Indirect Dark Matter Searches with *Fermi*-LAT

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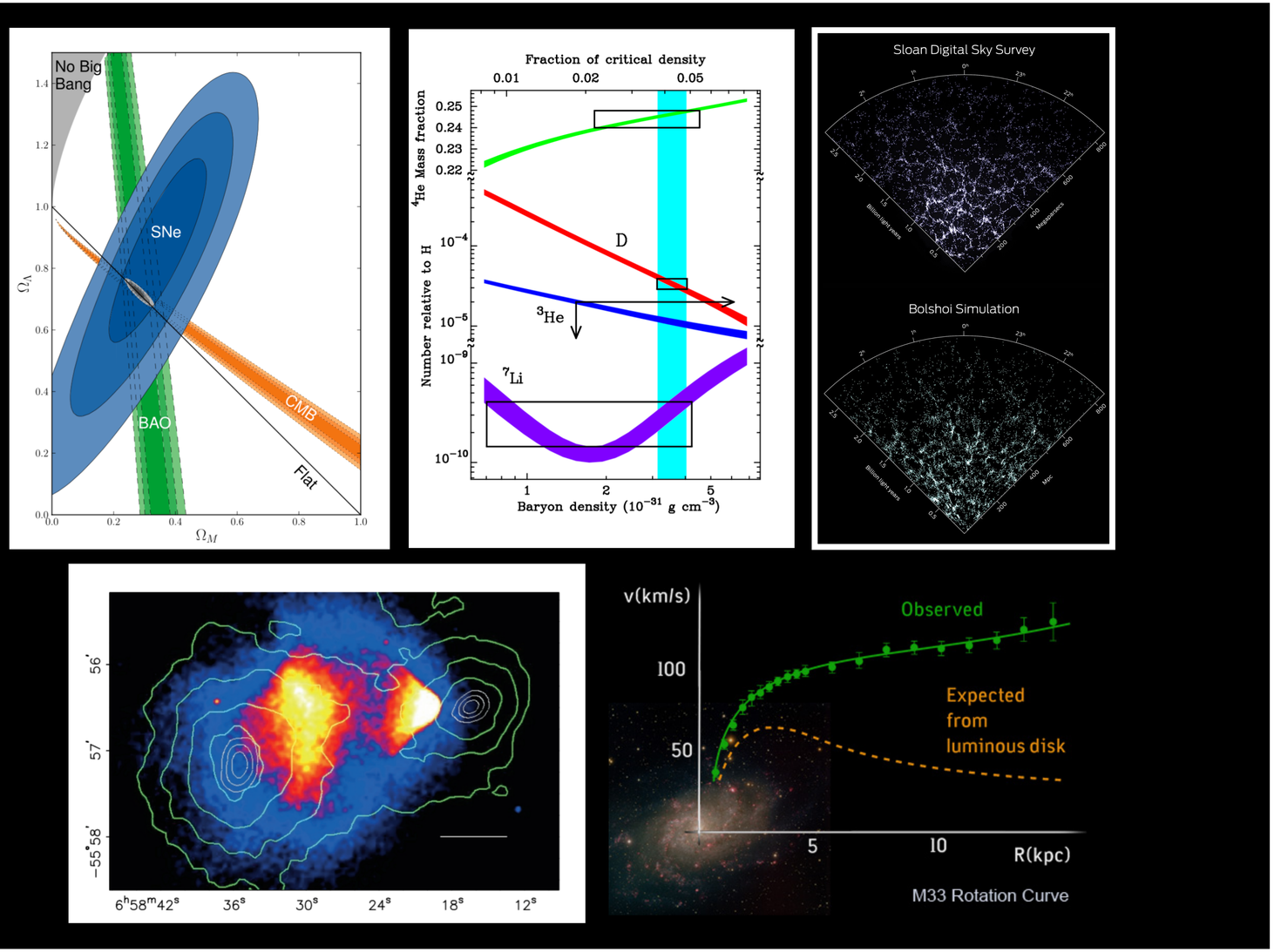
Würzburg Dark Matter Workshop
May 11, 2023

Outline

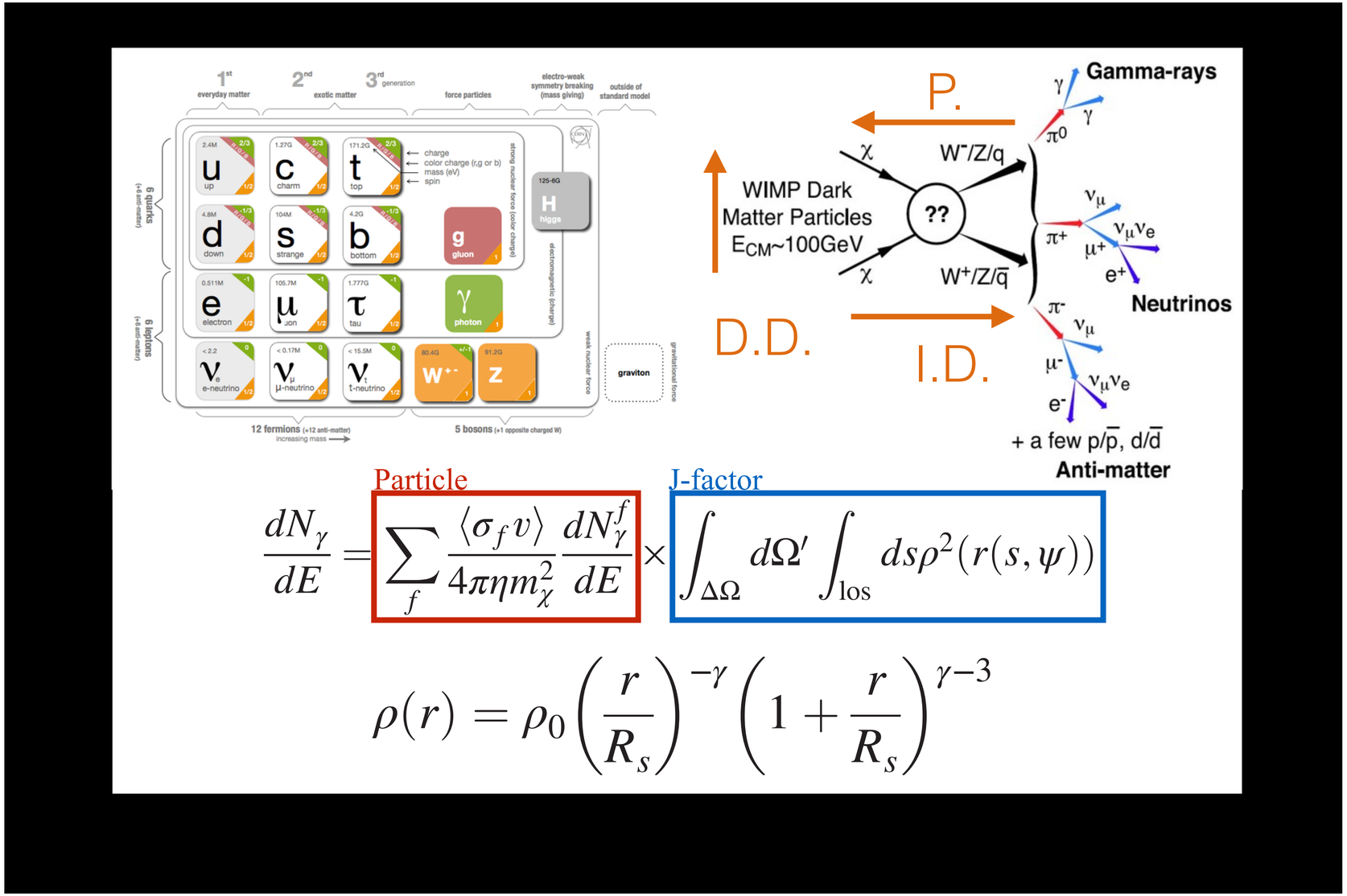
- Dark Matter (DM)
- The GC excess
- The Milky Way Dwarf Spheroidal Galaxies
- The Andromeda Galaxy
- Future Directions

The Dark Matter Paradigm



- Evidence for DM is found at all cosmological scales.
- Matter-energy density of the Universe:
  - Baryons: 4%
  - Dark Matter: 26%
  - Dark Energy: 70%

Detecting Dark Matter



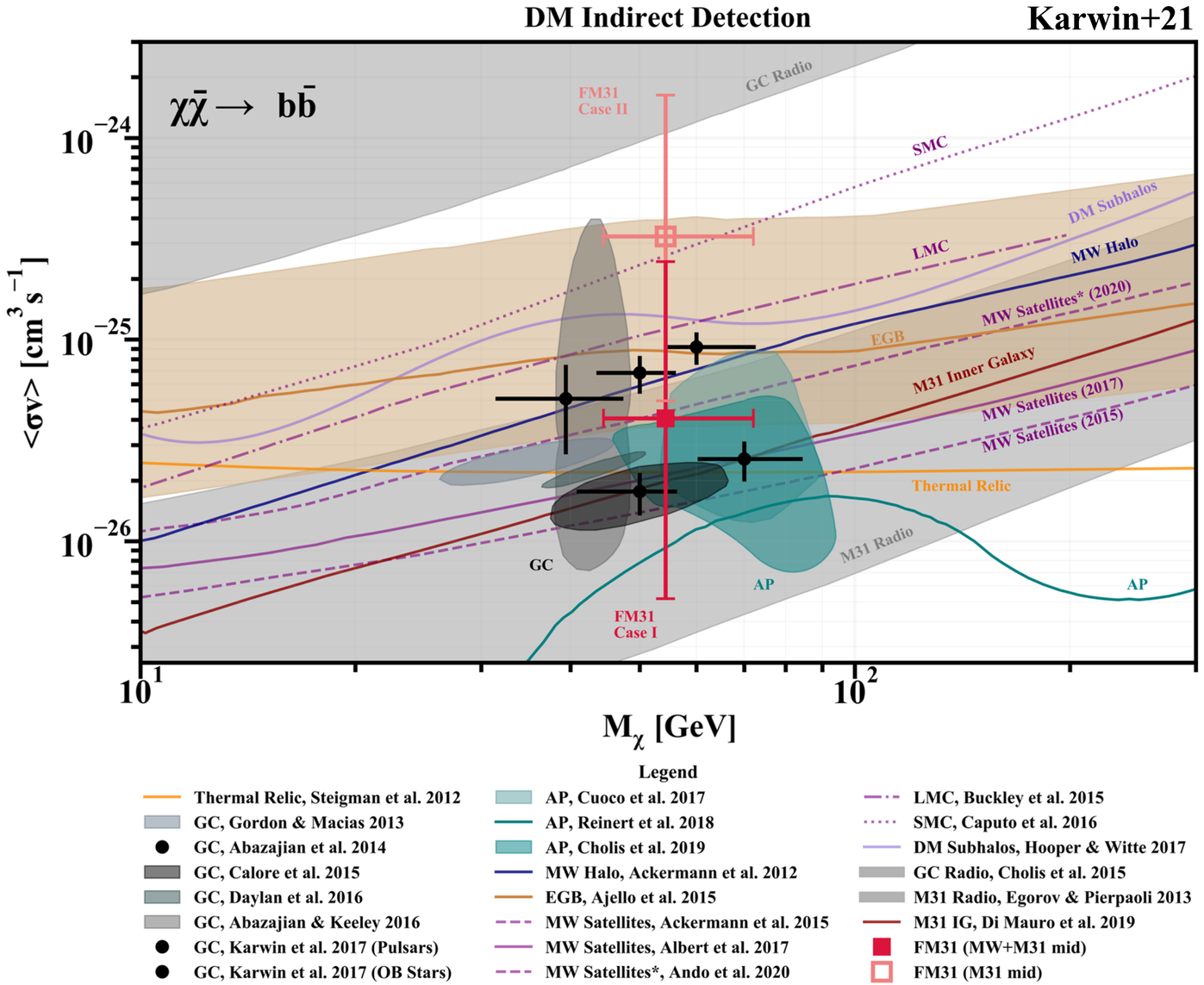
$$\frac{dN_\gamma}{dE} = \sum_f \frac{\langle \sigma_f v \rangle}{4\pi\eta m_\chi^2} \frac{dN_\gamma^f}{dE} \times \int_{\Delta\Omega} d\Omega' \int_{los} ds \rho^2(r(s,\psi))$$

Particle J-factor

$$\rho(r) = \rho_0 \left(\frac{r}{R_s}\right)^{-\gamma} \left(1 + \frac{r}{R_s}\right)^{\gamma-3}$$

- Historically, DM has been thought to likely be a particle.
- Discovering DM will require complementarity between different search methods and targets.

