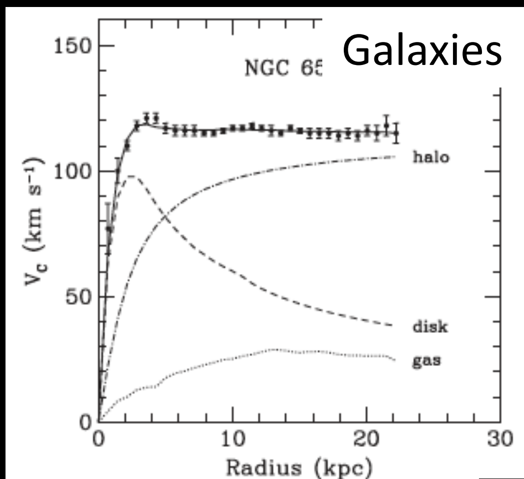
KMI School, Dec 17th 2022

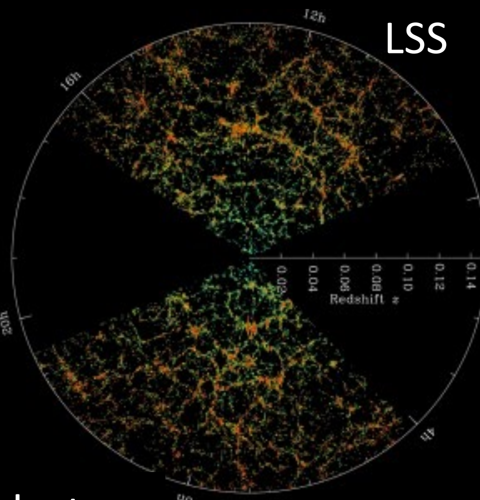
# *Astronomical anomalies: dark matter or astrophysics?*

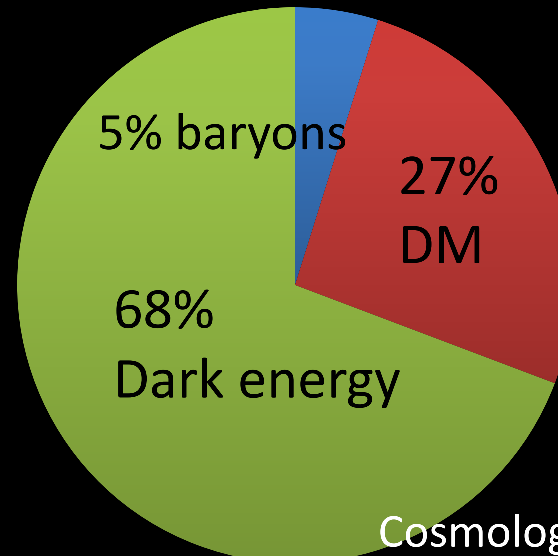
**Shunsaku Horiuchi**

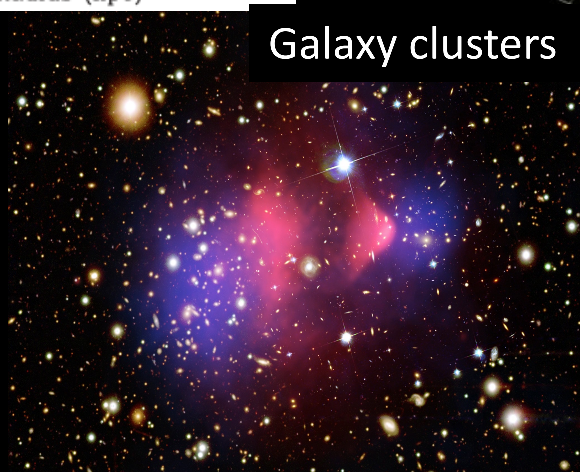
# *Dark matter: evidence*

- Astronomical data on many scales point to the presence of dark matter

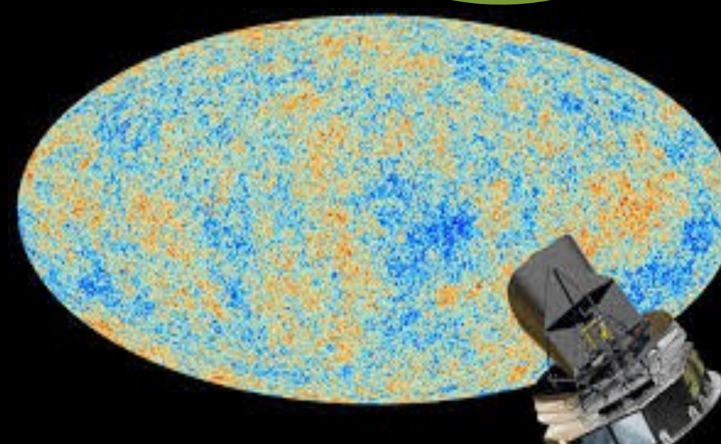



Cosmological



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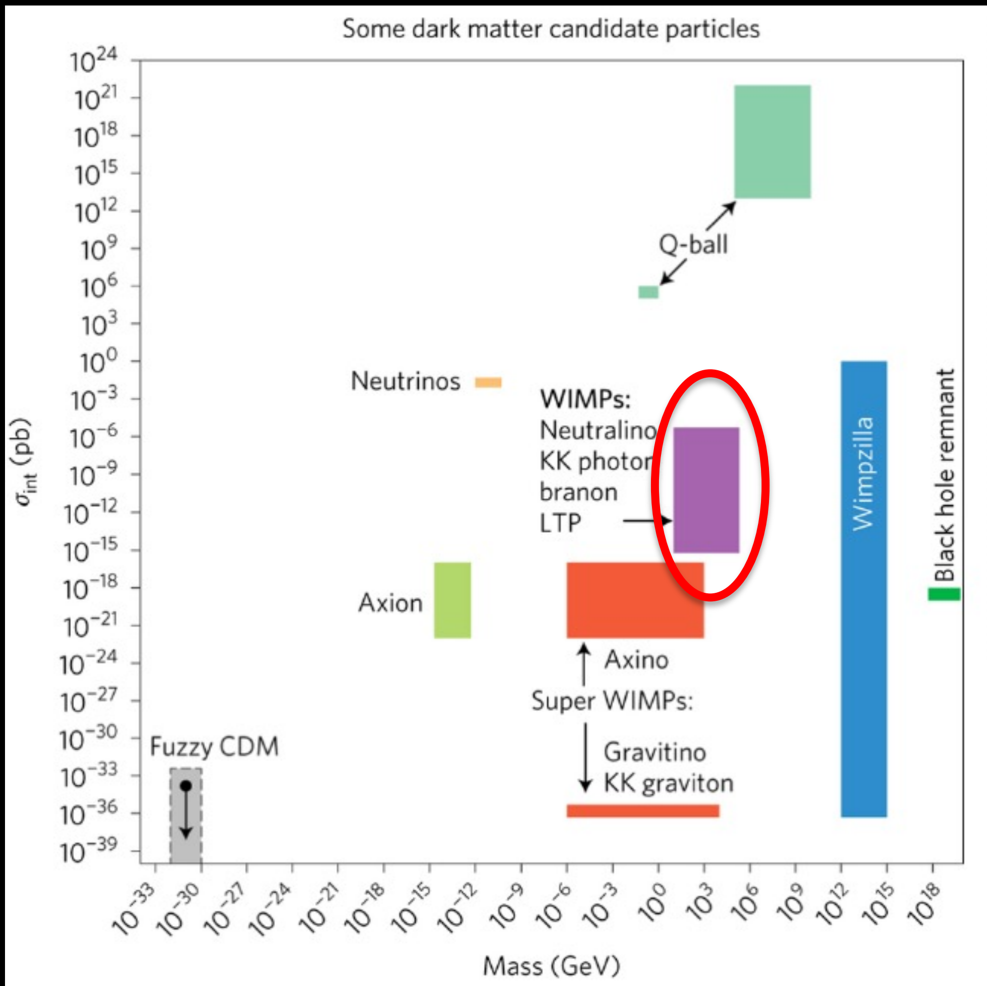
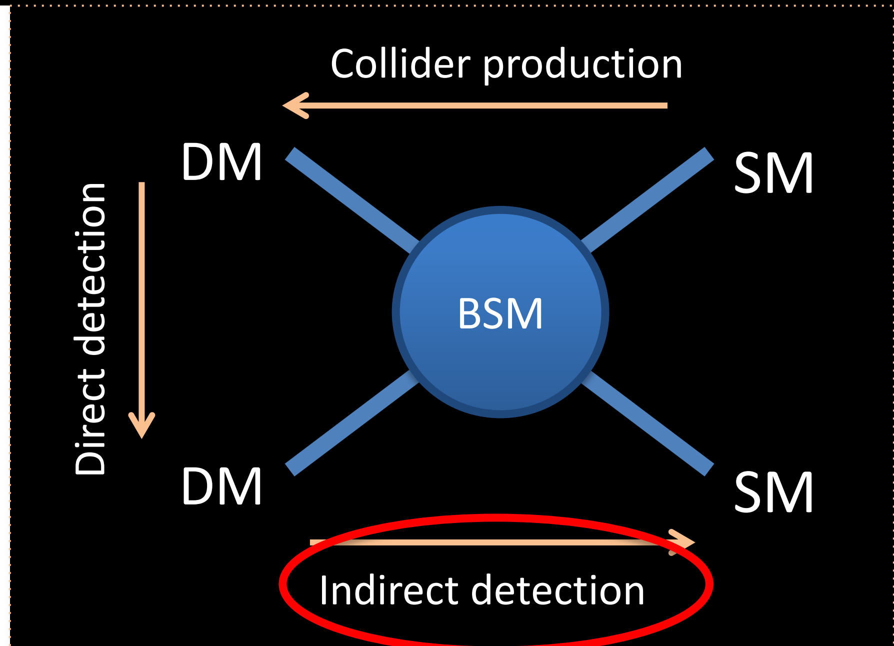
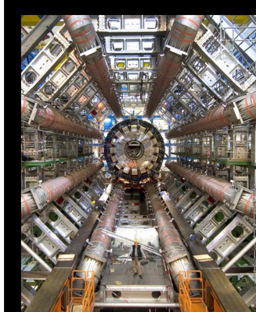
# What is dark matter?

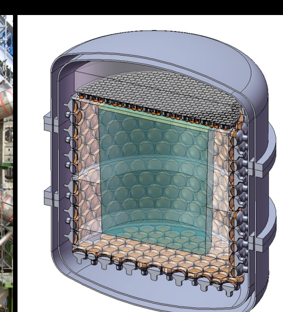
There is no stable, non-relativistic, and neutral particle(s) in the Standard Model that could be dark matter ➔ something new




*Conrad & Reimer 2017*





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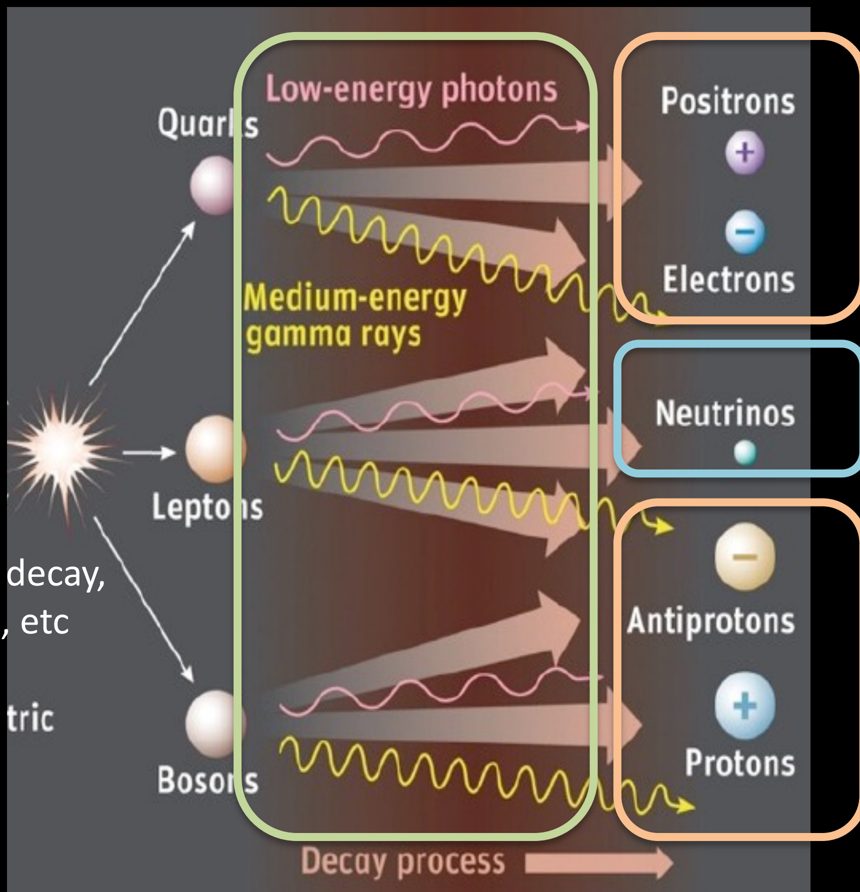
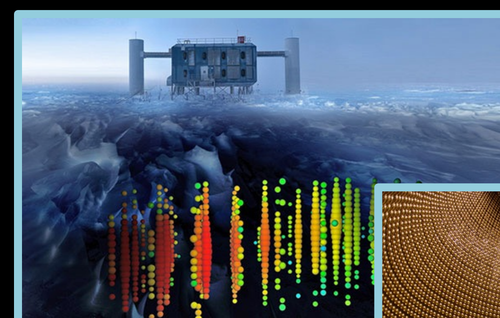
# The multi-messenger hunt

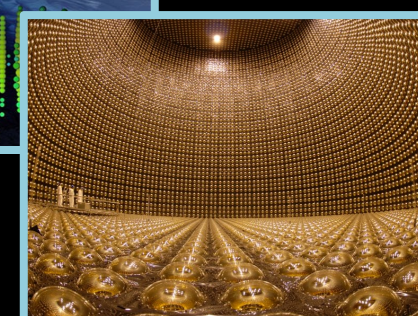
Particle
Dark matter

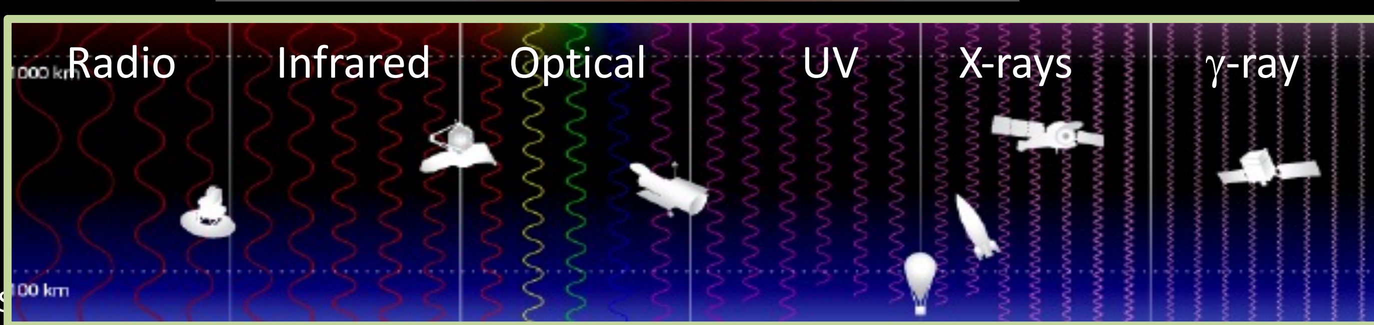
$\chi$

Annihilation, decay,
de-excitation, etc







# *Annihilation signal - photons*

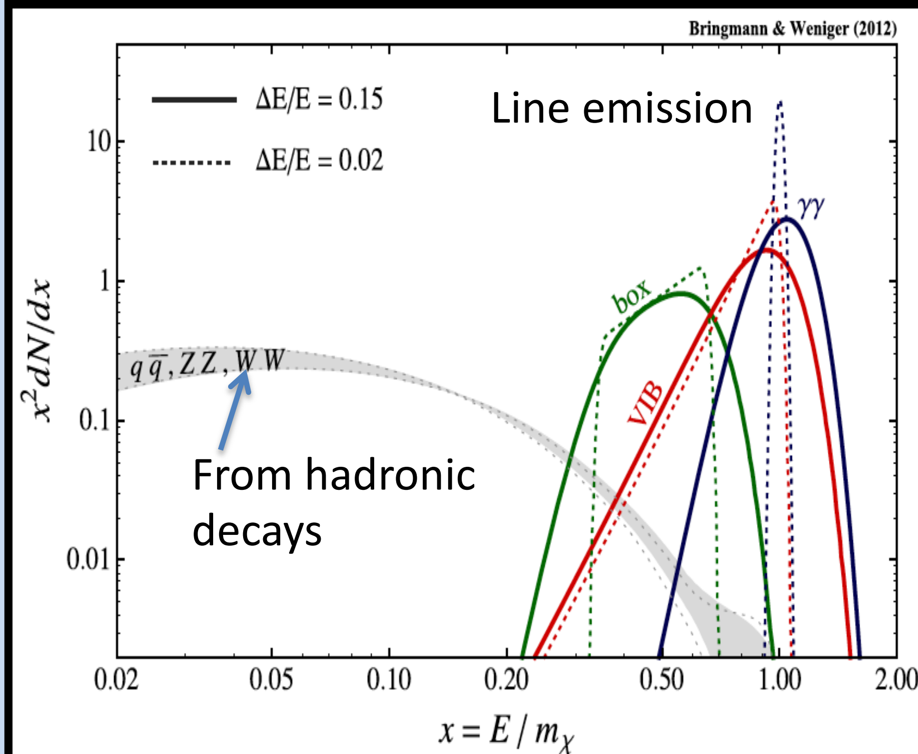
Annihilation of thermally produced DM (via hadronic decays) explains the spectrum

Spectral energy distribution per annihilation

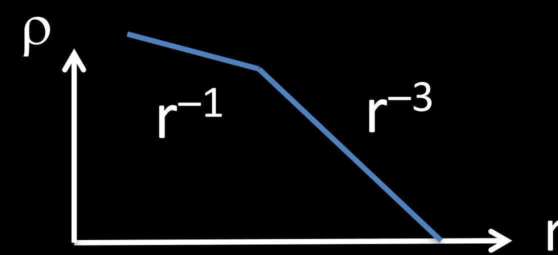
$$\Phi(E,\psi) = \frac{\sigma_A v}{8\pi m_\chi^2}\frac{dN_\gamma}{dE}\int d\ell\,\rho\left[r(\ell,\psi)\right]^2$$

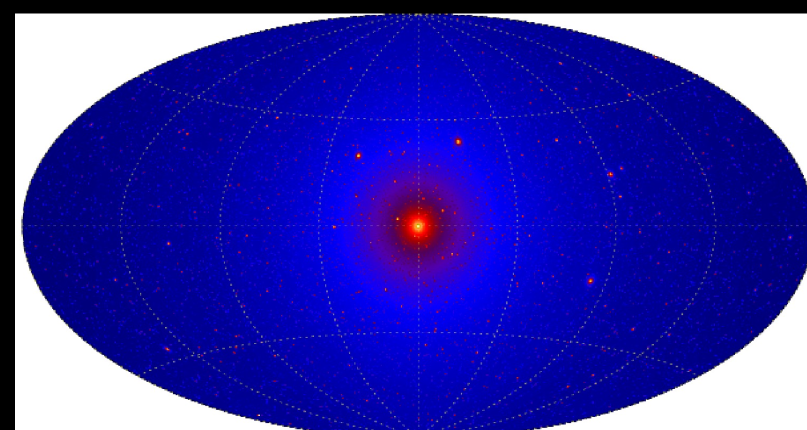
Boost or "J-factor"

**Prompt component**




**Dark matter distribution, eg, NFW**



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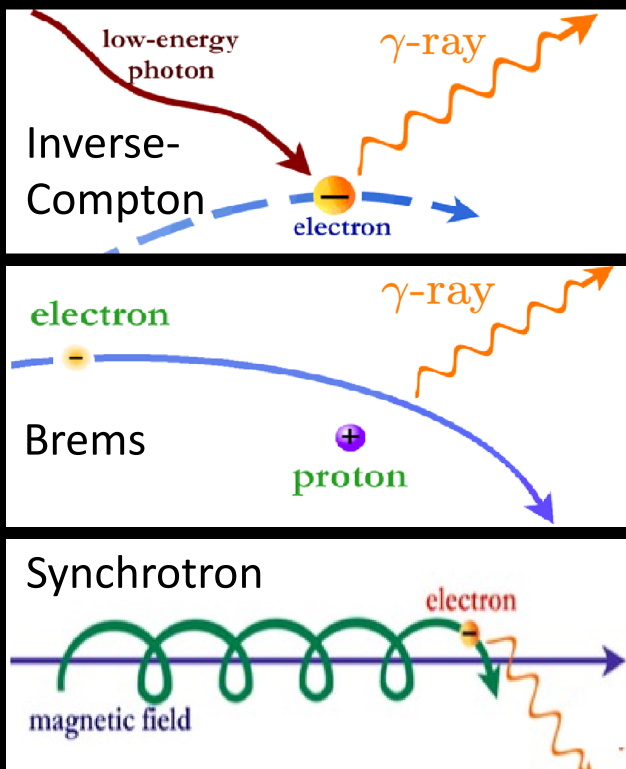
Spectral energy distribution per annihilation

Boost or "J-factor"

## Secondary component




## Charged particle propagation

- Source (injection properties)
- Diffusion
- Energy losses (IC, syn, hadronic,…)
- Advection
- Reacceleration

$$\frac{\partial}{\partial t}\frac{dn_e}{dE_e}(E_e,r,t) = \vec{\nabla}\cdot\left[D(E_e)\vec{\nabla}\frac{dn_e}{dE_e}(E_e,r,t)\right]$$

$$+\frac{\partial}{\partial E_e}\left[\frac{dE_e}{dt}(r)\frac{dn_e}{dE_e}(E_e,r,t)\right] + \delta(r)Q(E_e,t)$$

