Searching for Light Dark Matter

Nicole Bell

Collaborators

Giorgio Busoni, *James Dent, Matthew Dolan, Bhaskar Dutta, Sumit Ghost, Jason Kumar, Rafael Lang, Theo Motta,* ***Jayden Newstead,*** *Maura Ramirez-Quezada, Alex Ritter, Subir Sabharwal,* ***Sandra Robles***, *Anthony Thomas,* ***Michael Virgato***, *Tom Weiler*

Outline:

- Direct detection of light dark
  - Migdal effect
  - Inelastic dark matter

- Dark matter capture in Stars
  - Kinetic heating

- Indirect detection limits on annihilation of light dark matter
  - Annihilation to neutrinos

Dark Matter Direct Detection

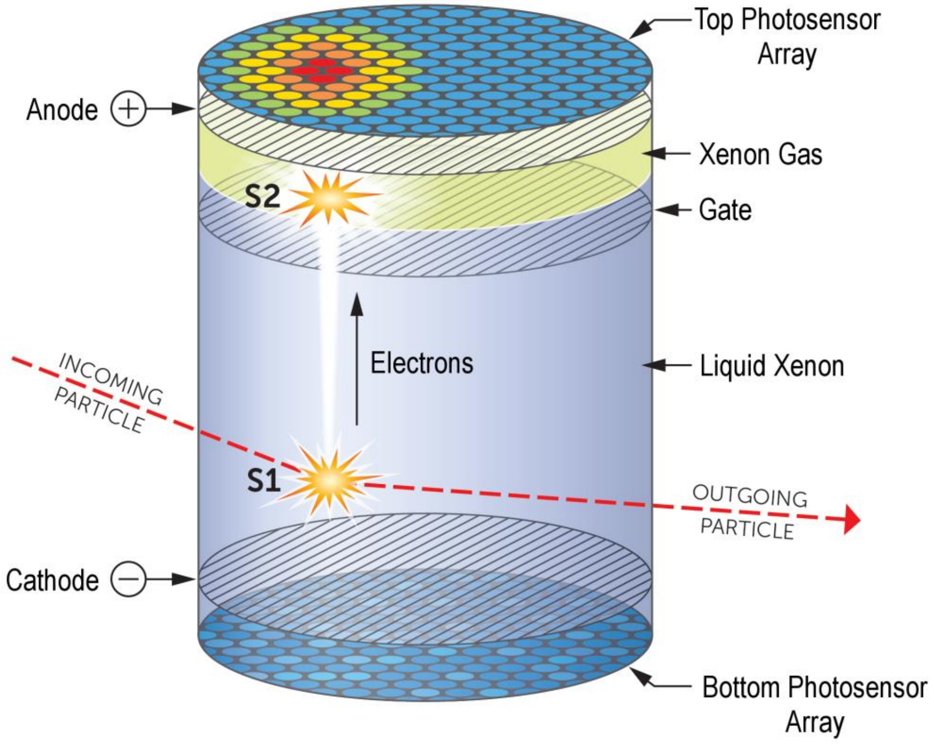
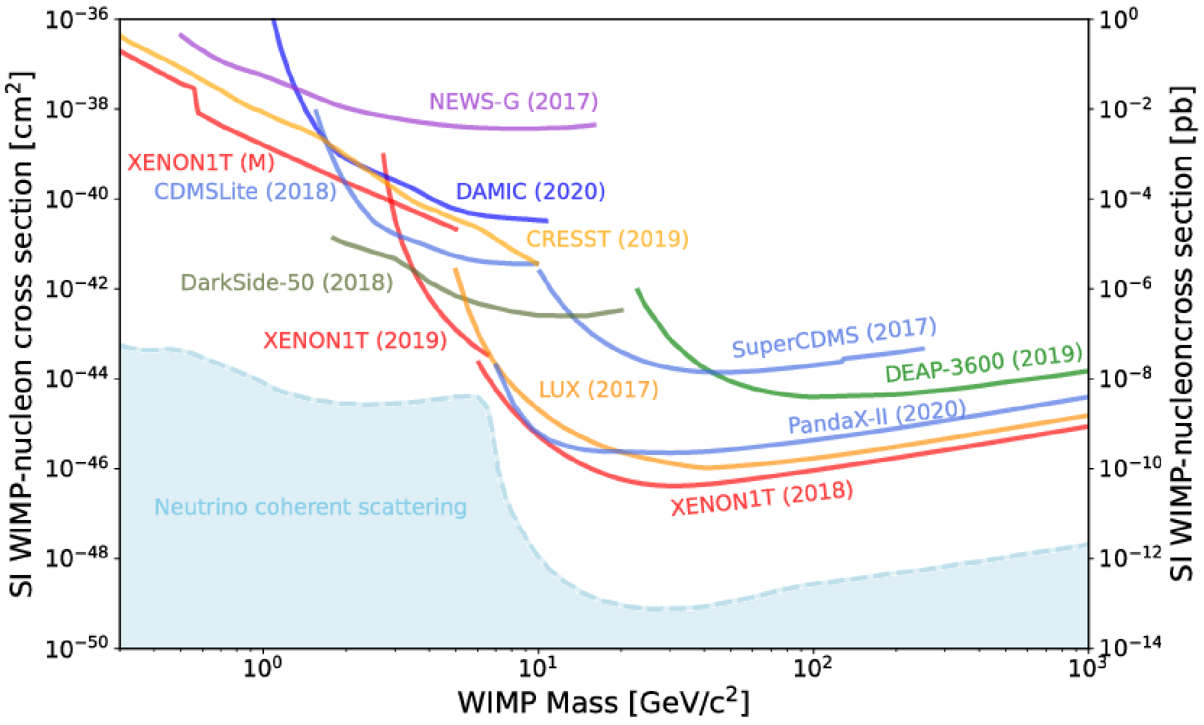


Image: J. Aalbers et al. arXiv:2203.02309

Direct Detection limits

Spin-independent (SI) interactions

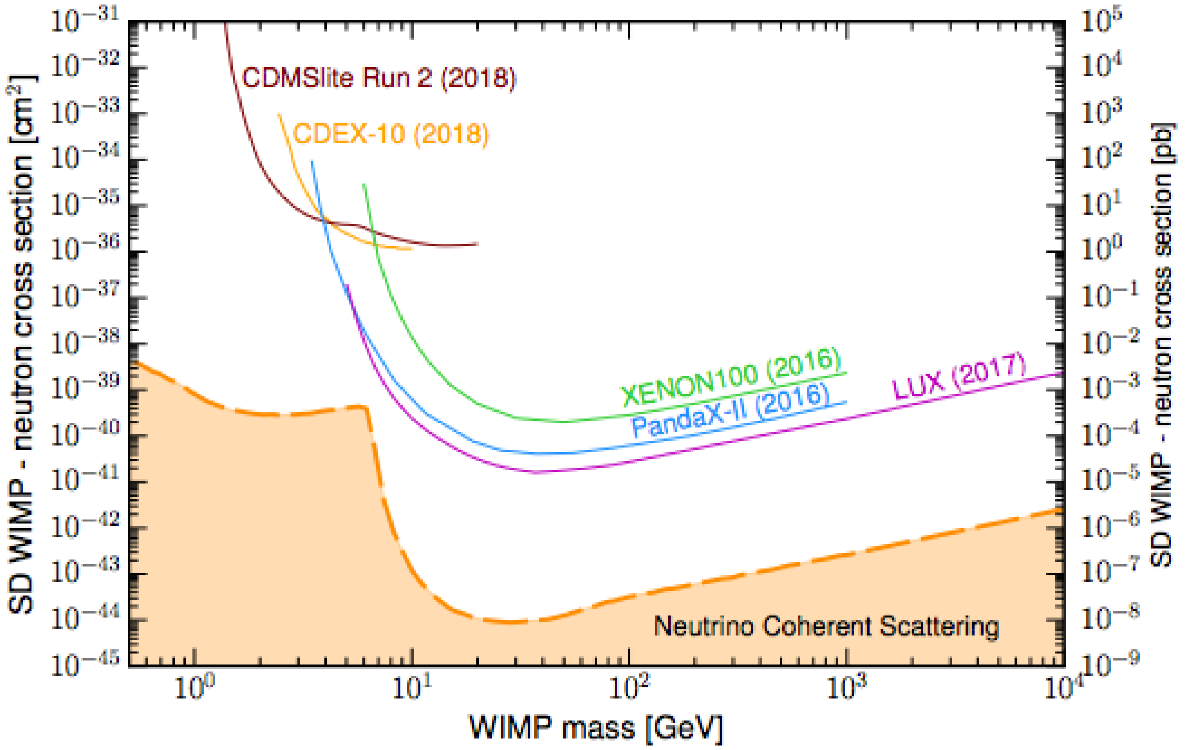
→ strong bounds due to coherent enhancement



J. Aalbers et al. arXiv:2203.02309

Spin-dependent (SD) interactions

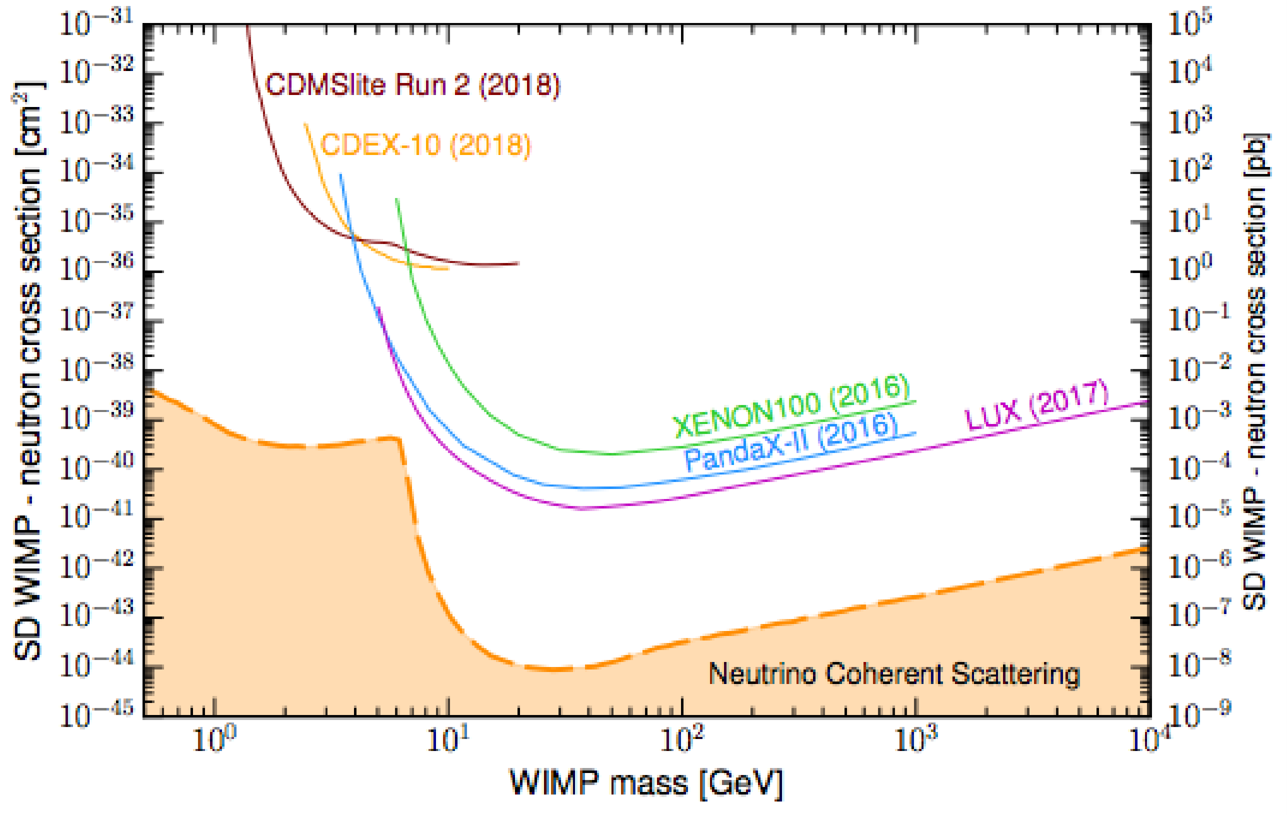
→ weaker bounds



S. Robles

Dark matter direct detection – low mass challenge

- Sub-GeV dark matter gives very low-energy recoil signals
  -- below experimental thresholds
  - New detection technologies, to achieve lower thresholds
  - New analyses to probe lower mass dark matter using existing detectors



New strategies to probe dark matter scattering

- New analyses to probe lower mass dark matter <u>using existing detectors</u>
  - New signals in addition to, or instead of, nuclear recoil
    - <u>Migdal effect</u>, electron scattering, “boosted” dark matter, …

- Complementary constraints from <u>dark matter capture in stars</u>
  - Heating (<u>Neutron stars</u>, <u>White Dwarfs</u>) or detection of annihilation products

Migdal effect

The ionization of an atom following a nuclear recoil

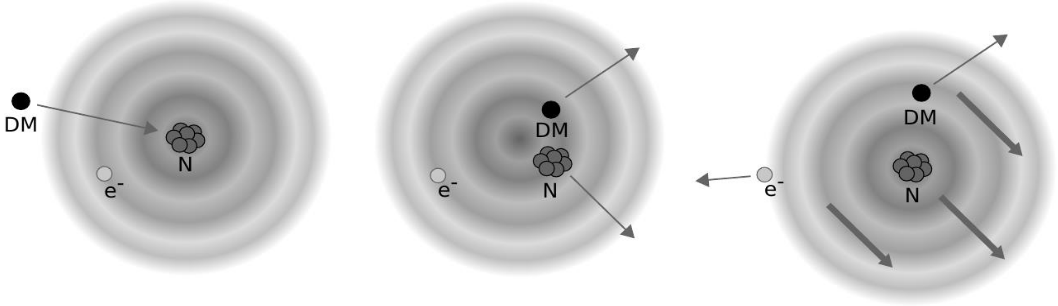


Image: M. Dolan et al.

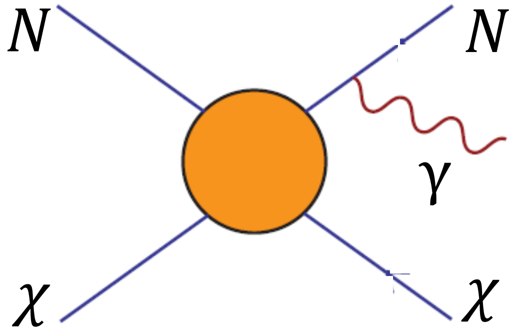
→ Useful in cases where the nuclear recoil is below threshold (i.e., low mass dark matter) and we can instead detect the ionization signal

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

Bremsstralung



$\chi + N \rightarrow \chi + N$ (elastic scattering)

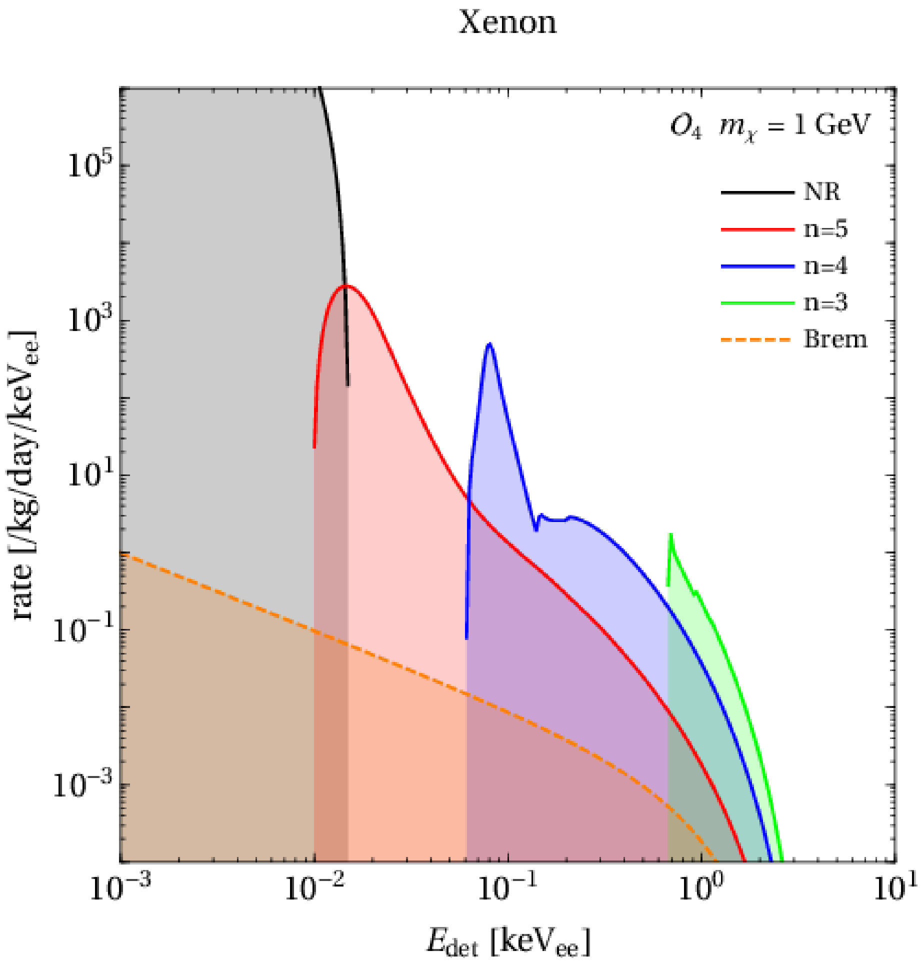
$\chi + N \rightarrow \chi + N + \gamma$ (inelastic)

