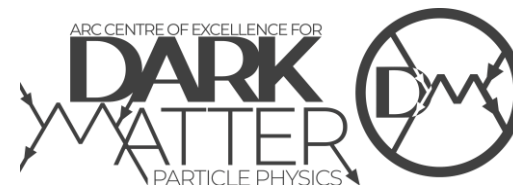# Dark Matter Searches with Astrophysics
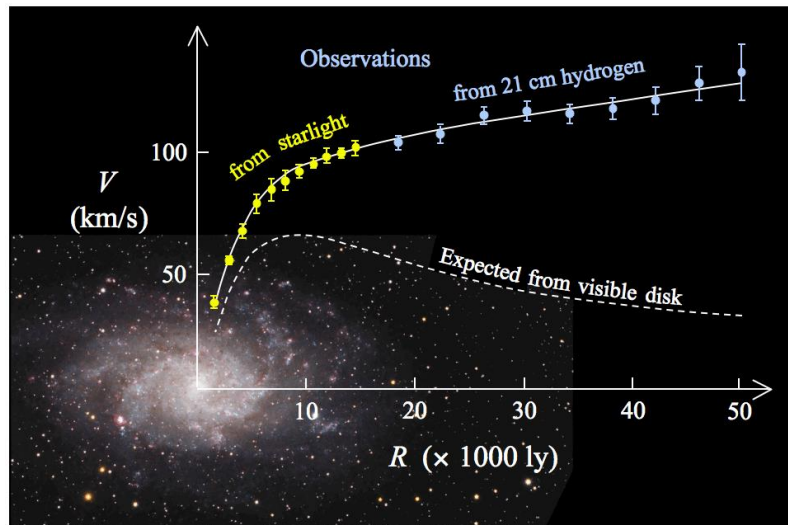
Nicole Bell
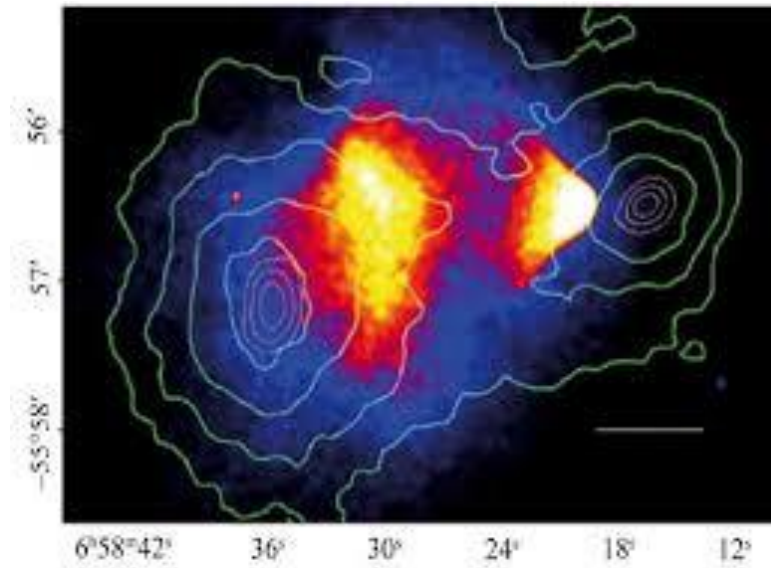### The University of Melbourne

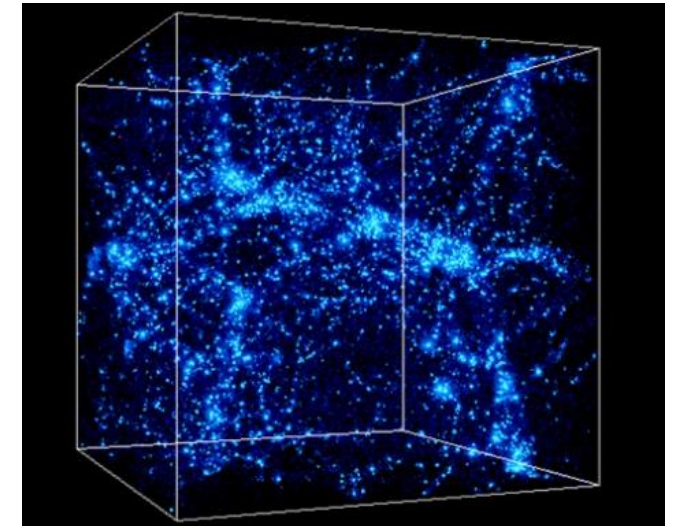# Evidence for dark matter

Astrophysical observations consistently point to the need for dark matter
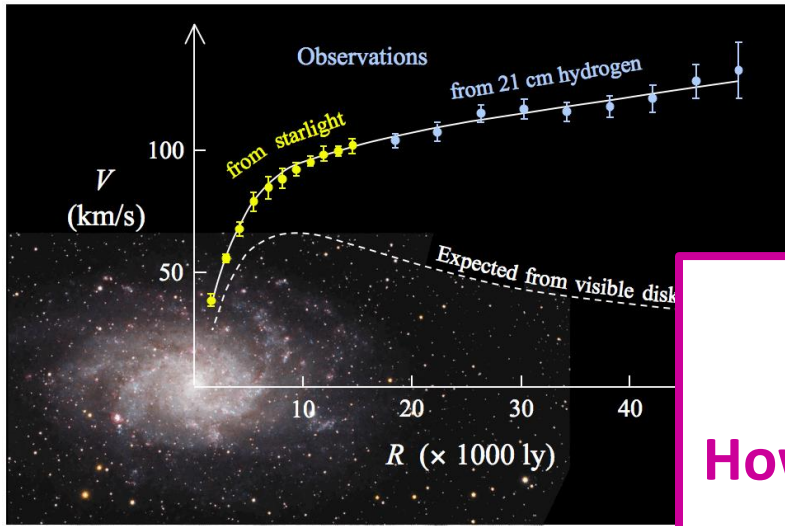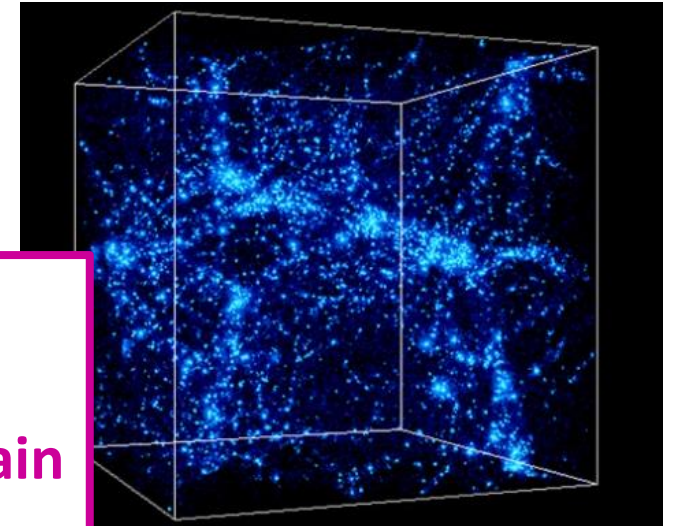

Galaxy rotation curves

Clusters of galaxies

Large Scale Structure
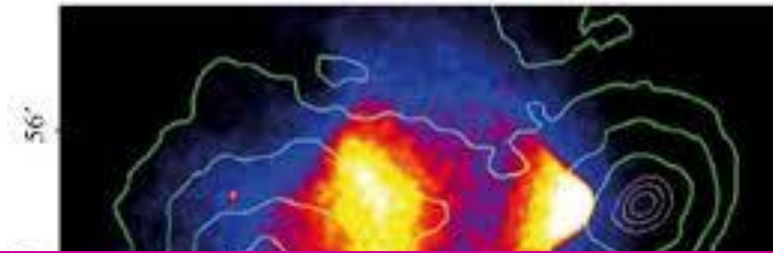
Evidence for dark matter

Astrophysical observations consistently point to the need for dark matter

Galaxy rotation curves

How do we use astrophysics to constrain dark matter <u>particle</u> properties?

Large Scale Structure

Looking for WIMP-type dark matter

Production in particle colliders
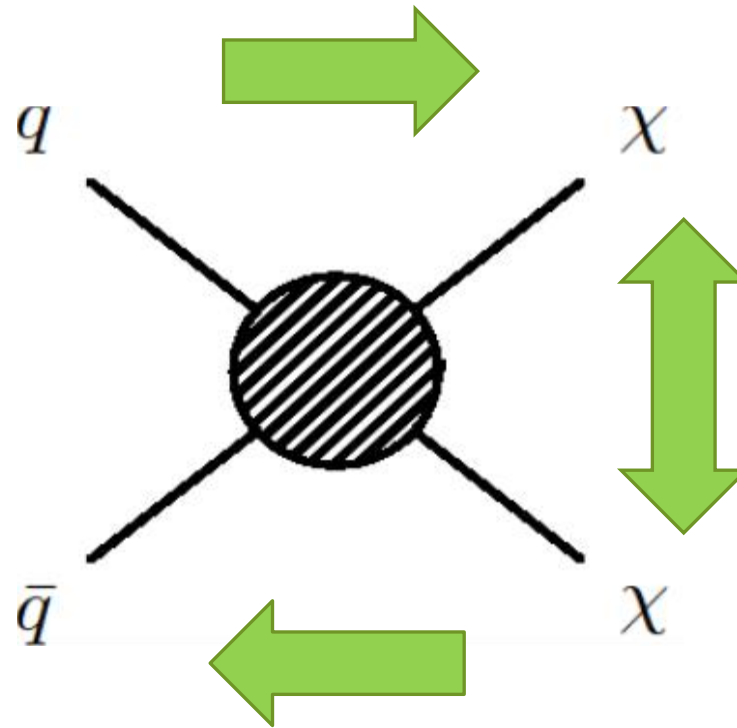
Scattering in direct detection experiments

Dark matter annihilation in the galaxy

Looking for WIMP-type dark matter

Production in particle colliders

Scattering in
direct detection **& neutrino** expts
and in stars

Dark matter annihilation in the galaxy
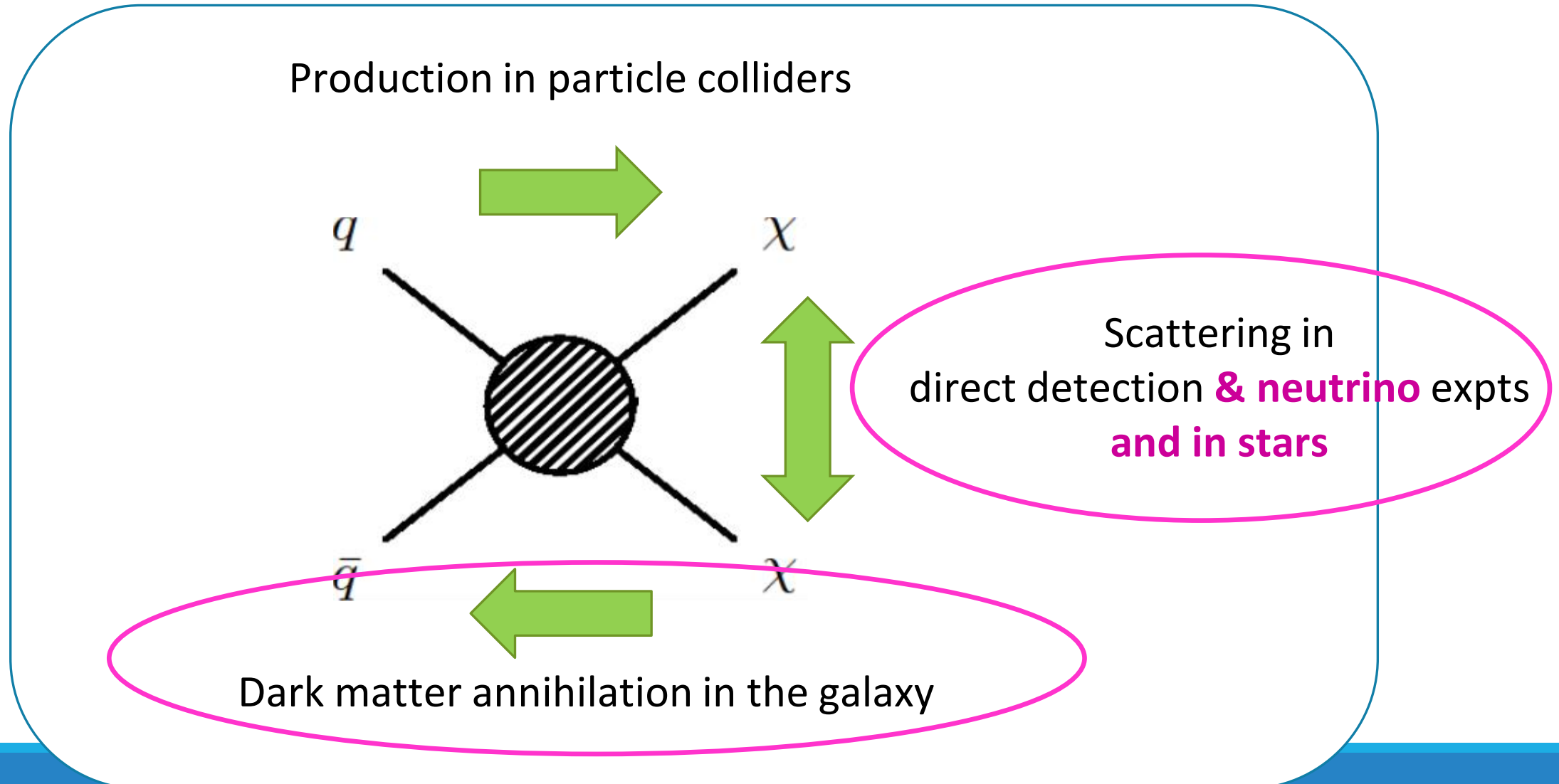
Indirect detection – Detecting dark matter annihilation in space
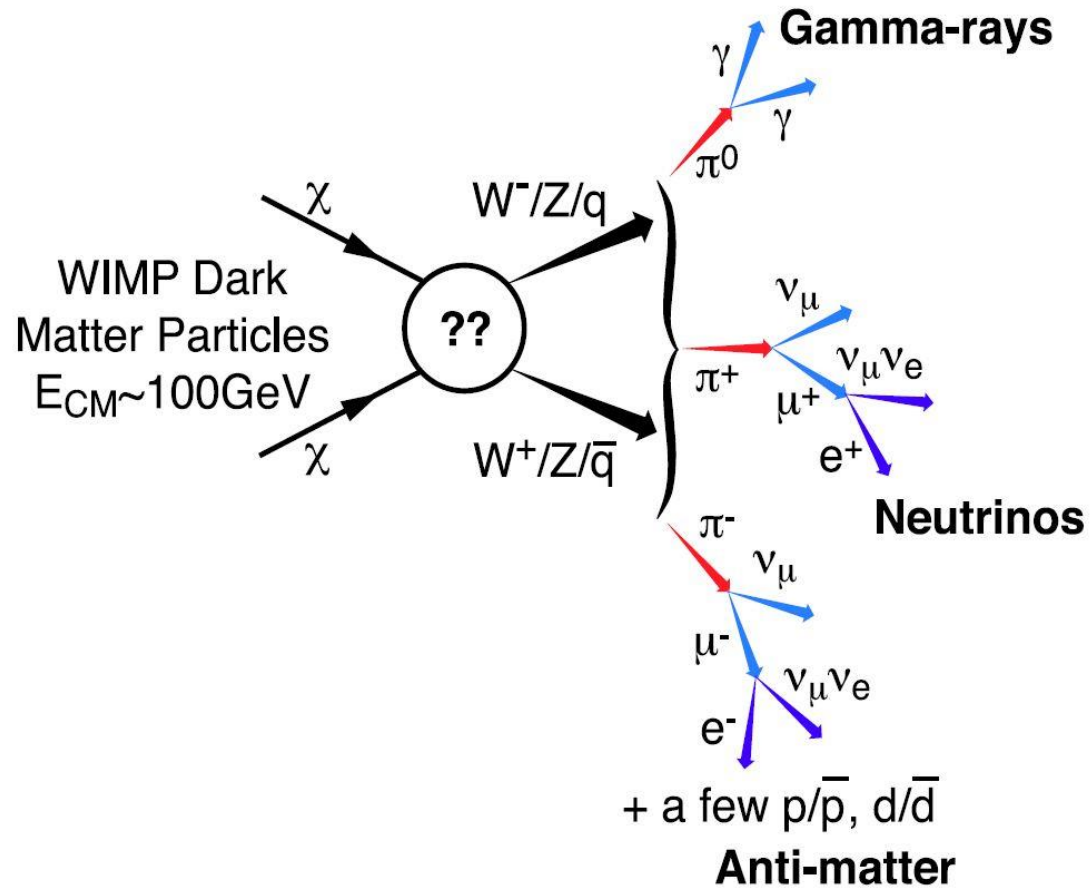
Indirect detection probes the dark matter annihilation cross-section

