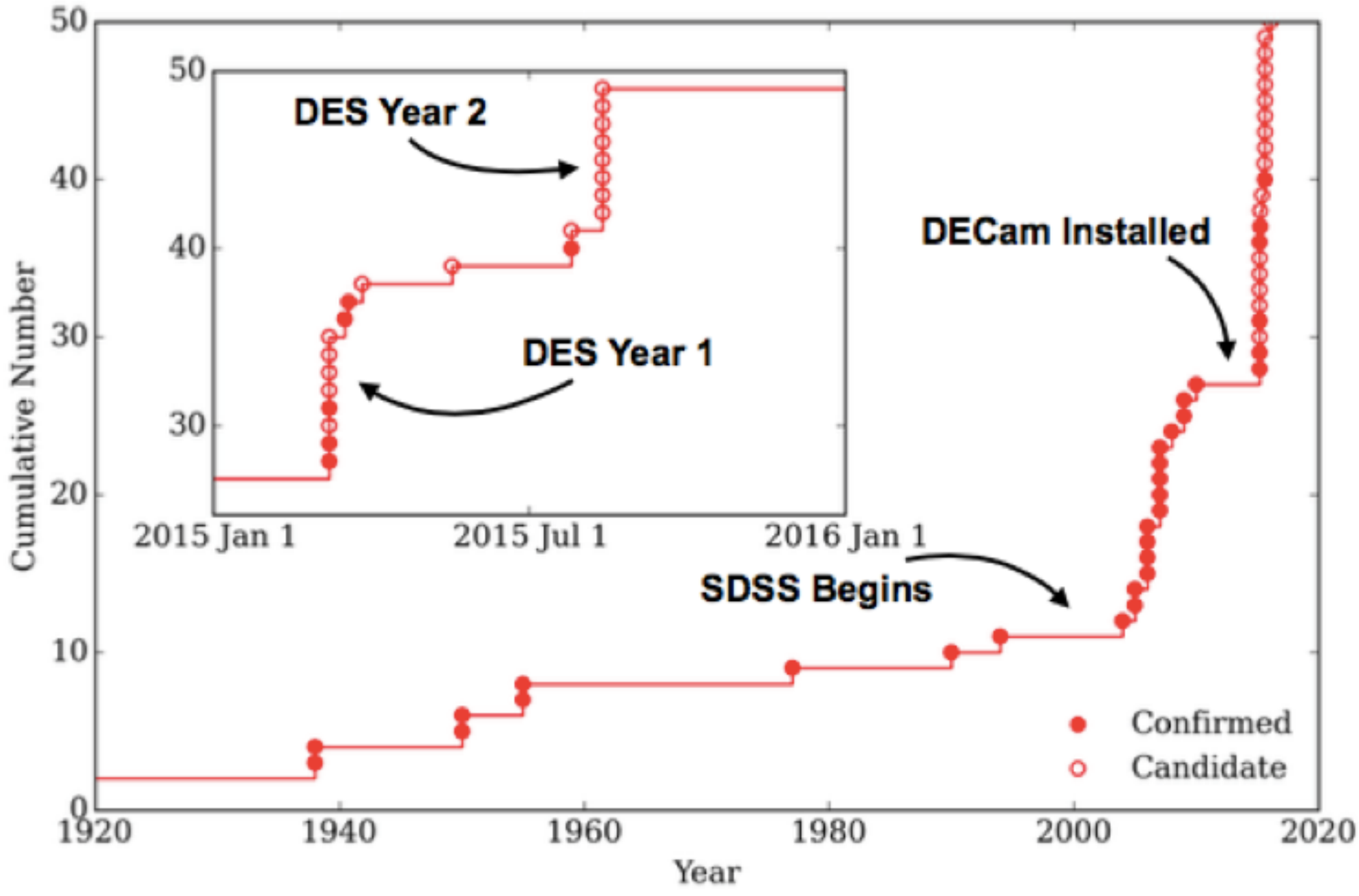
Dwarf Spheroidal Satellite Galaxies



Walker, ApJ, 667, L53

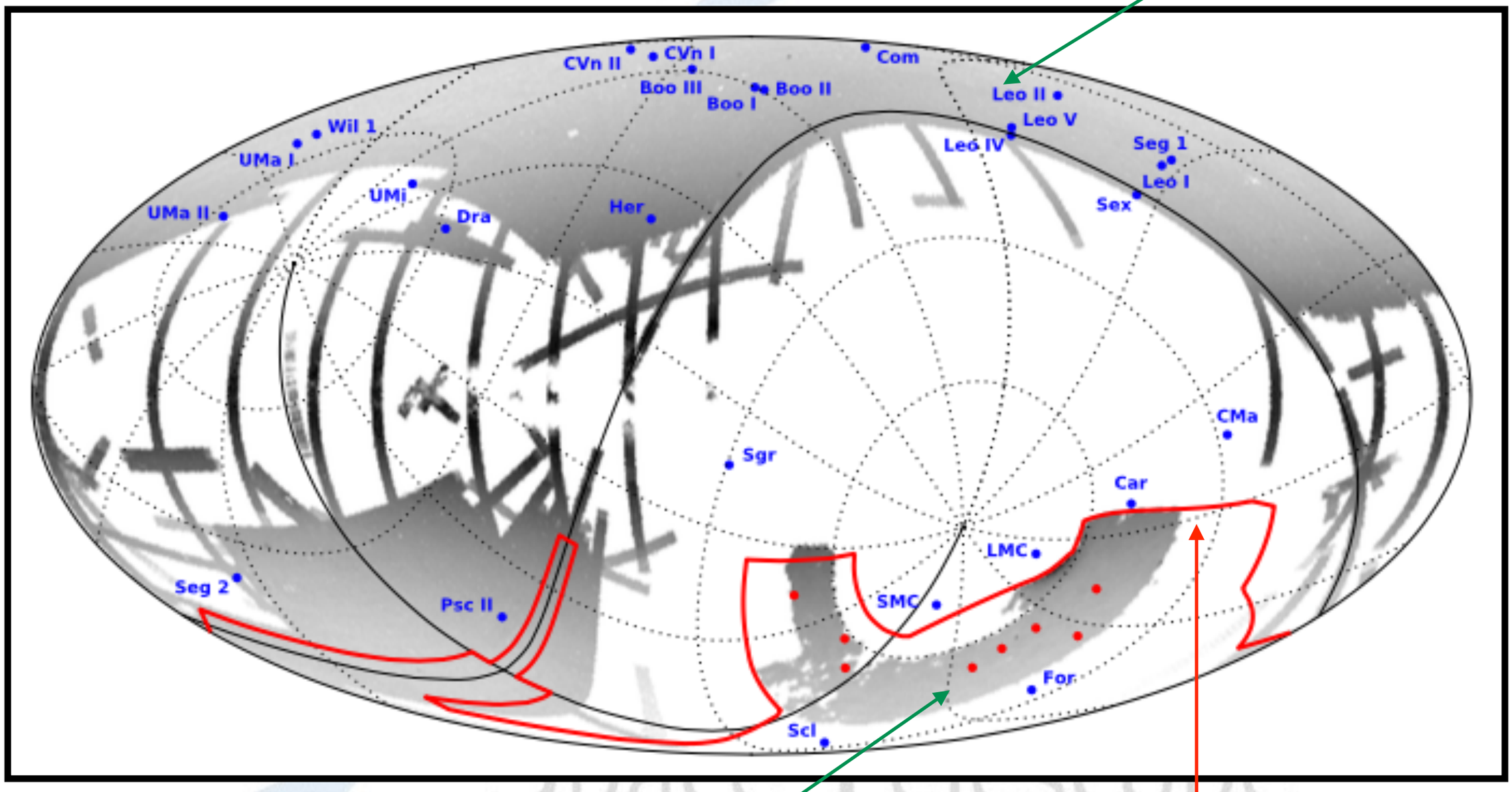
arXiv: 1503.02641

Dwarf Spheroidal Satellite Galaxies



DES Dwarf Candidates

SDSS sky coverage ~14k deg²



DES Year 1 Annual Release: new ~1.5k deg²

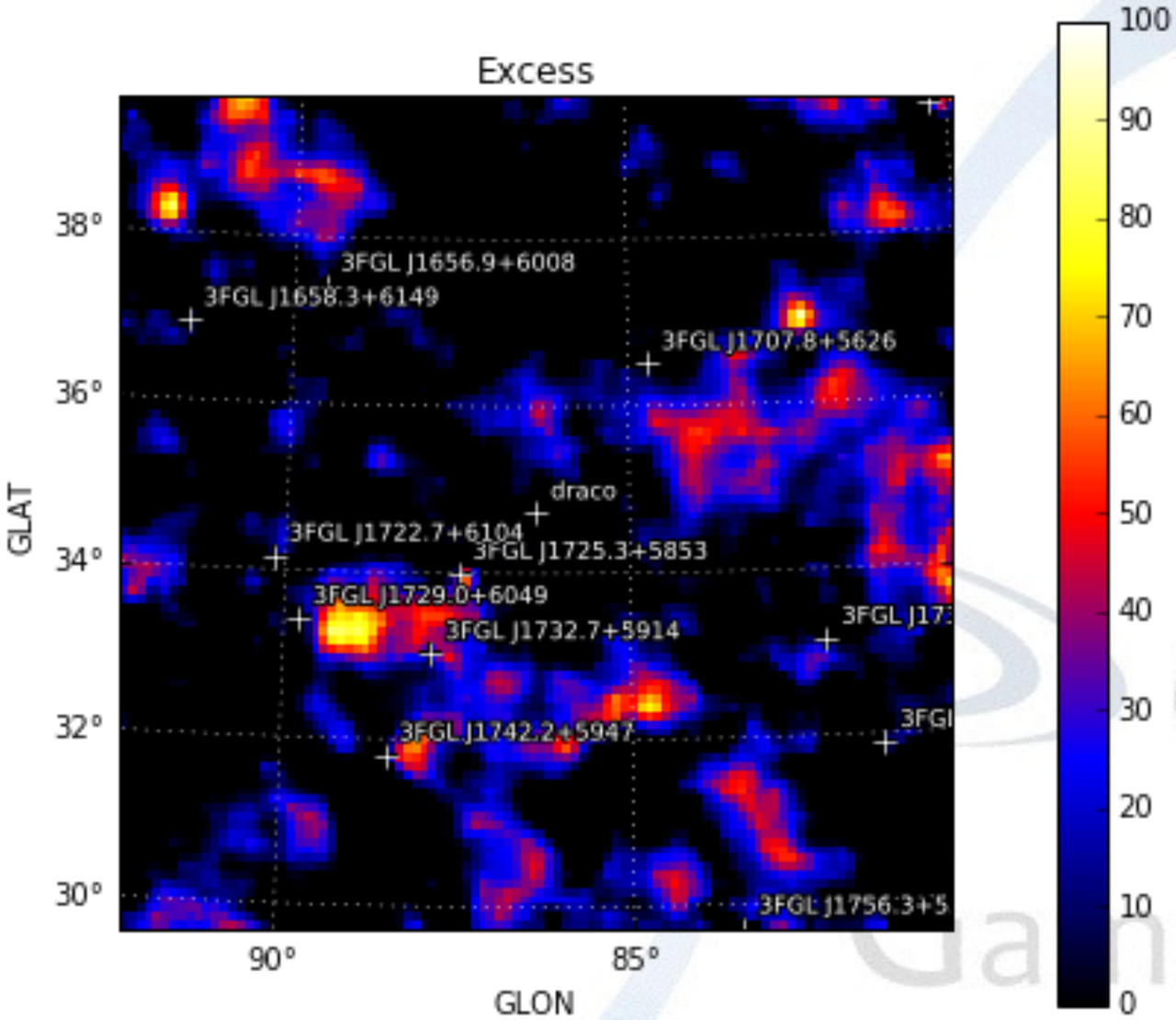
