Theory Frontier & Confronting Dark Matter with the Multi-wavelength Sky

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The Theory Frontier

- Theory Frontier connects to all the experimental frontiers and all the P5 Science Drivers
- Snowmass report [Craig et al 2211.05772] divided theory into fundamental + phenomenological + computational
    - Fundamental: quantum field theory (effective field theory, novel perturbative and non-perturbative methods), quantum gravity (holography, links to quantum information)
    - Phenomenology: model-building, precision flavor and collider physics, collider phenomenology, cosmology & particle astrophysics, neutrino physics, …
    - Computational: lattice field theory, quantum information, machine learning & artificial intelligence

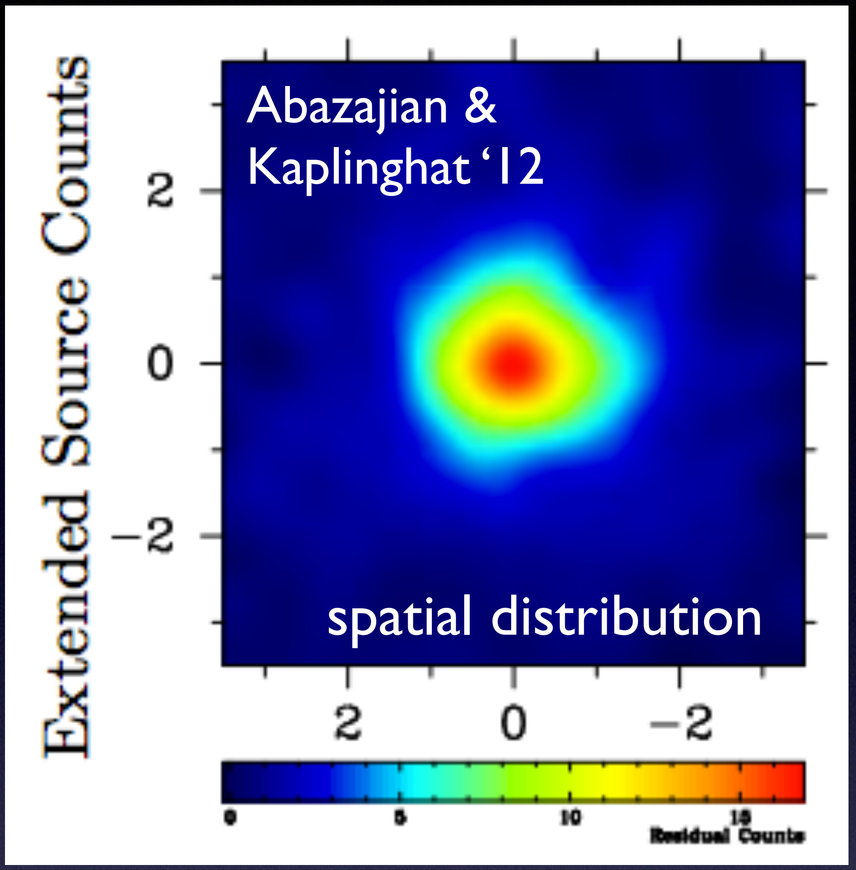
- “Emphatically support a broad and balanced program of theoretical research covering the entirety of high-energy physics, from fundamental to phenomenological to computational topics, both in connection to experiment and in its own right”
- Support a balanced HEP program of Projects and Research
- Support targeted bridge-building efforts to strengthen theory-experiment connections
- Support training of students and junior scientists, identify and cultivate talent at all stages, and strengthen commitment to improving diversity, equity, inclusion, and accessibility

