Dark Matter Capture in Neutron Stars

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with Giorgio Busoni, Sandra Robles, Michael Virgato, Anthony Thomas, Theo Motta and Filippo Anzuini

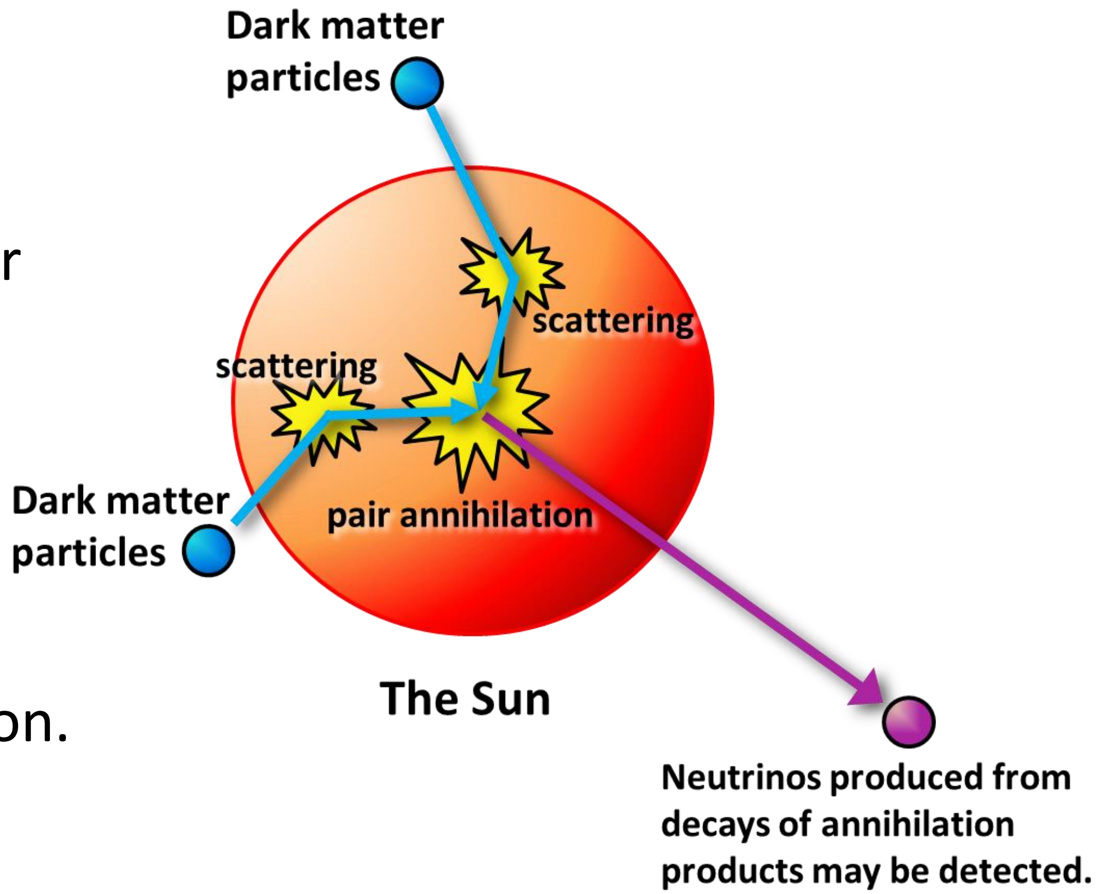
arXiv:1807.02840, arXiv:1904.09803, arXiv:2004.14888, arXiv:2010.13257, arXiv:2012.08918, 2108.02525

Dark Matter Capture in Stars

→ an alternative approach to DM-nucleon scattering experiments

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

- Accumulates and annihilates in centre of the star
- Only neutrinos escape Sun→ IceCube, SuperK



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

Capture, annihilation, evaporation

DM number density depends on the Capture, Annihilation and 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

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

The annihilation rate is then

$\Gamma_{ann} = \frac{1}{2}AN_\chi^2 = \frac{1}{2}C\tanh^2\left(\frac{t}{\tau_{eq}}\right) \quad \rightarrow \frac{1}{2}C$ when $t \gg \tau_{eq}$ (capture-annihilation equilib.)

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**

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

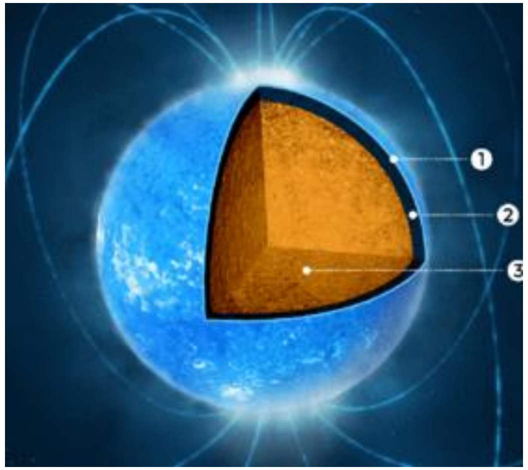
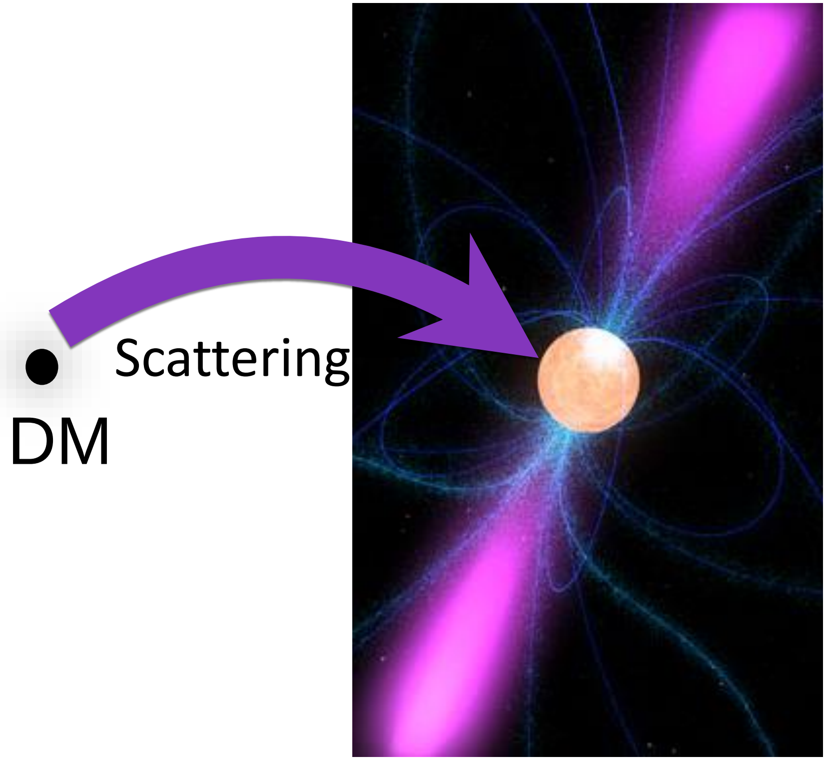


Image: NASA



Neutron Stars → Black holes?

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

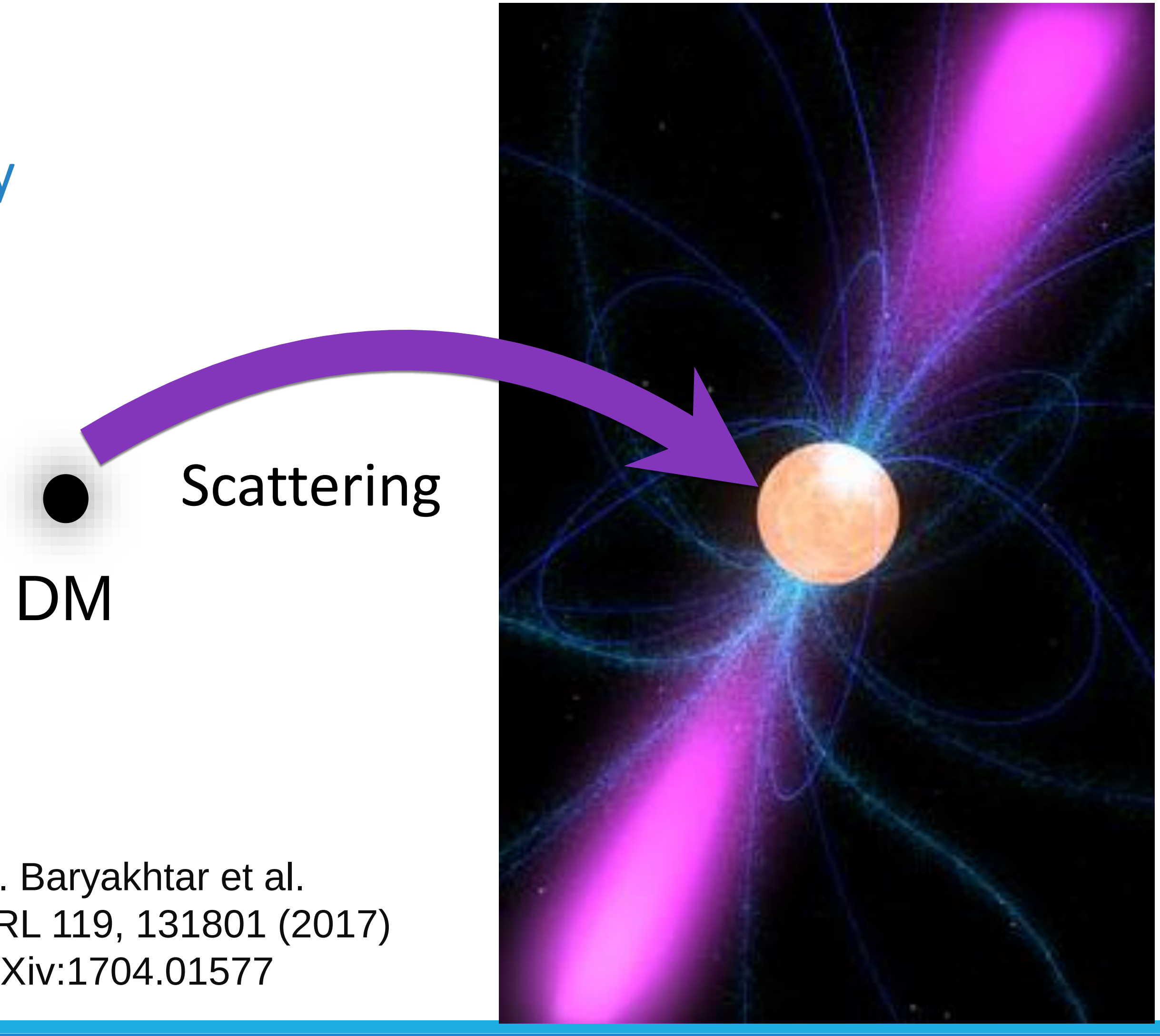
- Due to their density, neutron stars capture dark matter very efficiently

