Astroparticle Physics:

On the Capture of Dark Matter in Stars

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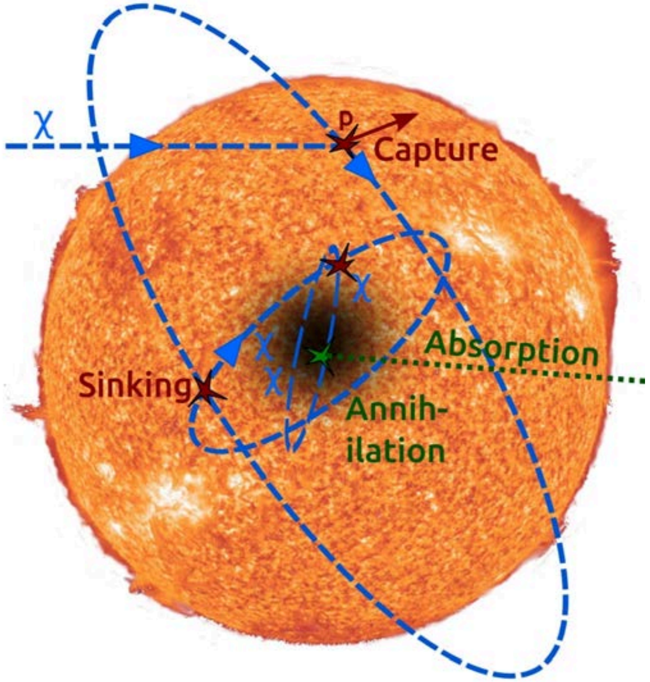
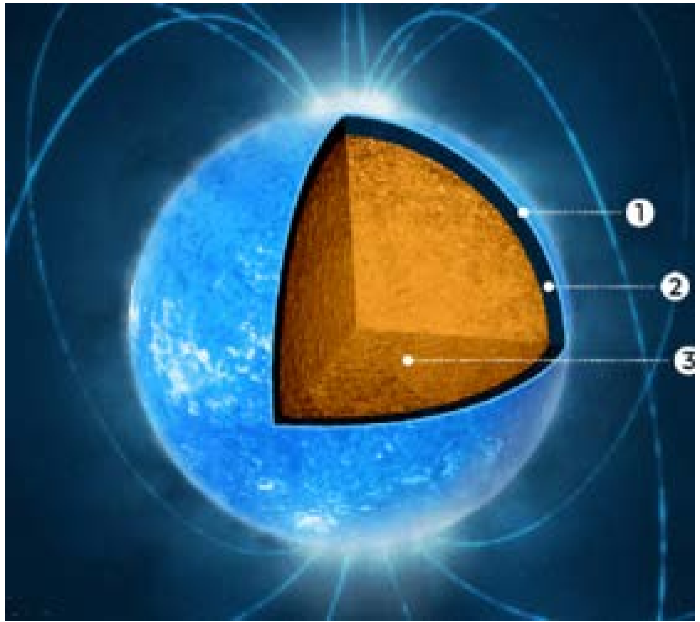
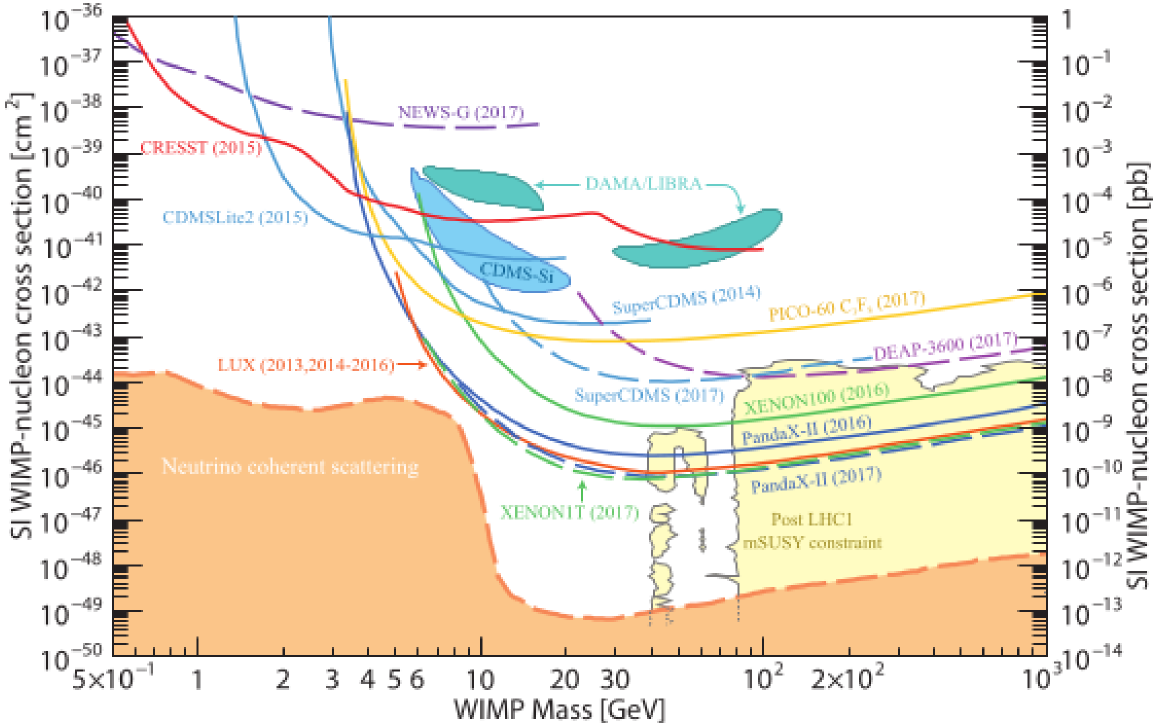
Outline

- Introduction
- Dark matter capture in the Sun
- Capture in Neutron Stars
  - Black Holes
  - Gravitational waves
  - Kinetic heating
    - DM-nucleon scattering
    - DM-lepton scattering
- Summary

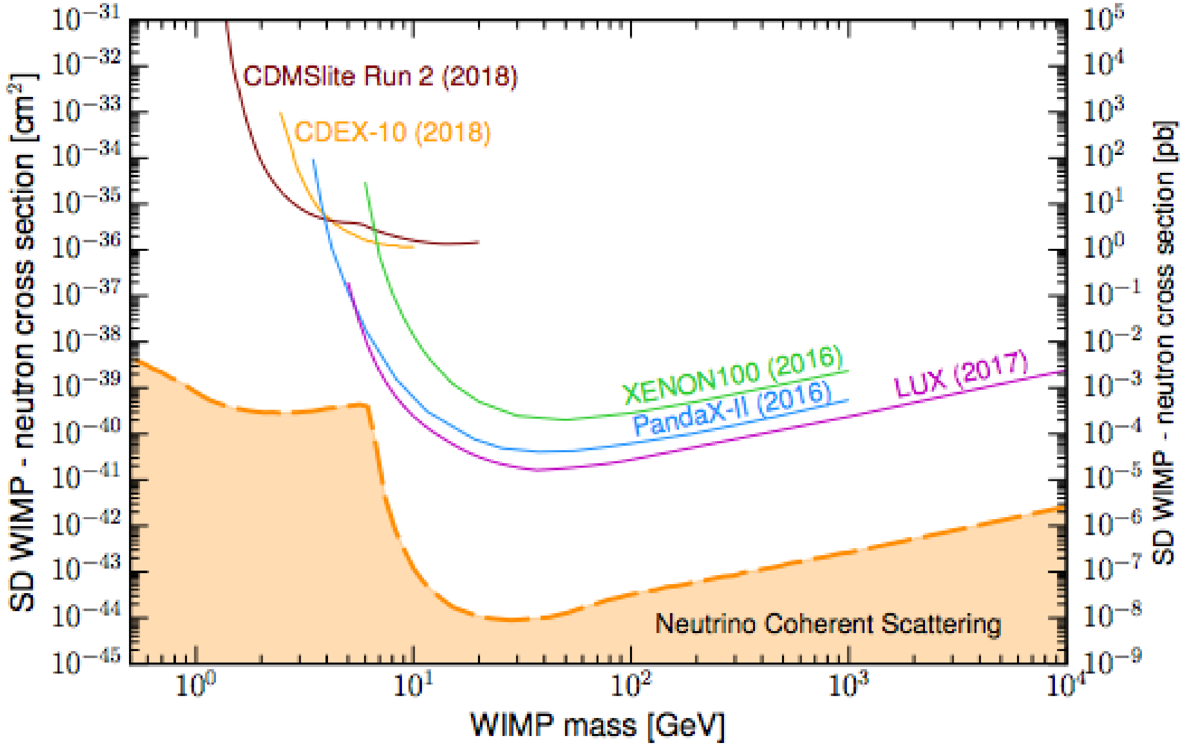




Introduction - Direct Detection



M. Tanabashi et al. (PDG) 2018



Spin-independent (SI) interactions
→ stringent bounds

Spin-dependent (SD) interactions
→ much weaker bounds

Introduction - Direct Detection

Sensitivity depends on interaction type

- Enhanced cross sections for SI scattering
- Smaller cross sections for SD scattering

Limited by kinematics

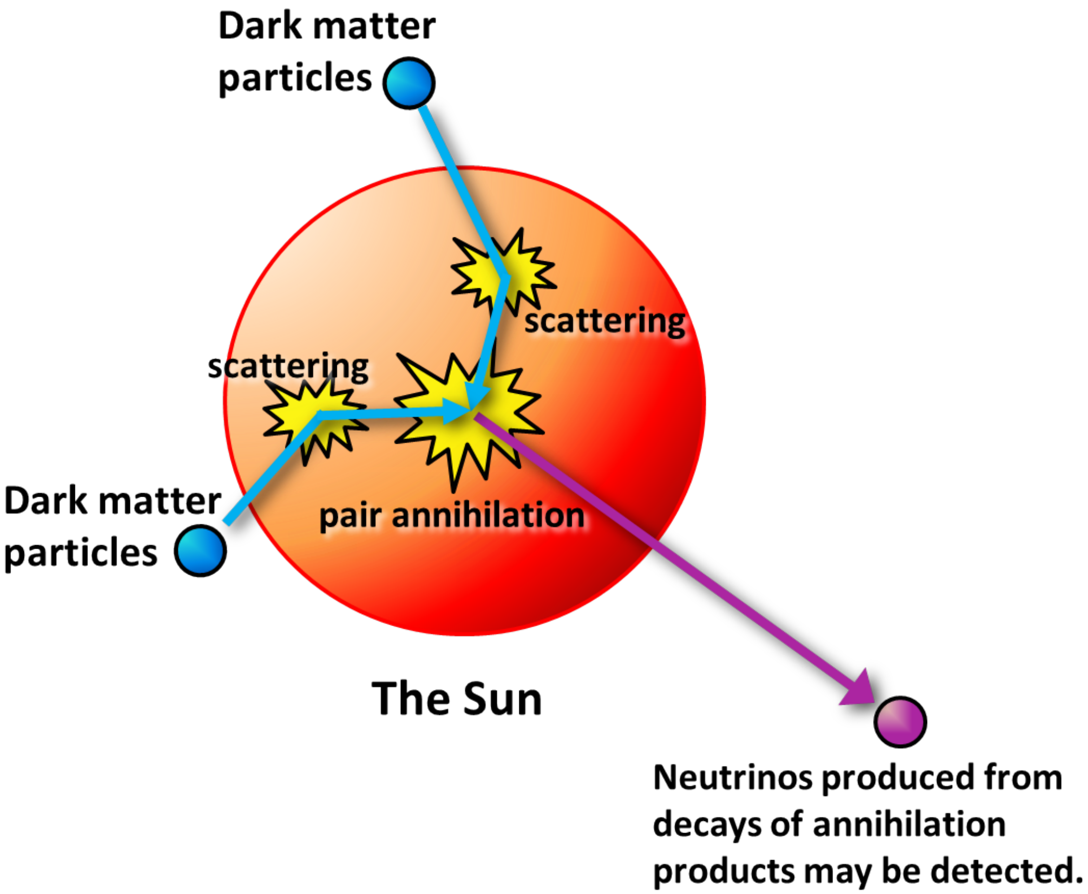
- Some interactions feature only momentum or velocity suppressed cross section → these are very small numbers
- Mass of the target nuclei (or electron mass)
- Experimental thresholds for detecting recoil energy

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

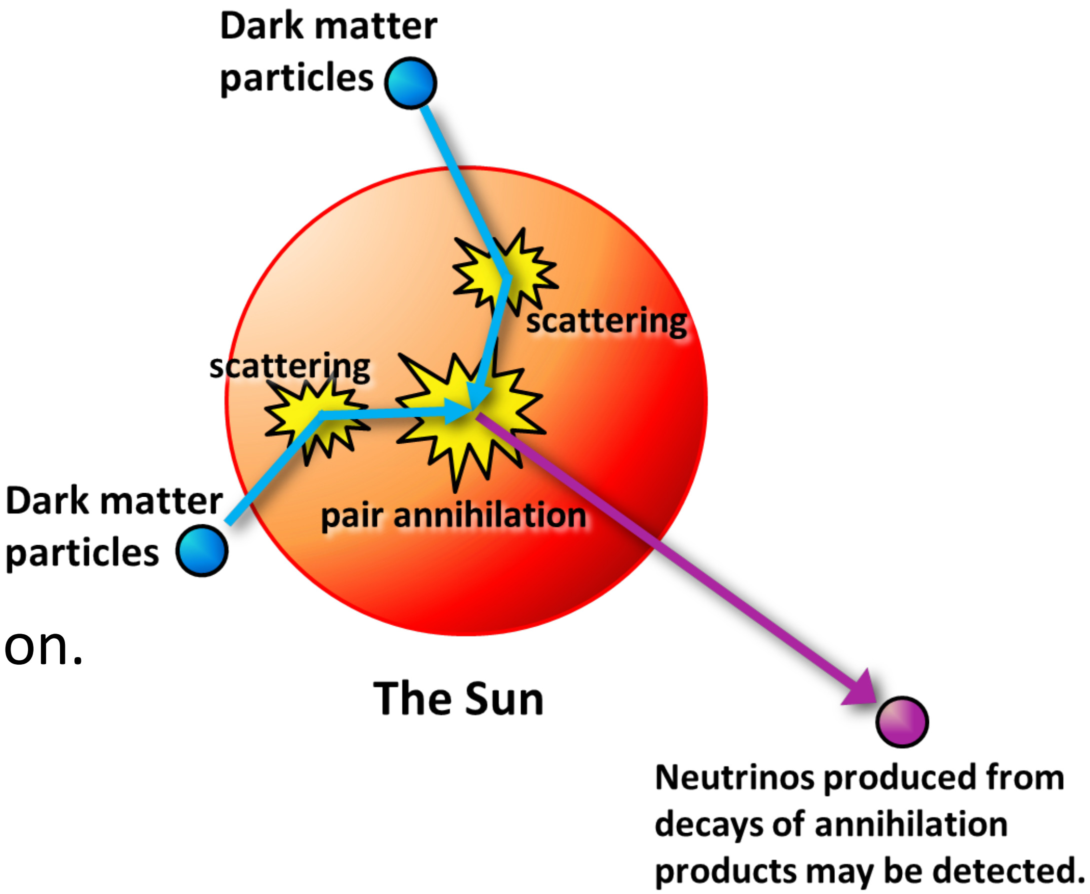
- Dark matter scatters, loses energy, becomes gravitationally bound to star
- Accumulates and annihilates in centre of Sun
- Only neutrinos escape Sun→ IceCube, SuperK

In equilibrium:

Annihilation rate = Capture rate

→ controlled by DM-nucleon scattering cross section.