→ **The most direct test of the thermal-relic dark matter paradigm**
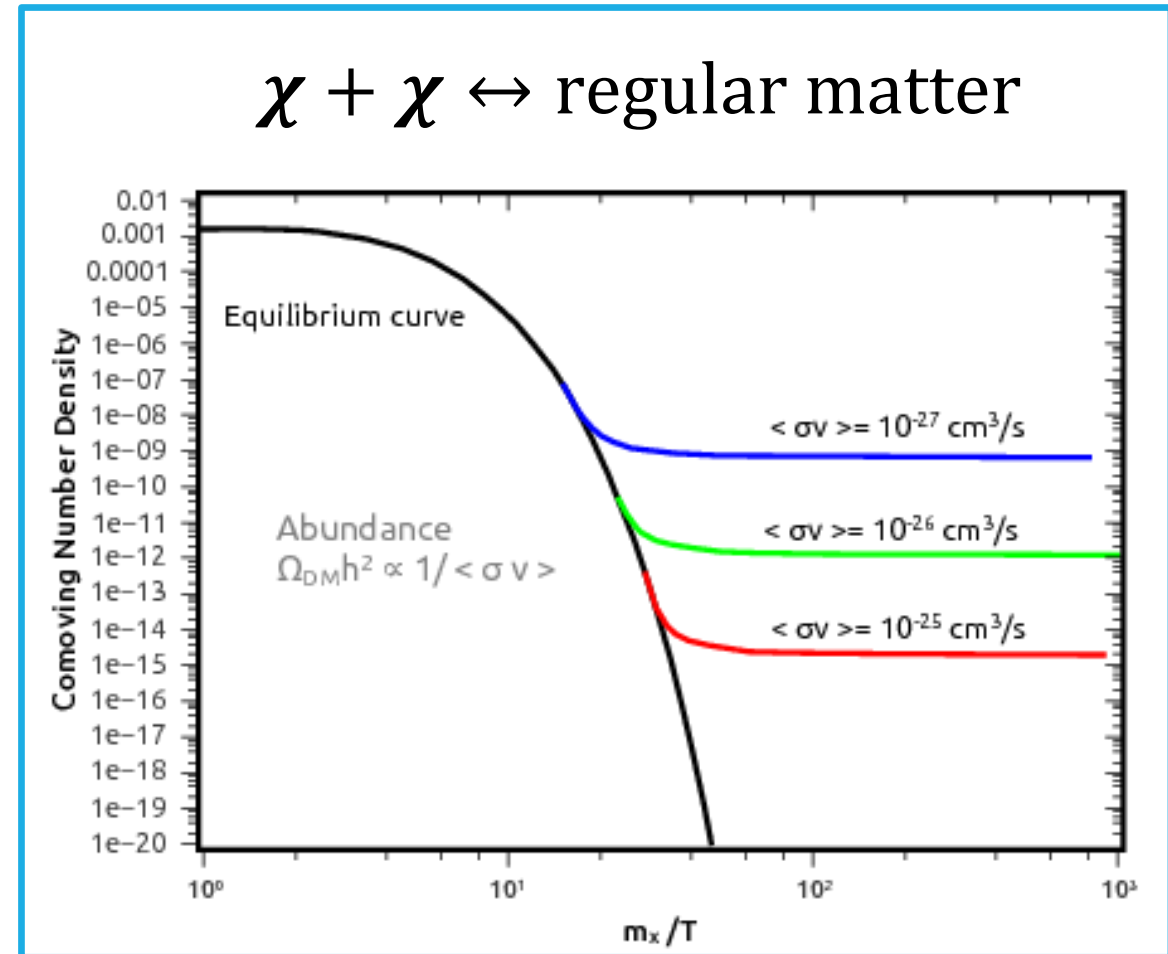
Thermal relic cross section (the WIMP miracle):

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:

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

$\chi + \chi \leftrightarrow$ regular matter
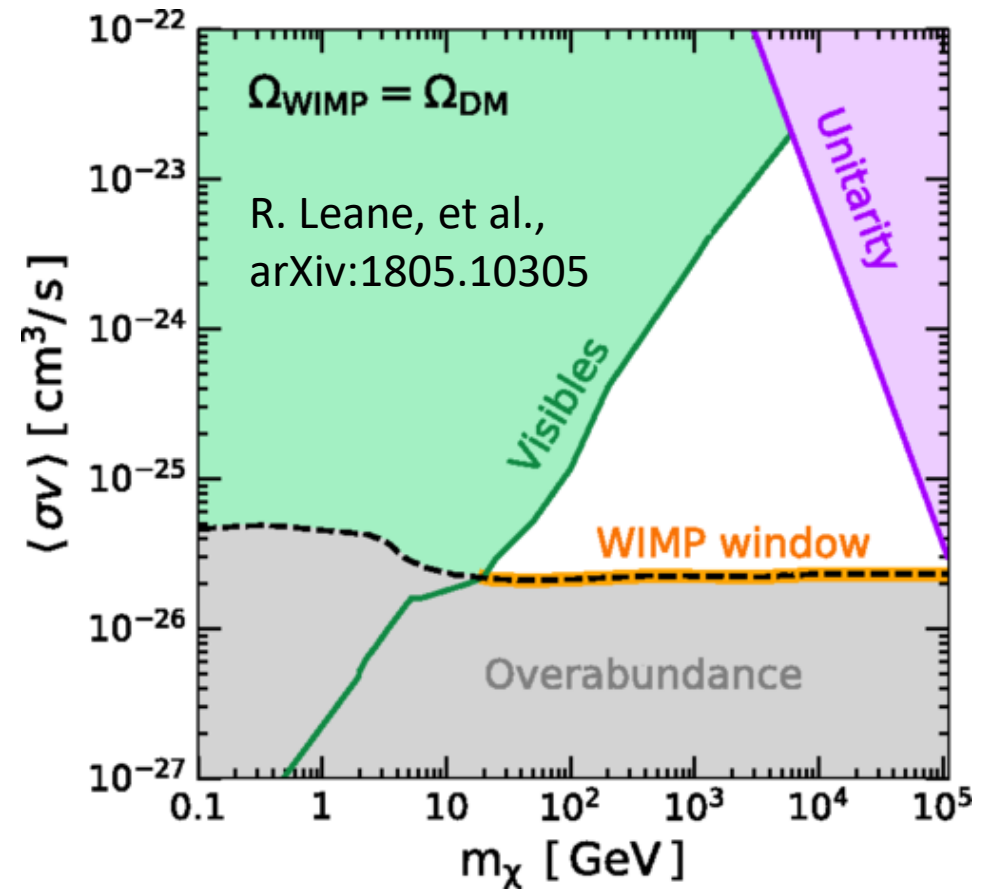
The WIMP window

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
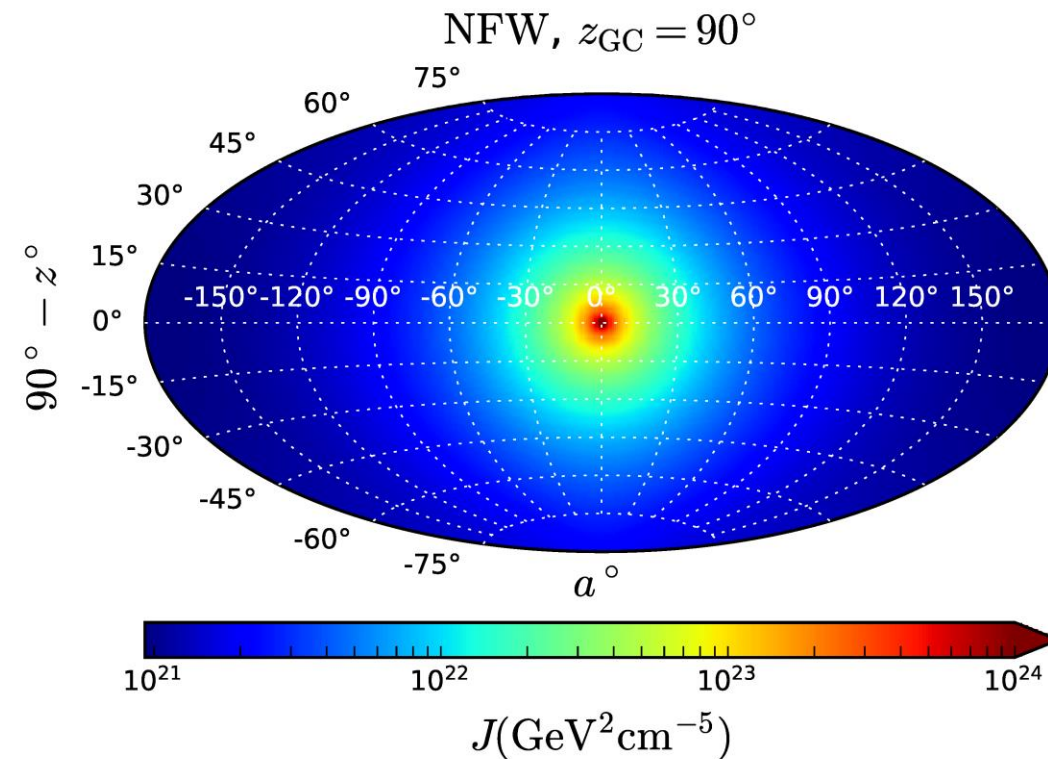
Dark matter annihilation signal

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

Annihilation cross section

Integral of (density)^2 along line of sight
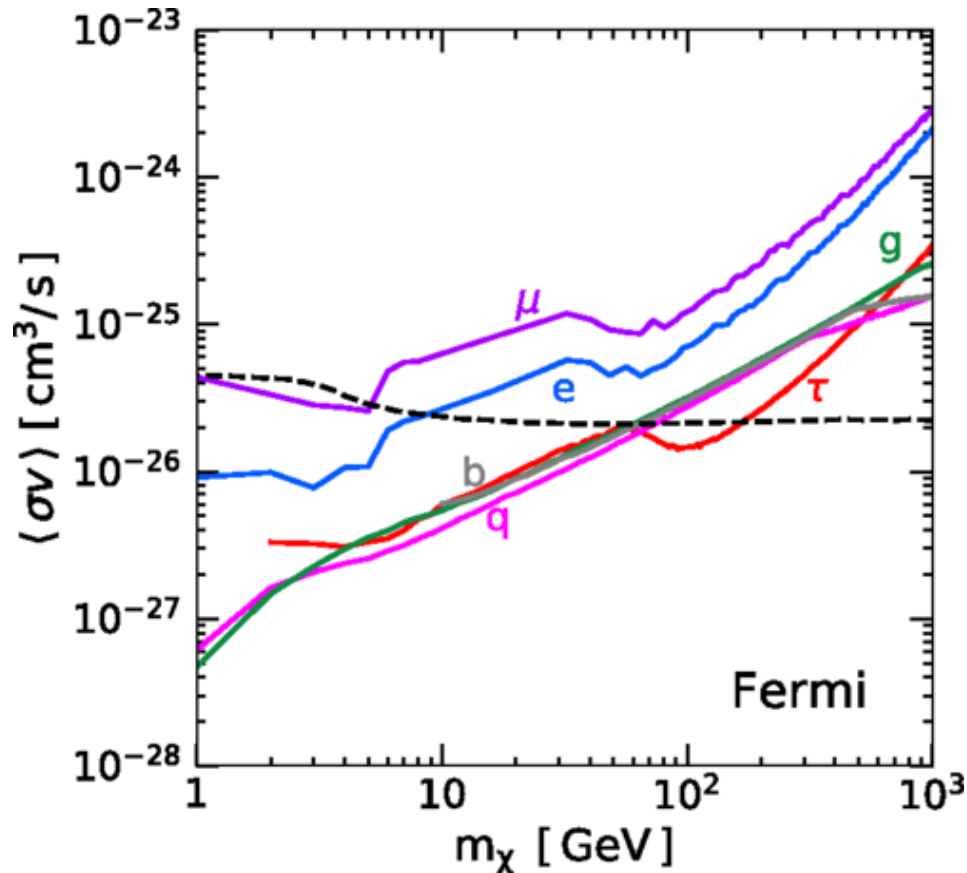
Spectrum per annihilation

Bell, Dolan, Robles, arXiv: 2005.01950
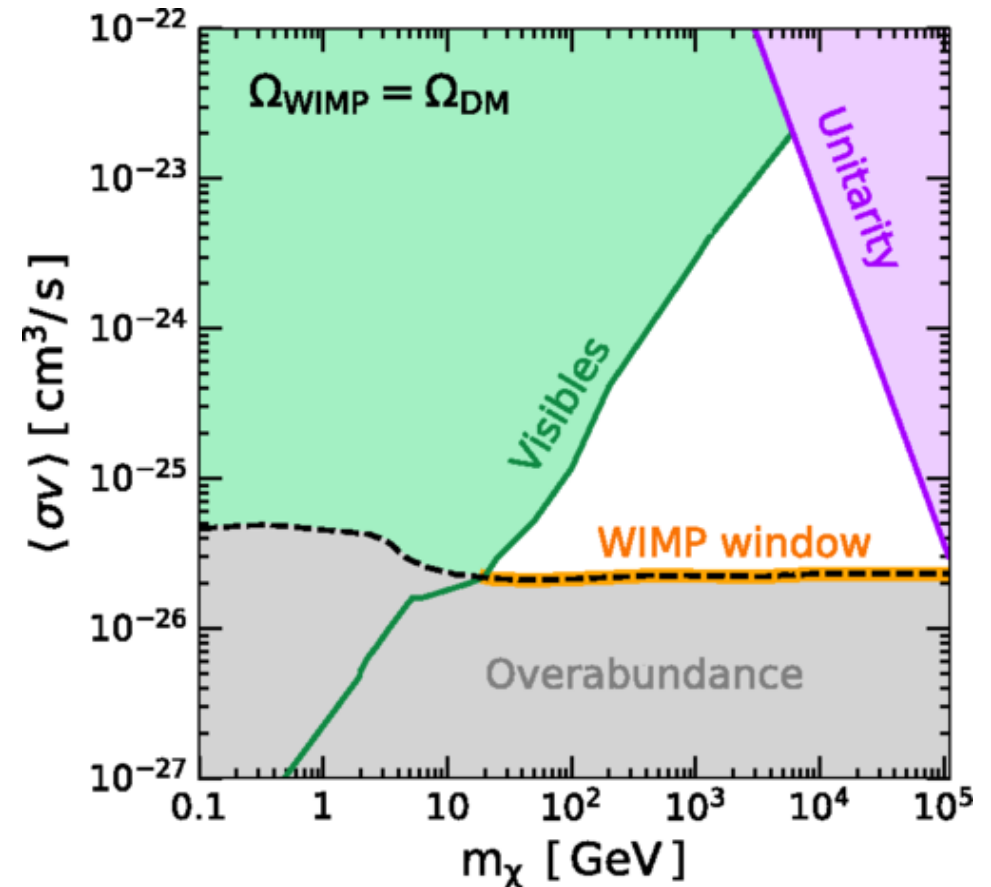
Indirect detection constraints
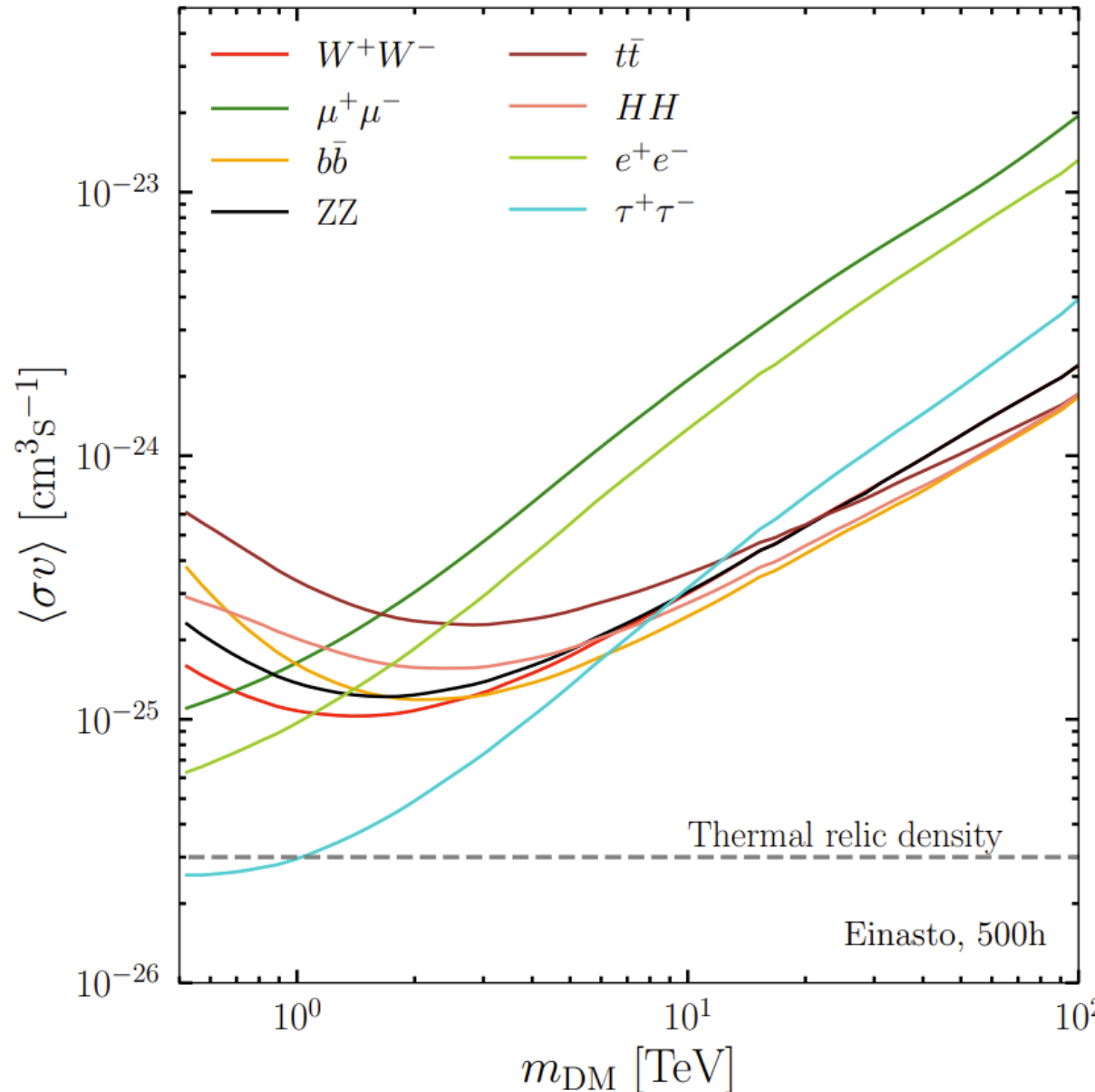
R. Leane, et al., arXiv:1805.10305

