Searching for dark matter emission with highly energetic cosmic messengers

5th ComHEP: Colombian meeting on High Energy Physics

Oscar Macías

December 2, 2020

Kavli IPMU (Tokyo U.) & GRAPPA (Amsterdam U.)

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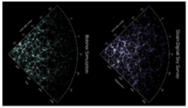
Introduction

What is the particle nature of dark matter?

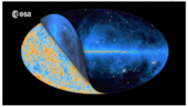
Rotation curves

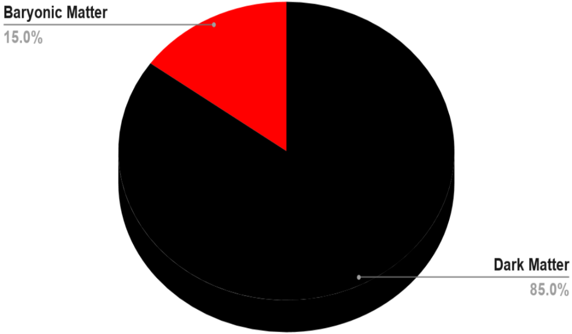
Galaxy clusters

Large Scale structures



Cosmic microwave background



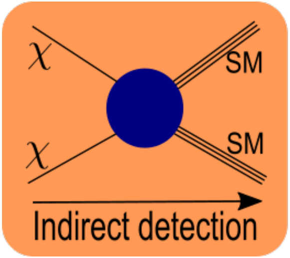


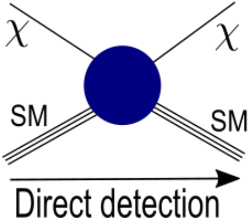
Dark matter makes up about 85% of the matter content of the Universe

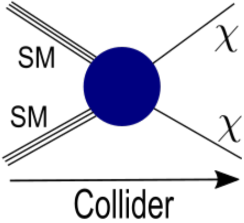
Indirect dark matter detection

One of the most promising search methods:

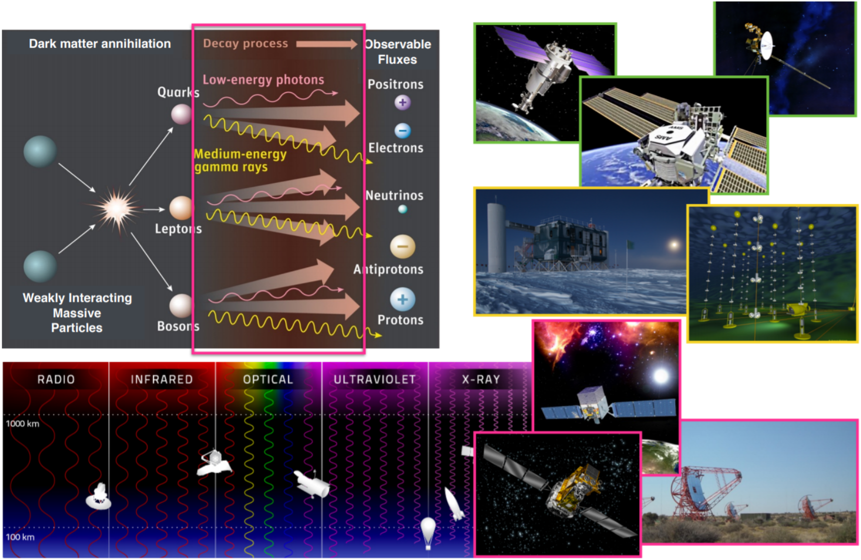
- **Indirect detection**: Look for Standard Model (SM) particles (electrons/positrons, gamma-rays, neutrinos, anti-/protons) produced by dark matter interactions.





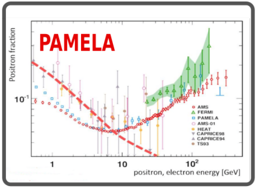


Multi-messenger astrophysical observations

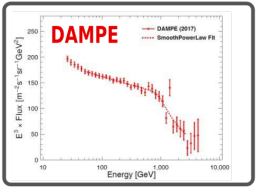


Credit: F. Calore

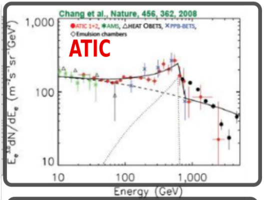
This is a very vibrant field full of mysteries to solve!



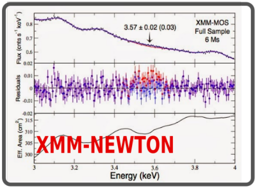
PAMELA



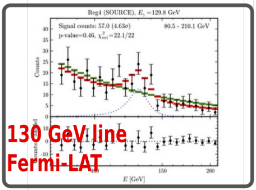
DAMPE



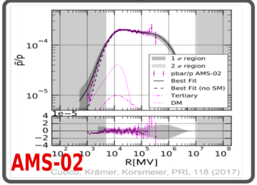
ATIC



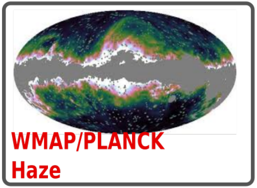
XMM-NEWTON



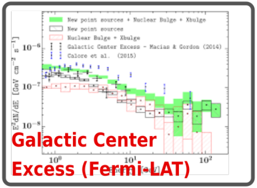
130 GeV line
Fermi-LAT



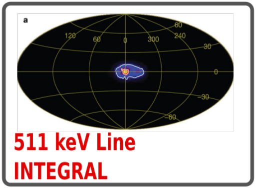
AMS-02



WMAP/PLANCK
Haze

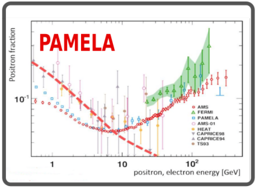


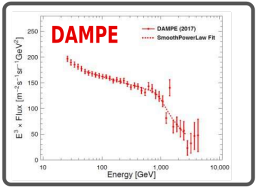
Galactic Center
Excess (Fermi-LAT)