→ probes the same quantity as direct detection experiments

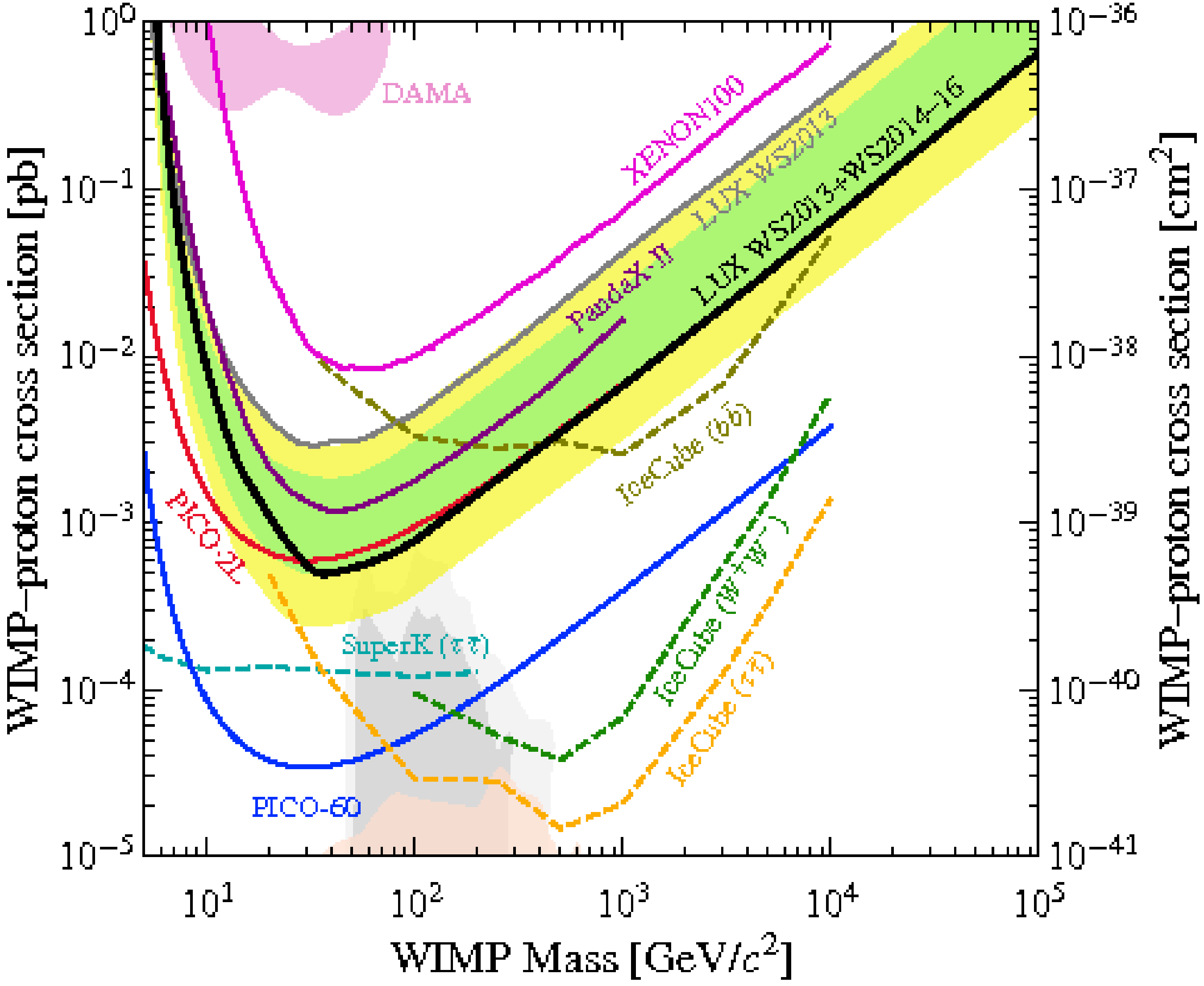


Solar WIMPs

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

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

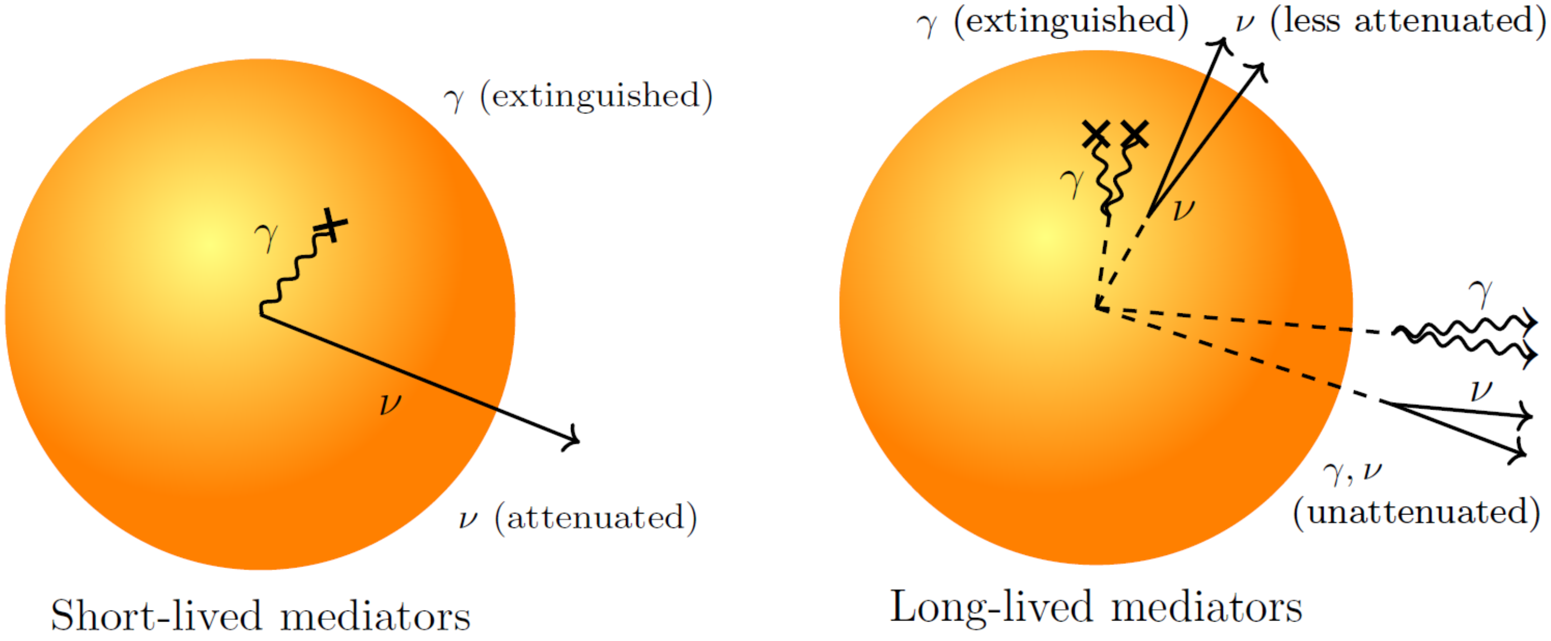
arXiv:1705.03380



Secluded models → long lived mediators

If captured DM annihilates to a light, long-lived mediator

- ➢ Annihilation products can escape the Sun
- ➢ If decay occurs beyond solar core → High energy neutrino signal less attenuated
- ➢ If decay occurs between Sun and Earth → solar gamma rays or cosmic rays



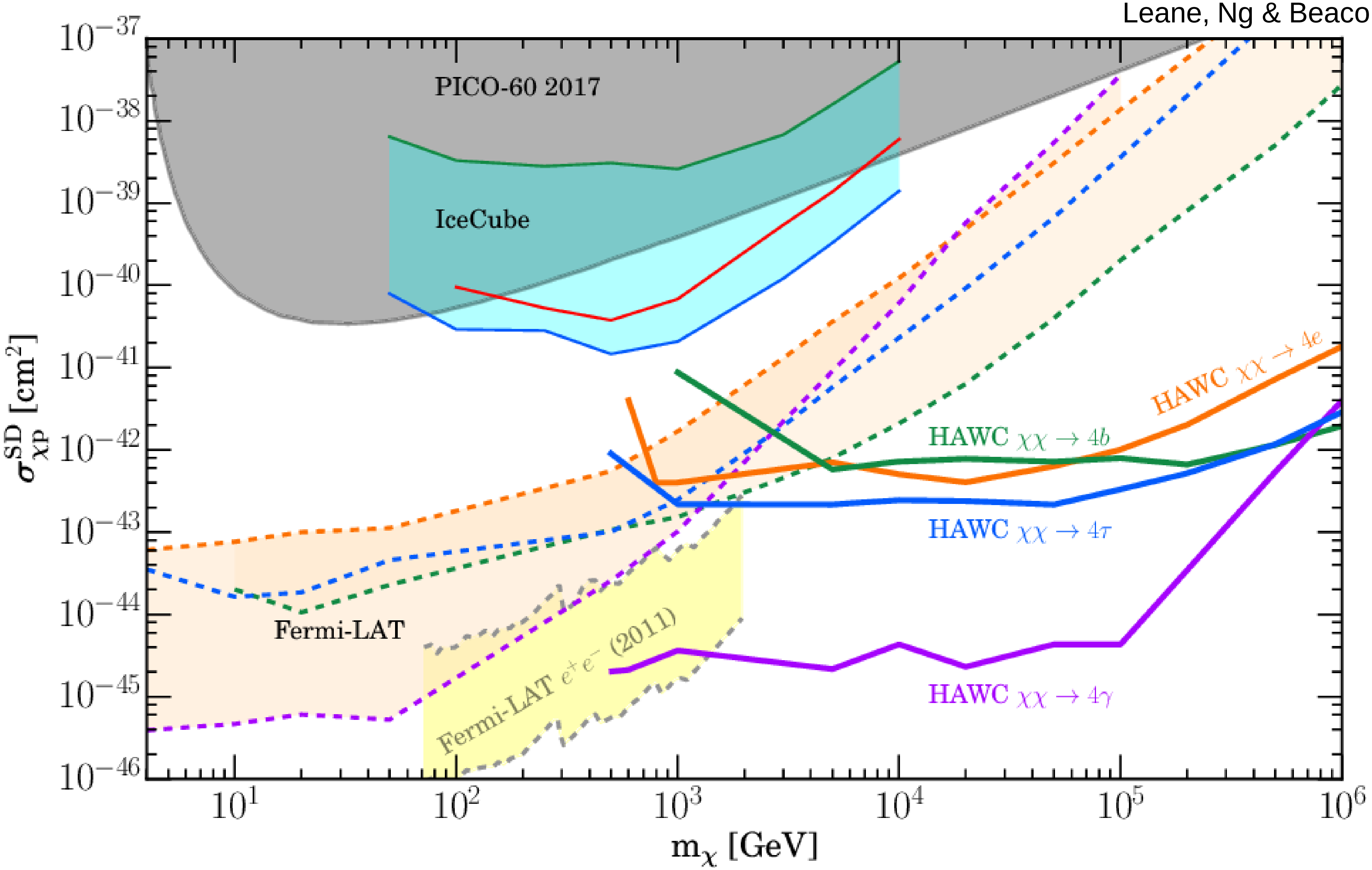
Batell, Pospolov, Ritz & Shang;
Pospolov & Ritz;
Schuster,Toro & Yavin;
Meade, Nussinov, Papucci & Volansky;
NFB & Petraki;
Feng, Smolinsky & Tanedo;
Leane, Ng & Beacom;