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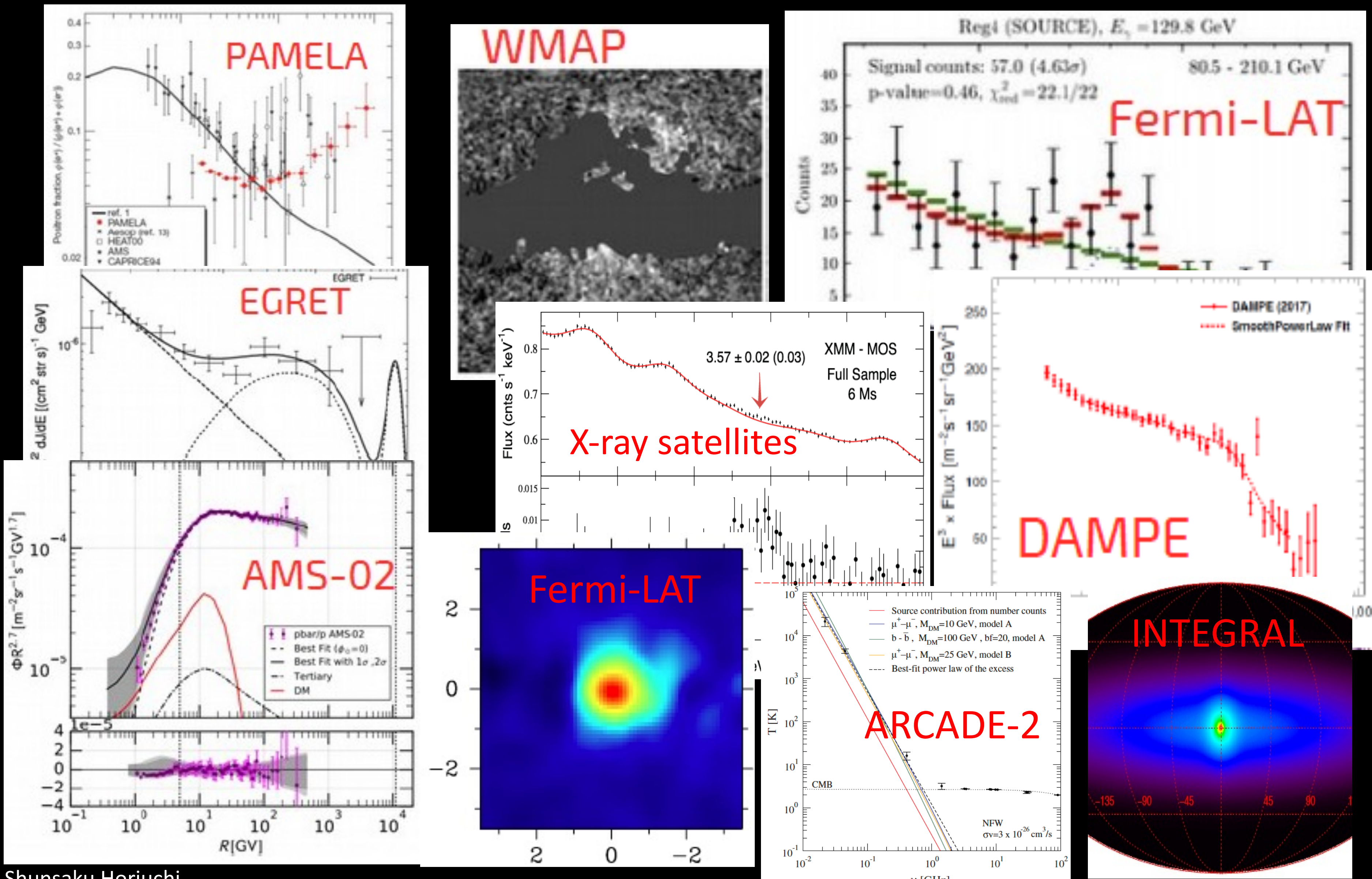
# *Many, many anomalies over the years*

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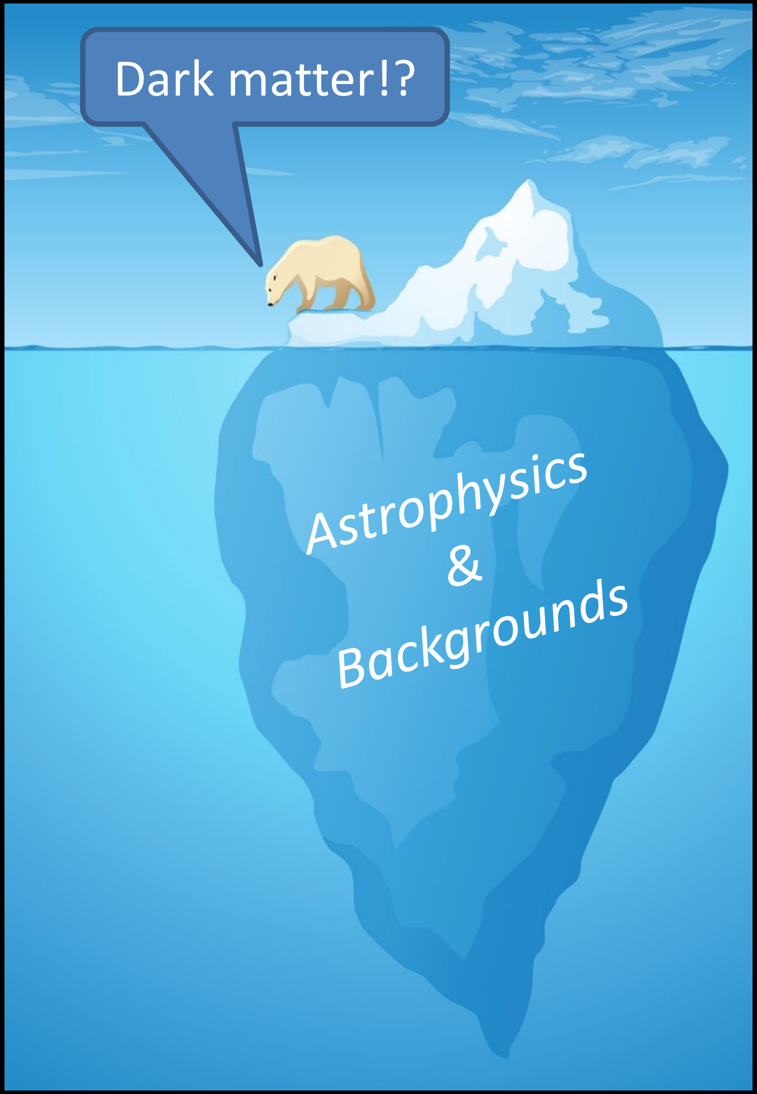
# *Types of anomalies*




**Excesses**

- Signal above known sources <u>and</u> known backgrounds
- 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

**Recurring theme: astrophysical <u>*systematics*</u>**

# *Anomalies for today*

**Story of continuum**

1. **GeV gamma-ray excess**

**Story of lines**

2. **511 keV line excess**
3. **130 GeV line**
4. **3.5 keV X-ray line**

**Story of anti-particles**

5. **Anti-proton**
6. **Positron (if time)**

**Main question:**

New astrophysics??
Or first non-gravitational evidence for dark matter??

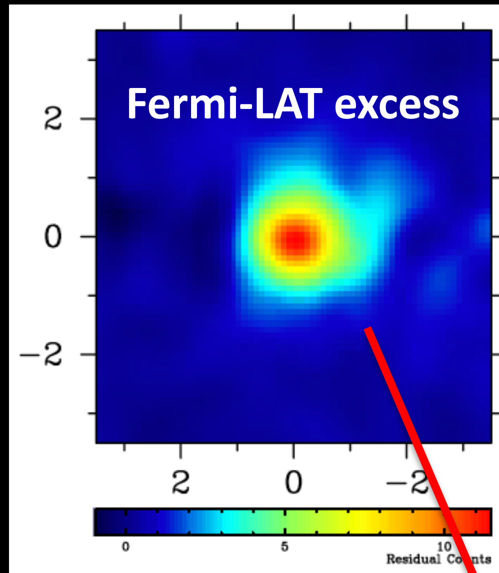
**For each:**

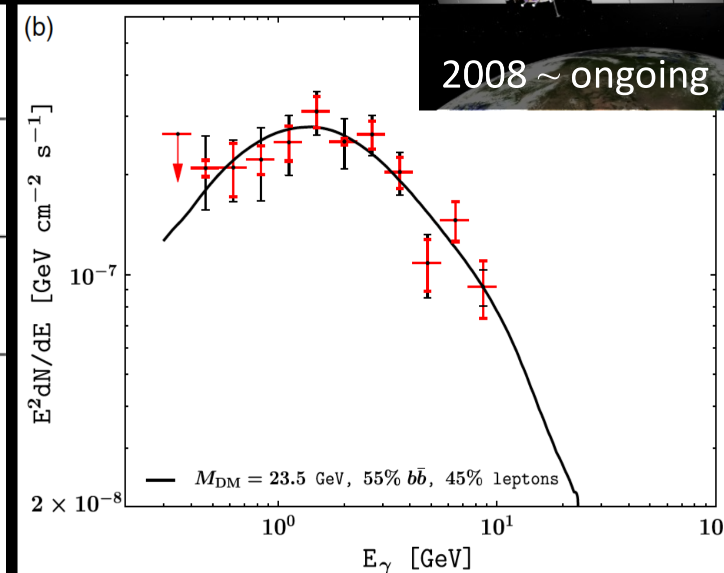
- Brief background
- Anomaly relative to what?
- Dark matter vs astrophysics
- Current status

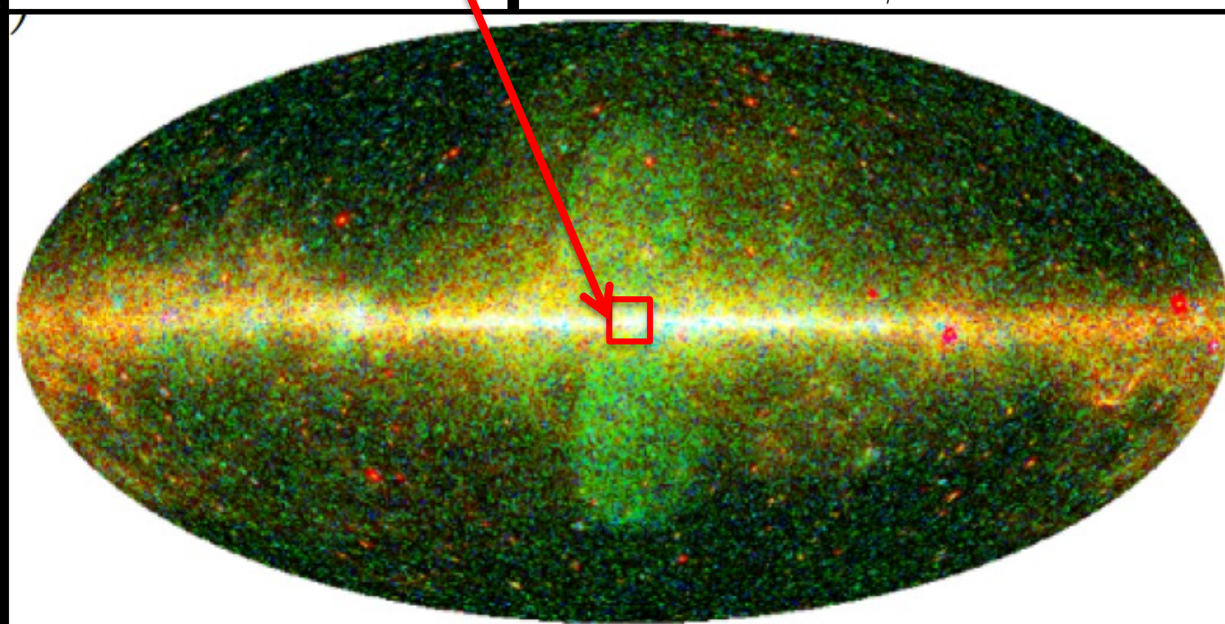
# *GeV gamma-ray excess*


**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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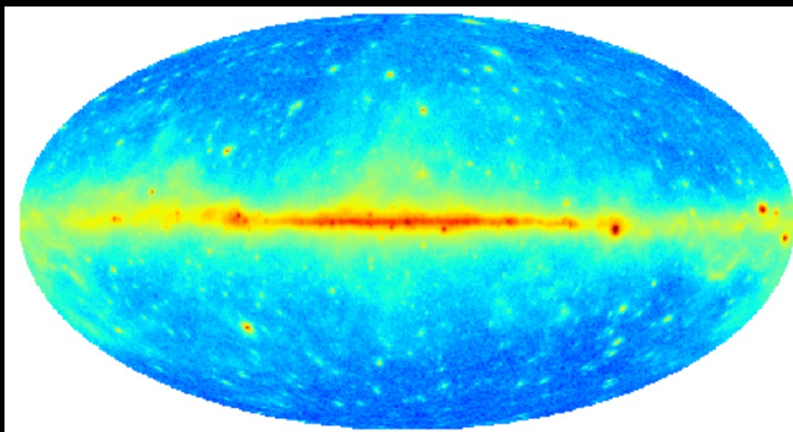
# *Excess relative to what?*

**Data**



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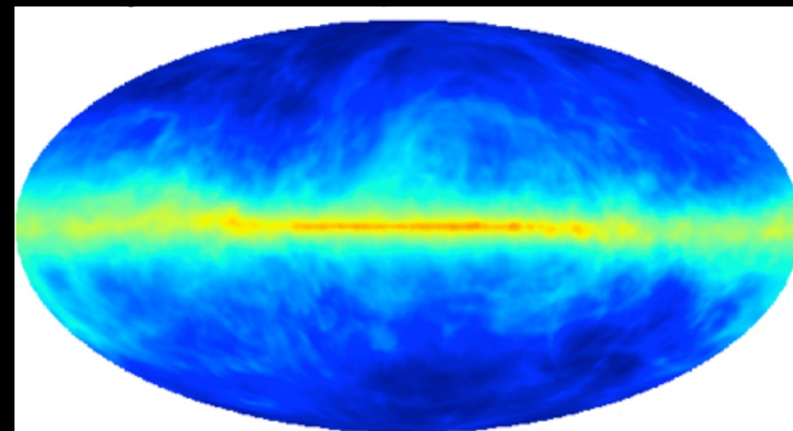
**Cosmic-ray related emission**



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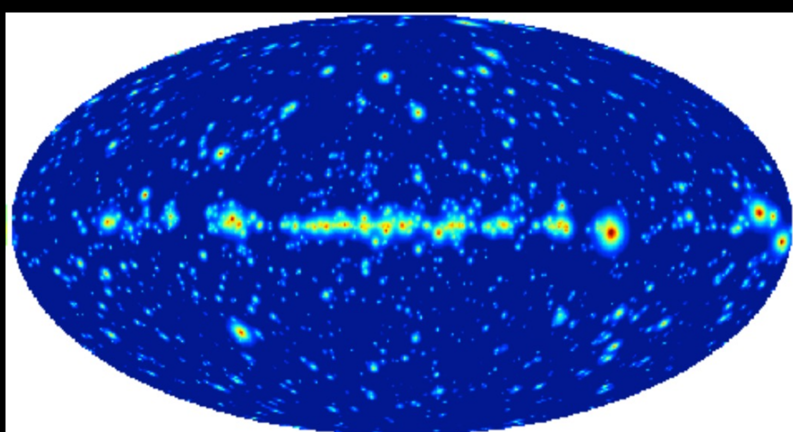
**Known sources**



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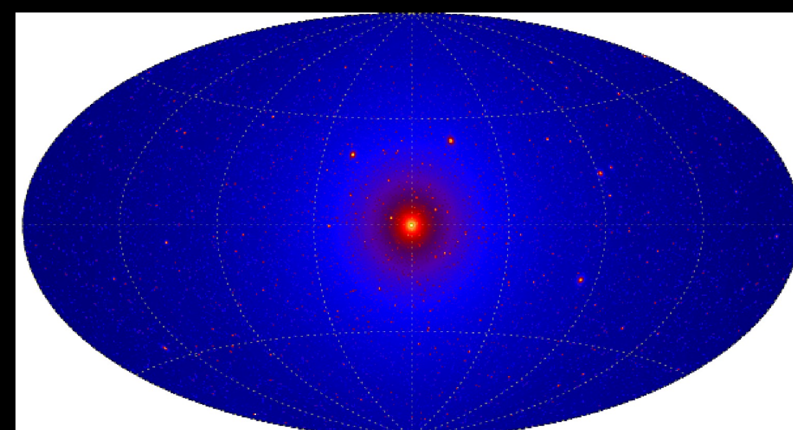
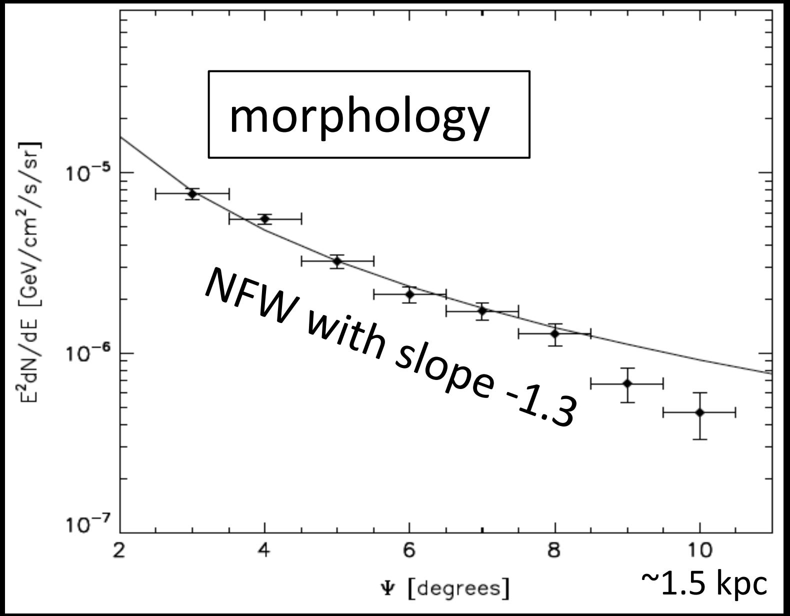
**New sources, e.g., dark matter**

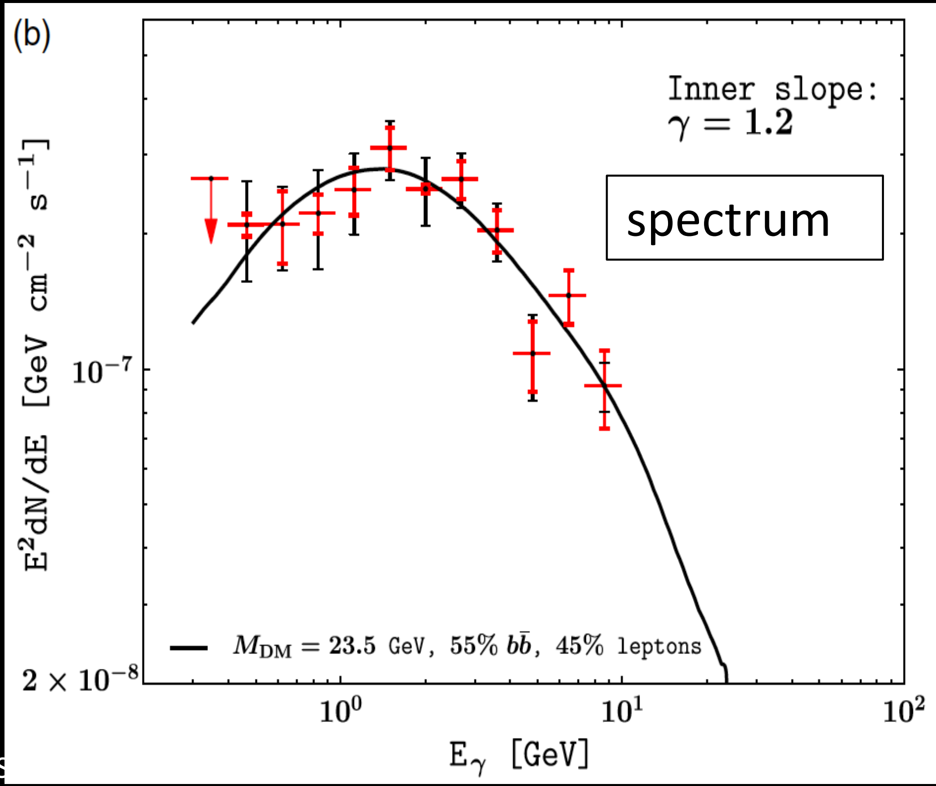


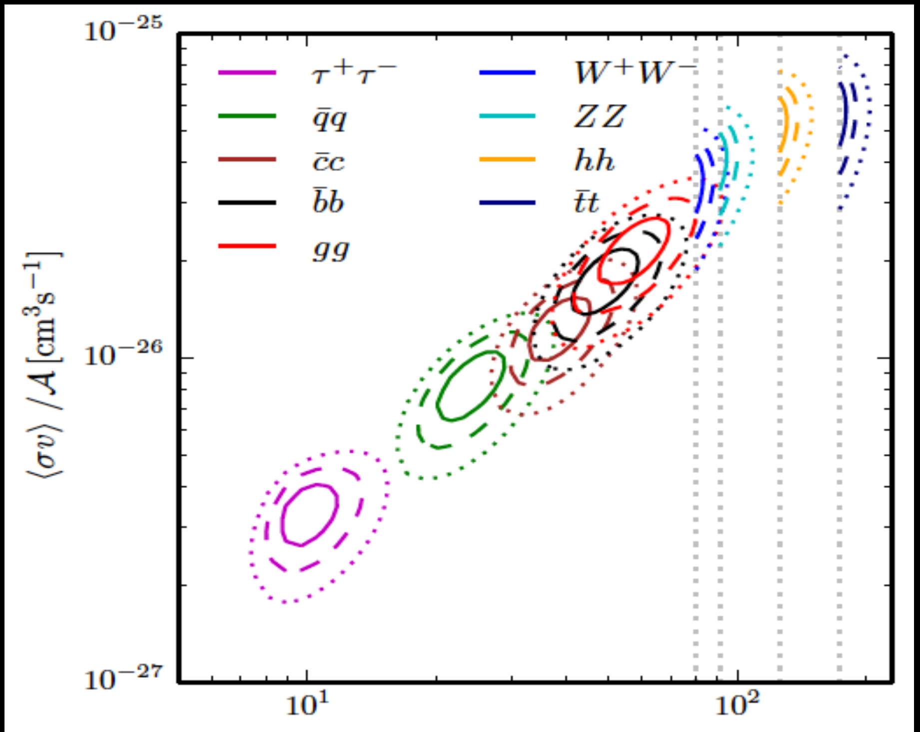
# *Is it dark matter?*

**All features consistent with WIMPs**

- Spectrum suggests 10~100 GeV mass, approx. thermal cross sections
- Spatial morphology largely spherical, NFW-like, and centered on dynamical center