- 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**

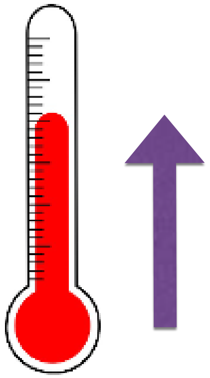
→ **Black hole formation possible but quite unlikely for *typical* WIMP-like dark matter**

Neutron Star Kinetic Heating

Collisions transfer the
dark matter kinetic energy
to the neutron star
→ heating



M. Baryakhtar et al.
PRL 119, 131801 (2017)
arXiv:1704.01577



T_{NS} ~1700 K

1 - 2 μm

near IR

Dark matter heating

→ from scattering plus annihilation

Baryakhtar, Bramante, Li, Linden and Raj

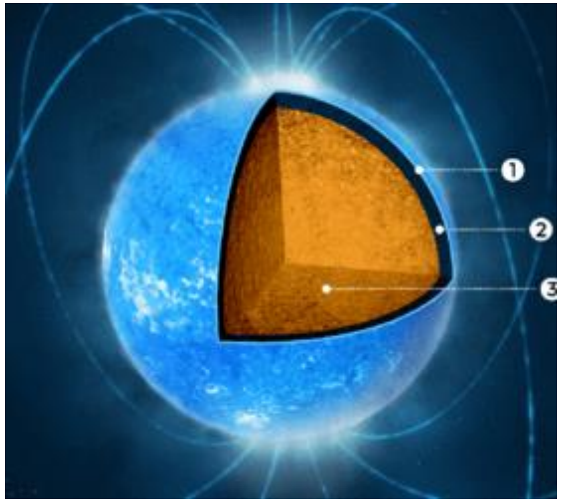
- Capture (plus subsequent energy loss)
  → DM ***kinetic energy*** heats neutron star ~ 1700K

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

Thermalisation is essentially guaranteed for unsuppressed DM-nucleon scattering. If there is some kinematic suppression of the scattering process, it can take much longer (velocity or momentum suppressions; inelastic, etc)

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	$< \mathcal{O}(100\ \mathrm{MeV})$	$\mathcal{O}(10\ \mathrm{GeV})$
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**

Direct Detection vs Neutron Stars

Operator			Coupling	Direct Detection	Momentum suppressed	DD vs NS
D1	SS	$(\bar{\chi}\chi)(\bar{q}q)$	y_q/Λ^2	SI	✗	NS or DD
D2	PS	$(\bar{\chi}\gamma_5\chi)(\bar{q}q)$	y_q/Λ^2	SI	✓	NS
D3	SP	$(\bar{\chi}\chi)(\bar{q}\gamma_5 q)$	y_q/Λ^2	SD	✓	NS
D4	PP	$(\bar{\chi}\gamma_5\chi)(\bar{q}\gamma_5 q)$	y_q/Λ^2	SD	✓	NS
D5	VV	$(\bar{\chi}\gamma_\mu\chi)(\bar{q}\gamma_\mu q)$	$1/\Lambda^2$	SI	✗	NS or DD
D6	VA	$(\bar{\chi}\gamma_\mu\chi)(\bar{q}\gamma_\mu\gamma_5 q)$	$1/\Lambda^2$	SI,SD	✓	NS
D7	AV	$(\bar{\chi}\gamma_\mu\gamma_5\chi)(\bar{q}\gamma_\mu q$	$1/\Lambda^2$	SD	✓	NS
D8	AA	$(\bar{\chi}\gamma_\mu\gamma_5\chi)(\bar{q}\gamma_\mu\gamma_5 q)$	$1/\Lambda^2$	SD	✗	NS

Projected neutron star heating sensitivity:

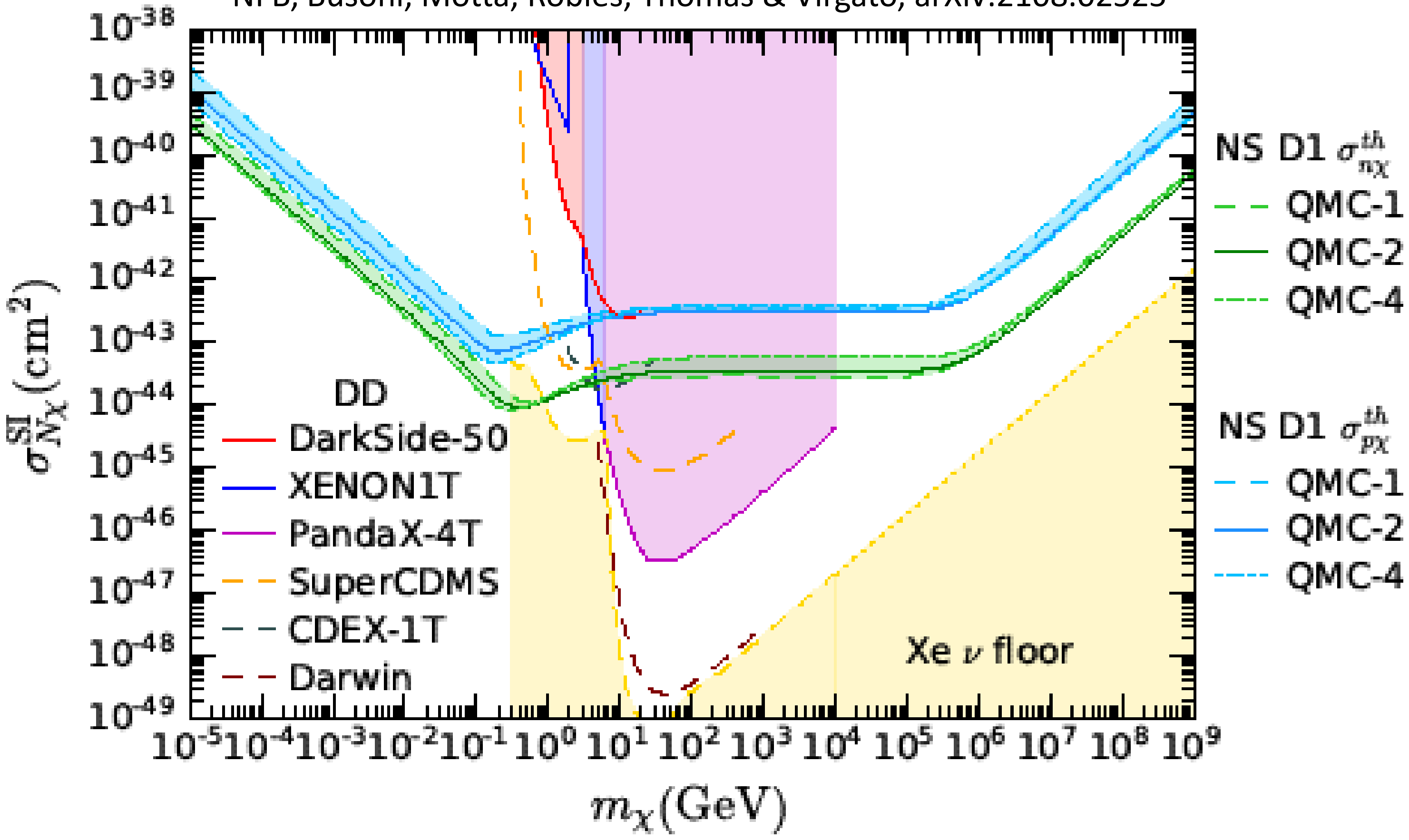
- comparable to direct detection experiments for scalar and vector interactions
- more sensitive than DD for all other interaction types (typically by orders of magnitude).

