Dark Matter Indirect Detection

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Outline

- Current constraints on DM annihilation and decay
- New developments in indirect detection of heavy neutralinos
- Anomaly watch: an update on the GeV Galactic Center excess (see also talk by Dessert for an update on the 3.5 keV line)

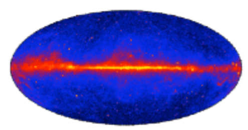
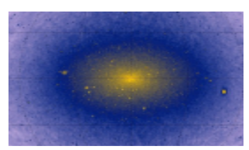
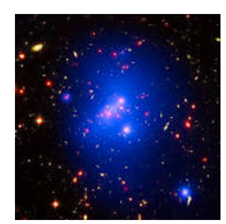
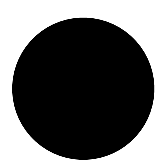
Dark matter, SUSY and indirect searches

- No good dark matter candidates within the SM.
- Enormous spectrum of possible candidates beyond the Standard Model, over a huge range of mass scales (10^{-21} eV → 100 $M_\odot$).
- Many possible origin scenarios, but one of the simplest is thermal freezeout:
  - DM in thermal equilibrium with SM in early universe - abundance depleted through annihilation reactions.
  - Predicts benchmark "thermal relic" annihilation rate - predictive target for annihilation searches:

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

  - Cross section is naturally generated for TeV-scale DM and weak-scale mediators - possible connection to DM candidates in SUSY.

Where to look?

- Dwarf galaxies 
- Galactic center 
- Galactic halo 
- Other galaxies and clusters 
- Dark matter subhalos 
- Extragalactic background radiation

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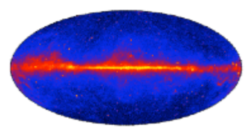
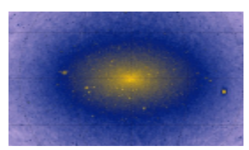
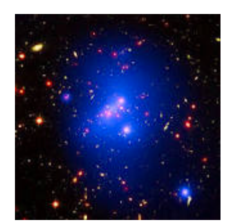
- Galactic center 
- Galactic halo 
- Other galaxies and clusters 
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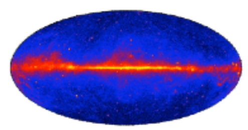
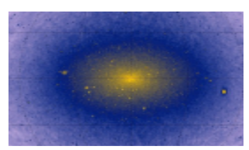
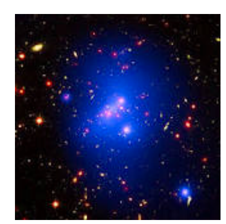
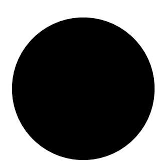
- Galactic center  high signal, high background, sensitive to presence of density cusp/core
- Galactic halo 
- Other galaxies and clusters 
- Dark matter subhalos 
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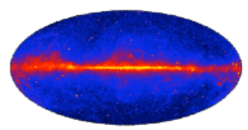
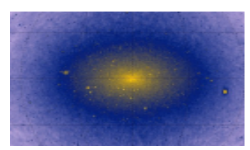
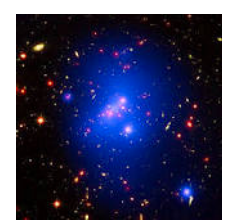
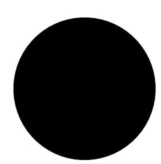
- Galactic center  high signal, high background, sensitive to presence of density cusp/core
- Galactic halo  large area, nearby, complex backgrounds
- Other galaxies and clusters 
- Dark matter subhalos 
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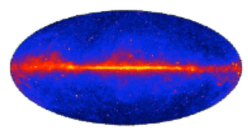
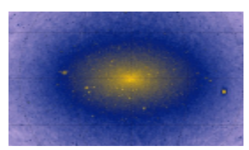
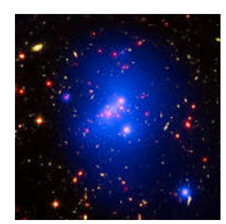
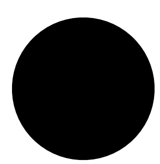
- Galactic center  high signal, high background, sensitive to presence of density cusp/core
- Galactic halo  large area, nearby, complex backgrounds
- Other galaxies and clusters  large dark matter content, (potentially) hold redshift information, sensitive to amount of substructure
- Dark matter subhalos 
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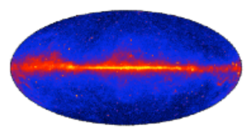
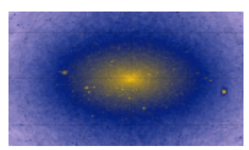
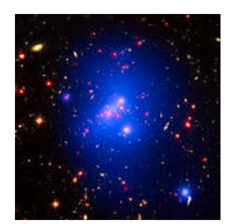
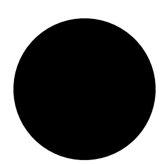
- Galactic center  high signal, high background, sensitive to presence of density cusp/core
- Galactic halo  large area, nearby, complex backgrounds
- Other galaxies and clusters  large dark matter content, (potentially) hold redshift information, sensitive to amount of substructure
- Dark matter subhalos  potentially numerous, probe small-scale structure
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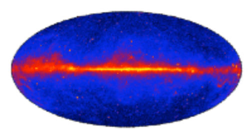
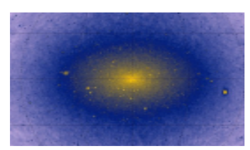
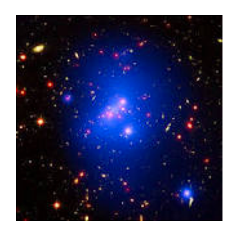
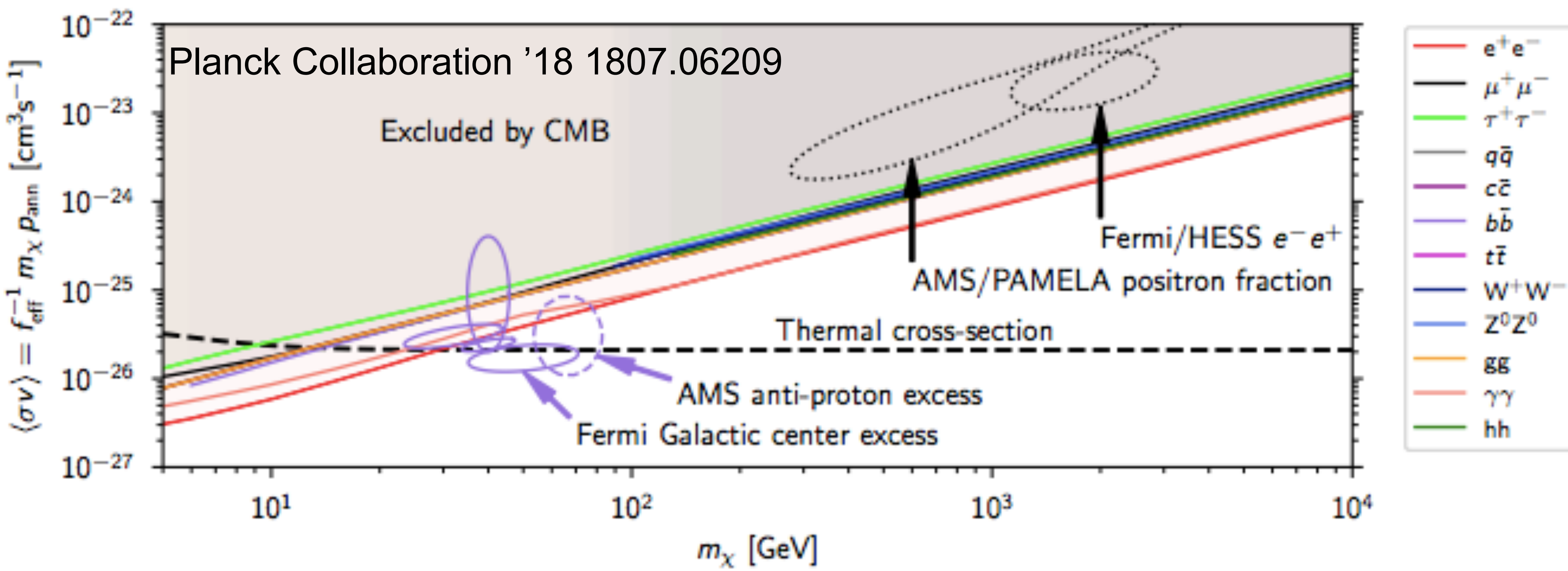
- Galactic center  high signal, high background, sensitive to presence of density cusp/core
- Galactic halo  large area, nearby, complex backgrounds
- Other galaxies and clusters  large dark matter content, (potentially) hold redshift information, sensitive to amount of substructure
- Dark matter subhalos — potentially numerous, probe small-scale structure
- Extragalactic background radiation — holds redshift information, probes halos at all scales

The status of annihilating DM



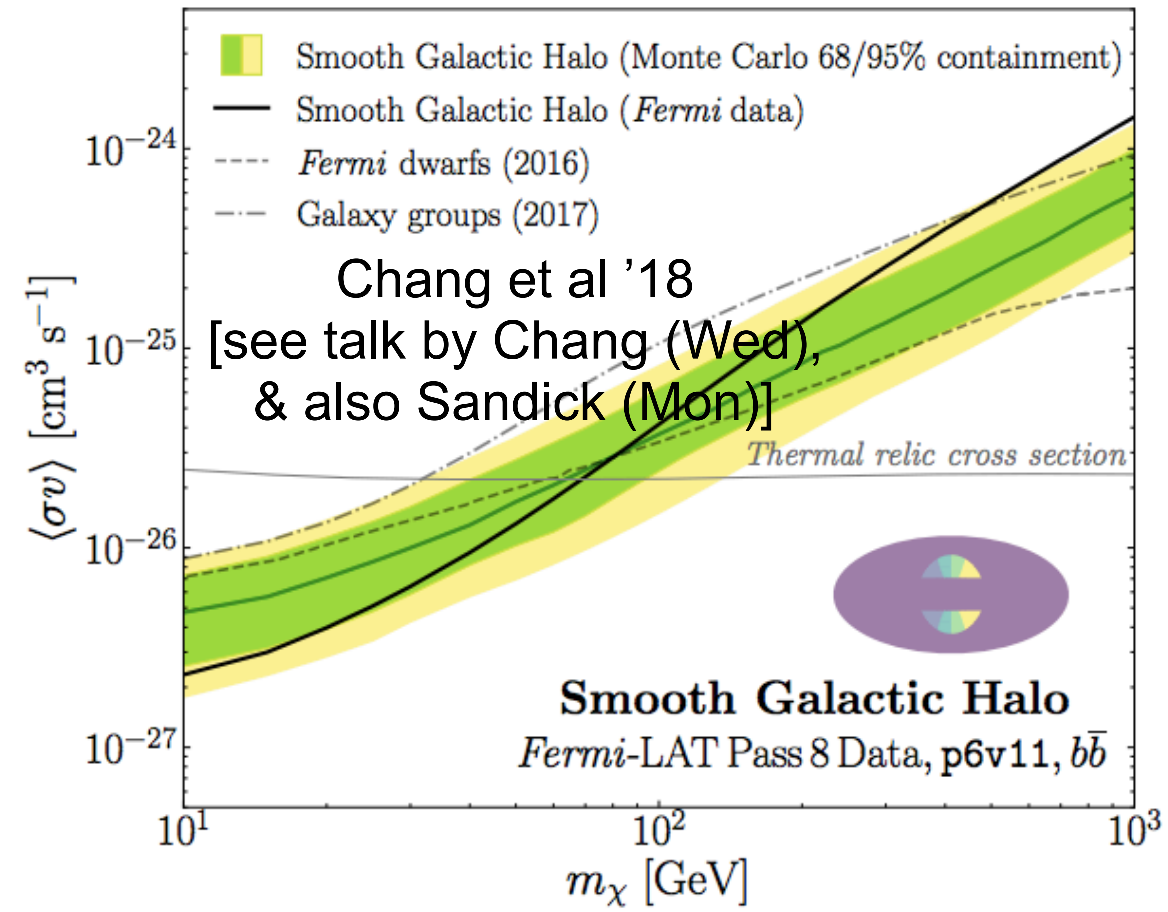
- CMB limits: thermal cross-section ruled out for DM below ~10 GeV unless there is a significant invisible/neutrino branching fraction.
- Consequently, GeV-scale or lighter DM typically requires a non-thermal origin or suppressed late-time annihilation rate (see Monday talk by Wu for one example).
- Depending on the channel, we can probe higher DM masses using other observations.

