The 2nd DMNet International Symposium, Sept 2022

# *Cosmic anomalies: dark matter or astrophysics?*

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VIRGINIA TECH

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KAVLI IPMU

wpi

U.S. DEPARTMENT OF ENERGY | Office of Science

NSF

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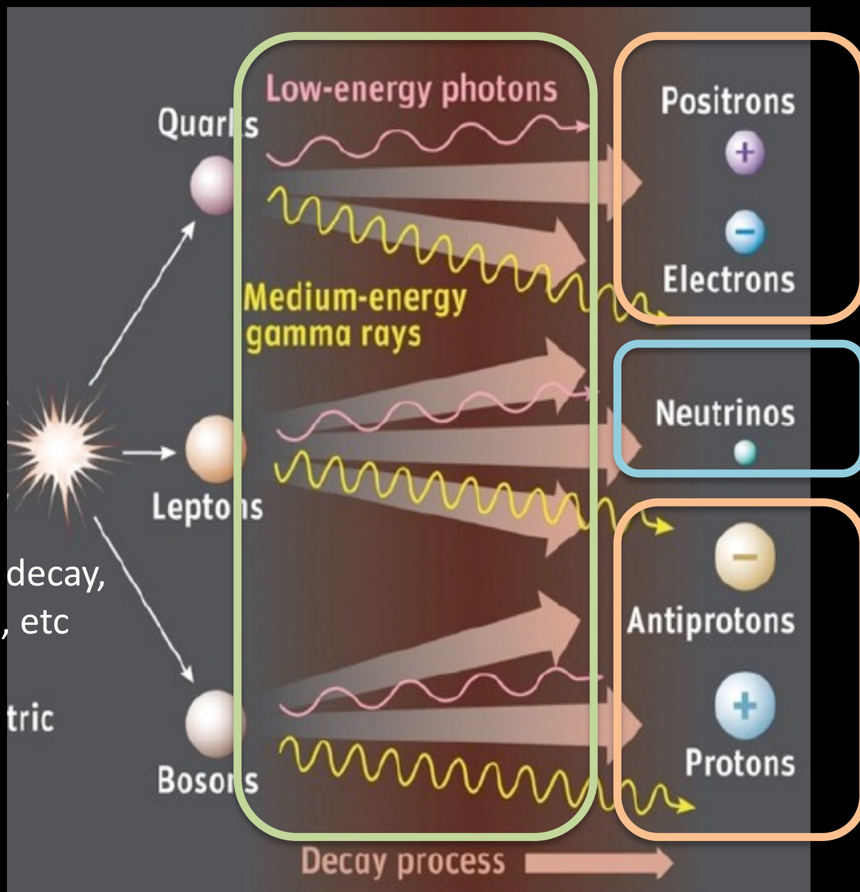
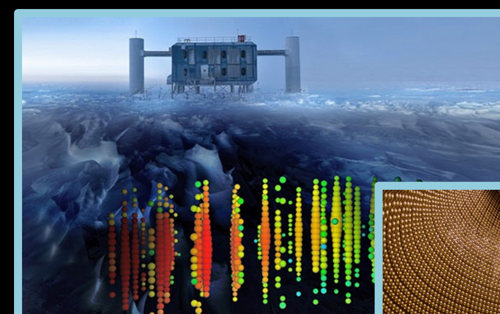
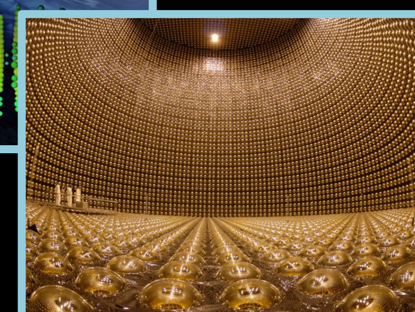
# *Indirect searches for dark matter*

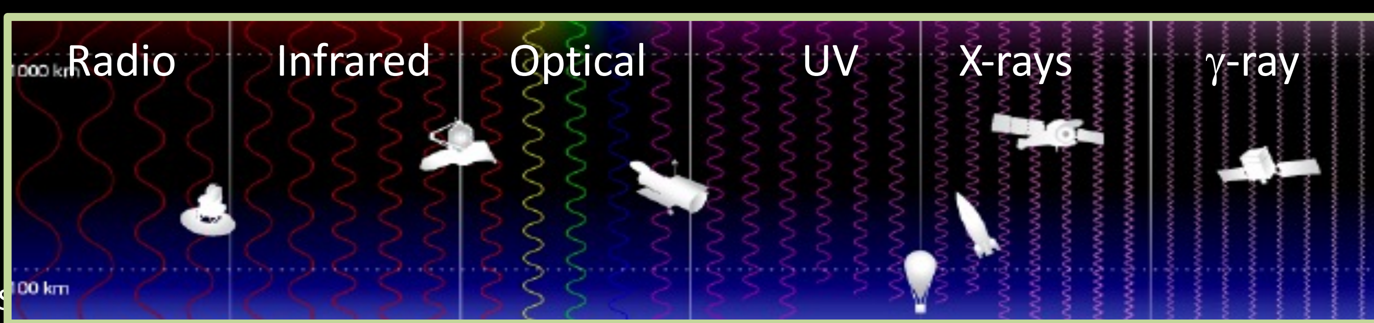
Particle
Dark matter
$\chi$

Annihilation, decay,
de-excitation, etc

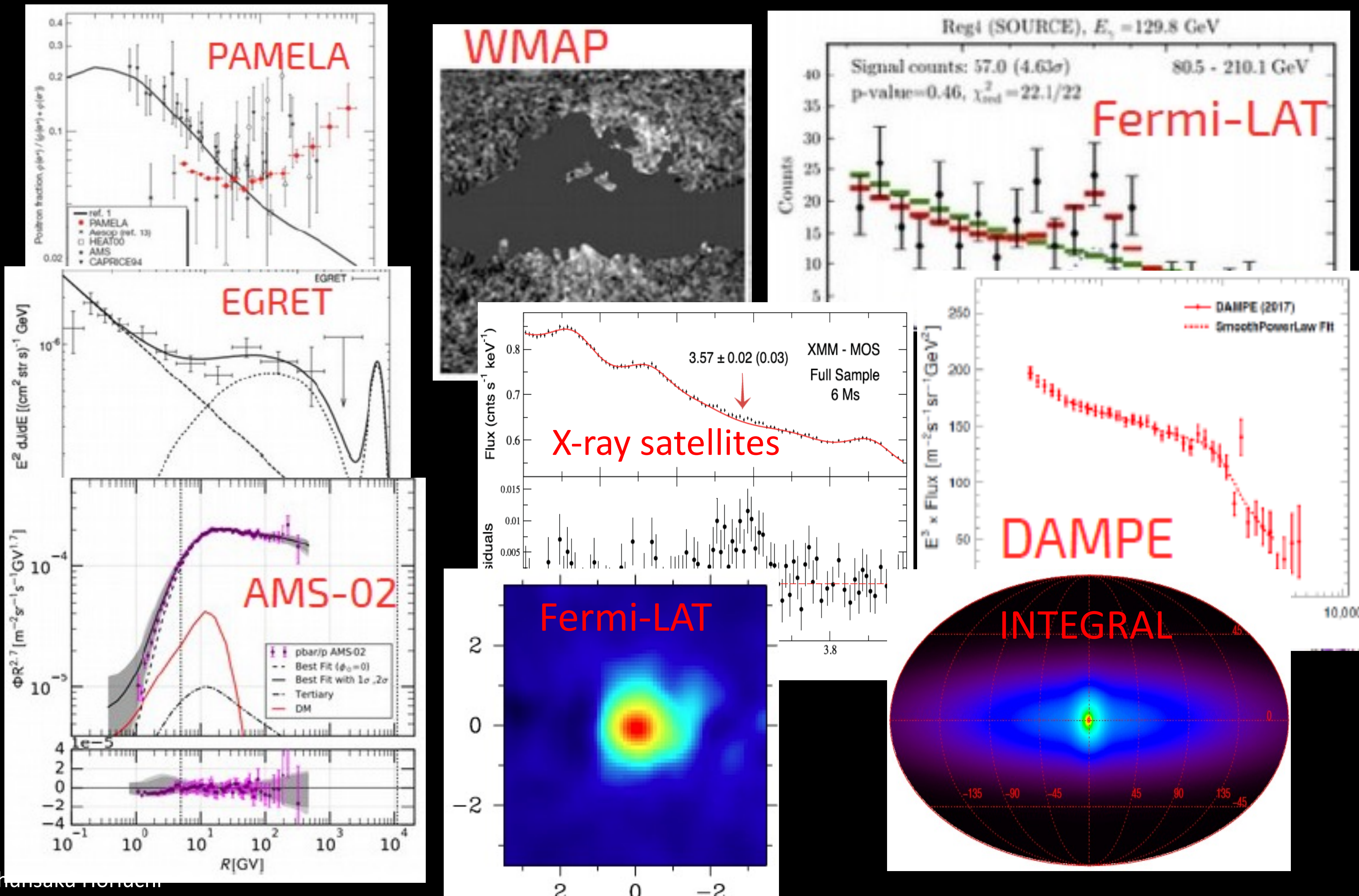






# *Many, many anomalies over the years*

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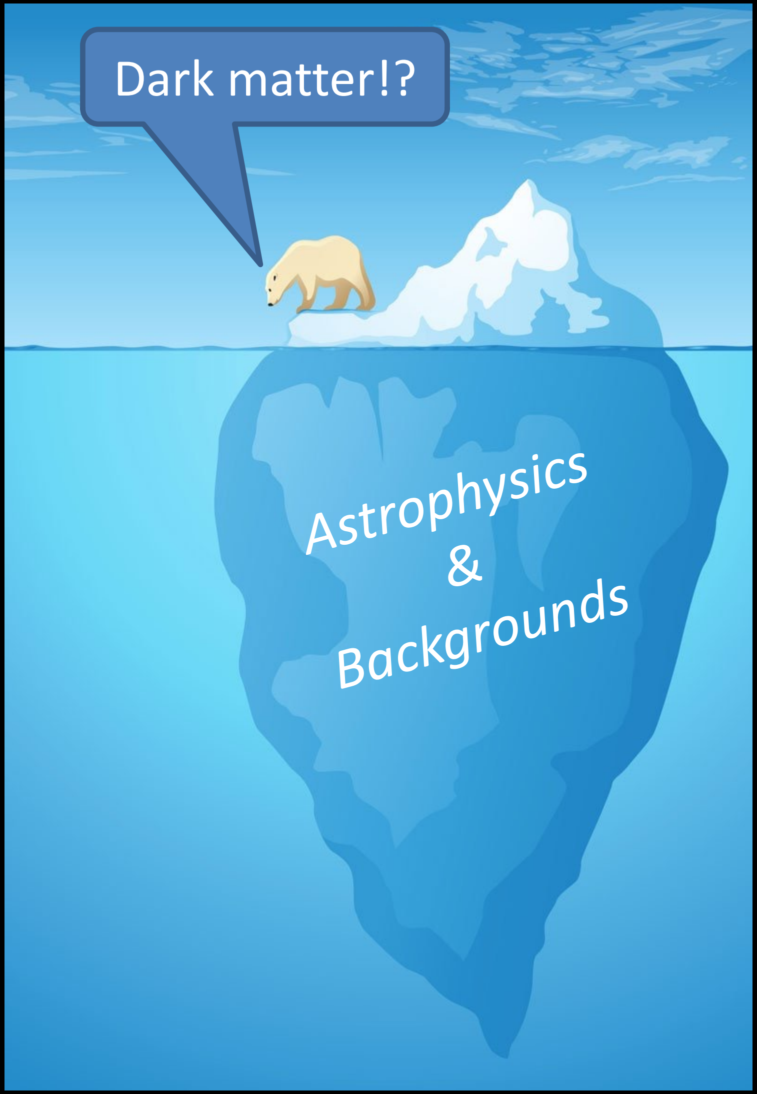
# Types of anomalies




**Excesses**

- ➢ Signal above known sources and known systematics
- ➢ Critically depends on
  - How confident we are at extrapolating source properties
  - How well we think we can model backgrounds

**Lines**

- ➢ Narrow excesses (consistent with energy resolution) in addition to known emission lines
- ➢ Critically depends on
  - Completeness of emission line databases
  - Calibration of detector

# *Anomalies for today*

**Two continuum excesses:**

1. **GeV gamma-ray excess**
2. **And maybe related anti-proton excess**

**Two lines**

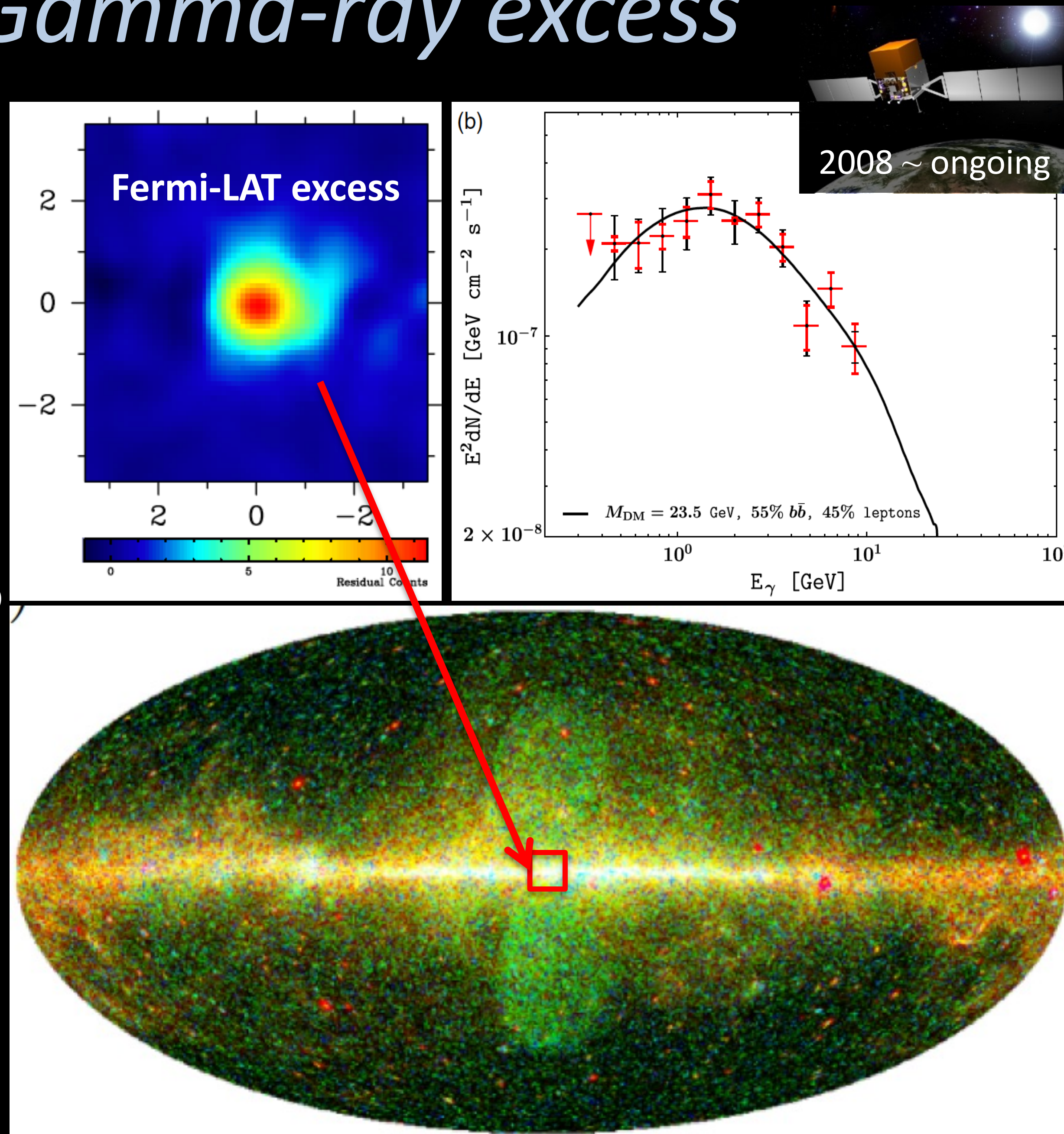
1. **3.5 keV X-ray line**
2. **(511 keV line excess)**

- Brief background
- Anomaly relative to what?
- Dark matter vs astrophysics
- Current status

# GeV Gamma-ray excess

**Excess:** unexplained excess found in Fermi-LAT data

- Since 2009
- Spectra peaks at ~GeV
- Seen out to ~10 deg
- Significance ~20–60σ
- Many systematics checks





