Capture of Dark Matter in Neutron Stars

Nicole Bell

with Giorgio Busoni and Sandra Robles

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

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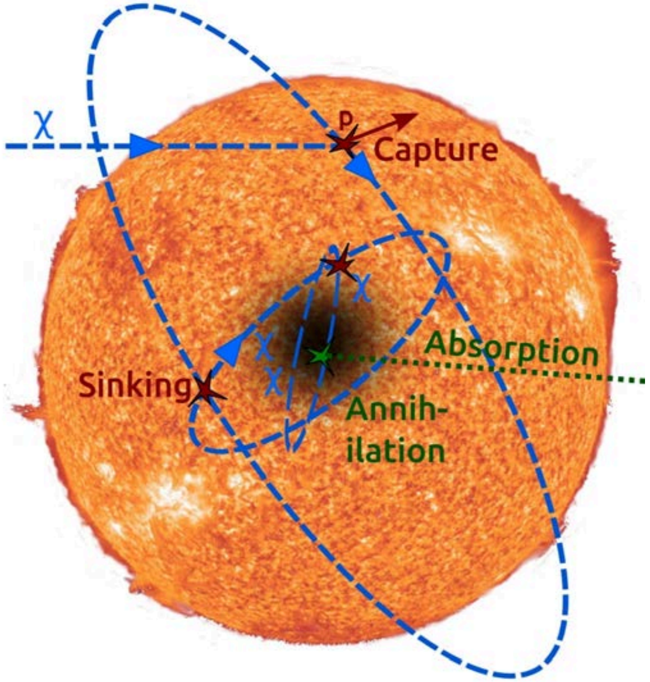
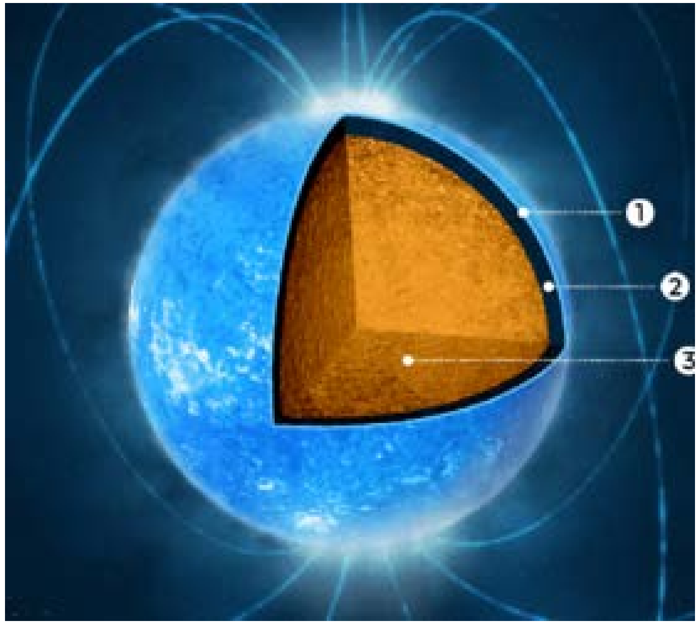
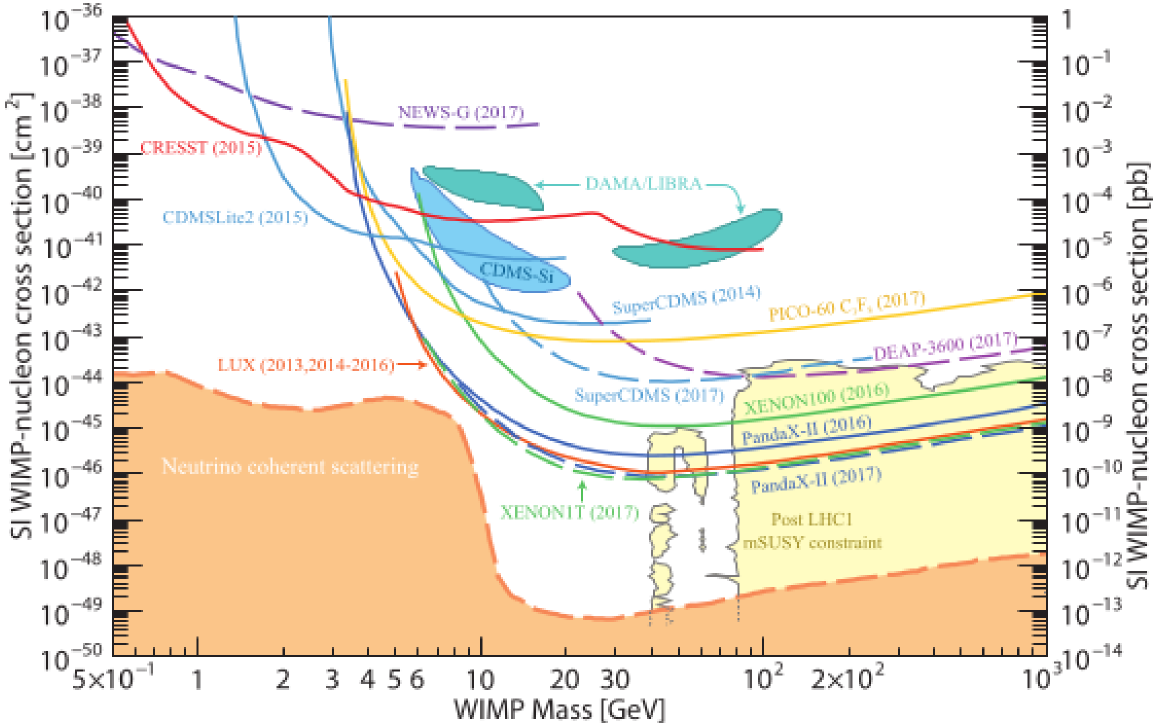
Outline



- Introduction
  - o Dark matter capture in the Sun
- Capture in Neutron Stars
  - o black holes, gravitational waves
  - o neutron star heating
    - ➢ DM-nucleon scattering
    - ➢ DM-lepton scattering
- Summary

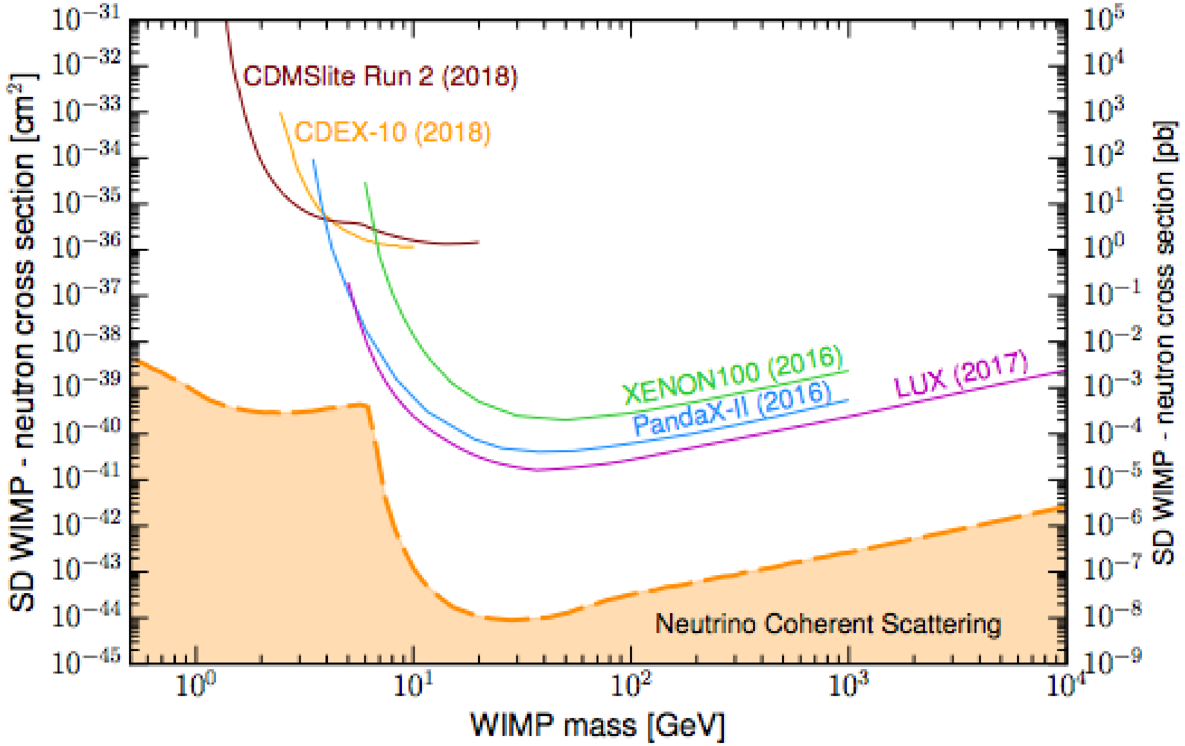


Searching for dark matter particles - Direct Detection



Spin-independent (SI) interactions
→ stringent bounds

M. Tanabashi et al. (PDG) 2018



Spin-dependent (SD) interactions
→ much weaker bounds

Searching for dark matter particles - Direct Detection

Sensitivity depends on interaction type

- Enhanced cross sections for SI (spin-independent) scattering
- Smaller cross sections for SD (spin-dependent) scattering

Limited by kinematics

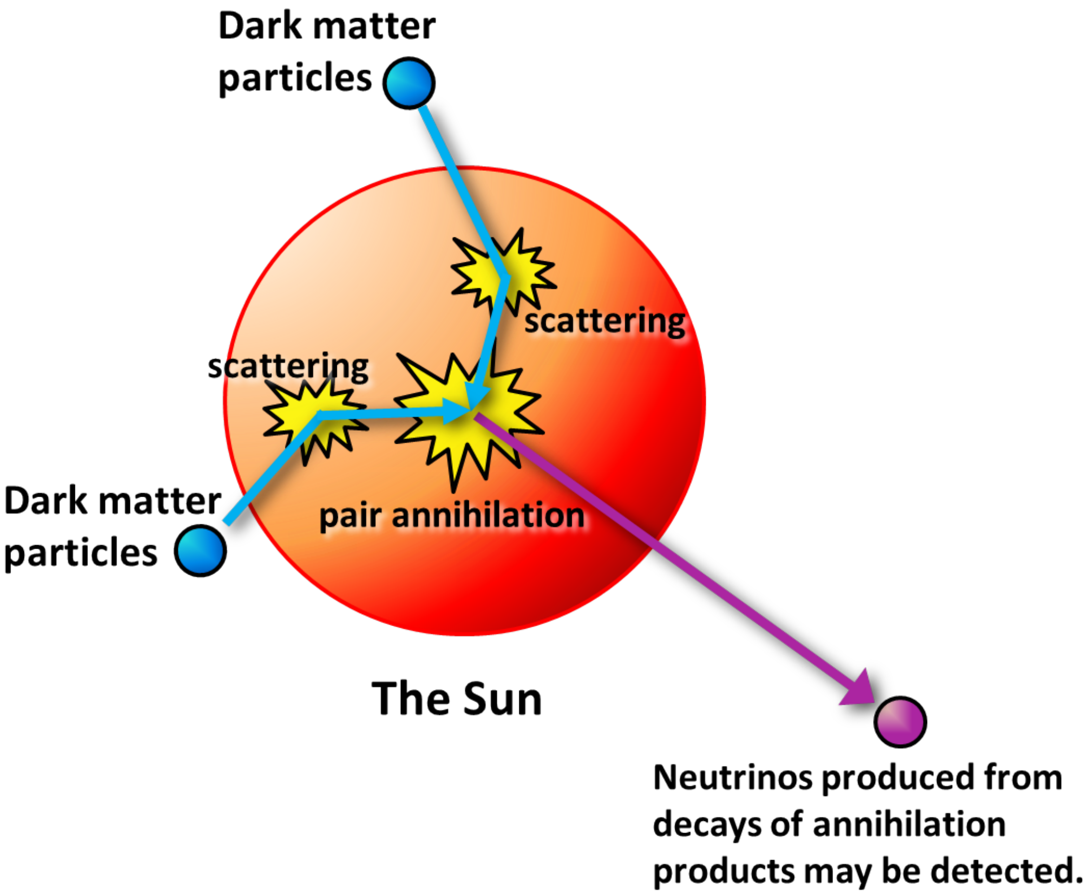
- Some interactions feature only momentum or velocity suppressed cross section → these are very small numbers
- Mass of the target nuclei (or electron mass)
- Experimental thresholds for detecting recoil energy

An alternative approach

→ capture in the Sun, Earth, or Neutron Stars

Dark matter can accumulate in the Earth, Sun, or other stars, in considerable amounts.

Complementary to direct detection experiments.



Solar WIMPs

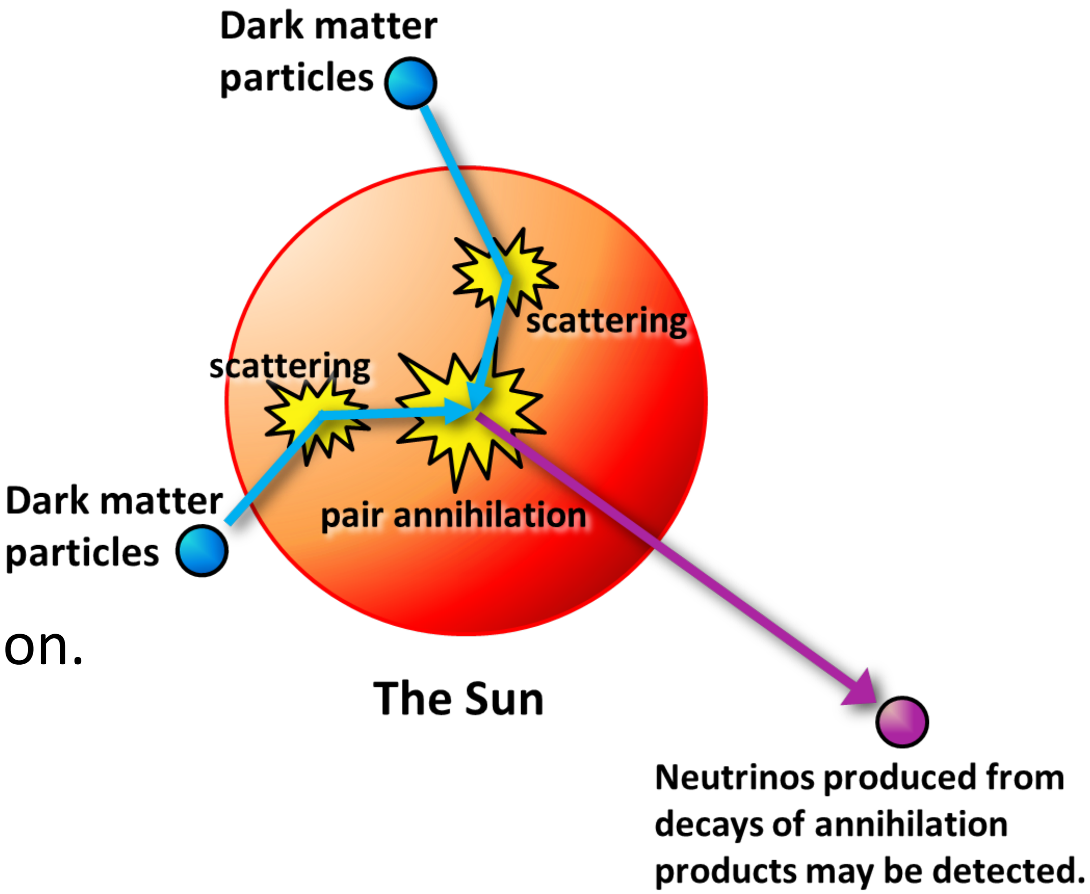
- Dark matter scatters, loses energy, becomes gravitationally bound to star
- Accumulates and annihilates in centre of Sun
- Only neutrinos escape Sun→ IceCube, SuperK

In equilibrium:

Annihilation rate = Capture rate

→ controlled by DM-nucleon scattering cross section.