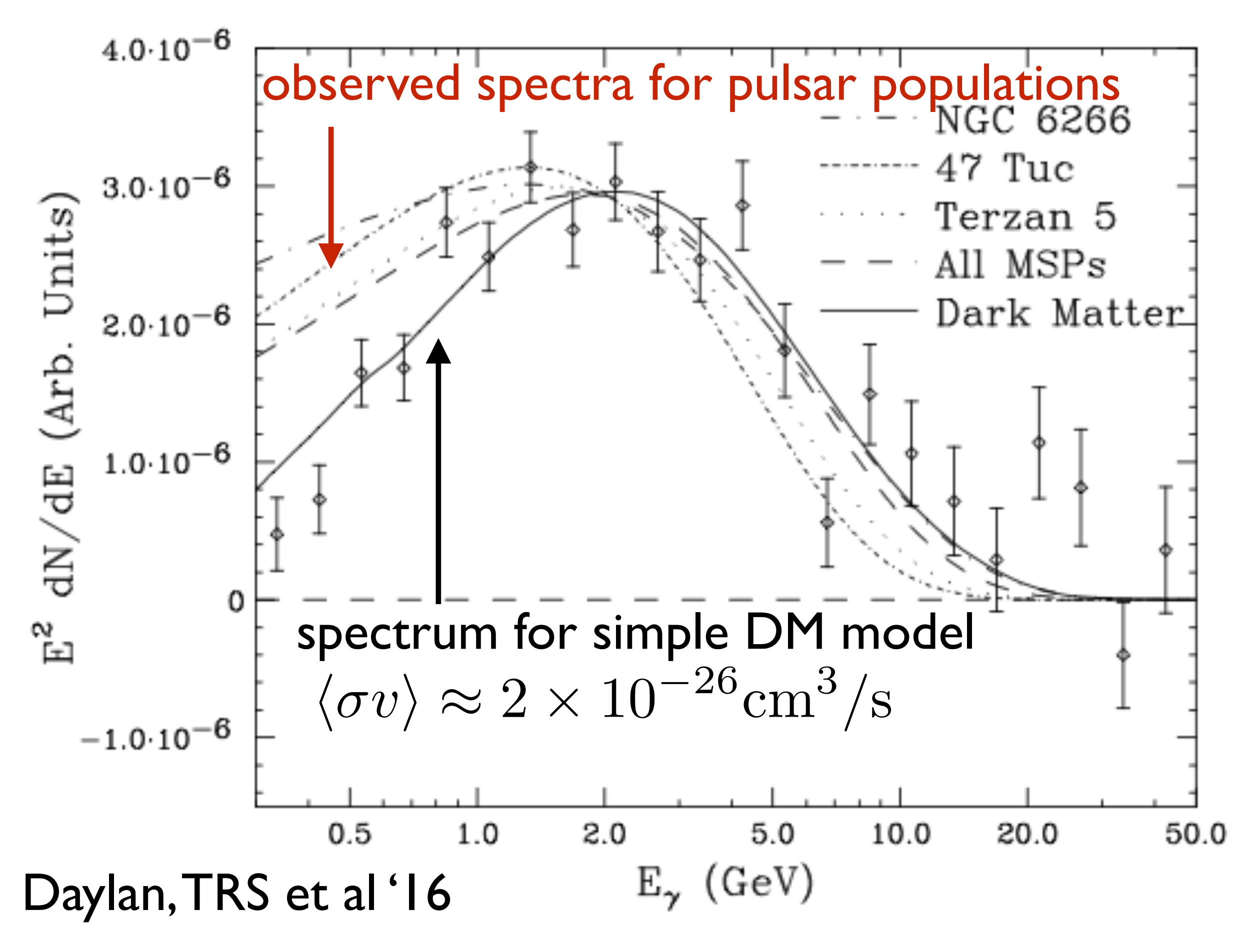
Confronting Dark Matter with the Multiwavelength Sky

- My proposal focused on the science driver to “identify the new physics of dark matter”
- Primarily phenomenology focused on data from Cosmic Frontier
- Three major thrusts:
  - Study an excess of GeV gamma rays originating from the inner Milky Way (the “Galactic Center excess”)
  - Develop new field-theoretic techniques to allow precise predictions of annihilation signals from heavy dark matter
  - Map out the possible effects of dark matter annihilation and decay on the early universe and cosmic microwave background

The Galactic Center Excess (GCE)

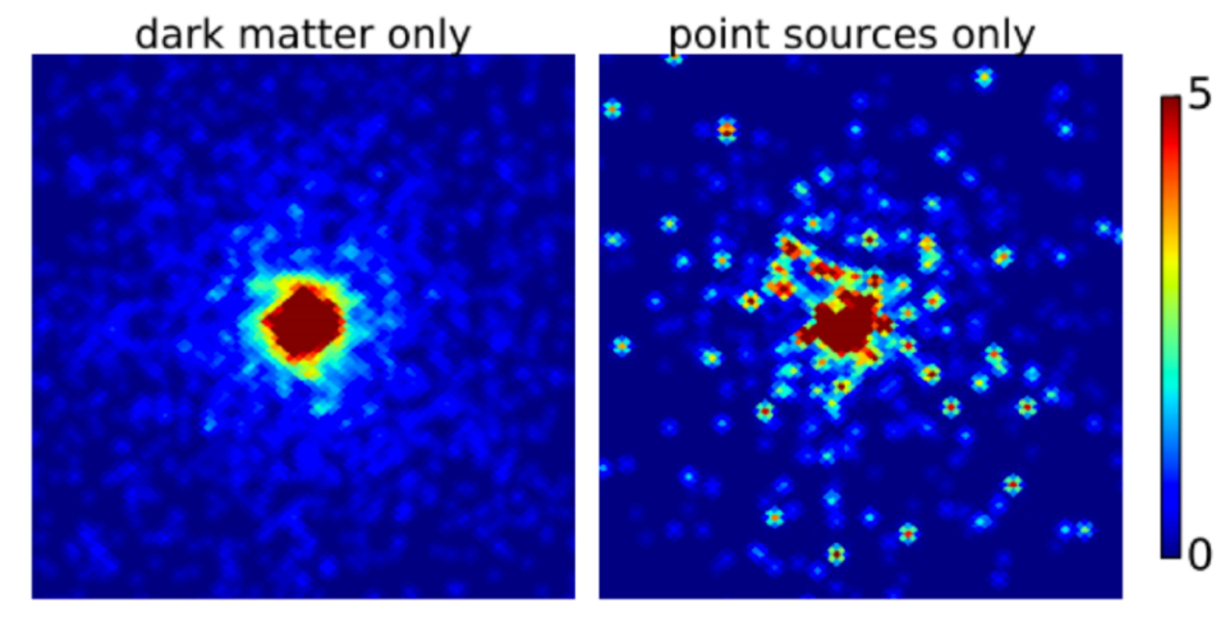
- Excess of gamma-ray photons, peak energy ~1-3 GeV, in the region within ~10 degrees of the Galactic Center.
- Discovered by Goodenough & Hooper '09, confirmed by Fermi Collaboration in analysis of Ajello et al '16 (and many other groups in interim).
- Simplest DM explanation: thermal relic annihilating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

