Title: Astro-particle Phenomena from Dark Matter and Cosmic Rays in MHD Galaxy Formation Simulations

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Abstract:

Over the last few decades, observations of diffuse gamma-ray emission in the Milky Way– in particular, the excess of GeV gamma-rays detected in the Milky Way's galactic center, and the massive gamma-ray bubbles (the "Fermi bubbles") centered about the Milky Way's disk– have challenged astrophysical models. Nearly all past studies of galactic gamma-ray emission make simplifying assumptions about cosmic ray (CR) propagation that may not be valid (e.g., steady-state equilibrium), but recent numerical breakthroughs have enabled fully time-dependent dynamical evolution of CRs in magnetohydrodynamic (MHD) simulations with resolved, multi-phase small-scale structure in the interstellar medium (ISM), allowing self-consistent comparisons to the Milky Way observations. In this talk, I will present new work in which we model diffuse gamma-ray emission in simulations of Milky Way-mass galaxies with fully-resolved, multi-species CR spectra. We find that the gamma-ray spectrum in the galactic center can fluctuate by up to an order of magnitude on million-year timescales due to highly variable star formation and losses from variable structure in the turbulent ISM, with some fluctuations consistent with the Fermi-LAT galactic center excess. I will also show that Fermi bubble-like features arise from stellar feedback in these simulations. Finally, I will present the first results from a new suite of cosmological simulations in which a dark sector with an ultra-light mediator gives rise to a long-range (kiloparsec-scale) self-interaction. The addition of a long-range dark matter self-interaction has dramatic effects on the formation of galaxies and their host halos, and will be testable by current and upcoming astronomical surveys.

Astro-particle Phenomena from Dark Matter and Cosmic Rays in MHD Galaxy Formation Simulations

Perimeter Institute Cosmology and Gravitation Seminar

1/6/2026

Isabel S. Sands (Caltech)

CALIFORNIA INSTITUTE OF TECHNOLOGY 1891

FIRE

Feedback In Realistic Environments

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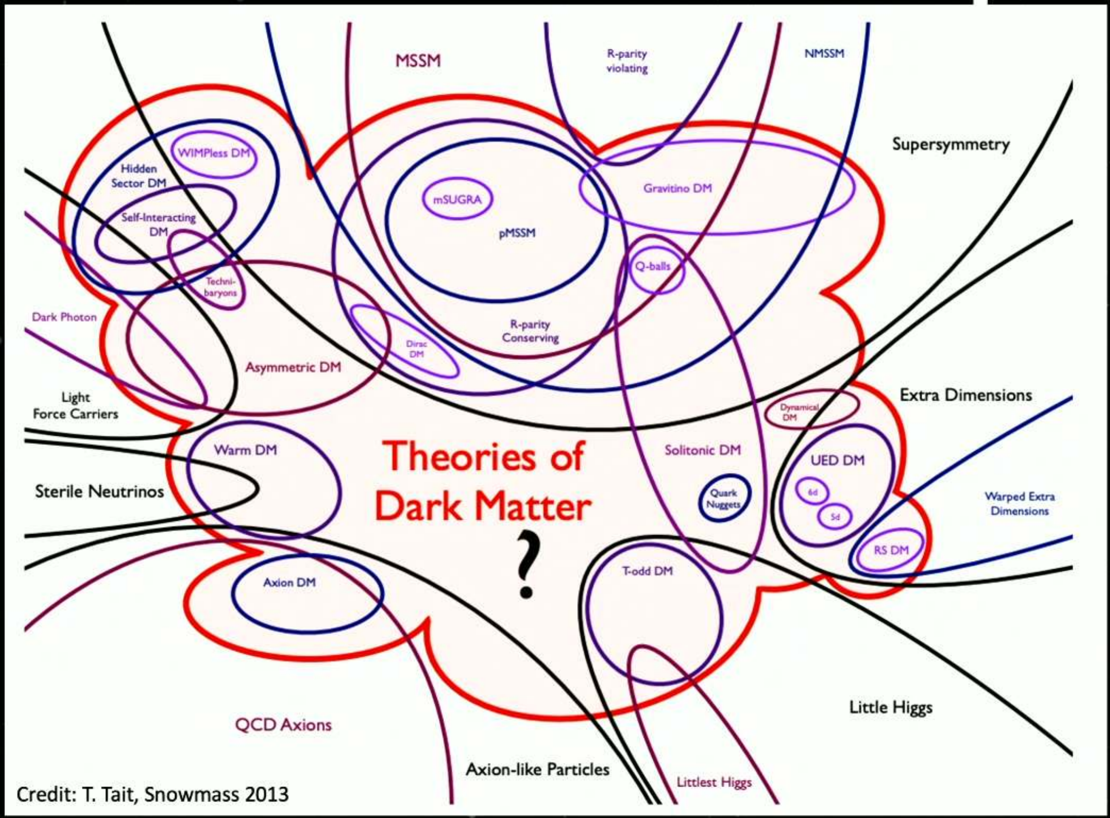
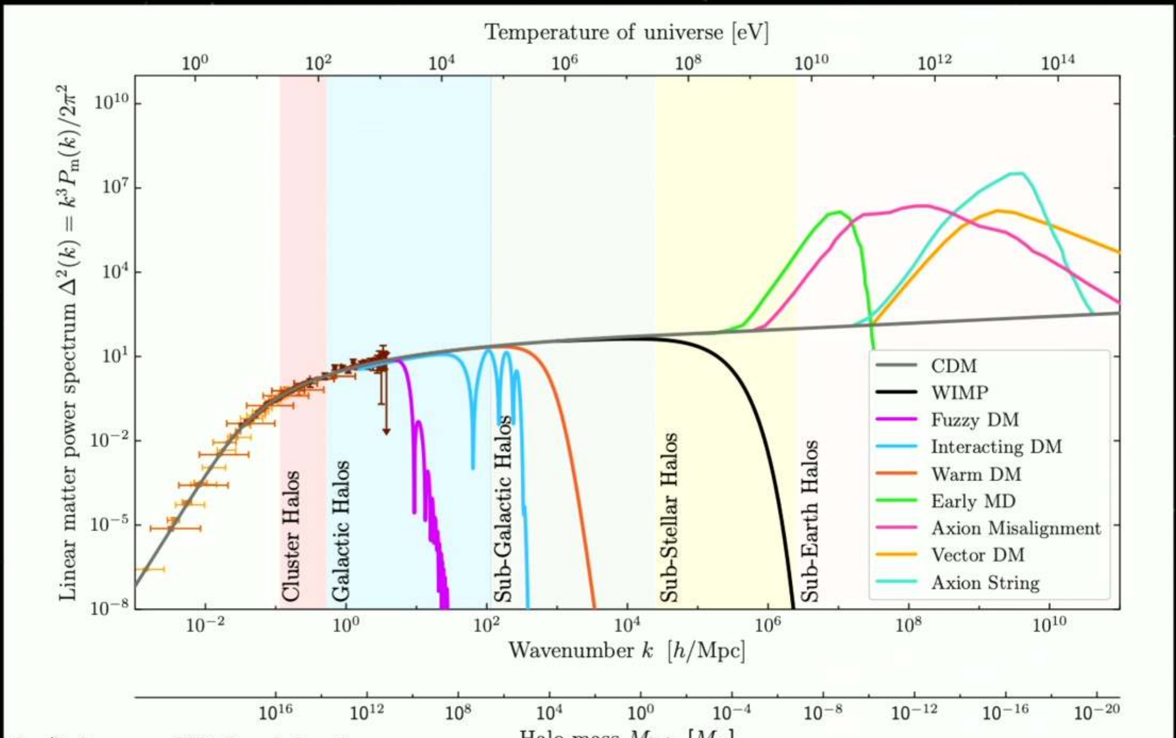
1. Baryons as Astrophysical Systematics to the Detection of Dark Matter