Leane, Ng & Beacom,
arXiv:1703.04629

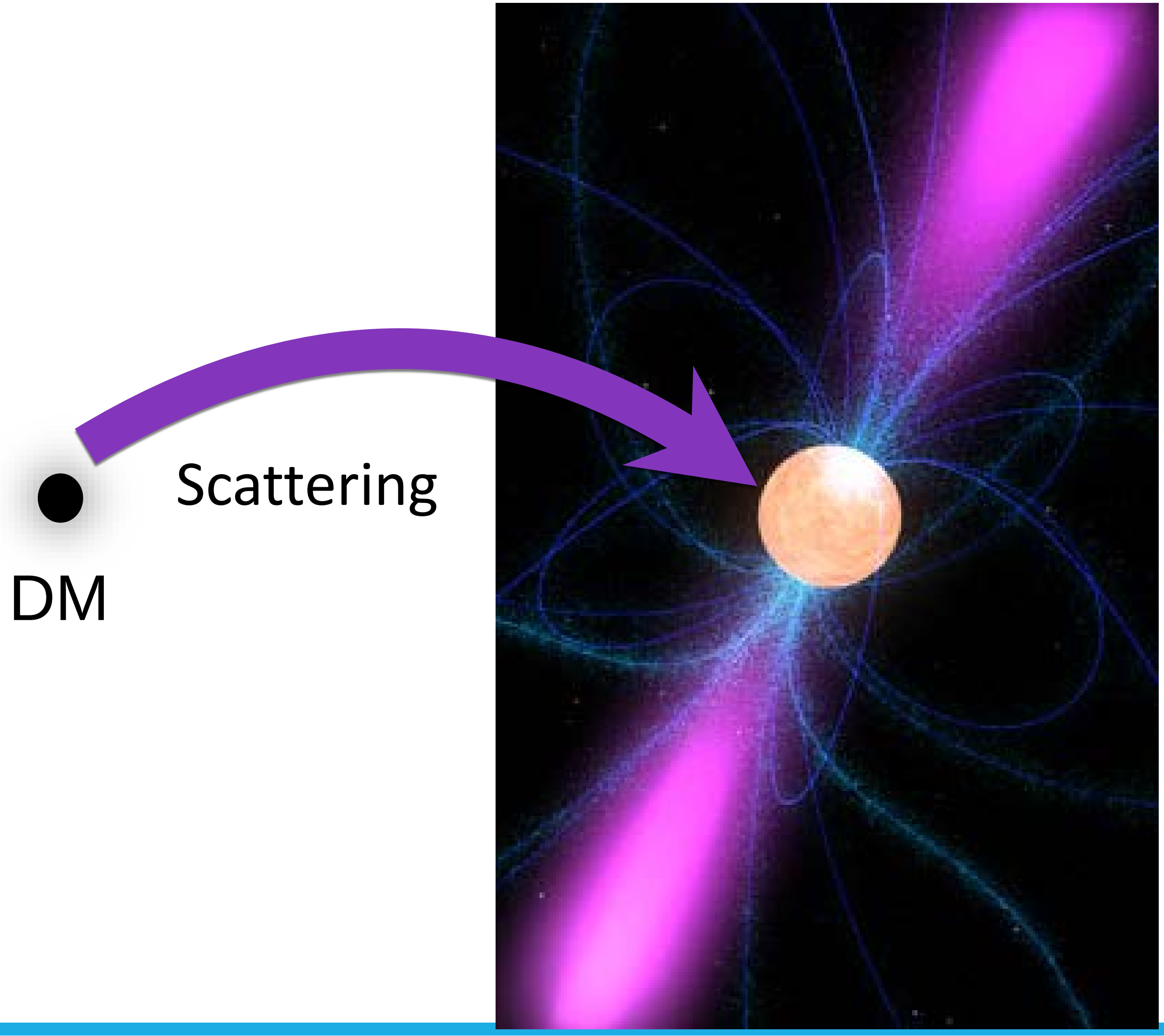
Secluded models → long lived mediators

HAWC arXiv:1808.05624

Leane, Ng & Beacom, arXiv:1703.04629



Neutron Stars



Scattering

DM

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

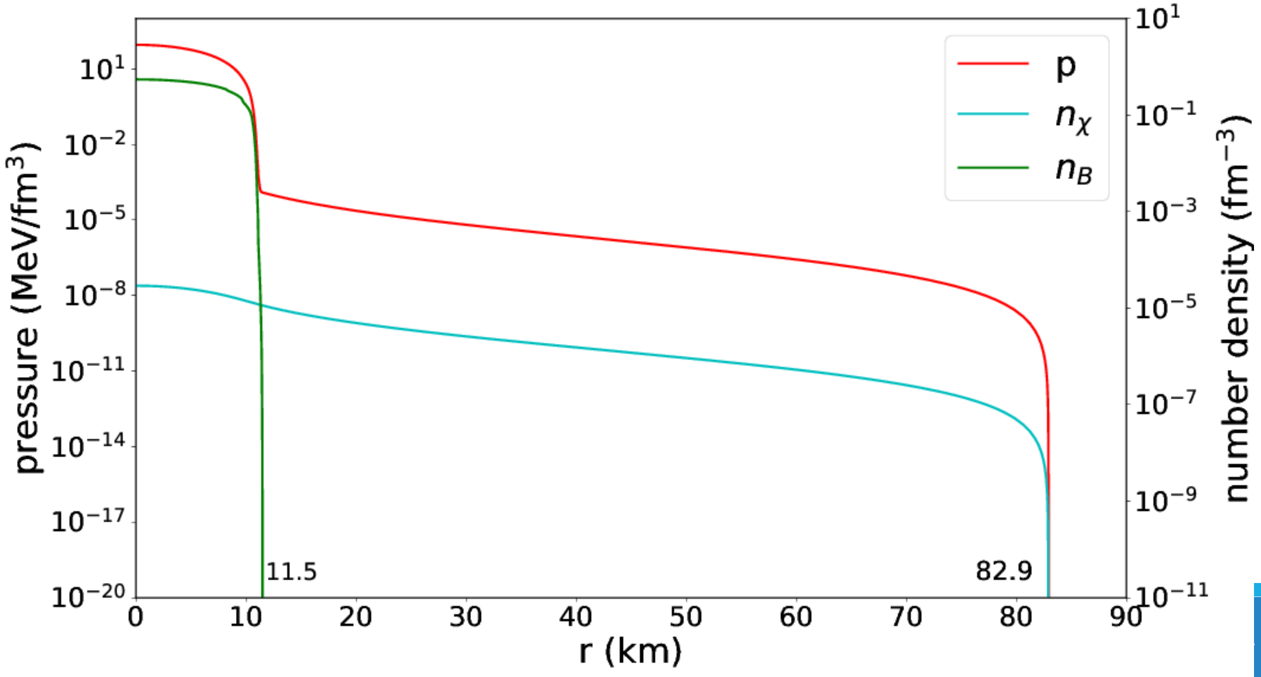
→ Black hole quite unlikely for typical WIMP-like dark matter

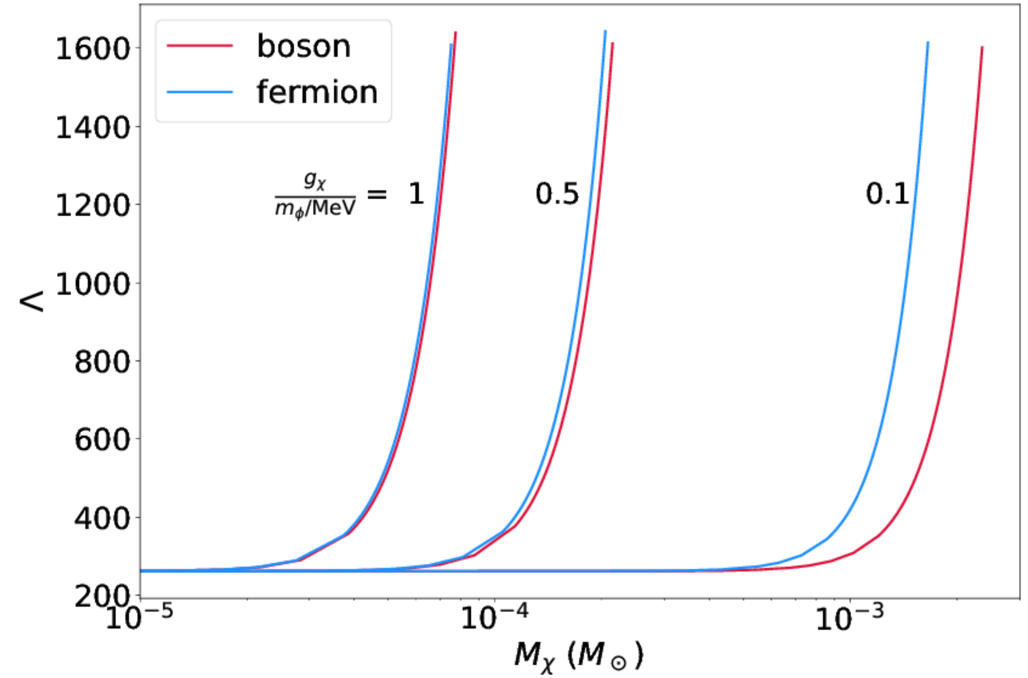
Neutron star mergers → gravitational waves

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 $\sim 10^{-4} M_{\odot}$





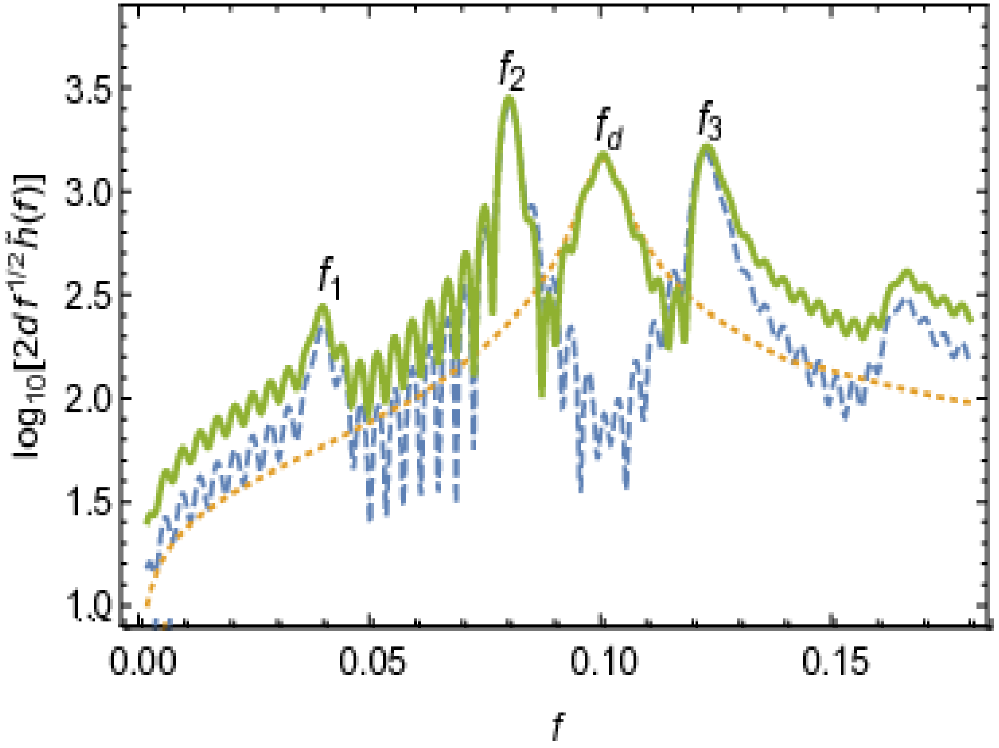
Neutron star mergers → gravitational waves

J.Ellis et al., 1710.05540

- **Heavier mediators → DM core**

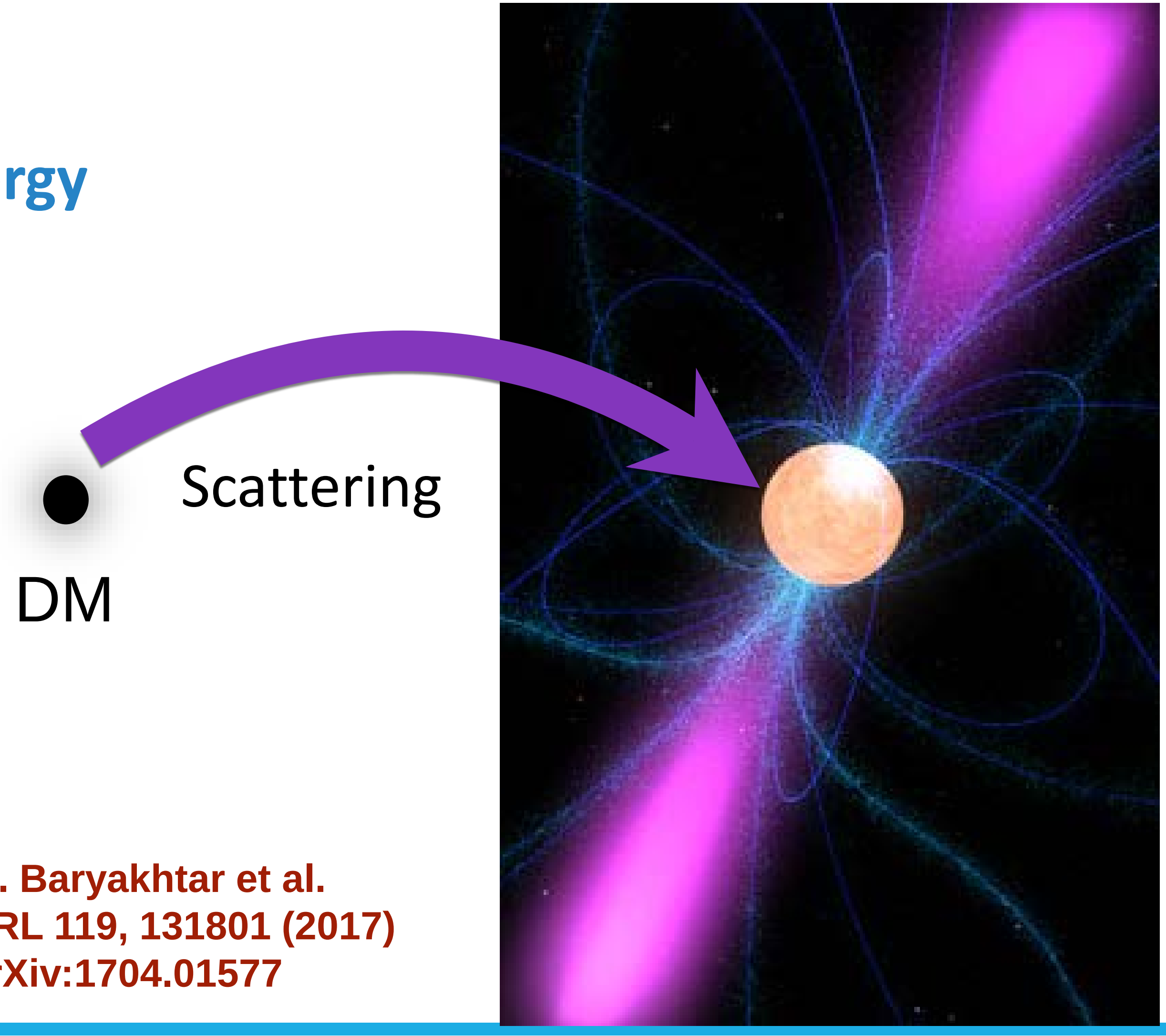
- Very large DM fraction from capture is unlikely. But mixed DM-neutron stars could form in some asymmetric DM models.

- If DM ~ 10% of NS mass
  ⟹ Distinctive gravitational wave signatures
  for NS-NS mergers.

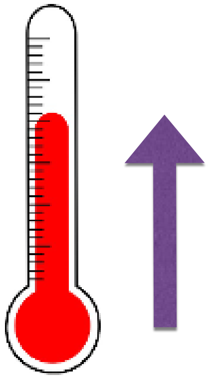


Neutron Star Kinetic Heating

Collisions transfer the
dark matter kinetic energy
to the neutron star
→ heats it up



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



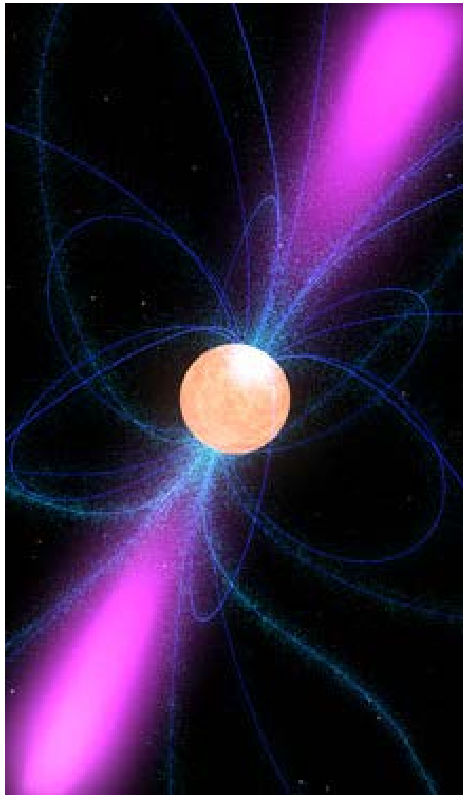
T_{NS} ~1700 K

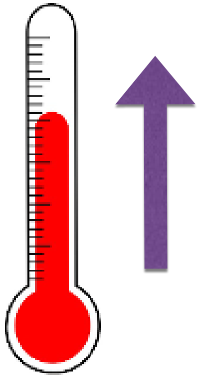
1 - 2 μm

near IR

Detecting the Heating

Nearby $\lesssim 50$ pc
isolated old NSs





T_{NS} ~1700 K

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M. Baryakhtar et al.
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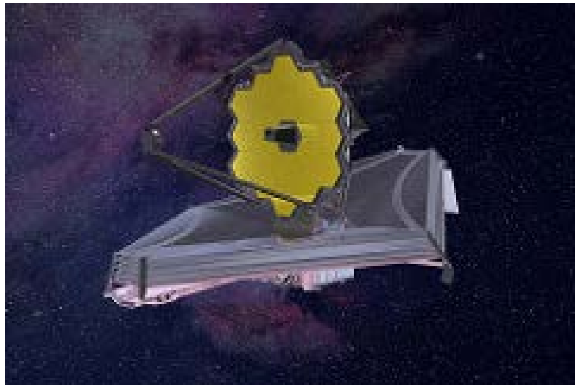
arXiv:1704.01577