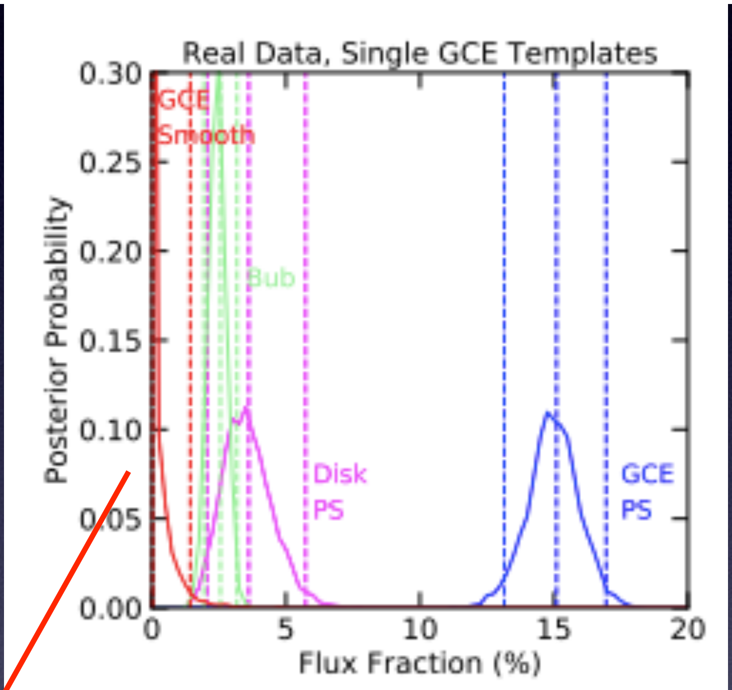


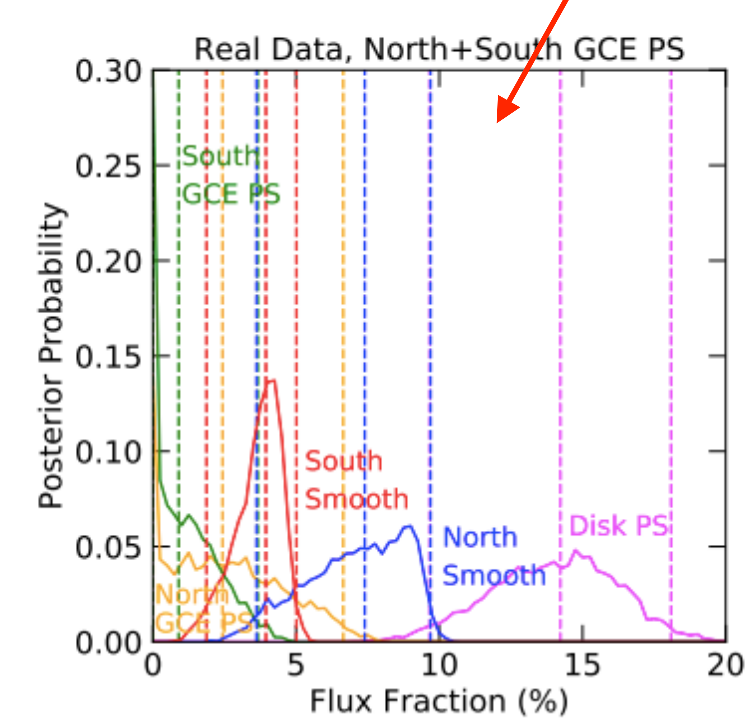


GCE + ECA

- One way to distinguish the DM and pulsar hypotheses is to look at the granularity of the signal
- 2016: developed a new method to probe non-Poissonian photon statistics from an unknown point source distribution [Lee, TRS et al '16]
- Found apparent evidence for point sources!
- 2019-2020 [Leane & TRS]: identified systematic biases in favor of point sources in the presence of signal/background mis-modeling