Kinetic Heating Sensitivity

Ball-park sensitivity
= geometric limit

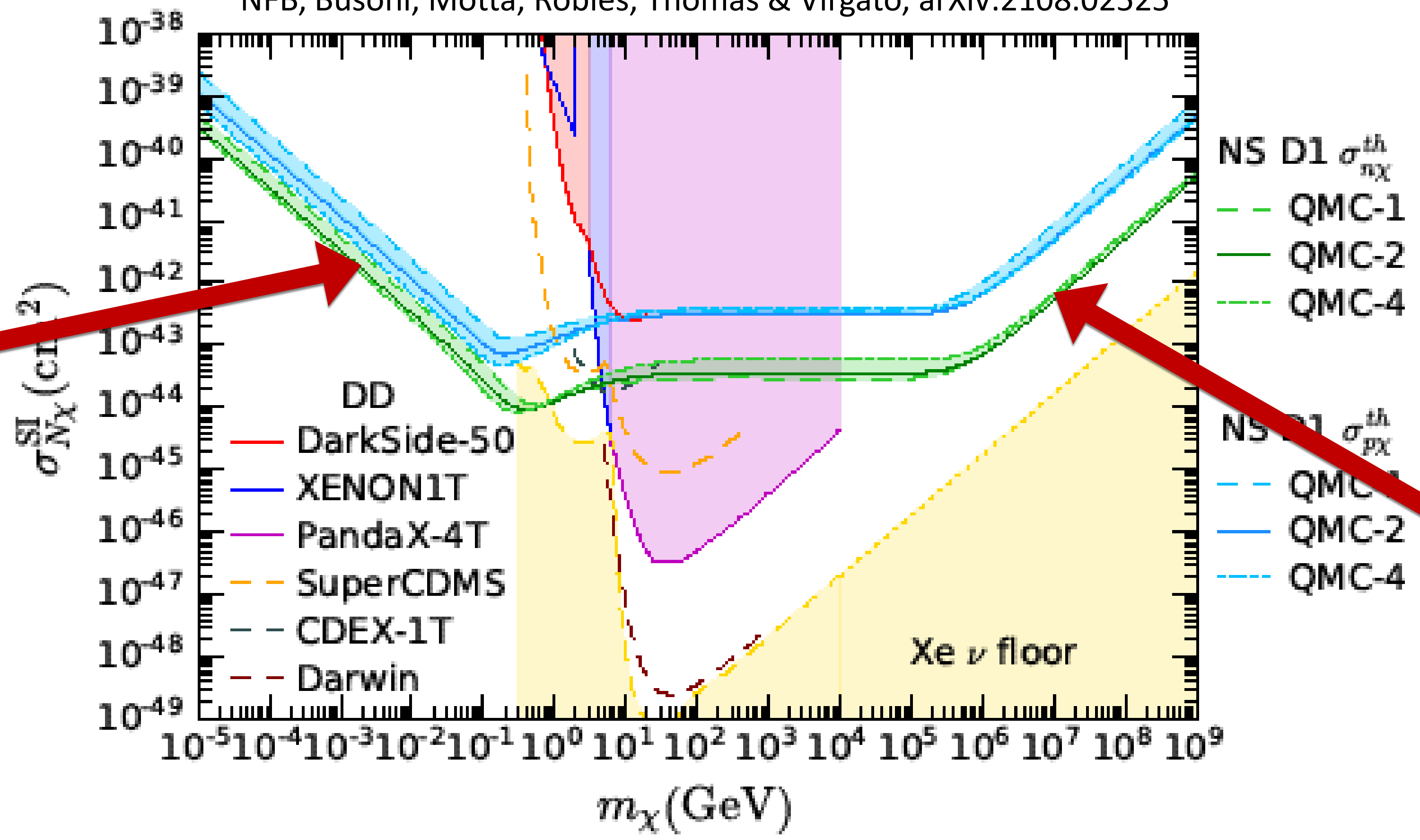
$\sigma_{th} \sim 10^{-45} \text{cm}^2$

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



Kinetic Heating Sensitivity

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

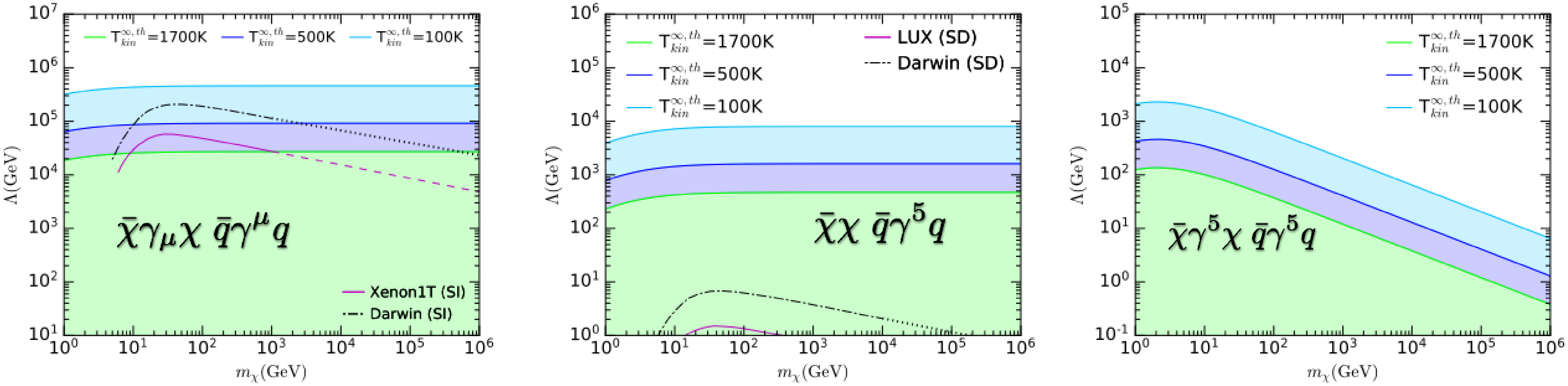


Pauli blocking from degenerate neutrons restricts scattering when $m_{DM} < 1$ GeV.
Need: momentum transfer > neutron Fermi momentum

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

Neutron star sensitivity: DM-nucleon interactions

unsuppressed SI scattering | **q^2 suppressed SD scattering** | **q^4 suppressed SD scattering**



NS sensitivity comparable to direct detection

NS sensitivity greatly surpasses direct detection experiments

NFB, Busoni, Robles, arXiv:1807.02840

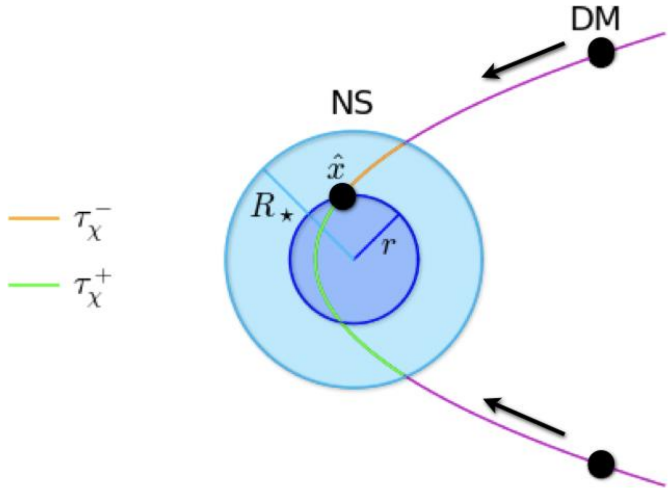
Improved capture calculations

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



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)

Two important effects neglected in all previous treatments:

- Momentum dependence of hadronic matrix elements
- Nucleon Interactions

→ This changes the capture cate by up to 3 orders of magnitude (biggest effect for heaver NSs)

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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

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

Nucleon level couplings become:

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

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

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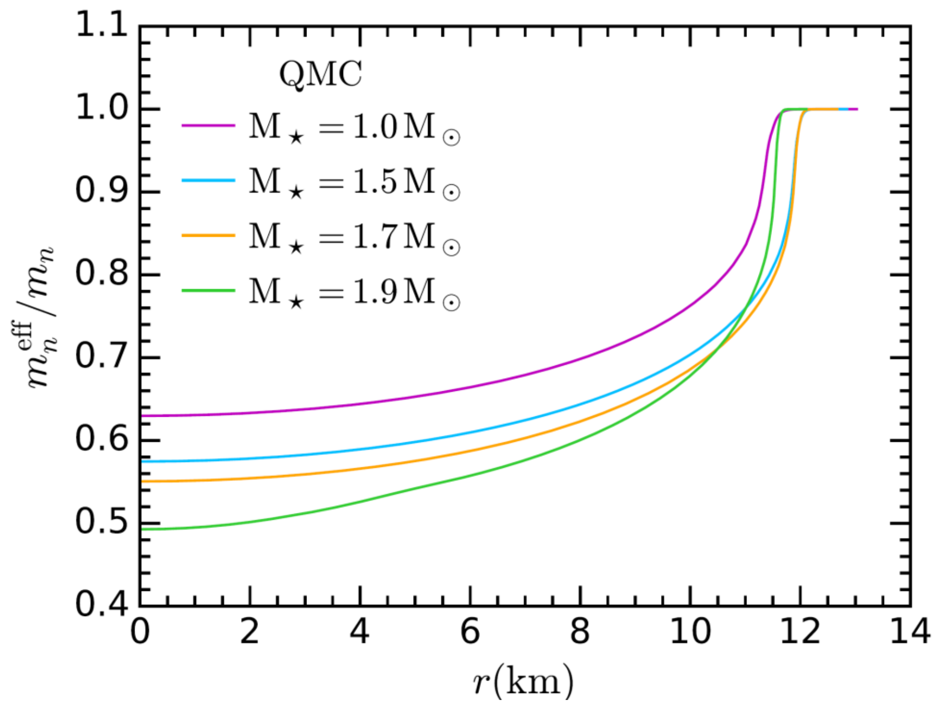
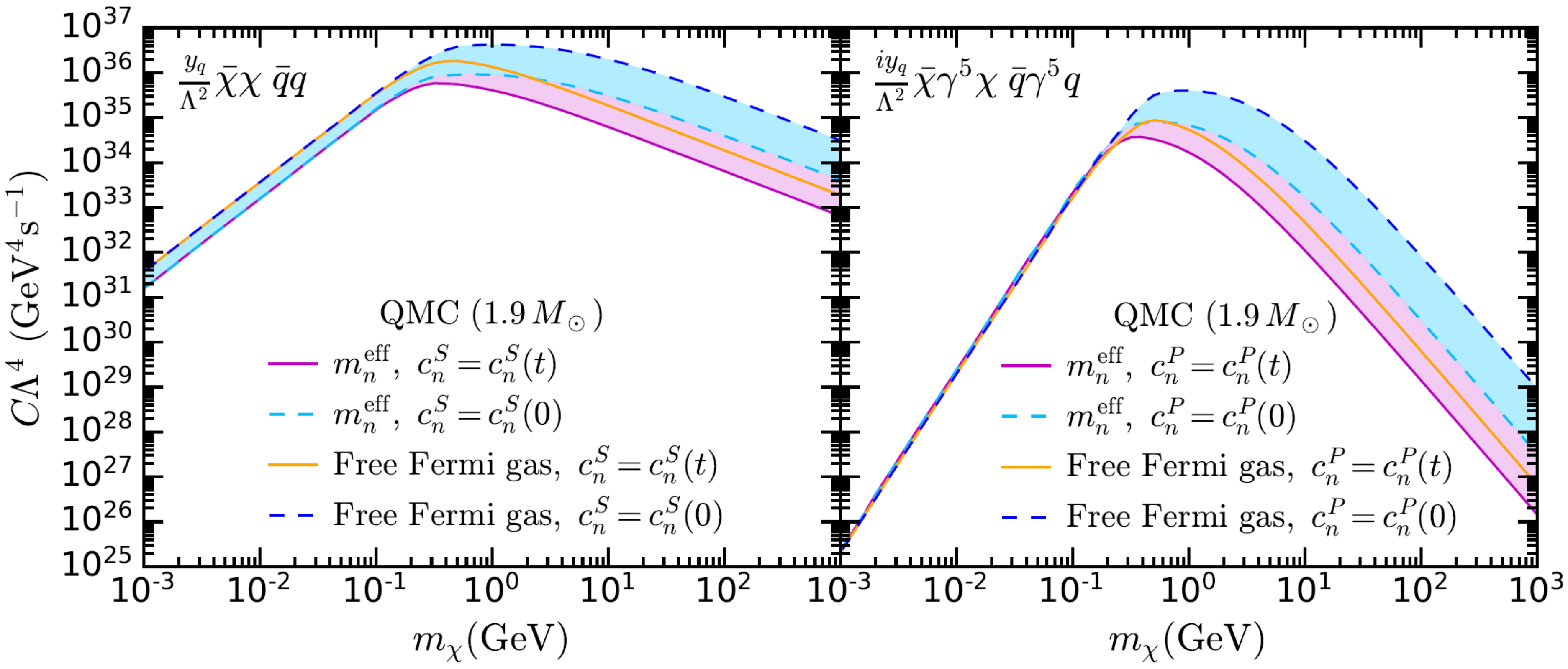
2. Nucleon Interactions:

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



Including nucleon structure and strong interactions:

→ capture rate altered by up to 3 orders of magnitude



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

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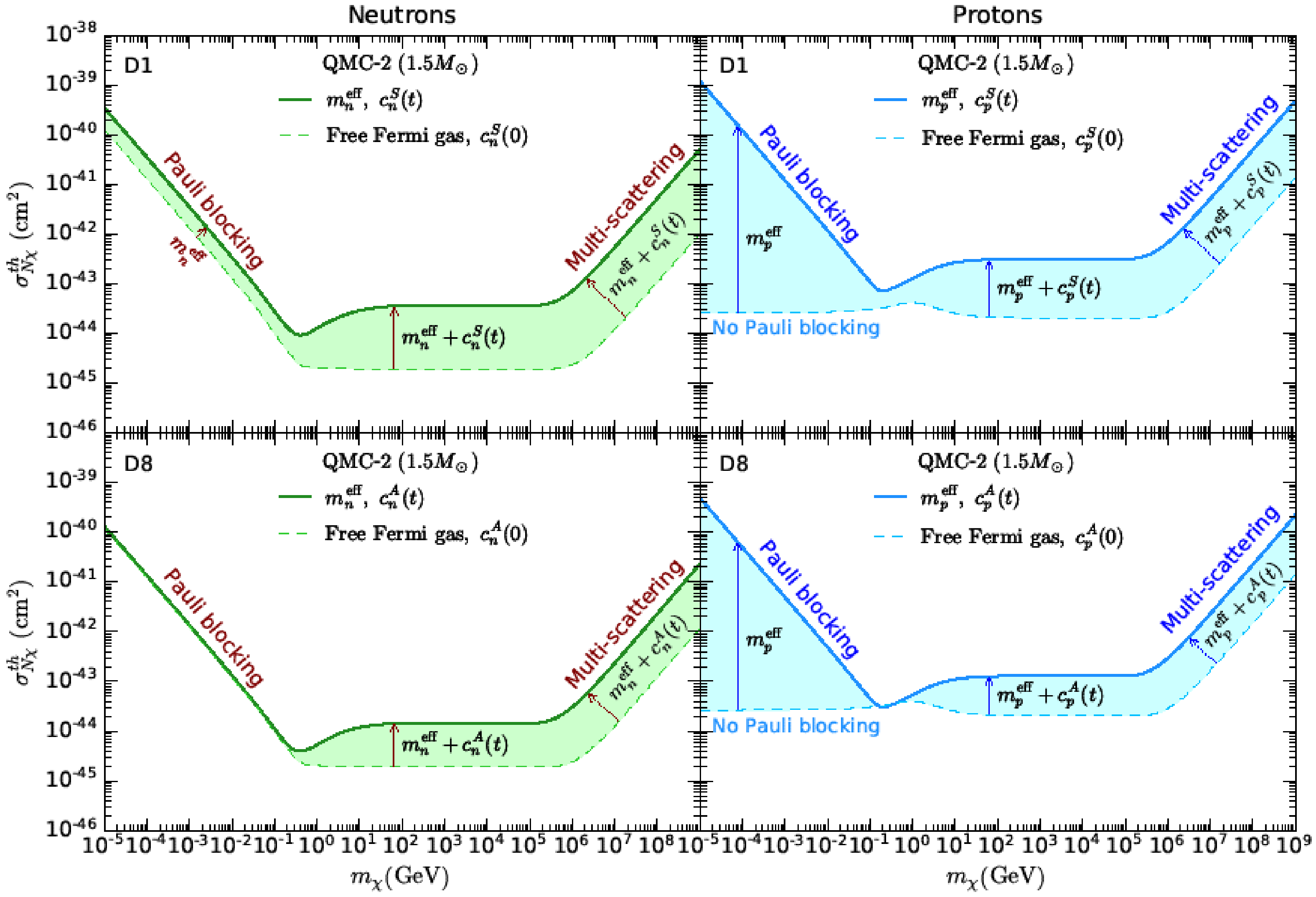
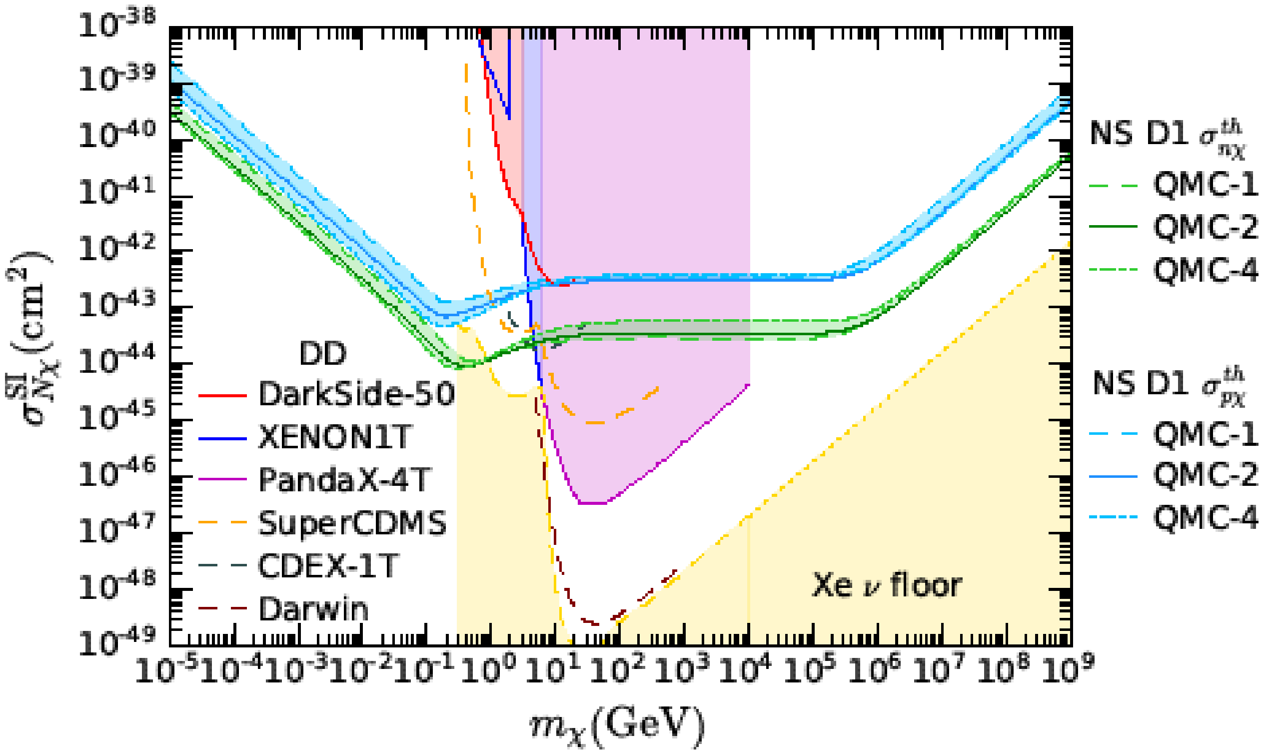


