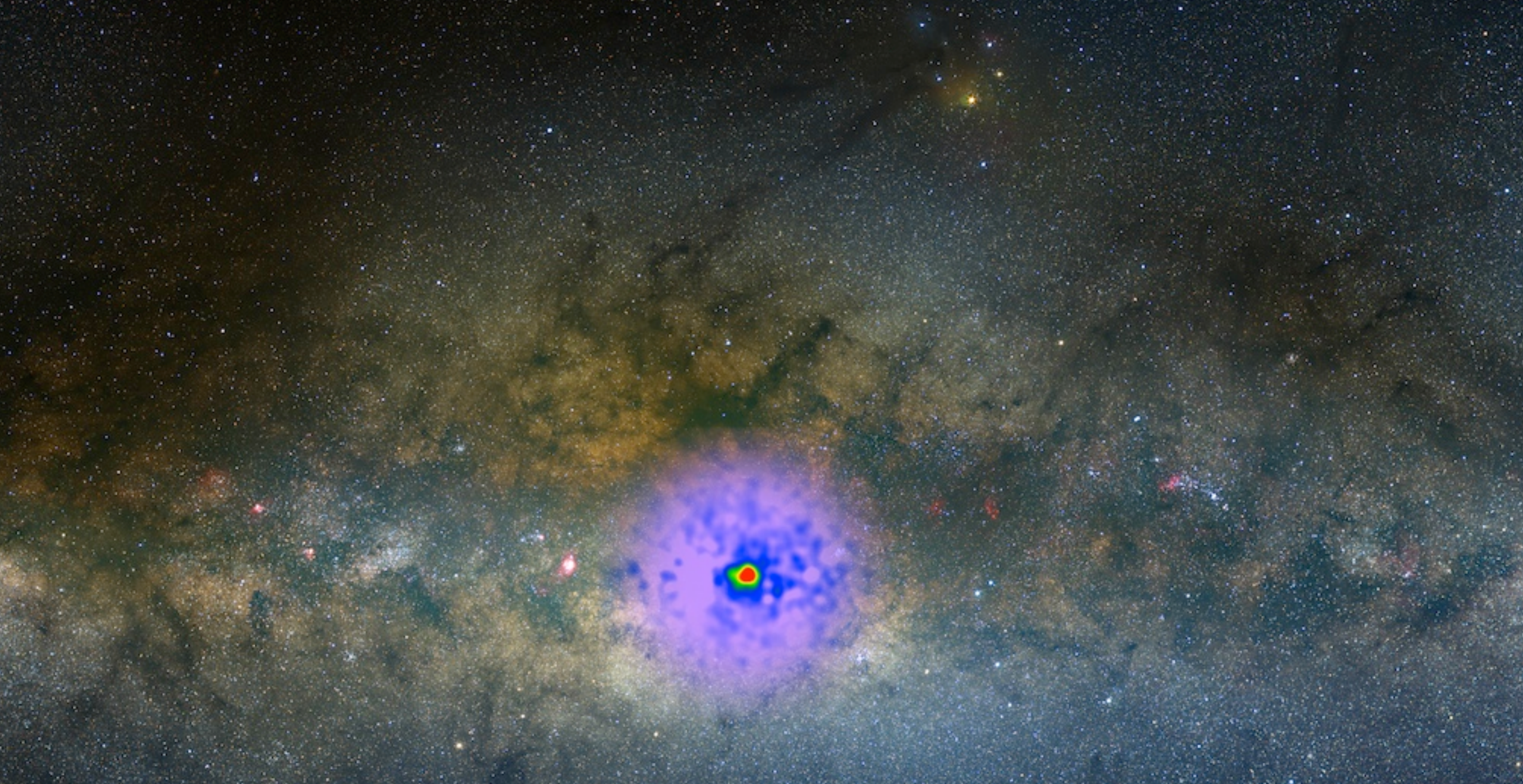
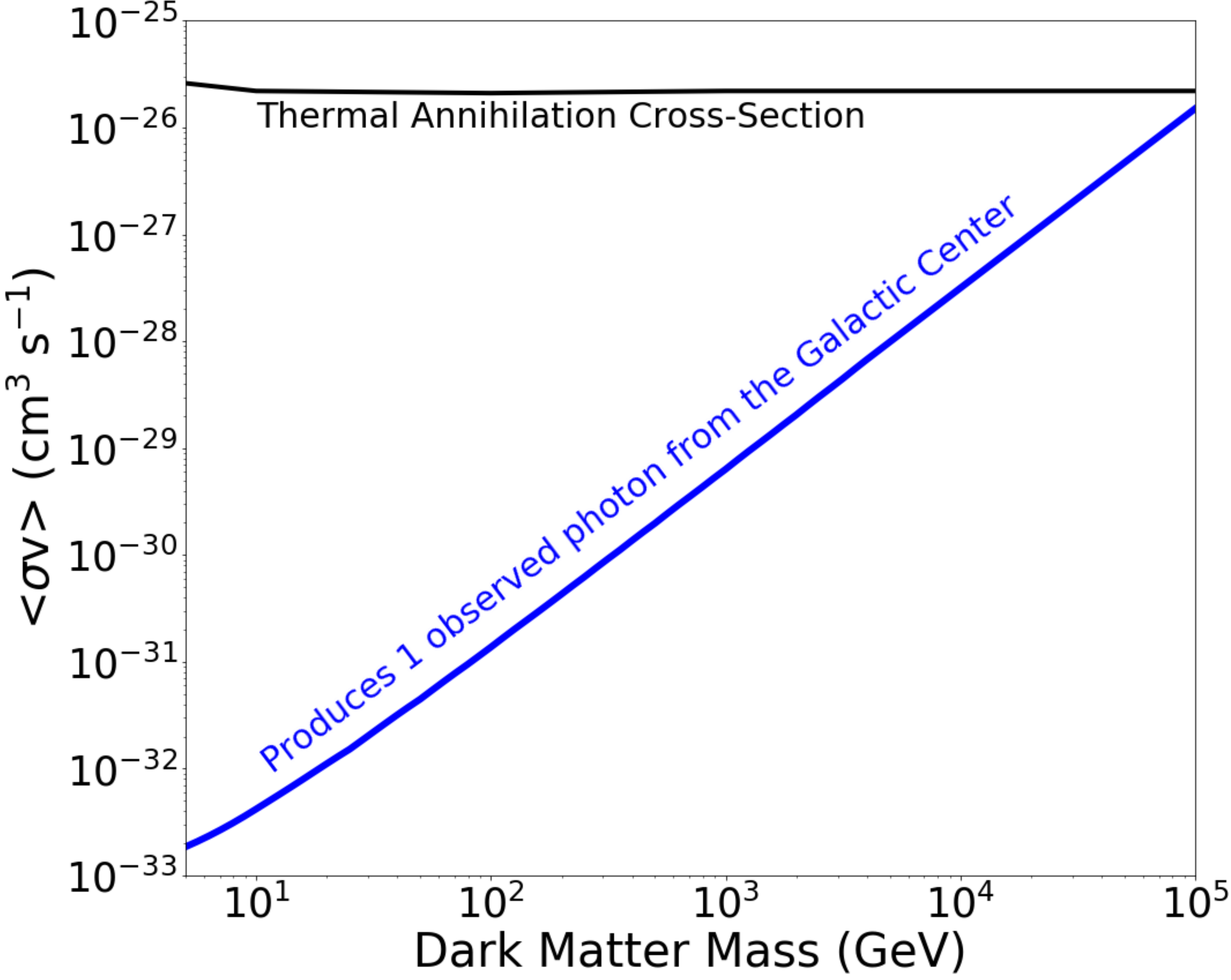


The Indirect Detection of Thermal Dark Matter

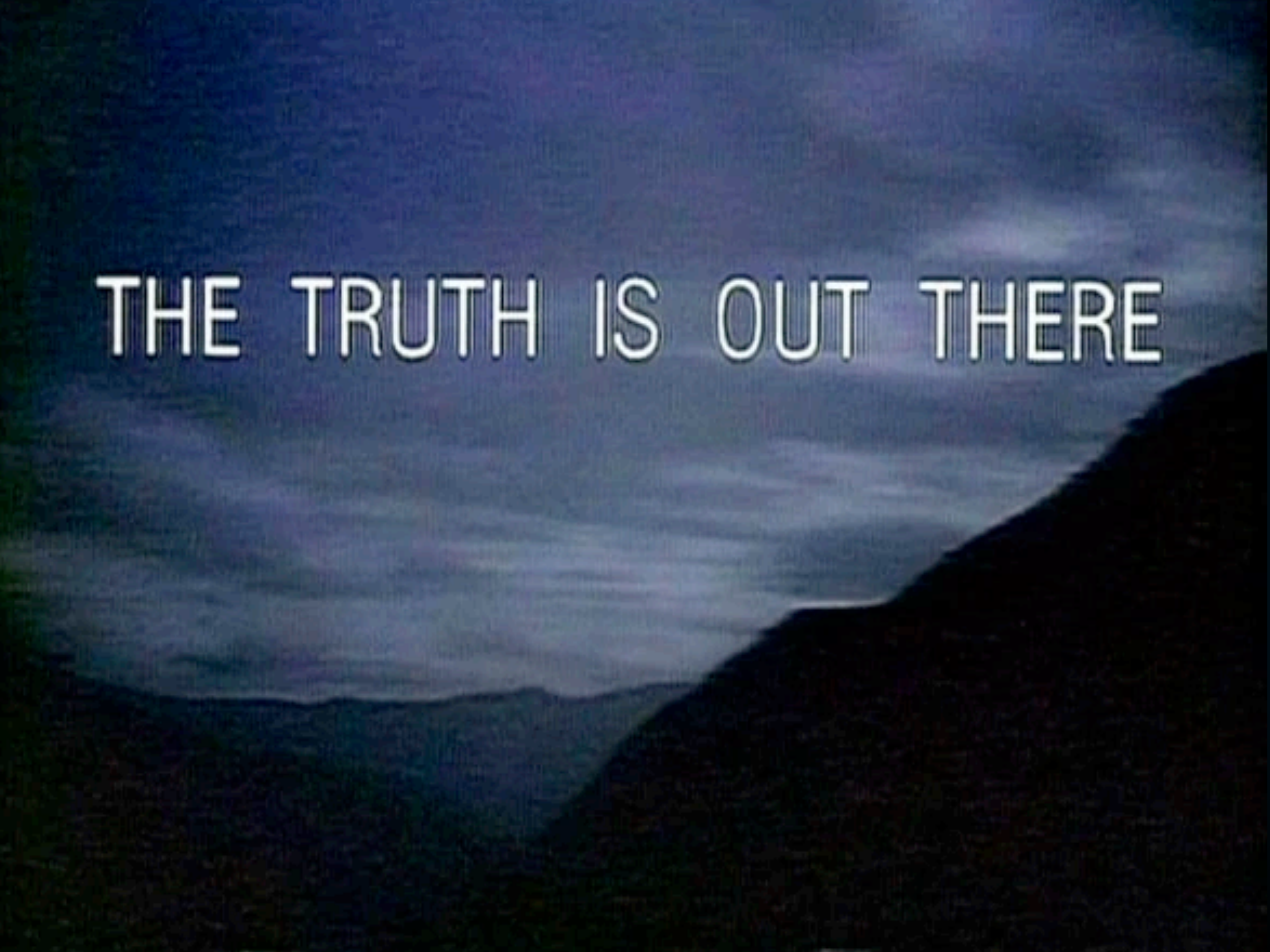
Tim Linden

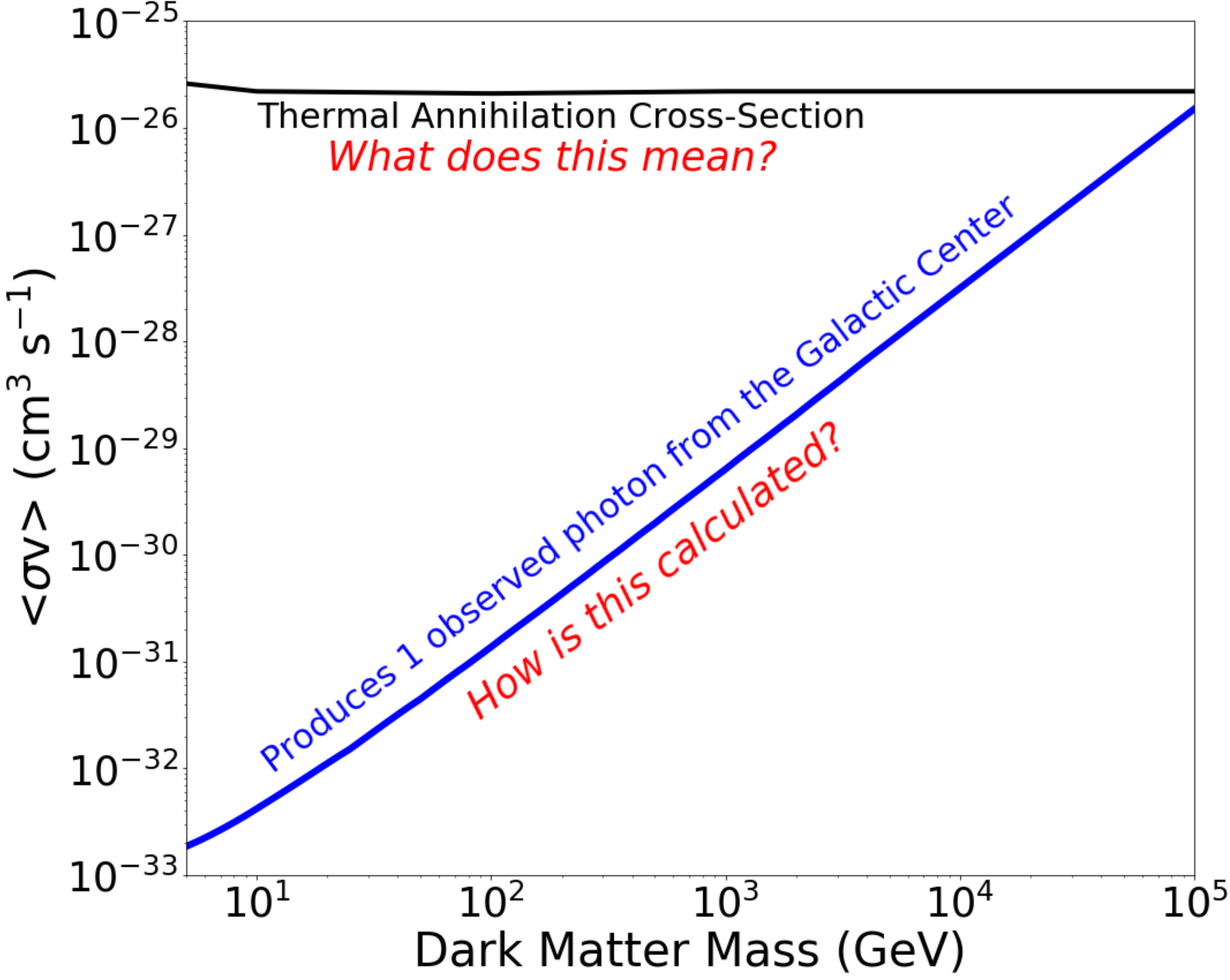
Case Western Reserve University
Michelson Postdoctoral Prize Lectures
Physics Department Colloquium 10/4/18

The Ohio State University
Center for Cosmology and Astroparticle Physics



Thermal Annihilation Cross-Section
Produces 1 observed photon from the Galactic Center
<σv> (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 TRUTH IS OUT THERE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10⁻²⁵
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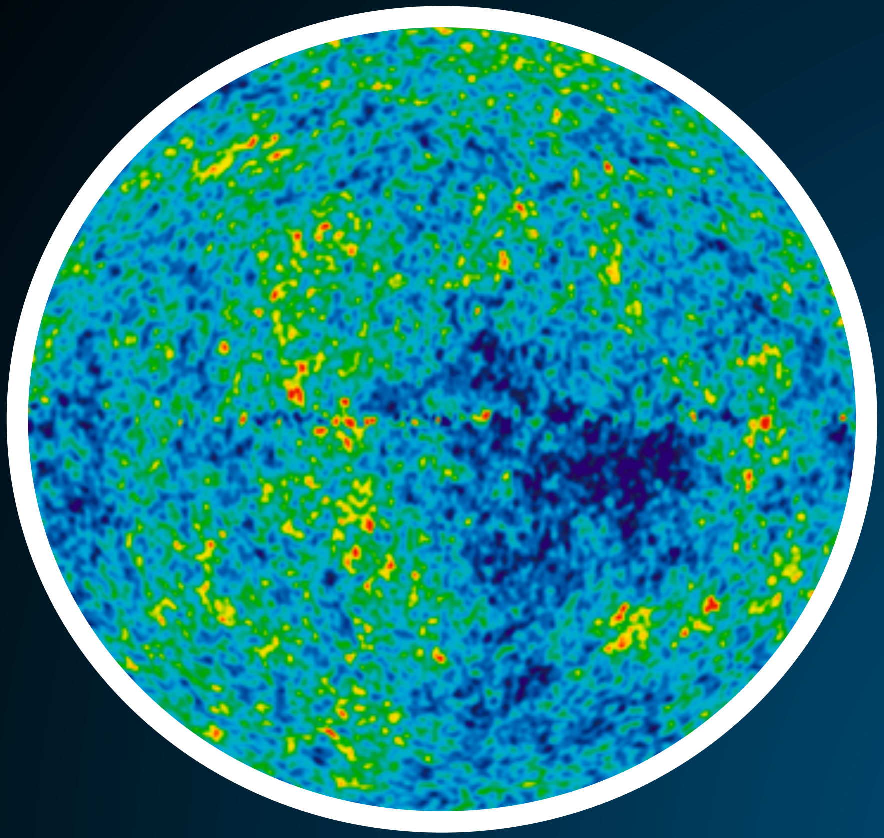
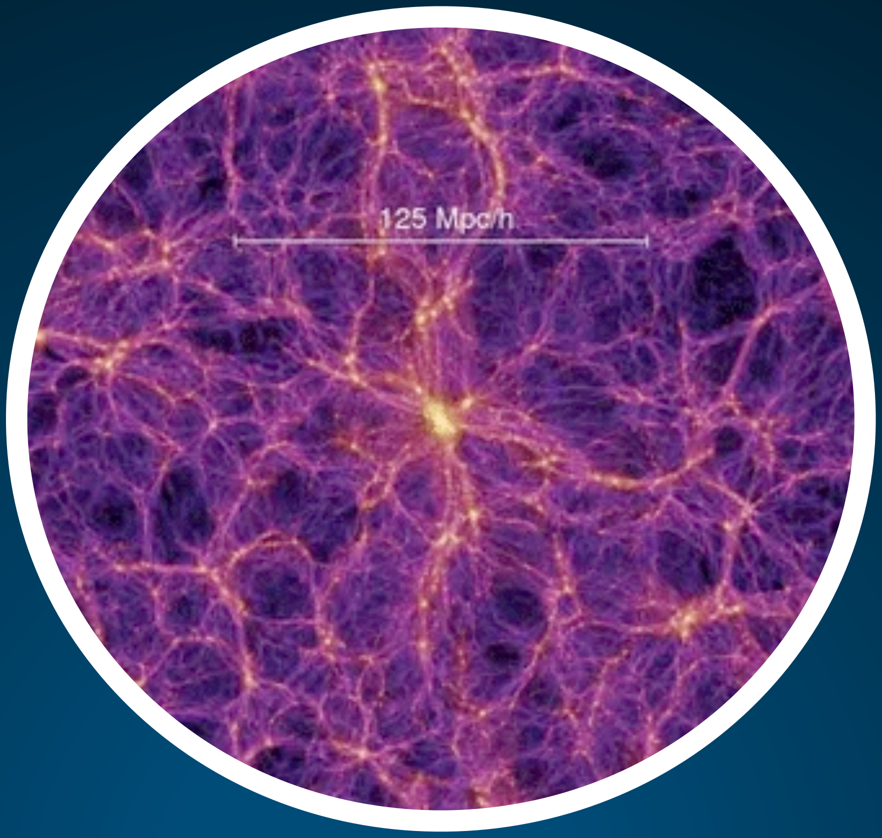
10⁻²⁸
10⁻²⁹
10⁻³⁰
10⁻³¹
10⁻³²
10⁻³³
10¹
10²
10³
10⁴
10⁵

Everything We Know About Dark Matter





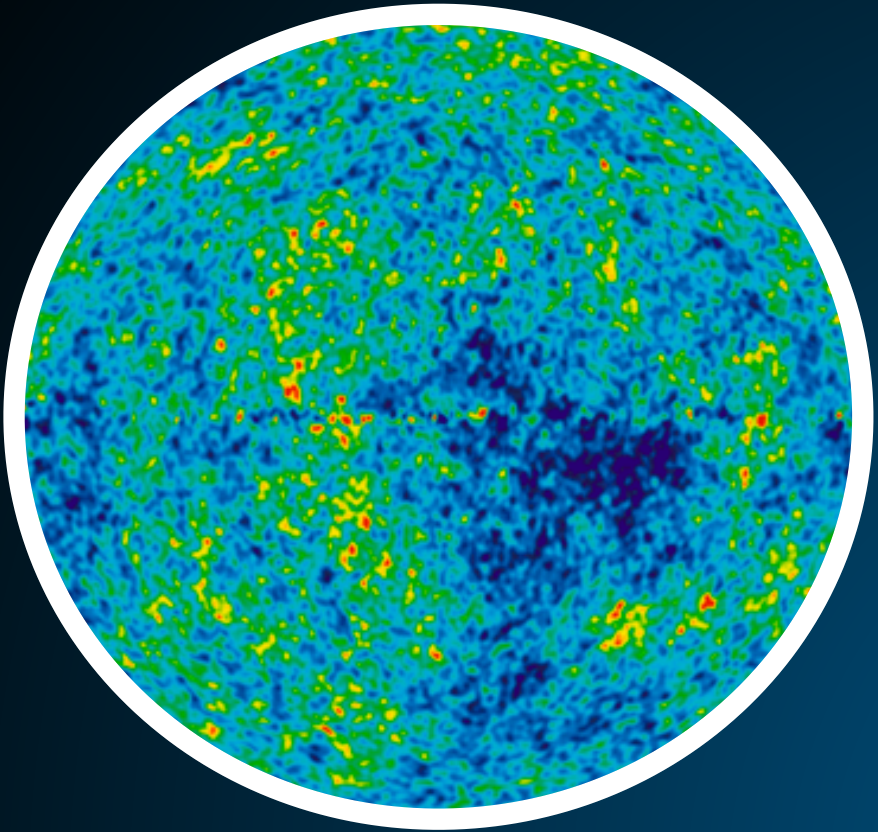
Stable - ***on cosmological timescales***

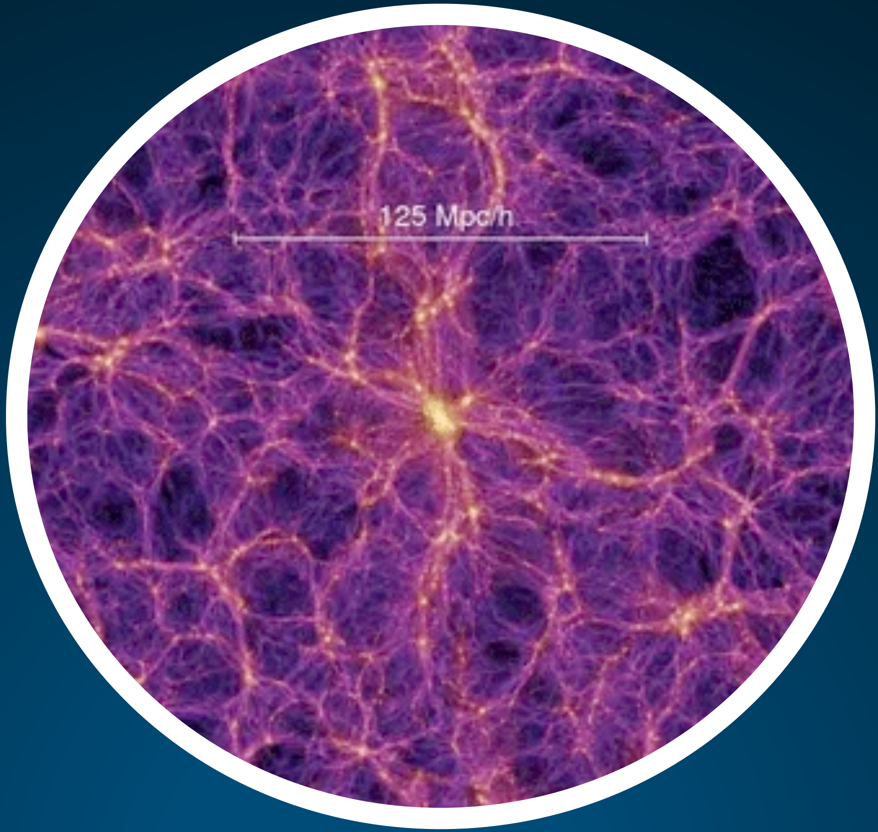
Dark - ***negligible electromagnetic cross-section***

Cold - ***not relativistic***

~5.3x as prevalent as baryonic matter

Everything We Know About Dark Matter





10^{-25} GeV

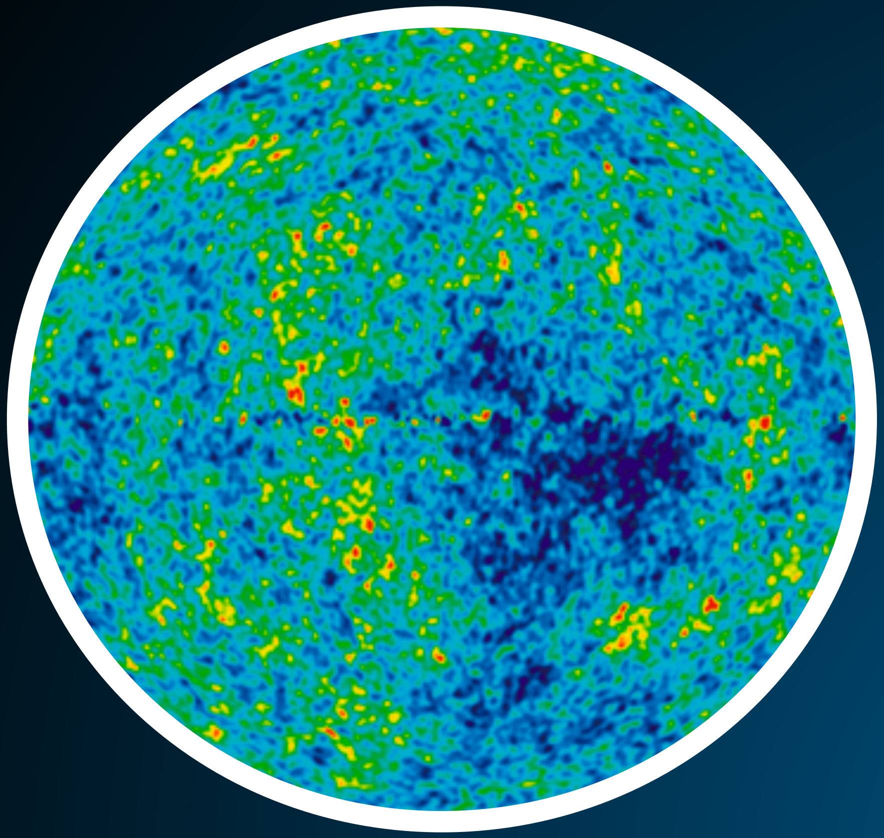
$\sigma_X > R_{UFD}$

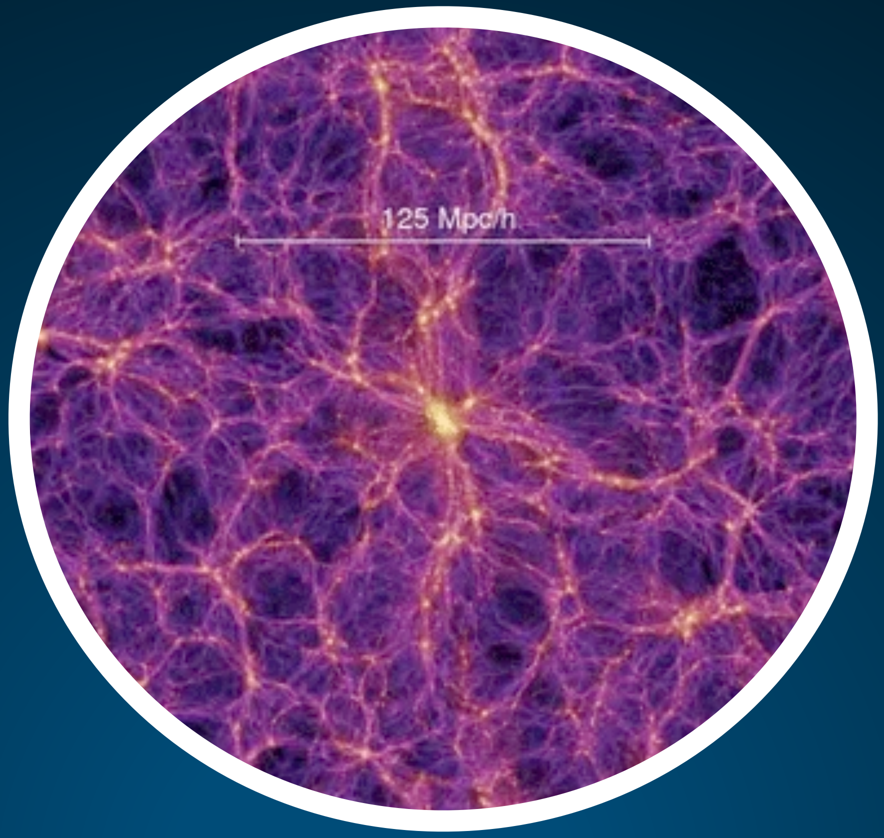
10^{62} GeV

$m_X > M_{UFD}$

slide concept courtesy of Asher Berlin

Everything We Know About Dark Matter





~100 GeV

Thermal
Dark Matter

10^{-25} GeV
$\sigma_X > R_{UFD}$

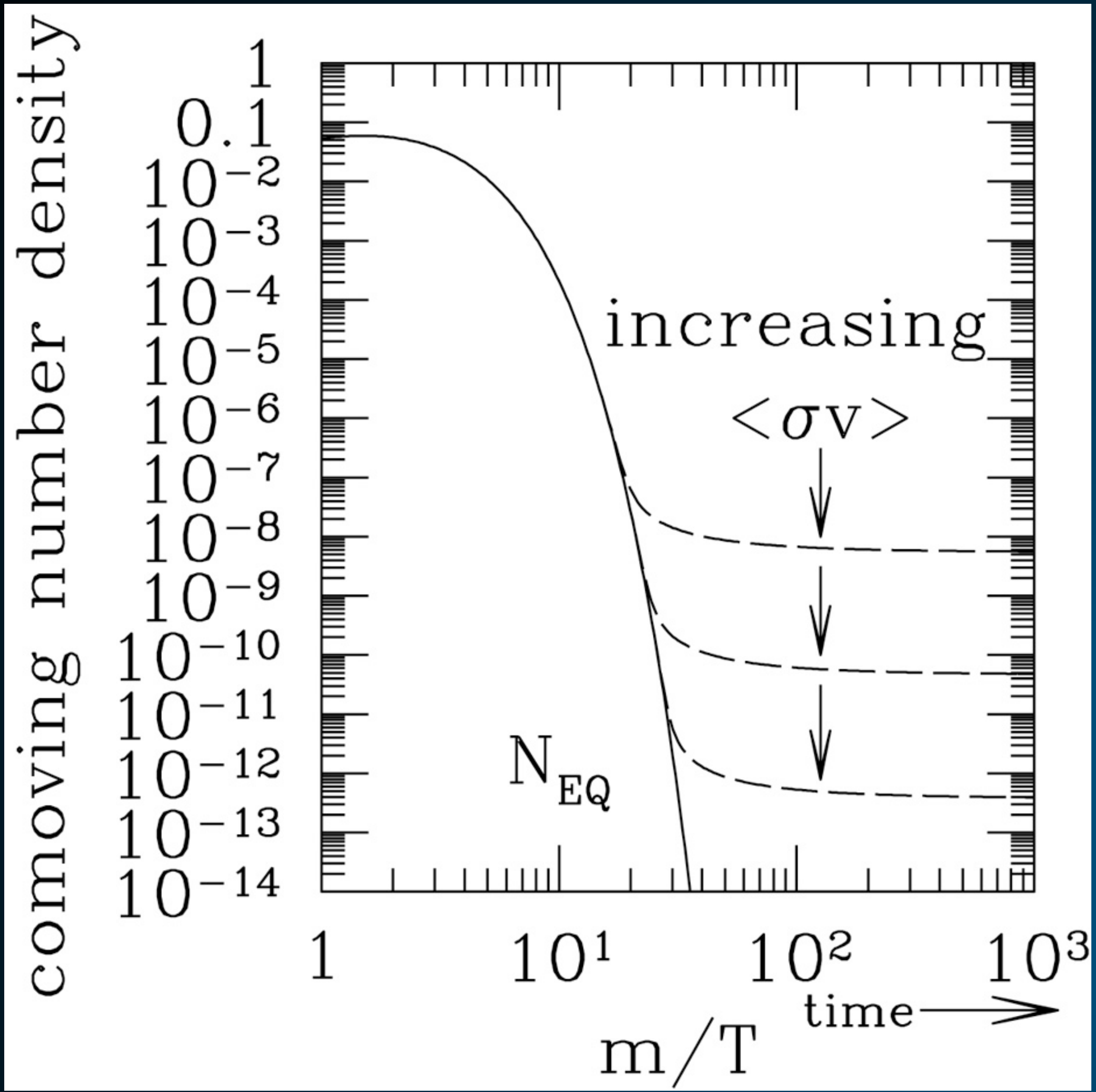
10^{62} GeV
$m_X > M_{UFD}$

slide concept courtesy of Asher Berlin

Thermal Dark Matter

artist: Sarah Szabo

The WIMP Miracle



A particle with a weak interaction cross-section and a mass on the weak scale is expected to naturally obtain the correct relic abundance through thermal freeze-out in the Earth universe.

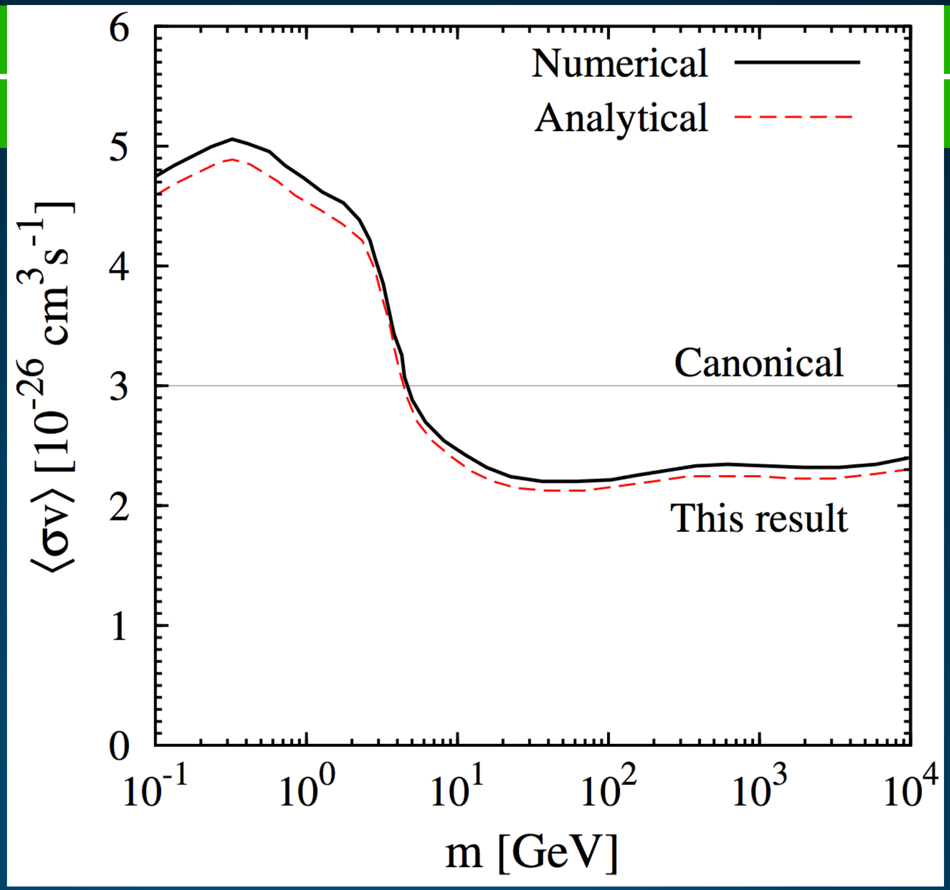
$$\frac{\Omega_\chi}{0.2} = \frac{x_{f.o}}{20}\left(\frac{10^{-8}\ \mathrm{GeV}^{-2}}{\sigma}\right)$$

$$< \sigma v > \ \sim\ 10^{-8}\,\mathrm{GeV}^{-2}\left(3\times 10^{-28}\right)\mathrm{GeV}^2\mathrm{cm}^2\, 10^{10}\frac{\mathrm{cm}}{\mathrm{s}}$$

$$< \sigma v > \ \sim\ 3\times 10^{-26}\ \frac{\mathrm{cm}^3}{\mathrm{s}}$$

The Thermal Miracle

WIMP Miracle



Steigman et al. (1204.3622)

N_{eff}

>3 MeV

$$N_{\rm eff} = N_\nu \left(\frac{4}{11}\right)^{-4/3} \left(\frac{T_\nu}{T_\gamma}\right)^4$$

$$N_{\rm eff}^{\rm equil} = N_\nu \left[1 + \frac{1}{N_\nu}\sum_{i=1}^{n} \frac{g_i}{2} F\left(\frac{m_i}{T_d}\right)\right]^{4/3}$$

Unitarity

< 124 TeV

$$\sigma \sim \frac{g^2}{m_\chi^4}$$

$$g \lesssim 4\pi$$

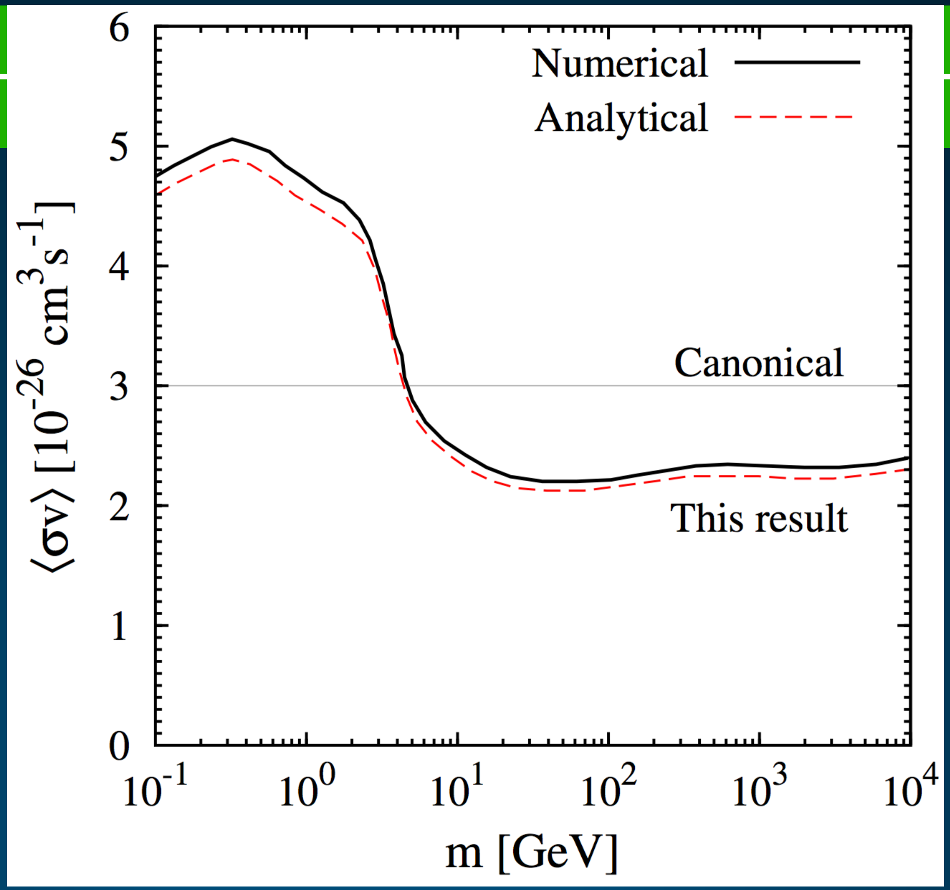
$$\frac{\Omega_\chi}{0.2} \gtrsim 10^{-8}\ {\rm GeV}^{-2} \left(\frac{m_\chi^2}{4\pi}\right)$$

$$x_f = ln\left(\frac{m_\chi^3 < \sigma v >}{H_{x=1}}\right)$$

WIMP Miracle

Lee-Weinberg
>10 GeV

if interaction is due to the weak force



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Thermal WIMPs - The Most Boring Model

1 new particle (can be motivated by more-complex physics)

1 new conserved quantity ("dark matter-ness", r-parity)

1 (maybe 0) new forces

Thermal WIMPs - The Most Boring Model

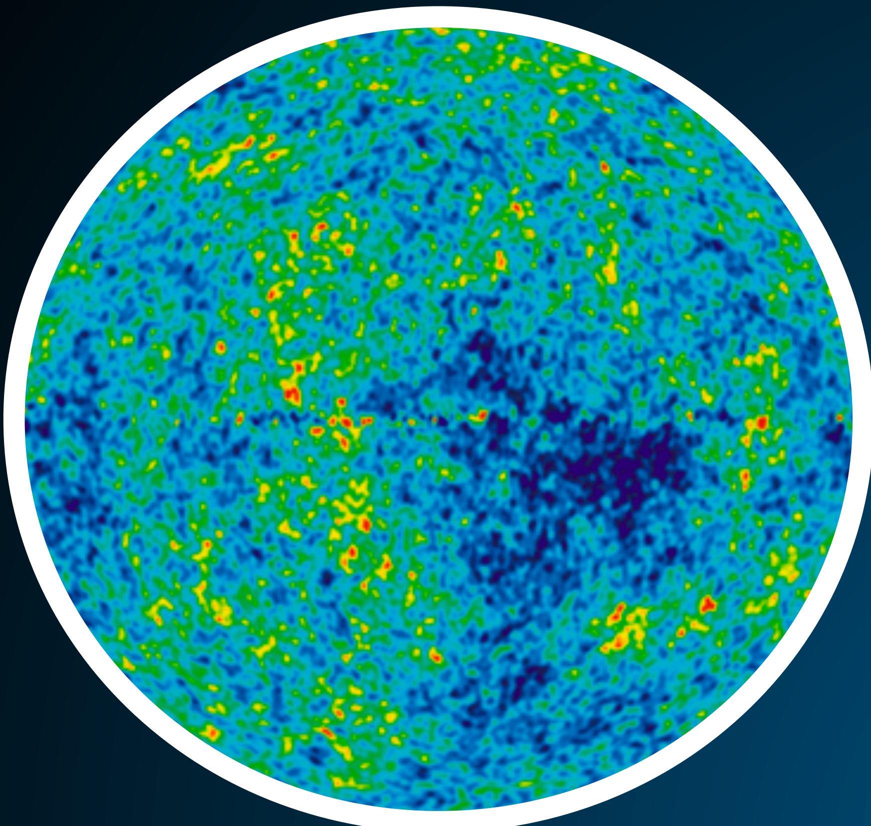
1 new particle (can be motivated by more-complex physics)

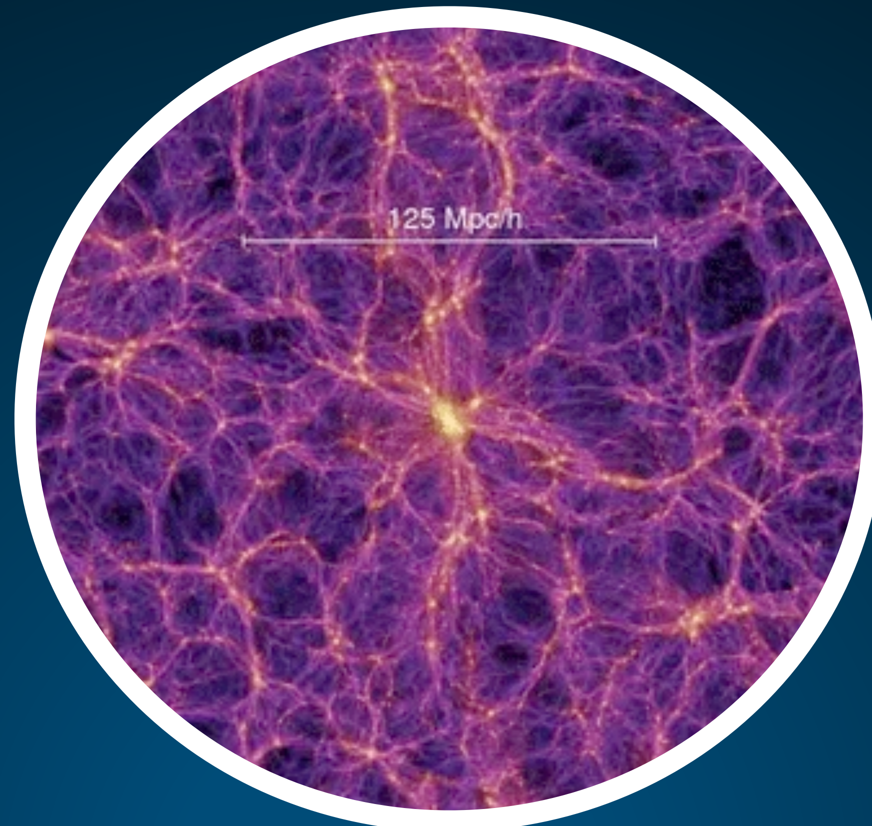
1 new conserved quantity ("dark matter-ness", r-parity)

1 (maybe 0) new forces

Ruling out this model leaves only *more* interesting possibilities.

