# Searching for Dark Matter Scattering on Earth and in Stars


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# Detecting Dark Matter Scattering

## Outline:

- Direct Detection Experiments
  - Status
  - Challenges
  - New directions

- Dark Matter Capture in Stars
  - Stars = "Nature's dark matter detectors"
  - Dark matter in the Sun, neutron stars, and white dwarfs

# Dark Matter Direct Detection

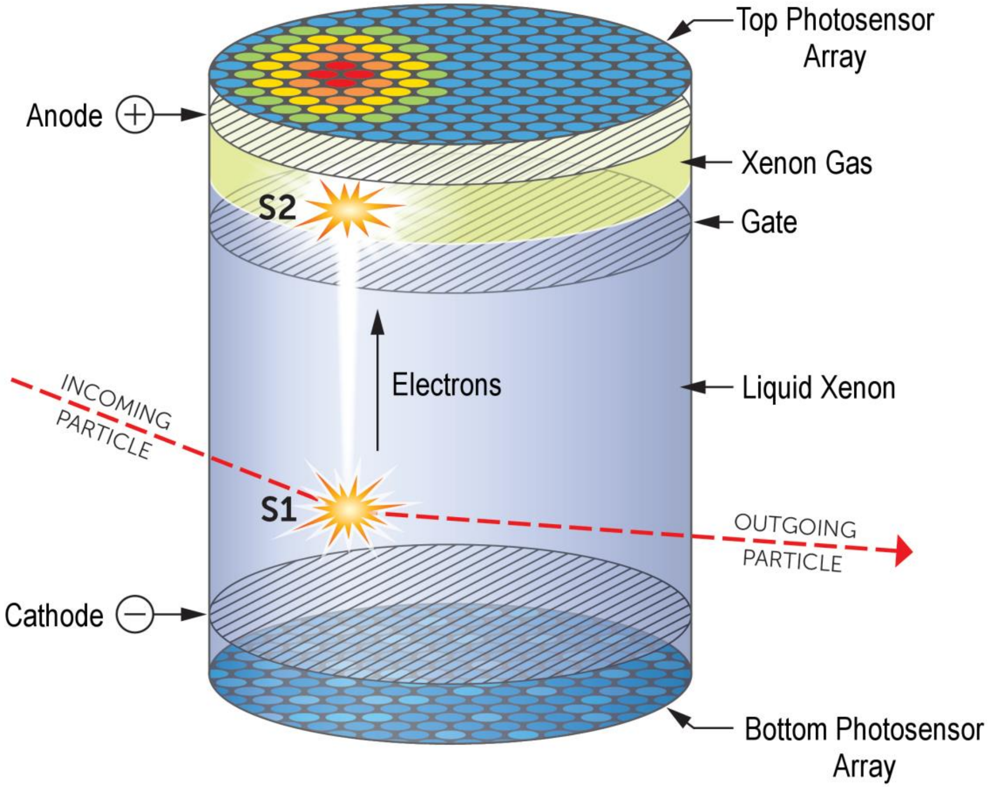
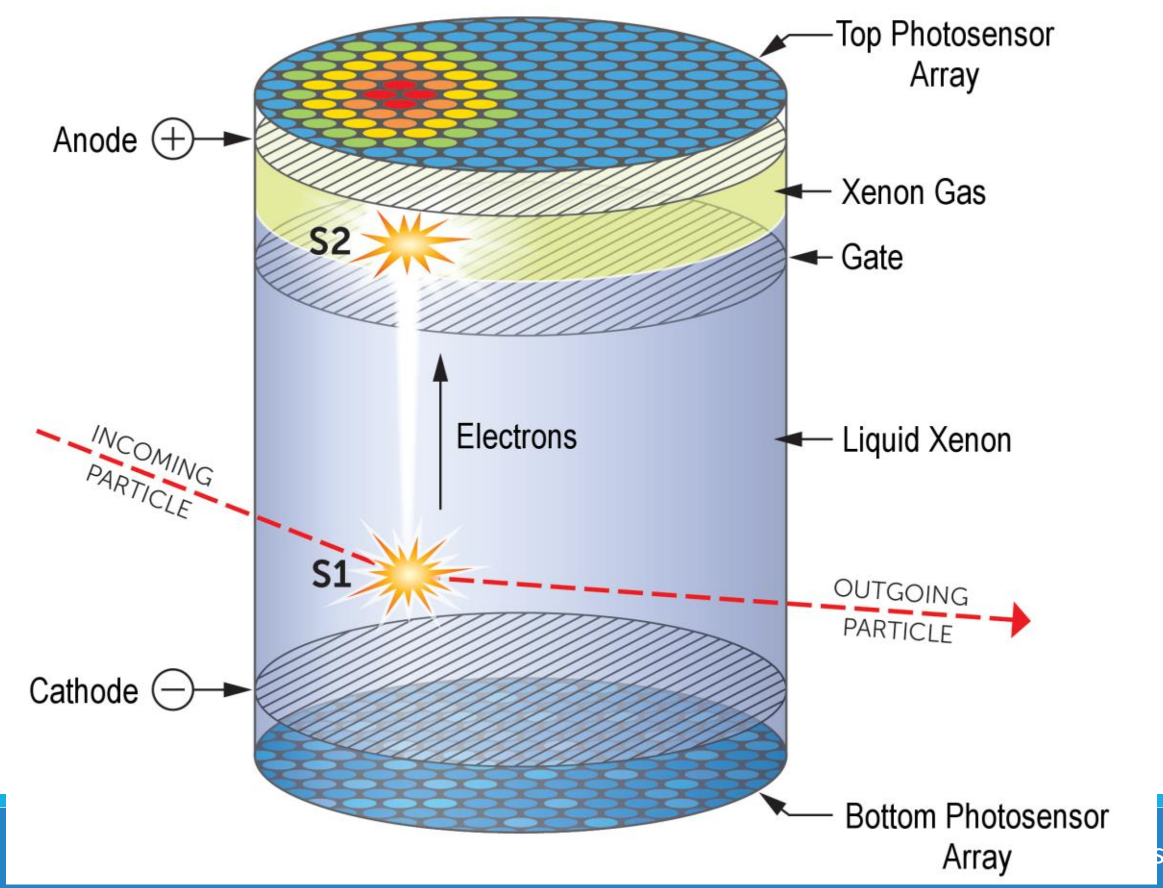
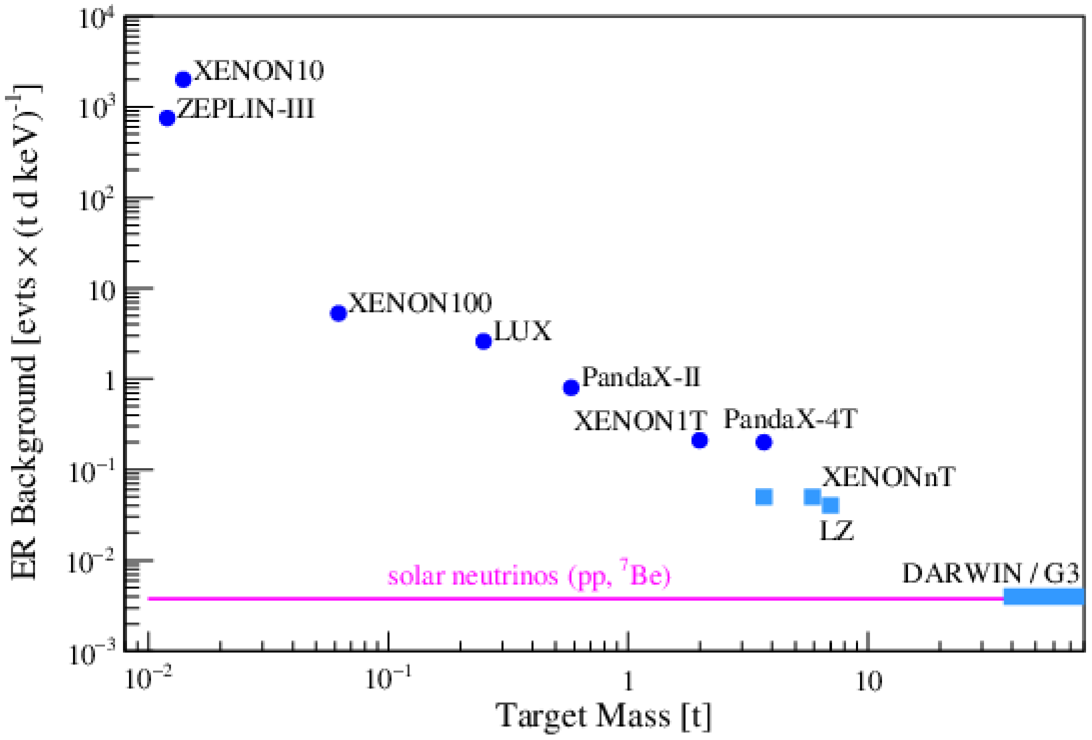



Image: arXiv:2203.02309

# Direct Detection Experiments

Nuclear recoil experiments search for the occasional collision of dark matter particles with nuclei in a detector



