# Overview of Indirect Searches for Dark Matter

Rebecca Leane
SLAC National Accelerator Laboratory

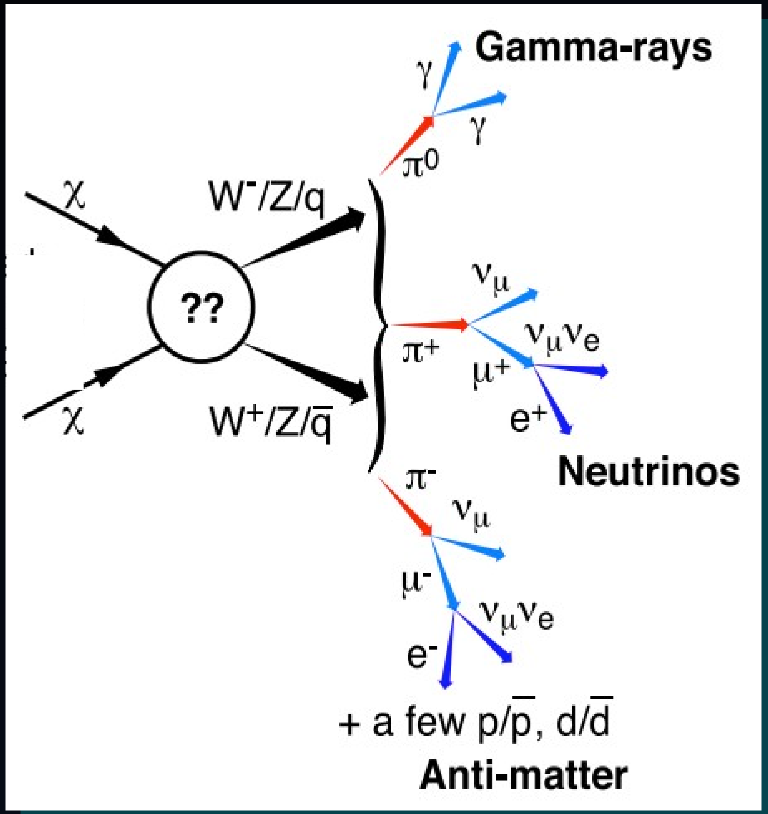
HEP/Astro Results Forum
May 19th 2022

# Why indirect detection is exciting

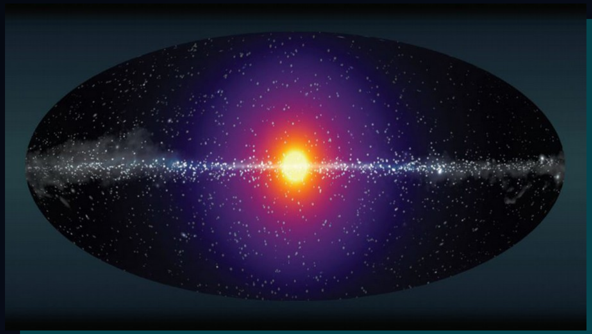
- Universe has been running experiments for us over very long time scales
- Can uniquely access specific scales: long decay lengths, smaller couplings, high energies
- Well defined target rates:
  *dark matter in its natural habitat*

# What are indirect DM searches?

Any search looking for DM annihilation or decay products.

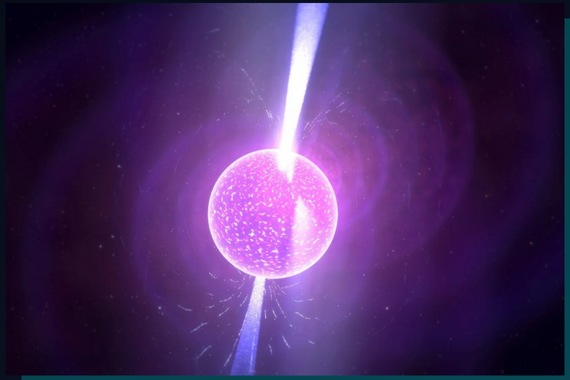



Baltz et al 0806.2911



Traditional:

Search for SM flux in DM halos,
or *effects* of the SM flux



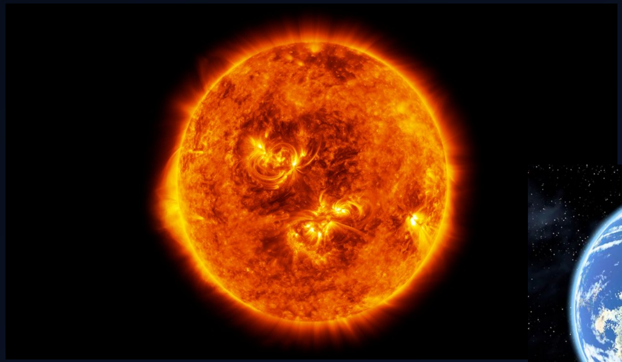
New Probes:

Search for SM flux from astrophysical bodies,
or *effects* of the SM flux

# Outline

- Traditional Indirect Detection
  - Ingredients for Searches
  - Gamma Rays: Galactic Center Excess
  - Antiprotons, positrons: anomalies?
  - Combining constraints

- New Probes of DM annihilation
  - DM in astrophysical objects
  - Ideal properties
  - Telescopes, new technologies



# Ingredients for Indirect Searches

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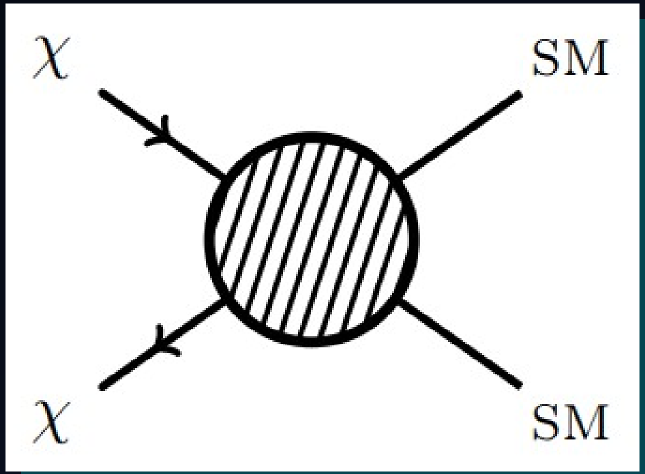
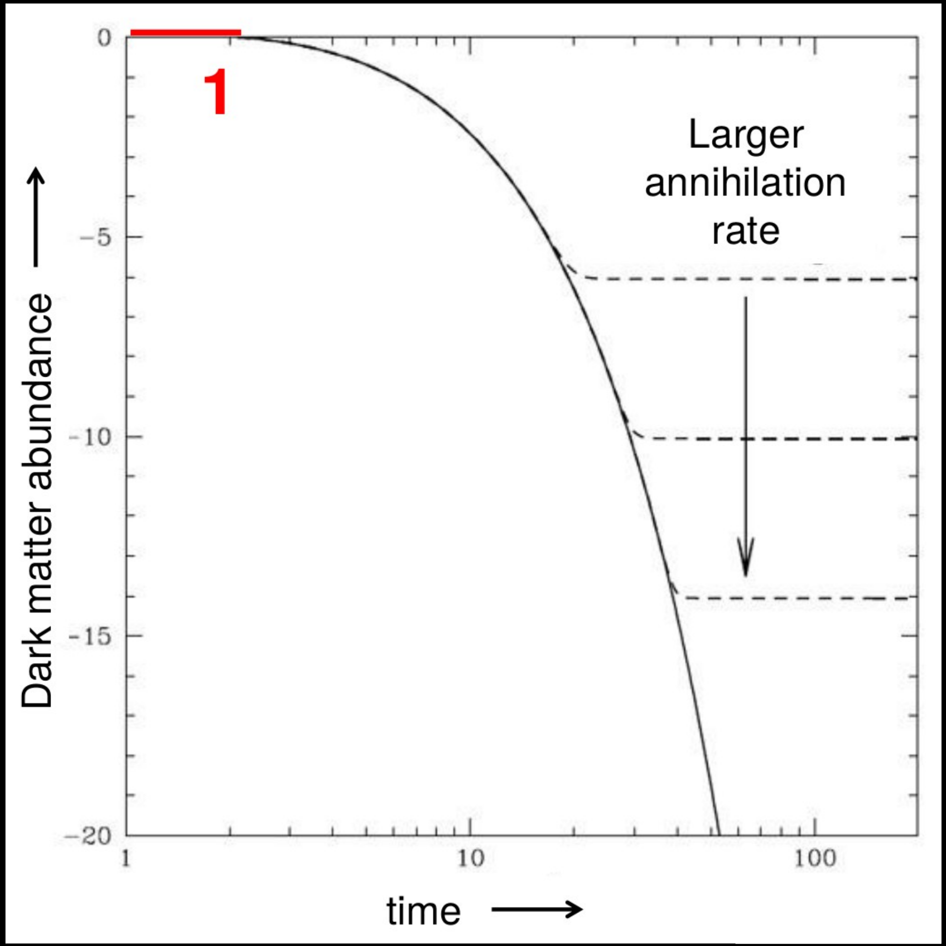
# Ingredient #1: DM Interaction Rate

- DM annihilation or decay rate
- Particle model dependent, usually fixed by relic abundance



# Ingredient #1: DM Interaction Rate

**1)** Thermal equilibrium:
DM + DM ⇒ visible particles
Visible particles ⇒ DM + DM



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**2)** Universe cools, only
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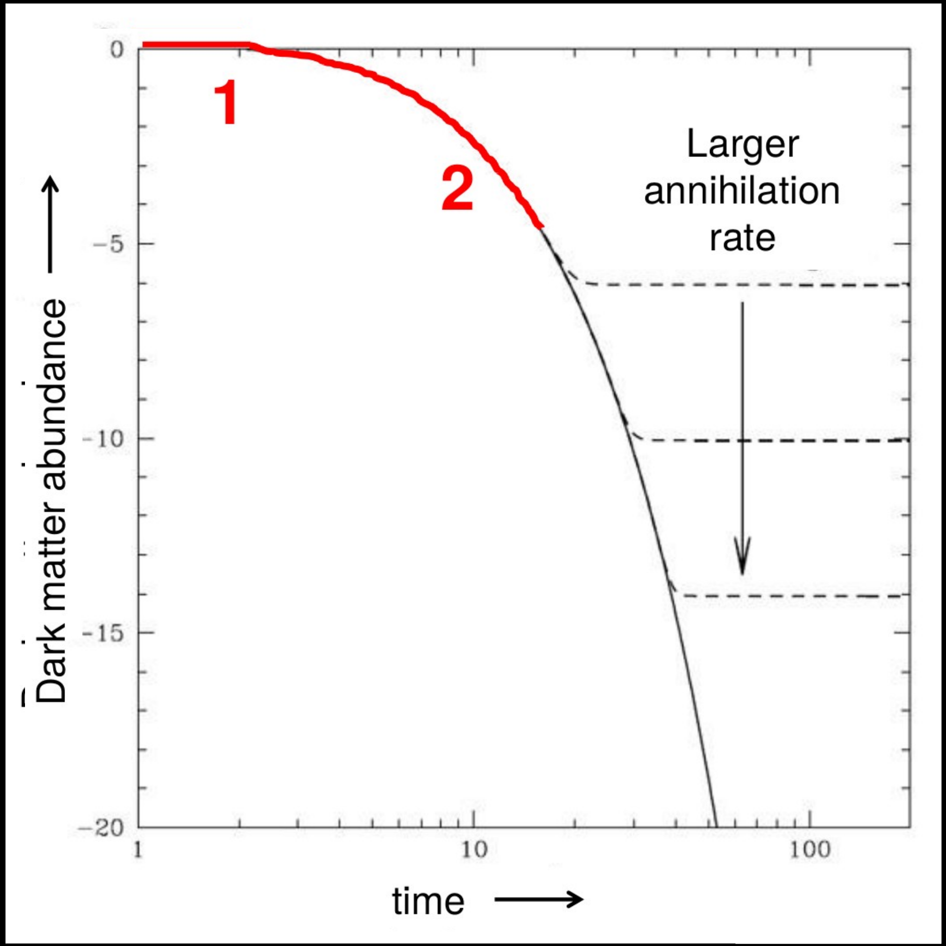
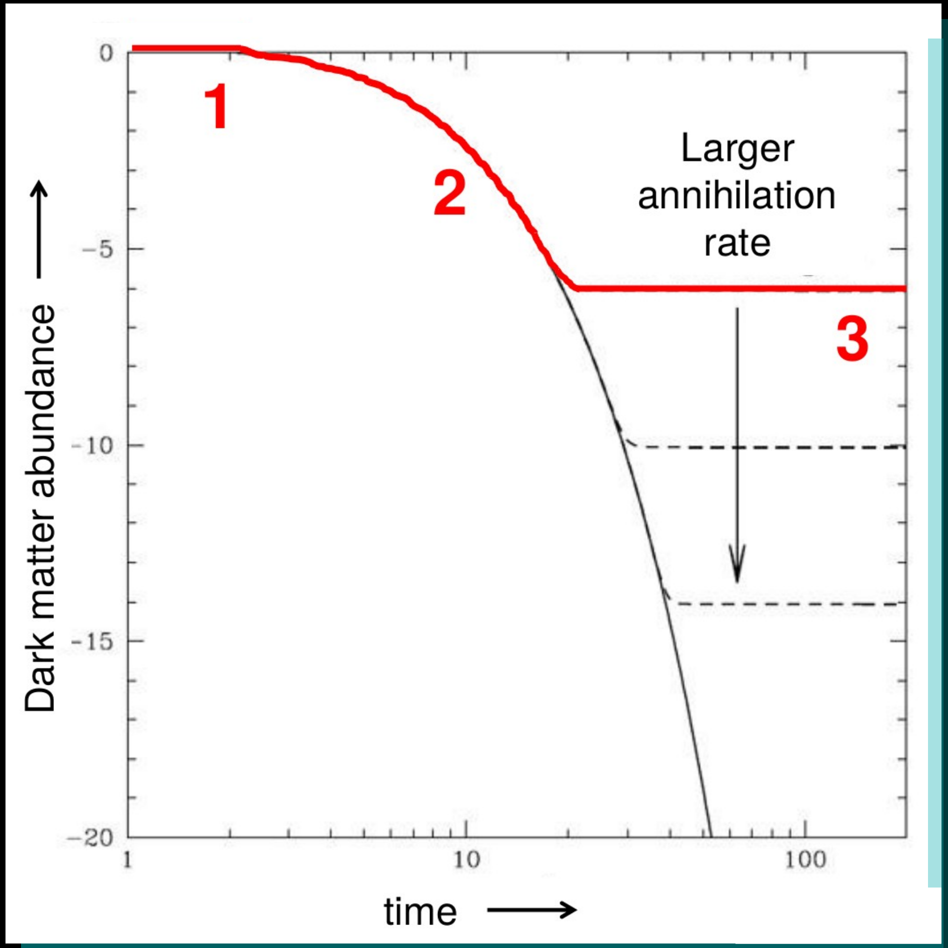


# Ingredient #1: DM Interaction Rate

**1)** Thermal equilibrium:
DM + DM ⇒ visible particles
Visible particles ⇒ DM + DM

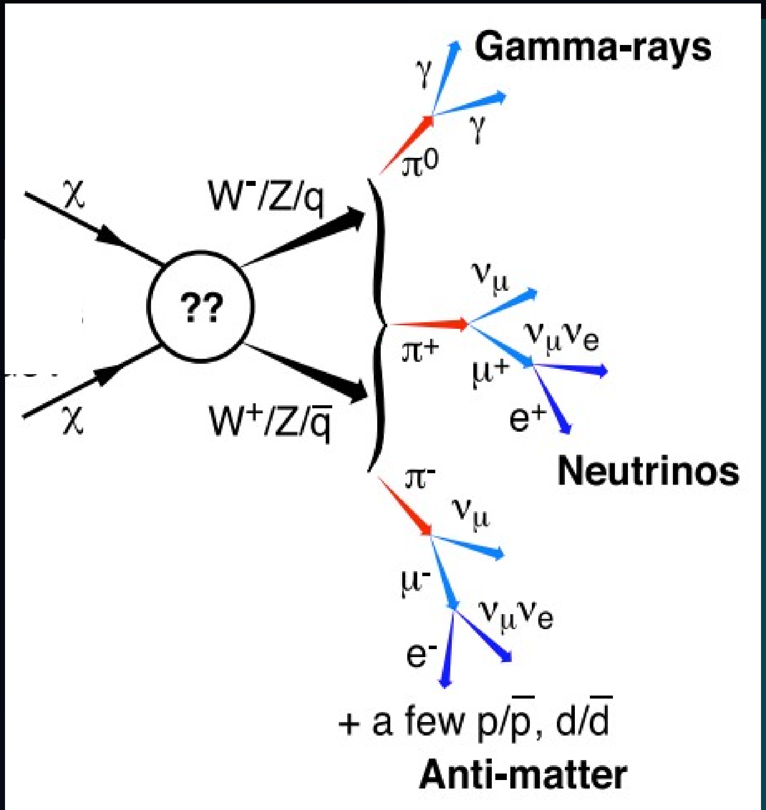
**2)** Universe cools, only
DM + DM ⇒ visible particles

**3)** Universe expands too fast.
No more annihilations.
DM abundance is set.



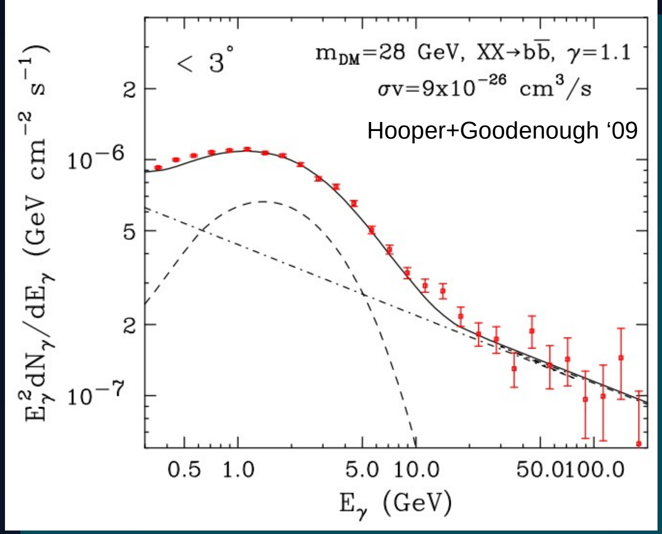

Predicts a particular annihilation rate for dark matter.

# Ingredient #2: Energy Spectrum




Baltz et al 0806.2911

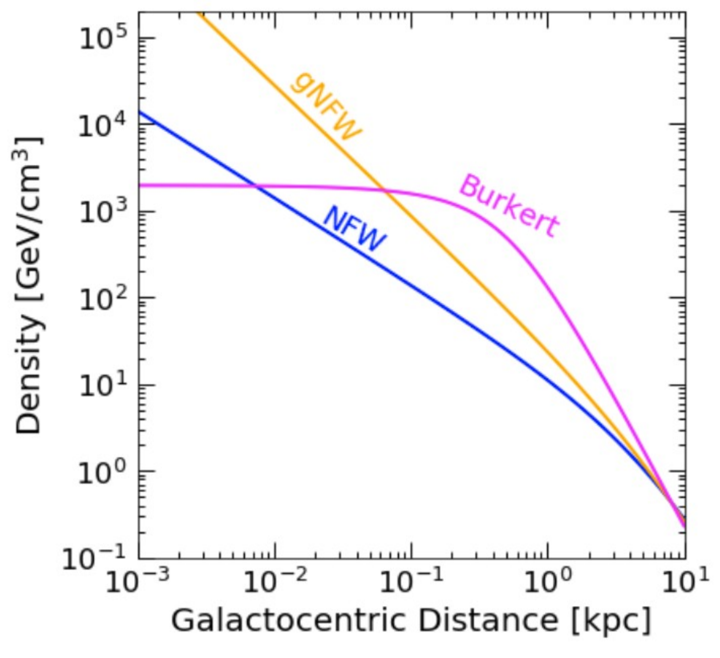
- Also driven by particle physics model
- Shape depends on:
  - branching ratios to final SM states
  - boosts of particles



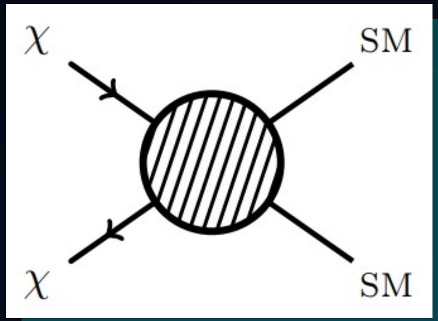
# Ingredient #3: DM Density+Distribution

- Line of sight integral over DM density
  - J-factor (annihilation)
  - D-factor (decay)

- DM density profiles not well-known
  - large uncertainties



# Indirect Detection Ingredients




Particle Physics    Astrophysics

(Neutral particles)

$$\Phi(E,\phi) = \frac{\Gamma}{4\pi m_\chi^a}\frac{dN}{dE}\int \rho[r,(\ell,\phi)]^a \, d\ell.$$

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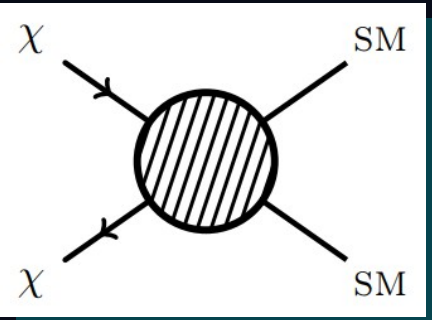
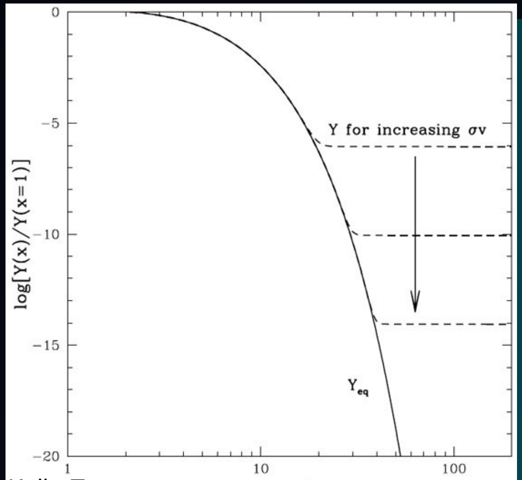



Annihilation cross section




Kolb+Turner

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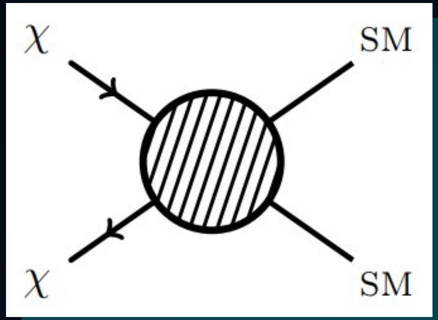


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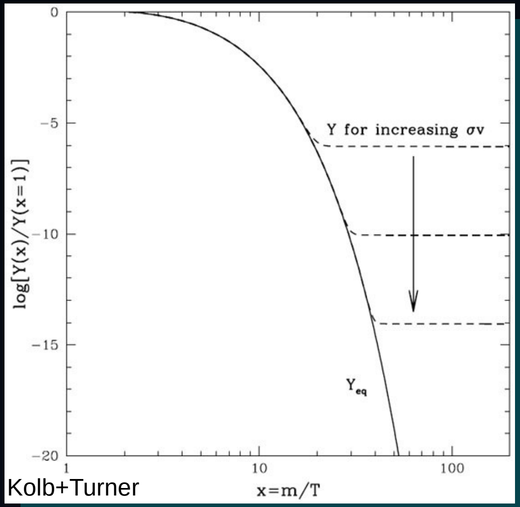
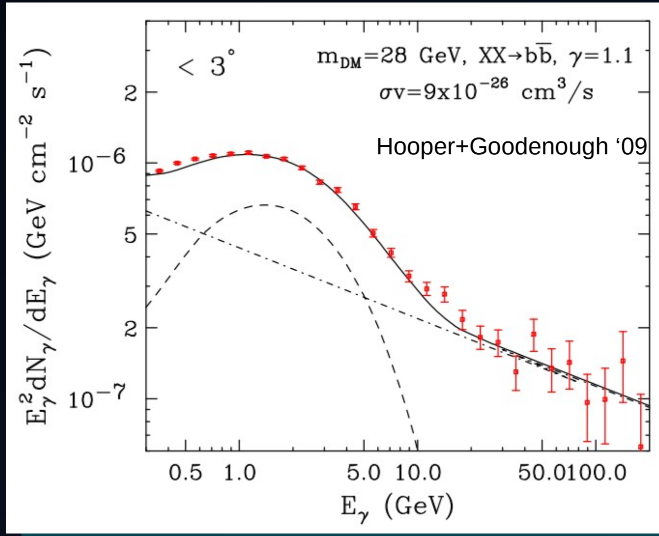



