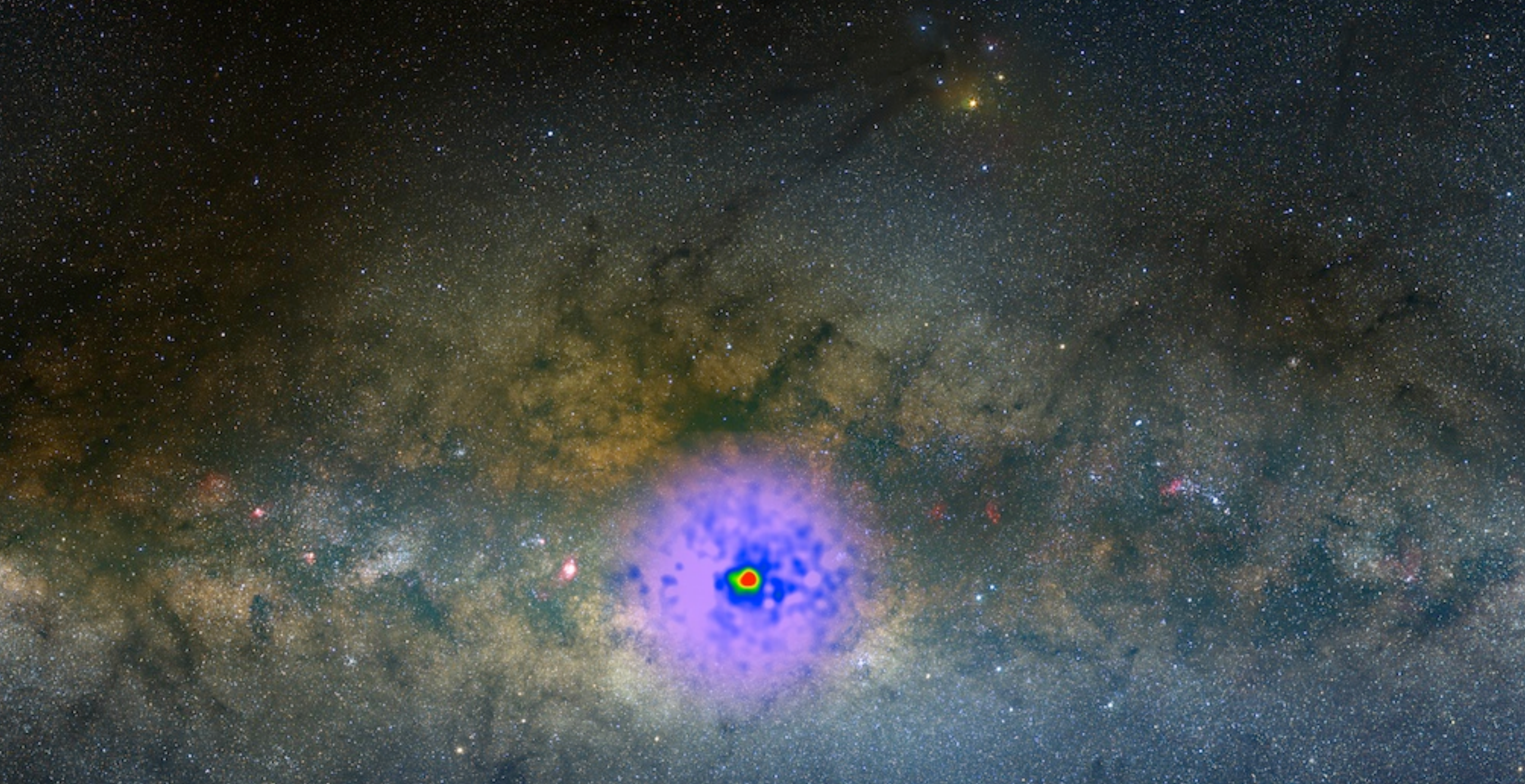

Two Futures for Dark Matter Indirect Detection

Tim Linden

Penn State Seminar
January 29, 2019

The Ohio State University
Center for Cosmology and AstroParticle Physics

The Theme

- Dark matter is an explosive and broadly expansive field.

- The next generation of telescopes will revolutionize our ability to probe both standard and esoteric dark matter models.

- The astrophysics is the dominant theoretical difficulty — must overcome astrophysical uncertainties to unlock the potential of upcoming experiments.

Where Are We Now?

Two Perspectives

REVIEW

https://doi.org/10.1038/s41586-018-0542-z

A new era in the search for dark matter

Gianfranco Bertone[1]* & Tim M. P. Tait[1,2]*

There is a growing sense of 'crisis' in the dark-matter particle community, which arises from the absence of evidence for the most popular candidates for dark-matter particles—such as weakly interacting massive particles, axions and sterile neutrinos—despite the enormous effort that has gone into searching for these particles. Here we discuss what we have learned about the nature of dark matter from past experiments and the implications for planned dark-matter searches in the next decade. We argue that diversifying the experimental effort and incorporating astronomical surveys and gravitational-wave observations is our best hope of making progress on the dark-matter problem.

The fall of natural weakly interacting massive particles

The existence of dark matter has been discussed for more than a century[1,2]. In the 1970s, astronomers and cosmologists began to build what is today a compelling body of evidence for this elusive component of the Universe, based on a variety of observations, including temperature anisotropies of the cosmic microwave background, baryonic acoustic oscillations, type Ia supernovae, gravitational lensing of galaxy clusters and rotation curves of galaxies[3,4]. The standard model of particle physics contains no suitable particle to explain these observations, and

the observed Higgs mass at the weak scale appears highly unnatural, requiring an incredibly fine-tuned cancellation between the individually much larger intrinsic contribution and the correction terms, such that their sum is the value observed at the Large Hadron Collider (LHC). Natural theories introduce additional particles and symmetries, which are arranged so that these large corrections cancel each other out, protecting the Higgs mass from the influence of heavy mass scales.

The prototypical natural theory is the minimal supersymmetric (SUSY) standard model, which introduces an additional partner for

Where Are We Now?

Two Perspectives

MIT-CTP/5020

GeV-Scale Thermal WIMPs: Not Even Slightly Dead

Rebecca K. Leane,[1,*] Tracy R. Slatyer,[1,†] John F. Beacom,[2,3,4,‡] and Kenny C. Y. Ng[5,§]

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[3] *Department of Physics, Ohio State University, Columbus, OH 43210, USA*
[4] *Department of Astronomy, Ohio State University, Columbus, OH 43210, USA*
[5] *Department of Particle Physics and Astrophysics, Weizmann Institute of Science, Rehovot 76100, Israel*

(Dated: July 13, 2018)

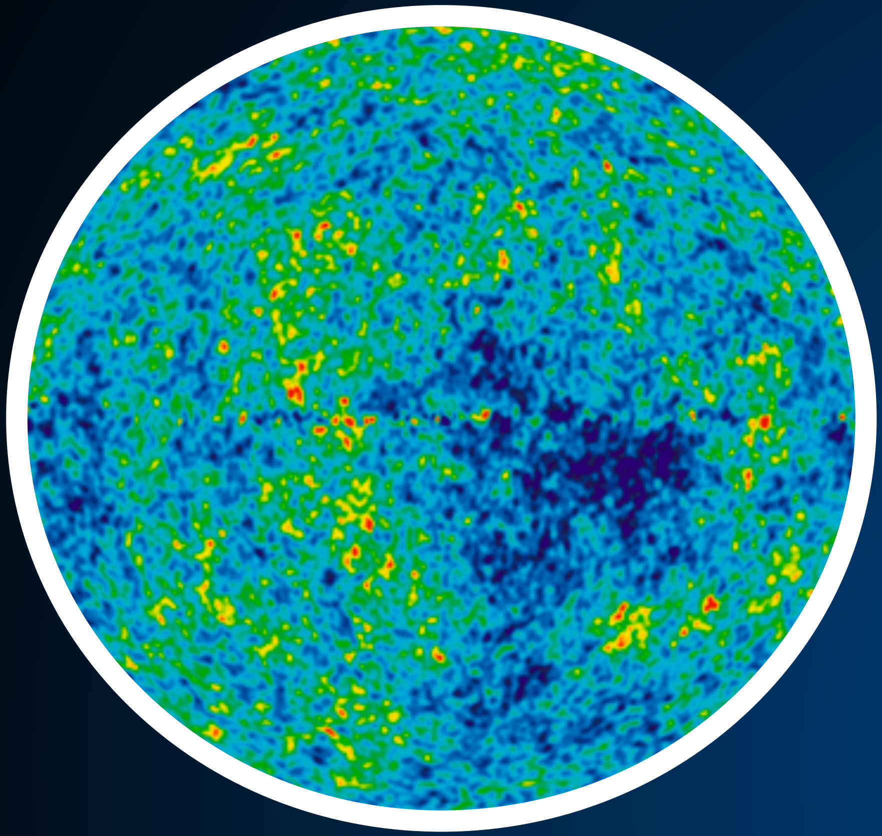
Weakly Interacting Massive Particles (WIMPs) have long reigned as one of the leading classes of dark matter candidates. The observed dark matter abundance can be naturally obtained by freeze-out of weak-scale dark matter annihilations in the early universe. This "thermal WIMP" scenario makes direct predictions for the total annihilation cross section that can be tested in present-day experiments. While the dark matter mass constraint can be as high as $m_\chi \gtrsim 100$ GeV for particular annihilation channels, the constraint on the *total* cross section has not been determined. We construct the first model-independent limit on the WIMP total annihilation cross section, showing that allowed combinations of the annihilation-channel branching ratios considerably weaken the sensitivity. For thermal WIMPs with s-wave $2 \to 2$ annihilation to visible final states, we find the dark matter mass is only known to be $m_\chi \gtrsim 20$ GeV. This is the strongest largely model-independent lower limit on the mass of thermal-relic WIMPs; together with the upper limit on the mass from the unitarity bound ($m_\chi \lesssim 100$ TeV), it defines what we call the "WIMP window". To probe the remaining mass range, we outline ways forward.

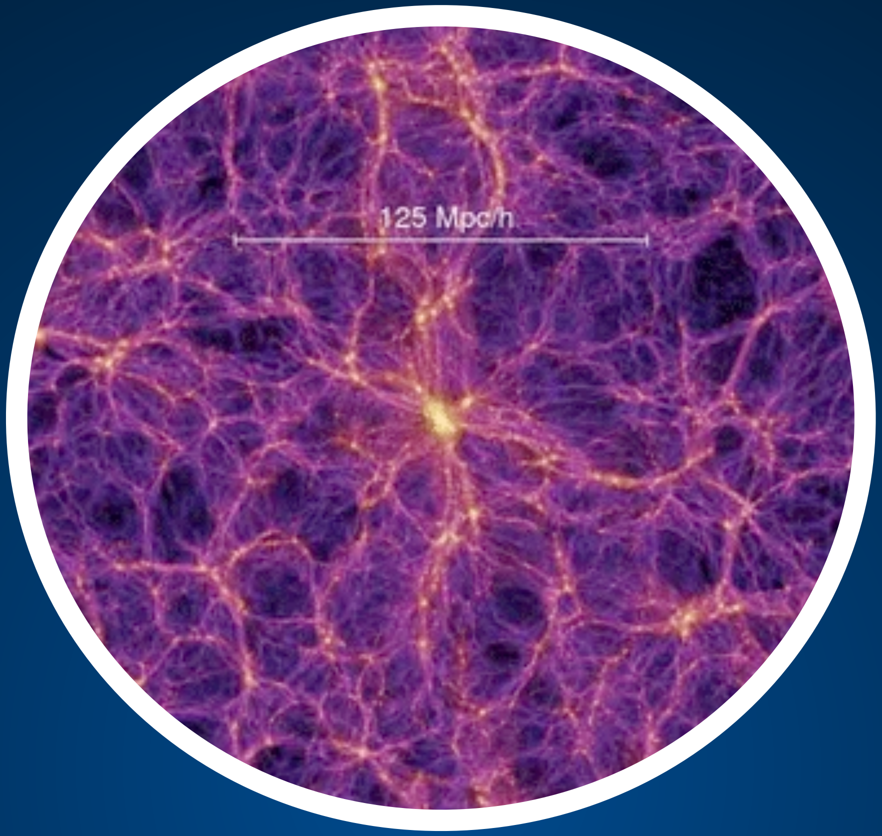
I. INTRODUCTION

A leading candidate for dark matter (DM) is a Weakly Interacting Massive Particle (WIMP) that is a thermal

scenarios. The branching ratios, coupling types and signals are model-dependent, and so the lack of observations may just be due to such features. For example, there can be interference effects, momentum suppression, or

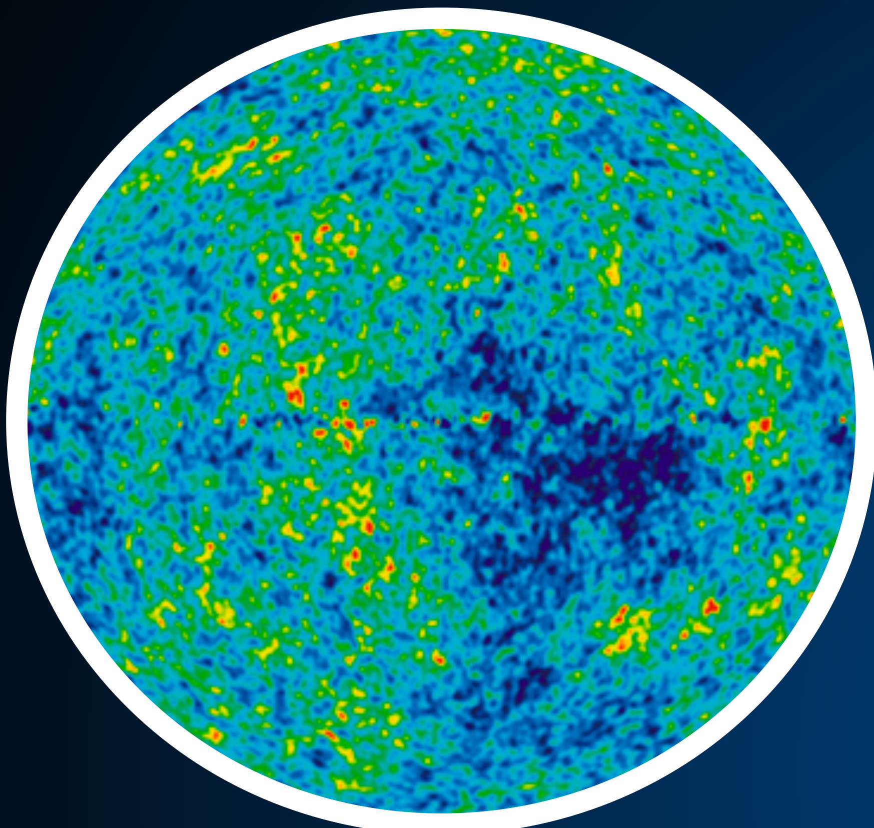
Gravitational Probes of Dark Matter

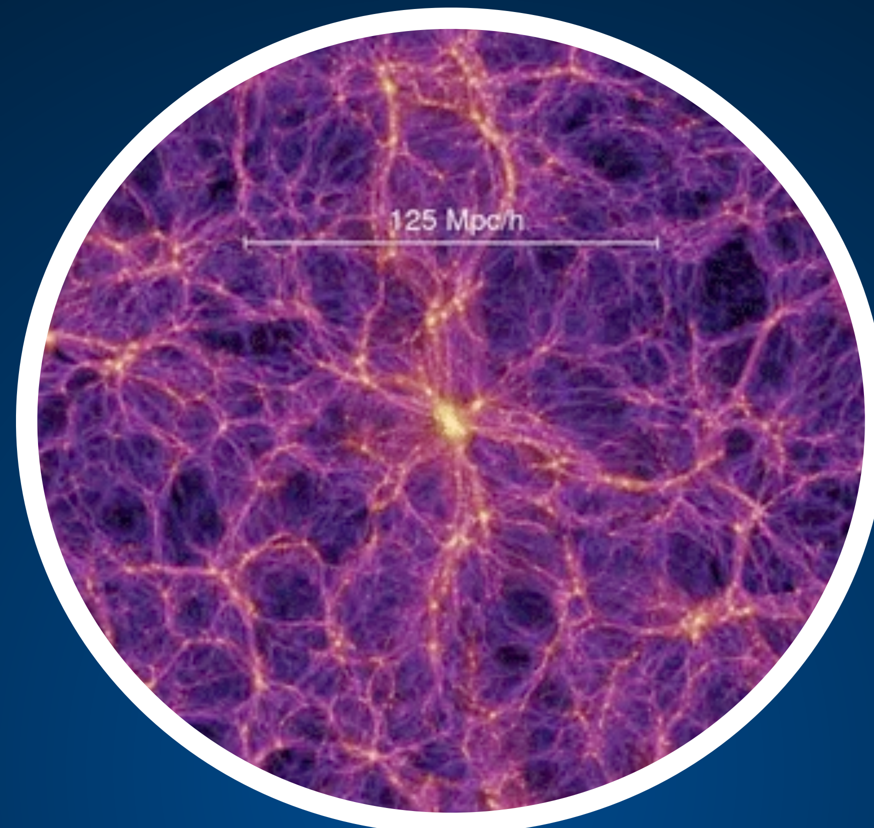




- Dark Matter is:
  - Dark
  - Cold
  - Stable

Gravitational Probes of Dark Matter





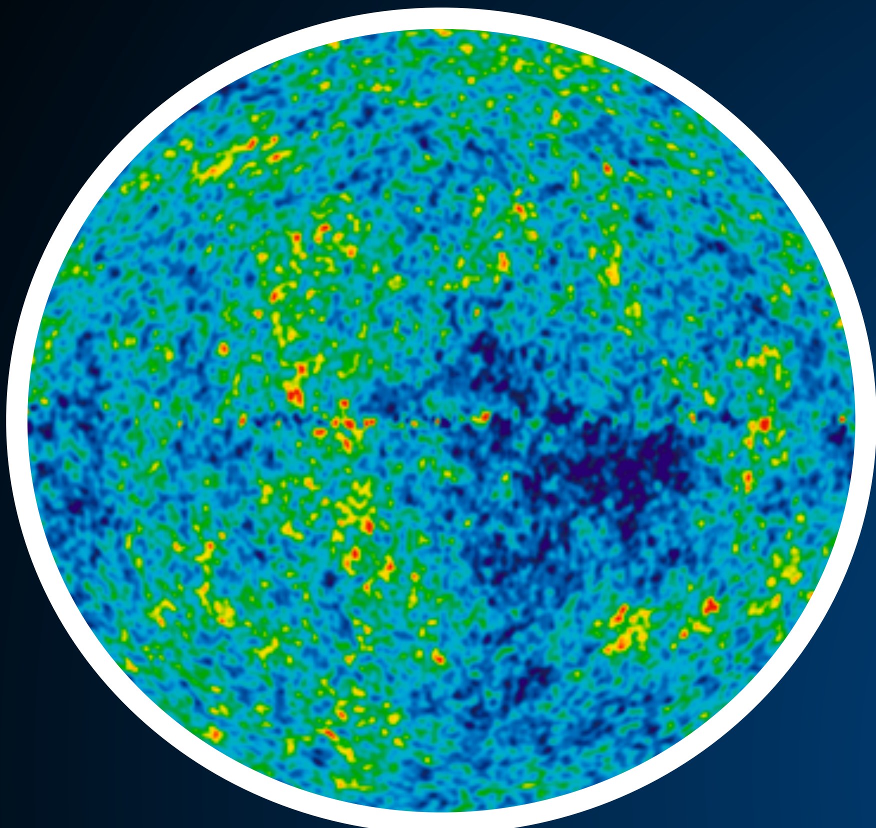
10^{-25} GeV

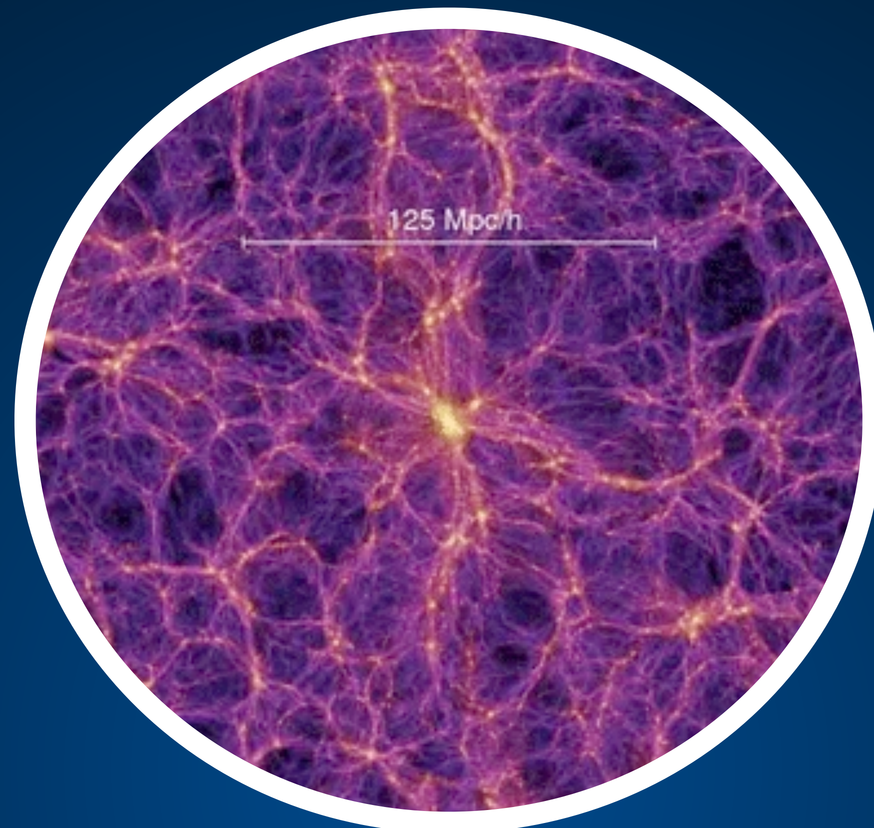
$\sigma_X > R_{dwarfs}$

10^{62} GeV

$m_X > M_{dwarfs}$

Well-Motivated Theoretical Targets





10^2 GeV

10^{-25} GeV

$\sigma_X > R_{dwarfs}$

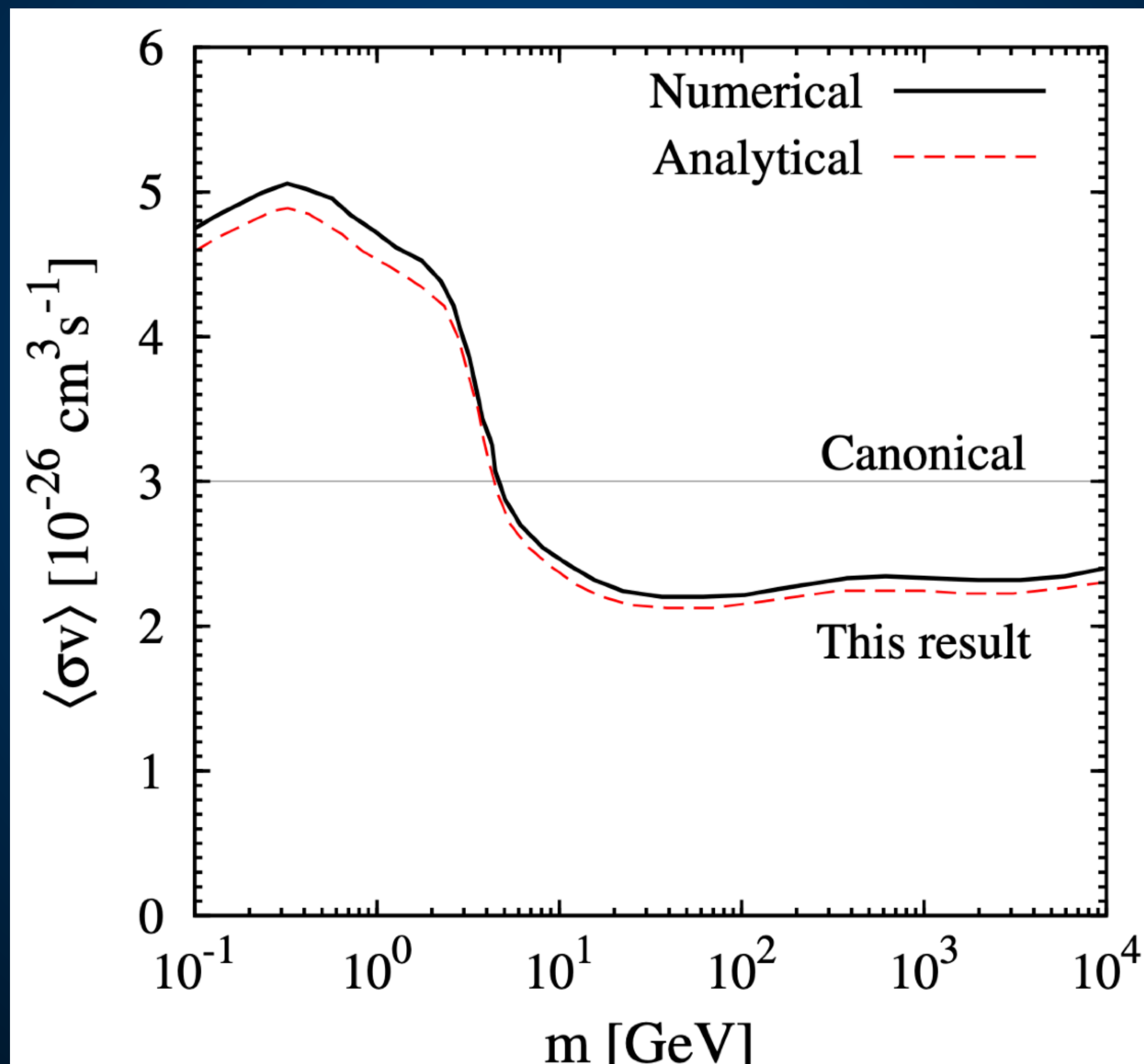
WIMP Miracle!

10^{62} GeV

$m_X > M_{dwarfs}$

0.1 GeV 10^2 GeV 10^4 GeV

WIMP Miracle!



Steigman, Dasgupta, Beacom (2012; 1204.3622)

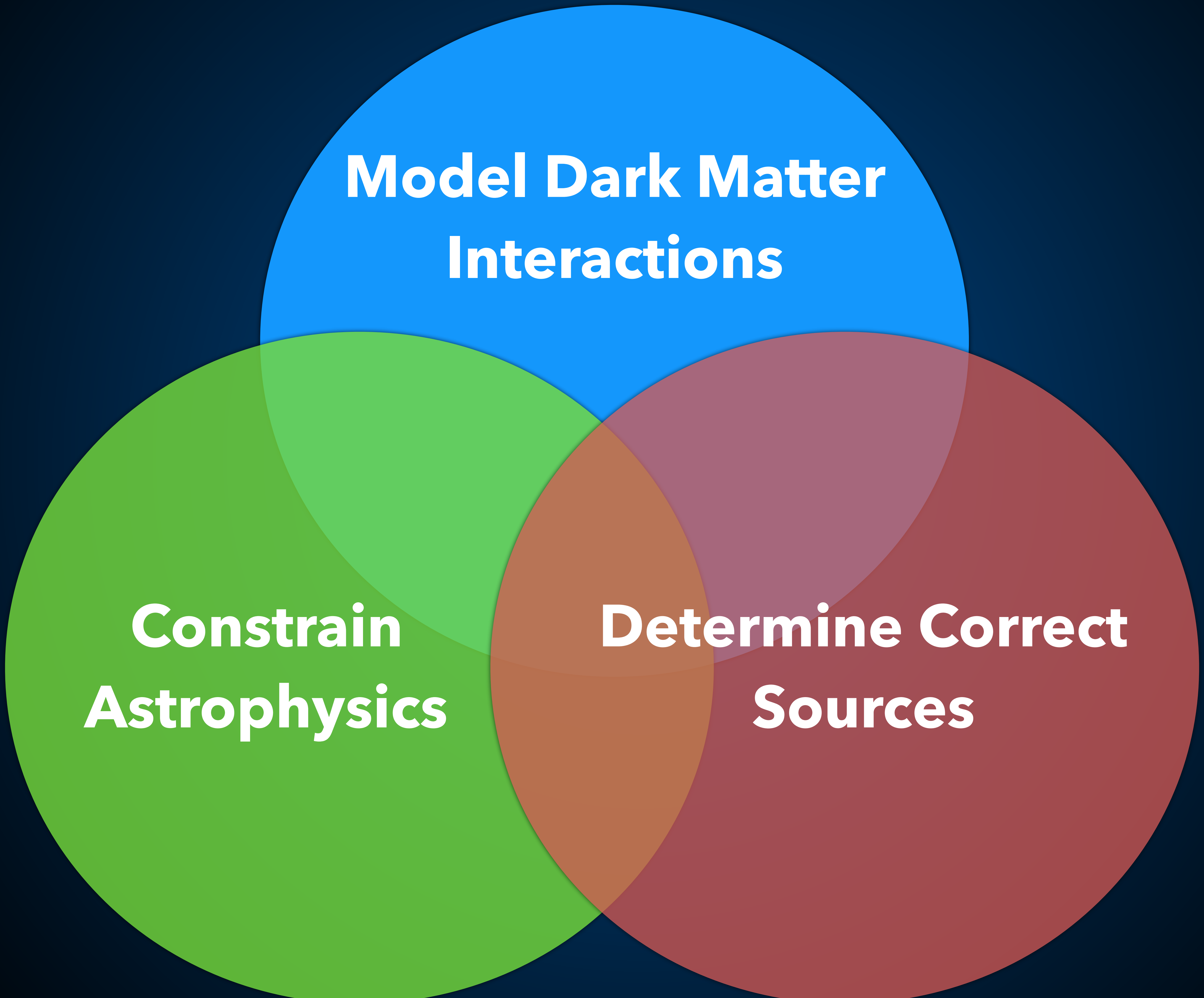
0.1 GeV 10^2 GeV 10^4 GeV

WIMP Miracle!

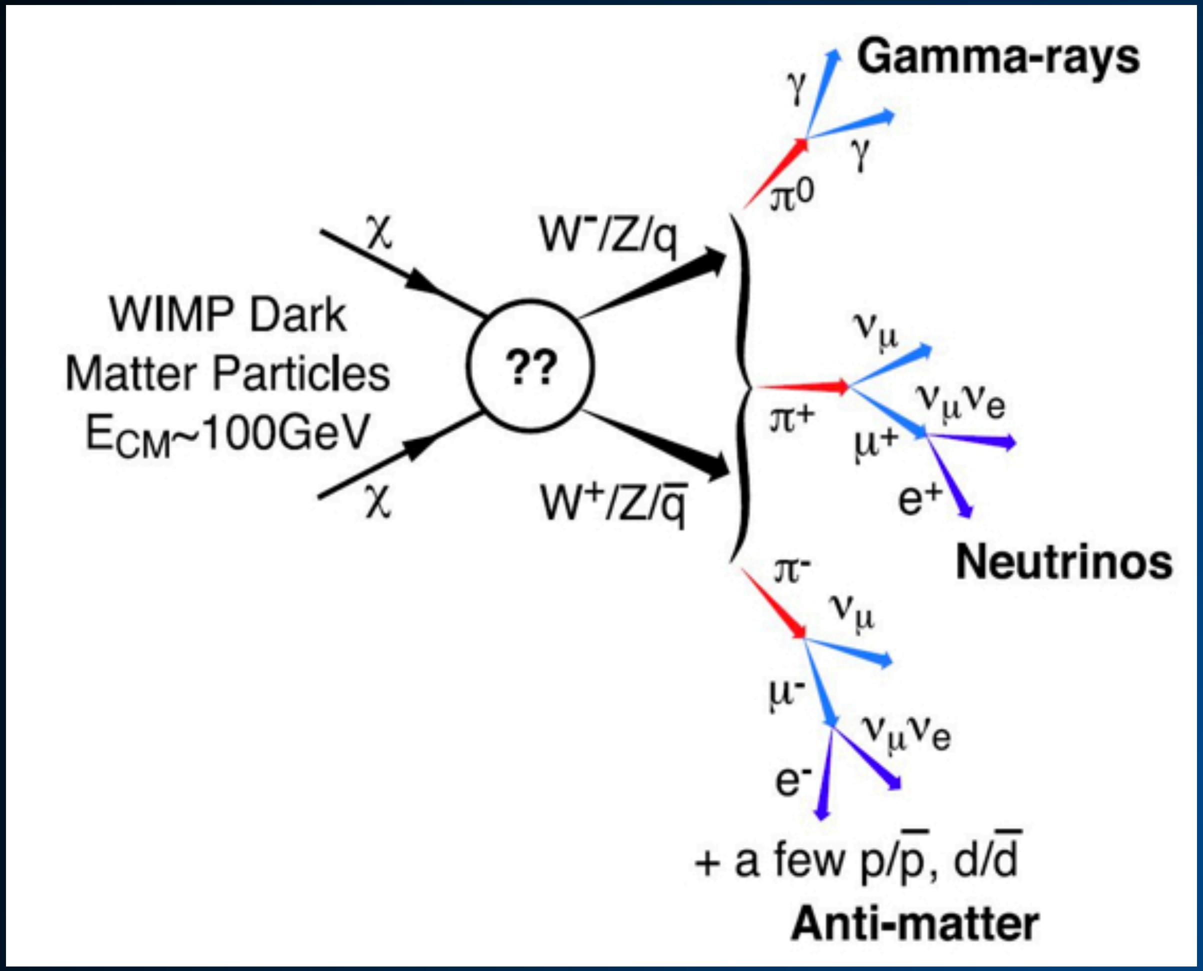
0.1 GeV | 10^2 GeV | 10^4 GeV

WIMP Miracle!