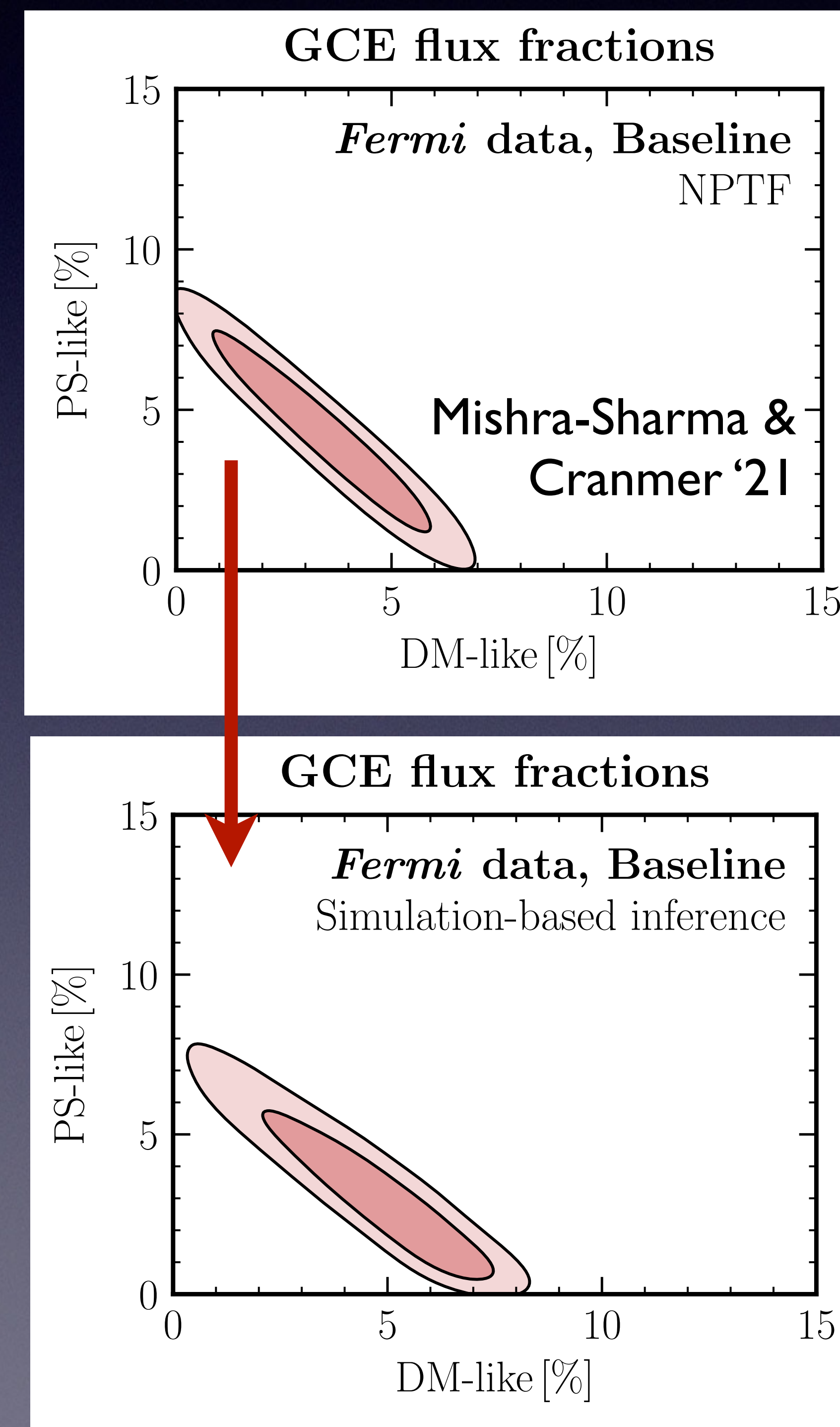




Example of how signal mismodeling can be confused for PSs - strong PS preference with default pipeline that goes away when GCE is allowed north/south asymmetry

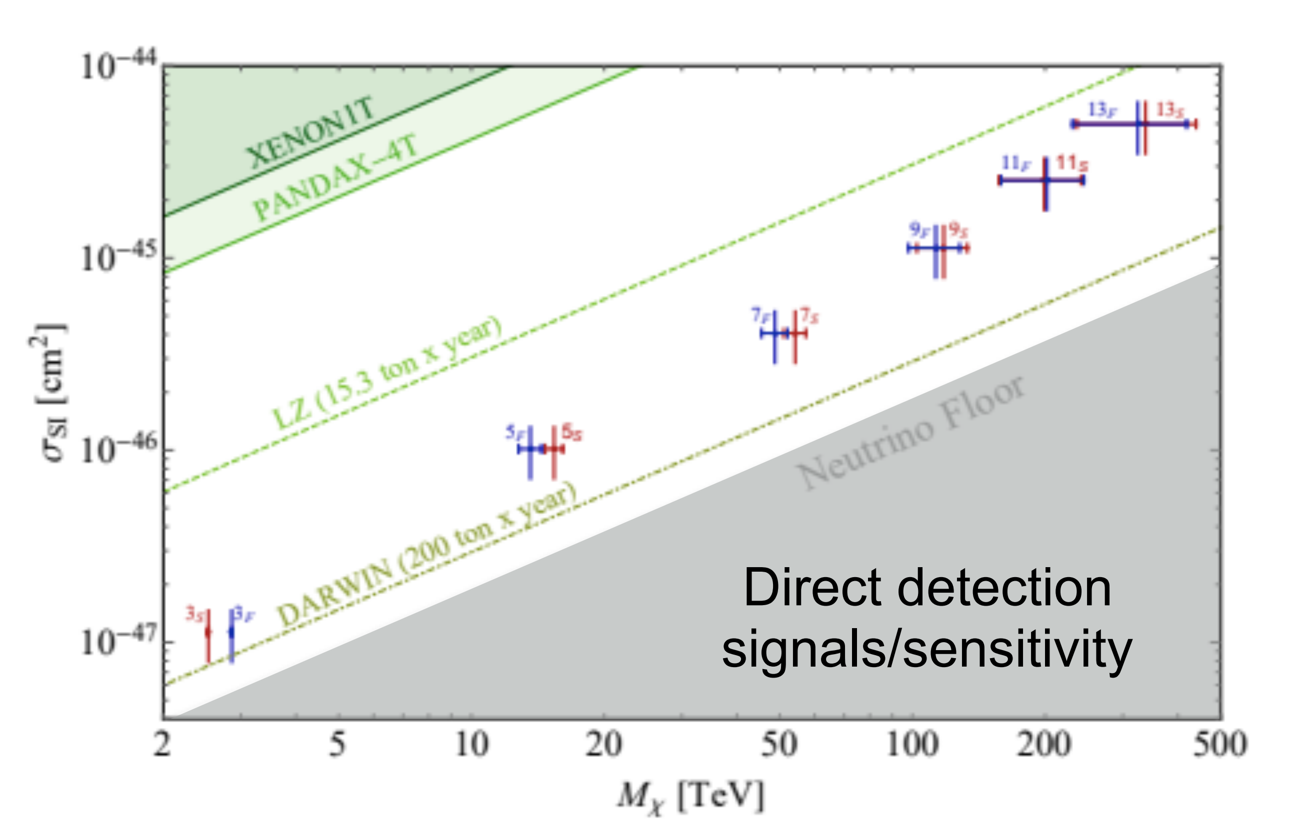
Where now/next?

