Overview of Dark Matter

– Perspectives on WIMPs

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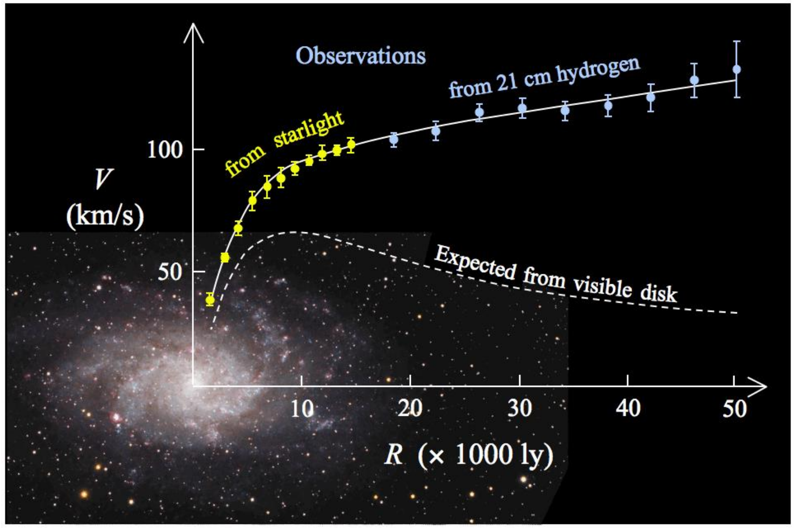
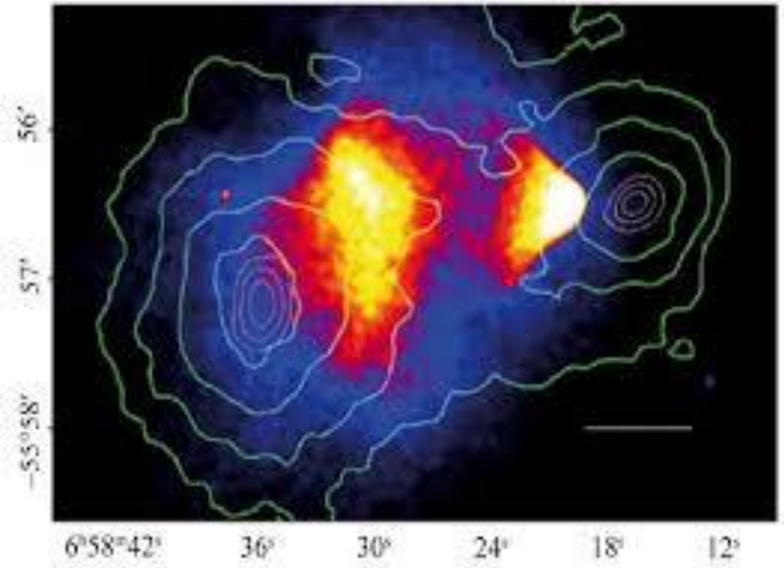
ARC CENTRE OF EXCELLENCE FOR DARK MATTER PARTICLE PHYSICS

Evidence for dark matter

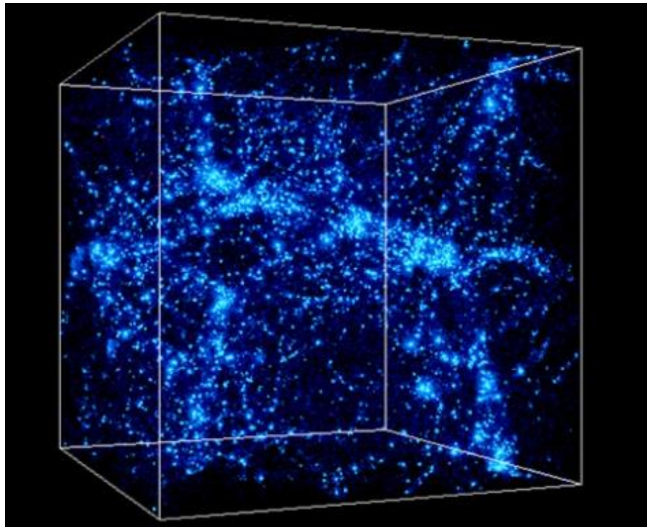
Astrophysical observations consistently point to the need for dark matter



Galaxy rotation curves



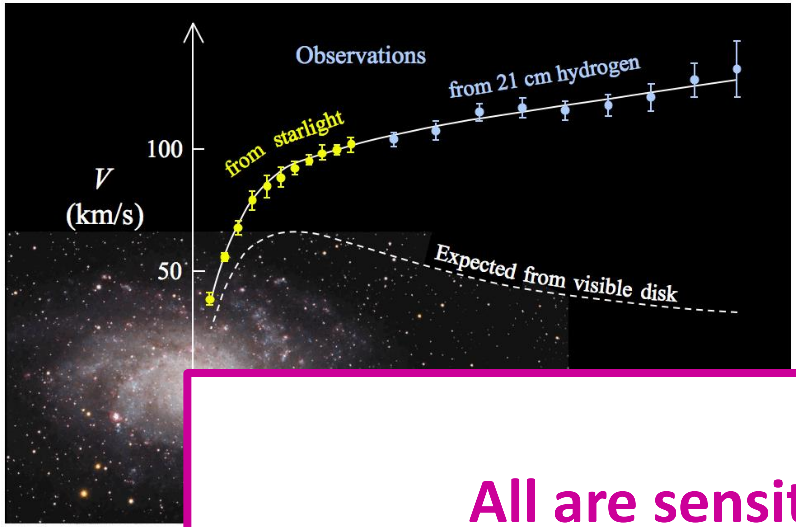
Clusters of galaxies

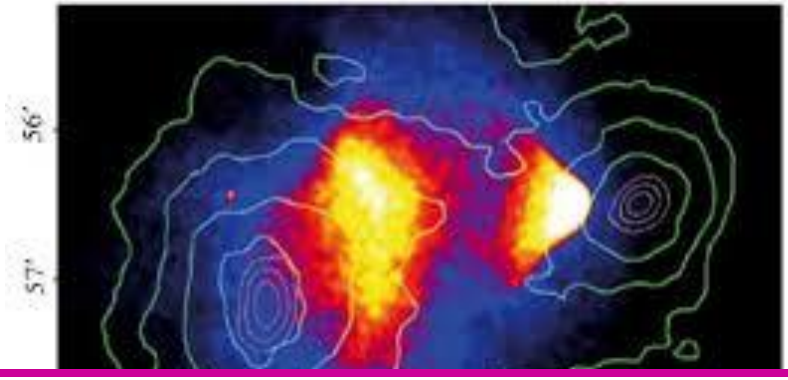


Large Scale Structure

Evidence for dark matter

Astrophysical observations consistently point to the need for dark matter

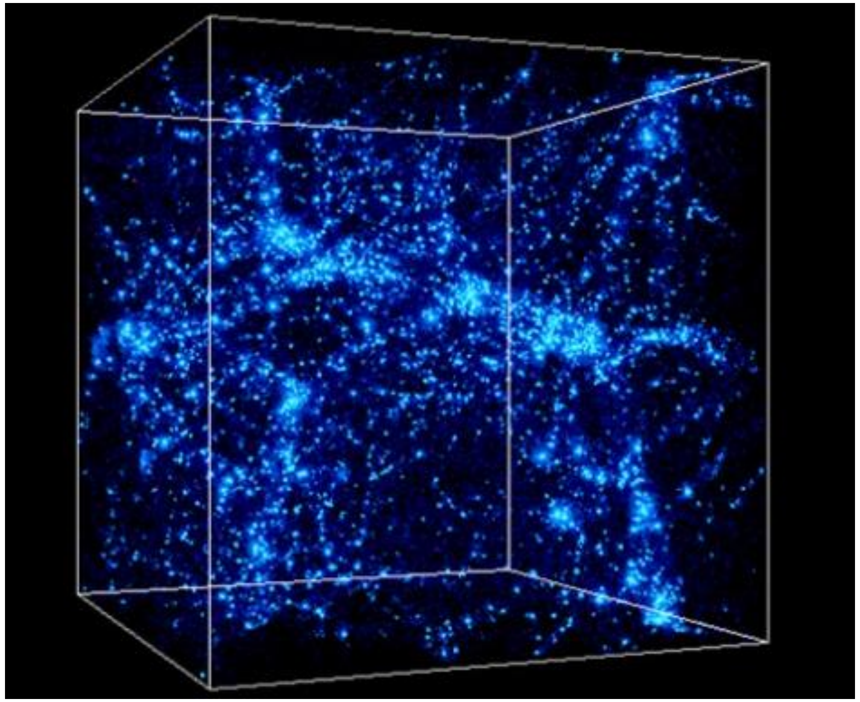




All are sensitive to dark matter's *gravitational influence*.

As yet, very little information on dark matter *particle properties*.

What do we know?

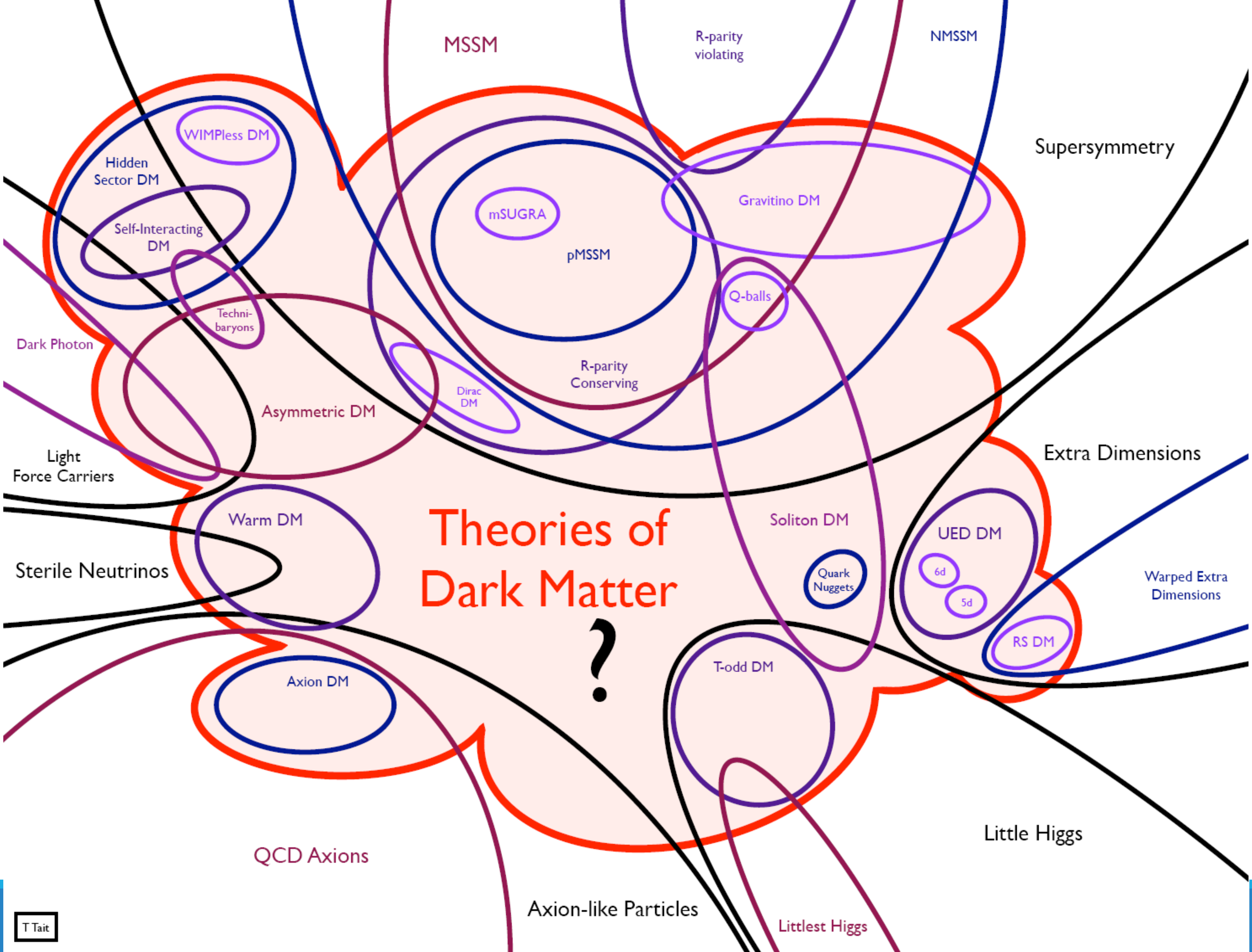


Dark → coupling to photons absent or highly suppressed.

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

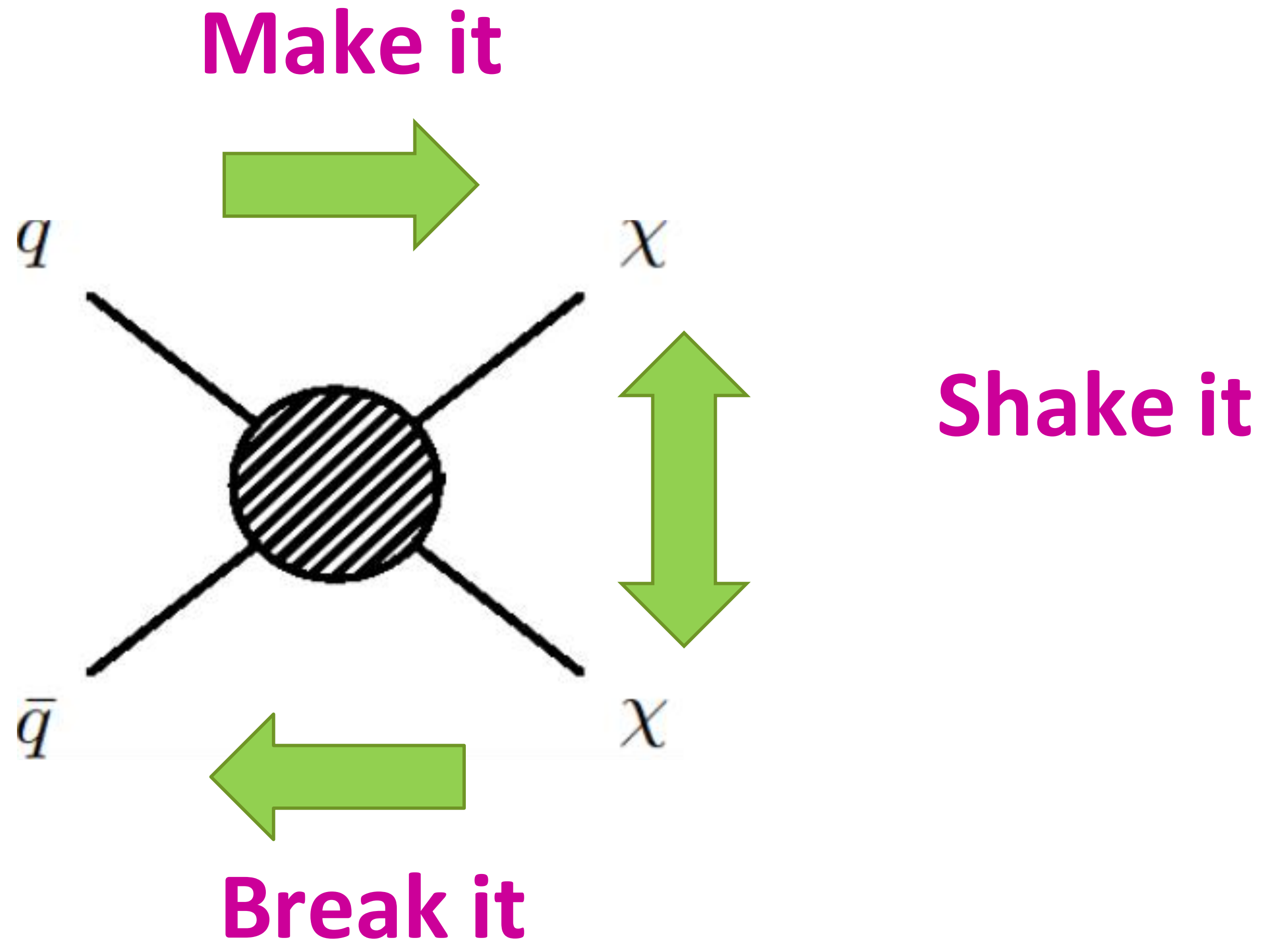


Theories of Dark Matter
?
MSSM
R-parity violating
NMSSM
Supersymmetry
WIMPless DM
Hidden Sector DM
Self-Interacting DM
Techni-baryons
mSUGRA
pMSSM
Gravitino DM
Q-balls
R-parity Conserving
Dirac DM
Dark Photon
Asymmetric DM
Light Force Carriers
Warm DM
Sterile Neutrinos
Soliton DM
Quark Nuggets
Extra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

Dark matter model space

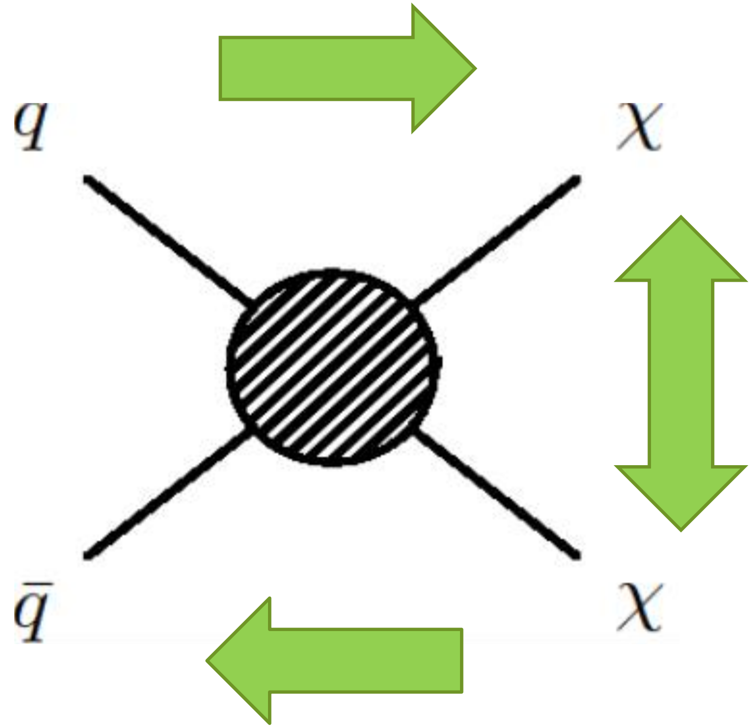
Image: Bertone and Tait

Looking for WIMPs



Looking for WIMPs

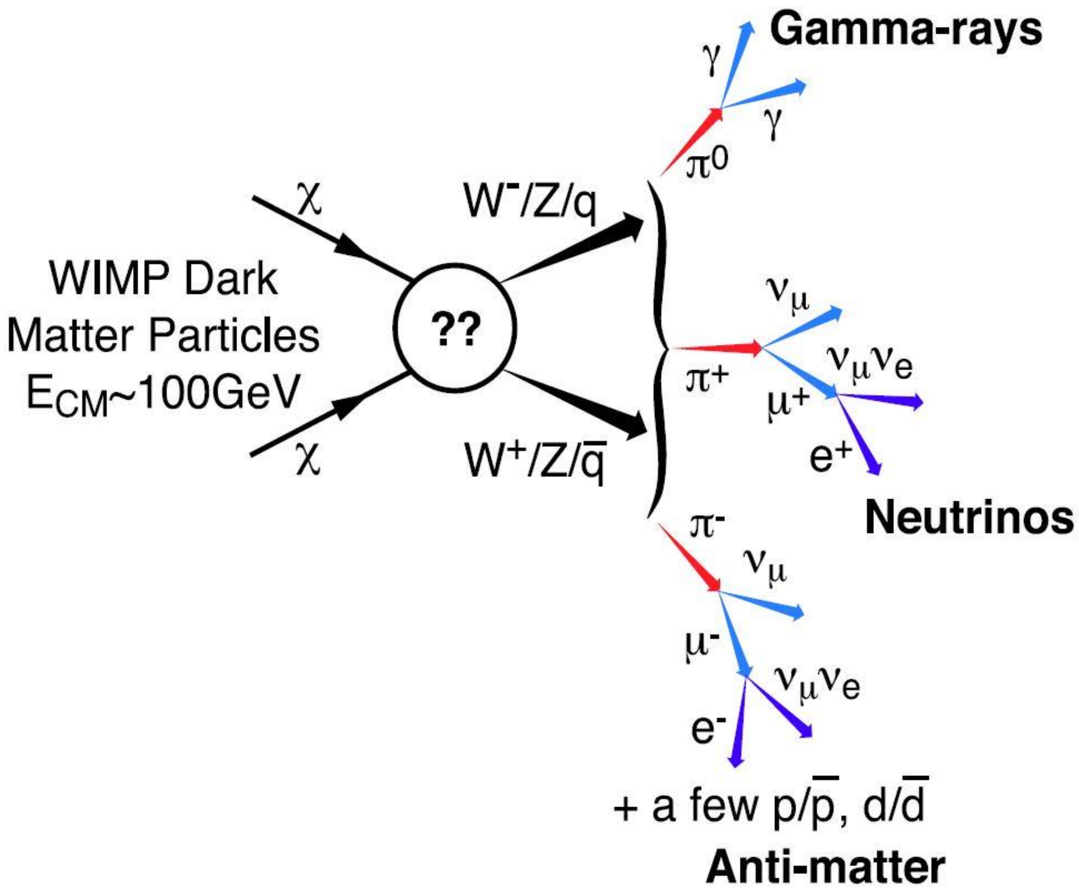
Collider production



Direct detection:
scattering in DM detectors on Earth (or in neutrino expts, or in stars)