The Program

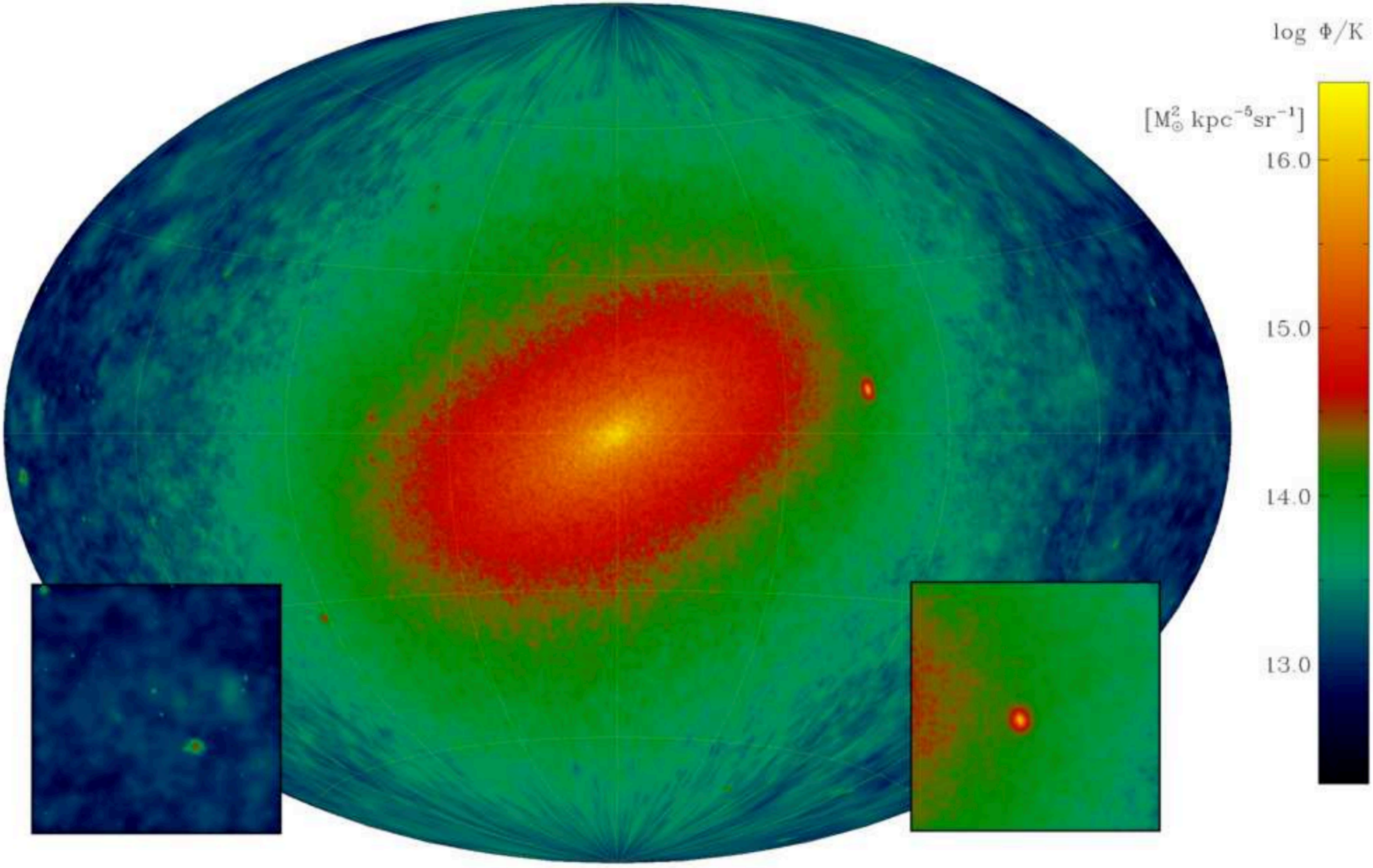

Model Dark Matter Interactions
Constrain Astrophysics
Determine Correct Sources

Progress Over the Last 10 Years

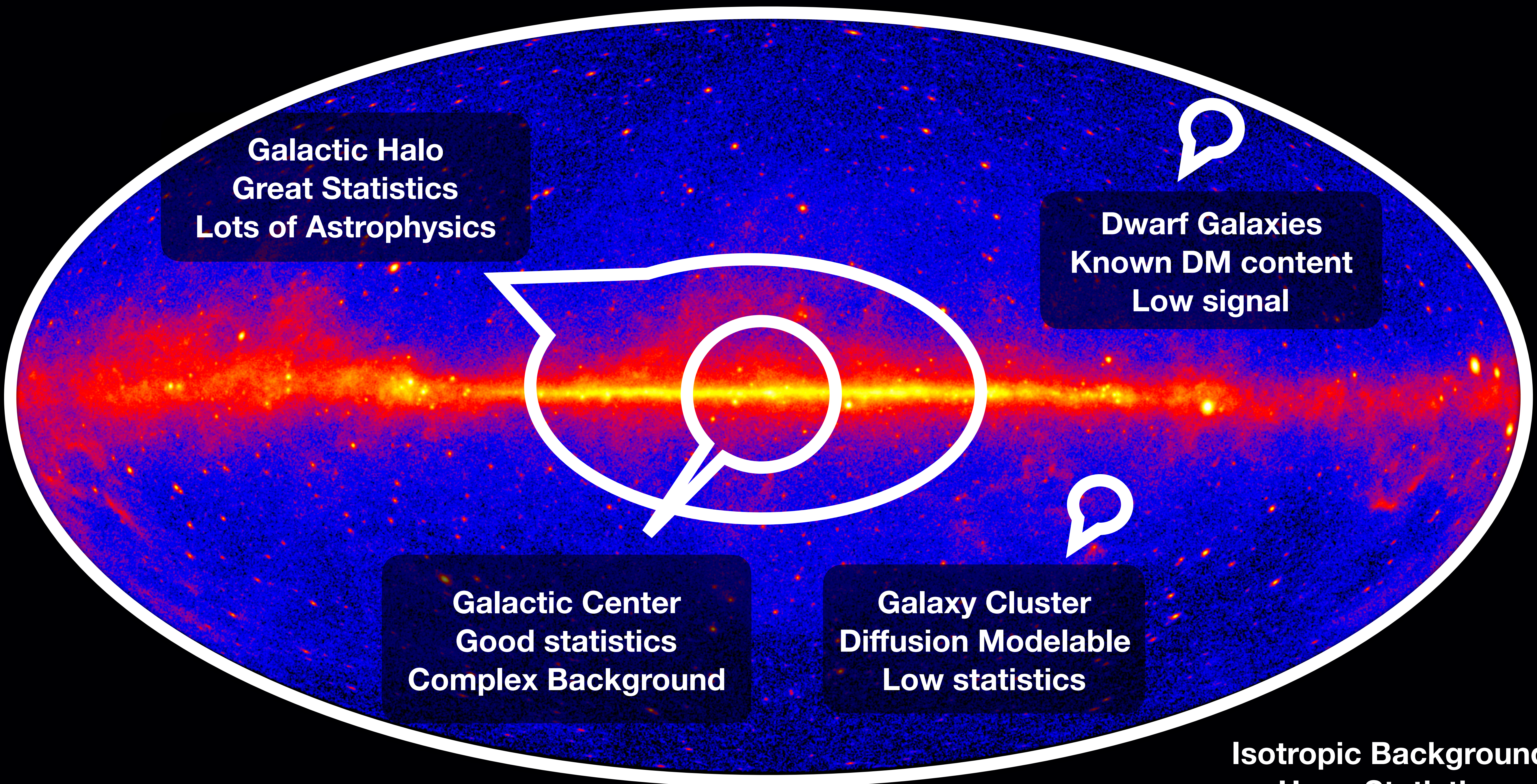


- **Search For:**
  - **Gamma-Rays**
  - **Cosmic-Rays**
  - **Neutrinos**

Insights from Computational Modeling

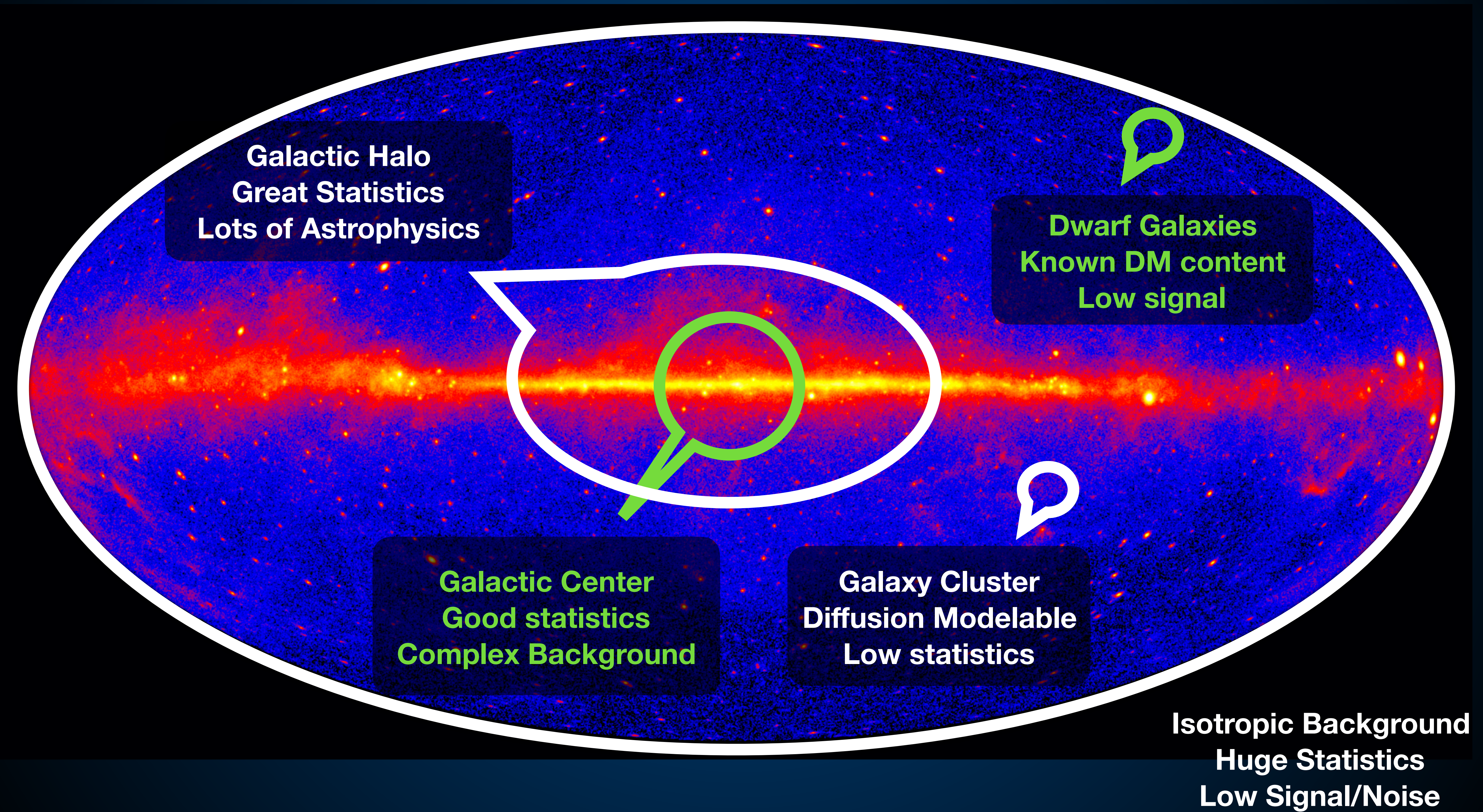


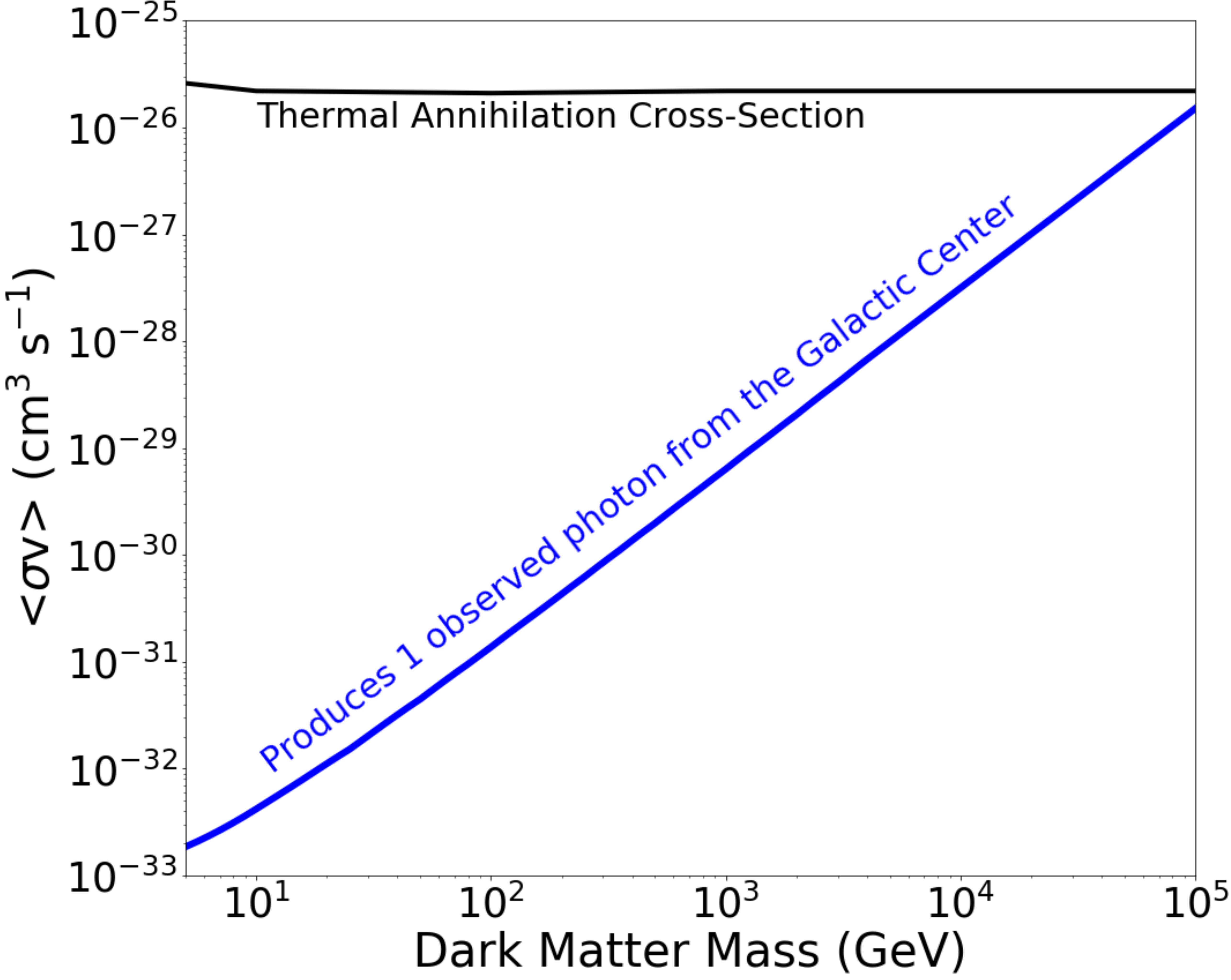
Determining the Correct Source Targets



Isotropic Background
Huge Statistics
Low Signal/Noise

Determining the Correct Source Targets




Thermal Annihilation Cross-Section
Produces 1 observed photon from the Galactic Center
$<\sigma v>$ (cm^3 s^{-1})
Dark Matter Mass (GeV)
10^{-25}
10^{-26}
10^{-27}
10^{-28}
10^{-29}
10^{-30}
10^{-31}
10^{-32}
10^{-33}
10^1
10^2
10^3
10^4
10^5

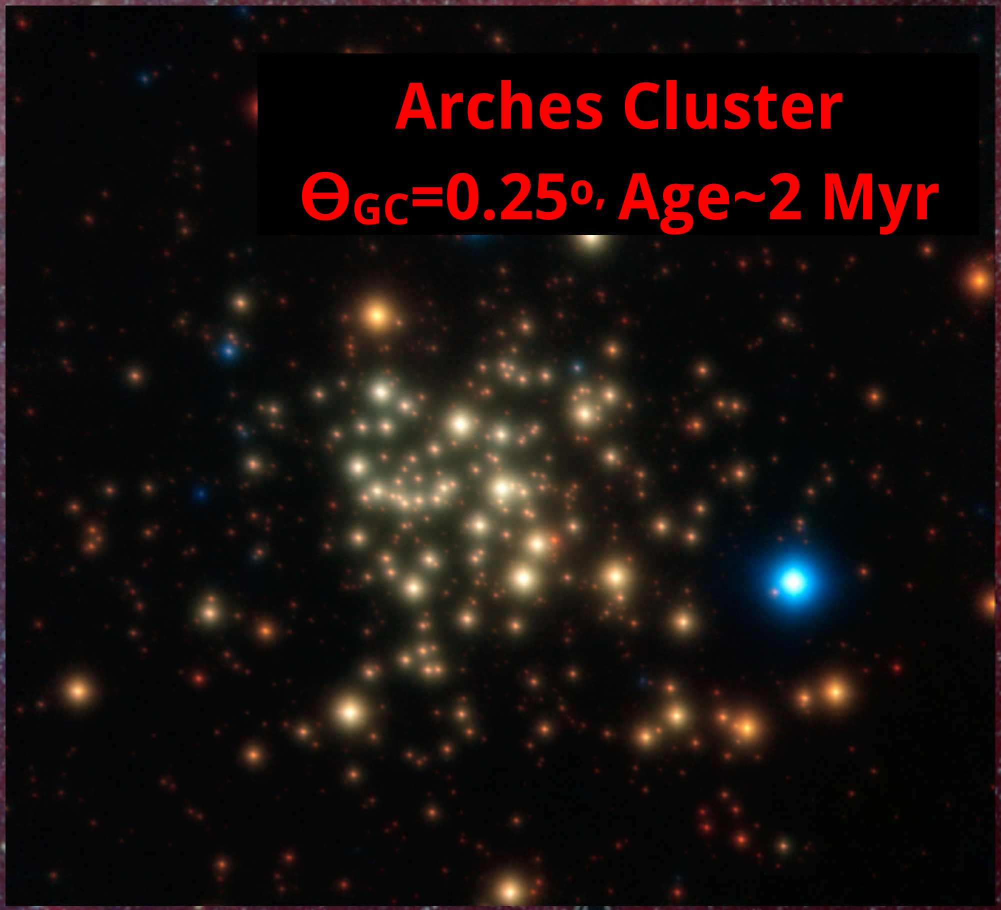
The Galactic Center is Complicated

Galactic Center is a dense star-forming environment.

3-20% of total Milky Way Star Formation

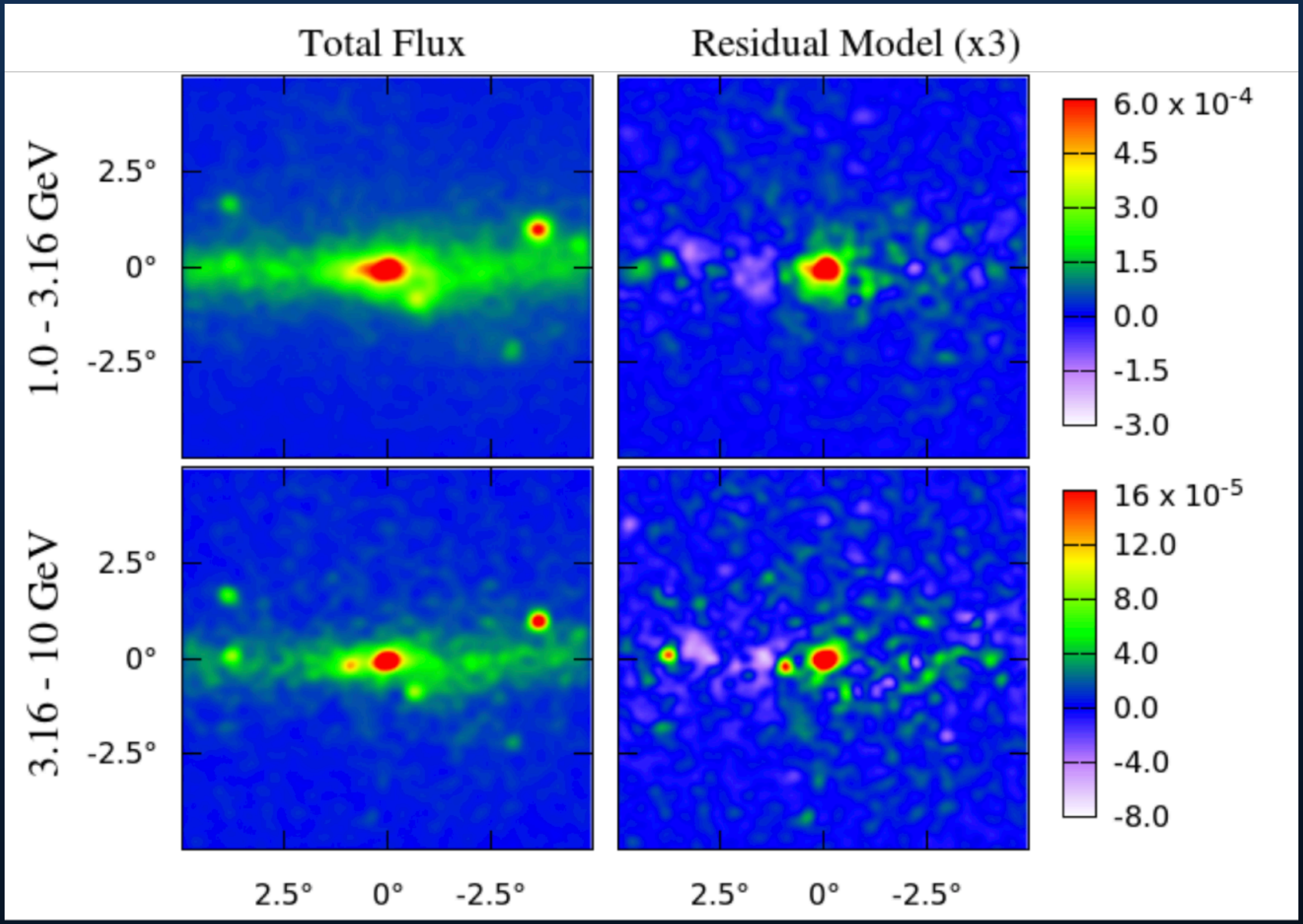
2-4% - ISOGAL Survey Immer et al. (2012)
2.5-5% - Young Stellar Objects Yusef-Zadeh et al. (2009)
5-10% - Infrared Flux Longmore et al. (2013)
10-20% - Wolf-Rayet Stars Rosslowe & Crowther (2014)
2% - Far-IR Flux Thompson et al. (2007)
2.5-6% - SN1a Schanne et al. (2007)

- **The Supernovae of these stars produce 10^{51} erg!**



The Galactic Center Excess

Daylan et al (including TL) (2014; 1402.6703)



<u>**There are four resilient features of the GeV Excess:**</u>

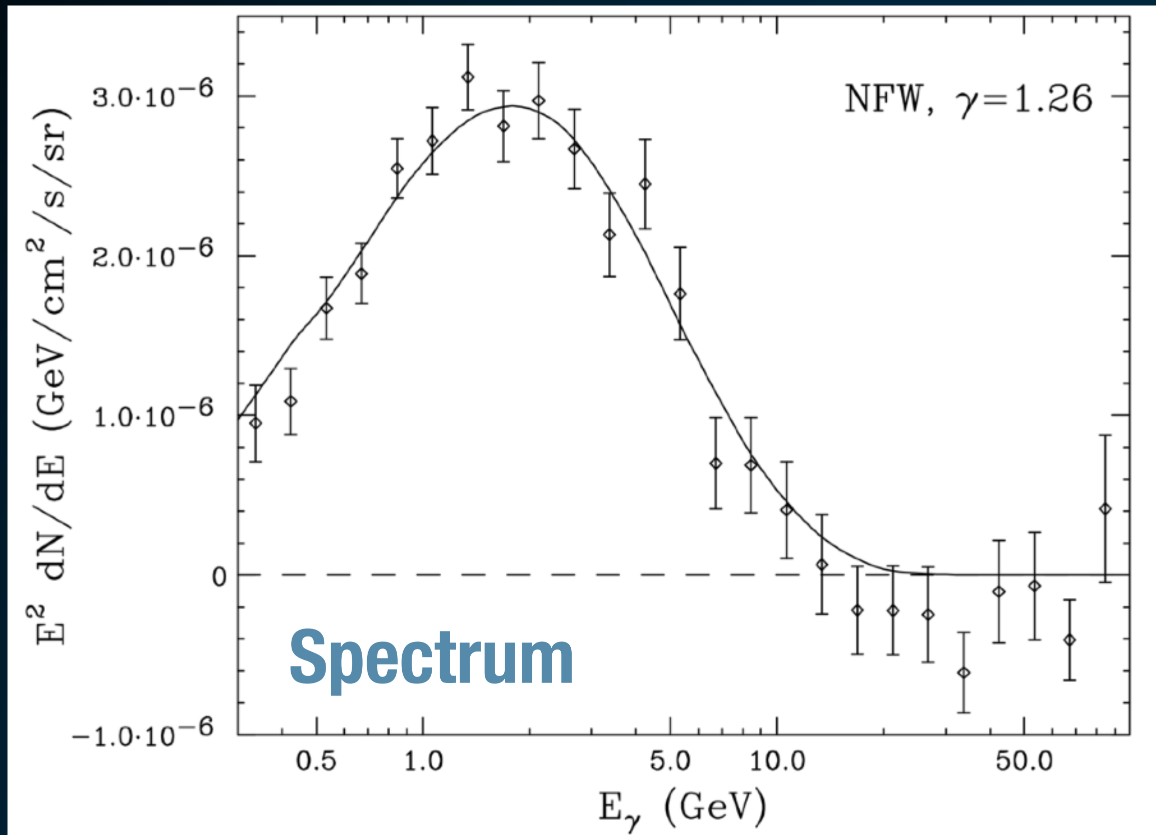
1.) High Luminosity of ~2 x 10^{37} erg s^{-1}

2.) A hard gamma-ray spectrum peaking at ~2 GeV.

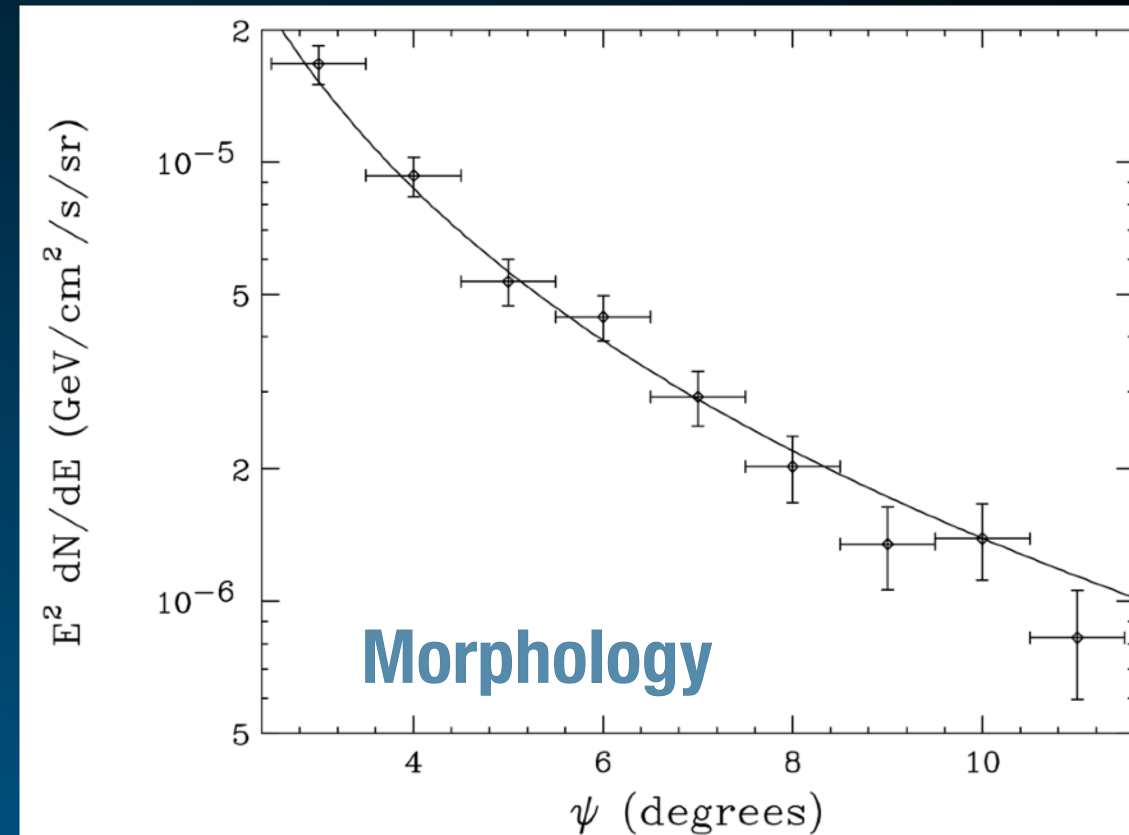
3.) A roughly spherically symmetric emission morphology.

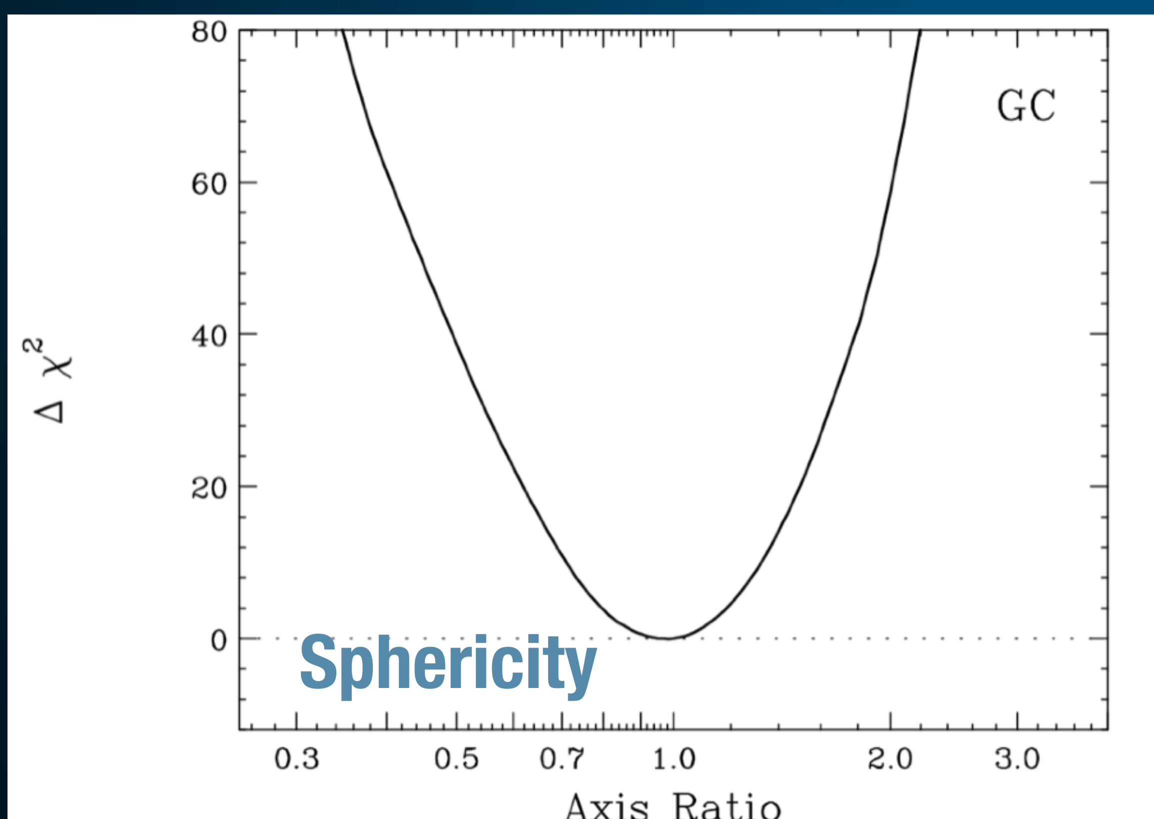
4.) Extension from roughly 0.1° to >10° from the Galactic Center.

