MACROS 2026 Workshop, Penn State University, Happy Valley

The Sun as a Dark Matter Laboratory: The Neutrino Messenger

Thong T.Q. Nguyen

IGC

PennState Eberly College of Science

Oskar Klein

Stockholm University

We gonna use neutrinos from the Sun to study

1. **Leptophilic Dark Matter**
   (TTQN, Tim Linden, Pierluca Carenza, Axel Widmark, *Accepted by PRD Letter*, **arXiv:2501.14864**)

2. **Spin-dependent Dark Matter-proton scattering**
   (TTQN, Tim Linden, *submitted to PRD*, **arXiv:2602.15113**)

3. **Millicharged Dark Matter** (TTQN, *in prep.*)

Tim Linden

Stockholm University

Pierluca Carenza

Stockholm U.

Axel Widmark

Columbia U.

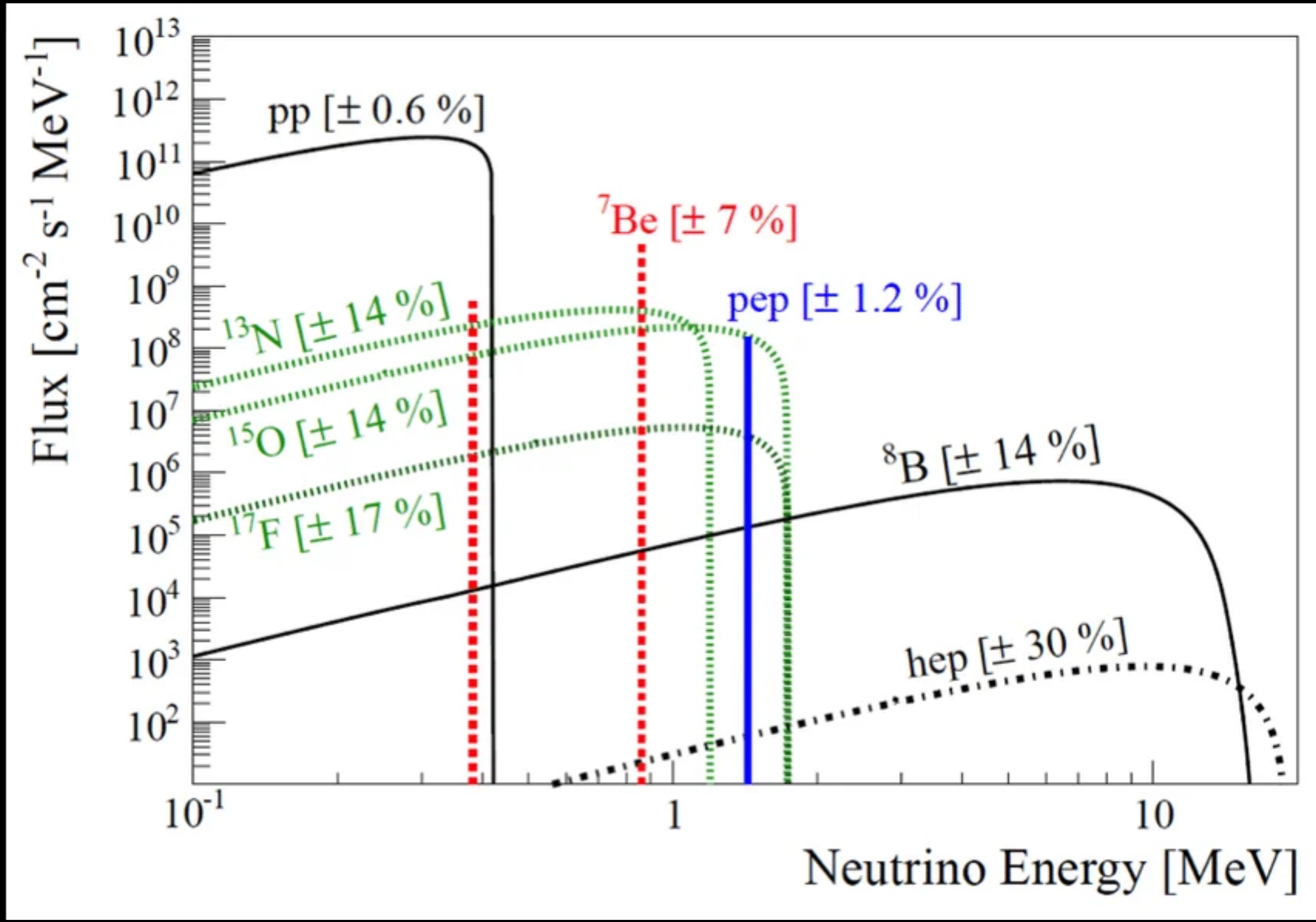
(Marie Curie Fellow)


WHEN DOES THE SUN RETURN?
WE LIVE IN SWEDEN

Solar Neutrino Observations

Measuring neutrino oscillations

- Solar neutrino deficit observed since 1970s (Raymond Davis) — the "solar neutrino problem.”
- Confirmed by Kamiokande (1989): observed flux ~ half of prediction.
- Resolved in 2001: Super-K + SNO proved neutrino oscillations are the cause.
- Solar model predictions now consistent with observations after accounting for oscillations.



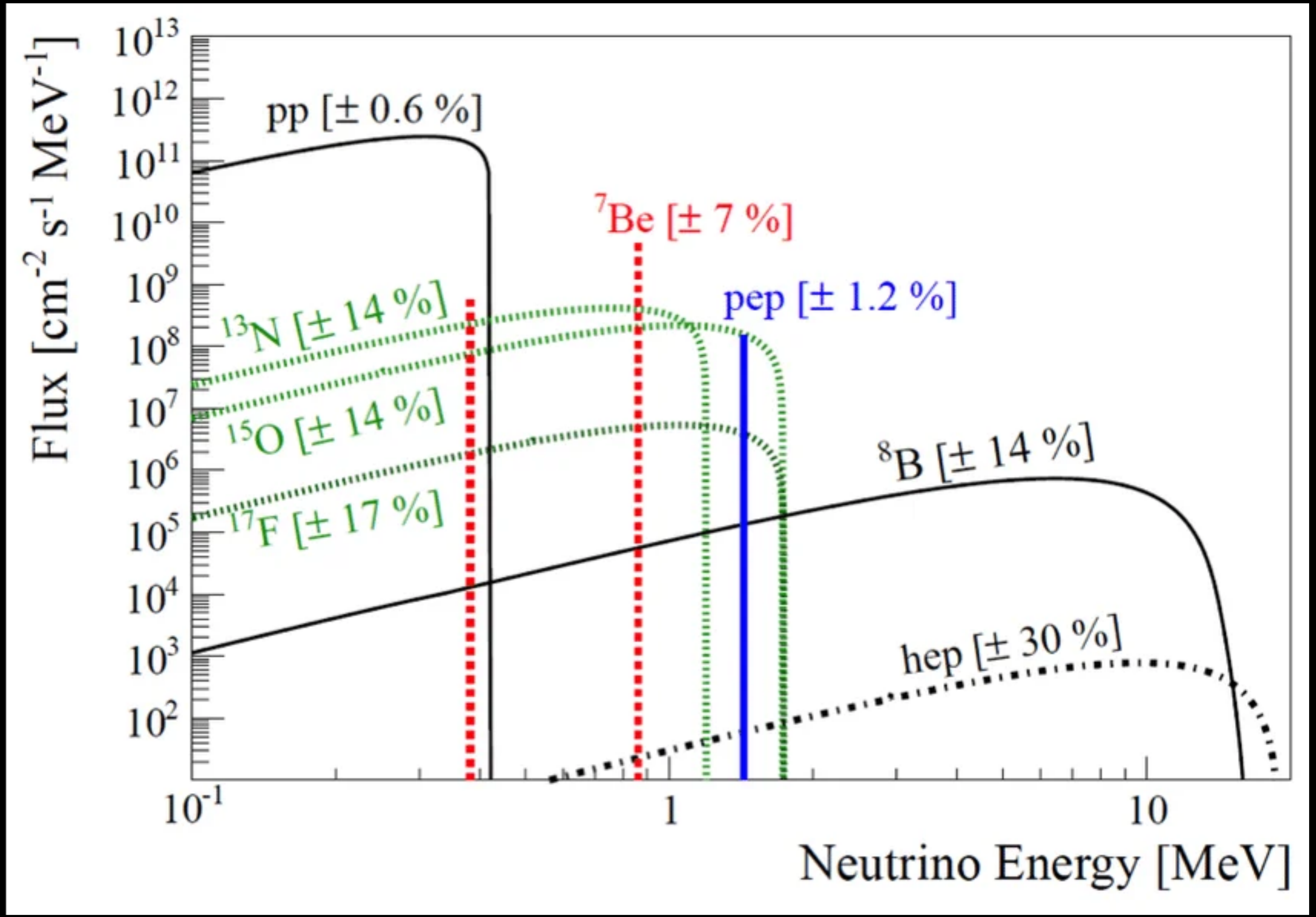
Solar Neutrino Observations

The Dark Matter Capture Explanation

However, before the confirmation of neutrino oscillation by SNO, there is hypothesis of Dark Matter accumulate inside the Sun:

- Press and Spergel, Faulkner and Gilliland (1985) : DM conduct energy out of the core, lower the central temperature, thus produce less neutrinos.

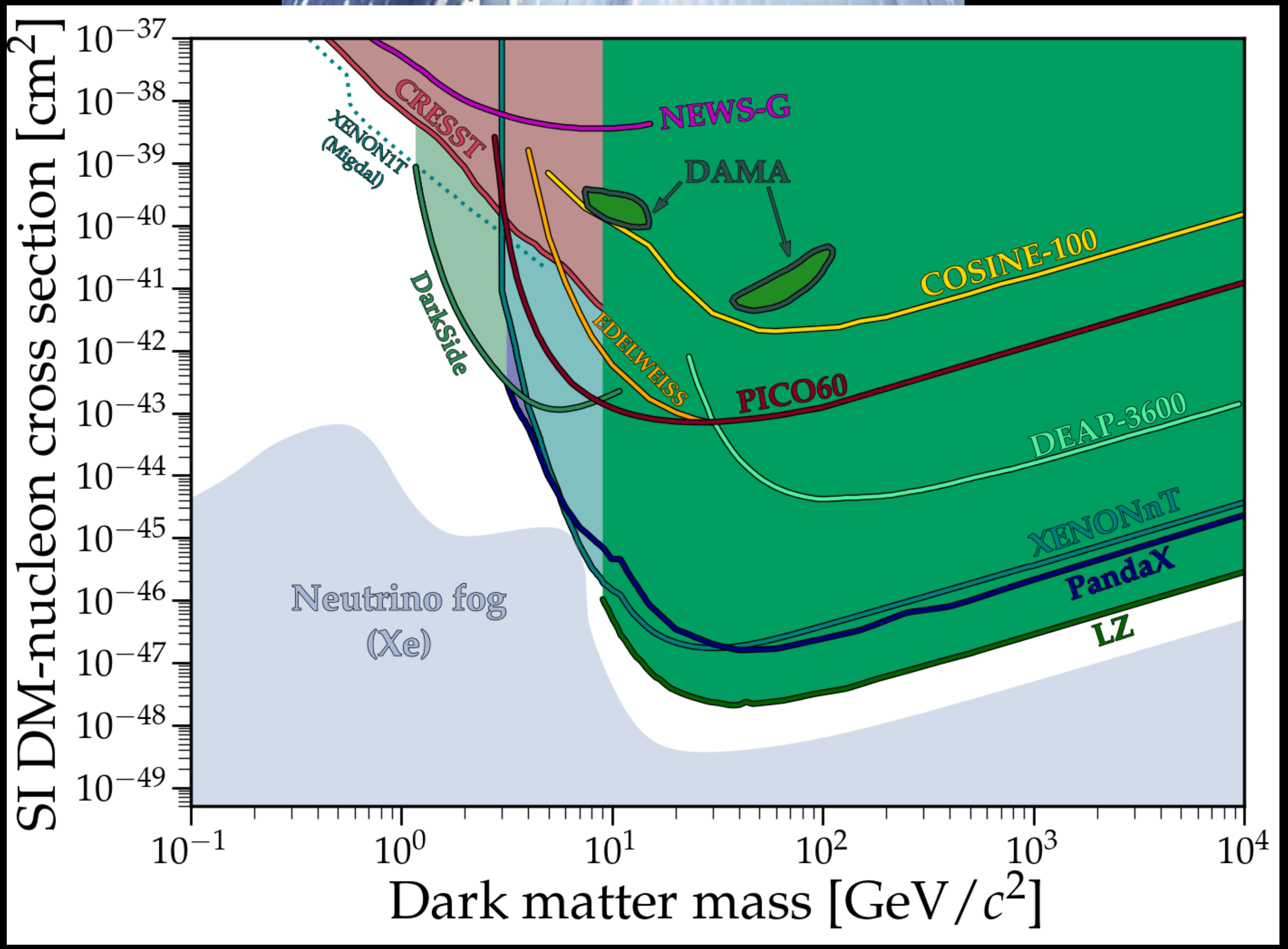
- Silk, Olive, and Srednicki (1985), Gaisser, Steigman and Tilav (1986) pointed out the neutrino signals from DM annihilation is completely distinct from the MeV-scale solar neutrinos




ν
ν

Dark Matter Detector = Neutrino Detector

Xenon1T vs Super-Kamiokande



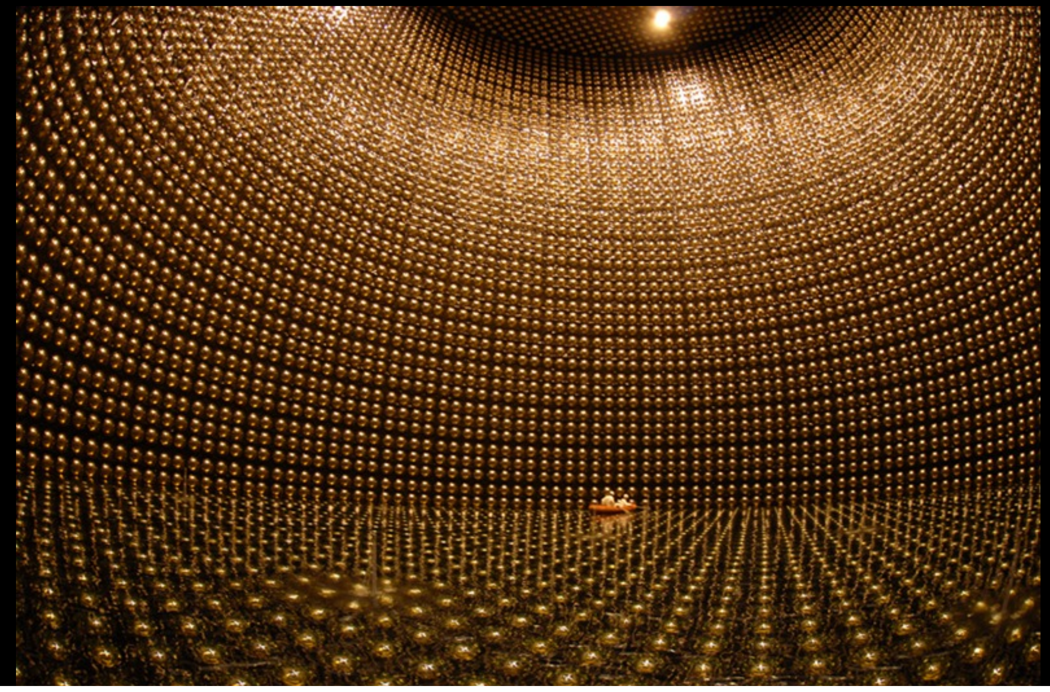
Thong Nguyen, Stockholm University

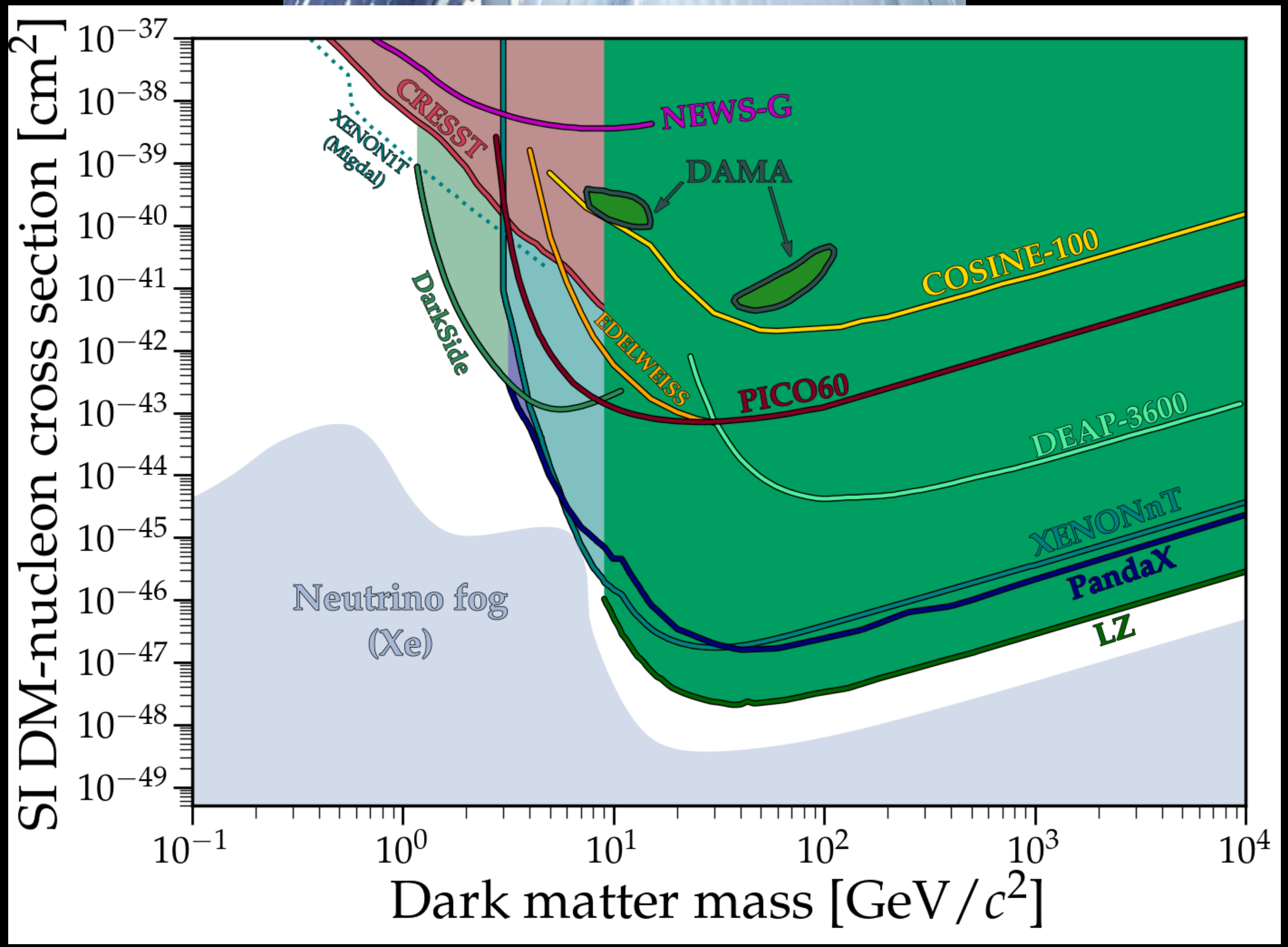
Neutrino Detector = Dark Matter Detector

Xenon1T vs Super-Kamiokande

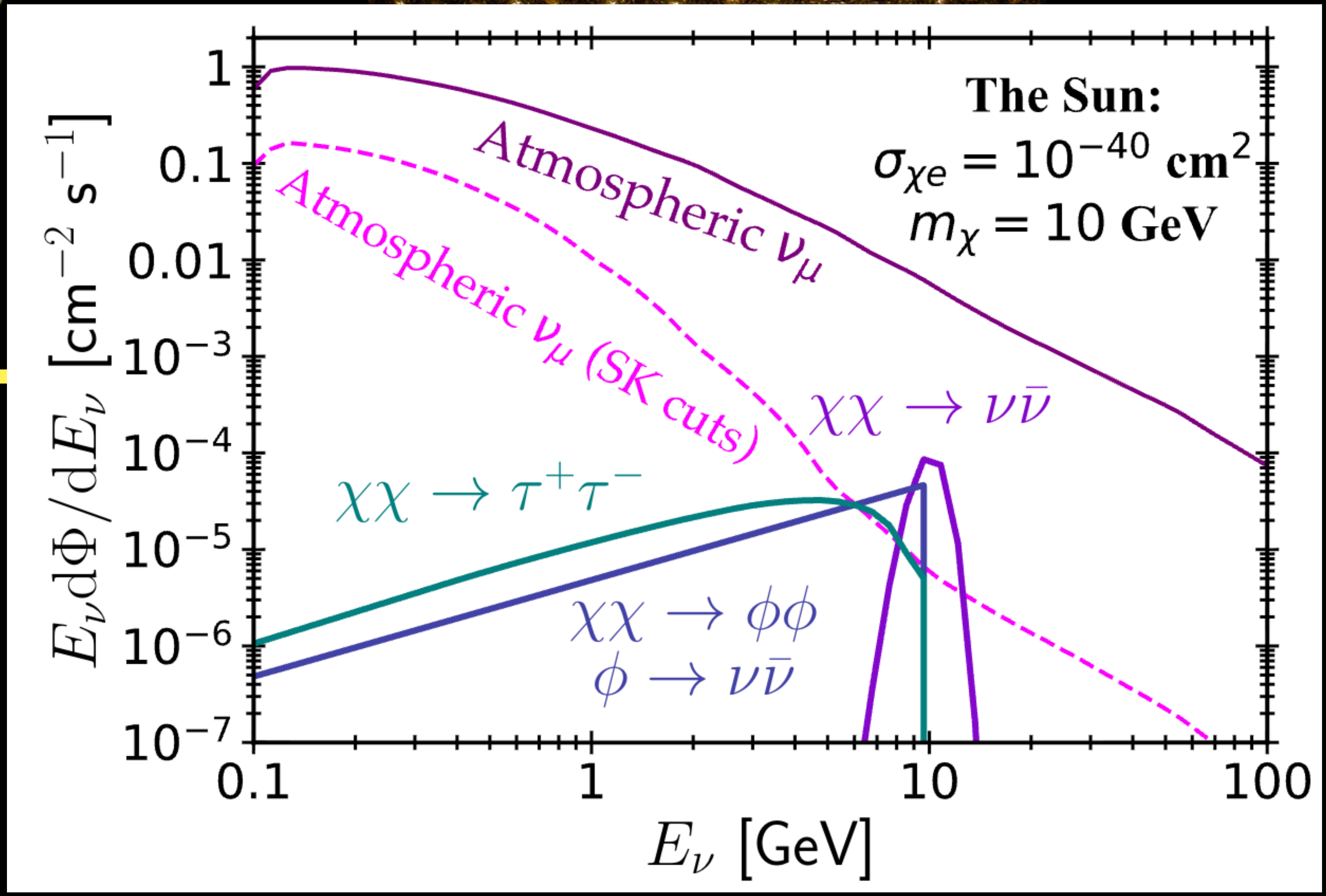
ν ←

ν →





Super-K is sensitive to neutrinos from DM annihilation inside the Sun! ←



What we know about Dark Matter?