Total DES Survey: 5k deg²

Koposov et al: ApJ, 805:130 (2015), arXiv: 1503.02079

DES Collaboration: ApJ, 807:50 (2015), arXiv: 1503.02584

Dwarf Spheroidal Satellite Galaxies: Combined

Draco



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

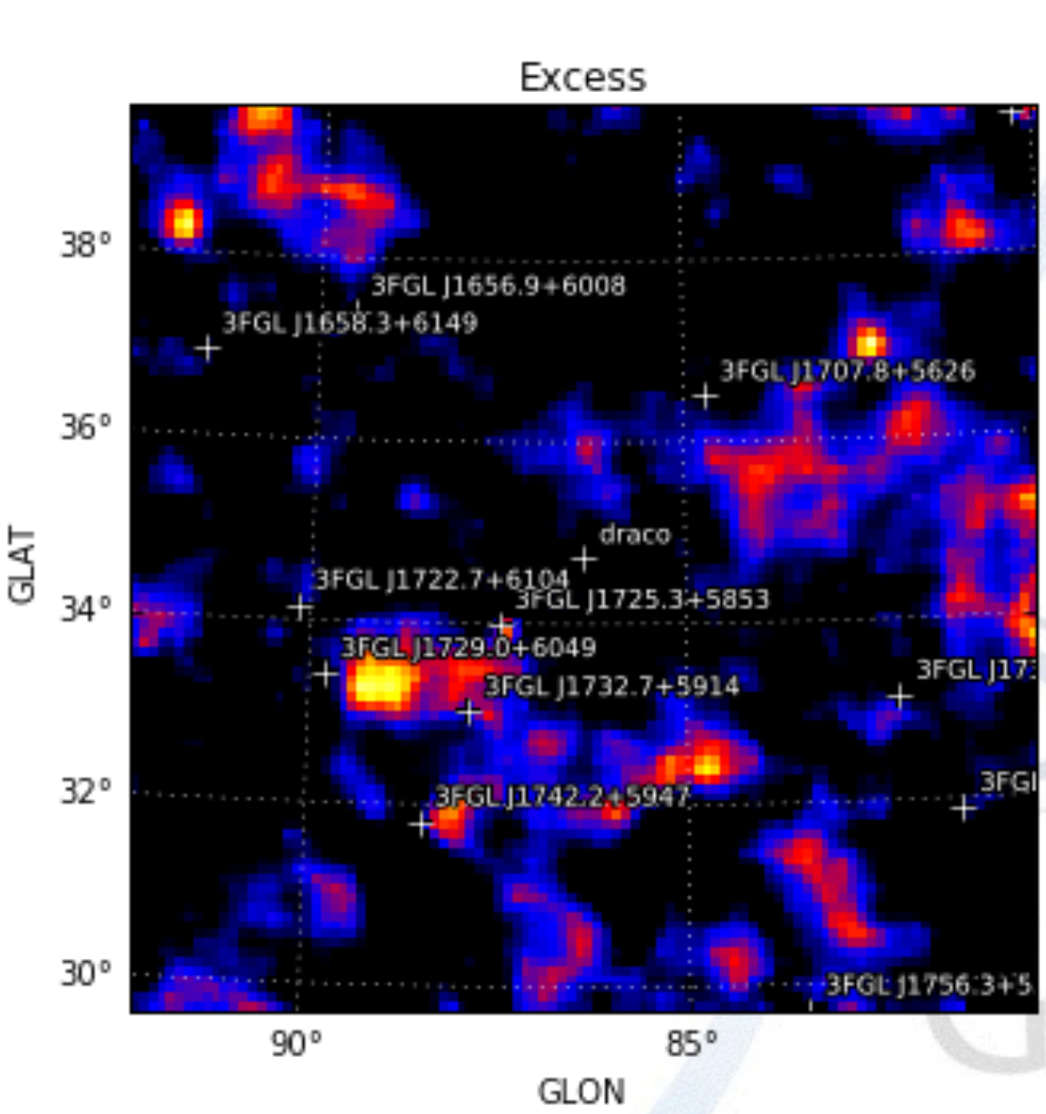
*ellipses have no uncertainties on the DM density in the Milky Way

