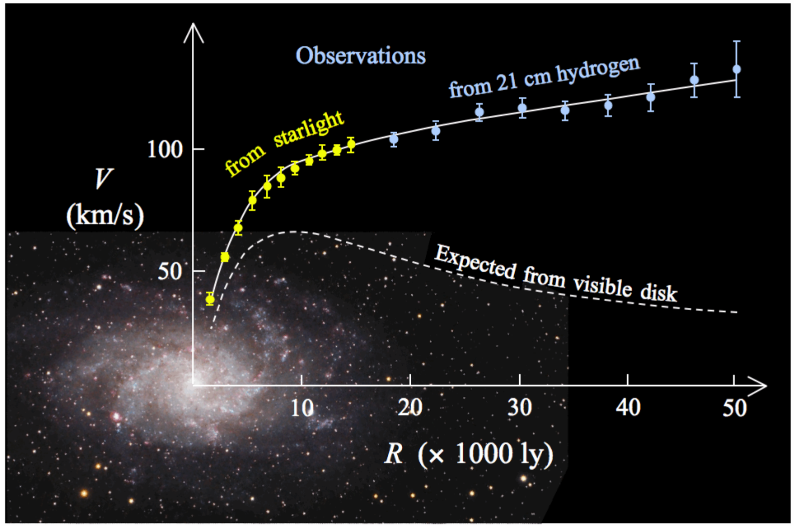
Theoretical perspective on Dark Matter searches

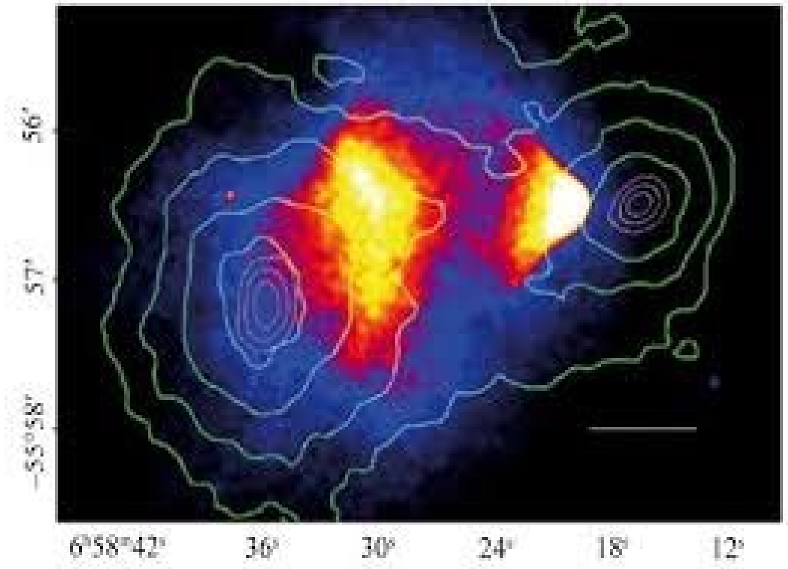
Nicole Bell

Evidence for dark matter

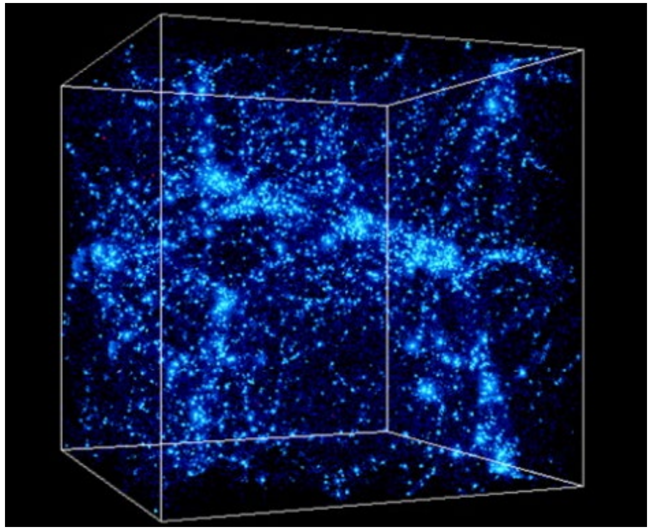
Astrophysical observations consistently point to the need for dark matter



Galaxy rotation curves



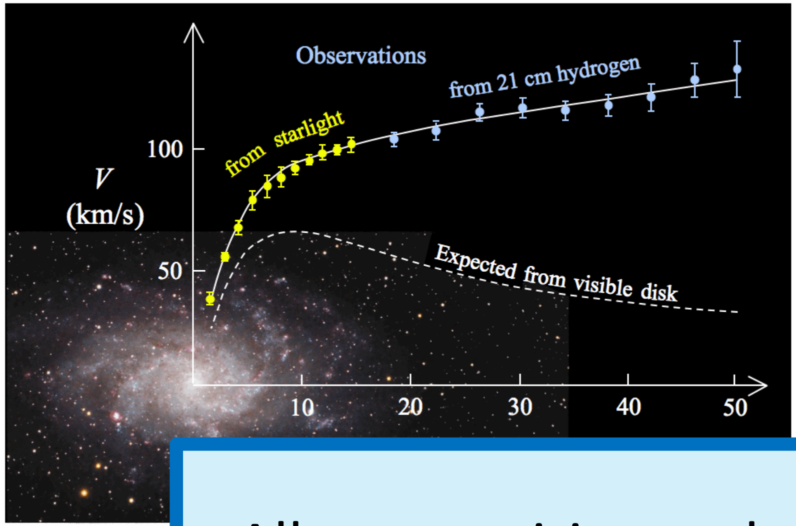
Clusters of galaxies

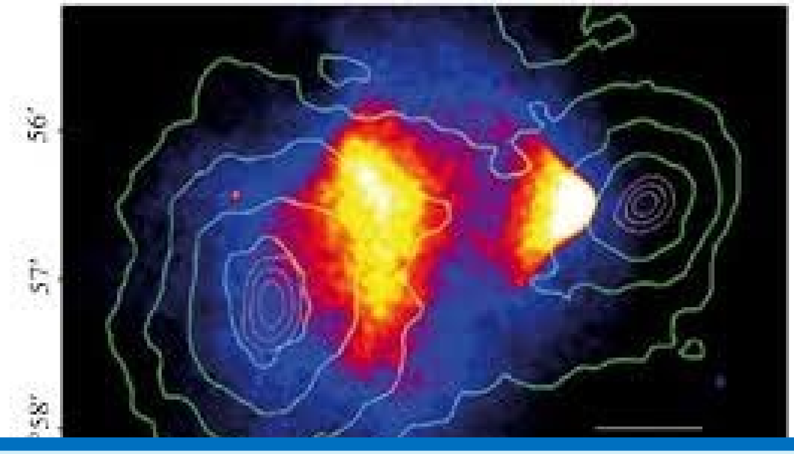


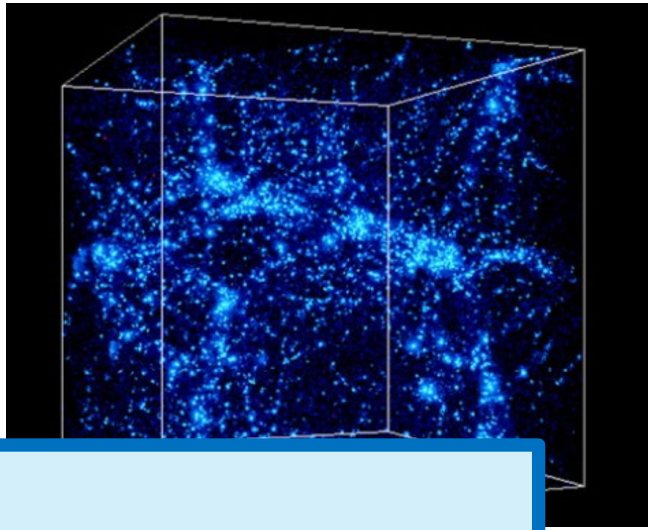
Large Scale Structure

Evidence for dark matter

Astrophysical observations consistently point to the need for dark matter



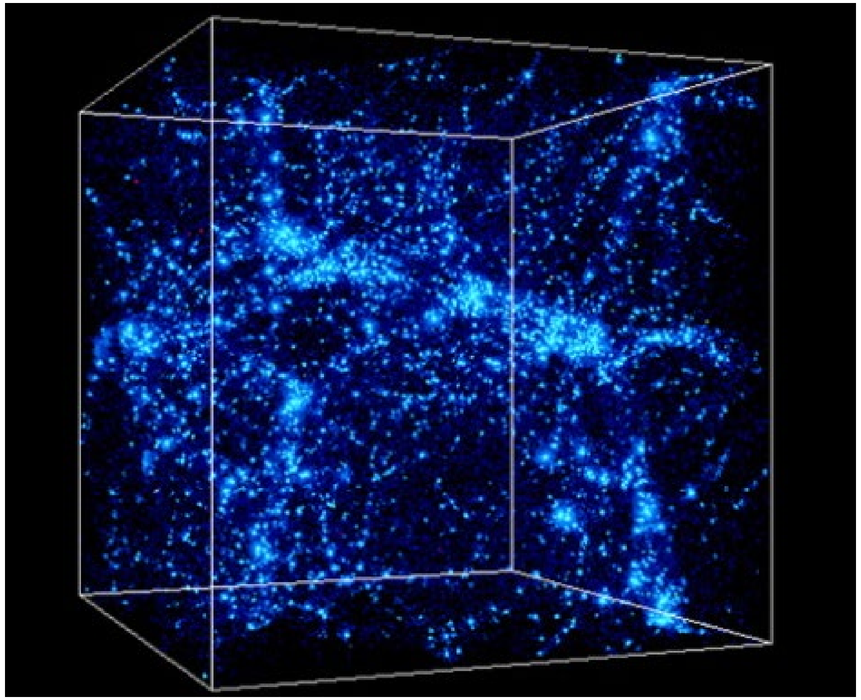




All are sensitive to dark matter's ***gravitational influence.***

As yet, very little information about the ***particle properties*** of dark matter.

What do we know?



Dark → coupling to photons absent or highly suppressed.

Cold (at least approximately):

→ non-relativistic by structure formation era

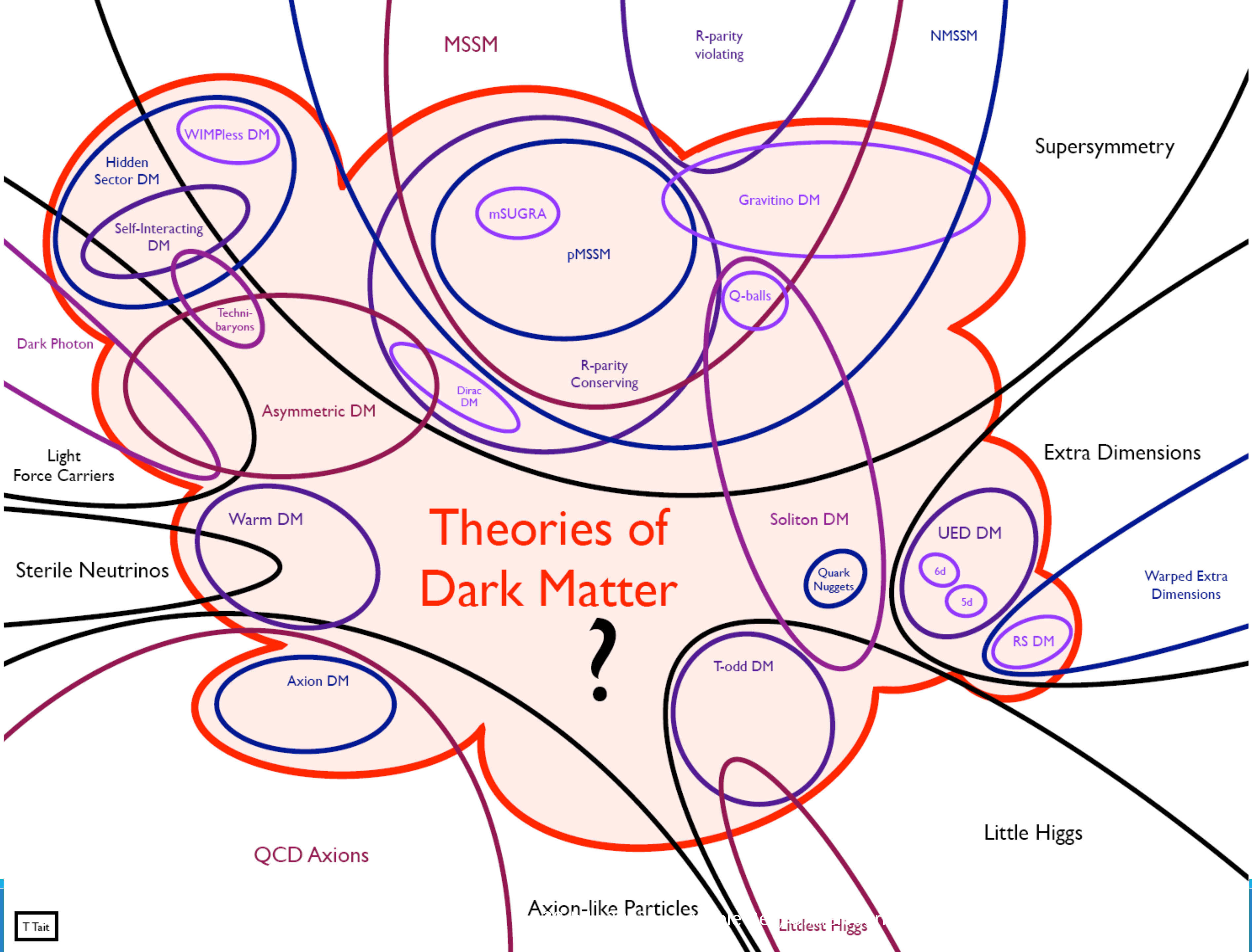
Distribution in the Universe: approximately understood

Abundance: about 5 times the energy density of visible matter

Mass: unknown

Couplings: unknown

Spectrum of dark-sector particles: unknown



MSSM
R-parity violating
NMSSM
Supersymmetry
WIMPless DM
Hidden Sector DM
Self-Interacting DM
Techni-baryons
mSUGRA
pMSSM
Gravitino DM
Q-balls
Dark Photon
R-parity Conserving
Dirac DM
Asymmetric DM
Light Force Carriers
Extra Dimensions
Warm DM
Theories of Dark Matter
?
Soliton DM
UED DM
6d
5d
Quark Nuggets
Warped Extra Dimensions
Sterile Neutrinos
RS DM
T-odd DM
Axion DM
Little Higgs
QCD Axions
Axion-like Particles
Littlest Higgs
T Tait

Dark matter model space

Image: Bertone and Tait

The WIMP miracle:

Correct relic density via thermal freezeout, provided:

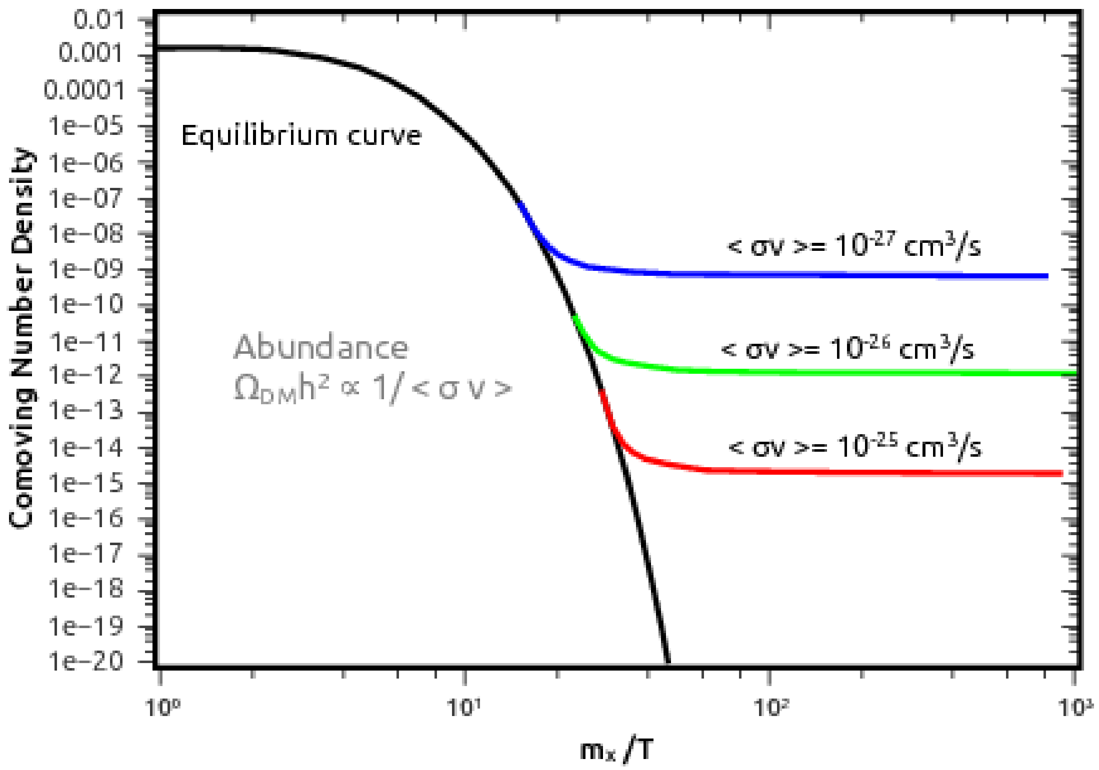
$$g \sim g_{weak} \quad \text{and} \quad m_\chi \sim \text{GeV-TeV}$$

$$\Omega_\chi \propto \frac{1}{\langle \sigma v \rangle_{ann}} \sim \frac{m_\chi^2}{g_\chi^4}$$