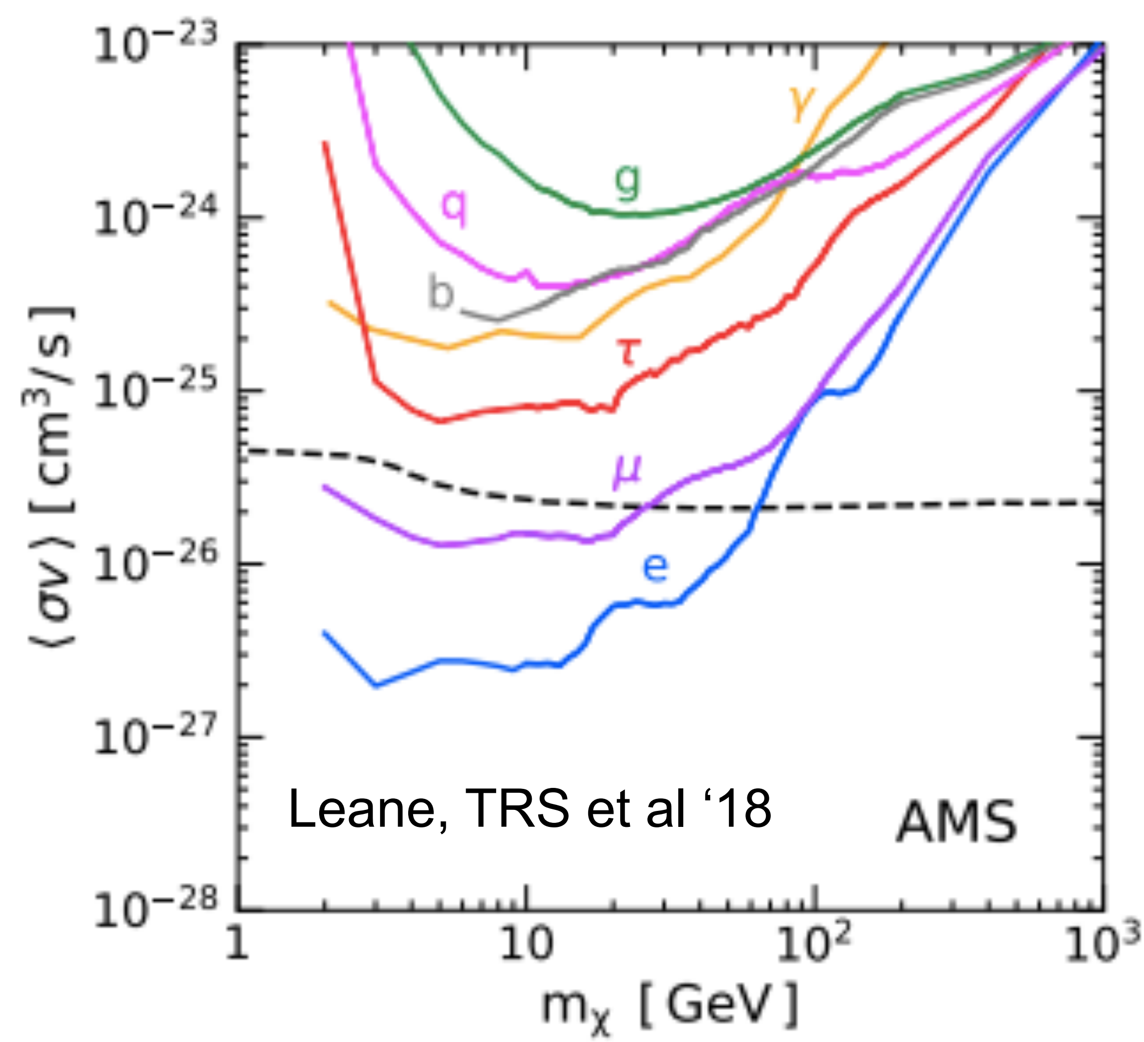
Cosmic rays and gamma rays

- 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.

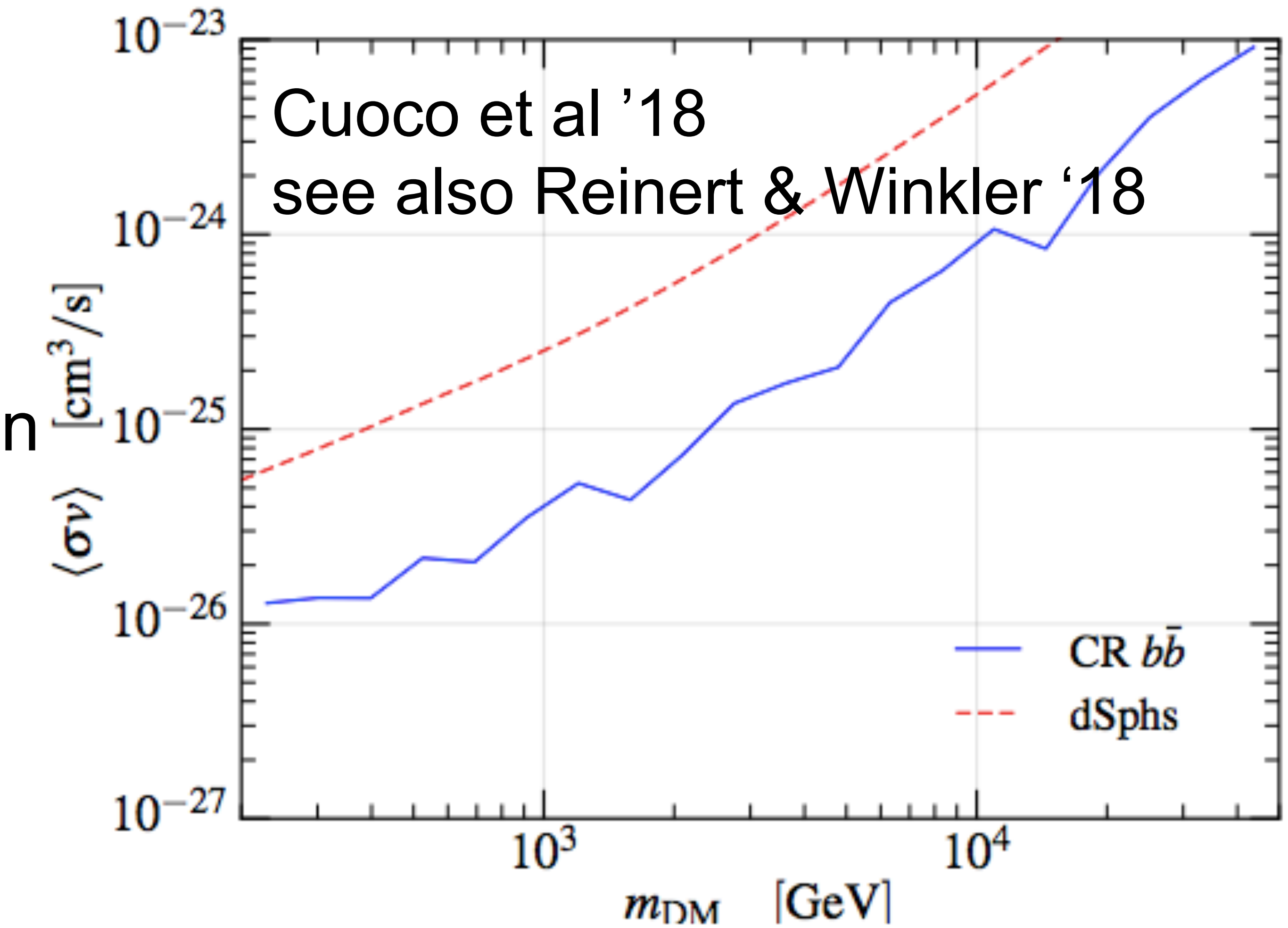
- Least constrained final states (in mass) are rich in leptons, especially muons, with thermal cross sections viable down to ~20 GeV - strongest limits come from AMS-02 positron flux measurements.

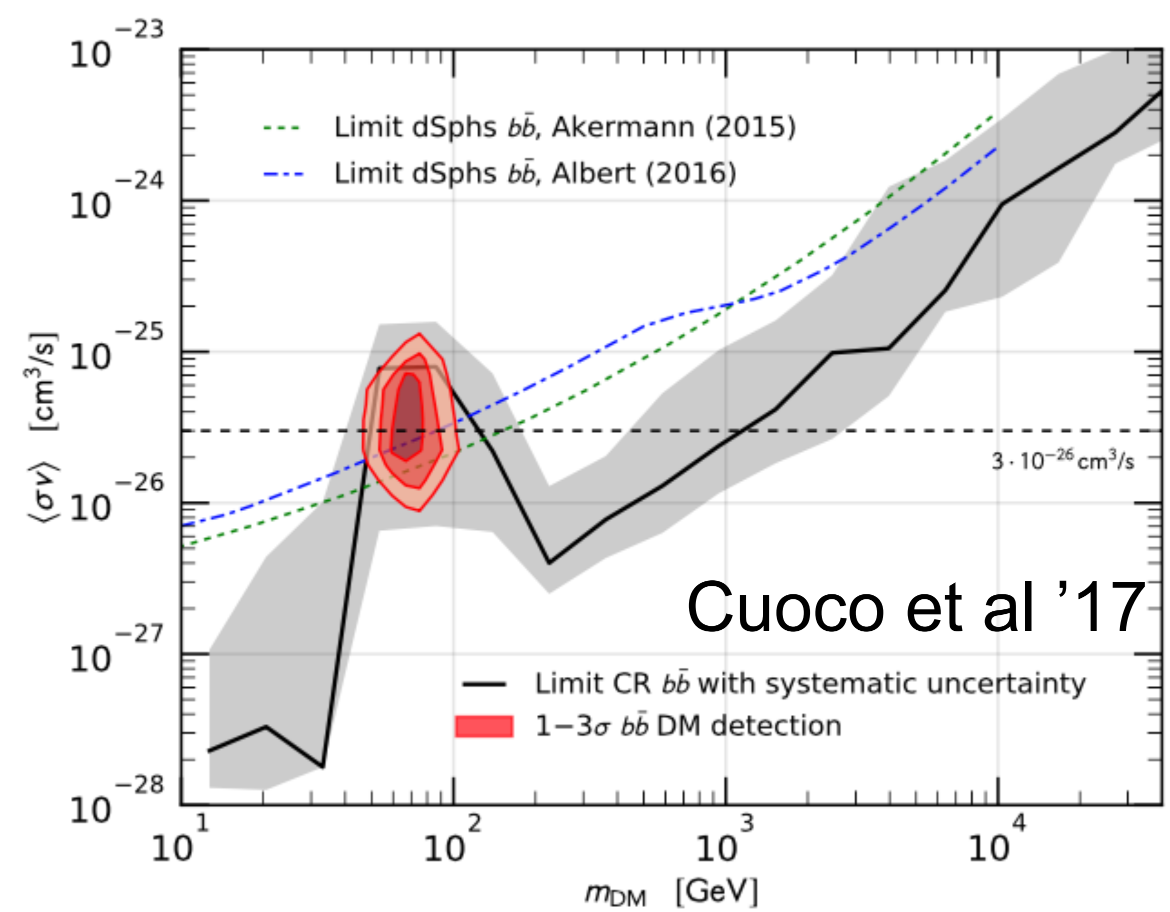




Antiprotons

- Can potentially set stronger limits than gamma rays, for hadronic channels, extending the mass reach up to several hundred GeV 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 debated [see Cuoco et al '19, Cholis et al '19, Reinert & Winkler '18, Cui et al '17, Cuoco et al '17]