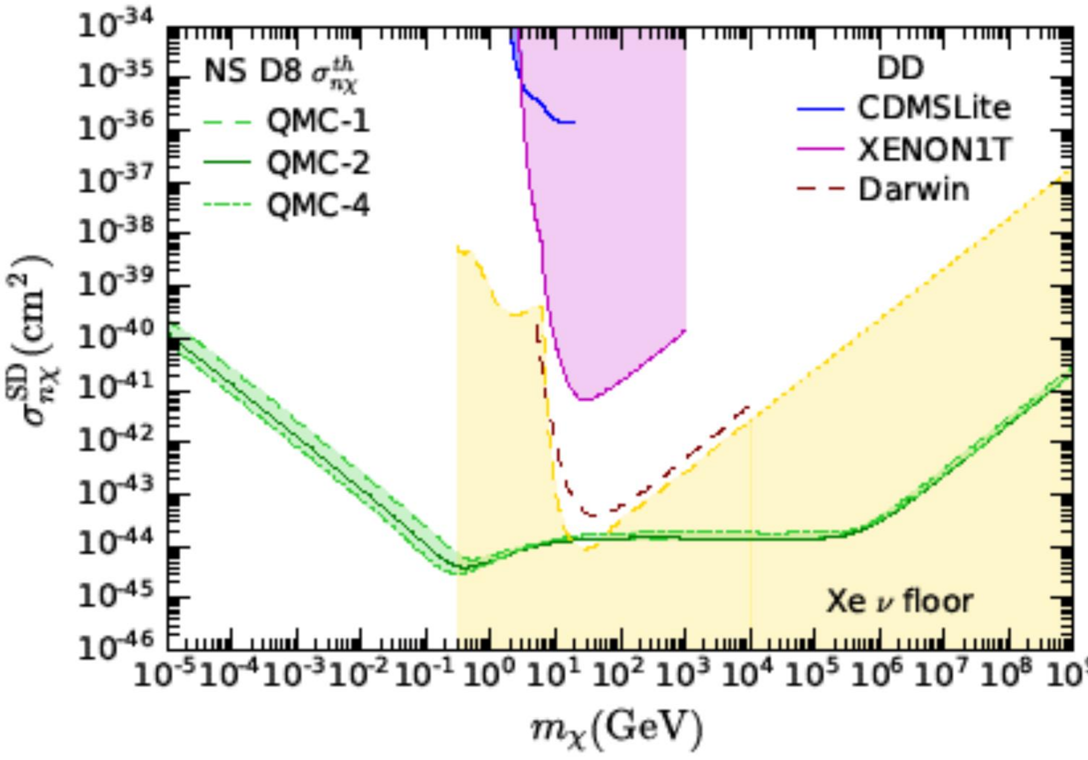
NFB, Busoni, Motta, Robles, Thomas and Virgato, arXiv:2108.02525

Kinetic Heating Sensitivity: nucleon scattering

Spin-Independent (SI)



Spin-Dependent (SD)



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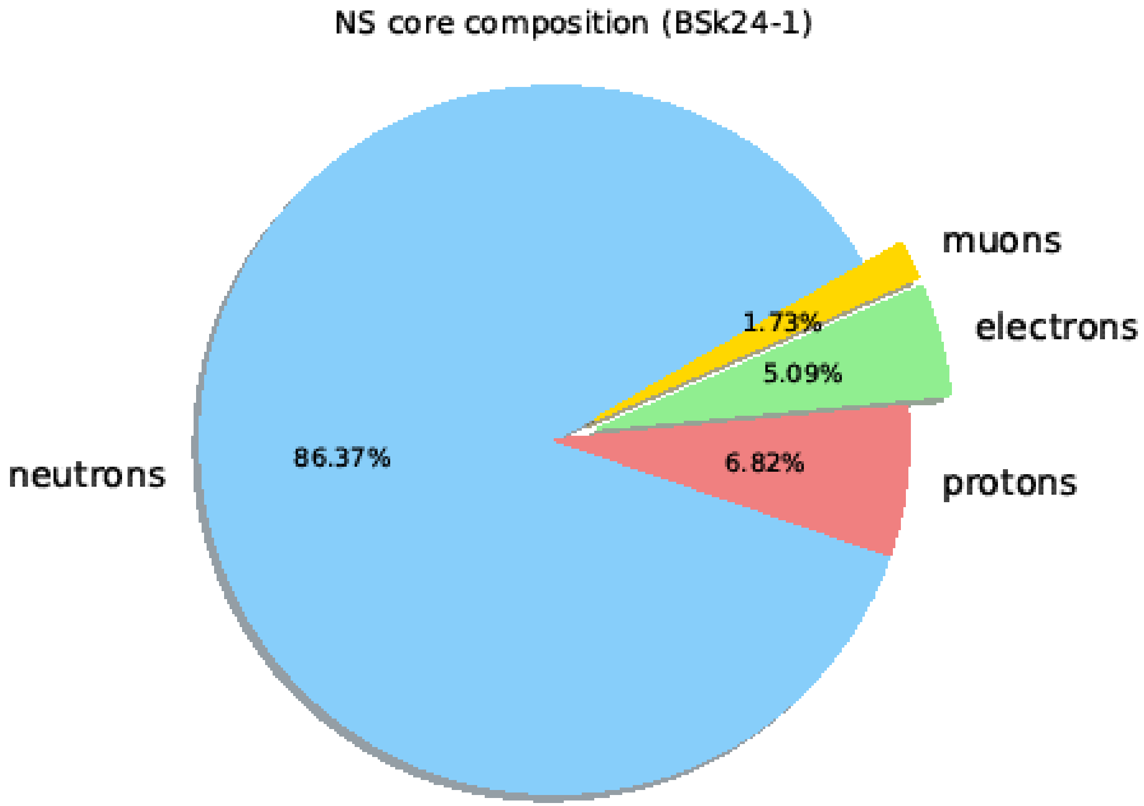
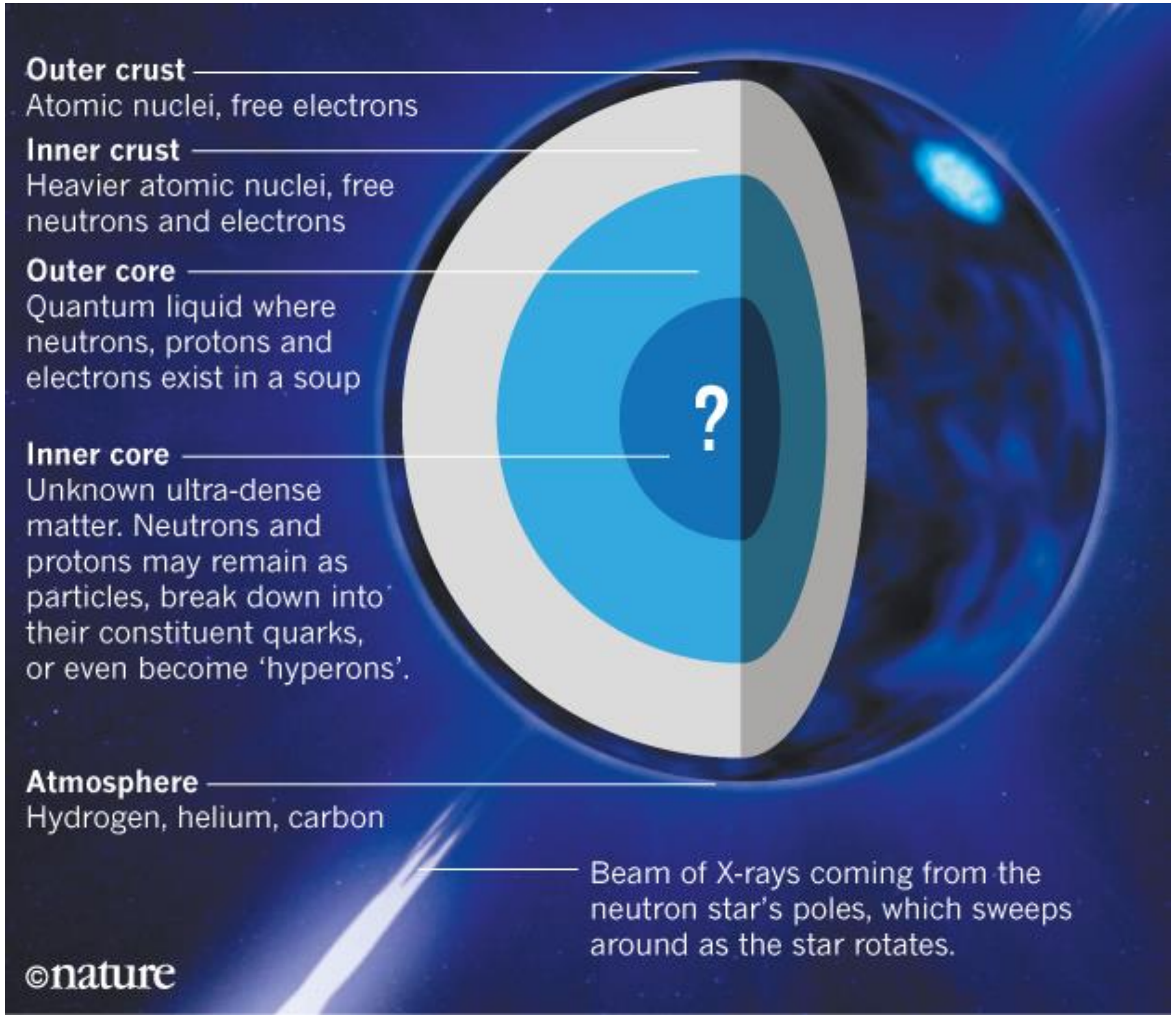
Leptons in Neutron Stars