Garrison-Kimmel+ (2017)

Dark Matter Parameter Space

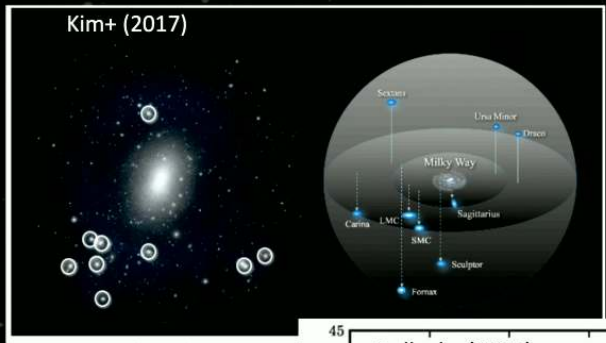


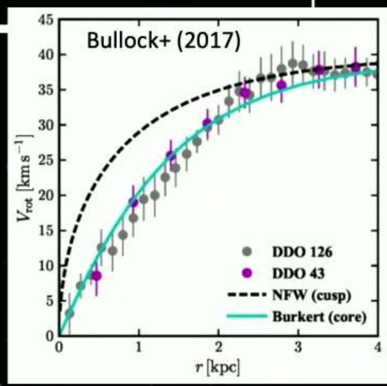
Testing DM in Galaxies

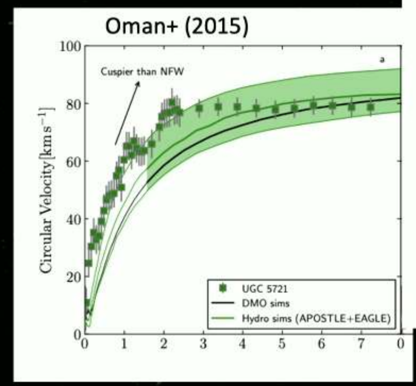


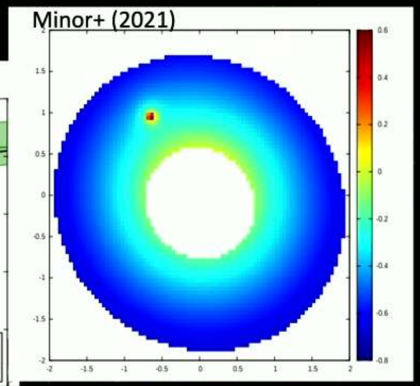
Credit: Snowmass2021 Cosmic Frontier

Testing DM in Galaxies

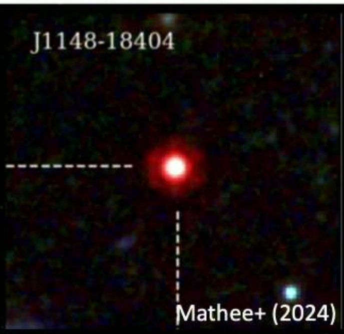








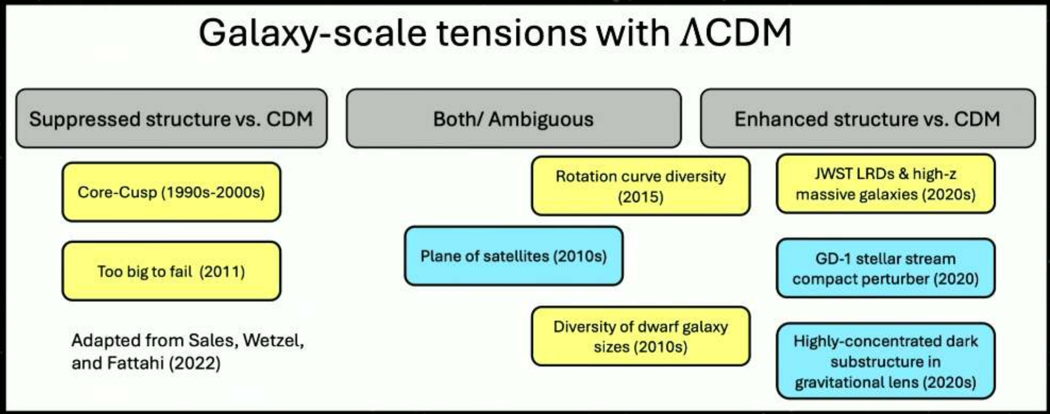
Bonaca & Price-Whelan



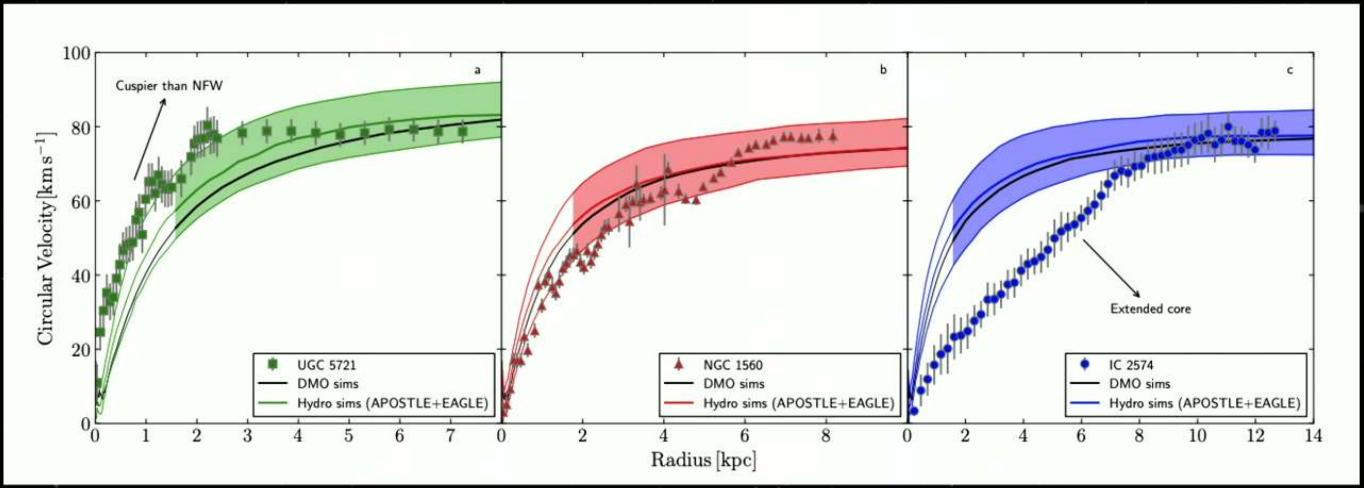
From suppression of “small scale” structure… to hints of enhanced substructure?

Challenges of Indirect Gravitational DM Detection in Galaxies

- How do we extricate signals of dark matter from complex baryonic physics?
  - e.g. Feedback, cosmic ray transport, dynamical effects
  - Many dark matter models have not been simulated alongside full MHD
- How do we interpret observational data? When is a tension really a tension?