Indirection detection:
annihilation in the galaxy

Indirect detection – Detecting dark matter annihilation in space



Indirect detection probes the dark matter annihilation cross-section

→ The most direct test of the thermal-relic dark matter paradigm

Thermal relic cross section (the WIMP miracle):

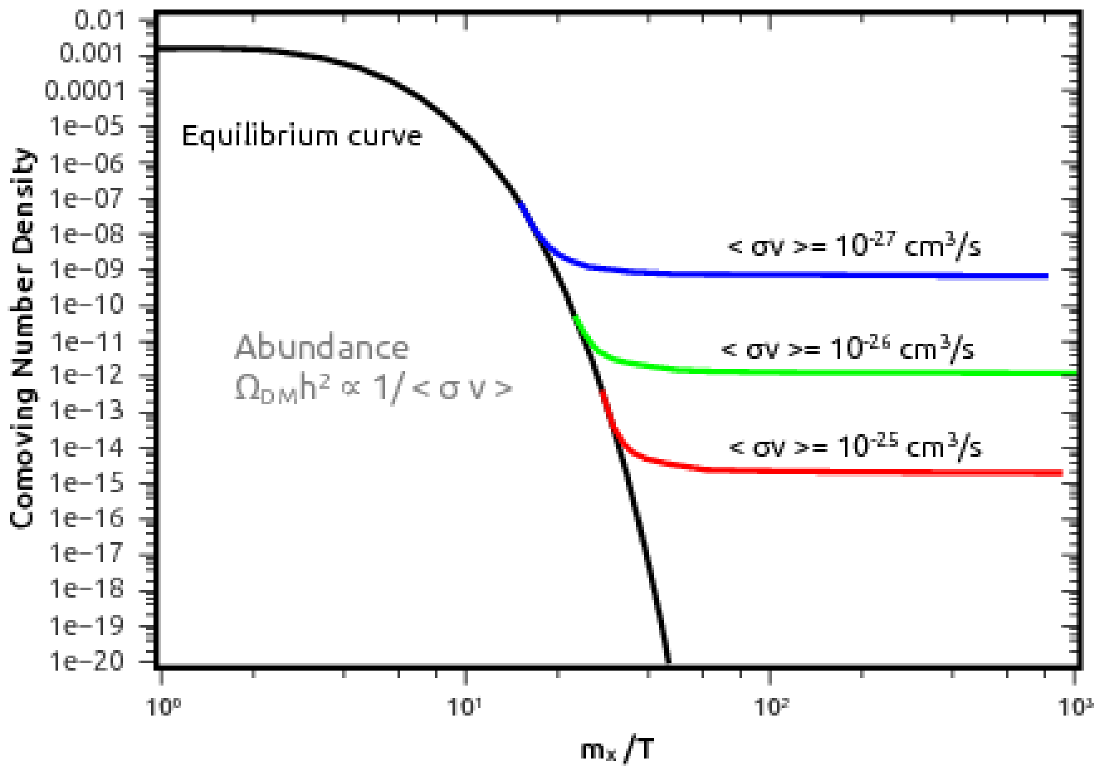
Relic DM density determined by the annihilation cross section:

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

Required annihilation cross section:

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

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



Is there room left for WIMPs?

We need WIMPs to annihilate efficiently in the early Universe, but to have escaped detection in direct, indirect and collider searches

Direct detection	Suppressed if scattering cross section depends on spin, velocity or momentum
Indirect detection	Suppressed if annihilation cross section is p-wave
Collider production	Suppressed if DM couples to the SM through hidden-sector portal interactions (e.g. a dark photon mediator)

Even for models with unsuppressed signals, much of the parameter space has not yet been searched!

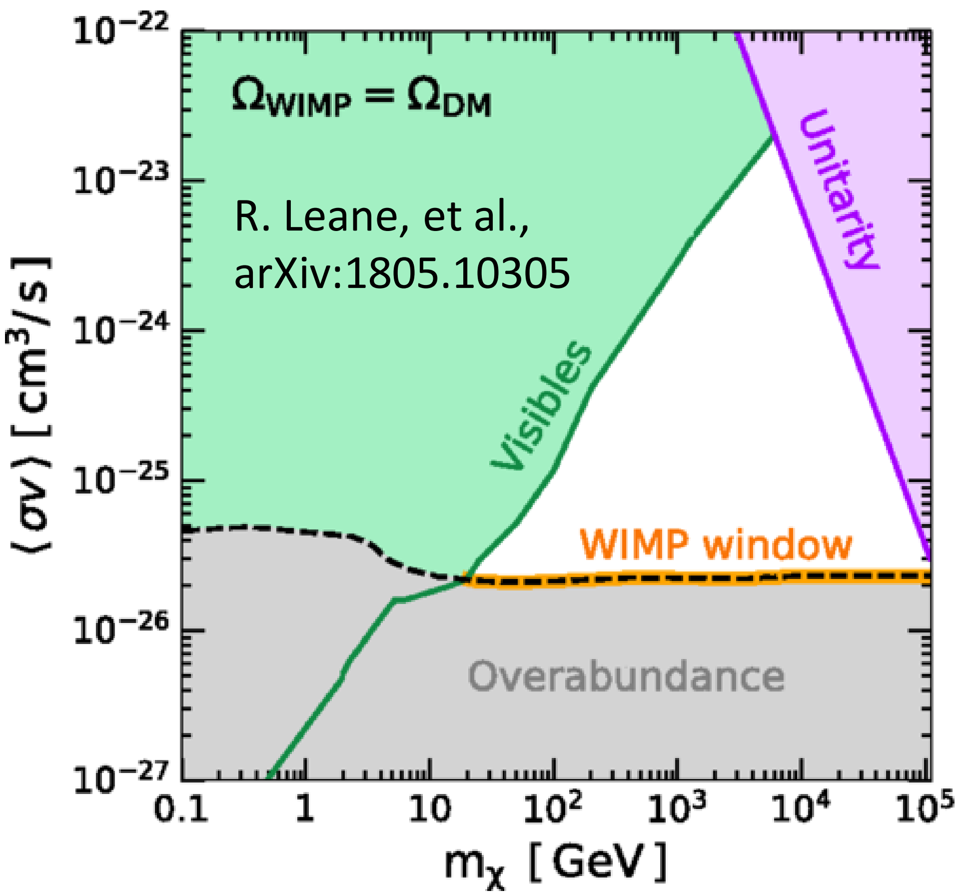
The WIMP window

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



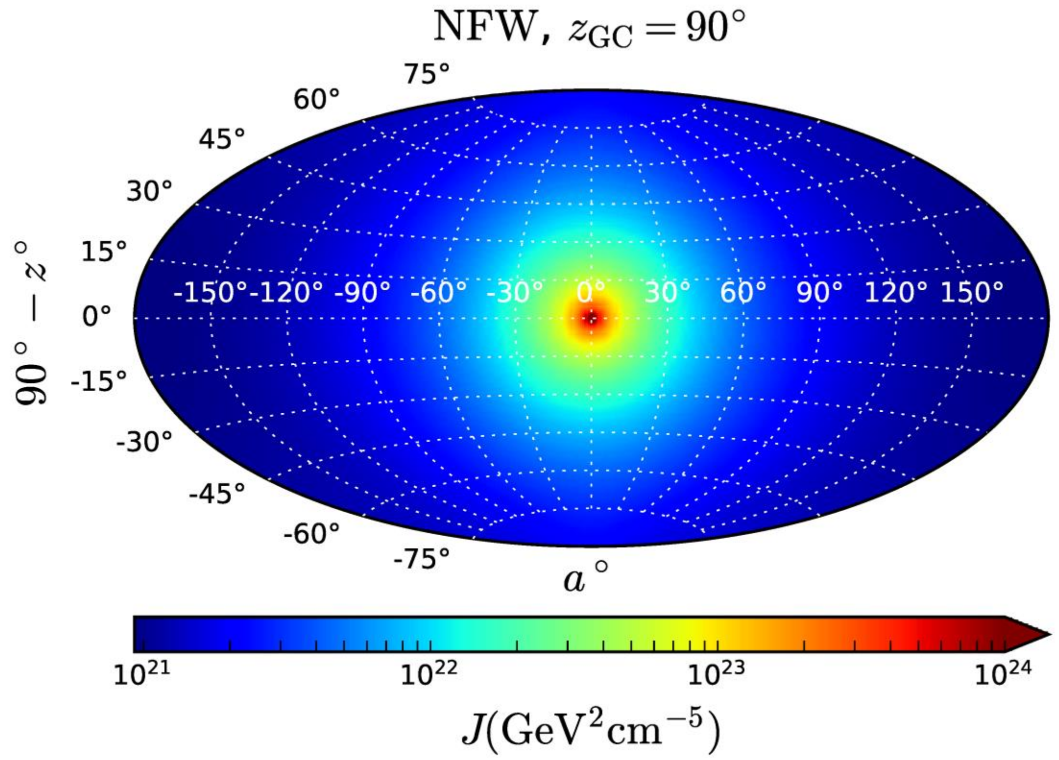
Dark matter annihilation signal

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

Annihilation cross section

Integral of (density)^2 along line of sight

Spectrum per annihilation

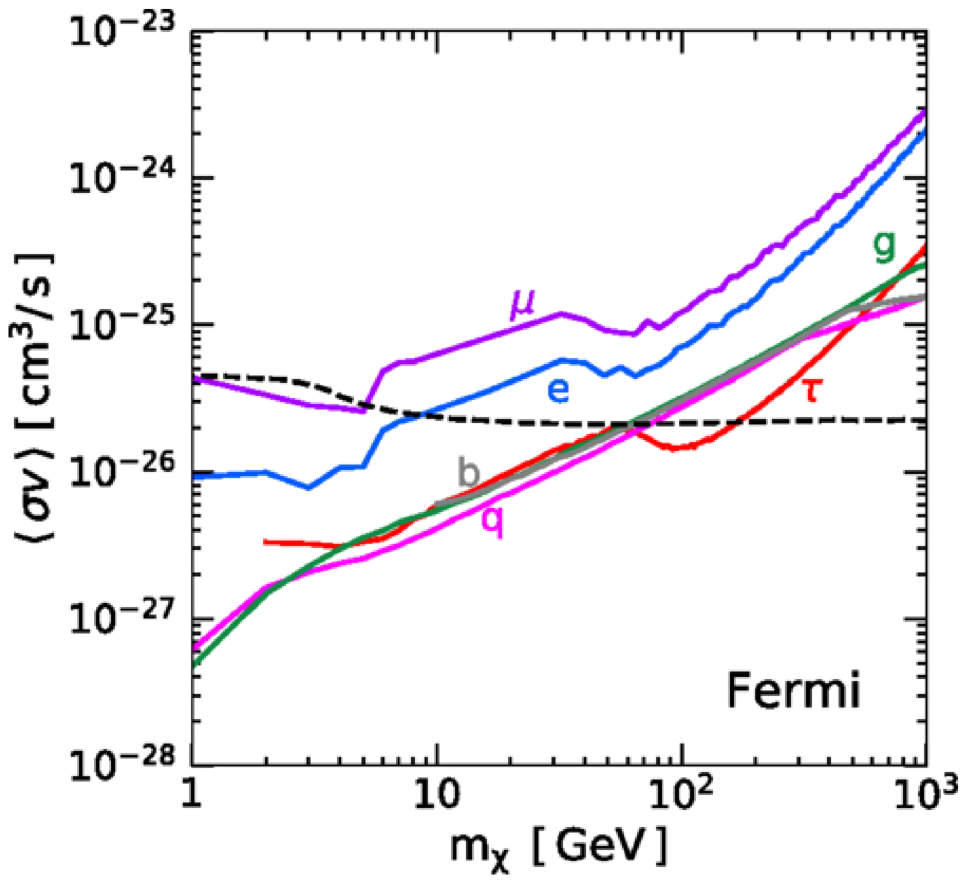


Bell, Dolan, Robles, arXiv: 2005.01950

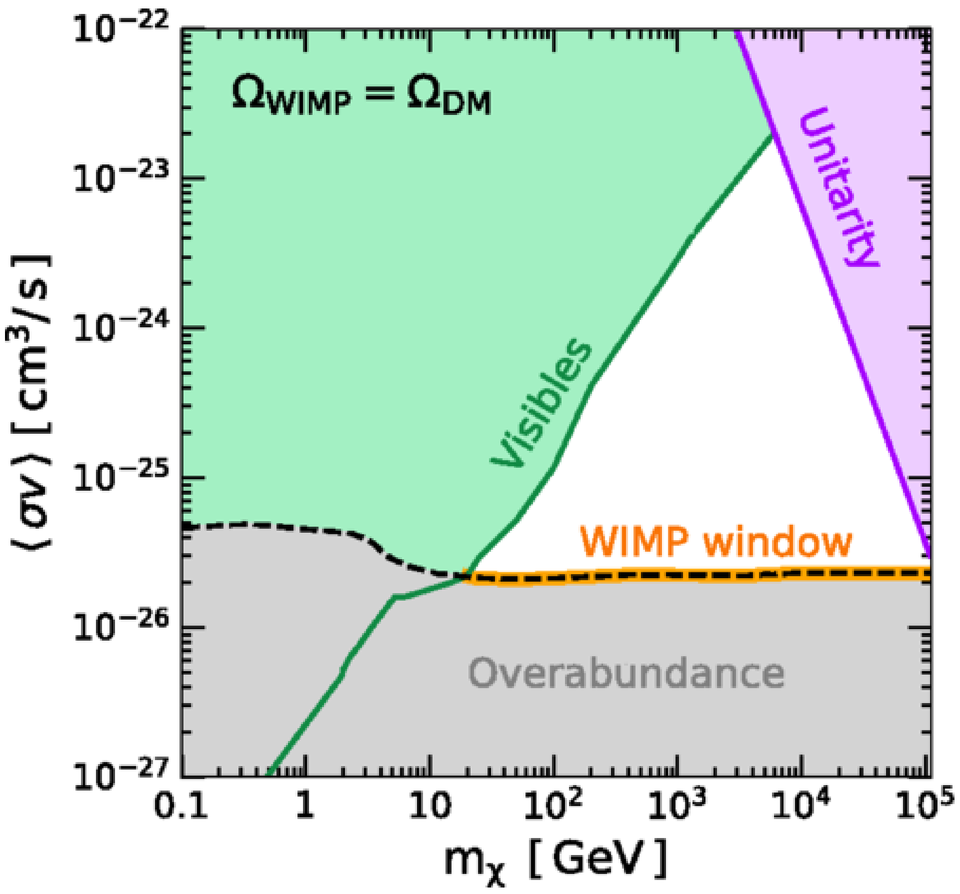
Indirect detection constraints

R. Leane, et al., arXiv:1805.10305

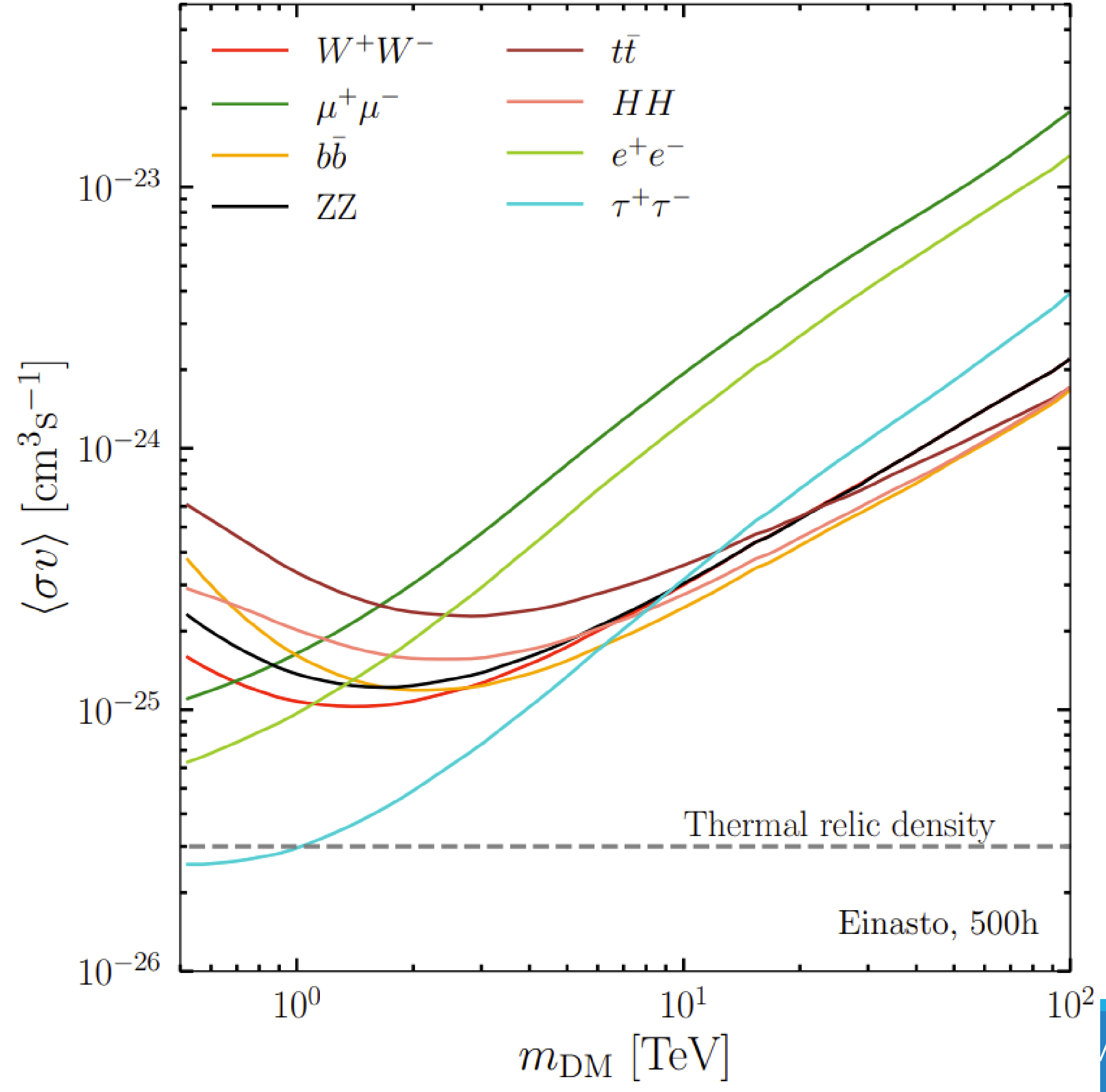
Fermi dSph limits



Annihilation to "visible" SM states



Closing the WIMP window: TeV gamma rays

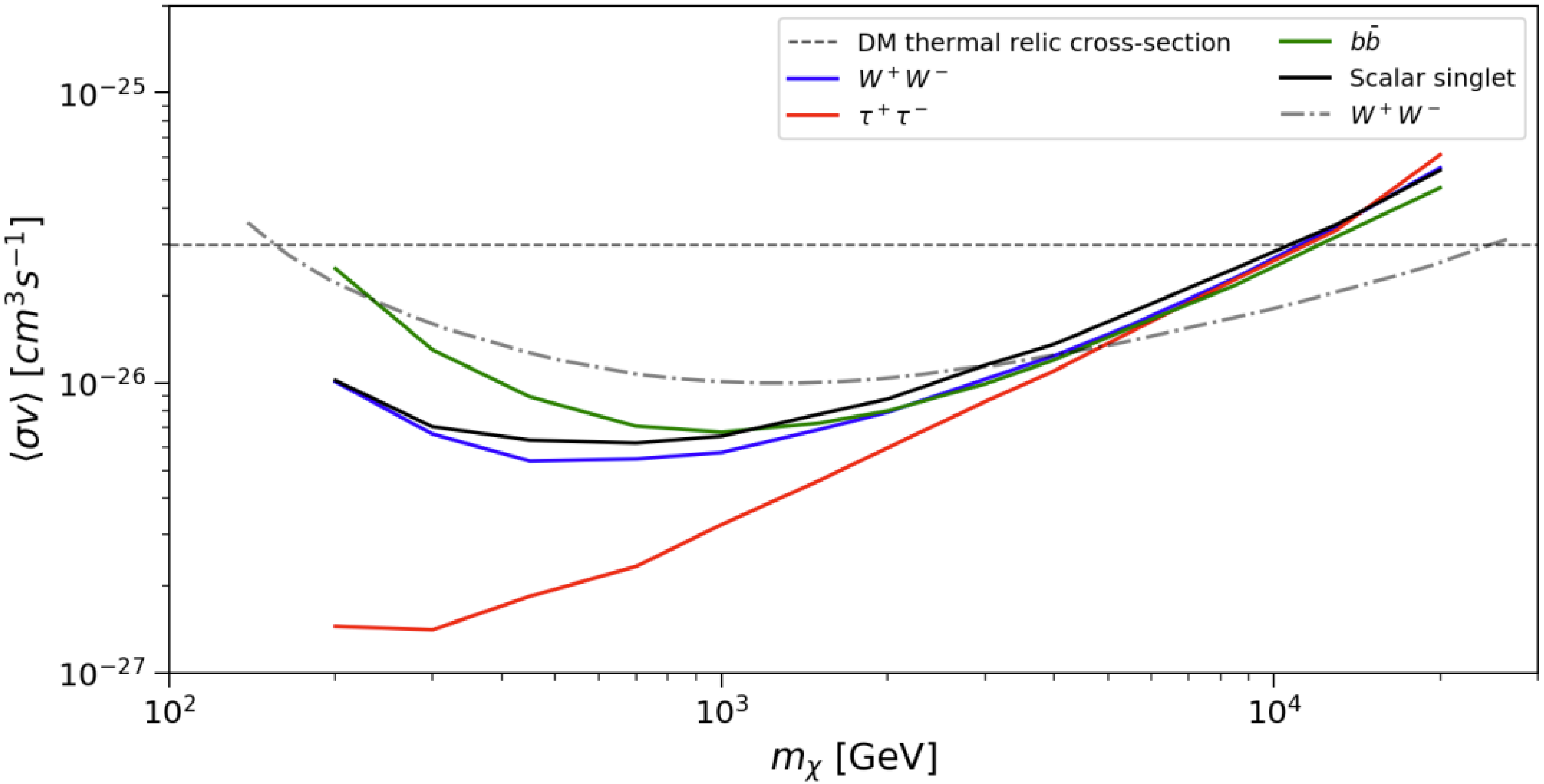


Projected sensitivity for current generation Cherenkov telescopes (HESS-like)

