Capture, Thermalization & Annihilation of Dark Matter in Neutron Stars

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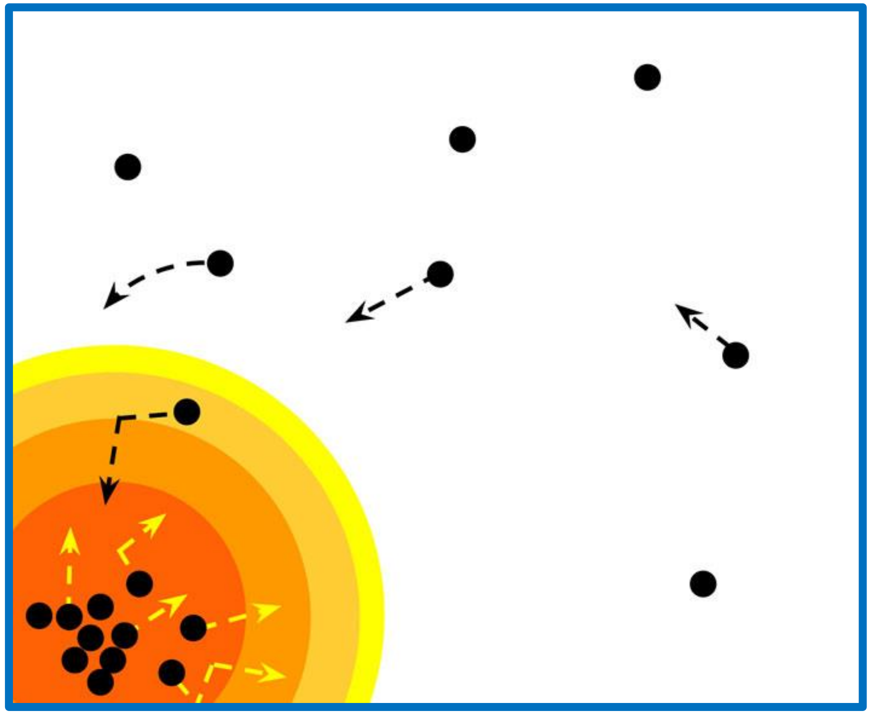
ARC CENTRE OF EXCELLENCE FOR DARK MATTER PARTICLE PHYSICS

