Dark Matter Capture in Neutron Stars

Nicole Bell

ARC Centre of Excellence for Dark Matter Particle Physics, The University of Melbourne, Australia

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

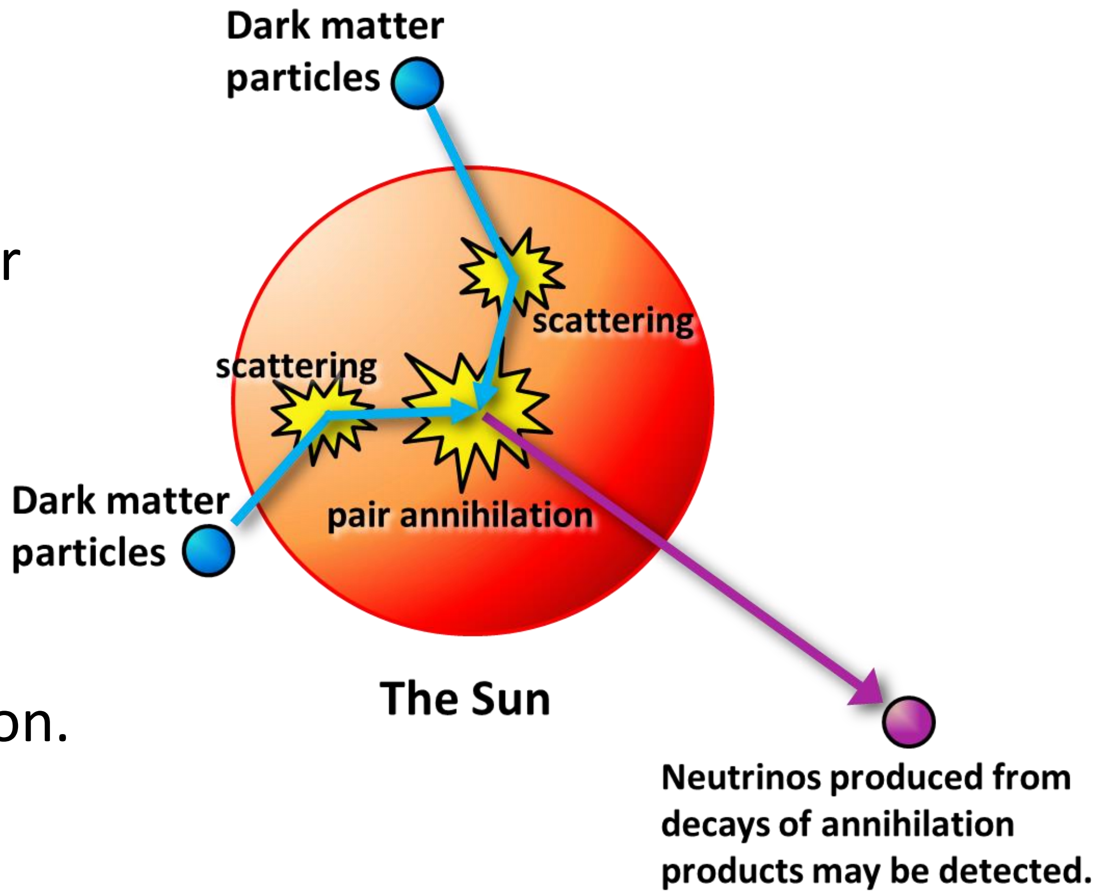
arXiv:1807.02840, arXiv:1904.09803, arXiv:2004.14888, arXiv:2010.13257, arXiv:2012.08918, arXiv:2108.02525

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

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

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**

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

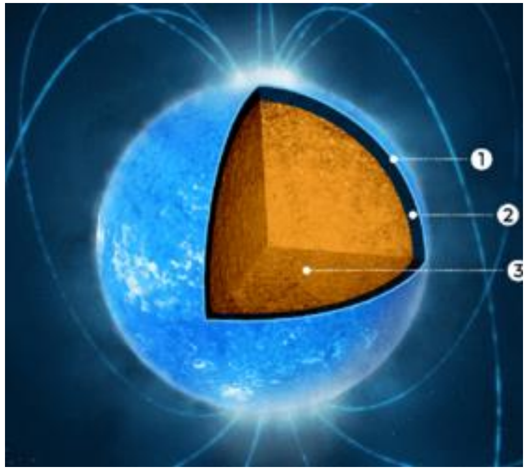
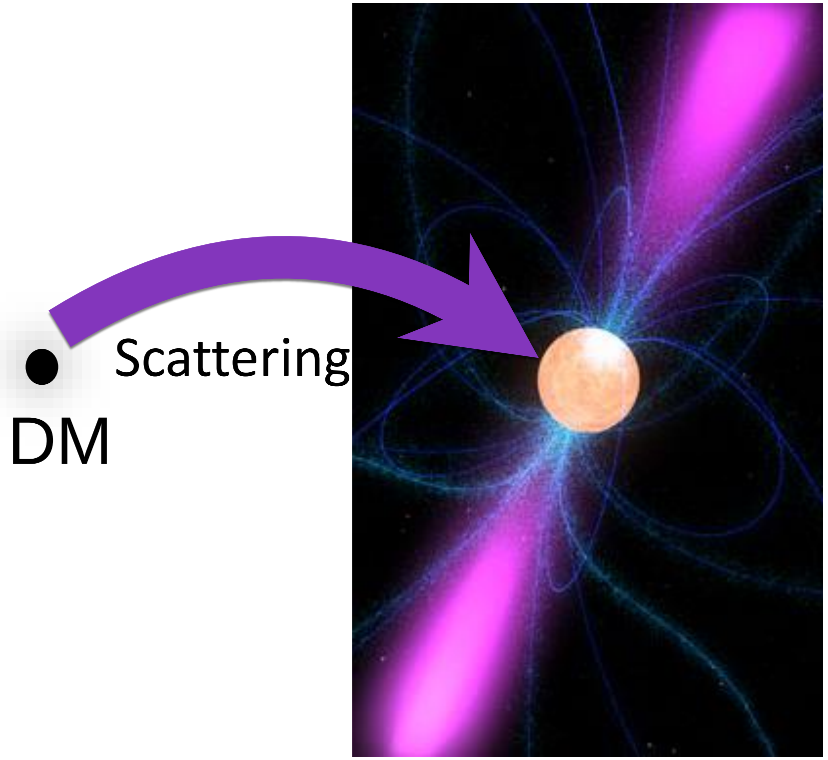


Image: NASA



Neutron Stars → Black holes?

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

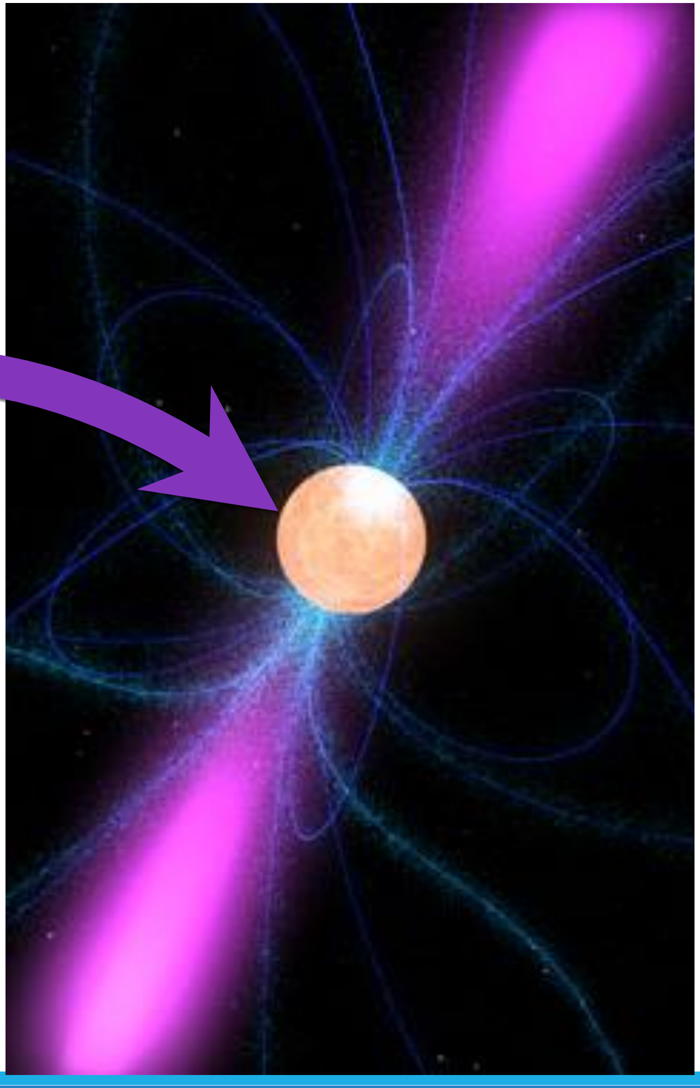
- Due to their density, neutron stars capture dark matter very efficiently

- 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 very tiny self-interaction is enough) **NFB, Petraki & Melatos, PRD 2013**