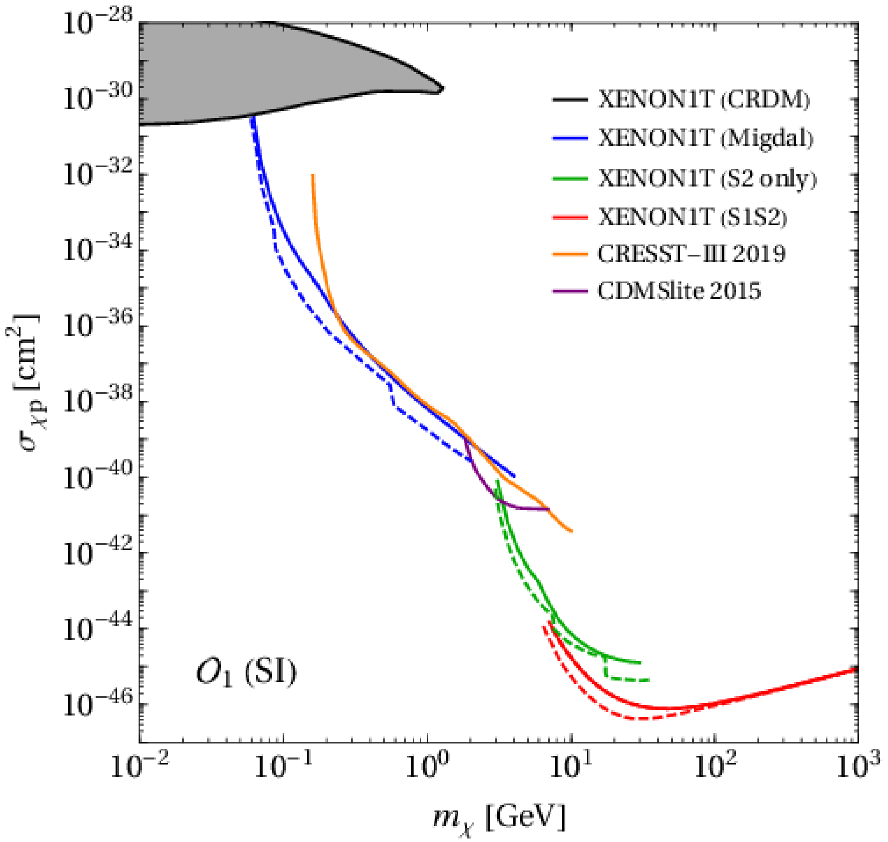
If the elastic nuclear recoil is below threshold, is a photon brem signal detectable?

In principle, yes. In fact, the kinematics for Migdal and Brem are the same.
But, the rates are suppressed compared to Midgal by a factor of $\sim \frac{E_R}{m_T}$

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

Migdal effect





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

Calibrating the Migdal effect

$$\frac{d^2R}{dE_{NR}dE_i} = \frac{d^2R_{iT}}{dE_{NR}dE_i} \times |Z_{ion}|^2$$

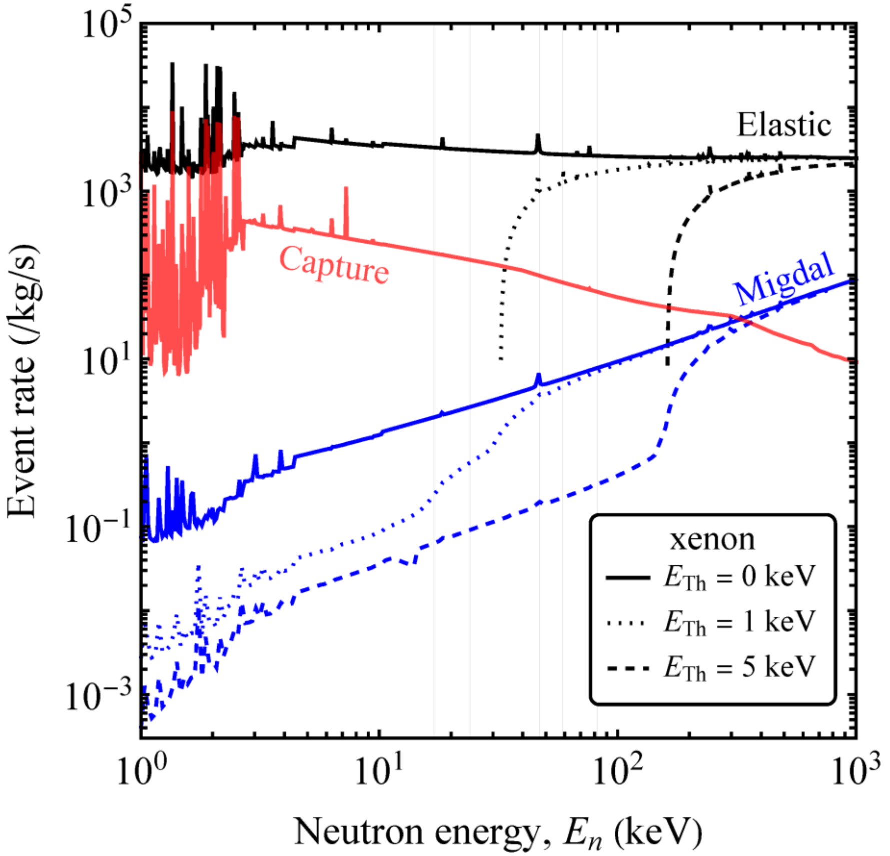
= (standard DM-nucleus recoil rate) x (ionization rate)

Migdal effect has not yet been observed
→ Need to calibrate theoretical uncertainties with experimental measurements
→ The *MIGDAL* experiment aims to do this using a high energy neutron source

But this will not achieve the aim of a calibration in the regime relevant for dark matter searches.

Calibrating the Migdal effect at low recoil energy

Neutron beam fired at Xenon target



Neutron energy below 30 keV is optimal for keeping majority of elastic scatters below experimental thresholds (1-5 keV).

Energy above 10 keV is away from most resonances.

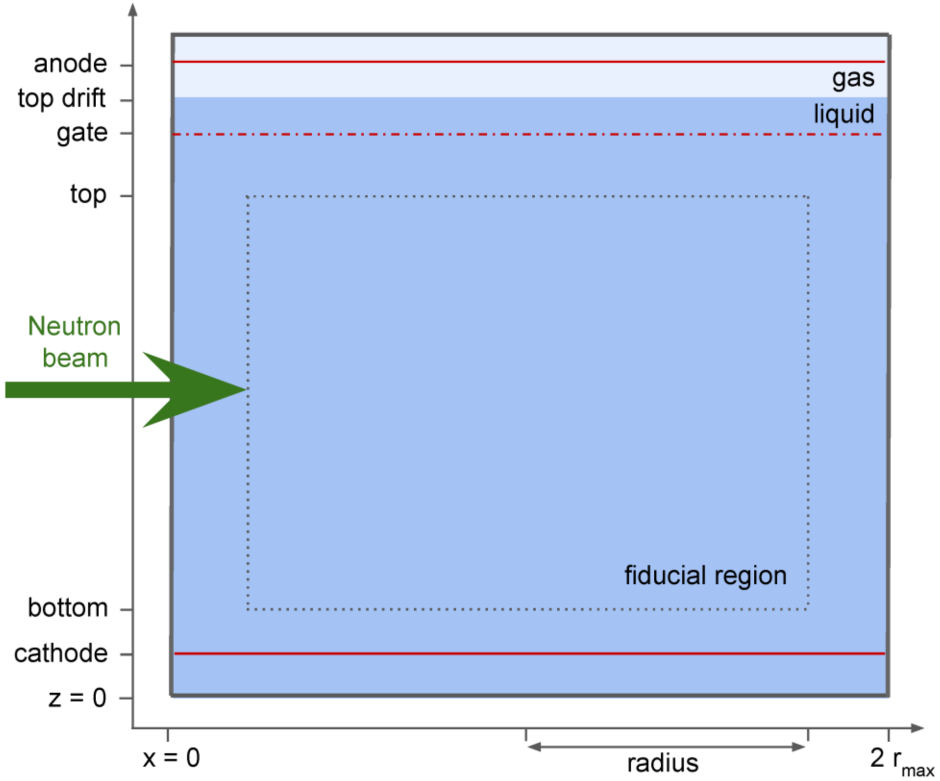
Assume a neutron energy of ~ 17 keV

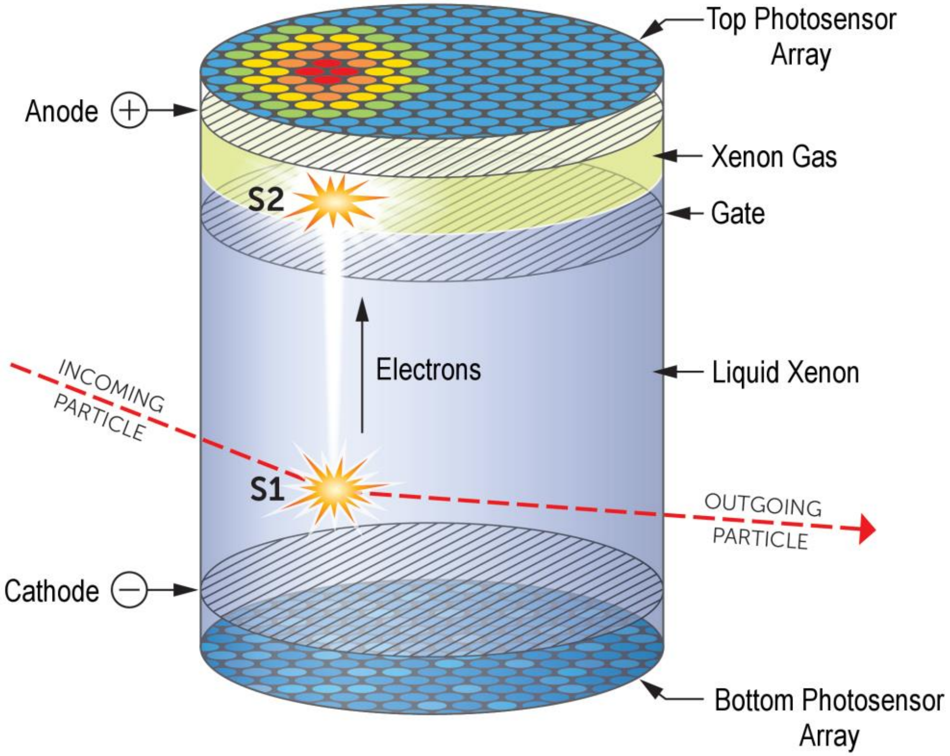
NFB, Dent, Lang, Newstead, Ritter, PRD, arXiv:2112.08514

Migdal calibration

Source	Calc. ratio
neutron (17 keV)	6.0×10^{-4}
reactor neutrinos	1.7×10^{-4}
SNS neutrinos	1.5×10^{-2}
^{51}Cr neutrinos	5.4×10^{-6}

10 kg Xenon detector





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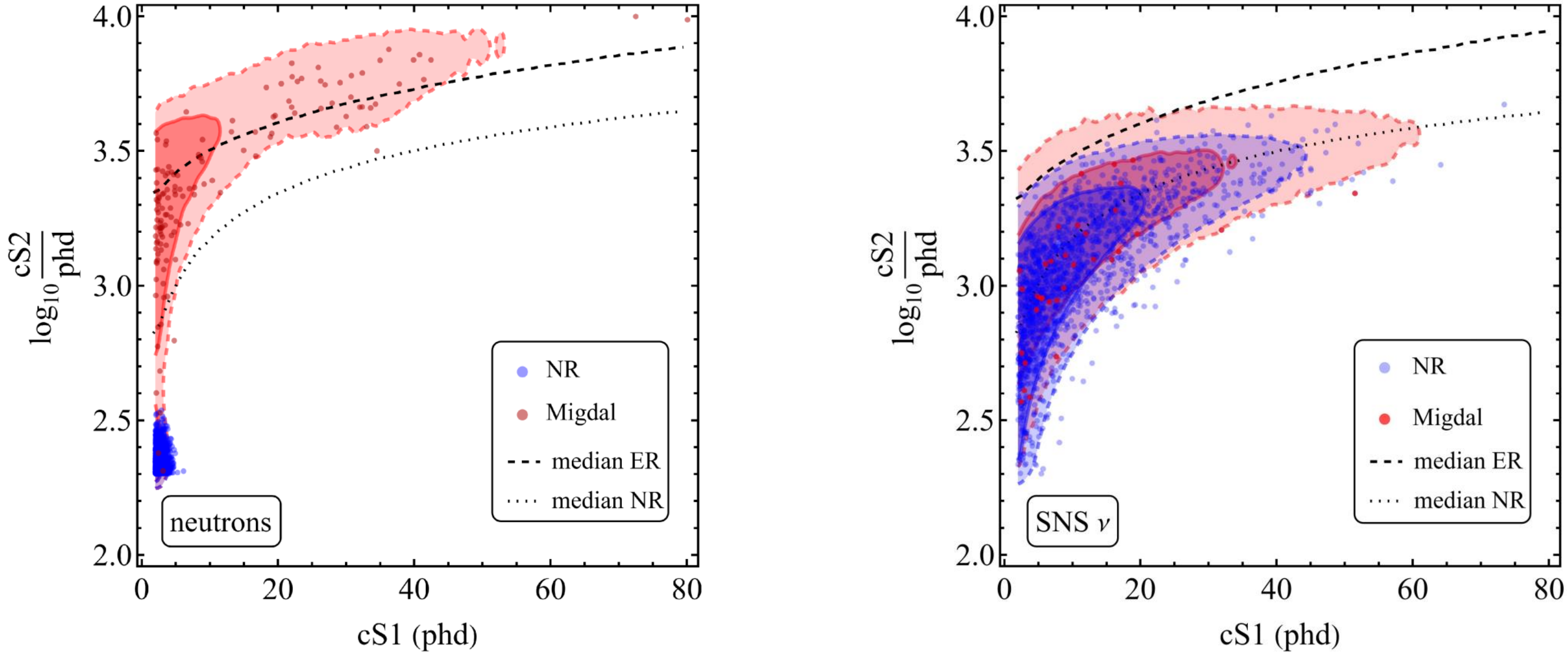


NFB, Dent, Lang, Newstead, Ritter, PRD, arXiv:2112.08514

Inelastic dark matter

Inelastic scattering

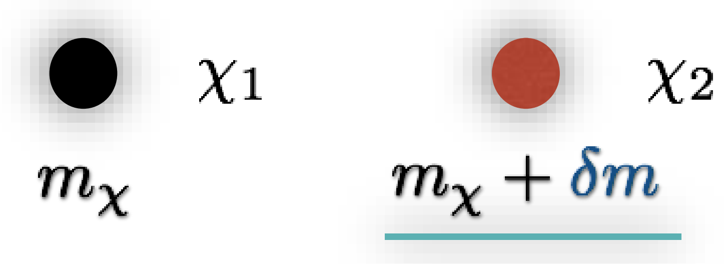
Standard direct detection searches look for DM-nucleon ***elastic*** scattering
The Migdal effect is type of ***inelastic*** scattering.