Energy spectrum



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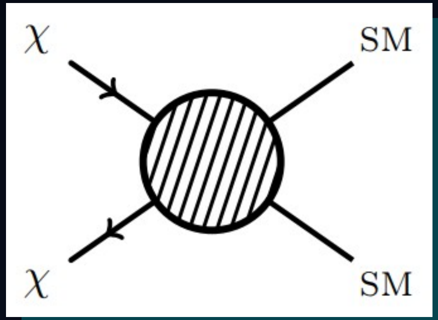


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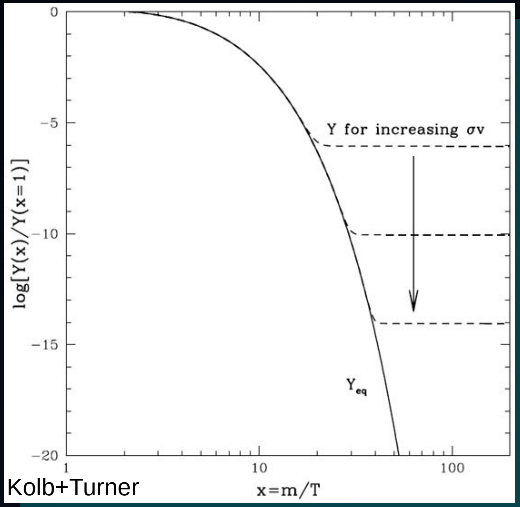
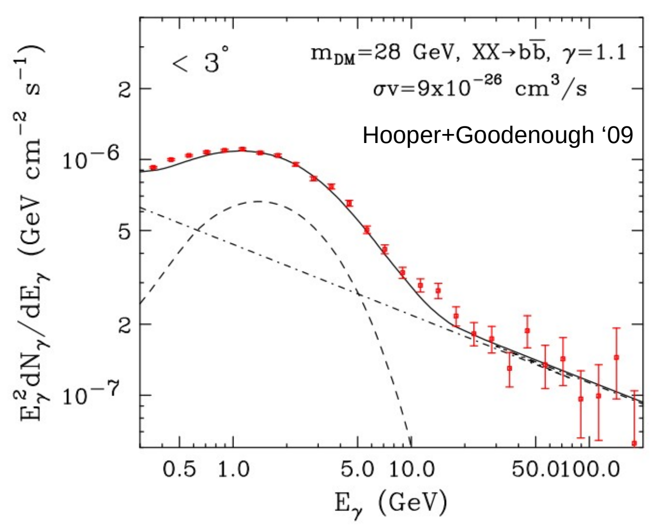
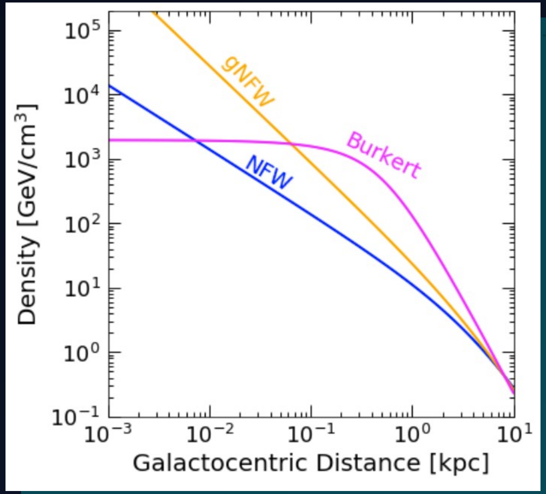
"J factor", DM density



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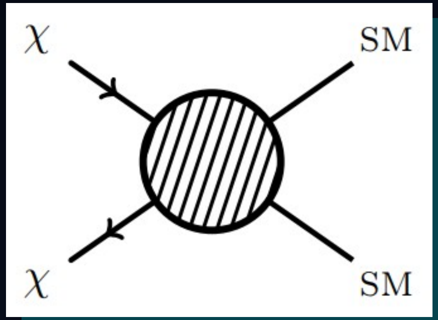


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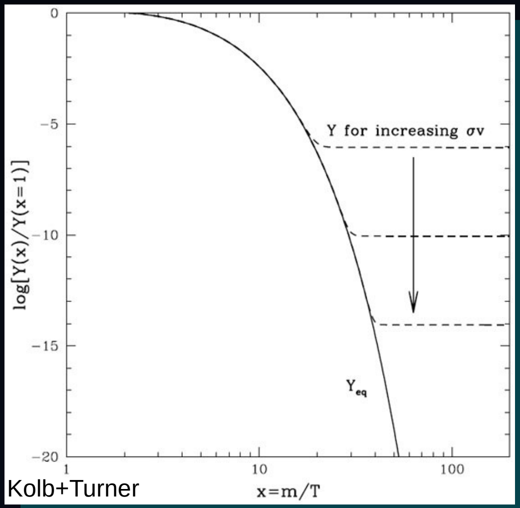
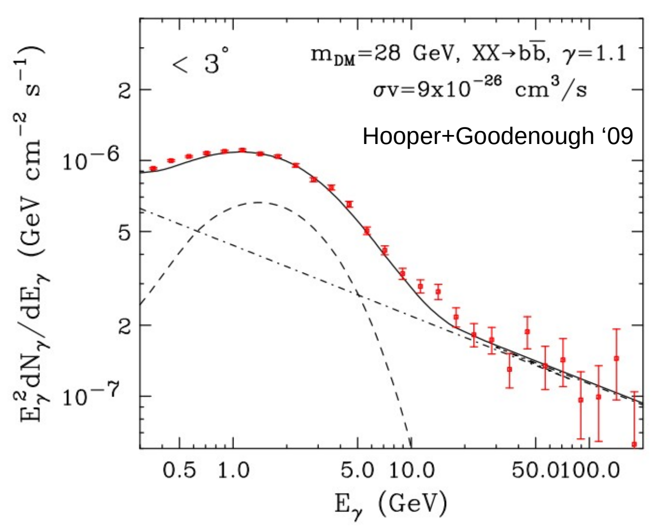
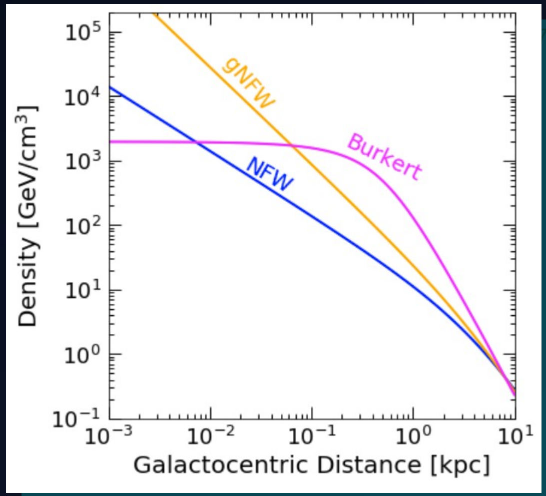
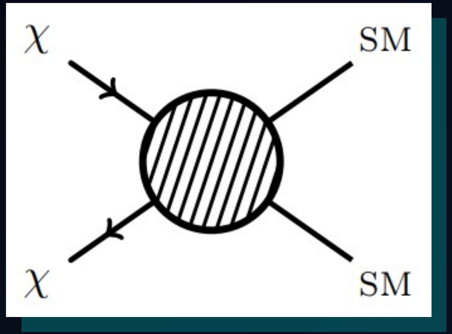



**Look where this is large!**

# Indirect Detection Ingredients

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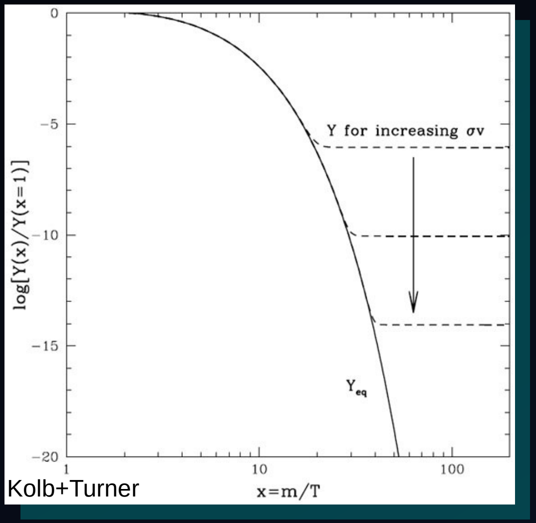


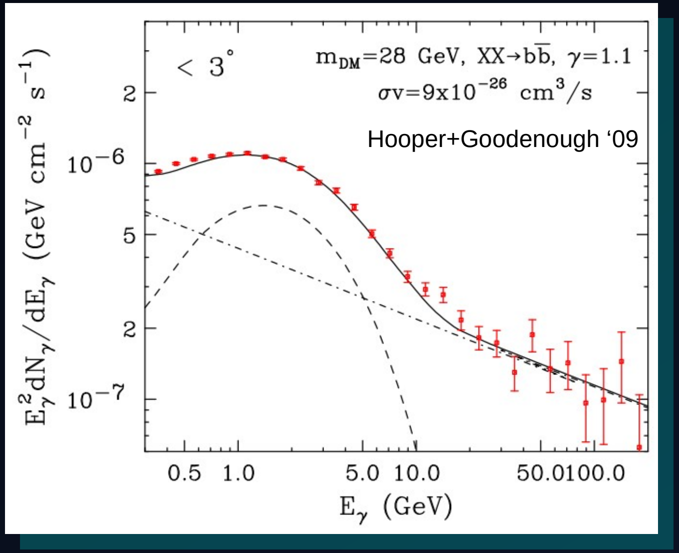


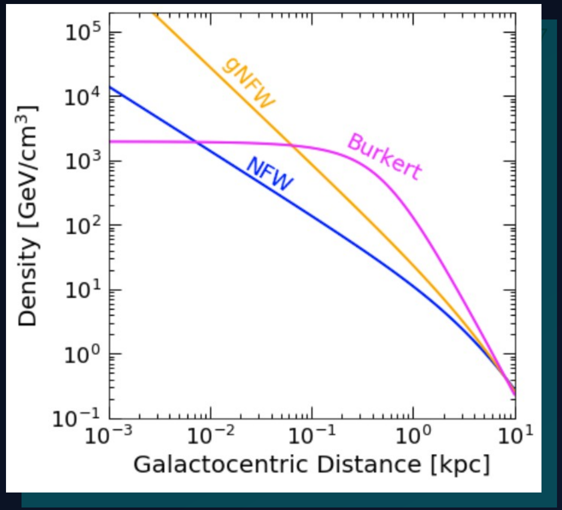


**Look where this is large!**

...or places with low background!

# Gamma Rays

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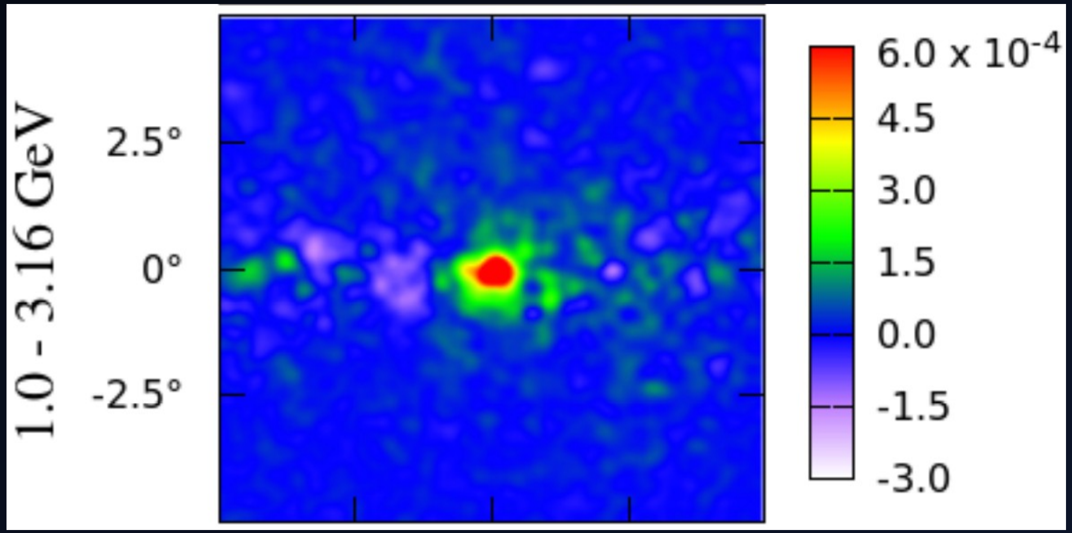
# Galactic Center Excess (GCE)

- Highly significant bright excess in gamma rays
- Detected by the Fermi gamma-ray Space Telescope




Daylan+, '14

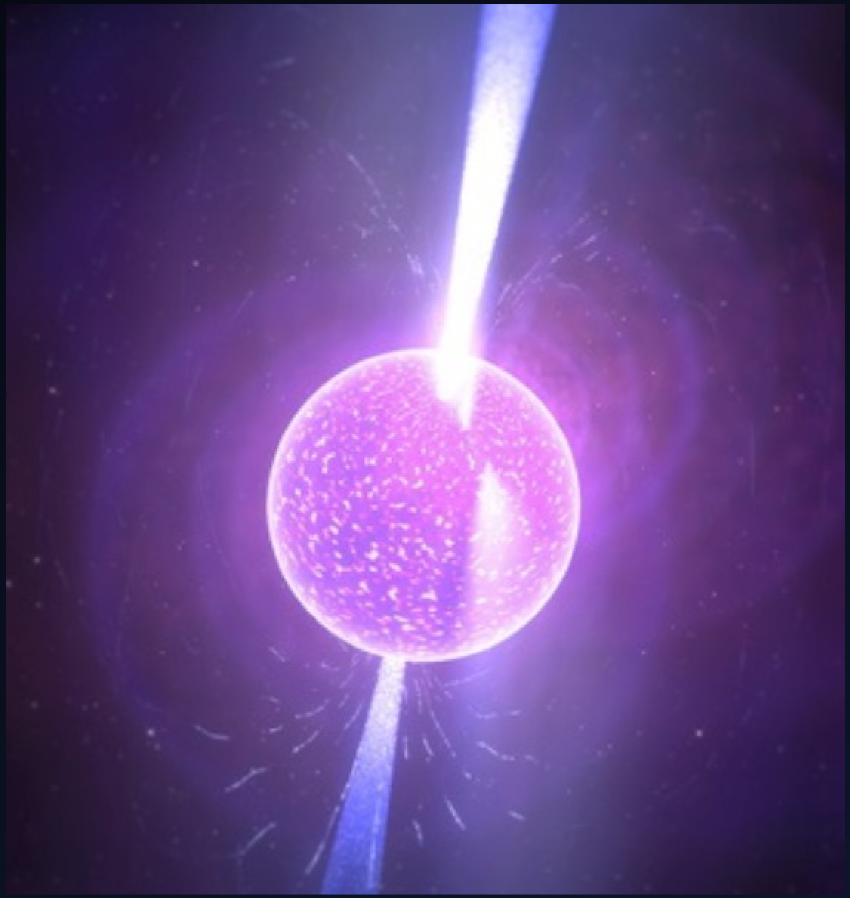
# Signal of Annihilating DM?

- Intensity of thermal particle dark matter
  - matches annihilation rate for correct abundance
- Morphology potentially consistent
  - potentially approximately spherical
  - extending well out of the center
- Spectrum consistent
  - invariant with position and shape

If dark matter, first evidence of dark-visible matter interactions:
want to get to the bottom of this!

# Pulsars as the Excess

- Pulsars are rapidly spinning neutron stars
- Pulsars also match the gamma-ray energy spectrum
- Pulsars appear as point sources to Fermi, which mean they have angular extent below detector thresholds



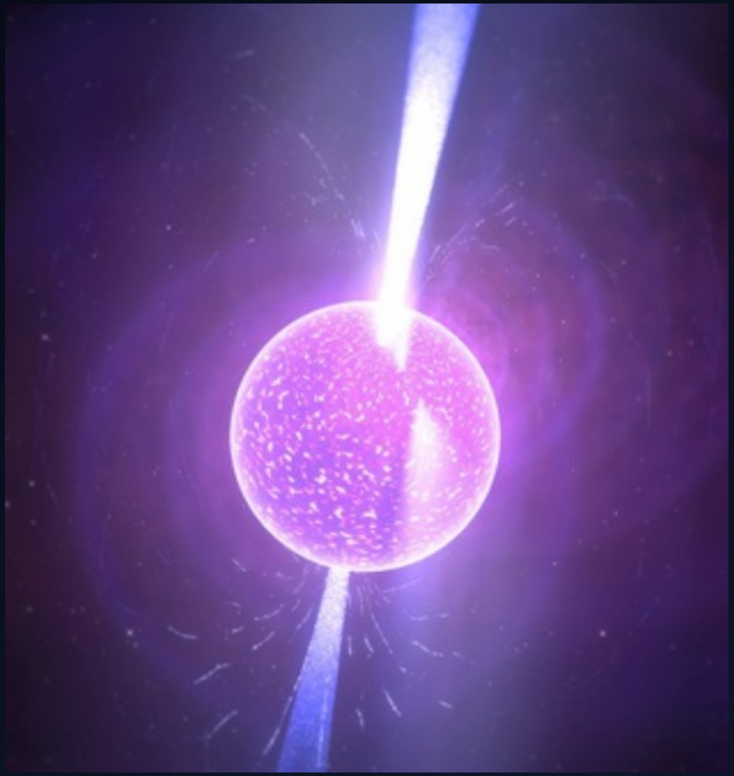
# Point Sources as the Excess

- Resolved Point Sources:

  Bright enough to be individually detected

- Unresolved Point Sources:

  Too dim to be individually detected, cannot be individually resolved, but collectively could explain excess

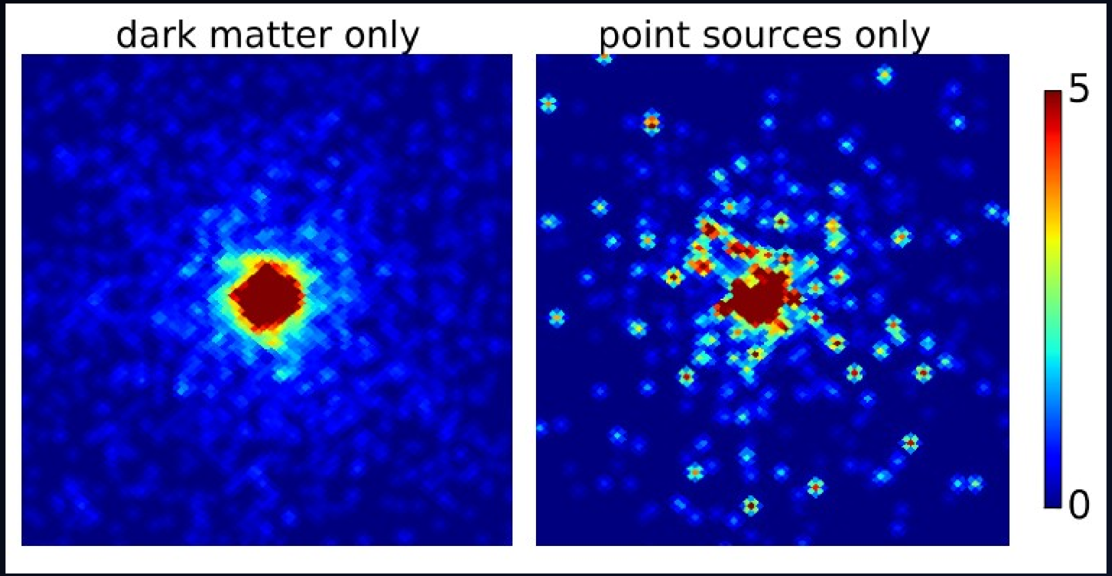


# Distinguishing DM vs. Point Sources

Counts of gamma rays from point sources exhibit different statistical behavior compared to those from annihilating dark matter:

Lee+ '15

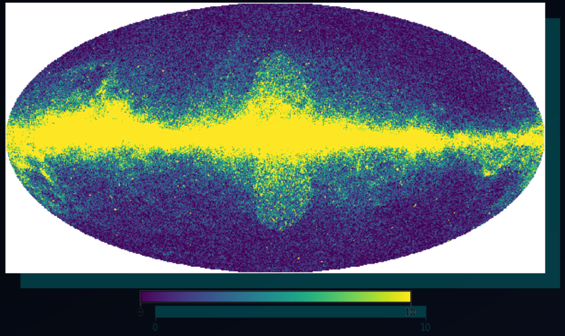
Dark matter: smooth continuous halo in the Galaxy




Point Sources: clumpy individual sources

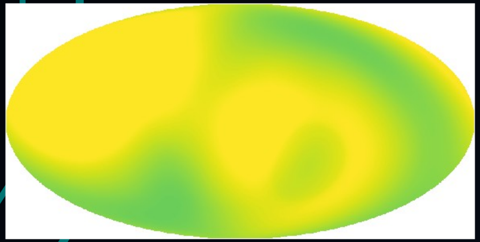
# Method 1: Template Fitting

Full sky



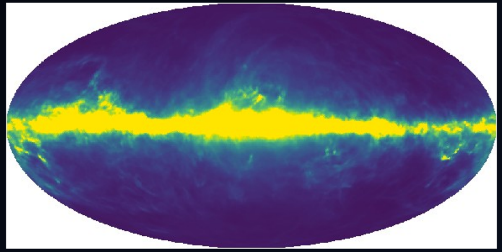
=

(Example combination)



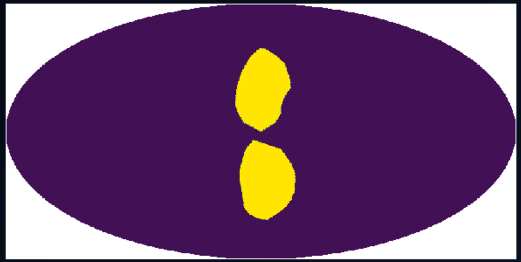
Isotropic

+



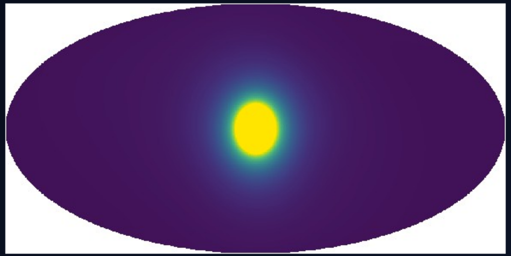
Diffuse

+



Bubbles

+



GCE

Build up picture of gamma ray sky by modeling individual components

Allow all components, or “templates” to float, see if smooth or clumpy is preferred for the GCE template (Lee+ 15)