Fermi dSph limits

Annihilation to "visible" SM states

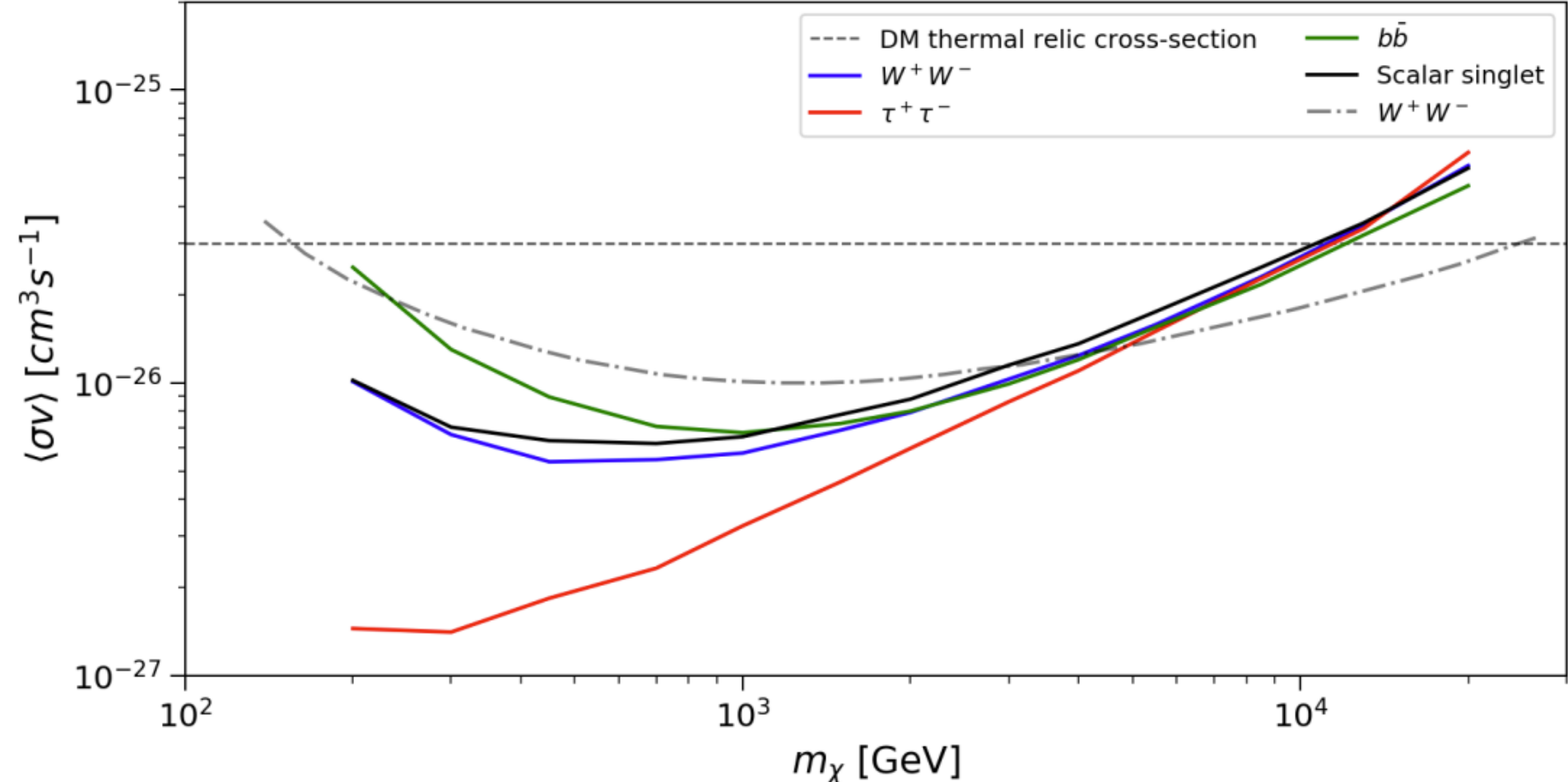# Closing the WIMP window: TeV gamma rays

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

Montanari, Moulin & Rodd, arXiv:2210.03140
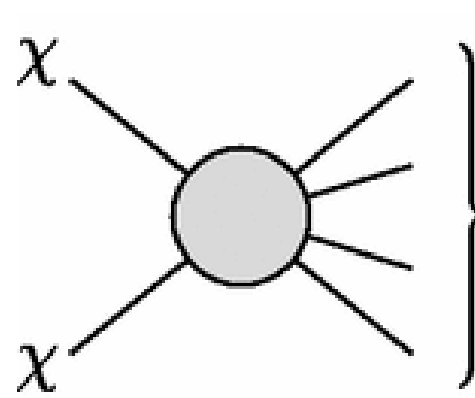
Closing the WIMP window: CTA projections

Mangipudi, Thrane & Balazs, arXiv:2112.10371

Closing the WIMP window: Neutrinos

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

$$\chi\chi \to \text{All Standard Model final states} = \text{"Visible" states: } \gamma\gamma, \bar{q}q, e^+e^-, \dots + \text{"Invisible" states: } \bar{\nu}\nu$$

Beacom, Bell, Mack, PRL 2007

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

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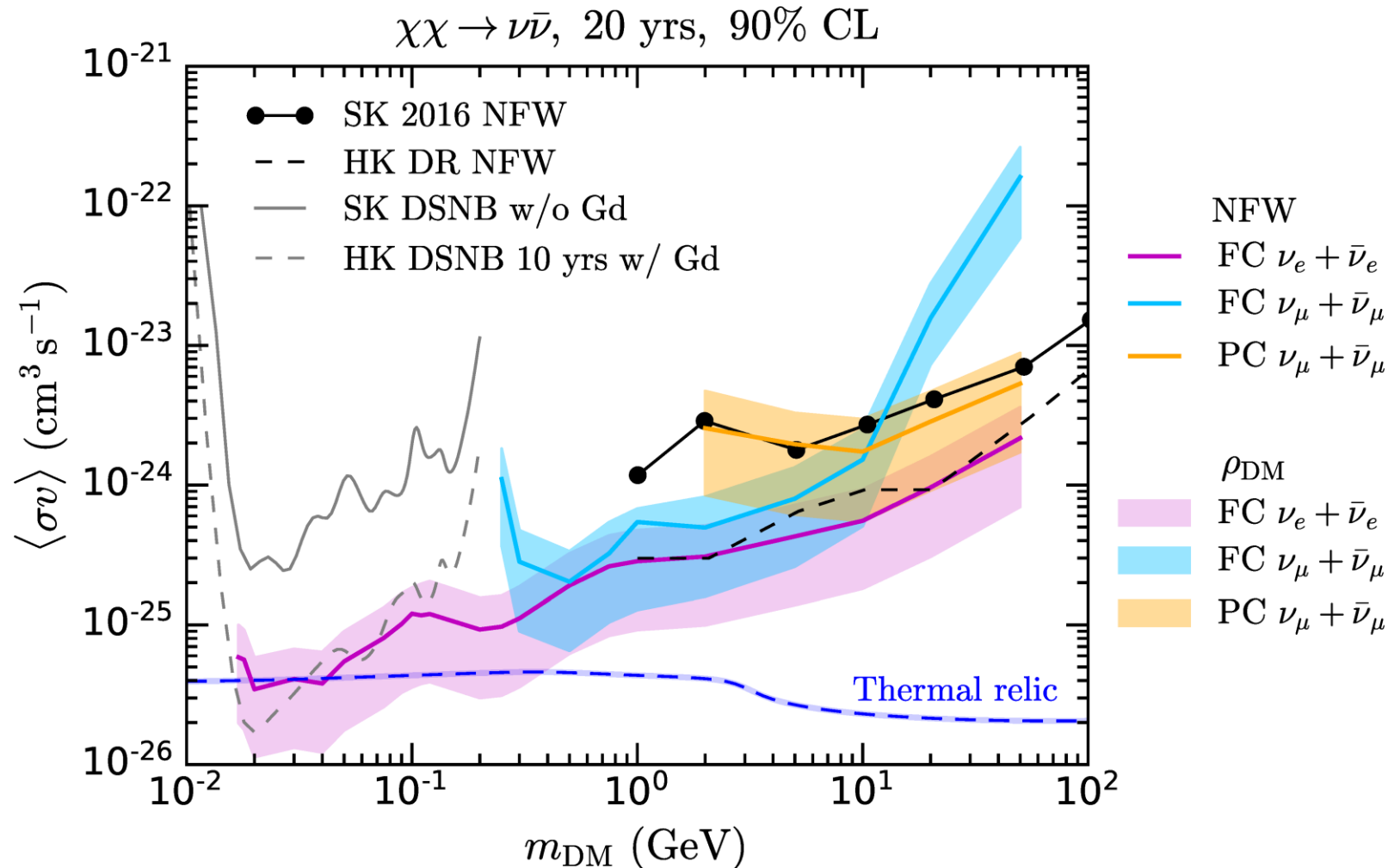

$\chi\chi \to \nu\bar{\nu}$, 20 yrs, 90% CL

Legend:
- SK 2016 NFW
- HK DR NFW
- SK DSNB w/o Gd
- HK DSNB 10 yrs w/ Gd

NFW
- FC $\nu_e + \bar{\nu}_e$
- FC $\nu_\mu + \bar{\nu}_\mu$
- PC $\nu_\mu + \bar{\nu}_\mu$

ρ_{DM}
- FC $\nu_e + \bar{\nu}_e$
- FC $\nu_\mu + \bar{\nu}_\mu$
- PC $\nu_\mu + \bar{\nu}_\mu$

Thermal relic

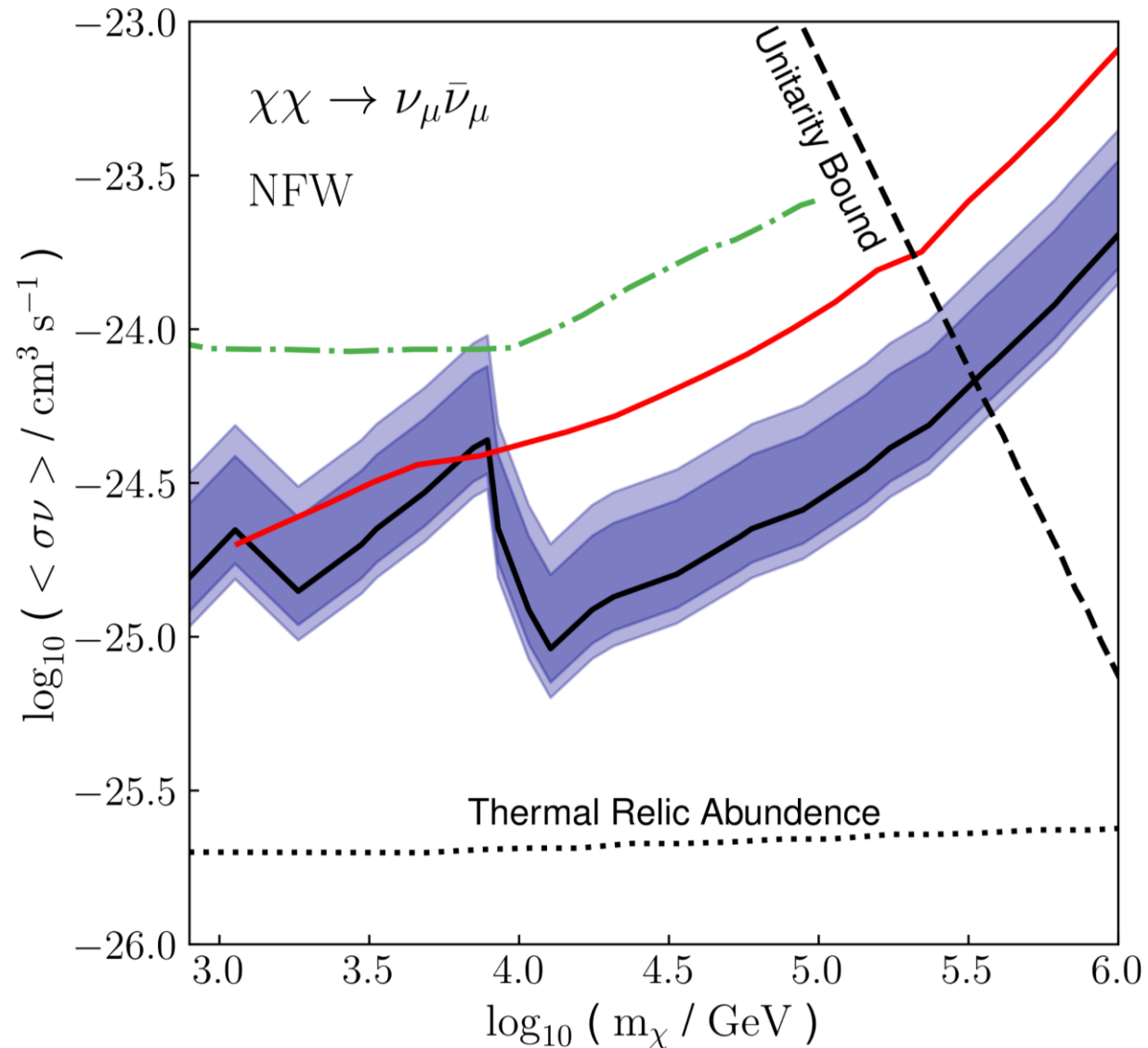Axis labels: $\langle \sigma v \rangle$ (cm^3 s^{-1}), m_{DM} (GeV)

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

NFW – central lines
Isothermal – upper
Moore - lower

Bell, Dolan, Robles, arXiv: 2005.01950
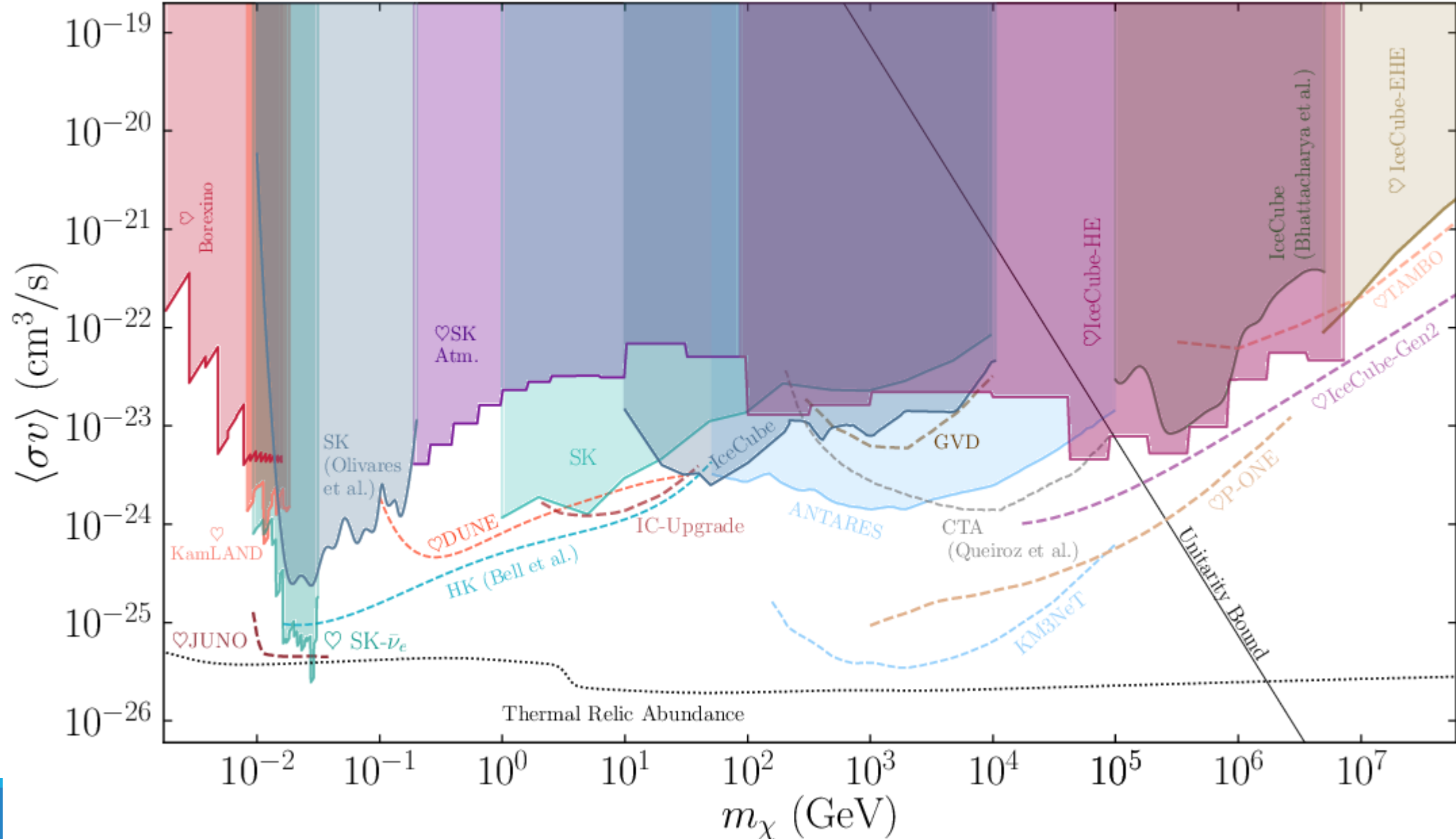
Annihilation to $\nu\bar{\nu}$ – large mass