→ probes the same quantity as direct detection experiments

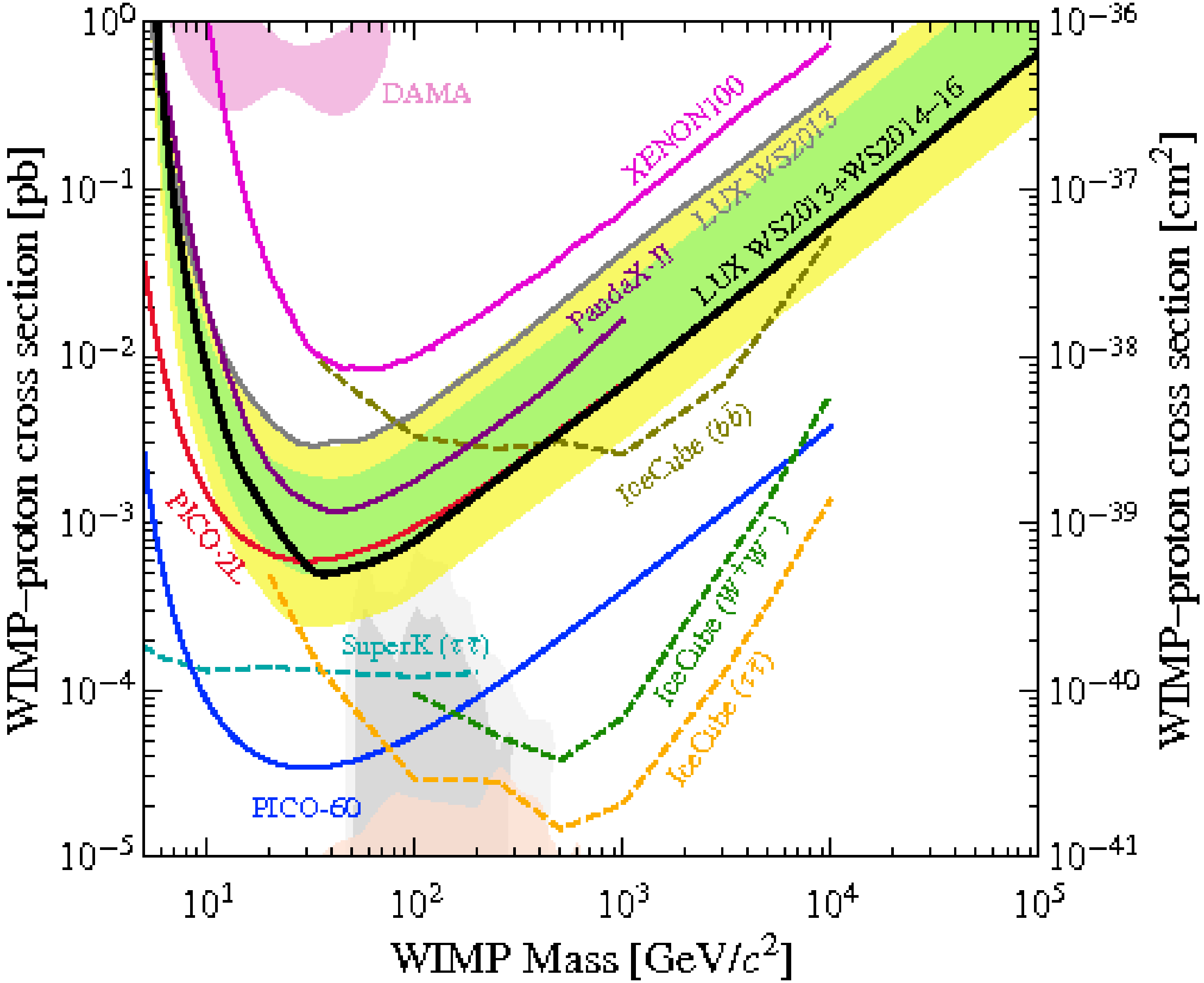


Solar WIMPs

- For *spin-independent* interactions:
  → direct detection wins

- For *spin-dependent* interactions:
  → strong solar WIMP limits

arXiv:1705.03380



Neutron Stars

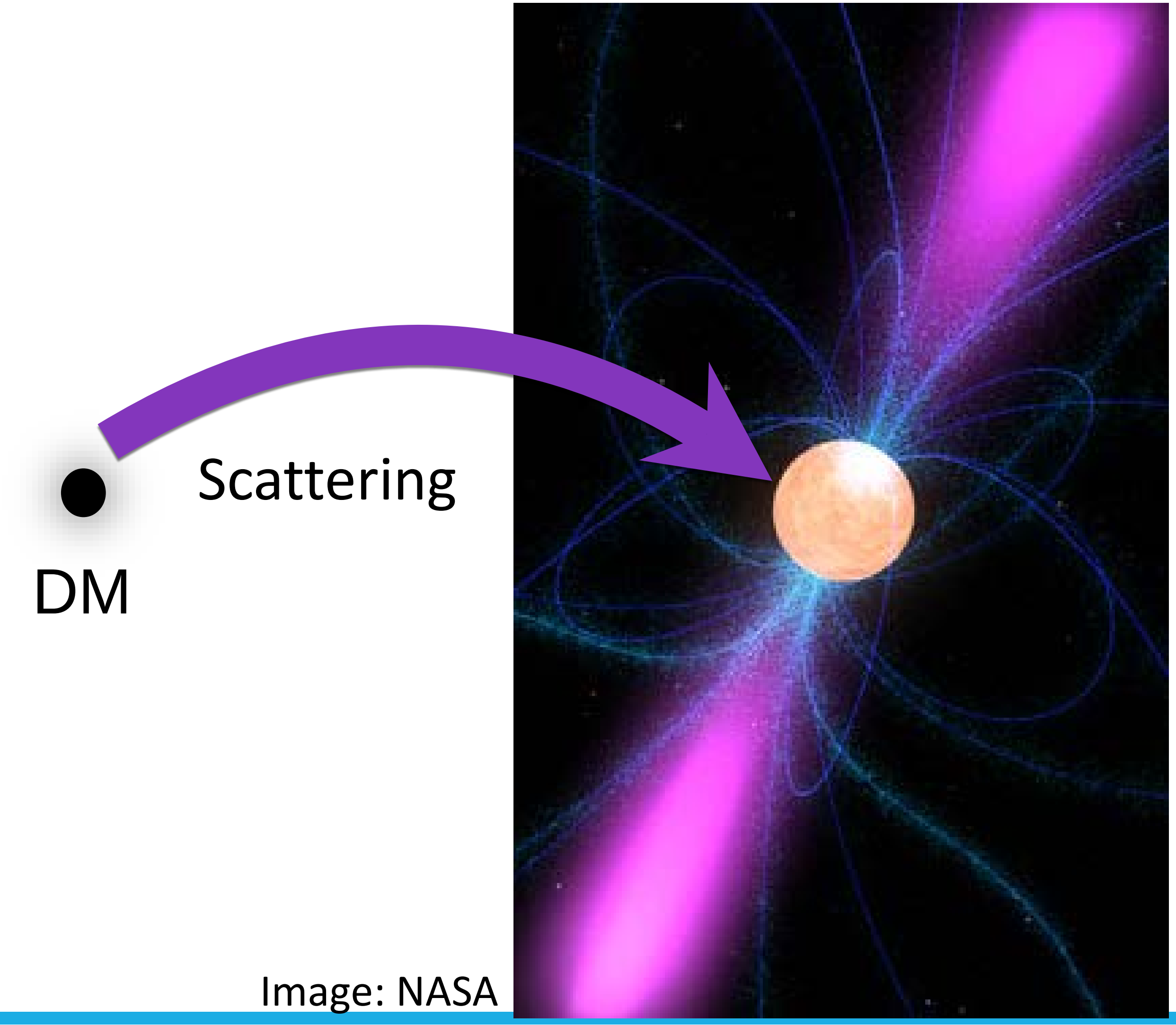


Image: NASA

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

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**

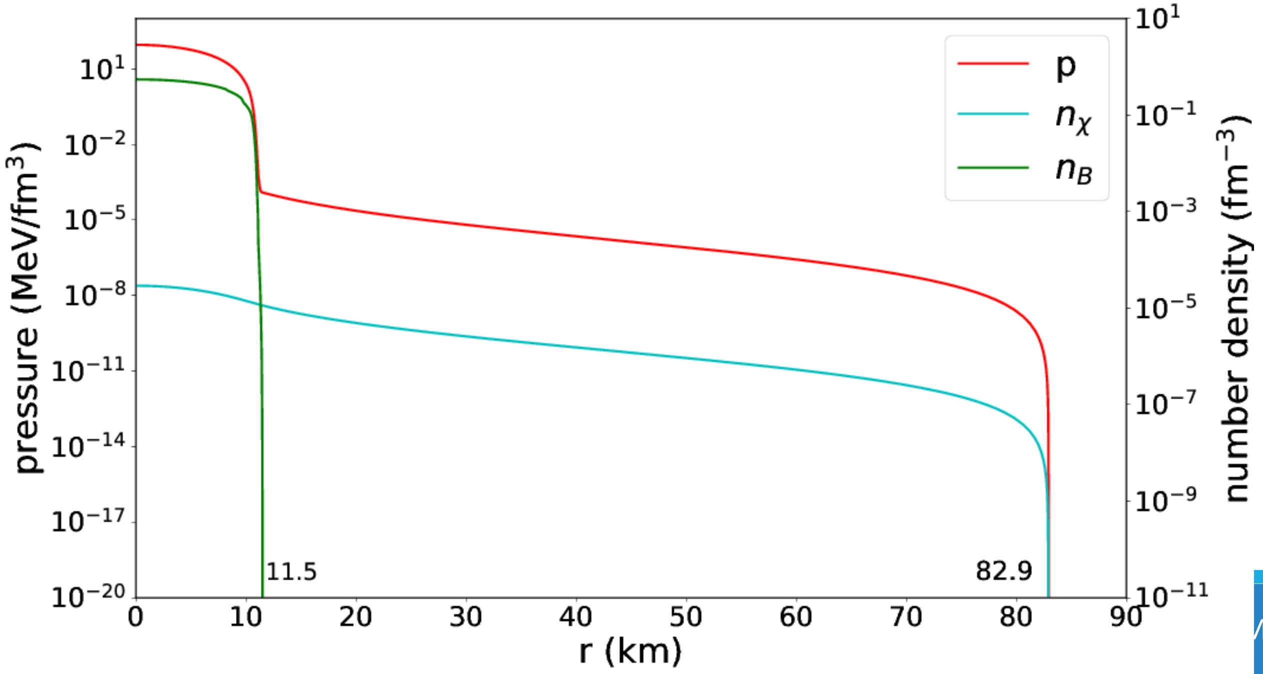
→ Black hole quite unlikely for *typical* WIMP-like dark matter

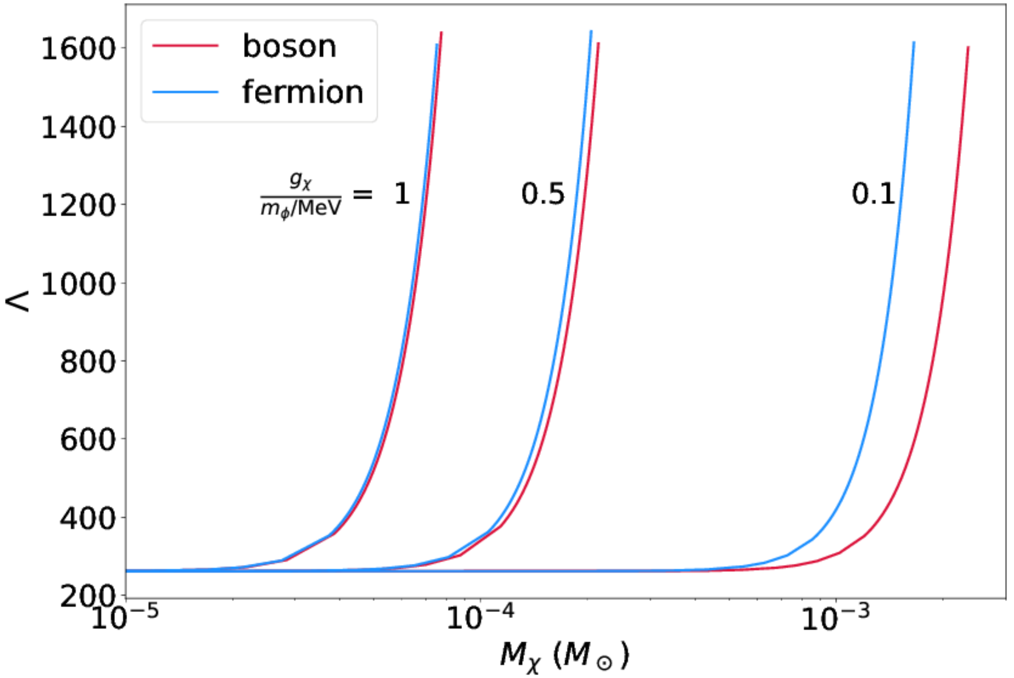
Neutron star mergers → gravitational waves