Required annihilation cross section:

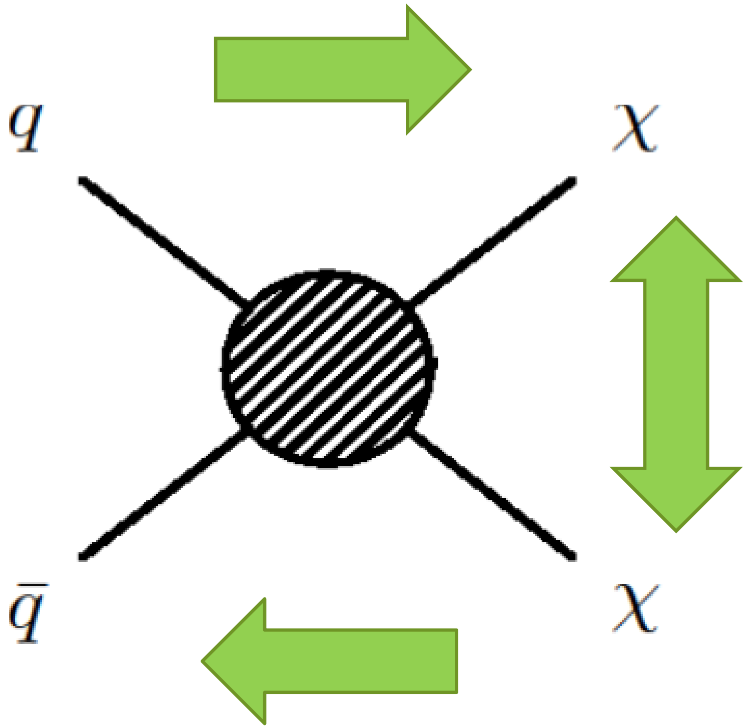
$$\langle \sigma v \rangle_{ann} \sim 2 \times 10^{-26} \text{cm}^3/s$$

$$\chi + \chi \leftrightarrow \text{regular matter}$$



Looking for WIMPs

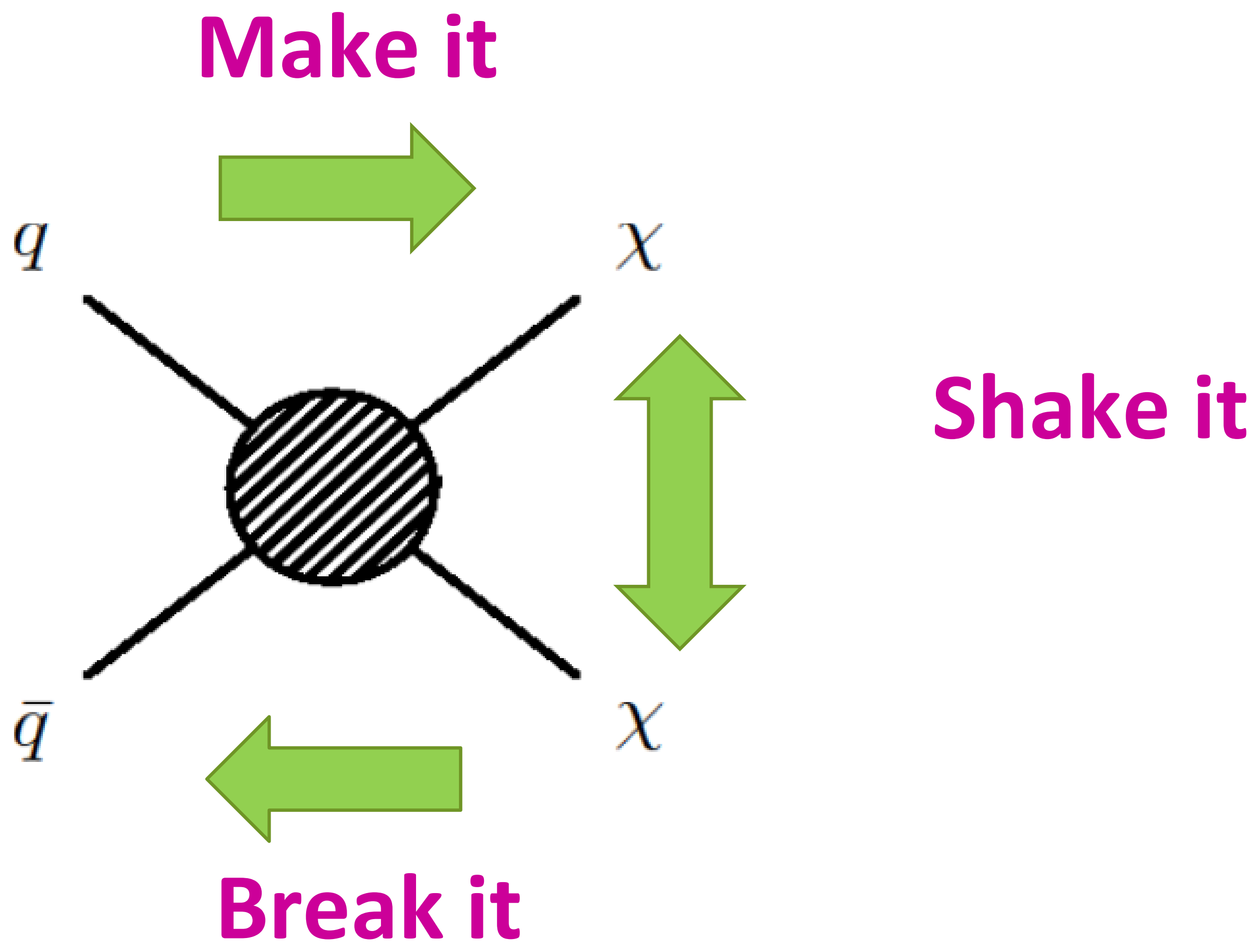
Production in particle colliders



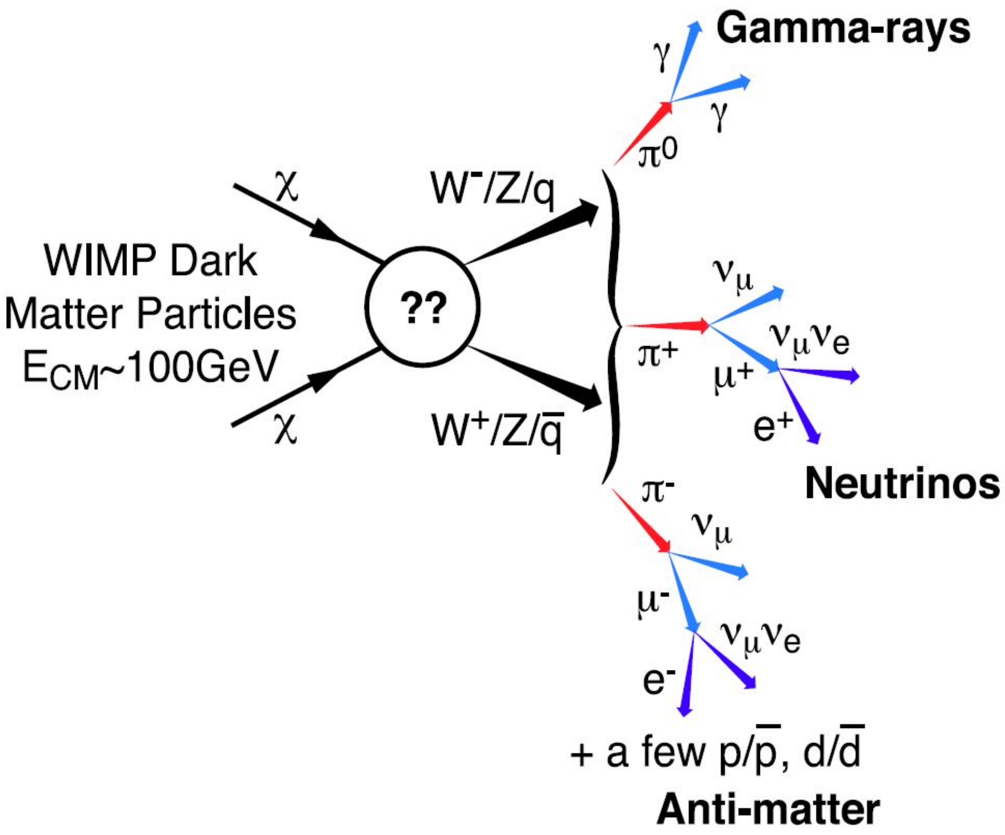
Scattering in dark matter detectors

Dark matter annihilation in the galaxy

Looking for WIMPs



Indirect detection – Detecting dark matter annihilation in space



Indirect detection probes the dark matter annihilation cross-section

→ The most direct detect test of the **thermal-relic WIMP paradigm**

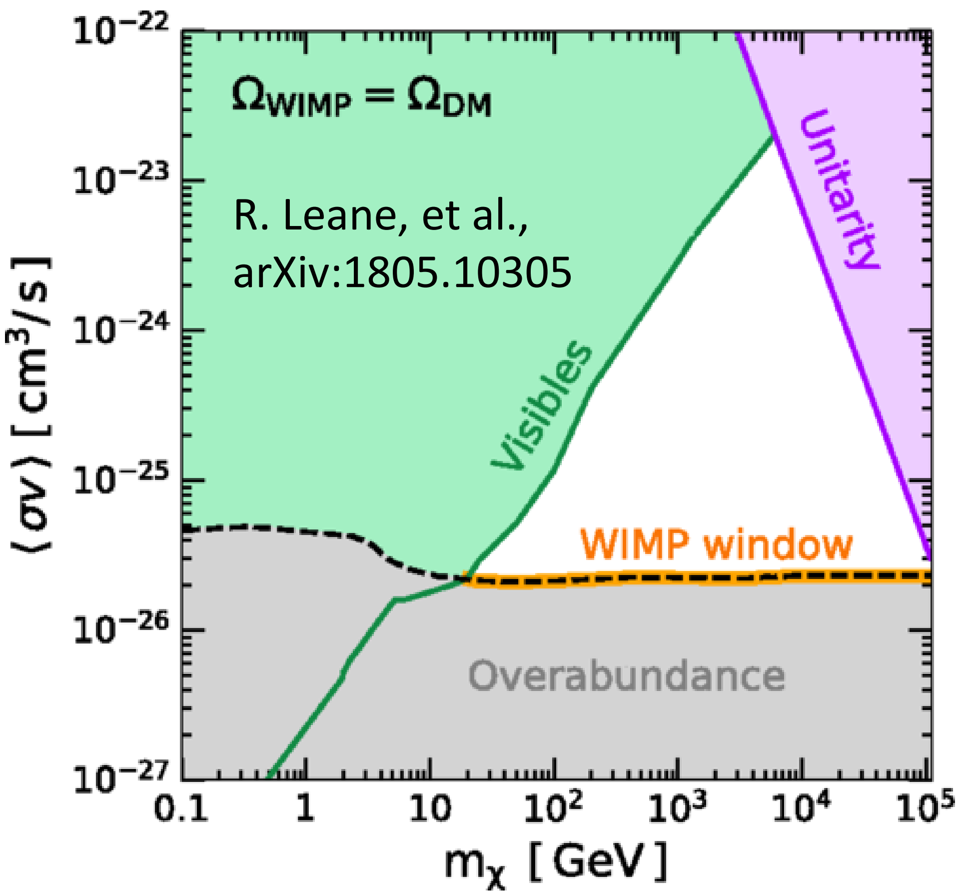
The WIMP window

Mass window for thermally produced WIMPs:

m_χ < 100 TeV from Unitarity limit

m_χ > MeV to avoid upsetting BBN

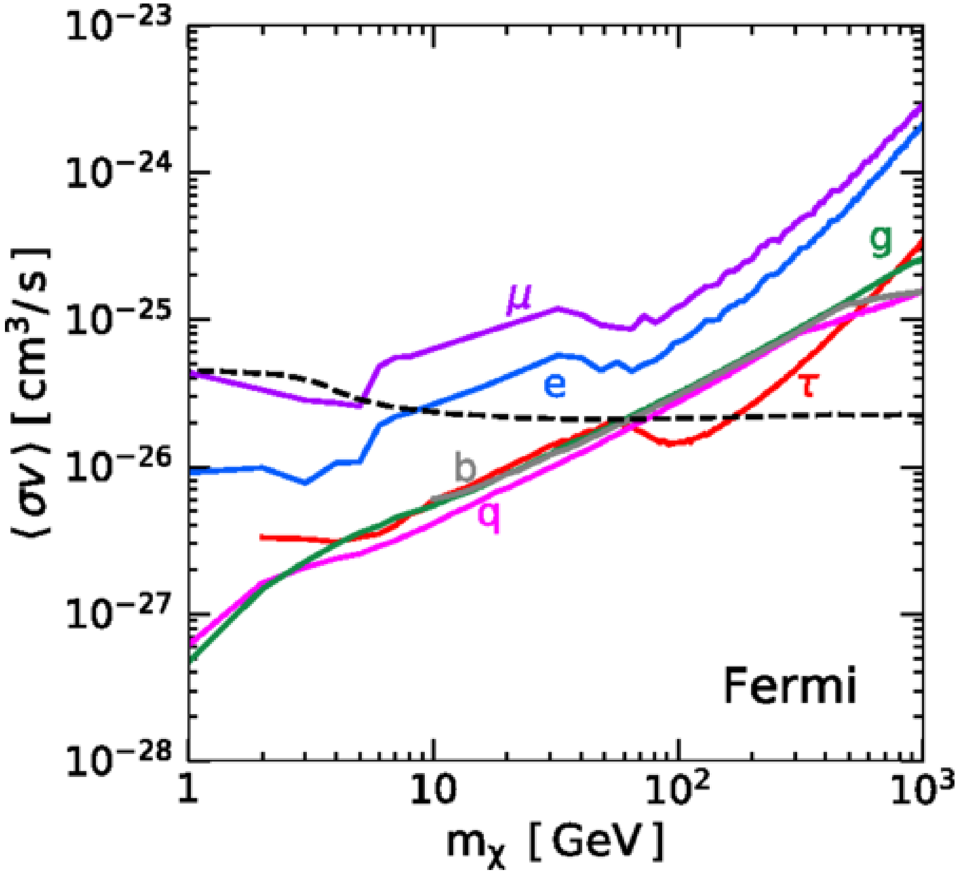
→ We need to test thermal-relic annihilation cross sections across the full mass window