- More modern analyses with updated background models find much weaker evidence for point sources
- Newer methods built on our 2016 techniques use neural networks - still suggest a hint of point sources
- Recently, my group studied properties of statistical method analytically+numerically [Bariuan & TRS '23], + explored viability of pulsar hypothesis [Dinsmore & TRS '22]
- Currently building methods for faster/more flexible inference, allowing further study of and marginalization over systematic uncertainties



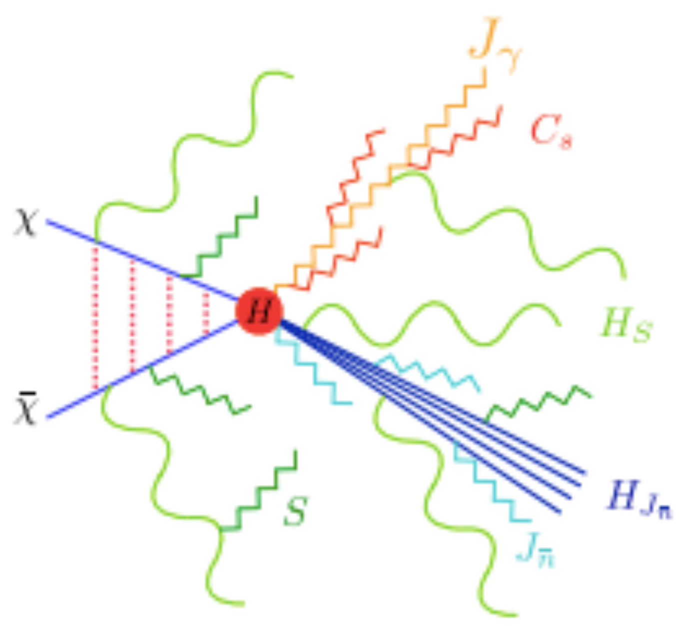
Effective field theory for heavy dark matter

- Simple models for heavy, weakly-interacting DM still remain untested by direct/collider searches (e.g. higgsino, wino, higher SU(2) representations)
- Indirect searches can have sensitivity - but computing the annihilation signal (from DM collisions in the halo) is theoretically challenging