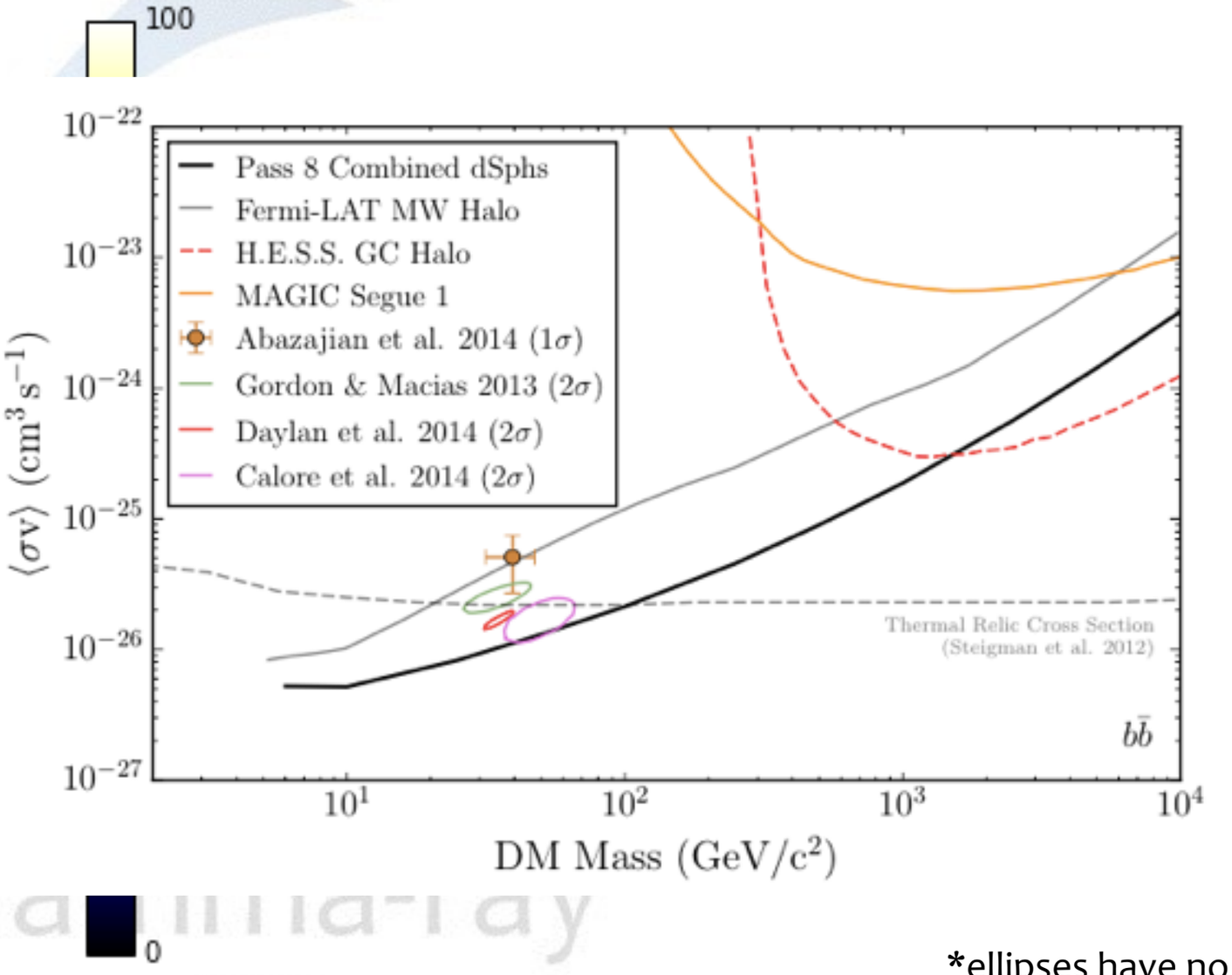
We actually got this working more or less…

