Dark Matter: What's Beyond the WIMP Lamppost?

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CCAPP

NSF

Importance of Dark Matter

A central problem of cosmology

Evolution of the Universe
Formation of galaxies
Surprises likely

A central problem of particle physics

Nature and unification of forces
Patterns of elementary particles
Surprises likely

"Powerball" problem of physics, building since 1930s

How to Look for Dark Matter

Look at motivated candidates:

Clear origin stories
Can help solve particle problems

- WIMPs
- Axions
- Sterile Neutrinos
- Primordial Black Holes

Bounded list, parameter spaces

Irresponsible to not fully test

Look at broad candidates:

Vague origin stories
May help solve cosmology problems

- Annihilation or decay
- Scattering
- Accelerator production
- Astronomical probes

Unbounded list, parameter spaces

Irresponsible to not explore

Outline

So many possibilities! Zoom in on two:

How to test thermal WIMP dark matter?

How to test sub-GeV WIMP-like dark matter?

Testing Thermal WIMP Dark Matter

What is a Minimal WIMP?

Only new particle in dark sector

Feeble interactions (maybe Weak)
Annihilates primarily in s-wave

Thermal relic of annihilation freezeout

No new physics in cosmic expansion history

Relic abundance gives total annihilation cross section

How to Test?

Astronomy:
No interactions
Structure to small scales

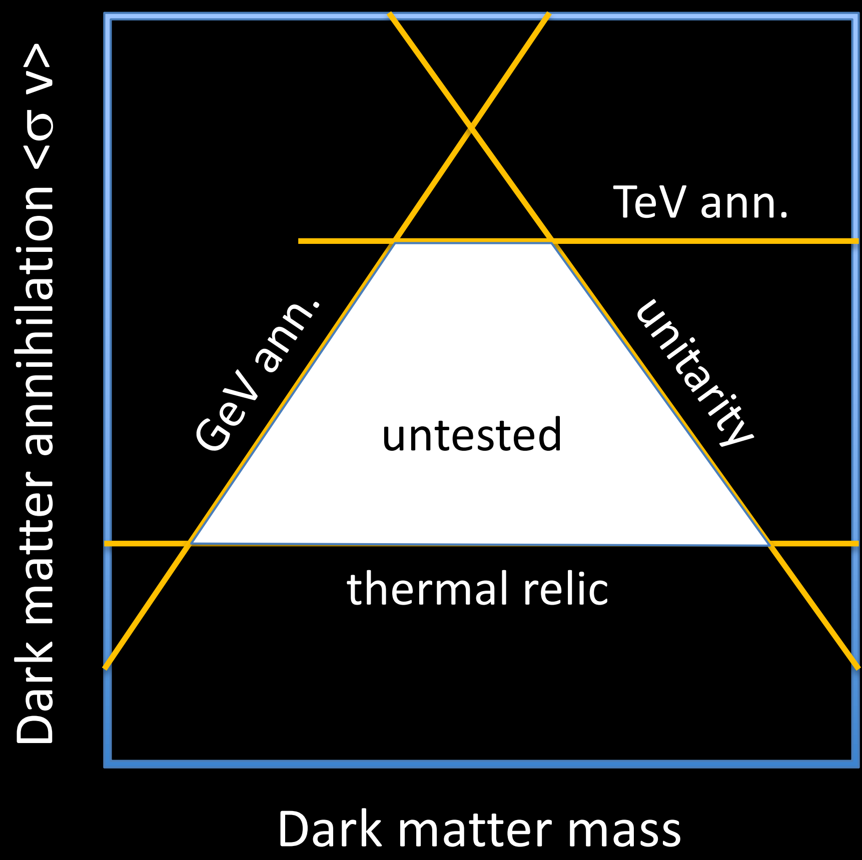
Scattering:
Feeble but possible
No guarantees!

Production:
Feeble but possible
No guarantees!

Annihilation:
Feeble but possible
Guaranteed! (*)

Critical test is the total annihilation cross section

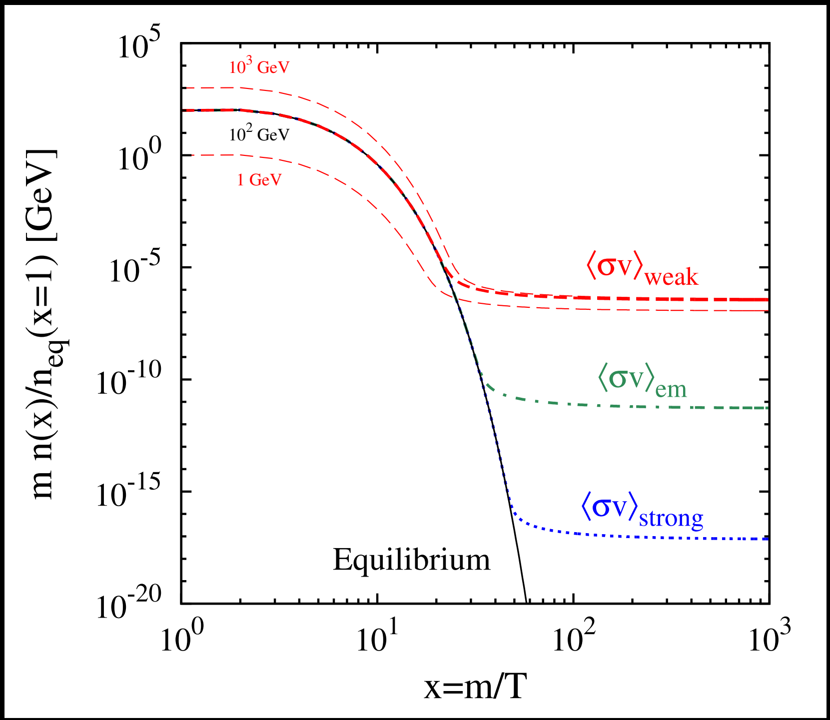
Cartoon Overview of Approach



Needs improved experimental sensitivity!

WIMP Floor: Thermal Relic Freezeout

Freezeout



Rollover due to threshold energy

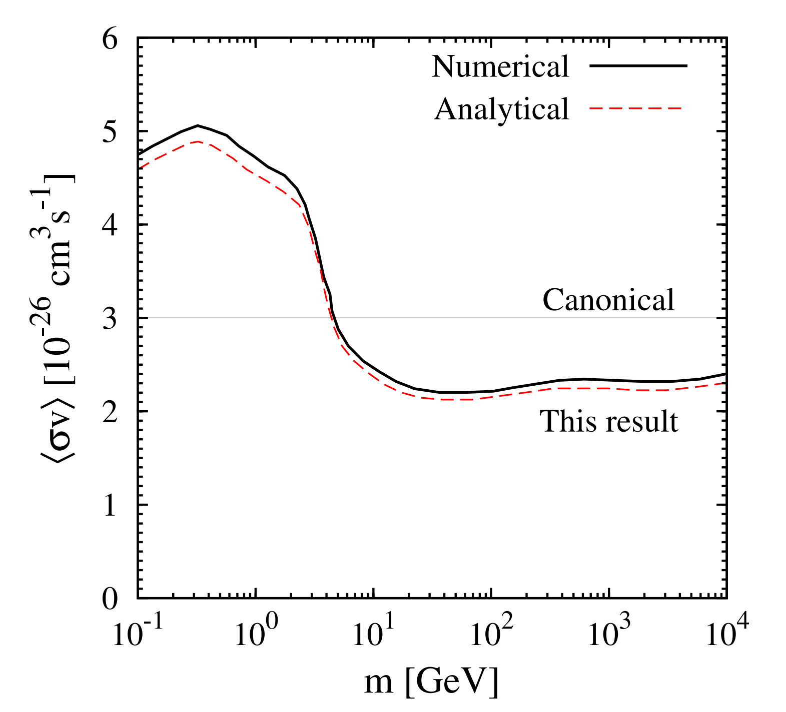
Plateau due to reaction rate falling below expansion rate