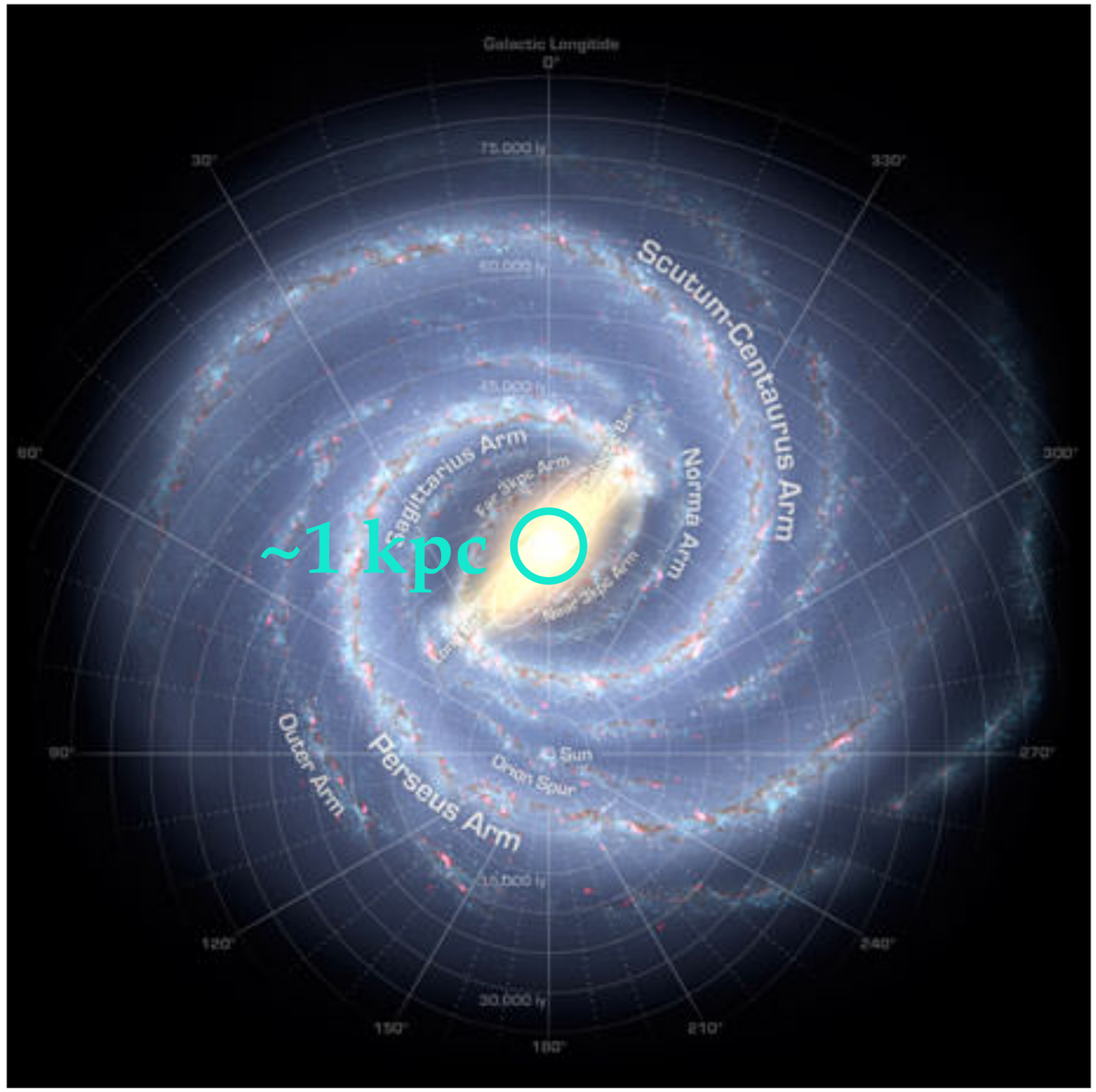
Overview of Dark Matter Searches



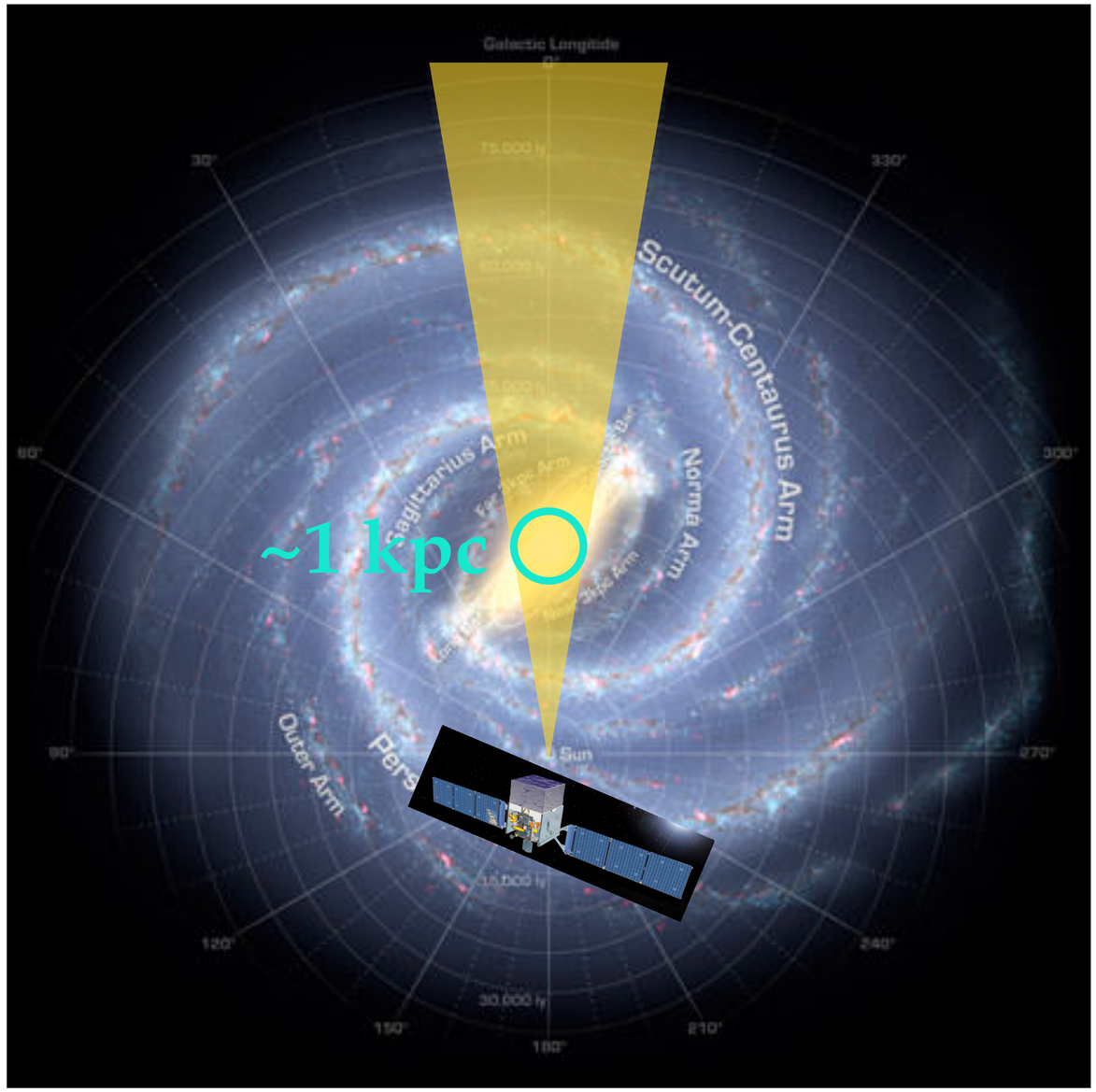
Numerous dark matter searches with the LAT:

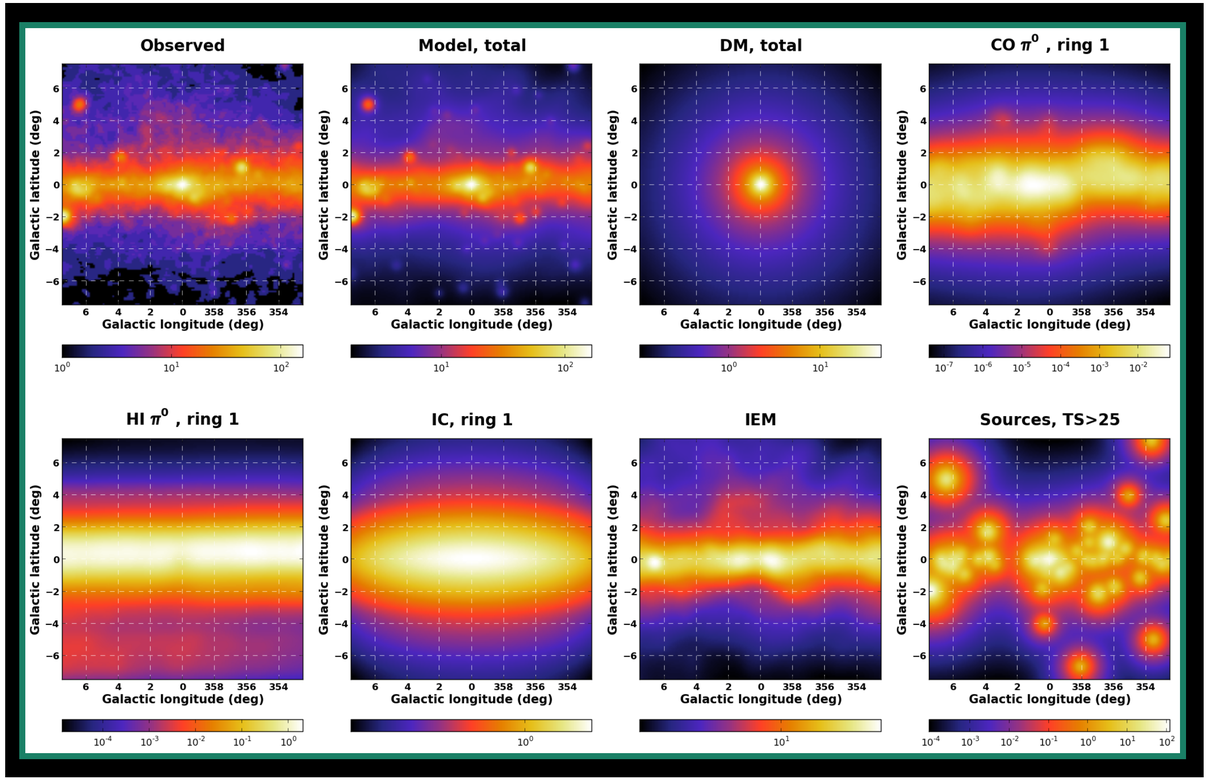
- Galactic center
- MW dwarf spheroidal galaxies
- LMC and SMC
- Dark matter sub-halos
- Milky Way halo
- M31 (center and halo)
- Extragalactic gamma-ray background

Observing the GC



Observing the GC



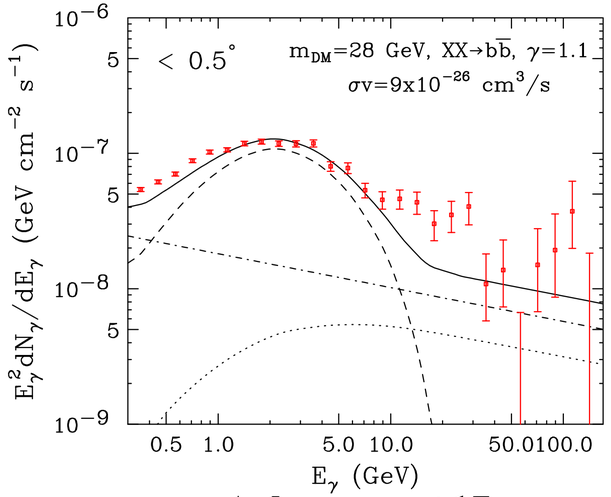


Karwin+2017

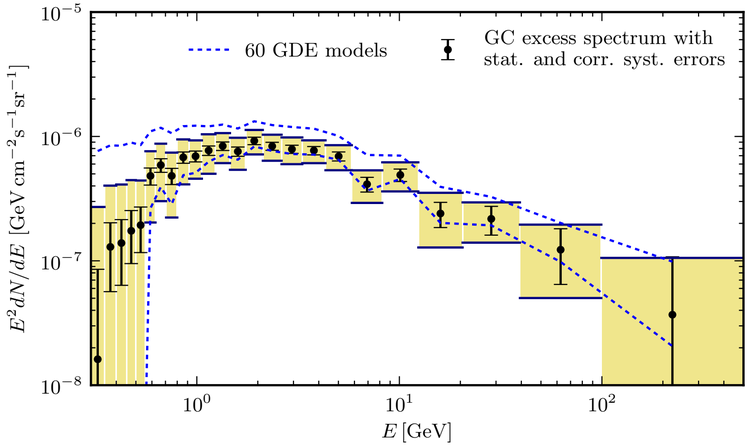
- **An excess above model predictions has been observed, although with significant systematic uncertainties.**
- Leading explanations include:
  1. Mis-modelling of the Galactic diffuse along the line of sight.
  2. An unresolved point source population, i.e. millisecond pulsars.
  3. DM annihilation.

