What indirect searches teach us about particle dark matter

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Cosmic Controversies
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What can we hope to learn?

- Mass scale of dark matter
  - For fermions, must be > few hundred eV (Tremaine-Gunn bound)
  - In general, must be > 10^{-21} eV (at lower masses wavelength suppresses small-scale structure)
  - As a fundamental particle, can be up to Planck mass - as a composite, can be much heavier.
- How does it interact? With itself, with other particles?
  - Strong self-interactions can modify observable DM distribution [see Saturday morning session]
  - Interactions with other particles can result in visible tracers, holding information on DM mass + quantum numbers + interactions

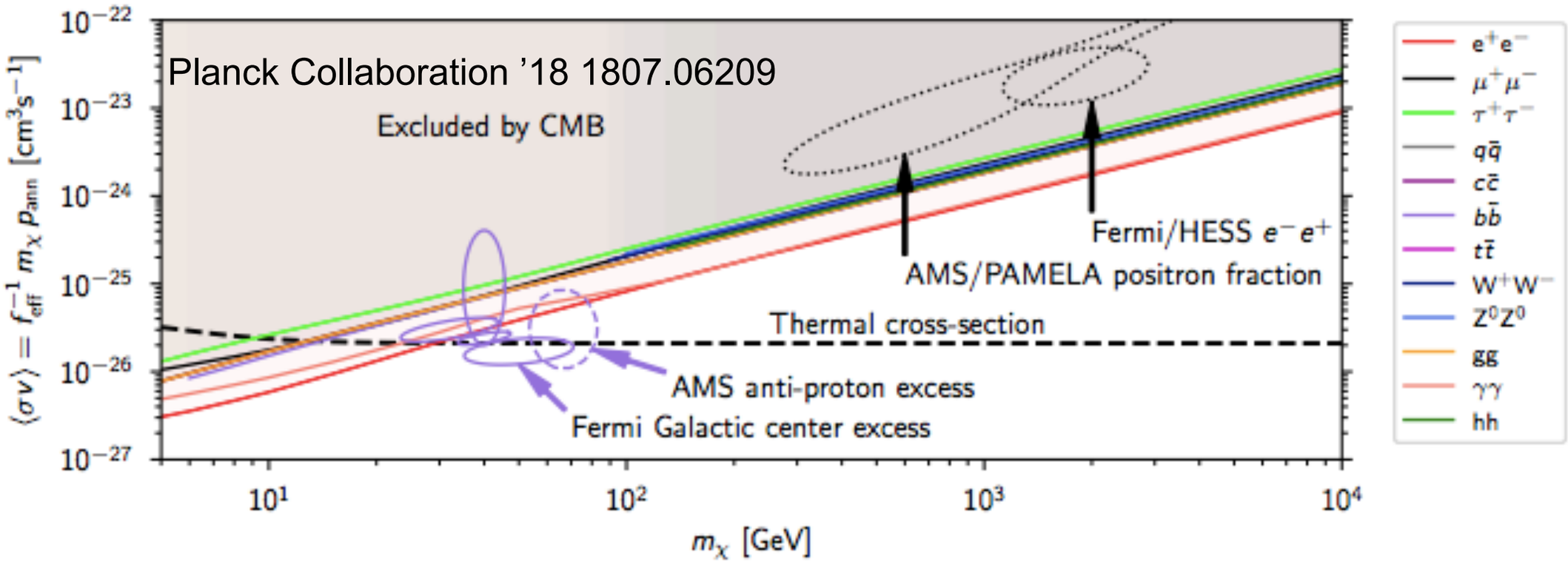
Mechanisms for indirect detection

- Decay into visible particles, directly or through intermediate states - lifetime must be >> age of universe
- Collisions that produce visible particles
- Oscillation into visible particles, and vice versa
- Scattering on visible particles leading to indirect signals [see talk by Dvorkin, & also direct-detection talks by Aprile, Essig]
- Can be tied to origin + abundance of DM - a simple example is thermal freezeout:
  - DM in thermal equilibrium with SM in early universe - abundance depleted through annihilation reactions. Gives a predictive target for indirect searches:

$$\boxed{\langle \sigma v \rangle \sim \frac{1}{m_{\rm Planck} T_{\rm eq}} \sim \frac{1}{(100{\rm TeV})^2} \approx 2 \times 10^{-26} {\rm cm}^3/{\rm s}}$$

  - Cross section is naturally generated for TeV-scale DM and weak-scale mediators - potential connections to supersymmetry (but not the only option)

The status of annihilating DM



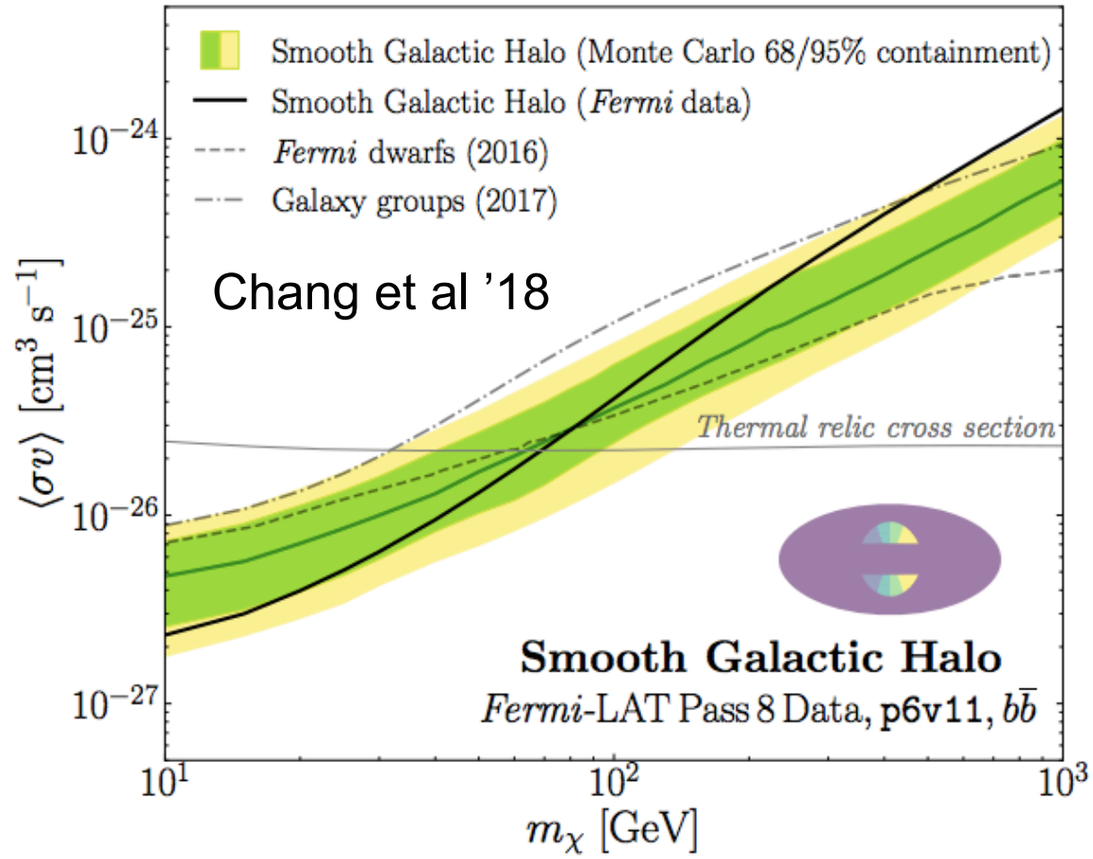
- CMB limits: production of ionizing particles during cosmic dark ages modifies the CMB via late scattering of the photons on the extra free electrons.
- Thermal cross-section ruled out for DM <u>below ~10 GeV</u> unless there is a significant invisible/neutrino branching fraction.
- Consequently, GeV-scale or lighter DM typically requires a non-thermal origin or suppressed late-time annihilation rate - implies specific structures for interactions.
- Depending on the channel, we can probe higher DM masses using other observations.

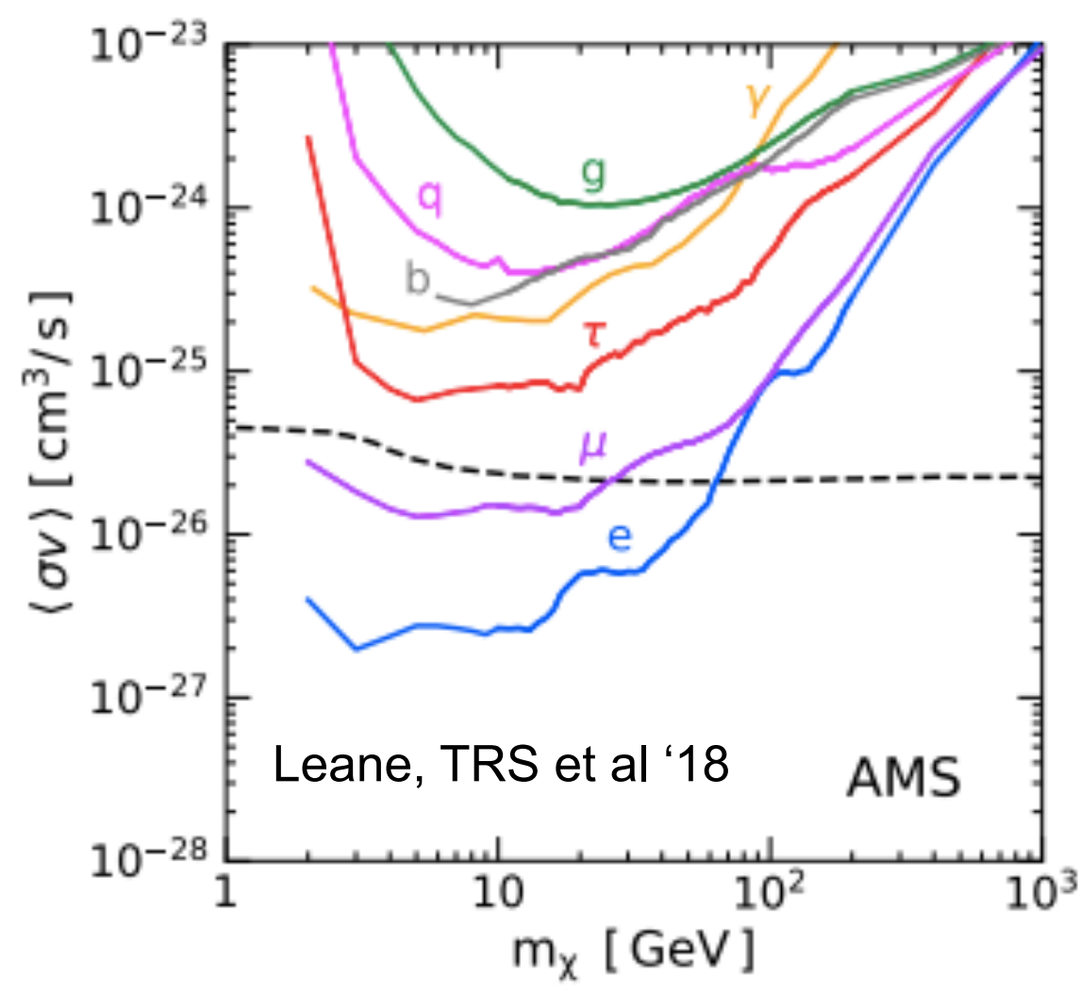
Cosmic rays and gamma rays

- Measurements of cosmic rays by AMS-02, and gamma-rays by Fermi-LAT, H.E.S.S., VERITAS, HAWC, set the strongest indirect bounds on GeV+ annihilating DM.

- For hadronic final states, several observations with Fermi-LAT (dwarf galaxies, outer Galactic halo) give comparable constraints, testing the thermal cross section up to ~100 GeV.

- Least constrained final states (in mass) are rich in leptons, especially muons, with thermal cross sections viable down to ~20 GeV - strongest limits come from AMS-02 positron flux measurements.