Significant Freedom

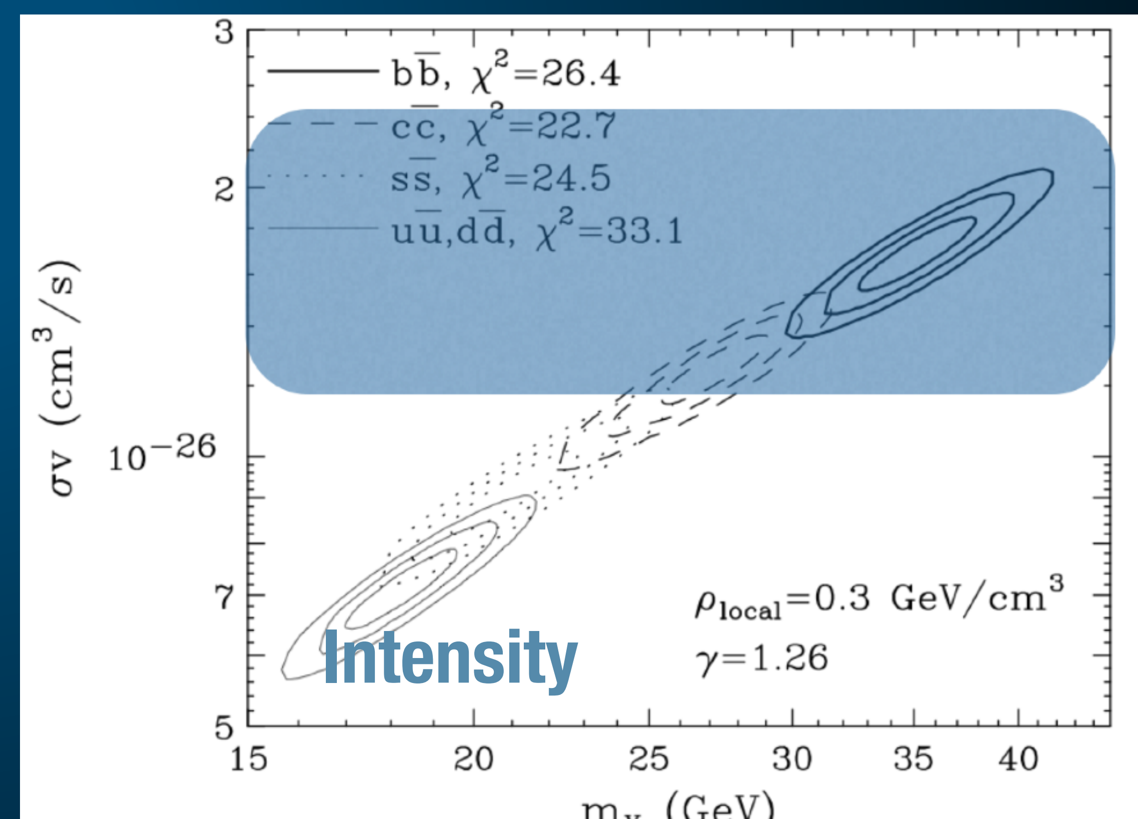


Constrained





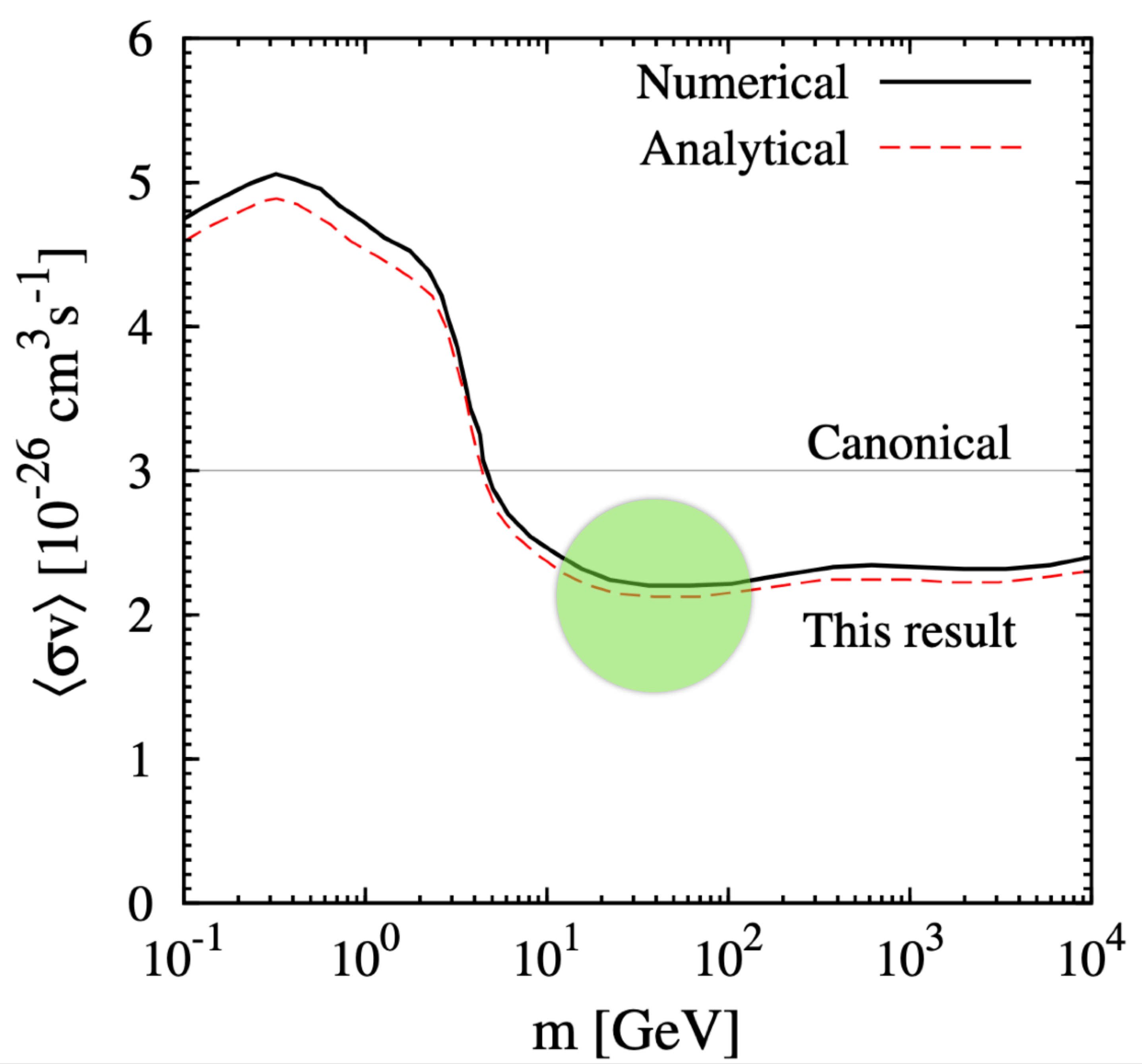
Constrained



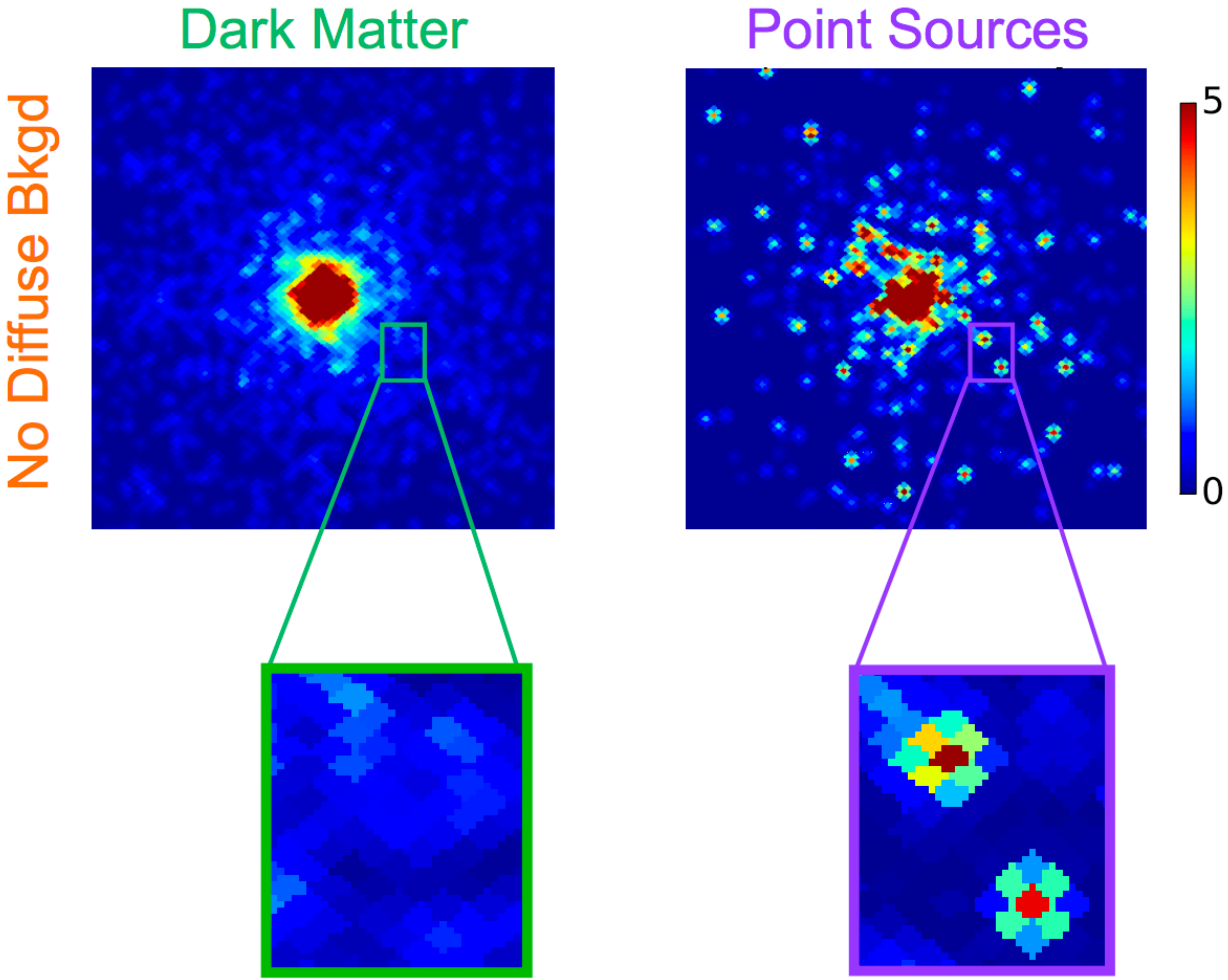
Constrained

0.1 GeV 10² GeV 10⁴ GeV

WIMP Miracle!



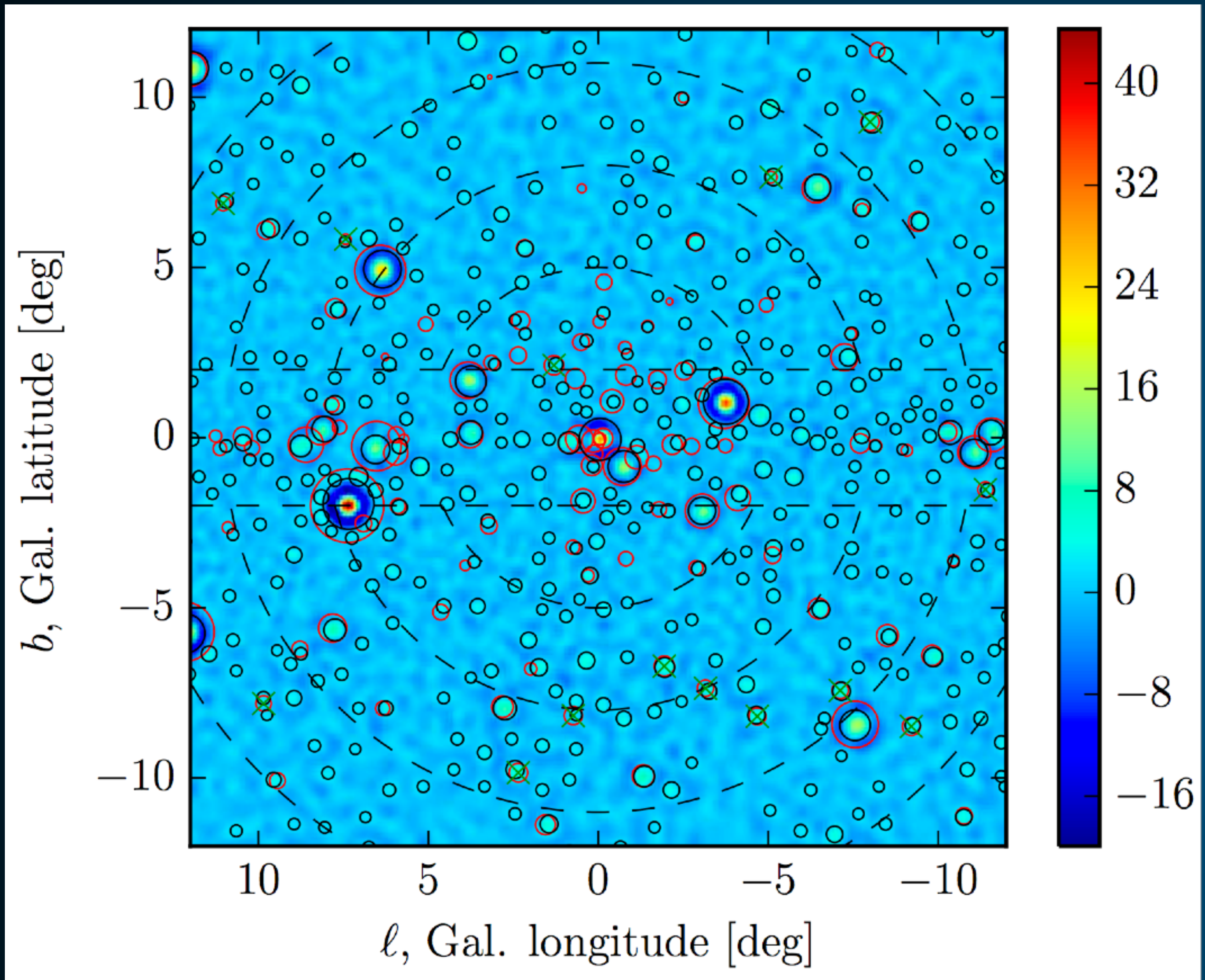
Steigman, Dasgupta, Beacom (2012; 1204.3622)



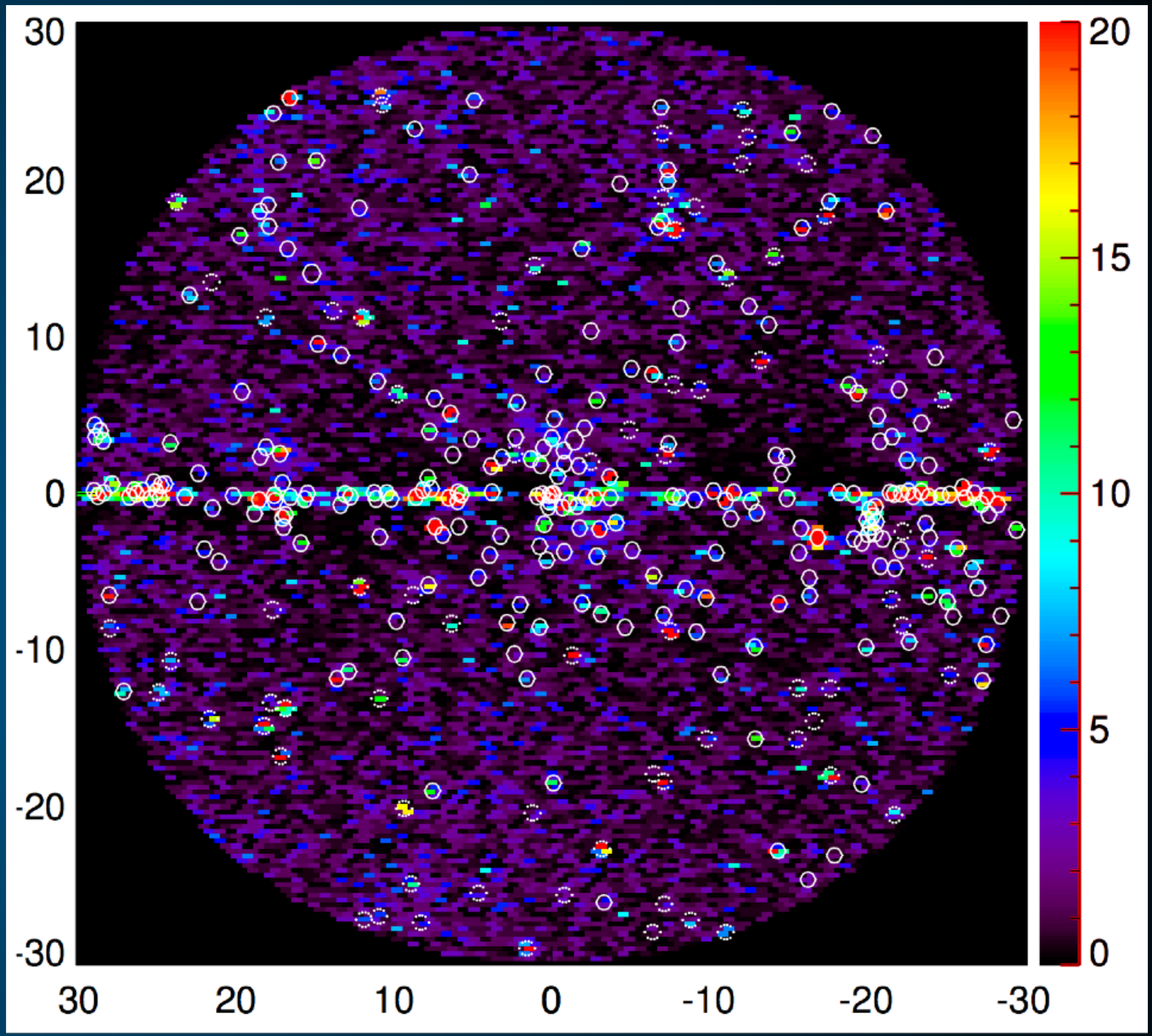
slide from Mariangela Lisanti

Evidence for Point Source Fluctuations?

Bartels et al. (2015)



Lee et al. (2015)

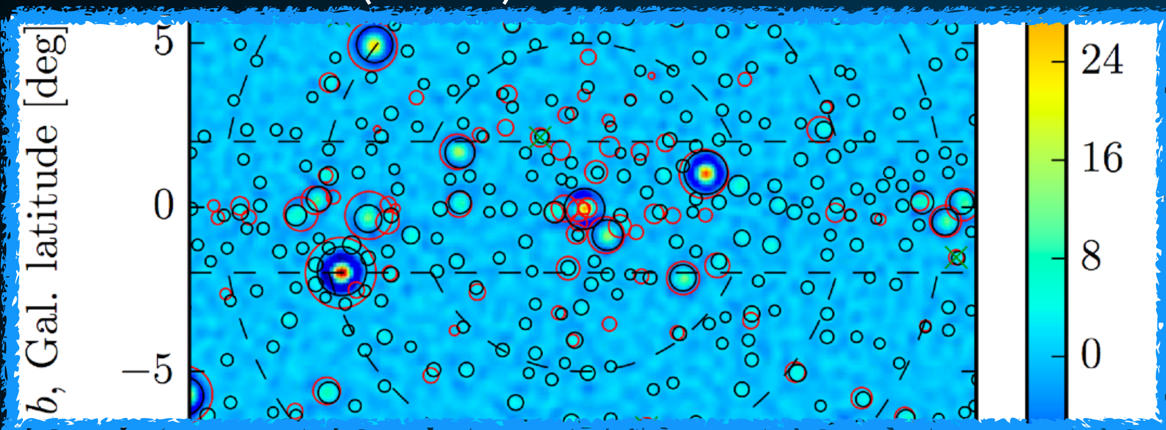


- **Recent analyses of hot-spots and cold spots in the GC region find evidence for the presence of a population of sub-threshold point sources.**

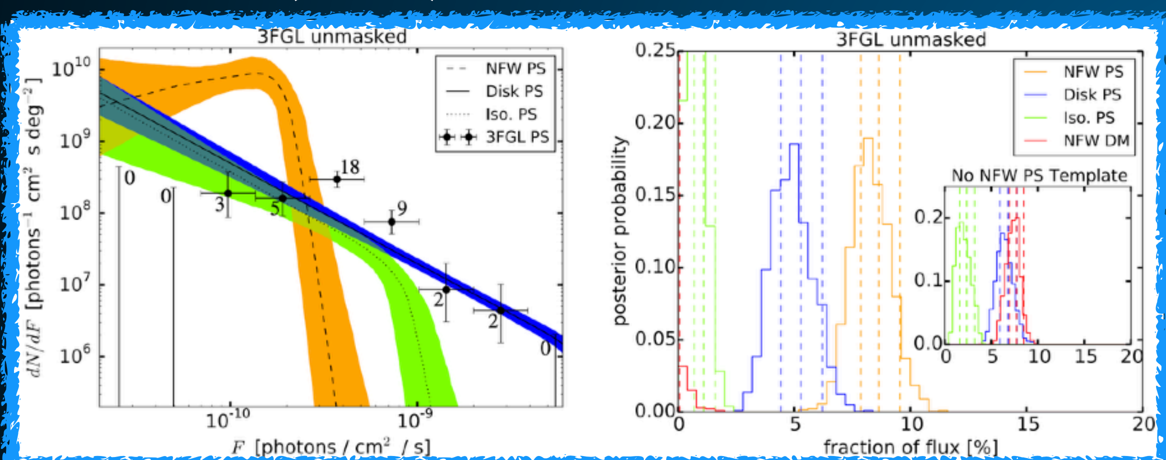
Evidence for Point Source Fluctuations?

Morphological Evidence Supports

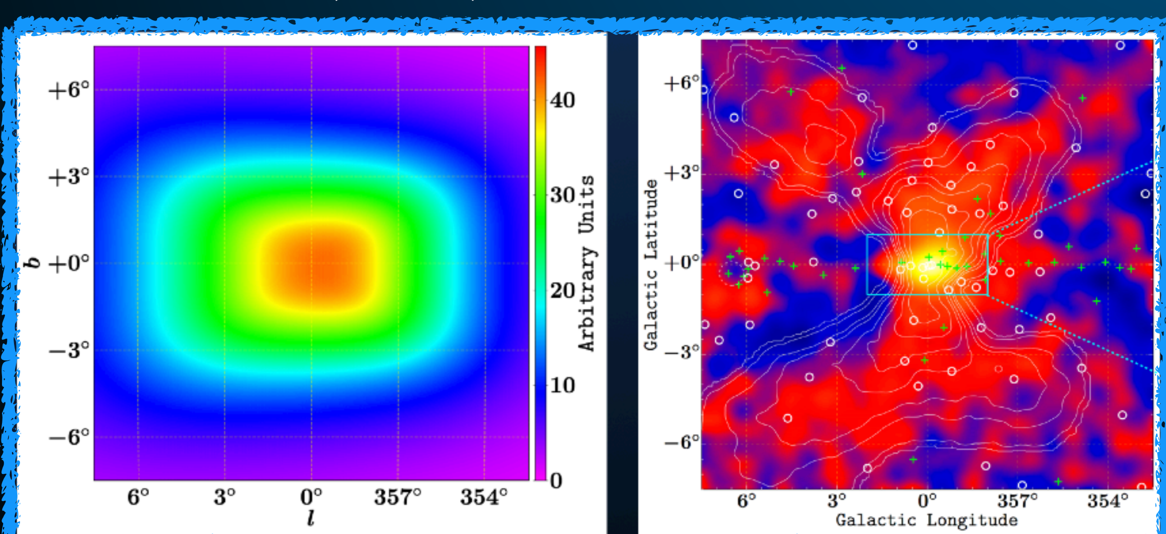
Bartels et al. (2015)



Lee et al. (2015)

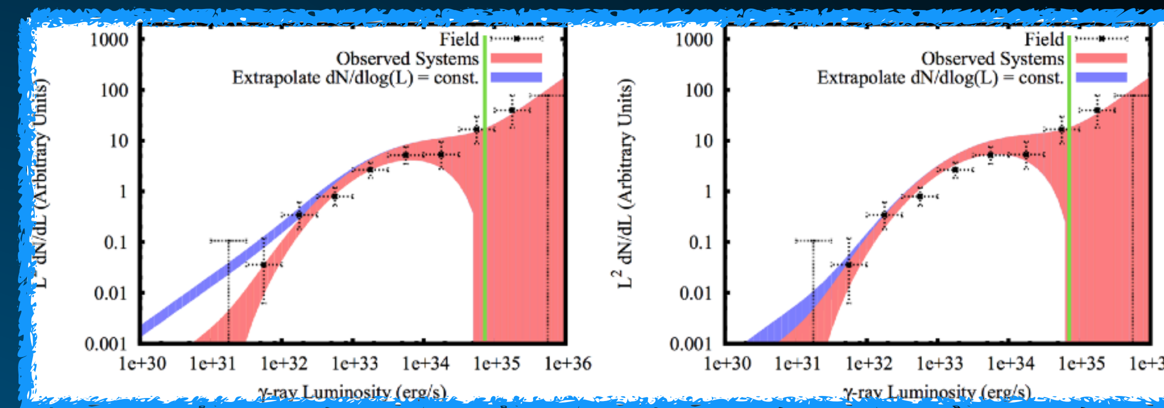


Macias et al. (2016)

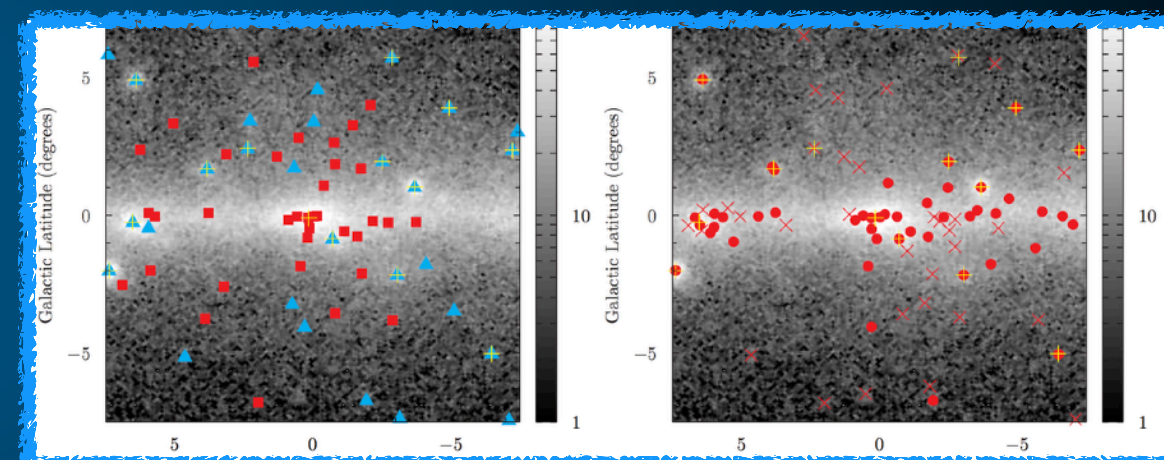


Source Models Oppose

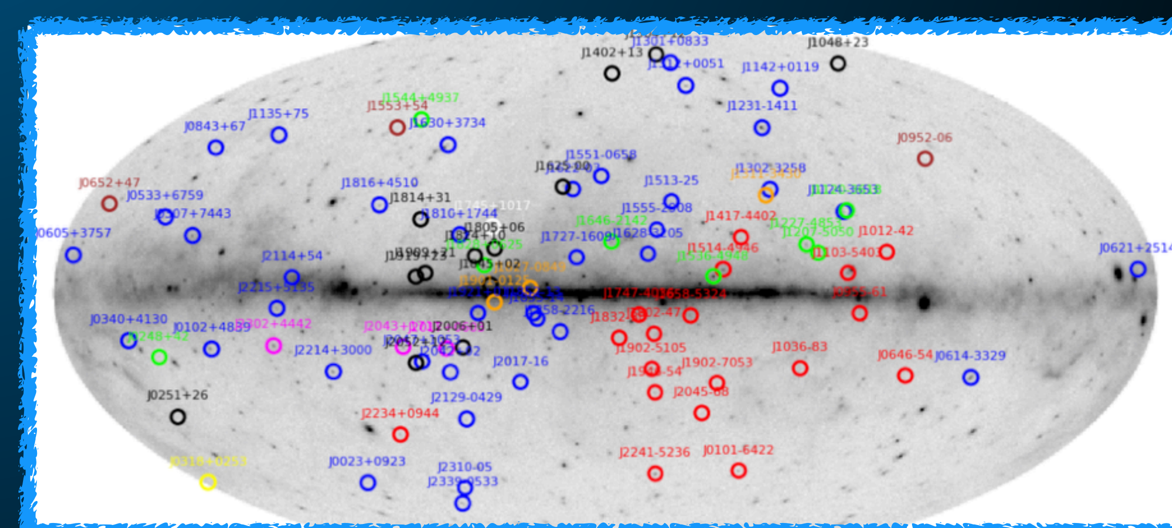
Cholis, Hooper, TL (2014)

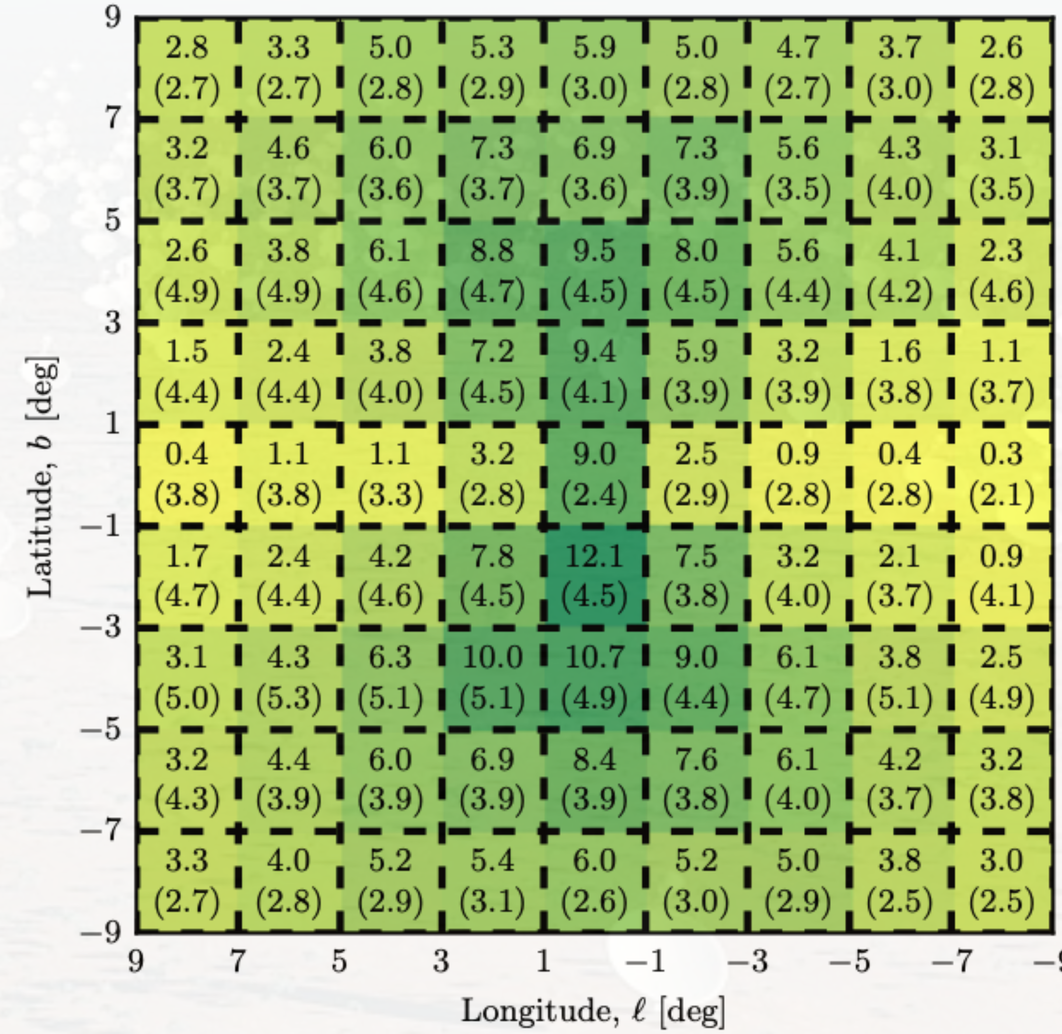


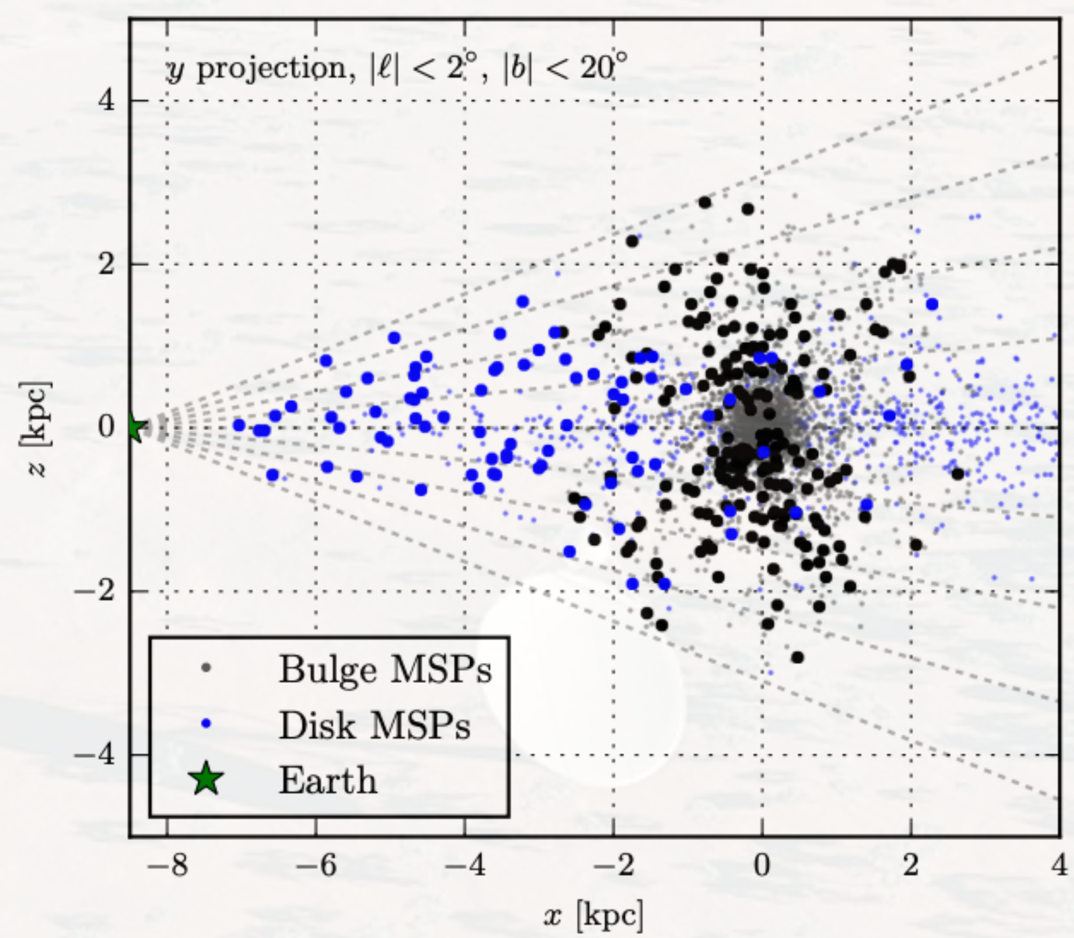
Fermi-LAT Collaboration (2016)