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



Beta equilibrium in the core determines the composition:

- Degenerate neutrons
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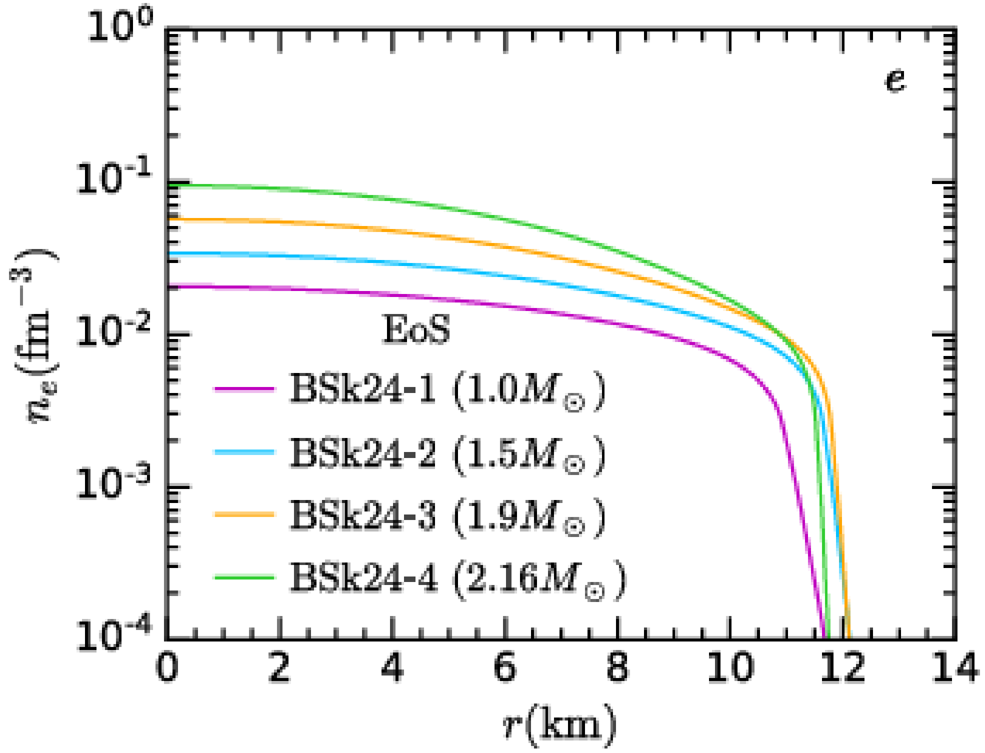
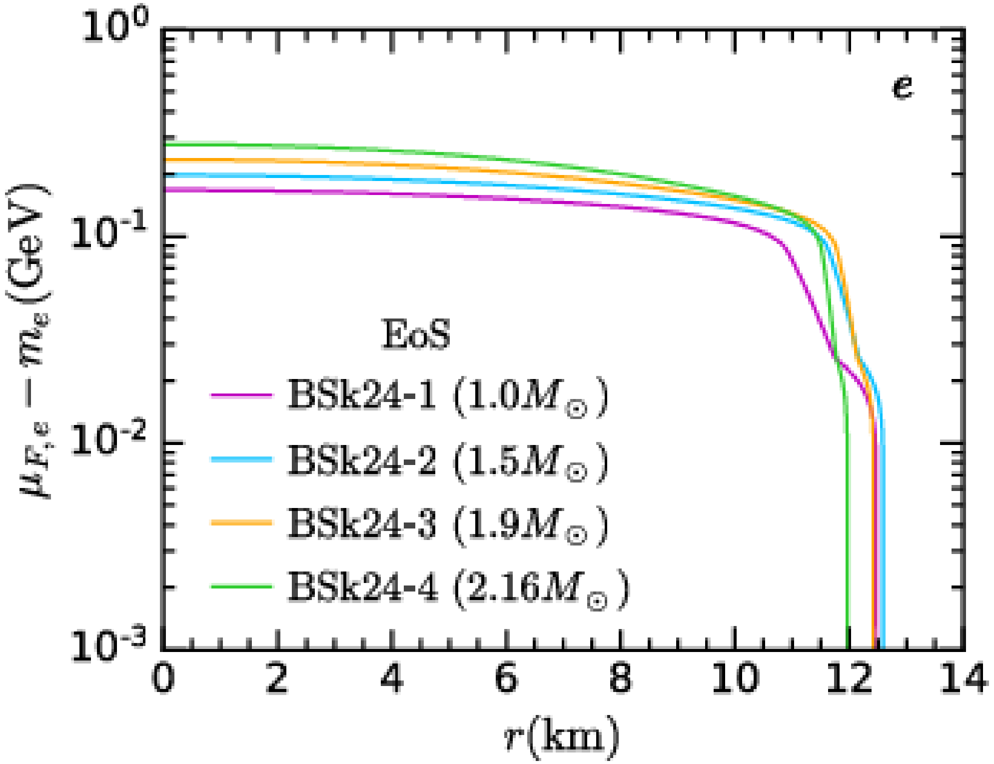
Leptons in Neutron Stars