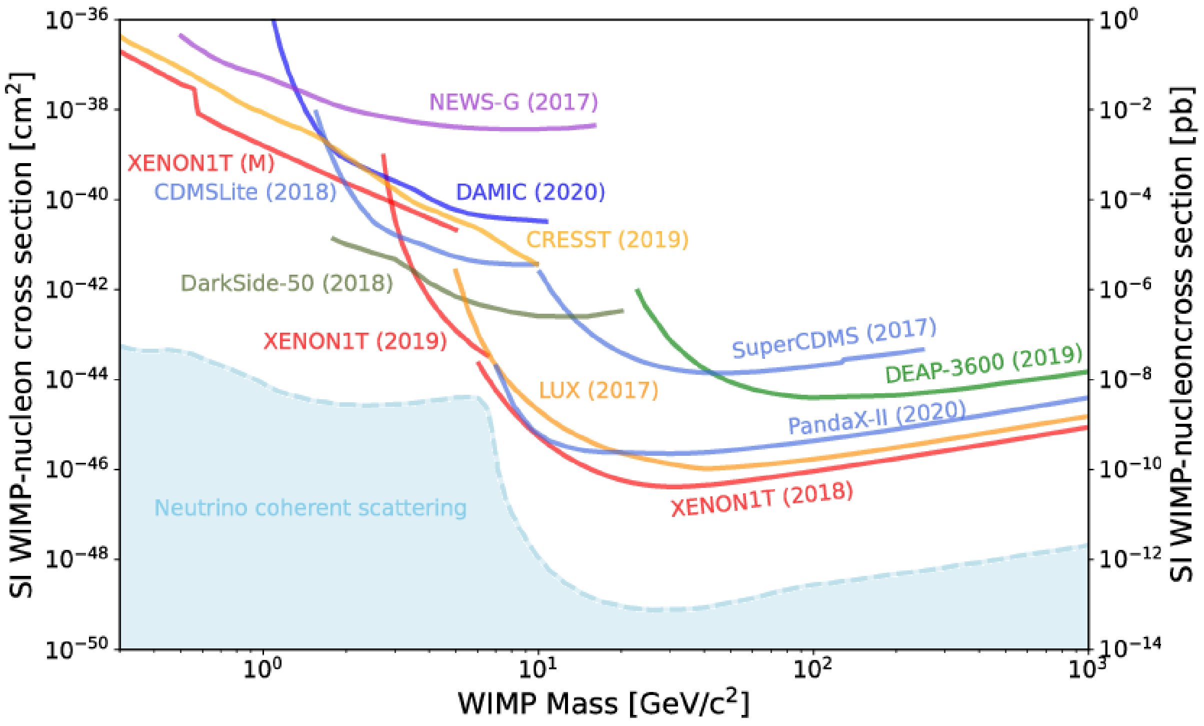




Images from: arXiv:2203.02309

# Direct Detection limits

## Spin-independent (SI) interactions

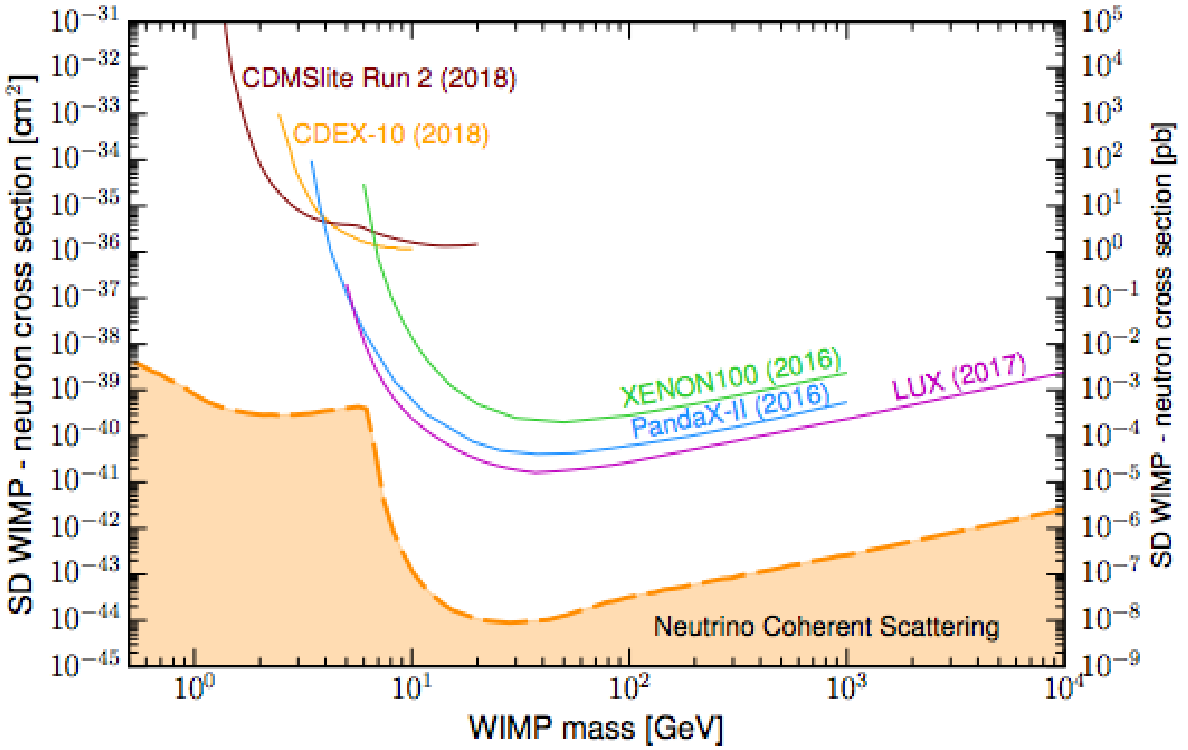
→ strong bounds due to coherent enhancement




J. Aalbers et al. arXiv:2203.02309

## Spin-dependent (SD) interactions

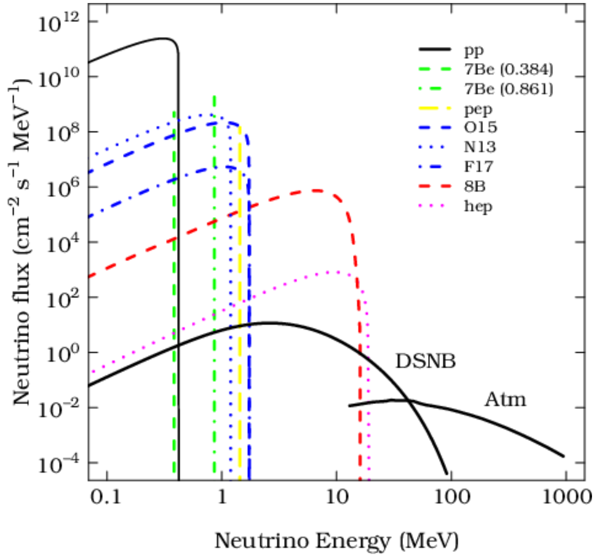
→ weaker bounds




M. Tanabashi et al. (PDG) 2018

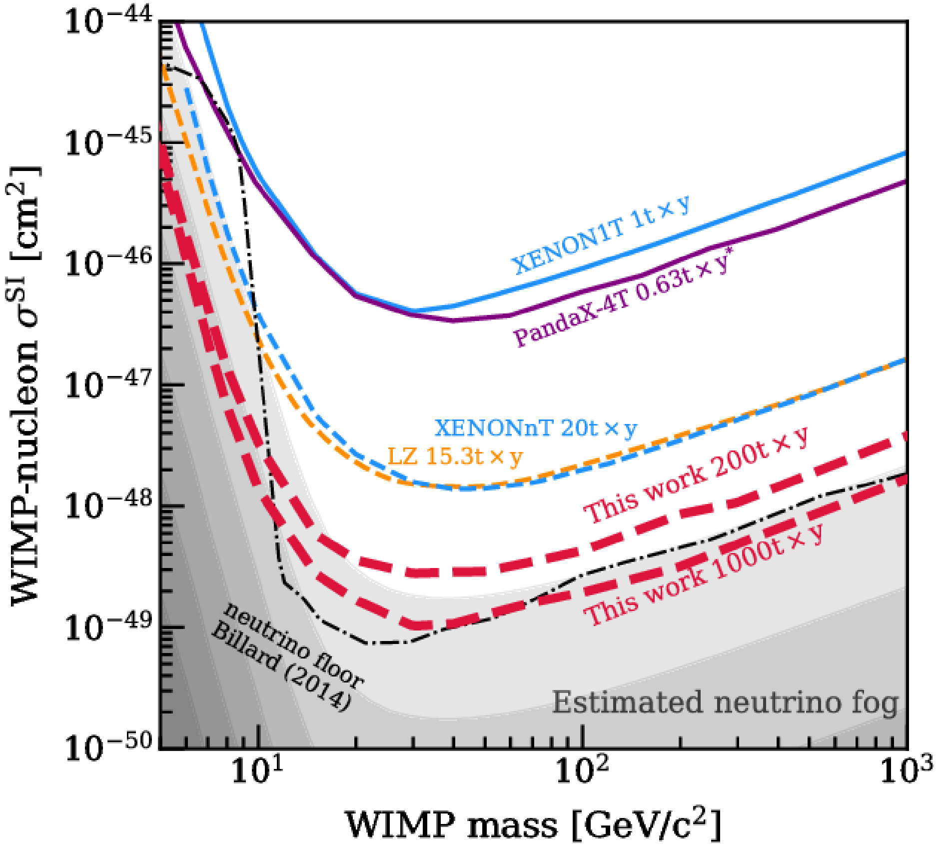
# Dark matter direct detection - challenges

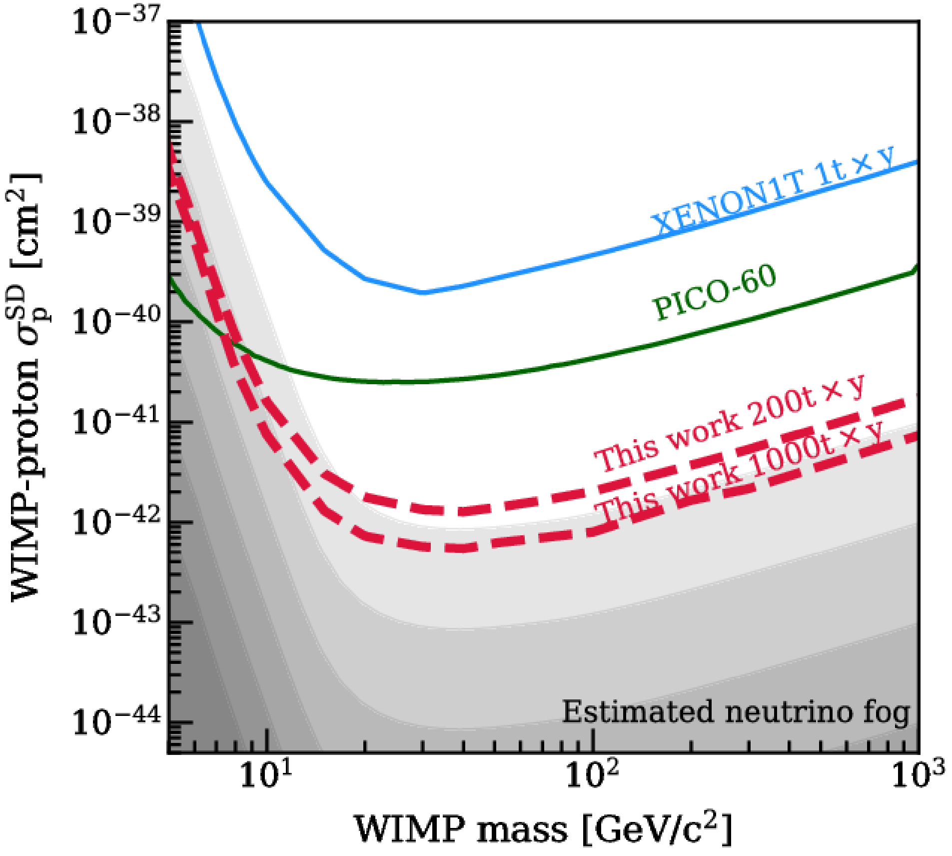
- Next generation experiments will approach the "neutrino floor", where solar, atmospheric and supernova neutrinos become an important background
  - Development of directional detection capabilities
    - CYGNUS experiment




- Low mass WIMPs have recoil signals below experimental thresholds
  - New, low threshold, experiments
  - Development of new detection technologies

# Next generation experiments will reach the neutrino floor




J. Aalbers et al. arXiv:2203.02309

# New strategies to probe dark matter scattering

- New detectors and new detector technologies

- New analyses to probe lower mass dark matter <u>using existing detectors</u>
  - Migdal effect
  - Boosted dark matter

    → Boost the dark matter to higher energies, to make it more detectable

      → Cosmic-ray upscattered dark matter, supernova dark matter, etc.

- Complementary constraints from <u>dark matter capture in stars</u>
  - Dark matter annihilation in the Sun
  - Dark matter heating of neutron stars or white dwarfs

# Migdal effect

The ionization of an atom following a nuclear recoil

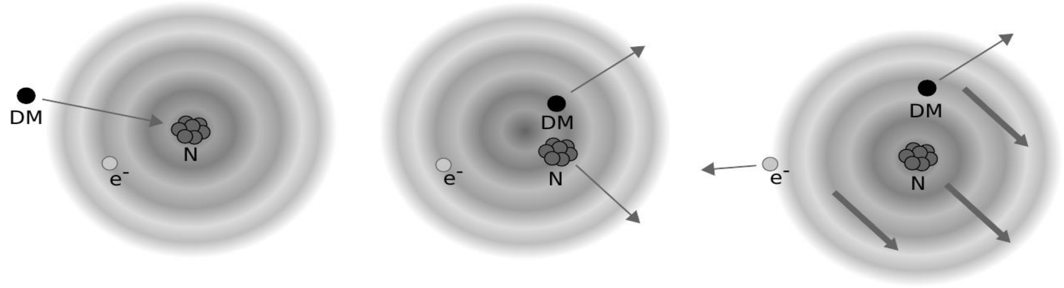



Image: Dolan et al.