Desai, Li & Meighen-Berger arXiv:2302.10542

Projection for 10 years of P-ONE
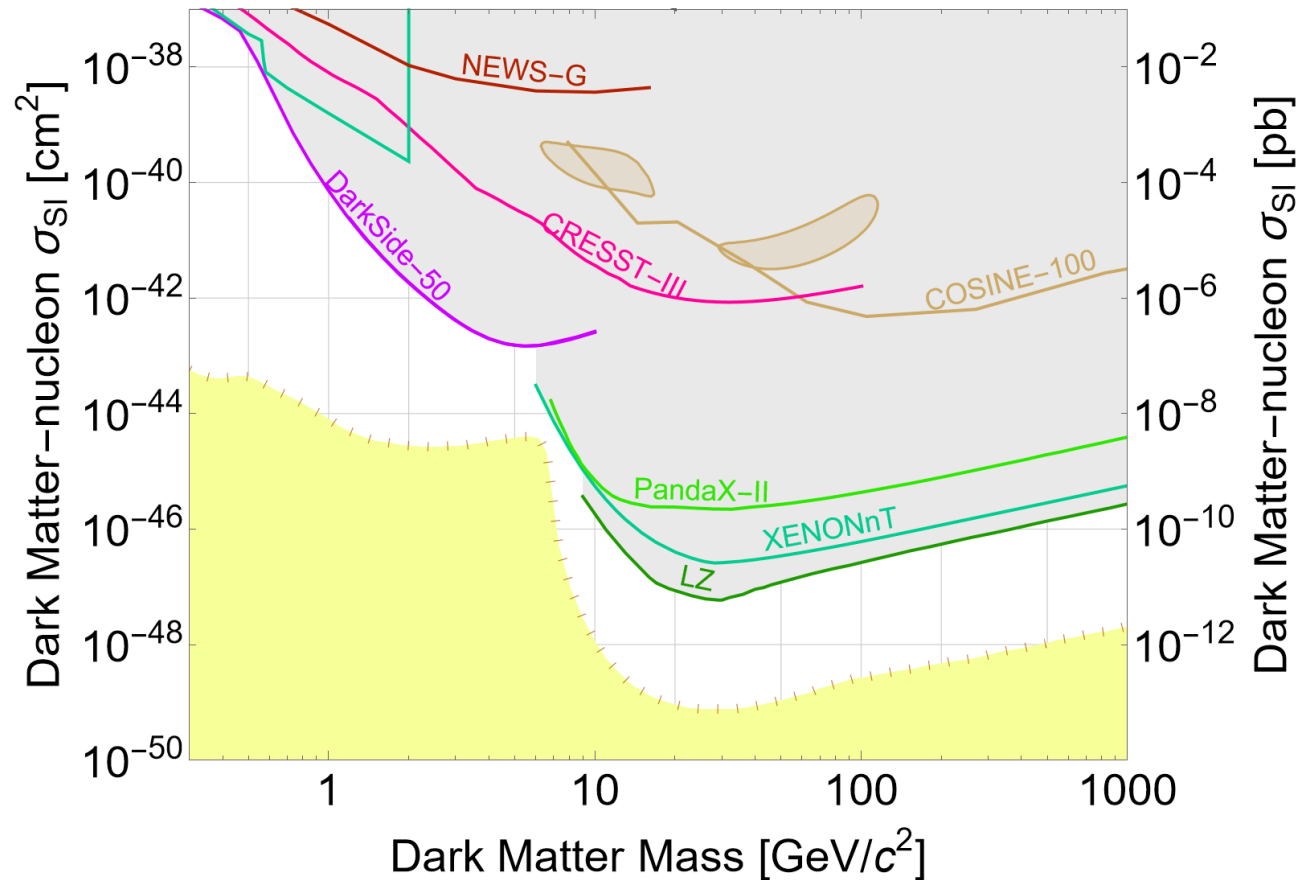
Annihilation to $\nu\bar{\nu}$
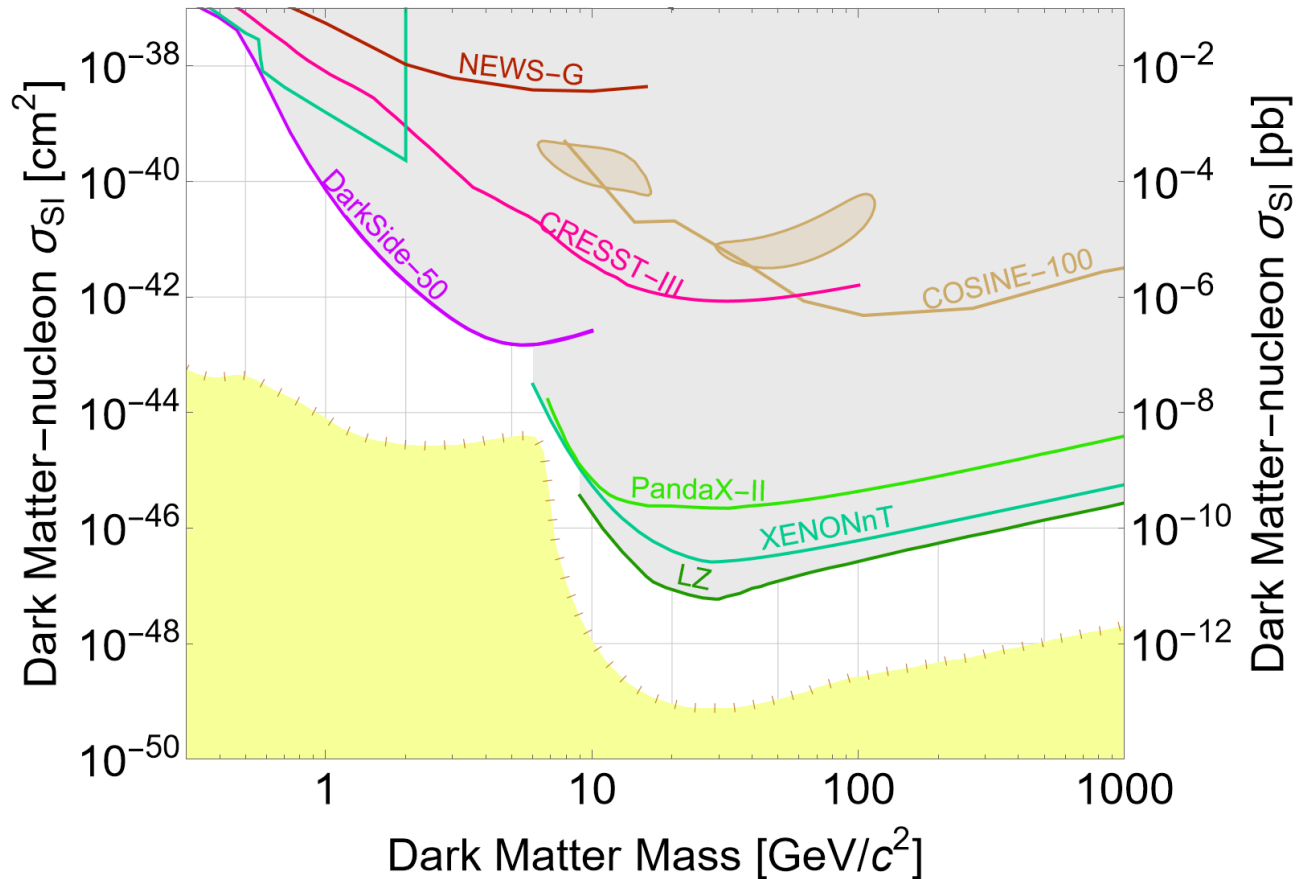
Arguelles et al, arXiv: 1912.09486

Dark matter scattering

Direct Detection bounds

Dark matter scattering

Direct Detection bounds

How can we improve or complement this with astrophysics?

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

$m_\chi = 1$ MeV
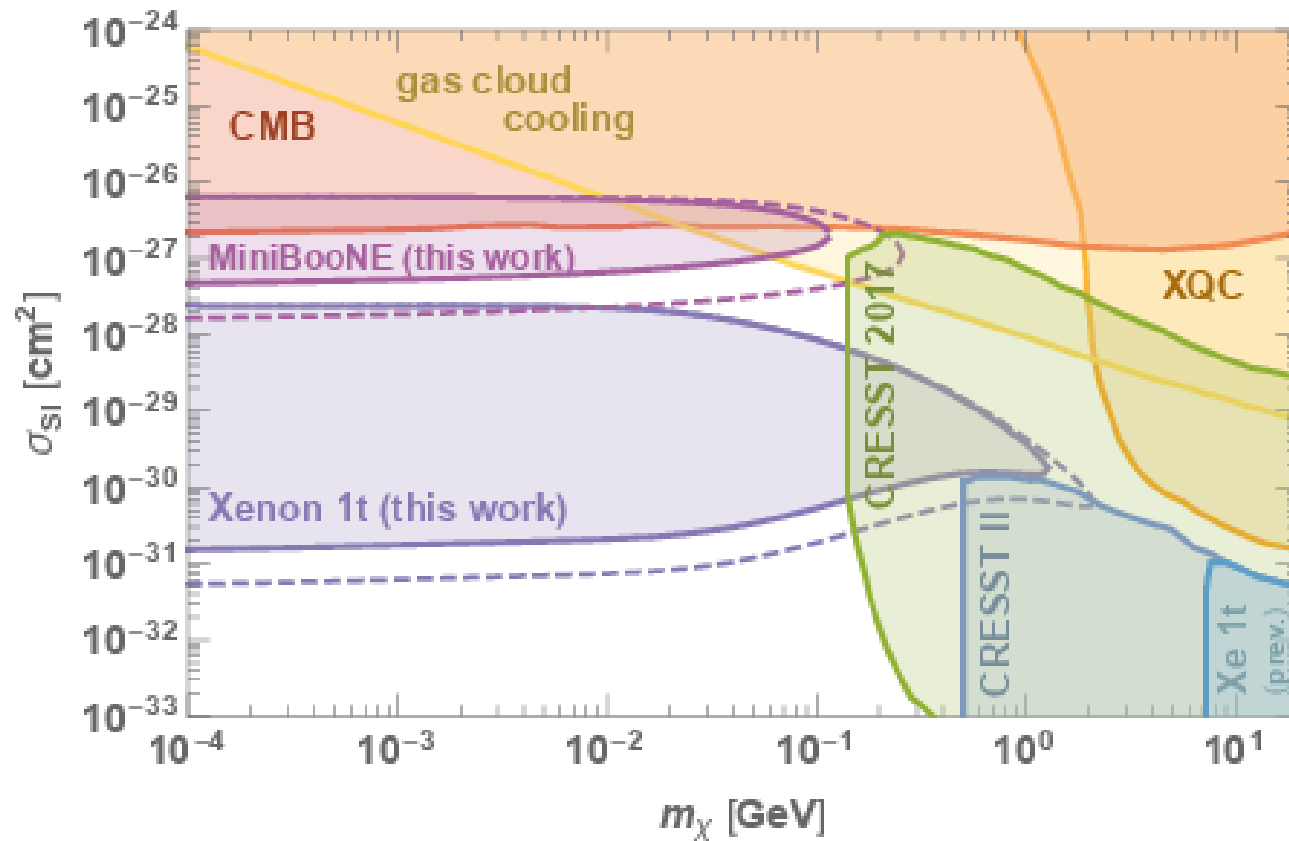$m_{mediator} = 1$ GeV
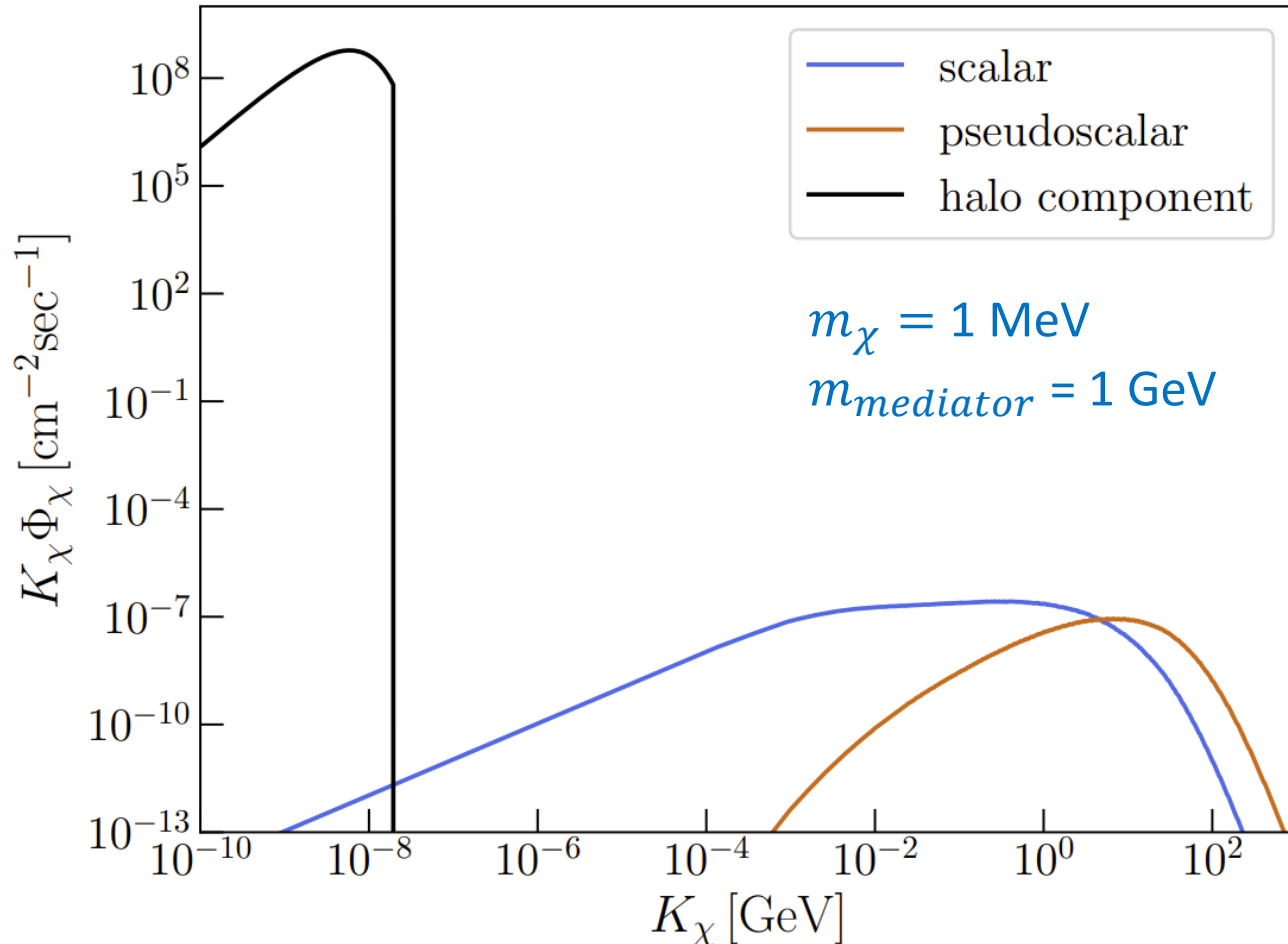
Assume the DM-nucleon scattering cross section is non-zero

→ 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 of relativistic energies:

- 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 direct detection exp cannot see pseudoscalar-type interactions, as the cross section is suppressed as p^4
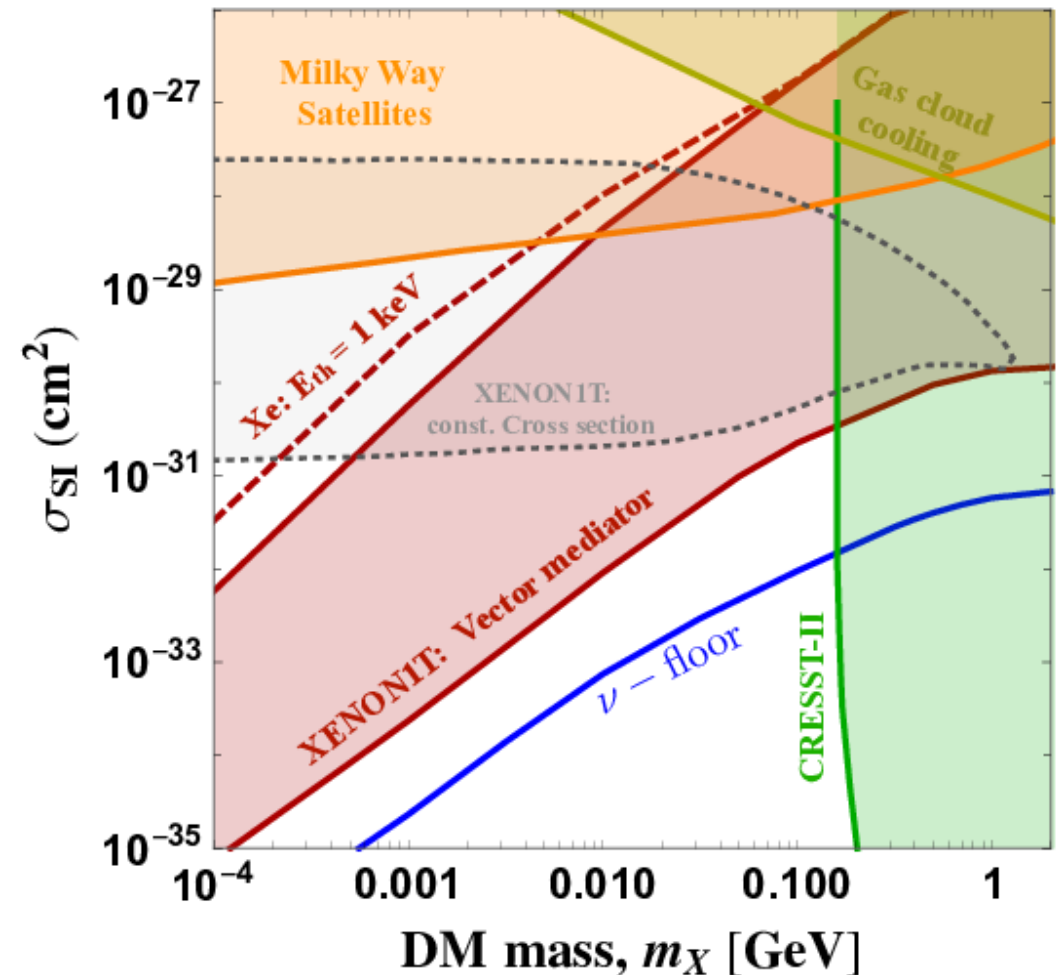
Disadvantages:
- Observable signals scale with **two** powers of the scattering cross section

Cosmic ray up-scattered dark matter

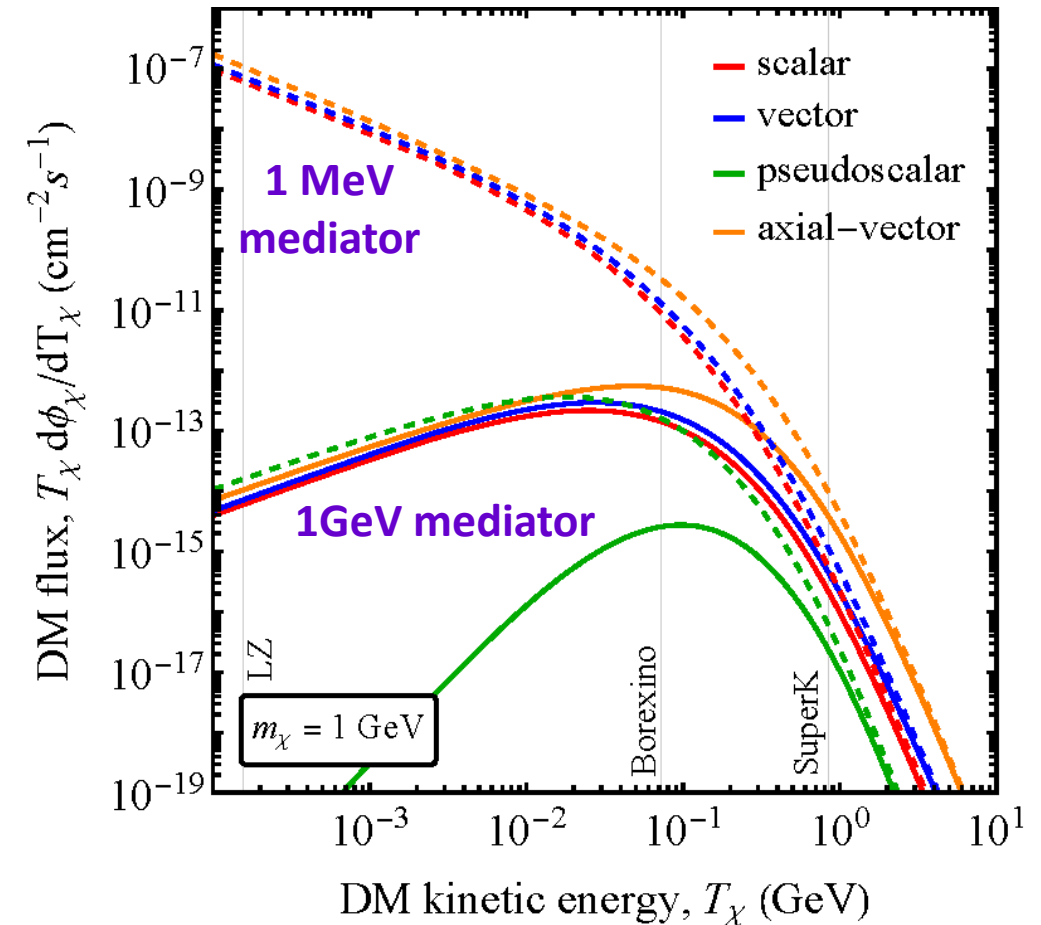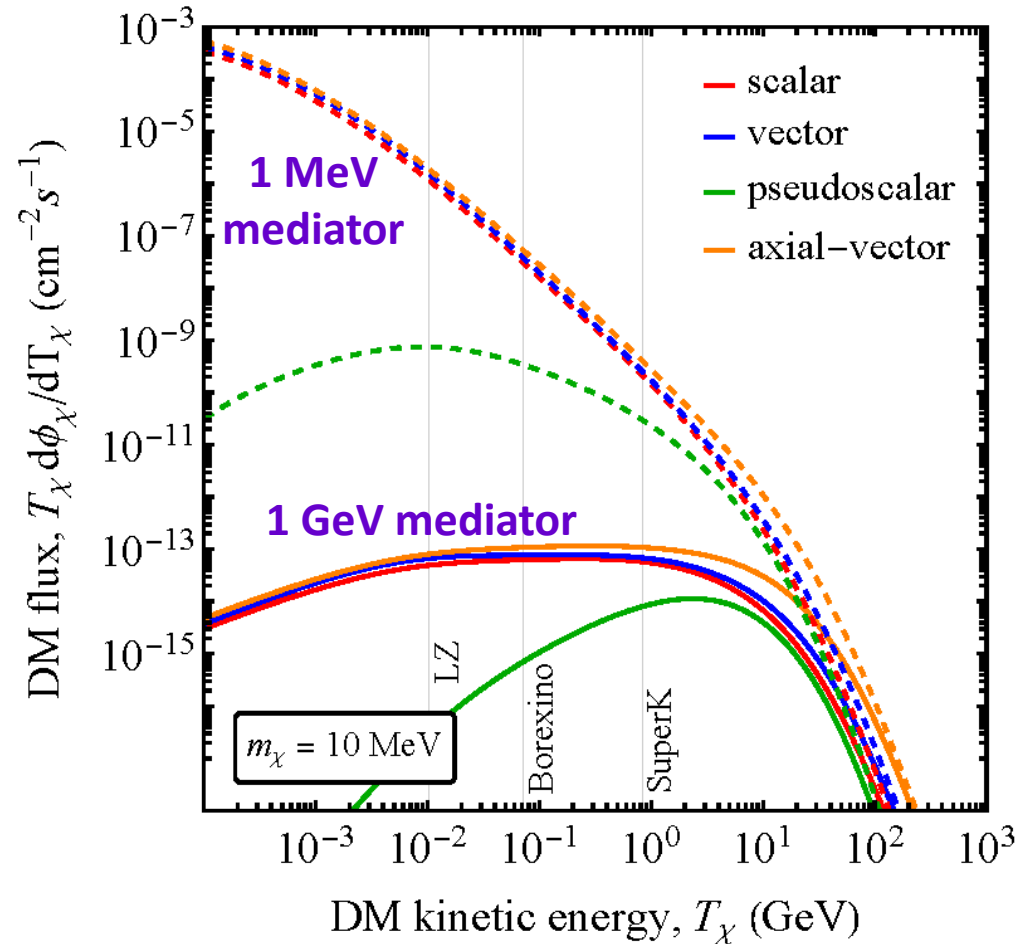Dent, Dutta, Newstead, Shoemaker,
arXiv:1907.03782

Very big cross-sections

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

- Composite DM?

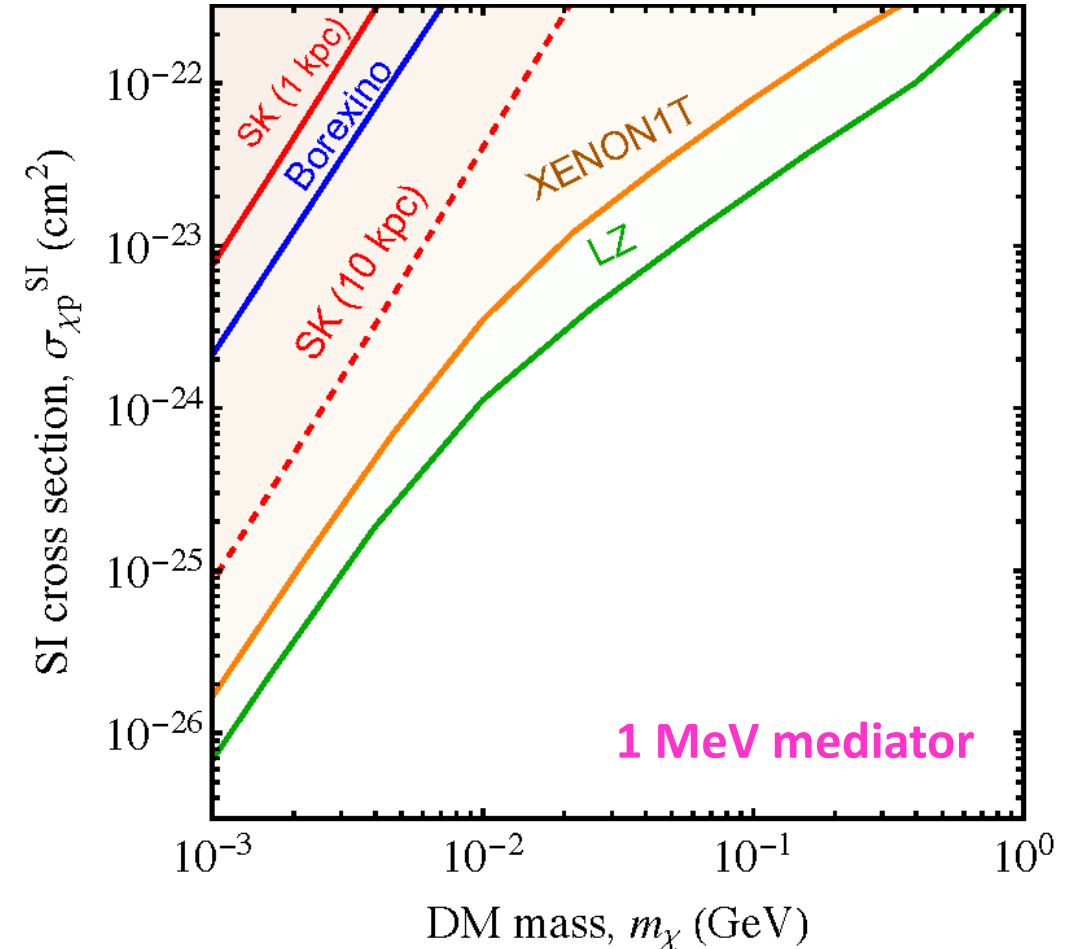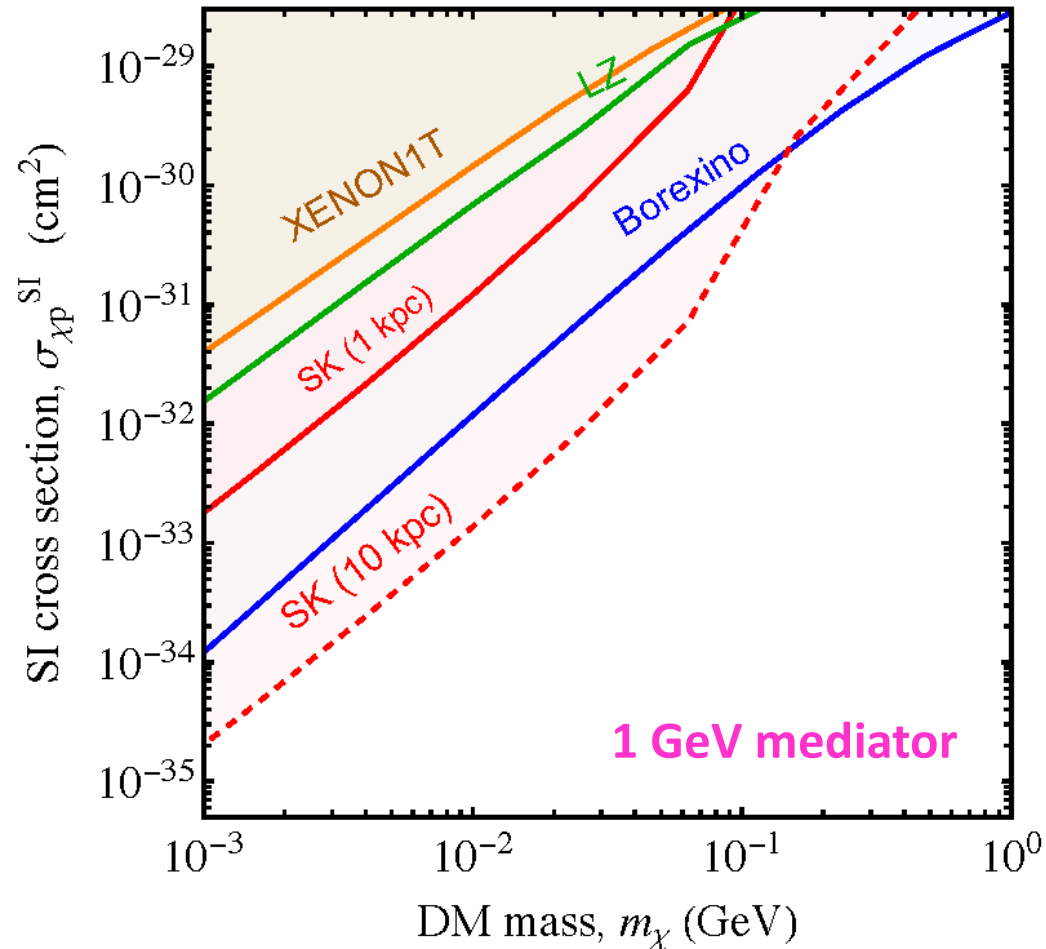→ These limits are model dependent.

CR-upscattered DM: kinetic energy spectrum

Bell, Newstead and Shaukat Ali, in preparation

Boosted DM – neutrino vs direct detection exps.