Goodenough & Hooper (2009)
Vitale & Morselli (2009)
Hooper & Goodenough (2011)
Hooper & Linden (2011)
Boyarsky et al (2011)
Abazajian & Kaplinghat (2012)
Gordon & Macias (2013)
Macias & Gordon (2014)
Abazajian et al (2014, 2015)
Calore et al (2014)
Daylan et al (2014)
Hooper & Slatyer (2013)
Huang et al (2013)
Zhou et al (2014)
Daylan et al (2014)
Calore et al (2014)
Selig et al (2015)
Huang et al (2015)
Gaggero et al (2015)
Carlson et al (2015, 2016)
de Boer et al (2016)
Yang & Aharonian (2016)
Fermi Coll. (2016)
Abazajian et al (2018, 2020)
Horiuchi et al (2016)
Linden et al (2016)
Ackermann et al (2017)
Horiuchi et al (2016)
Linden et al (2016)
Ackermann et al (2017)
Macias et al (2019)
Bartels et al (2018)
Balaji et al (2018)
Zhong et al (2019)
Chang et al (2020)
Buschmann et al (2020)
Leane & Slatyer (2020)
List et L (2020)
Murgia (2020)
Di Mauro (2020)
Burns et al (2020)
Di Mauro (2021)
Calore et al (2021)
Cholis et al (2022)
McDermott et al (2022)
…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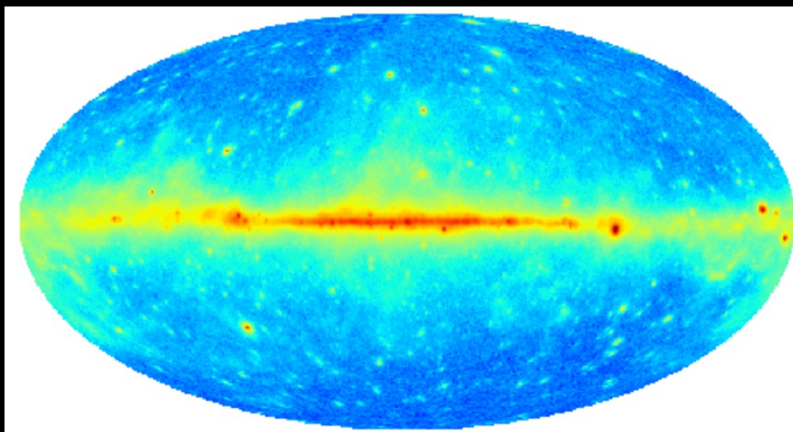
# *Excess relative to what?*

**Data**



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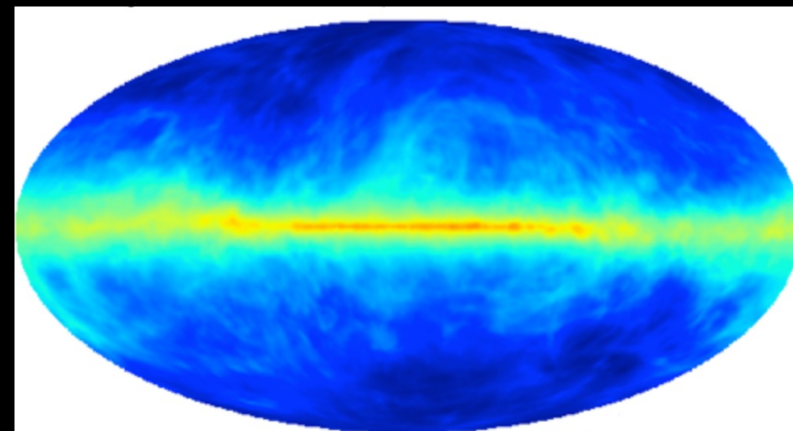
**Cosmic-ray related emission**



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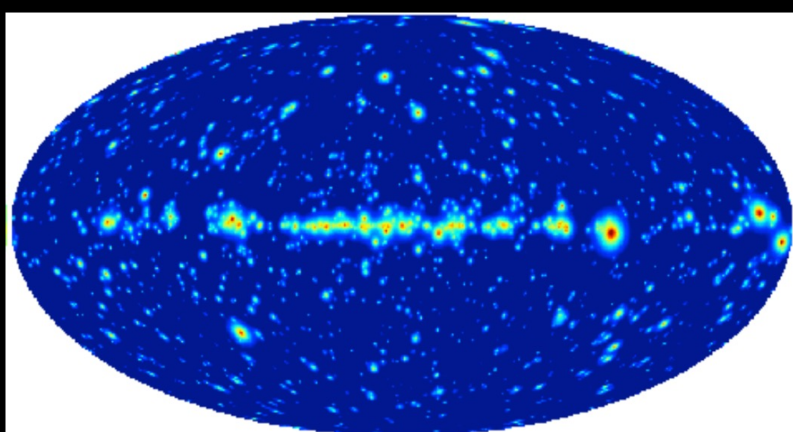
**Known sources**



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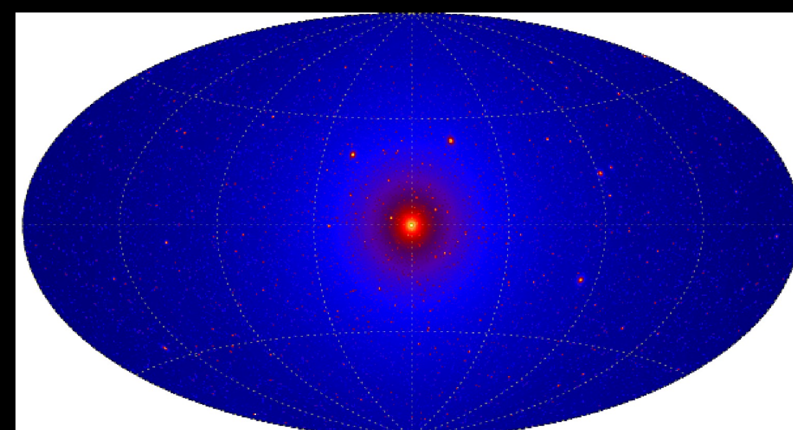
**New sources, e.g., dark matter**



# *Interpretations*

**Is it dark matter?**

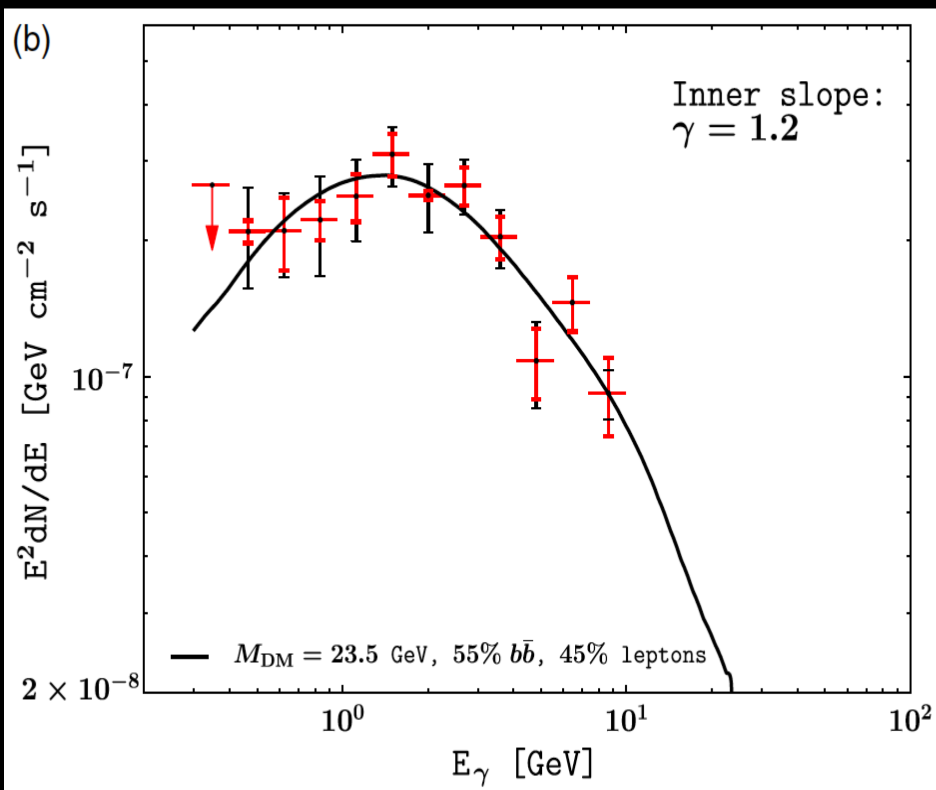
Candidate: WIMPs

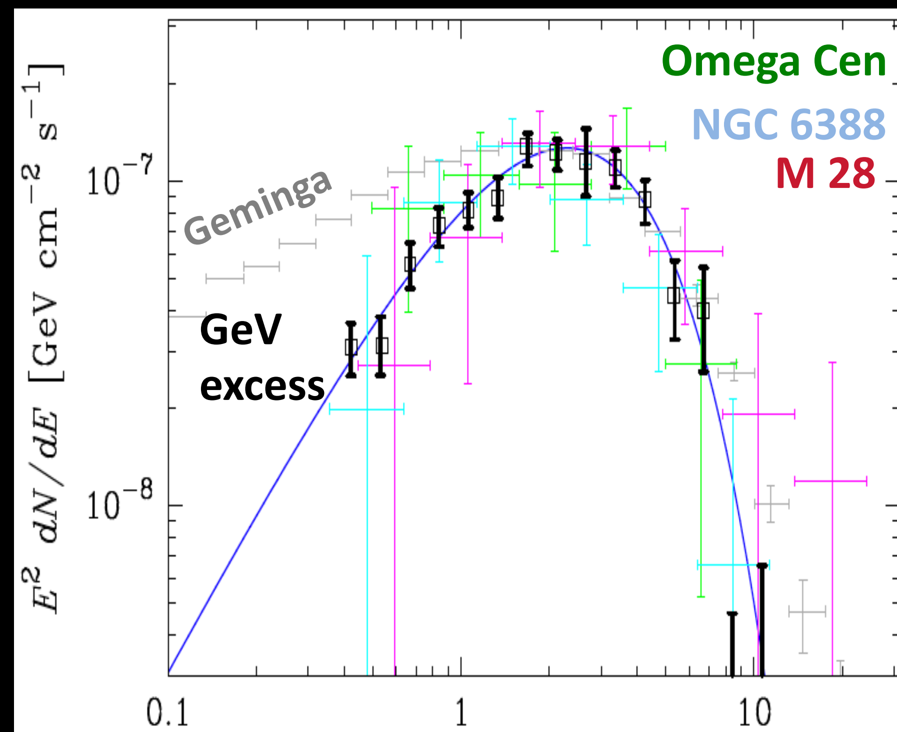
- Spectra: O(100) GeV mass, various hadronic channels
- Approx. thermal cross section

**Is it astrophysics?**

Candidate: millisecond pulsars

- Hundreds seen in gamma rays
- Spectra: similar to the GeV excess
- $O(10^4)$ needed in the Galactic Center (quite reasonable)




*Abazajian (2011)*

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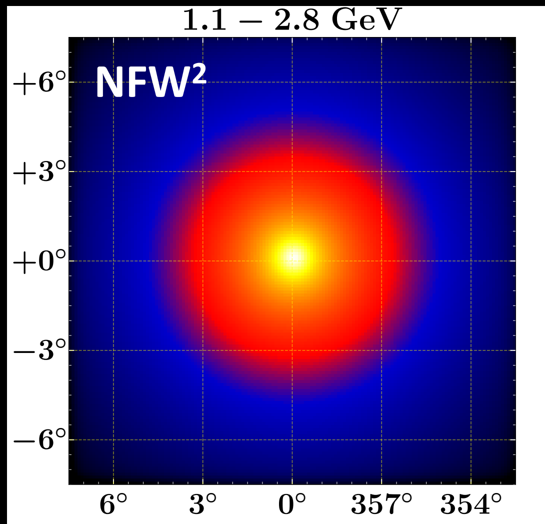
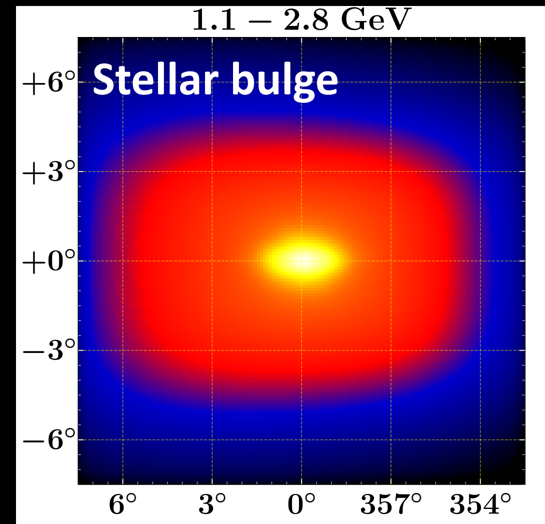
# *Hypotheses*

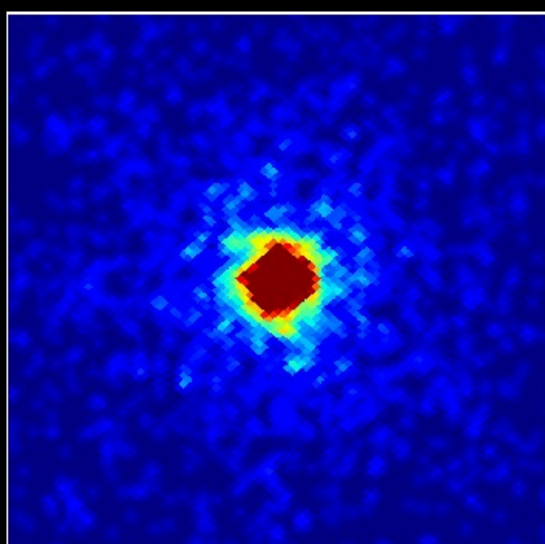
**Dark matter annihilation**



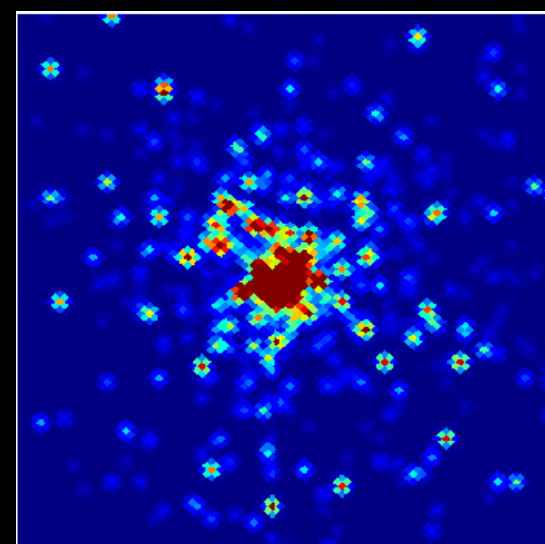

**Astrophysics (pulsar)**




**VS**



**VS**



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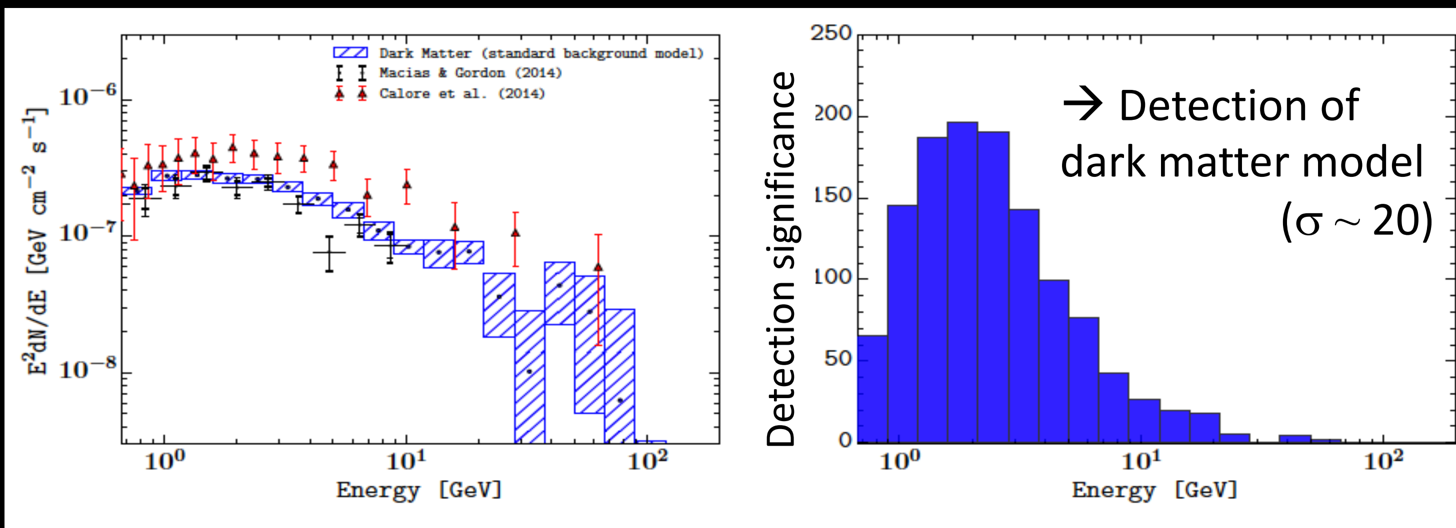
nature astronomy
LETTERS
https://doi.org/10.1038/s41550-018-0414-3