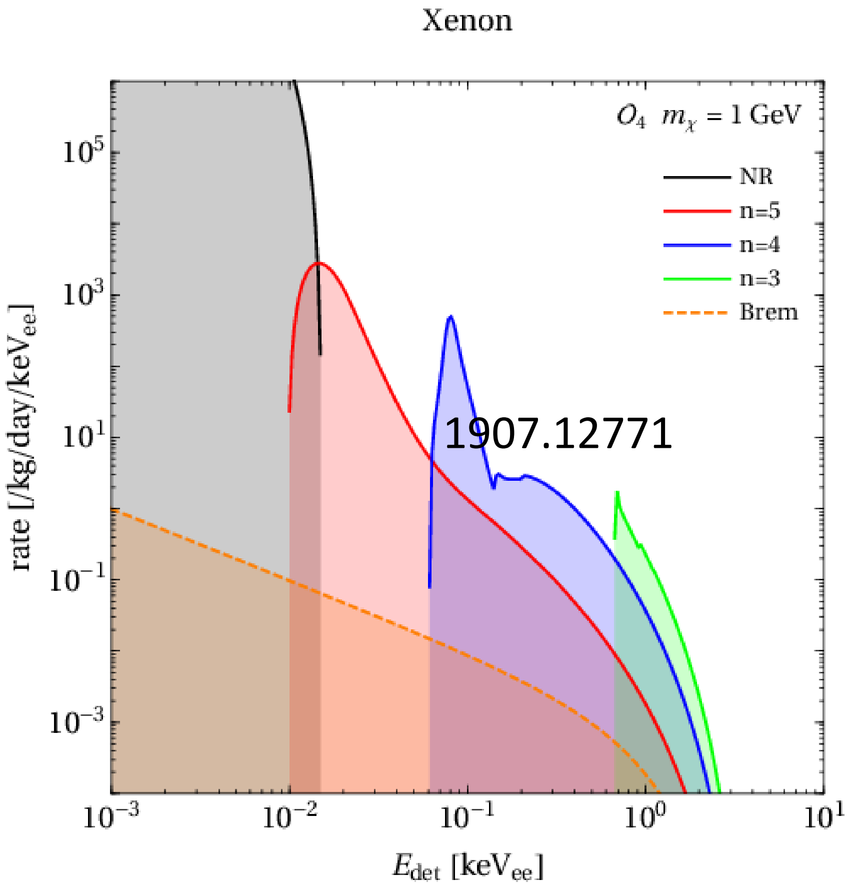
→ Useful in cases where the nuclear recoil is below threshold (i.e., low mass dark matter) and we can instead detect the ionization signal

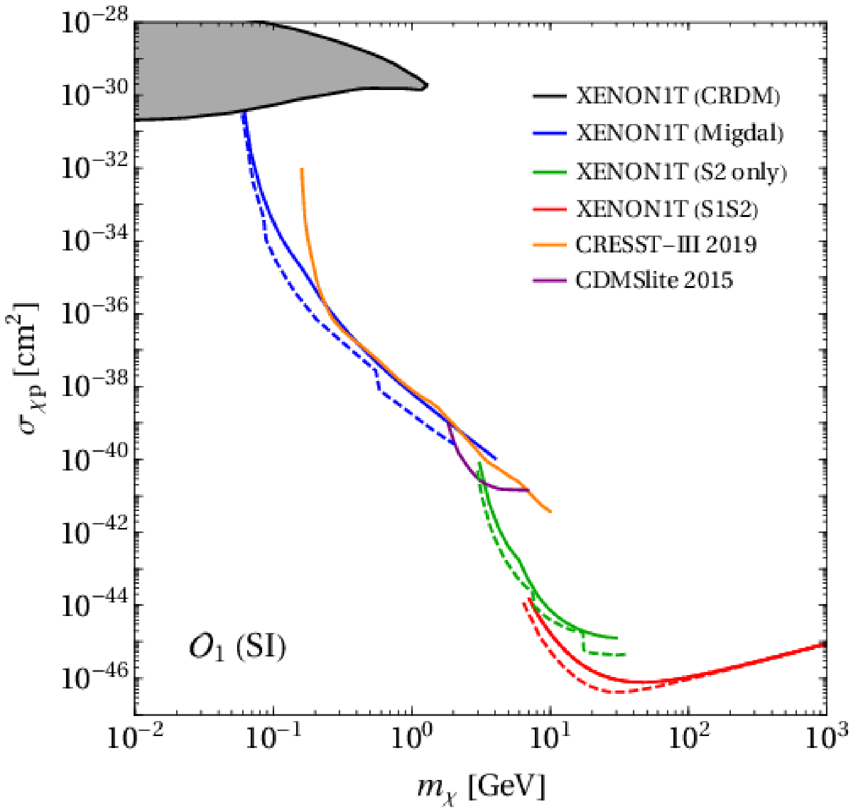
Nuclear recoil: $E_{R,max} = \frac{2\mu_T^2}{m_T} v_{max}^2$

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

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

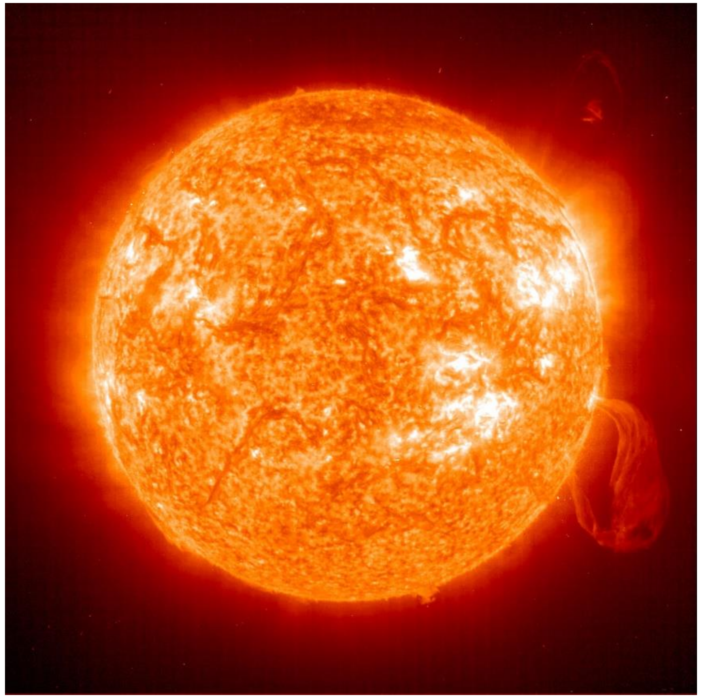
# Migdal effect



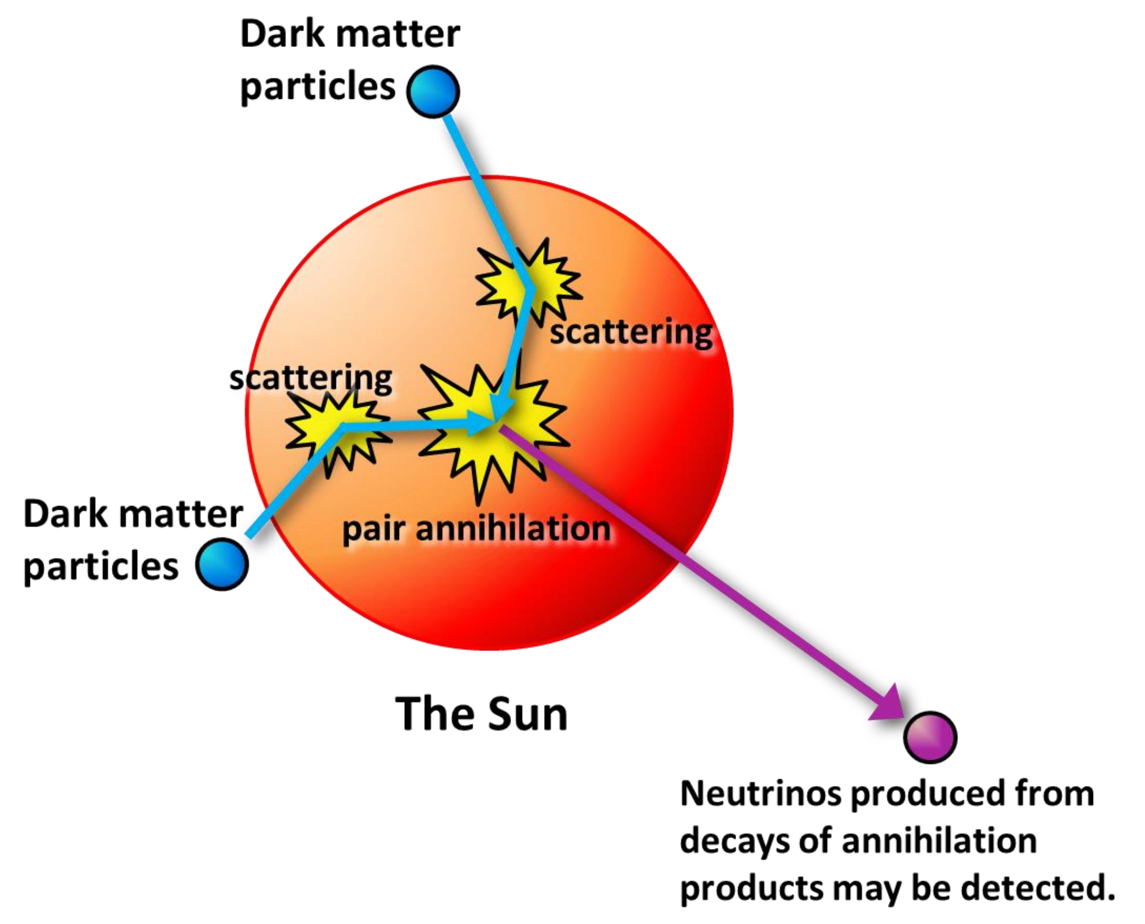

NFB, Dent, Newstead, Sabharwal & Weiler, arXiv: 1905.00046

# Dark Matter Capture in Stars



# 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

# Capture, annihilation, evaporation

DM number density depends on Capture, Annihilation & Evaporation rates:

$$\frac{dN_\chi}{dt} = C - AN_\chi^2 - EN_\chi$$

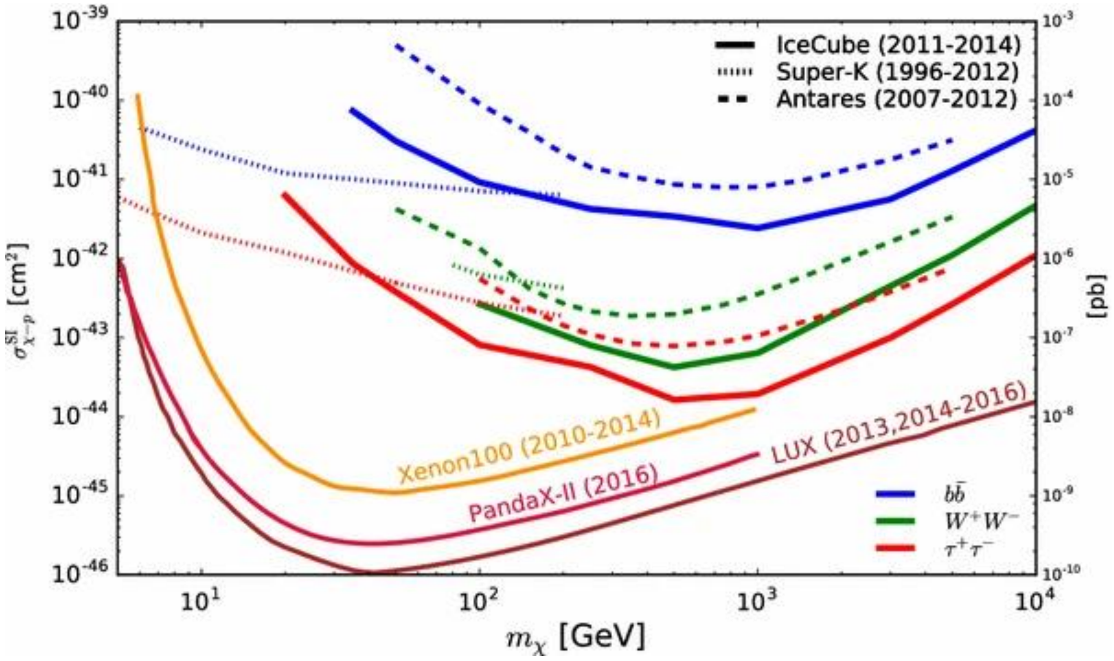
Neglecting evaporation (negligible in the Sun for $m_\chi > 4$ GeV) we have