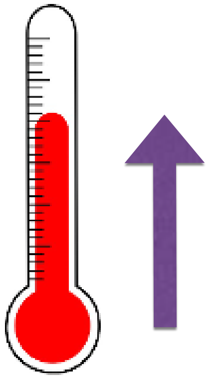
→ **Black hole formation possible but quite unlikely for *typical* WIMP-like dark matter**

Neutron Star 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

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

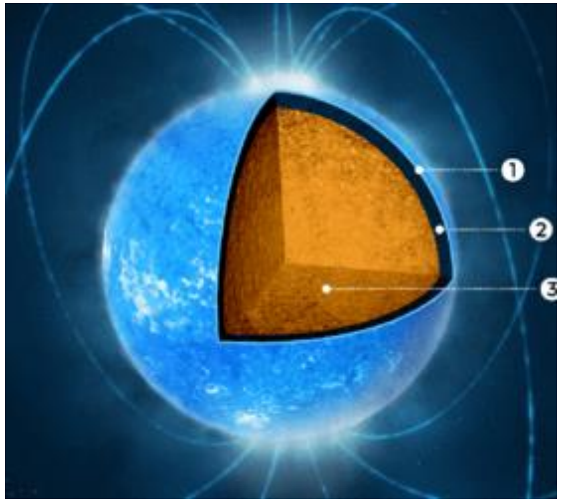
- **Annihilation** of thermalised dark matter
  → DM ***rest mass energy*** heats neutron star ~ additional 700K

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)

- 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 $v \ll c$	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

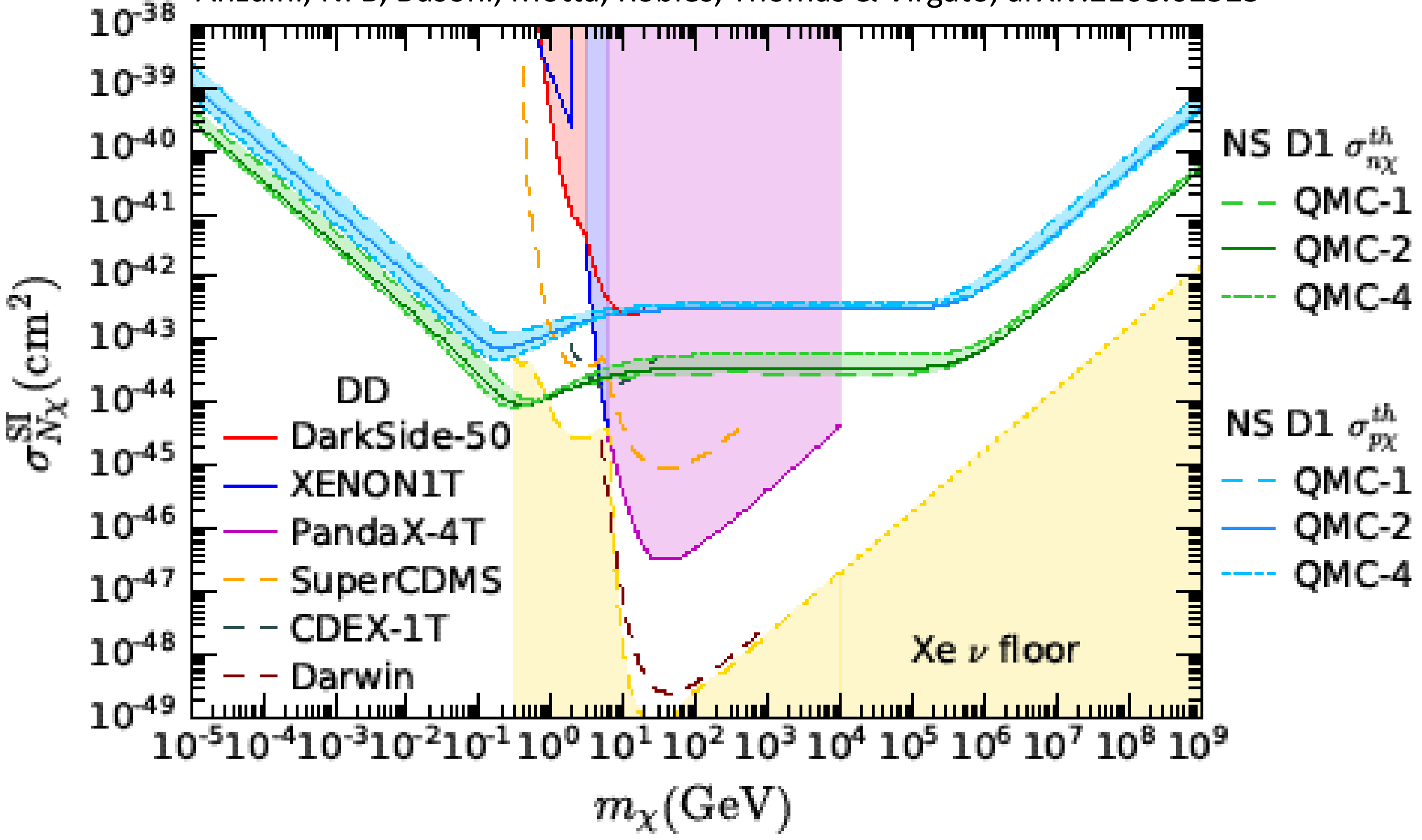


- **no velocity/momentum suppression → sensitive to interactions that direct detection cannot probe**
- **not limited by recoil detection thresholds → sensitive to very low mass DM**
- **Similar sensitivity to SI and SD scattering**

Kinetic Heating Sensitivity

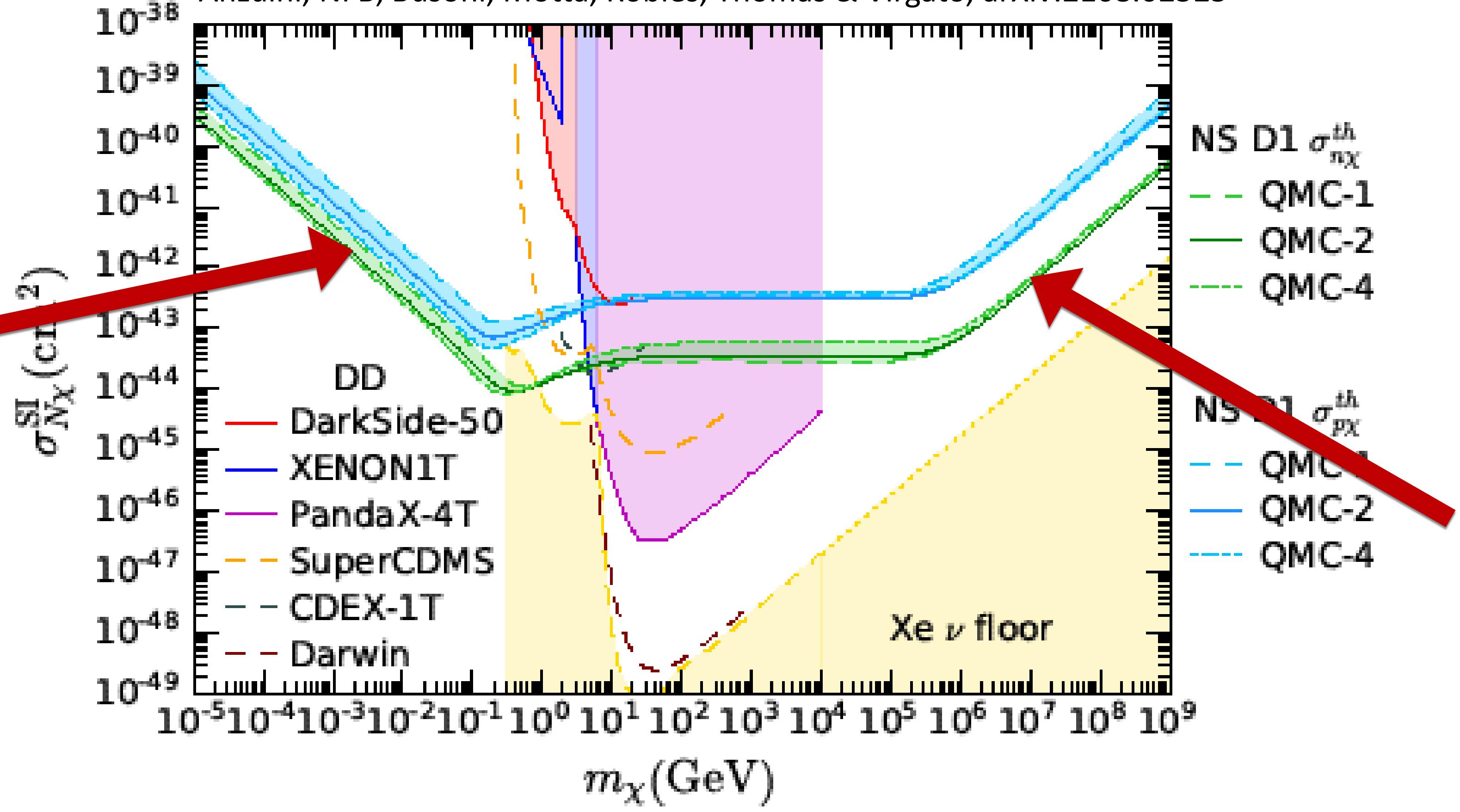
Ball-park sensitivity = geometric cross section $\sim 10^{-45}\mathrm{cm}^2$