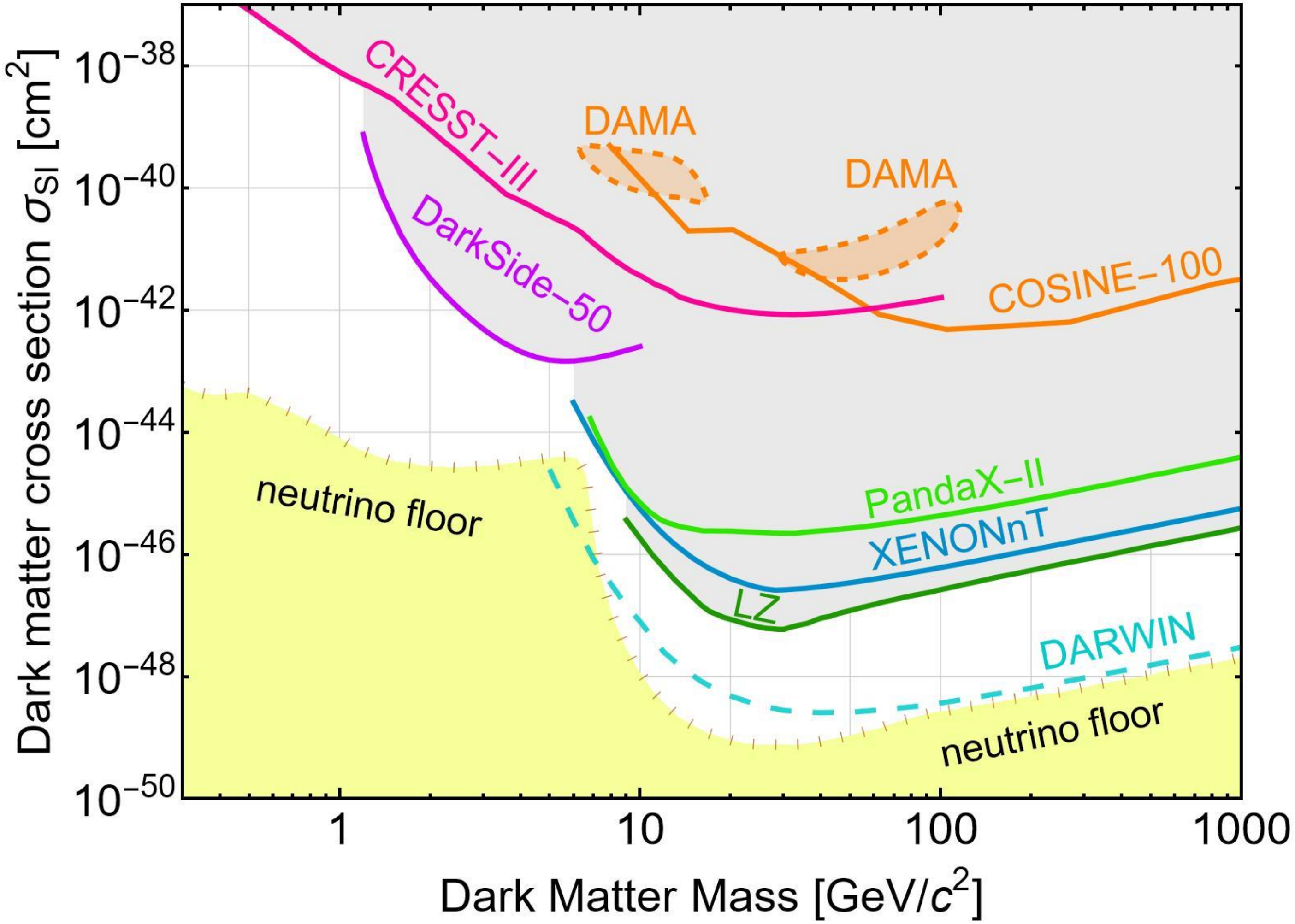
Dark Matter Capture in Stars

→ an alternative approach to Dark Matter Direct Detection experiments

- The Sun
- **Neutron Stars**
- White Dwarfs



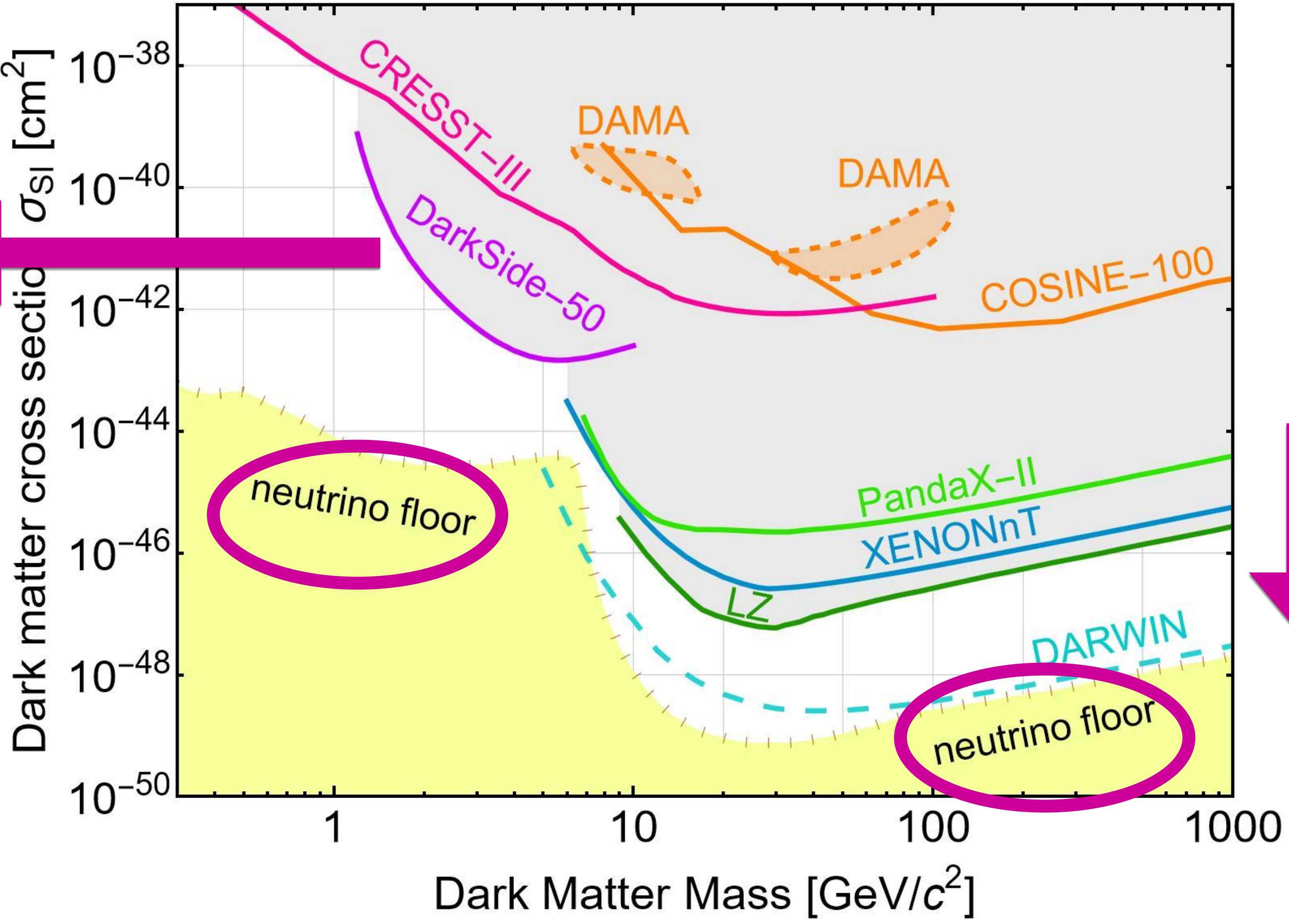
Dark Matter Direct Detection



Dark matter – nucleon-recoil experiments

Direct Detection Frontiers

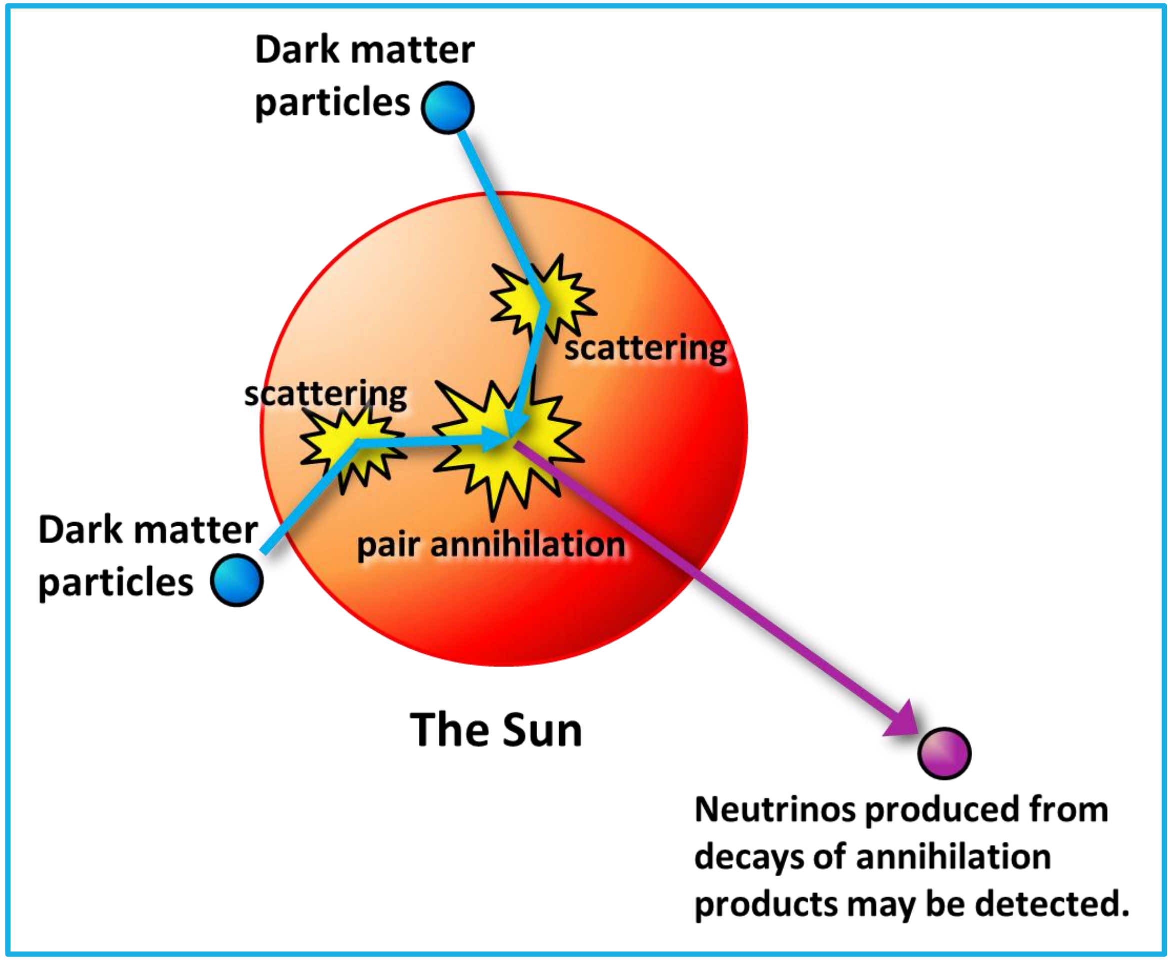
Lower energy thresholds



Larger detectors;
Lower backgrounds

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 $\sigma^{\text{scattering}}_{\text{darkmatter}-\text{nucleon}}$

→ probes the same quantity as nucleon-recoil dark matter experiments

Capture, annihilation, evaporation

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

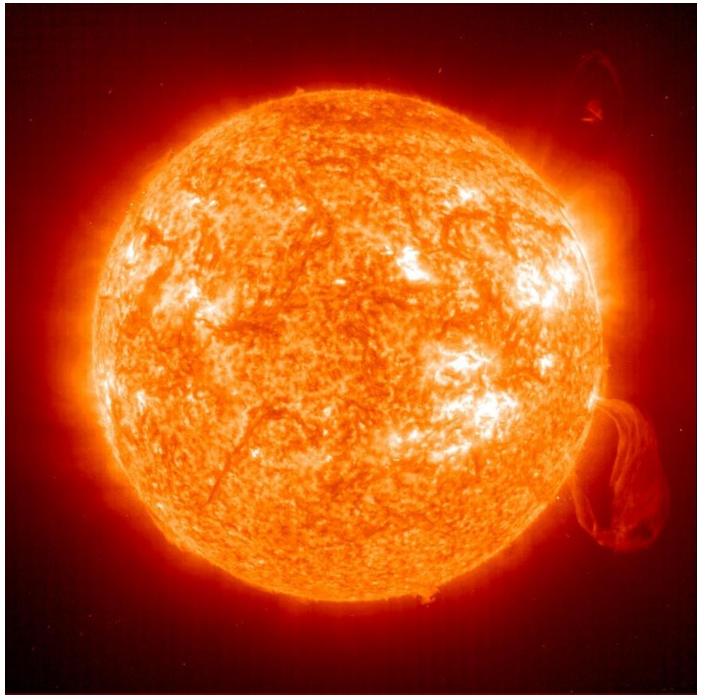
$$\frac{dN_\chi}{dt} = C - AN_\chi^2 - EN_\chi$$

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

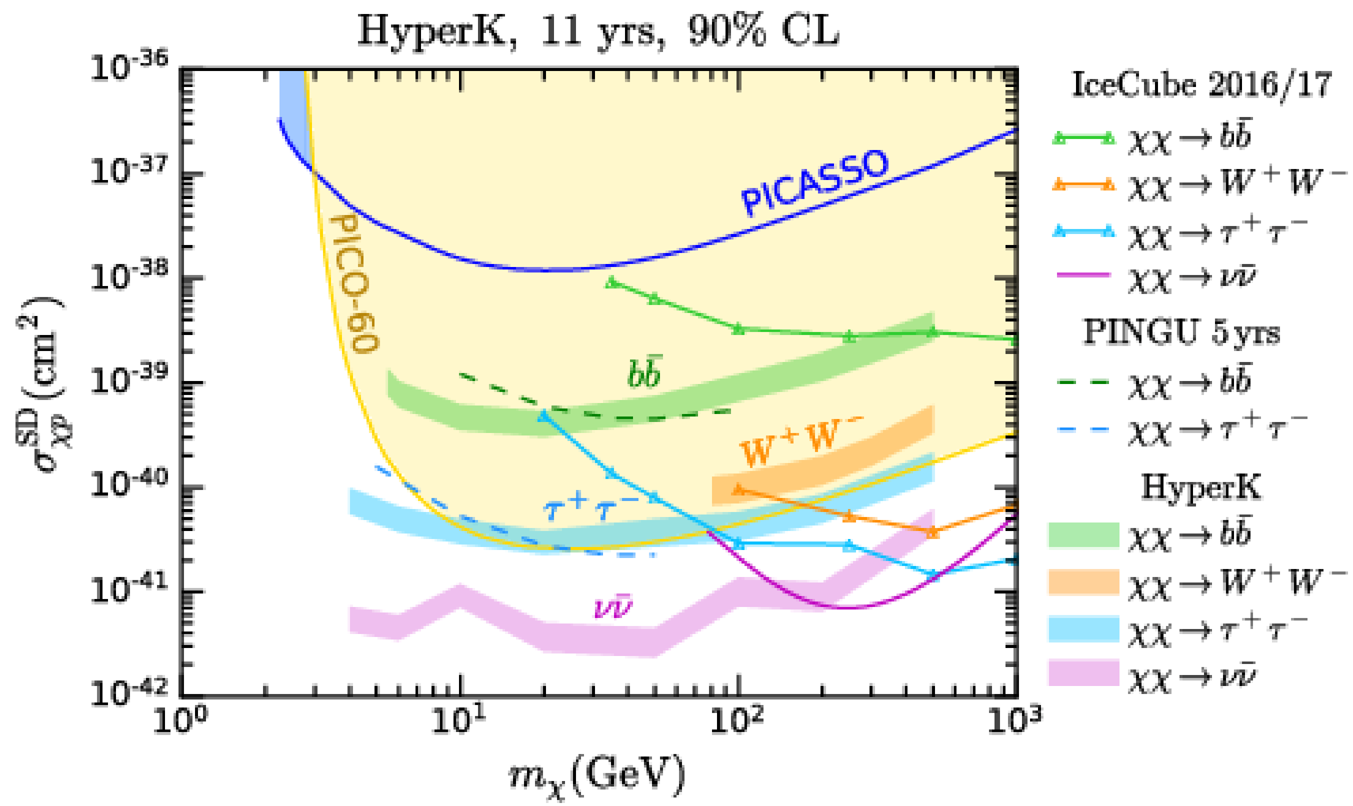
Capture-annihilation equilibrium when $t \gg \tau_{eq}$: $$\Gamma_{ann} = \frac{1}{2} AN_\chi^2 = \frac{1}{2} C$$

Dark matter capture in the Sun



Annihilation of DM captured in the Sun to Neutrinos

Spin-Dependent (SD)

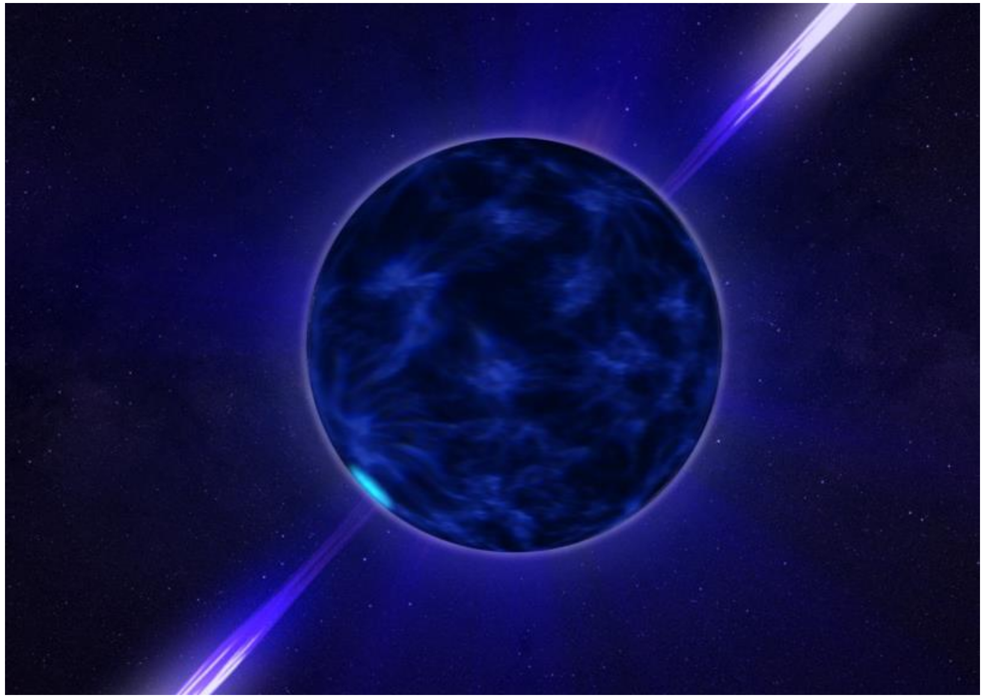


NFB, Dolan & Robles, JCAP 11, 004 (2021)

Spin-dependent (SD) interactions:
- solar DM searches competitive or better than direct detection experiments

Spin-independent (SI) interactions:
- direct detection experiments win.

Dark Matter Capture in Neutron Stars

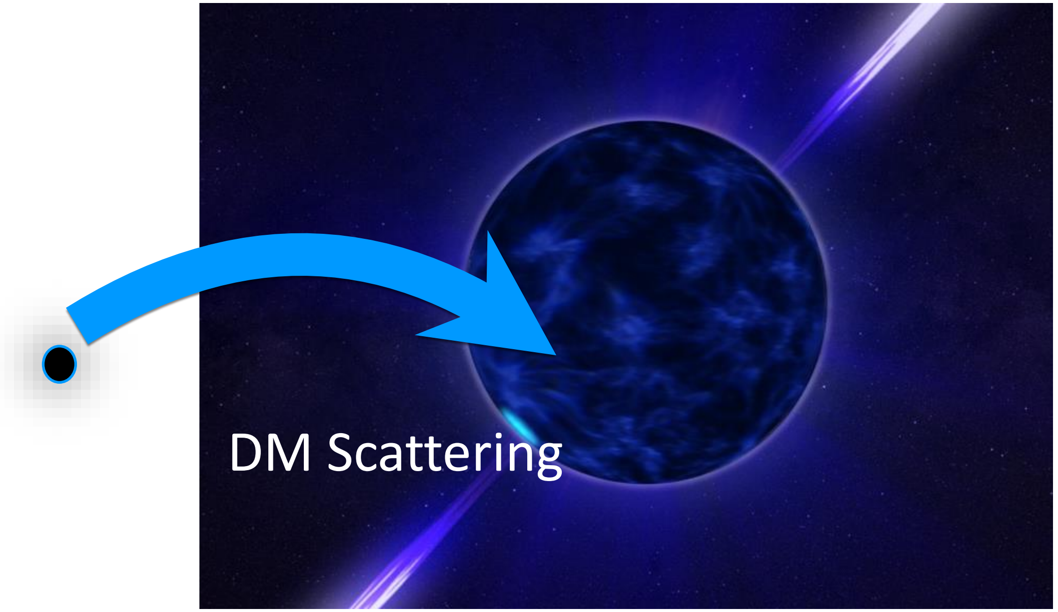


Neutron Stars

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**

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



Neutron Stars → Black holes?