Nelson, Reddy & Zhou, 1803.03266

- Light DM + light mediators (MeV scale)
  - **DM component extents to large radii → NS dark matter halo**

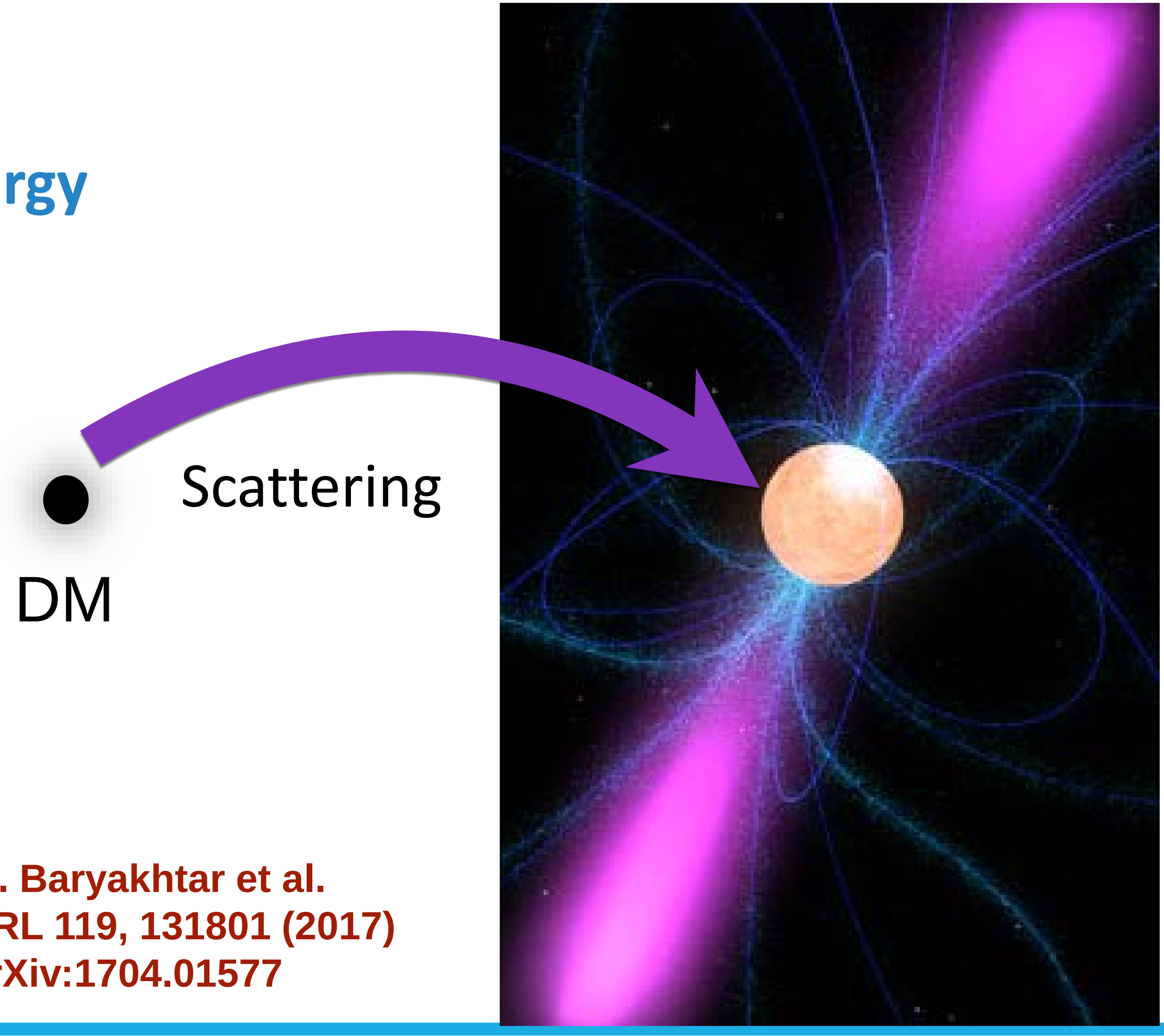
- Increases the NS tidal deformability, Λ.
  - LIGO observation of NS-NS merger, GW170817, constrains $\Lambda < 800$
  - strong bounds, even for small DM component $\sim 10^{-4} M_\odot$



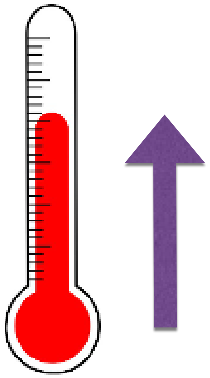


Neutron Star Kinetic Heating

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

Bramante, Delgardo and Martin; Raj, Tanedo and Yu

- 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

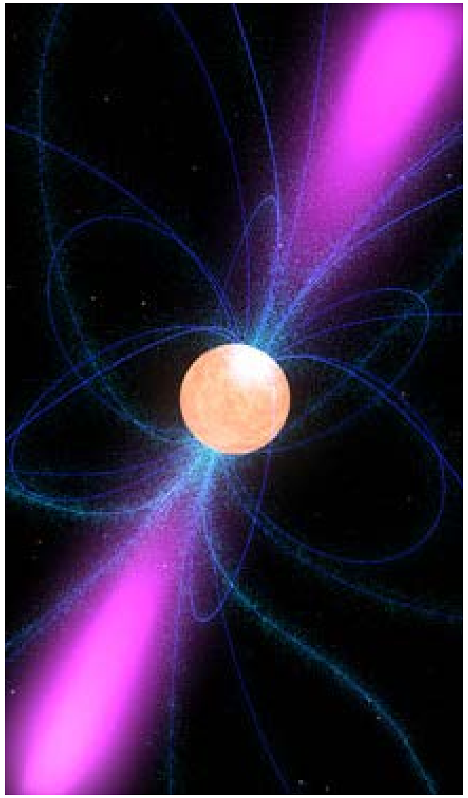
- Early cooling is dominated by neutrino emission
- Photon emission dominates at late times

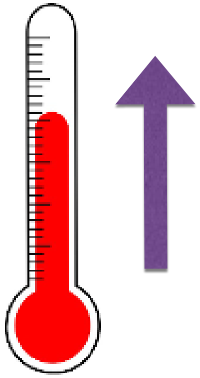
Coolest known neutron star (PSR J2144-3933) has a temperature of 4.2 x 10^4 K.
Astrophys.J. 874 (2019) no.2, 175

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





$T_{NS} \sim 1700$ K

1 - 2 μm

near IR

M. Baryakhtar et al.
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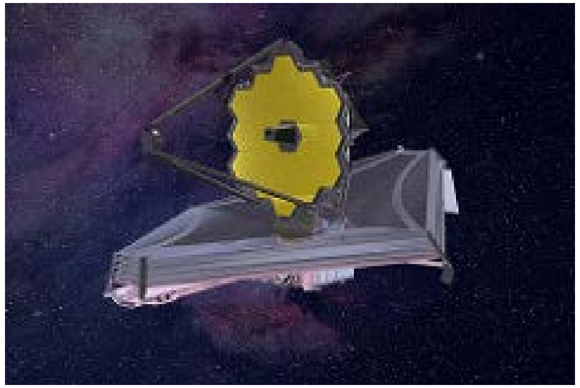
FAST (radio)



JWST (NIRCam)

Neutron Star Heating: Advantages

✓High probability of gravitational capture.

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

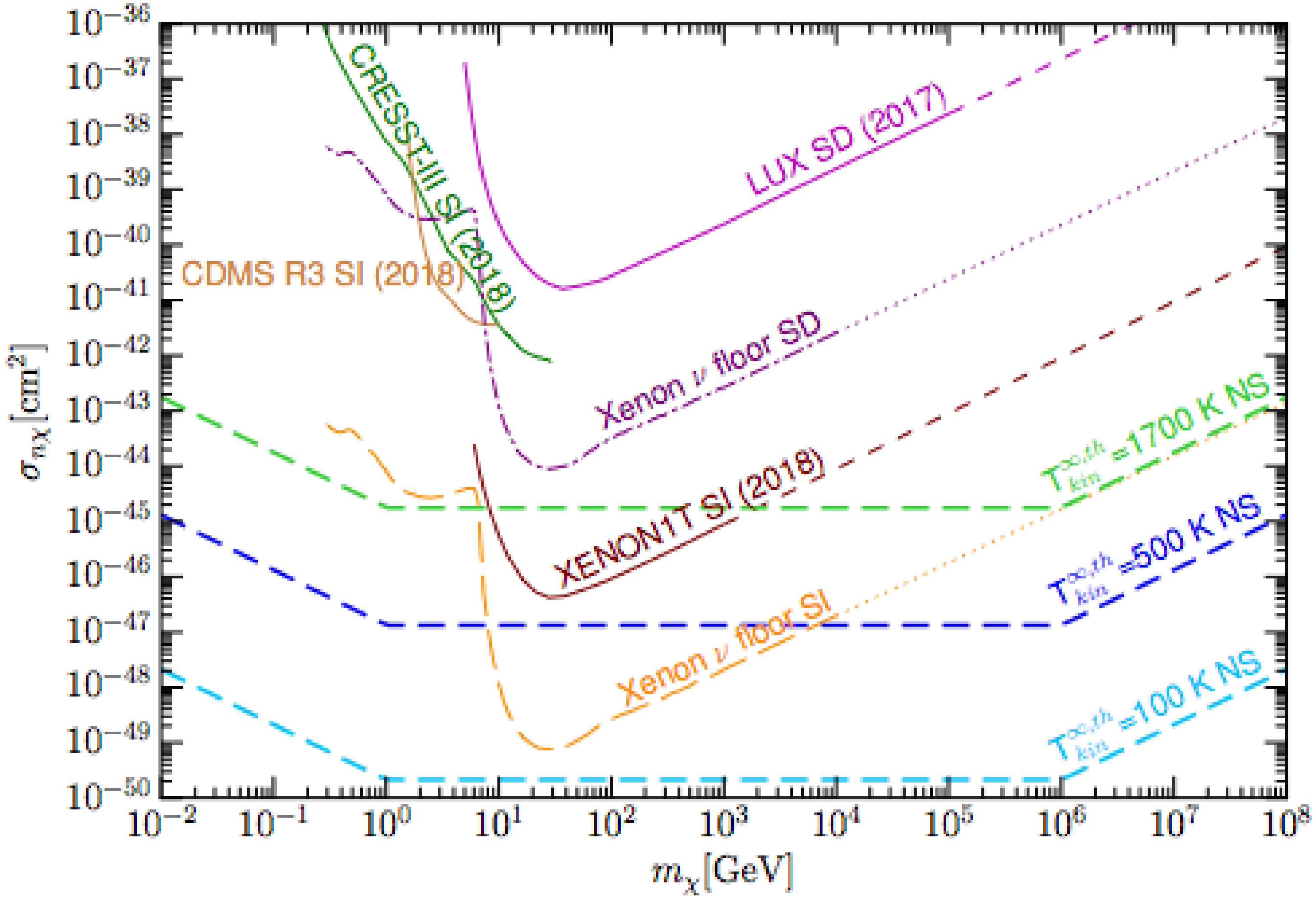
✓Cross section for efficient trapping $\mathcal{O}\left(10^{-45}\ \mathrm{cm}\right)$ for large DM mass range

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

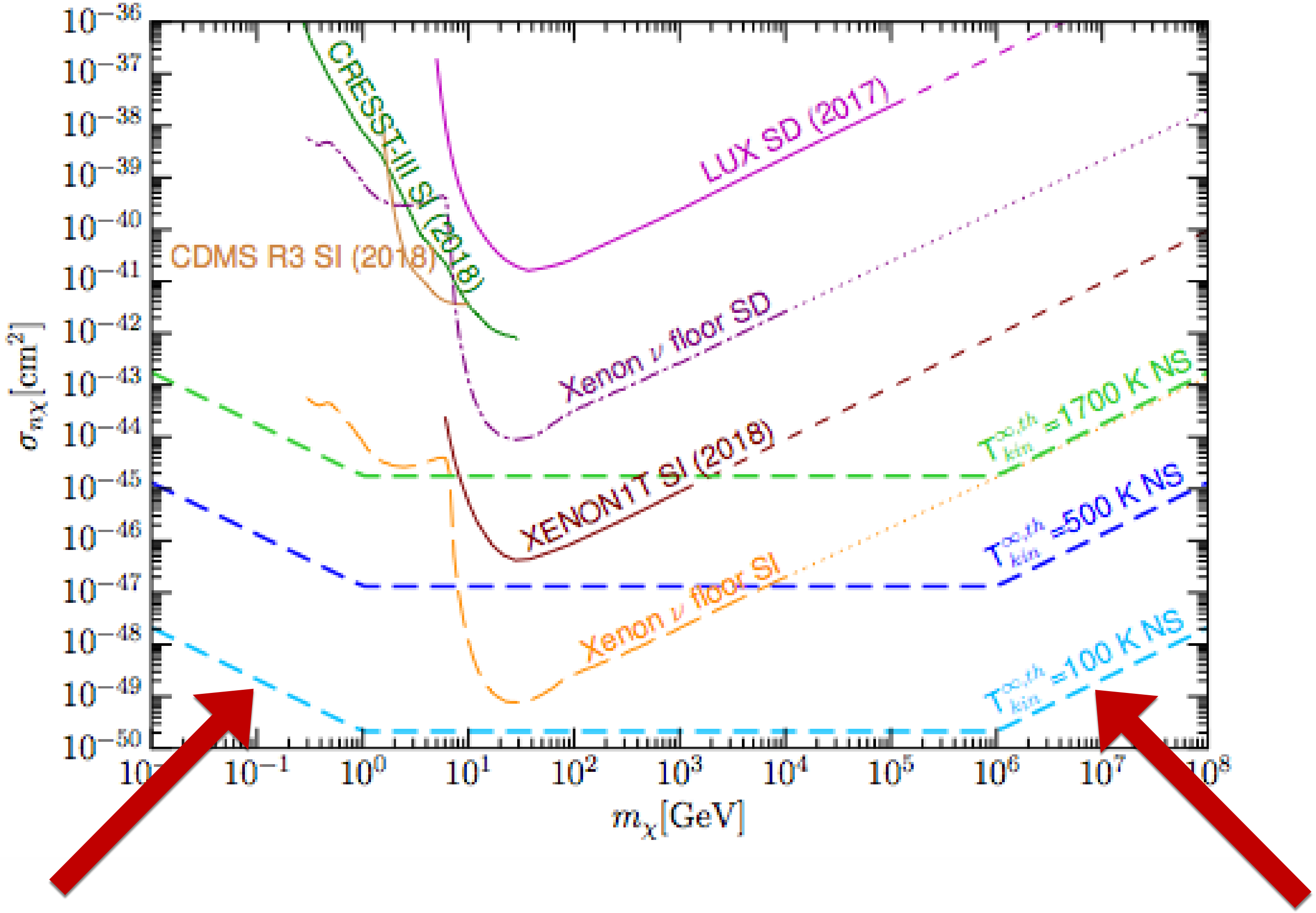
✓Similar sensitivity to SI and SD cross scattering