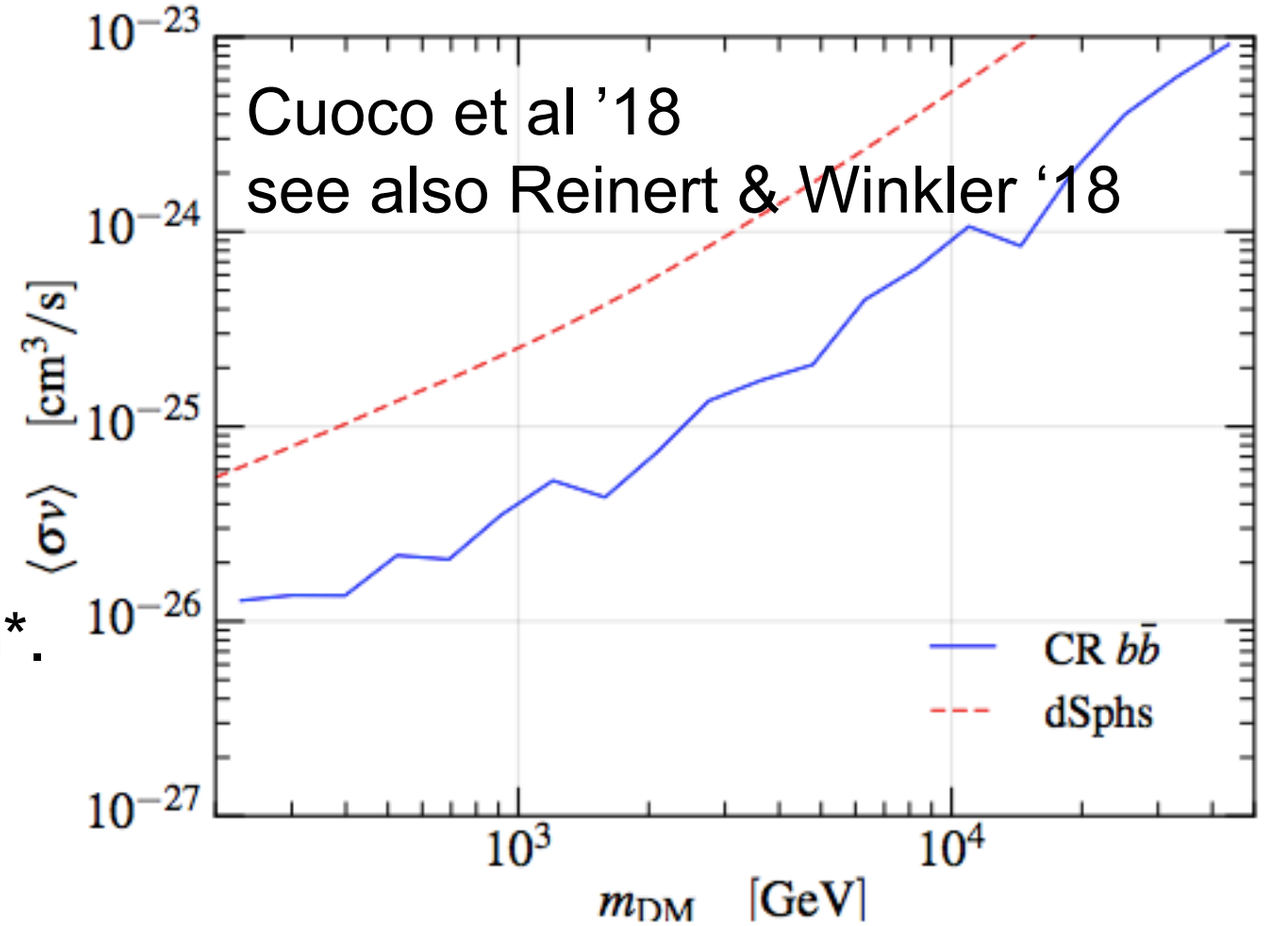


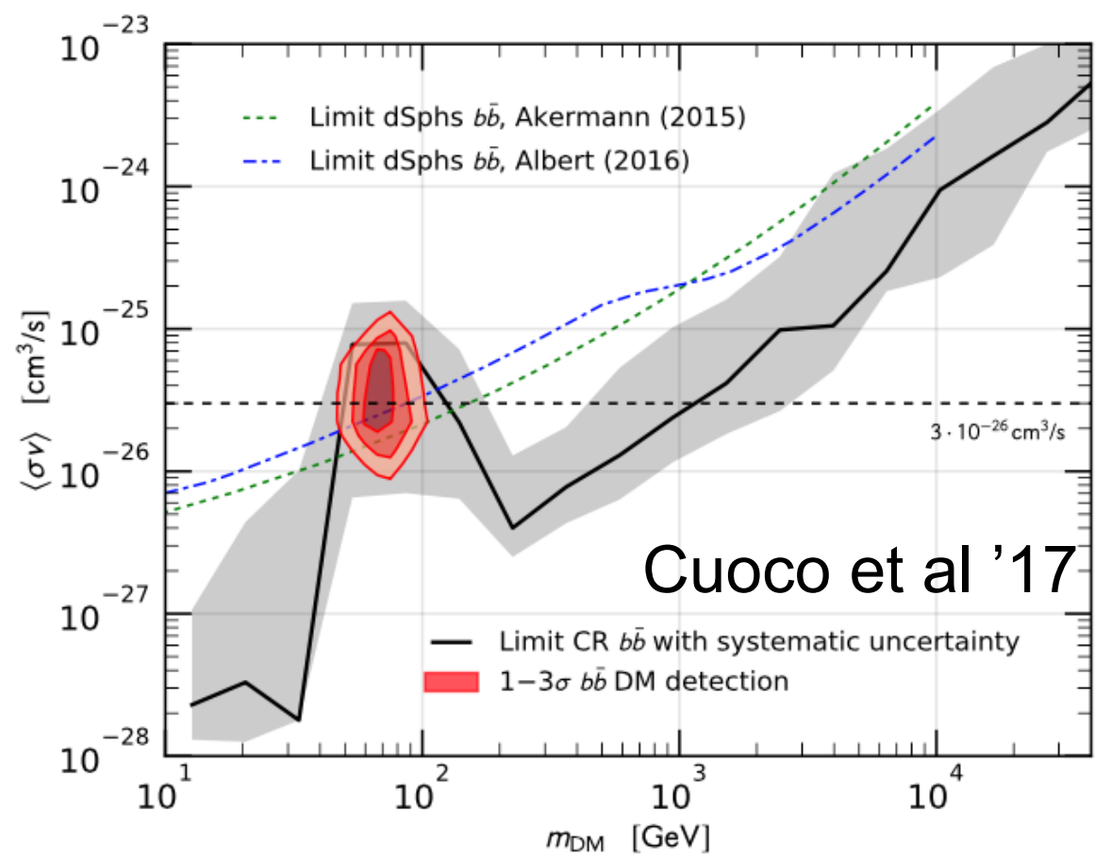


Antiprotons

- Can potentially set stronger limits than gamma rays, for hadronic channels, extending the mass reach up to <u>several hundred GeV</u> for a thermal cross-section*.

- At low energies, there are hints of an excess.
  - Corresponds to a ~thermal cross section and ~40-130 GeV DM mass.
  - Significance level is still highly debated [see Boudaud et al ’19, Cuoco et al ’19, Cholis et al ’19, Reinert & Winkler ’18, Cui et al ’17, Cuoco et al ’17] - depends sensitively on model for correlations between bins.