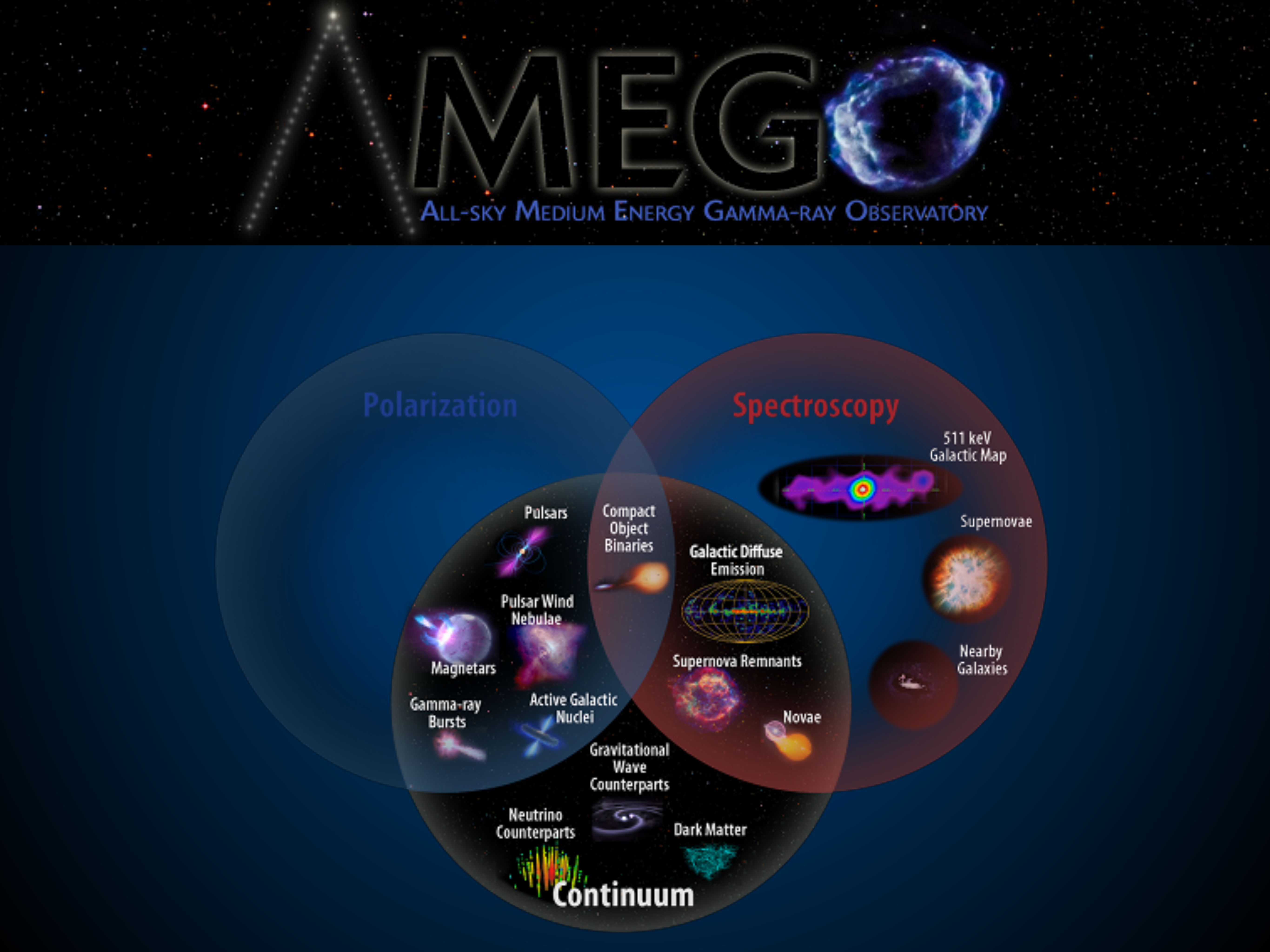
Paul Ray (Private Communication)



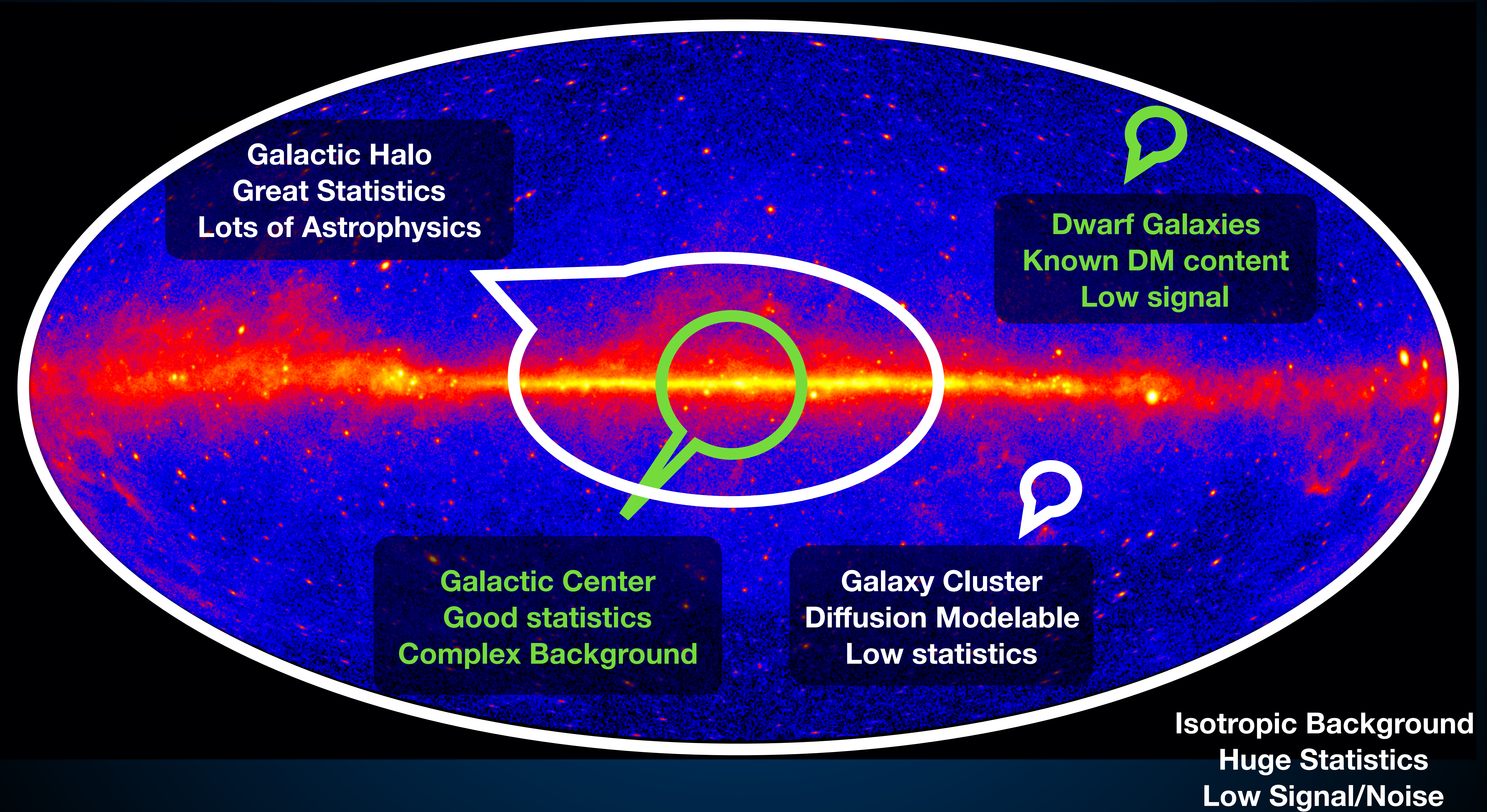




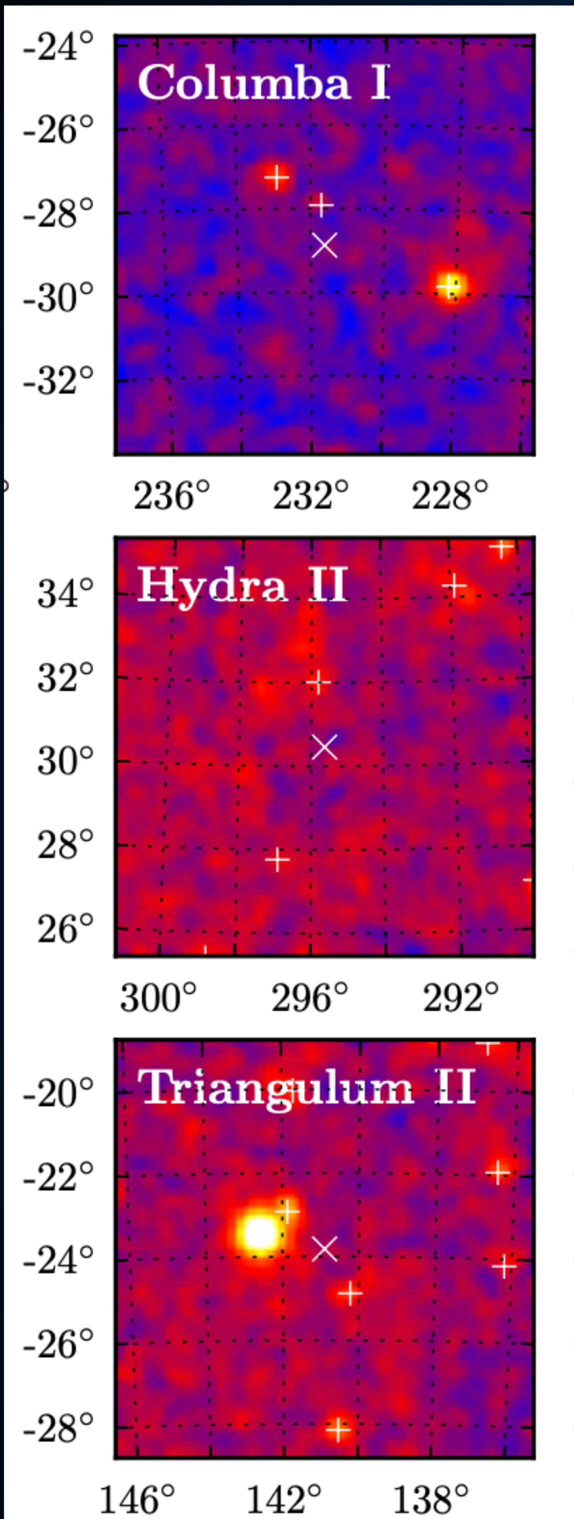
Calore et al. (2015; 1512.06825)

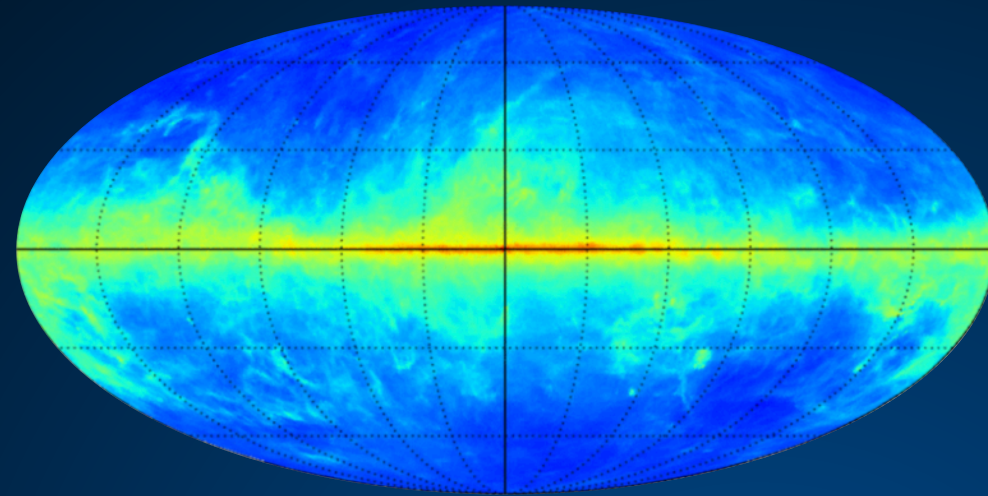

AMEGO
All-sky Medium Energy Gamma-ray Observatory
Polarization
Spectroscopy
511 keV Galactic Map
Supernovae
Nearby Galaxies
Pulsars
Compact Object Binaries
Galactic Diffuse Emission
Pulsar Wind Nebulae
Magnetars
Supernova Remnants
Gamma-ray Bursts
Active Galactic Nuclei
Novae
Gravitational Wave Counterparts
Neutrino Counterparts
Dark Matter
Continuum

A Cleaner Regime

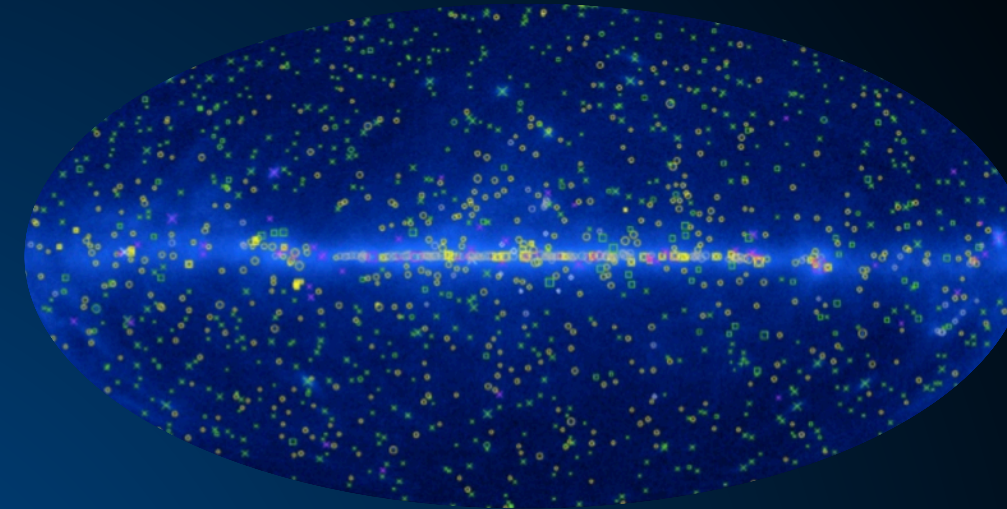


Clean != No Astrophysics



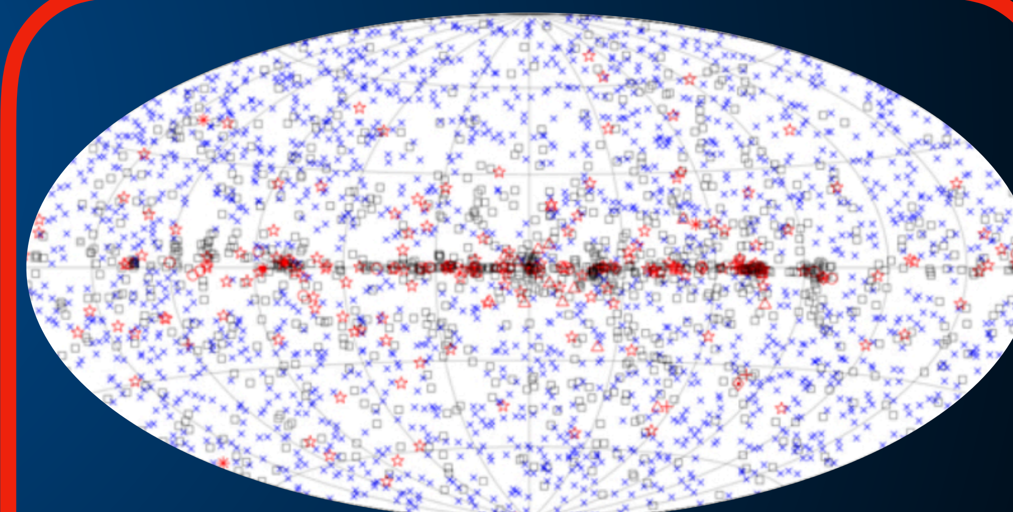


Galactic Diffuse



Point Sources

Isotropic Emission

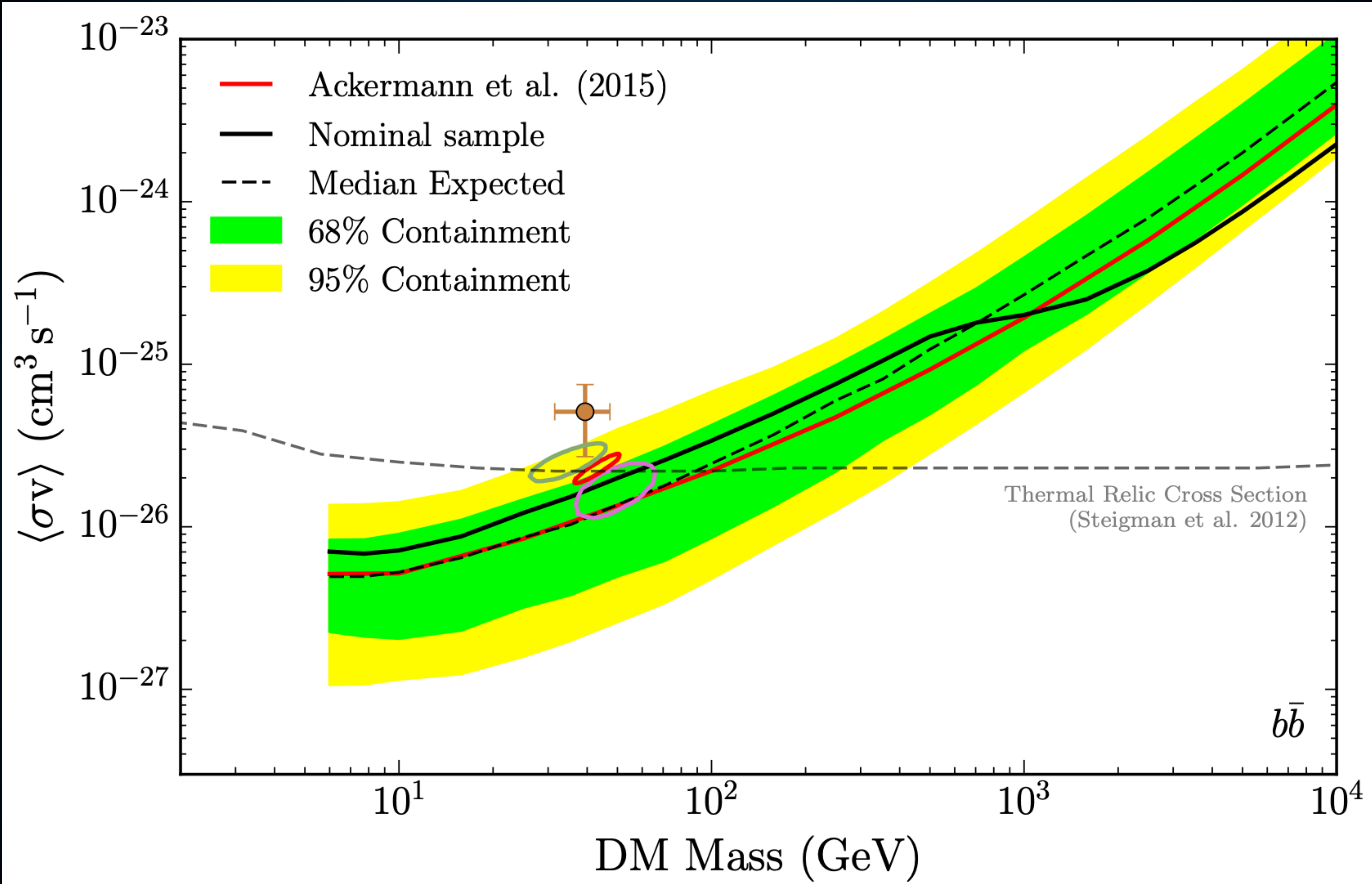


Sub-Threshold Sources

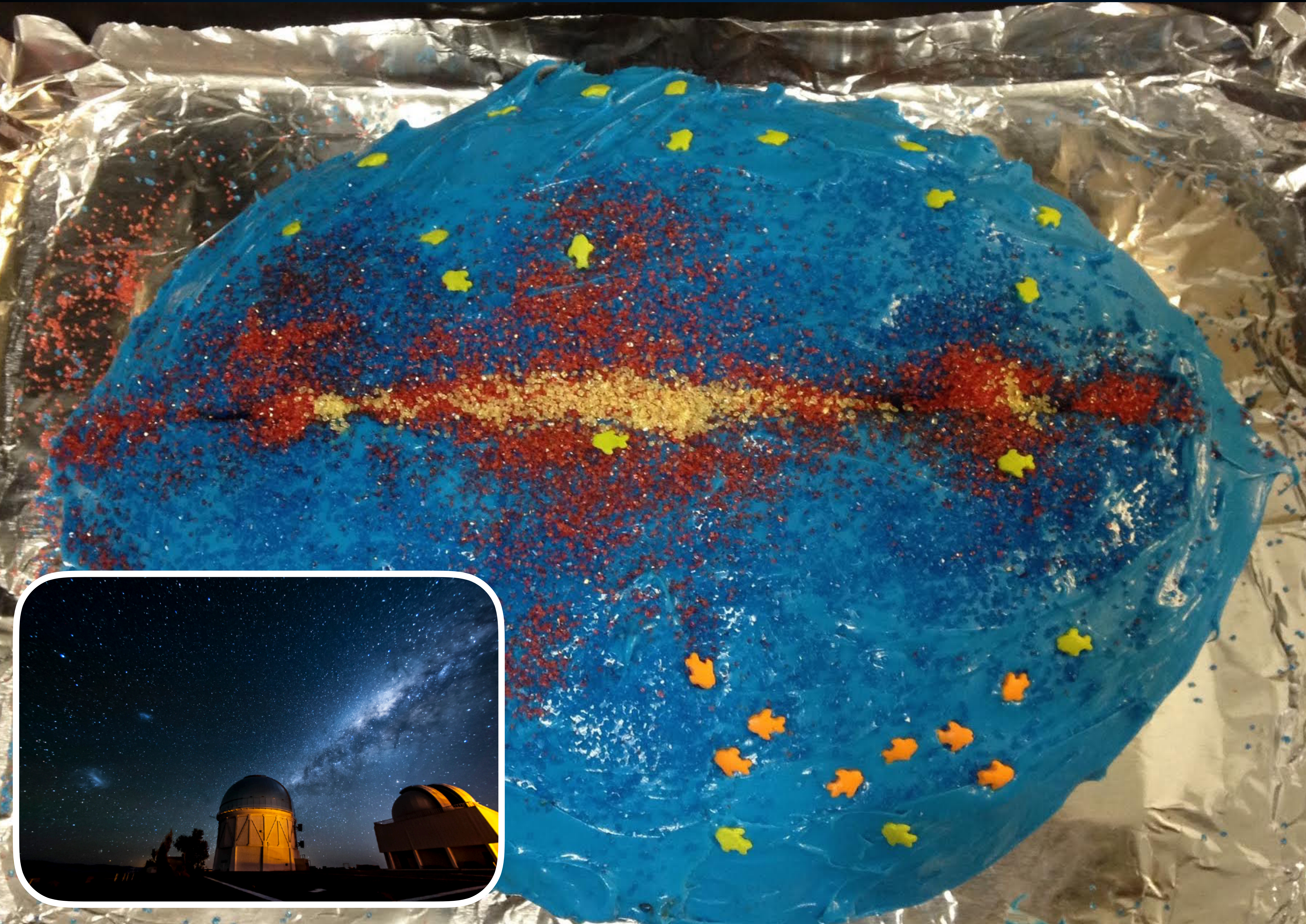
- **The emission is dim**
  - **Observational Challenge**
  - **Statistical Challenge**

A Cleaner Regime

Fermi-LAT Collaboration (2017; 1611.03184)



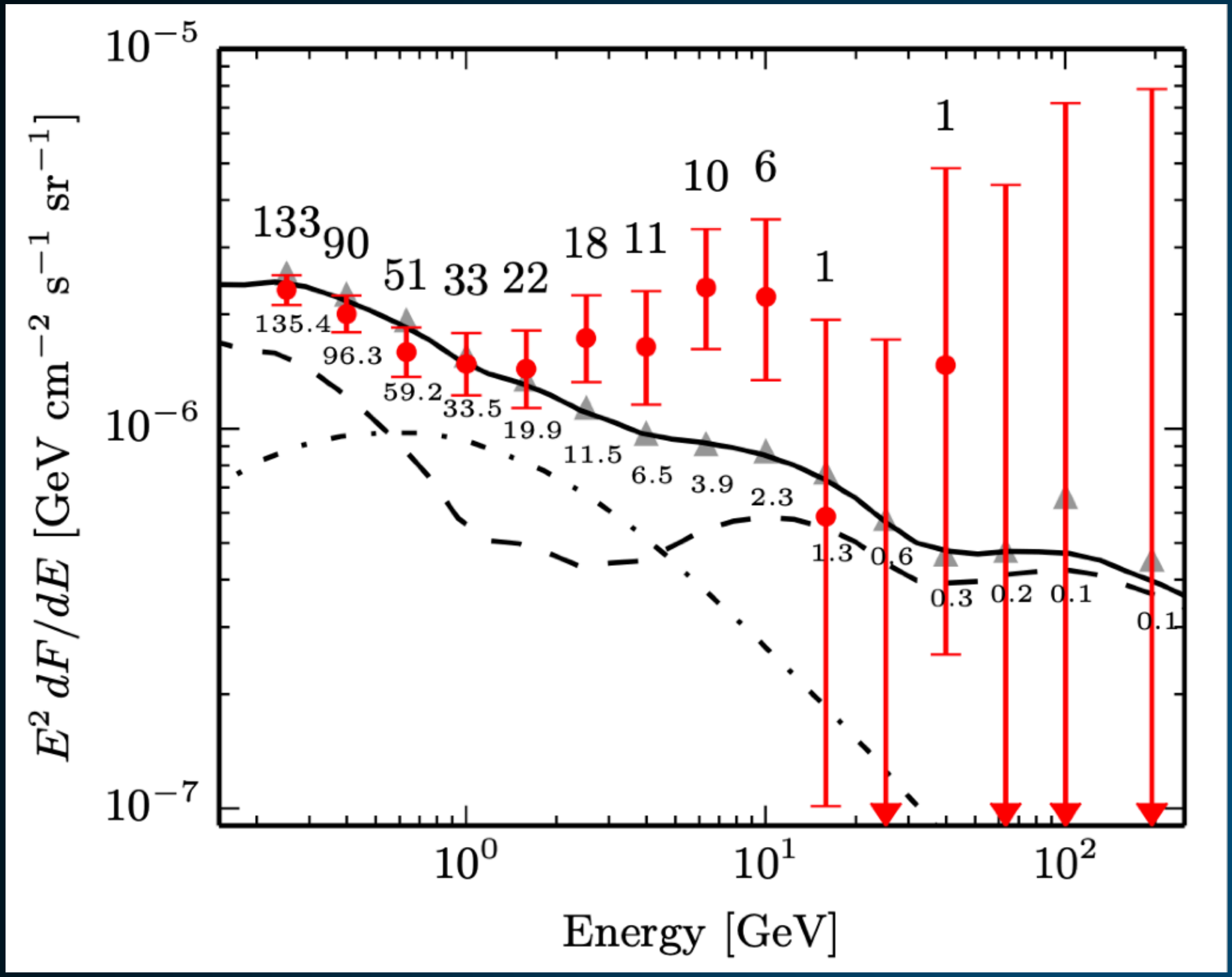
Observations Produce New Directions



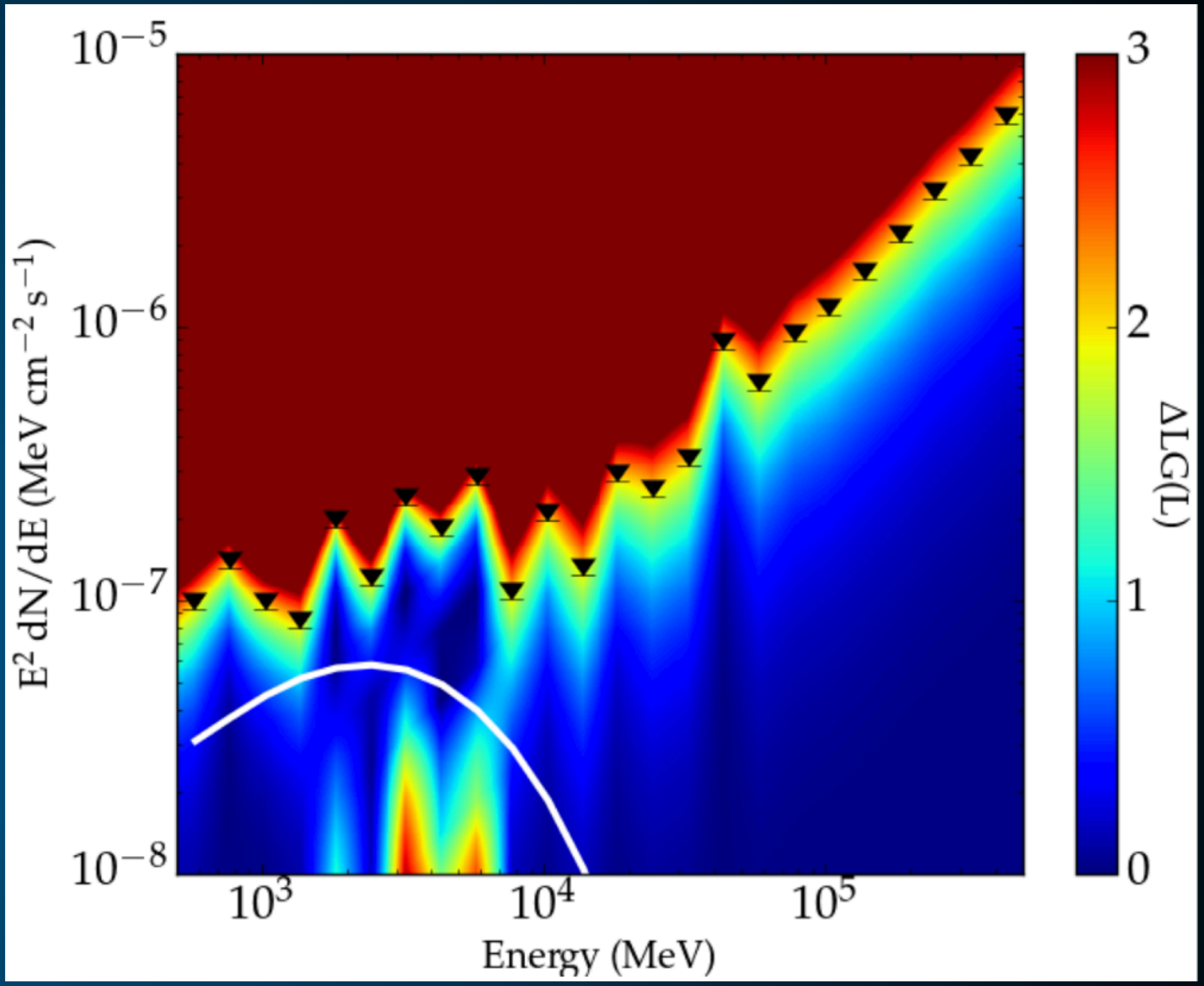
The Reticulum II Excess!

New Observations Lead to Exciting Possibilities

Geringer-Sameth et al. (2015; 1503.02320)



Hooper & TL (2015; 1503.06209)

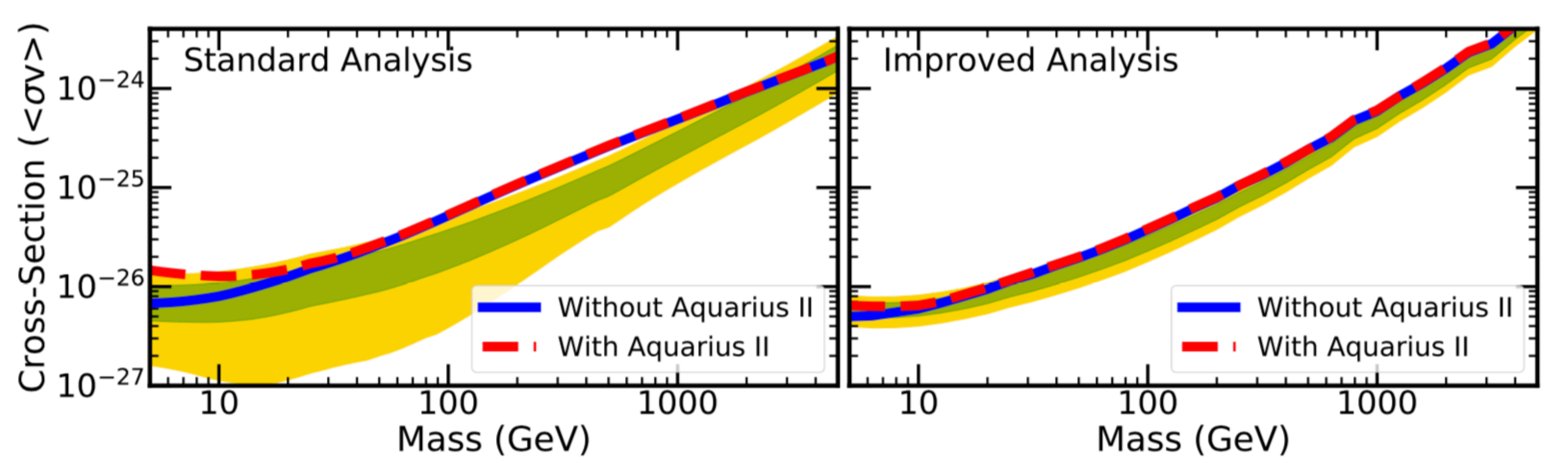


- **Detection of Reticulum II Dwarf resulted in immediate 3-sigma evidence for dark matter annihilation.**

The Reticulum II Excess!

