# Physics Prospects of Future Dark Matter Searches

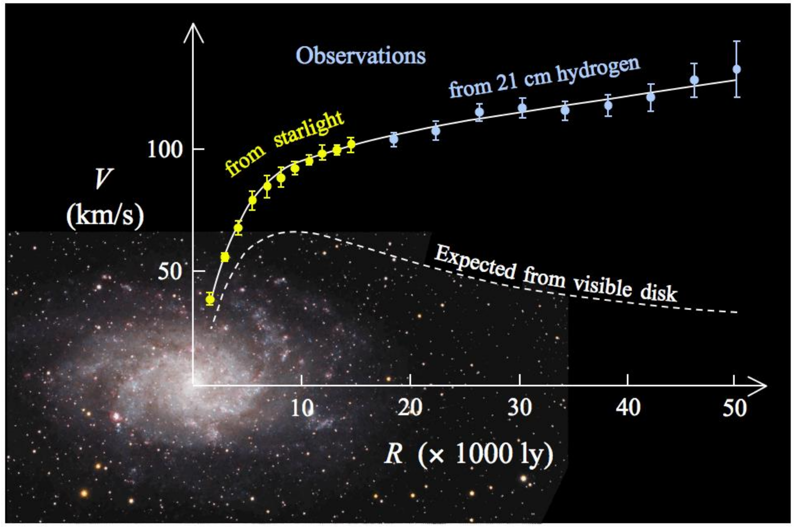
## *– perspectives on WIMPs*

Nicole Bell

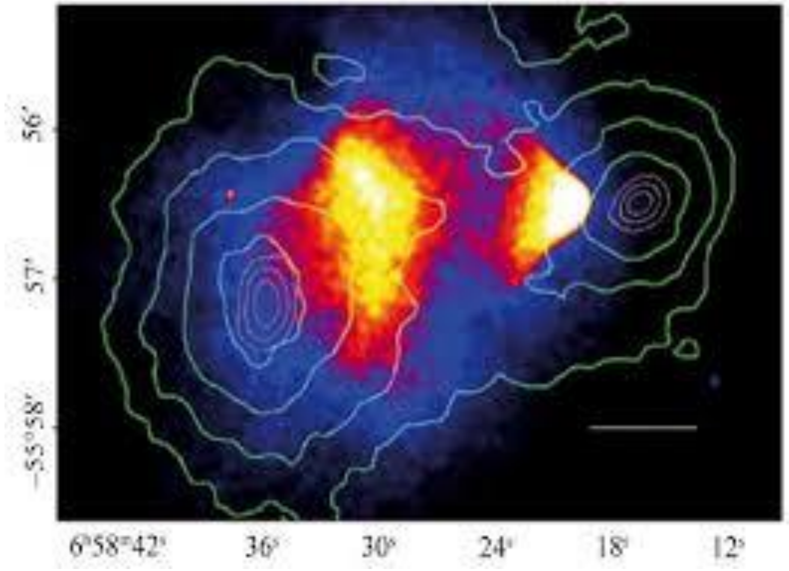
The University of Melbourne

# Evidence for dark matter

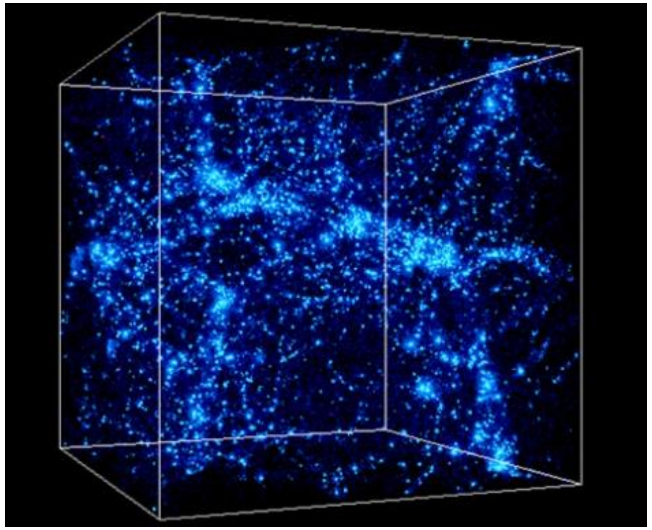
Astrophysical observations consistently point to the need for dark matter




Galaxy rotation curves



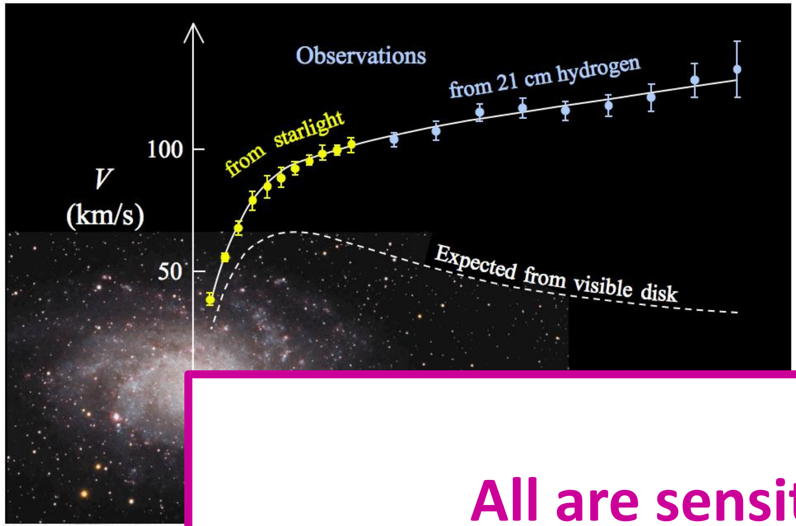

Clusters of galaxies

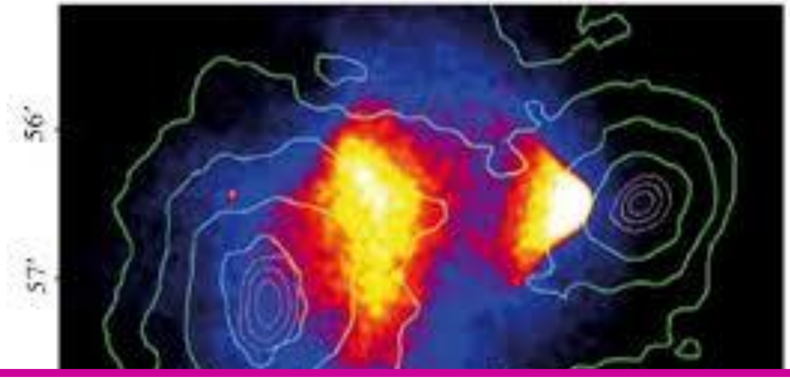


Large Scale Structure

# Evidence for dark matter

Astrophysical observations consistently point to the need for dark matter

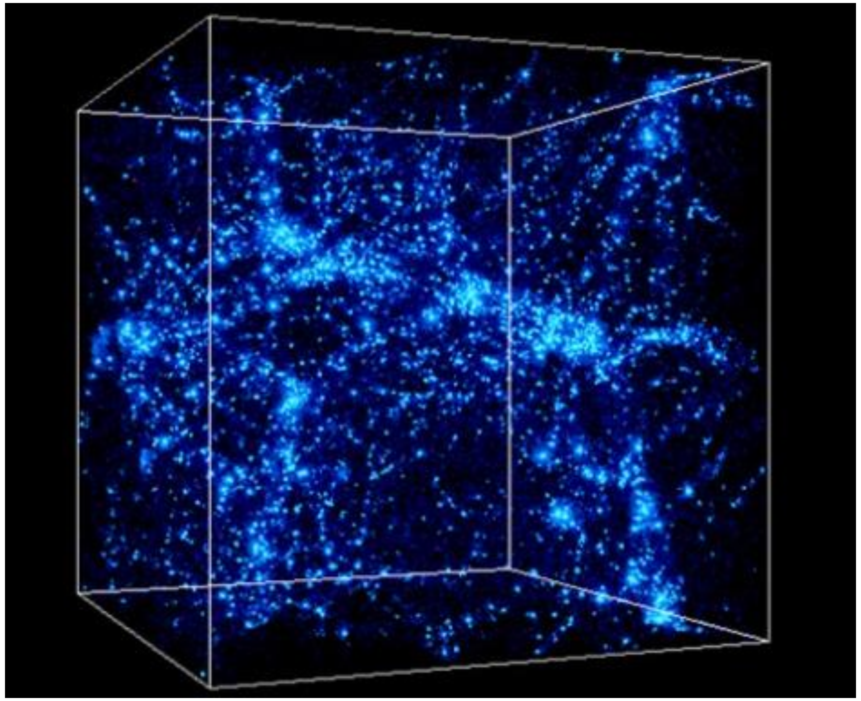



**All are sensitive to dark matter's *gravitational influence*.**

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

# What do we know?



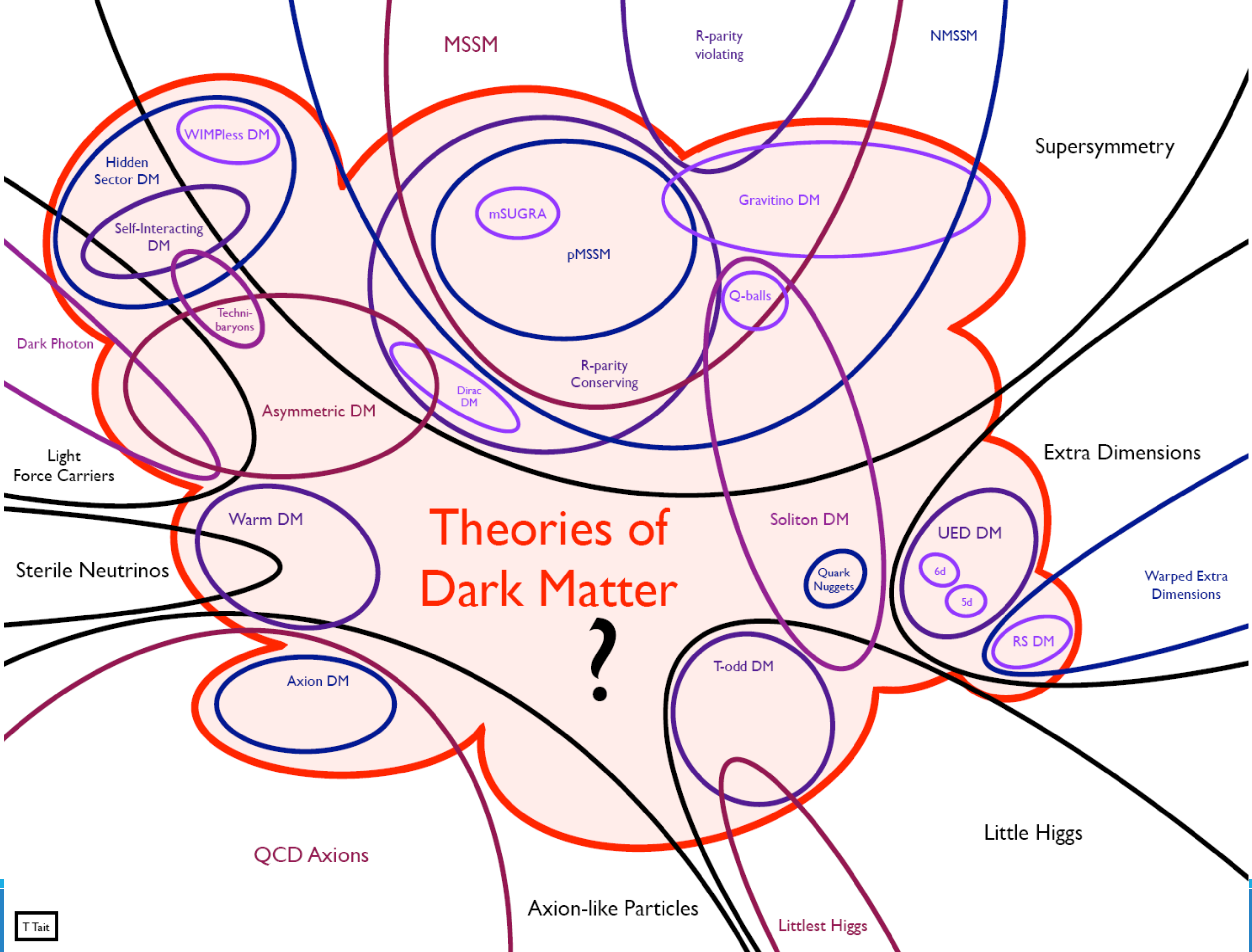
**Dark** → coupling to photons absent or highly suppressed.

**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

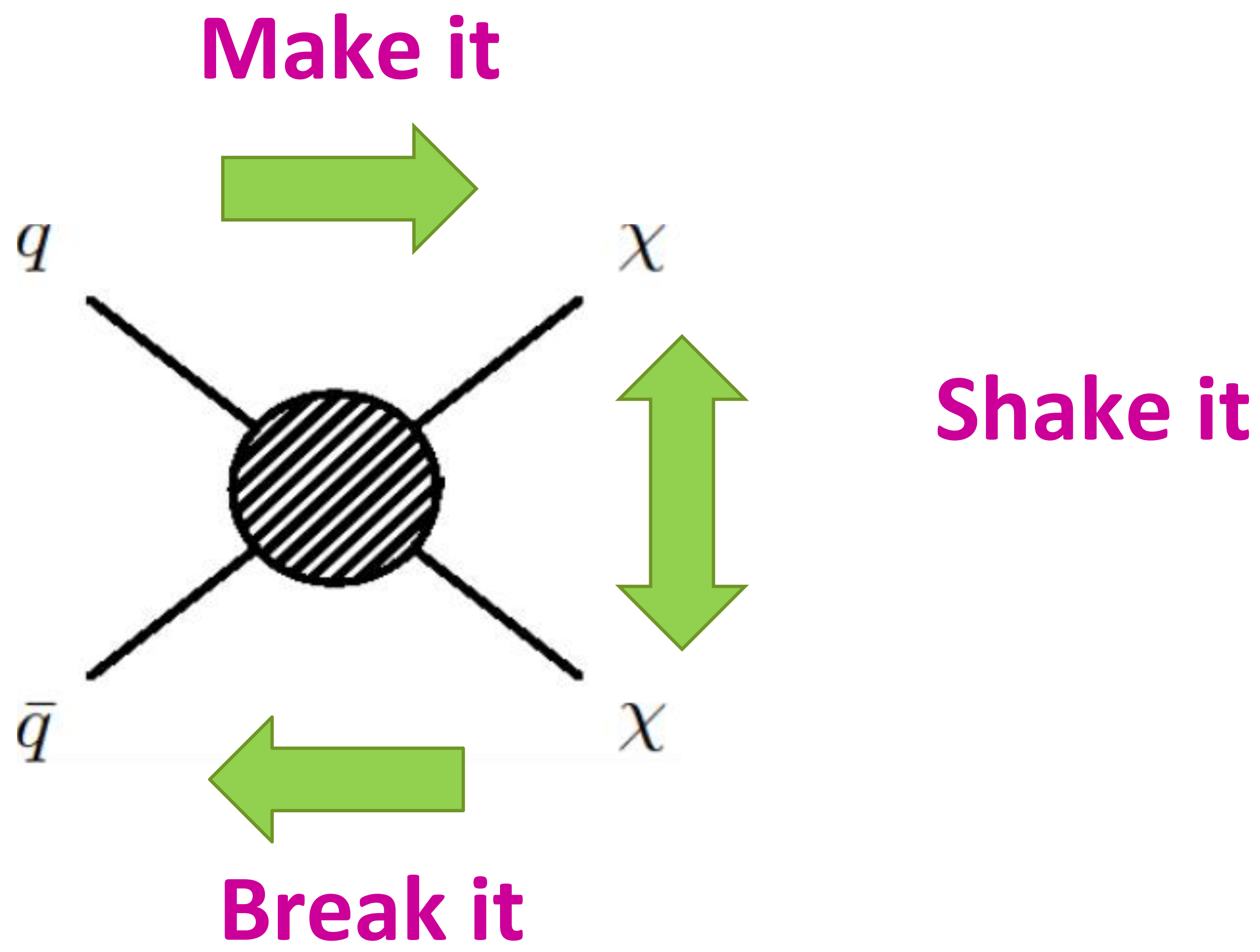
**Mass:** unknown
**Couplings**: unknown
**Spectrum of dark-sector particles:** unknown


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
Extra Dimensions
Warm DM
Theories of Dark Matter
?
Soliton DM
Quark Nuggets
UED DM
6d
5d
RS DM
Warped Extra Dimensions
Sterile Neutrinos
Axion DM
T-odd DM
Little Higgs
QCD Axions
Axion-like Particles
Littlest Higgs
T Tait

# Dark matter model space

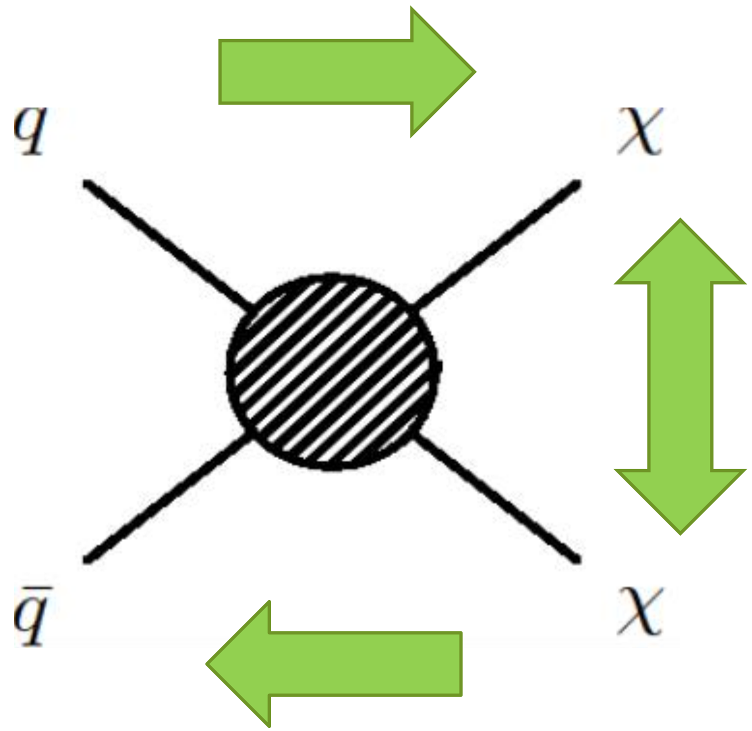

Image: Bertone and Tait

# Looking for WIMPs



# Looking for WIMPs

**Collider production**

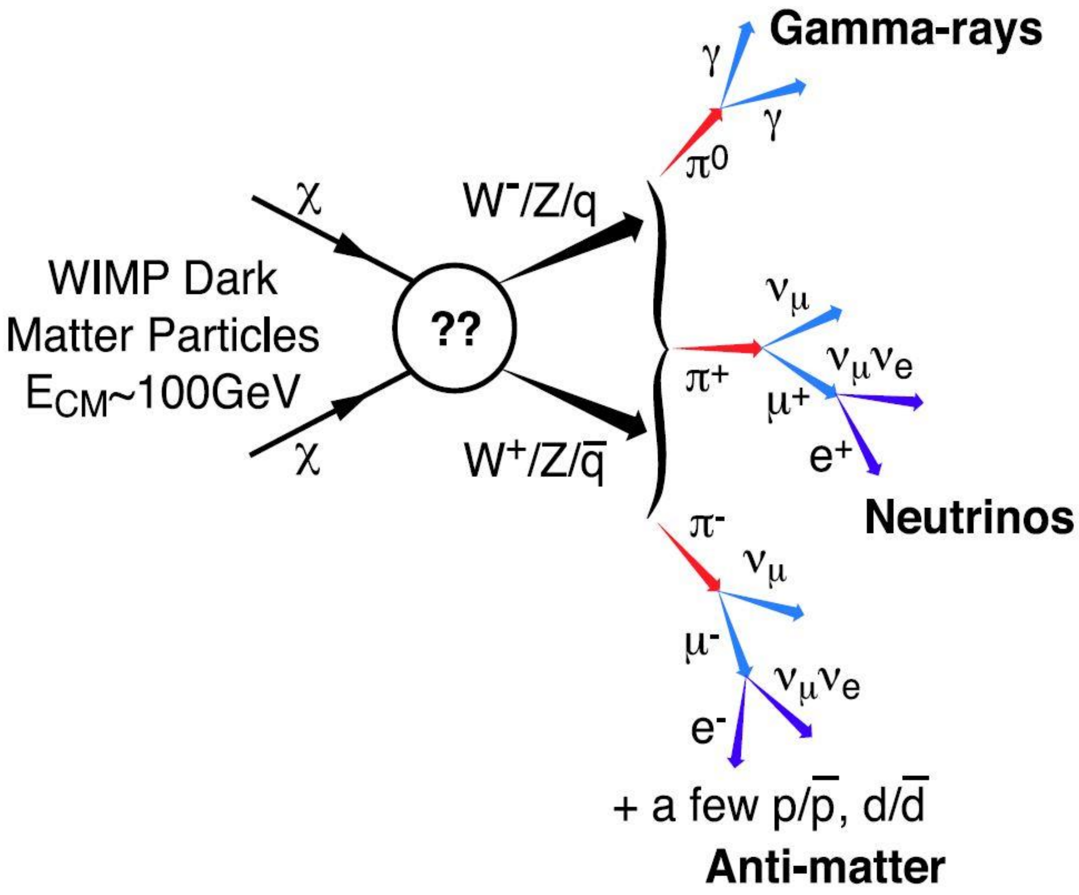



**Direct detection:**
*scattering in DM detectors on Earth (or in neutrino expts, or in stars)*

**Indirection detection:**
*annihilation in the galaxy*

# Indirect detection

# 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):

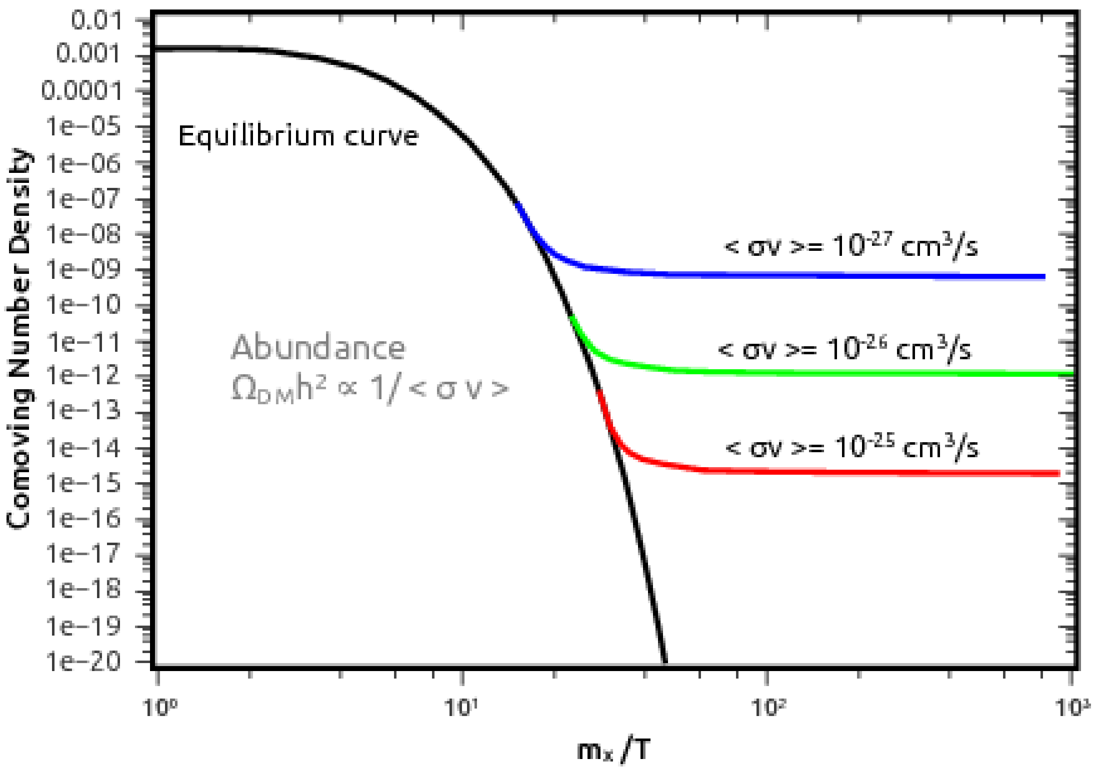
Relic DM density determined by the annihilation cross section:

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

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!