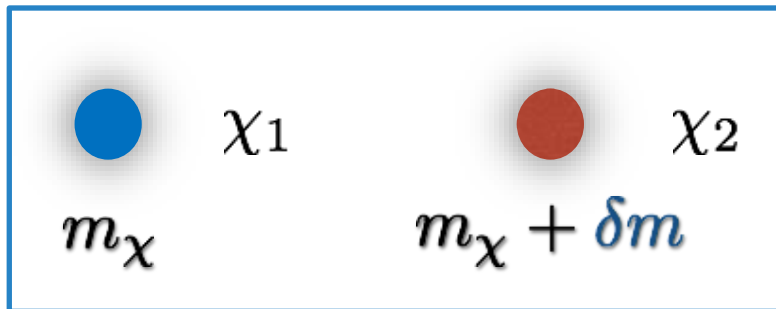Bell, Newstead and Shaukat Ali, in preparation

Boosted DM – Inelastic models

$$\chi_1\, n \to \chi_2\, n$$

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

χ_1 χ_2

m_χ $m_\chi + \delta m$

- 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
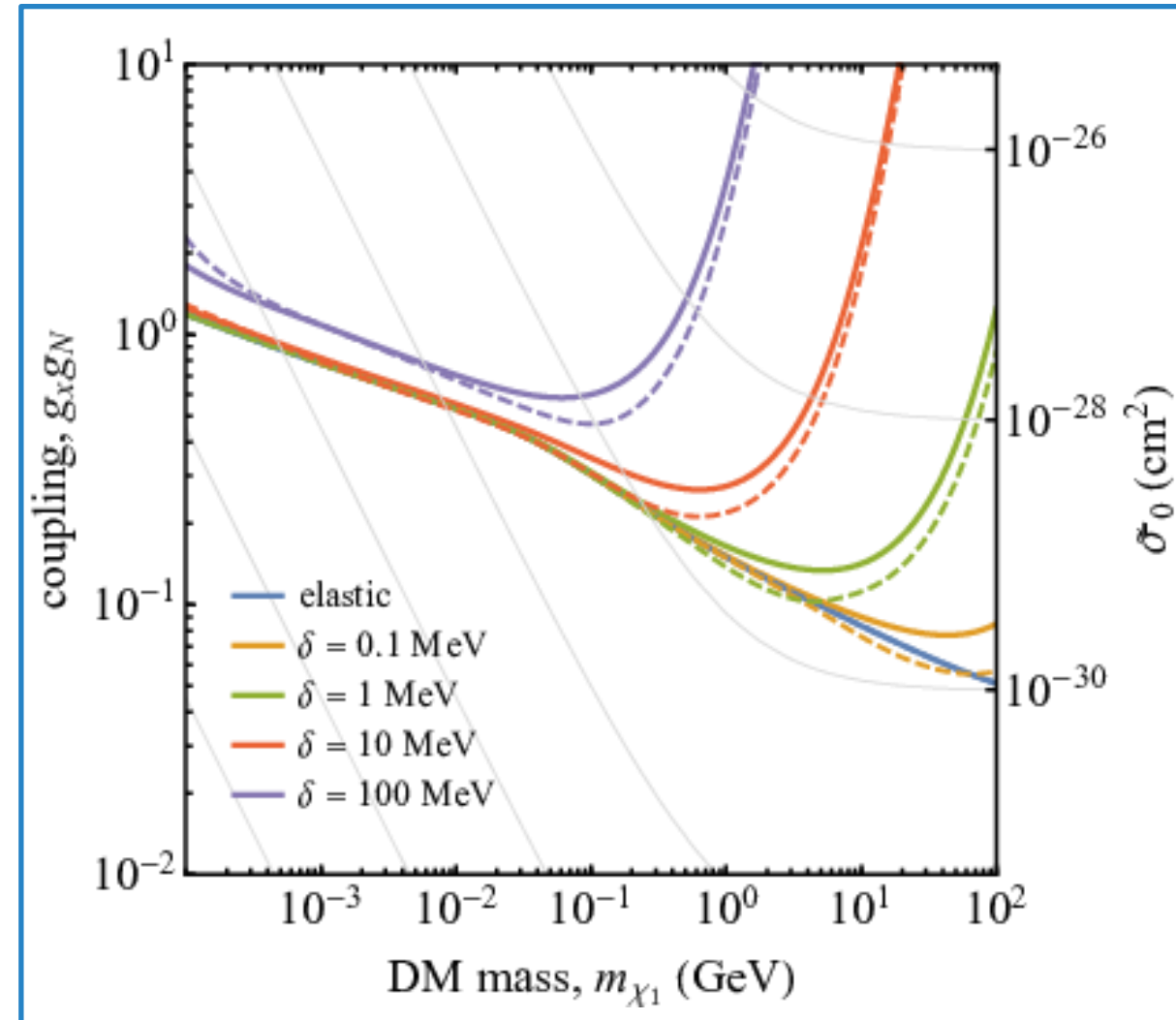
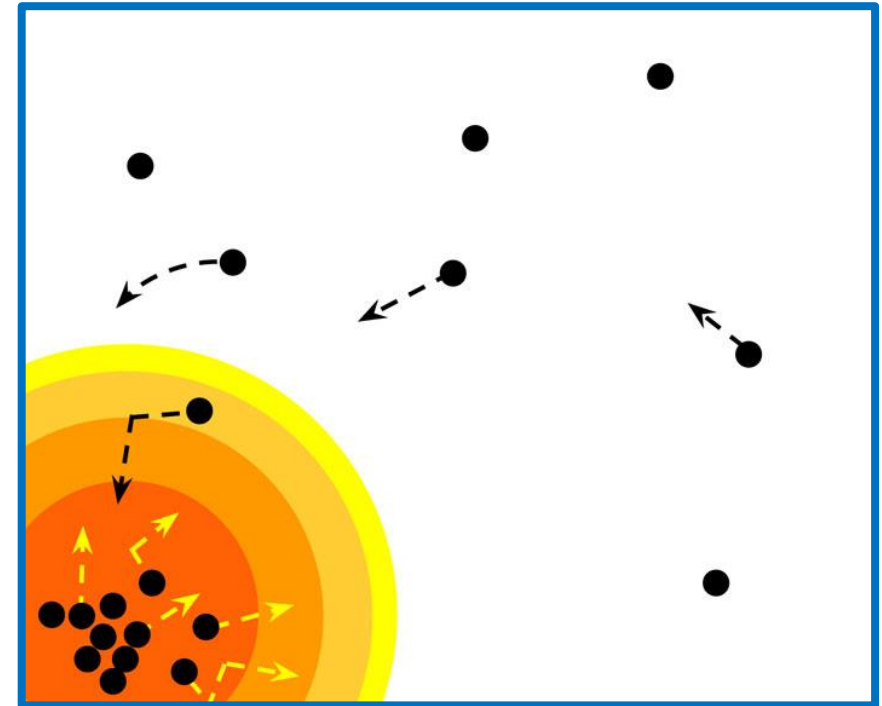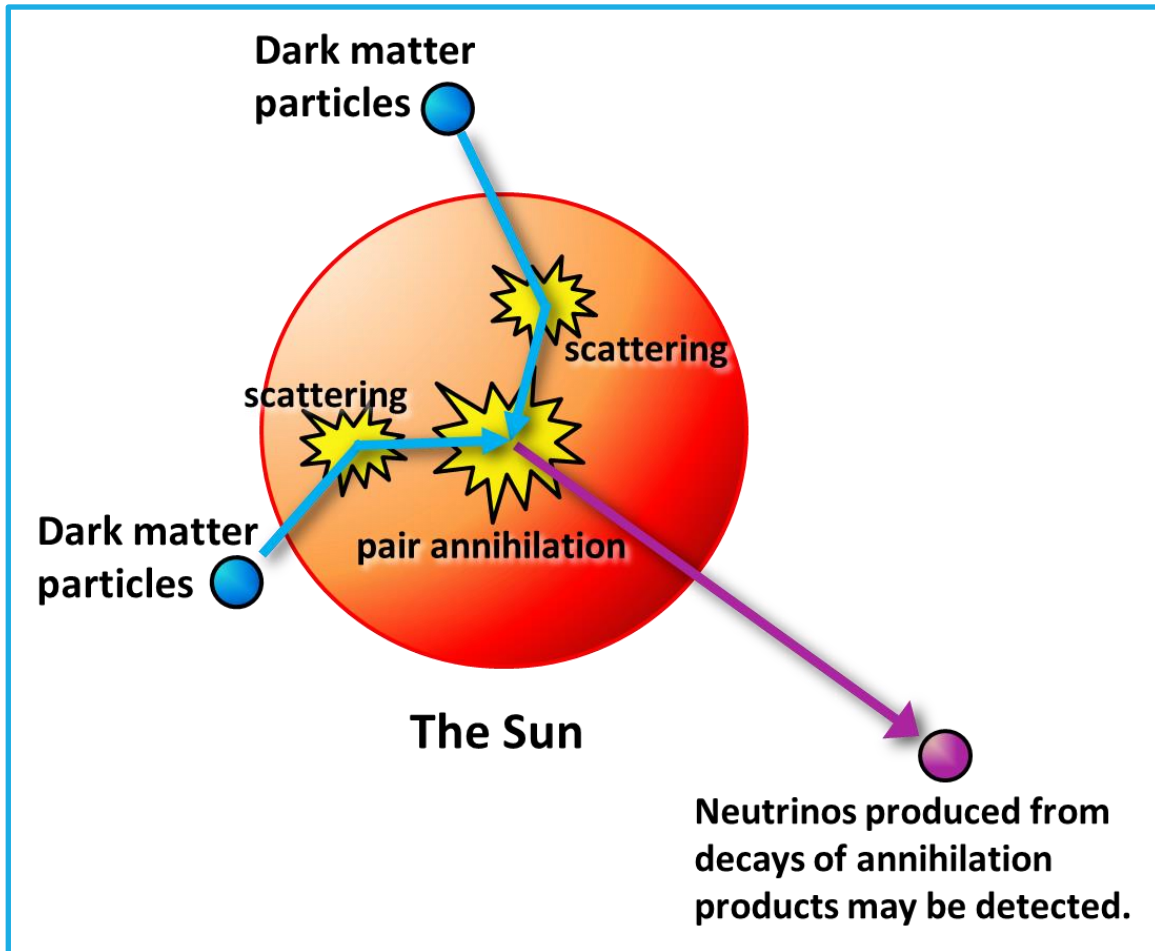# Dark Matter Capture in Stars

→ 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*

The Sun

Neutrinos produced from decays of annihilation products may be detected.

- Dark matter scatters, loses energy, becomes gravitationally bound to star

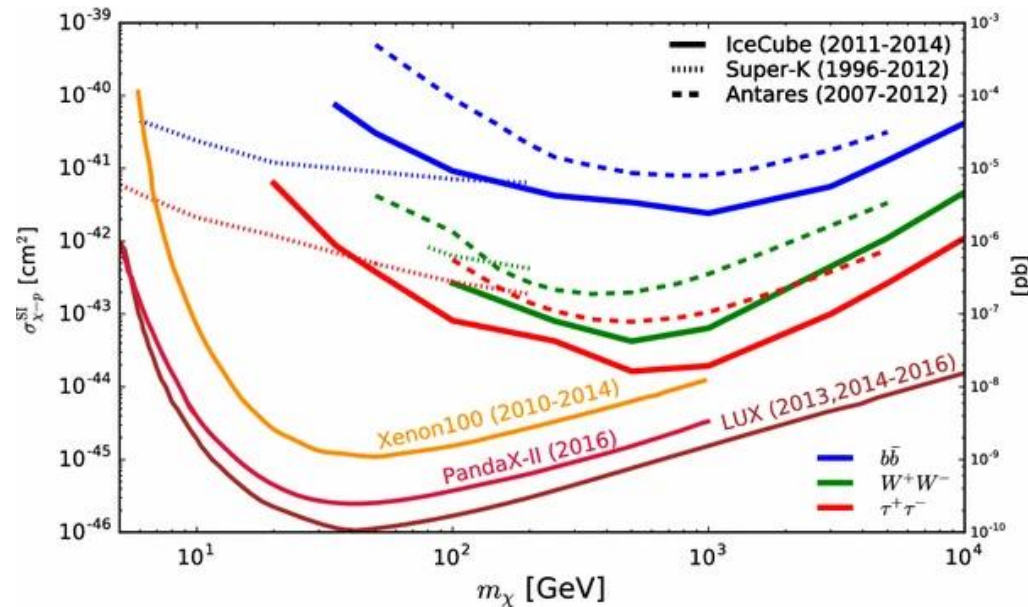- Accumulates and annihilates in centre of the star → neutrinos escape

In equilibrium:

Annihilation rate = Capture rate
→ controlled by DM-nucleon scattering cross section
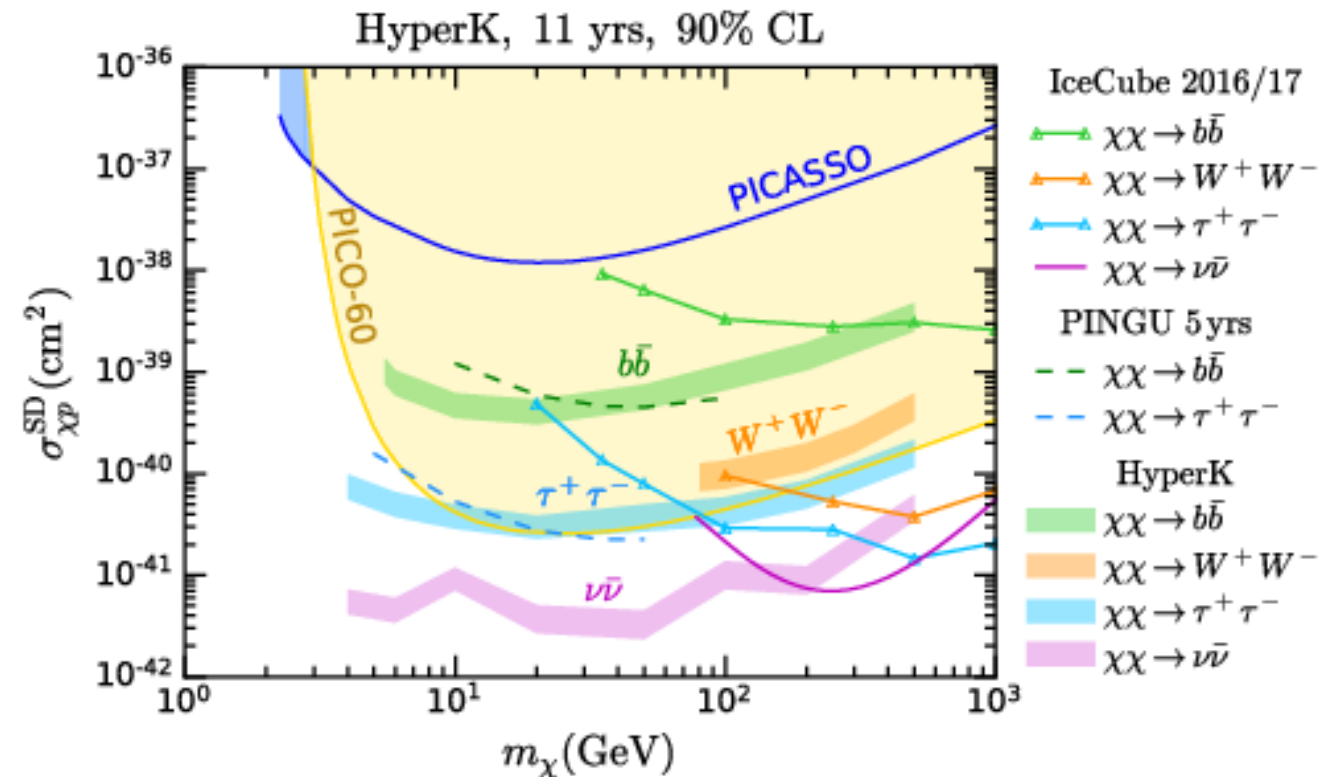→ probes the same quantity as dark matter direct detection experiments

Dark matter annihilation in the Sun – Neutrinos

Spin-Independent (SI)

Spin-Dependent (SD)

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

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 (Bell & Petraki, JCAP 2011)