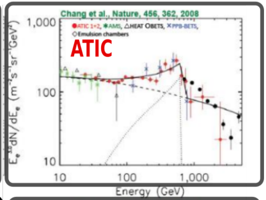


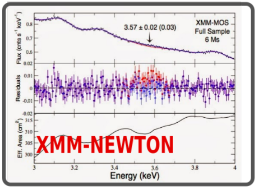
511 keV Line
INTEGRAL

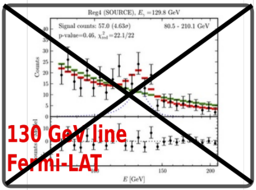
Most dark matter detection claims remain open questions

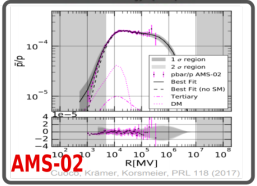


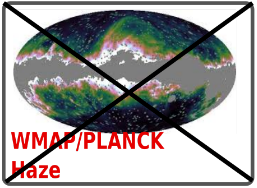


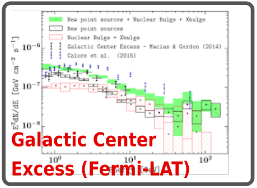


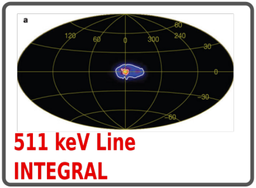












Searches for DM particles with $10\ \mathrm{GeV} \leq M_{\mathrm{DM}} \leq 10^3\ \mathrm{GeV}$

The Galactic Center Excess (GCE)

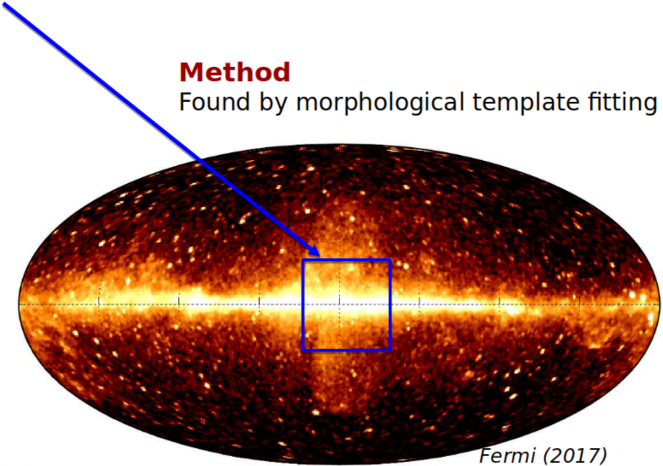
From the Galactic Center out to mid-latitudes

Goodenough & Hooper (2009)
Vitale & Morselli, Phys.Lett.B (2009)
Hooper & Goodenough, PRD (2011)
Hooper & Linden, PRD (2011)
Boyarsky et al. PRD (2011)
Abazajian & Kaplinghat, PRD (2012)
Gordon & Macias, PRD (2013)
Hooper & Slatyer PRD (2013)
Huang et al. PRD (2013)
Macias & Gordon, PRD (2014)
Abazajian et al. PRD (2014, 2015)
Calore et al. JCAP (2014)
Zhou et al. PRD (2014)
Daylan et al. PRD (2014)
Macias et al. MNRAS (2016)
Selig et al. JCAP (2015)
Huang et al. PRD (2015)
Gaggero et al. PRD (2015)
Carlson et al. PRD (2015, 2016)
Yang & Aharonian, A&A (2016)
Horiuchi et al. JCAP (2016)
Lee et al. PRL (2016)
Linden et al. PRD (2016)
Ackermann et al. ApJ (2017)
Ajello et al. ApJ (2017)
Macias et al. Nat. Astr. (2018)
Bartels et al. Nat. Astr. (2018)
Macias et al. JCAP (2019)
Abazajian et al. (2020)
...

(not a complete list)

Method

Found by morphological template fitting



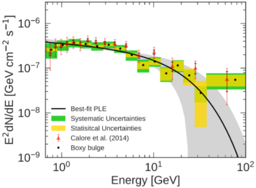
Fermi (2017)

Current Status on the Fermi GeV excess

The Spectrum

- Thousands of (hypothetical) millisecond pulsars in the Galactic bulge could cause the emission.
- Millisecond pulsars could have been formed: (i) in-situ, (ii)dinamically, (iii) disrupted globular clusters, or a combination of these.

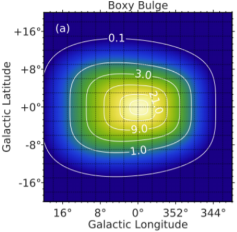
Macias et al. *JCAP* 09 (2019) 042



The Spatial Morphology

- Excess emission traces the stellar population of the Galactic bulge rather than the DM profile.
- This suggests an astrophysical origin for the GeV excess. [Macias et al. Nat. Astr.(2018), Bartels et al. Nat. Astr. (2018)]

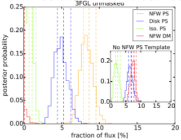
Abazajian et al. *PRD* 102(2020) 4,043012