Omega ~ 1/<σ v>

Steigman, Dasgupta, Beacom (2012)

Thermal Relic Freezeout: Critical Cross Section

WIMP DM <σ v>



Steigman, Dasgupta, Beacom (2012)

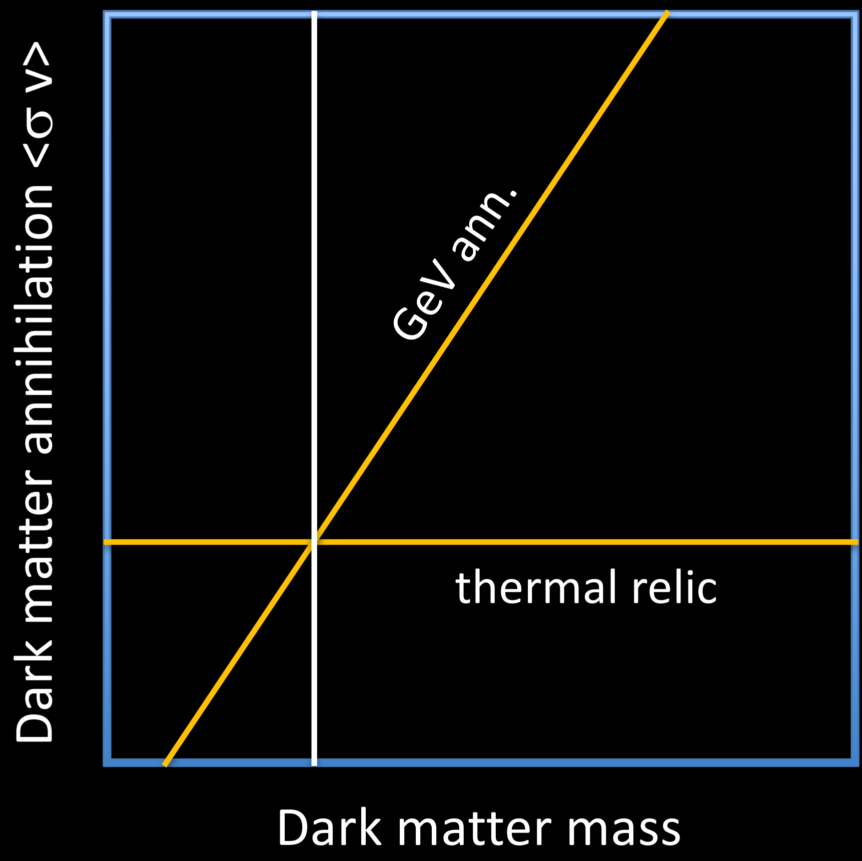
Above the line: sin of omission

Minor component of the DM

Below the line: sin of commission

You just killed the universe

WIMP Left Edge: GeV Annihilation Searches

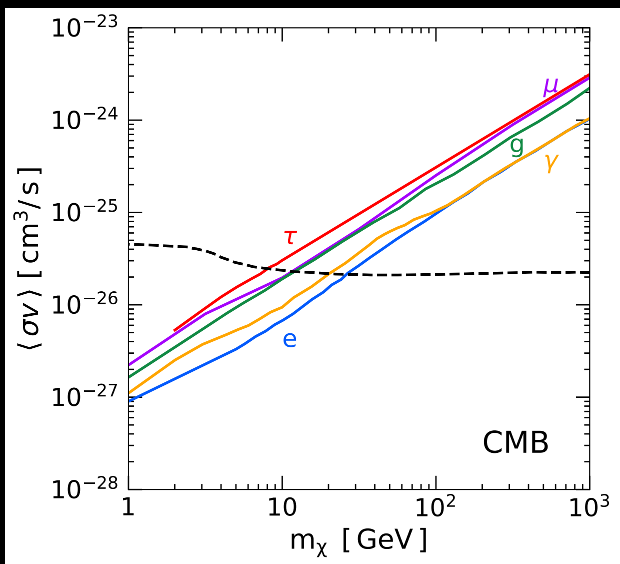


Usual thinking:
Left of white line is boring
Right of white line is interesting

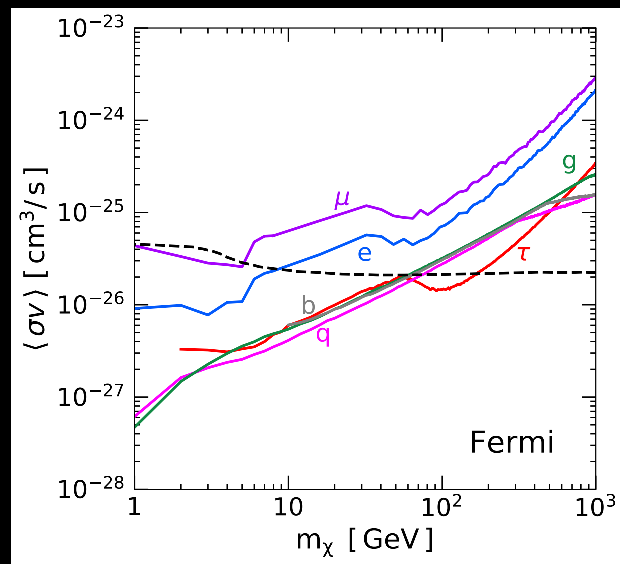
This is exactly wrong.
Leftward is the only place we have *begun* to probe thermal WIMPs