Montanari, Moulin & Rodd, arXiv:2210.03140

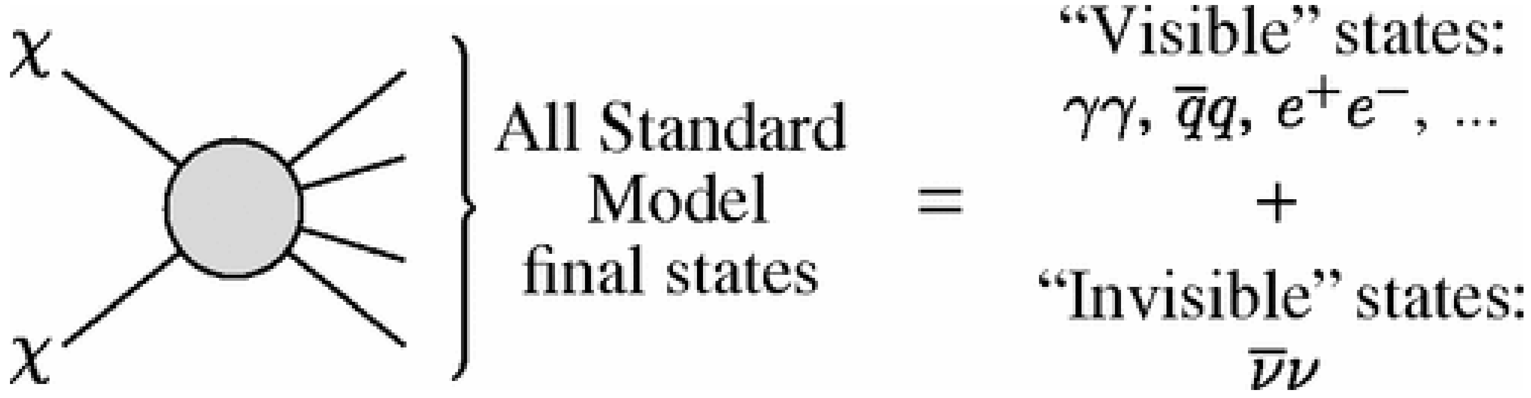
Closing the WIMP window: CTA projections

Mangipudi, Thrane & Balazs, arXiv:2112.10371



Closing the WIMP window: Neutrinos

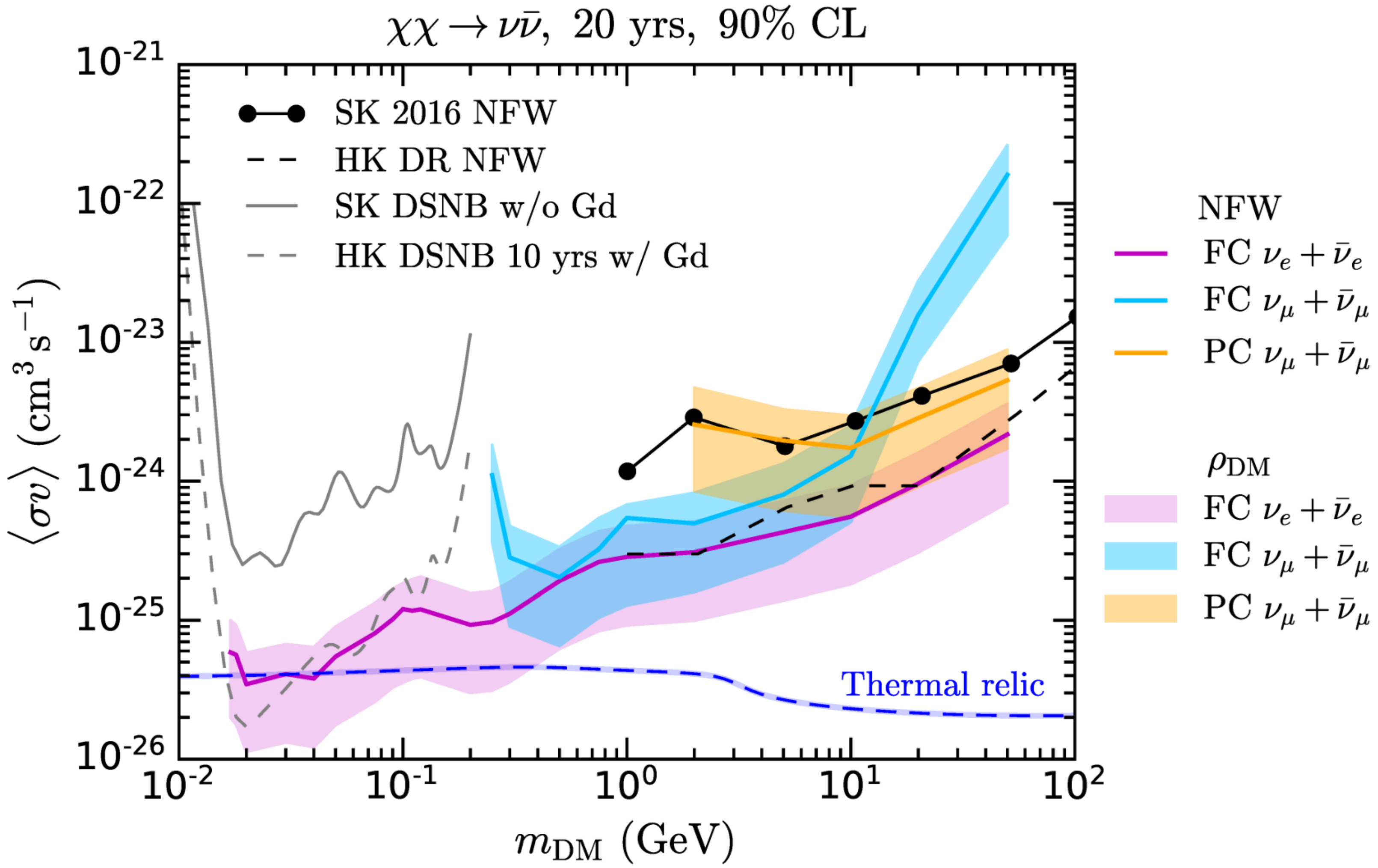
- Indirect detection limits – typically neglect the possibility that dark matter may annihilate to "invisible" or hard-to-detect final states.



Beacom, Bell, Mack, PRL 2007

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

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



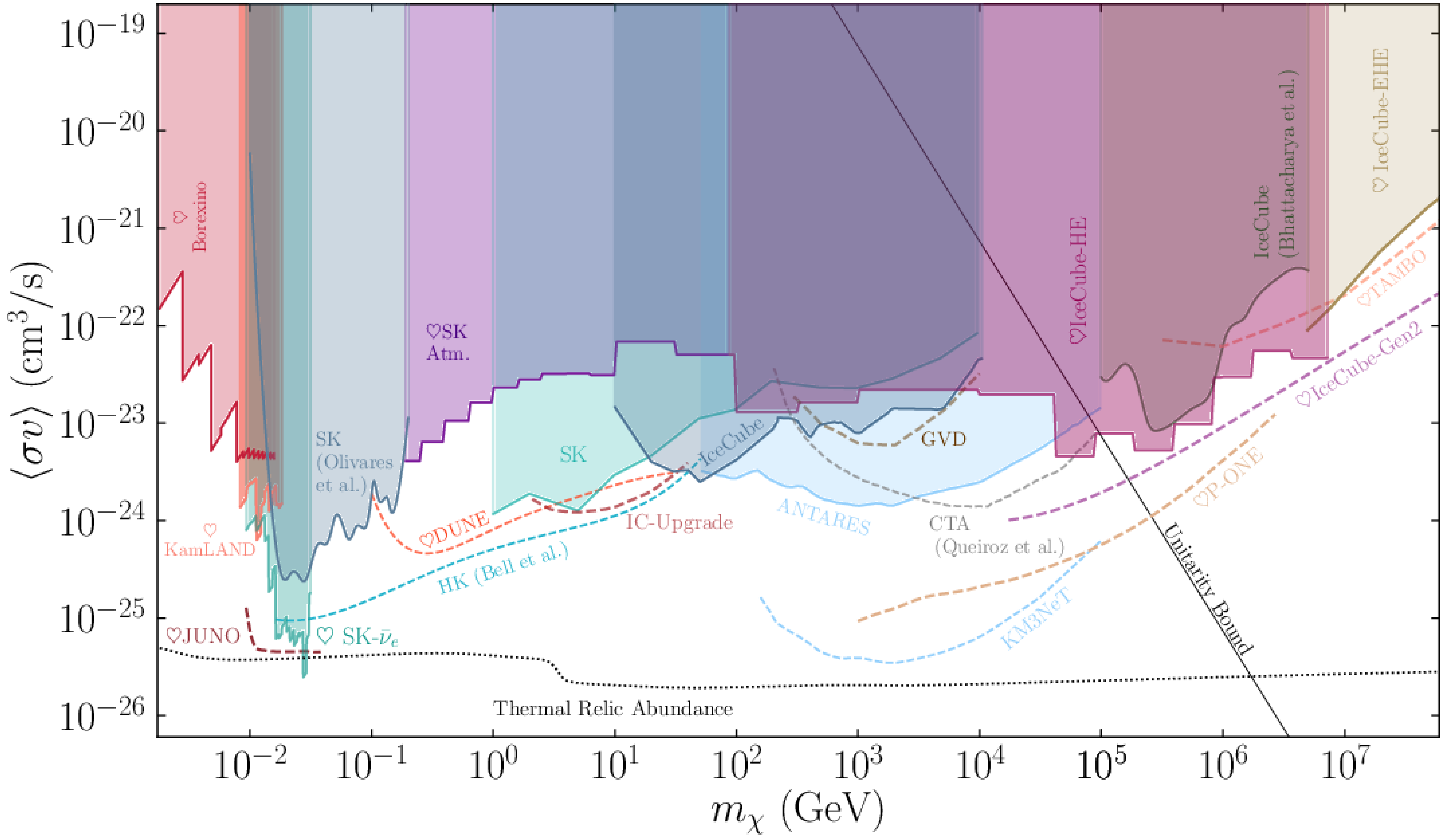
Thermal relic sensitivity for $m_\chi \sim 30$ MeV