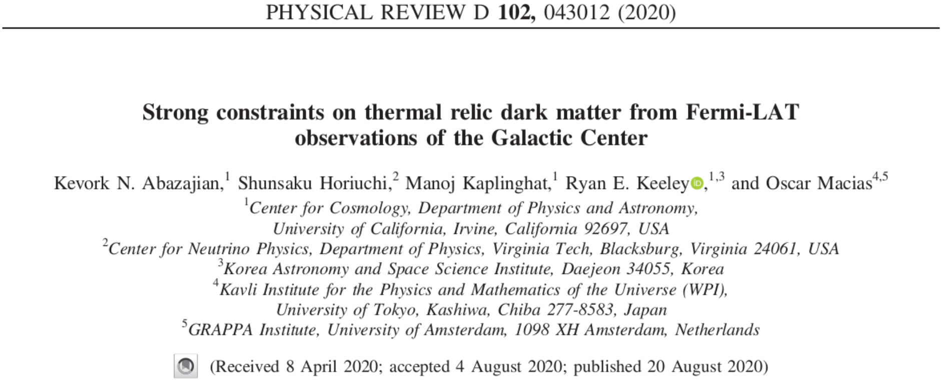


Statistical distribution of photons

- Point source explanation suggests clustering of photons (non-poissonian distribution).
- Methods used: (i)non-poissonian fit, (ii) wavelet method. No consensus yet. See Lee et al (2015), Leane&Slatyer(2019), Buschmann et al. (2020), Bartels et al (2015), Balaji et al. (2018)

Lee et al. *PRL 116.051103*





PHYSICAL REVIEW D **102,** 043012 (2020)

Strong constraints on thermal relic dark matter from Fermi-LAT observations of the Galactic Center

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[2]*Center for Neutrino Physics, Department of Physics, Virginia Tech, Blacksburg, Virginia 24061, USA*
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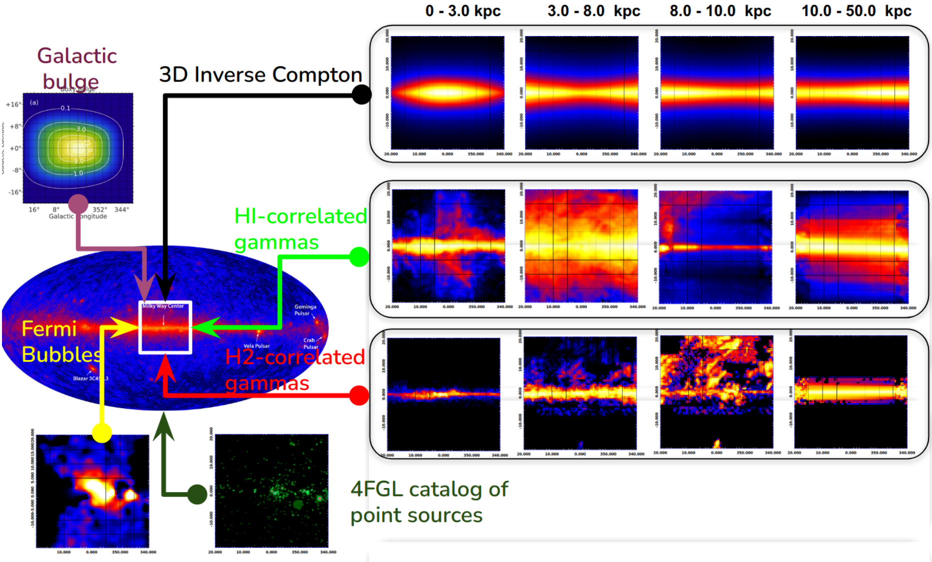
(Received 8 April 2020; accepted 4 August 2020; published 20 August 2020)

Astrophysical background model for the Galactic Center



0 - 3.0 kpc

3.0 - 8.0 kpc

8.0 - 10.0 kpc

10.0 - 50.0 kpc

Galactic bulge

3D Inverse Compton

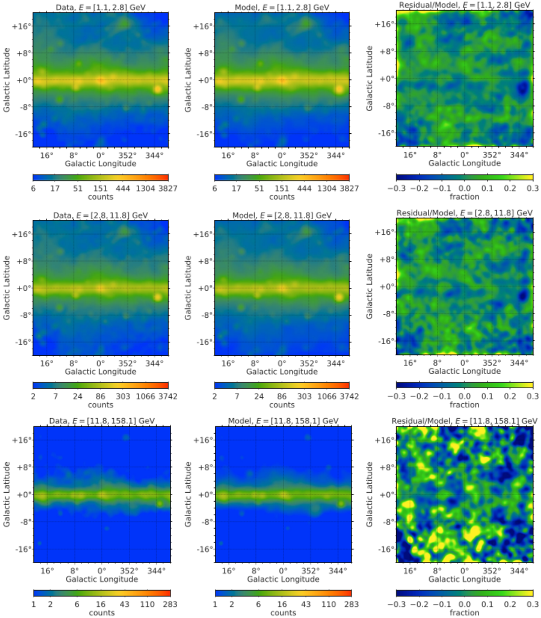
HI-correlated gammas

Fermi Bubbles

H2-correlated gammas

4FGL catalog of point sources

Results of the maximum-likelihood analysis

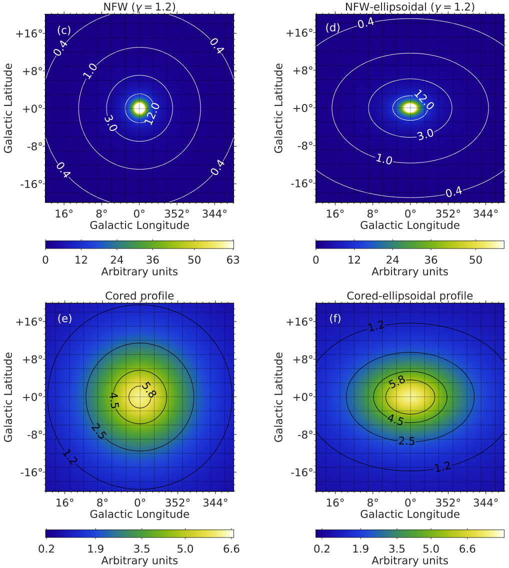


Summary:

- Astrophysical background model explains the data at the 30% level.
- Residual emission does not resemble a dark matter map.
- There is no support for additional extended sources such as dark matter emission maps.