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



Kinetic Heating Sensitivity

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

Direct Detection vs Neutron Stars

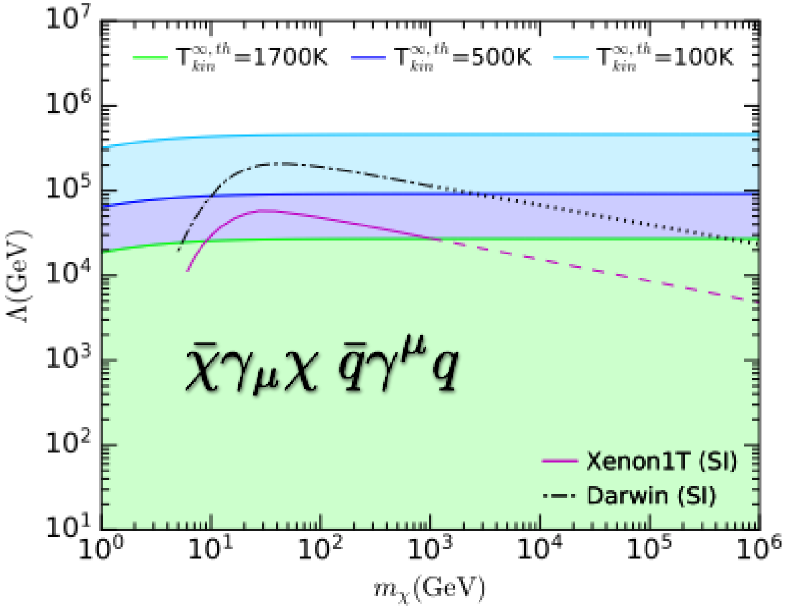
Operator			Coupling	Direct Detection	Momentum suppressed	DD vs NS
D1	SS	$(\bar{\chi}\chi)(\bar{q}q)$	y_q/Λ^2	SI	✗	NS or DD
D2	PS	$(\bar{\chi}\gamma_5\chi)(\bar{q}q)$	y_q/Λ^2	SI	✓	NS
D3	SP	$(\bar{\chi}\chi)(\bar{q}\gamma_5 q)$	y_q/Λ^2	SD	✓	NS
D4	PP	$(\bar{\chi}\gamma_5\chi)(\bar{q}\gamma_5 q)$	y_q/Λ^2	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:

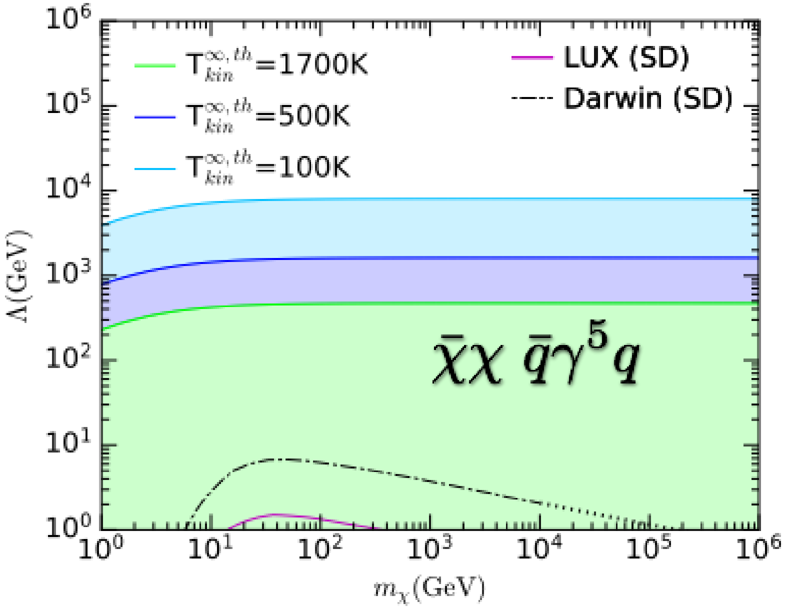
- comparable to direct detection experiments for scalar and vector interactions
- more sensitive than DD for all other interaction types (typically by orders of magnitude).