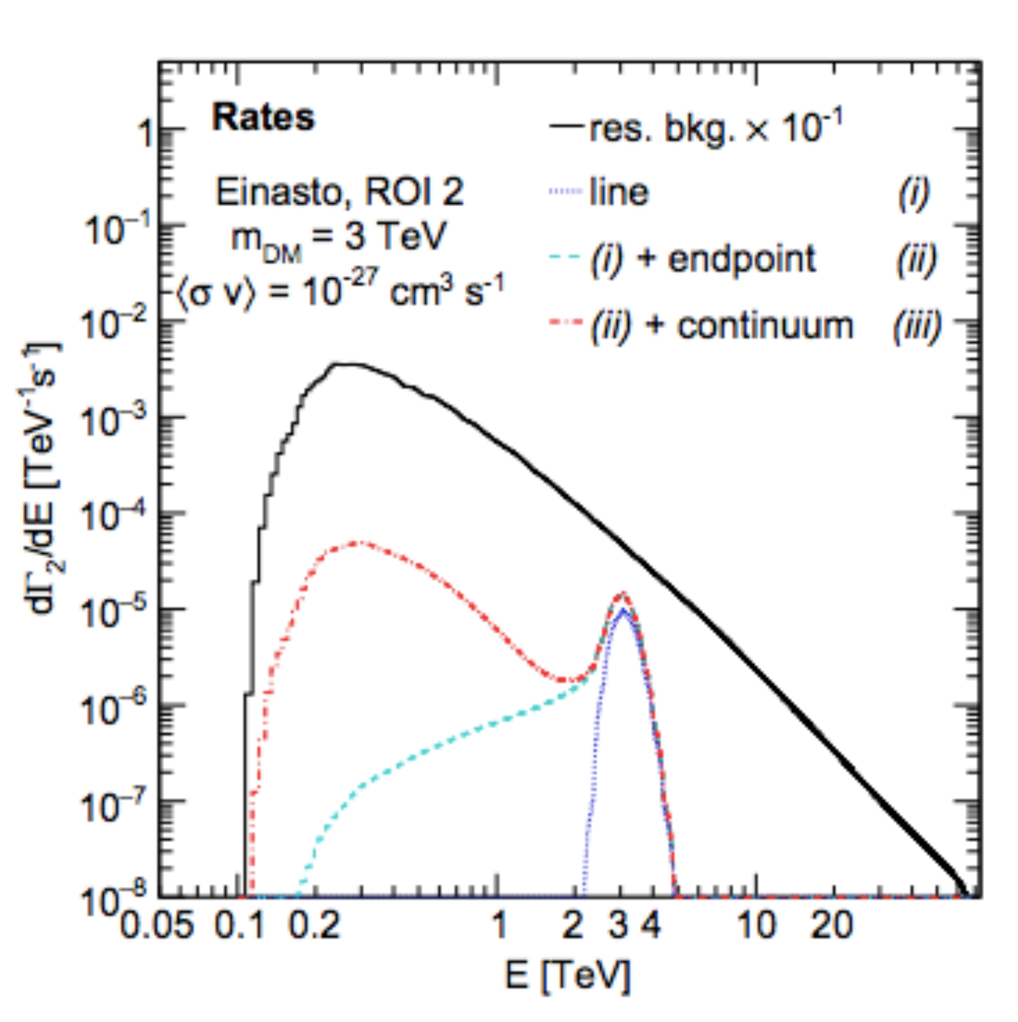


- Weakly-interacting DM with mass $\gtrsim m_W/\alpha_W \sim 2.4$TeV feels an effective potential from W exchange that can support bound states [studied in Asadi, TRS et al '16]
- Bound state formation and wavefunction deformation by the potential (Sommerfeld enhancement) boosts annihilation [Hisano et al '03, '04]
- m_W/m_{DM} hierarchy leads to large Sudakov logs that need to be resummed

The wino and beyond



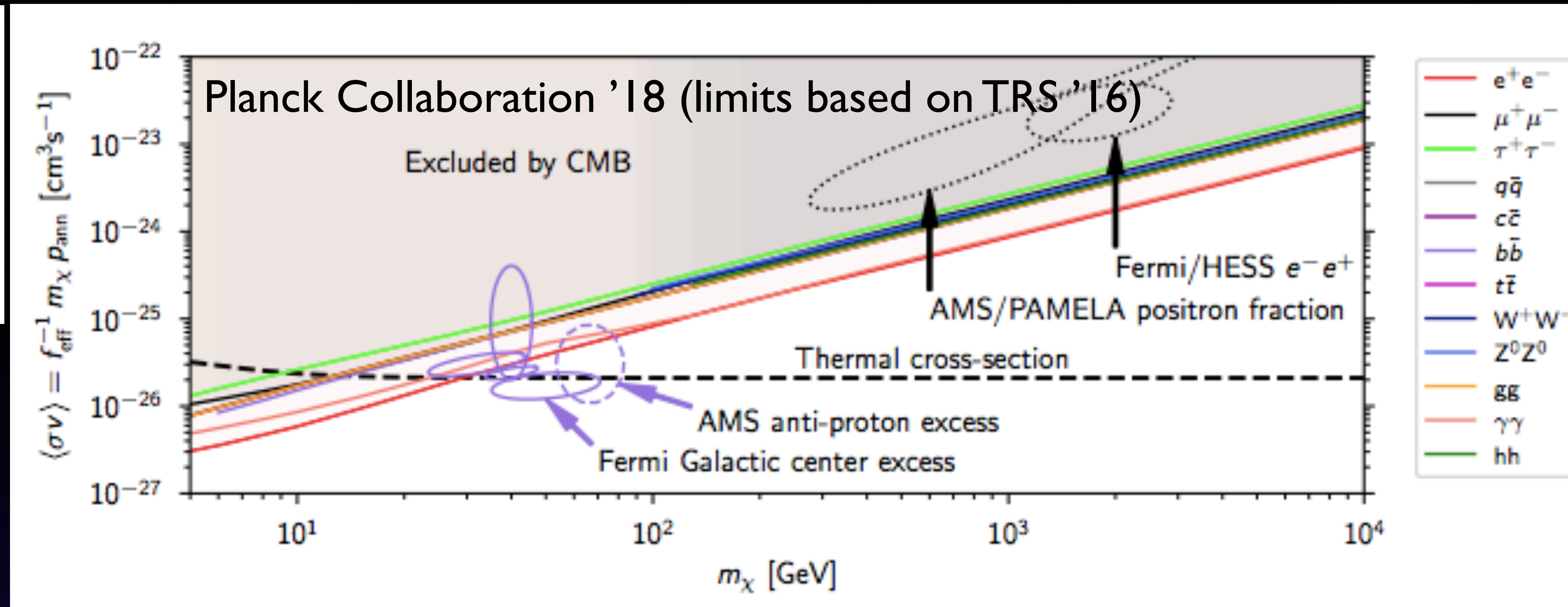
- We used methods of soft collinear effective theory (originally developed for perturbative QCD at colliders) to work out the resummation for <u>wino</u> dark matter annihilation to next-to-leading-log order [Baumgart, TRS et al '18, '19]
- We proved a theorem that let us factorize the different physical effects and compute the gamma-ray spectrum to high precision
- We showed this photon spectrum was already in some tension with null results from the H.E.S.S. telescope [Rinchiuso, TRS et al '18]
- Ongoing work: extending SCET and bound-state results to higher representations of SU(2) (wino=triplet representation)