Dark matter-nucleus scattering can exhibit inelasticity in various ways:

- by exciting a low-lying nuclear state
- Migdal effect
- changing the dark matter particle mass: $\chi_1 + n \rightarrow \chi_2 + n$

Inelastic dark matter

Two *almost degenerate* dark matter states:



Inelastic because the $\chi_1 - \chi_1$ couple is absent and hence the dominant interaction is

$$\boldsymbol{\chi_1}\, n \rightarrow \boldsymbol{\chi_2}\, n$$

Kinematically forbidden unless mass splitting is small, $\delta m \ll m$

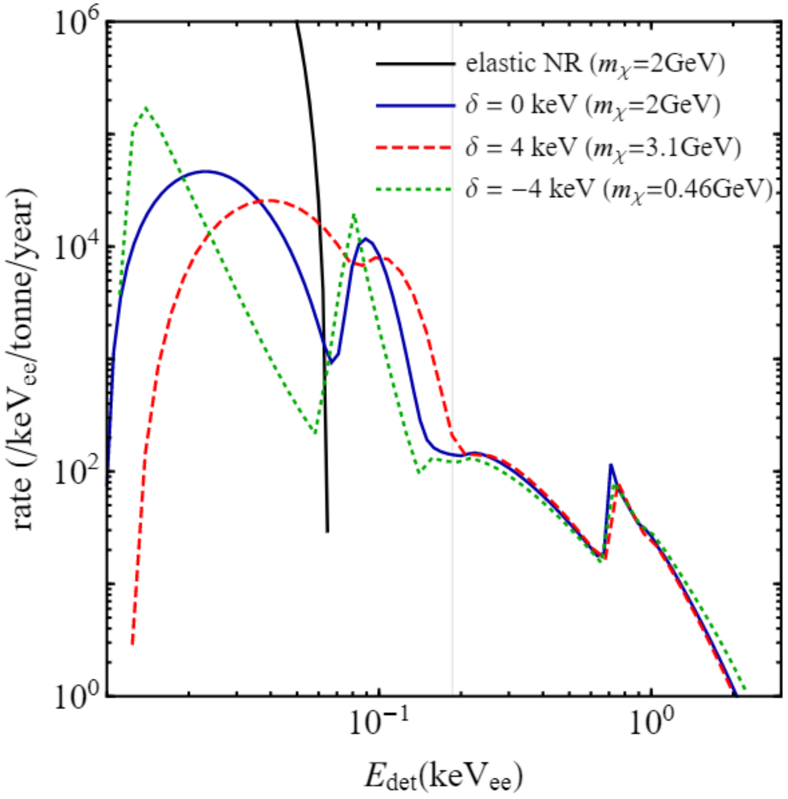
Direct detection experiments restricted to keV mass splittings, e.g., δ < 180 keV for Xenon

Bigger mass splittings accessible if DM is quasi-relativistic

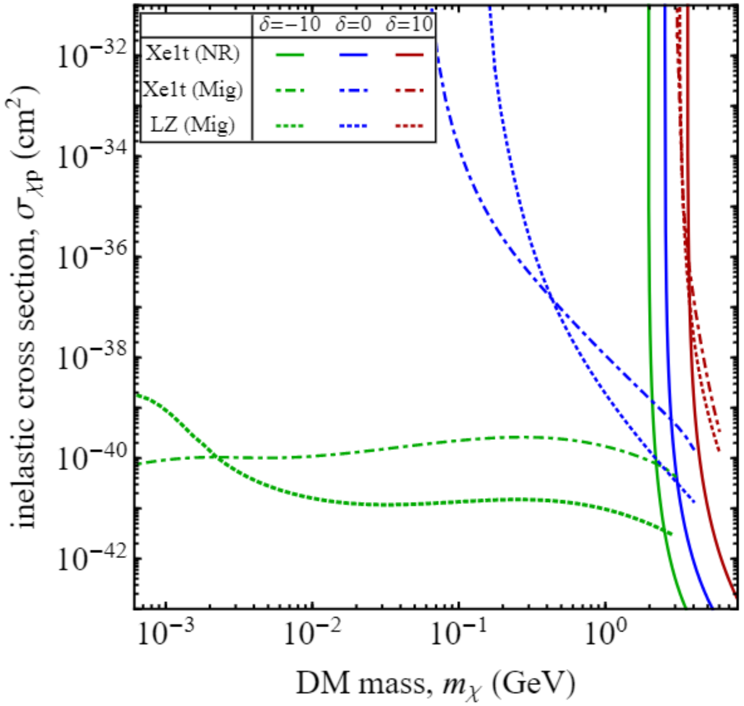
- DM scattering in neutron stars: δm ~ 300 MeV
- Boosted (e.g. Cosmic Ray upscattered) DM: δm ~100 MeV

Direct Detection of Inelastic DM via Migdal Effect

NFB, Dent, Dutta,
Ghosh, Kumar,
Newstead,
arXiv:2103.05890



Degeneracies between mass and mass splitting.



For exothermic scattering, the Migdal effect provides xenon-based detectors with sensitivity to dark matter with $\mathcal{O}$(MeV) mass, far beyond what can be obtained with nuclear scattering.

Boosted Dark Matter

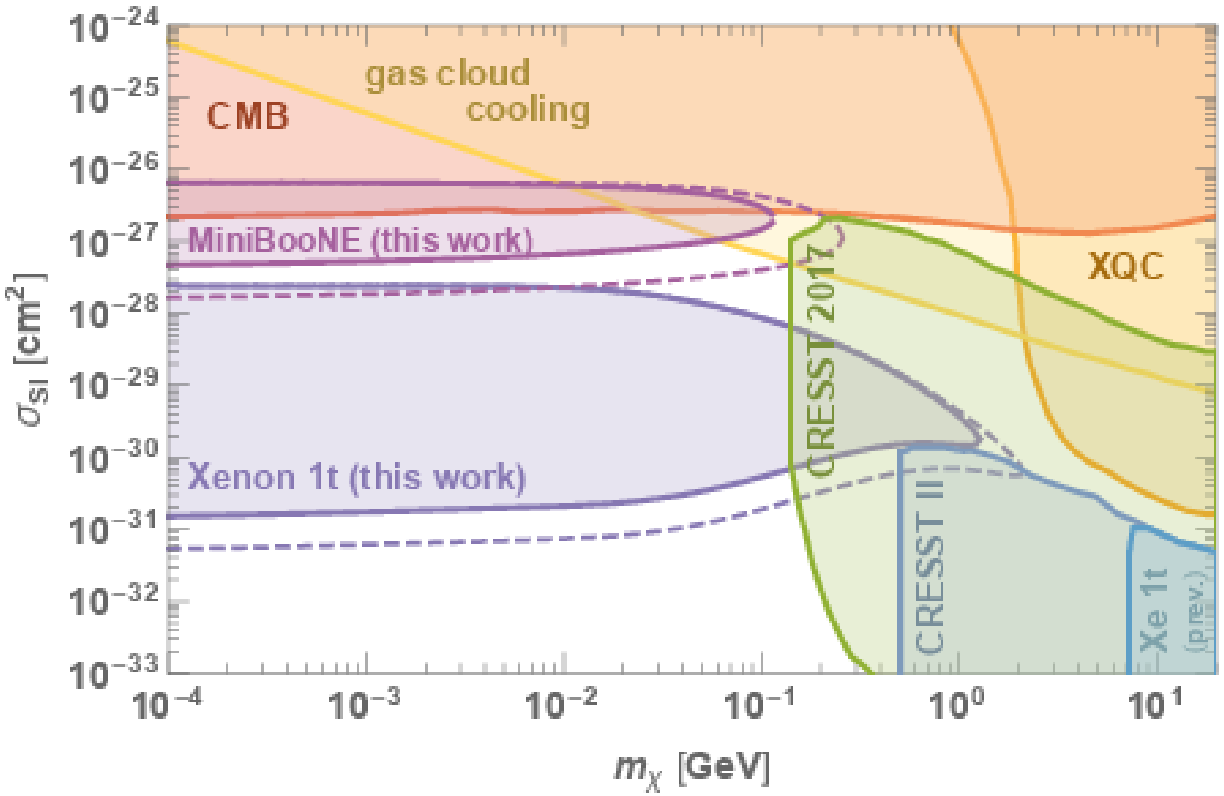
Halo dark matter
  → highly nonrelativistic
    → low energy nuclear recoils in direct detection experiments

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

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

Cosmic ray up-scattered dark mater

Bringmann & Pospelov, PRL 2019

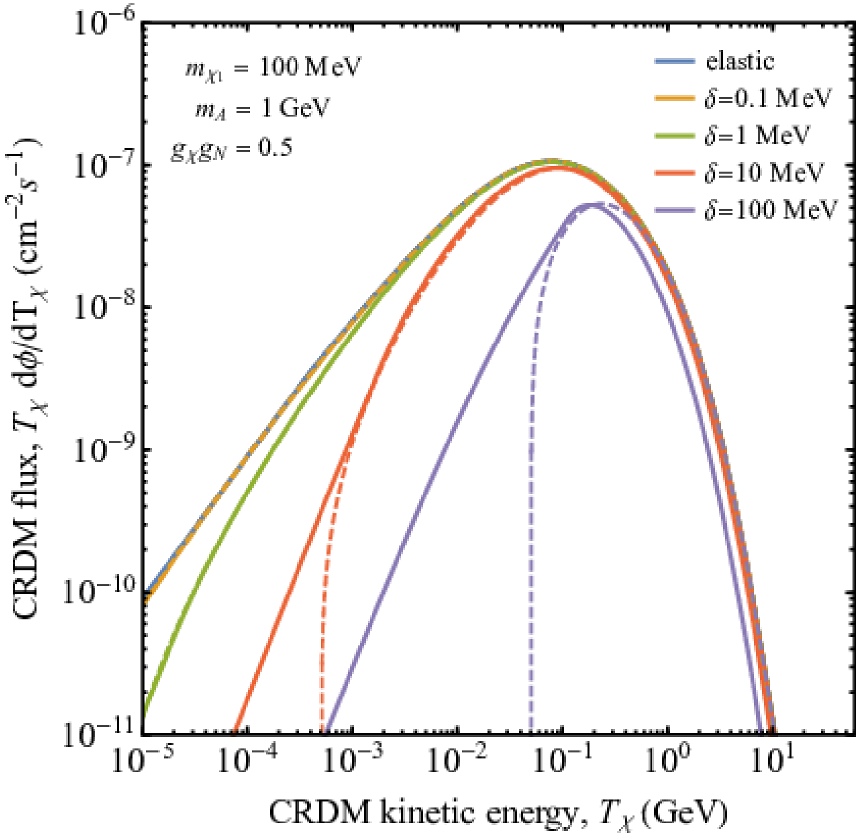


Allows light dark to be constrained using existing experiments.

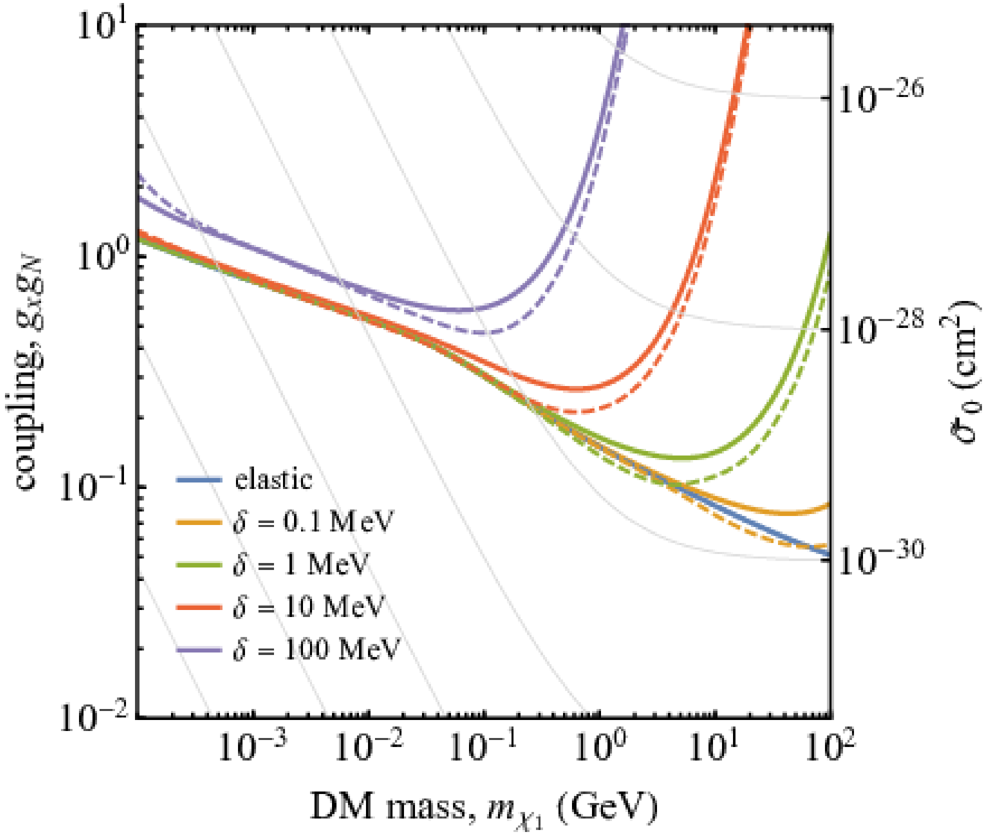
Note that dark matter absorption in the earth imposes upper limit on the cross sections that can be constrained.

Cosmic-ray Upscattered Inelastic DM

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

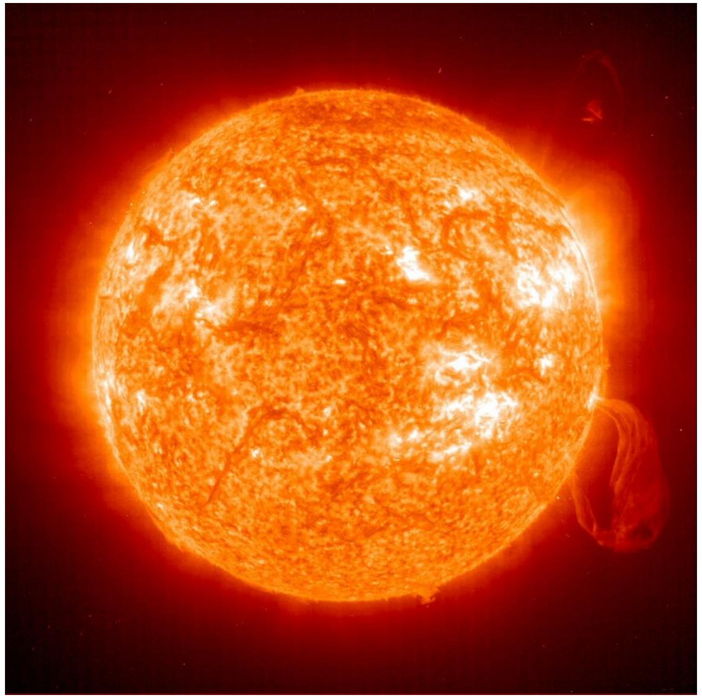


DM can be boosted to relativistic energies by scattering with cosmic rays



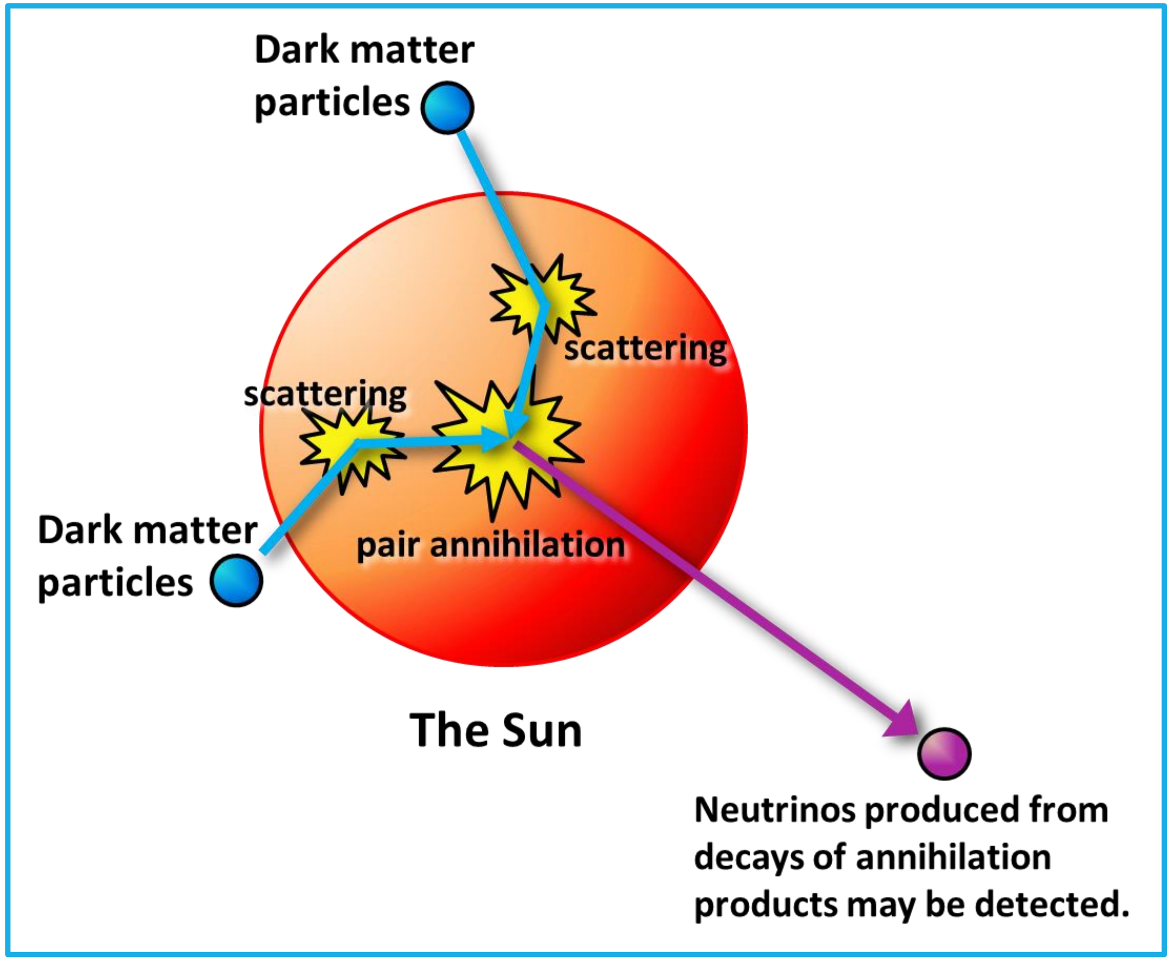
Allows (i) detection of light DM, and (ii) access to large inelastic mass splittings