Neutron star sensitivity: DM-nucleon interactions

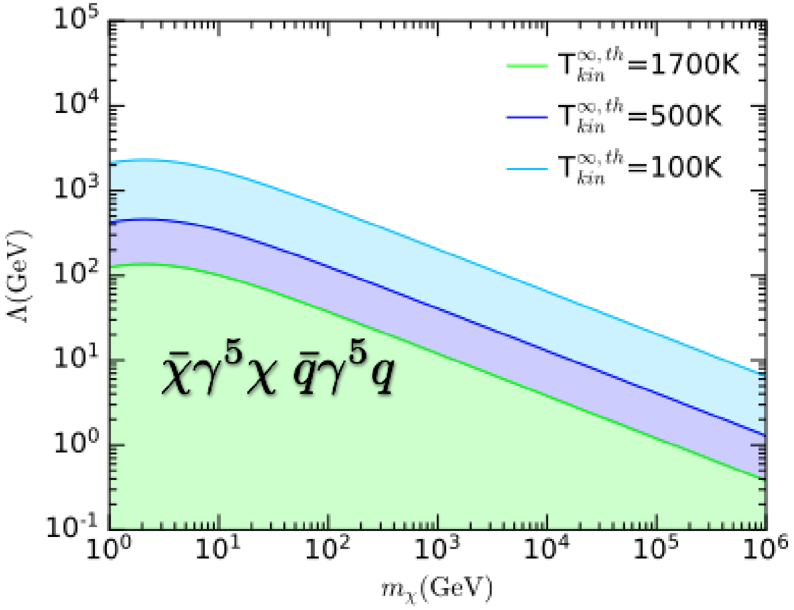
unsuppressed SI scattering



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

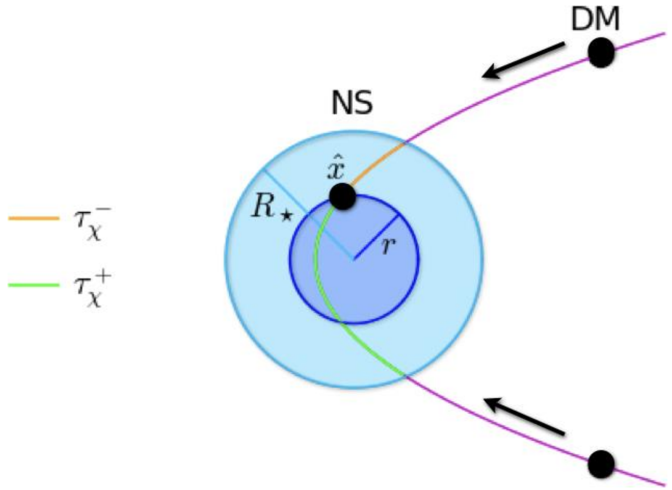
Improved capture calculations

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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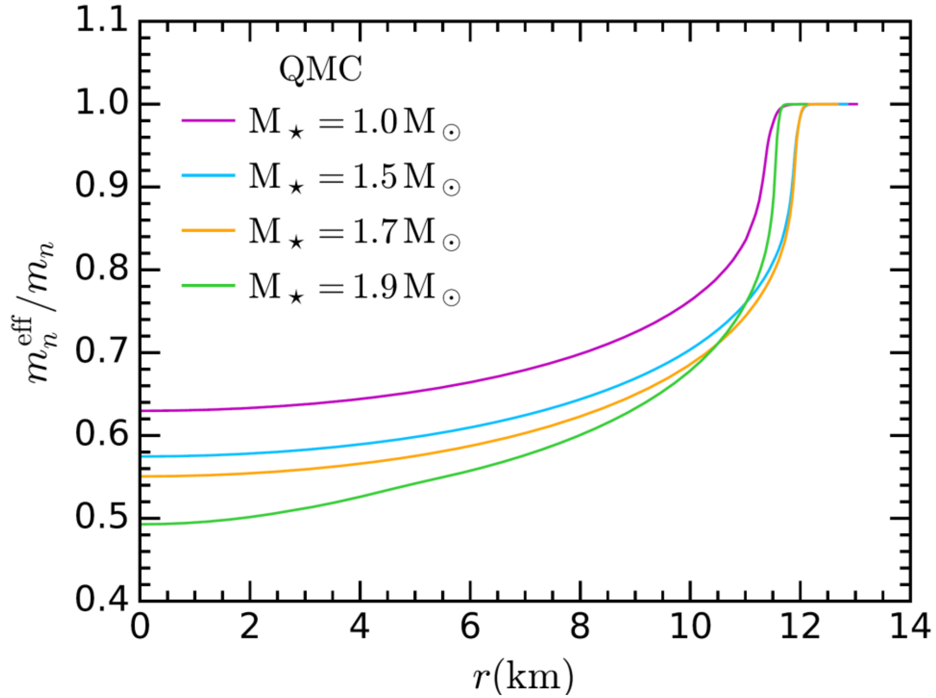
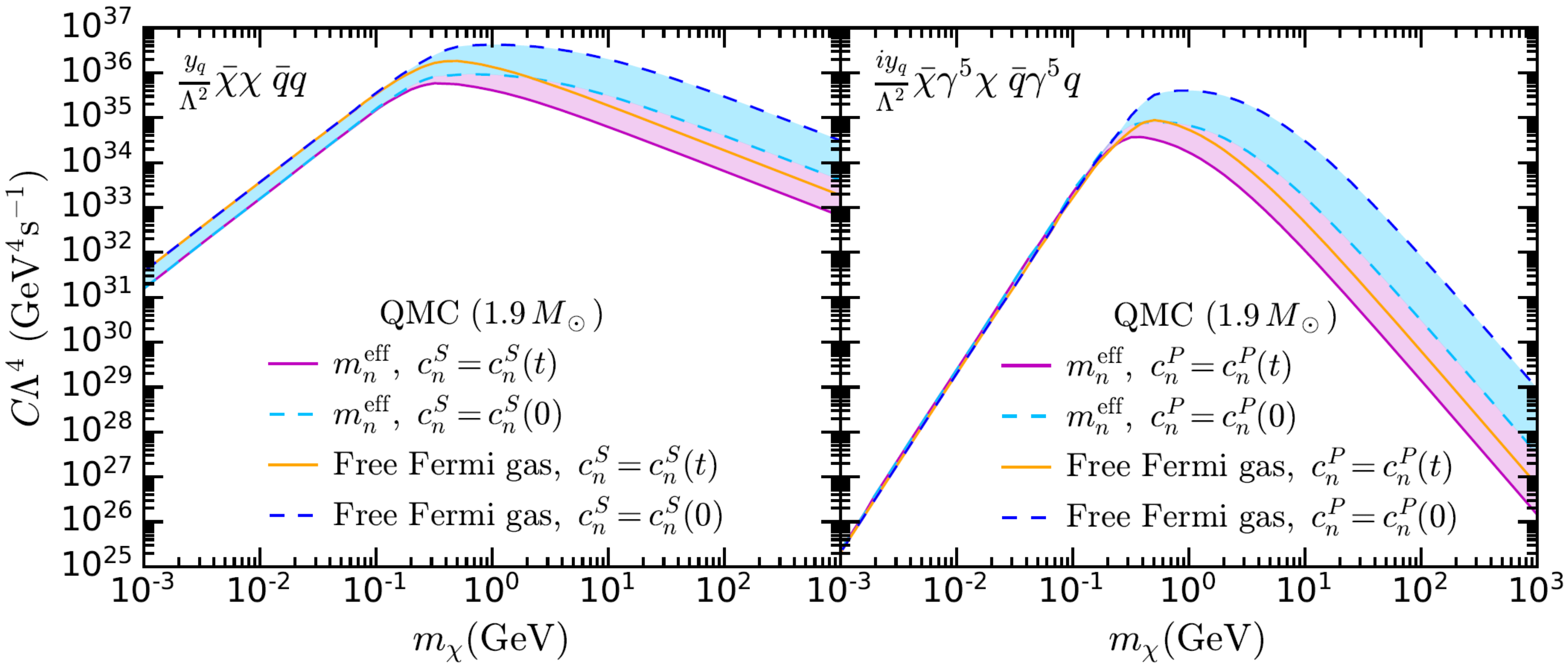
2. Nucleon Interactions:

- *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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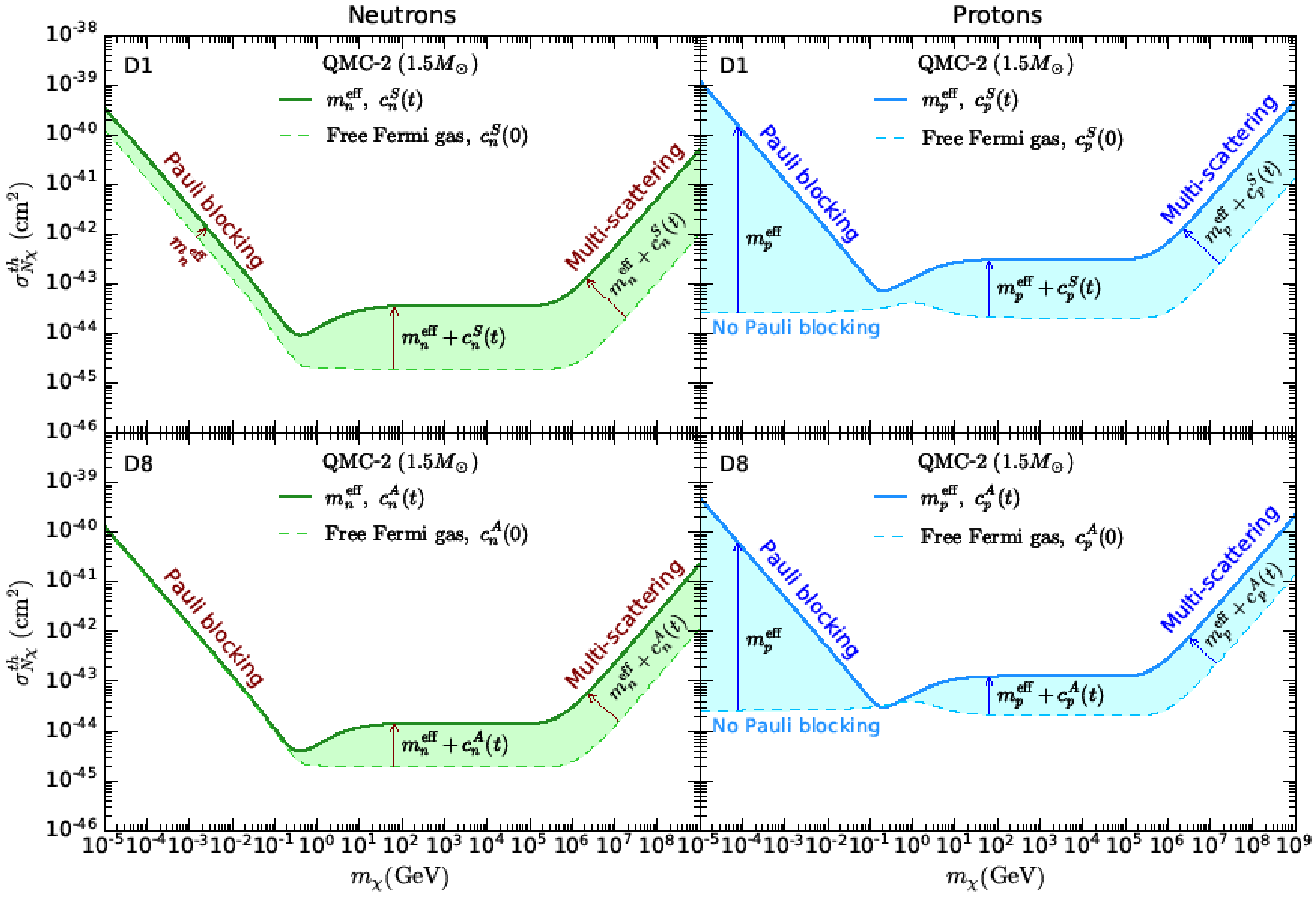
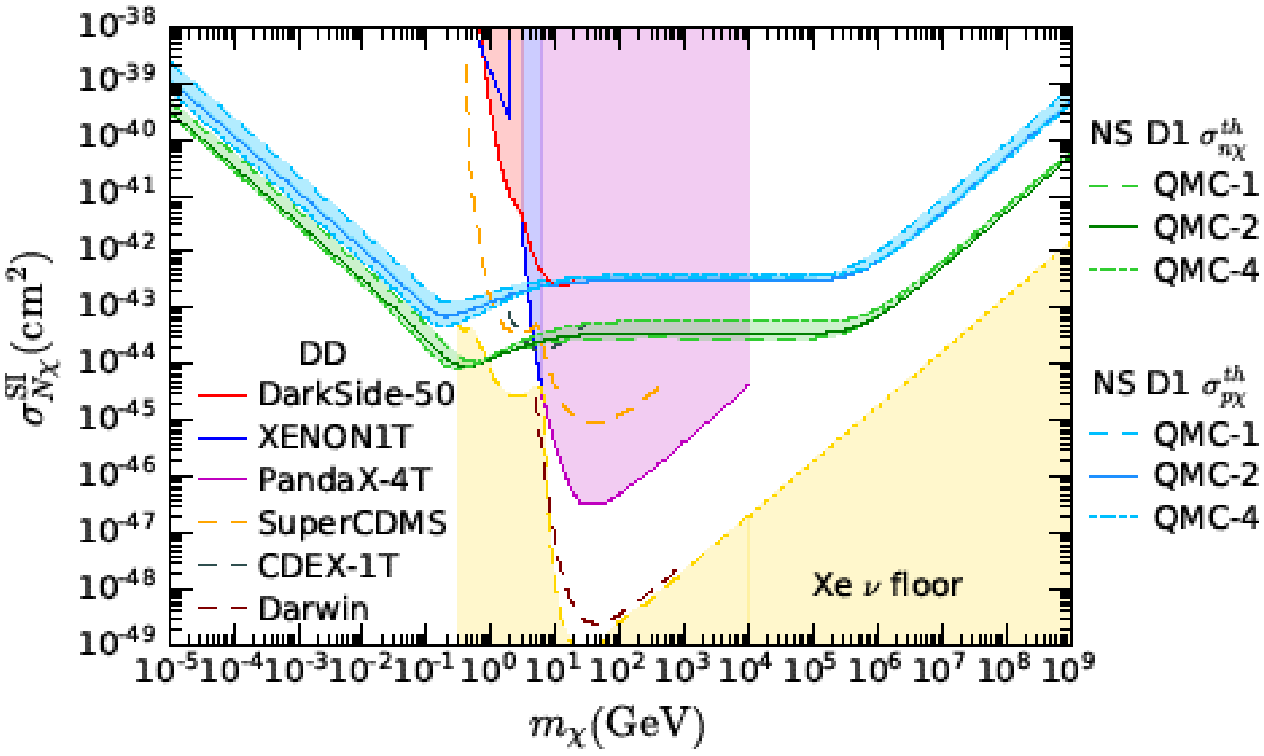