The Dark Matter Questionnaire

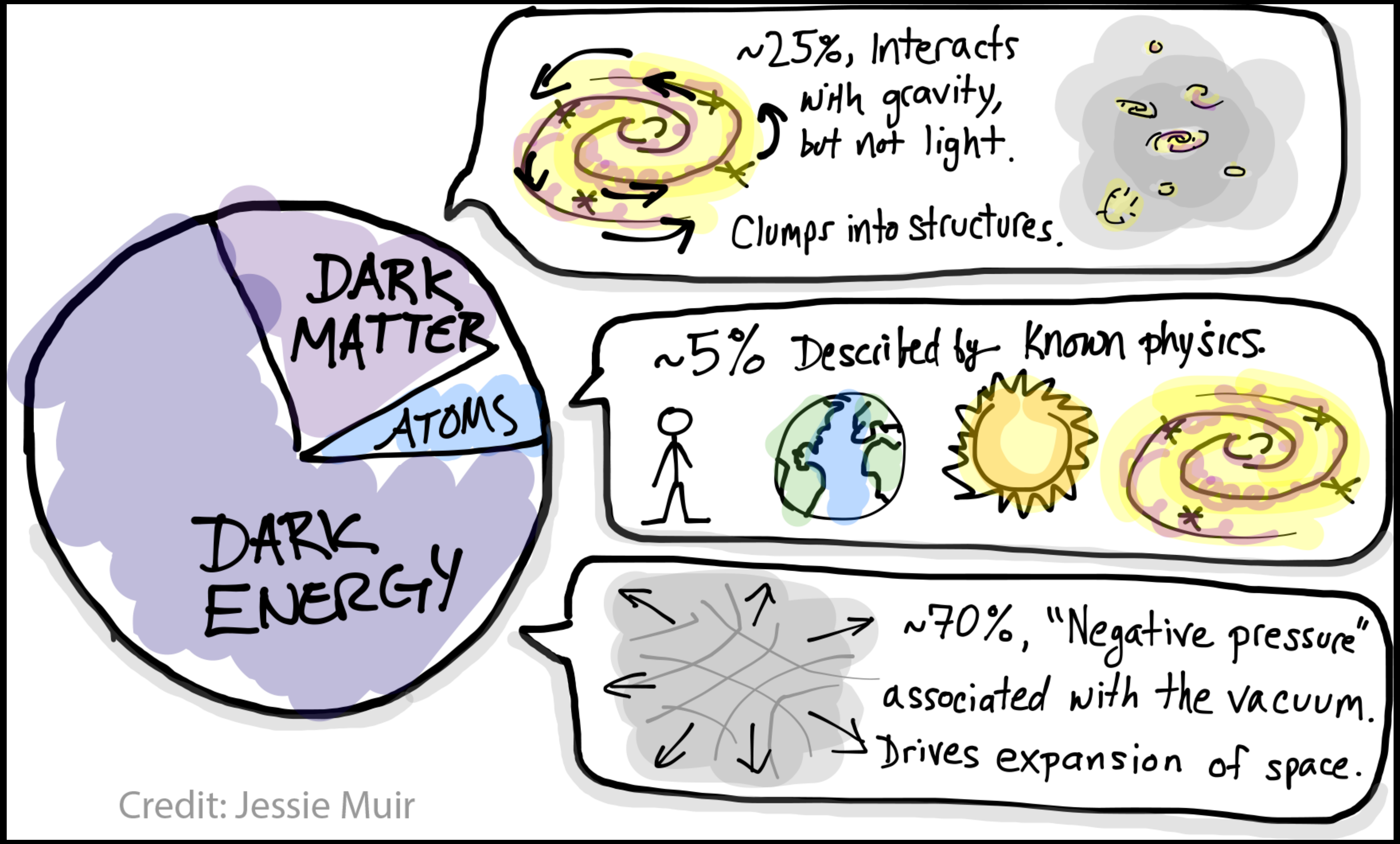
- [ ] Mass
- [ ] Spin
- [ ] Stable?
  - [ ] Yes - [ ] No

Couplings:

- [x] Gravity
- [ ] Weak Interaction?
- [ ] Higgs?
- [ ] Quarks / Gluons?
- [ ] Leptons?

Thermal Relic?

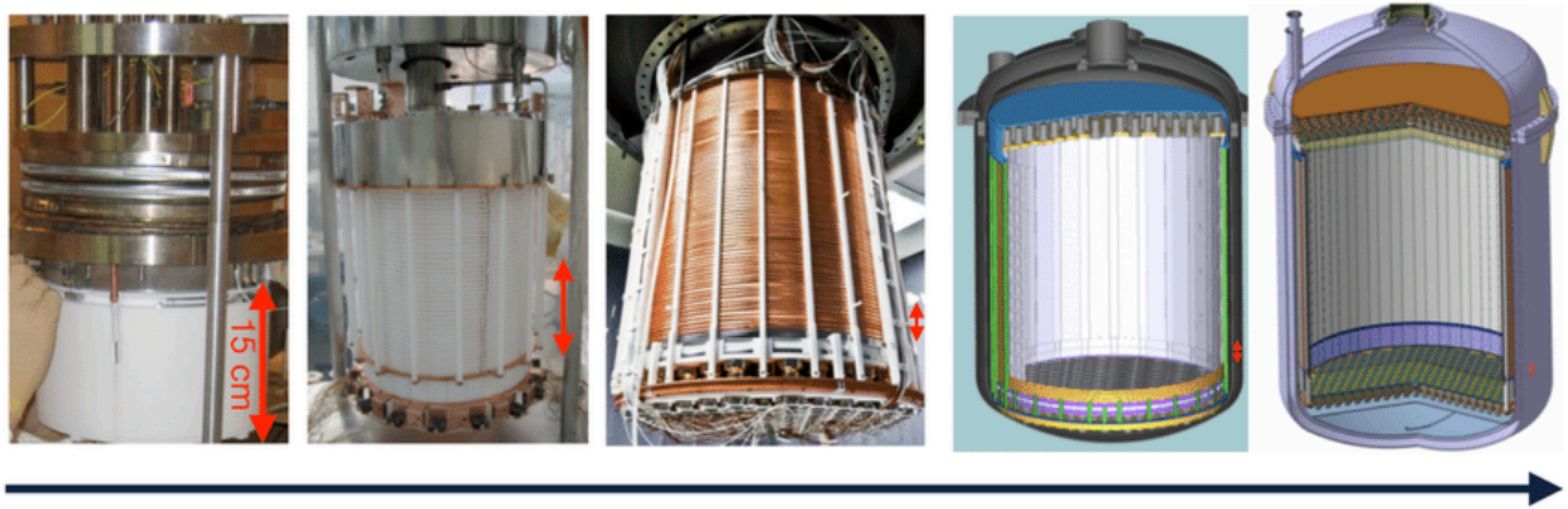
- [ ] Yes - [ ] No



Credit: Jessie Muir

Direct Detection

Study non-gravitational interaction between DM and normal matter



XENON10	XENON100	XENON1T	XENONnT	DARWIN
2005 – 2007	2008 – 2016	2012 – 2018	2019 – 2023	2025 –
~15 kg	~62 kg	~2 t	~5.9 t	40 t
15 cm	30 cm	1 m	1.5 m	2.6 m
~10^{-43} cm^2	~10^{-45} cm^2	~10^{-47} cm^2	~10^{-48} cm^2	~10^{-49} cm^2

Thong Nguyen, Stockholm University

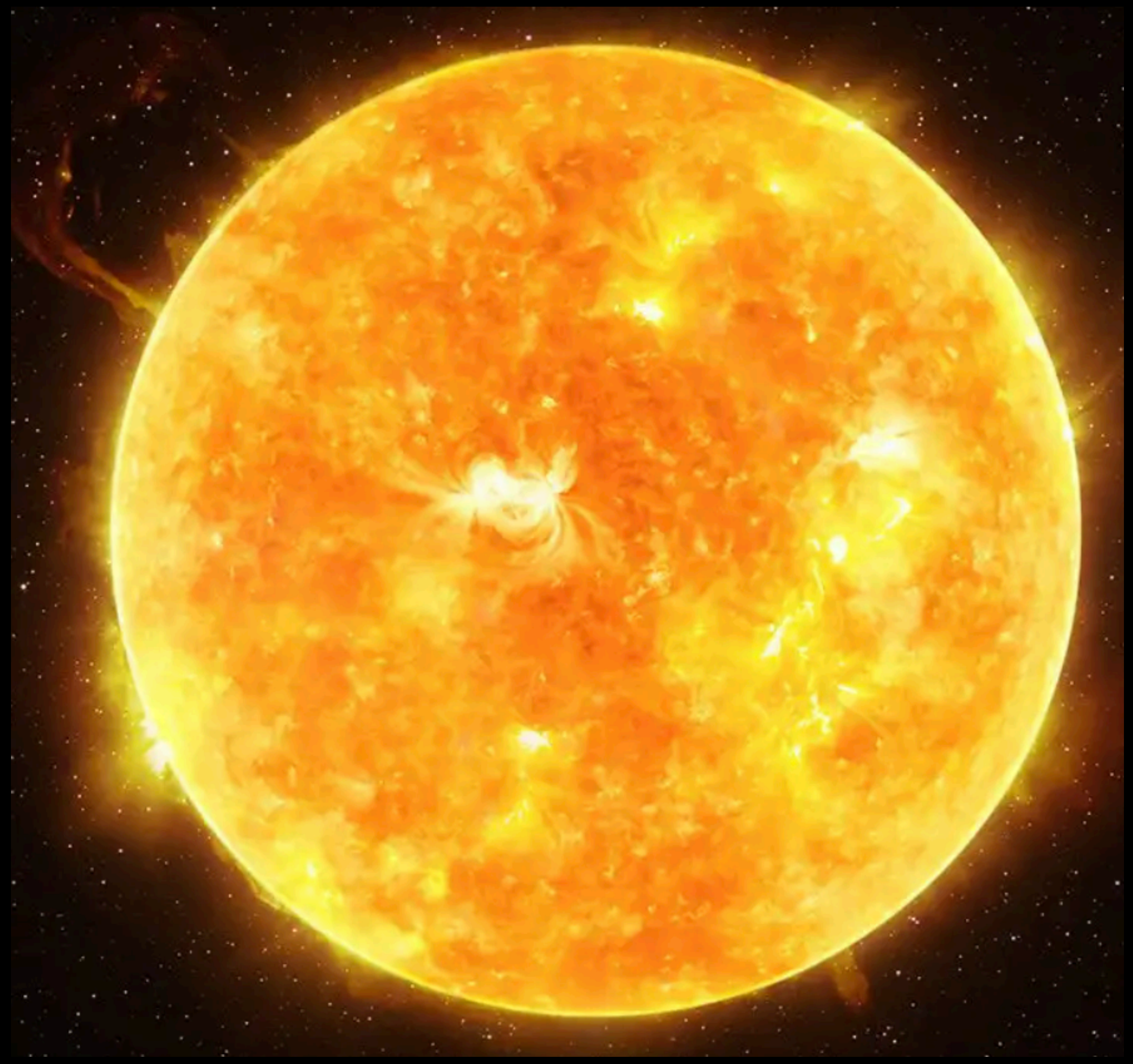
The Sun as Natural Dark Matter Detector

Large Exposure from the Heaven!

XENONnT:

- 7000 kg
- 700 days

5×10^{6} kg day



The Sun:

- 3×10^{30} kg
- 2×10^{10} days

6×10^{40} kg day

Thong Nguyen, Stockholm University

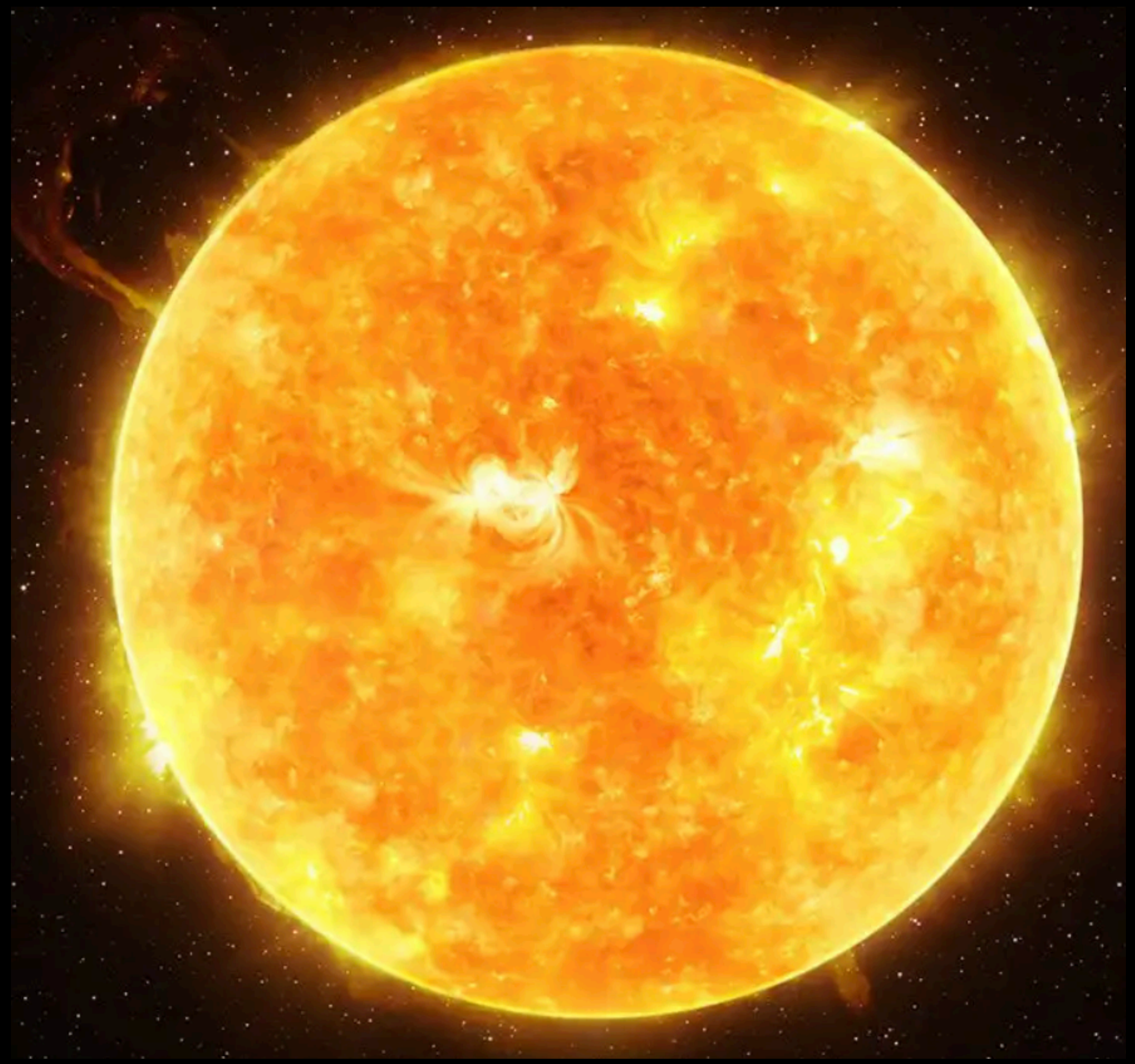
The Sun as Natural Dark Matter Detector

Large Exposure from the Heaven!

XENONnT:

- 7000 kg
- 700 days

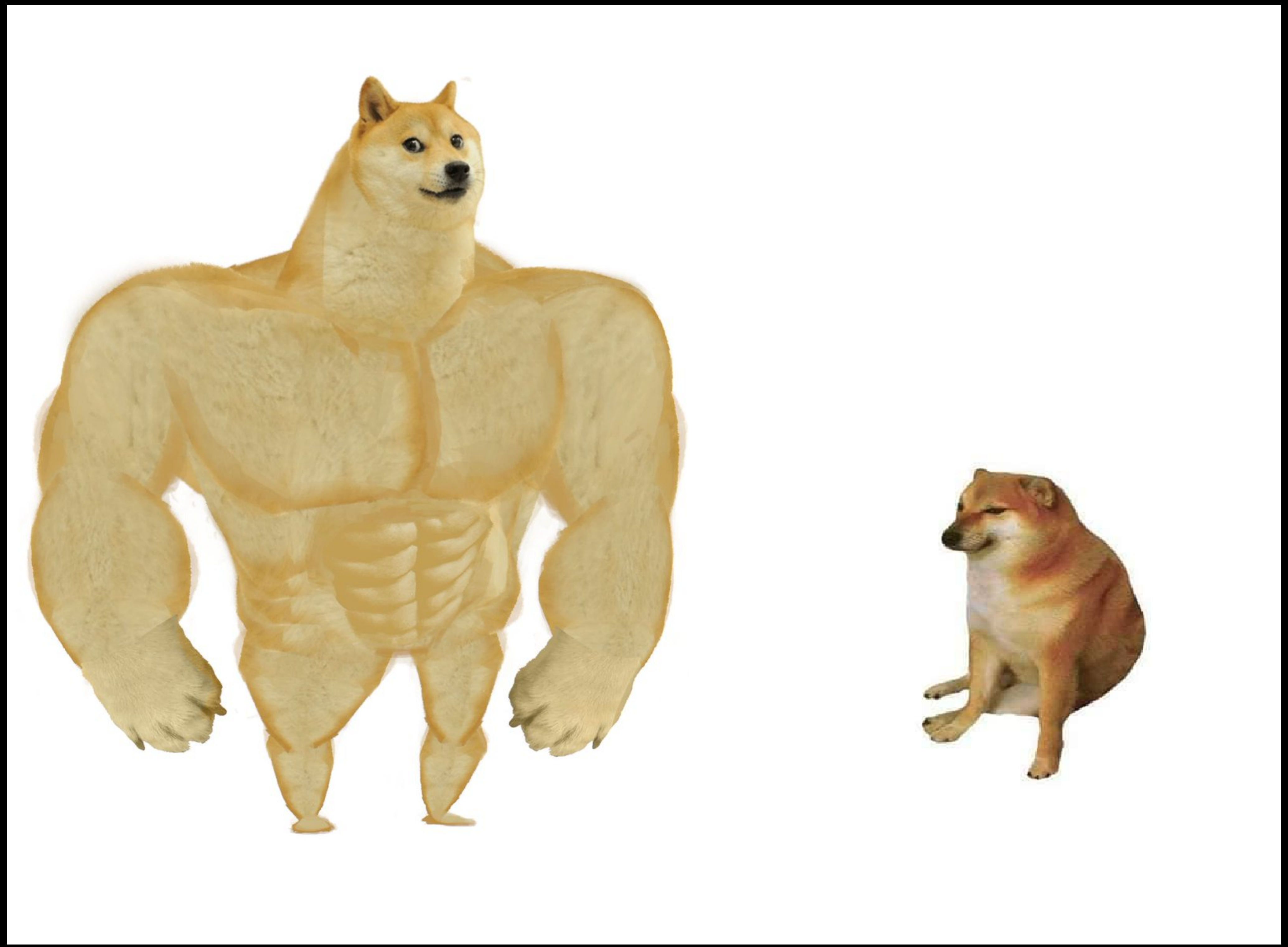
5×10^{6} kg day



The Sun:

- 3×10^{30} kg
- 2×10^{10} days

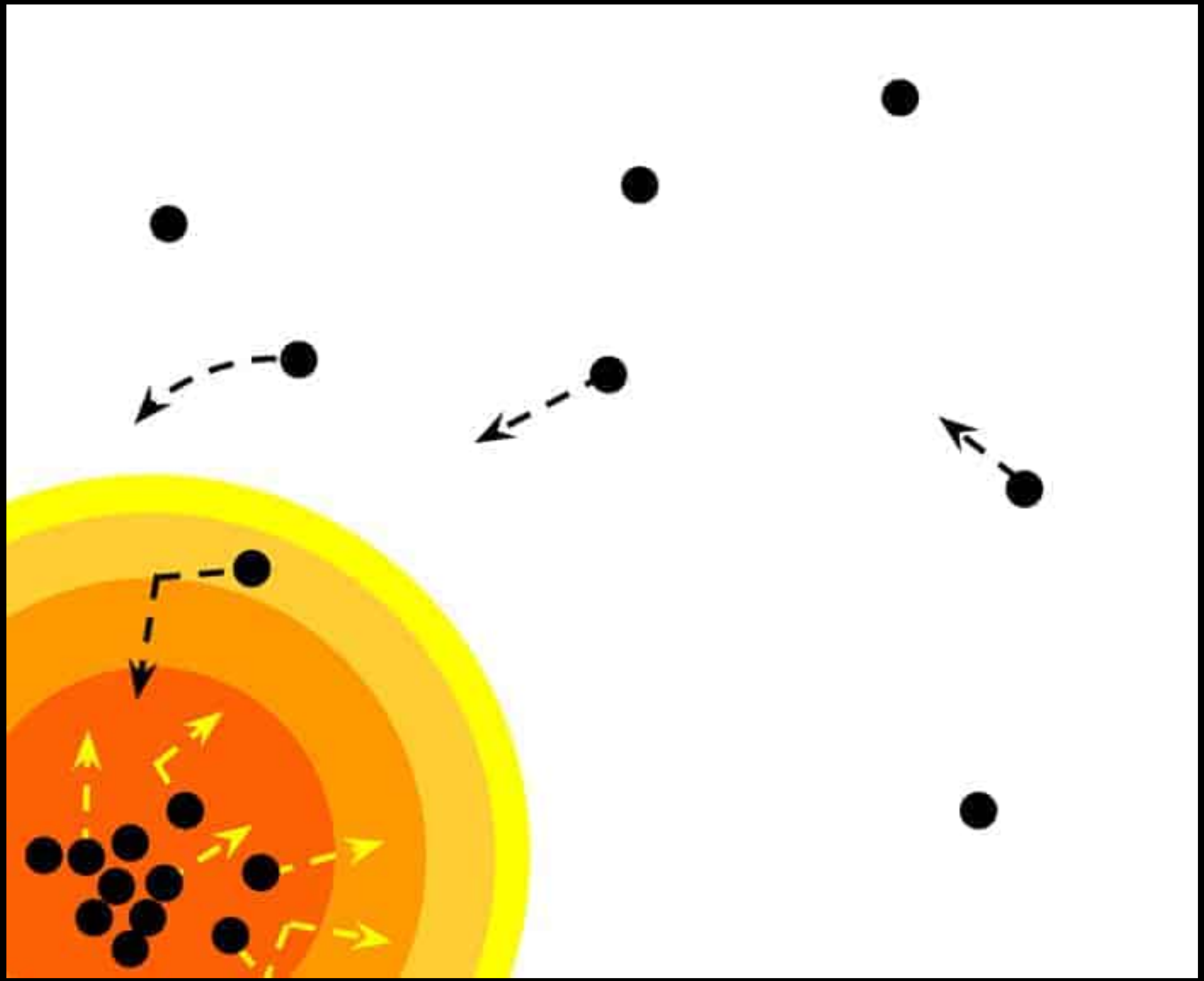
6×10^{40} kg day



Thong Nguyen, Stockholm University

Dark Matter Capture in The Sun

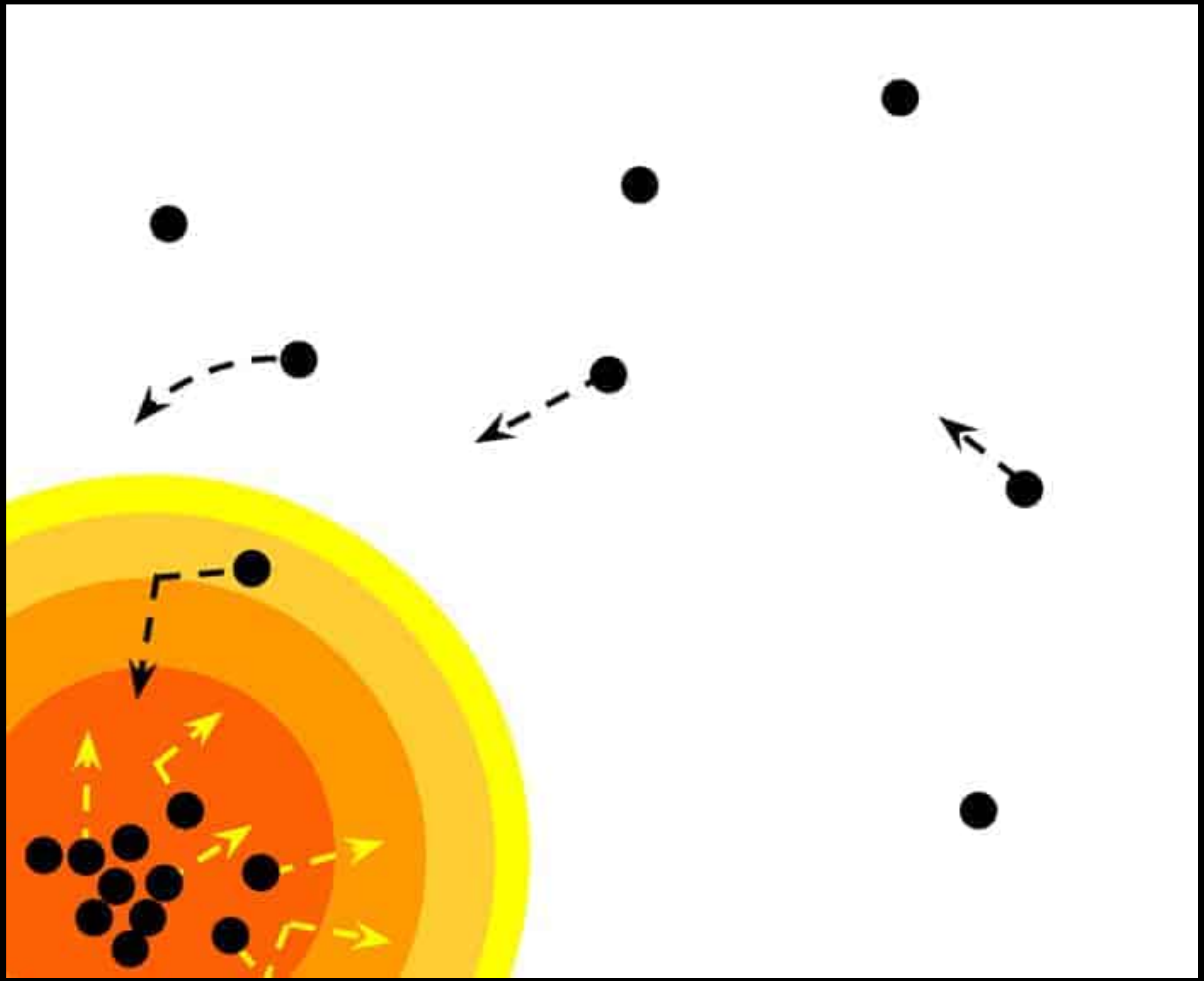
A novel idea first proposed by Press and Spergel, 1985