NFW – central lines
Isothermal – upper
Moore - lower

Bell, Dolan, Robles, arXiv: 2005.01950

Annihilation to $\nu\bar{\nu}$

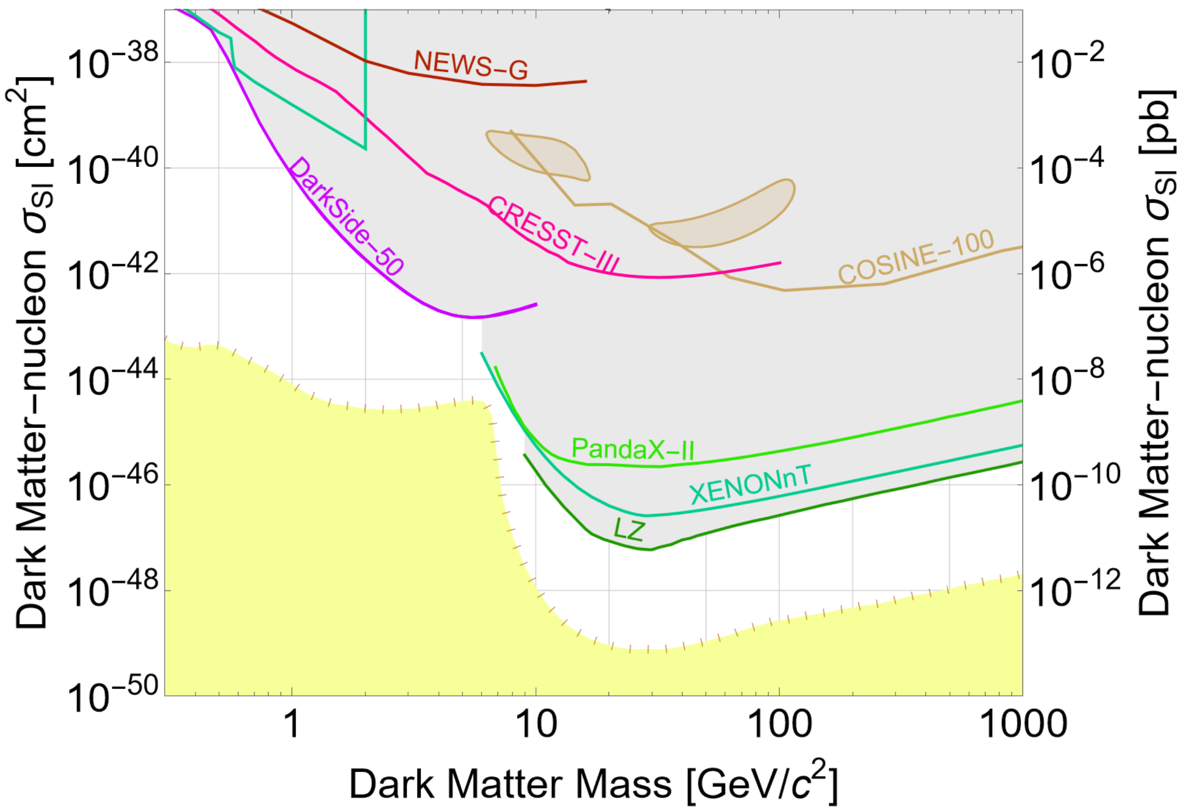
Arguelles et al, arXiv: 1912.09486



Direct Detection

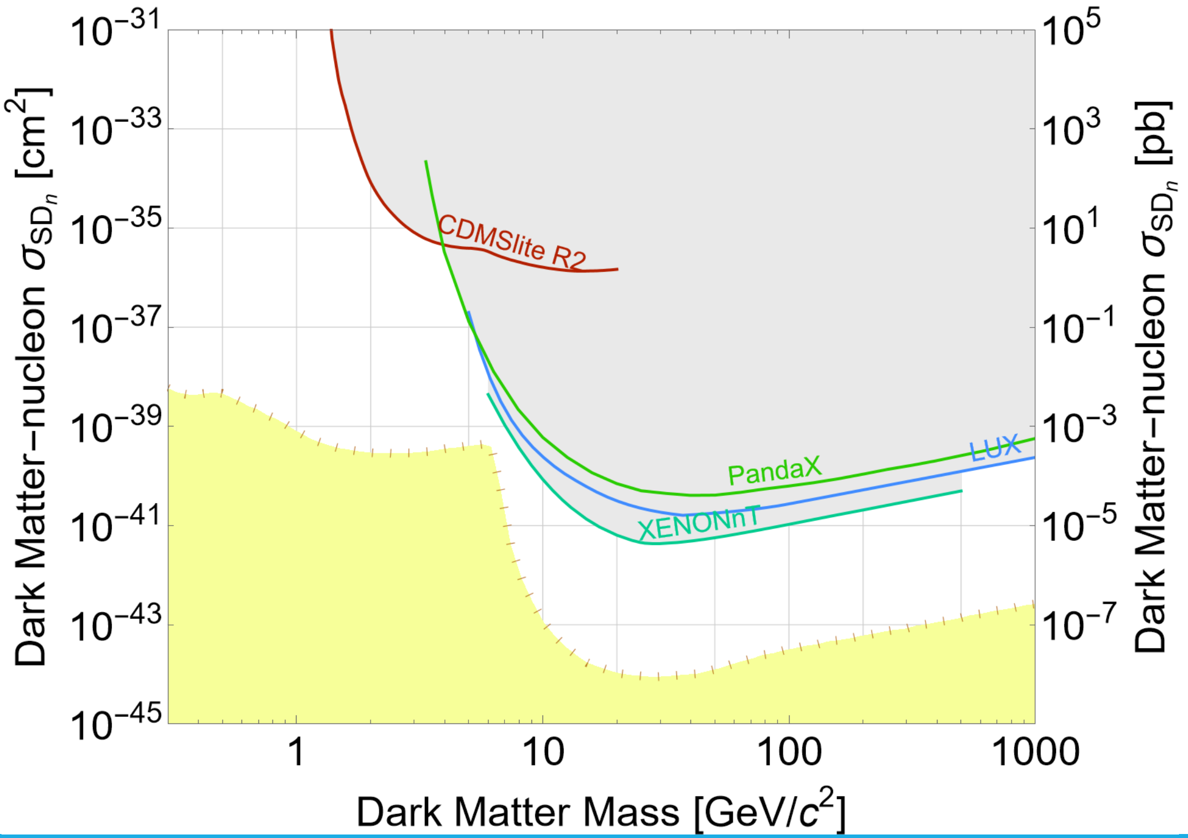
Spin-independent (SI) interactions

→ strong bounds due to coherent enhancement

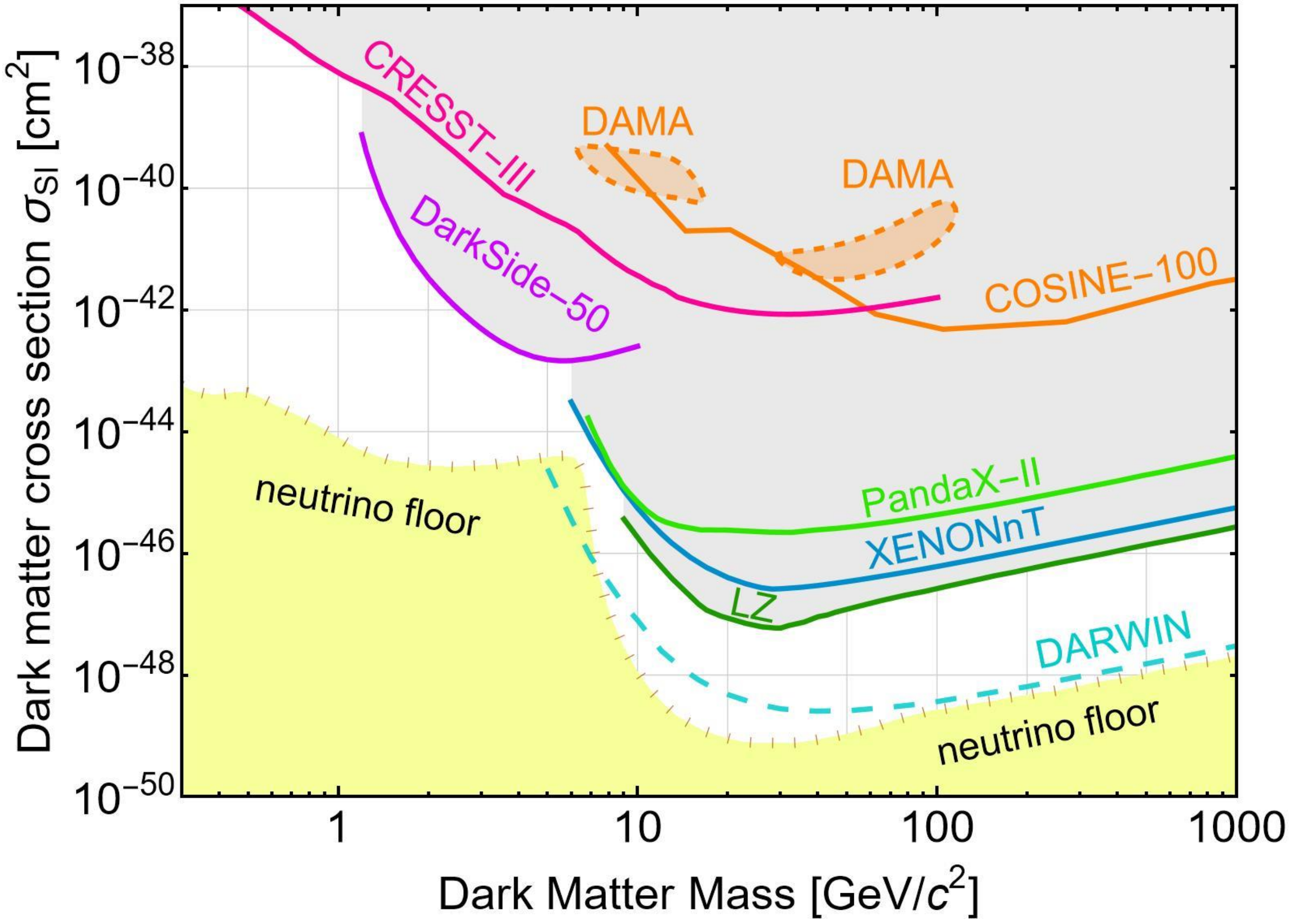


Spin-dependent (SD) interactions

→ weaker bounds

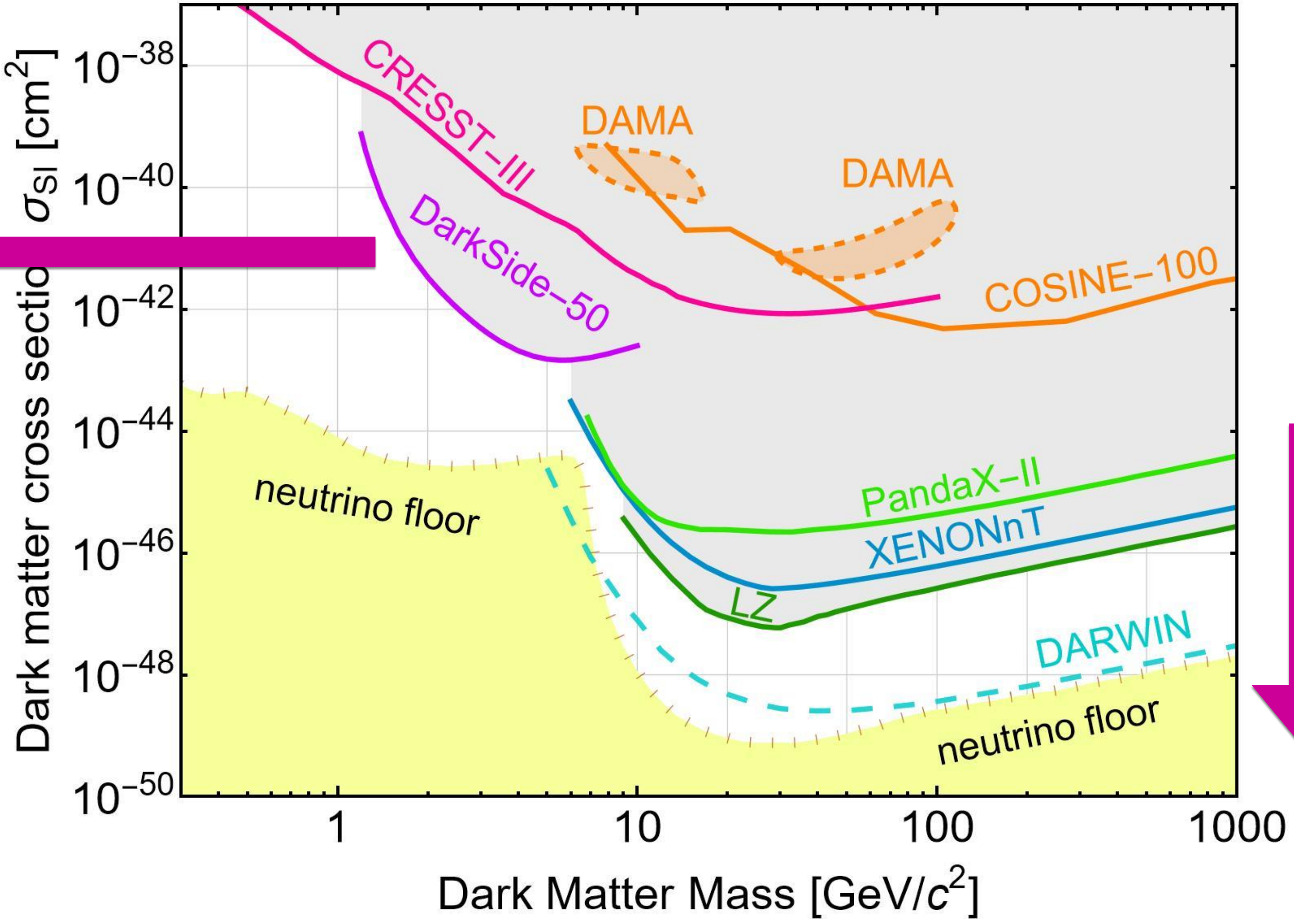


Direct Detection – future challenges



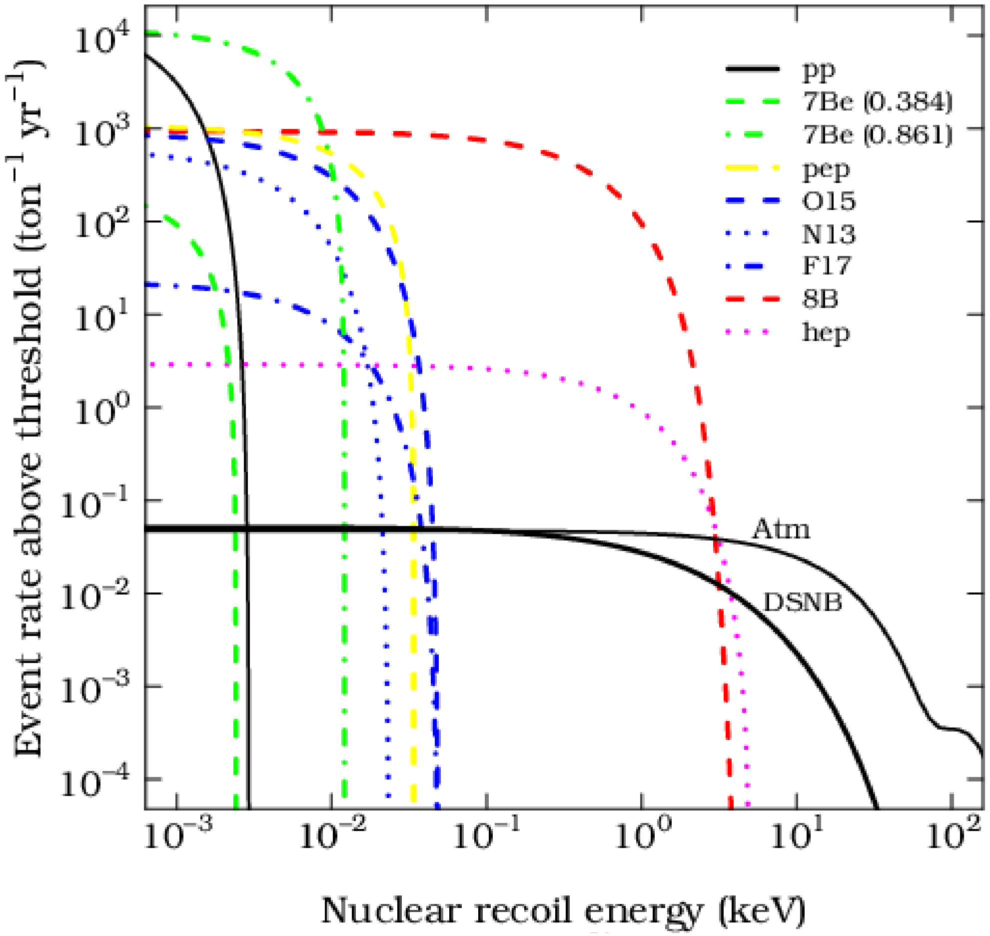
Direct Detection – future challenges

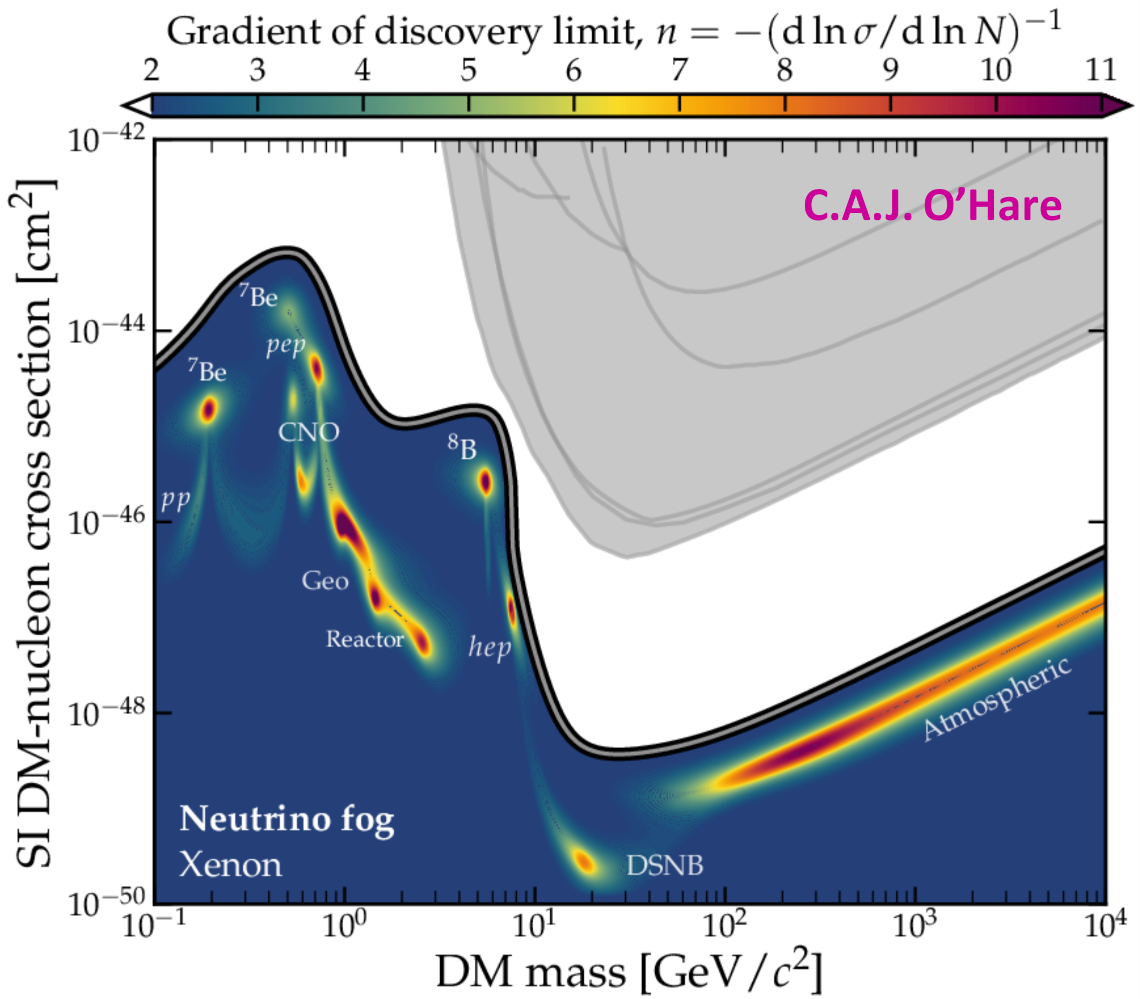
Lower thresholds



Larger detectors;
Lower backgrounds

Neutrino floor

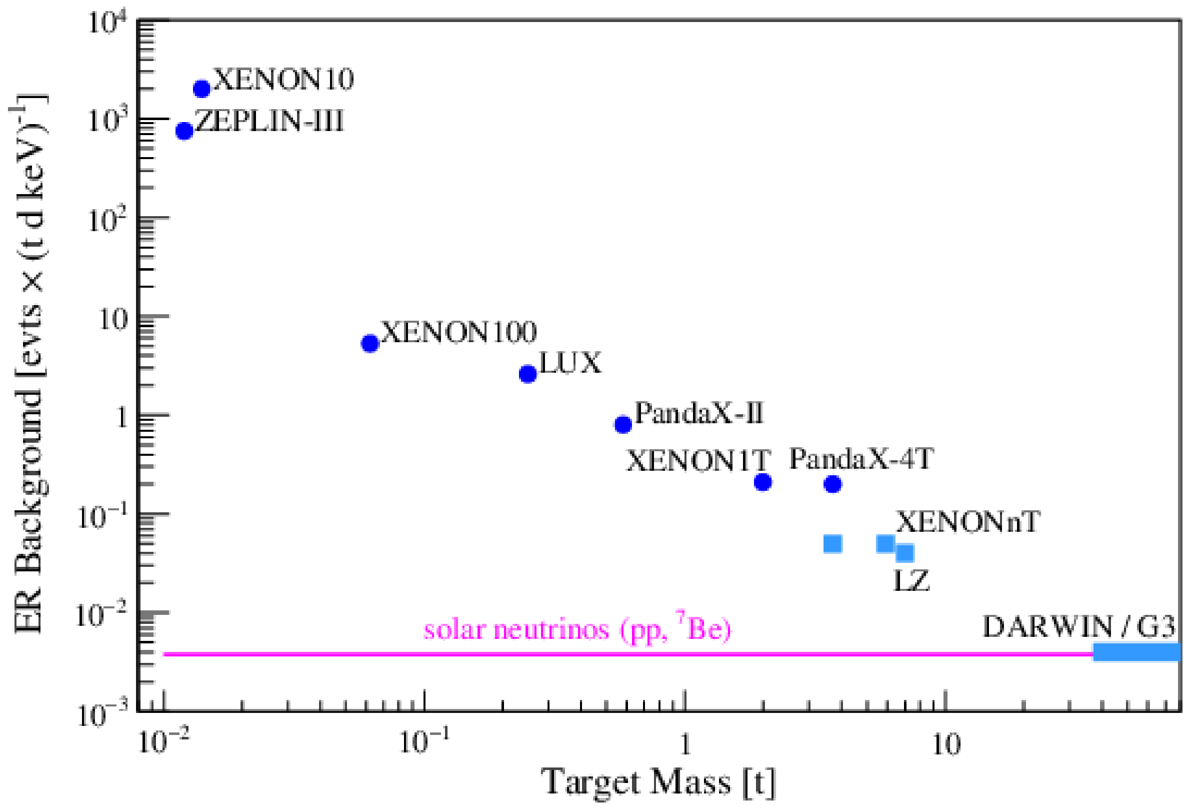


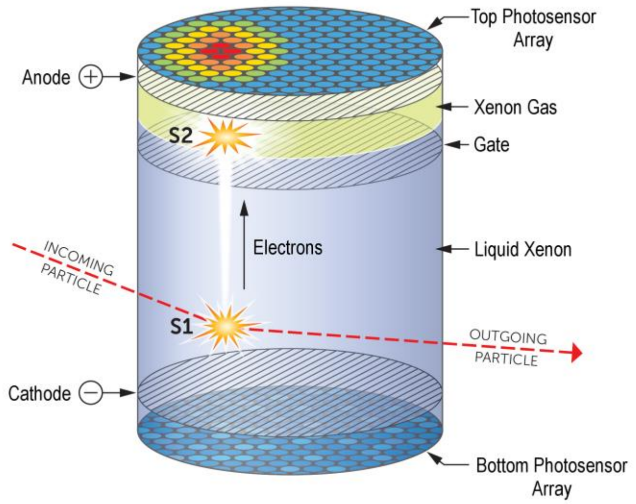


arXiv:2203.07361

Toward the neutrino floor

Next generation liquid noble gas experiments will reach the neutrino floor:





Images from: arXiv:2203.02309

New strategies to probe dark matter scattering

- High mass WIMPS → new techniques to search below the neutrino floor
  - Directional detection!

- Low mass WIMPS → new analyses using existing detectors
  - Migdal effect **(see talk by Jay Newstead tomorrow)**
  - “Boosted” (i.e. more energetic) dark matter

- Low mass WIMPS → new experimental techniques

- Complementary constraints from astrophysics
  - Dark matter capture in the Sun, neutron stars, etc.