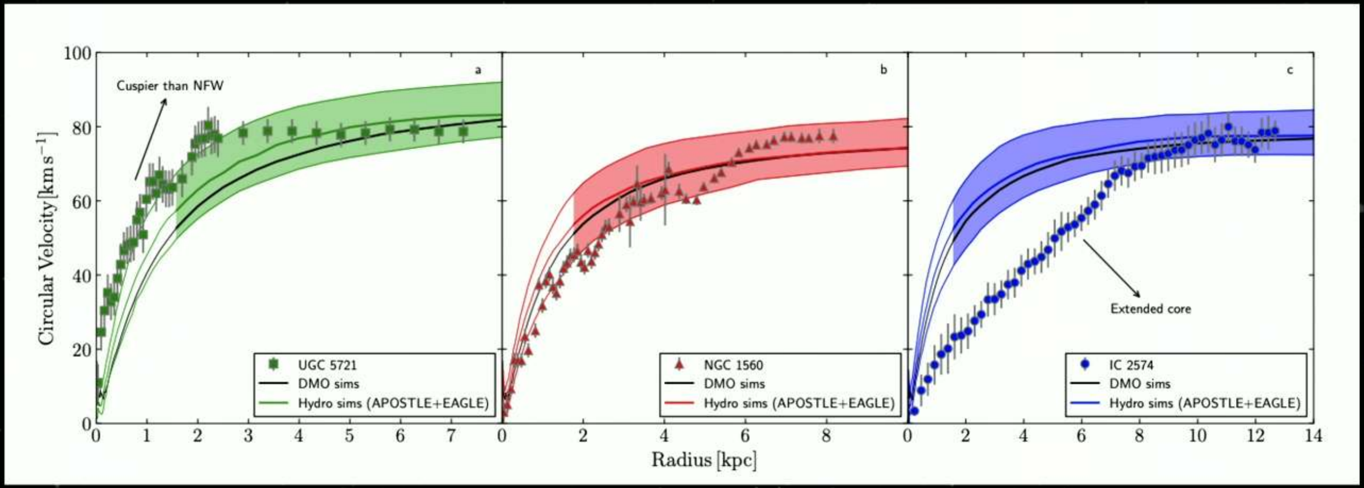
A Case Study: Diversity of Rotation Curves



From Oman et. al. (2015), Sales et. al. (2022)

Observed rotation curves can be cuspier or more cored than those from simulations
Baryons or strongly-self interacting DM?

A Case Study: Diversity of Rotation Curves

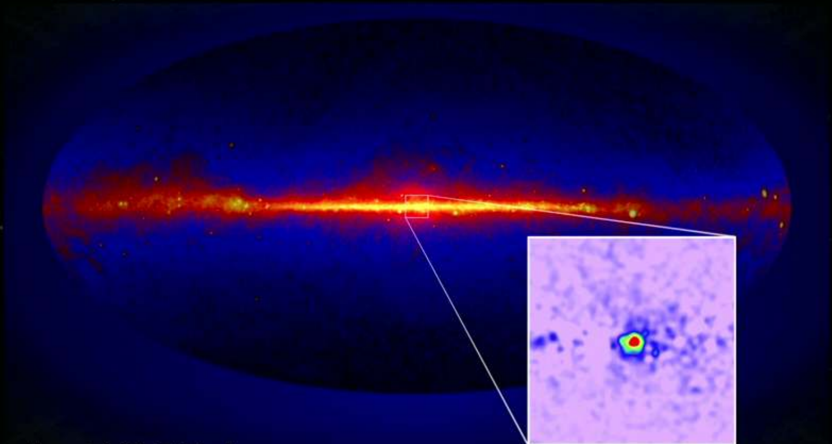


From Oman et. al. (2015), Sales et. al. (2022)

Observed rotation curves can be cuspier or more cored than those from simulations
Baryons or strongly-self interacting DM?

Challenges of Indirect Detection via standard model products

- Look for e.g., gamma-rays from annihilating DM
  - Many astrophysical sources: diffuse emission from cosmic rays, AGN, pulsars, etc.
  - Unconstrained cosmic ray transport
  - Milky Way galactic center:
    - Uncertainties in magnetic fields, gas structure, stellar population



Fermi-LAT; T. Linden

Feedback in Realistic Environments (FIRE) Simulation Overview

- Numerical galaxy formation with dark matter and magnetohydrodynamics using Meshless Finite Mass (MFM) method
- Star formation criteria:
  - Cool, molecular, self-shielding gas
- Feedback mechanism:
  - Type Ia and Type II Supernovae
  - Winds from OB stars
  - AGB mass loss
  - Radiative feedback
- "Extra" physics
  - Cosmic rays
  - Active galactic nuclei (AGN)
  - Exotic DM

Credit: FIRE Collaboration


Image credit: A. Mellinger & T. Linden
2.1 Modeling Diffuse gamma-ray emission in MHD simulations of Milky Way Analogs
... in the galactic center
arXiv:2509.18351
With Philip F. Hopkins (Caltech), Sam Ponnada (Caltech), Lina Necib (MIT), Dusan Keres (UCSD), and Yen-Hsing (Julius) Lin (UCSD)
Isabel Sands
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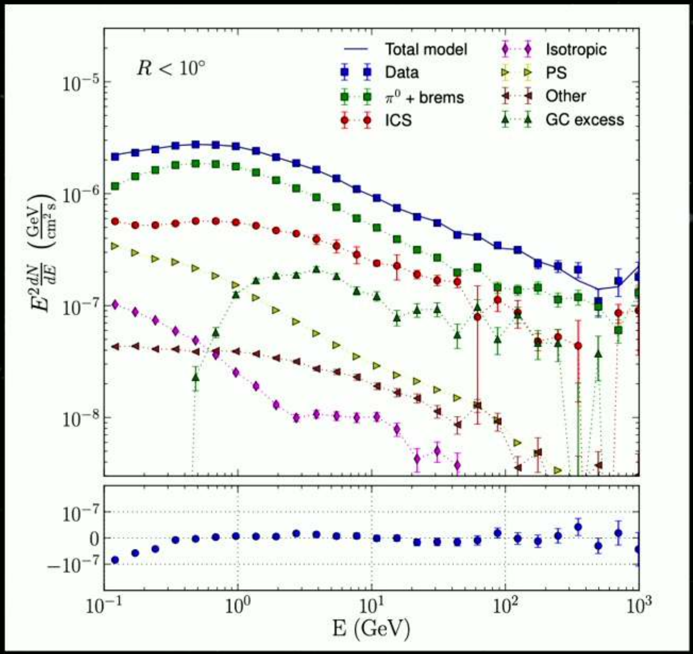
Introduction

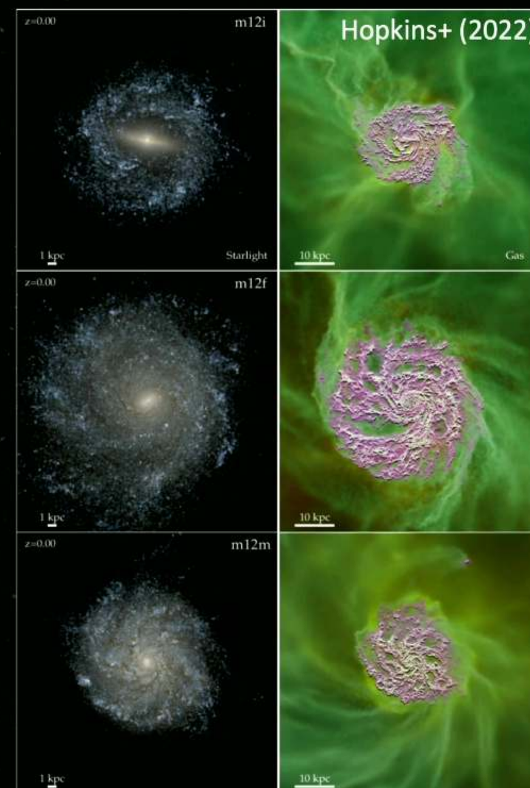
- ~ 1-10 GeV excess of gamma-rays in the MW's galactic center, potentially consistent with annihilating WIMP or millisecond pulsar population
- **Past analysis:** phenomenological CR propagation codes (e.g., GALPROP)
  - Fit to templates; assume steady-state equilibrium, axisymmetric CR distribution, etc.
- **With simulations**: self-consistent evolution of cosmic rays over time
  - Determine impact of dynamical processes (e.g., galactic winds, magnetic fields, turbulence)