GeV Annihilation Searches: Various Channels

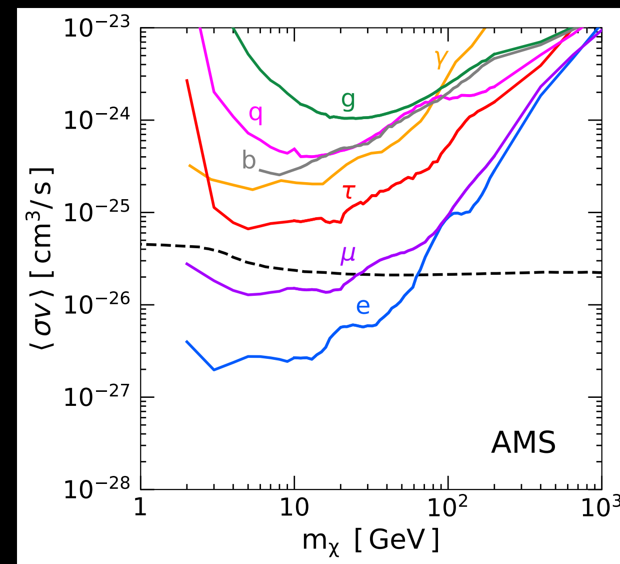
CMB injection



Fermi gammas



AMS CRs

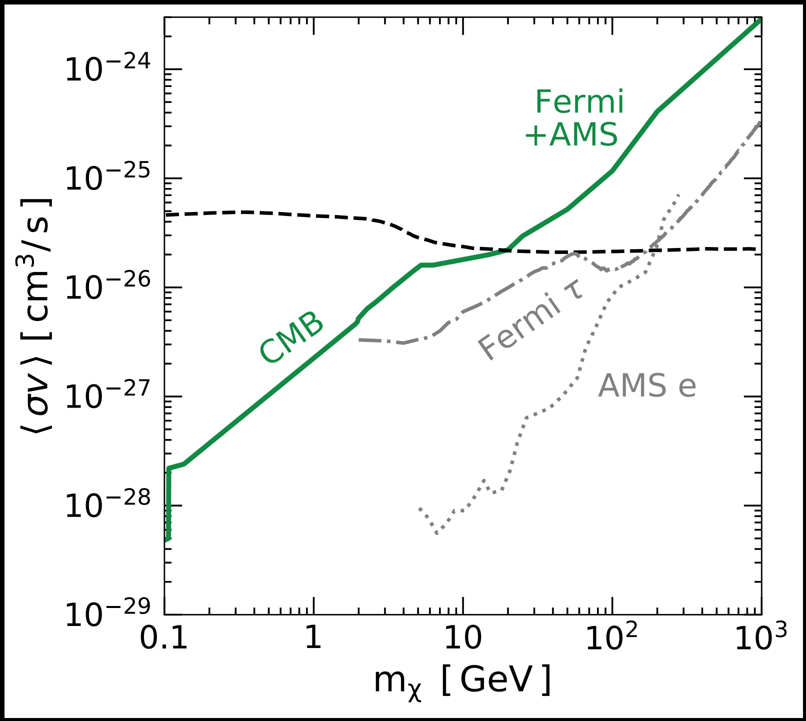


Leane, Slatyer, Beacom, Ng (2018)

Probing the total cross section requires combining all channels

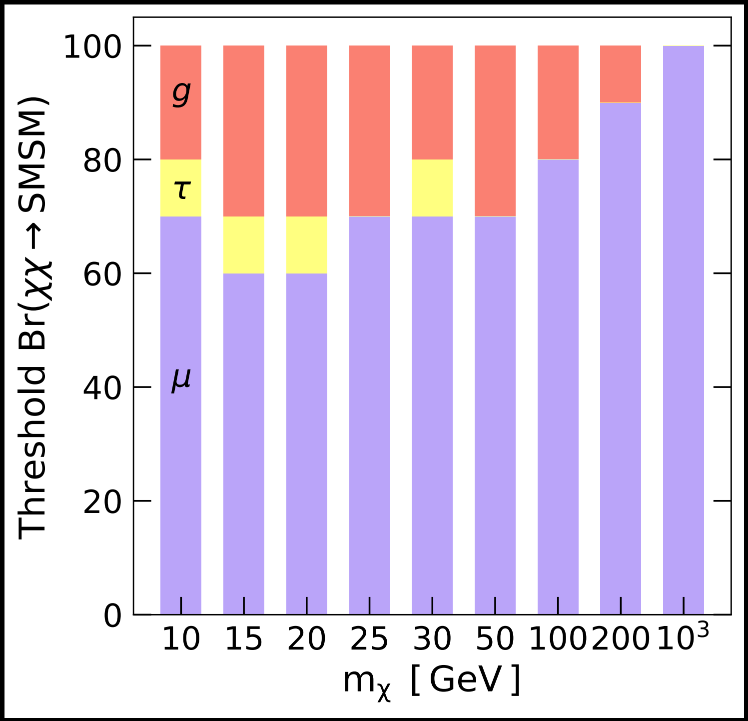
GeV Annihilation Searches: Combined Results

WIMP DM <σ v>



Leane, Slatyer, Beacom, Ng (2018)

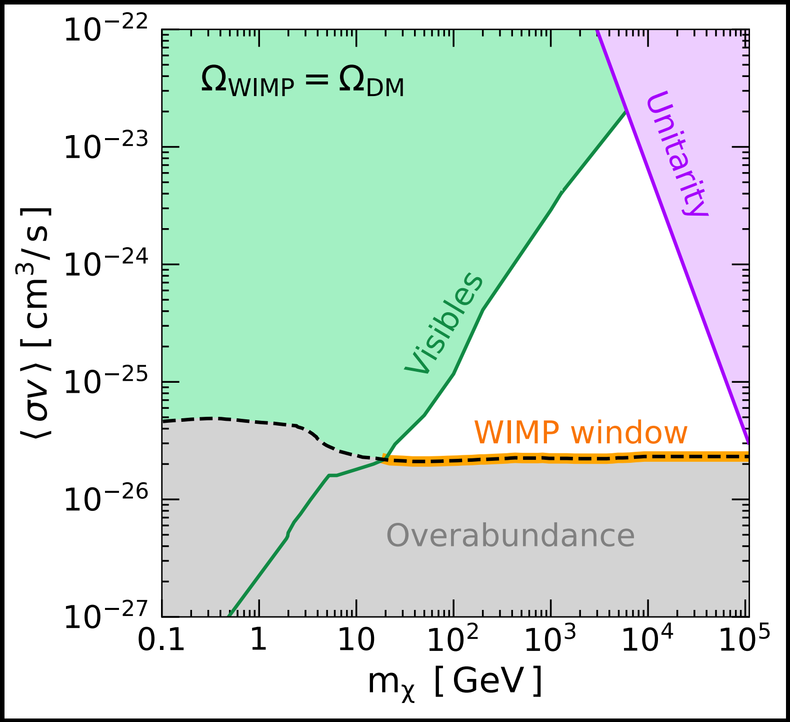
Branching ratios



First and only such limit!

GeV Annihilation Searches: WIMP Window, Frontier

Big Picture



Leane, Slatyer, Beacom, Ng (2018)

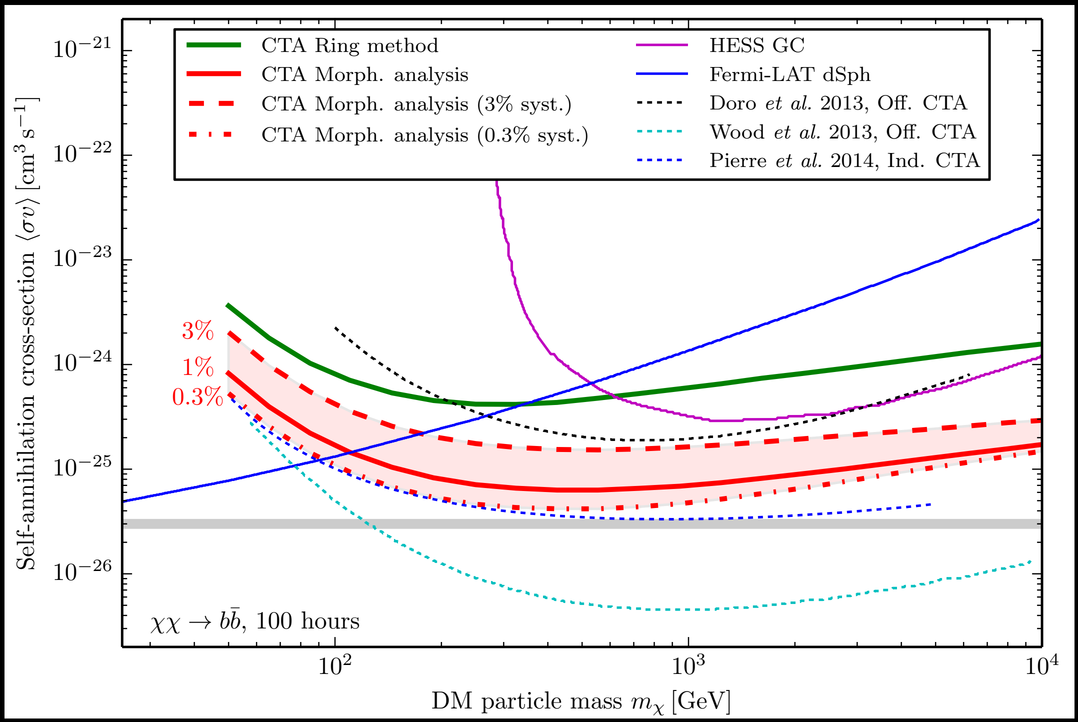
WIMP window is the labeled line

Whitespace is so far untested

CMB sensitivity is maxed out
Fermi sensitivity can improve
AMS sensitivity can improve a lot