→ $$N_\chi(t) = \sqrt{\frac{C}{A}} \tanh\left(\frac{t}{\tau_{eq}}\right)$$ where $$\tau_{eq} = 1/\sqrt{CA}$$

Capture-annihilation equilibrium when $t \gg \tau_{eq}$: $$\Gamma_{ann} = \frac{1}{2}AN_\chi^2 = \frac{1}{2}C$$

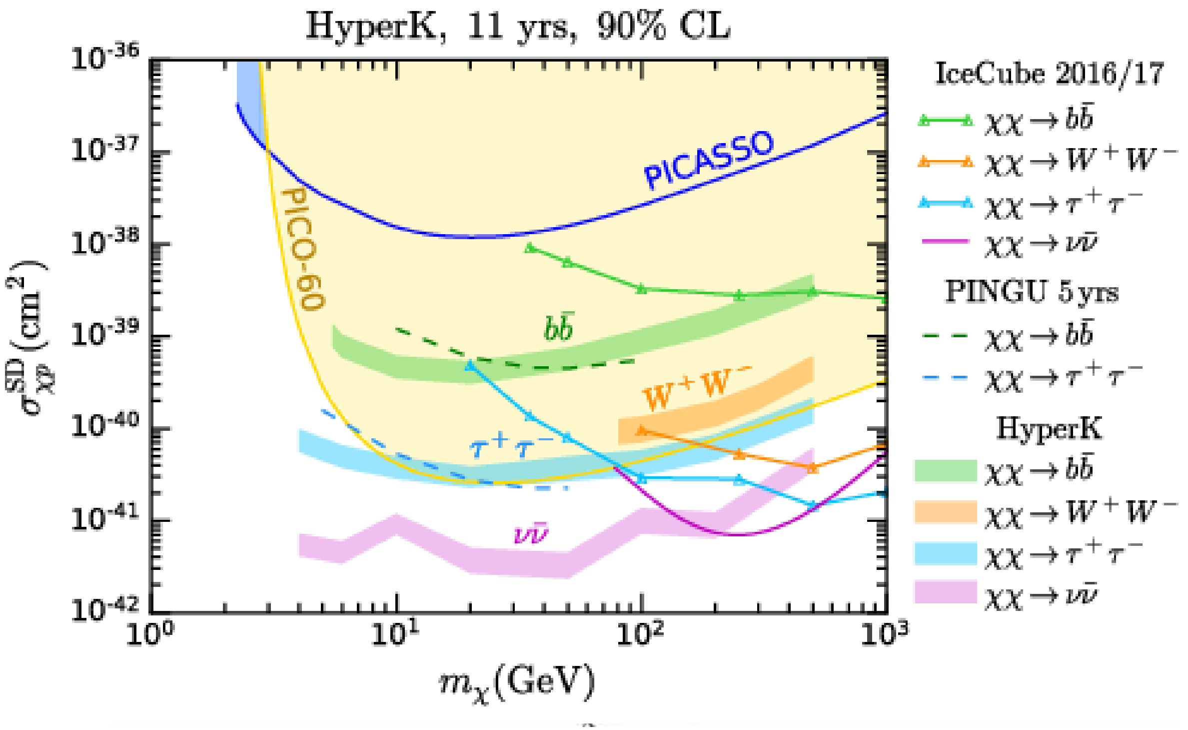
# Annihilation of DM captured in the Sun to Neutrinos

**Spin-Independent (SI)**




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

**Spin-Dependent (SD)**

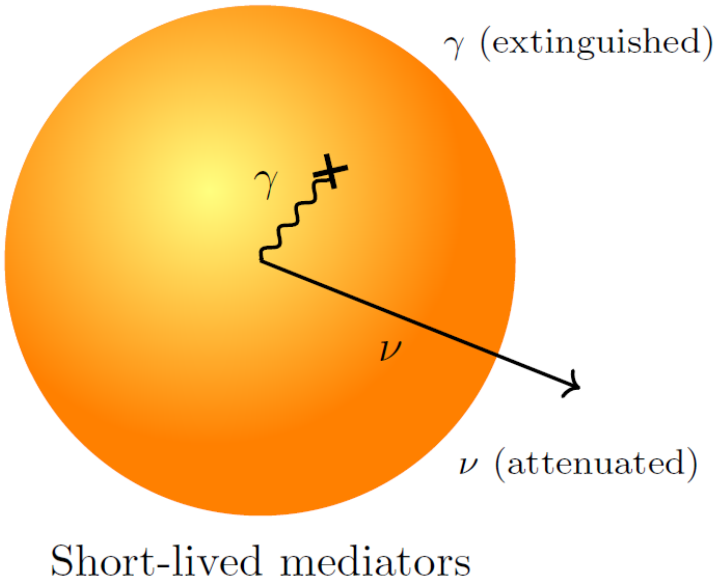


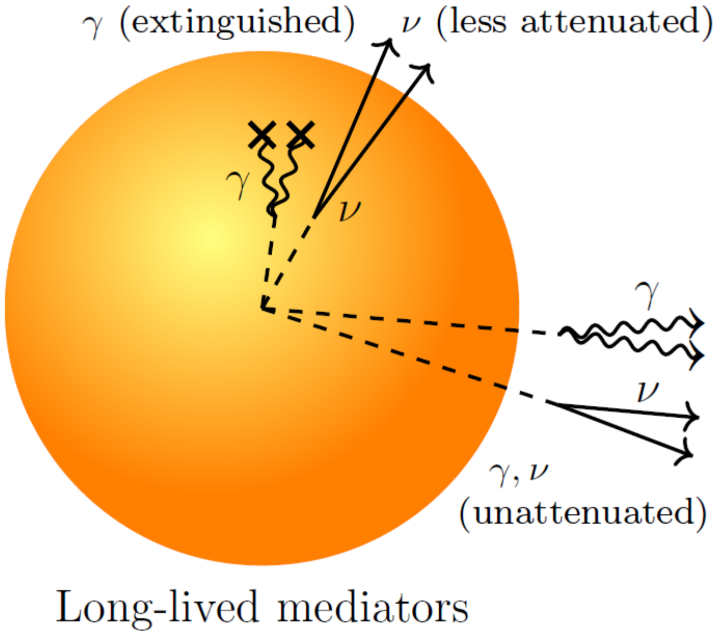

NFB, Dolan & Robles, arXiv:2107.04216

# 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
- If decay occurs beyond solar core → High energy neutrino signal less attenuated
- If decay occurs between Sun and Earth → solar gamma rays or cosmic rays




Leane, Ng & Beacom, arXiv:1703.04629

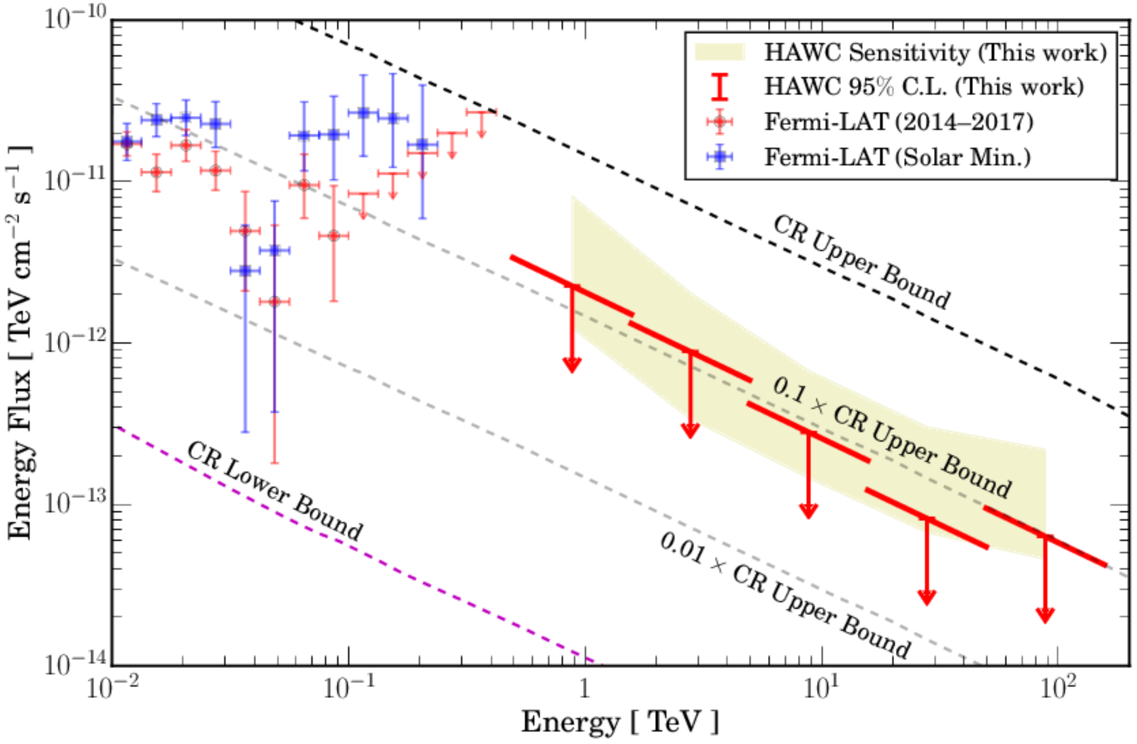
# Annihilation to dark mediators → *Solar gamma rays*

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.