Everything We Know About Dark Matter





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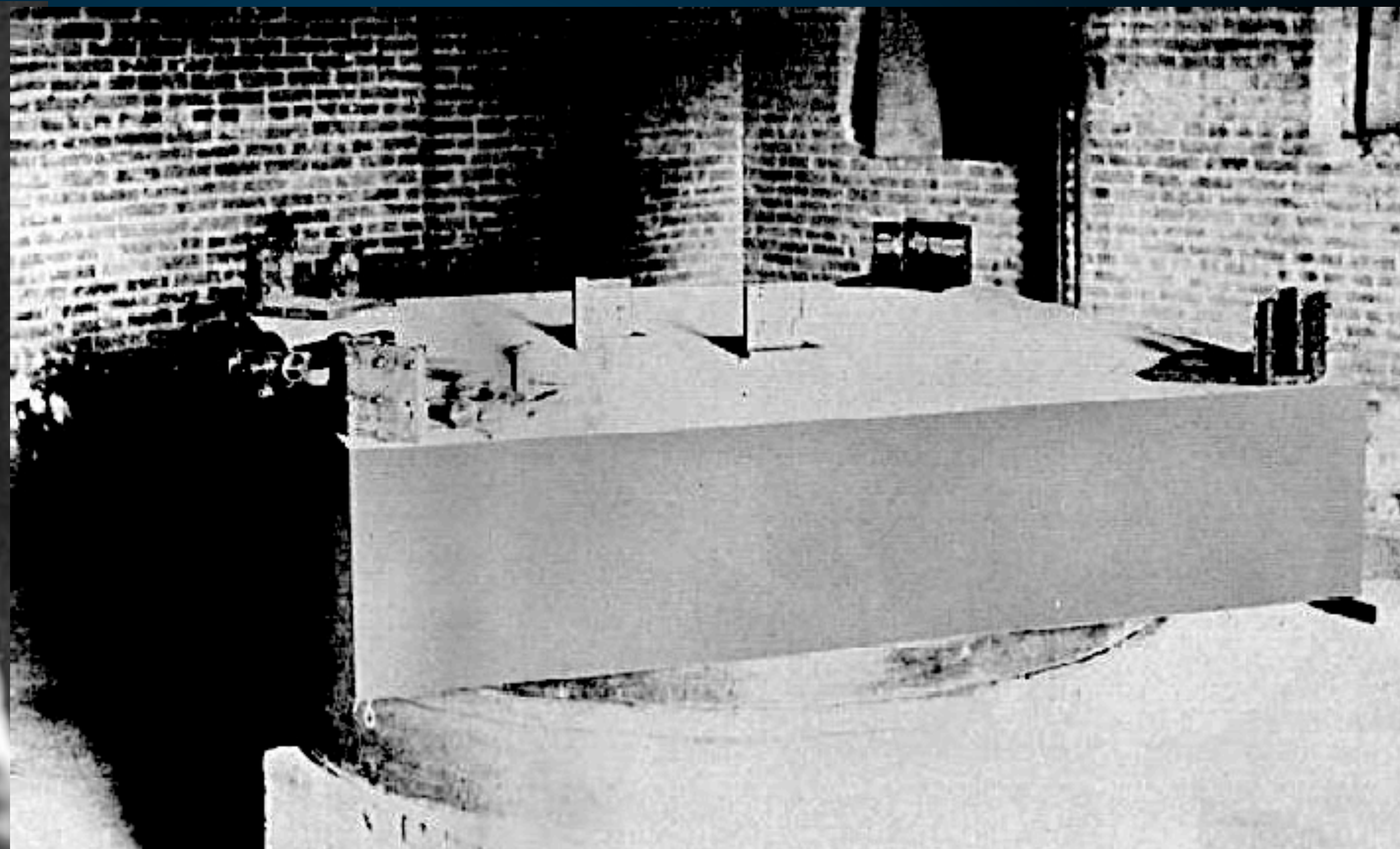
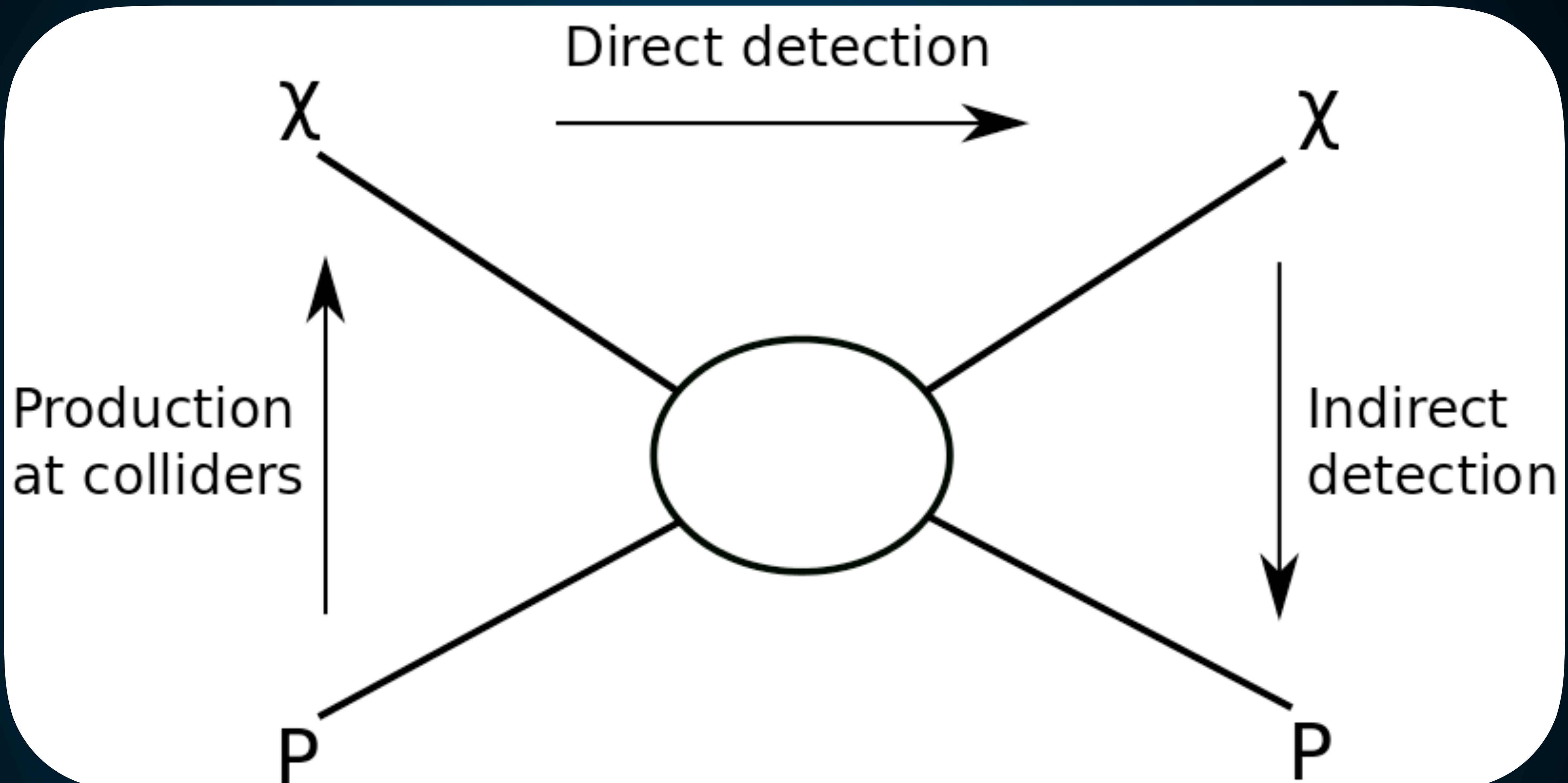
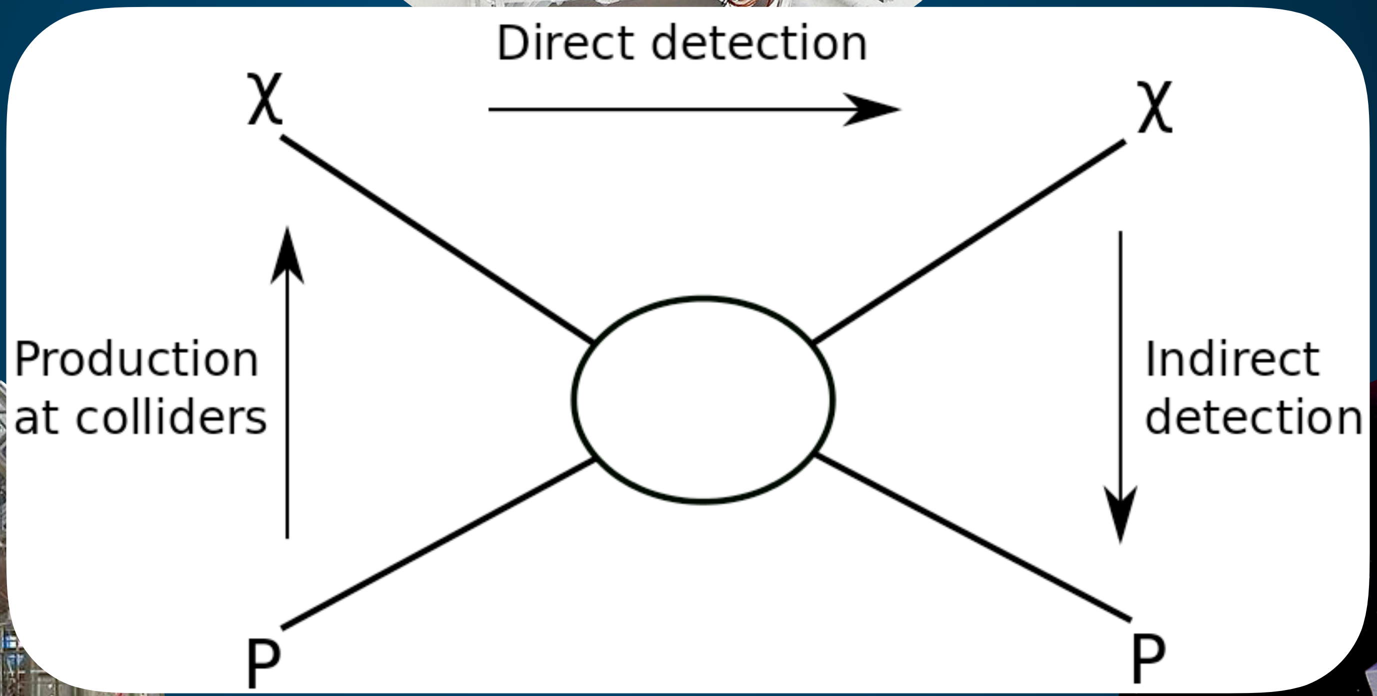
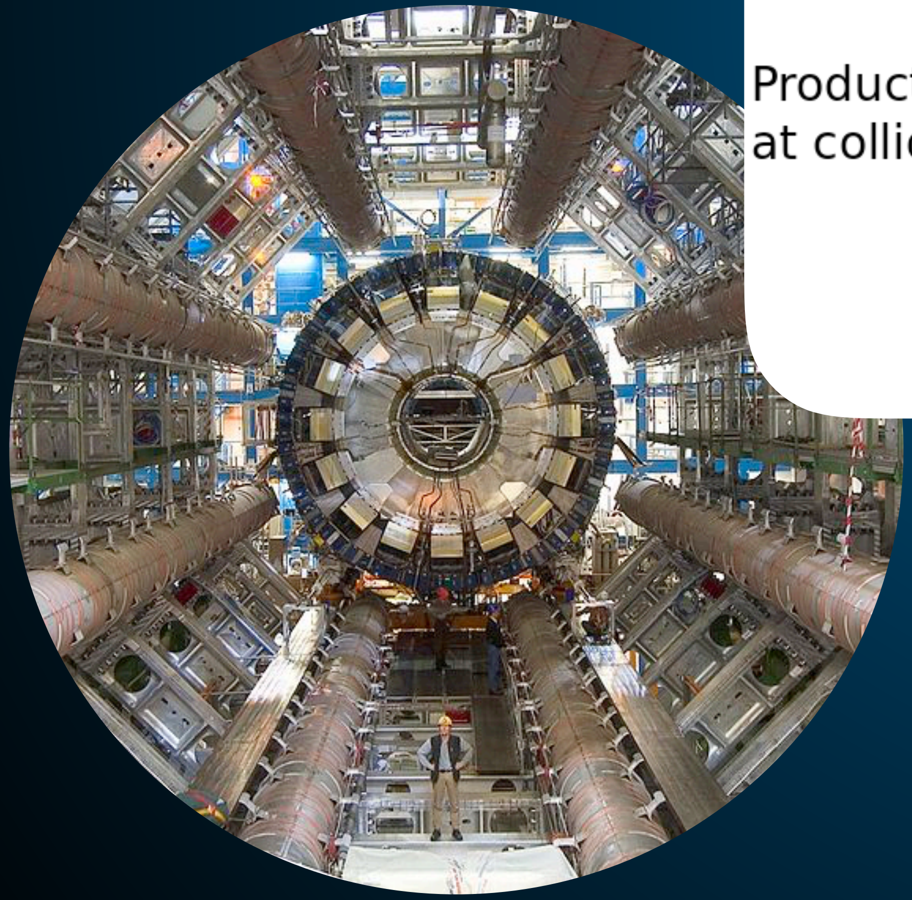


Dark Matter in Thermal Equilibrium

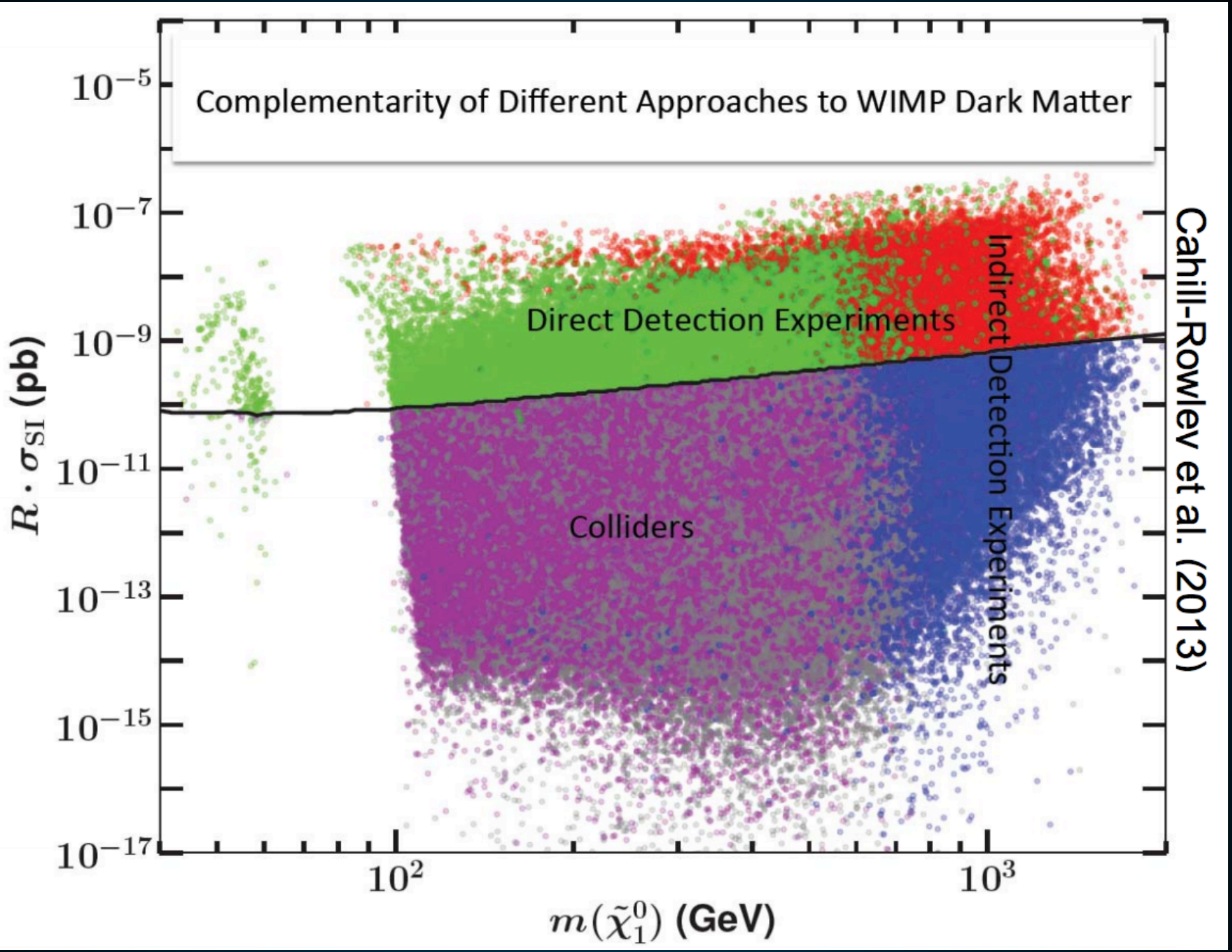


Dark Matter Complementarity



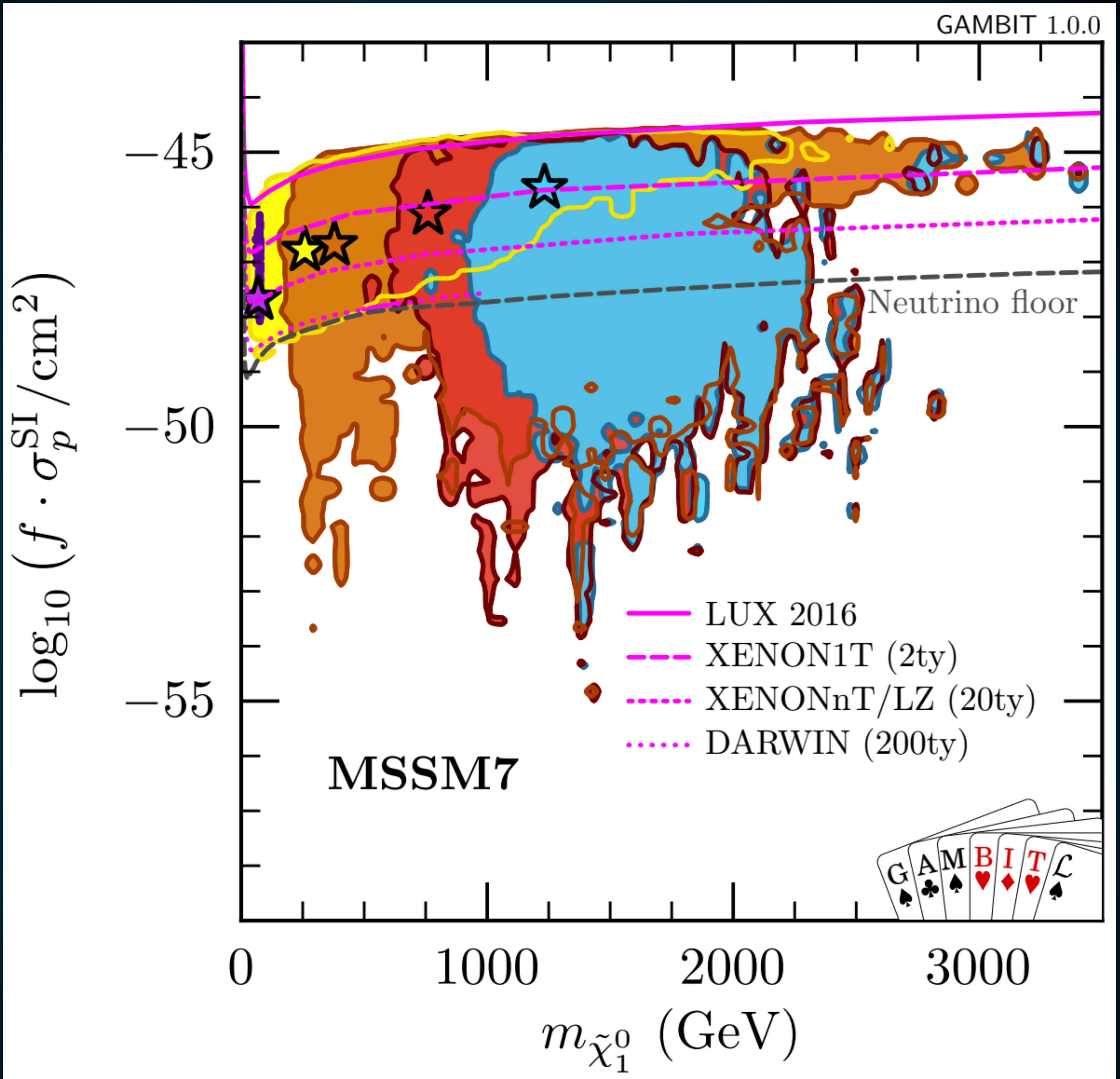


Dark Matter Complementarity



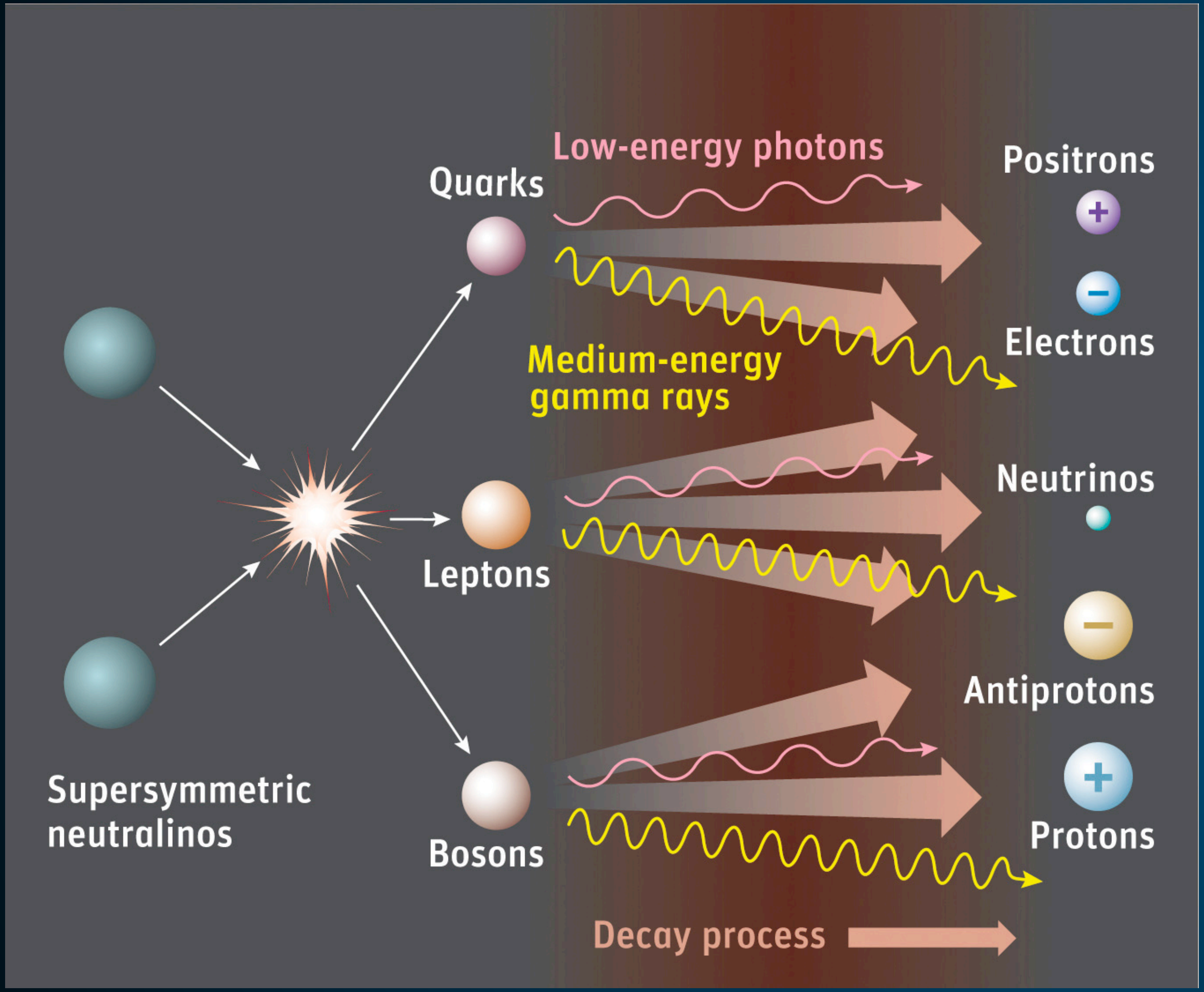
Dark Matter Complementarity

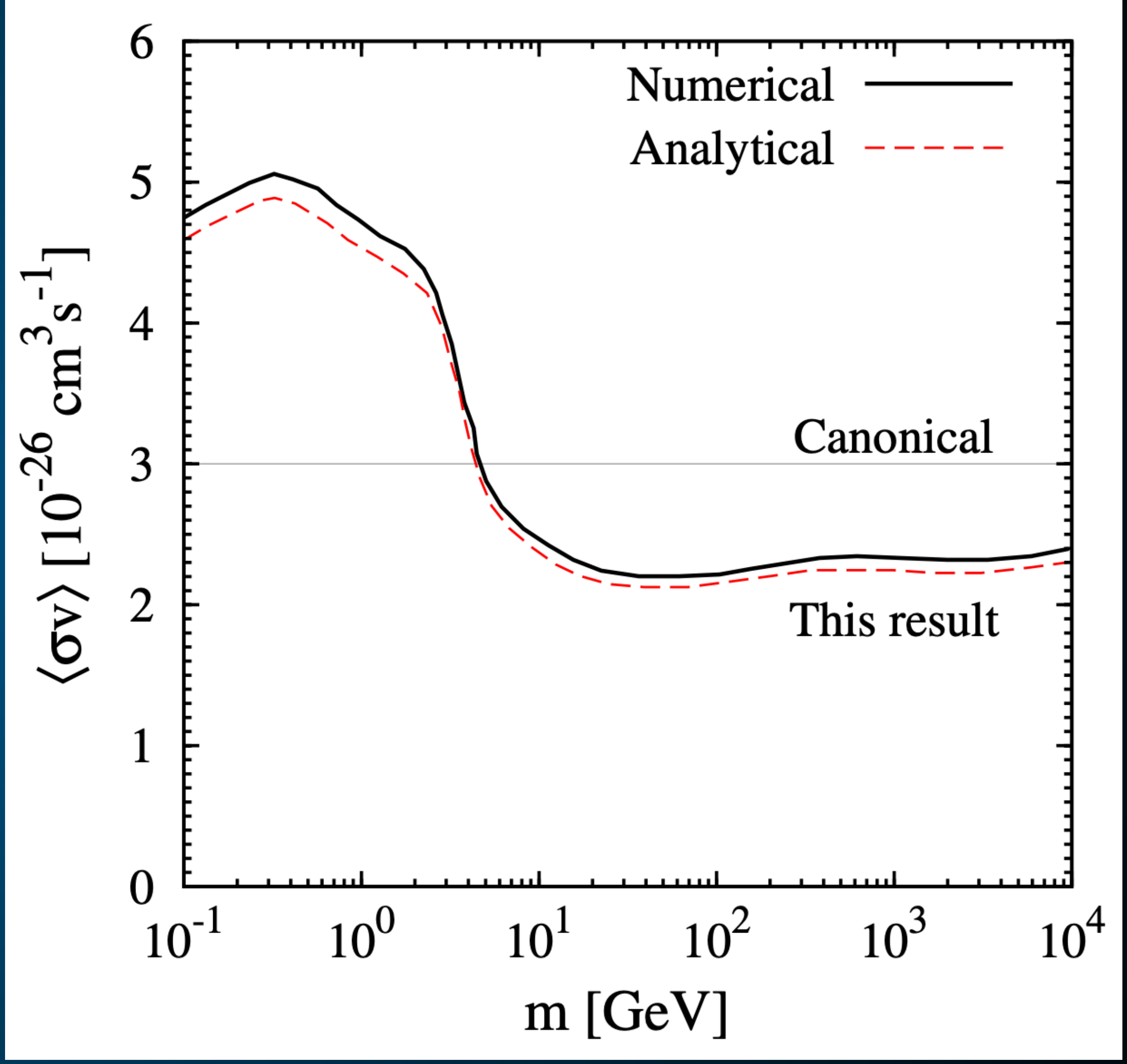
Gambit Collaboration (1705.07917)



Why Indirect Detection?

$$\langle \sigma v \rangle \sim 10^{-8}\ \mathrm{GeV}^{-2}\left(3\times10^{-28}\ \mathrm{GeV}^2\ \mathrm{cm}^2\right)\ 10^{10}\ \frac{\mathrm{cm}}{\mathrm{s}} = 3\times10^{-26}\ \frac{\mathrm{cm}^3}{\mathrm{s}}$$





Steigman et al. (1204.3622)

How Do We Know Anything About the Energy of the Signals?

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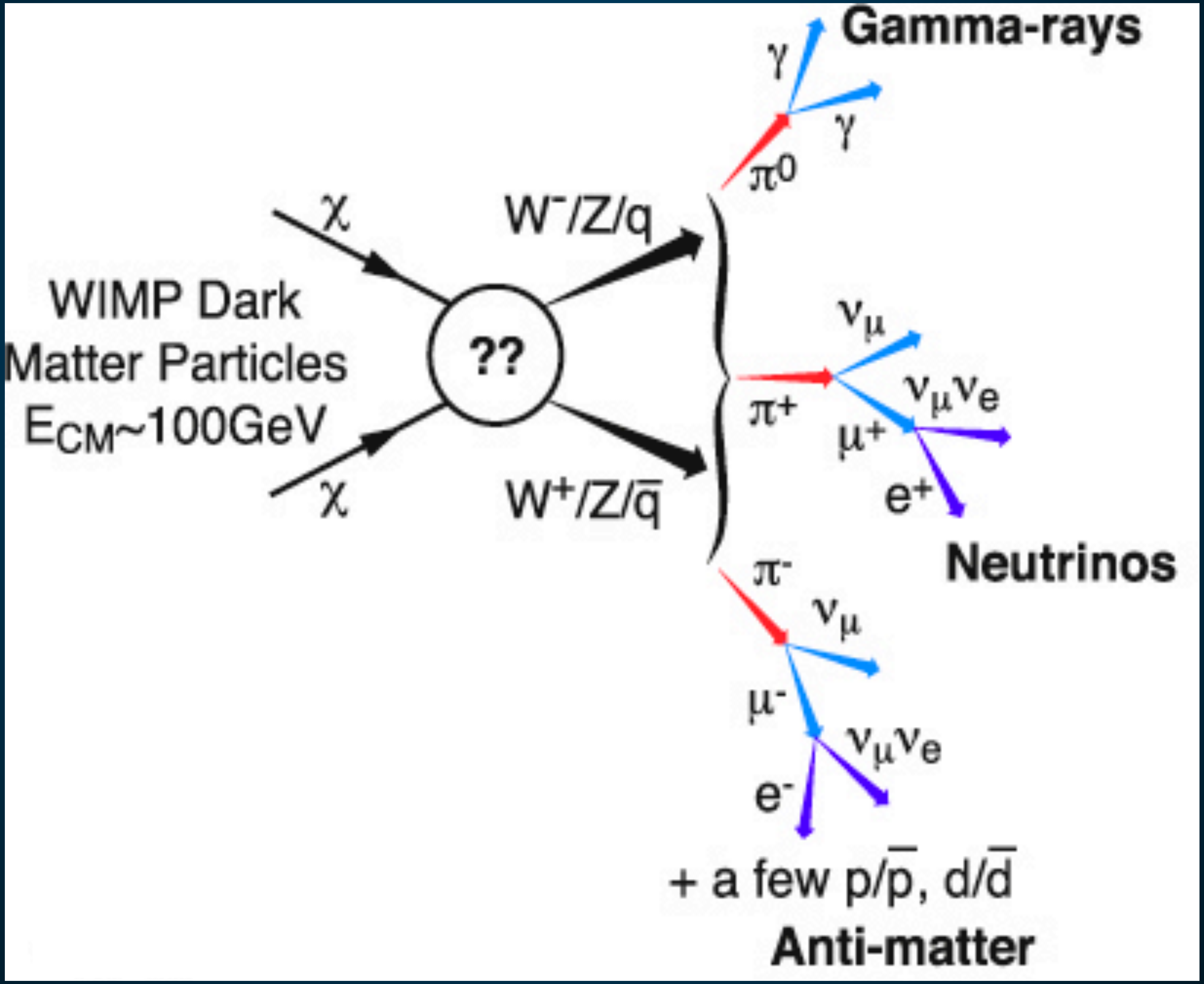

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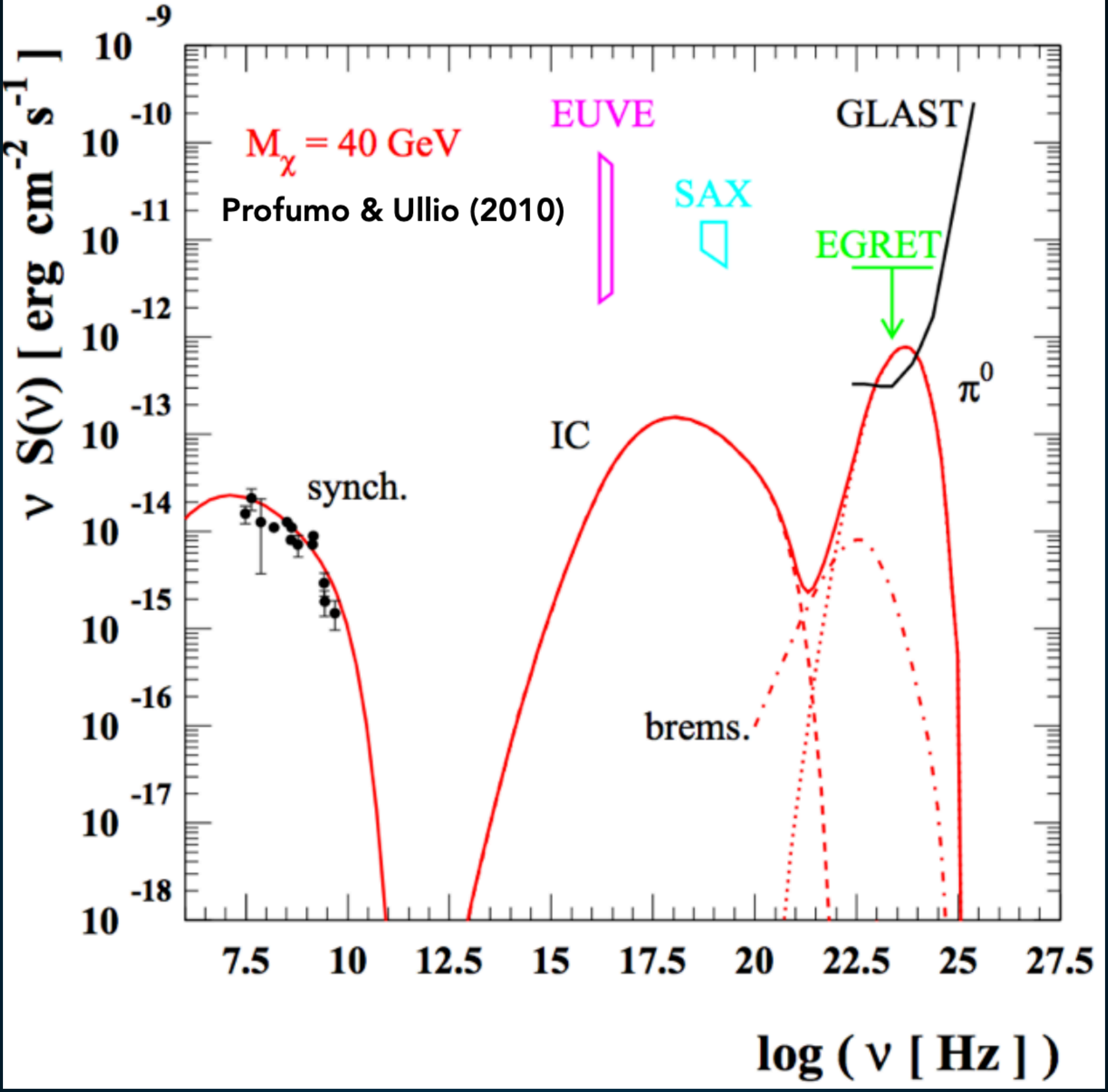

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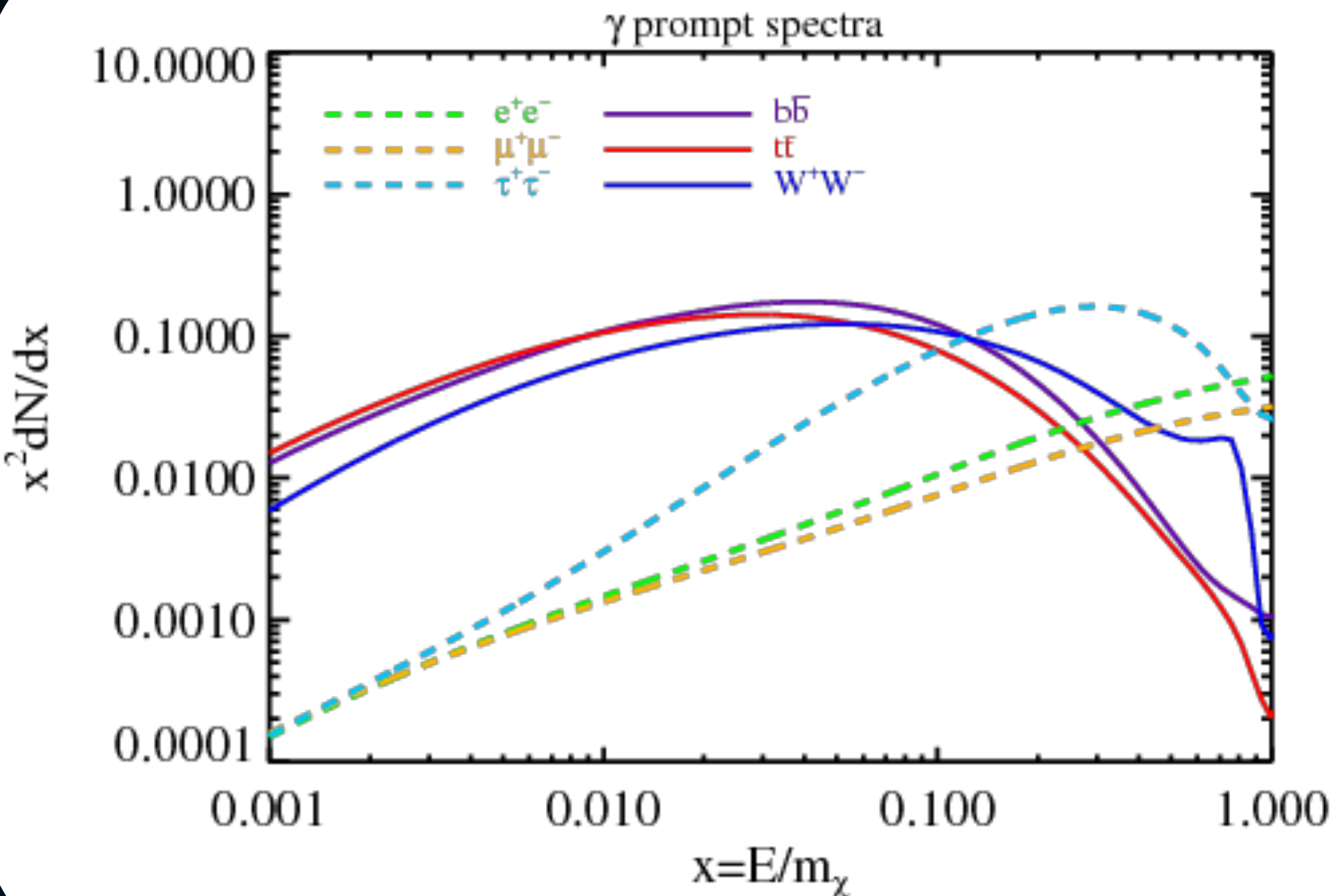
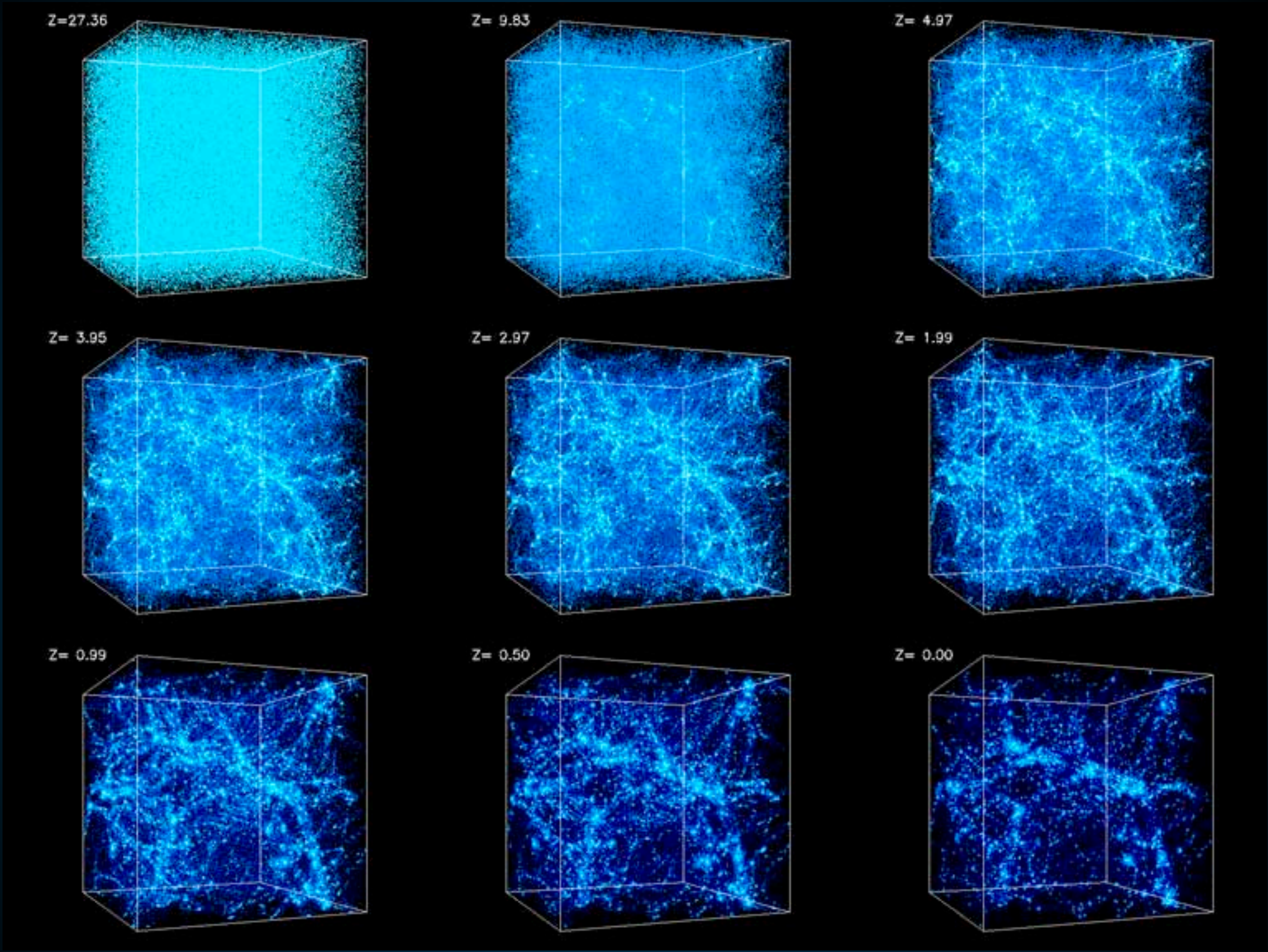


How Do We Know Anything About the Location of the Signals?



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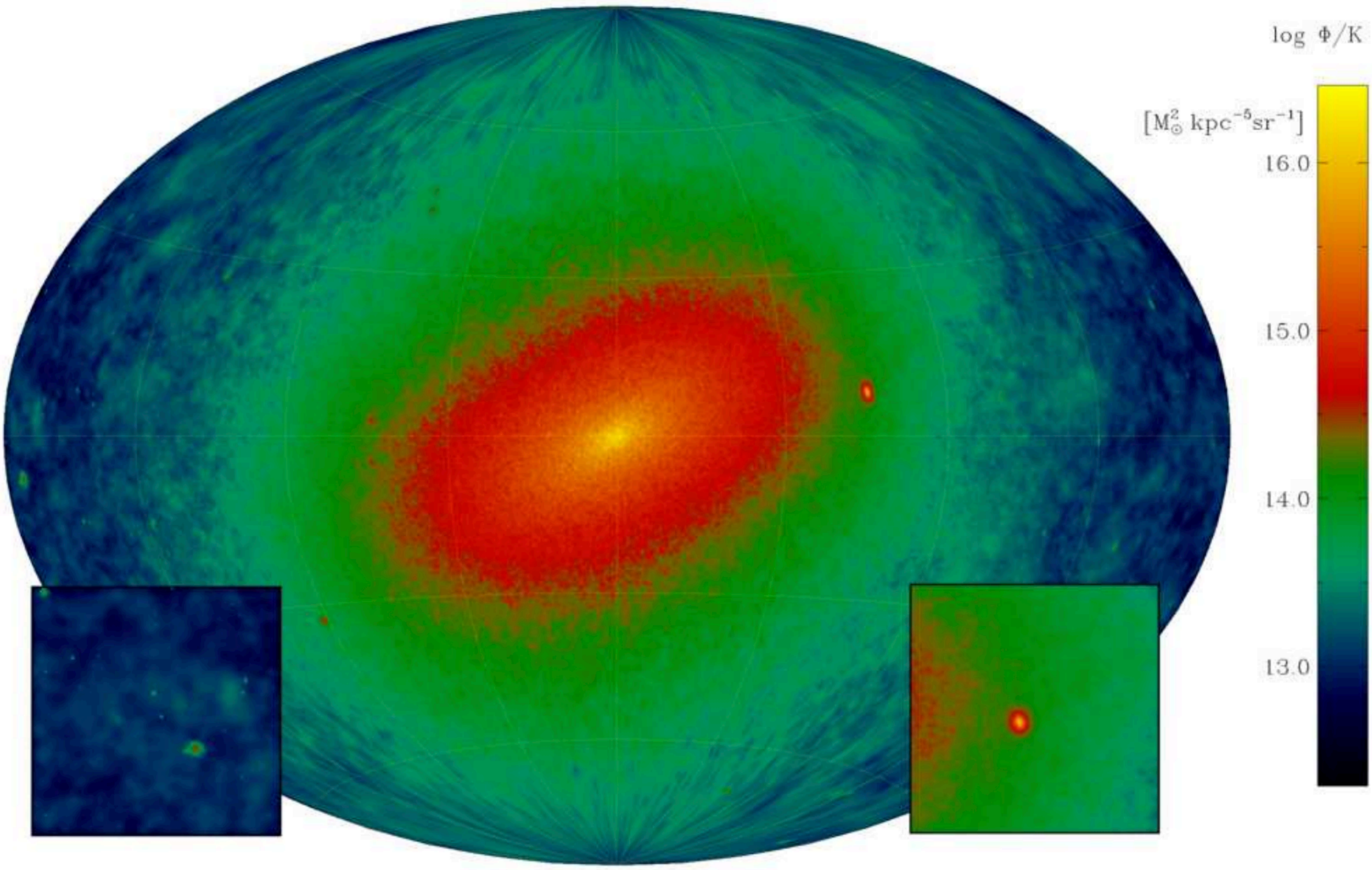
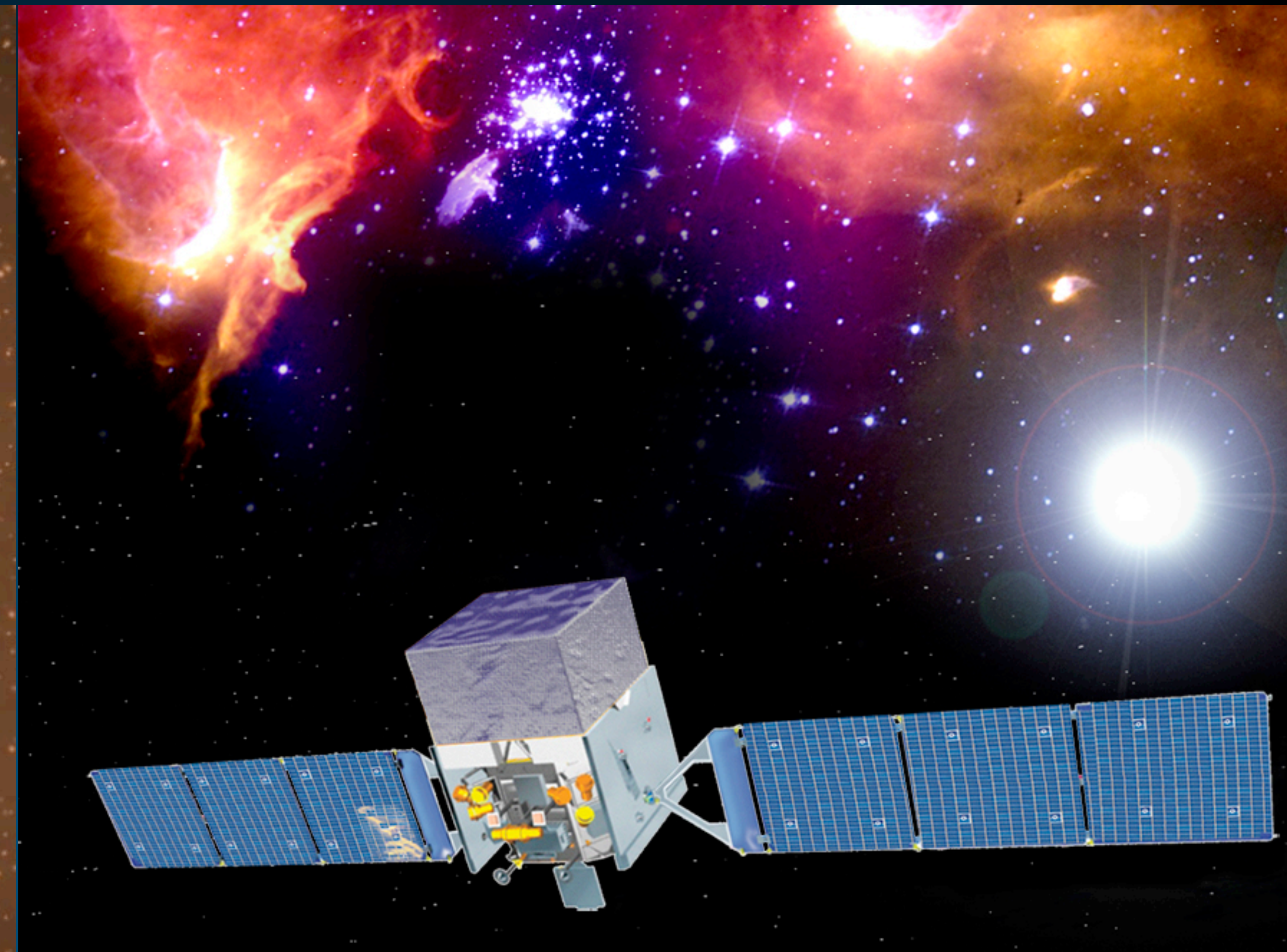
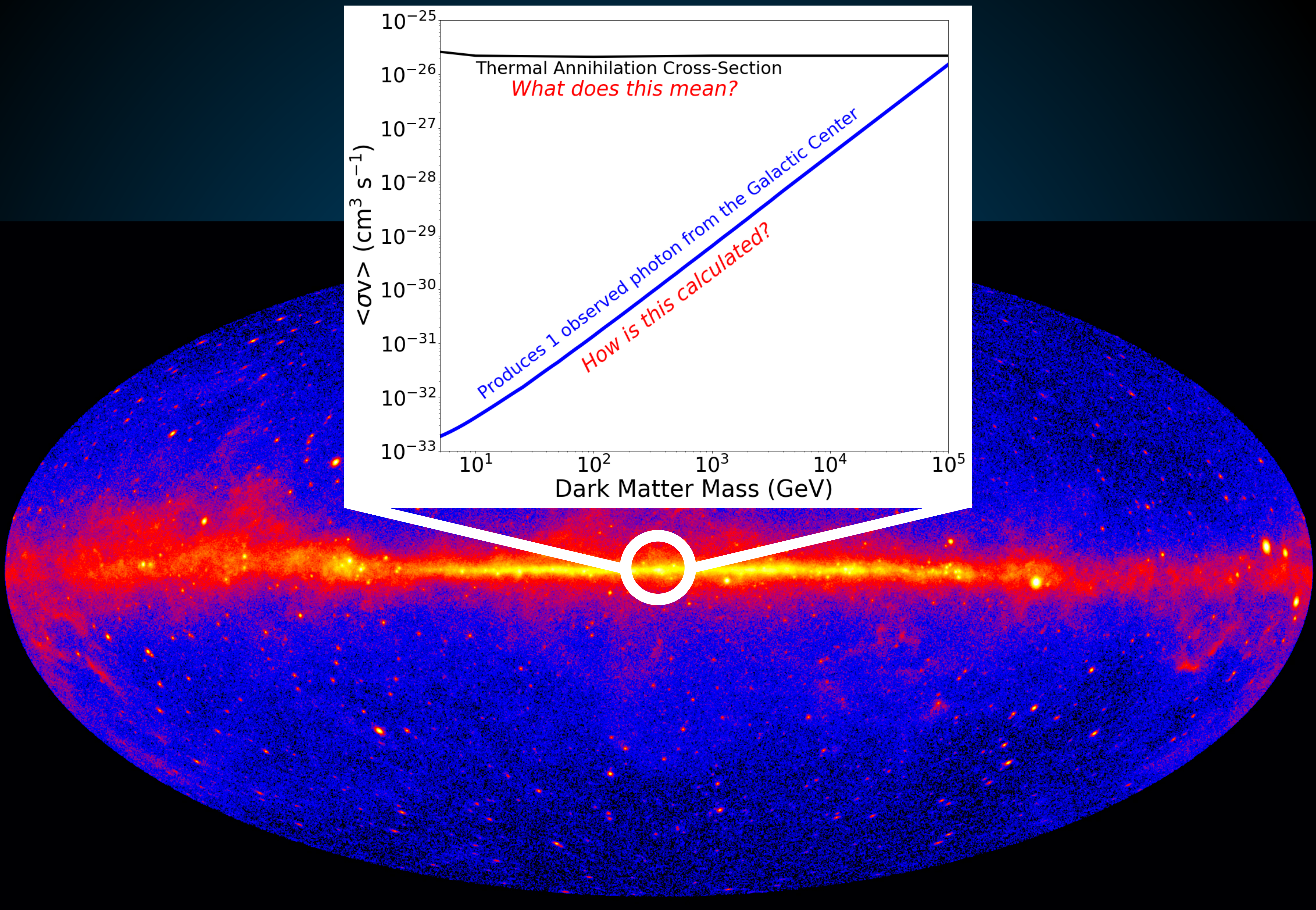


Why Indirect Detection?



- For a standard dark matter density profile, the annihilation rate within 5^{o} of the Galactic center is $\sim 1 \times 10^{38}$ ann s^{-1}.

