The Complementarity of Astrophysical and Terrestrial Searches for Dark Matter

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CERN Council Open Symposium on the Update of the European Strategy for Particle Physics

Theory Frameworks to be Discussed:

The Minimal WIMP

Hidden Dark Sectors

The Minimal WIMP

WIMPs provide a lamppost to guide searches for dark matter

Basic Assumptions

Single particle that does not interact with itself

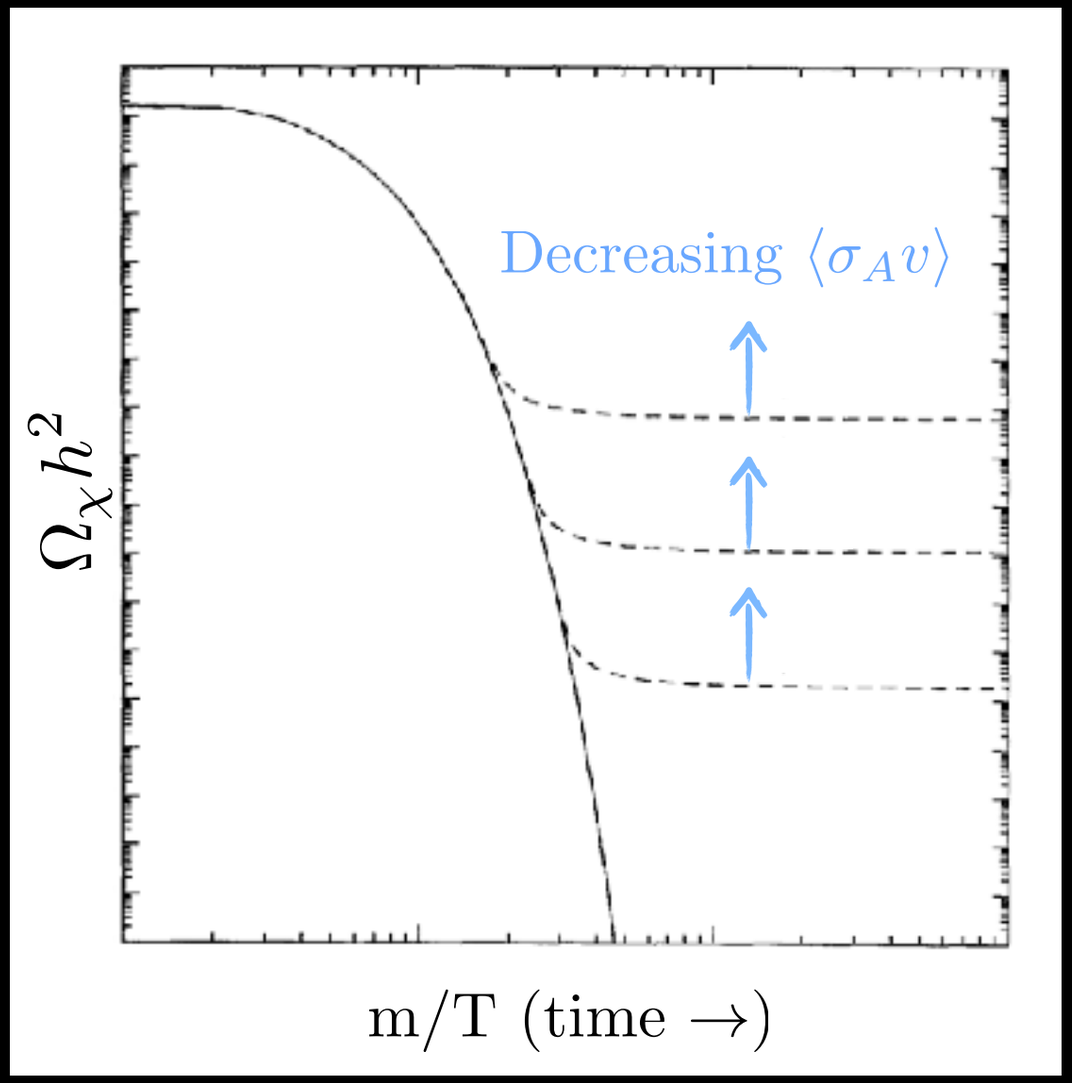
Interacts weakly with Standard Model

$2 \rightarrow 2$ annihilations primarily in s-wave

Annihilations set thermal abundance today

The Minimal WIMP

Weakly interacting particle with mass ~100 GeV to 1 TeV gives observed density today



$$\Omega_\chi h^2 \simeq \frac{3 \times 10^{-27} \mathrm{cm}^3/\mathrm{s}}{\langle \sigma_A v \rangle}$$

$$\simeq 0.1 \cdot \left(\frac{0.01}{\alpha}\right)^2 \left(\frac{m_\chi}{100\ \mathrm{GeV}}\right)^2$$

Planck + WMAP

$$\Omega_\chi h^2 = 0.1199 \pm 0.0027$$

Planck Collaboration [1303.5076]

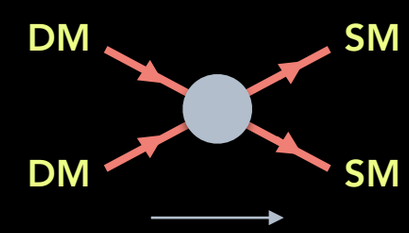
How to Search for WIMPs

More Model-Independent Tests

Gravitational Interactions

plethora of small-scale structure

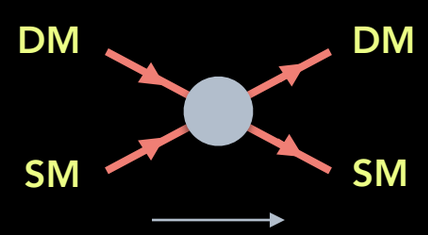
Annihilations



required to set thermal abundance

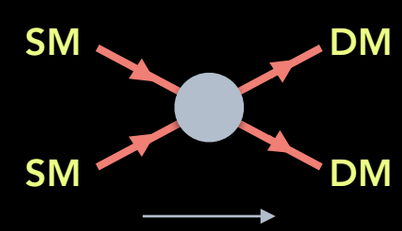
More Model-Dependent Tests

Scattering



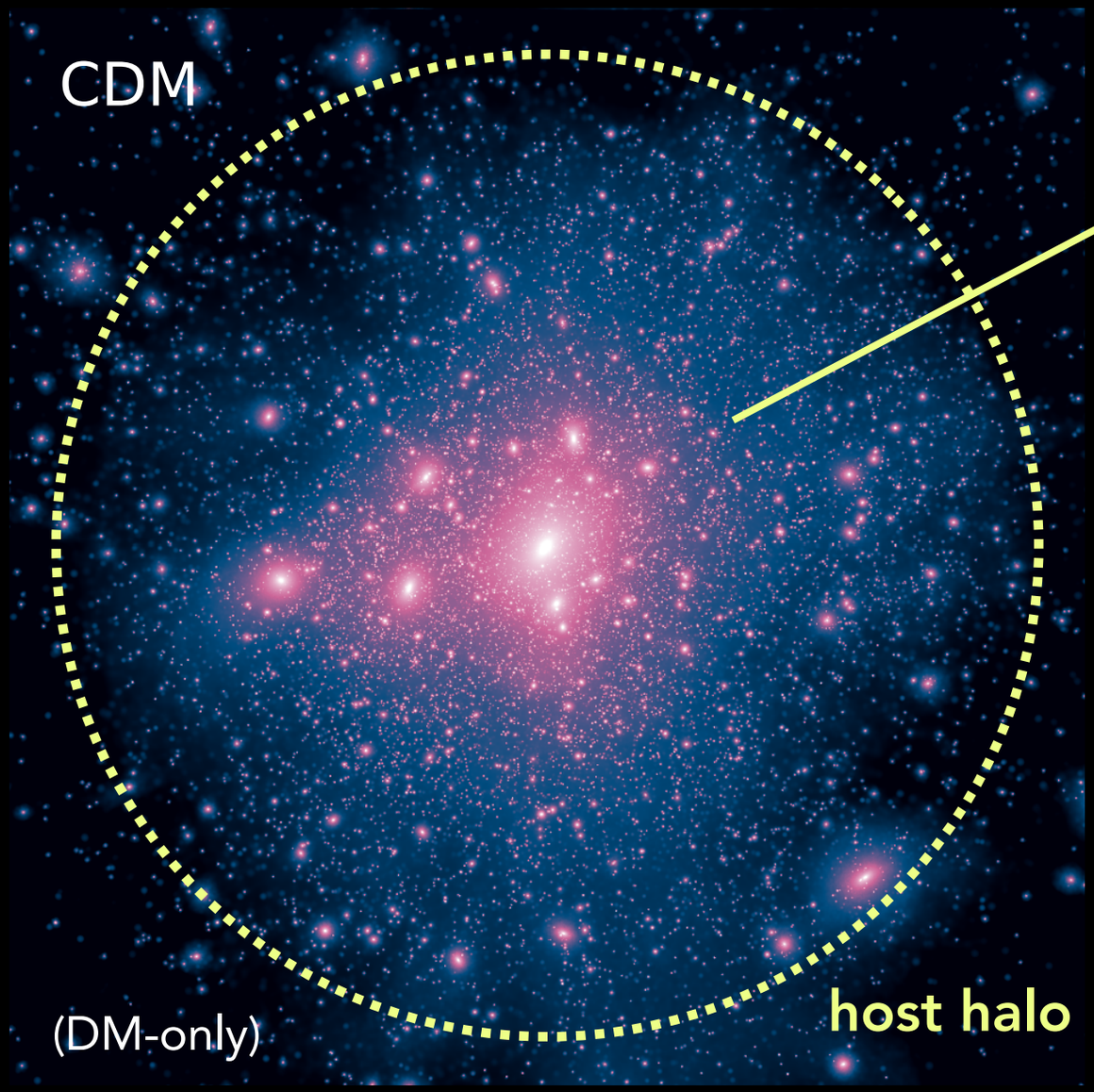
particle must be cosmologically stable

Production



production of associated states
sometimes more promising

Tests of Small-Scale Structure



Vogelsberger et al. (2016)

Dark Matter Subhalos

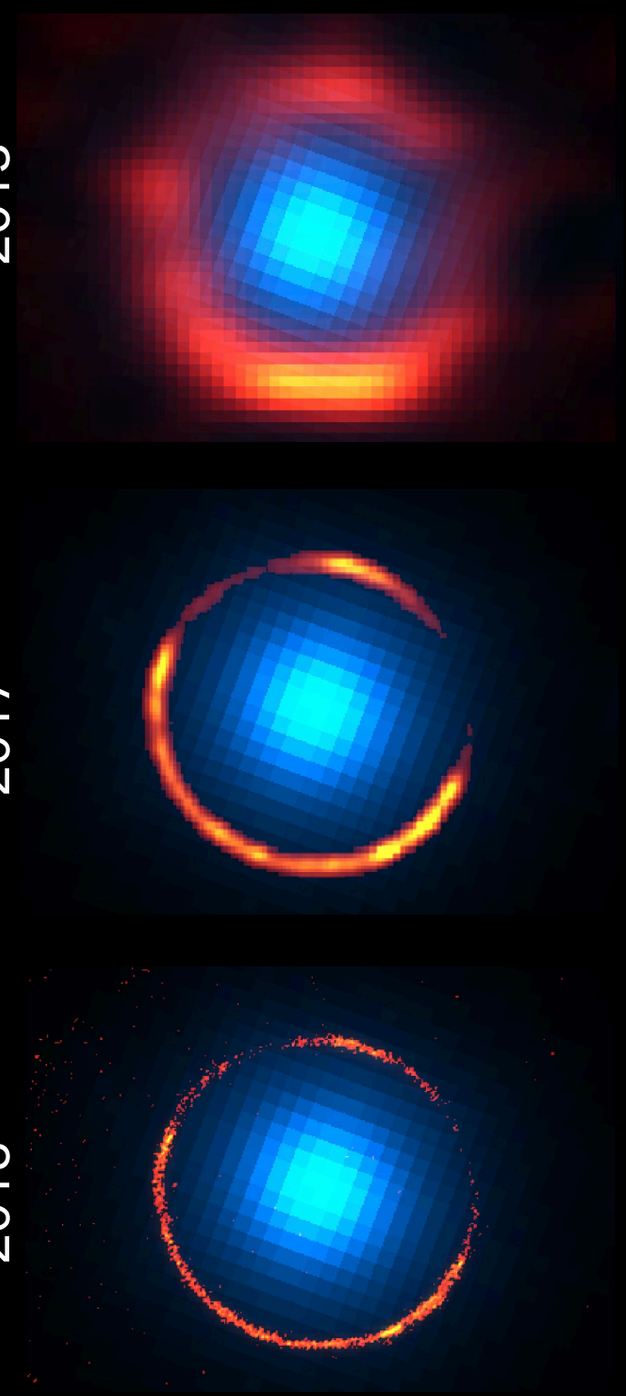
Low-mass dark matter halos that do not contain galaxies

Mass distribution depends on fundamental properties of dark matter

CDM predicts an abundance down to Earth-scale masses ($\sim 10^{-6}\ M_\odot$)