# Method 2: Wavelets

Use wavelet transform to look for peaks in the data

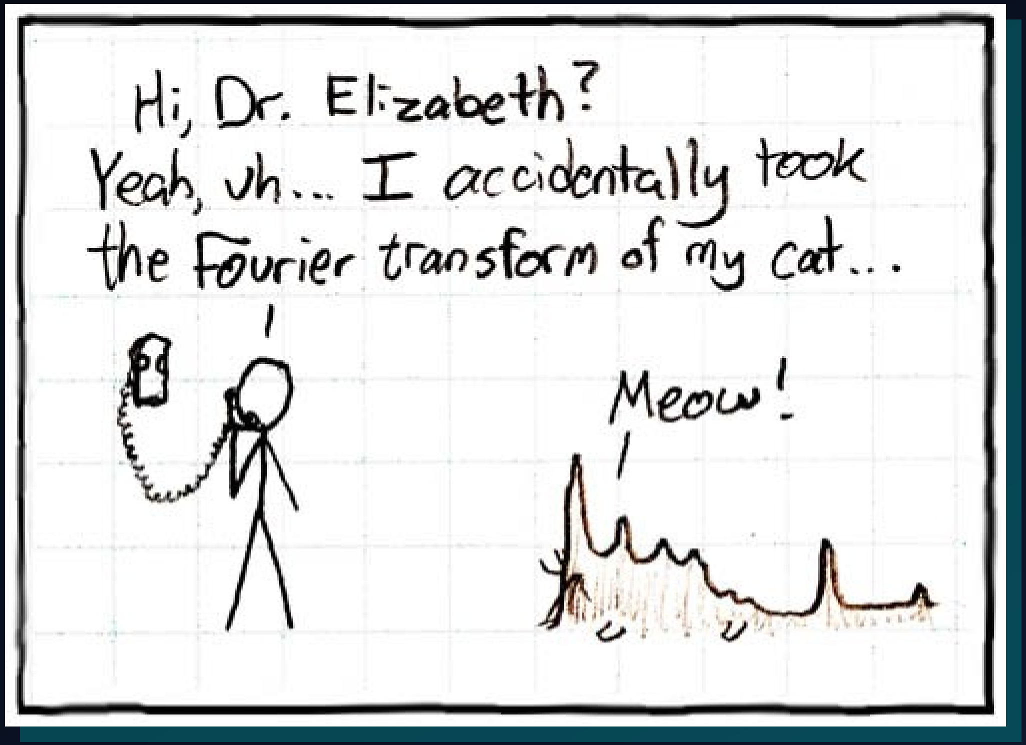
As before,

Clumpy (peaks):

point sources

Smooth (no peaks):

either no point sources,
or very faint point sources




xkcd

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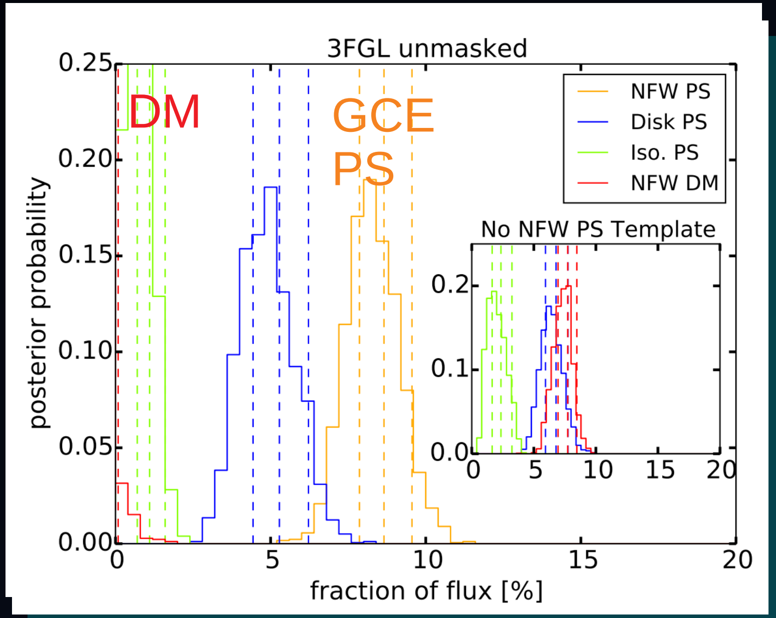
# Evidence for Point Sources at the Galactic Center: 2015 Status

## 1. Template Fitting




Lee, Lisanti, Safdi, Slatyer, Xue (PRL '15)

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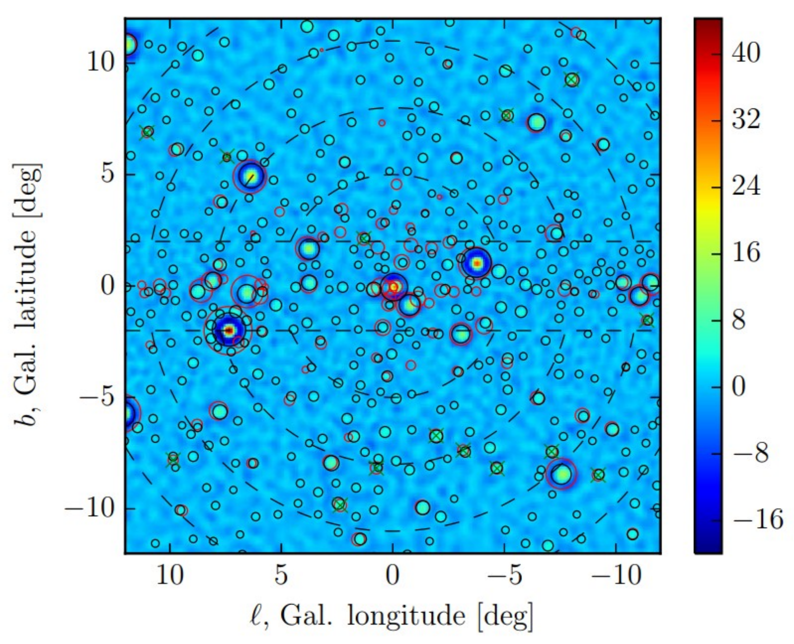


Bartels, Krishnamurthy, Weniger (PRL '15)

Consensus towards point source explanation,
evidence for "clumpy" rather than "smooth" signal

# The Double Plot Twist of 2019…

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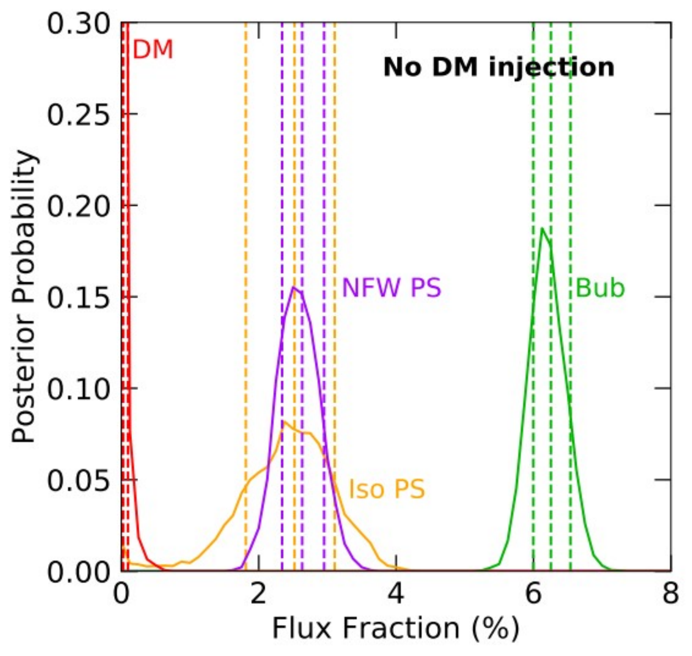
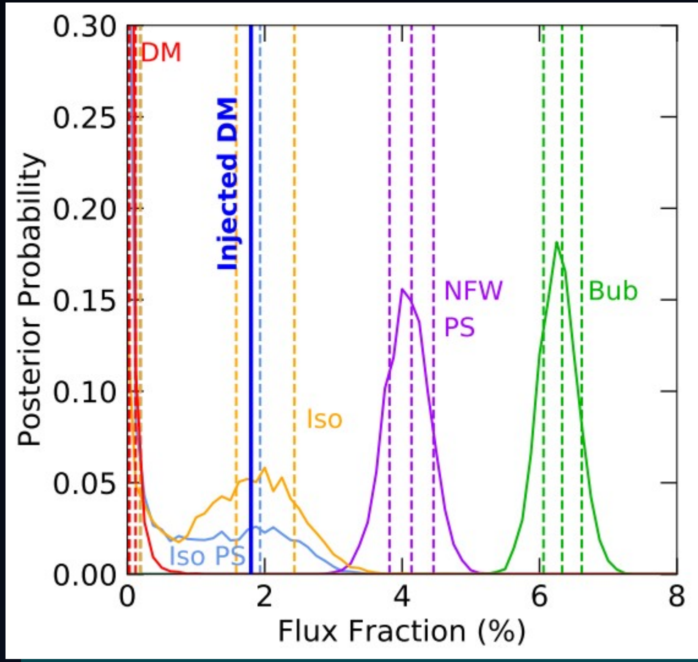
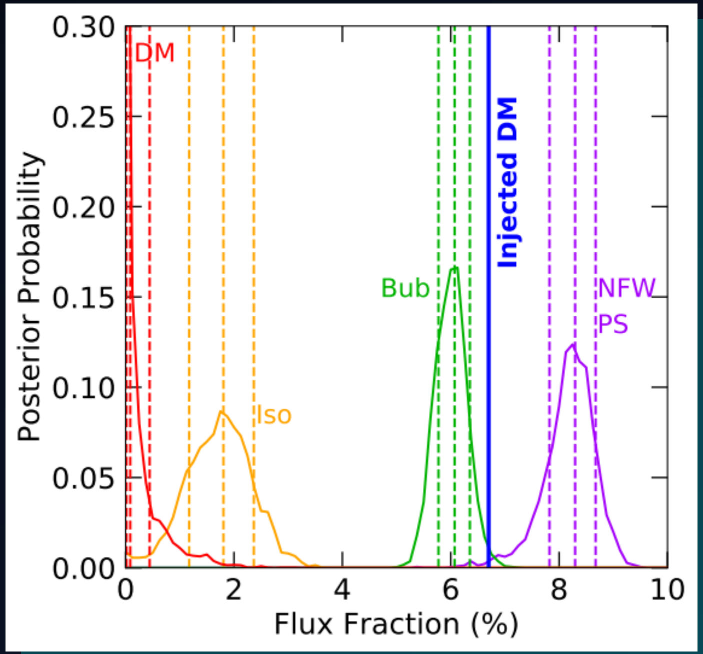
# Dark Matter Strikes Back

RL+Slatyer, PRL ‘19

*Mismodeling can hide a dark matter signal !*




Systematics not under control, need to be understood to claim any robust result

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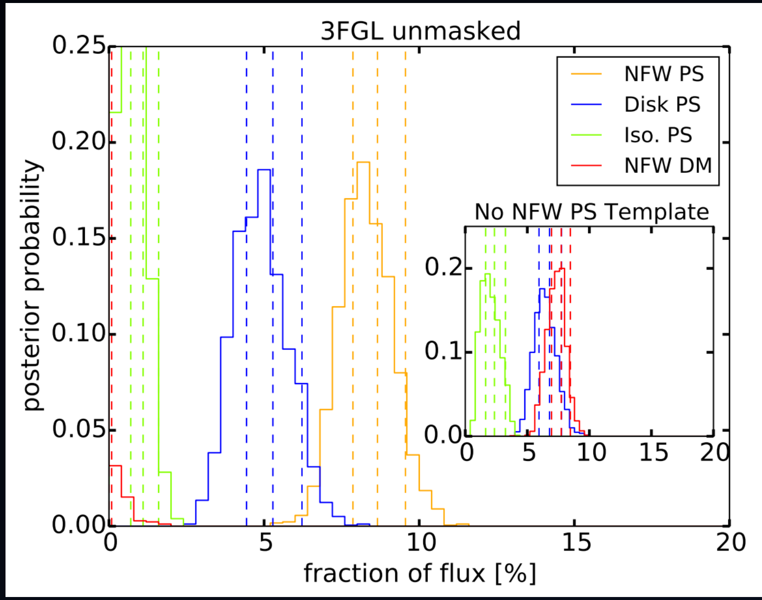


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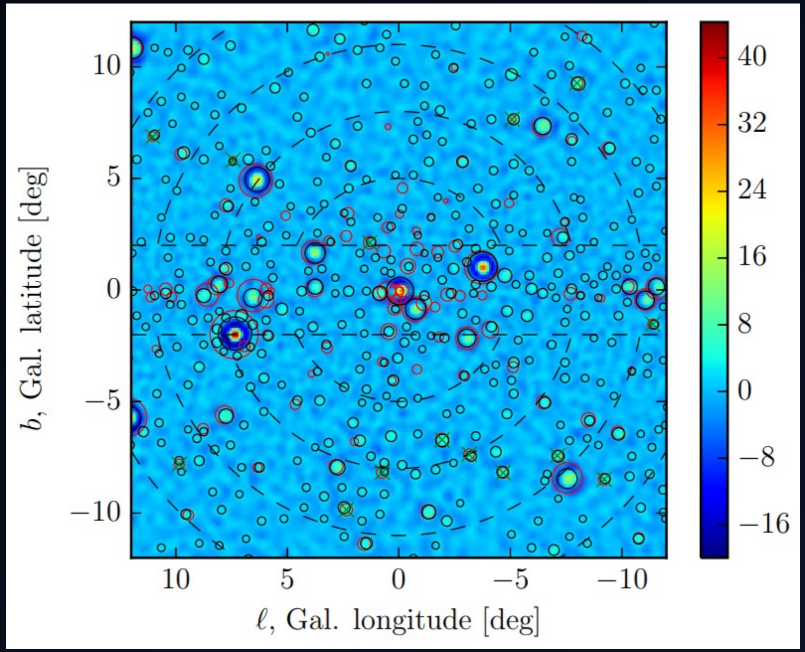


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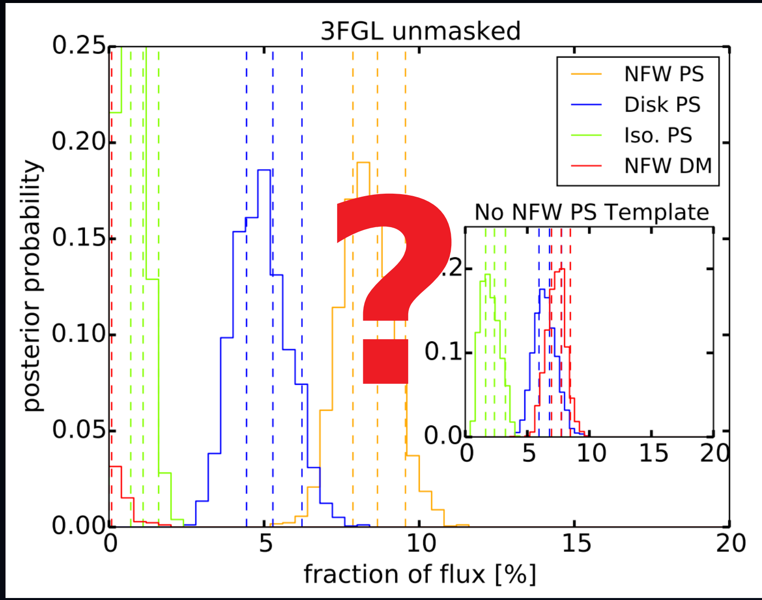


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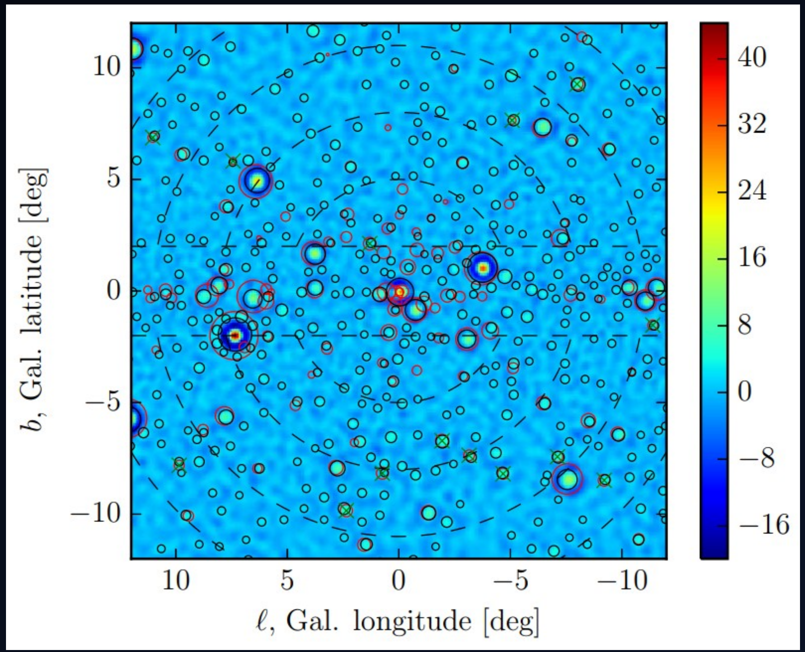


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**Systematic Issues**

**RL**+Slatyer (PRL '19)

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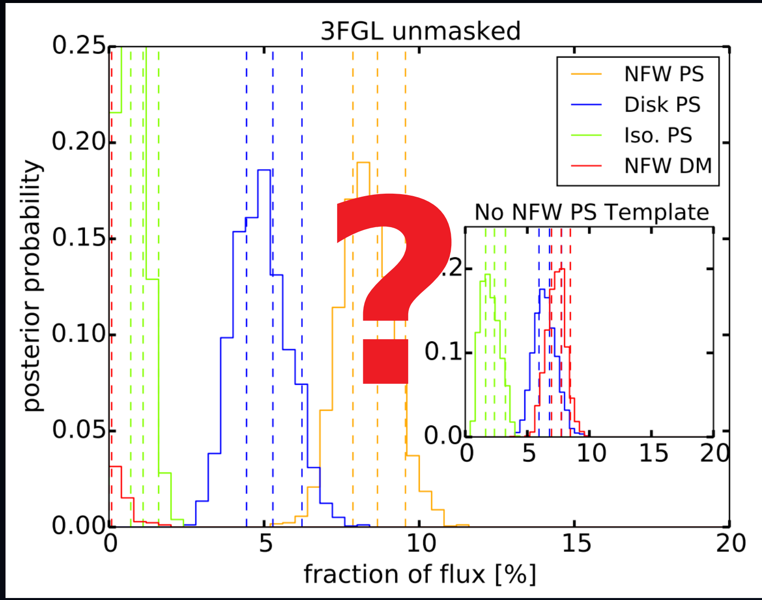


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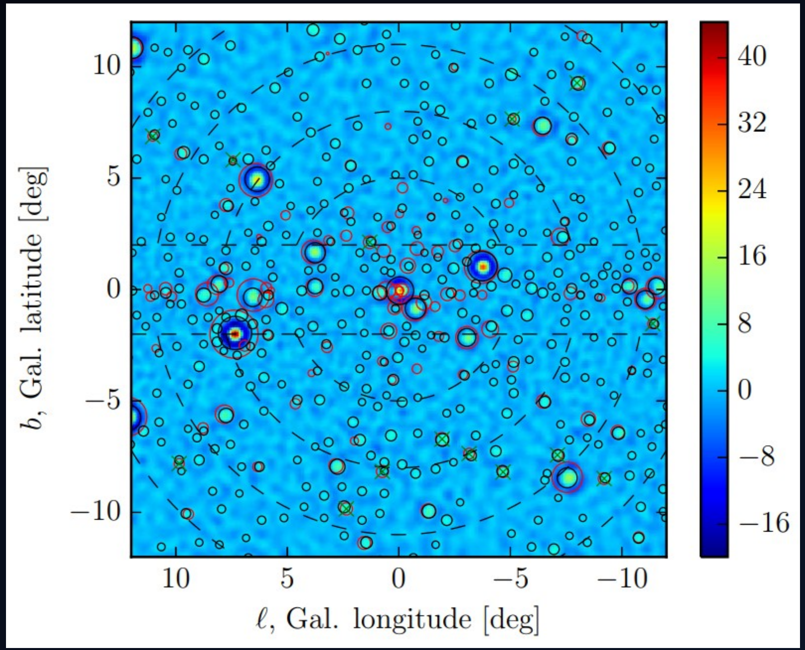


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# Wavelet Method Update

Updated to mask out Fermi's new point source catalog.

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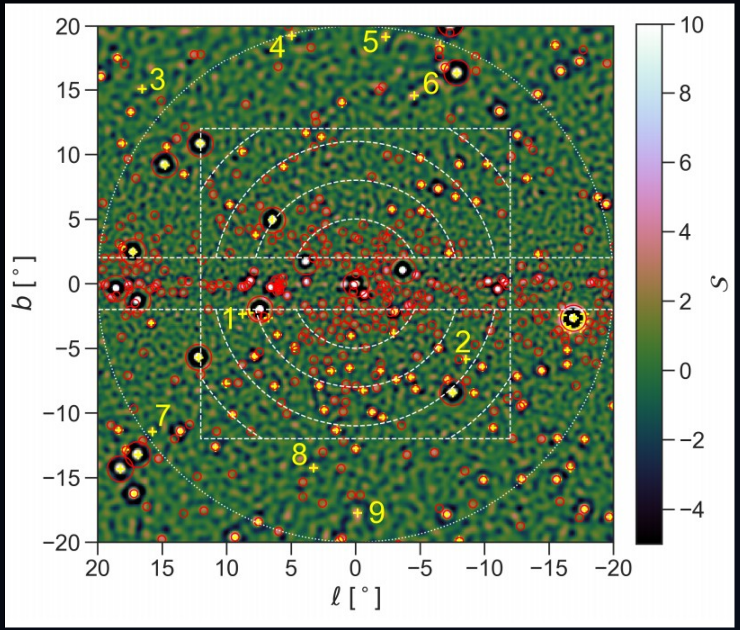


Turns out the 2015 paper correctly found point sources

Zhong, McDermott, Cholis, Fox PRL '19

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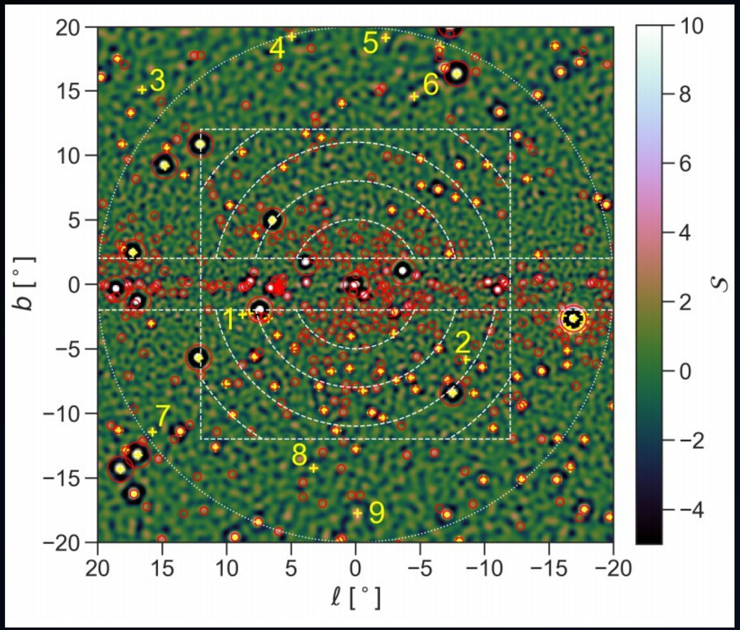


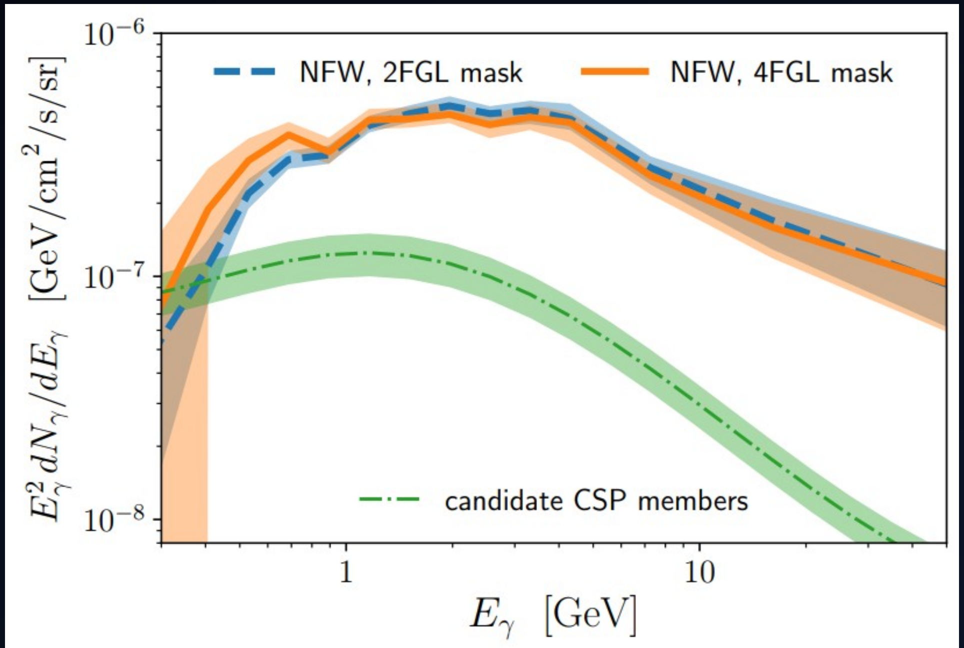


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...but **not** point sources that can explain the excess.