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

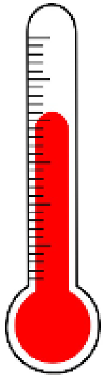
- Due to their density, neutron stars capture dark matter very efficiently
- Can neutron stars accumulate so much dark matter that they would collapse to back holes? **Yes**, but typically only if:
  - Non-annihilating DM (e.g. asymmetric DM)
  - DM is bosonic (and condenses to a small self gravitating BEC), or
  - DM is fermionic with attractive self-interactions, and
  - No repulsive-self interactions that prevent collapse (even very very 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

- **Capture of dark matter** (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

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

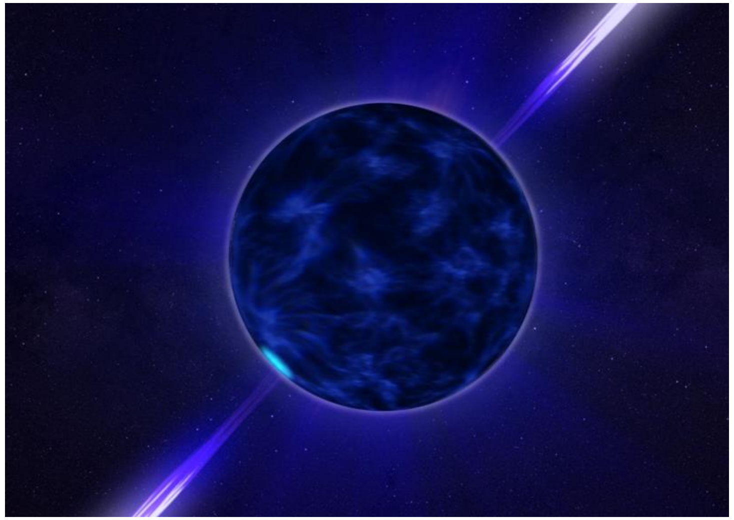
- Early cooling is dominated by neutrino emission
- Photon emission dominates at late times

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

Neutron Star Heating: Advantages

	Direct Detection experiments	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
Target mass	~ 1 ton	~ 1 solar mass



Neutron Star Heating: Advantages

Completely different kinematics to direct detection experiments, because the **dark matter is relativistic**

- **No velocity/momentum suppression of cross sections**
  → ***Sensitivity to interactions that direct detection experiments will never see***

- **not limited by recoil detection thresholds**
  → **sensitive to very low mass DM**

- **Similar sensitivity to SI and SD scattering**

Improved capture calculations

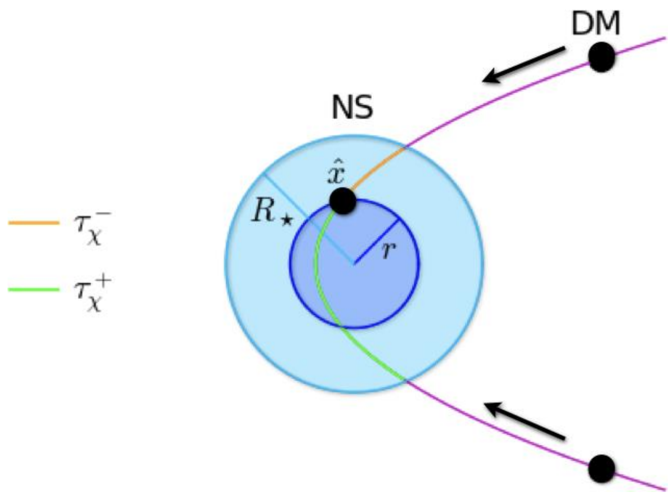
NFB, Busoni, Robles & Virgato,
JCAP 09, 028 (2020), JCAP 03, 086 (2021)

Early treatments of the capture process used various simplifying assumptions.

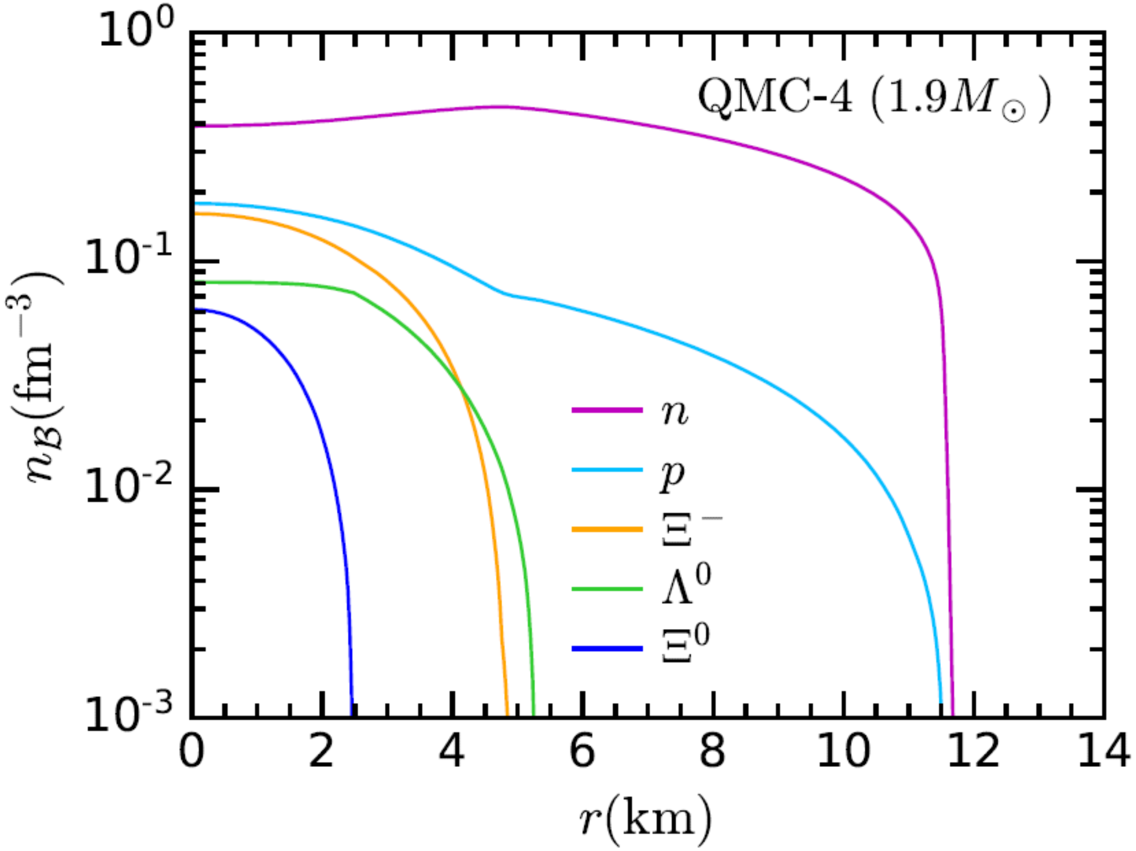
Important physical effects include:

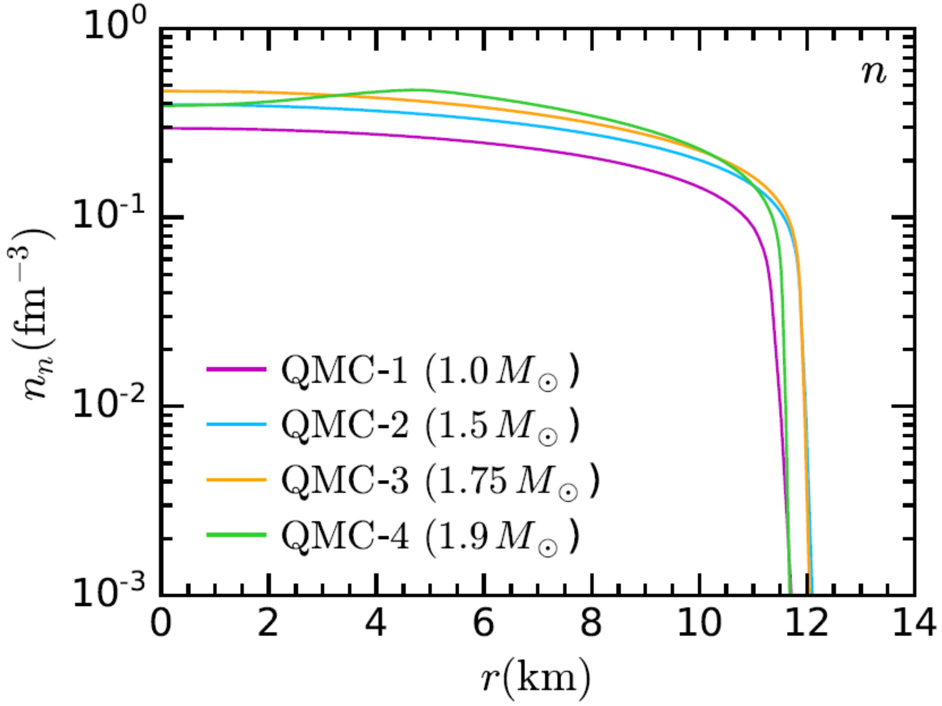
- Consistent treatment of NS structure
  - Radial profiles of EoS dependent parameters, and GR corrections by solving the TOV eqns.
- Gravitational focusing
  - DM trajectories bent toward the NS star
- Fully relativistic (Lorentz invariant) scattering calculation
  - Including the fermi momentum of 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**

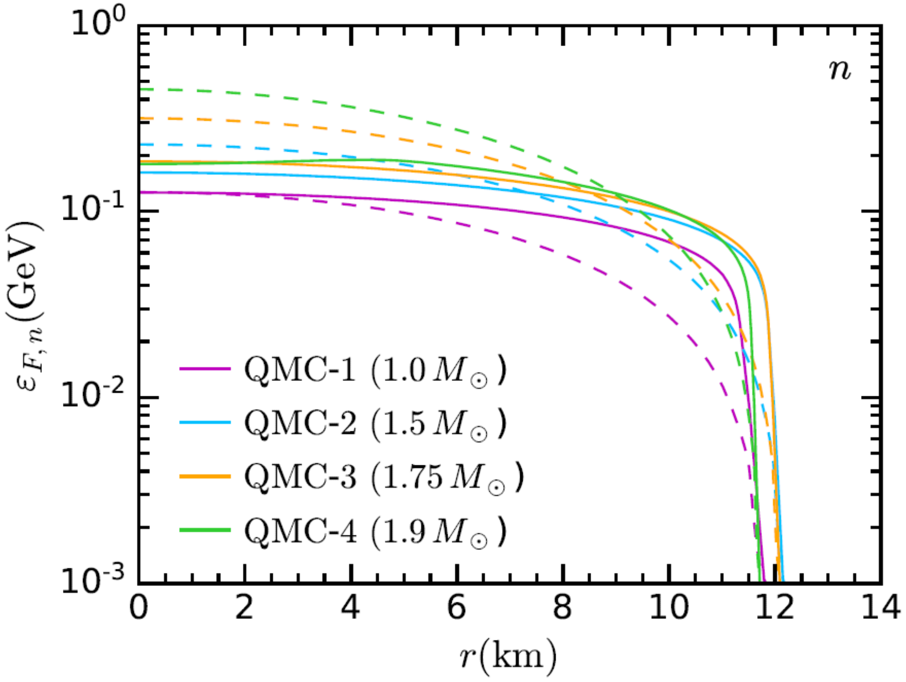
NFB, Busoni, Motta, Robles, Thomas, & Virgato, PRL 2021