The GC Excess Spectrum

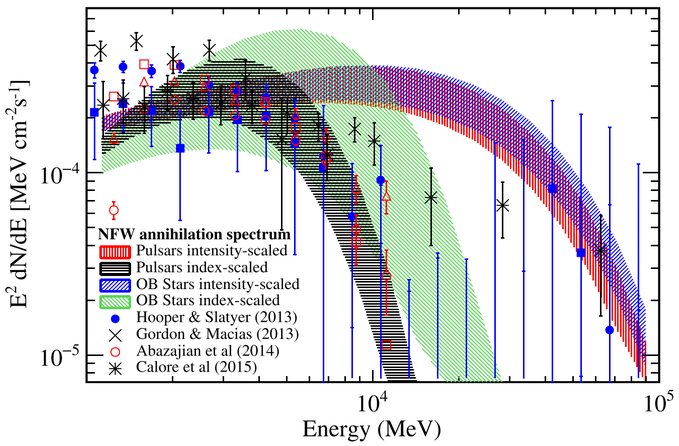
Goodenough & Hooper 2009



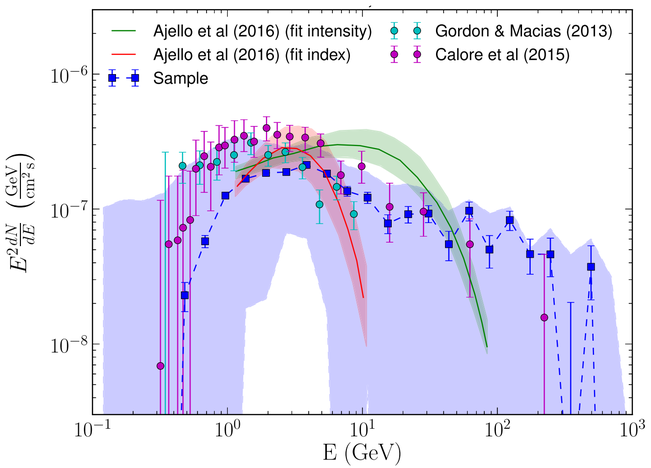
Calore+2015



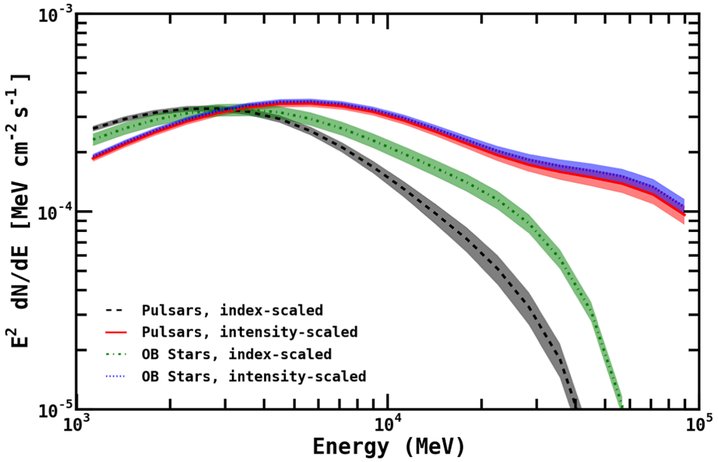
Ajello+16



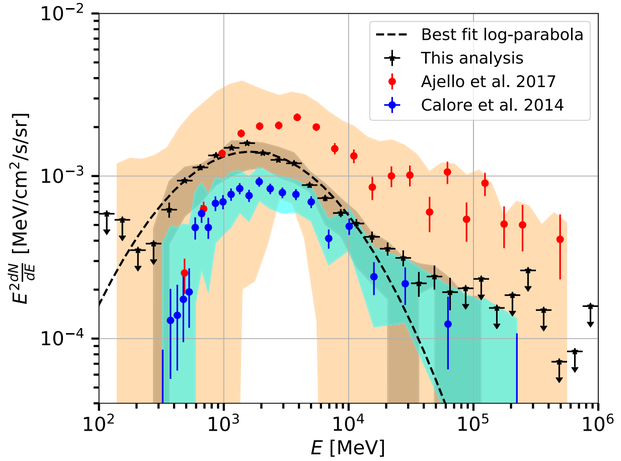
Ackermann+17



Karwin+2017



Di Mauro 21

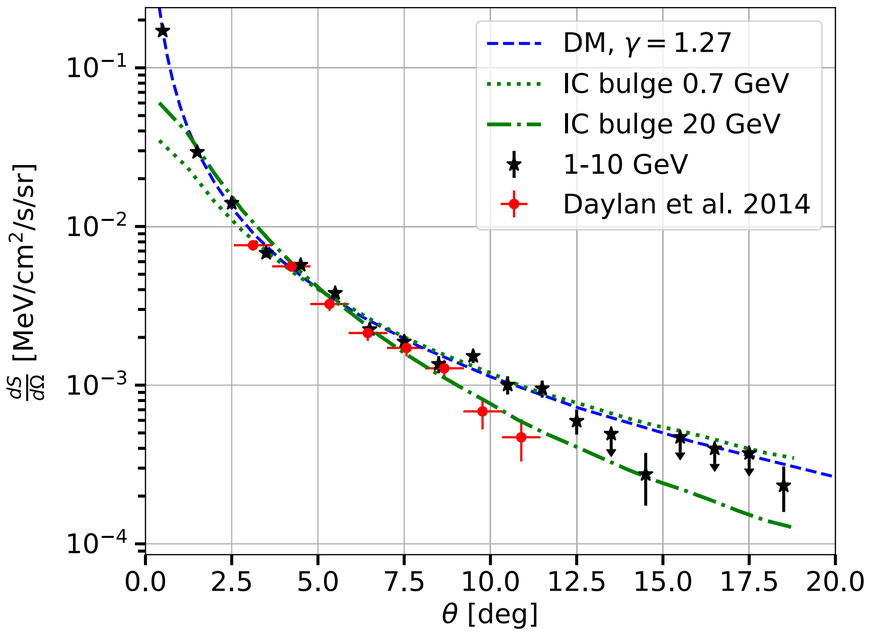


- It's generally agreed that there exists a systematic excess towards the GC.
- The uncertainty in the spectrum is dominated by systematics relating to the Galactic diffuse model.

Spherically Symmetric or Tracing Stellar Populations

Spherically Symmetric

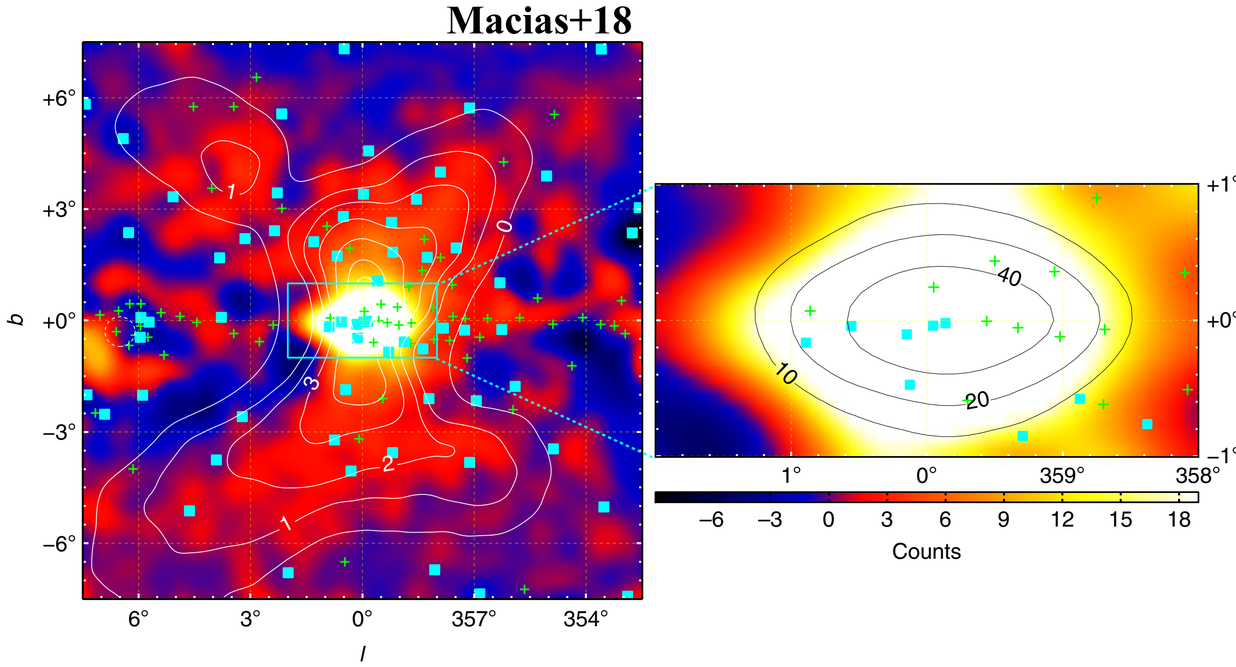
Di Mauro 21



- Consistent with an NFW profile with an inner slope of ~1.1-1.3
- Centroid is consistent with dynamical center of Galaxy, although may be slightly offset.

Tracing Stellar Populations

Macias+18



- Traces stellar populations in the X-shaped bulge, boxy bulge, and nuclear bulge.

Spherically Symmetric or Tracing Stellar Populations

Possible Evidence For Dark Matter Annihilation In The Inner Milky Way From The Fermi Gamma Ray Space Telescope

Lisa Goodenough[1] and Dan Hooper[2,3]

Oct 2009: https://arxiv.org/abs/0910.2998

Background model systematics for the Fermi GeV excess

Francesca Calore,[a] Ilias Cholis[b] and Christoph Weniger[a]

Mar 2015: https://arxiv.org/abs/1409.0042

Dark matter interpretation of the *Fermi*-LAT observation toward the Galactic Center

Christopher Karwin,[*] Simona Murgia,[†] and Tim M. P. Tait[‡]

May 2017: https://arxiv.org/abs/1612.05687

The Fermi-LAT GeV excess as a tracer of stellar mass in the Galactic bulge

Richard Bartels[1*], Emma Storm[1], Christoph Weniger[1] and Francesca Calore[2]

Oct 2018: https://arxiv.org/abs/1711.04778

Galactic bulge preferred over dark matter for the Galactic centre gamma-ray excess

Oscar Macias[1*], Chris Gordon[2], Roland M. Crocker[3], Brendan Coleman[2], Dylan Paterson[2], Shunsaku Horiuchi[1] and Martin Pohl[4,5]

May 2018: https://arxiv.org/abs/1611.06644

Strong evidence that the galactic bulge is shining in gamma rays

Oscar Macias,[a,b,c] Shunsaku Horiuchi,[a] Manoj Kaplinghat,[d] Chris Gordon,[e] Roland M. Crocker[f] and David M. Nataf[g]

Sep 2019: https://arxiv.org/abs/1901.03822

Characteristics of the Galactic Center excess measured with 11 years of *Fermi*-LAT data

Mattia Di Mauro[*]

March 2021: https://arxiv.org/abs/2101.04694

Assessing the Impact of Hydrogen Absorption on the Characteristics of the Galactic Center Excess

Martin Pohl[1,2], Oscar Macias[3,4], Phaedra Coleman[5], and Chris Gordon[5]

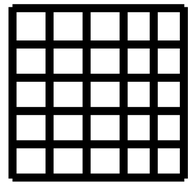
April 2022: https://arxiv.org/abs/2203.11626

A Phantom Menace: On the Morphology of the Galactic Center Excess

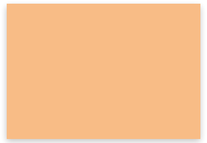
Samuel D. McDermott,[1] Yi-Ming Zhong,[2] and Ilias Cholis[3]

Sep 2022: https://arxiv.org/abs/2209.00006

Point-like (i.e. millisecond pulsars) or Smooth (i.e. DM)