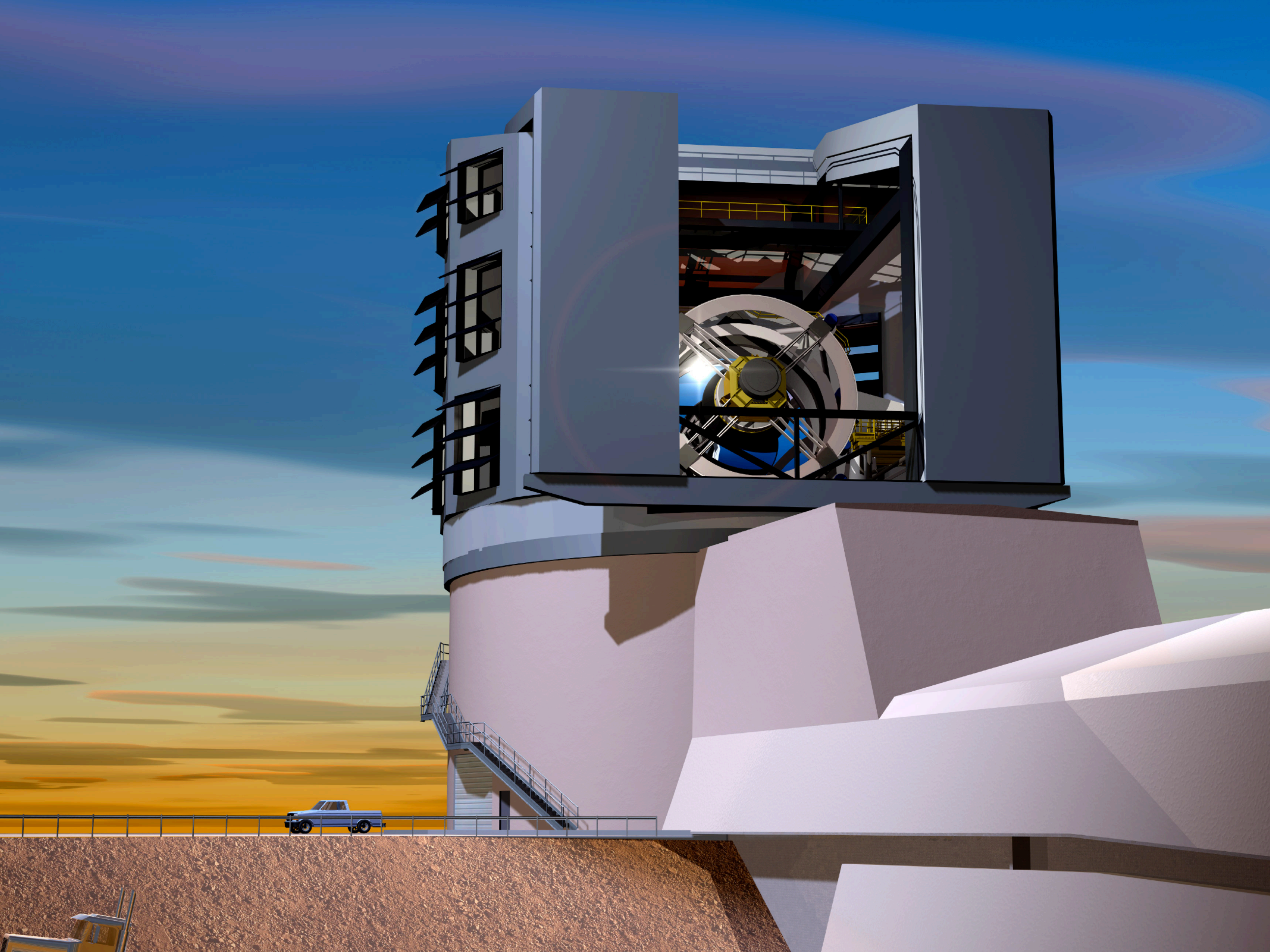
New Observations Lead to More Work

TL (TBS)

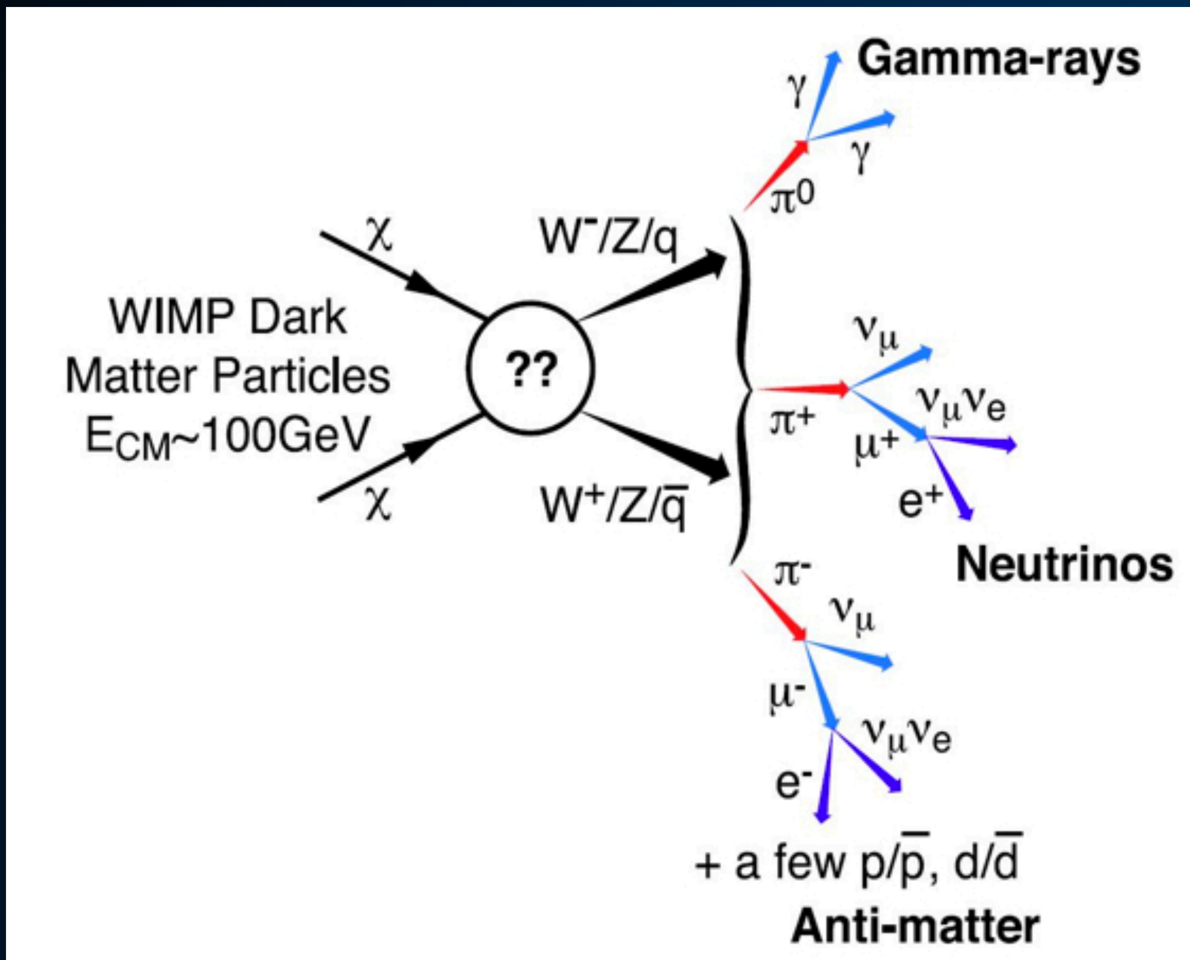


- **Systematic Uncertainties in Gamma-Ray Modeling are dominating the uncertainty in results.**

- **New methods are under development to take into account these uncertainties.**



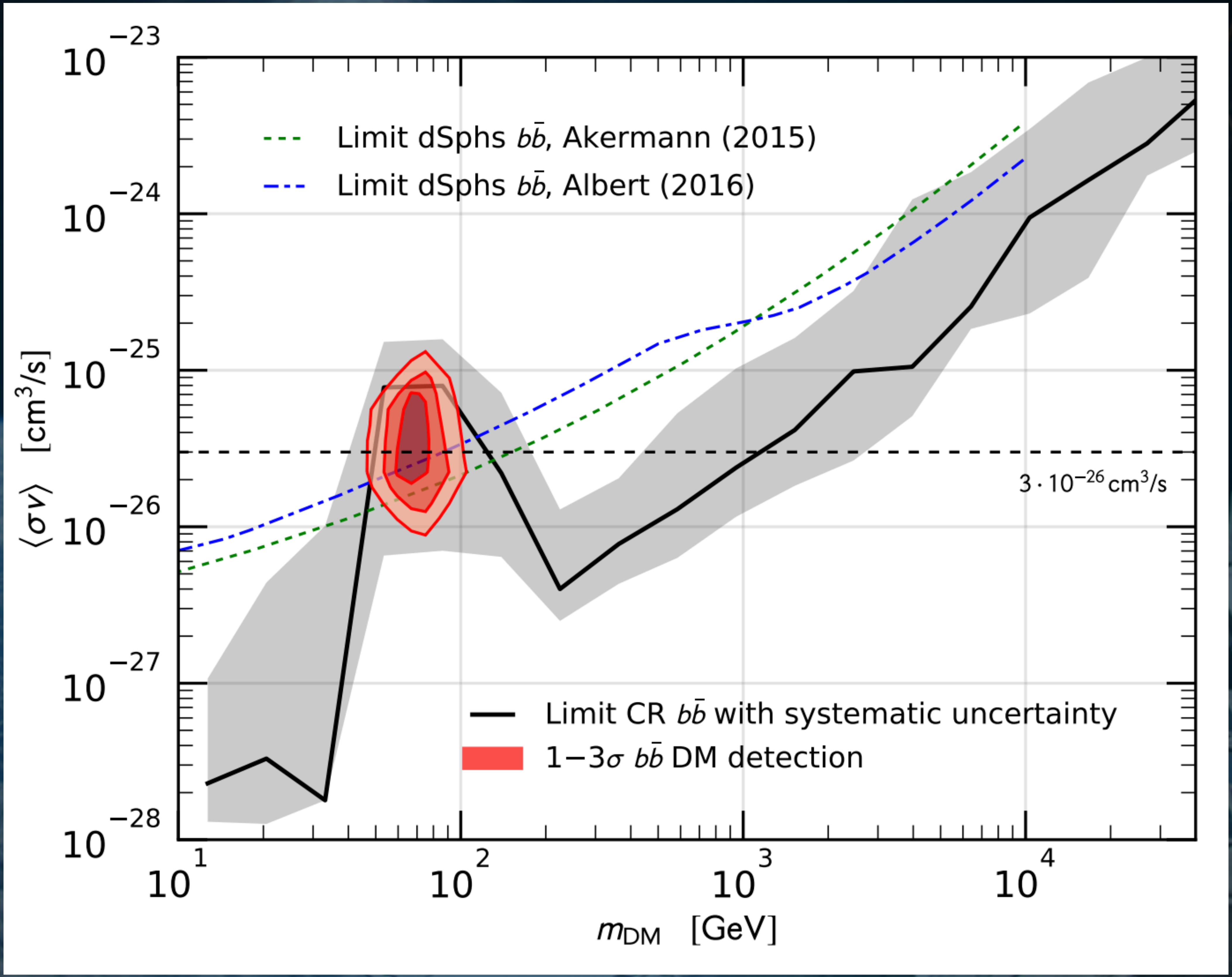
Progress Over the Last 10 Years



- Search For:
  - Gamma-Rays
  - Cosmic-Rays
  - Neutrinos

Cosmic-Ray Antimatter Searches

Cosmic-Ray Antimatter Searches



Cuoco et al. (2016)

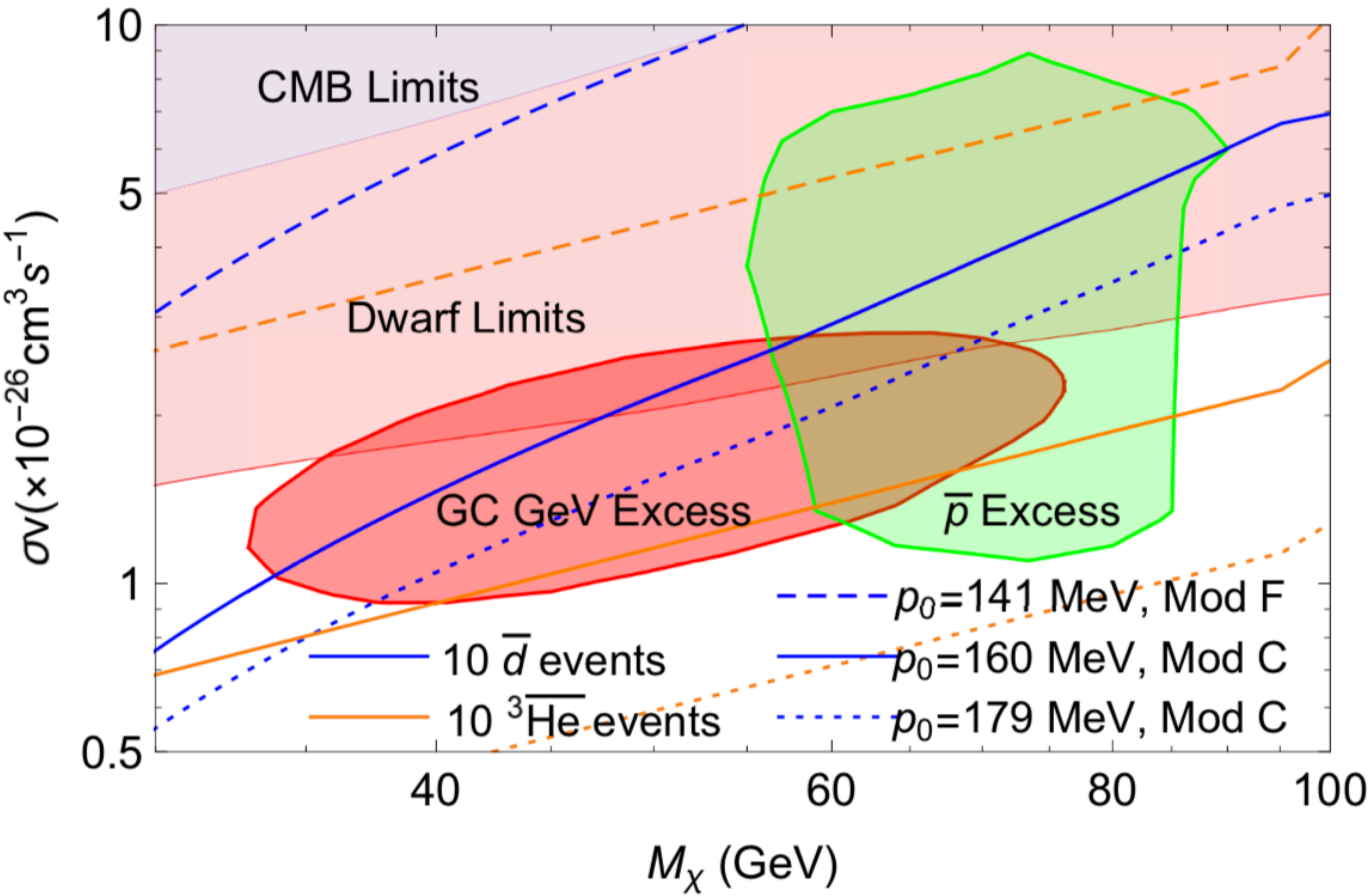
Cosmic-Ray Antimatter Searches

To date, we have observed eight events in the mass region from 0 to 10 GeV with Z= –2. All eight events are in the helium mass region.

Currently (having used 50 million core hours to generate 7 times more simulated events than measured events and having found no background events from the simulation), our best evaluation of the probability of the background origin for the eight $\overline{\mathrm{He}}$ events is less than 3×10^{-8}. For the two $^4\overline{\mathrm{He}}$ events our best evaluation of the probability (upon completion of the current 100 million core hours of simulation) will be less than 3×10^{-3}.

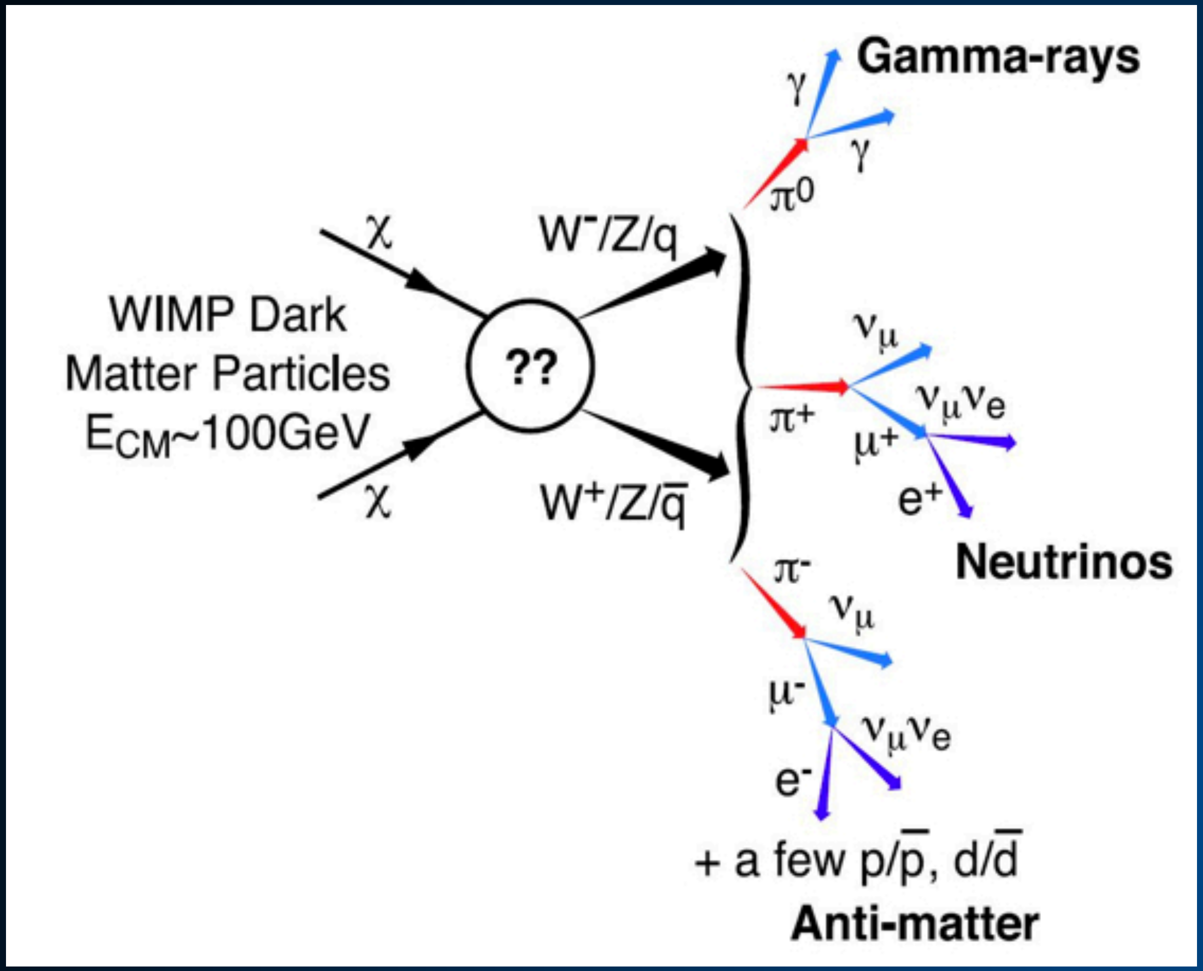
Note that for $^4\overline{\mathrm{He}}$, projecting based on the statistics we have today, by using an additional 400 million core hours for simulation the background probability would be 10^{-4}. Simultaneously, continuing to run until 2023, which doubles the data sample, the background probability for $^4\overline{\mathrm{He}}$ would be 2×10^{-7}, i.e., greater than 5-sigma significance.

Cosmic-Ray Antimatter Searches



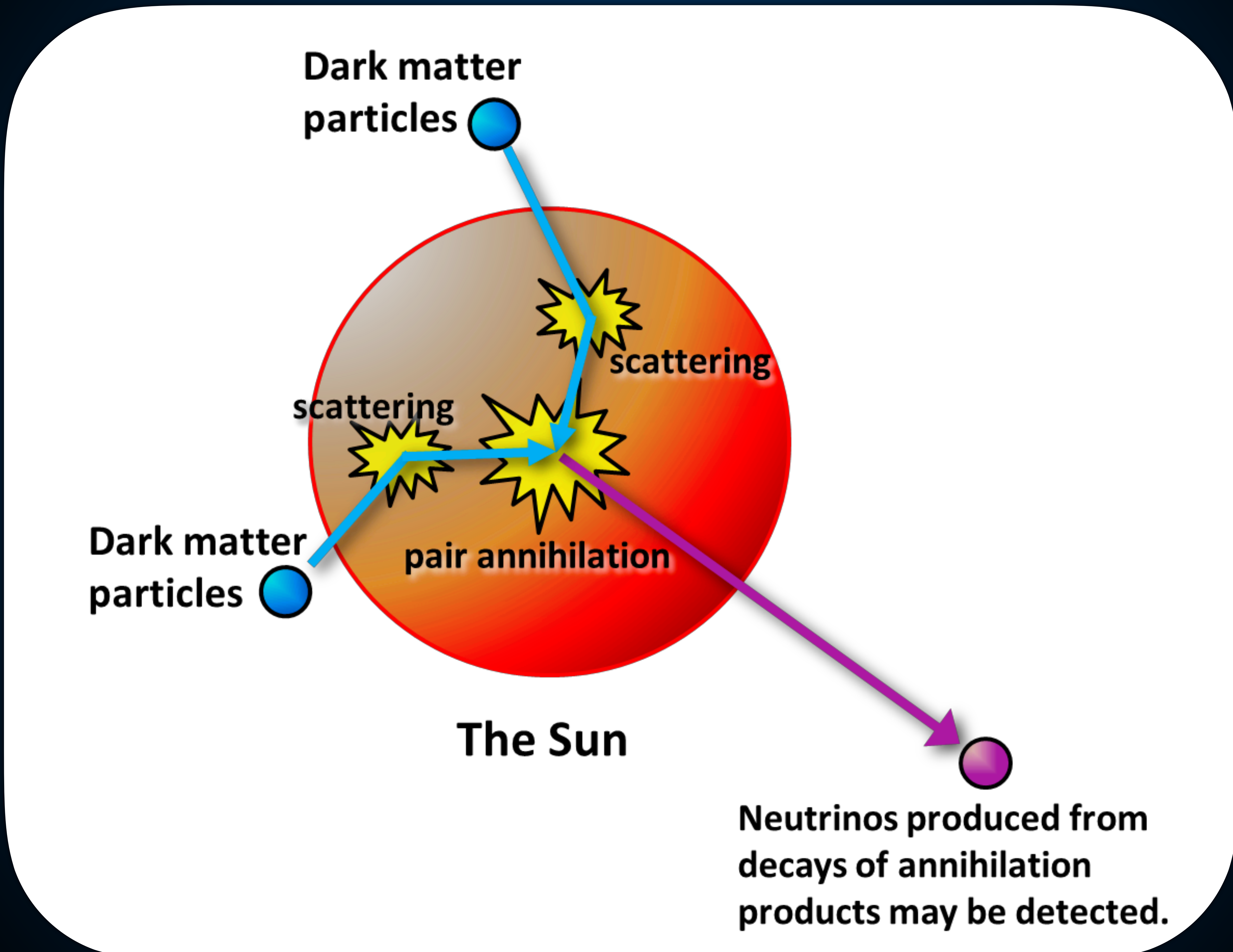
The Future is Bright

Progress Over the Last 10 Years



- Search For:
  - Gamma-Rays
  - Cosmic-Rays
  - Neutrinos

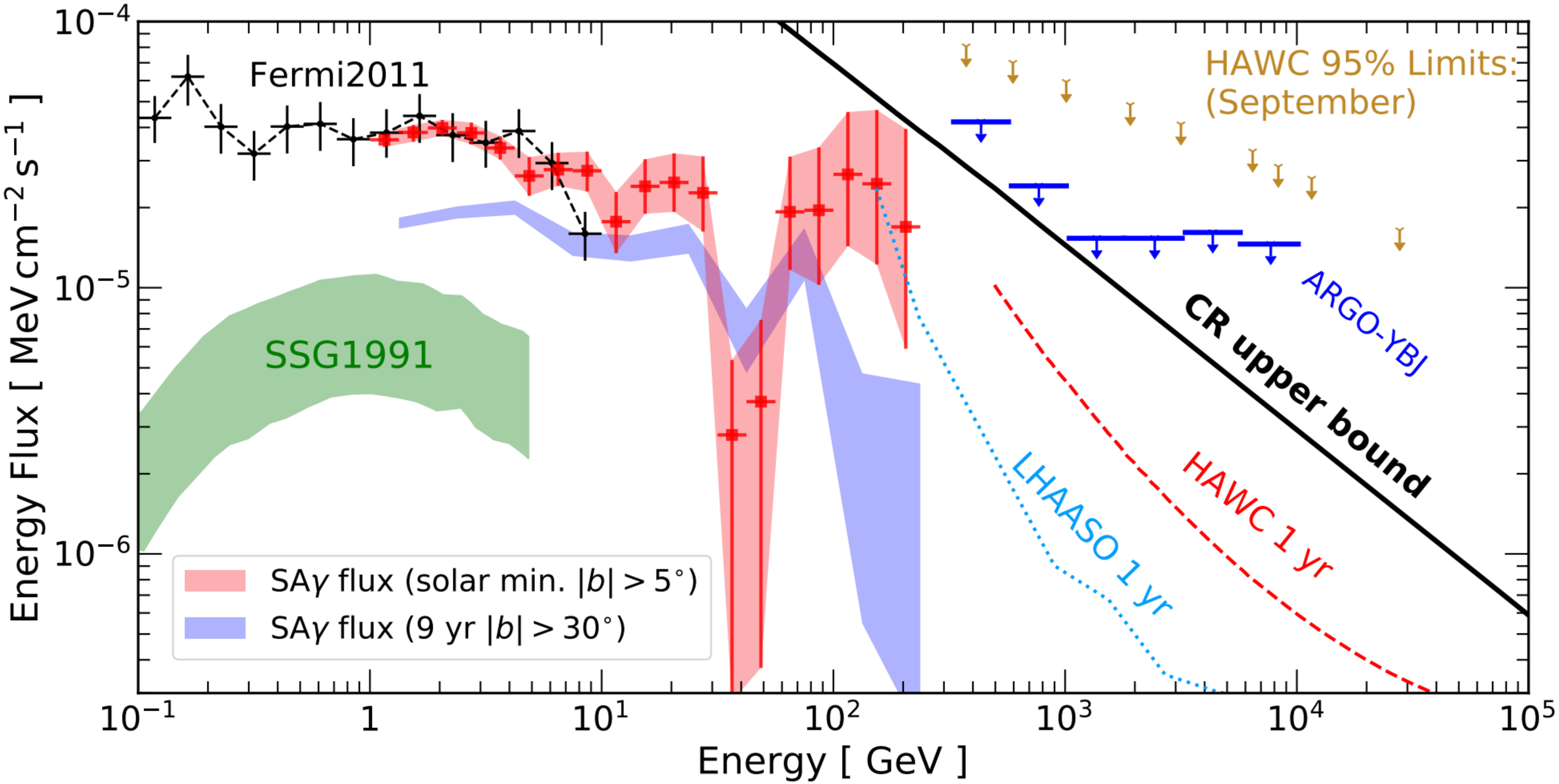
Harnessing the Power of the Sun

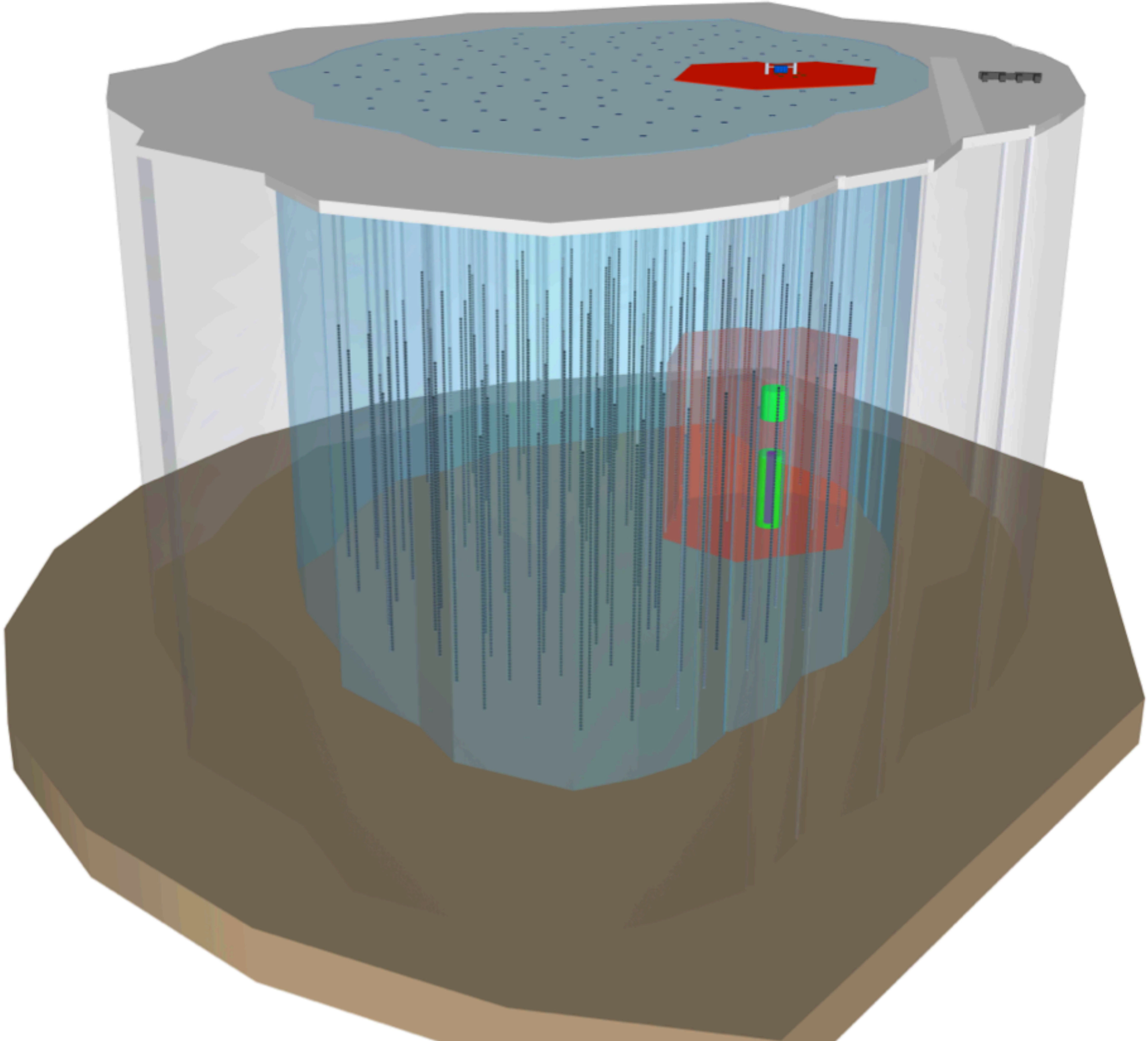


Harnessing the Power of the Sun

Tang et al. (including TL) (2018; 1804.06846)

TL et al. (2018; 1803.05436)





Where Are We Now?

Two Perspectives

MIT-CTP/5020

GeV-Scale Thermal WIMPs: Not Even Slightly Dead

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(Dated: July 13, 2018)

Weakly Interacting Massive Particles (WIMPs) have long reigned as one of the leading classes of dark matter candidates. The observed dark matter abundance can be naturally obtained by freeze-out of weak-scale dark matter annihilations in the early universe. This "thermal WIMP" scenario makes direct predictions for the total annihilation cross section that can be tested in present-day experiments. While the dark matter mass constraint can be as high as $m_\chi \gtrsim 100$ GeV for particular annihilation channels, the constraint on the *total* cross section has not been determined. We construct the first model-independent limit on the WIMP total annihilation cross section, showing that allowed combinations of the annihilation-channel branching ratios considerably weaken the sensitivity. For thermal WIMPs with s-wave $2 \to 2$ annihilation to visible final states, we find the dark matter mass is only known to be $m_\chi \gtrsim 20$ GeV. This is the strongest largely model-independent lower limit on the mass of thermal-relic WIMPs; together with the upper limit on the mass from the unitarity bound ($m_\chi \lesssim 100$ TeV), it defines what we call the "WIMP window". To probe the remaining mass range, we outline ways forward.

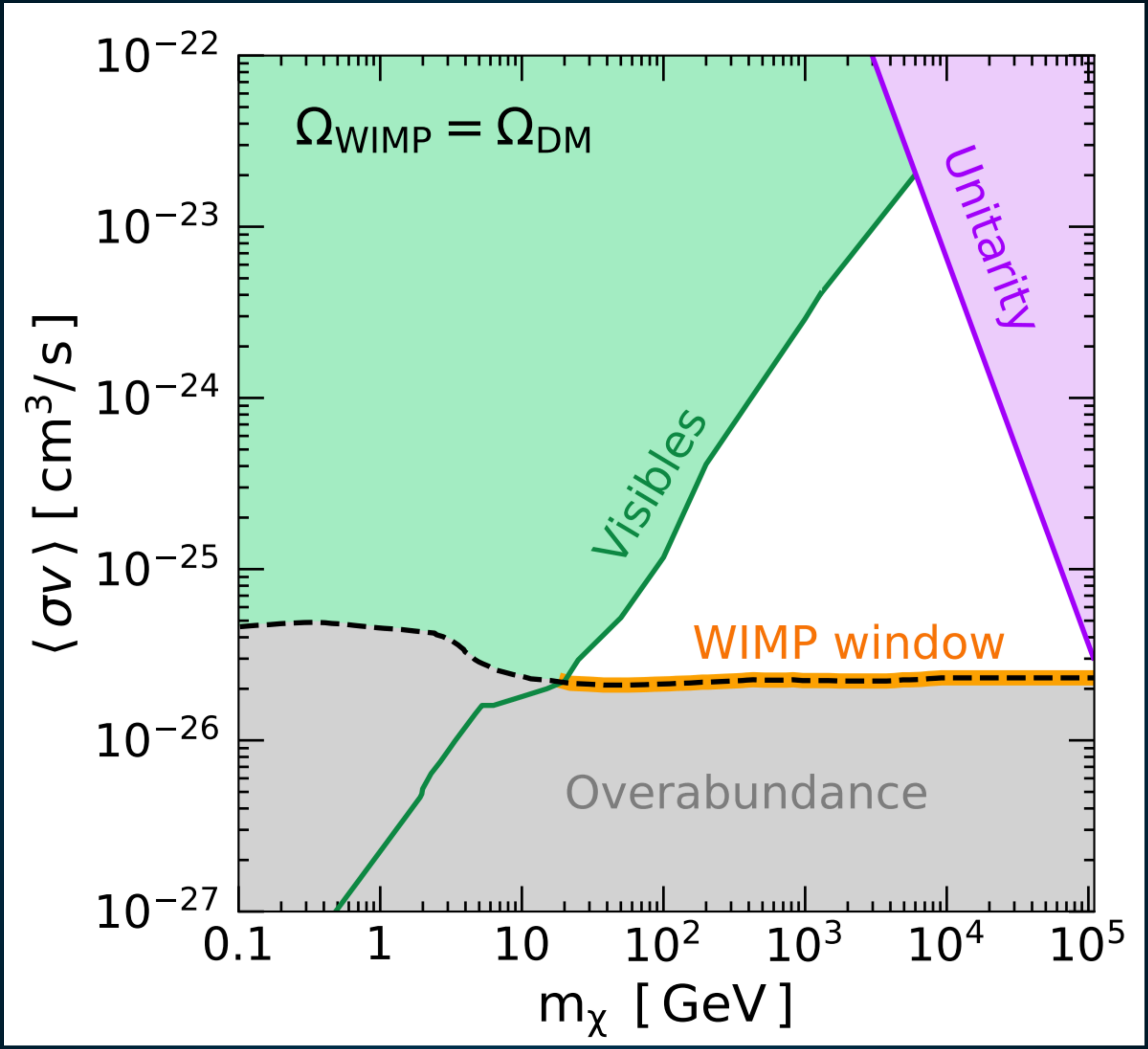
I. INTRODUCTION

A leading candidate for dark matter (DM) is a Weakly Interacting Massive Particle (WIMP) that is a thermal

scenarios. The branching ratios, coupling types and signals are model-dependent, and so the lack of observations may just be due to such features. For example, there can be interference effects, momentum suppression, or

Where Are We Now?

Two Perspectives



Where Are We Now?