**Solar gamma-ray measurements:**



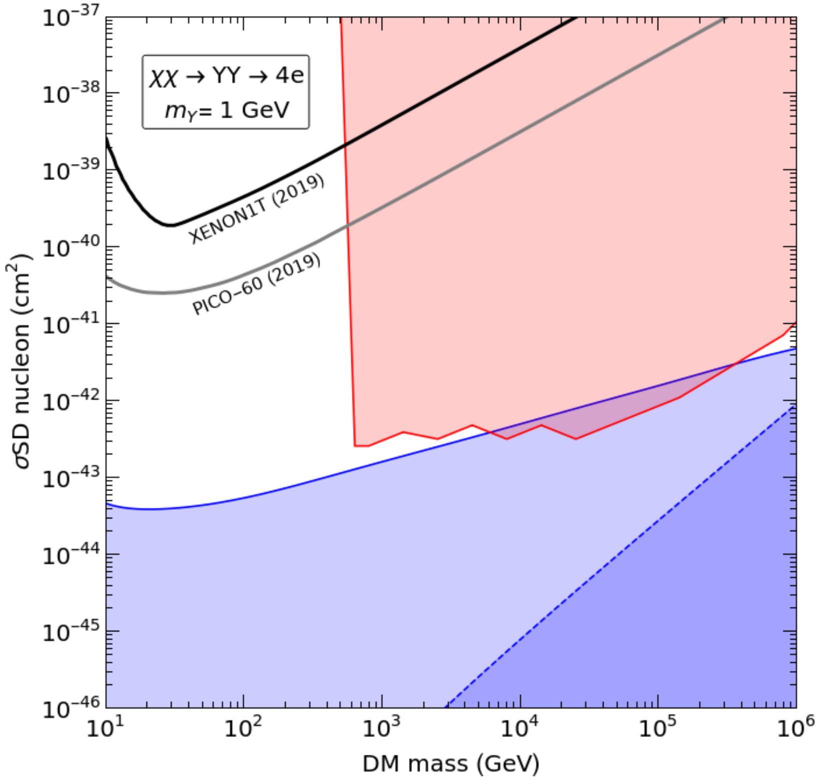

HAWC collaboration, Phys Rev. D 98 123001 (2018)

# Simple (model independent) limits

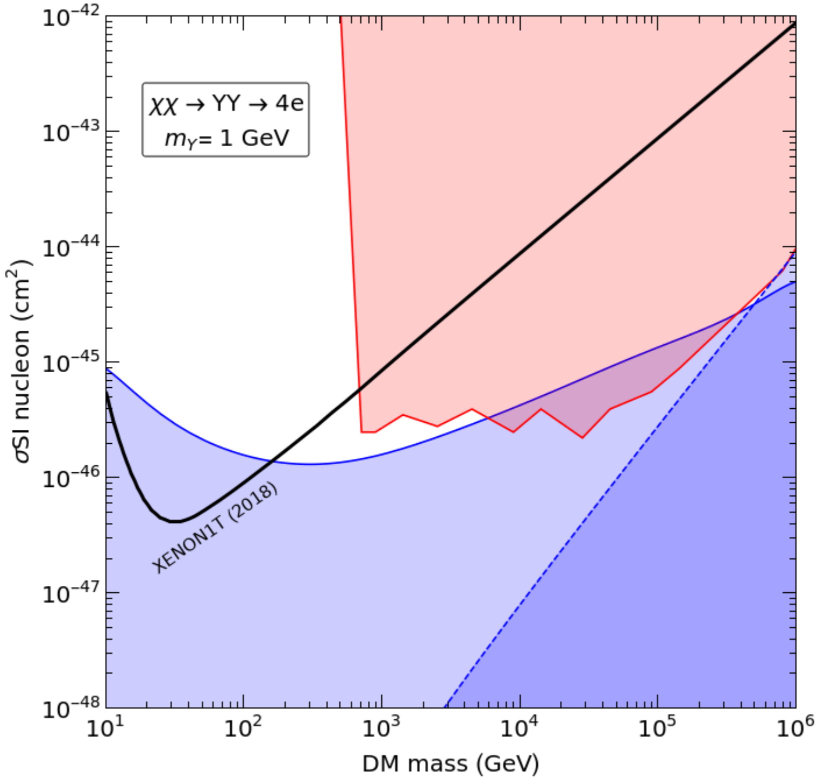
NFB, Dent & Sanderson, arXiv:2103.16794

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

**Spin-Dependent (SD)**




**Spin-Independent (SI)**

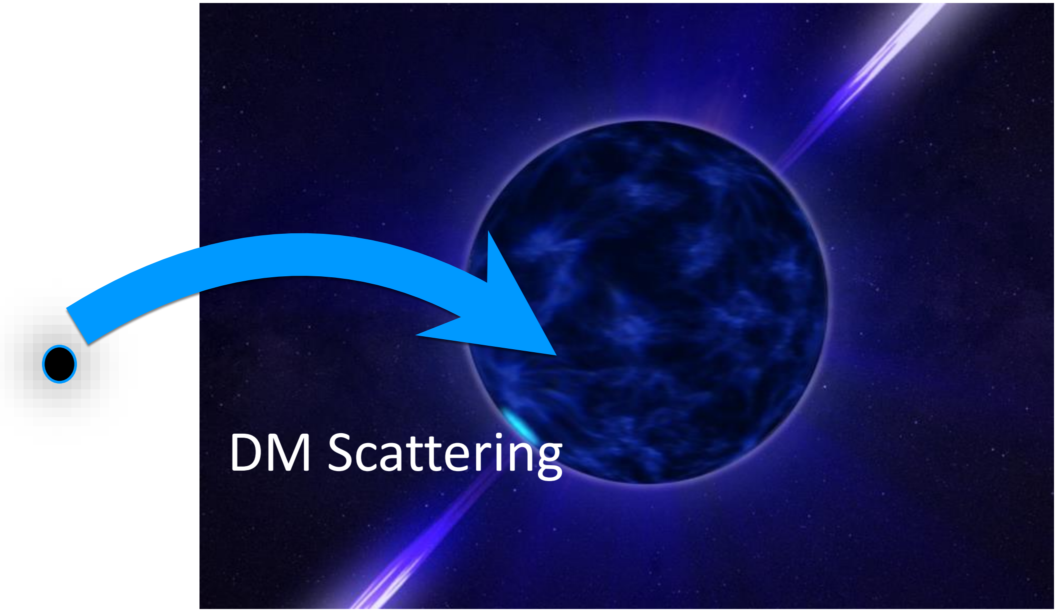


# Neutron Stars

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**

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



# Neutron Stars → Black holes?

Kouvaris; Kouvaris & Tinyakov; McDermott, Yu & Zurek; Bramante, Fukushima & Kumar; NFB, Petraki & Melatos; Bertone, Nelson & Reddy; and others.

- Due to their density, neutron stars capture dark matter very efficiently

- Can neutron stars accumulate so much dark matter that they would collapse to back holes? Yes, but typically only if:
  - No annihilation (e.g. asymmetric DM)
  - DM is bosonic and condenses to a small self gravitating BEC, or
  - DM is fermionic with attractive self-interactions, and
  - No repulsive-self interactions that prevent collapse (even very <u>very</u> tiny self-interaction is enough) **NFB, Petraki & Melatos, PRD 2013**

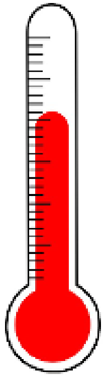
→ **Black hole formation possible but quite unlikely for *typical* WIMP-like dark matter**

# 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**

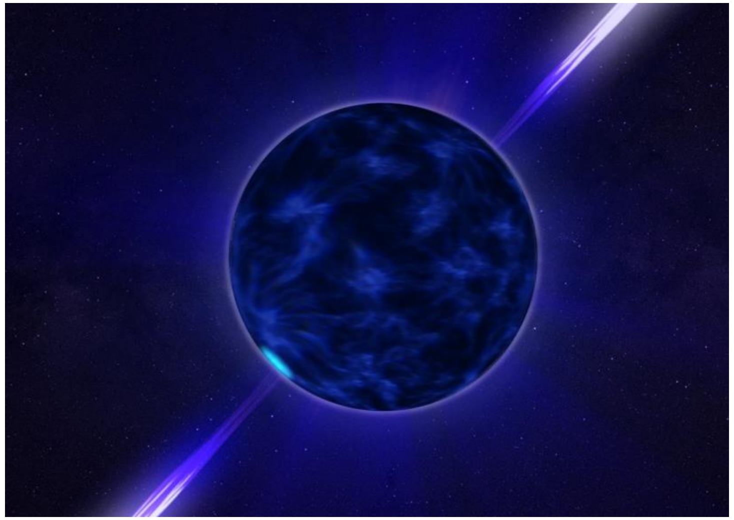


Coolest known neutron star (PSR J2144-3933) has a temperature of ~ 4.2 x $10^4$ K.

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

# Neutron Star Heating: Advantages

| | Direct Detection | Neutron stars |
|---|---|---|
| DM velocity | Non-rel<br>$v \ll c$ | Quasi-rel.<br>$v \sim 0.5\ c$ |
| Cross-sections | Can be suppressed by velocity/momentum | Unsuppressed |
| Momentum transfer | $< \mathcal{O}(100\ \mathrm{MeV})$ | $\mathcal{O}(10\ \mathrm{GeV})$ |
| Density | Normal matter | Extremely high density |

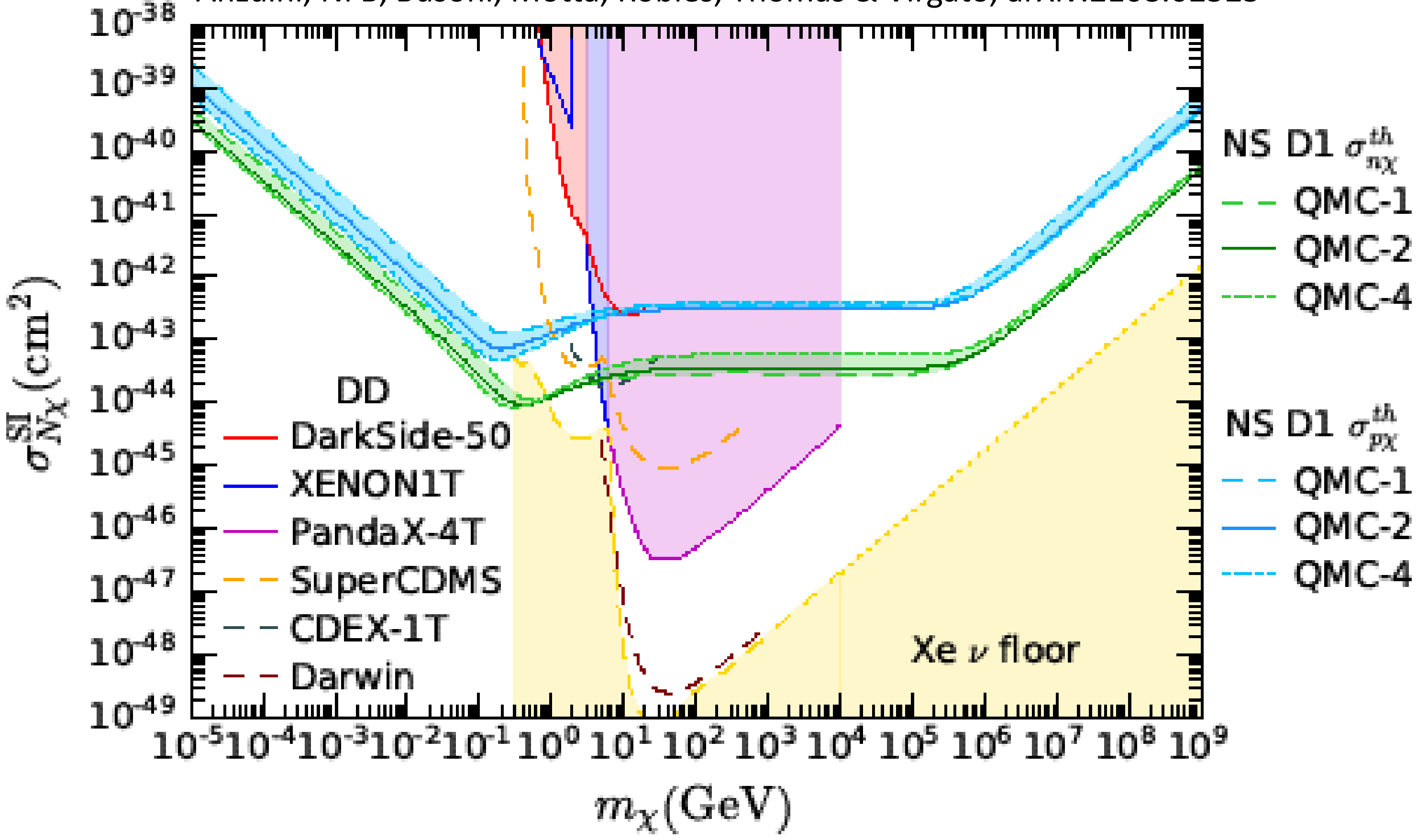


- **no velocity/momentum suppression → sensitive to interactions that direct detection cannot probe**
- **not limited by recoil detection thresholds → sensitive to very low mass DM**
- **Similar sensitivity to SI and SD scattering**