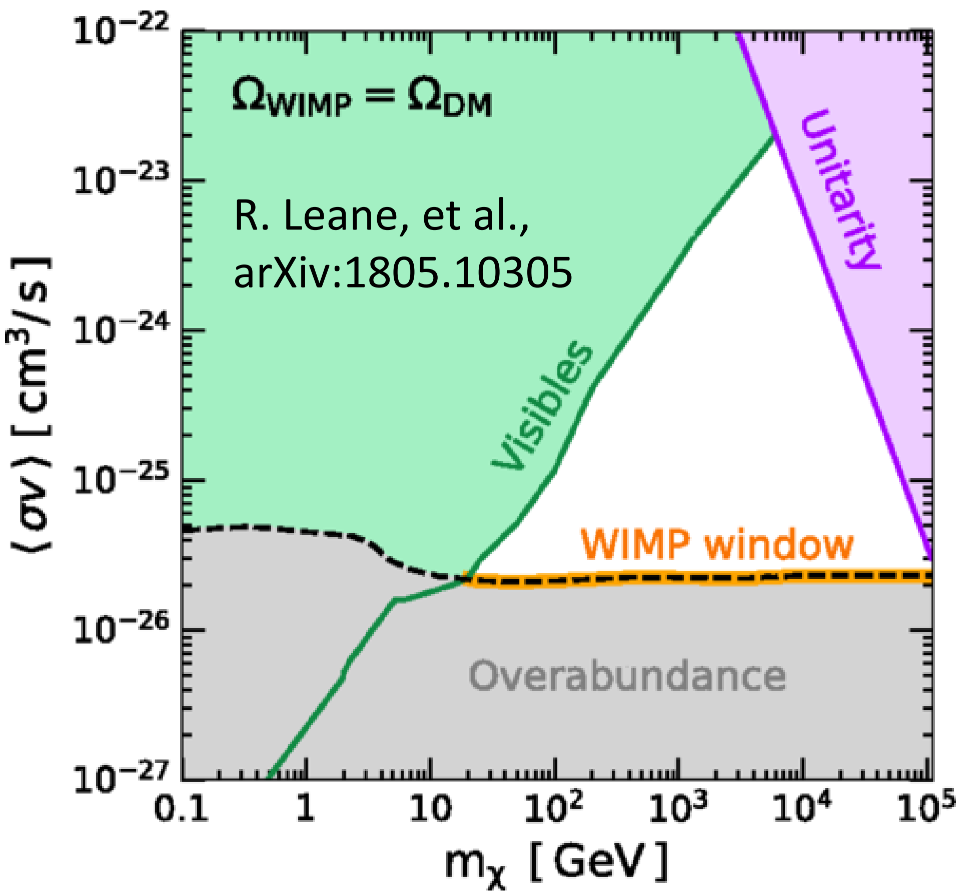
# The WIMP window

**Mass window for thermally produced WIMPs:**

$m_\chi$ < 100 TeV  from Unitarity limit

$m_\chi$ > MeV  to avoid upsetting BBN

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



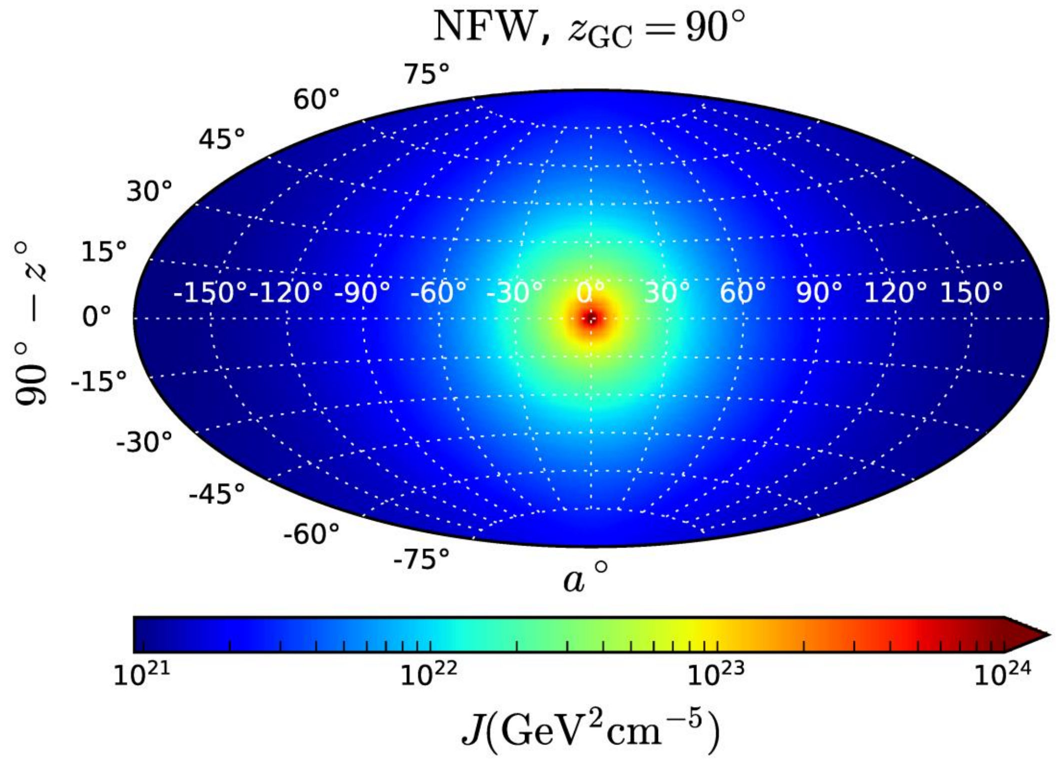
# Dark matter annihilation signal

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

Annihilation cross section

Integral of (density)$^2$ along line of sight

Spectrum per annihilation

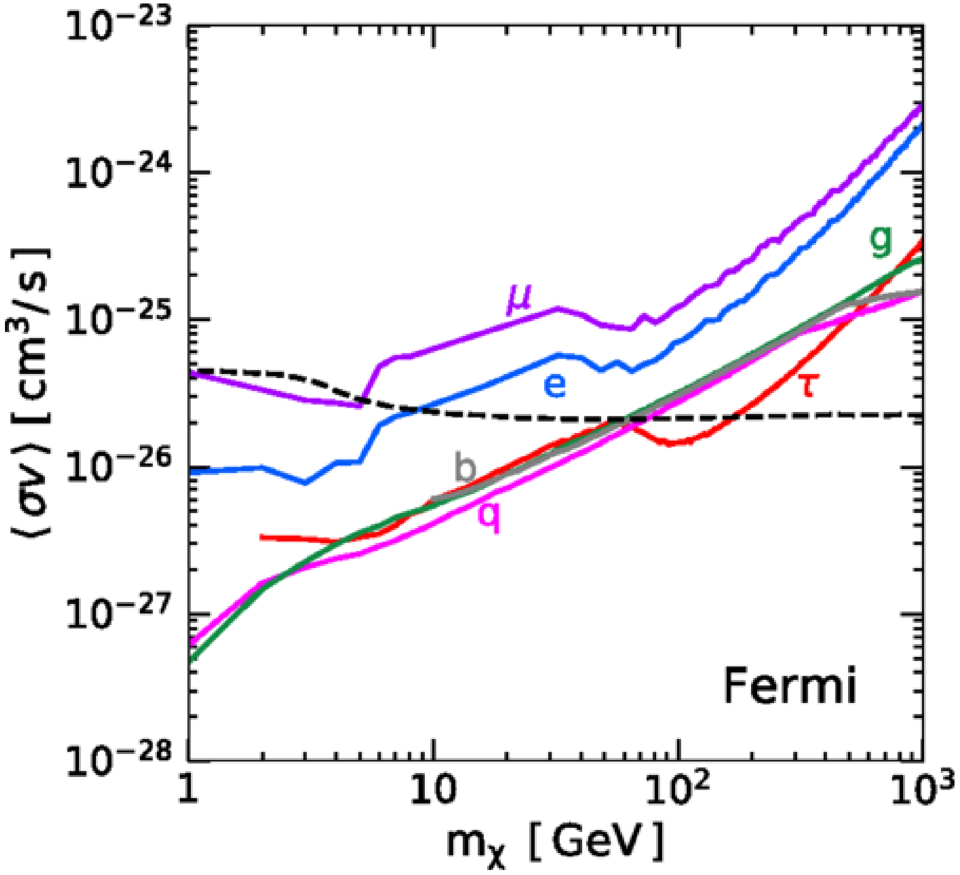



Bell, Dolan, Robles, arXiv: 2005.01950

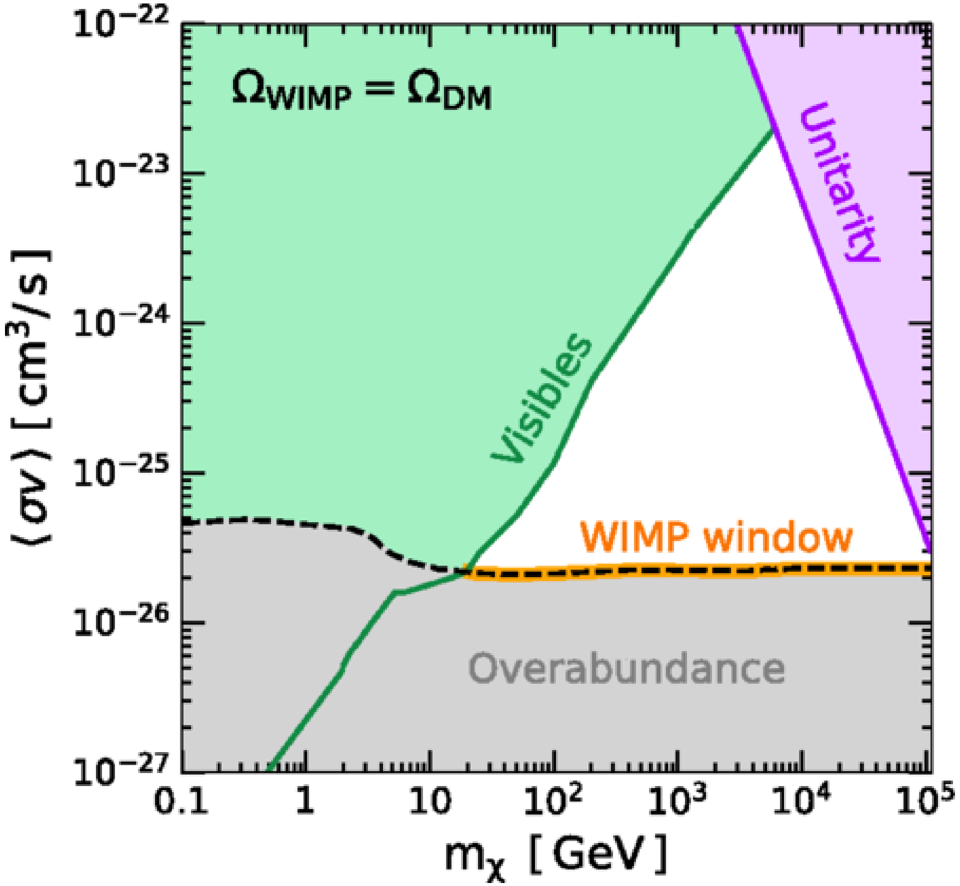
# Indirect detection constraints

R. Leane, et al., arXiv:1805.10305

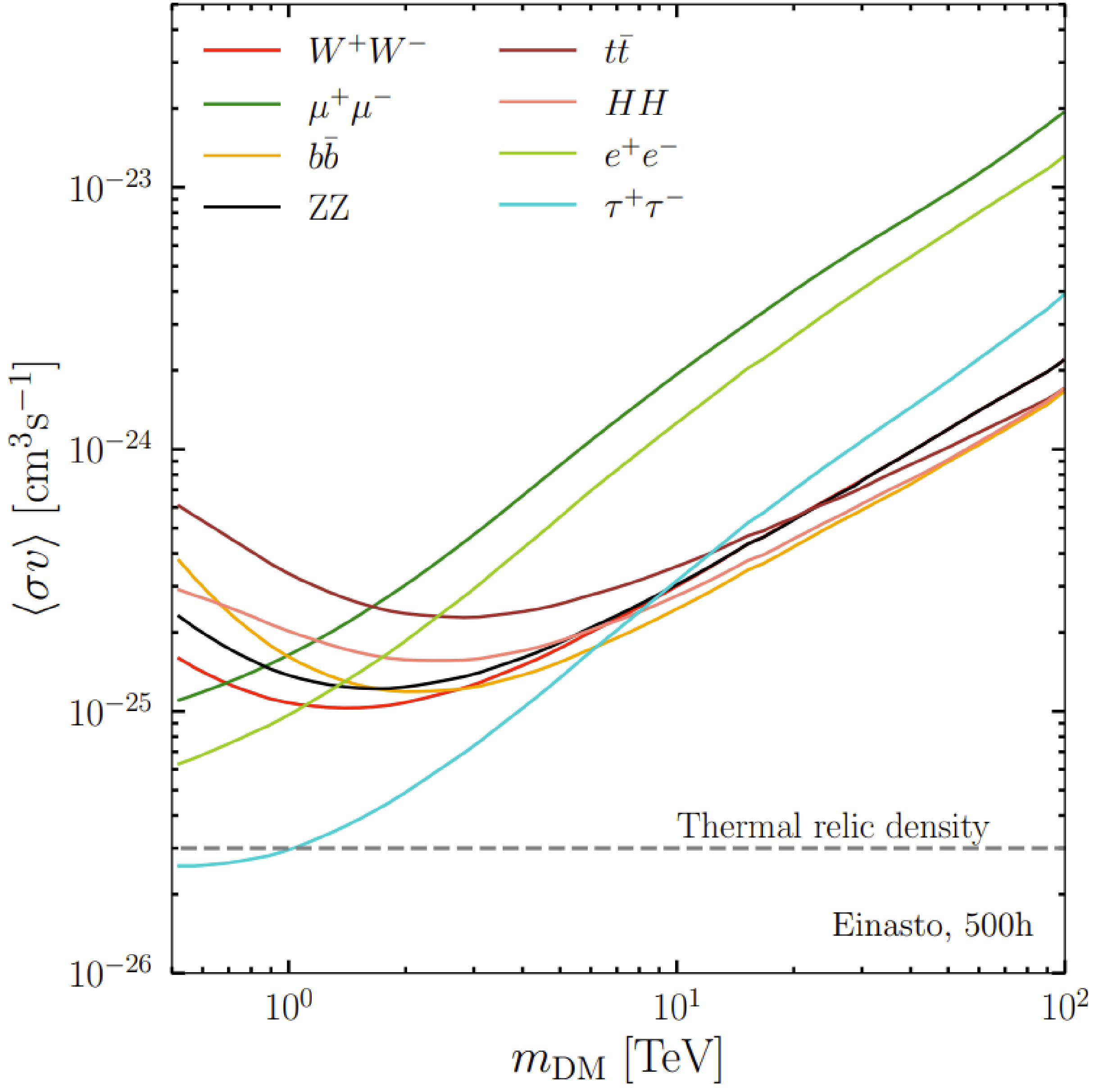
**Fermi dSph limits**




**Annihilation to "visible" SM states**



# Closing the WIMP window: TeV gamma rays

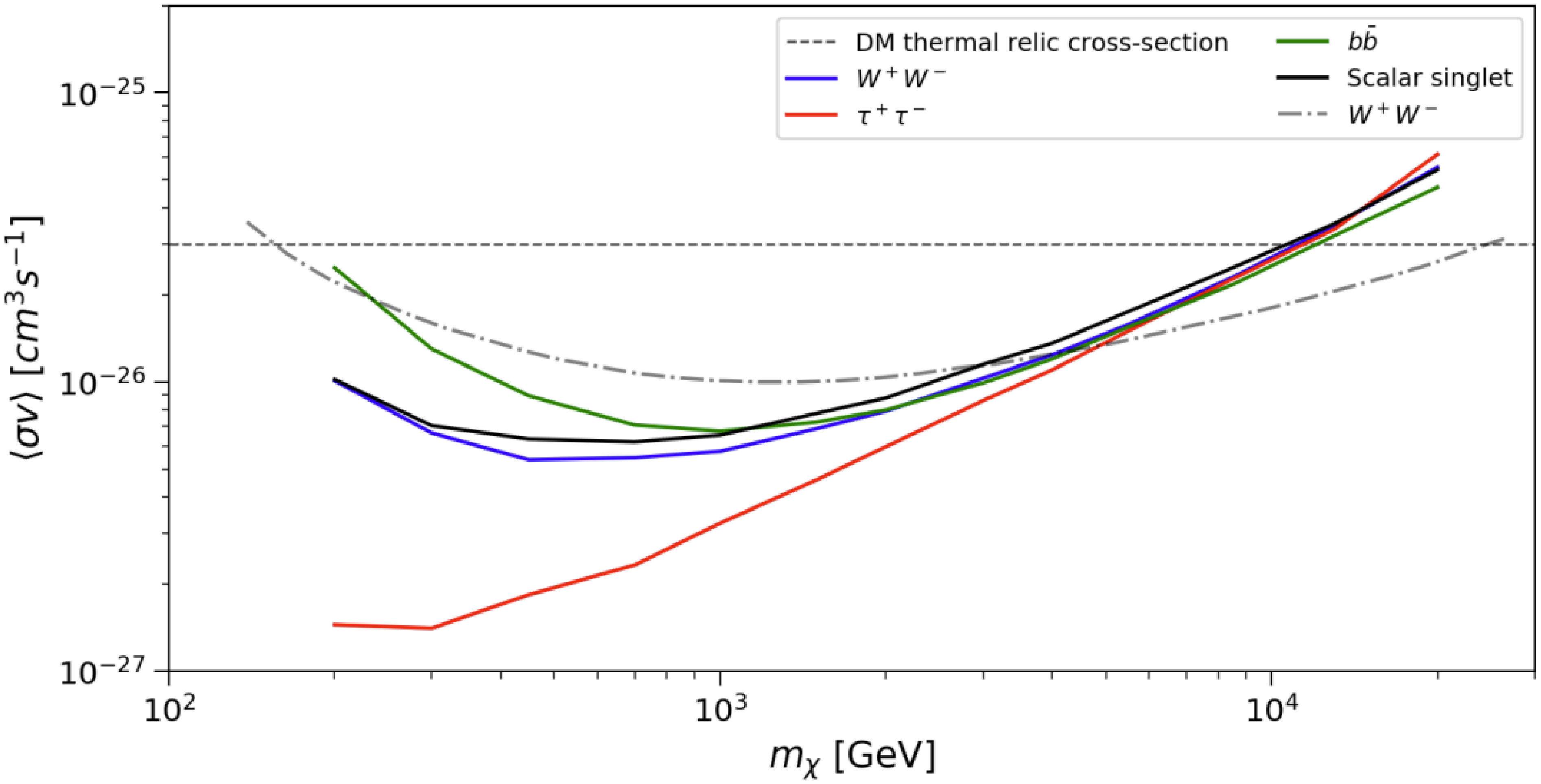



Projected sensitivity for current generation Cherenkov telescopes (HESS-like)

Montanari, Moulin & Rodd, arXiv:2210.03140

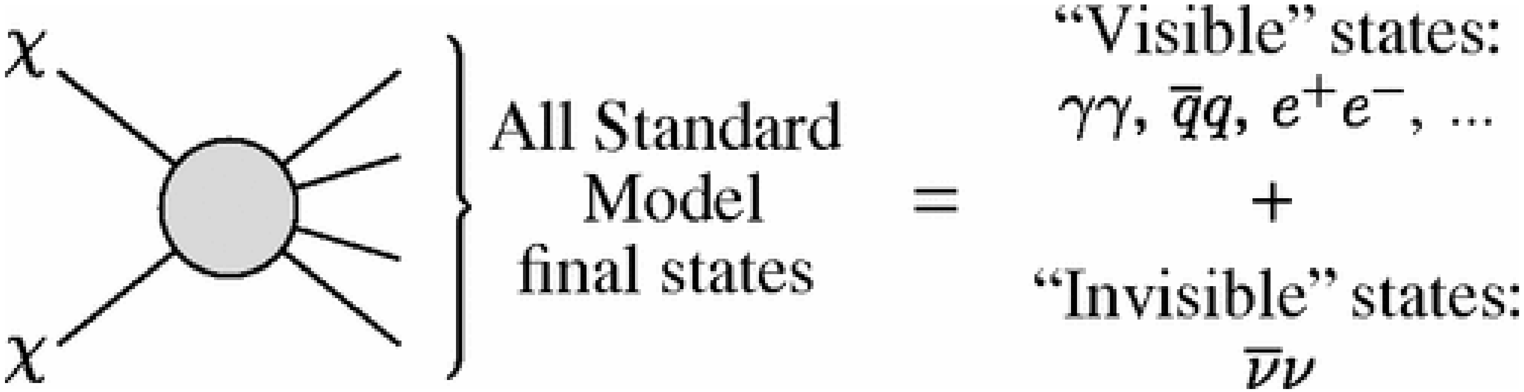
# Closing the WIMP window:  CTA projections

Mangipudi, Thrane & Balazs, arXiv:2112.10371



# Closing the WIMP window: Neutrinos

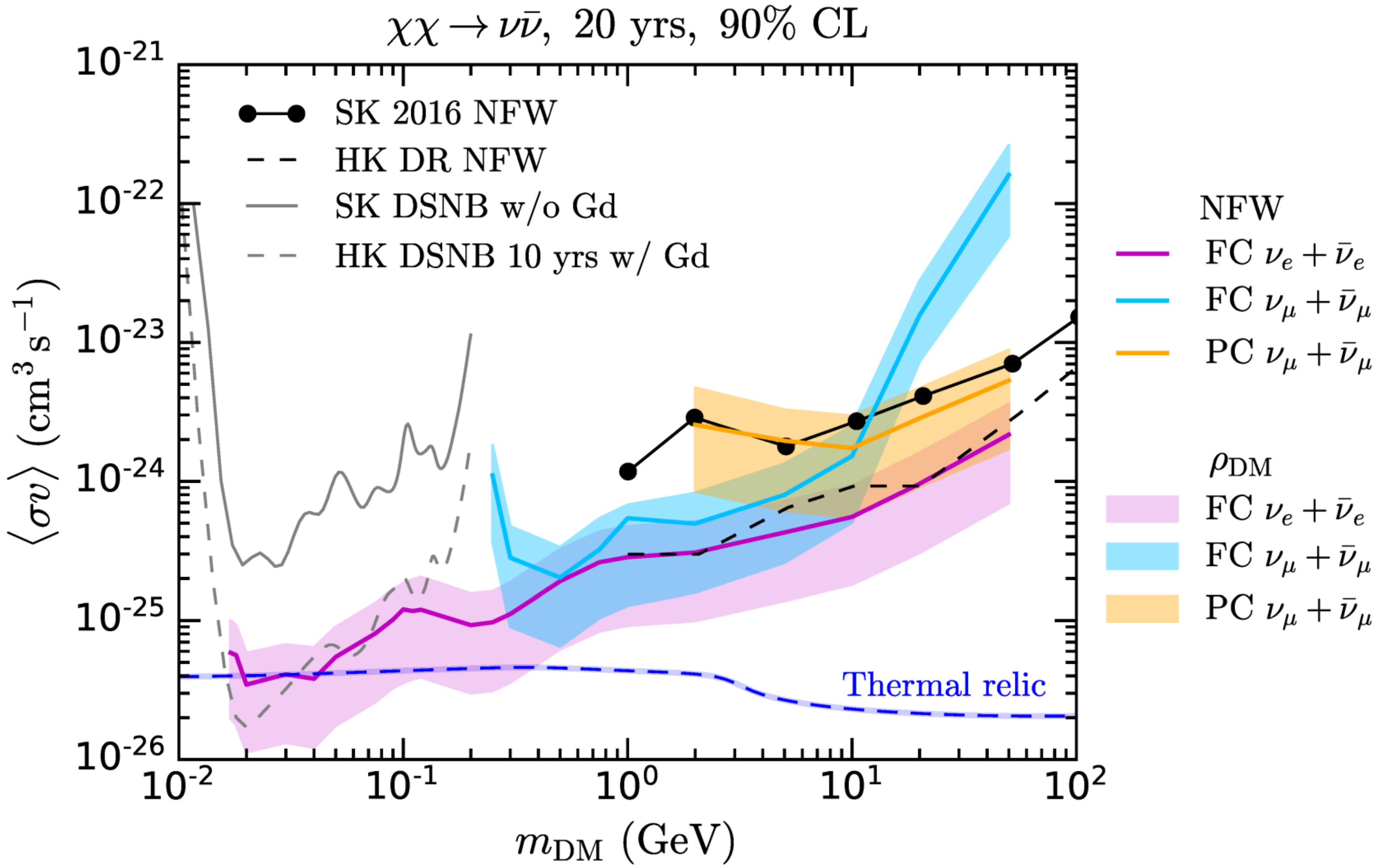
- Indirect detection limits – typically neglect the possibility that dark matter may annihilate to "invisible" or hard-to-detect final states.