Two Perspectives

REVIEW

https://doi.org/10.1038/s41586-018-0542-z

A new era in the search for dark matter

Gianfranco Bertone[1]* & Tim M. P. Tait[1,2]*

There is a growing sense of 'crisis' in the dark-matter particle community, which arises from the absence of evidence for the most popular candidates for dark-matter particles—such as weakly interacting massive particles, axions and sterile neutrinos—despite the enormous effort that has gone into searching for these particles. Here we discuss what we have learned about the nature of dark matter from past experiments and the implications for planned dark-matter searches in the next decade. We argue that diversifying the experimental effort and incorporating astronomical surveys and gravitational-wave observations is our best hope of making progress on the dark-matter problem.

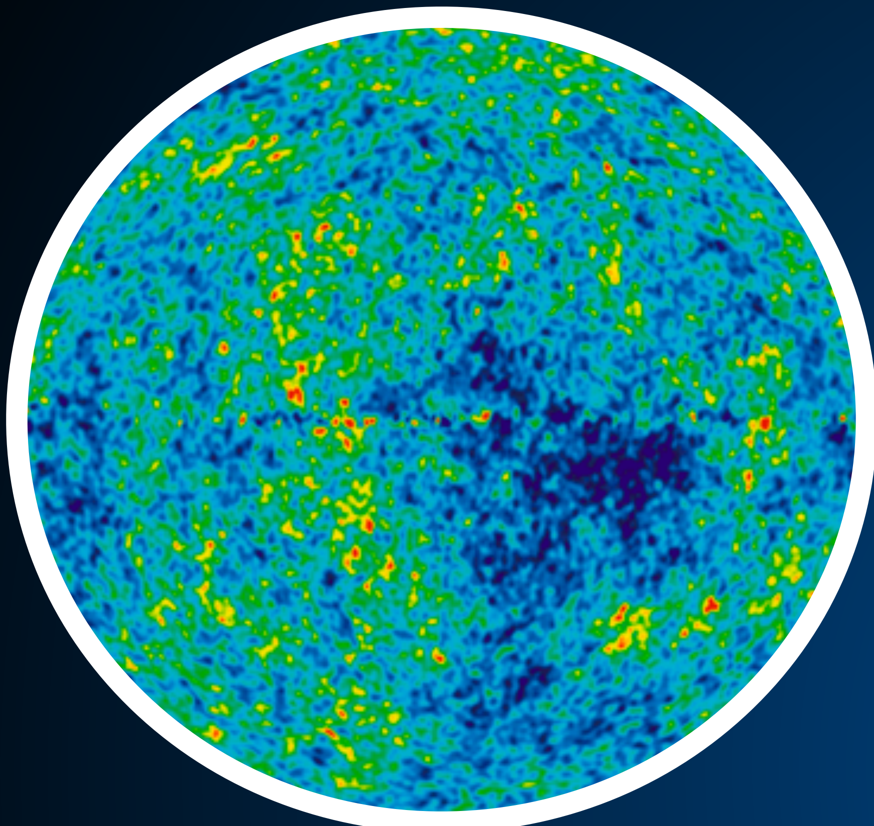
The fall of natural weakly interacting massive particles

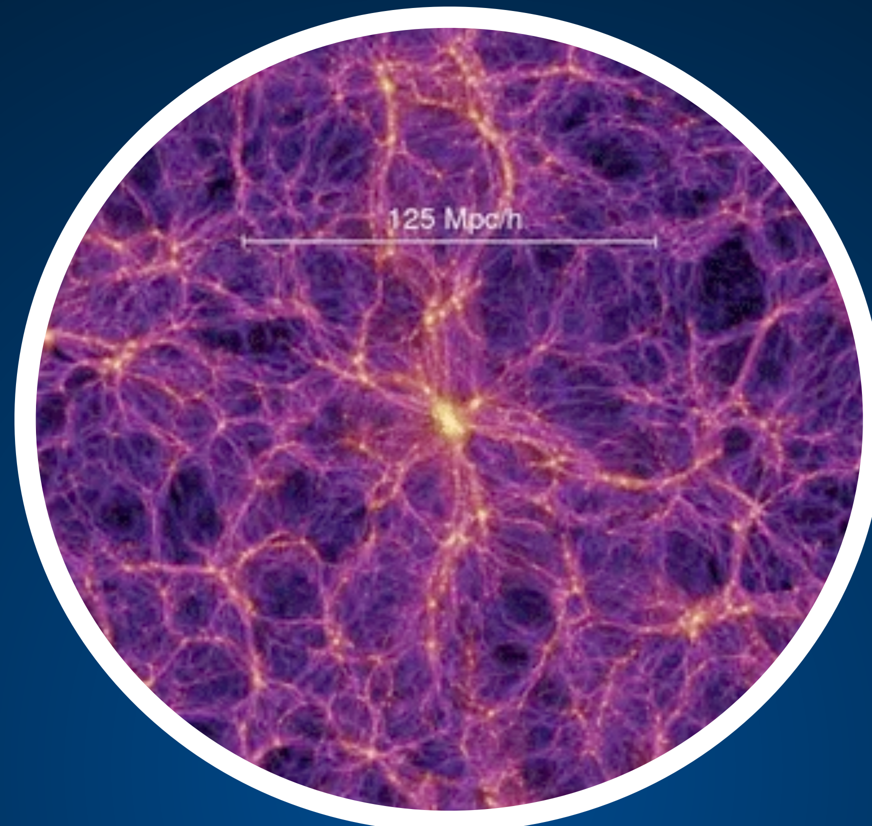
The existence of dark matter has been discussed for more than a century[1,2]. In the 1970s, astronomers and cosmologists began to build what is today a compelling body of evidence for this elusive component of the Universe, based on a variety of observations, including temperature anisotropies of the cosmic microwave background, baryonic acoustic oscillations, type Ia supernovae, gravitational lensing of galaxy clusters and rotation curves of galaxies[3,4]. The standard model of particle physics contains no suitable particle to explain these observations, and

the observed Higgs mass at the weak scale appears highly unnatural, requiring an incredibly fine-tuned cancellation between the individually much larger intrinsic contribution and the correction terms, such that their sum is the value observed at the Large Hadron Collider (LHC). Natural theories introduce additional particles and symmetries, which are arranged so that these large corrections cancel each other out, protecting the Higgs mass from the influence of heavy mass scales.

The prototypical natural theory is the minimal supersymmetric (SUSY) standard model, which introduces an additional partner for

Well-Motivated Theoretical Targets





10^2 GeV

WIMP Miracle!

10^{-25} GeV

$\sigma_X > R_{dwarfs}$

10^{62} GeV

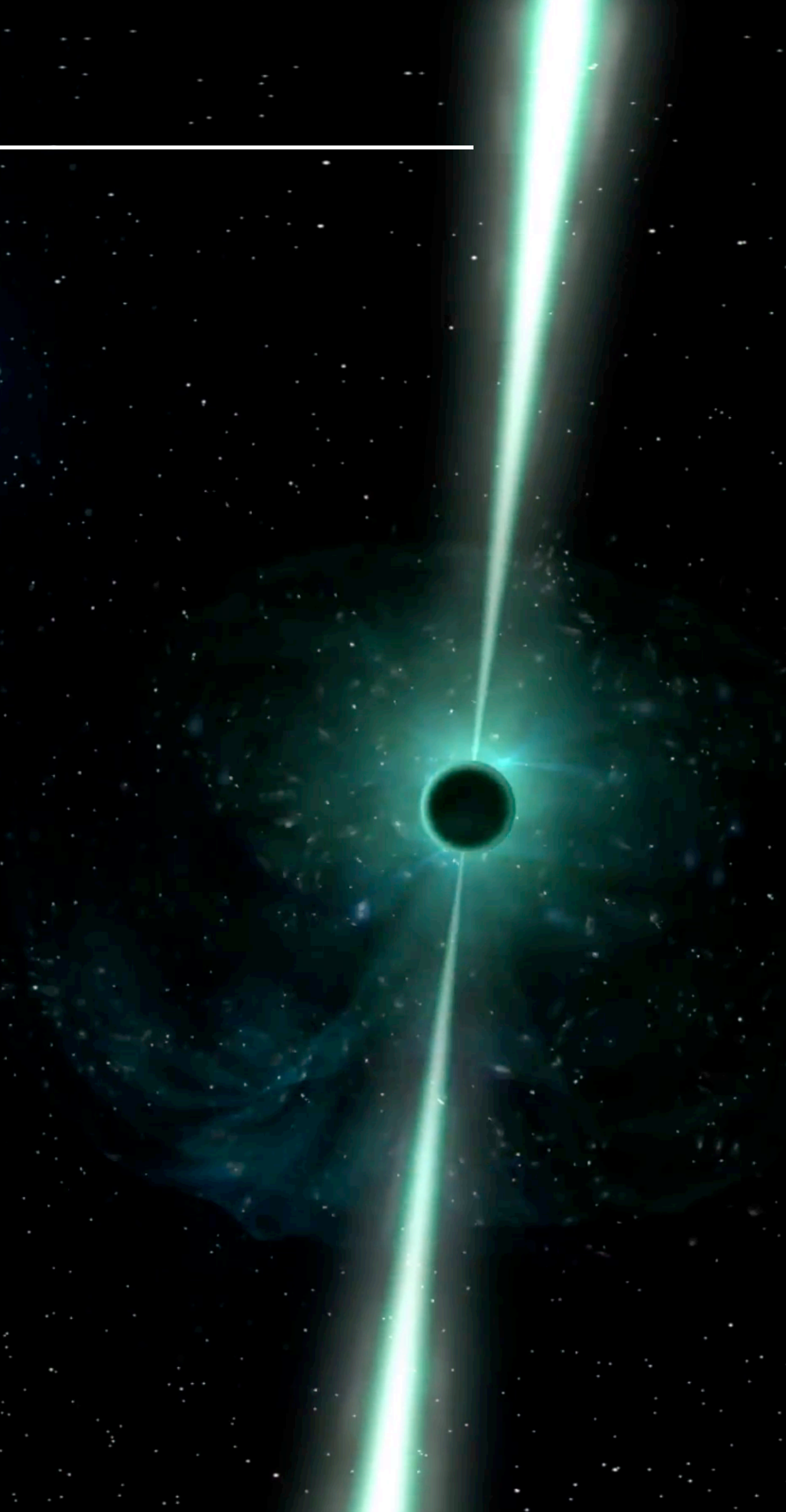
$m_X > M_{dwarfs}$

Where Are We Now?

Two Perspectives

What is a Neutron Star?

- **Neutron Star**
  - Mass = 1.4 M_o
  - Radius = 10 km
- **Subclass: Pulsar**
  - Magnetic Field = 10^{10} T
  - Rotation Period = ~1 s



Why Neutron Stars?

- **Sensitive probes of rare processes:**
    1. **Nuclear densities over macroscopic distances**
    2. **Strongest magnetic fields in the universe**

- **Precise measurements are possible**

Neutron Stars: The Ultimate Direct Detection Experiment

$$N_{X_n} \sim M_n t_n$$

Xenon-1T

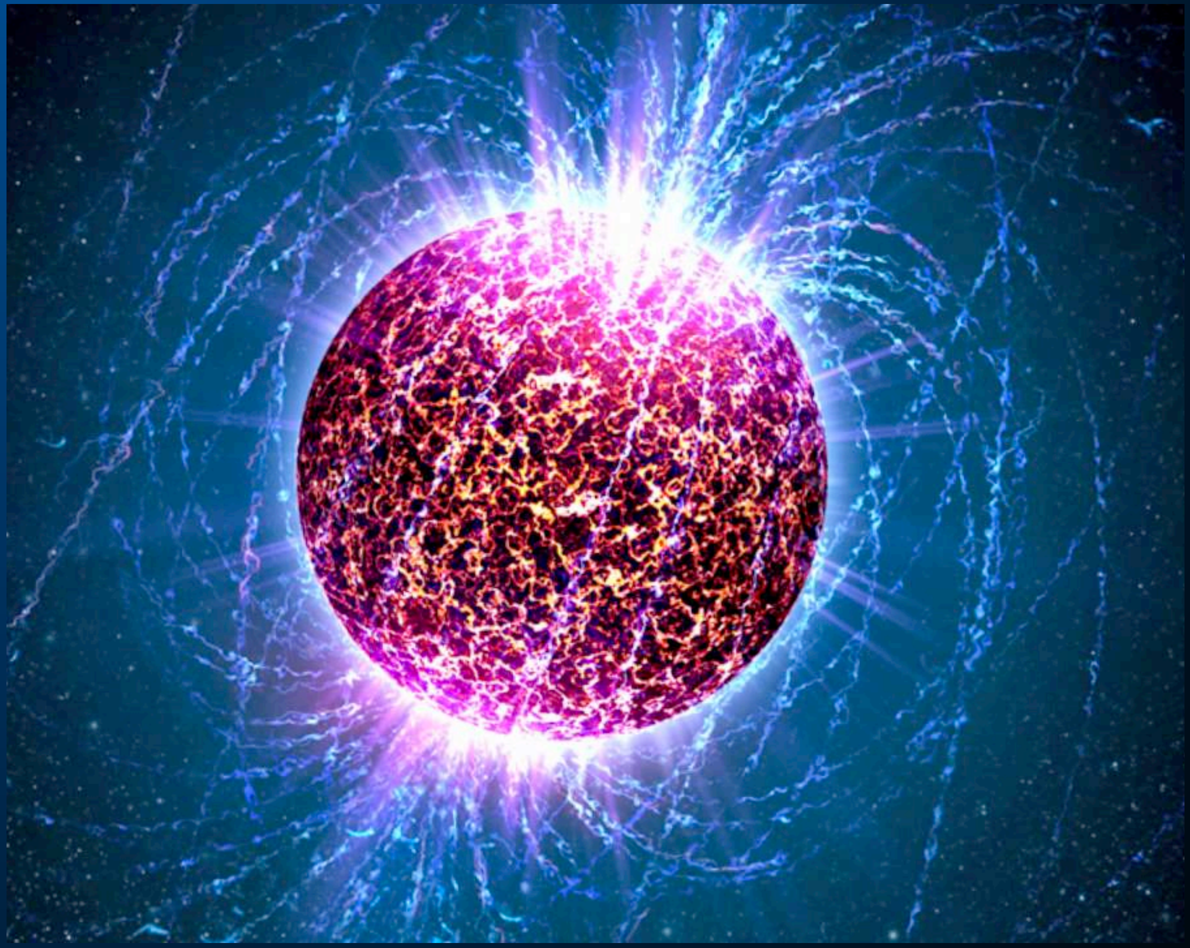
- 1000 kg
- 1000 days

10^6 kg day

Neutron Star

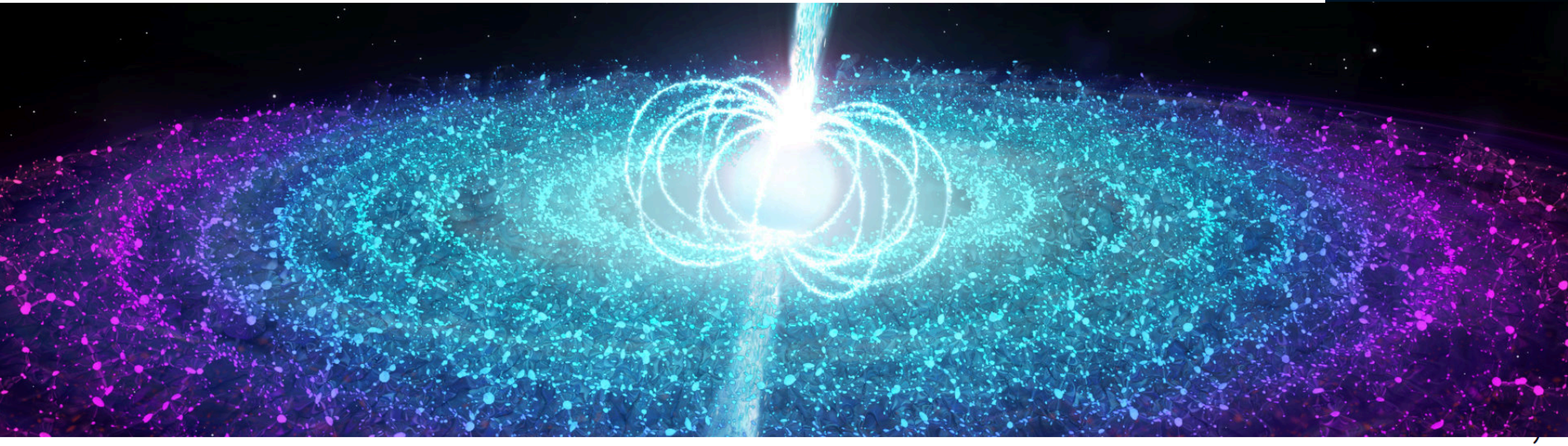
- 10^{30} kg
- 10^{12} days

10^{42} kg day



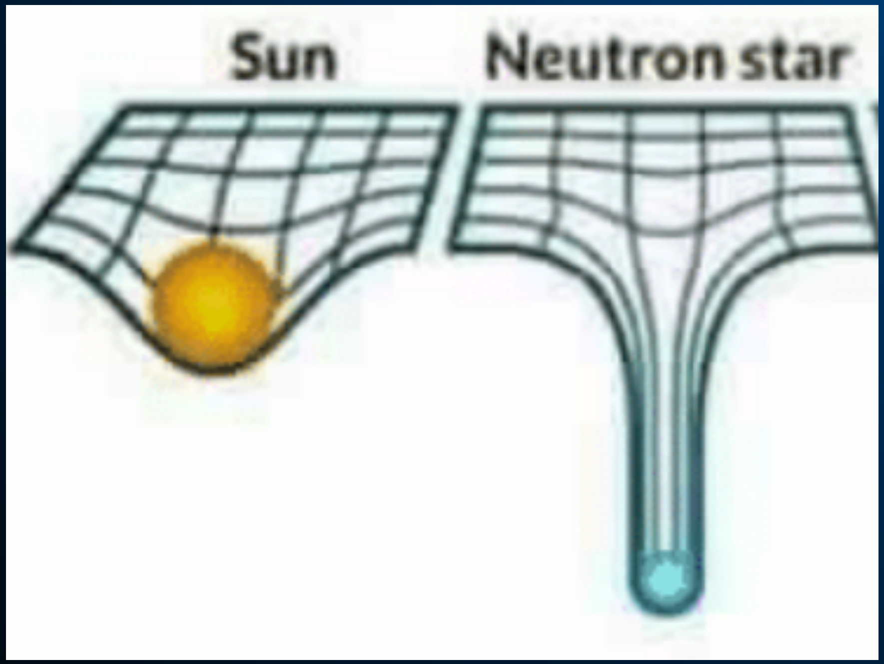
Part I: Dark Matter-Neutron Star Interactions

Neutron Stars: The Optimal WIMP Detection Experiment



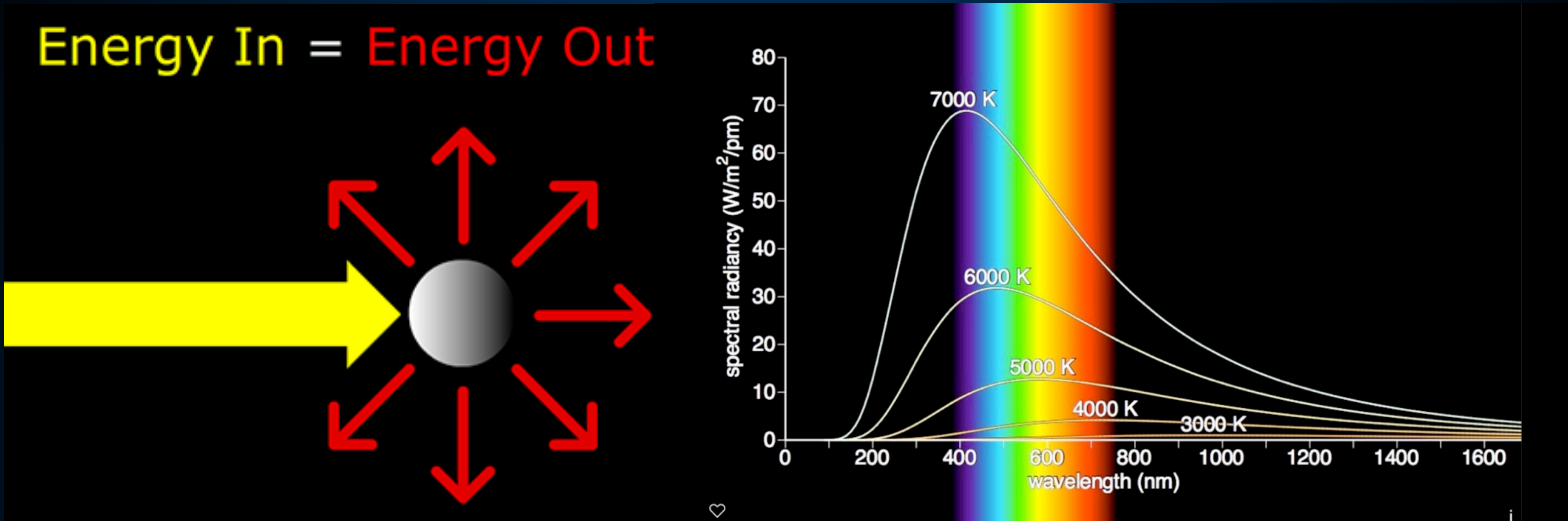
$$\sigma_{\rm sat}^{\rm single} \simeq \pi R^2 m_{\rm n}/M \simeq 2\times10^{-45}\ {\rm cm}^2\ \left(\frac{1.5\ {\rm M}_\odot}{M}\right)\left(\frac{R}{10\ {\rm km}}\right)^2$$

- **Neutron Stars are optically thick to dark matter.**



- **Neutron stars gravitationally attract nearby dark matter**

Dark Matter Induced Heating



DM-NS collisions impart significant energy into the NS:

$$E_\mathrm{s} \simeq m_\mathrm{x} \left(\gamma - 1\right)$$

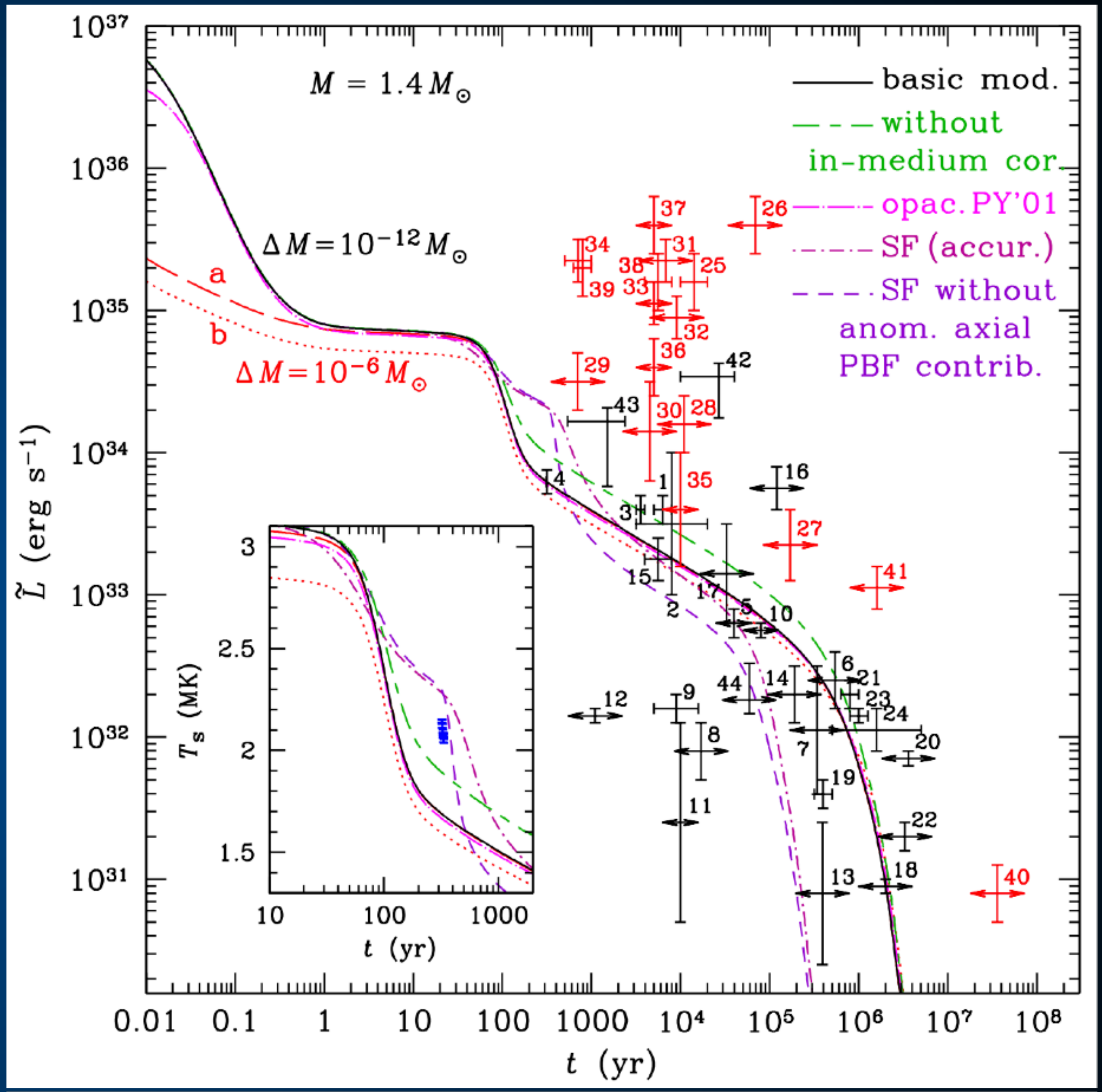
This induces blackbody emission of luminosity:

$$\dot{E}_\mathrm{k} = \frac{E_\mathrm{s} \dot{m}}{m_\mathrm{x}} f \simeq 1.4 \times 10^{25} \ \mathrm{GeV \ s^{-1}}$$

Baryakhtar, Bramante, Li, TL, Raj (1704.01577)

Detecting Thermal Neutron Star Emission

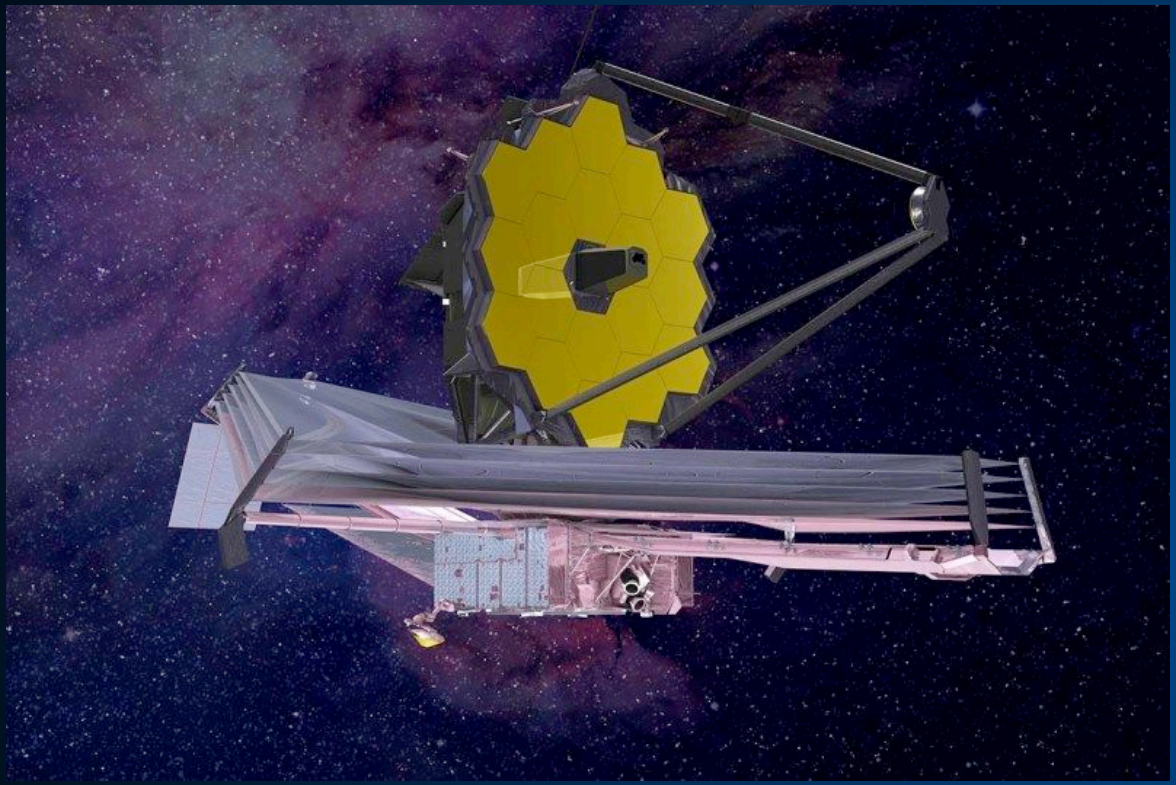
Potekhin & Chabrier (1711.07662)

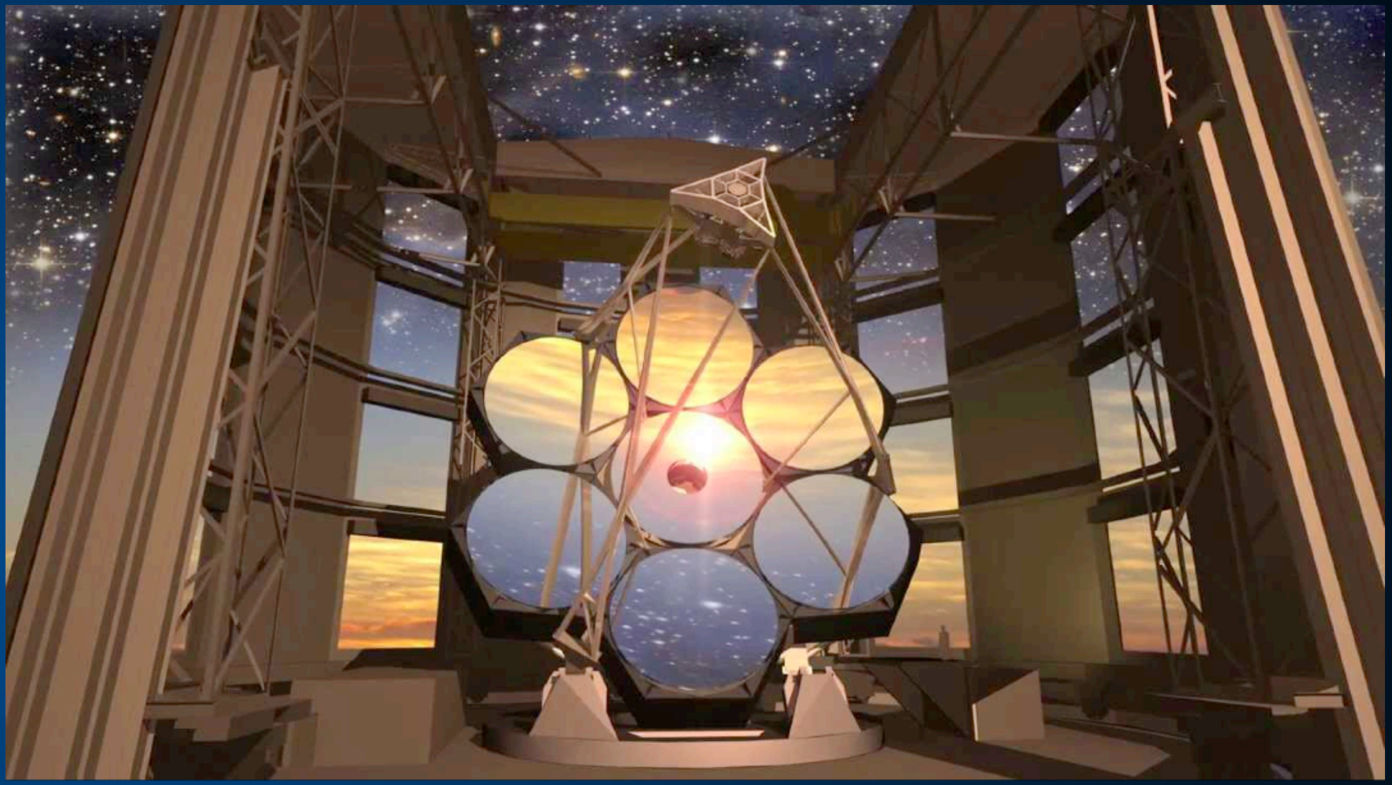


- Thermal emission detected from young neutron stars.
- Older neutron stars continue cooling.
- Dark matter sets a minimum temperature of ~2000 K (10^{22} erg)