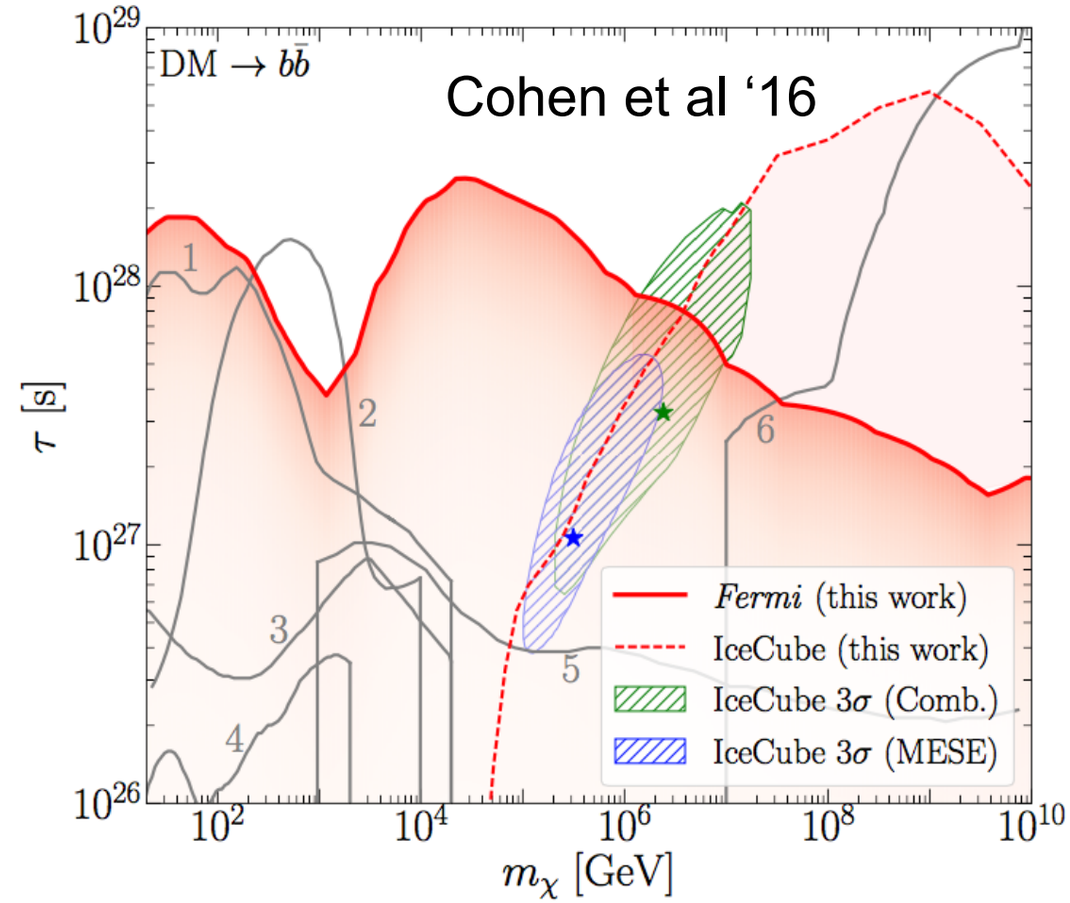


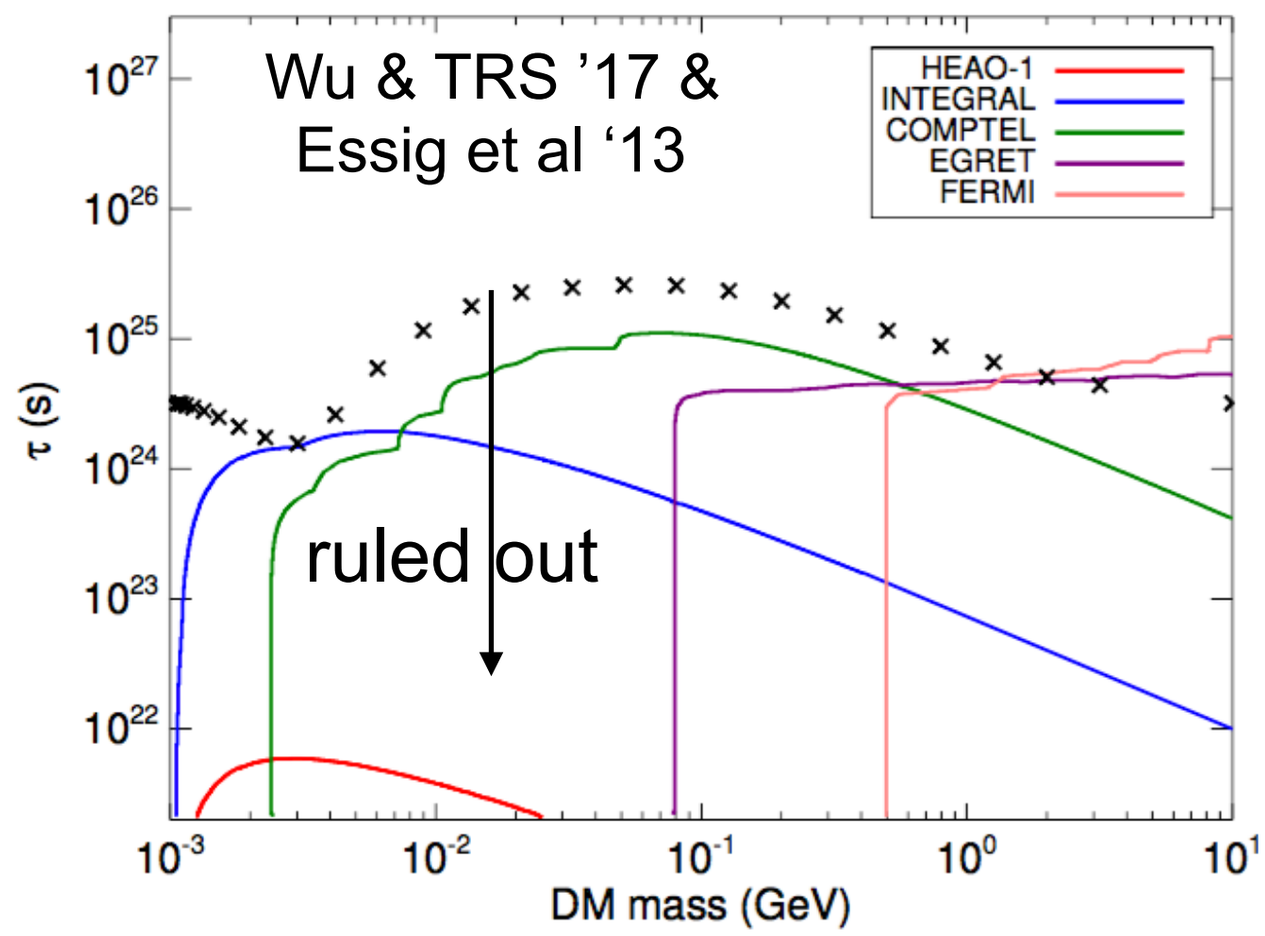


*if estimates for systematic uncertainties in cosmic-ray propagation are adequate

Decaying dark matter

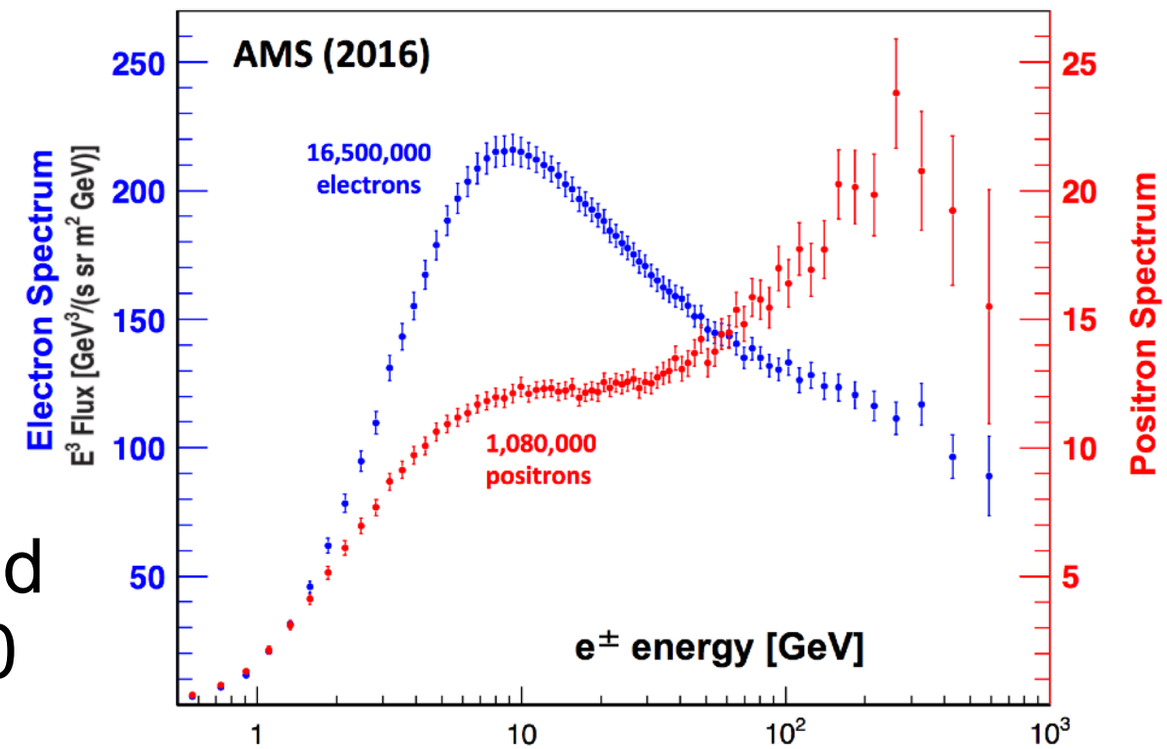
- GeV+ decaying DM constrained by dwarf galaxies, galaxy clusters, extragalactic gamma-ray background, Milky Way halo.
- Lifetime lower limits ~$10^{27\text{-}28}$ s, for DM masses in the 10-10^{10} GeV range, for representative hadronic decay channels.
- For sub-GeV DM, comparable lifetime limits for photon-rich channels; for e^+e^- final state, lifetime limit ~$10^{24\text{-}25}$ s from photon searches and CMB bounds





Status of anomalies I

- There are several statistically significant deviations between data & best background models that could be DM signals.

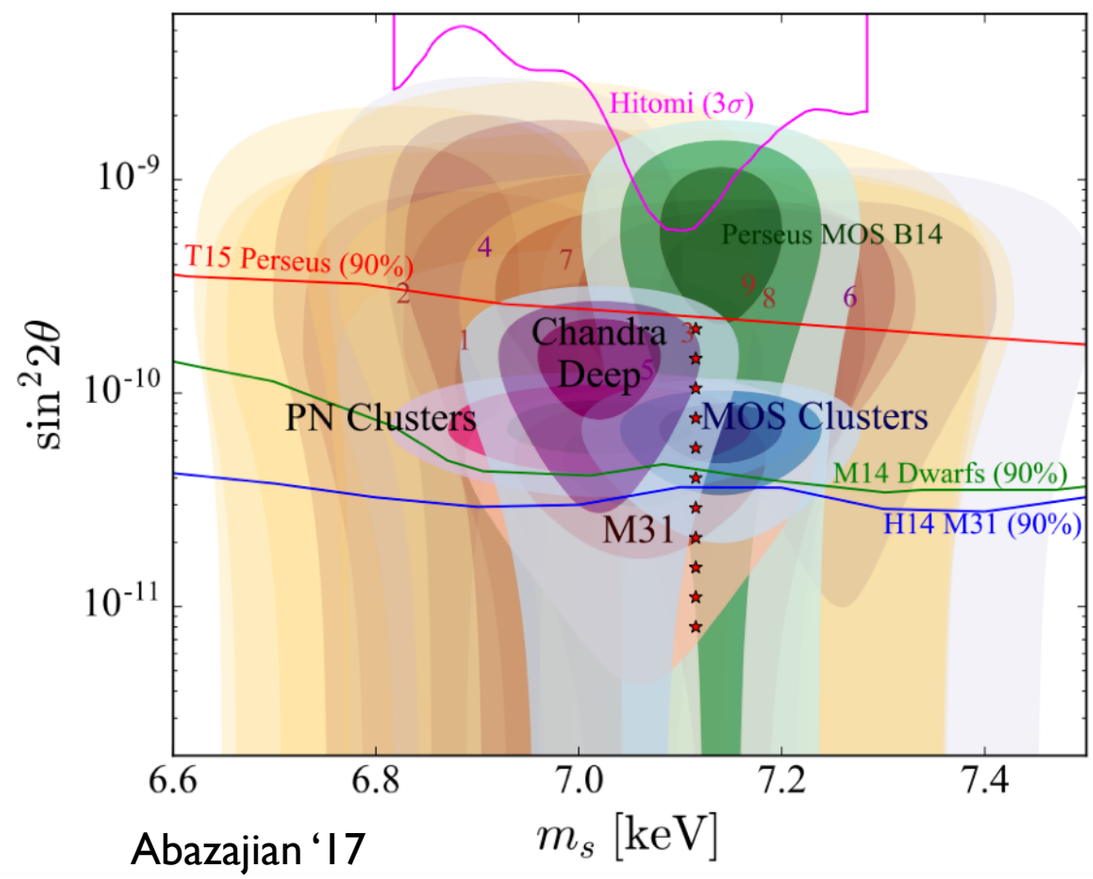


Sam Ting, 8 December 2016, CERN colloquium

- PAMELA/AMS-02 positron excess:
  - Cosmic-ray positron flux is enhanced relative to electron flux between ~10 and several hundred GeV.
  - Highly statistically significant.
- DM explanation: TeV-scale DM annihilating or decaying dominantly into leptons (if annihilation, requires rate >> thermal).
- Recent observations of nearby pulsars suggest they produce abundant TeV-scale positrons that likely explain the excess [e.g. Hooper et al ’17].

Status of anomalies II

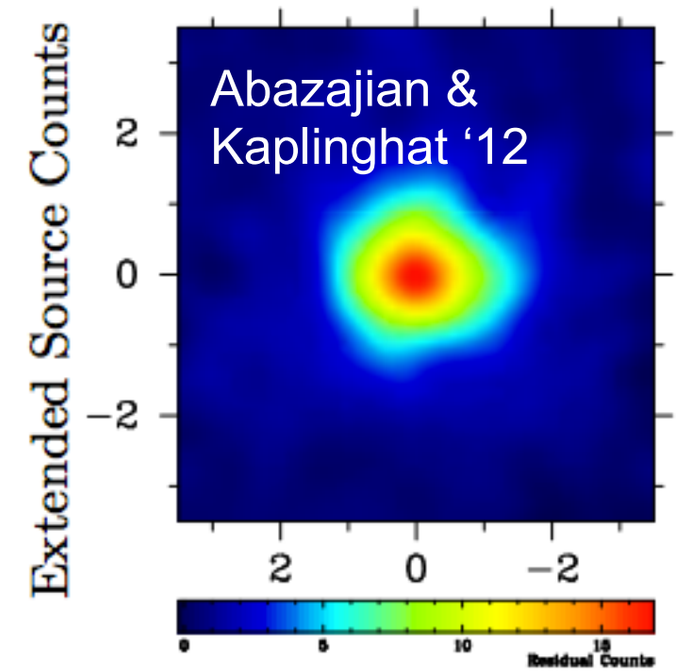
- 3.5 keV X-ray spectral line:
  - Observed originally in stacked galaxy clusters [Bulbul et al ’14, Boyarsky et al ’14], subsequently in other regions.
  - Individual signals are modestly significant (~4σ).
  - Simplest DM explanation: 7 keV sterile neutrino decaying into neutrino+photon. (Other explanations involving annihilation, oscillations etc are possible.)
  - Possible non-DM contributions: atomic lines (from K, Cl, Ar, possibly others), charge-exchange reactions between heavy nuclei and neutral gas.
  - Simple decay explanation seems inconsistent with null results in other searches [e.g. Dessert et al ’18; but see also Boyarsky et al ’18].