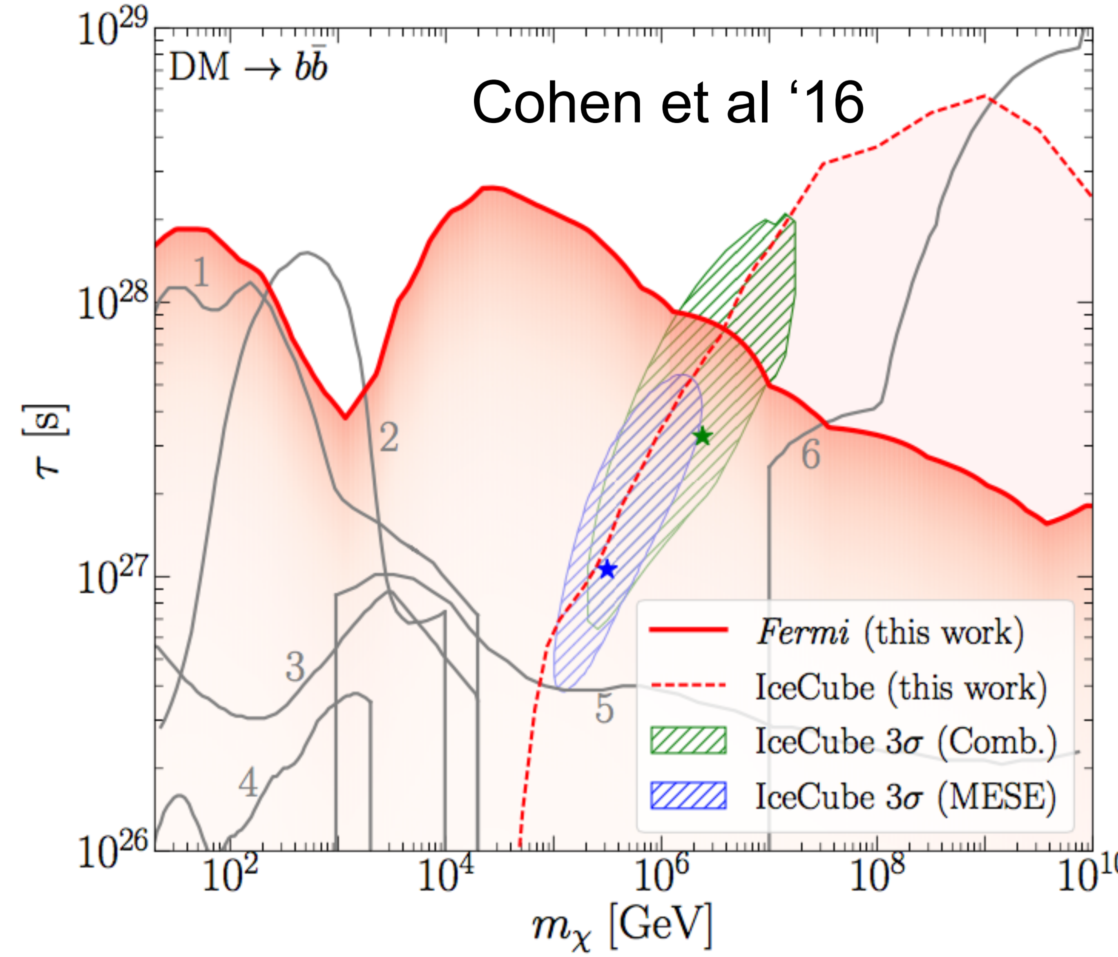


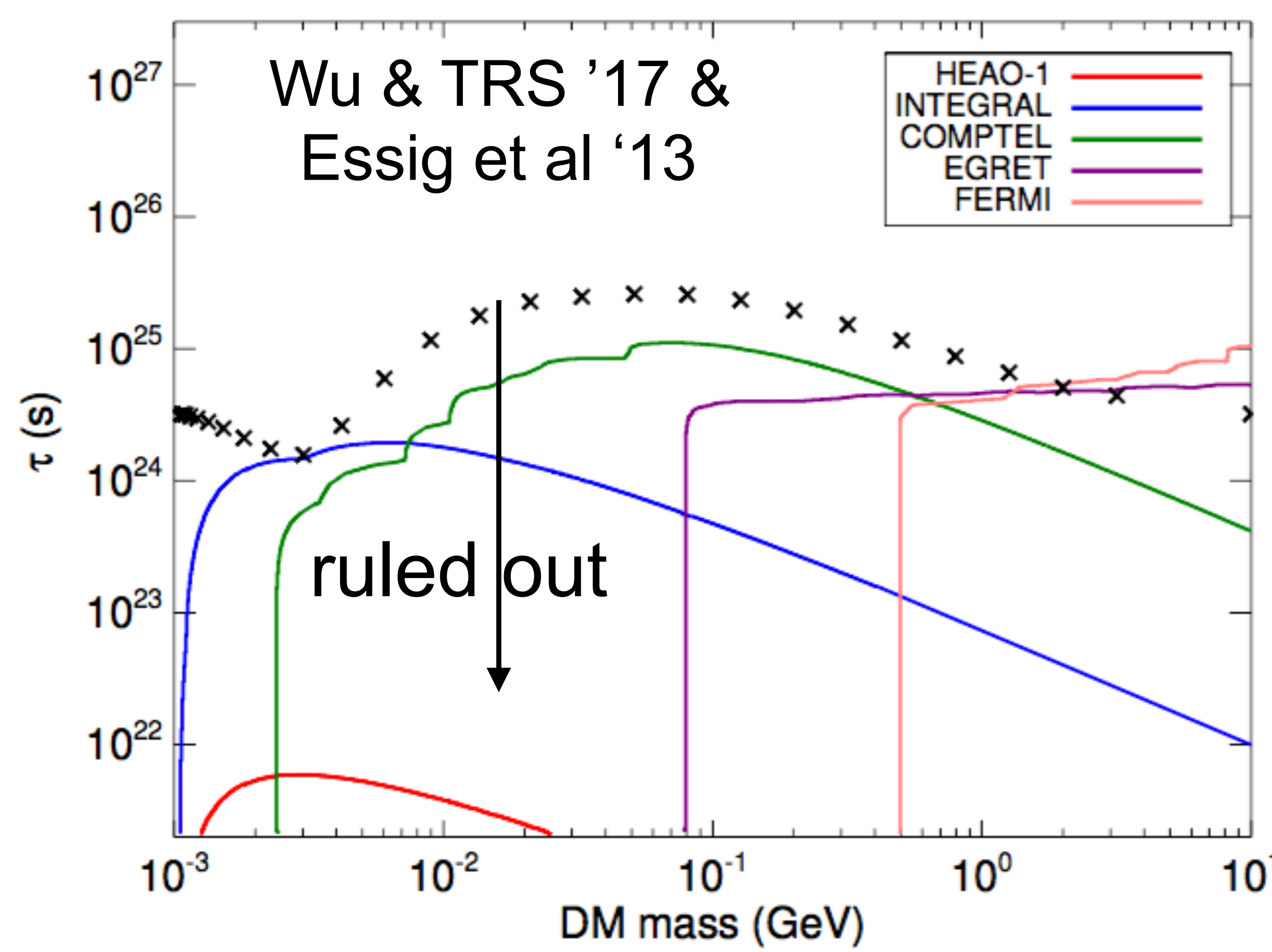


*if estimates for systematic uncertainties in cosmic-ray propagation are adequate

Decaying dark matter

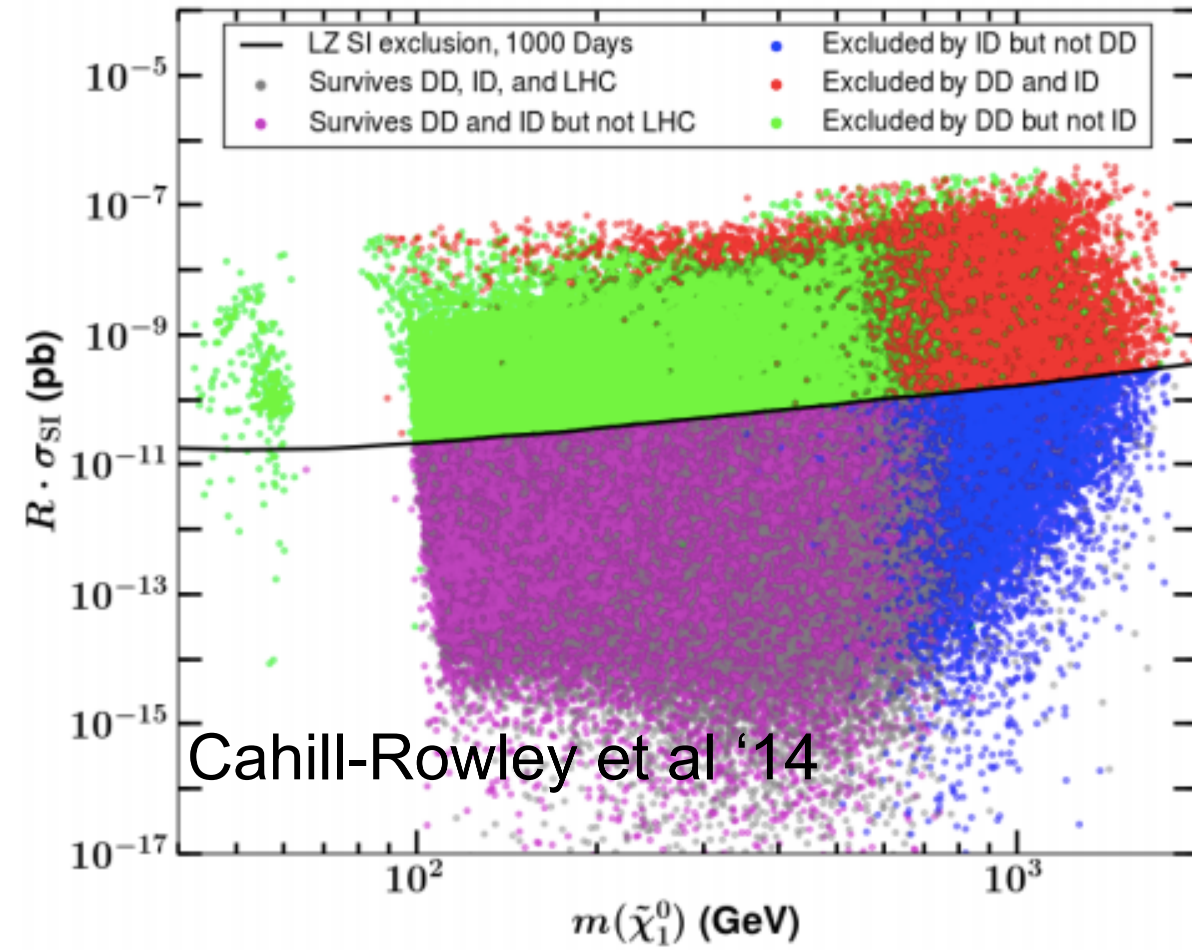
- GeV+ decaying DM constrained by dwarf galaxies, galaxy clusters, extragalactic gamma-ray background, Milky Way halo.
- Lifetime lower limits ~10^{27-28} s, for DM masses in the 10-10^{10} GeV range, for representative hadronic decay channels.
- For sub-GeV DM, comparable lifetime limits for photon-rich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