Short-lived mediators

Long-lived mediators
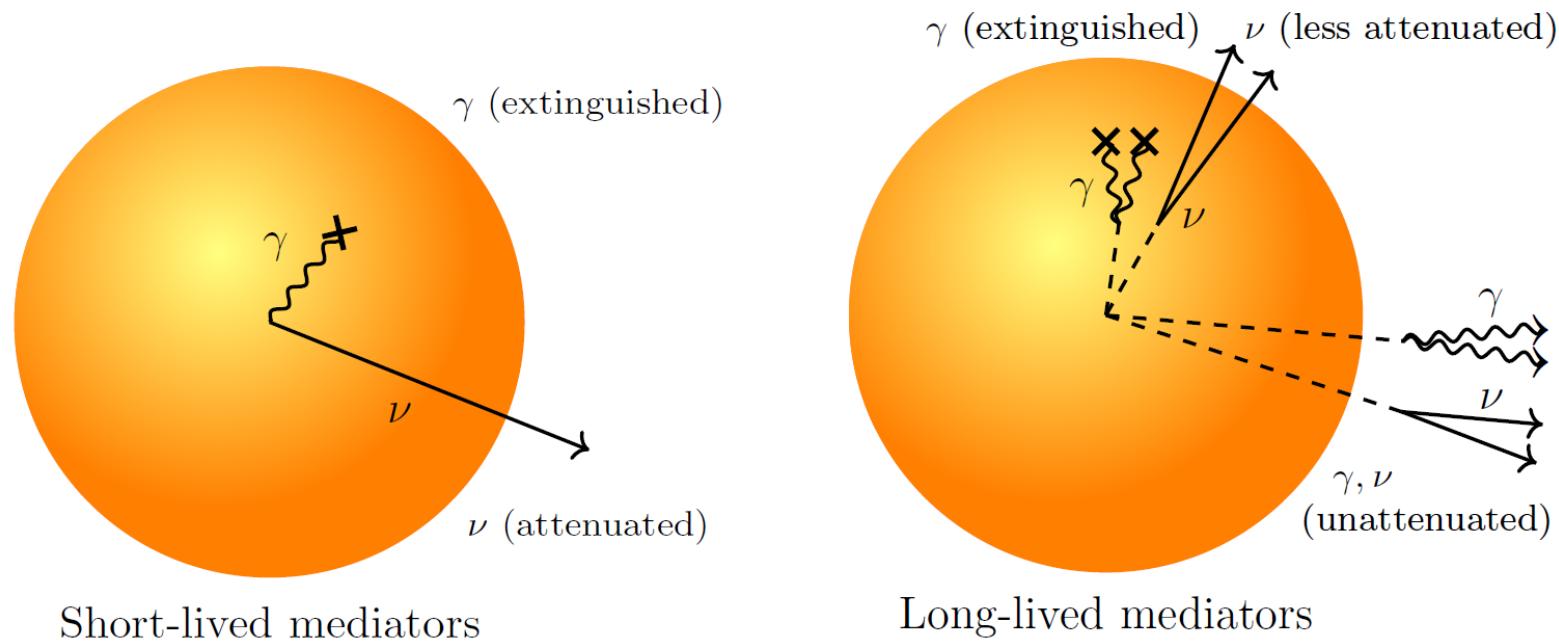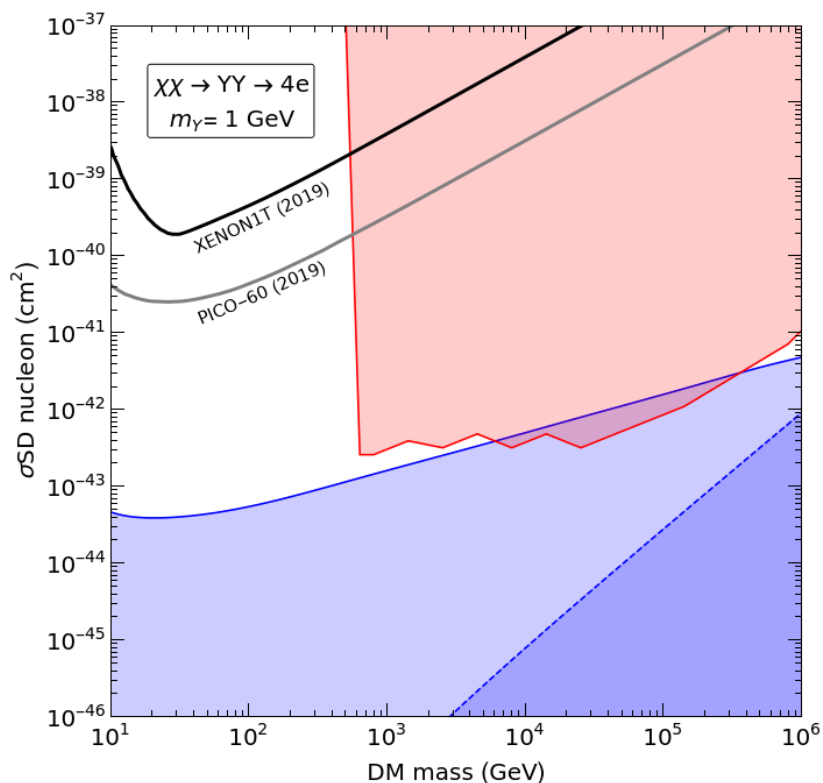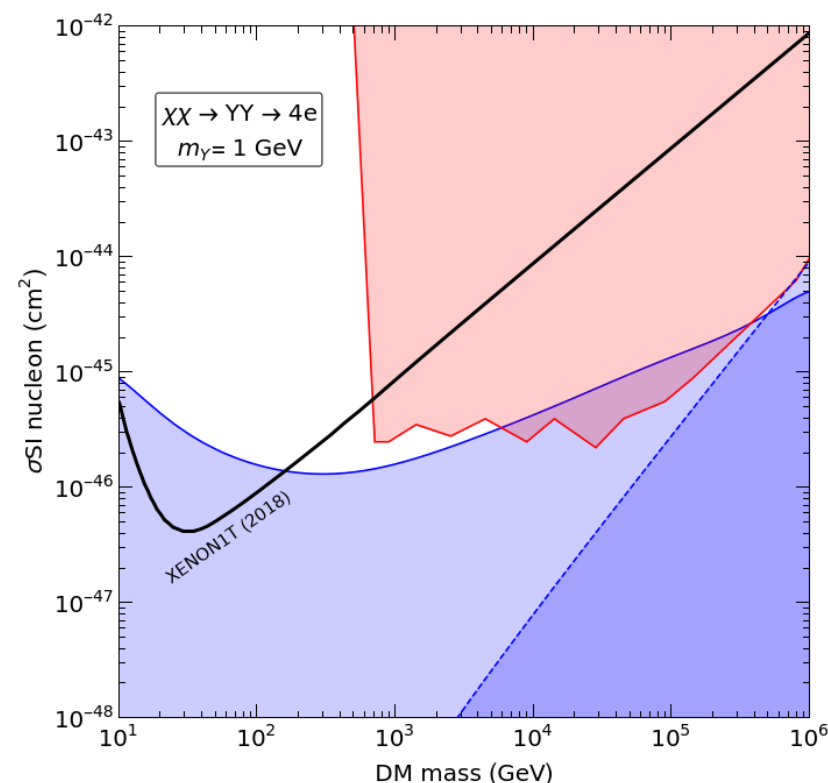
Leane, Ng & Beacom, arXiv:1703.04629

Gamma Rays from the Sun

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

Spin-Dependent (SD)

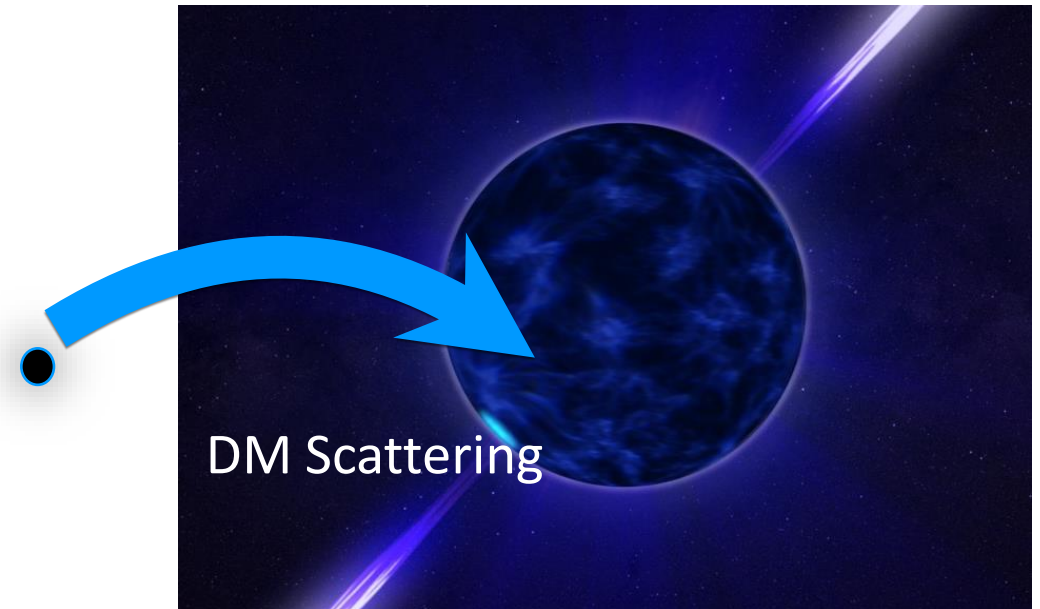**Spin-Independent (SI)**

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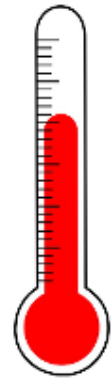
$$\sigma_{th} \sim \pi R^2 \frac{m_n}{M_*} \sim 10^{-45} \text{cm}^2$$

DM Scattering

Neutron star heating

→ 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 ∼ 4.2×10^4 K

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

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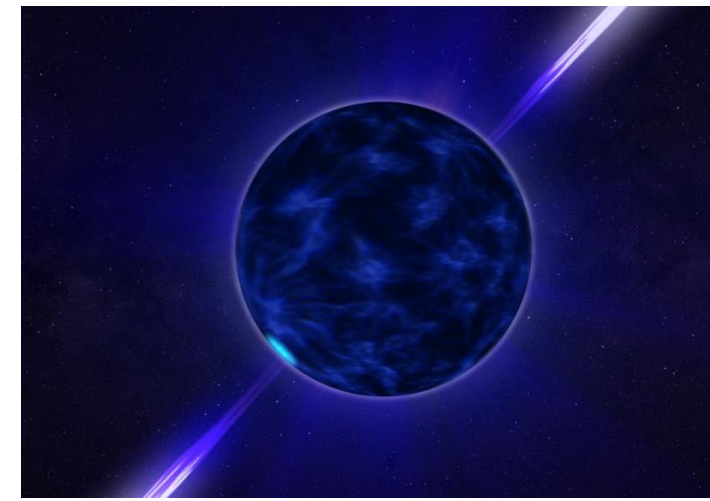
Completely different kinematic regime to direct detection experiments, because **DM is relativistic** upon infall to the NS:

- **No velocity/momentum suppression**
  → *Sensitivity to interactions that direct detection experiments will <u>never</u> 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
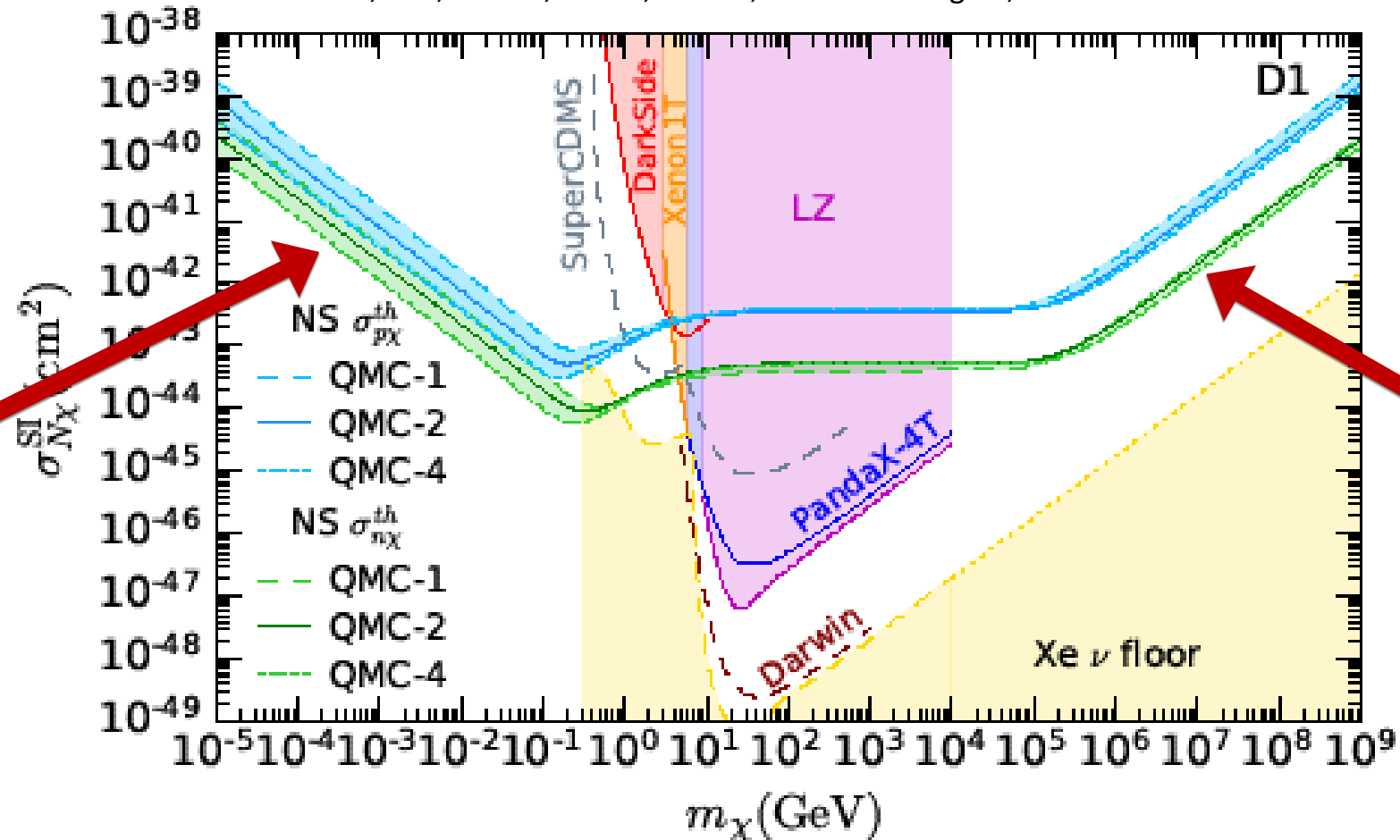
NS Heating Sensitivity (projected limits)

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

Anzuini, Bell, Busoni, Motta, Robles, Thomas & Virgato, arXiv:2108.02525
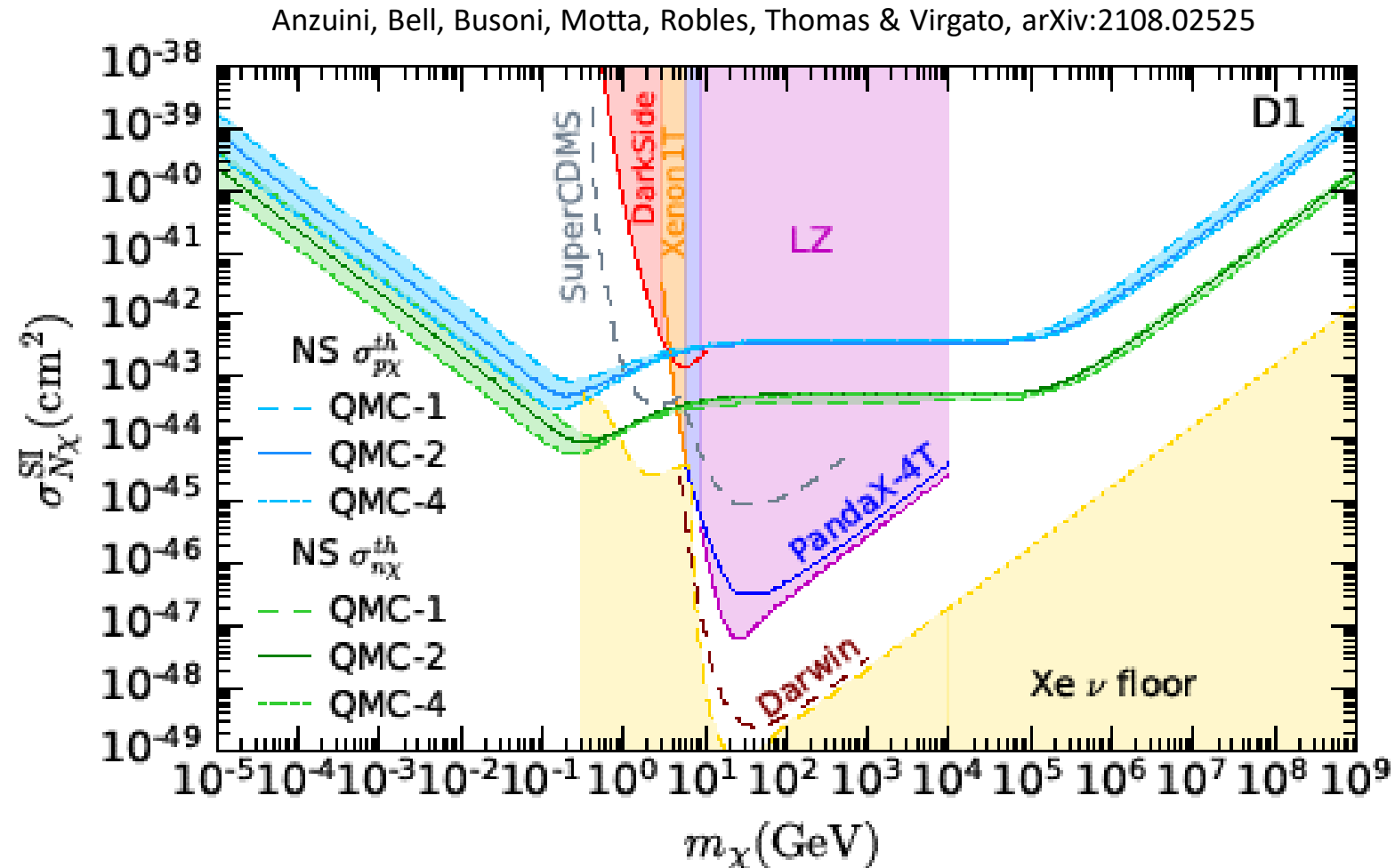
NS Heating Sensitivity (projected limits)