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




*Macias et al (2018)*

**↖ WITHOUT bulge**
(representative of previous studies)

nature astronomy
LETTERS
https://doi.org/10.1038/s41550-018-0414-3

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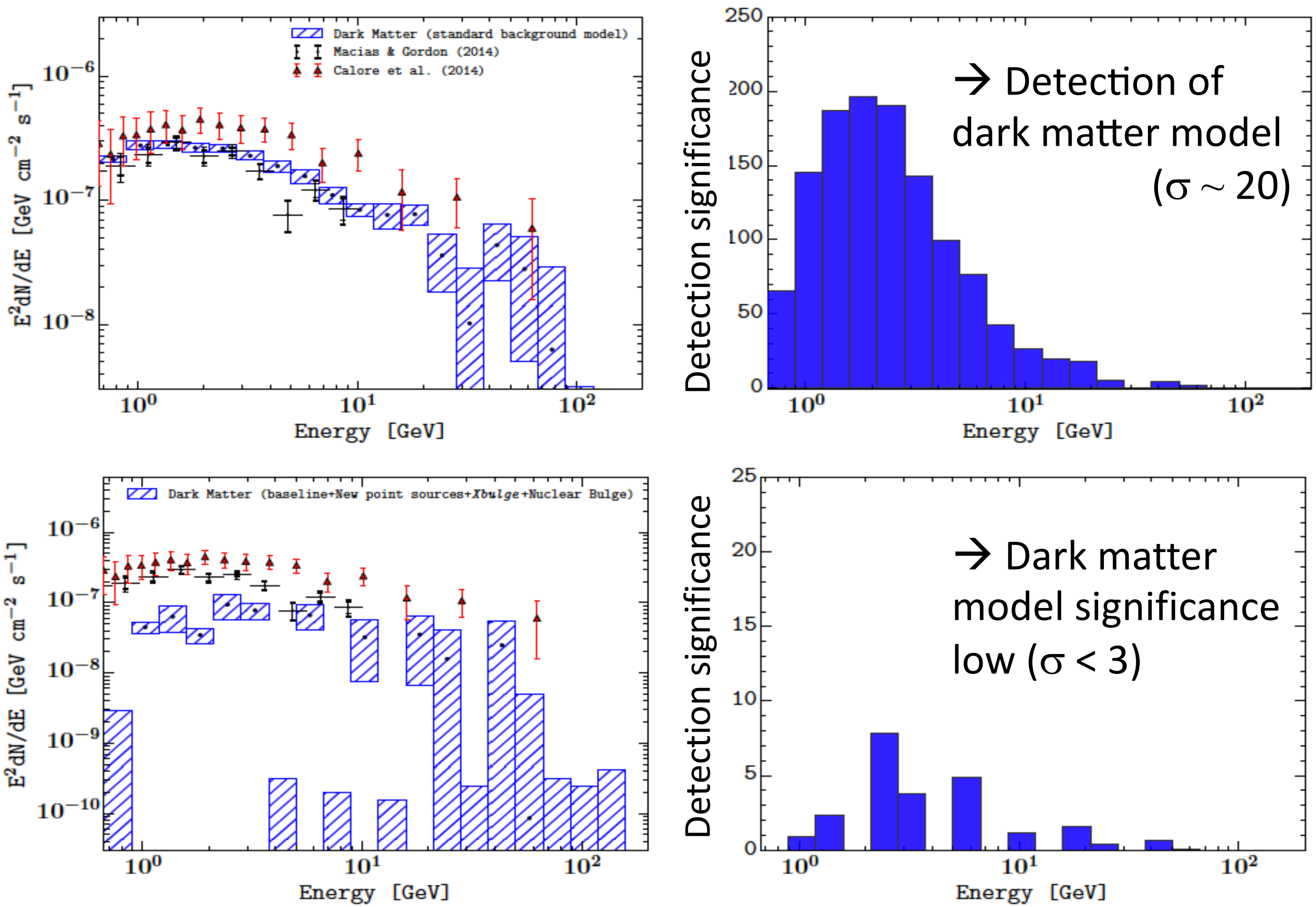
*Macias et al (2018)*




**↖ WITHOUT bulge**
(representative of previous studies)

**← WITH bulge**
Including our new extended bulge, the **data no longer shows evidence for a spherical excess**

*Also Bartels et al (2018)*

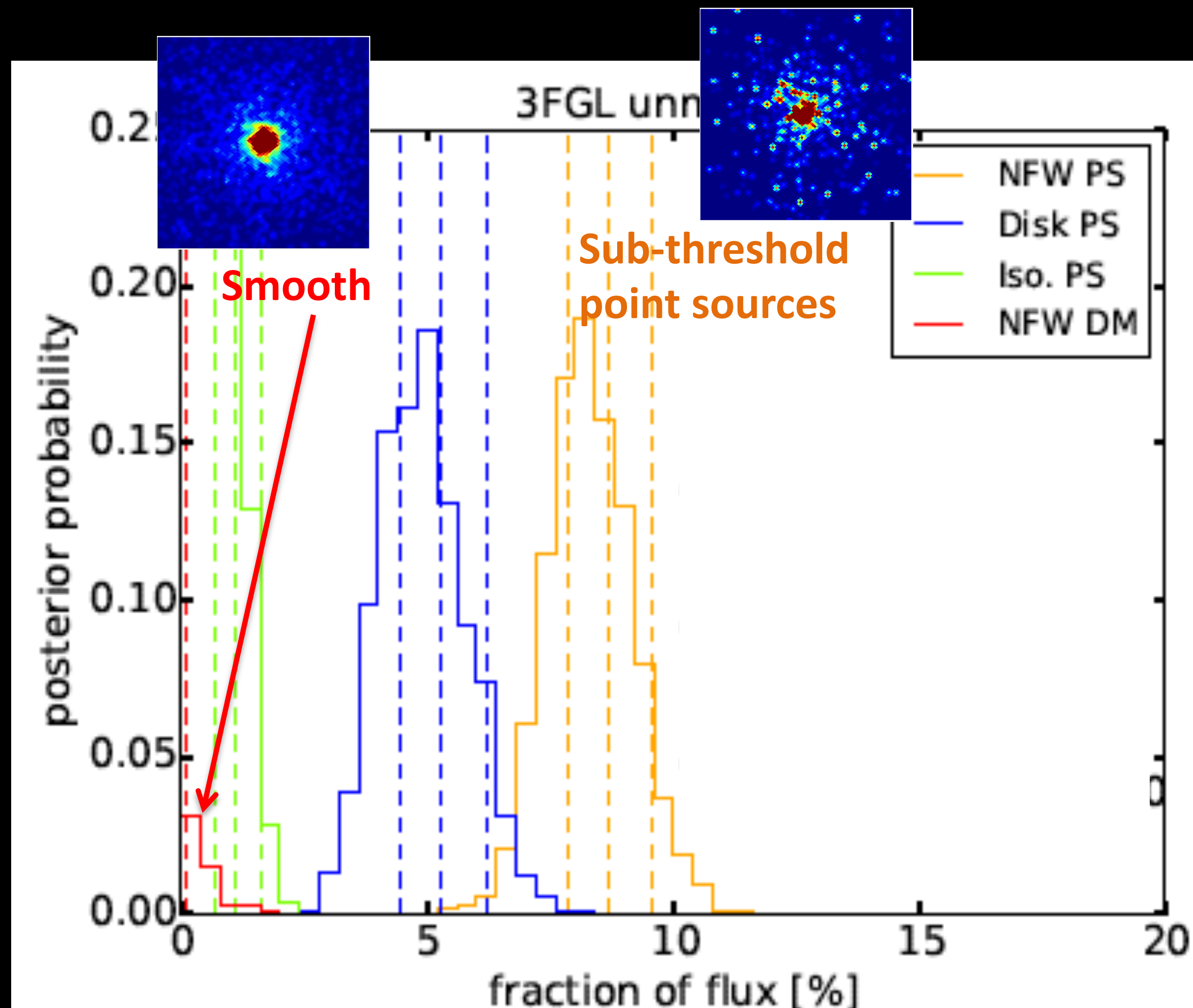
PRL 116, 051103 (2016) PHYSICAL REVIEW LETTERS week ending 5 FEBRUARY 2016

# Evidence for Unresolved $\gamma$-Ray Point Sources in the Inner Galaxy

Model as smooth (DM motivated) & grainy (pulsar motivated) templates

Results:

- Smooth: ~0%
- Grainy: ~8.7%




*Lee et al (2016)*
*See also Bartels et al (2016)*

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PRL 116, 051103 (2016) PHYSICAL REVIEW LETTERS week ending 5 FEBRUARY 2016

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

Model as smooth (DM motivated) & grainy (pulsar motivated) templates

Results:

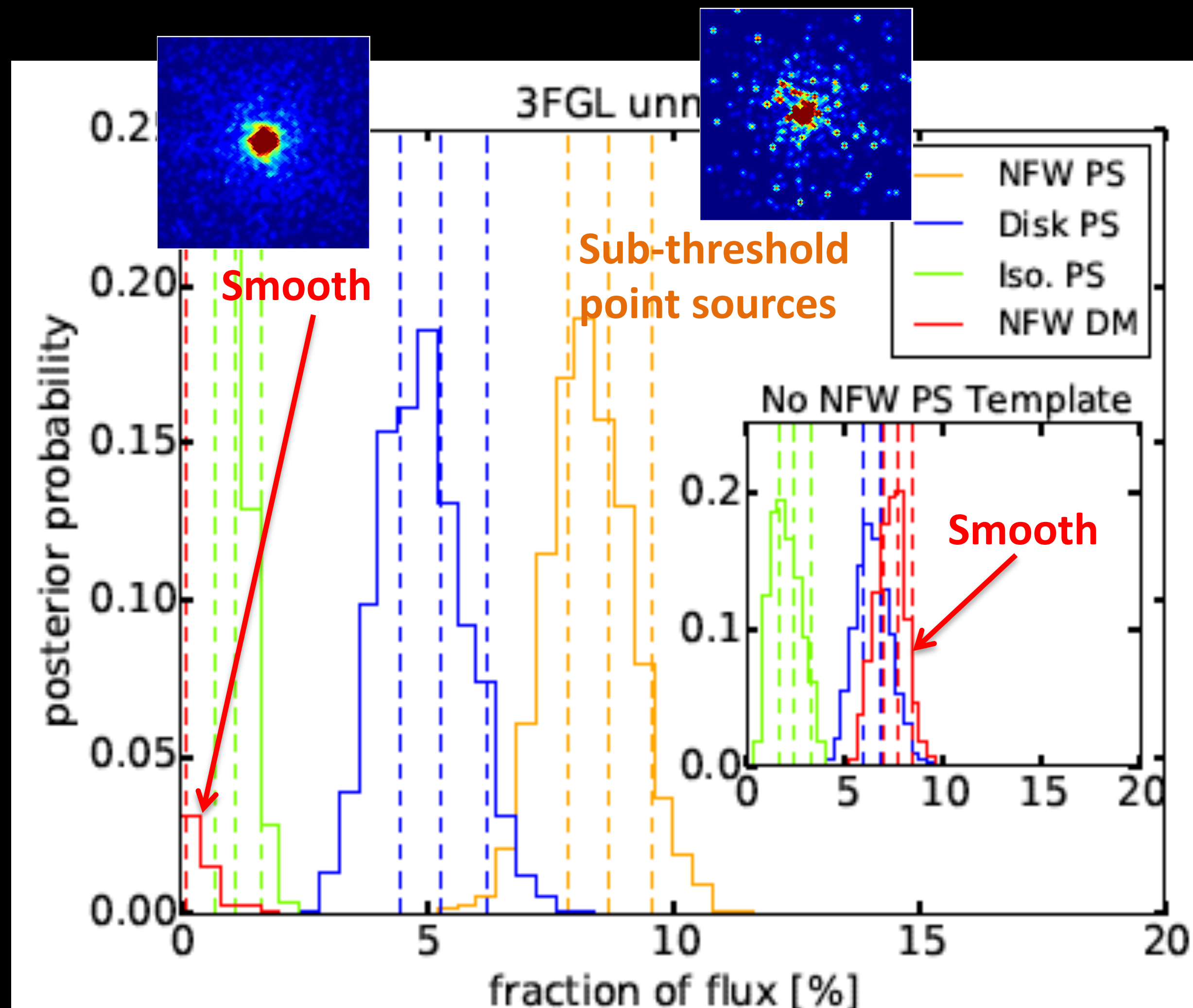
- Smooth: ~0%
- Grainy: ~8.7%

If grainy model is not added, smooth becomes ~8%

➔ **Preference for sub-threshold point sources over smooth dark matter**

➔ **Could be faint pulsars**

*Lee et al (2016)*
*See also Bartels et al (2016)*

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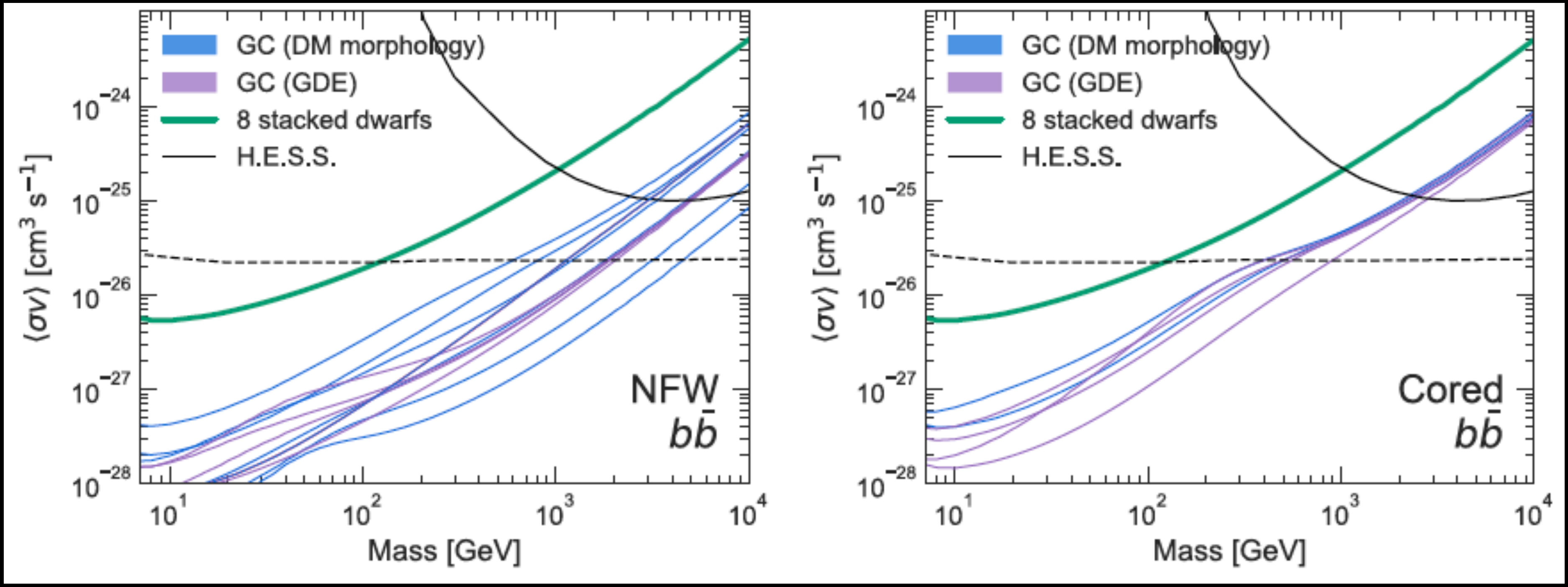
# Dark matter implications

Perhaps we found a physically-motivated, *better astrophysical model* which provides a better explanation of the data than DM annhilation

➔ **Constrains thermal dark matter up to ~500 GeV**

*Abazajian et al (2020)*




- Impacts of NFW slope [0.5,1.5] & sphericity
- Impacts of background modeling

- Impacts of core (1 kpc) & sphericity
- Impacts of background modeling

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# Ongoing developments

**Morphology**

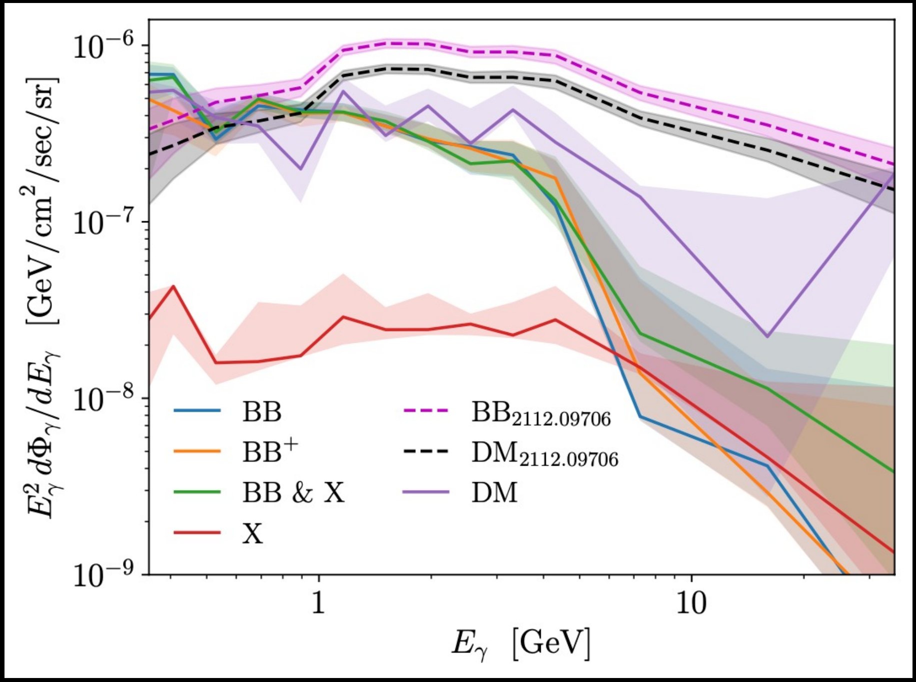
Many new strategies, some find preference for the bulge, others do not. Systematic comparison warranted.