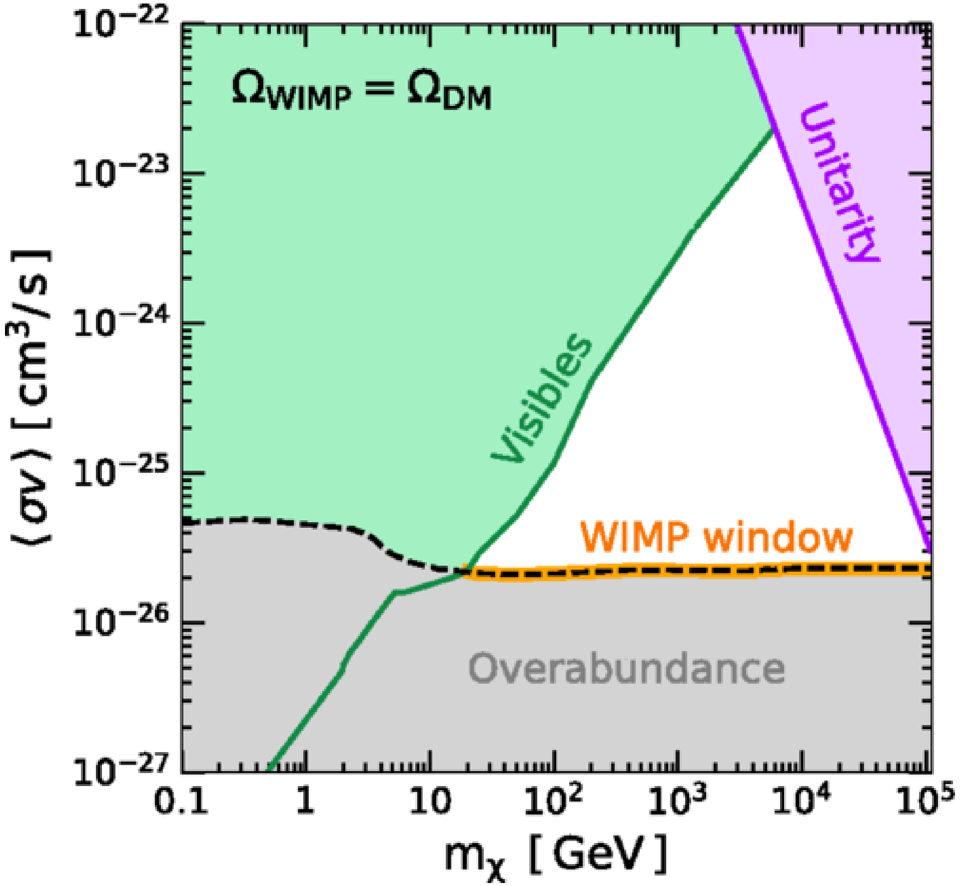
Indirect detection constraints

R. Leane, et al., arXiv:1805.10305

Fermi dSph limits

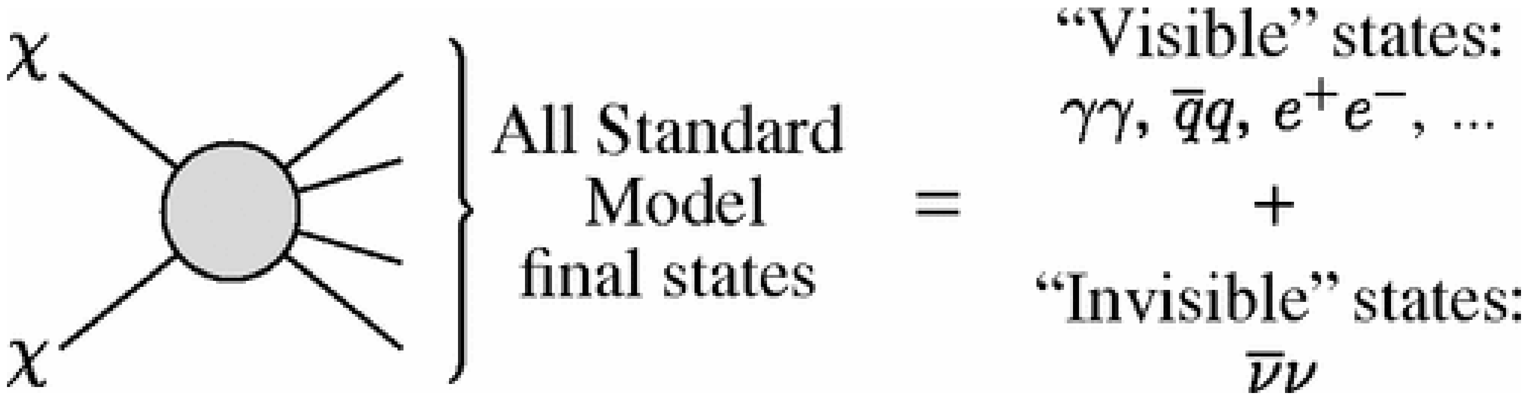


Annihilation to "visible" SM states



Annihilation to neutrinos

- Indirect detection limits – typically neglect the possibility that dark matter may annihilate to “invisible” or hard-to-detect final states.



Beacom, NFB, Mack, PRL 2007

- **We must probe annihilation to neutrinos to fully test the WIMP hypothesis.**

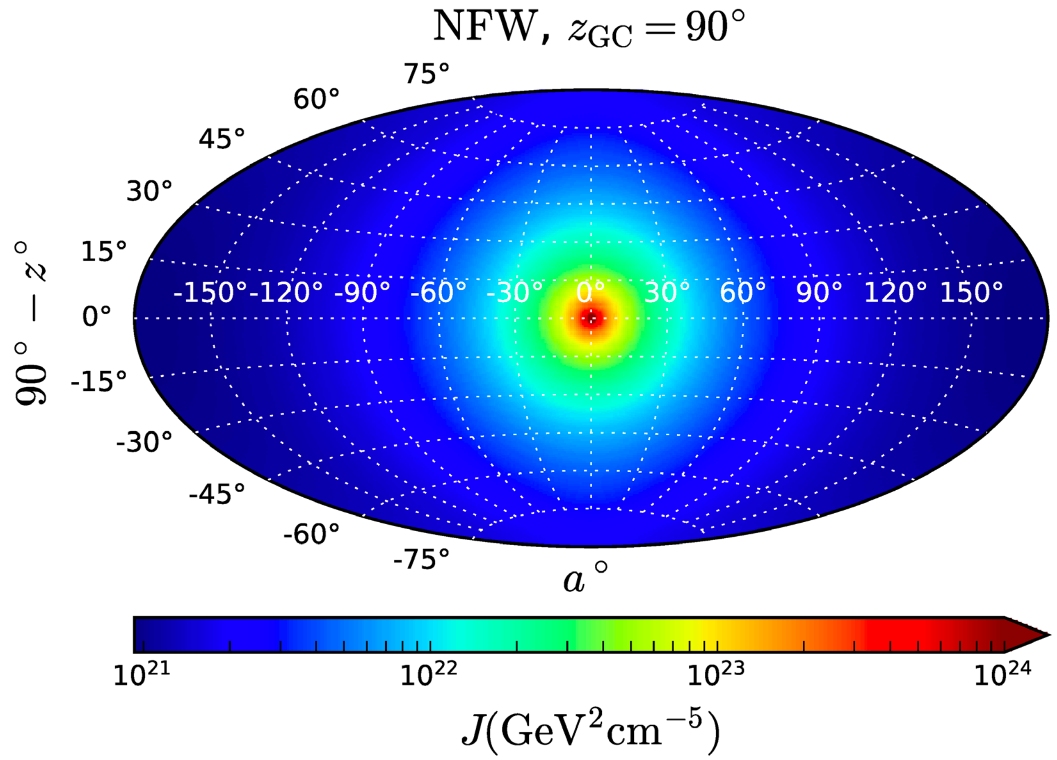
Dark matter annihilation signal

$$\frac{d\Phi_{\nu\Delta\Omega}}{dE_\nu} = \langle\sigma v\rangle \frac{J_{\Delta\Omega}}{8\pi m_{DM}^2} \frac{dN_\nu}{dE_\nu}$$

Annihilation cross section

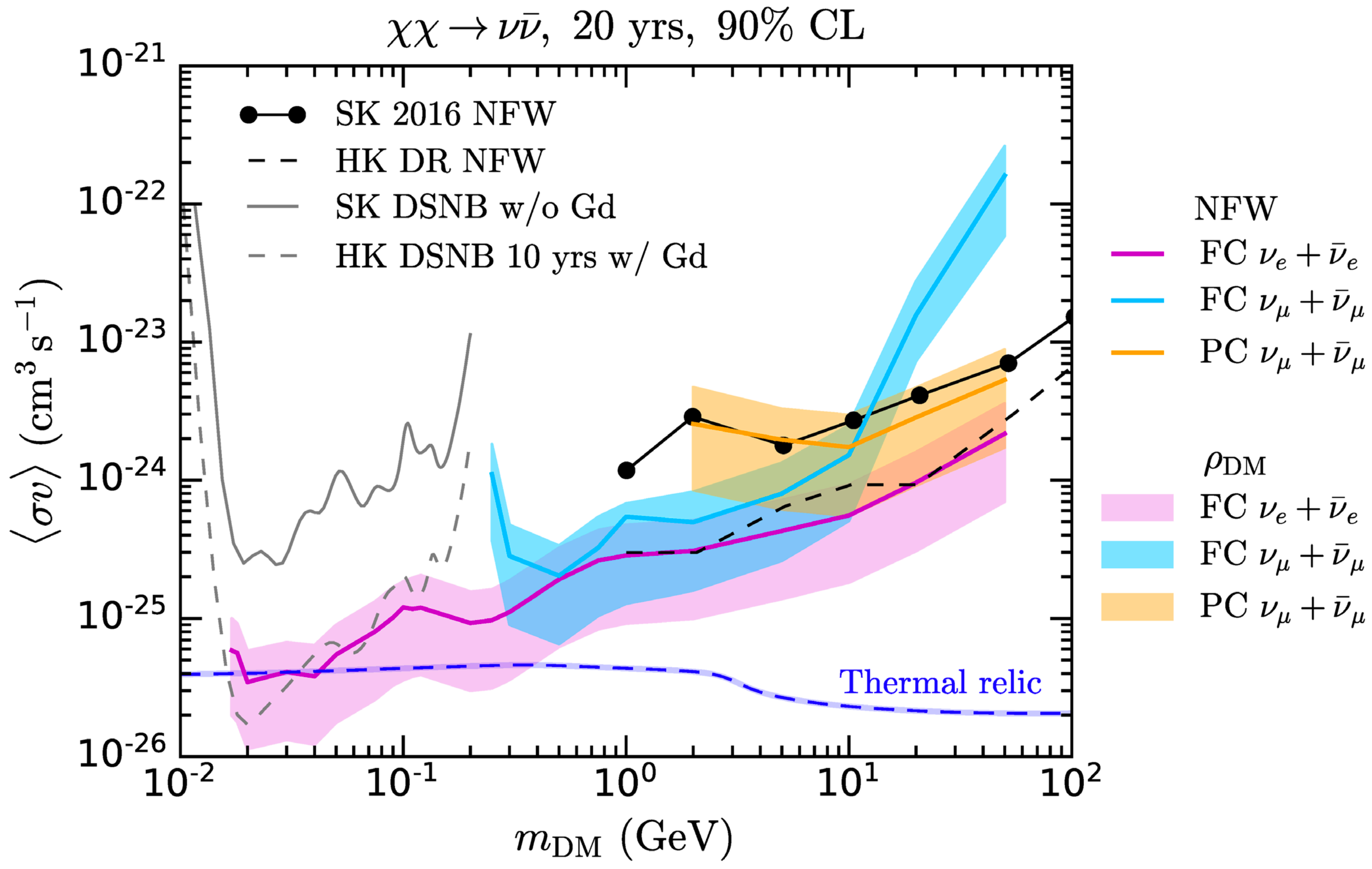
Integral of (density)^2 along line of sight

Spectrum per annihilation



NFB, Dolan, Robles, arXiv: 2005.01950

Annihilation cross section limits: $\chi\chi \rightarrow \nu\bar{\nu}$



Thermal relic sensitivity for DM mass of ~ 30 MeV

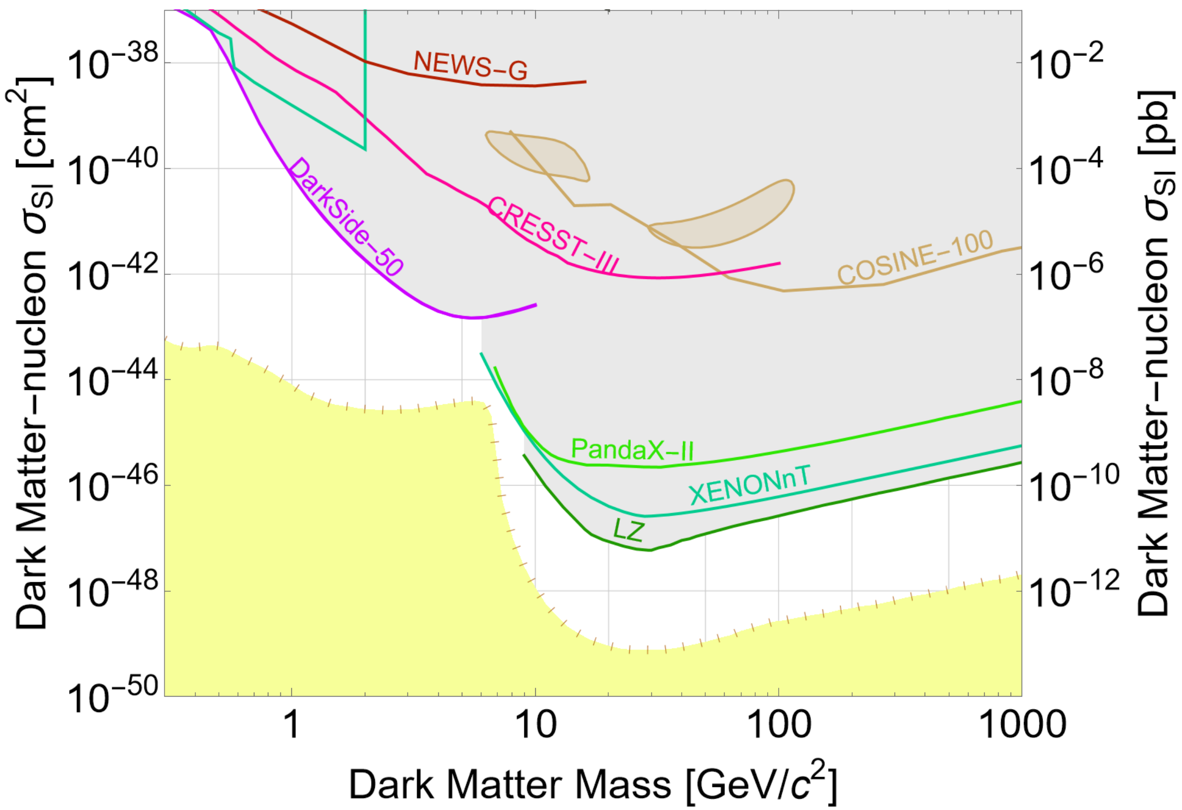
NFW – central lines
Isothermal – upper
Moore - lower

NFB, Dolan, Robles, arXiv: 2005.01950

Direct Detection limits

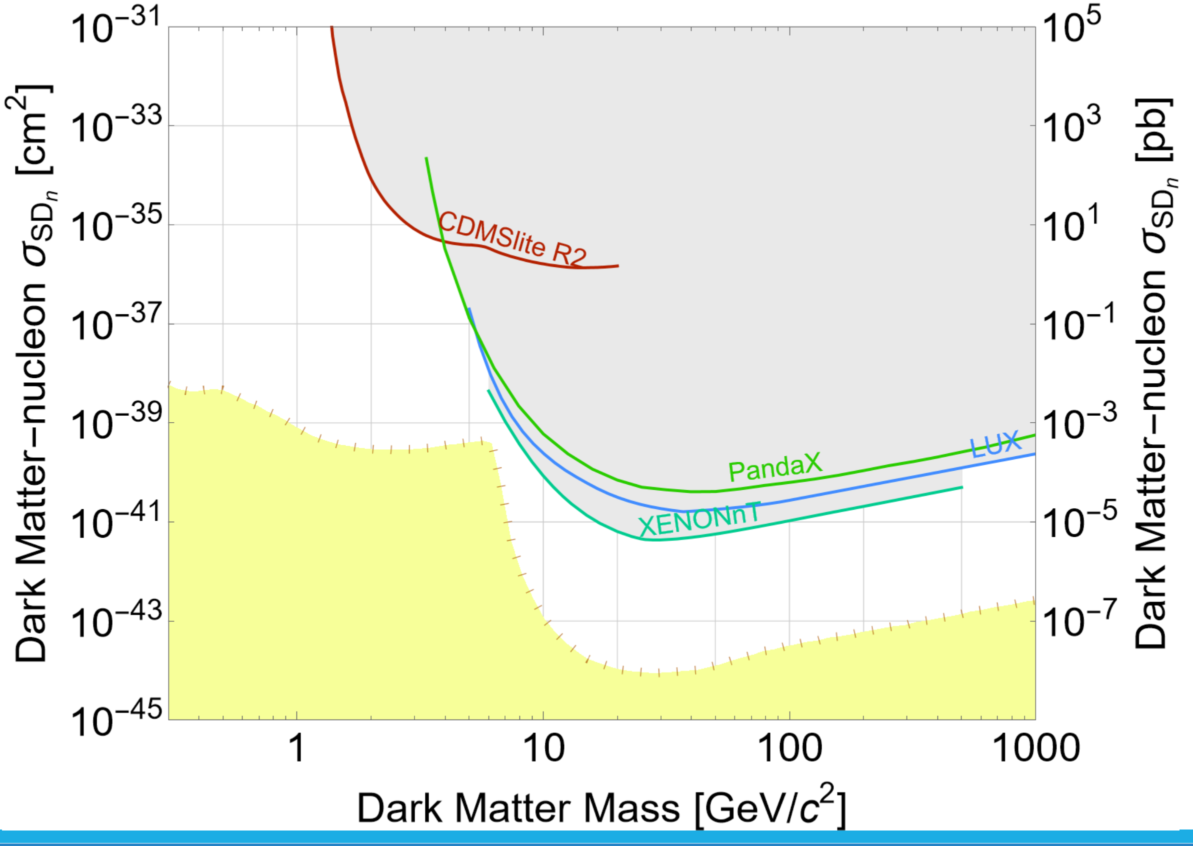
Spin-independent (SI) interactions

→ strong bounds due to coherent enhancement



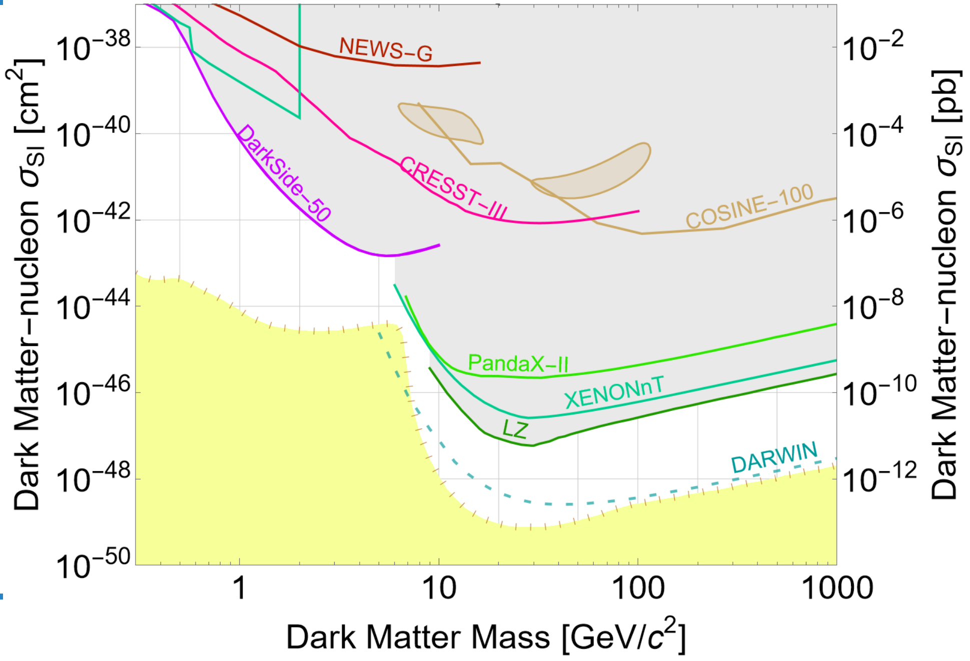
Spin-dependent (SD) interactions

→ weaker bounds



Dark matter direct detection - challenges

- We are approaching the "neutrino floor", where solar, atmospheric and supernova neutrinos are an irreducible background
  - Development of directional detection capabilities
    - CYGNUS experiment **(see talk by Lachlan McKie)**