Detecting Thermal Emission

- Observations at 2000 K require infrared telescopes



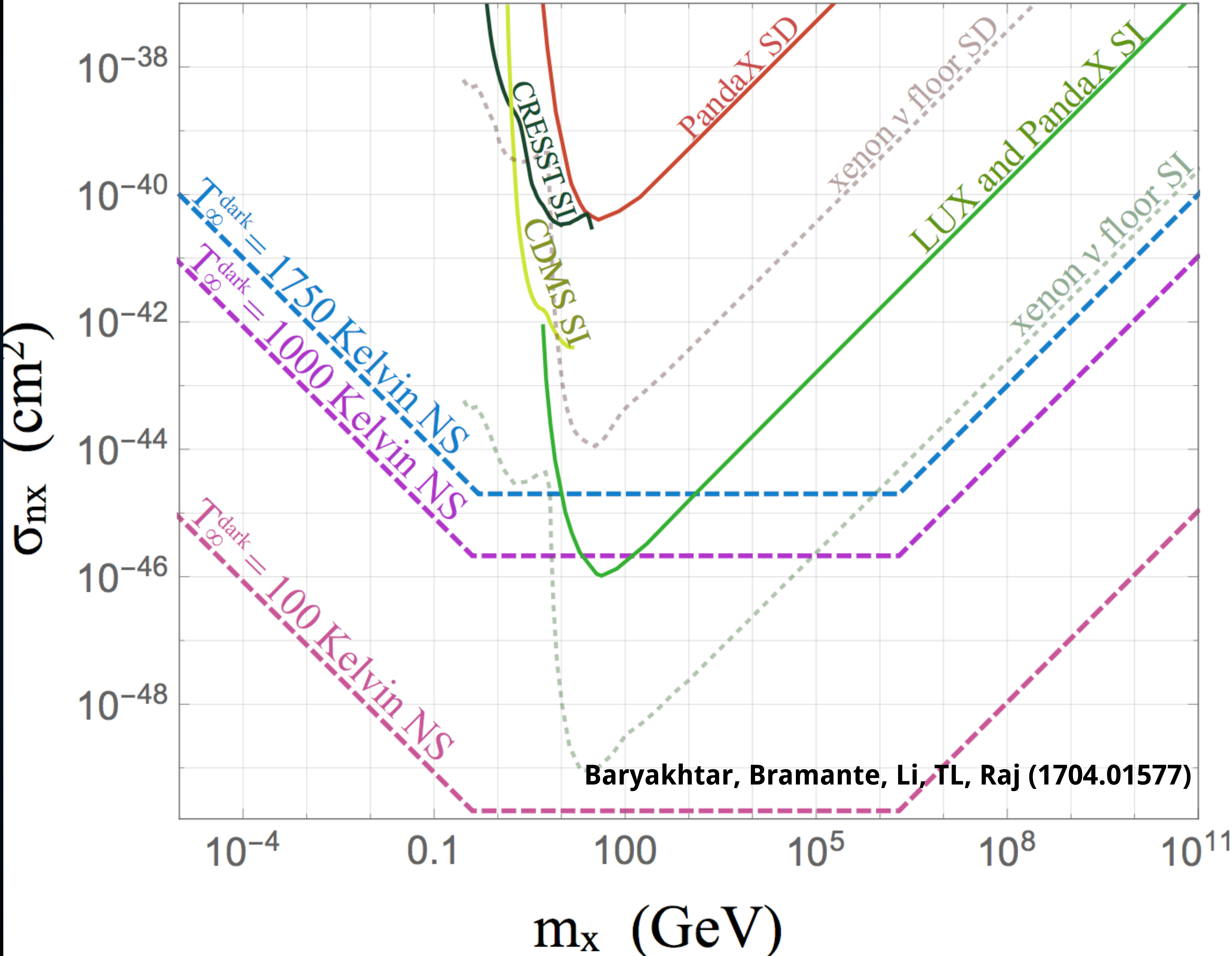


JWST
10 nJy in 10^4 s

GMT
0.5 nJy in 10^5 s

- A pulsar at 10 pc would have a flux of ~2 nJy at 2 microns

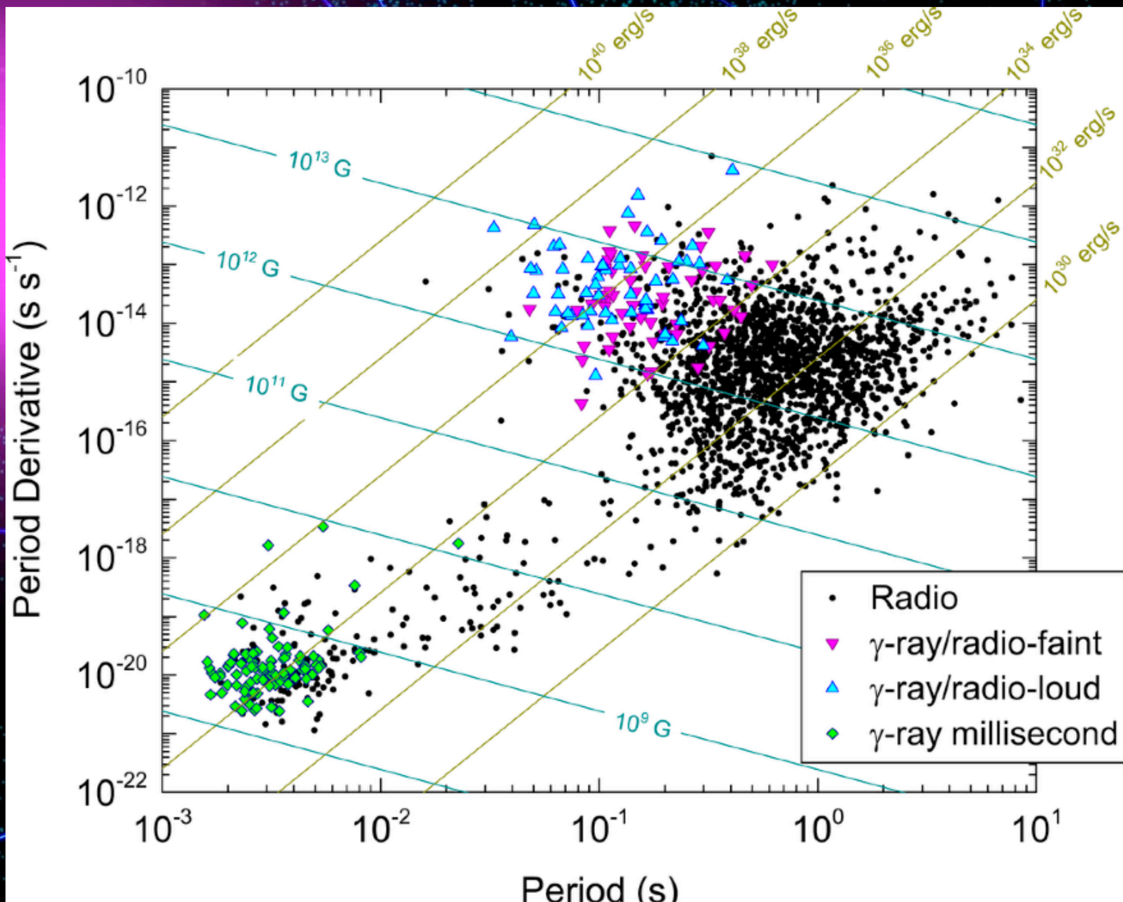
Baryakhtar, Bramante, Li, TL, Raj (1704.01577)



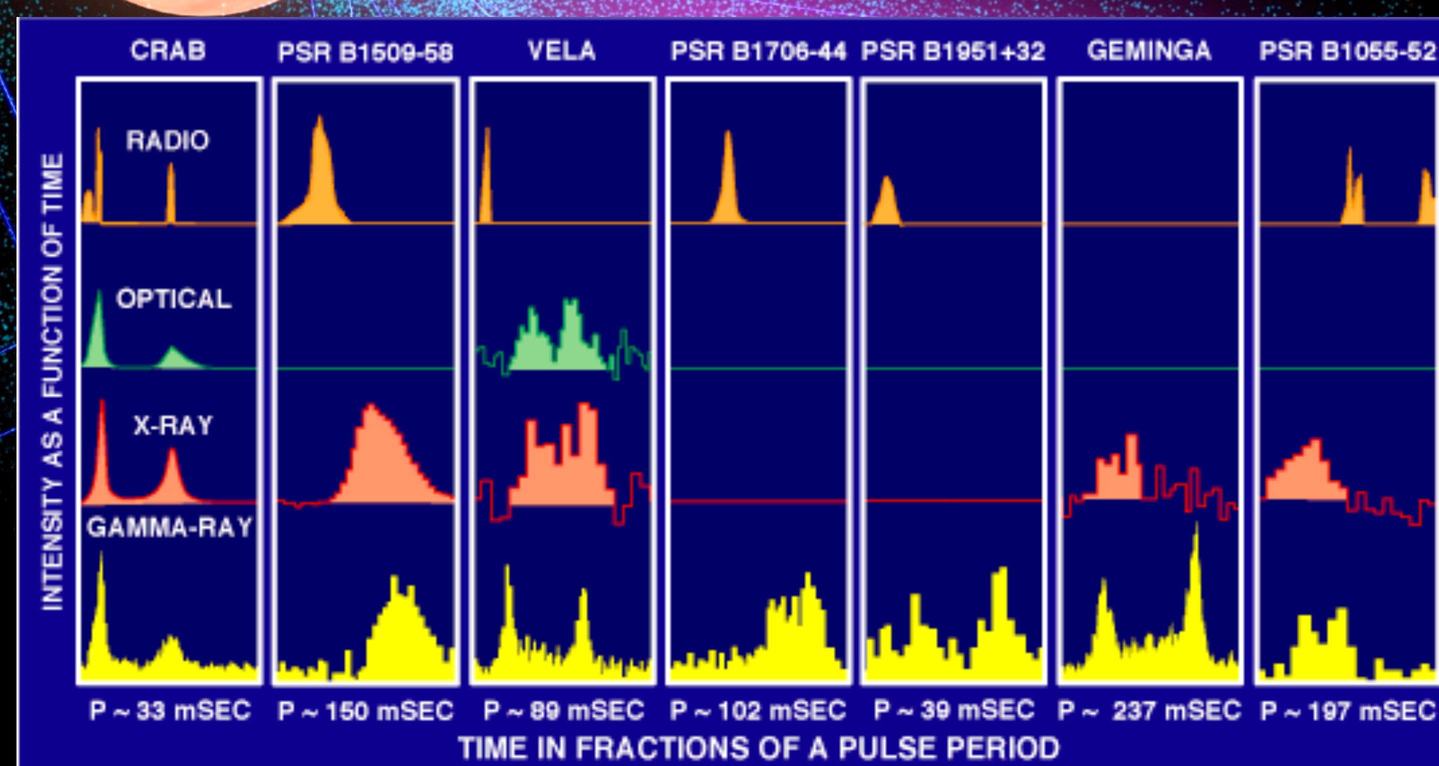
PandaX SD
xenon ν floor SD
LUX and PandaX SI
xenon ν floor SI
CRESST SI
CDMS SI
$T_\infty^{dark} = 1750$ Kelvin NS
$T_\infty^{dark} = 1000$ Kelvin NS
$T_\infty^{dark} = 100$ Kelvin NS
Baryakhtar, Bramante, Li, TL, Raj (1704.01577)
10^{-38}
10^{-40}
10^{-42}
10^{-44}
10^{-46}
10^{-48}
10^{-4}
0.1
100
10^5
10^8
10^{11}
σ_{nx} (cm^2)
m_x (GeV)

Part II: Finding the Right Neutron Star

Radio Pulses: A Blessing and a Curse

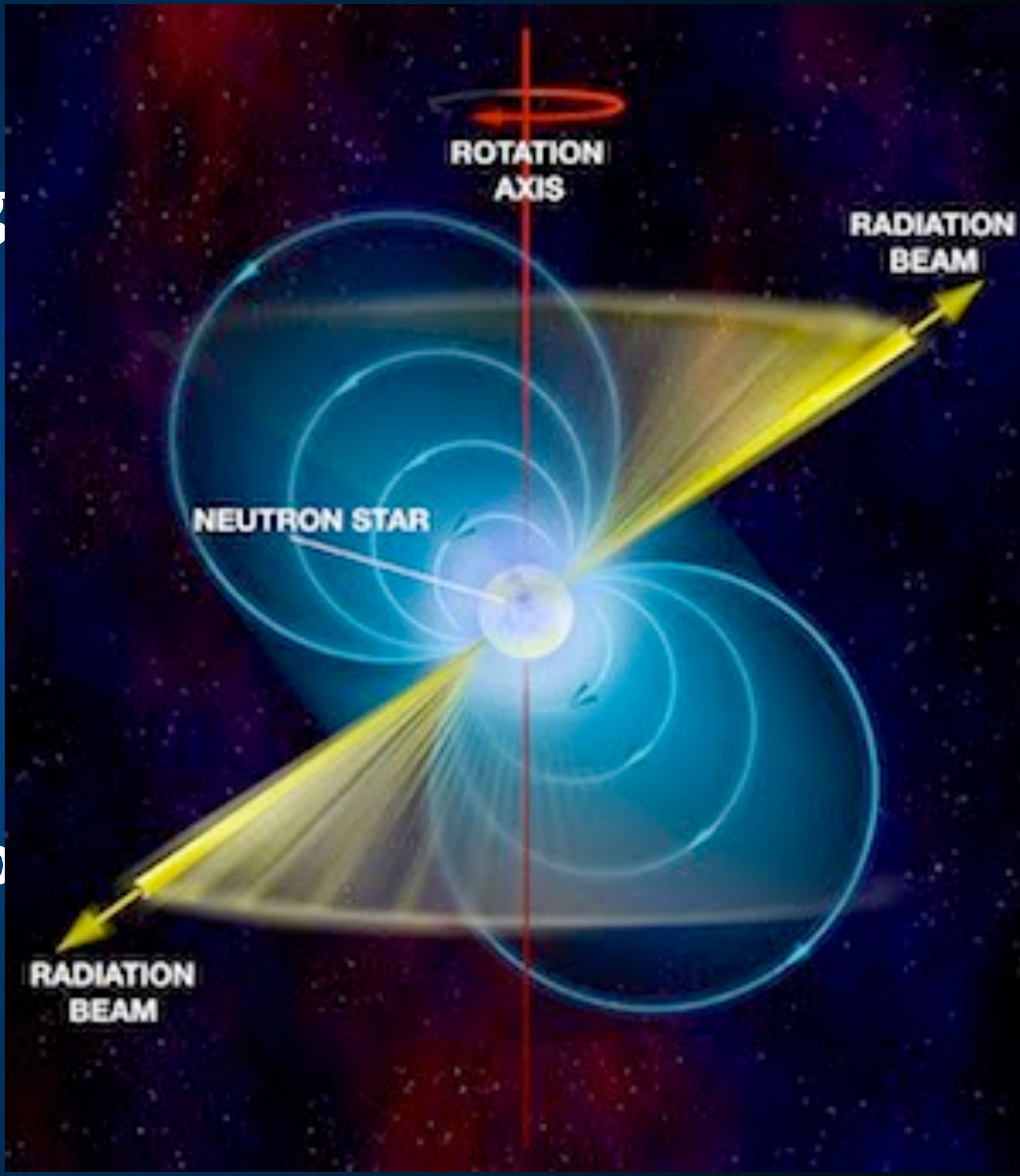


Harding (2016; J Plasma Phys 82)

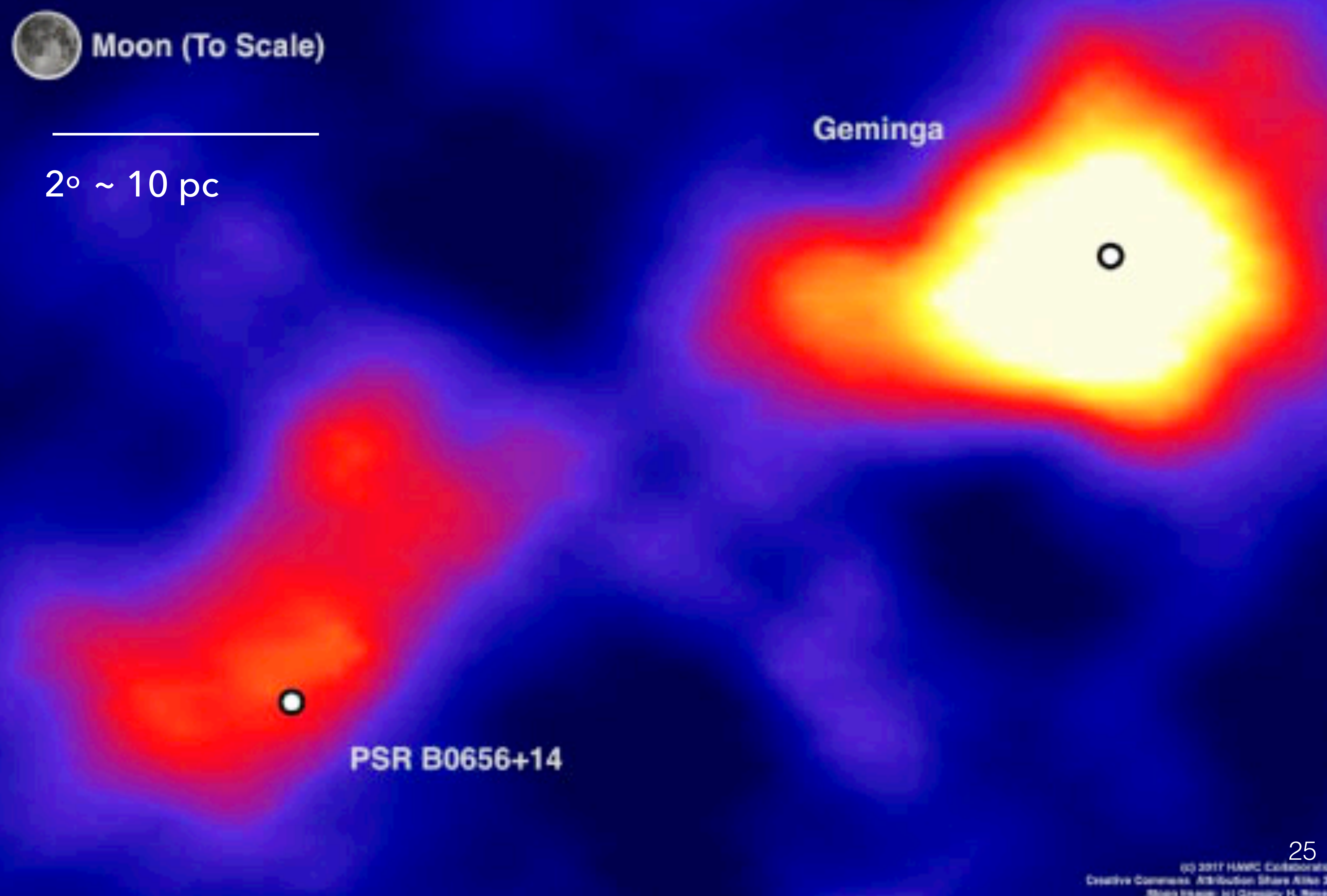


Radio Pulses: A Blessing and a Curse

- Tauris and Manchester (1998) calculated the pulsar beaming angle.
- This varies between 10-30%.
- 1/f pulsars are unseen in radio surveys.



A New Method for Detecting Invisible Pulsars

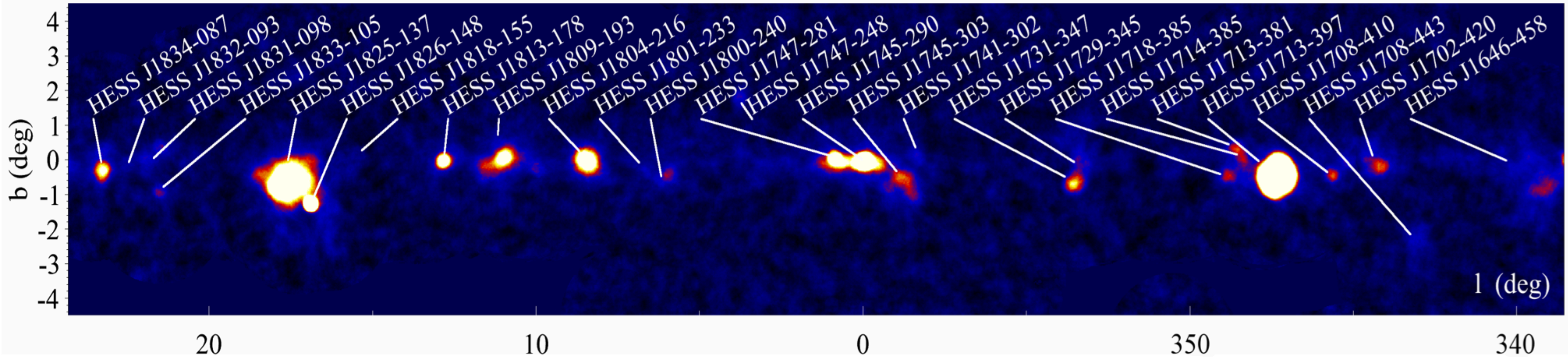


Astrophysical Implications of TeV Halos

- TeV halo observations solve many astrophysical puzzles

  - Prove that pulsars produce the positron excess
    (Hooper, Cholis, TL, Fang 1702.08436)
  - Explain the TeV gamma-ray excess
    (TL & Buckman 1707.01905)
  - Explain inhomogeneities in cosmic-ray diffusion ,
    (Hooper & TL 1711.07482) (Evoli, TL, Morlino, 1807.09263)
  - Explain TeV gamma-rays from the Galactic center
    (Hooper et al. 1705.09293)
  - Provide insight into the formation and evolution of galactic pulsars (Sudoh, TL & Beacom, TBS)

Discovering Invisible Pulsars at TeV Energies



The H.E.S.S. Galactic plane survey

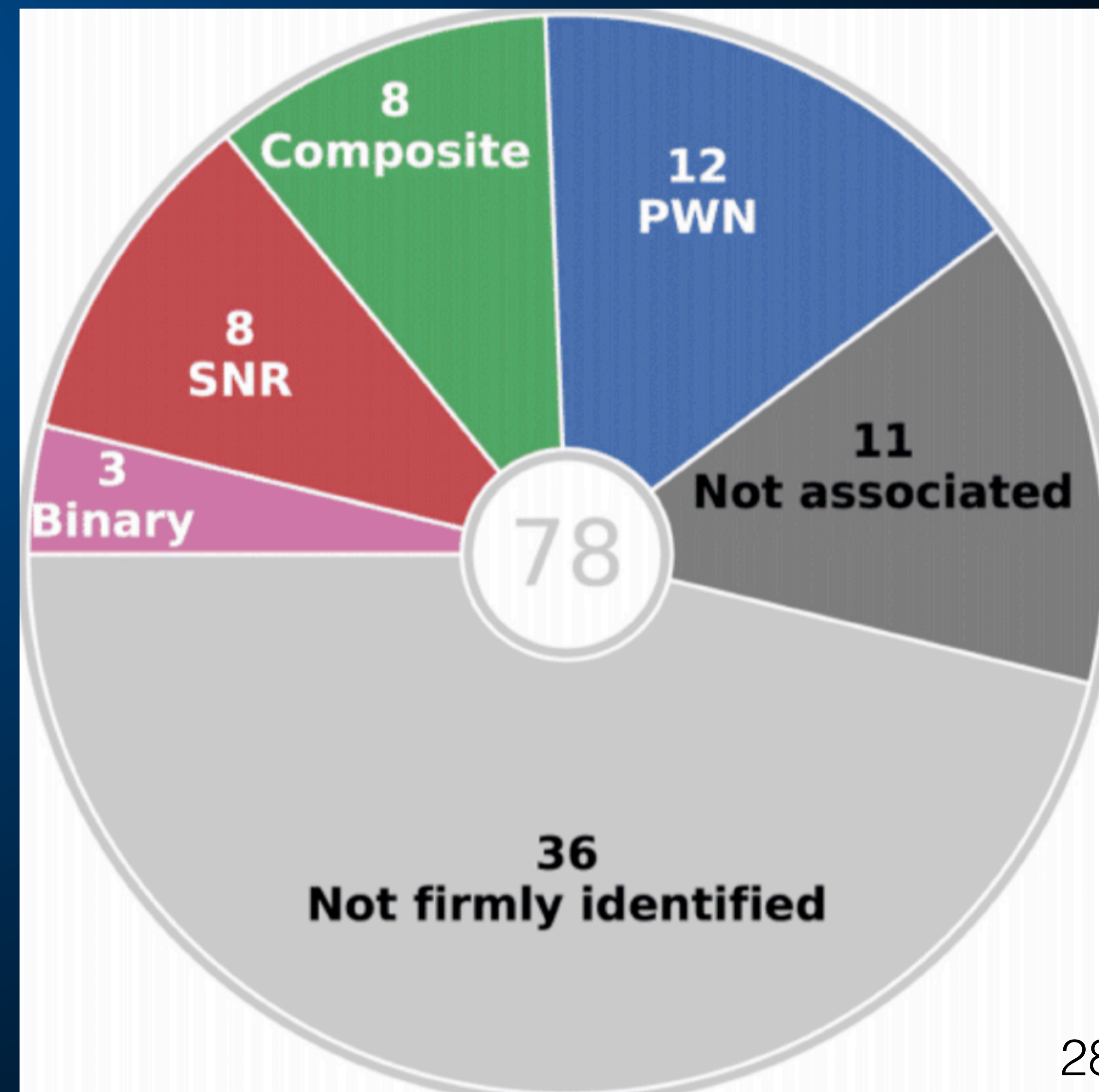
H.E.S.S. Collaboration, H. Abdalla[1], A. Abramowski[2], F. Aharonian[3,4,5], F. Ait Benkhali[3], E.O. Angüner[21], M. Arakawa[43], M. Arrieta[15], P. Aubert[24], M. Backes[8], A. Balzer[9], M. Barnard[1], Y. Becherini[10], J. Becker Tjus[11], D. Berge[12], S. Bernhard[13], K. Bernlöhr[3], R. Blackwell[14], M. Böttcher[1], C. Boisson[15], J. Bolmont[16], S. Bonnefoy[37], P. Bordas[3], J. Bregeon[17], F. Brun*[26], P. Brun[18], M. Bryan[9], M. Büchele[36], T. Bulik[19], M. Capasso[29], S. Carrigan[3,48], S. Caroff[30], A. Carosi[24], S. Casanova[21,3], M. Cerruti[16], N. Chakraborty[3], R.C.G. Chaves*[17,22], A. Chen[23], J. Chevalier[24], S. Colafrancesco[23], B. Condon[26], J. Conrad[27,28], I.D. Davids[8], J. Decock[18], C. Deil*[3], J. Devin[17], P. deWilt[14], L. Dirson[2], A. Djannati-Ataï[31], W. Domainko[3], A. Donath*[3], L.O'C. Drury[4], K. Dutson[33], J. Dyks[34], T. Edwards[3], K. Egberts[35], P. Eger[3], G. Emery[16], J.-P. Ernenwein[20], S. Eschbach[36], C. Farnier[27,10], S. Fegan[30], M.V. Fernandes[2], A. Fiasson[24], G. Fontaine[30], A. Förster[3], S. Funk[36], M. Füßling[37], S. Gabici[31], Y.A. Gallant[17], T. Garrigoux[1], H. Gast[3,49], F. Gaté[24], G. Giavitto[37], B. Giebels[30], D. Glawion[25], J.F. Glicenstein[18], D. Gottschall[29], M.-H. Grondin[26], J. Hahn[3], M. Haupt[37], J. Hawkes[14], G. Heinzelmann[2], G. Henri[32], G. Hermann[3], J.A. Hinton[3], W. Hofmann[3], C. Hoischen[35], T. L. Holch[7], M. Holler[13], D. Horns[2], A. Ivascenko[1], H. Iwasaki[43], A. Jacholkowska[16], M. Jamrozy[38], D. Jankowsky[36], F. Jankowsky[25], M. Jingo[23], L. Jouvin[31], I. Jung-Richardt[36], M.A. Kastendieck[2], K. Katarzyński[39], M. Katsuragawa[44], U. Katz[36], D. Kerszberg[16], D. Khangulyan[43], B. Khélifi[31], J. King[3], S. Klepser[37], D. Klochkov[29], W. Kluźniak[34], Nu. Komin[23], K. Kosack[18], S. Krakau[11], M. Kraus[36], P.P. Krüger[1], H. Laffon[26], G. Lamanna[24], J. Lau[14], J.-P. Lees[24], J. Lefaucheur[15], A. Lemière[31], M. Lemoine-Goumard[26], J.-P. Lenain[16], E. Leser[35], T. Lohse[7], M. Lorentz[18], R. Liu[3], R. López-Coto[3], I. Lypova[37], V. Marandon*[3], D. Malyshev[29], A. Marcowith[17], C. Mariaud[30], R. Marx[3], G. Maurin[24], N. Maxted[14,45], M. Mayer[7], P.J. Meintjes[40], M. Meyer[27], A.M.W. Mitchell[3], R. Moderski[34], M. Mohamed[25], L. Mohrmann[36], K. Morå[27], E. Moulin[18], T. Murach[37], S. Nakashima[44], M. de Naurois[30], H. Ndiyavala[1], F. Niederwanger[13], J. Niemiec[21], L. Oakes[7], P. O'Brien[33], H. Odaka[44], S. Ohm[37], M. Ostrowski[38], I. Oya[37], M. Padovani[17], M. Panter[3], R.D. Parsons[3], M. Paz Arribas[7], N.W. Pekeur[1], G. Pelletier[32], C. Perennes[16], P.-O. Petrucci[32], B. Peyaud[18], Q. Piel[24], S. Pita[31], V. Poireau[24], H. Poon[3], D. Prokhorov[10], H. Prokoph[12], G. Pühlhofer[29], M. Punch[31,10], A. Quirrenbach[25], S. Raab[36], R. Rauth[13], A. Reimer[13], O. Reimer[13], M. Renaud[17], R. de los Reyes[3], F. Rieger[3,41], L. Rinchiuso[18], C. Romoli[4], G. Rowell[14], B. Rudak[34], C.B. Rulten[15], S. Safi-Harb[50], V. Sahakian[6,5], S. Saito[43], D.A. Sanchez[24], A. Santangelo[29], M. Sasaki[36], M. Schandri[36], R. Schlickeiser[11], F. Schüssler[18], A. Schulz[37], U. Schwanke[7], S. Schwemmer[25], M. Seglar-Arroyo[18], M. Settimo[16], A.S. Seyffert[1], N. Shafi[23], I. Shilon[36], K. Shiningayamwe[8], R. Simoni[9], H. Sol[15], F. Spanier[1], M. Spir-Jacob[31], Ł. Stawarz[38], R. Steenkamp[8], C. Stegmann[35,37], C. Steppa[35], I. Sushch[1], T. Takahashi[44], J.-P. Tavernet[16], T. Tavernier[31], A.M. Taylor[37], R. Terrier[31], L. Tibaldo[3], D. Tiziani[36], M. Tluczykont[2], C. Trichard[20], M. Tsirou[17], N. Tsuji[43], R. Tuffs[3], Y. Uchiyama[43], D.J. van der Walt[1], C. van Eldik[36], C. van Rensburg[1], B. van Soelen[40], G. Vasileiadis[17], J. Veh[36], C. Venter[1], A. Viana[3,46], P. Vincent[16], J. Vink[9], F. Voisin[14], H.J. Völk[3], T. Vuillaume[24], Z. Wadiasingh[1], S.J. Wagner[25], P. Wagner[7], R.M. Wagner[27], R. White[3], A. Wierzcholska[21], P. Willmann[36], A. Wörnlein[36], D. Wouters[18], R. Yang[3], D. Zaborov[30], M. Zacharias[1], R. Zanin[3], A.A. Zdziarski[34], A. Zech[15], F. Zefi[30], A. Ziegler[36], J. Zorn[3], and N. Żywucka[38]

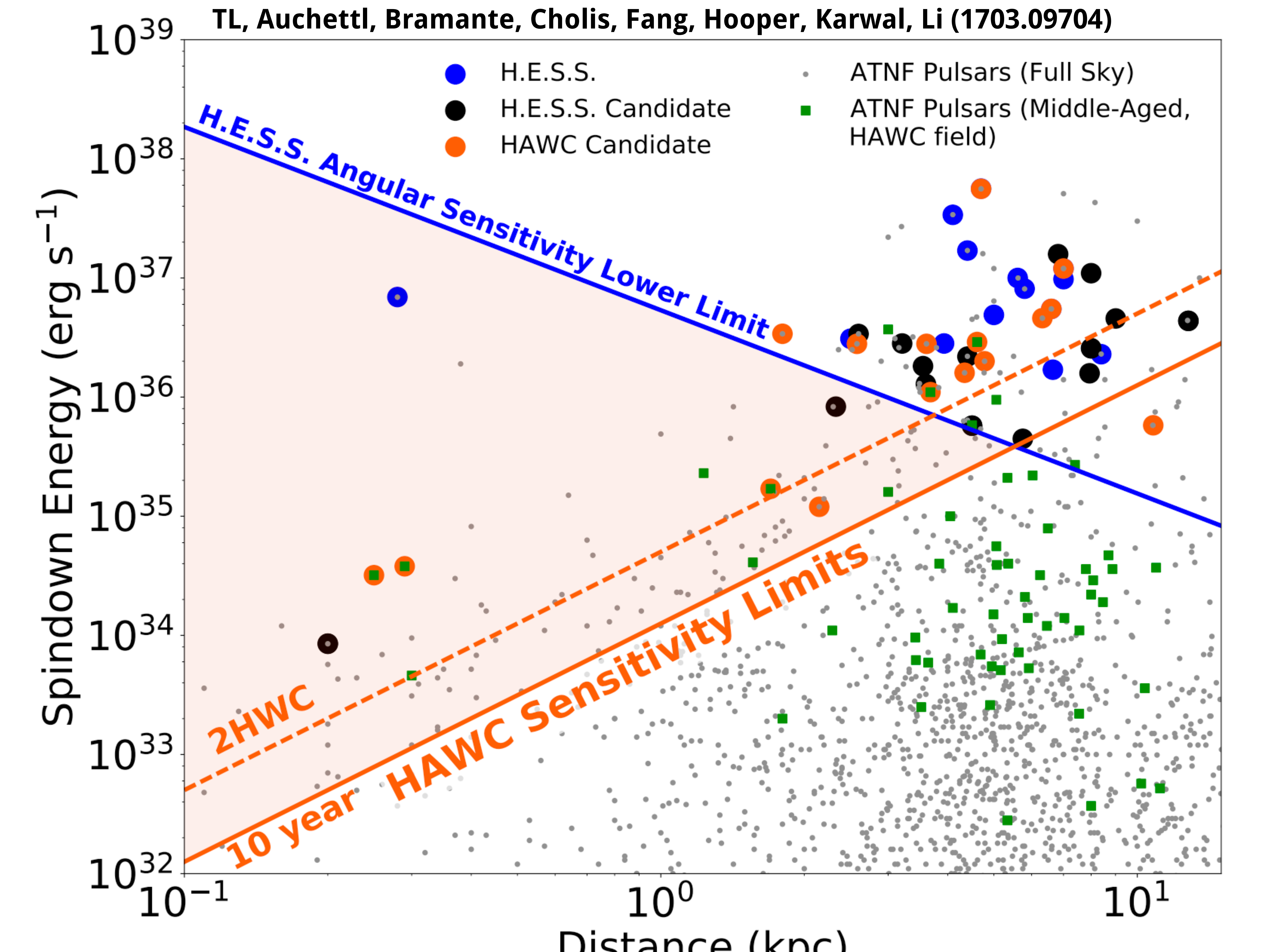
(Affiliations can be found after the references)

April 10, 2018

ABSTRACT

We present the results of the most comprehensive survey of the Galactic plane in very high-energy (VHE) γ-rays, including a public release of Galactic sky maps, a catalog of VHE sources, and the discovery of 16 new sources of VHE γ-rays. The High Energy Spectroscopic System (H.E.S.S.) Galactic plane survey (HGPS) was a decade-long observation program carried out by the H.E.S.S. I array of Cherenkov telescopes in Namibia from 2004 to 2013. The observations amount to nearly 2700 h of quality-selected data, covering the Galactic plane at longitudes from $\ell = 250°$ to $65°$ and latitudes $|b| \leqslant 3°$. In addition to the unprecedented spatial coverage, the HGPS also features a relatively high angular resolution ($0.08° \approx 5$ arcmin mean point spread function 68% containment radius), sensitivity ($\lesssim 1.5\%$ Crab flux for point-like sources), and energy range (0.2 to 100 TeV). We constructed a catalog of VHE γ-ray sources from the HGPS data set with a systematic procedure for both source detection and characterization of morphology and spectrum. We present this likelihood-based method in detail, including the introduction of a model component to account for unresolved, large-scale emission along the Galactic plane. In total, the resulting HGPS catalog contains 78 VHE sources, of which 14 are not reanalyzed here, for example, due to their complex morphology, namely shell-like sources and the Galactic center region. Where possible, we provide a firm identification of the VHE source or plausible associations with sources in other astronomical catalogs. We also studied