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

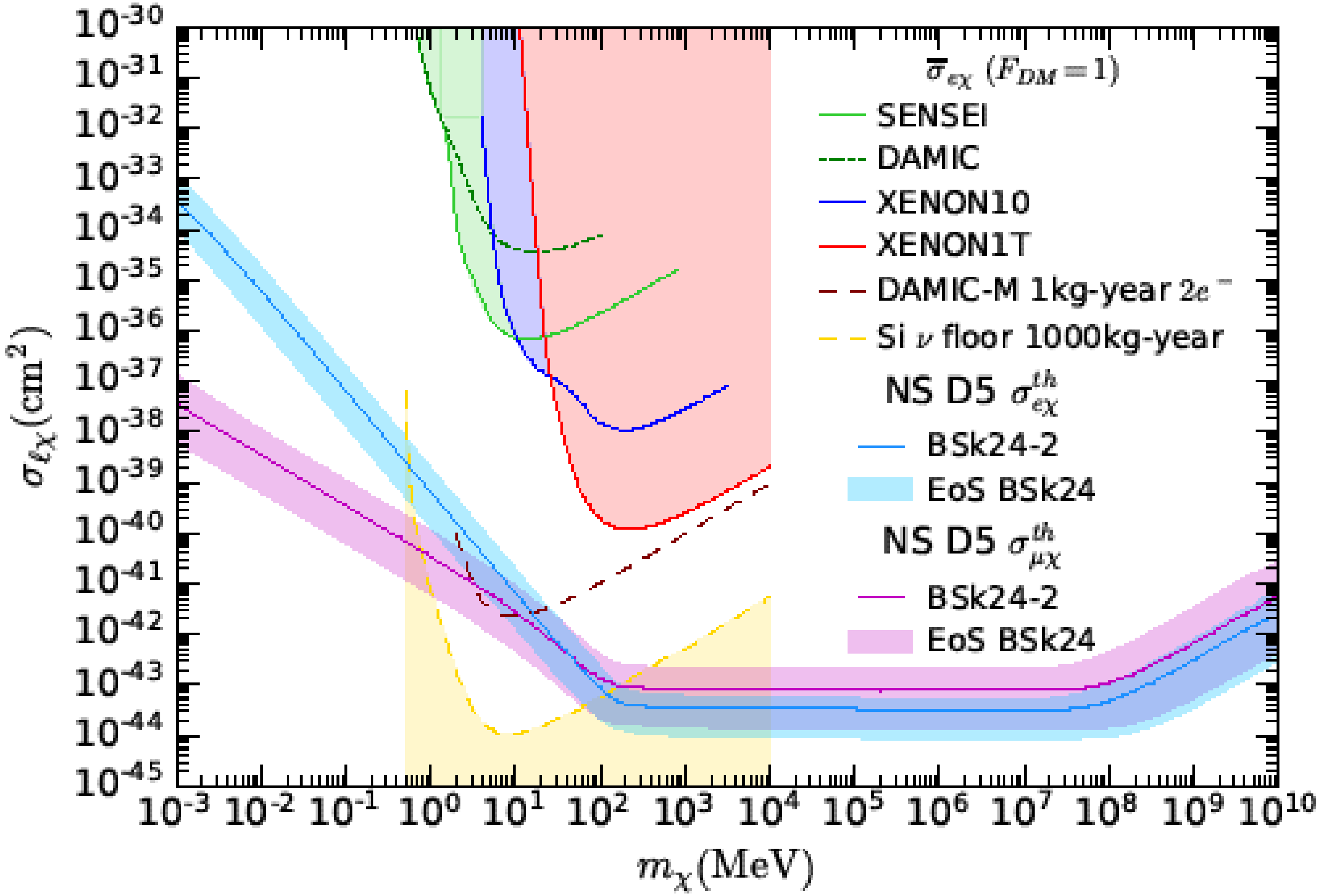




NFB, Busoni, Robles & Virgato arXiv:2010.13257

Lepton scattering – improved treatment (relativistic)

NFB, Busoni, Robles & Virgato arXiv:2010.13257



Muon scattering

Electron scattering

Summary & Conclusions

Dark matter capture in stars

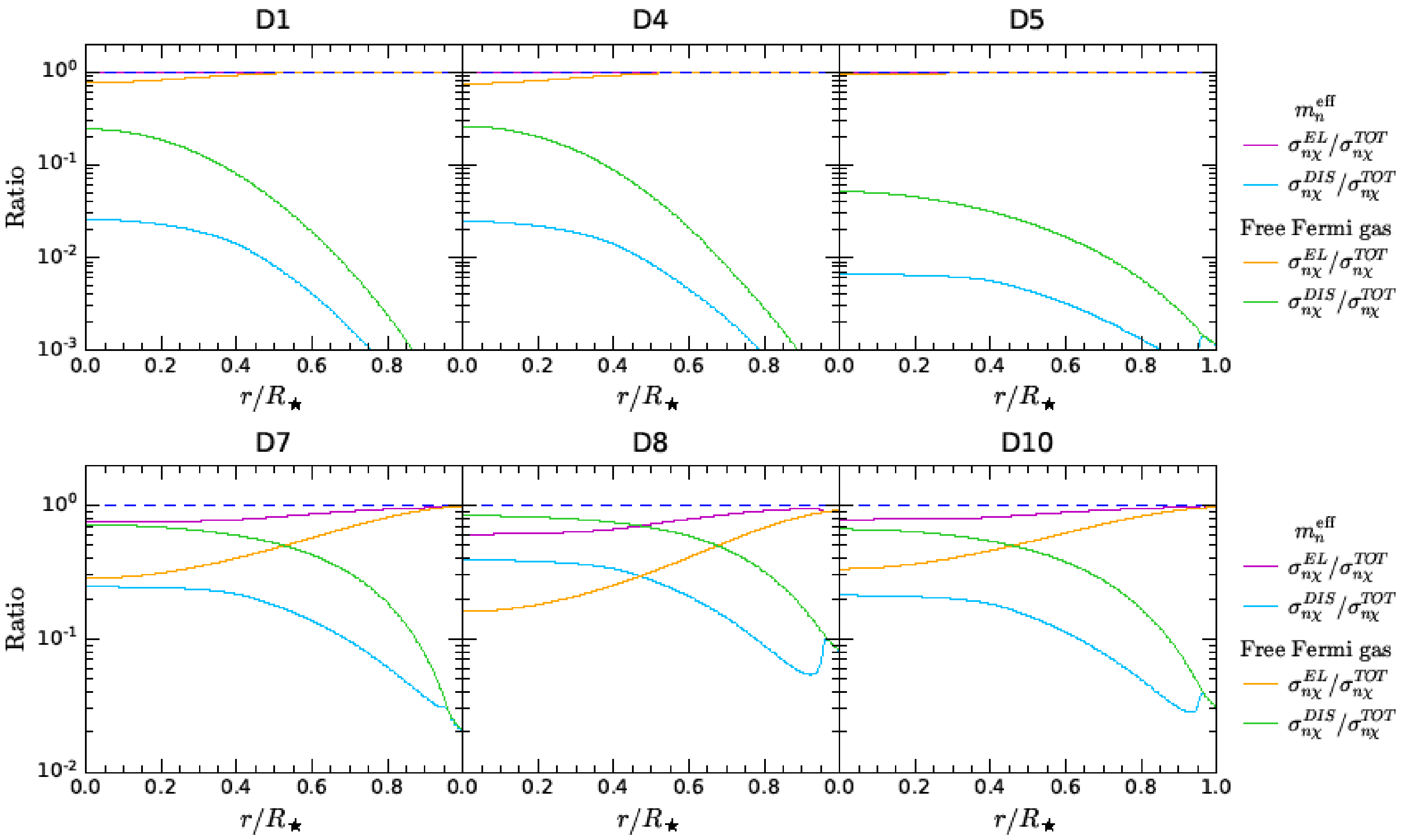
→ cosmic laboratory to probe dark matter scattering interactions

- Neutron stars probe a completely different kinematic regime to direct detection
  - Scattering of quasi-relativistic dark matter

    →no velocity or momentum suppressions
- Capture calculations have recently been significantly refined and improved.
- Neutron Star kinetic heating sensitivity would potentially be better than current and forthcoming direct detection experiments, for both nuclear-recoil and electron-recoil scattering.

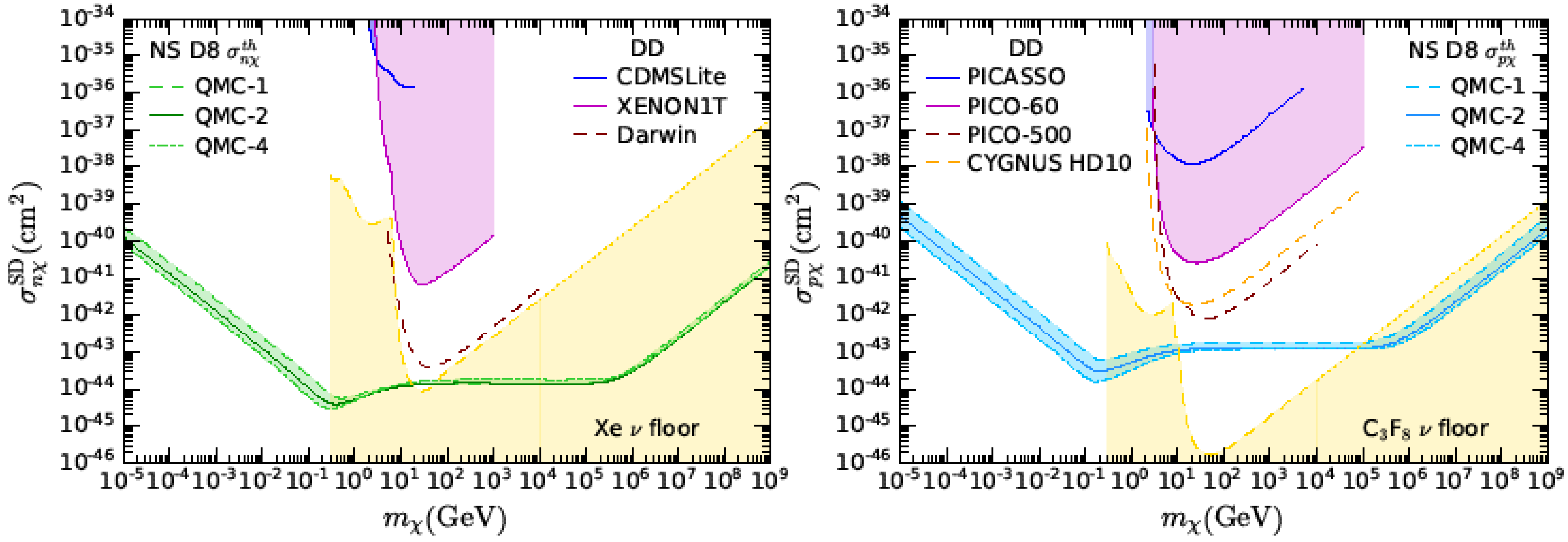
Backup slides

Deep inelastic scattering contribution is subdominant



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

Spin-dependent



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

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

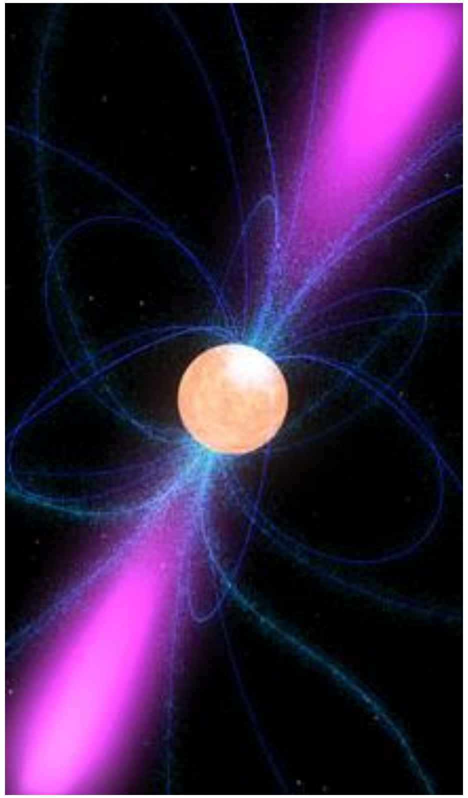
Old isolated neutron stars should cool to: 1000 K after ~ 10 Myr
100 K after ~ 1 Gyr