FAST (radio)



JWST (NIRCam)

Dark matter annihilation

→ additional heating

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

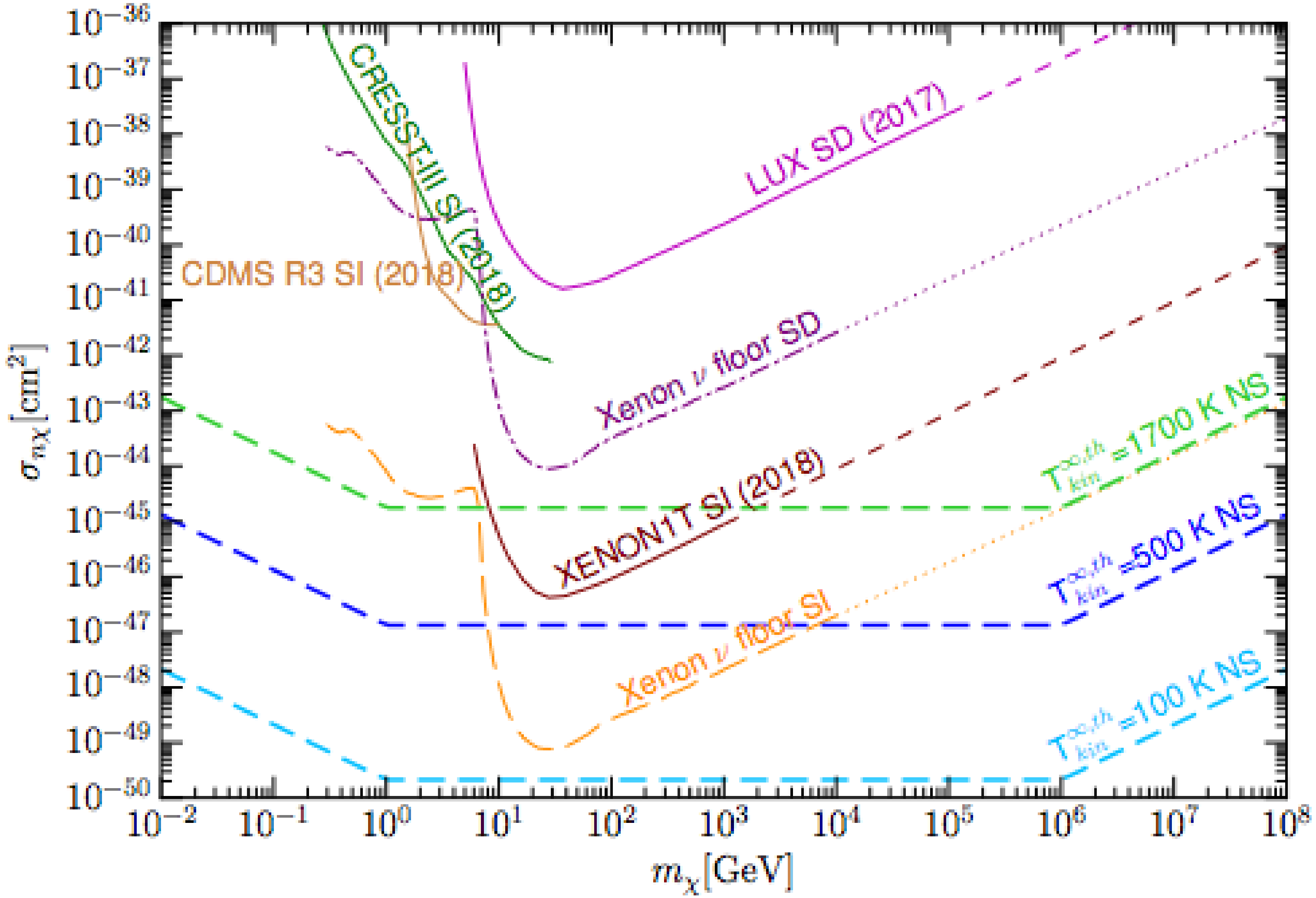
Thermalisation is essentially guaranteed for unsuppressed DM-nucleon scattering. If there is some kinematic suppression of the scattering process, it can take much longer (velocity or momentum suppressions; inelastic, etc)

Neutron Star Heating: Advantages

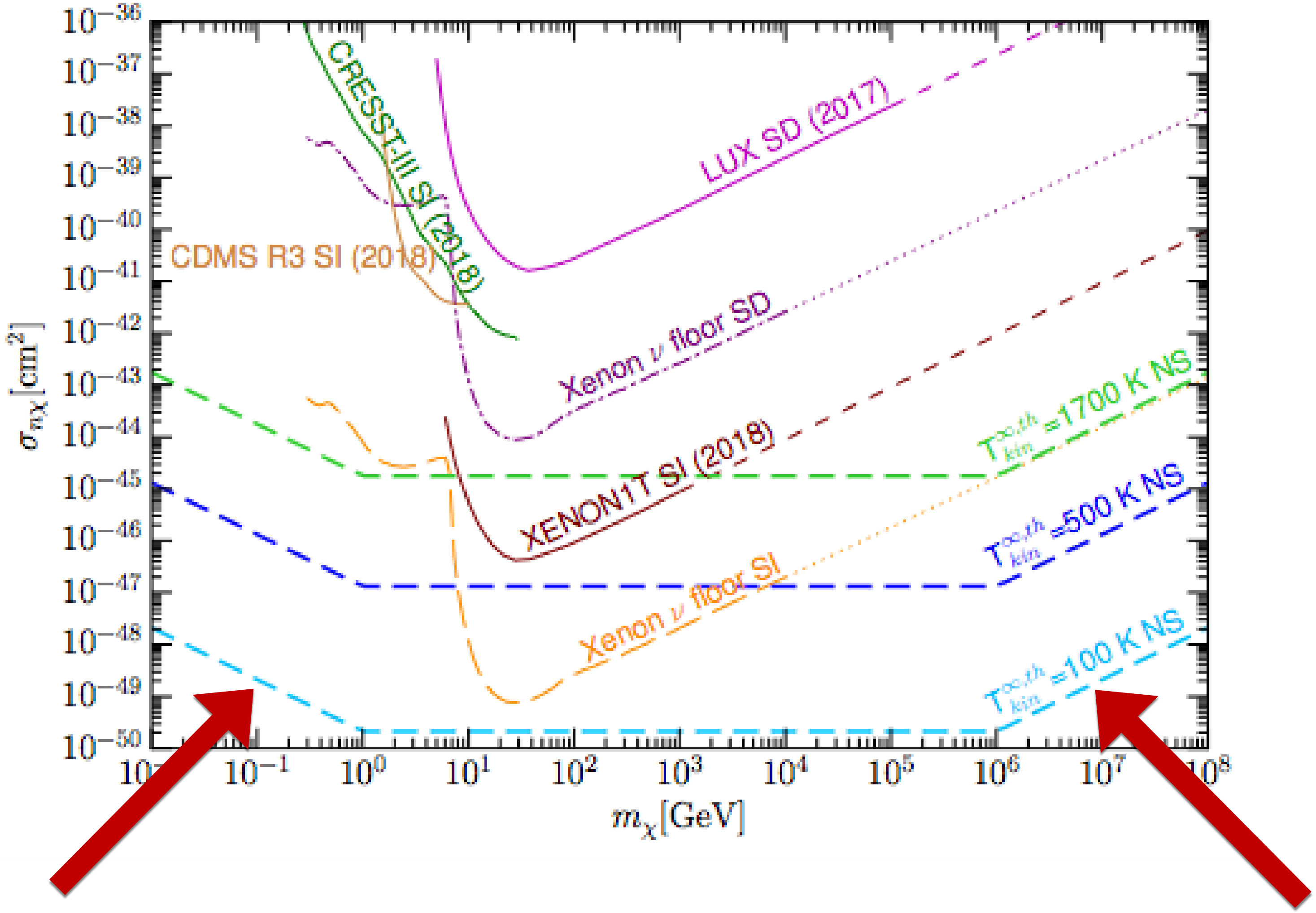
- ✓Higher probability of gravitational capture.
- ✓DM particles accelerated to $\mathcal{O}(0.5c)$ → ~~momentum suppression~~

- ✓Cross section for efficient trapping $\mathcal{O}\left(10^{-45}\ cm\right)$
- ✓Unlike direct detection, not restricted by **recoil detection threshold.**
- ✓SI and SD cross sections of similar size
- ✓Elastic and inelastic scattering cross sections of **same order of magnitude.**

Kinetic Heating: Sensitivity



Kinematics

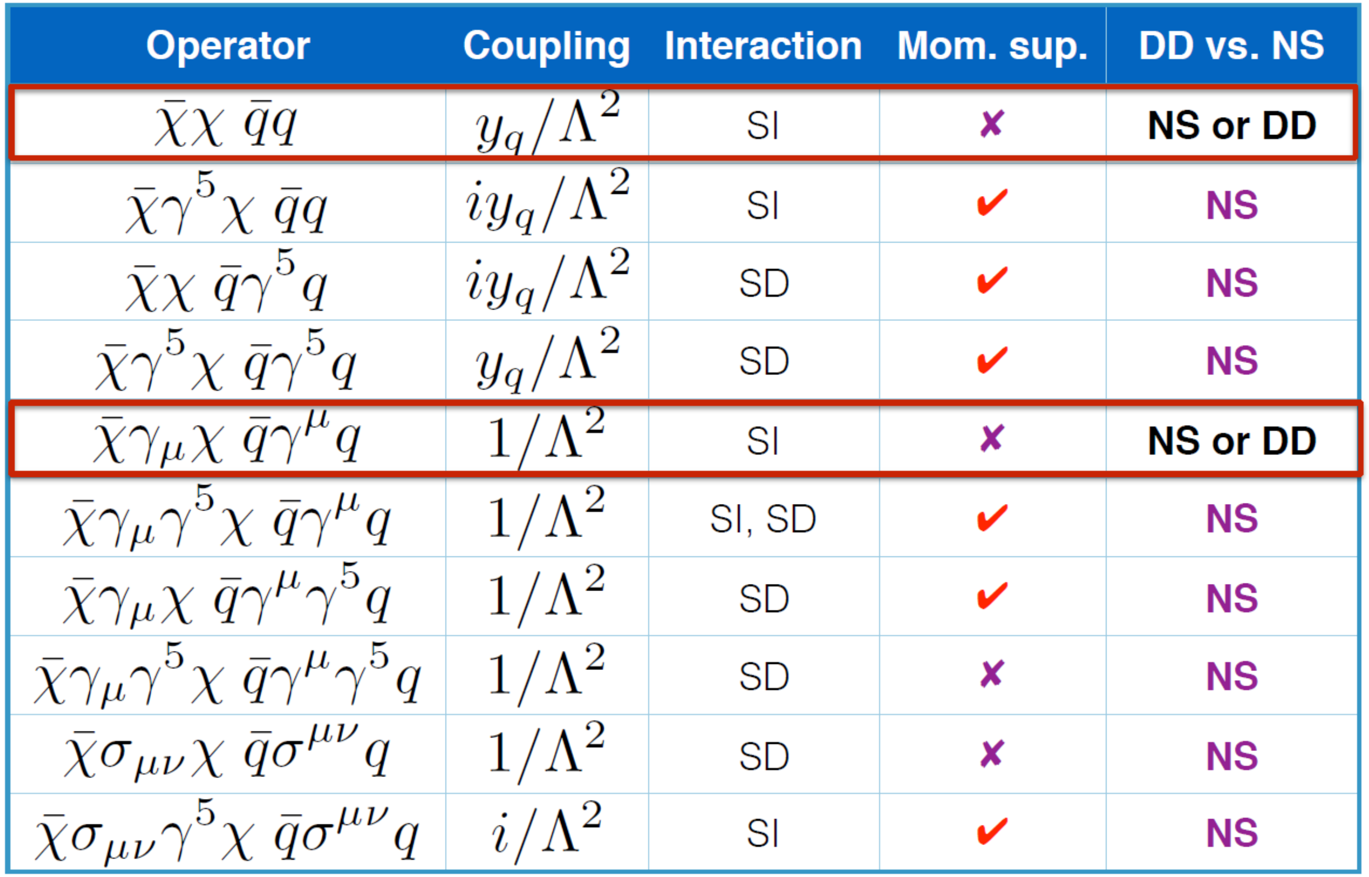


Pauli blocking from degenerate neutrons restricts scattering when $m_{DM} < 1$ GeV.