*Macias et al (2019), Abazajian et al (2020), di Mauro (2021), Calore et al (2021), Pohl et al (2022), McDermott et al (2022)*

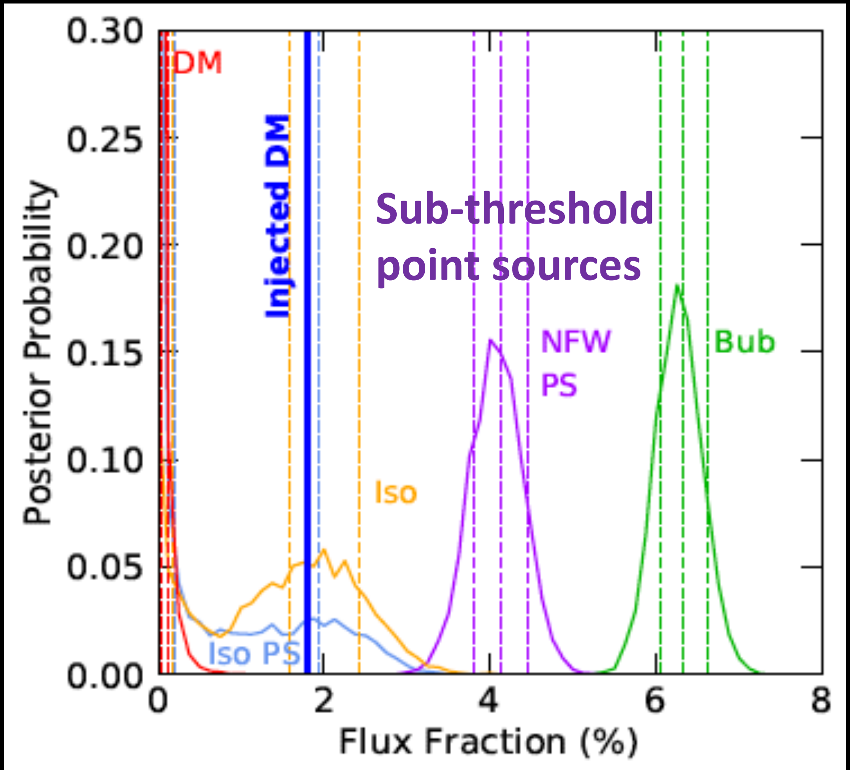
**Point sources**

Faint end is experimentally indistinguishable from a smooth source. Including more information could help.

*Leane & Slatyer (2019, 2020), Chang et al (2019), Zhong et al (2019), Buschmann et al (2020), Calore et al (2021)*




*McDermott et al (2022)*




*Leane & Slatyer (2020)*

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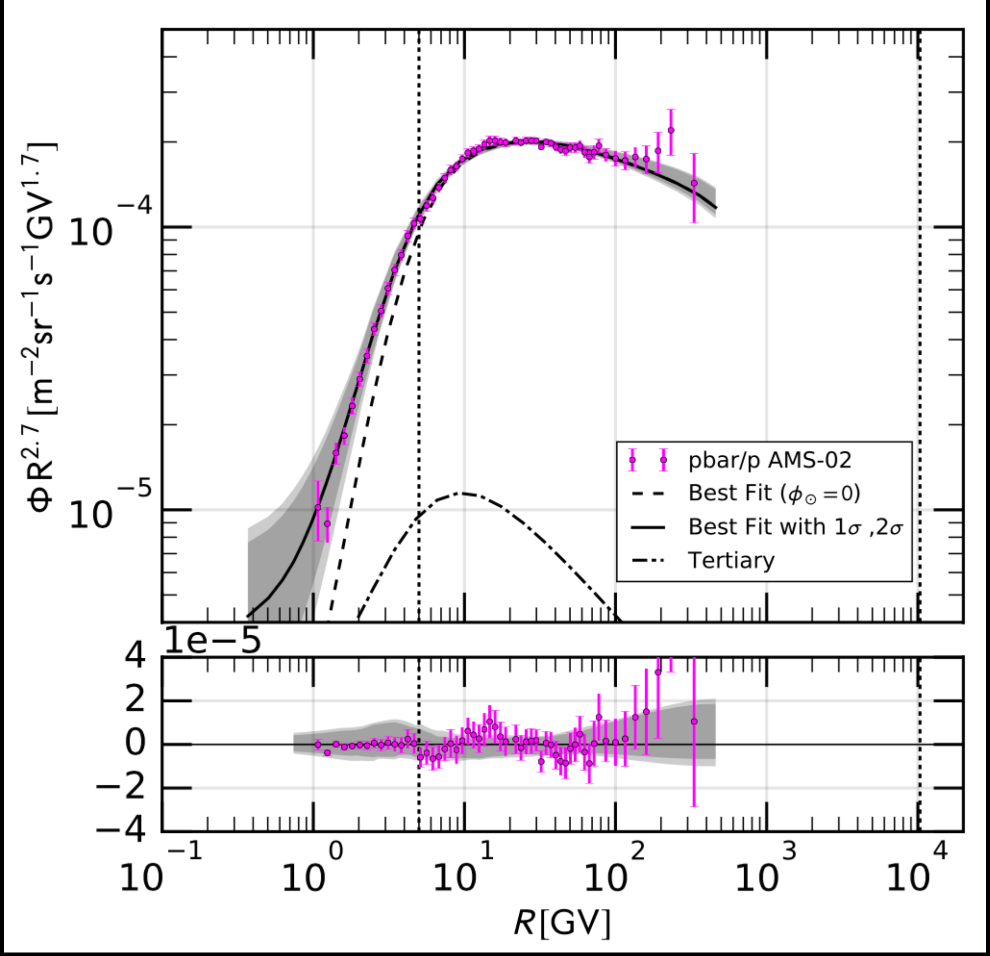
# Anti-proton excess

Anti-protons are useful probes of new physics

**Relative to what?**
Secondaries produced by pp collisions of astrophysical cosmic rays.

Excesses seen in PAMELA & precision data by AMS-02




*Cuoco et al (2017)*

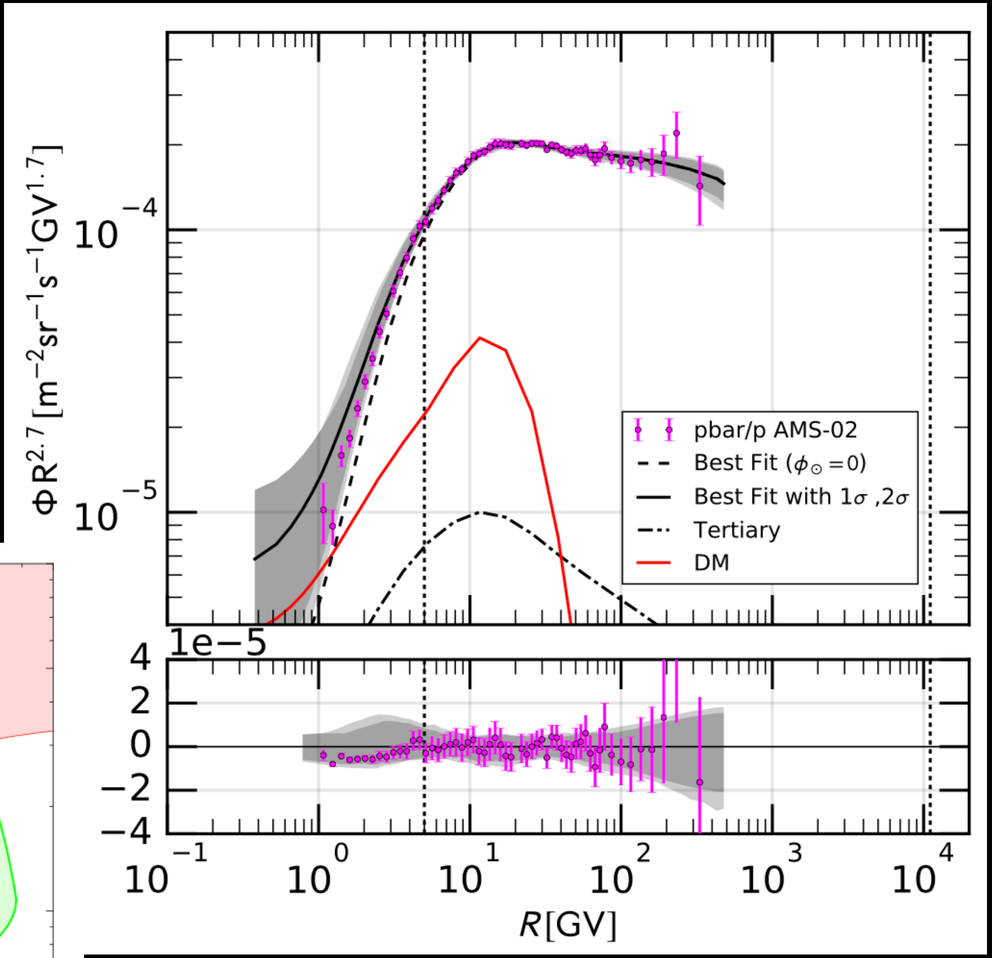
# *Anti-proton excess*

Anti-protons are useful probes of new physics

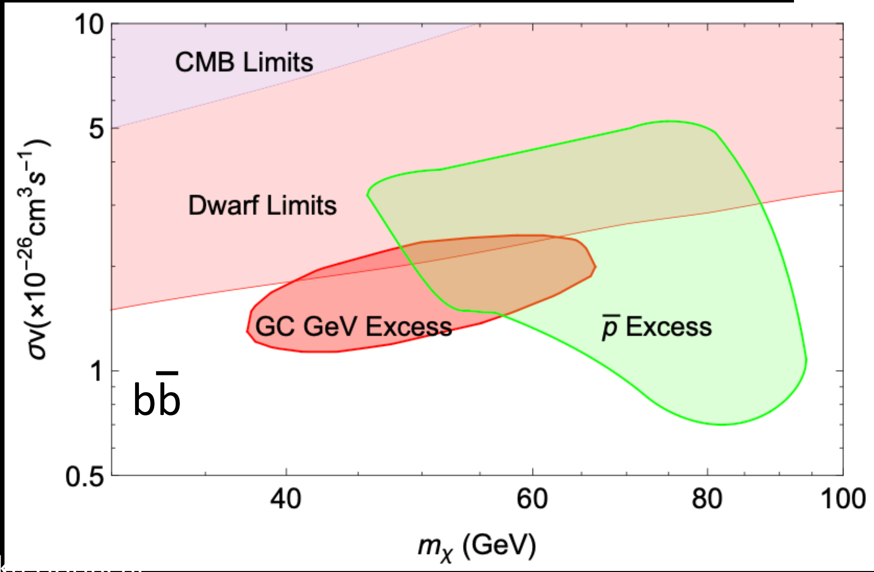
**Relative to what?**
Secondaries produced by pp collisions of astrophysical cosmic rays.

Excesses seen in PAMELA & precision data by AMS-02

Is it dark matter? Intriguing




*Cuoco et al (2017)*




*Cholis et al (2019)*

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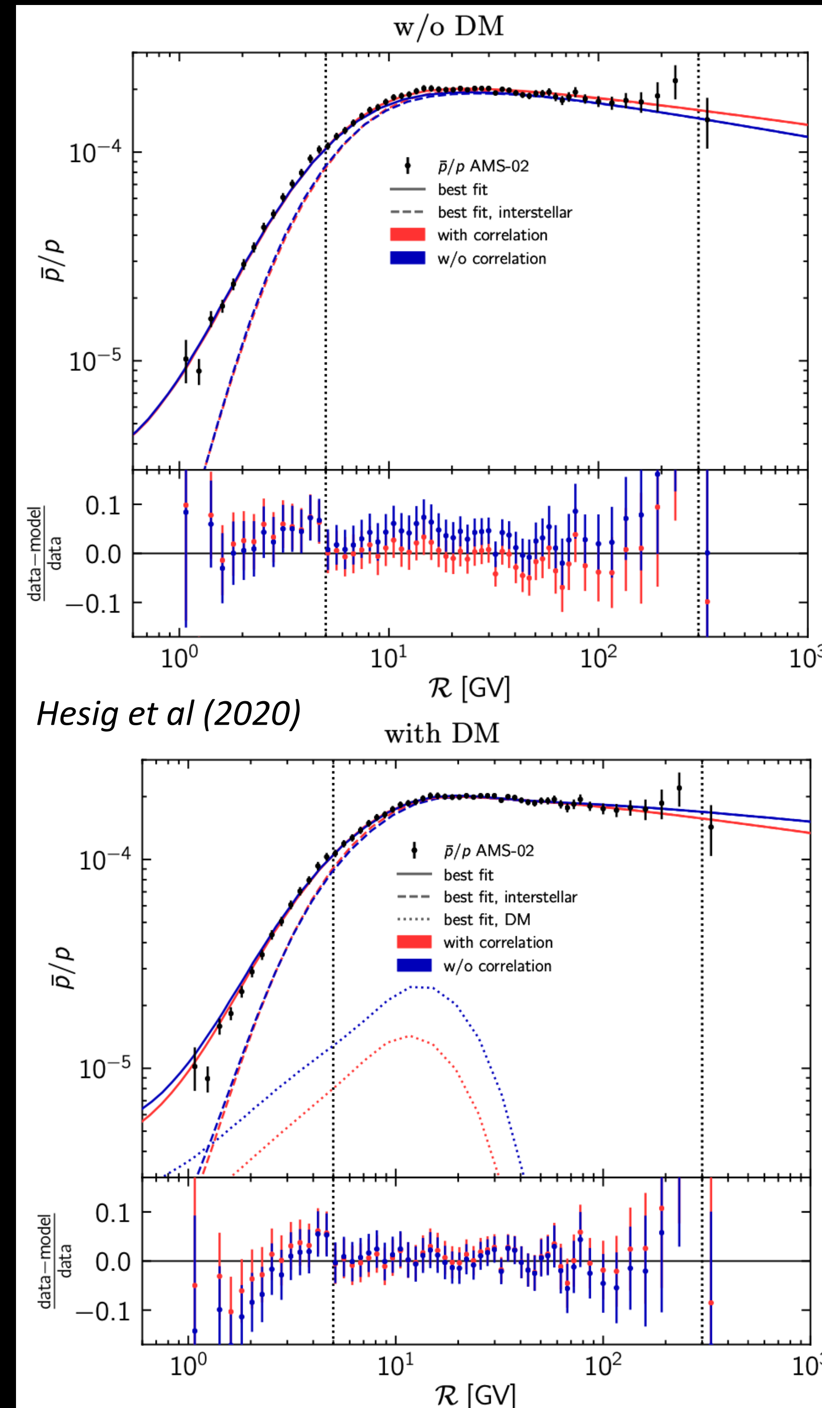
# Systematics

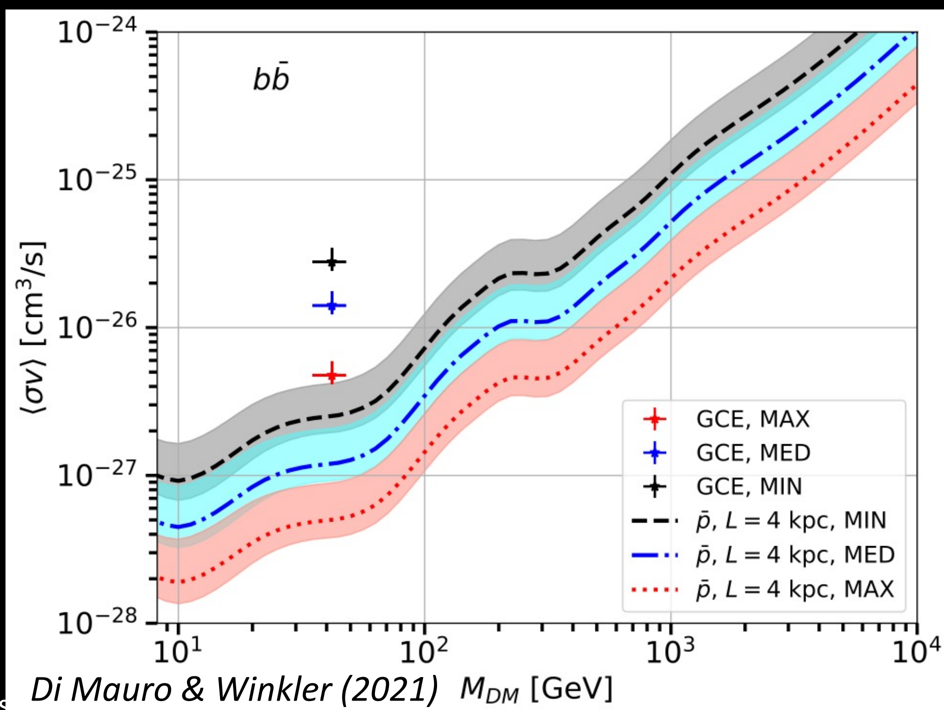
But systematics are a concern

- Cross sections
- Solar modulation
- Injection & propagation
- Correlating errors