See also Macias et al. (2018), Bartels et al. (2018), and Macias et al. (2019).

The dark matter distribution of the Galactic Center



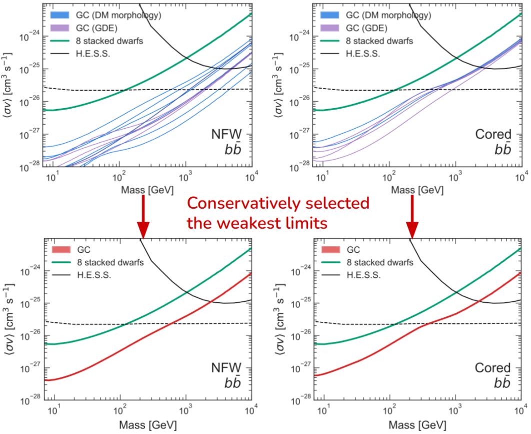
Results from hydrodynamic simulations:

- Cored dark matter profiles are preferred to cuspy ones [Guedes et al. ApJ. 742, 76 (2011).]
- Predict ellipsoidal morphologies rather than fully spherical [Weinberg et al. ApJ. 580, 627 (2002)].

Accounted for uncertainties in the DM profile parameters using a Bayesian approach.

We can place 95% C.L. upper limits on DM properties.

95% confidence level upper limits on $\langle \sigma v \rangle$



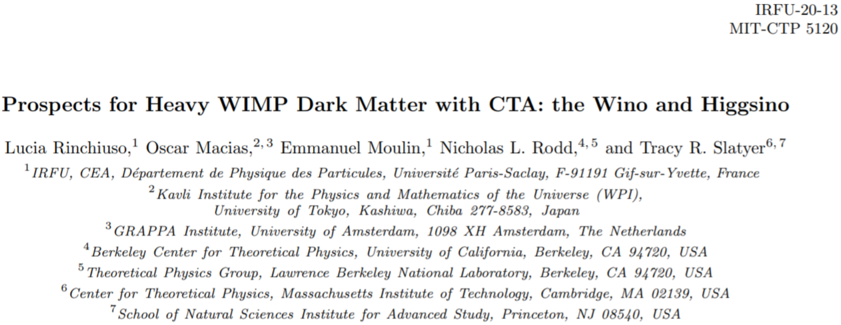
Conservatively selected the weakest limits

Summary:

- Accounted for uncertainties in the astrophysical background model and dark matter distribution.
- Thermal dark matter particles ruled out for $m_{\rm dm} \leq 400$ GeV.
- Results reproducible using our publicly available code

`https://github.com/oscar-macias/Fermi_GC_limits`

CTA sensitivity to DM particles with $10^3~\mathrm{GeV} \leq M_{\mathrm{DM}} \leq 10^5~\mathrm{GeV}$



IRFU-20-13
MIT-CTP 5120

Prospects for Heavy WIMP Dark Matter with CTA: the Wino and Higgsino

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[2] *Kavli Institute for the Physics and Mathematics of the Universe (WPI), University of Tokyo, Kashiwa, Chiba 277-8583, Japan*
[3] *GRAPPA Institute, University of Amsterdam, 1098 XH Amsterdam, The Netherlands*
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[5] *Theoretical Physics Group, Lawrence Berkeley National Laboratory, Berkeley, CA 94720, USA*
[6] *Center for Theoretical Physics, Massachusetts Institute of Technology, Cambridge, MA 02139, USA*
[7] *School of Natural Sciences Institute for Advanced Study, Princeton, NJ 08540, USA*

See more details in:

- **arXiv:2008.00692**

Computation of the γ-ray spectra and annihilation rate

Wino dark matter:

- Sommerfeld enhancement. [Hisano et al.(2004)]
- Continuum emission of photons from the decay of final state W and Z bosons. [Cirelli et al. (2010)]
- Sudakov double logarithms of the form $\alpha_W \ln^2(m_{\mathrm{DM}}/m_W)$ [Hryczuk et al. (2011)].
- Inclusion of endpoint photons, which have $E = zm_{\mathrm{DM}}$ with $1 - z \ll 1$. [Baumgart et al. (2015)].

Used full next-to-leading logarithmic (NLL) accuracy in the spectrum.

Higgsino dark matter:

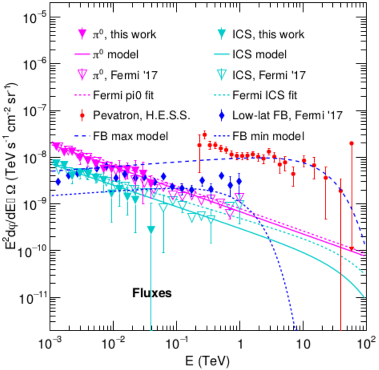
- Sommerfeld enhancement. [Hisano et al.(2004)]
- Only tree-level annihilation rate.
- Caveat: we are missing $\mathcal{O}(1)$ corrections to the annihilation rate and photon production!

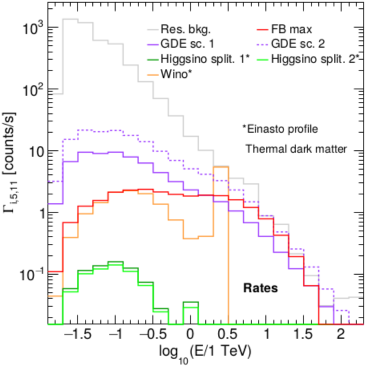
Splitting between charged and neutral states:

Scenario 1: $\delta m_N = 200$ keV and $\delta m_+ = 350$ MeV.