- DM scattering with nucleons and electrons inside the Sun
- Lose Kinetic Energy.
- DM Velocity below the Sun's Escape Velocity!
- Being captured! Enhance the DM density inside the Sun

Dark Matter Capture in The Sun

A novel idea first proposed by Press and Spergel, 1985



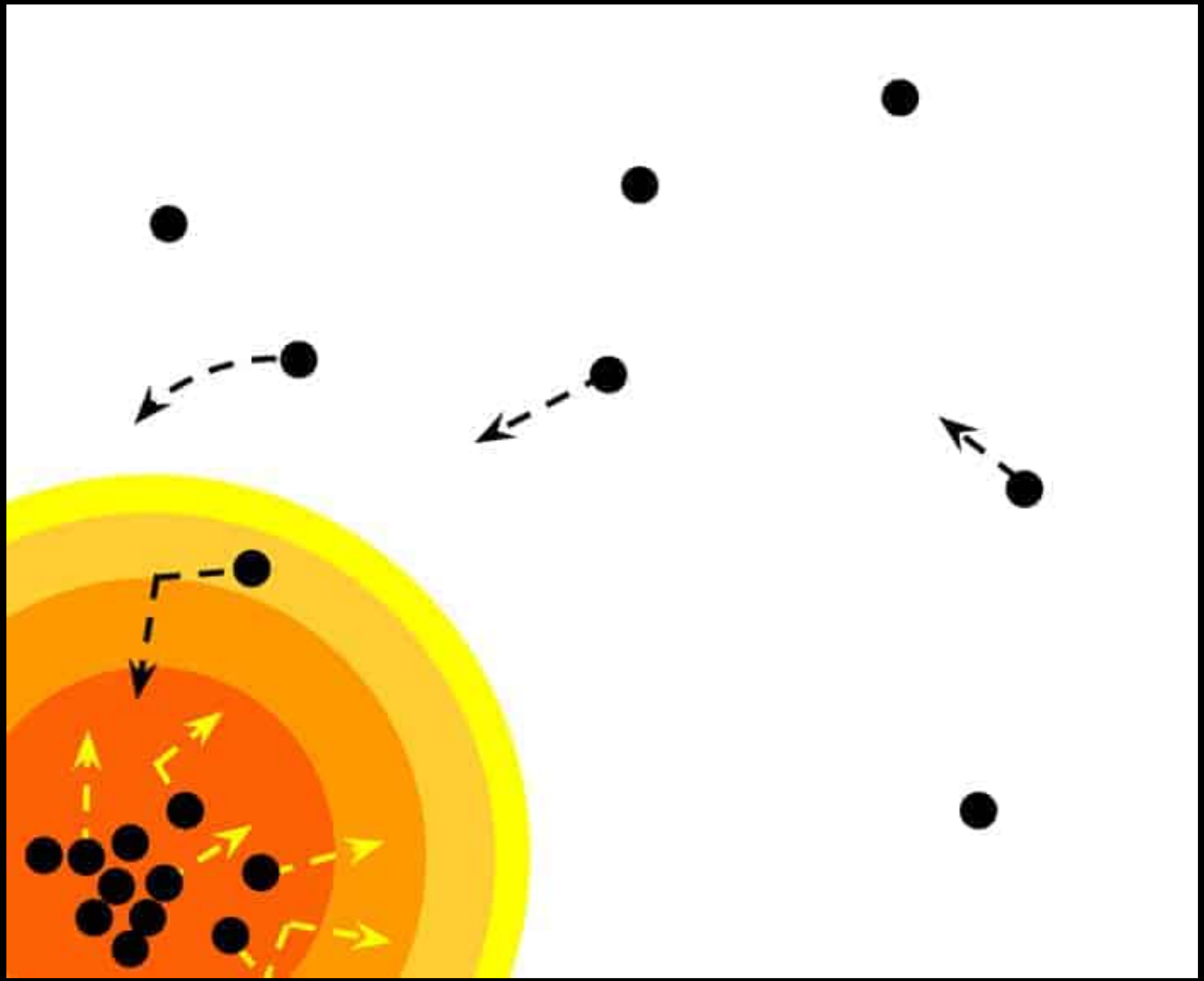
Capture Rate:

$$C_\odot^{\mathrm{weak}} = \int_0^{R_\odot} \mathrm{d}r 4\pi r^2 \frac{\rho_\chi}{m_\chi} \int_0^\infty \mathrm{d}u_\chi \frac{f_{v_\odot}(u_\chi)}{u_\chi} \times \int_0^{v_{\mathrm{esc}}(r)} \mathrm{d}v \times w(r) R_e^-(w \to v)$$

$[\mathrm{s}^{-1}]$

Dark Matter Capture in The Sun

A novel idea first proposed by Press and Spergel, 1985



DM Halo velocity distribution

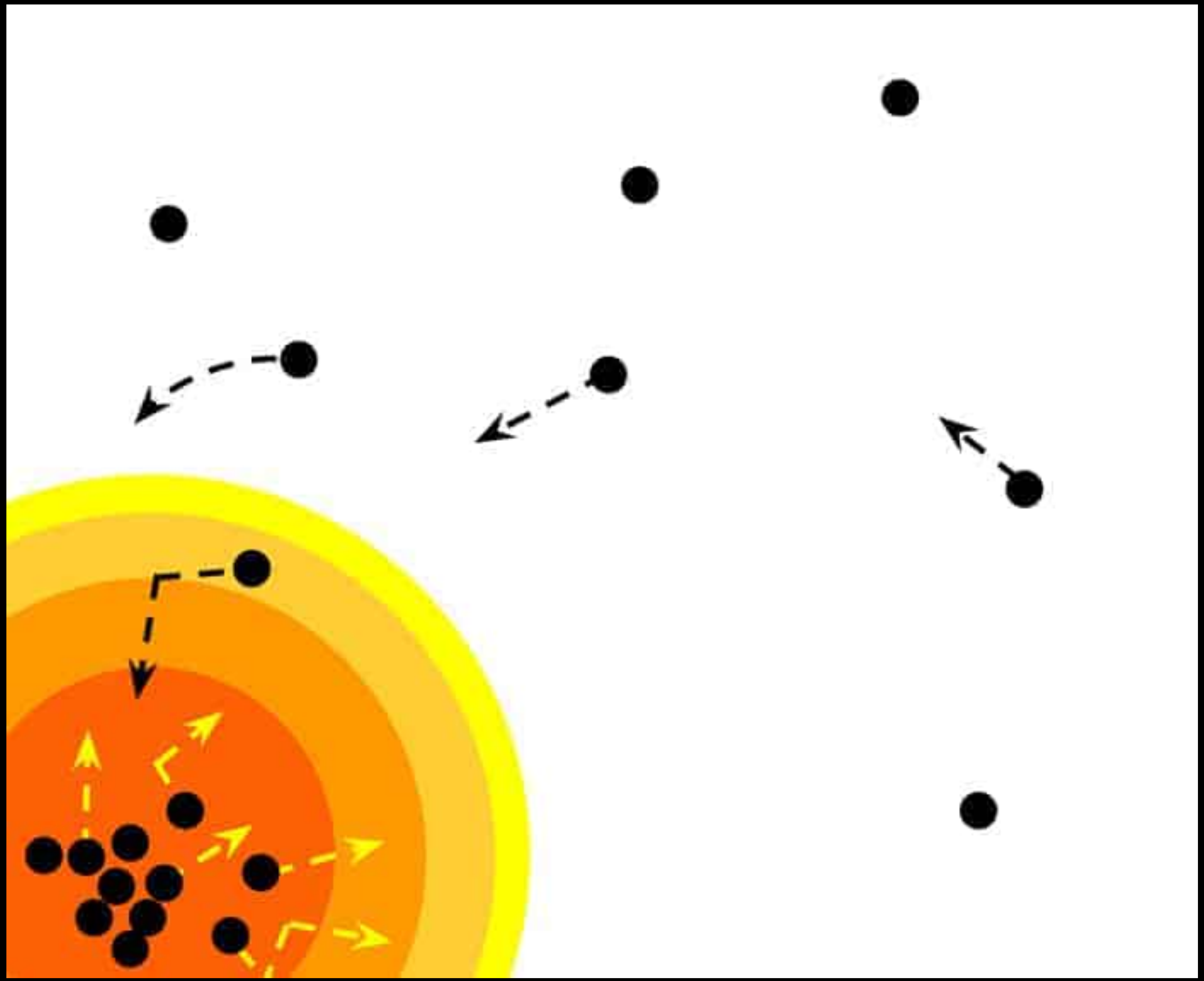
Capture Rate: $0.4\ \mathrm{GeV/cm^3}$

$$C_\odot^{\rm weak} = \int_0^{R_\odot} \mathrm{d}r 4\pi r^2 \frac{\rho_\chi}{m_\chi} \int_0^\infty \mathrm{d}u_\chi \frac{f_{v_\odot}(u_\chi)}{u_\chi} \times \int_0^{v_{\rm esc}(r)} \mathrm{d}v \times w(r) R_e^-(w \to v)$$

$[\mathrm{s}^{-1}]$

Dark Matter Capture in The Sun

A novel idea first proposed by Press and Spergel, 1985



DM Halo

velocity distribution

Capture Rate: $0.4\ \mathrm{GeV/cm^3}$

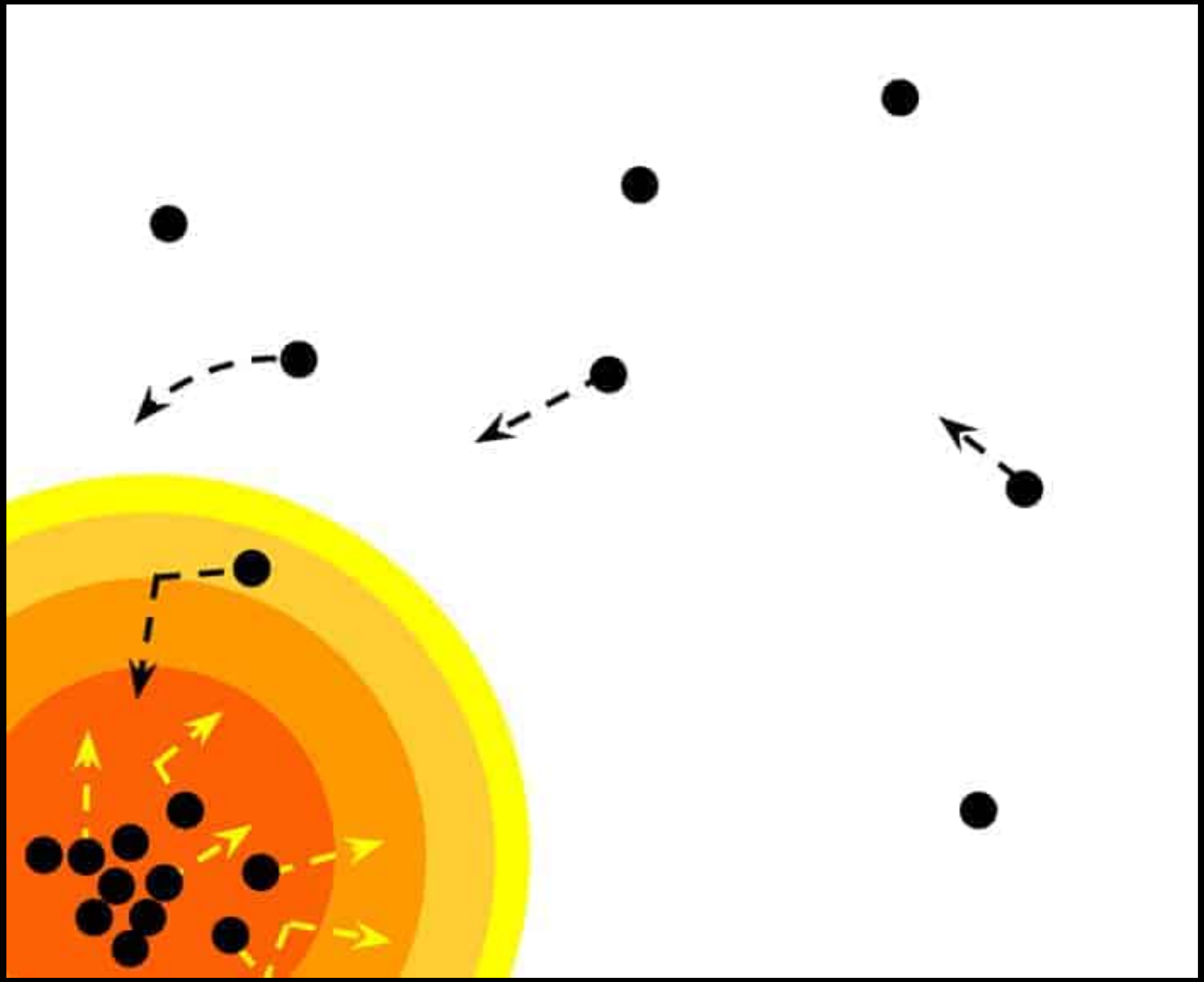
$$C_{\odot}^{\mathrm{weak}} = \int_0^{R_\odot} \mathrm{d}r 4\pi r^2 \frac{\rho_\chi}{m_\chi} \int_0^\infty \mathrm{d}u_\chi \frac{f_{v_\odot}(u_\chi)}{u_\chi} \times \int_0^{v_{\mathrm{esc}}(r)} \mathrm{d}v \times w(r) R_e^-(w \to v)$$

$[\mathrm{s}^{-1}]$

$$w^2(r) = u_\chi^2 + v_{\mathrm{esc}}^2(r)$$

Dark Matter Capture in The Sun

A novel idea first proposed by Press and Spergel, 1985



DM Halo

velocity distribution

Capture Rate:

$0.4\ \mathrm{GeV/cm^3}$

$$C_{\odot}^{\mathrm{weak}} = \int_0^{R_\odot} \mathrm{d}r 4\pi r^2 \frac{\rho_\chi}{m_\chi} \int_0^{\infty} \mathrm{d}u_\chi \frac{f_{v_\odot}(u_\chi)}{u_\chi} \times \int_0^{v_{\mathrm{esc}}(r)} \mathrm{d}v \times w(r) R_e^-(w \to v)$$

$[\mathrm{s}^{-1}]$

$$w^2(r) = u_\chi^2 + v_{\mathrm{esc}}^2(r)$$

Scattering Rate

$\propto n_e(r)\sigma_{\chi e}$

Thong Nguyen, Stockholm University

Tools/Packages for DM capture in the Sun

Also calculate for the Earth and other objects

Dark Matter Capture in Celestial Objects: Treatment Across Kinematic and Interaction Regimes

Asteria (arXiv:2309.00669)

Rebecca K. Leane,[a,b] **Juri Smirnov**[c]

[a] *SLAC National Accelerator Laboratory, 2575 Sand Hill Rd, Menlo Park, CA 94025, USA*
[b] *Kavli Institute for Particle Astrophysics and Cosmology, Stanford University, Stanford, CA 94035, USA*
[c] *Department of Mathematical Sciences, University of Liverpool, Liverpool, L69 7ZL, United Kingdom*

E-mail: rleane@slac.stanford.edu, juri.smirnov@liverpool.ac.uk

WIMPYC (arXiv:2510.21185)

WimPyC: an extension module of WimPyDD for the calculation of WIMP capture in celestial bodies

Sunghyun Kang,[a,b] **Stefano Scopel,**[a,b] **Gaurav Tomar**[c]

[a] Center for Quantum Spacetime, Sogang University, 35 Baekbeom-ro, Mapo-gu, Seoul, 121-742, South Korea
[b] Department of Physics, Sogang University, 35 Baekbeom-ro, Mapo-gu, Seoul, 121-742, South Korea
[c] School of Basic Sciences and Humanities, APJ Abdul Kalam Technological University, CET Campus, Thiruvananthapuram, Kerala 695016, India

E-mail: francis735@naver.com, scopel@sogang.ac.kr, tomar@ktu.edu.in

DarkCapPy: Dark Matter Capture and Annihilation

Adam Green and Philip Tanedo

agree019@ucr.edu, flip.tanedo@ucr.edu

Department of Physics & Astronomy, University of California, Riverside, CA 92521

(arXiv:1808.03700)

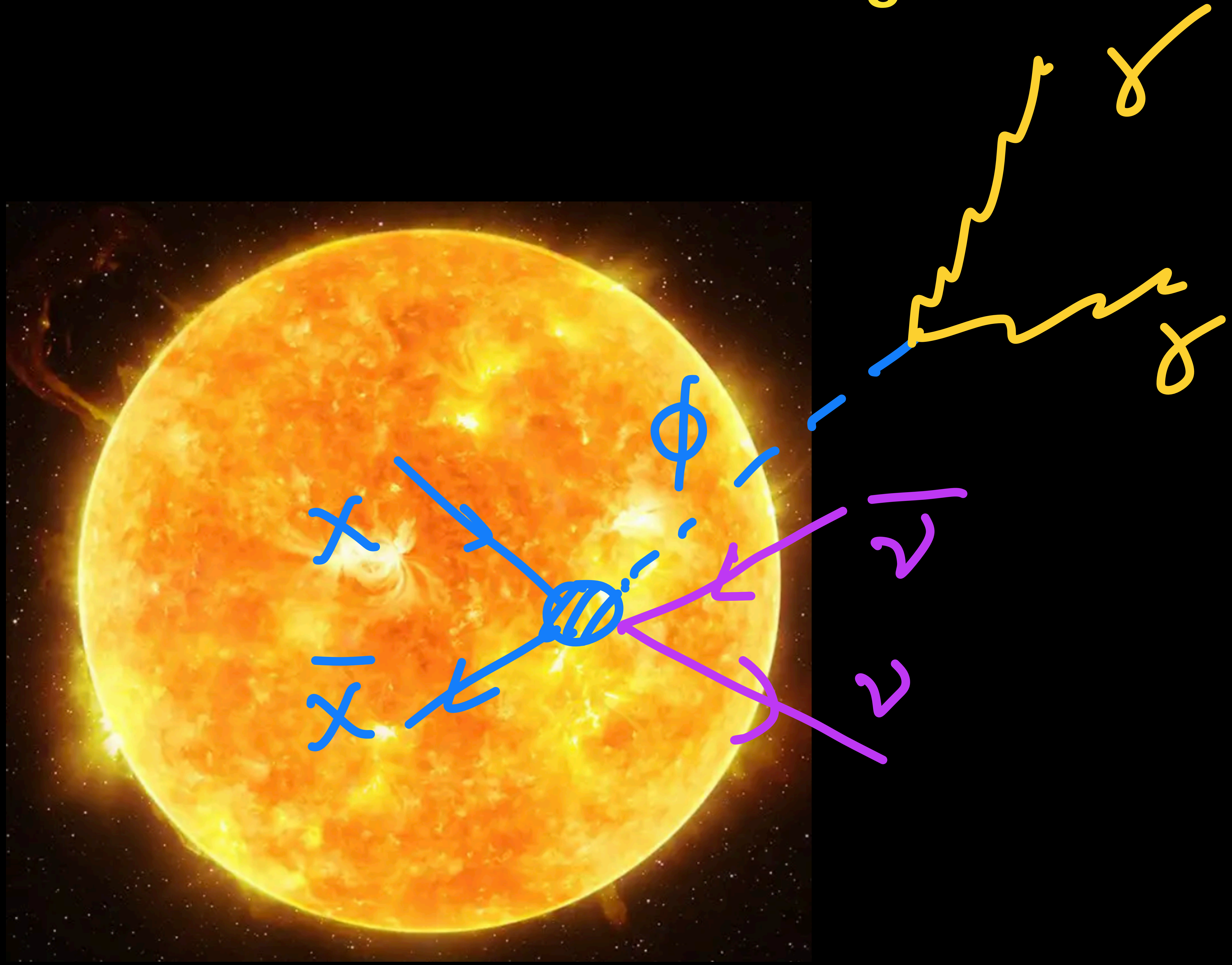
χarov: a tool for neutrino flux generation from WIMPs

(arXiv:2007.15010)

Qinrui Liu[a] **Jeffrey Lazar**[a,b] **Carlos A. Argüelles**[b] **Ali Kheirandish**[c,d]

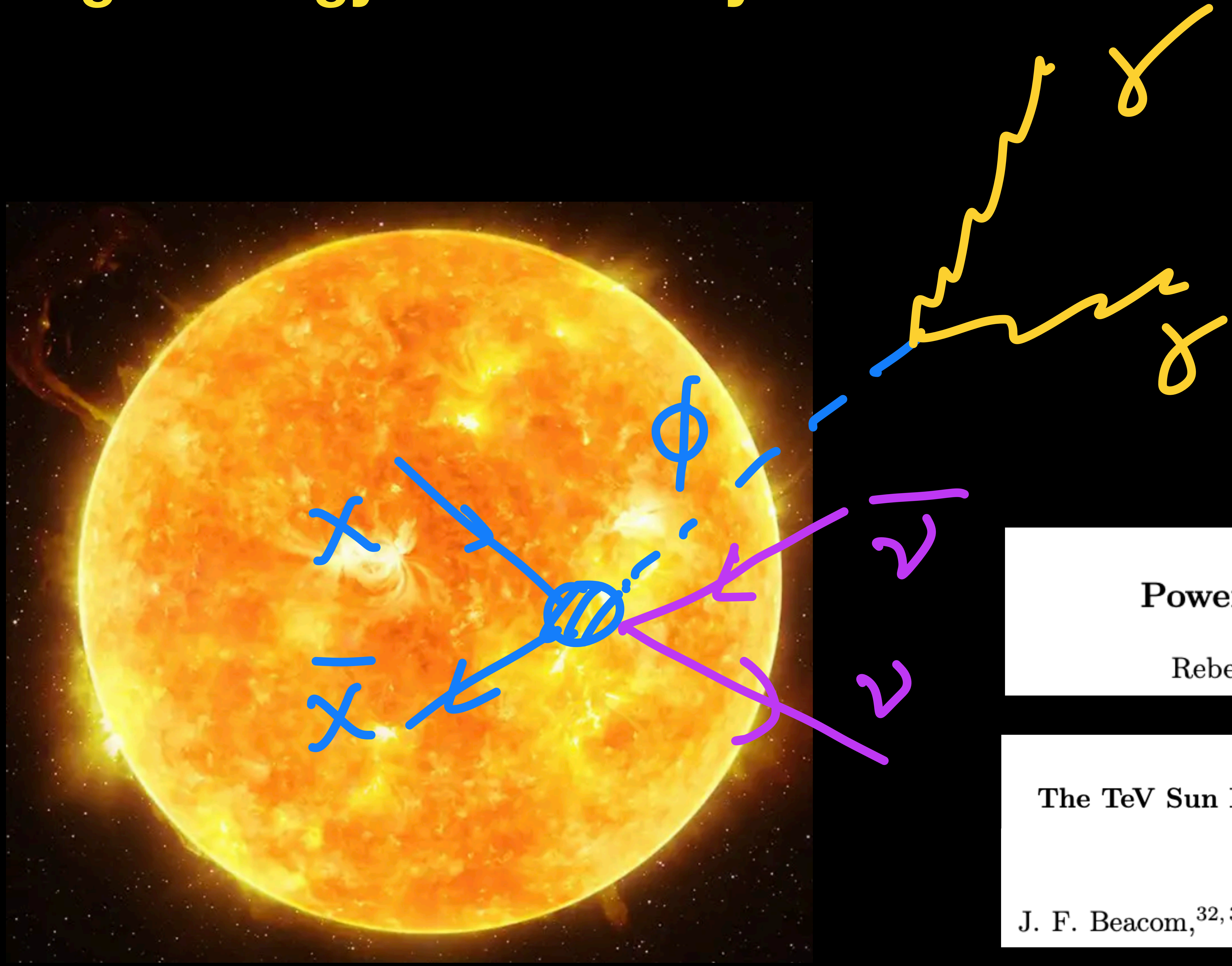
Dark Matter annihilation in the Sun

Possible indirect detection signals



Dark Matter annihilation in the Sun

High-Energy Gamma Ray



HAWC

Powerful Solar Signatures of Long-Lived Dark Mediators

Rebecca K. Leane,[1,2] Kenny C. Y. Ng,[1,3,4] and John F. Beacom[1,3,5]