→ Removes need for DM
→ Constraints GeV excess




*Hesig et al (2020)*



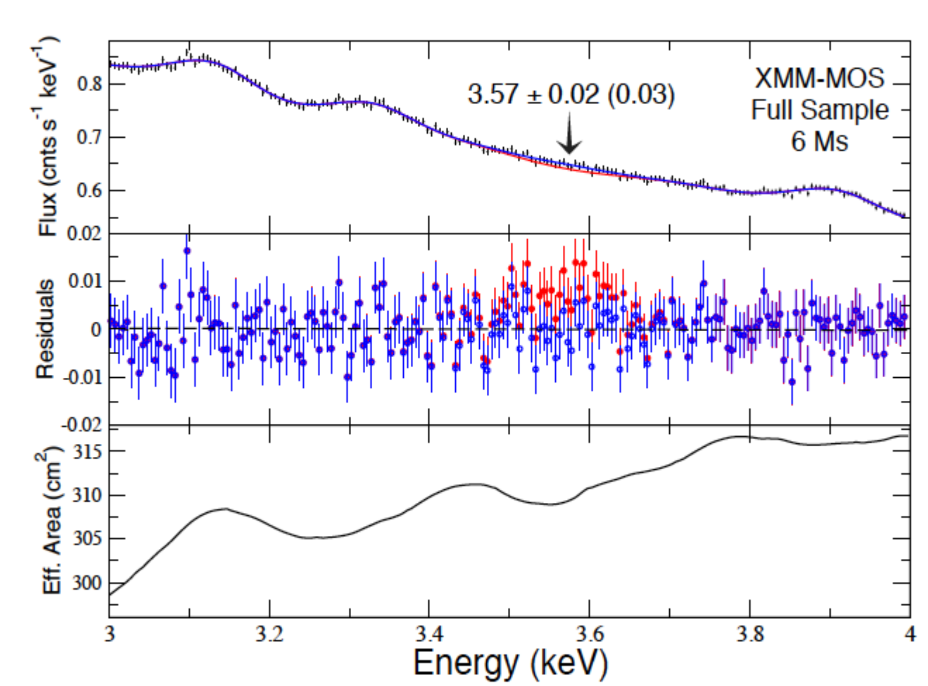

*Di Mauro & Winkler (2021)*

# X-ray lines

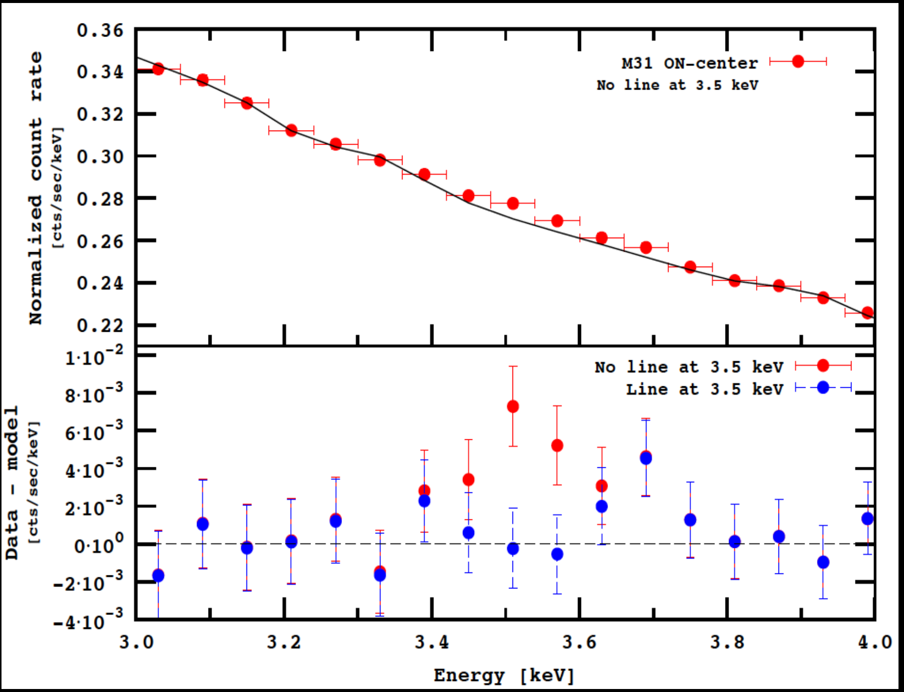
**Line:** X-ray contains many atomic transition lines, but unexpected lines found

$E_\gamma = 3.5$ keV

- 73 galaxy clusters 4 to 5σ with XMM
- Range z = 0.01 to 0.35
- Perseus 2.2σ with Chandra
- Perseus 2.3σ with XMM
- M31 3σ with XMM
- Combined ~4σ




*Bulbul et al (2014)*




*Boyarsky et al (2014)*

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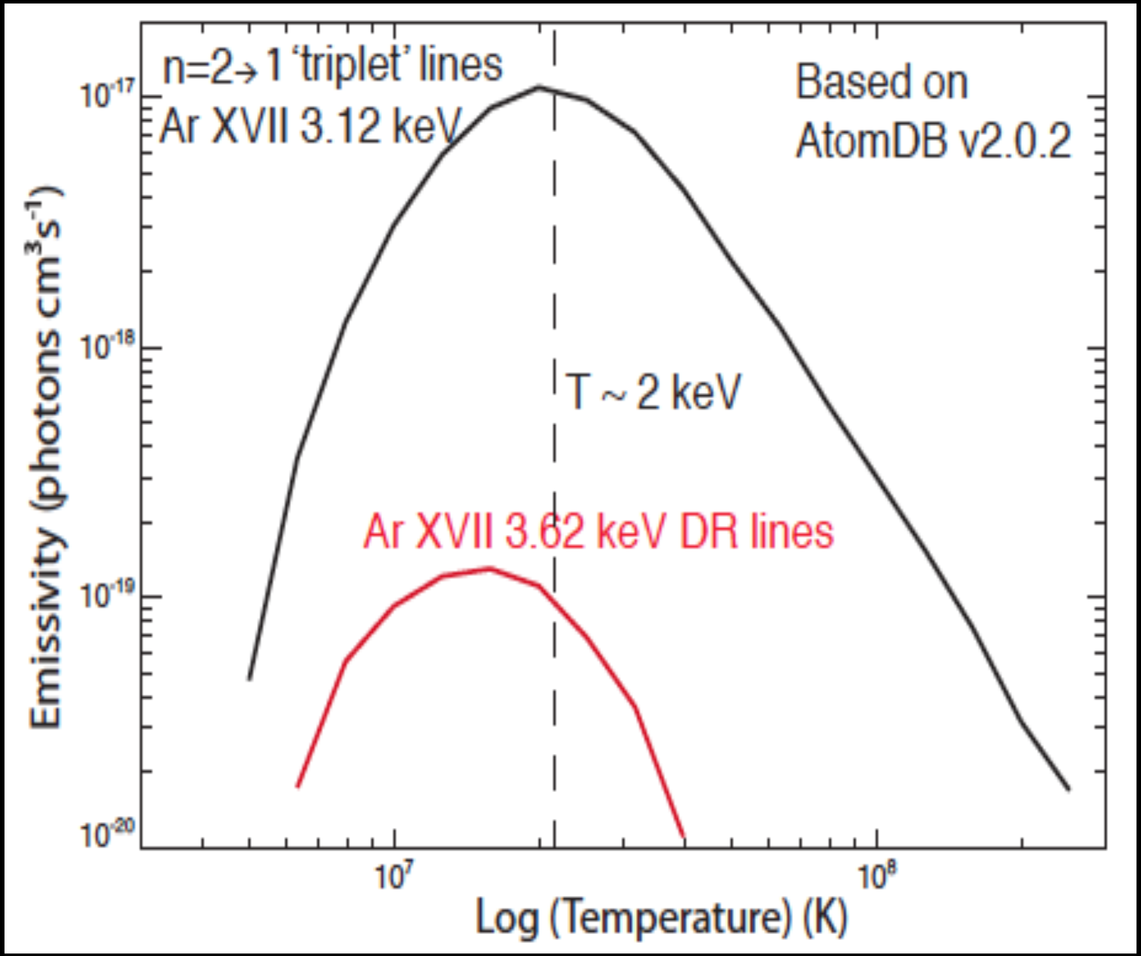
# Metal line origin?

**Relative to:** modeling the complex atomic line emissions of the plasma.
The 3.5 keV line is difficult to explain with current models.




*Bulbul et al (2014)*

Many nuclei have accompanying lines that produce a problem, e.g., Ar XVII

Charge exchange eg H – S XVI causes ~3.5 keV line

*Gu et al (2015)*

but also predicts strong lower ~2.6 keV line

*Cappelluti et al (2019)*

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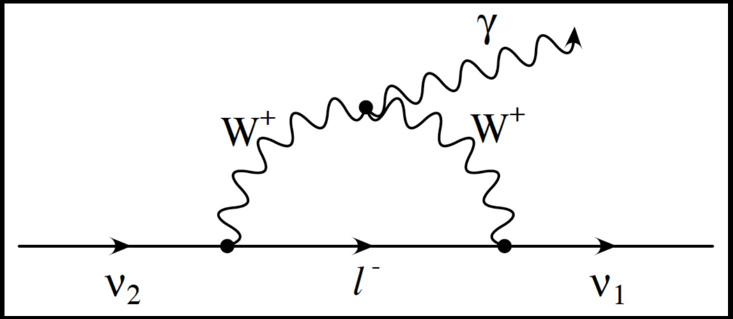
# *Is it dark matter?*

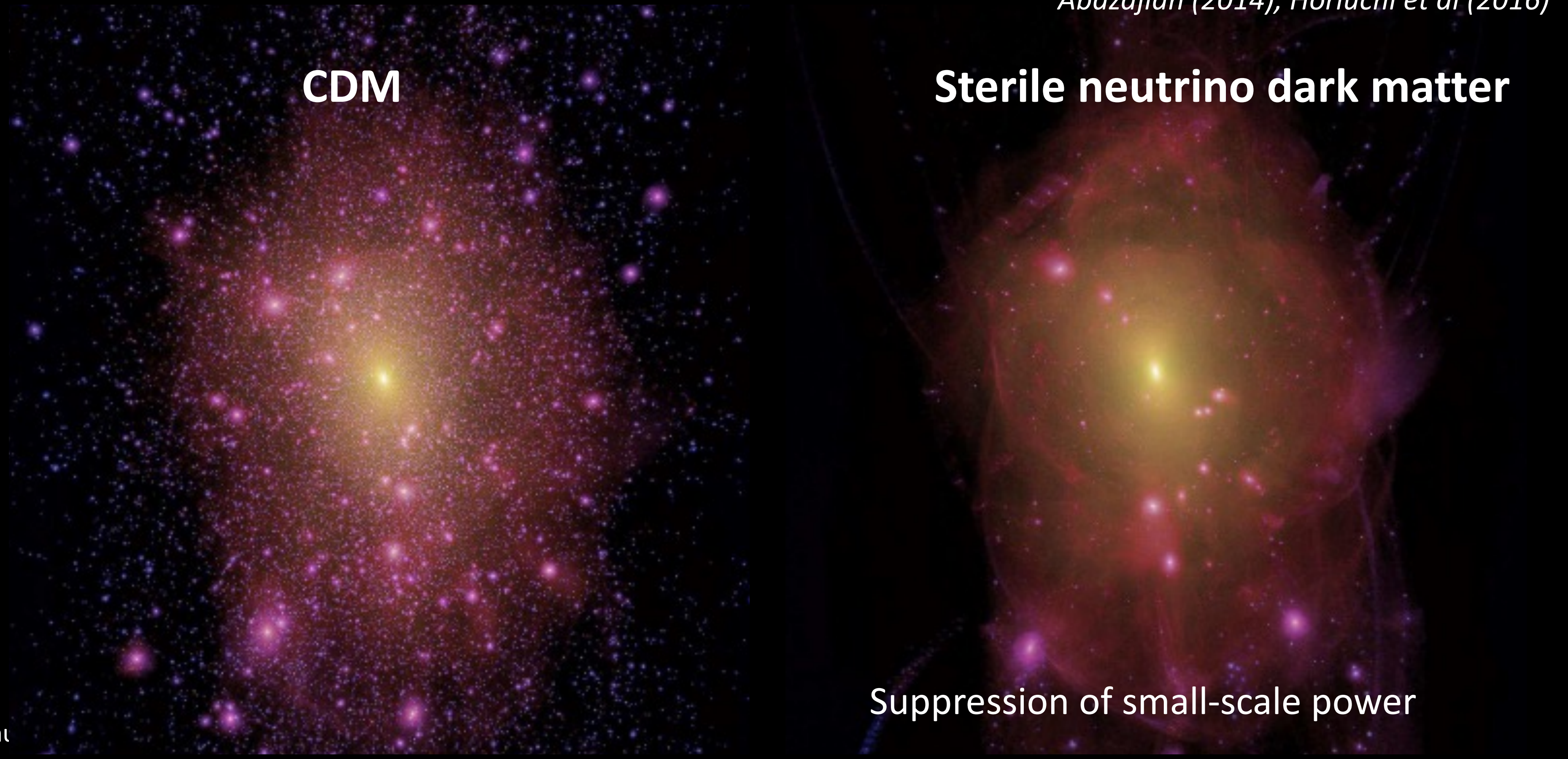



**keV sterile neutrino dark matter:** can radiatively decay to active neutrinos + X-ray

$$E_\gamma = m_s/2$$

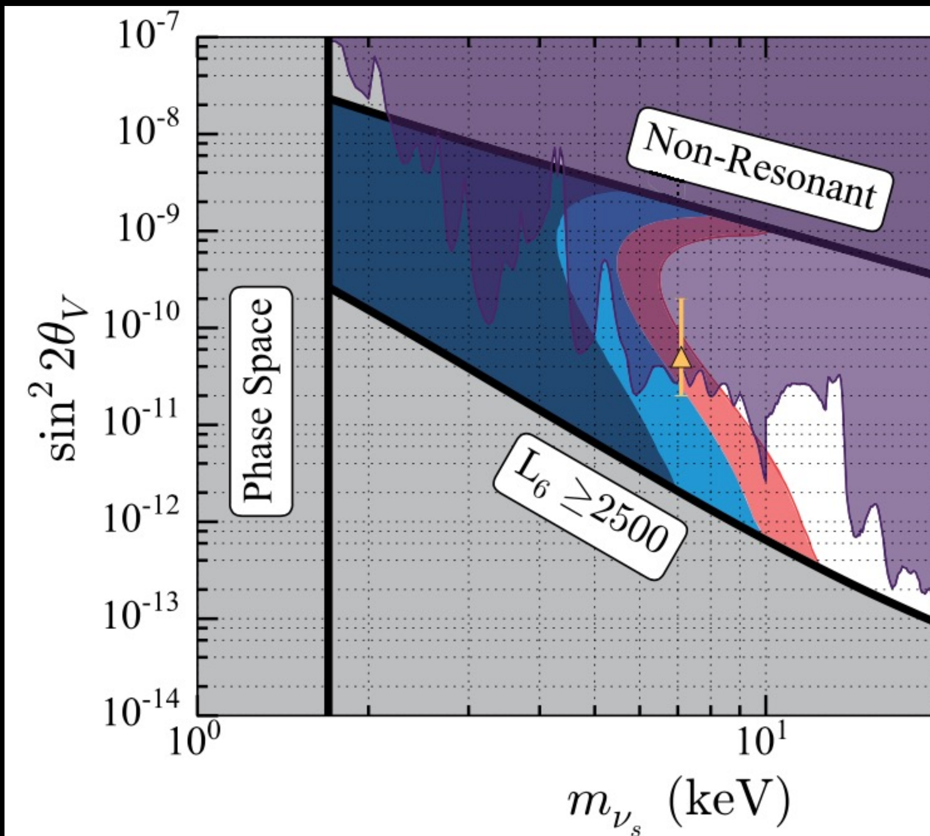
It can be produced via oscillations and has attractive features beyond CDM

*Abazajian (2014), Horiuchi et al (2016)*

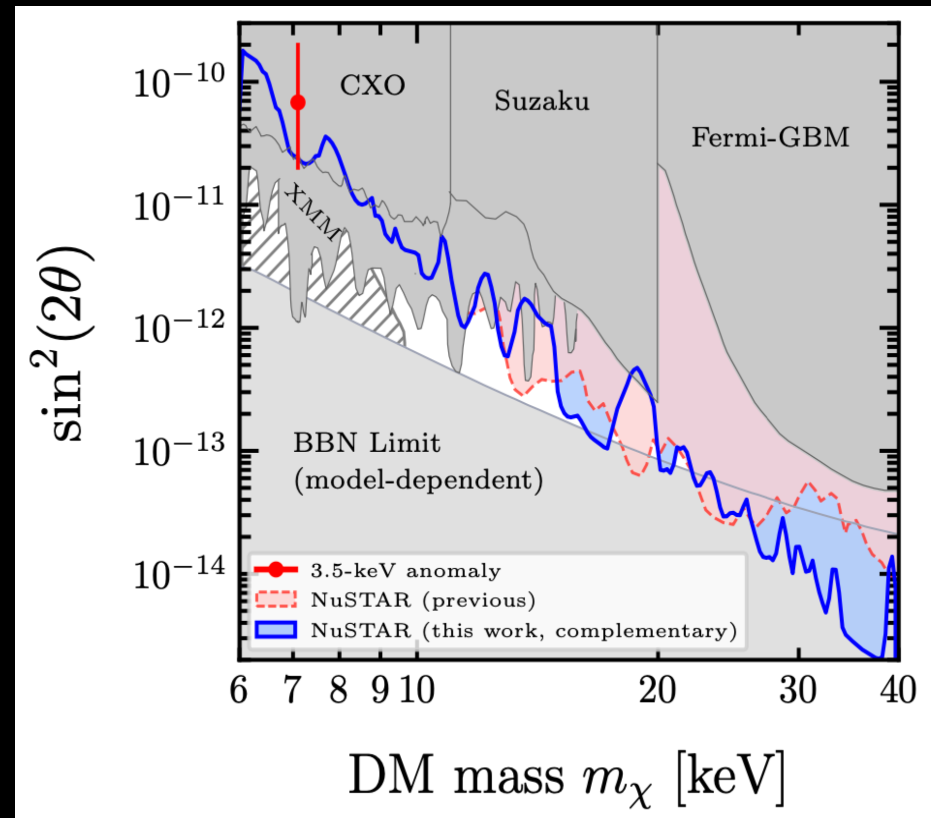


# Many constraints

Other X-rays, Galaxy satellites, Lyman-alpha, phase-space limits




Cherry & Horiuchi (2017) See also Schneider (2016), DES (2021)