- For a $1\ m^2$ instrument, this produces a flux of 10^{-4} ann s^{-1}.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What does this mean?
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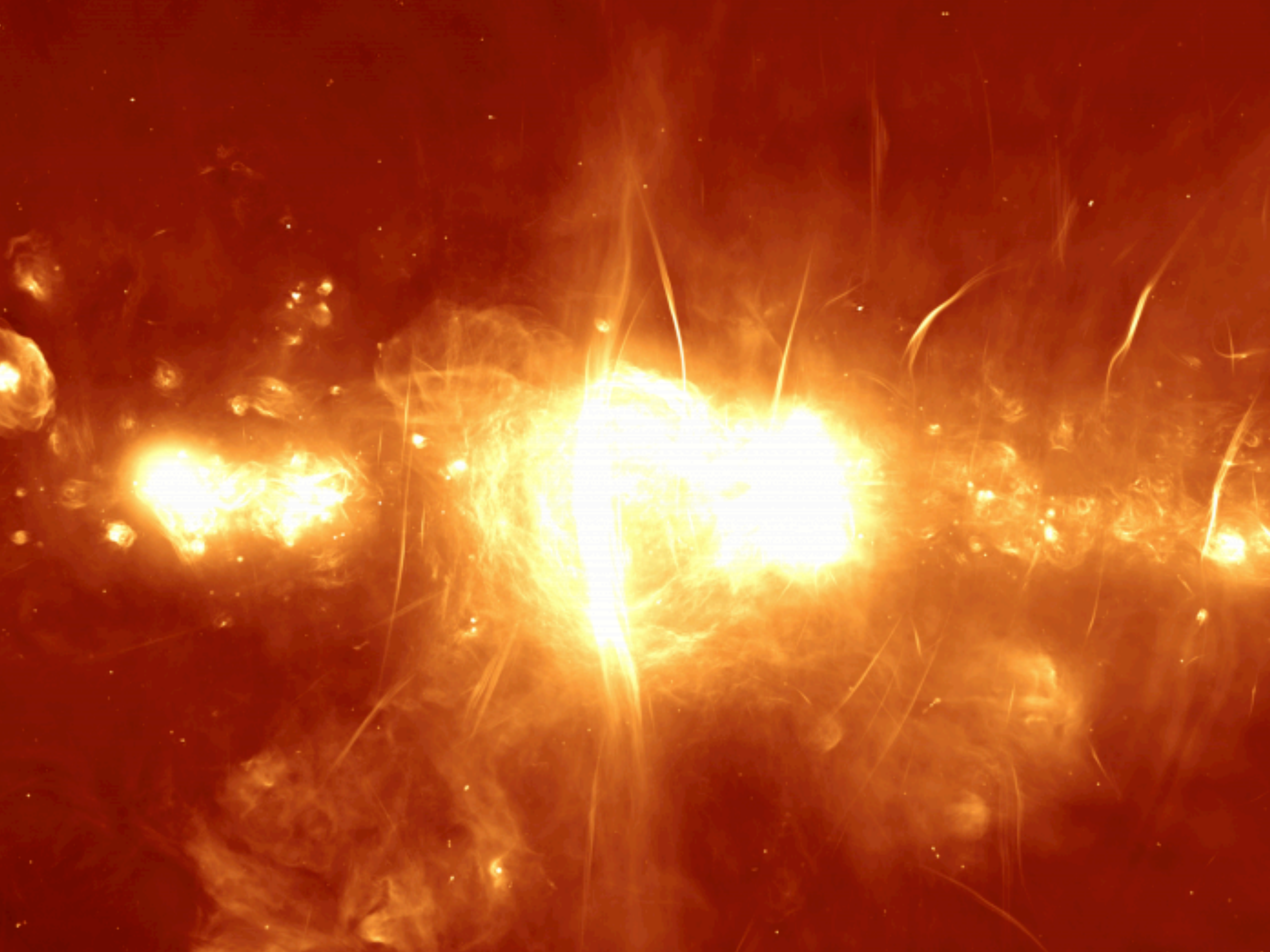
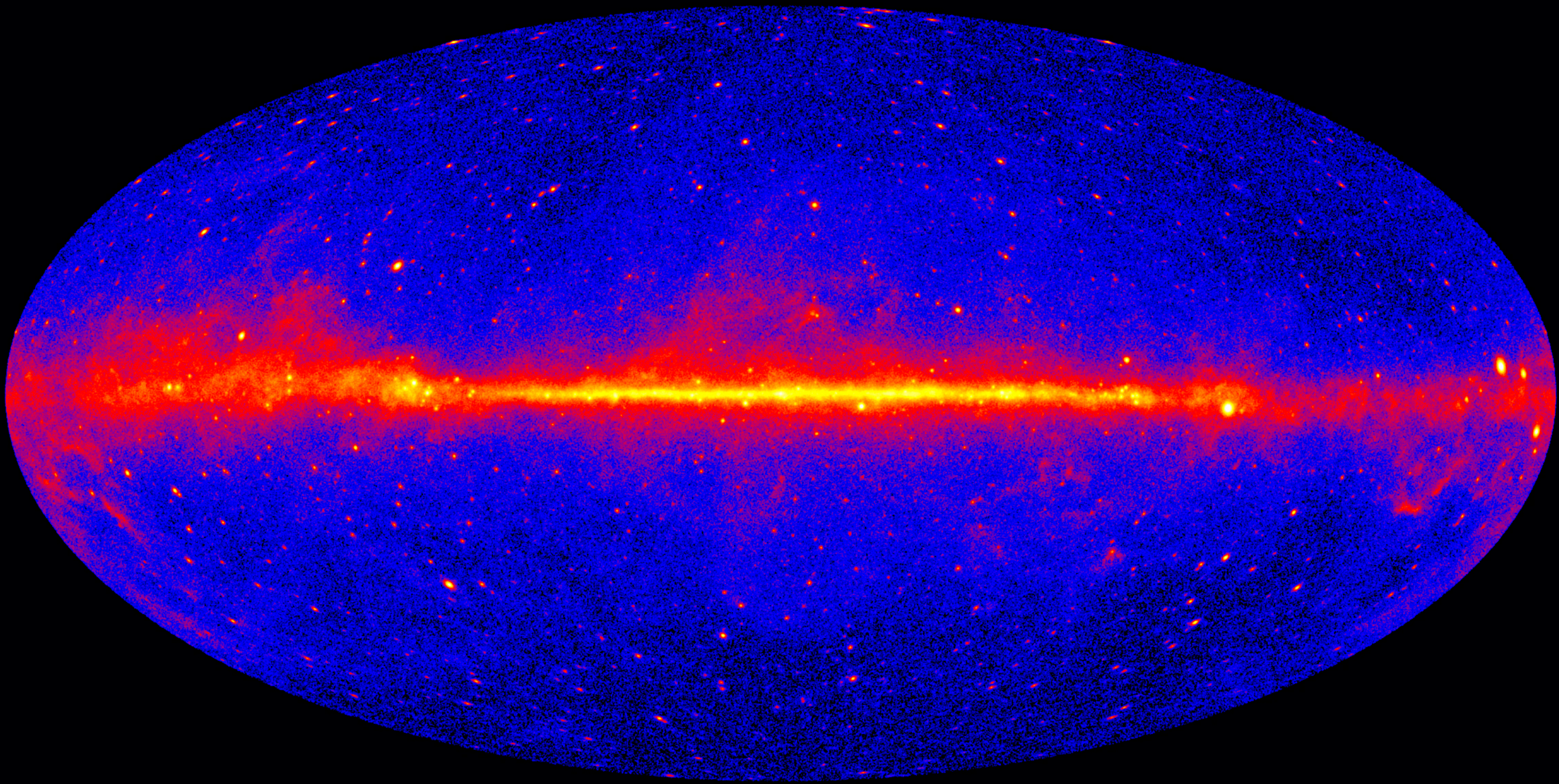
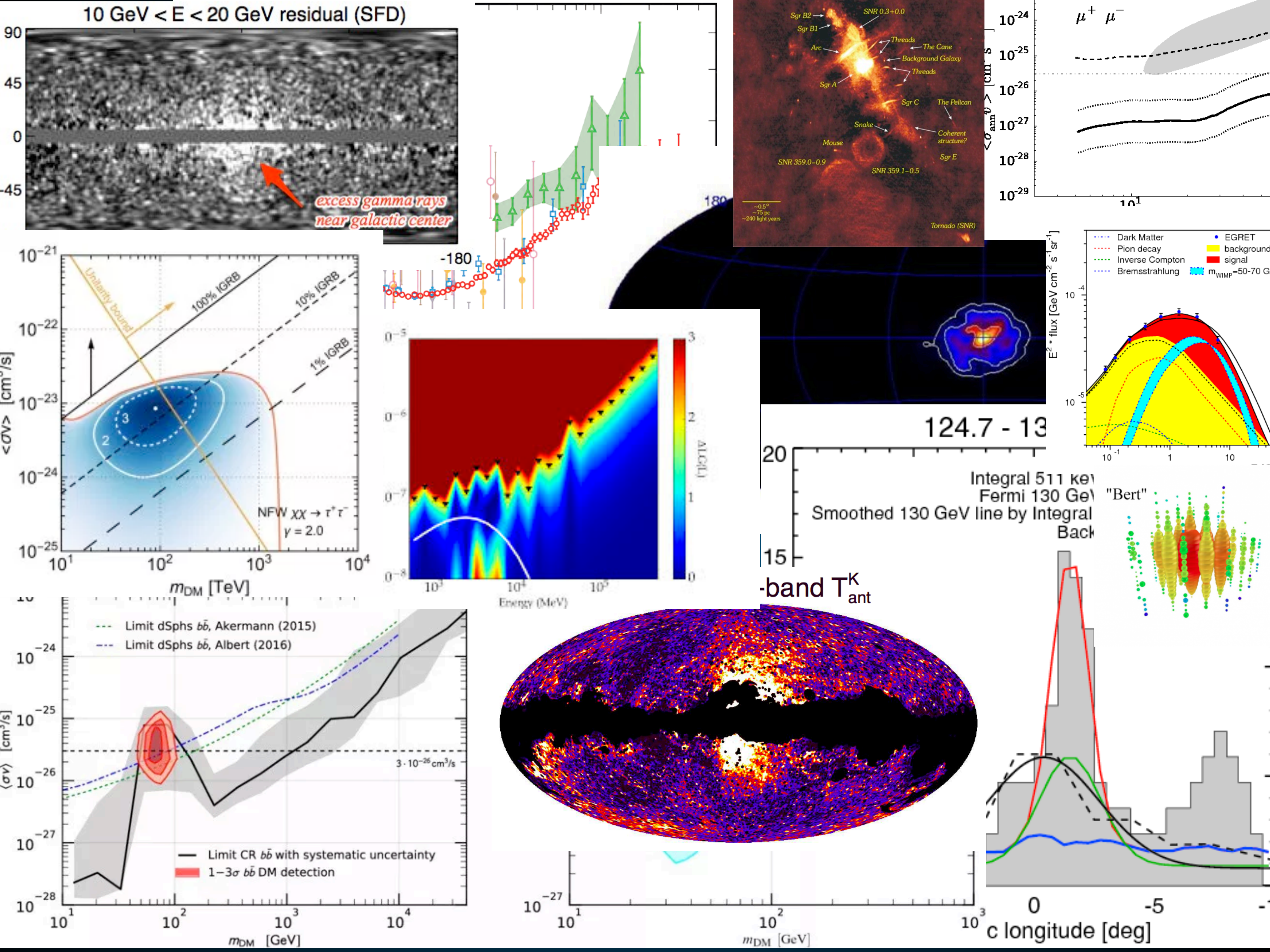
10⁻³⁰
10⁻³¹
10⁻³²
10⁻³³
10¹
10²
10³
10⁴
10⁵
Dark Matter Mass (GeV)

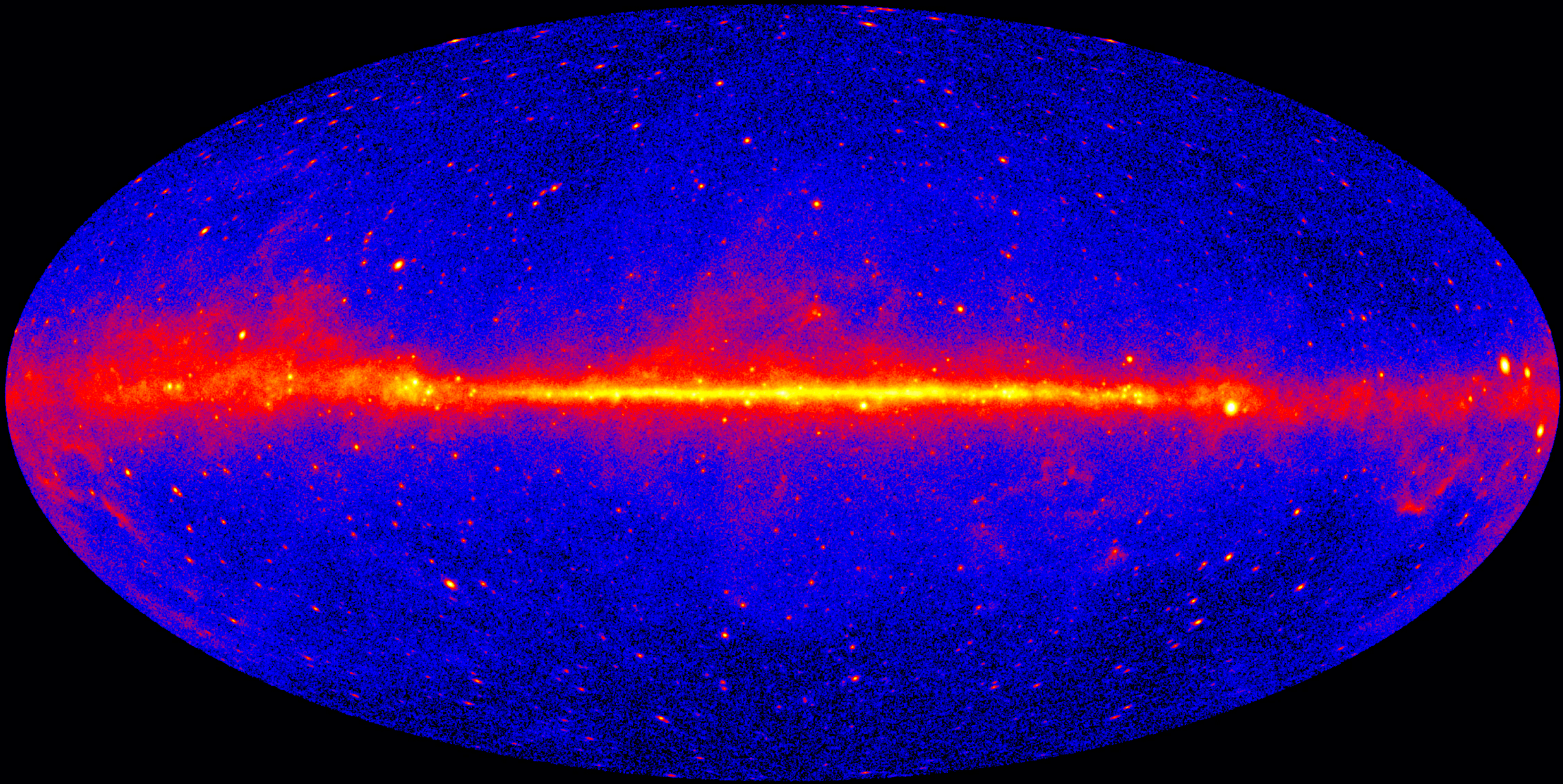






10 GeV < E < 20 GeV residual (SFD)
excess gamma rays near galactic center
Sgr B2
Sgr B1
SNR 0.3+0.0
Threads
The Cane
Arc
Background Galaxy
Sgr A
Sgr C
The Pelican
Snake
Coherent structure?
Mouse
Sgr E
SNR 359.0-0.9
SNR 359.1-0.5
Tornado (SNR)
$\mu^+ \mu^-$
Unitarity bound
100% IGRB
10% IGRB
1% IGRB
NFW $\chi\chi \to \tau^+\tau^-$
$\gamma = 2.0$
m_{DM} [TeV]
<σv> [cm³/s]
Energy (MeV)
ΔLG(L)
Dark Matter
Pion decay
Inverse Compton
Bremsstrahlung
EGRET
background
signal
m_{WIMP}=50-70 G
E^2 * flux [GeV cm^{-2} s^{-1} sr^{-1}]
124.7 - 13
Integral 511 keV
Fermi 130 GeV
Smoothed 130 GeV line by Integral
Back
"Bert"
-band T_{ant}^K
Limit dSphs $b\bar{b}$, Akermann (2015)
Limit dSphs $b\bar{b}$, Albert (2016)
$3 \cdot 10^{-26}$ cm³/s
Limit CR $b\bar{b}$ with systematic uncertainty
1−3σ $b\bar{b}$ DM detection
m_{DM} [GeV]
⟨σv⟩ [cm³/s]
c longitude [deg]

What produces the background?

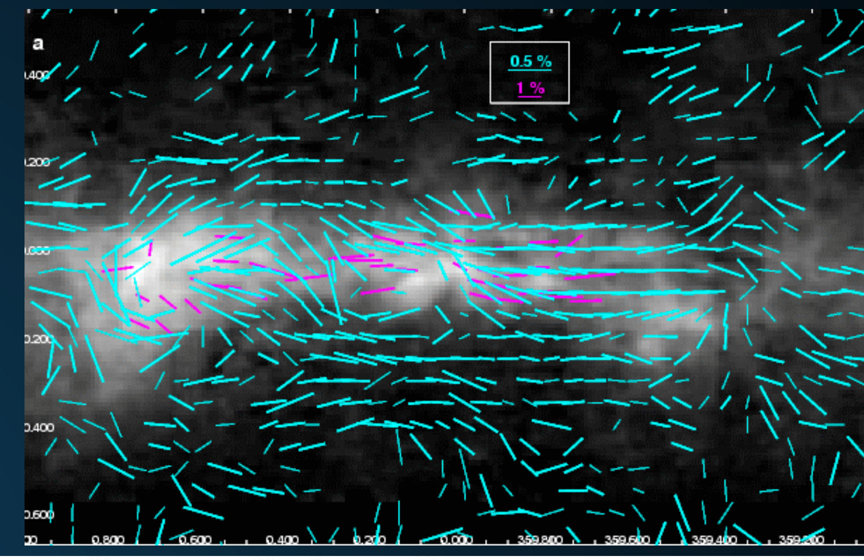


Start with a source of relativistic cosmic-rays

- Supernova Explosions
- Supernova Remnants
- Pulsars
- Shocks/Mergers

COSMIC-RAY ACCELERATION AND PROPAGATION

Start with a source of relativistic cosmic-rays



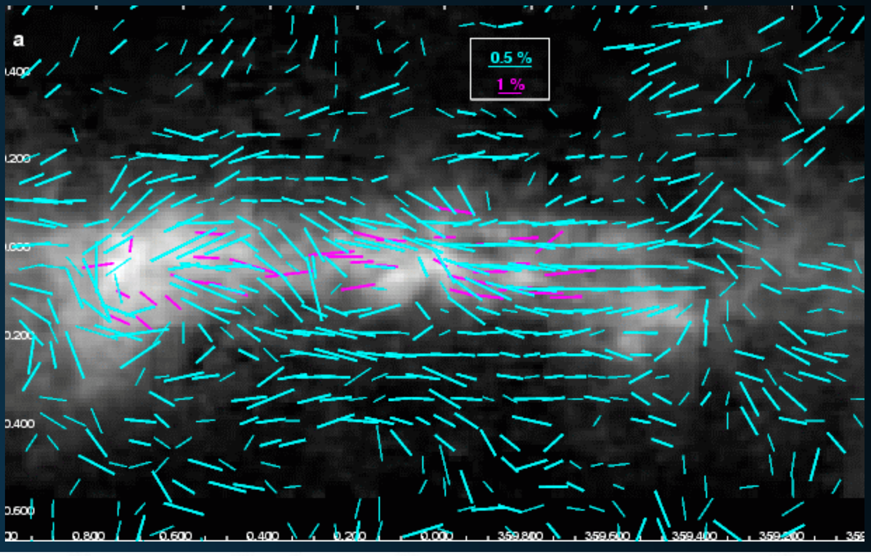
cosmic rays propagate

$$\frac{\partial \psi}{\partial t} = q(\vec{r},p) + \vec{\nabla}\cdot(D_{xx}\vec{\nabla}\psi - \vec{V}\psi) + \frac{\partial}{\partial p} p^2 D_{pp} \frac{\partial}{\partial p} \frac{1}{p^2}\psi - \frac{\partial}{\partial p}\left[\dot{p}\psi - \frac{p}{3}(\vec{\nabla}\cdot\vec{V})\psi\right] - \frac{1}{\tau_f}\psi - \frac{1}{\tau_r}\psi$$

Solved Numerically:
e.g. Galprop

- **If they propagate to Earth, can be detected:**
  - **AMS-02/PAMELA**
  - **CREAM/HEAT/CAPRICE**

Start with a source of relativistic cosmic-rays



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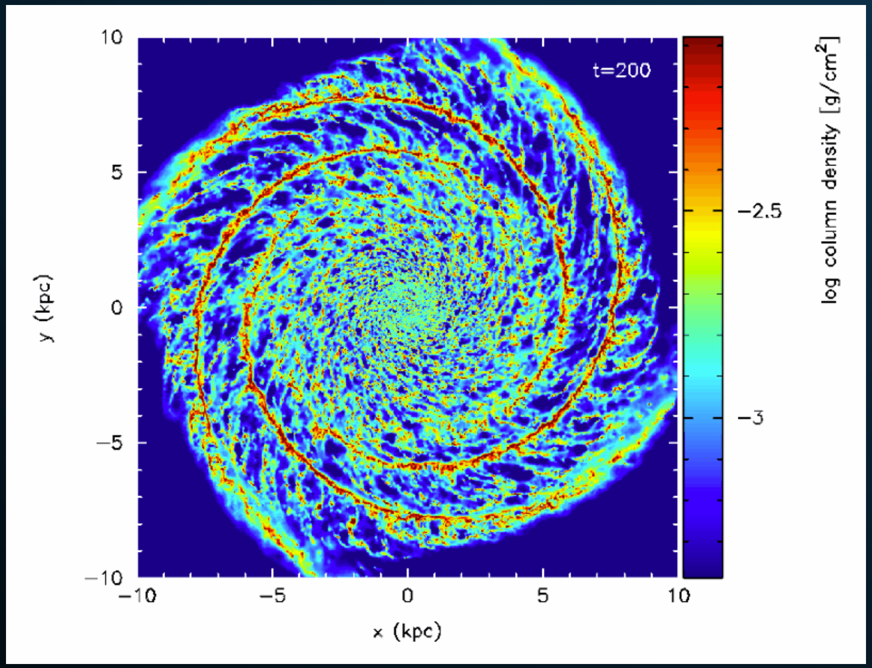
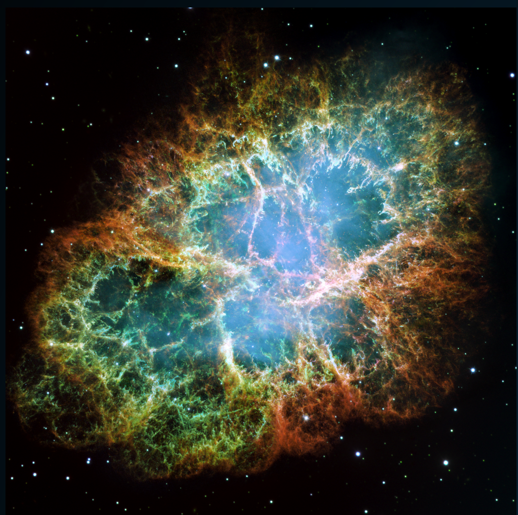
Gas/ISRF

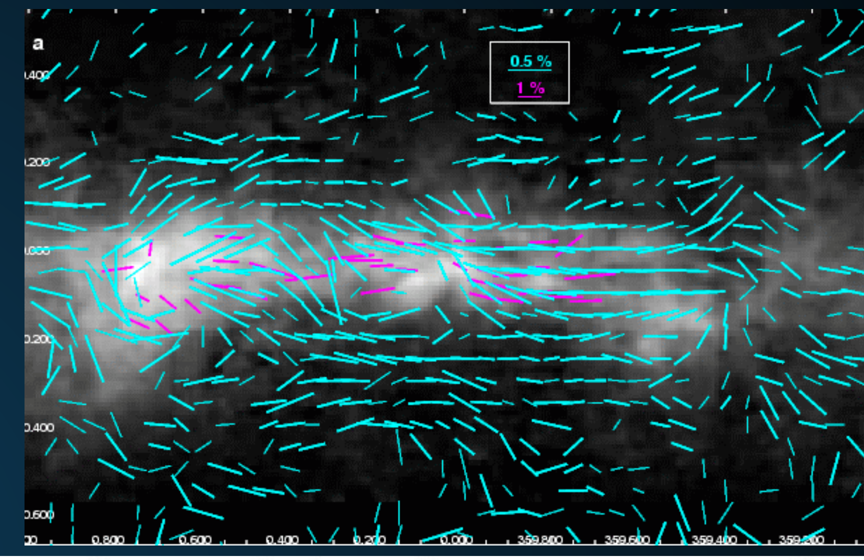


- **Alternatively can collide with Galactic gas or the interstellar radiation field.**

COSMIC-RAY ACCELERATION AND PROPAGATION



Start with a source of relativistic cosmic-rays



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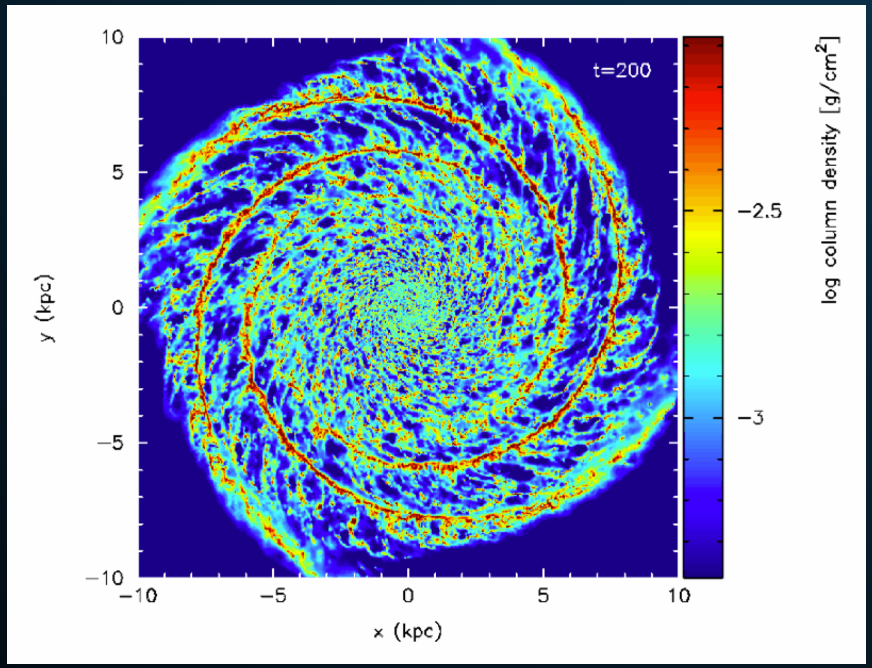
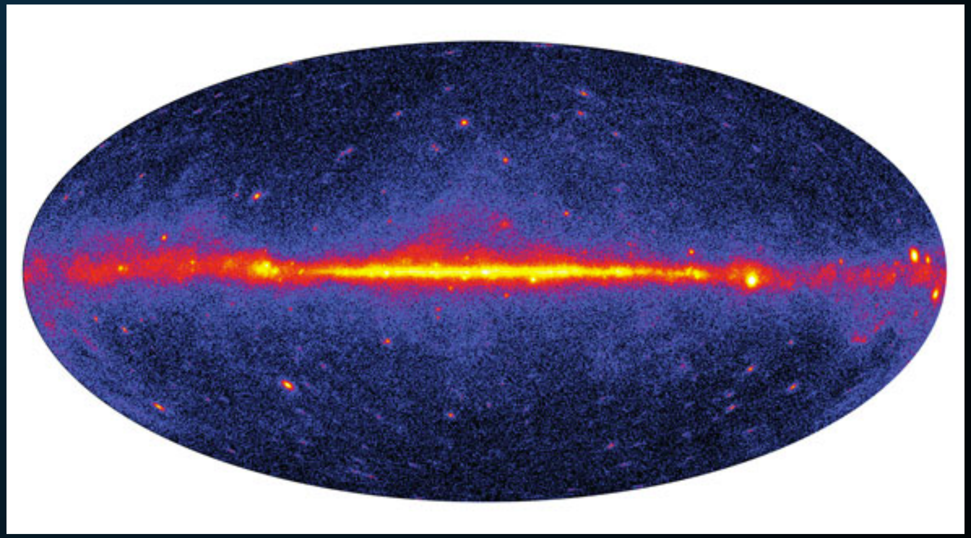
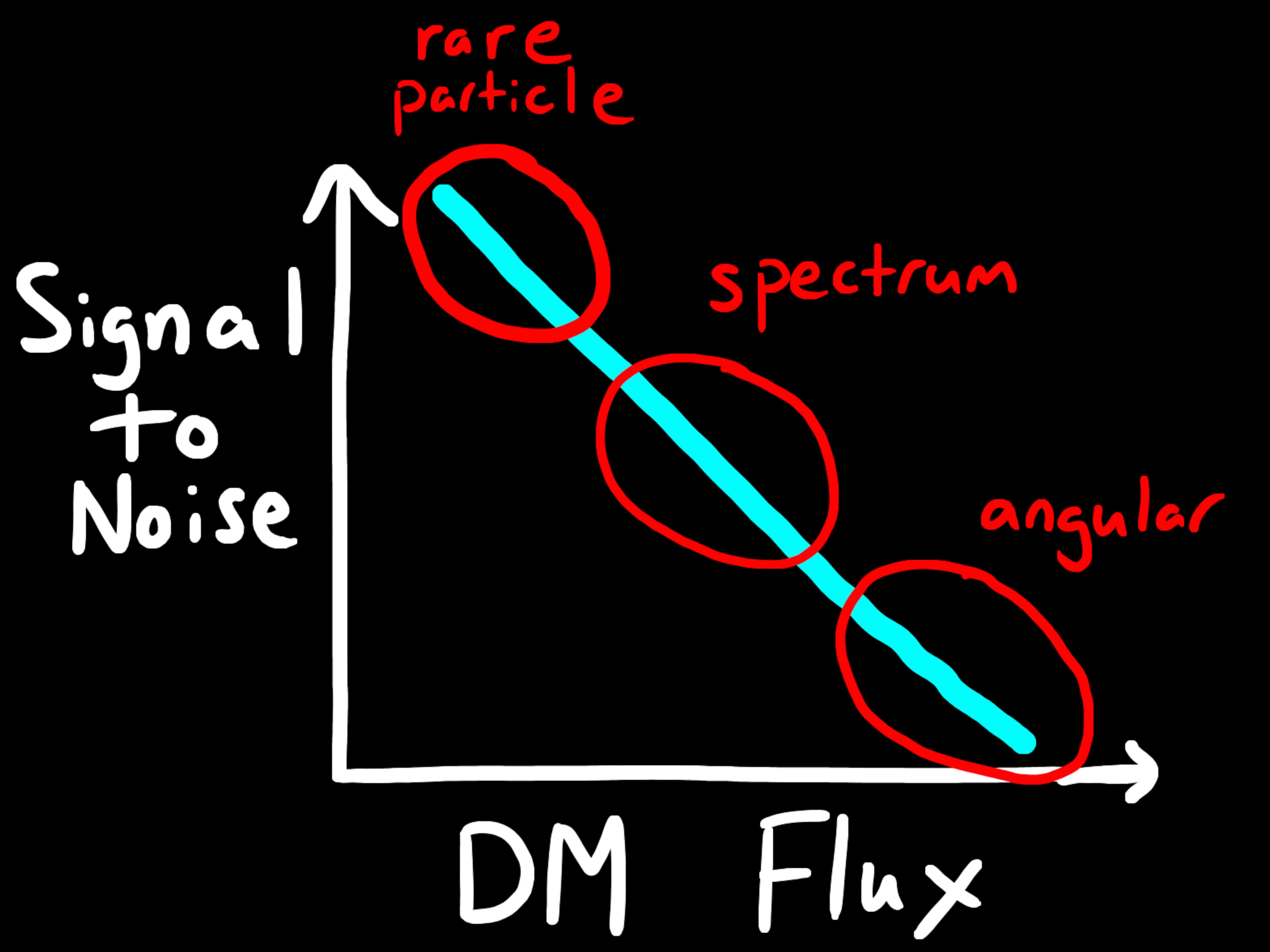




The Techniques

- **Three Methods to Separate Dark Matter Signals:**
  - **Rare Particle Detection**
  - **Spectral Features**
  - **Angular Mapping**


rare particle
spectrum
angular
Signal to Noise
DM Flux

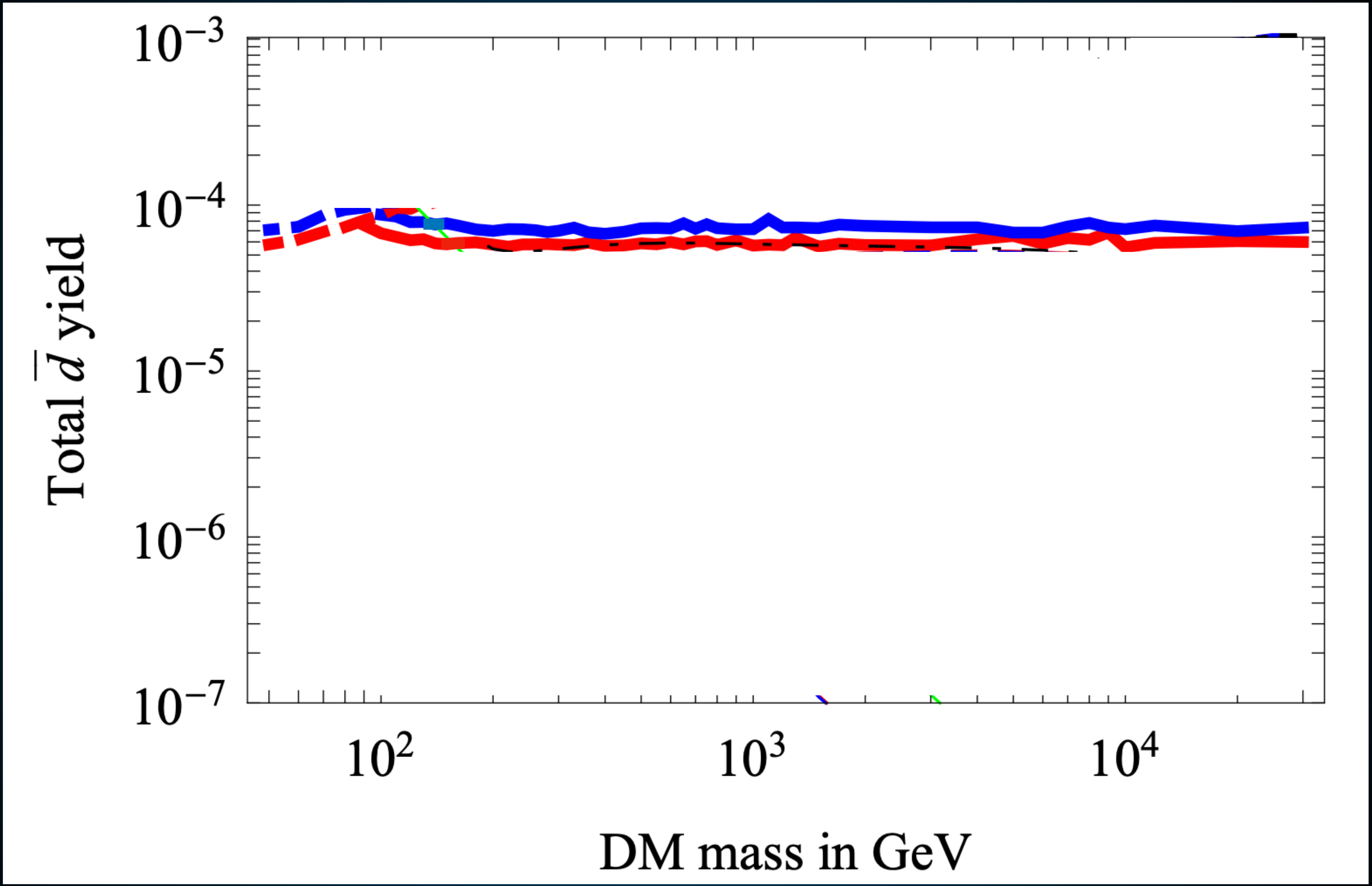
Rare Particle Detection

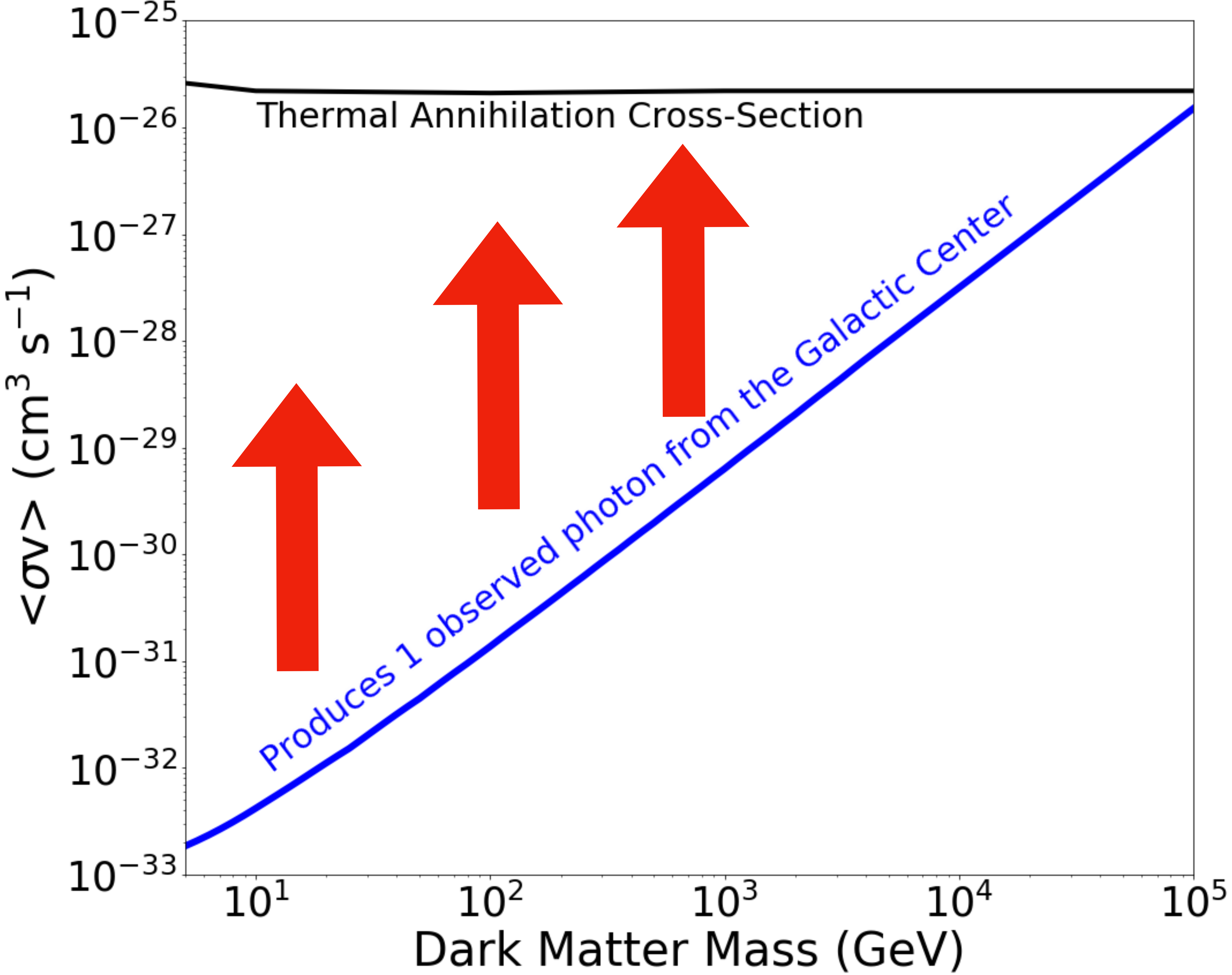
Exploiting the fact that the universe is mostly matter

Rare Particle Detection

Kadastik et al. (2009; 0908.1578)

Exploiting the fact that the universe is mostly matter





10^{-25}
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Dark Matter Mass (GeV)

Rare Particle Detection

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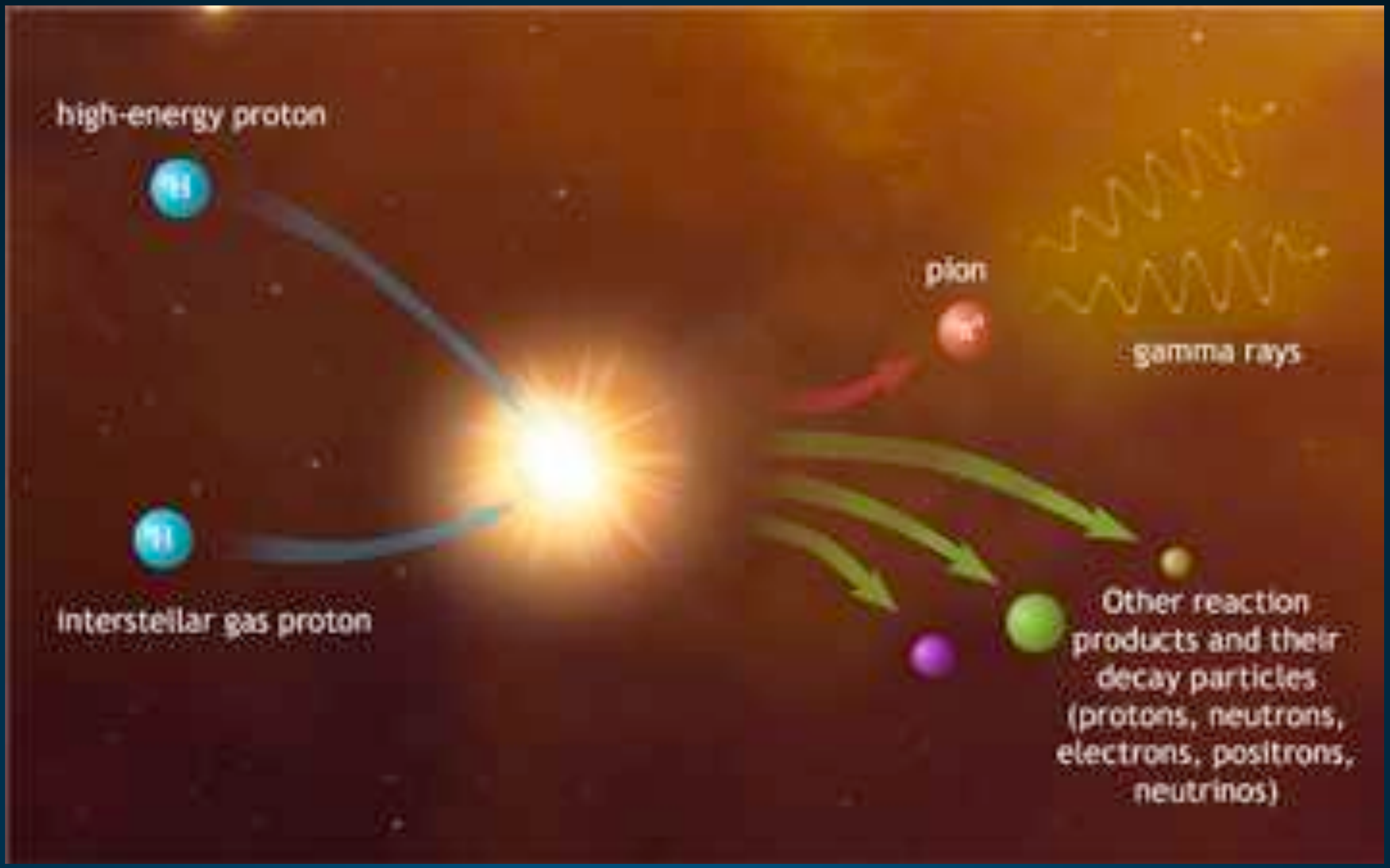


$$p + p \longrightarrow p + p + p + \bar{p} + n + \bar{n}$$

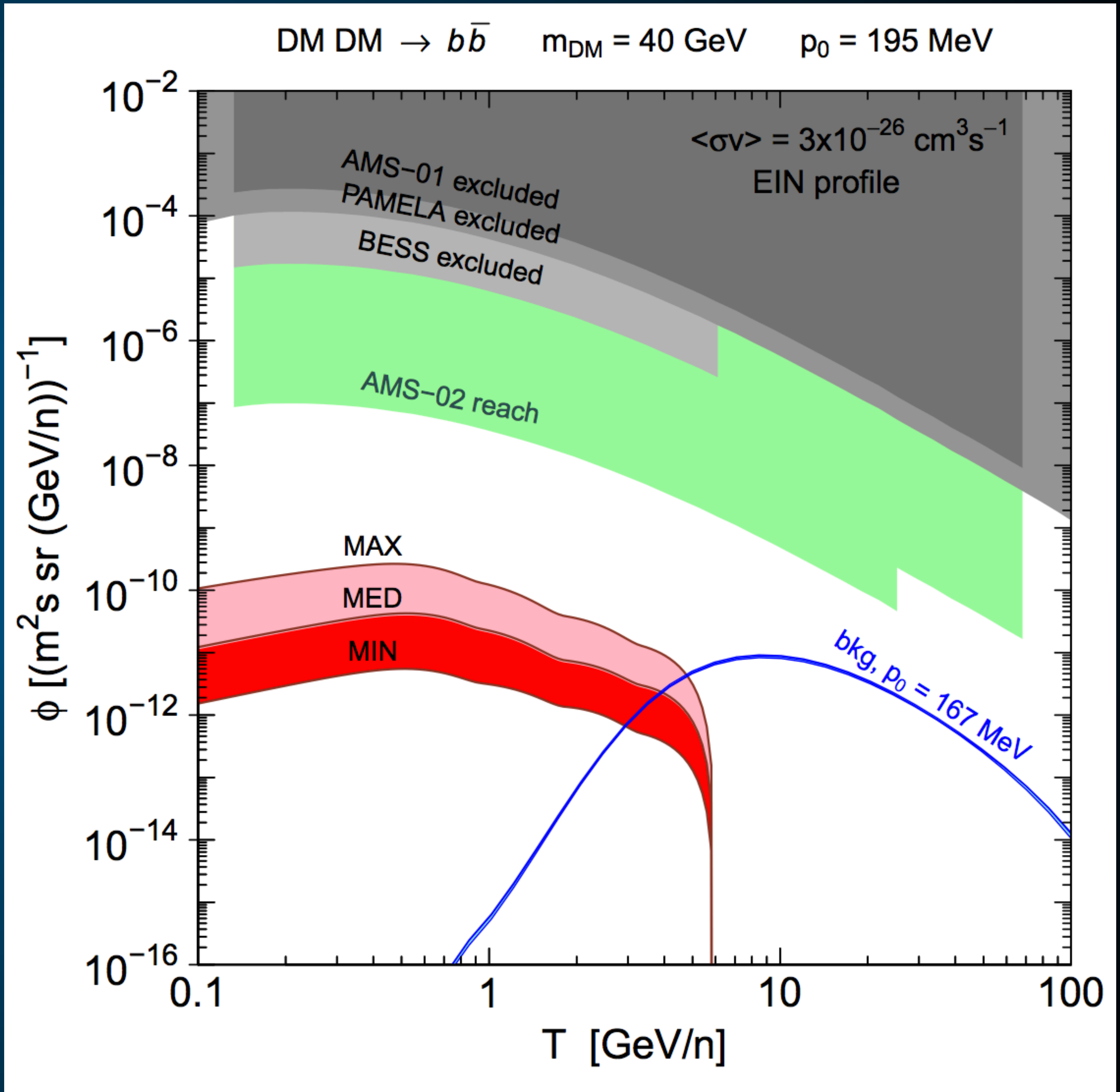
- **Kinematic threshold makes background negligible below 10 GeV.**

Rare Particle Detection

Exploiting the fact that the universe is mostly matter

$$\chi + \chi \longrightarrow p + \bar{p} + n + \bar{n}$$

- **Dark matter annihilation occurs in the lab frame.**
- **Dark matter signal dominate at low energies.**
- **Energies can't change due to propagation!**

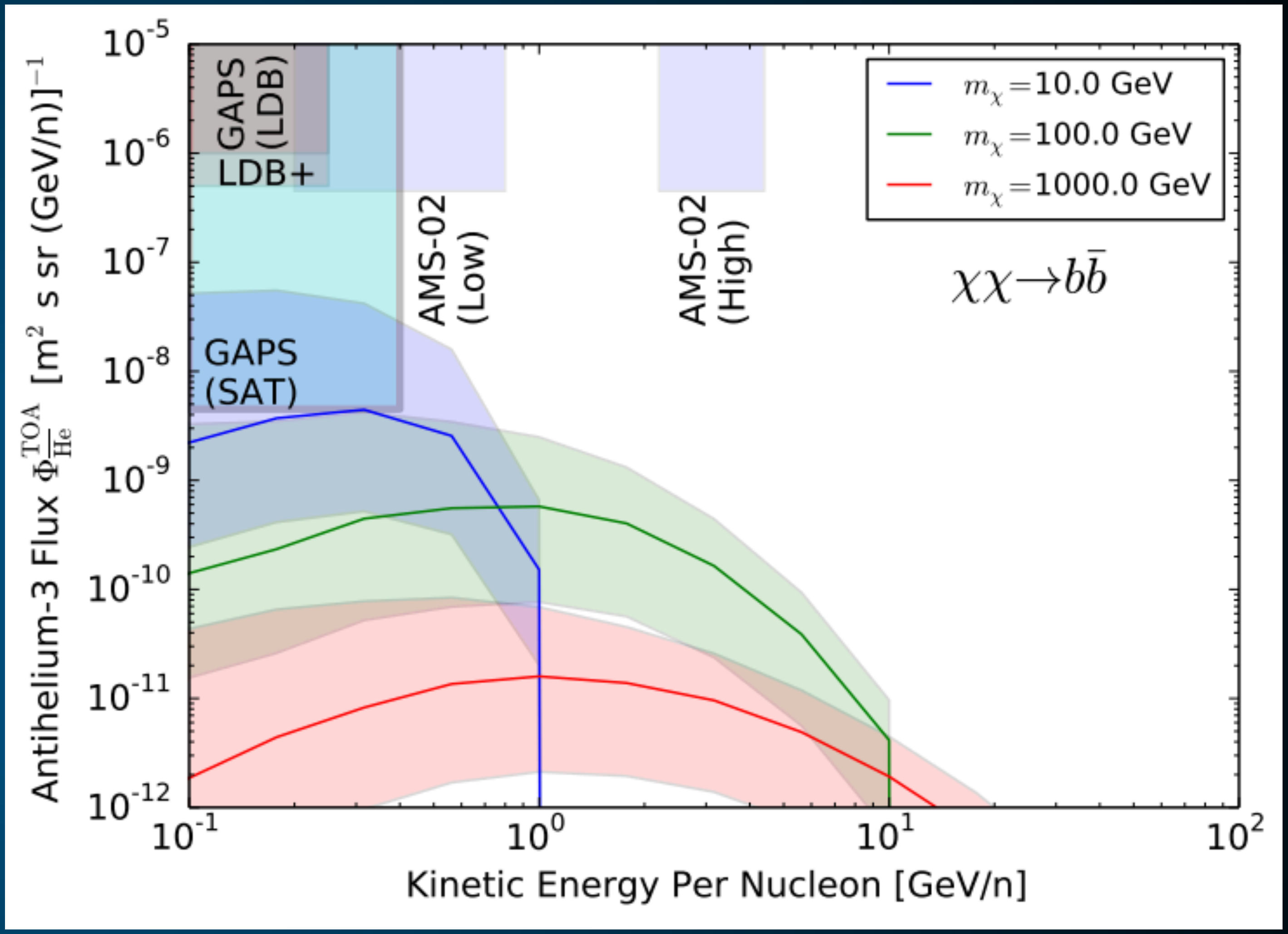


Cirelli et al. (1401.4017)

Rare Particle Detection

Exploiting the fact that the universe is mostly matter

- **Dark matter signal is even more dominant in the case of anti-Helium.**
- **Depending on coupling, anti-Helium signal does not need to be much smaller.**



Carlson, Coogan, TL, Profumo, Ibarra & Wild (2014; 1401.2461)

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.