Radial profiles







Anzuini, NFB, Busoni, Motta, Robles, Thomas and Virgato, JCAP 11, 056 (2021)

Momentum dependence of hadronic matrix elements

DM is relativistic upon infall to NS

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

i.e. We can no longer treat nucleons as point particles

Nucleon level couplings suppressed as:

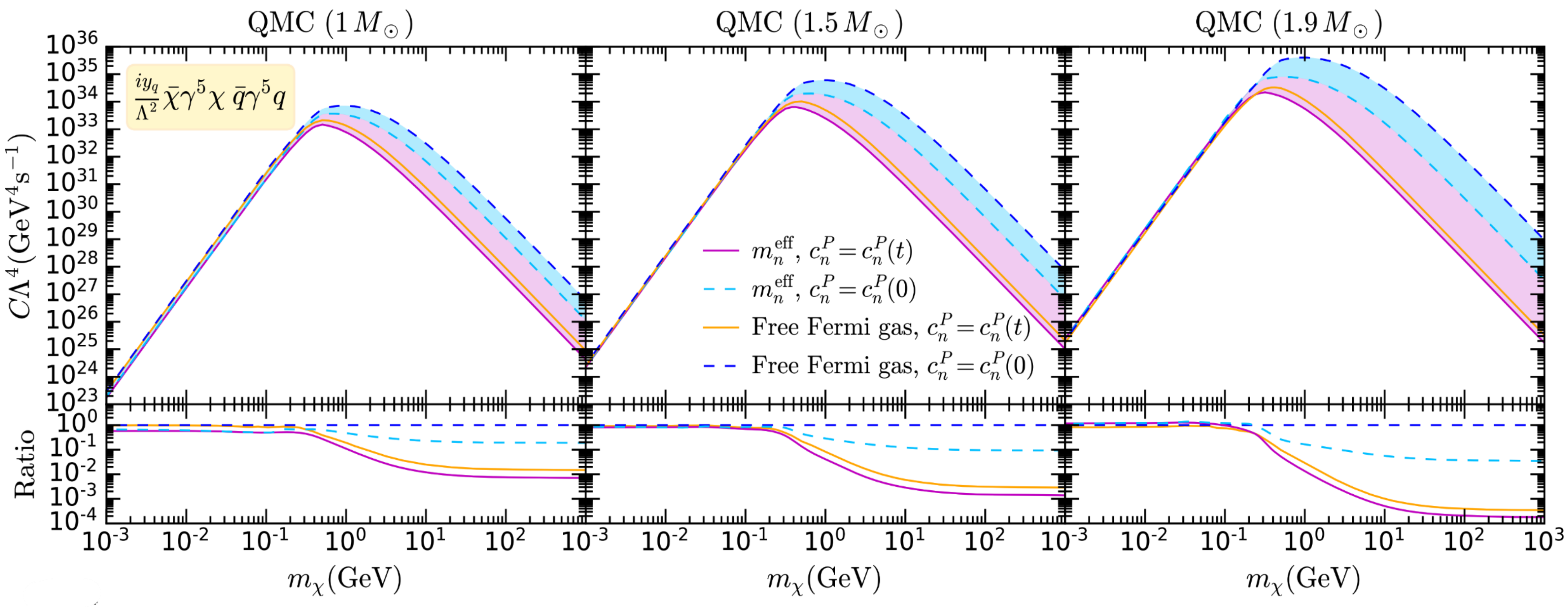
$$c_n(q) = \frac{c_n(0)}{\left(1-q^2/Q_0^2\right)^2} \quad \text{with } Q_0 \sim 1\ \text{GeV}$$

Note however, that the deep-inelastic scattering rate is always subdominant.

NFB, Busoni, Motta, Robles, Thomas, Virgato, Phys. Rev. Lett. 127, 111803 (2021)

Including nucleon structure and nucleon interactions:

→ capture rate suppressed by > 3 orders of magnitude

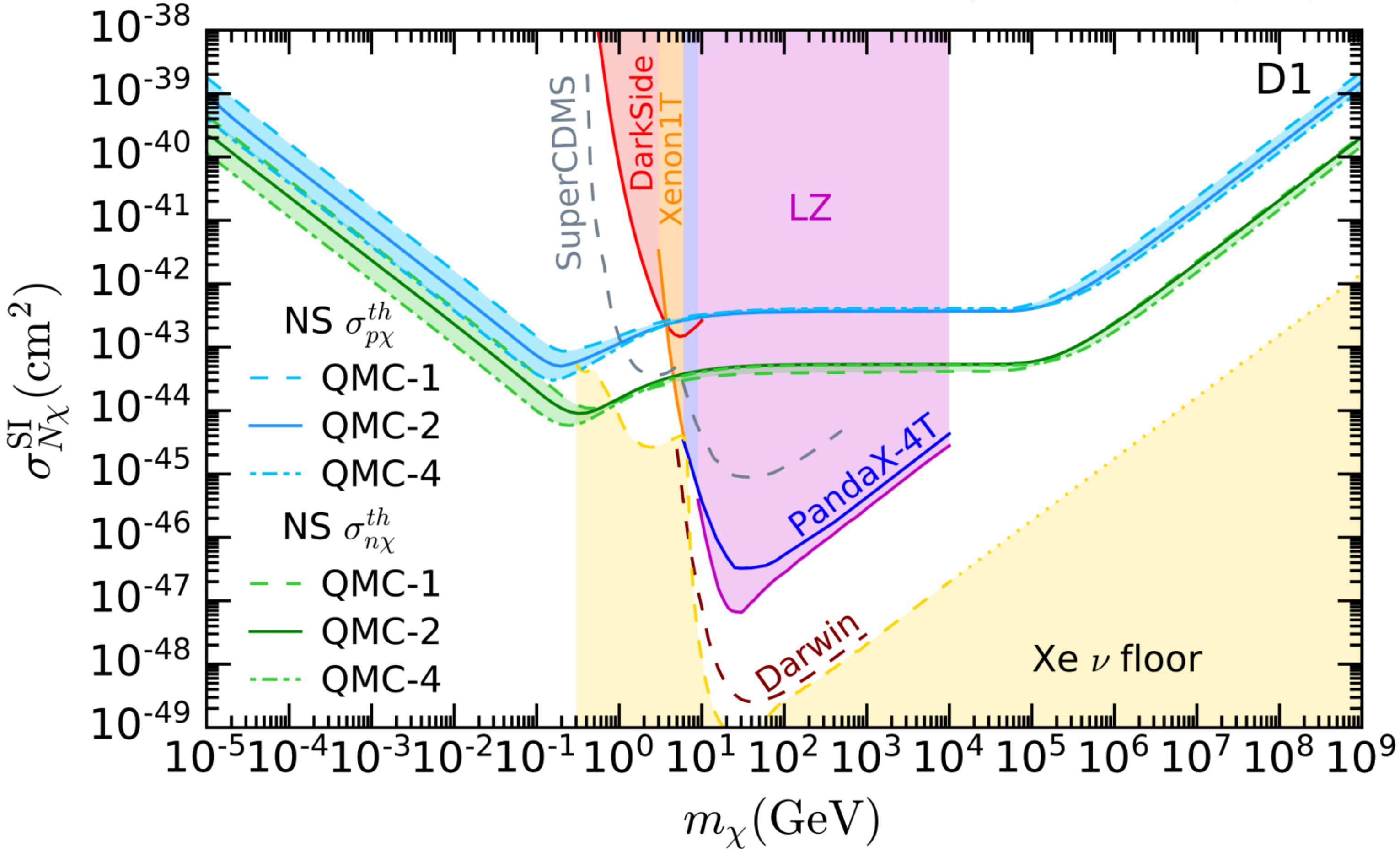


NFB, Busoni, Motta, Robles, Thomas & Virgato, Phys. Rev. Lett. 127, 111803 (2021)

NS Heating Sensitivity (projected limits)

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

Anzuini, NFB, Busoni, Motta, Robles, Thomas and Virgato, JCAP 11, 056 (2021)



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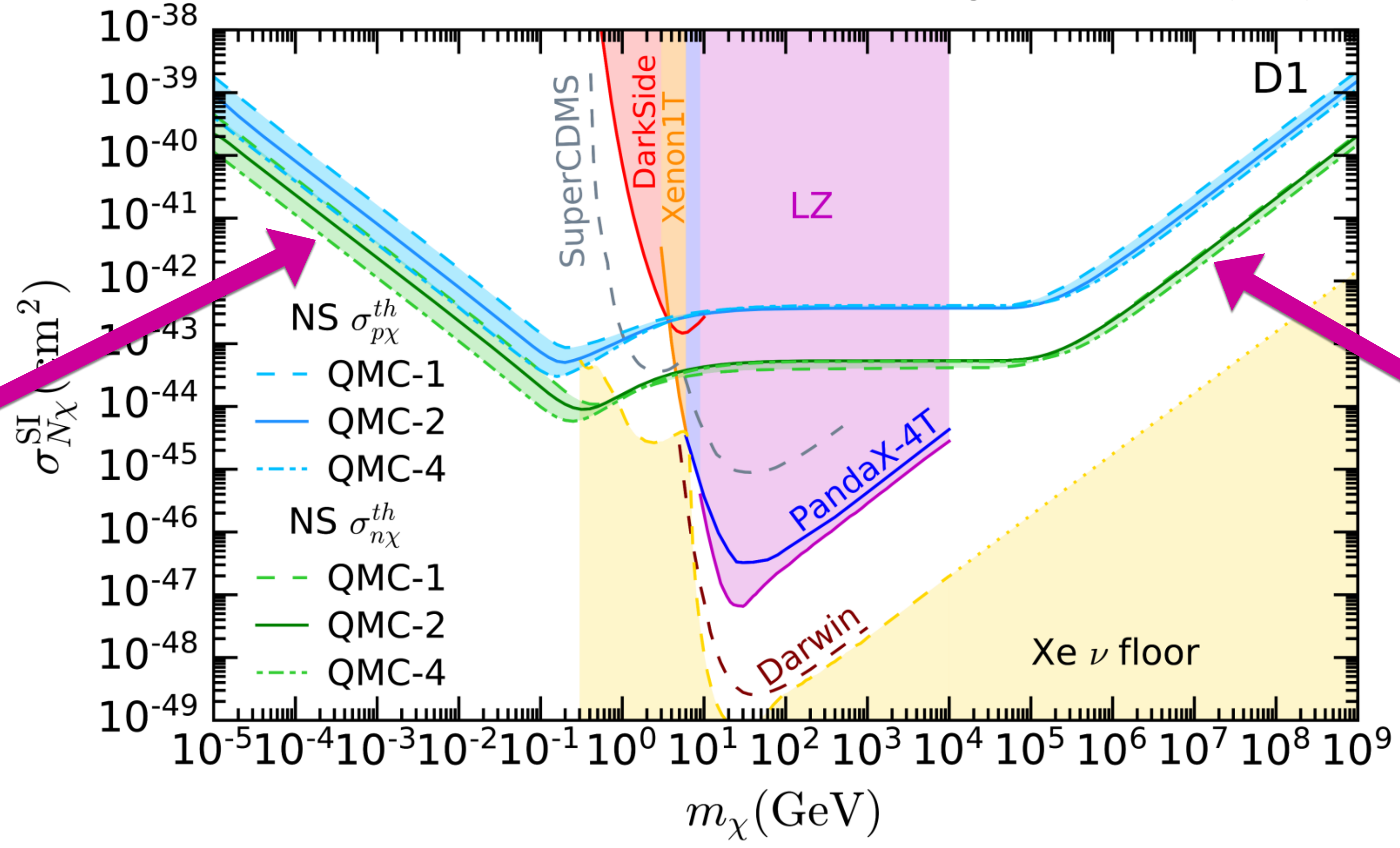
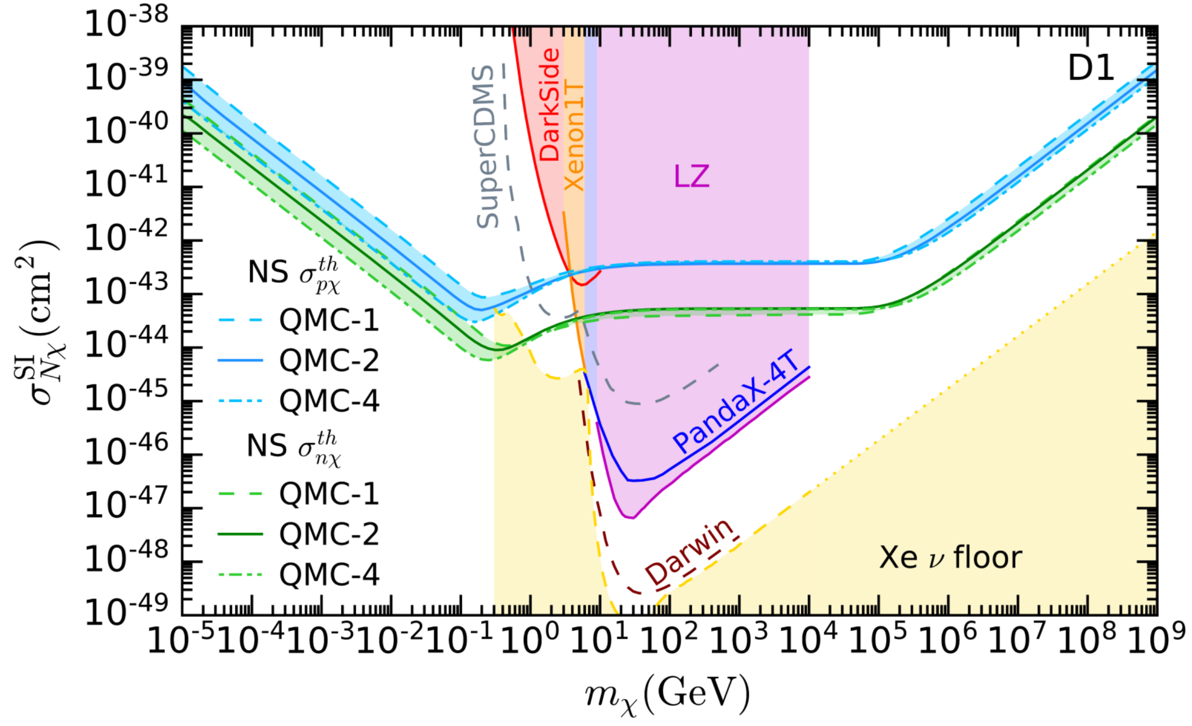