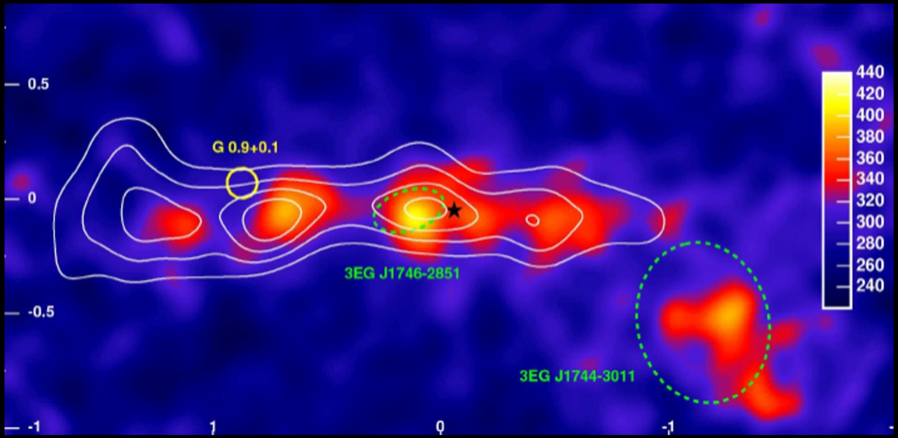




*Calore et al (2014)*

# *Galactic Center is rich & complex*

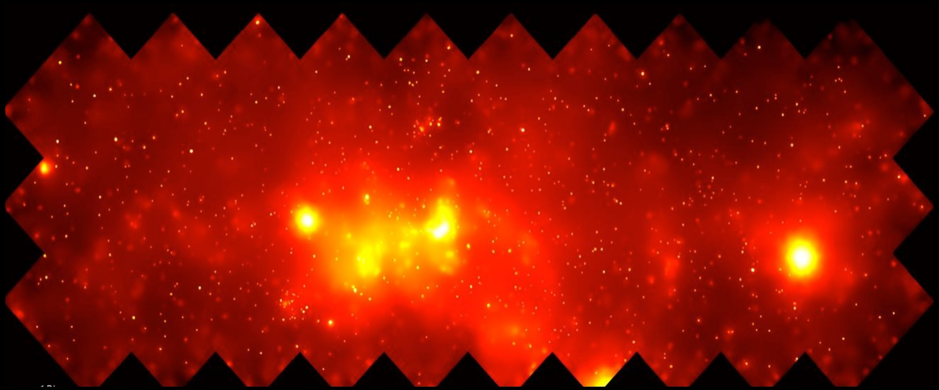
Supernova remnants

Supermassive black hole

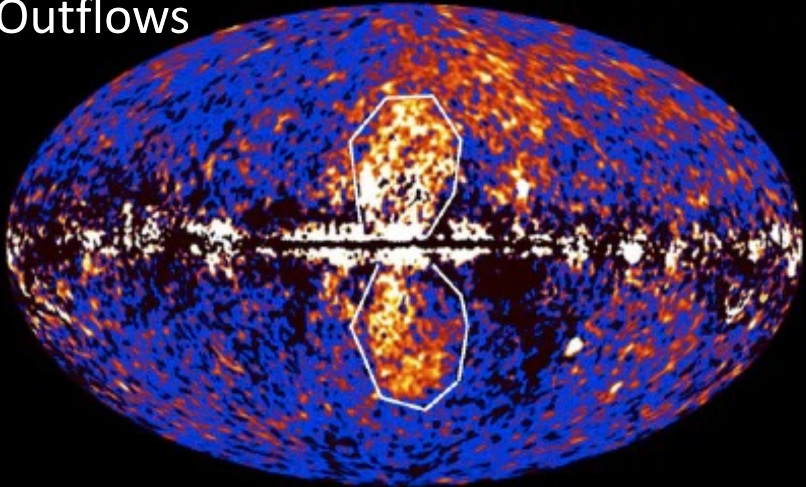



**➔ Multiple source classes injecting ~$10^{38}$ erg/s**

Pulsars



Outflows



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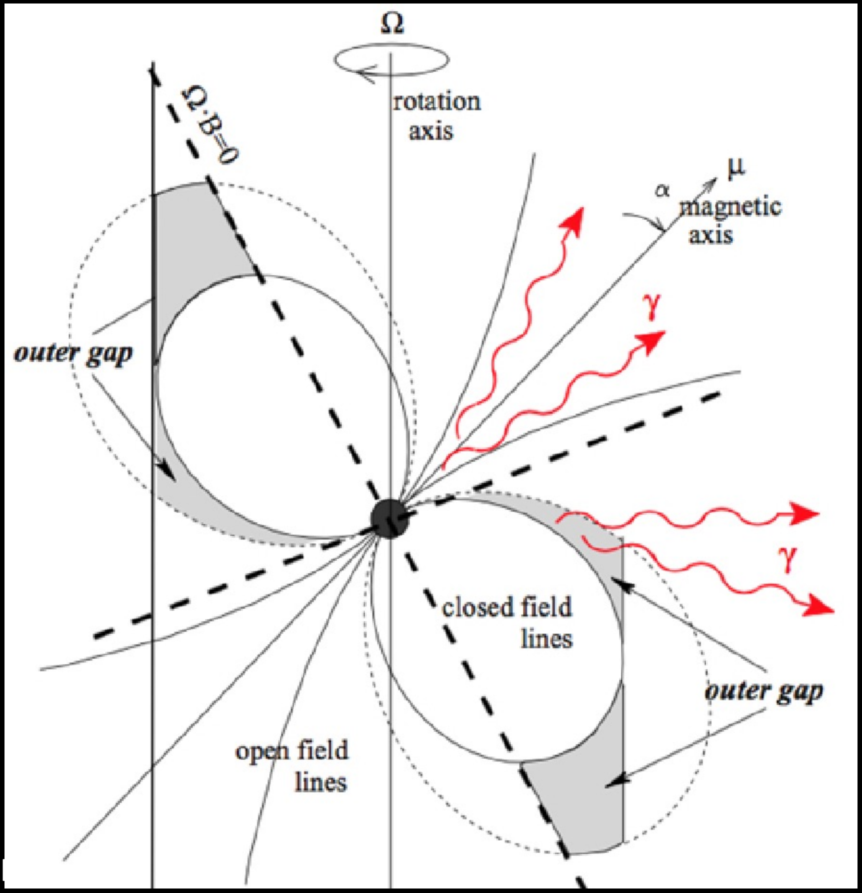
# Millisecond pulsars

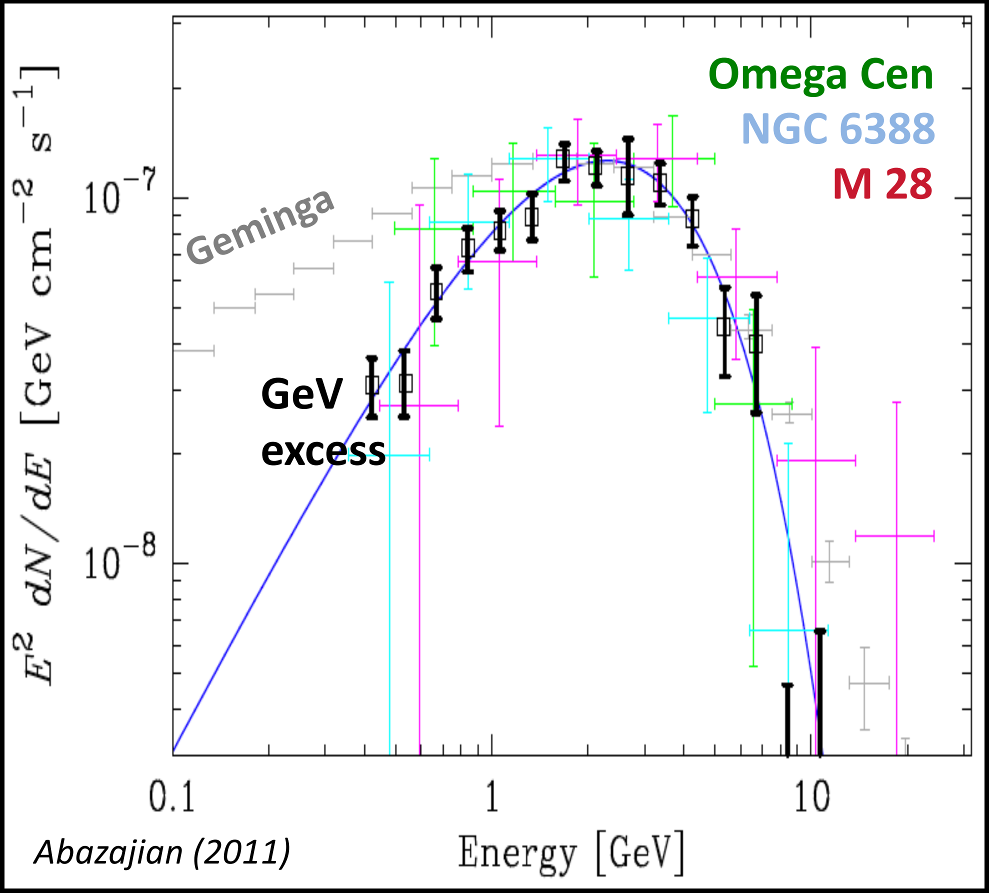
**A strongly motivated candidate**

- Rapidly spinning old neutron stars
  - Likely created by binary effects
- Known sources (100s found) but not modeled in the galactic center

✓ Spectra are very similar to the GeV excess

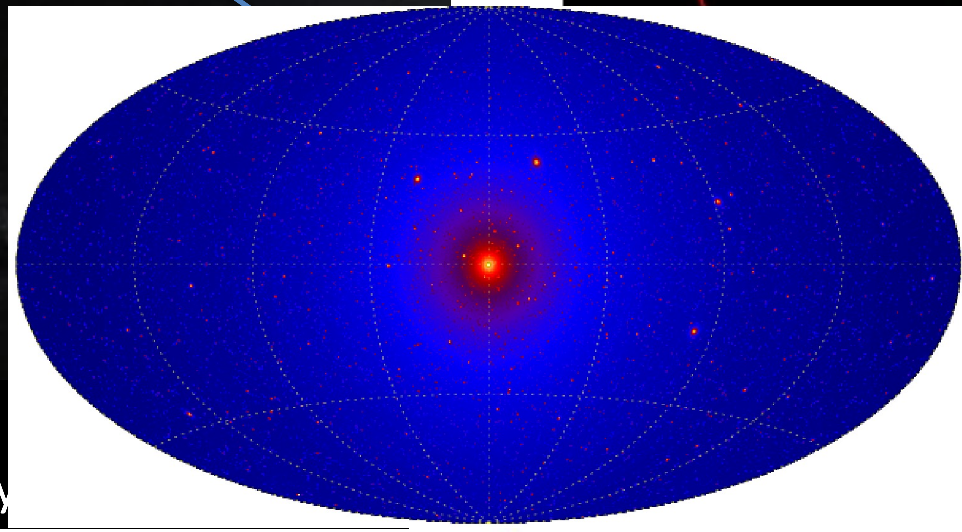
✓ *O*($10^4$) needed in the Galactic Center (quite reasonable)



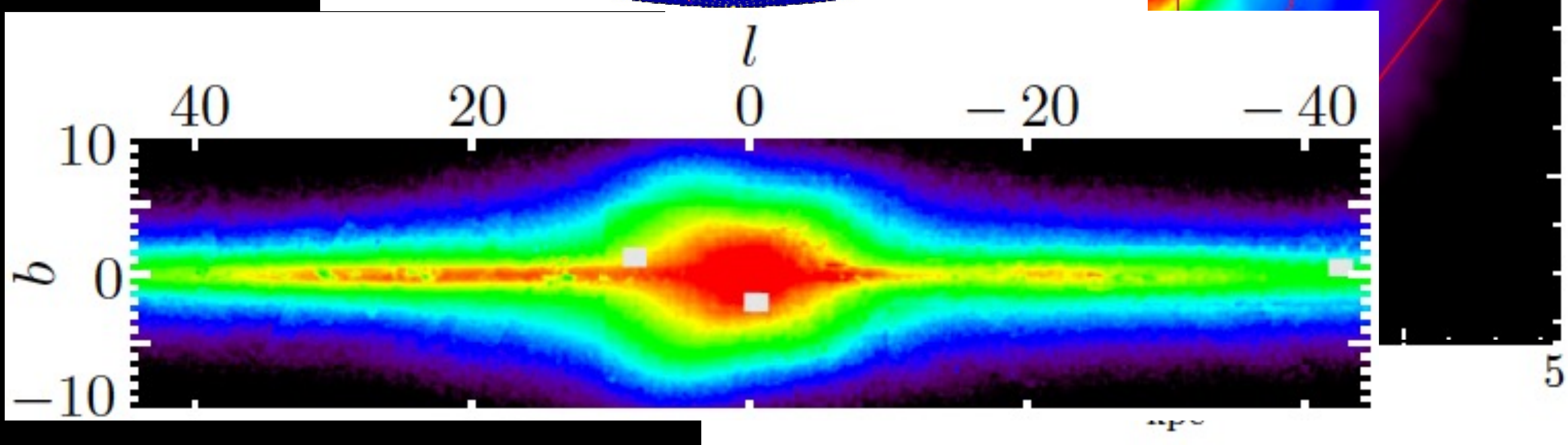



# Millisecond pulsar morphology

Bulge: ~1/3 mass of the Galaxy and very old (> 8 Gyrs)



The boxy bulge: ...
rectangle, not sy...

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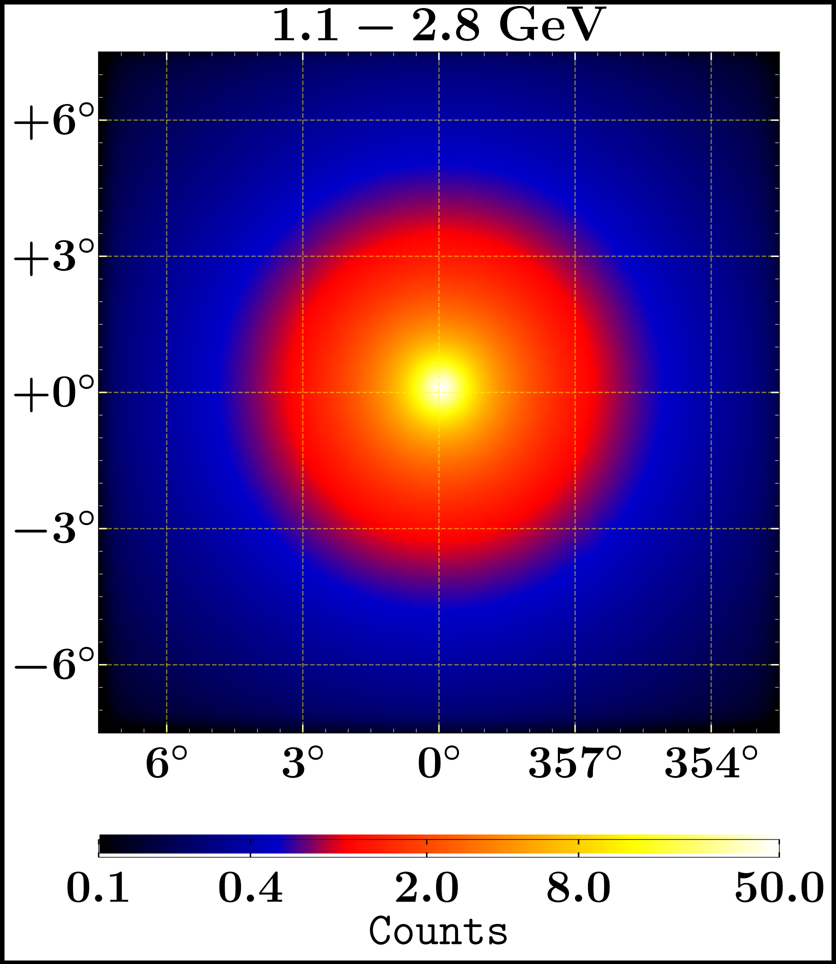
*Bland-Hawthorn & Gerhard (2017)*

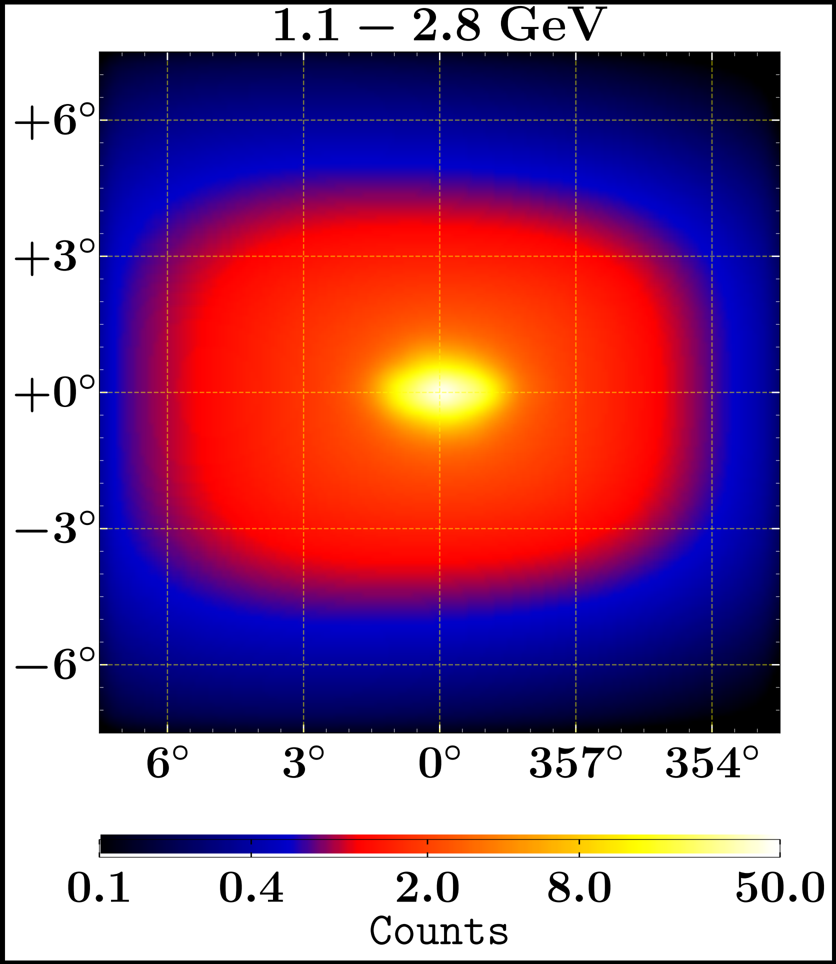
# *The hypothesis*

**Dark matter annihilation**




**VS**

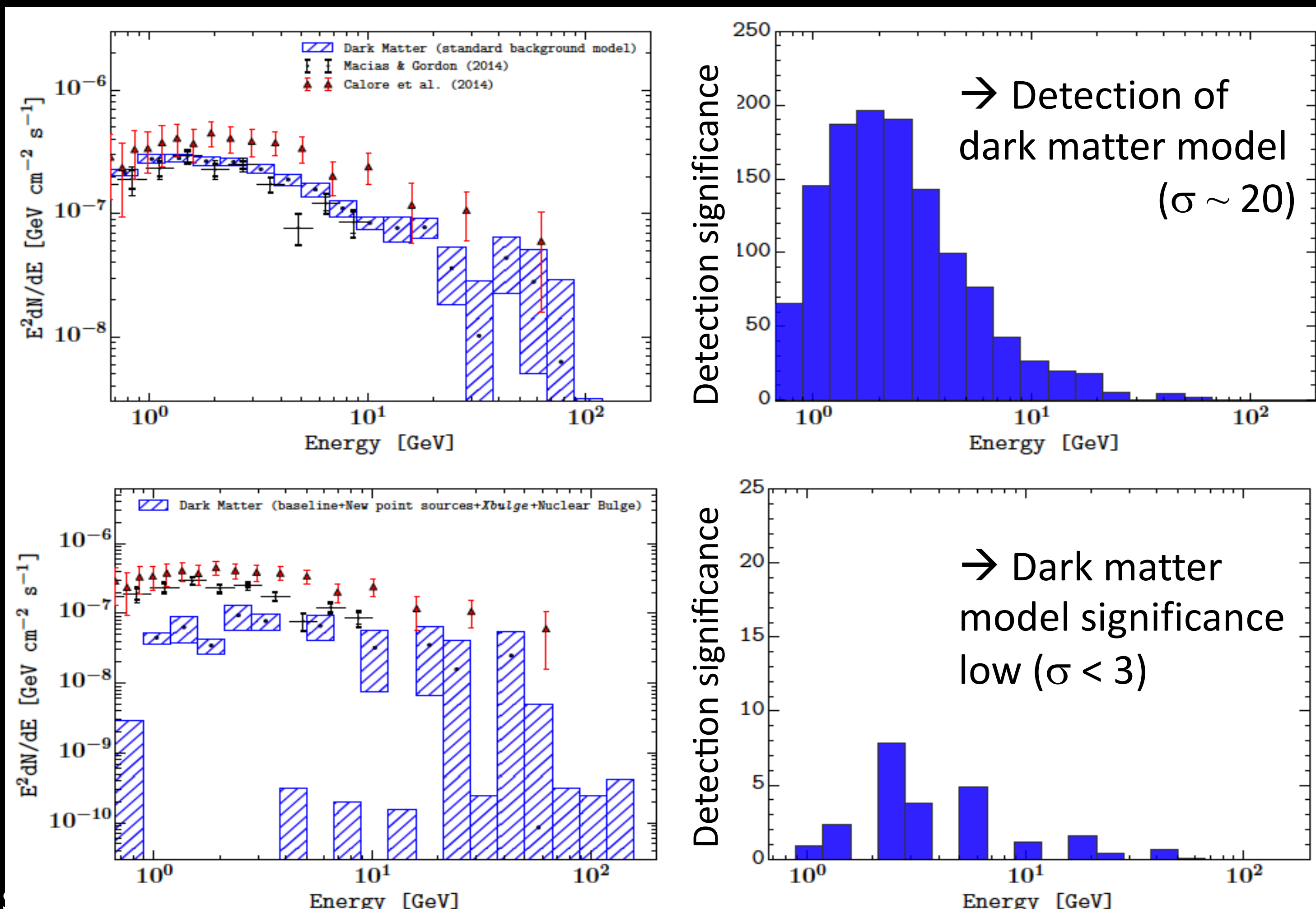
**Astrophysics (pulsar)**




(Here: Freudenreich 1998)

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)

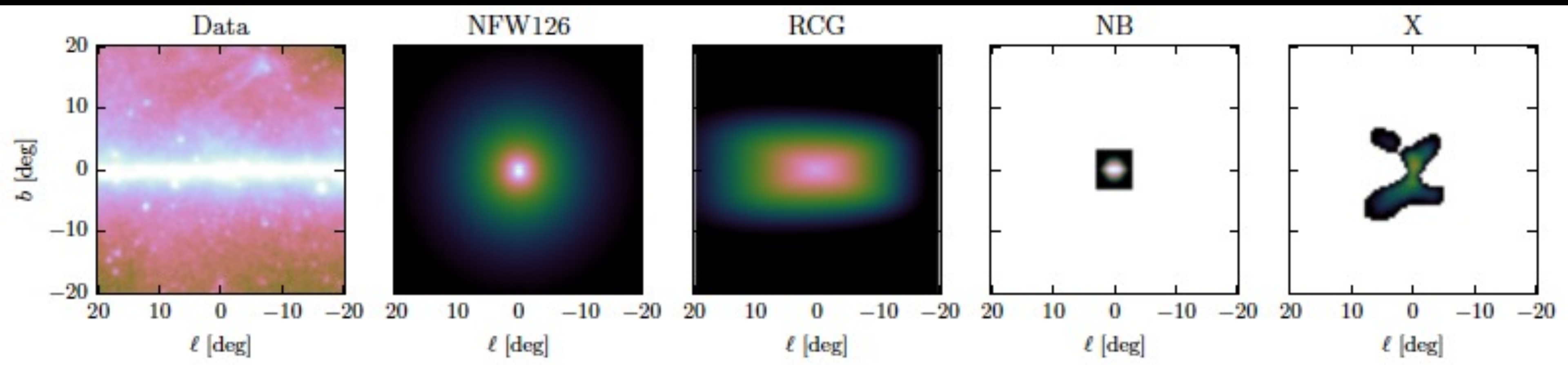
**← WITH bulge** Including our new extended bulge, the **data no longer needs a dark matter component**

# *SkyFACT : a hybrid approach*

SkyFACT = **Sky F**actorization with **A**daptive **C**onstrained **T**emplates

Hybrid method to study diffuse gamma rays that combines adaptive spatial-spectral template regression and image reconstruction to account for small-scale model inaccuracies.

*Storm et al (2017)*




> We demonstrated that the stellar bulge model provides a significantly better fit ($> 10\sigma$) to the data than the DM-emission related Einasto or contracted NFW profiles. Hence the GCE appears to simply trace stellar mass in the bulge, not the dark matter density squared

Fit in central 40x180 degrees, which facilitates the fitting of gas template rings (x3) and provides leverage to disentangle components.