Boosted Dark Matter

Halo dark matter

→ highly nonrelativistic $v \sim 10^{-3}c$

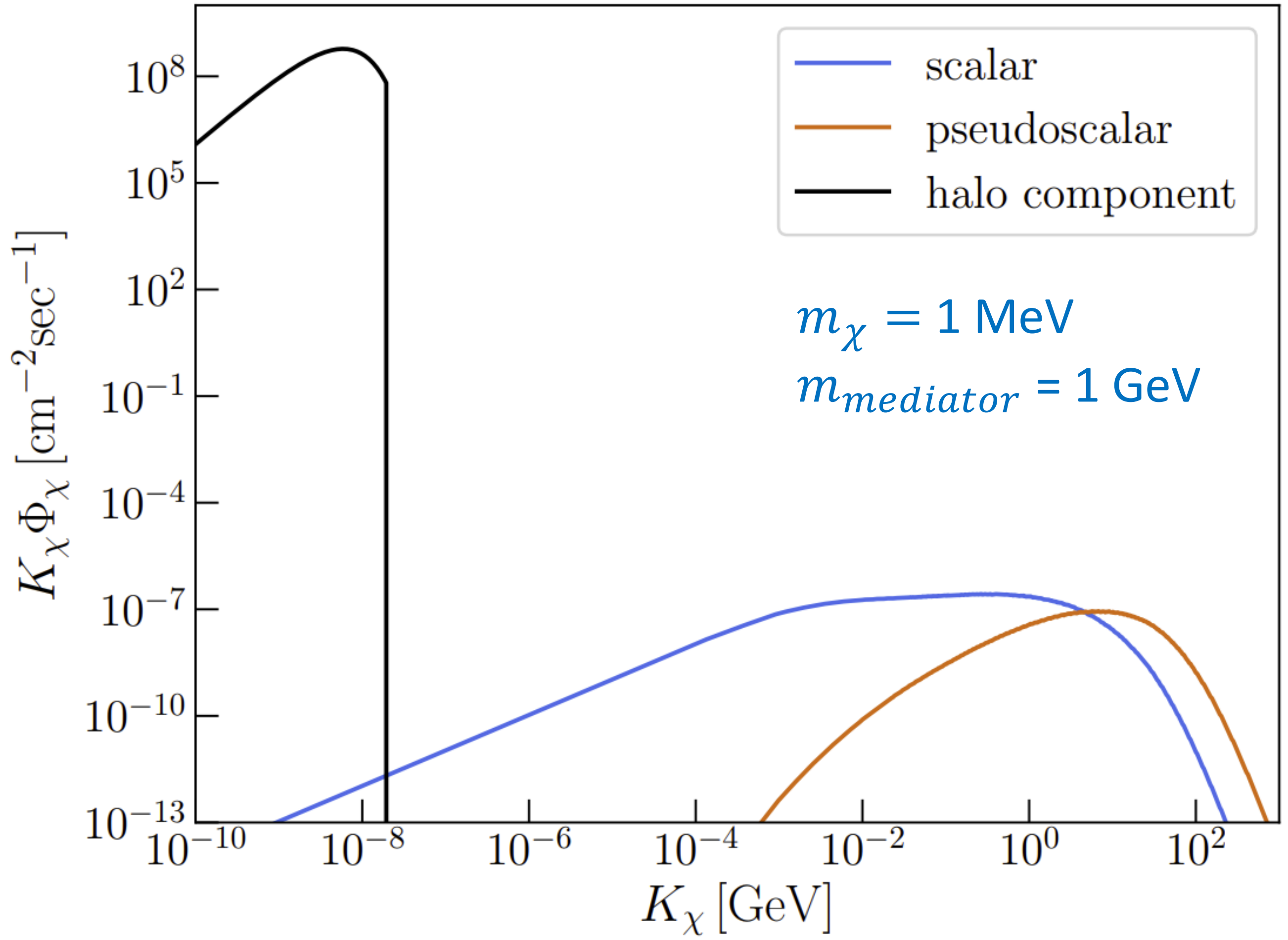
→ low energy recoils in direct detection experiments: $E_{R,max} = \frac{2\mu_T^2}{m_T} v_{max}^2$

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 mater (CRDM)

Y. Ema et al, arXiv:2011.10939



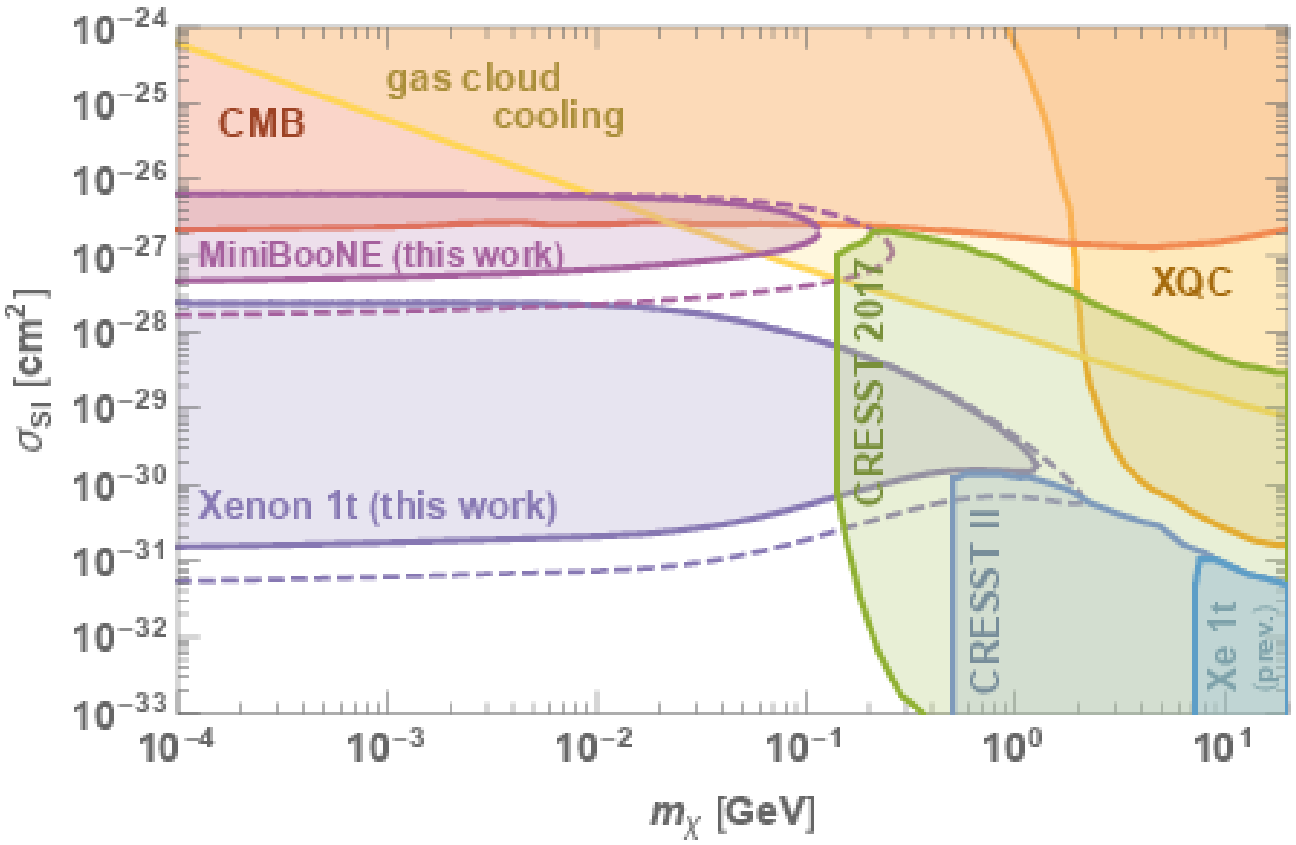
Assume the DM-nucleon scattering cross section is non-zero

→ cosmic rays will ***unavoidably*** scatter with DM, producing a (small) high energy DM flux.

→Light boosted DM is visible in direct detection experiments

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

Bringmann & Pospelov, PRL 2019



Allows light dark to be constrained using existing experiments.

Note:

- these are BIG cross sections
- DM absorption in the earth imposes upper limit on the cross sections that can be probed

Cosmic ray up-scattered dark mater (CRDM)

Advantages:

- Detectable signals for **light DM** in direct detection experiments
- Energetic enough to be seen in **neutrino experiments**
  →which have higher energy thresholds, but **significantly larger target mass**
- Removes velocity or momentum suppressions
  → e.g. standard DD expts cannot see pseudoscalar interactions, because $\sigma \propto p^4$

Disadvantages:

- Observable signals scale with **two** powers of the scattering cross section

Questions: How to distinguish heavy non-relativistic DM from light relativistic DM?

- **Directional information** would help

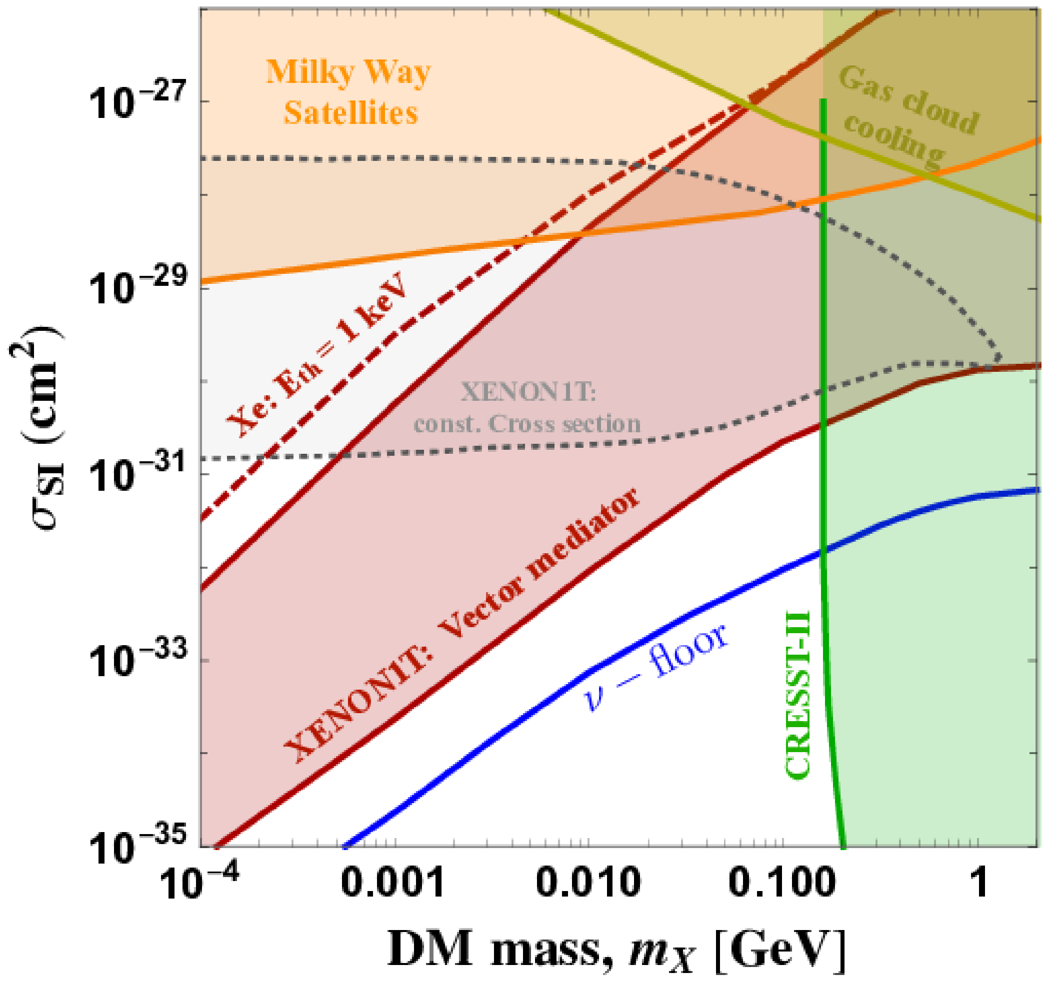
Cosmic ray up-scattered dark matter

Dent, Dutta, Newstead, Shoemaker, arXiv:1907.03782

Very big cross-sections

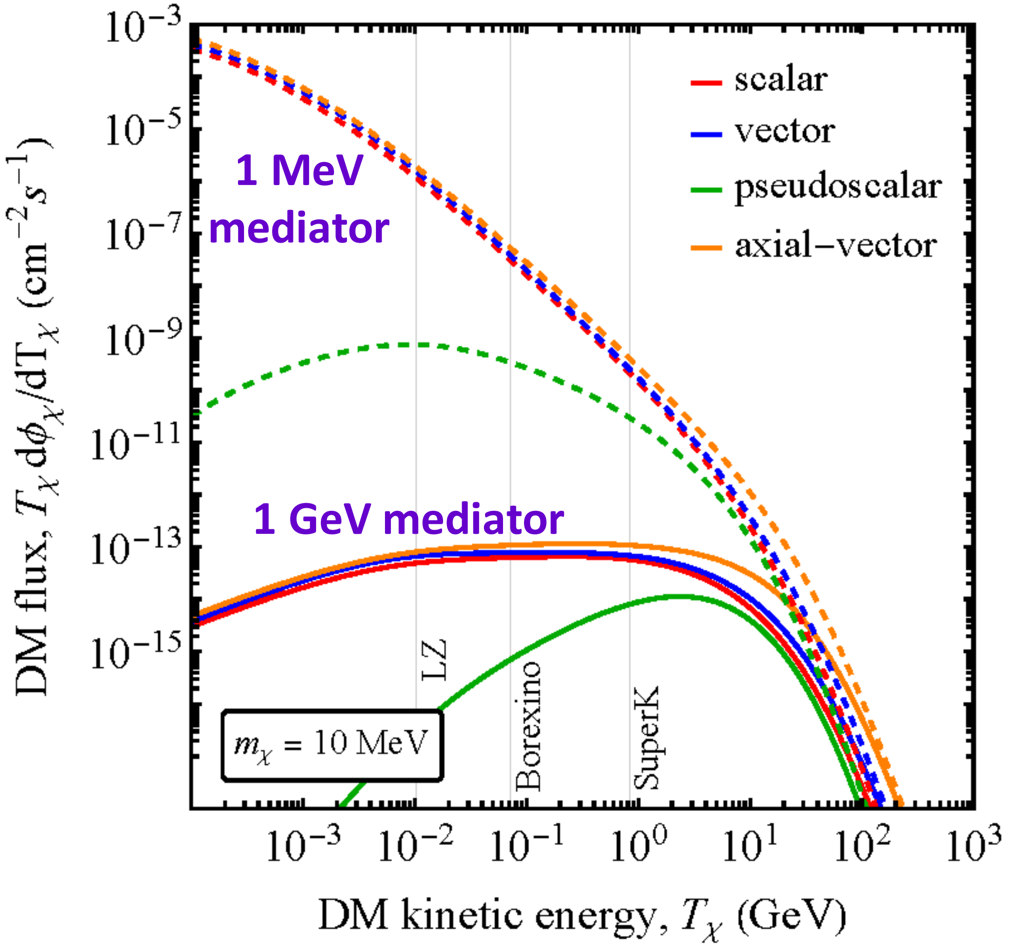
- Light mediators?
  → Energy dep. of cross section matters
  → Other constraints
- Composite DM?

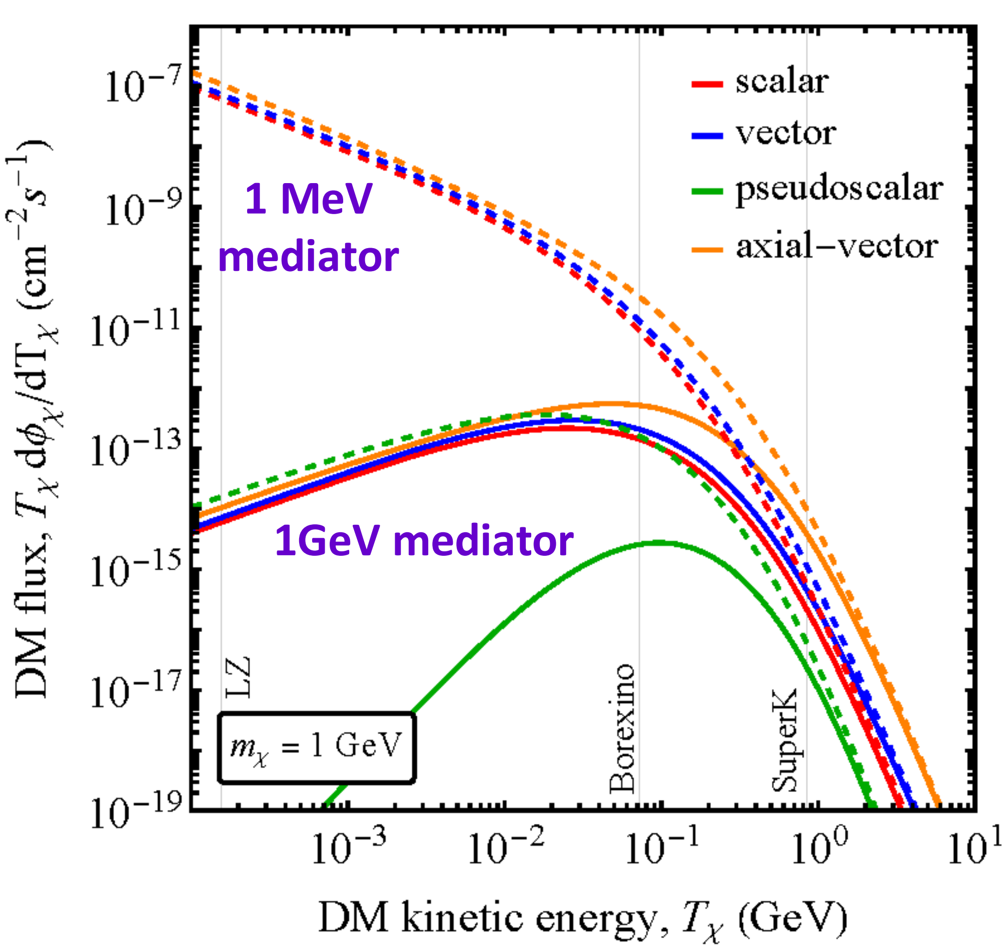
→ These limits are model dependent.



CR-upscattered DM: kinetic energy spectrum

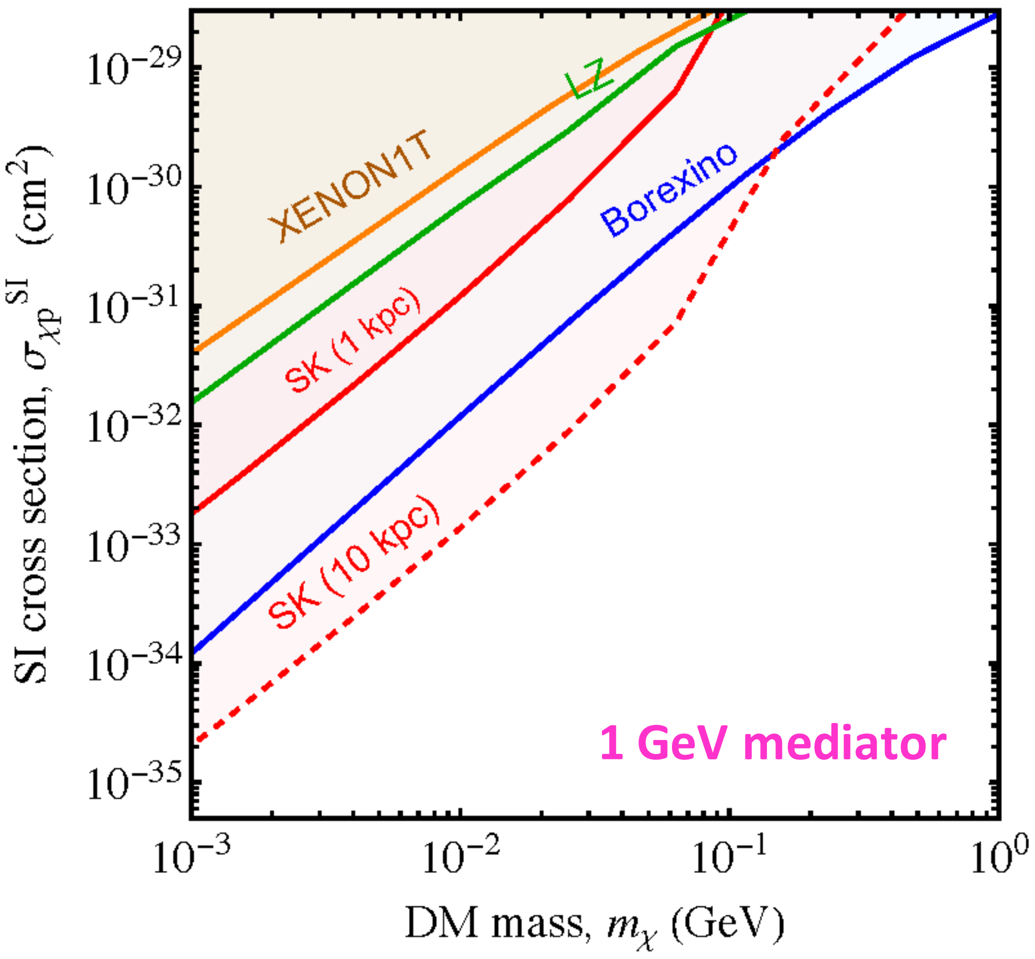
Bell, Newstead and Shaukat Ali, arXiv:2309.11003

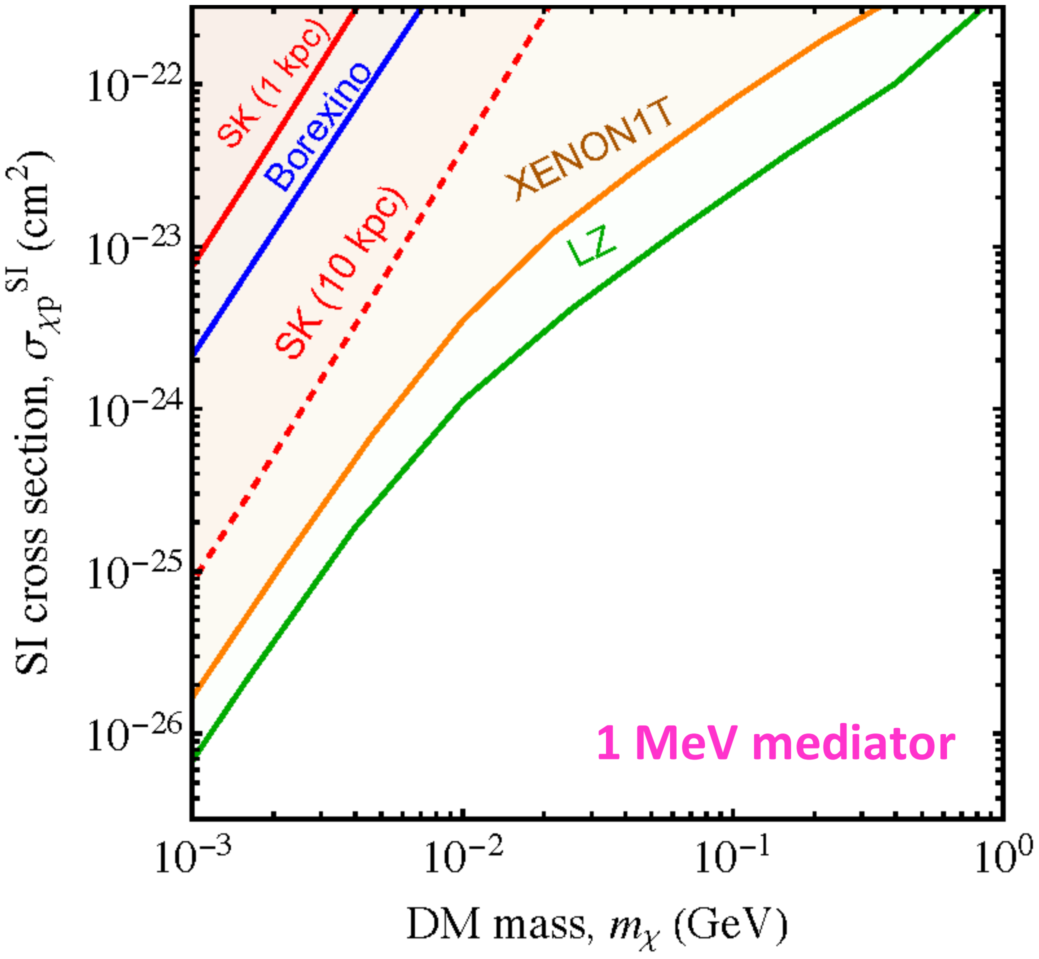




Boosted DM – neutrino vs direct detection exps.