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

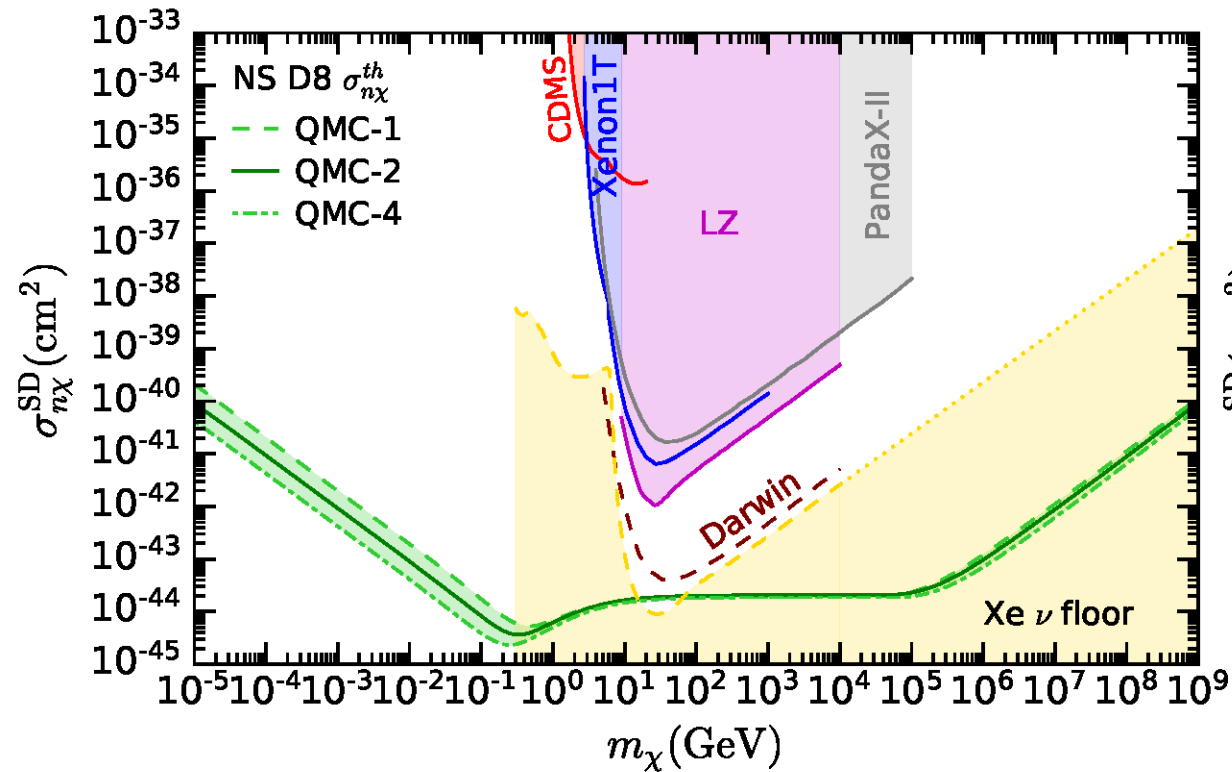Anzuini, Bell, Busoni, Motta, Robles, Thomas & Virgato, arXiv:2108.02525
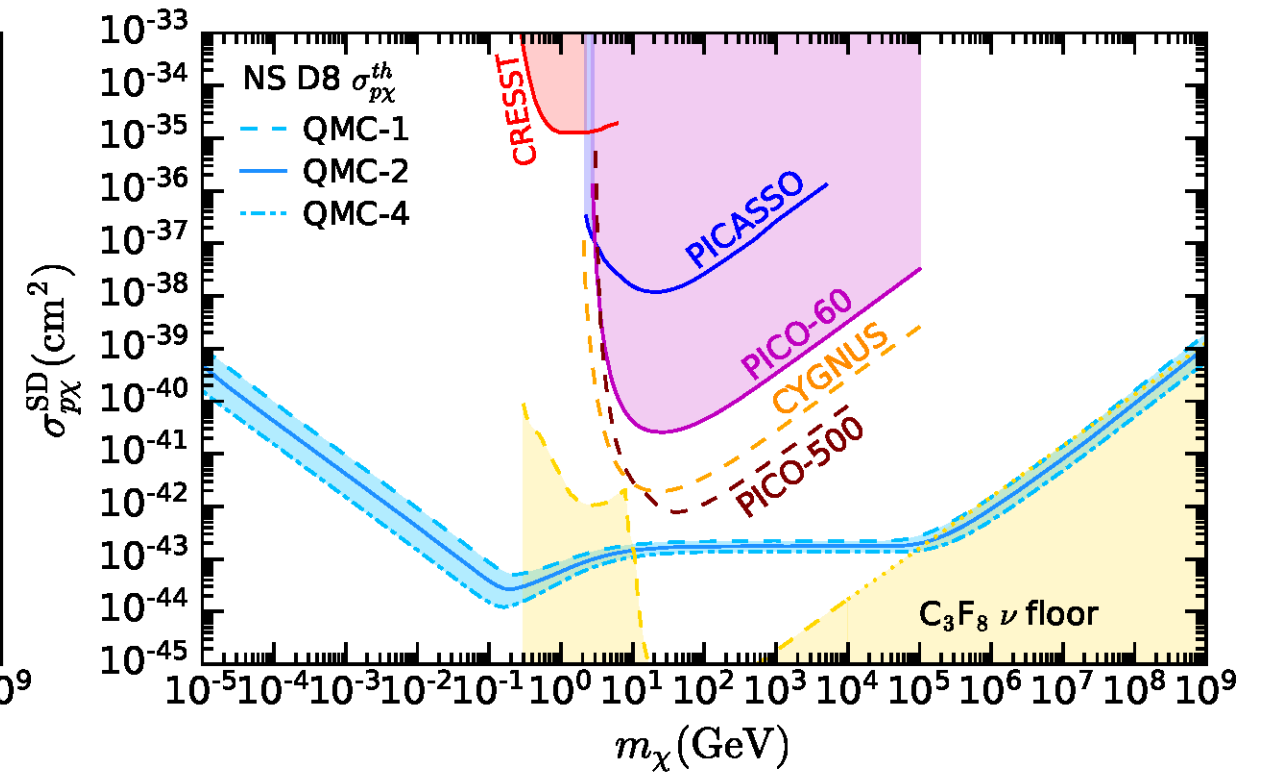

Pauli blocking from degenerate neutrons

Momentum transfer in single collision not sufficient for capture

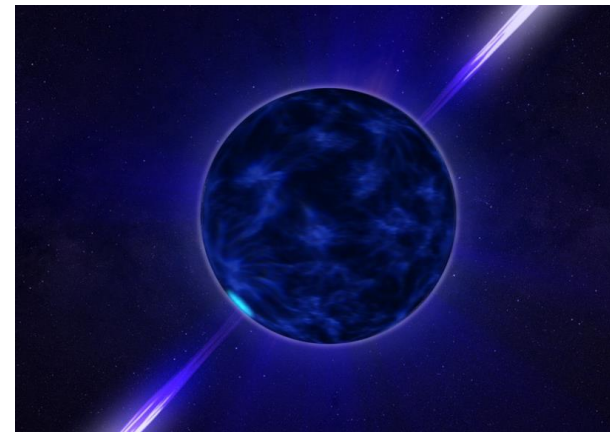# NS Heating Sensitivity: SD nucleon scattering

**DM-neutron (SD scattering)**

DM-proton (SD scattering)

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

Leptons in Neutron Stars

NS core composition (BSk24-1)

- muons — 1.73%
- electrons — 5.09%
- protons — 6.82%
- neutrons — 86.37%
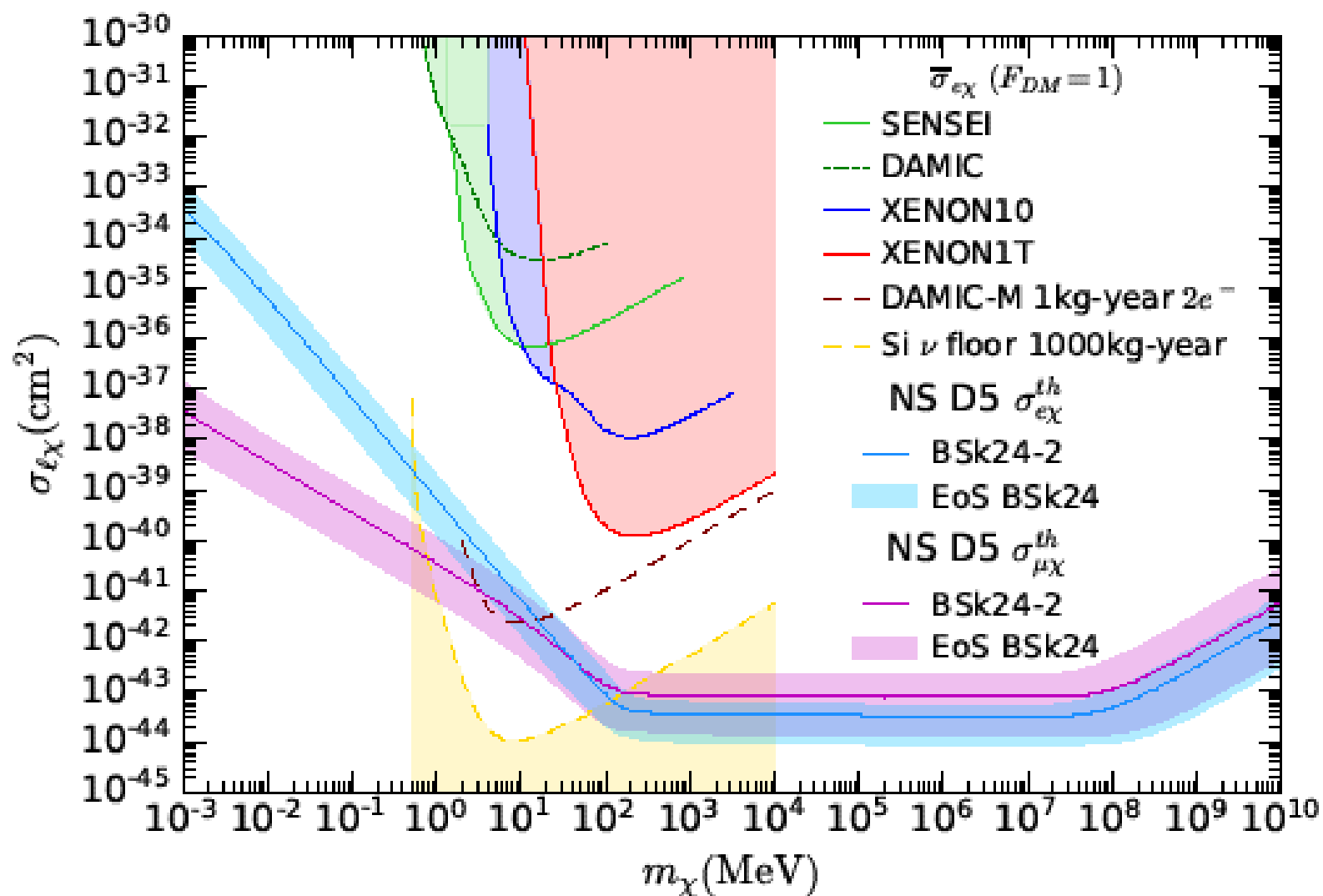
Beta equilibrium in the core determines the composition:

- Degenerate neutrons

- Smaller and approximately equal electron and proton abundances

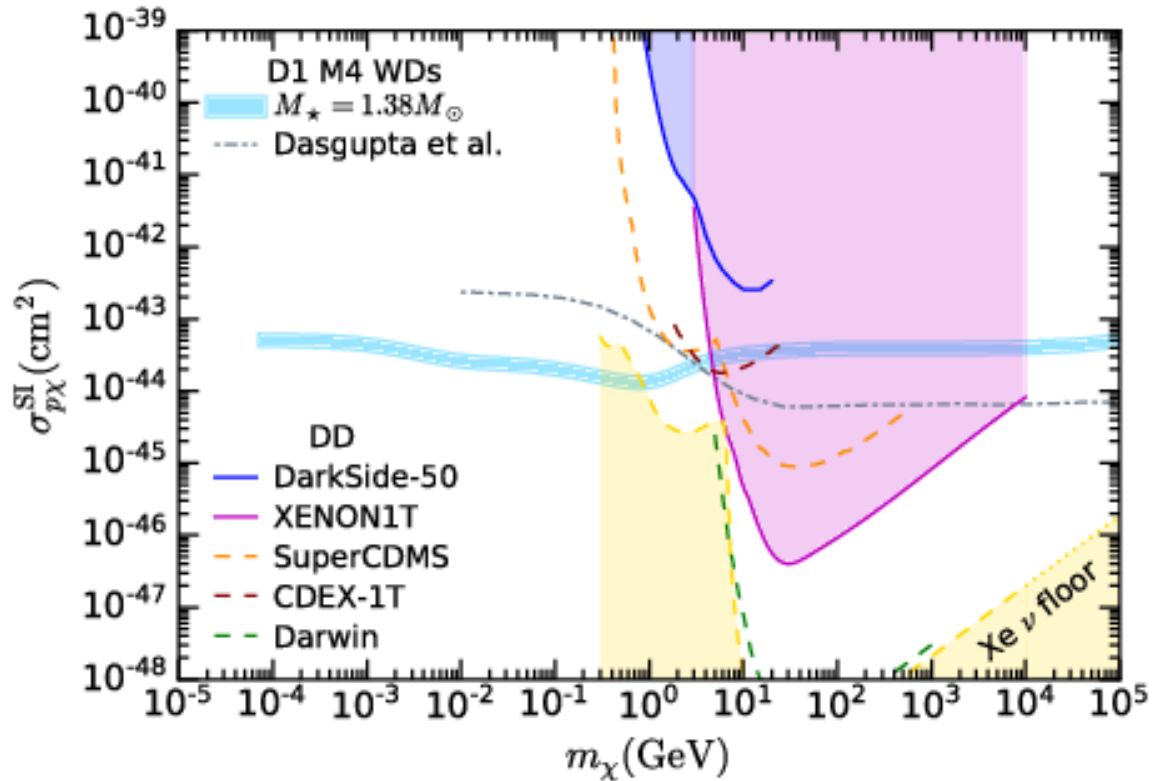- Small muon component
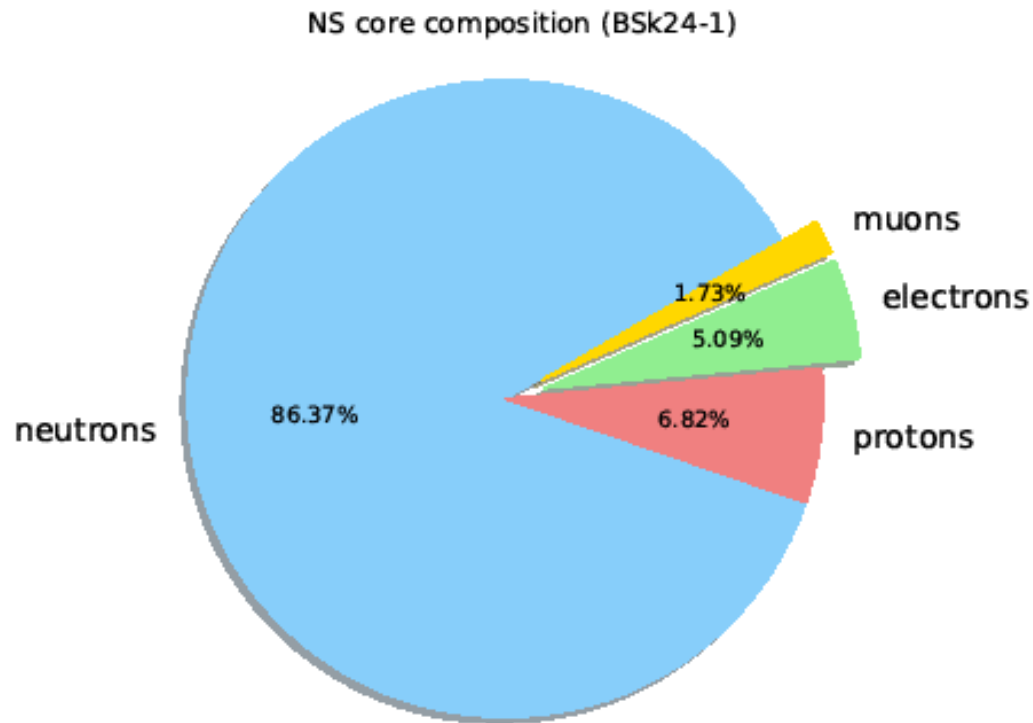
NS Heating Sensitivity: lepton scattering

Bell, Busoni, Robles & Virgato arXiv:2010.13257

Muon scattering
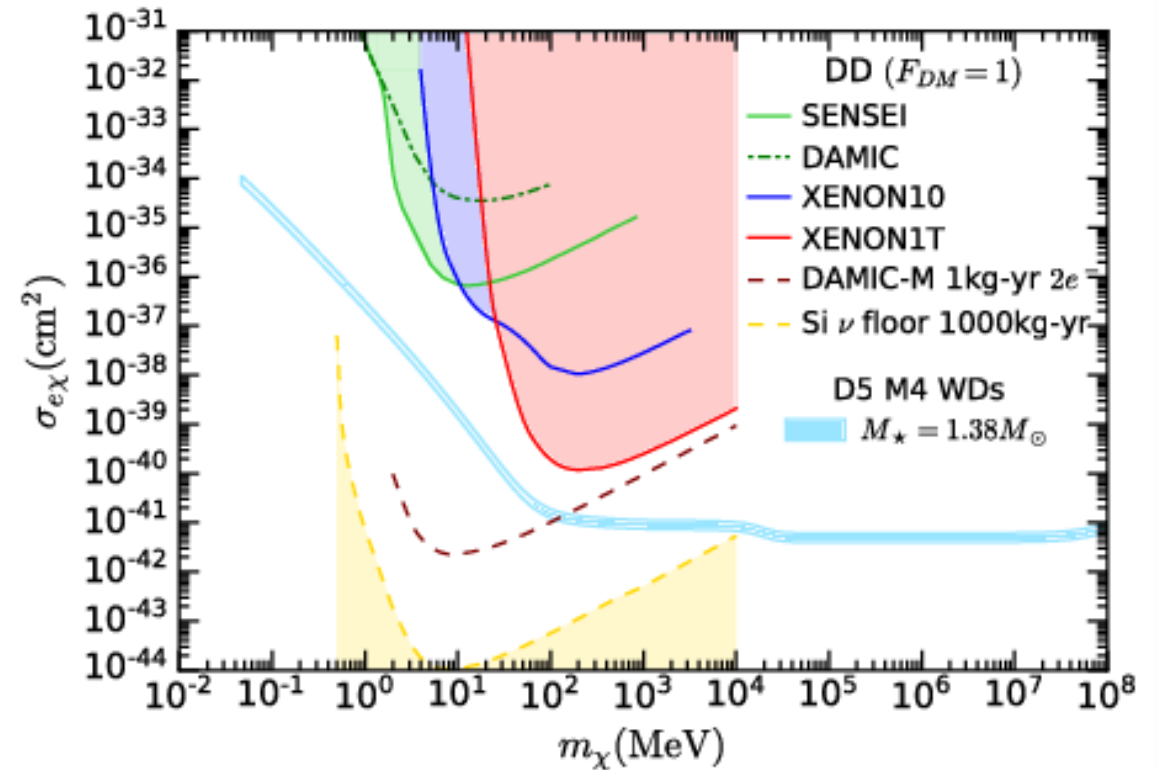
Electron scattering

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