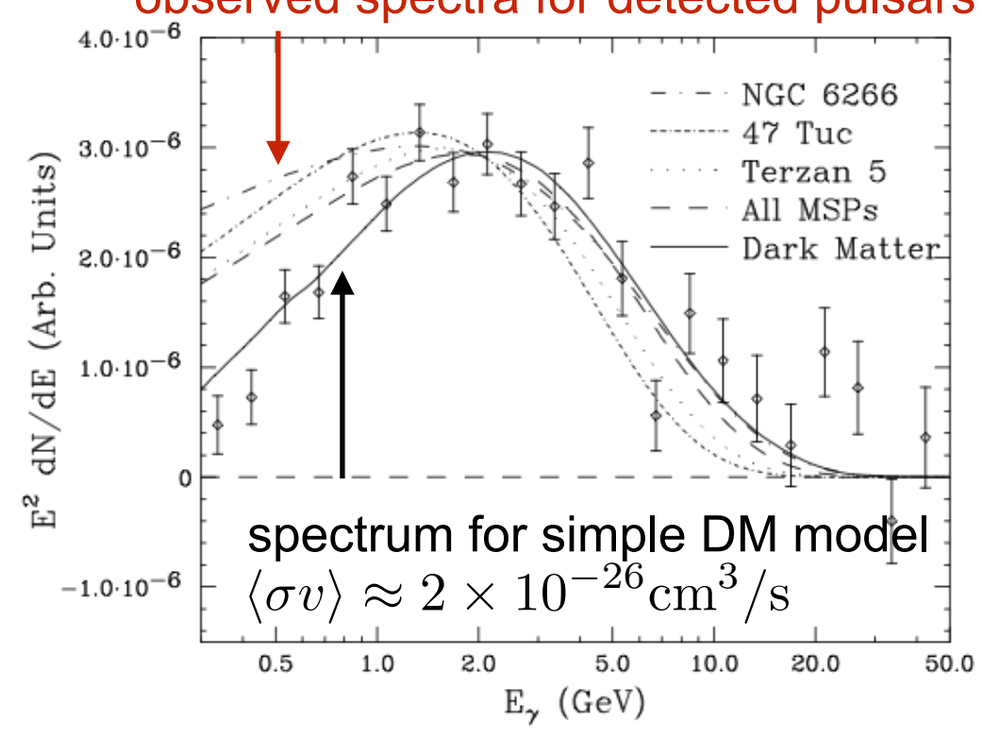
Abazajian ‘17

Status of anomalies III

- The GeV Galactic Center Excess (GCE):
  - Excess of gamma-ray photons, peak energy ~1-3 GeV, in the region within ~10 degrees of the Galactic Center.
  - Discovered by Goodenough & Hooper ’09, confirmed by Fermi Collaboration in analysis of Ajello et al ’16 (and many other groups in interim).
  - Simplest DM explanation: thermal relic annihilating DM at a mass scale of O(10-100) GeV
  - Leading non-DM explanation: population of pulsars below Fermi’s point-source detection threshold



observed spectra for detected pulsars



Daylan, TRS et al ‘16

Status of the GCE - a renewed controversy?

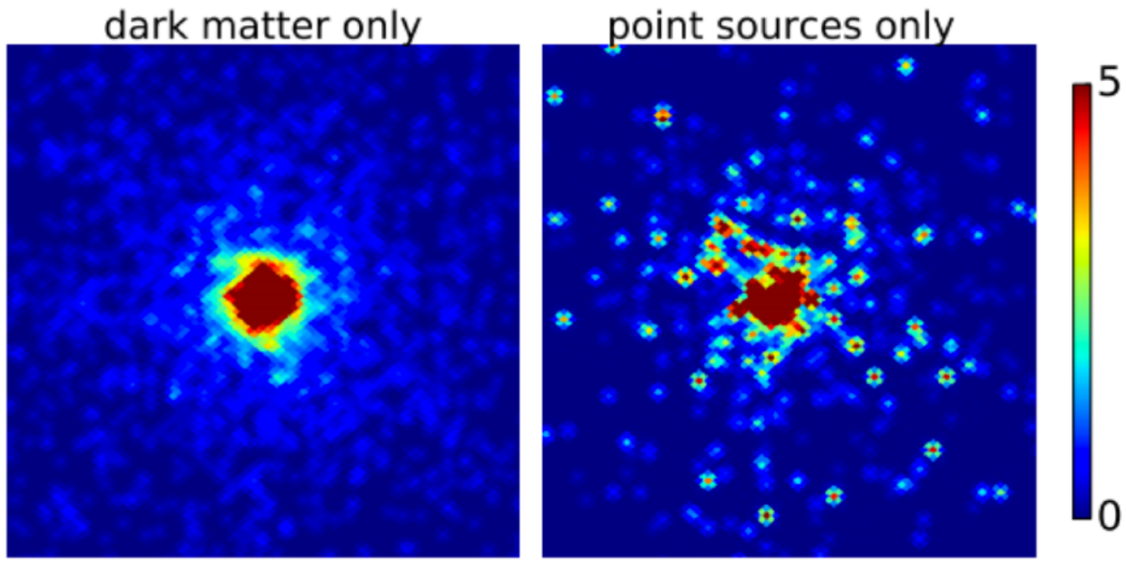
- Arguments against the DM explanation:
  - Spatial morphology of excess was originally characterized as spherical, but can also be described as Bulge-like extended emission + a central symmetric core [Macias et al ’18, Bartels et al ’18, Macias et al ’19]. If the extended emission is robustly Bulge-like, suggests a stellar origin, but sensitive to background modeling.
  - Constraints from other searches - limits from dwarf galaxies are in some tension with DM explanation [e.g. Keeley et al ’18], but depends on Milky Way density determination.
  - Photon statistics.

Photon statistics

Lee, Lisanti, Safdi, TRS & Xue ’16

<u>DM origin hypothesis</u>

signal traces DM density squared, expected to be ~smooth near GC with subdominant small-scale structure



<u>Pulsar origin hypothesis</u>

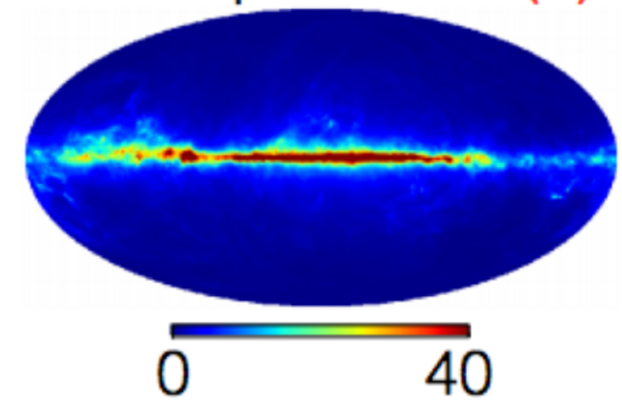
signal originates from a collection of compact objects, each one a faint gamma-ray point source

- We may be able to distinguish between hypotheses by looking at clumpiness of the photons (see Malyshev & Hogg ’11; Lee, Lisanti & Safdi ’15).
- If we are looking at dark matter (or another diffuse source, like an outflow), we expect a fairly smooth distribution - fluctuations described by Poisson statistics.
- In the pulsar case, we might instead see many “hot spots” scattered over a fainter background - non-Poissonian fluctuations, higher variance.
- Related analysis by Bartels et al ’16, using wavelet approach - found evidence for small-scale power in inner Galaxy.

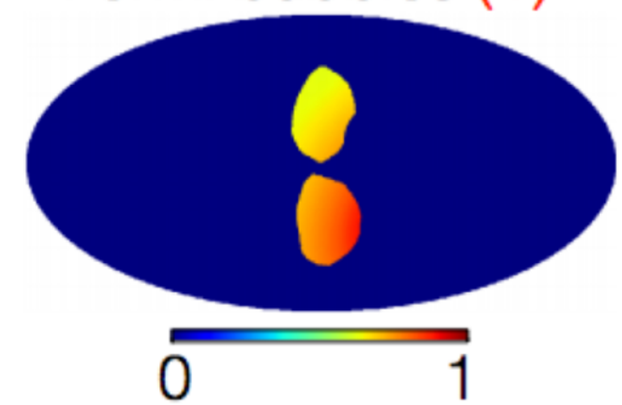
Non-Poissonian template fitting

- Model sky (within some energy bin) as linear combination of spatial templates
- Evaluate P(data|model) as a function of template coefficients + other parameters - maximize P (frequentist), or use it to derive posterior probability distributions for the parameters (Bayesian).
- Templates may either have
  - Poissonian statistics
  - Point-source-like statistics - extra degrees of freedom describing number of sources as a function of brightness

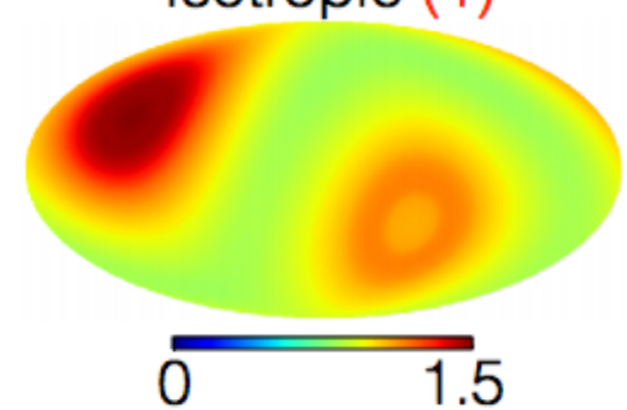
Fermi p6 diffuse (1)



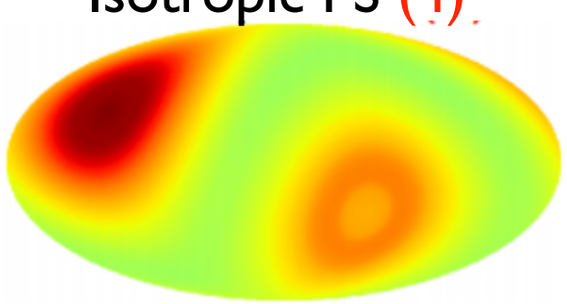
Fermi bubbles (1)



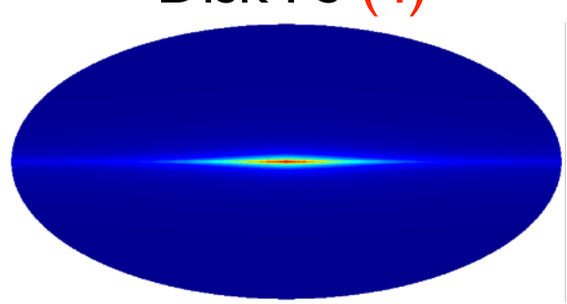
Isotropic (1)



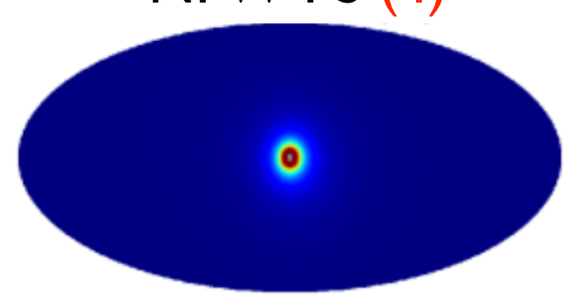
Isotropic PS (4)



Disk PS (4)

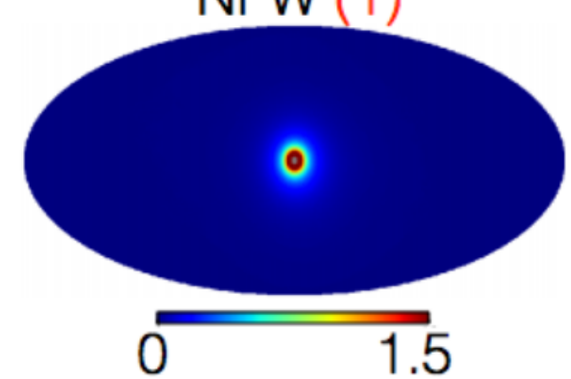


NFW PS (4)