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	Interaction	Mom. sup.	DD vs. NS
$\bar{\chi}\chi\,\bar{q}q$	y_q/Λ^2	SI	✘	**NS or DD**
$\bar{\chi}\gamma^5\chi\,\bar{q}q$	iy_q/Λ^2	SI	✔	**NS**
$\bar{\chi}\chi\,\bar{q}\gamma^5 q$	iy_q/Λ^2	SD	✔	**NS**
$\bar{\chi}\gamma^5\chi\,\bar{q}\gamma^5 q$	y_q/Λ^2	SD	✔	**NS**
$\bar{\chi}\gamma_\mu\chi\,\bar{q}\gamma^\mu q$	$1/\Lambda^2$	SI	✘	**NS or DD**
$\bar{\chi}\gamma_\mu\gamma^5\chi\,\bar{q}\gamma^\mu q$	$1/\Lambda^2$	SI, SD	✔	**NS**
$\bar{\chi}\gamma_\mu\chi\,\bar{q}\gamma^\mu\gamma^5 q$	$1/\Lambda^2$	SD	✔	**NS**
$\bar{\chi}\gamma_\mu\gamma^5\chi\,\bar{q}\gamma^\mu\gamma^5 q$	$1/\Lambda^2$	SD	✘	**NS**
$\bar{\chi}\sigma_{\mu\nu}\chi\,\bar{q}\sigma^{\mu\nu}q$	$1/\Lambda^2$	SD	✘	**NS**
$\bar{\chi}\sigma_{\mu\nu}\gamma^5\chi\,\bar{q}\sigma^{\mu\nu}q$	i/Λ^2	SI	✔	**NS**

Projected neutron star kinetic heating sensitivity comparable to direct detection experiments for scalar and vectorinteractions

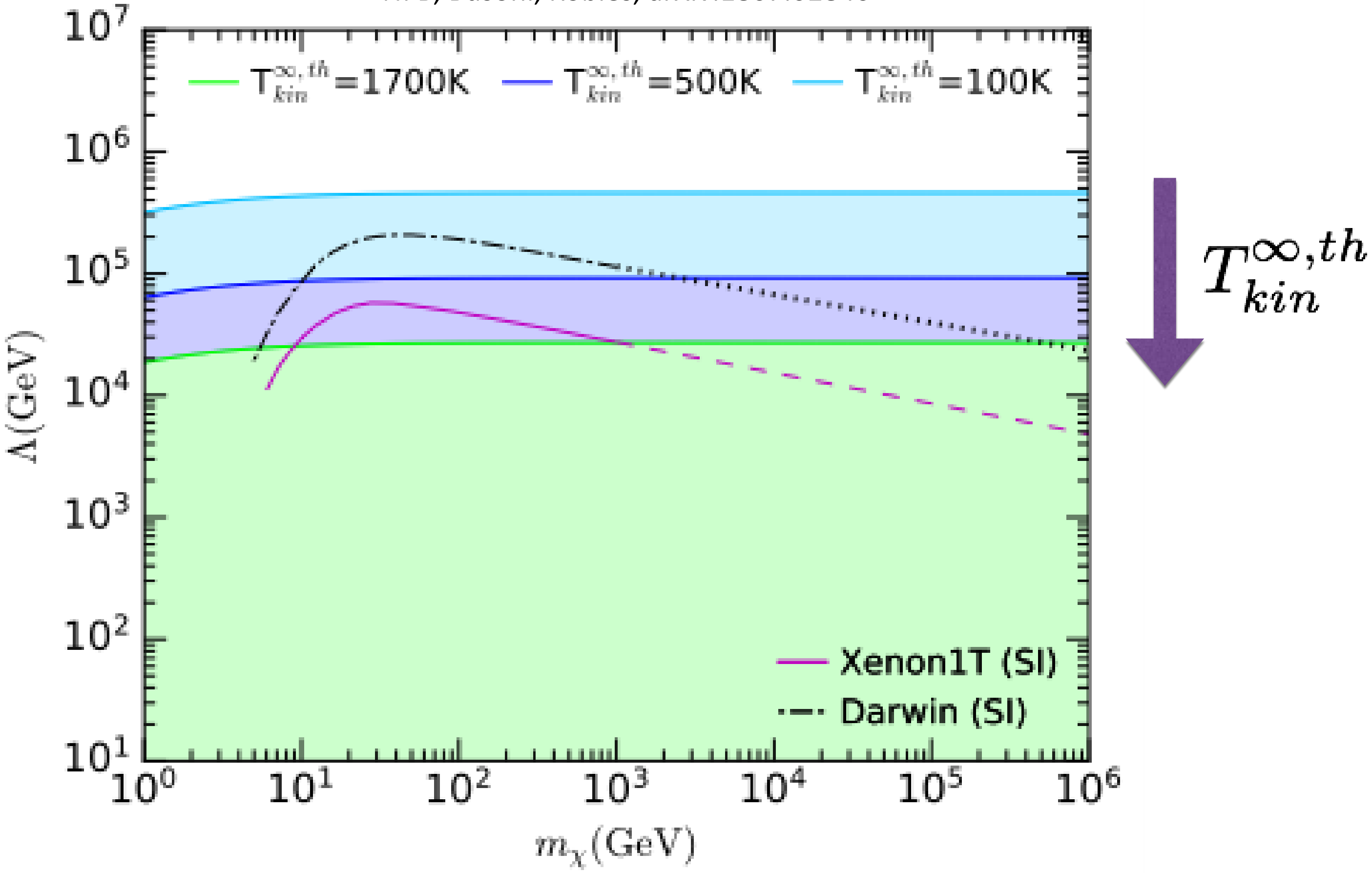
For all other interaction types, neutron stars have greater sensitivity, typically by orders of magnitude.

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

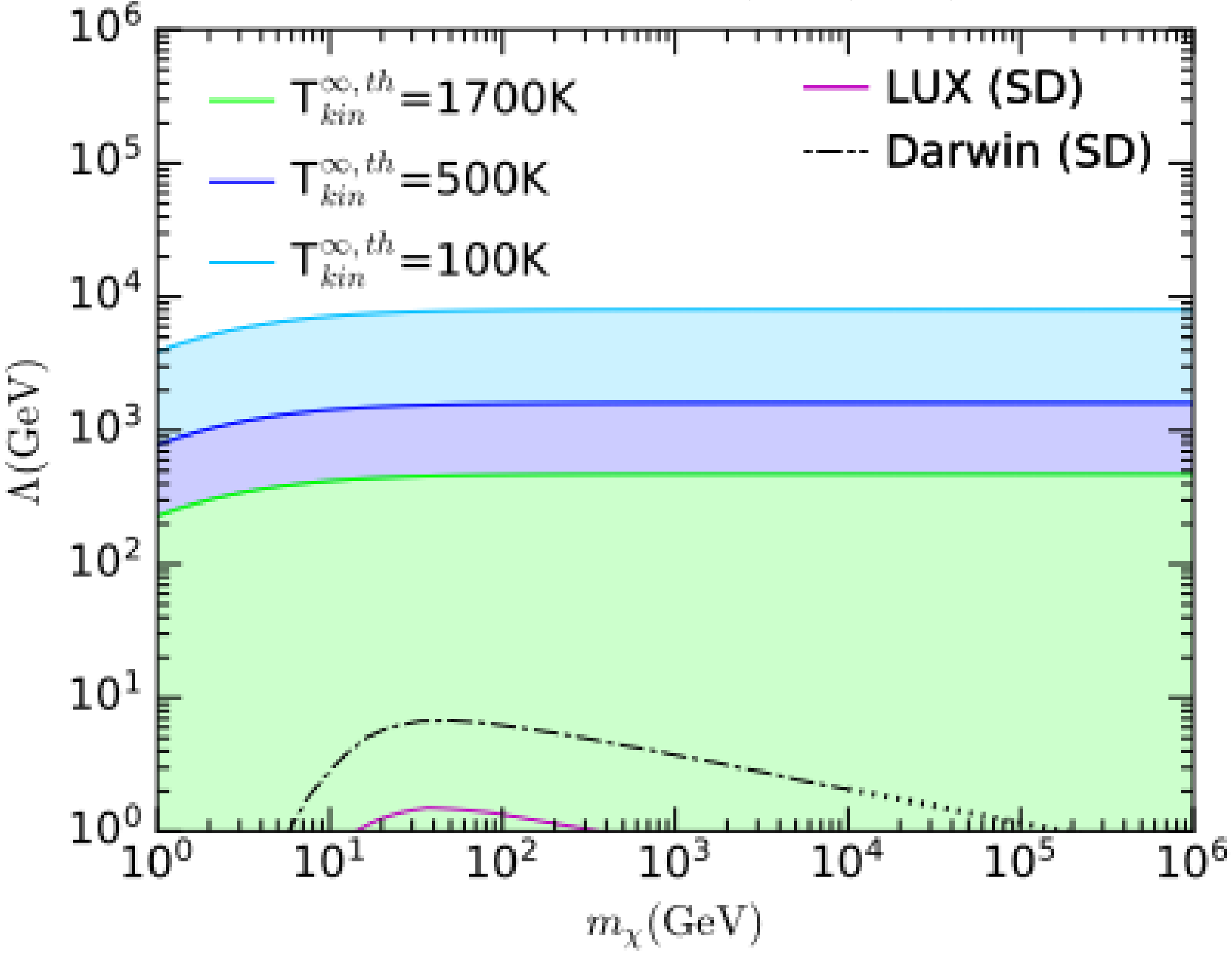
$$\frac{d\sigma}{d\cos\theta} = \frac{c_N^P m_N^2}{\Lambda^4} \frac{\mu^2 q_{tr}^2}{8\pi(\mu+1)^2}$$

Momentum suppressed

Relativistic limit – Neutron Star regime

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

NFB, Busoni, Robles, arXiv:1807.02840



Spin-dependent scattering (pseudoscalar)

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

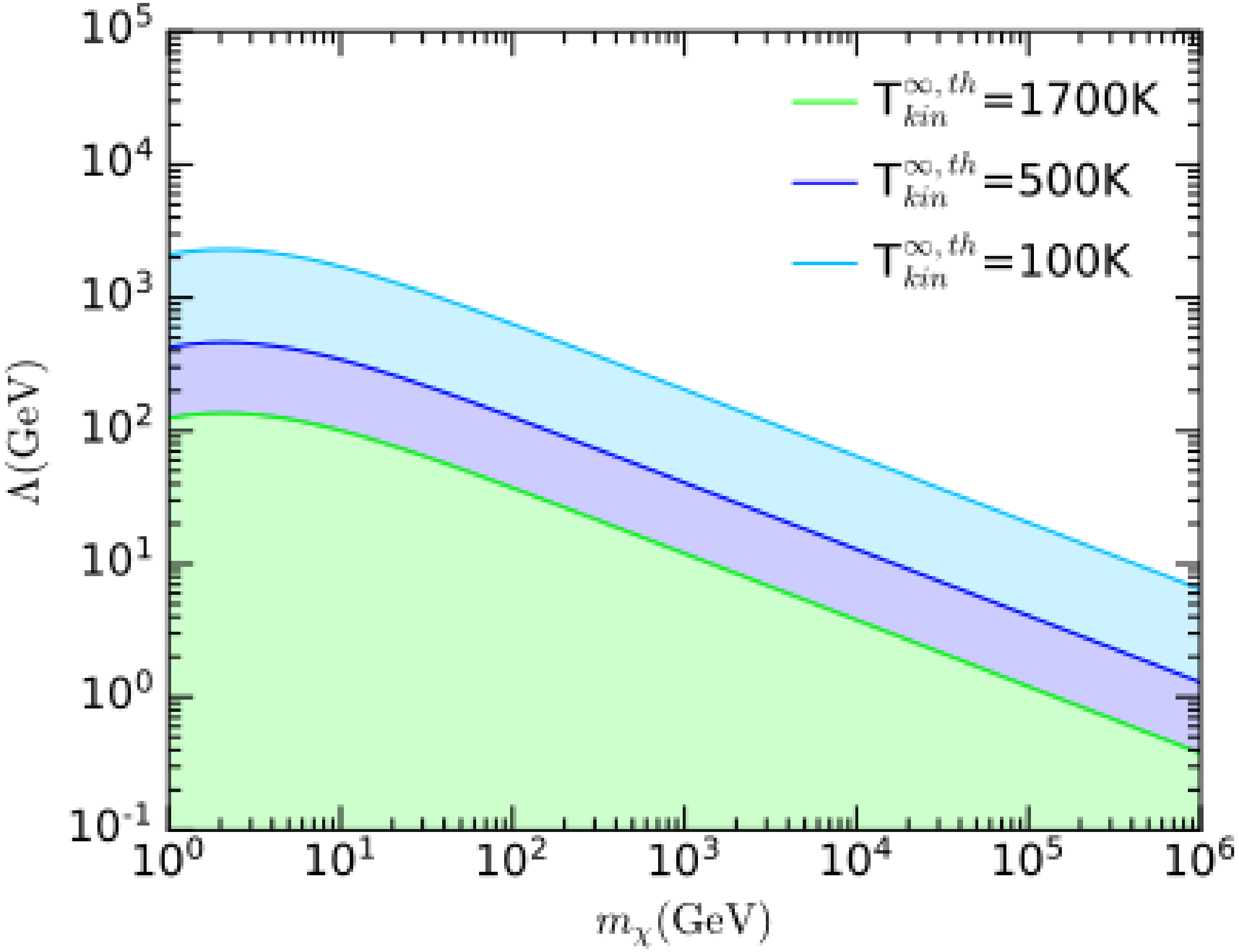
Non relativistic limit – Direct Detection regime

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

Momentum suppressed as q^4 and SD

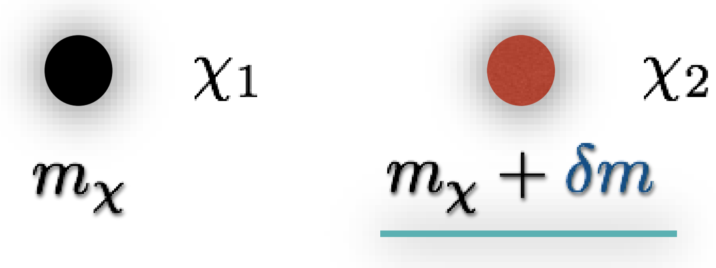
Relativistic limit – Neutron Star regime

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


NFB, Busoni, Robles, arXiv:1807.02840

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:

$\chi_1 + n \rightarrow \chi_1 + n$ highly suppressed

$\chi_1 + n \rightarrow \chi_2 + n$ 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

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

Maximum mass splitting

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

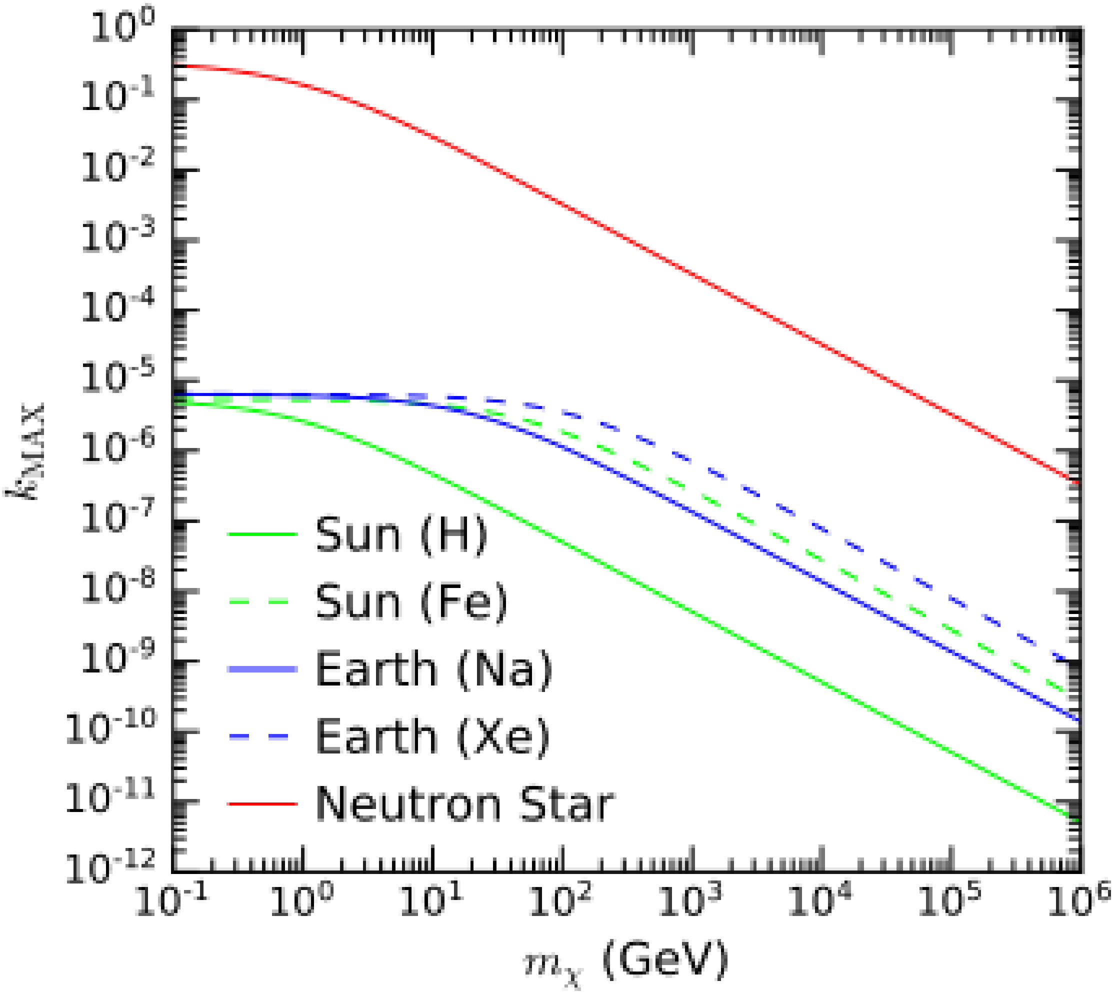
$$\boxed{k_{MAX} = \sqrt{1 + \frac{2}{\mu\sqrt{B}} + \frac{1}{\mu^2}} - 1 - \frac{1}{\mu}}$$