Credit: Fermi-LAT

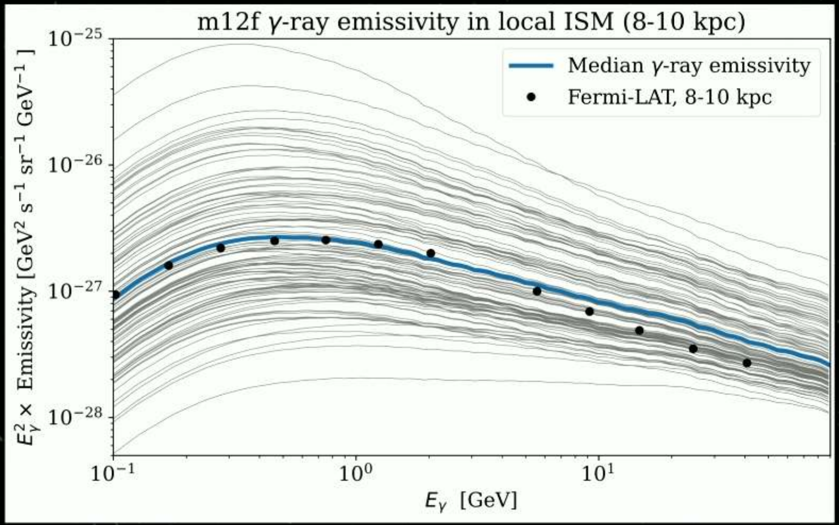
Simulations + Modeling

- We model γ -ray emission in multi-bin cosmic ray simulations (Hopkins + 2022)
  - First spectral CR-MHD simulations
  - FIRE-2 physics
  - Controlled restart of single-bin CR simulation at z = 0.05.
  - Includes resolved spectra of e^-/e^+, $p/\bar{p}$, + heavier nuclei in MeV-TeV energy bins
  - Single power-law injection from SNe and fast winds; $\varepsilon_{\text{inj}}^{CR} \sim 0.1$
  - Power-law CR scattering rate
  - 3 Milky Way analogs (m12f, m12i, m12m)

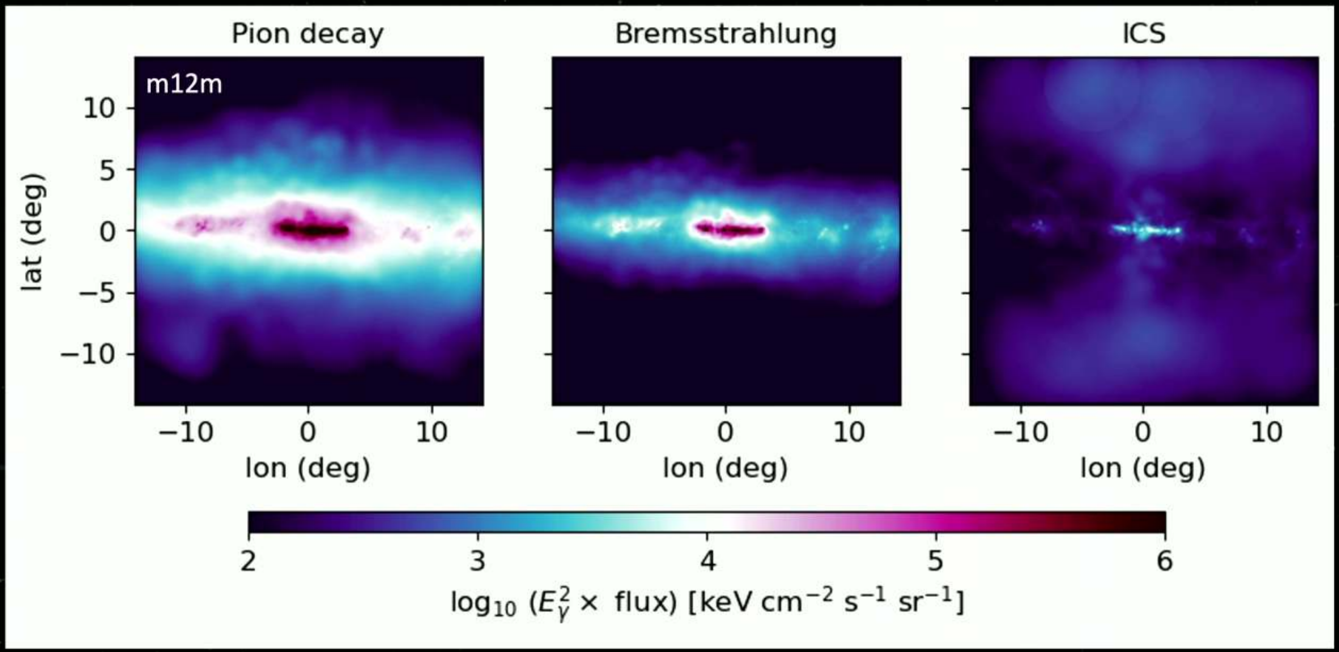


Simulations + Modeling

- Construct γ -ray emission from:
  - Pion decay (Kafexhiu+ 2014)
    - ∝ gas density, p abundance
  - Inverse Compton Scattering
    - ∝ radiation field, e^-/e^+ abundance
  - Relativistic Bremsstrahlung
    - ∝ gas density, e^-/e^+abundance
- NO pulsar injection, AGN, annihilating dark matter (yet)