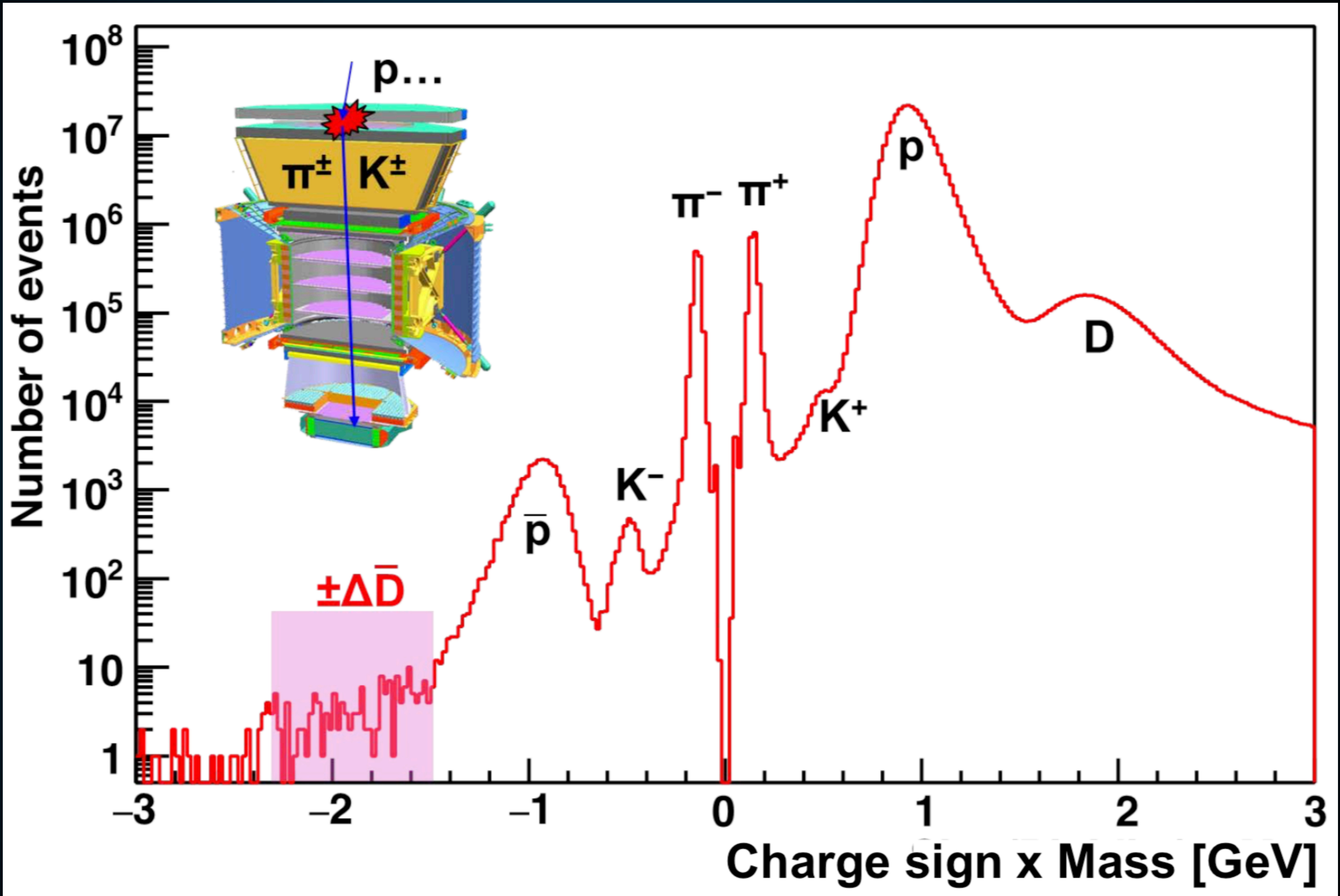
Currently (having used 50 million core hours to generate 7 times more simulated events than measured events and having found no background events from the simulation), our best evaluation of the probability of the background origin for the eight $\overline{\mathrm{He}}$ events is less than 3×10^{-8}.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

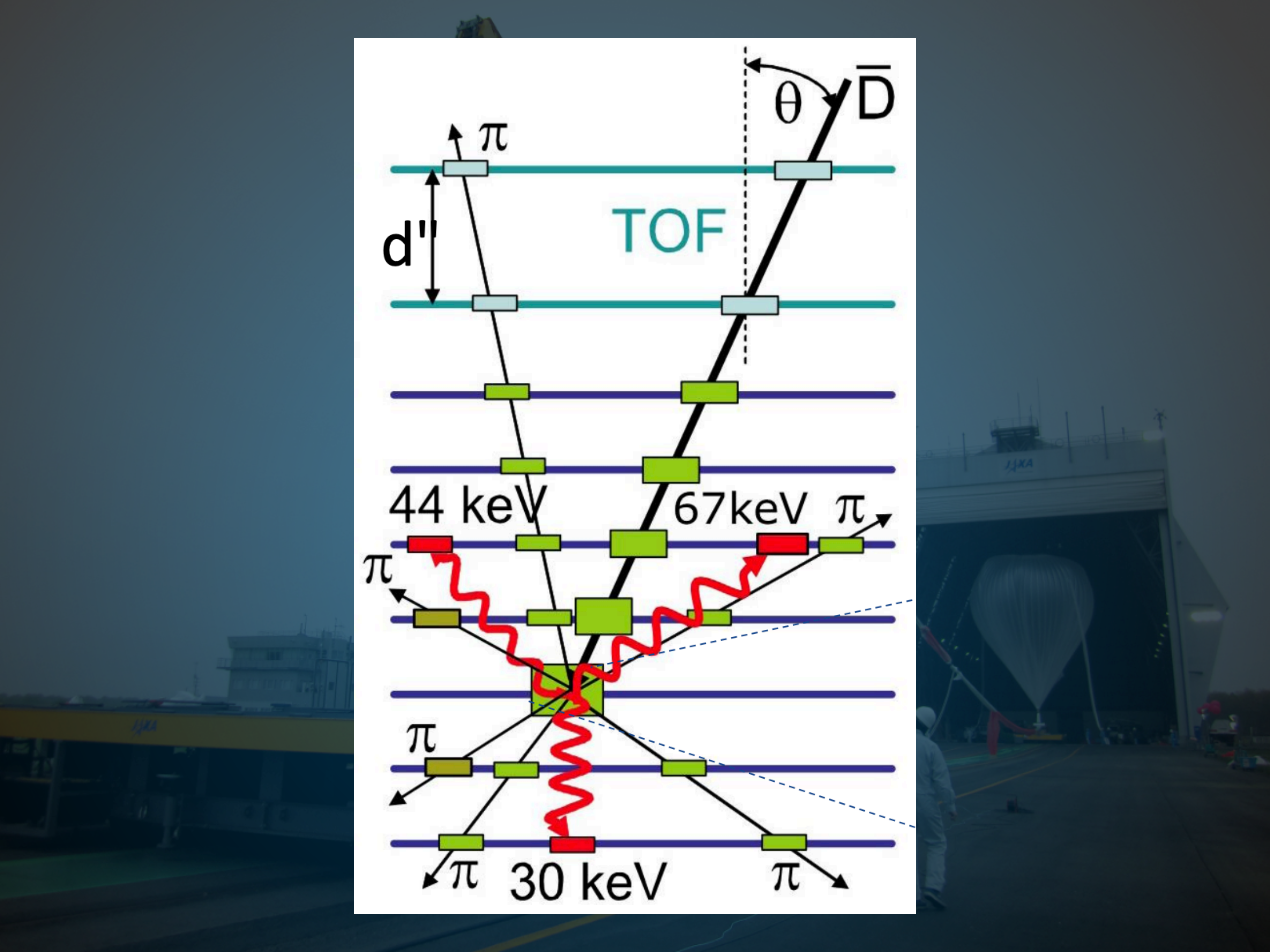
slide from Sam Ting

Rare Particle Detection

Exploiting the fact that the universe is mostly matter




JAXA

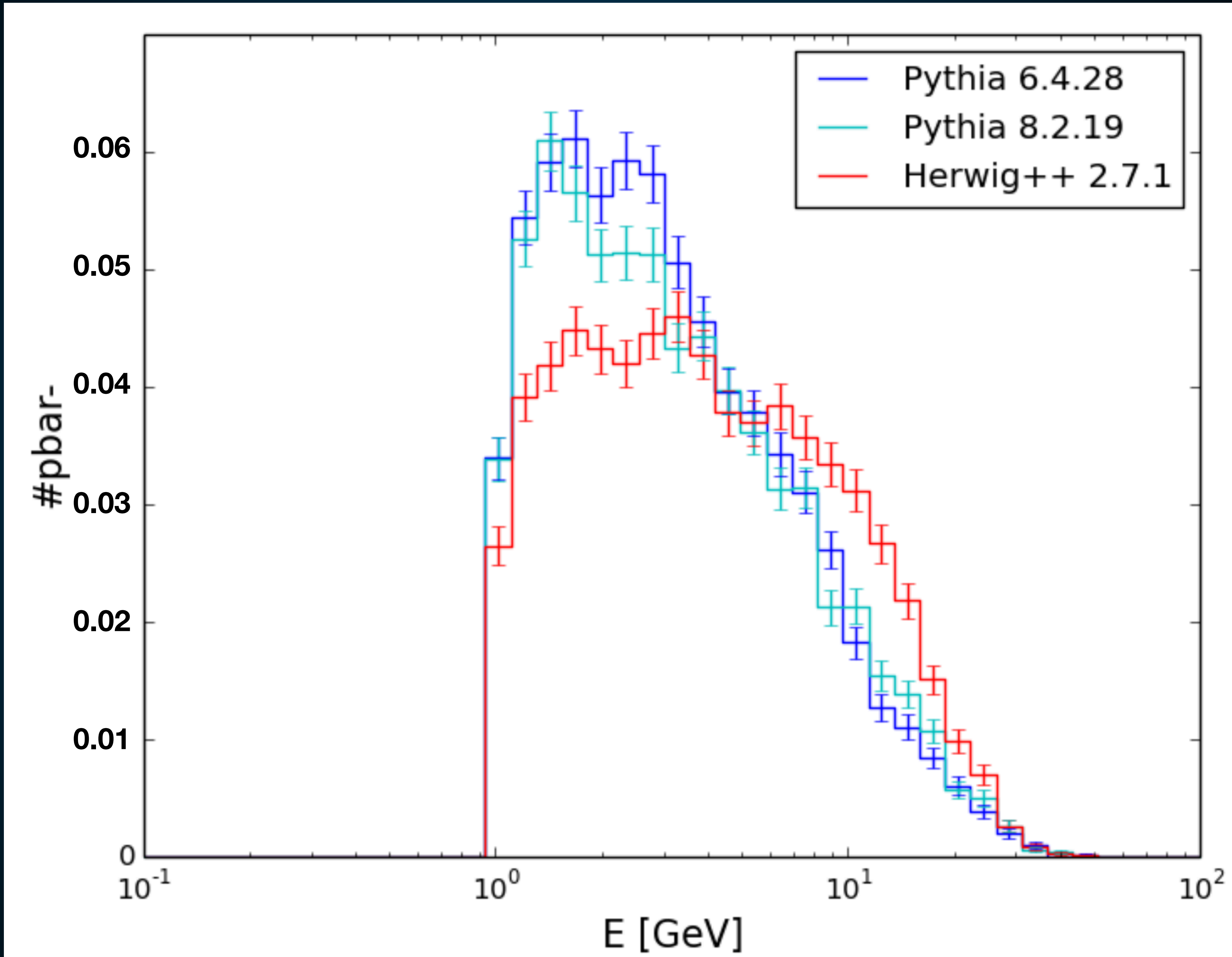


θ
D̄
π
d''
TOF
44 keV
67keV
π
π
π
π
π
30 keV

Spectral Features

Joachim Kip (2017)

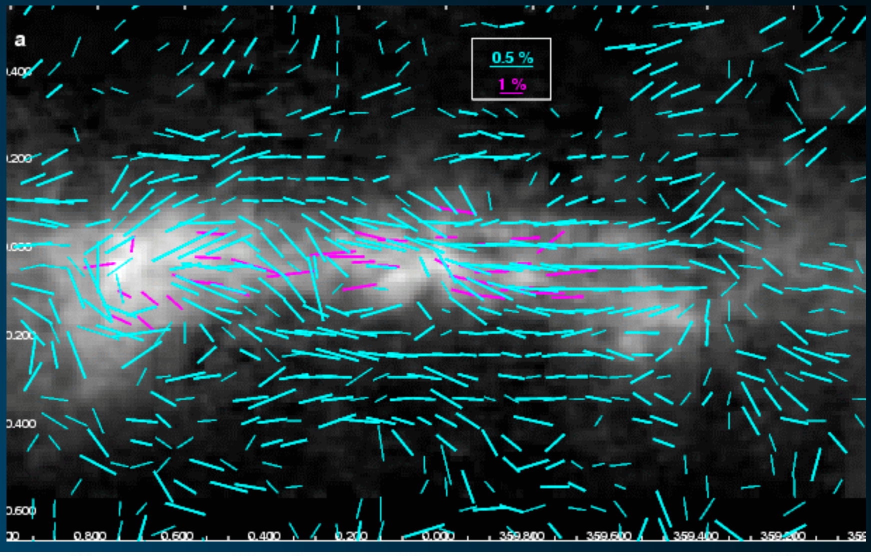
Things that go bump in the night



Spectral Features

Things that go bump in the night

Start with a source of relativistic cosmic-rays

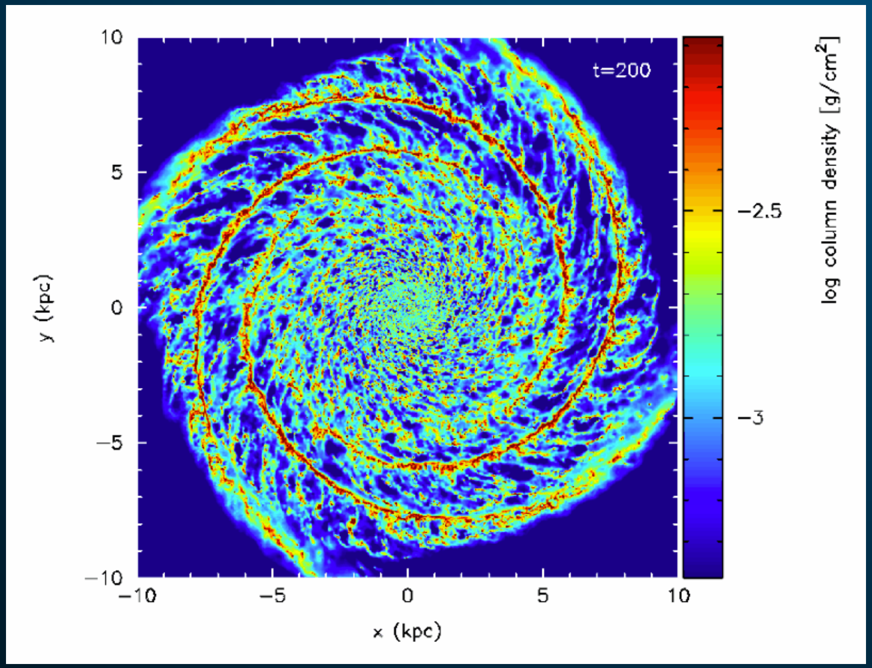


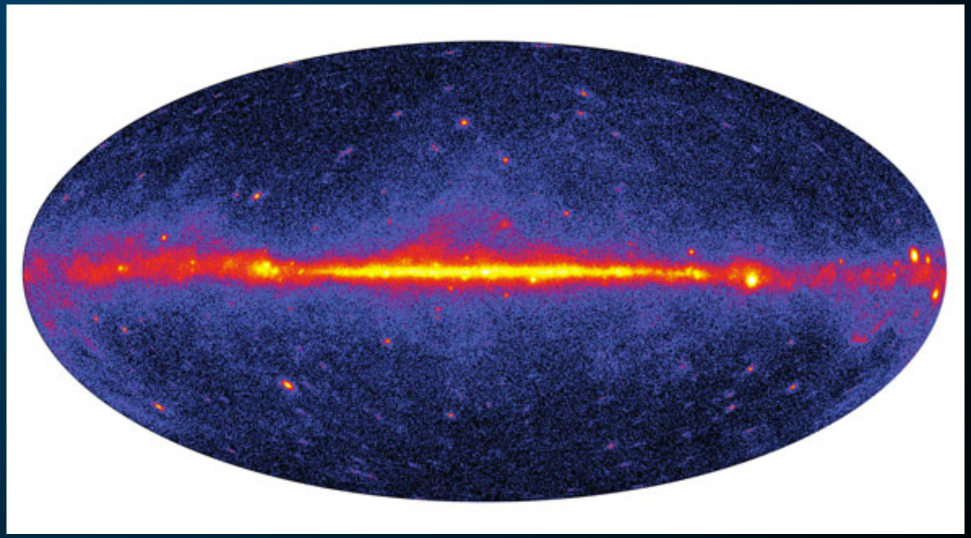
cosmic rays propagate

$$\frac{\partial \psi}{\partial t} = q(\vec{r}, p) + \vec{\nabla} \cdot (D_{xx} \vec{\nabla} \psi - \vec{V} \psi) + \frac{\partial}{\partial p} p^2 D_{pp} \frac{\partial}{\partial p} \frac{1}{p^2} \psi - \frac{\partial}{\partial p} \left[\dot{p} \psi - \frac{p}{3} (\vec{\nabla} \cdot \vec{V}) \psi \right] - \frac{1}{\tau_f} \psi - \frac{1}{\tau_r} \psi$$

Solved Numerically:
e.g. Galprop

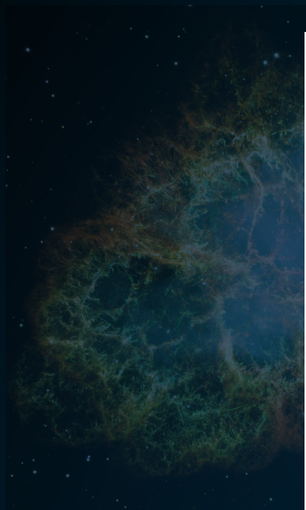
Gas/ISRF

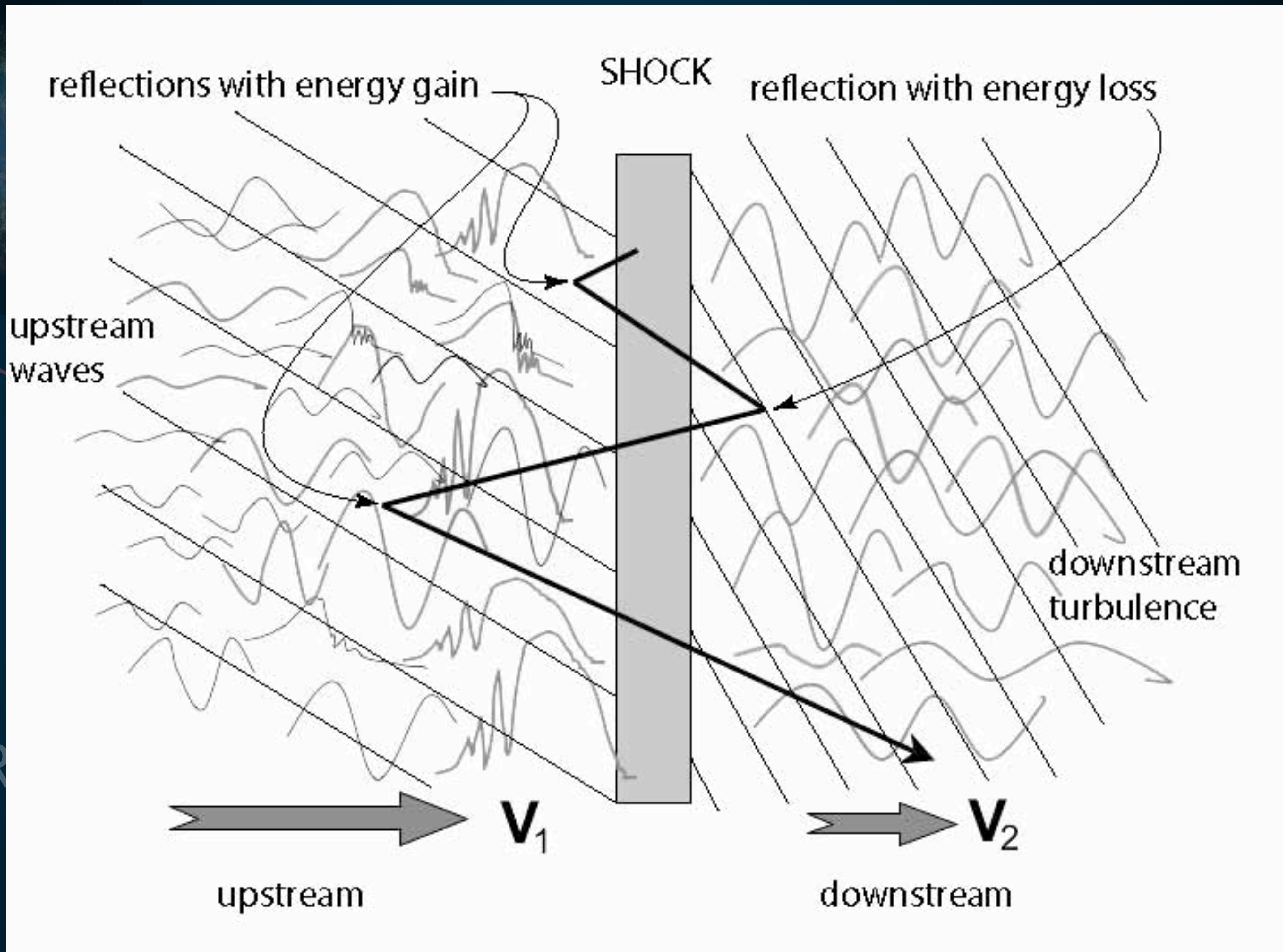




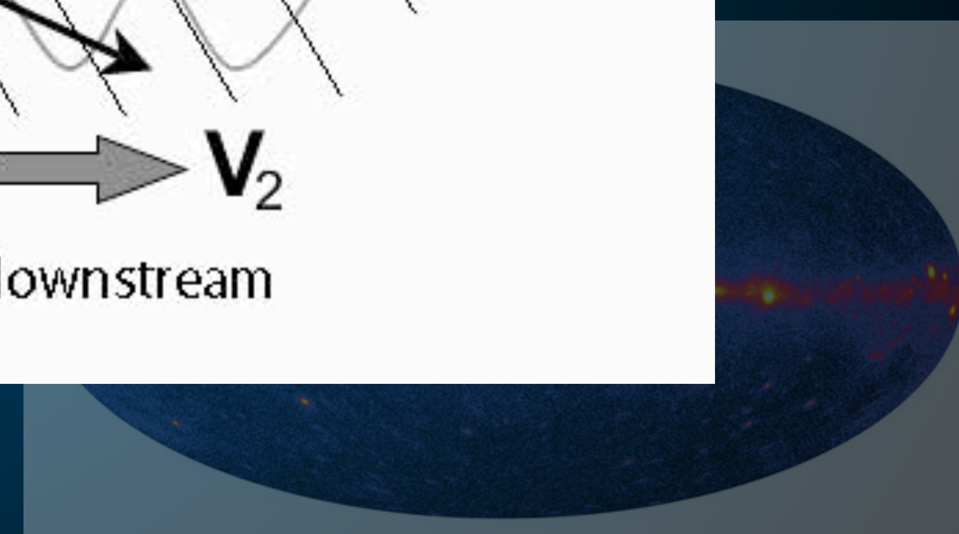
Spectral Features

Things that go bump in the night



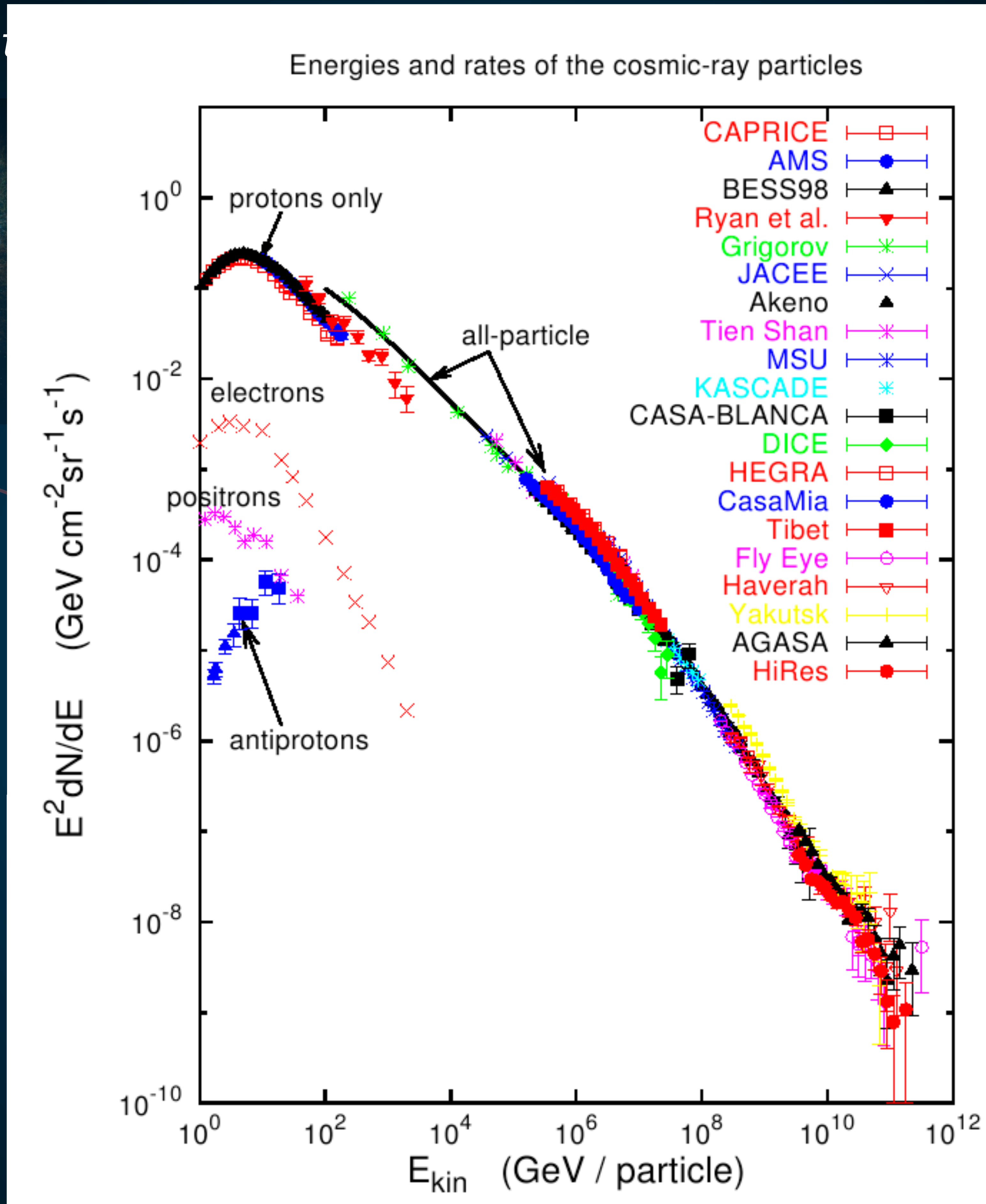


Gas/ISR

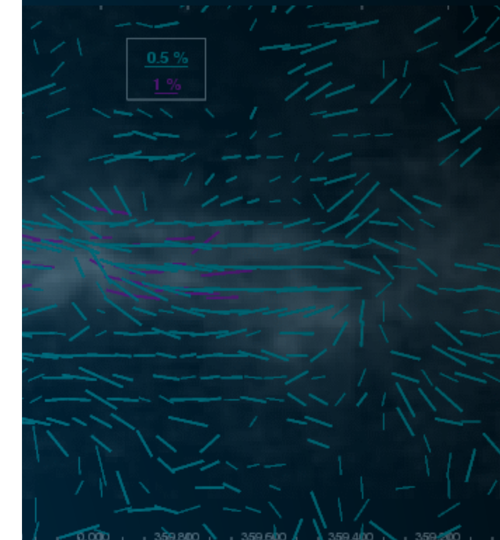


Spectral Features

Things that



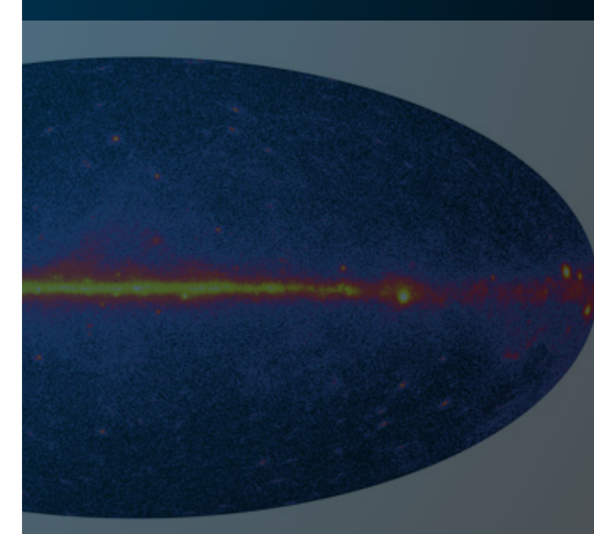
mic-rays



$$-\frac{\partial}{\partial p}\left[\dot{p}\psi - \frac{p}{3}(\vec{\nabla}\cdot\vec{V})\psi\right] - \frac{1}{\tau_f}\psi - \frac{1}{\tau_r}\psi$$

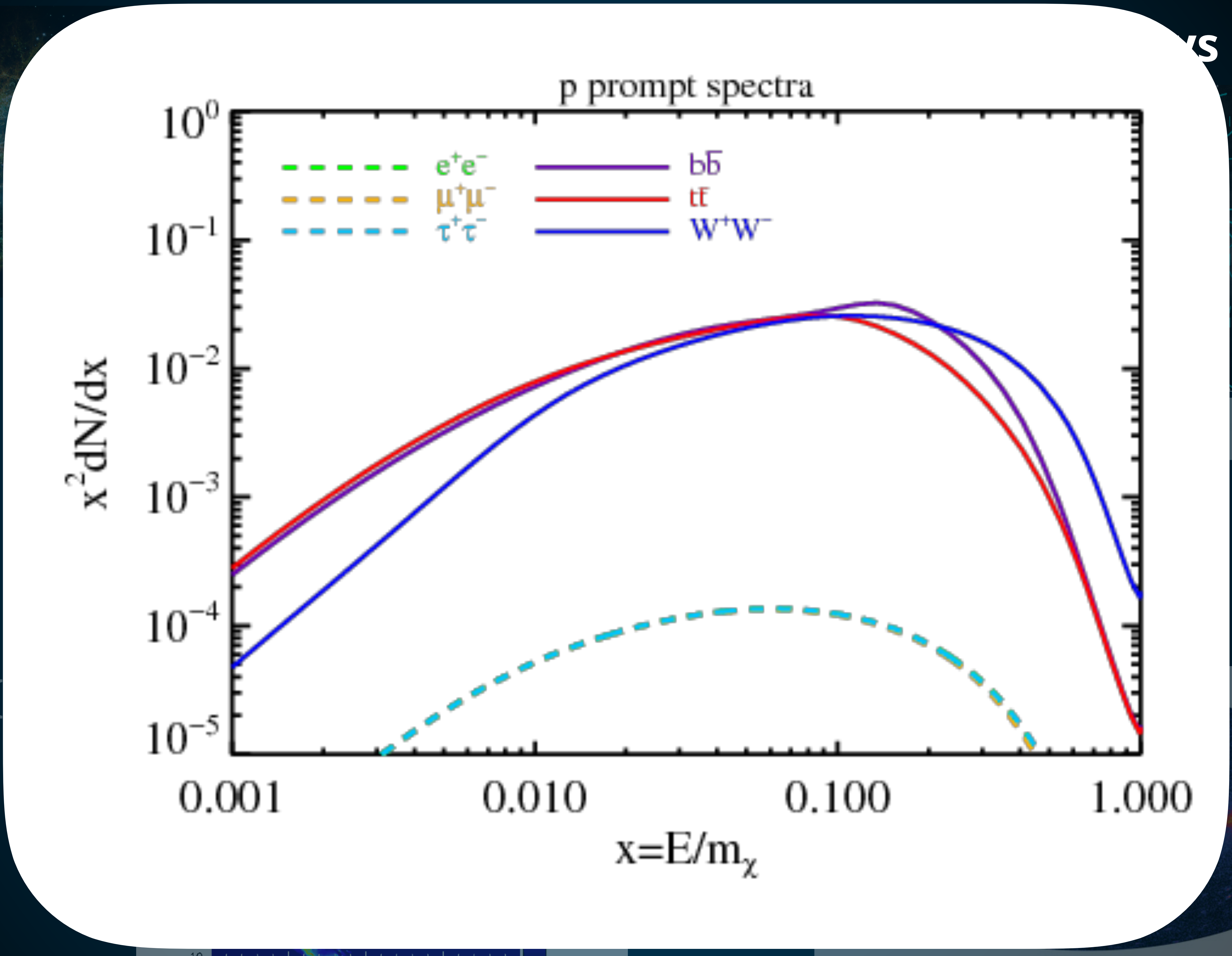
y:

Gas/ISRF



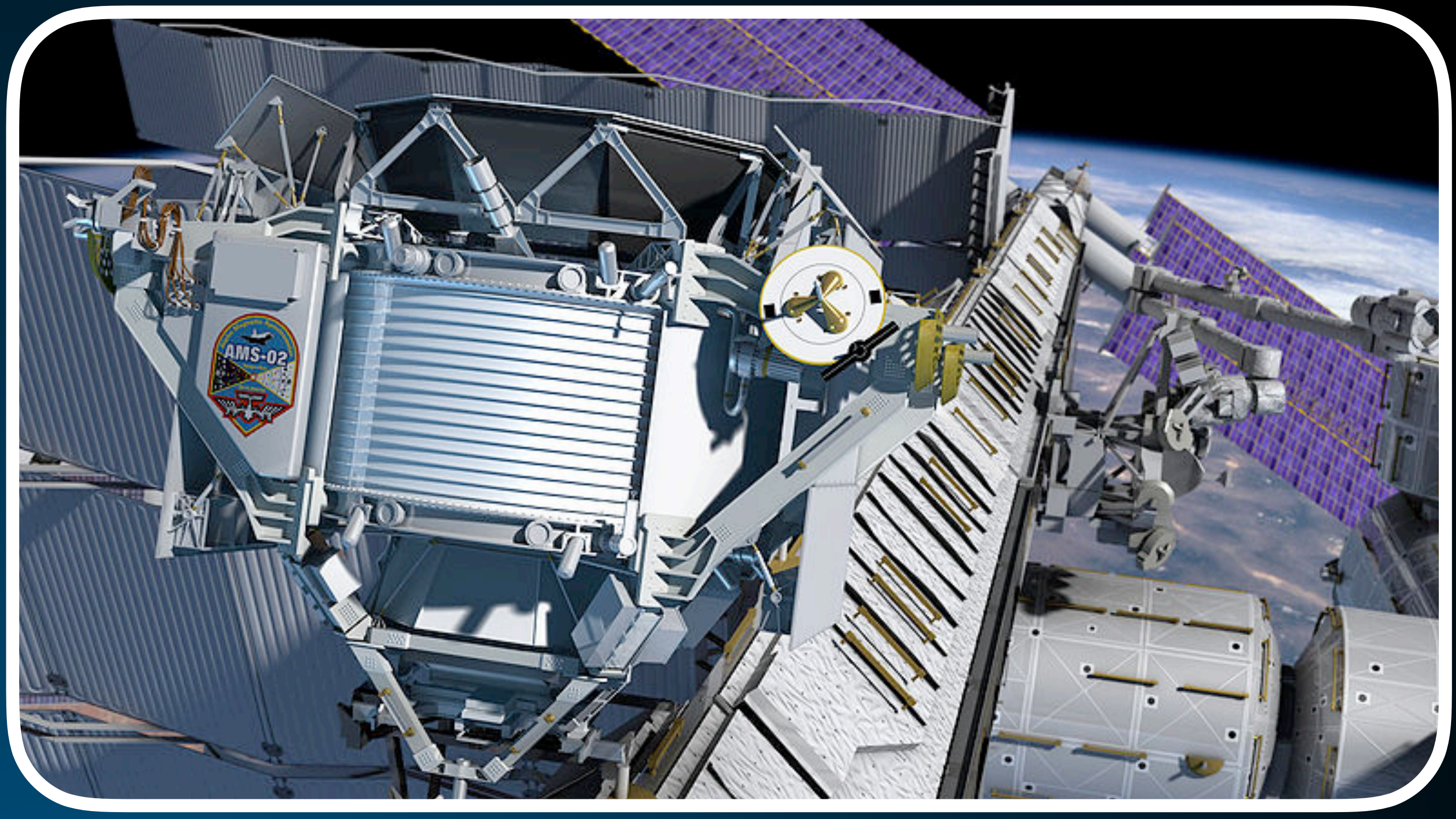
Spectral Features

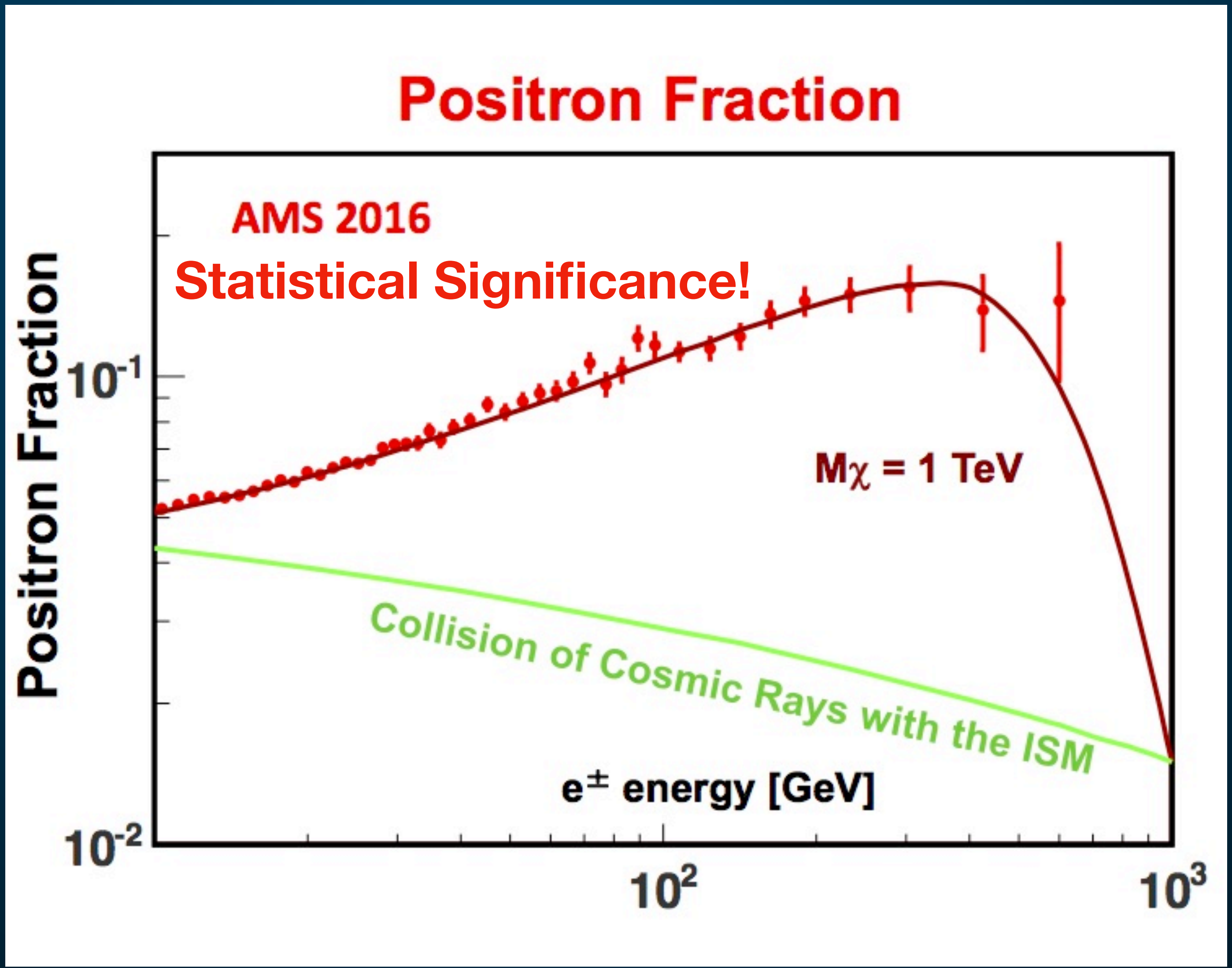
Things that go bump in the night



Spectral Features

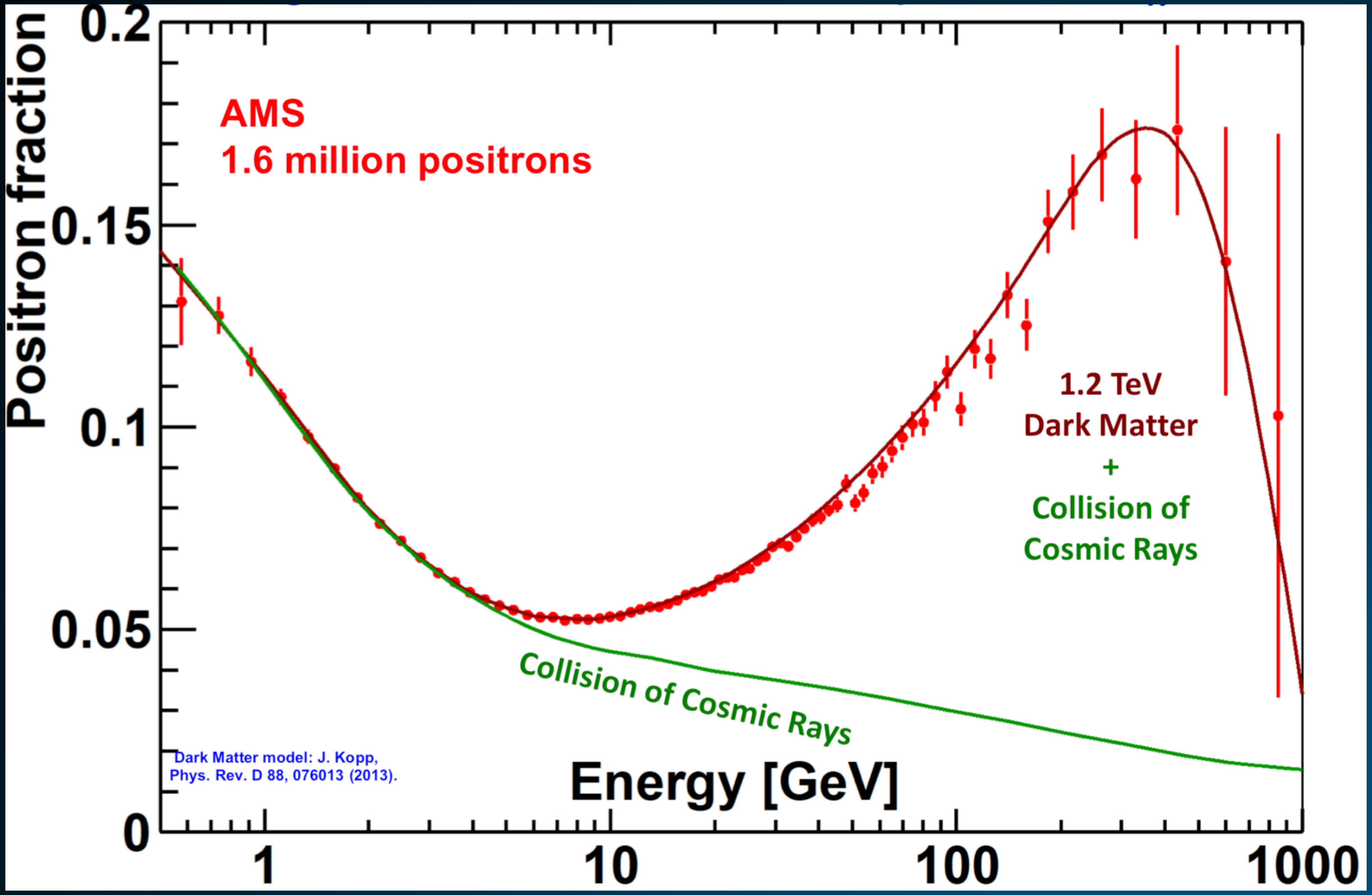
Part 1: The Positron Excess

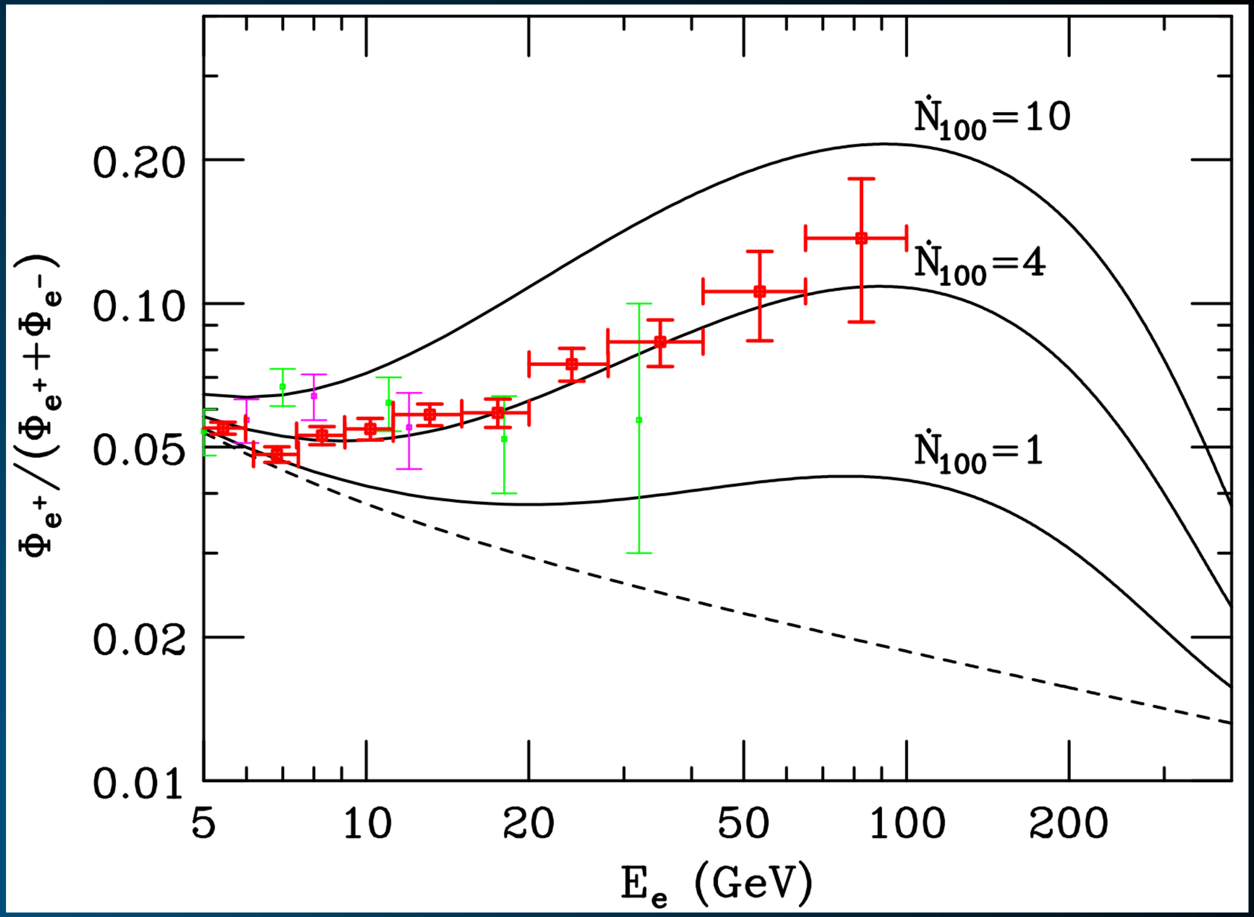




Spectral Features

Part 1: The Positron Excess





Dark Matter Models

- *Highly Sommerfeld Enhanced*
- *Leptophilic*

Pulsar Models

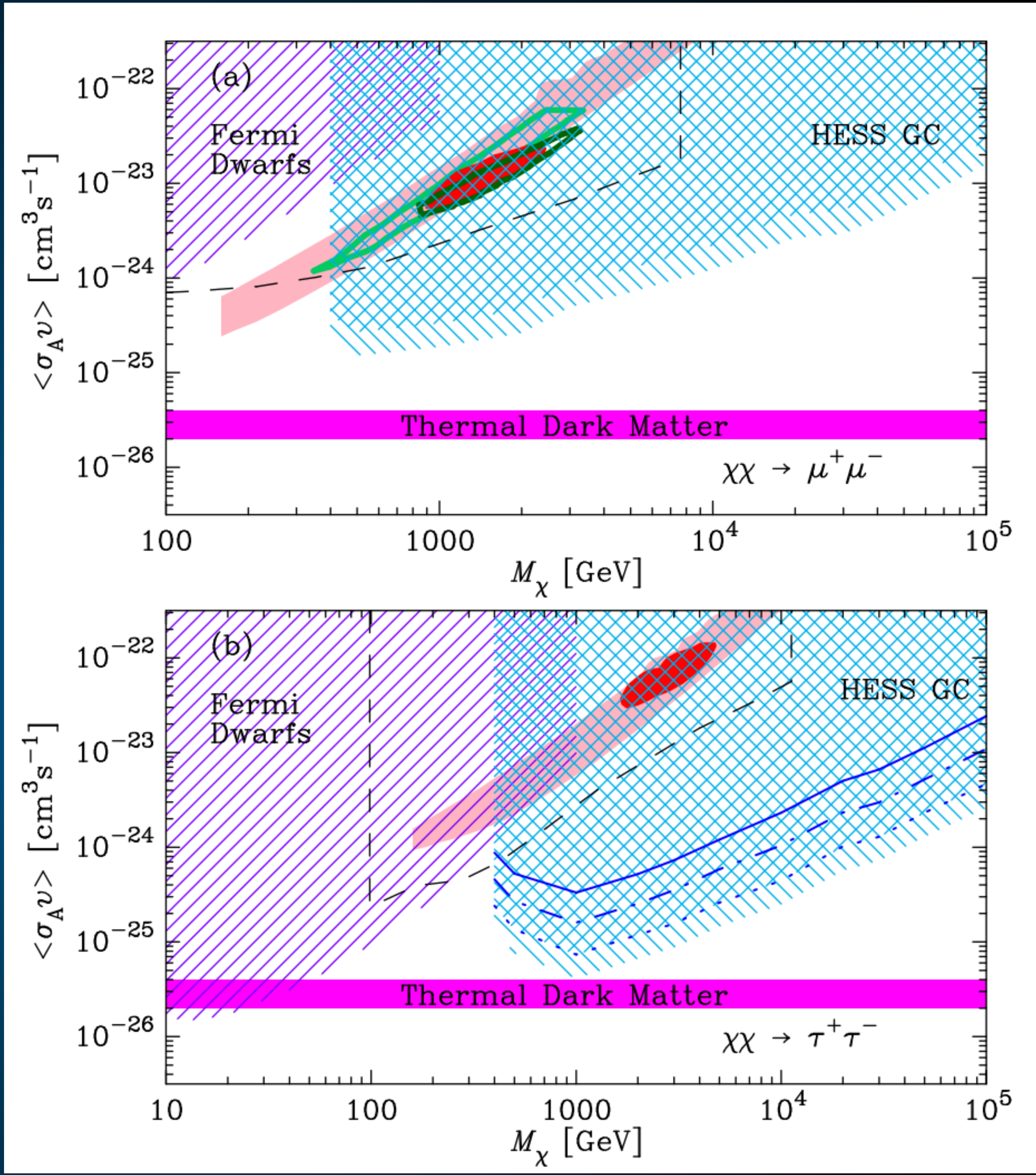
- *Efficient e+e- Production*
- *Hard e+e- Spectrum*

Spectral Features

Abazajian & Harding (2012; 1110.6151)

Part 1: The Positron Excess

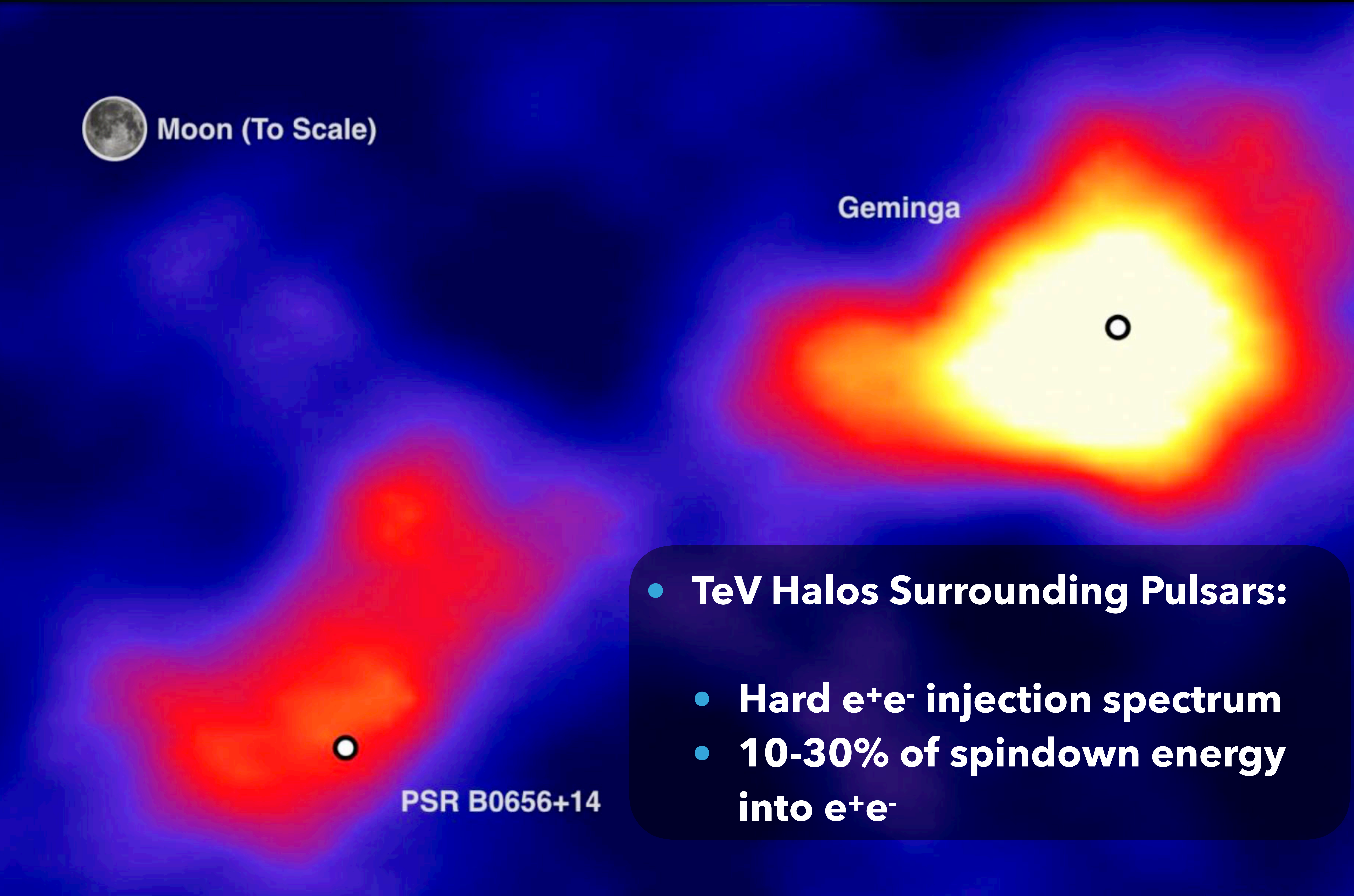
Gamma-Ray Observations are in strong tension with dark matter models.