*Bartels et al (2018)*

# Evidence for dark matter

| Base | Source | $\log(\mathcal{L}_{\rm Base})$ | $\log(\mathcal{L}_{\rm Base+Source})$ | $\mathrm{TS}_{\rm Source}$ | $\sigma$ | Number of source parameters |
|---|---|---|---|---|---|---|
| baseline | FB | -172461.4 | -172422.3 | 78 | 6.9 | 19 |
| baseline | NFW-s | -172461.4 | -172265.3 | 392 | 18.4 | 19 |
| baseline | Boxy bulge | -172461.4 | -172238.7 | 445 | 19.7 | 19 |
| baseline | X-bulge | -172461.4 | -172224.1 | 475 | 20.5 | 19 |
| baseline | NFW | -172461.4 | -172167.9 | 587 | 23.0 | 19 |
| baseline | NB | -172461.4 | -171991.8 | 939 | 29.5 | 19 |
| baseline | NP | -172461.4 | -169804.1 | 5315 | 55.7 | $64 \times 19$ |
| baseline+NP | FB | -169804.1 | -169773.6 | 61 | 5.8 | 19 |
| baseline+NP | NB | -169804.1 | -169697.2 | 214 | 13.0 | 19 |
| baseline+NP | Boxy bulge | -169804.1 | -169663.7 | 281 | 15.3 | 19 |
| baseline+NP | NFW | -169804.1 | -169623.3 | 362 | 17.6 | 19 |
| baseline+NP | X-bulge | -169804.1 | -169616.2 | 376 | 18.0 | 19 |
| baseline+NP+Boxy bulge | NFW | -169663.7 | -169598.2 | 131 | 9.7 | 19 |
| baseline+NP+Boxy bulge | NB | -169663.7 | -169566.0 | 195 | 12.4 | 19 |
| baseline+NP+Boxy bulge+NB | NFW | -169566.0 | -169553.3 | 25 | 2.7 | 19 |
| baseline+NP+Boxy bulge+NFW | NB | -169598.2 | -169553.3 | 90 | 7.6 | 19 |
| baseline+NP+NFW | Boxy bulge+NB | -169623.3 | -169553.0 | 140 | 10.0 | $2 \times 19$ |
| baseline+NP+NFW | X-bulge+NB | -169623.3 | -169531.0 | 185 | 10.8 | $2 \times 19$ |
| baseline+NP+NB | X-bulge | -169697.2 | -169542.0 | 310 | 16.1 | 19 |
| baseline+NP+NB | Boxy bulge | -169697.2 | -169566.0 | 262 | 14.6 | 19 |
| baseline+NP+NB | NFW | -169697.2 | -169599.0 | 197 | 12.4 | 19 |
| baseline+NP+NB+NFW | X-bulge | -169598.9 | -169531.0 | 136 | 9.9 | 19 |
| baseline+NP+X-bulge+NB | NFW | -169542.0 | -169531.0 | 22 | 2.4 | 19 |

Gas + IC
+ sources
+ Loop I
+ Sun & Moon

**➔ NFW detected at low significance when bulge is included**

*Macias et al (2018)*

# Evidence for dark matter

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| baseline+NP+Boxy bulge+NFW | NB | -169598.2 | -169553.3 | 90 | 7.6 | 19 |
| baseline+NP+NFW | Boxy bulge+NB | -169623.3 | -169553.0 | 140 | 10.0 | $2 \times 19$ |
| baseline+NP+NFW | X-bulge+NB | -169623.3 | -169531.0 | 185 | 10.8 | $2 \times 19$ |
| baseline+NP+NB | X-bulge | -169697.2 | -169542.0 | 310 | 16.1 | 19 |
| baseline+NP+NB | Boxy bulge | -169697.2 | -169566.0 | 262 | 14.6 | 19 |
| baseline+NP+NB | NFW | -169697.2 | -169599.0 | 197 | 12.4 | 19 |
| baseline+NP+NB+NFW | X-bulge | -169598.9 | -169531.0 | 136 | 9.9 | 19 |
| baseline+NP+X-bulge+NB | NFW | -169542.0 | -169531.0 | 22 | 2.4 | 19 |

baseline = Gas + IC + sources + Loop I + Sun & Moon

**➔ NFW detected at low significance when bulge is included**

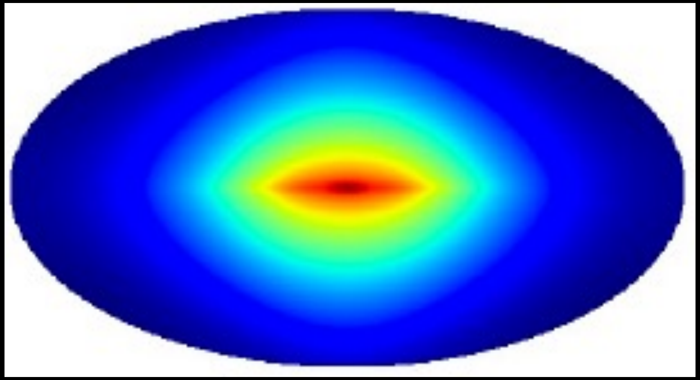
*Macias et al (2018)*

# *Background systematics*

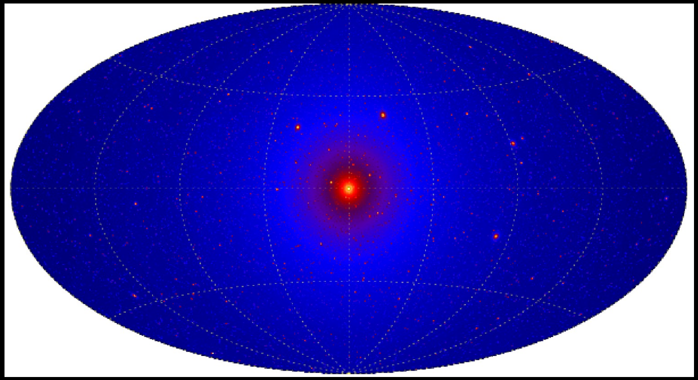
**Many astrophysical systematics**

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

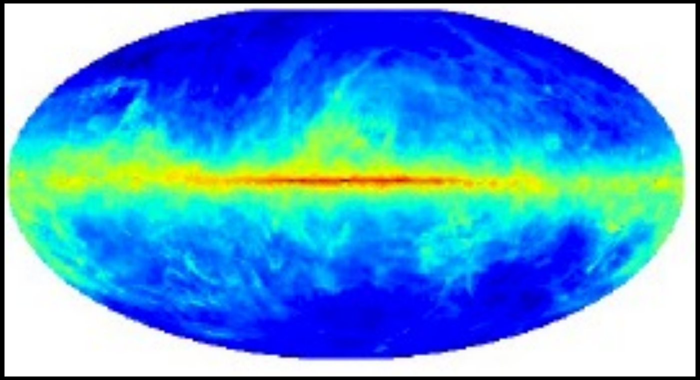
IC



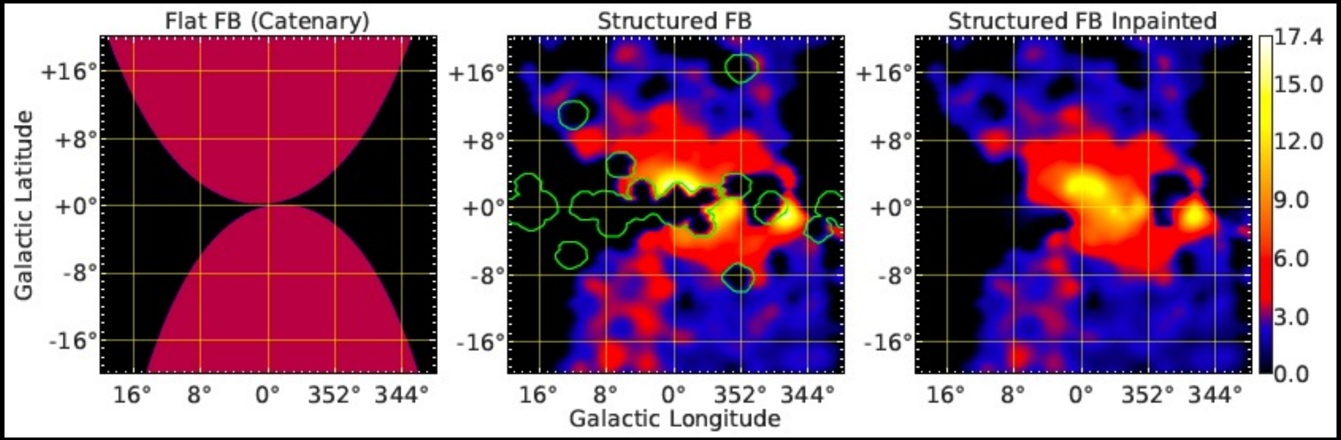
Dark matter



gas



Fermi bubble

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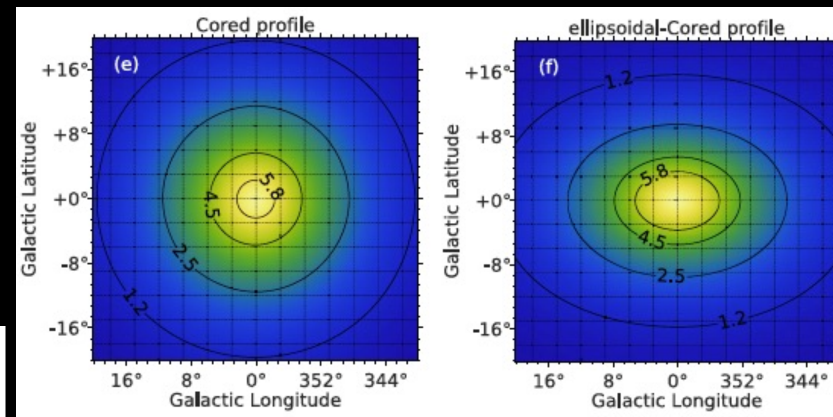
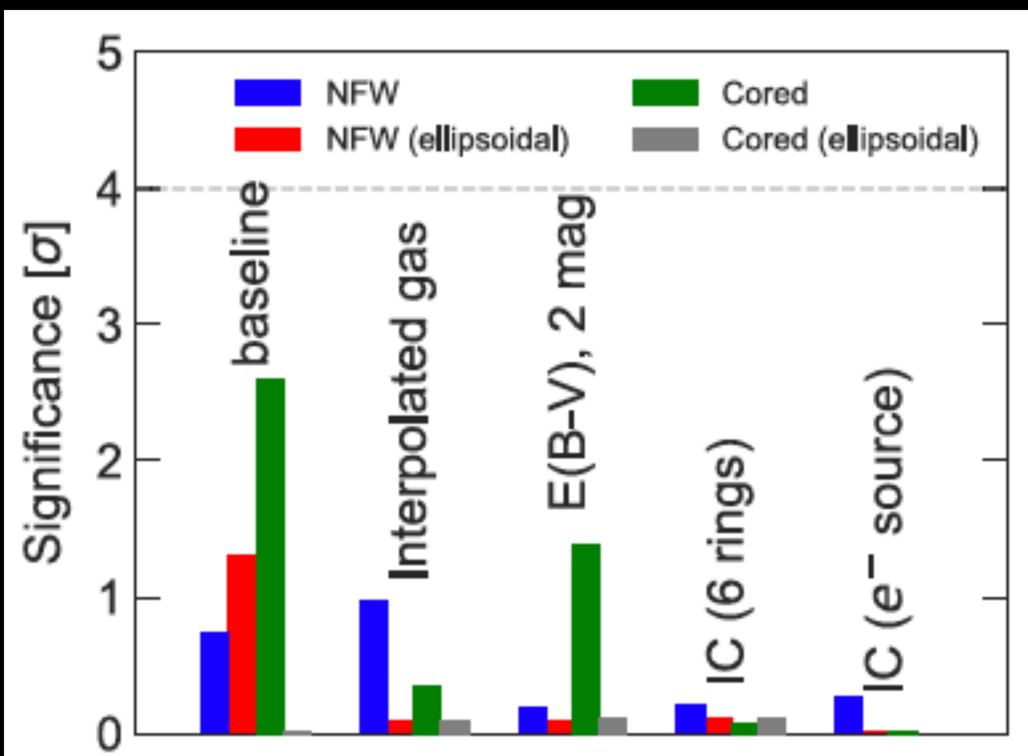
# *Some systematics*

**For example:**

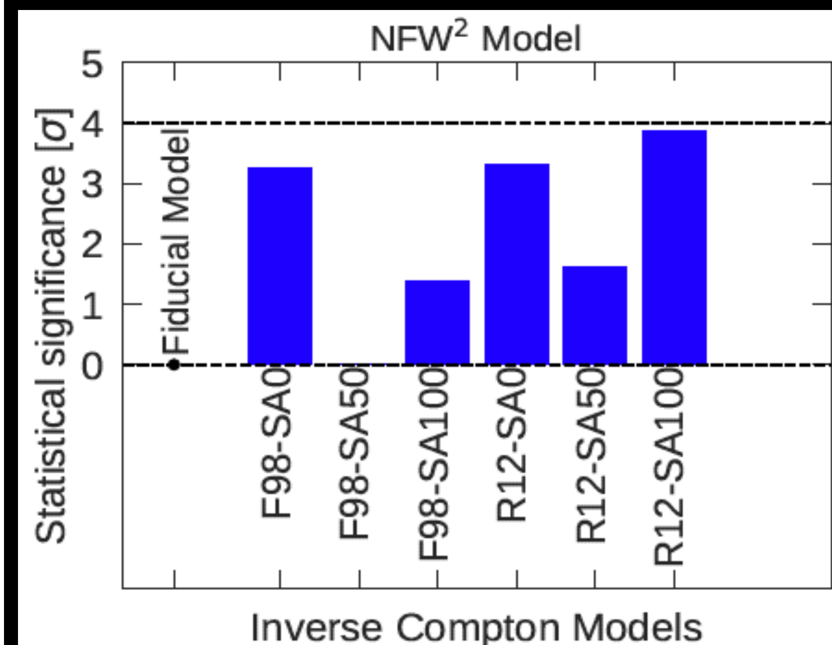
1. IC: photon distributions, $e^{+/-}$ distributions
2. Dark matter: slope, cores, asymmetry
3. Gas: distributions, dark gas models
4. Bulge: different tracers

**➔ Dark matter model not detected**



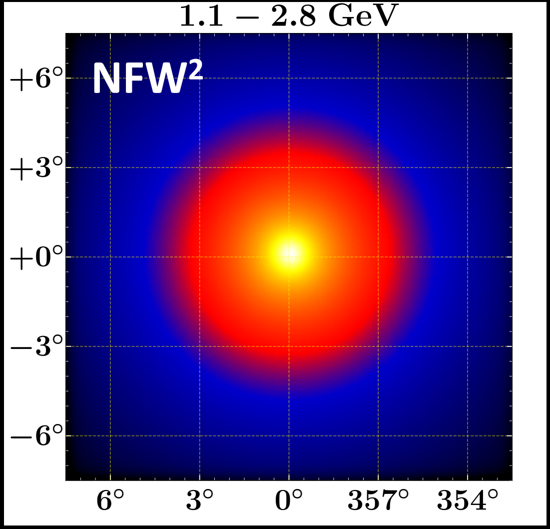

*Abazajian, Horiuchi, et al (2020)*



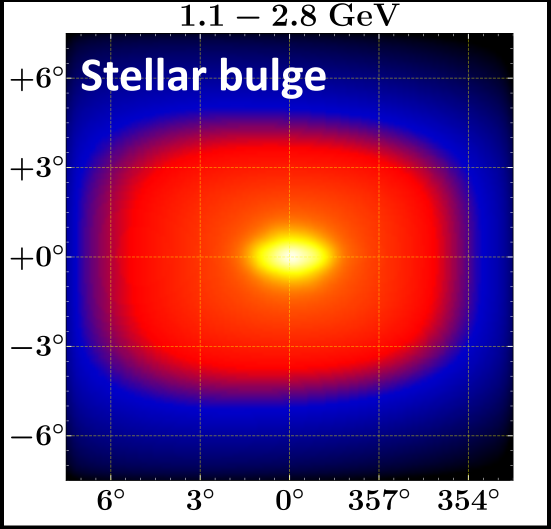

*Macias, Horiuchi et al (2018, 2019)*

# *Hypotheses*

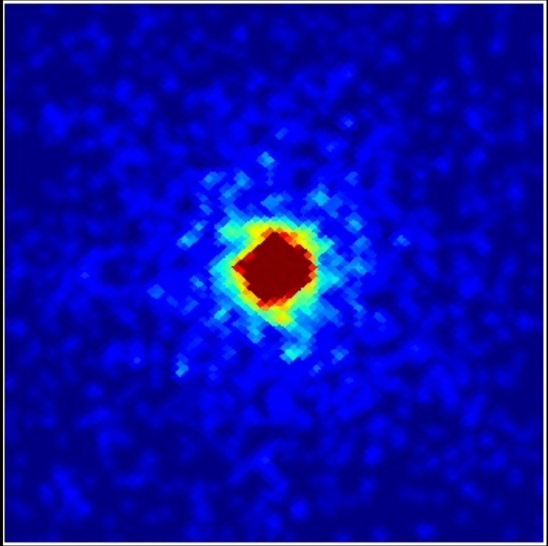
**Dark matter annihilation**



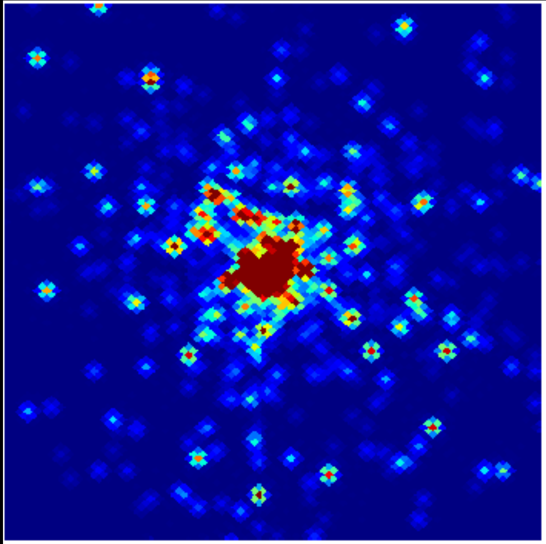

**Astrophysics (pulsar)**




**VS**



**VS**



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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

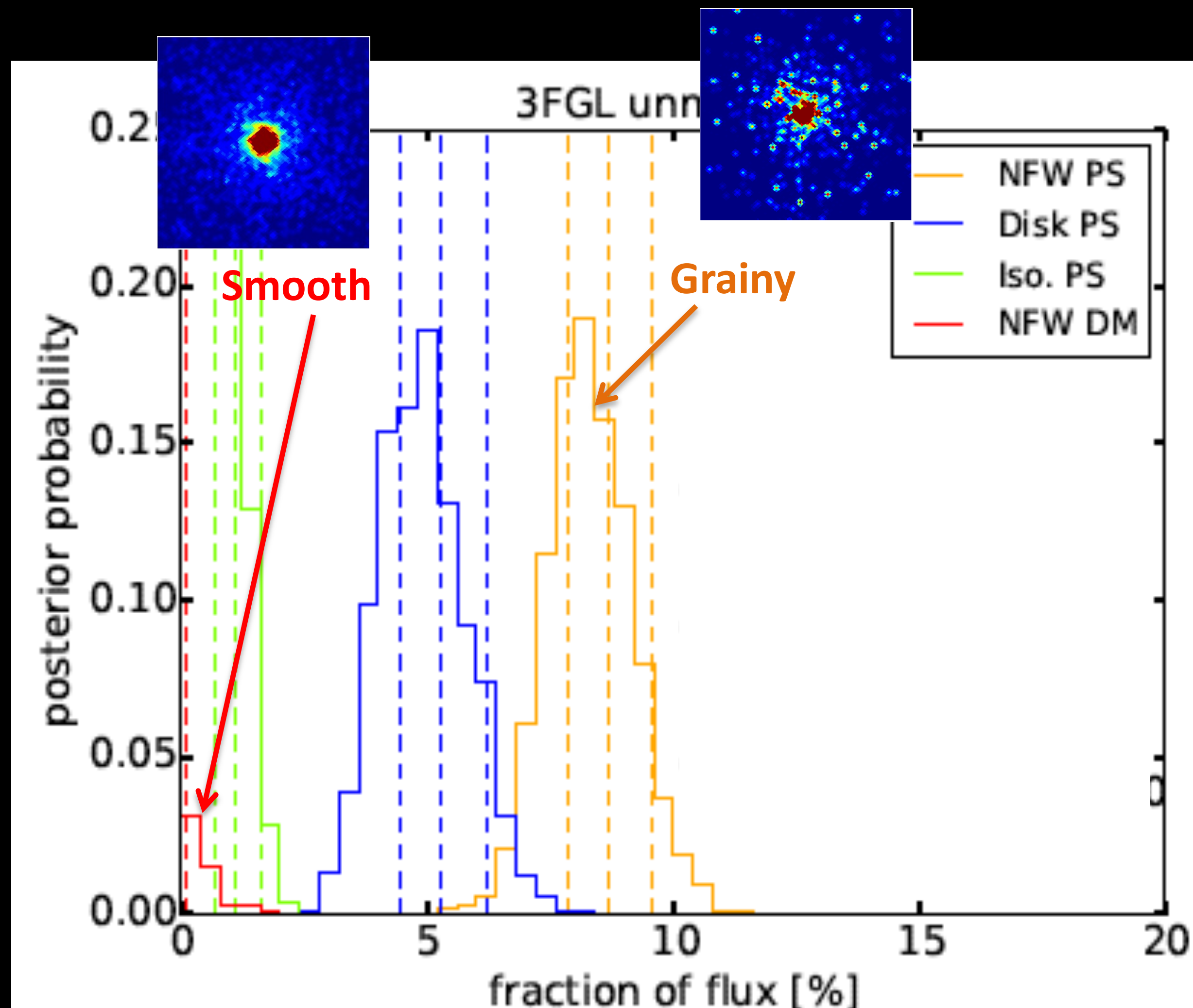
Results:
- Smooth: ~0%
- Grainy: ~8.7%

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

➔ **Preference for grainy over smooth source**

➔ **Grainy motivates faint pulsars**

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

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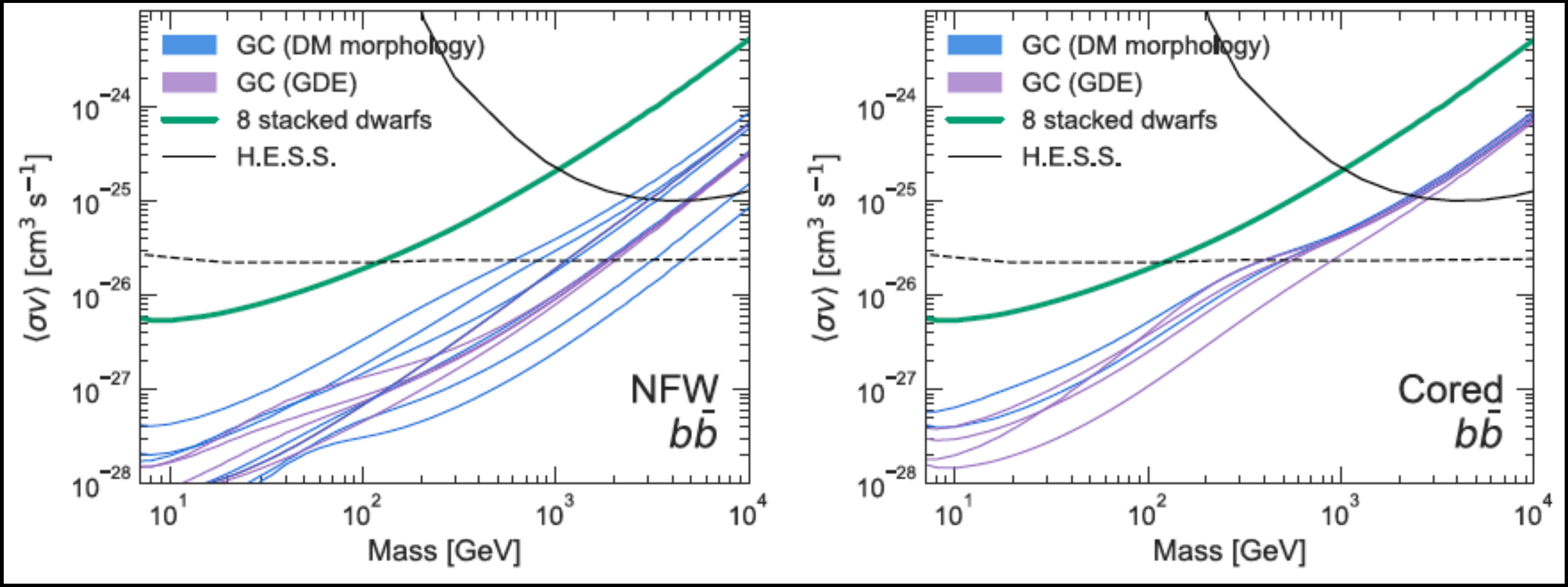
# *Dark matter implications*