The TeV Sun Rises: Discovery of Gamma rays from the Quiescent Sun with HAWC

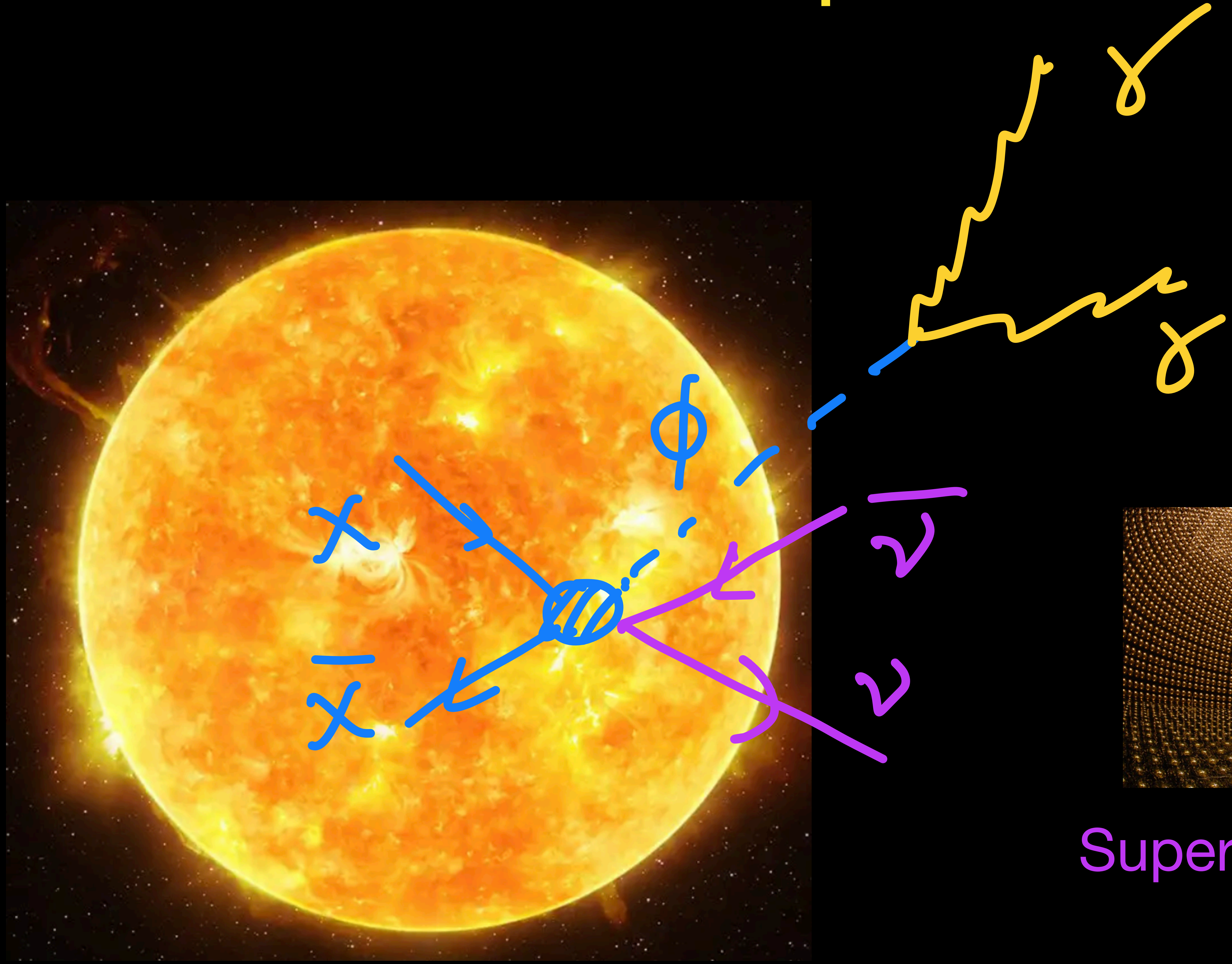
(HAWC Collaboration)

J. F. Beacom,[32,33,34] T. Linden,[35] K. C. Y. Ng,[36] A. H. G. Peter,[32,33,34,37] and B. Zhou [38]

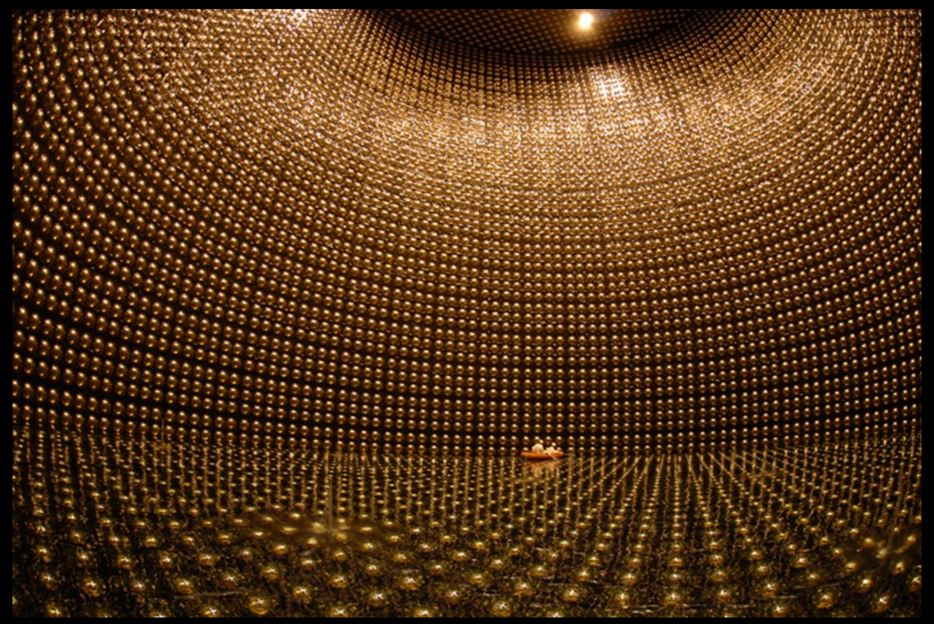
Thong Nguyen, Stockholm University

Leptophilic Dark Matter in the Sun

Dark Matter annihilation to produce indirect detection signal




HAWC

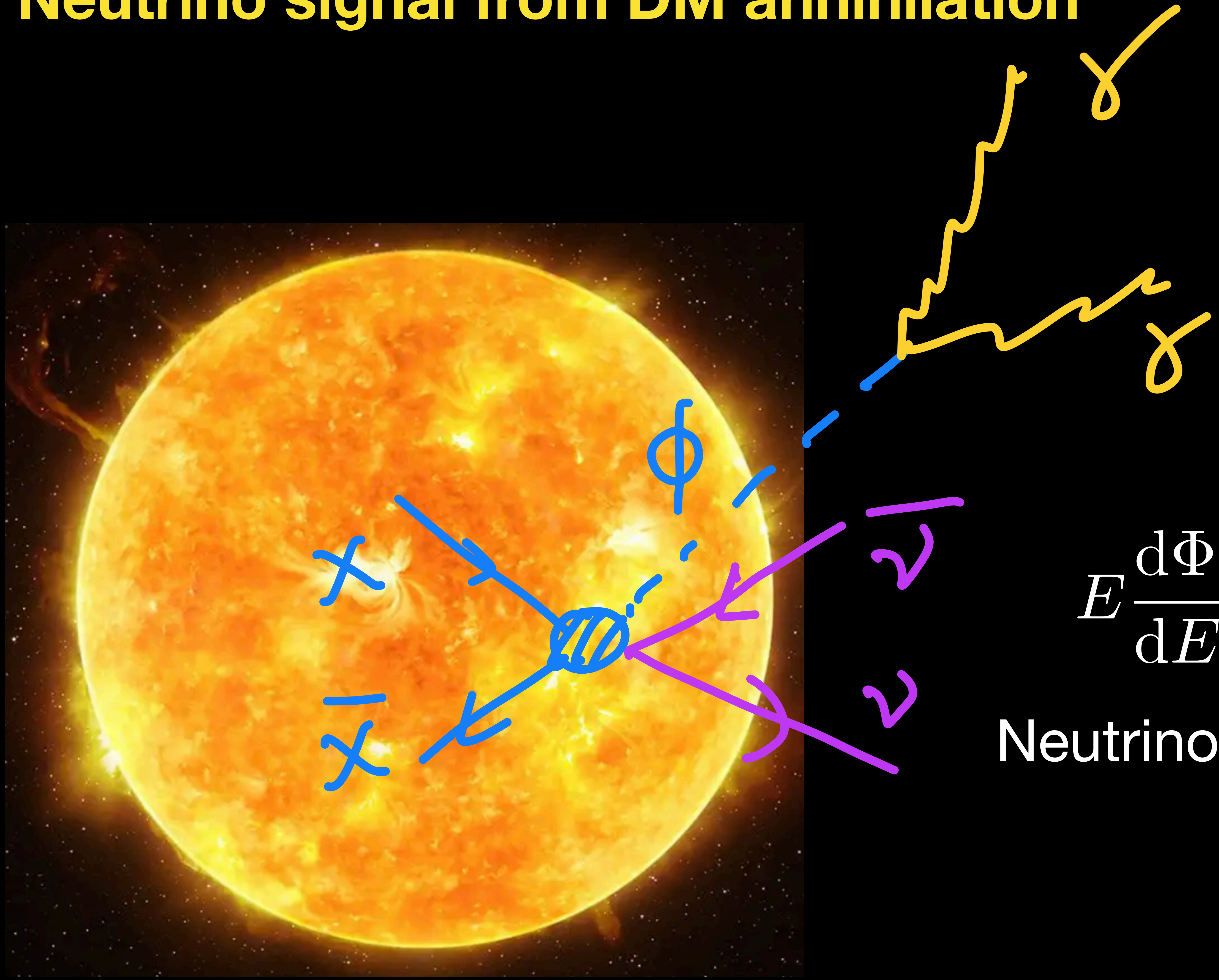

Super-Kamiokande


IceCube

Thong Nguyen, Stockholm University

Dark Matter annihilation in the Sun

Neutrino signal from DM annihilation



Annihilation Rate:

$$\Gamma = \frac{C}{2}$$

$$E\frac{\mathrm{d}\Phi_\nu}{\mathrm{d}E_\nu} = \frac{\Gamma_{\chi\chi\to\nu\bar{\nu}}}{4\pi D^2} \times E_\nu\frac{\mathrm{d}N_\nu}{\mathrm{d}E_\nu} \times P_{\mathrm{surv}}$$

Neutrino Flux

Neutrino Spectrum

Thong Nguyen, Stockholm University

Tools for calculating Neutrino spectra from the Sun

My Biased Selection

χaroν: a tool for neutrino flux generation from WIMPs

Qinrui Liu[a] **Jeffrey Lazar**[a,b] **Carlos A. Argüelles**[b] **Ali Kheirandish**[c,d]

[a]Department of Physics & Wisconsin IceCube Particle Astrophysics Center, University of Wisconsin, Madison, WI 53706, USA
[b]Department of Physics & Laboratory for Particle Physics and Cosmology, Harvard University, Cambridge, MA 02138, USA
[c]Department of Physics, The Pennsylvania State University, University Park, PA 16802, USA
[d]Center for Multimessenger Astrophysics, Institute for Gravitation & the Cosmos, The Pennsylvania State University, University Park, PA 16802, USA

E-mail: qliu246@wisc.edu, jeffrey.lazar@icecube.wisc.edu, carguelles@fas.harvard.edu, kheirandish@psu.edu

PPPC 4 DMν: A Poor Particle Physicist Cookbook for Neutrinos from Dark Matter annihilations in the Sun

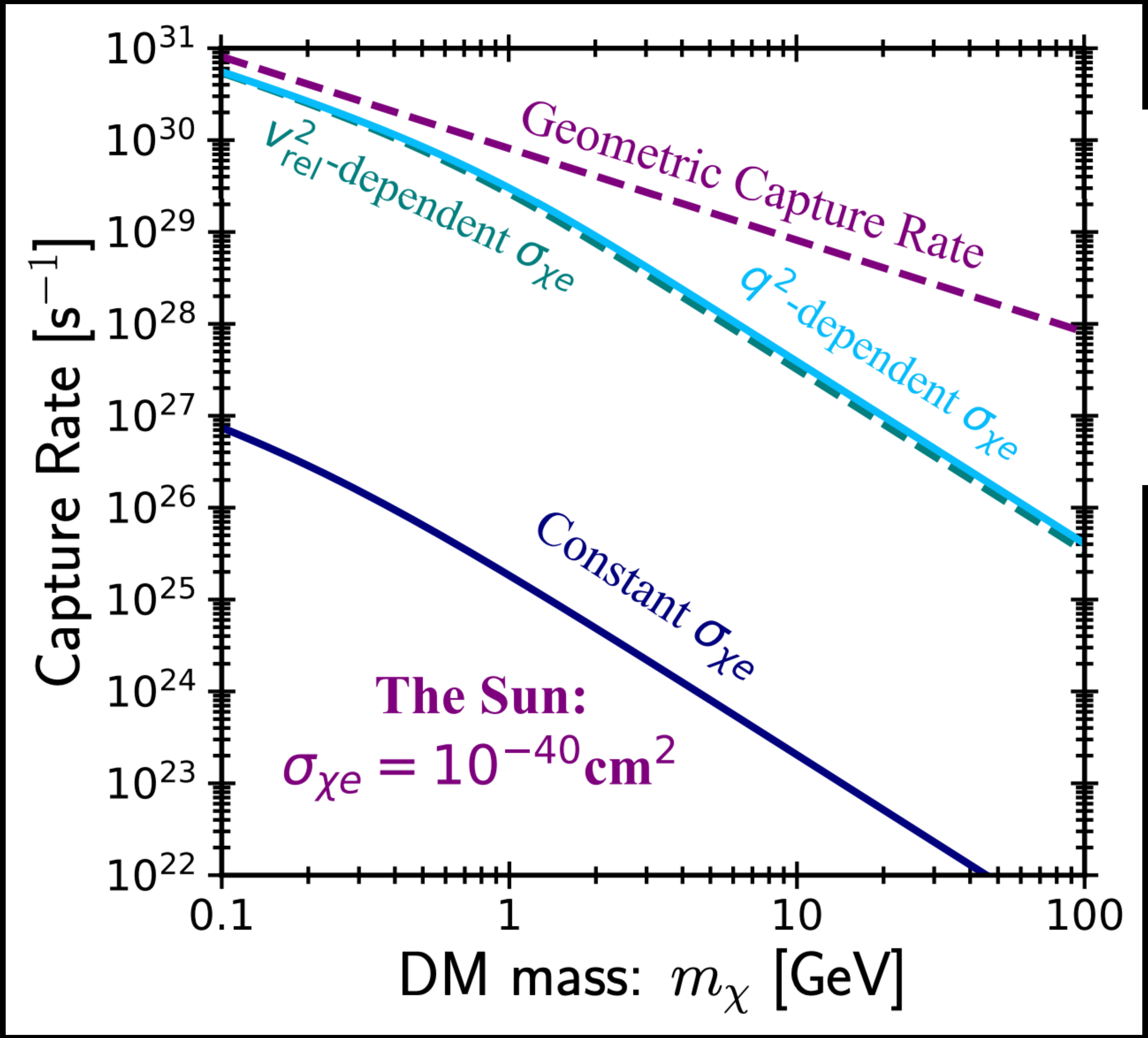
Pietro Baratella[a], **Marco Cirelli**[b], **Andi Hektor**[c,d], **Joosep Pata**[c], **Morten Piibeleht**[c] and **Alessandro Strumia**[c,e]

(a) Scuola Normale Superiore and INFN, Piazza dei Cavalieri 7, 56126 Pisa, Italy
(b) Institut de Physique Théorique, CNRS URA 2306 & CEA-Saclay, 91191 Gif-sur-Yvette, France
(c) National Institute of Chemical Physics and Biophysics, Ravala 10, Tallinn, Estonia
(d) Helsinki Institute of Physics, P.O. Box 64, FI-00014, Helsinki, Finland
(e) Dipartimento di Fisica dell'Università di Pisa and INFN, Italy

1. Leptophilic Dark Matter

Leptophilic dark matter capture in the Sun

For constant, velocity, and momentum-dependent DM-electron cross sections



Super-Kamiokande Strongly Constrains Leptophilic Dark Matter Capture in the Sun

Thong T.Q. Nguyen,[1,*] Tim Linden,[1,†] Pierluca Carenza,[1,‡] and Axel Widmark[1,2,§]

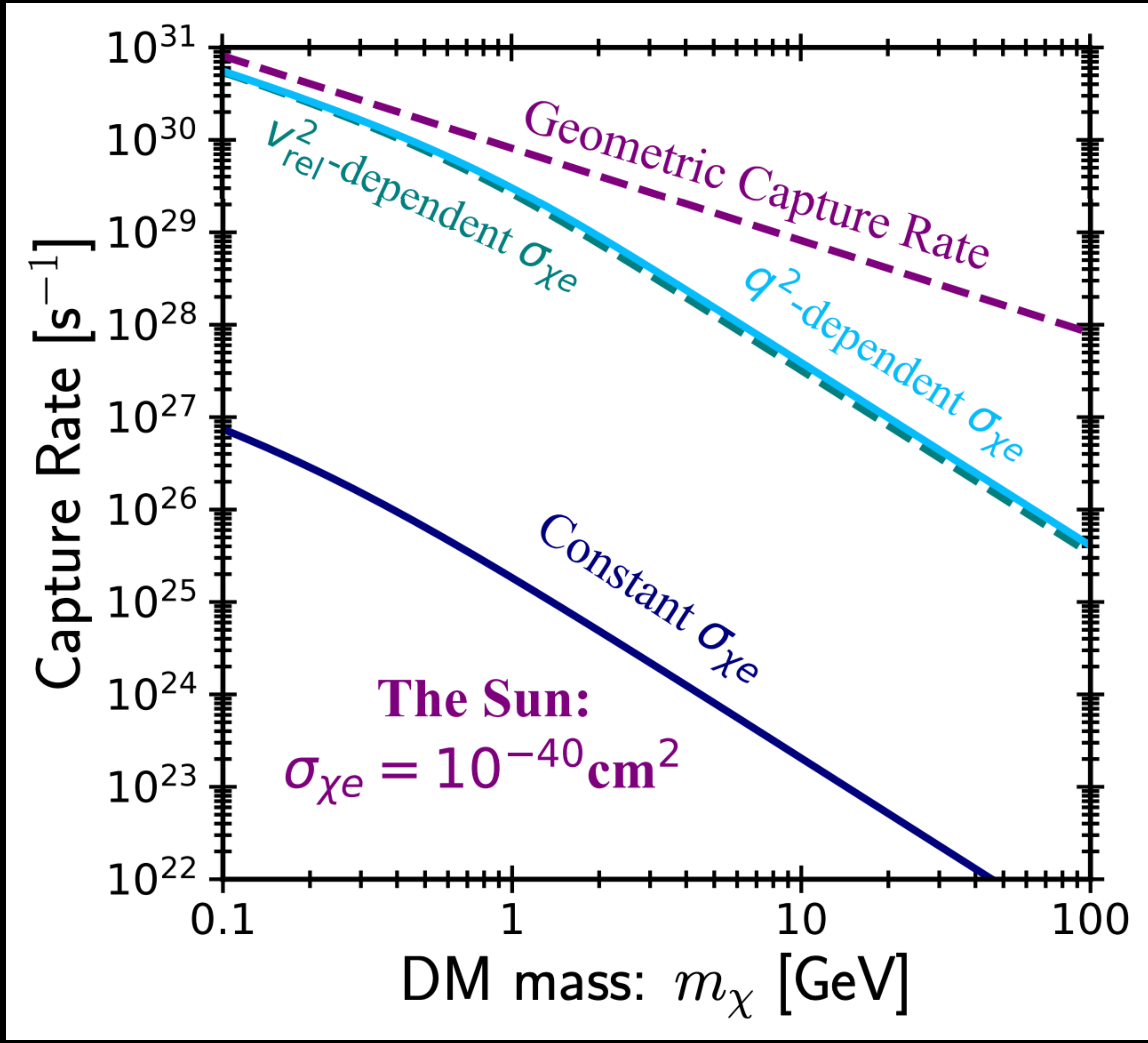
[1] *Stockholm University and The Oskar Klein Centre for Cosmoparticle Physics, Alba Nova, 10691 Stockholm, Sweden*
[2] *Columbia University, 116th and Broadway, New York, NY 10027 USA*

The Sun can efficiently capture leptophilic dark matter that scatters with free electrons. If this dark matter subsequently annihilates into leptonic states, it can produce a detectable neutrino flux. Using 10 years of Super-Kamiokande observations, we set constraints on the dark-matter/electron scattering cross-section that exceed terrestrial direct detection searches by more than an order of magnitude for dark matter masses below 100 GeV, and reach cross-sections as low as $\sim 4 \times 10^{-41}$ cm^{-2}.

We calculate the Capture Rate of DM-electron scattering: The number of DM being accumulated per second in the Sun

Leptophilic dark matter capture in the Sun

For constant, velocity, and momentum-dependent DM-electron cross sections



Super-Kamiokande Strongly Constrains Leptophilic Dark Matter Capture in the Sun

Thong T.Q. Nguyen,[1,*] Tim Linden,[1,†] Pierluca Carenza,[1,‡] and Axel Widmark[1,2,§]
[1] *Stockholm University and The Oskar Klein Centre for Cosmoparticle Physics, Alba Nova, 10691 Stockholm, Sweden*
[2] *Columbia University, 116th and Broadway, New York, NY 10027 USA*

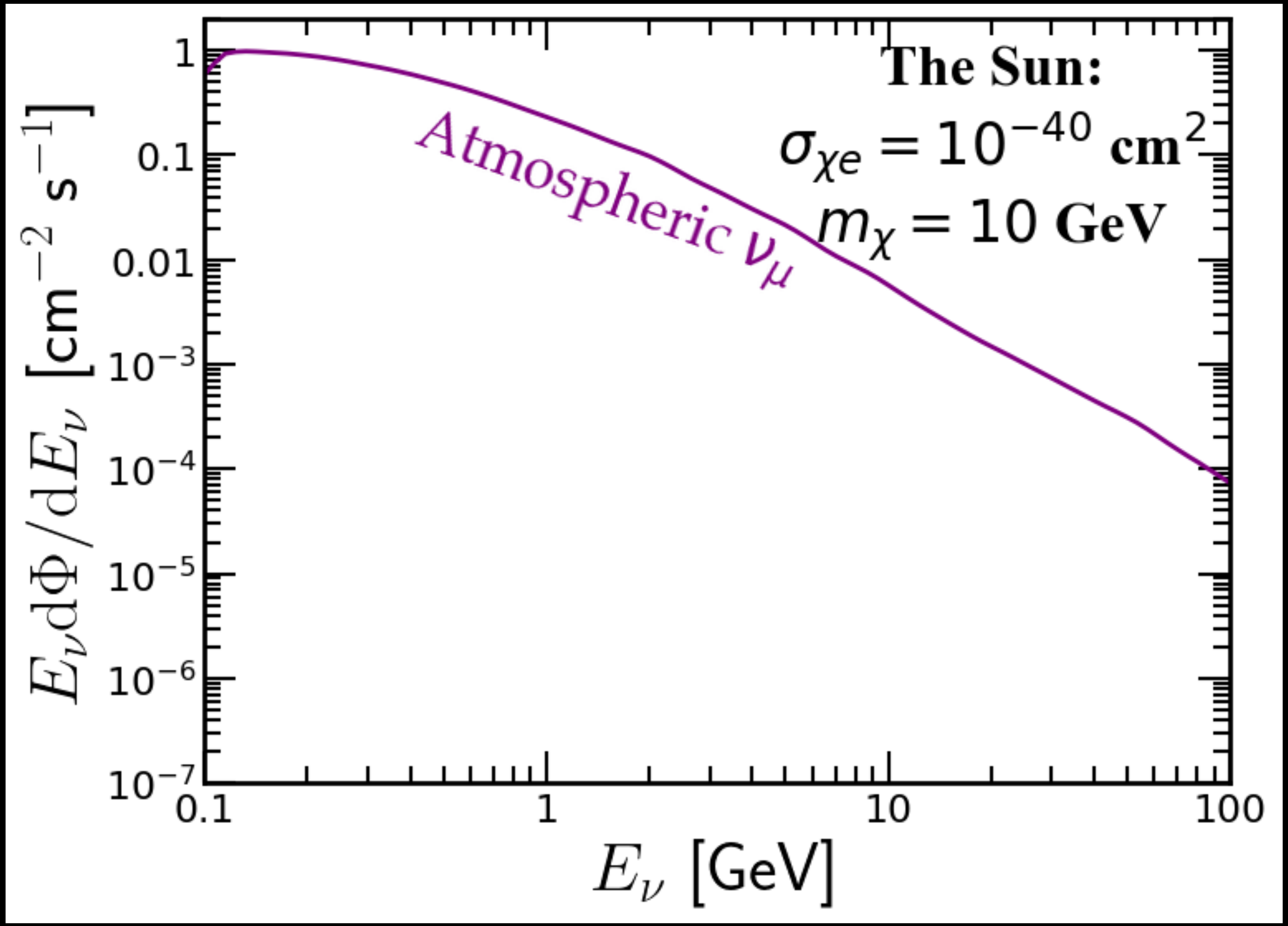
The Sun can efficiently capture leptophilic dark matter that scatters with free electrons. If this dark matter subsequently annihilates into leptonic states, it can produce a detectable neutrino flux. Using 10 years of Super-Kamiokande observations, we set constraints on the dark-matter/electron scattering cross-section that exceed terrestrial direct detection searches by more than an order of magnitude for dark matter masses below 100 GeV, and reach cross-sections as low as ~ 4 $\times 10^{-41}$ cm^{-2}.