Bell, Newstead and Shaukat Ali, arXiv:2309.11003

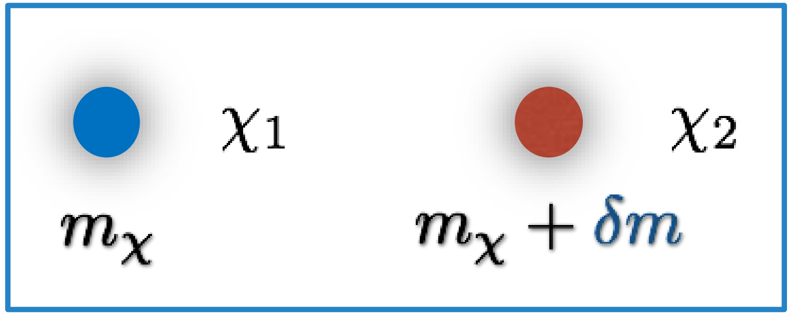




Boosted DM – Inelastic models

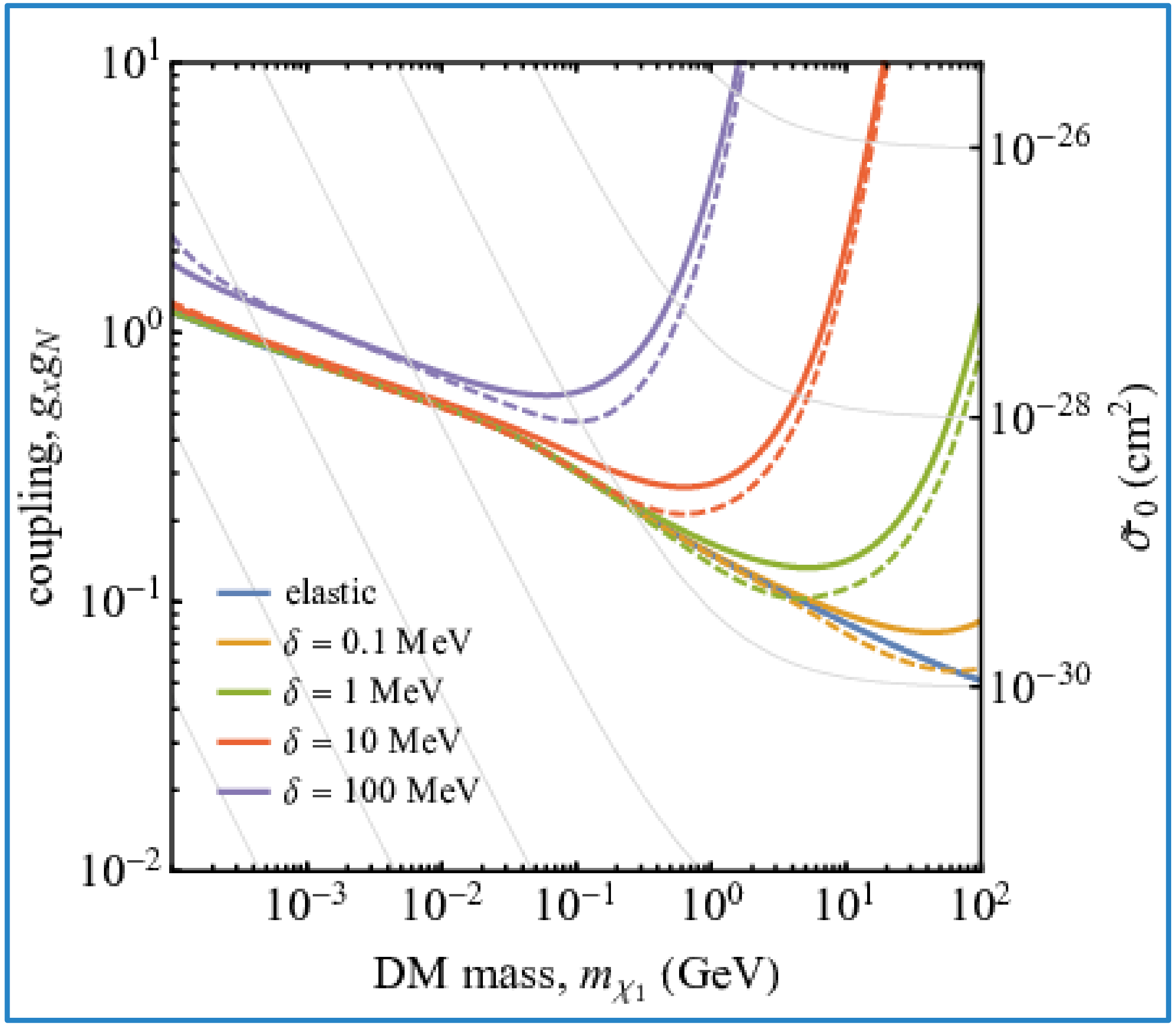
$$\chi_1\, n \rightarrow \chi_2\, n$$

Boosting to relativistic energies
→ enables inelastic scattering
with large mass gap



- Direct detection of non-rel DM, restricted to keV mass gaps $\delta m < \mathcal{O}(100)$ keV
- Boosted CR-DM: $\delta m \sim 100$ MeV

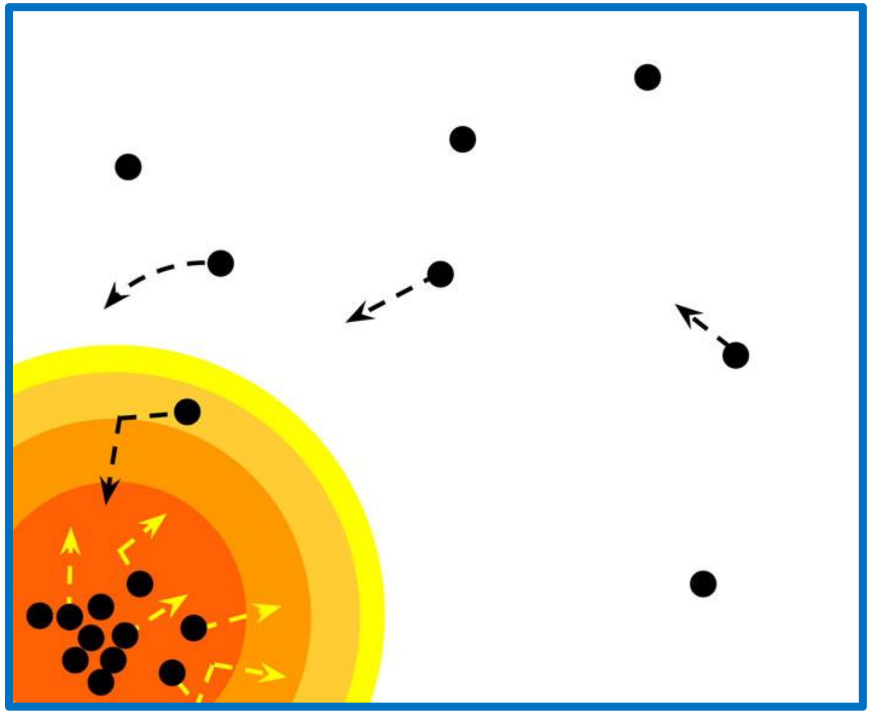
Bell, Dent, Dutta, Ghosh, Kumar, Newstead, Shoemaker arXiv:2108.00583



Dark Matter Capture in Stars

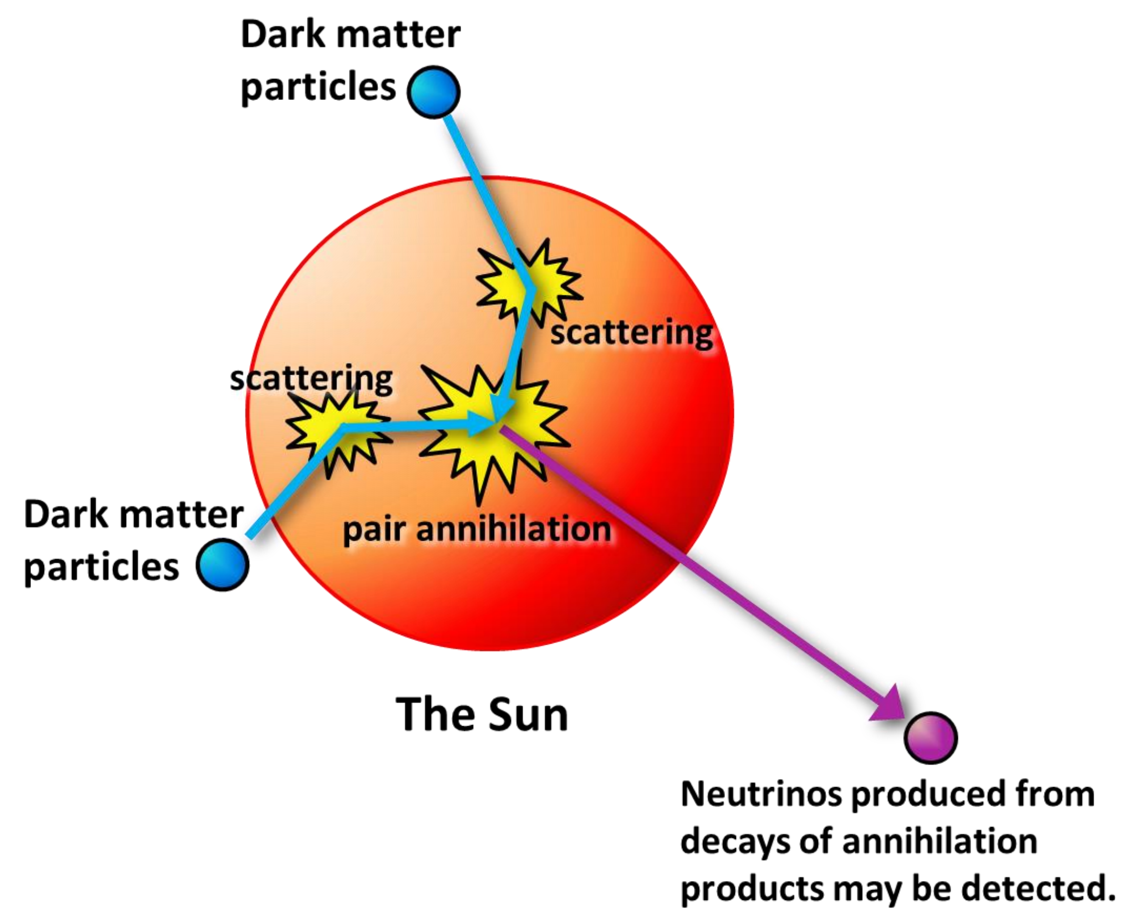
→ an alternative approach to Dark Matter Direct Detection experiments

- 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:

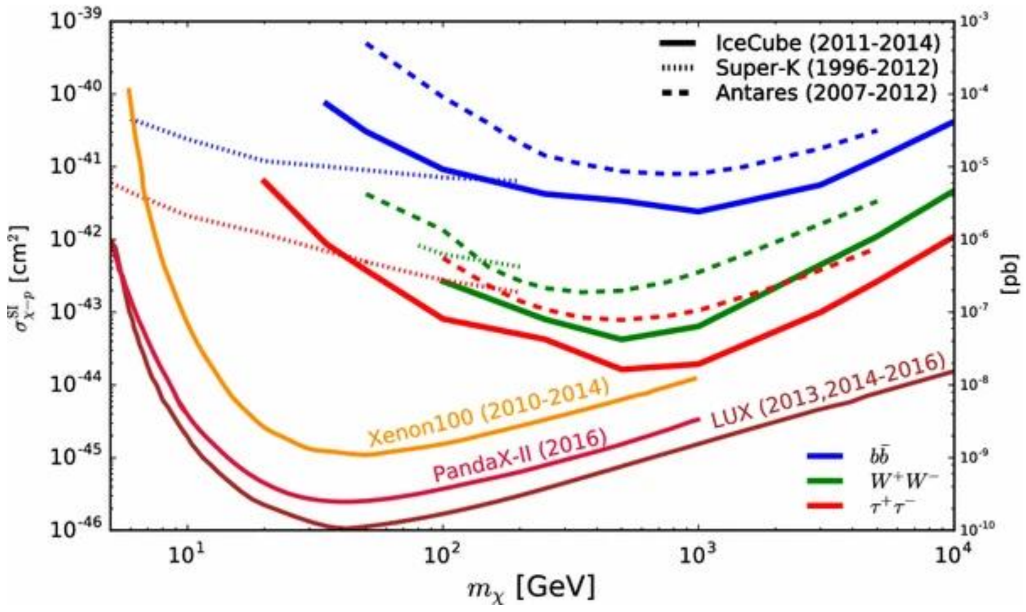
Annihilation rate = Capture rate

→ controlled by DM-nucleon scattering cross section

→ probes the same quantity as dark matter direct detection experiments

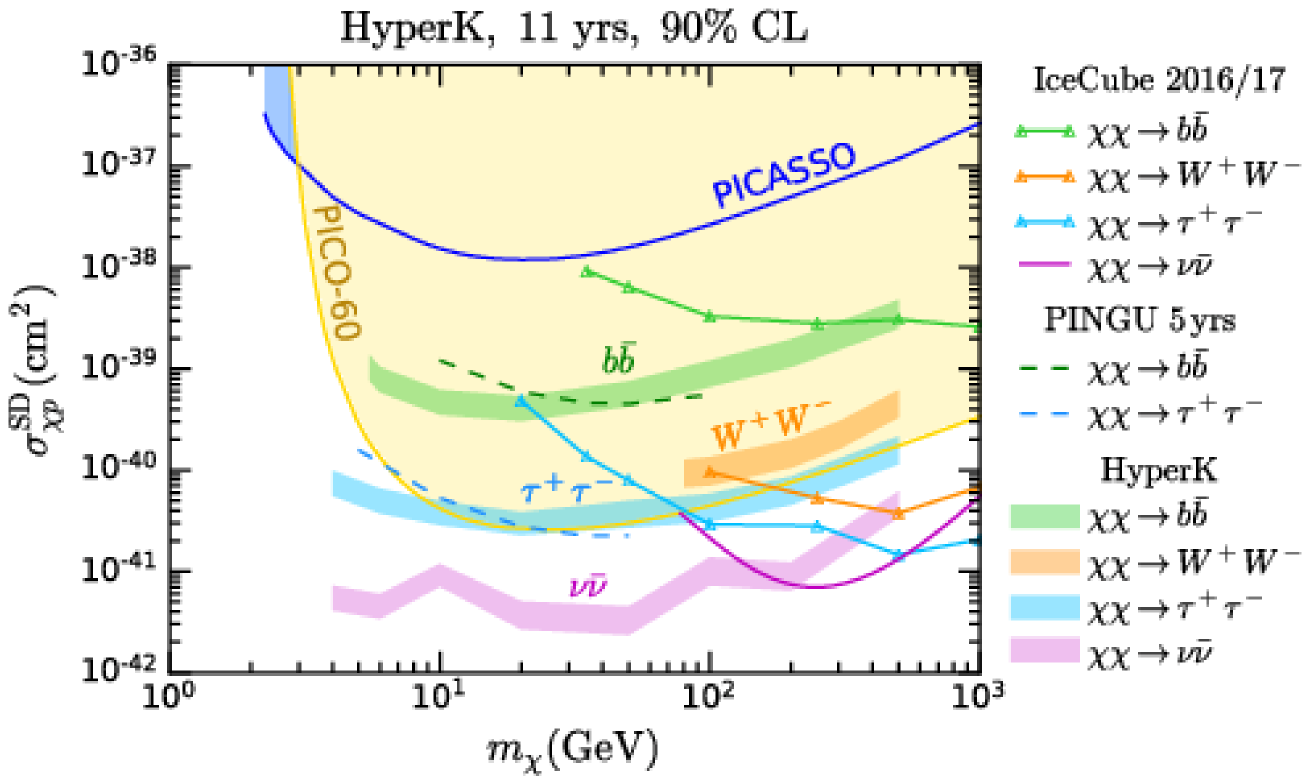
Dark matter annihilation in the Sun – Neutrinos

Spin-Independent (SI)



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

Spin-Dependent (SD)

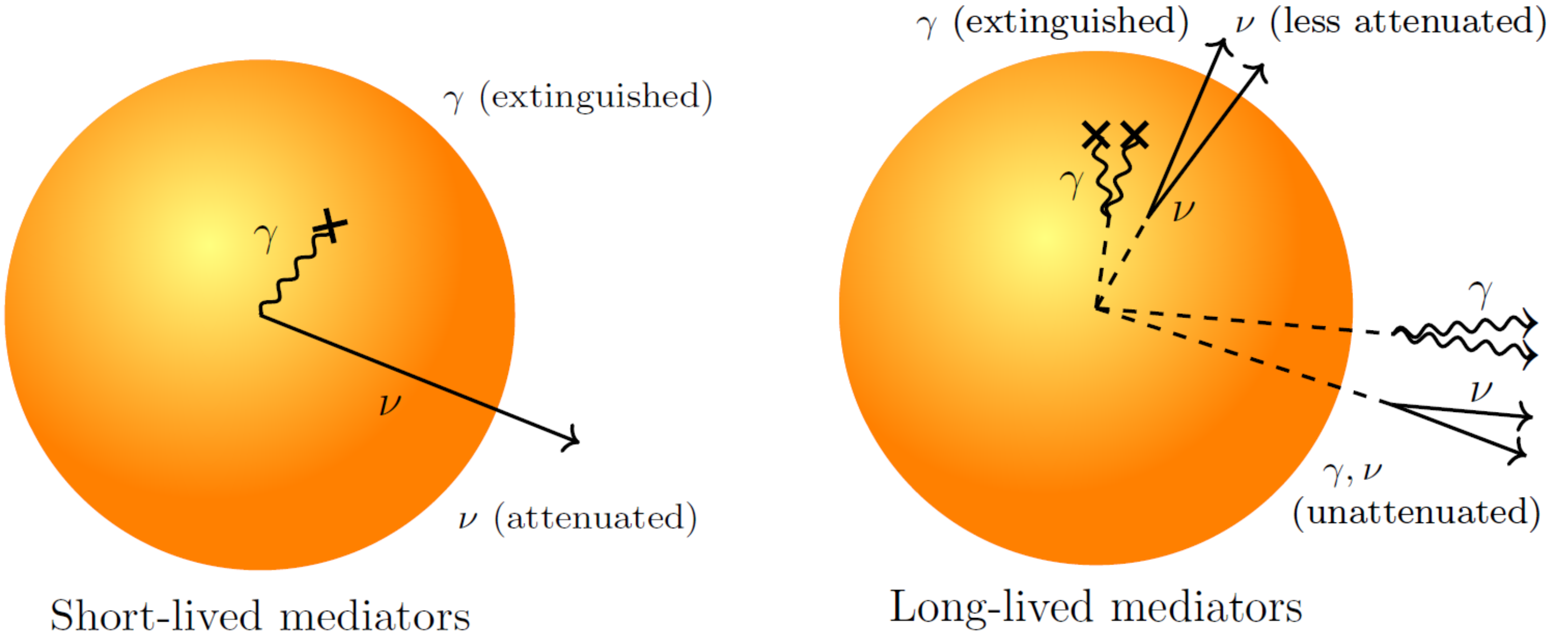


Bell, Dolan & Robles, arXiv:2107.04216

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):