Fermi-LAT Collaboration, PRL, arXiv: 1503.02641

Dwarf Spheroidal Satellite Galaxies: Combined

Draco





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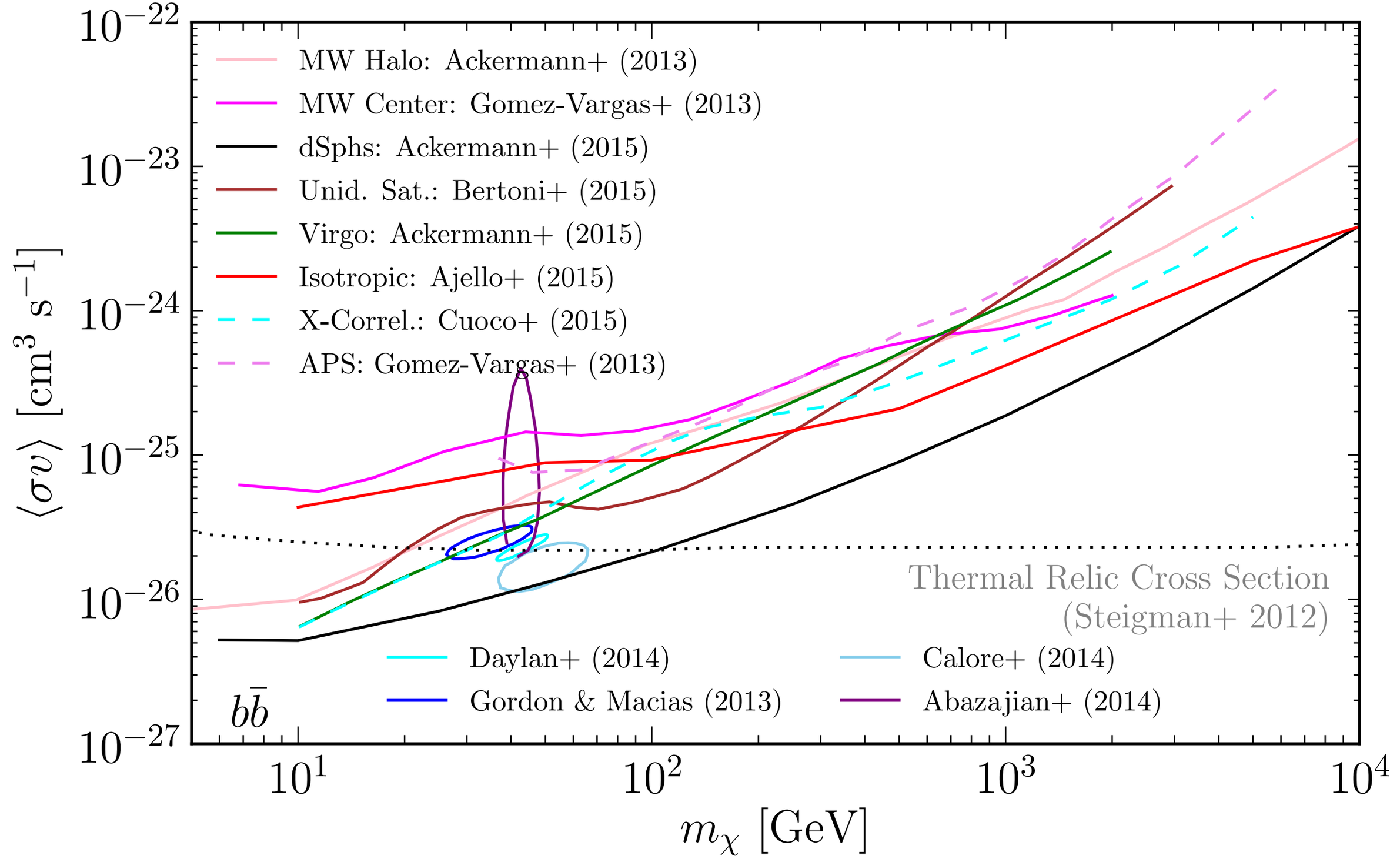
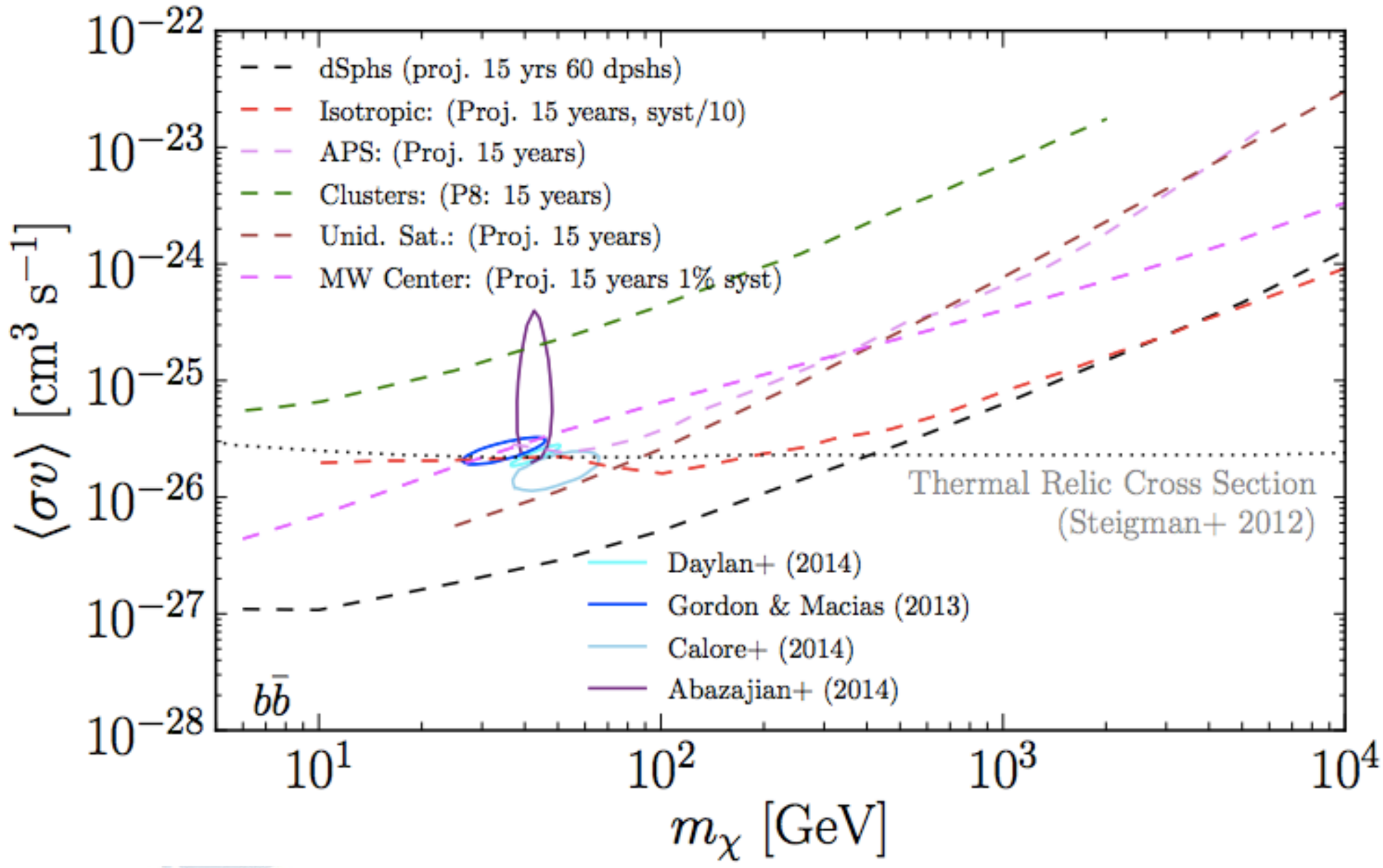
Summary of Fermi-LAT Dark Matter Searches