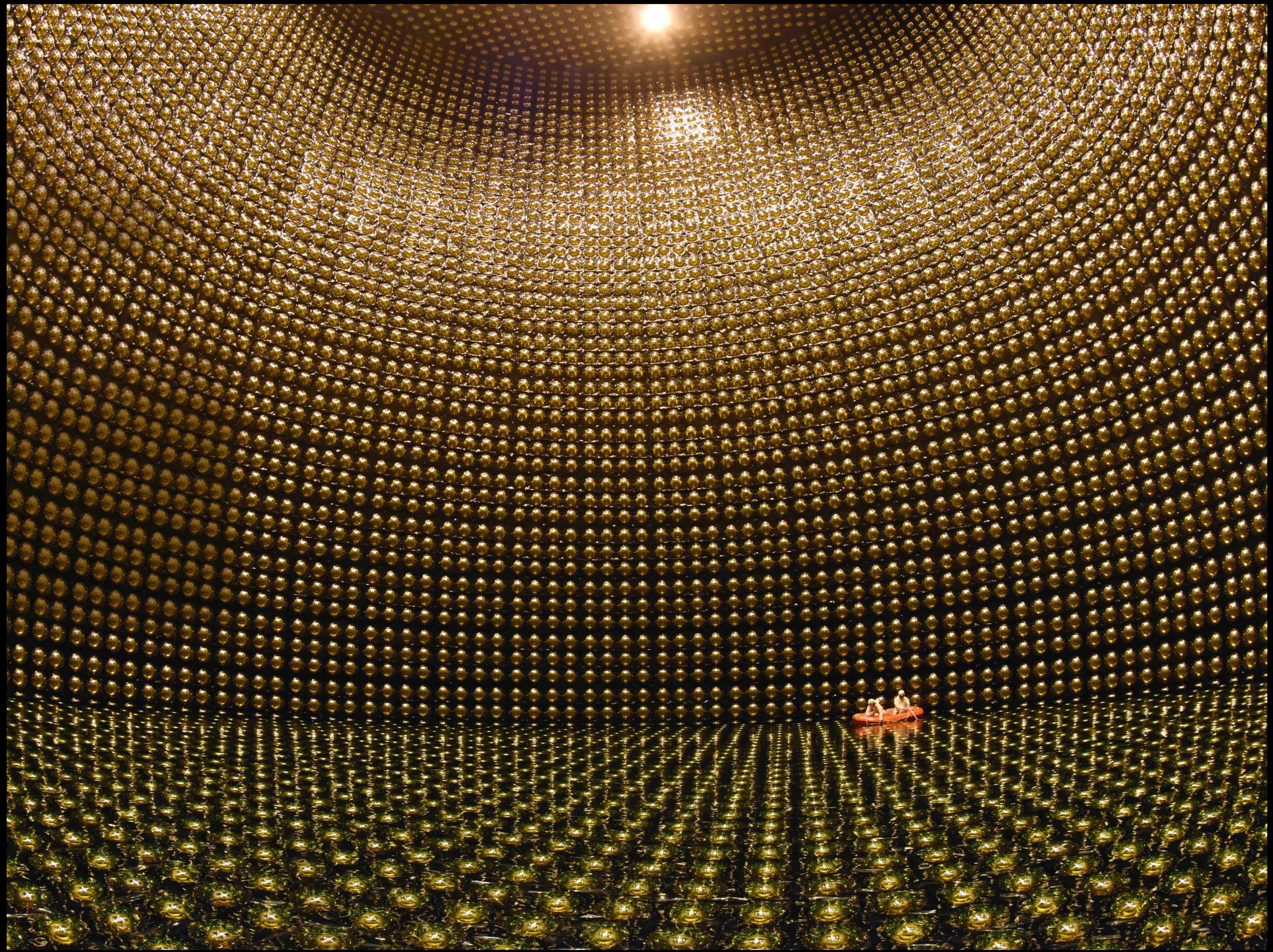
We calculate the Capture Rate of DM-electron scattering: The number of DM being accumulated per second in the Sun

We fixed a long-standing 17-year problem for DM-electron capture in the Sun

Super-Kamiokande observation

Using Super-K atmospheric neutrino background





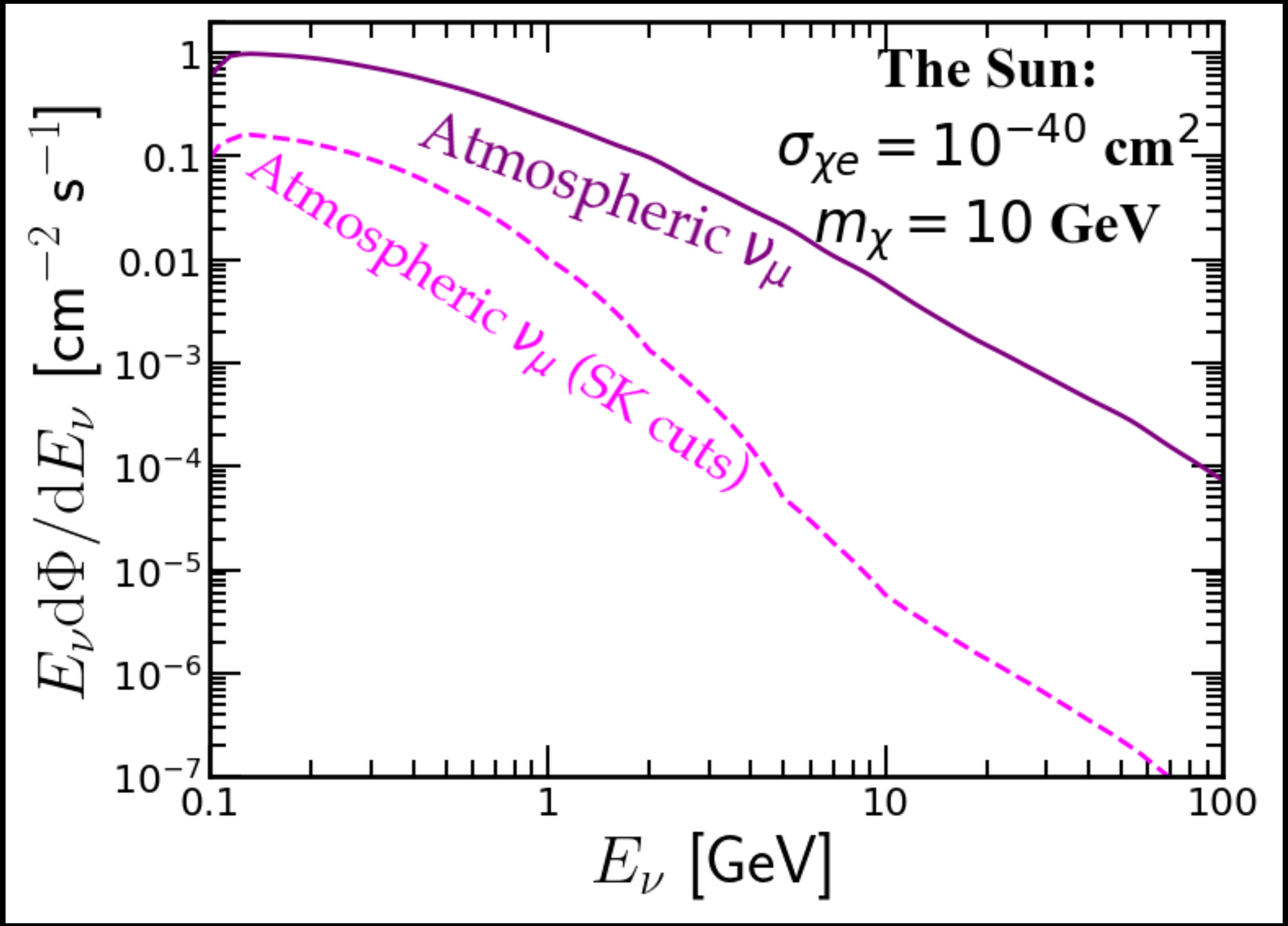
Super-K Water Cherenkov

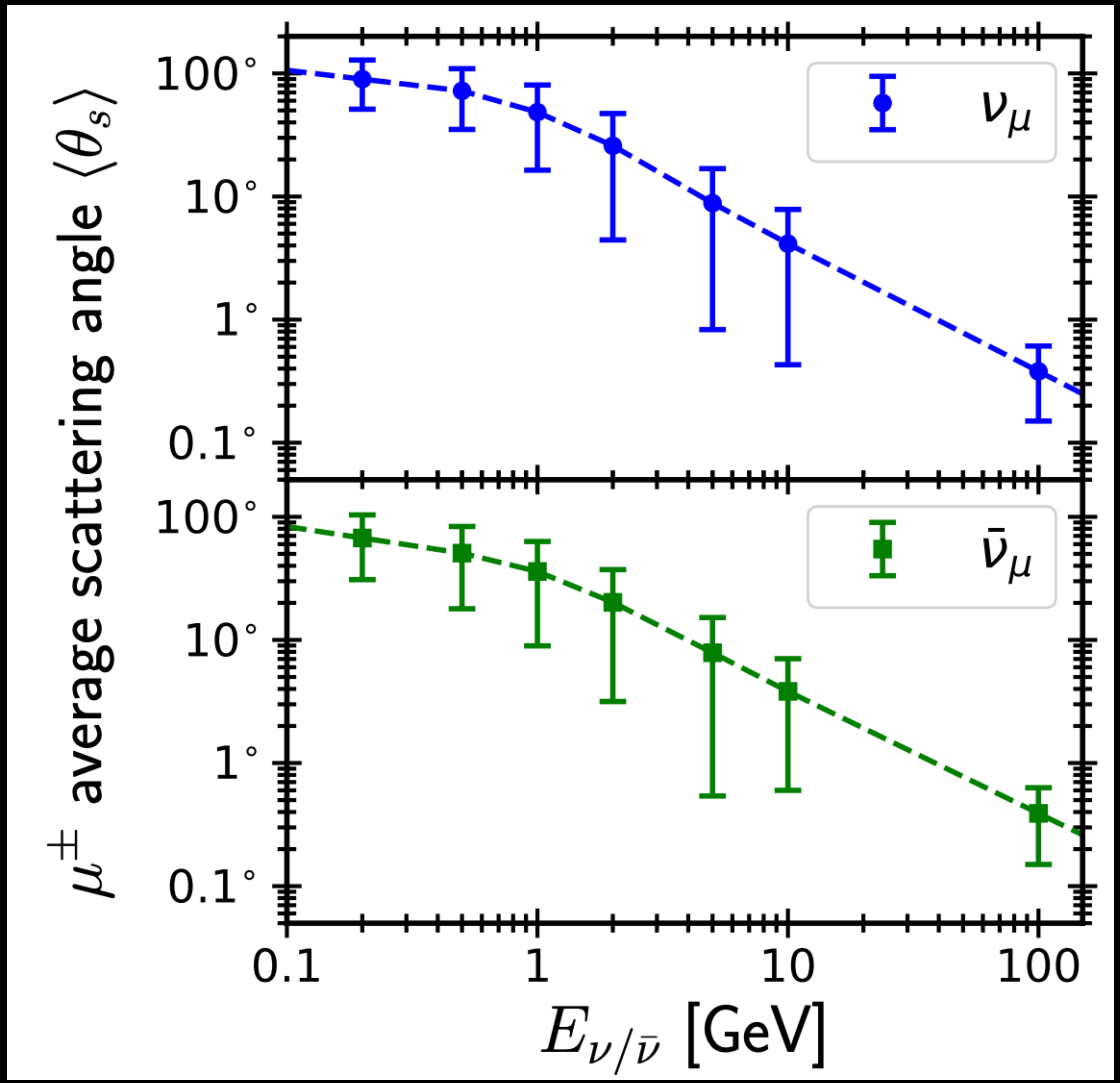
Neutrino detector, Japan

Thong Nguyen, Stockholm University

Super-Kamiokande observation

Using Super-K angular resolution to reduce background

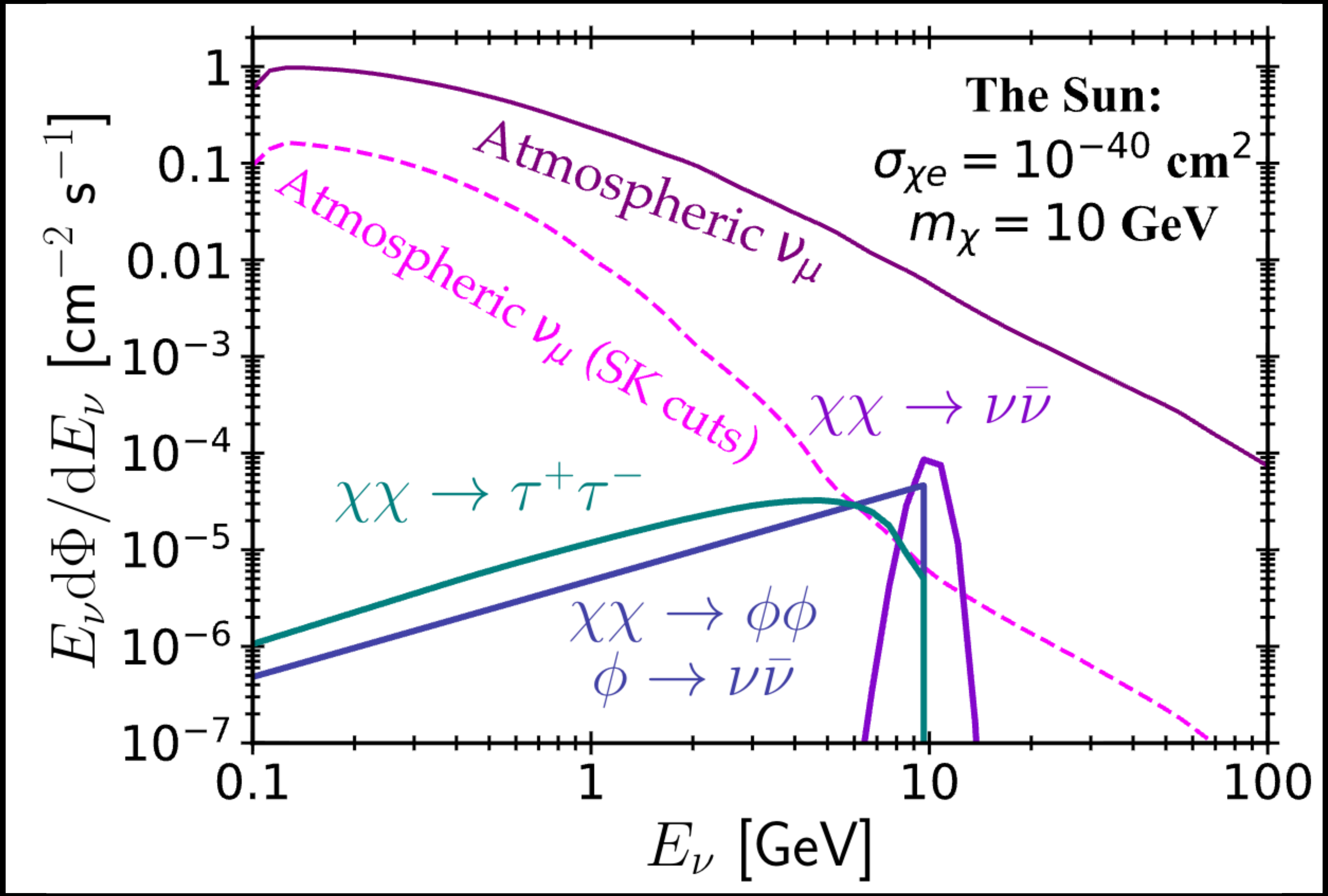




Thong Nguyen, Stockholm University

Neutrinos from leptophilic DM annihilation inside the Sun

Consider leptophilic annihilation channels

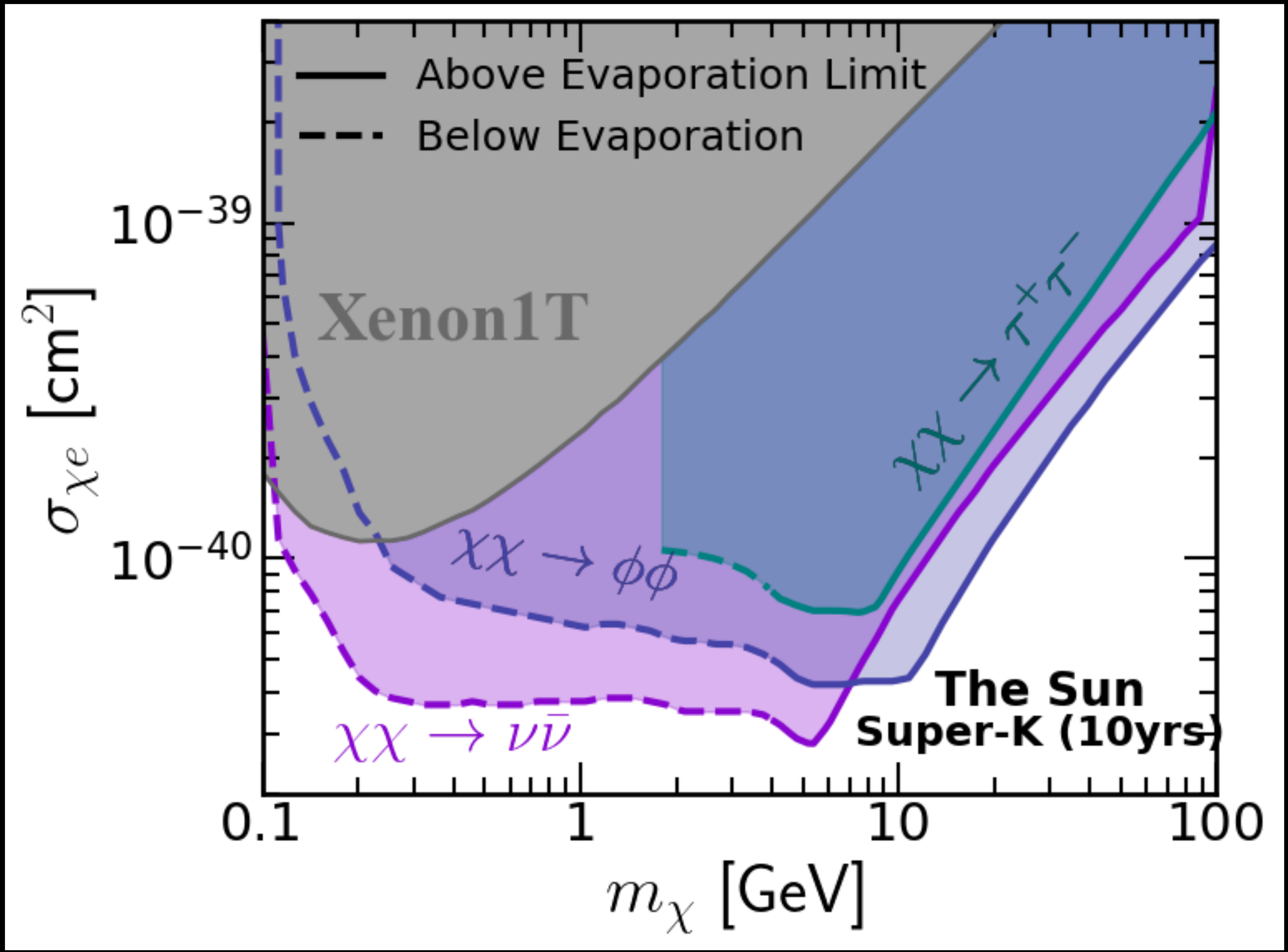


We calculate the fluxes and numbers of neutrino events from DM annihilation inside the Sun, and from Atmospheric Background.

Thong Nguyen, Stockholm University

Constraints on Leptophilic Dark Matter

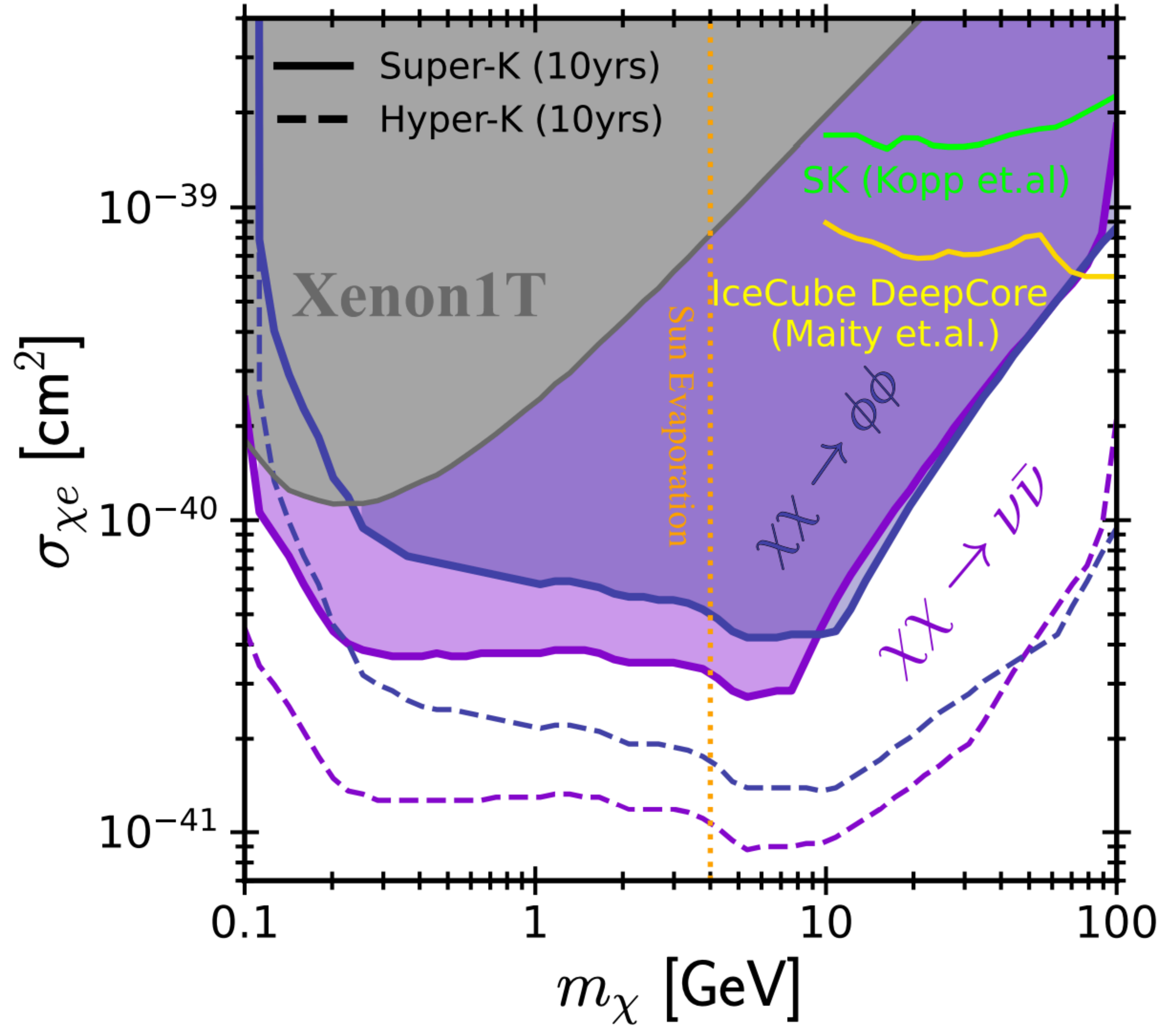
Using 10-year Super-K observation on atmospheric muon neutrino

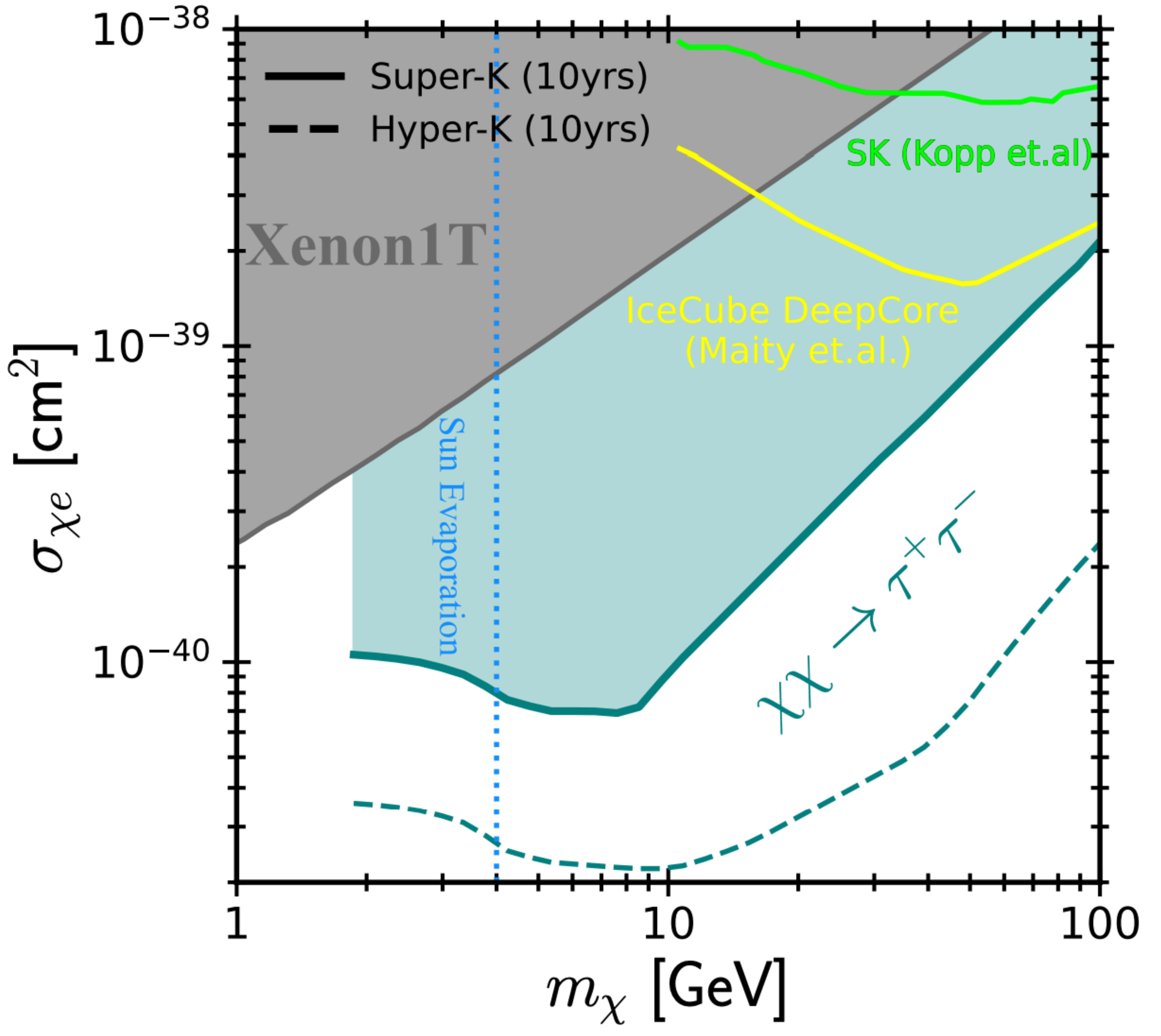


TTQN, Tim Linden, Pierluca Carenza, Axel Widmark (arXiv:2501.14864)

