Theoretical Astrophysics At Fermilab

Dan Hooper

"Cosmic Day" Meeting, Fermilab

October 30, 2023

Theoretical Astrophysics at Fermilab

- Fermilab has a remarkably distinguished legacy in the field of cosmology
- More than any other single institution in the world, Fermilab has led the movement that brought the fields of particle physics and cosmology together
- Fermilab (with UC) launched the first large-scale cosmological survey (SDSS) in the 1990s – this was the beginning of the observation/experimental astrophysics program at FNAL
- A few years ago, the *Theoretical Astrophysics Group* became the *Theoretical Astrophysics Department* and part of the newly formed Theory Division (but our hearts still lie in Astrophysics)

A few of our “Greatest Hits”

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- In 1993, Scott Dodelson proposed that sterile neutrinos could be produced through oscillations in the early universe
- In 1995, Josh Frieman proposed that dark energy could be driven by a slowly rolling scalar field
- In 1996, Albert Stebbins proposed that B-mode polarization could be used as a probe of inflation

Themes of Theoretical Astrophysics at Fermilab: The Big Questions

- What is the nature of dark matter?
- What is the nature of dark energy?
- Why does our universe contain more matter than antimatter?
- How has our universe evolved over time? Did inflation take place? If so, how did it play out?

What are the laws that govern our universe? And how can we use astrophysical/cosmological observations to learn more about these laws?

Themes of Theoretical Astrophysics at Fermilab: The Not Quite As Big Questions

- How did the universe become reionized?
- How are cosmic rays accelerated?
- Where do high-energy neutrinos come from?
- How have baryons impacted large-scale structure?
- How have neutrinos impacted large-scale structure?

Themes of Theoretical Astrophysics at Fermilab: The People

Staff Members:

- Nick Gnedin (Department Head)
- Albert Stebbins
- Dan Hooper
- Gordan Krnjaic

Postdocs:

- Hongwan Liu (David Schramm Fellow)
- Anastasia Sokolenko
- Elena Pinetti
- Huangyu Xiao

Nick Gnedin

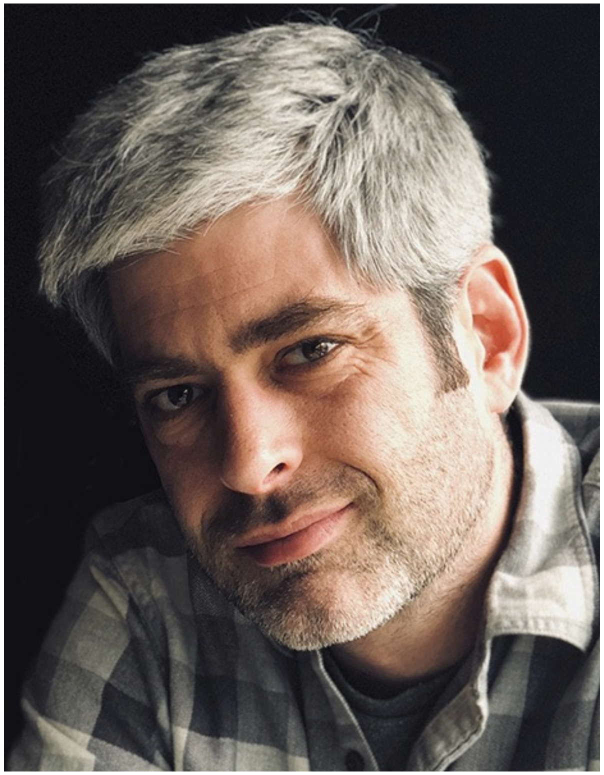
- Numerical cosmology
- Reionization
- Structure formation
- Galaxy formation, stellar feedback
- The Lyman-alpha forest

Albert Stebbins

- 21 cm cosmology
- Cosmic microwave background
- Gravitational lensing
- Cosmic Strings
- Dynamical dark energy

Dan Hooper

- Dark matter
- Gamma-ray astrophysics
- High-energy neutrino astrophysics
- Cosmic ray physics
- Early universe cosmology



Gordan Krnjaic

- Accelerator probes of dark matter
- Early universe cosmology
- Dark matter model building
- Testing exotic physics with cosmology

Hongwan Liu

- Cosmological probes of exotic physics
- Dark matter detection and models

- Recently arrived from NYU and Princeton
- Will be joining the faculty at BU next year

Anastasia Sokolenko

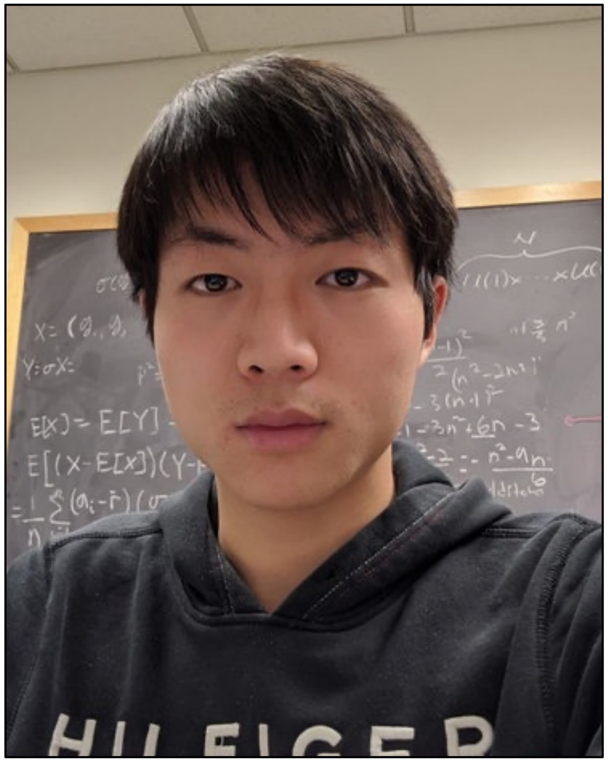
- Dark matter
- Gamma-ray astrophysics
- Intergalactic magnetic fields