Beacom, Bell, Mack, PRL 2007

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

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



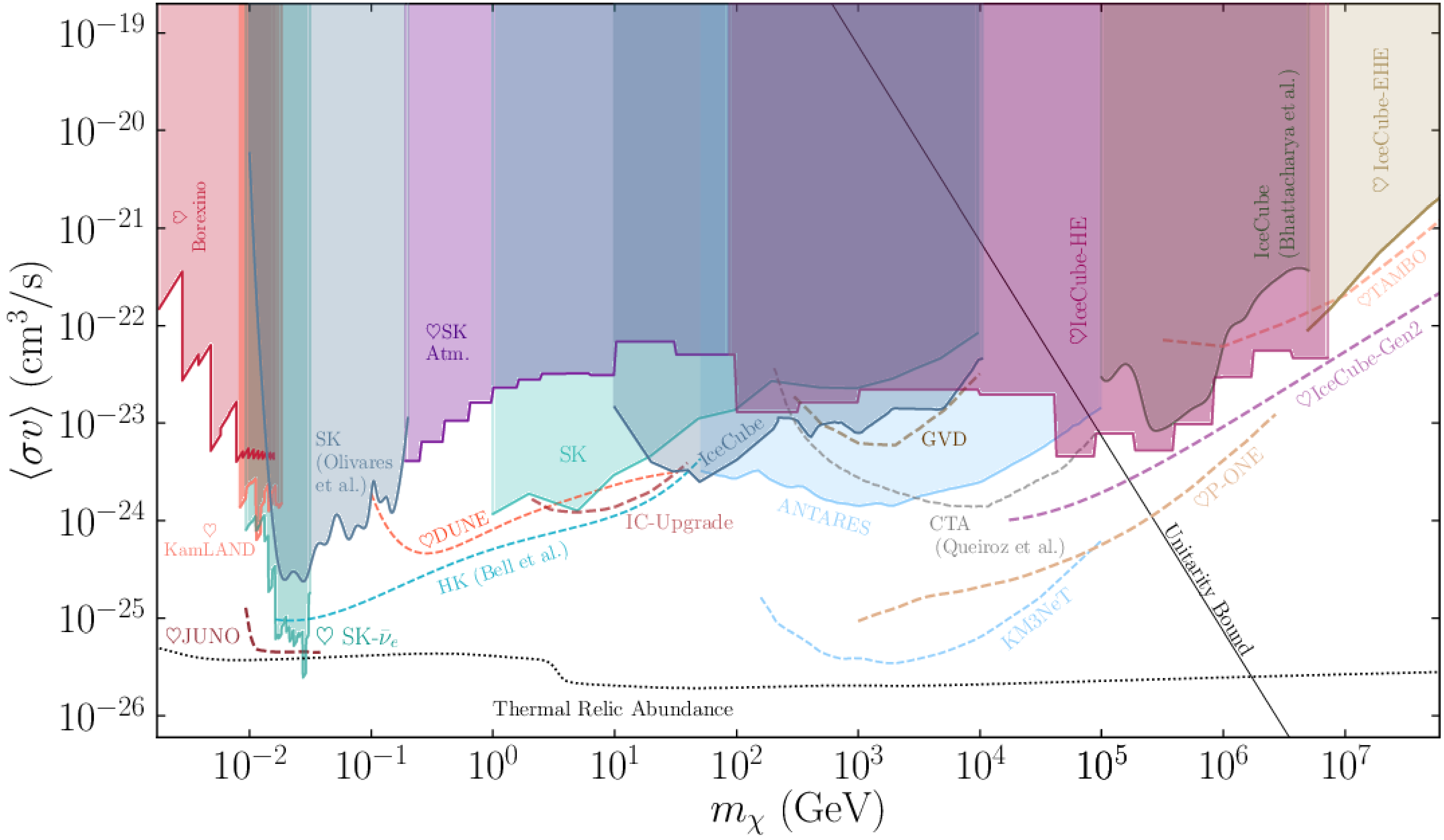

Thermal relic sensitivity for $m_\chi$~30 MeV

NFW – central lines
Isothermal – upper
Moore - lower

Bell, Dolan, Robles, arXiv: 2005.01950

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

Arguelles et al, arXiv: 1912.09486

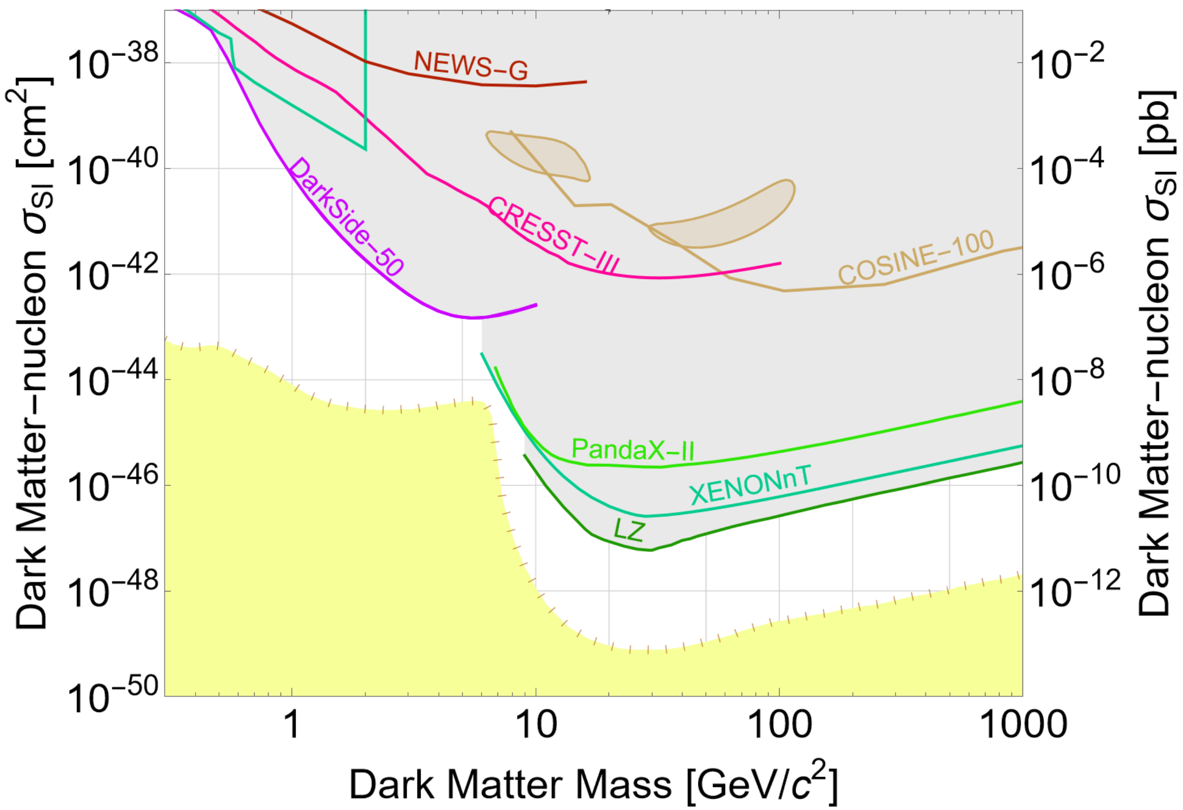


# Direct detection

# Direct Detection

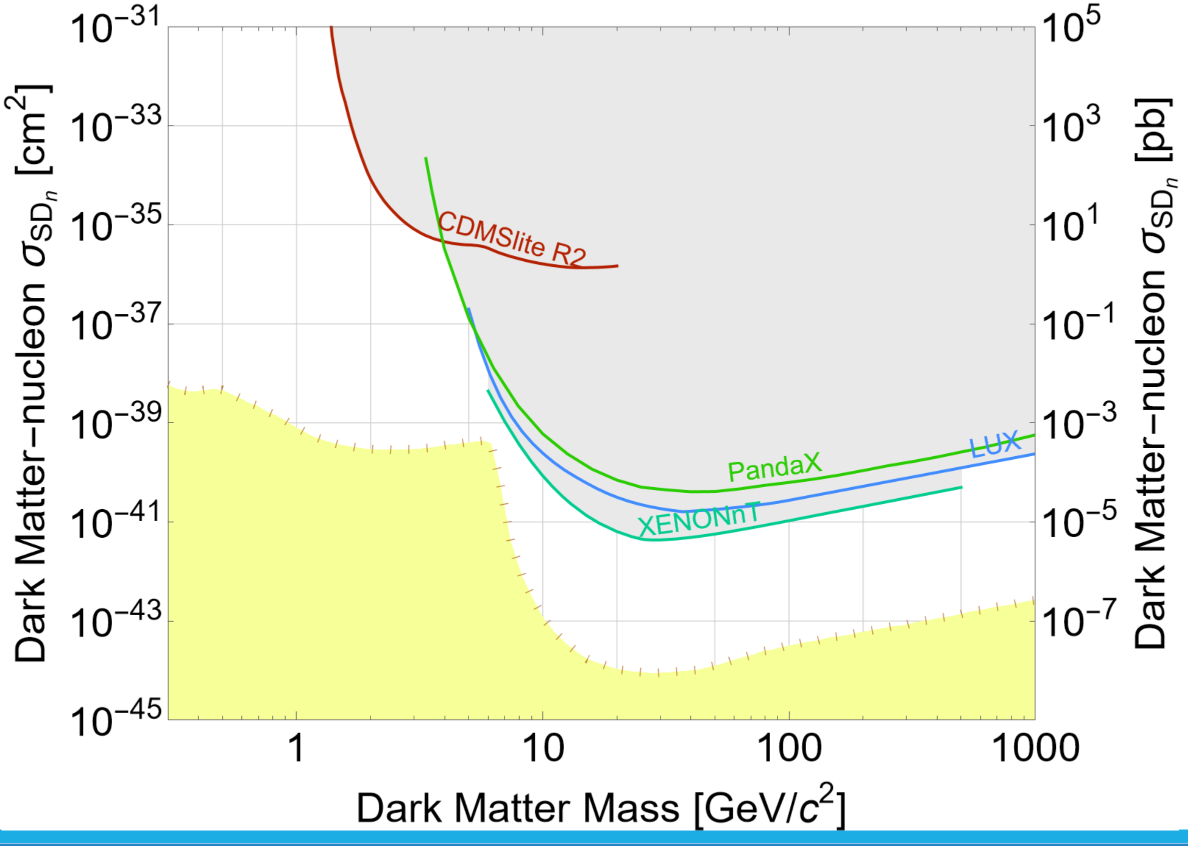
## Spin-independent (SI) interactions

→ strong bounds due to coherent enhancement

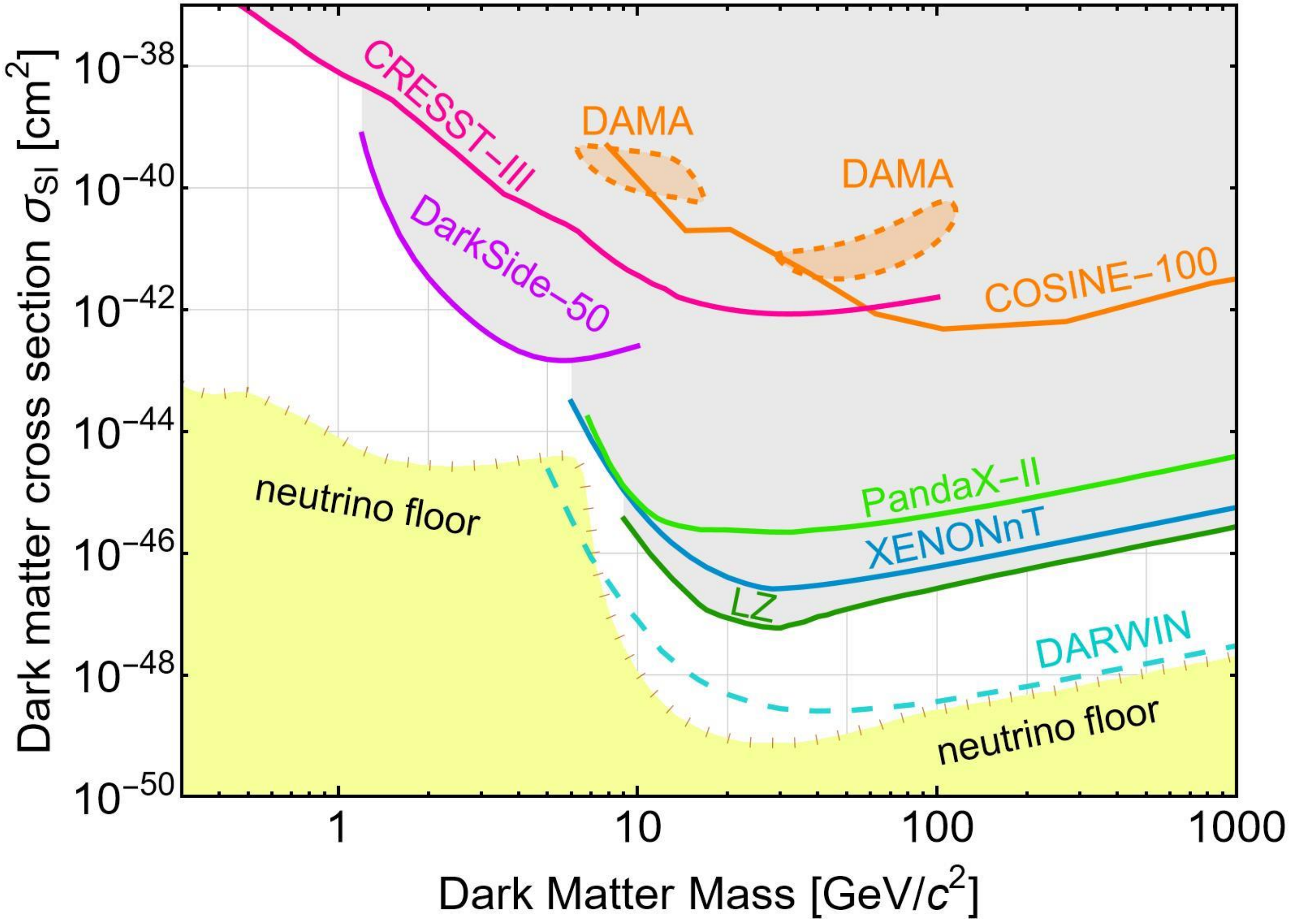



## Spin-dependent (SD) interactions

→ weaker bounds

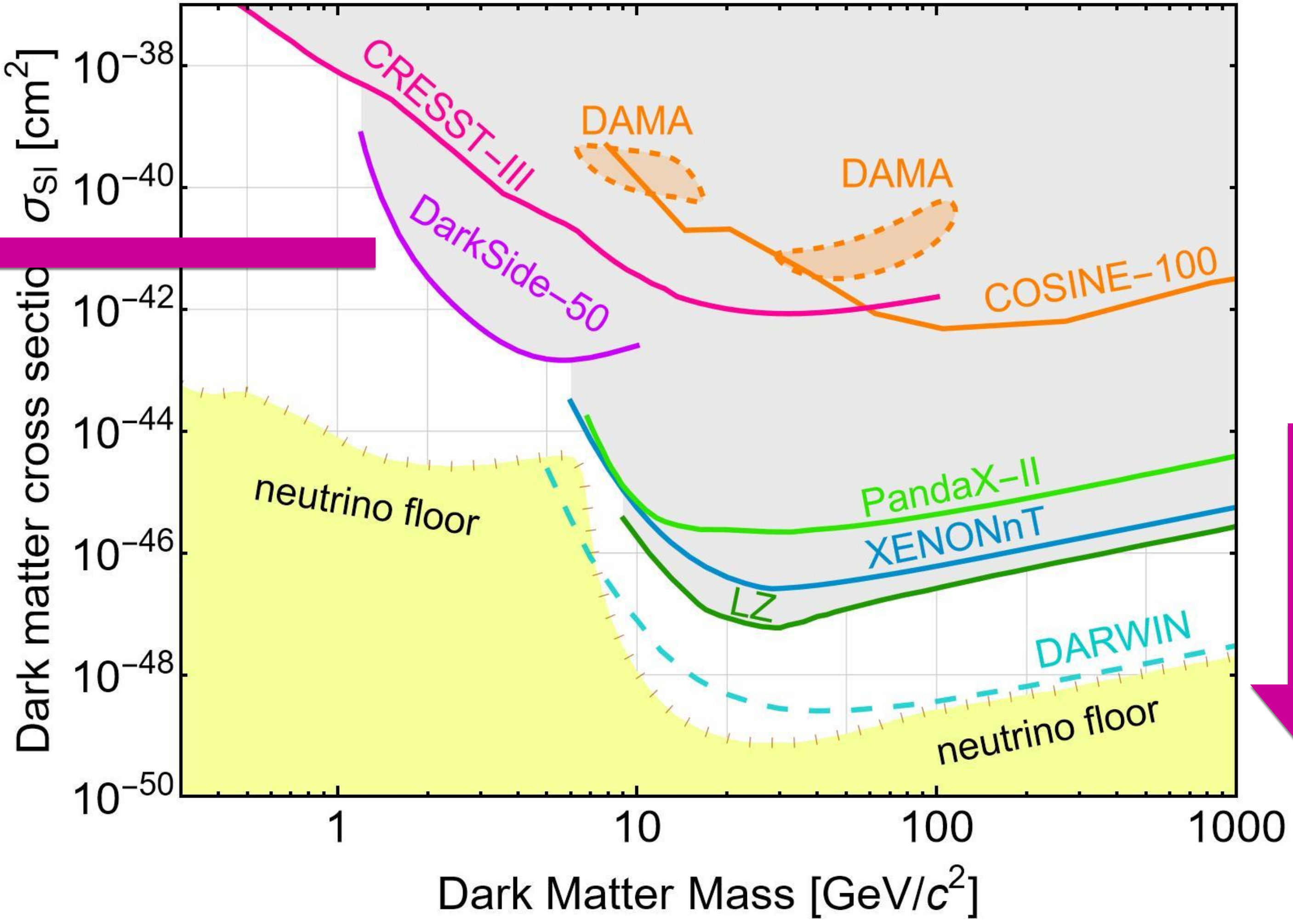


# Direct Detection – future challenges



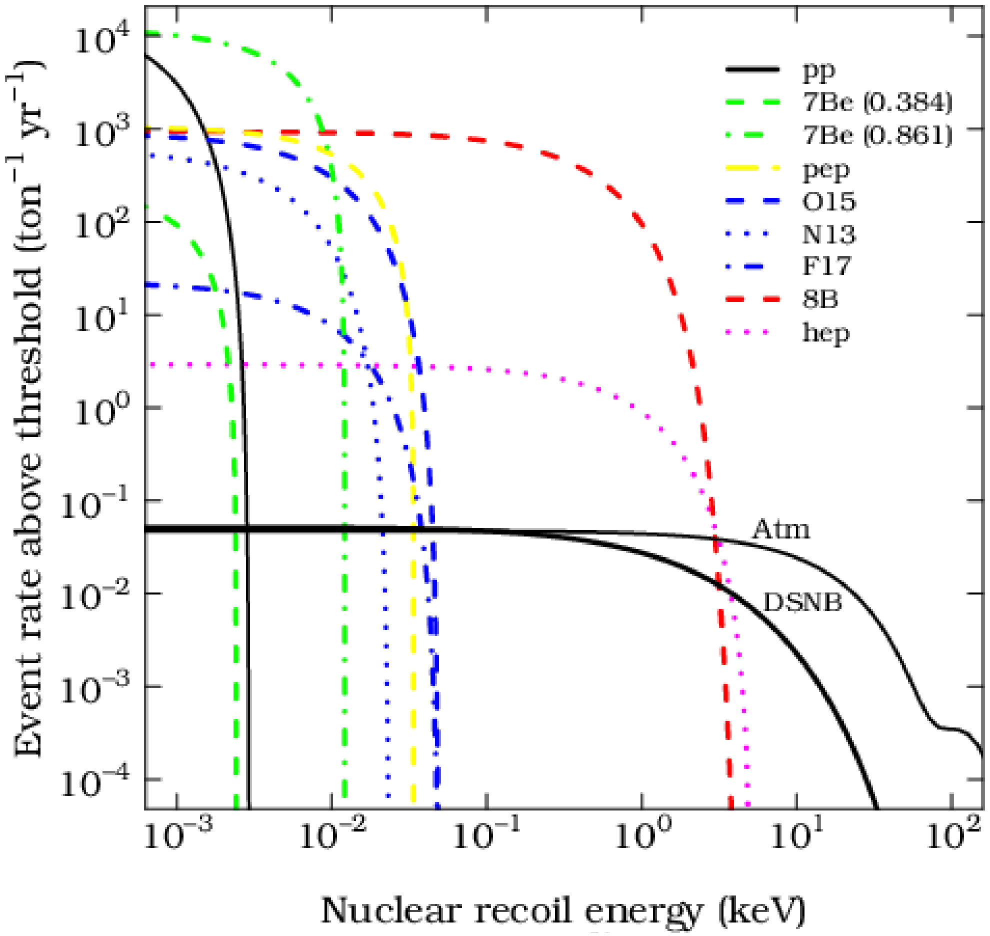
# Direct Detection – future challenges

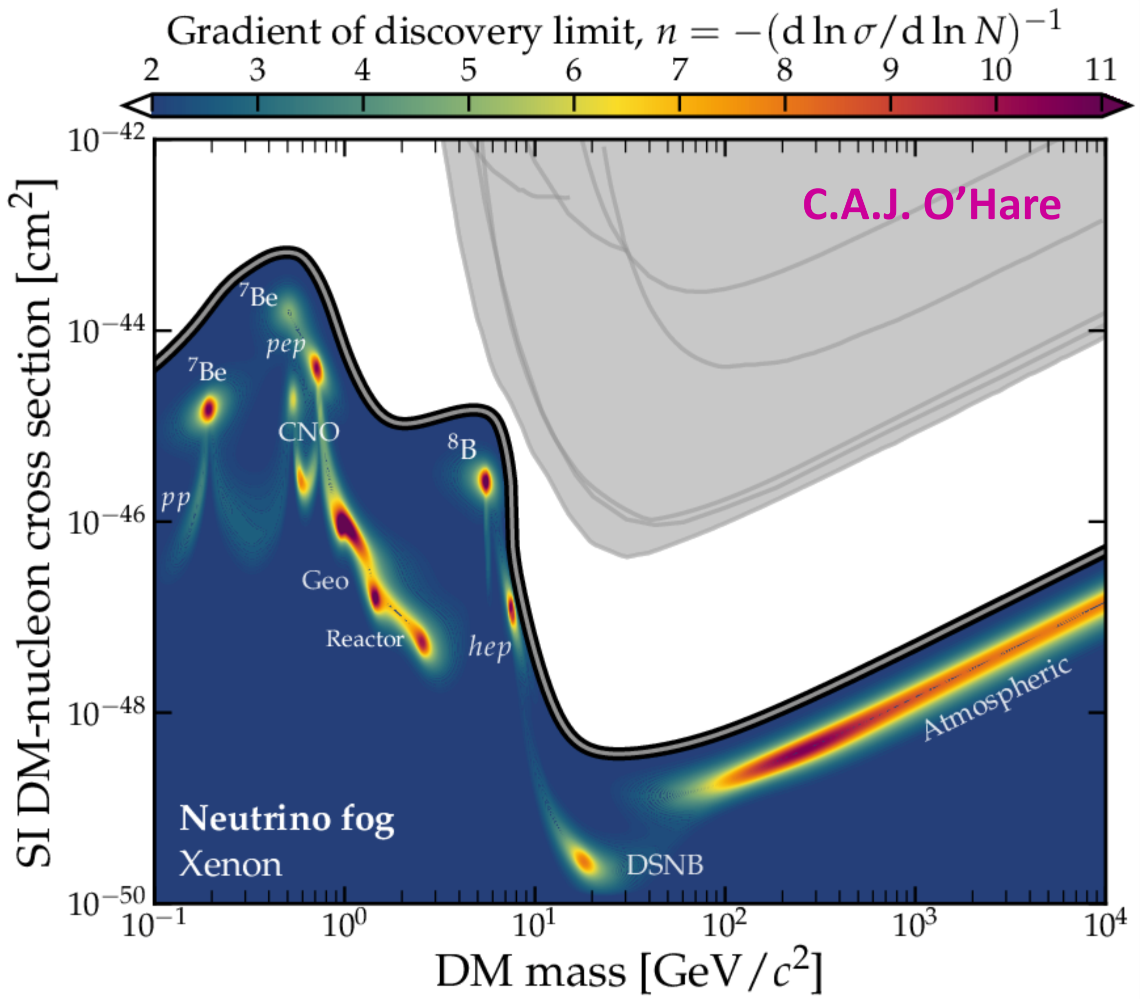