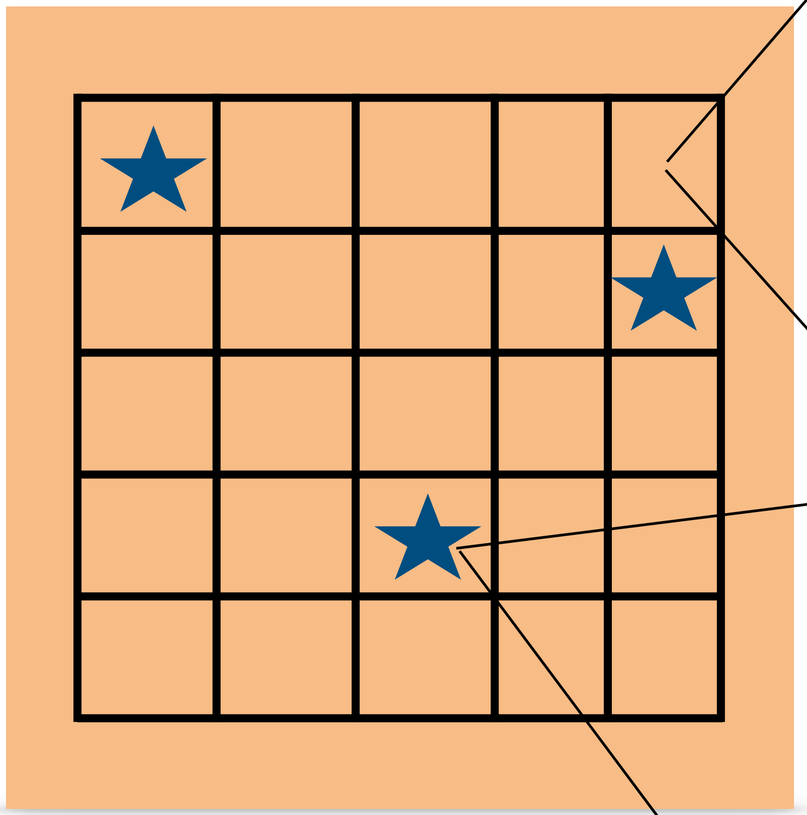


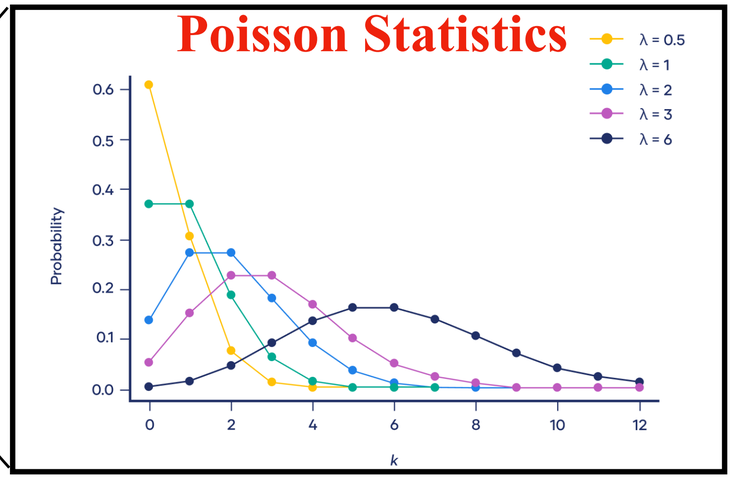
Spatial Pixels

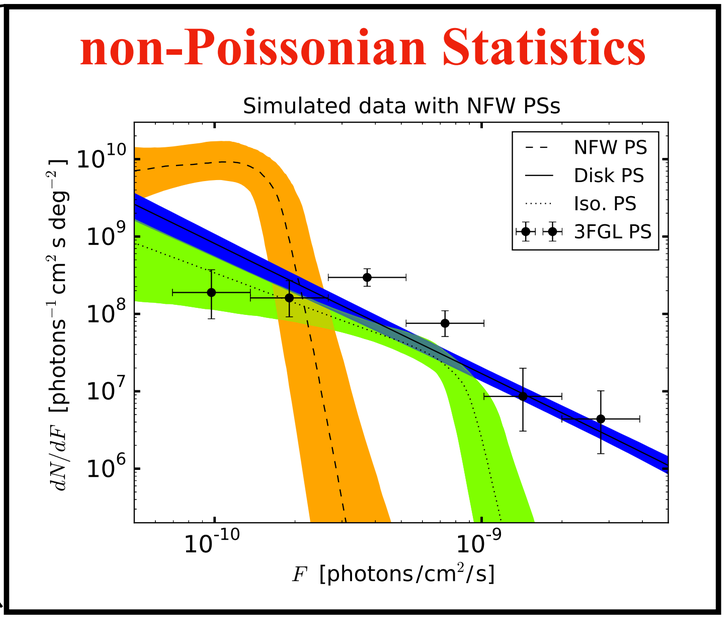


Smooth Emission Template

Unresolved point source







- Lee+16 developed a method to test for non-Poissonian photon statistics.
- They concluded that the GC excess favors a point-like interpretation.

Point-like (i.e. millisecond pulsars) or Smooth (i.e. DM)

Evidence for Unresolved γ-Ray Point Sources in the Inner Galaxy

Samuel K. Lee,[1,2] Mariangela Lisanti,[3] Benjamin R. Safdi,[4] Tracy R. Slatyer,[4] and Wei Xue[4]

Feb 2016: https://arxiv.org/abs/1506.05124

Strong Support for the Millisecond Pulsar Origin of the Galactic Center GeV Excess

Richard Bartels,[*] Suraj Krishnamurthy,[†] and Christoph Weniger[‡]

Feb 2016: https://arxiv.org/abs/1506.05104

Revival of the Dark Matter Hypothesis for the Galactic Center Gamma-Ray Excess

Rebecca K. Leane[1,*] and Tracy R. Slatyer[1,2,†]

Dec 2019: https://arxiv.org/abs/1904.08430

Characterizing the nature of the unresolved point sources in the Galactic Center: An assessment of systematic uncertainties

Laura J. Chang,[1] Siddharth Mishra-Sharma,[2] Mariangela Lisanti,[1] Malte Buschmann,[3] Nicholas L. Rodd,[4,5] and Benjamin R. Safdi[3]

Jan 2020: https://arxiv.org/abs/1908.10874

Testing the Sensitivity of the Galactic Center Excess to the Point Source Mask

Yi-Ming Zhong,[1] Samuel D. McDermott,[2] Ilias Cholis,[3] and Patrick J. Fox[2]

June 2020: https://arxiv.org/abs/1911.12369

Foreground mismodeling and the point source explanation of the Fermi Galactic Center excess

Malte Buschmann,[1] Nicholas L. Rodd,[2,3] Benjamin R. Safdi,[1] Laura J. Chang,[4] Siddharth Mishra-Sharma,[5] Mariangela Lisanti,[4] and Oscar Macias[6,7]

July 2020: https://arxiv.org/abs/2002.12373

The enigmatic Galactic Center excess: Spurious point sources and signal mismodeling

Rebecca K. Leane[*] and Tracy R. Slatyer[†]

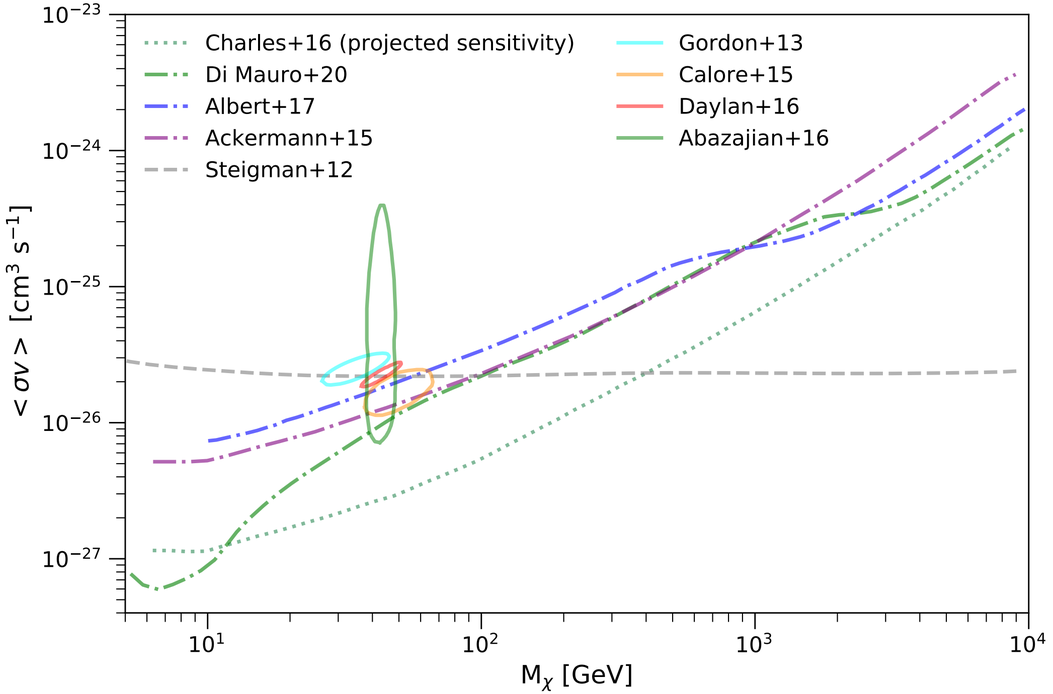
Sep 2020: https://arxiv.org/abs/2002.12371

The Status of the Galactic Center Gamma-Ray Excess

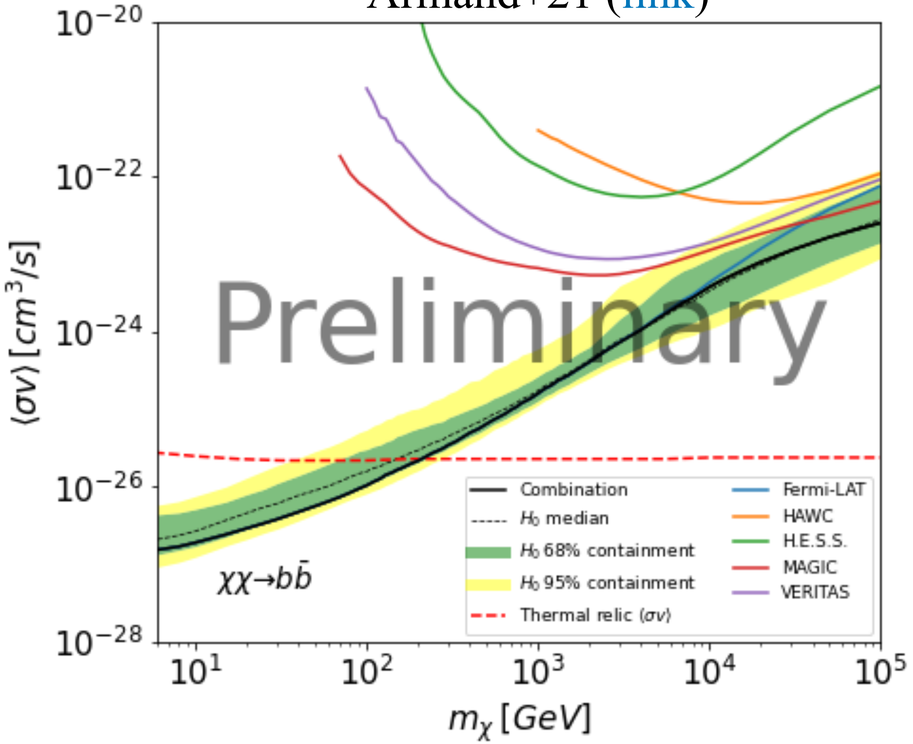
Dan Hooper

Sep 2022: https://arxiv.org/pdf/2209.14370.pdf

The Milky Way Dwarf Spheroidal Galaxies



Armand+21 (link)

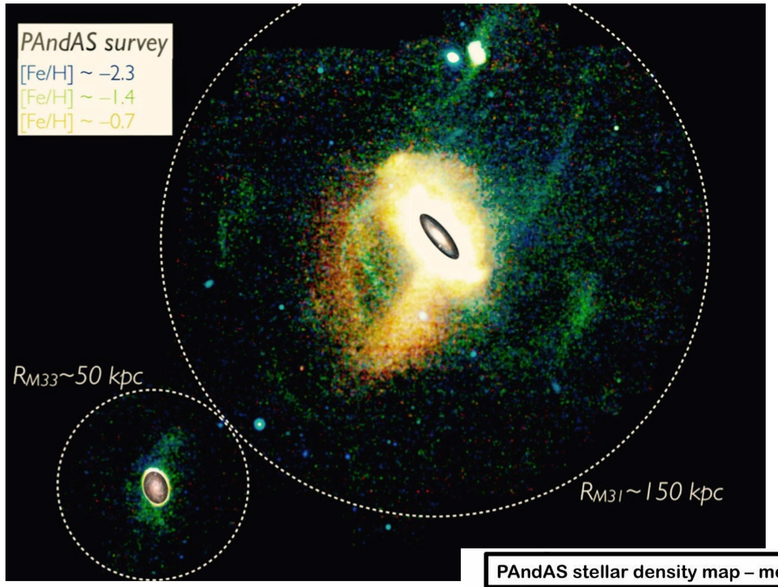


- Projected sensitivity is for 60 dwarfs and 15 years.
- Combined search in production with LAT, HAWC, HESS, MAGIC, and VERITAS.
- Also working on updated comprehensive dwarf analysis (following Albert+17) within LAT DMNP working group (led by myself, Alex McDaniel, and Marco Ajello), which will include:
  - More data
  - Most recent dwarf census
  - Improved handling of astrophysical mis-modeling
  - J-factor systematic uncertainty