- Low mass WIMPs have recoil signals below experimental thresholds
  - New, lower threshold experiments
  - New strategies for testing dark matter scattering

New strategies to probe dark matter scattering

- New analyses to probe lower mass dark matter <u>using existing detectors</u>
  - New signals in addition to or instead of nuclear recoil
    - Migdal effect, electron scattering
  - "Boosted" (i.e. more energetic) dark matter
    - Cosmic-ray upscattered dark matter, supernova dark matter, etc.

- Complementary constraints from <u>dark matter capture in stars</u>
  - Sun → detection of annihilation products
  - Neutron stars or white dwarfs → heating

➢ see talk by Matthew Dolan

Migdal effect

The ionization of an atom following a nuclear recoil

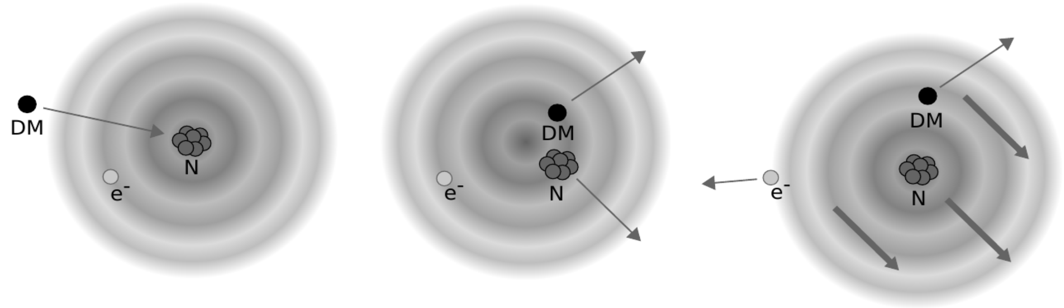


Image: M. Dolan et al.

→ Useful in cases where the nuclear recoil is below threshold (i.e., low mass dark matter) and we can instead detect the ionization signal

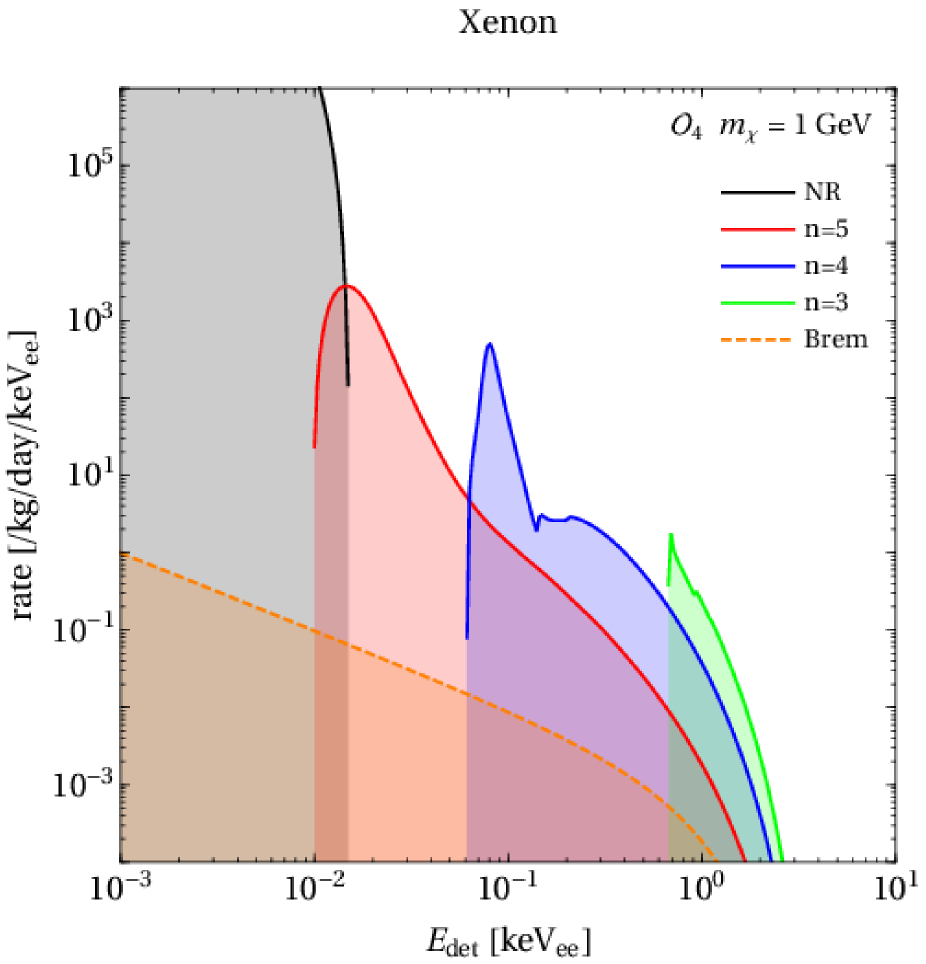
Nuclear recoil: $E_{R,max} = \frac{2\mu_T^2}{m_T} v_{max}^2$

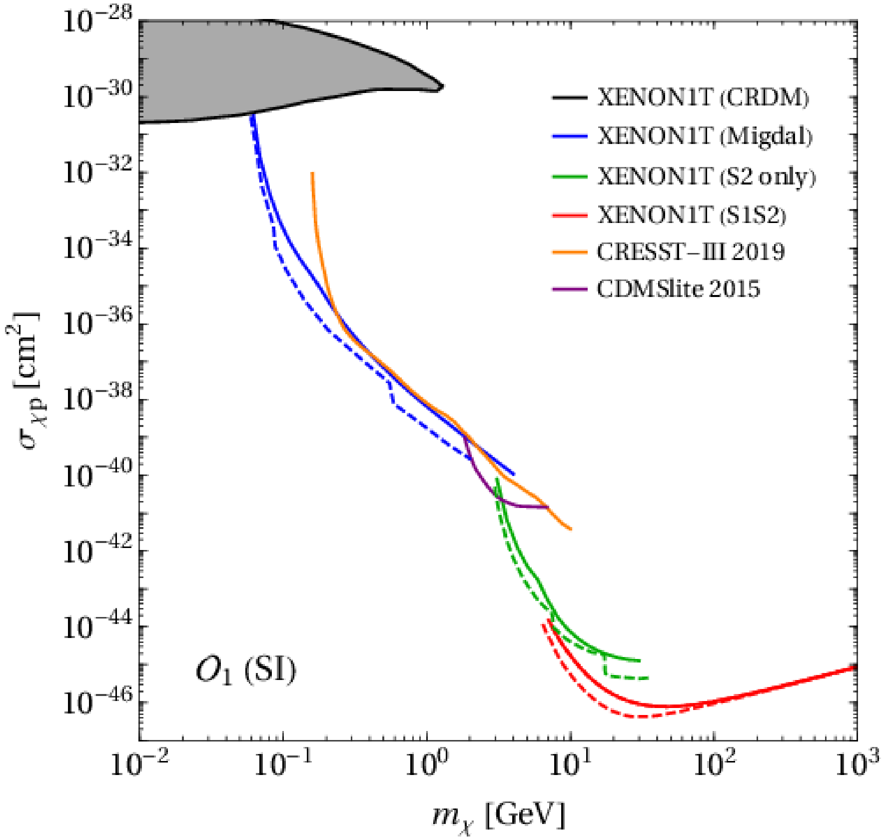
Migdal electrons: $E_{EM,max} = \frac{\mu_T}{2} v_{max}^2$

m_T = Target mass
μ_T = DM-nucleon reduced mass

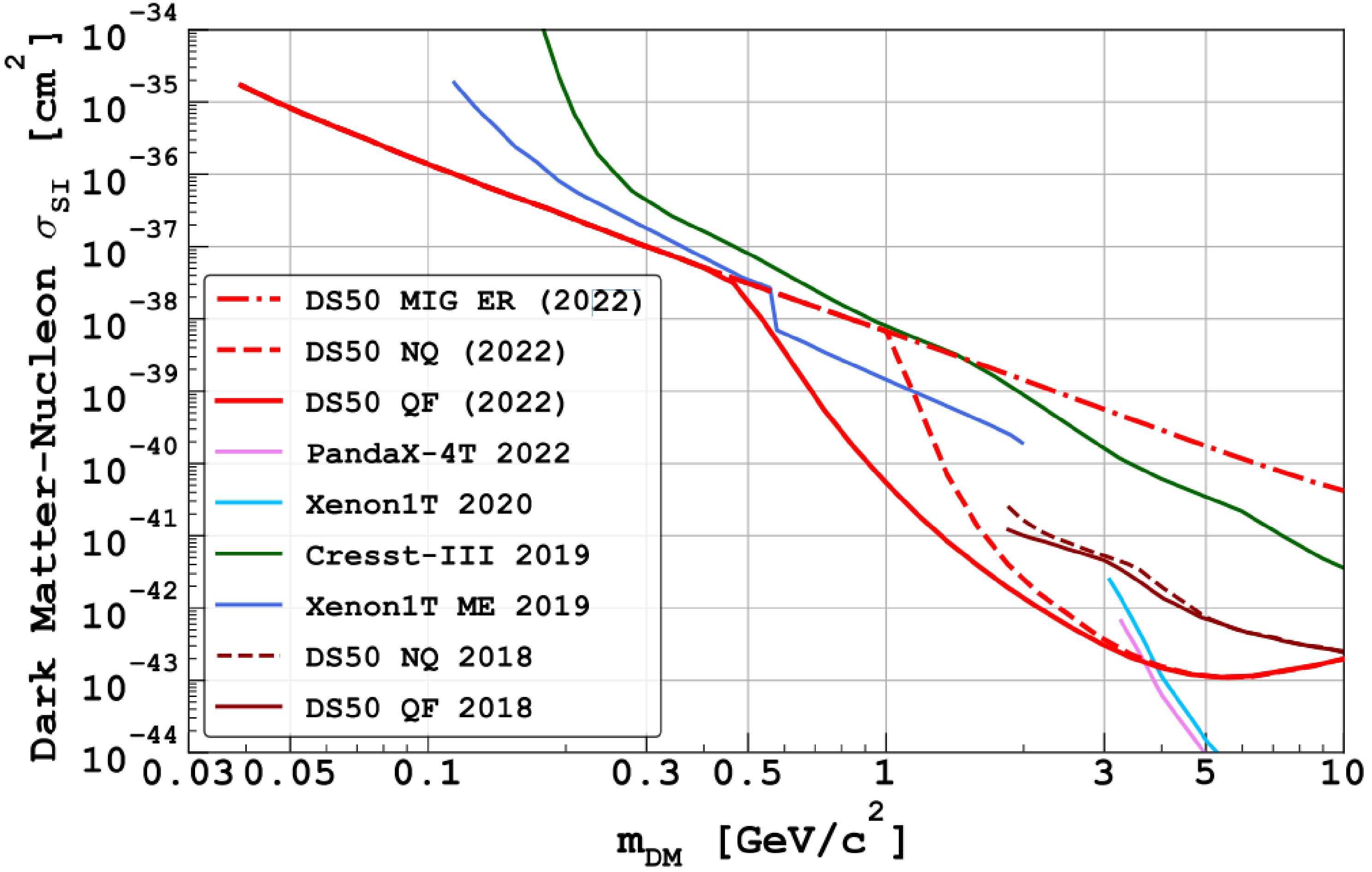
Migdal effect

NFB, Dent, Newstead, Sabharwal, Weiler, arXiv:1905.00046





Migdal limits



Migdal limits from DarkSide experiment arXiv:2207.11967

Doping the detector with a lighter element

e.g. Hydrodgen-doped liquid Xenon

→ Better kinematics for the scattering of light dark matter → Larger recoil energy → signal above threshold

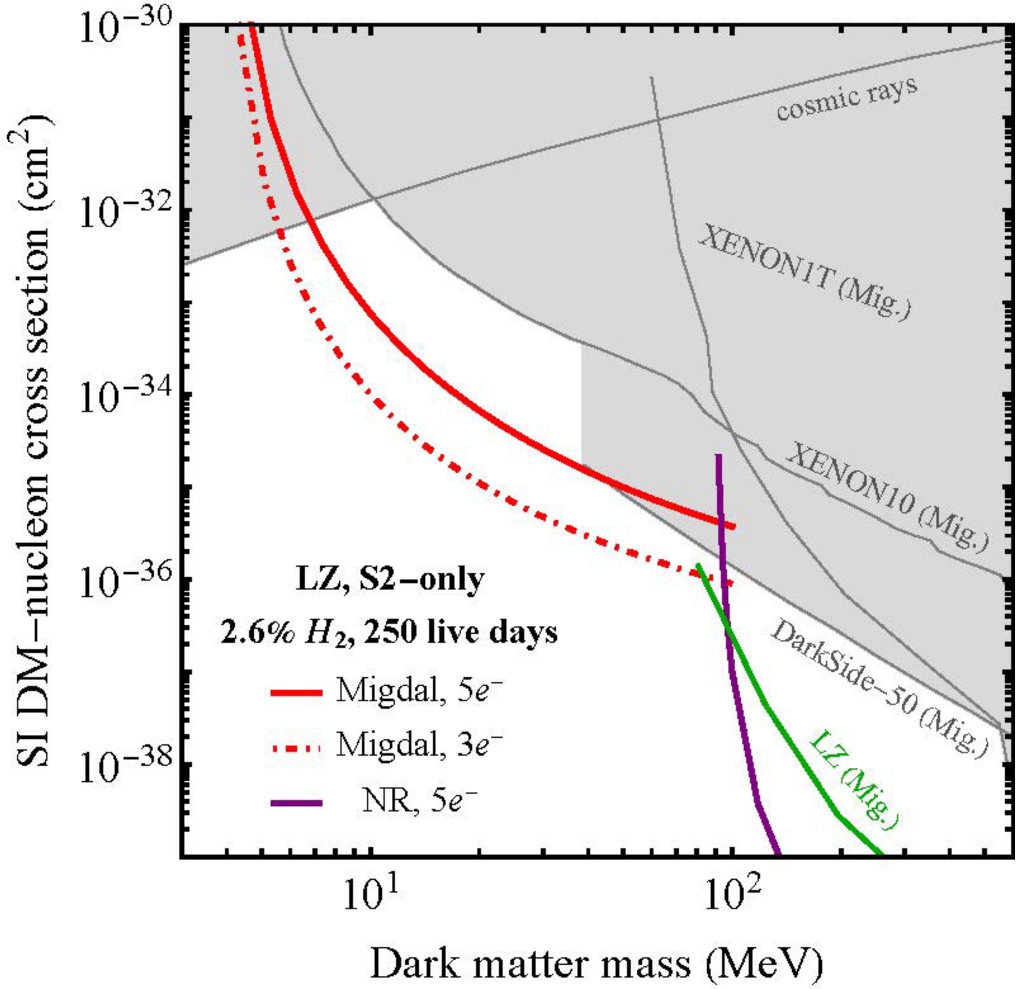
Specific proposal : HydroX = upgrade of LZ, by doping with H_2