Lower thresholds




Larger detectors;
Lower backgrounds

# Neutrino floor

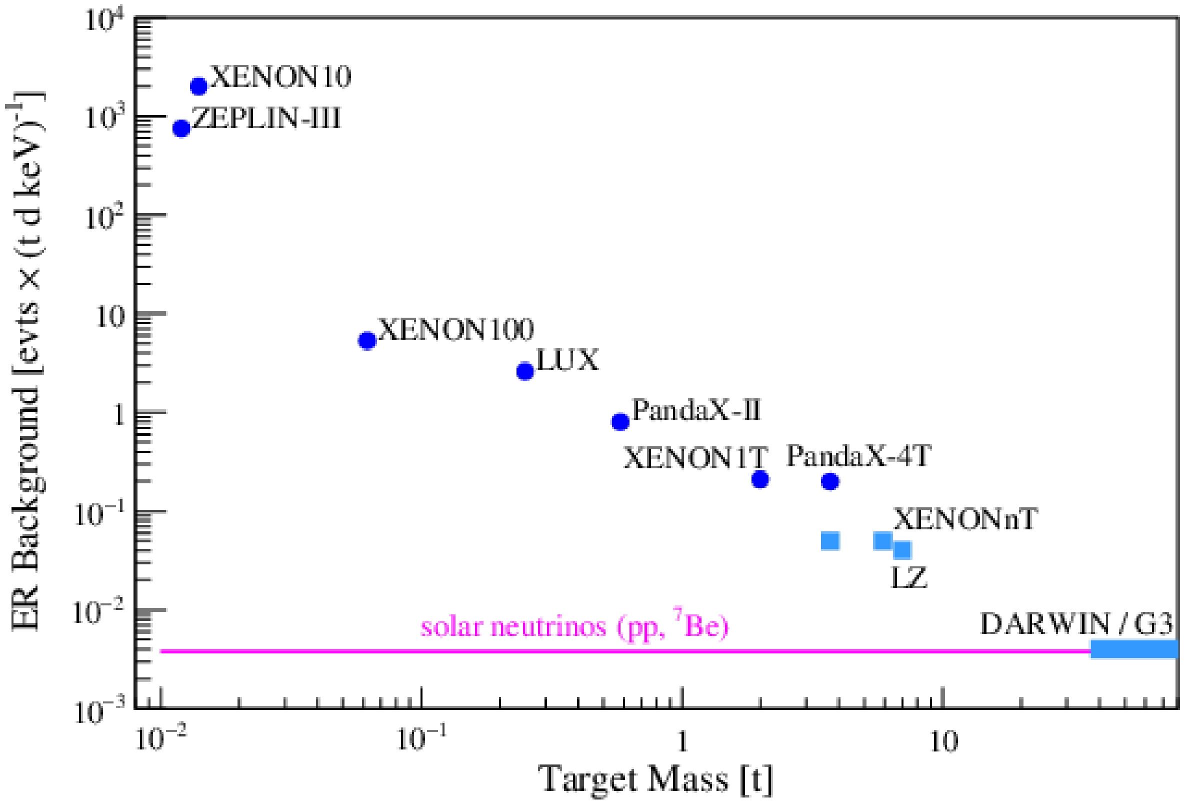



arXiv:2203.07361

# Toward the neutrino floor

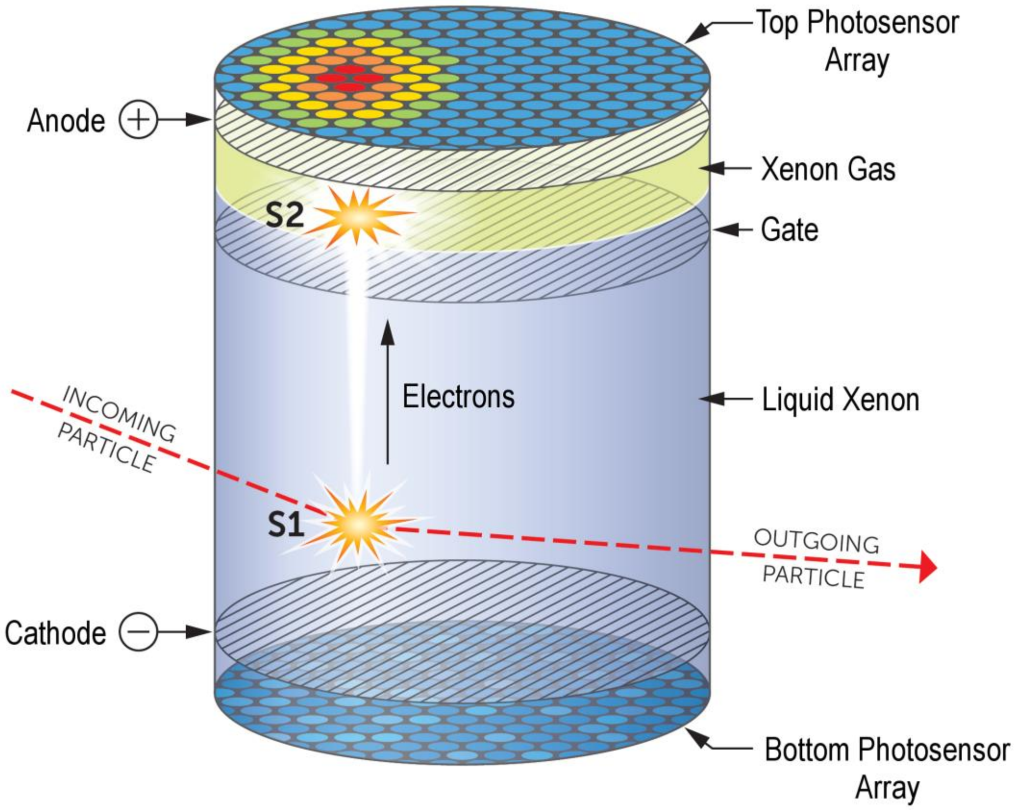
Next generation liquid noble gas experiments will reach the neutrino floor:

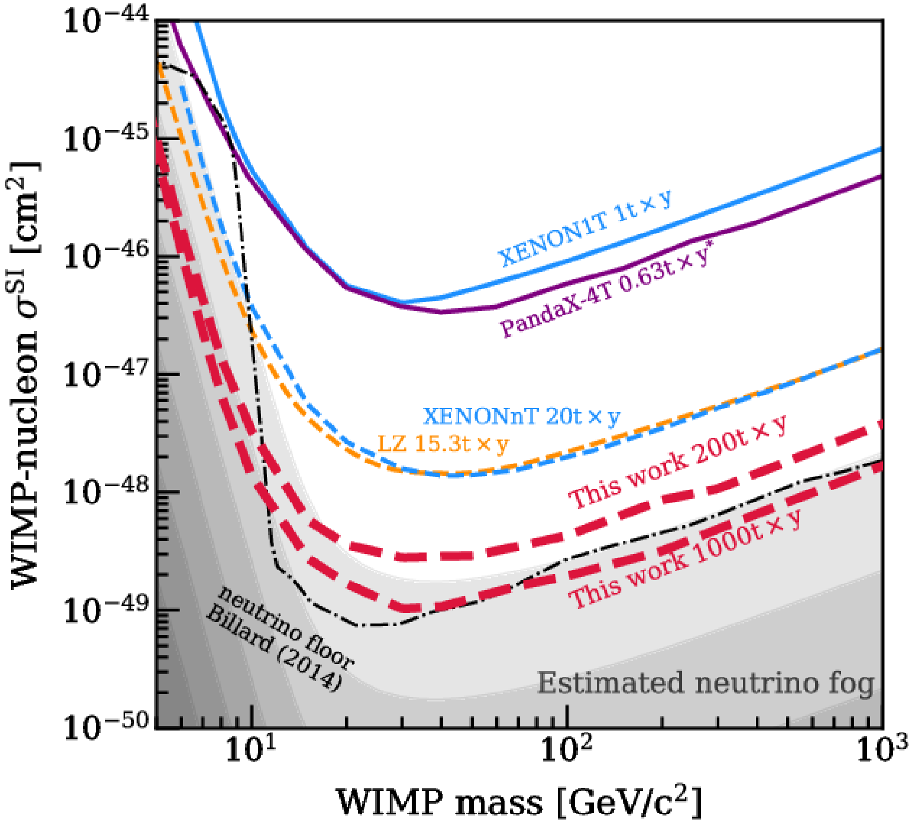



Images from: arXiv:2203.02309

# DARWIN/XLZD: Generation-3 liquid-Xenon experiment

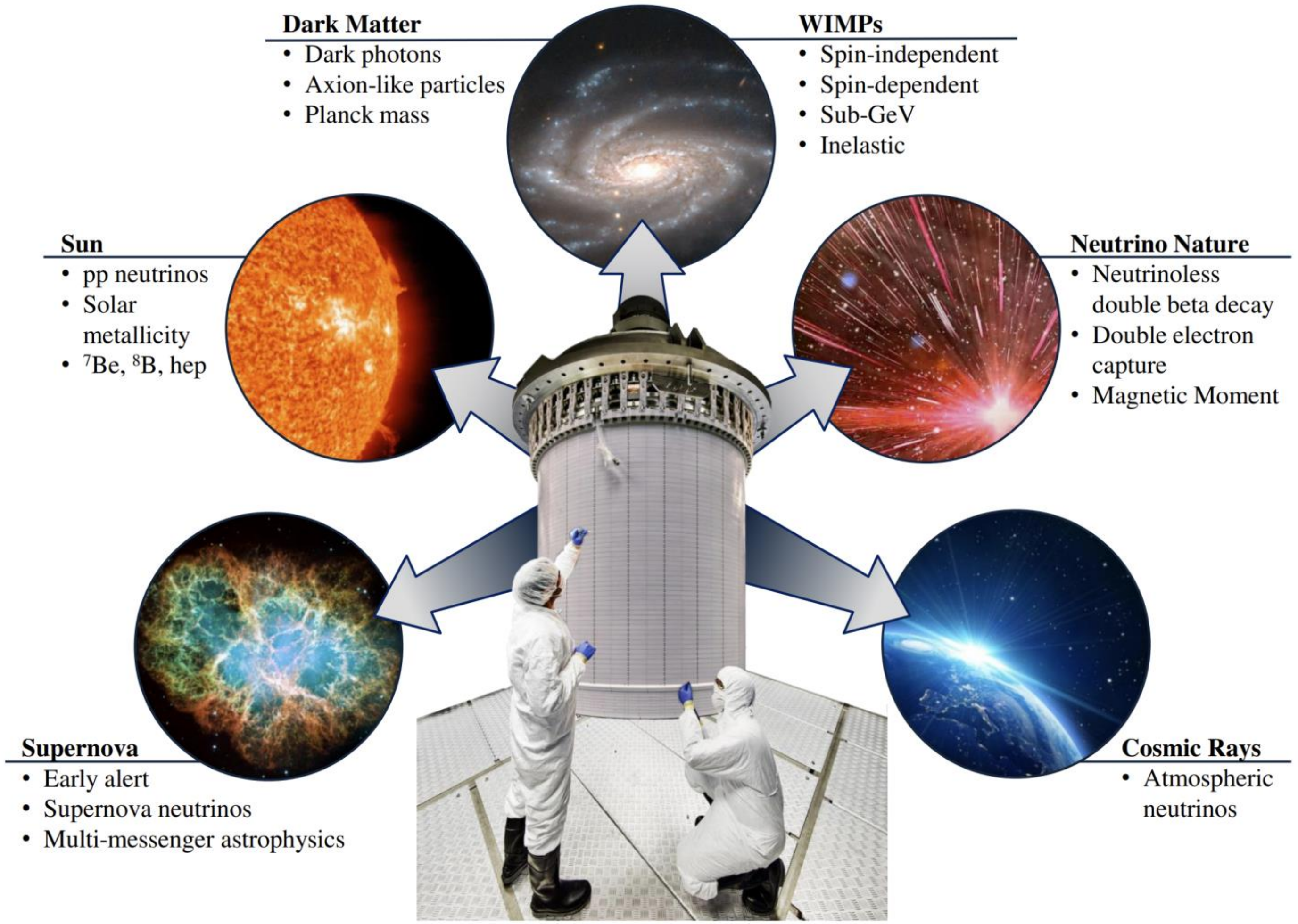
Images from: arXiv:2203.02309



# Gen 3 liquid noble gas experiment

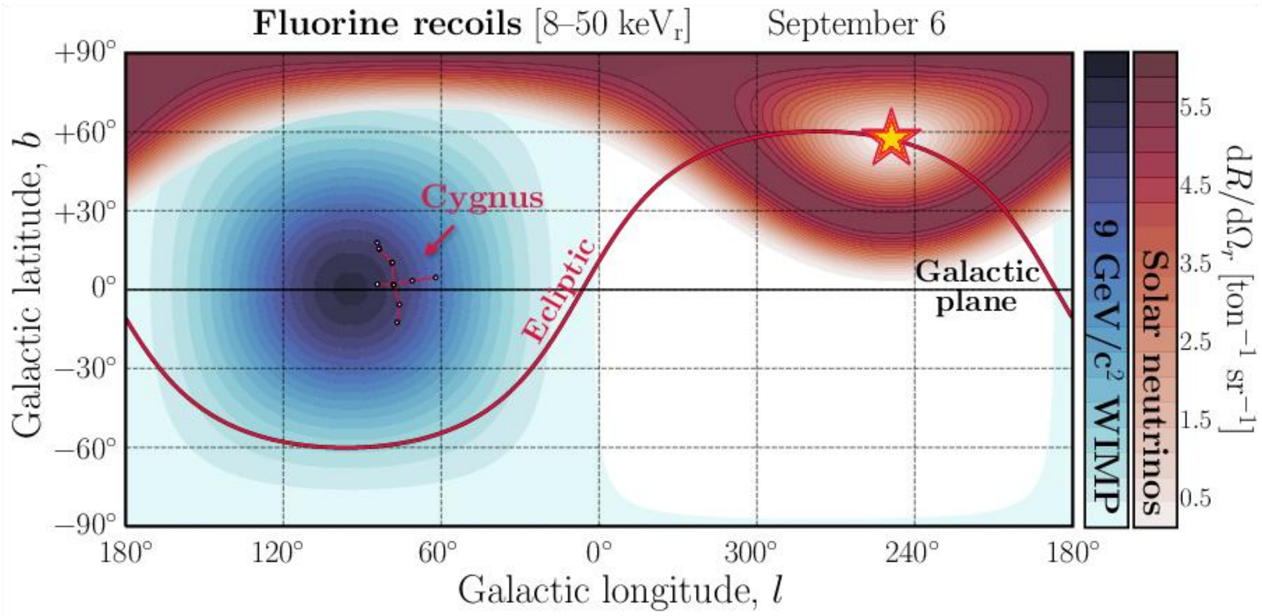
Next generation dark matter experiments will be multi-purpose dark matter/neutrino/astroparticle observatories

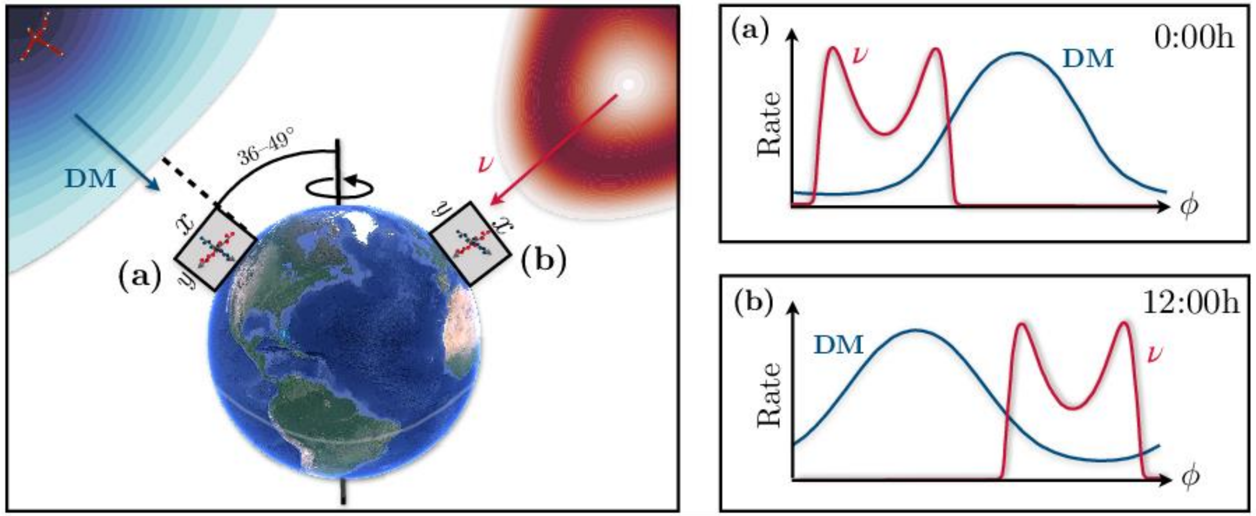


# Below the neutrino floor: – directional detection

Due to the motion of the solar system, the dark matter signal is aligned with a particular direction on the sky (the direction of the Cygnus constellation).