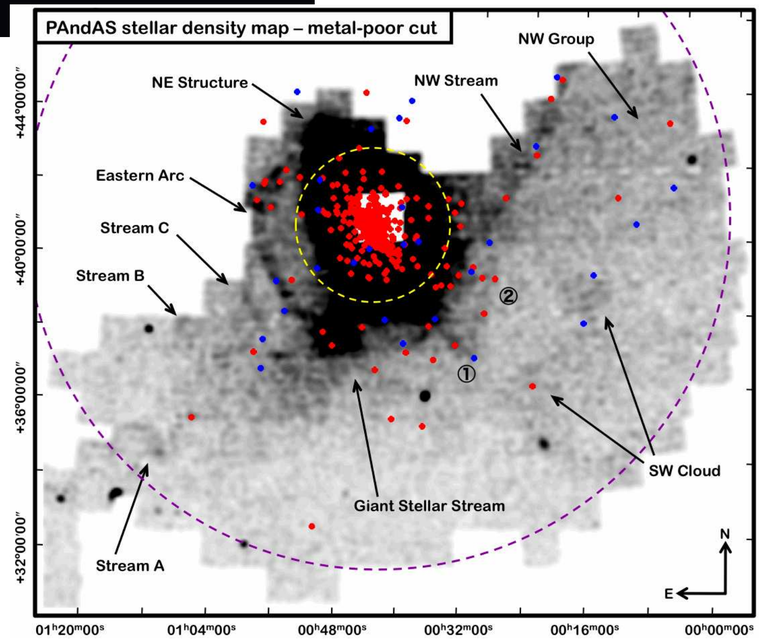
Credit: Miguel Claro

The Andromeda Galaxy

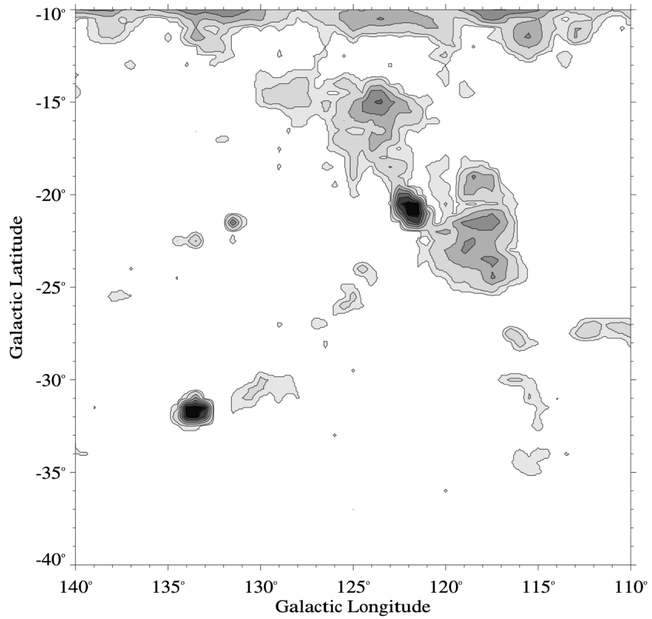
Inner galaxy

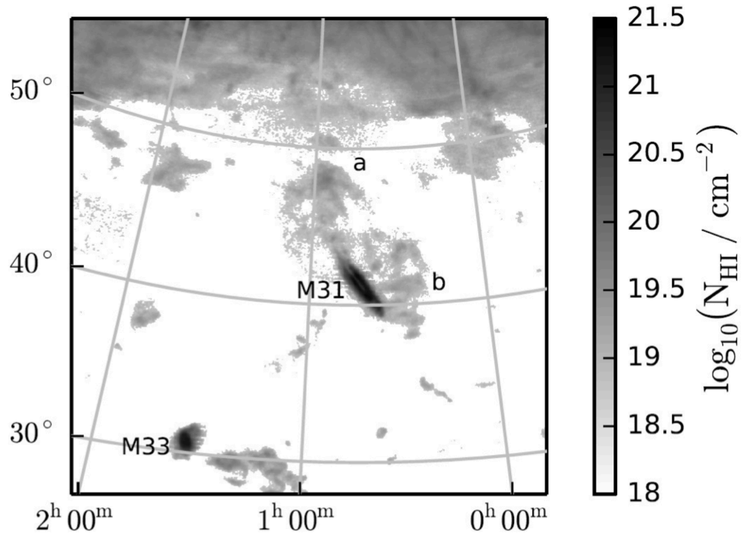


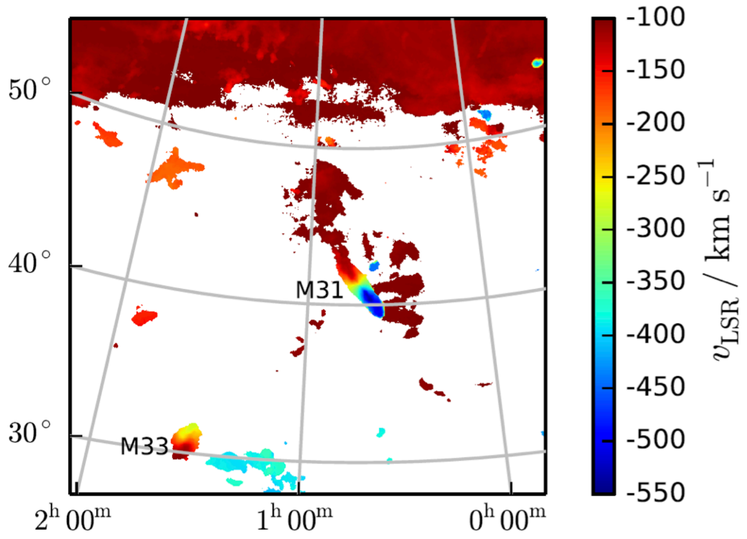
Outer halo



The Andromeda Galaxy







HIGH-VELOCITY CLOUDS: BUILDING BLOCKS OF THE LOCAL GROUP

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Received 1998 February 20; accepted 1998 November 9

A survey of HI gas toward the Andromeda galaxy

J. Kerp[1], P. M. W. Kalberla[1], N. Ben Bekhti[1], L. Flöer[1], D. Lenz[1], and B. Winkel[2, 1]

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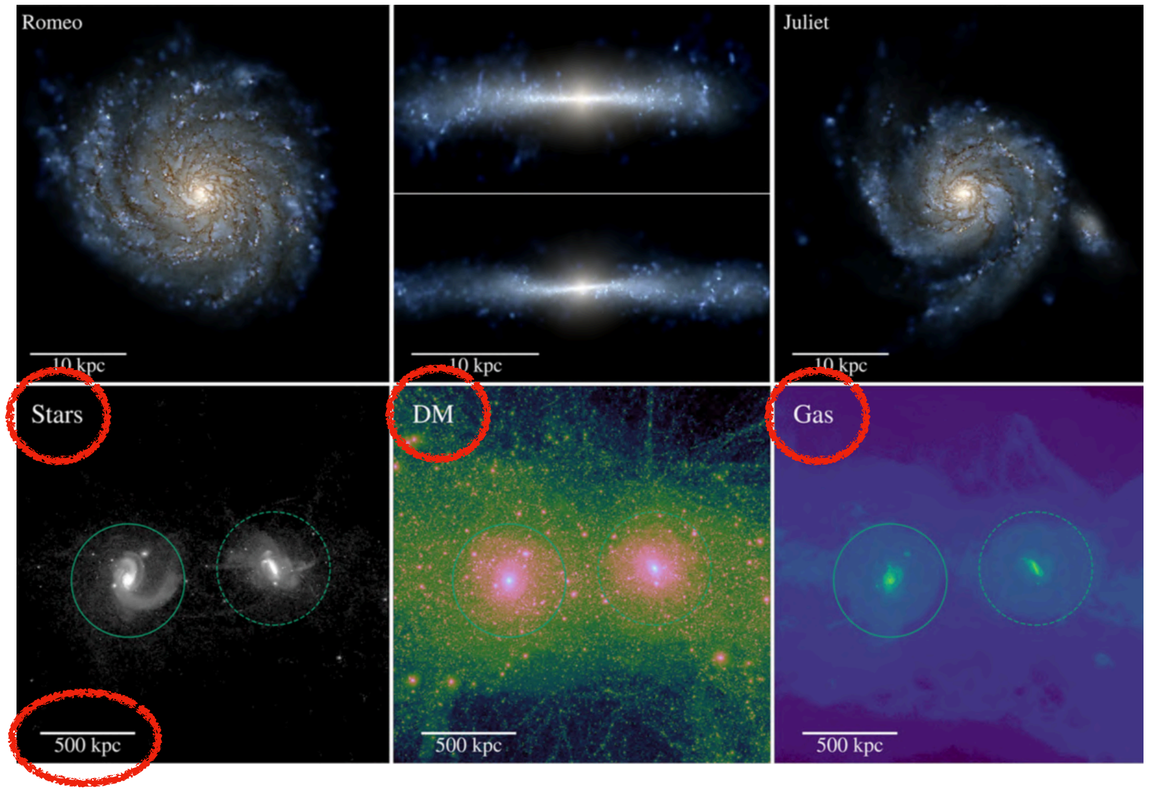
[2] Max-Planck-Institut für Radioastronomie, Auf dem Hügel 69, 53121 Bonn, Germany

Received 23 April 2015 / Accepted 16 February 2016

The M31 System

The big picture (illustrative)

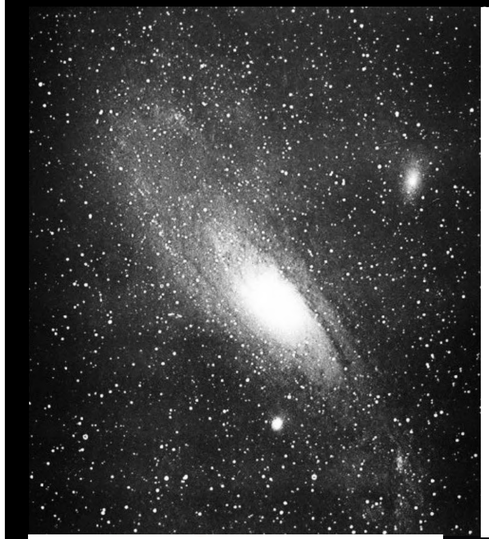


MW-M31-Like Pairs (for example) from Garrison-Kimmel et al. 2018 (link)

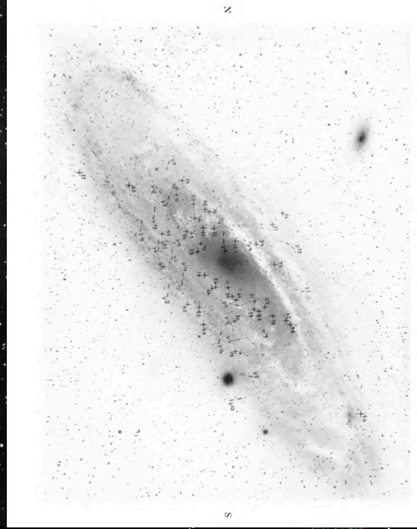
- The entire M31 DM halo is seen from the outside, so we see the extended integral signal. For the MW we see through the halo, so it can be easily confused with diffuse components.
- Line of sight ostensibly includes:
  M31 DM halo + secondary M31 emission + local DM filament between M31 and MW + MW DM halo.