Roach et al (2022)

***Origin not yet settled*** **b**ut oscillation-based production of ~7.1 keV sterile neutrino strained; use other production mechanisms

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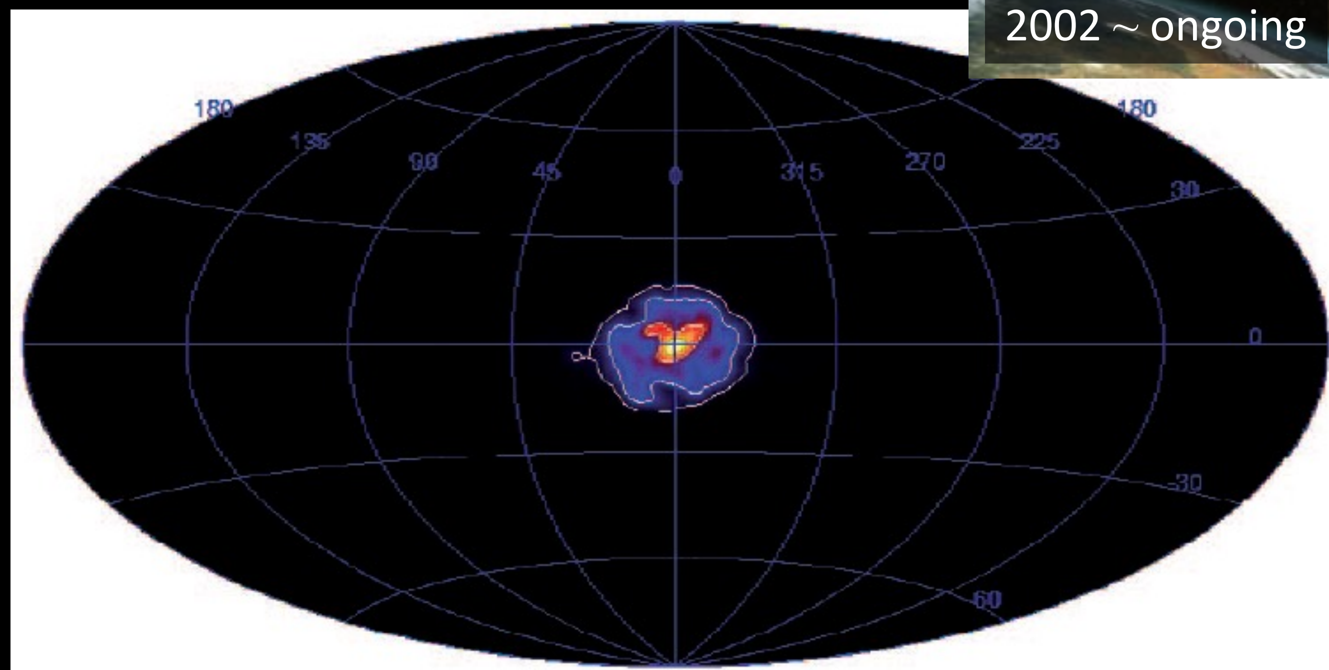
# *511 keV line excess*

**Excess:** Strong signal of positronium decays seen by INTEGRAL
(requires ~$2 \times 10^{43}$ e+ /s)


**Relative to:** various astrophysical sources

Supernovae
X-ray binaries
NS mergers




*Knodlseder et al 2005, Weidenspointer et al 2008, Siegert et al 2016*

The signal is **much too luminous** in the Galactic Center :

Bulge / disk ~ 1
But predicted < 0.5

→ Is it a dark matter related phenomenon??

*e.g., Boehm et al (2004) Finkbeiner & Weiner (2007)*

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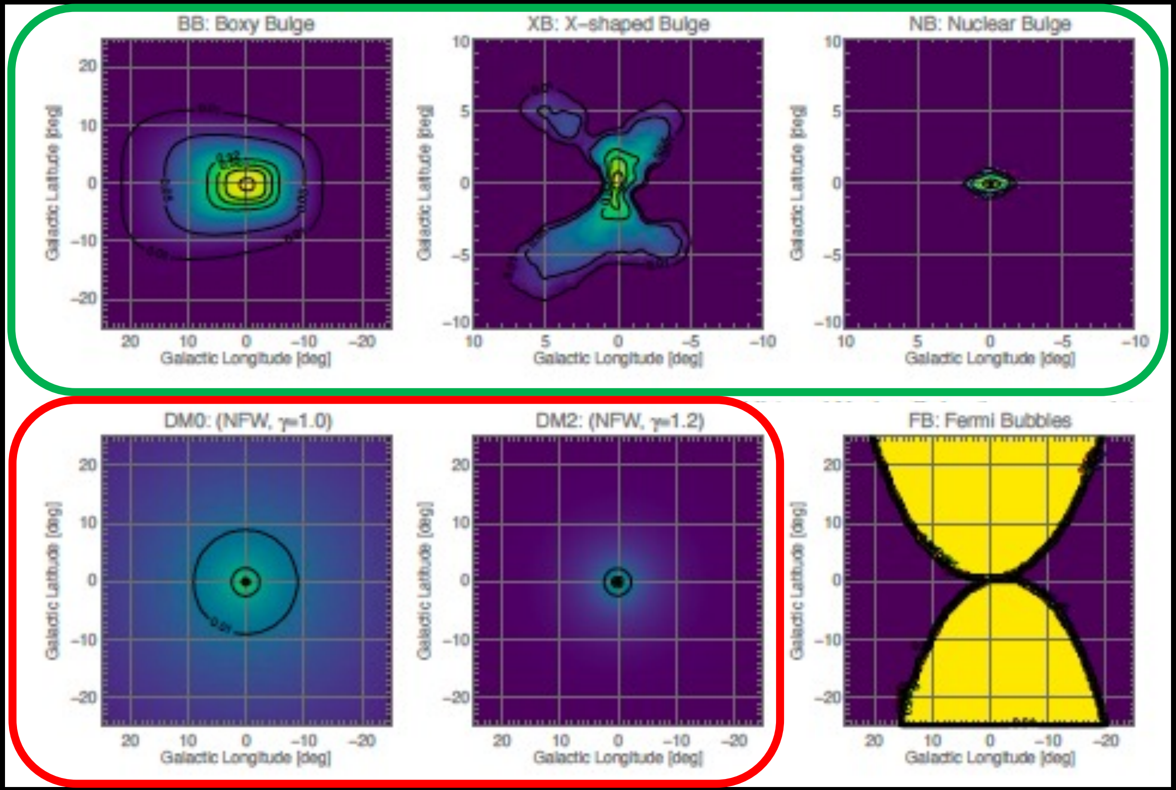
# Detailed morphology study

Which model combinations best describe the data?

*Siegert et al (2021)*




| Baseline model | Add. source | $\Delta AIC_{\pm}$ |
|---|---|---|
| IC | HI | 15.6 |
| IC | FB | 35.1 |
| IC | BB | 281.5 |
| IC | CO | 303.6 |
| IC | HI+CO | 382.6 |
| IC | NB | 507.6 |
| IC | DM2 | 510.6 |
| IC | DM0 | 597.6 |
| IC | BB+NB | 618.2 |
| IC+BB+NB | CO | -3.7 |
| IC+BB+NB | DM2 | -1.3 |
| IC+BB+NB | DM0 | 2.5 |
| IC+BB+NB | CO+HI | 15.4 |
| IC+BB+NB | HI | 16.0 |
| IC+BB+NB+HI | DM0 | 5.6 |
| IC+BB+NB+HI+CO | DM0 | 5.9 |

When mutually exclusive, dark matter and bulge are both detected

When simultaneously added, the dark matter significance become negligible

➔ *Astrophysically motivated model* removes the need for a symmetric DM model

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# *Concluding remarks*

- Astronomical observations create ample opportunities to further our study of dark matter
- **There have been many, many searches & anomalies. This is natural as we push the frontier of sensitivity. It is expected and should not be discouraged.**
    - Dark matter is usually capable of explaining these anomalies, given dark matter's rich phenomenology
    - Meanwhile, most anomalies have been explained by non-DM effects: a combination of backgrounds and astrophysical sources. We should not be discouraged. This leads to improved sensitivity to dark matter.
    - Some anomalies still remain debated, including the GeV excess and the 3.5 keV line
- **In the future we can expect some resolution to current anomalies, but at the same time, new anomalies & surprises**

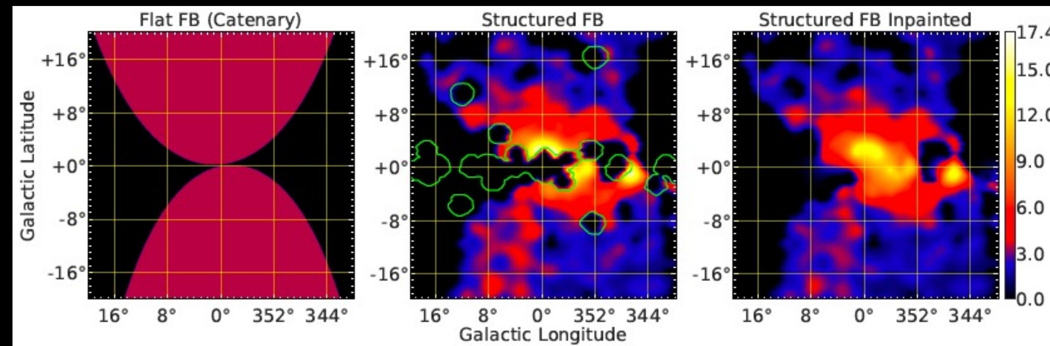
Thank you!

# *BACKUP*

# Systematics

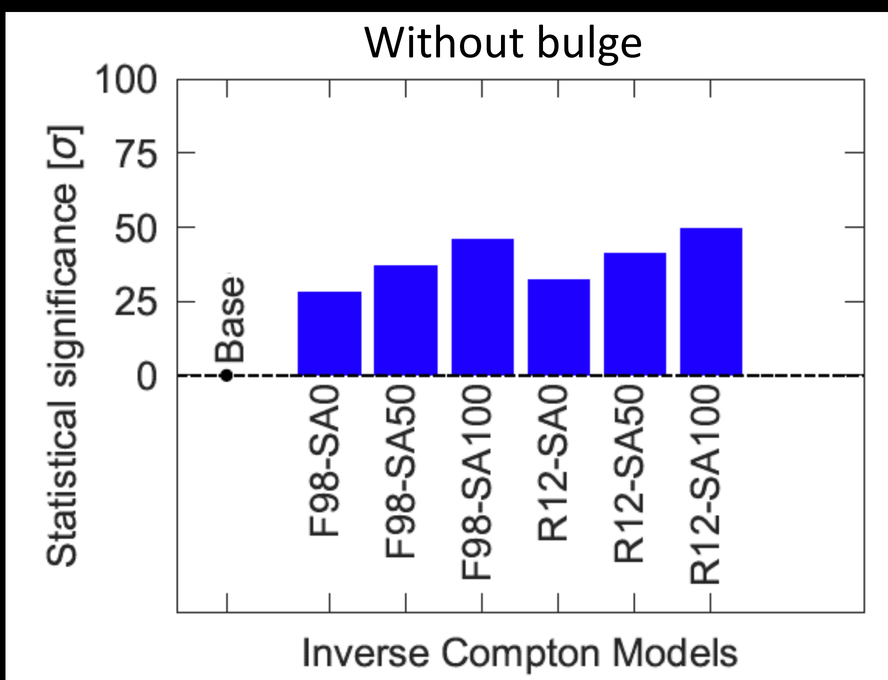
**Many astrophysical systematics**

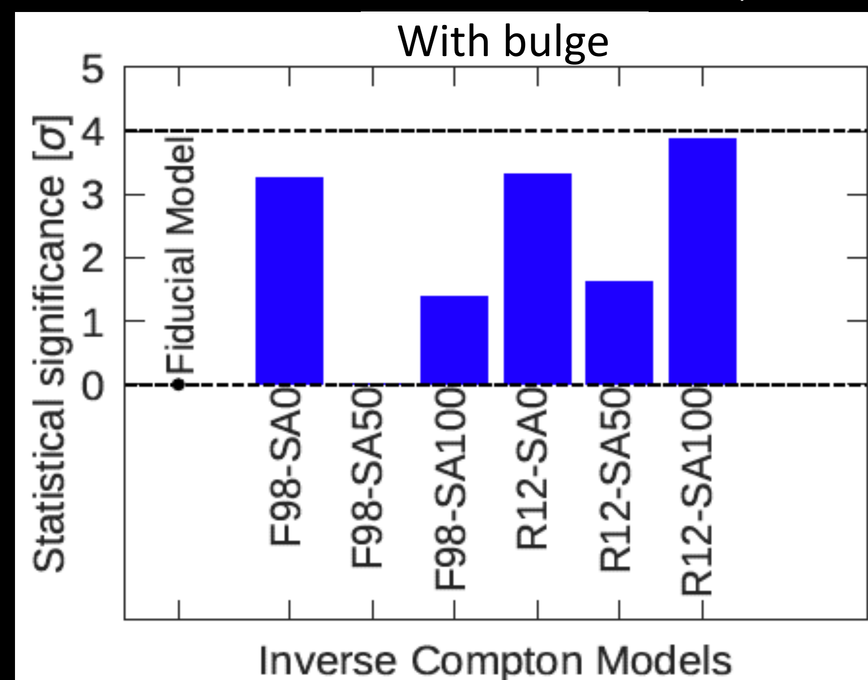
1. Bulge model
2. Fermi bubble model
3. Background (IC models)
4. Background (gas maps)
5. Point source catalogs
6. Galactic disk masks




Significance of NFW$^2$ for bulge and IC model combinations

*Macias et al (2018, 2019)*



# Systematics

**Gas maps:** using the gas maps used by the Fermi Diffuse models yield the same conclusions

| Base | Source | $\log(\mathcal{L}_{\text{Base}})$ | $\log(\mathcal{L}_{\text{Base+Source}})$ | $\text{TS}_{\text{Source}}$ | $\sigma$ | Number of source parameters |
|---|---|---|---|---|---|---|
| baseline+NB+Boxy | NFW | -172005.9 | -171999.0 | 13.8 | 1.4 | 19 |
| baseline+NFW | NB+Boxy | -172167.9 | -171999.0 | 337.8 | 18.3 | $2 \times 19$ |
| baseline$^\star$ | NFW | -173565.0 | -172929.2 | 1272 | 34.6 | 19 |
| baseline$^\star$+NFW | NB+Boxy | -172929.2 | -172533.0 | 792.4 | 28.2 | $2 \times 19$ |
| baseline$^\star$+NB+Boxy | NFW | -172547.4 | -172533.0 | 28.8 | 3.0 | 19 |

**Point sources:** using none or the 2FIG point source catalog yield the same conclusions

| Base | Source | $\log(\mathcal{L}_{\text{Base}})$ | $\log(\mathcal{L}_{\text{Base+Source}})$ | $\text{TS}_{\text{Source}}$ | $\sigma$ | Number of source parameters |
|---|---|---|---|---|---|---|
| baseline | 2FIG | -172461.4 | -170710.5 | 3501 | 37.3 | $81 \times 19$ |
| baseline+2FIG | Boxy | -170710.5 | -170536.3 | 348.4 | 18.7 | 19 |
| baseline+2FIG | NFW | -170710.5 | -170484.6 | 452 | 19.9 | 19 |
| baseline+2FIG | NB | -170710.5 | -170470.5 | 480 | 20.6 | 19 |
| baseline+2FIG+NB | NFW | -170470.5 | -170387.8 | 165 | 11.1 | 19 |
| baseline+2FIG+NB | Boxy | -170470.5 | -170317.2 | 306.6 | 17.5 | 19 |
| baseline+2FIG+NB+Boxy | NFW | -170317.2 | -170313.5 | 7.4 | 0.5 | 19 |

**Galactic plane mask:** using a $|b| < 1$ deg mask yields the same conclusions

| Base | Source | $\log(\mathcal{L}_{\text{Base}})$ | $\log(\mathcal{L}_{\text{Base+Source}})$ | $\text{TS}_{\text{Source}}$ | $\sigma$ | Number of source parameters |
|---|---|---|---|---|---|---|
| baseline | NFW | -430824.6 | -430696.9 | 255 | 14.4 | 19 |
| baseline | Boxy | -430824.6 | -430626.1 | 397 | 18.5 | 19 |
| baseline | NP | -430824.6 | -430189.9 | 1269 | 35.6 | $22 \times 19$ |
| baseline+NP | NFW | -430189.9 | -430097.0 | 186 | 12.0 | 19 |
| baseline+NP | Boxy | -430189.9 | -430035.8 | 308 | 16.1 | 19 |
| baseline+NP+Boxy | NFW | -430035.8 | -430026.3 | 19 | 2.0 | 19 |

# *Dark matter systematics*

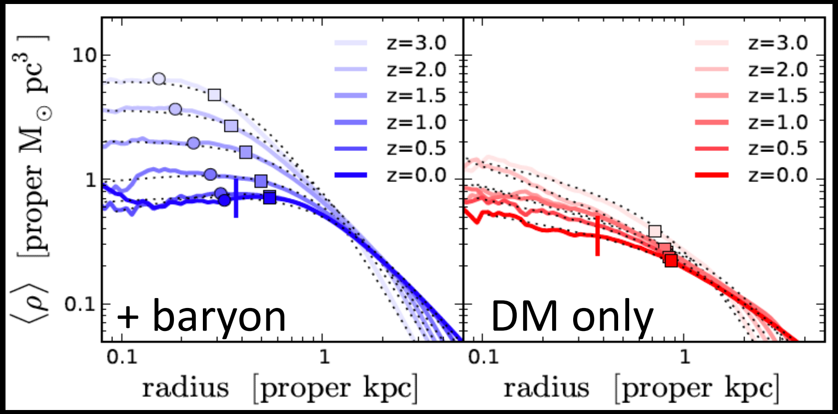
1. Inner slope, including cores
2. Asymmetry