Directional detection cannot enable us to separate dark matter signal from neutrino background



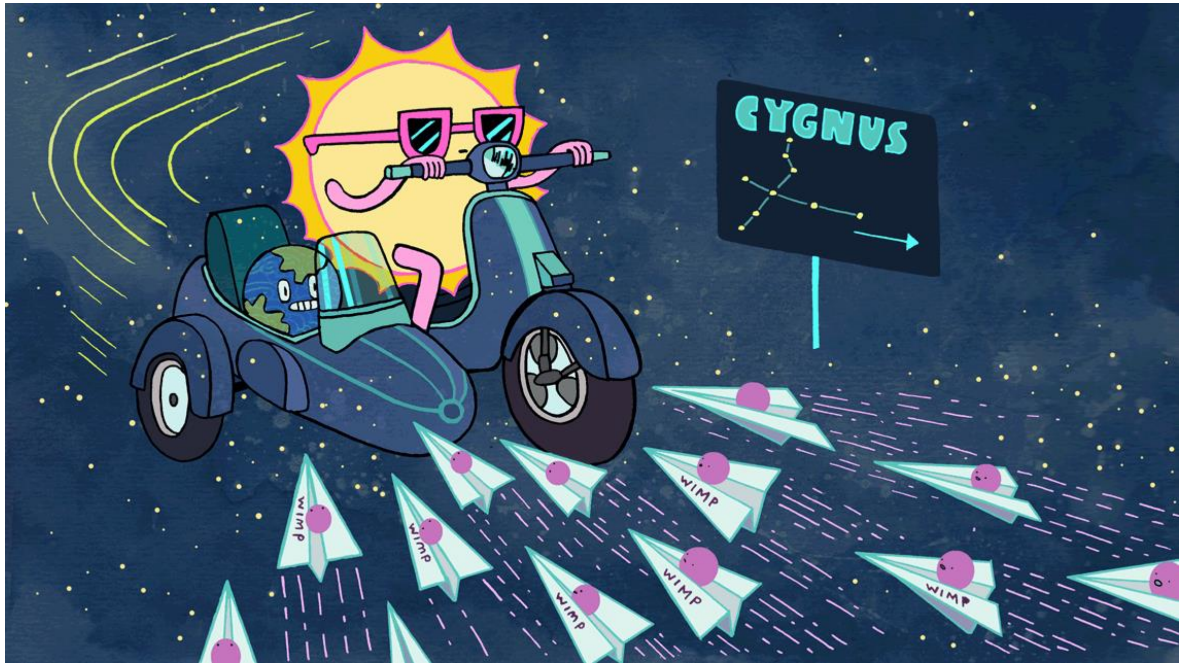




Vahsen, O'Hare & Loomba arXiv:2102.04596

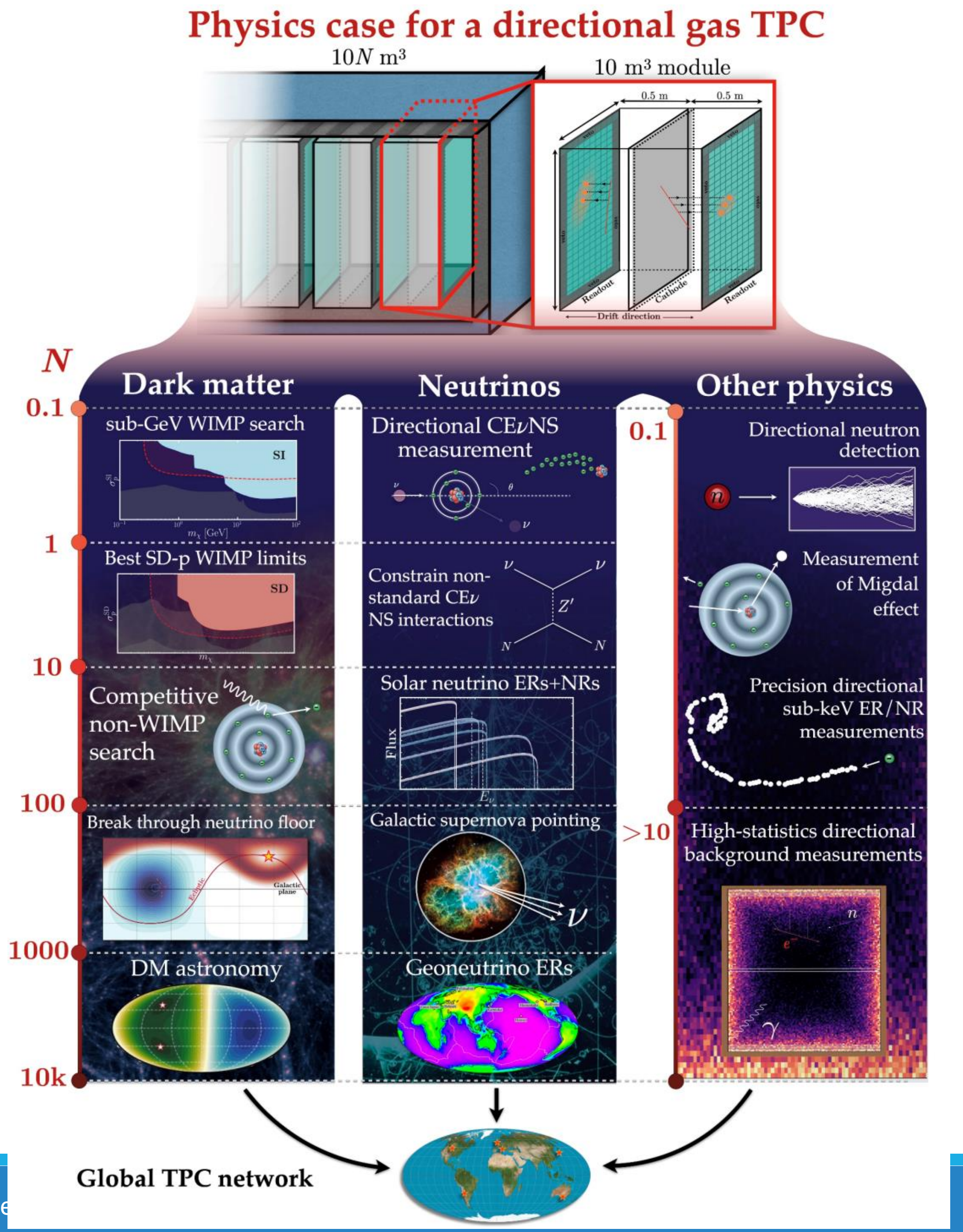
# Directional detection

CYGNUS project: a directional gas TPC

→ Dark matter and neutrino applications




Artwork by Sandbox Studio, Chicago with Corinne Mucha



# 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
  - "Boosted" (i.e. more energetic) dark matter
- Low mass WIMPS → new experimental techniques with low threshold
- Complementary constraints from astrophysics
  - Dark matter capture in the Sun, neutron stars, etc.

# Migdal effect

The ionization of an atom following a nuclear recoil

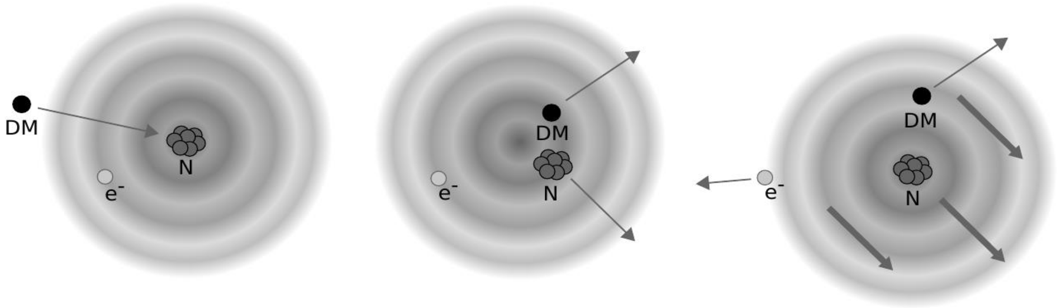



Image: M. Dolan et al.

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

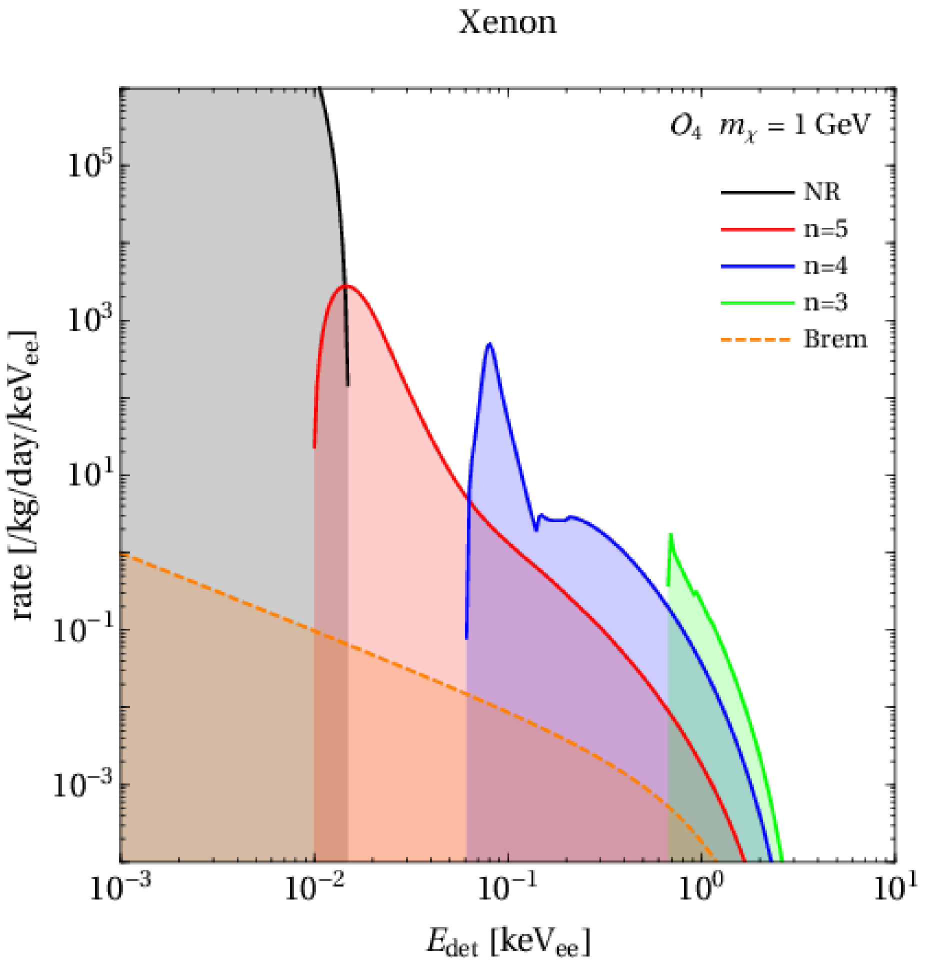
Nuclear recoil: $$E_{R,max} = \frac{2\mu_T^2}{m_T} v_{max}^2$$

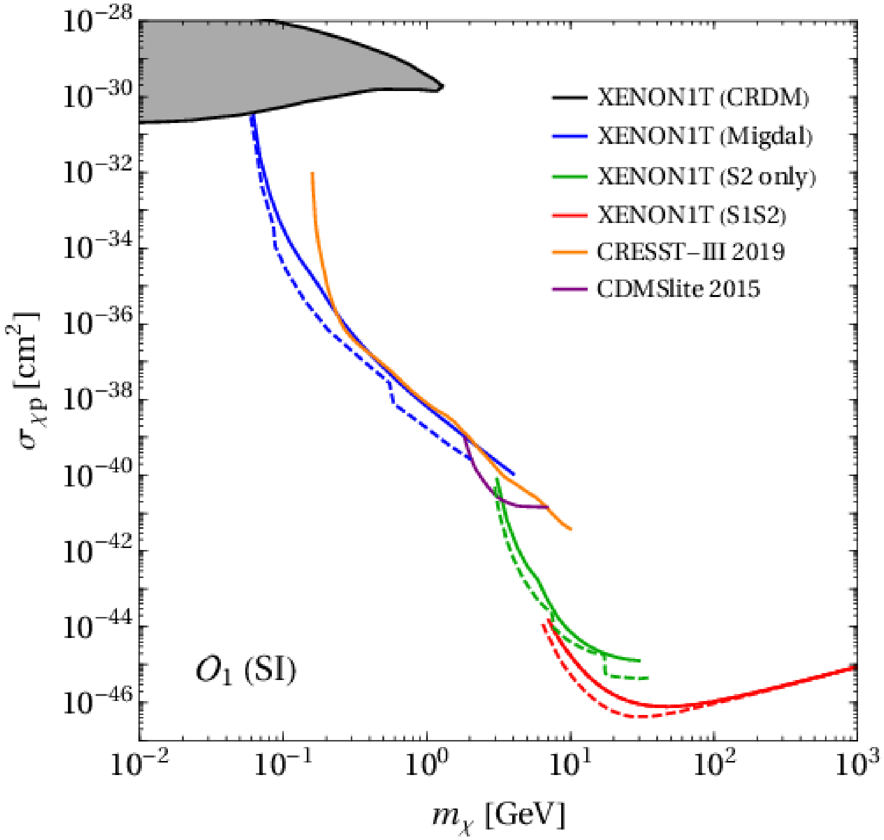
Migdal electrons: $$E_{EM,max} = \frac{\mu_T}{2} v_{max}^2$$

$m_T$ = Target mass
$\mu_T$ = DM-nucleon reduced mass

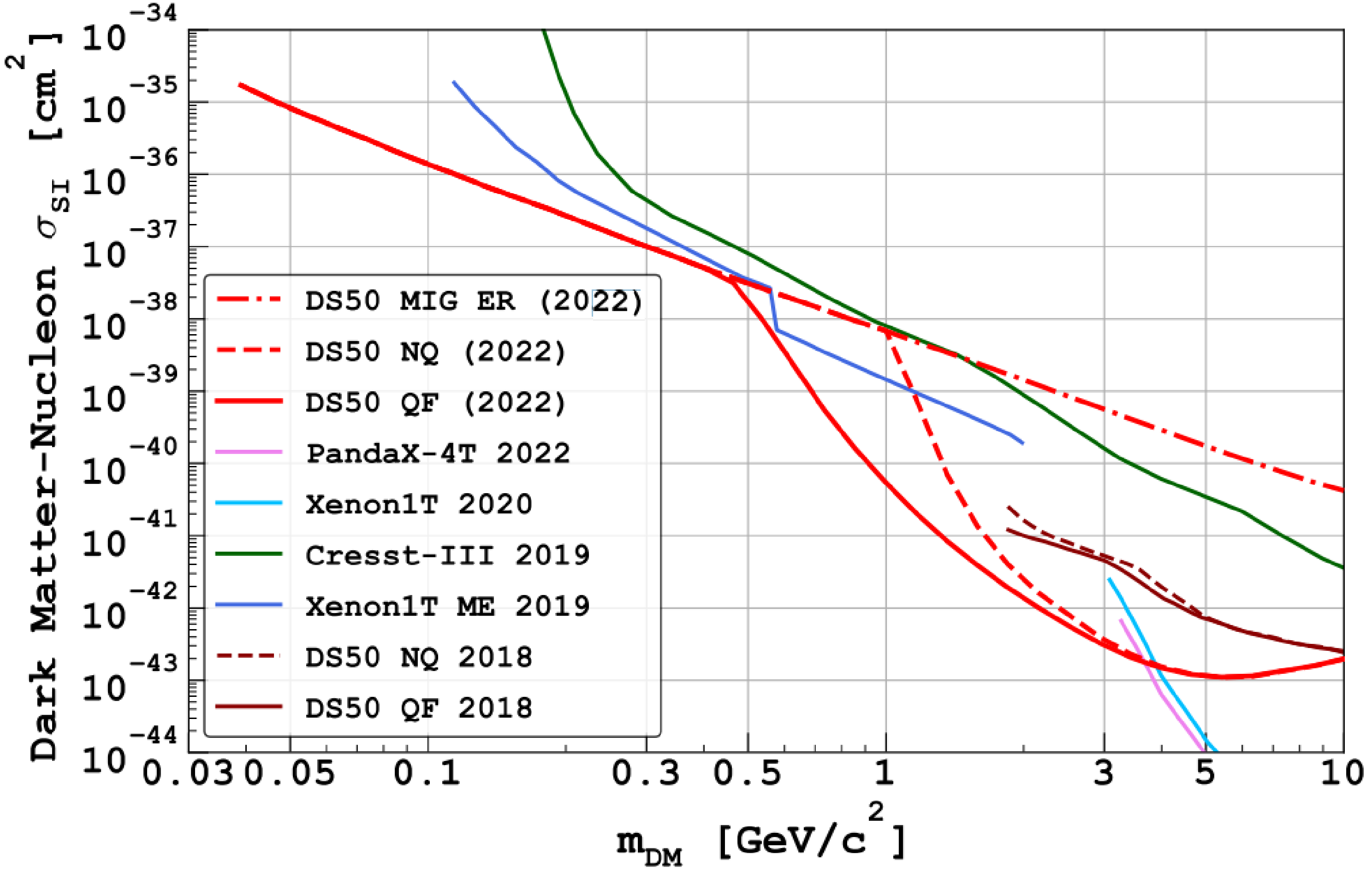
# Migdal effect

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

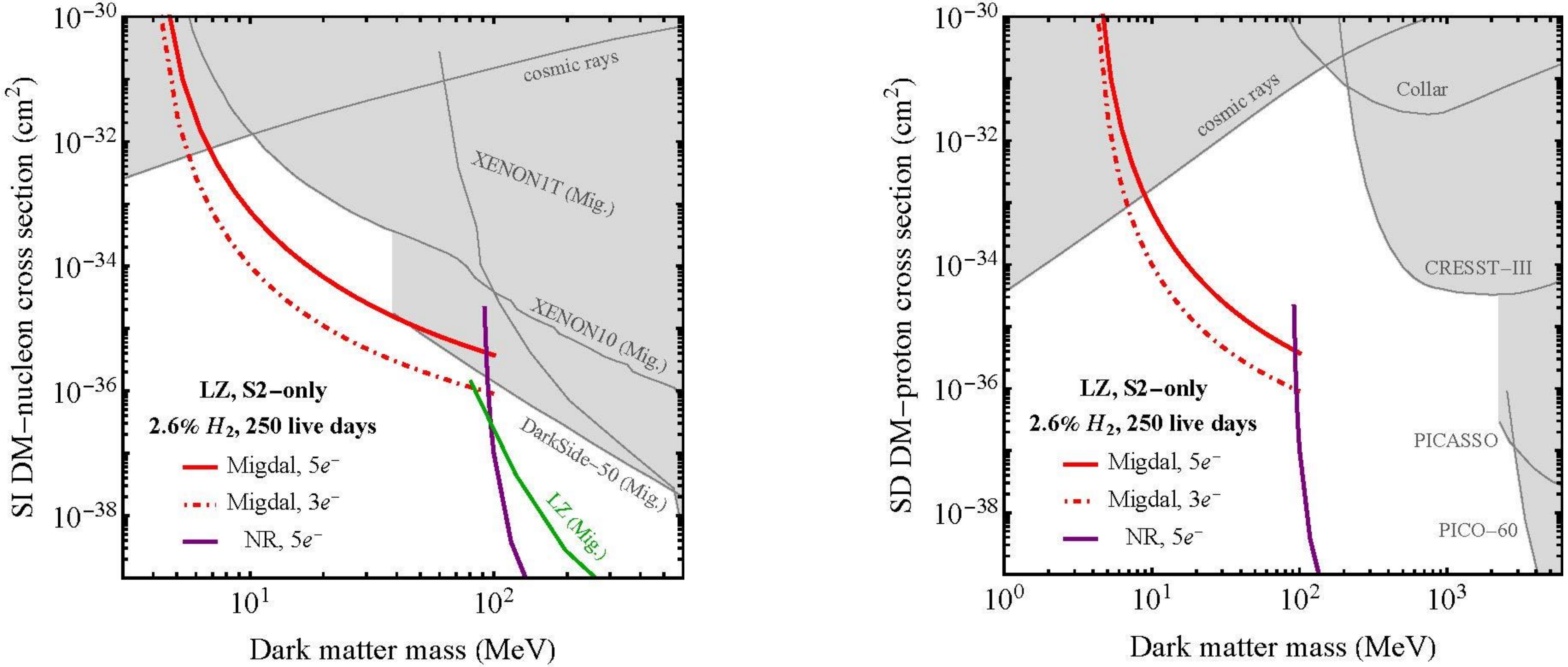
Specific proposal : HydroX = upgrade of LZ, by doping with $H_2$

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

→ **The best sensitivity to light WIMPs**

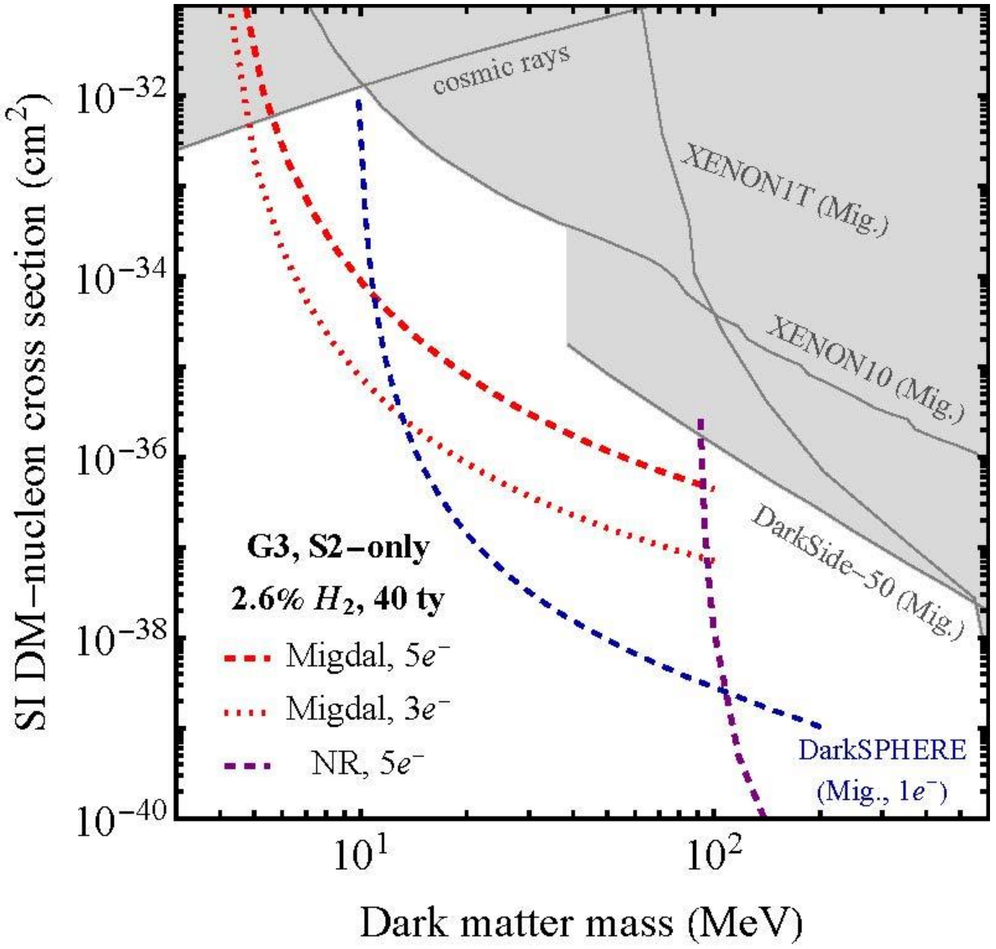
# Migdal effect in H-doped liquid Xenon

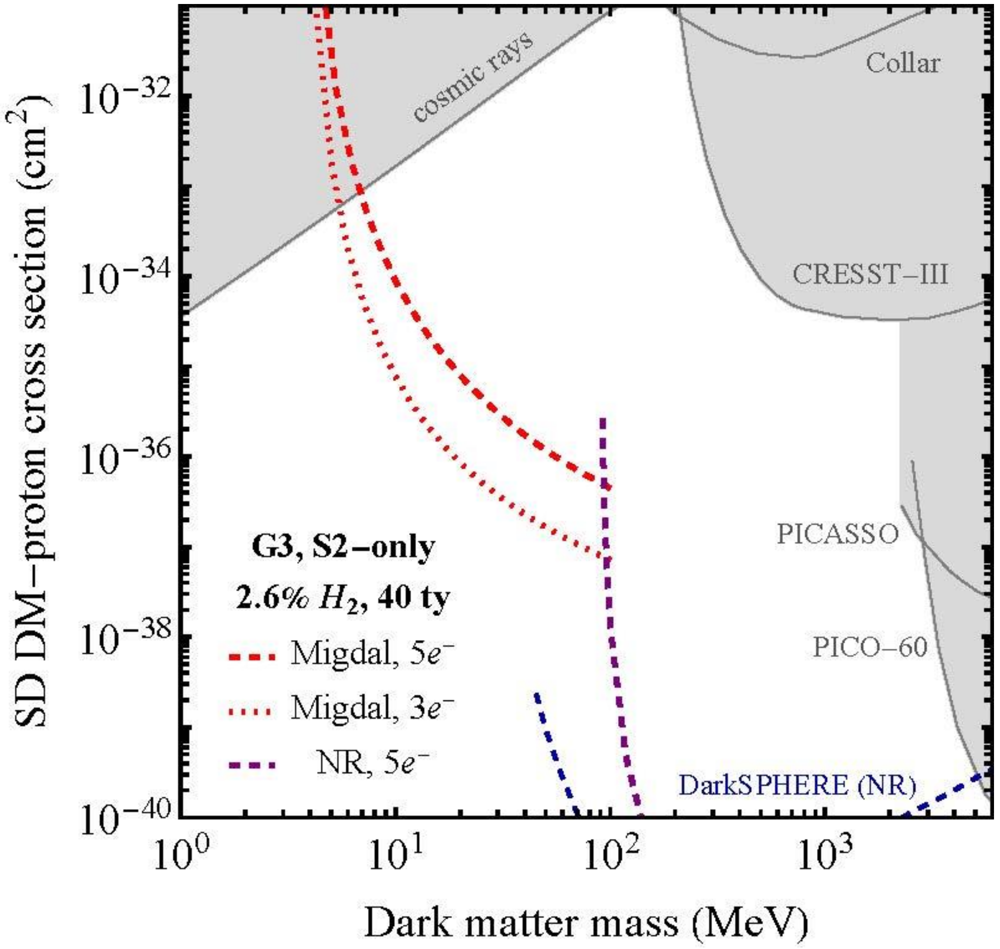
NFB, Cox, Dolan, Newstead, Ritter, arXiv:2305.04690