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

**➔ 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

# *However…*

*PRL 123 (2019) 241101*

**Dark Matter Strikes Back at the Galactic Center**

Rebecca K. Leane[1,*] and Tracy R. Slatyer[1,2,†]

[1] *Center for Theoretical Physics, Massachusetts Institute of Technology, Cambridge, MA 02139, USA*
[2] *School of Natural Sciences, Institute for Advanced Study, Einstein Drive, Princeton, NJ 08540, USA*



**A Phantom Menace: On the Morphology of the Galactic Center Excess**

Samuel D. McDermott,[1] Yi-Ming Zhong,[2] and Ilias Cholis[3]

[1] *Fermi National Accelerator Laboratory, Batavia, Illinois, 60510, USA*
[2] *Kavli Institute for Cosmological Physics, University of Chicago, Chicago, IL 60637, USA*
[3] *Department of Physics, Oakland University, Rochester, Michigan, 48309, USA*

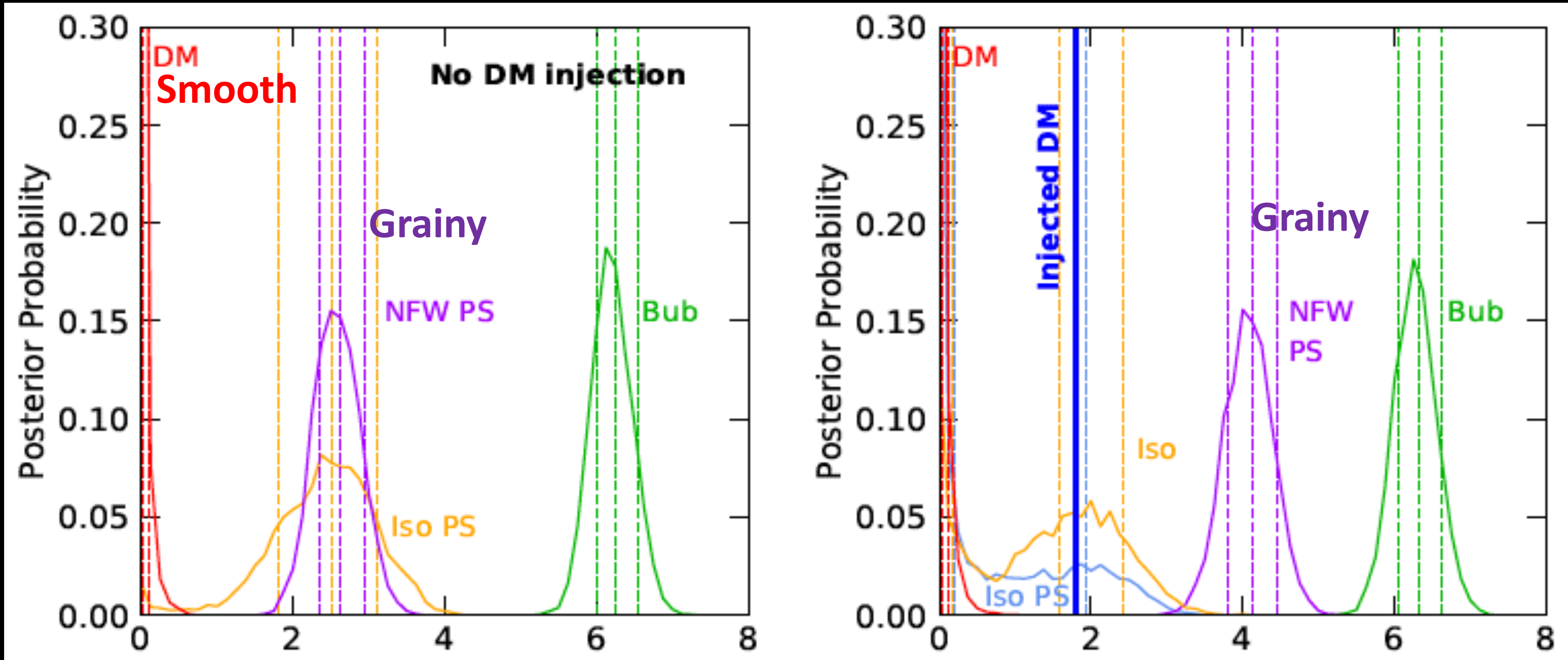
*arXiv:2209.00006*

# *Ongoing developments*

**Smooth vs grainy**

Faint end is experimentally indistinguishable from a smooth source.

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




*Leane & Slatyer (2019, 2020)*

**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)*

# *STORY OF THREE LINES*

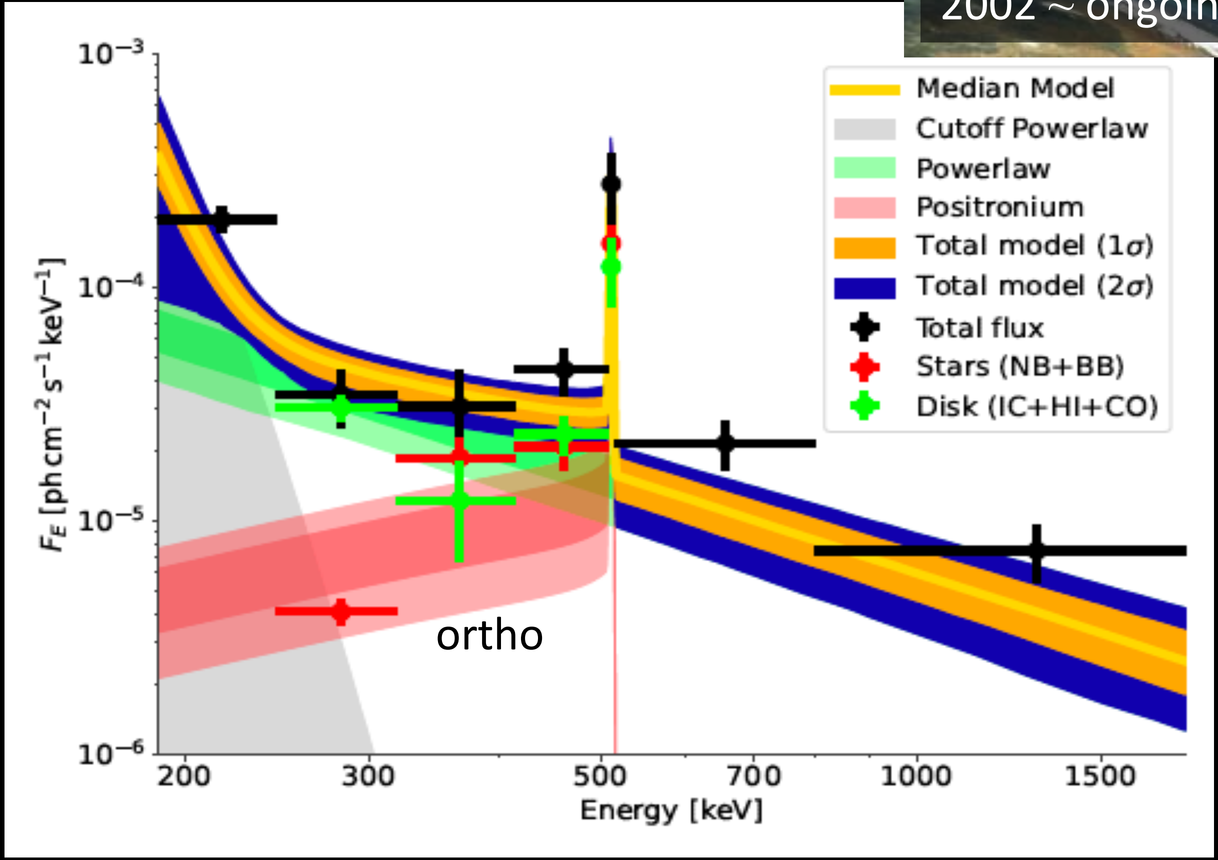
Shunsaku Horiuchi

# *511 keV excess*

**Excess:** Strong signal of positronium decays seen by INTEGRAL (requires ~$2\times10^{43}$ e+ /s)


**Relative to:** various astrophysical sources in the Milky Way

- Supernovae
- $\gamma$-ray burst
- Microquasars
- X-ray binaries
- NS mergers

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

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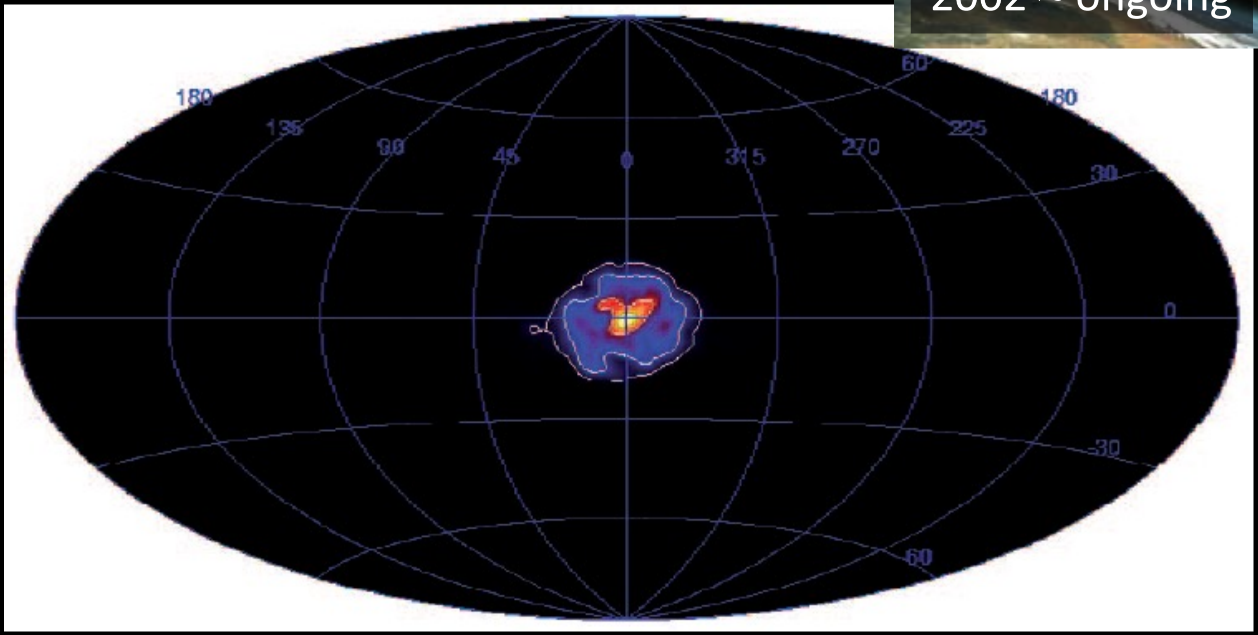
**Relative to:** various astrophysical sources in the Milky Way

Supernovae
$\gamma$-ray burst
Microquasars
X-ray binaries
NS mergers

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

- Bulge / disk ~ 1
- But predicted < 0.5




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

Maybe a dark matter related phenomenon *e.g., Boehm et al (2004), Finkbeiner & Weiner (2007)*

# *Detailed morphology study*

Which model combinations best describe the data?

| Map | Process/Population |
|---|---|
| BB | stars (1.25–4.9 $\mu$m) |
| NB | stars (2.2–240 $\mu$m) |
| XB | stars (3.4–4.6 $\mu$m) |
| IC | $e^{\pm} + \gamma \rightarrow e^{\pm} + \gamma$ |
| CO | CO, J = 1 $\rightarrow$ 0 at 115 GHz |
| HI | H, F = 1 $\rightarrow$ 0 at 21 cm |
| DM0 | Dark matter, $\rho^2_{\rm NFW}(\gamma = 1.0)$ |
| DM2 | Dark matter, $\rho^2_{\rm NFW}(\gamma = 1.2)$ |
| FB | Fermi Bubbles (GeV) |

*Siegert et al (2021)*

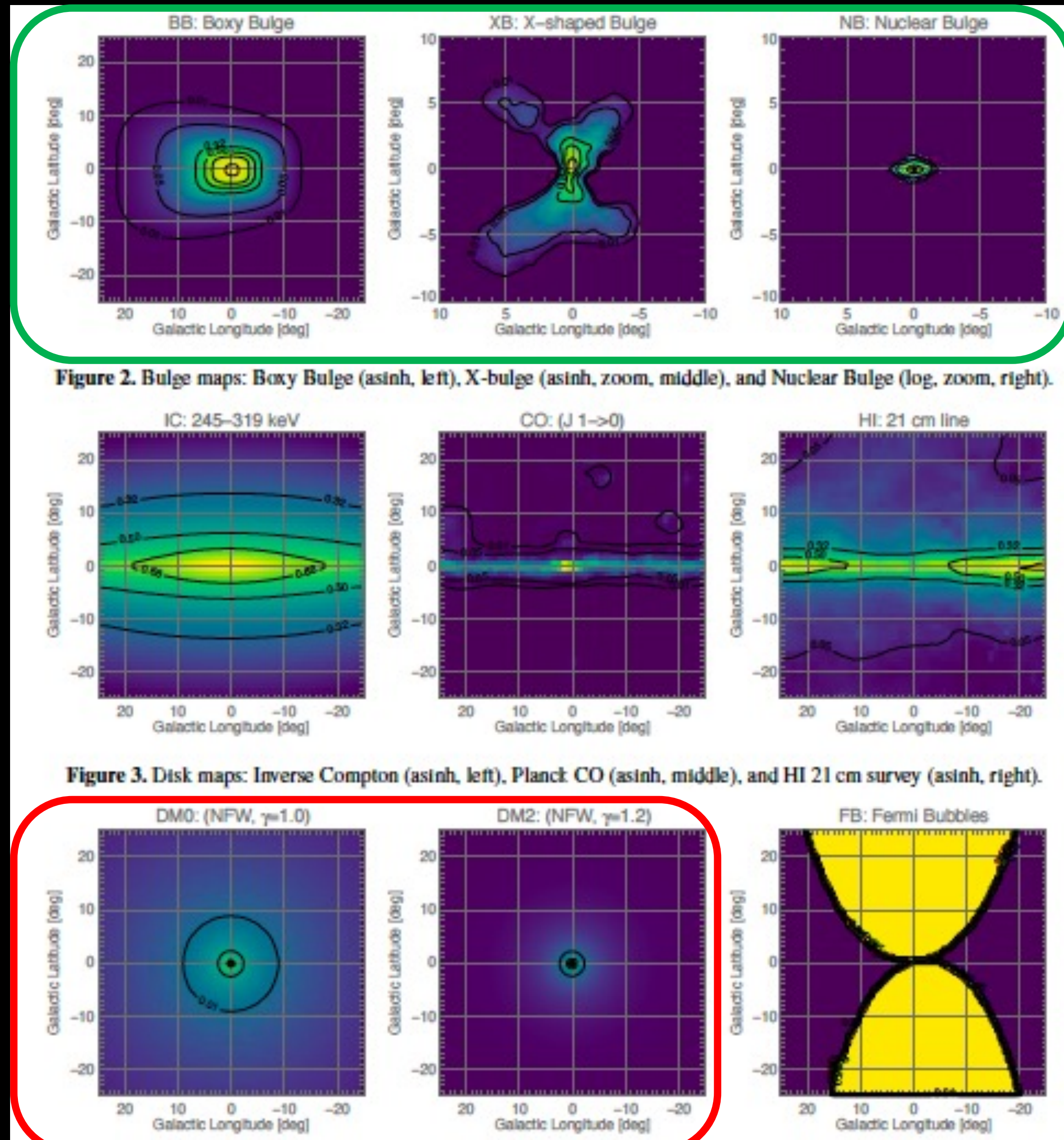



**Figure 2.** Bulge maps: Boxy Bulge (asinh, left), X-bulge (asinh, zoom, middle), and Nuclear Bulge (log, zoom, right).

**Figure 3.** Disk maps: Inverse Compton (asinh, left), Planck CO (asinh, middle), and HI 21 cm survey (asinh, right).

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# *Detailed morphology study*

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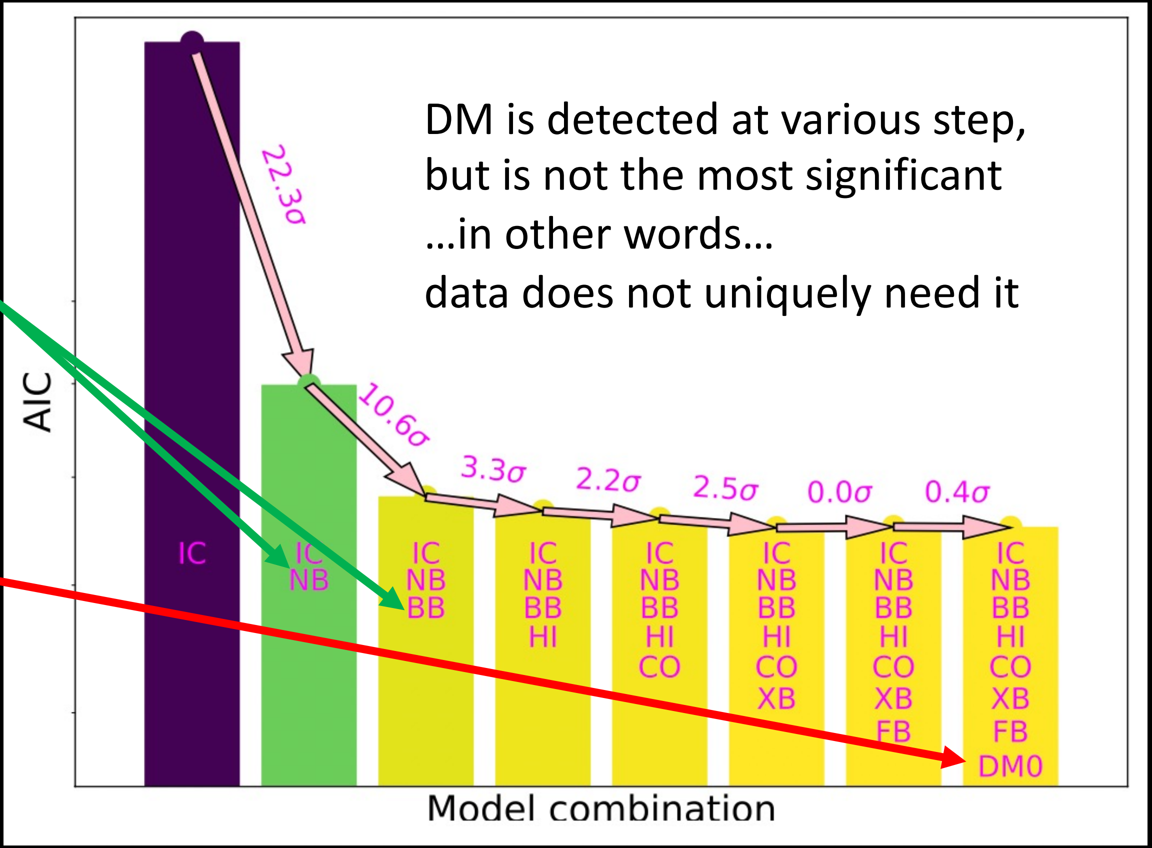
*Siegert et al (2021)*

Add sources sequentially:




**Parallels with GeV excess:**

- When mutually exclusive, dark matter and bulge are both detected
- When simultaneously added, the dark matter significance become negligible

***→ Better astrophysical model*** provides a good description of the data and excludes a symmetric DM model

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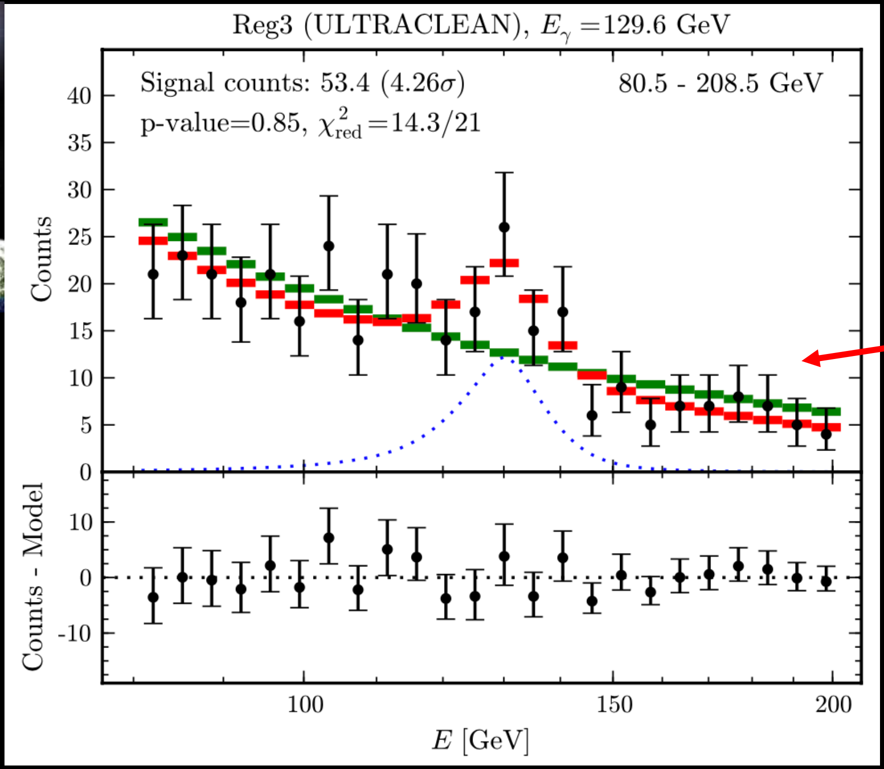
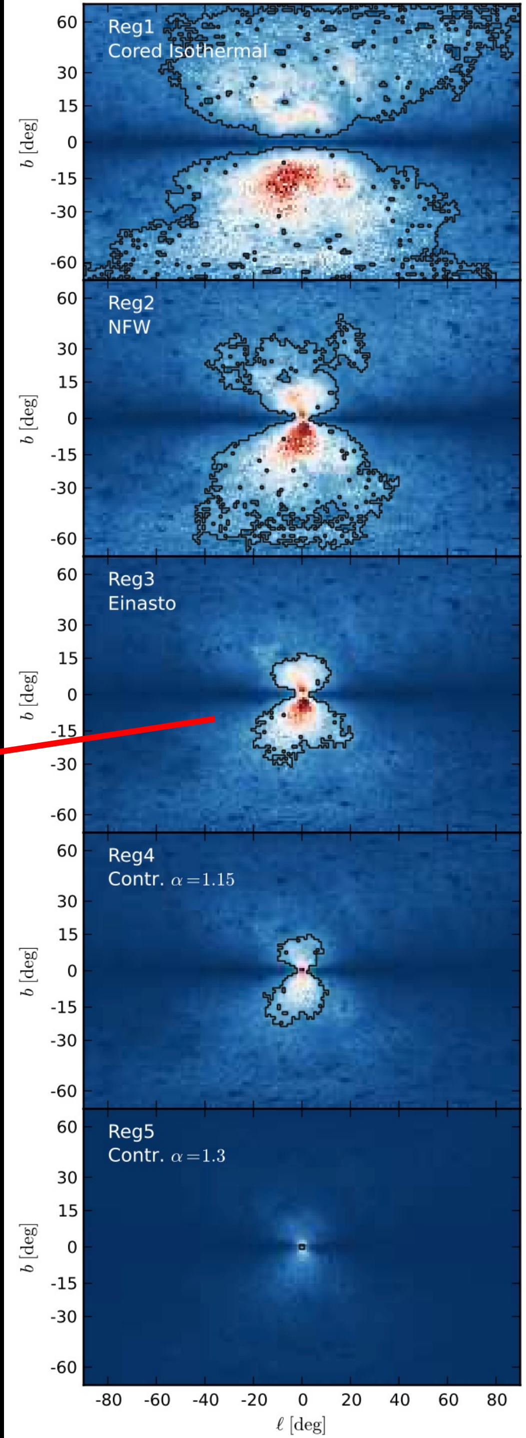
# *Gamma-ray line*

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

*Weniger (2012)*




Significance: 3.2σ (after trials factor)

Subsequently observed in galaxy clusters and unassociated LAT sources too.