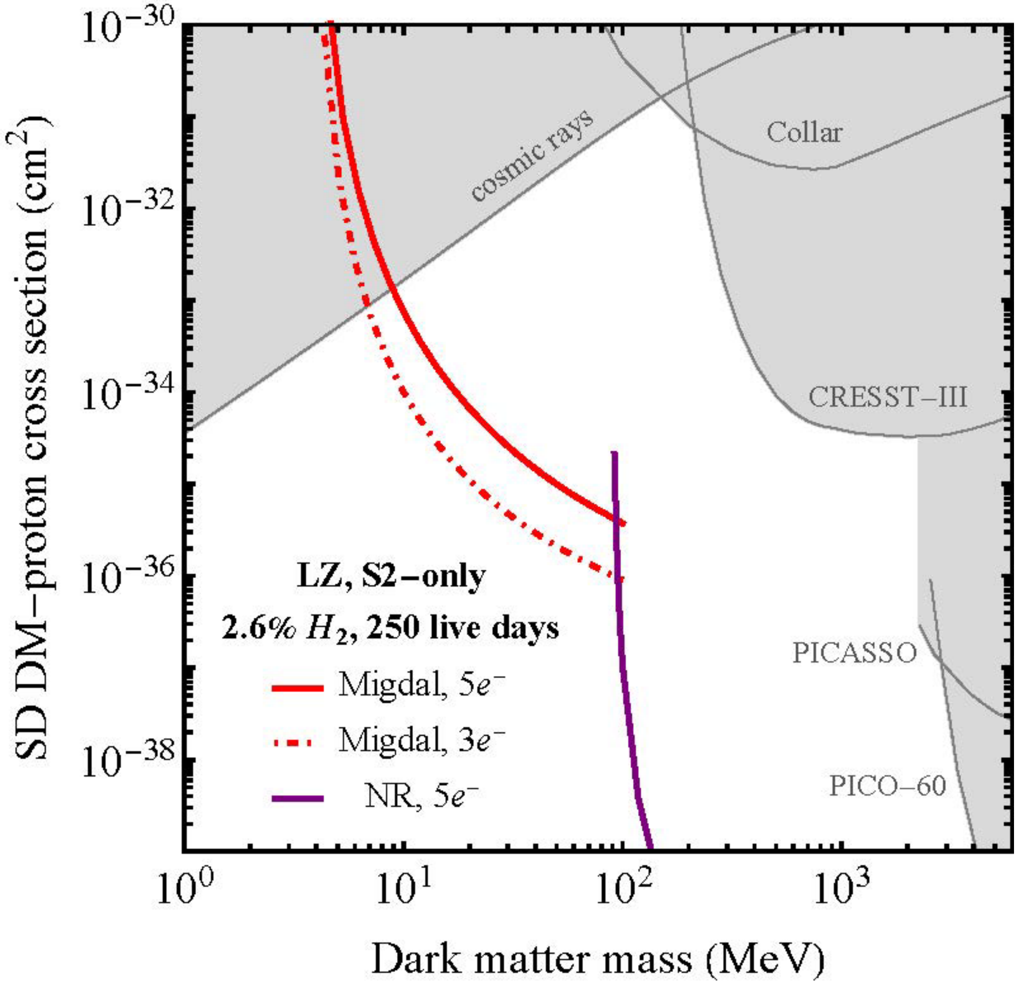
What if we combine (i) doping with light element and (ii) Migdal effect?

→ **The best sensitivity to light WIMPs**

Migdal effect in H-doped liquid Xenon

NFB, Cox, Dolan, Newstead, Ritter, arXiv:2305.04690





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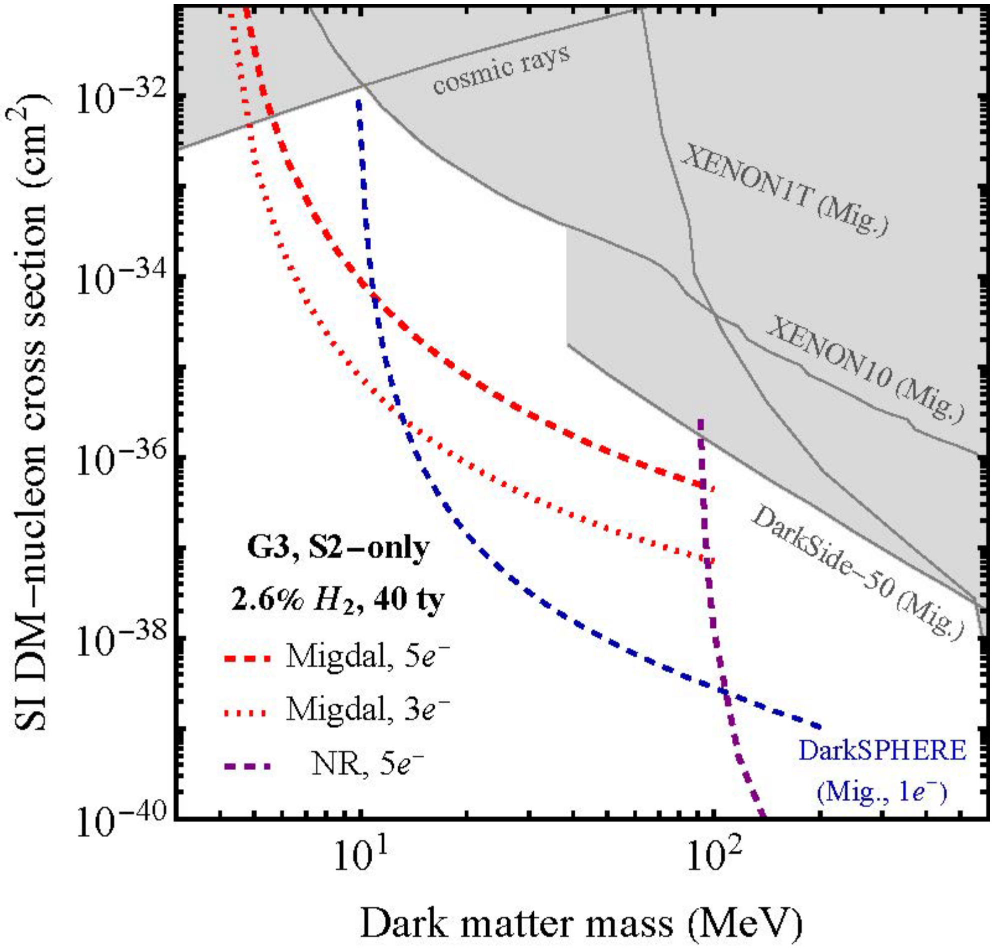
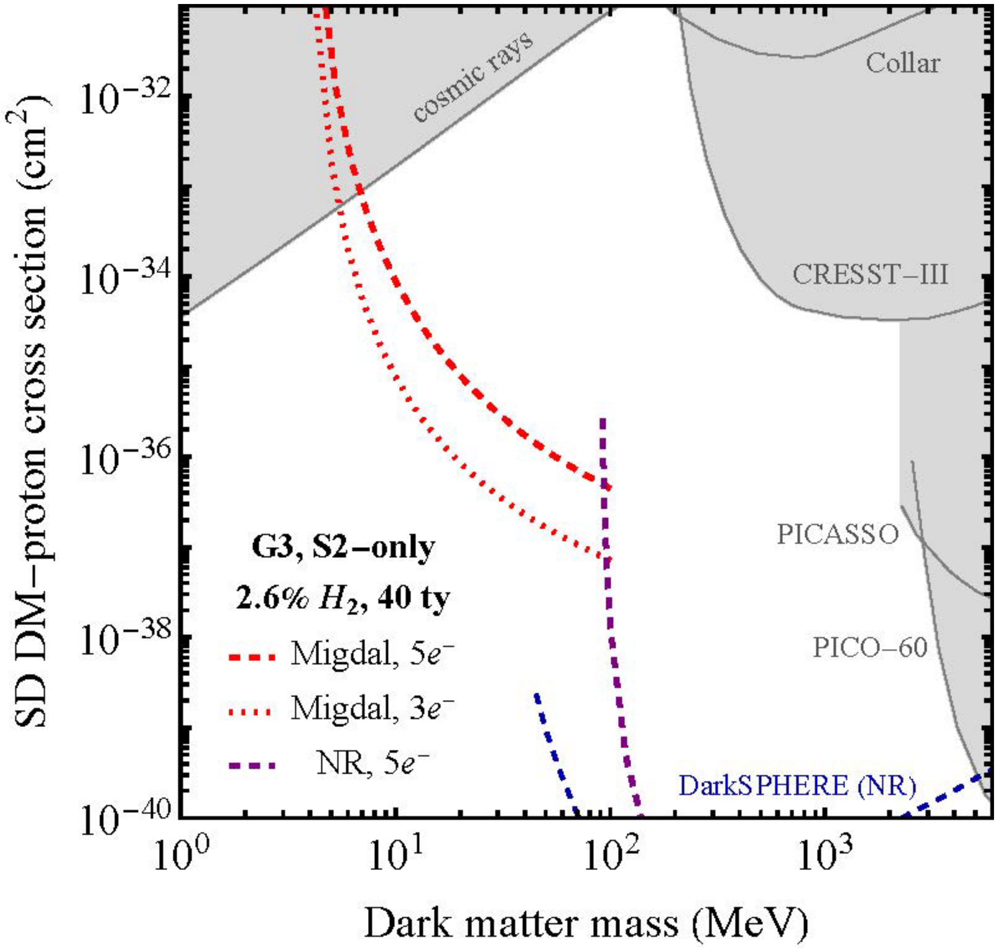
NFB, Cox, Dolan, Newstead, Ritter, arXiv:2305.04690





Boosted Dark Matter

Halo dark matter

→ highly nonrelativistic

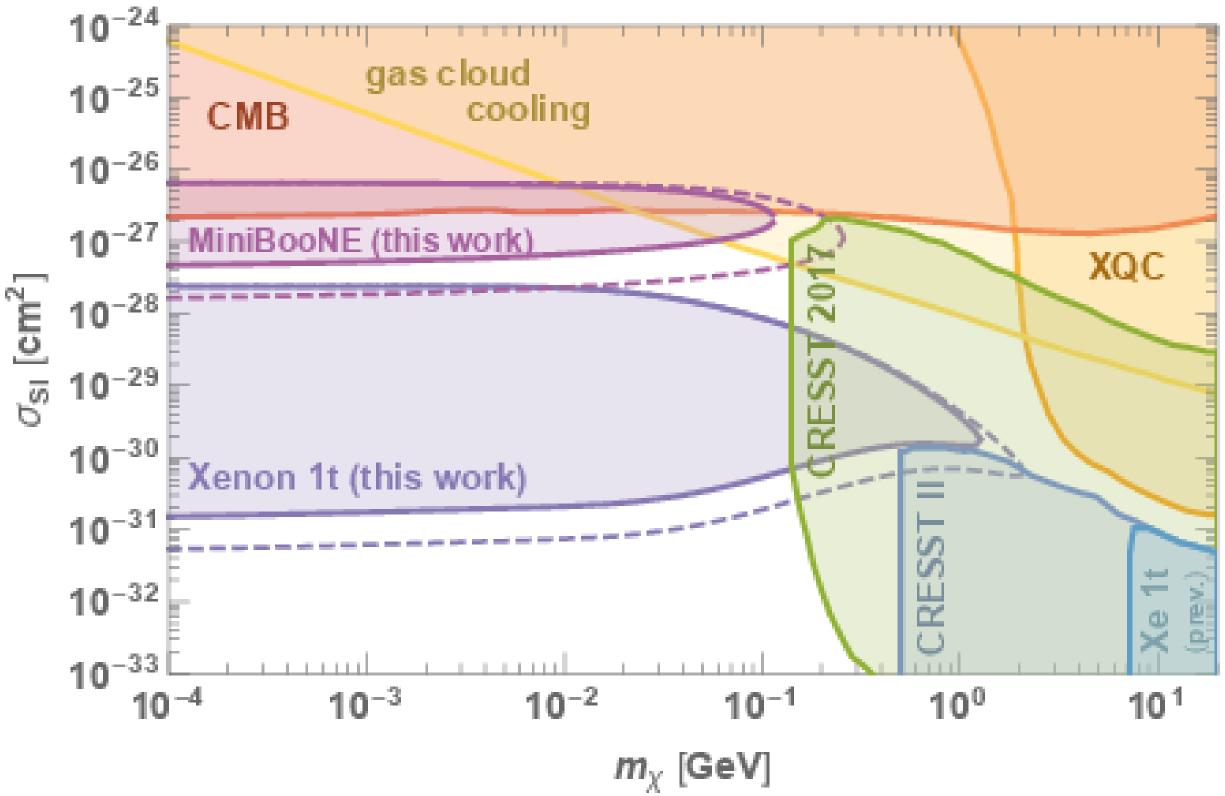
→ low energy nuclear recoils in direct detection experiments

Could there be a population of higher-energy dark matter?

- Boosted DM produced from decay/annihilation of heavier dark states
- Cosmic-ray upscattered dark matter ("inverse direct detection")
- DM produced in cosmic ray interactions in the atmosphere ("CR beam dump")
- Solar reflected dark matter
- Supernova dark matter (light dark matter produced in galactic supernova)

Cosmic ray up-scattered dark matter – sub-GeV masses

Bringmann & Pospelov, PRL 2019



Allows light dark to be constrained using existing experiments.

Note that dark matter absorption in the earth imposes upper limit on the cross sections that can be constrained.

Cosmic Ray up-scattered dark mater

Dent, Newstead et al, PRD 2020

Distinguishing heavy non-relativistic DM from light relativistic DM?

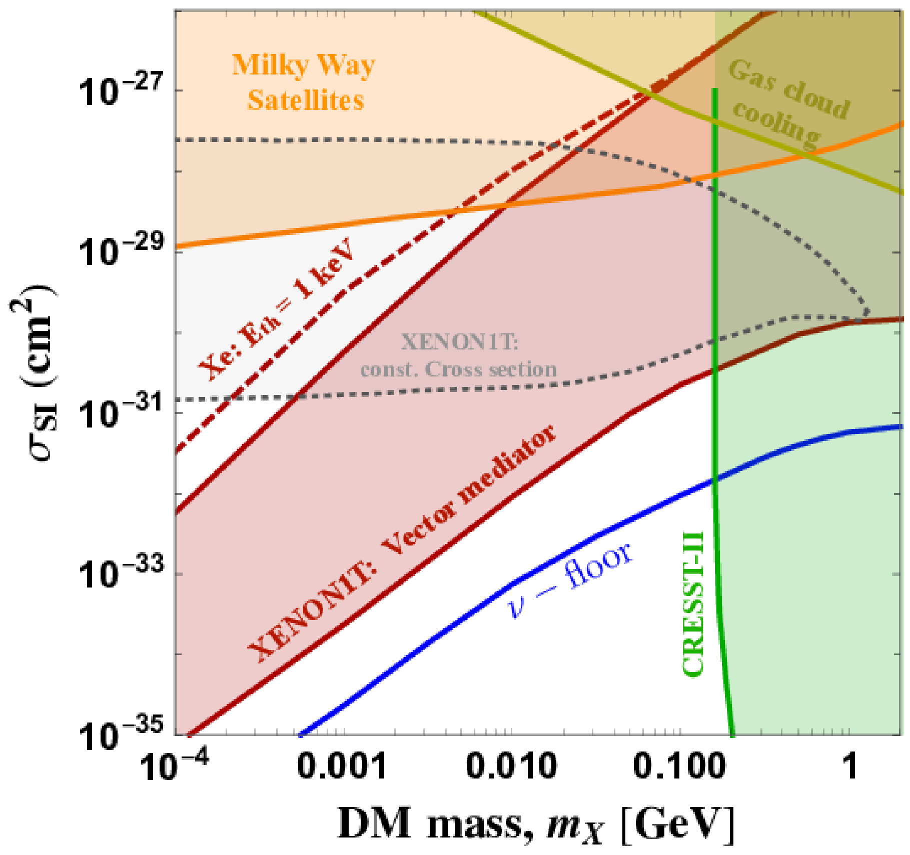
- Directional information would help

Very big cross-sections?