Scenario 2: $\delta m_N = 2$ GeV and $\delta m_+ = 480$ MeV.

Computation of expected Cherenkov Telescope Array rates





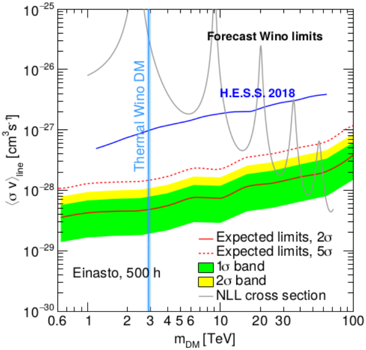
Astrophysical background:

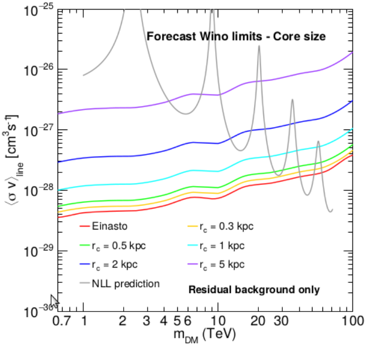
- Model 1: simulated using GALPROP V56.
- Model 2: extrapolation of Fermi background model.

CTA expected rate:

- Dominated by irreducible CR background.
- Assumed Einasto DM profile.
- Assumed 500 h of observations.

Expected 95% C.L. upper limits on $\langle\sigma v\rangle_{\rm line}$: Wino dark matter



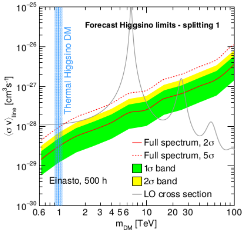


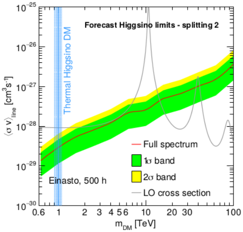
Wino sensitivity:

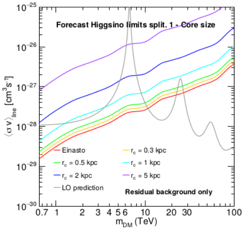
- CTA will have the best sensitivity to the thermal Wino dark matter.
- Uncertainties in the dark matter profile parameters provide the biggest source of uncertainties.

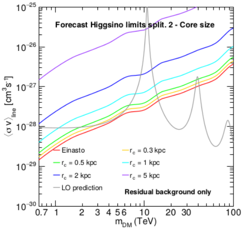
[*] Assumed $\frac{dN_\gamma}{dE} = 2\delta(E - m_{\rm DM}) + \frac{dN_\gamma^{\rm ep}}{dE} + \frac{dN_\gamma^{\rm ct}}{dE}$, and $\langle\sigma v\rangle_{\rm line} = \langle\sigma v\rangle_{\gamma\gamma+\gamma Z/2}$

Expected 95% C.L. upper limits on $\langle \sigma v \rangle_{\mathrm{line}}$: Higgsino DM









Higgsino dark matter:

- Included only leading order (LO) contributions to the annihilation rate and photon spectra.
- However, promising prospects for CTA sensitivity to thermal Higgsinos.
- Uncertainties in the dark matter profile parameters provide the biggest source of uncertainties.

Searches for DM particles with $10^4\ \mathrm{GeV} \le M_{\mathrm{DM}} \le 10^{16}\ \mathrm{GeV}$

Journal of Cosmology and Astroparticle Physics
An IOP and SISSA journal

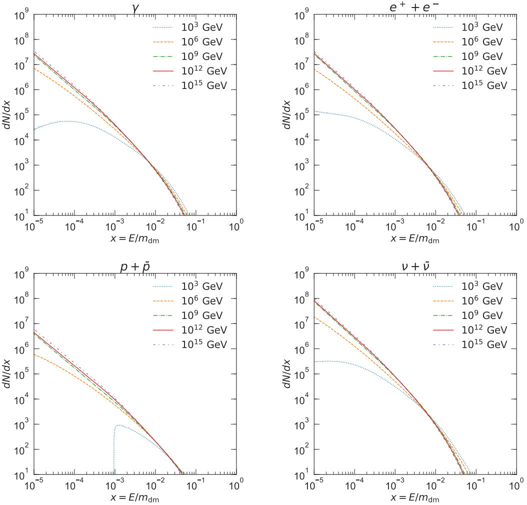
Probing heavy dark matter decays with multi-messenger astrophysical data

Koji Ishiwata,[a] Oscar Macias,[b,c] Shin'ichiro Ando[c,b]
and Makoto Arimoto[d]

See more details in:

- JCAP 01 (2020) 003 [**arXiv:1907.11671**]

Computation of the Cosmic Ray Spectra at Source

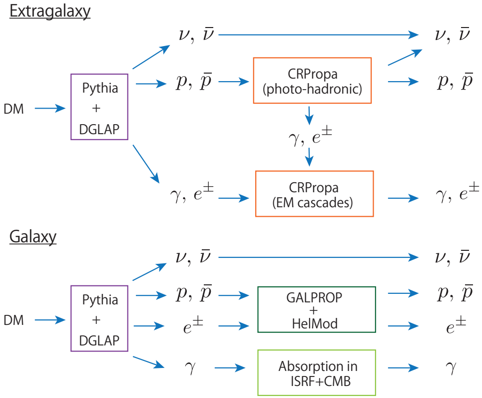


The dark matter spectra at source for different masses and decaying channels.