E. Charles et al, arXiv:1605.02016

Future WIMP Dark Matter Searches

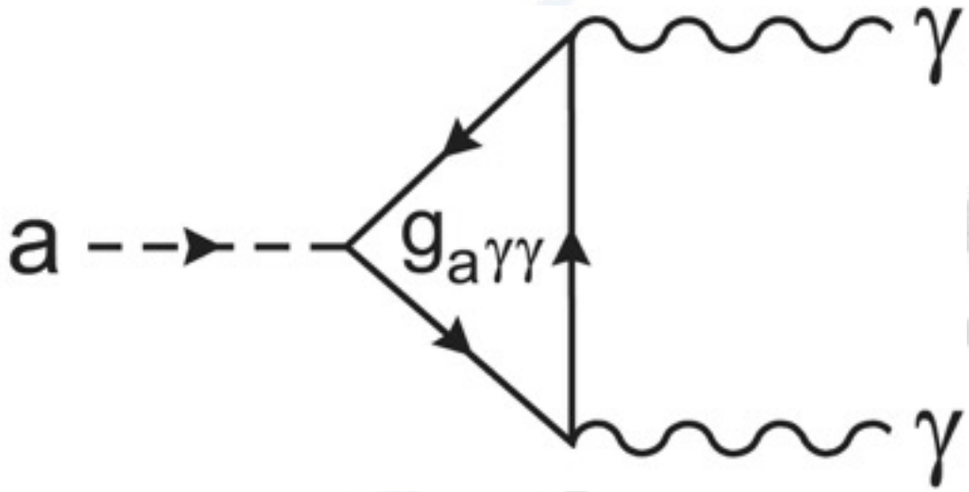


E. Charles et al, arXiv:1605.02016

And now for something completely different…

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**



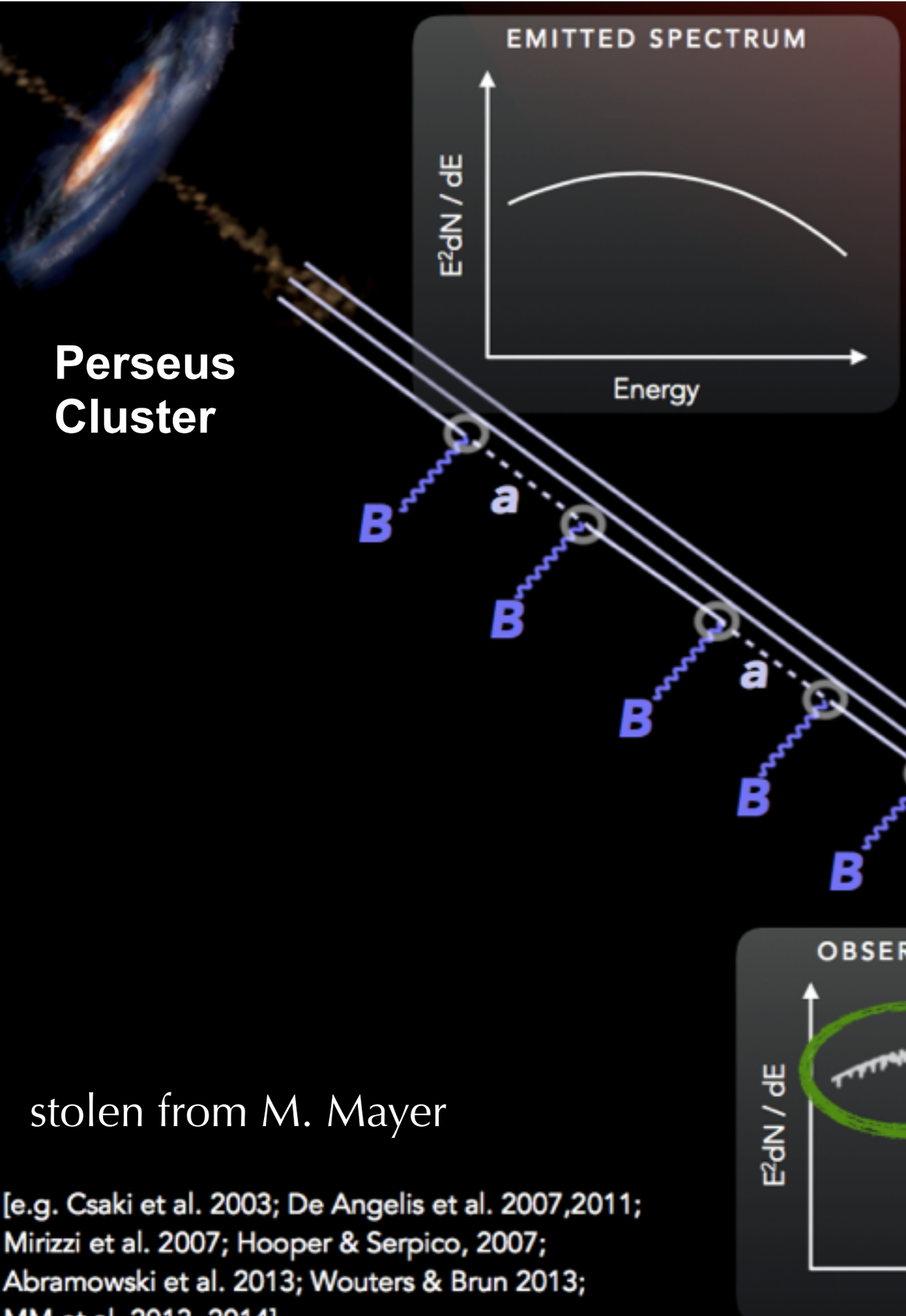
We can make strong magnets…
What else has a strong magnetic field?

- **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

- Interact with SM via photon-ALP oscillations
  - mass/photon coupling ind. parameters
  - DM candidate!
  - coupling to gamma-rays in astrophysical B fields
    - light ALPs $m_a \lesssim \mu eV$