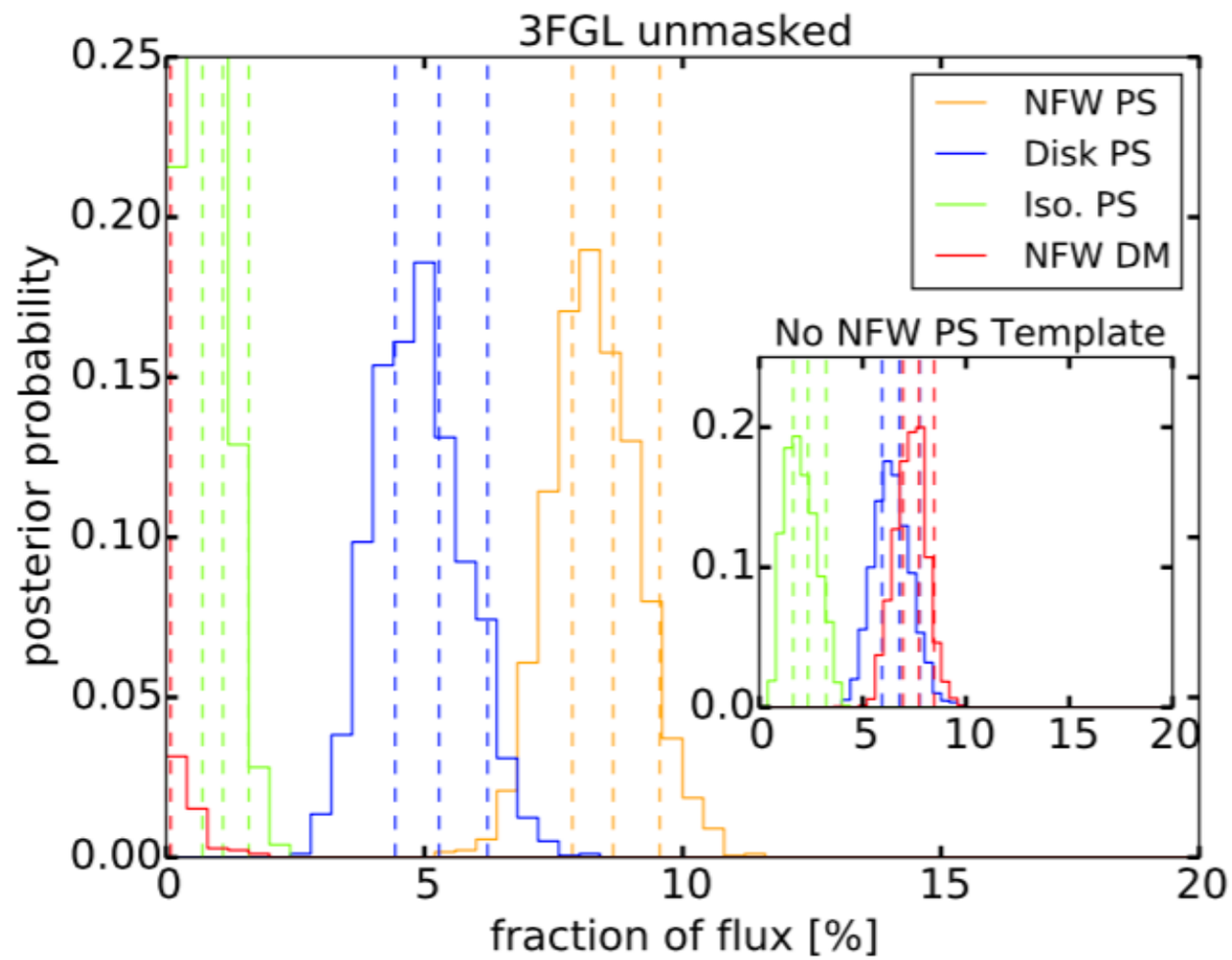
Point source templates

NFW (1)



A preference for point sources

- Restrict to region within 30° of Galactic Center, mask plane at ±2°.
- Compare fit with and without point-source (PS) template peaked toward GC, “NFW PS”.
- In both cases there is a smooth “DM” template peaked toward GC, “NFW DM”.

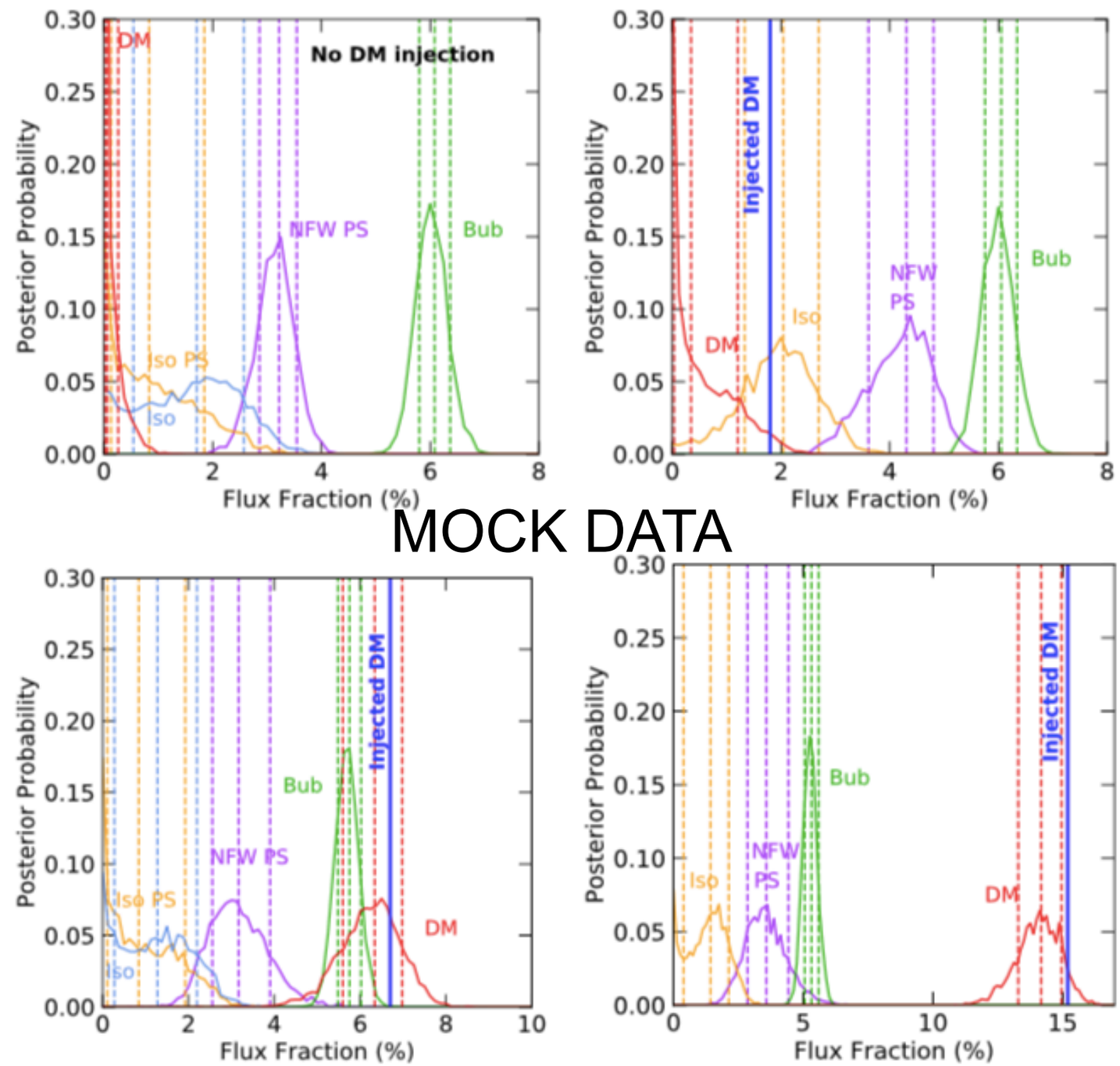


- 2016 result: if “NFW PS” is absent, “NFW DM” template absorbs excess. If “NFW PS” is present, “NFW PS” absorbs full excess, drives “NFW DM” to zero.

A new test for systematics

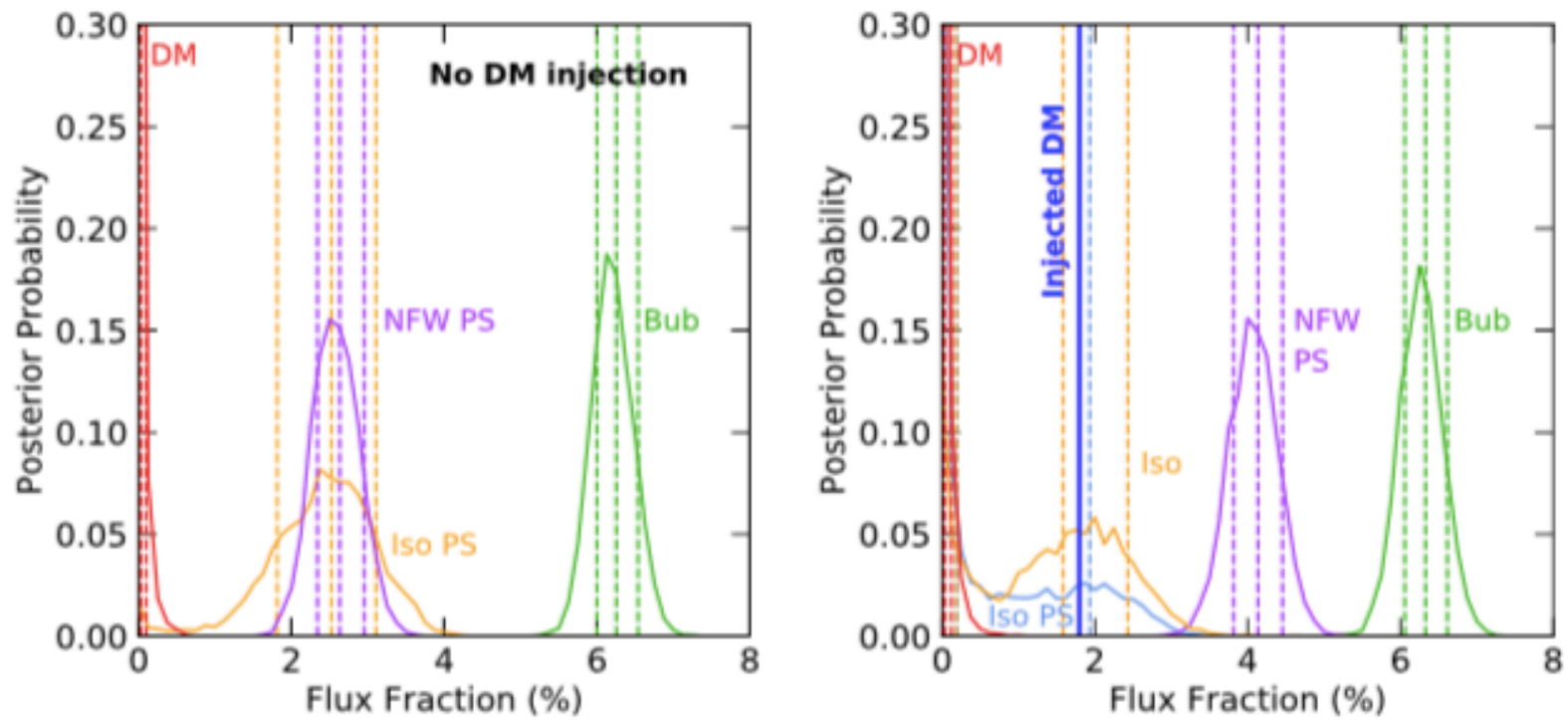
Leane & TRS '19

- In any template-based analysis, errors in the background templates can lead to misleading results for the signal templates.
- One way to test for problems: inject simulated signal, check that pipeline can recover it.
- First perform test on simulated data - all templates are thus "correct" (GCE = point sources).