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

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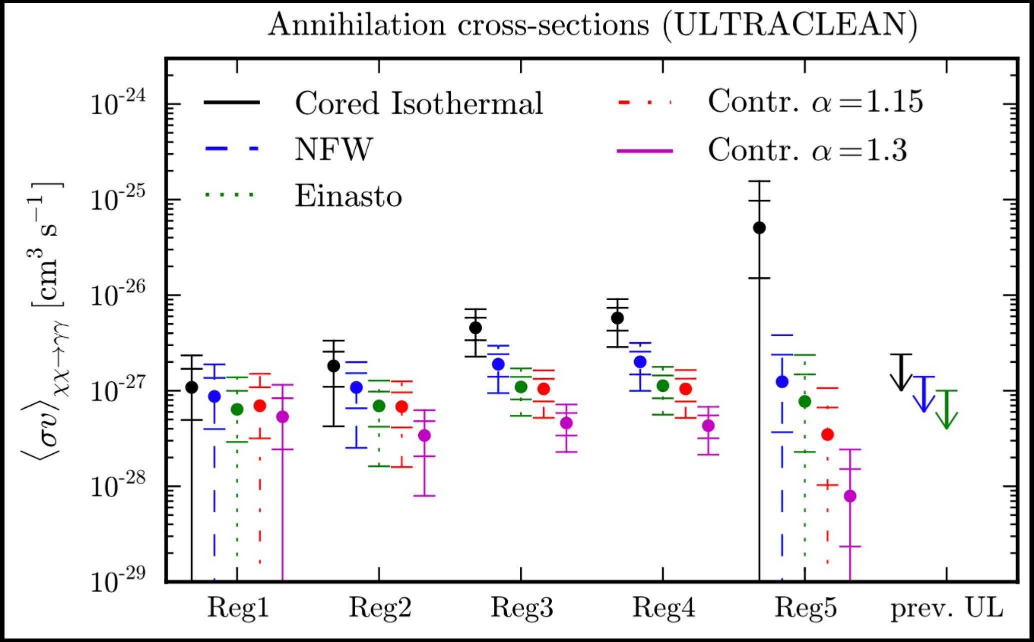
# *Origin of the 130 GeV line*

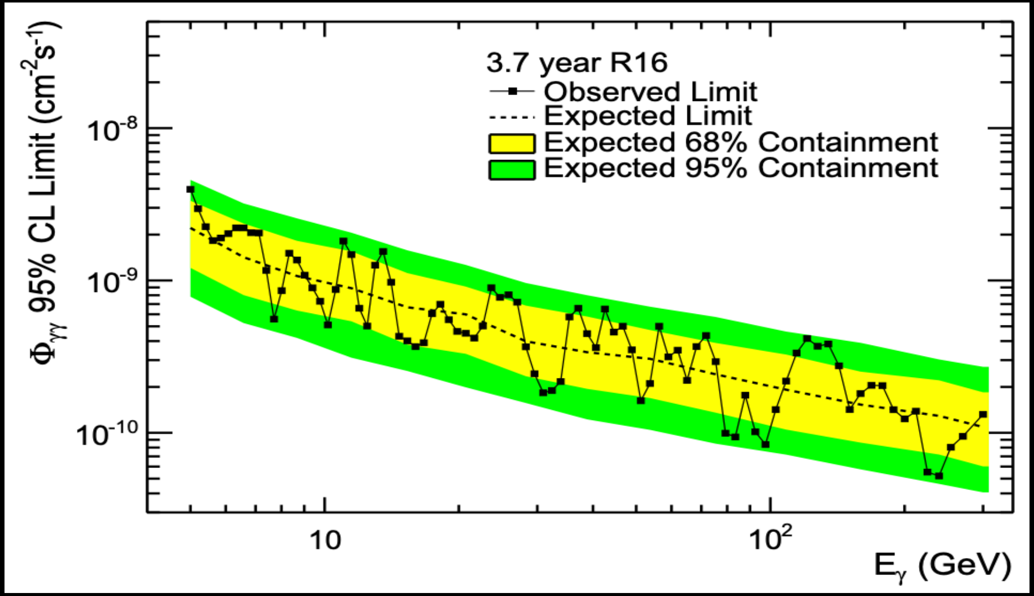
If interpreted as dark matter →

*Weniger (2012)*




However, ultimately the line disappeared:
***updated understanding of detector calibration***

*Fermi collab. (2014)*

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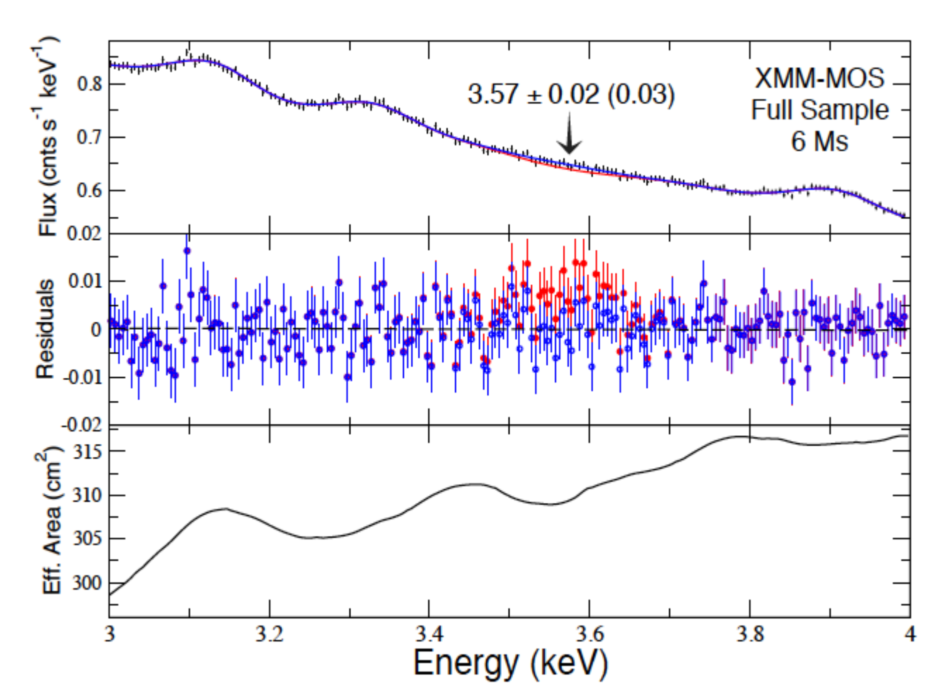
# X-ray lines

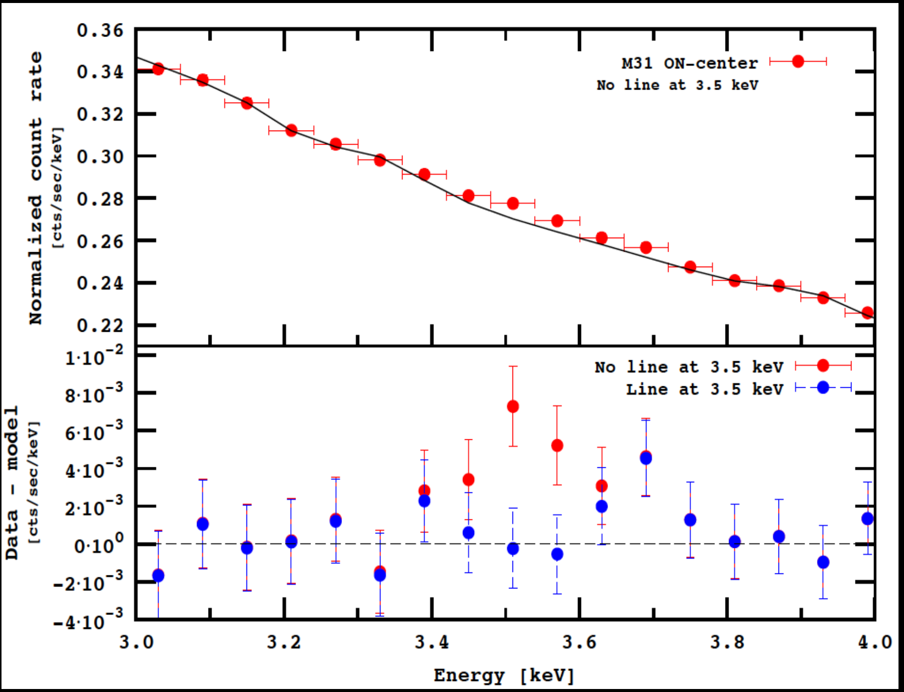
**Line:** X-ray regime contains many atomic transition lines, but unexpected lines are sometimes found

$E_{\gamma} = 3.5$ 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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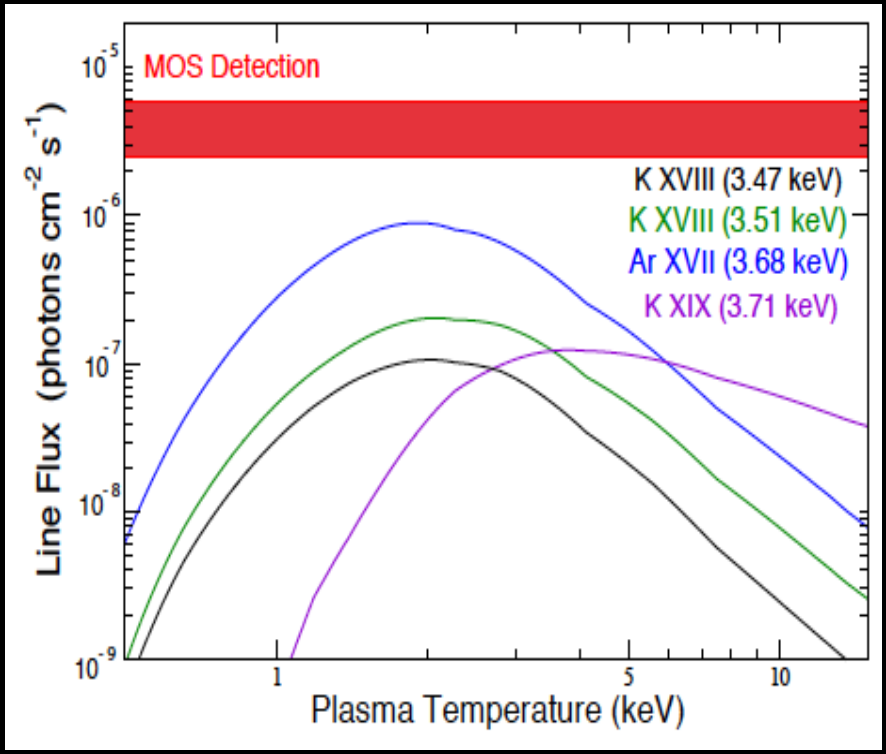
# Metal line origin?

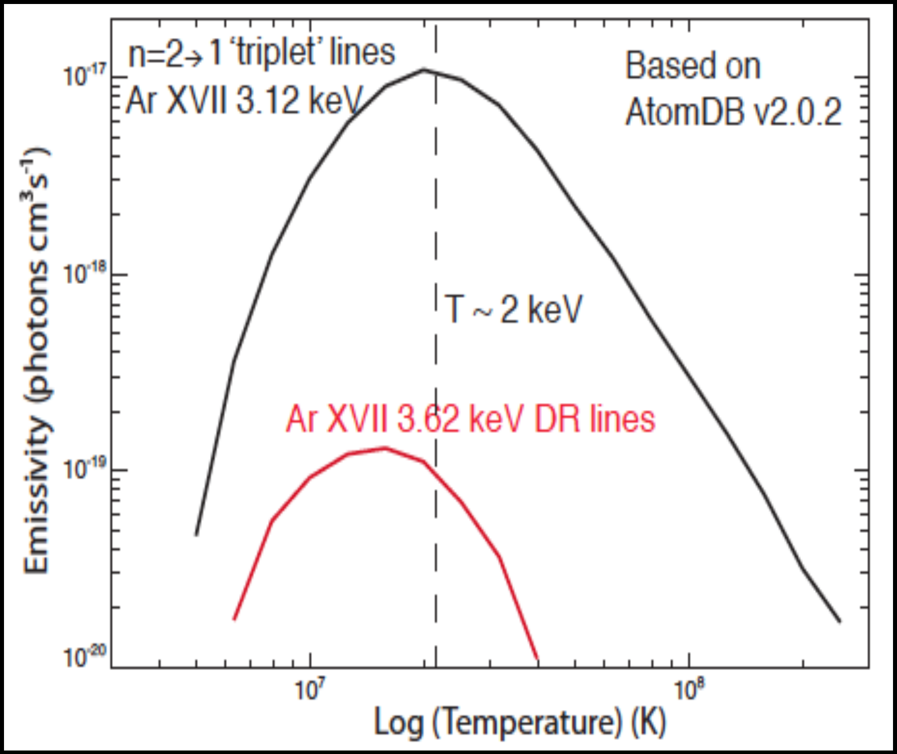
**Relative to:** modeling the complex atomic line emissions of the plasma.
The line is difficult to explain with current models.

*Bulbul et al (2014)*



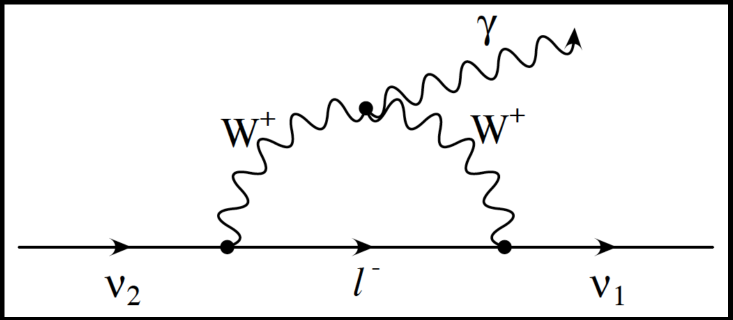

Fluxes of known lines in the 3.5 keV energy range are too small for typical plasma temperatures

*Bulbul et al (2014)*




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

# *Is it dark matter?*

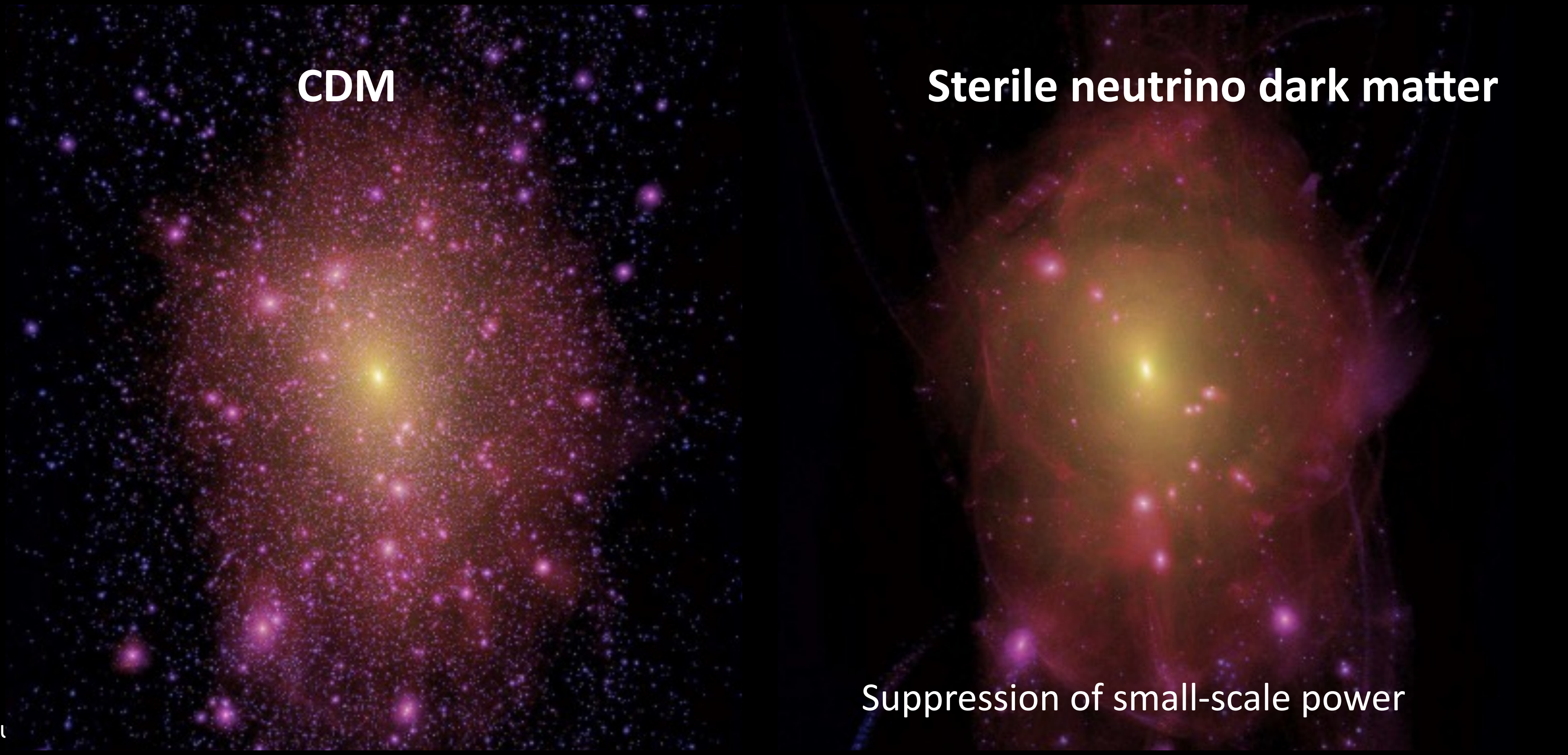



**keV sterile neutrino dark matter:** can radiatively decay to active neutrinos + X-ray

$$E_\gamma = m_s/2$$

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

*Abazajian (2014)*



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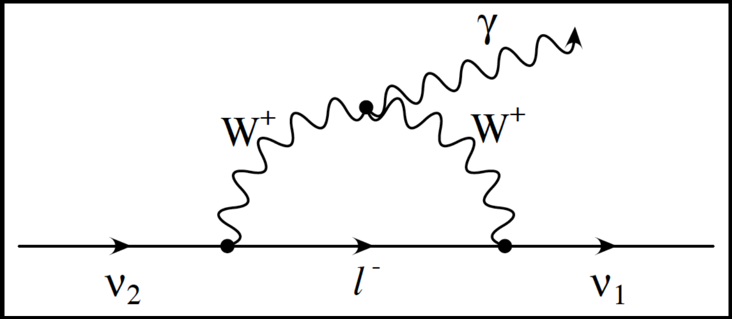


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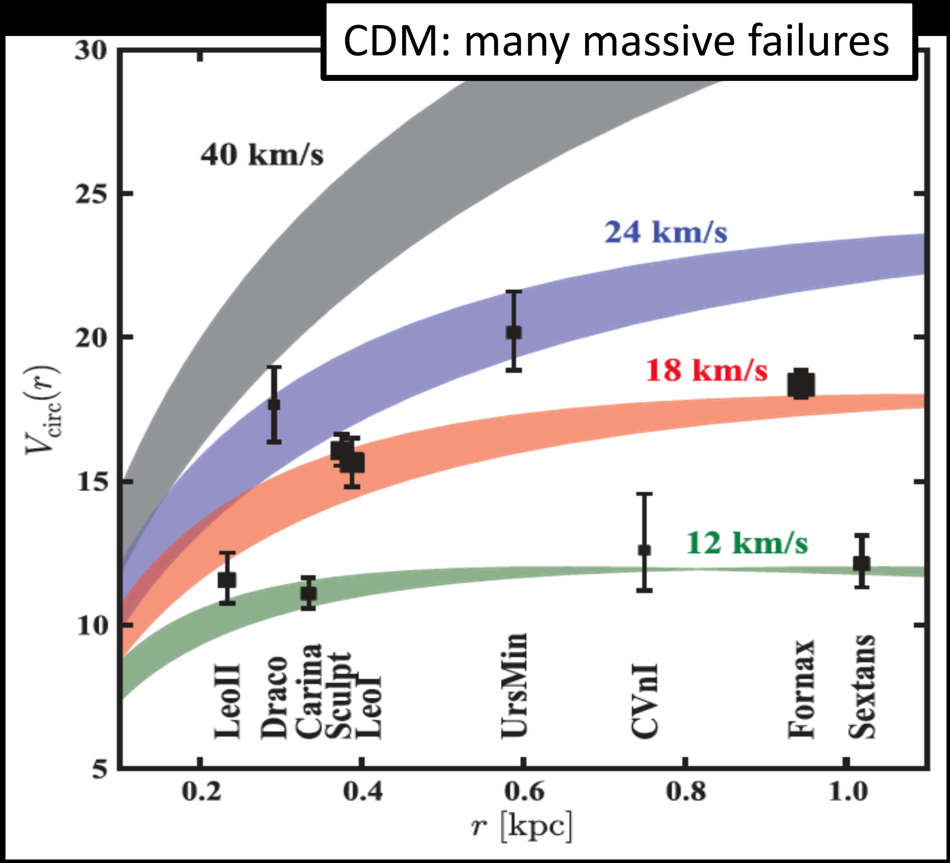