Calculation method:

- For $m_{\rm dm} \geq 10^6$ GeV we use the DGLAP [Dokshitzer-Gribov-Lipatov-Altarelli-Parisi] equations in the QCD calculations involving DM yields.
- For $m_{\rm dm} \leq 10^6$ GeV we use the Monte Carlo code `pythia 8.2`.
- Caveat: we did not include EW corrections in our DM spectra.
- Notice that this can now be done using results in Bauer et al. [arXiv:2007.15001]. See https://github.com/nickrodd/HDMSpectra.

Propagation of Cosmic Rays



We used customized versions of GALPROP, HelMod, and CRPropa for the propagation of (extra-)Galactic CRs.

Extra-galactic cosmic rays

For $p/\bar{p}$:

- $p + \gamma_{\mathrm{bg}} \to p + \pi$
- $p + \gamma_{\mathrm{bg}} \to p + e^{+} + e^{-}$

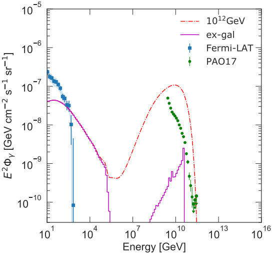
For $e^{\pm}$ and γ:

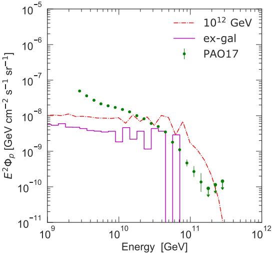
- $e^{\pm} + \gamma_{\mathrm{bg}} \to e^{\pm} + \gamma_{\mathrm{bg}}$
- $e^{\pm} + \gamma_{\mathrm{bg}} \to e^{\pm} + e^{+} + e^{-}$
- $\gamma + \gamma_{\mathrm{bg}} \to e^{+} + e^{-}$
- $\gamma + \gamma_{\mathrm{bg}} \to e^{+} + e^{-} + e^{+} + e^{-}$

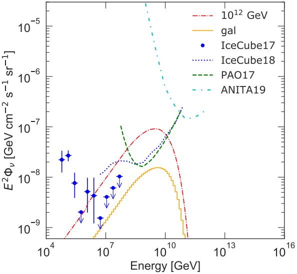
Galactic cosmic rays

Includes detailed models for interstellar and local radiation fields.

Examples of Cosmic Ray Spectra at Earth







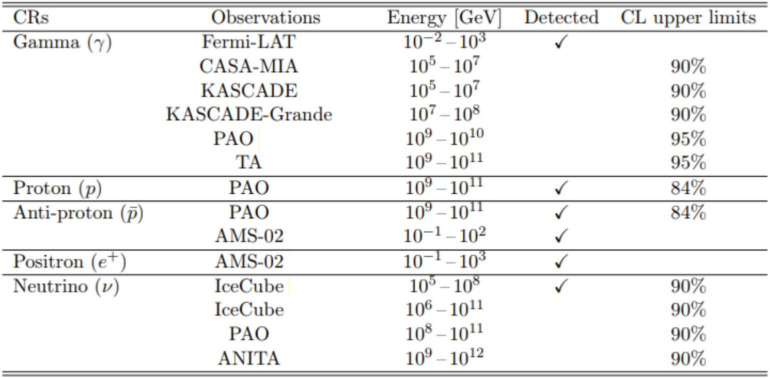
Assumptions for this example:

- $m_{\mathrm{dm}} = 10^{12}$ GeV
- $\tau_{\mathrm{dm}} = 10^{27}$ s

Propagation parameter setup:

- Galactic $->$ arXiv:1704.06337
- extra-galactic $->$ CRpropa default

Ultra High Energy Cosmic Ray Observations

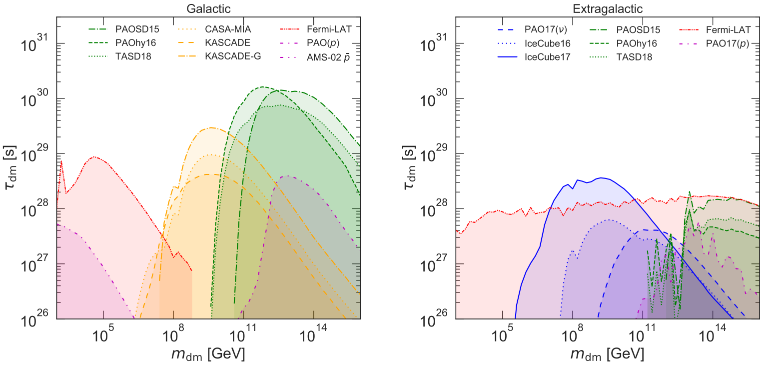


CRs	Observations	Energy [GeV]	Detected	CL upper limits
Gamma (γ)	Fermi-LAT	$10^{-2} - 10^{3}$	✓	
	CASA-MIA	$10^{5} - 10^{7}$		90%
	KASCADE	$10^{5} - 10^{7}$		90%
	KASCADE-Grande	$10^{7} - 10^{8}$		90%
	PAO	$10^{9} - 10^{10}$		95%
	TA	$10^{9} - 10^{11}$		95%
Proton (p)	PAO	$10^{9} - 10^{11}$	✓	84%
Anti-proton ($\bar{p}$)	PAO	$10^{9} - 10^{11}$	✓	84%
	AMS-02	$10^{-1} - 10^{2}$	✓	
Positron (e^{+})	AMS-02	$10^{-1} - 10^{3}$	✓	
Neutrino (ν)	IceCube	$10^{5} - 10^{8}$	✓	90%
	IceCube	$10^{6} - 10^{11}$		90%
	PAO	$10^{8} - 10^{11}$		90%
	ANITA	$10^{9} - 10^{12}$		90%

Cosmic ray data considered in this work:

- Used **measurements** or **upper limits** of γ, ν, p, $\bar{p}$ and $e^{\pm}$ CRs.