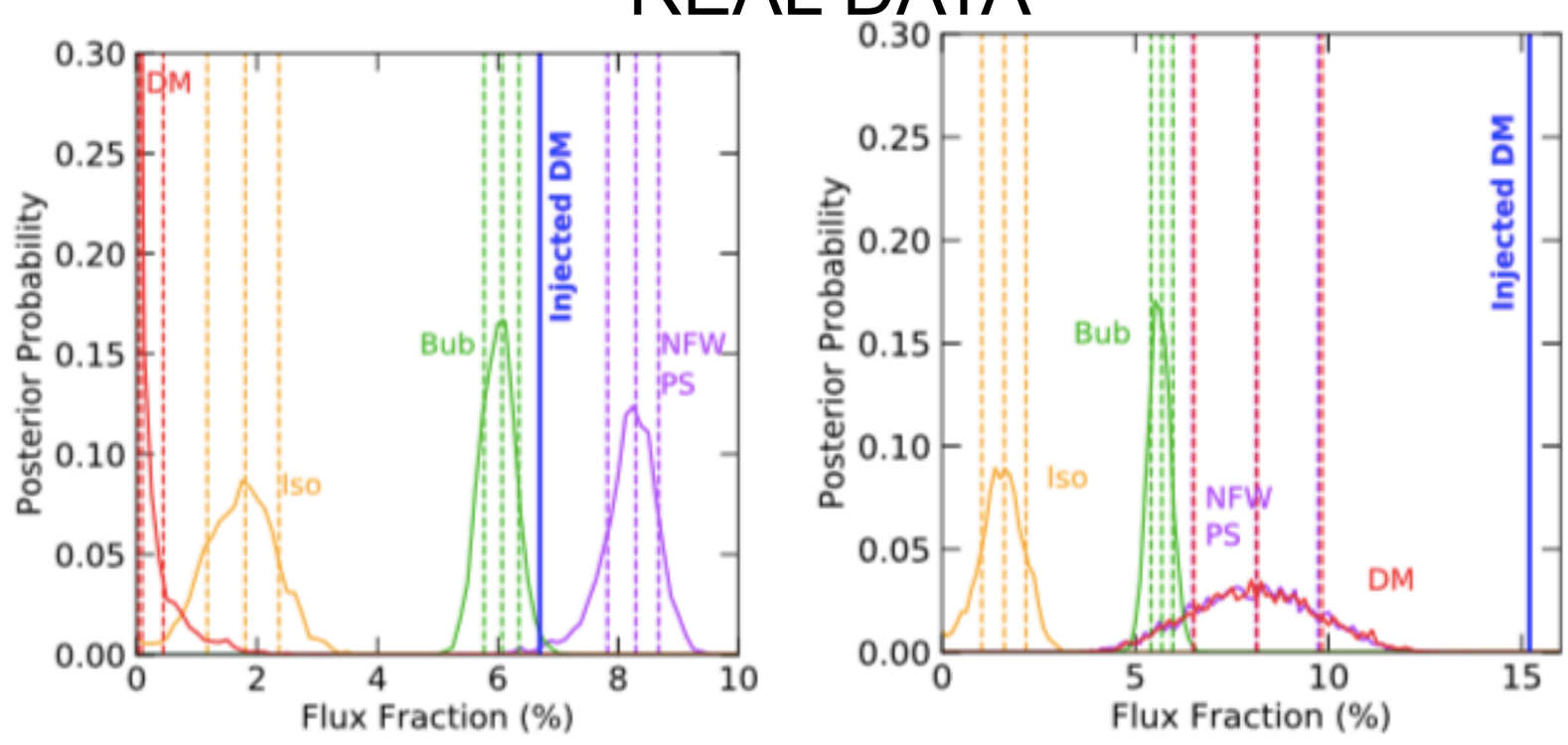


Dark matter strikes back?

- Injecting a simulated DM signal into real data, the signal is not correctly recovered.
- Even for injected DM signal ~5x larger than GCE, fit attributes signal to PSs.
- Indicates a discrepancy between simulated/real data - large enough to potentially hide a O(1) smooth contribution to GCE.
- But note: this does <u>not</u> mean the answer is DM, just that there's a systematic to understand (if we want to use this method to distinguish scenarios).

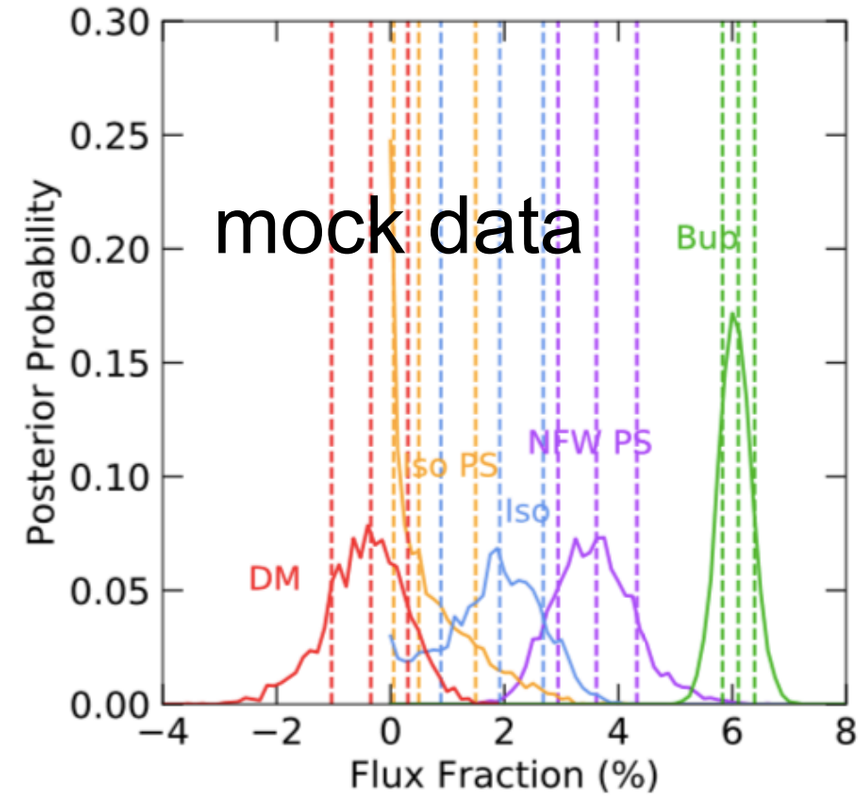


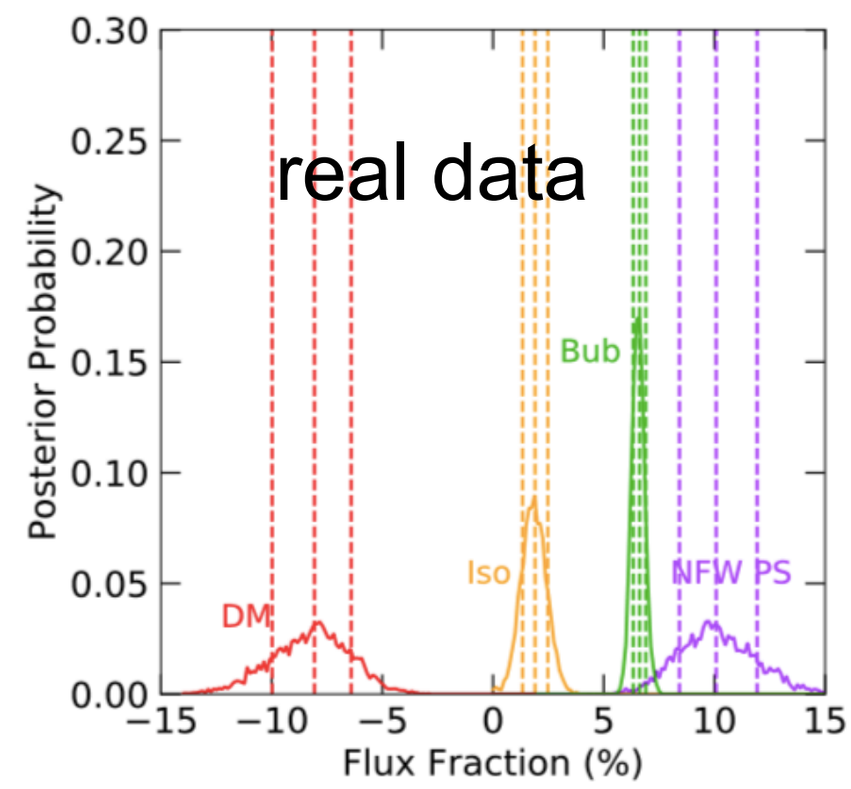
REAL DATA



A complementary analysis

- Instead of injecting a fake DM signal, we can relax the prior on the DM template so its coefficient can run negative.
- Not physical, but allows us to test if the fit is driven into an unphysical region.
- In real data we find the fit prefers a very negative DM coefficient - in simulated data with correct templates the posterior is typically skewed only slightly negative.
- Work in progress by my group and others to understand and correct this behavior [e.g. initial study by Chang et al 1908.10874].





Summary

- Indirect searches for DM currently exclude thermal relic (~weak-scale) annihilation cross sections for DM up to 10s-hundreds of GeV in mass, depending on the annihilation final state.

- Over most final states, for DM masses from keV-EeV, decay lifetimes of $10^{27\text{-}28}$ s can likewise be excluded.

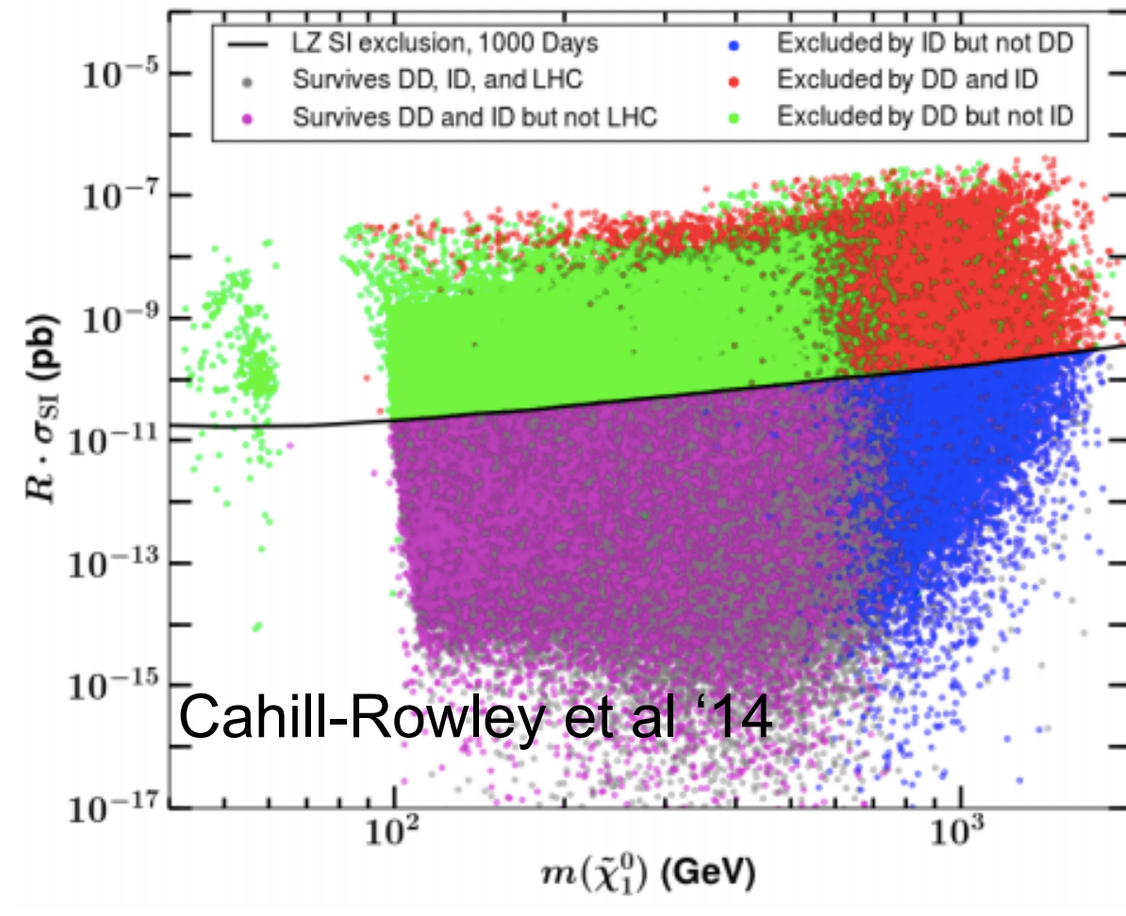
- There are several indirect-detection anomalies that might hold clues to DM and are not yet fully resolved, although all are either of low significance or have possible astrophysical origins.