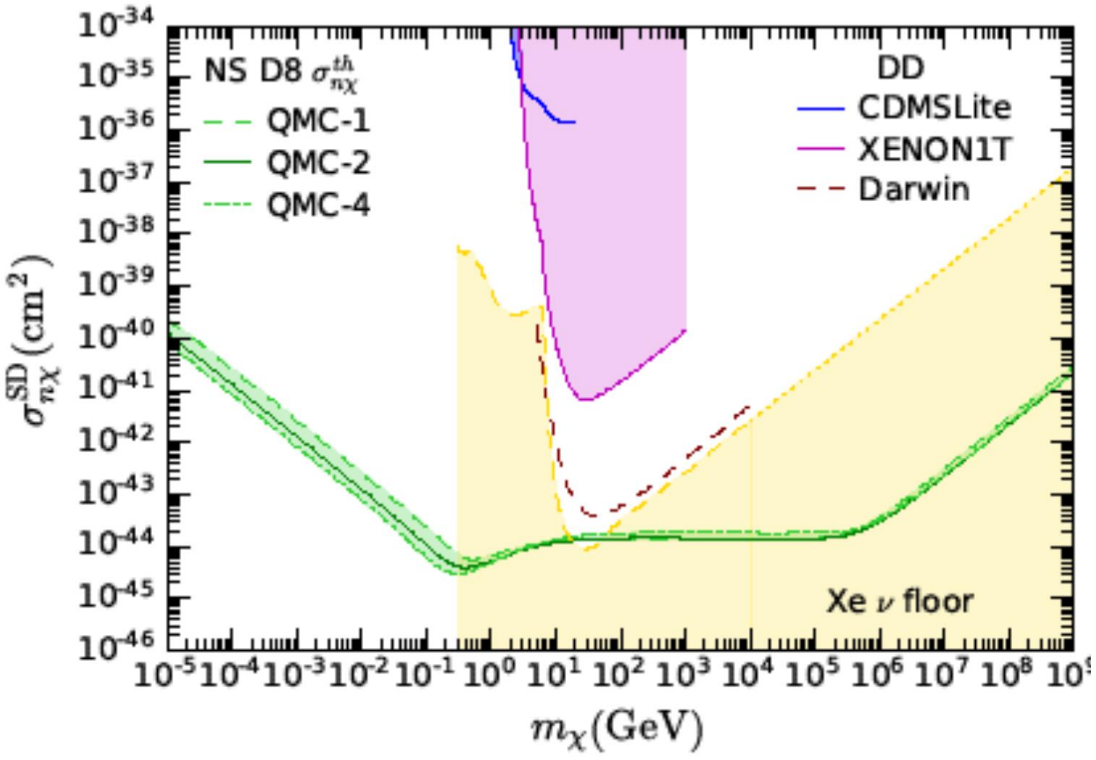
Anzuini, NFB, Busoni, Motta, Robles, Thomas and Virgato, arXiv:2108.02525

Kinetic Heating Sensitivity: nucleon scattering

Spin-Independent (SI)



Spin-Dependent (SD)



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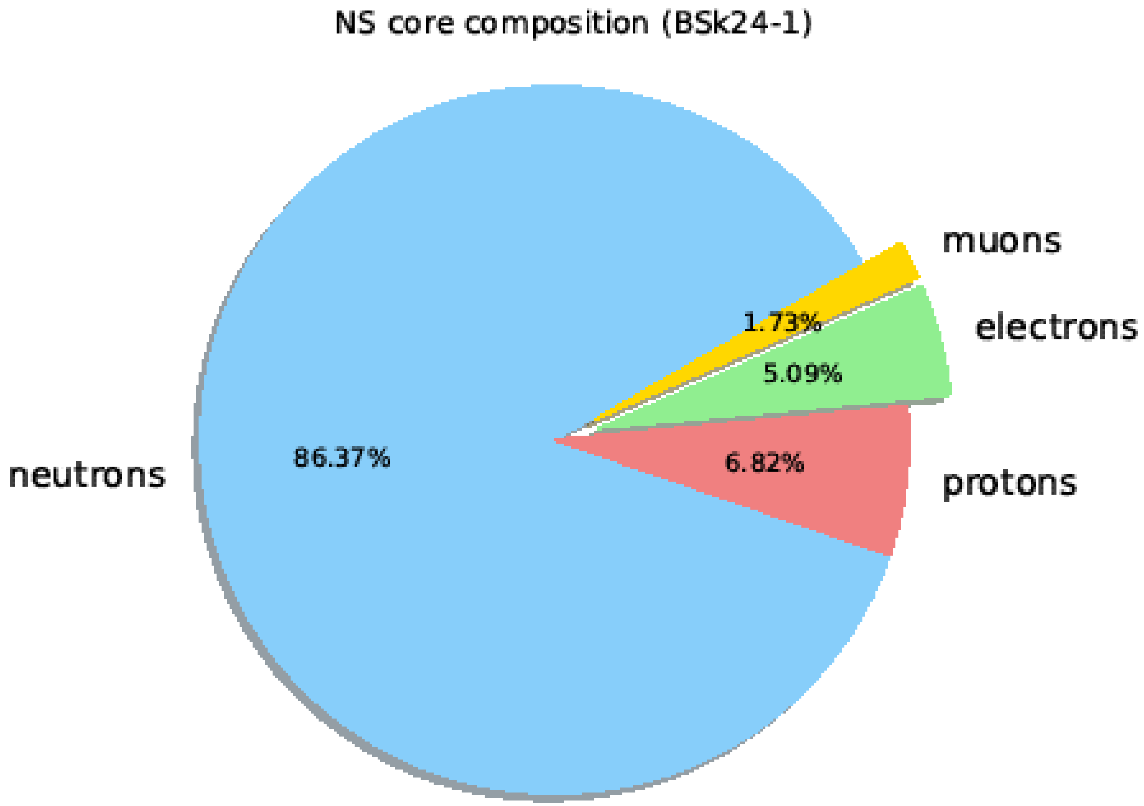
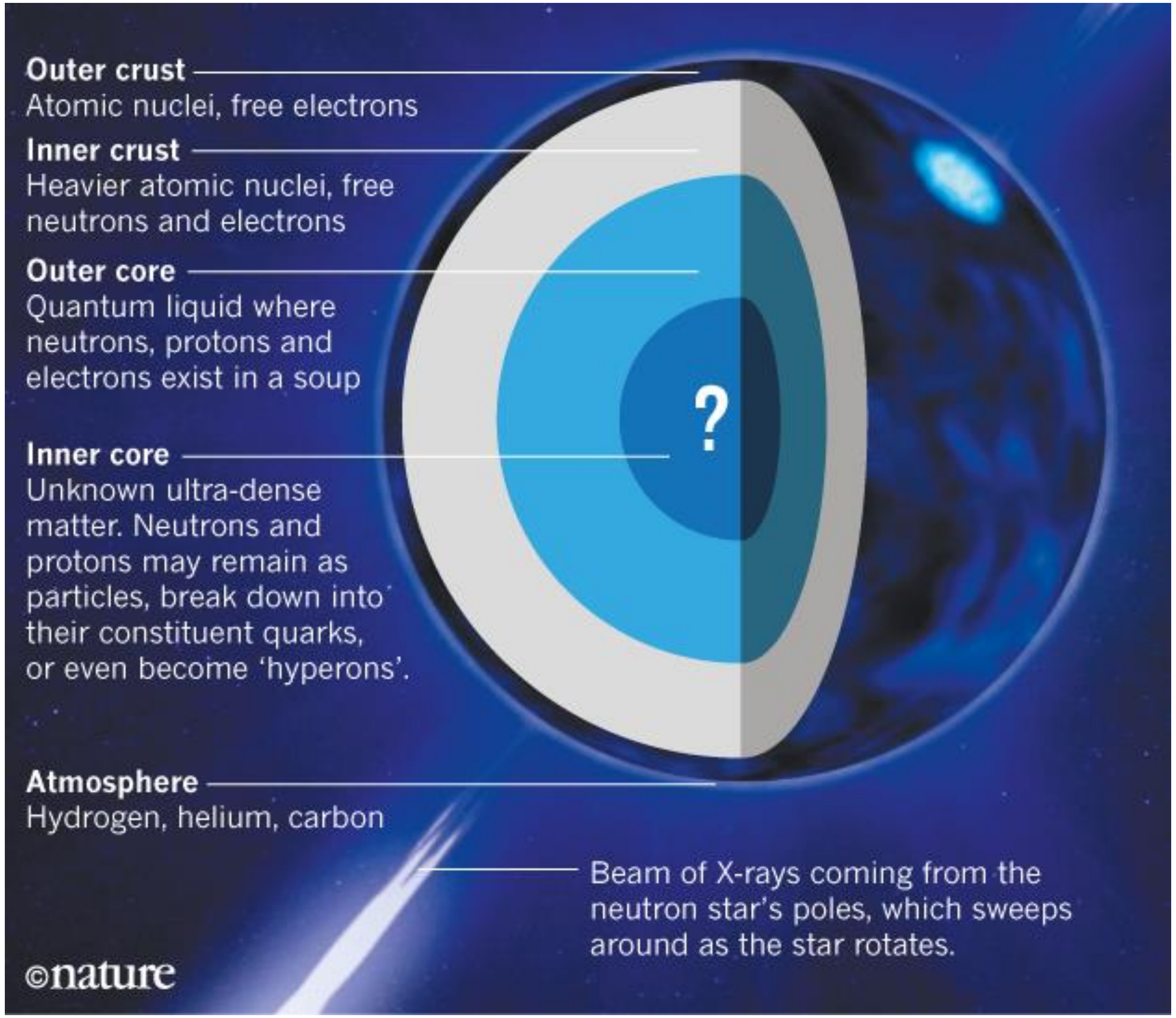
Leptons in Neutron Stars