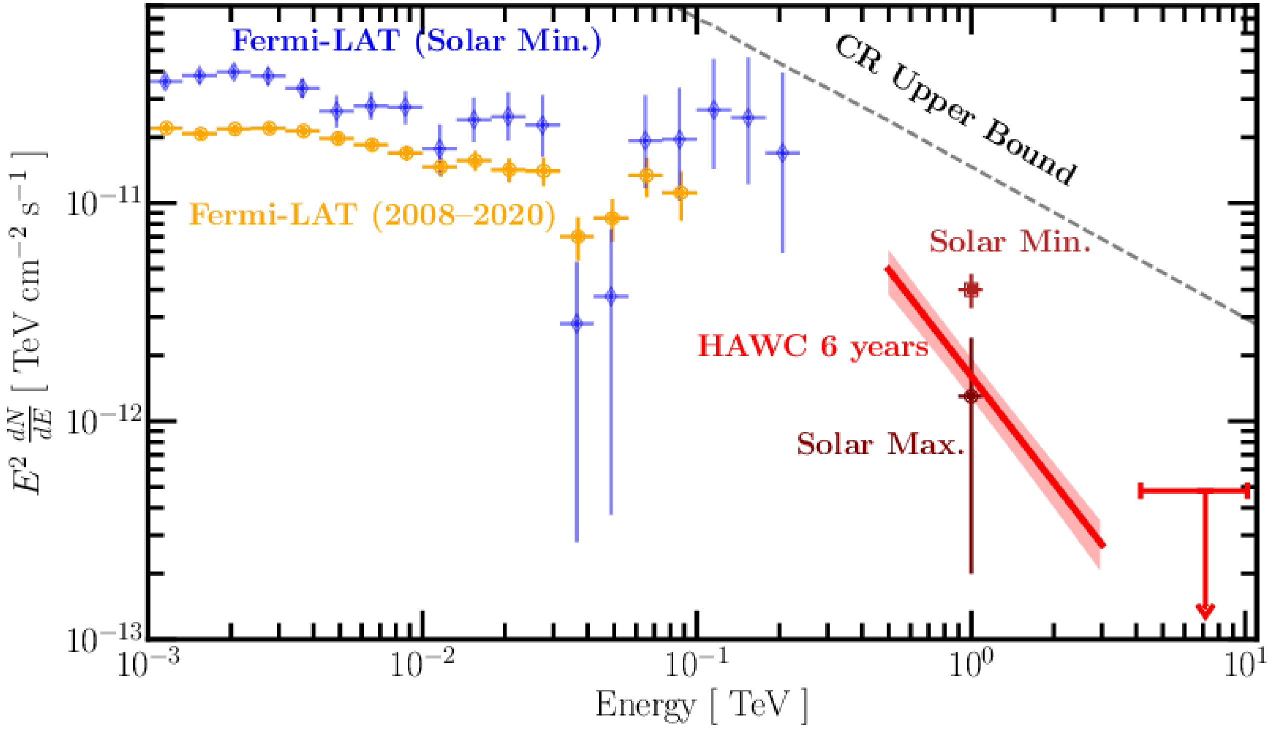
- ➢ Annihilation products can escape the Sun
- ➢ Decay between Sun and Earth → solar gamma rays or cosmic rays (Batell arXiv:0910.1567)
- ➢ Decay beyond solar core → less attenuation of neutrino signal (NFB & Petraki, JCAP 2011)



Leane, Ng & Beacom, arXiv:1703.04629

Annihilation to dark mediators → *Solar gamma rays*

Solar gamma-ray measurements: Fermi-LAT and HAWC



HAWC collaboration, Phys Rev. Lett 131 , 051201 (2023)

Dark matter annihilation, e.g.:

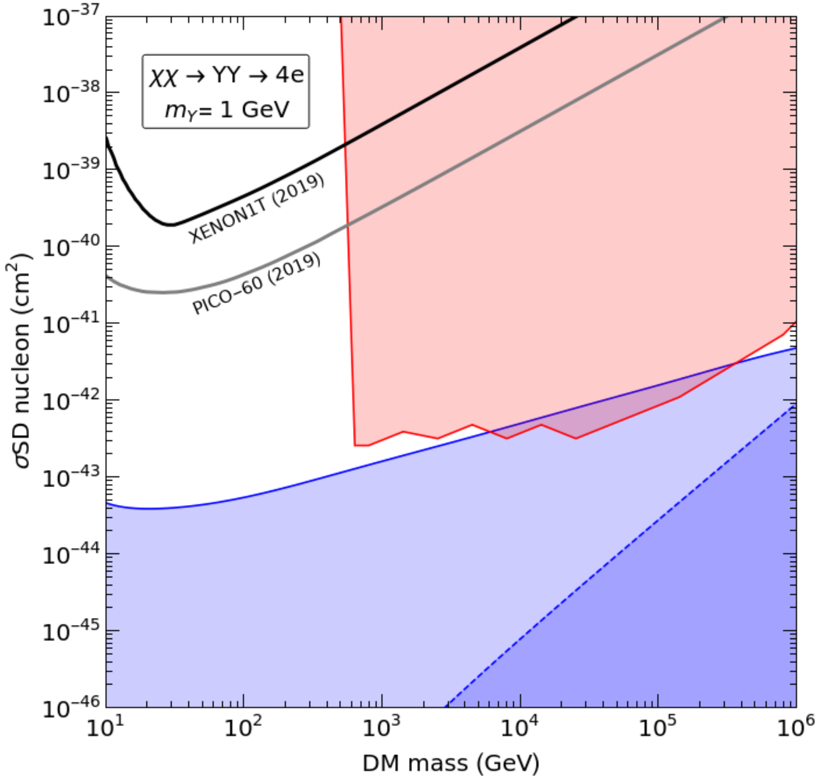
$$\chi\chi \rightarrow \gamma_D \gamma_D \rightarrow e^+e^-e^+e^-$$

Electron final states radiate photons. Quark final states produce photons via hadronization or decay.

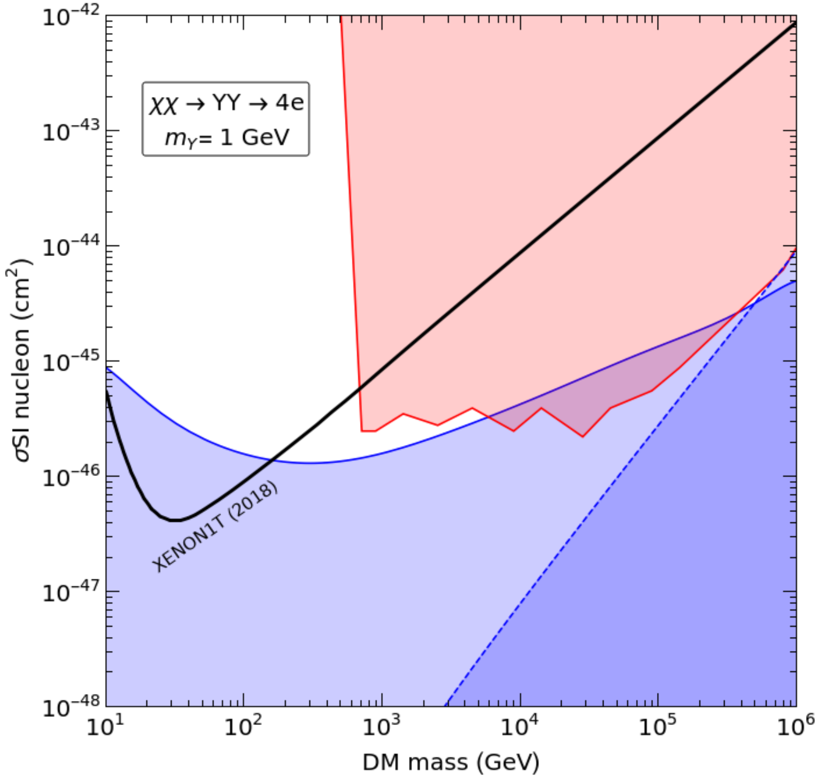
Gamma Rays from the Sun

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

Spin-Dependent (SD)



Spin-Independent (SI)



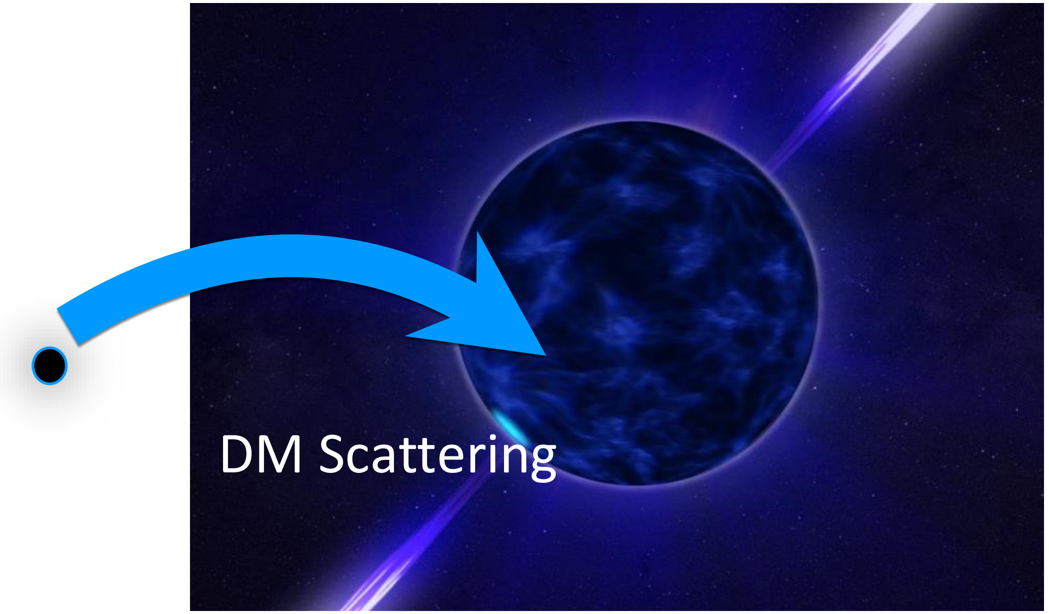
Bell, Dent
& Sanderson,
arXiv:2103.16794

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**

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

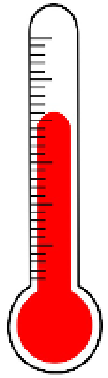


Neutron star heating

Baryakhtar et al
arXiv:1704.01577

→ from dark matter scattering plus annihilation

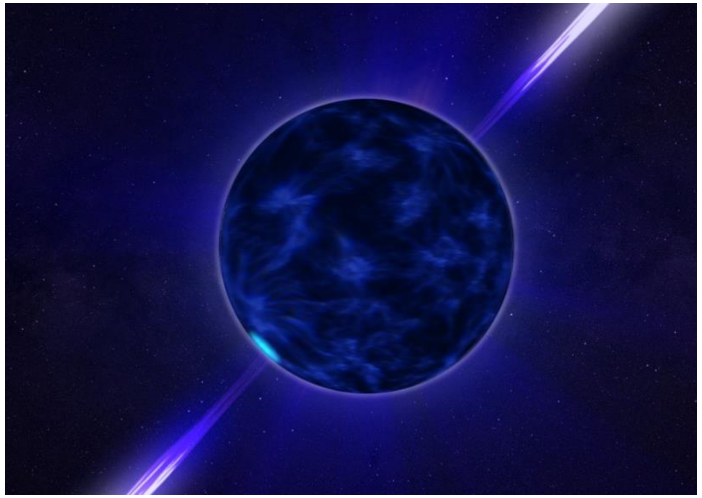
- **Capture** (plus subsequent energy loss)
  → DM ***kinetic energy*** heats neutron star ~ **1700K**
- **Annihilation** of thermalised dark matter
  → DM ***rest mass energy*** heats neutron star ~ **additional 700K**



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

Old isolated neutron stars should cool to below 1000 K after ~ 10 Myr

DM capture in Neutron Stars



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

- **No velocity/momentum suppression**
  → ***Sensitivity to interactions that direct detection experiments will never be able to see***

- 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

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

Improved capture calculations

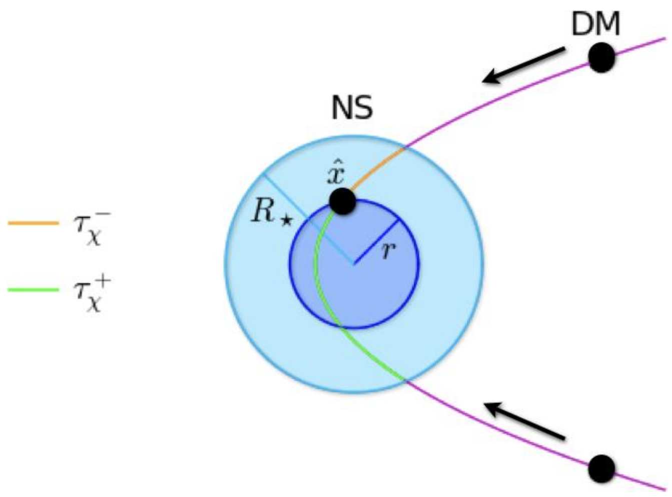
NFB, Busoni, Robles & Virgato,
JCAP 09, 028 (2020), JCAP 03, 086 (2021)

Early treatments of the capture process used various simplifying assumptions.

Important physical effects include:

- Consistent treatment of NS structure
  - Radial profiles of EoS dependent parameters, and GR corrections by solving the TOV eqns.
- Gravitational focusing
  - DM trajectories bent toward the NS star
- Fully relativistic (Lorentz invariant) scattering calculation
  - Including the fermi momentum of the target particle
- Pauli blocking
  - Suppresses the scattering of low mass dark matter
- Neutron star opacity
  - Optical depth
- Multi-scattering effects
  - For large DM mass, probability that a collision results in capture is less than 1
- **Momentum dependence of hadronic form factors**
- **Nucleon interactions**

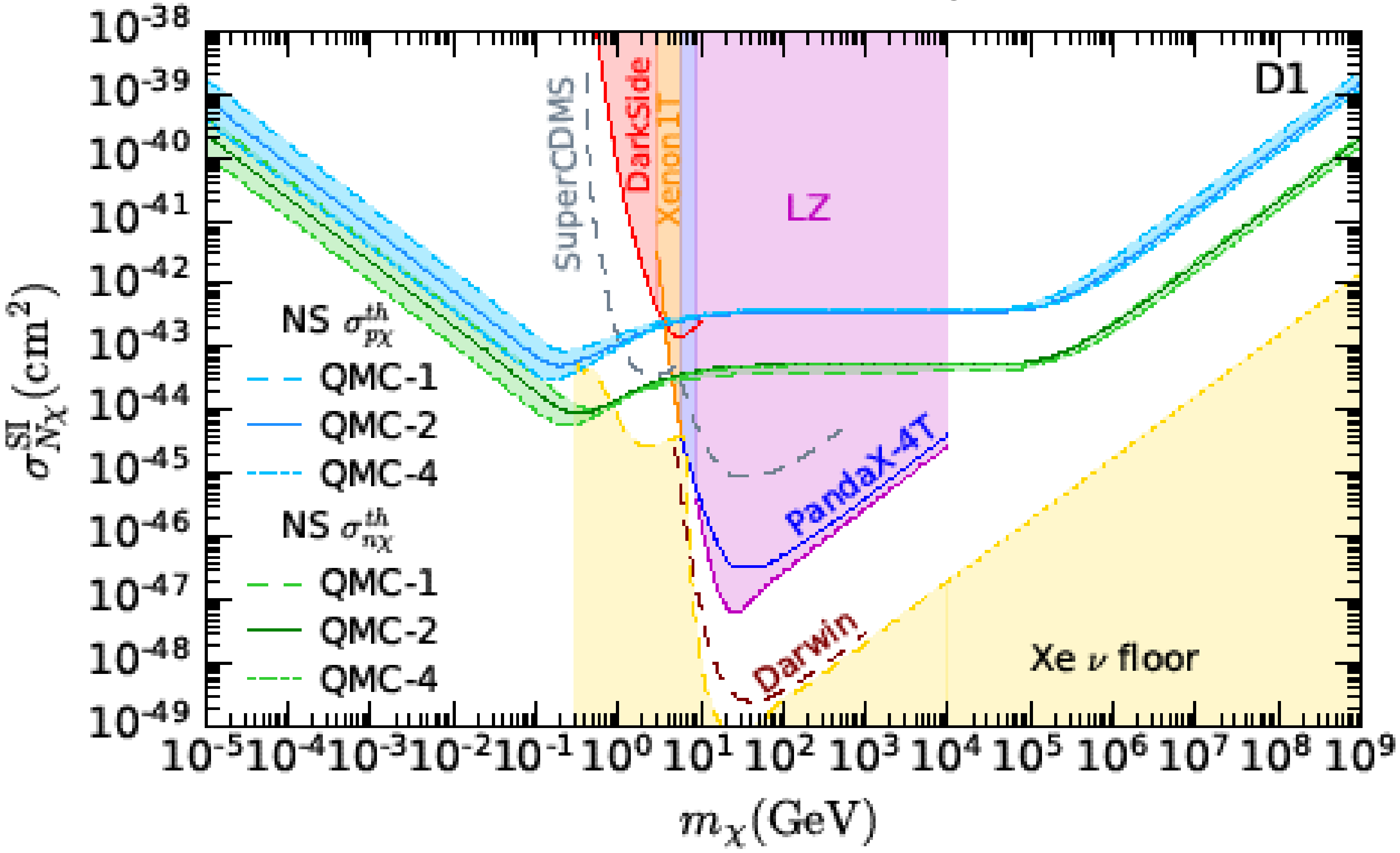
} NFB, Busoni, Motta, Robles, Thomas, & Virgato, PRL 2021



NS Heating Sensitivity (projected limits)