Constraints on Leptophilic Dark Matter

Projections for Hyper-K (10 years)

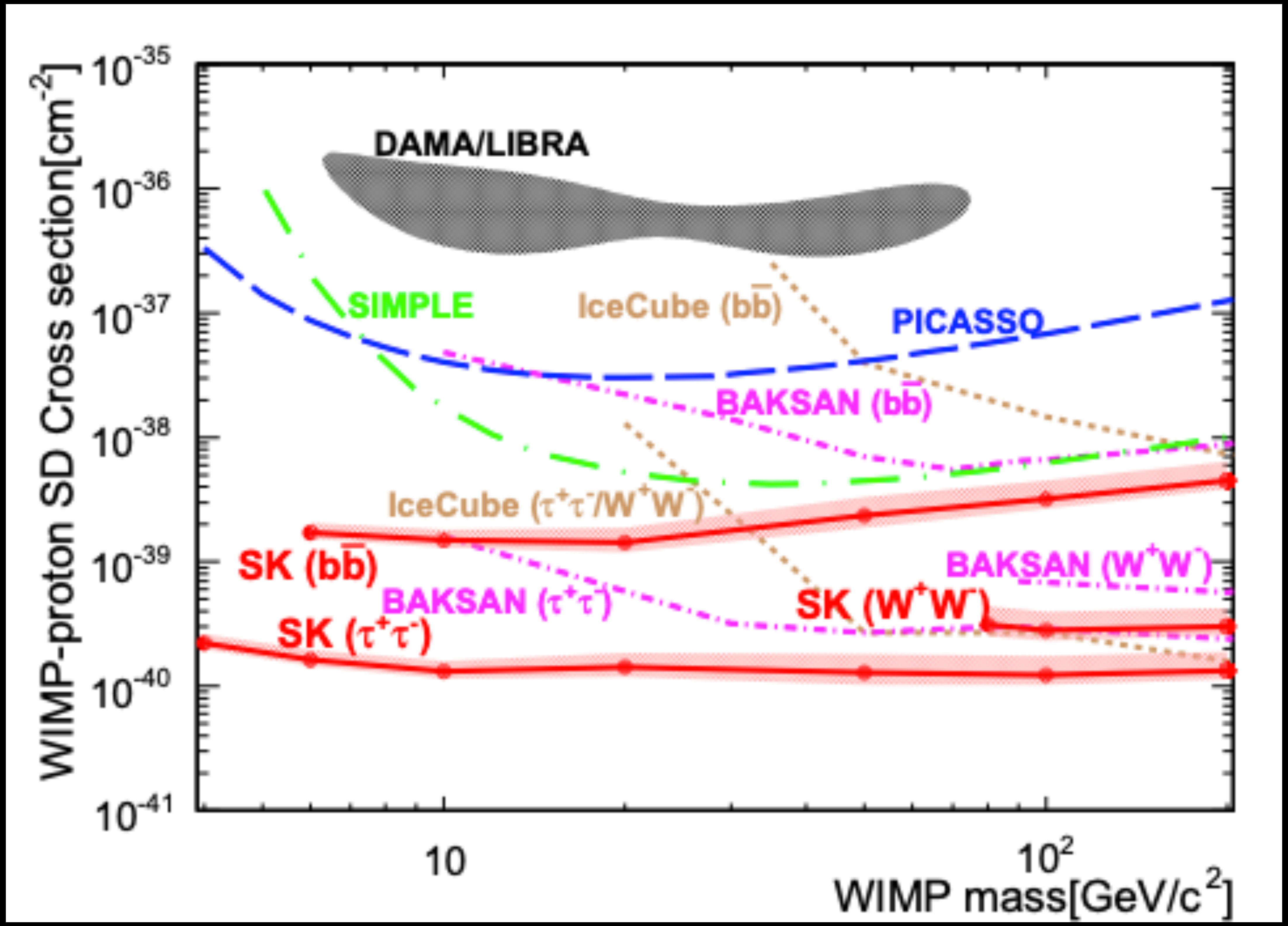




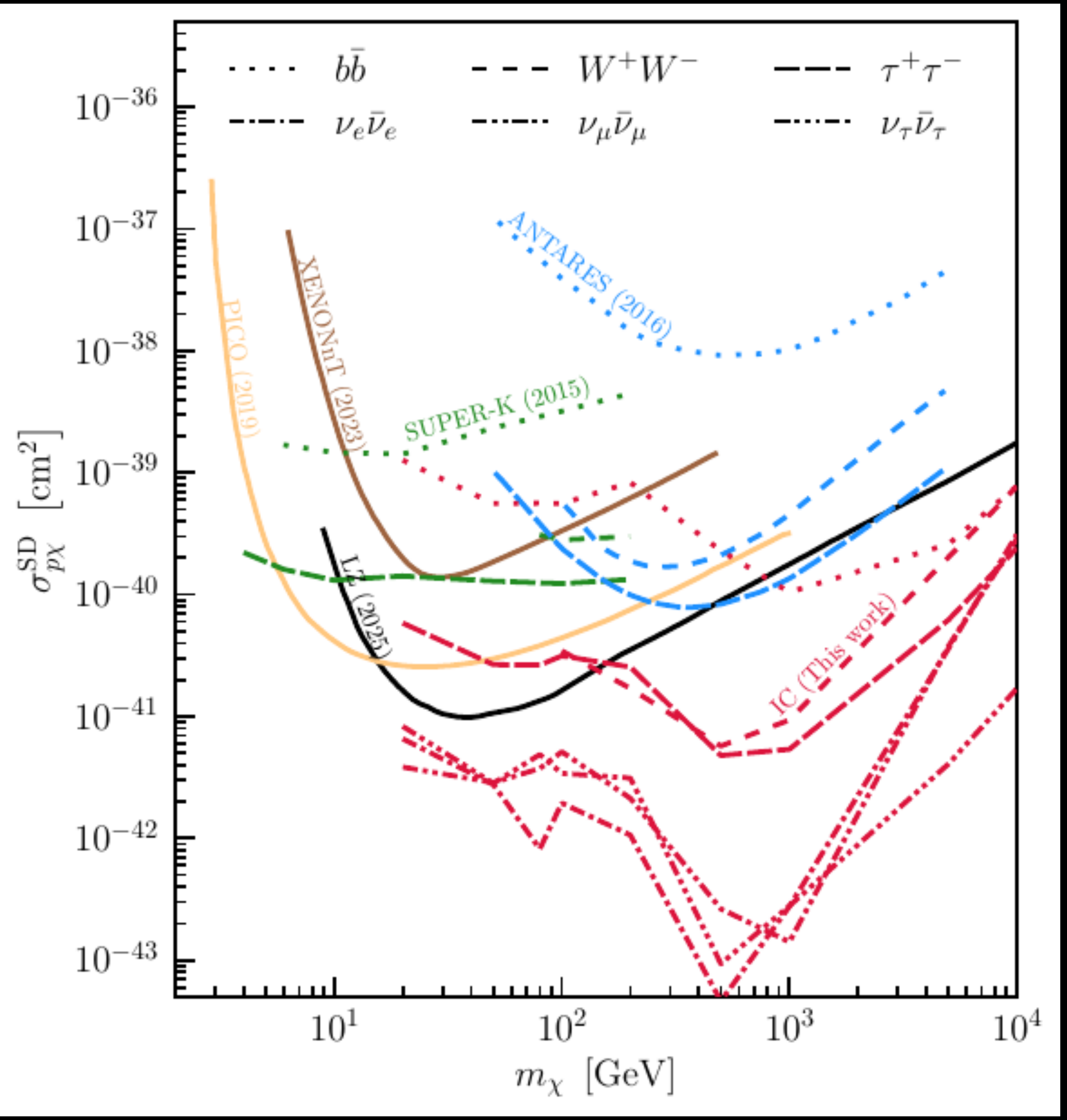
TTQN, Tim Linden, Pierluca Carenza, Axel Widmark (arXiv:2501.14864)

An Active Research Direction

Analysis results from Experimental Collaborations



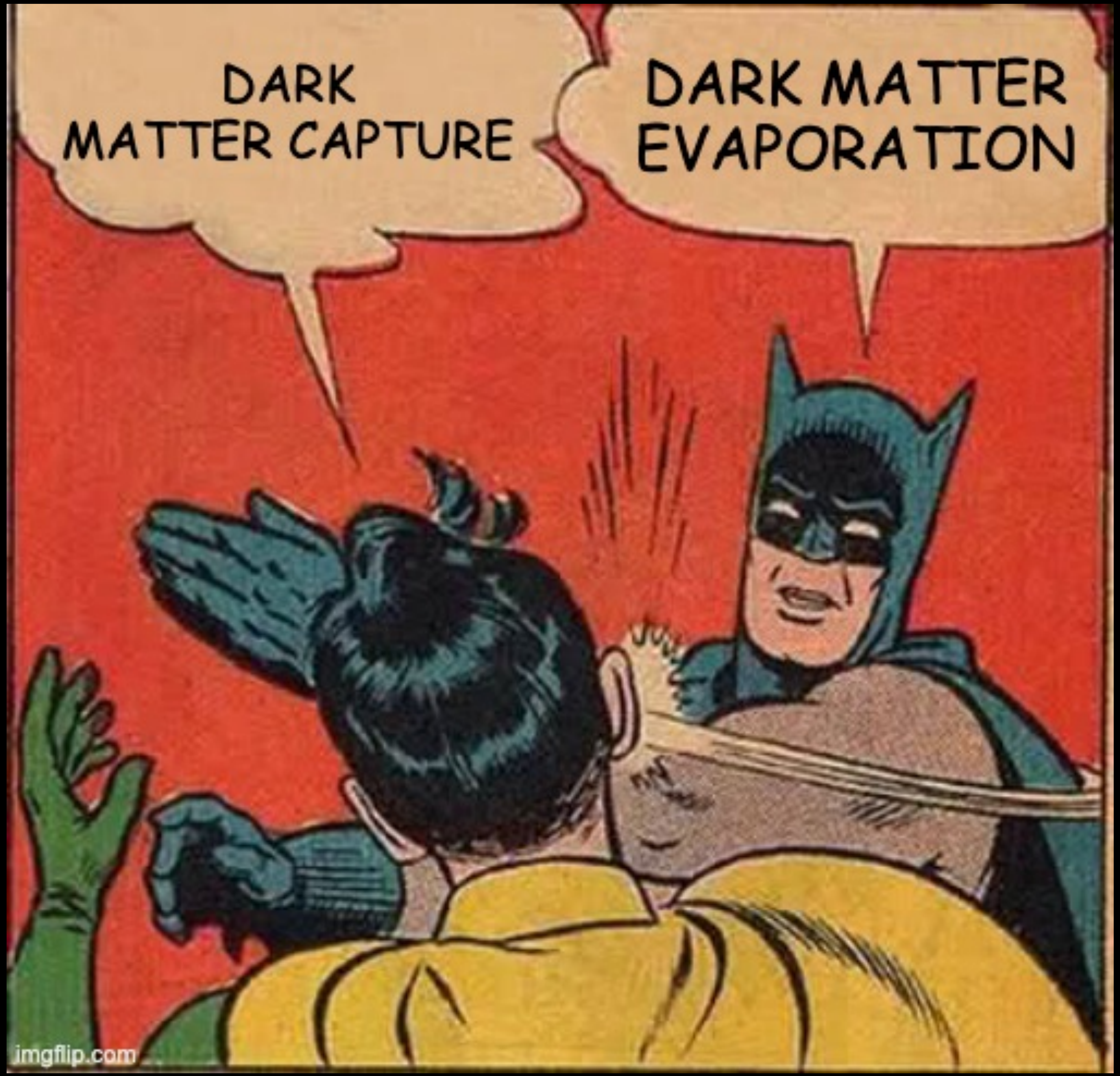
Super-K Collaboration, PRL 2015



IceCube, 2025

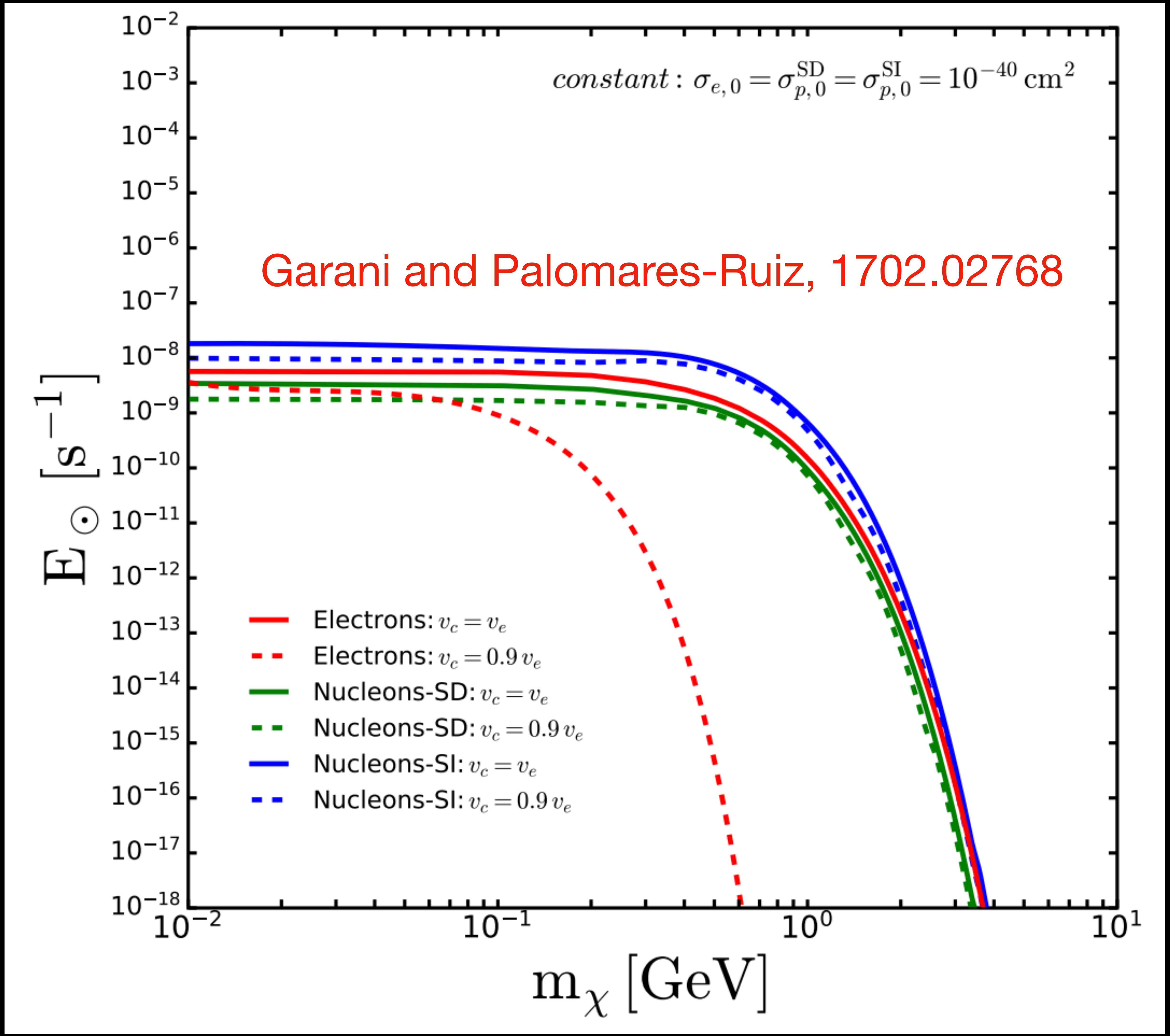
Thong Nguyen, Stockholm University

Dark Matter Evaporation



Dark Matter evaporation in the Sun

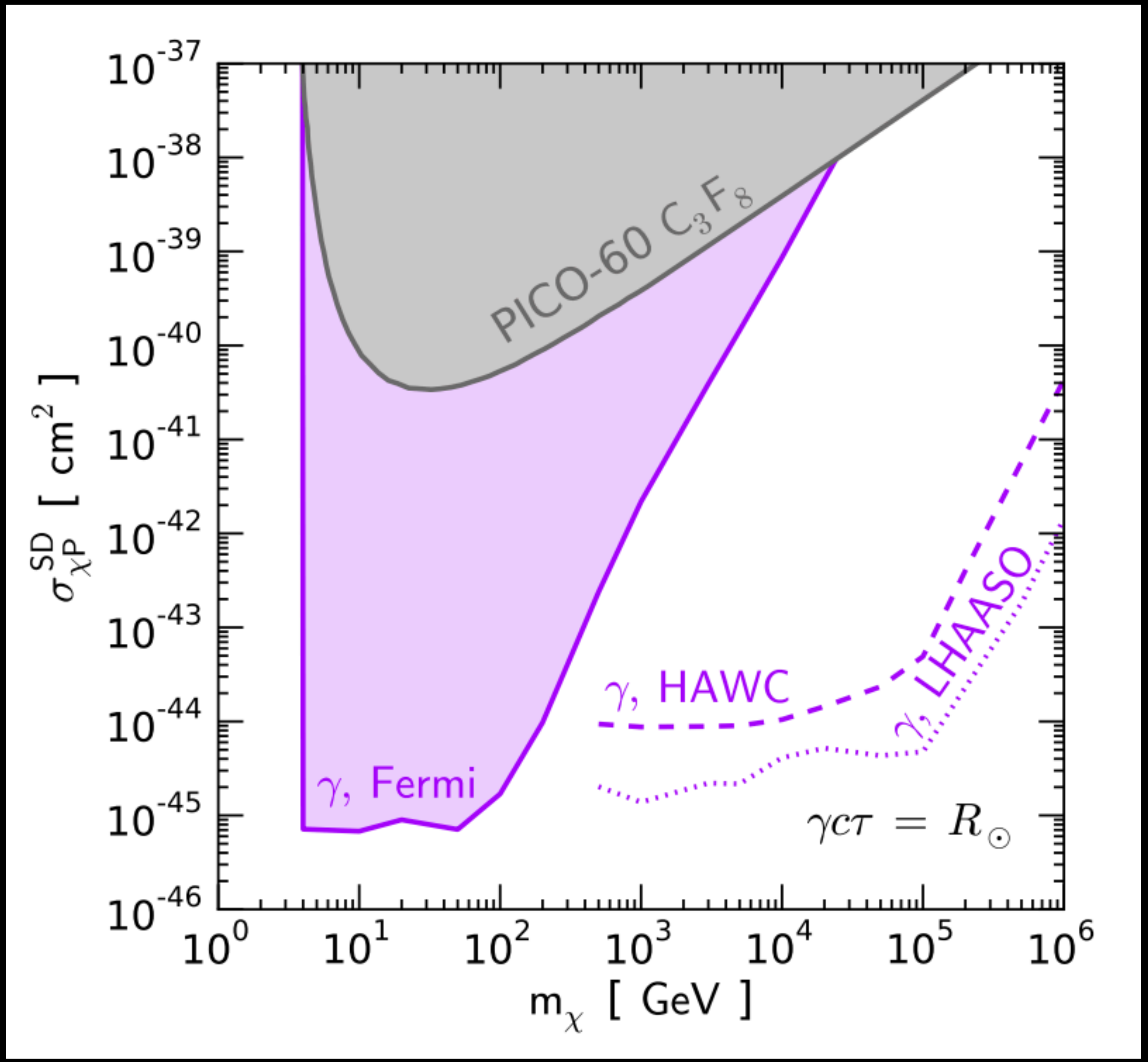
- Fast electrons/nucleons in the Sun can up-scatter captured DM.
- The up-scattered DM can exceed the Sun's escape velocity.
- Light DM can "evaporate" from the Sun.
- Previous results: DM below 4 GeV is fully evaporated.