Pauli blocking from degenerate neutrons

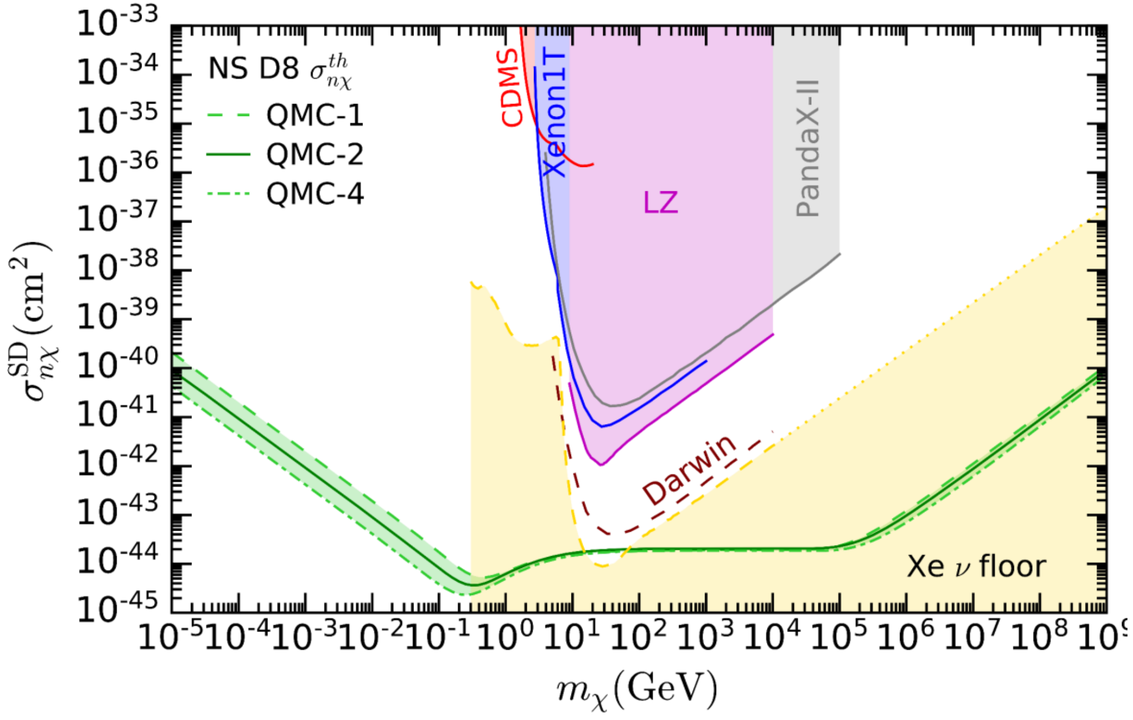
Momentum transfer in single collision not sufficient for capture

NS Heating Sensitivity:

Spin-independent scattering



Spin-dependent scattering



Anzuini, NFB, Busoni, Motta, Robles, Thomas and Virgato, JCAP 11, 056 (2021)

Direct Detection vs Neutron Star Capture

	Operator		Spin-independent (SI) or dependent (SD) scattering	momentum suppressed	Direct detection constraints?
D1	scalar-scalar	$(\bar{\chi}\chi)(\bar{q}q)$	**SI**	✘	**Yes, strong**
D2	pseudoscalar-scalar	$(\bar{\chi}\gamma_5\chi)(\bar{q}q)$	**SI**	✓	–
D3	scalar-pseudoscalar	$(\bar{\chi}\chi)(\bar{q}\gamma_5 q)$	**SD**	✓	–
D4	pseudoscalar-pseudoscalar	$(\bar{\chi}\gamma_5\chi)(\bar{q}\gamma_5 q)$	**SD**	✓✓	–
D5	vector-vector	$(\bar{\chi}\gamma_\mu\chi)(\bar{q}\gamma_\mu q)$	**SI**	✘	**Yes, strong**
D6	vector-axialavector	$(\bar{\chi}\gamma_\mu\chi)(\bar{q}\gamma_\mu\gamma_5 q)$	**SI,SD**	✓	–
D7	axialvector-vector	$(\bar{\chi}\gamma_\mu\gamma_5\chi)(\bar{q}\gamma_\mu q$	**SD**	✓	–
D8	axialvector-axialvector	$(\bar{\chi}\gamma_\mu\gamma_5\chi)(\bar{q}\gamma_\mu\gamma_5 q)$	**SD**	✘	**Yes, weaker**

Direct detection constraints are weak/non-existent for momentum suppressed scattering.
Is neutron star capture potentially sensitive?

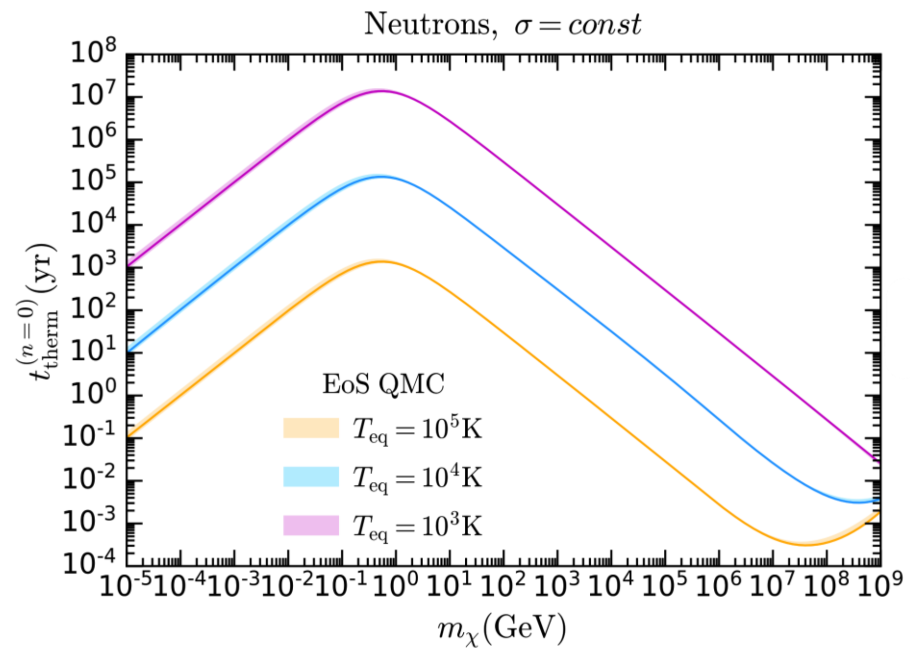
How quickly does dark matter deposit energy?

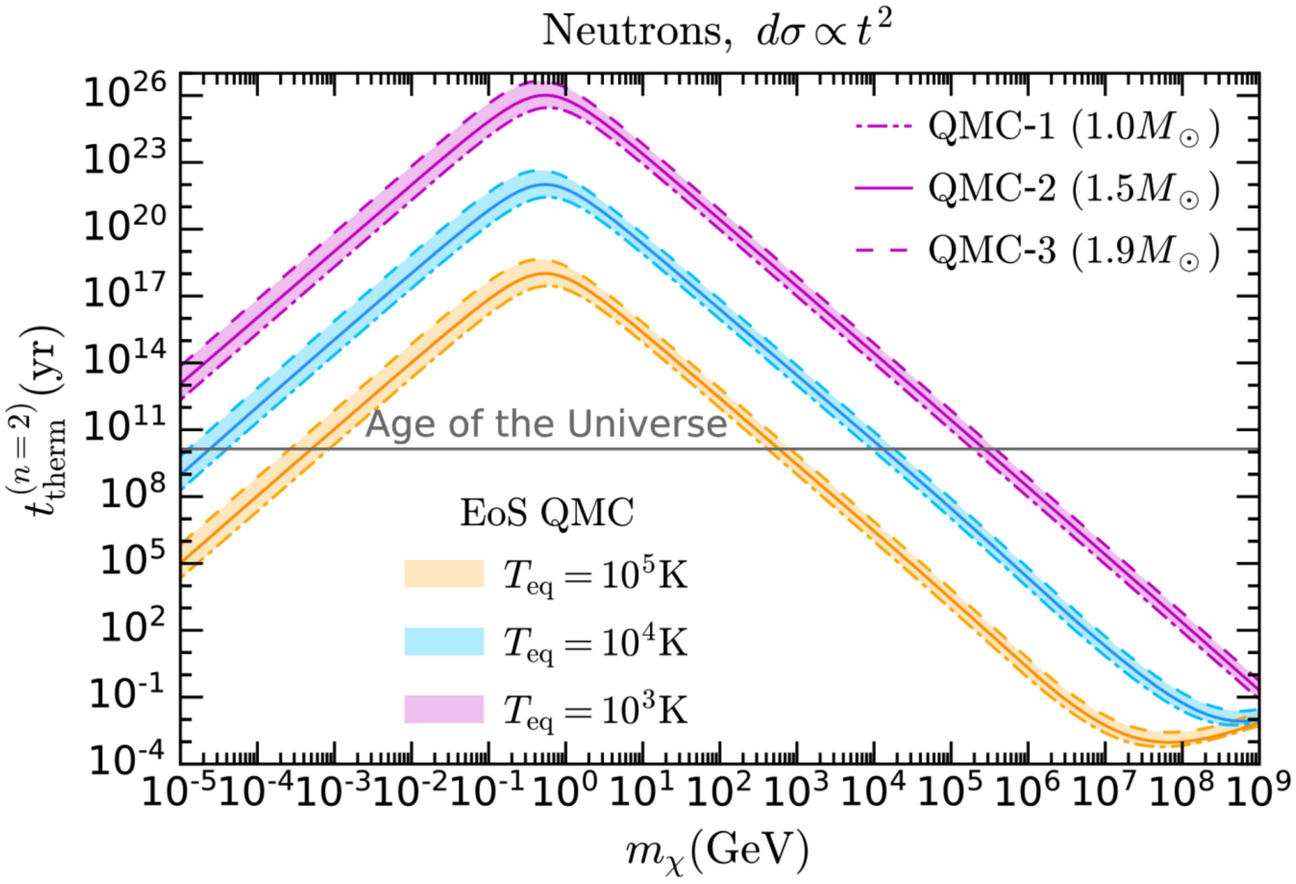
- Initial collision → transfers a small fraction of the DM kinetic energy
- Further collisions → transfer the rest of the energy
- DM eventually thermalises with the star

How long does this take?