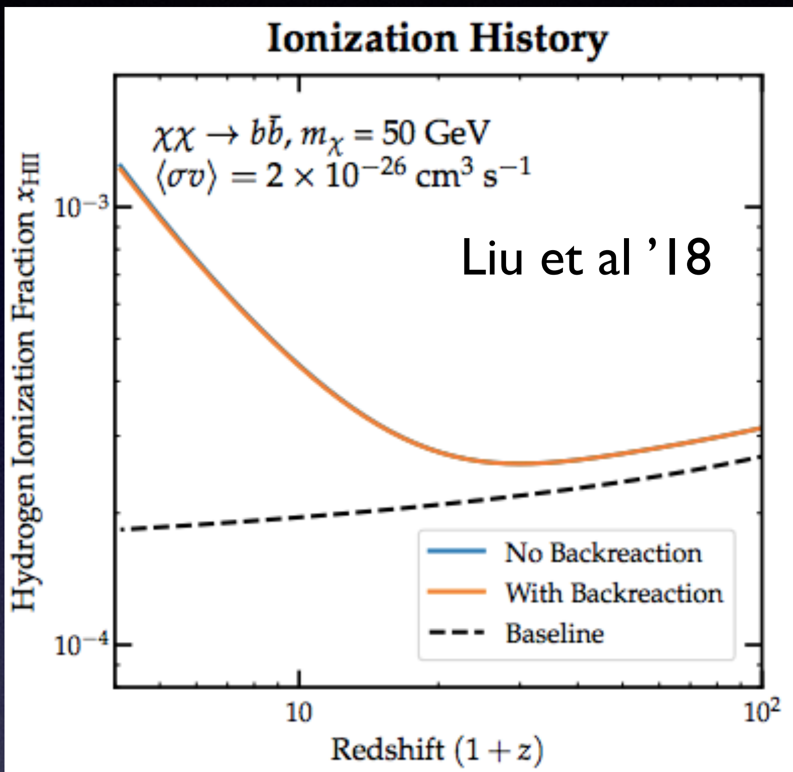


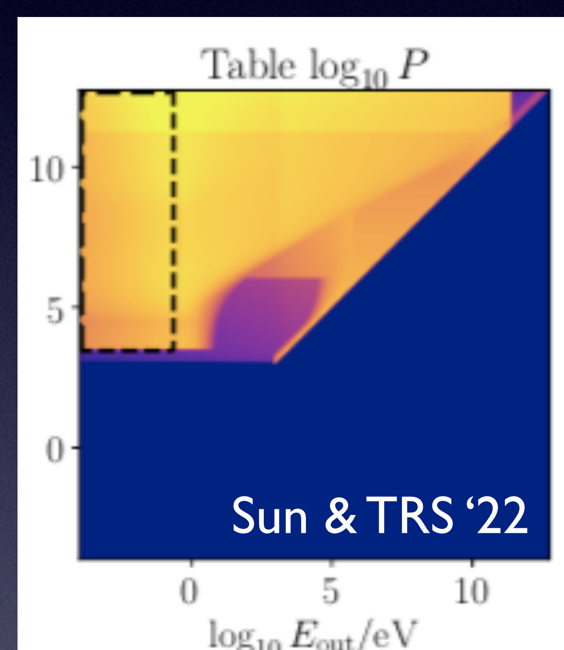
Energy injection in the early universe

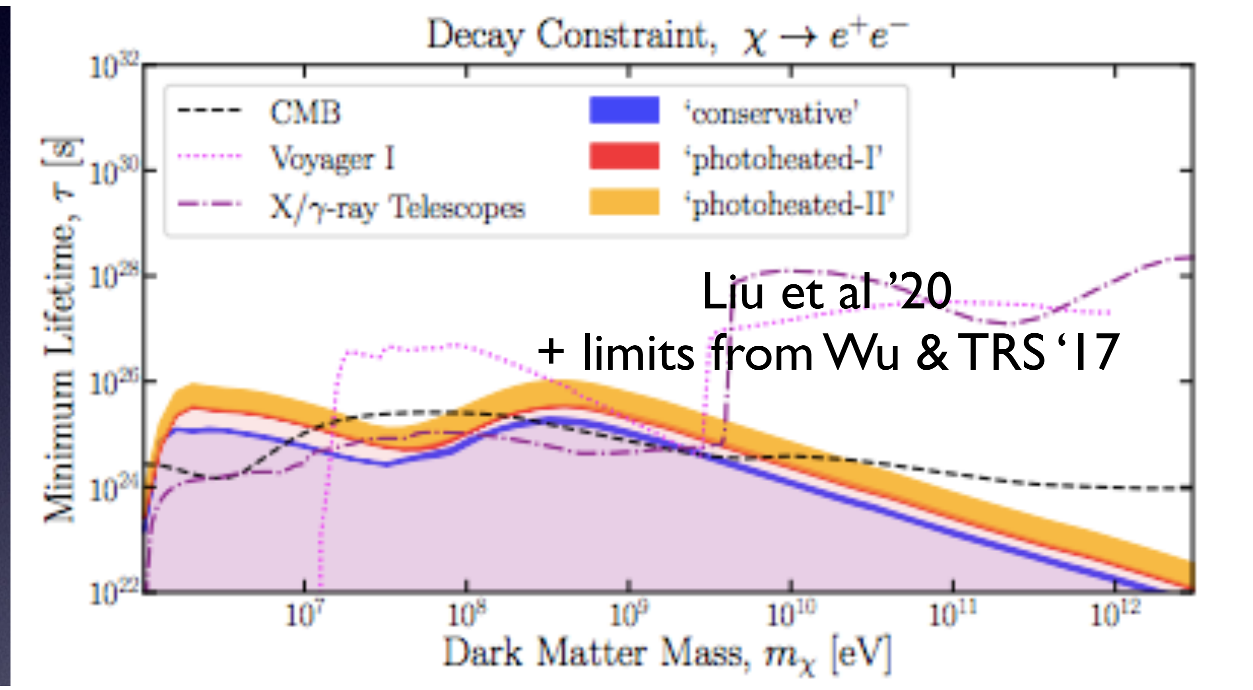
- Dark matter annihilation, decay, or scattering in the early universe could lead to energy flow between the dark and visible sectors
- Has implications for signals in the CMB, 21cm radiation, Lyman-alpha forest, first stars, etc
- Built a comprehensive public code package DarkHistory that tracks secondary particle cascades from energy injection in the early universe + calculates effect on cosmic ionization+temperature