# Migdal effect in H-doped liquid Xenon

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



# Boosted Dark Matter

Halo dark matter

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

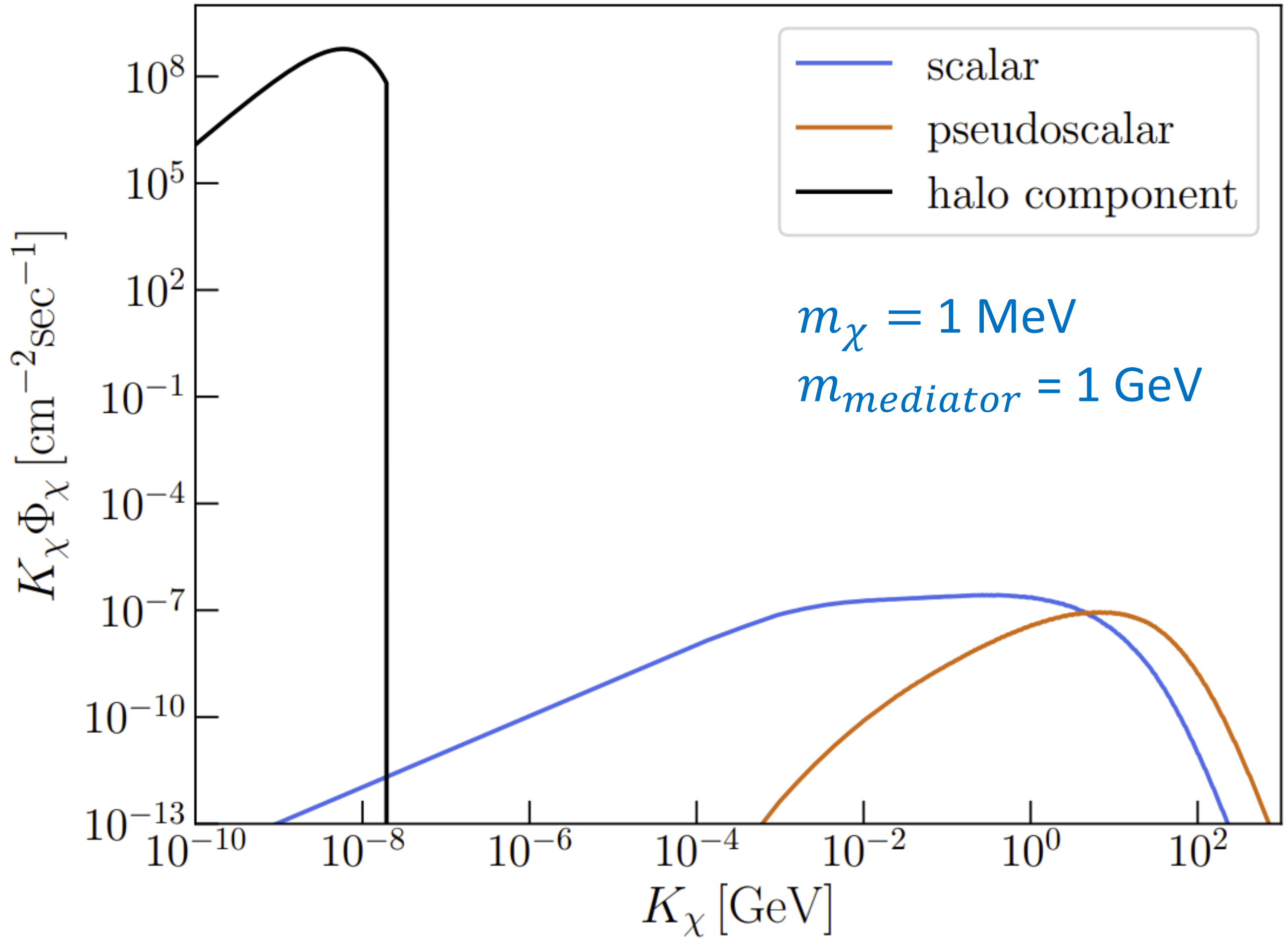
→ low energy recoils in direct detection experiments: $E_{R,max} = \frac{2\mu_T^2}{m_T} v_{max}^2$

**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



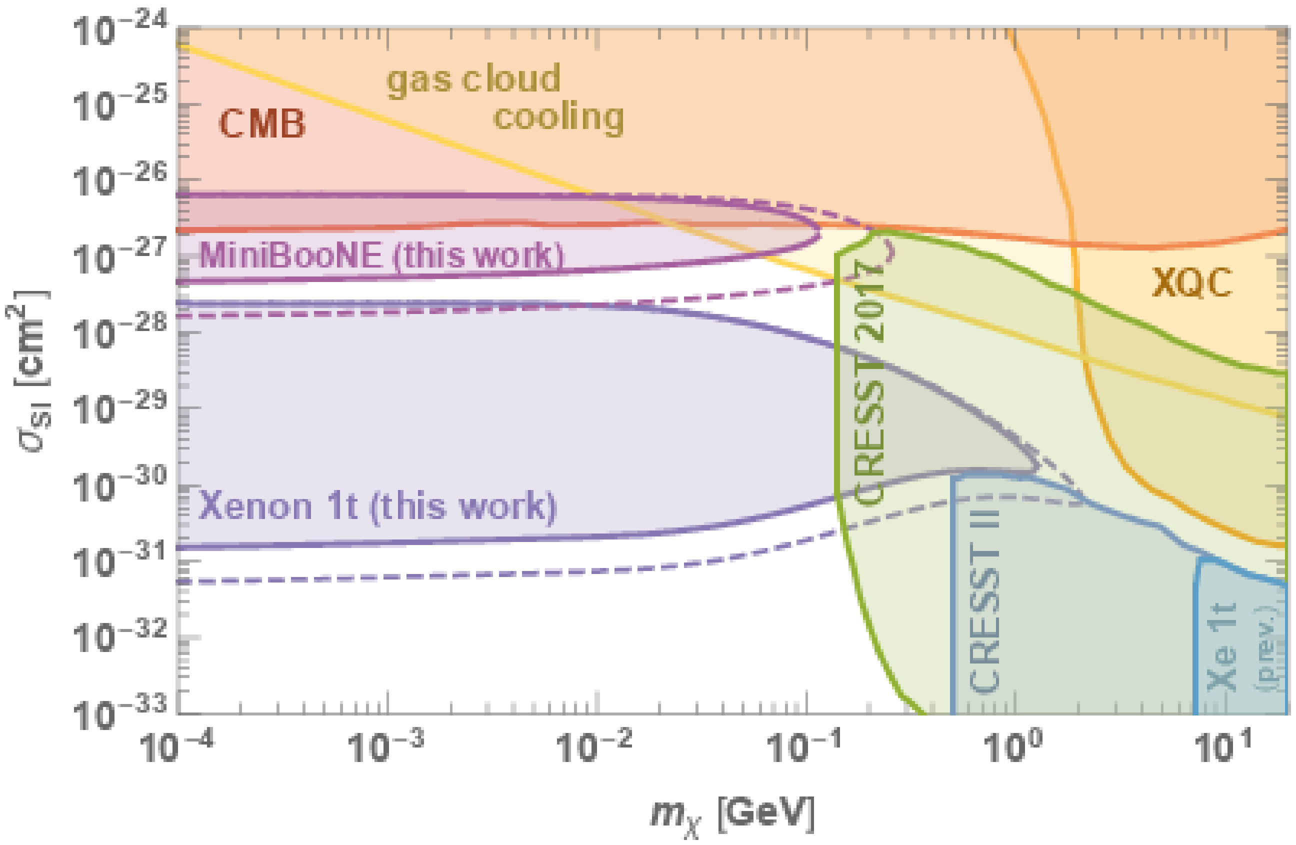

Assume the DM-nucleon scattering cross section is non-zero

→ 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:

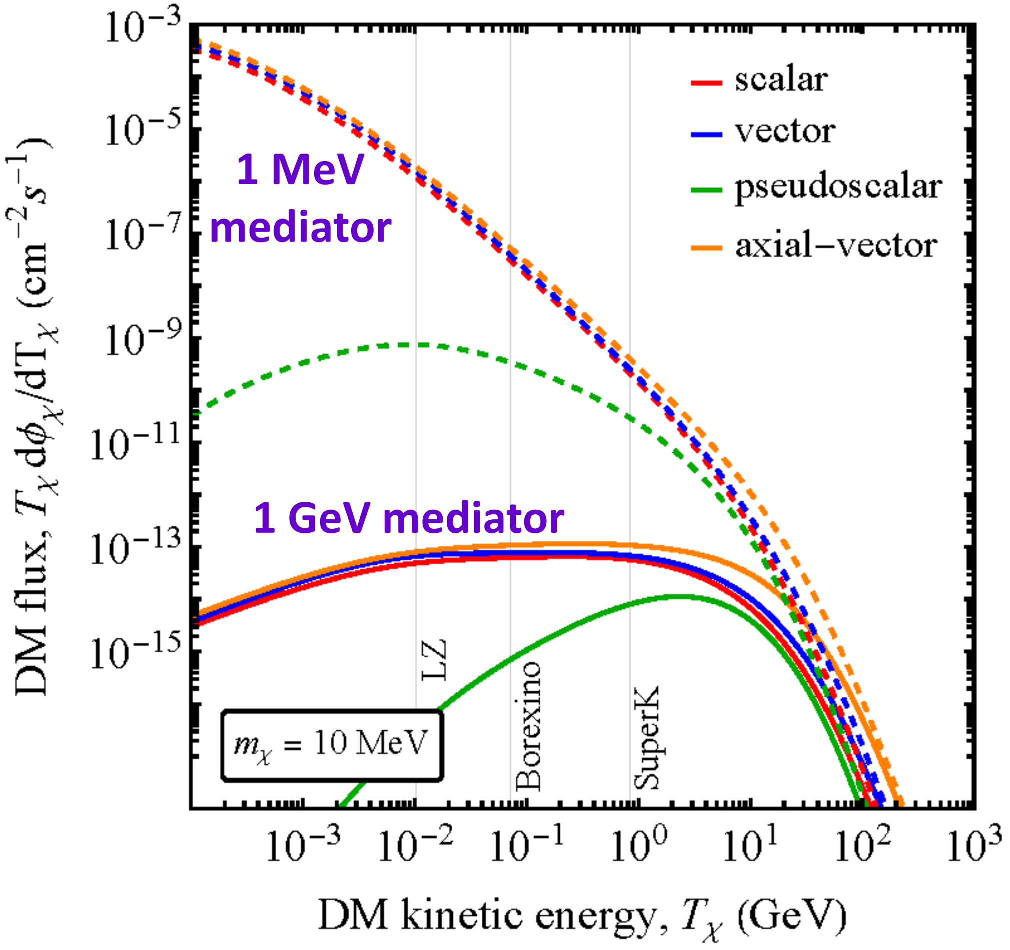
- Observable signals scale with **two** powers of the scattering cross section

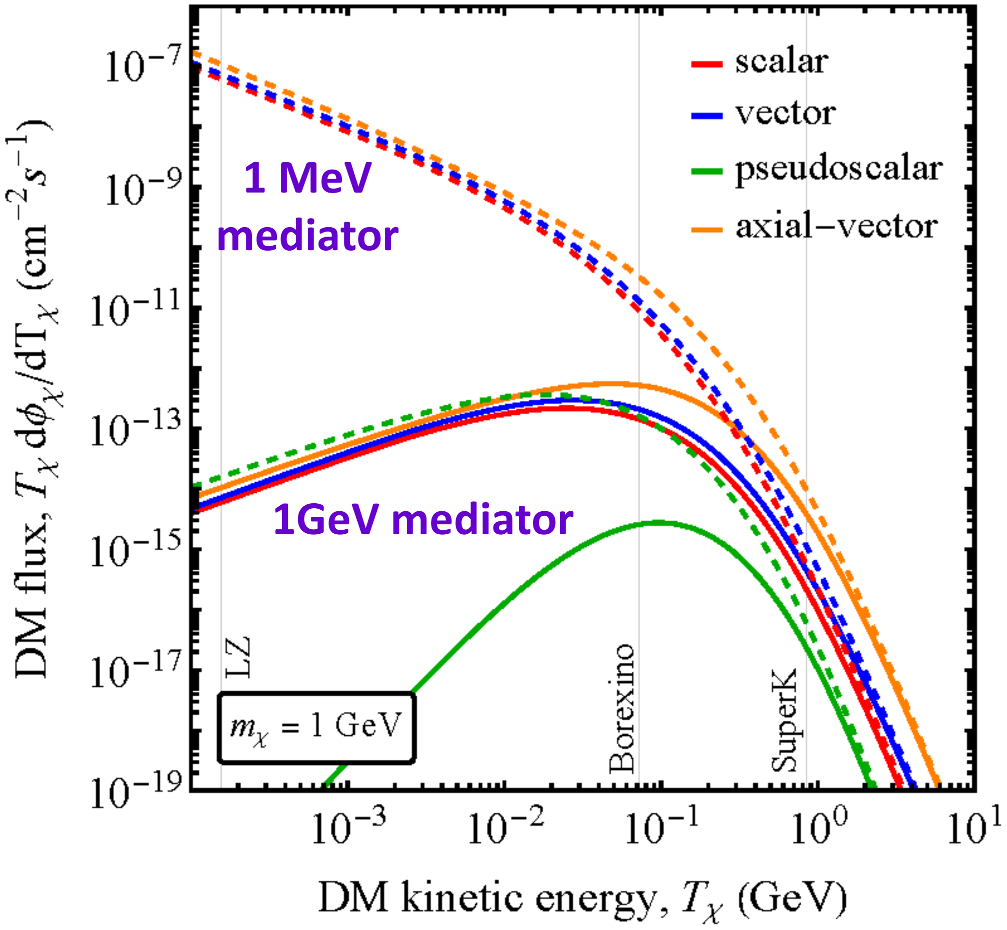
Questions: How to distinguish heavy non-relativistic DM from light relativistic DM?

- **Directional information** helps

# CR-upscattered DM: kinetic energy spectrum

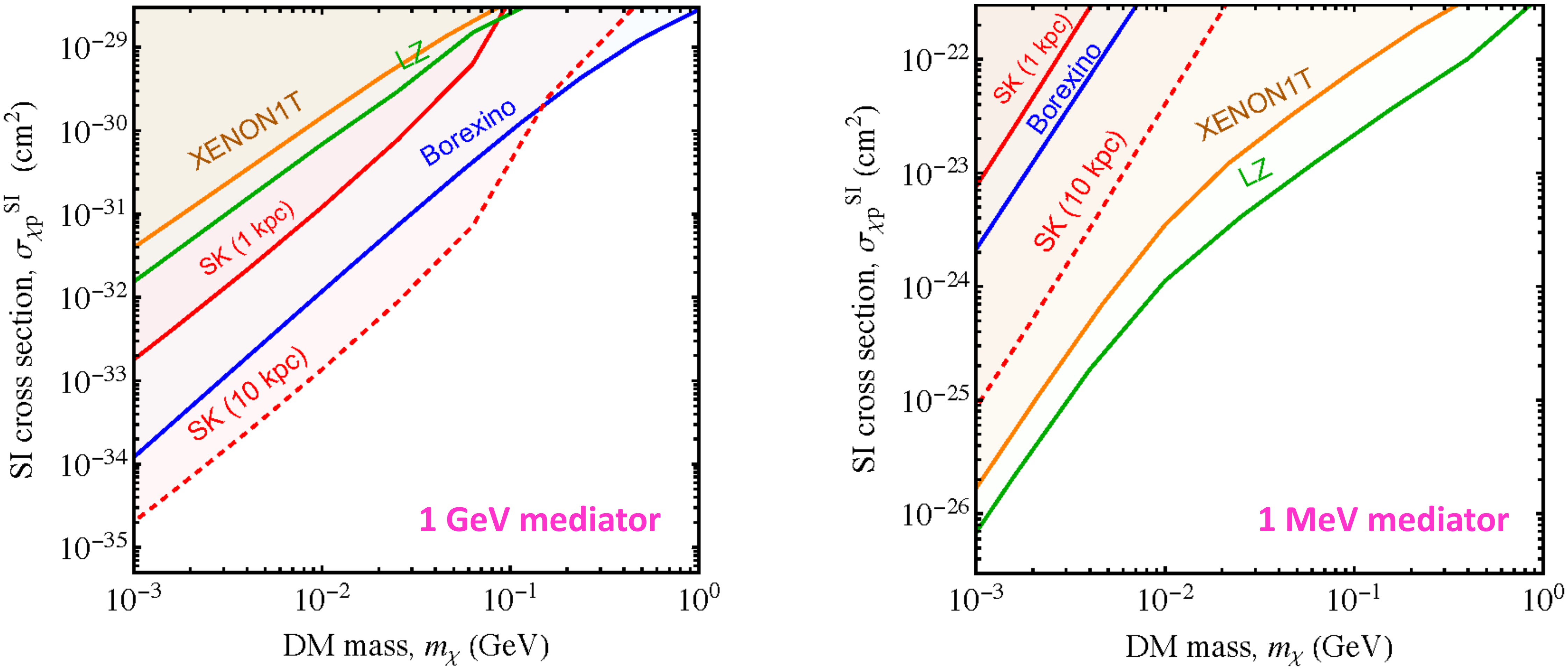
Bell, Newstead and Shaukat Ali, arXiv:2309.11003



# Boosted DM – neutrino vs direct detection exps.

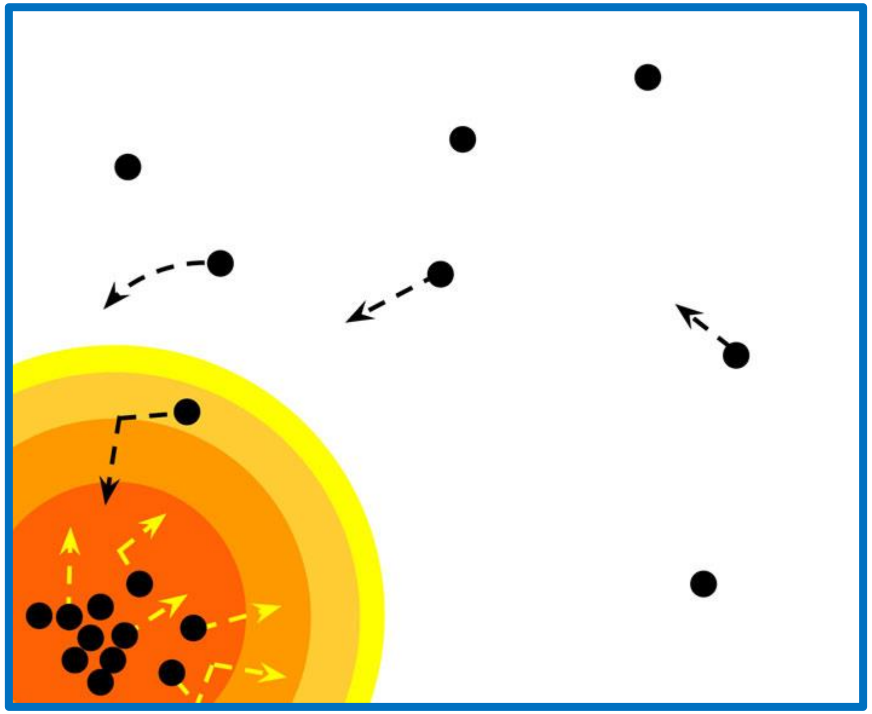
Bell, Newstead and Shaukat Ali, arXiv:2309.11003



# Dark Matter Capture in Stars

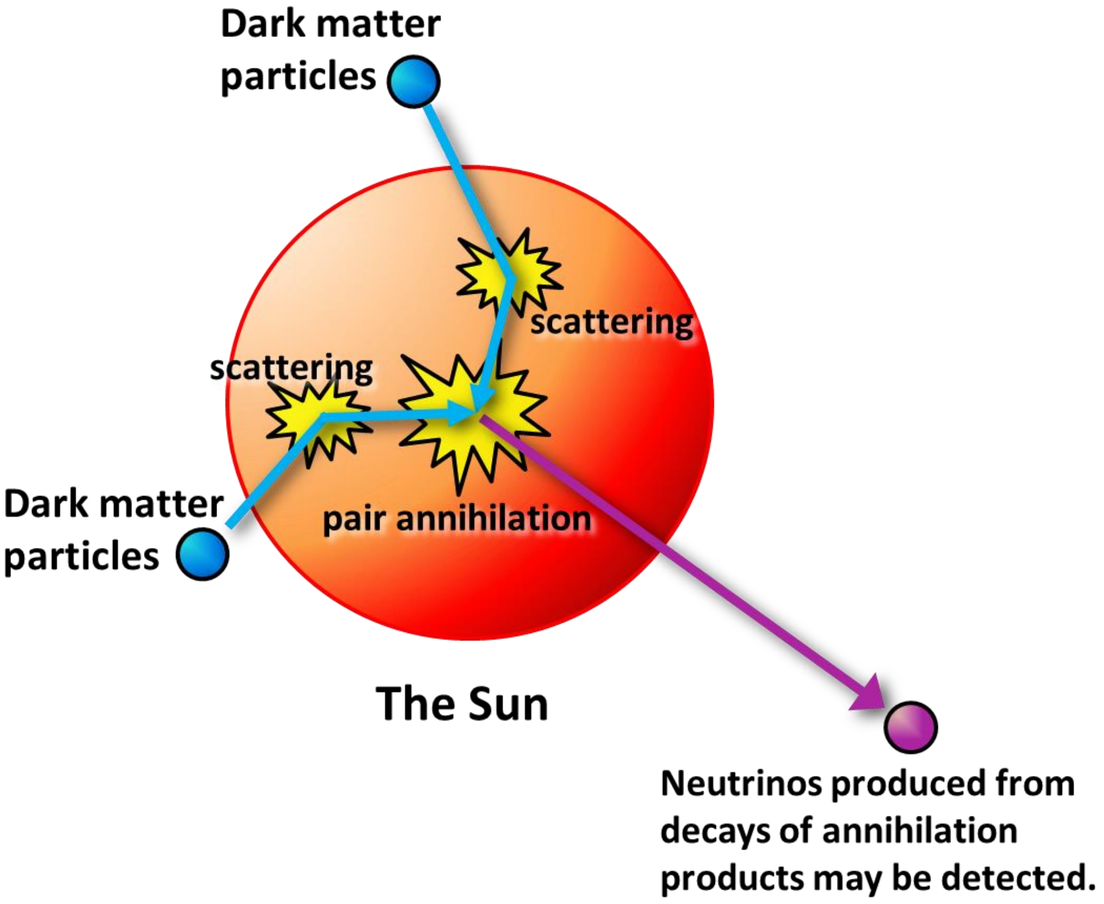
→ an alternative approach to Dark Matter Direct Detection experiments