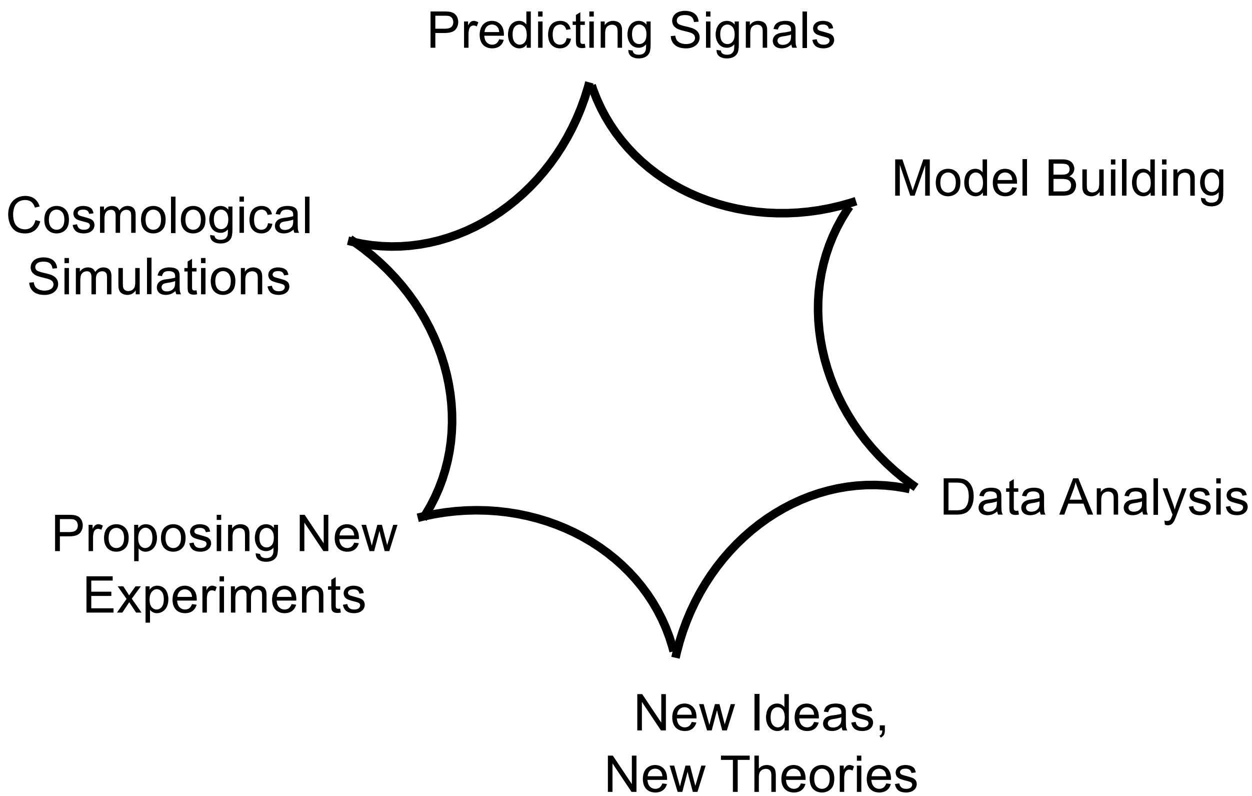
Elena Pinetti

- Dark matter indirect detection
- Gamma-ray and X-ray astrophysics
- Early universe cosmology

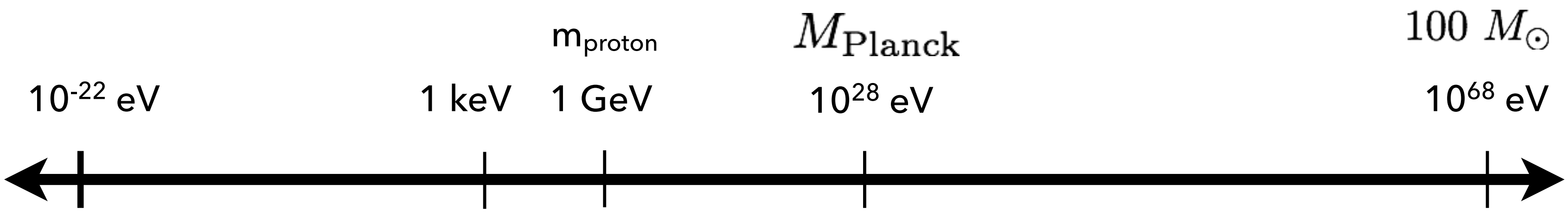
Huangyu Xiao

- Dark matter
- Axions
- Cosmological probes of exotic physics
- Early universe cosmology