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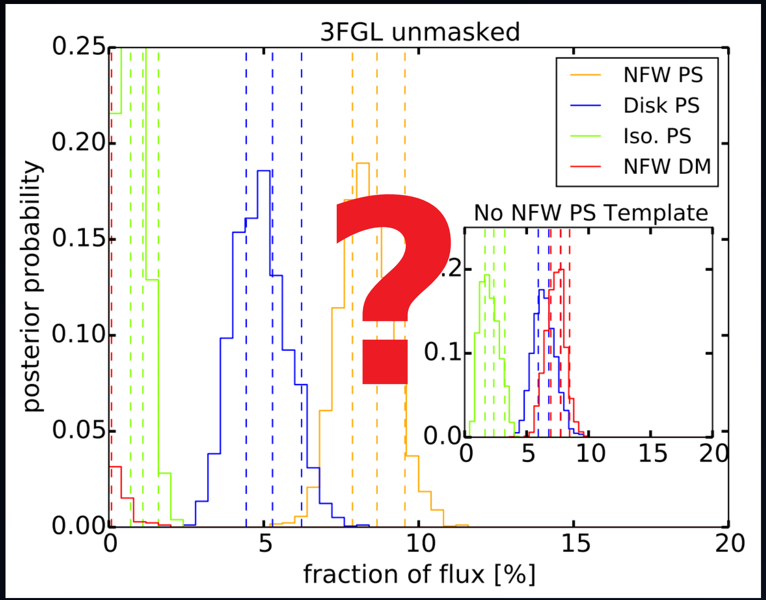


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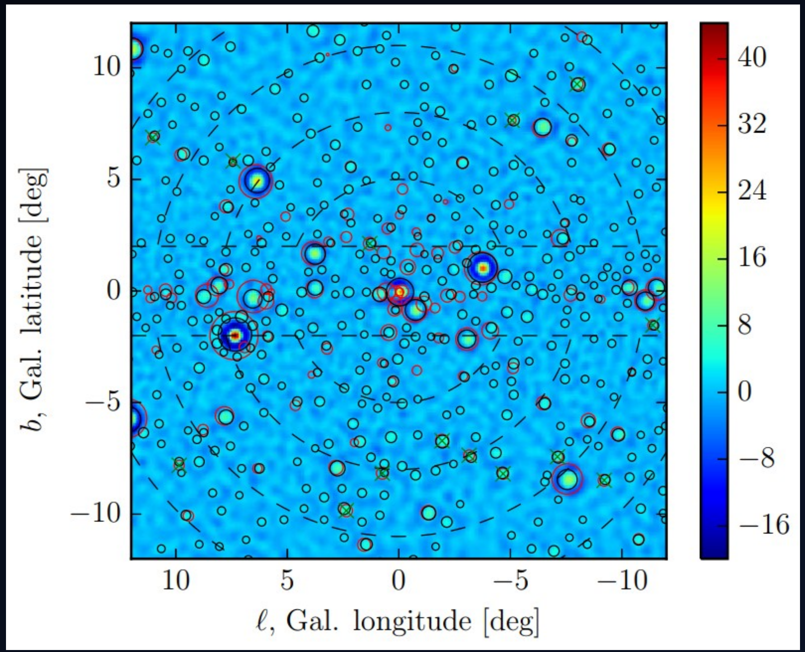


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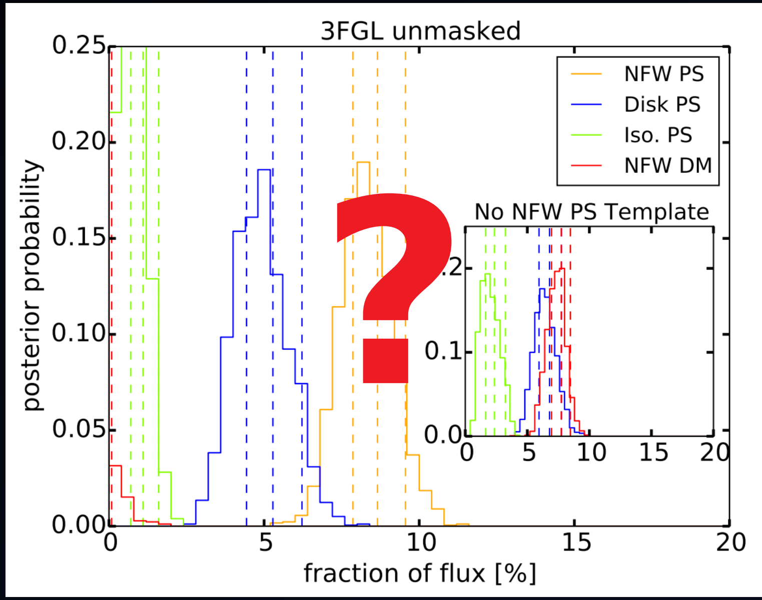


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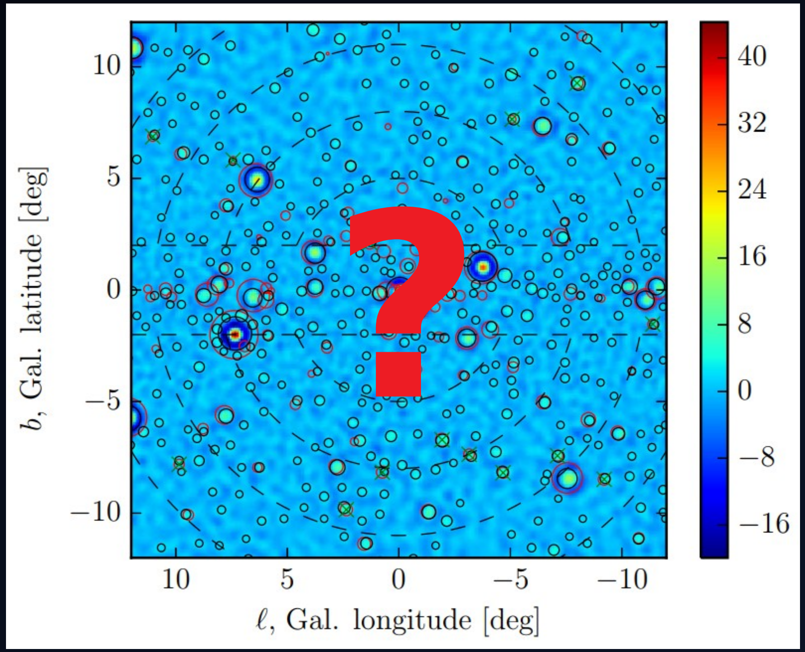
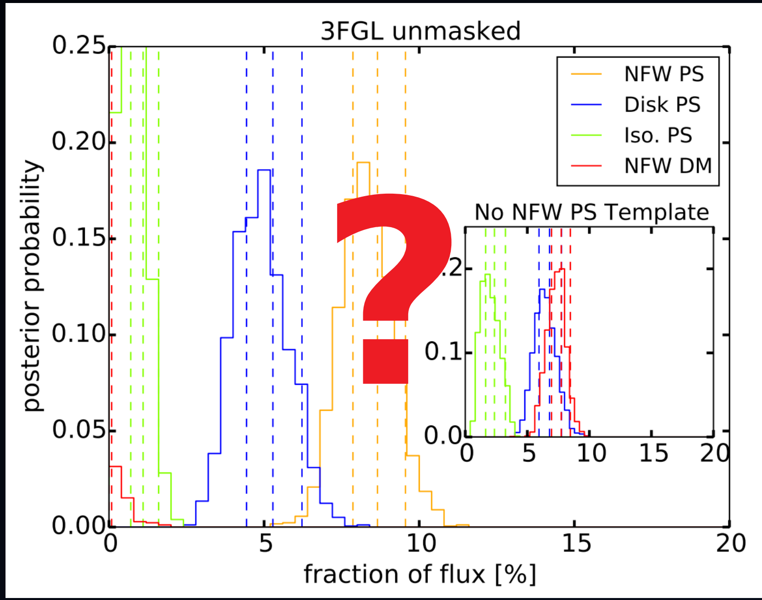



Bartels, Krishnamurthy, Weniger (PRL '15)

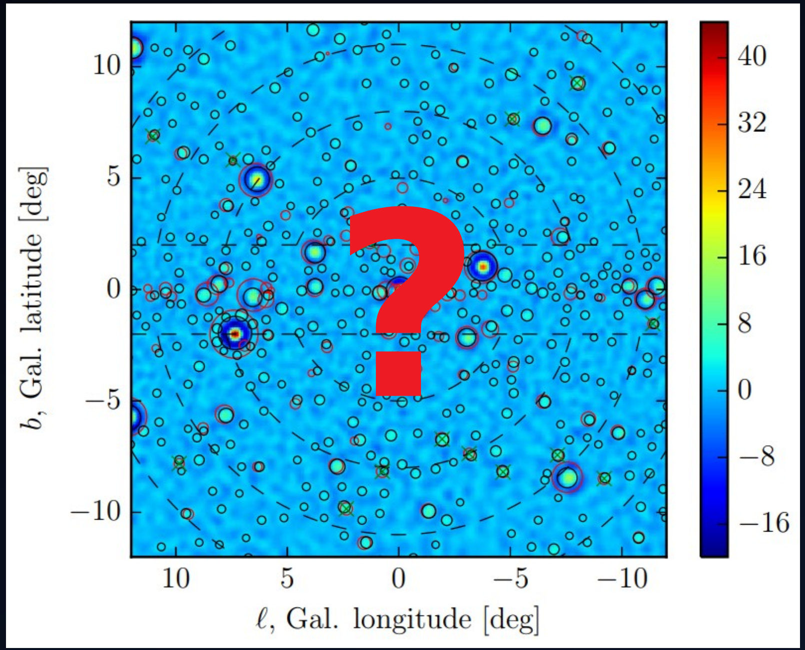
**Systematic Issues**
**RL**+Slatyer (PRL '19)

**Shown these point sources are not bulk of excess**
Zhong, McDermott, Cholis, Fox PRL '19

# Evidence for Point Sources at the Galactic Center:




Lee, Lisanti, Safdi, Slatyer, Xue (PRL '15)




Bartels, Krishnamurthy, Weniger (PRL '15)

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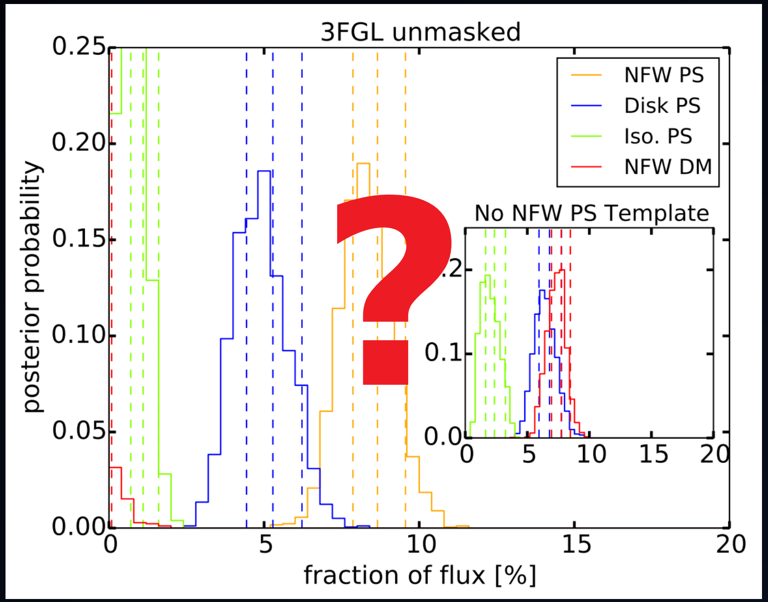
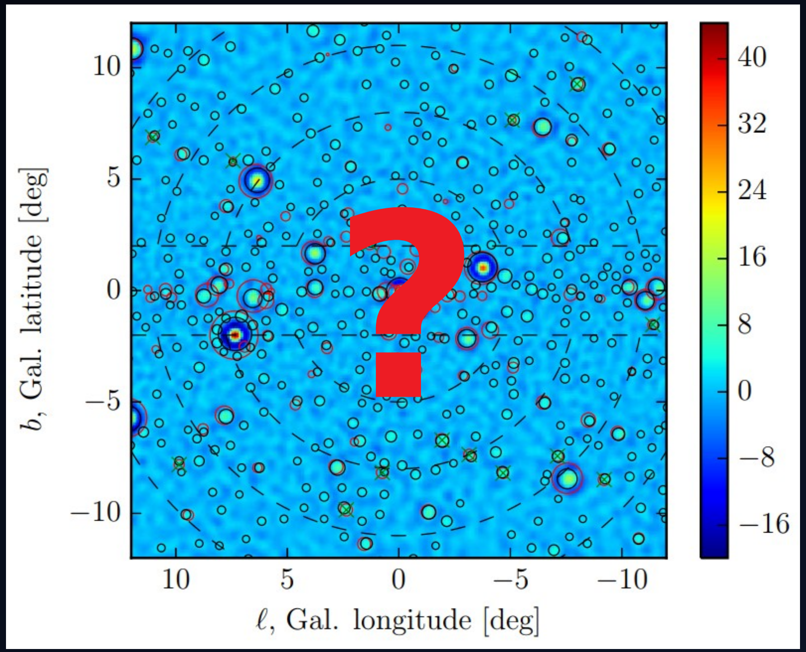



Lee, Lisanti, Safdi, Slatyer, Xue (PRL '15)




Bartels, Krishnamurthy, Weniger (PRL '15)

**Systematic Issues**
**RL**+Slatyer (PRL '19)
**Improvements**
Buschmann+, PRD '20

**Shown these point sources are not bulk of excess**
Zhong, McDermott, Cholis, Fox PRL '19

Rebecca Leane

# Spurious Point Sources

- Breaking signal template into north and south pieces:
  removes the point source evidence in our region (sims give spurious PS)

- More broadly, **any** mismodeling might cause a spurious point source signal:
  - incorrect model leads to increased variance relative to the data
  - This is also a feature of a point source signal!

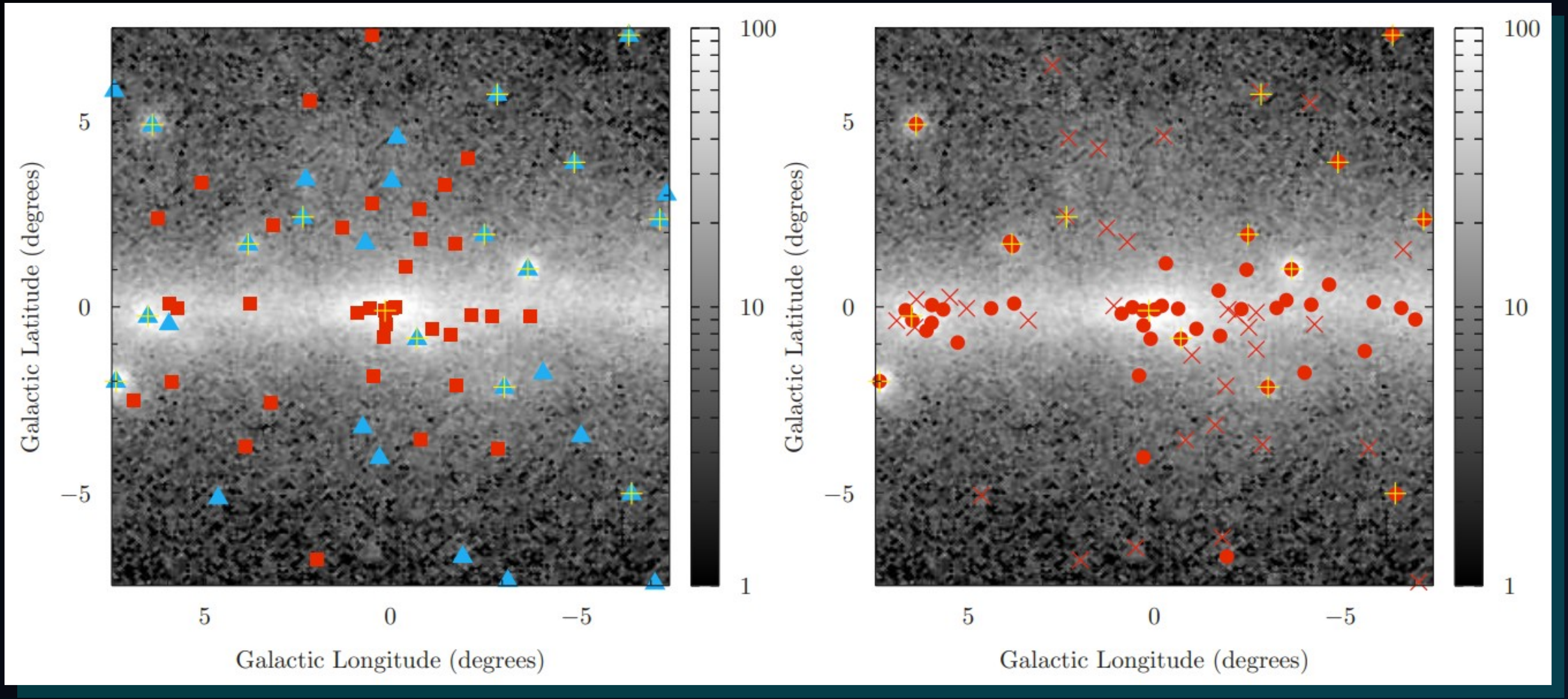
Systematics still not well enough controlled

RL+Slatyer, PRL ‘20

RL+Slatyer, PRD ‘20

# Systematics: Point Source ID?

Fermi Collaboration '15




Point source catalog 1 (3FGL)

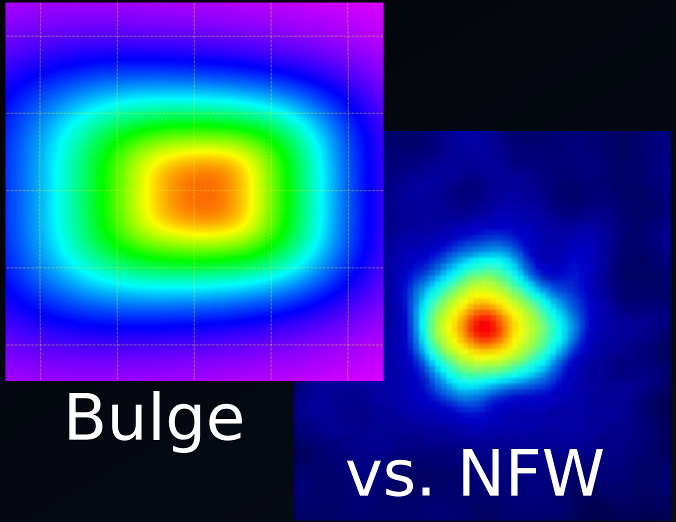
Point source catalog 2 (1FIG)

Different point sources "found" in different diffuse models!

Key point: all diffuse models are not good

# Current Picture

## Morphology

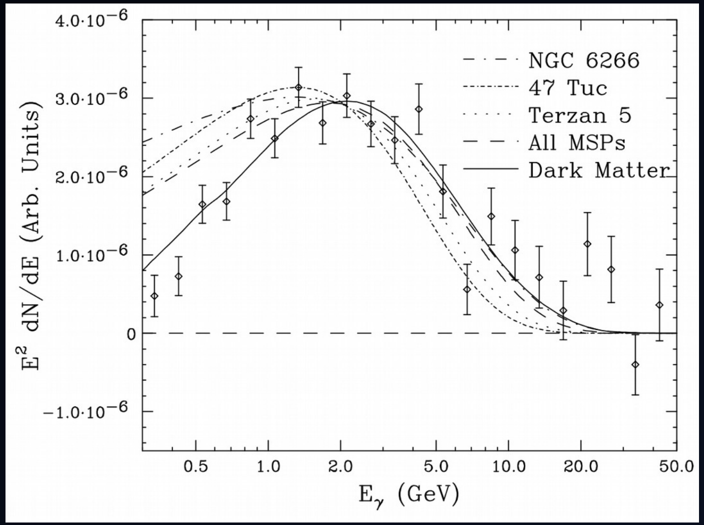


Bulge vs. NFW

Not robustly known, but big implications

Bartels+, ‘17
Macias+, ‘19
Calore+, ‘21
Di Mauro, ‘21
Cholis+, ‘21
Pohl+, ‘22

## Energy Spectrum

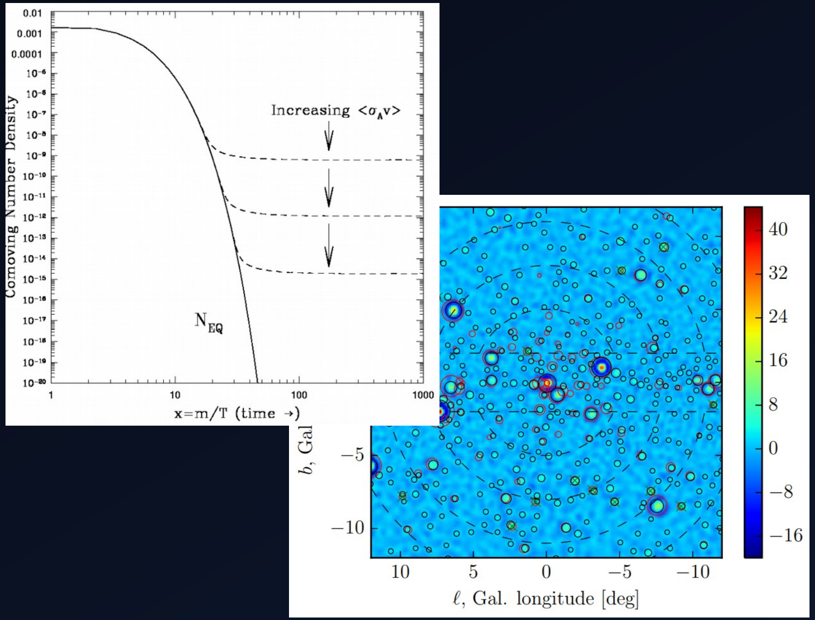



Comparable to millisecond pulsars

Can be well fit with DM annihilating to hadrons

## Intensity

Well-explained by DM (Predicted by thermal relic cross section)




Tension for pulsars strong constraints on pulsar luminosity function

# Current Picture

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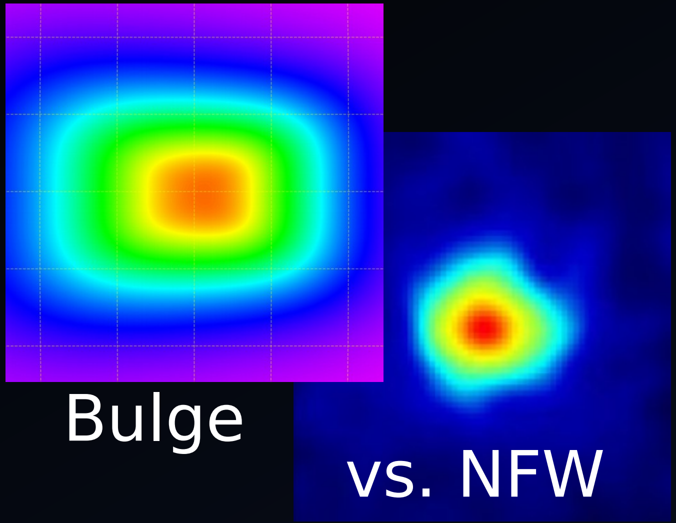