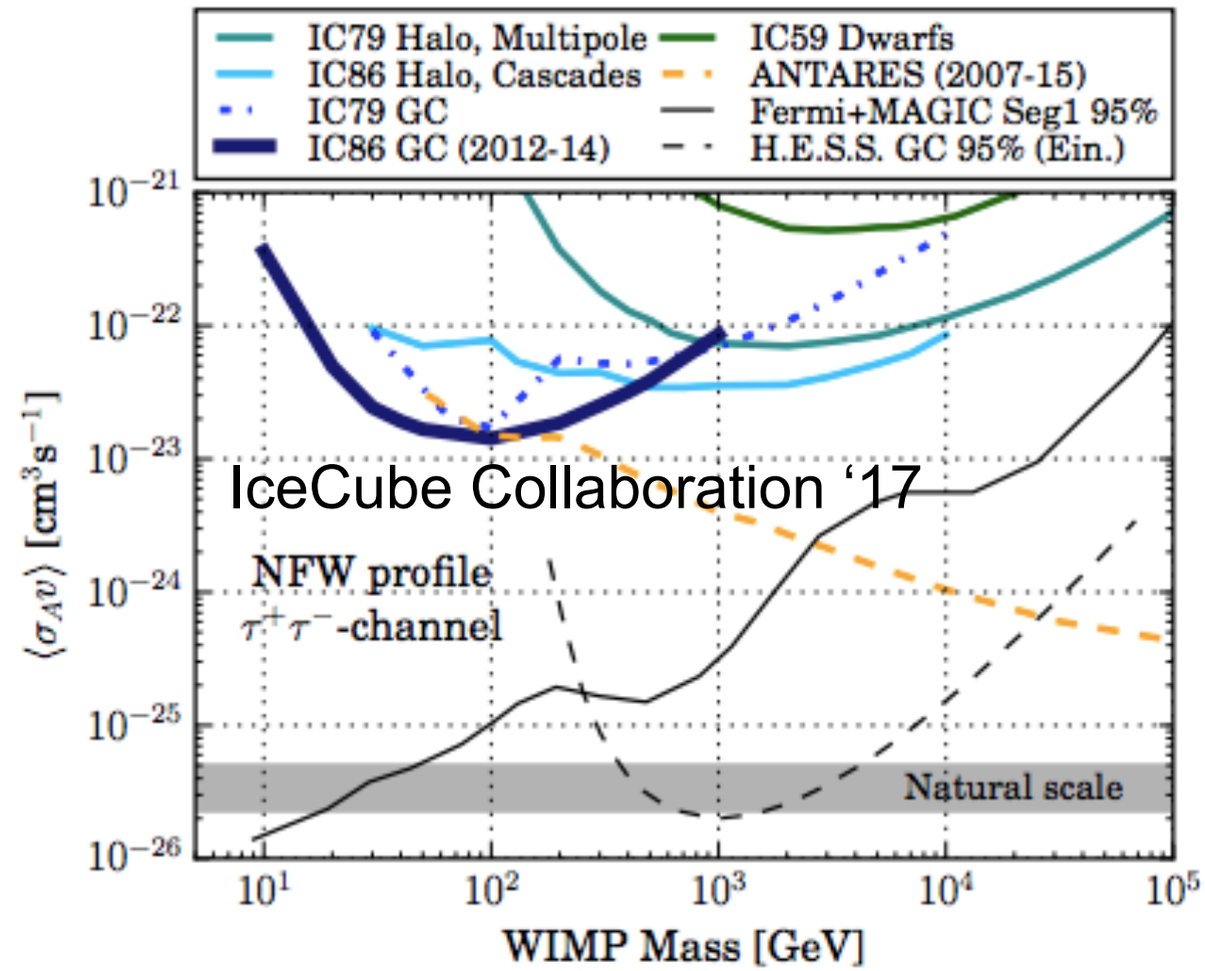
- Previous arguments that the Galactic Center excess cannot be DM due to photon statistics may be premature - need to understand systematics from (mis)modeling of backgrounds to make this claim robust.

BONUS SLIDES

Heavy neutralinos

- For scans over supersymmetric models, typically indirect detection is most powerful for high-mass DM.
- Complements collider searches, which can probe sub-TeV masses.
- Some of the strongest limits come from high-energy gamma ray telescopes such as H.E.S.S. and VERITAS.
- At even higher masses, neutrino searches can dominate.

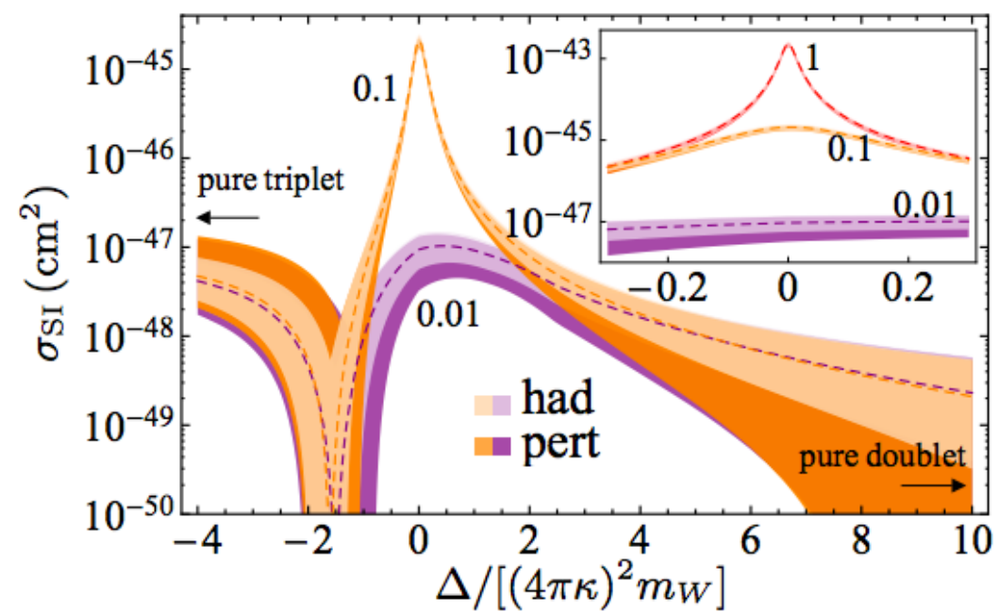




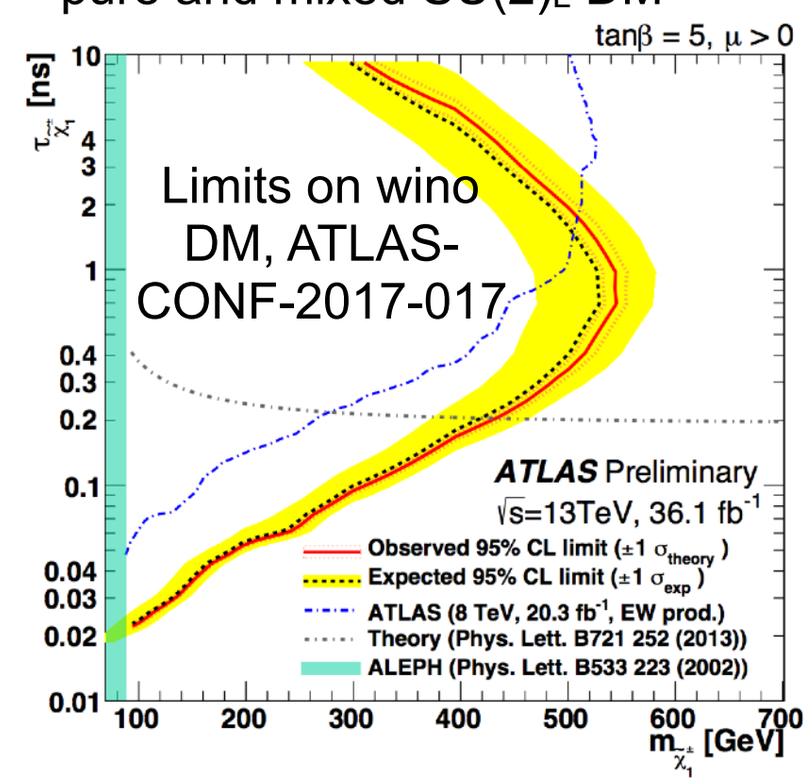
Limiting cases: the wino and higgsino

- Pure or near-pure higgsinos and winos produce the right dark matter abundance for masses of 1 TeV, 3 TeV respectively.
- Difficult to detect at colliders due to their high masses.
- Direct detection signals are well below current limits.
- Indirect detection offers hope - the wino is likely excluded unless the DM density is very low at the GC [Rinchiuso et al ’18], the higgsino can potentially be probed by CTA [Hryczuk et al ’19].

Hill & Solon ‘14



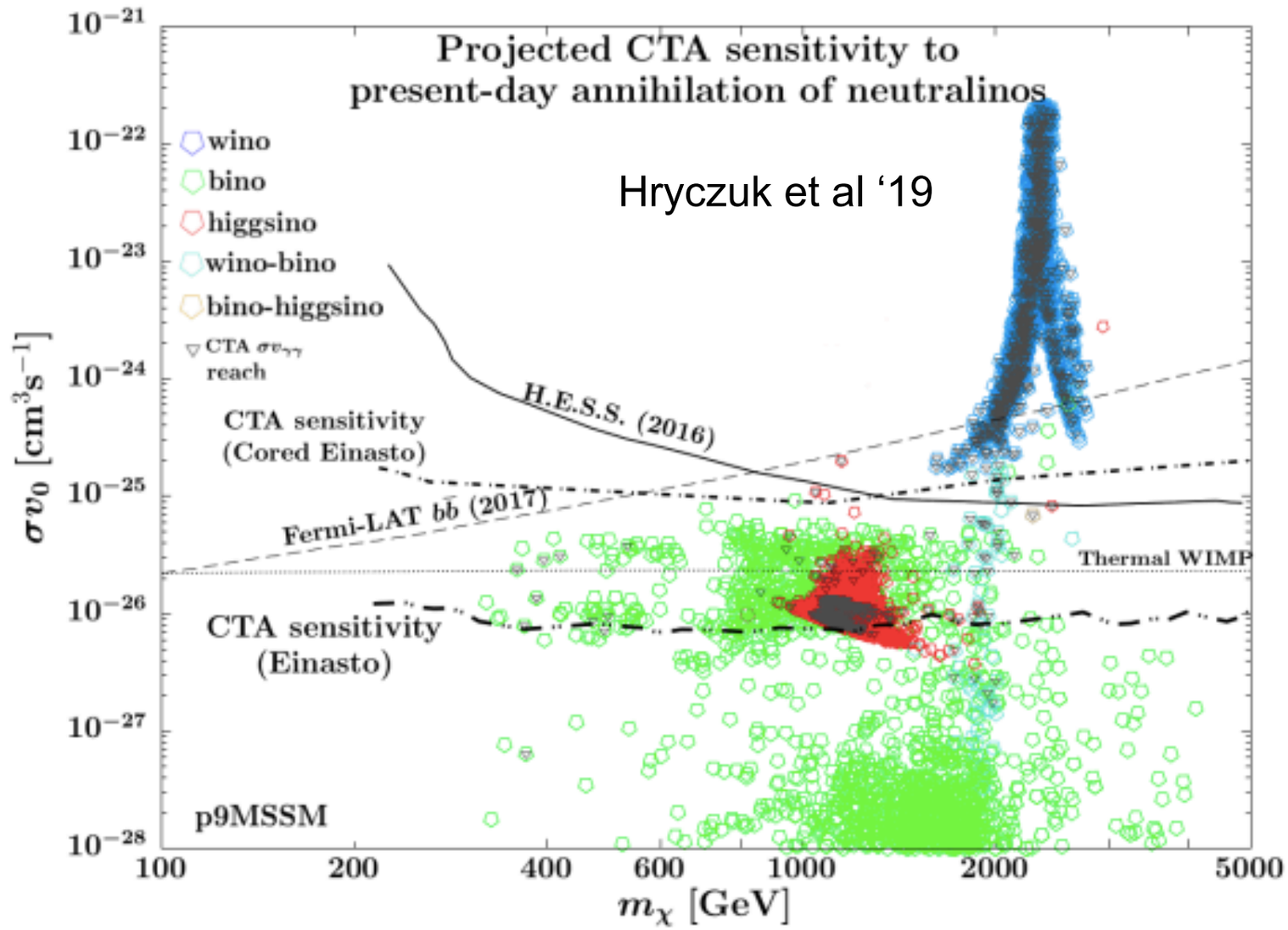
Predictions for direct detection of pure and mixed $SU(2)_L$ DM



