Dark Matter Capture in Neutron Stars

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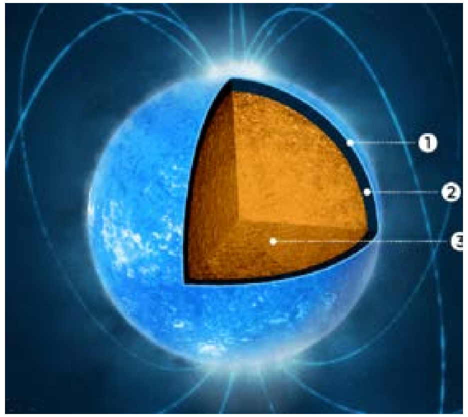
arXiv:1807.02840 (JCAP 2018), arXiv:1904.09803 (JCAP 2019), arXiv:2004.14888

Dark Matter Capture in Stars

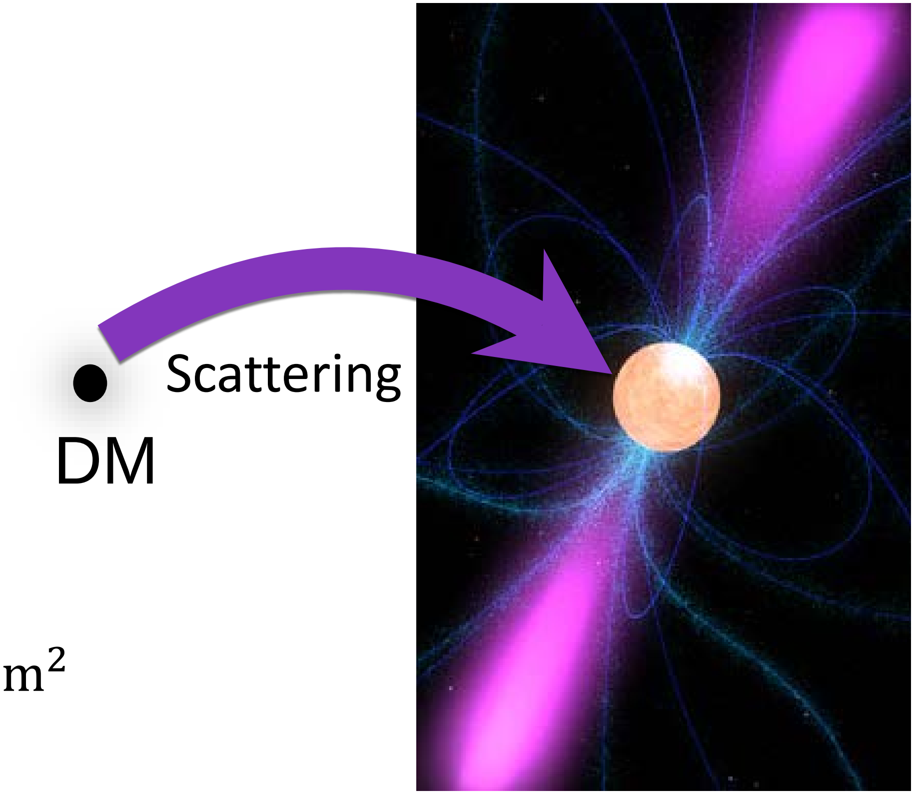
→ an alternative approach to DM-nucleon scattering experiments

Considerable quantities of dark matter can accumulate in the Earth, Sun or other stars.



Due to their extreme density, ***neutron stars*** capture dark matter very efficiently.

Image: NASA



NS Capture probability is of order unity when $\sigma_{n\chi} > \sigma_{th} \sim 10^{-45}\mathrm{cm}^2$

Neutron Stars → Black holes?

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

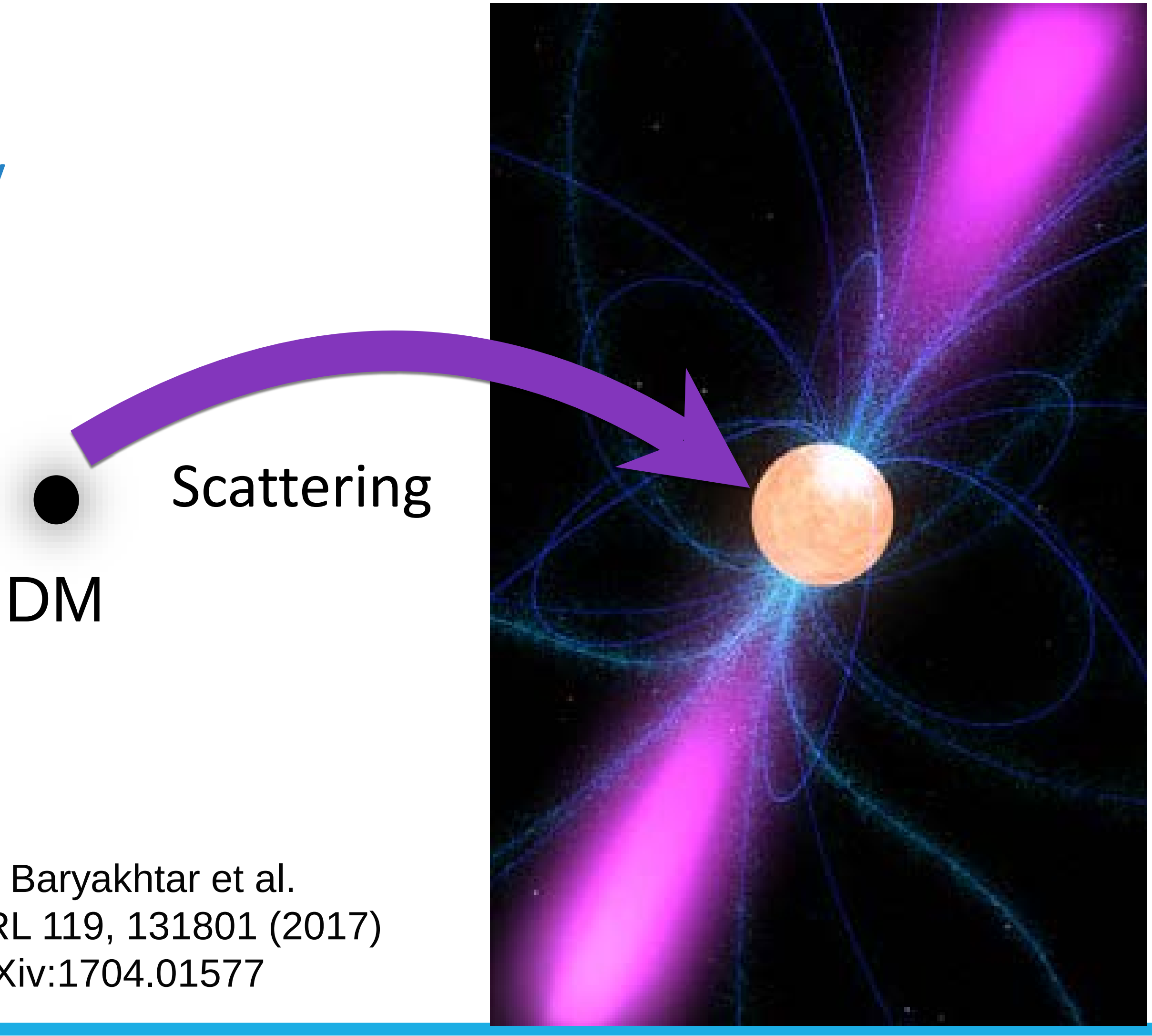
- Due to their density, neutron stars capture dark matter very efficiently