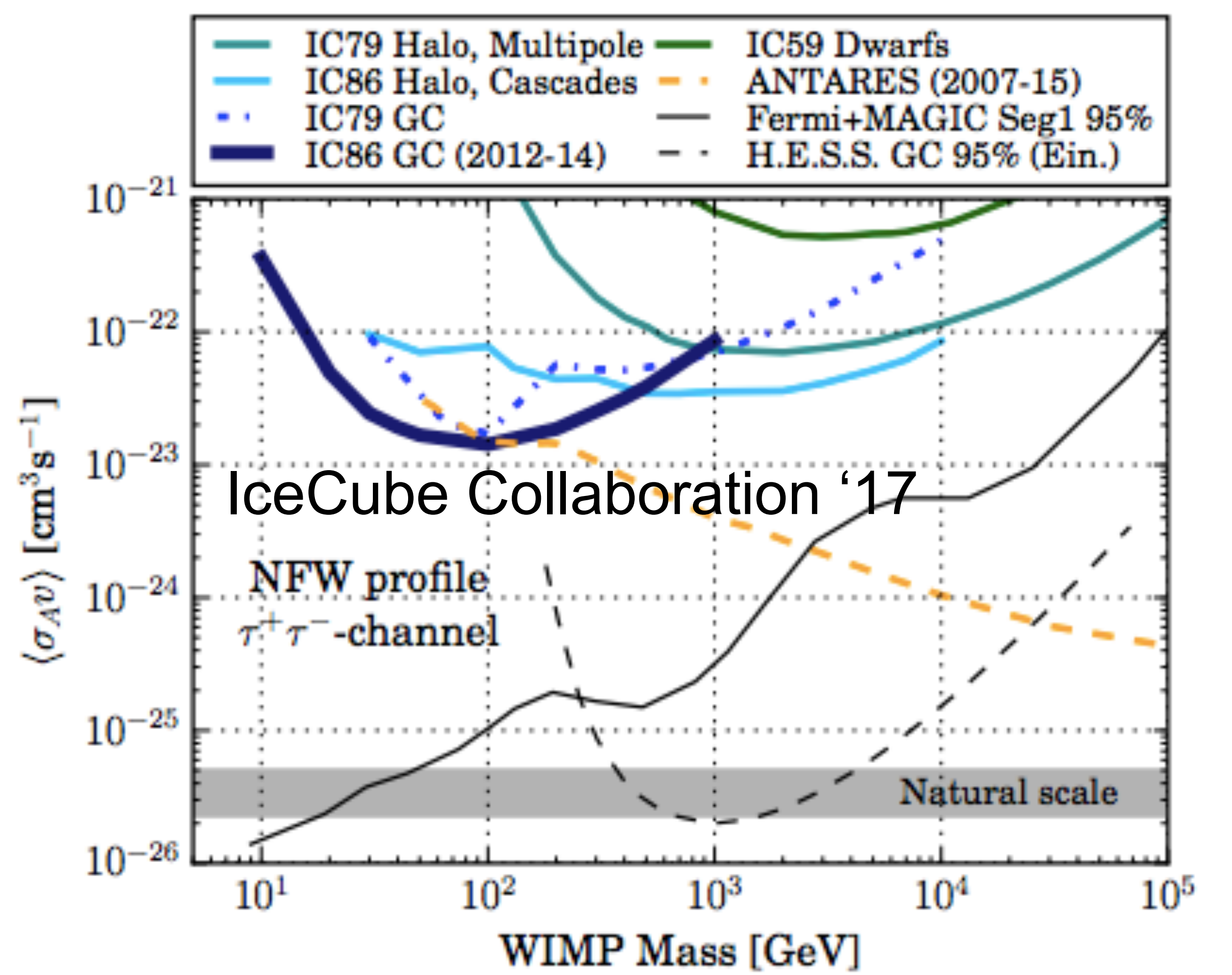




Heavy neutralinos

- For scans over SUSY models (e.g. phenomenological MSSM), 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 (see preceding talk by Carsten Rott).

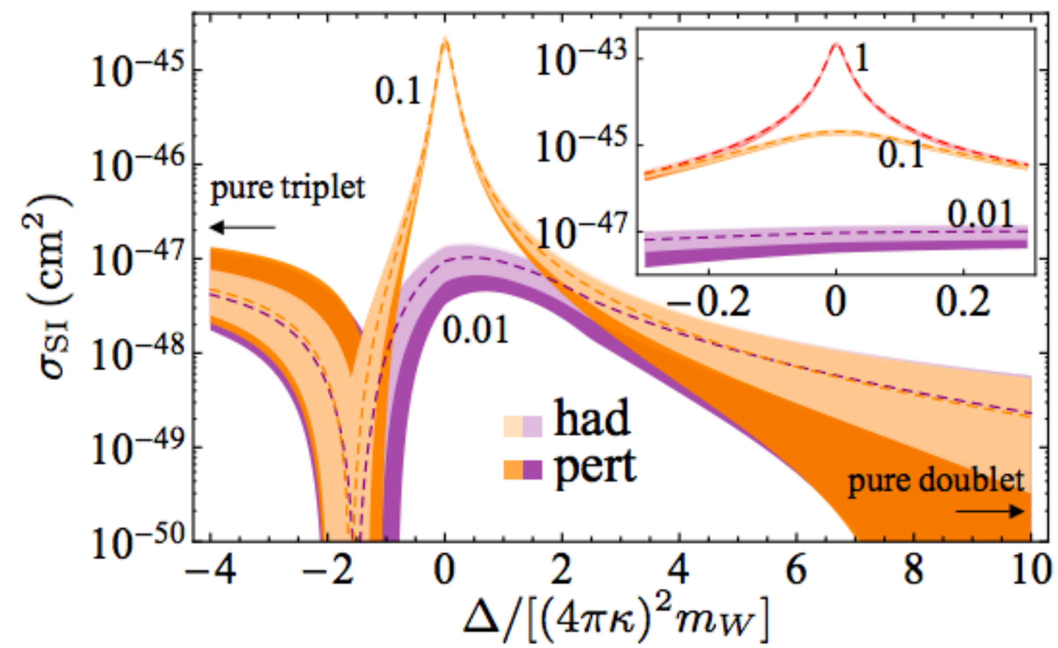




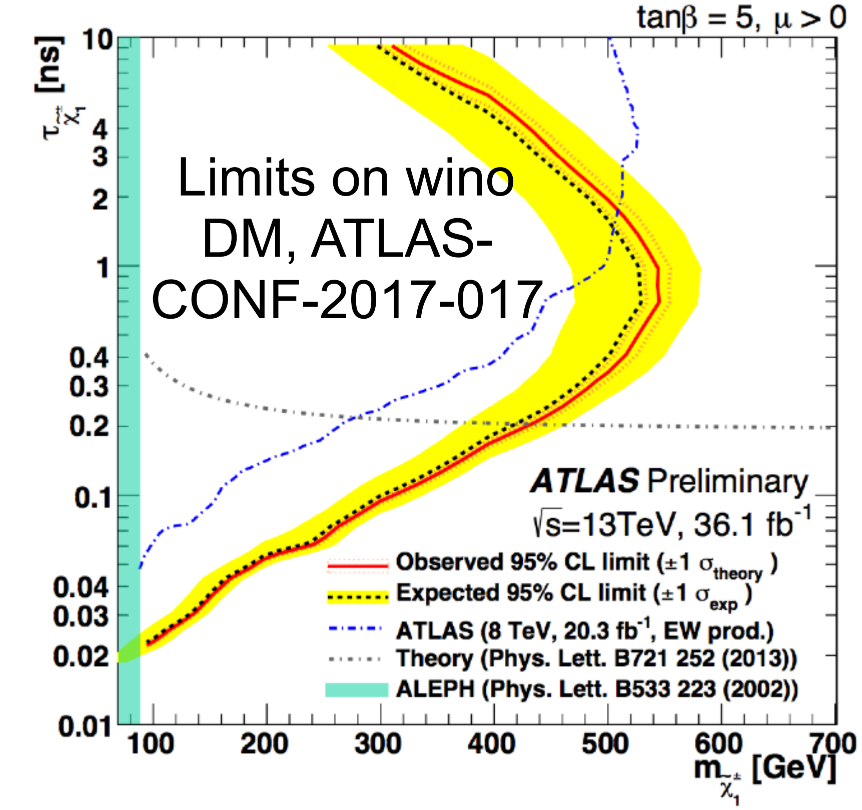
Limiting cases: the wino and higgsino

- 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.
- However, the wino in particular predicts a strong indirect detection signal - at a 3 TeV thermal mass, long-range interactions from W/Z exchanges enhance the annihilation rate.

Hill & Solon ‘14



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



Limits on wino DM, ATLAS-CONF-2017-017

Consequences of a large mass hierarchy m_{DM}/m_W

1. Sommerfeld enhancement - long-range attractive potential enhances annihilation processes

2. Bound states - formation of bound states + subsequent decay acts as a new annihilation channel

3. Large logs from small force carrier masses - big radiative corrections to annihilation rate/spectrum, need to be resummed.