Predicting Signals
Model Building
Data Analysis
New Ideas,
New Theories
Proposing New
Experiments
Cosmological
Simulations

The Dark Matter Landscape



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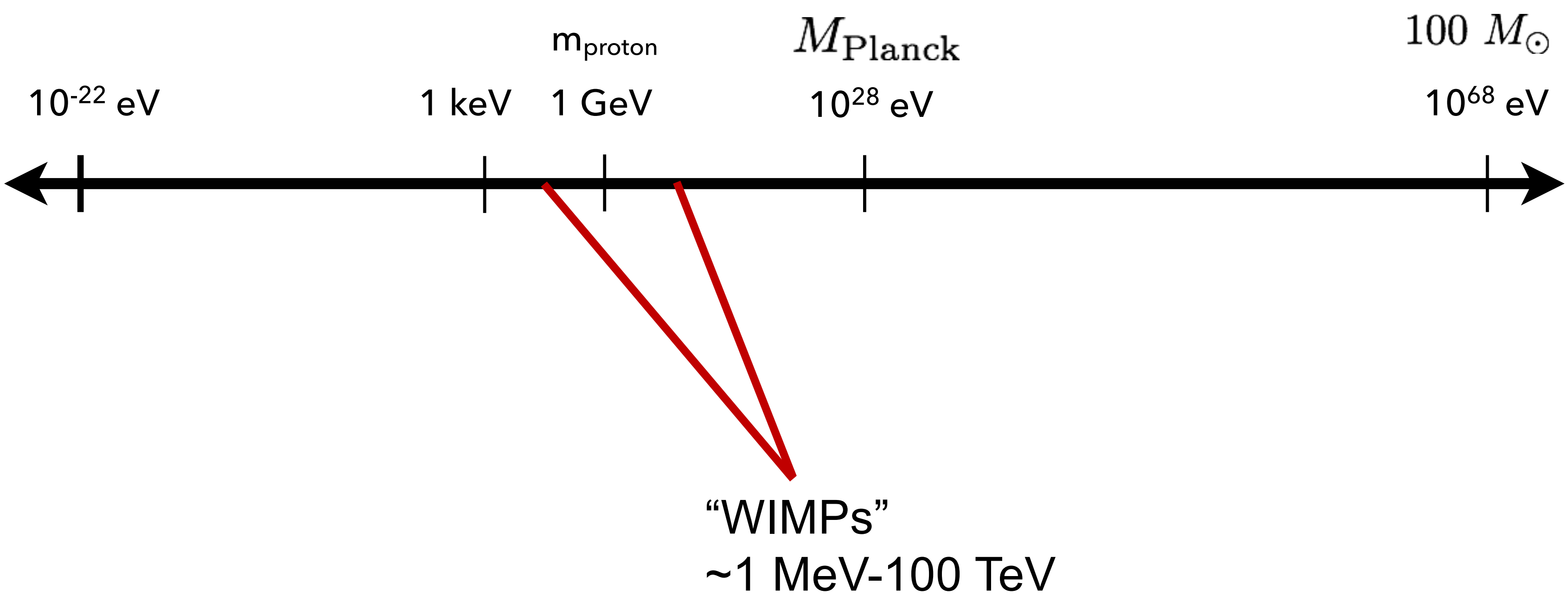

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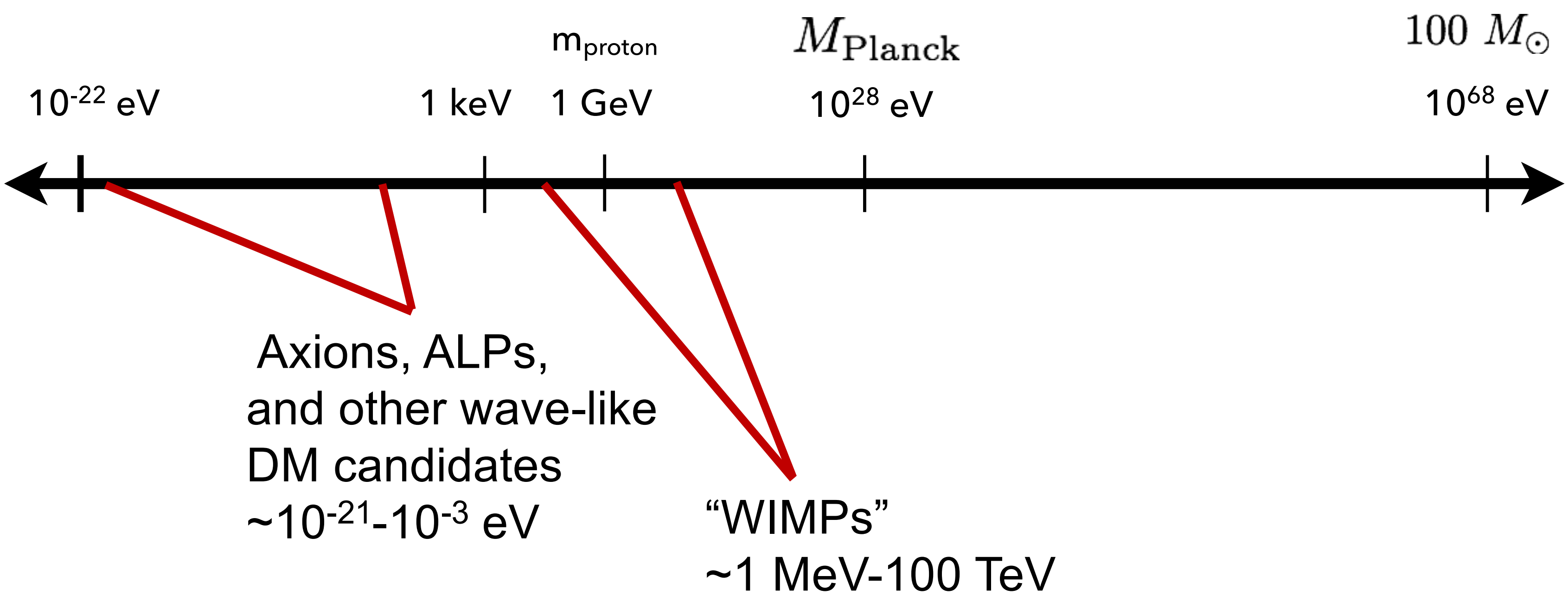