WIMP Ceiling: New Sensitivity

CTA Sensitivity



Silverwood, Weniger, Scott, Bertone (2015)

TeV range has great potential for improved sensitivity in all of gamma rays, cosmic rays, and neutrinos

WIMP Right Edge: Unitarity Bound

Roughly,
$\sigma < 4\pi/(M\,v)^2$

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Unitarity Limits on the Mass and Radius of Dark-Matter Particles

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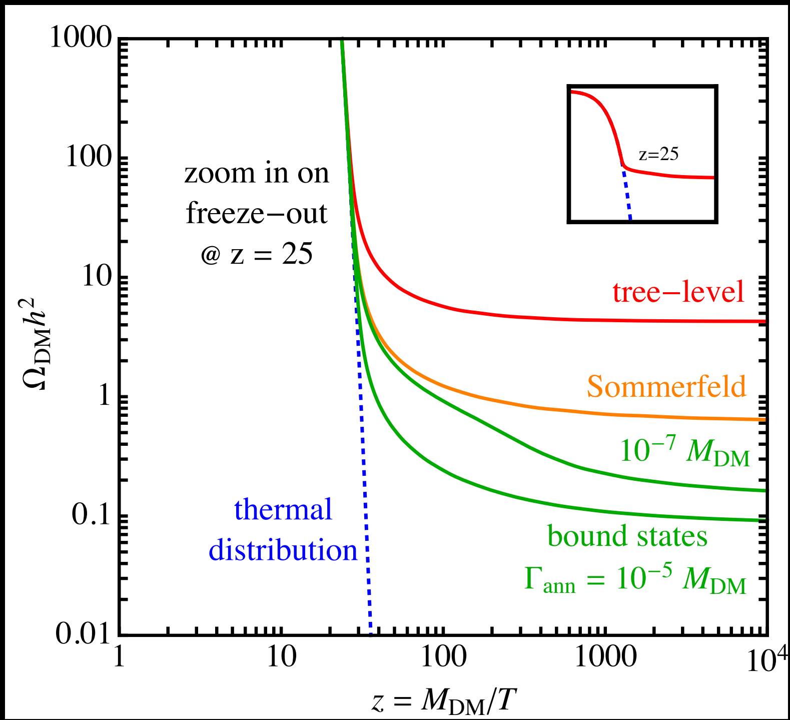
(Received 5 October 1989)

Using partial-wave unitarity and the observed density of the Universe, we show that a stable elementary particle which was once in thermal equilibrium cannot have a mass greater than 340 TeV. An extended object which was once in thermal equilibrium cannot have a radius less than 7.5×10^{-7} fm. A lower limit to the relic abundance of such particles is also found.

Simple, but important new theoretical developments since 1990

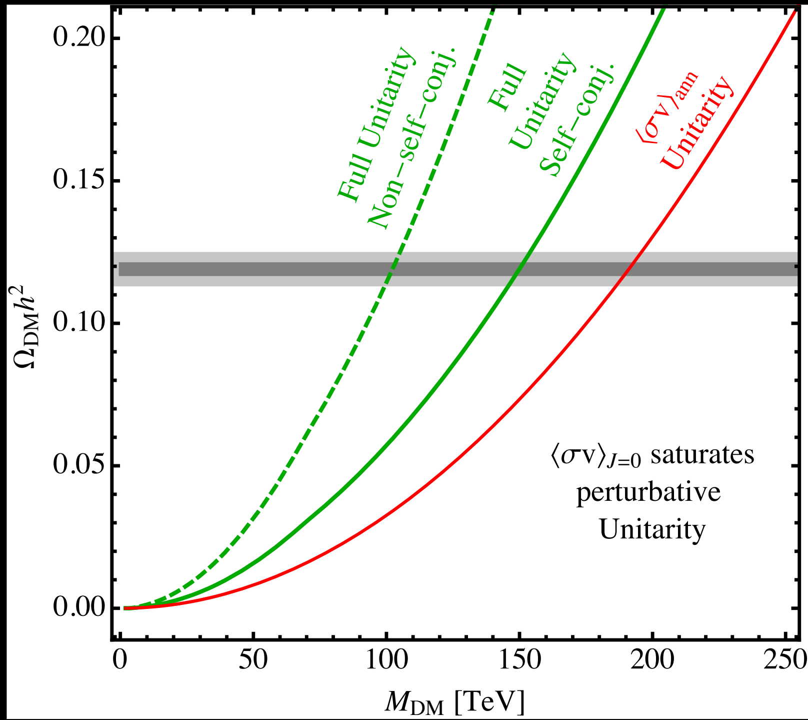
Unitarity Bound: New Results

Altered Freezeout



Smirnov, Beacom (2019)