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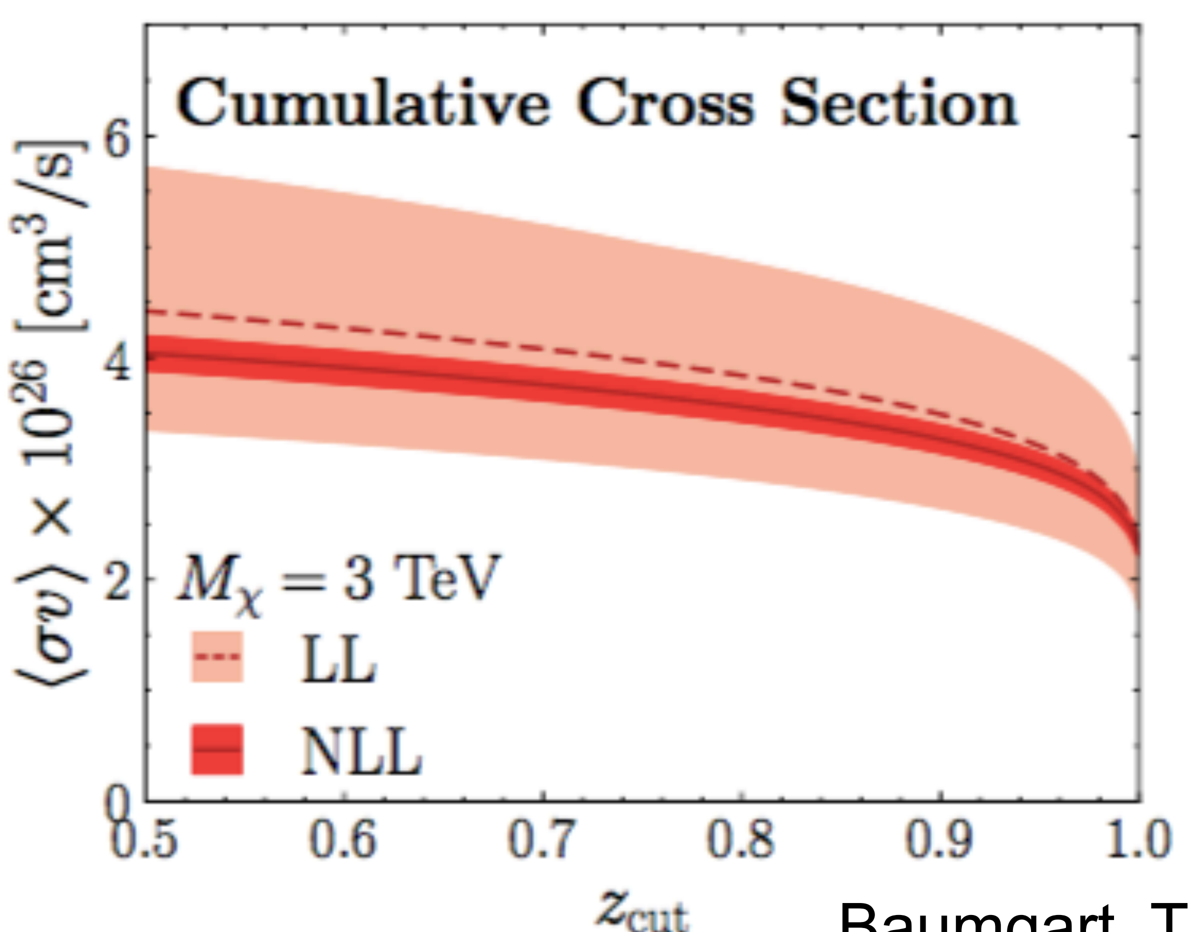
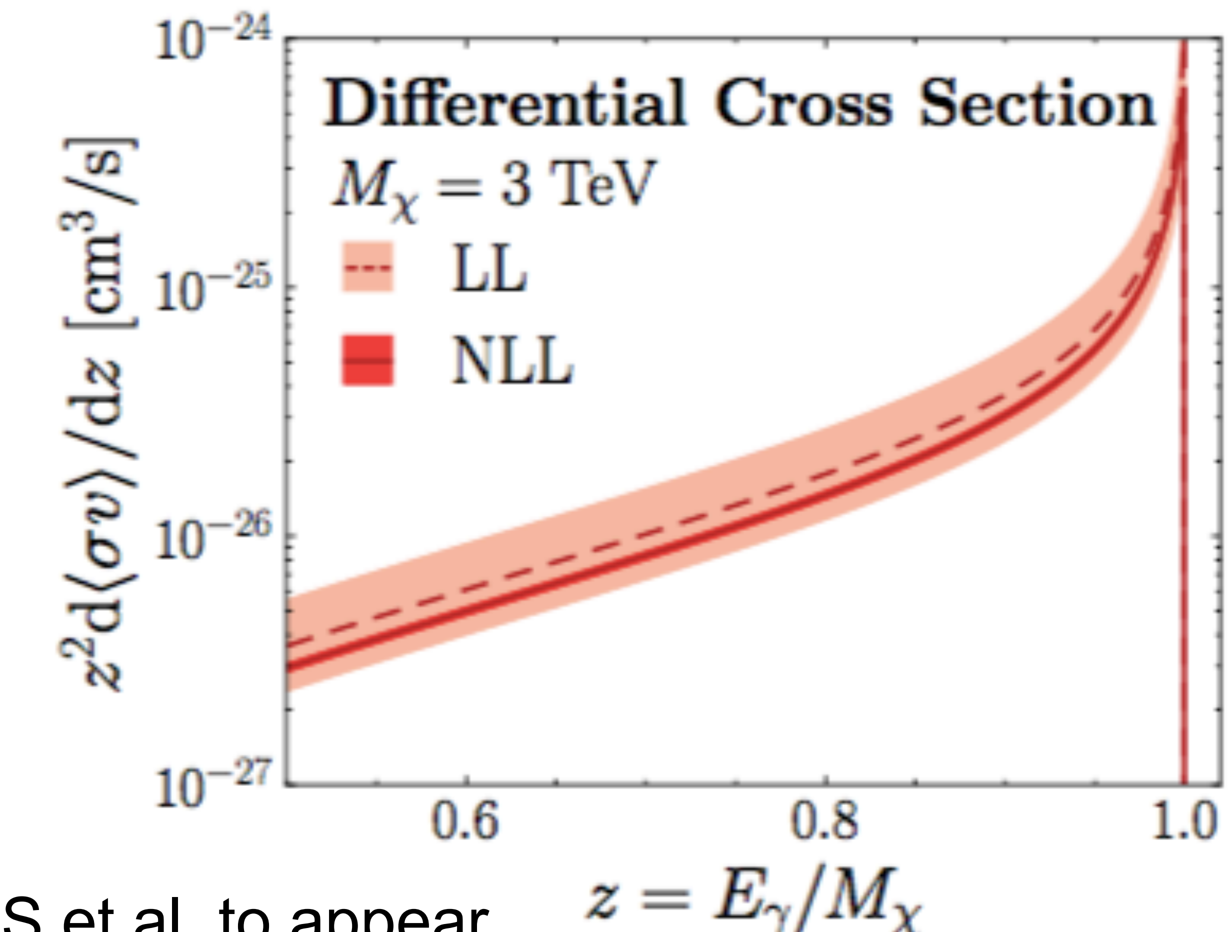
A high-precision gamma-ray spectrum for the wino

Baumgart, Cohen, Moulin, Moult, Rinchiuso, Rodd, TRS, Stewart & Vaidya '19

- We have computed the full resummed hard photon spectrum analytically to next-to-leading-log (NLL), including the Sommerfeld enhancement. [See also Beneke et al '19 for region very close to endpoint.]

- Our theory uncertainties are now at the level of 5%.





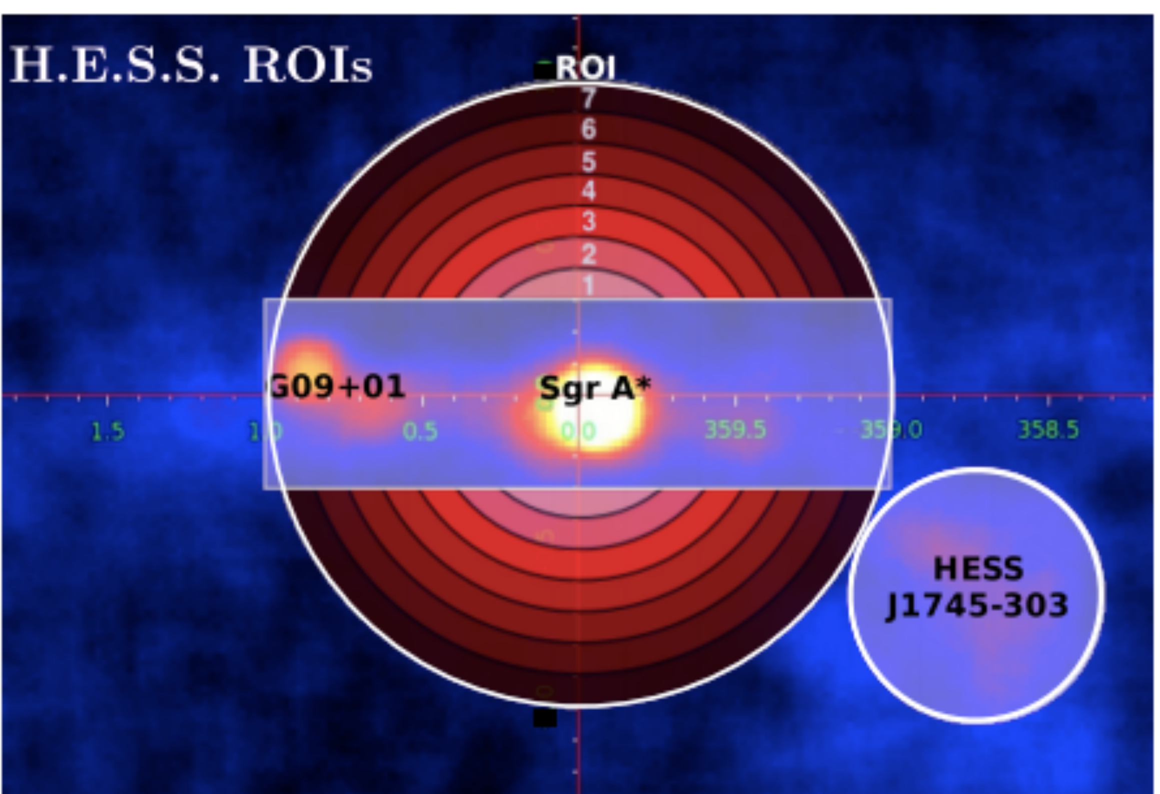
Baumgart, TRS et al, to appear

Hunting the wino with H.E.S.S

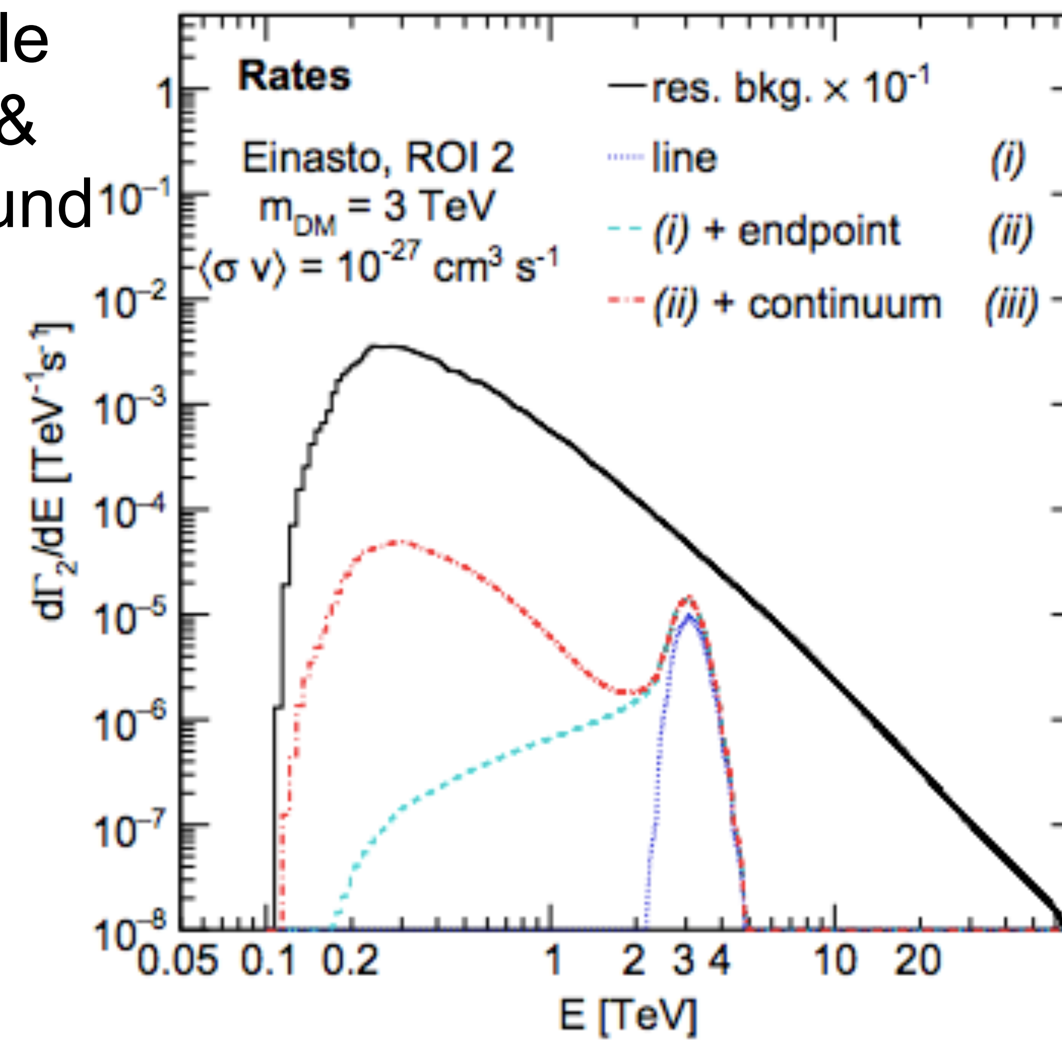
Rinchiuso, Rodd, Moult, Moulin, Baumgart, Cohen, TRS, Stewart & Vaidya '18

- In work led by Lucia Rinchiuso (H.E.S.S), we have forecast the constraints that current and future H.E.S.S observations of the Galactic Center could set on thermal winos.
- We consider a range of choices for the DM density profile, simulate backgrounds from cosmic rays and known gamma-ray sources, and account for the H.E.S.S. energy resolution.
- We perform a likelihood analysis on simulated data, binned in energy + distance from the Galactic Center.