Spectral Features

Hooper, Cholis, TL, Fang (2017; 1702.08436)

Part 1: The Positron Excess

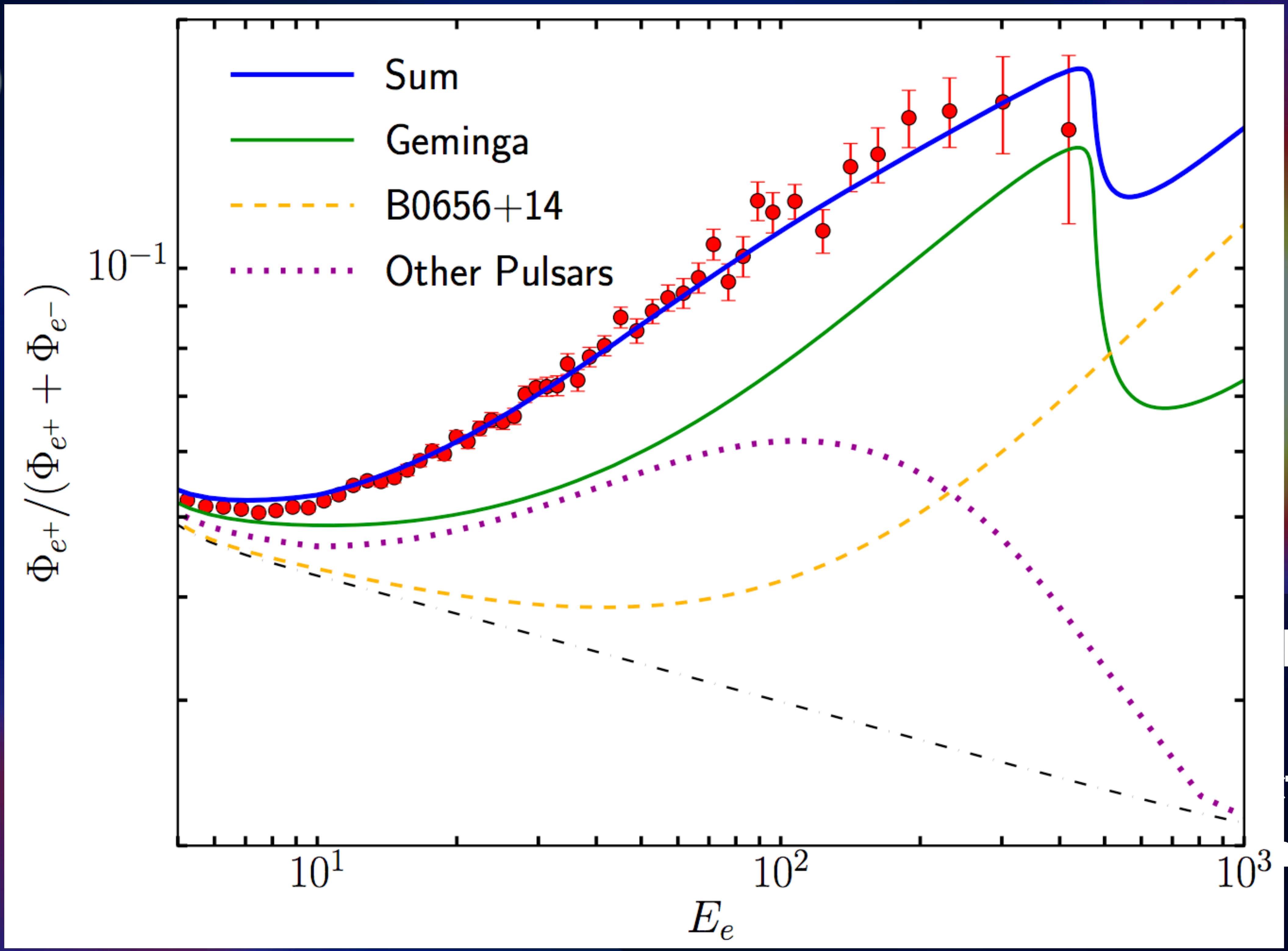


- **TeV Halos Surrounding Pulsars:**
  - **Hard e^+e^- injection spectrum**
  - **10-30% of spindown energy into e^+e^-**

Spectral Features

Hooper, Cholis, TL, Fang (2017; 1702.08436)

Part 1: The Positron Excess



lsars:

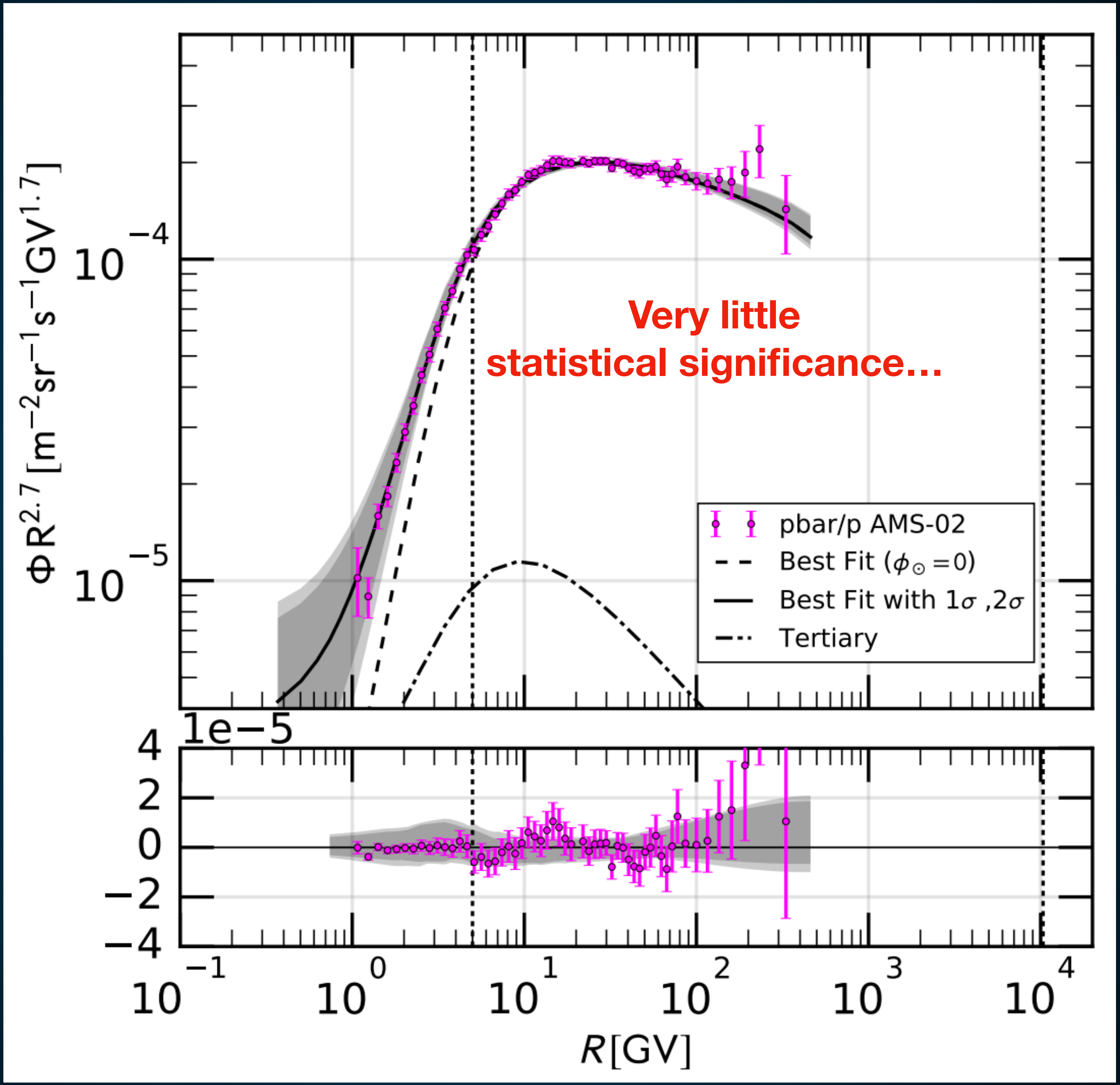
trum

ergy

Spectral Features

Cuoco et al. (2016; 1610.03071)

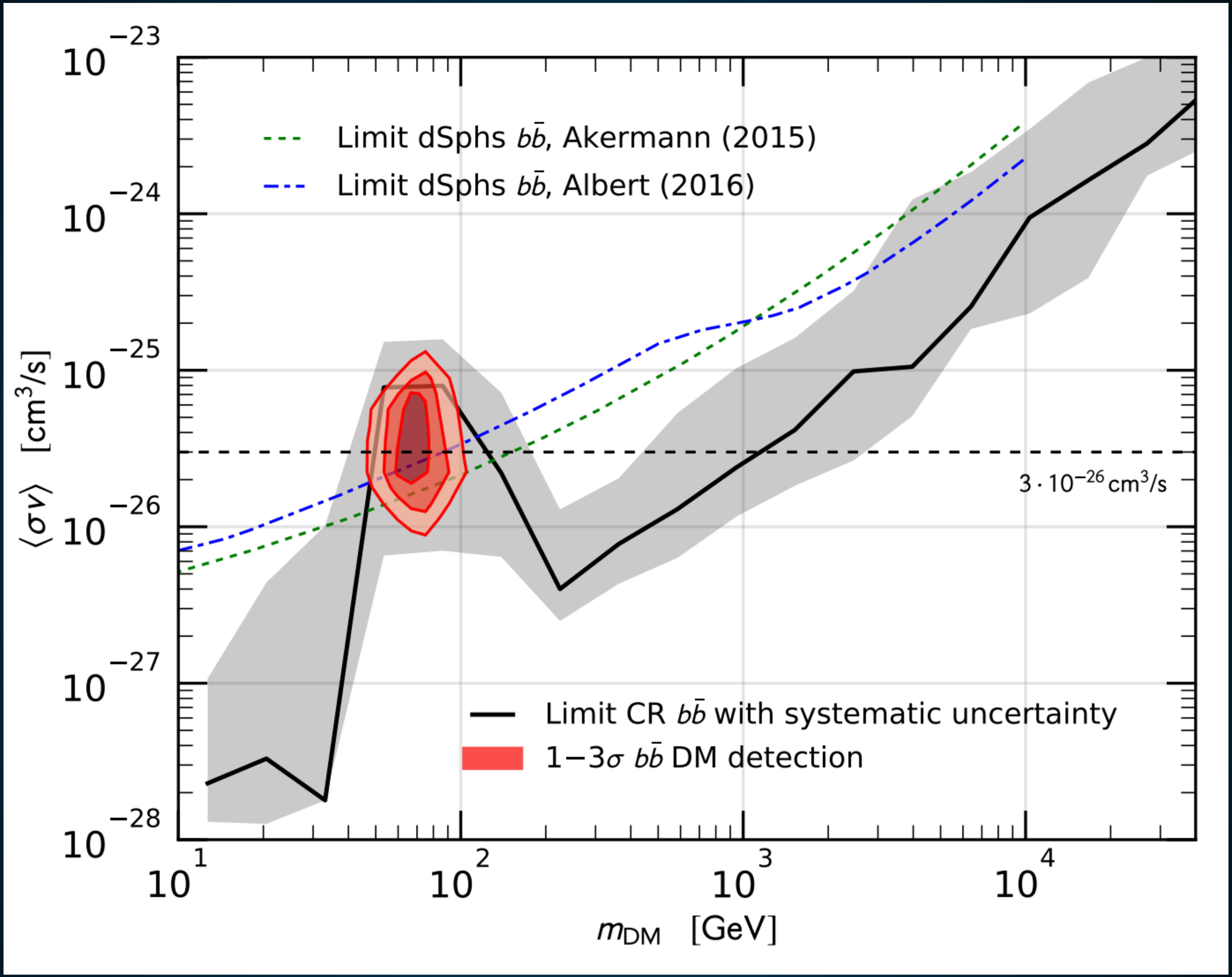
Part 2: The Antiproton Excess



Spectral Features

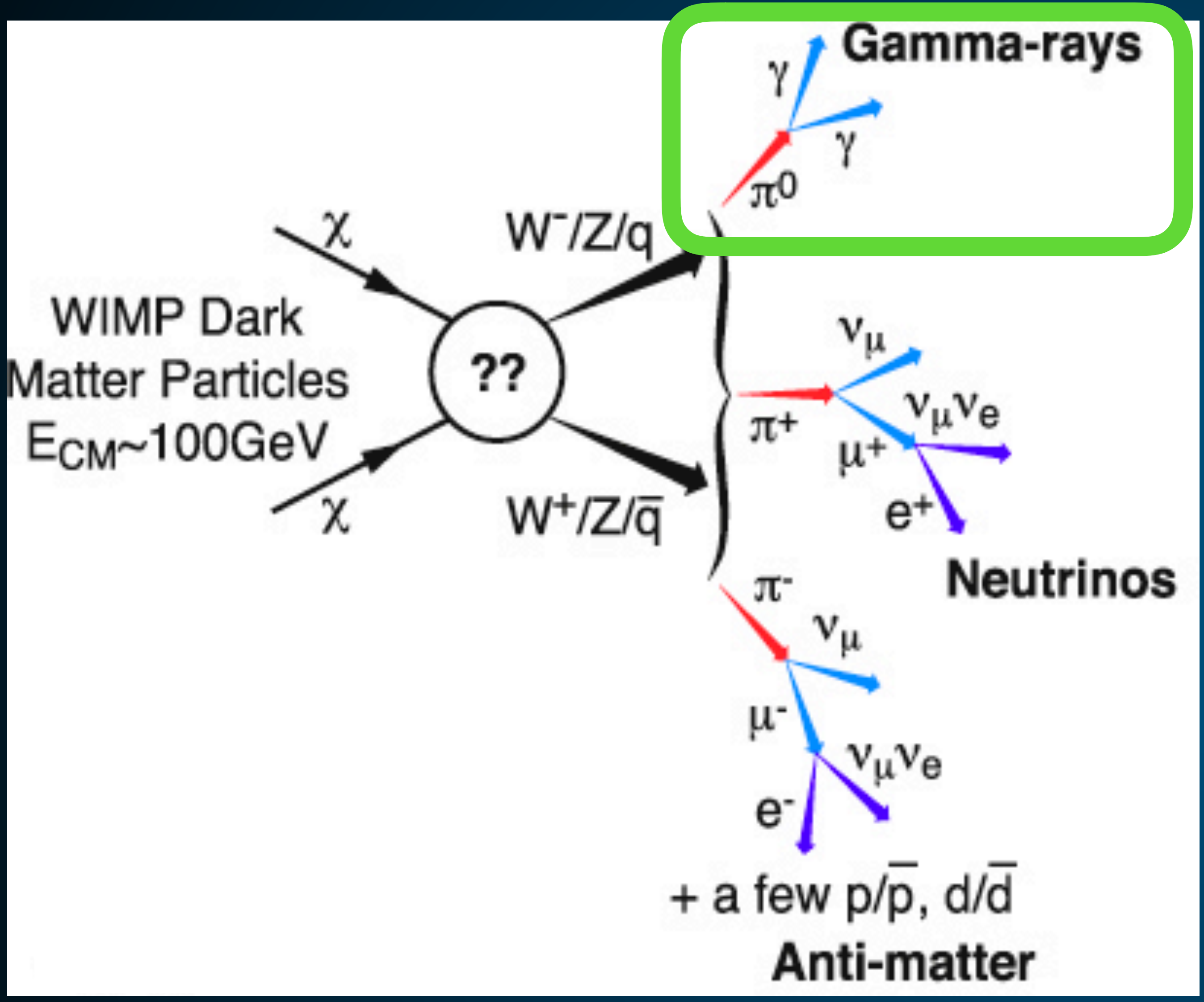
Cuoco et al. (2016; 1610.03071)

Part 2: The Antiproton Excess



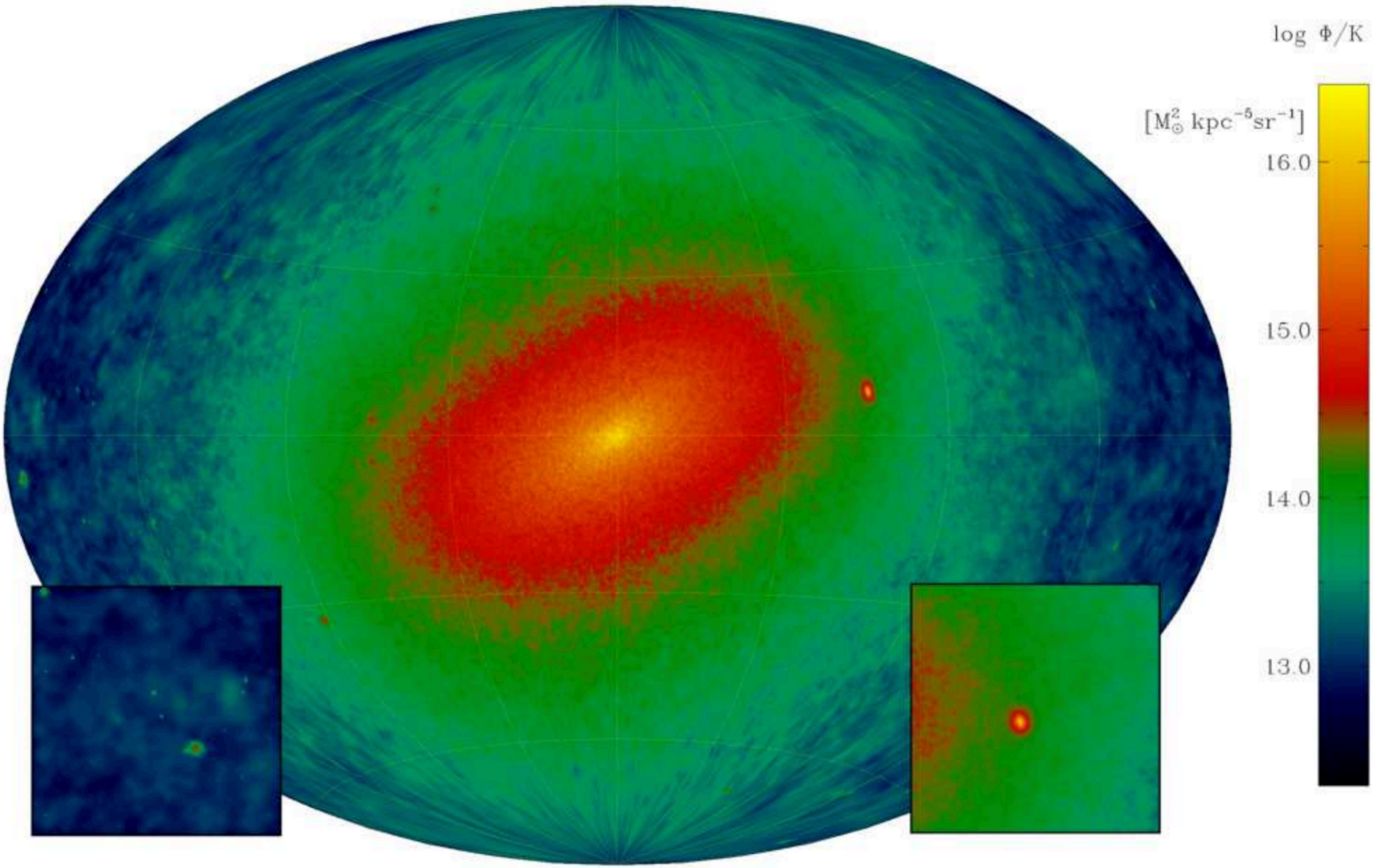
Angular Mapping

Using Gravity to Determine Where the Dark Matter Really Is



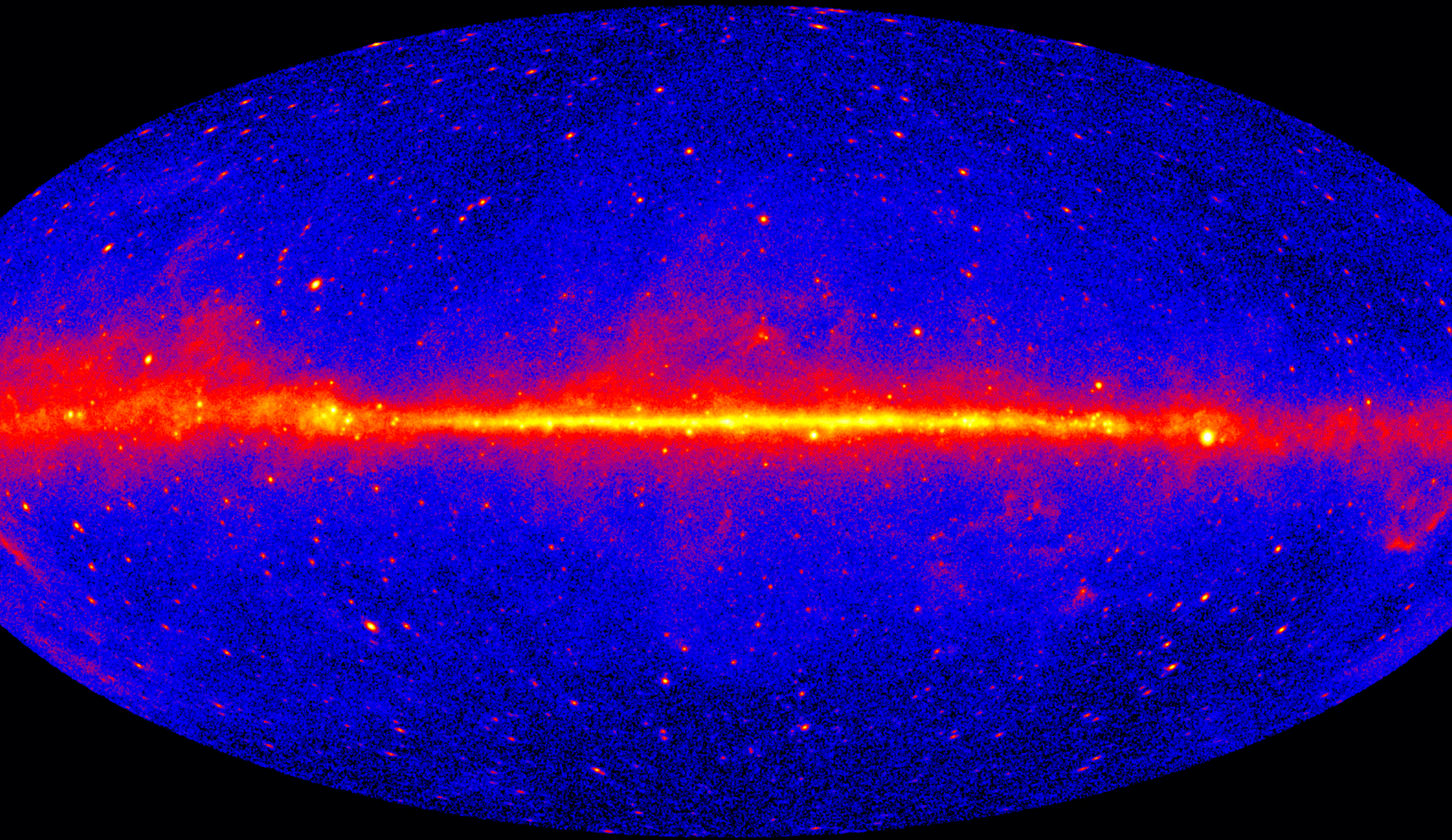
Angular Mapping

Using Gravity to Determine Where the Dark Matter Really Is



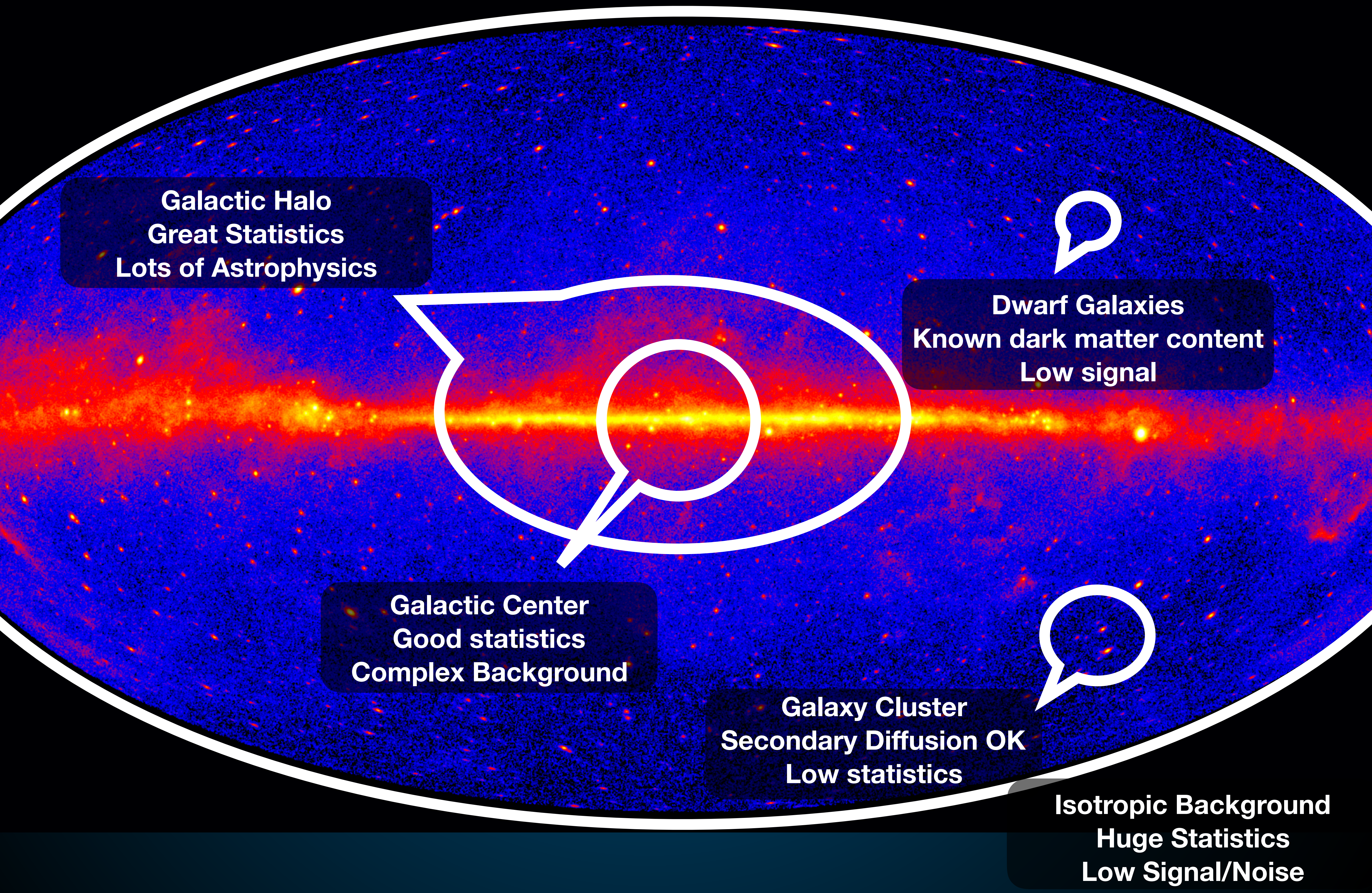
Angular Mapping

Using Gravity to Determine Where the Dark Matter Really Is



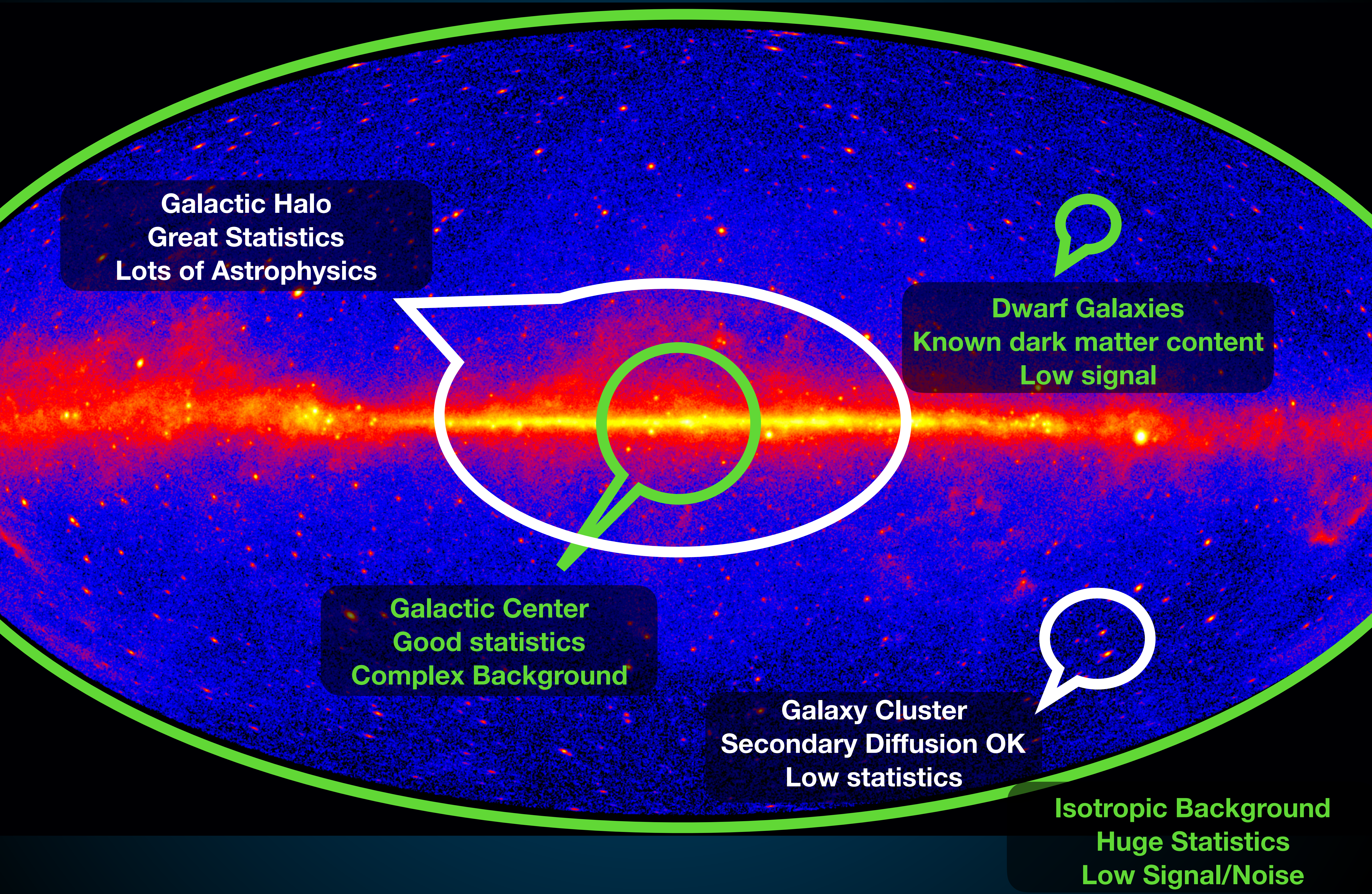
Angular Modeling

Using Gravity to Determine Where the Dark Matter Really Is



Angular Modeling

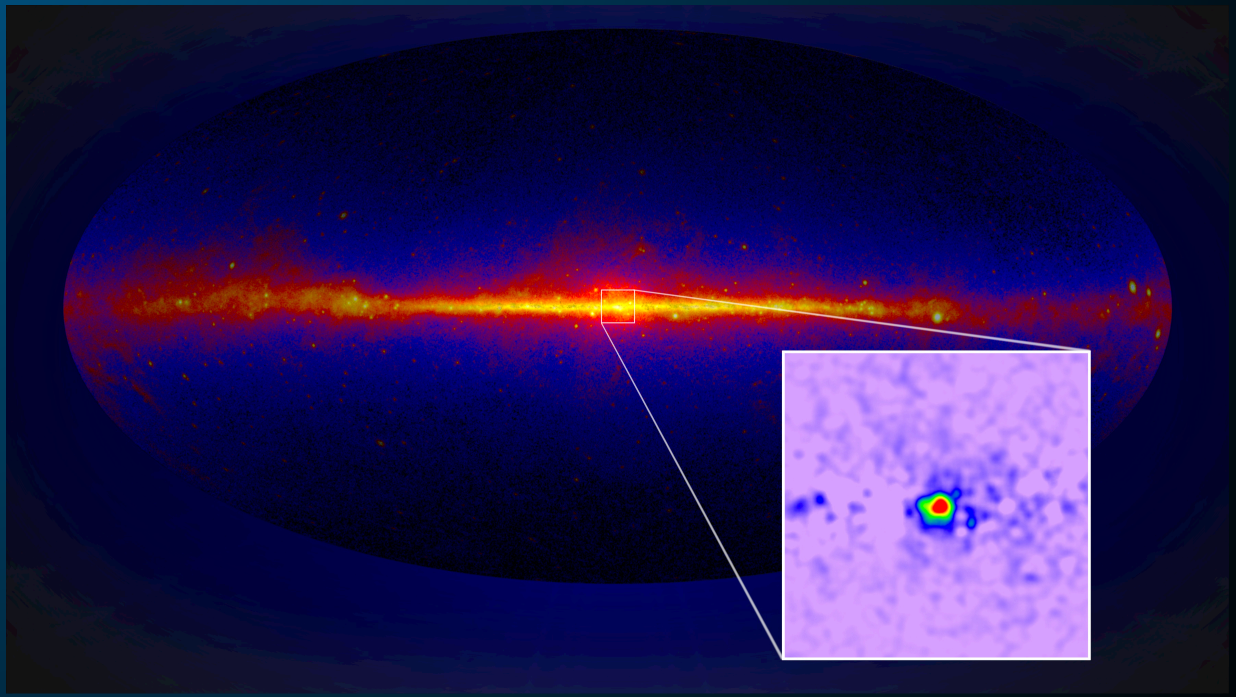
Using Gravity to Determine Where the Dark Matter Really Is



Angular Mapping

Part 1: The Galactic Center

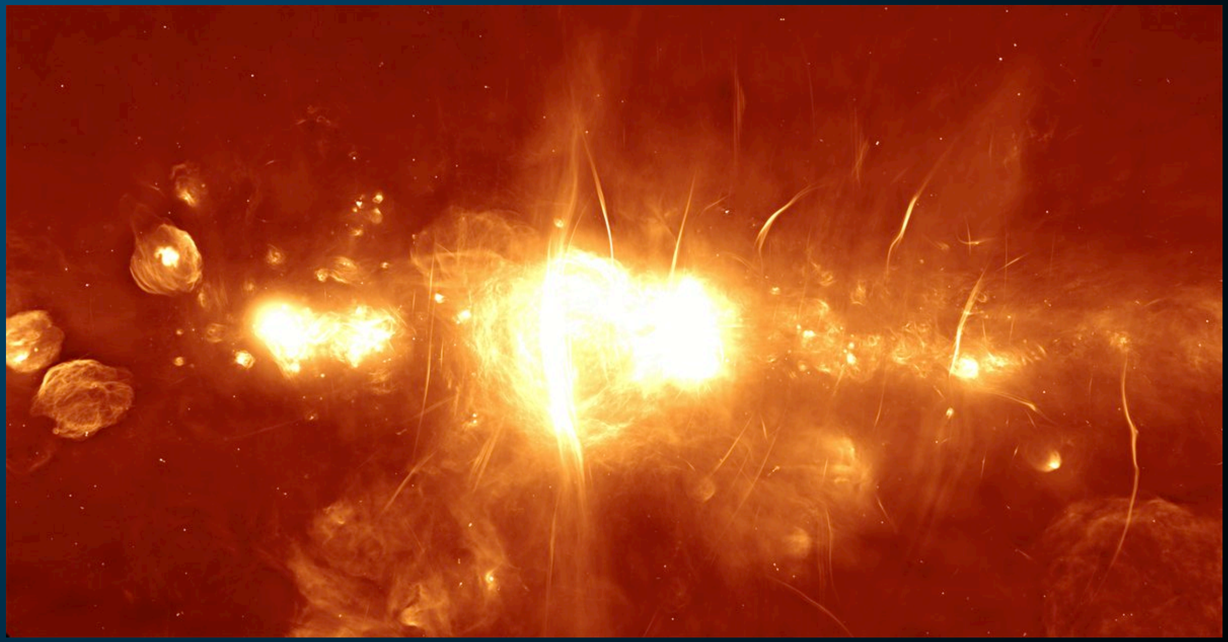
- **Model:**
  - **100 GeV dark matter particle annihilates to bb**
  - **Annihilation Rate is Thermal Cross-Section**
- **Expected Galactic Center Flux (above 1 GeV):**
  - **2×10^{-11} erg cm^{-2} s^{-1}**
- **Observed Flux:**
  - **1×10^{-10} erg cm^{-2} s^{-1}**



Angular Mapping

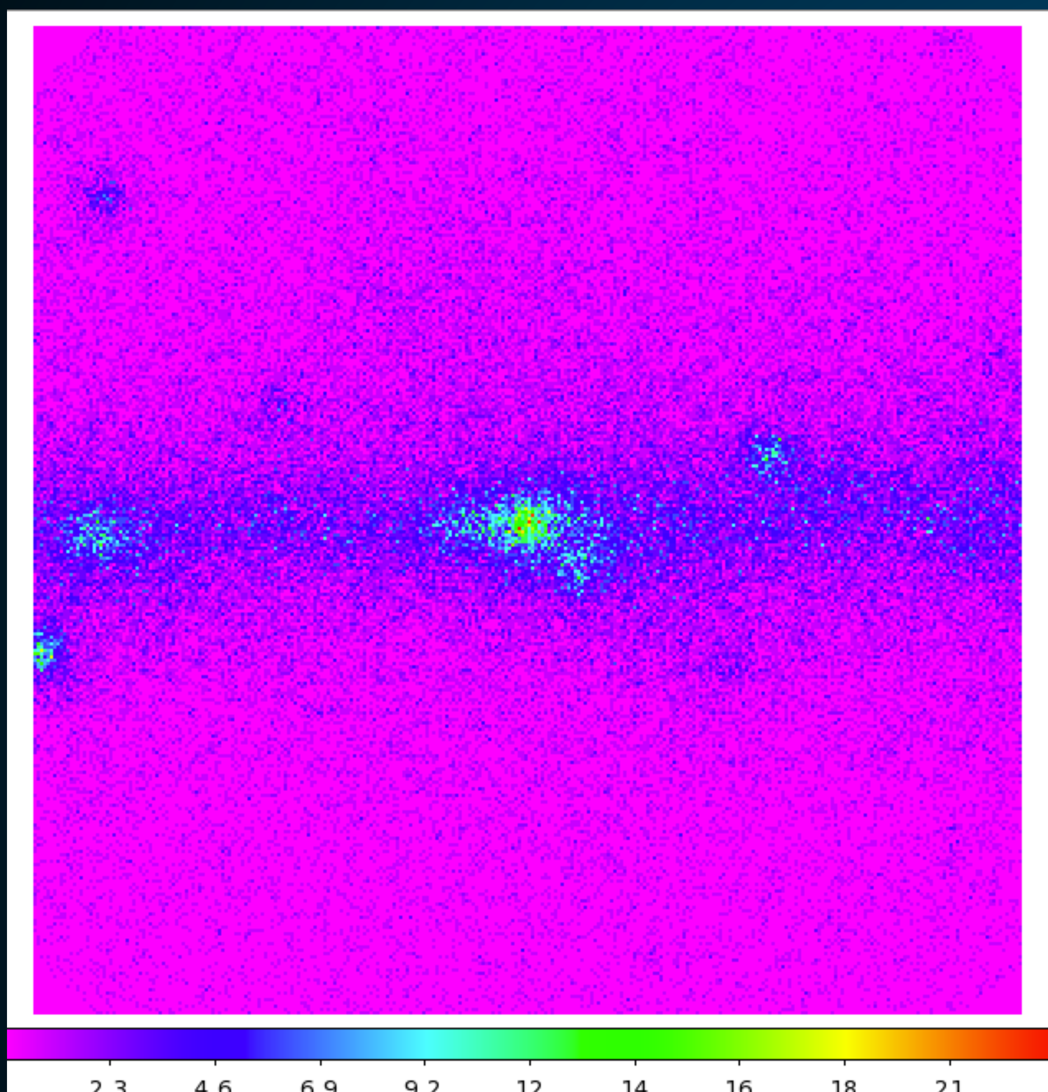
Part 1: The Galactic Center

- **Model:**
  - **100 GeV dark matter particle annihilates to bb**
  - **Annihilation Rate is Thermal Cross-Section**
- **Expected Galactic Center Radio Flux:**
  - **2×10^{-13} erg cm^{-2} s^{-1}**
- **Observed Flux:**
  - **5×10^{-10} erg cm^{-2} s^{-1}**



Angular Mapping

Part 1: The Galactic Center



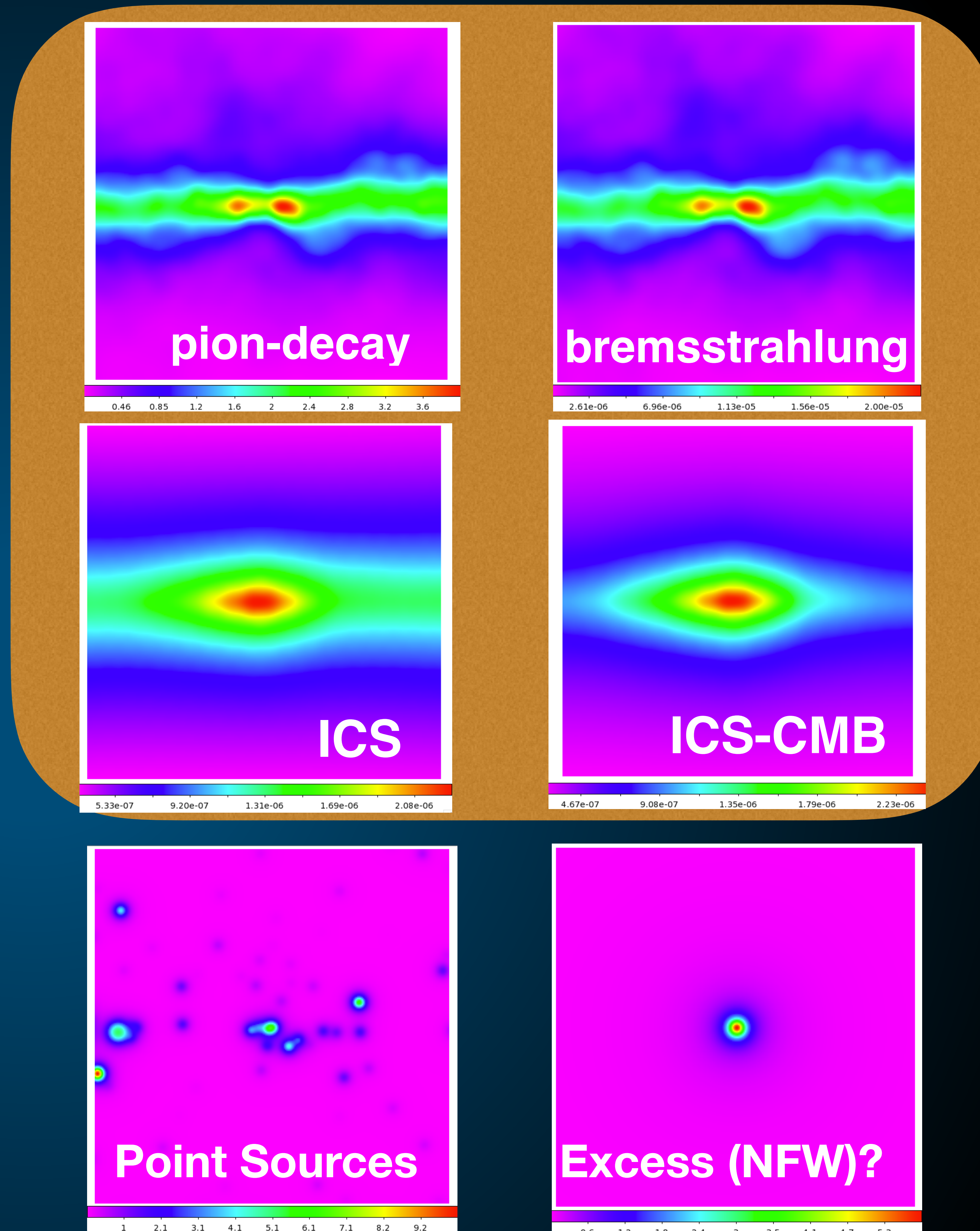
Data

750 — 950 MeV

Best Angular Resolution Cut

10º x 10º ROI

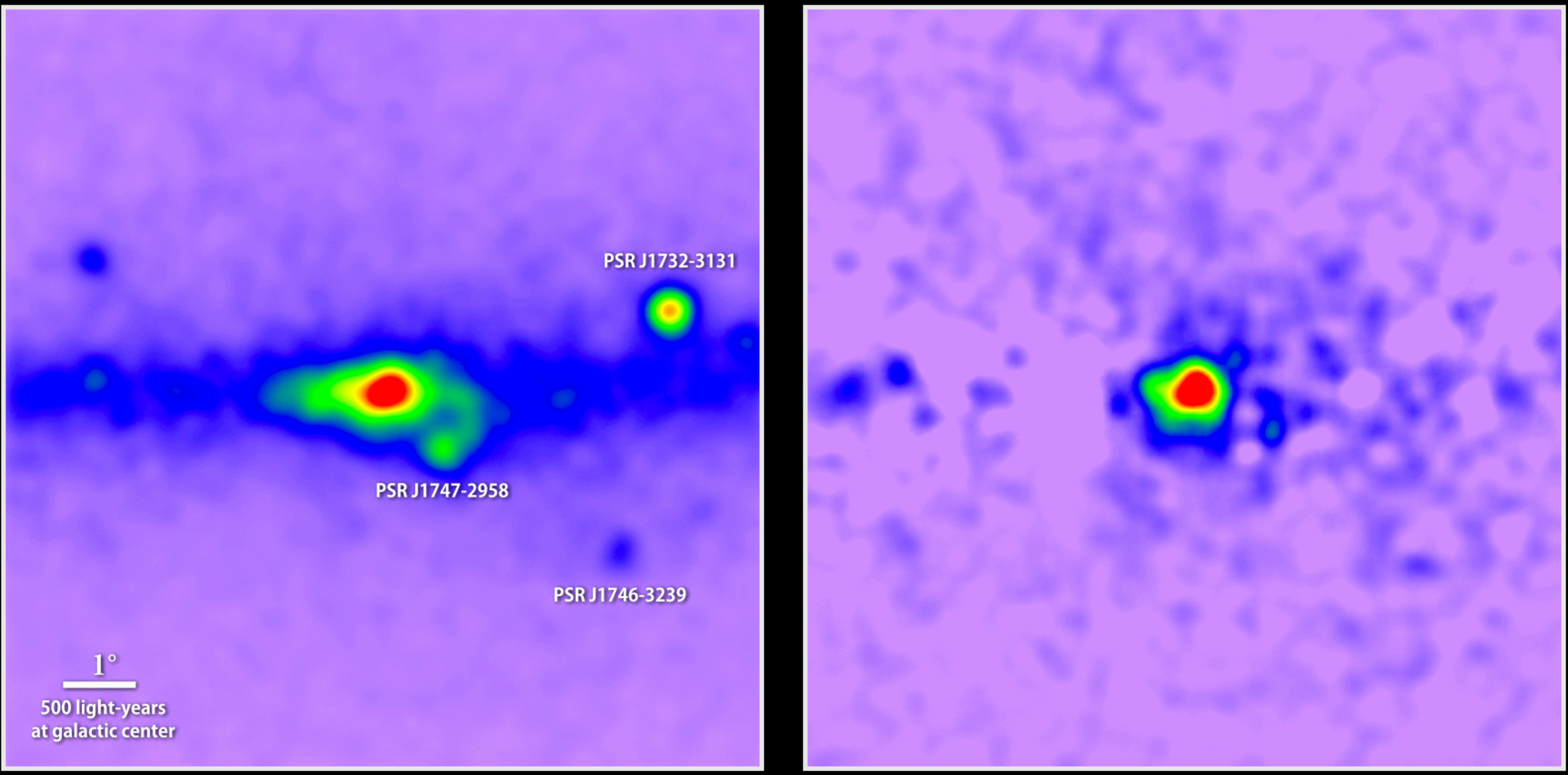
=



Angular Mapping

Part 1: The Galactic Center

Uncovering a gamma-ray excess at the galactic center

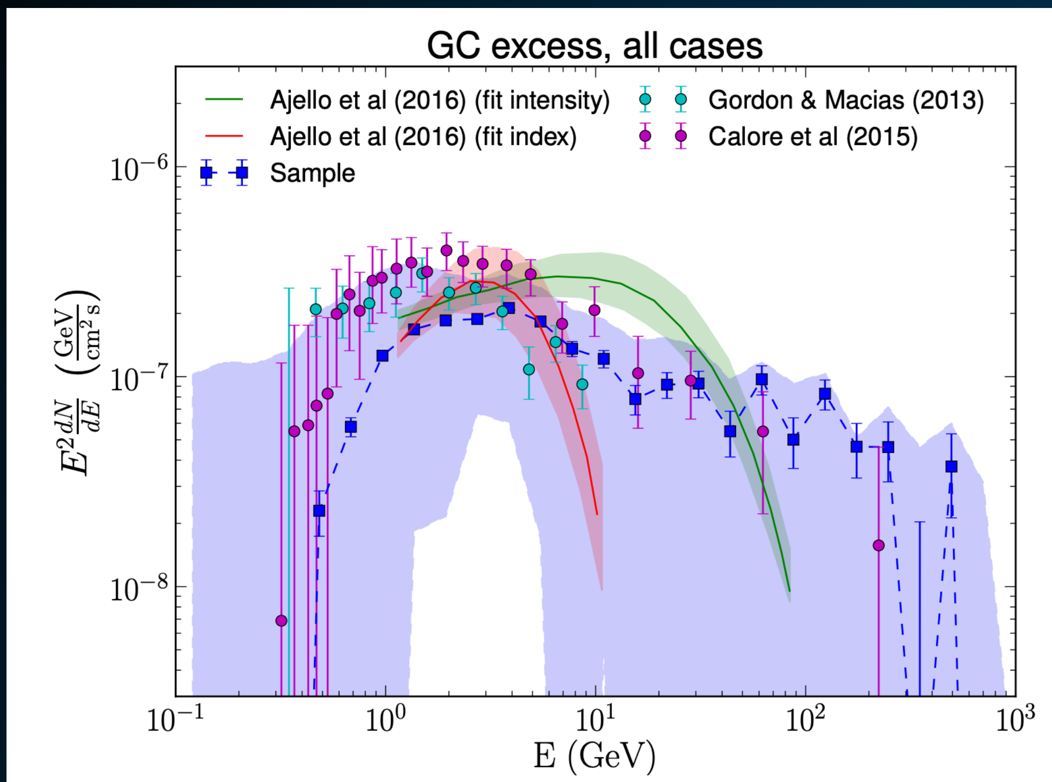


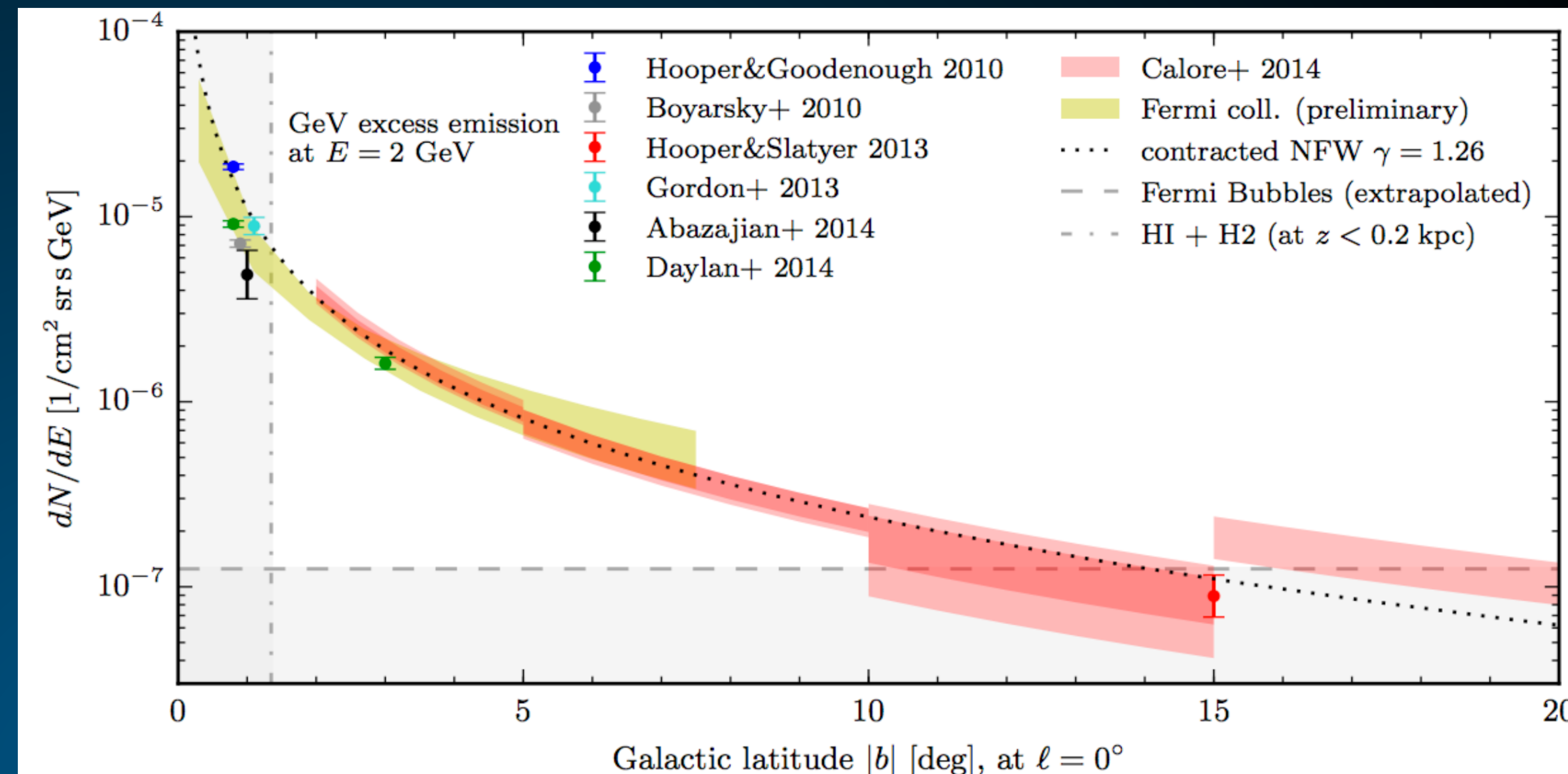
Unprocessed map of 1.0 to 3.16 GeV gamma rays