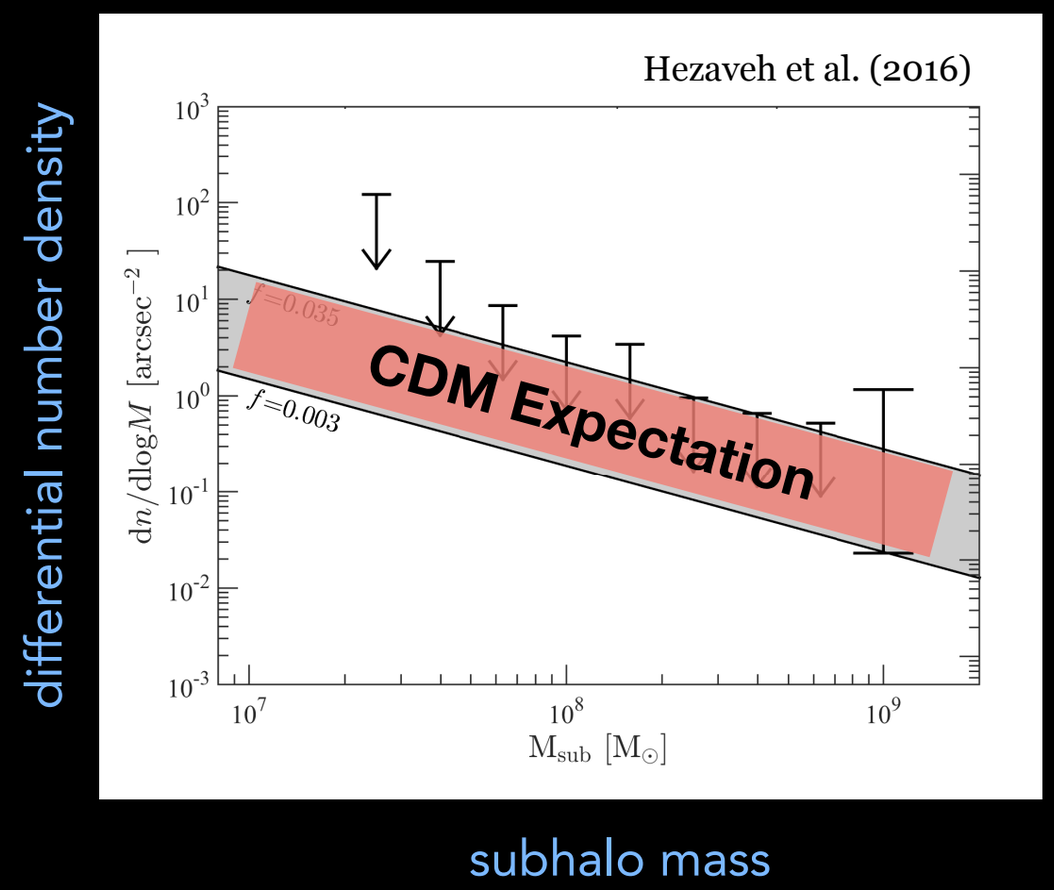
Tests of Small-Scale Structure

ALMA Image of SPT0418



Current constraints on subhalo mass function

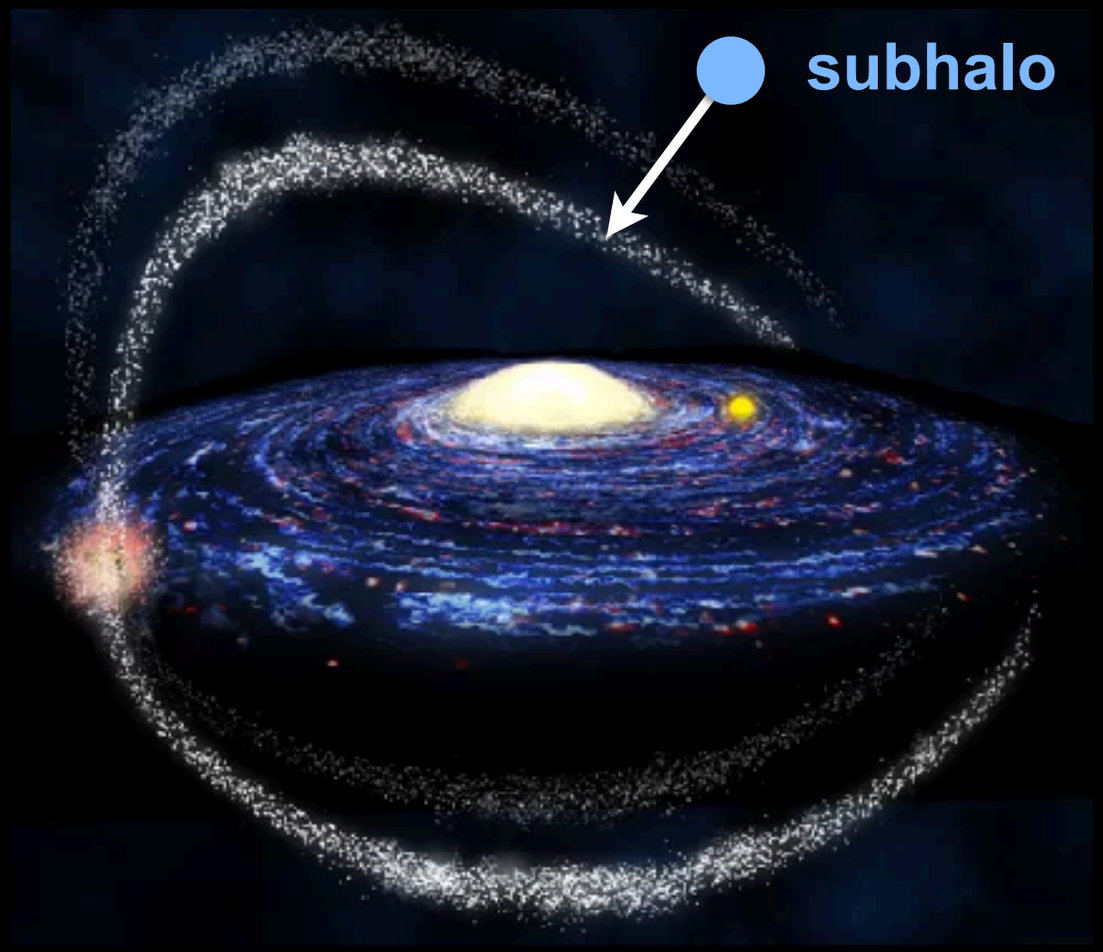
ALMA Science Verification Data



Proposed strong lensing analyses over next decade will probe the CDM regime

Tests of Small-Scale Structure

Dark matter subhalos in the Milky Way halo can perturb stellar streams



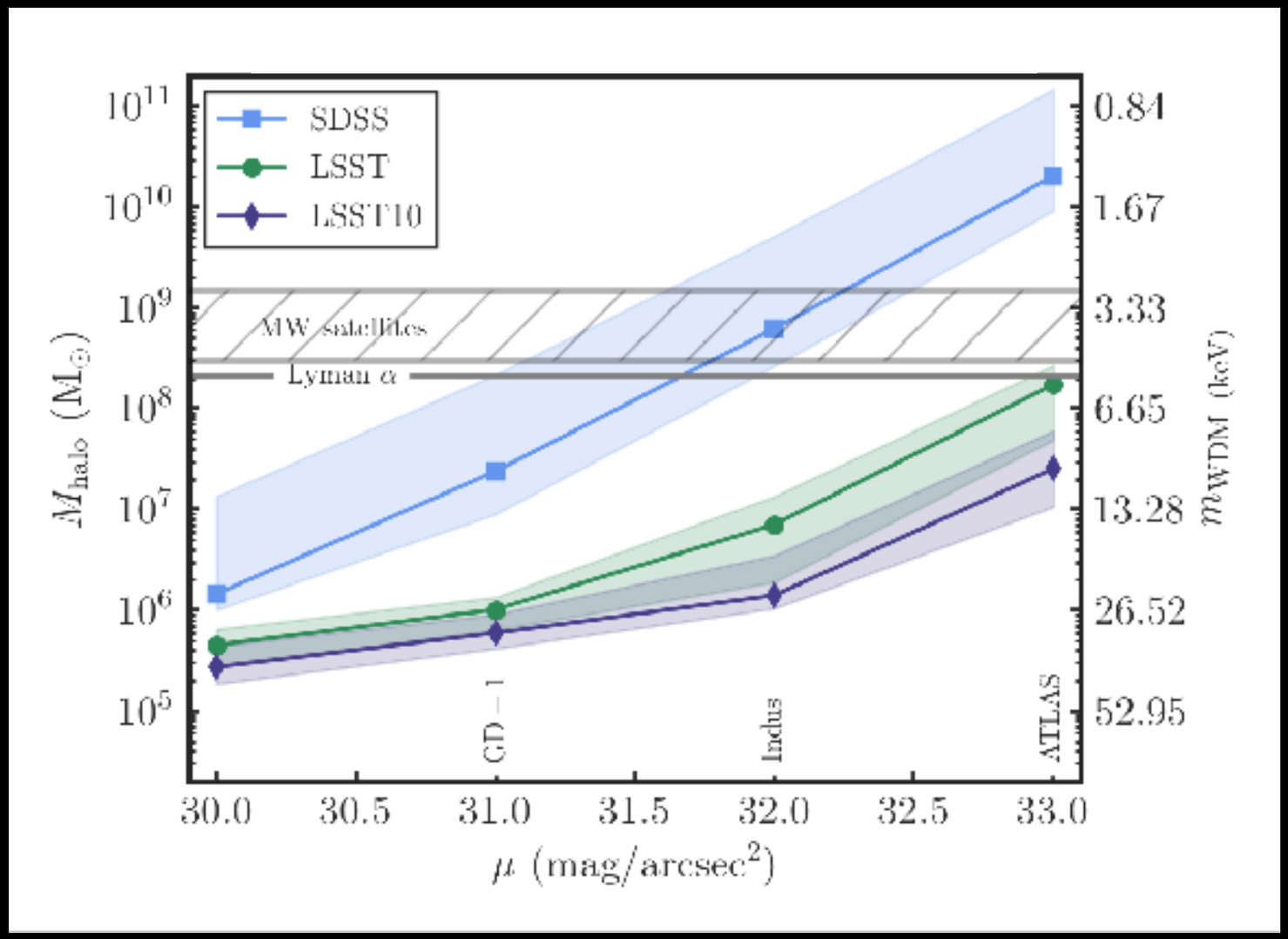
In some cases a subhalo can actually *break* the stream by flying through it

e.g., Ngan and Carlberg (2014); Erkal et al. (2016)

Tests of Small-Scale Structure

LSST will have sensitivity to subhalo masses down to ~10^6 $M_\odot$, testing models beyond CDM with stream breaks

minimum detectable subhalo mass

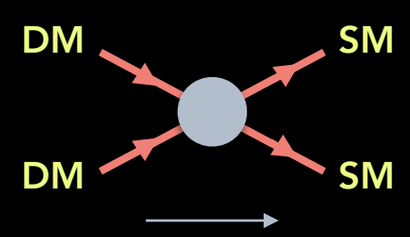


stream surface brightness

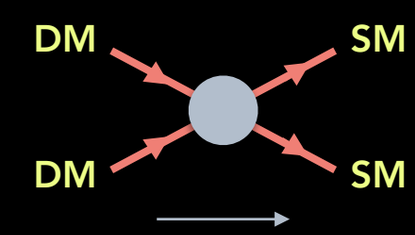
LSST Dark Matter Working Group [1902.01055]

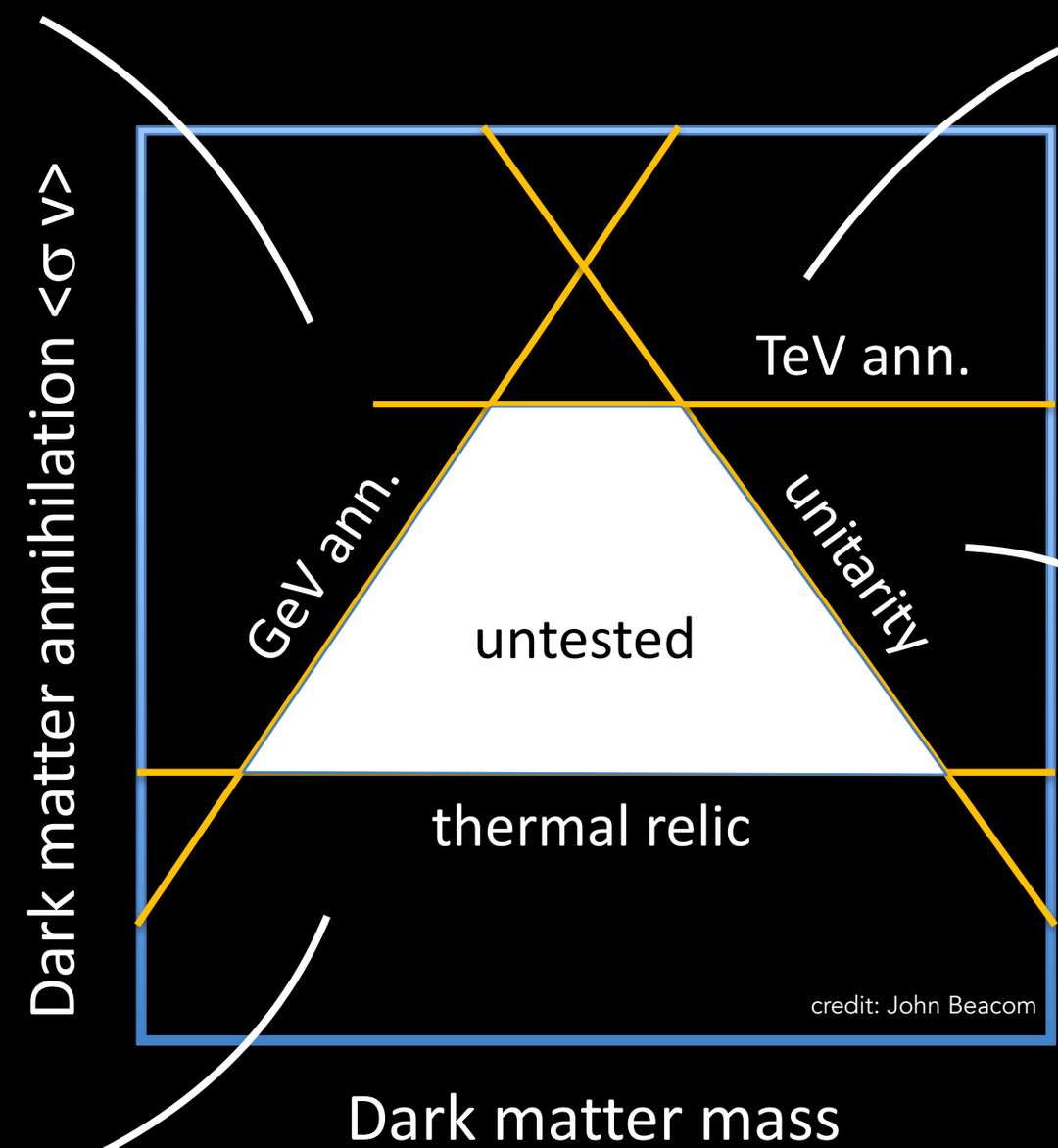
WIMP Annihilation

Annihilations to final states with GeV energies



Annihilations to final states with TeV energies





Unitarity bound roughly set by

$$\sigma < \frac{4\pi}{(Mv)^2}$$

Griest and Kamionkowski (1990)

