Talk @ Dark Matter and Neutrino, Institut Henri Poincaré, Paris 🗼🥐🇫🇷🥖, France 2025

Stockholm University
Oskar Klein

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

Thong T.Q. Nguyen

Based on: 2501.14864

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}.

Tim Linden

Stockholm University

Pierluca Carenza

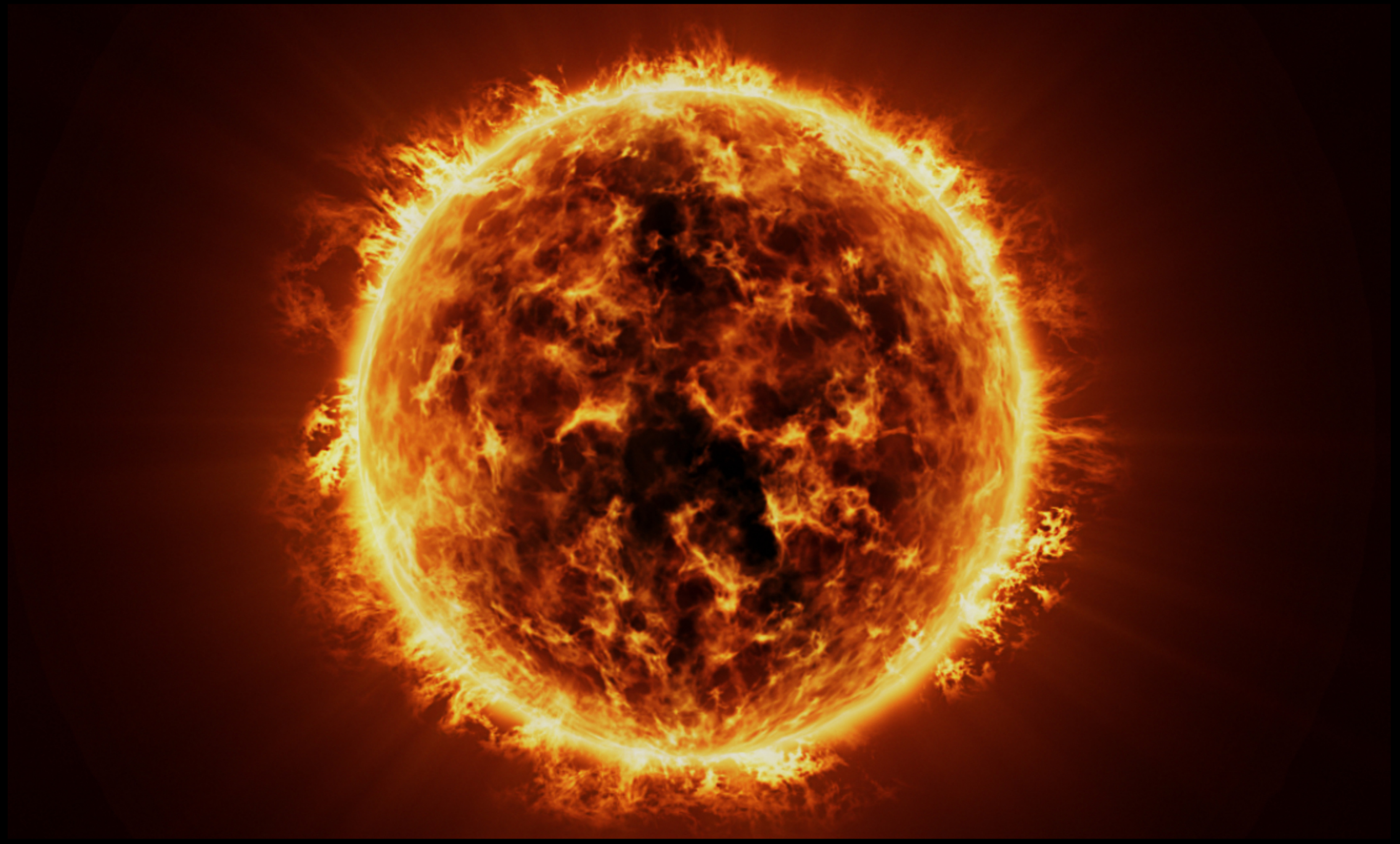
Stockholm U.