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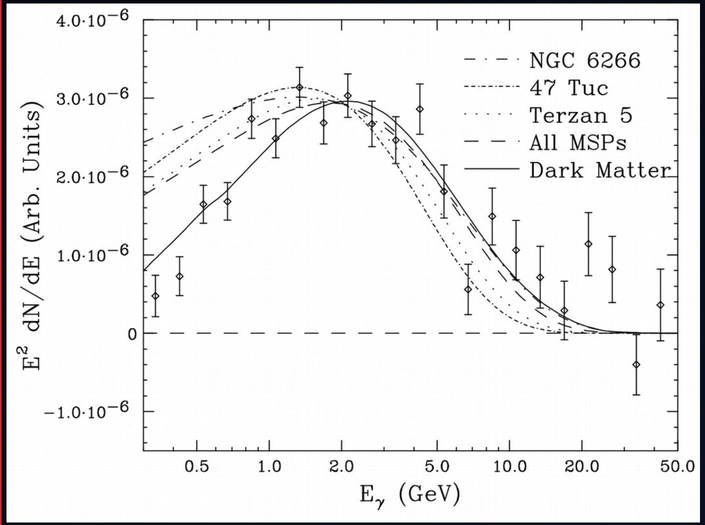


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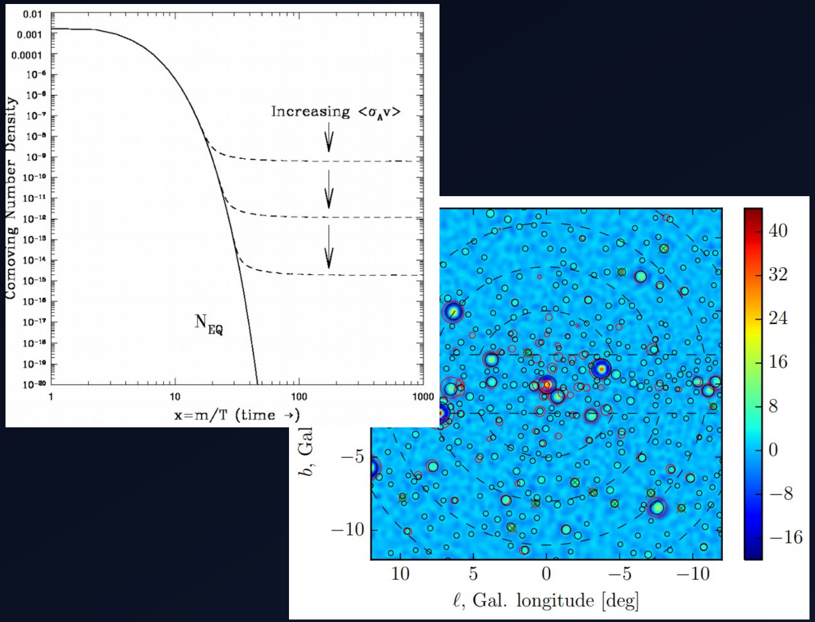


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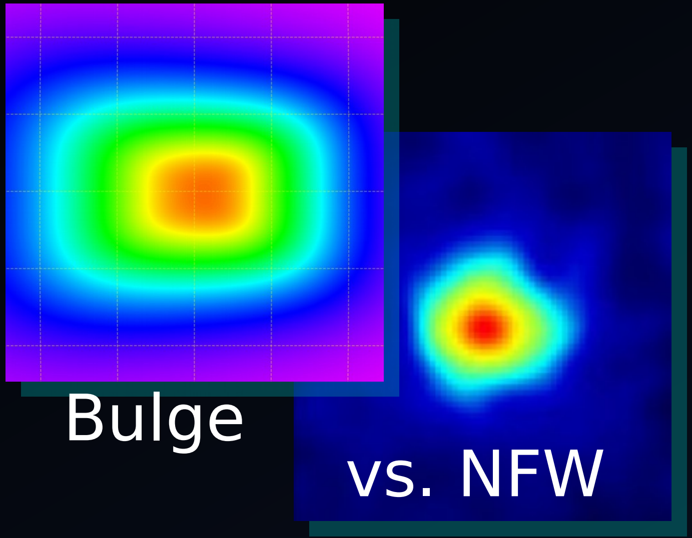


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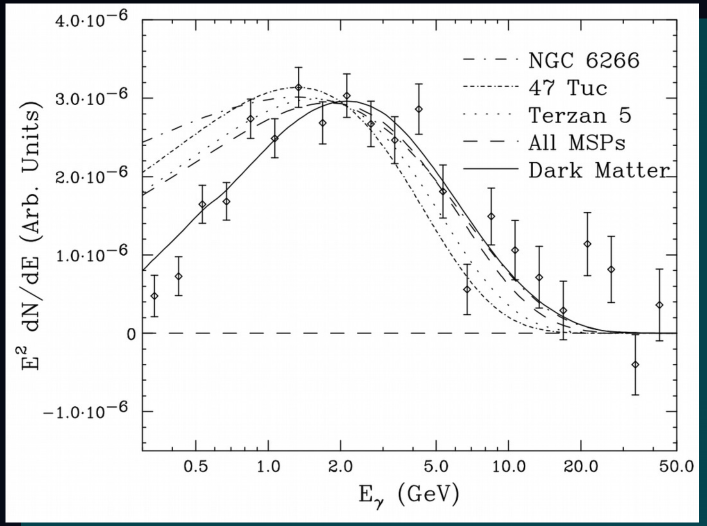


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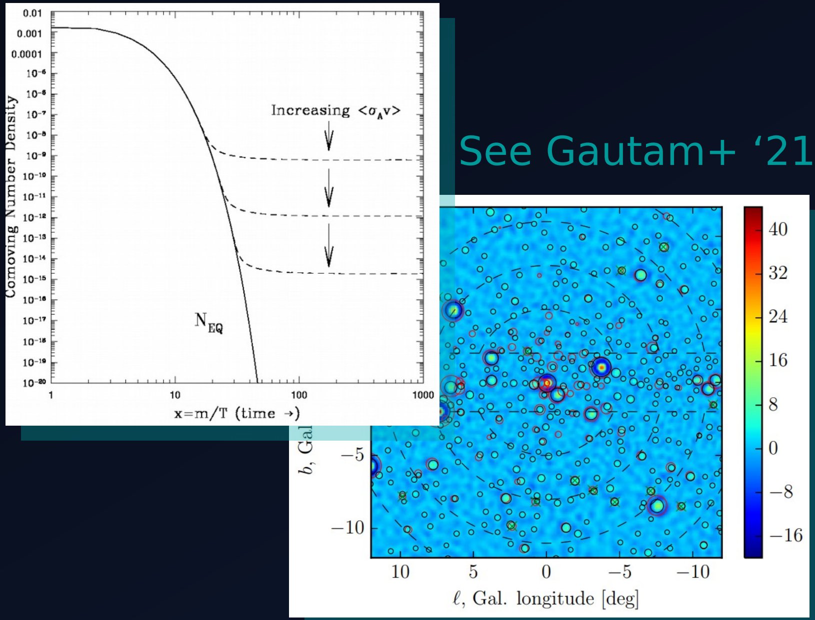



See Gautam+ '21

Tension for pulsars
strong constraints on pulsar luminosity function

# Other avenues for GCE

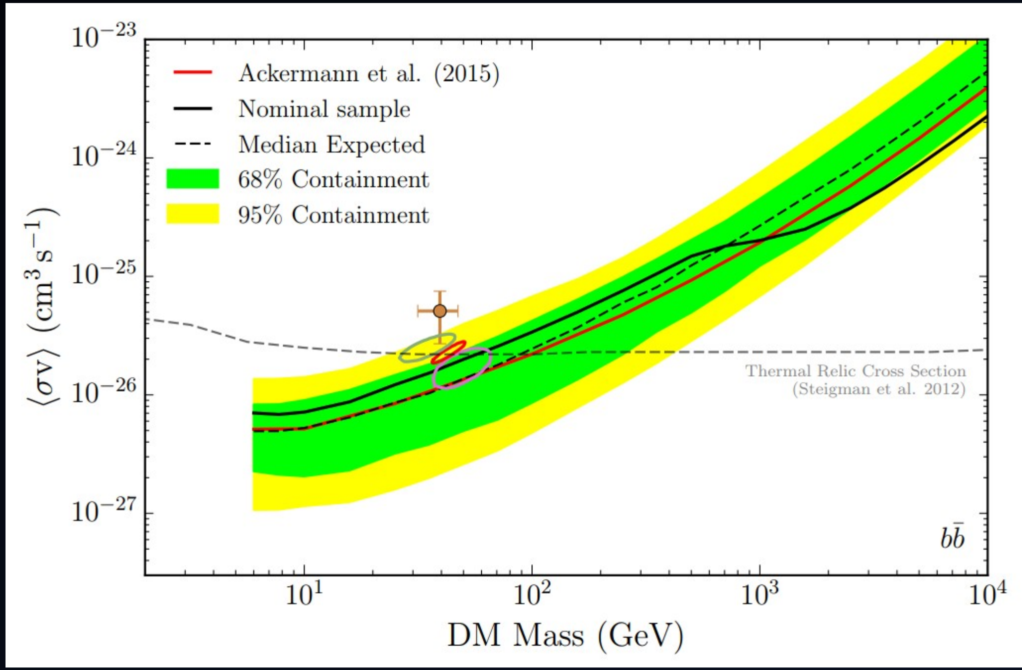
- Detect pulsars directly in radio

- Alternate fitting techniques:
  - SkyFACT+pixel counts: Calore, Donato, Manconi '21
  - Weighted likelihoods: Di Mauro '21
  - Machine learning: List+'20, List+ '21

- Energy spectrum: systematics large for Fermi below a GeV
  - Measurements with MeV gamma-ray telescopes can shed light

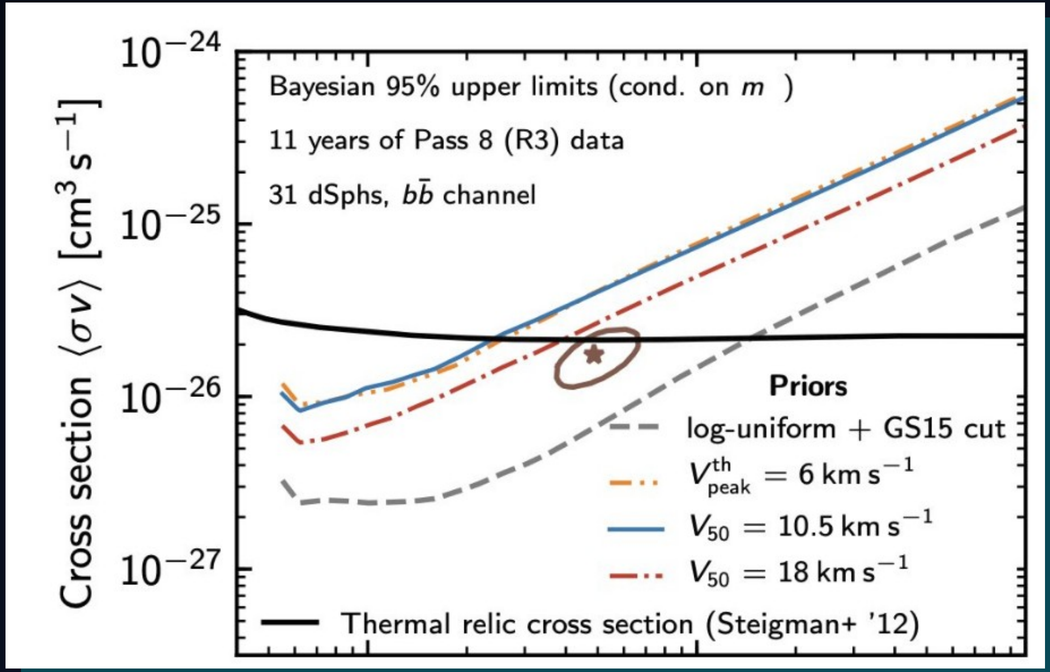
# Signals from Dwarf Spheroidal Galaxies

- No strong tension with GCE at the moment, though if the GCE really is DM, signal might appear soon
- Keep in mind systematics here!




Ackermann+, ‘16

Ando+, ‘20




DM density uncertainties weaken limits further

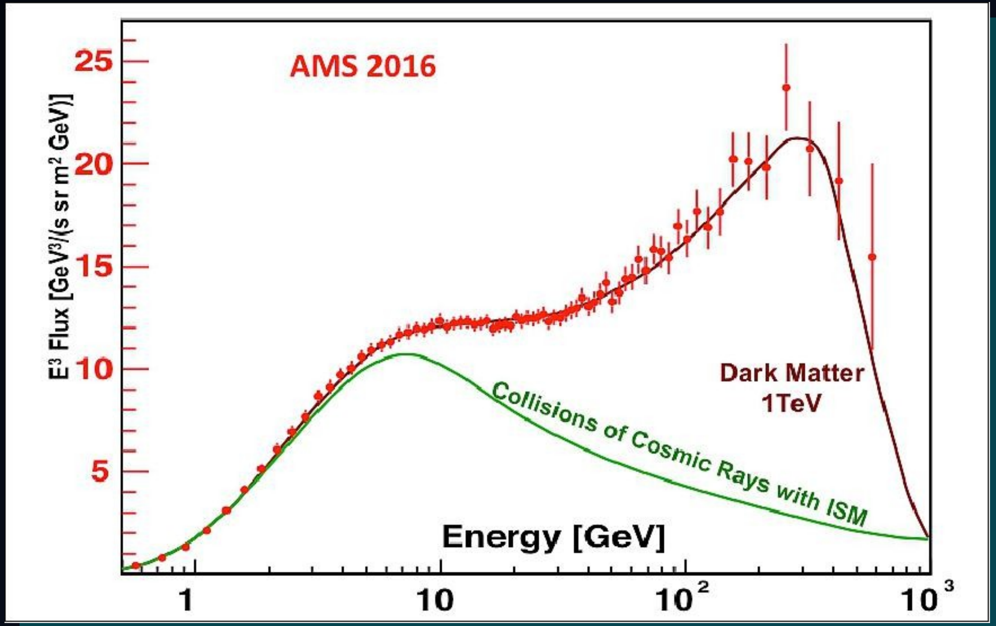
See also Chang, Necib ‘20

# Positron Excess

Rebecca Leane

# Positron Excess

- Observed by PAMELA, AMS-02, recently DAMPE
- If DM, needs to be ~TeV
- But, could be pulsars…



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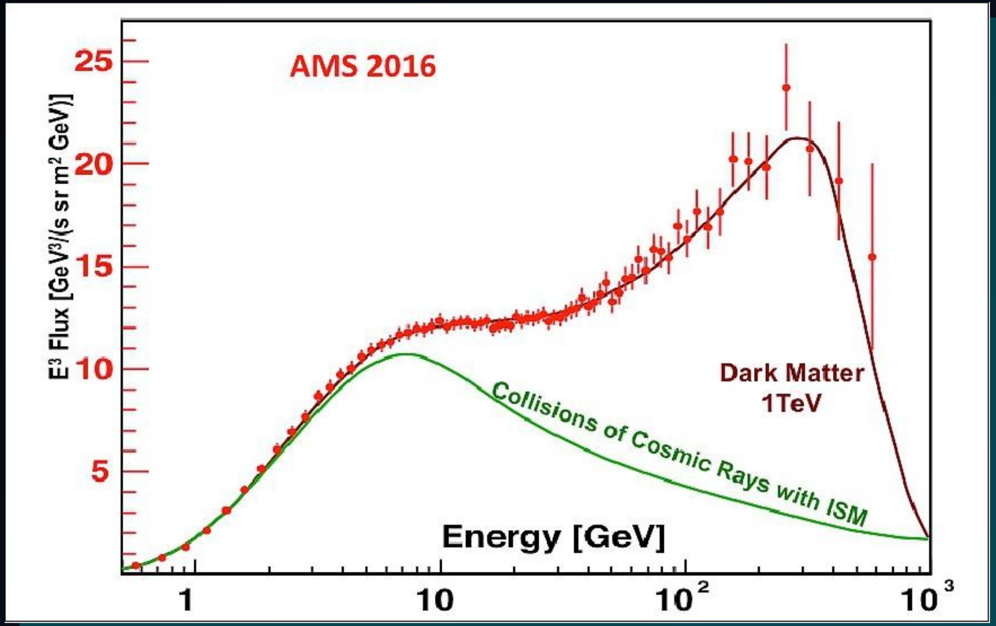
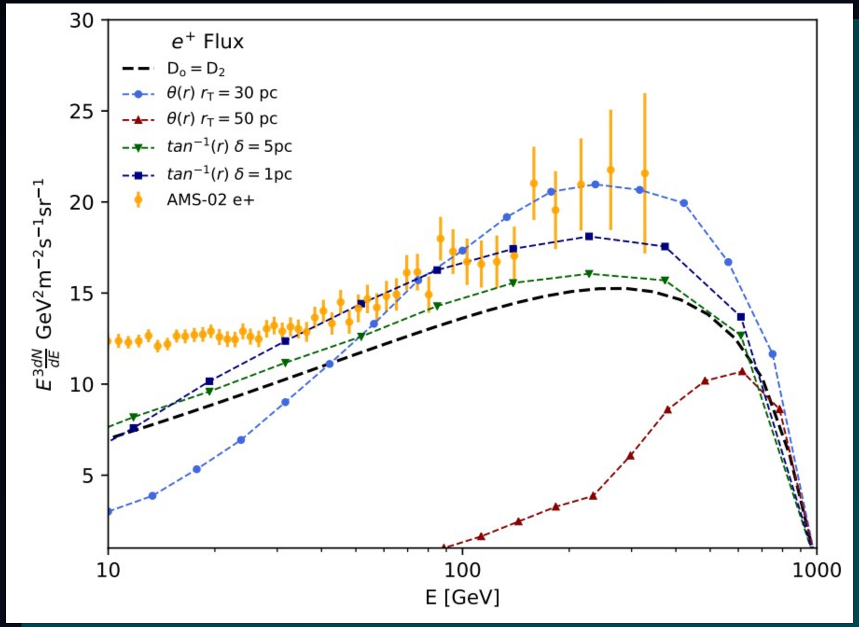



Excess cannot be due to main pulsar candidates if Galactic diffusion similar to diffusion in regions of nearby pulsars

HAWC Collab, '17

Implies diffusion coefficient is not uniform

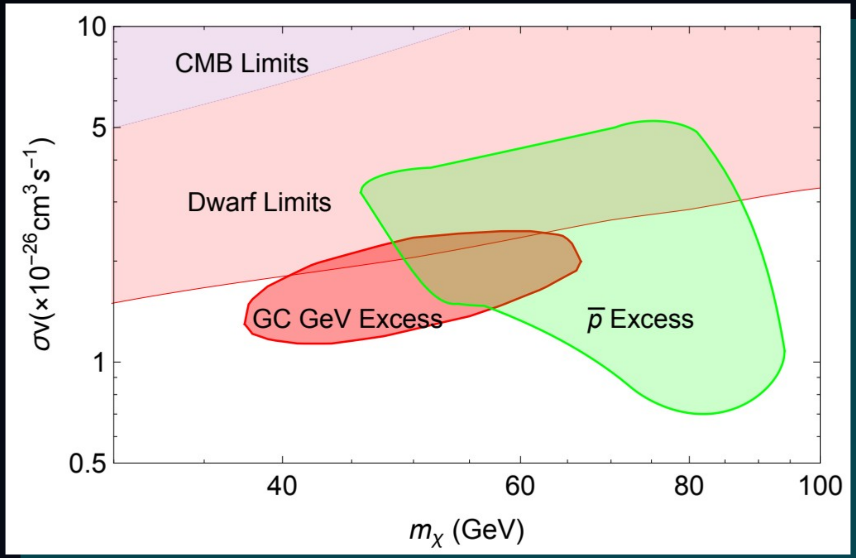
Profumo et al '18
Hooper+Linden '17

# Antiproton Excess

Rebecca Leane

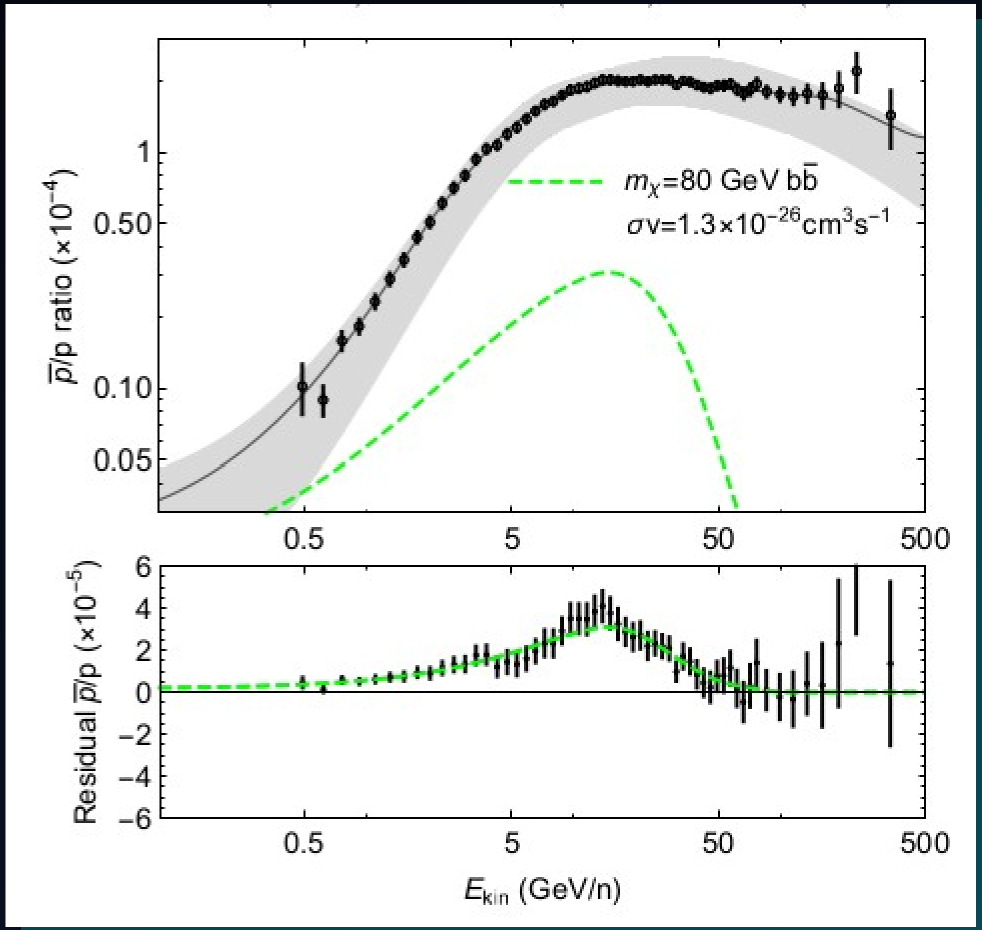
# Antiproton Excess

- Excess in antiprotons, AMS
- AMS correlated uncertainties?
  - Quantifying systematics
- Link to GCE?