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

Kinetic Heating: Sensitivity



Kinematics



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	$(\bar{\chi}\chi)(\bar{q}q)$	$\mathrm{y_q}/\Lambda^2$	SI	✗	NS or DD
D2	PS	$(\bar{\chi}\gamma_5\chi)(\bar{q}q)$	$\mathrm{y_q}/\Lambda^2$	SI	✓	NS
D3	SP	$(\bar{\chi}\chi)(\bar{q}\gamma_5 q)$	$\mathrm{y_q}/\Lambda^2$	SD	✓	NS
D4	PP	$(\bar{\chi}\gamma_5\chi)(\bar{q}\gamma_5 q)$	$\mathrm{y_q}/\Lambda^2$	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:

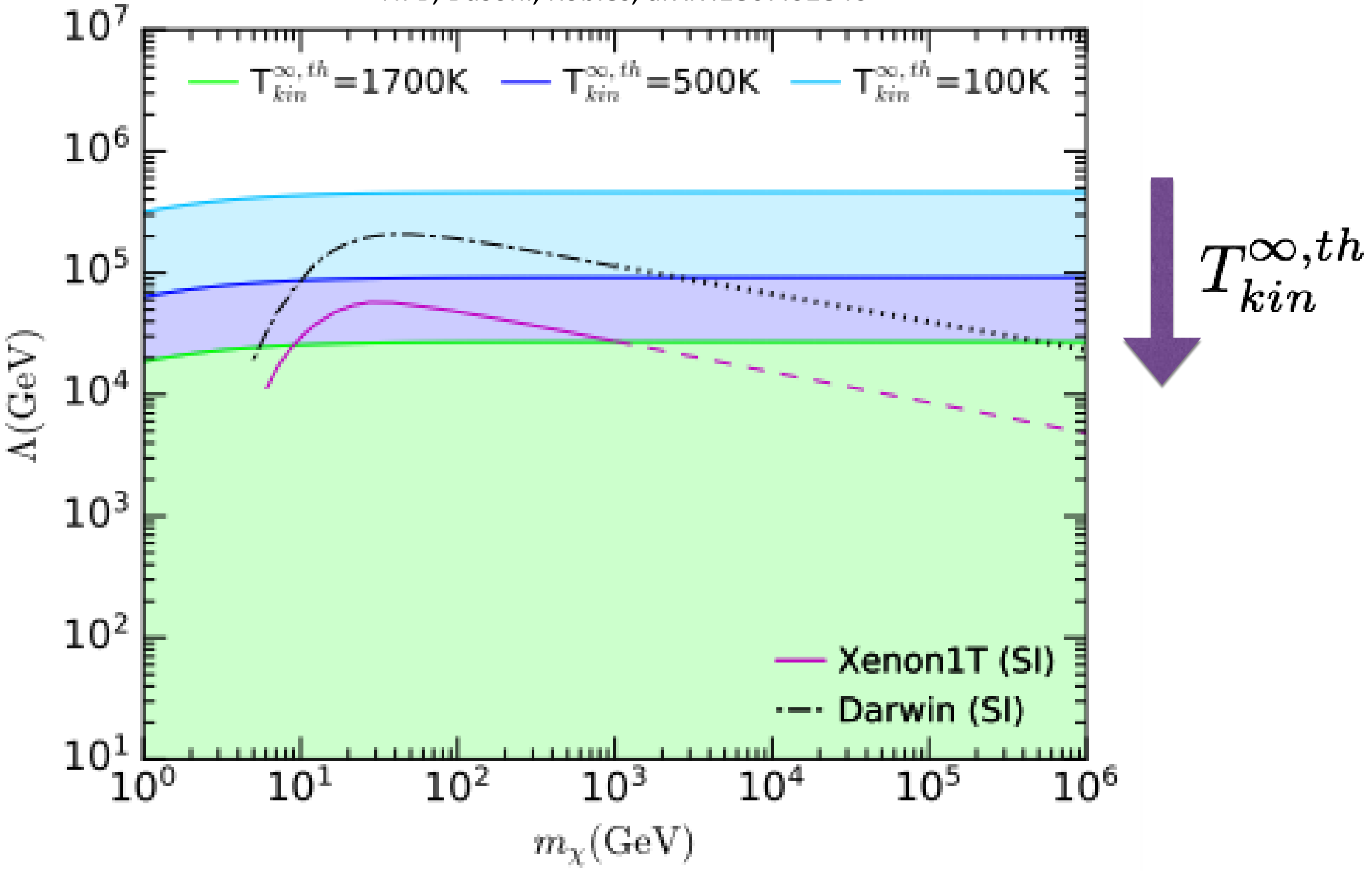
- comparable to direct detection experiments for scalar and vector interactions
- more sensitive than DD for all other interaction types (typically by orders of magnitude.

Neutron star sensitivity - SI scattering

$$\bar{\chi}\gamma_\mu\chi\ \bar{q}\gamma^\mu q$$

Neutron star kinetic heating sensitivity comparable to Xenon 1T Direct Detection limits for vector-vector interaction

NFB, Busoni, Robles, arXiv:1807.02840



Momentum suppressed scattering

$$\bar{\chi}\chi\,\bar{q}\gamma^5 q$$

Non relativistic limit – Direct Detection regime

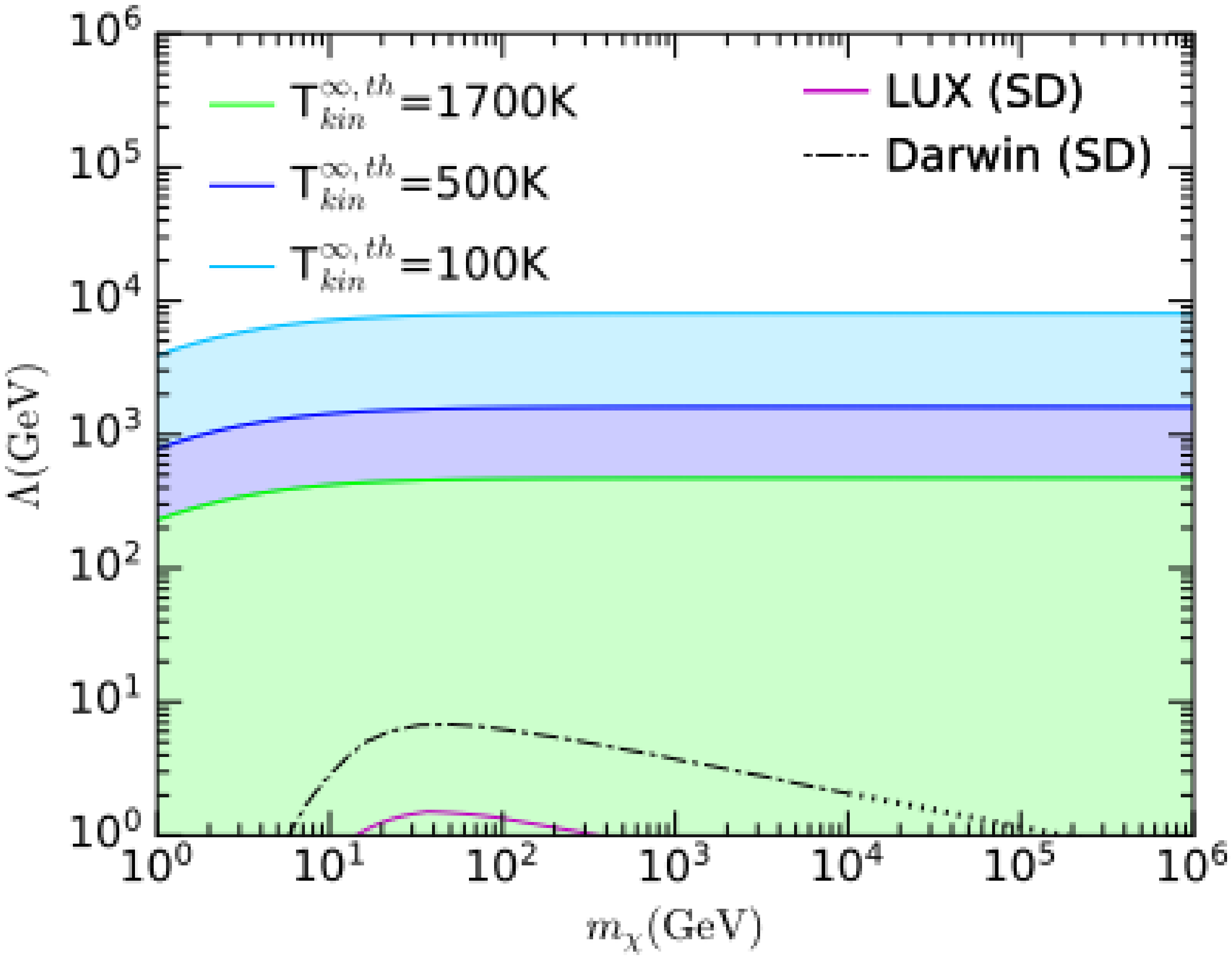
$$\frac{d\sigma}{d\cos\theta} = \frac{c_N^P m_N^2}{\Lambda^4}\,\frac{\mu^2 q_{tr}^2}{8\pi(\mu+1)^2}$$

Momentum suppressed

Relativistic limit – Neutron Star regime

$$\frac{d\sigma}{d\cos\theta} = \frac{c_N^P m_N^2}{\Lambda^4}\,\frac{t\,(t-4m_\chi^2)}{32\pi s}$$

NFB, Busoni, Robles, arXiv:1807.02840



Spin-dependent scattering (pseudoscalar)

$$\bar{\chi}\gamma^5\chi\,\bar{q}\gamma^5 q$$

Non relativistic limit – Direct Detection regime

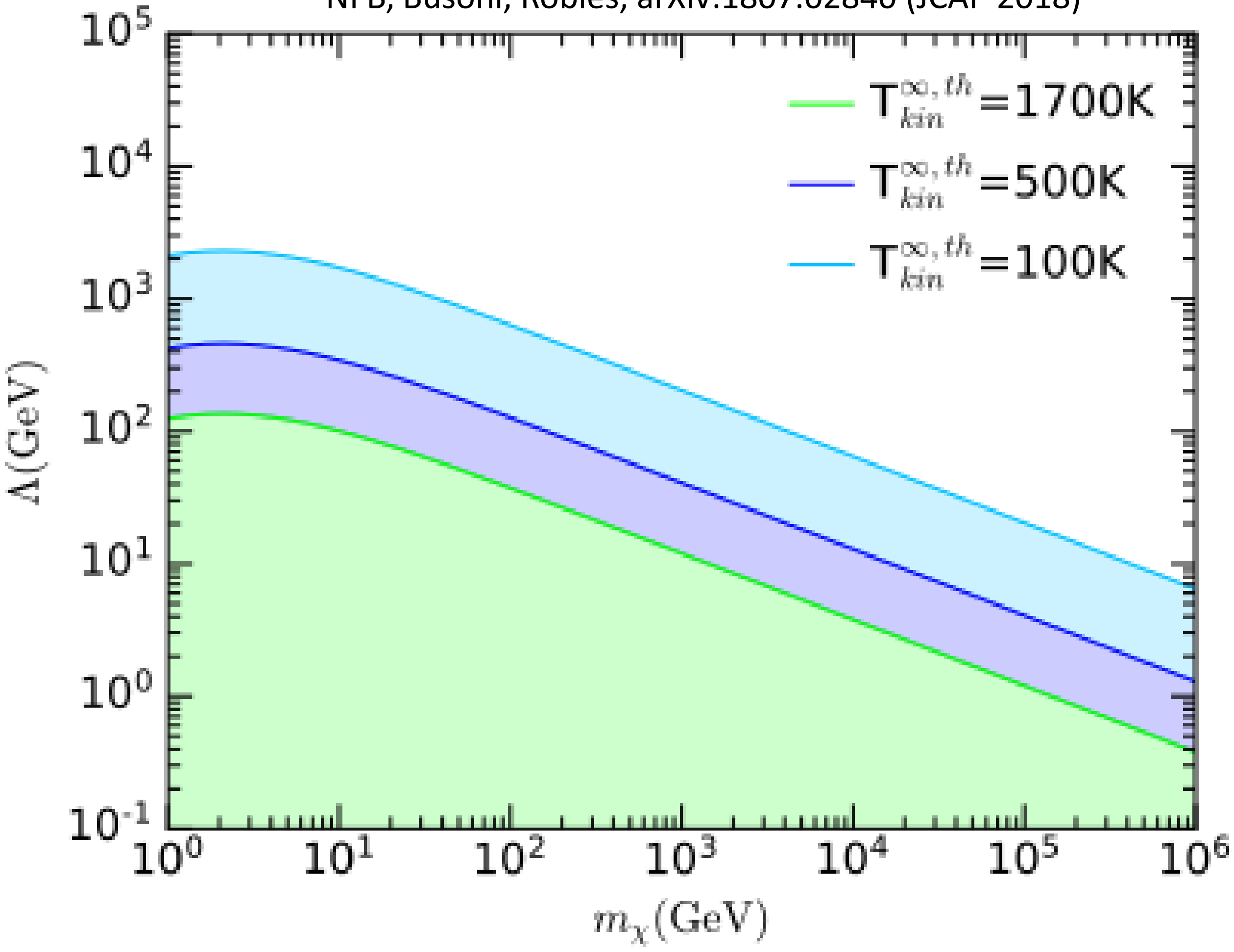
$$\frac{d\sigma}{d\cos\theta} = \frac{c_N^P m_N^2}{\Lambda^4}\frac{\mu^2 q_{tr}^4}{32\pi(\mu+1)^2 m_\chi^2}$$