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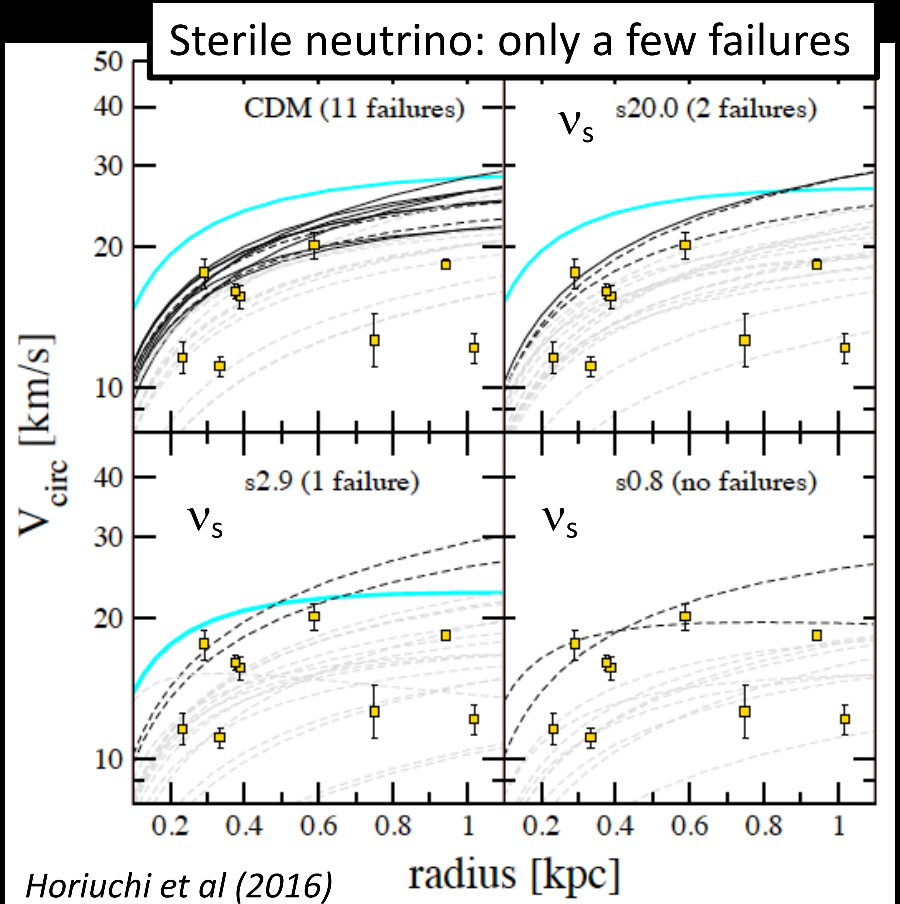
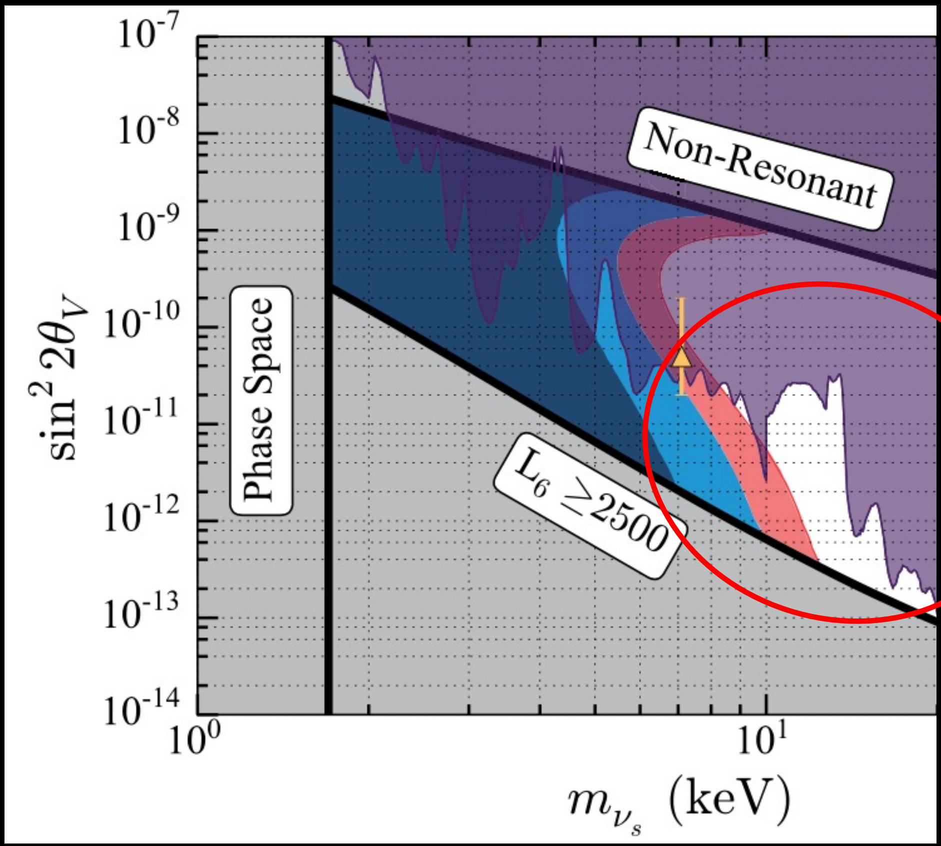
*Boylan-kolchin et al (2011, 2012)*

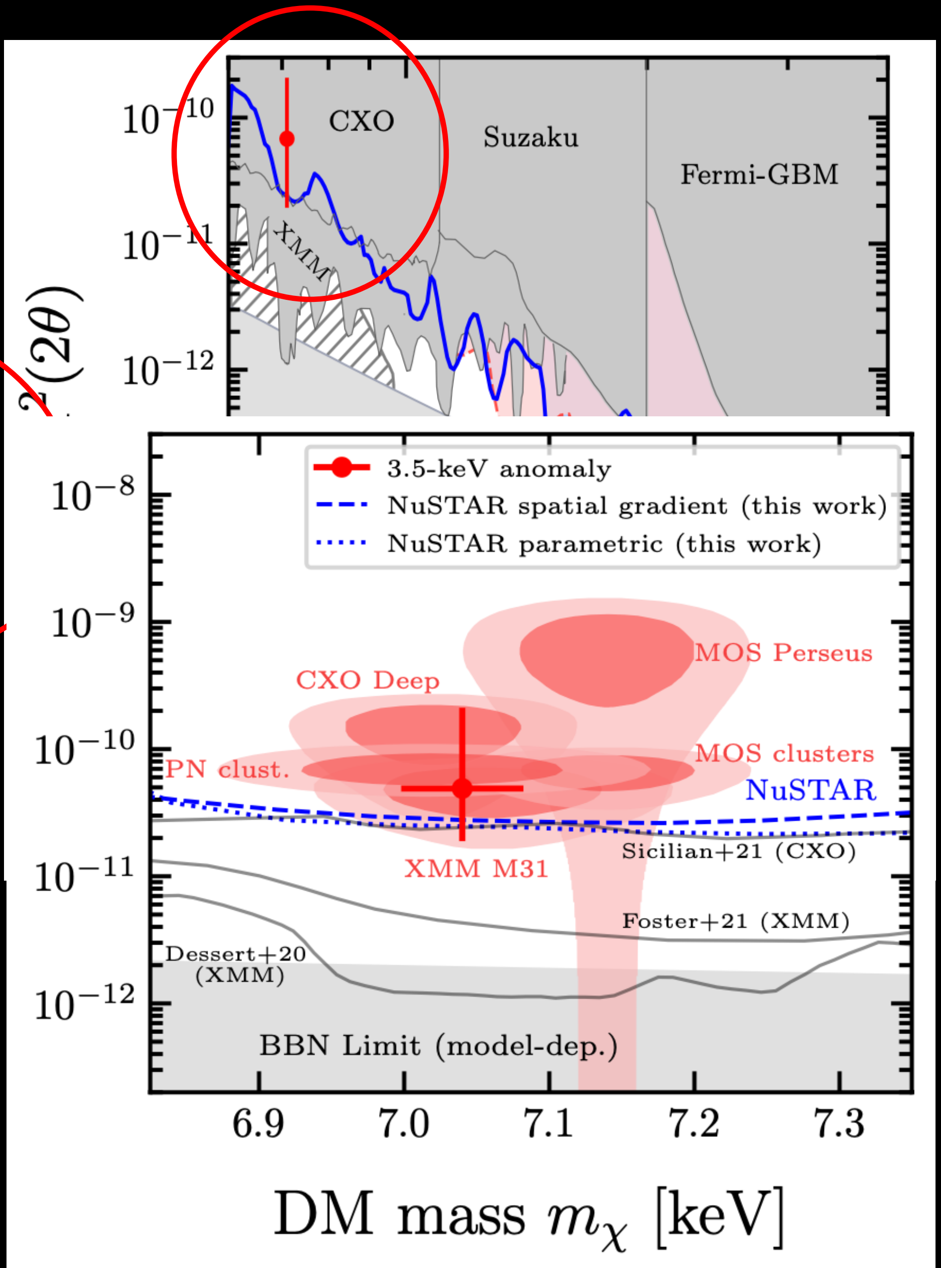



*Horiuchi et al (2016)*

# *Many constraints*




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




**Oscillation-based production of ~7.1 keV sterile neutrino constrained, but no obvious astrophysical explanation**

# *STORY OF ANTI-PARTICLES*

Shunsaku Horiuchi

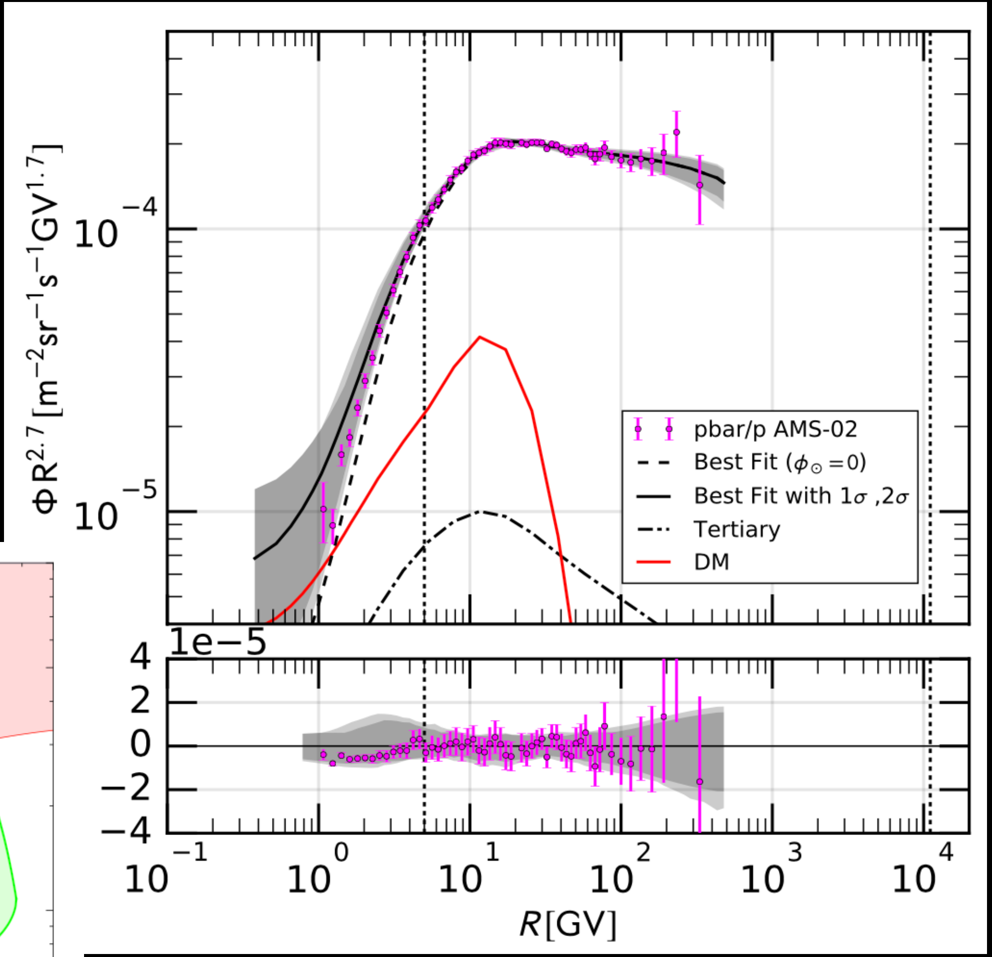
# *Anti-proton excess*

Anti-protons are useful probes of new physics

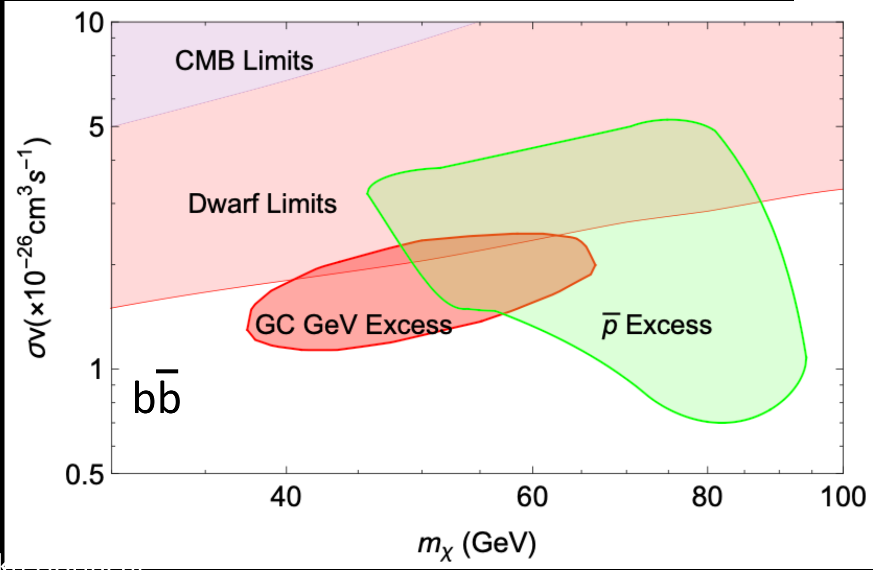
**Excess, relative to what?**
Secondaries produced by pp collisions of astrophysical cosmic rays.

Excesses in PAMELA & AMS-02 (usually at ~3–6$\sigma$)

Is it dark matter? Intriguing connection to GeV excess




*Cuoco et al (2017)*




*Cholis et al (2019)*

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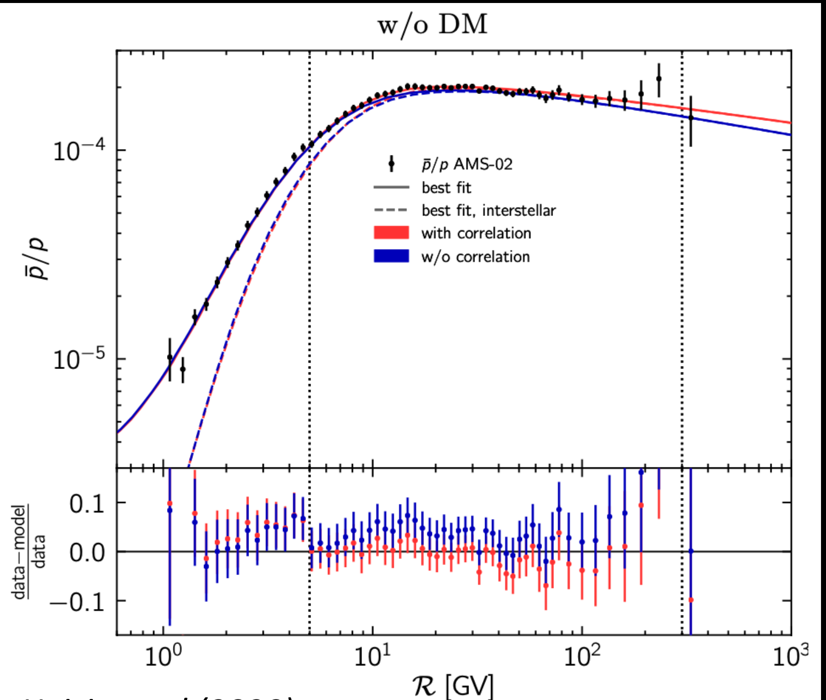
# *Systematics*

But systematics are a major concern

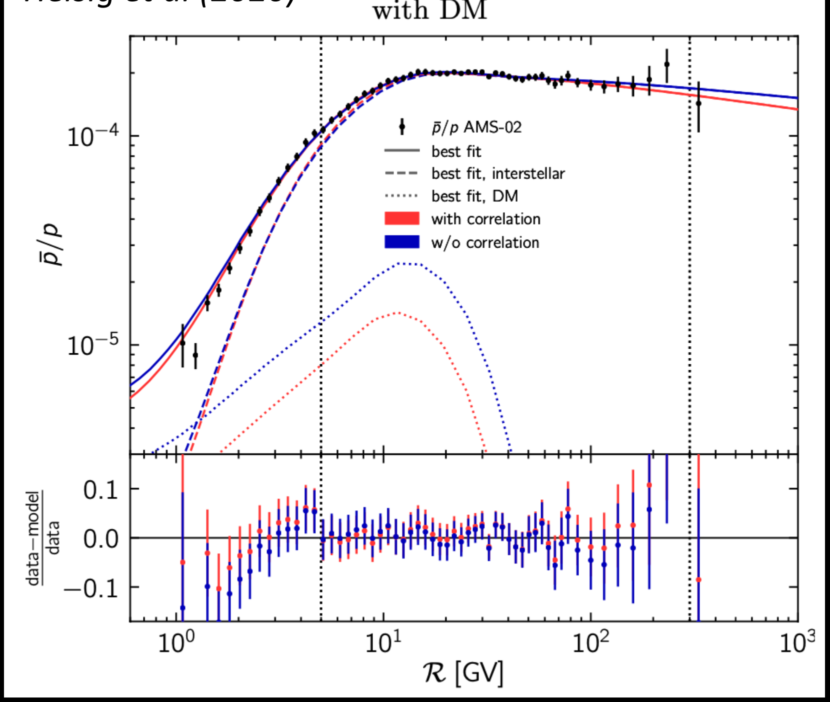
- Cross sections
- Solar modulation
- Injection & propagation
- Correlating errors

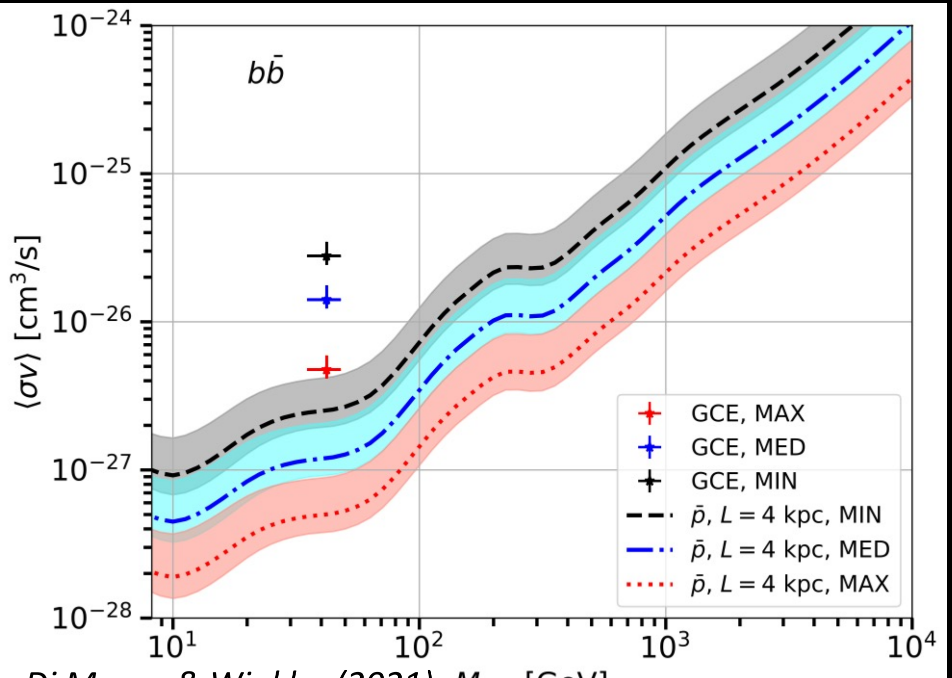
➔ **Removes need for DM**

➔ **Actually constraints GeV excess**




*Heisig et al (2020)*




*Di Mauro & Winkler (2021)*

Shuns

# *Positron excess*

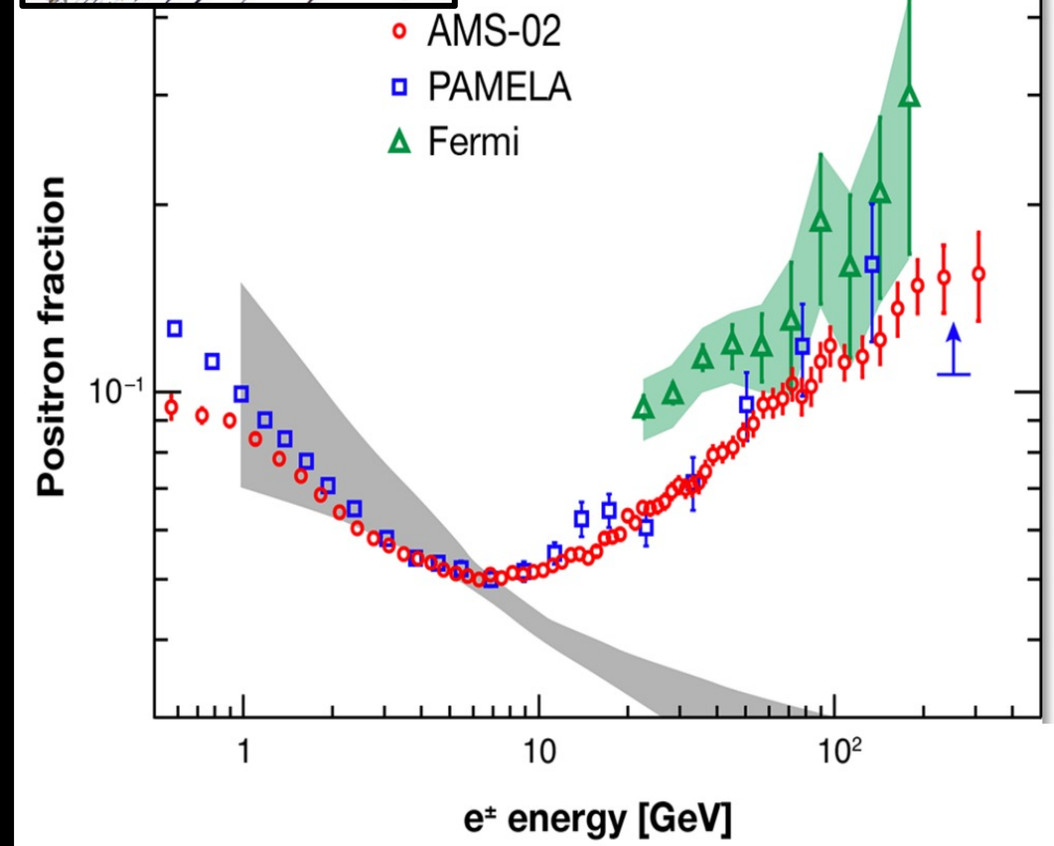
Positrons are ~1/10 electrons, but sensitive to local sources

**Excess**: seen in positrons relative to electrons by many experiments, but became prominent with the PAMELA satellite measurements

*PAMELA collaboration (2008)*

Later confirmed by Fermi-LAT and AMS-02

*Fermi collaboration (2012)*
*AMS-02 collaboration (2014)*

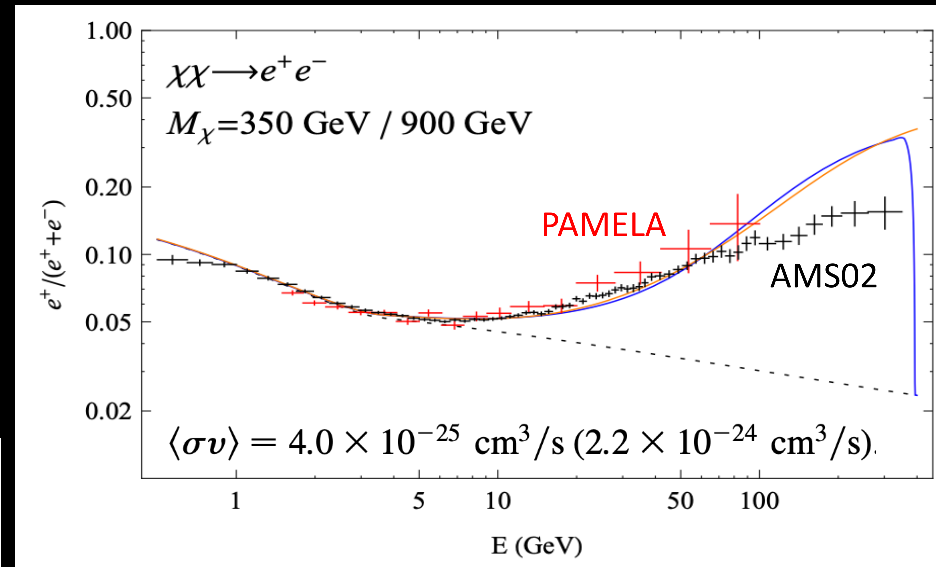


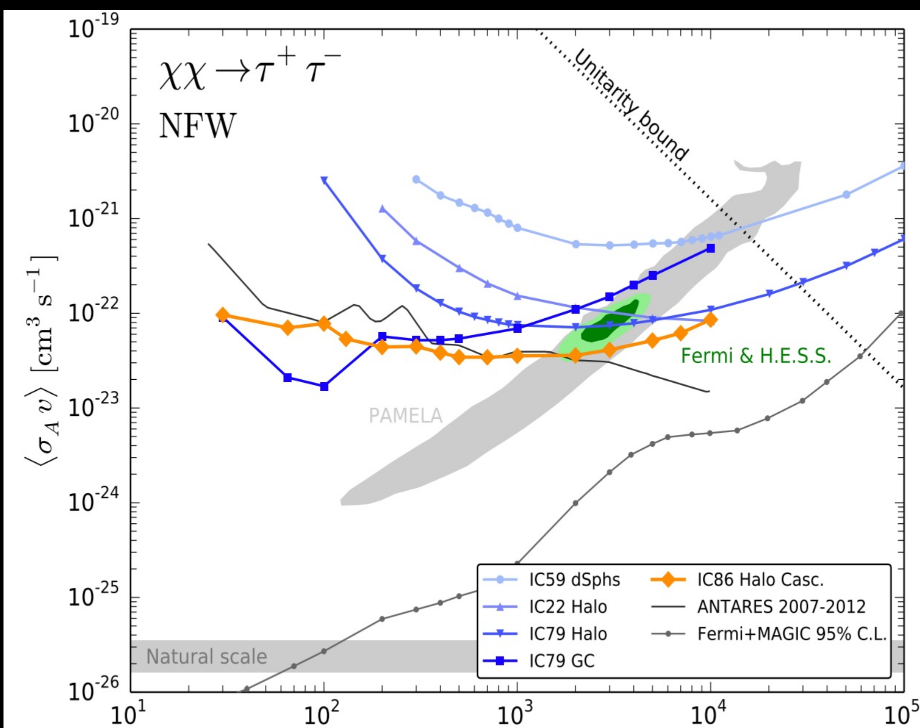

**Relative to**: secondary positrons from CR-induced charged meson decays.
Background model do not predict a rising fraction
→ suggests some new source