Cholis et al ‘19

See also Hooper, RKL, Tsai, Wegsman, Witte ‘19



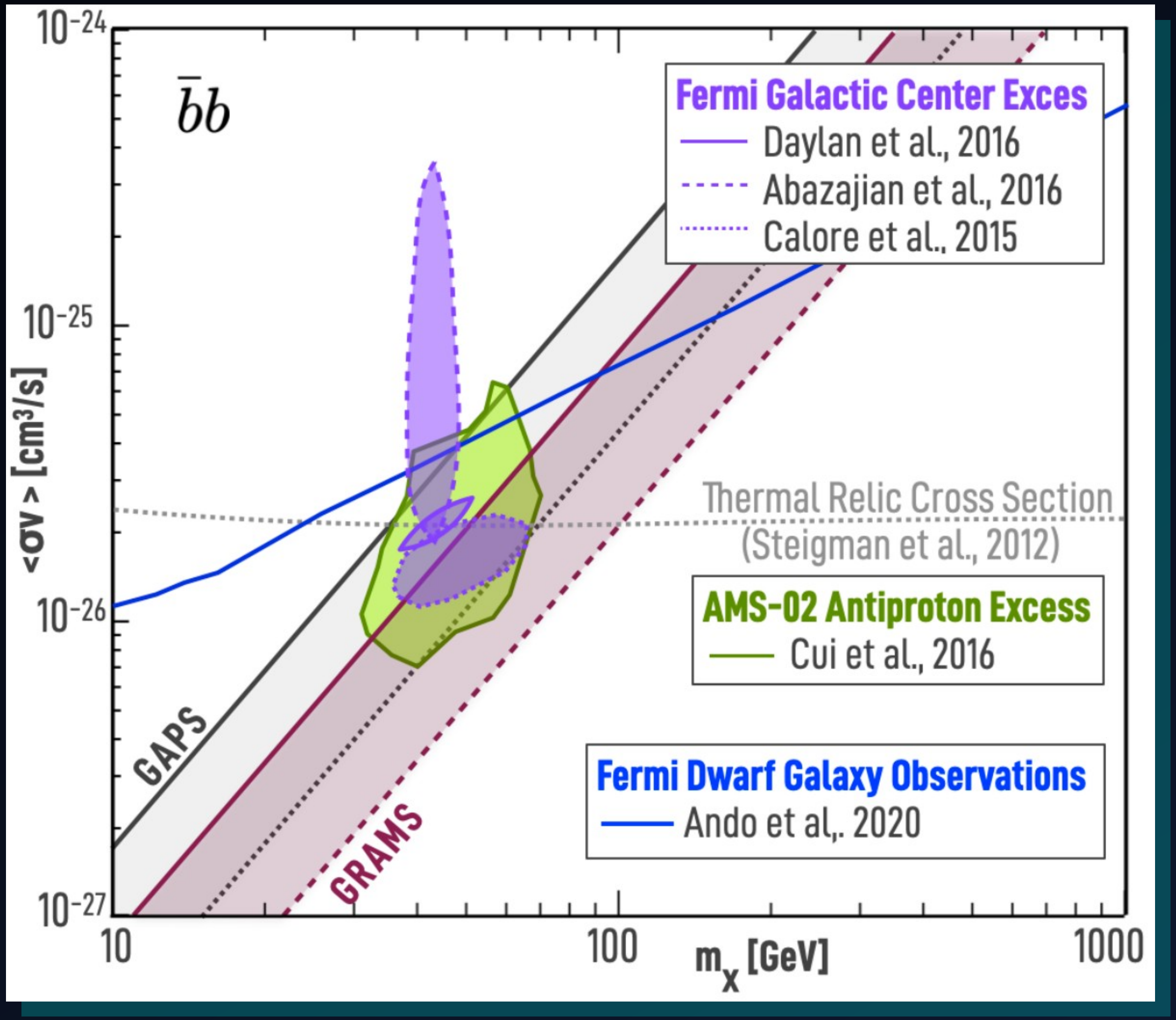

Cuoco et al ‘16 and ‘19, Cui et al ‘16 and ‘19,
Cholis et al ‘19
Boudaud ‘19
Heisig ‘20
Calore et al, ‘22

# Anti-Nuclei?

- AMS-02 collaboration: observation of several candidate anti-deuterons and antihelium nuclei events

- Tentative, need verification or refutation w/ other experiments

- GAPS, GRAMS: Different identification techniques, reducing systematic uncertainties (2023 flight)




Leane+, '22

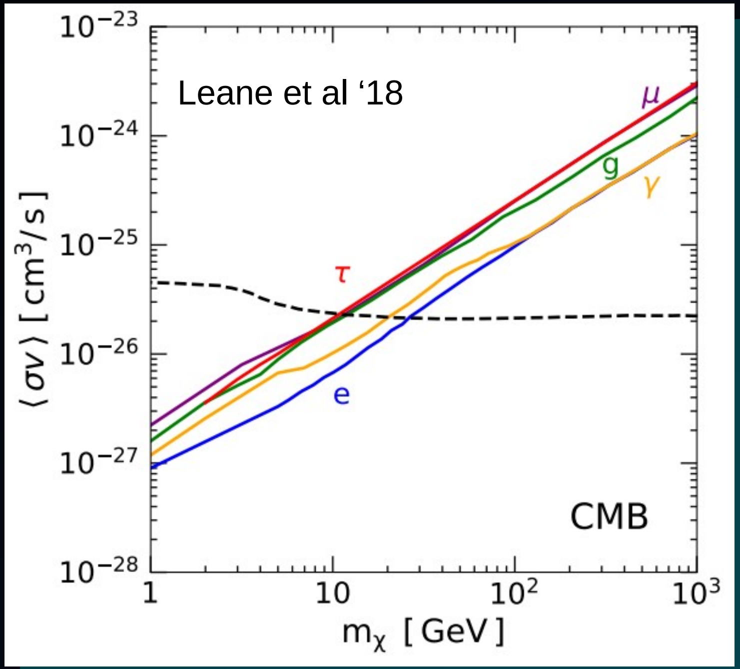
# Snowmass2021 Cosmic Frontier White Paper: Puzzling Excesses in Dark Matter Searches and How to Resolve Them

Rebecca K. Leane[*1,2], Seodong Shin[†3], Liang Yang[‡4], Govinda Adhikari[4], Haider Alhazmi[5], Tsuguo Aramaki[6], Daniel Baxter[7], Francesca Calore[8], Regina Caputo[9], Ilias Cholis[10], Tansu Daylan[11,12], Mattia Di Mauro[13], Philip von Doetinchem[14], Ke Han[15], Dan Hooper[16,17,18], Shunsaku Horiuchi[19,20], Doojin Kim[21], Kyoungchul Kong[22], Rafael F. Lang[23], Qing Lin[24,25], Tim Linden[26], Jianglai Liu[15,27,28], Oscar Macias[29], Siddharth Mishra-Sharma[30,31,32], Alexander Murphy[33], Meshkat Rajaee[3], Nicholas L. Rodd[34], Aditya Parikh[31], Jong-Chul Park[35], Maria Luisa Sarsa[36], Evan Shockley[18], Tracy R. Slatyer[32], Volodymyr Takhistov[20], Felix Wagner[37], Jingqiang Ye[38], Gabrijela Zaharijas[39], Yi-Ming Zhong[18], Ning Zhou[15], and Xiaopeng Zhou[40]

**ArXiv: 2203.06859**

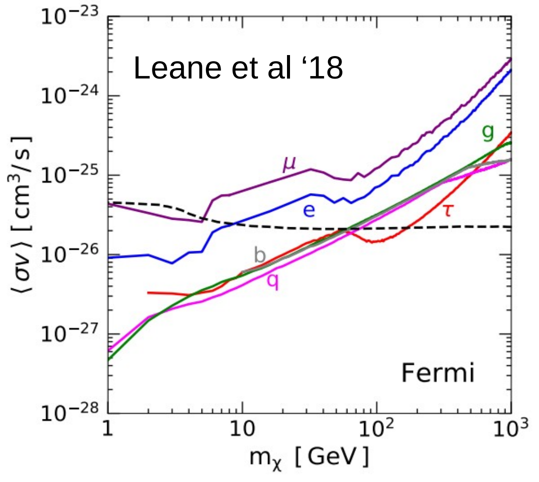
# Dark Matter Annihilation Bounds

## Strongest low mass

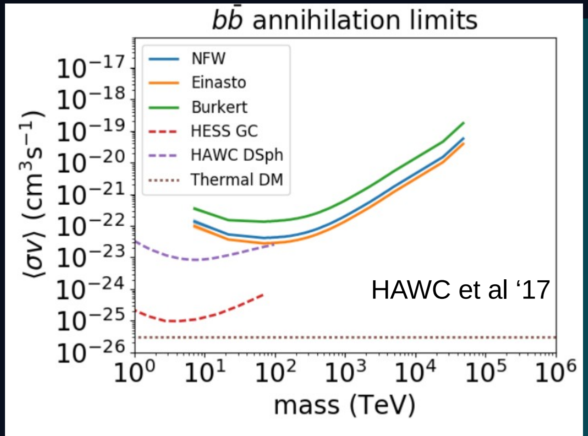



Also see Slatyer '15

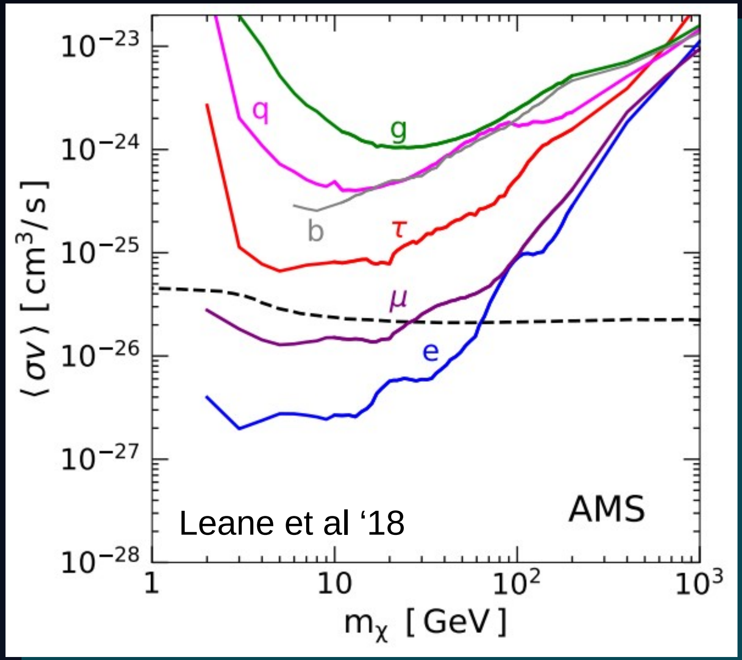
## Strongest for hadrons




Also see Fermi Collab '16



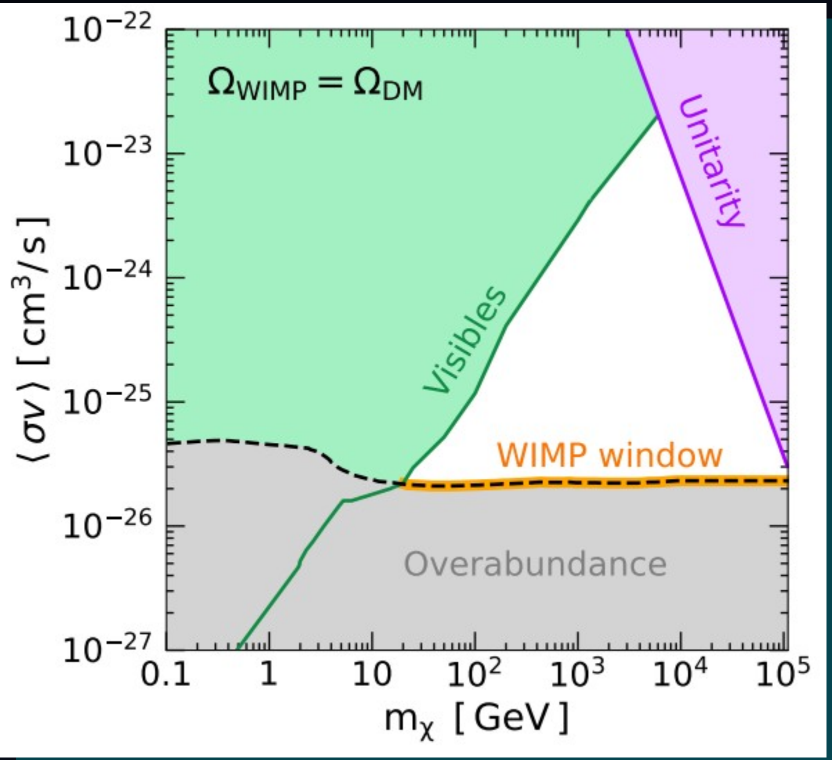

## Strongest for leptons




Also see AMS collab '14

(strongest *and most robust* bounds)

# Combining All Constraints




Leane+, '18

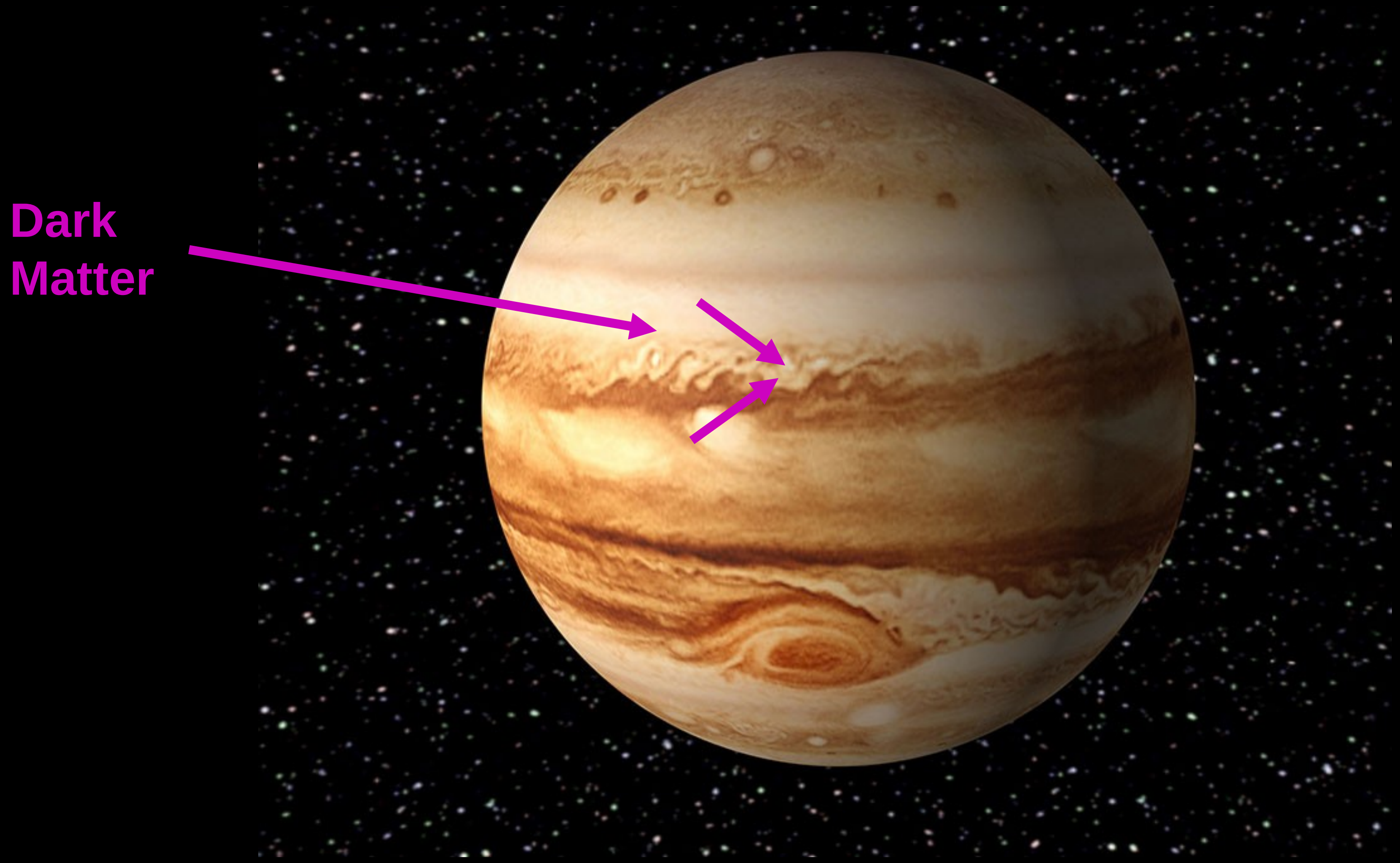
WIMP is not dead!

S-wave 2→2 thermal DM to visible states have mass greater than ~20 GeV

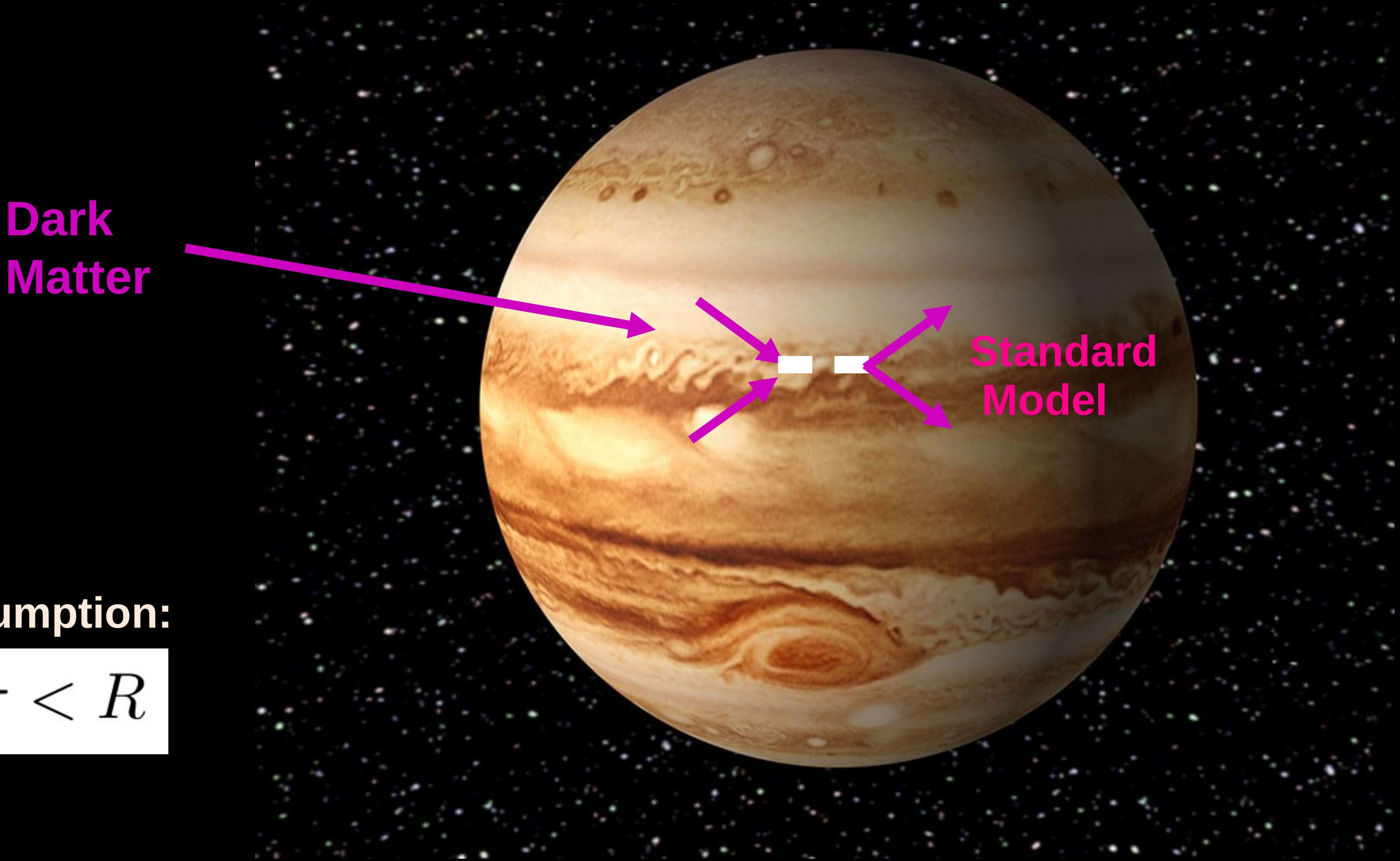
# New probes of the DM annihilation rate