The Andromeda Galaxy

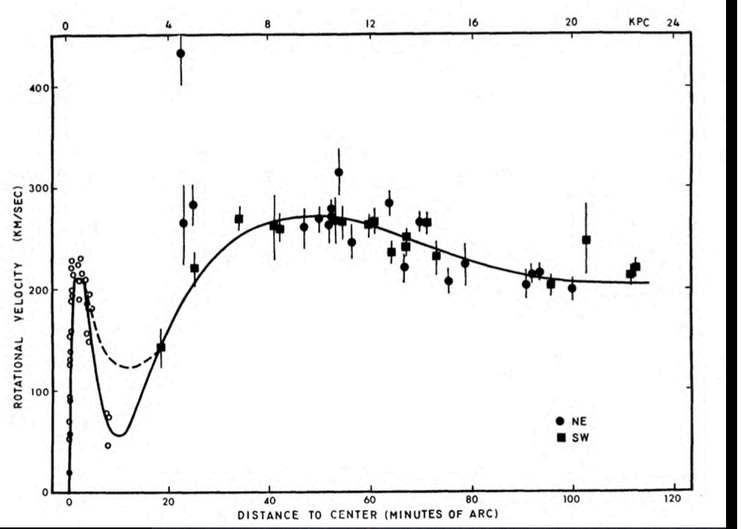
Roberts 1893

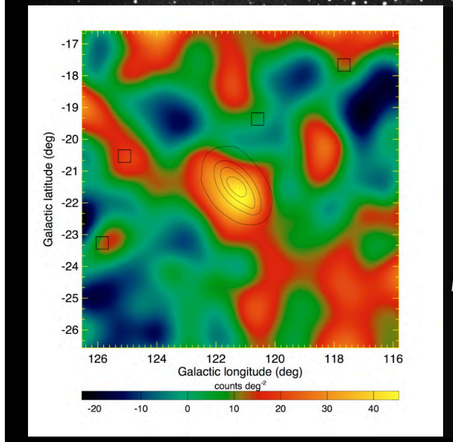


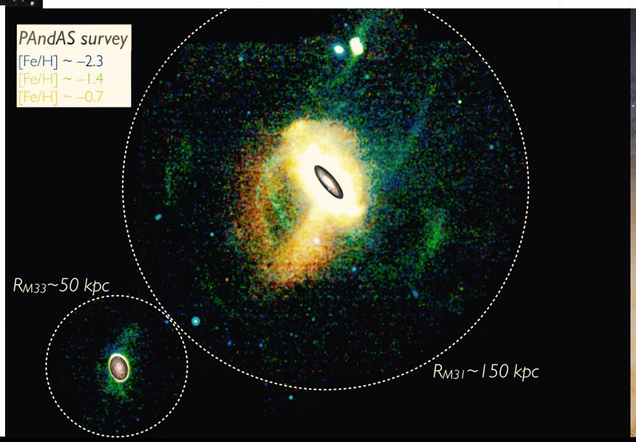
Hubble 1929



Rubin and Ford 1970





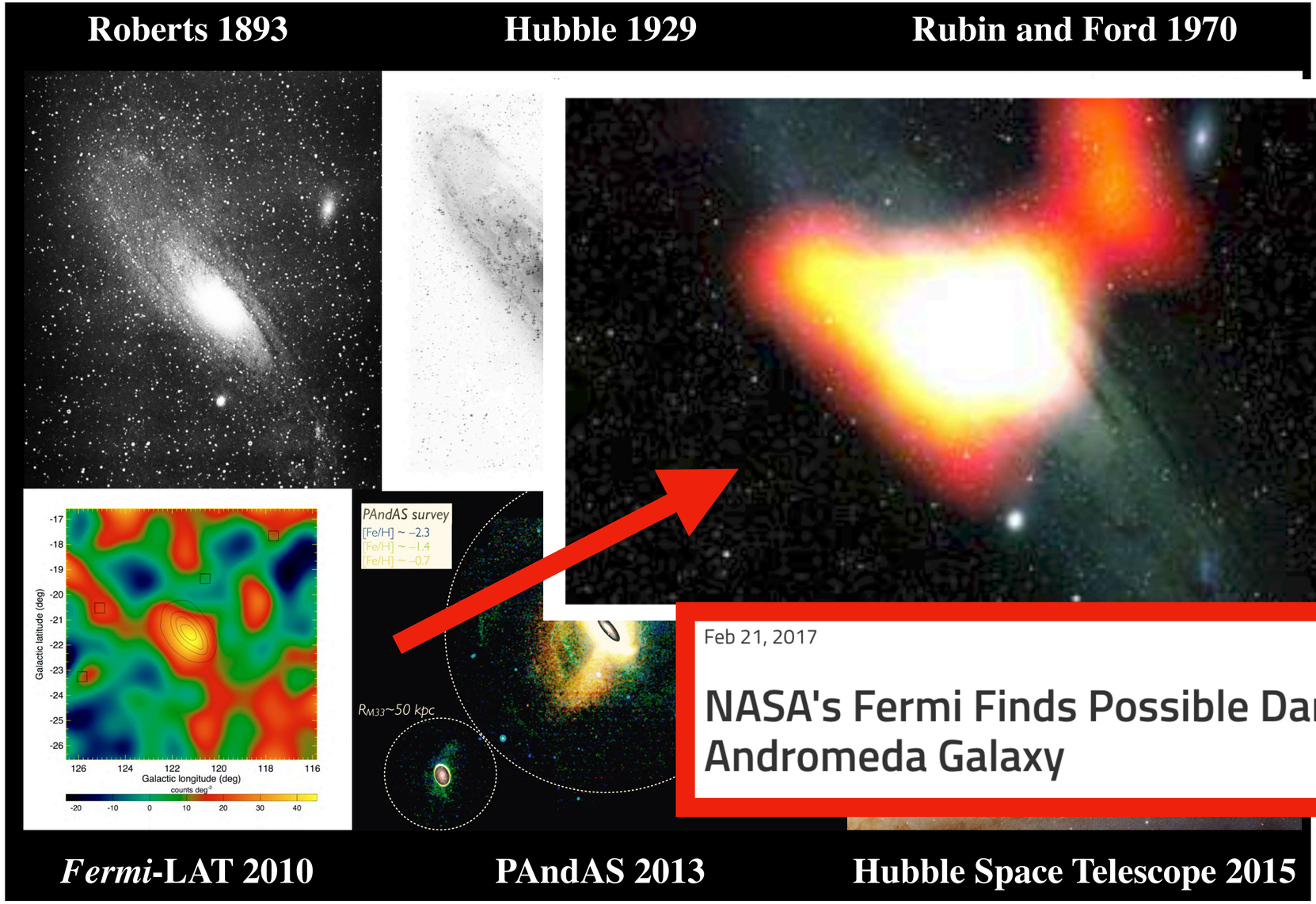


Fermi-LAT 2010

PAndAS 2013

Hubble Space Telescope 2015

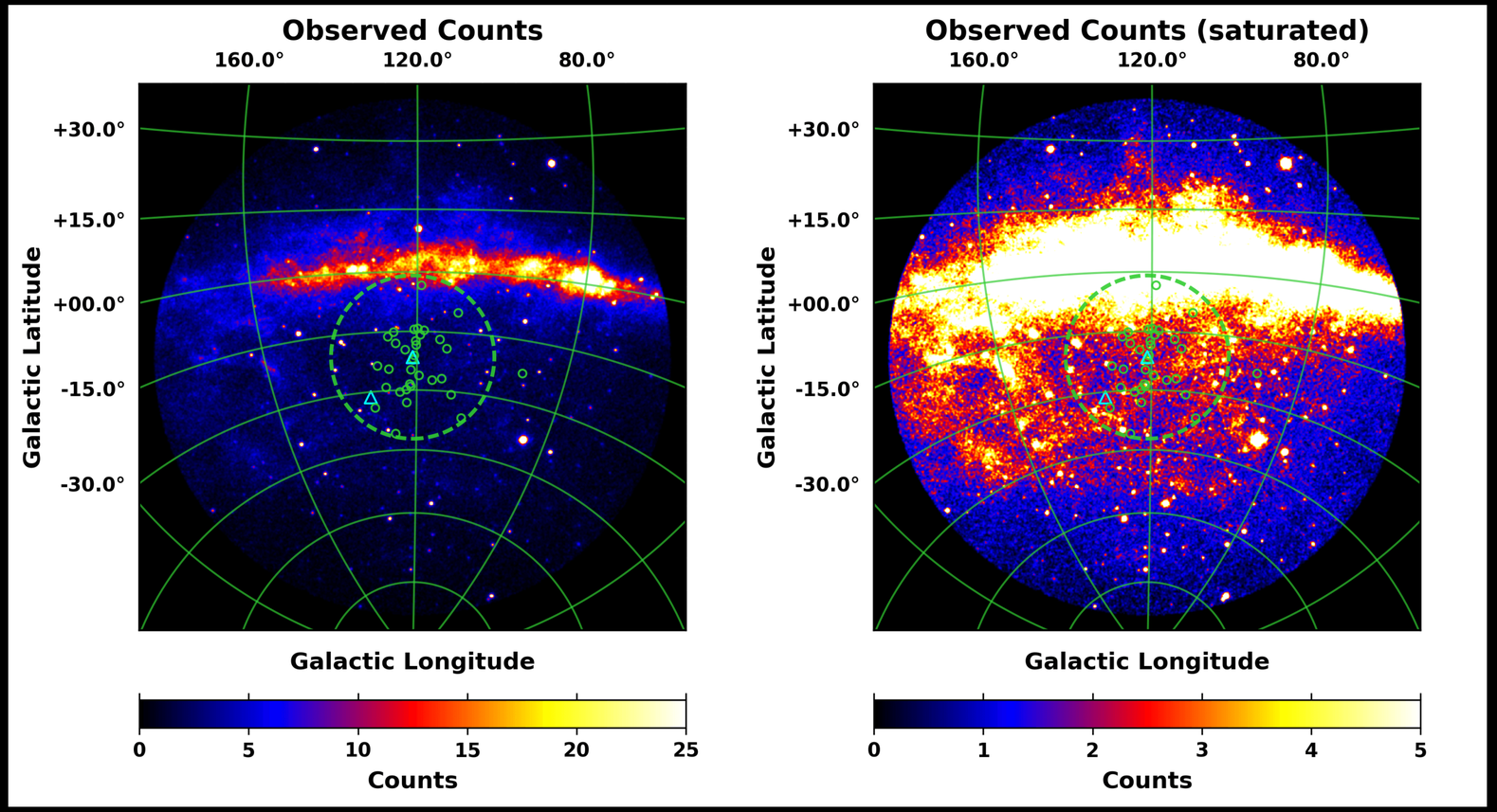
The Andromeda Galaxy



Feb 21, 2017

NASA's Fermi Finds Possible Dark Matter Ties in Andromeda Galaxy

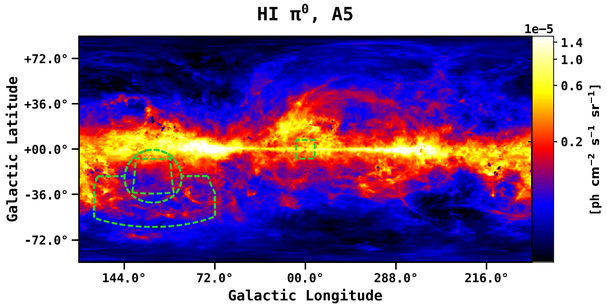
Fermi-LAT Observations

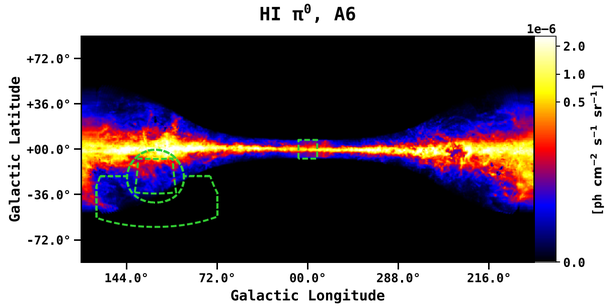


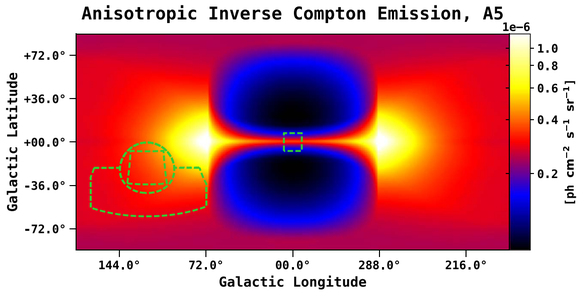
Karwin+19, ApJ, 880, 95.

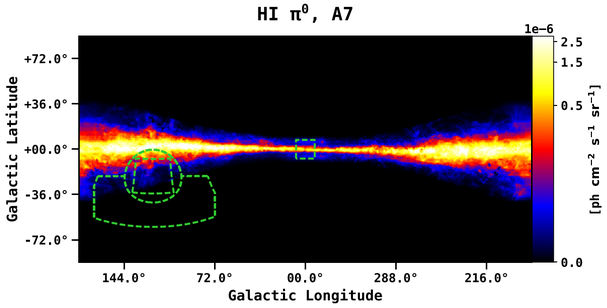
- Data: 7.6 years (2008-08-04 to 2016-03-16)
- Full ROI is a 60° radius centered at the position of M31
- Energy range: 1-100 GeV in 20 bins logarithmically spaced
- left: full count range. right: saturated counts, emphasizing lower counts at high latitudes.
- Dashed green circle (21° in radius) corresponds to a 300 kpc projected radius, for an M31-MW distance of 785 kpc
- M31 and M33 are shown with cyan triangles, and the rest of M31's dwarf galaxy population are shown with small green circles.
- **The primary purpose of the overlay is to provide a qualitative representation of M31's outer halo and to show its relationship to the MW disk**.