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:

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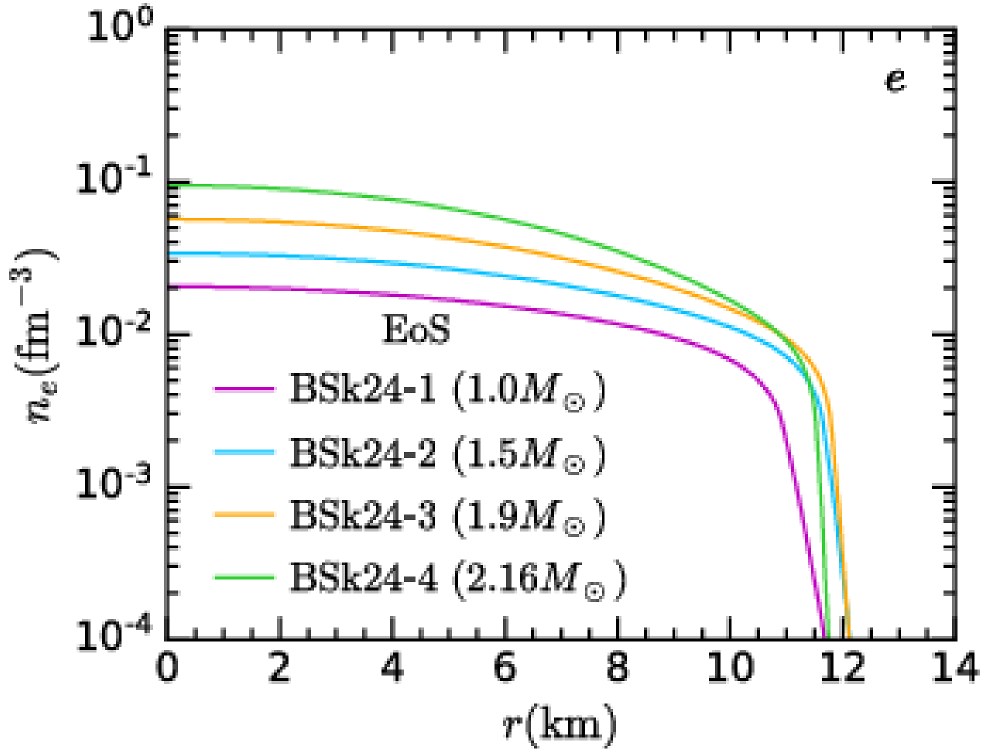
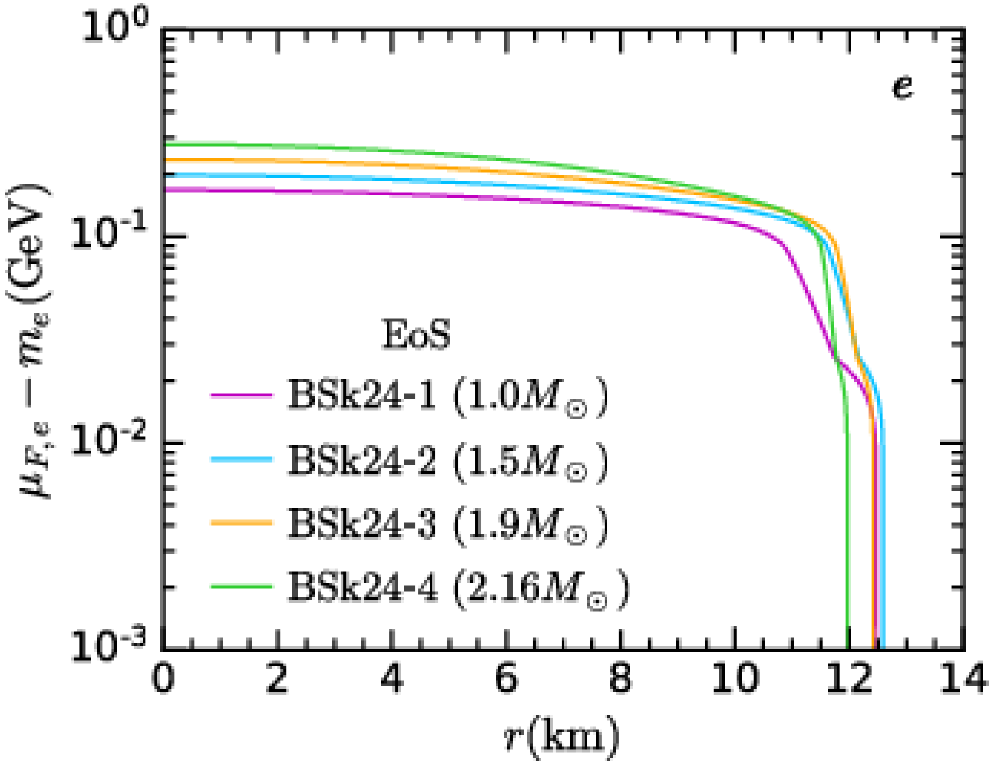
Leptons in Neutron Stars

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

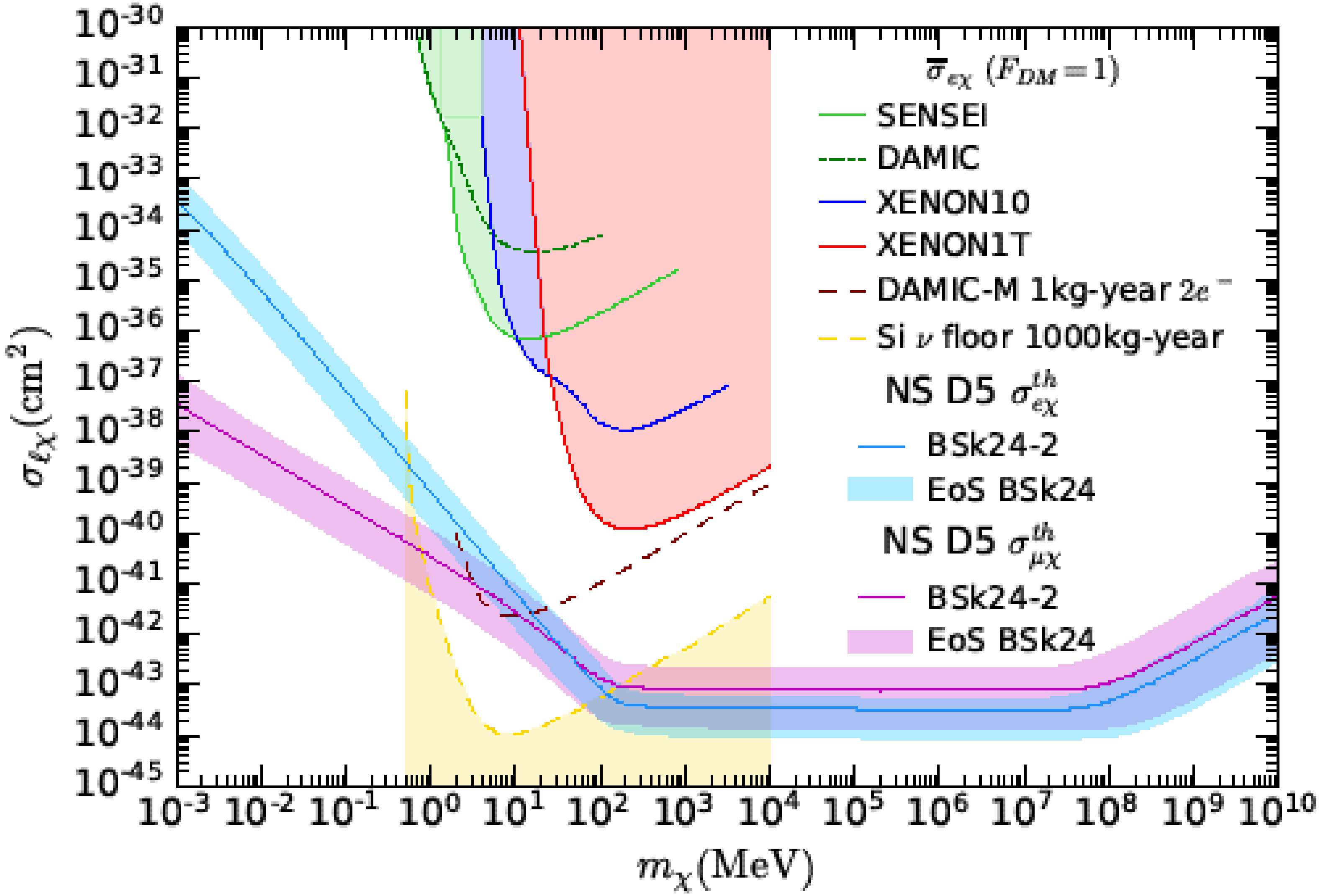




NFB, Busoni, Robles & Virgato arXiv:2010.13257

Lepton scattering – improved treatment (relativistic)