- 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**

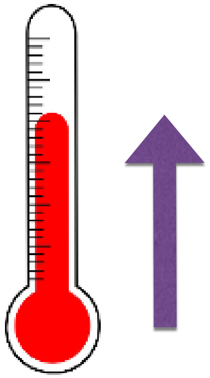
→ Black hole formation quite unlikely for *typical* WIMP-like dark matter

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)

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 $\lesssim$ 50 pc
isolated old NSs

M. Baryakhtar et al.
PRL 119, 131801 (2017)
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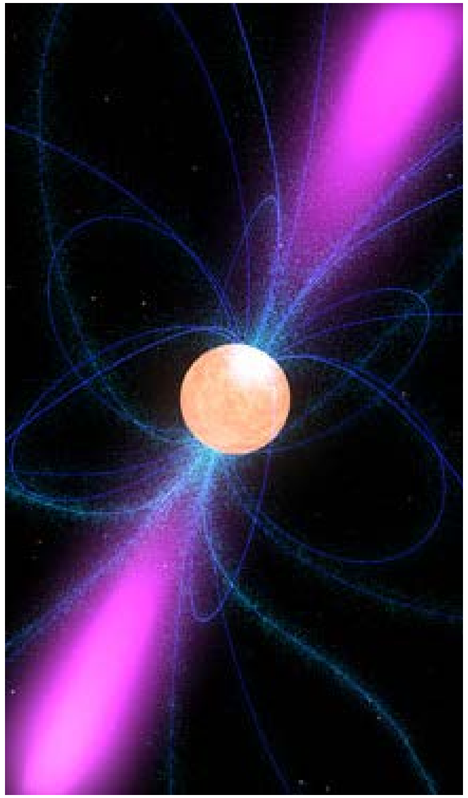
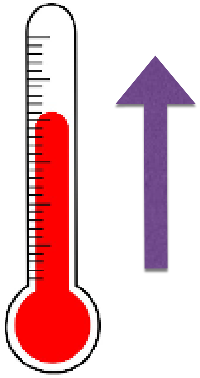
FAST (radio)





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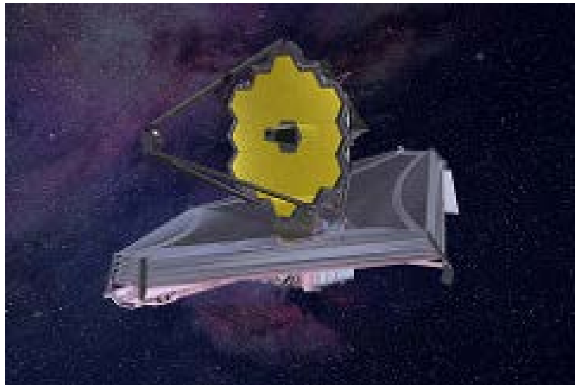


JWST (NIRCam)

Neutron Star Heating: Advantages

✓High probability of gravitational capture.

✓DM particles accelerated to $\mathcal{O}(0.5c)$ → **no momentum suppression**

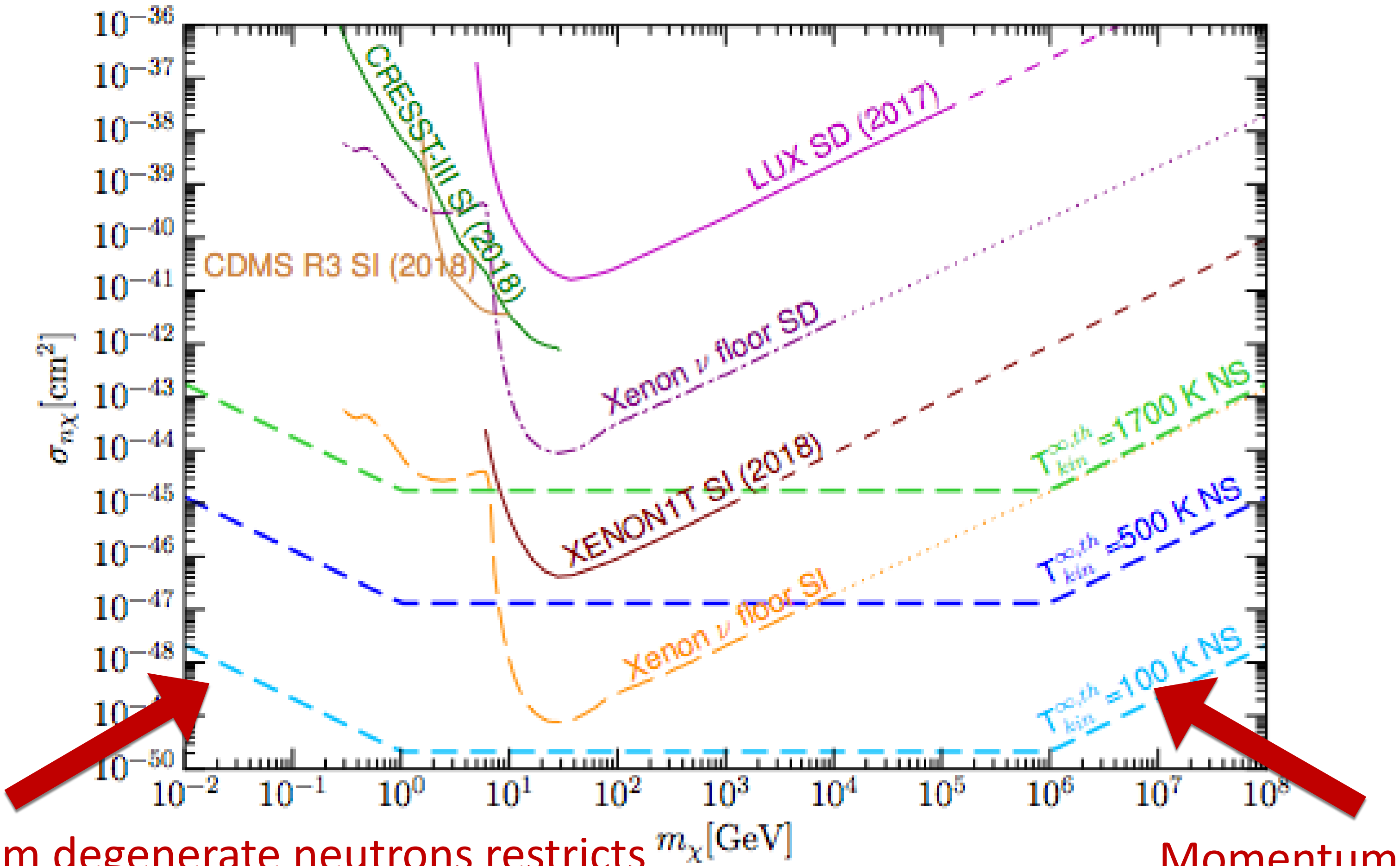
✓Cross section for efficient trapping $\mathcal{O}\left(10^{-45}\ \mathrm{cm}\right)$ for large DM mass range