# Kinetic Heating Sensitivity (projected limits)

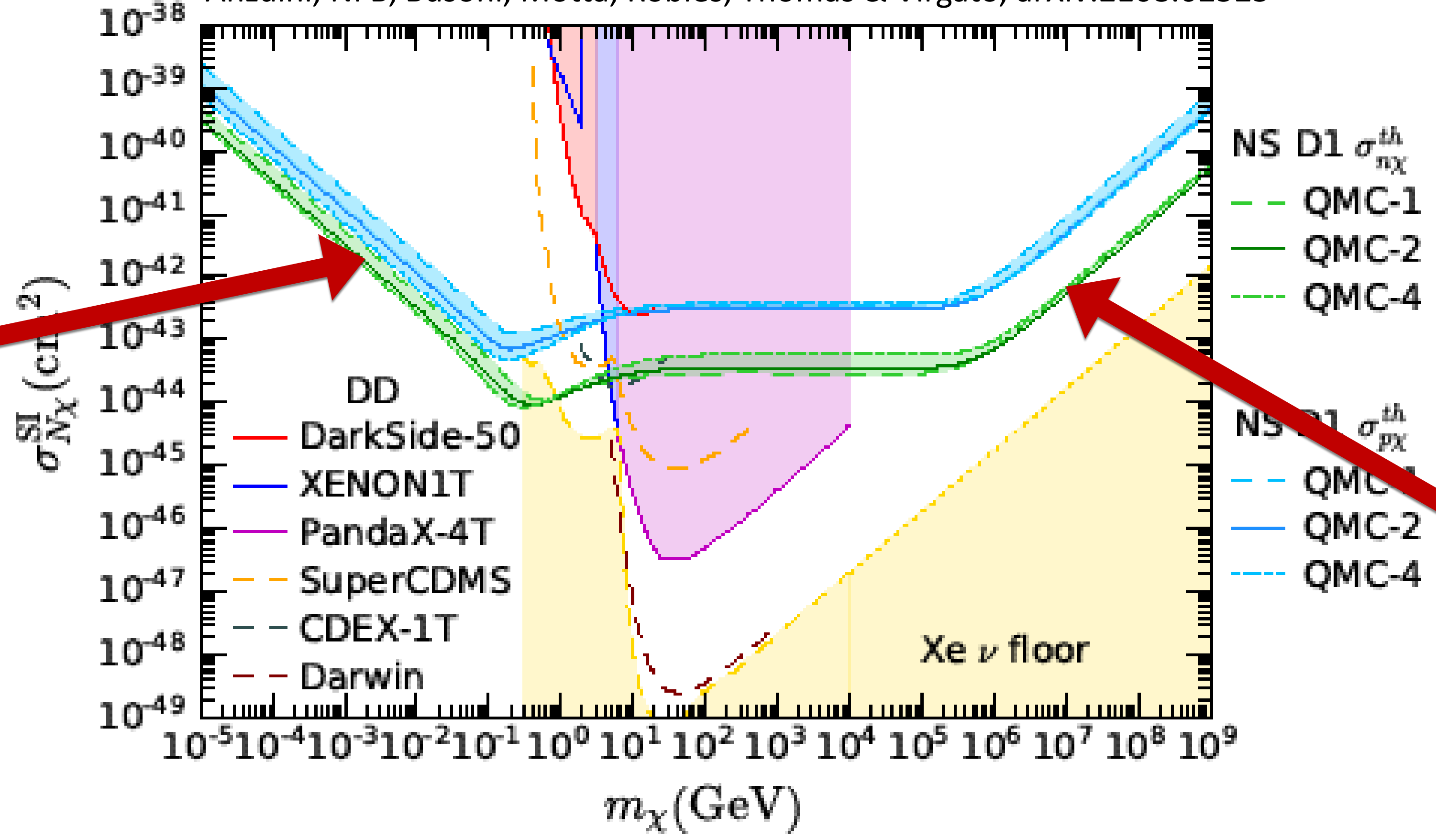
**Ball-park sensitivity**
**= geometric cross section**
**$\sim 10^{-45}\,\mathrm{cm}^2$**

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



# Kinetic Heating Sensitivity (projected limits)

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



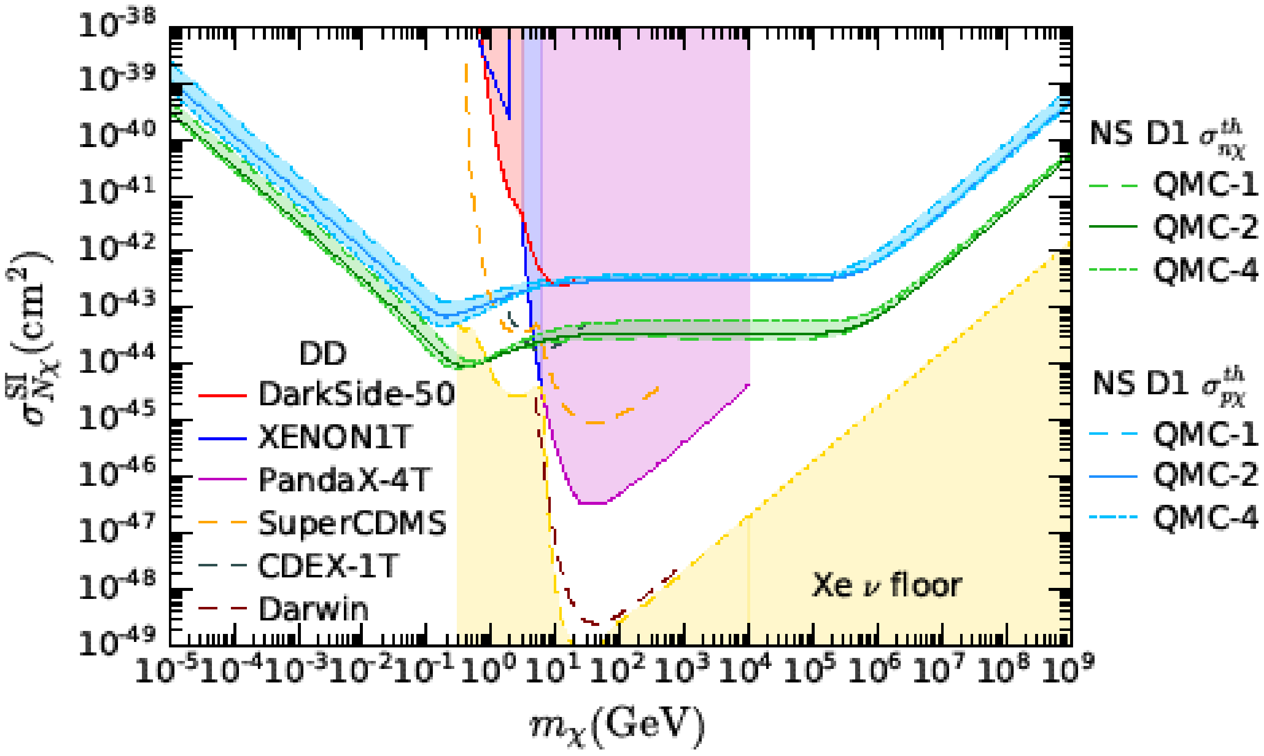

Pauli blocking from degenerate neutrons restricts scattering when $m_{DM} < 1$ GeV.

Need: momentum transfer > neutron Fermi momentum

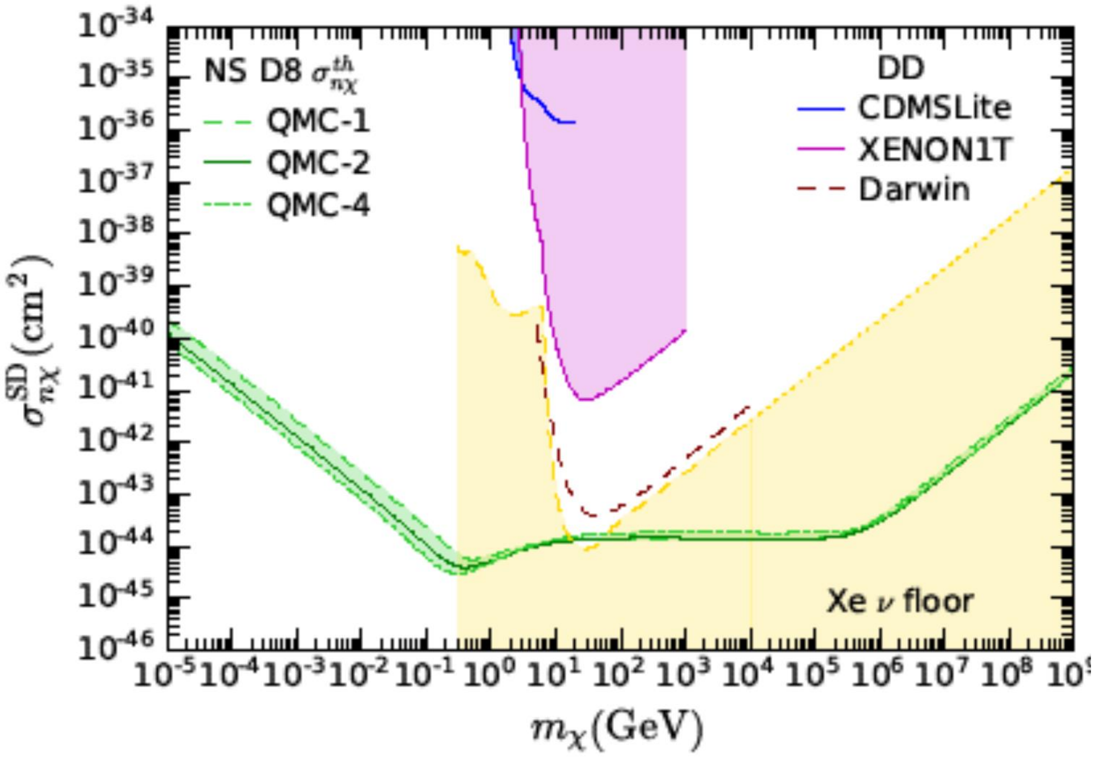
Momentum transfer in single collision not sufficient for capture when $m_{DM} > 10^6$ GeV