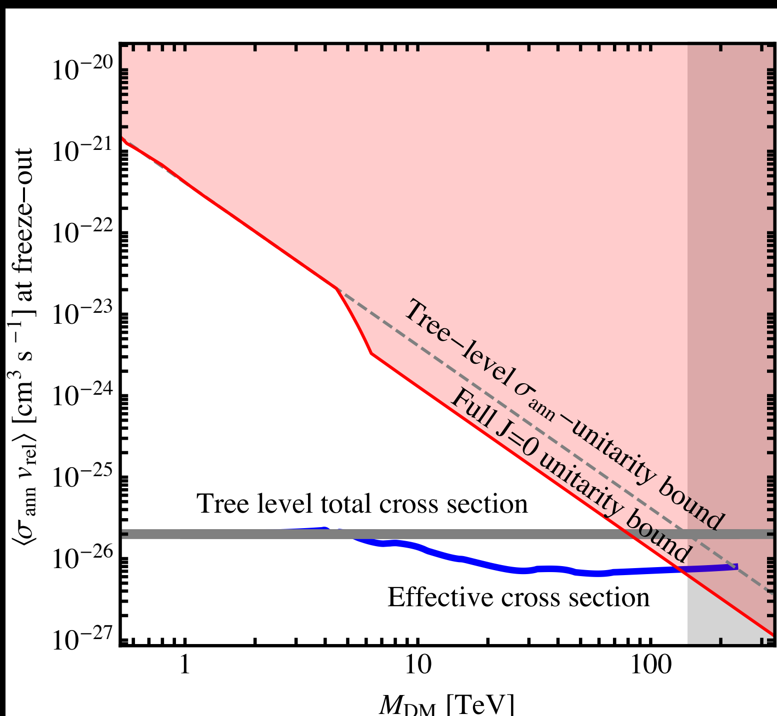
Altered Maximum Mass



Maximum mass is lower

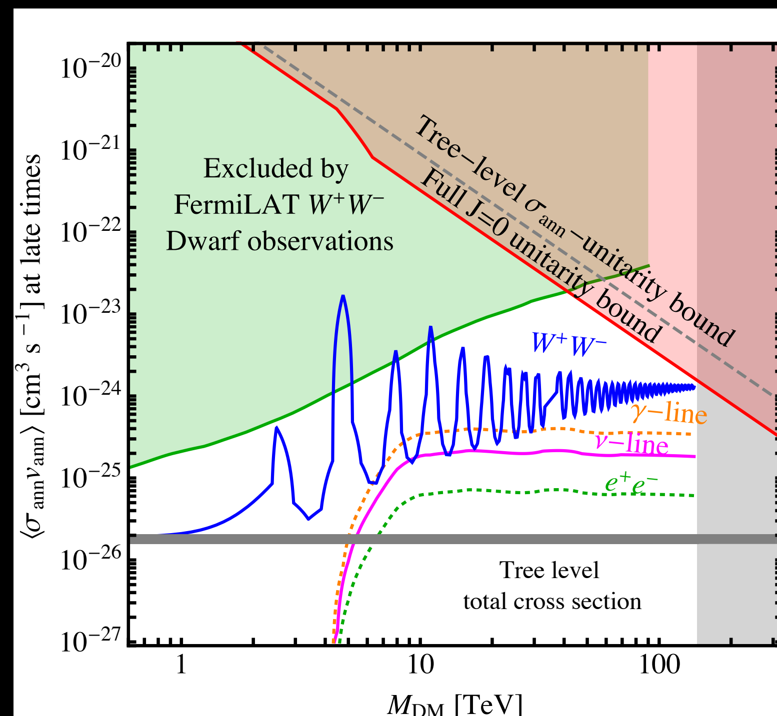
Unitarity Bound: New Implications

Early Universe



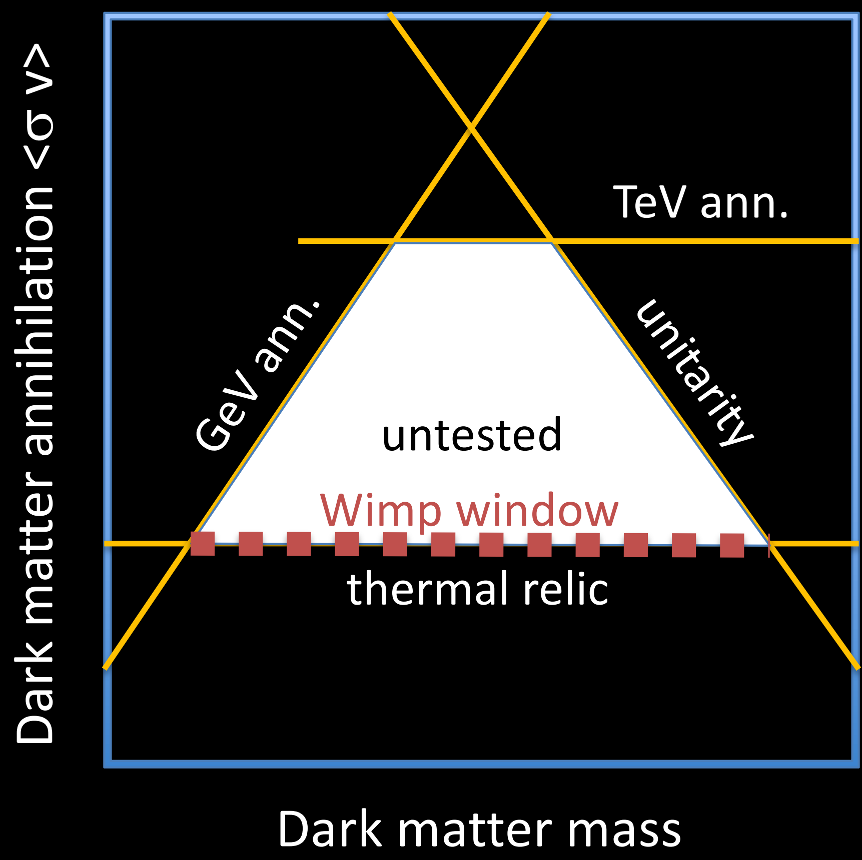
Smirnov, Beacom (2019)

Late Universe



New formation and annihilation signals

WIMP Box: Future



With a comprehensive approach, we can fully test thermal WIMPs:

Close the whitespace

Probe branching ratios

Testing Sub-GeV WIMP-like Dark Matter

Why Do We Care?

Low masses seemingly within reach

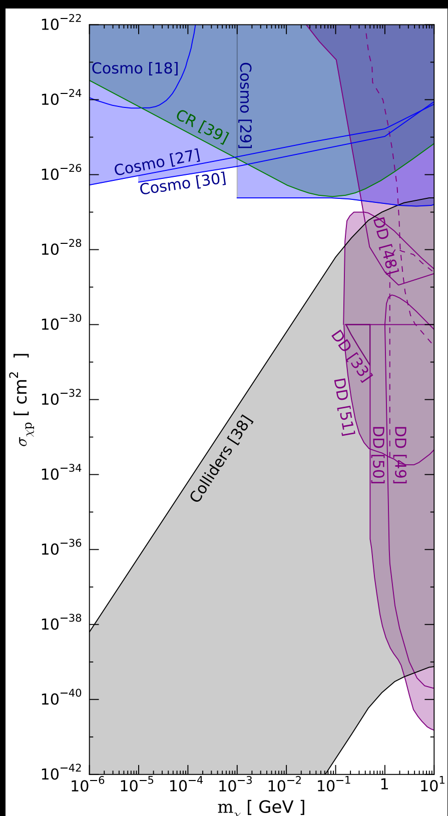
But hard to test!

Existing limits allow SM-sized cross sections

New approaches are needed to make sure these are probed

Prior Constraints

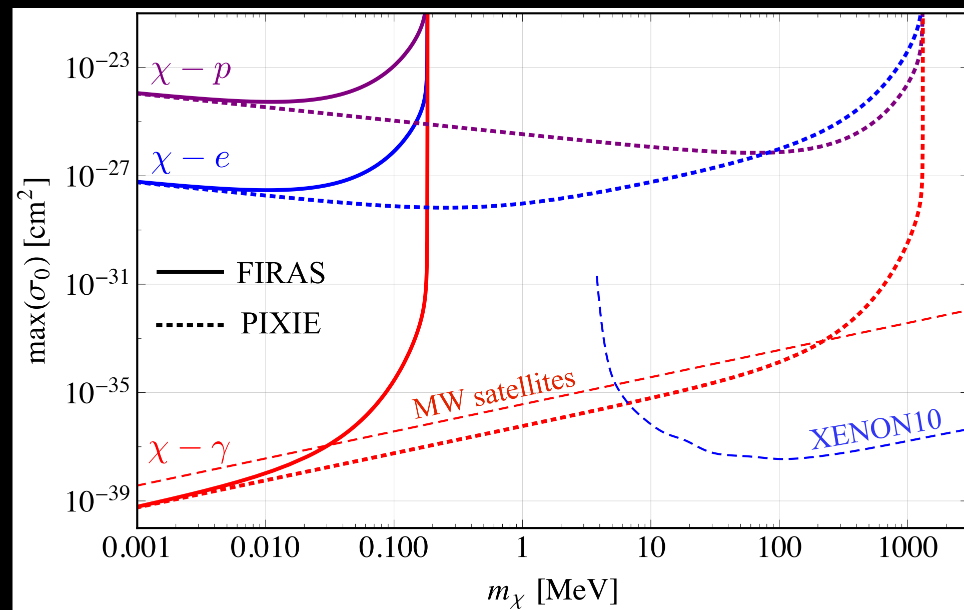
DM-proton



Cappiello, Ng, Beacom (2019)