Over-predict relic abundance

GeV Annihilation Constraints

CMB

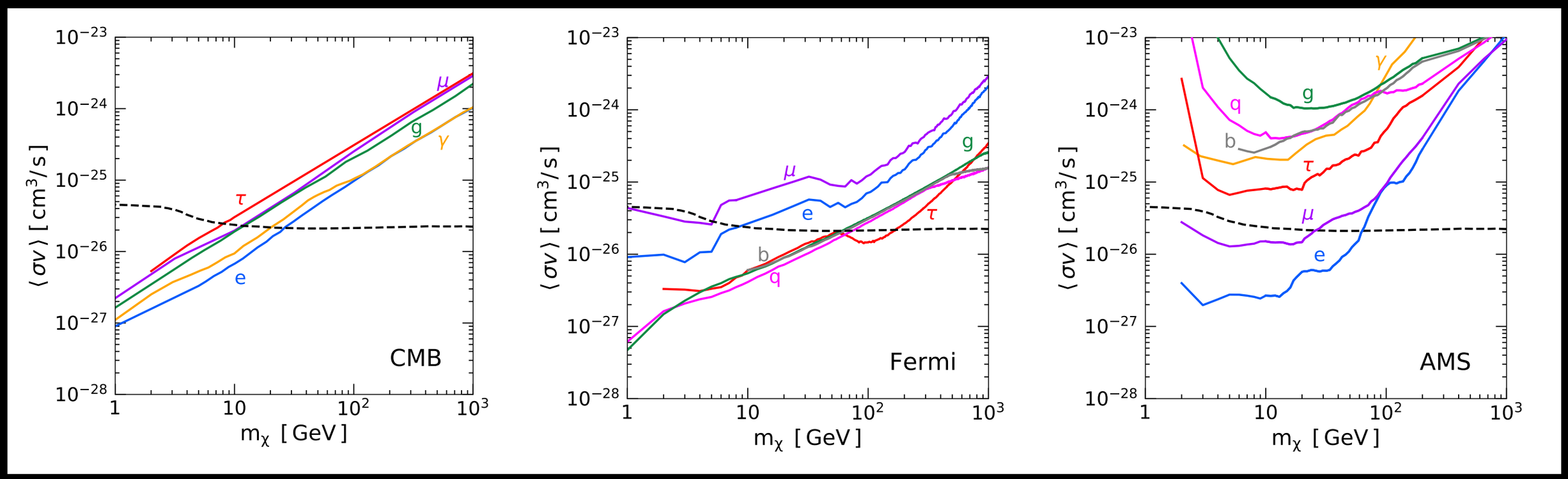
annihilations inject energy

Fermi

gamma-rays from annihilations

AMS

cosmic rays from annihilations

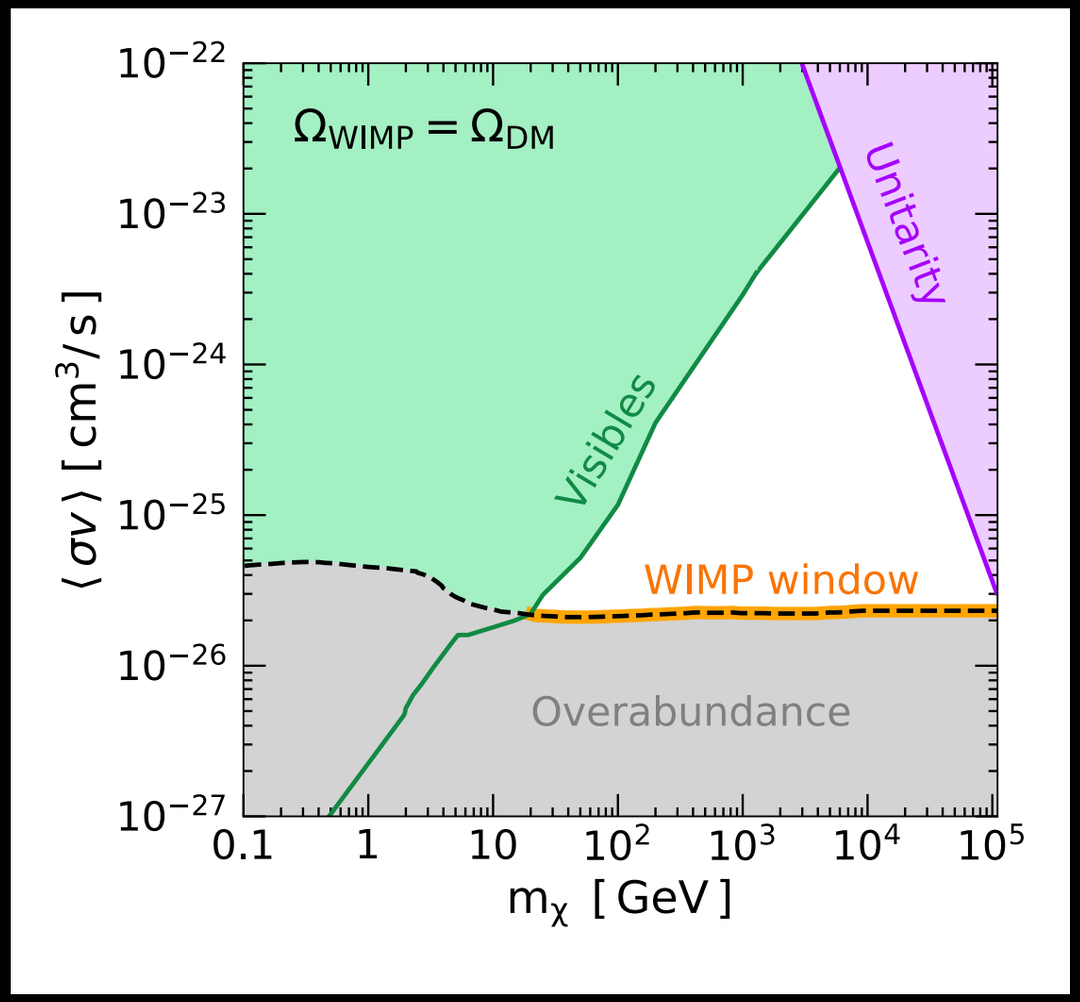


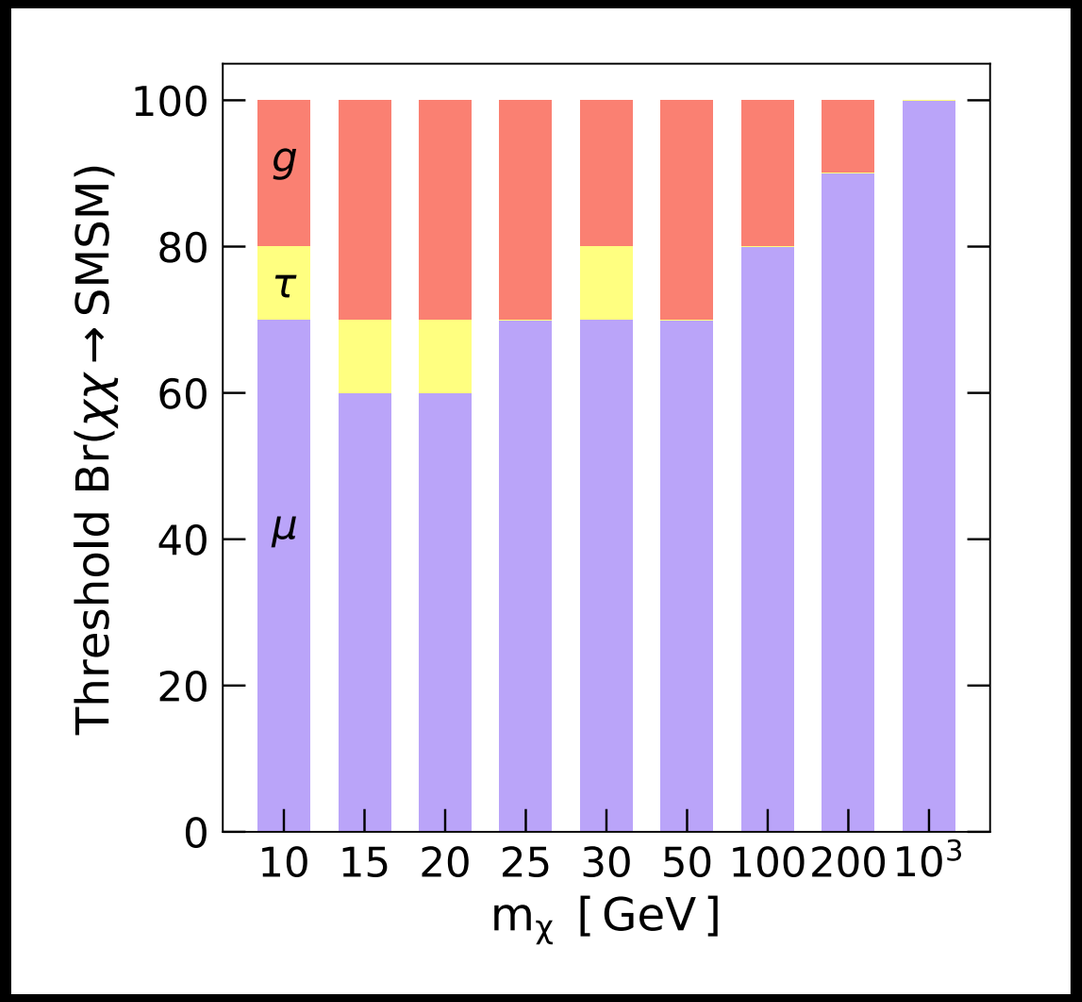
Leane et al. [1805.10305]

Allowed WIMP Window

Standard presentation assumes 100% branching fraction to given final state

Varying over branching fractions opens up parameter space

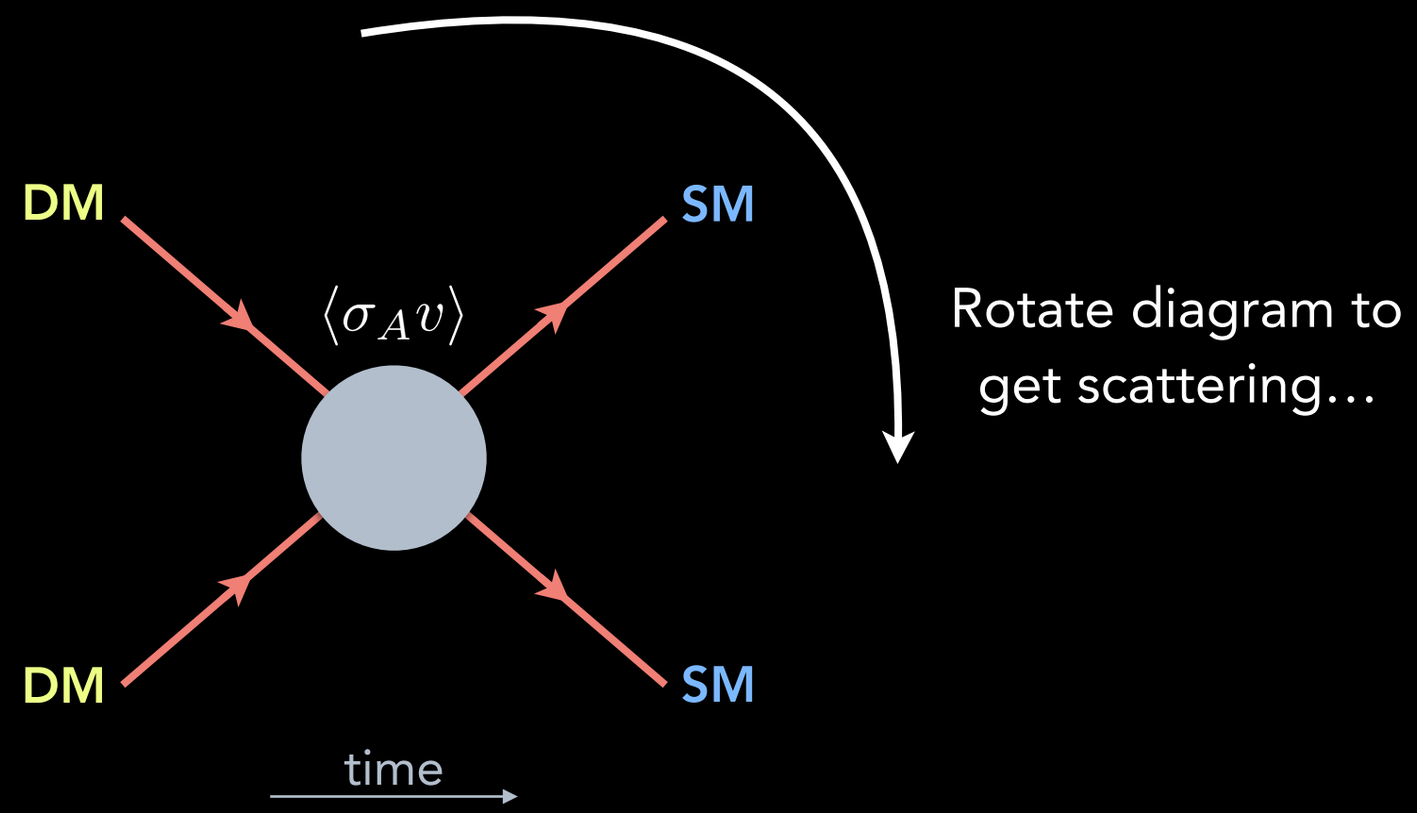




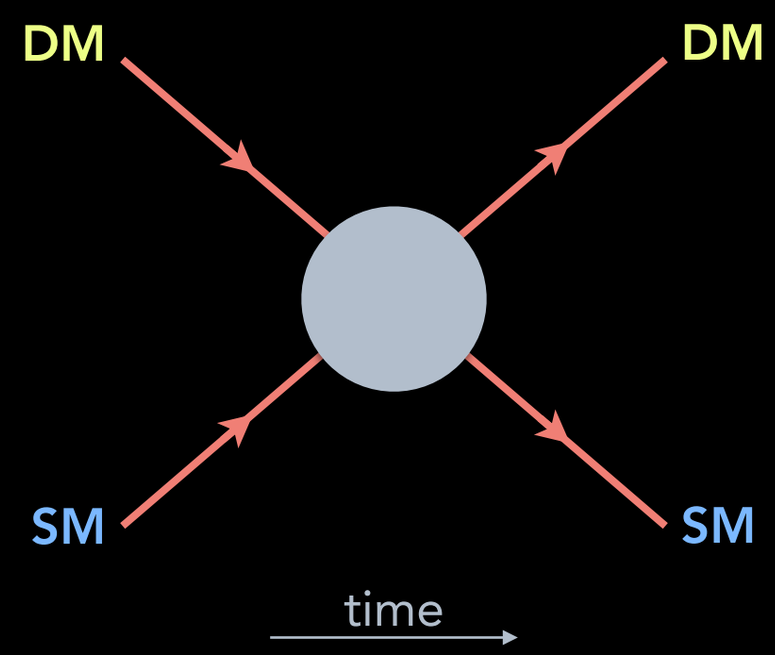
Leane et al. [1805.10305]

Rotating the Diagram…

Indirect detection constrains annihilation cross section,
the key quantity that feeds into relic abundance calculation