γ-ray Flux Maps



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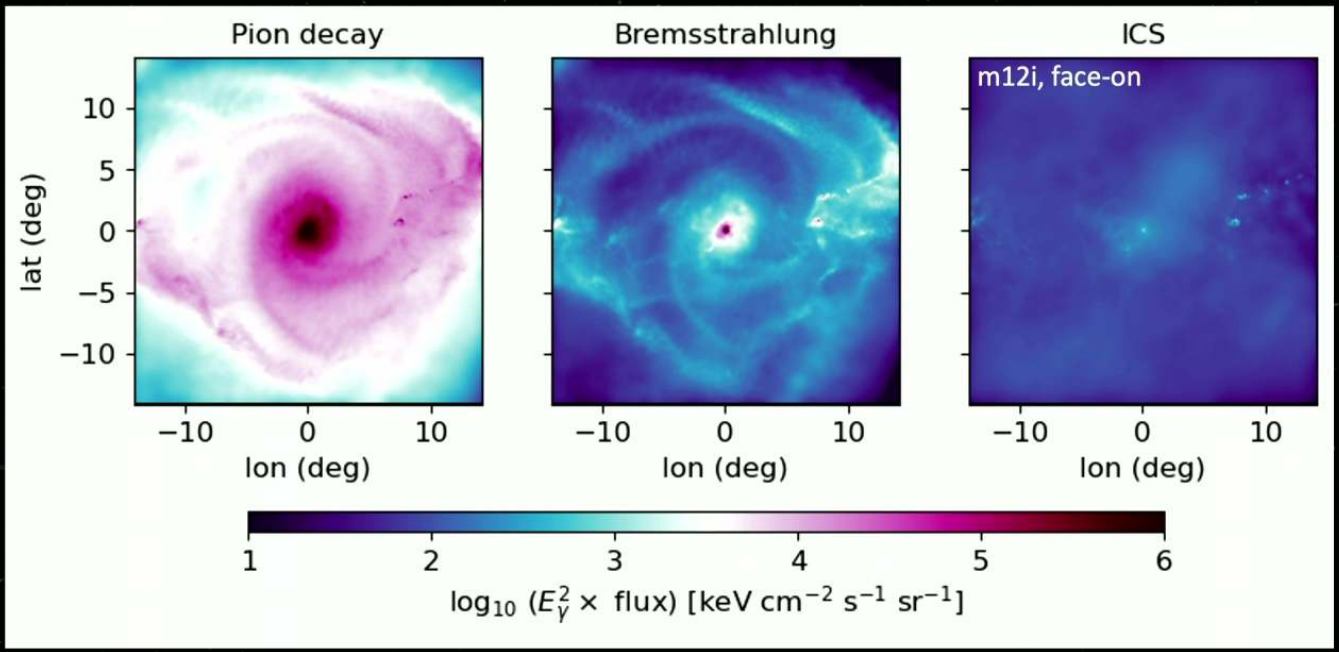
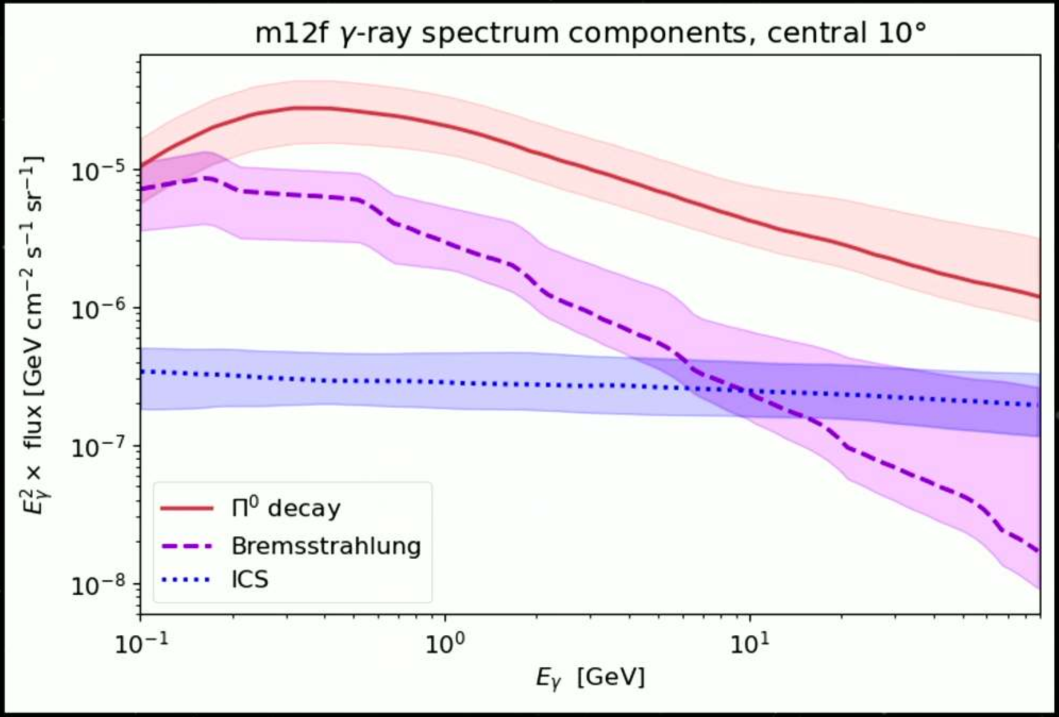
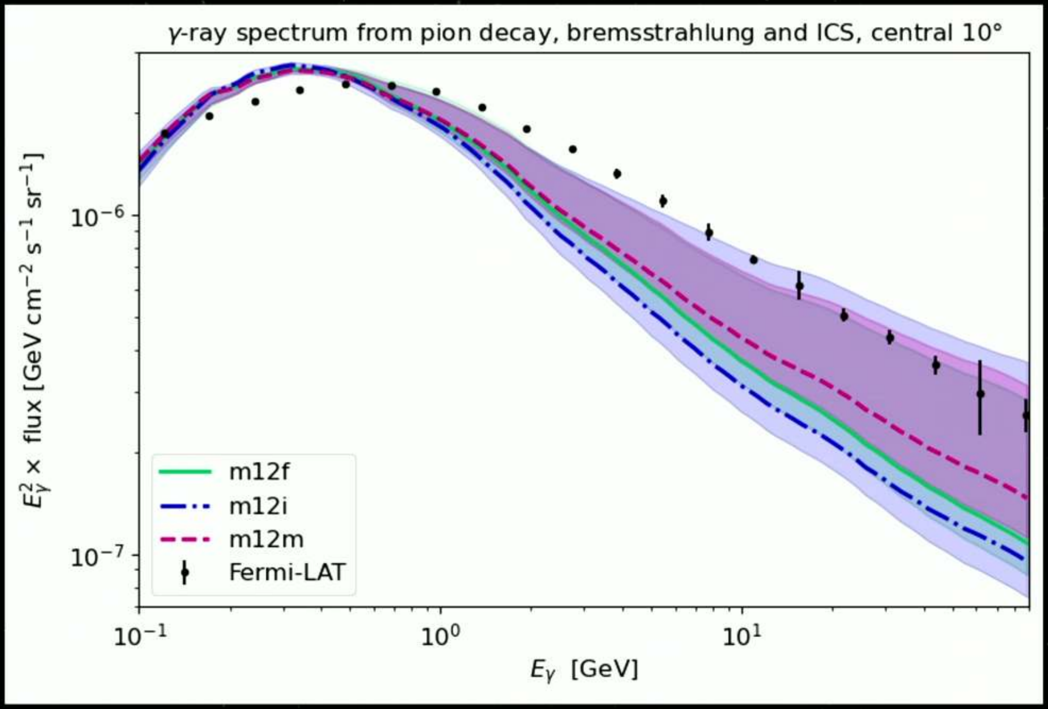