- If the cross section is momentum suppressed, the rate of collisions will get slower … and slower … … …

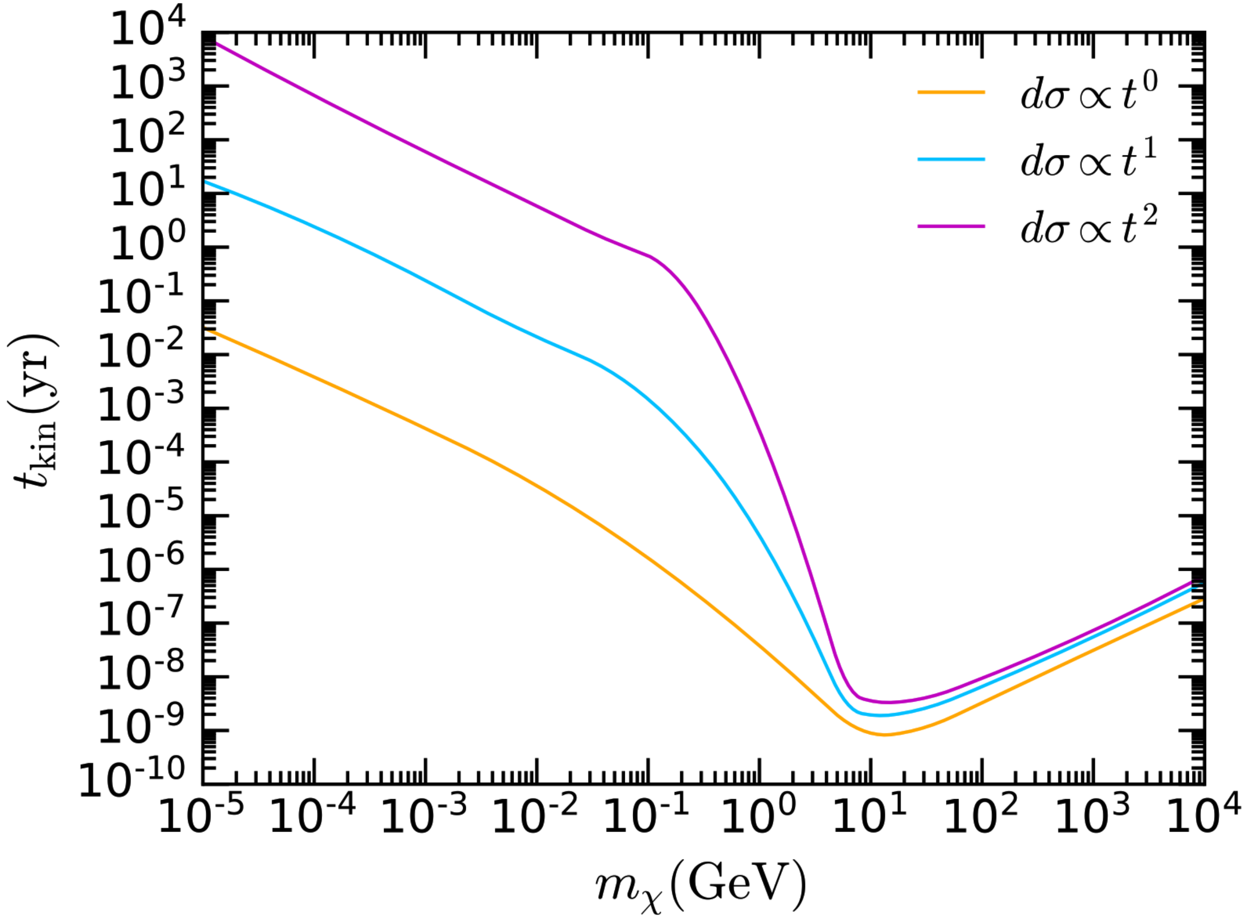
Full thermalization can take > than age of Universe…





NFB, Busoni, Robles & Virgato, JCAP 04, 006 (2024).

But … 99% of the kinetic energy is deposited quickly



$d\sigma \propto t^0$ unsuppressed

$d\sigma \propto t^1 = q^2_{\rm transfer}$

$d\sigma \propto t^2 = q^4_{\rm transfer}$

Energy deposit is slower for momentum suppressed interactions.

But all timescales are short

NFB, Busoni, Robles & Virgato, JCAP 04, 006 (2024).

Annihilation of *not-quite-thermalized* dark matter?

The annihilation rate of thermalized DM is well understood.

For *non-thermalized* DM, capture-annihilation equilibrium is delayed:

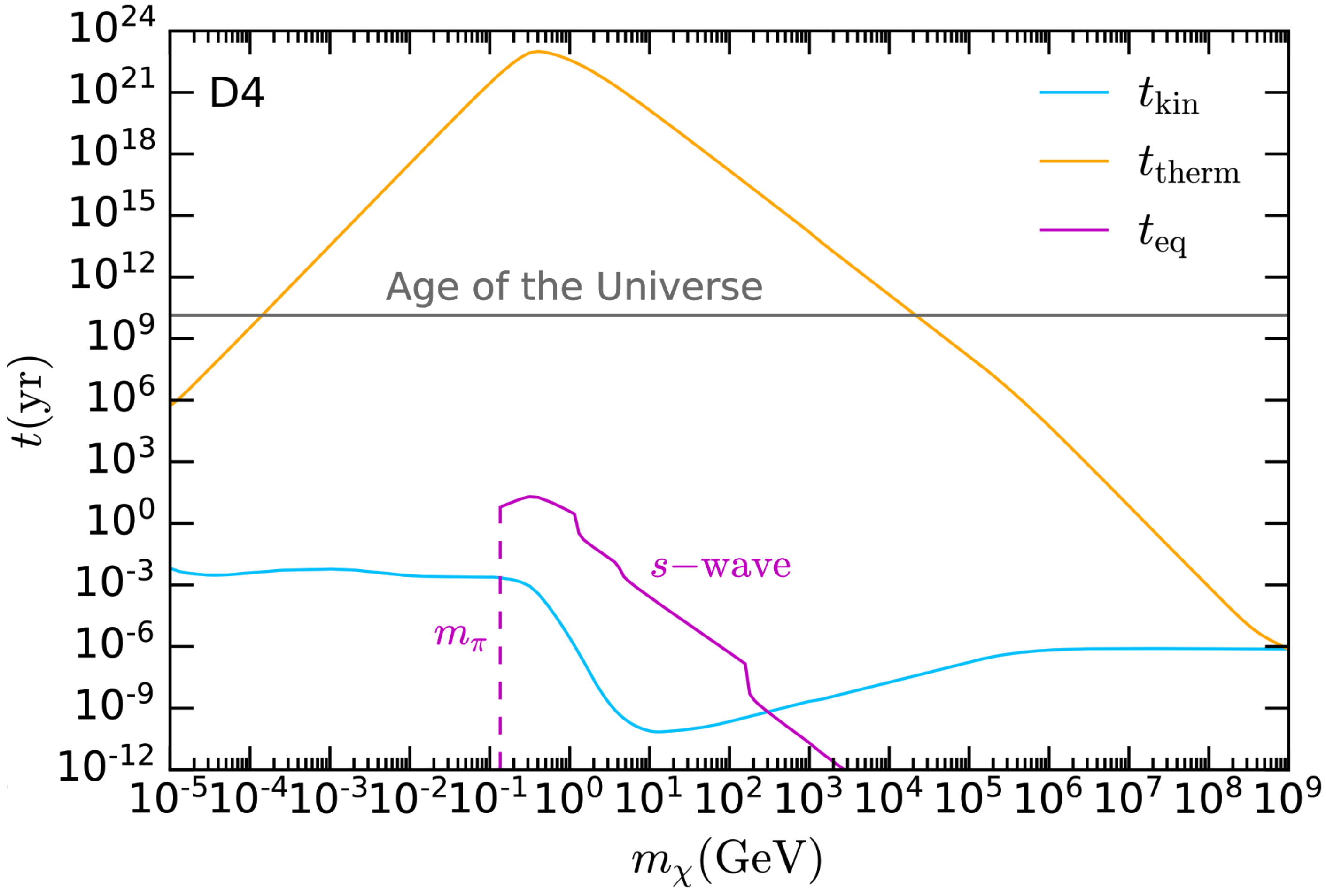
$$t_{EQ} = \frac{1}{\sqrt{\mathrm{CA}}} \quad \rightarrow \quad \frac{1}{\sqrt{\mathrm{CA}}}\left(\frac{t_* + t_{\mathrm{therm}}}{t_*}\right)^{\frac{\alpha}{2(2+n)}}$$

Importantly: t_{EQ} can be shorter than t_{therm}

→ Annihilation can be efficient even if complete thermalization is never reached

NFB, Busoni, Robles & Virgato, JCAP 04, 006 (2024).

Annihilation of *not-quite-thermalized* dark matter?



Kinetic heating (99%) is fast.

Capture-annihilation equilib. is also fast.

(Full thermalization, *much* longer)

NFB, Busoni, Robles & Virgato, JCAP 04, 006 (2024).