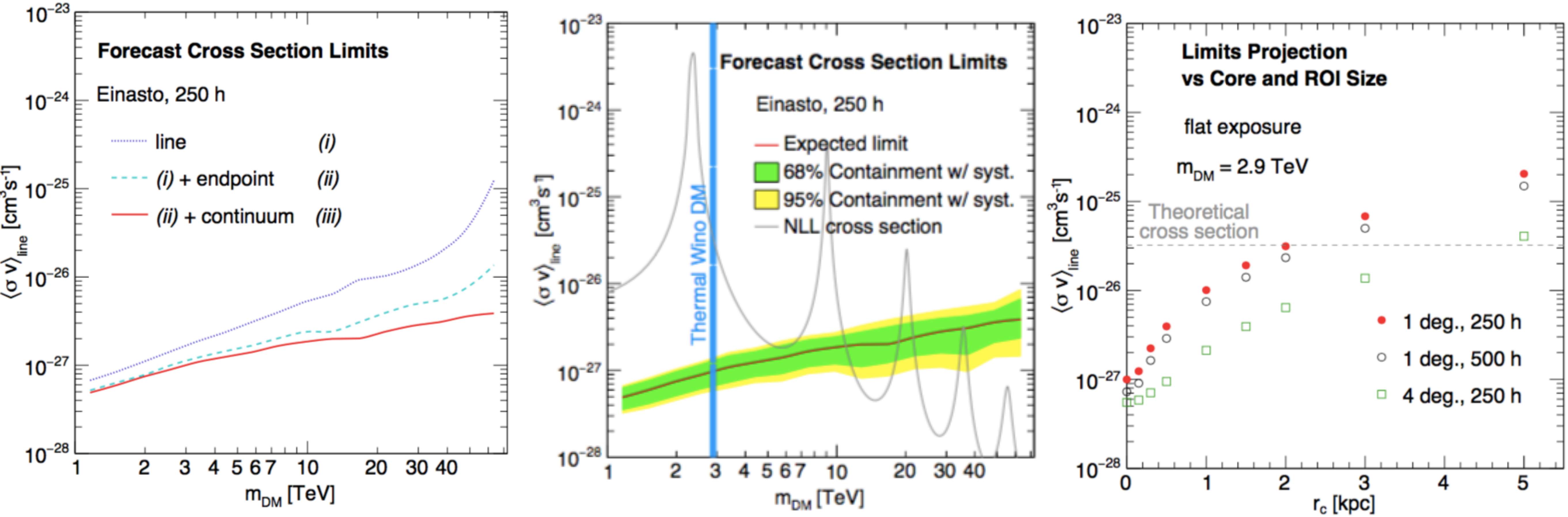
Spatial regions tested



Example signal & background



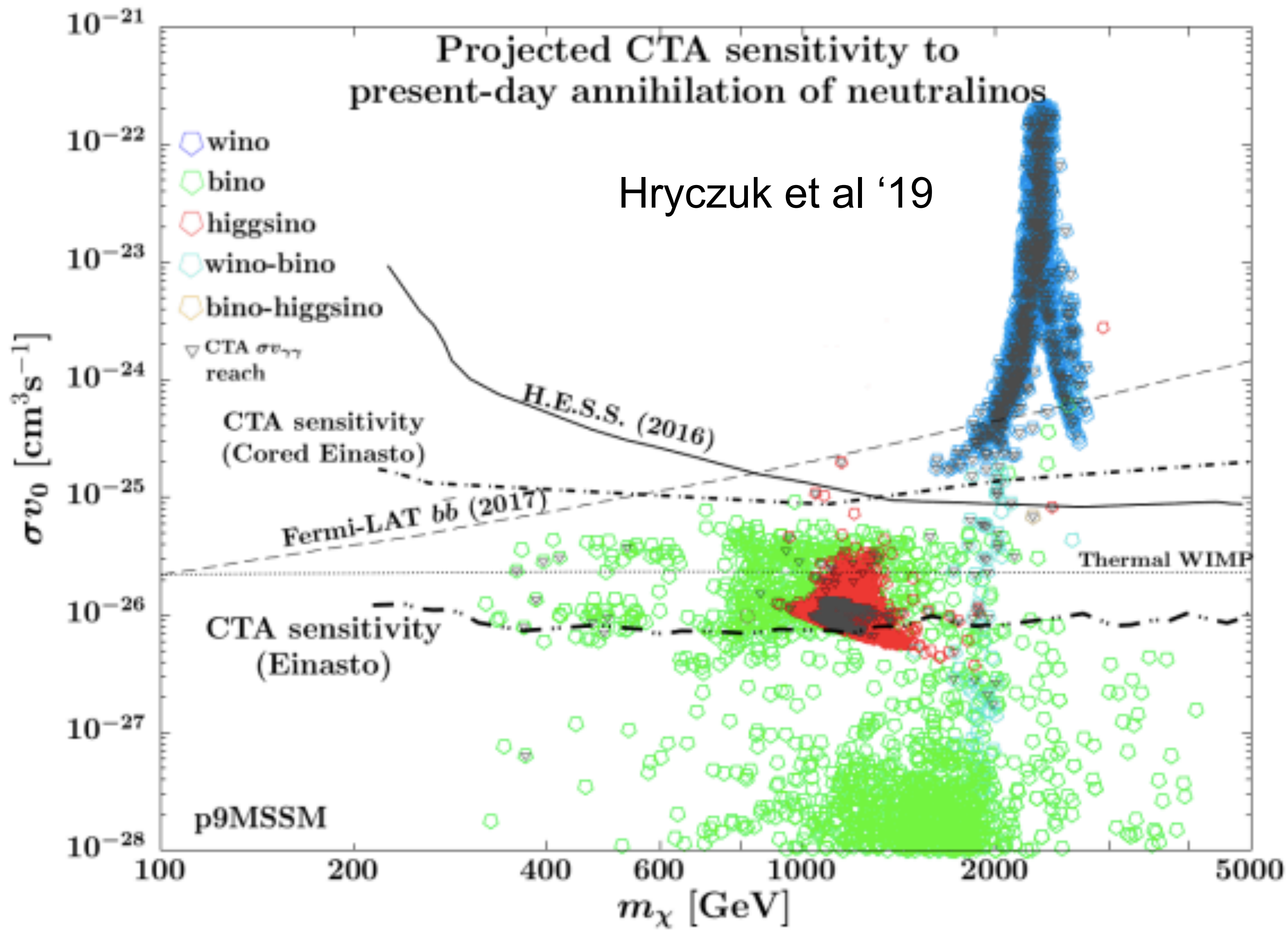
Forecast limits for H.E.S.S



- Using full spectrum improves limits by a factor ~1.5 for thermal wino compared to previous analyses including only the (resummed) gamma-ray line at the endpoint.
- Since this is a Galactic Center analysis, there is degeneracy between the limits and the DM density profile. However, an analysis of current data should have sensitivity to exclude thermal wino DM even if the Milky Way's DM density profile has a flat core, provided that the core radius is below 2 kpc.
- "Inner Galaxy Survey" strategy by H.E.S.S could test nearly 5kpc core sizes.

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.

Status of the GeV Galactic Center Excess (GCE)

- Apparent new gamma-ray component found in Fermi Gamma-Ray Space Telescope public data

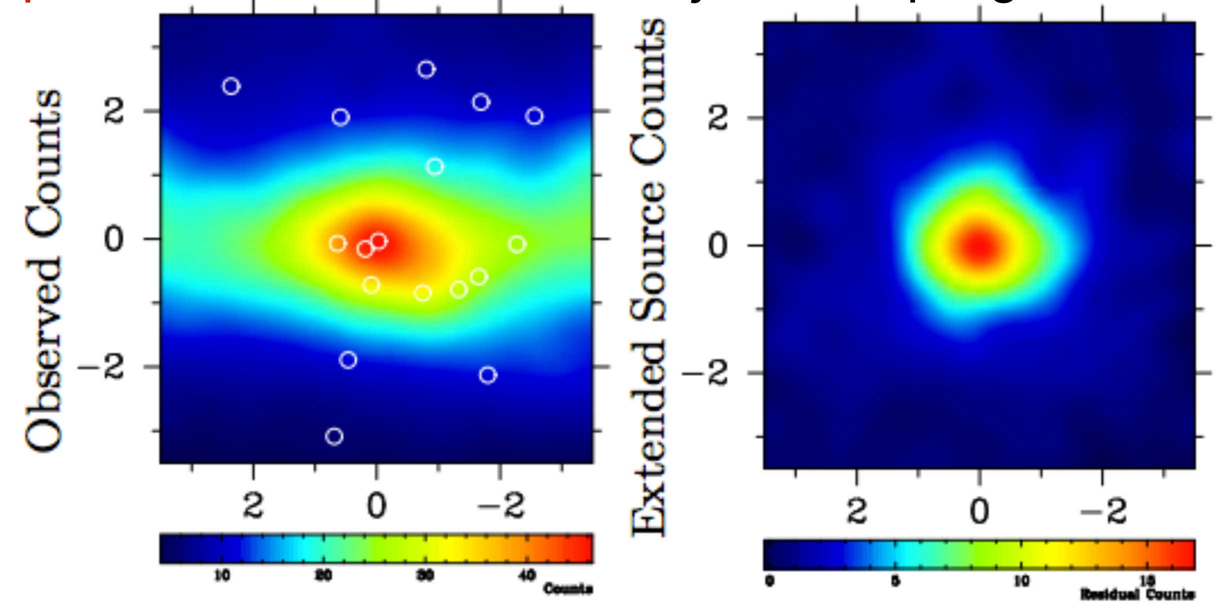
- Initial discovery '09 by Goodenough & Hooper, in the Galactic Center (GC), confirmed by Fermi Collaboration in analysis of Ajello et al '16 (and many other groups in interim)

- Photons peak around 1-3 GeV in energy

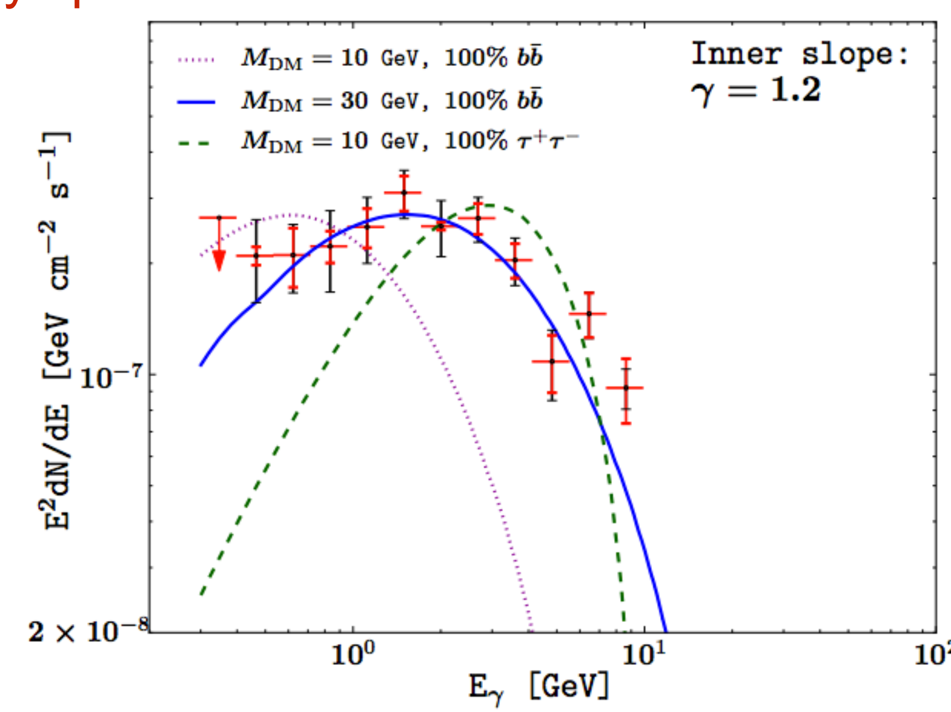
- Rate agrees well with expectations for thermal relic annihilating DM

- Excess is not disk-like, ~symmetric around the GC, steeply peaked at GC. Can also be well-described as Bulge-like extended emission + central symmetric core [Macias et al '18, Bartels et al '18].