# Kinetic Heating Sensitivity: nucleon scattering

**Spin-Independent (SI)**

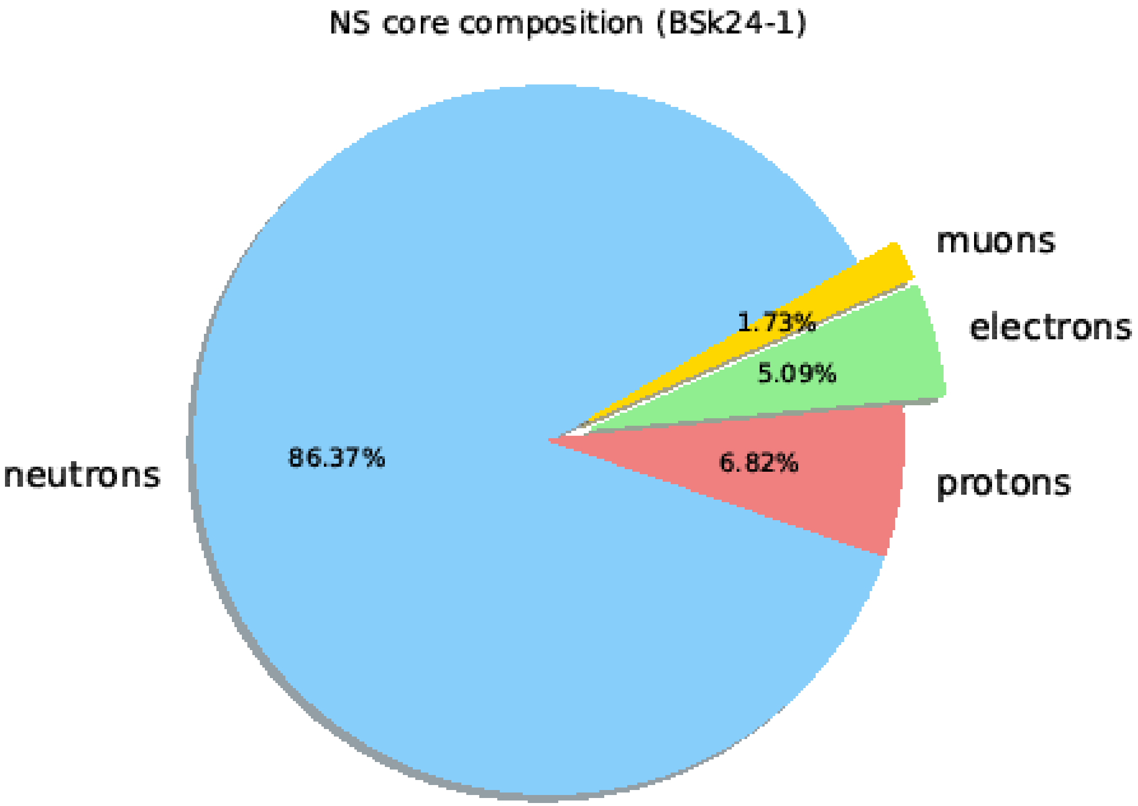



**Spin-Dependent (SD)**




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

# Leptons in Neutron Stars



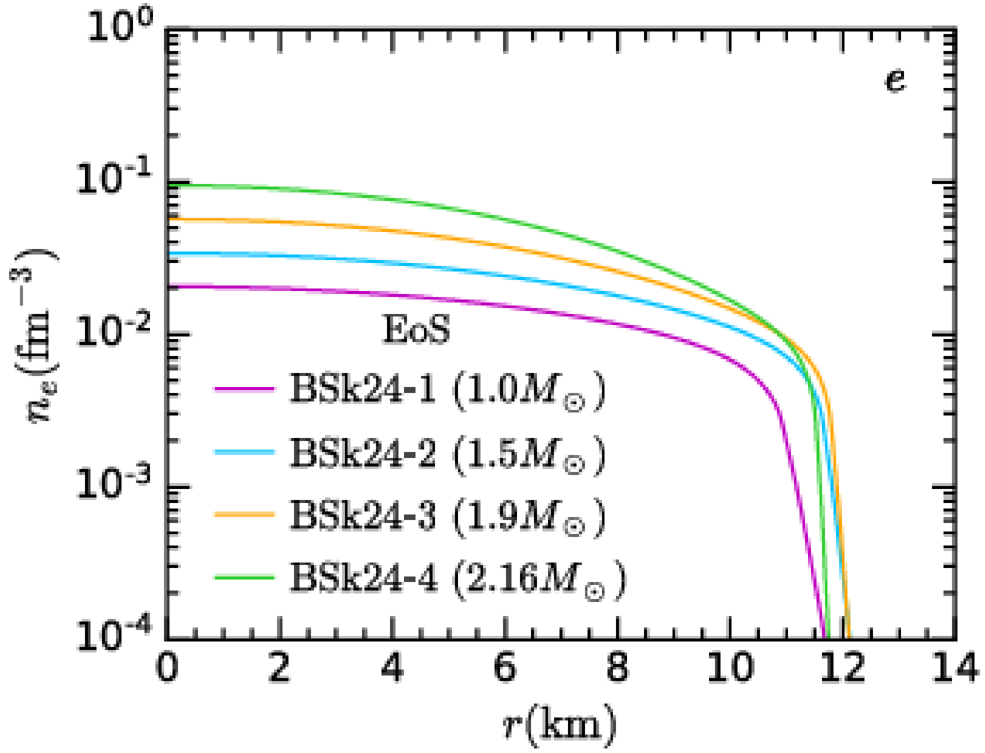

Beta equilibrium in the core determines the composition:

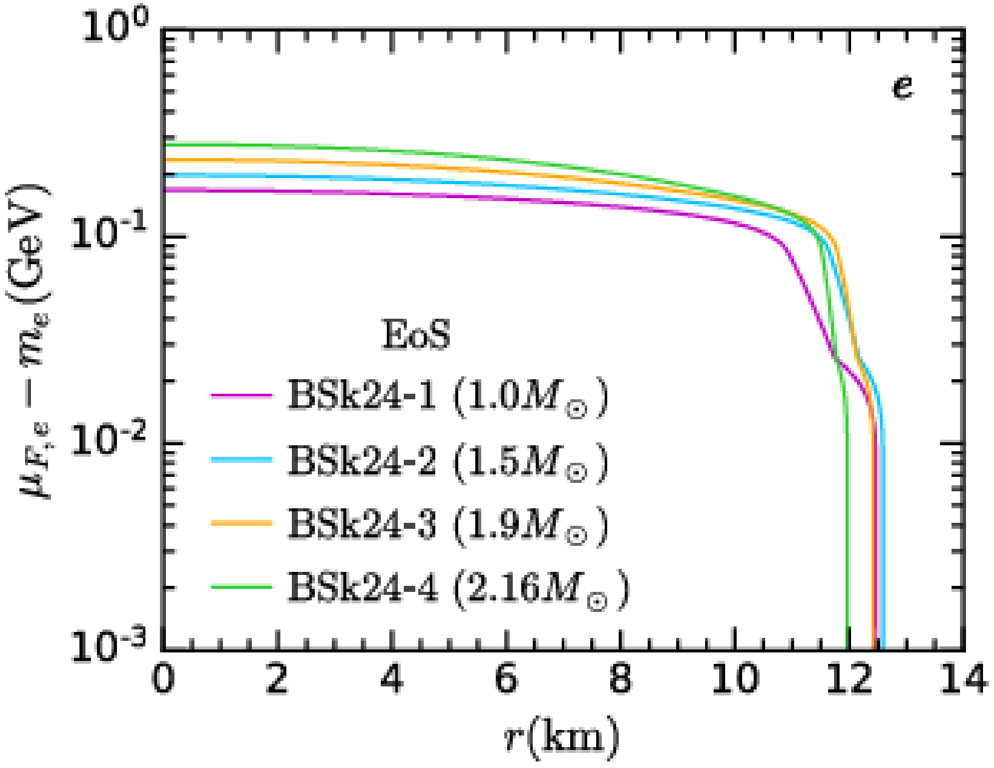
- Degenerate neutrons
- Smaller and approximately equal electron and proton abundances
- Small muon component

# Leptons in Neutron Stars

Lepton density of few % in NS core, lower in crust.

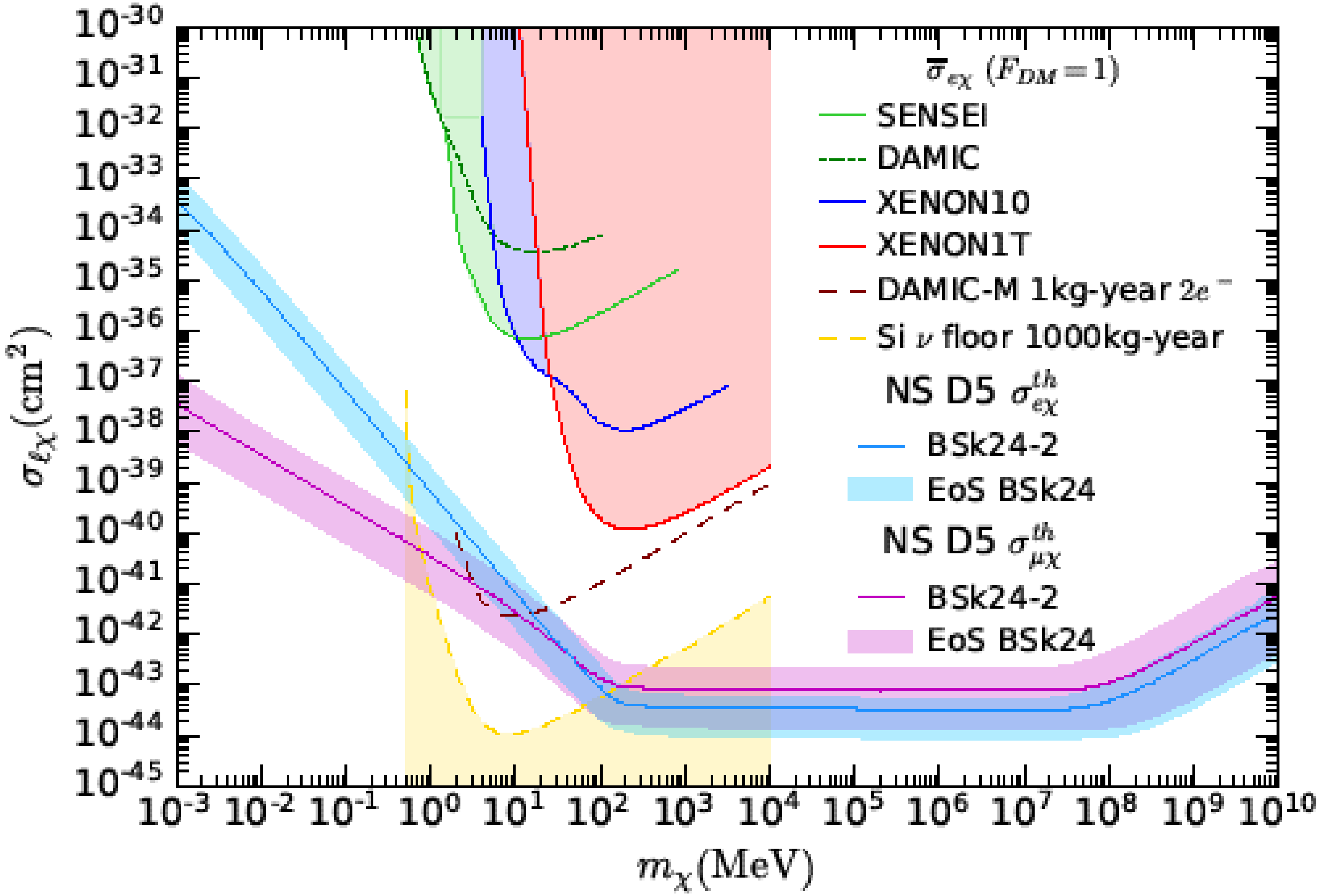
Fermi-momentum ~ constant in core.