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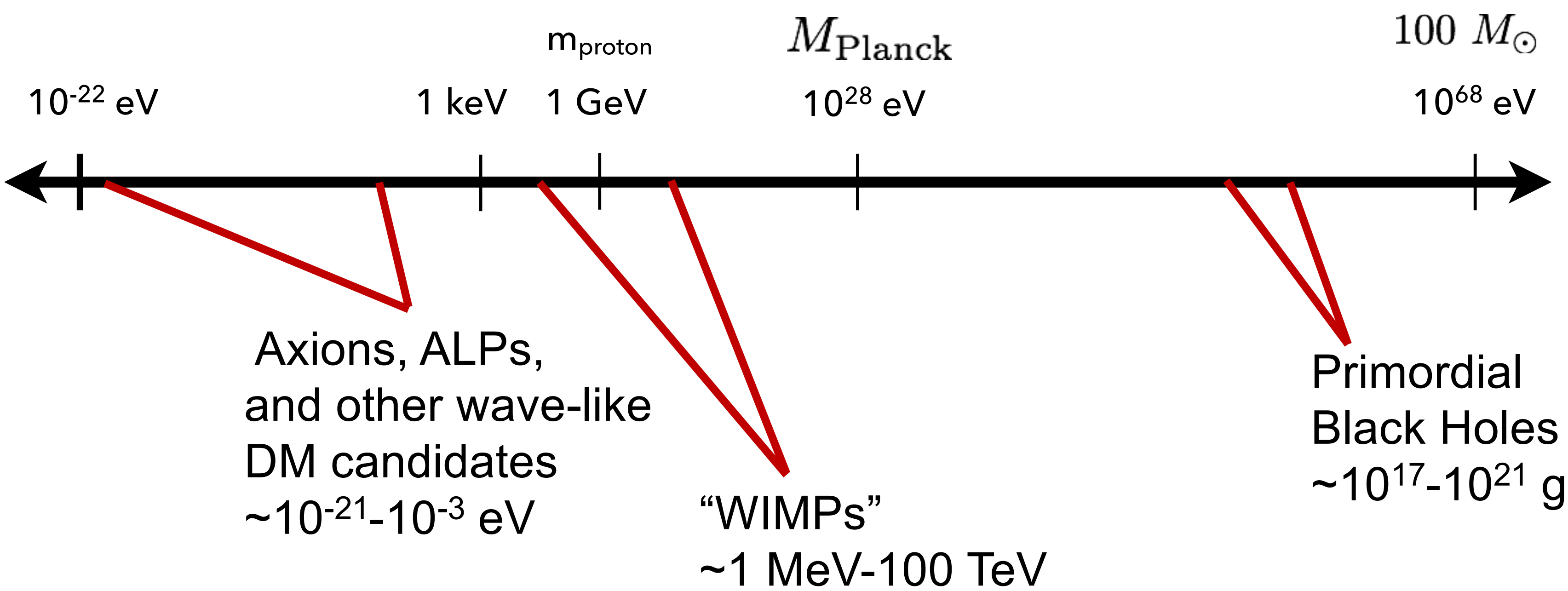