Momentum suppressed by q^4 and SD

Relativistic limit – Neutron Star regime

$$\frac{d\sigma}{d\cos\theta} = \frac{c_N^P m_N^2}{\Lambda^4}\frac{t^2}{32\pi s}$$

NFB, Busoni, Robles, arXiv:1807.02840 (JCAP 2018)



Inelastic dark matter

Two *almost degenerate* dark matter states: χ_1 and χ_2

Inelastic in the sense that the dominant interaction is off-diagonal:

$\chi_1 + n \to \chi_1 + n$	highly suppressed
$\chi_1 + n \to \chi_2 + n$	kinematically forbidden except for $\delta m \ll m$

Well motivated if dark matter is quasi-Dirac (small Majorana mass)

Inelastic dark matter

Assume all dark matter in Universe today is in χ_1 state

→ The only scattering process is $\chi_1 n \rightarrow \chi_2 n$

- Xenon based DD experiments restricted to $\delta m < 180\ \mathrm{keV}$
- Capture in the Sun can probe only slightly higher mass splittings
- Neutron stars can probe much higher mass splittings, because the dark matter has a lot more kinetic energy (quasi-relativistic, due to acceleration on infall) $\delta m < 330\ \mathrm{MeV}$

Inelastic scattering cross section

Maximum mass splitting

$$k = \frac{\delta m}{m_\chi} \leq k_{\mathrm{MAX}}$$

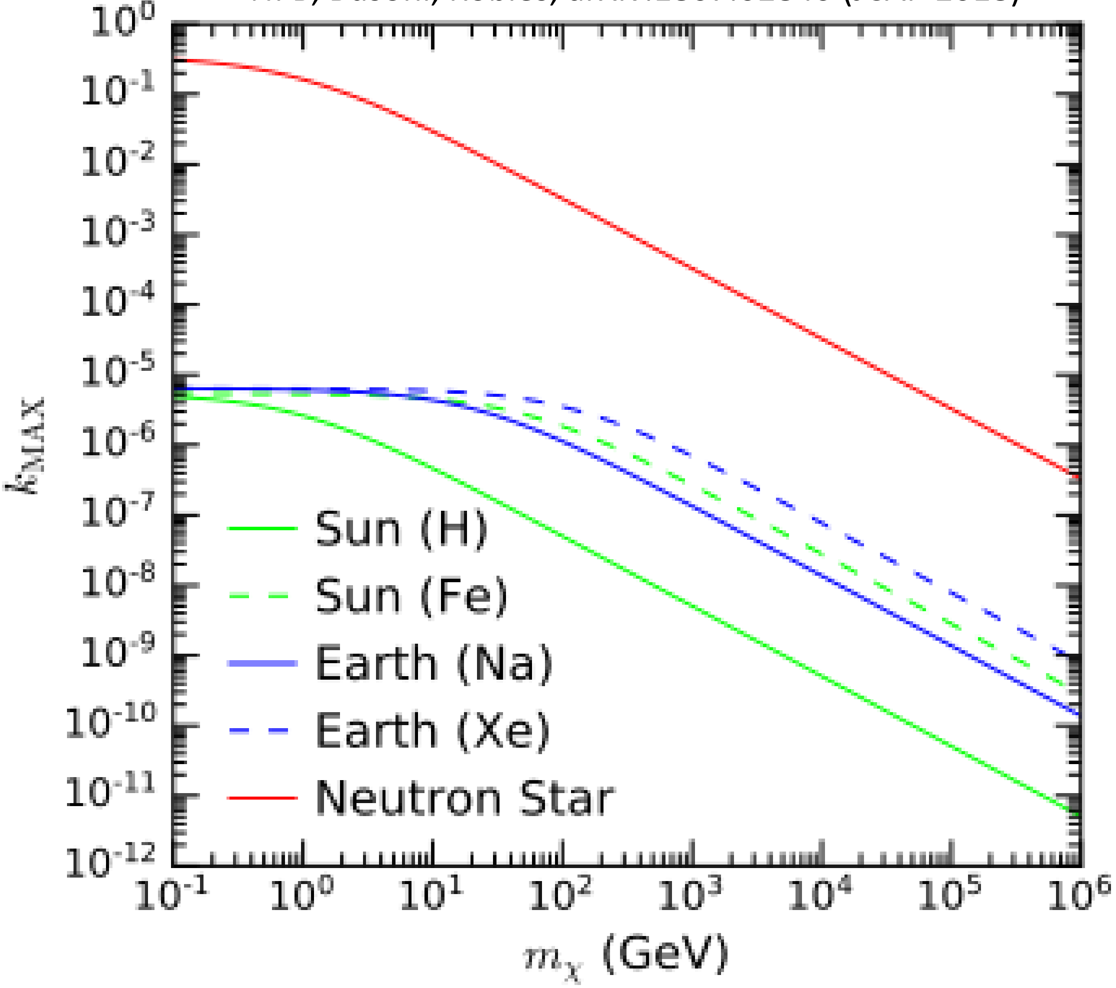
$$\boxed{k_{MAX} = \sqrt{1 + \frac{2}{\mu\sqrt{B}} + \frac{1}{\mu^2}} - 1 - \frac{1}{\mu}}$$

$$B = 1 - \frac{2GM_\star}{c^2 R_\star} \simeq 0.55$$

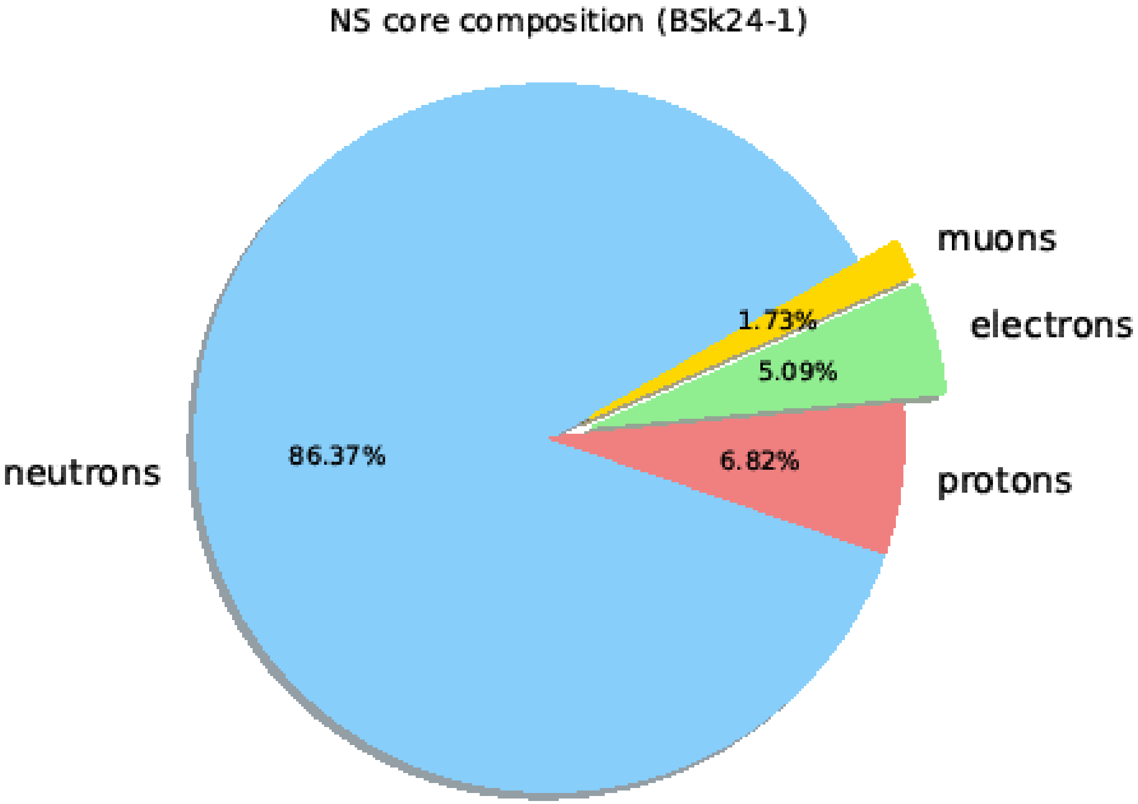
$$\mu = \frac{m_\chi}{m_T}$$

In NSs
$m_T = m_n$

NFB, Busoni, Robles, arXiv:1807.02840 (JCAP 2018)



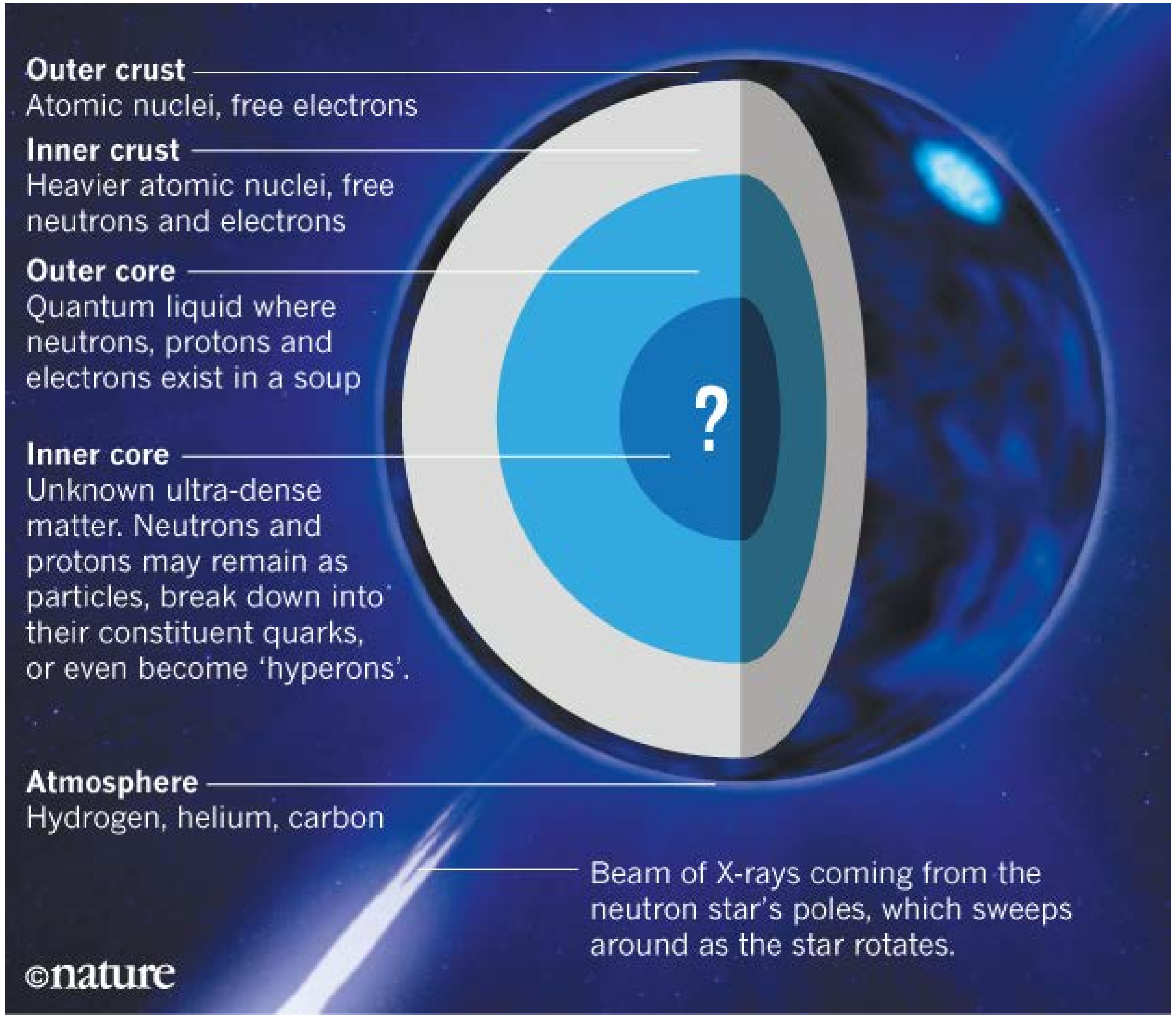
Leptons in Neutron Stars



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:

- Degenerate neutrons
- Smaller and approximately equal electron and proton abundances
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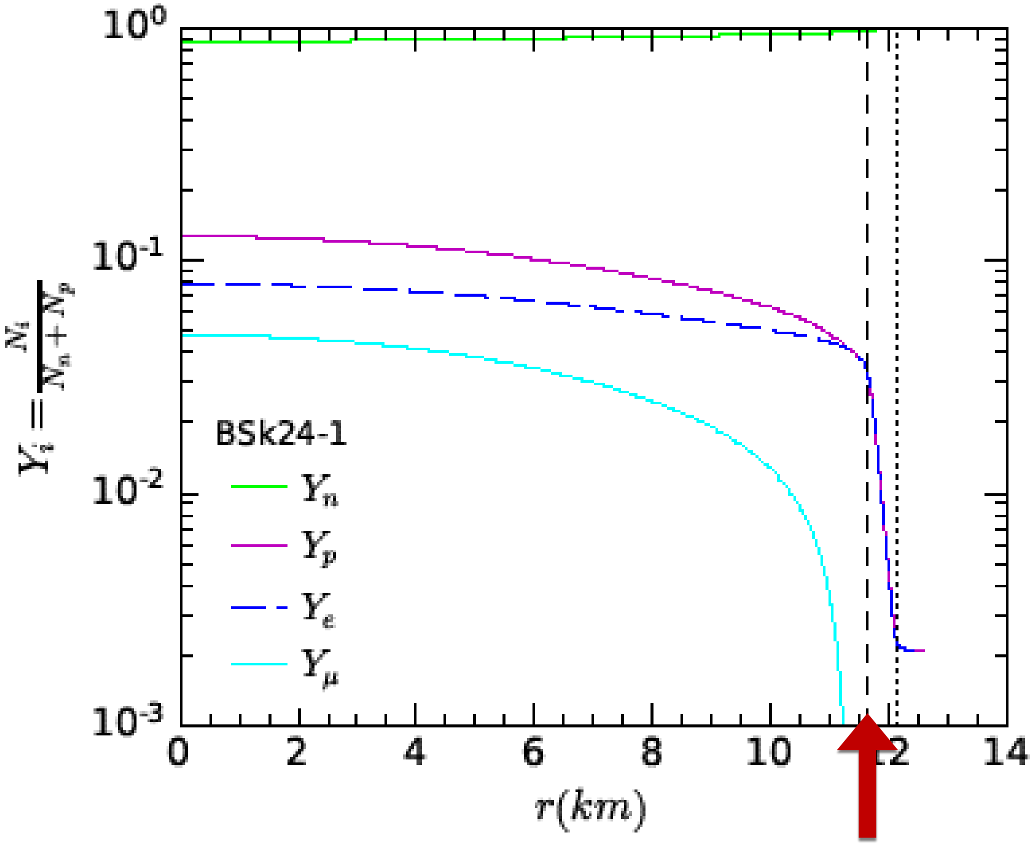
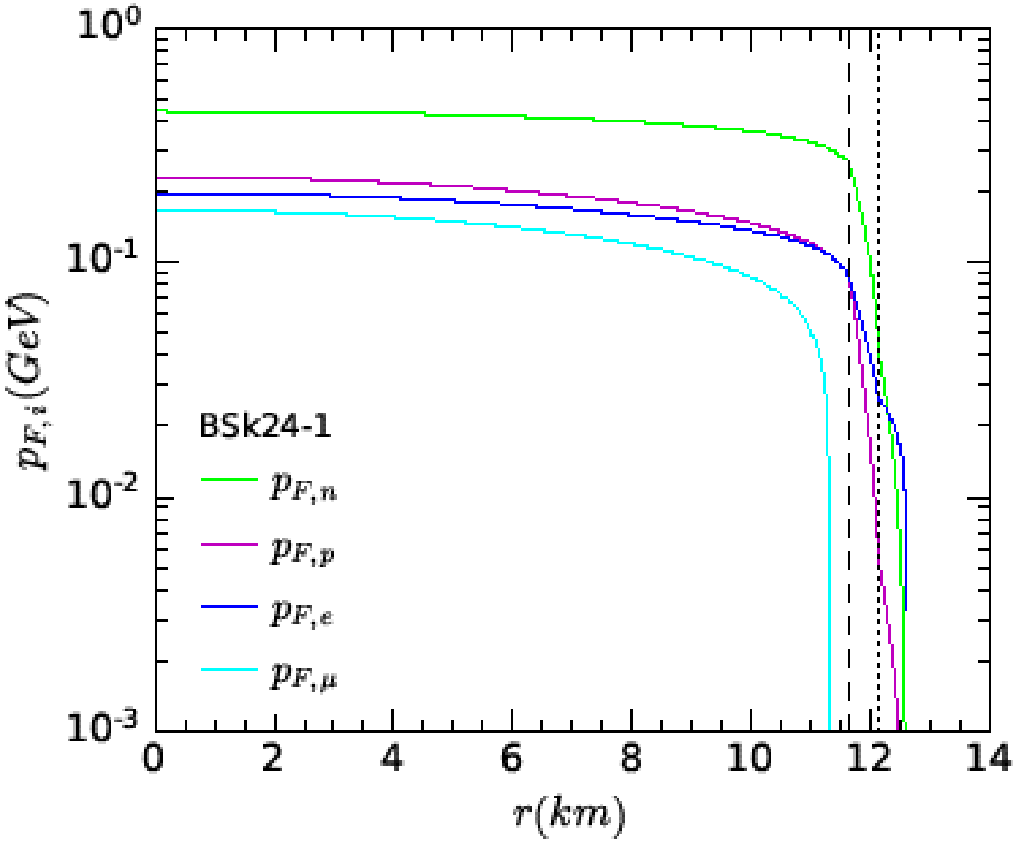
Leptons in Neutron Stars

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

Fermi-momentum ~ constant in core.

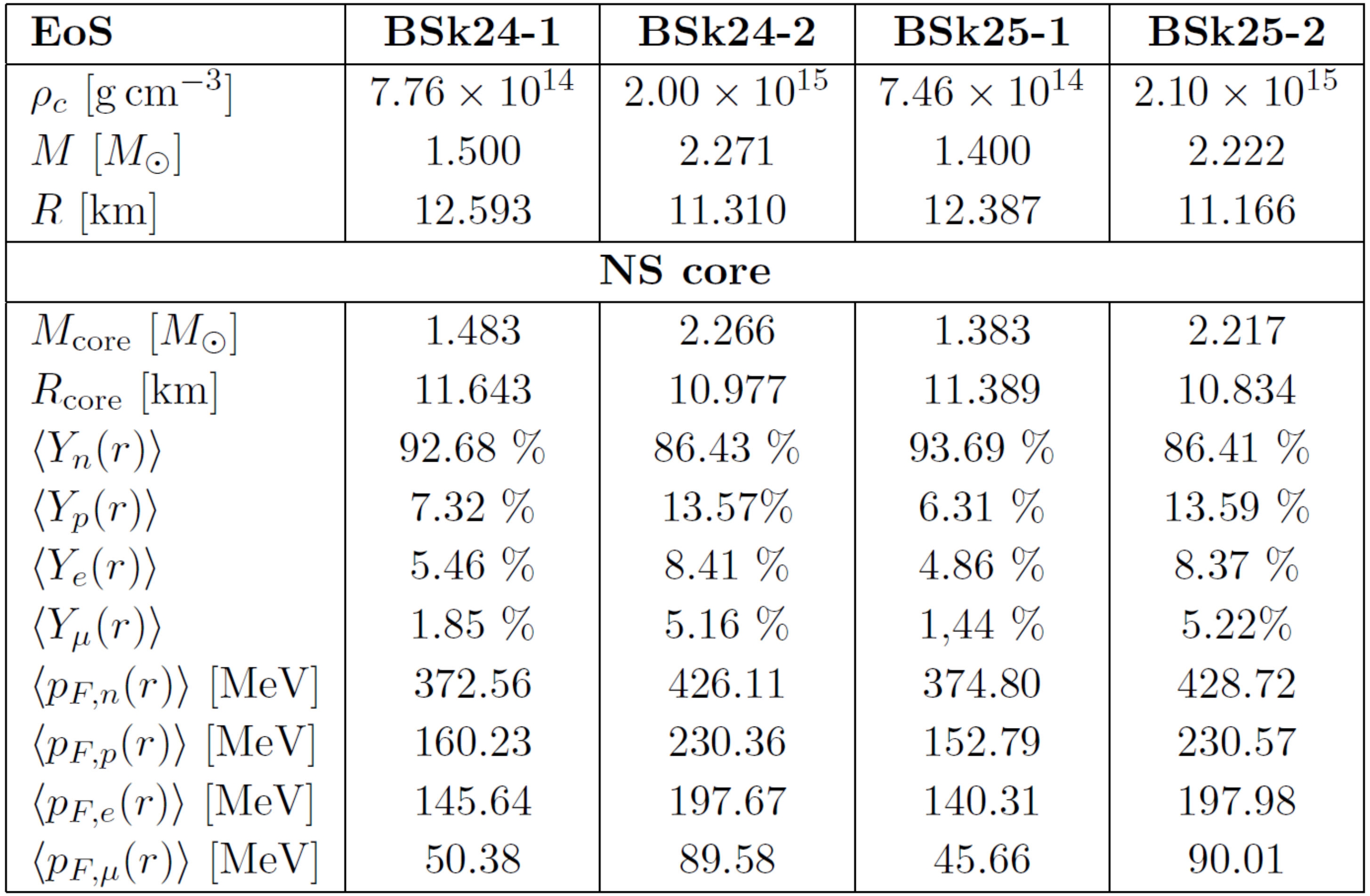




crust-core boundary

Neutron Star Equation of State

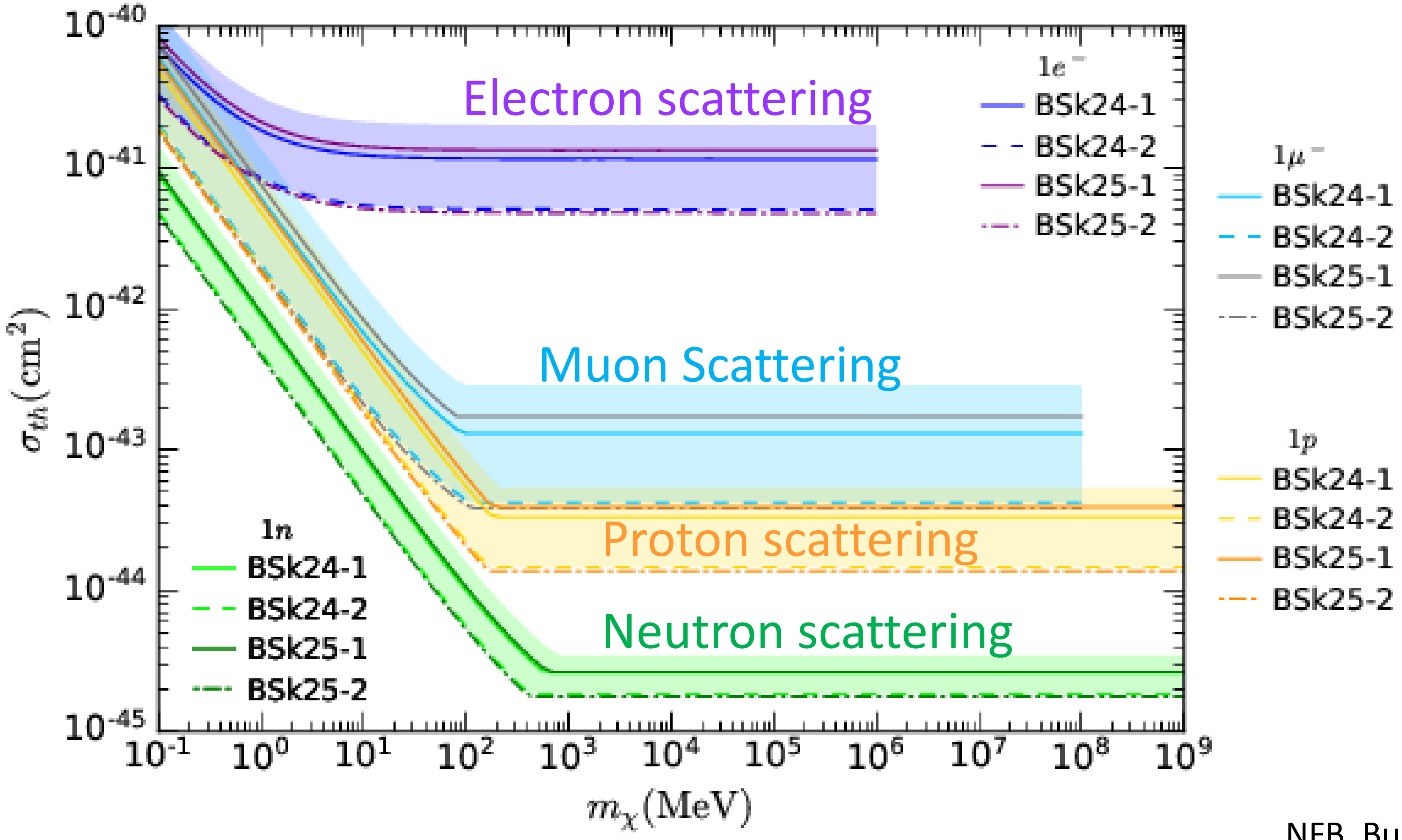
Pearson et al, Mon. Not. Roy. Astron. Soc. 481 no. 3, (2018)



EoS	**BSk24-1**	**BSk24-2**	**BSk25-1**	**BSk25-2**
ρ_c $[\mathrm{g\,cm^{-3}}]$	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_{core} $[M_\odot]$	1.483	2.266	1.383	2.217
R_{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

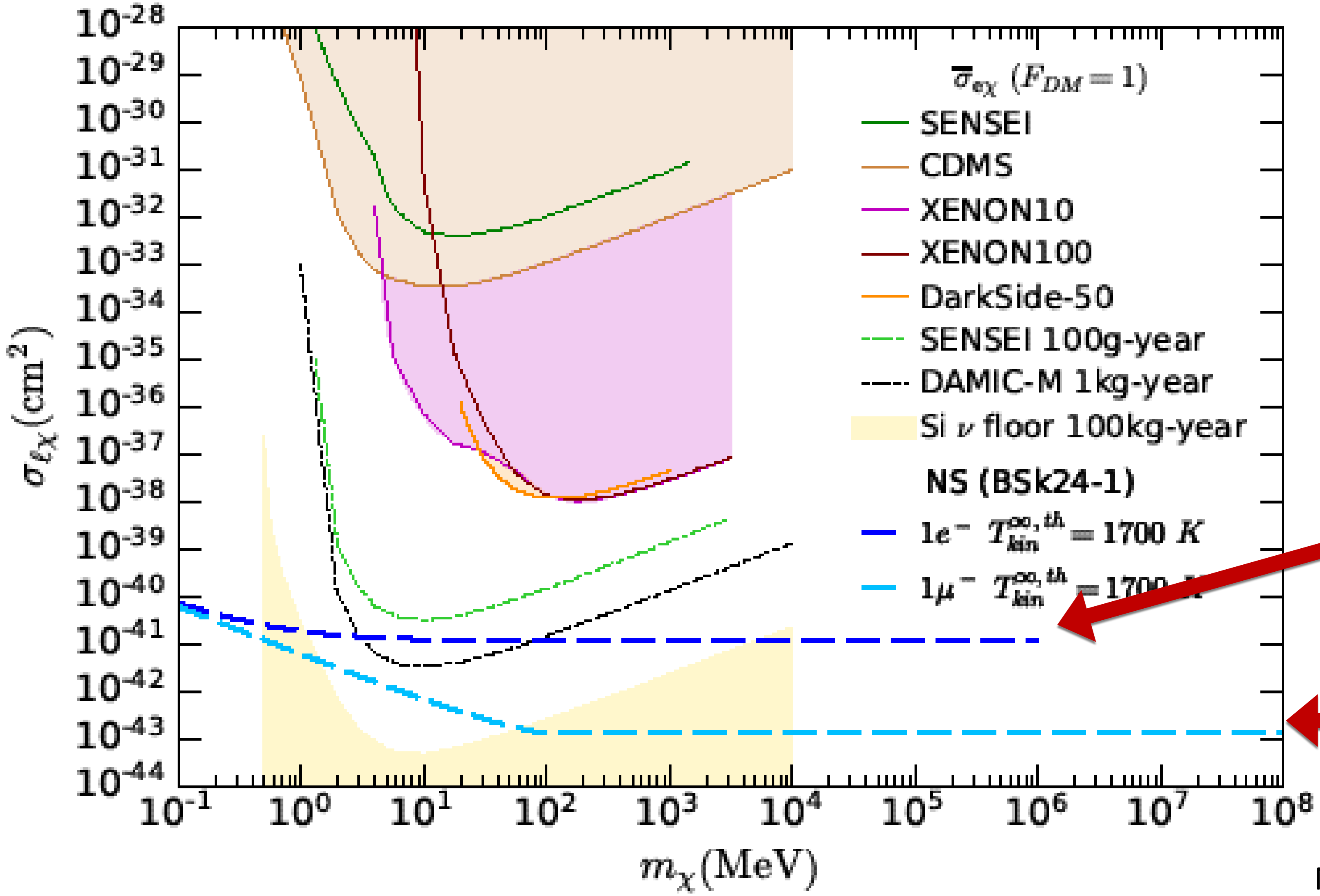
Composition varies according to the neutron star EoS