Heating is fast for all parameters of interest

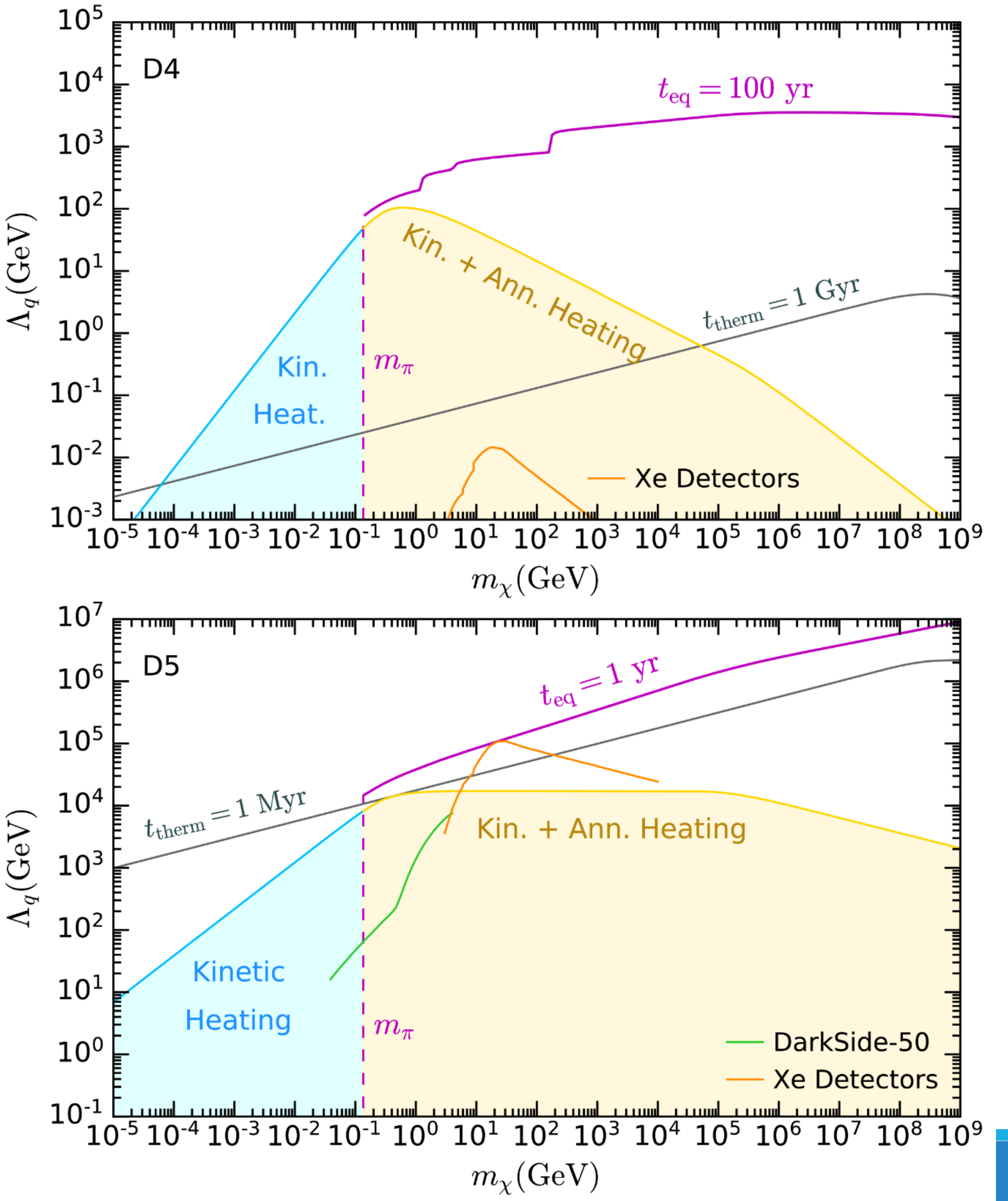
For cross sections large enough for capture to occur near the geometric limit, NS heating is fast.

Even in the case that:

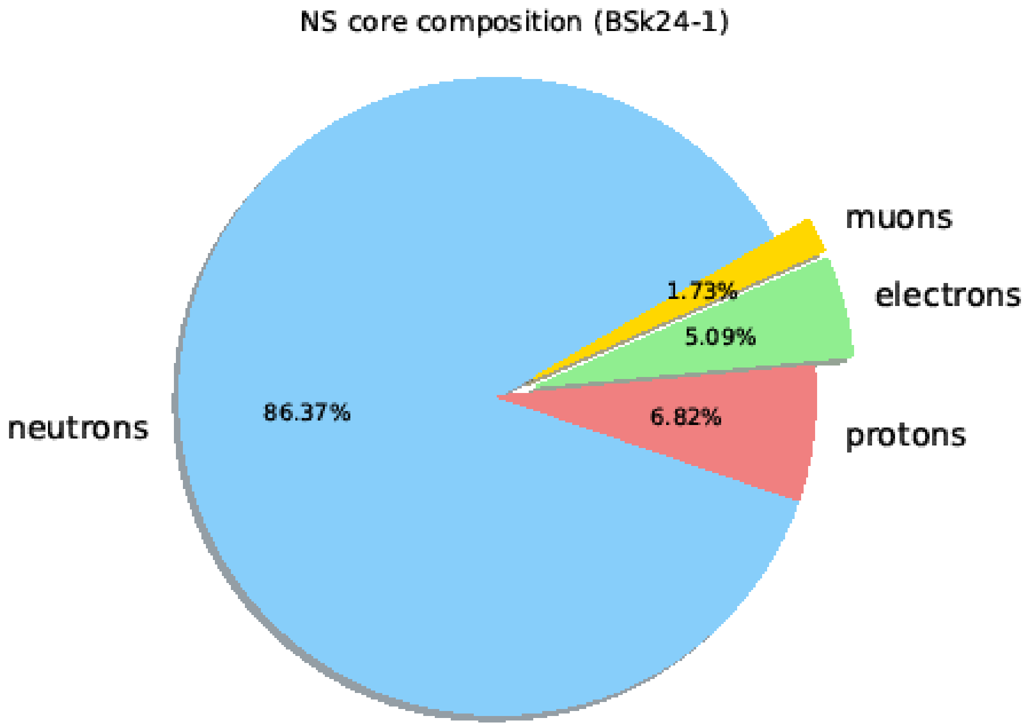
- Scattering is momentum suppressed, or
- Annihilation is p-wave suppressed

  or both.

NFB, Busoni, Robles & Virgato, JCAP 04, 006 (2024).



Leptons in Neutron Stars

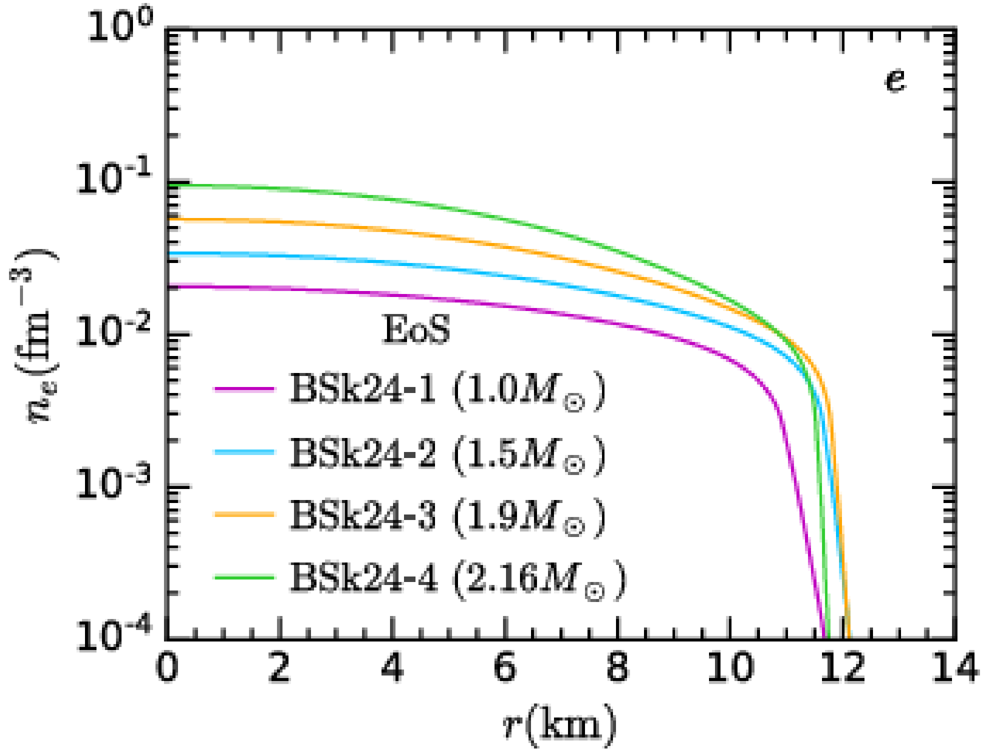


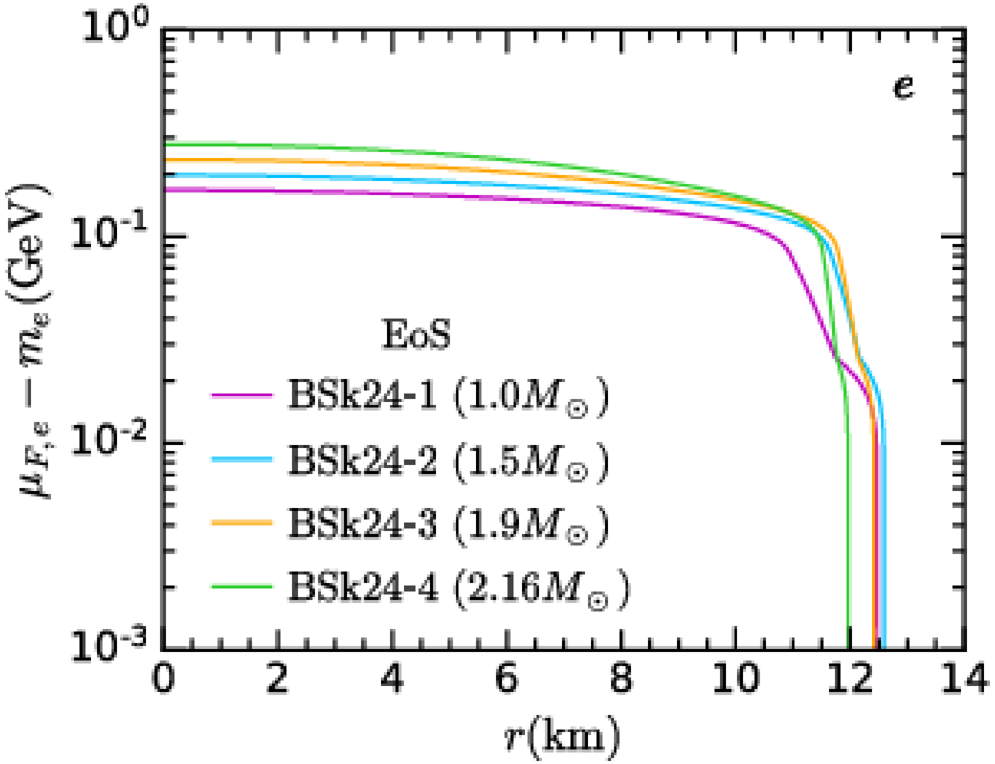
Beta equilibrium in the core determines the composition:

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

Leptons in Neutron Stars

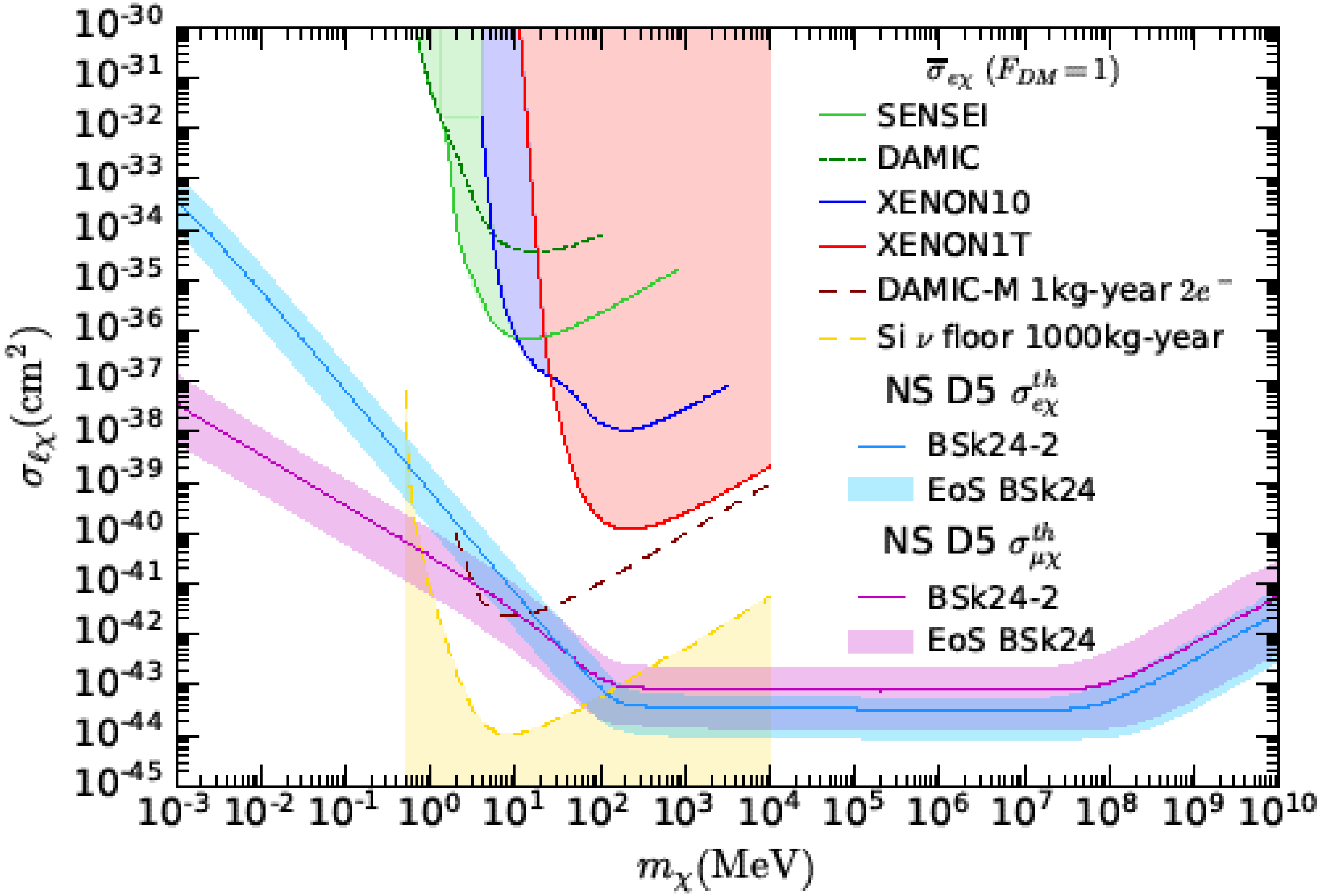
Lepton density of few % in NS core, lower in crust.
Fermi-momentum ~ constant in core.