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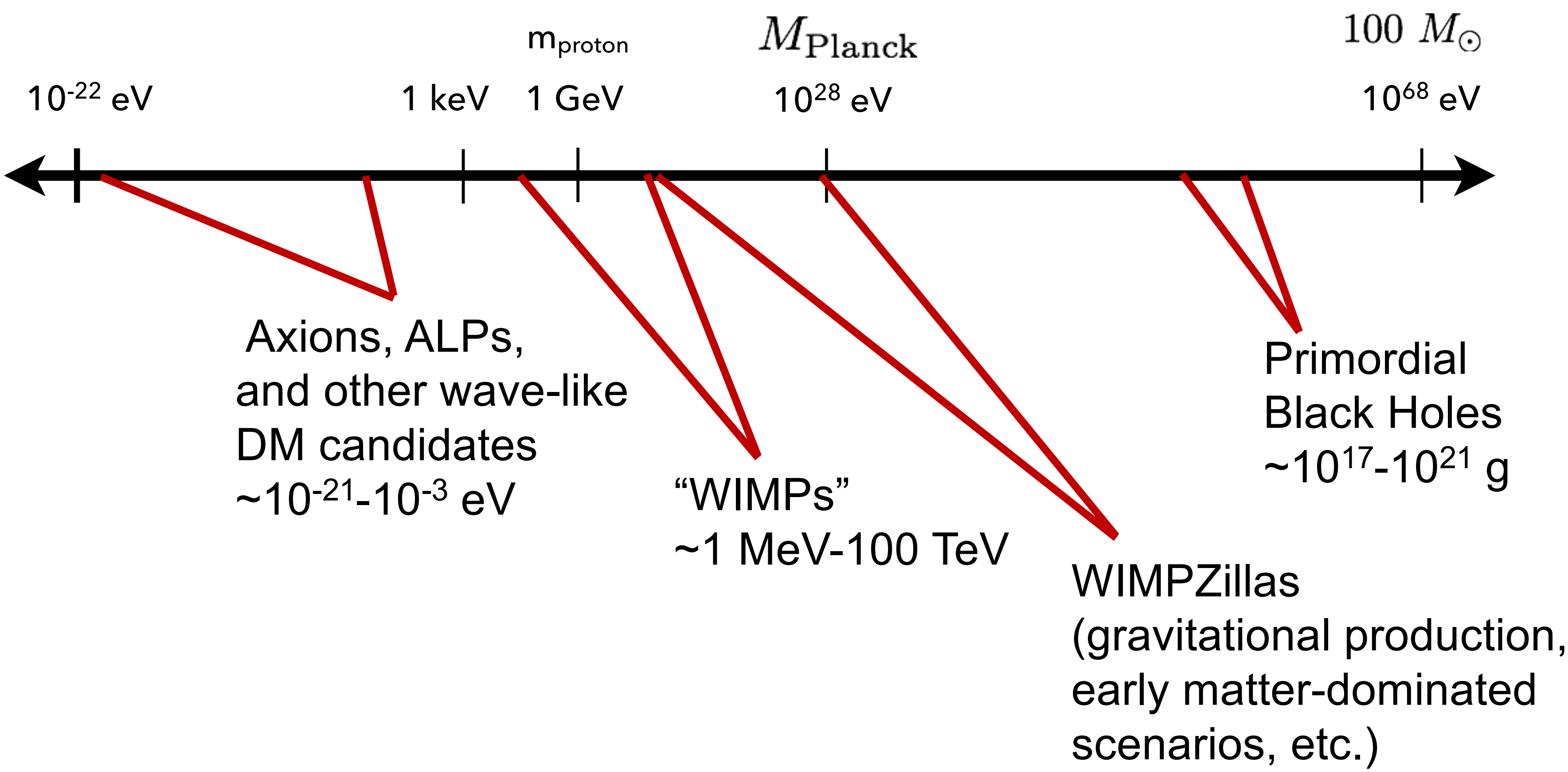