Lots of nice work by Farrar group on parts near 1 GeV

DM-electron

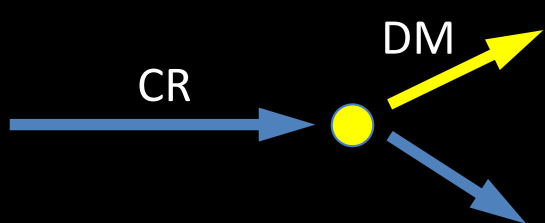


Ali-Haimoud, Chluba, Kamionkowski (2015)

Limits below 1 GeV are poor

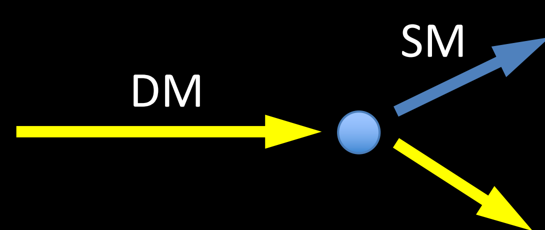
Scattering of Dark Matter with Cosmic Rays

Part 1:
CR downscattering
Cappiello, Ng, Beacom (2019)



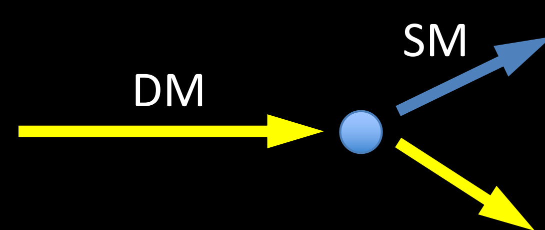
(in the halo)

Part 2:
DM upscattering
Bringmann, Pospelov (2019)
Ema, Sala, Sato (2019)



(in the detector)

Part 3:
DM upscattering redux
Cappiello, Beacom (2019)



(in the detector)

These are new and rapidly developing ideas

Part 1: Cosmic-Ray Downscattering

Cosmic-ray beam:

Luminosity known (*)

Major loss processes known (*)

Dark-matter target:

Density, distribution known

Velocities known

Protons:

Small energy loss per collision

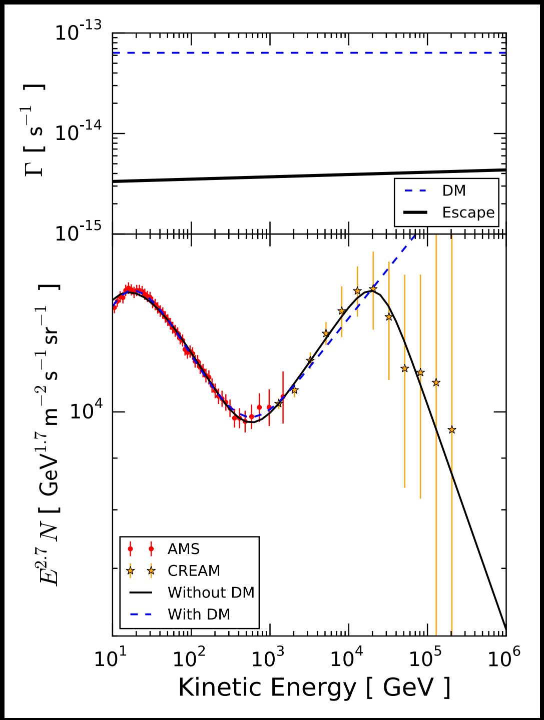
Electrons:

Large energy loss per collision

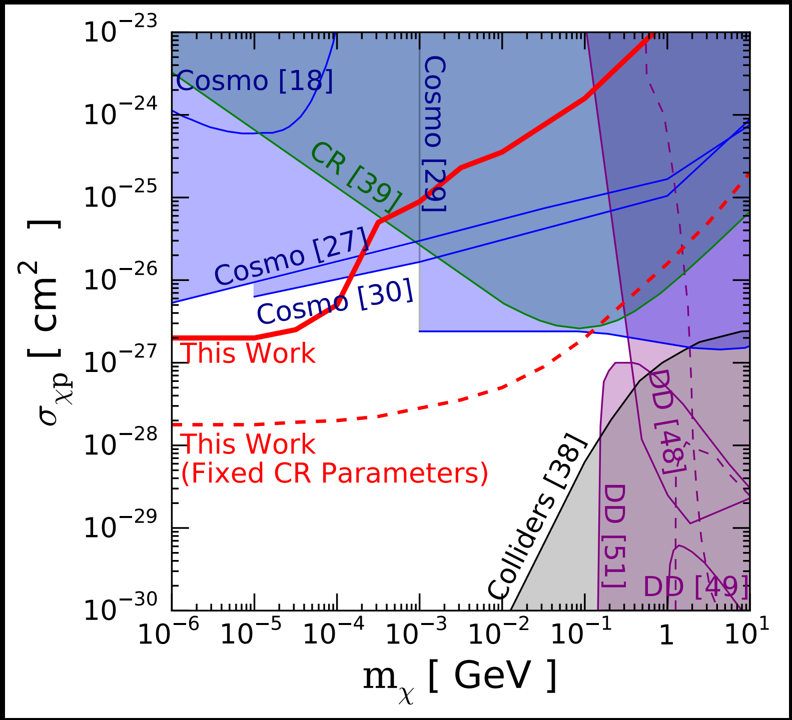
Care needed to make tests model-independent

Cosmic-Ray Downscattering: Protons

Spectrum



Constraints

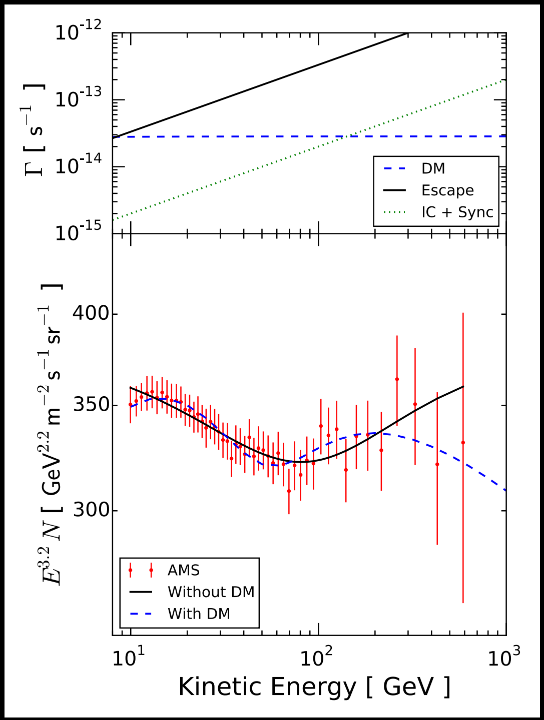


Cappiello, Ng, Beacom (2019)