✓Unlike direct detection, not restricted by **recoil detection threshold.**

✓Similar sensitivity to SI and SD cross scattering

✓Elastic and inelastic scattering cross sections of **same order of magnitude.**

Kinetic Heating Sensitivity



NFB, Busoni, Robles,
arXiv:1807.02840

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

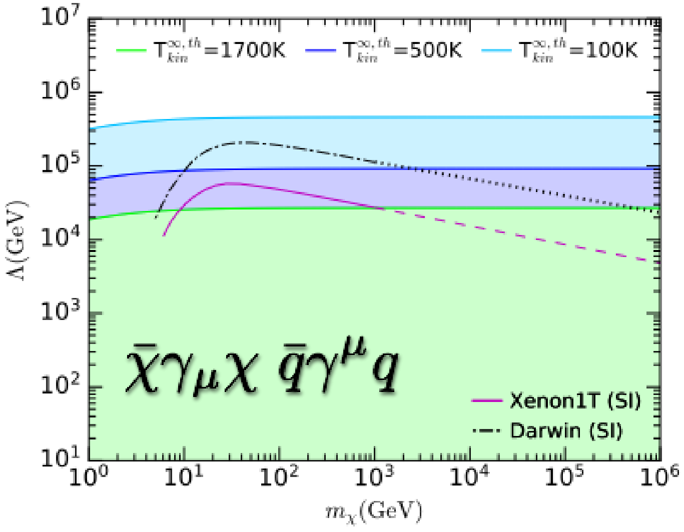
Operator			Coupling	Direct Detection	Momentum suppressed	DD vs NS
D1	SS	$(\bar{\chi}\chi)(\bar{q}q)$	y_q/Λ^2	SI	✗	NS or DD
D2	PS	$(\bar{\chi}\gamma_5\chi)(\bar{q}q)$	y_q/Λ^2	SI	✓	NS
D3	SP	$(\bar{\chi}\chi)(\bar{q}\gamma_5 q)$	y_q/Λ^2	SD	✓	NS
D4	PP	$(\bar{\chi}\gamma_5\chi)(\bar{q}\gamma_5 q)$	y_q/Λ^2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

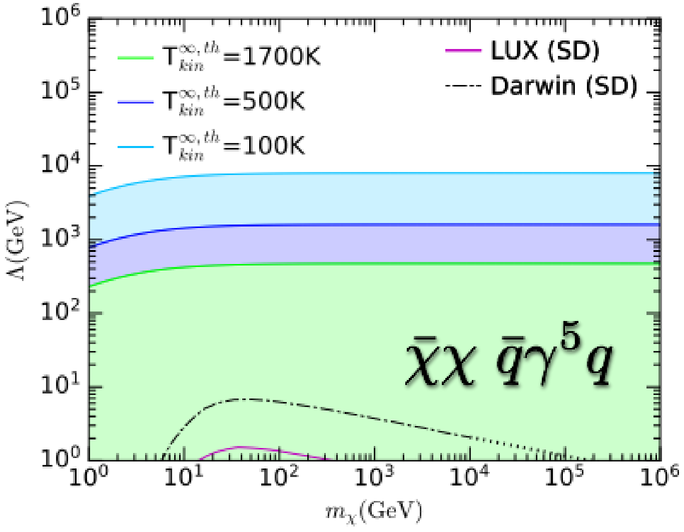
- comparable to direct detection experiments for scalar and vector interactions
- more sensitive than DD for all other interaction types (typically by orders of magnitude.