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

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



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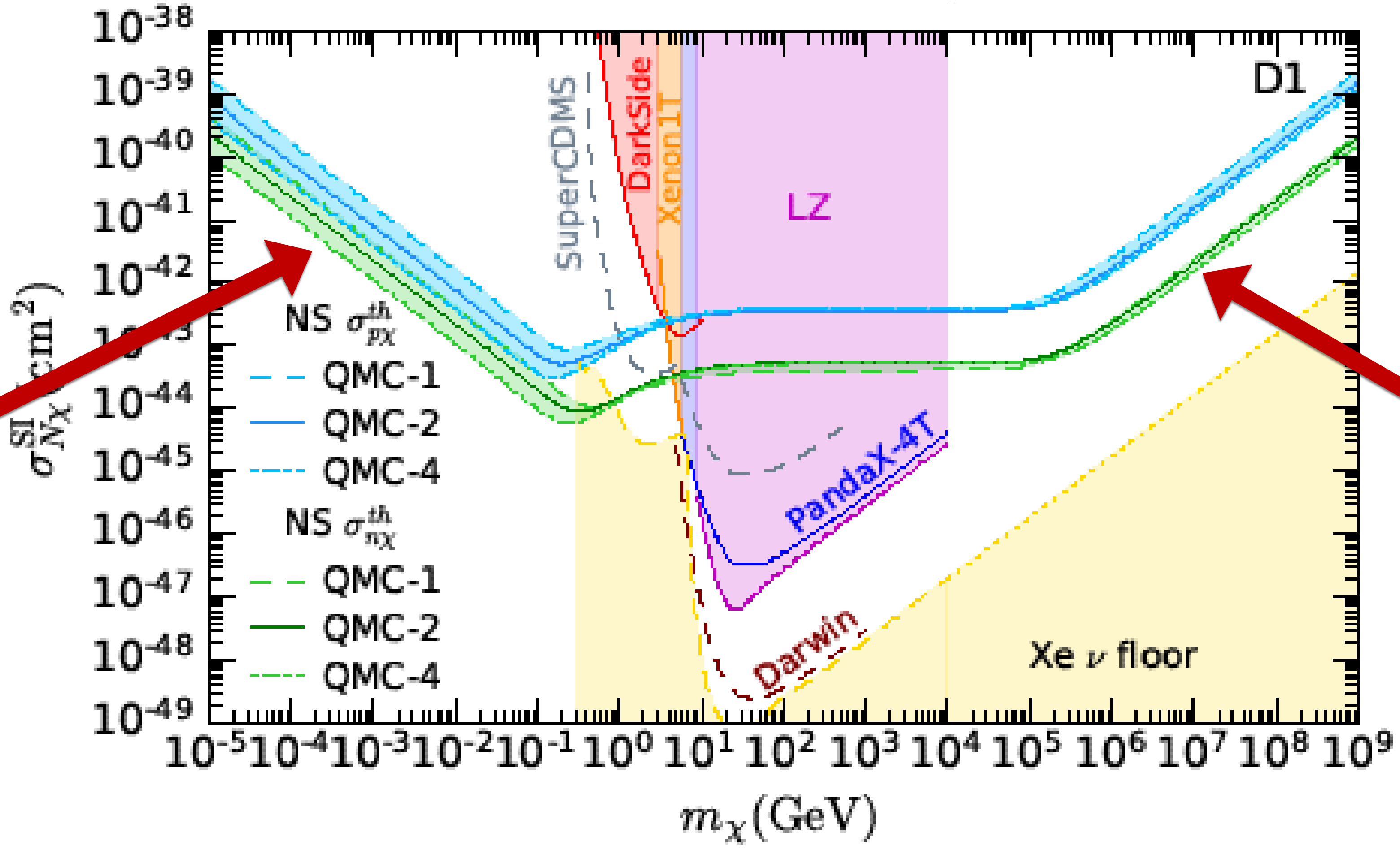
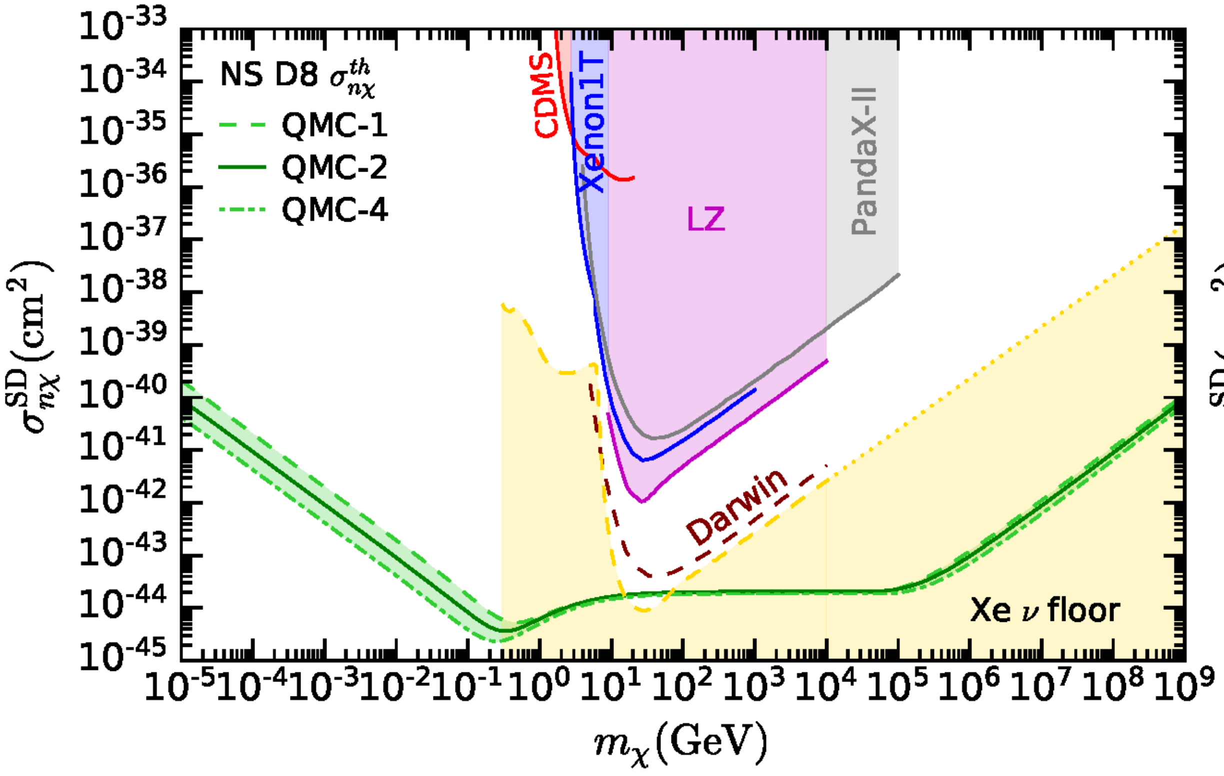


Pauli blocking from degenerate neutrons

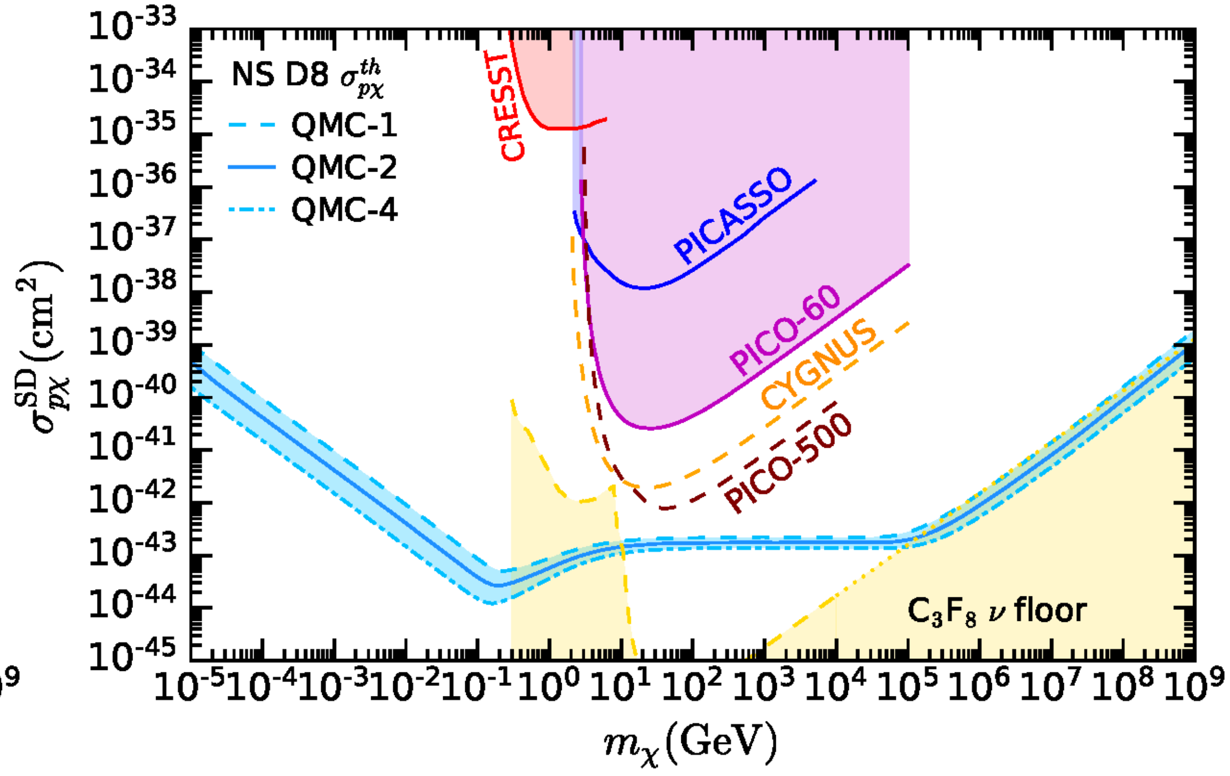
Momentum transfer in single collision not sufficient for capture

NS Heating Sensitivity: SD nucleon scattering

DM-neutron (SD scattering)

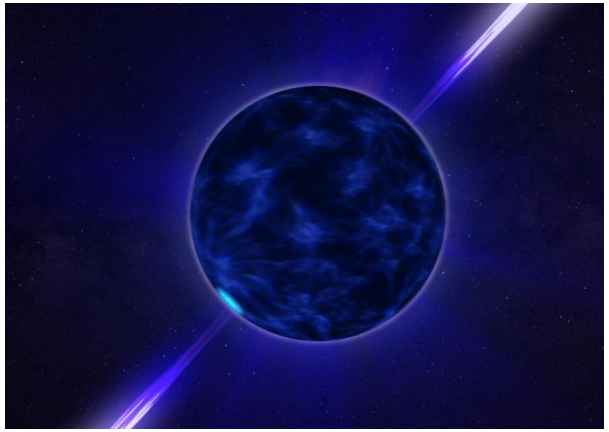


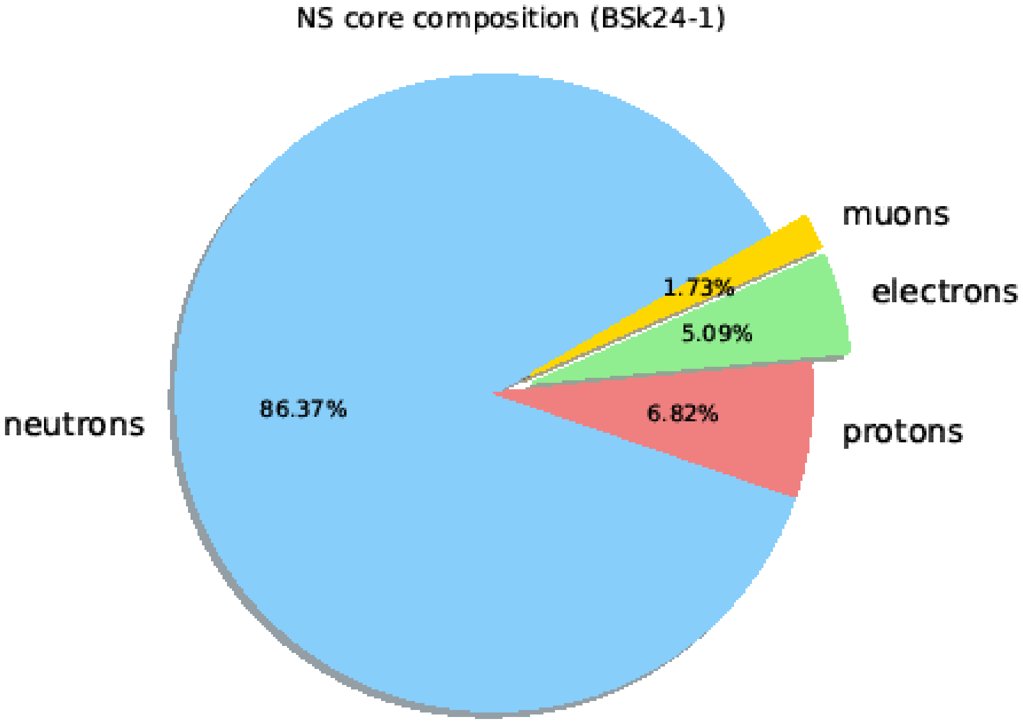
DM-proton (SD scattering)



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

Leptons in Neutron Stars

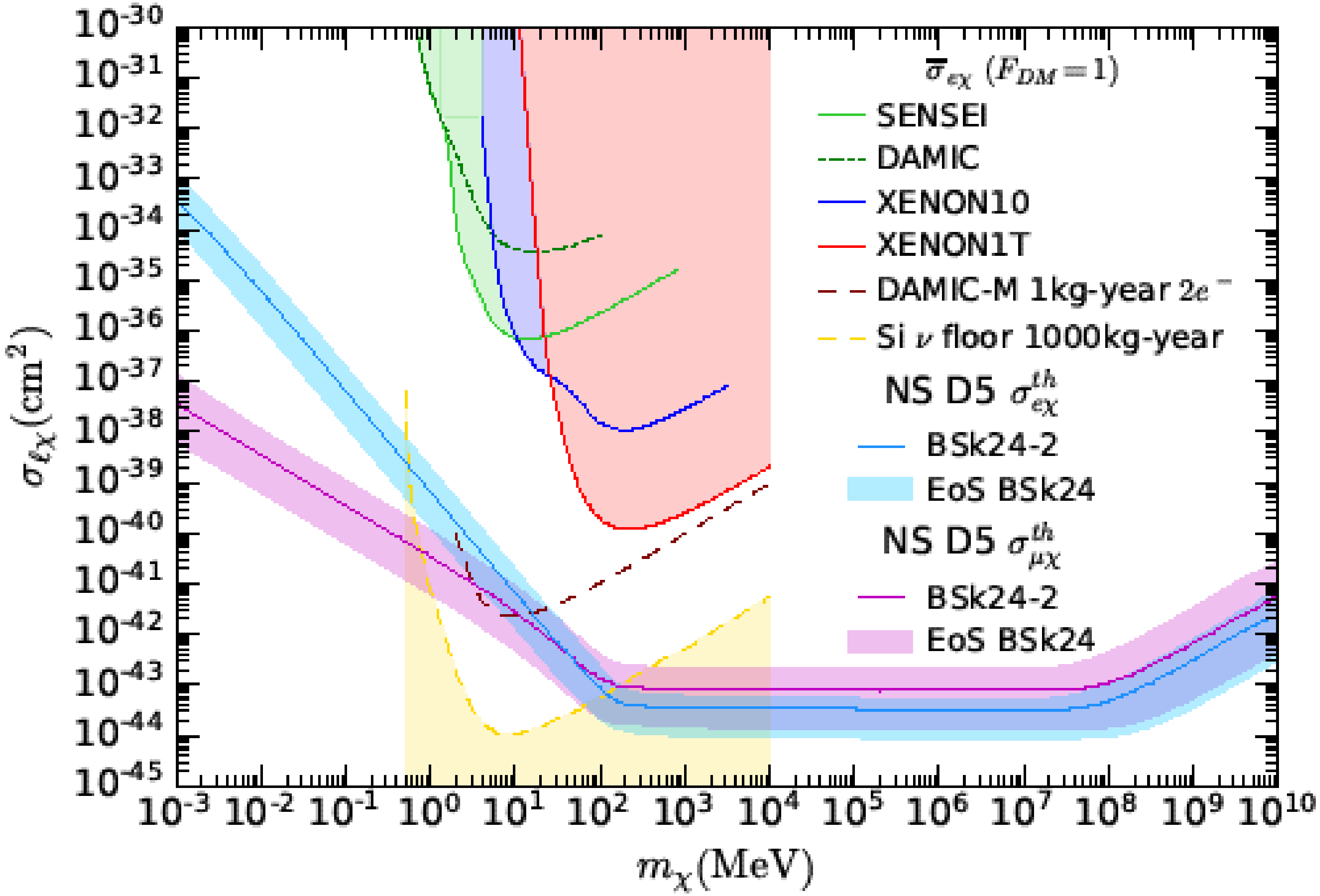




Beta equilibrium in the core determines the composition:

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

NS Heating Sensitivity: lepton scattering



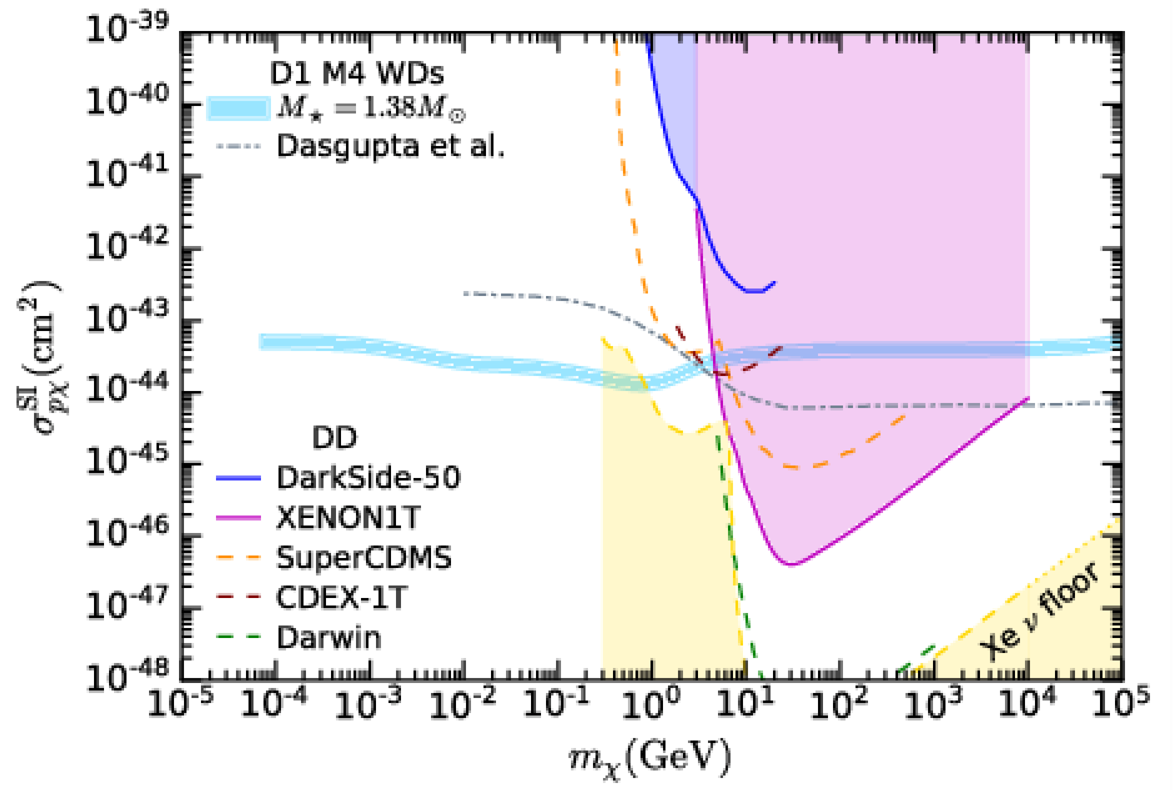
Bell, Busoni, Robles & Virgato arXiv:2010.13257

Muon scattering

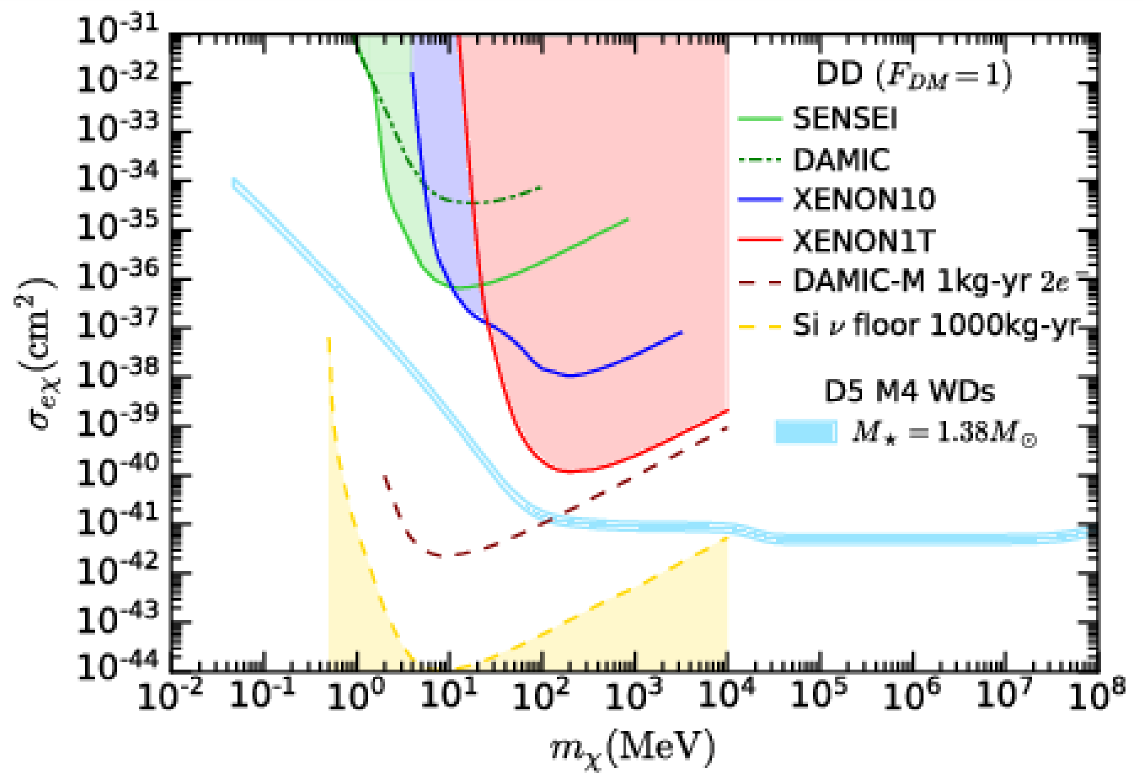
Electron scattering

White dwarfs in M4 globular cluster

DM-nucleon scattering



DM-electron scattering



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

Summary

Testing the thermal-relic hypothesis with indirect detection

- Upcoming observations will make significant progress in closing the WIMP window
- Important to test DM annihilation to neutrinos

Boosted (high energy) dark matter

- Cosmic ray upscattering is inevitable
- Can be seen in neutrino experiments
- Limits are model dependent

Dark matter capture in stars

- Relativistic DM (boosted upon infall to neutron star)
- Can probe low mass dark matter, and look below the neutrino floor