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 $$\tau_{eq} = 1/\sqrt{CA}$$

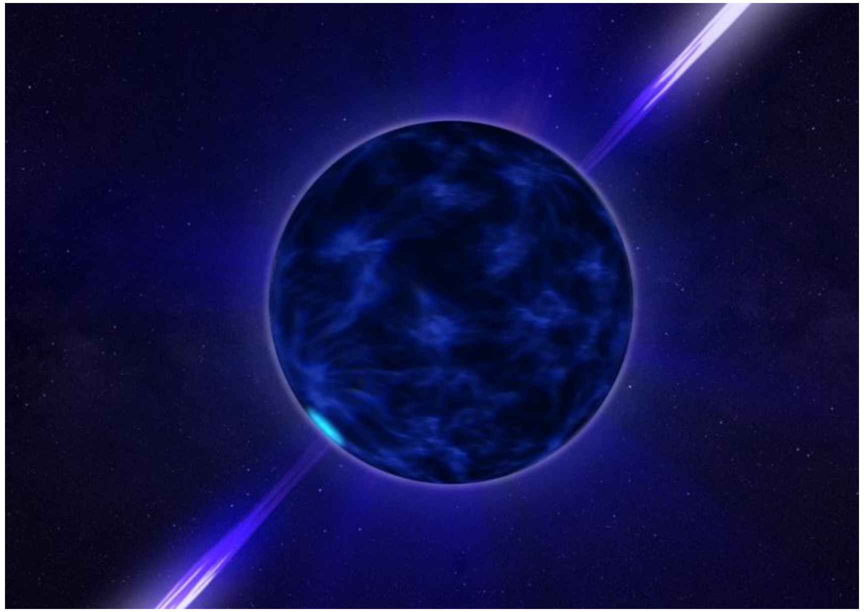
Capture-annihilation equilibrium when $t \gg \tau_{eq}$: $$\Gamma_{ann} = \frac{1}{2}AN_\chi^2 = \frac{1}{2}C$$

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**

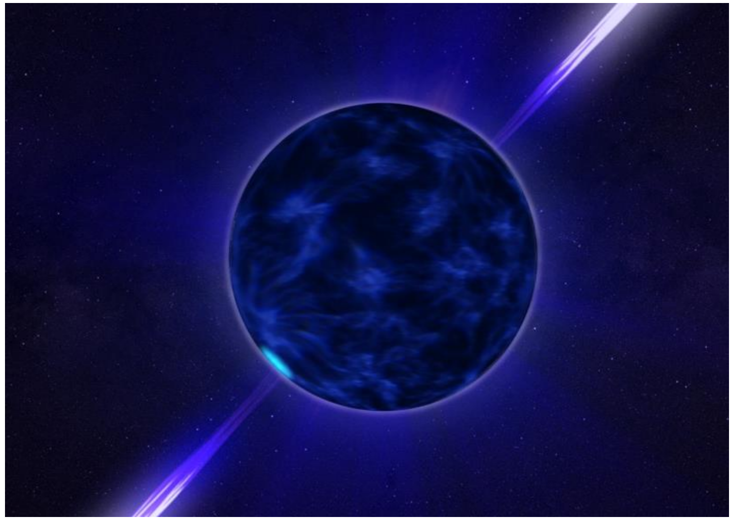
$$\sigma_{th} \sim \pi R^2 \frac{m_n}{M_*} \sim 10^{-45}\text{cm}^2$$



Heats the star to ~ 2000 K (Baryakhtar et al,PRL 2017)
- Kinetic energy transferred in capture/thermalisation
- Rest mass energy transferred if DM annihilates

Neutron Star Heating: Advantages

	Direct Detection	Neutron stars
DM velocity	Non-rel $v \ll c$	Quasi-rel. $v \sim 0.5\, c$
Cross-sections	Can be suppressed by velocity/momentum	Unsuppressed
Momentum transfer	$< \mathcal{O}(100 \text{ MeV})$	$\mathcal{O}(10 \text{ GeV})$
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**

Improved capture calculations

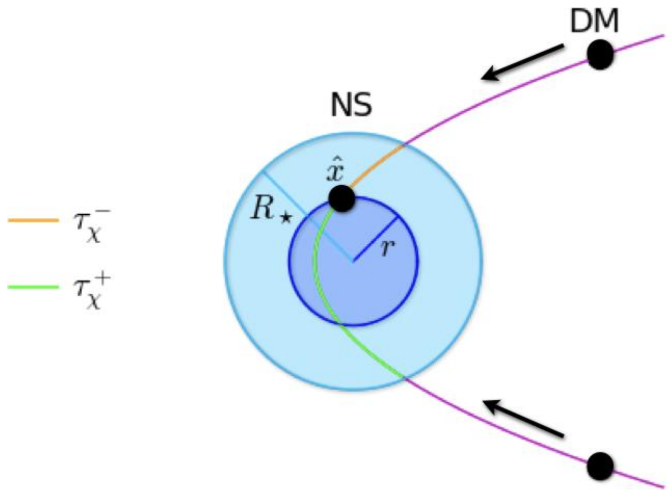
NFB, Busoni, Robles & Virgato,
JCAP 09, 028 (2020), JCAP 03, 086 (2021)

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



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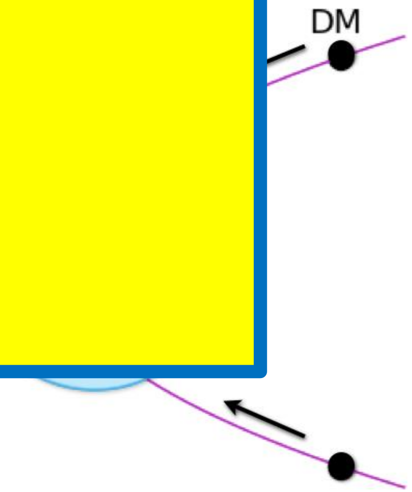
ns.

See talks from

Sandra Robles and Michael Virgato

later in the program



  - Optical depth
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- **Momentum dependence of hadronic form factors**
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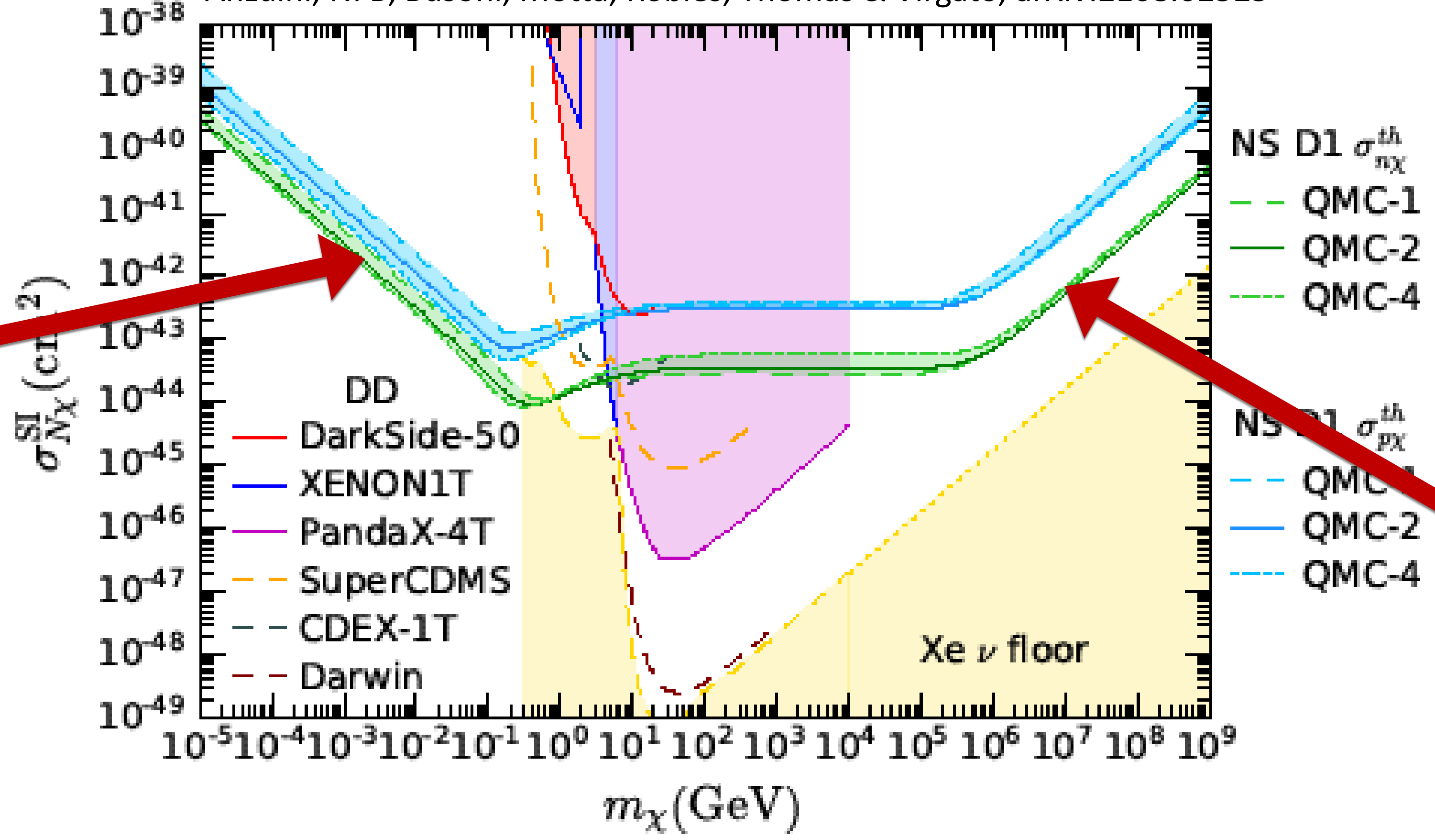
NFB, Busoni, Motta, Robles, Thomas, & Virgato, PRL 2021

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

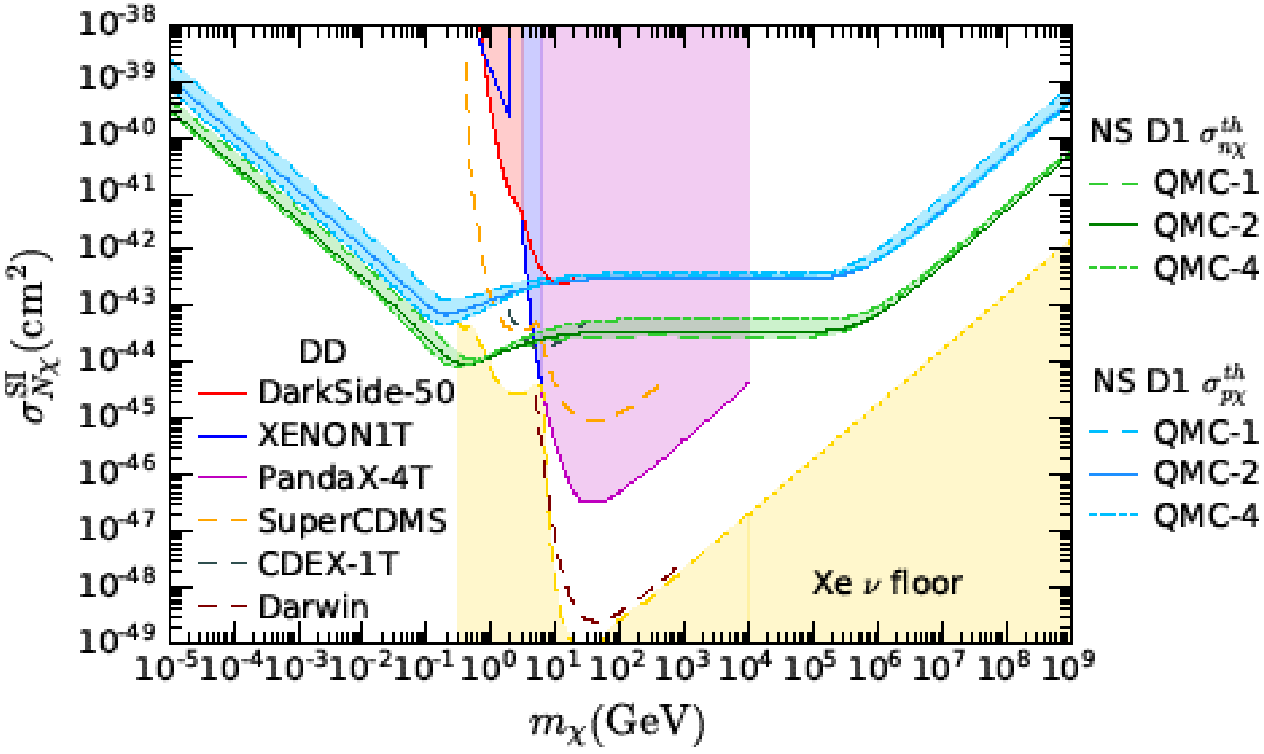
Pauli blocking from degenerate neutrons restricts scattering when $m_{DM} < 1$ GeV.

Need: momentum transfer > neutron Fermi momentum

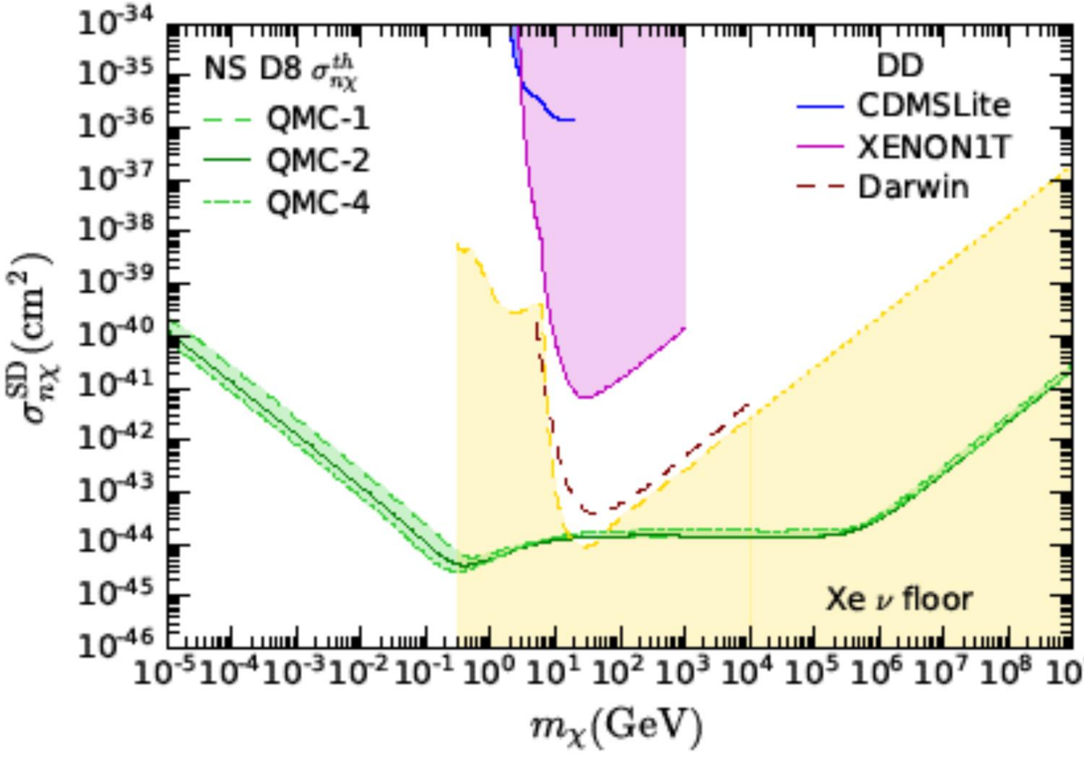
Momentum transfer in single collision not sufficient for capture when $m_{DM} > 10^6$ GeV