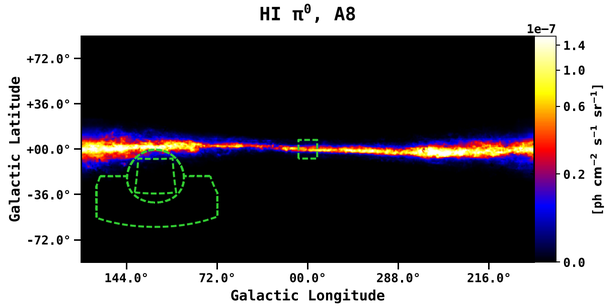
M31 Interstellar Emission Model

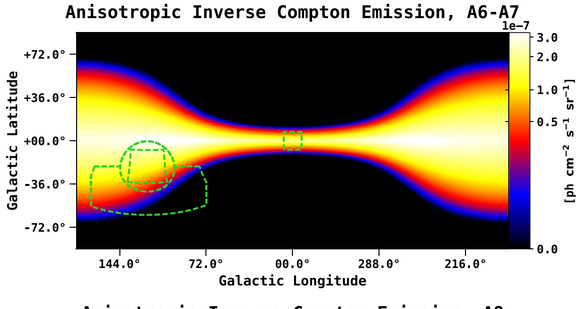


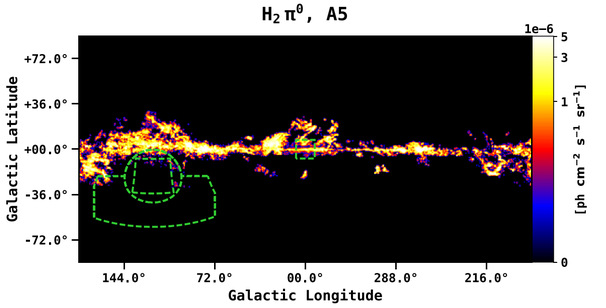


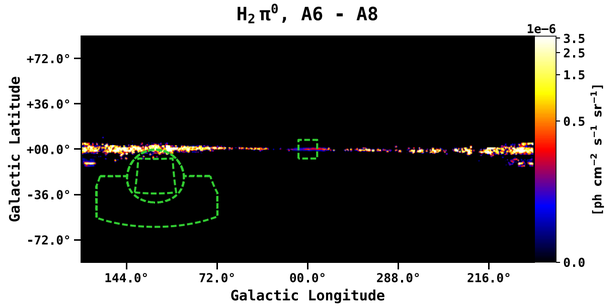


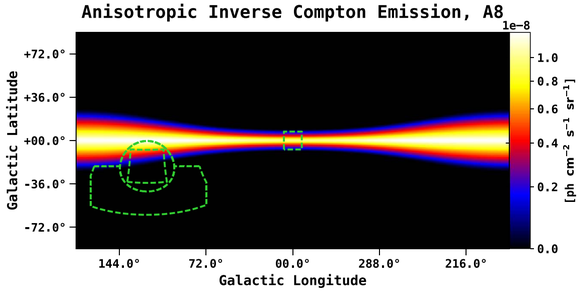


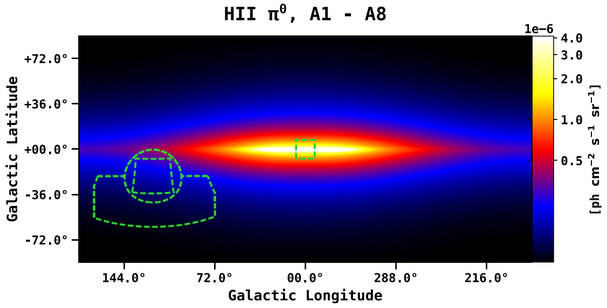


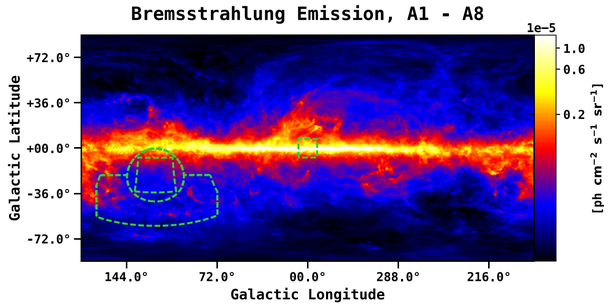


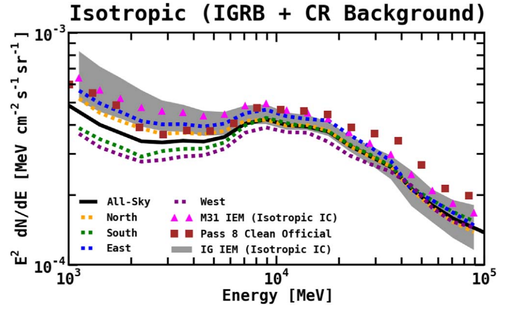






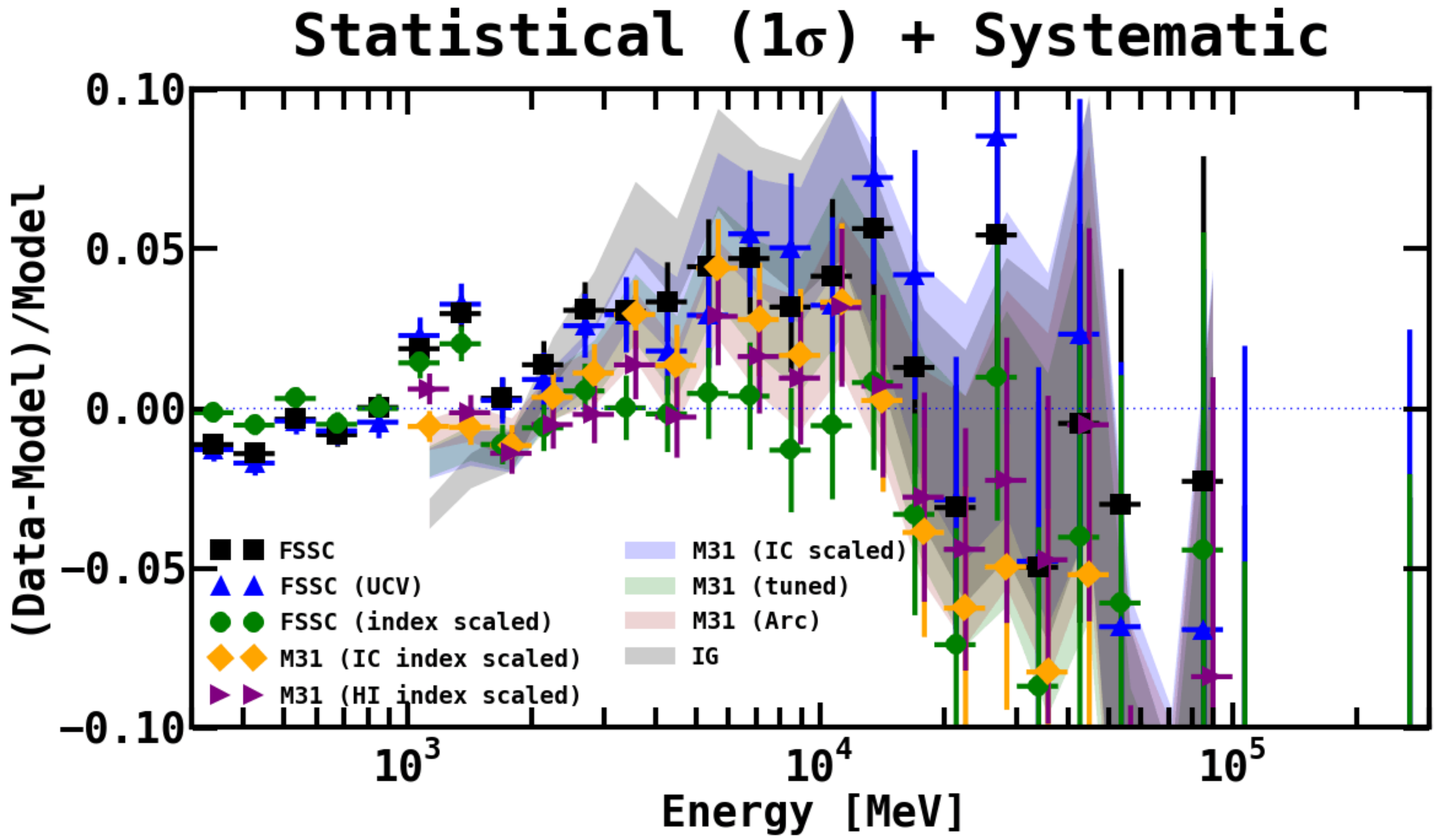






Karwin+19

A Systematic Excess

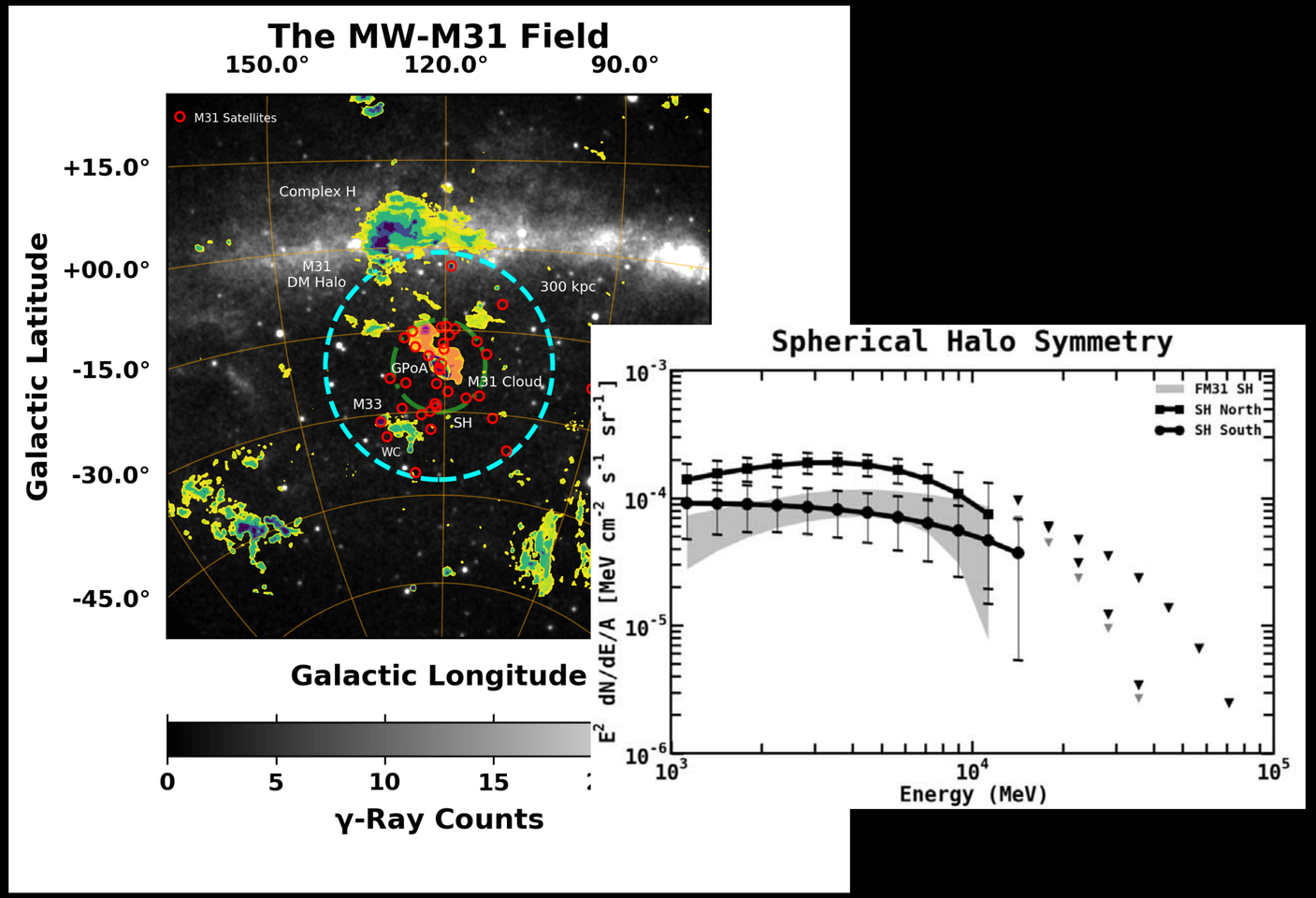


- We perform 9 main variations of the fit, using 3 different IEMs.
- We conclude that a systematic excess is present between ~3-20 GeV at the level of ~3-5%.
- The signal has a radial extension upwards of ~120 - 200 kpc.

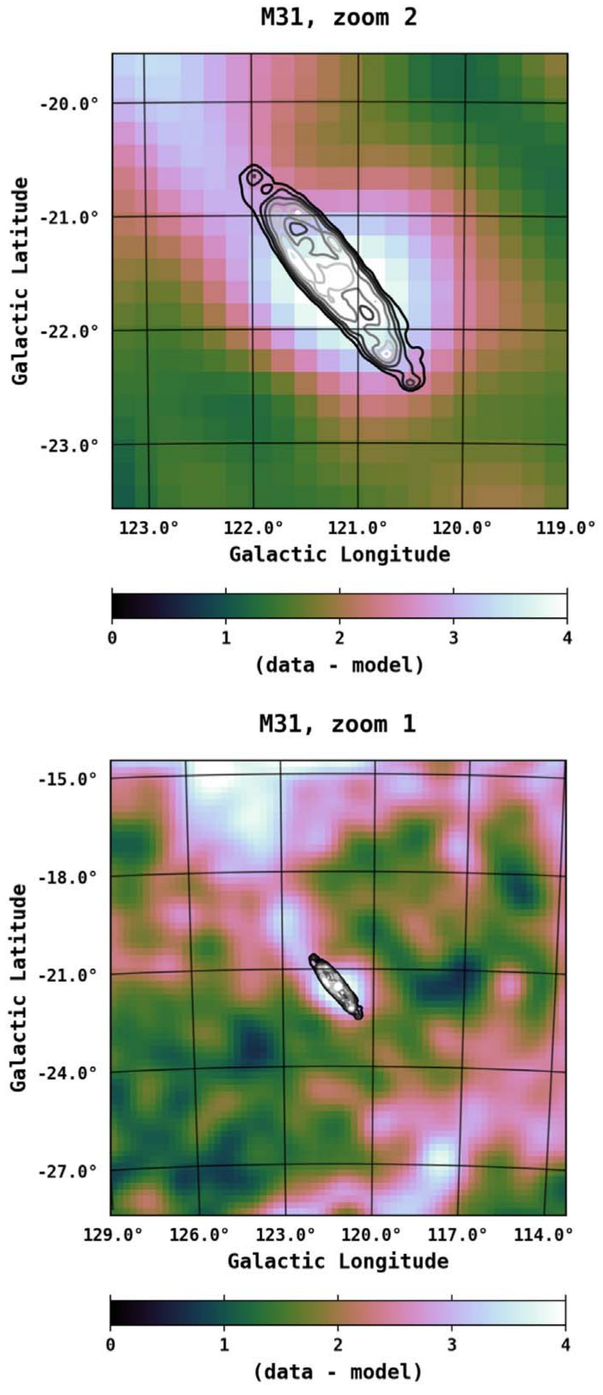
Karwin+19

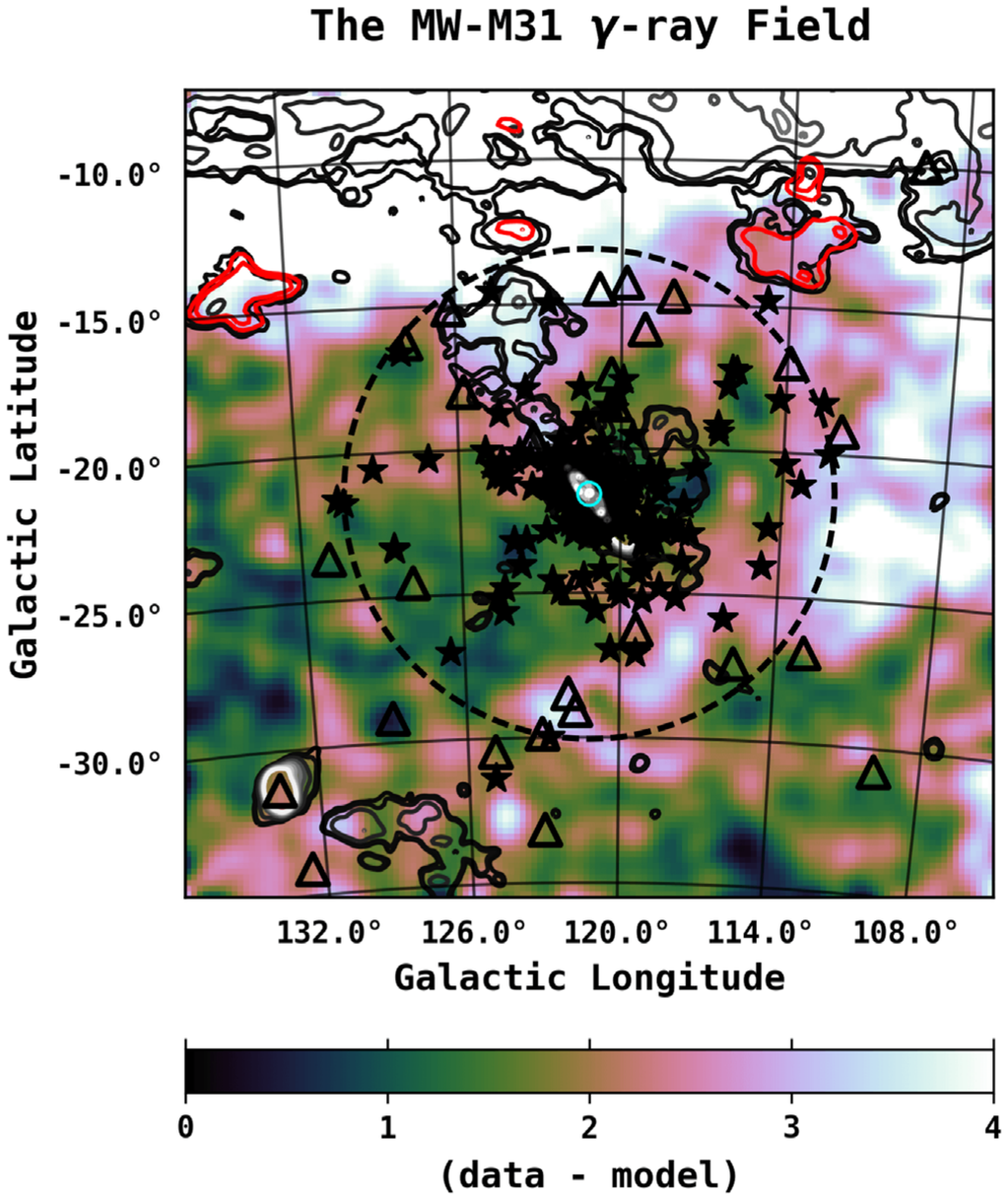
The M31 System

Karwin+21, PRD, 103(2), 023027.