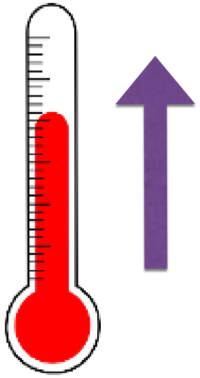
Detecting the Heating

Nearby ≲ 50 pc
isolated old NSs

M. Baryakhtar et al.
PRL 119, 131801 (2017)
arXiv:1704.01577

FAST (radio)

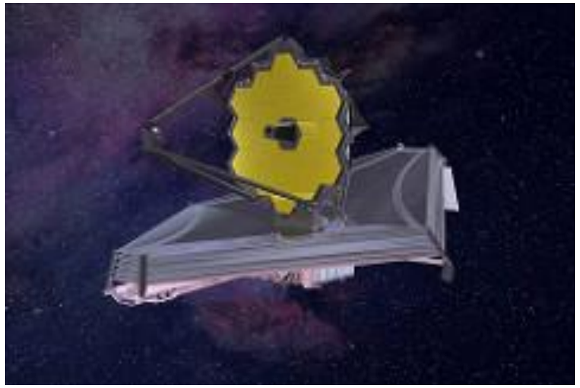




T_{NS} ~ 2000 K

1 - 2 μm

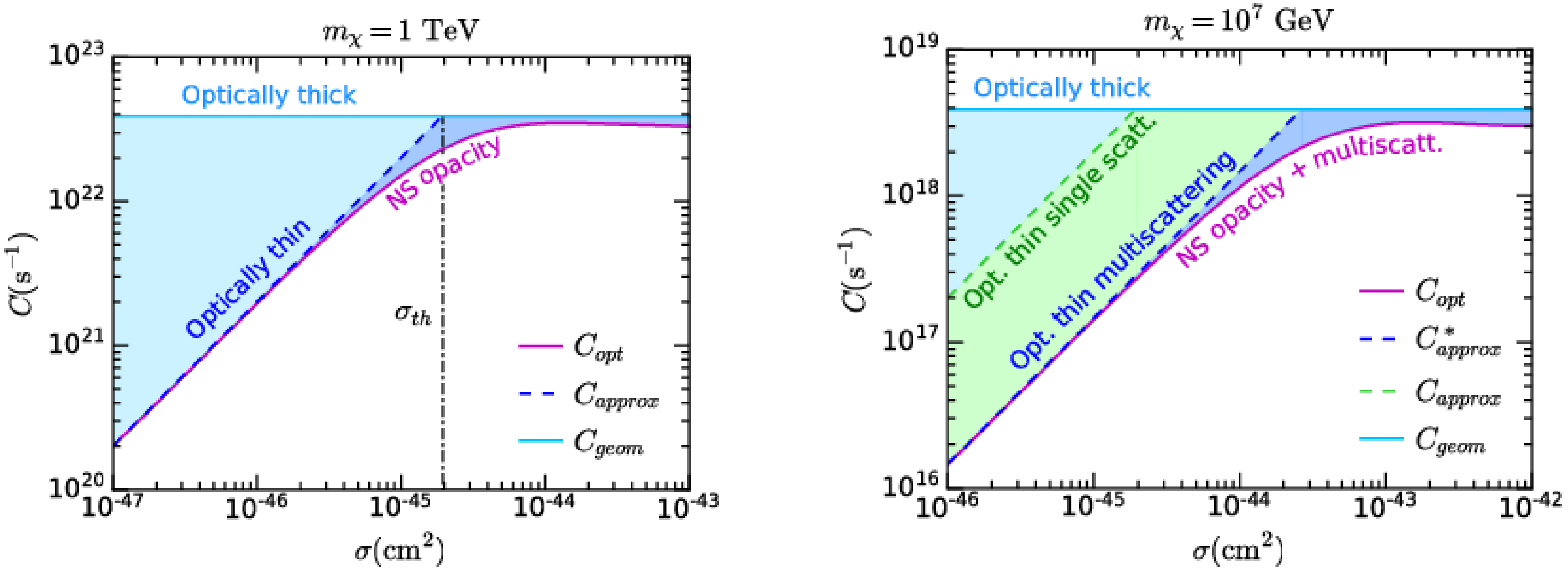
near IR



JWST (NIRCam)

Neutron star opacity

NFB, Busoni, Robles & Virgato arXiv:2004.14888



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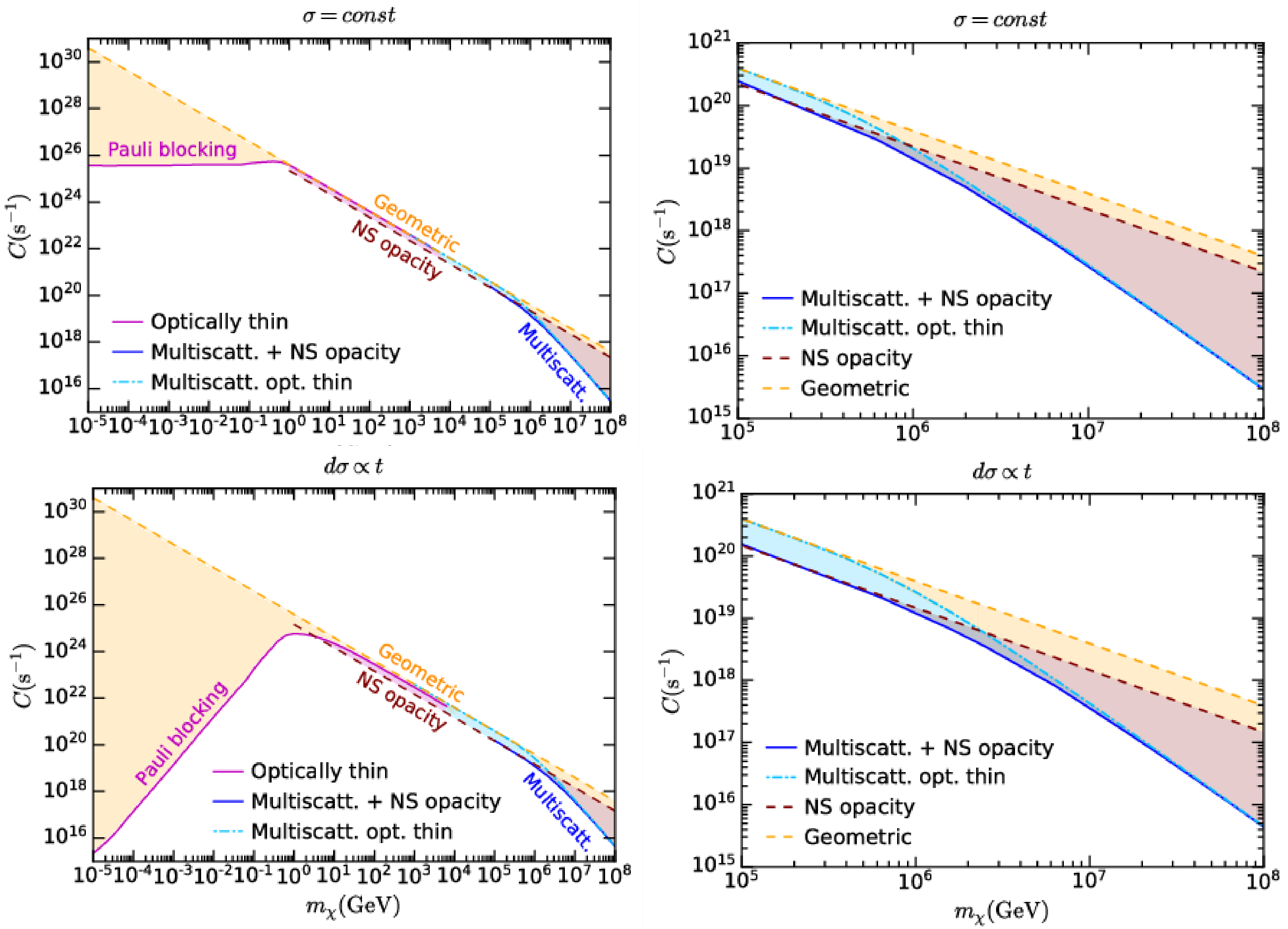

Including Pauli blocking, multiscattering and opacity effects.