Rebecca Leane

# DM capture in celestial bodies



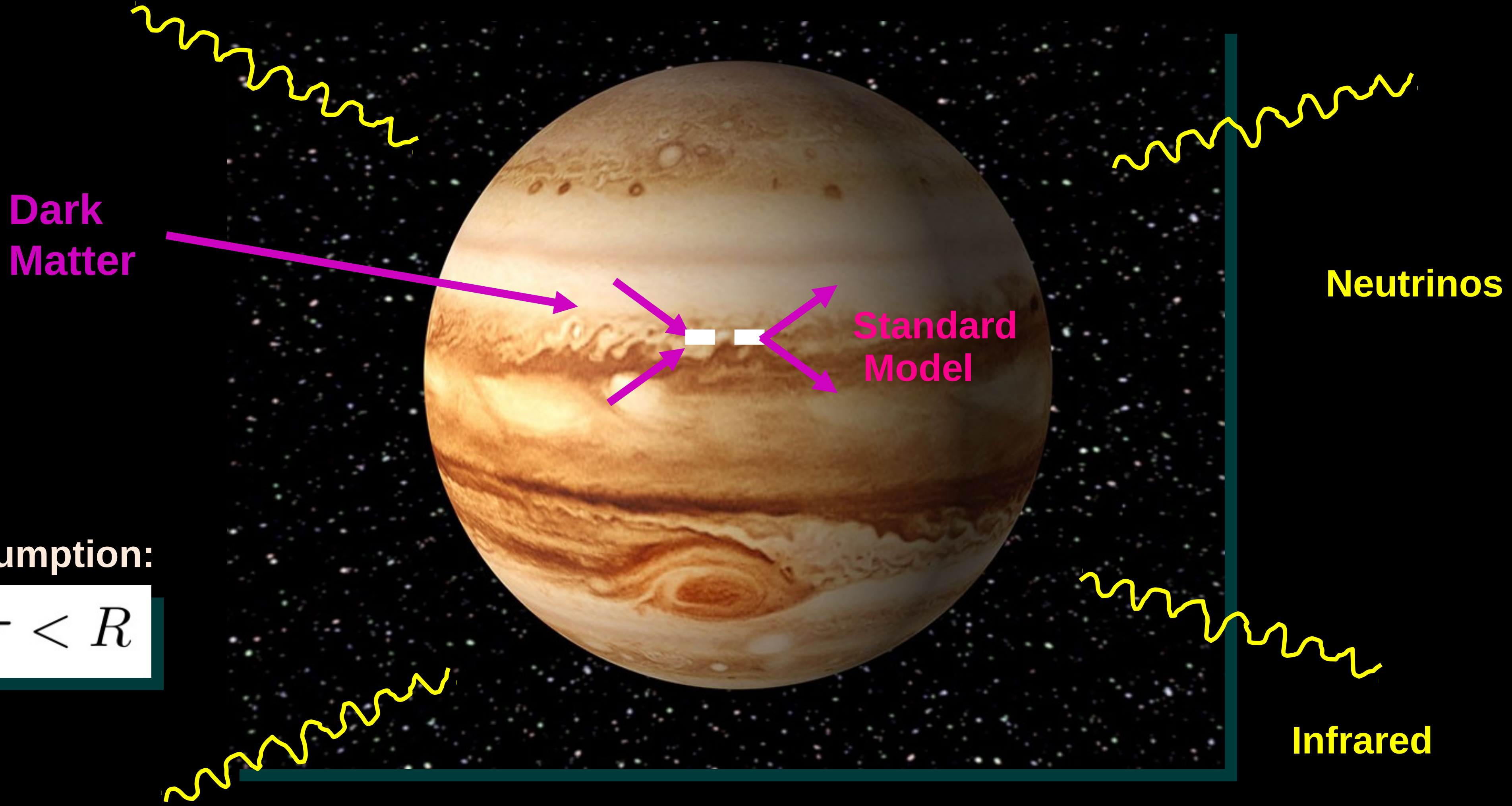
# DM capture in celestial bodies




**Assumption:**

$$\gamma c\tau < R$$

# DM capture in celestial bodies

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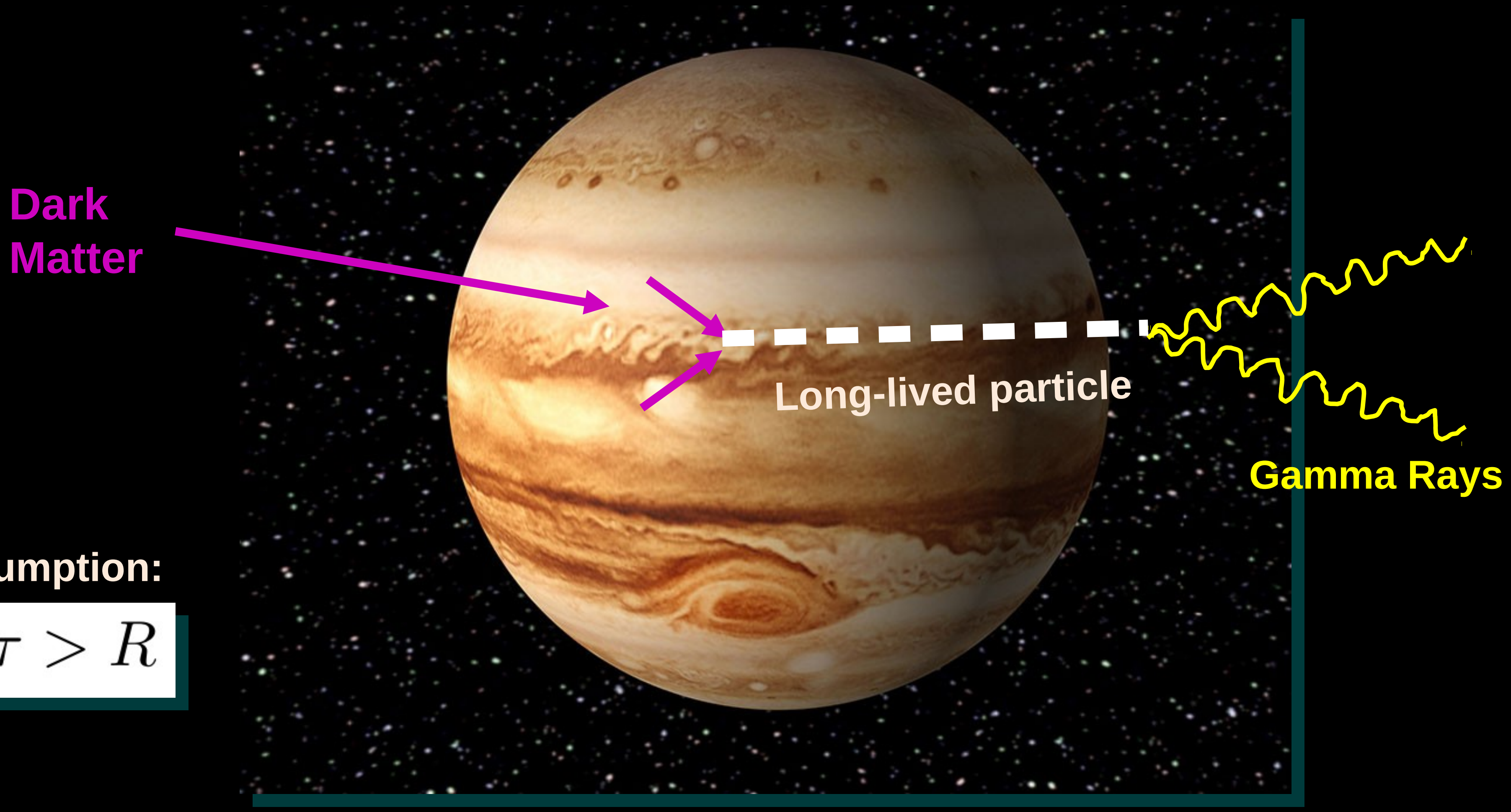


Assumption:

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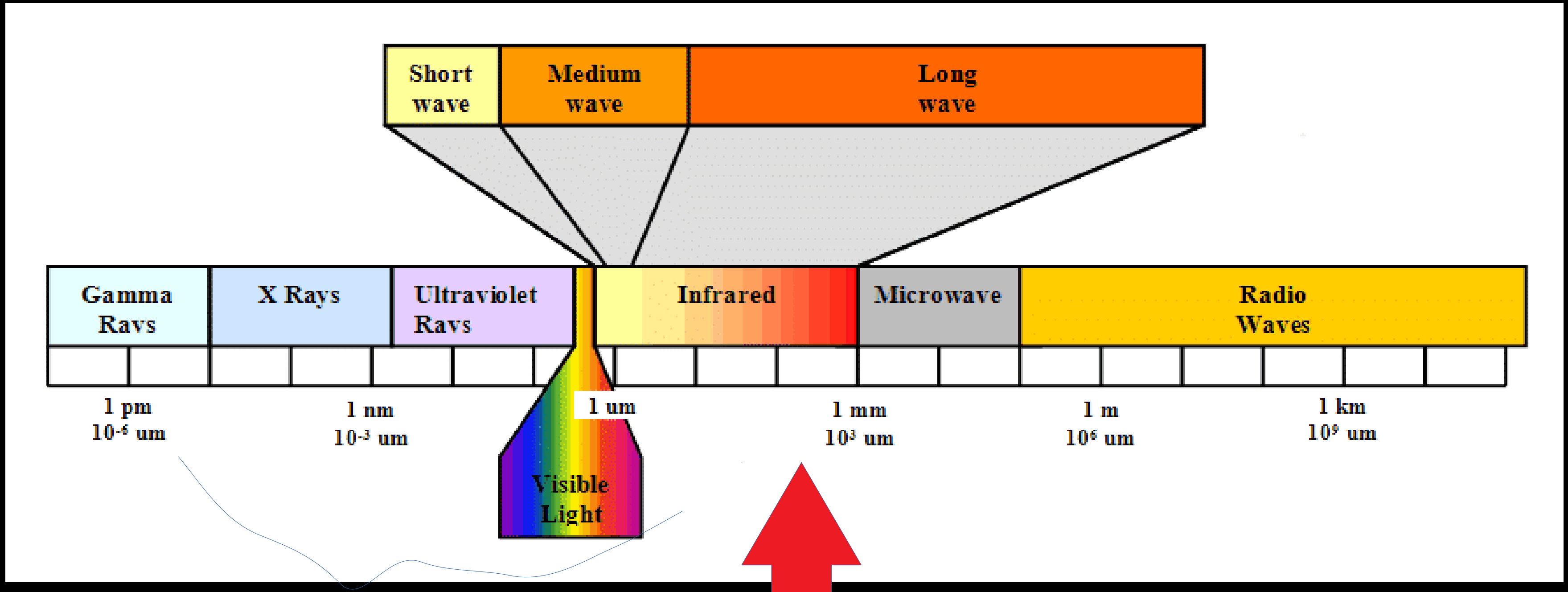
# Detecting Dark Matter Heating




Dust extinction, limits distance

Coldest stars/planets ~ 50 K

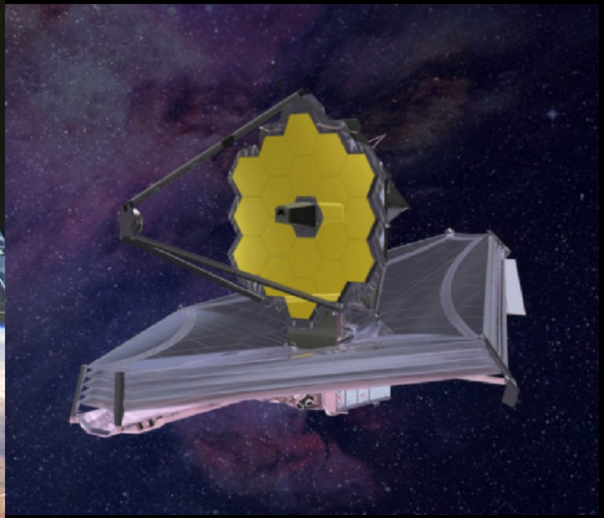
# Detecting Dark Matter Heating

## Hubble

Near-infrared
Optical
Ultraviolet

~0.12-2 microns

Data obtained
~31 years elapsed

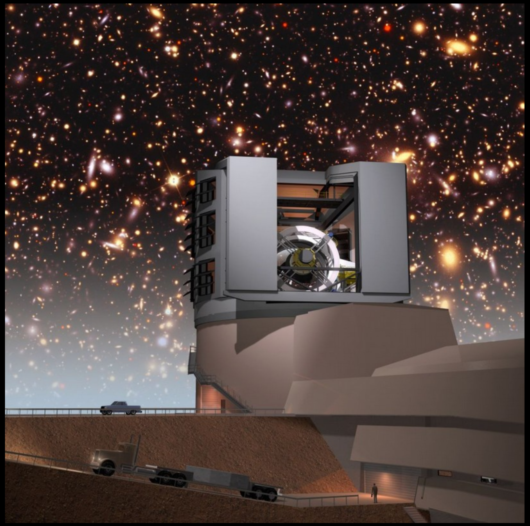


## Webb

Full Infrared
Optical

~0.5 – 28 microns

Awaiting Data
Launched 2021!

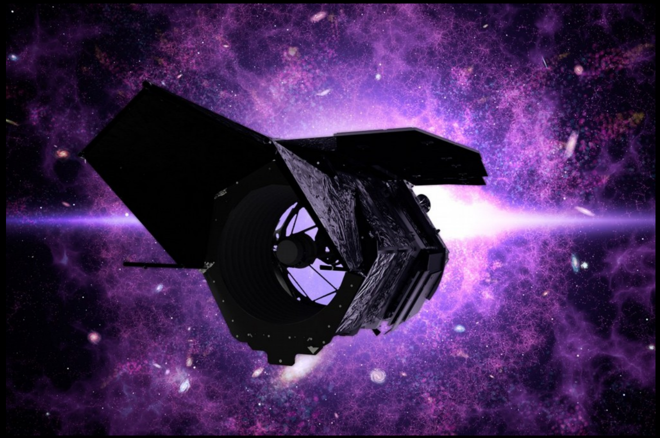


## Rubin

Near-infrared
Optical

~0.32–1.06 microns

Awaiting Data
First light 2022/23



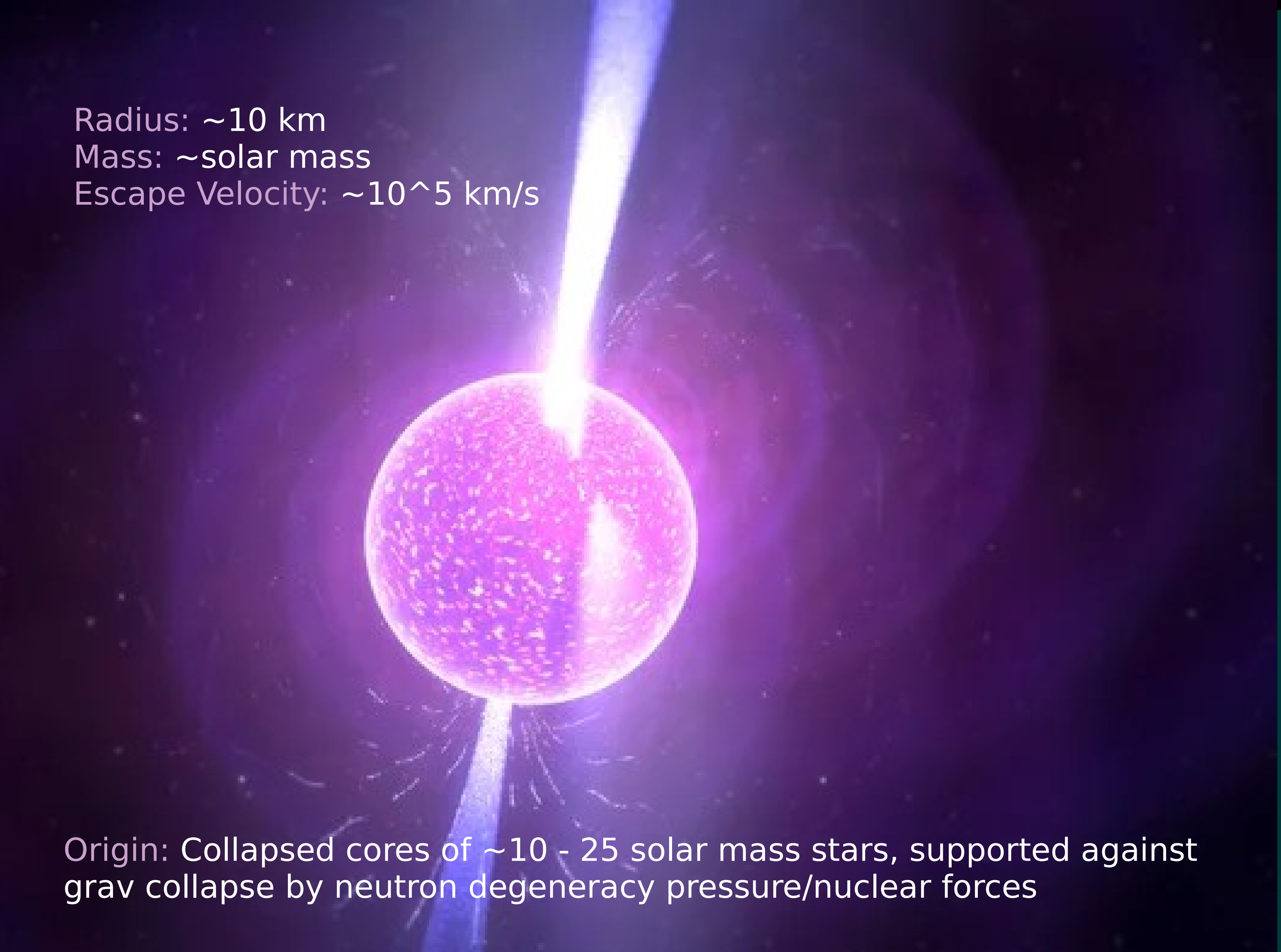
## Roman

Near-infrared
Optical

~0.5 – 2 microns

Awaiting Data
Launch 2025

# NEUTRON STARS



Radius: ~10 km
Mass: ~solar mass
Escape Velocity: ~10^5 km/s

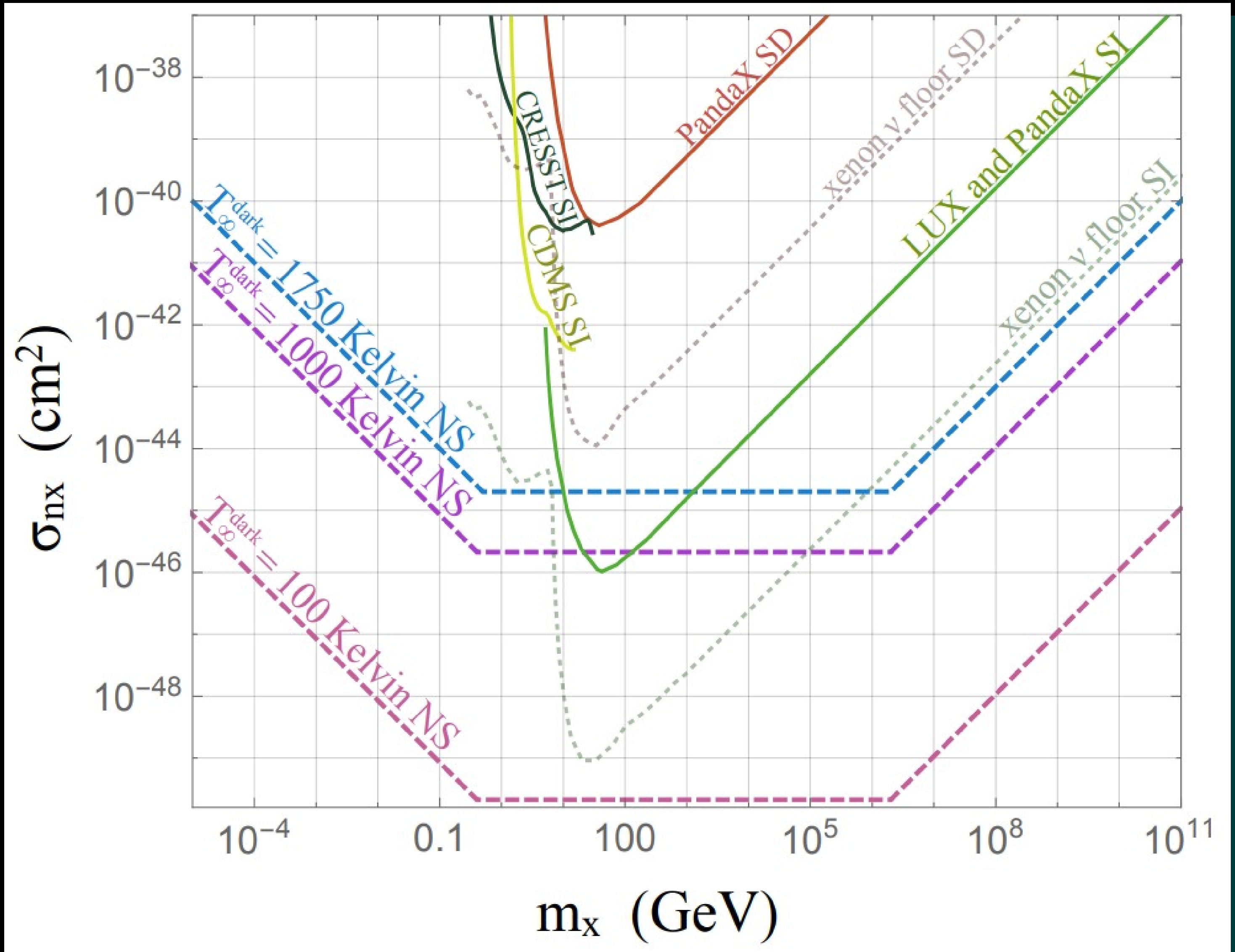
Origin: Collapsed cores of ~10 - 25 solar mass stars, supported against grav collapse by neutron degeneracy pressure/nuclear forces

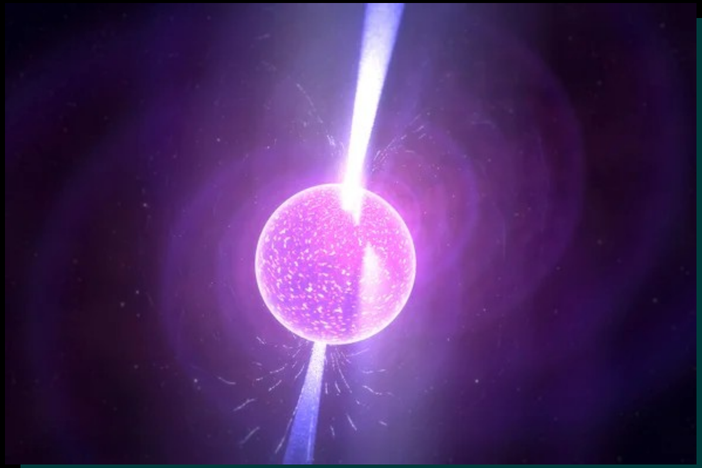
Gould, Draine, Romani, Nussinov 1989
Goldman, Nussinov 1989
Starkman, Gould, Esmailzadeh, Dimopoulos 1990
Bertone, Fairbairn 2007
Kouvaris 2007
Gonzalez, Reisenegger 2010
Kouvaris, Tinyakov 2011
McDermott, Yu, Zurek 2011
Bramante, Fukushima, Kumar 2013
Bell, Melatos, Petraki 2013
Bramante, Linden 2014
Bertoni, Nelson, Reddy 2014
Bramante, Elahi 2015
Baryakhtar, Bramante, Li, Linden, Raj 2017
Bramante, Delgado, Martin 2017
Raj, Tanedo, Yu 2017
Chen, Lin 2018
Jin, Gao 2018
Garani, Genolini, Hambye 2018
Acevedo, Bramante, Leane, Raj 2019
Hamaguchi, Nagata, Yanagi 2019
Camargo, Queiroz, Sturani 2019
Joglekar, Raj, Tanedo, Yu 2019
Garani, Heeck 2019
Bell, Busoni, Robles 2019
Keung, Marfatia, Tseng 2020
Bell, Busoni, Robles 2020
Bai, Berger, Korwar, Orlofsky 2020
Bell, Busoni, Motta, Robles, Thomas, Virgato 2020
Leane, Linden, Mukhopadhyay, Toro 2021