# *Is it dark matter?*

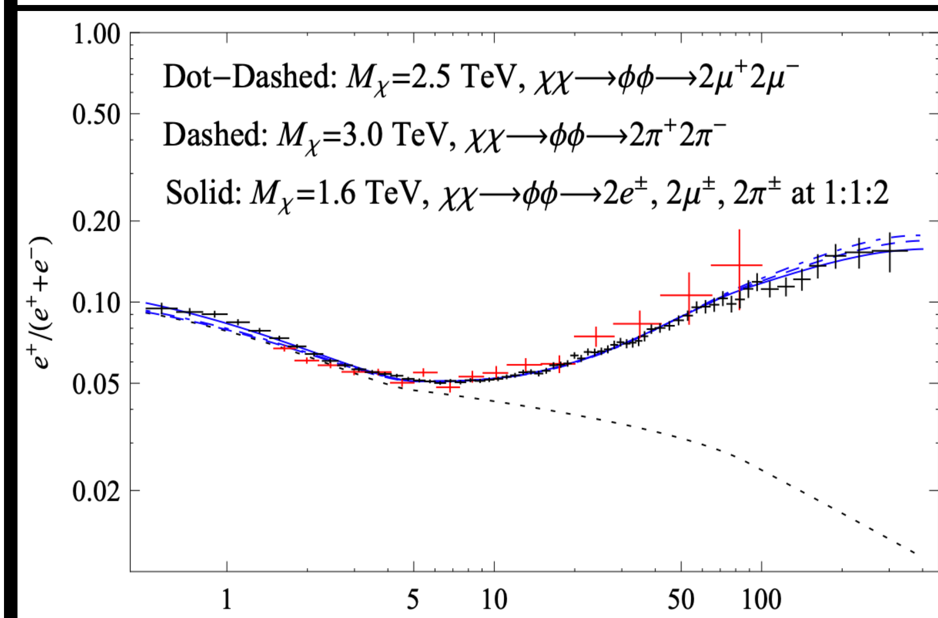
**Some tweaks:** dark matter are a source of local positrons, but

- Quite massive & large cross sections
- Constraints limit channels to *e* and $\mu$
- New data cannot be matched with annihilation into 2-body final states




*IceCube 2016*




*Cholis & Hooper (2014)*

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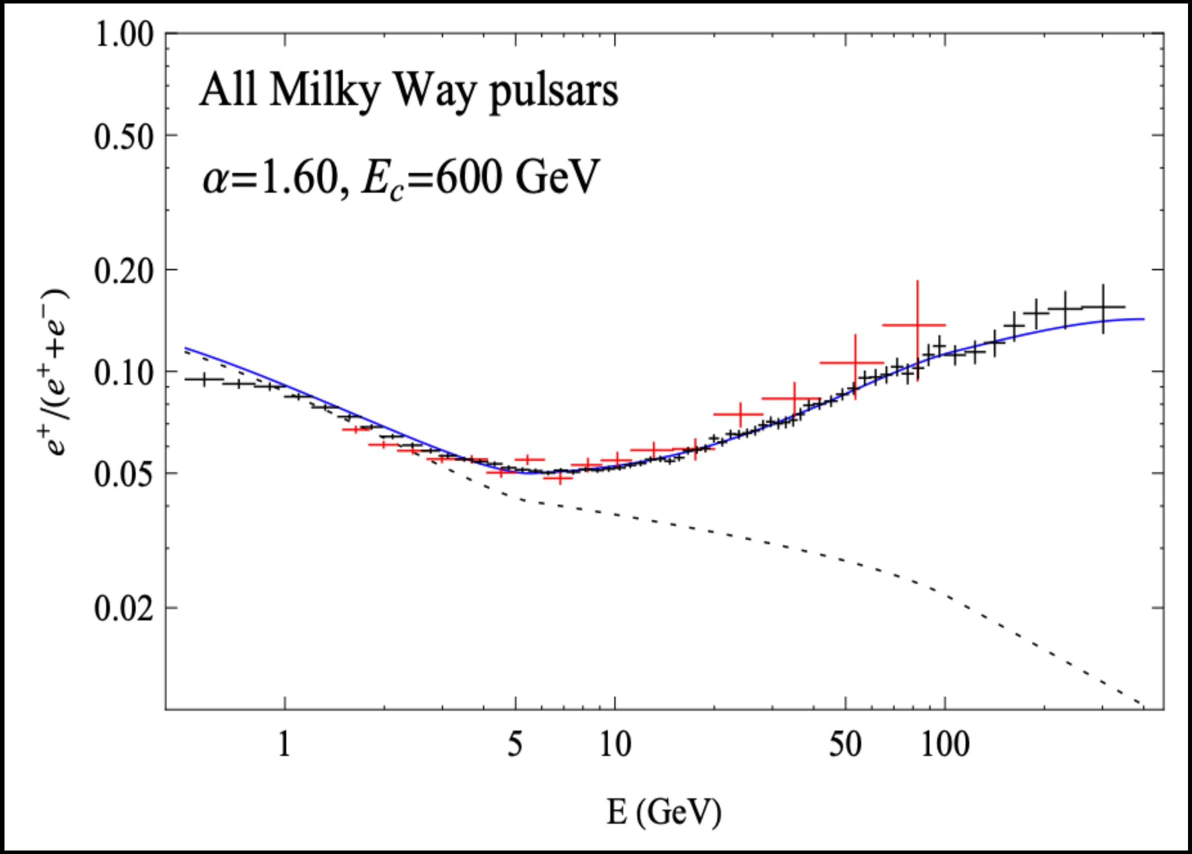
# *Astrophysical possibilities*

**Pulsars:** common, suitable leptonic systems. Readily explains $e^+$ fraction.
Main uncertainties are:

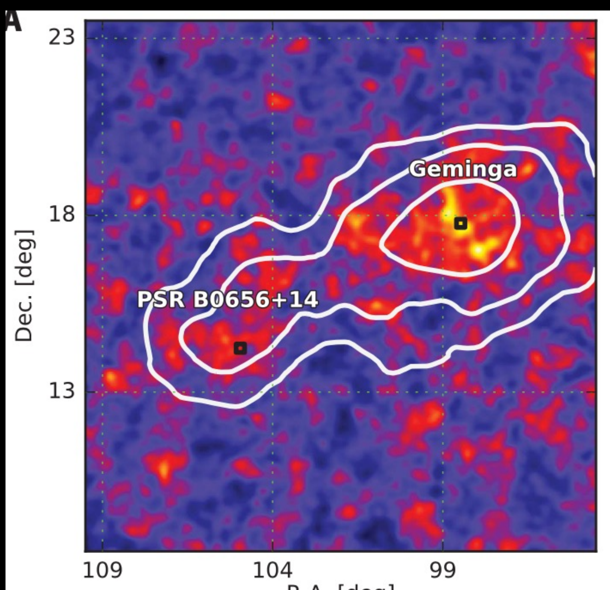
- Injection e+e- properties
- Propagation physics (global vs local)

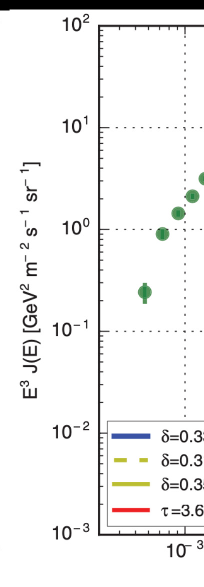



*Cholis & Hooper (2014)*

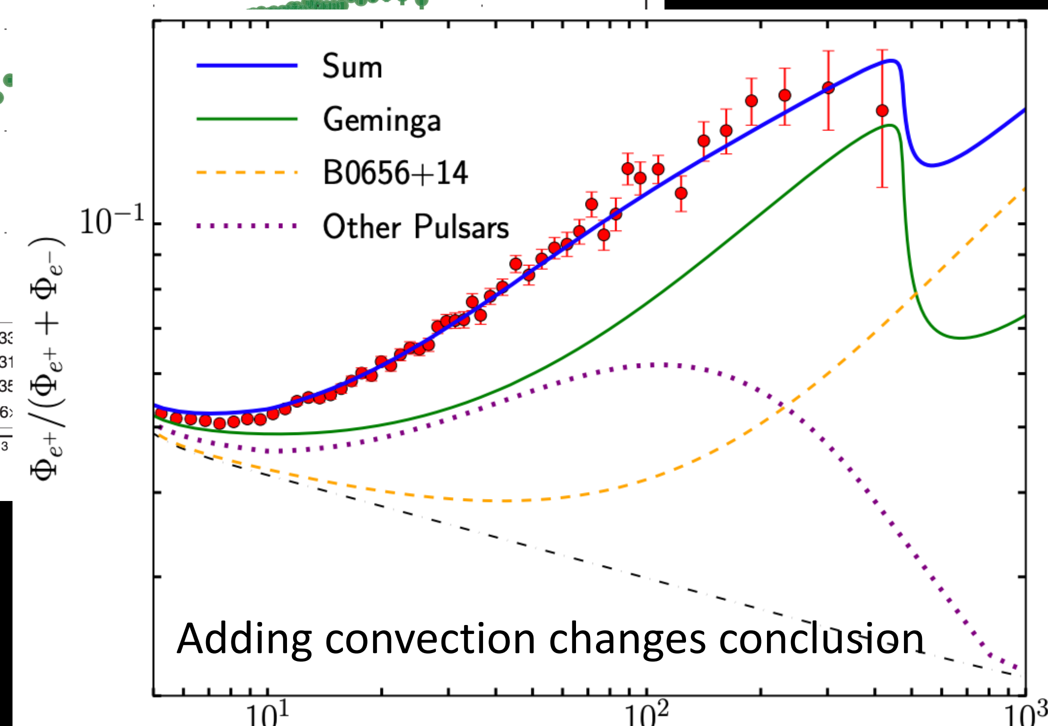
# *Importance of propagation*

**TeV halos:** HAWC discovered very small halos, showing strong local enhancement of diffusive transport → argued to rule out large pulsar contributions to $e^+$ excess




*HAWC collab (2017)*




*Hooper et al (2017)*

Pulsar scenario works, with
***flexible cosmic-ray propagation***

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# *Concluding remarks*

- Astronomical observations have revolutionized our understanding of high-energy phenomena in the Milky Way. At the same time, this has created opportunities to further searches of dark matter physics

- **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

- **In the future we can expect some resolutions to current anomalies, but at the same time, also new anomalies & surprises → stay tuned!**

**Thank you!**

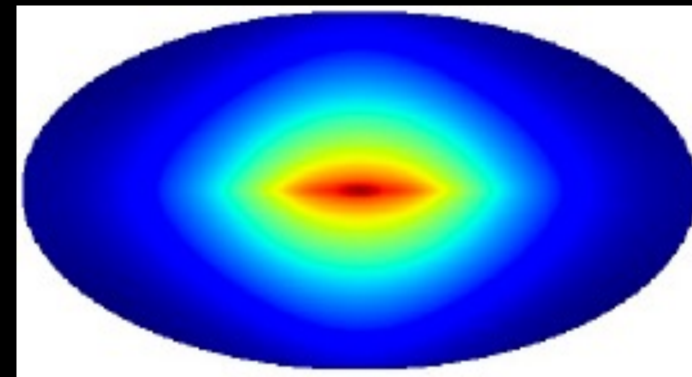
# *BACKUP*

# *Background systematics*

**Many astrophysical systematics**

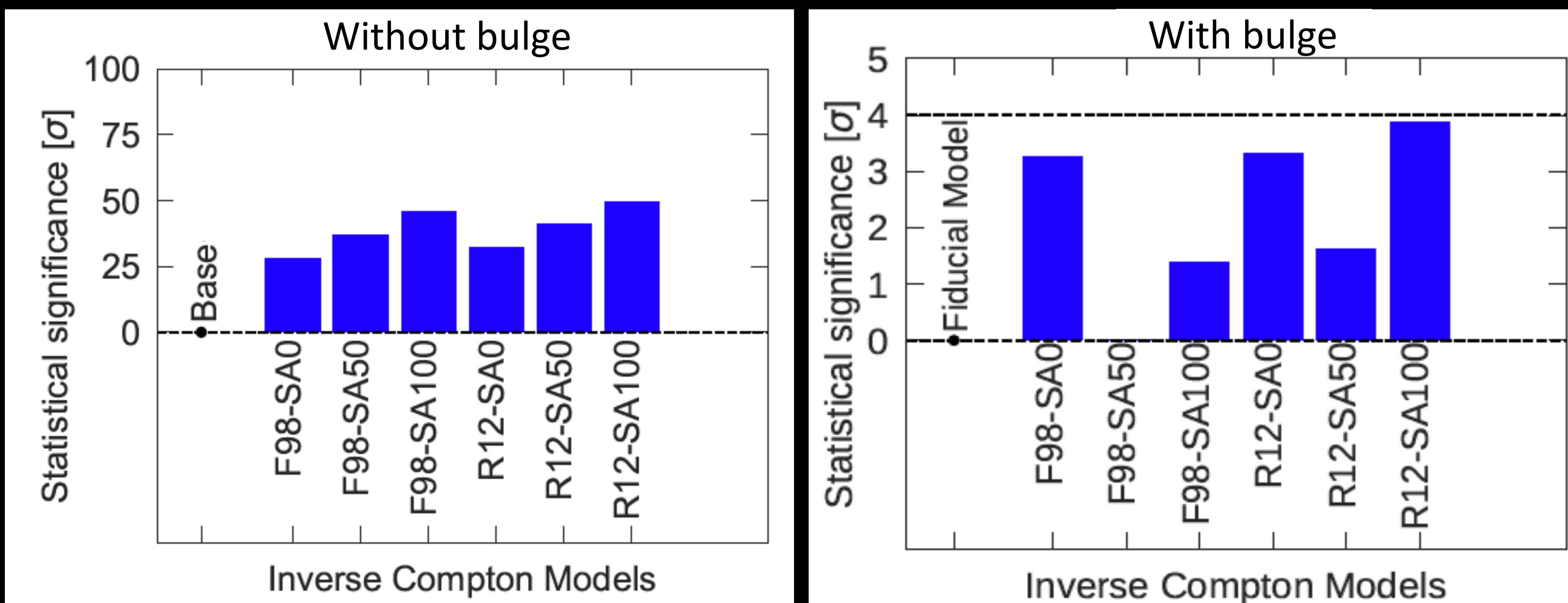
1. Bulge model
2. Fermi bubble model
3. Background (IC models)
4. Background (gas maps)
5. Point source catalogs

IC



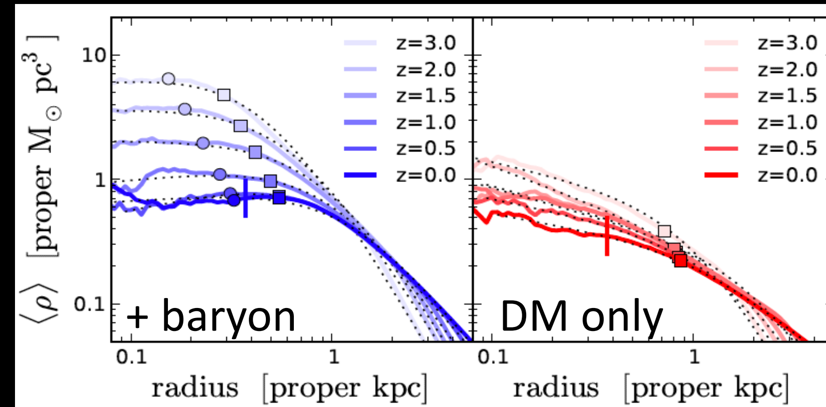
**Significance of NFW² for bulge and IC model combinations**

*Macias et al (2018, 2019)*



# More systematics

*Kuhlen et al (2012)*



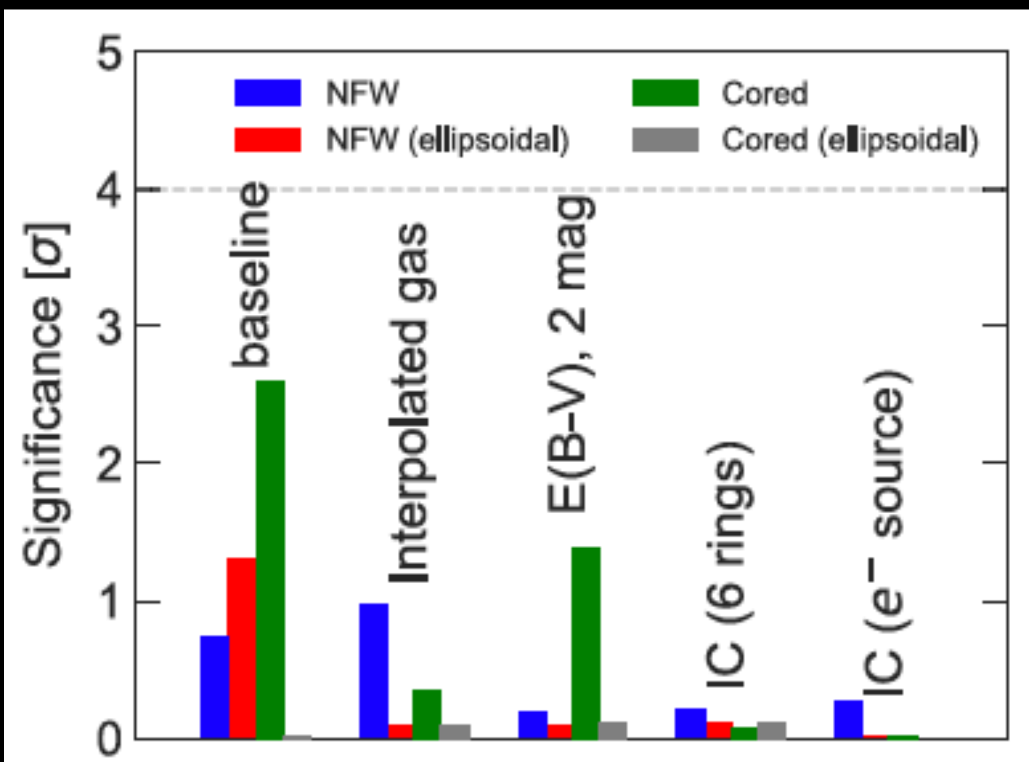

**Dark matter variations:**

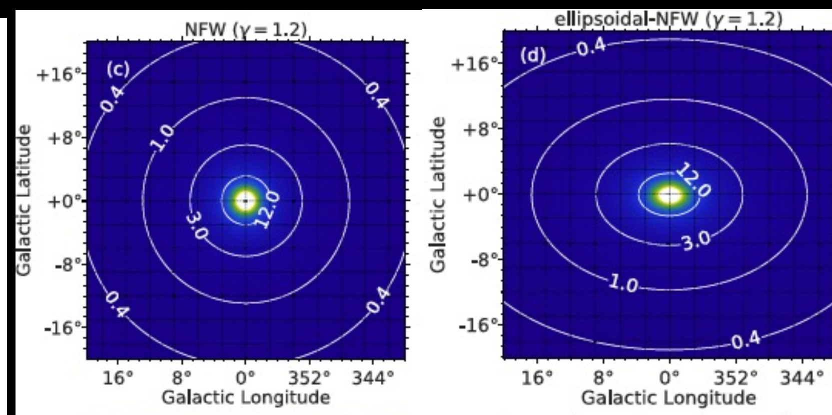
1. Inner slope, including cores
2. Asymmetry

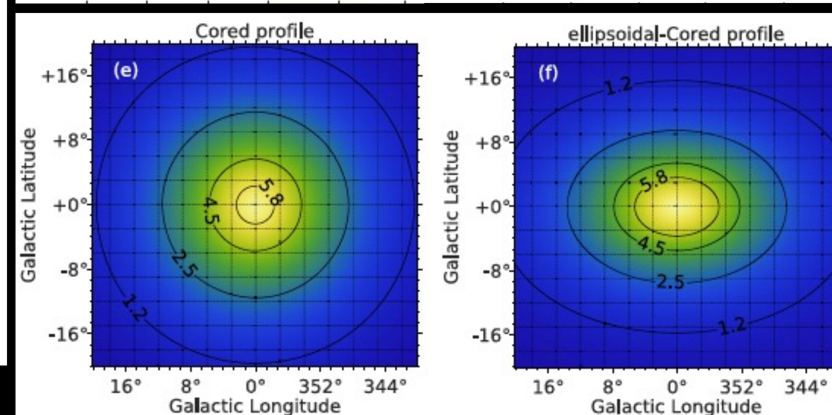
➔ Try $\gamma$ [0.5,1.5], 1kpc core, axis ratio 0.7

*Eg, bulge kinematics, Eris, FIRE simulations*

**➔ Dark matter model not detected**




Shunsaku Horiuchi

*Abazajian, Horiuchi, et al (2020)*

| Baseline model | Add. source | $\Delta\mathrm{AIC}_{511}$ | $\Delta\mathrm{AIC}_{oPs}$ | $\Delta\mathrm{AIC}_{\pm}$ |
|---|---|---|---|---|
| IC | HI | 10.9 | 4.7 | 15.6 |
| IC | FB | 25.2 | 9.9 | 35.1 |
| IC | BB | 89.1 | 192.4 | 281.5 |
| IC | CO | 64.6 | 239.0 | 303.6 |
| IC | HI+CO | 104.5 | 278.1 | 382.6 |
| IC | NB | 123.8 | 383.8 | 507.6 |
| IC | DM2 | 134.8 | 375.8 | 510.6 |
| IC | DM0 | 164.3 | 433.3 | 597.6 |
| IC | BB+NB | **162.0** | **456.2** | **618.2** |
| IC+BB+NB | CO | -2.0 | -1.7 | -3.7 |
| IC+BB+NB | DM2 | -0.5 | -0.8 | -1.3 |
| IC+BB+NB | DM0 | 3.6 | -1.1 | 2.5 |
| IC+BB+NB | CO+HI | -1.4 | 16.8 | 15.4 |
| IC+BB+NB | HI | **-0.3** | **16.3** | **16.0** |
| IC+BB+NB+HI | DM0 | 4.8 | 0.8 | 5.6 |
| IC+BB+NB+HI+CO | DM0 | 4.6 | 1.3 | 5.9 |