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

Kinetic Heating Sensitivity: lepton scattering



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

Muon scattering

Electron scattering

White Dwarf Heating from DM Capture

Advantages of White Dwarfs over Neutron Stars:

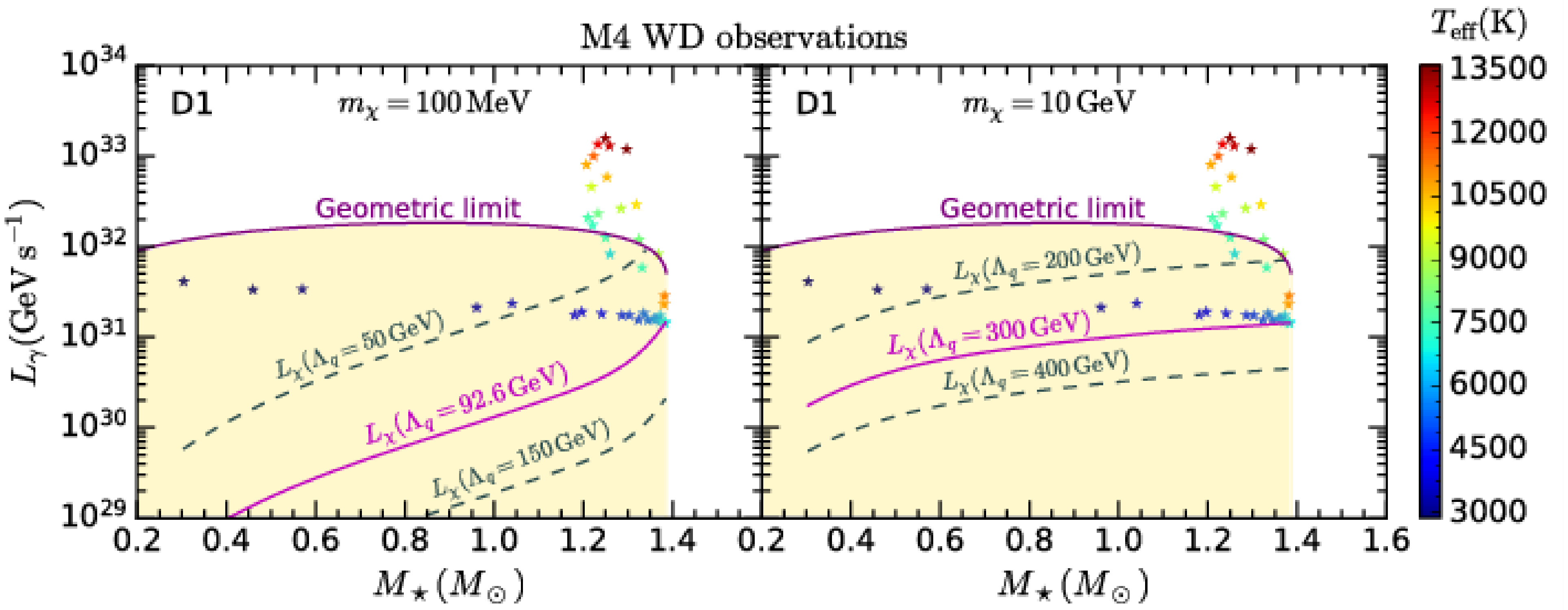
- Existence of observational data!
- Physics of WD's much better constrained than NSs
    - Well-defined mass-radius relation
    - Less uncertainty of the equation-of-state
    - Better understood luminosity-age relations

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

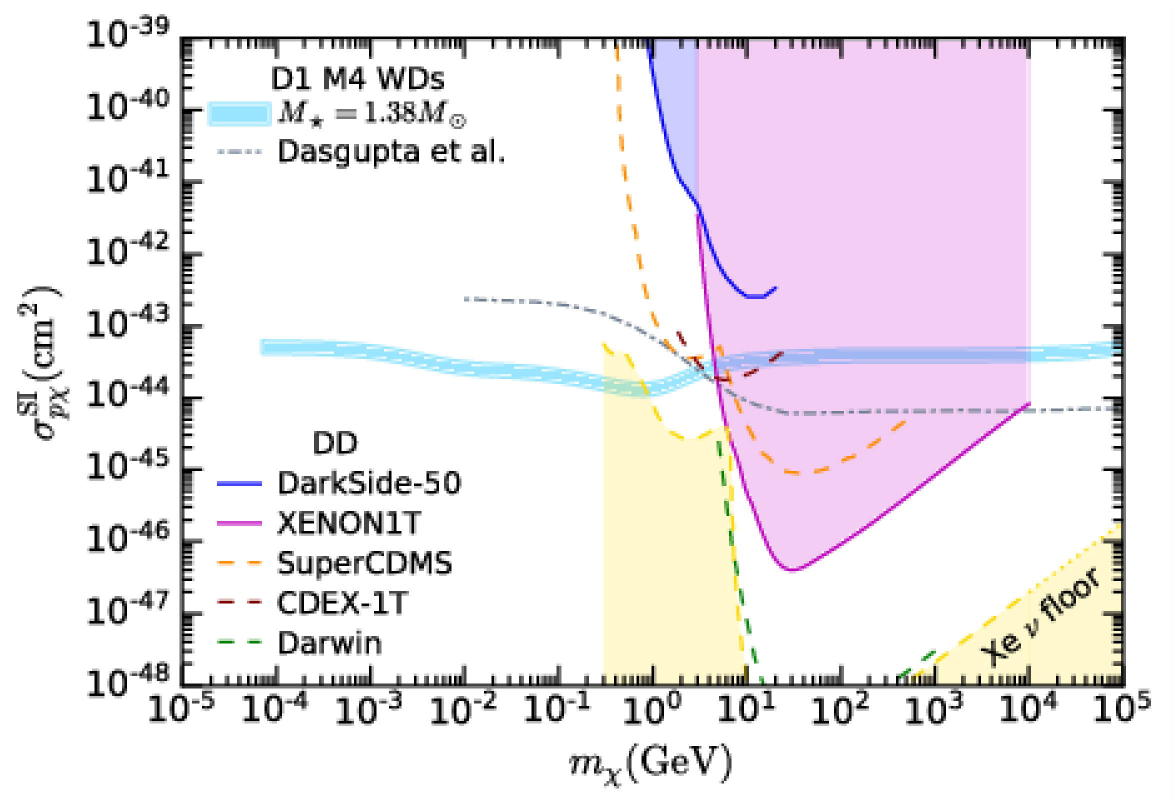
Best limits come from heavy stars (large capture rate) with low luminosity.



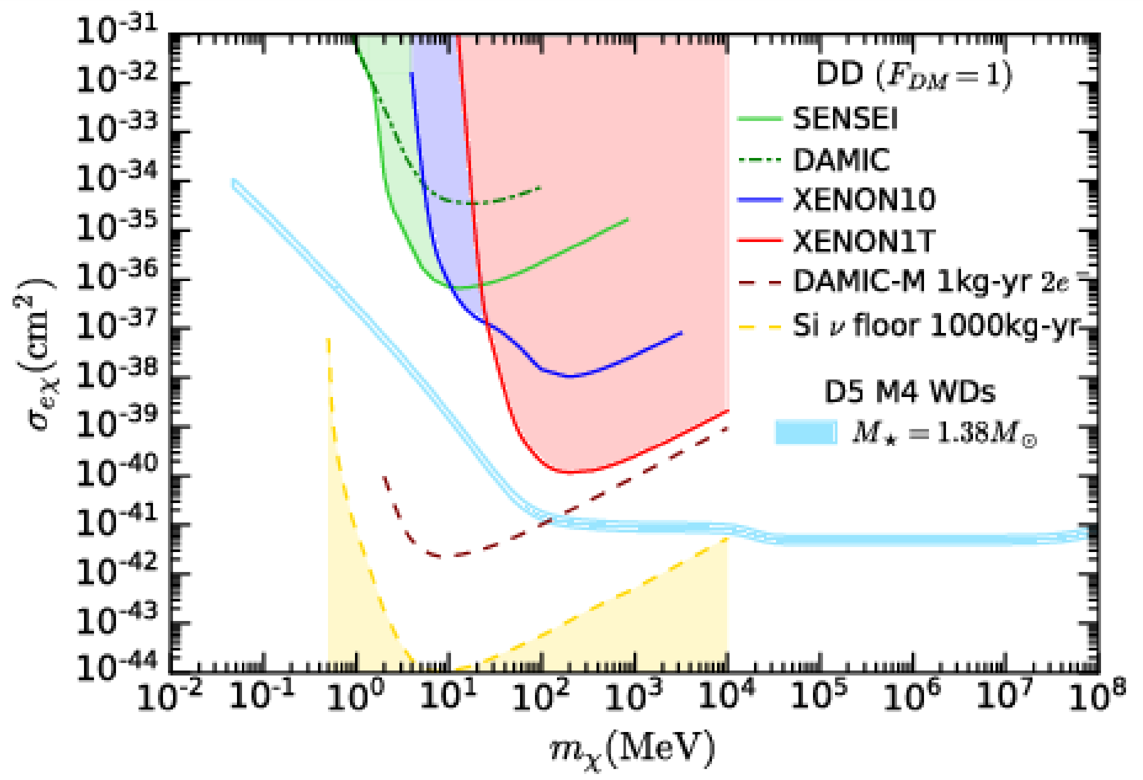
NFB, Busoni, Ramirez-Quezada, Robles & Virgato, JCAP 10, 083 (2021)

White dwarfs in M4 globular cluster

DM-nucleon scattering



DM-electron scattering



NFB, Busoni, Ramirez-Quezada, Robles & Virgato, JCAP 10, 083 (2021)

Summary

Neutron Stars/white dwarfs: cosmic laboratory to probe dark matter scattering

Capture of relativistic dark matter

- no velocity/momentum suppression → potentially better than direct detection

Thermalization of captured dark matter

- Fast if scattering un-suppressed; otherwise, very slow (> age of universe)

Annihilation of partially thermalized dark matter

- can be efficient even *without* full thermalization

Potential sensitivity to interactions difficult/impossible to see in direct detection expts