NFB, Busoni, Robles & Virgato arXiv:2010.13257



Muon scattering

Electron scattering

Summary & Conclusions

Dark matter capture in stars

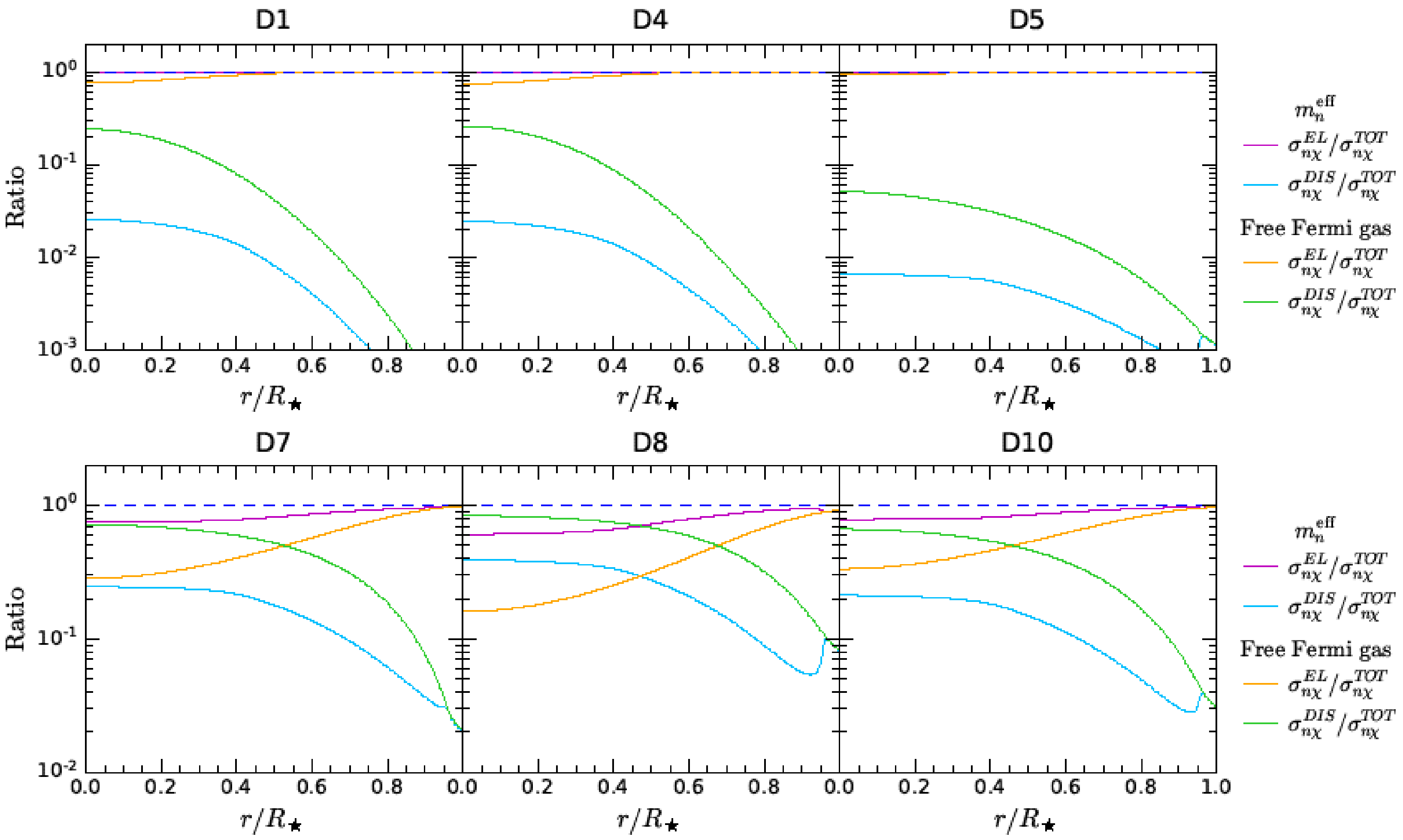
→ cosmic laboratory to probe dark matter scattering interactions

- 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.

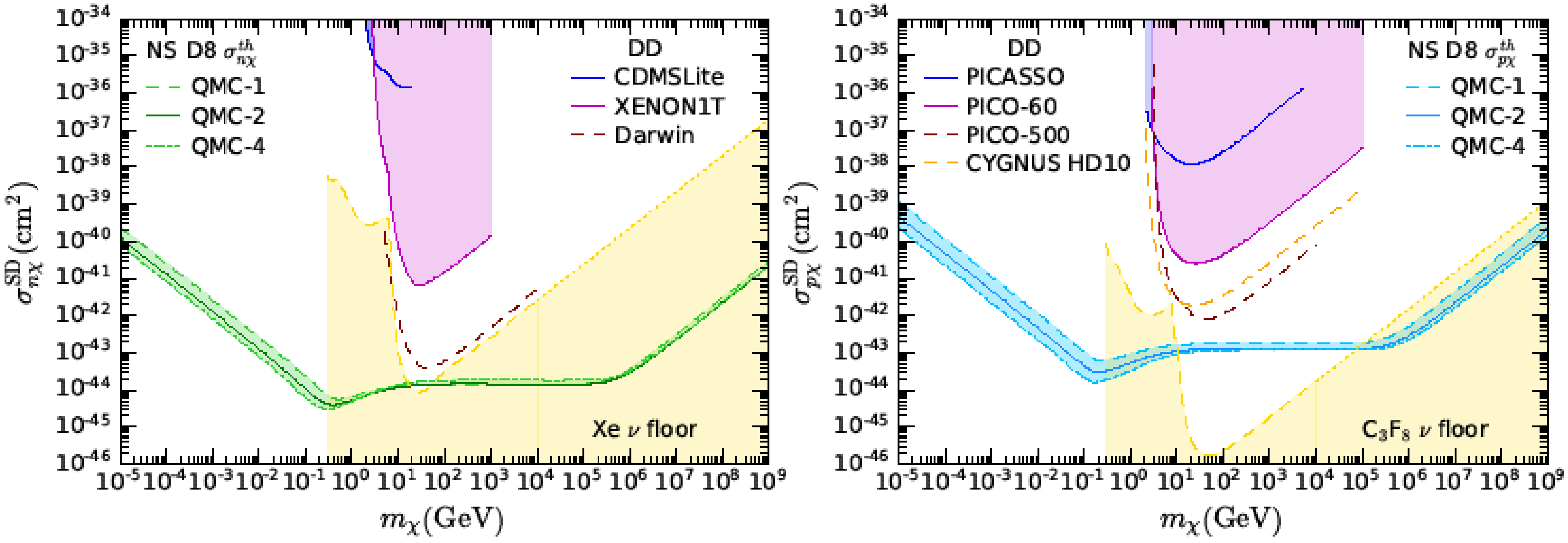
Backup slides

Deep inelastic scattering contribution is subdominant



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

Spin-dependent



Anzuini, 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

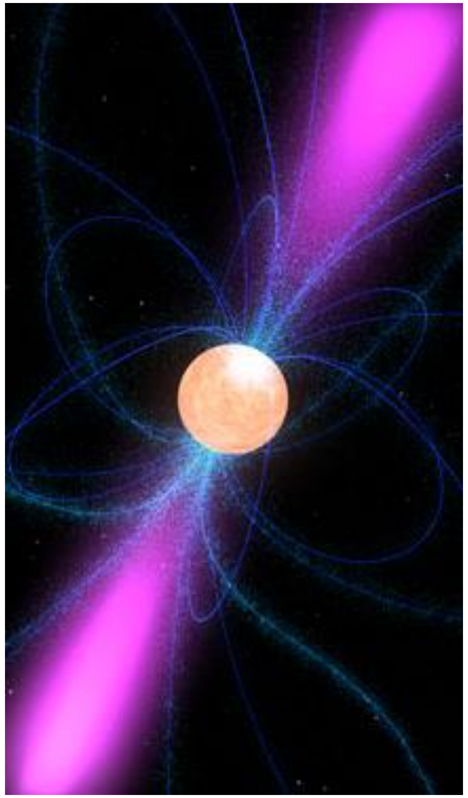
- Early cooling is dominated by neutrino emission
- Photon emission dominates at late times