+ even more

Baryakhtar, Bramante, Li, Linden, Raj 2017

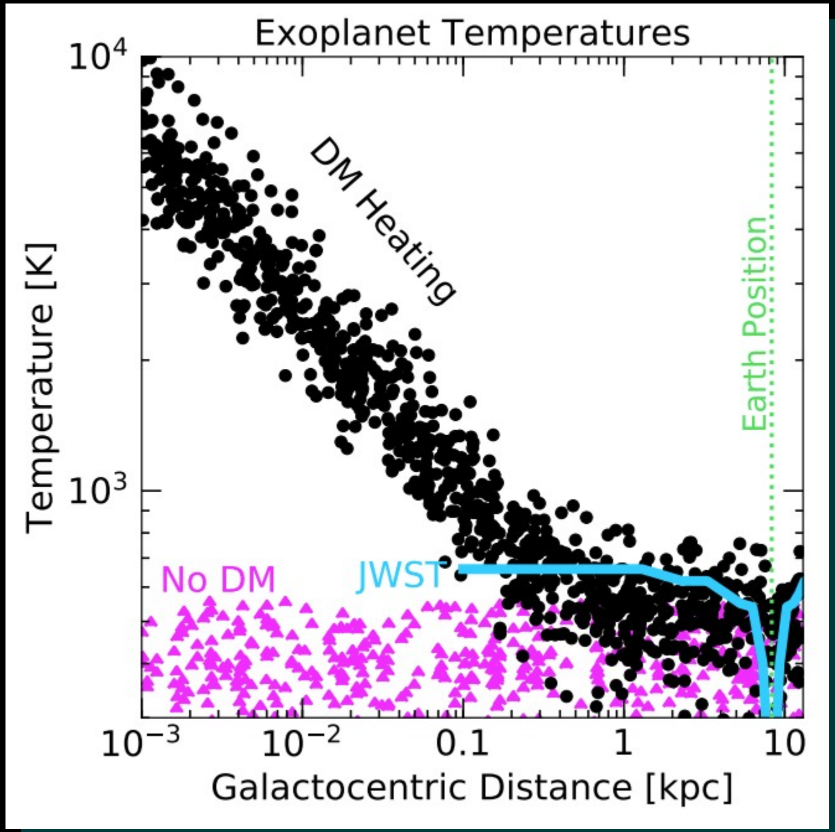
# NEUTRON STARS

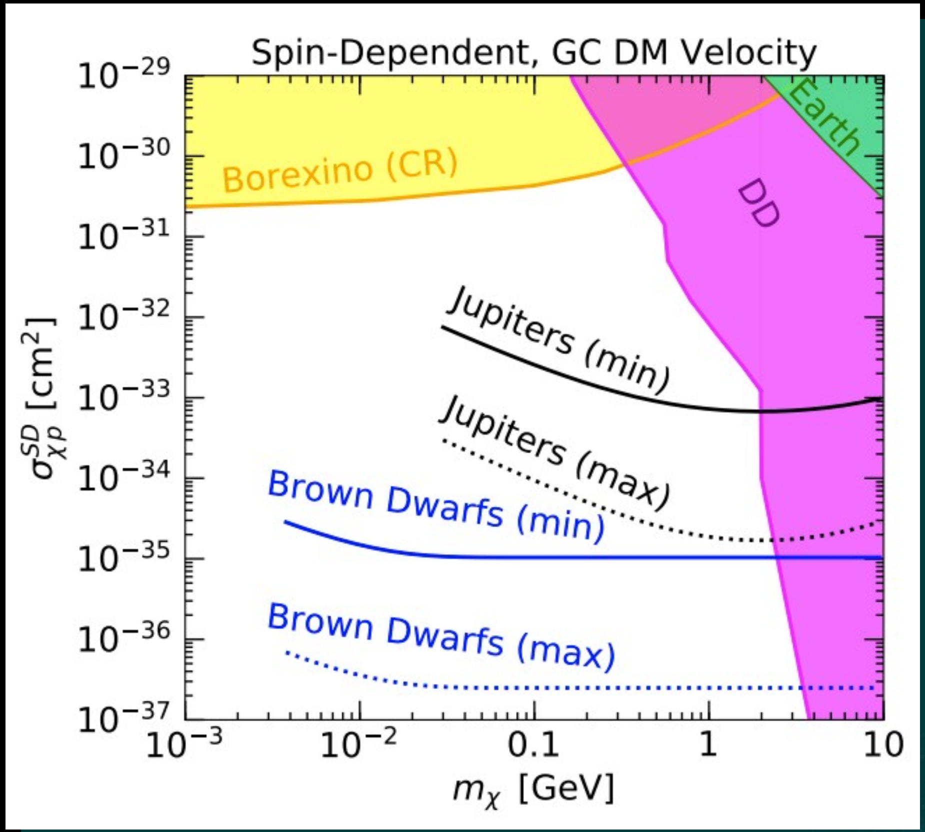


See also Bell, Busoni, Motta, Robles, Thomas, Virgato 2020

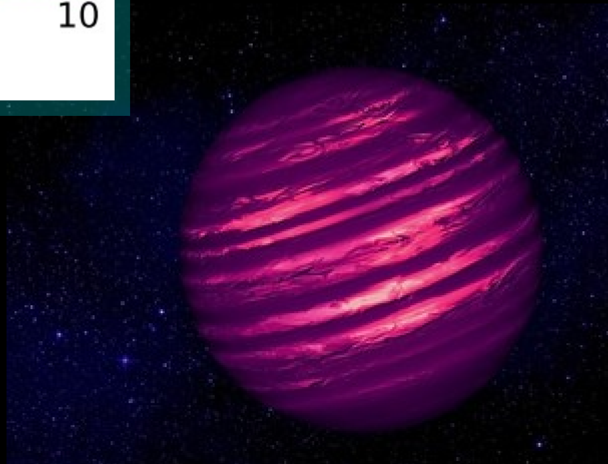
# EXOPLANETS



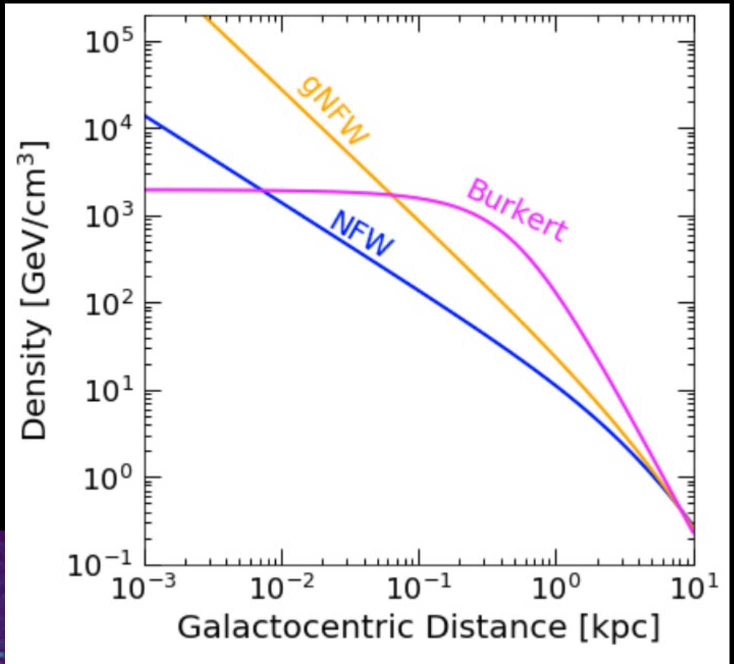

Exoplanets can potentially be used to map the Galactic DM density

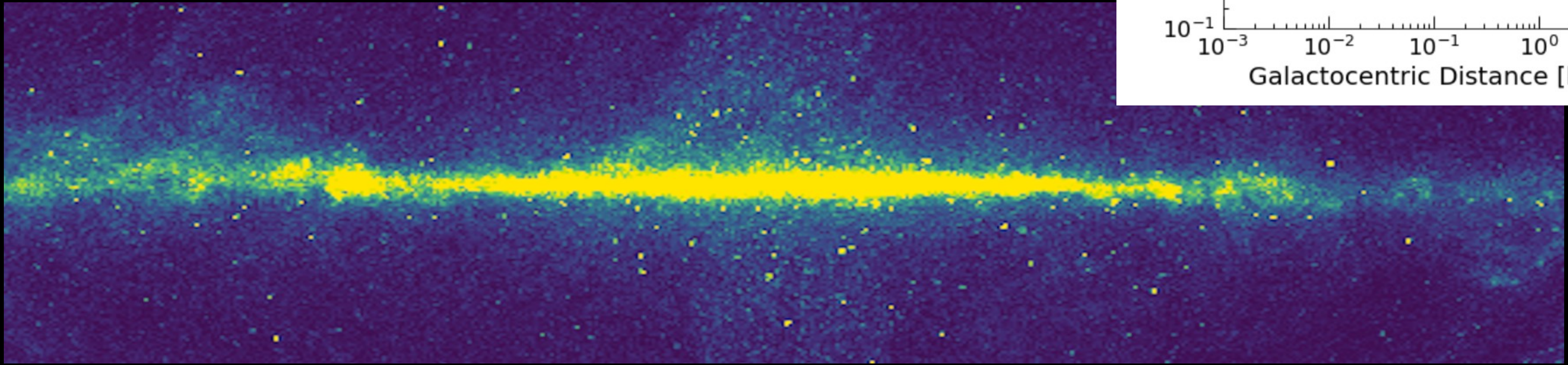
Leane + Smirnov, 2020



# Galactic Center Signal

- Galactic Center benefits:
  - High DM density
  - Lower DM velocity
  - Lots of neutron stars and brown dwarfs present



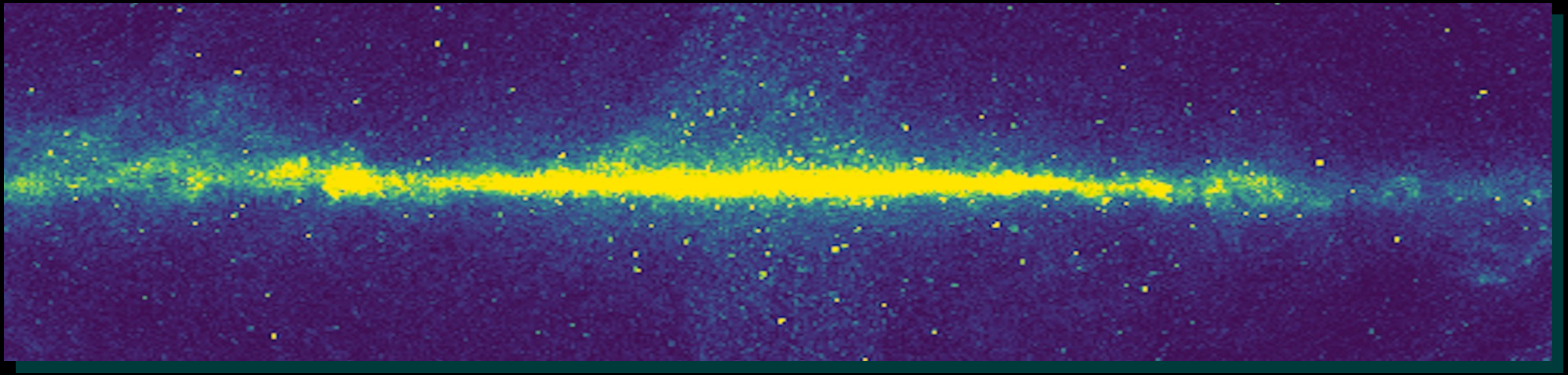



Rebecca Leane (SLAC)

# Galactic Center **Population** Signal

Use all the neutron stars, all the brown dwarfs

Indirect detection flux with celestial objects!



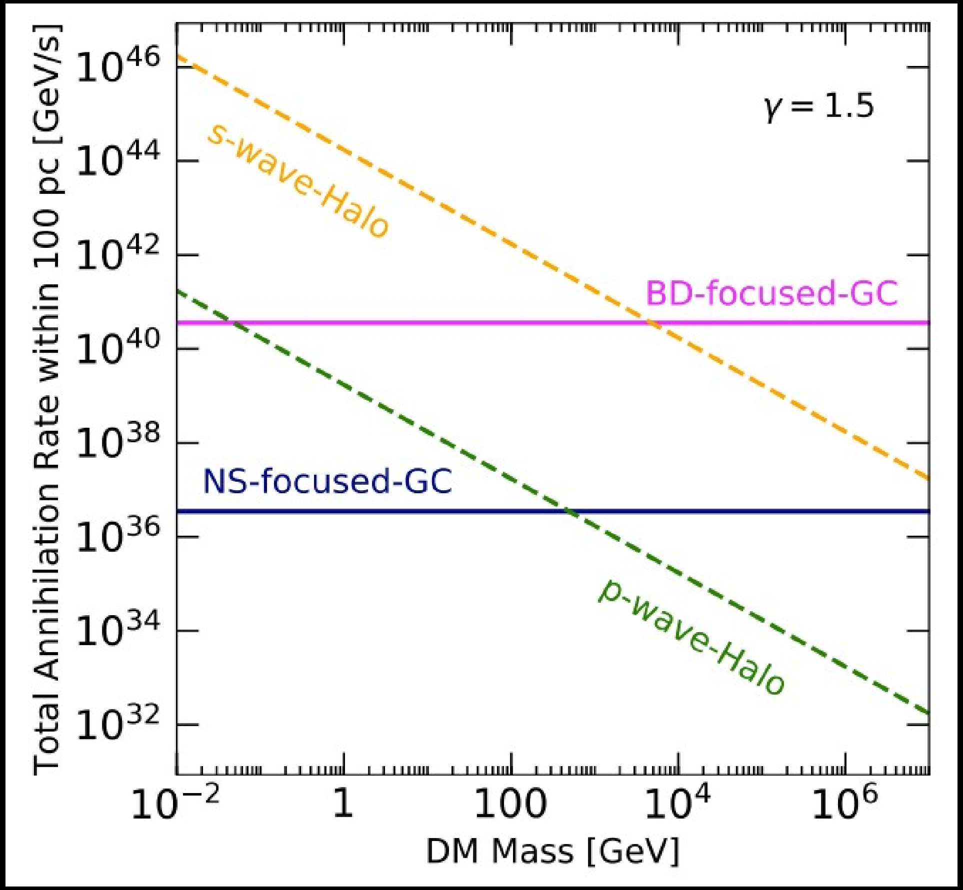
RL, Linden, Mukhopadyay, Toro, 2021

# Comparison with Halo Annihilation

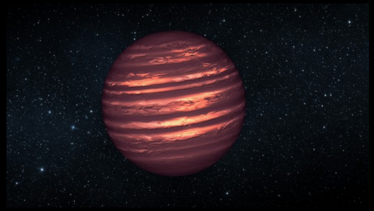
- Signal morphology:
  DM density squared,
  vs DM density*stellar density

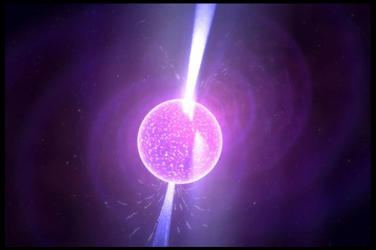
- Celestial-body "focused" annihilation
  "focuses" rate above halo levels

- Only s-wave detectable in the halo,
  and only for lighter DM masses

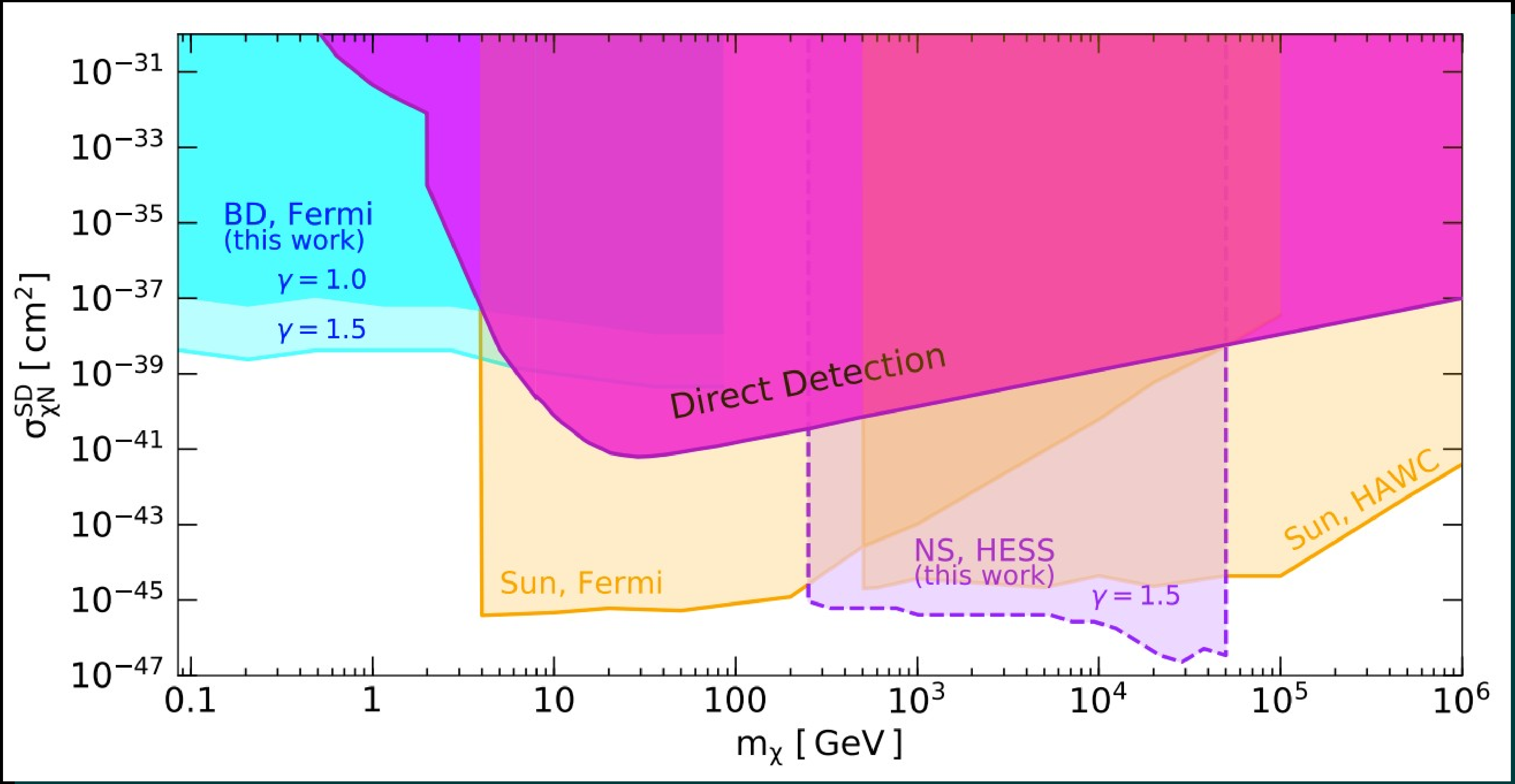



RL, Linden, Mukhopadyay, Toro, 2021





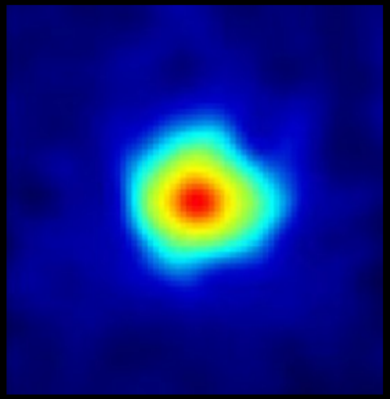
# New Limits w/ Brown Dwarfs and Neutron Stars




**RKL**, Linden, Mukhopadyay, Toro, 2021

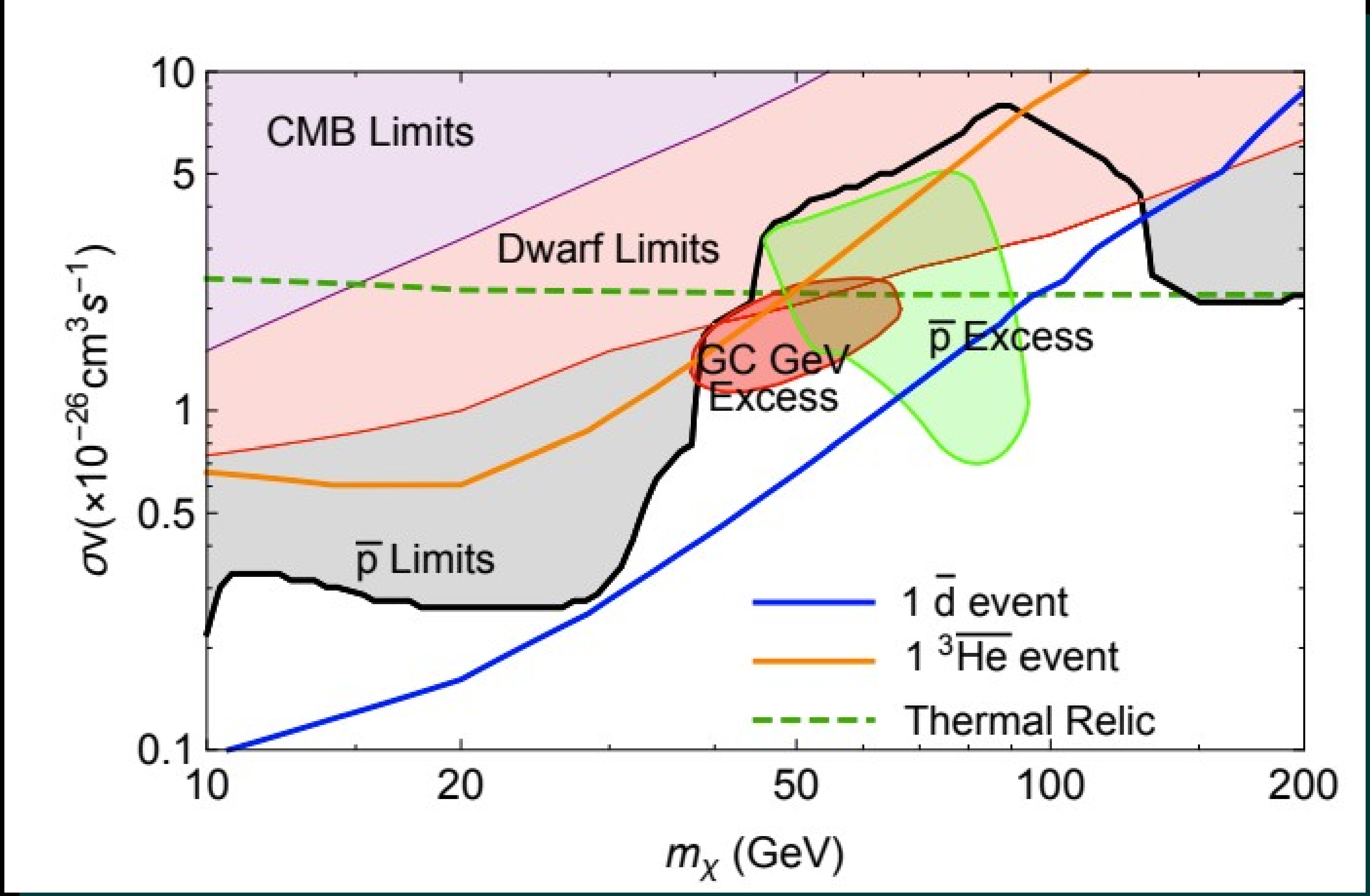
# Summary

- Traditional indirect detection:
  - Galactic Center Excess: systematics!
  - Other anomalies exist, investigations ongoing
  - Total constraints: WIMP far from ruled out

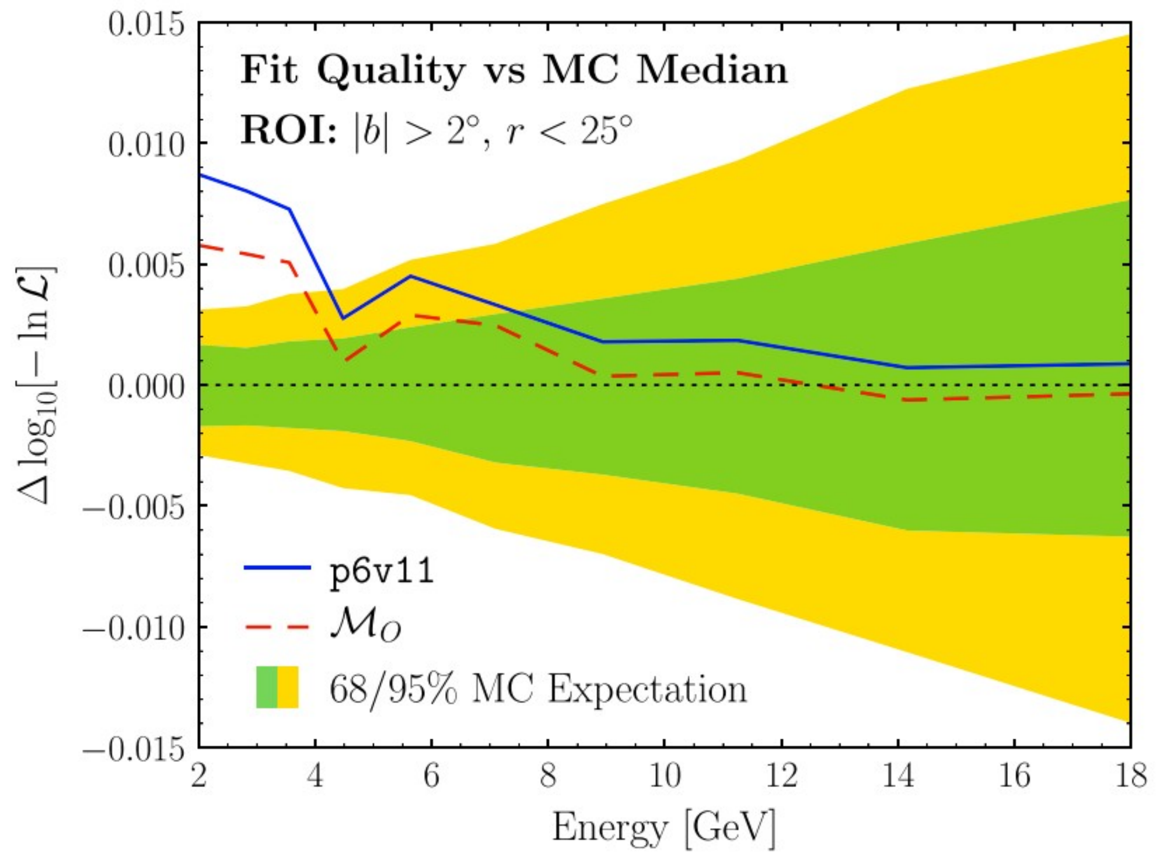


- Plethora of new searches for DM in astrophysical objects
  - New technologies and searches coming soon, also, hopefully DM!

# Extra Slides


CMB Limits
Dwarf Limits
GC GeV Excess
p̄ Excess
p̄ Limits
1 d̄ event
1 $^3\overline{He}$ event
Thermal Relic
$\sigma v (\times 10^{-26} cm^3 s^{-1})$
$m_\chi$ (GeV)
10
5
1
0.5
0.1
10
20
50
100
200

# Key Point: All diffuse models are not good




Buschmann+, ‘20

- Even the best diffuse models are far from good fits to the data
- Fitting to real data, and simulating based on best-fit parameters, does not return likelihoods expected within Poisson noise
- There is clearly a systematic here
- Better diffuse models are key to moving forward