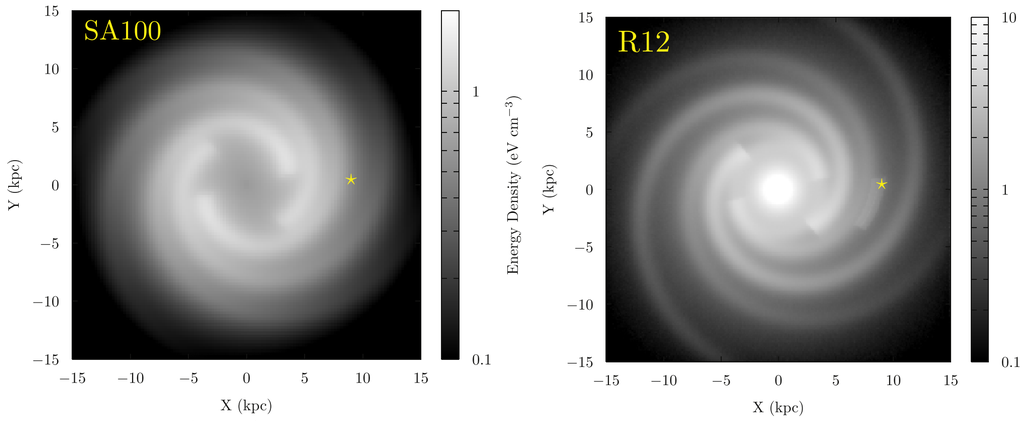
- For the DM interpretation we fit just to the SH region.
- We exclude the IG because of there is a high uncertainty in the contribution from standard astrophysical processes.
- We exclude the FOH because the observations approach the MW plane toward the top of the field, which complicates the analysis.


M31, zoom 2
-20.0°
-21.0°
-22.0°
-23.0°
Galactic Latitude
123.0°
122.0°
121.0°
120.0°
119.0°
Galactic Longitude
0
1
2
3
4
(data - model)
M31, zoom 1
-15.0°
-18.0°
-21.0°
-24.0°
-27.0°
Galactic Latitude
129.0°
126.0°
123.0°
120.0°
117.0°
114.0°
Galactic Longitude
0
1
2
3
4
(data - model)


The MW-M31 γ-ray Field
-10.0°
-15.0°
-20.0°
-25.0°
-30.0°
Galactic Latitude
132.0°
126.0°
120.0°
114.0°
108.0°
Galactic Longitude
0
1
2
3
4
(data - model)

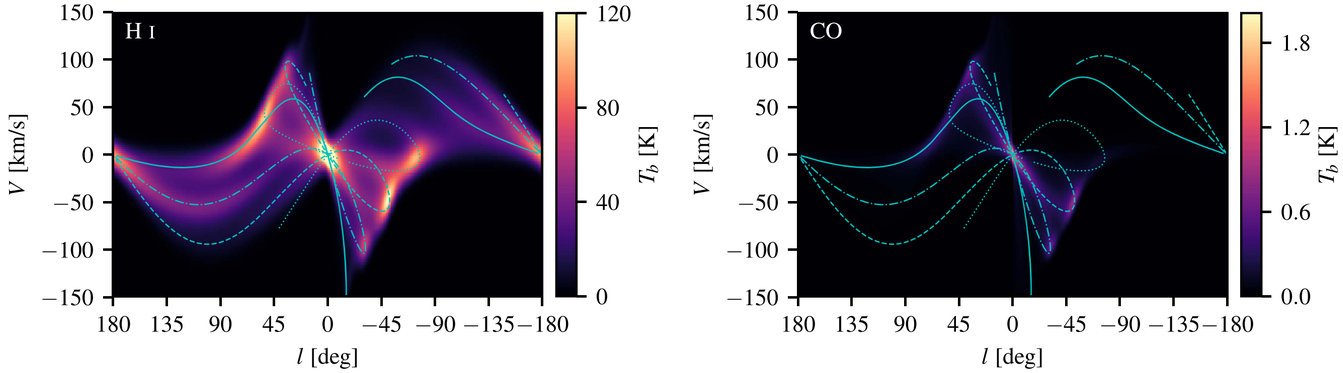
Future Directions: Galactic Diffuse Models

Three-dimensional spatial models for the cosmic ray and radiation field densities in the Milky Way



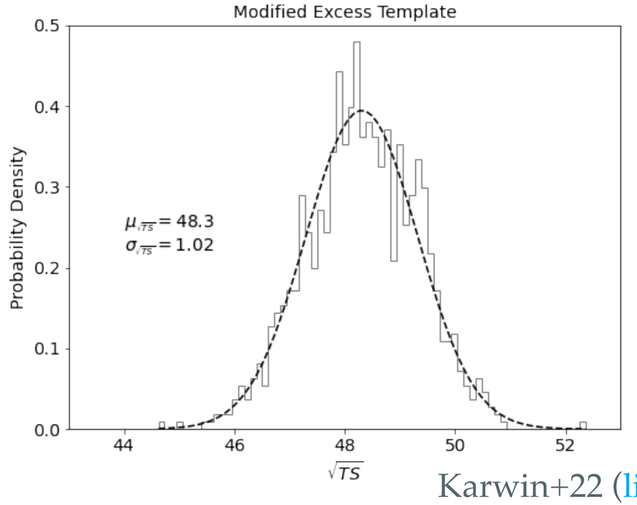
Porter+17 (link)

Three-dimensional spatial distribution of Interstellar gas in the Milky Way



Johannesson+18 (link)

Improved models of the small-scale structure relating to the underlying gas distributions

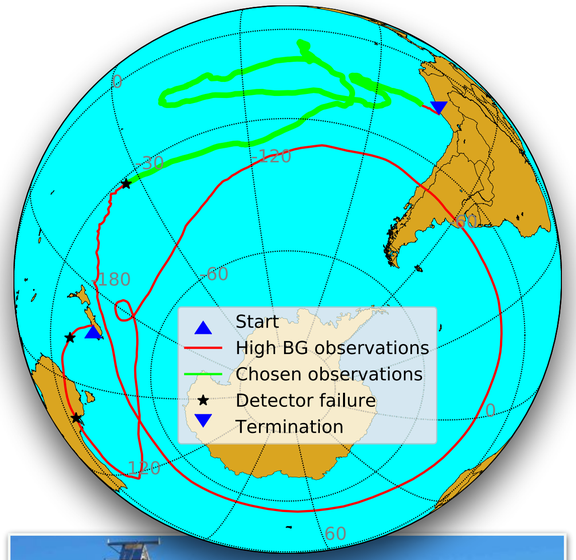


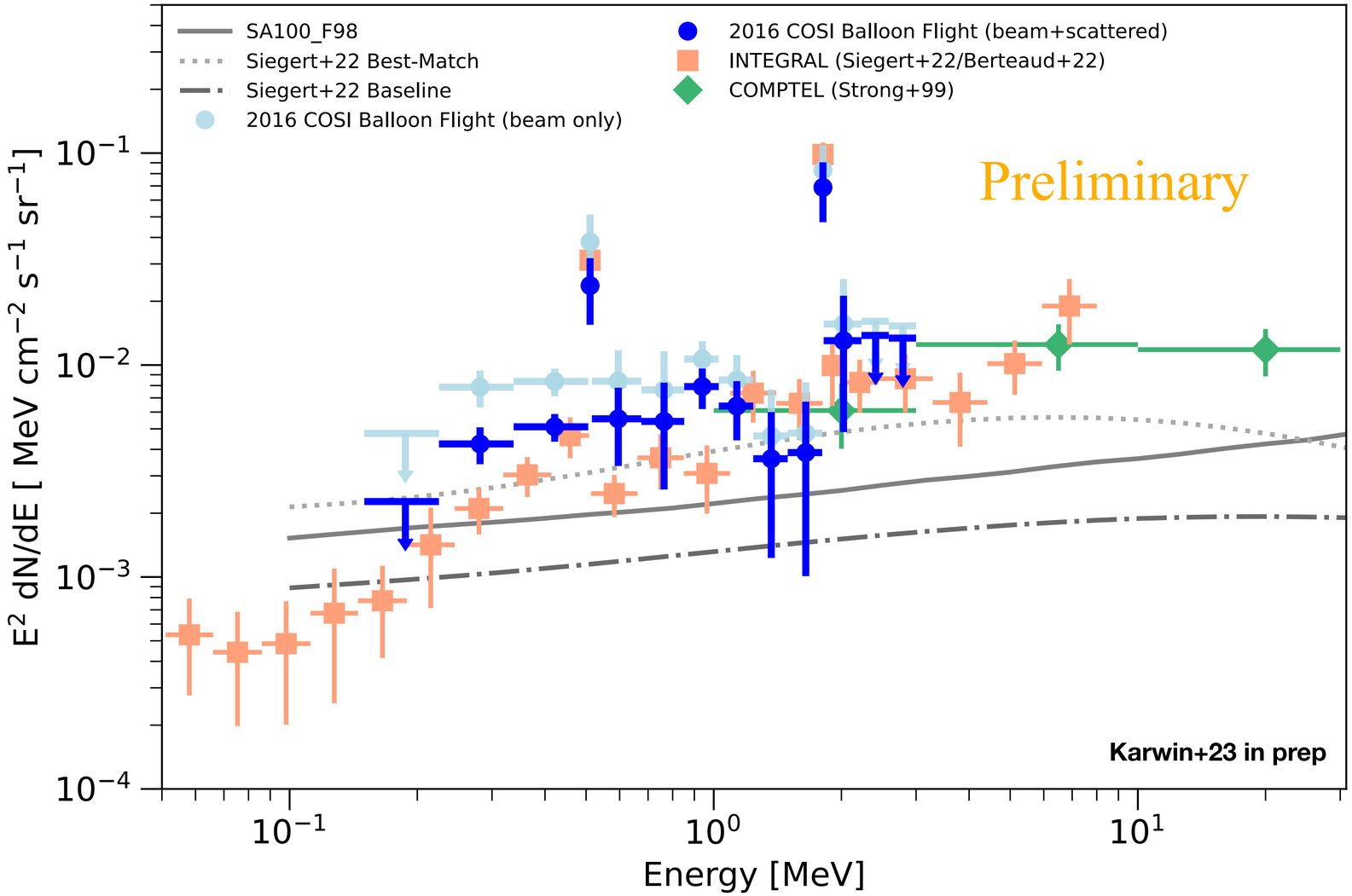
Karwin+22 (link)

Improvements to the Galactic Diffuse model:

- 3D models for the CR and ISRF densities.
- 3D models for the gas distributions.
- Improved modeling of the small-scale structure in the gas.

Measuring the Galactic Diffuse with the 2016 Ballon Data





Extra: The Andromeda Galaxy

Recent Papers:

- June 2019: Search for Gamma-Ray Emission from Dark Matter Particle Interactions from the Andromeda and Triangulum Galaxies with the Fermi Large Area Telescope (link)
- July 2019: Fermi-LAT Observations of Gamma-Ray Emission Toward the Outer Halo of M31 (link)
- October 2020: GeV Gamma-ray Emission from M33 and Arp 299 (link)
- May 2020: The Gamma-ray Emission of Star-Forming Galaxies (link)
- Jan 2021: Dark Matter Interpretation of the Fermi-LAT Observations Toward the Outer Halo of M31 (link)
- April 2021: Gamma-Ray Image Reconstruction of the Andromeda Galaxy (link)
- June 2021: Giant Cosmic-Ray Halos Around M31 and the Milky Way (link)
- Sep 2022: The Android Gamma-ray Excess: Background Systematics of the Millisecond Pulsars and Dark Matter Interpretations (link)