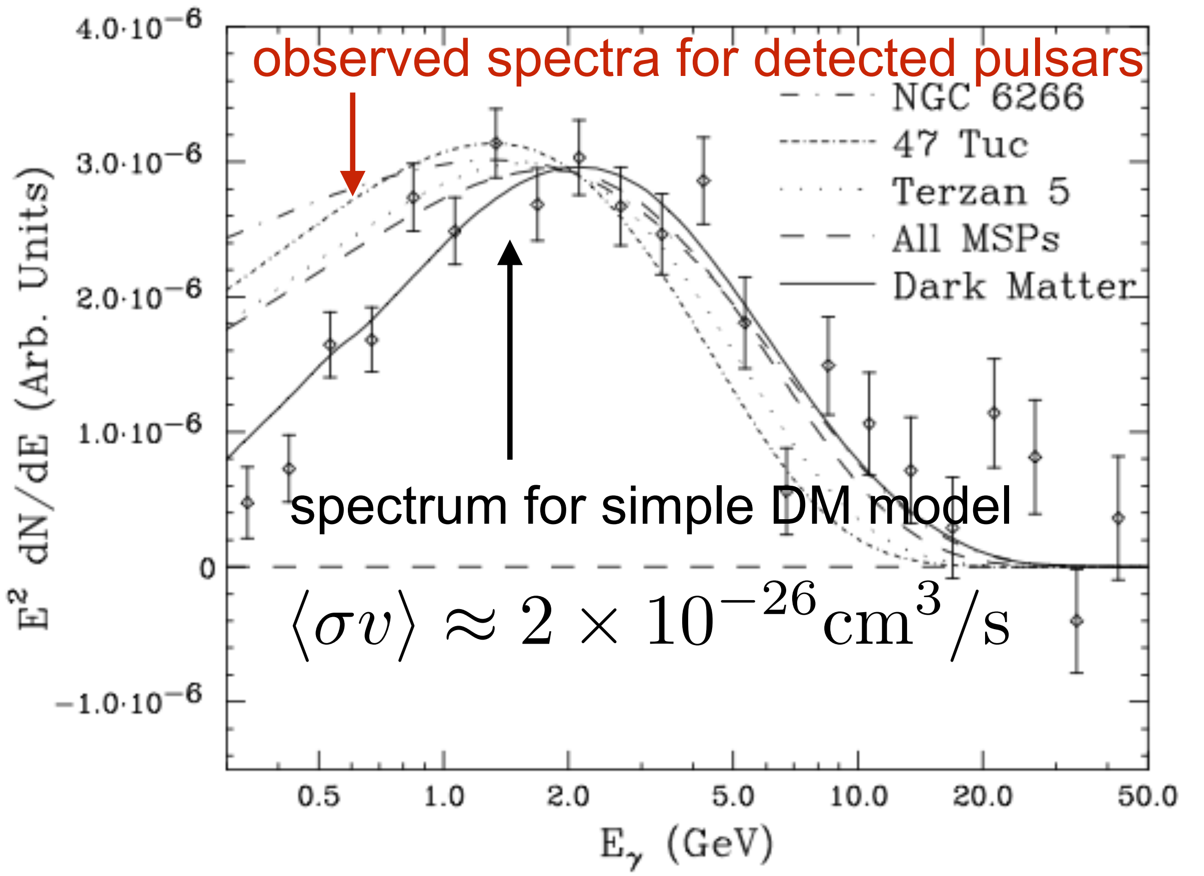
spatial distribution Abazajian & Kaplinghat '12



energy spectrum Gordon & Macias '13



Hypotheses



Daylan, TRS et al '16

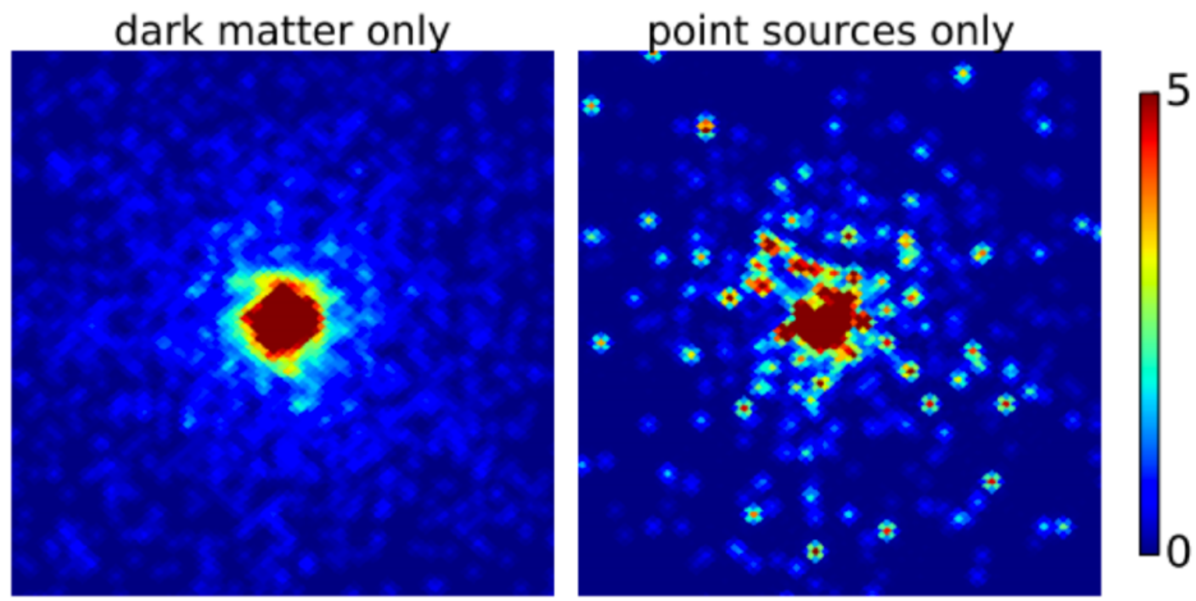
- Dark matter annihilation:
    - predicts overall rate correctly
    - morphology + spectrum are easy to accommodate (depending on confidence level in studies arguing the emission traces the stellar Bulge)
- Leading conventional explanation: a new population of stars or other point sources - most discussed candidate is millisecond pulsars (MSPs), spinning neutron stars.
    - gamma-ray spectrum ~matched by observed pulsars
    - overall rate potentially reasonable (requires 100s-10,000s of pulsars depending on luminosity function)
    - morphology not predicted, but seems possible to accommodate

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



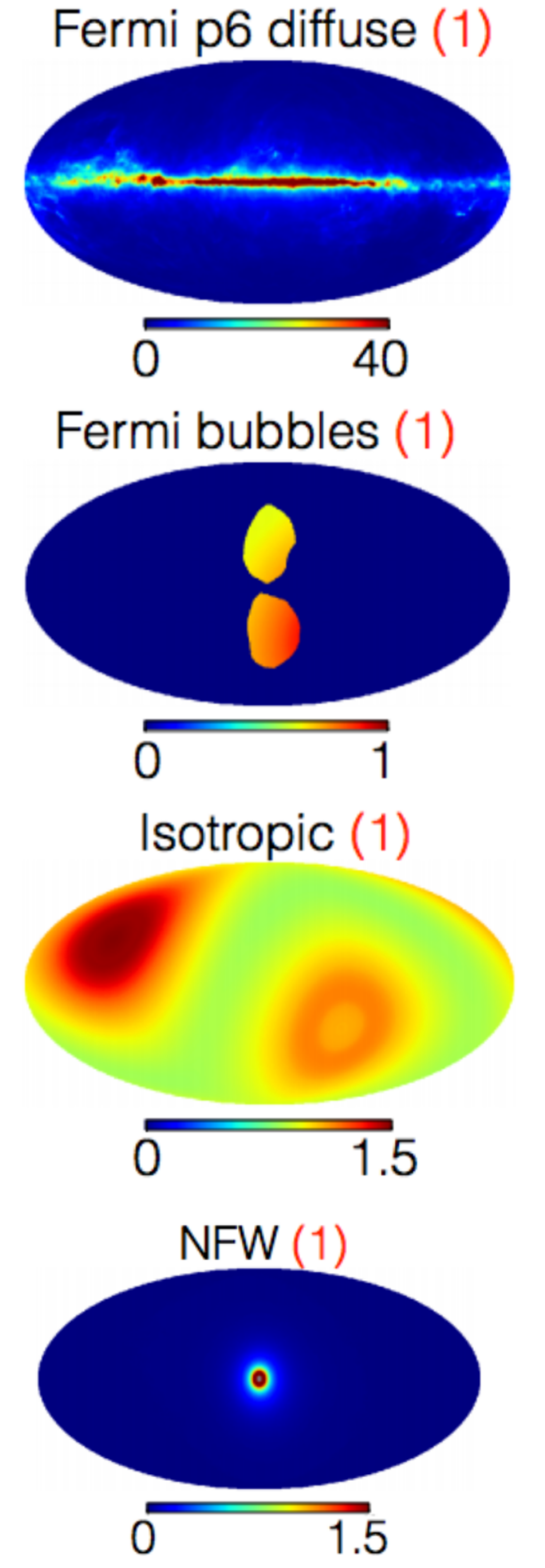
<u>Pulsar origin hypothesis</u>

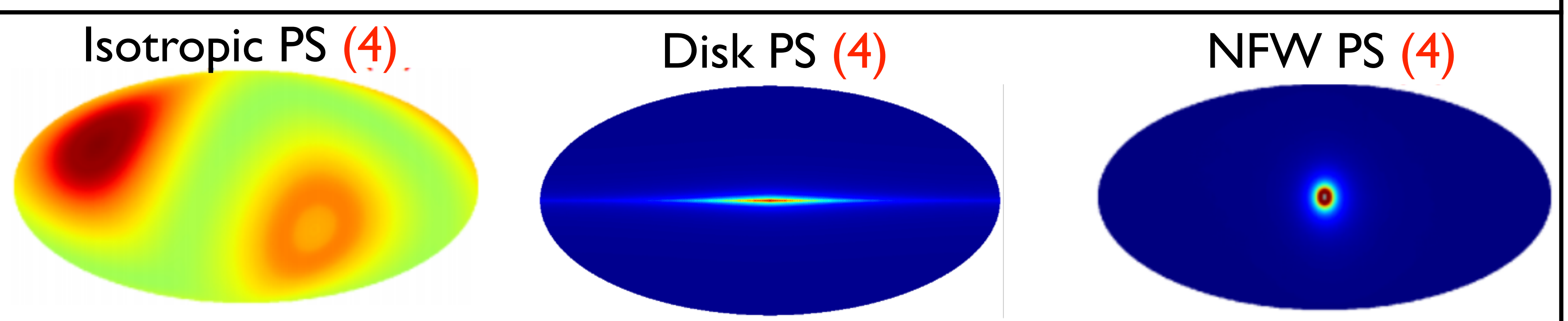
signal originates from a collection of compact objects, each one a faint gamma-ray point source

- 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.