Neutron star sensitivity - SI scattering

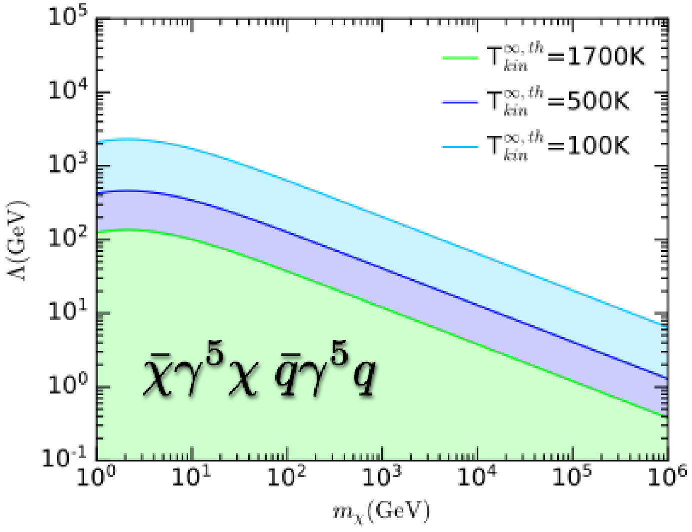
SI scattering



q^2 suppressed SD scattering



q^4 suppressed SD scattering

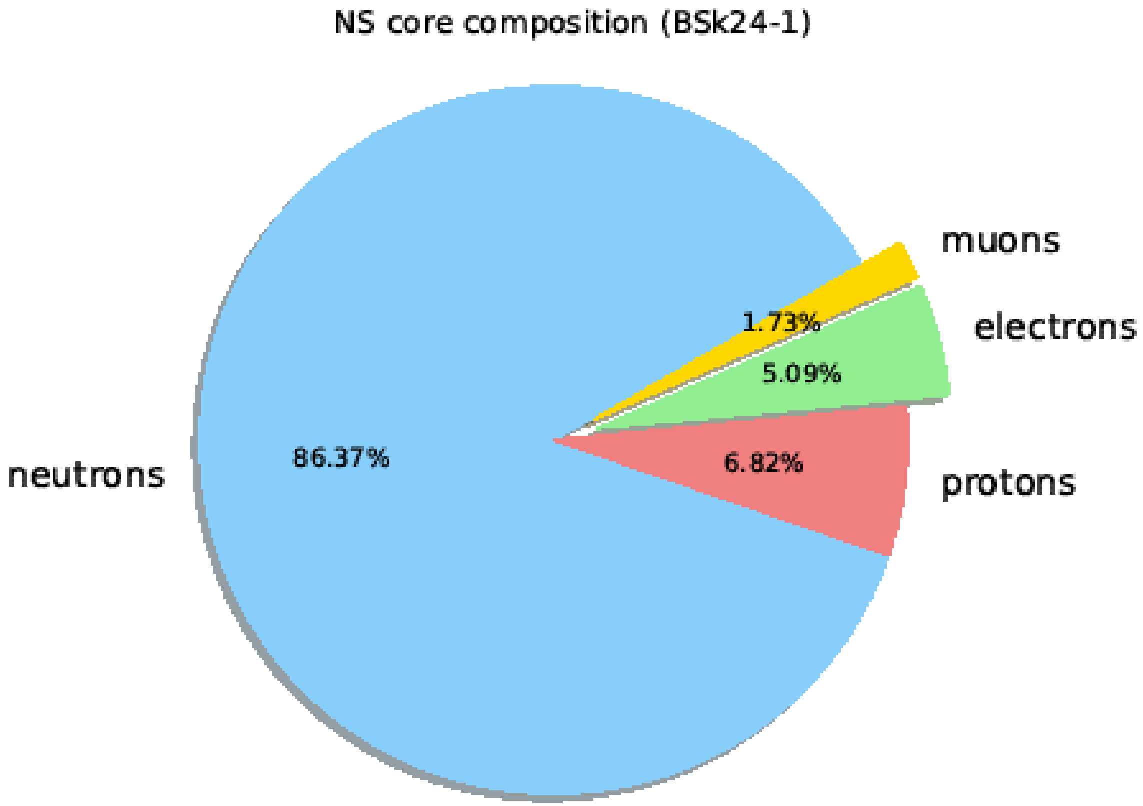


NS sensitivity comparable to direct detection

NS sensitivity greatly surpasses direct detection experiments

NFB, Busoni, Robles, arXiv:1807.02840

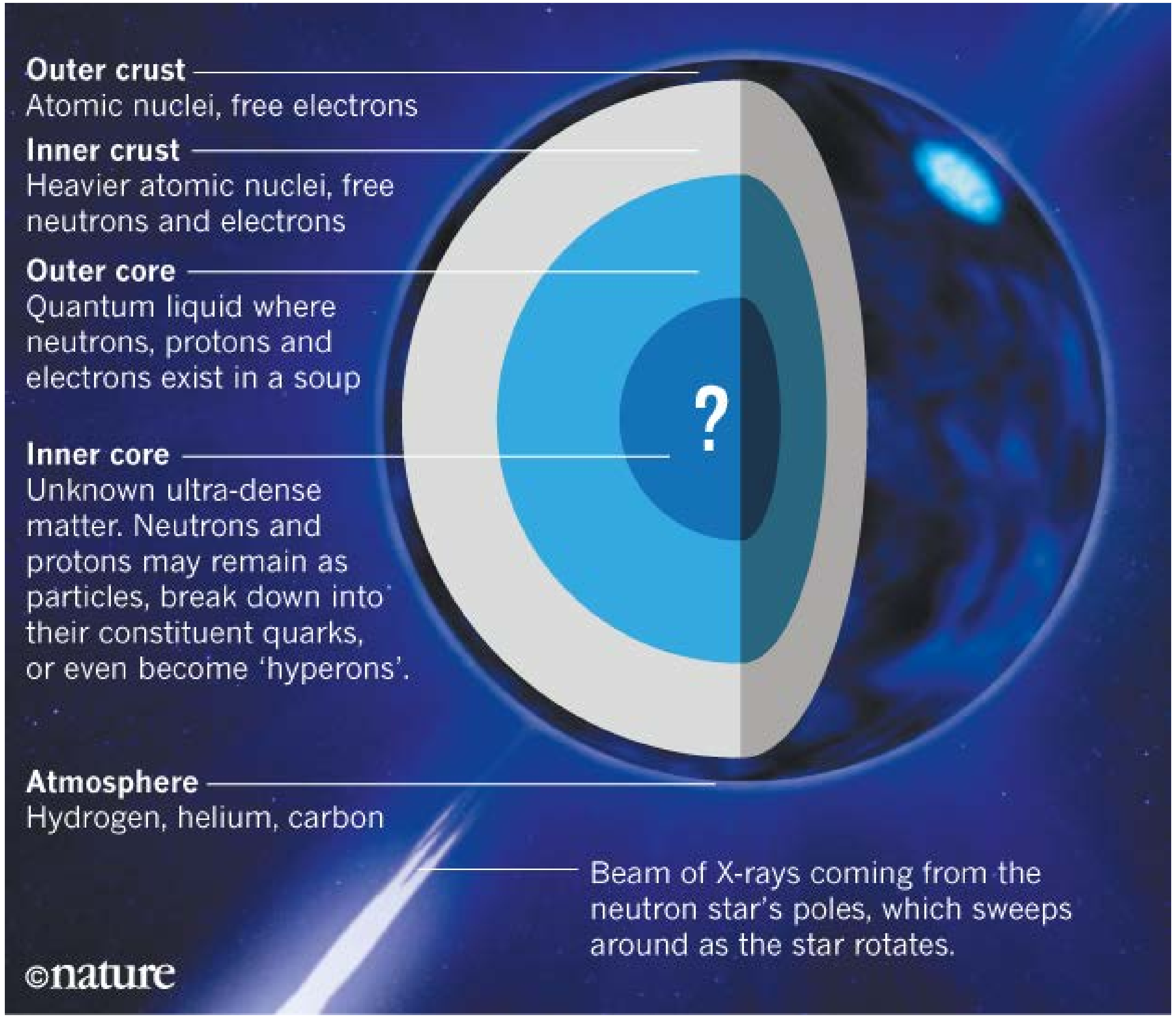
Leptons in Neutron Stars



Beta-decay 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-decay equilibrium in the core determines the composition:

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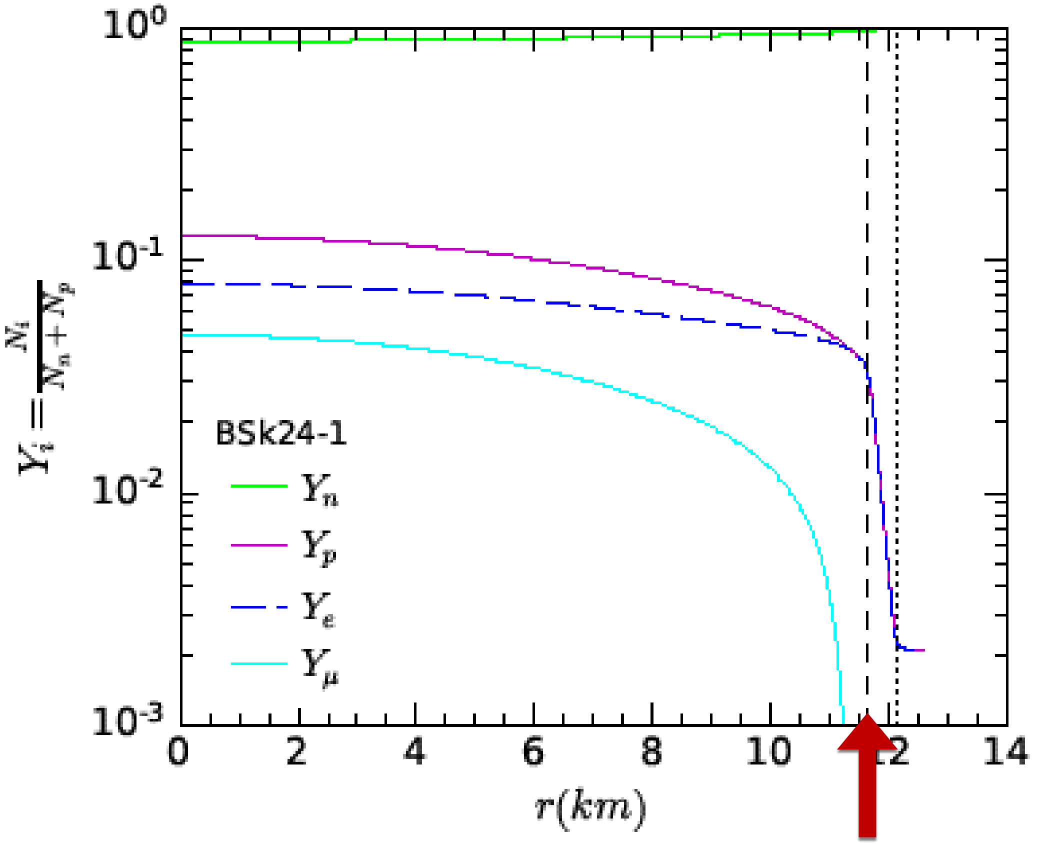
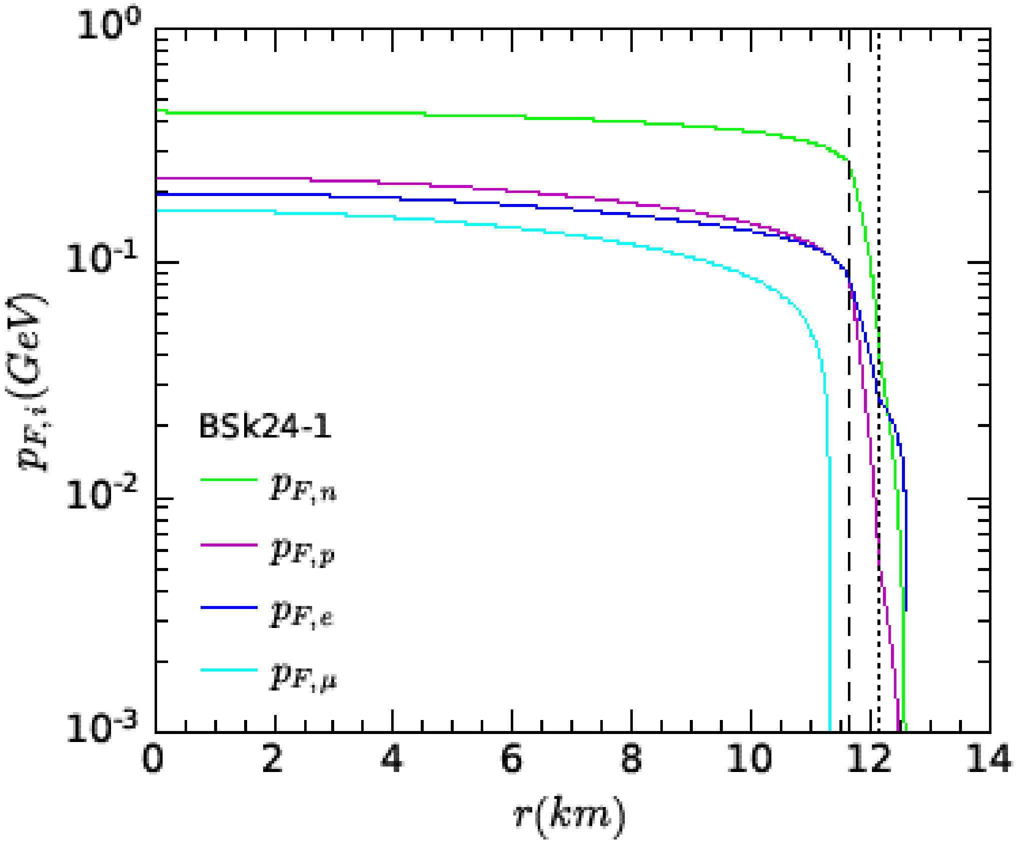
Leptons in Neutron Stars

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

Fermi-momentum ~ constant in core.