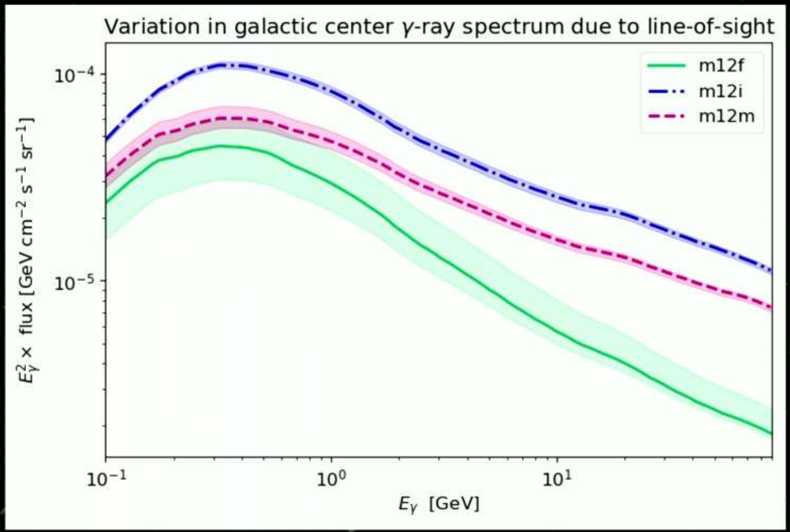
Galactic Center γ-ray Spectrum

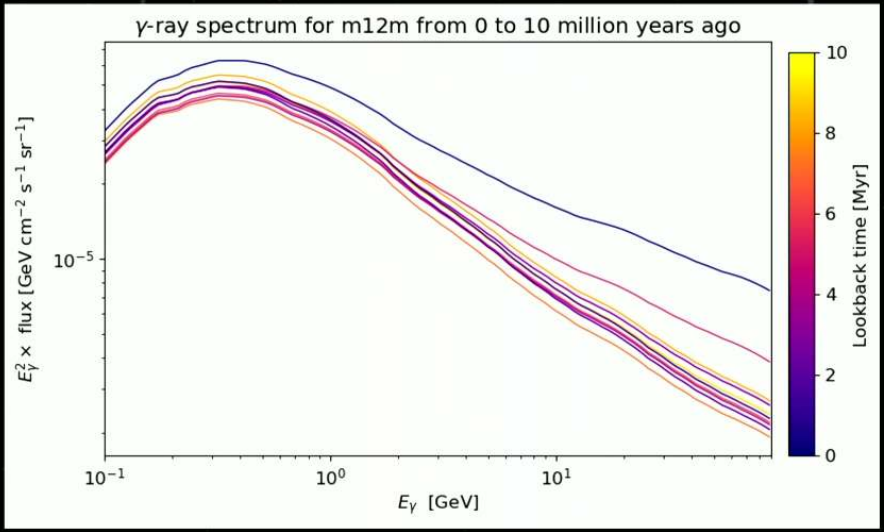


Galactic Center γ-ray Spectrum

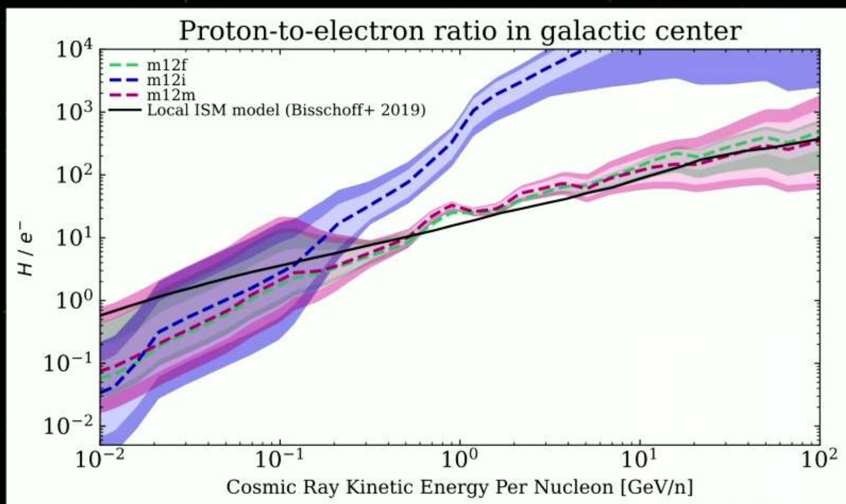


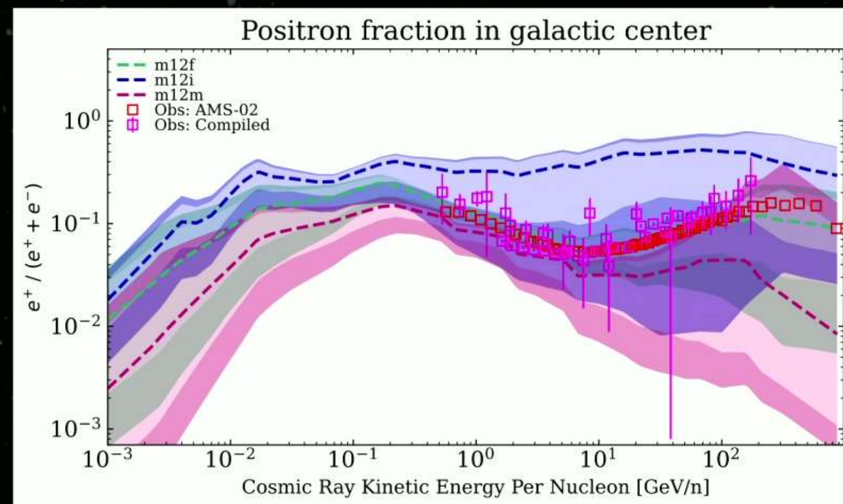
Variation over time and viewing angle





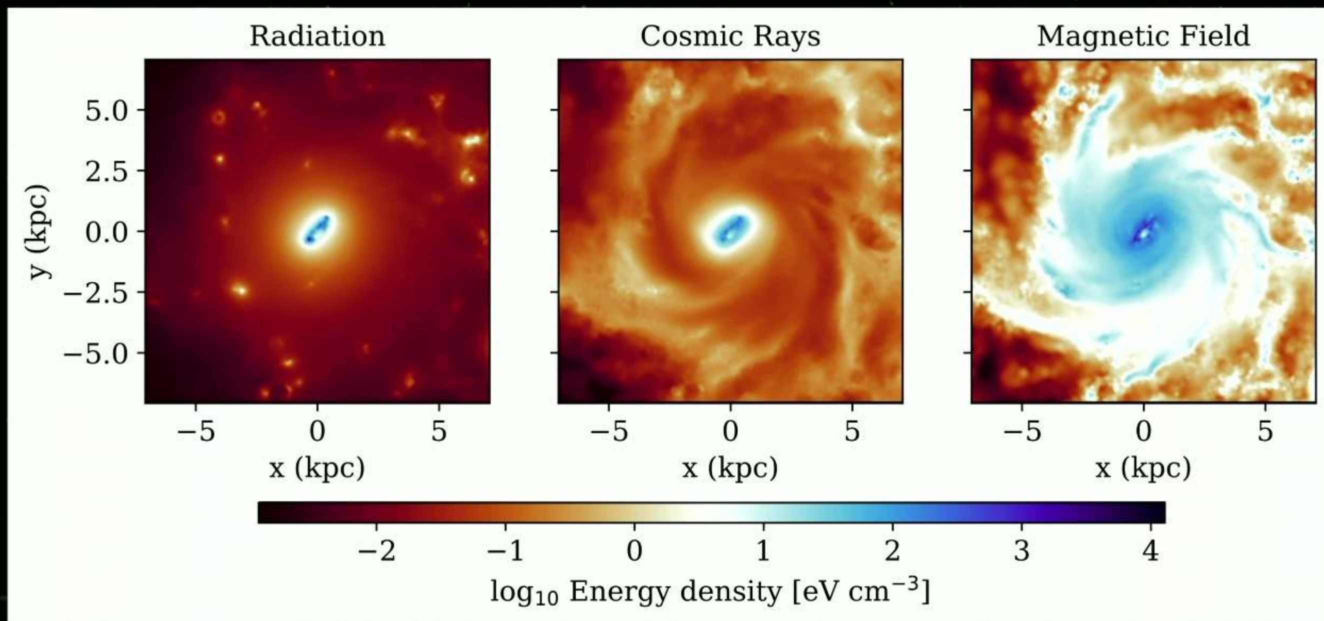
What drives variation?





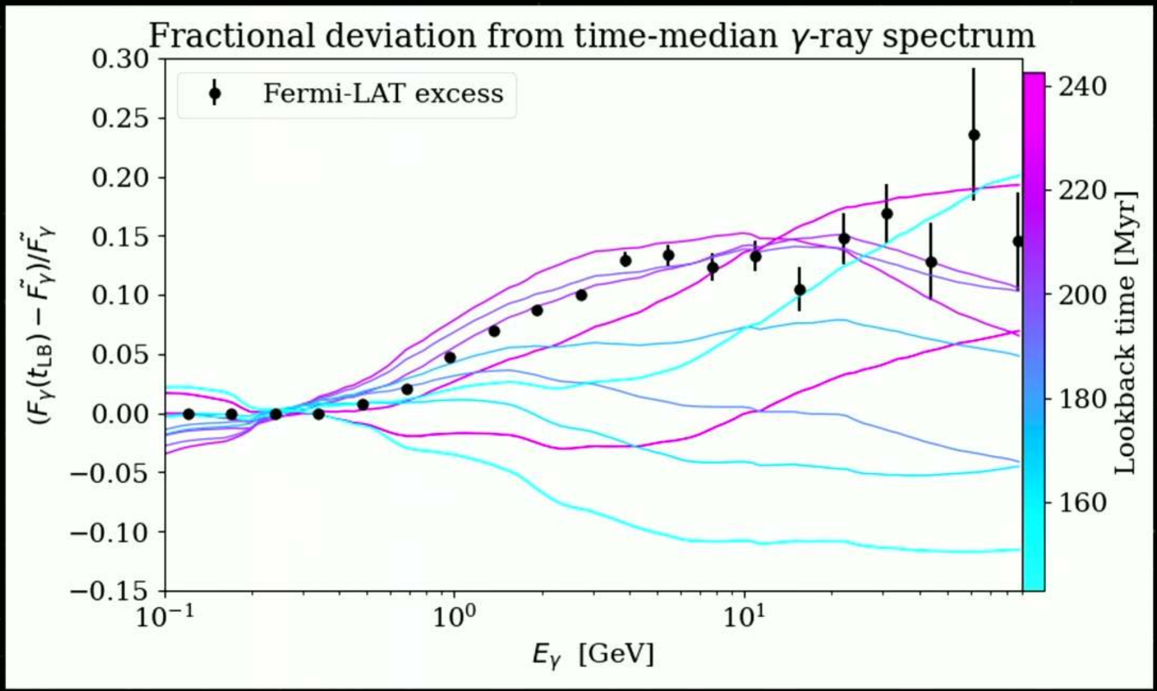
-> Loss rates are variable in space and time

What drives variation?