- The Sun
- Neutron Stars
- White Dwarfs



# Dark Matter Capture in Stars

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

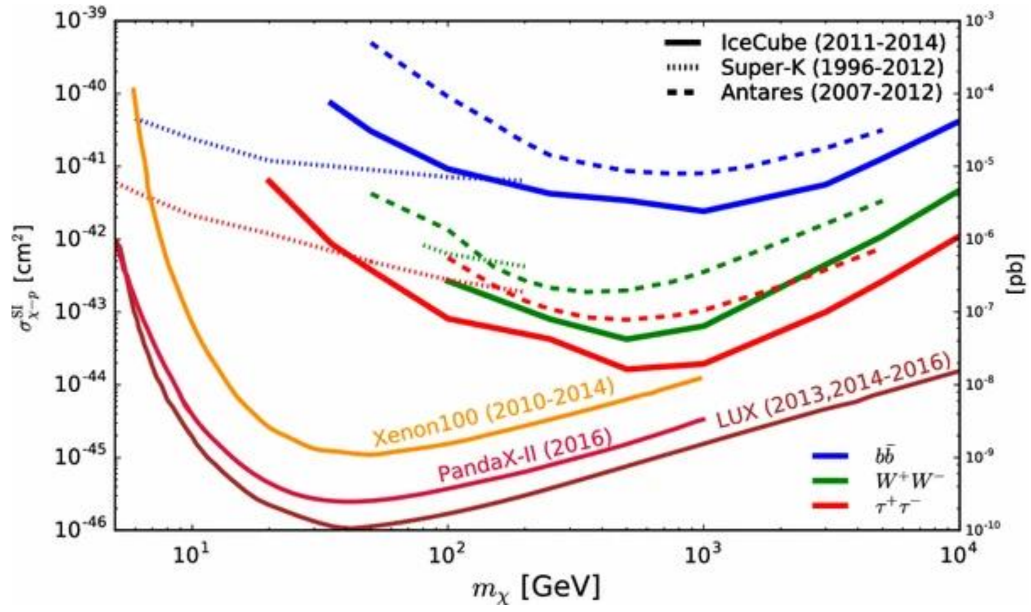



- Dark matter scatters, loses energy, becomes gravitationally bound to star
- Accumulates and annihilates in centre of the star → neutrinos escape

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

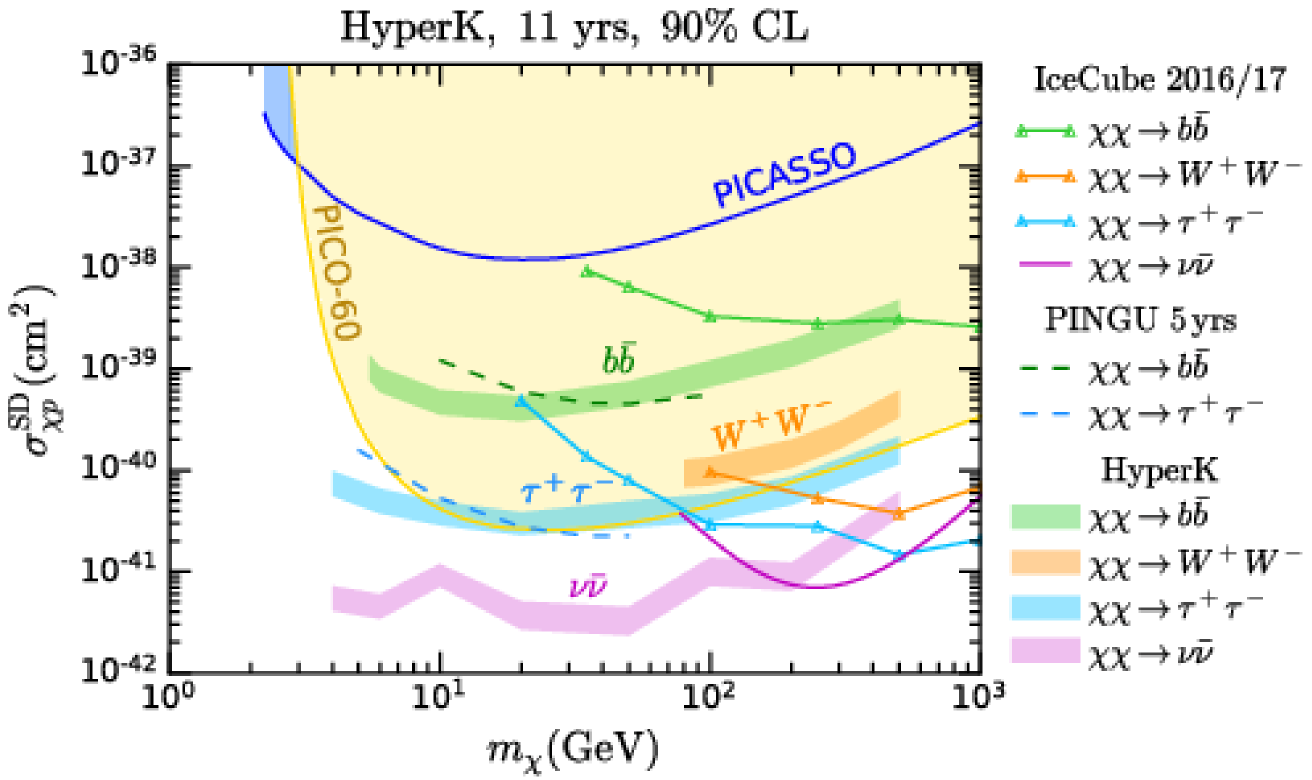
# Dark matter annihilation in the Sun – Neutrinos

**Spin-Independent (SI)**




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

**Spin-Dependent (SD)**

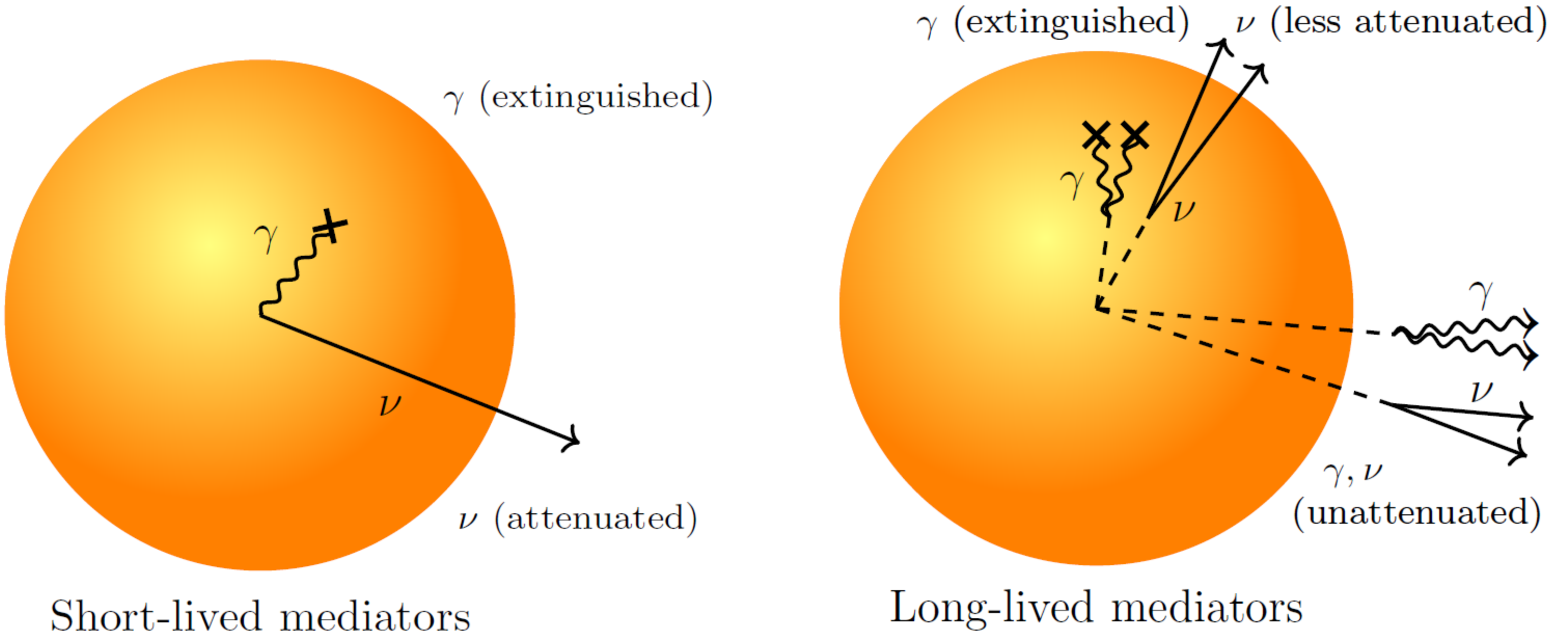



Bell, Dolan & Robles, arXiv:2107.04216

# 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):

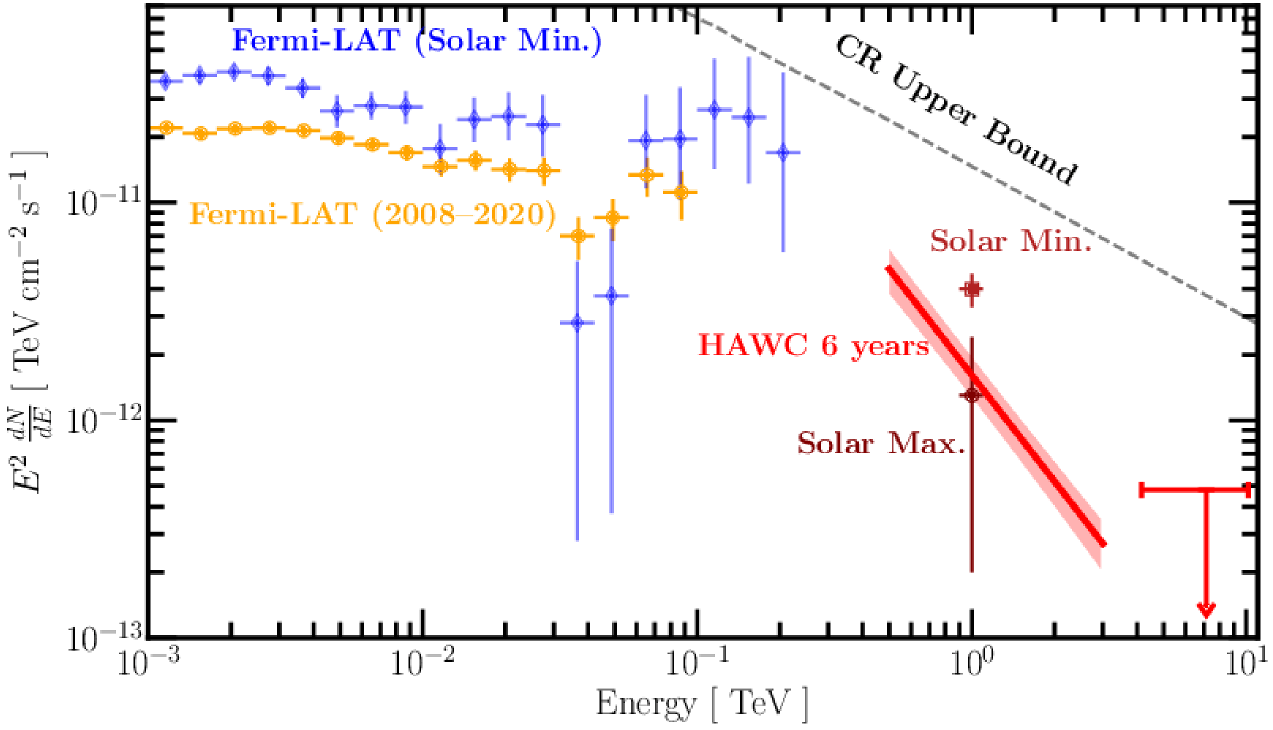
- ➢ Annihilation products can escape the Sun
- ➢ Decay between Sun and Earth → solar gamma rays or cosmic rays (Batell arXiv:0910.1567)
- ➢ Decay beyond solar core → less attenuation of neutrino signal (NFB & Petraki, JCAP 2011)




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.:

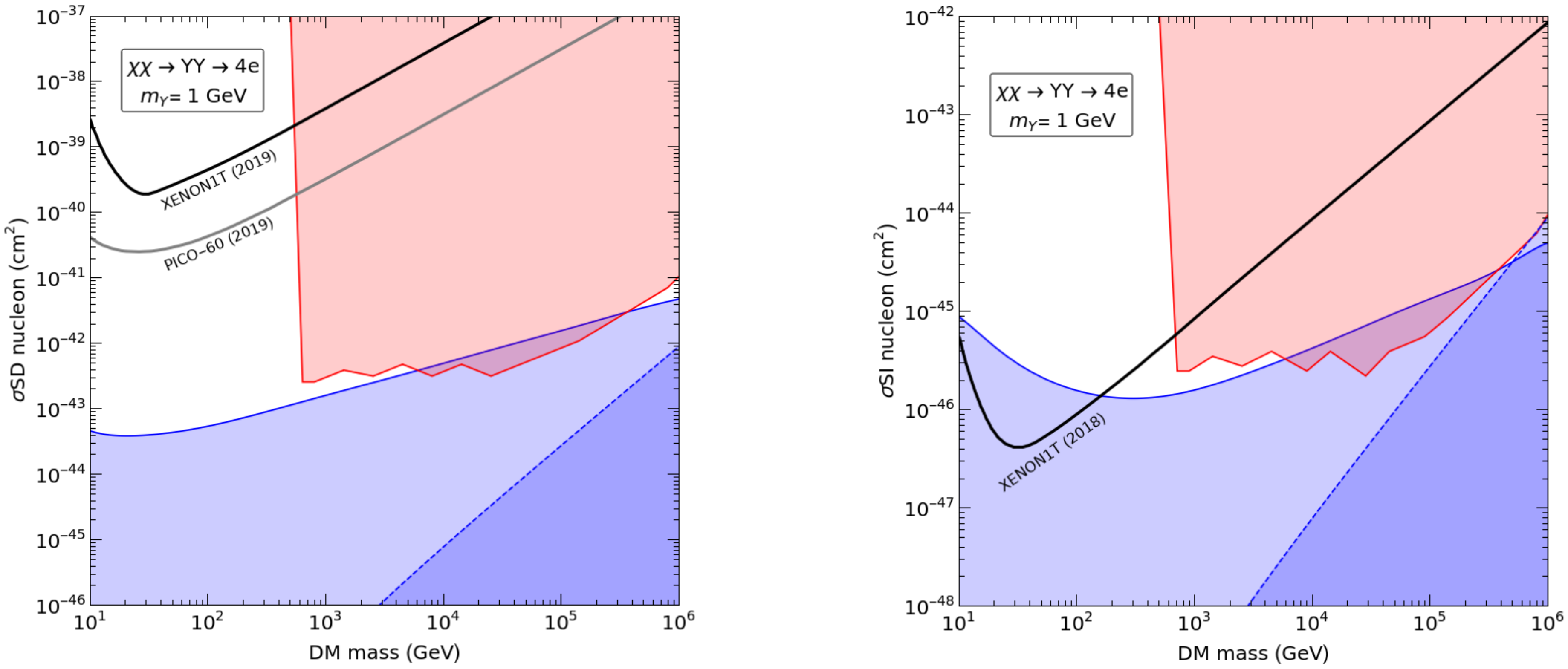
$$\chi\chi \rightarrow \gamma_D\gamma_D \rightarrow e^+e^-e^+e^-$$

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)**



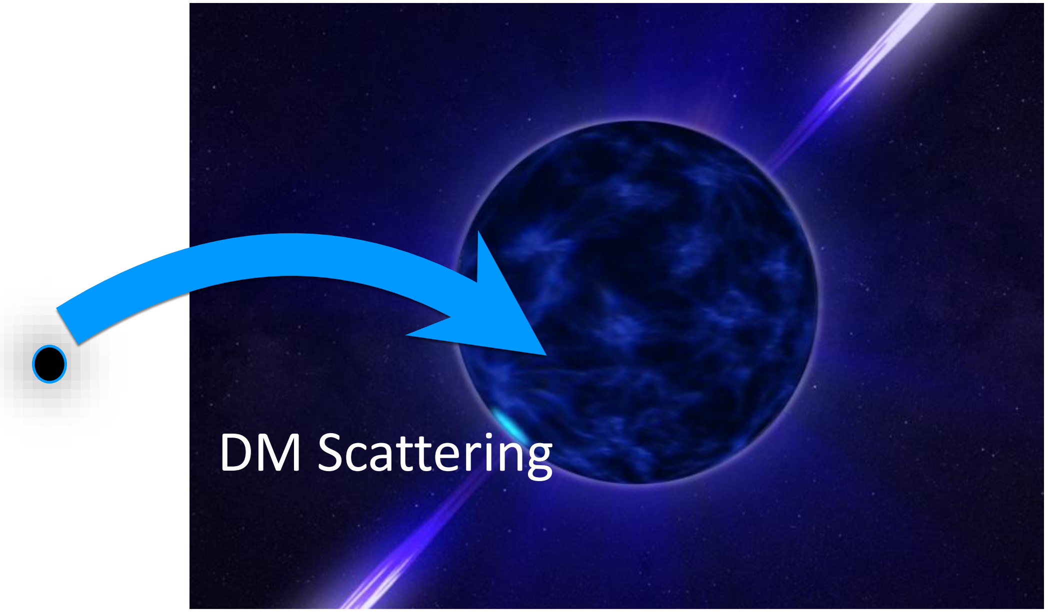

Bell, Dent
& Sanderson,
arXiv:2103.16794

# 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**

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



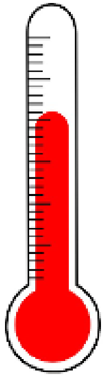
Baryakhtar et al
arXiv:1704.01577

# Neutron star heating

## → from dark matter scattering plus annihilation

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

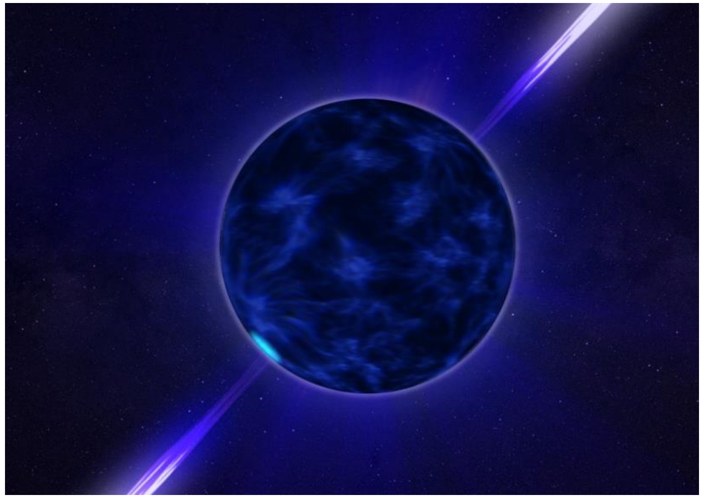
- **Annihilation** of thermalised dark matter
  → DM ***rest mass energy*** heats neutron star ~ **additional 700K**



Coolest known neutron star (PSR J2144-3933) has a temperature of ~ 4.2 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

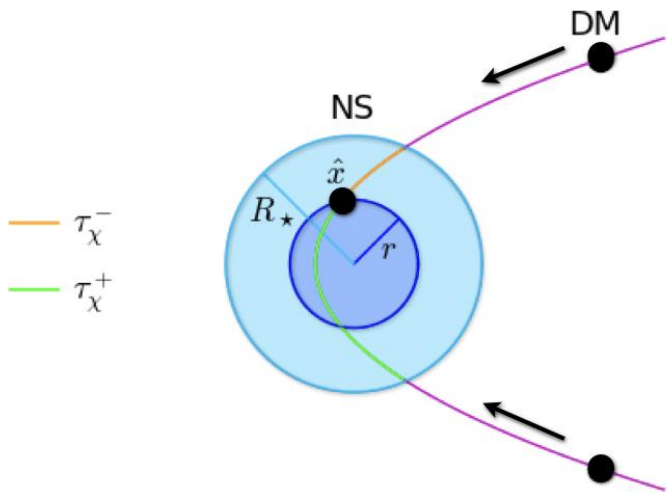
NFB, Busoni, Robles & Virgato,
JCAP 09, 028 (2020), JCAP 03, 086 (2021)

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**

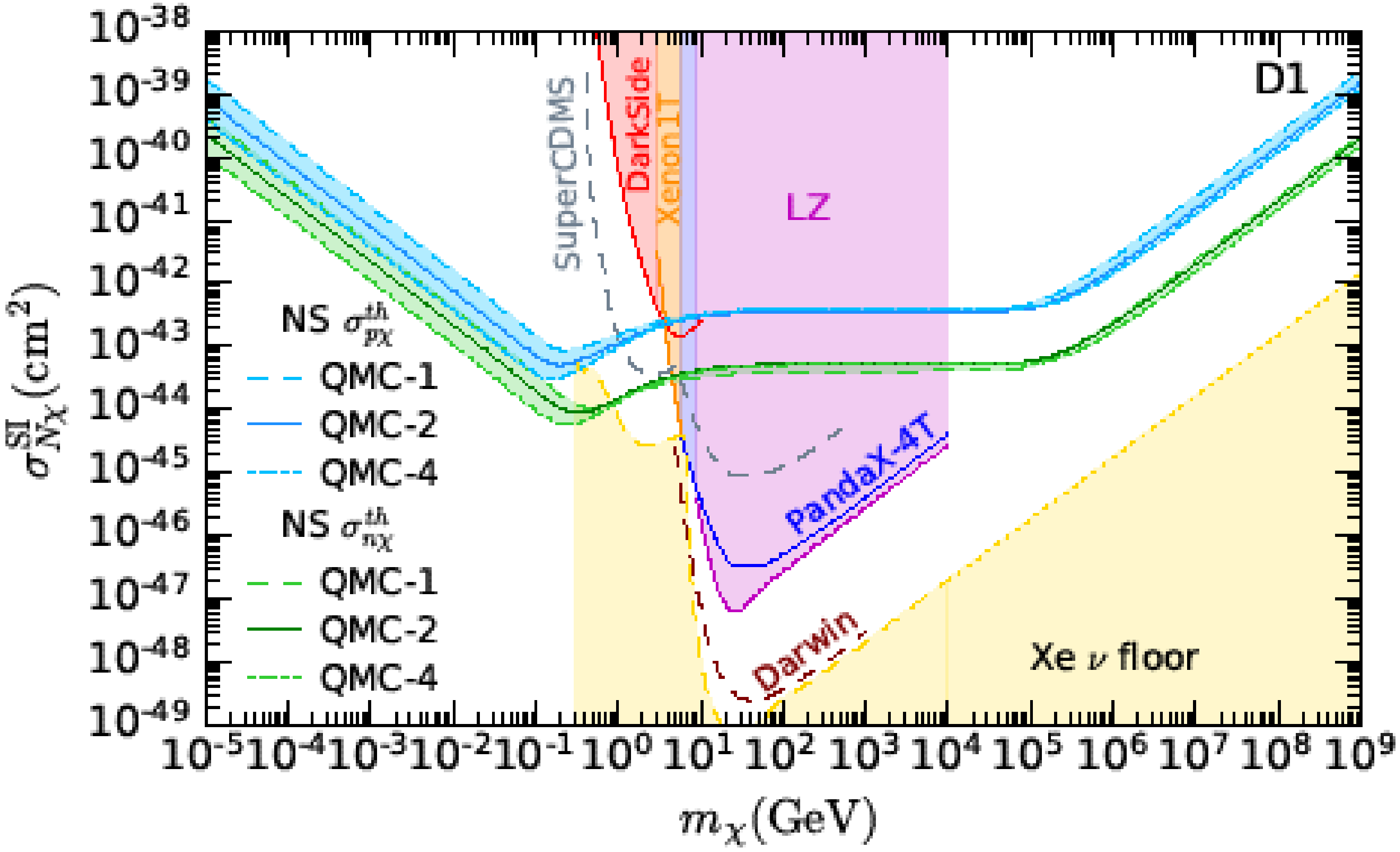
NFB, Busoni, Motta, Robles, Thomas, & Virgato, PRL 2021