NFB, Busoni, Robles & Virgato arXiv:2010.13257

# Kinetic Heating Sensitivity: lepton scattering




NFB, Busoni, Robles & Virgato arXiv:2010.13257

Muon scattering

Electron scattering

# White Dwarf Heating from DM Capture

Advantages of White Dwarfs over Neutron Stars:

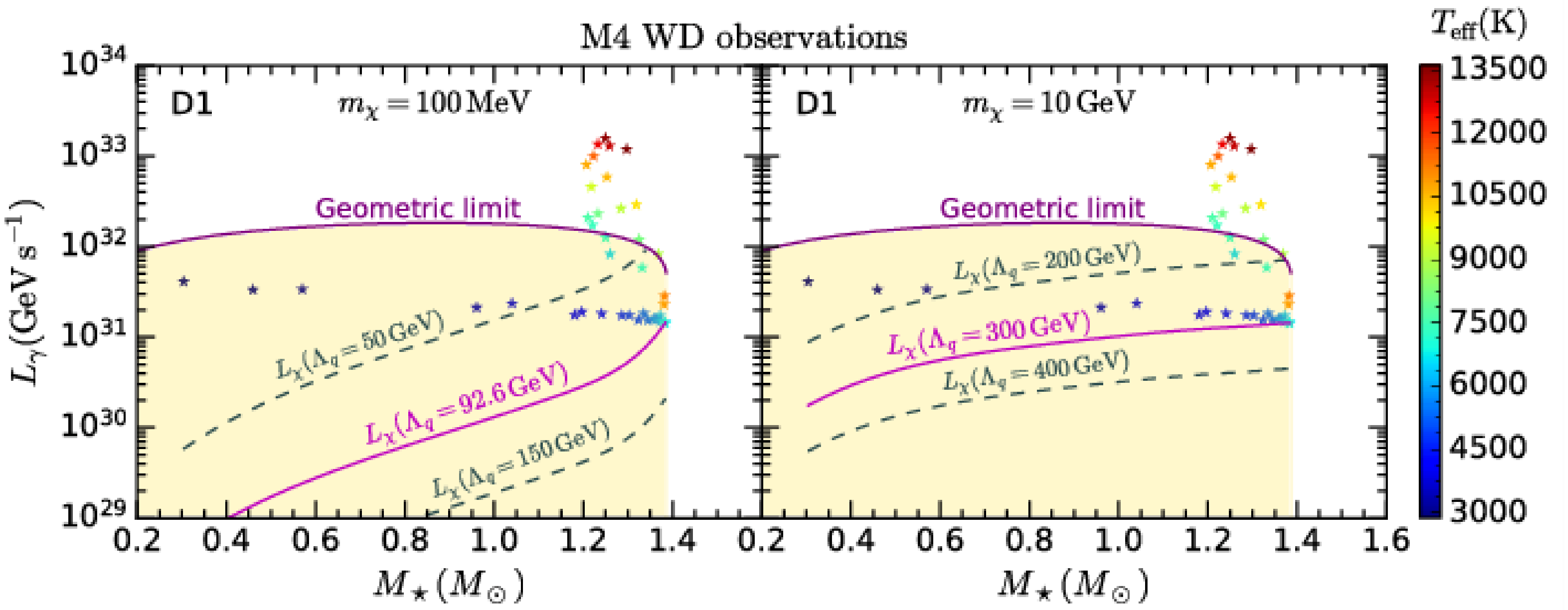
- Existence of observational data!
- Physics of WD's much better constrained than NSs
    - Well-defined mass-radius relation
    - Less uncertainty of the equation-of-state
    - Better understood luminosity-age relations

We can equate observed luminosity of WD in DM rich environment with the heating rate due to DM annihilation.

We will consider WD's in the M4 globular cluster, assuming M4 formed in a DM subhalo.

# White dwarfs in M4 globular cluster

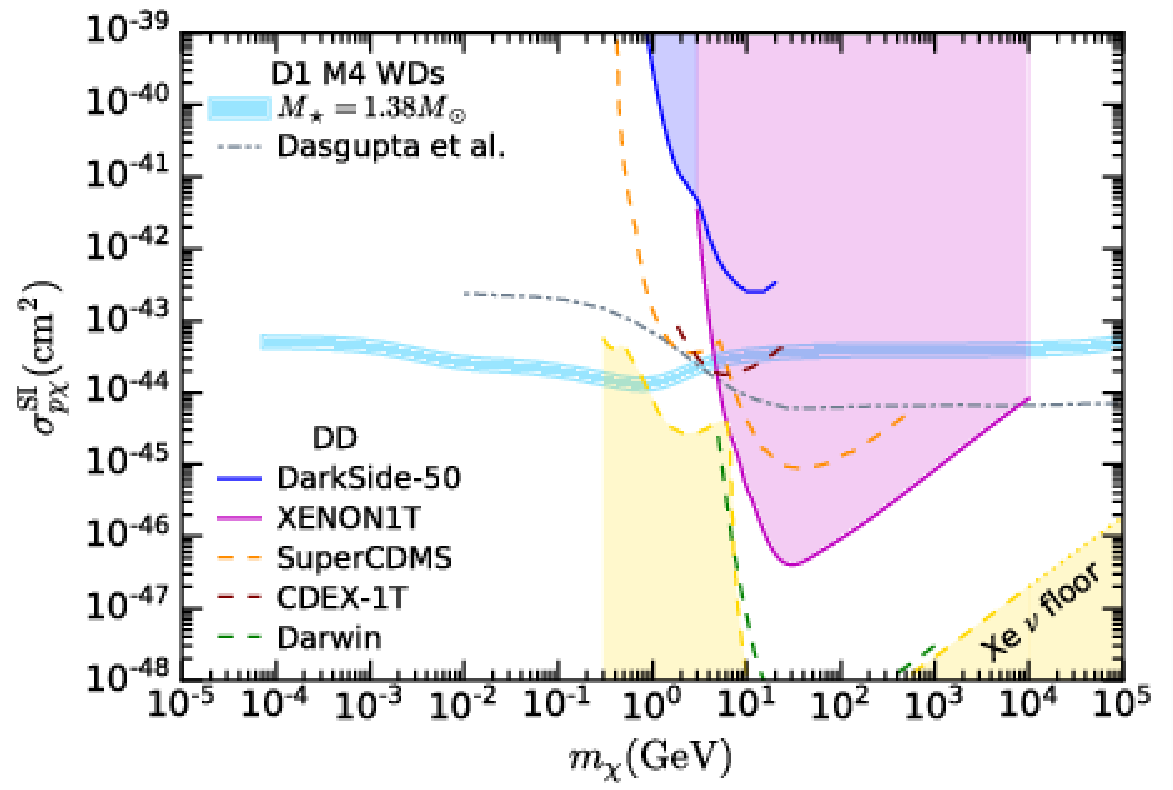
Best limits come from heavy stars (large capture rate) with low luminosity.



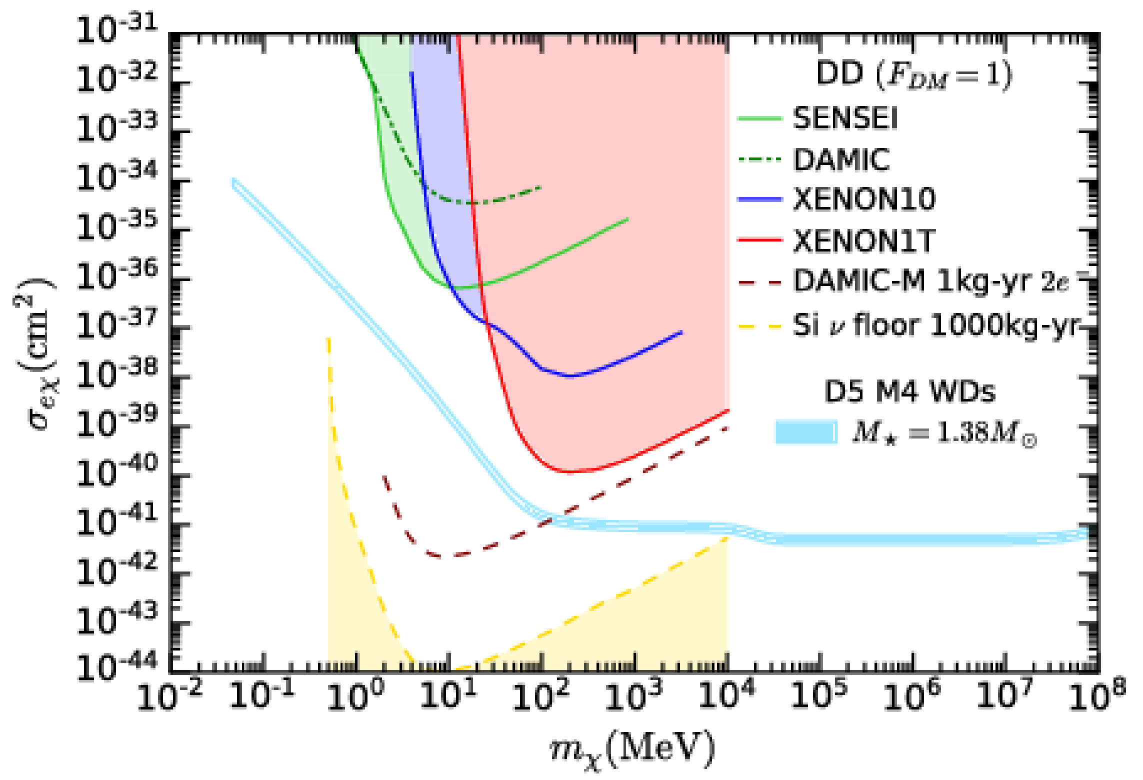

NFB, Busoni, Ramirez-Quezada, Robles & Virgato, arXiv:2104.14367

# White dwarfs in M4 globular cluster

## DM-nucleon scattering




## DM-electron scattering




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

# Summary

- Key challenges in the detection of dark matter scattering:
  - Net generation experiments will reach the “neutrino floor”
  - Low mass DM signals fall below experimental thresholds

- New approaches:
  - New detectors technologies
    → light dark matter detection; directional detection
  - New analyses using existing detectors
    → e.g. Migdal effect; Boosted dark matter

- Complementary information from dark matter capture in stars:
  - Neutrons or gamma rays from the Sun
  - Heating of neutron stars or dwarfs

# Backup slides

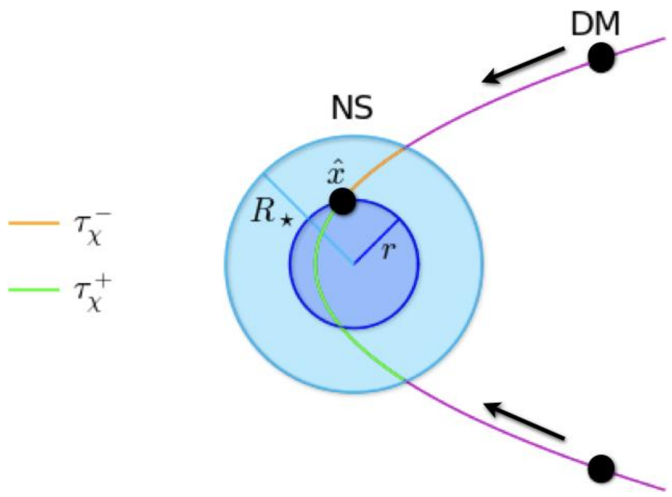
# Improved capture calculations

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 Tolman-Oppenheimer-Volkov 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



# Two critical effects neglected in all previous treatments:

**Nucleon Structure and Strong Interactions in Dark Matter Capture in Neutron Stars**

Nicole F. Bell,[1,*] Giorgio Busoni,[2,†] Theo F. Motta,[3,‡] Sandra Robles,[1,§] Anthony W. Thomas,[3,¶] and Michael Virgato[1,**]

**Phys. Rev. Lett. 127, 111803 (2021)**

(see also JCAP 11, 11 (2011))

## 1. Momentum dependence of hadronic matrix elements:

- *Nuclear recoil experiments* – calculated in zero momentum transfer limit
- *Neutron star scattering* – momentum transfer $\sim 10\ \mathrm{GeV}$ → couplings suppressed

## 2. Nucleon Interactions:

- *Free fermi gas approach* neglects strong interactions of nucleons
- Correct approach uses an *effective nucleon mass*