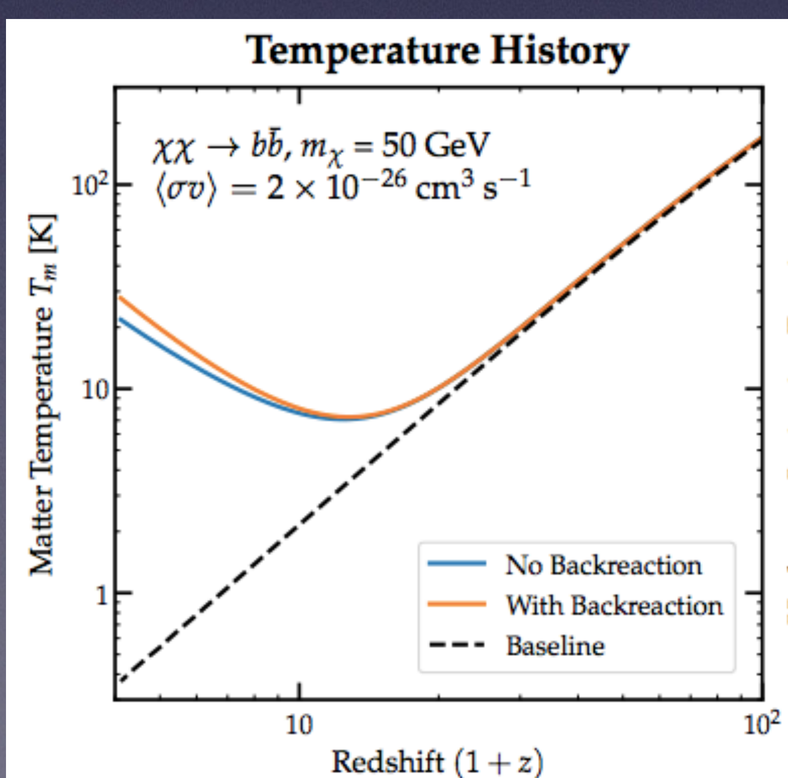
```python
bbbar_noBR = main.evolve(
    DM_process='swave', mDM=50e9,
    sigmav=2e-26,
    primary='b', start_rs=3000.,
    coarsen_factor=32, backreaction=False,
    struct_boost=phys.struct_boost_func()
)
```

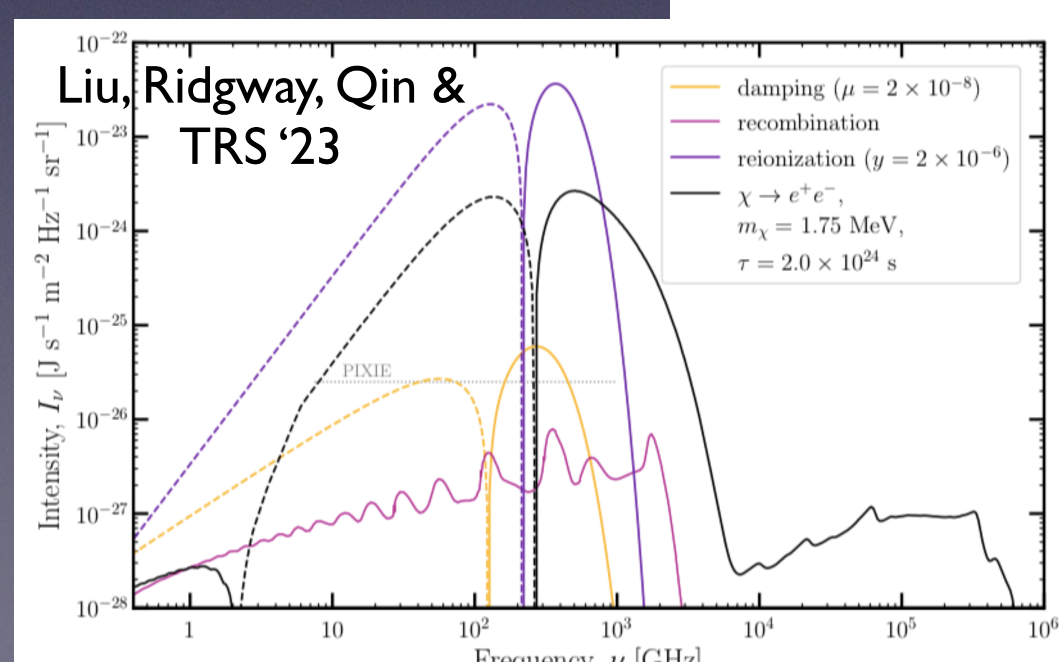












CMB bounds set some of the strongest and most robust limits on light annihilating/decaying dark matter