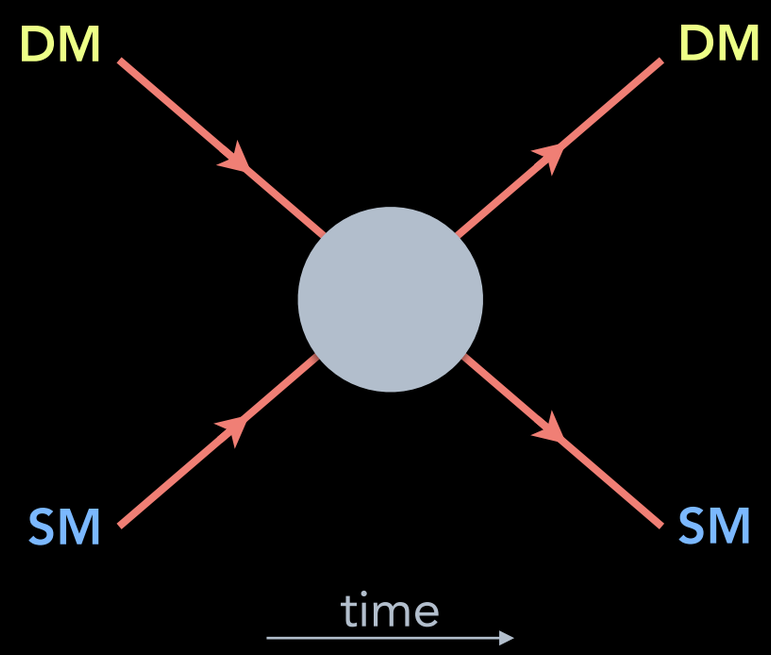


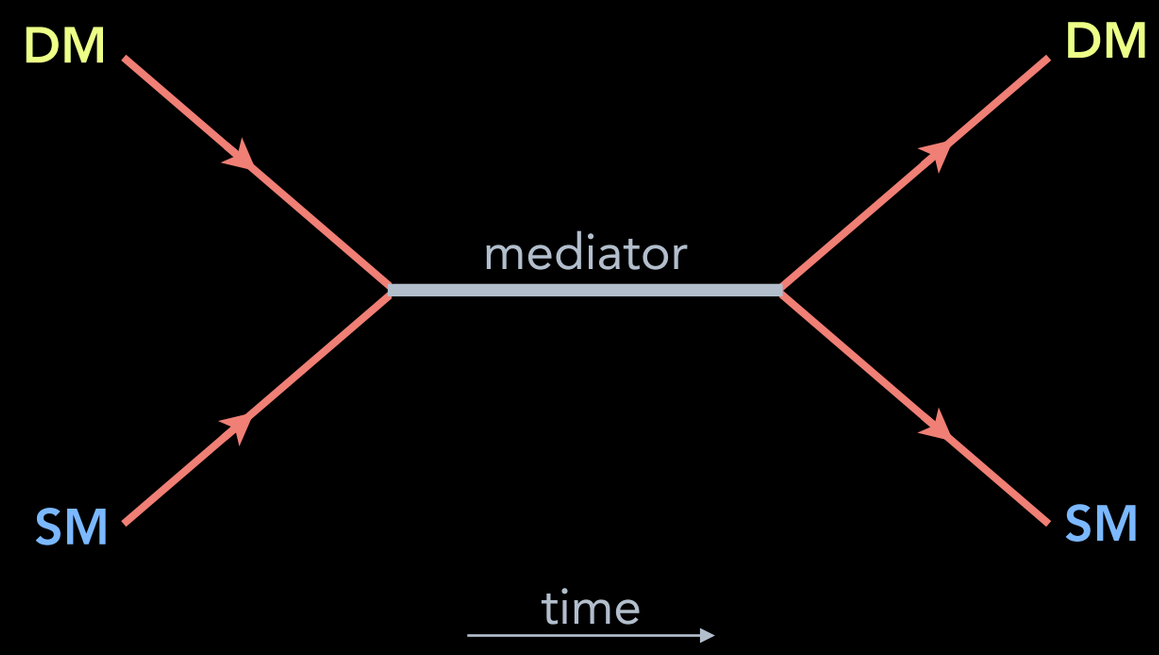
Rotating the Diagram…



Rotating the Diagram…

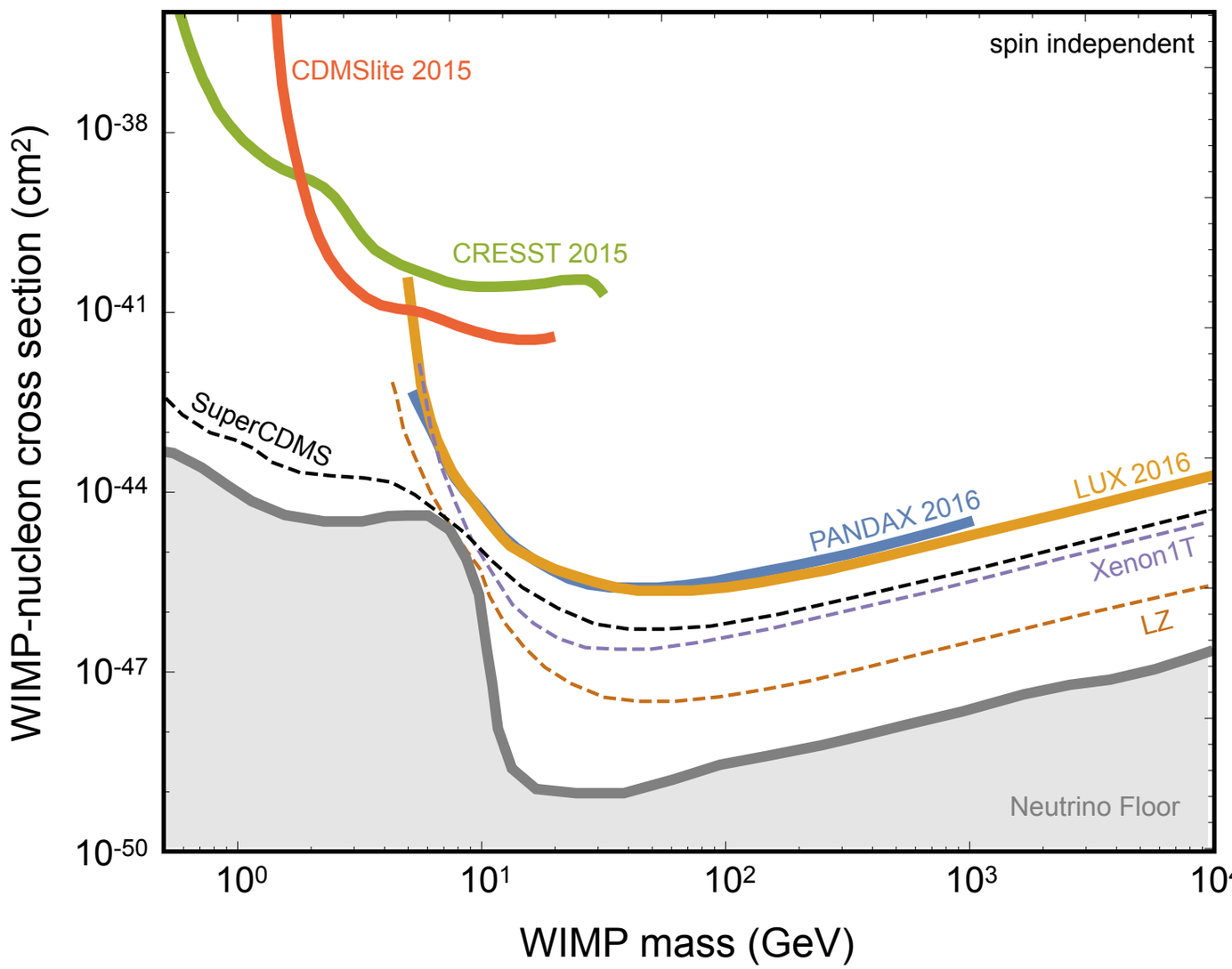
Scattering rate depends on mediator and couplings;
predictions are more model-dependent



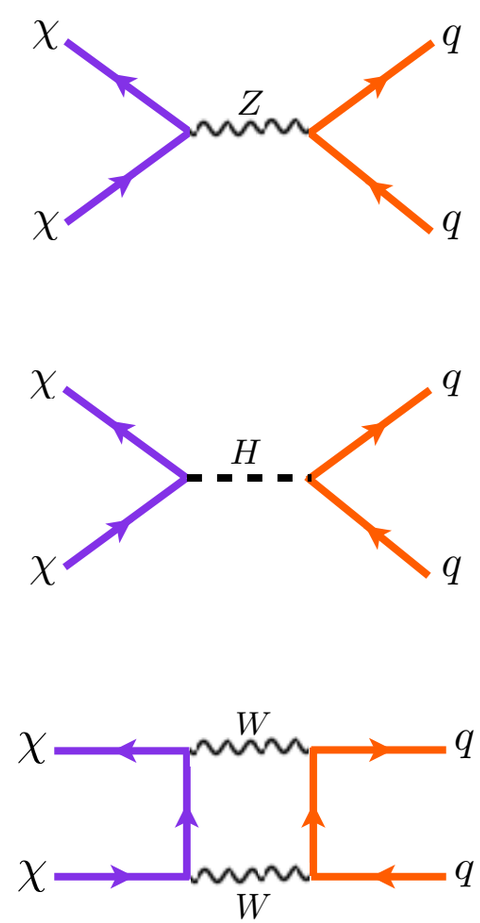


Direct Detection of WIMPs

Current experiments are probing Higgs-exchange regime

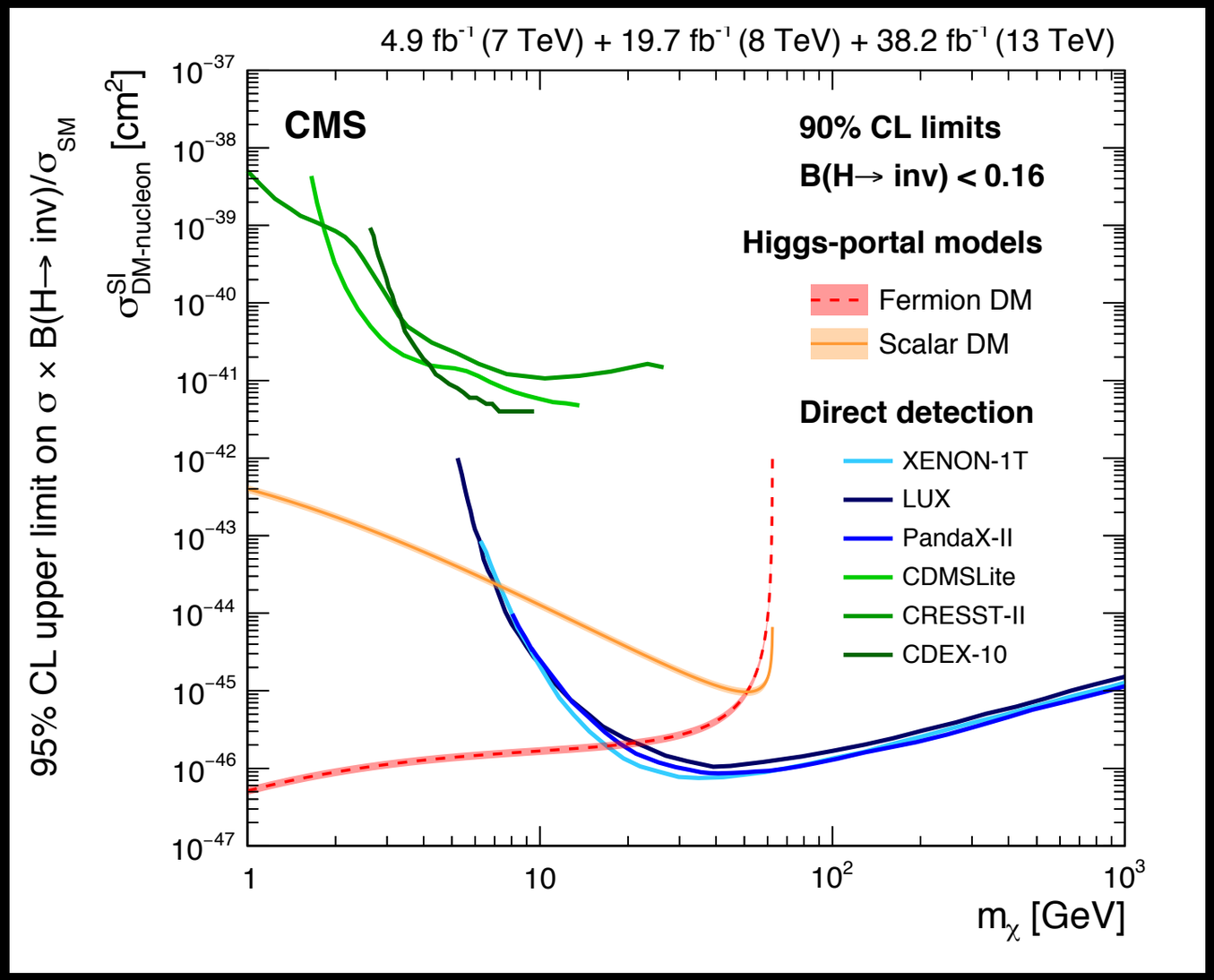


Primary Weak Interactions



Invisible Decays of the Higgs

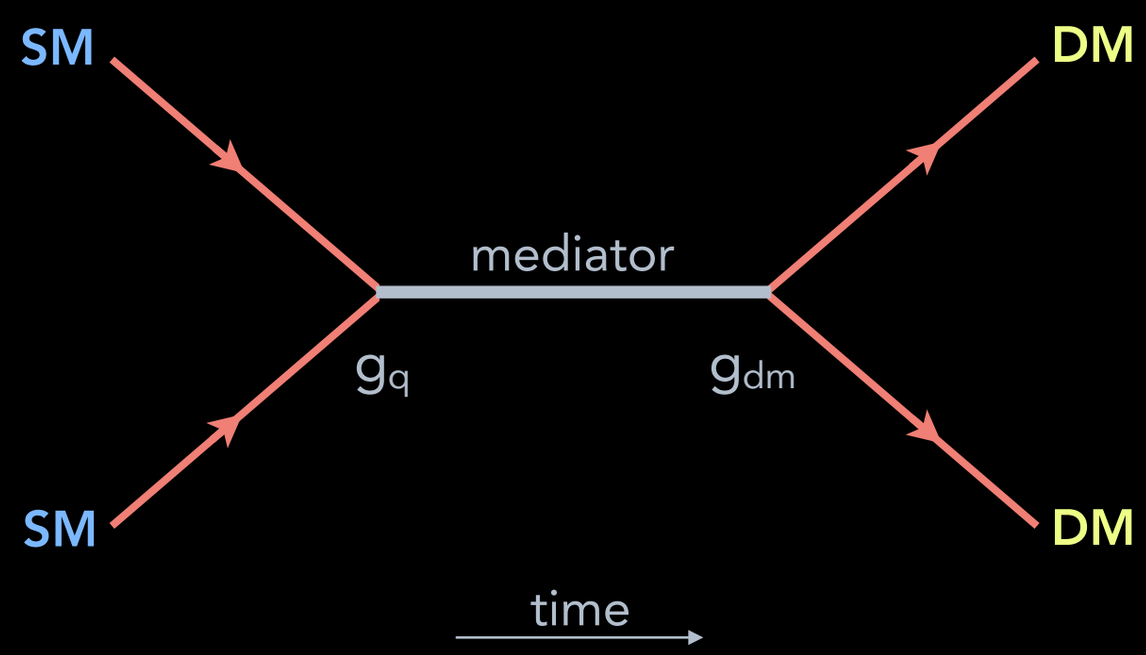
H→inv searches at colliders currently provide strongest constraints on Higgs portal models with m_χ <10-20 GeV



CMS Collaboration [1809.05937]

Simplified Models

Simplified models allow for translation of LHC to direct detection limits for wider breadth of scenarios



Specify mediator mass,
type and strength of couplings,
and dark matter mass

See talks by M. McCullough and C. Doglioni

Minimal Dark Matter

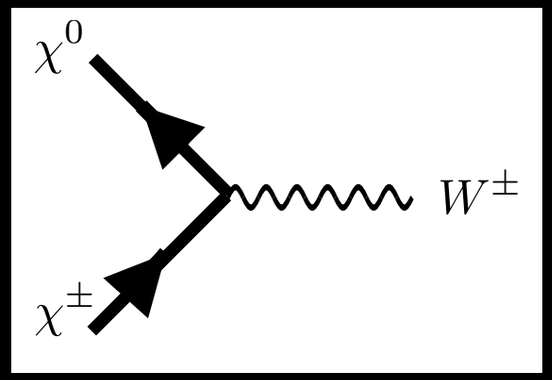
Minimal Dark Matter Models generically live at TeV-scale mass

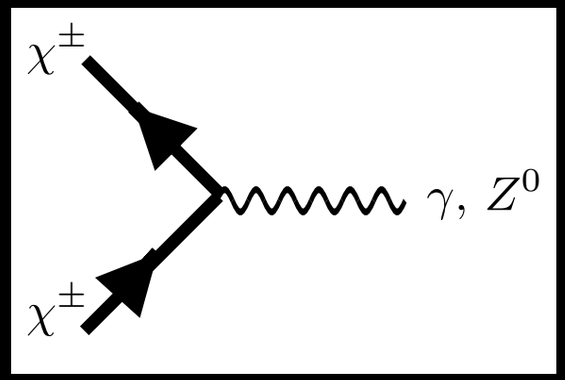
Cirelli et al. [hep-ph/0512090]

Example: Add SU(2) triplet to Standard Model

credit: T. Cohen

Two interaction vertices allowed:



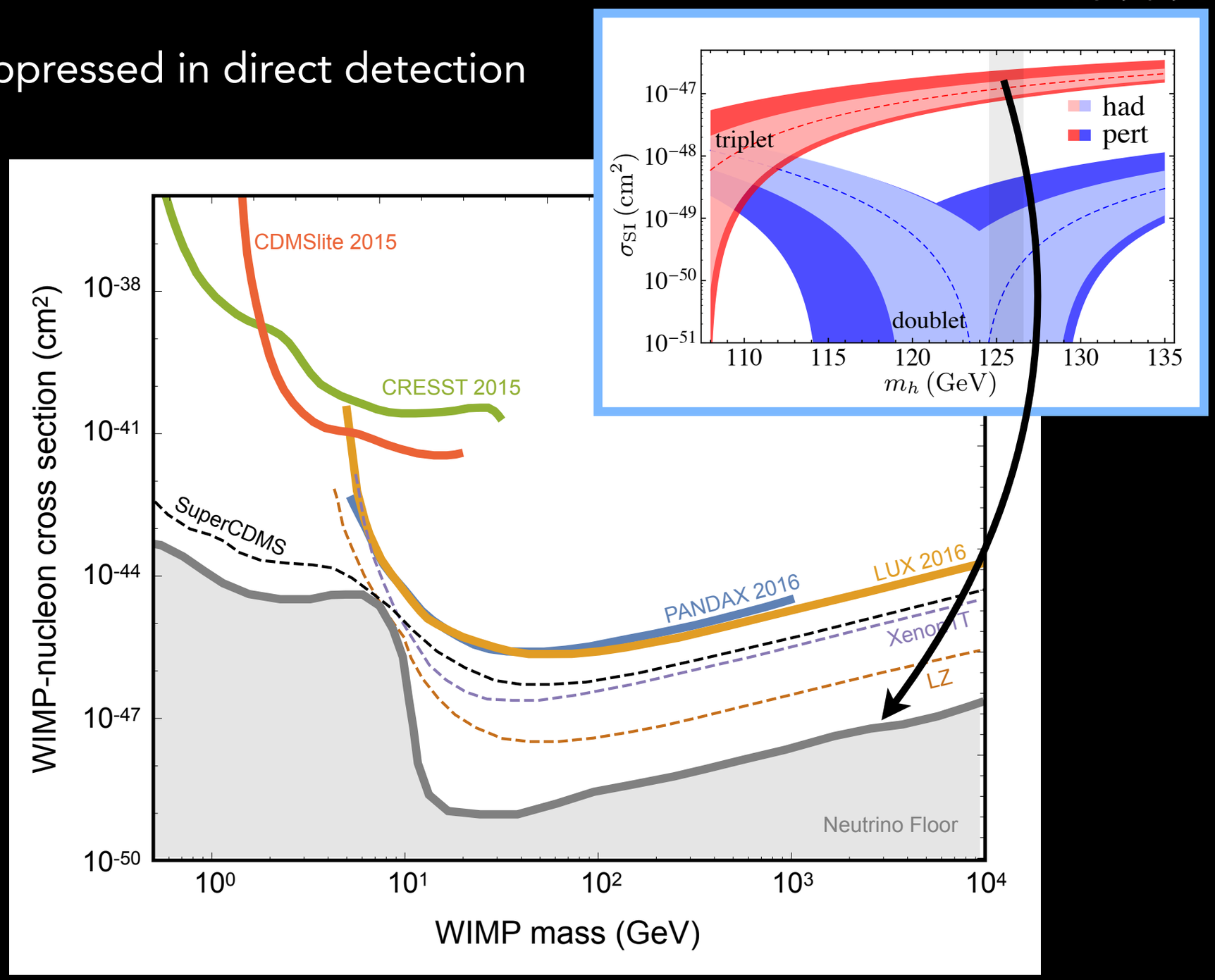


credit: T. Cohen

Wino Dark Matter

Wino signal suppressed in direct detection

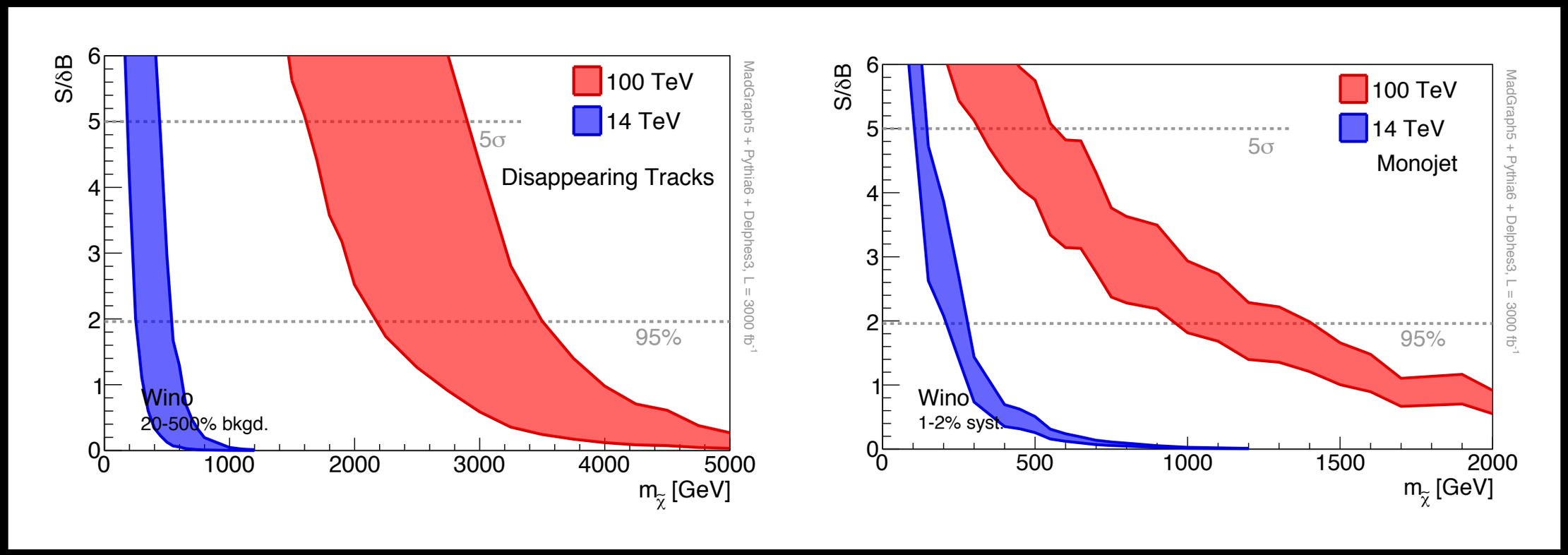
Hill and Solon [1309.4092]



Production at Colliders

Searches for disappearing tracks may probe TeV-scale winos at future colliders

Estimates for 3 ab^{-1} data



Low & Wang [1404.0682]

See talk by M. McCullough for projections

Wino Dark Matter

Annihilation signatures are promising due to Sommerfeld enhancement

Hisano, Matsumoto, Nojiri [hep-ph/0307216]

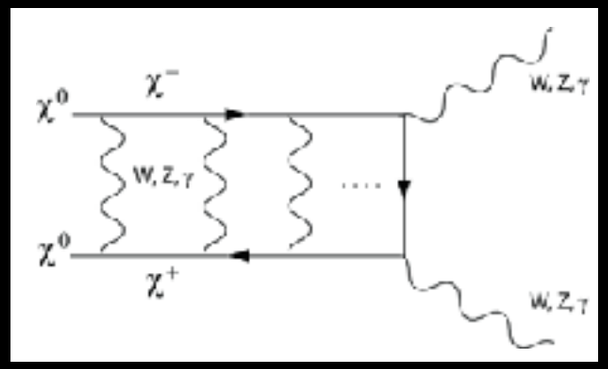
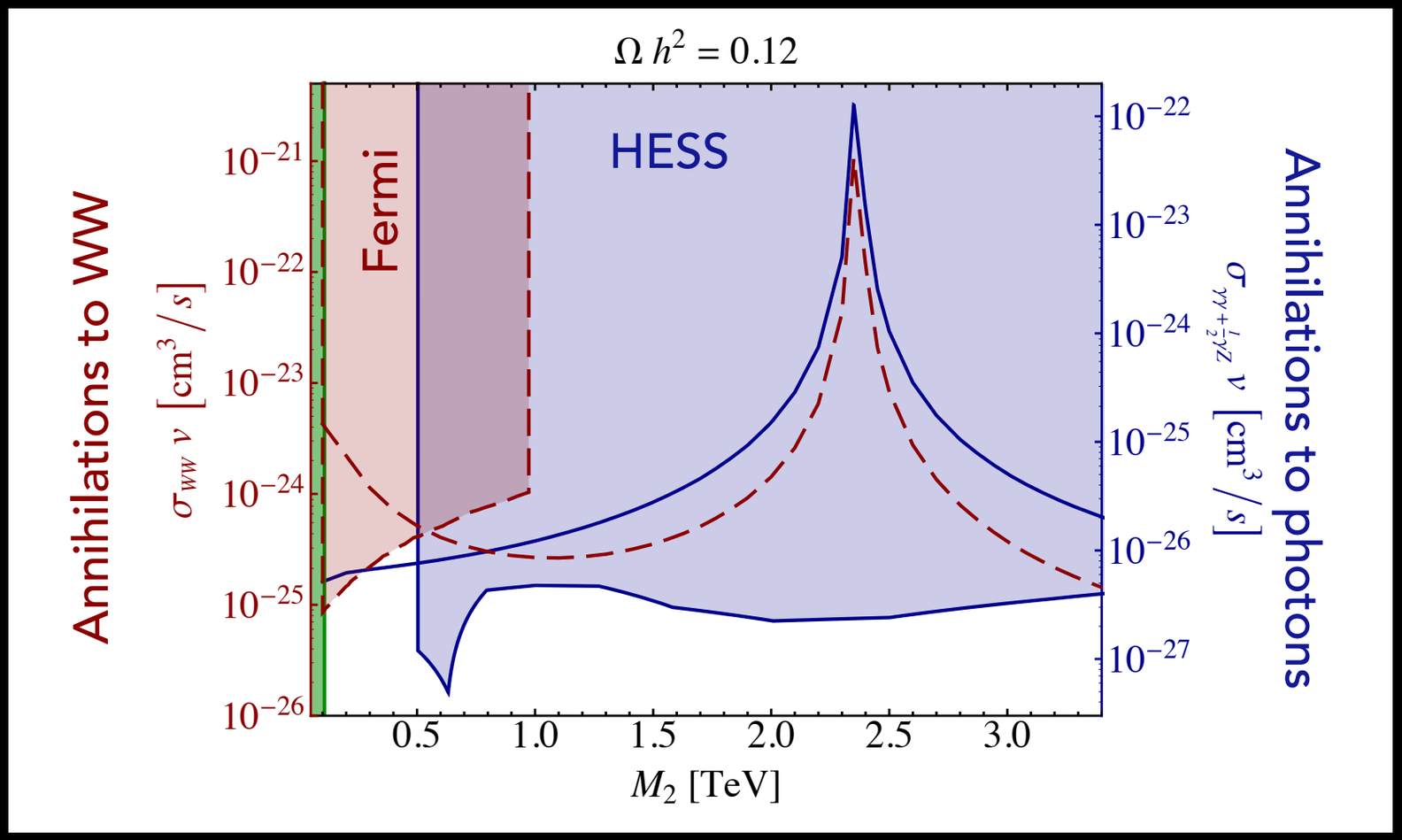


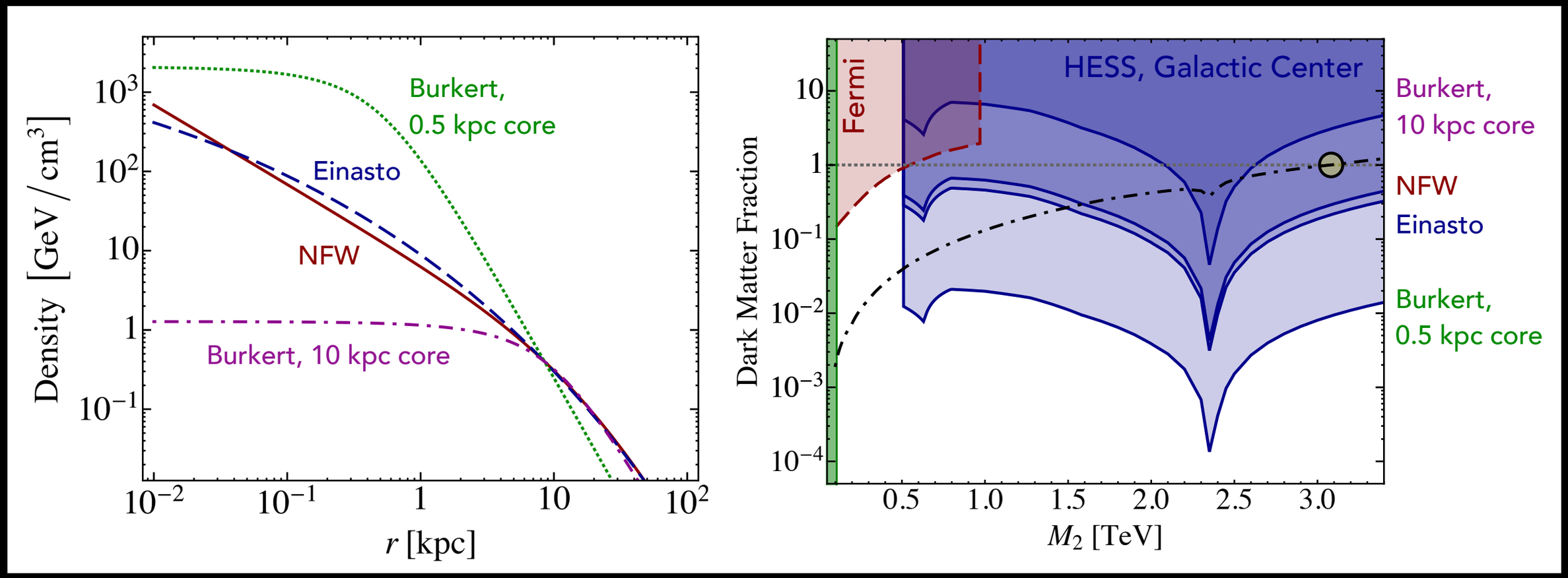
image credit: T. Cohen



Cohen, ML, Pierce, & Slatyer [1307.4082]

Wino Dark Matter

Wino can only constitute all the dark matter for extreme density profiles not generically produced in simulations of Milky Way-like galaxies



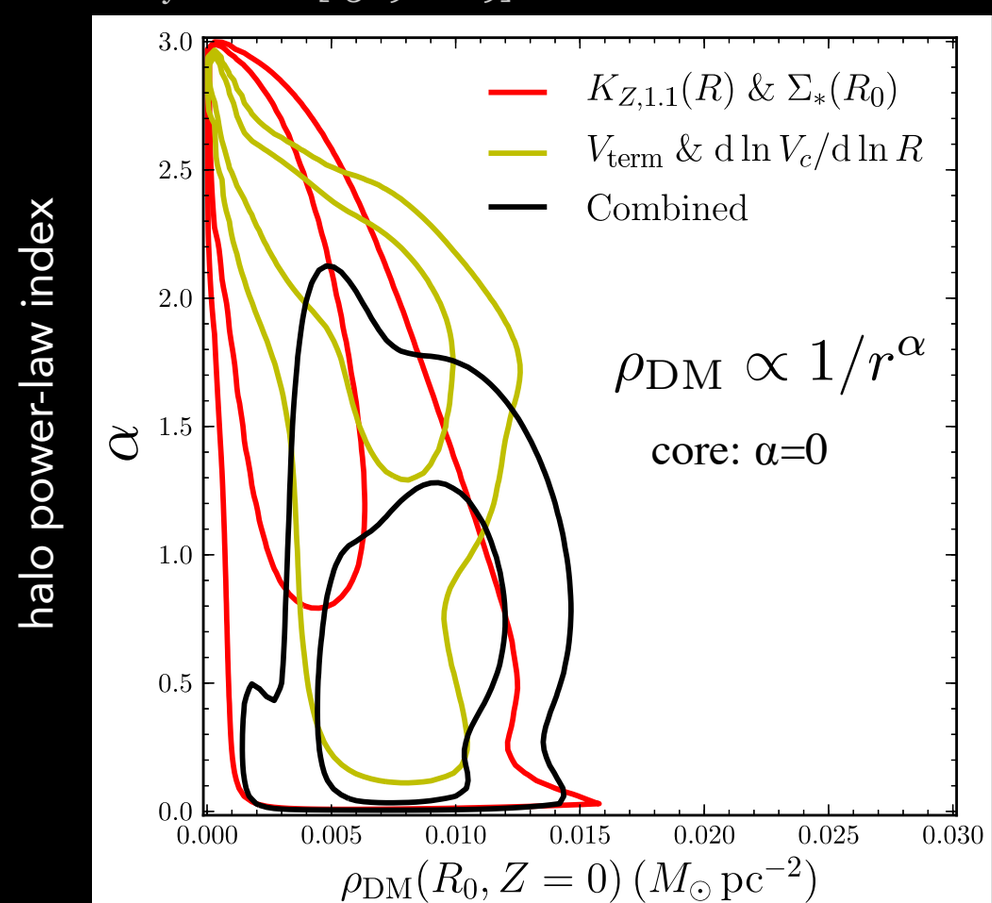
Cohen, ML, Pierce, & Slatyer [1307.4082]