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

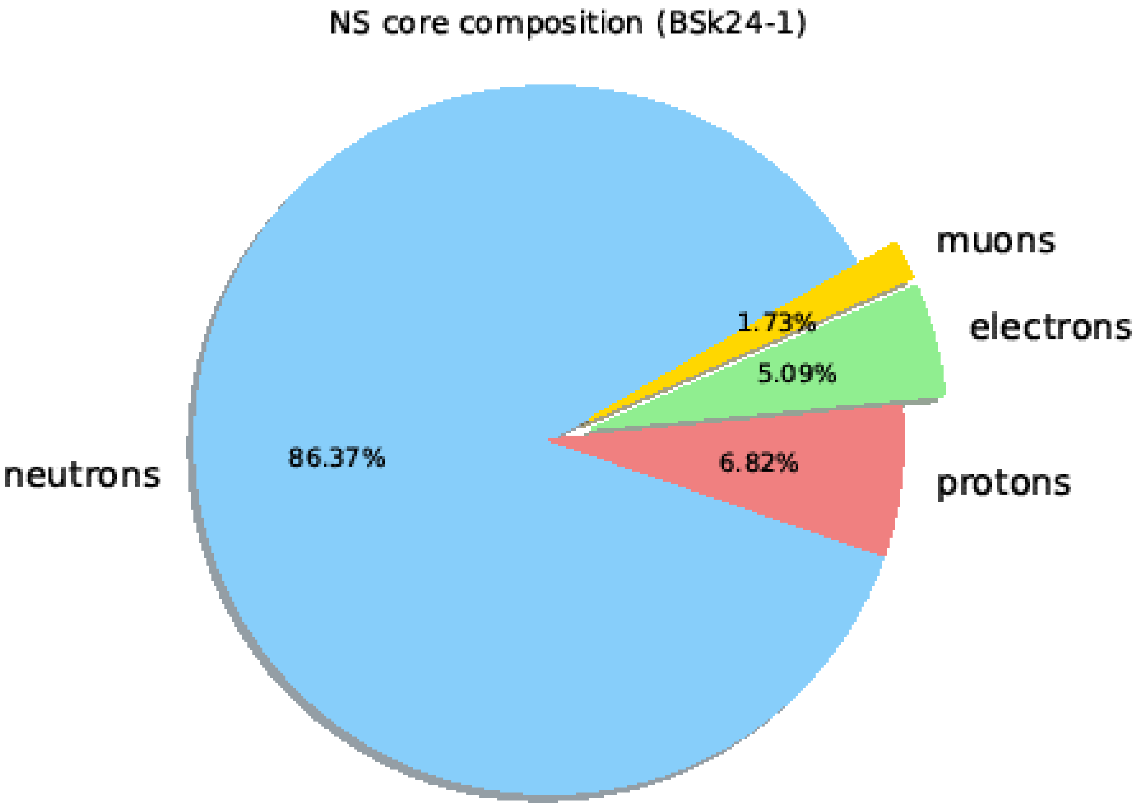
$$\mu = \frac{m_\chi}{m_T}$$

In NSs

$$m_T = m_n$$



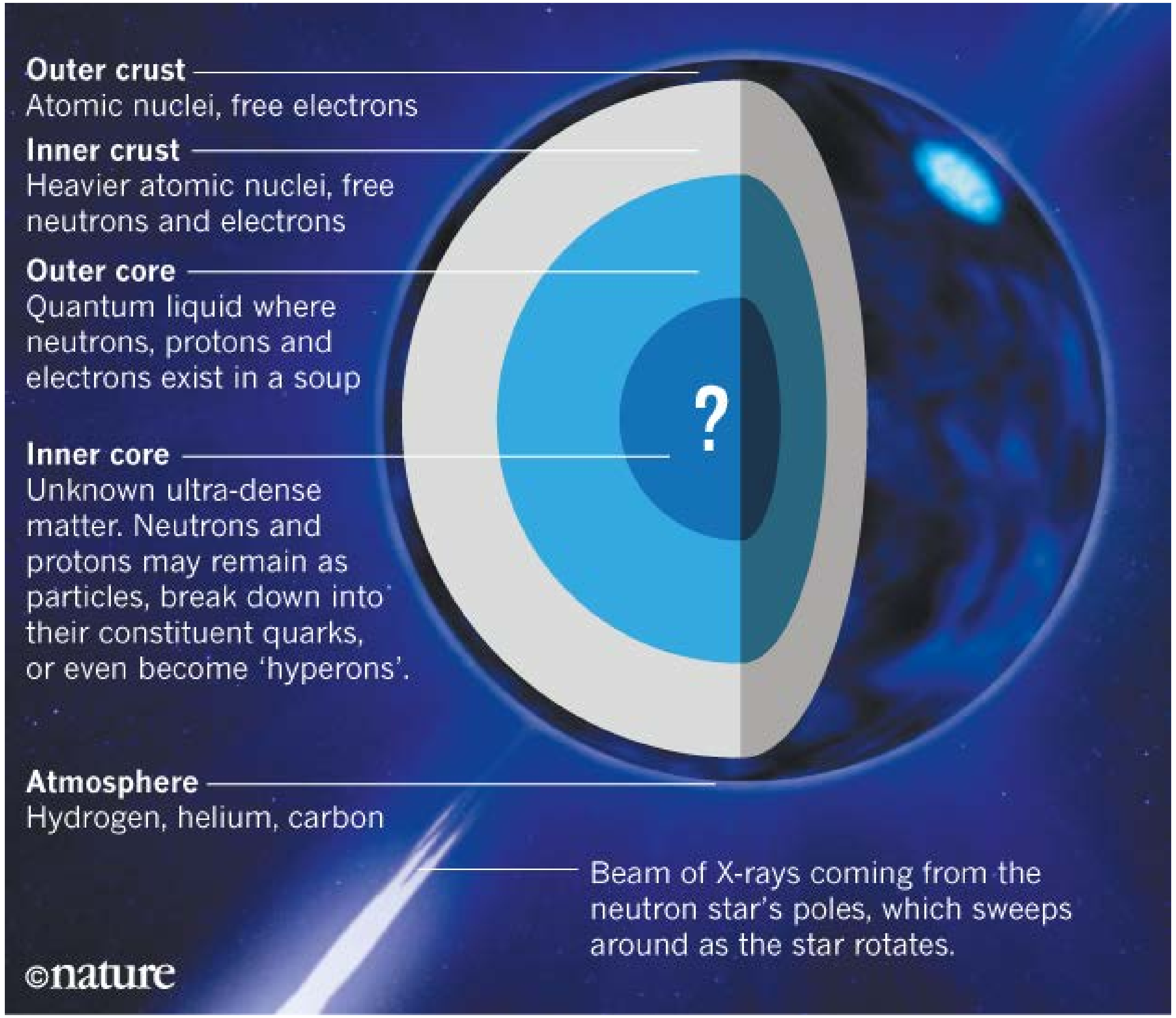
Leptons in Neutron Stars



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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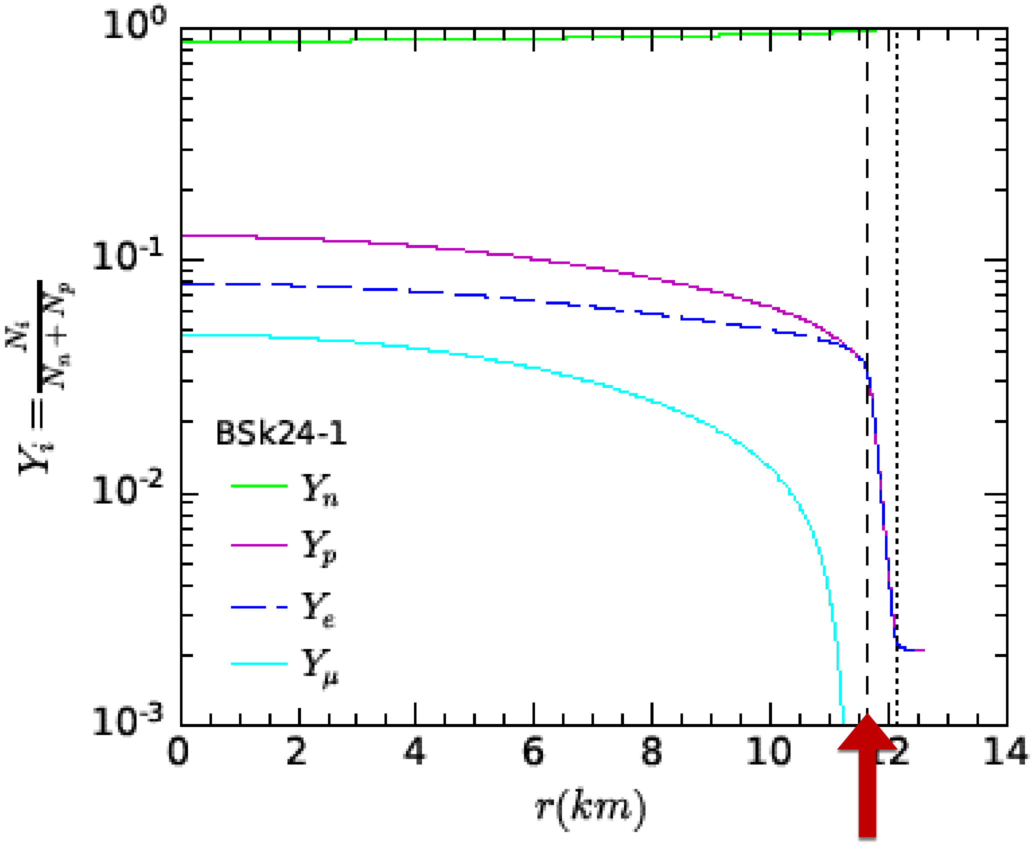
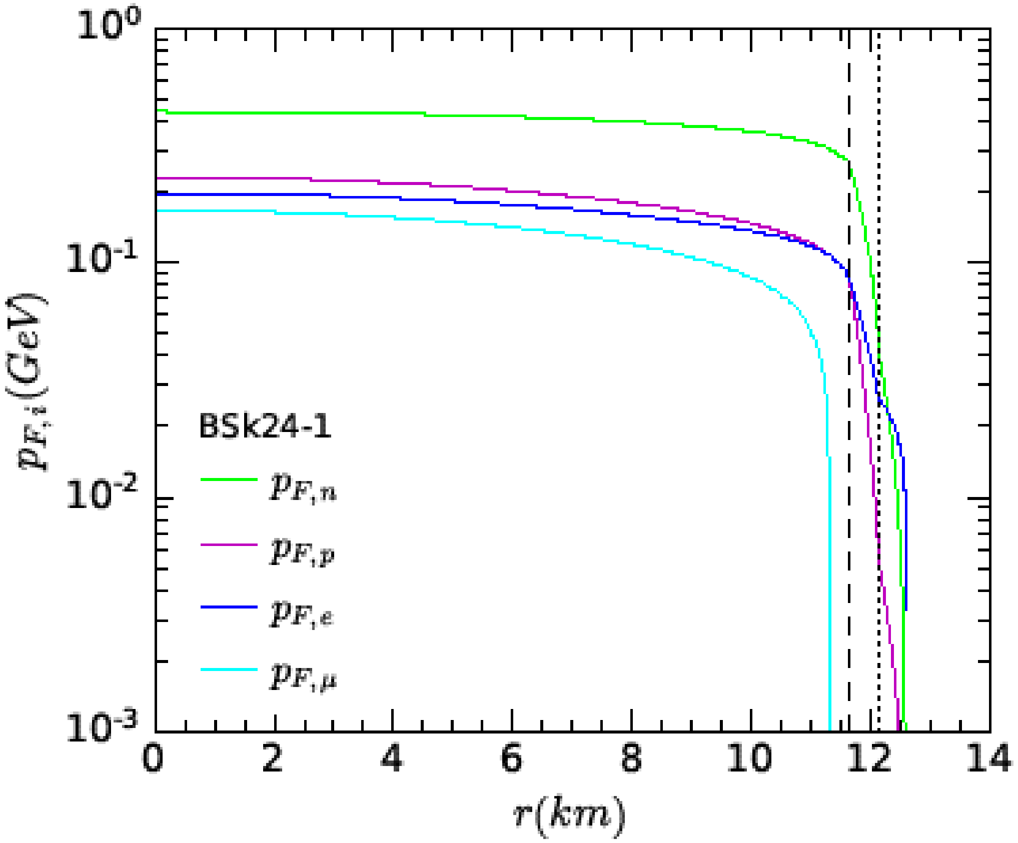
Leptons in Neutron Stars

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

Fermi-momentum ~ constant in core.