Main Results:



Used γ, ν, p, $\bar{p}$ and $e^{\pm}$ CRs measurements:

- We excluded dark matter lifetimes of 10^{28} s or shorter for all the masses investigated in this work.
- The most stringent constraints reach 10^{30} s for very heavy dark matter of masses of $\sim 10^{11}$–10^{14} GeV.

Conclusions

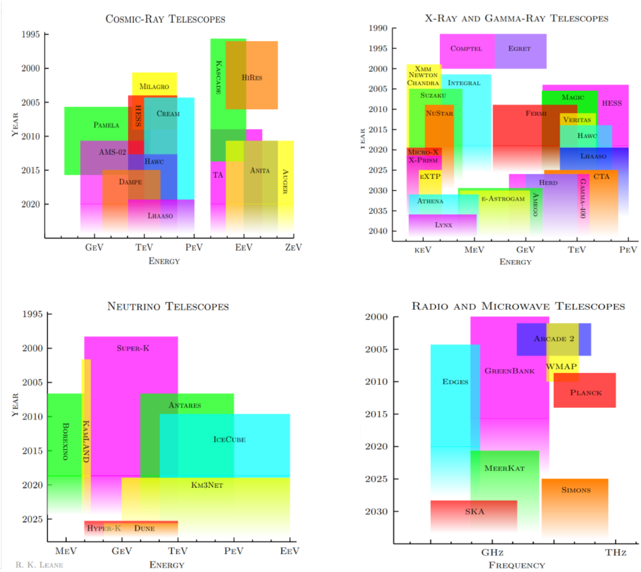
- Fermi LAT γ-ray observations of the Galactic Center ruled out thermal dark matter particles with $m_{\mathrm{DM}} \lesssim$ 400 GeV.

- CTA will probe thermal Winos. It is also potentially possible that thermal Higgsinos will probed by CTA.

- Ultra high energy cosmic ray observations (or null detections) allow to impose strong robust constraints on super heavy dark matter candidates.

Backup slides

Multimessenger Astrophysics

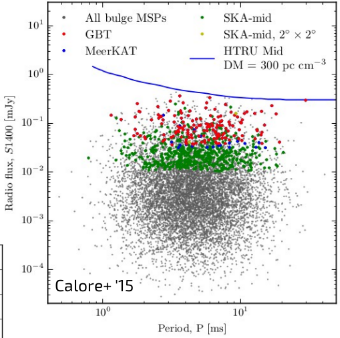


Radio detection of individual MSPs in the Galactic Center

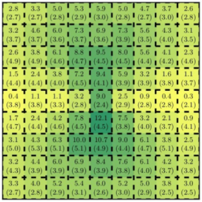
Radio detection prospects (Calore+ '15)

(Bulge population is just below sensitivity of Parkes HTRU mid-lat survey)

- GBT targeted searches ~100h: ~3 bulge MSPs
- MeerKAT mid-lat survey ~300h: ~30 bulge MSPs



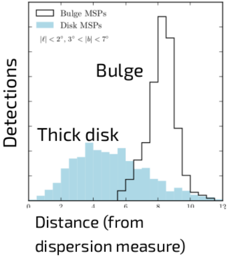
Calore+ '15



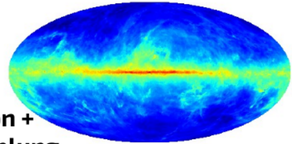
18° × 18°

2.8 (2.7)	3.3 (2.7)	5.0 (2.8)	5.3 (2.9)	5.9 (3.0)	5.0 (2.8)	4.7 (2.7)	3.7 (3.0)	2.6 (2.8)
3.2 (3.7)	4.6 (3.7)	6.0 (3.6)	7.3 (3.7)	6.9 (3.6)	7.3 (3.9)	5.6 (3.5)	4.3 (4.0)	3.1 (3.5)
2.6 (4.9)	3.8 (4.9)	6.1 (4.6)	8.8 (4.7)	9.5 (4.5)	8.0 (4.5)	5.6 (4.4)	4.1 (4.2)	2.3 (4.6)
1.5 (4.4)	2.4 (4.4)	3.8 (4.0)	7.2 (4.5)	9.4 (4.1)	5.9 (3.9)	3.2 (3.9)	1.6 (3.8)	1.1 (3.7)
0.4 (3.8)	1.1 (3.8)	1.1 (3.3)	3.2 (2.8)	9.0 (2.4)	2.5 (2.9)	0.9 (2.8)	0.4 (2.8)	0.3 (2.1)
1.7 (4.7)	2.4 (4.4)	4.2 (4.6)	7.8 (4.5)	12.1 (4.5)	7.5 (3.8)	3.2 (4.0)	2.1 (3.7)	0.9 (4.1)
3.1 (5.0)	4.3 (5.3)	6.3 (5.1)	10.0 (5.1)	10.7 (4.9)	9.0 (4.4)	6.1 (4.7)	3.8 (5.1)	2.5 (4.9)
3.2 (4.3)	4.4 (3.9)	6.0 (3.9)	6.9 (3.9)	8.4 (3.9)	7.6 (3.8)	6.1 (4.0)	4.2 (3.7)	3.2 (3.8)
3.3 (2.7)	4.0 (2.8)	5.2 (2.9)	5.4 (3.1)	6.0 (2.6)	5.2 (3.0)	5.0 (2.9)	3.8 (2.5)	3.0 (2.5)

(SKA)

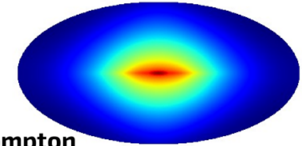


Statistical Method: Morphological template fitting



Neutral pion + Bremsstrahlung

+

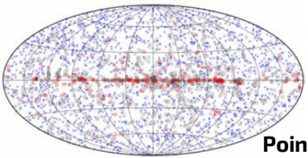


Inverse Compton

+

Fermi bubbles, isotropic background, Loop I, Earth limb, Sun, ...