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

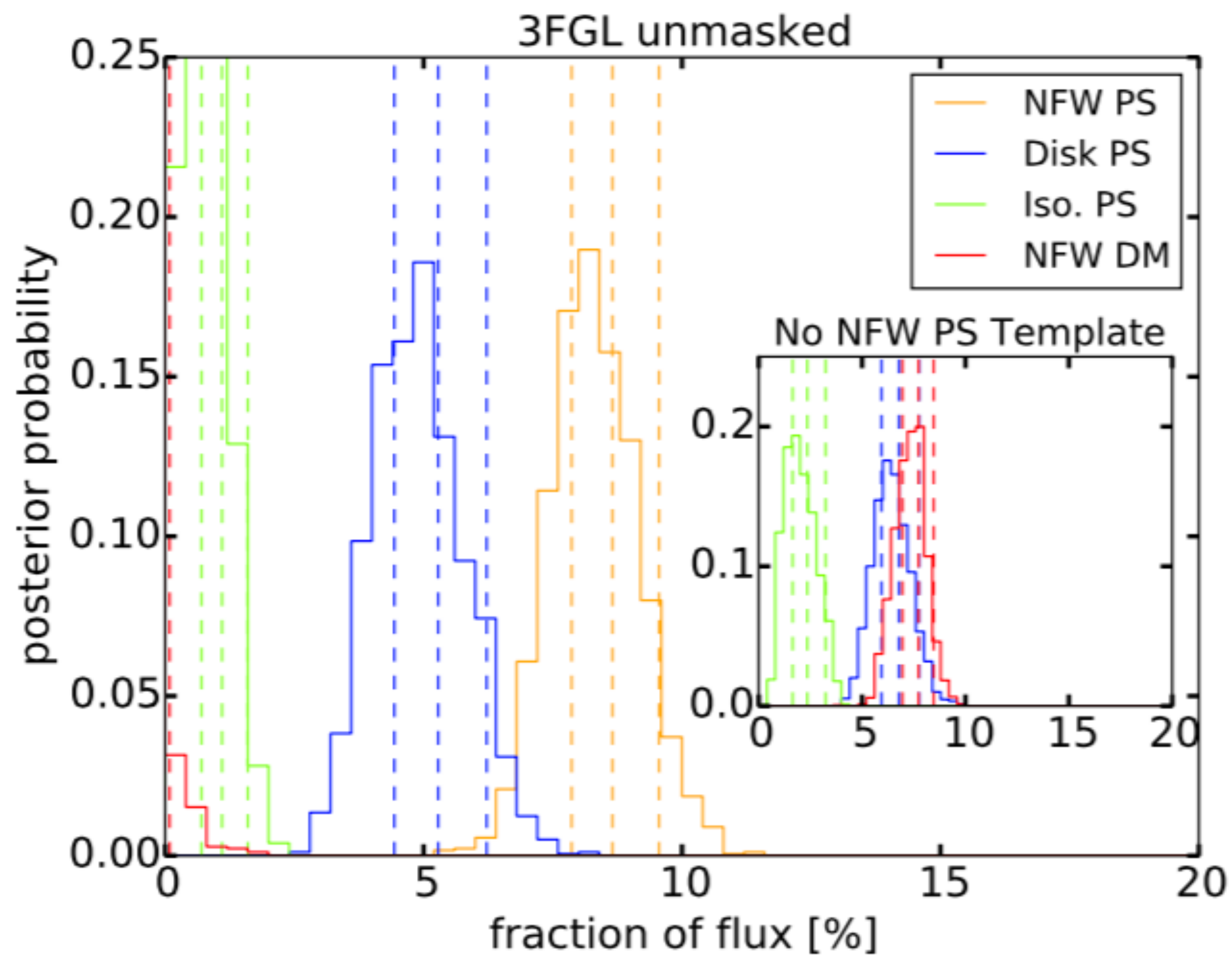




Point source templates

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".

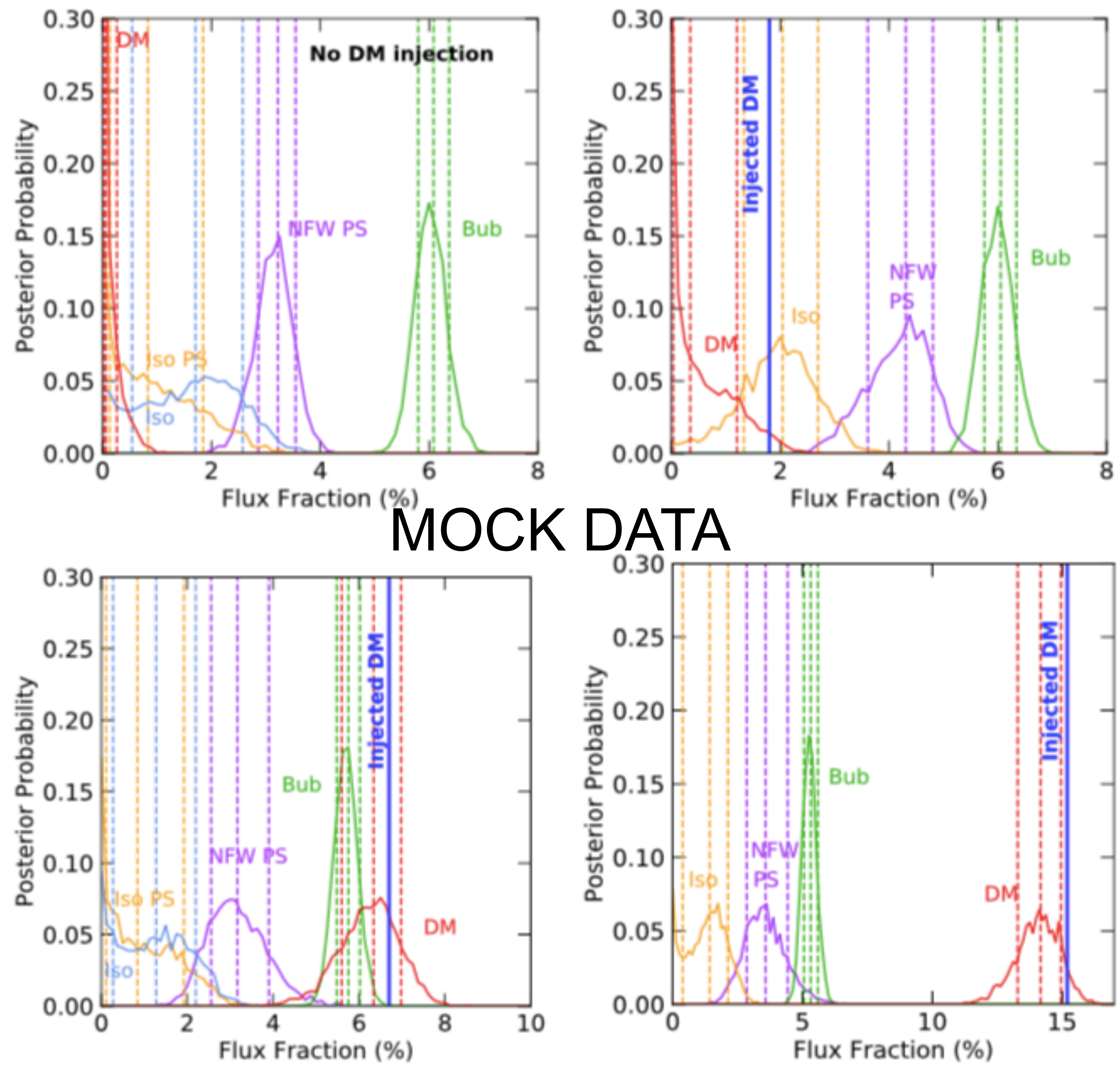


- 2016 result: if "NFW PS" is absent, "NFW DM" template absorbs excess. If "NFW PS" is present, "NFW PS" absorbs full excess, drives "NFW DM" to zero.

A new test for systematics

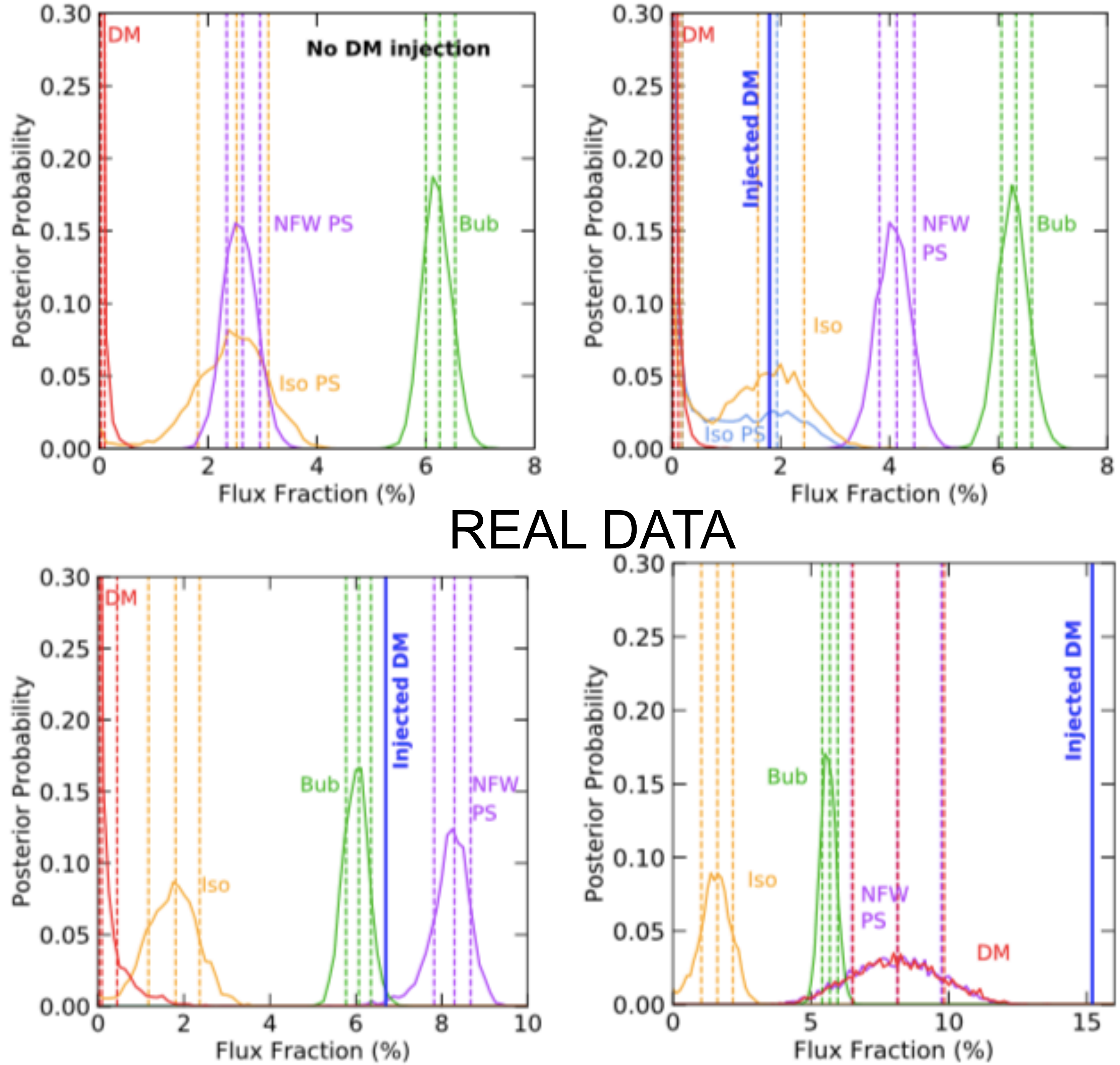
Leane & TRS ‘19

- 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).



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.

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.

- Indirect searches are particularly complementary to other methods for TeV+ DM:

  - Collider experiments cannot effectively probe this parameter space - some of the simplest WIMP models are unconstrained by both the LHC and direct detection.

  - Interactions between DM and any lighter force carriers (including W/Z bosons, for DM heavier than ~2 TeV) can naturally lead to large annihilation cross-section enhancements.

- Standard theoretical methods frequently break down at these masses. There is an active and ongoing program to adapt effective field theory techniques to make precise predictions for heavy WIMPs. For the thermal wino, we have achieved percent-level precision, & substantial sensitivity improvements.

- There are two indirect-detection anomalies that could hint at annihilation of O(100) GeV thermal DM (antiprotons, Galactic Center excess). Previous work claiming GCE cannot be DM due to photon statistics may be premature - need to understand systematics from (mis)modeling of backgrounds to make this claim robust.