Future limits from CTA

- Recent analysis (Hryczuk et al ’19) explores expected sensitivity of the Cherenkov Telescope Array (CTA) for phenomenological MSSM

- CTA expected to carve deep into higgsino-like region (green points = bino-like, red points = higgsino-like, blue points = wino-like) assuming an Einasto-like density profile



- In work to appear soon (led by L. Rinchiuso), we have studied the effects of including a central core in the dark matter profile, + including Galactic diffuse emission backgrounds.

- Preliminary results indicate the CTA may have sensitivity to the thermal Higgsino for any core radius smaller than ~1kpc.

Proof-of-principle example

- One possible cause of such a discrepancy would be if there is a new point-source population (<u>not</u> associated with the GCE) that we are not modeling correctly.

- Simple example as a demonstration (not the actual answer): suppose there were point sources in the base of the Fermi Bubbles (e.g. small dense gas clumps illuminated by cosmic-ray flux through the Bubbles).

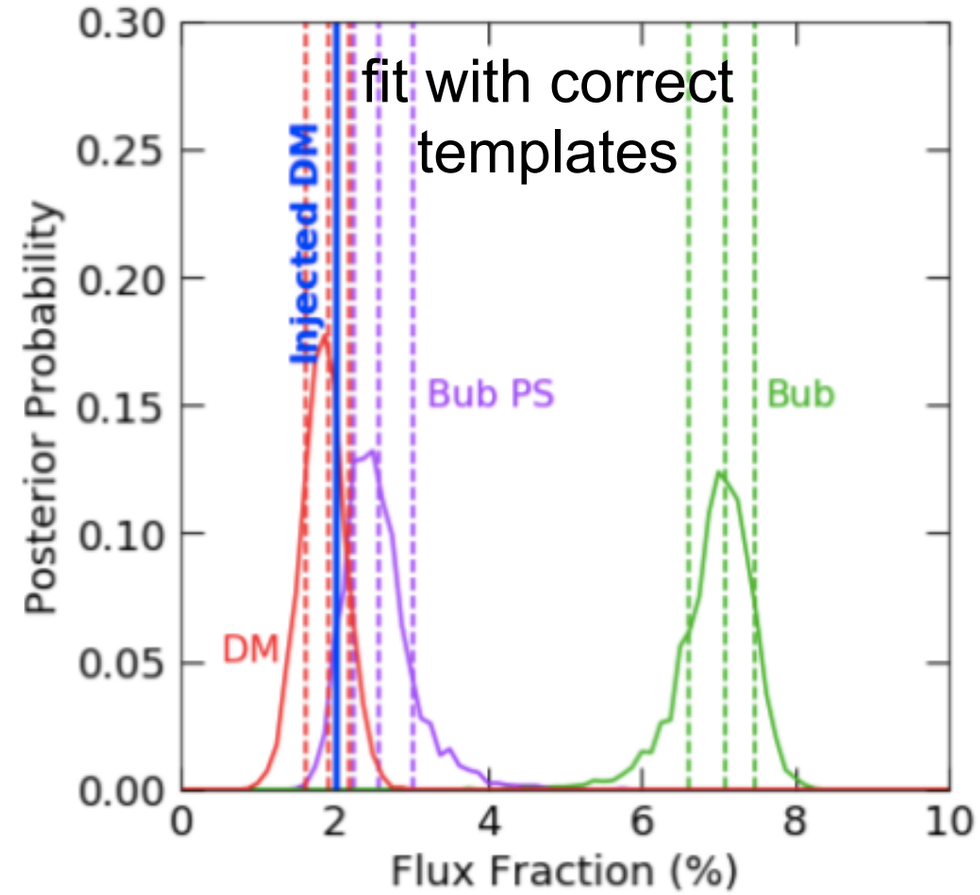
- No template in the fit can perfectly describe this population. To try to explain it, the fit could assign these PSs to the GCE, driving down the DM component to maintain the correct total GCE flux.

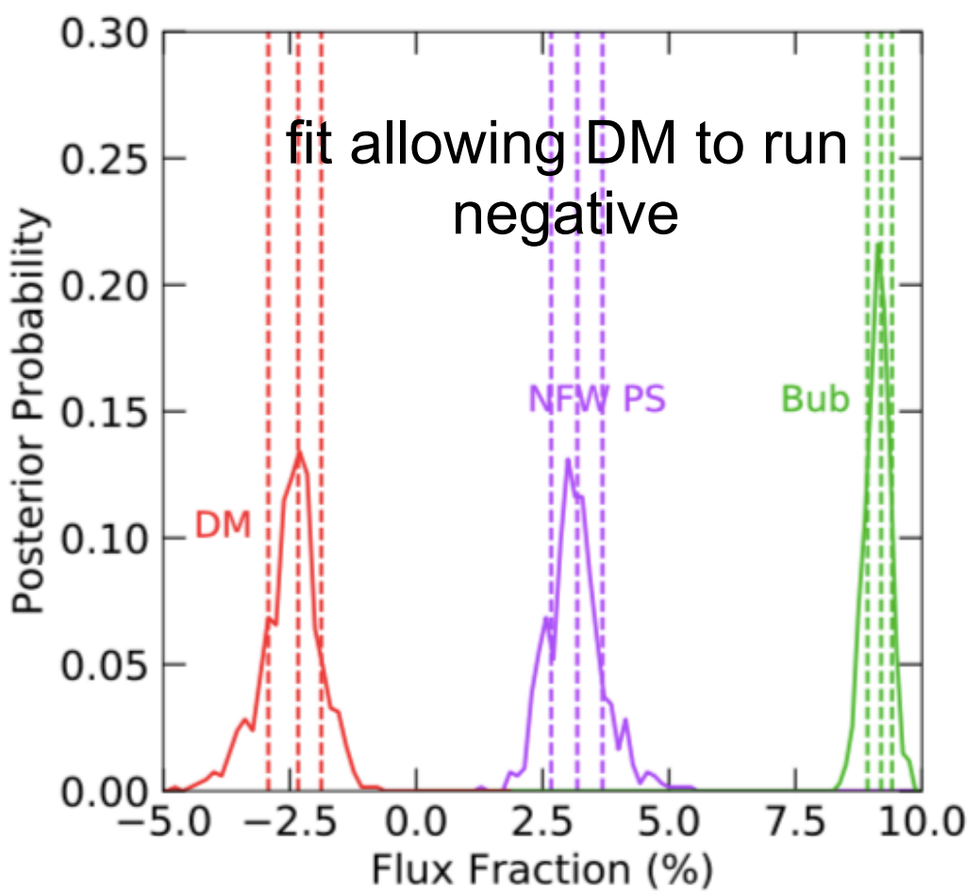
- We demonstrated this scenario can indeed lead to a failure of the injection test, similar to what is observed in real data.

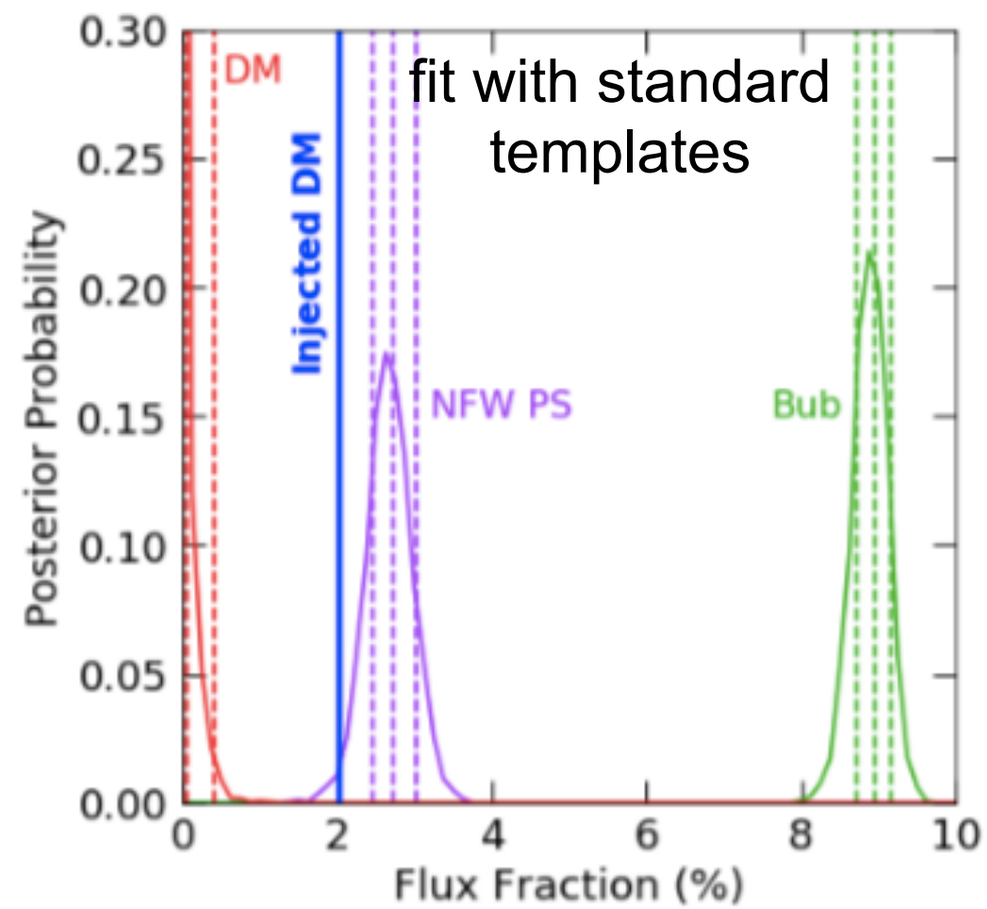
- Similarly, mis-modeling of the Galactic diffuse emission could also be a contributor to the problem.

Proof-of-principle example: plots

- This example behaves similarly to the real data, but is not as extreme
- The real data does not appear to contain Bubbles-correlated PSs







Explanations for failure of injection test

- Chang et al [arXiv:1908.10874] make the argument that if the underlying source count function (SCF) is fairly soft (many faint PSs) then:
  - the NPTF will often still reconstruct a (wrong) hard SCF
  - additional injected DM signals can naturally be reconstructed incorrectly in this case
  - the presence of at least some point sources is quite robust to this particular systematic error - unlikely to be a spurious detection if this is the sole problem
- Does not (at least at this stage) seem to quantitatively explain degree to which injection test is failed - plausible to absorb O(GCE) injected signals, but in real data much larger injections are mis-reconstructed
- Probably need other systematic errors as well - not obvious if near-threshold PSs are also robust to these systematics