Kinetic Heating Sensitivity: nucleon scattering

Spin-Independent (SI)

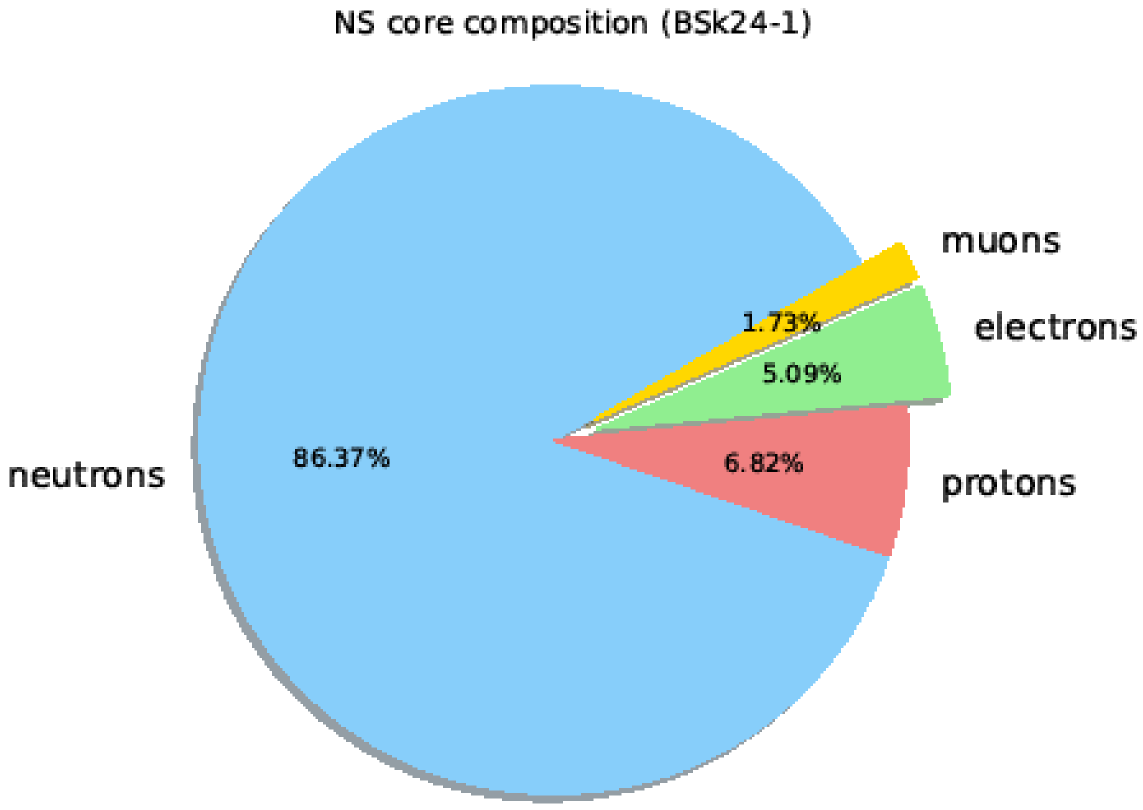


Spin-Dependent (SD)



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

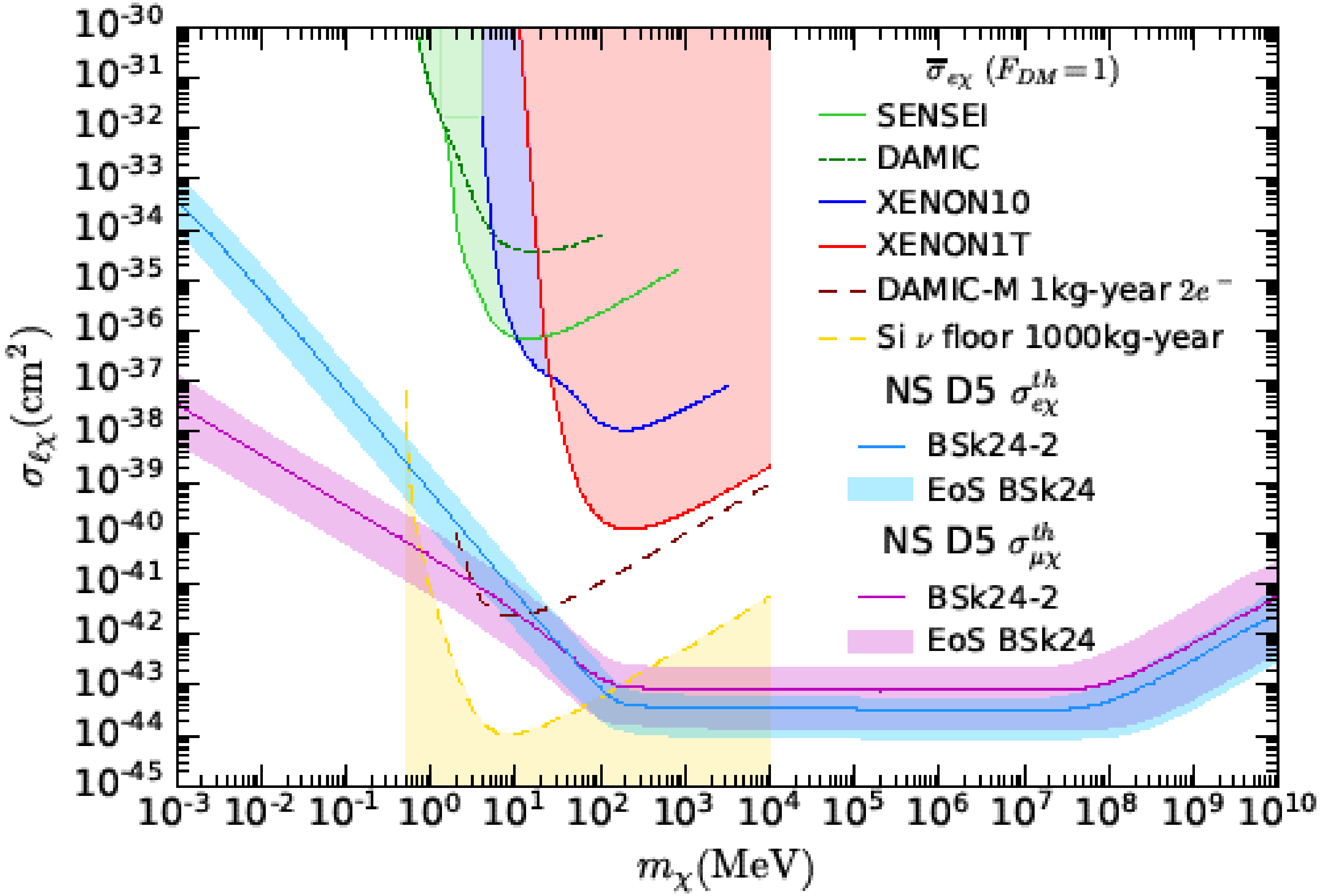
Leptons in Neutron Stars



Beta equilibrium in the core determines the composition:

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

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:

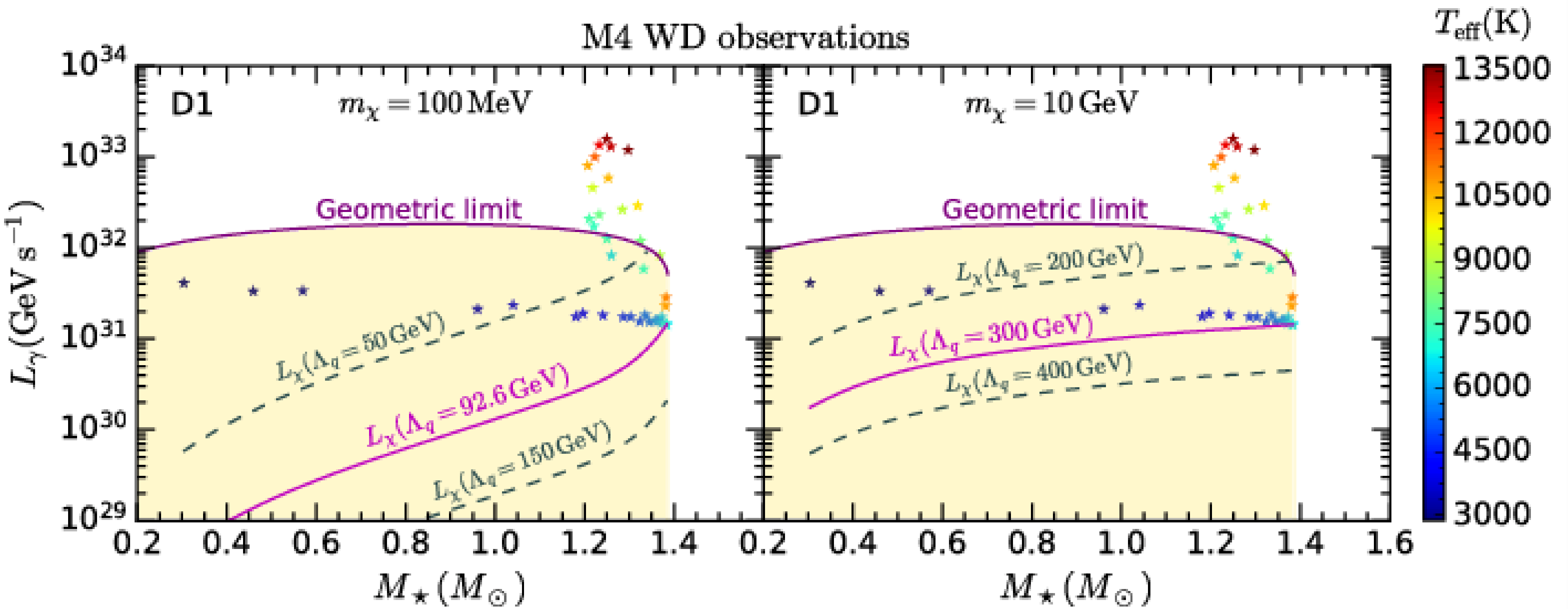
- Existence of observational data!
- Physics of WD's much better constrained than NSs
    - Well-defined mass-radius relation
    - Less uncertainty of the equation-of-state
    - Better understood luminosity-age relations

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

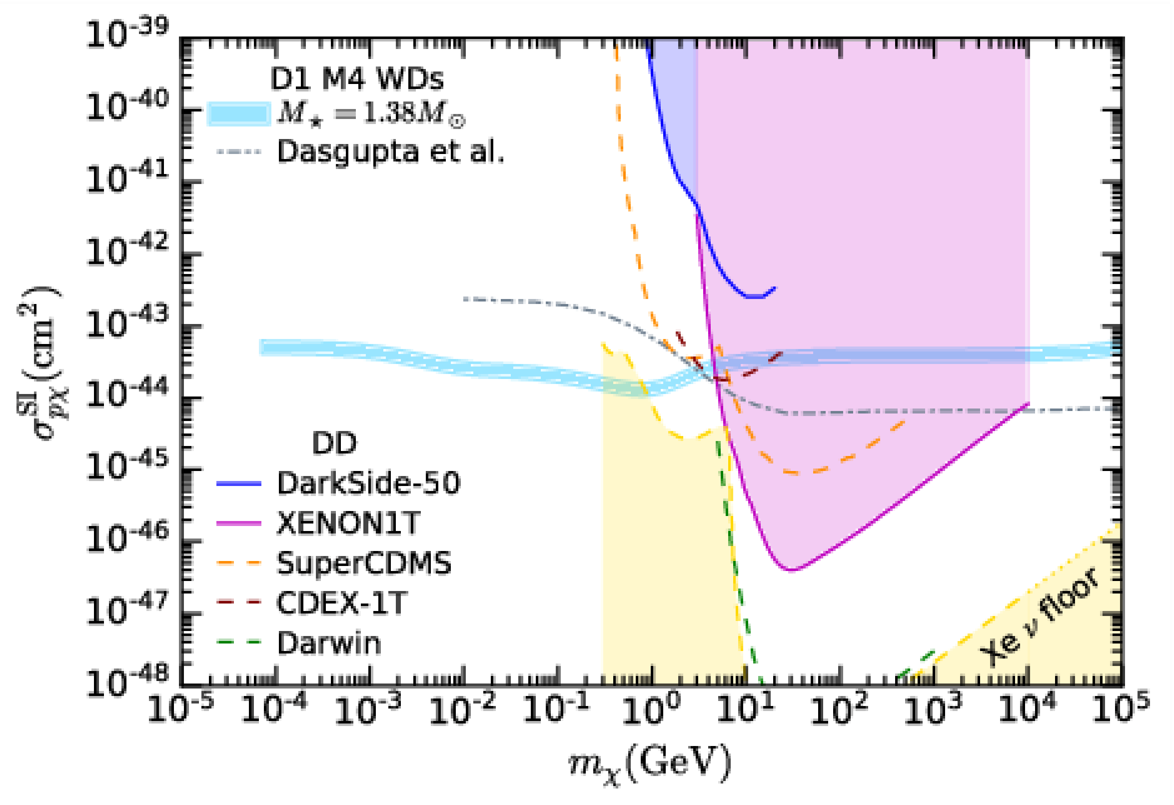
Best limits come from heavy stars (large capture rate) with low luminosity.



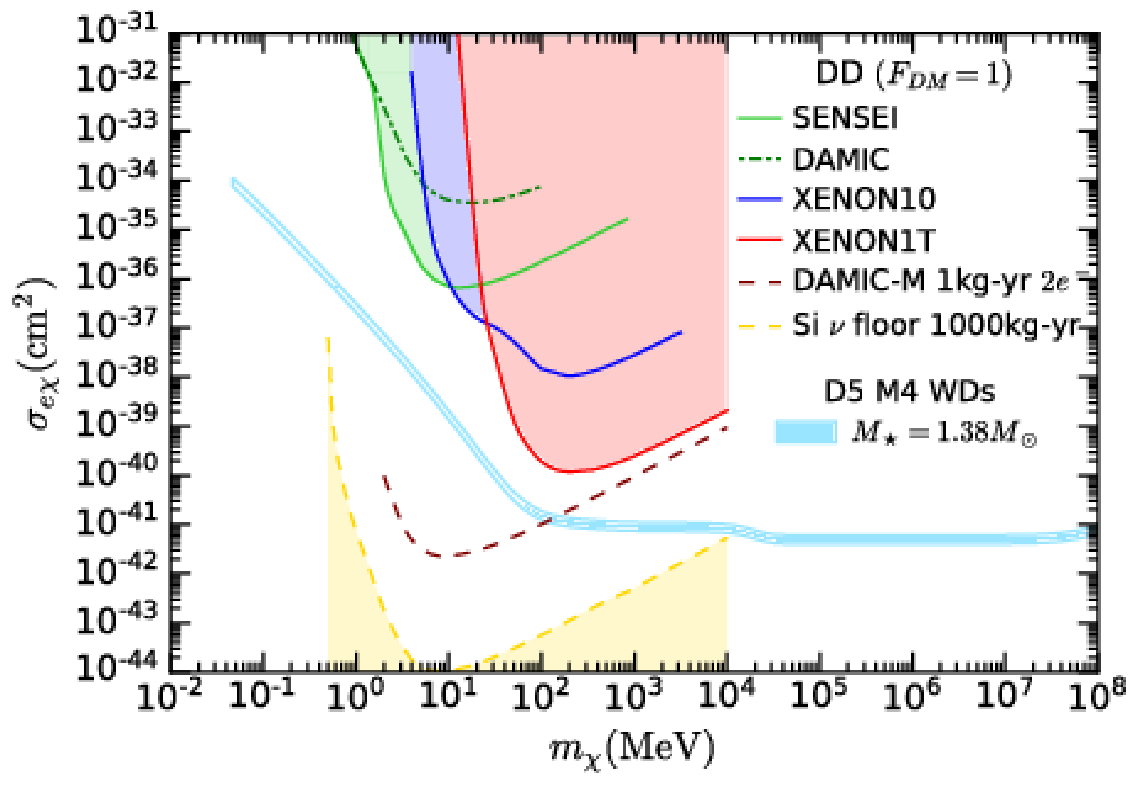
NFB, Busoni, Ramirez-Quezada, Robles & Virgato, arXiv:2104.14367