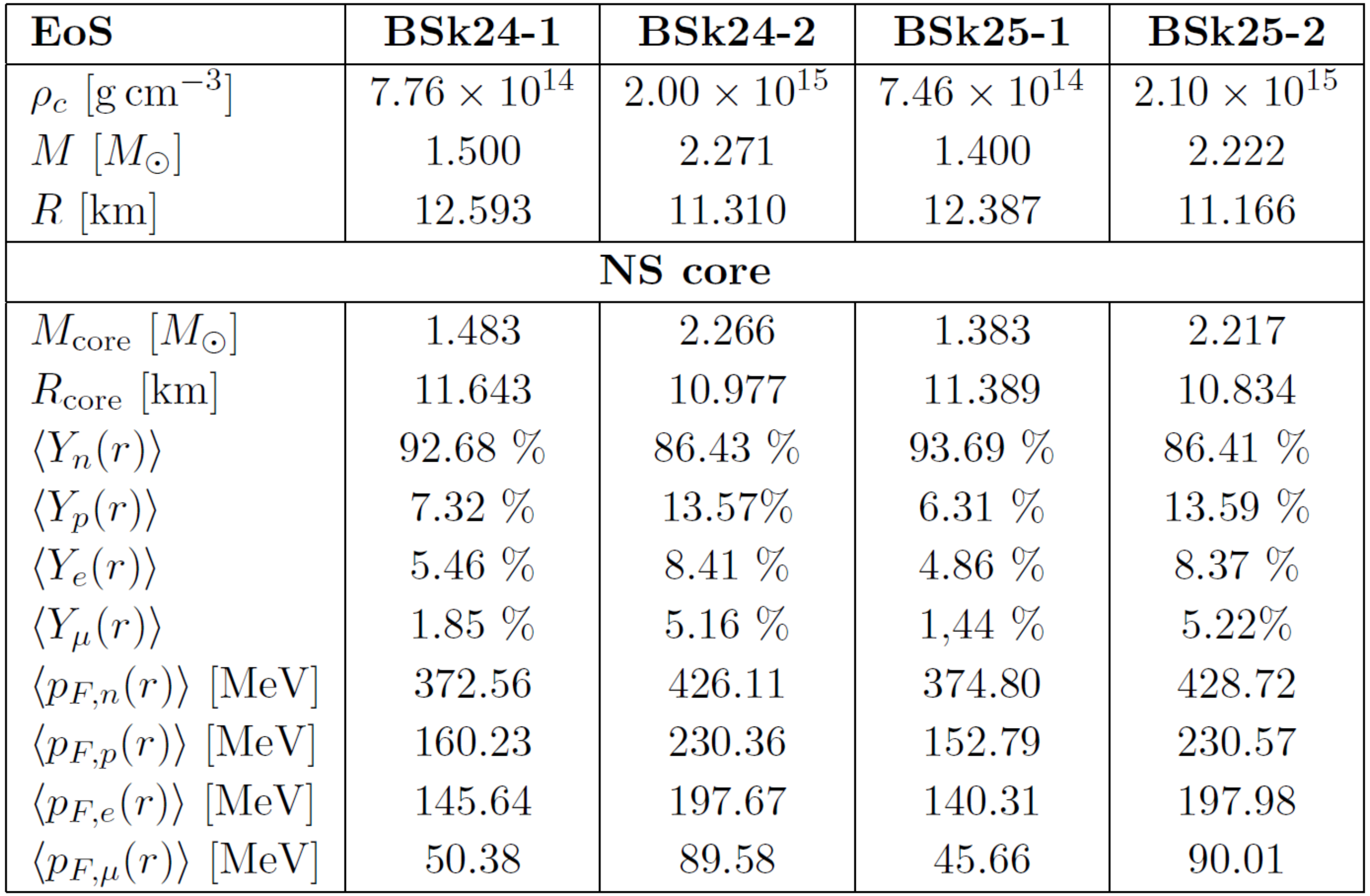


crust-core boundary



Neutron Star Equation of State

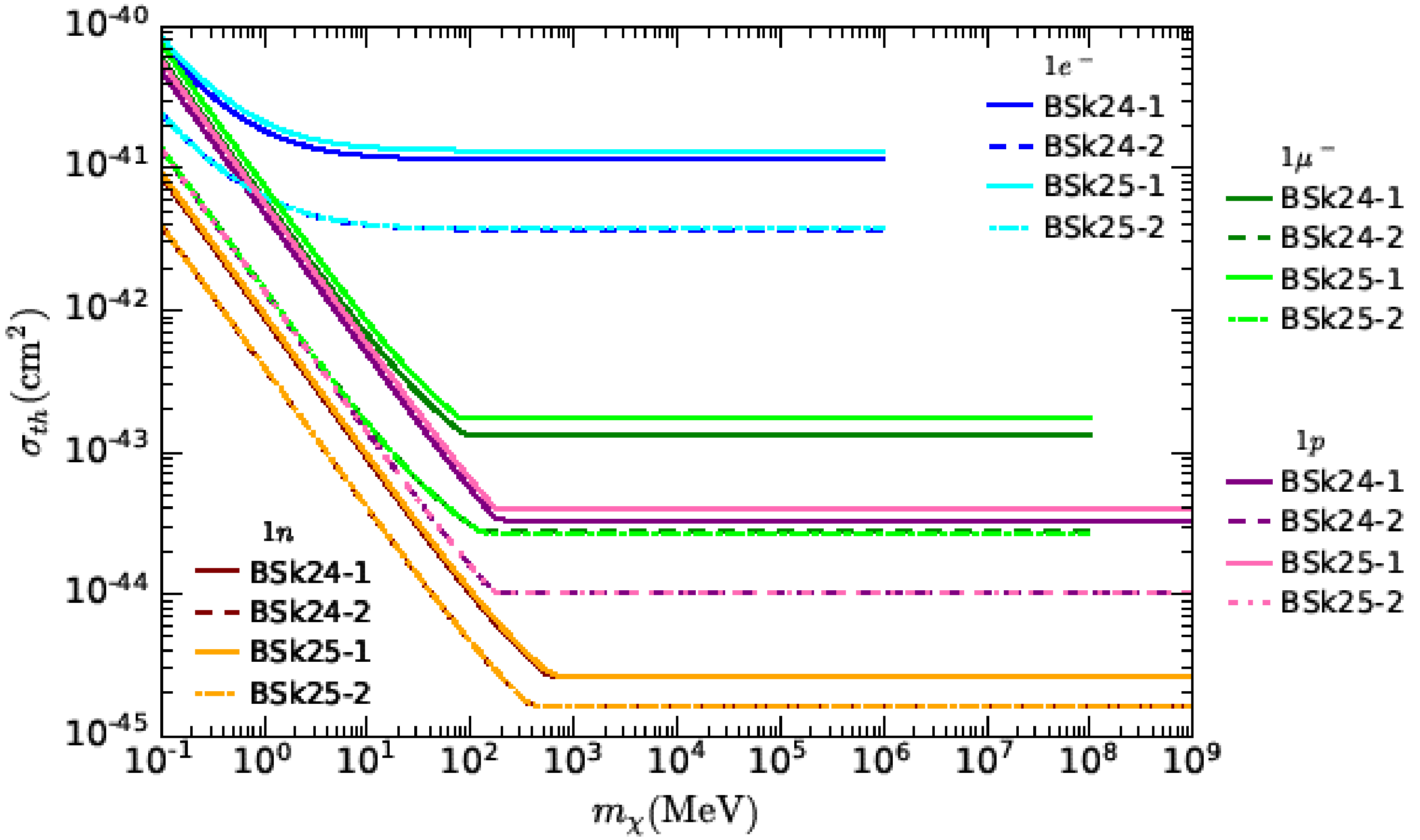
Pearson et al, Mon. Not. Roy. Astron. Soc. 481 no. 3, (2018)



EoS	**BSk24-1**	**BSk24-2**	**BSk25-1**	**BSk25-2**
ρ_c [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

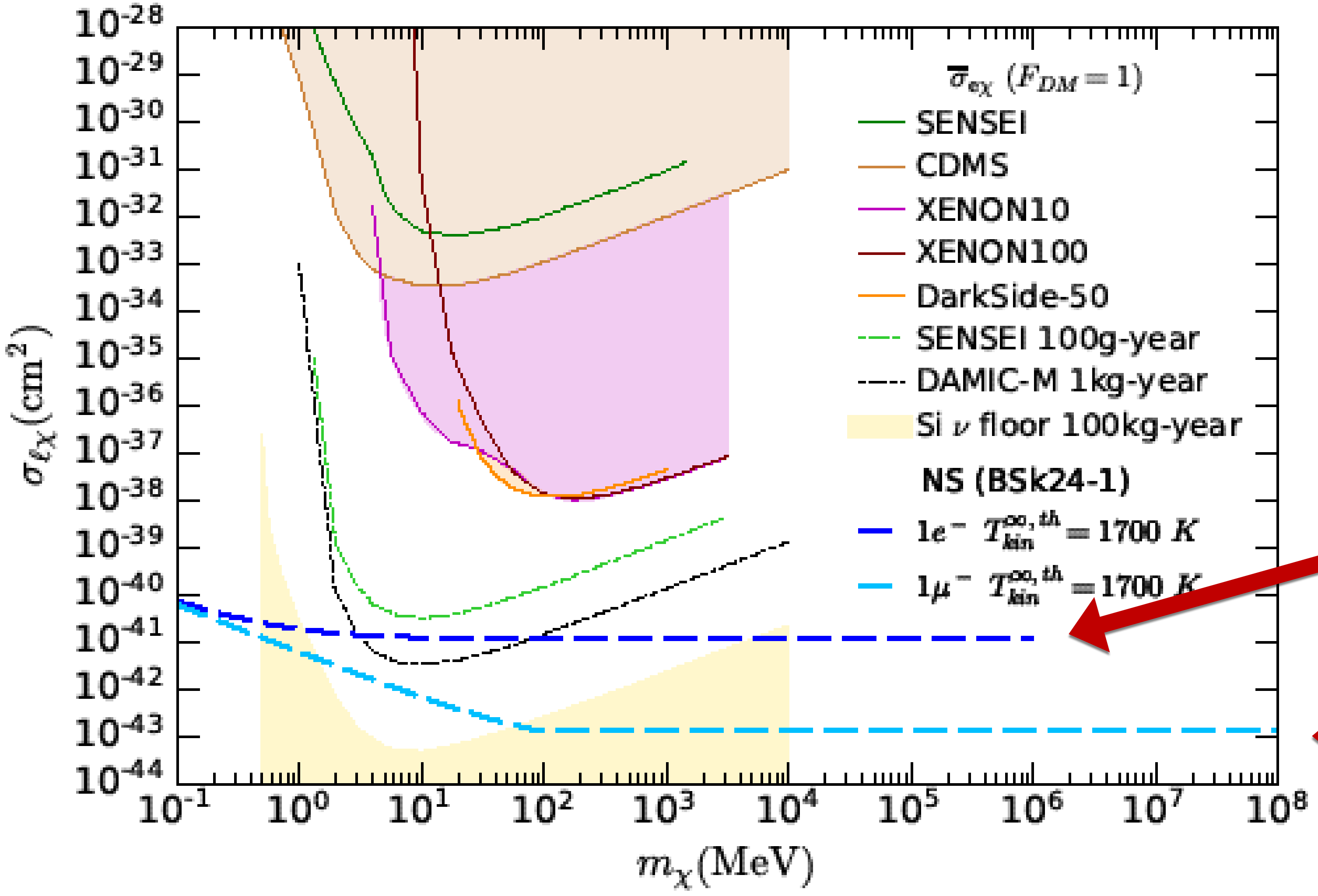
Composition varies according to the neutron star EoS

Insensitive to details of NS Equation of State



NFB, Busoni & Robles arXiv:1904.09803

Neutron star limits on leptophilic DM



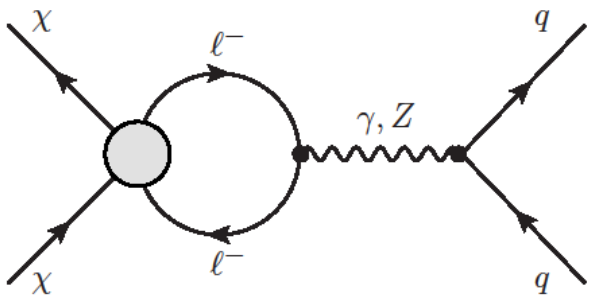
Electron scattering

Muon scattering

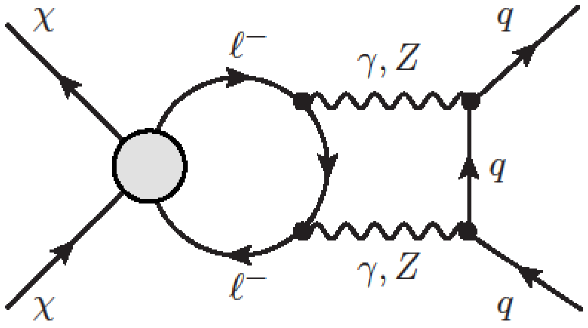
NFB, Busoni & Robles arXiv:1904.09803

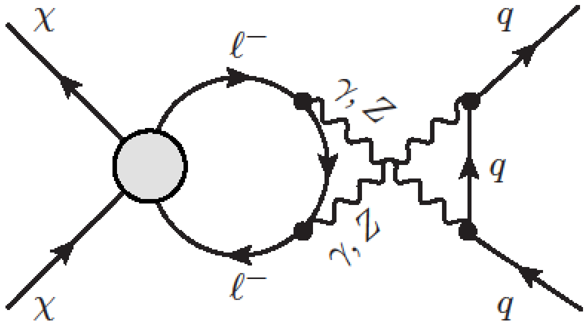
Leptophilic dark matter → loop-level quark couplings

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

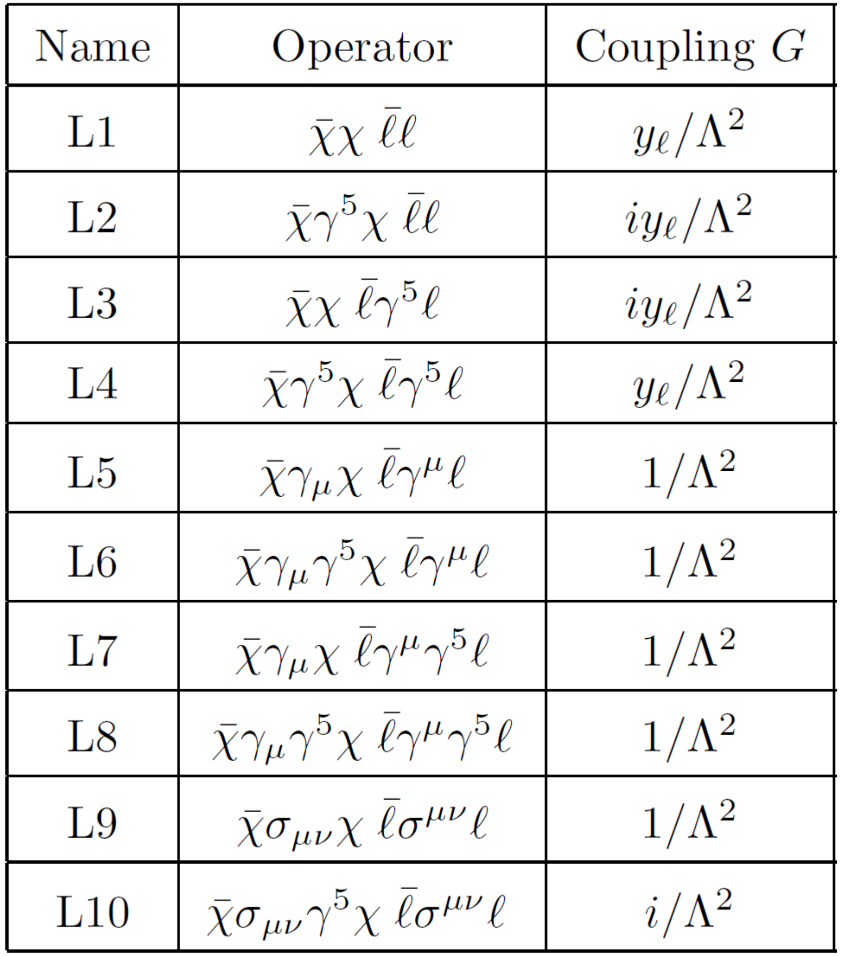


Other cases suppressed by Z-mass or by two loops.