- Need light mediators

  → Energy dependence of cross section is important. (Dent et al)

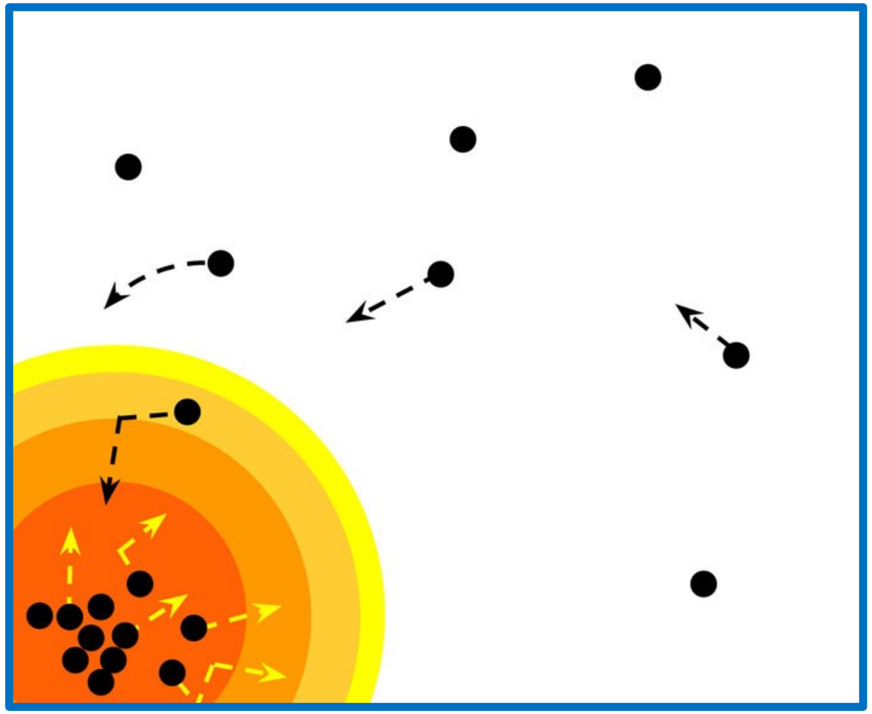
  → These limits are model dependent.



Dark Matter Capture in Stars

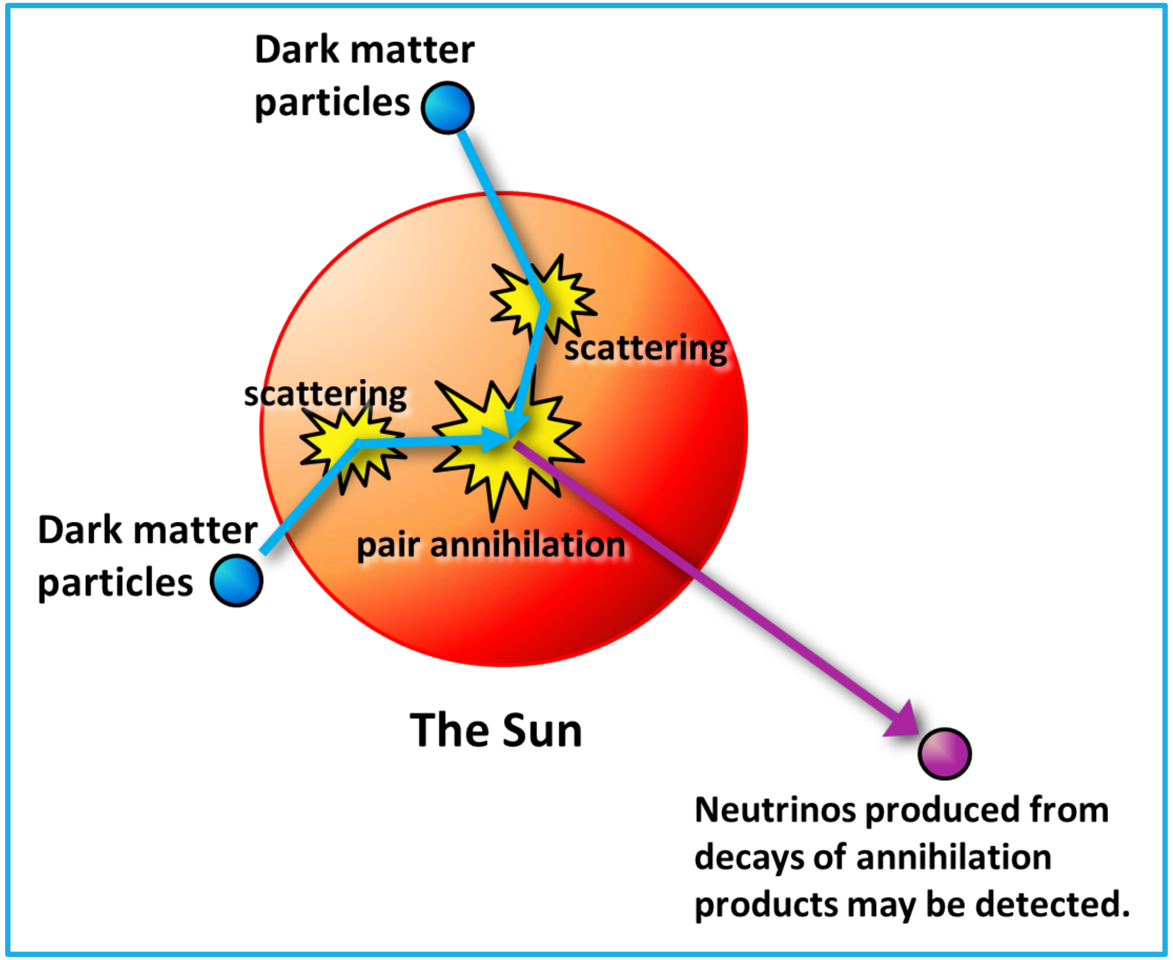
→ an alternative approach to Dark Matter Direct Detection experiments

- The Sun
- Neutron Stars
- White Dwarfs



Dark Matter Capture in Stars

→ *an alternative approach to Dark Matter Direct Detection experiments*



- Dark matter scatters, loses energy, becomes gravitationally bound to star
- Accumulates and annihilates in centre of the star → neutrinos escape

In equilibrium:

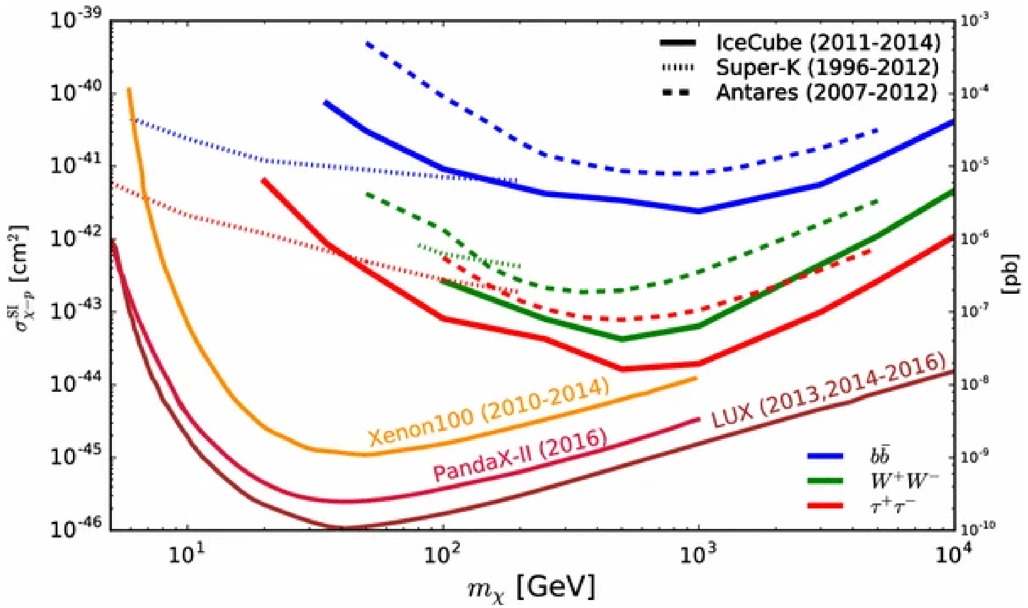
Annihilation rate = Capture rate

→ controlled by DM-nucleon scattering cross section

→ probes the same quantity as dark matter direct detection experiments

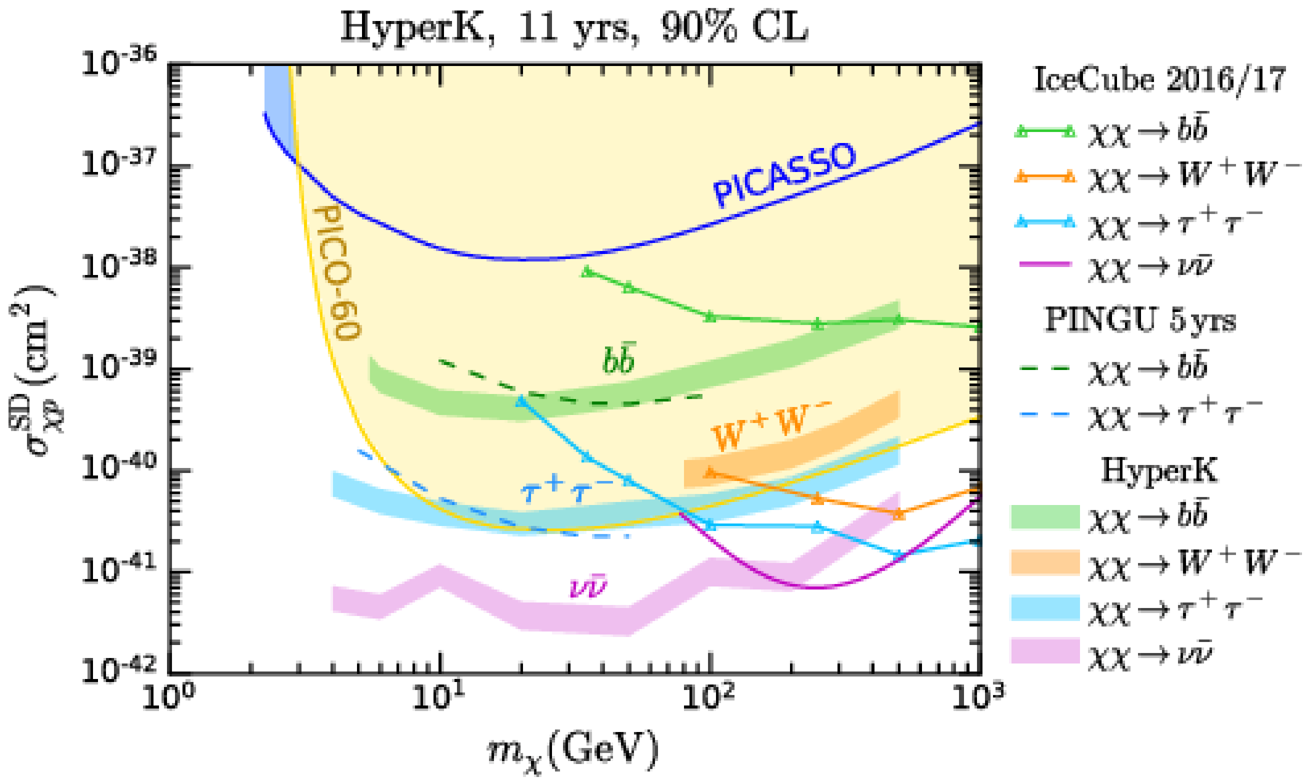
Dark matter annihilation in the Sun – Neutrinos

Spin-Independent (SI)



IceCube Collaboration, E. Phys. J. C 77 (2017)

Spin-Dependent (SD)

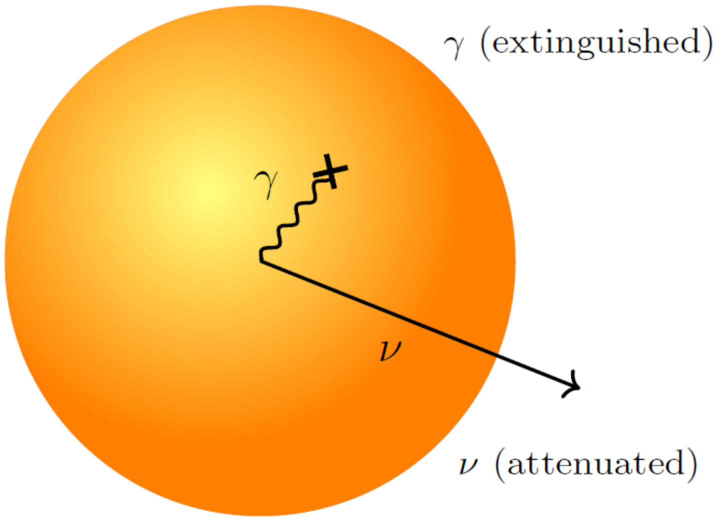


NFB, Dolan & Robles, arXiv:2107.04216

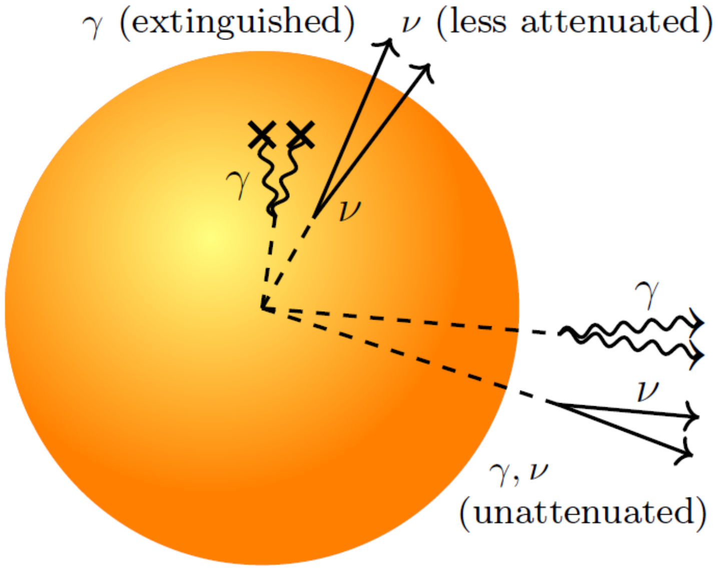
Gamma Rays from the Sun → long lived dark-sector particles

If captured DM annihilates to a light, long-lived mediator (e.g. a dark photon):

- Annihilation products can escape the Sun
- Decay between Sun and Earth → solar gamma rays or cosmic rays (Batell arXiv:0910.1567)
- Decay beyond solar core → less attenuation of neutrino signal (NFB & Petraki, JCAP 2011)



Short-lived mediators



Long-lived mediators

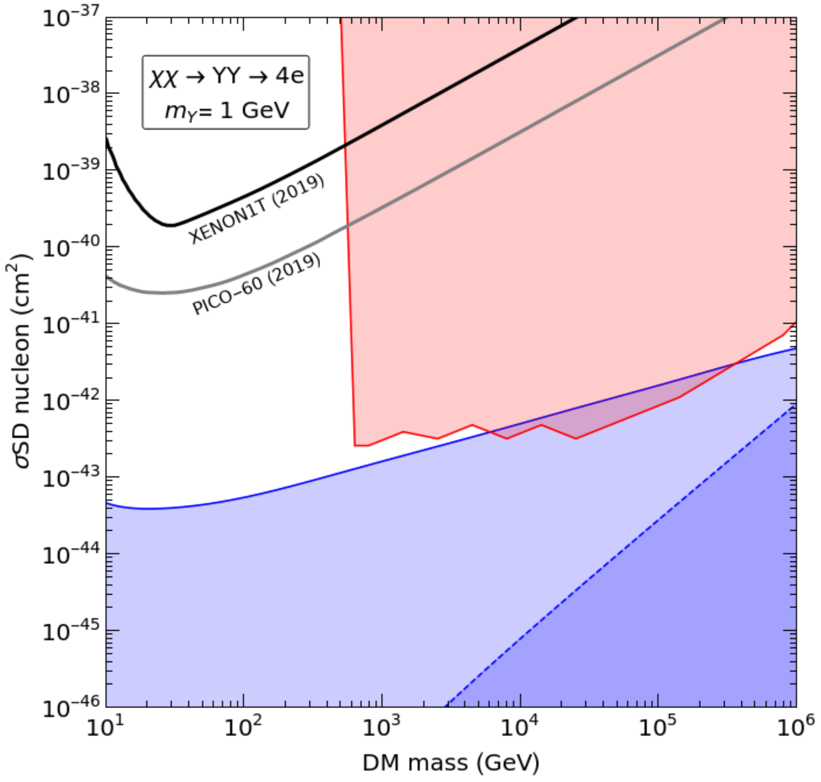
Leane, Ng & Beacom, arXiv:1703.04629

Gamma Rays from the Sun

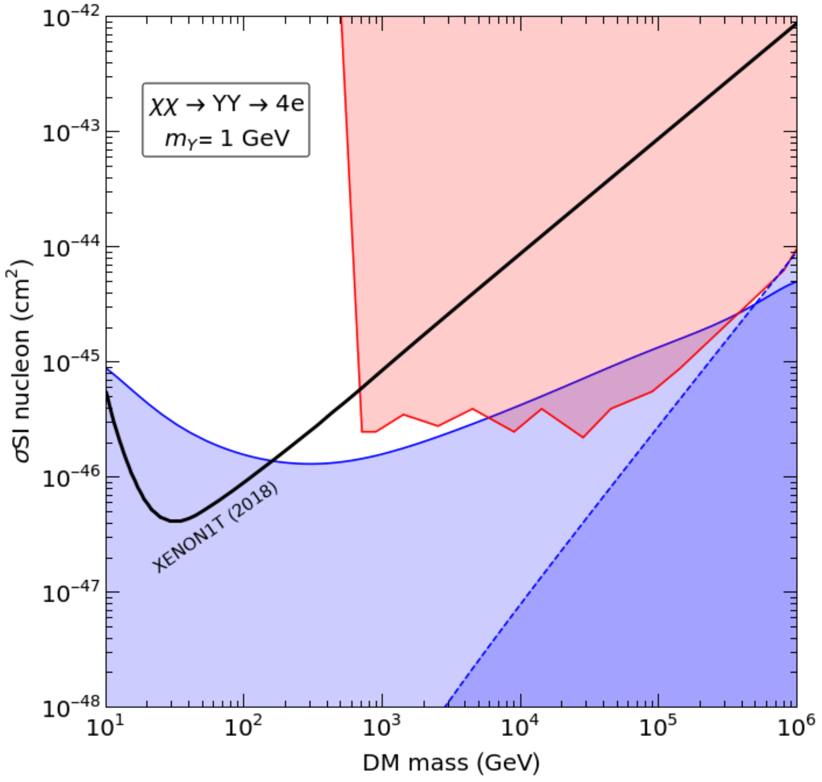
NFB, Dent & Sanderson, arXiv:2103.16794, PRD 2021