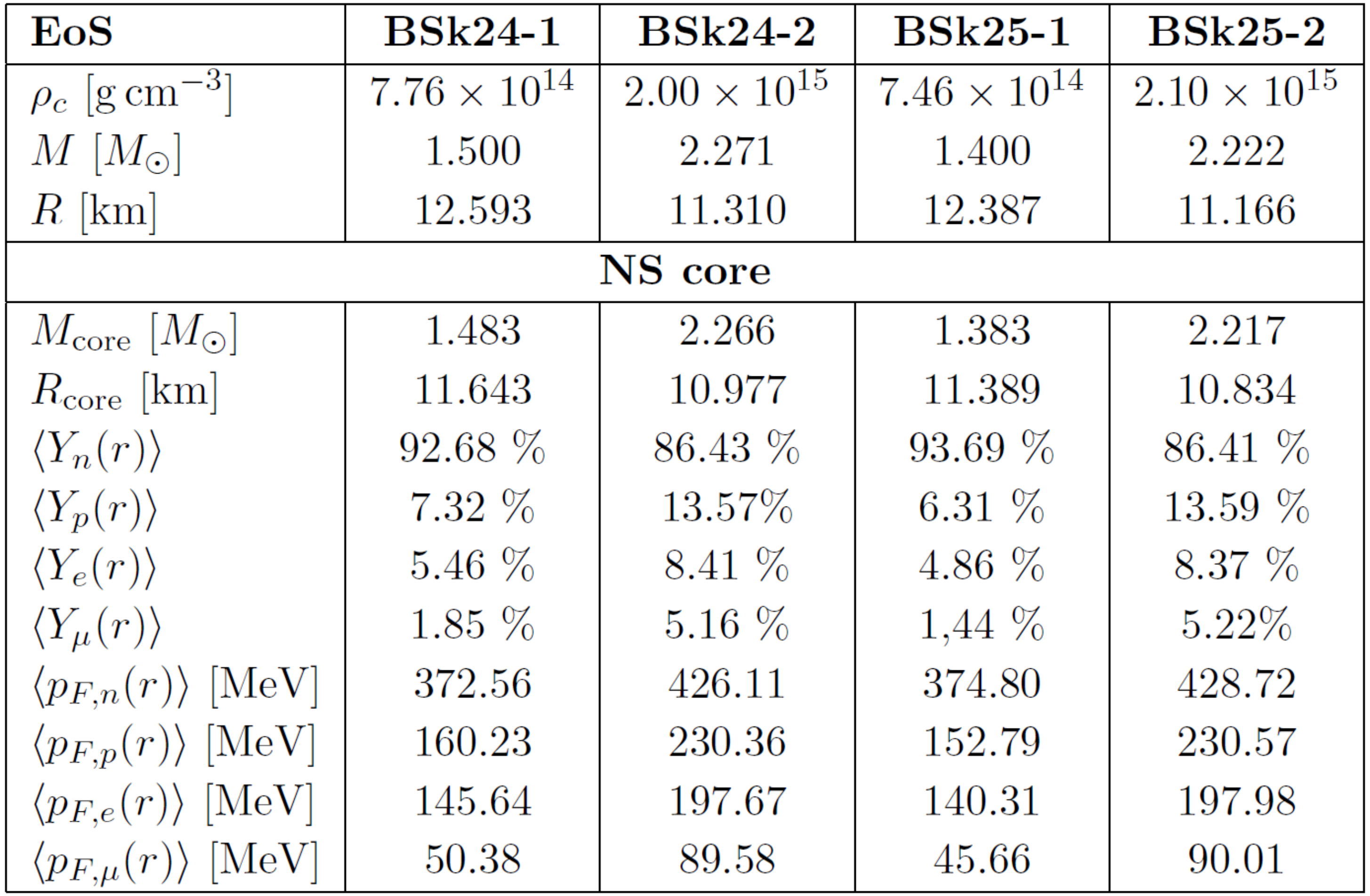


crust-core boundary



Neutron Star Equation of State

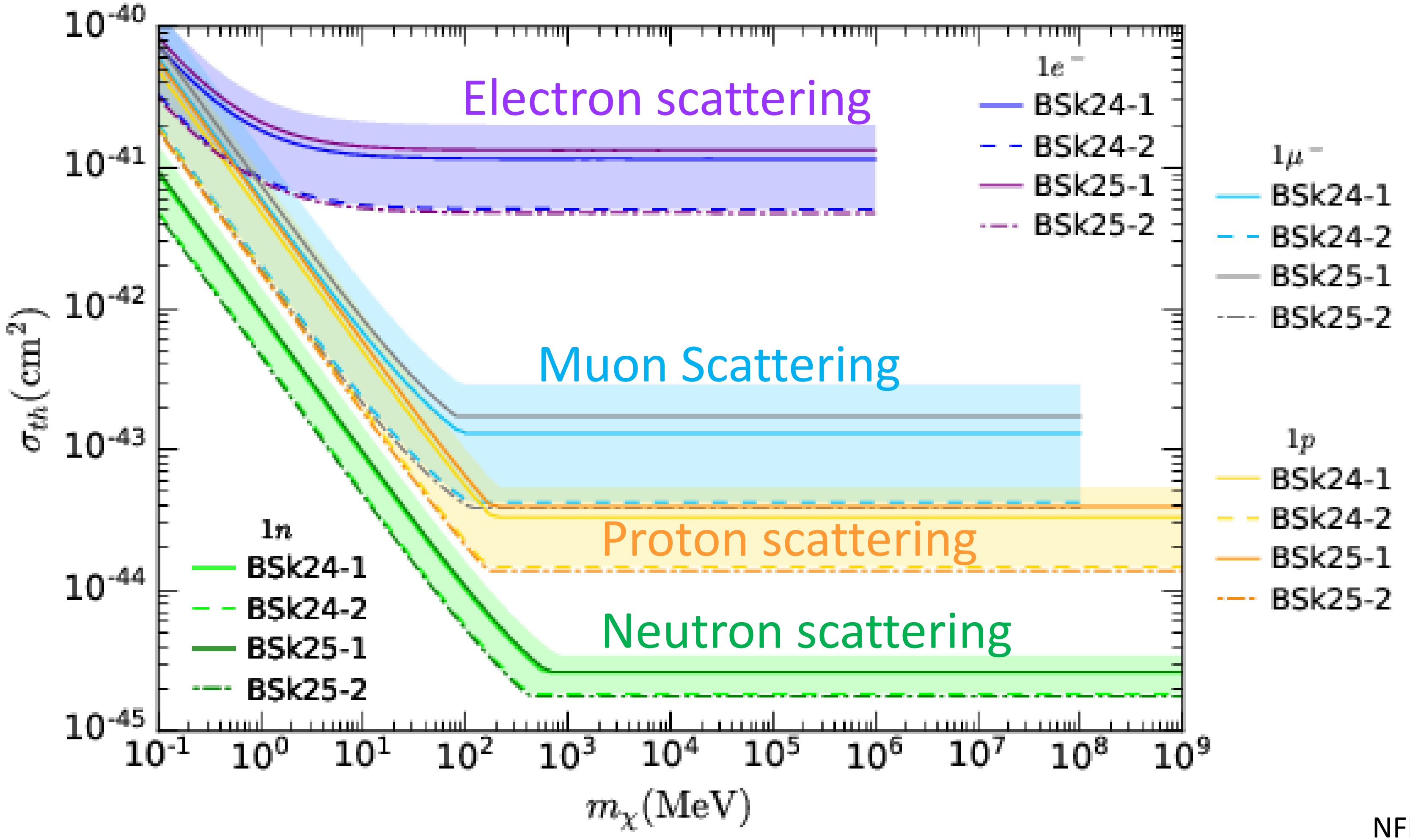
Brussels-Montreal EoS functionals from Pearson et al, Mon. Not. Roy. Astron. Soc. 481 no. 3, (2018)



EoS	**BSk24-1**	**BSk24-2**	**BSk25-1**	**BSk25-2**
ρ_c [g cm^{-3}]	7.76×10^{14}	2.00×10^{15}	7.46×10^{14}	2.10×10^{15}
M [$M_\odot$]	1.500	2.271	1.400	2.222
R [km]	12.593	11.310	12.387	11.166
NS core				
$M_{\rm core}$ [$M_\odot$]	1.483	2.266	1.383	2.217
$R_{\rm core}$ [km]	11.643	10.977	11.389	10.834
$\langle Y_n(r) \rangle$	92.68 %	86.43 %	93.69 %	86.41 %
$\langle Y_p(r) \rangle$	7.32 %	13.57%	6.31 %	13.59 %
$\langle Y_e(r) \rangle$	5.46 %	8.41 %	4.86 %	8.37 %
$\langle Y_\mu(r) \rangle$	1.85 %	5.16 %	1,44 %	5.22%
$\langle p_{F,n}(r) \rangle$ [MeV]	372.56	426.11	374.80	428.72
$\langle p_{F,p}(r) \rangle$ [MeV]	160.23	230.36	152.79	230.57
$\langle p_{F,e}(r) \rangle$ [MeV]	145.64	197.67	140.31	197.98
$\langle p_{F,\mu}(r) \rangle$ [MeV]	50.38	89.58	45.66	90.01

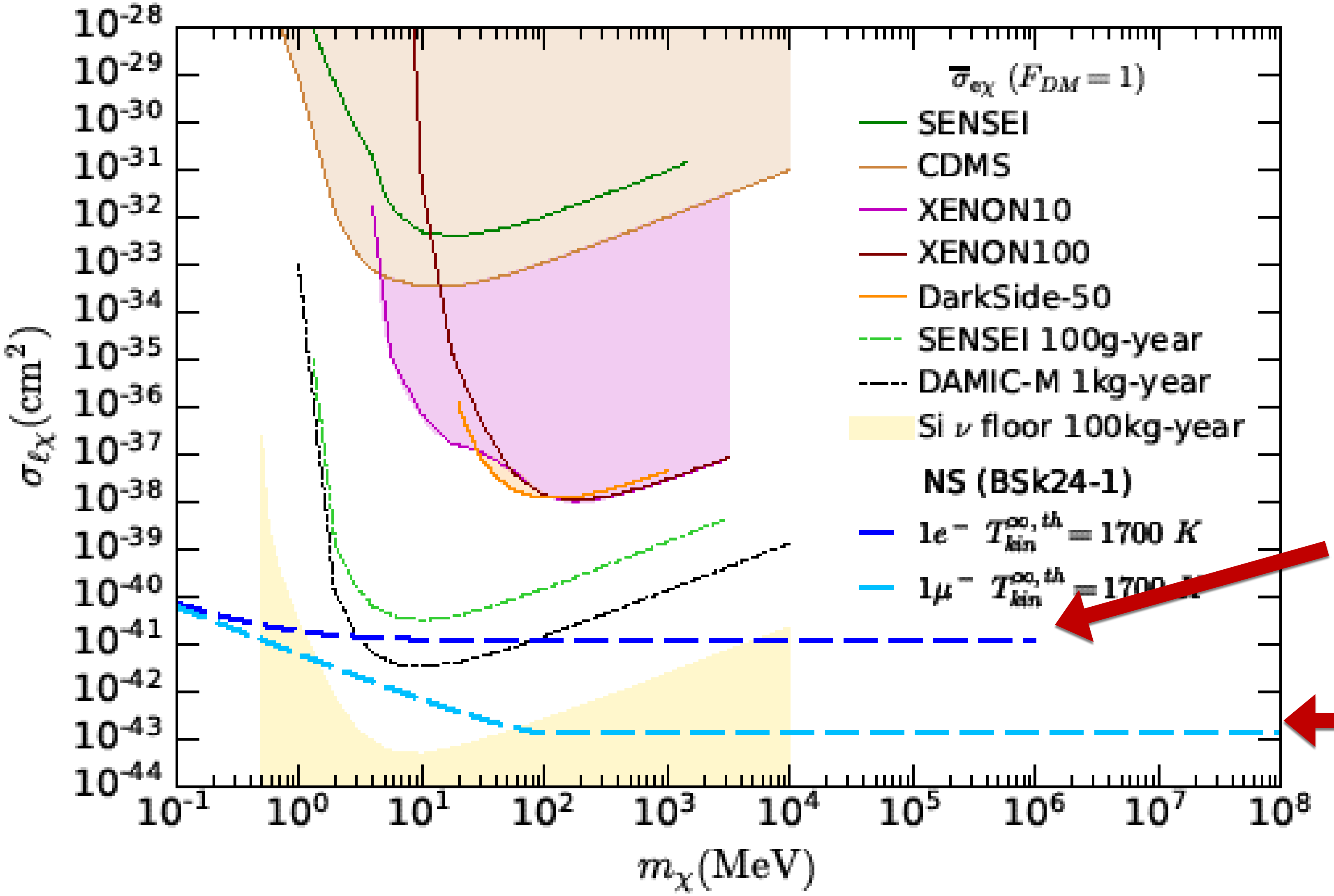
Composition varies according to the neutron star EoS