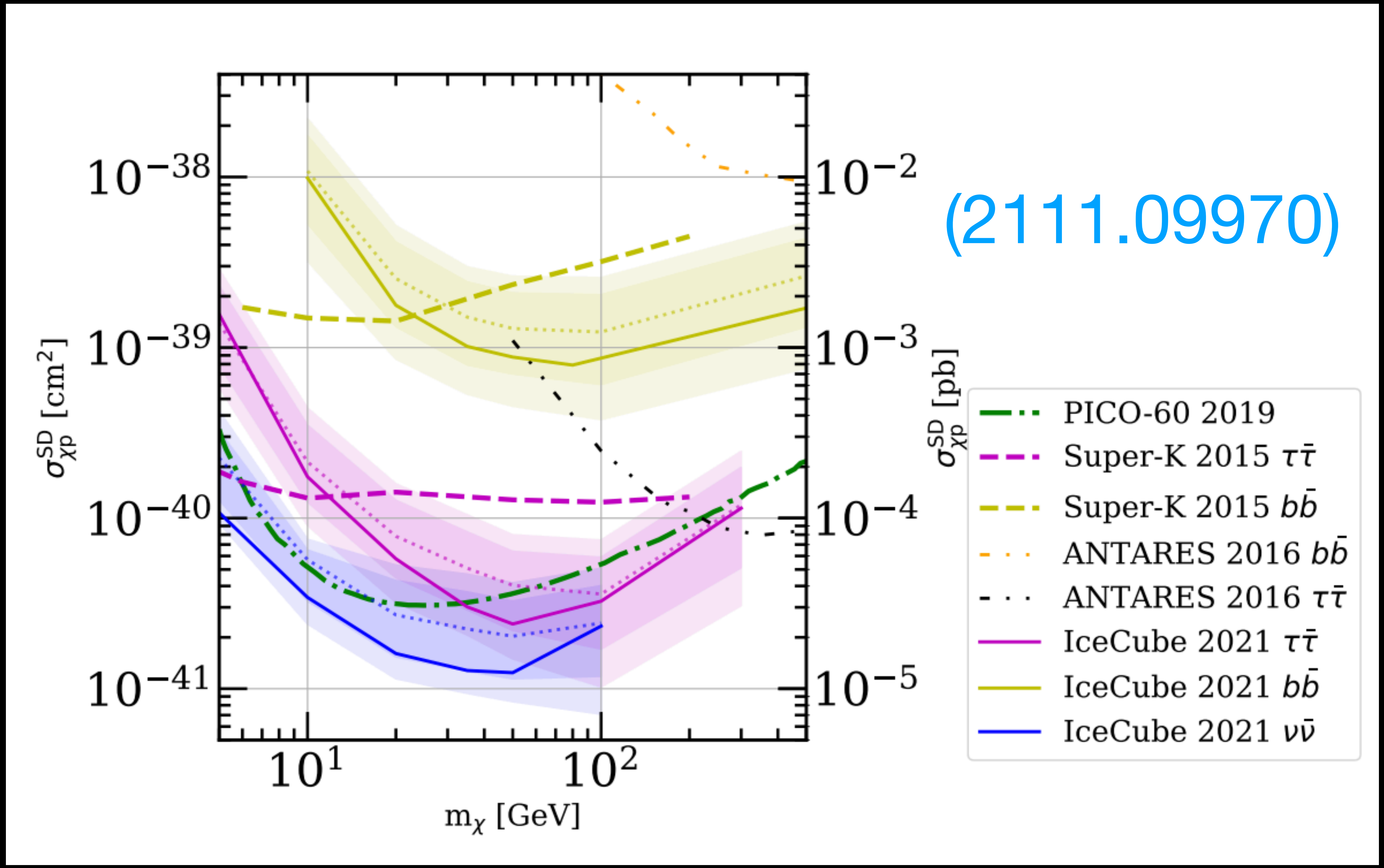
Thong Nguyen, Stockholm University

Previous results with the Evaporation Cutoff

Both gamma-ray and neutrino observations

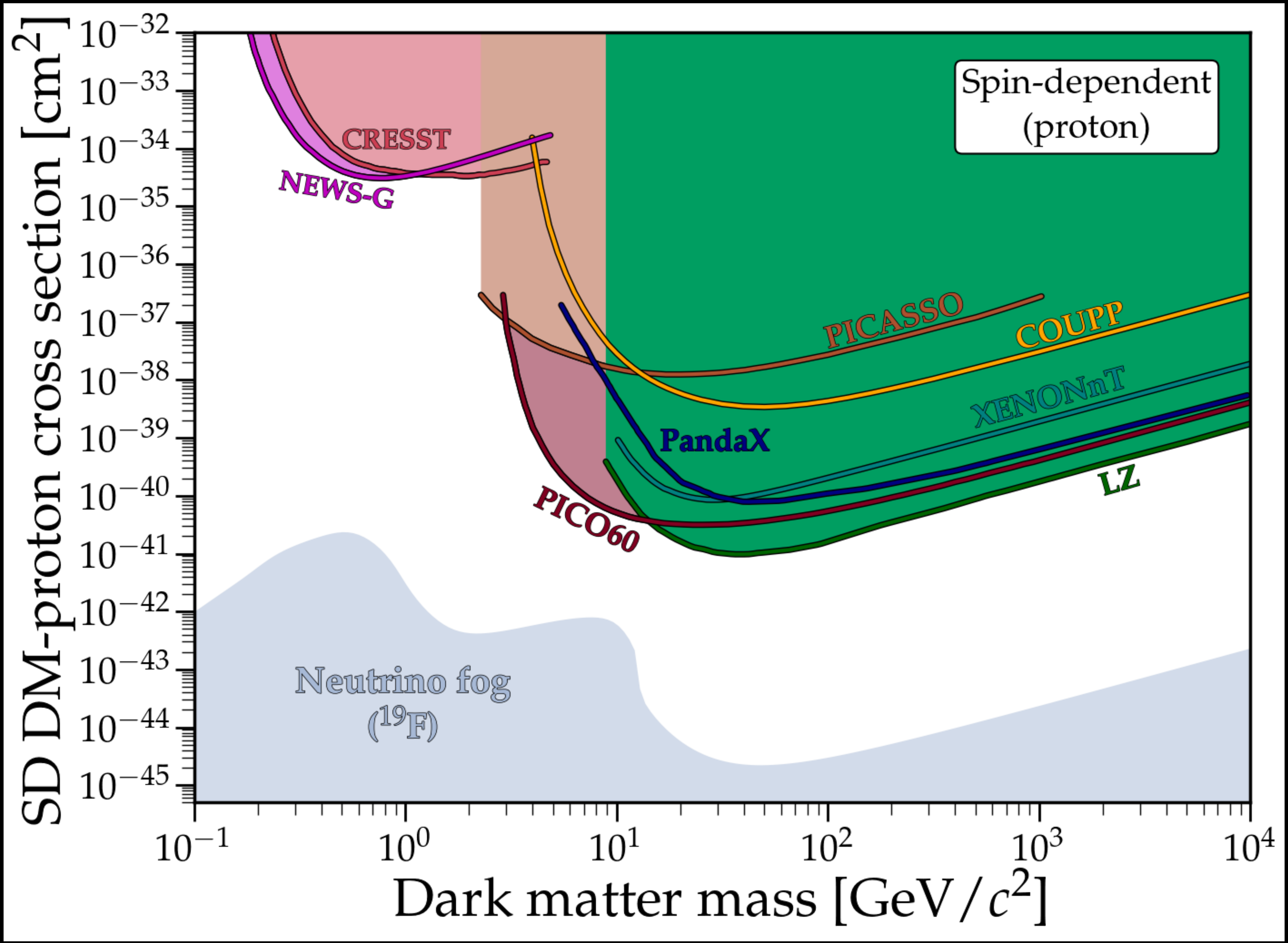


(1703.04629)



(2111.09970)

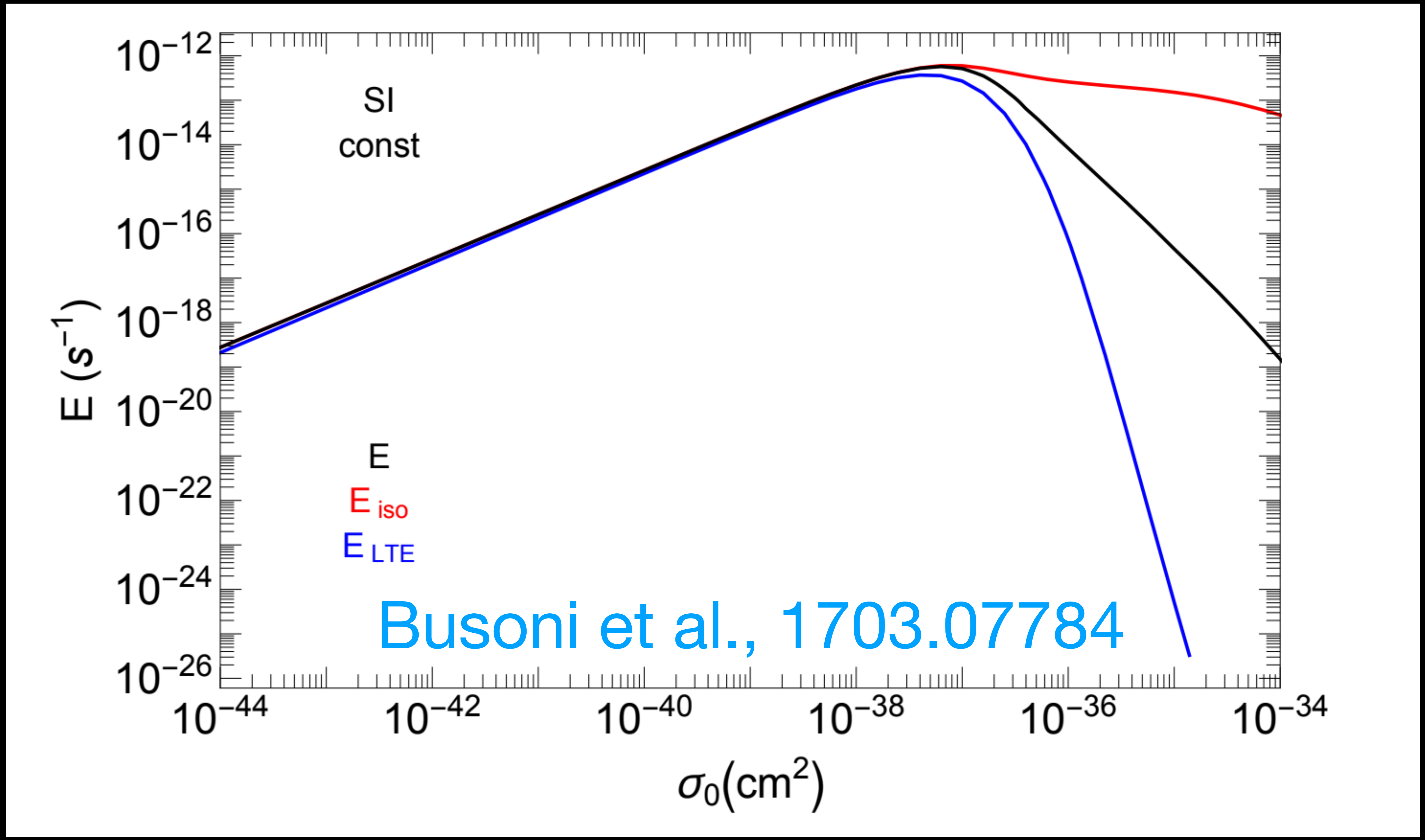
2. Spin-dependent DM-proton cross section below Evaporation Limit

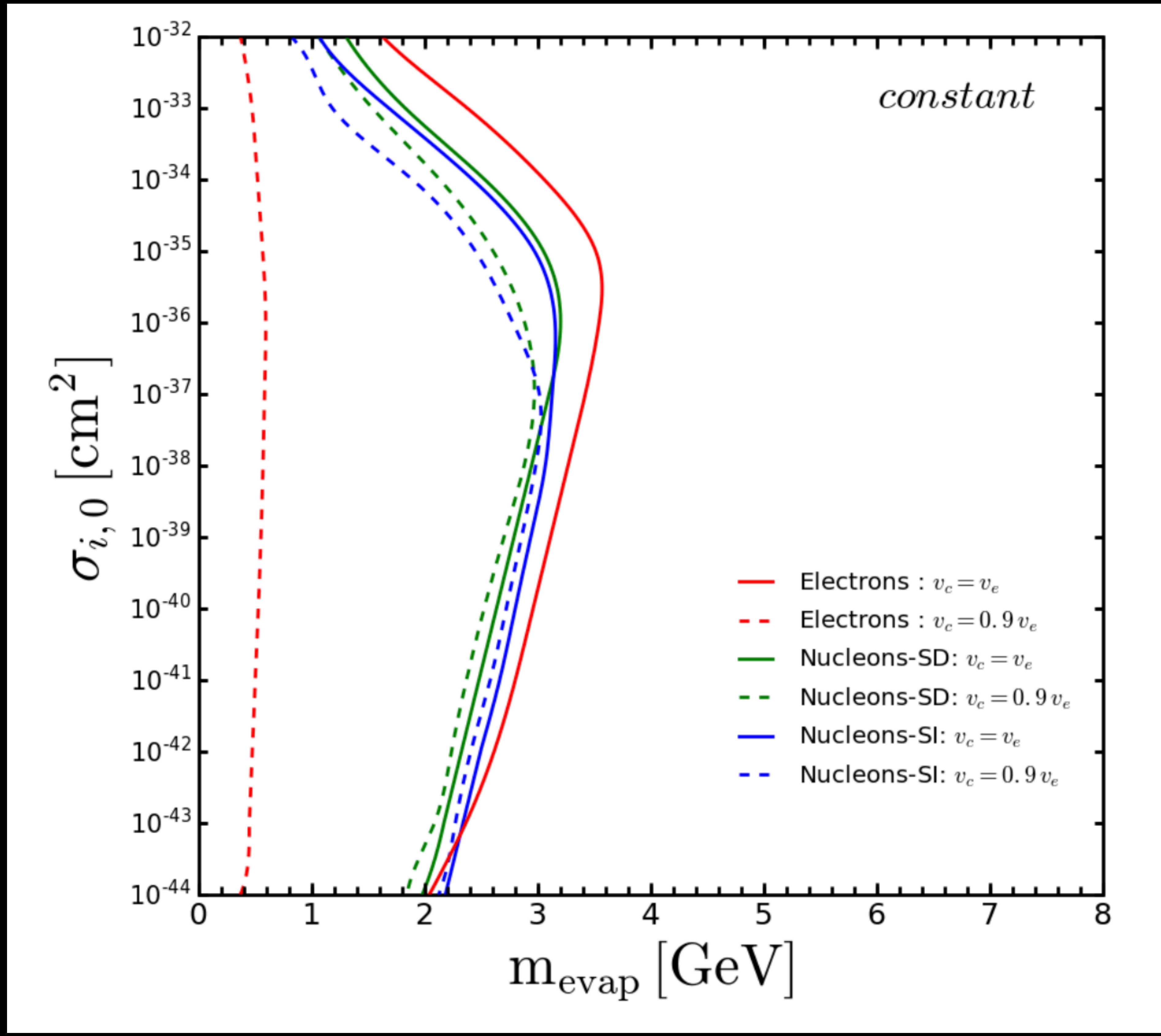


Spin-dependent (proton)
CRESST
NEWS-G
PICASSO
COUPP
XENONnT
PandaX
PICO60
LZ
Neutrino fog (^{19}F)
SD DM-proton cross section [cm^2]
Dark matter mass [GeV/c^2]
10^{-32}
10^{-33}
10^{-34}
10^{-35}
10^{-36}
10^{-37}
10^{-38}
10^{-39}
10^{-40}
10^{-41}
10^{-42}
10^{-43}
10^{-44}
10^{-45}
10^{-1}
10^{0}
10^{1}
10^{2}
10^{3}
10^{4}

Evaporation is suppressed at high cross section

Dark Matter in the Local Thermal Equilibrium (LTE)





Garani and Palomares-Ruiz, 1702.02768

Thong Nguyen, Stockholm University

Below the Evaporation Limit

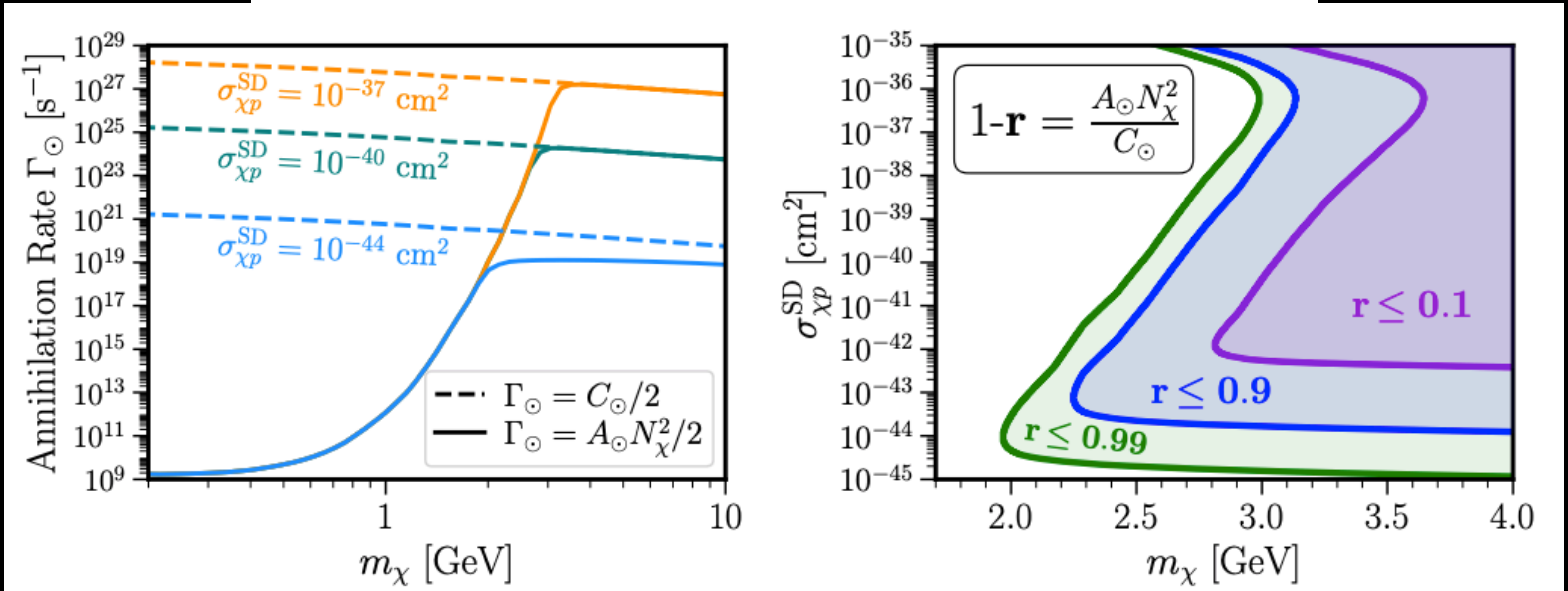
The competition between Evaporation and Annihilation

The Sun Can Strongly Constrain Spin-Dependent Dark Matter Nucleon Scattering Below the Evaporation Limit

Thong T.Q. Nguyen[1,*] and Tim Linden[1,2,†]

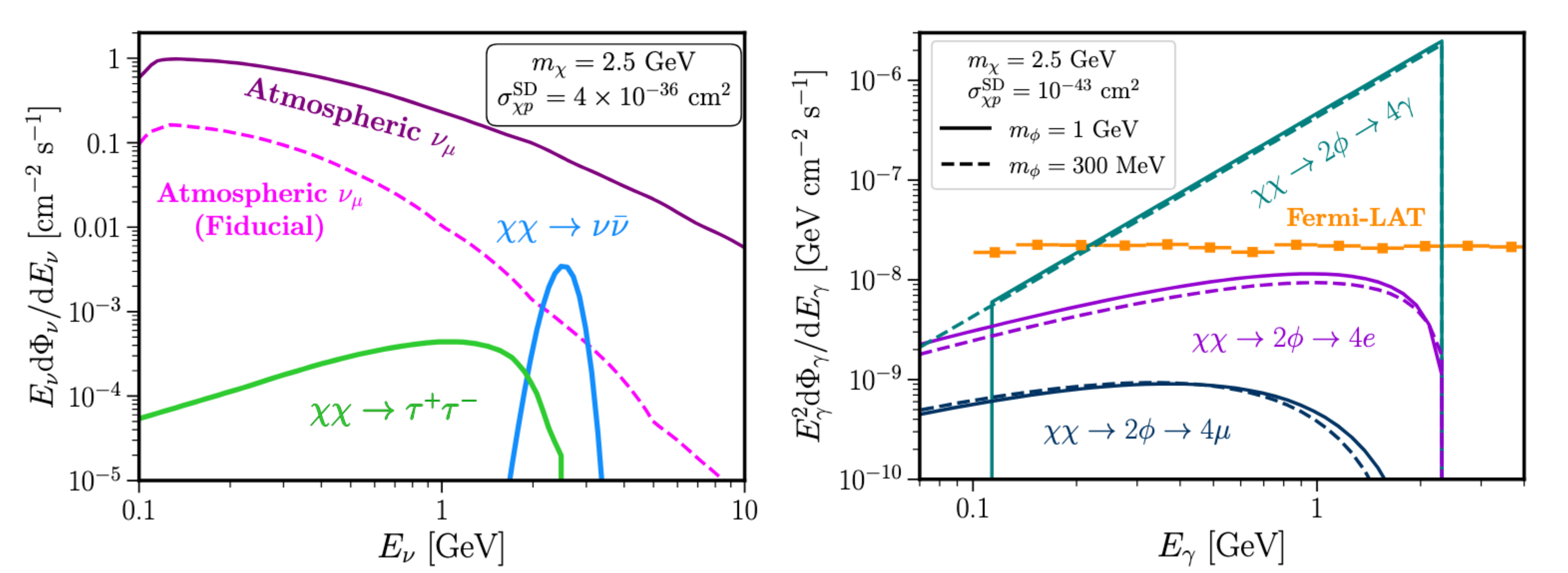
[1] *Stockholm University and The Oskar Klein Centre for Cosmoparticle Physics, Alba Nova, 10691 Stockholm, Sweden*

[2] *Erlangen Centre for Astroparticle Physics (ECAP), Friedrich-Alexander-Universität Erlangen-Nürnberg, Nikolaus-Fiebiger-Str. 2, 91058 Erlangen, Germany*



Can we see anything?

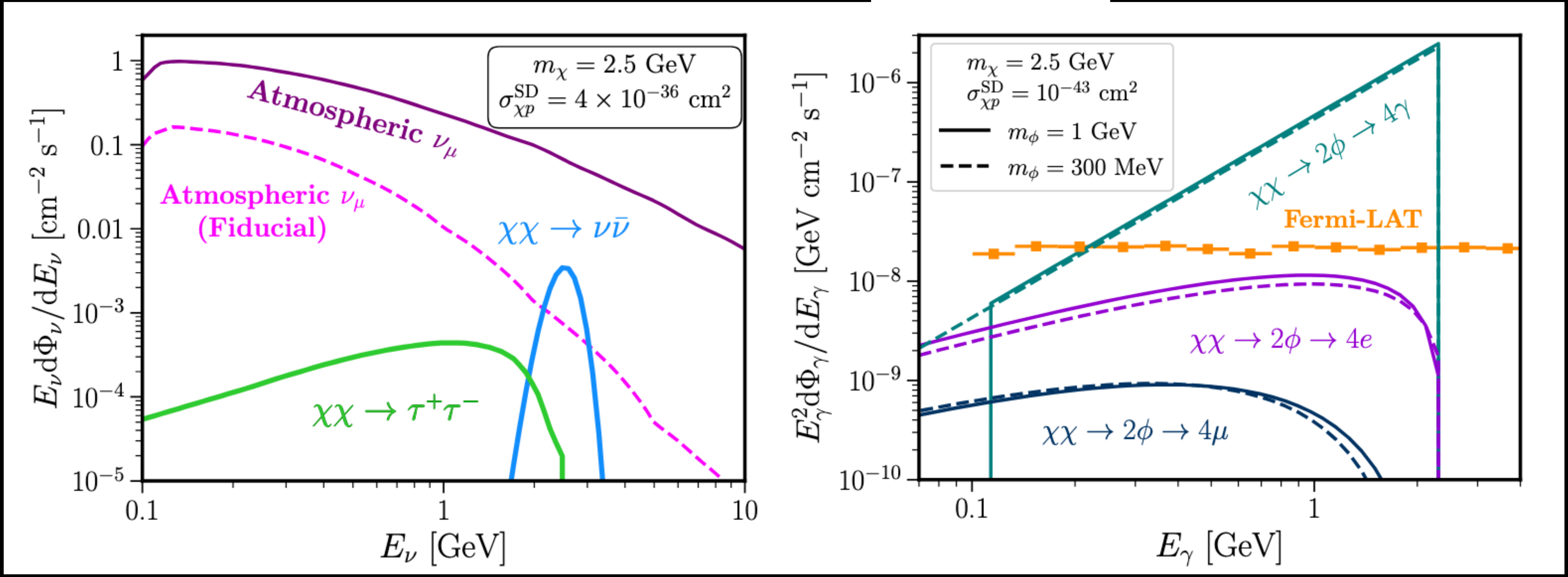
Neutrino and Gamma-Ray signals



Thong Nguyen, Stockholm University

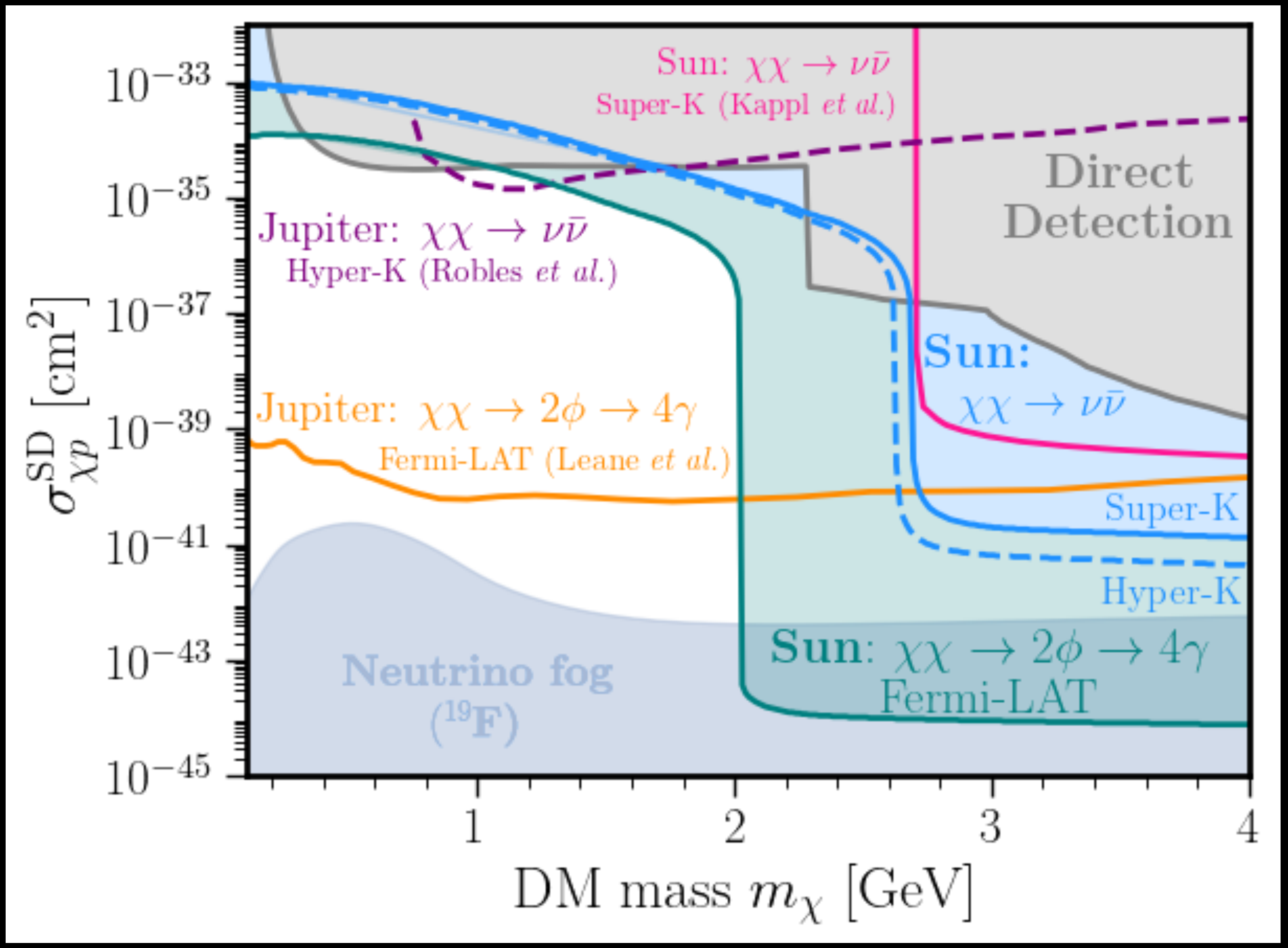
Can we see anything?