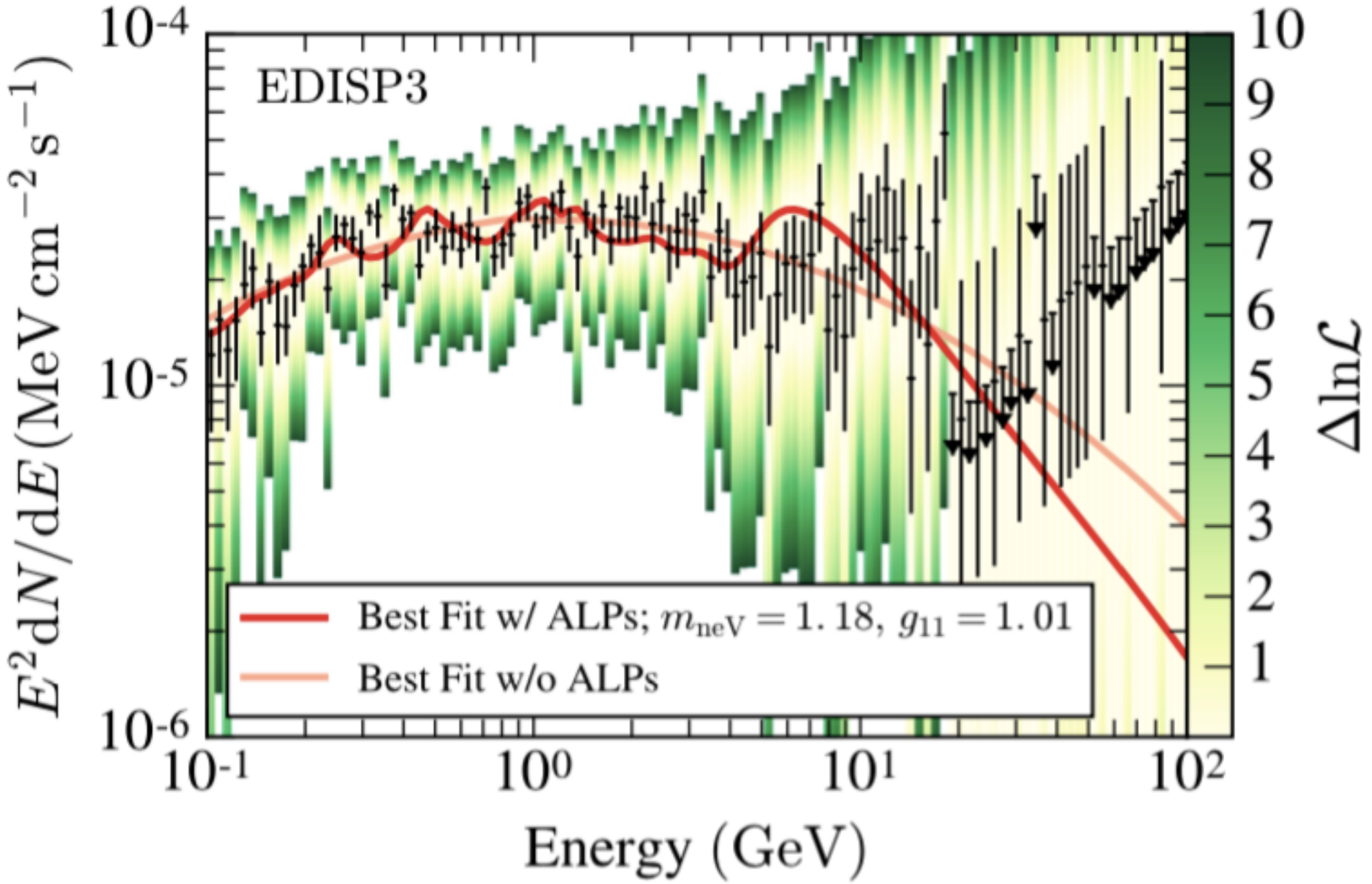


stolen from M. Mayer

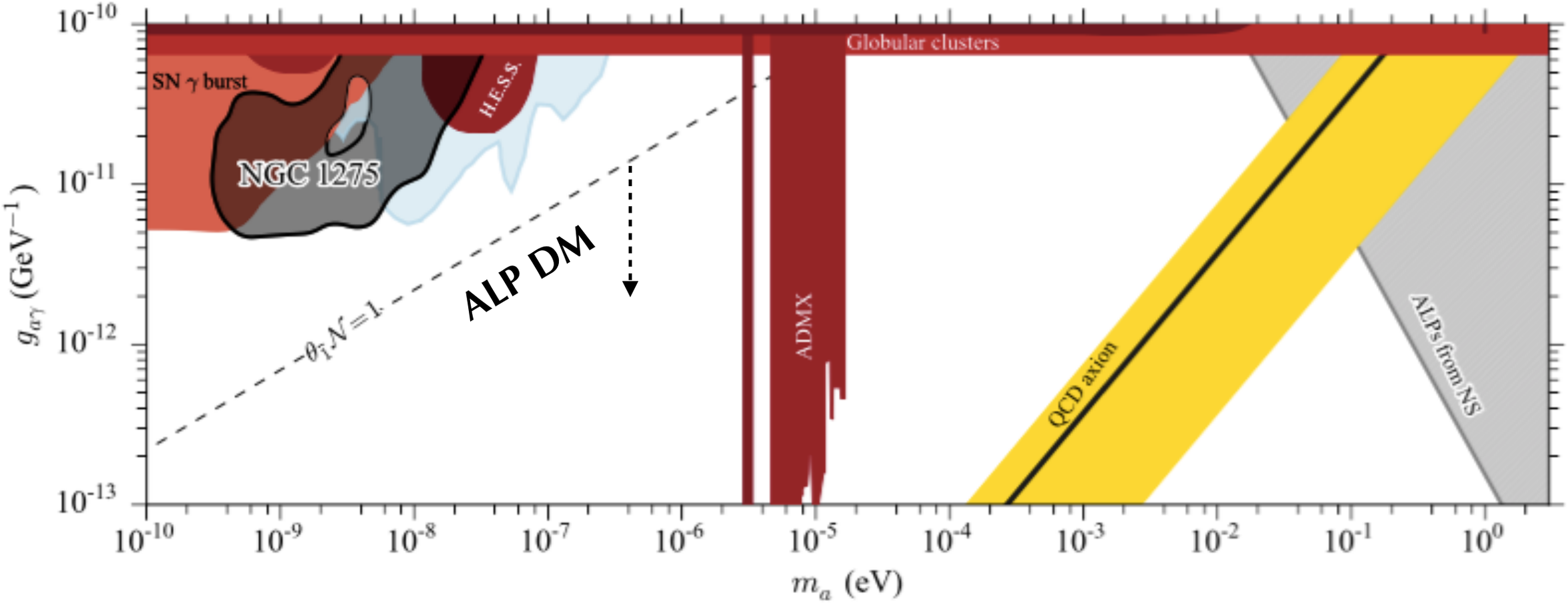
[e.g. Csaki et al. 2003; De Angelis et al. 2007,2011; Mirizzi et al. 2007; Hooper & Serpico, 2007; Abramowski et al. 2013; Wouters & Brun 2013; MM et al. 2013, 2014]