Insensitive to details of NS Equation of State



NFB, Busoni & Robles arXiv:1904.09803

Neutron star limits on leptophilic DM



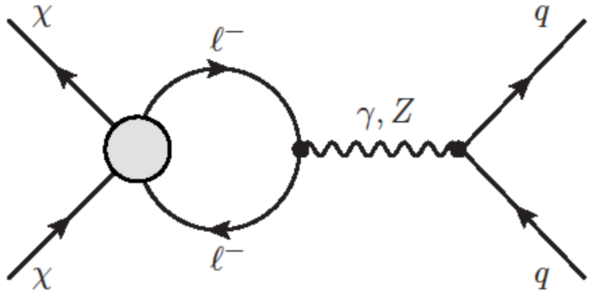
Electron scattering

Muon scattering

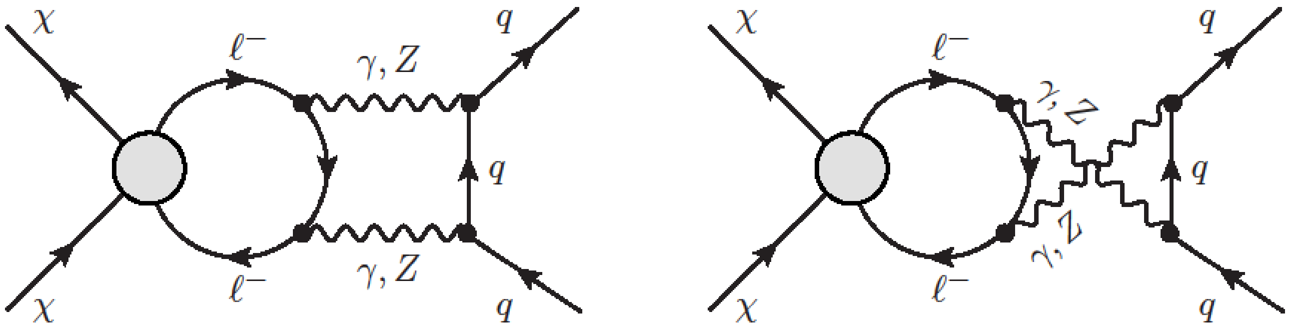
NFB, Busoni & Robles arXiv:1904.09803

Leptophilic dark matter → loop-level quark couplings

1-loop photon-mediated diagrams are the most important.
(Non-zero only for certain operators)



Other cases suppressed by Z-mass or by two loops.

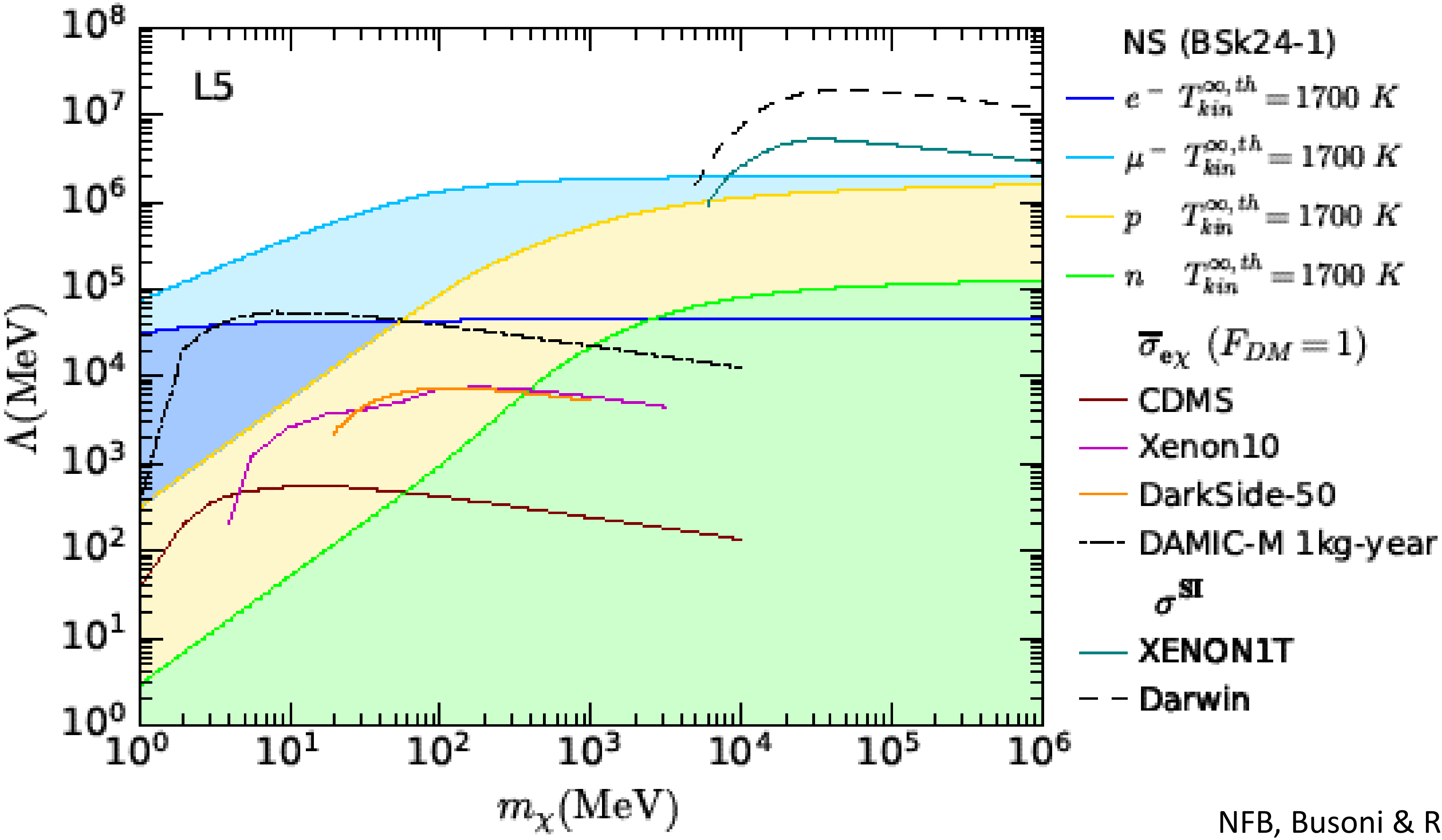


Lepton operators → Quark operators

Name	Operator	Coupling G
L1	$\bar{\chi}\chi\,\bar{\ell}\ell$	y_ℓ/Λ^2
L2	$\bar{\chi}\gamma^5\chi\,\bar{\ell}\ell$	iy_ℓ/Λ^2
L3	$\bar{\chi}\chi\,\bar{\ell}\gamma^5\ell$	iy_ℓ/Λ^2
L4	$\bar{\chi}\gamma^5\chi\,\bar{\ell}\gamma^5\ell$	y_ℓ/Λ^2
L5	$\bar{\chi}\gamma_\mu\chi\,\bar{\ell}\gamma^\mu\ell$	$1/\Lambda^2$
L6	$\bar{\chi}\gamma_\mu\gamma^5\chi\,\bar{\ell}\gamma^\mu\ell$	$1/\Lambda^2$
L7	$\bar{\chi}\gamma_\mu\chi\,\bar{\ell}\gamma^\mu\gamma^5\ell$	$1/\Lambda^2$
L8	$\bar{\chi}\gamma_\mu\gamma^5\chi\,\bar{\ell}\gamma^\mu\gamma^5\ell$	$1/\Lambda^2$
L9	$\bar{\chi}\sigma_{\mu\nu}\chi\,\bar{\ell}\sigma^{\mu\nu}\ell$	$1/\Lambda^2$
L10	$\bar{\chi}\sigma_{\mu\nu}\gamma^5\chi\,\bar{\ell}\sigma^{\mu\nu}\ell$	i/Λ^2

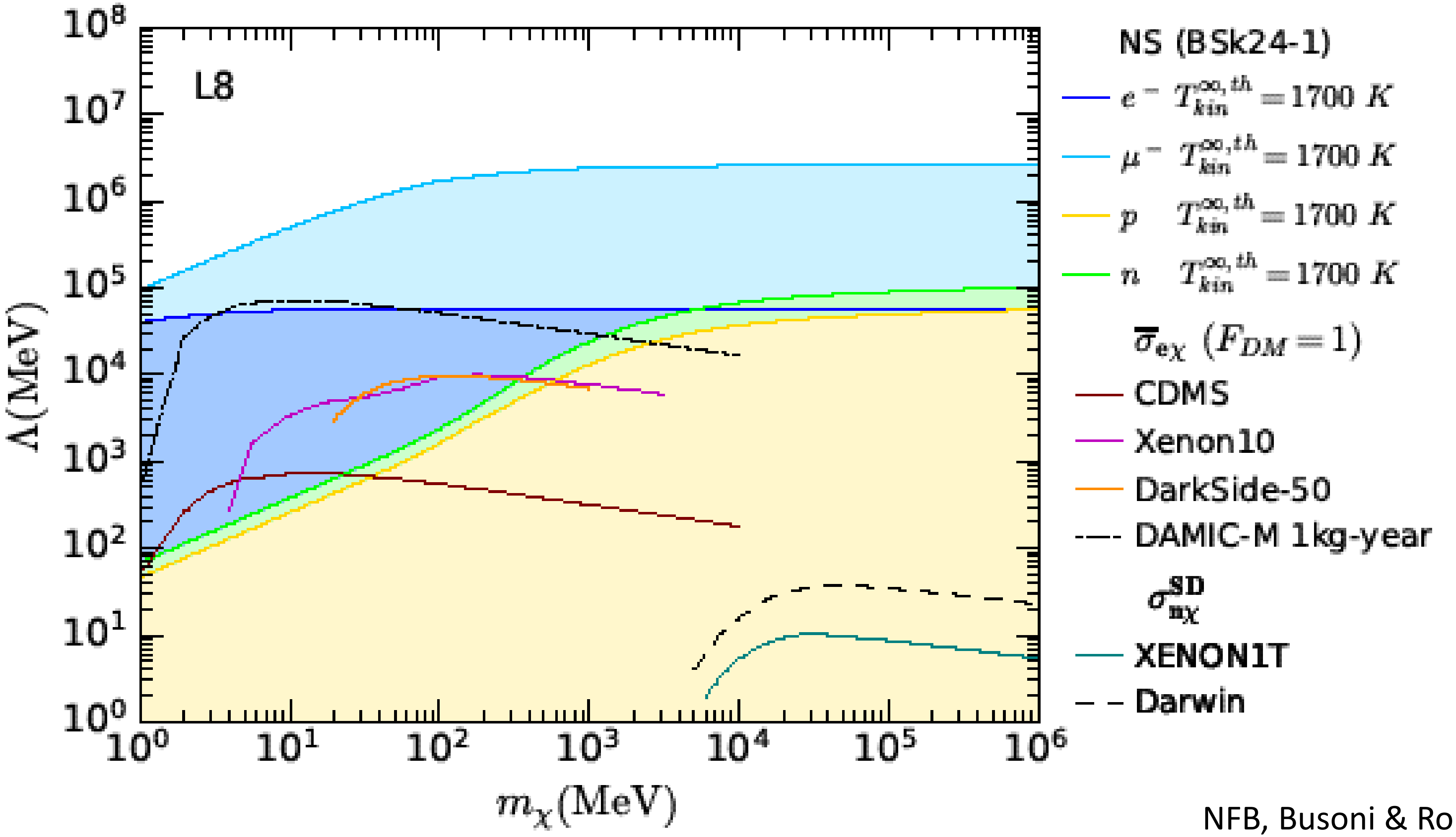
Operator	Coupling	Induced by
D1	2 loop (γ, Z)	L1
D2	-	-
D3	2 loop (γ, Z)	L3
D4	-	-
D5	1 loop (γ) 1 loop (Z)	L5 L5, L7
D6	1 loop (γ) 1 loop (Z)	L6 L6, L8
D7	1 loop (Z)	L5, L7
D8	1 loop (Z)	L6, L8

Vector interactions (L5)