+



Point sources

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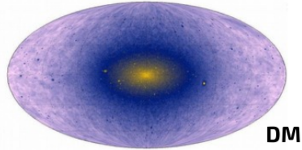
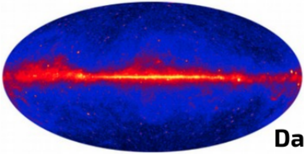


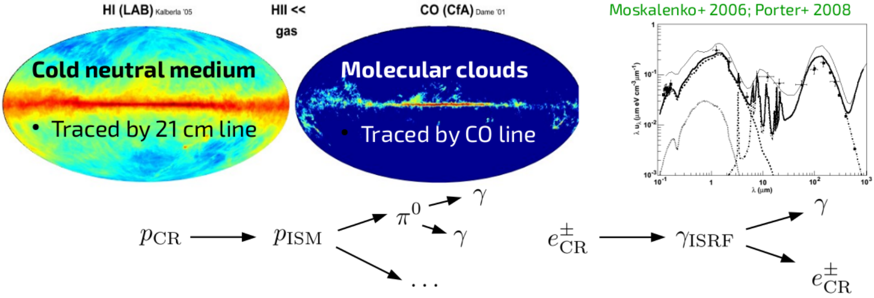
DM signal

=



Data

The Uncertainties in the Galactic Diffuse emission model



Strong+ 2000; Porter & Strong 2005; Moskalenko+ 2006; Porter+ 2008

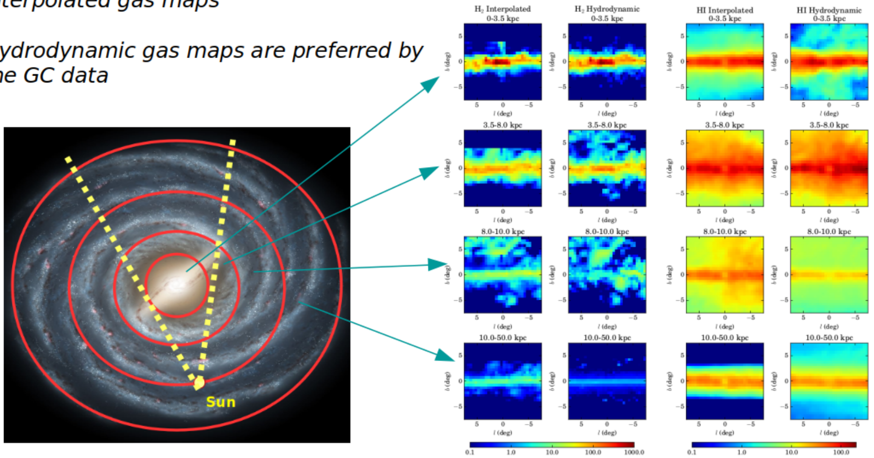
Main Problems affecting the Interstellar gas maps:

- Poor observational resolution towards the Galactic Center (GC)
- Simplified solutions introduce an avoidable bias to GC analyses

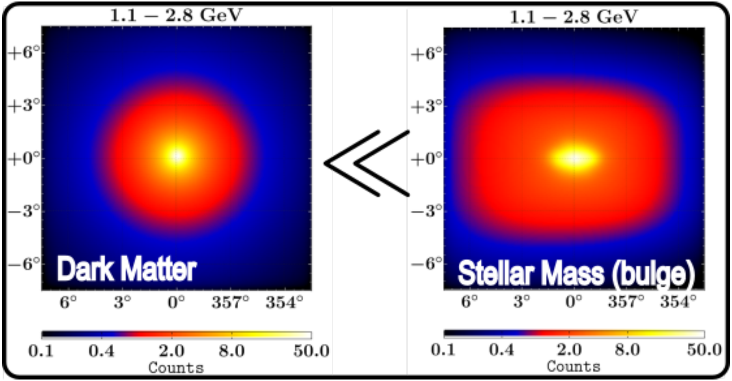
Hydrodynamic maps avoid bias introduced by other methods

- *Fermi diffuse emission model uses interpolated gas maps*
- *Hydrodynamic gas maps are preferred by the GC data*

Macias et al. **Nat. Astr. (2018)**



Evidence for thousands of new millisecond pulsars in the Bulge



Dark Matter strongly disfavored by our analysis

Our results show that a new population of about 5000 new millisecond pulsars is the most likely explanation of the Galactic Center Excess.

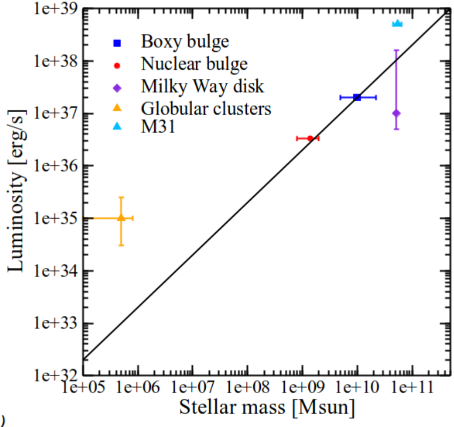
Macias et al. Nat. Astr. (2018)

Gamma-ray luminosity in the Galactic Center

Gamma ray to mass ratios
Shows environmental dependence of MSP gamma rays

- Boxy bulge, nuclear bulge, Milky Way disk (from MSPs) consistent with each other.
- Globular clusters higher by factor ~10-40, explained by large dynamical channel.
- M31 also higher, consistent with its higher encounter rate; LMXB is also consistent with 20-25% dynamical origin (vs no such signs in the Milky Way LMXB)

Voss & Gilfanov (2007)



See also Bartels et al (2017)