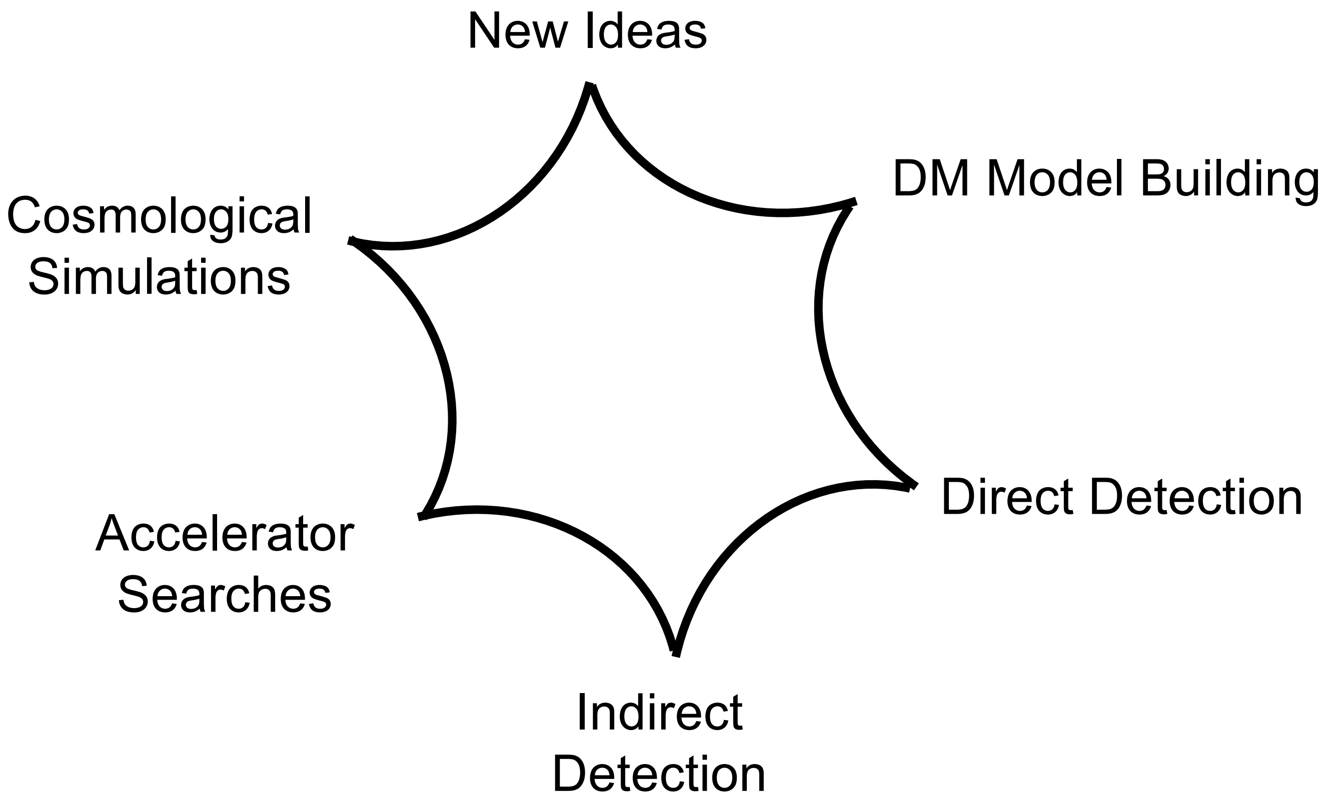
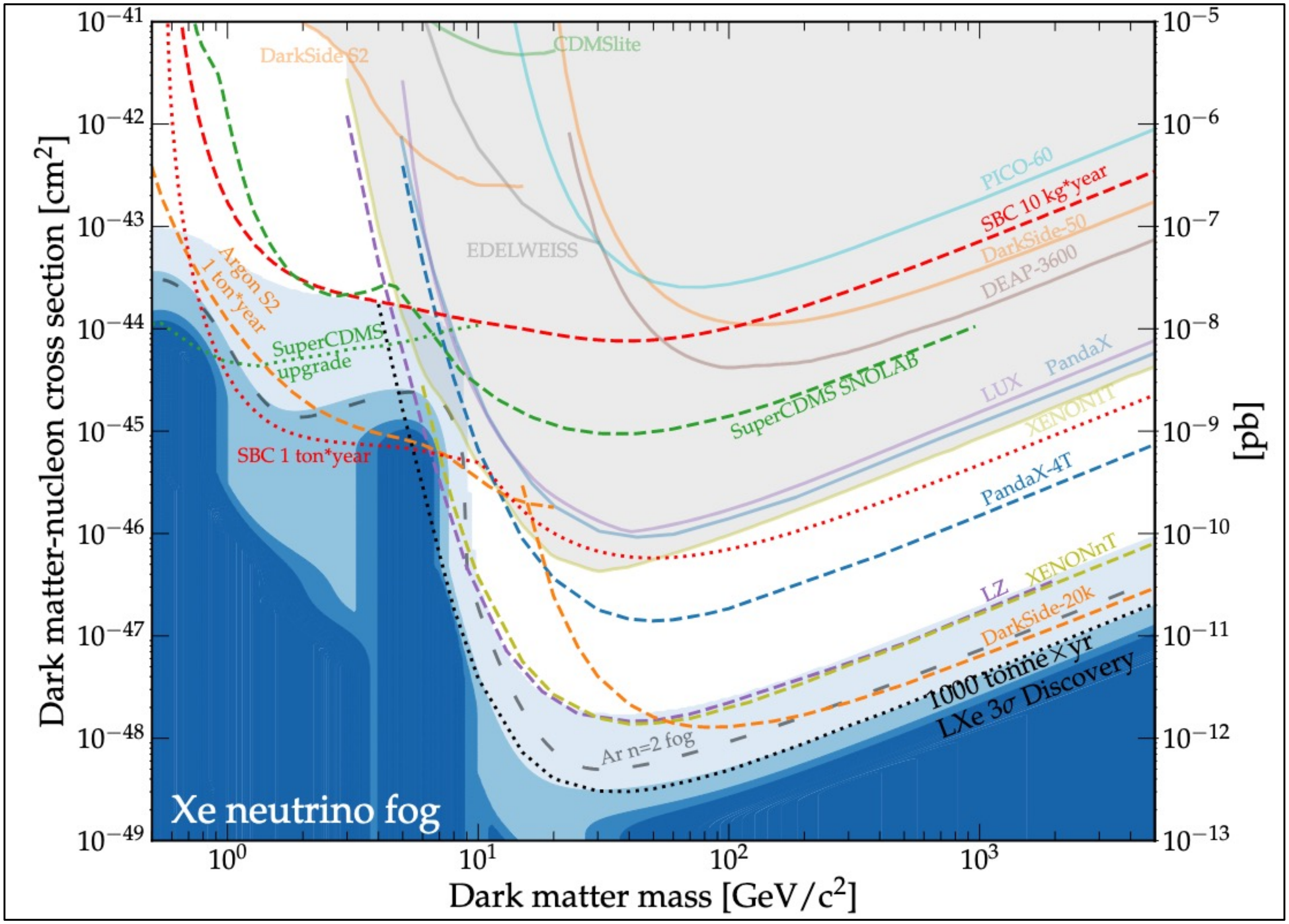