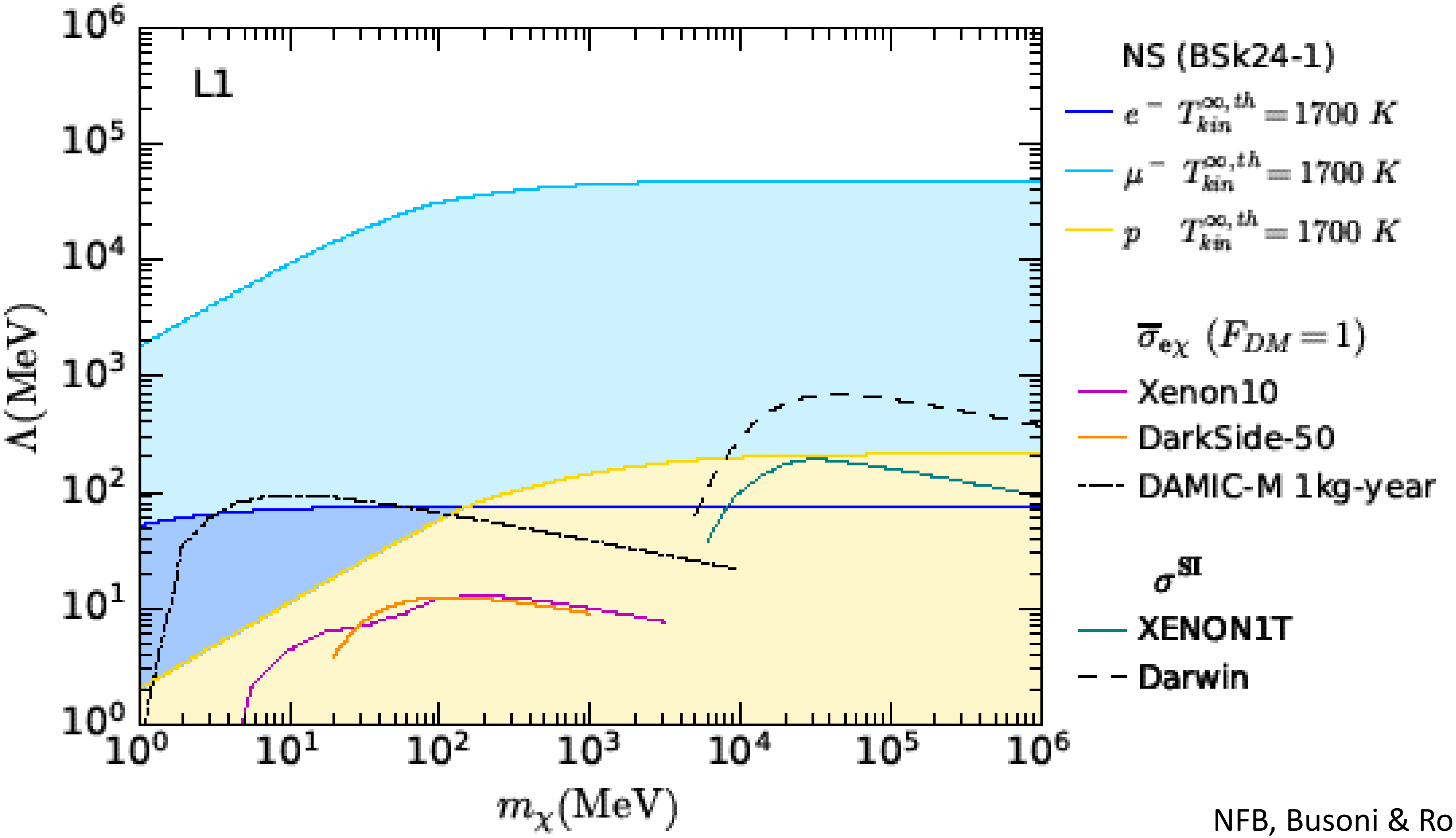
NFB, Busoni & Robles arXiv:1904.09803

Axial-vector interactions (L8)



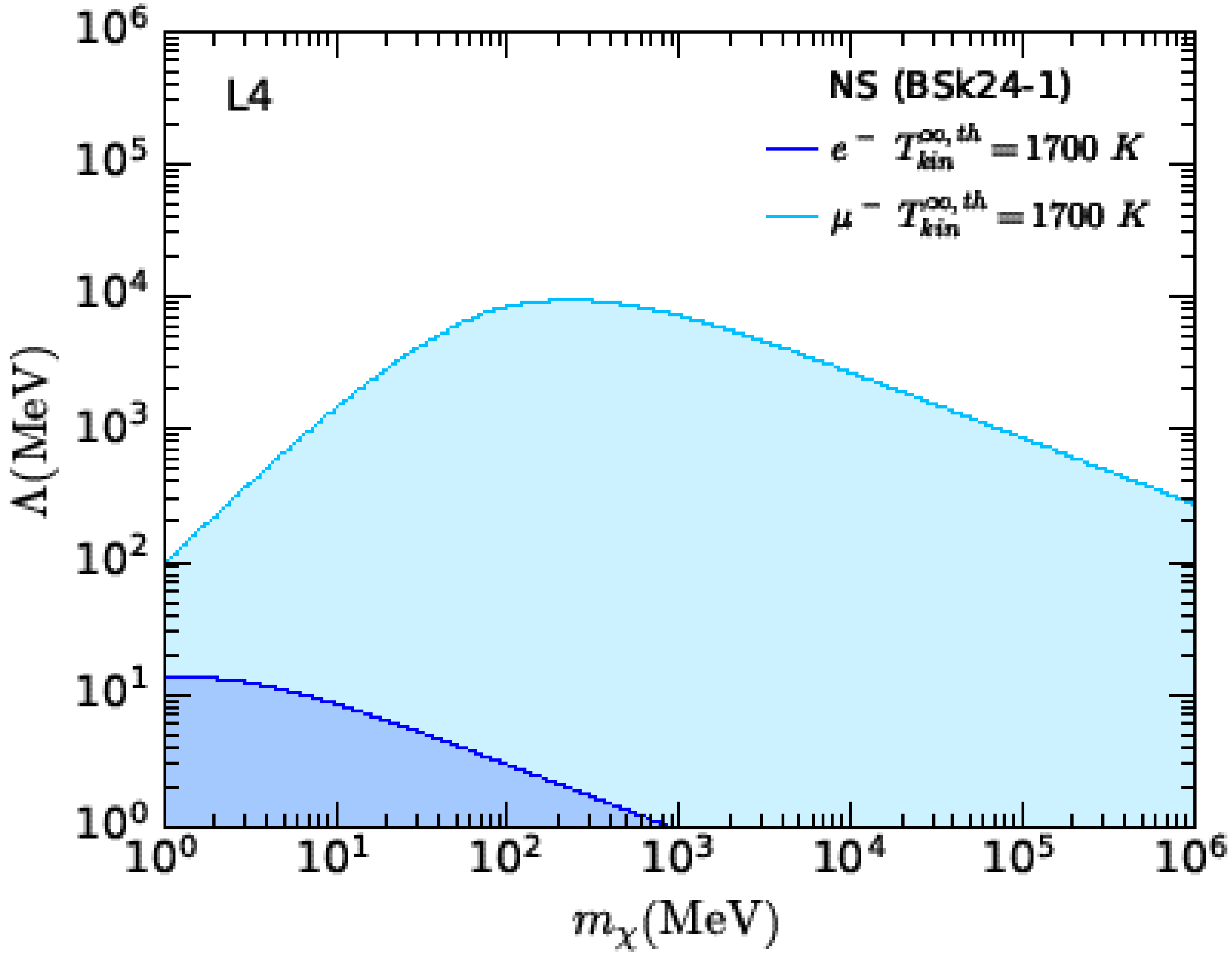
NFB, Busoni & Robles arXiv:1904.09803

Scaler interactions (L1)



NFB, Busoni & Robles arXiv:1904.09803

Pseudo-scaler interactions (L4)



NFB, Busoni & Robles arXiv:1904.09803

Unknowns

Are there other sources of neutron star heating?

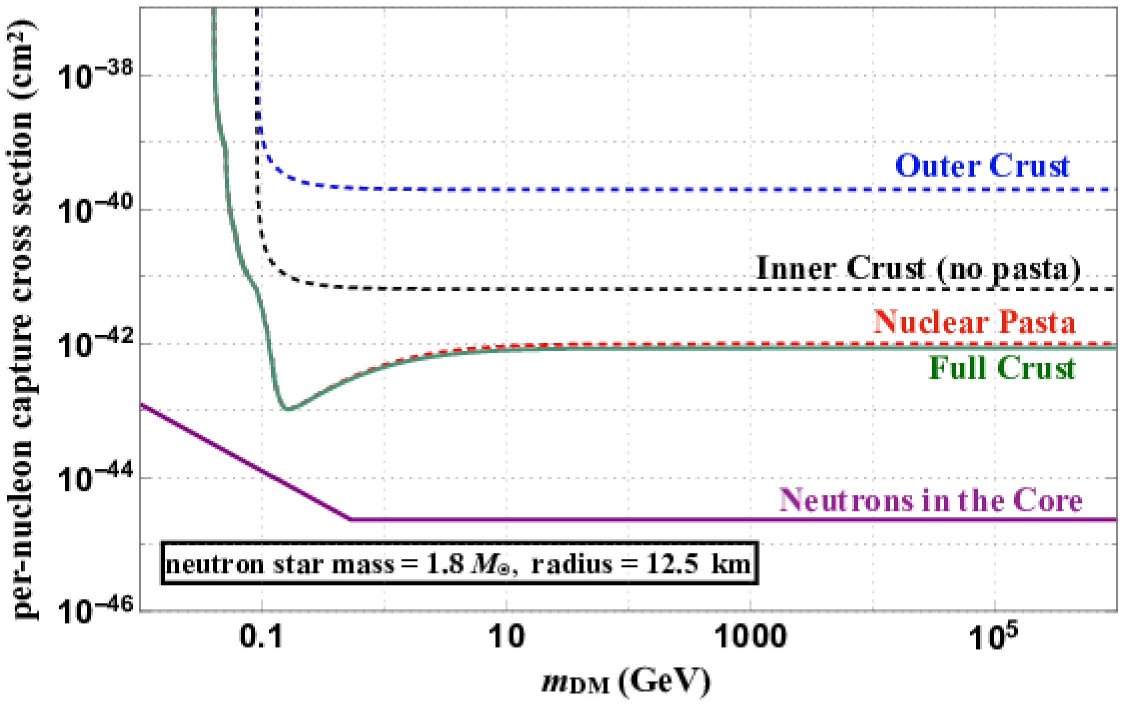
Rotochemical Heating (Hamaguchi et al., arXiv:1905.02991)

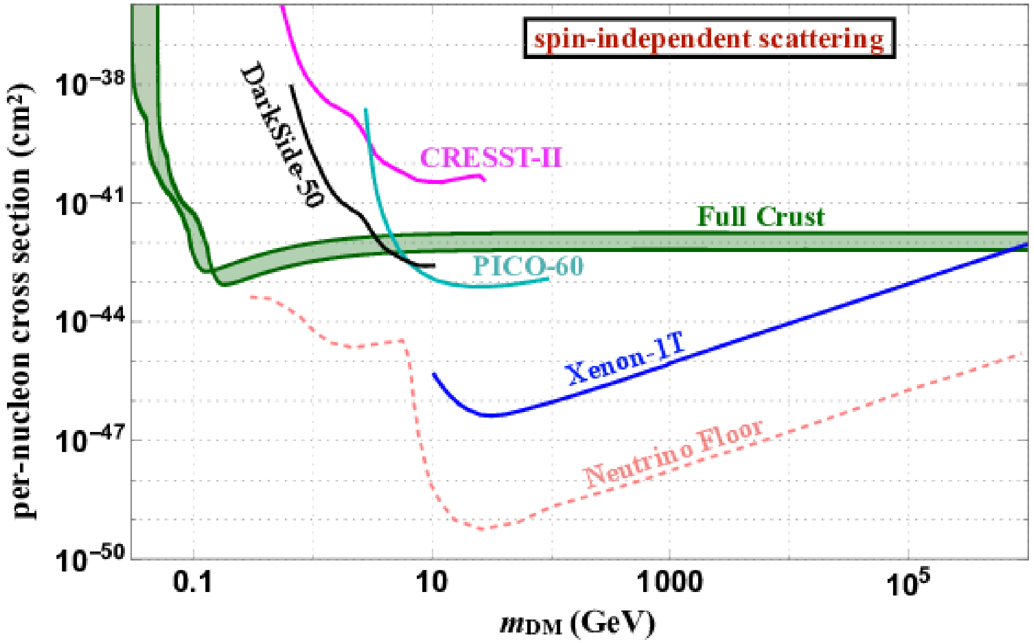
- For rotating pulsars, slow down in rotation may drive NS out of beta equilibrium
- Resulting imbalance in chemical potential induces *rotochemical heating*
- Dark matter may be observable for ordinary pulsars, but masked by rotochemical heating in millisecond pulsars with period < 7ms.

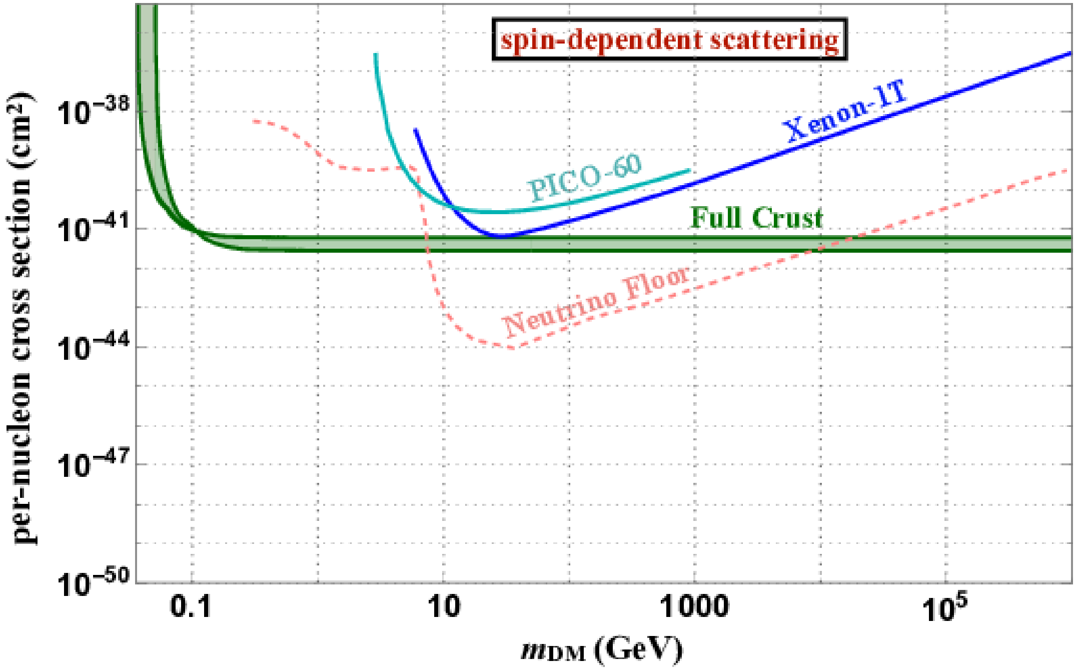
Are the uncertainties in the NS composition sufficiently well understood?

Scattering in the crust alone

Acevedo, Bramante, Leane & Raj, arXiv:1911.06334







Even scattering in just the crust gives interesting sensitivity at low DM mass

Summary & Conclusions

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

- Neutron Stars → completely different kinematic regime to direct detection experiments
  - Scattering of quasi-relativistic dark matter with neutron stars:
    - no velocity or momentum suppressions
    - access larger mass splittings in inelastic models
    - 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 nucleon and electron scattering.