White dwarfs in M4 globular cluster

DM-nucleon scattering



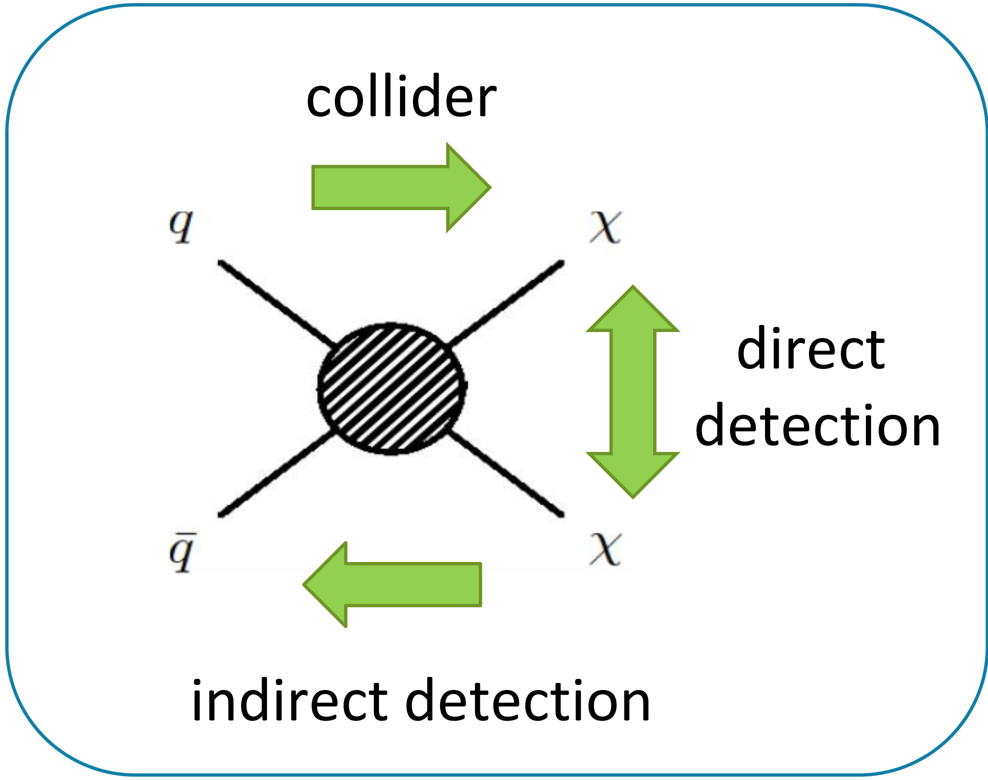
DM-electron scattering



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

WIMP parameter space

DM must annihilate efficiently in the early Universe but to have escaped detection in direct, indirect and collider searches



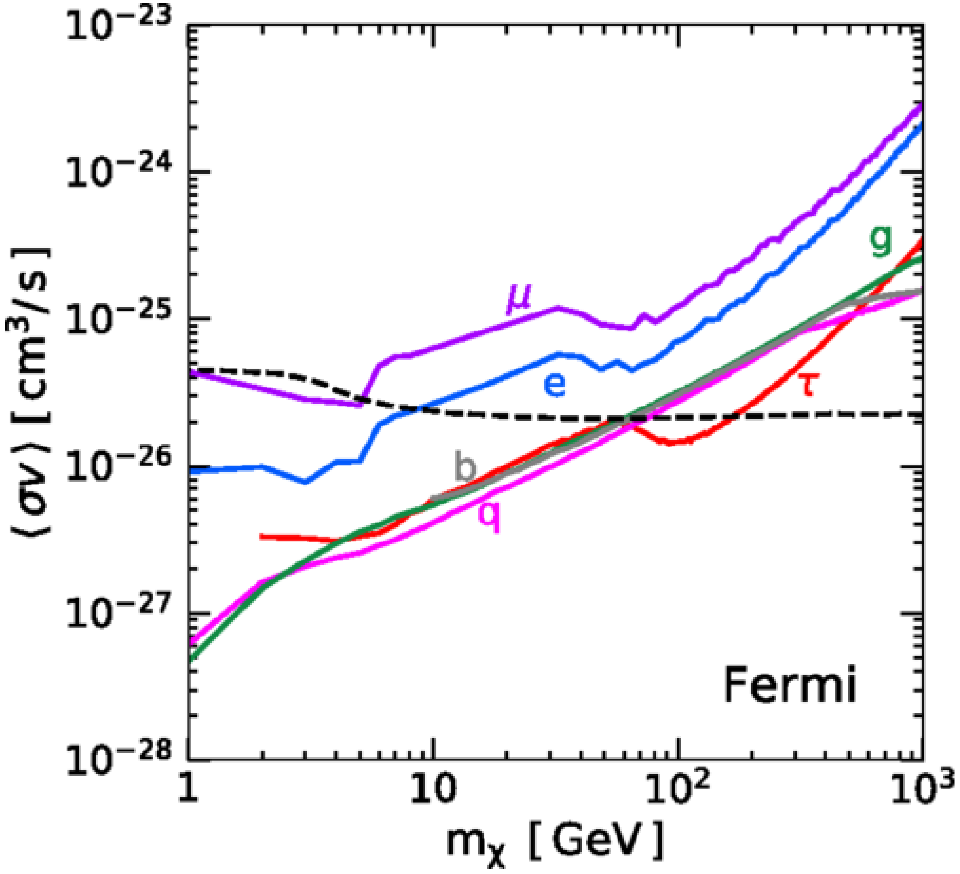
Search complementarity:

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)

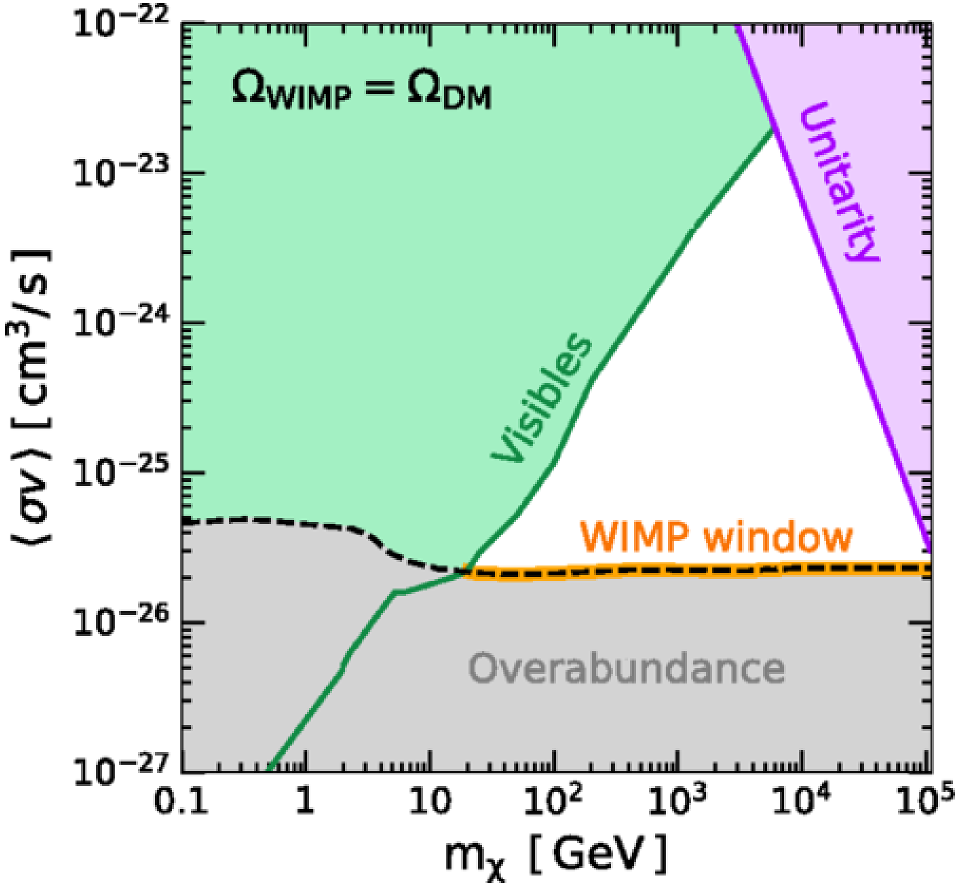
Indirect detection constraints

R. Leane, et al., arXiv:1805.10305

Fermi dSph limits

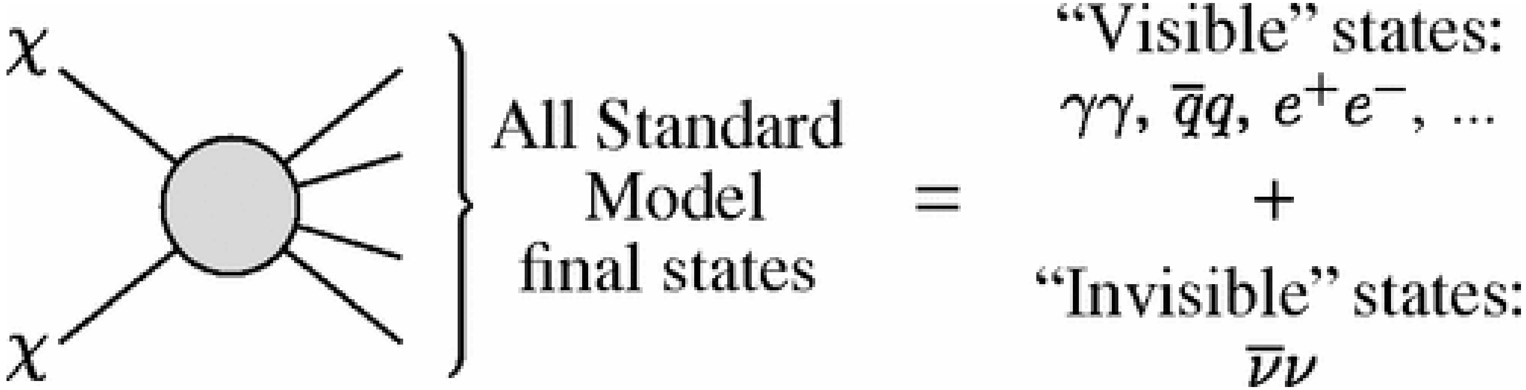


Annihilation to "visible" SM states



Annihilation to neutrinos

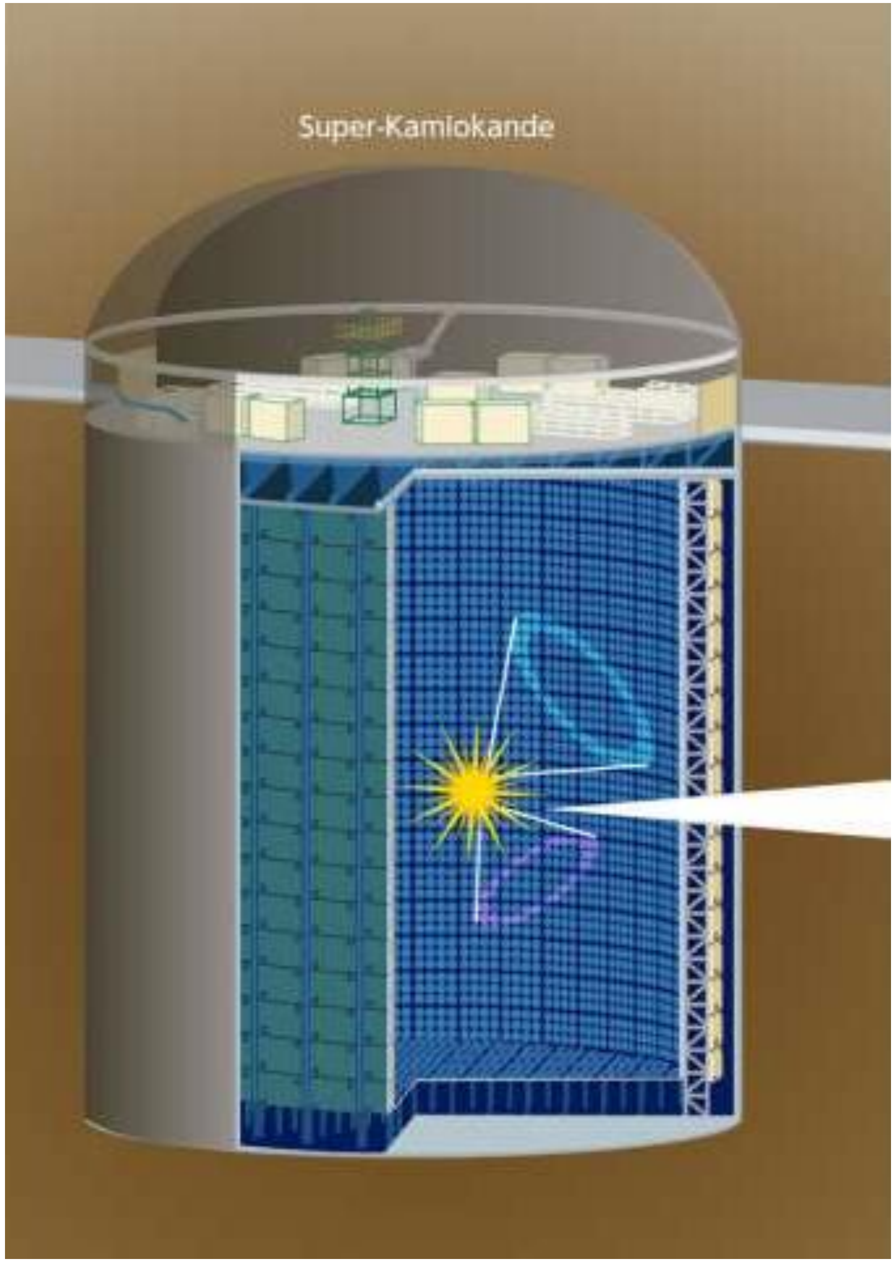
- Indirect detection limits – typically neglect the possibility that dark matter may annihilate to “invisible” or hard-to-detect final states.



- Can DM annihilate to neutrinos without producing charged fermions?
  - Yes, e.g., “neutrino portal” models
- **Annihilation to neutrinos – can we probe thermal-relic cross sections**?

Hyper-Kamiokande

- Next generation water-Cherenkov detector.
- Currently under construction
- Fiducial volume:
  - Hyper-K: 188 kT
  - Super-K: 22 kT



Hyper-K simulation

Neutrino flux from DM annihilation

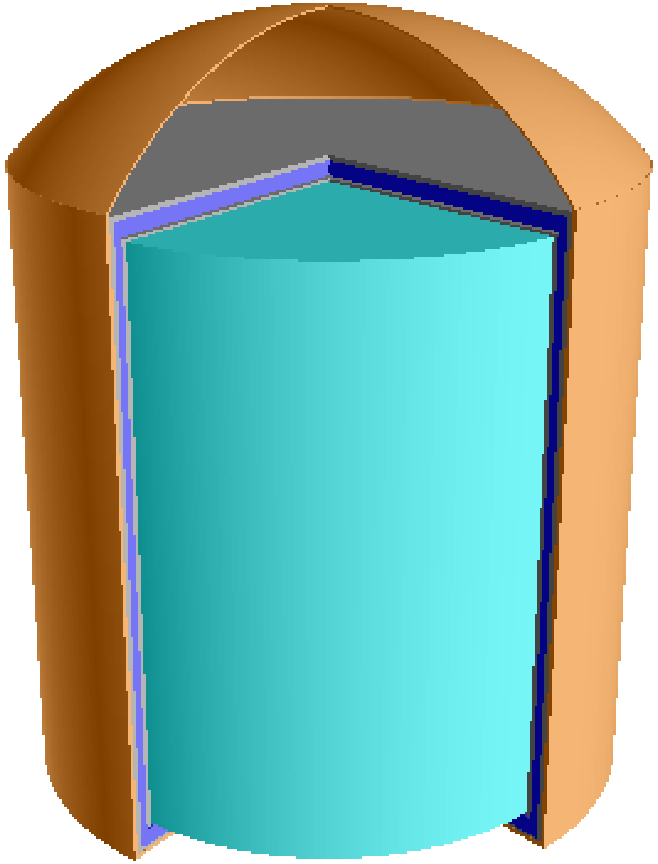
- DarkSUSY

Atmospheric neutrino background

- Honda et al – above 100 MeV
- Fluka – below 100 MeV Next generation water-Cherenkov detector.