HAWC gamma ray measurements provide strong constraints, for both spin-dependent *and* spin-independent scattering

Spin-Dependent (SD)



Spin-Independent (SI)

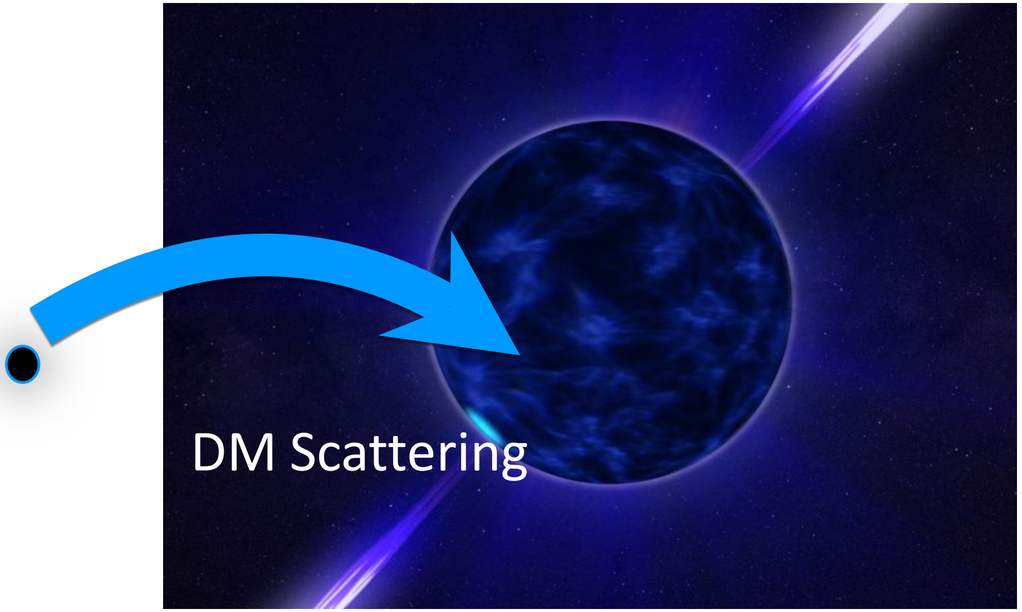


Neutron Stars

Due to their extreme density, ***neutron stars*** capture dark matter ***very*** efficiently.

Capture probability saturates at order unity when the cross section satisfies the **geometric limit**

$$\sigma_{th} \sim \pi R^2 \frac{m_n}{M_*} \sim 10^{-45}\mathrm{cm}^2$$



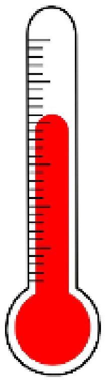
- **see talks by Michael Virgato and Giorgio Busoni**

Neutron star heating

→ from dark matter scattering plus annihilation

- **Capture** (plus subsequent energy loss)
  → DM ***kinetic energy*** heats neutron star ~ **1700K** (Baryakhtar et al)

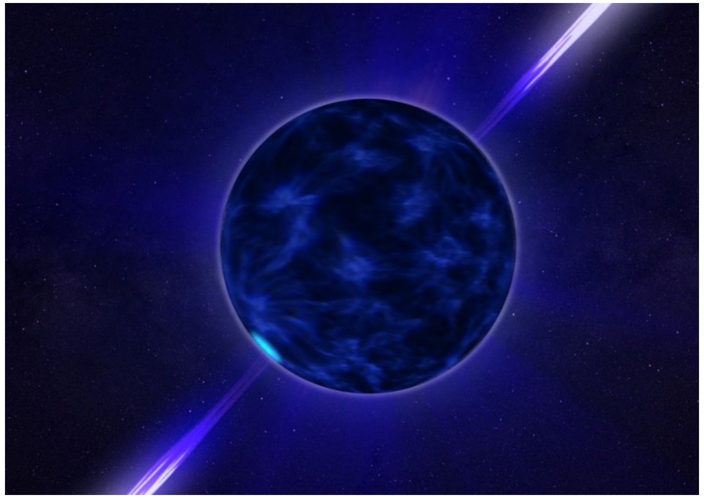
- **Annihilation** of thermalised dark matter
  → DM ***rest mass energy*** heats neutron star ~ **additional 700K**



Coolest known neutron star (PSR J2144-3933) has a temperature of ~ 4.2 x 10^4 K.

Old isolated neutron stars should cool to: 1000 K after ~ 10 Myr
100 K after ~ 1 Gyr

DM capture in Neutron Stars



Completely different kinematic regime to direct detection experiments, because DM is quasi-relativistic upon infall to the NS:

- **No velocity/momentum suppression**

  → ***Sensitivity to interactions that direct detection experiment will <u>never</u> be able to probe***

- **Must take momentum dependence of hadronic couplings into account**

$$c_n(q) = \frac{c_n(0)}{\left(1 - q^2/Q_0^2\right)^2} \quad \text{with } Q_0 \sim 1 \text{ GeV}$$

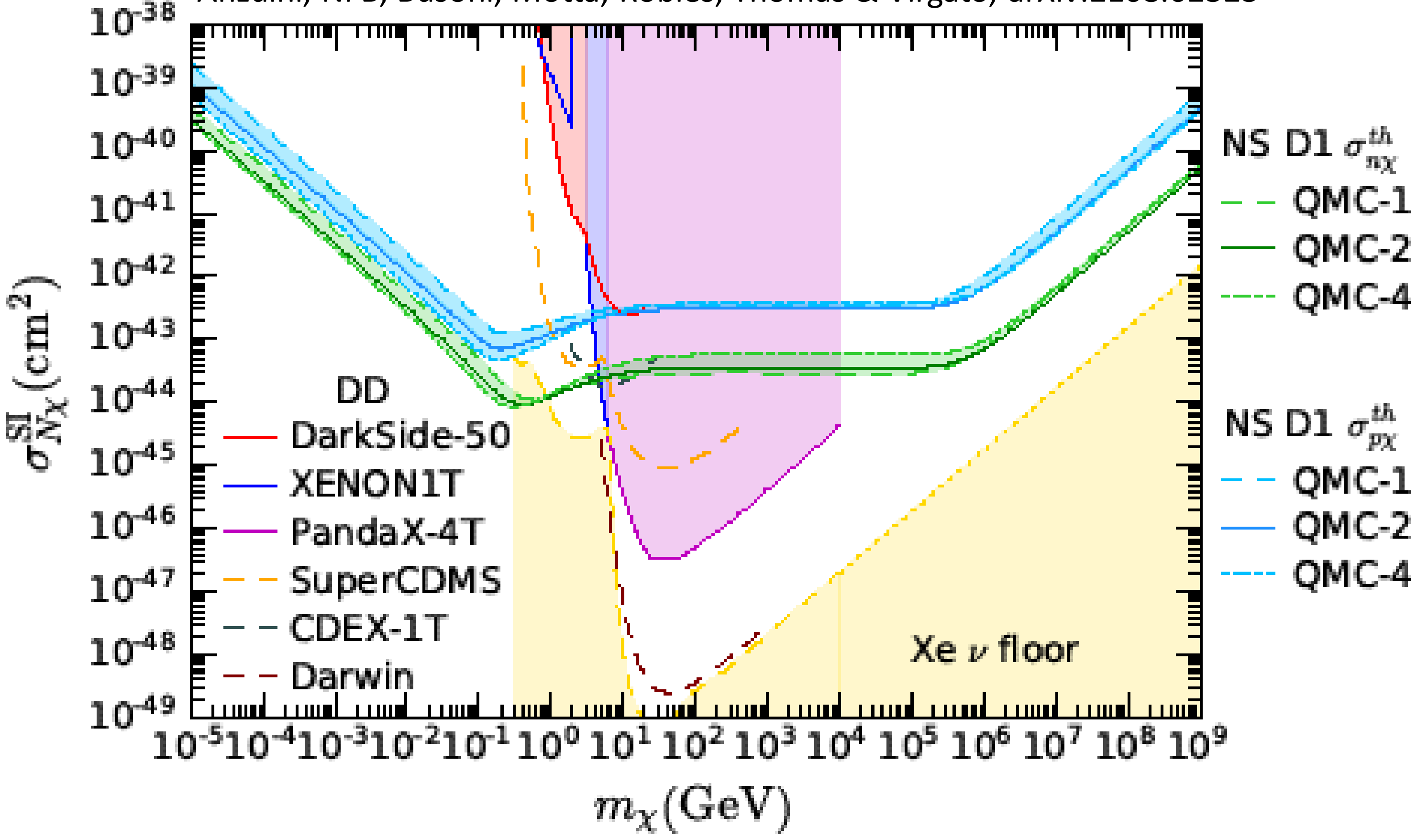
→ which changes the capture rate by several orders of magnitude

NFB, Busoni, Motta, Robles, Thomas, Virgato, PRL 2021

NS Heating Sensitivity (projected limits)

Ball-park sensitivity
= geometric
cross section
$\sim 10^{-45}\text{cm}^2$

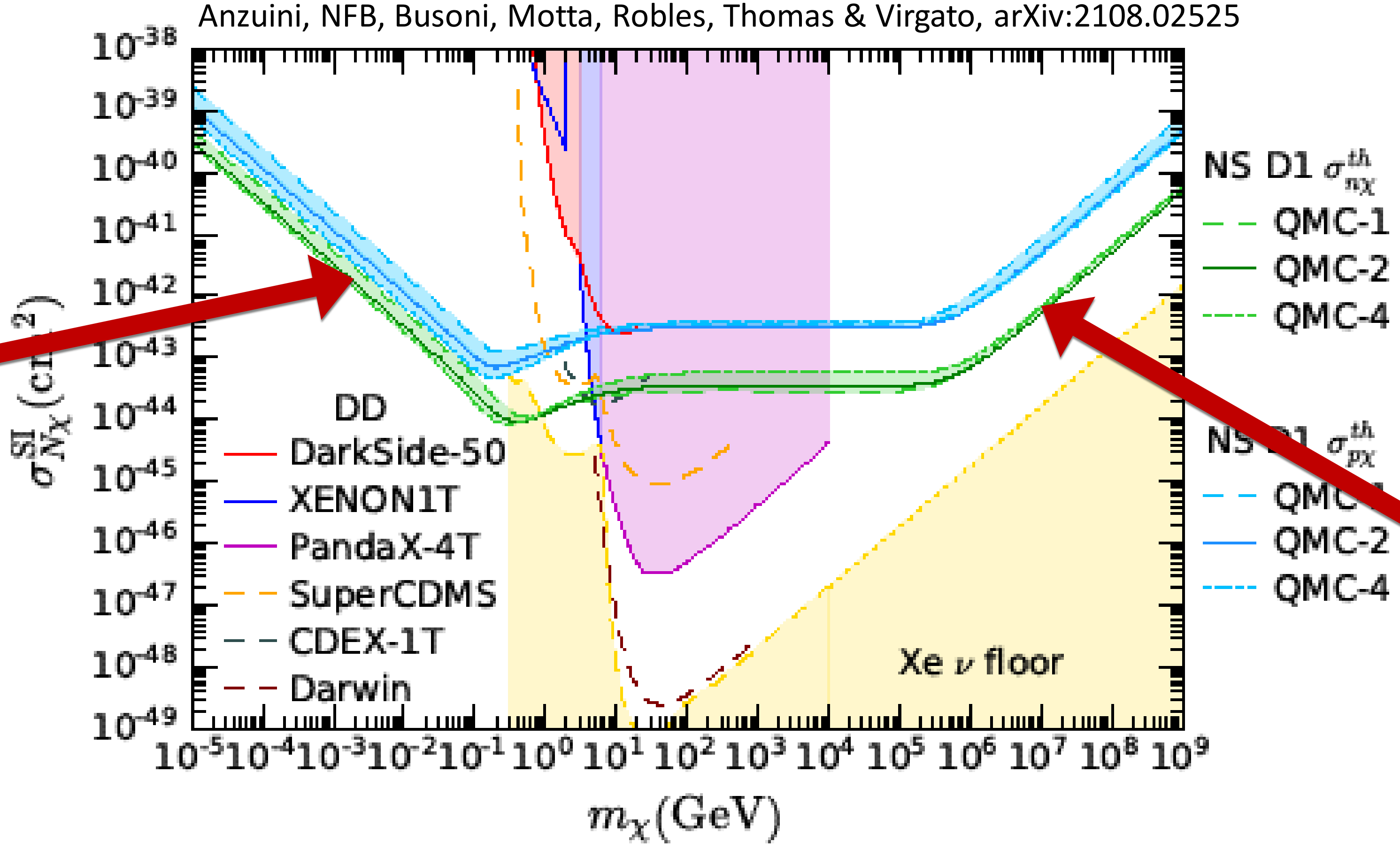
Anzuini, NFB, Busoni, Motta, Robles, Thomas & Virgato, arXiv:2108.02525



NS Heating Sensitivity (projected limits)