Known sources removed

Angular Mapping

Part 1: The Galactic Center





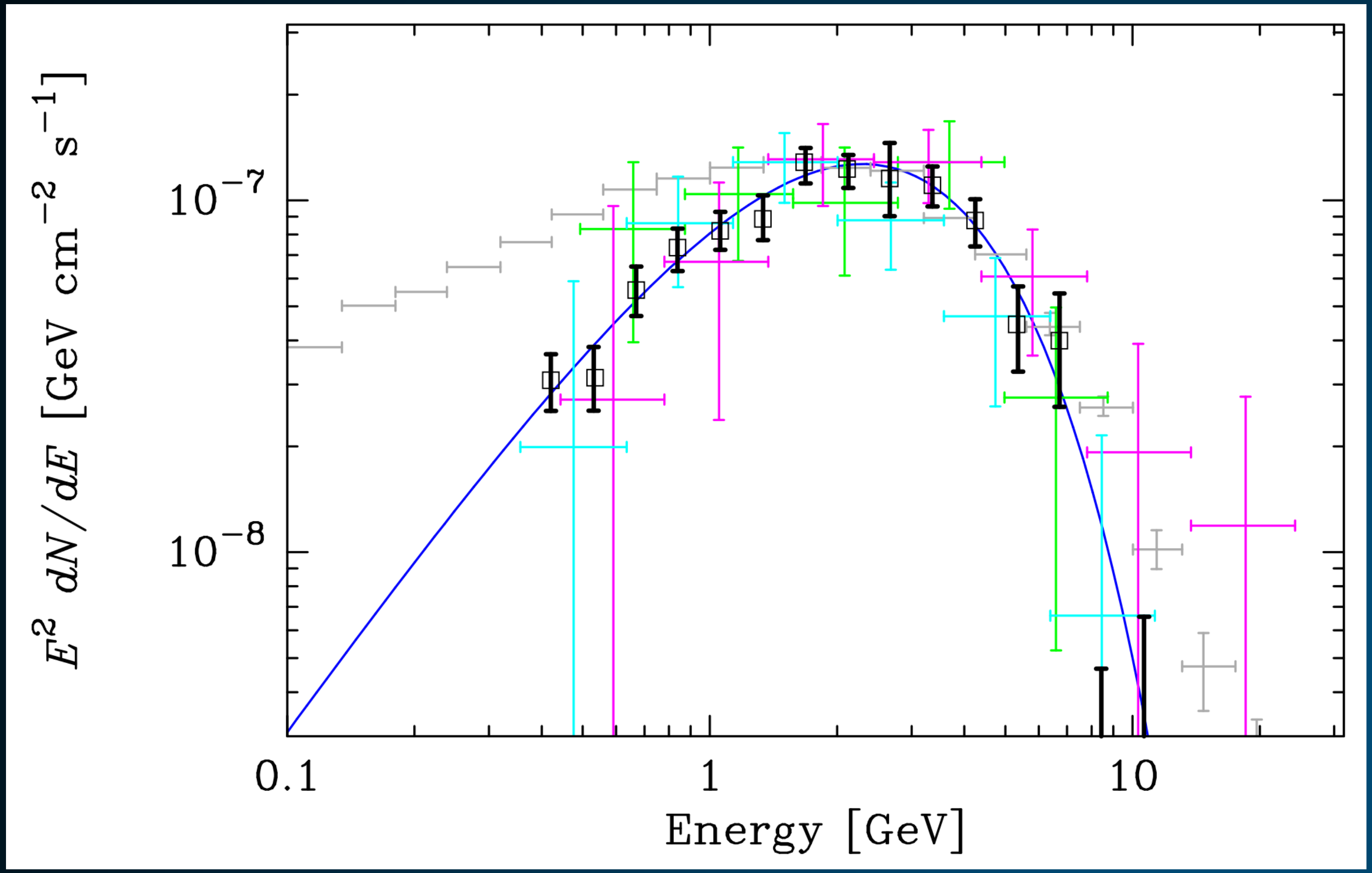
- **Result is extremely significant.**

- **Spectrum and morphology match expectations from dark matter.**

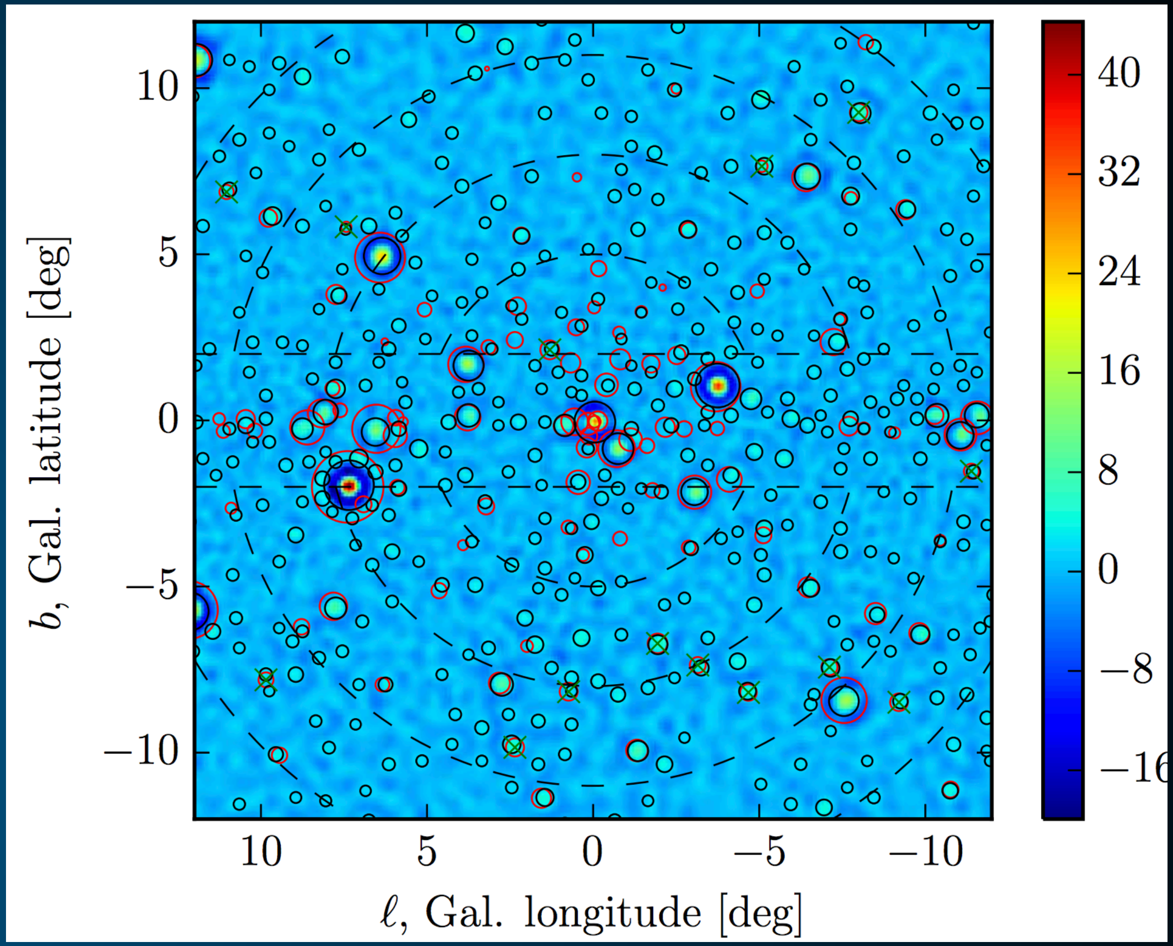
Angular Mapping

Part 1: The Galactic Center

Abazajian (1011.4275)



Bartels et al. (1506.05104)

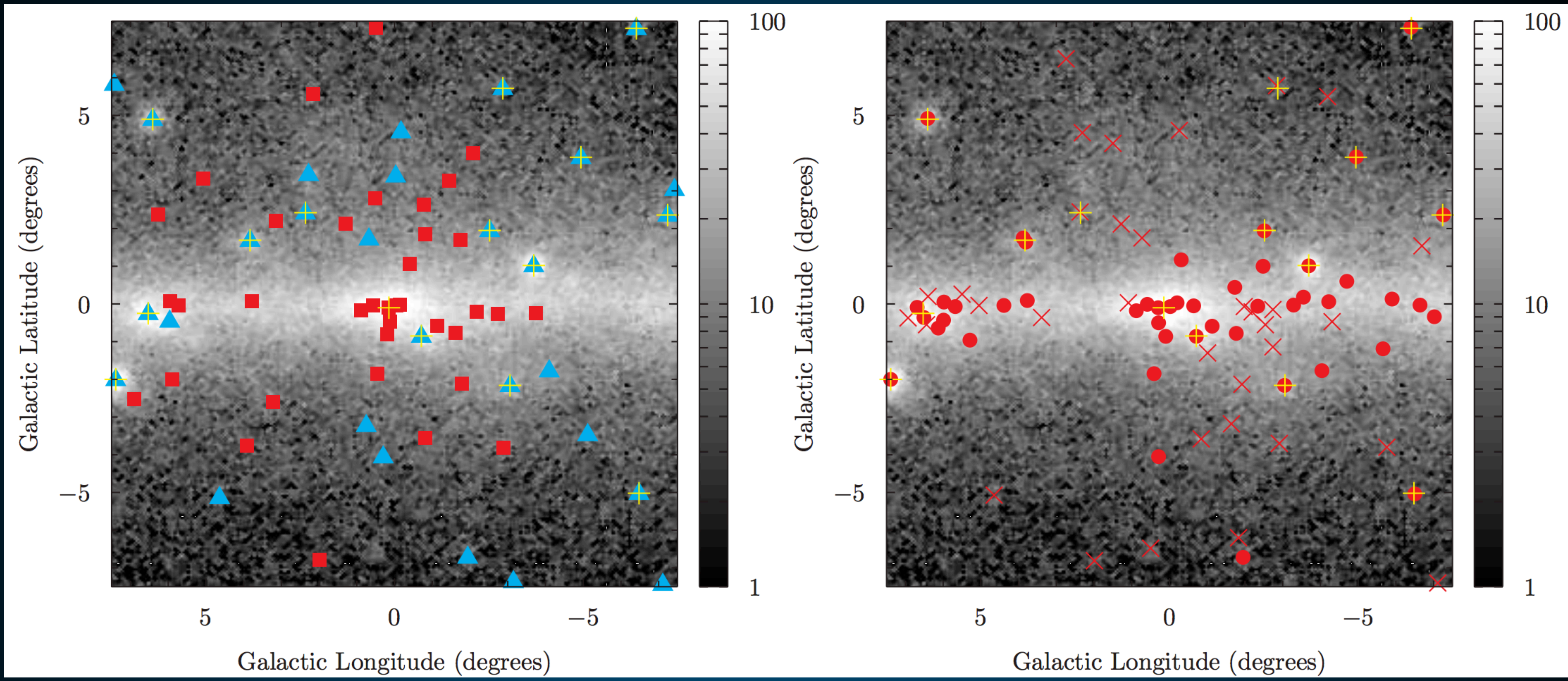


- **However, this emission may also be produced by a population of pulsars clustered in the Galactic bulge.**

Angular Mapping

Part 1: The Galactic Center

Fermi-LAT Collaboration (1511.02938)

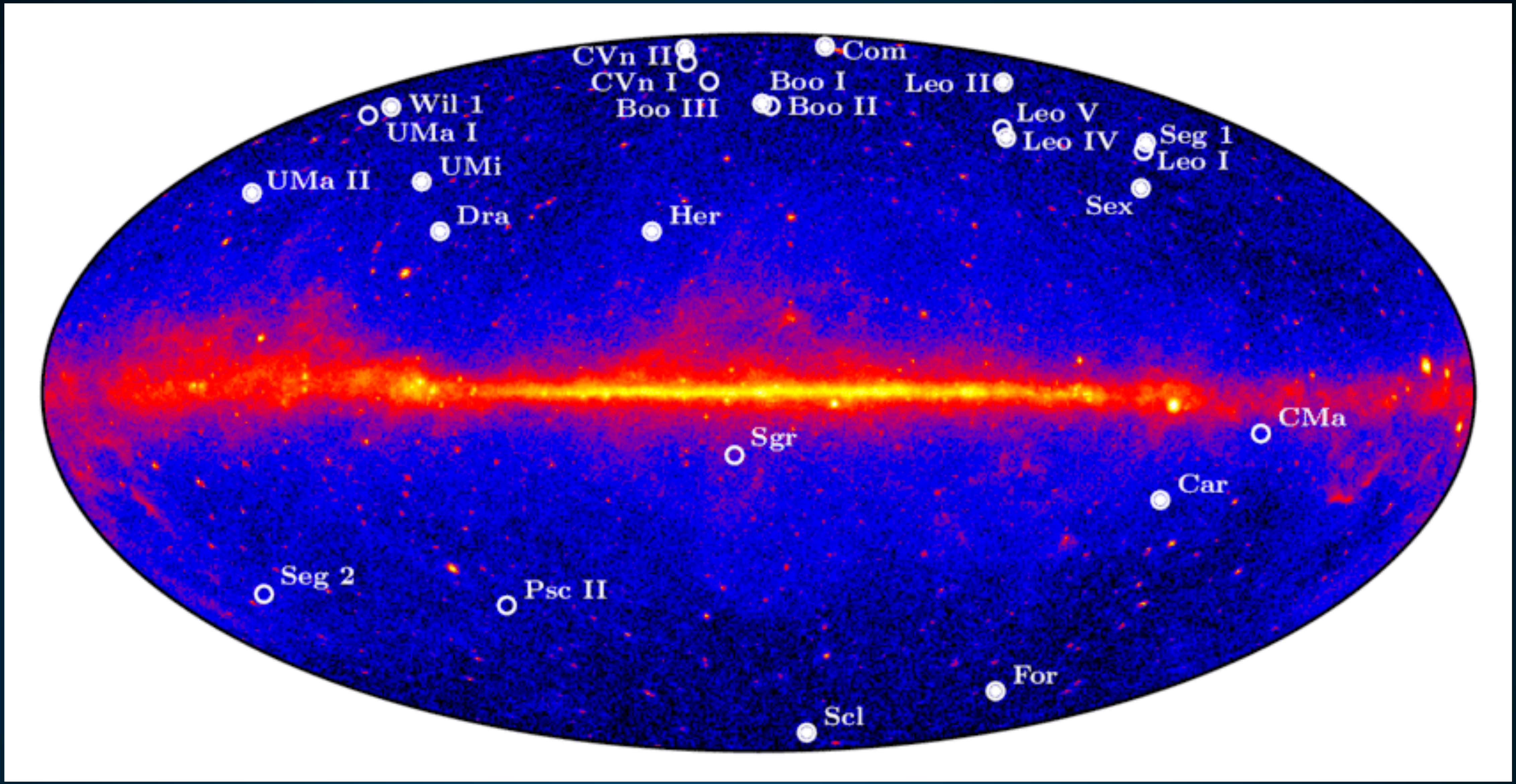


- **Models are very uncertain!**

Angular Mapping

Fermi-LAT Collaboration (2016; 1611.03184)

Part 2: Dwarf Spheroidal Galaxies

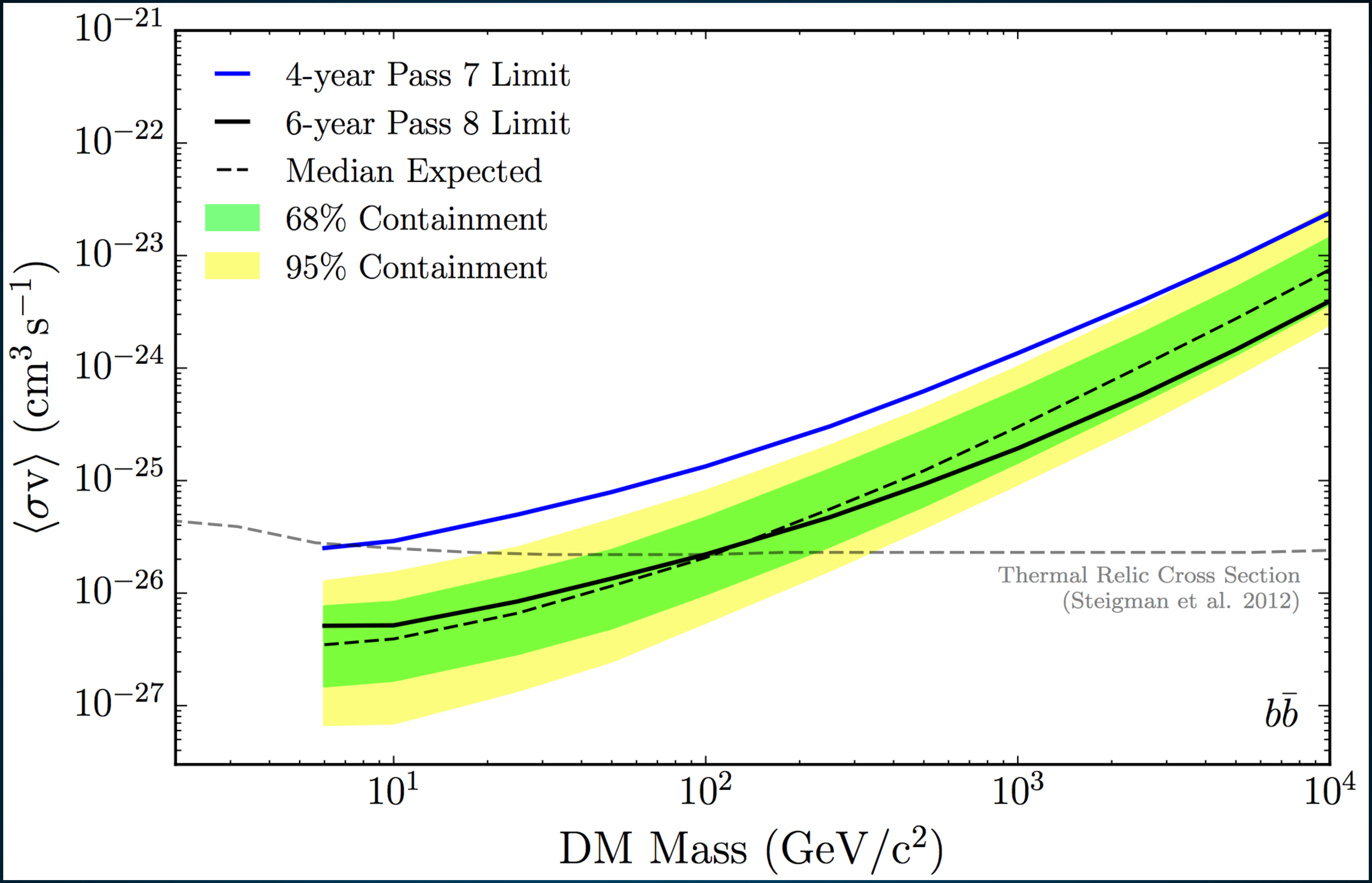


- **Dwarf Spheroidal Galaxies**
  - **Much dimmer dark matter signal**
  - **Dark Matter density is measured by rotation curves**
  - **Very little background**

Angular Mapping

Part 2: Dwarf Spheroidal Galaxies

Fermi-LAT Collaboration (2016; 1611.03184)

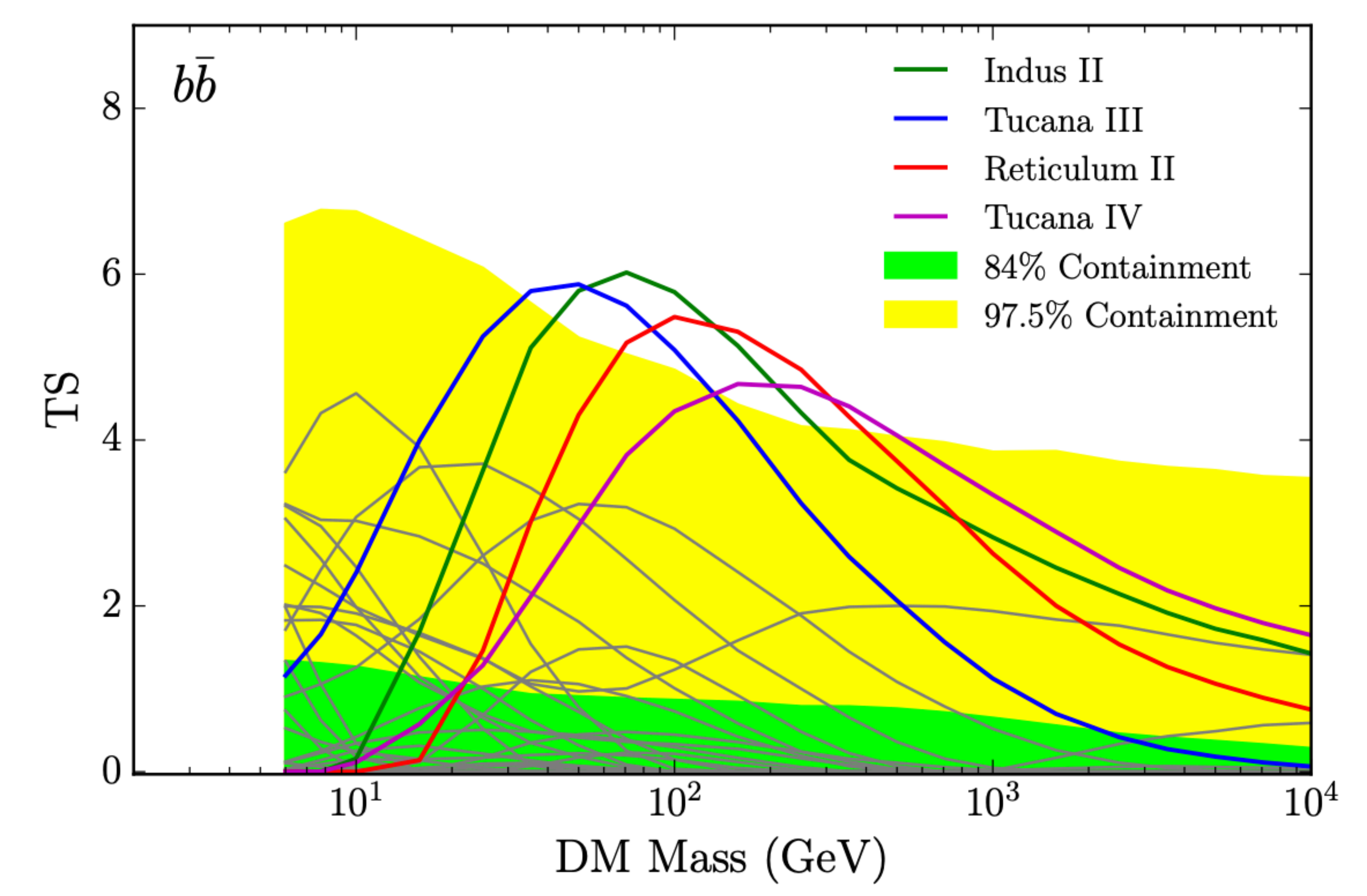


- **Constrains hit the thermal cross-section!**

Angular Mapping

Part 2: Dwarf Spheroidal Galaxies

Fermi-LAT Collaboration (2016; 1611.03184)



- **Even in easy systems, mismodeling is a significant issue.**

The Two Types of Dark Matter

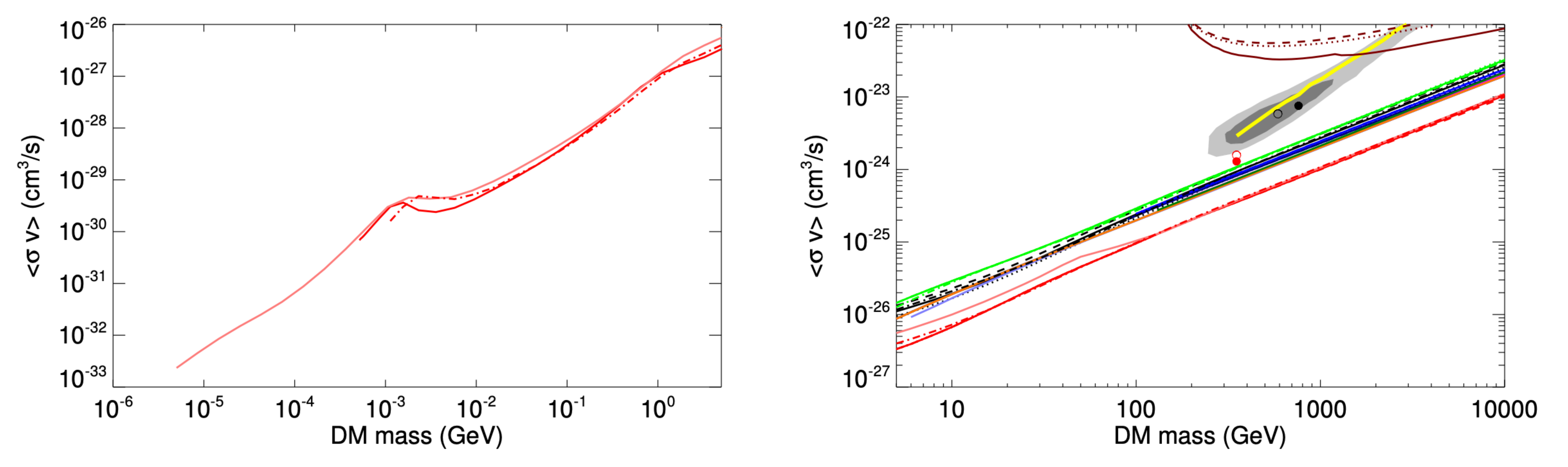
- **Dark Matter signals that have low statistical significance.**

- **Dark Matter signals that might also be pulsars.**

Odds and Ends

Slatyer (2015; 1506.03811)

Cosmic Microwave Background Limits

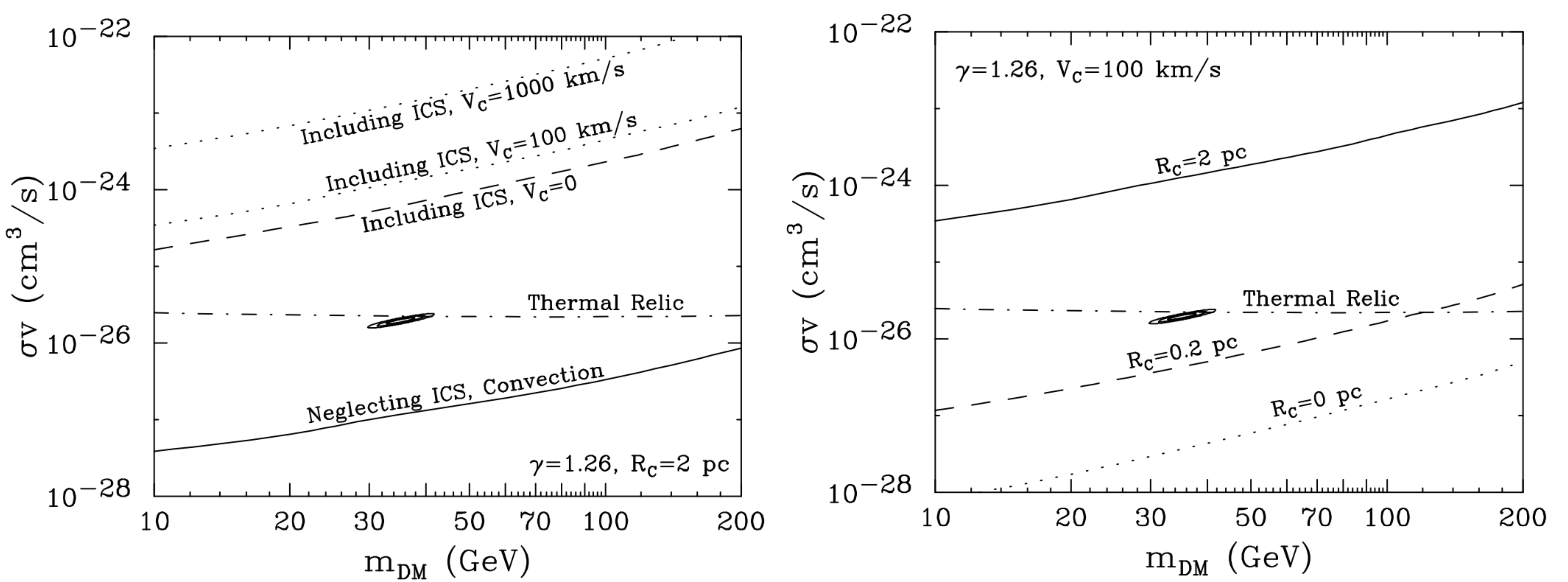


- **Very strong constraints on light dark matter.**
- **Cosmic-variance limited. Constraints will not improve much.**

Odds and Ends

Cholis, Hooper, TL (1408.6224)

Radio Detection Limits



- **Radio telescopes are very sensitive.**
- **Propagation of electrons near sources is highly uncertain.**

Looking Forward

How to End a Talk When You Don't Have a Conclusion

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

Looking Forward

How to End a Talk When You Don't Have a Conclusion

MIT-CTP/5020

GeV-Scale Thermal WIMPs: Not Even Slightly Dead

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[1] *Center for Theoretical Physics, Massachusetts Institute of Technology, Cambridge, MA 02139, USA*
[2] *Center for Cosmology and AstroParticle Physics (CCAPP), Ohio State University, Columbus, OH 43210, USA*
[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.

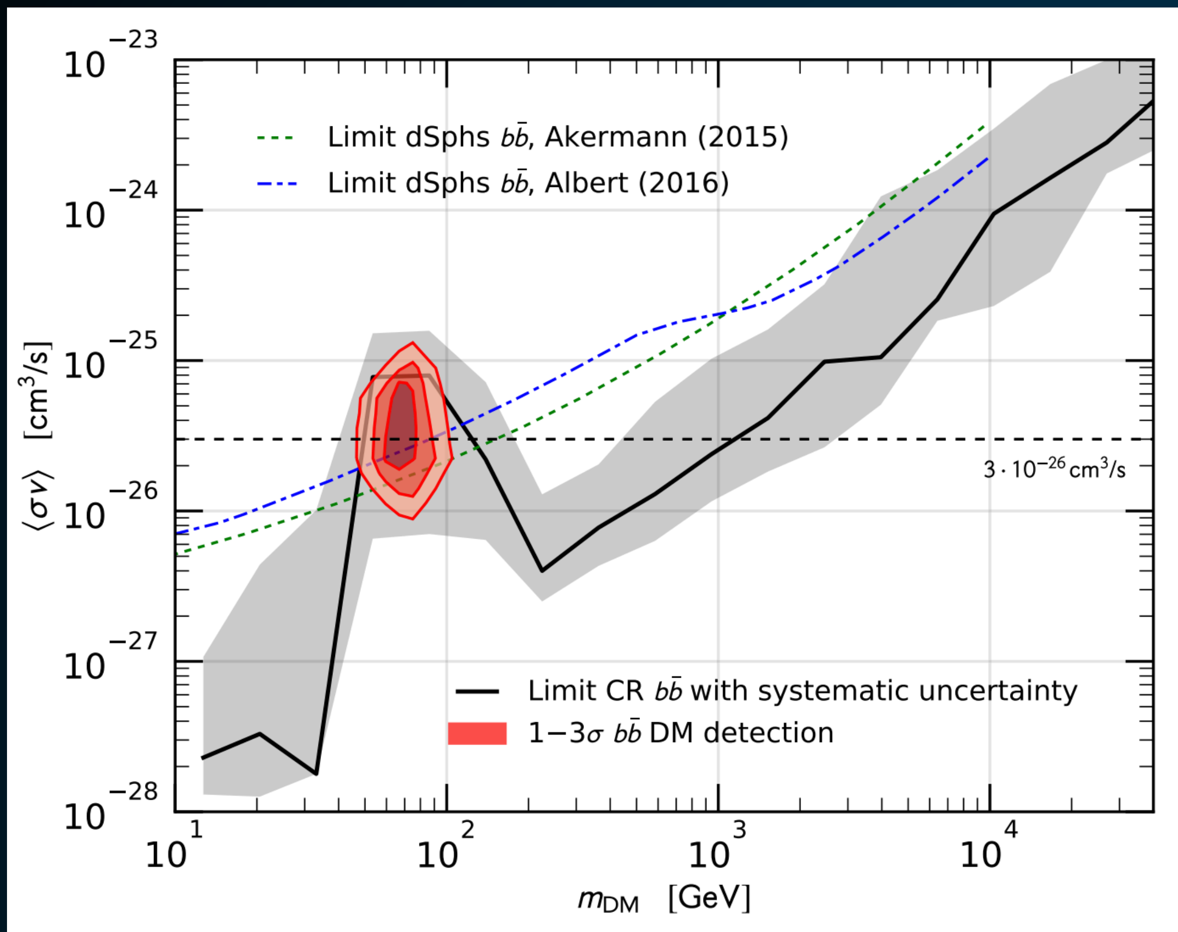
I. INTRODUCTION

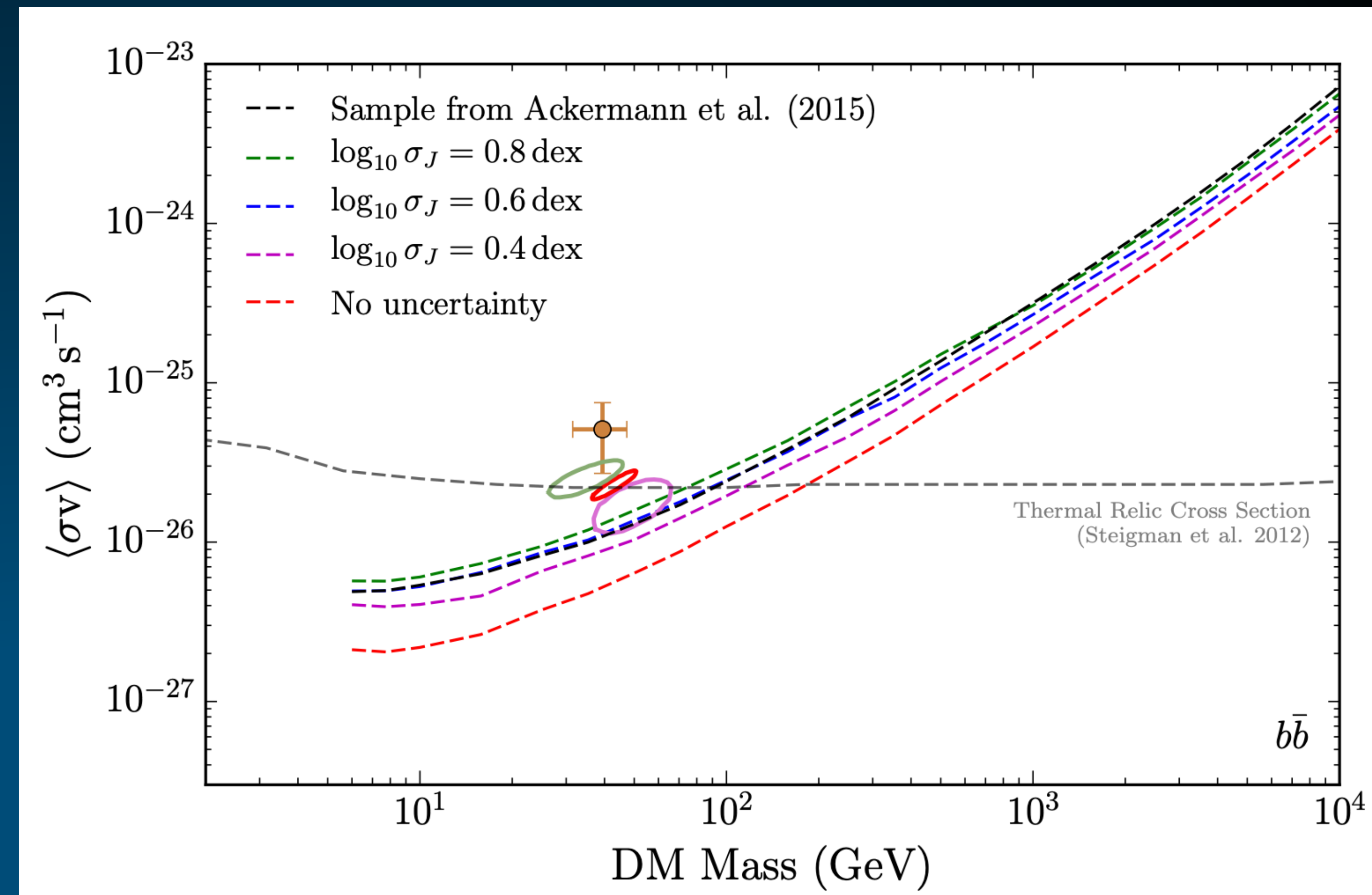
A leading candidate for dark matter (DM) is a Weakly Interacting Massive Particle (WIMP) that is a thermal

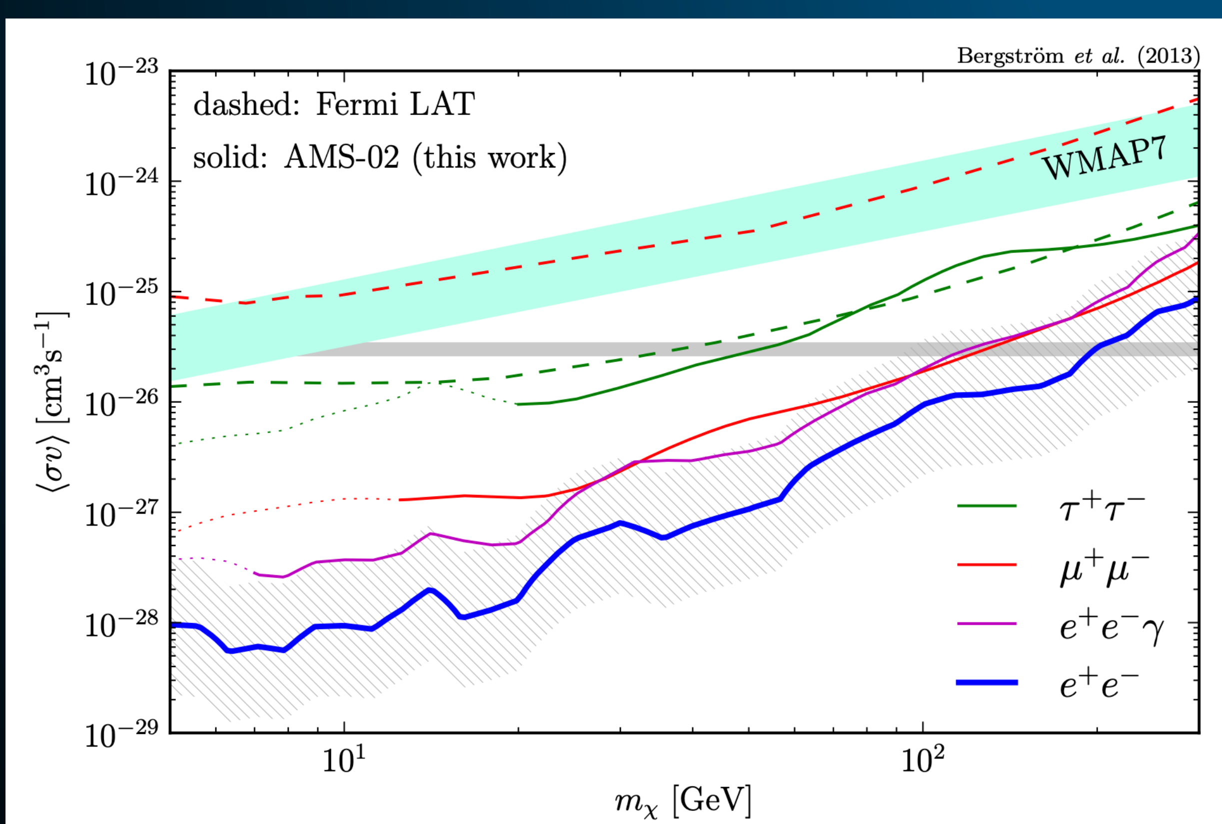
scenarios. The branching ratios, coupling types and signals are model-dependent, and so the lack of observations may just be due to such features. For example, there can be interference effects, momentum suppression, or