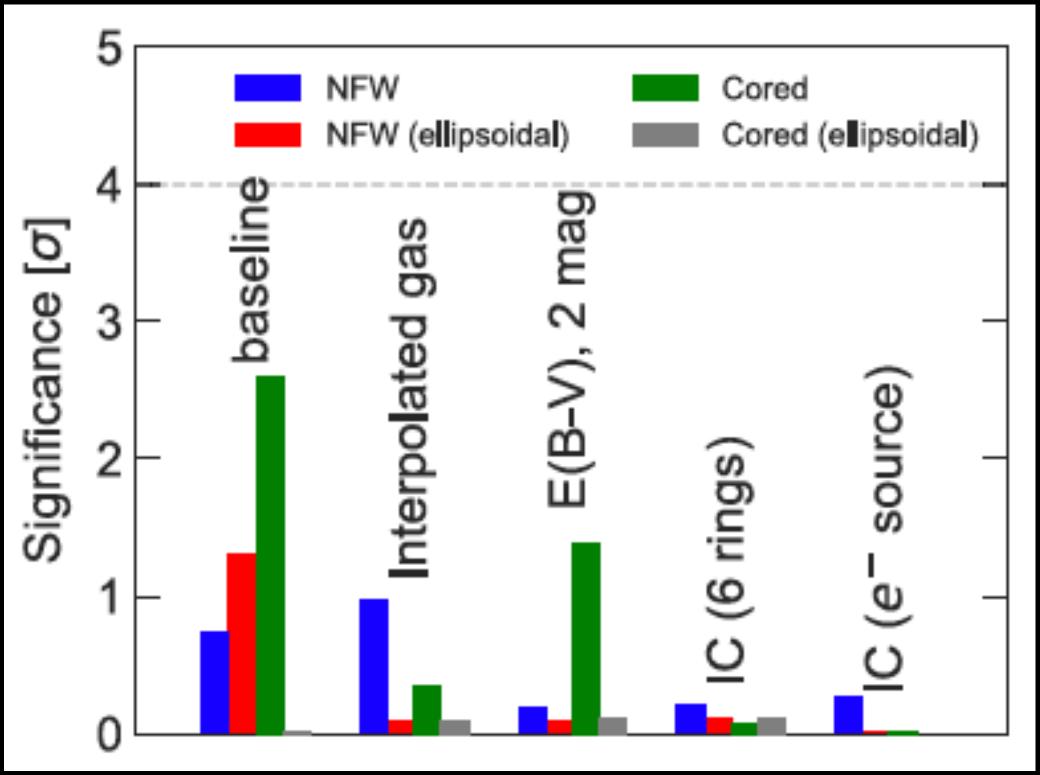
➔ Try $\gamma$ [0.5,1.5], 1kpc core, axis ratio 0.7

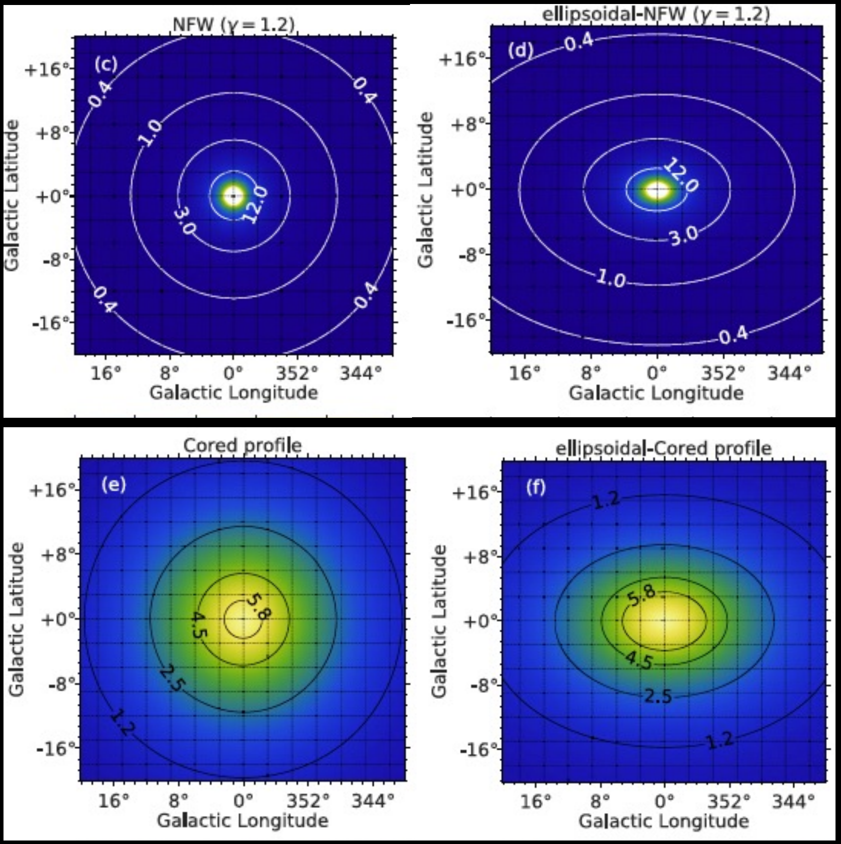
*Eg, bulge kinematics, Eris, FIRE simulations*

**➔ Again dark matter model not detected**

*Kuhlen et al (2012)*




*Abazajian, Horiuchi, et al (2020)*

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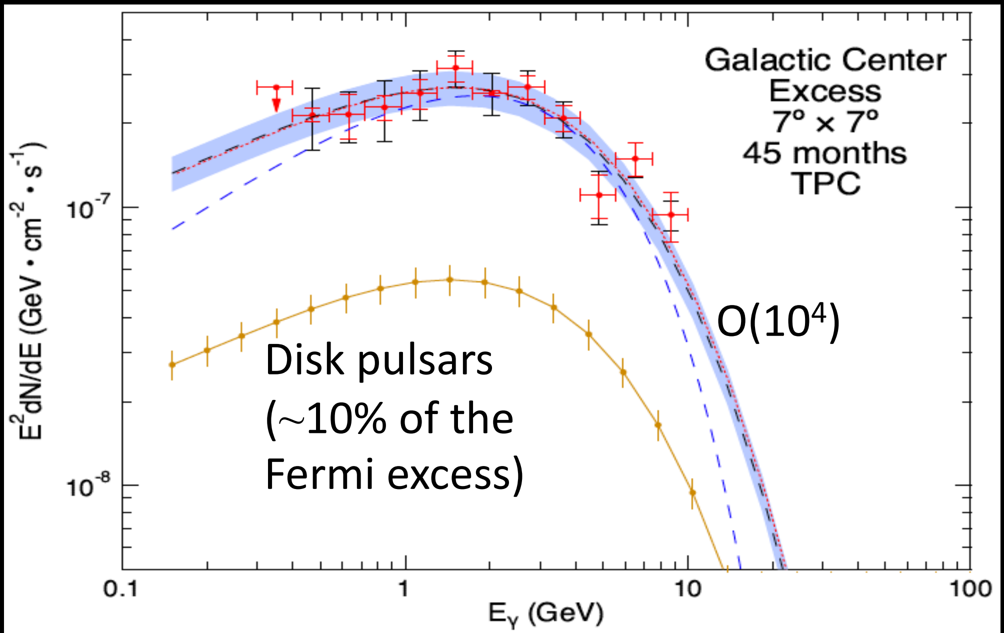
# *Pulsar population synthesis*

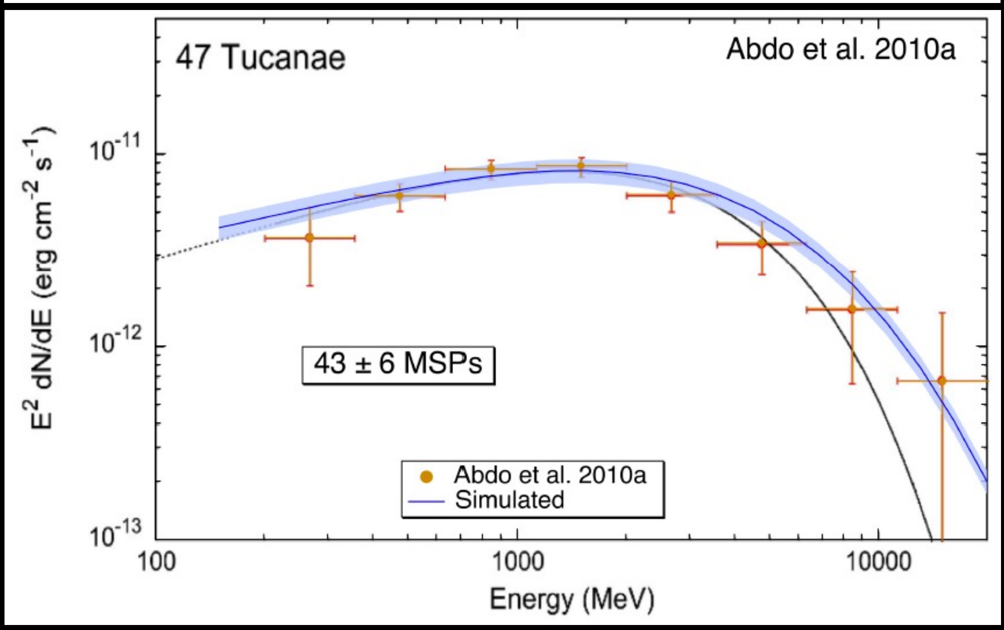
**Millisecond pulsar population**
Shows reasonable millisecond pulsar population model works

The bulge may host $O(10^4)$ millisecond pulsars below detection threshold

Also consistent with disk and globular cluster gamma rays

*Gonthier et al (2018)*
*See also Song et al (2021)*

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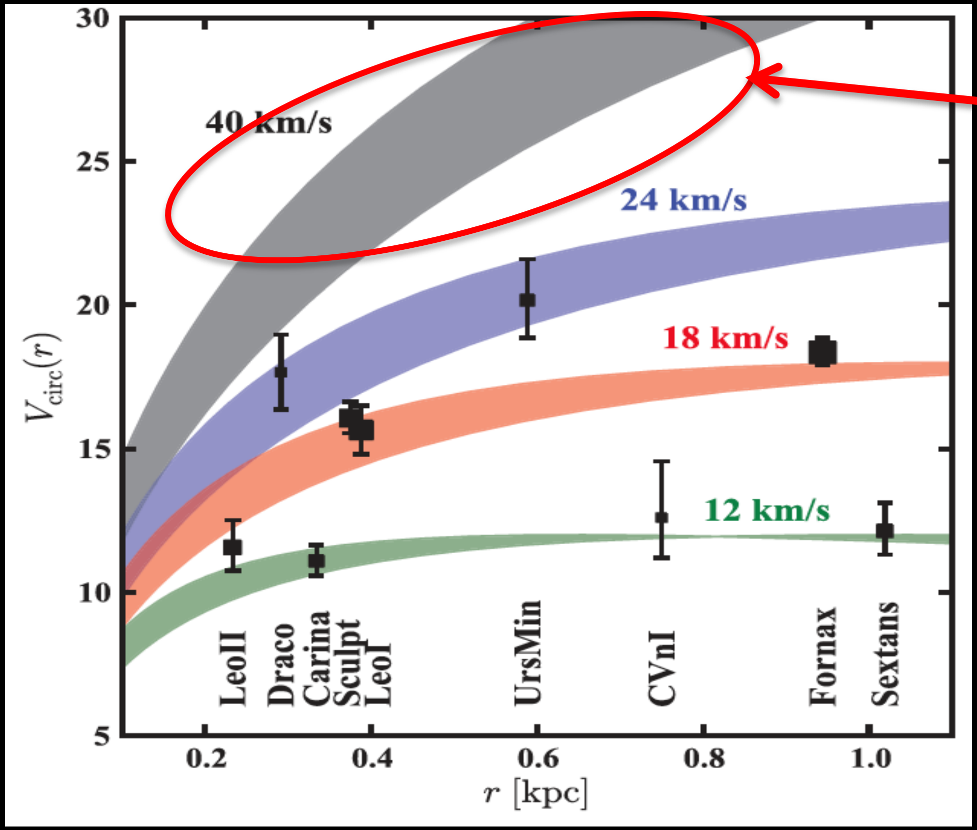
# *Small-scale structure anomalies*

**CDM is challenged by observations on small scales**

1. Core/cusp problem: inner density profile steeper than data
2. Missing satellites problem: expect *O*(100) satellites but see ~10
3. Too big to fail problem: massive subhalos are too dense to match data




*Boylan-kolchin et al (2011, 2012), Aquarius sims*

**"Massive failures"**
Subhalos with $V_{max}$ > 25 km/s that do not find observational counterparts: why do these not "light" up?

Between 5 – 40 (median ~20) "*massive failures*" based on 48 realizations of the Milky Way Halo

*Garrison-Kimmel et al (2014)*

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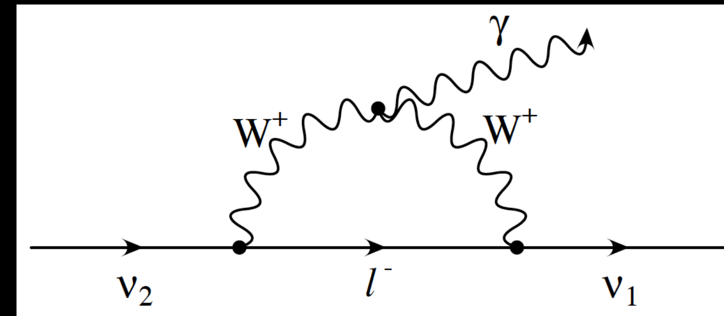
# Is it dark matter?



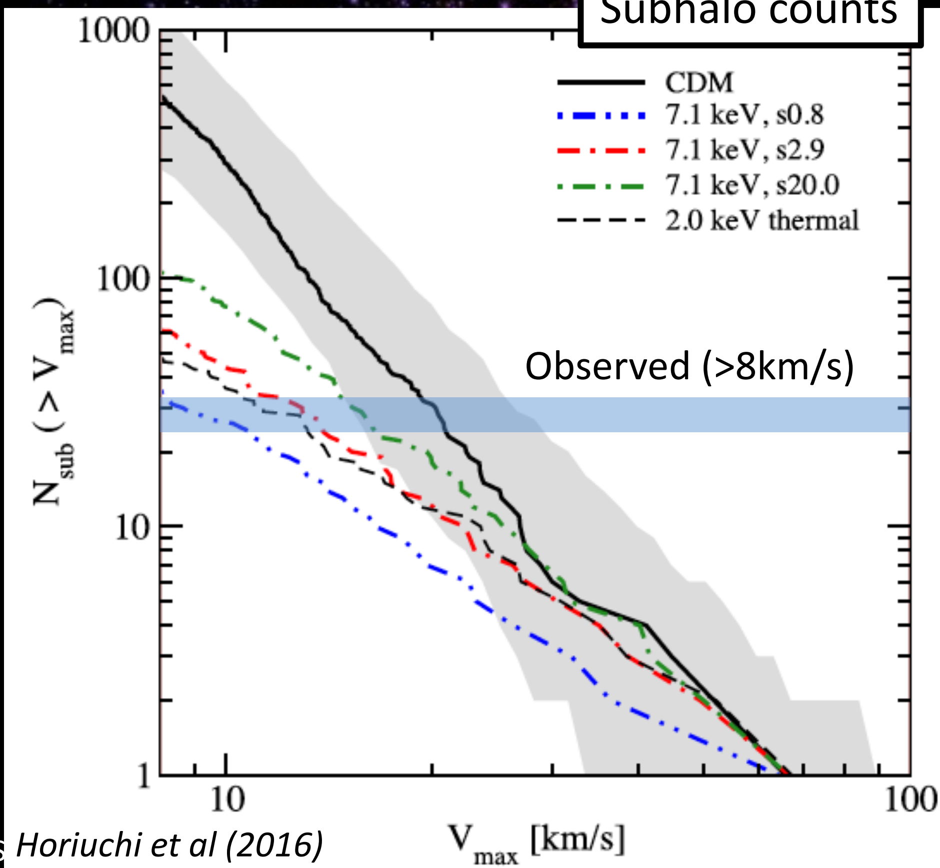

**keV sterile neutrino dark matter:** can radiatively decay to active neutrinos + X-ray

$$E_\gamma = m_s/2$$

It can be produced via oscillations and has attractive features beyond CDM

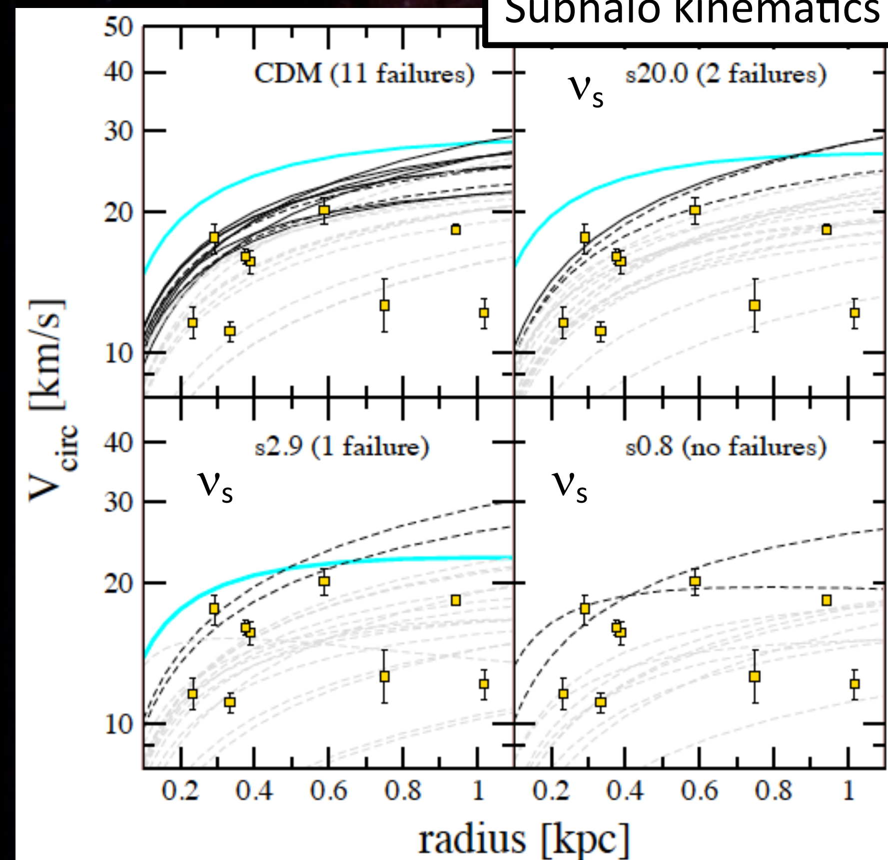
Abazajian (2014)