Milky Way Density Profile

~9 kpc cores for the Milky Way technically allowed by dynamics

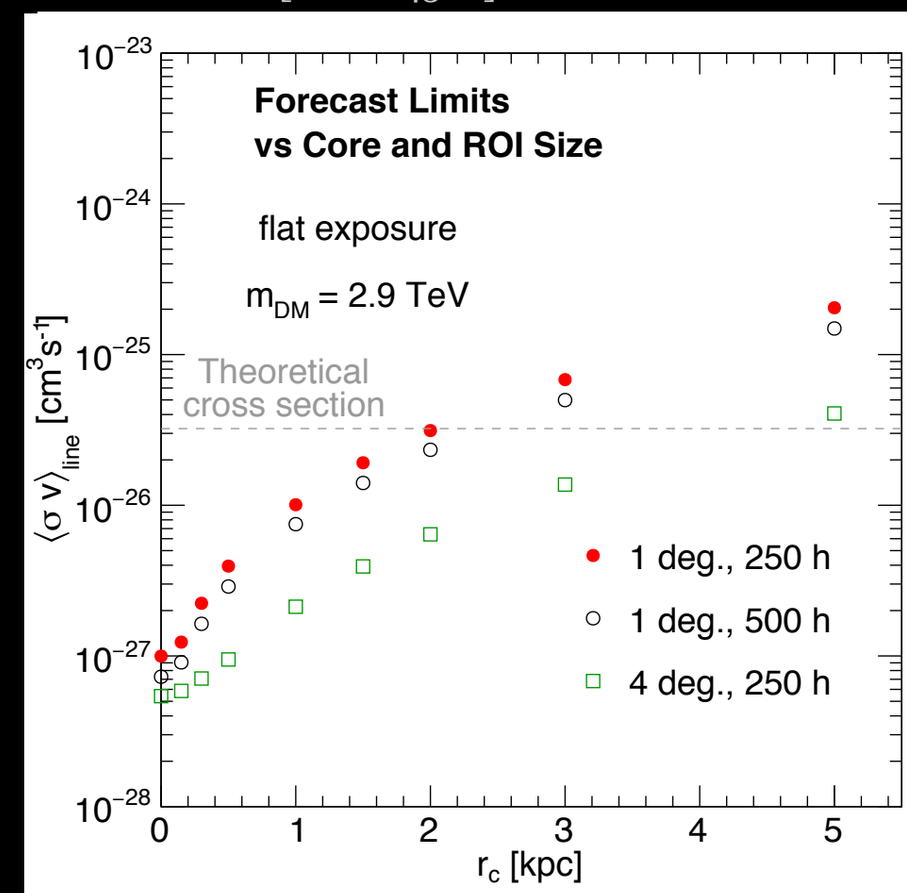
HESS will be able to exclude winos for <1 kpc cores

Bovy and Rix [1309.0809]



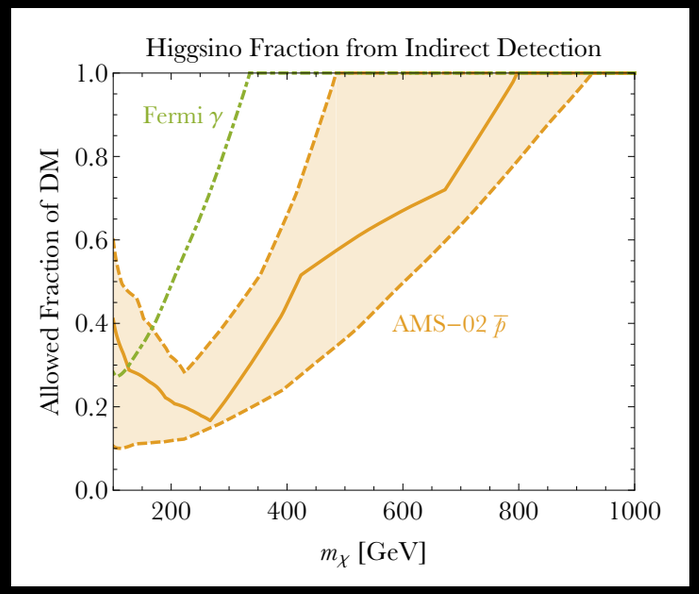
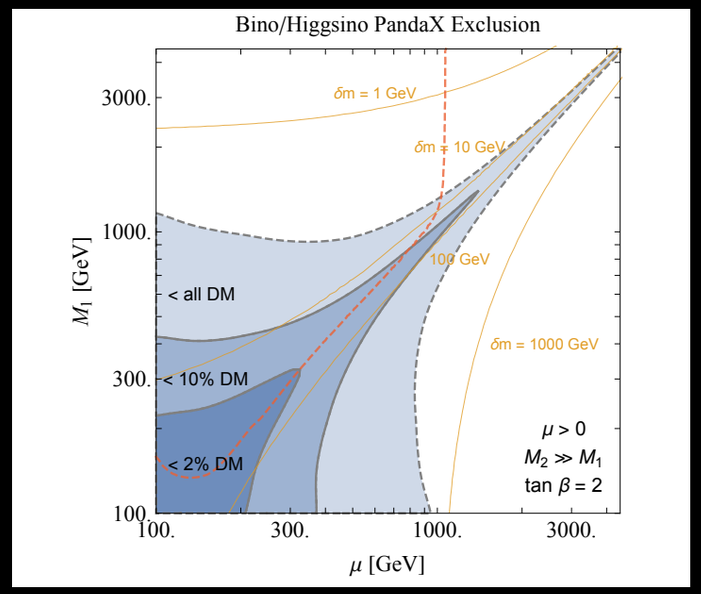
local dark matter density

Rinchiuso et al. [1808.04388]



Constraints on core size should dramatically improve with *Gaia*

Higgsino Dark Matter

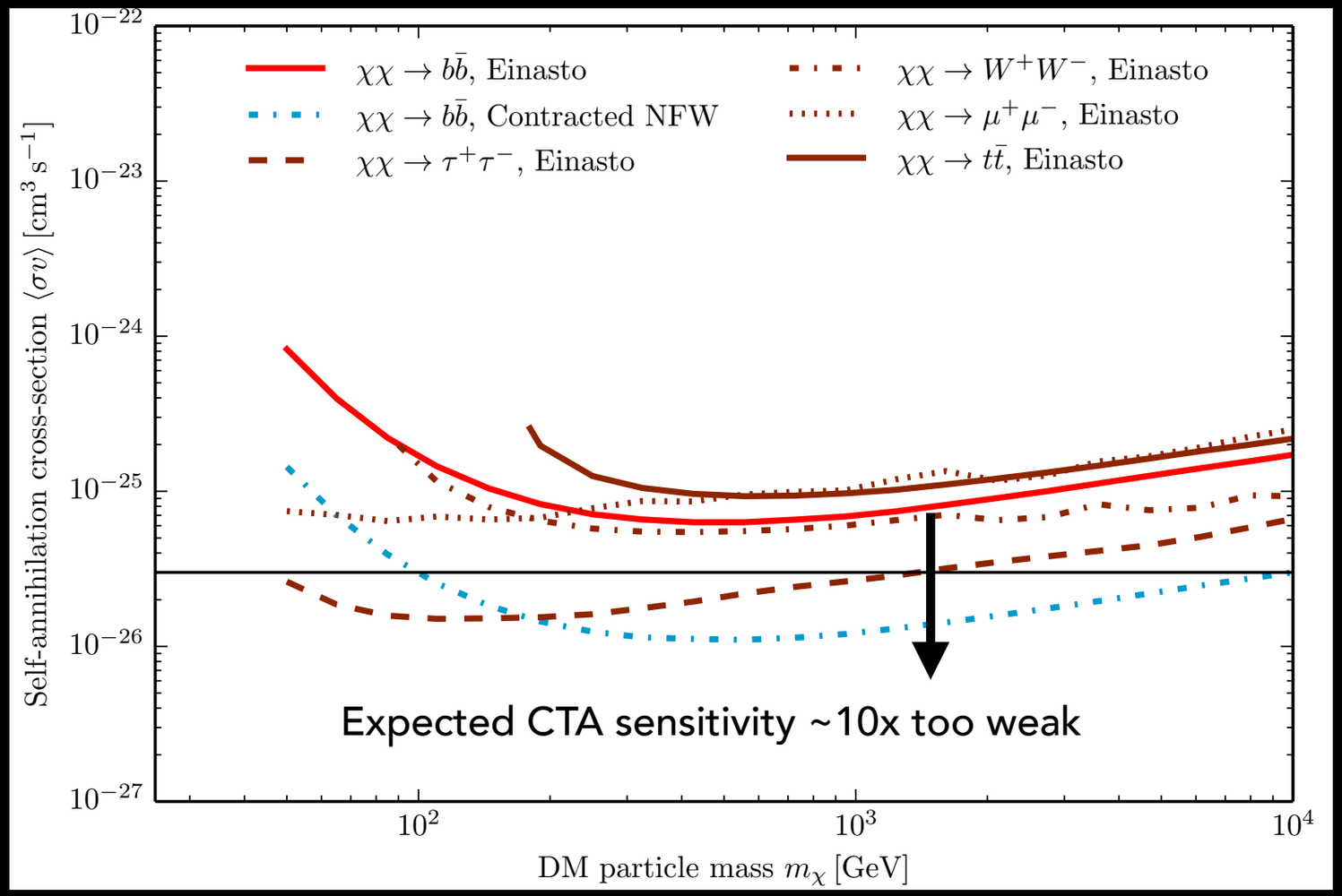
	Direct Detection	Indirect Detection
Pure Higgsino	Suppressed	
Bino/Higgsino Mixture		Suppressed

Krall and Reece [1705.04843]

Higgsino Dark Matter

Pure Higgsinos will continue to remain challenging for future TeV observatories

Silverwood et al. [1408.4131]



Future collider searches can play an important role here (see talk by M. McCullough)

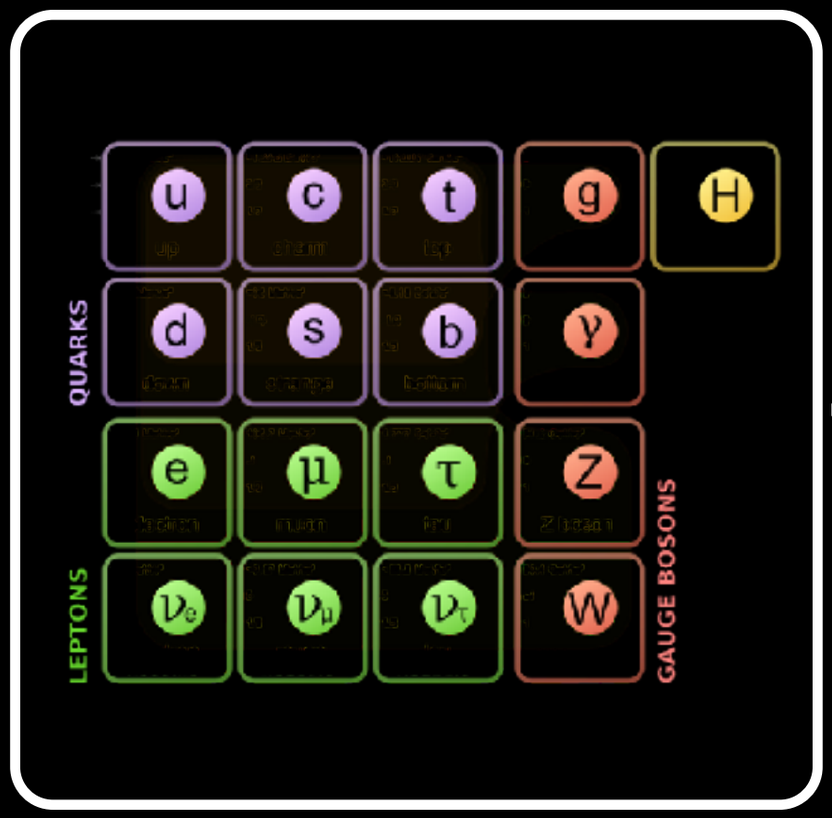
Theory Frameworks to be Discussed:

The Minimal WIMP

Hidden Dark Sectors

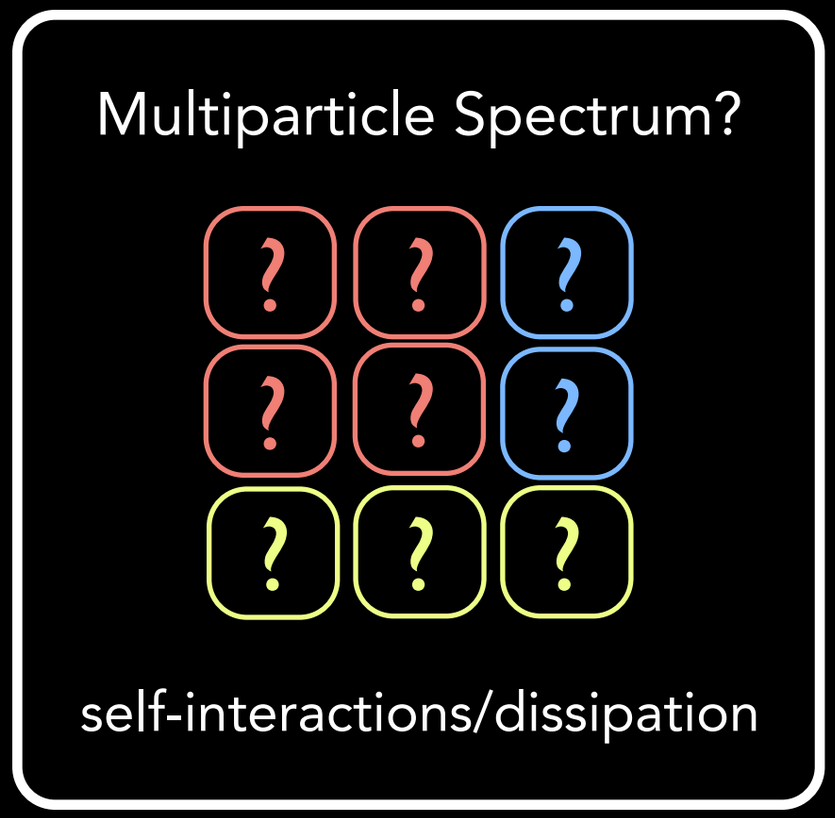
Hidden Sector Dark Matter

Visible Sector

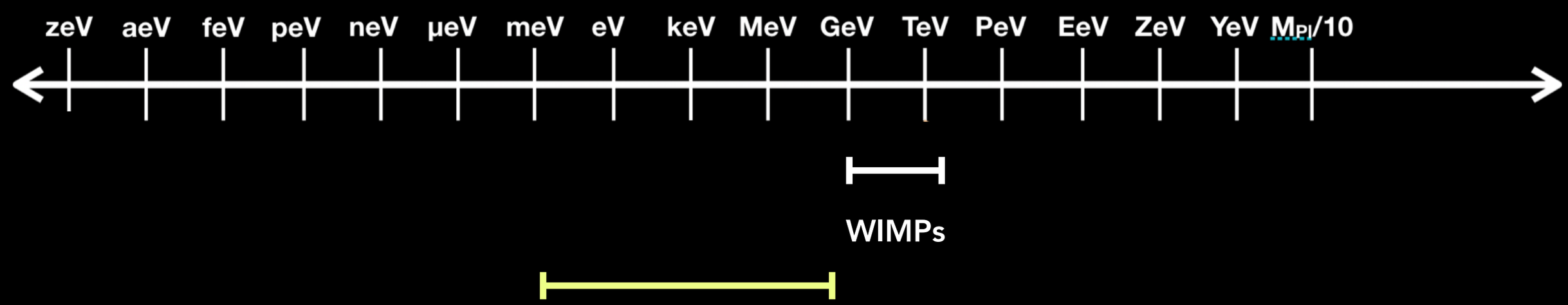


Mediator(s)