New Ideas
DM Model Building
Direct Detection
Indirect Detection
Accelerator Searches
Cosmological Simulations

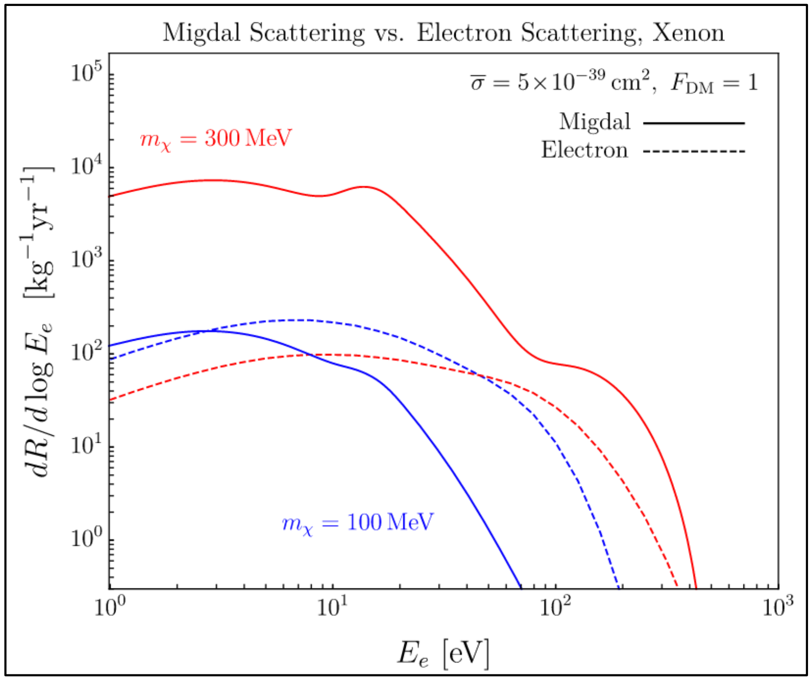
Direct Searches for WIMPs



Snowmass CF Dark Matter Direct Detection, arXiv:2203.08084

Theory Input for Direct Detection of Low-Mass DM

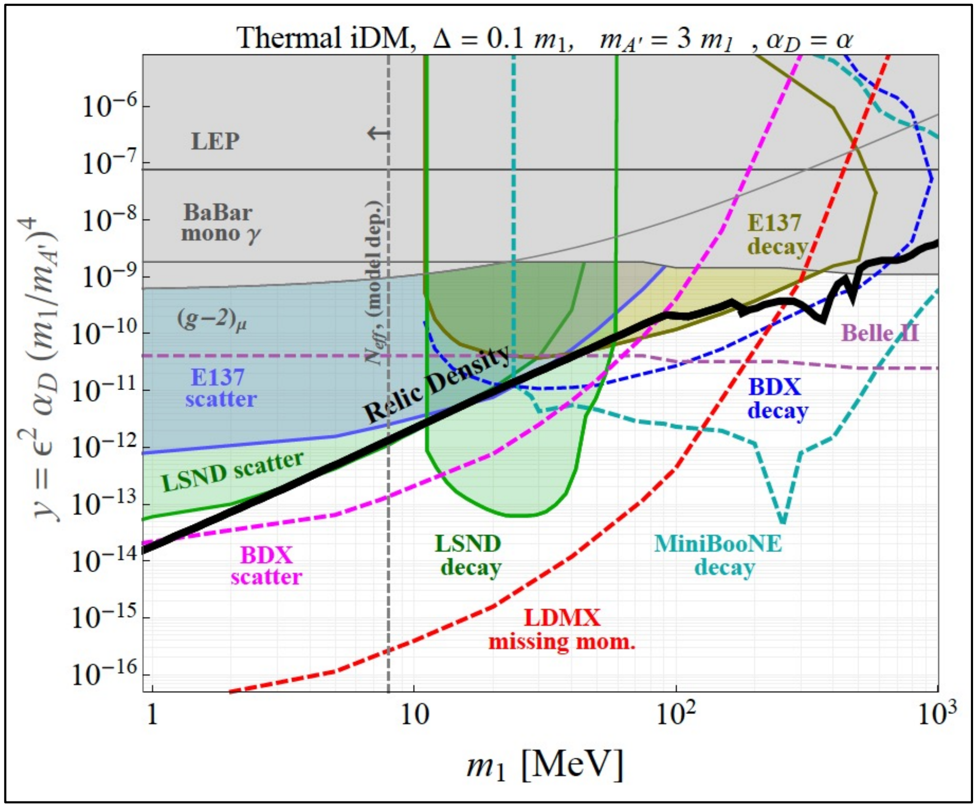
- Searches for relatively heavy dark matter particles ($> 1 - 10$ GeV) generally rely on scattering with nuclei; the signals and consequent strategies can be different for lighter particles, and theory has made significant advances in this area in recent years
- When a dark matter particle scatters elastically off a nucleus, it can take some time for the atomic electrons to catch up with the motion of the nucleus, resulting in the ionization and excitation of the atom – this is known as the Migdal effect
- Krnjaic, Baxter and collaborators have shown that Migdal scattering can be the dominant signal for dark matter that couples comparably to electrons and nucleons (such as through a dark photon)
- This has important implications for experiments looking for low-mass WIMPs, such as SENSEI, Super-CDMS, DAMIC