Light Curves

NGC 1275

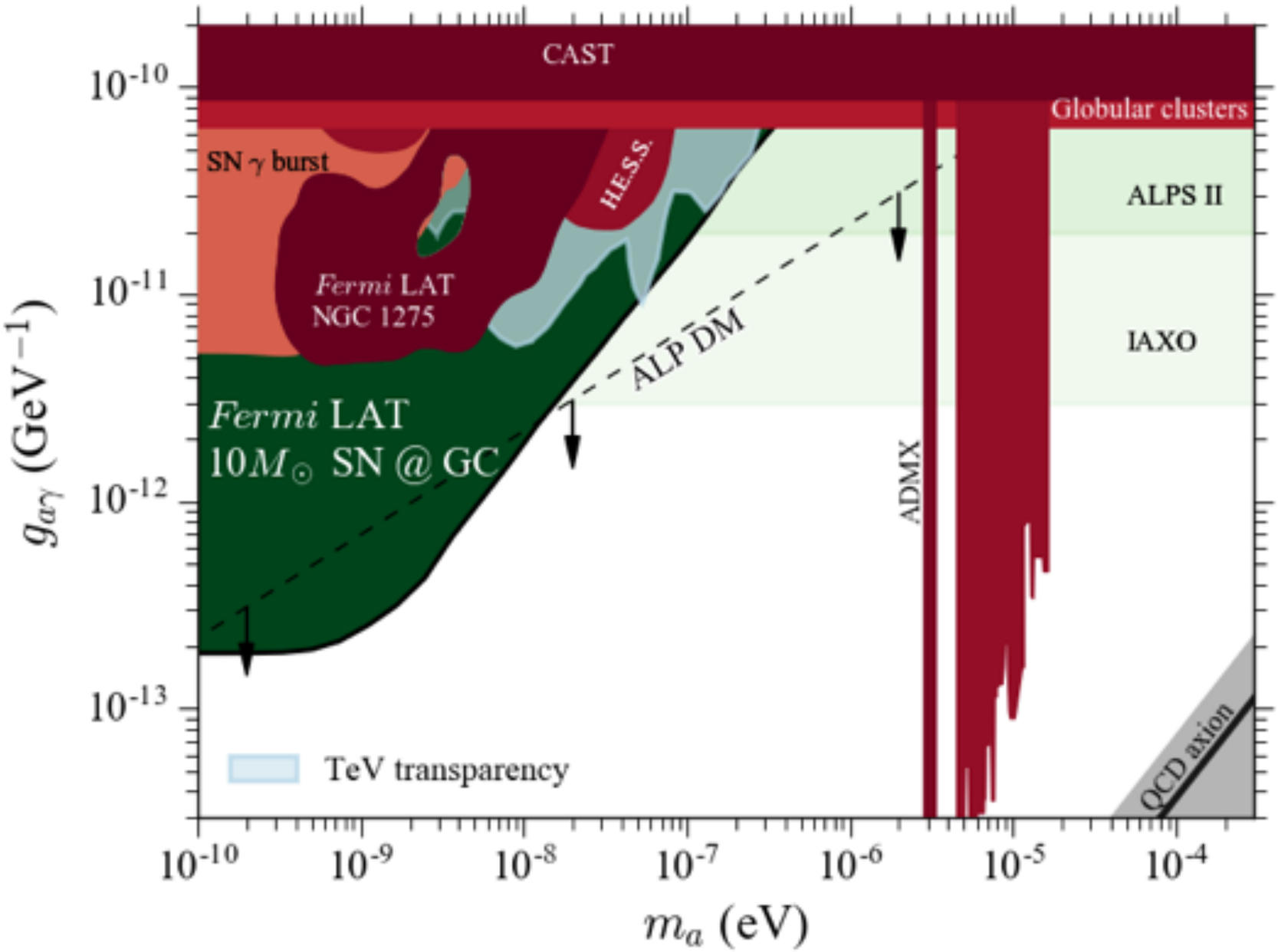


Current Axion Limits



MeV Dark Matter: Axions

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



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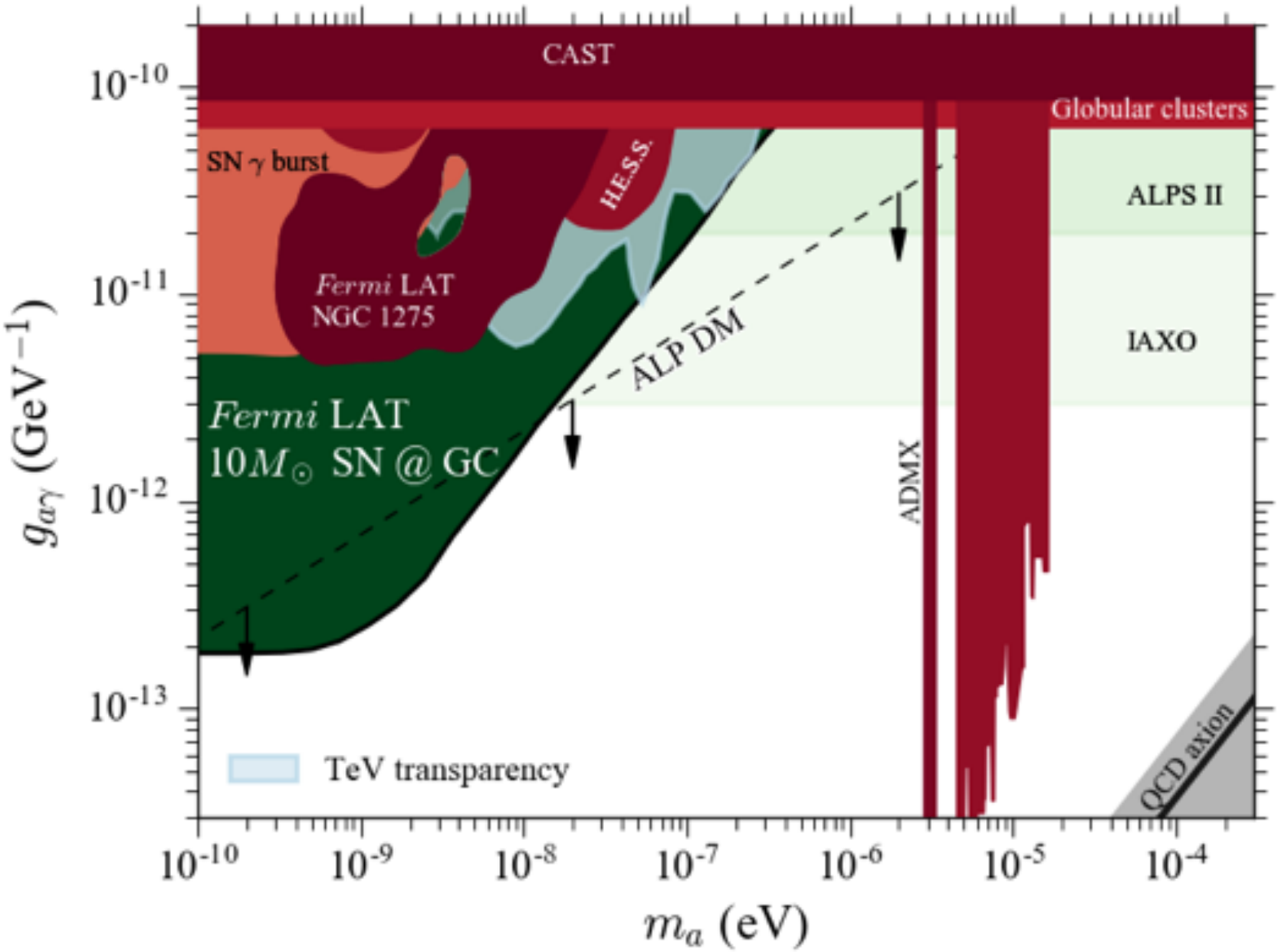
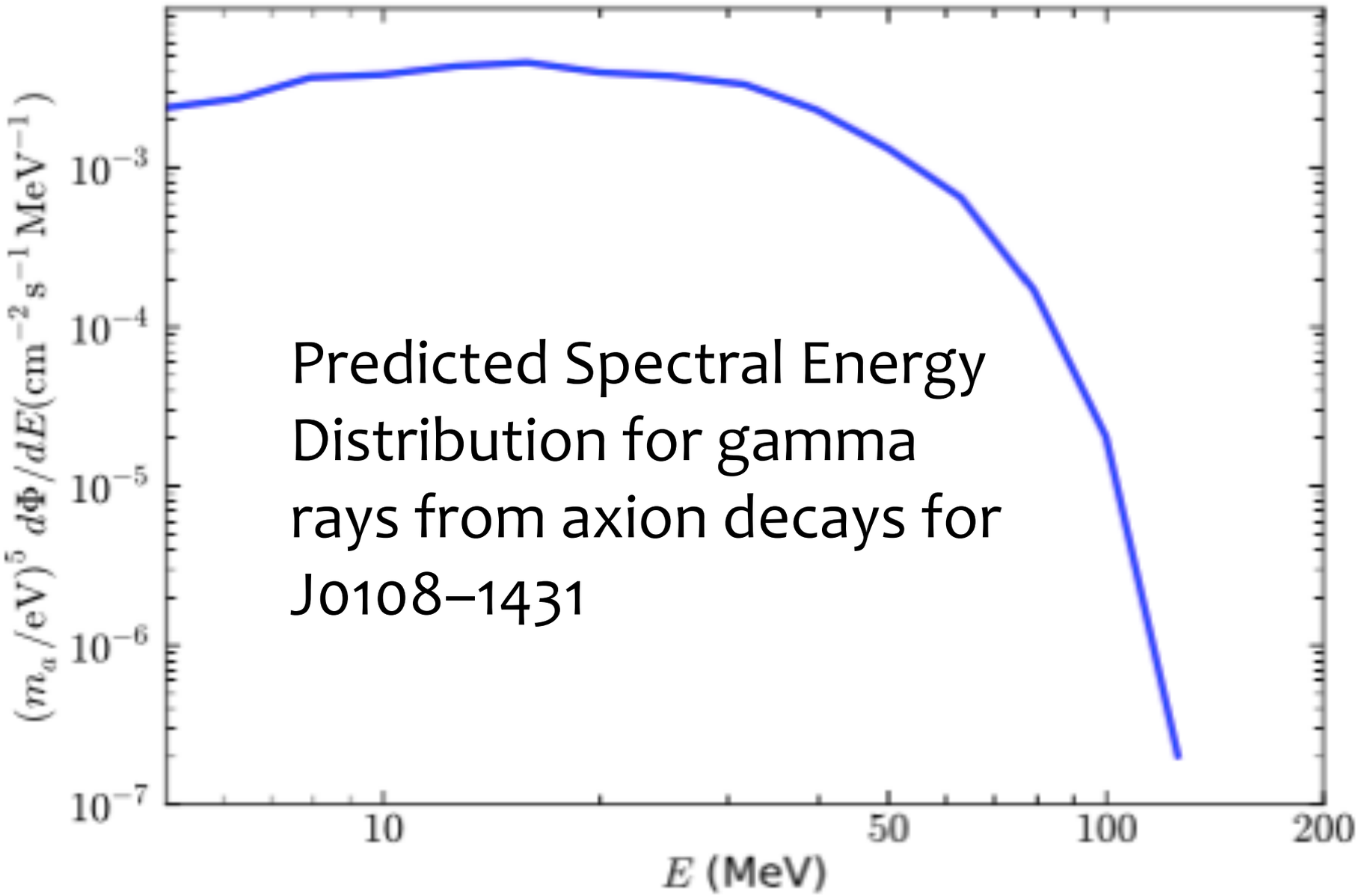