Hidden Sector



Hidden Sector Dark Matter



Many viable hidden-sector DM models for meV-to-GeV masses

asymmetric, warm, freeze-out, freeze-in, SIMPs, ELDERs,
axionlike particles, dark photons, scalars…

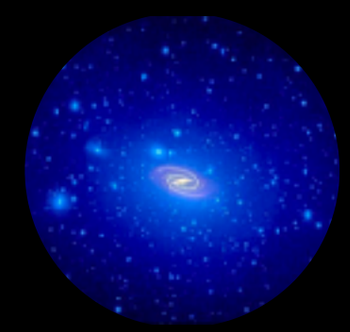
Lighter mass scales for both dark matter and mediators leads to distinctive phenomenology compared to WIMPs

How to Search for Dark Sectors

Gravitational Interactions

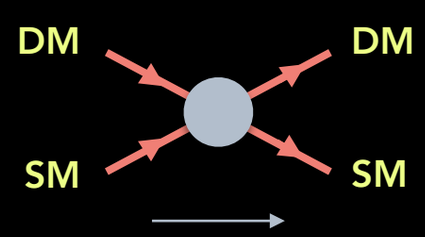
non-trivial DM interactions can affect small-scale structure

Galactic-Scale Observables



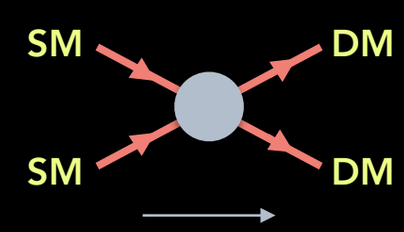
self-interactions can occur near centers of galaxies

Scattering or Absorption



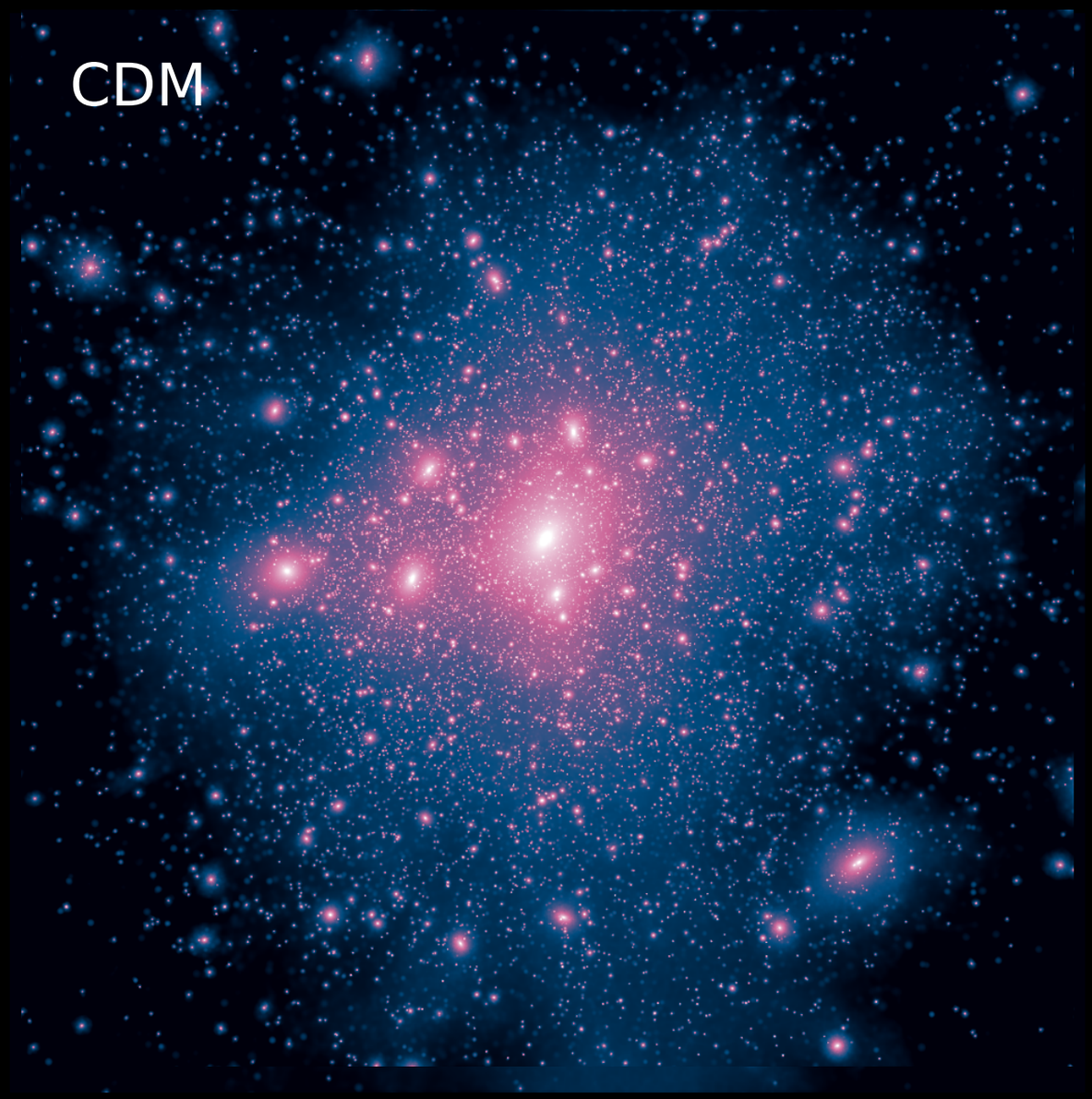
recoil energies typically smaller than WIMPs

Production



Either in colliders or beam-dump experiments

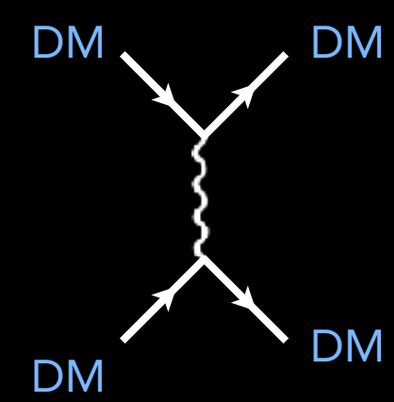
Tests of Small-Scale Structure



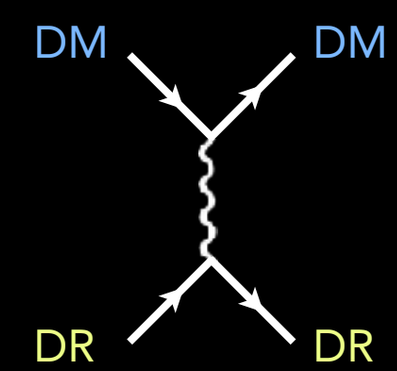
Vogelsberger et al. (2016)

SIDM example that suppresses formation of low-mass subhalos:

Dark Matter Self Interacting



Scattering off Dark Radiation



Dissipative dark sectors can also affect small-scale structure

Observational constraints on subhalo masses powerful test of dark sectors

Galactic-Scale Observables

Over the age of the Universe,
~one self-interaction near galactic center if

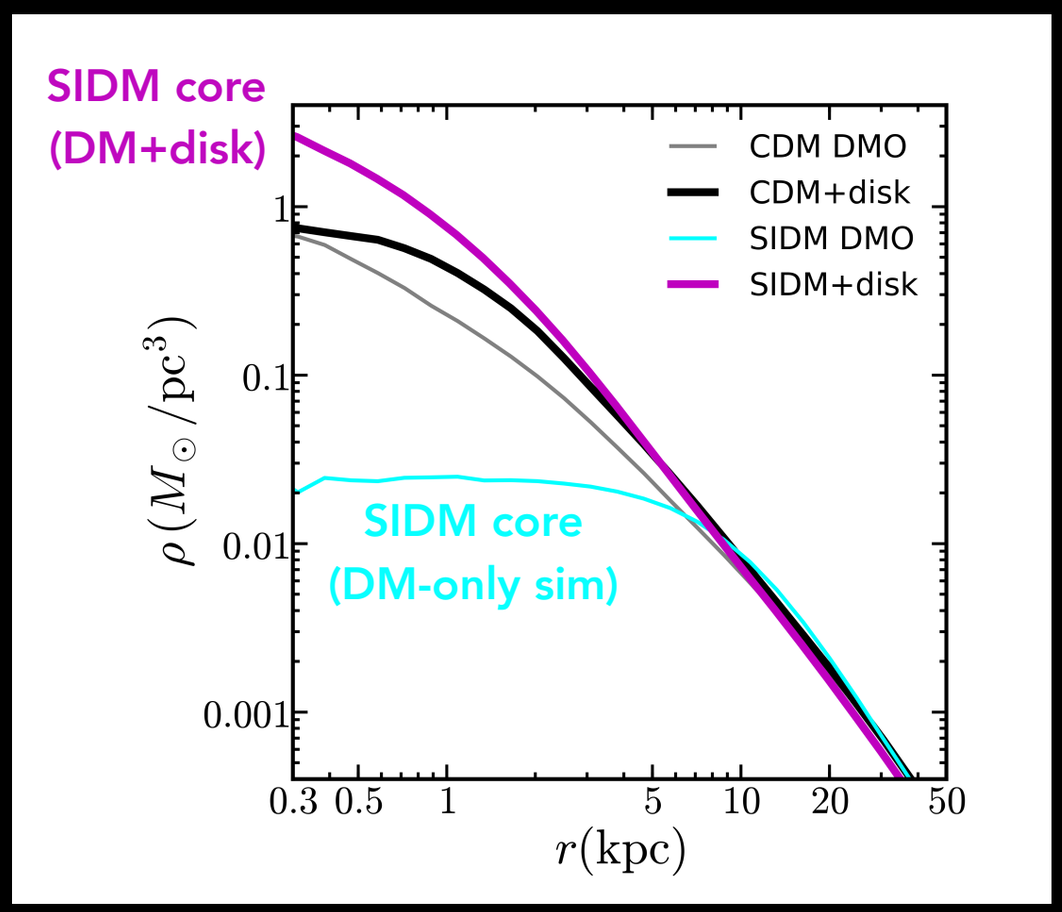
$$\frac{\sigma}{m_\chi} \sim 1\,\frac{\text{barn}}{\text{GeV}}$$

such cross sections typical in e.g., hidden sector models with light mediators

Self-interactions can affect dark matter density distributions
on galactic scales

Galactic-Scale Observables

An Example: Core v. Cusp Problem



Robles et al. [1903.01469]

Standard Statement:

Self-interactions cause dark matter halos to thermalize near center, producing cored density profiles

More Accurately:

Dark matter halo also feels baryonic gravitational potential

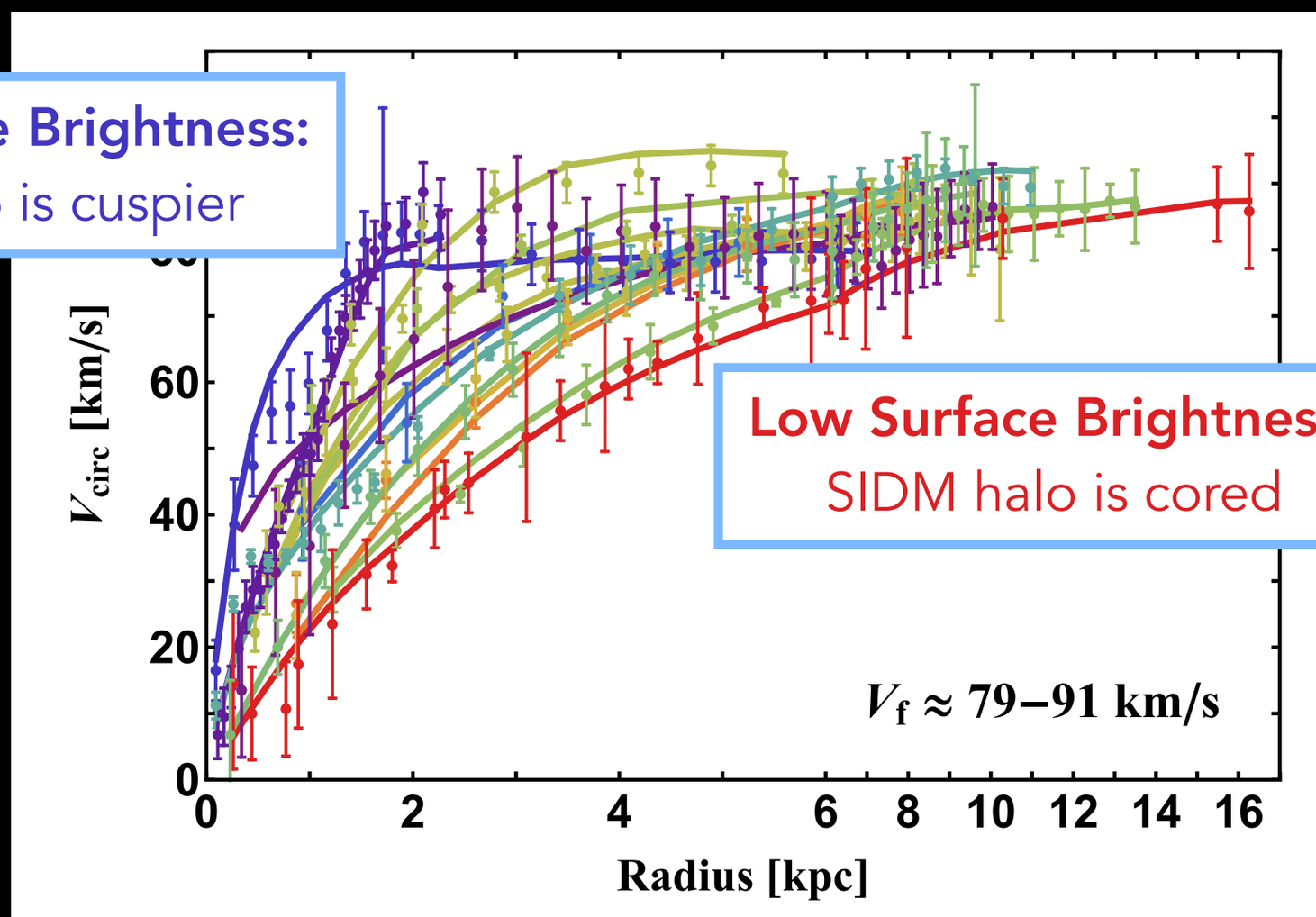
If stars are concentrated near center, dark matter will be too