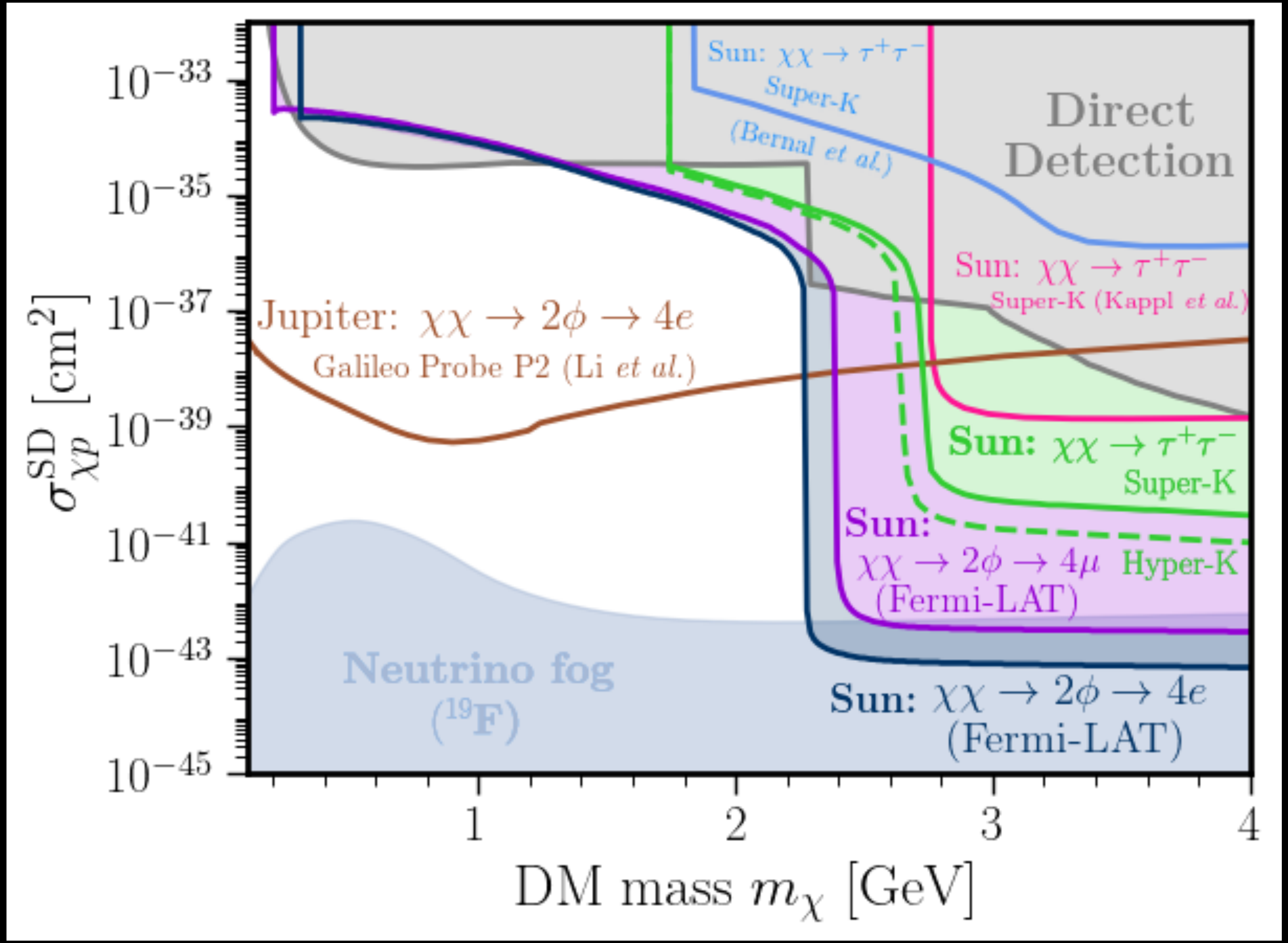
Neutrino and Gamma-Ray signals



Constraints on Spin-dependent DM-proton scattering

Extending Analysis down to 0.1 GeV DM mass





Massless final state channels

Leptonic final state channels

Thong Nguyen, Stockholm University

3. Millicharged Dark Matter

Constraints and Projections for Millicharged Dark Matter in the Sun with Water Cherenkov Neutrino Detectors

Thong T.Q. Nguyen[1,*]

[1] *Stockholm University and The Oskar Klein Centre for Cosmoparticle Physics, Alba Nova, 10691 Stockholm, Sweden*

Millicharged particles are well-motivated dark matter candidates that have been extensively investigated in terrestrial experiments. Recently, Berlin and Hooper (2024) proposed using the IceCube Neutrino Observatory to search for high-energy neutrinos produced by the capture and annihilation of millicharged dark matter in the Sun, deriving new constraints in the strong interaction regime where the millicharge is $q_\chi \sim 10^{-3}$–10^{-2}, and for small fractional abundances where direct detection and other probes lose sensitivity. In this work, I point out that the lower energy threshold of water Cherenkov detectors makes Super-Kamiokande and the future Hyper-Kamiokande sensitive to neutrinos from the annihilation of lighter millicharged dark matter, complementing the high-mass reach of IceCube. I find that Super-Kamiokande can constrain previously unexplored parameter space at $m_\chi \sim (2$–$100)$ GeV, while Hyper-Kamiokande will be sensitive to fractional abundances as small as $f_\chi \simeq 5 \times 10^{-6}$, nearly an order of magnitude below current IceCube limits.

Millicharged Dark Matter

Strongly-coupled regime for subdominant Dark Matter Fraction

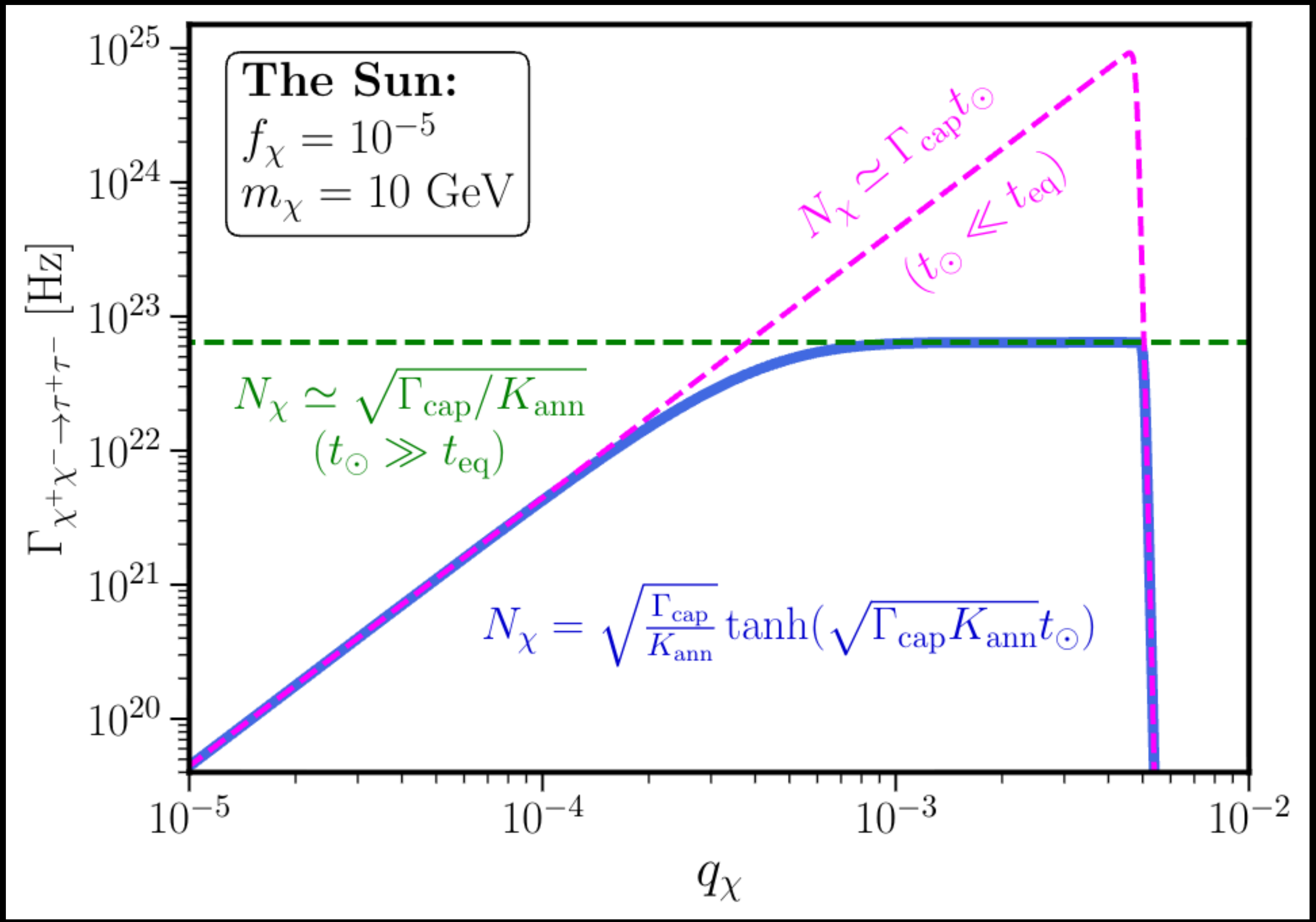
- Millicharged Dark Matter model can be an extension of the Standard Model, with extra U(1)’.
- Usually interacts with the Standard Model through a very light dark photon kinetic mixing with the SM photon
- Dark Matter can carry charge, but it has to make up only a fraction of the total dark matter density
- CMB and BBN constraints:

$$f_\chi \leq 0.01$$

Millicharged Dark Matter in the Sun

Original idea from Berlin and Hooper (arXiv:2407.04768)

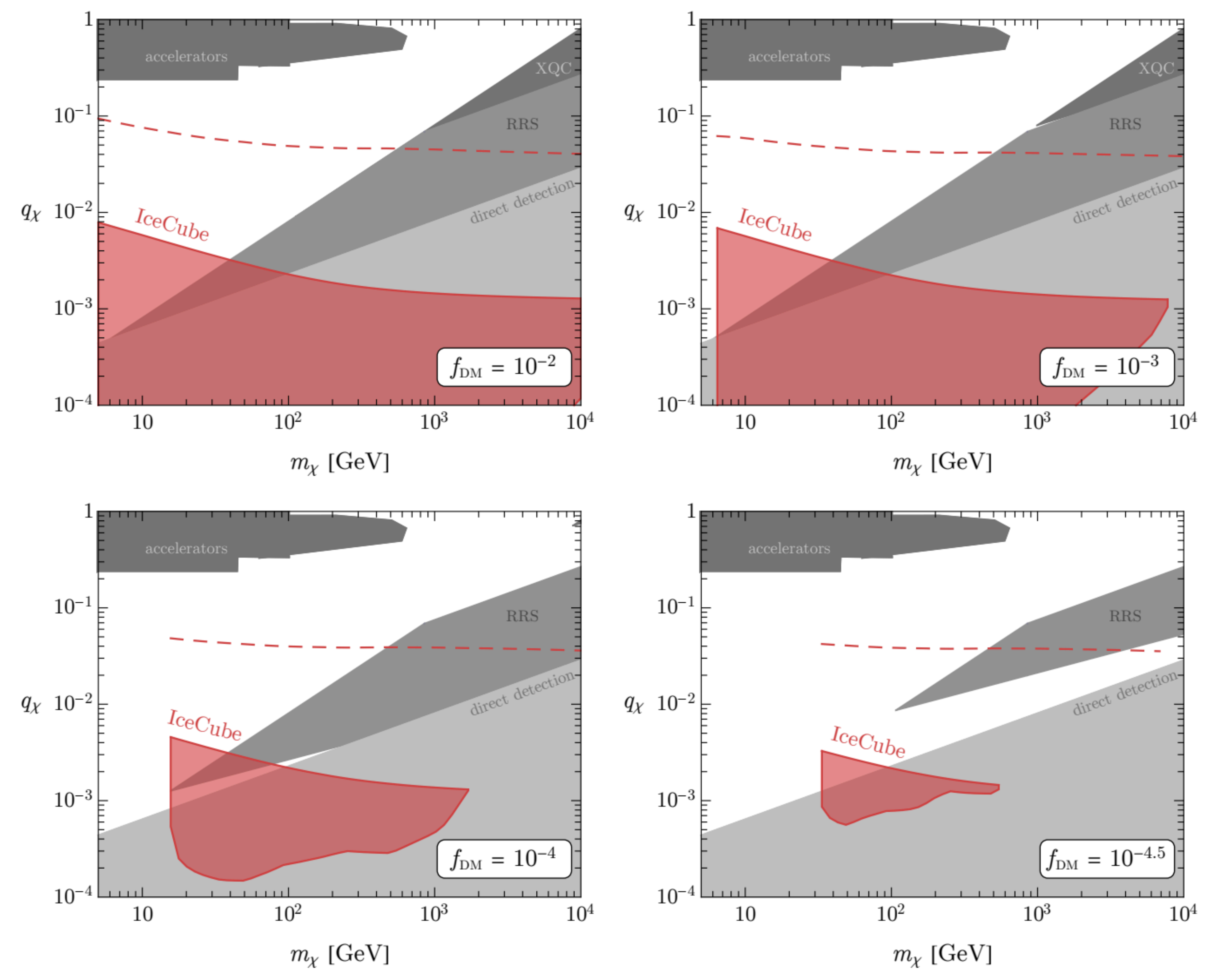
- Strongly-coupled Millicharged DM will be captured by the Sun with the maximum (geometric) capture rate
- They can annihilate to tau pairs and produce neutrinos that can be observed by IceCube
- If the charge is big, the DM will form bound states with nuclei inside the Sun through Coulomb potential
- This bound state will suppress the DM annihilation



Thong Nguyen, Stockholm University

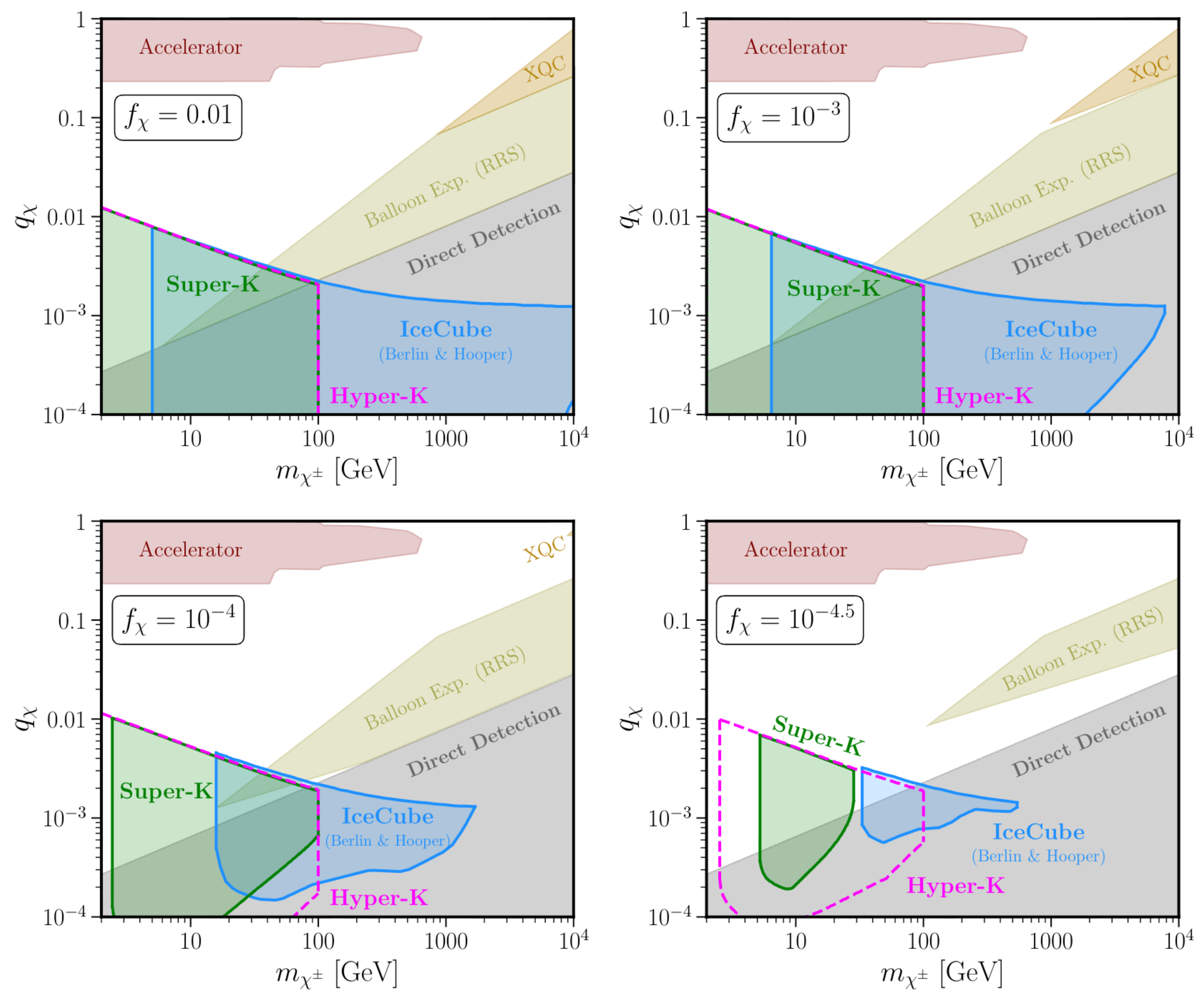
IceCube constraints on Millicharged DM

Berlin and Hooper (arXiv:2407.04768)



Super-K constraints on Millicharged DM

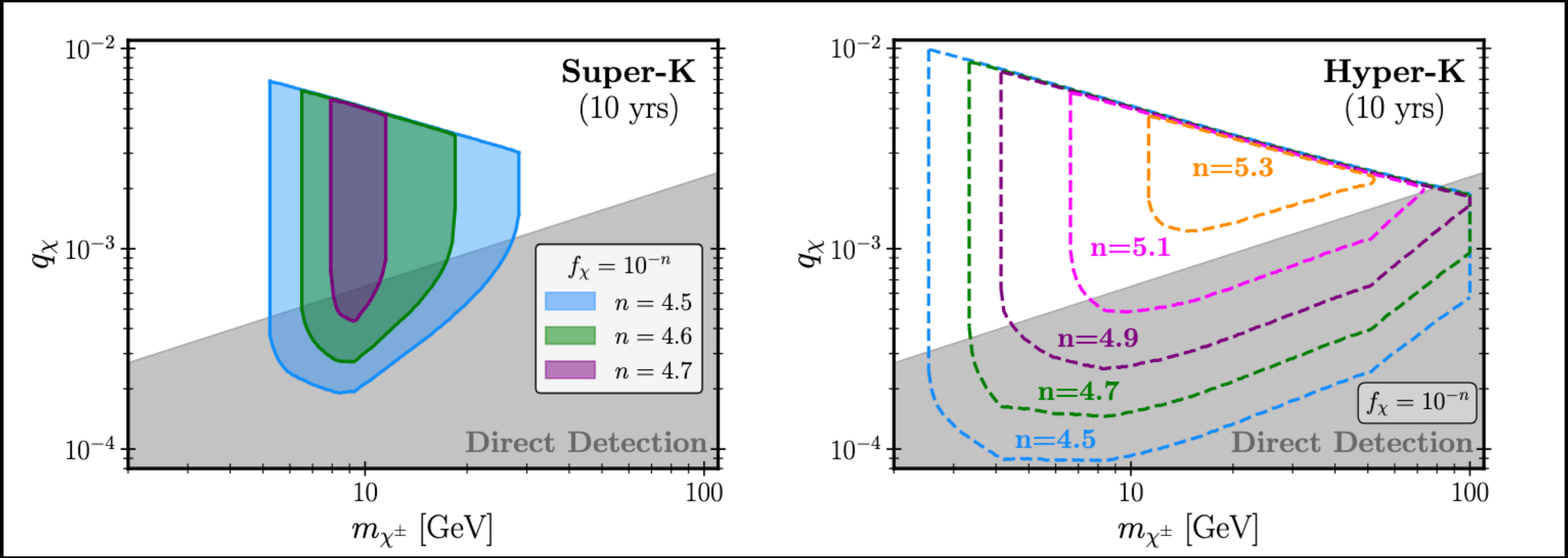
Preliminary results



Thong Nguyen, Stockholm University

Super-K / Hyper-K sensitivities

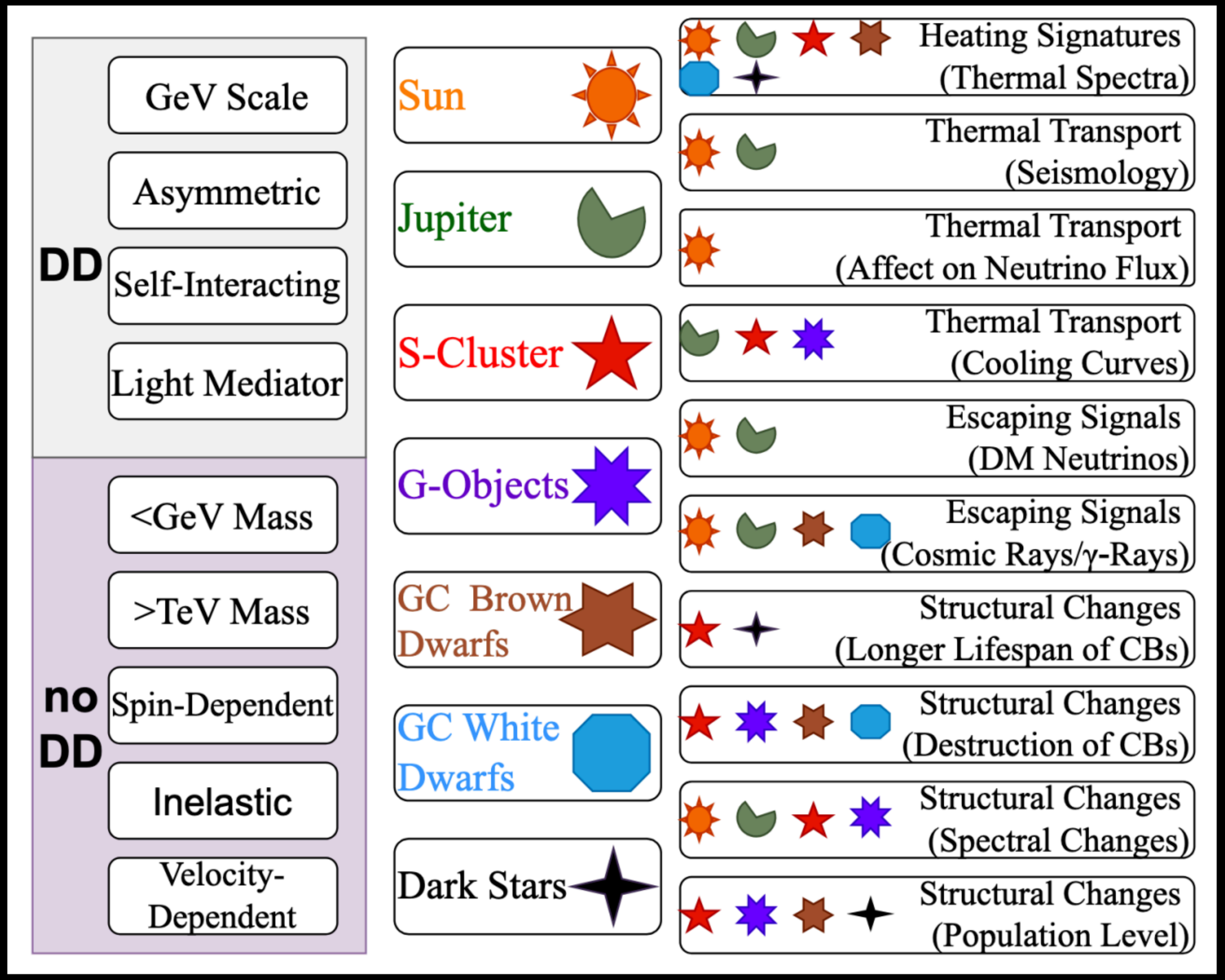
Preliminary results



Thong Nguyen, Stockholm University

Conclusion

- The Sun is cool for Dark Matter Searches
- Neutrinos are one of the important smoking-gun signals for DM.
- It is an active research direction!




Thank you for listening!
Chiao is searching for Dog-matter too!
thong.nguyen@fysik.su.se