Sensitivity can be substantially improved

Cosmic-Ray Downscattering: Electrons

Spectrum



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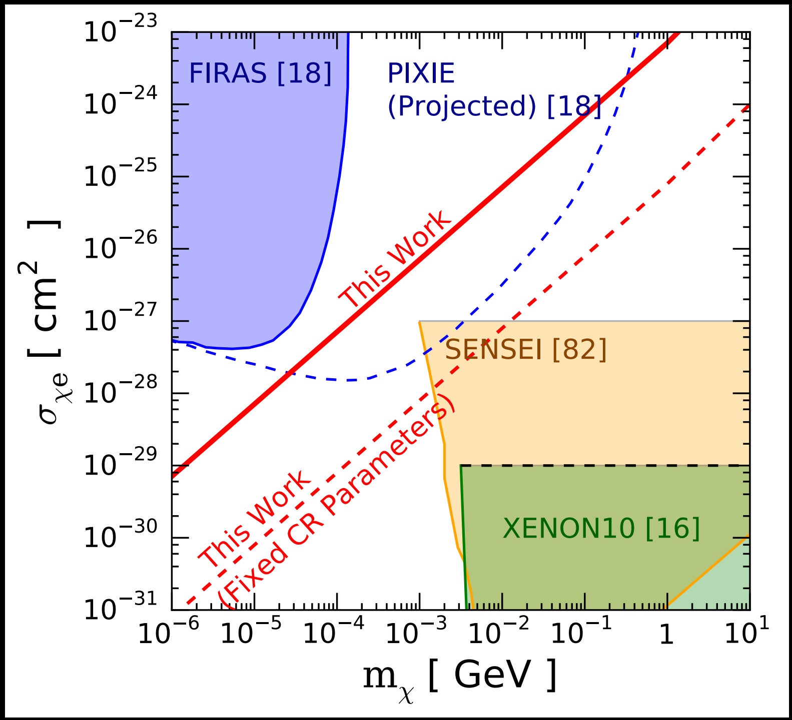


Sensitivity can be substantially improved

Cappiello, Ng, Beacom (2019)

Part 2: Dark-Matter Upscattering

Primary cosmic-ray beam:
Reasonably known

Secondary dark-matter beam:
Reasonably known

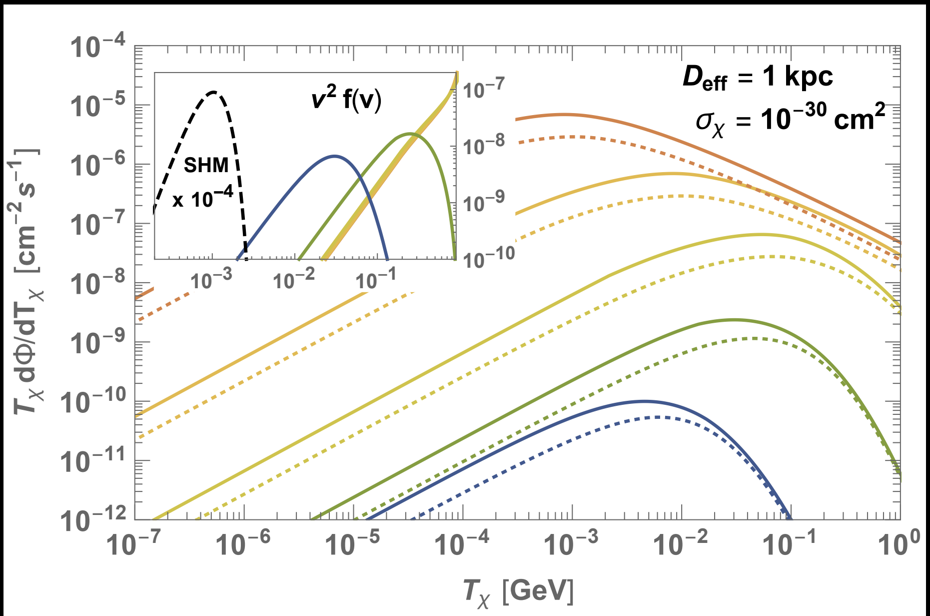
Laboratory target:
Well known

Ordinary direct detection:
Requires a ~ keV threshold,
meaning ton-scale detectors

Boosted direct detection:
Requires a ~ MeV threshold,
meaning kton-scale detectors

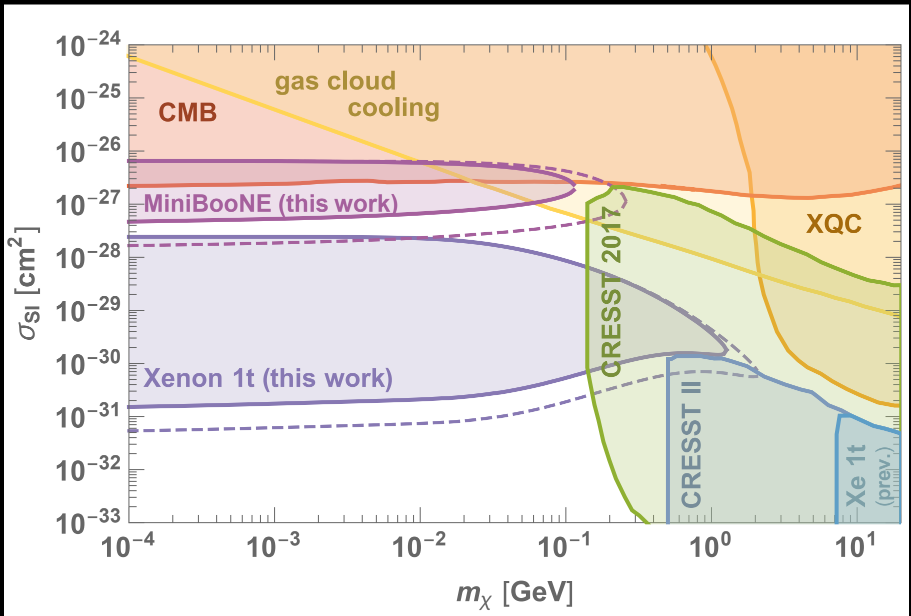
Dark-Matter Upscattering: Protons

Spectrum



Bringmann, Pospelov (2019)

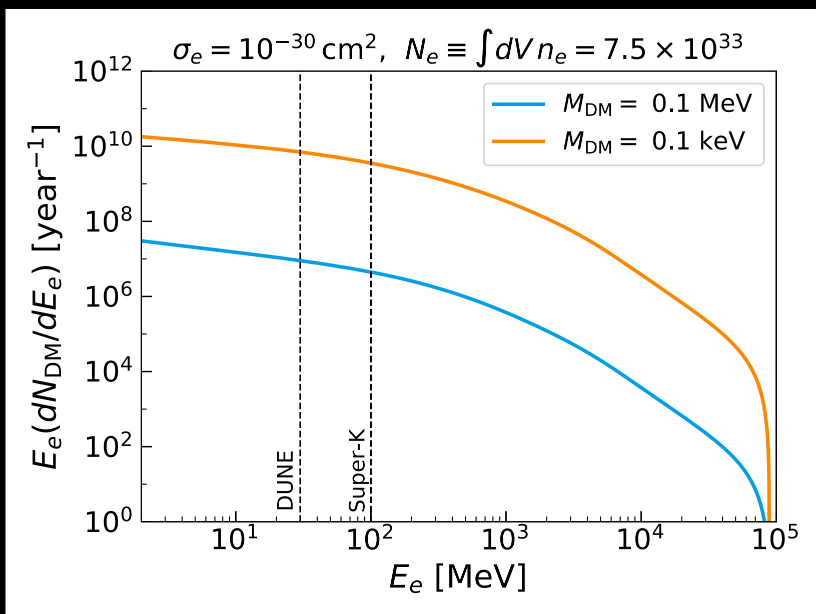
Constraints



Very exciting new sensitivity!