Galactic-Scale Observables

An Example: Core v. Cusp Problem

SIDM yields wide variation of halo distributions (depending on galaxy properties)

May explain observed diversity of rotation curves



High Surface Brightness:
SIDM halo is cuspier

Low Surface Brightness:
SIDM halo is cored

data: SPARC galaxies
lines: SIDM theory

Ren et al. [1808.05695]

Galactic-Scale Observables

An Example: Core v. Cusp Problem

Hydrodynamic simulations of halos will play a crucial role in making both the SIDM and CDM predictions more robust

need to better understand role of baryonic feedback in halo formation

Dwarfs & low-surface brightness galaxies provide excellent SIDM laboratories; observational evidence will continue to improve

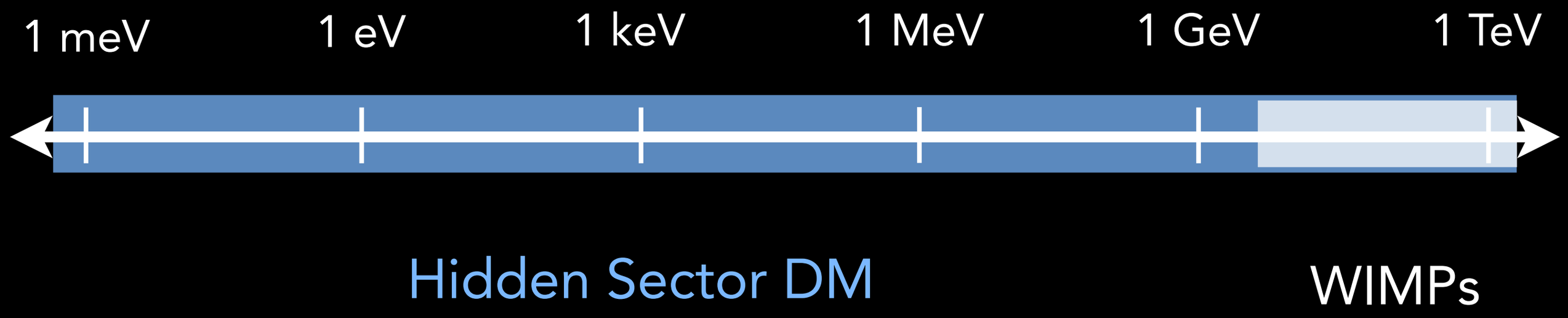
these systems are expected to be cored in SIDM scenario

Complementarity

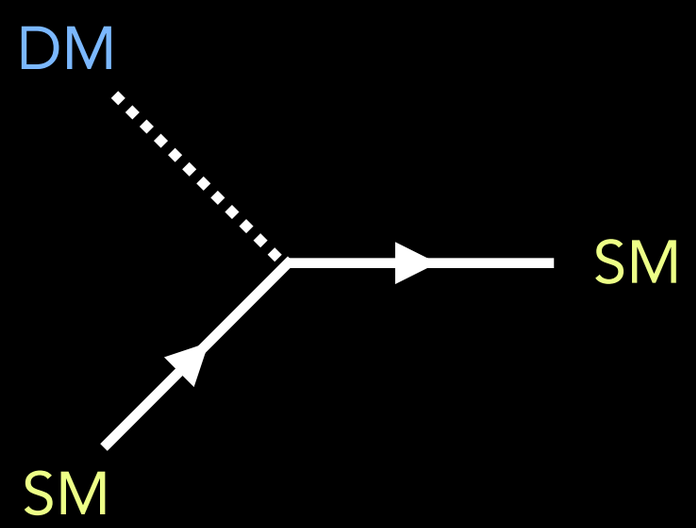
Many models with self interactions naturally have baryonic interactions

see e.g., Del Nobile, Kaplinghat, and Yu [1507.04007]

Both astrophysical and terrestrial searches needed to uncover complete dark matter model

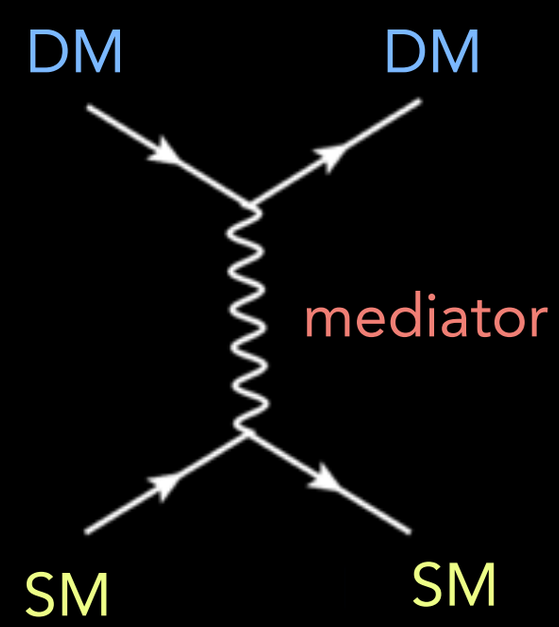


DM Absorption

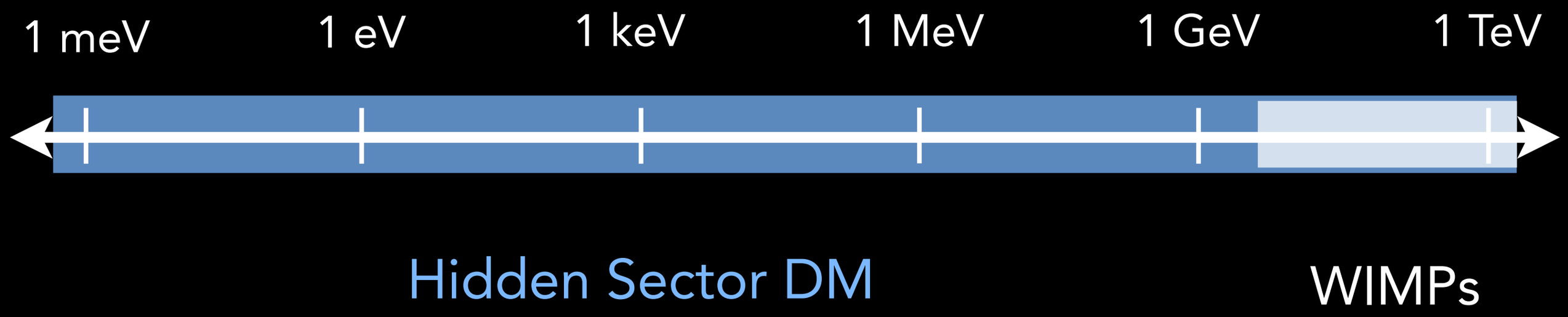


(bosonic DM < 1 keV)

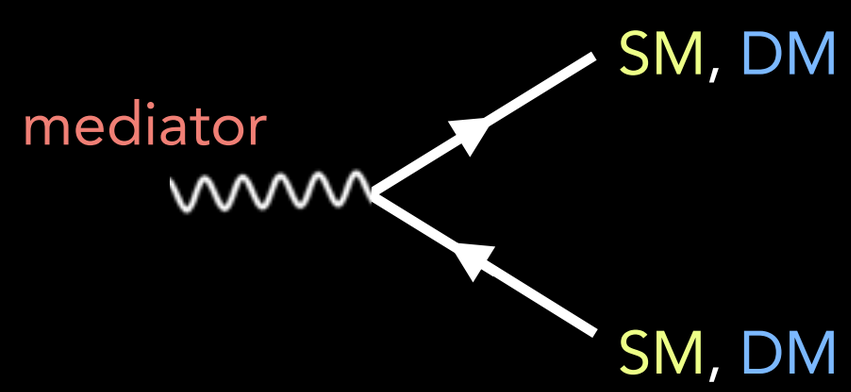
DM Scattering



need to probe interactions w/ nuclei <u>and</u> electrons



Mediator Production/Decay



(at beam-dumps or colliders…)

Dark Sectors at Colliders

If the dark-sector states are produced at the LHC, they can lead to novel phenomenology such as:

displaced vertices

large particle multiplicities

multiple resonances

lepton or photon jets

semi-visible or emerging jets

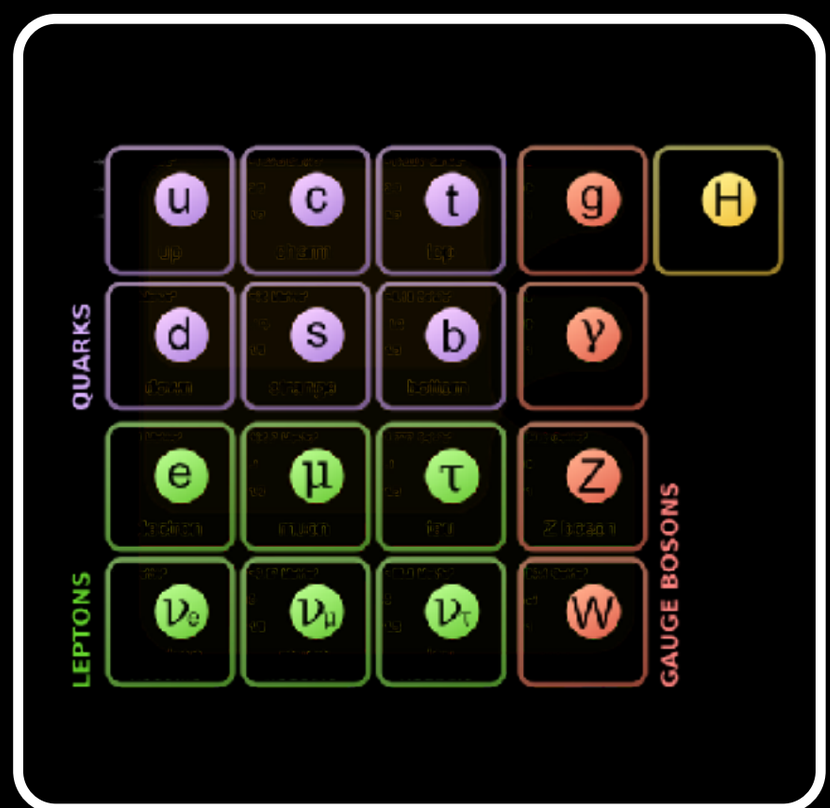
Hidden Valleys provide a classic example of such phenomenology

Strassler and Zurek [hep-ph/0604261]; Zurek [1001.2563]

Dark Sectors at Colliders

An Illustrative Example

Visible Sector | **Mediator(s)** | **Hidden Sector**



Z'

Scalar Quarks

χ_1 χ_2

2 flavors

$SU_d(2)$

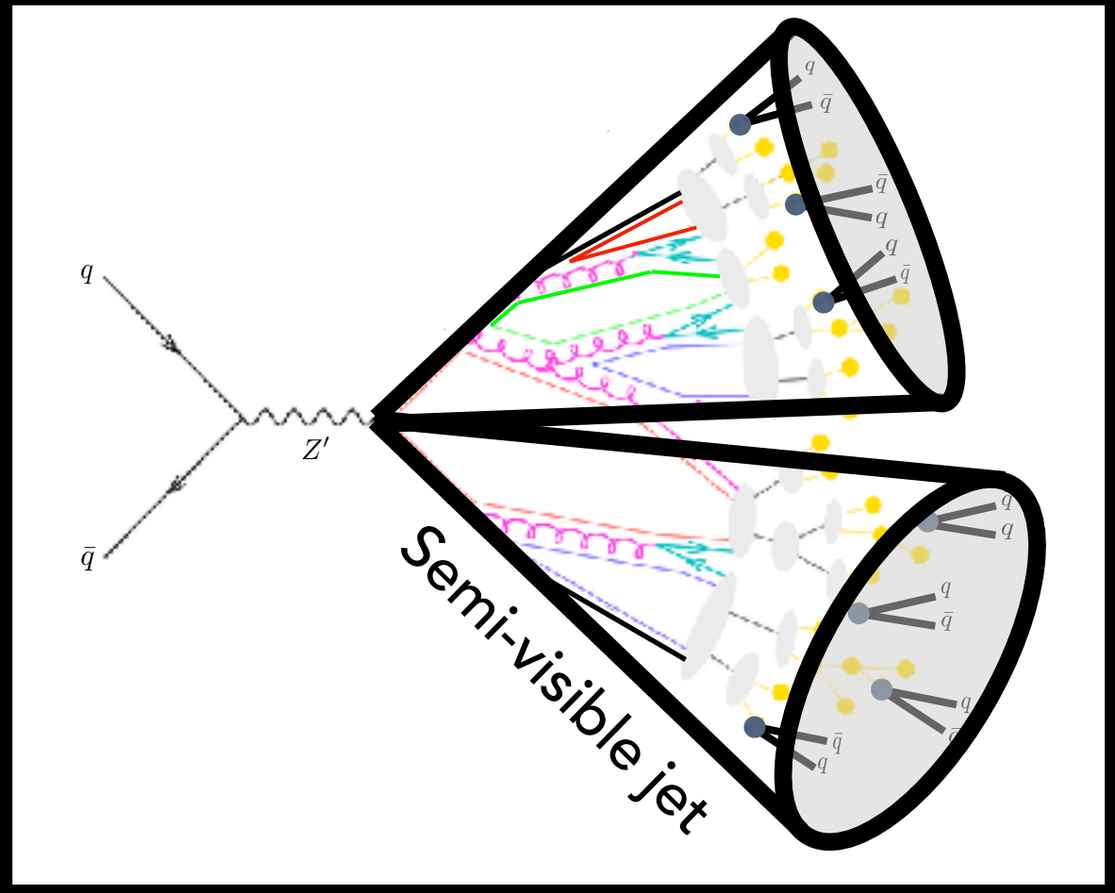
Cohen, ML, H. K. Lou [1503.00009]
Cohen, ML, H. K. Lou, and S. Mishra-Sharma [1707.05326]

Dark Sectors at Colliders

An Illustrative Example

Direct detection signal is highly suppressed, falling beneath neutrino floor

Dedicated collider searches have discovery potential



Cohen, ML, H. K. Lou, and S. Mishra-Sharma [1707.05326]

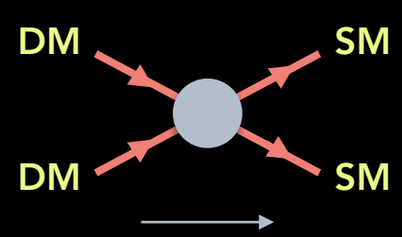
Conclusions

Over next few decades, important advancements in both astrophysical and terrestrial probes will test WIMPs and Hidden Dark Sectors

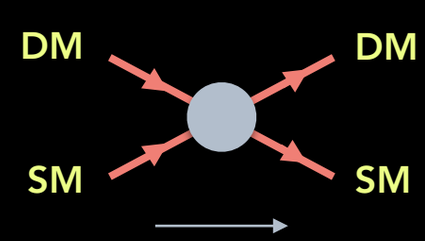
Gravitational Interactions

Galactic-Scale Observables

Annihilations



Scattering or Absorption



Production