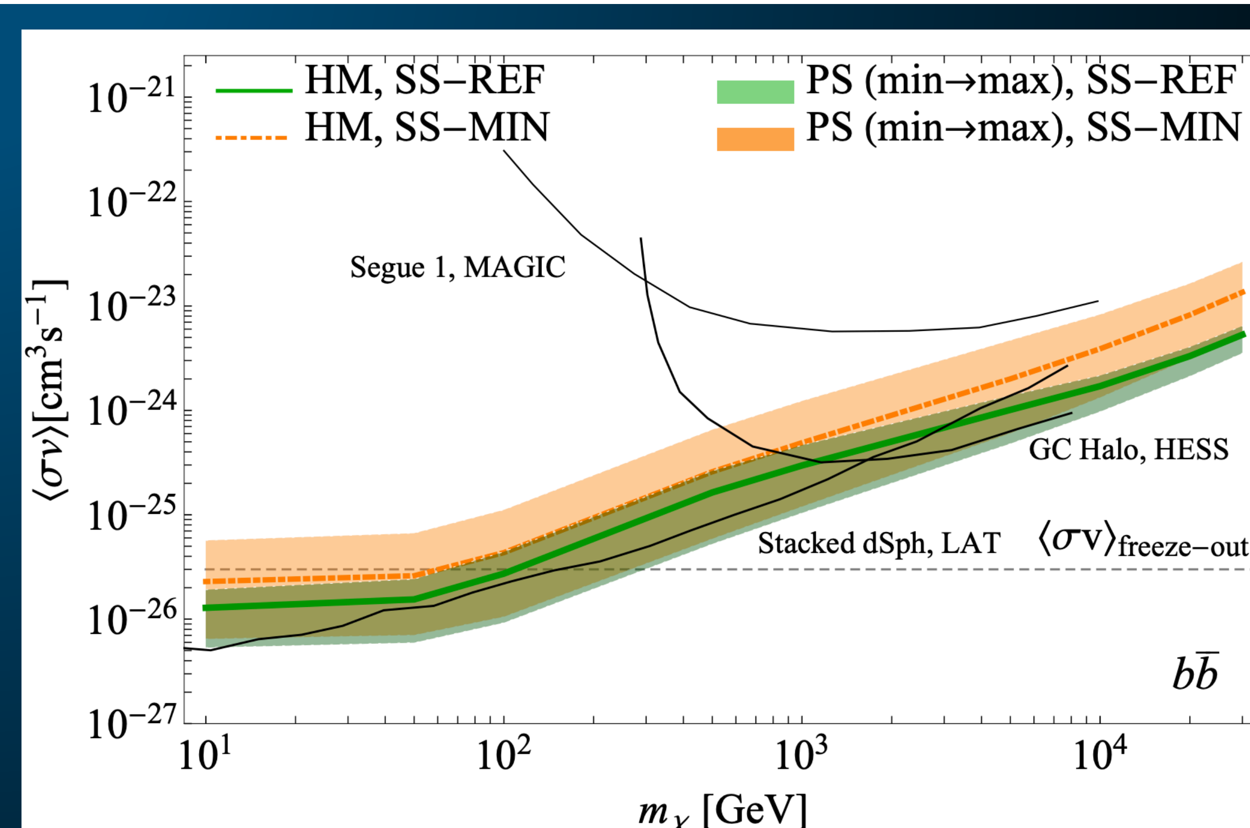
Looking Forward

How to End a Talk When You Don't Have a Conclusion



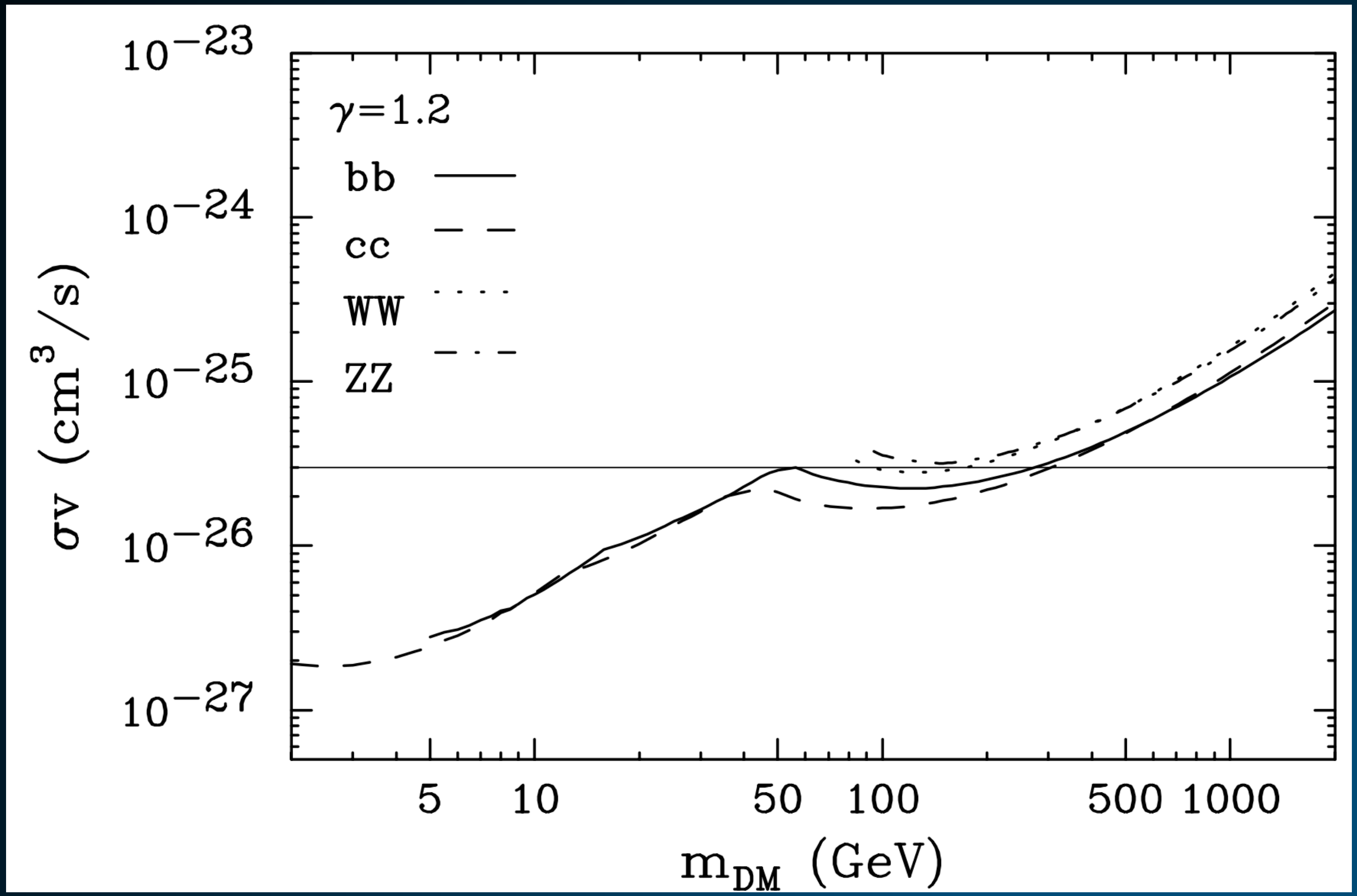


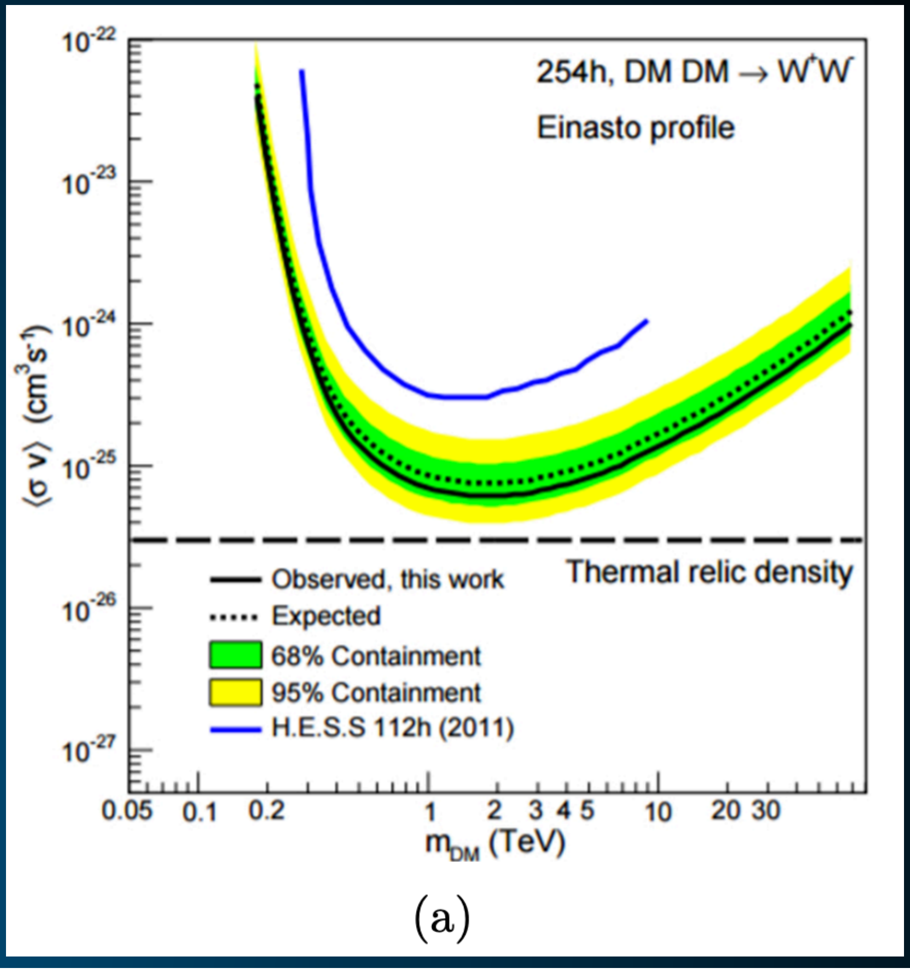


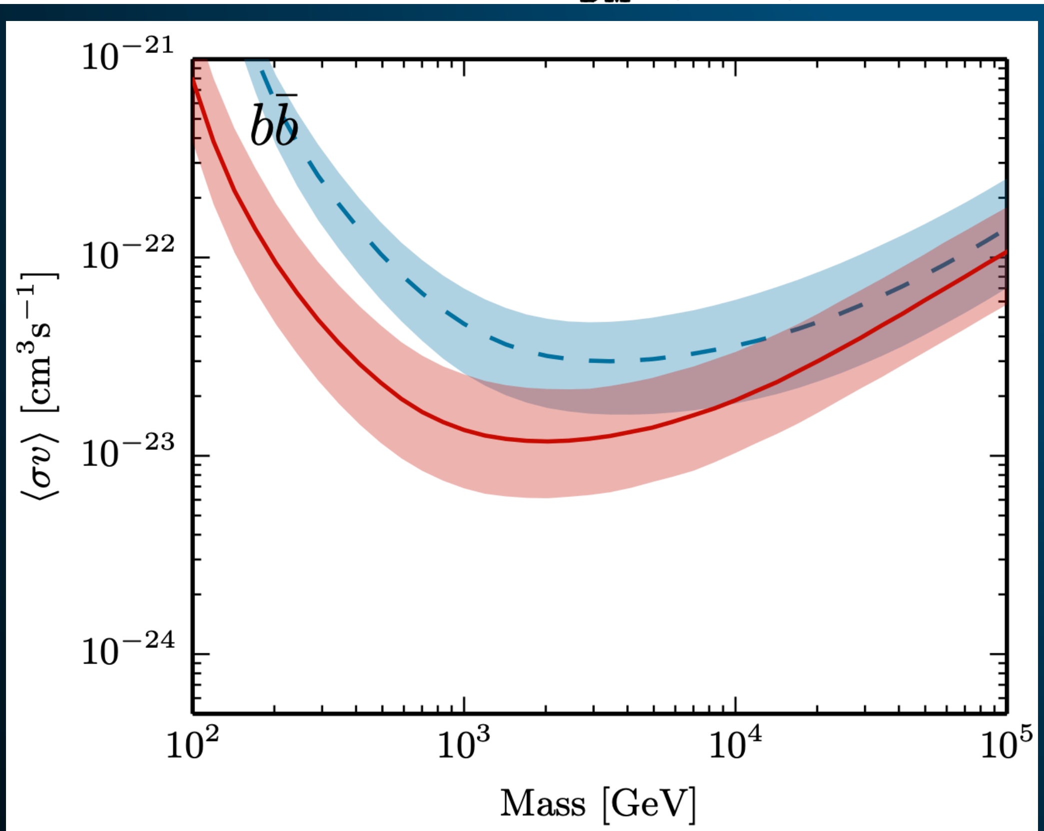


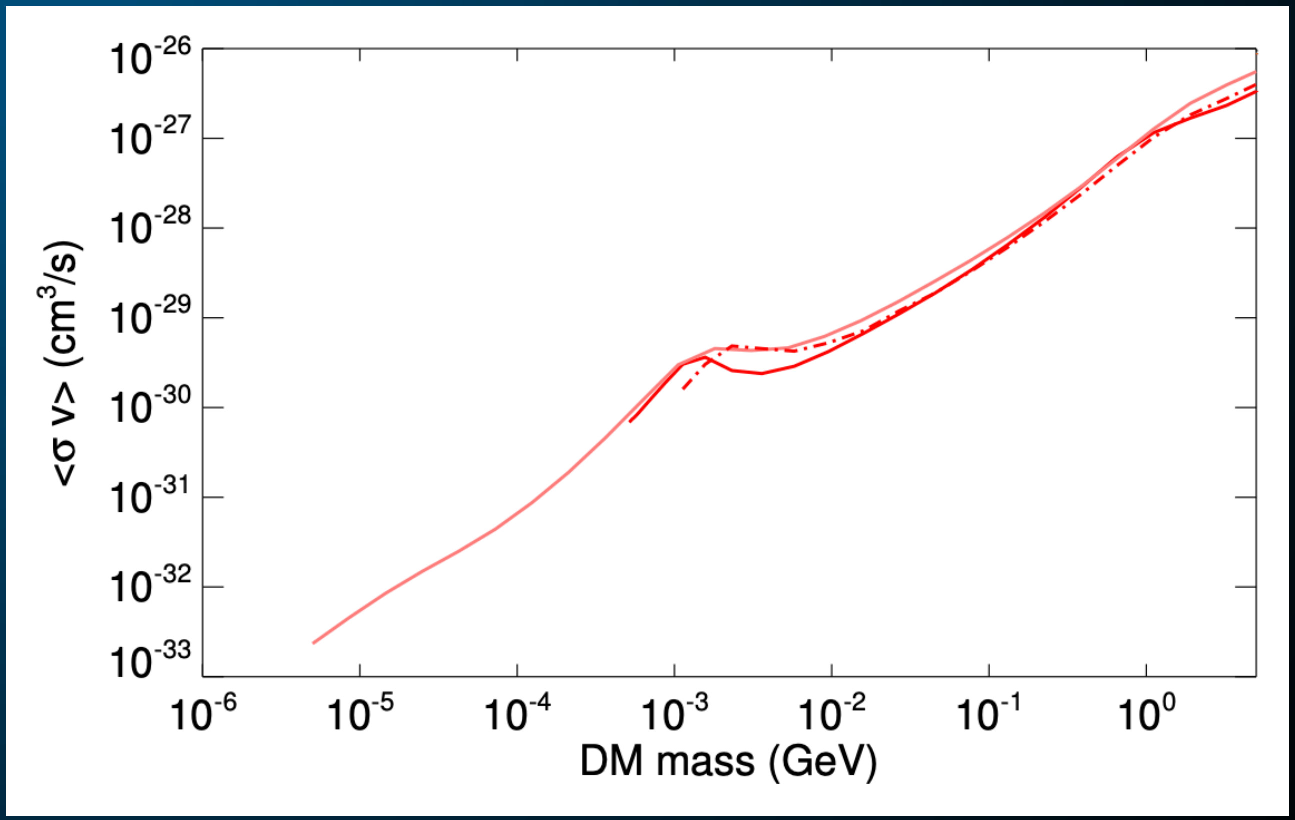
Looking Forward

How to End a Talk When You Don't Have a Conclusion





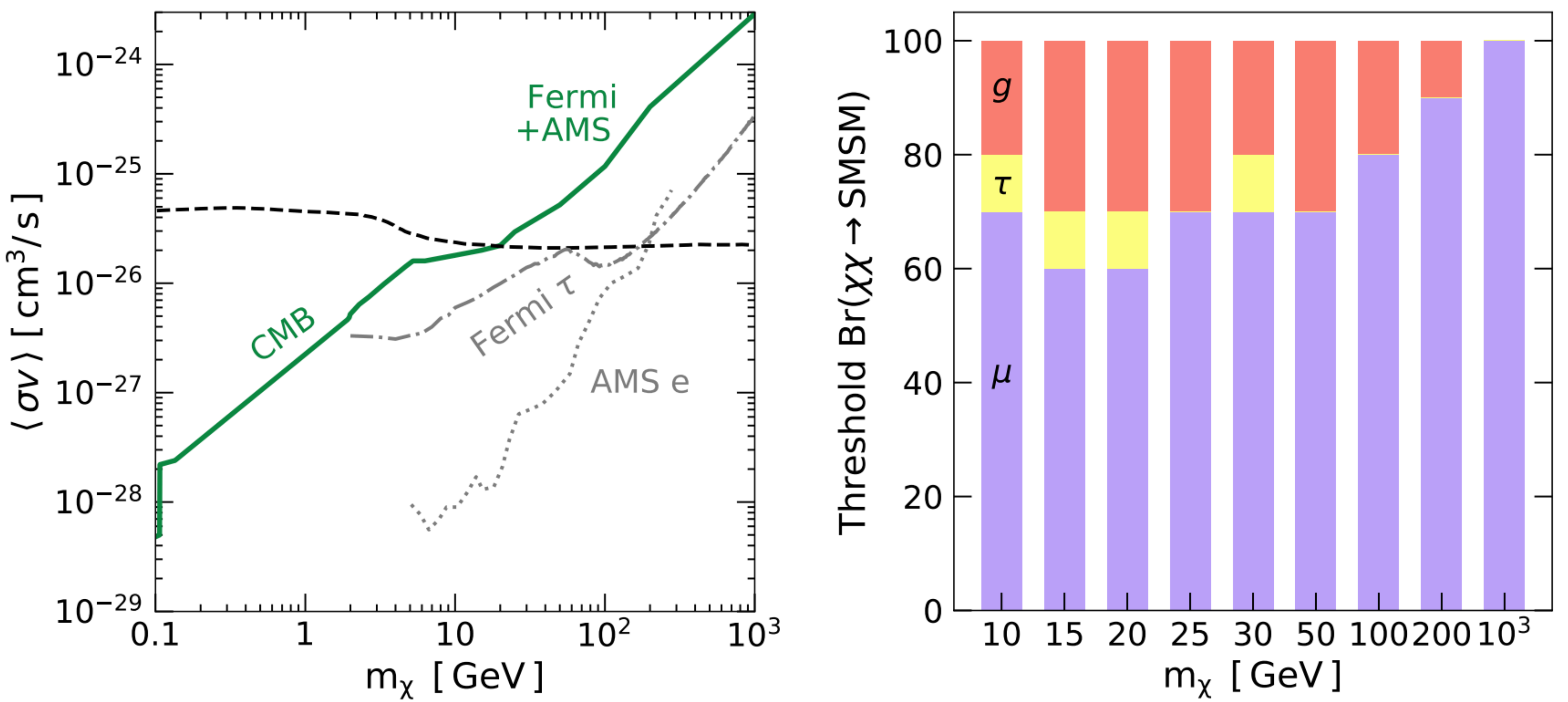




Looking Forward

Leane et al. (2018; 1805.10305)

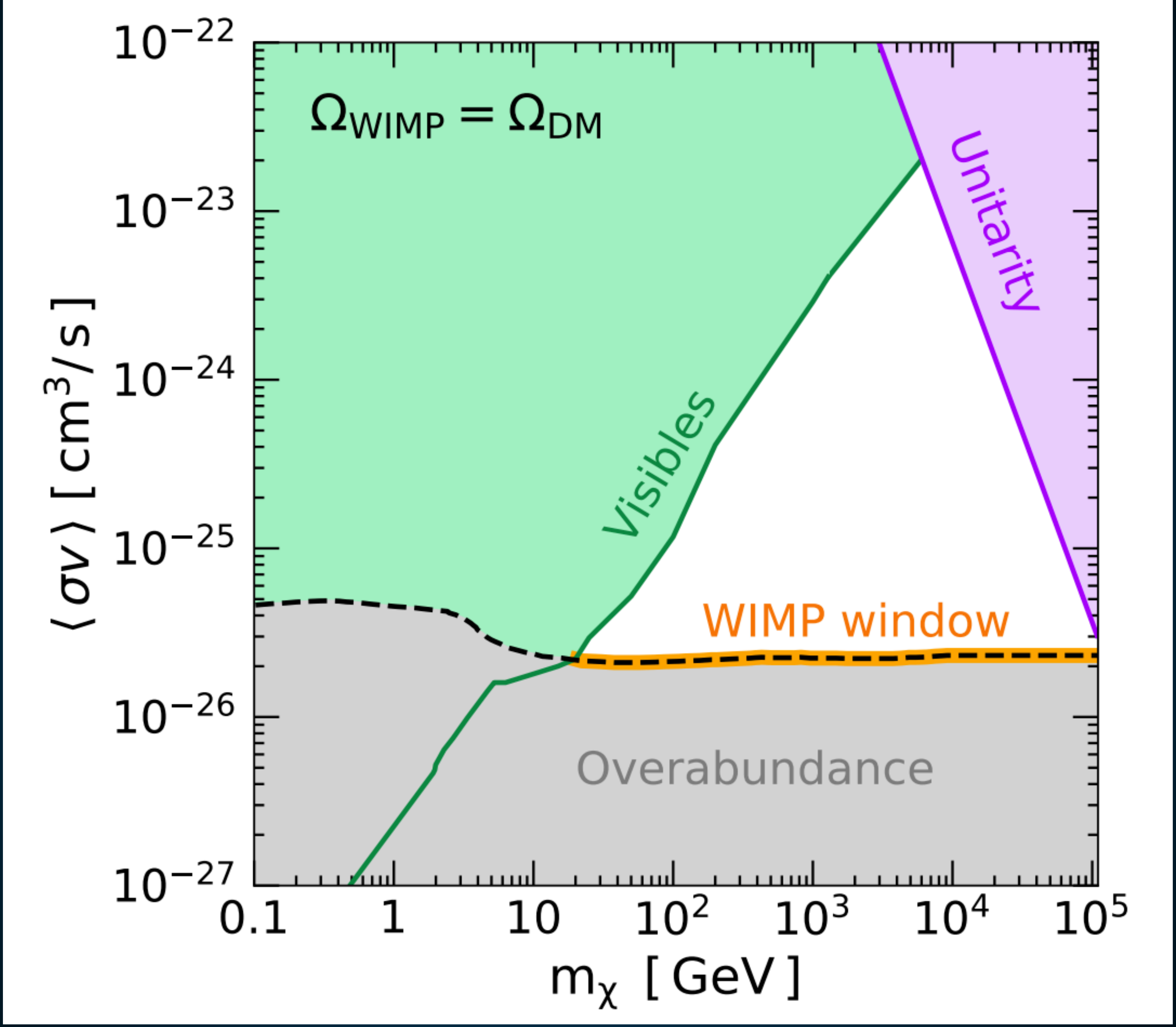
How to End a Talk When You Don't Have a Conclusion



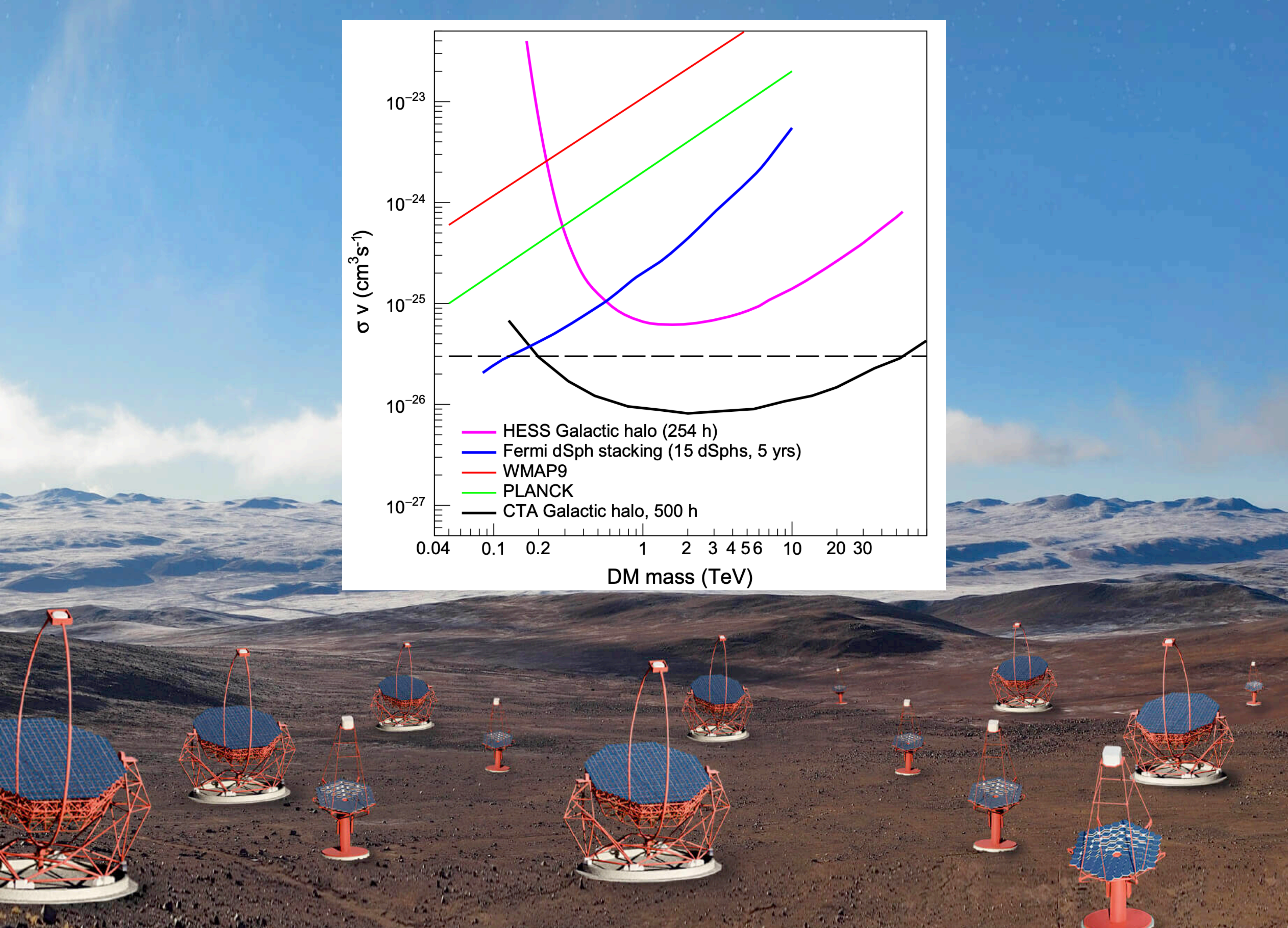
Looking Forward

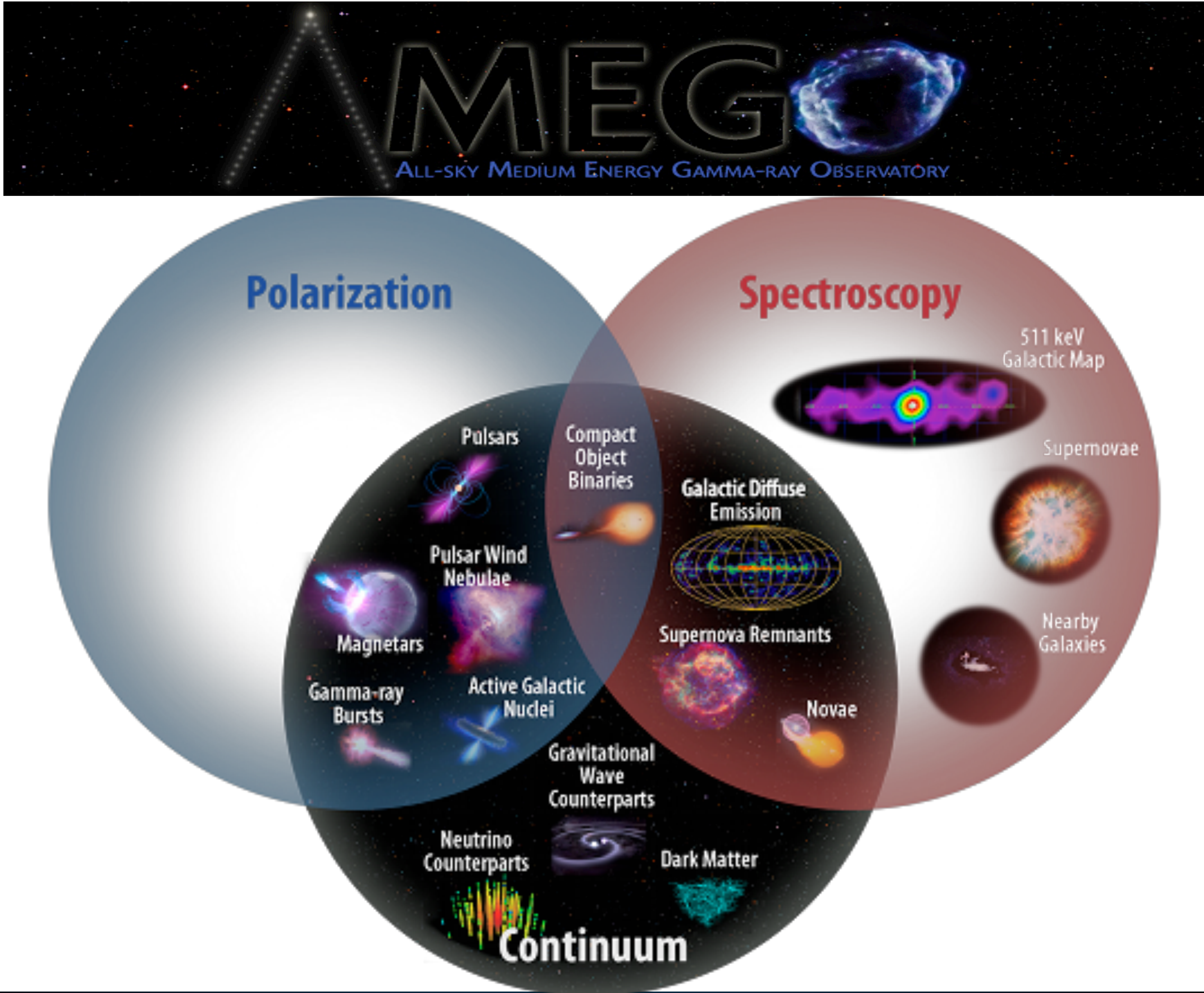
Leane et al. (2018; 1805.10305)

How to End a Talk When You Don't Have a Conclusion

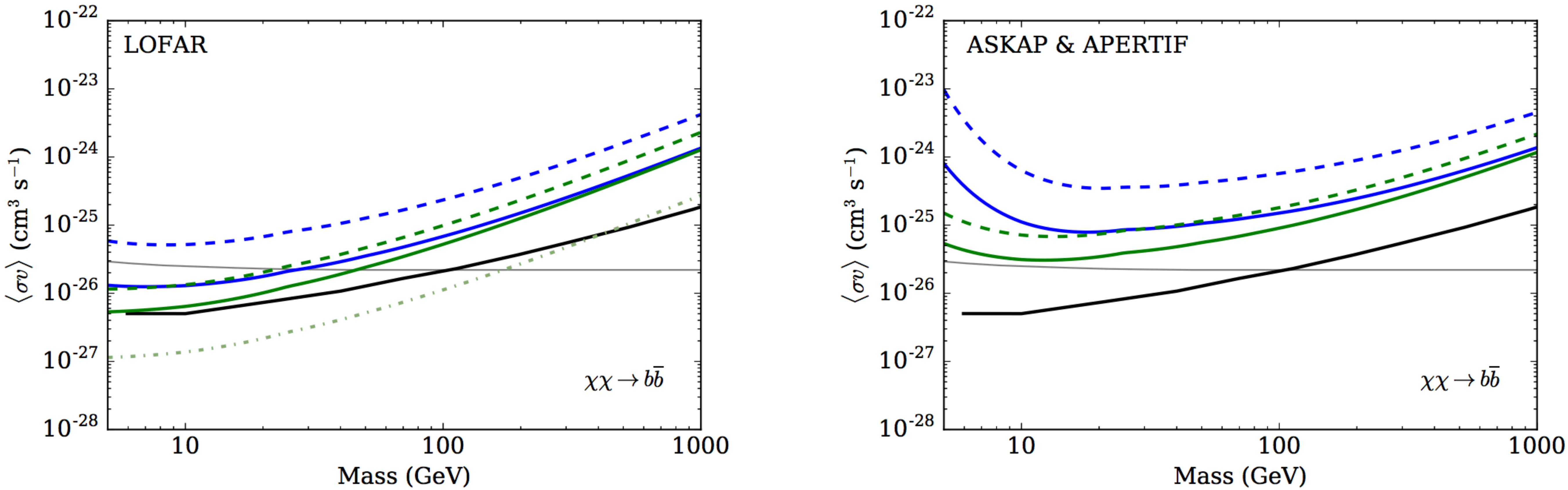


Morselli (2017; 1709.01483)

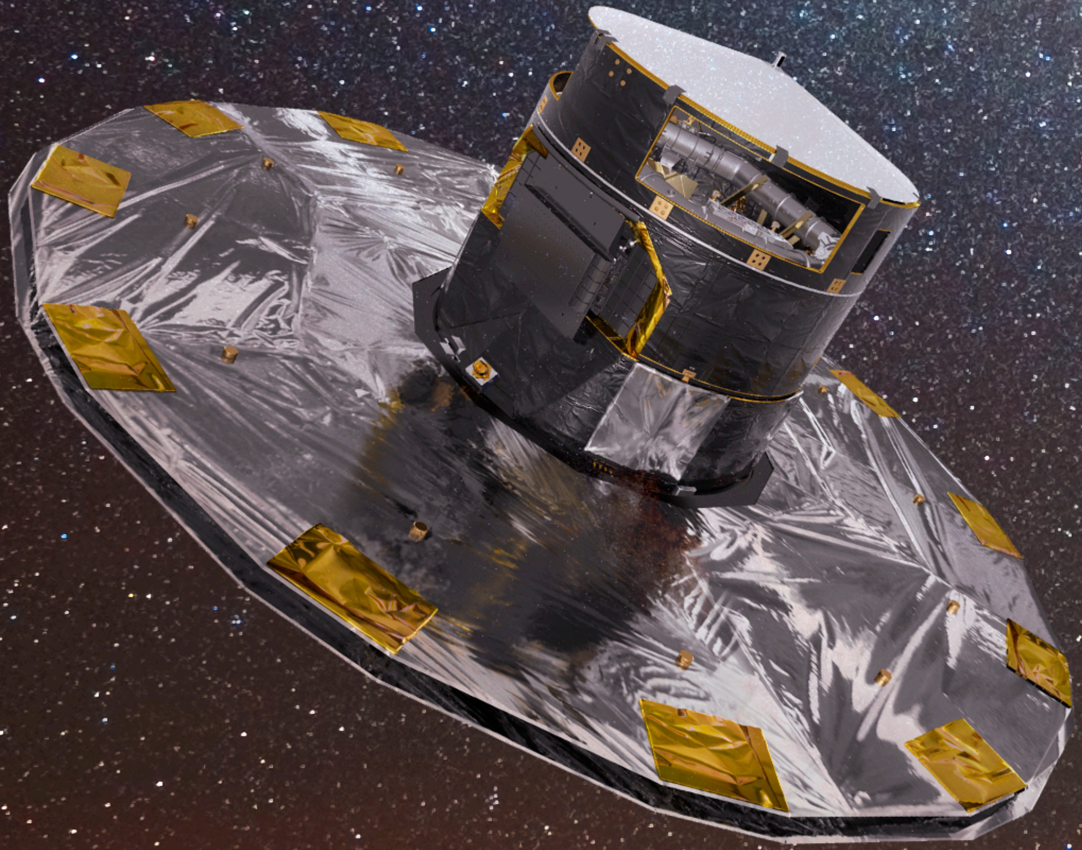


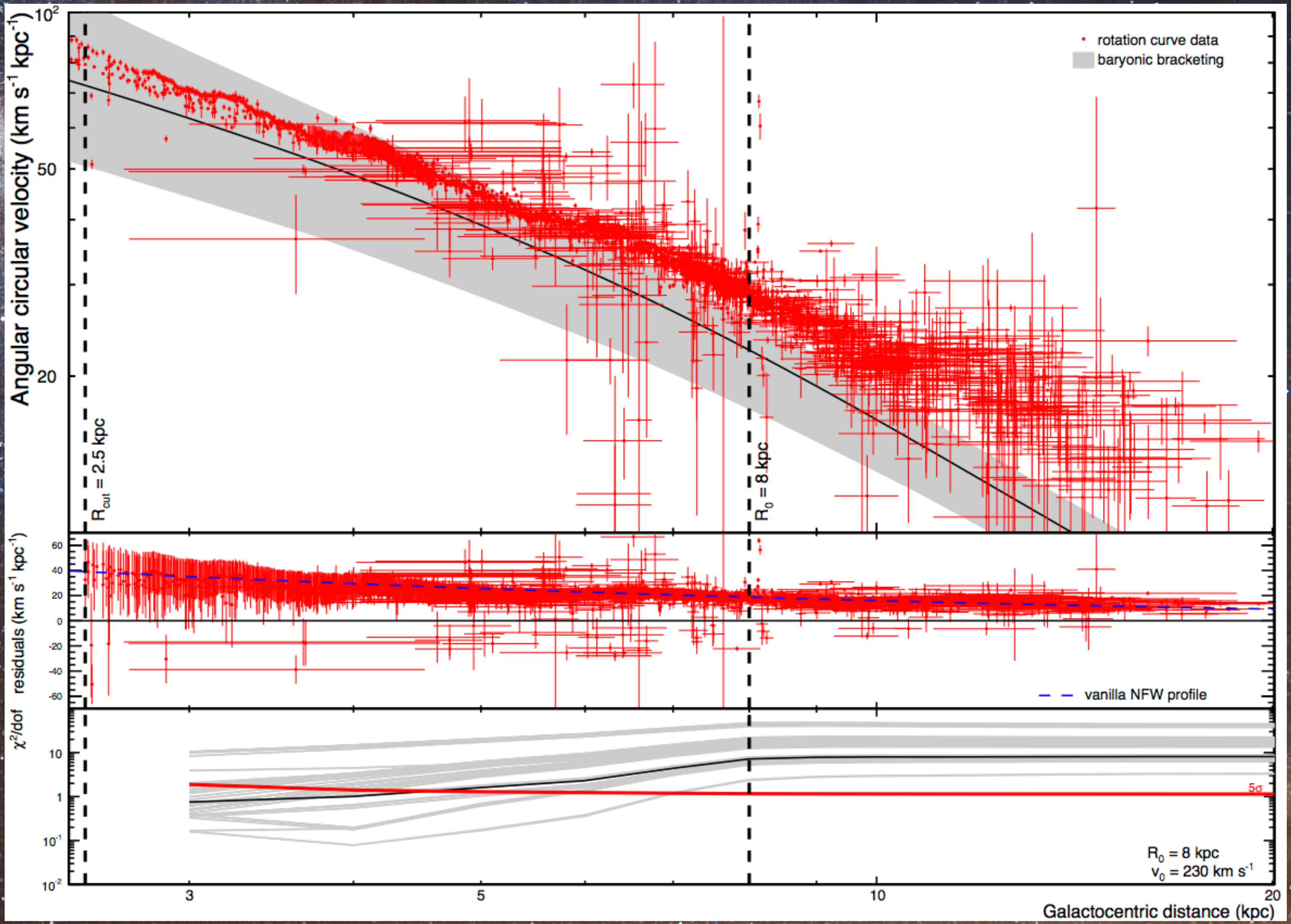

AMEGO
ALL-SKY MEDIUM ENERGY GAMMA-RAY OBSERVATORY
Polarization
Spectroscopy
511 keV Galactic Map
Supernovae
Nearby Galaxies
Pulsars
Compact Object Binaries
Galactic Diffuse Emission
Pulsar Wind Nebulae
Magnetars
Supernova Remnants
Gamma-ray Bursts
Active Galactic Nuclei
Novae
Gravitational Wave Counterparts
Neutrino Counterparts
Dark Matter
Continuum

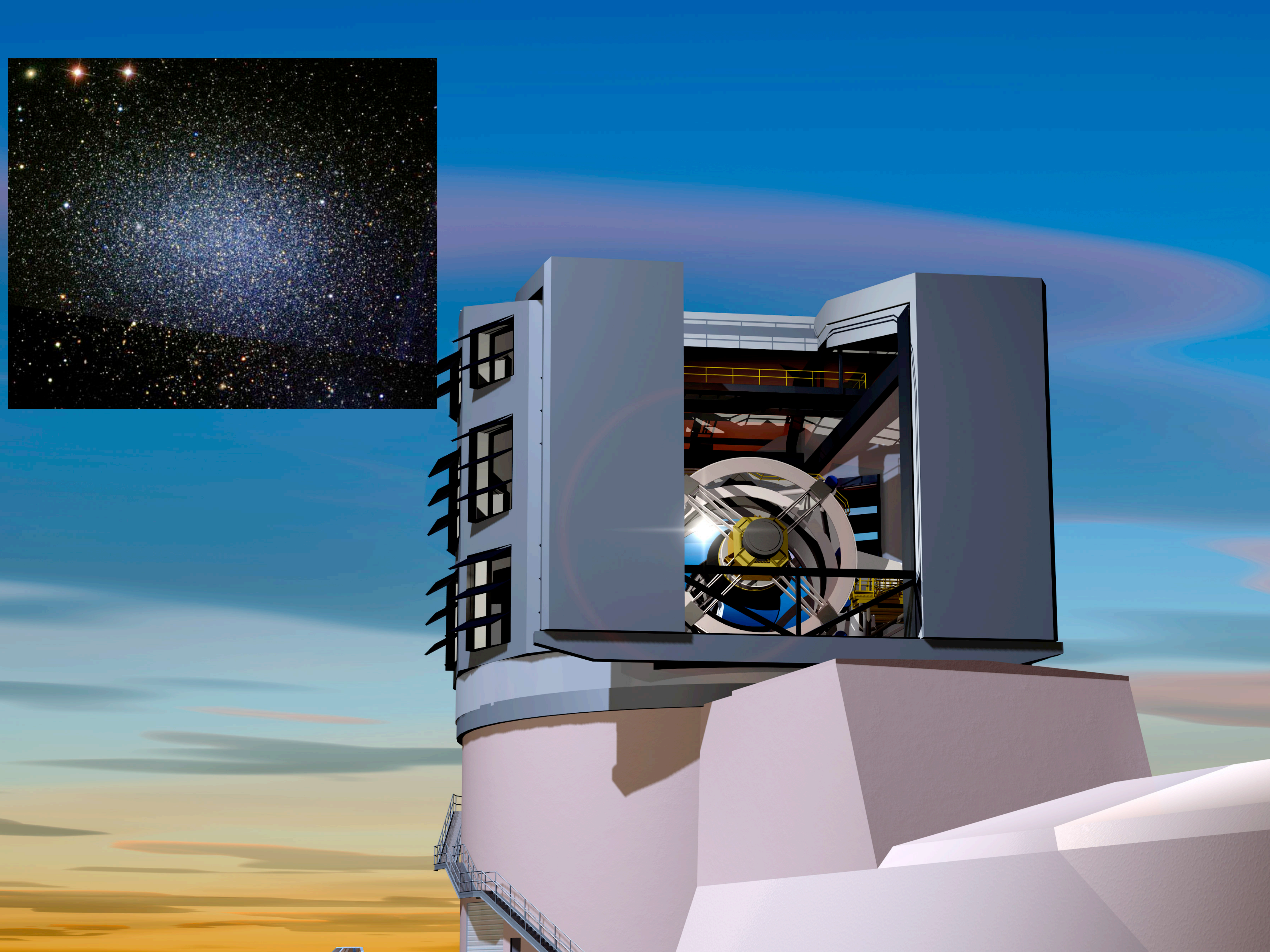
Storm et al. (2016; 1607.01049)

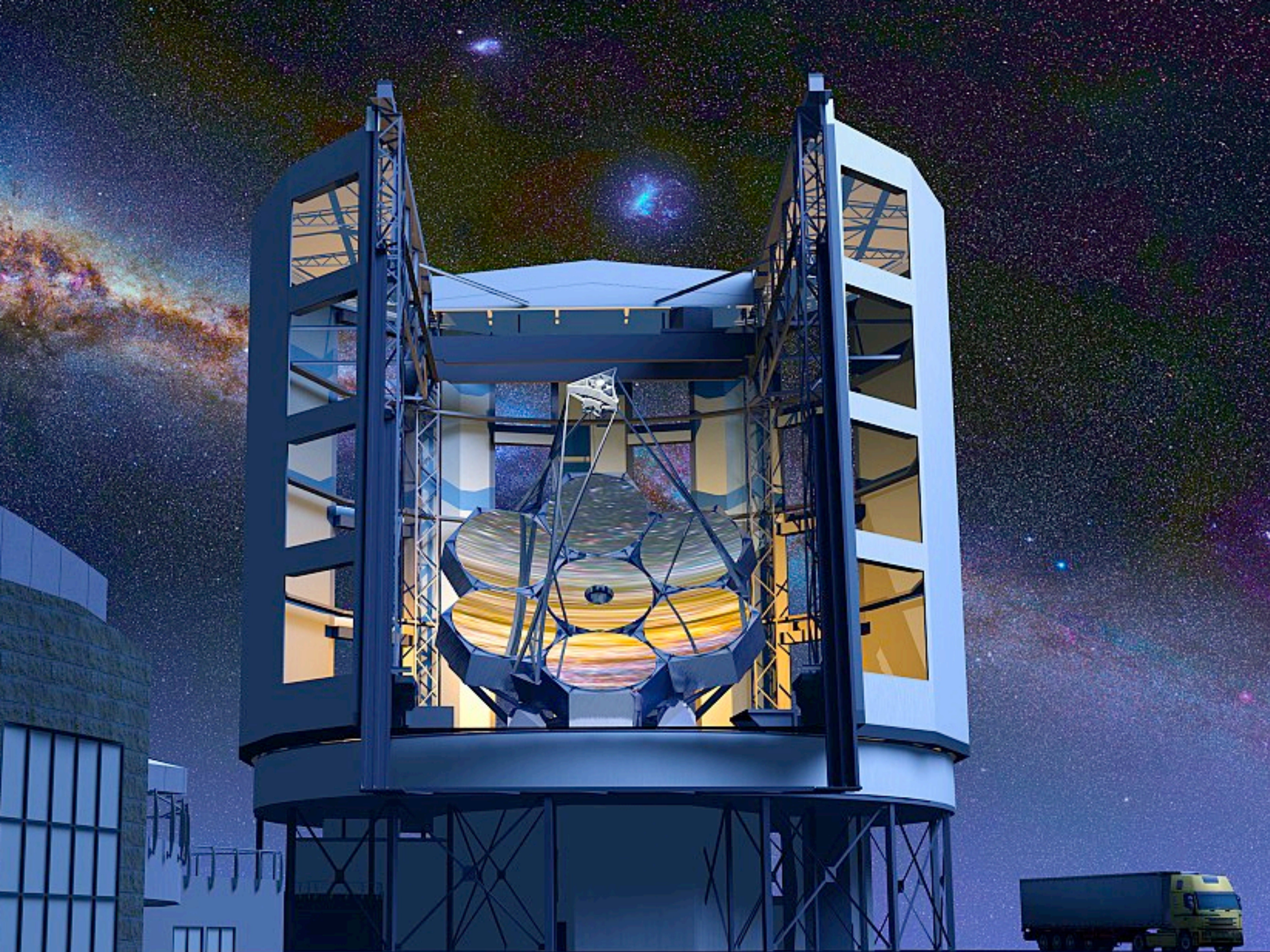


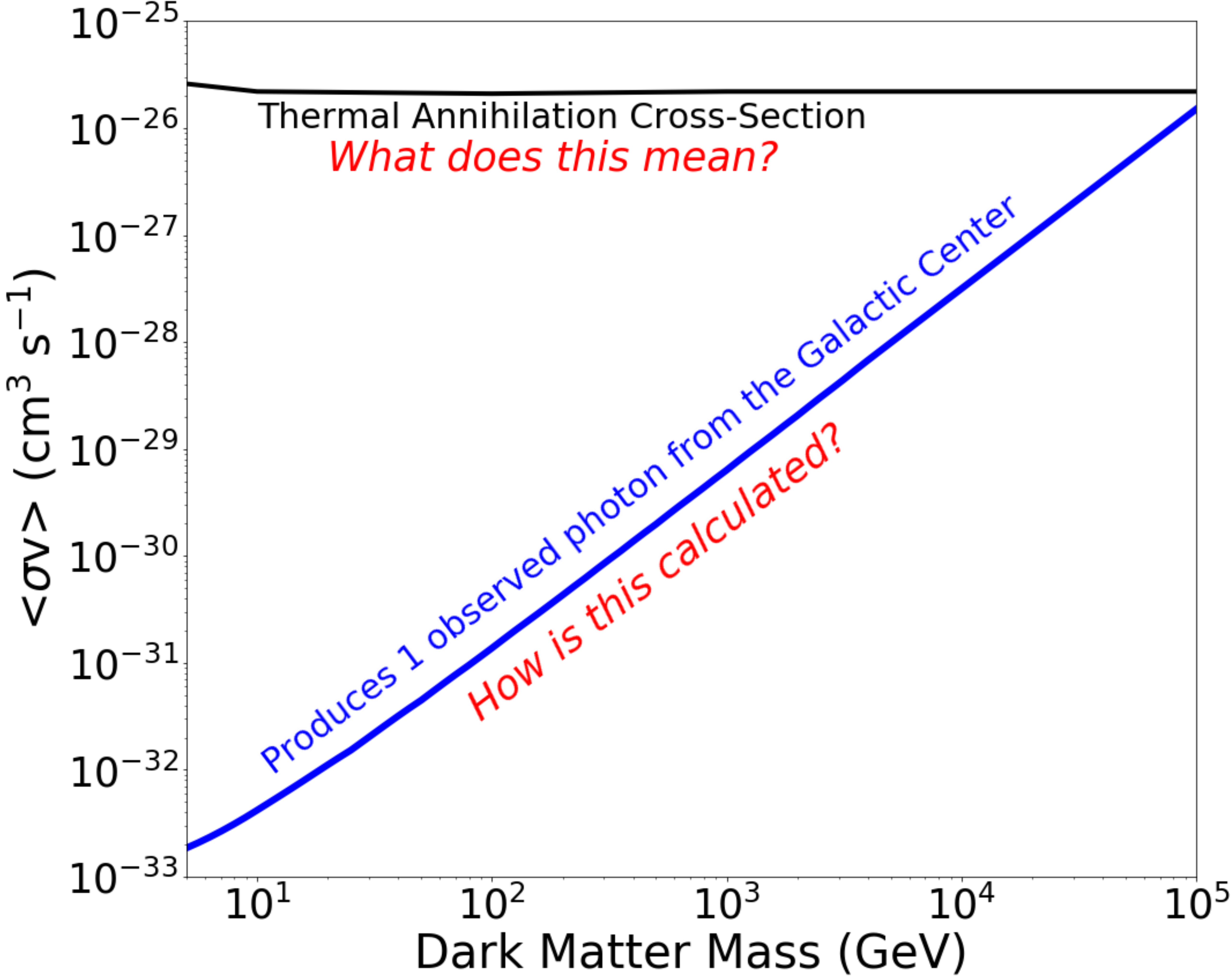
Iocco et al. (2015; 1502.03821)





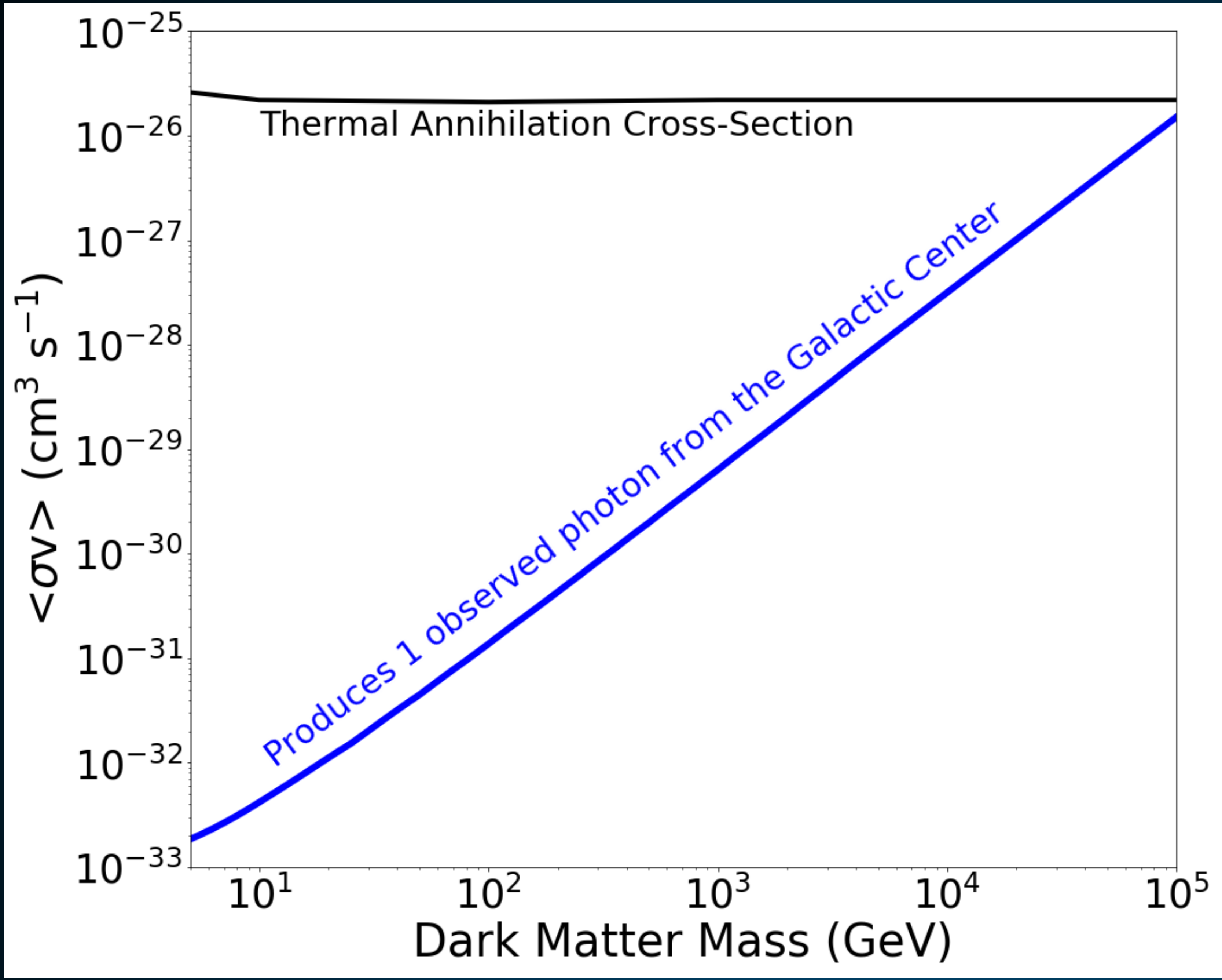





Thermal Annihilation Cross-Section
What does this mean?
Produces 1 observed photon from the Galactic Center
How is this calculated?
$\langle\sigma v\rangle$ (cm^3 s^{-1})
10^{-25}
10^{-26}
10^{-27}
10^{-28}
10^{-29}
10^{-30}
10^{-31}
10^{-32}
10^{-33}
10^1
10^2
10^3
10^4
10^5
Dark Matter Mass (GeV)

Looking Forward

How to End a Talk When You Don't Have a Conclusion



Looking Forward

How to End a Talk When You Don't Have a Conclusion

Origin of the Cosmic Ray Galactic Halo Driven by Advected Turbulence and Self-Generated Waves

Carmelo Evoli,[1,2,*] Pasquale Blasi,[1,2,3,†] Giovanni Morlino,[1,2,3,‡] and Roberto Aloisio[1,2,§]

[1]*Gran Sasso Science Institute, Viale F. Crispi 7, L'Aquila, Italy*
[2]*INFN/Laboratori Nazionali del Gran Sasso, Via G. Acitelli 22, Assergi (AQ), Italy*
[3]*INAF/Osservatorio Astrofico di Arcetri, L.go E. Fermi 5, Firenze, Italy*

The diffusive paradigm for the transport of Galactic cosmic rays is central to our understanding of the origin of these high energy particles. However it is worth recalling that the normalization, energy dependence and spatial extent of the diffusion coefficient in the interstellar medium are fitted to the data and typically are not derived from more basic principles. Here we discuss a scenario in which the diffusion properties of cosmic rays are derived from a combination of wave self-generation and advection from the Galactic disc, where the sources of cosmic rays are assumed to be located. We show for the first time that a halo naturally arises from these phenomena, with a size of a few kpc, compatible with the value that typically best fits observations in simple parametric approaches to cosmic ray diffusion. We also show that transport in such a halo results in a hardening in the spectra of primary cosmic rays at ~ 300 GV.

Introduction – Understanding cosmic-ray (CR) propagation in the Galaxy and its implications for observations at different energies and with different messengers is one of the challenges of modern astroparticle physics.

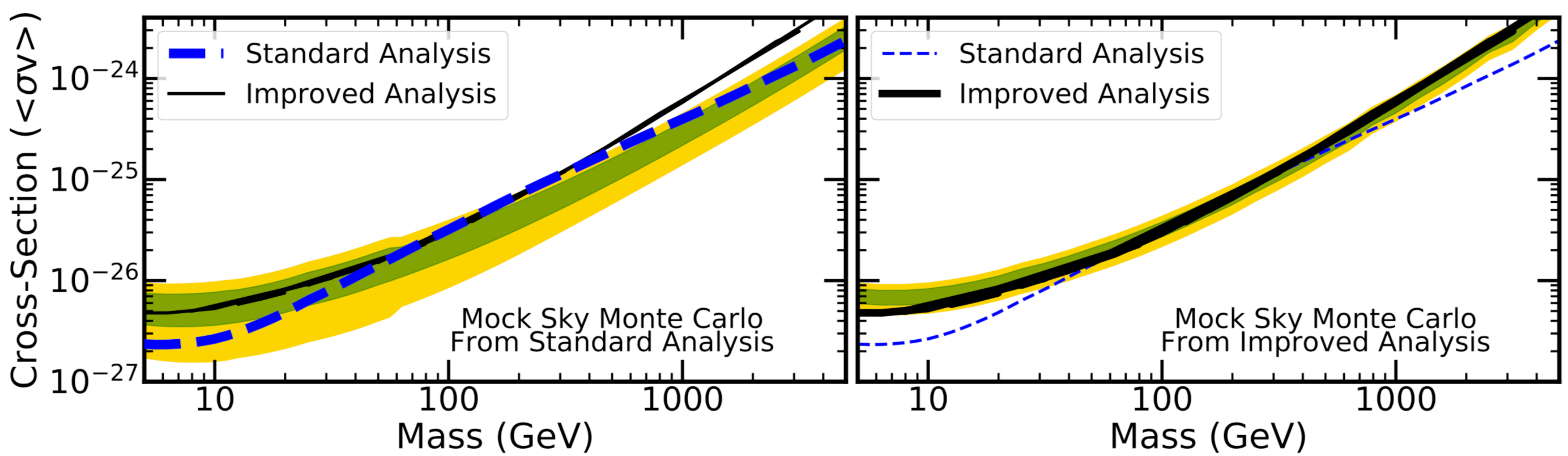
The standard scenario adopted to describe Galactic propagation in terms of properties of the interstellar turbulence is the so called *galactic halo model* proposed by Ginzburg and Syrovatskii in 1964 [1] and described in detail in [2]. The halo model is usually implemented assuming that CRs are produced by sources located in the thin Galactic disc and then diffuse by scattering off random magnetic fluctuations in a low-density confinement region ("halo") extending well be-

grammage that scales with rigidity as $R^{-1/3}$, that is claimed to be consistent with the diffusion coefficient expected from transport in a turbulence with Kolmogorov spectrum, $D(R) \sim 10^{28}(R/\mathrm{GV})^{1/3}$ cm^2 s^{-1}.