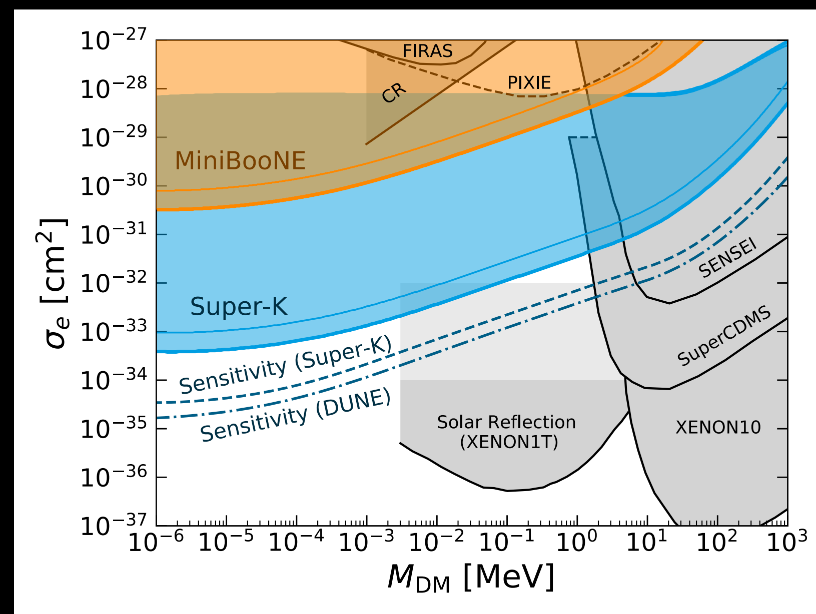
Dark-Matter Upscattering: Electrons

Spectrum



Ema, Sala, Sato (2019)

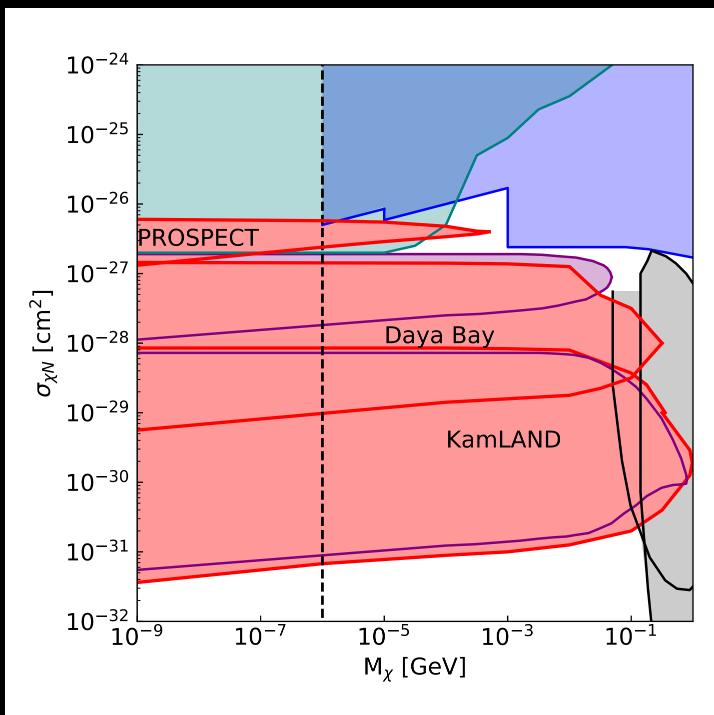
Constraints



Very exciting new sensitivity!

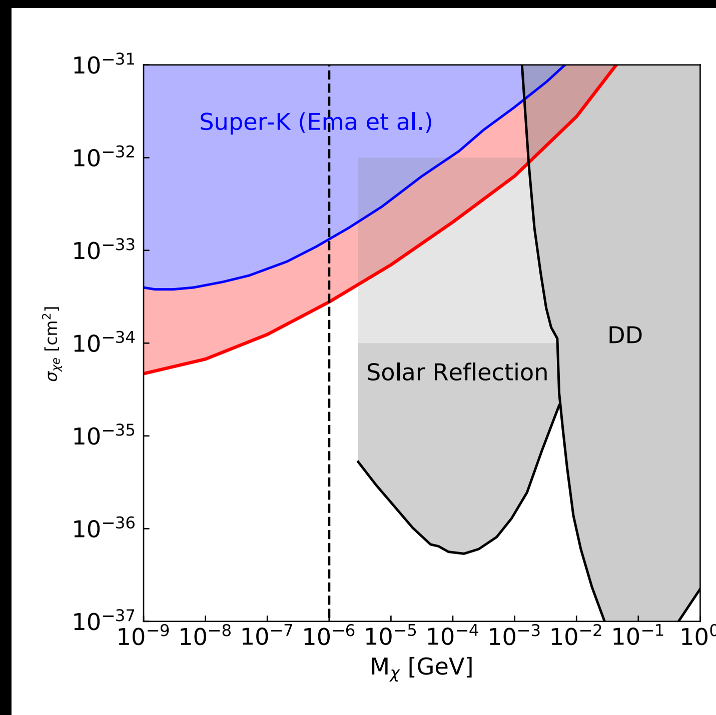
Part 3: Dark-Matter Upscattering Redux

DM-proton



Cappiello, Beacom (2019)

DM-electron

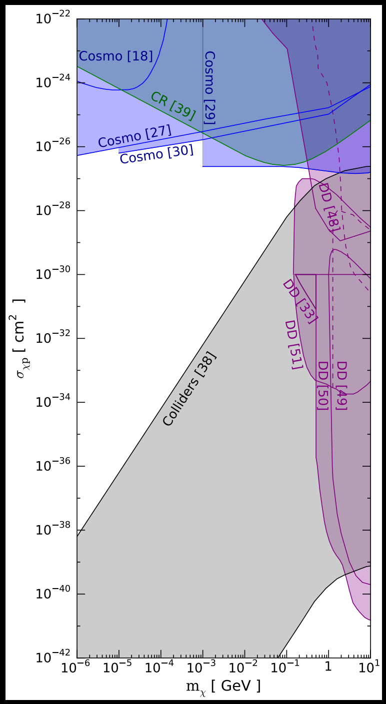


Big gains, potential for more

Sub-GeV WIMP-like Dark Matter: Future

DM-proton

See new steps:
Rogers+, 2111.10386,
Wang+, 2111.13644



DM-electron

The field needs a similar figure for electrons

We can strongly test sub-GeV WIMP-like dark matter

Concluding Perspectives

Conclusions

Dark matter an essential problem of cosmology and particle physics

Must fully test well-motivated candidates like thermal WIMPs

Must explore broadly for new types of candidates

Look under many lampposts and in between

And look at my great young collaborators Cappiello, Leane, Ng, Smirnov!