Krnjaic, Baxter, arXiv:1908.00012, 2011.09477

Accelerator Searches for keV-GeV Dark Matter

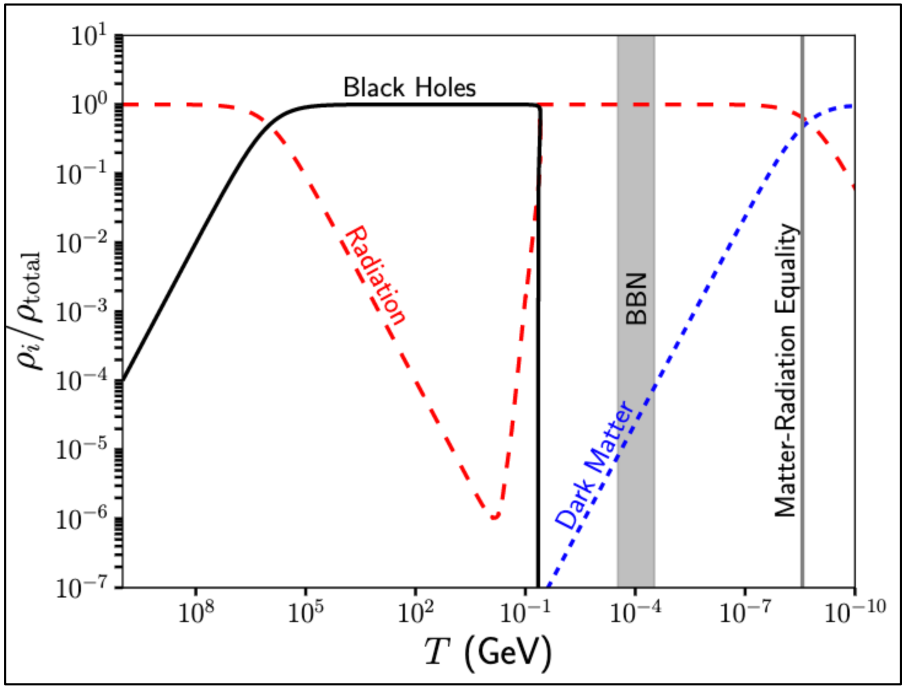
- If dark matter is sub-GeV, it must not have Standard Model interactions, and requires new forces
- The most compelling models are those that are predictive and testable
- The intensity frontier provides a suite of new ways to explore this class of scenarios



Krnjaic and collaborators

New Ideas for the Production of Dark Matter: Via Hawking Radiation of Primordial Black Holes

- If black holes made up even a trace fraction of the total energy density after inflation, this fraction would increase as the universe expands, likely coming to dominate the total energy density
- If these black holes were lighter than ~10^8 grams, they would evaporate before BBN
- Hawking radiation of these black holes could easily have produced the measured abundance of dark matter
- This novel mechanism for dark matter's production can lead to interesting gravitational wave and CMB signals, and has motivated a great deal of further research



Hooper, Krnjaic, McDermott, arXiv:1905.01301, 2004.00618, 2006.03608, 2010.01134

Casting A Wide Net in the Search for Dark Matter

- Numerous studies on indirect searches for DM (Hooper, Krnjaic, Pinetti, Sokolenko)
  - Projections for CTA, e-Astrogam, AMIGO
  - New constraints on sub-GeV dark matter from X-ray telescopes
  - Proposal to target cosmic voids as a probe of annihilating dark matter
  - Identifying TeV halos as the source of the cosmic ray positron excess
  - Refinement of the predicted antideuteron and antihelium fluxes from dark matter
  - Analysis of the AMS cosmic ray antiproton spectrum
- Long-standing program to use the Lyman-Alpha Forest to constrain DM (Gnedin)
- Studies of DM's distribution on small-scales in scenarios with an early matter dominated era (Blinov, Stebbins, 2107.10293, Hooper, 1906.00010)
  - Identifying new dark matter freeze-in scenarios
  - Proposed a new dark matter candidate in fraternal Twin Higgs models
  - Constraining ultralight dark matter interactions with neutrinos
  - DM production via Hawking evaporation
- DM pheno/model building/production mechanisms (Krnjaic, Hooper, Sokolenko, Xiao)
- DM Connections with muon g-2 (Krnjaic, Hooper, 2107.09067)

Summary

- Snowmass identified the following five science drivers of the cosmic frontier:
  - Dark matter
  - Dark energy
  - Inflation
  - Neutrinos
  - Exploring the unknown
- The activities of Fermilab's Theoretical Astrophysics Department are closely aligned with this scientific program
- At present, we are particularly strong in the areas of dark matter, exploring the unknown, and high-energy neutrino astrophysics
- Looking forward, we plan to increase our involvement in theory efforts related to cosmic surveys and CMB science (*ie*. dark energy, inflation, neutrinos, and more)
- We strive to strike a healthy balance between the theory problems that are directly relevant to current and planned experiments, and to theory questions that could one day form the foundations of future paradigms in cosmology and particle physics