An independent piece of evidence of the existence of a magnetized halo comes from observations in the radio band of diffuse synchrotron emission, revealing the presence of electrons and magnetic fields above and below the Galactic plane [6]. The existence of a halo of several kpc size can be inferred from a comparison between numerical models for the CR electron distribution and the morphology of the radio emission [7, 8]. It is worth mentioning that radio halos with a

Looking Forward

How to End a Talk When You Don't Have a Conclusion



Accounting for Astrophysical Mismodeling Significantly Affects Dark Matter Annihilation Constraints from Dwarf Spheroidal Galaxies

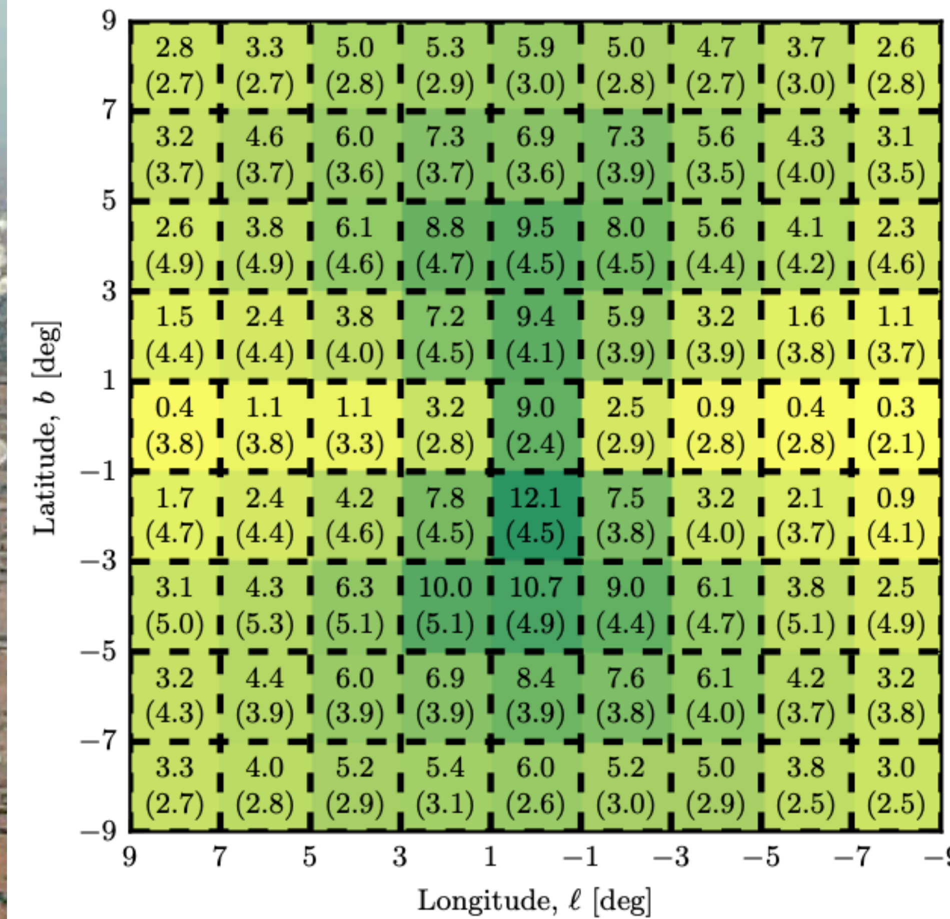
Tim Linden*
Center for Cosmology and AstroParticle Physics (CCAPP), and Department of Physics, The Ohio State University Columbus, OH, 43210

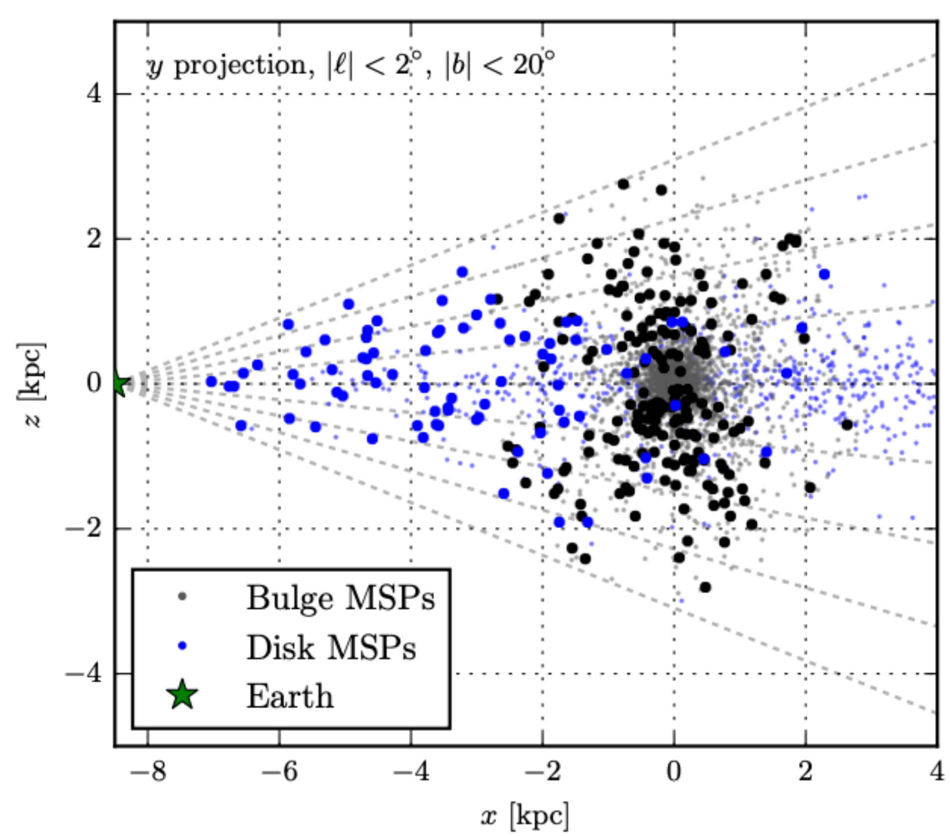
Fermi-LAT observations have strongly constrained dark matter annihilation through the joint-likelihood analysis of dwarf spheroidal galaxies (dSphs). These constraints are expected to be robust because dSphs have measureable dark matter content and produce negligible astrophysical emission. However, each dSph is dim, with a typical flux that falls below the accuracy of the background model. We show that this significantly diminishes the reliability of previous joint-likelihood algorithms, and develop an improved analysis that directly accounts for the effect of background mismodeling. This method produces more robust limits and detections of dark matter in both real and mock data. We calculate improved limits on the dark matter annihilation cross-section,

Looking Forward

Calore et al. (2016; 1512.06825)

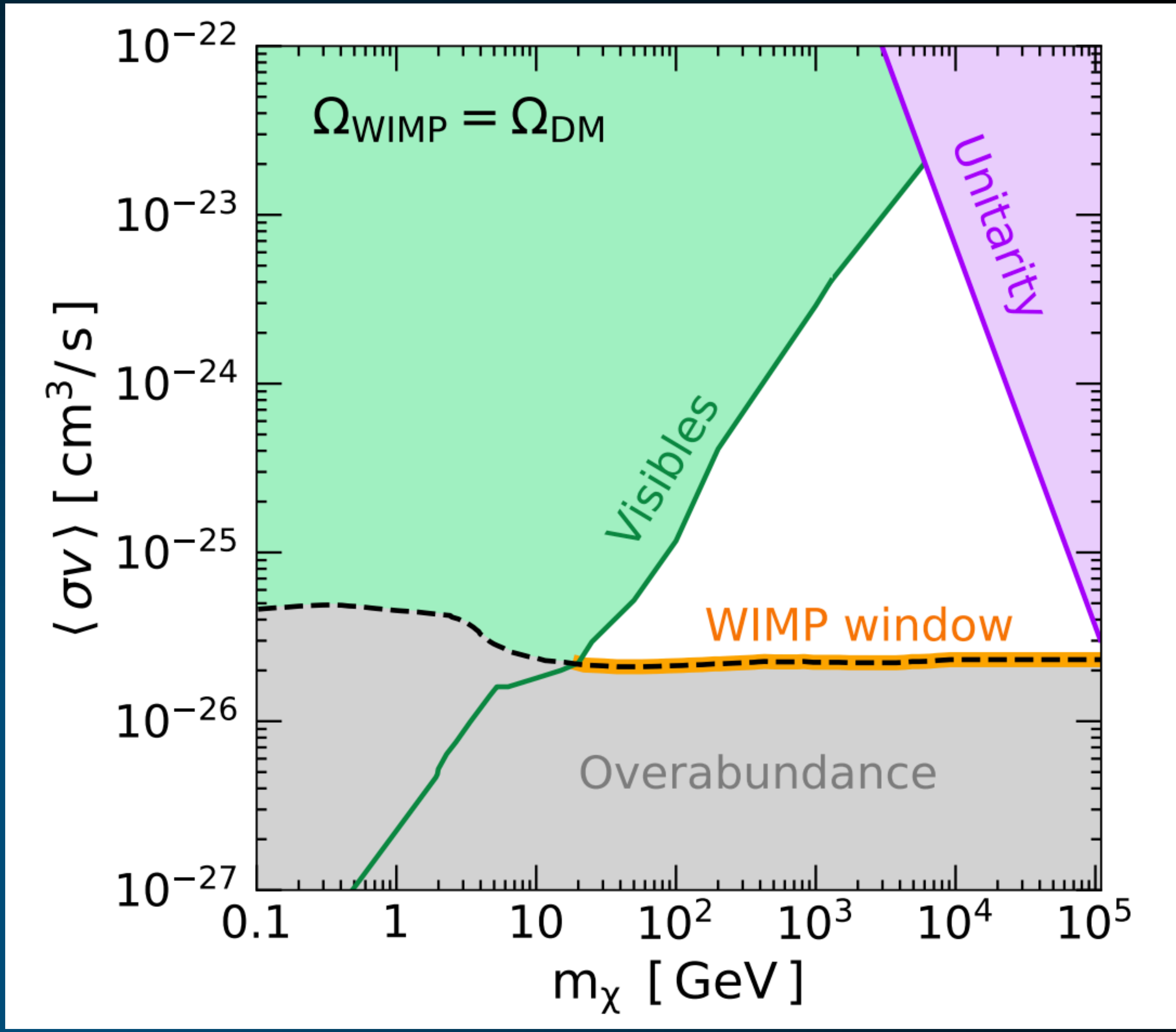
How to End a Talk When You Don't Have a Conclusion





Null Results are Interesting!

- **non-Thermal Dark Matter**
  - **Axions**
  - **Sterile Neutrinos**
- **Dark Sectors**
- **Modifications to Gravity**
- **Primordial Black Holes**
- **Q-balls**
- **Asymmetric Dark Matter**
- **Coannihilations, Resonances**
- **Self-Interacting Dark Matter, Light Mediators**



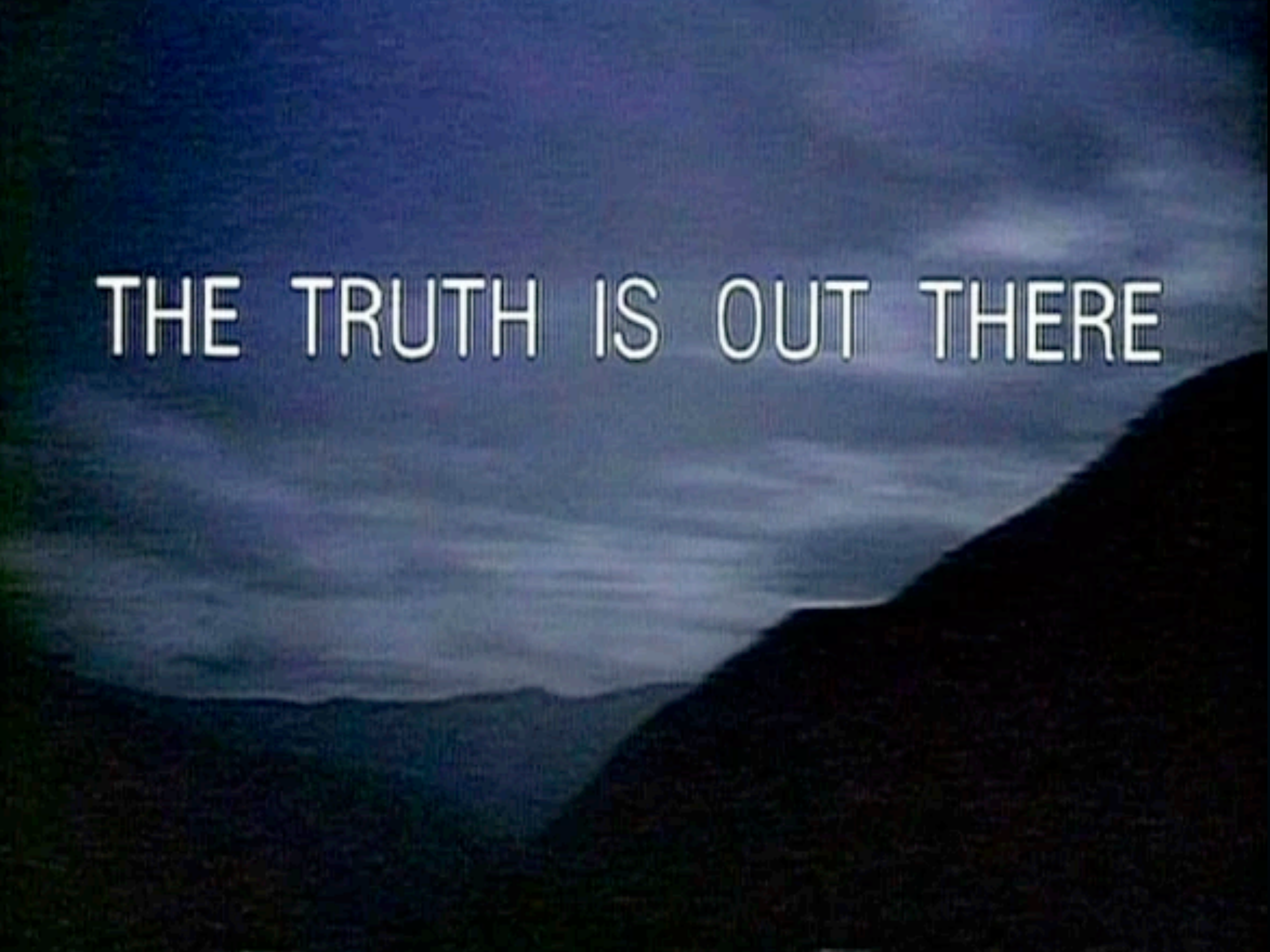
10^{-25} GeV

$\sigma_X > R_{UFD}$

10^{62} GeV

$m_X > M_{UFD}$

slide concept courtesy of Asher Berlin


THE TRUTH IS OUT THERE

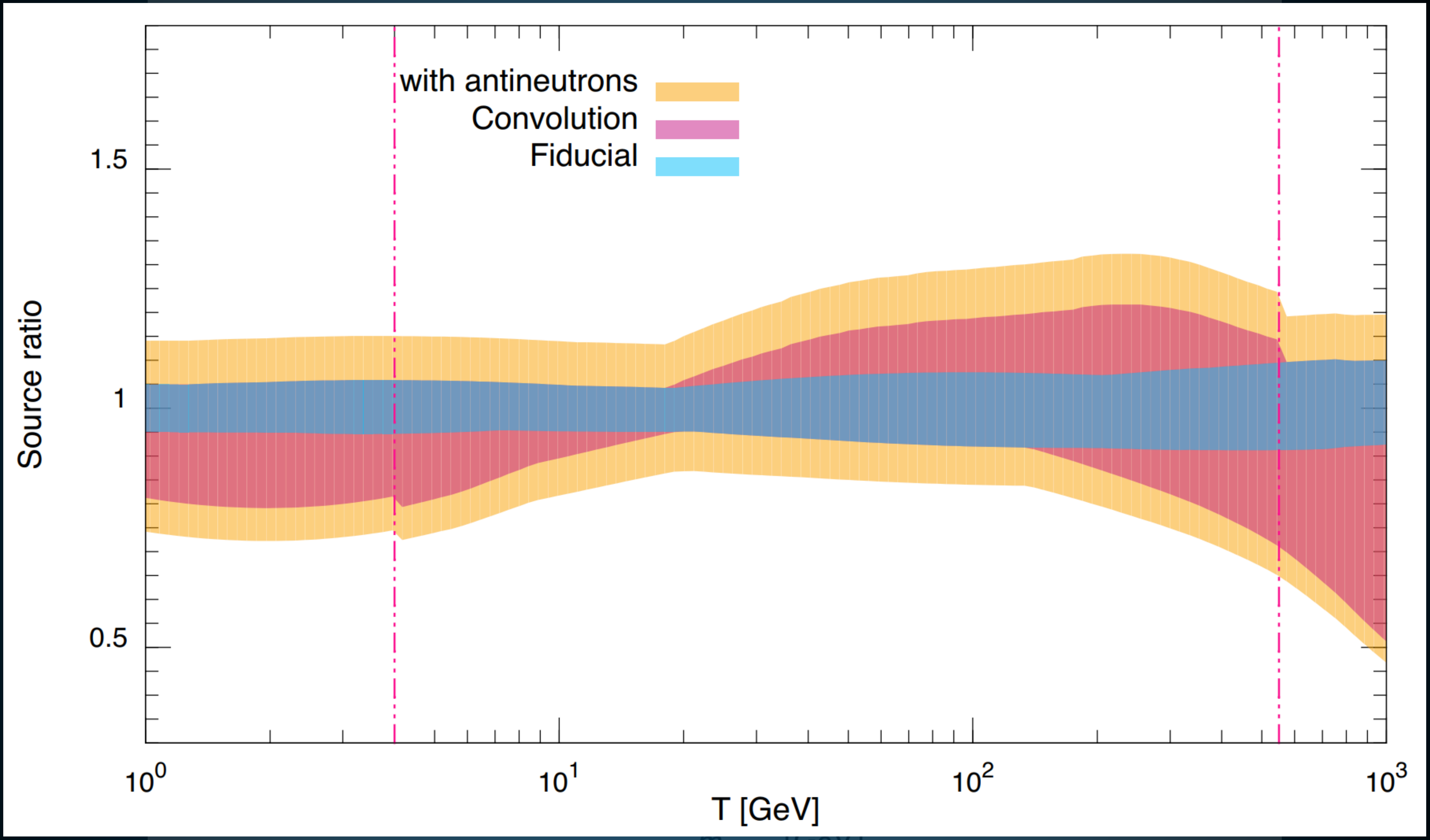
Conclusions

Extra Slides

Spectral Features

di Mauro et al. (2014; 1408.0288)

Part 2: The Antiproton Excess

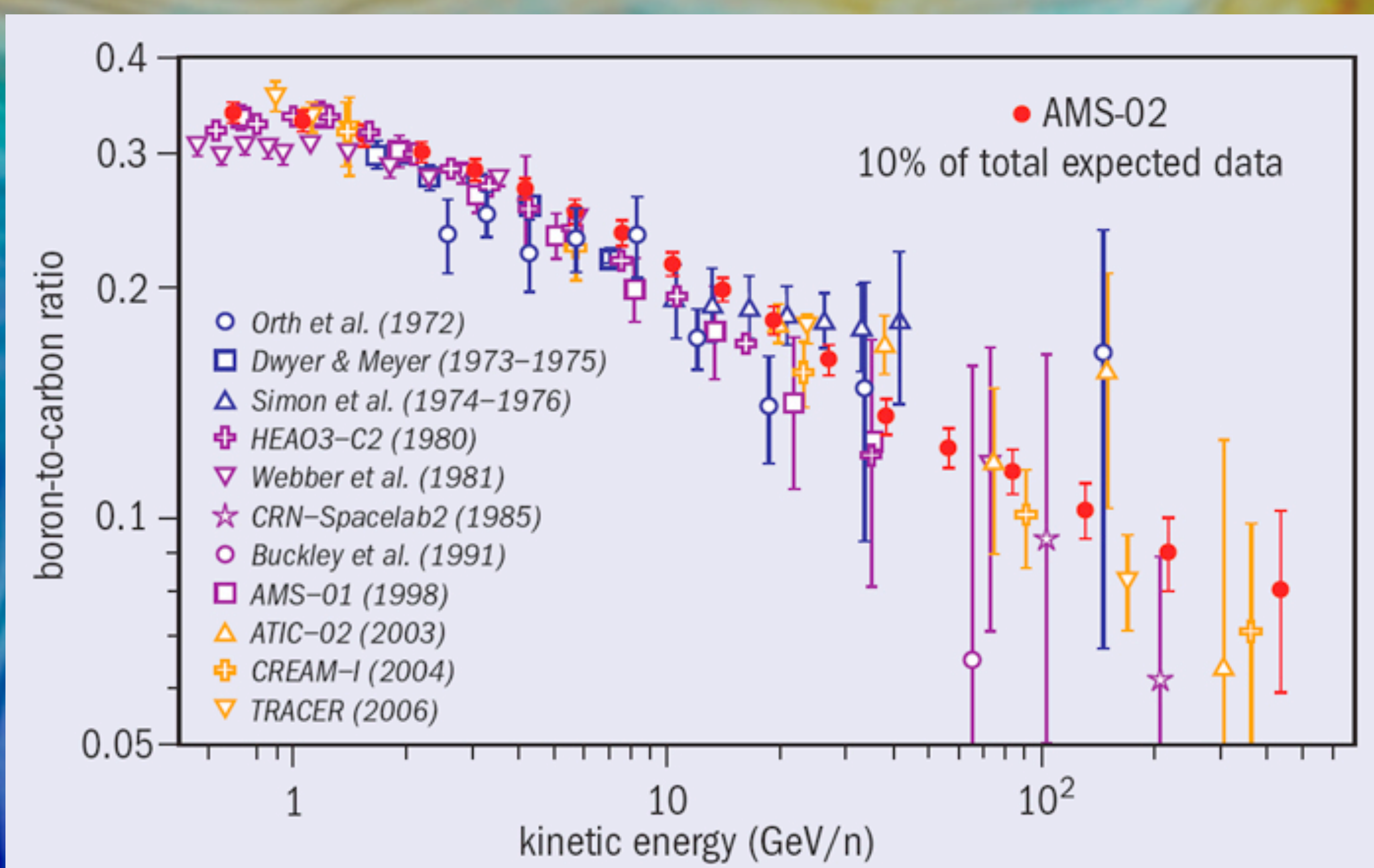


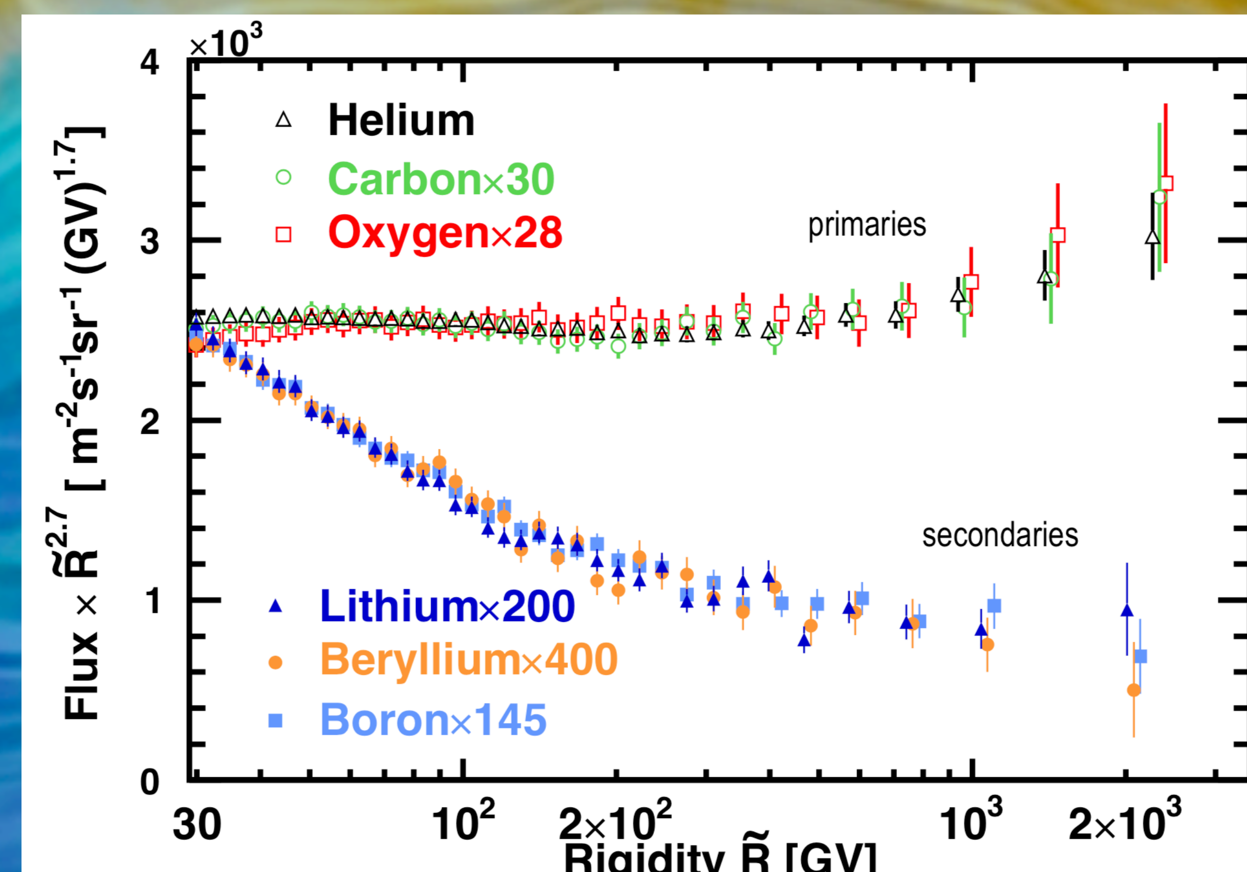
Spectral Features

Pretending We Understand How Diffusion Works

$$\frac{\partial f}{\partial t} = -V_{w,i}\frac{\partial f}{\partial x_i} + \frac{\partial}{\partial x_i}\kappa_{ij}\frac{\partial f}{\partial x_j} - V_{D,i}\frac{\partial f}{\partial x_i} + \frac{1}{3}\frac{\partial V_{w,i}}{\partial x_i}\frac{\partial f}{\partial \ln p} + Q$$

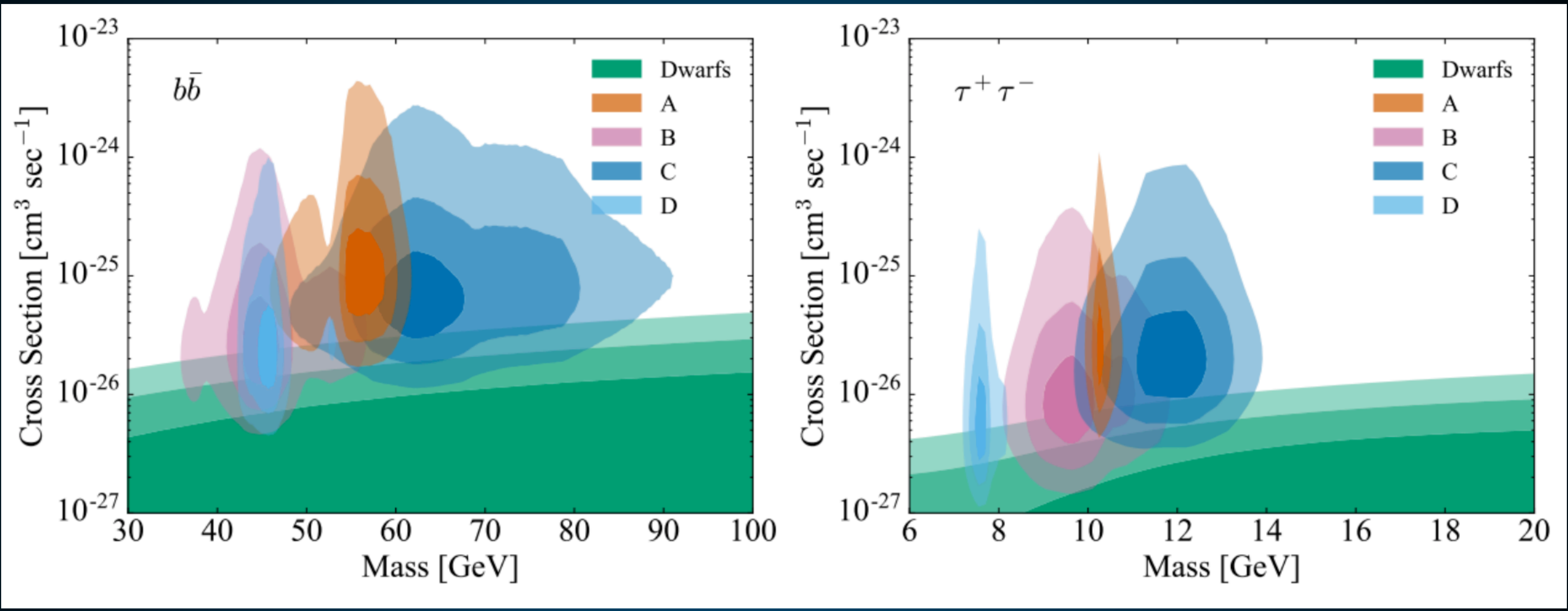
advection **diffusion** **drift** **energy change**





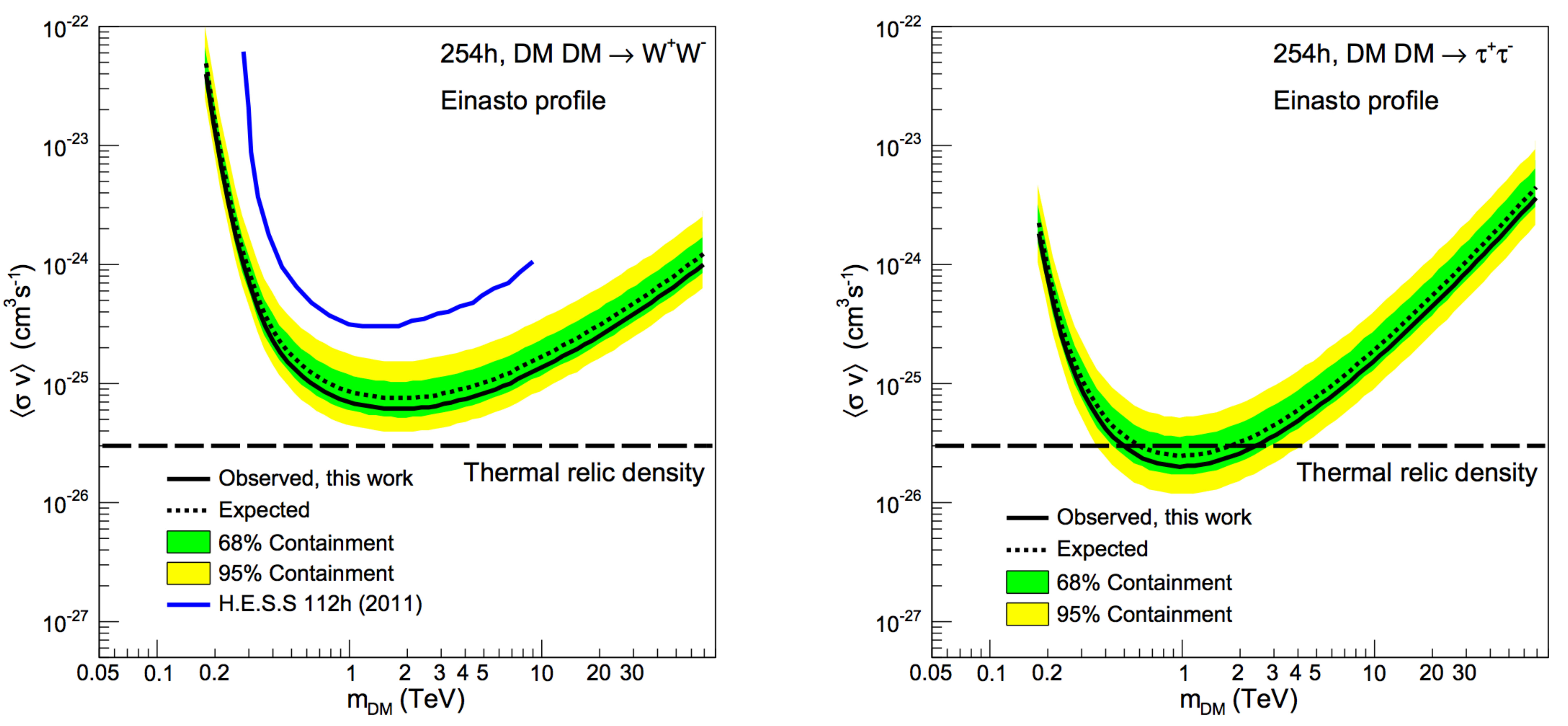
Are Dwarf Constraints in Tension with the Galactic Center Excess?

Keeley et al. (1710.03215)

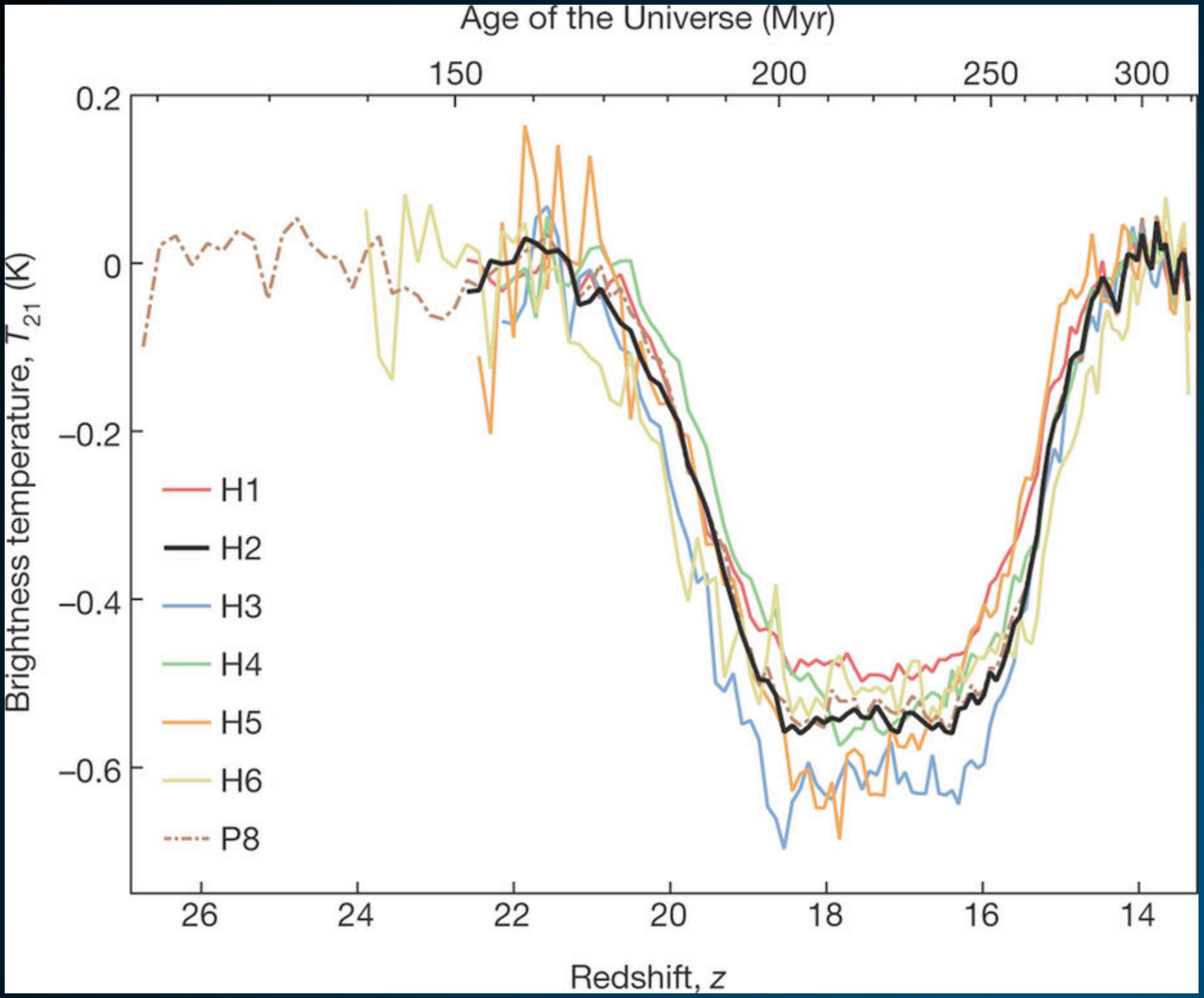


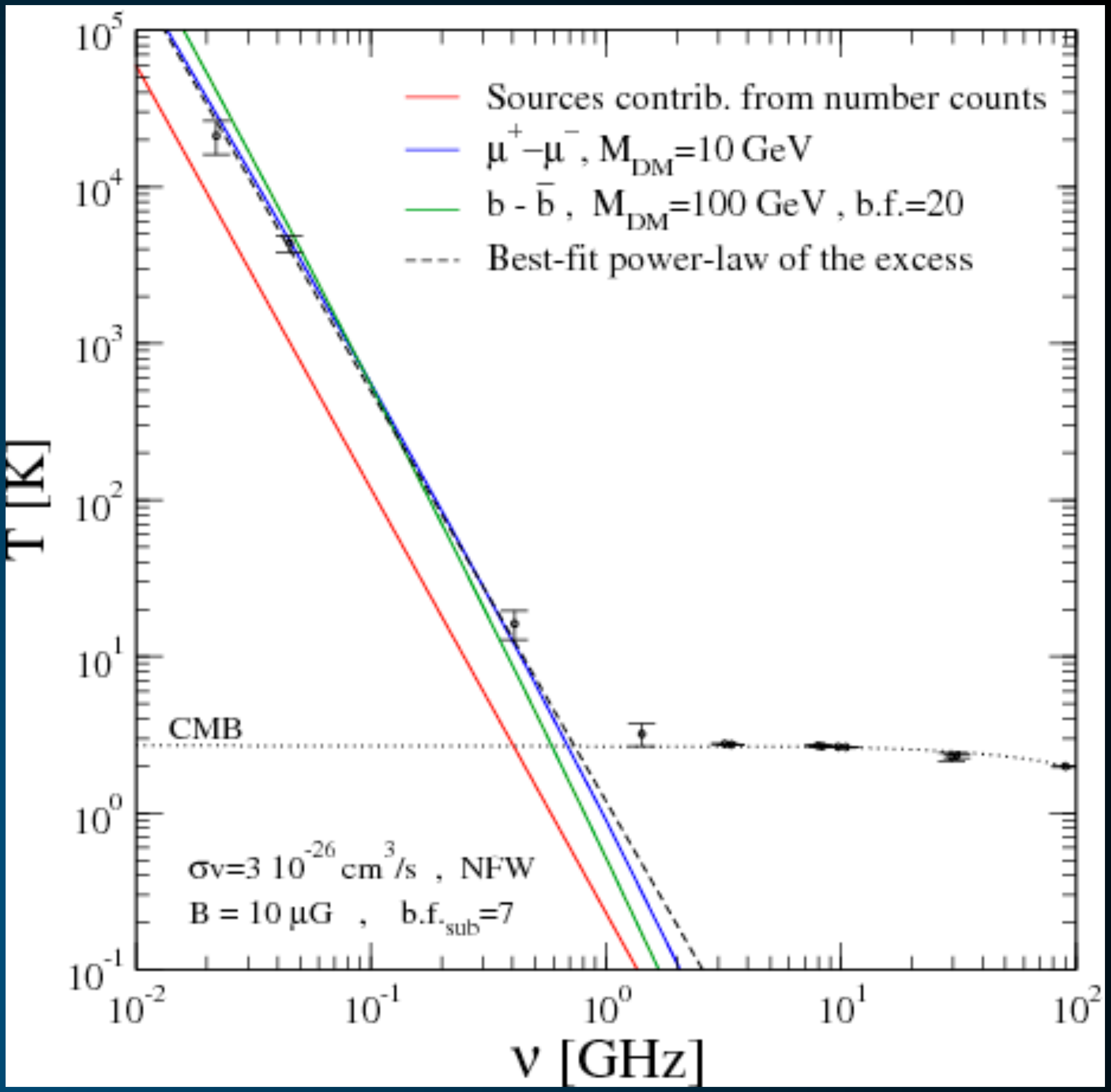
HESS Galactic Center Constraints

HESS Collaboration



EDGES/ARCADE Observations





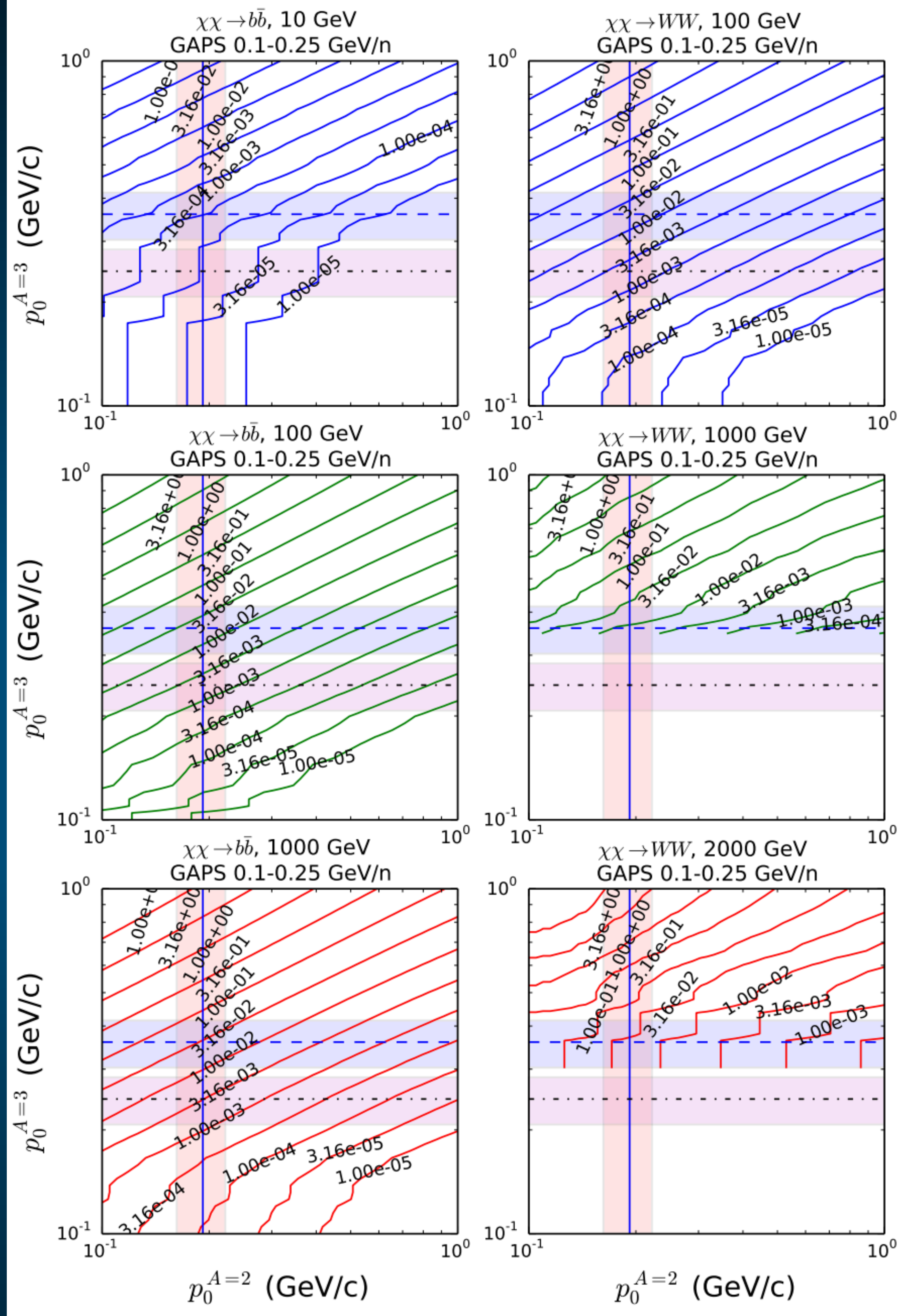
EDGES - Strong constraints

ARCADE - A Possible Signal?

Coalescence Models

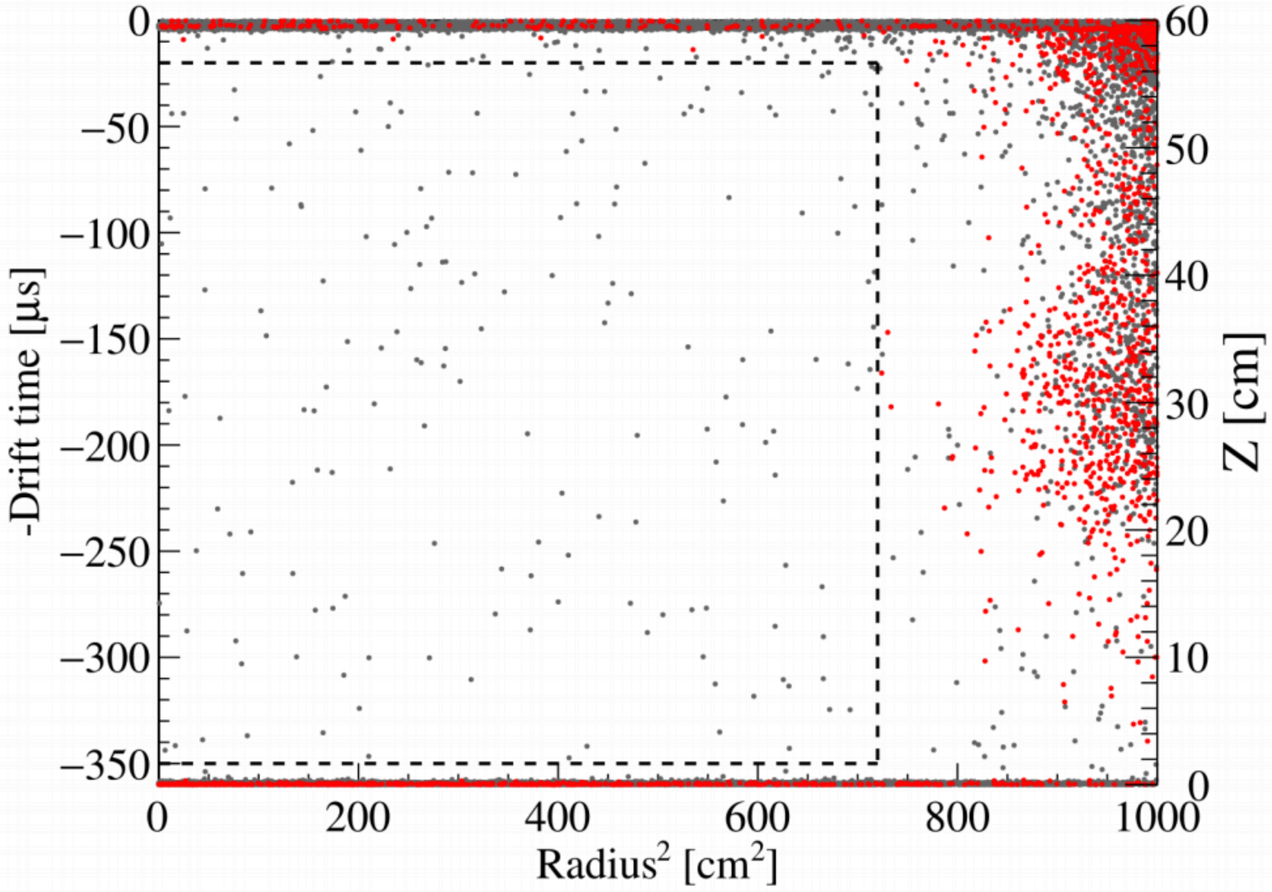
Formation of anti-particles determined from "coalescence momentum" that associates the binding energy of the atom with its formation probability.

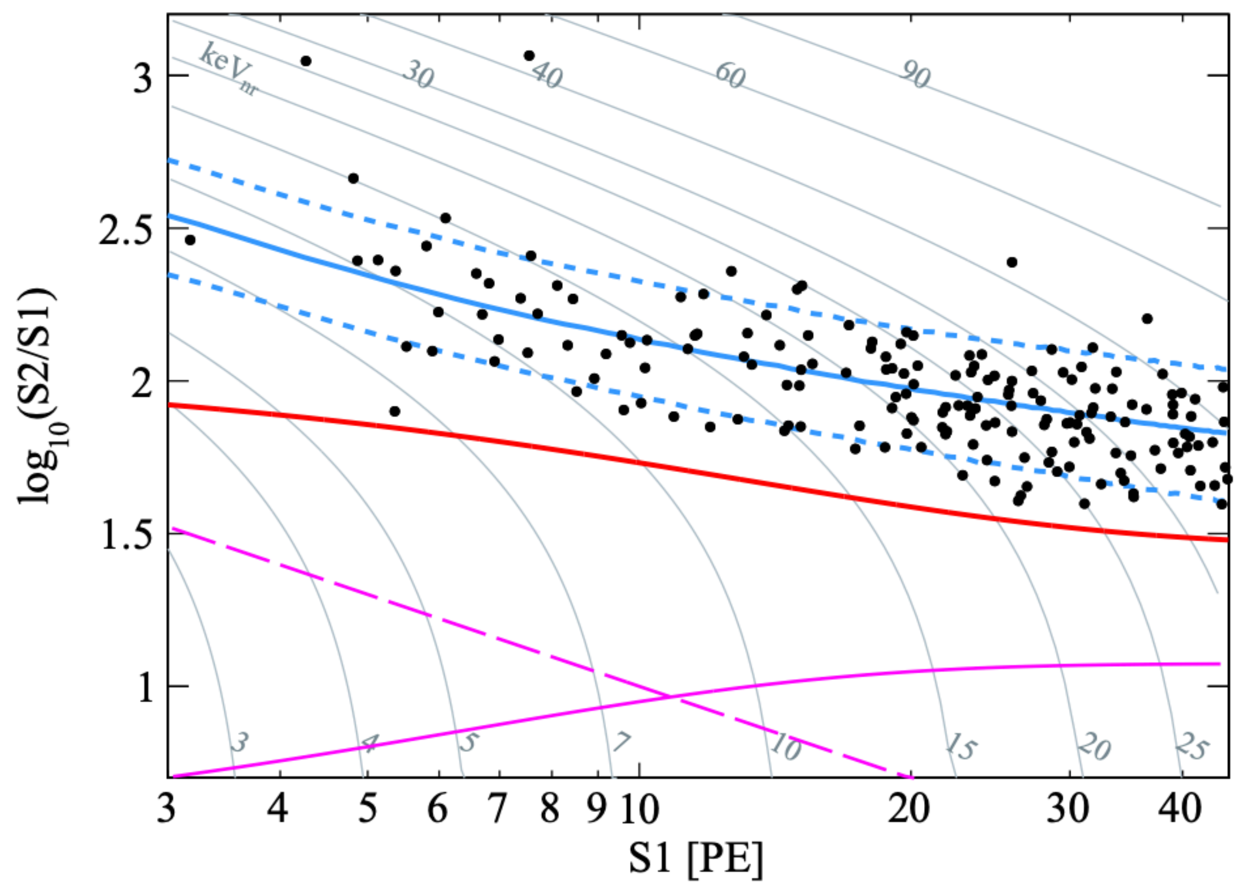
Binding energy of anti-Helium > anti-deuterium, leads to larger formation probability.



Advantages of Direct Detection

Panda-XII Collaboration (1708.06917)





- **Direct detection offers superb background rejection.**
- **Can set constraints on dark matter through the observation of 0 events.**