# NS Heating Sensitivity (projected limits)

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

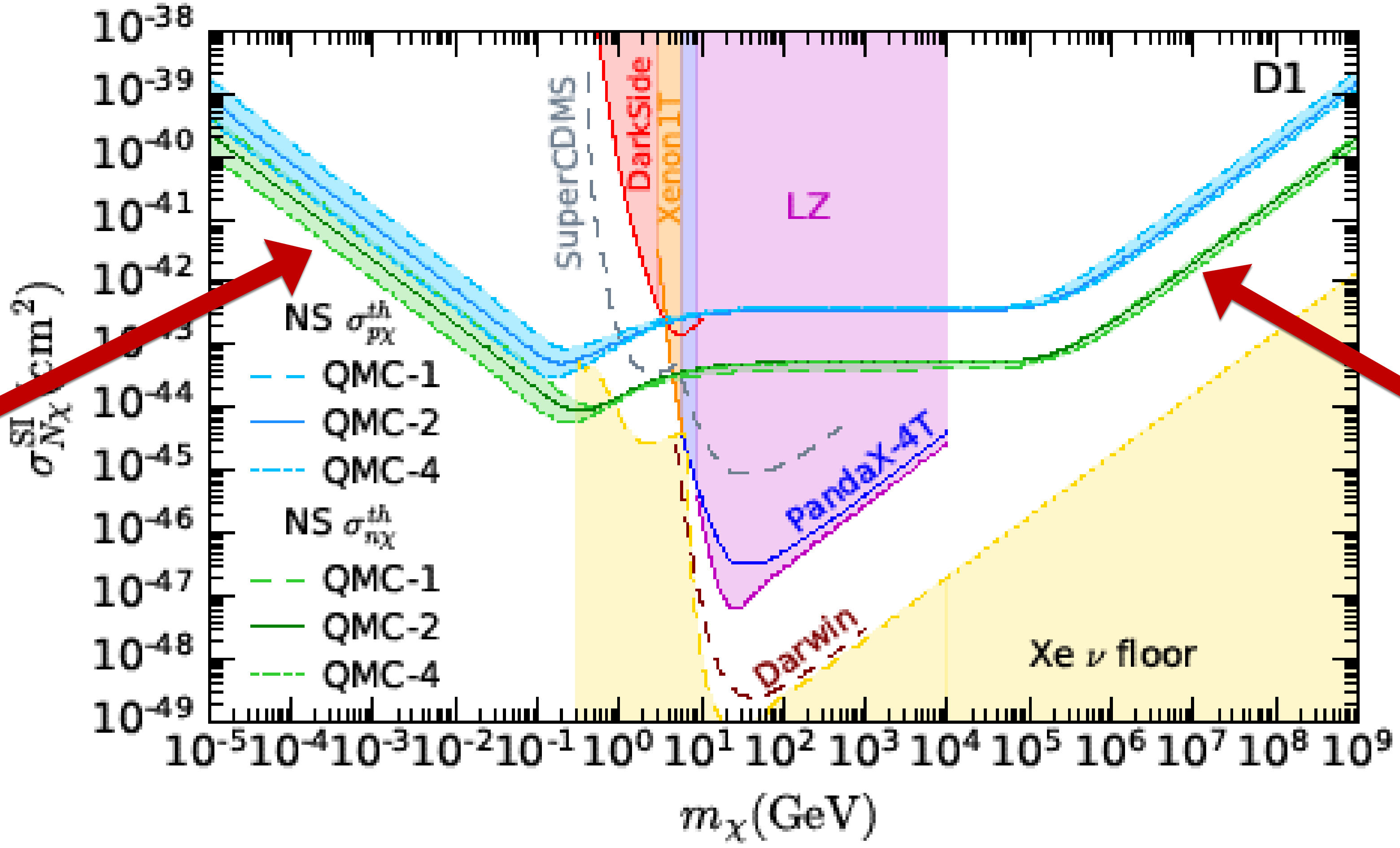
Anzuini, Bell, Busoni, Motta, Robles, Thomas & Virgato, arXiv:2108.02525



# 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

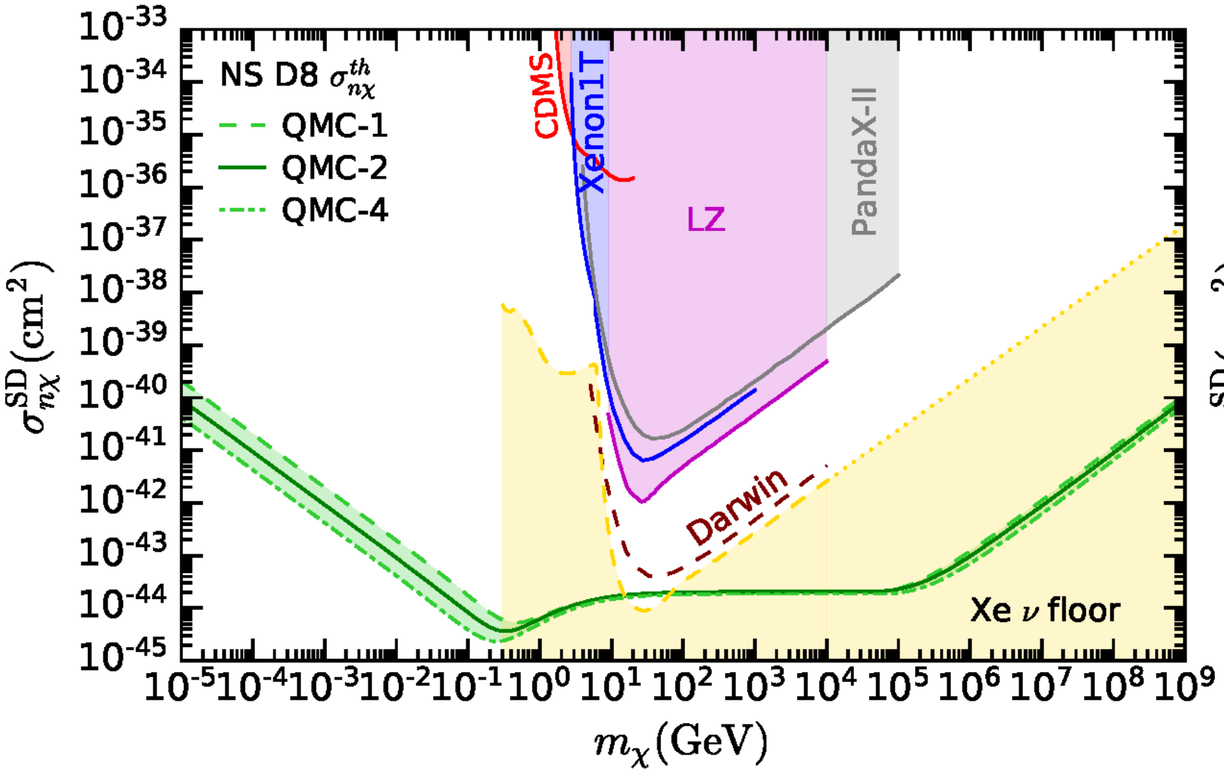



Pauli blocking from degenerate neutrons

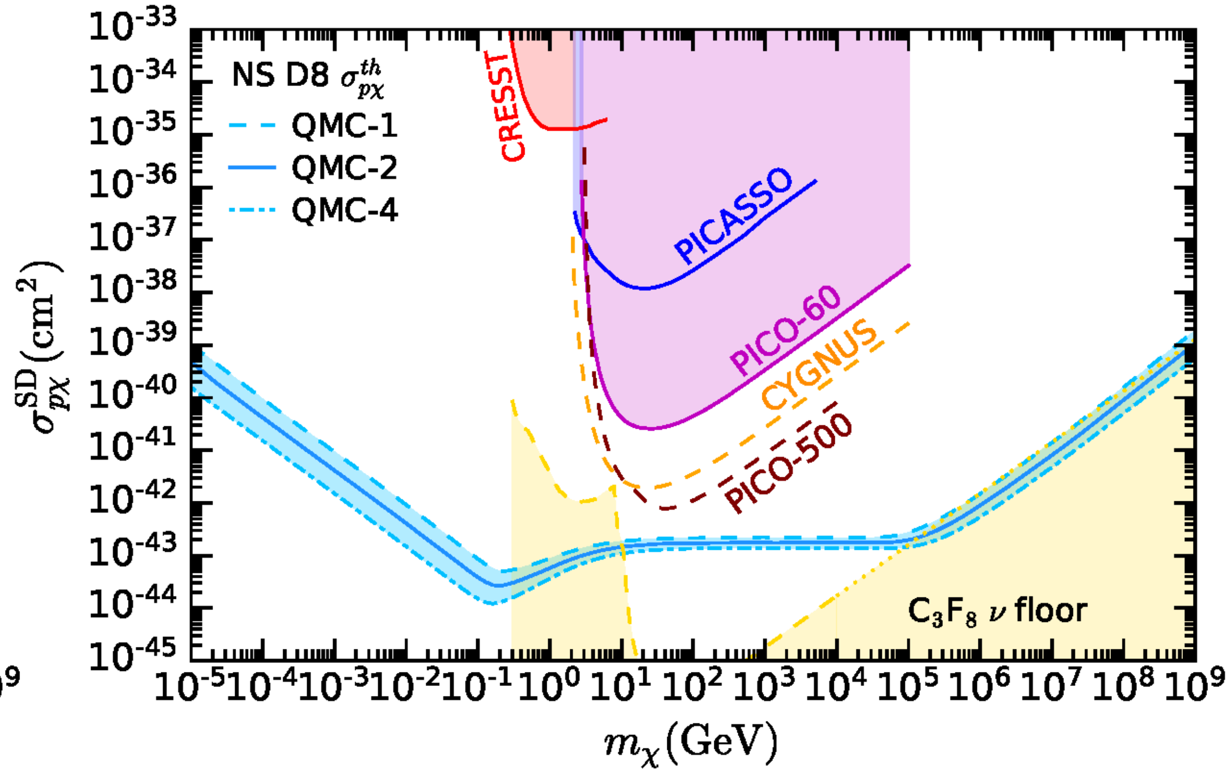
Momentum transfer in single collision not sufficient for capture

# NS Heating Sensitivity: SD nucleon scattering

**DM-neutron (SD scattering)**

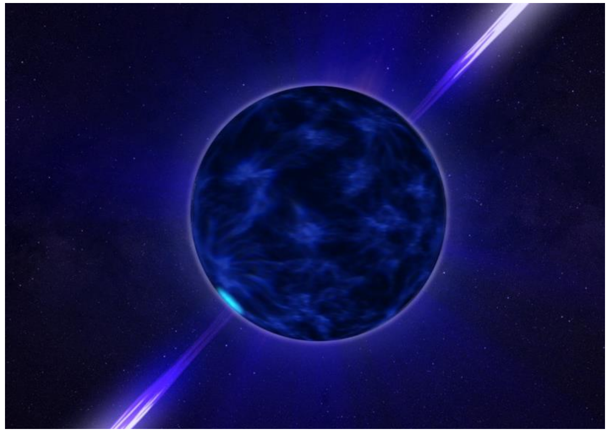


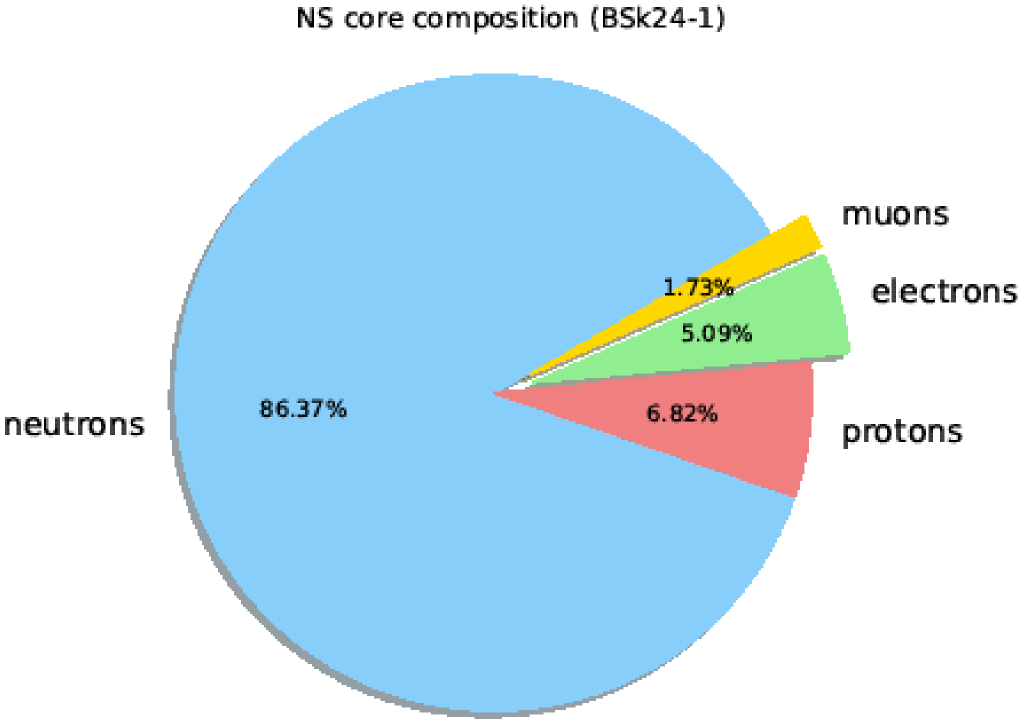

**DM-proton (SD scattering)**




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

# Leptons in Neutron Stars

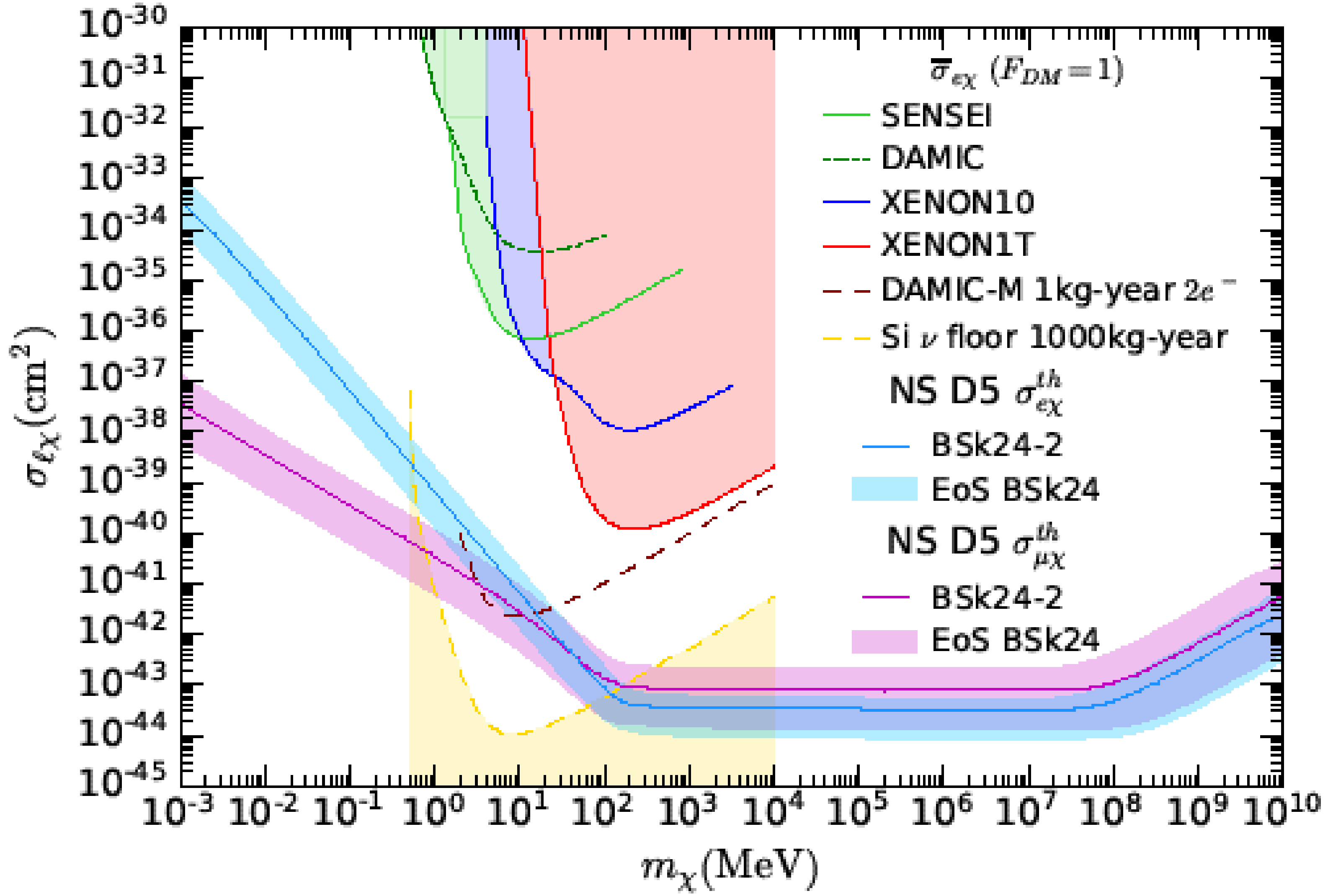





Beta equilibrium in the core determines the composition:

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

# NS Heating Sensitivity:  lepton scattering



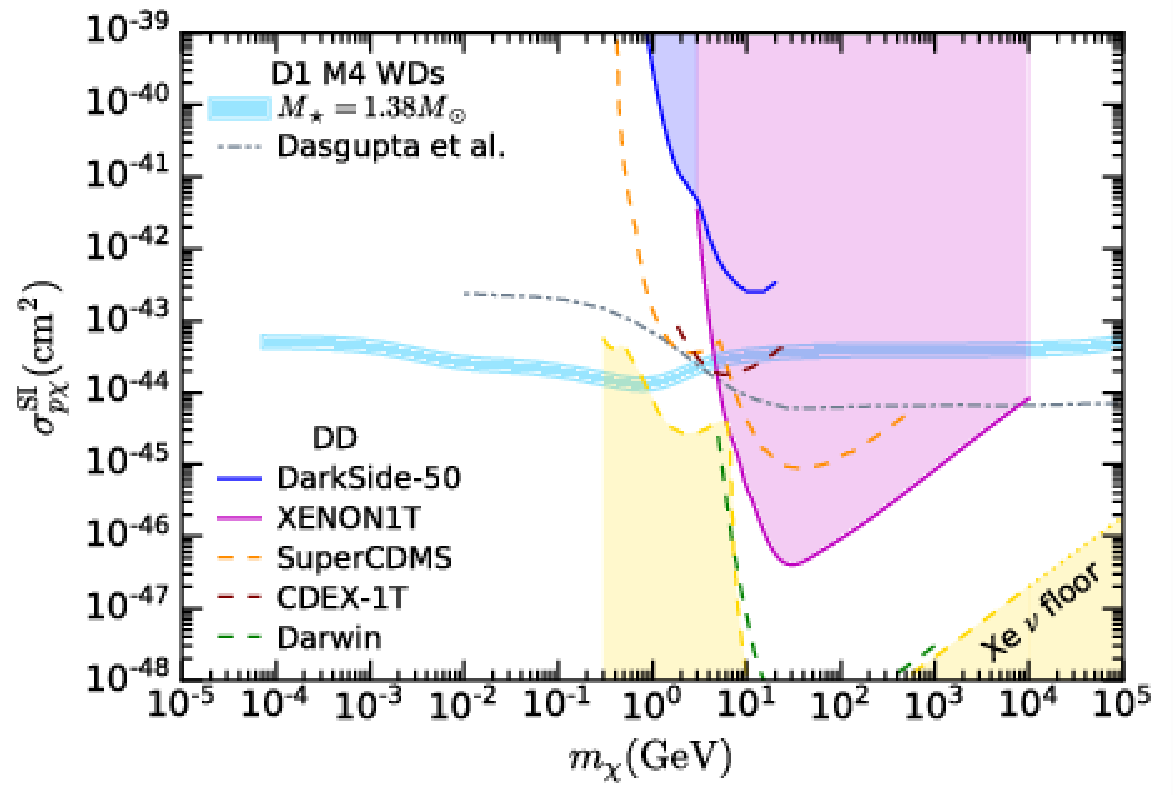

Bell, Busoni, Robles & Virgato arXiv:2010.13257

Muon scattering

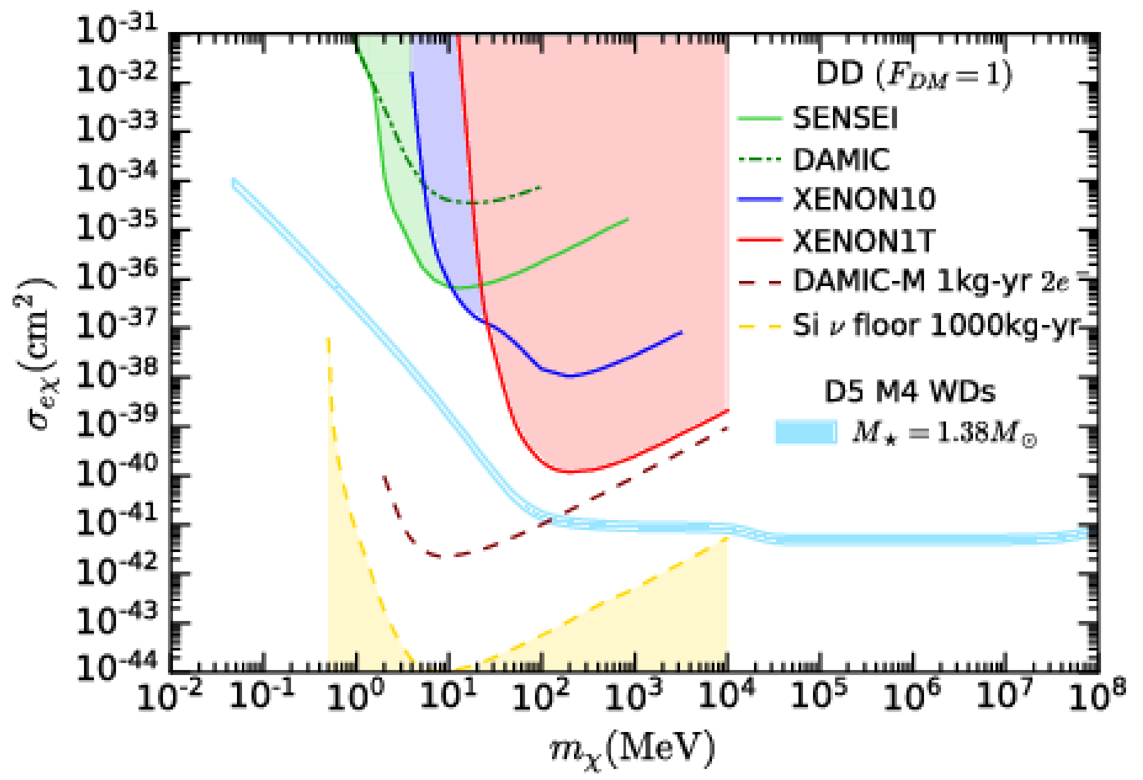
Electron scattering

# 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

**Direct Detection**

- *Directional* detection to search below the neutrino floor
- Migdal effect to probe lower mass DM
- Boosted dark matter to probe low mass DM

**Dark matter capture in stars**

- Relativistic DM. Probe of low mass dark matter; can look below the neutrino floor