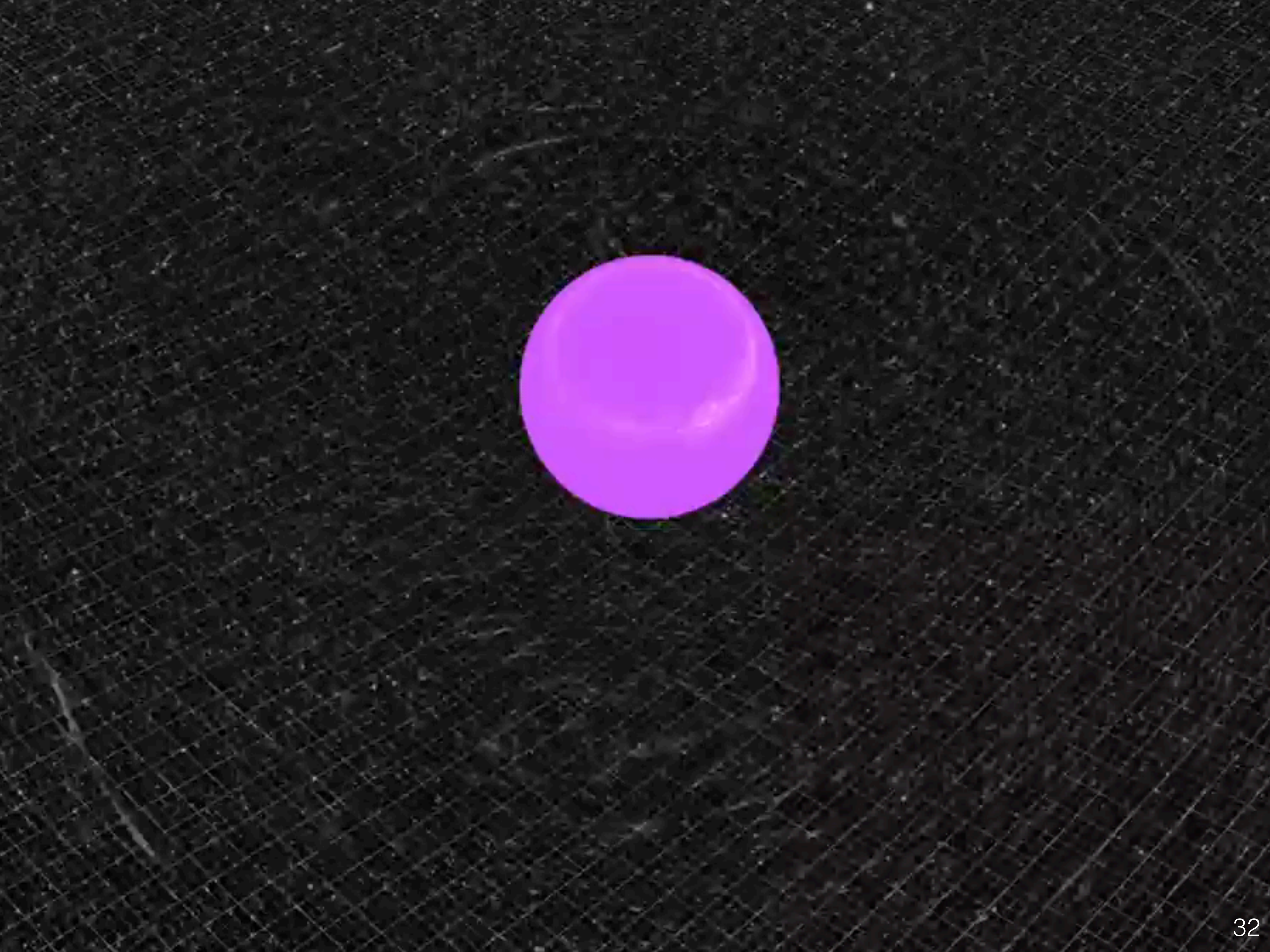

TL, Auchettl, Bramante, Cholis, Fang, Hooper, Karwal, Li (1703.09704)
H.E.S.S.
H.E.S.S. Candidate
HAWC Candidate
ATNF Pulsars (Full Sky)
ATNF Pulsars (Middle-Aged, HAWC field)
H.E.S.S. Angular Sensitivity Lower Limit
2HWC
10 year HAWC Sensitivity Limits
Spindown Energy (erg s^{-1})
Distance (kpc)
10^{39}
10^{38}
10^{37}
10^{36}
10^{35}
10^{34}
10^{33}
10^{32}
10^{-1}
10^{0}
10^{1}

Part III: Transient Signals

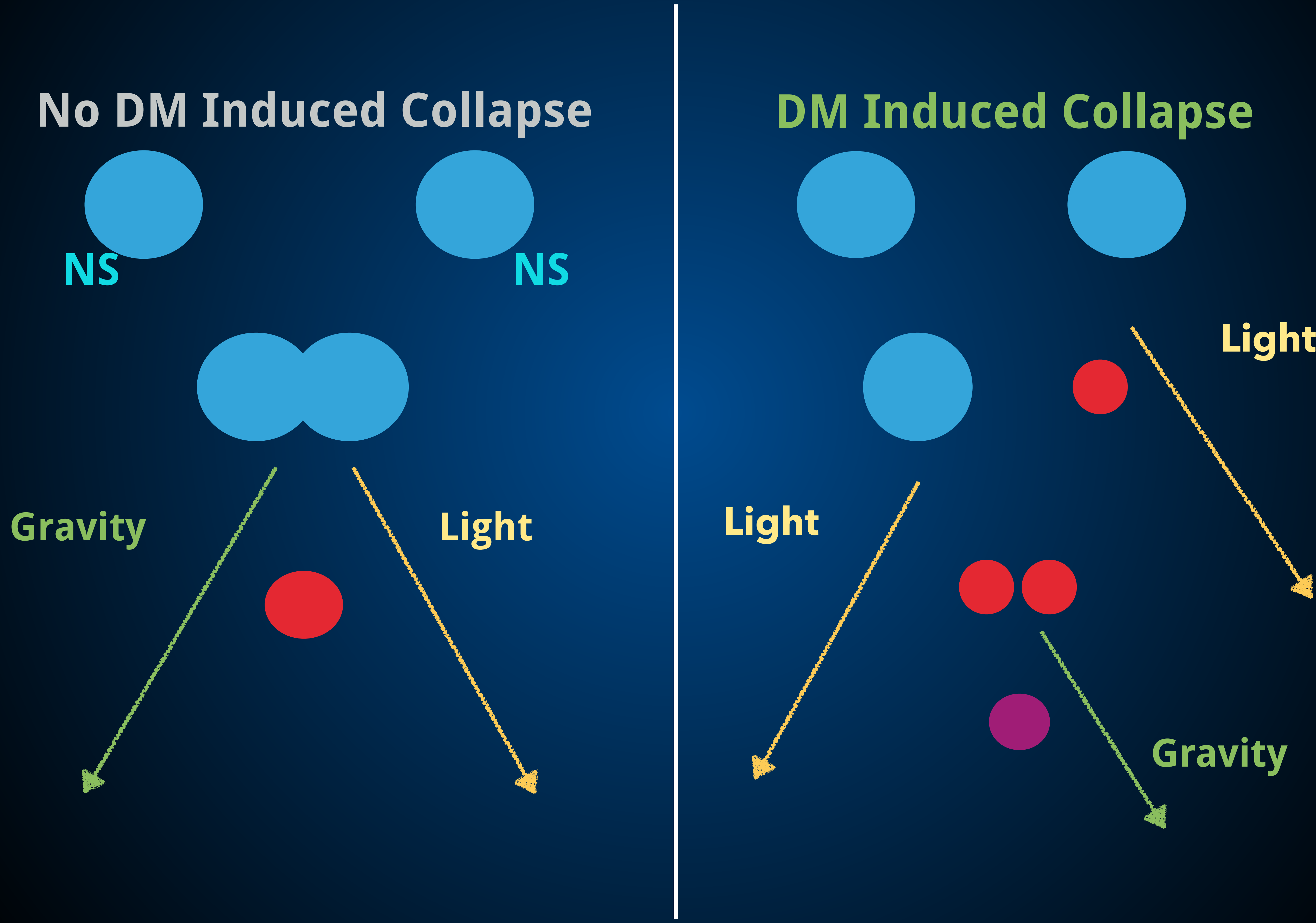
The Secret Life of Dark Matter Inside a Neutron Star

- **Capture -** DM hits neutron and elastically scatters
- **Thermalization -** Trapped dark matter thermalizes with neutron superfluid. If dark matter can annihilate, it will.
- **Collapse -** Dark matter degeneracy pressure not capable of preventing collapse.

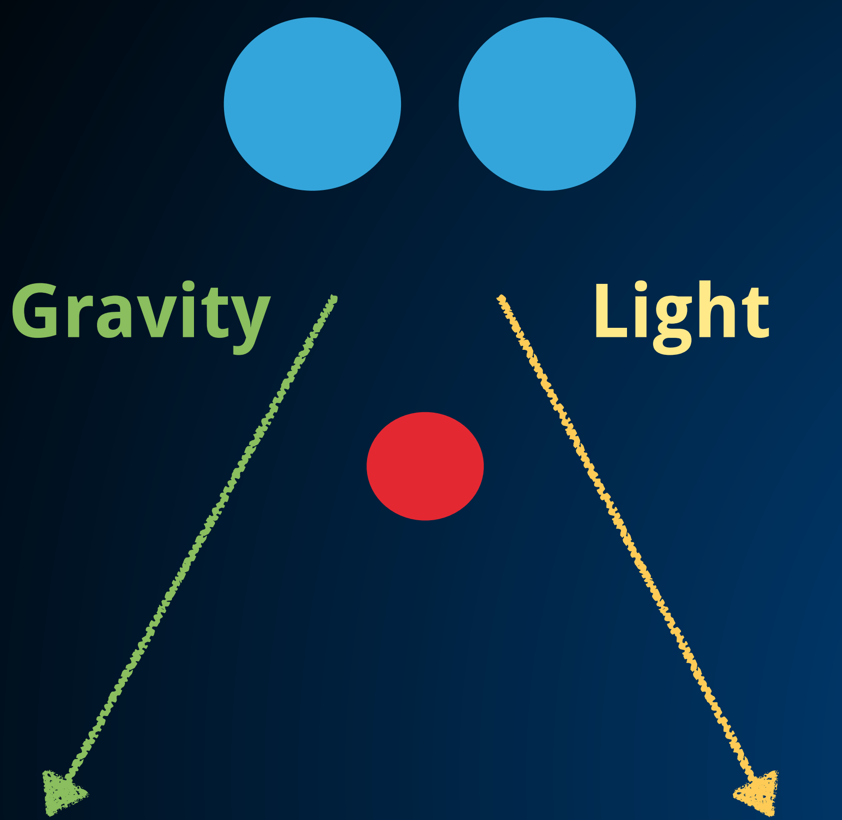
Bramante & TL (1405.1031)
Bramante & TL (1601.06784)
Bramante, TL, Tsai (1706.00001)



An Electromagnetic Signal



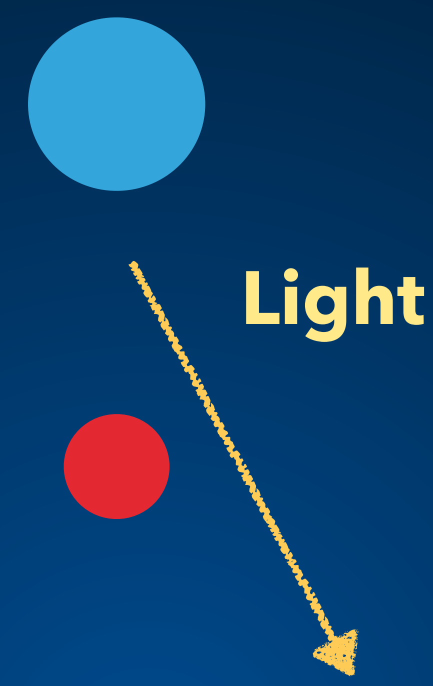
New Phenomena



Merger Kilonovae

Electromagnetic signals and gravitational waves jointly identified.

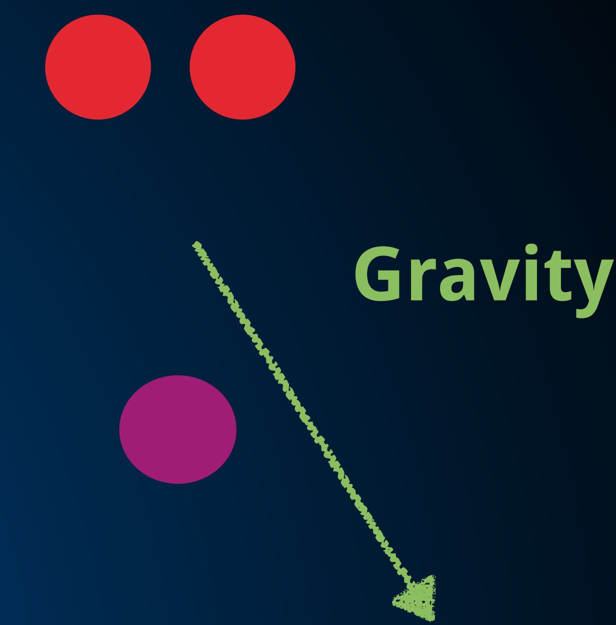
(proportional to ρ^{-1}_{DM})



Quiet Kilonovae

Electromagnetic signals without gravitational waves.

(proportional to ρ_{DM}).

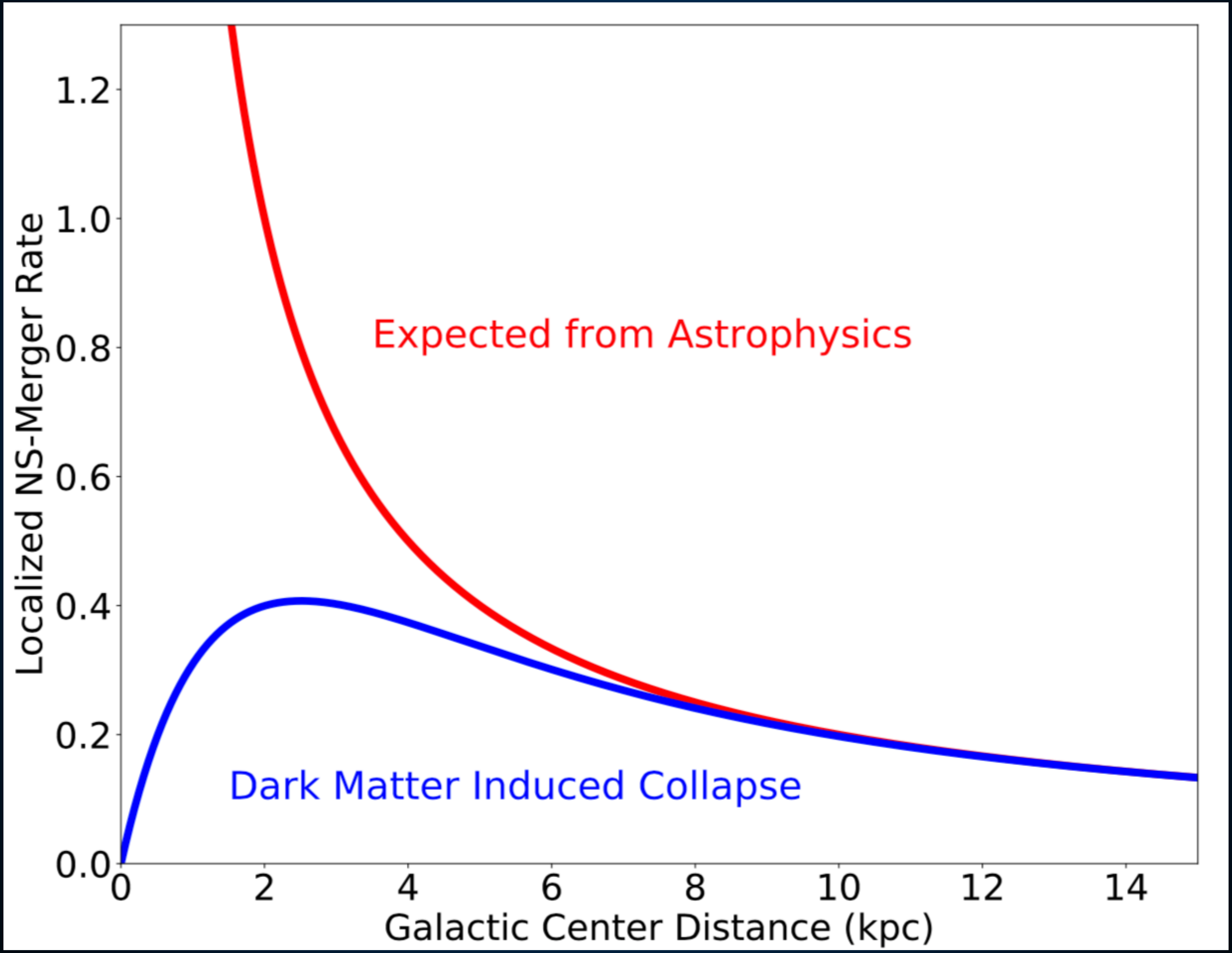


Dark Mergers

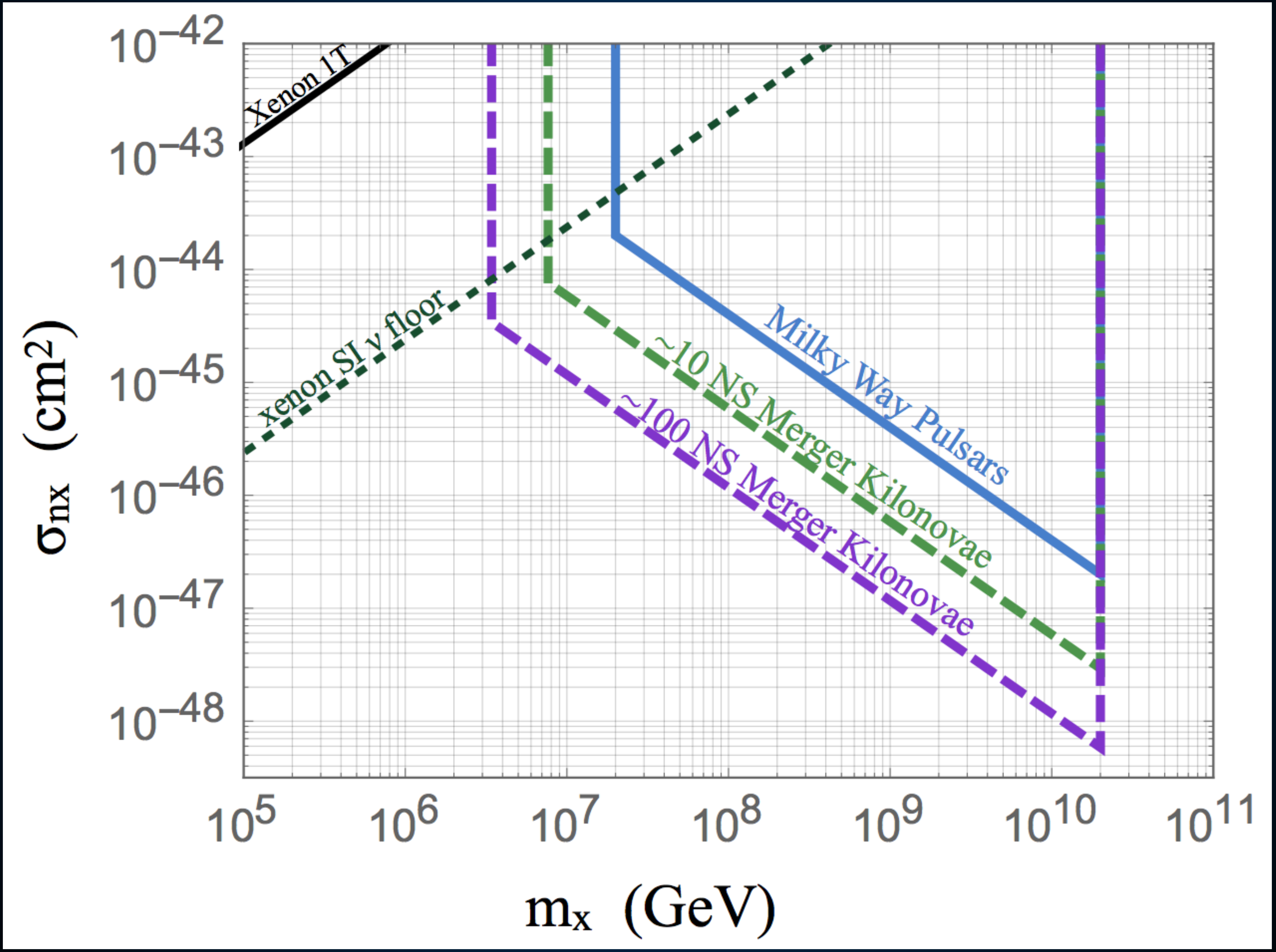
Gravitational waves without any electromagnetic signal.

(proportional to ρ_{DM}).

Merger Kilonovae

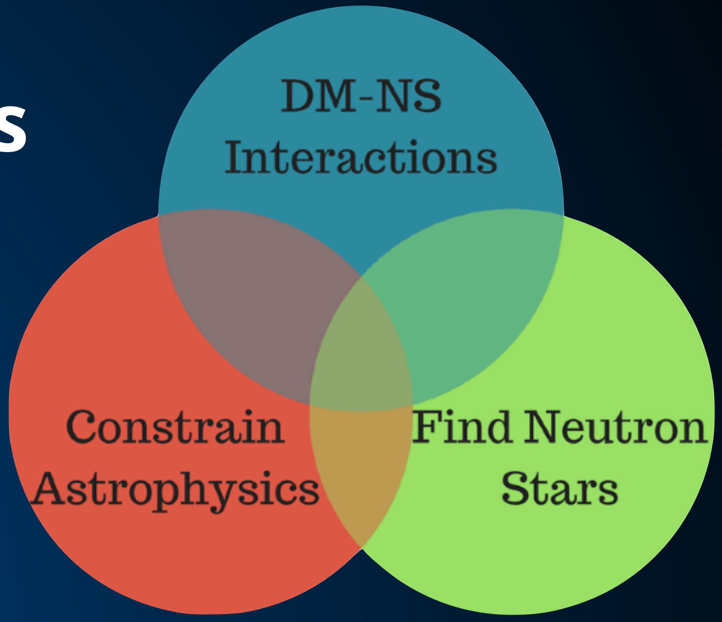


Constraining Dark Matter - Merger Kilonovae



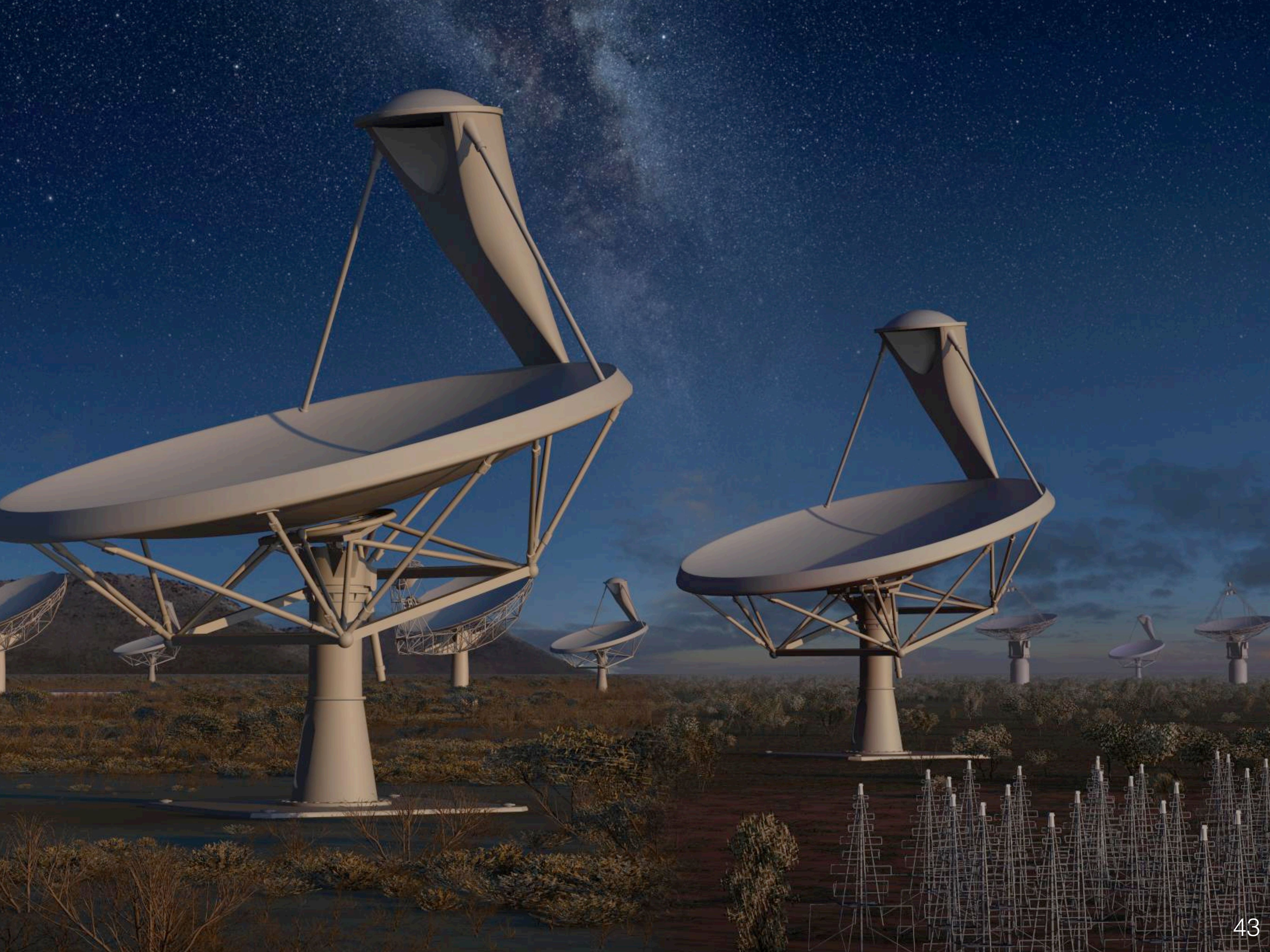
The Program

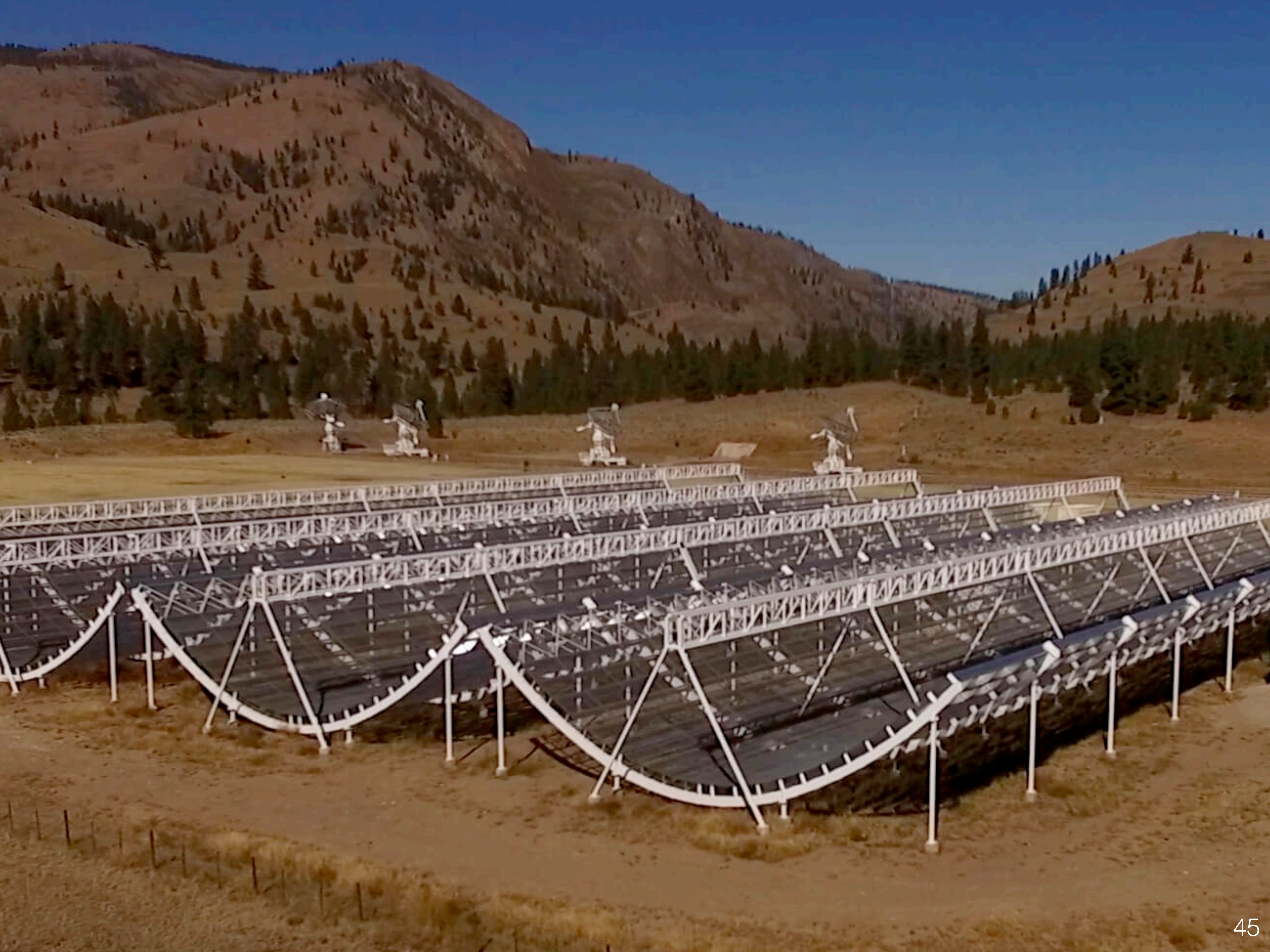
1. **Understand Dark Matter/Neutron Star Interactions**
   - **Can set strong constraints on WIMP models**
   - **Can probe extremely generic dark matter models.**



2. **Differentiate dim dark matter signals from astrophysics**
   - **Need detailed models of neutron star physics.**
   - **Requires observations of pulsars with "special" attributes**
     1. **Nearby**
     2. **Not Beamed Towards Earth**


VLZ 6000-00





The Theme

- Dark matter is an explosive and broadly expansive field.

- The next generation of telescopes will revolutionize our ability to probe both standard and esoteric dark matter models.

- The astrophysics is the dominant theoretical difficulty — must overcome astrophysical uncertainties to unlock the potential of upcoming experiments.

Where Are We Now?

Two Perspectives

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GeV-Scale Thermal WIMPs: Not Even Slightly Dead

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Weakly Interacting Massive Particles (WIMPs) have long reigned as one of the leading classes of dark matter candidates. The observed dark matter abundance can be naturally obtained by freeze-out of weak-scale dark matter annihilations in the early universe. This "thermal WIMP" scenario makes direct predictions for the total annihilation cross section that can be tested in present-day experiments. While the dark matter mass constraint can be as high as $m_\chi \gtrsim 100$ GeV for particular annihilation channels, the constraint on the *total* cross section has not been determined. We construct the first model-independent limit on the WIMP total annihilation cross section, showing that allowed combinations of the annihilation-channel branching ratios considerably weaken the sensitivity. For thermal WIMPs with s-wave $2 \to 2$ annihilation to visible final states, we find the dark matter mass is only known to be $m_\chi \gtrsim 20$ GeV. This is the strongest largely model-independent lower limit on the mass of thermal-relic WIMPs; together with the upper limit on the mass from the unitarity bound ($m_\chi \lesssim 100$ TeV), it defines what we call the "WIMP window". To probe the remaining mass range, we outline ways forward.

[hep-ph] 11 Jul 2018

I. INTRODUCTION

A leading candidate for dark matter (DM) is a Weakly Interacting Massive Particle (WIMP) that is a thermal

scenarios. The branching ratios, coupling types and signals are model-dependent, and so the lack of observations may just be due to such features. For example, there can be interference effects, momentum suppression, or

Where Are We Now?

Two Perspectives

REVIEW

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A new era in the search for dark matter

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There is a growing sense of 'crisis' in the dark-matter particle community, which arises from the absence of evidence for the most popular candidates for dark-matter particles—such as weakly interacting massive particles, axions and sterile neutrinos—despite the enormous effort that has gone into searching for these particles. Here we discuss what we have learned about the nature of dark matter from past experiments and the implications for planned dark-matter searches in the next decade. We argue that diversifying the experimental effort and incorporating astronomical surveys and gravitational-wave observations is our best hope of making progress on the dark-matter problem.

The fall of natural weakly interacting massive particles

The existence of dark matter has been discussed for more than a century[1,2]. In the 1970s, astronomers and cosmologists began to build what is today a compelling body of evidence for this elusive component of the Universe, based on a variety of observations, including temperature anisotropies of the cosmic microwave background, baryonic acoustic oscillations, type Ia supernovae, gravitational lensing of galaxy clusters and rotation curves of galaxies[3,4]. The standard model of particle physics contains no suitable particle to explain these observations, and

the observed Higgs mass at the weak scale appears highly unnatural, requiring an incredibly fine-tuned cancellation between the individually much larger intrinsic contribution and the correction terms, such that their sum is the value observed at the Large Hadron Collider (LHC). Natural theories introduce additional particles and symmetries, which are arranged so that these large corrections cancel each other out, protecting the Higgs mass from the influence of heavy mass scales.

The prototypical natural theory is the minimal supersymmetric (SUSY) standard model, which introduces an additional partner for

Conclusions

- We must both probe standard dark matter paradigms and also branch out.
- Separating astrophysics from dark matter signals is critical — detailed modeling is necessary.
- The observations are coming!