Neutrinos cross sections

- GENIE



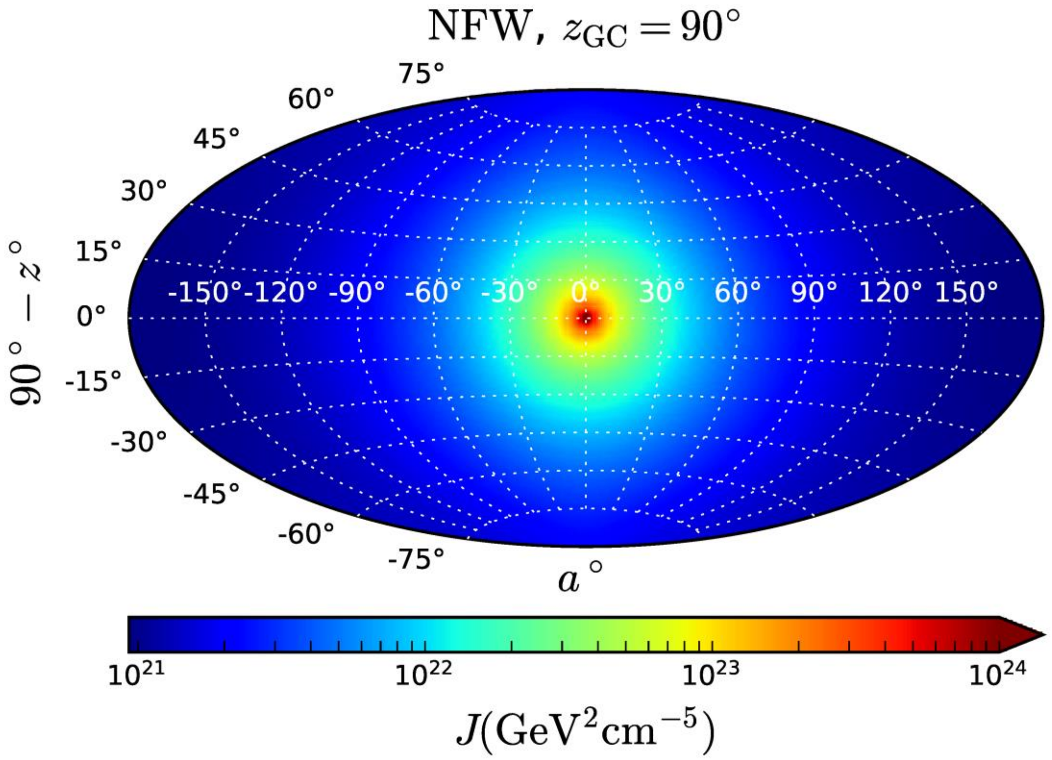
Dark matter annihilation signal

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

Annihilation cross section

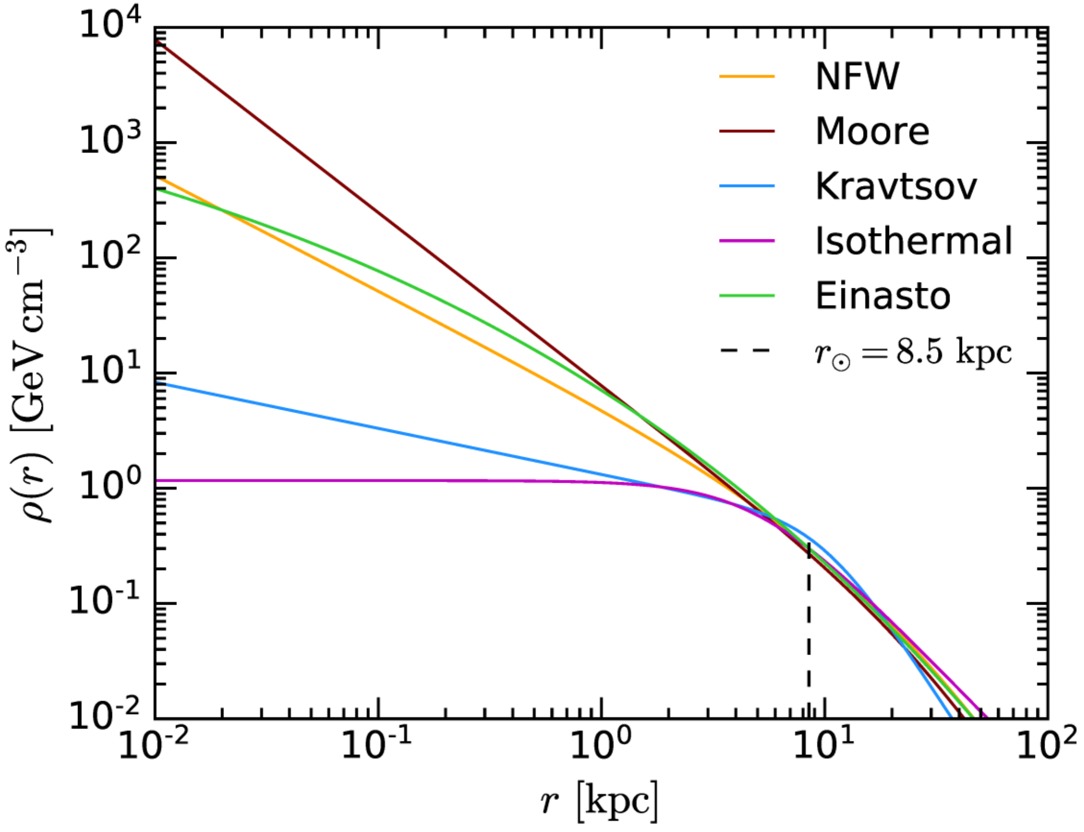
Integral of (density)^2 along line of sight

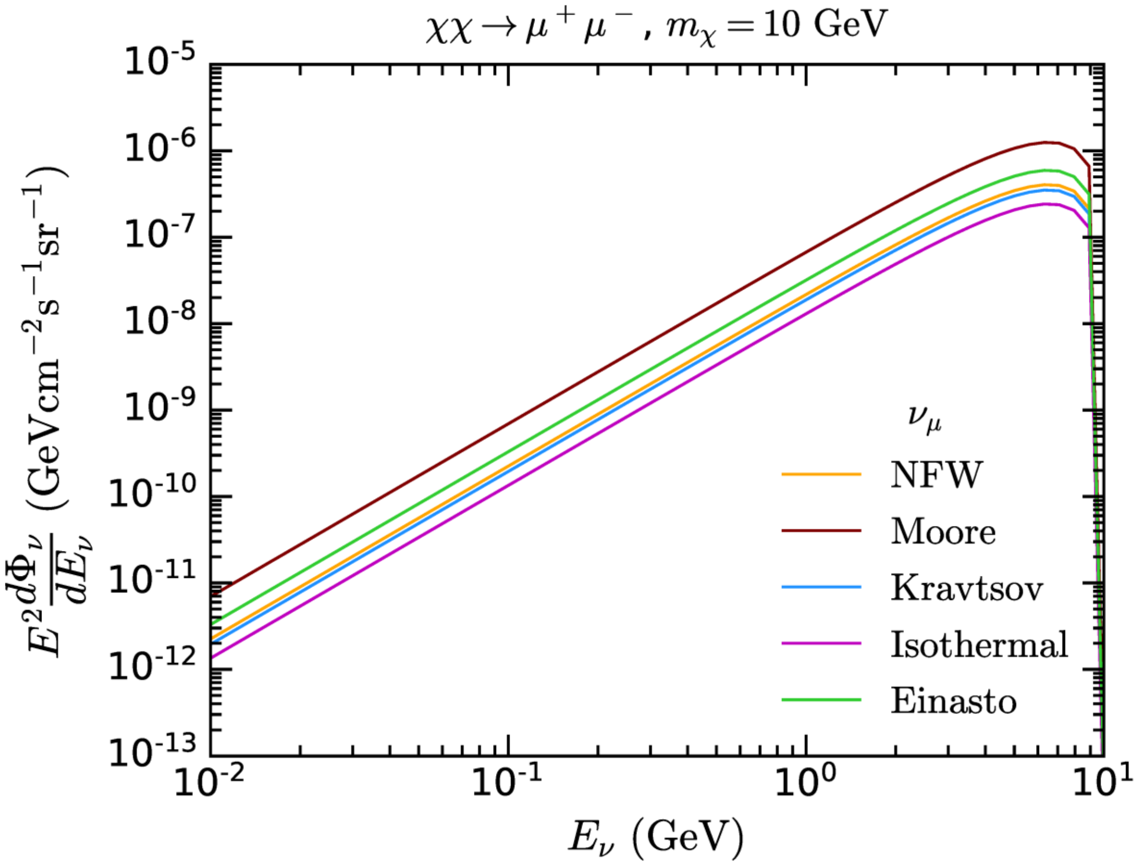
Spectrum per annihilation



NFB, Dolan, Robles, arXiv: 2005.01950

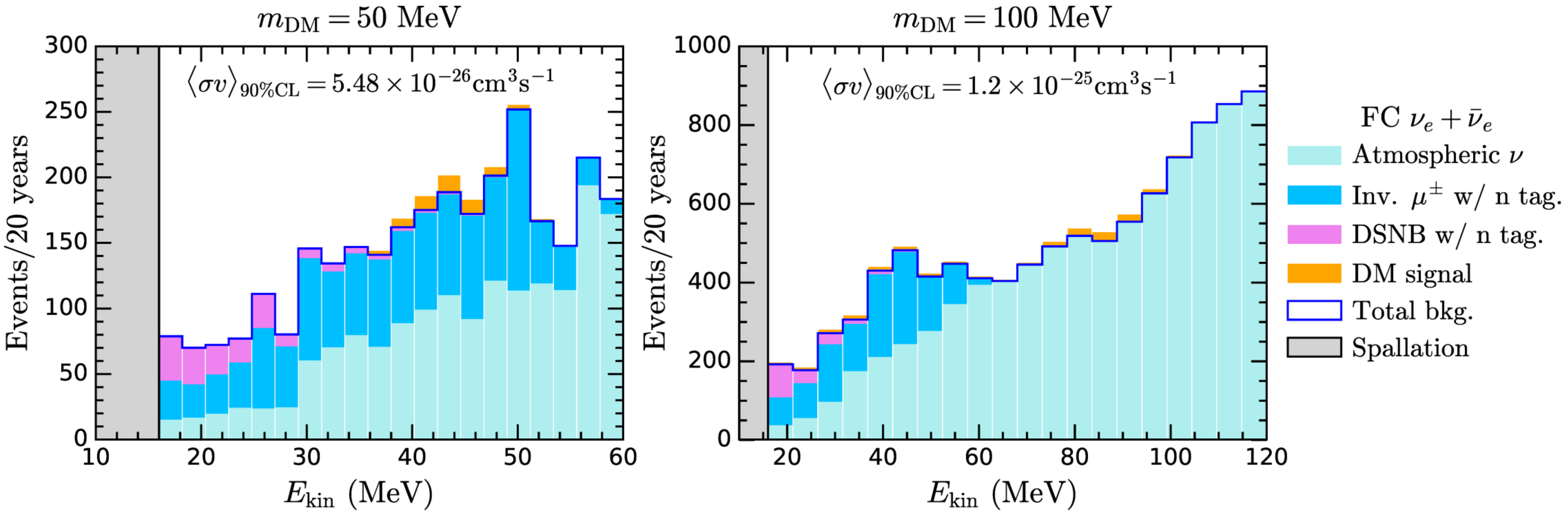
Dependence on halo profile is mild, as we undertake an all-sky analysis