Insensitive to details of NS Equation of State



NFB, Busoni & Robles arXiv:1904.09803

Neutron star limits on leptophilic DM



NFB, Busoni & Robles
arXiv:1904.09803

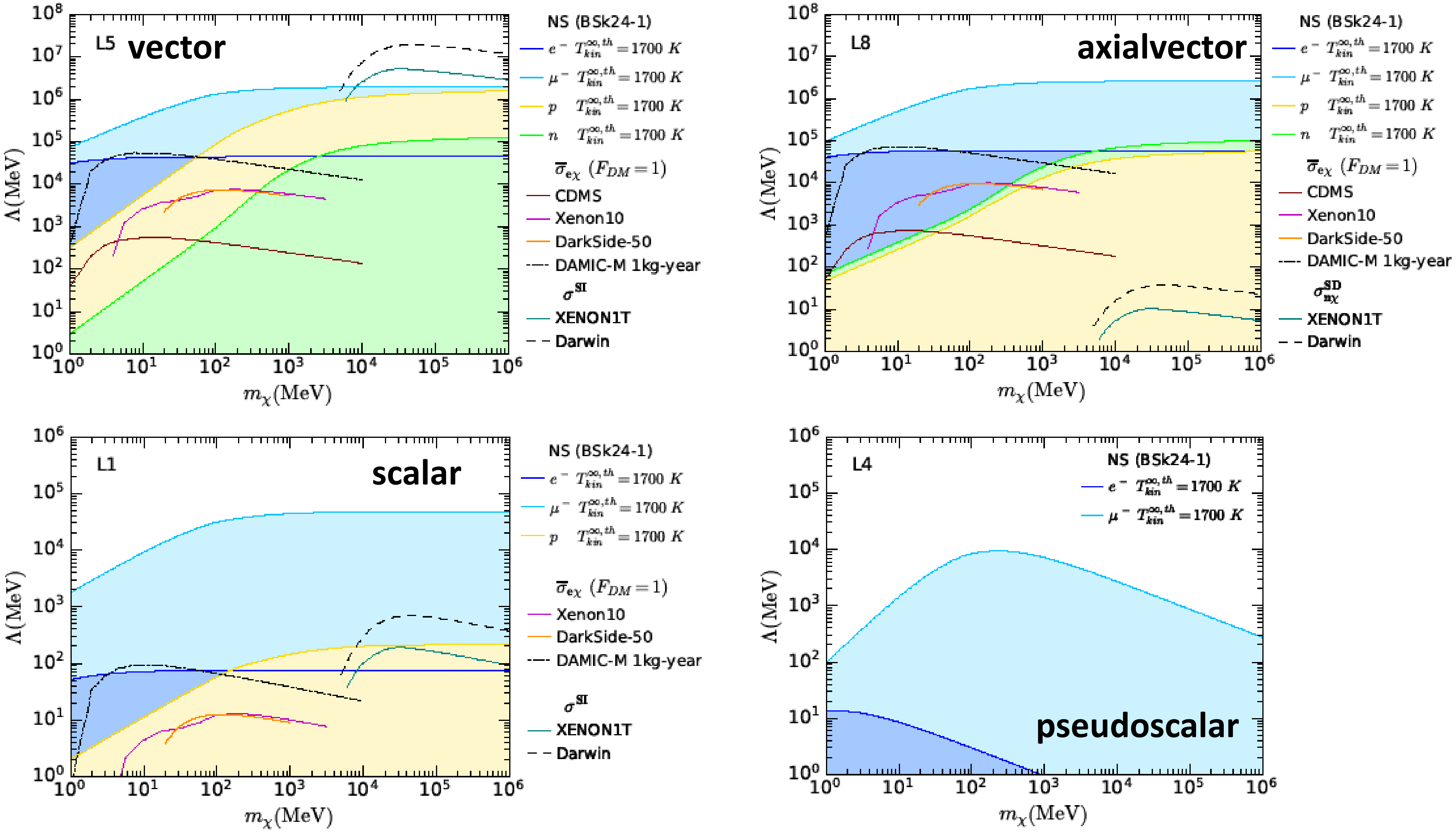
Electron scattering

Muon scattering

Leptophilic DM

NFB, Busoni & Robles arXiv:1904.09803

NS sensitivity has the potential to greatly surpass electron-recoil direct detection experiments.