Subhalo counts



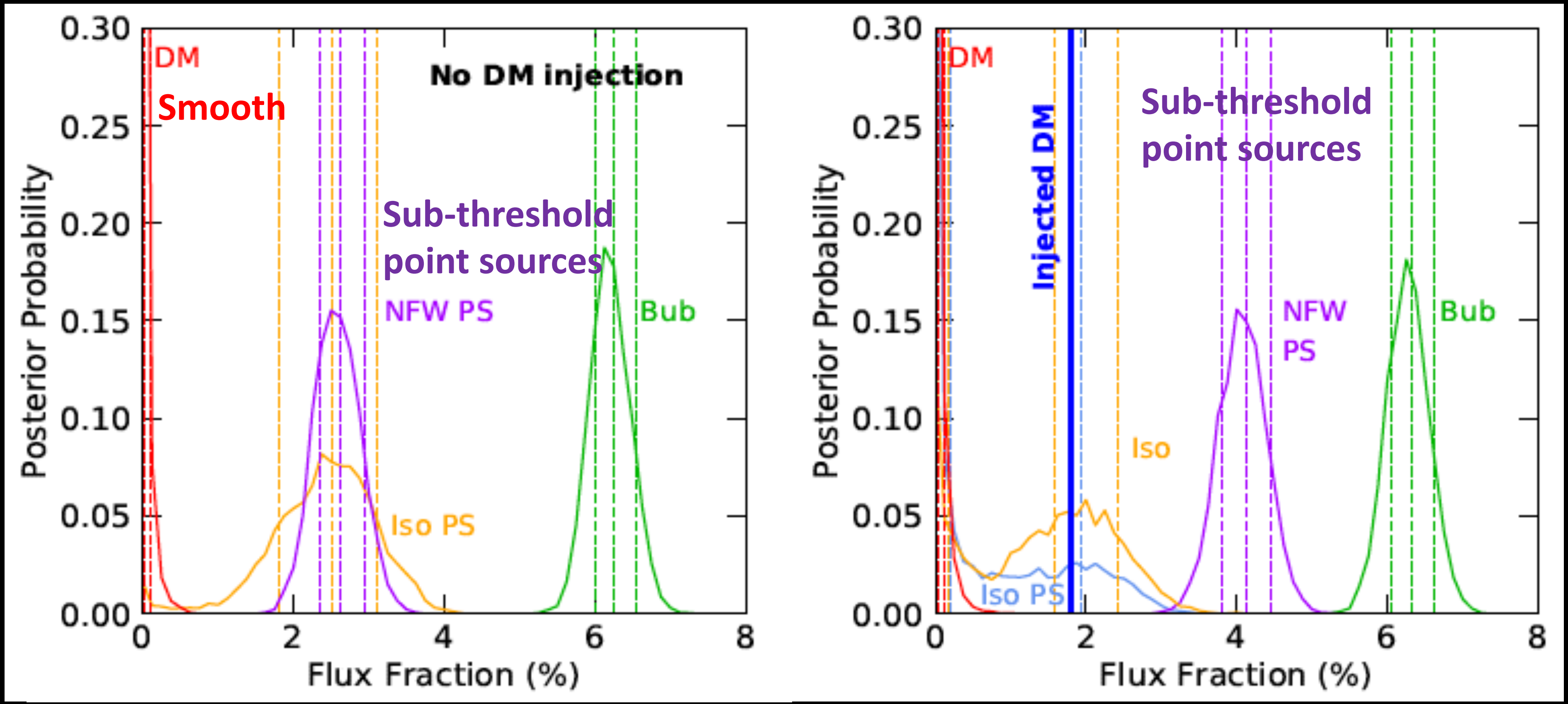

Horiuchi et al (2016)

Subhalo kinematics



# More developments

- Ultra-faint point population is degenerate with a smooth diffuse source
- Injected dark matter erroneously absorbed by sub-threshold point-source model
- Impacts of mismodeling diffuse model appears problematic



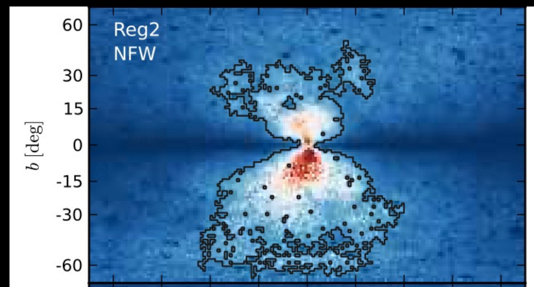

*Leane & Slatyer (2019, 2020)*
*Also Chang et al (2019), Zhong et al (2019), Buschmann et al (2020),*

→ **Can be confident there's substantial point sources**
→ **Allows DM signal to be hiding**

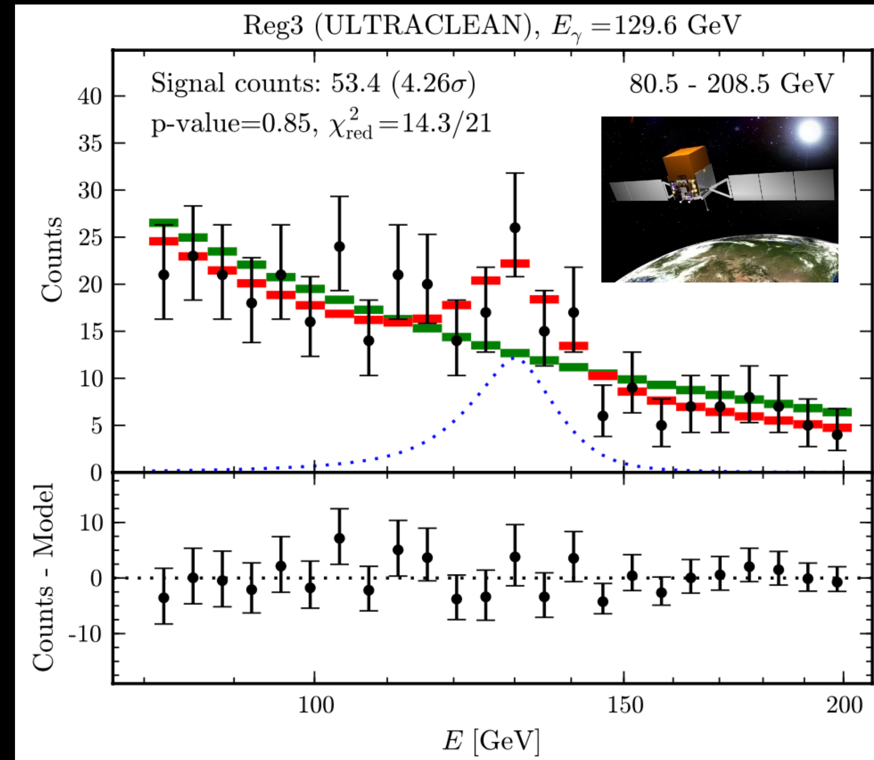
# *Gamma-ray line*

**Line:** ~130 GeV from Galactic Center region
**Relative to:** power-law diffuse emission

3.2σ sig.
(after trials
factor)




*Weniger (2012)*

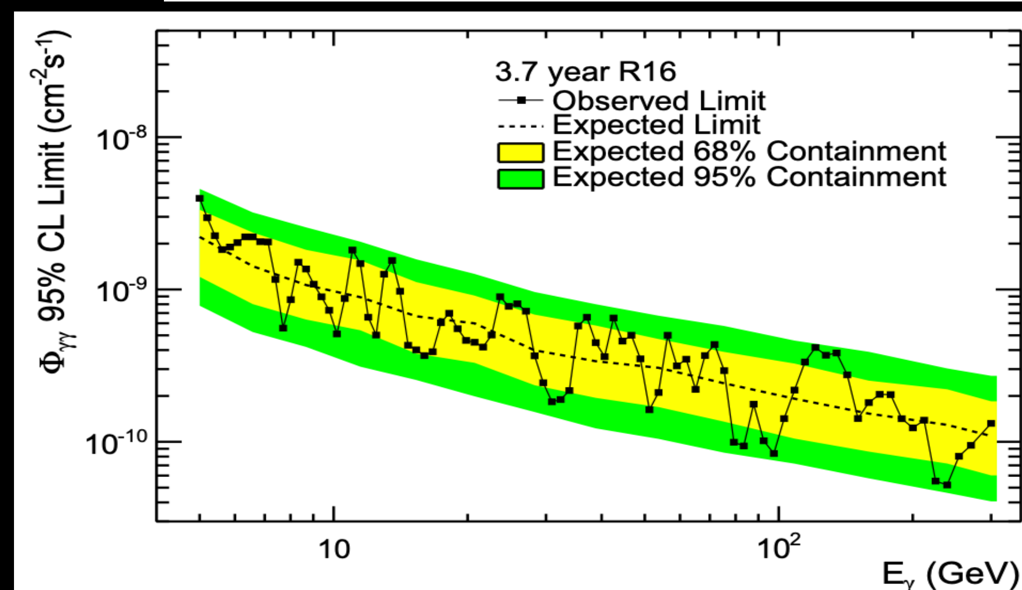



Subsequently observed in galaxy clusters and unassociated LAT sources too.

*Hektor et al (2013)*
*Su & Finkbeiner (2013)*

Ultimately the line disappeared with *updated understanding of detector calibration*

*Fermi collab. (2014)*

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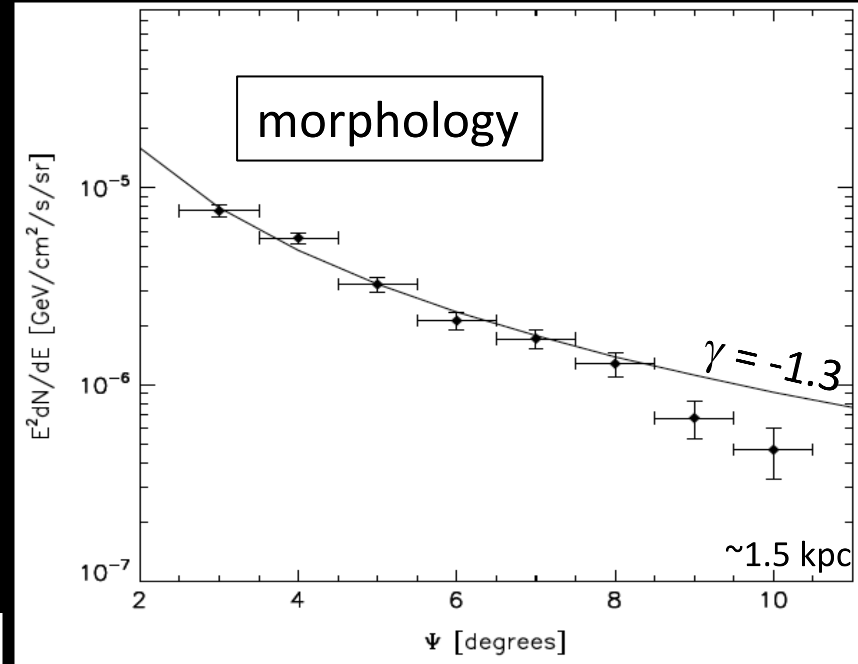
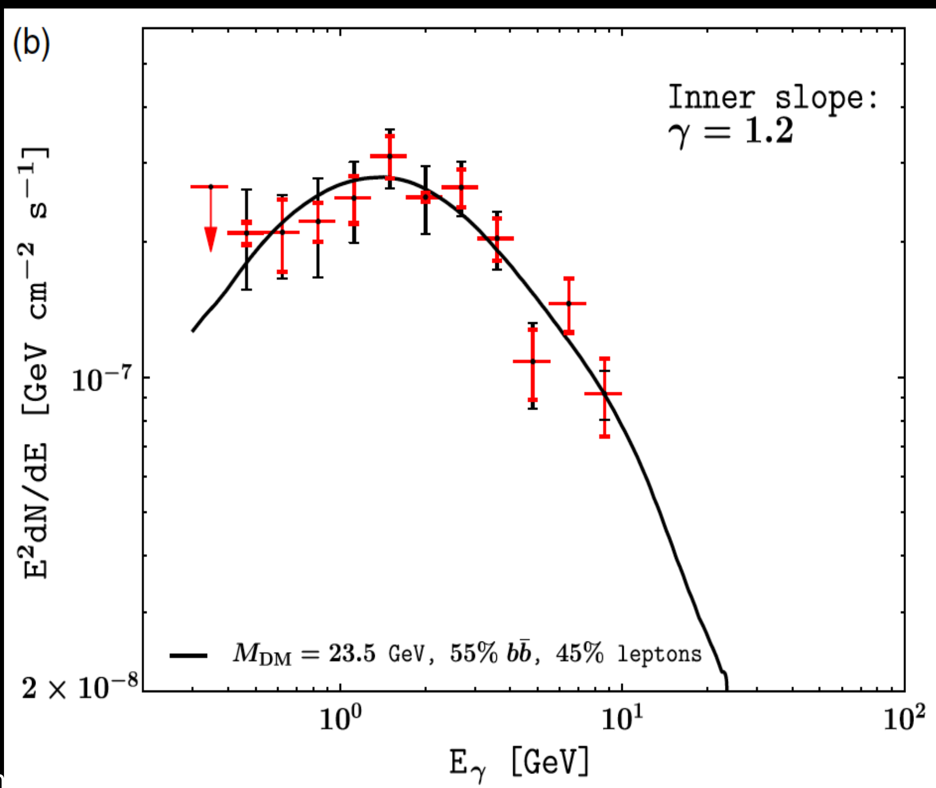
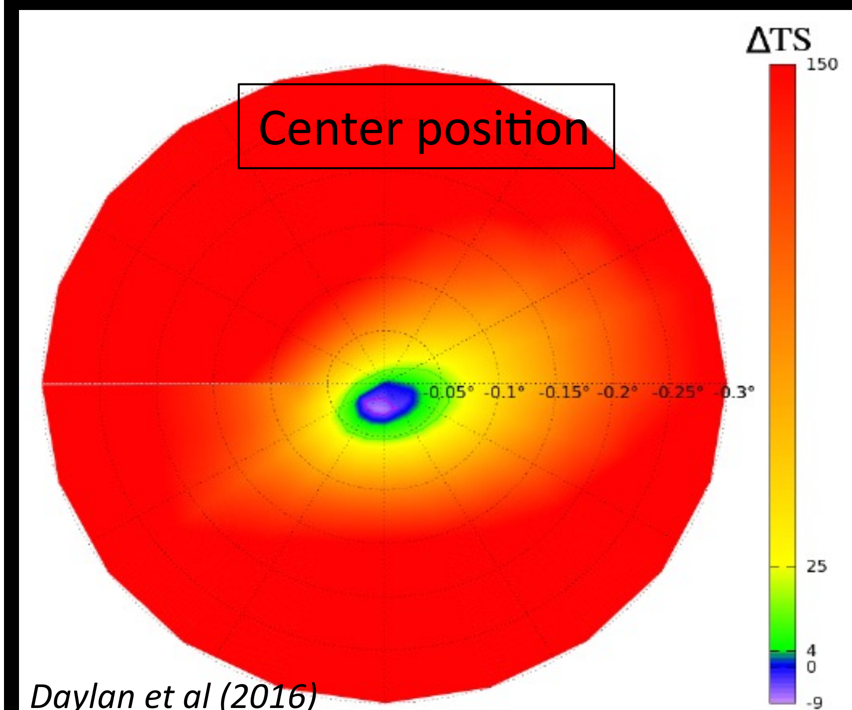
# *Is it dark matter?*

**All features consistent with WIMPs**

- Spectrum suggests O(100) GeV mass, approx. thermal cross sections
- J-factor well known
- Spatial morphology largely spherical, NFW-like, and centered on dynamical center




Shun