+ star formation rate; all mutually correlated, dynamical quantities that vary in space & time

What does this mean for the galactic center γ-ray excess?



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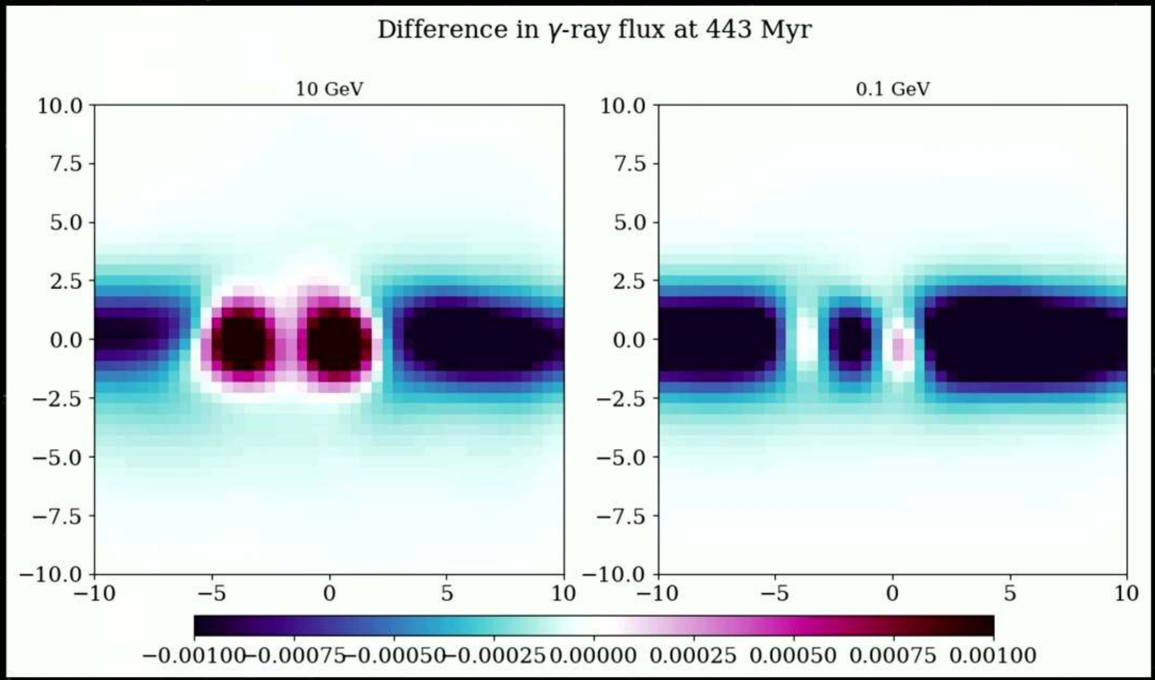
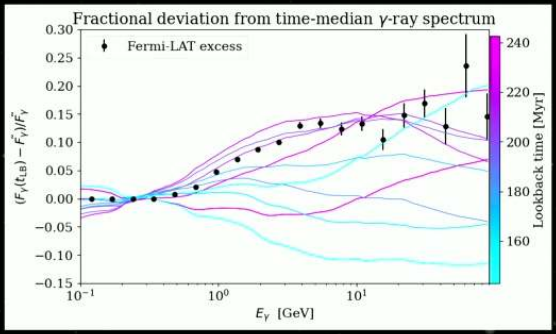


PRELIMINARY

Summary + Next Steps

- Constructed γ-ray emission from multi-bin cosmic ray simulations
- γ-ray spectrum fluctuates by order of magnitude over time, driven by varying B-fields, star formation rate, etc.
- Time-varying diffuse γ-ray emission is consistent with Fermi-LAT GeV excess
- arXiv: 2509.18351



What's next:

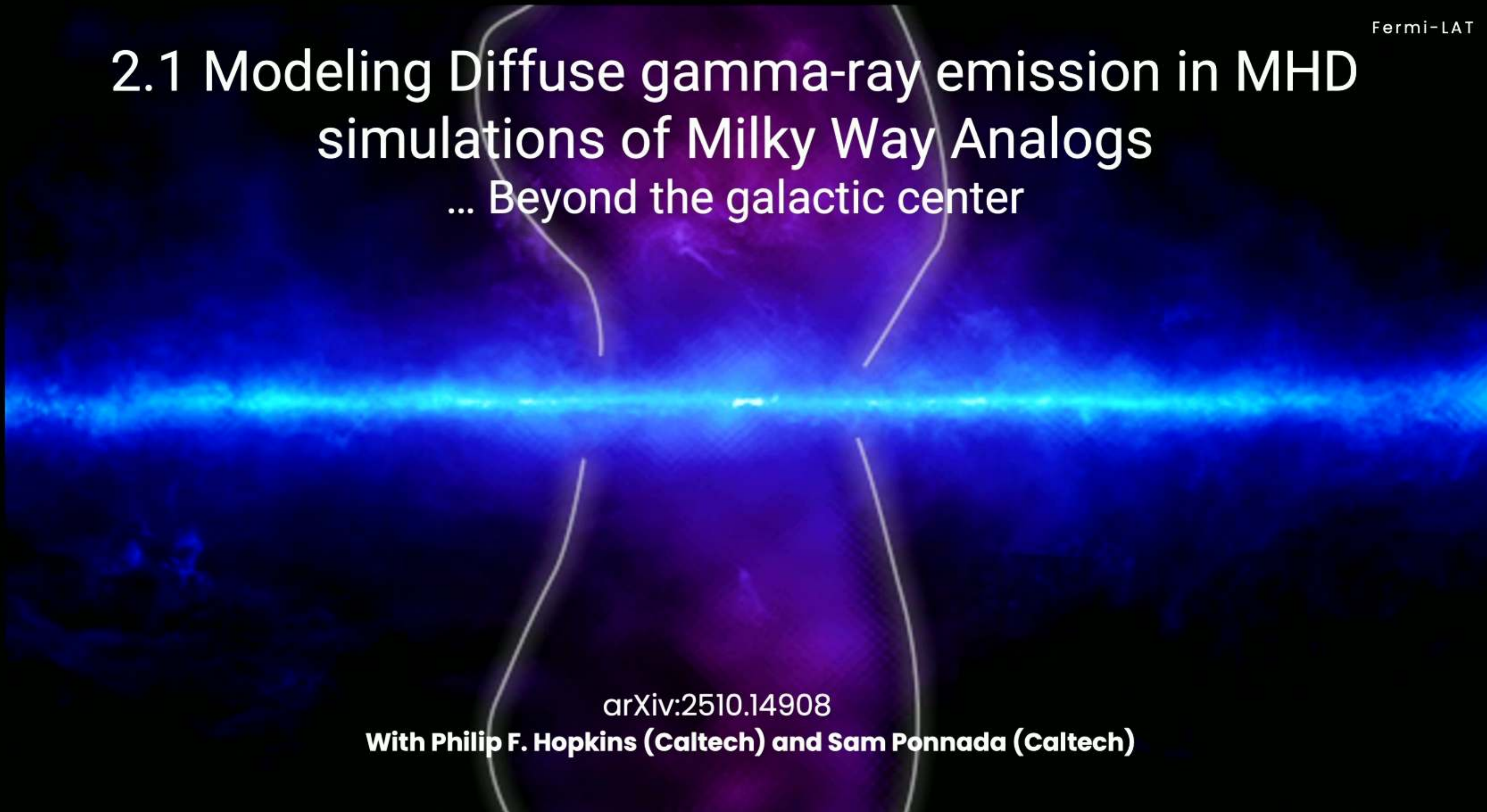
- New simulations with CR + AGN
- Extend γ-ray modeling to simulated analogs of e.g. dwarfs, LMC, M31