Ball-park sensitivity = geometric cross section $\sim 10^{-45}\mathrm{cm}^2$

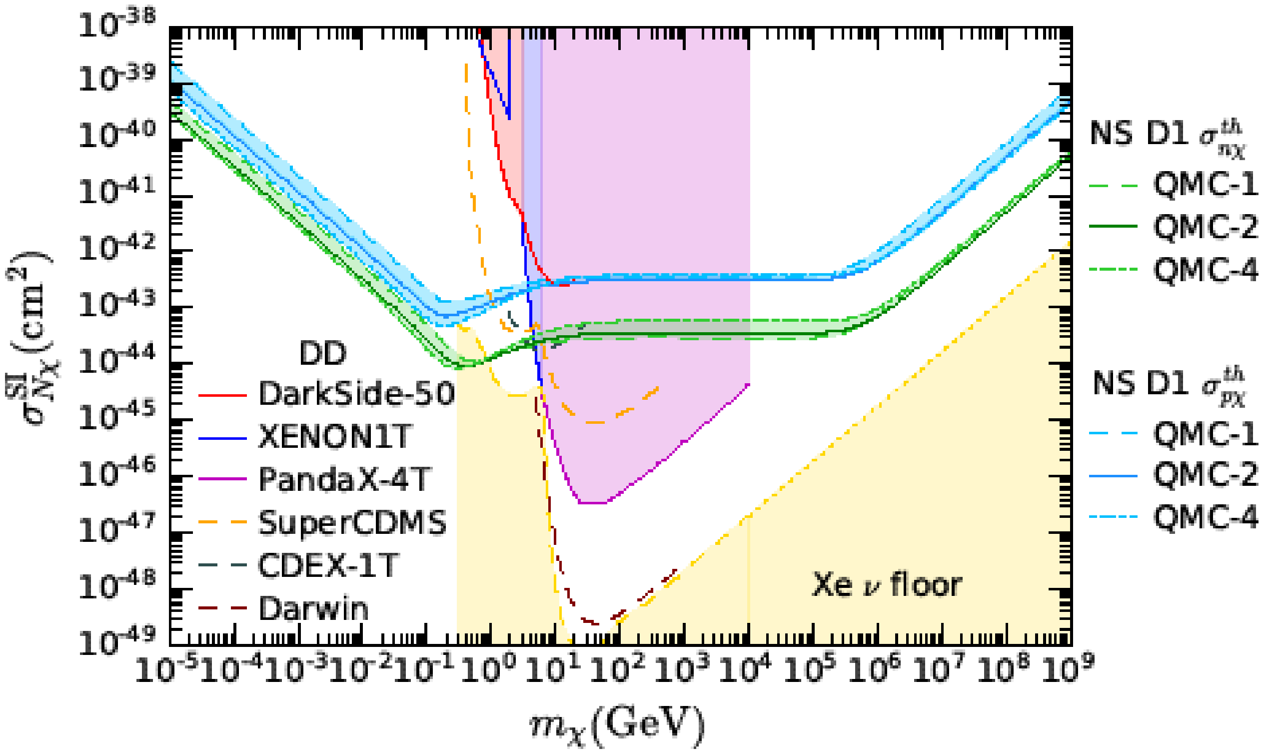
Pauli blocking from degenerate neutrons



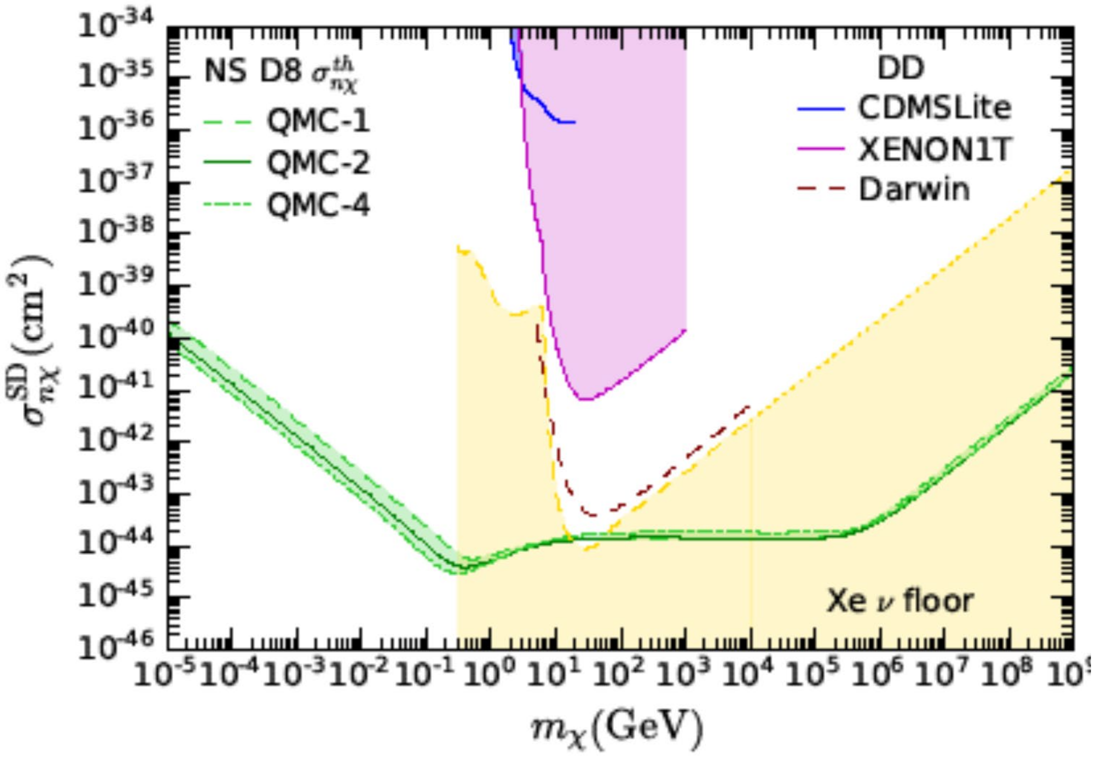
Momentum transfer in single collision not sufficient for capture

NS Heating Sensitivity: nucleon scattering

Spin-Independent (SI)

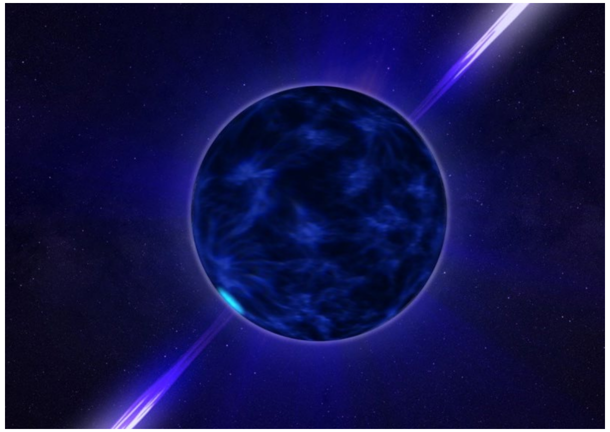


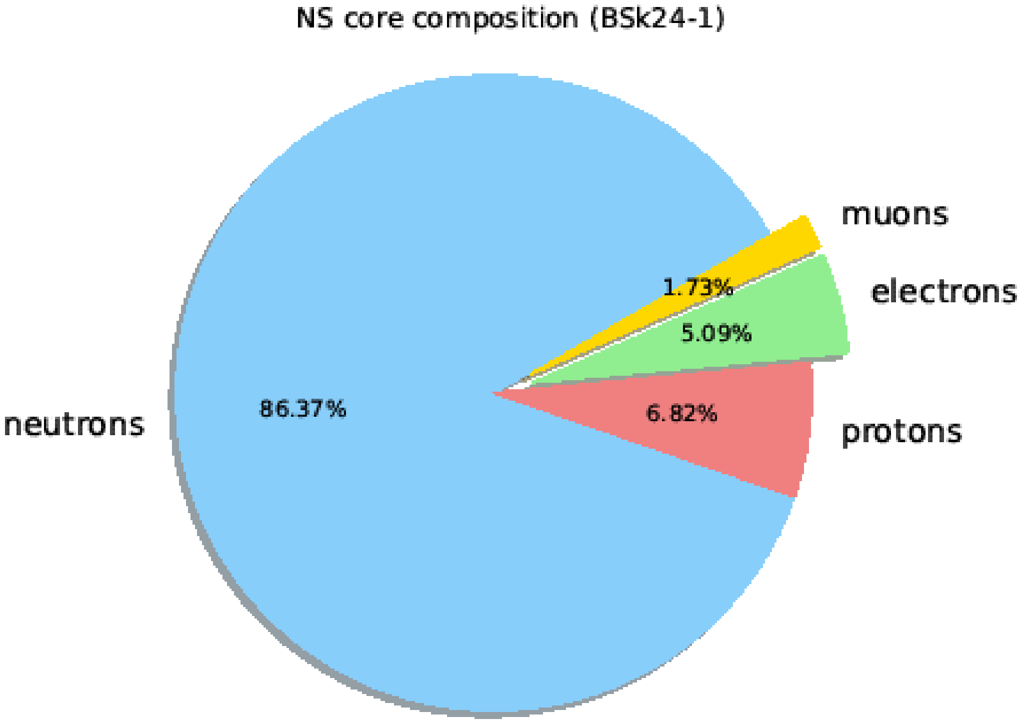
Spin-Dependent (SD)



Anzuini, NFB, Busoni, Motta, Robles, Thomas and Virgato, arXiv:2108.02525

Leptons in Neutron Stars

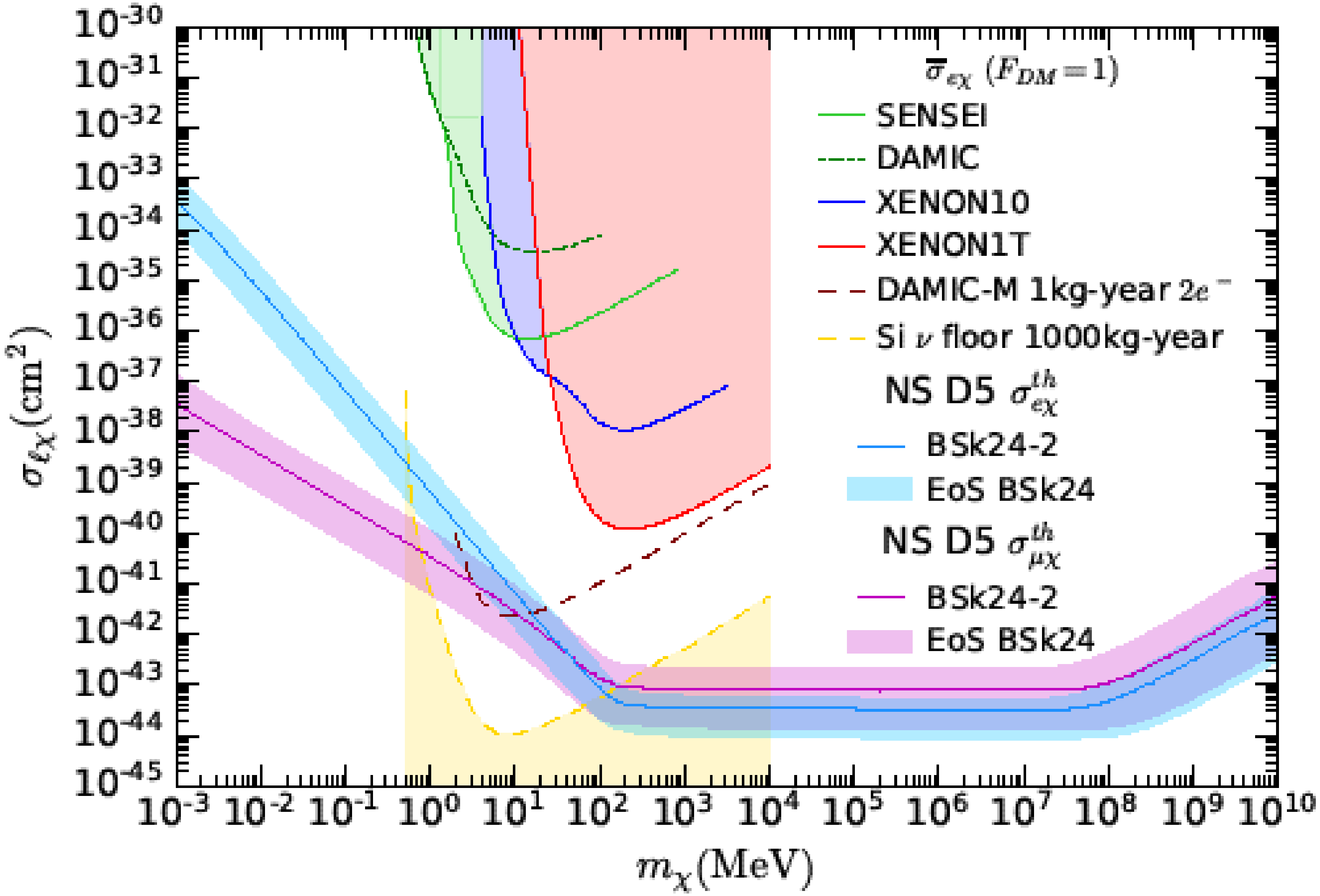




Beta equilibrium in the core determines the composition:

- Degenerate neutrons
- Smaller and approximately equal electron and proton abundances
- Small muon component

NS Heating Sensitivity: lepton scattering



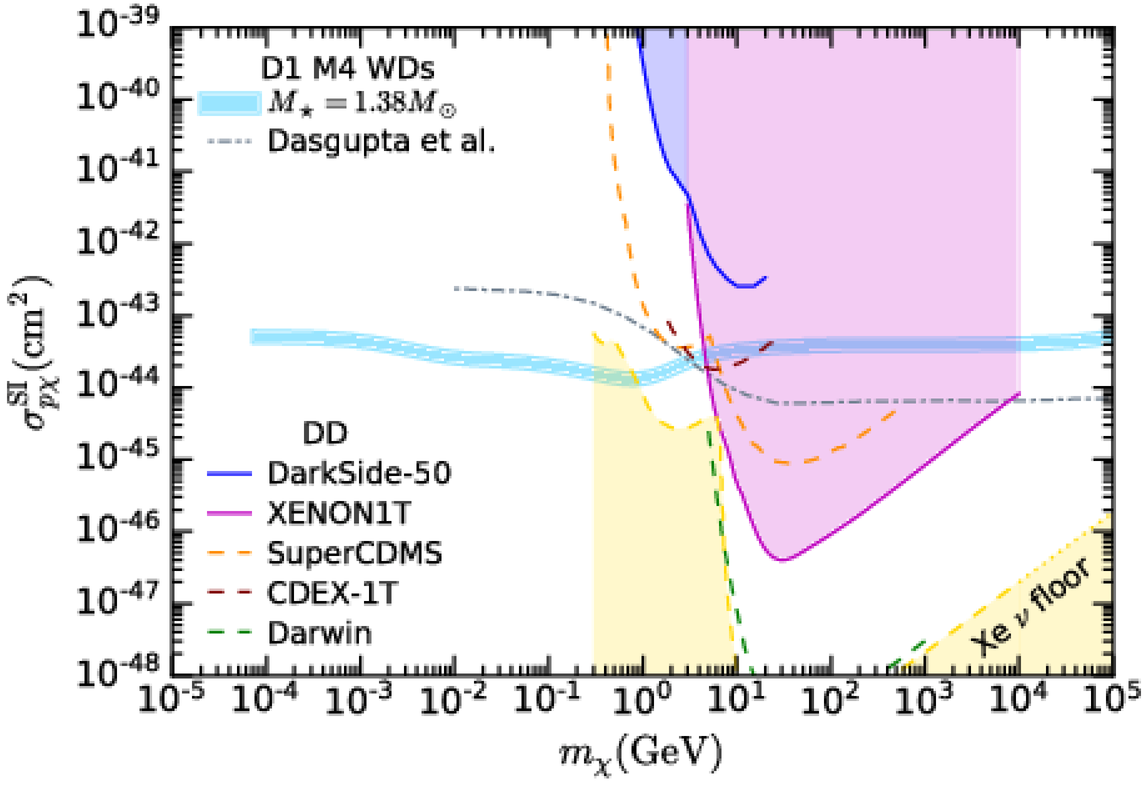
NFB, Busoni, Robles & Virgato arXiv:2010.13257

Muon scattering

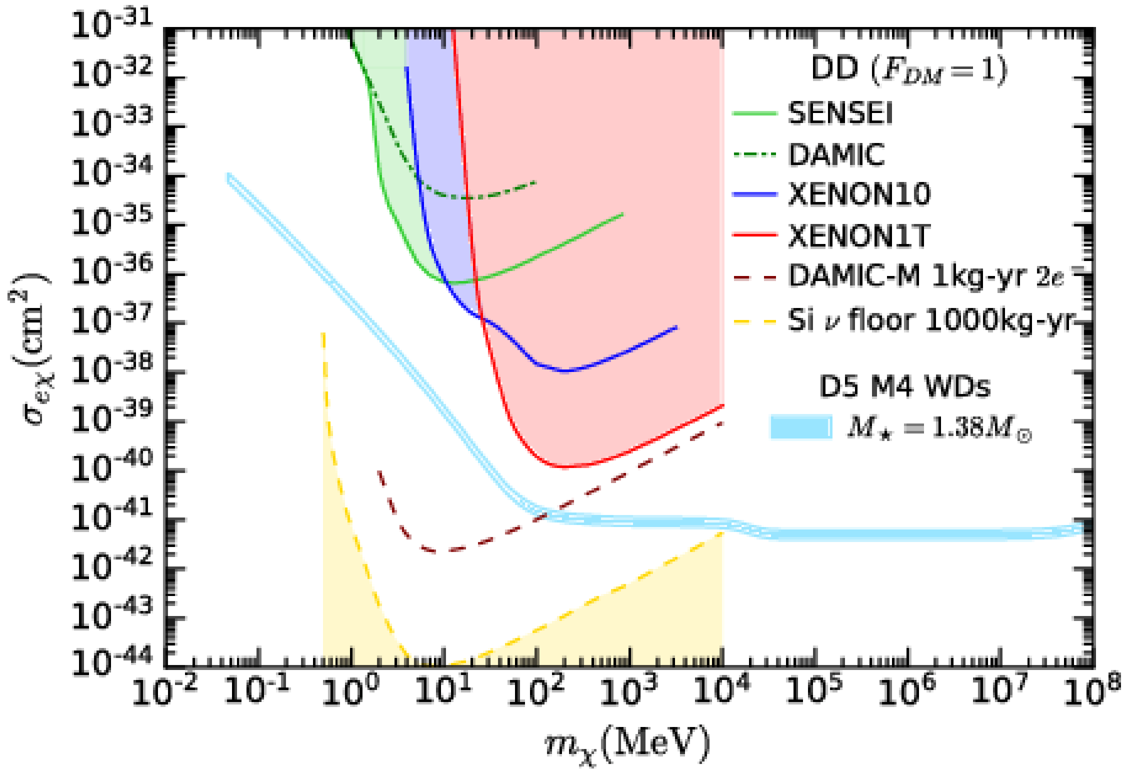
Electron scattering

White dwarfs in M4 globular cluster

DM-nucleon scattering



DM-electron scattering



NFB, Busoni, Ramirez-Quezada, Robles & Virgato, arXiv:2104.14367

Summary

Quite some way to go in testing the thermal WIMP hypothesis.
- Couplings to neutrinos hardest to test.

Direct detection of low mass WIMPs
- Migdal effect
- Doping of detectors with lighter elements
- Boosting dark matter to higher energies (e.g. cosmic ray scattering)

Dark matter capture in stars
- Can probe low mass WIMPs, and look below the neutrino floor