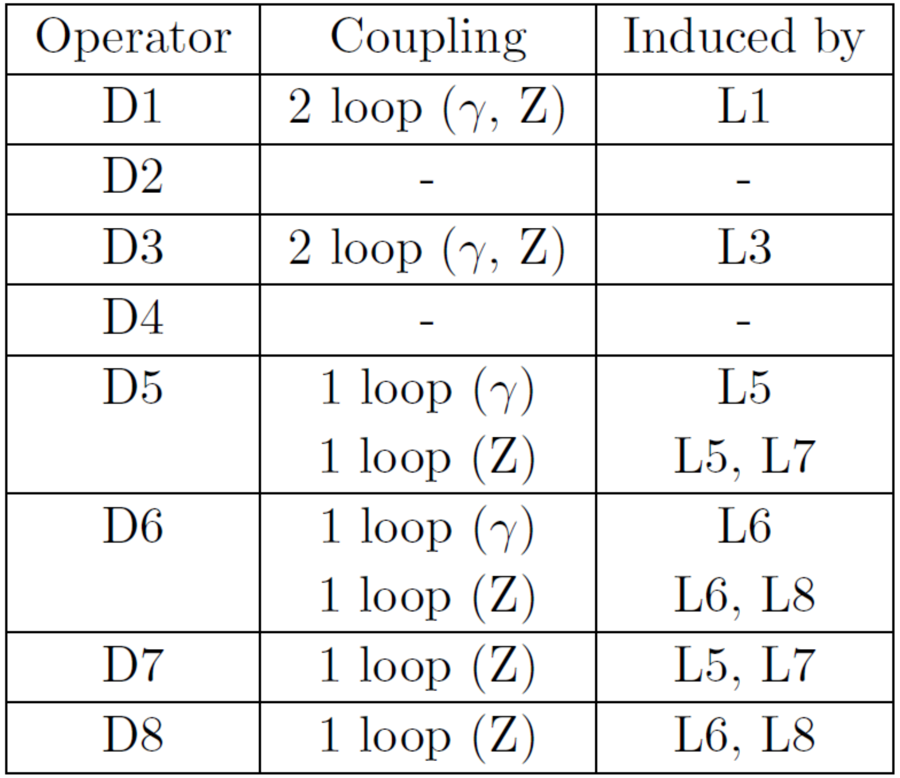




Lepton operators → Quark operators



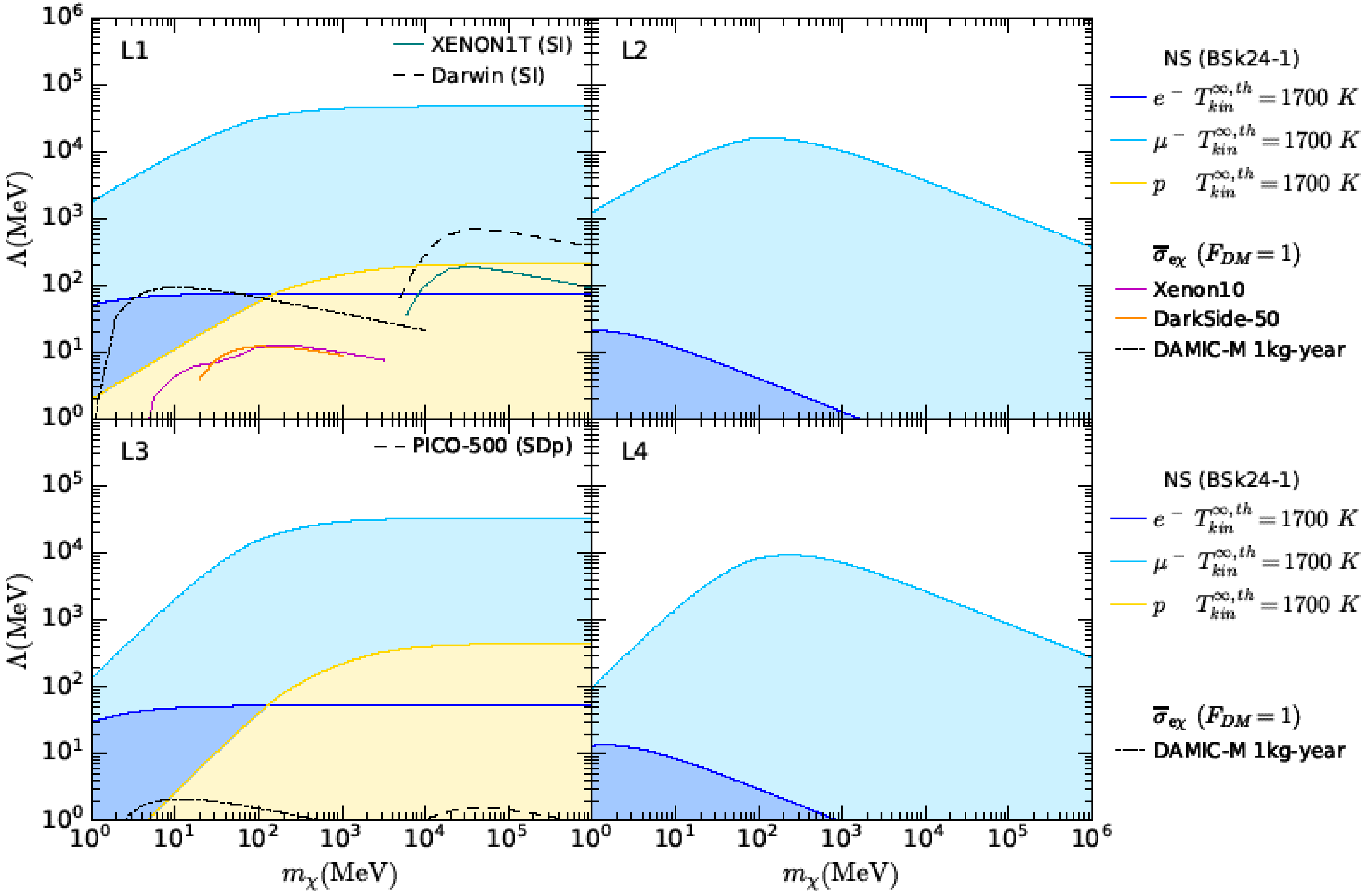
Name	Operator	Coupling G
L1	$\bar{\chi}\chi\,\bar{\ell}\ell$	y_ℓ/Λ^2
L2	$\bar{\chi}\gamma^5\chi\,\bar{\ell}\ell$	iy_ℓ/Λ^2
L3	$\bar{\chi}\chi\,\bar{\ell}\gamma^5\ell$	iy_ℓ/Λ^2
L4	$\bar{\chi}\gamma^5\chi\,\bar{\ell}\gamma^5\ell$	y_ℓ/Λ^2
L5	$\bar{\chi}\gamma_\mu\chi\,\bar{\ell}\gamma^\mu\ell$	$1/\Lambda^2$
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



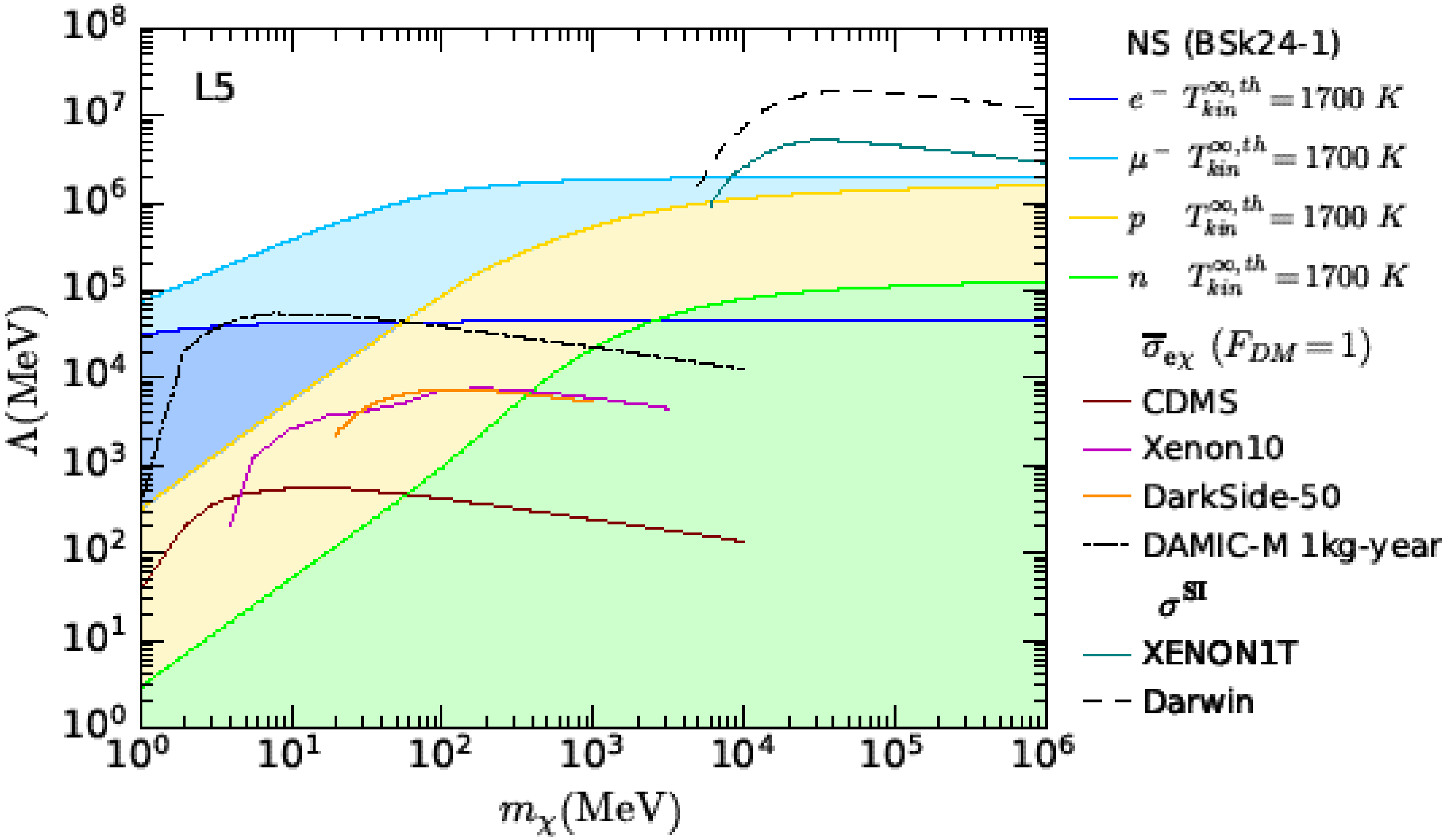
Operator	Coupling	Induced by
D1	2 loop (γ, Z)	L1
D2	-	-
D3	2 loop (γ, Z)	L3
D4	-	-
D5	1 loop (γ) 1 loop (Z)	L5 L5, L7
D6	1 loop (γ) 1 loop (Z)	L6 L6, L8
D7	1 loop (Z)	L5, L7
D8	1 loop (Z)	L6, L8

Scalar interactions

NFB, Busoni & Robles arXiv:1904.09803



Vector interactions (L5)



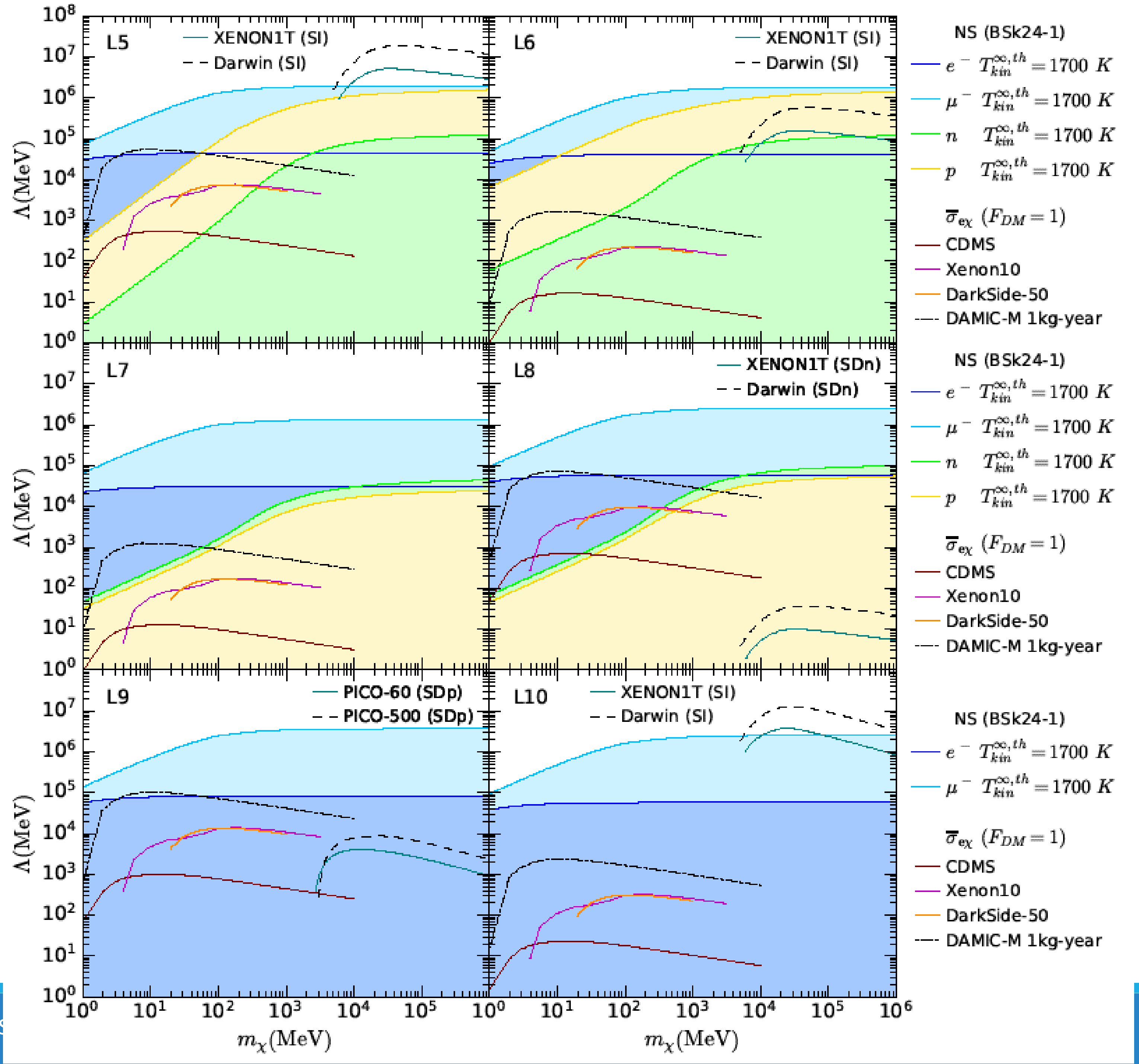
NFB, Busoni & Robles arXiv:1904.09803

Vector interactions

Very good NS sensitivity for muon and electron scattering.

DD more sensitive only for vector-vector scattering of > 1GeV DM.

NFB, Busoni & Robles arXiv:1904.09803



Summary & Conclusions

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

- Solar capture → interesting new results

- 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.