Future directions:

- Inject sample source populations into simulations :
  - Annihilating dark matter
  - Point sources (e.g. pulsars)
- Develop new GALPROP templates informed by simulations

2.1 Modeling Diffuse gamma-ray emission in MHD simulations of Milky Way Analogs

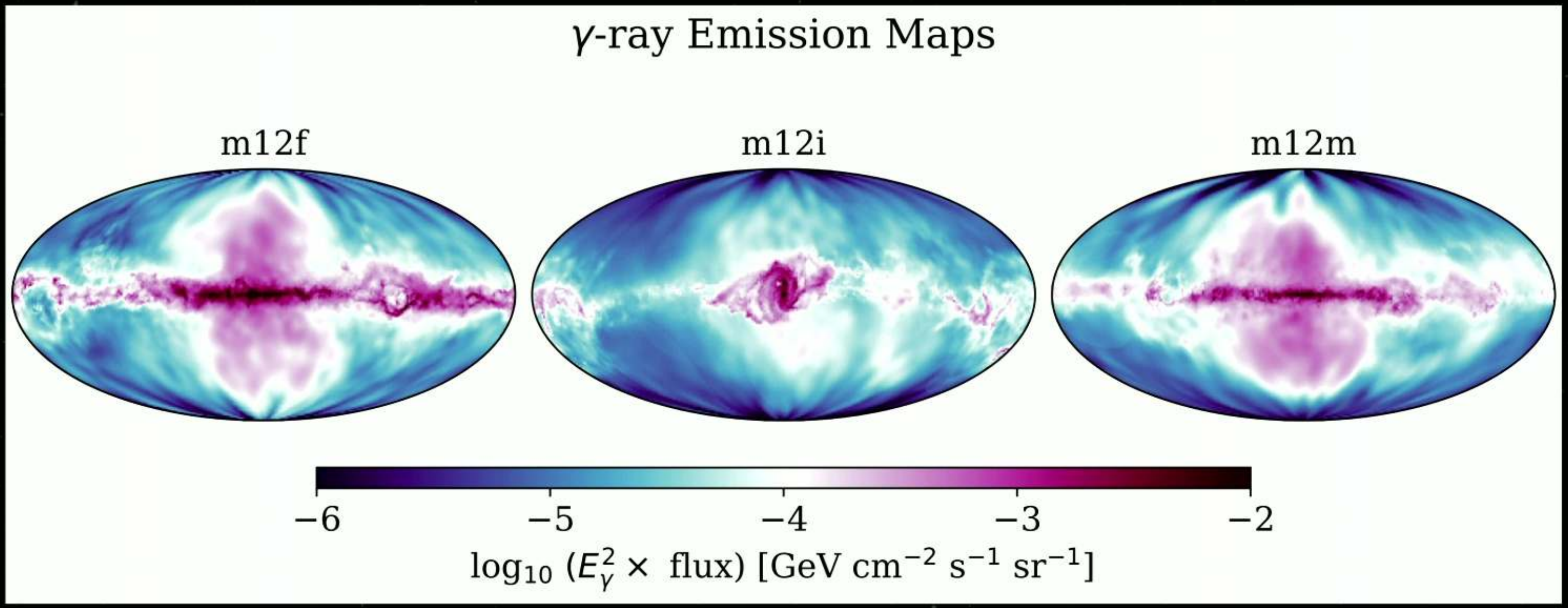
… Beyond the galactic center



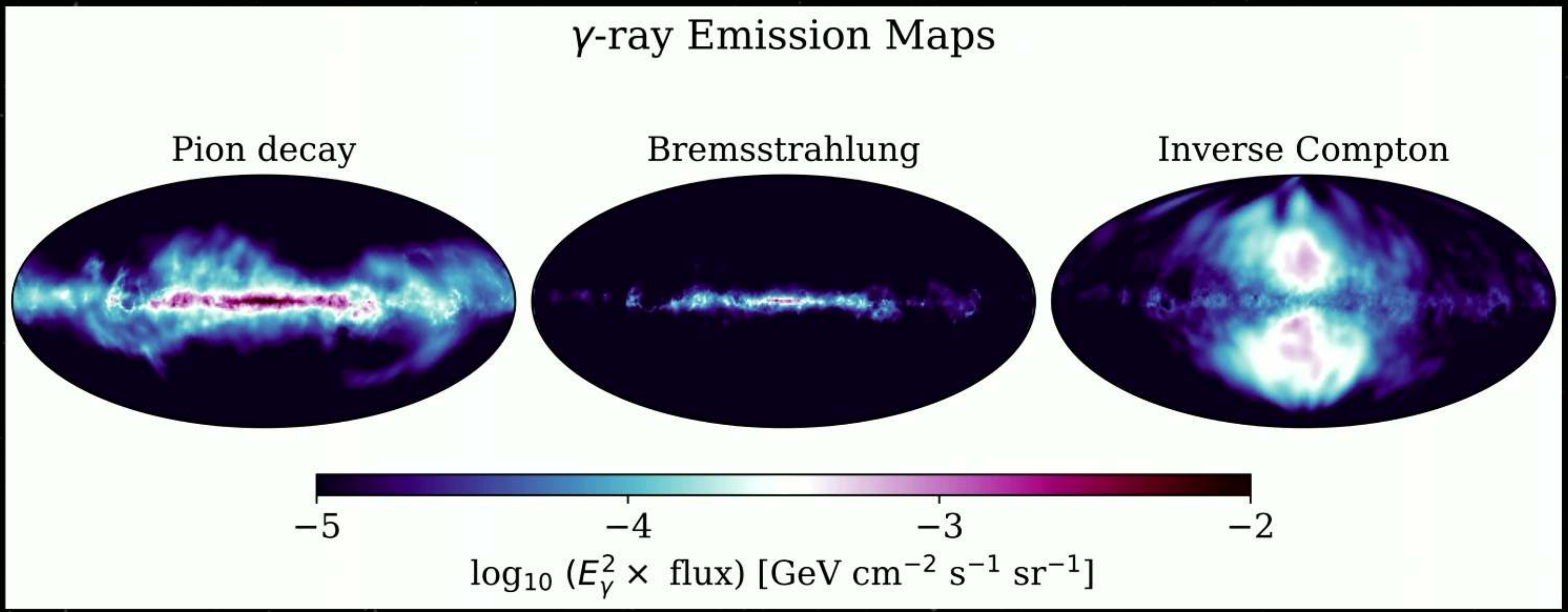
arXiv:2510.14908

With Philip F. Hopkins (Caltech) and Sam Ponnada (Caltech)

Beyond the Galactic Center: bubbles



Beyond the Galactic Center: bubbles



Spectrum of gamma-ray bubbles