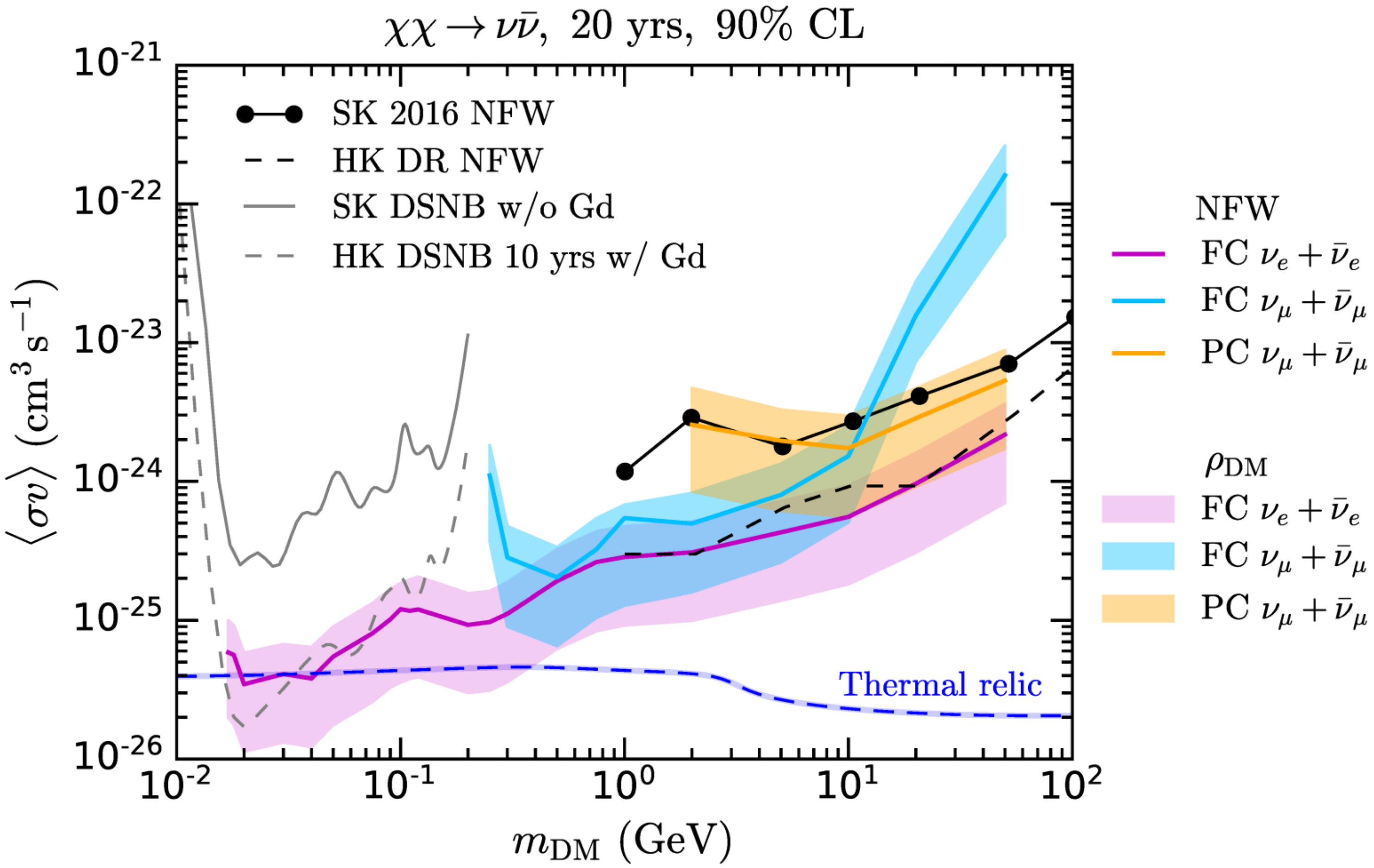
NFB, Dolan, Robles, arXiv: 2005.01950

Dark matter annihilation signal + background



NFB, Dolan, Robles, arXiv: 2005.01950

Cross section limits: $\chi\chi \rightarrow \boldsymbol{\nu\bar{\nu}}$

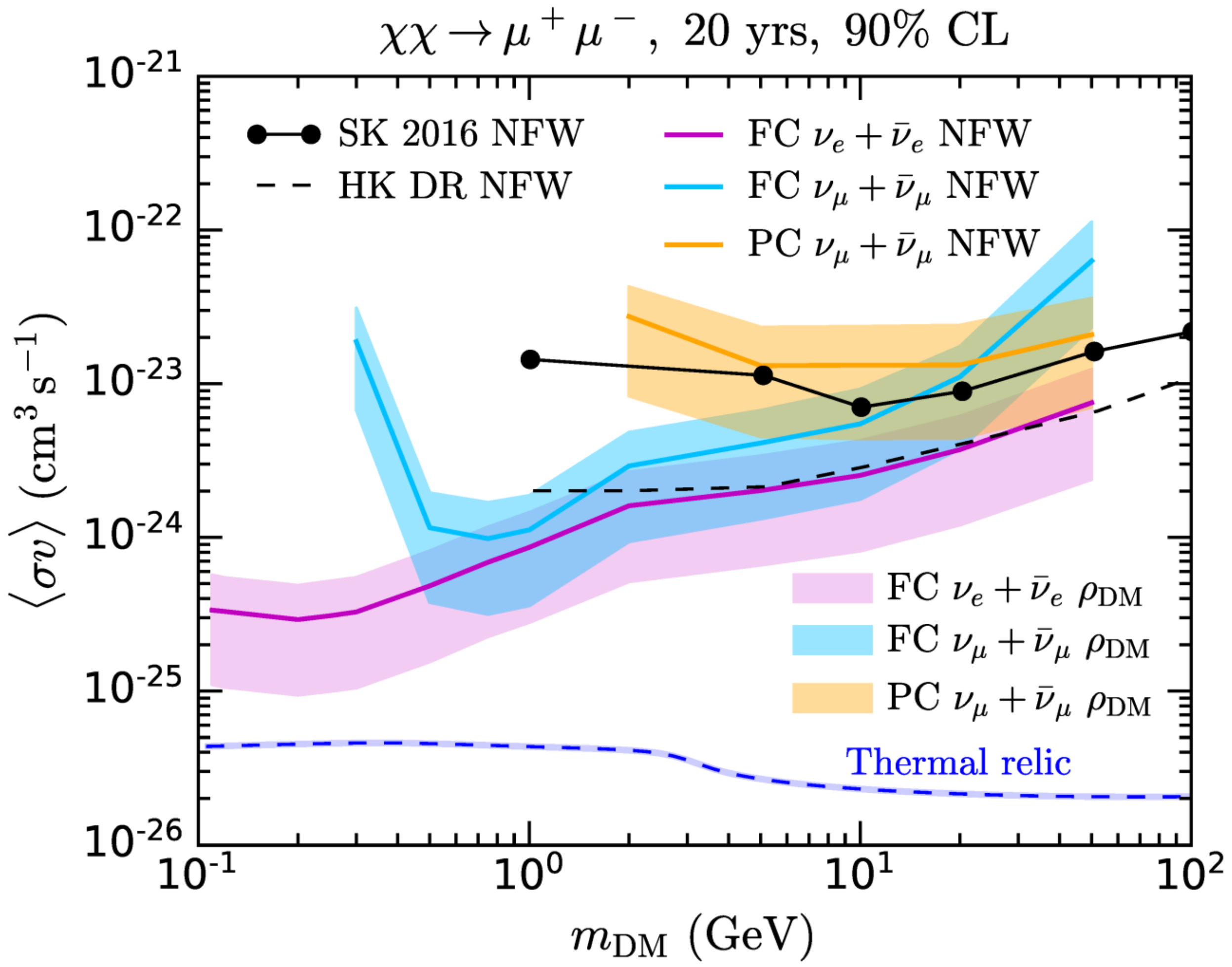


Thermal relic sensitivity for DM mass of ~ 30 MeV

NFW – central lines
Isothermal – upper
Moore - lower

NFB, Dolan, Robles, arXiv: 2005.01950

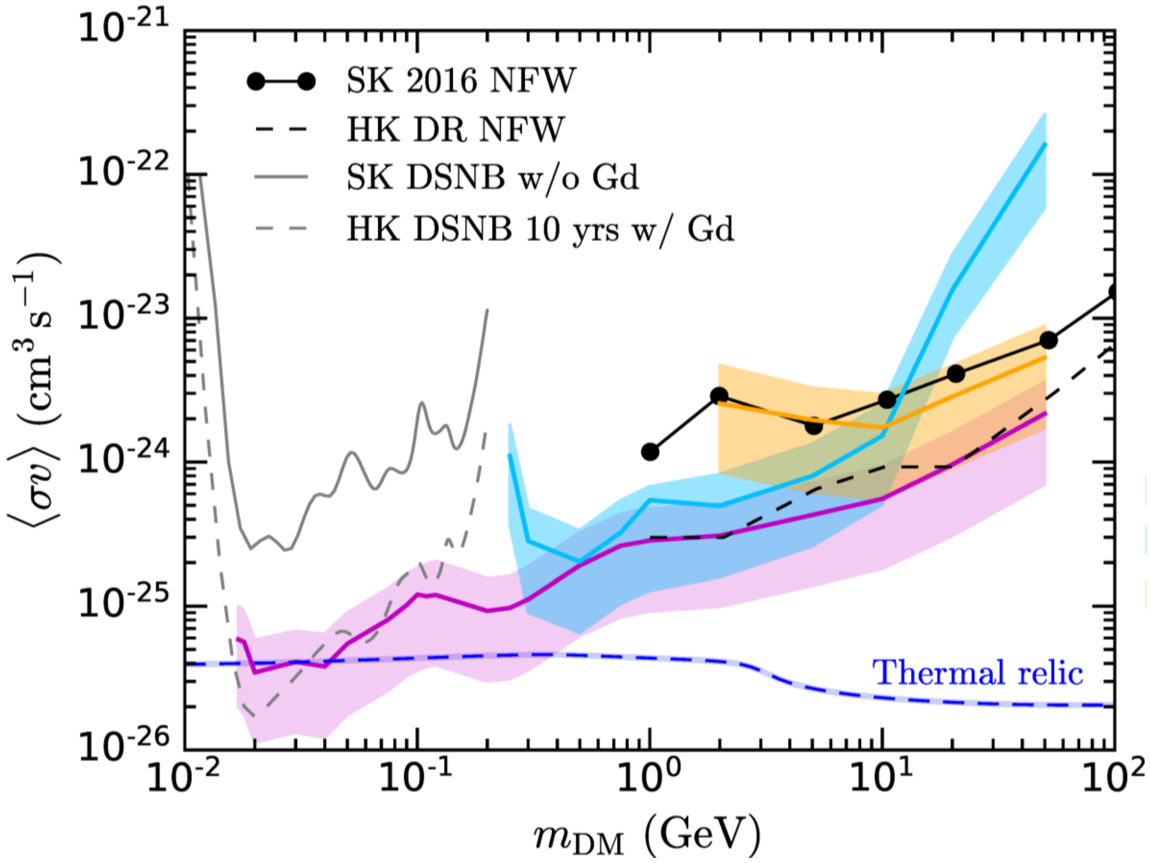
Cross section limits: $\chi\chi \rightarrow \mu^+\mu^-$



NFB, Dolan, Robles, arXiv: 2005.01950

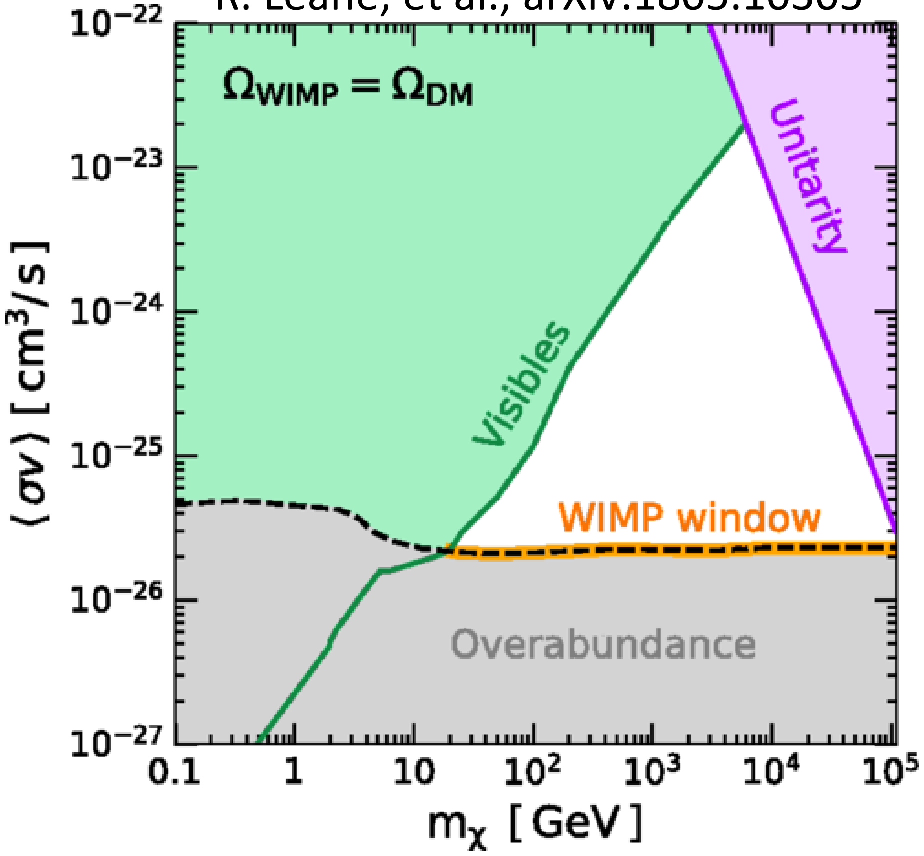
Conservative indirect detection limits

Annihilation to "invisible" SM states

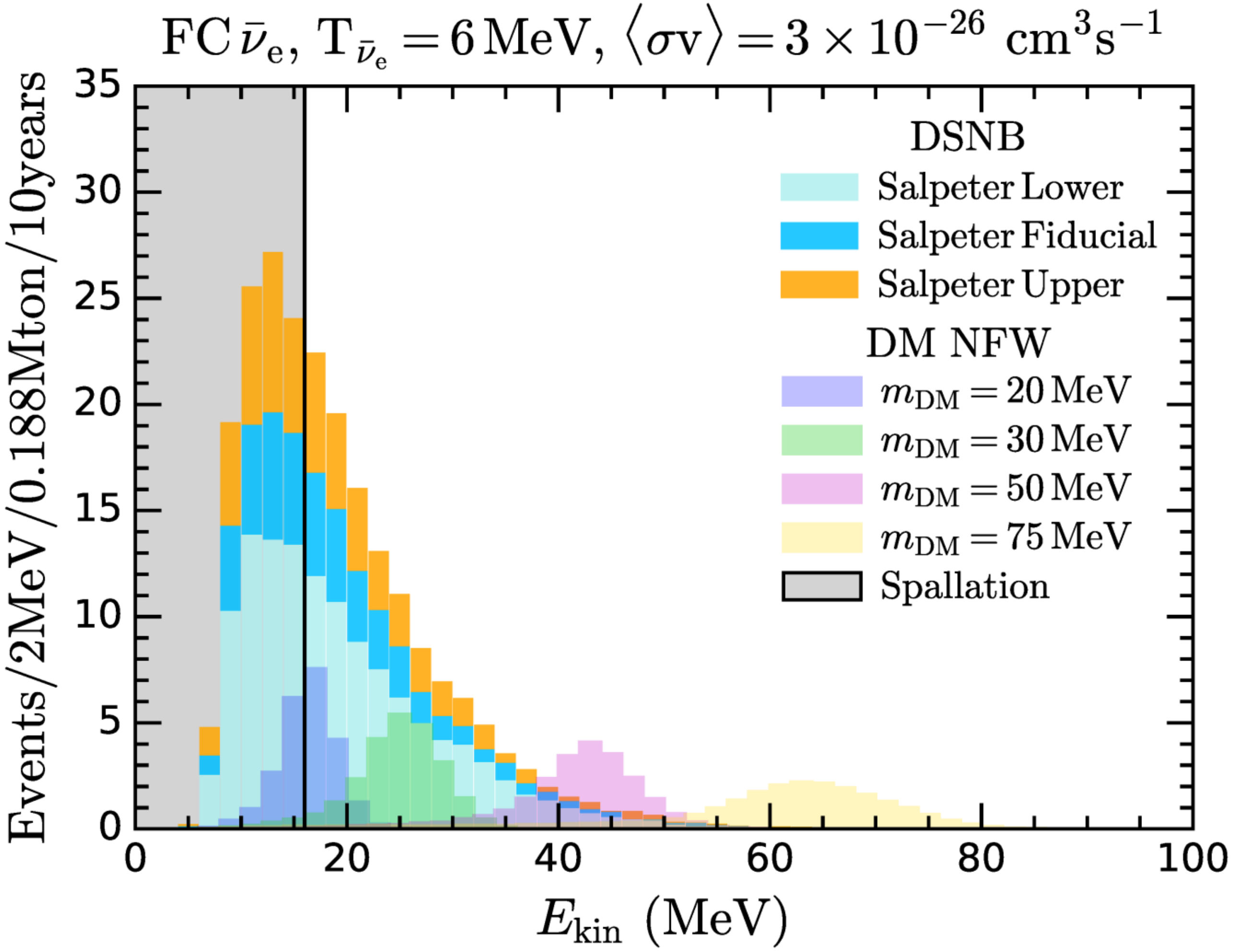


Annihilation to "visible" SM states

R. Leane, et al., arXiv:1805.10305



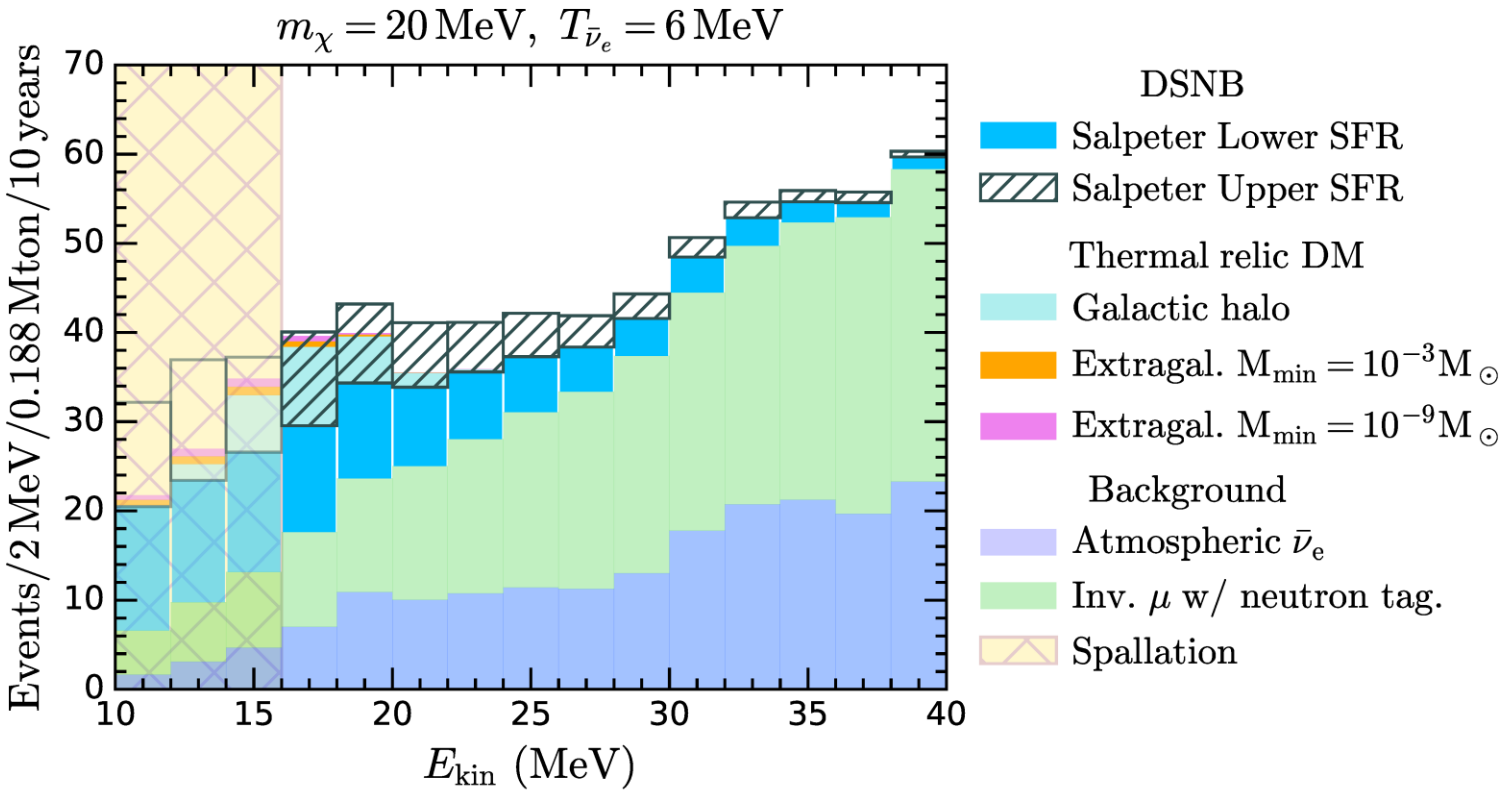
DM signal + DSNB (diffuse supernova neutrino background)



A dark matter light DM annihilation signal impairs the ability to do DSNB model discrimination

NFB, Dolan, Robles, arXiv: 2205.14123

DSNB + DM + atmospheric nu background



A possible DM signal makes DSNB model discrimination difficult:

High SFR looks like **Low-SFR + DM**

Angular information can help separate the two signals

NFB, Dolan, Robles, arXiv: 2205.14123

Summary

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

- New approaches:
    - New techniques, or new analyses using existing detectors, such as Migdal.

- Alternative approach: dark matter capture in stars:
    - heating of neutrons stars/white dwarfs – limits extend to low mass DM.

- Complementary information from indirect detection

Backup slides

Cooling and Heating

In the standard NS cooling scenario, nucleons and charged leptons in beta equilibrium

$$C\,\frac{dT^\infty}{dt} = -\boldsymbol{L}_{\boldsymbol{\nu}}^{\infty} - \boldsymbol{L}_{\boldsymbol{\gamma}}^{\infty} + \boldsymbol{L}_{\boldsymbol{DM}}^{\infty} + \boldsymbol{L}_{\text{other heating}}^{\infty}$$

= cooling by ν and γ emission + heating due to dark matter

- Early cooling is dominated by neutrino emission
- Photon emission dominates at late times

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

Astrophys.J. 874 (2019) no.2, 175

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

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)

1. Momentum dependence of hadronic matrix elements:

- *Nuclear recoil experiments* – calculated in zero momentum transfer limit
- *Neutron star scattering* – momentum transfer ~ 10 GeV → couplings suppressed

2. Nucleon Interactions:

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

Changes the answers by up to 3 orders of magnitude!