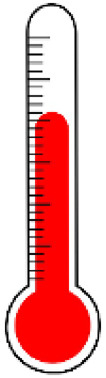
Coolest known neutron star (PSR J2144-3933) has a temperature of 4.2 x 10^4 K.
Astrophys.J. 874 (2019) no.2, 175

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





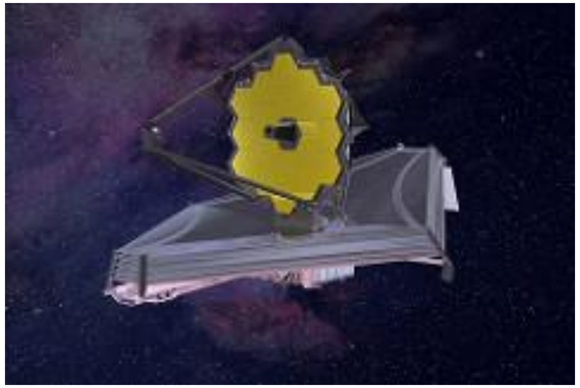
T_{NS} ~ 2000 K

1 - 2 μm

near IR

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

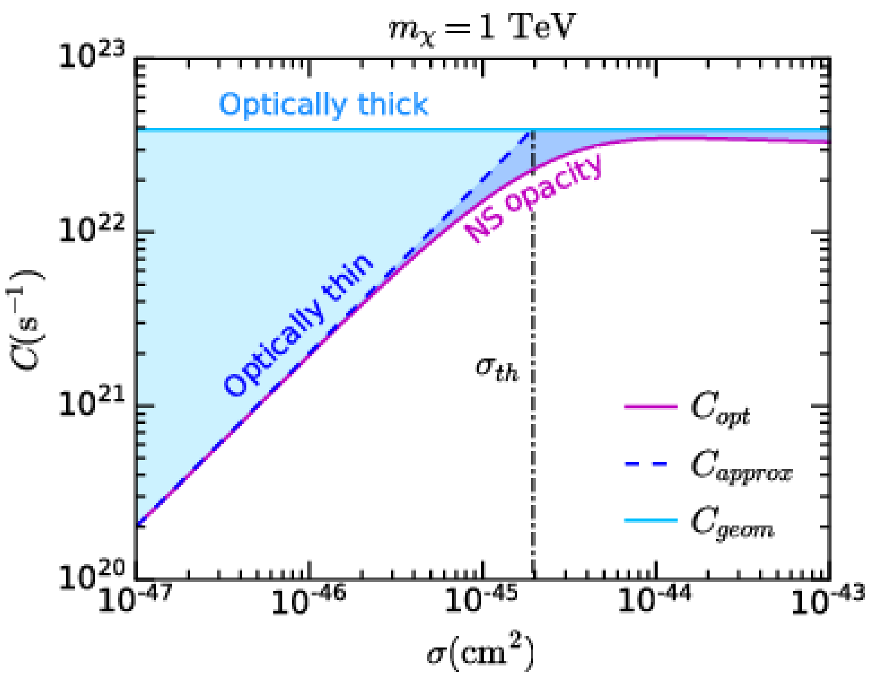
FAST (radio)

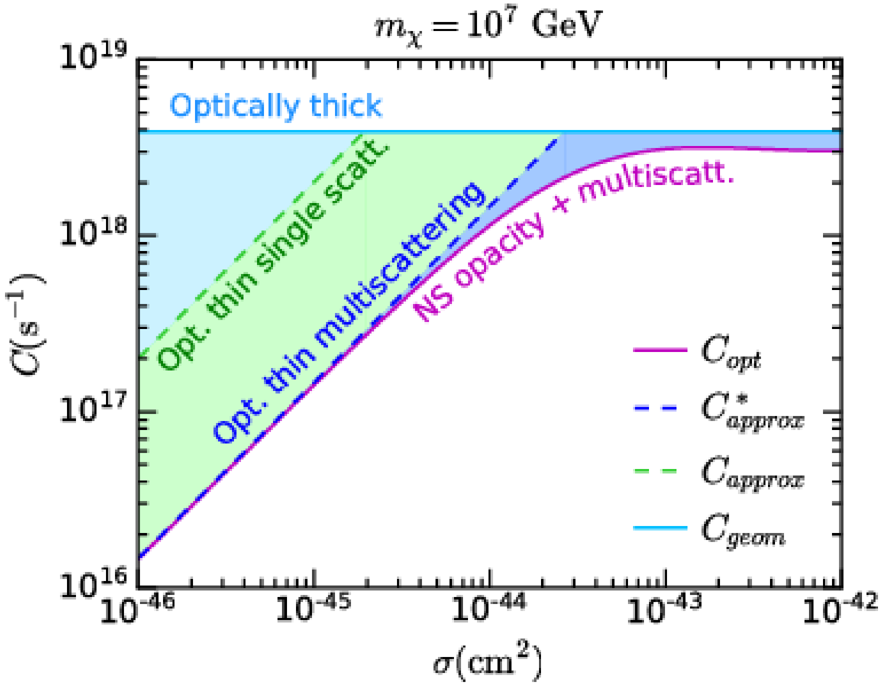


JWST (NIRCam)

Neutron star opacity

NFB, Busoni, Robles & Virgato arXiv:2004.14888





Improved capture calculations

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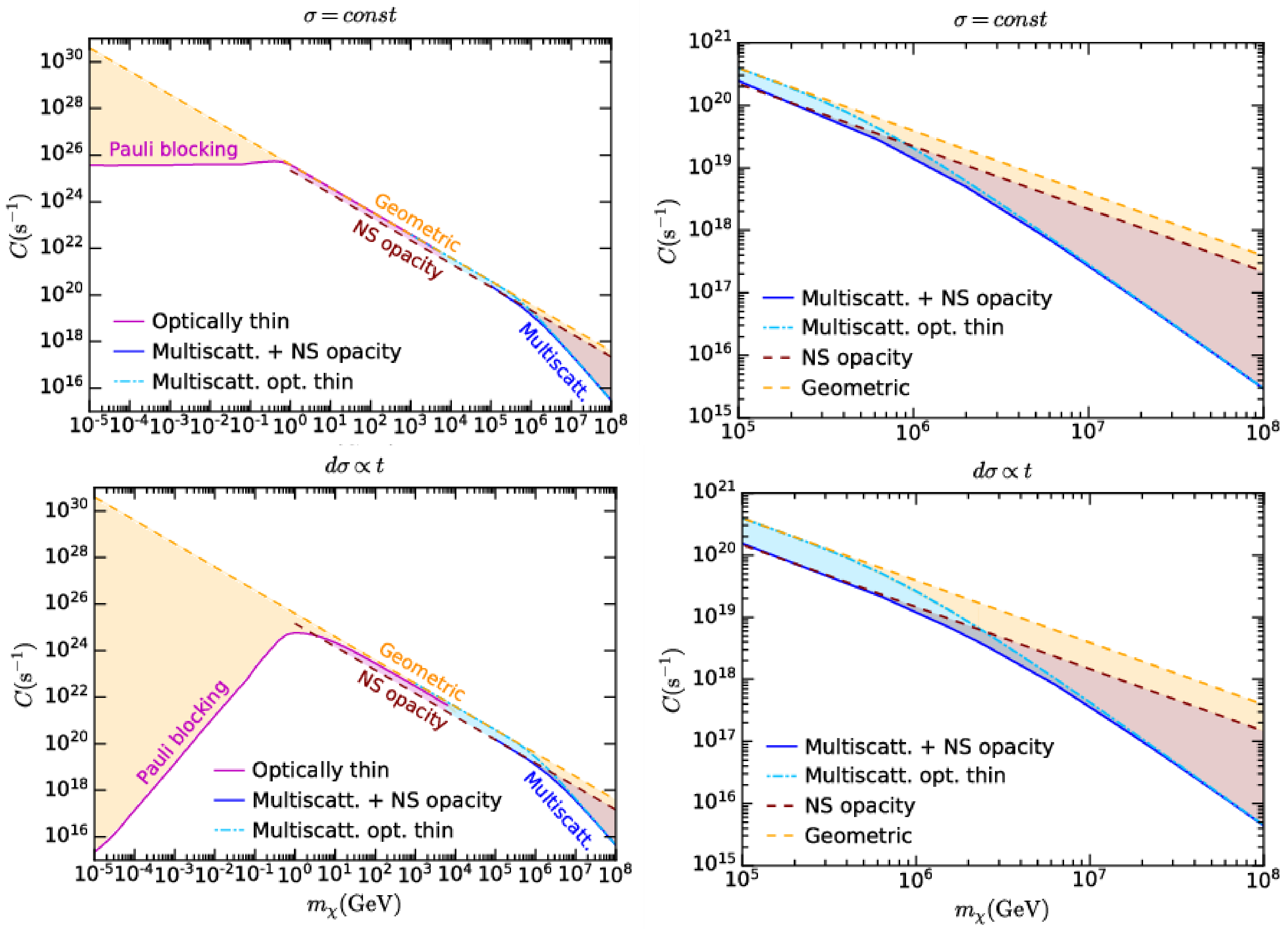

Including Pauli blocking, multiscattering and opacity effects.