Limited by PSF @<100 MeV

Axions in Pulsars



Predicted Spectral Energy Distribution for gamma rays from axion decays for J0108–1431

arXiv:1602.00091

Pulsar Targets

What characteristics are we looking for in a good target?

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

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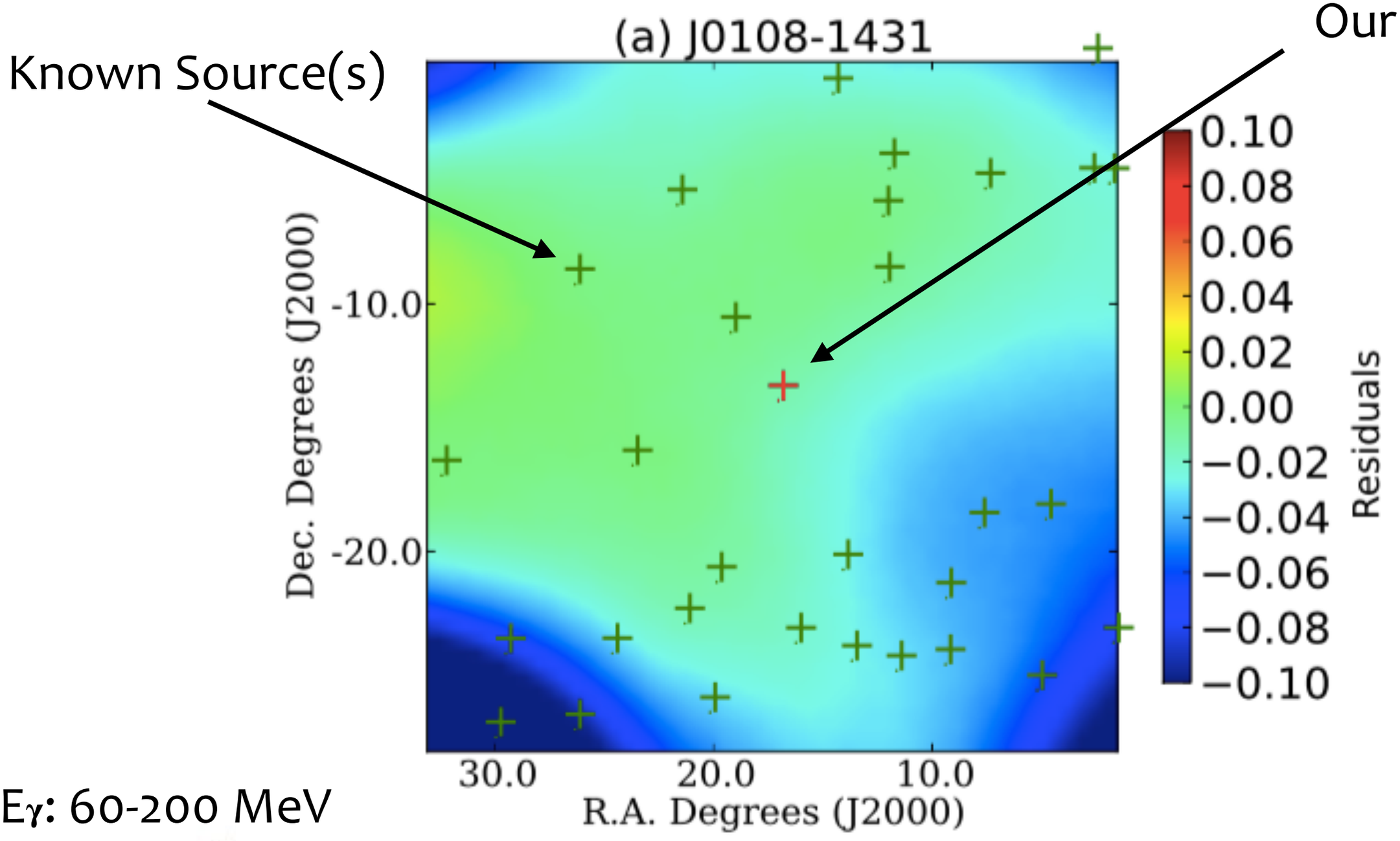
Close

Away from galactic plane

Measured B-Field

Pulsar Target!



E_γ: 60-200 MeV

No excess, set a limit: 7.9×10^{-2} eV

Fin

- **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!