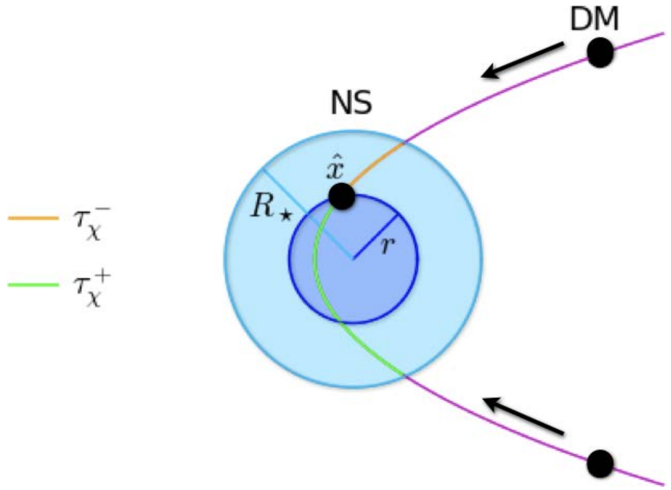
Improved capture calculations

NFB, Busoni, Robles & Virgato arXiv:2004.14888

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



Neutron star opacity

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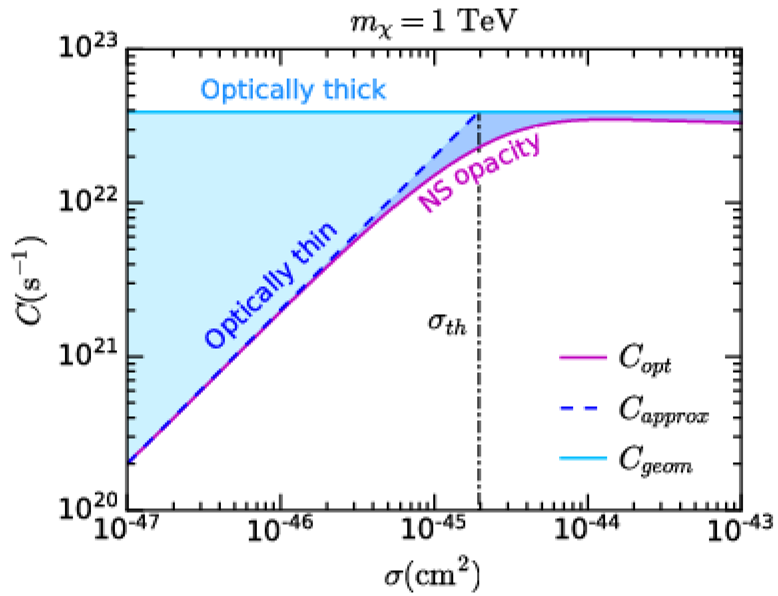

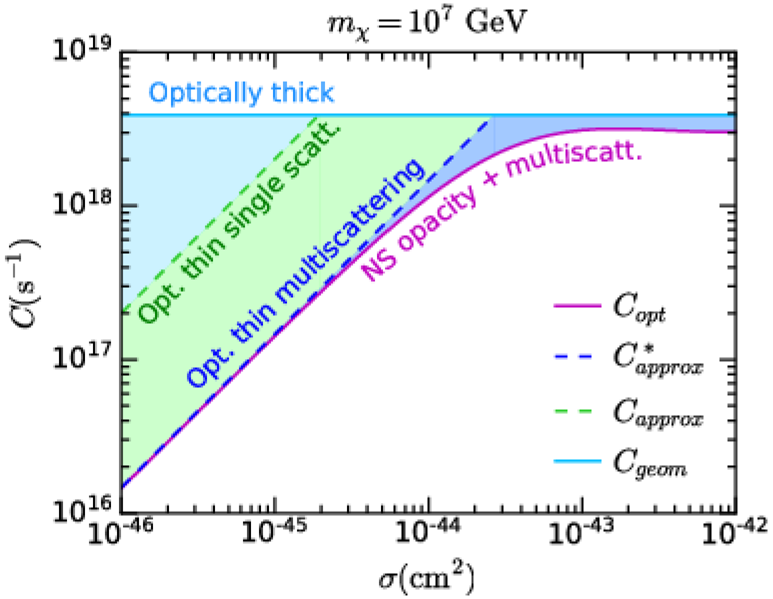

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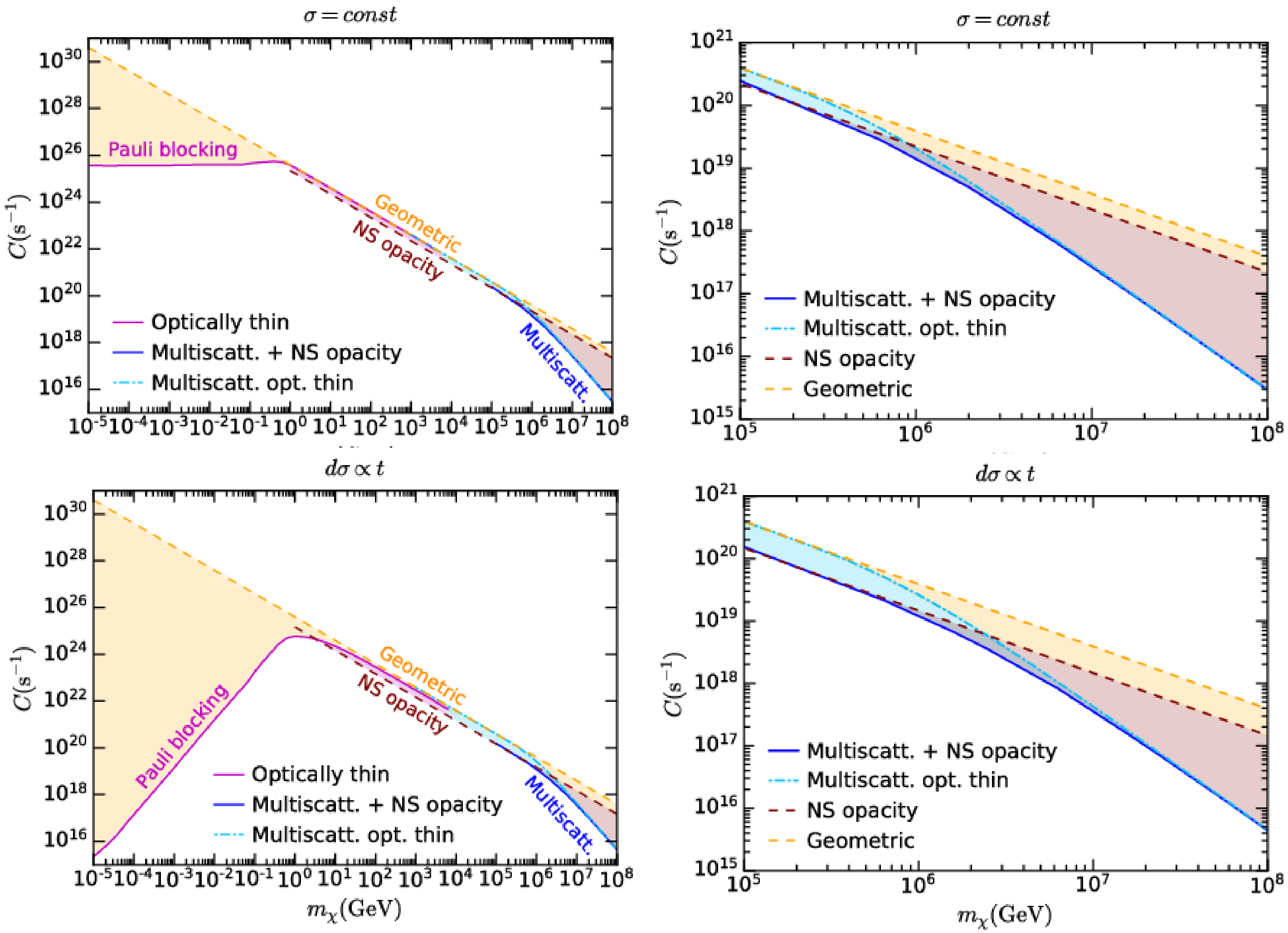

Including Pauli blocking, multiscattering and opacity effects.

Summary & Conclusions

Dark matter capture in stars → cosmic laboratory to probe DM scattering interactions

- Completely different kinematic regime to direct detection experiments
    - Scattering of quasi-relativistic dark matter →no velocity or momentum suppressions
- Excellent sensitivity to DM-lepton scattering cross sections, with electron and especially muon scattering.
- Neutron Star kinetic heating sensitivity is better than current and forthcoming direct detection experiments, for both nuclear-recoil and electron-recoil scattering.
- Capture calculations have recently been refined and improved.