Axel Widmark

Columbia U.

(Marie Curie Fellow)

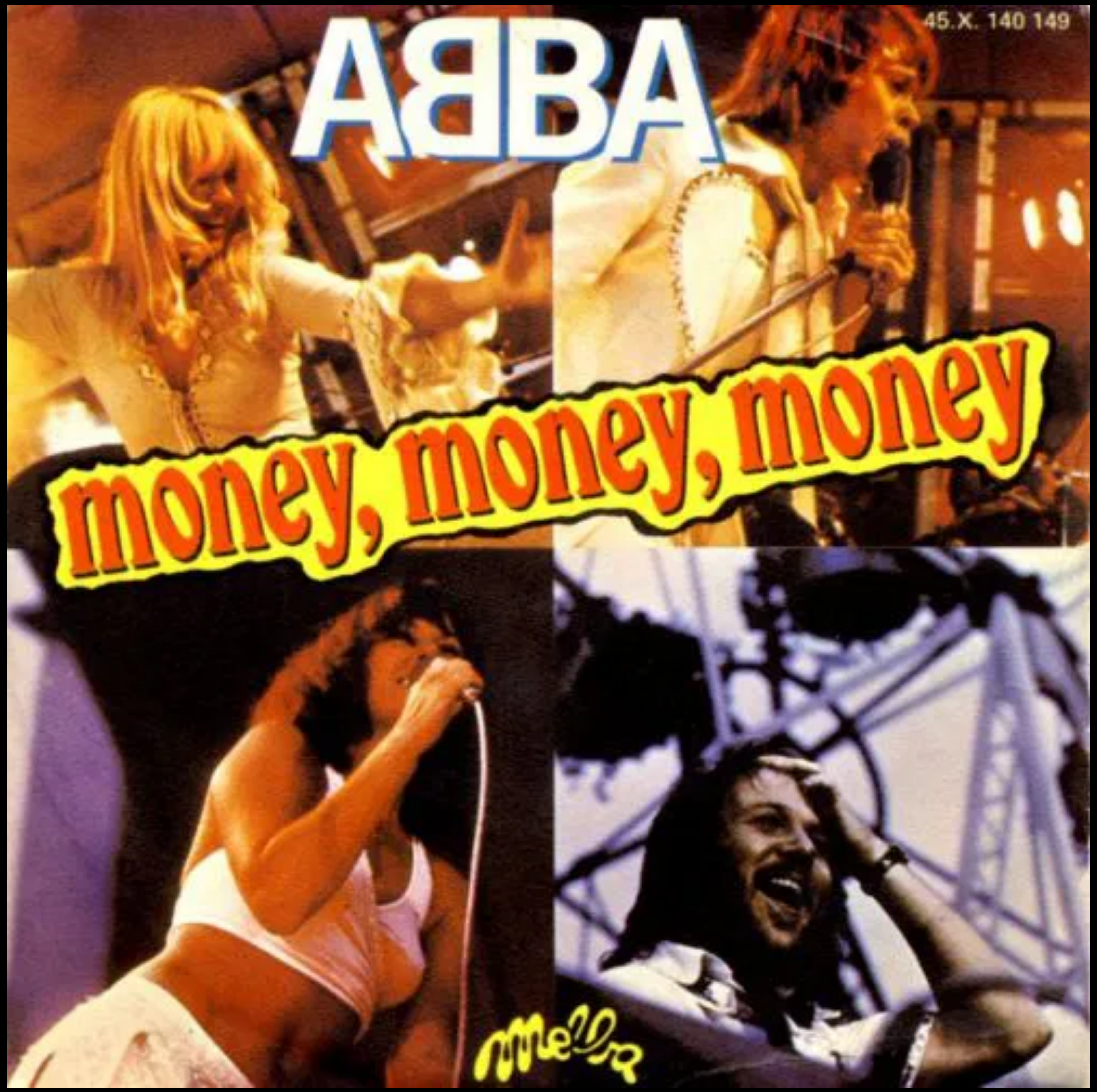
The Sun as a Dark Matter Detector



See John Beacom's talk on why the Sun is important!

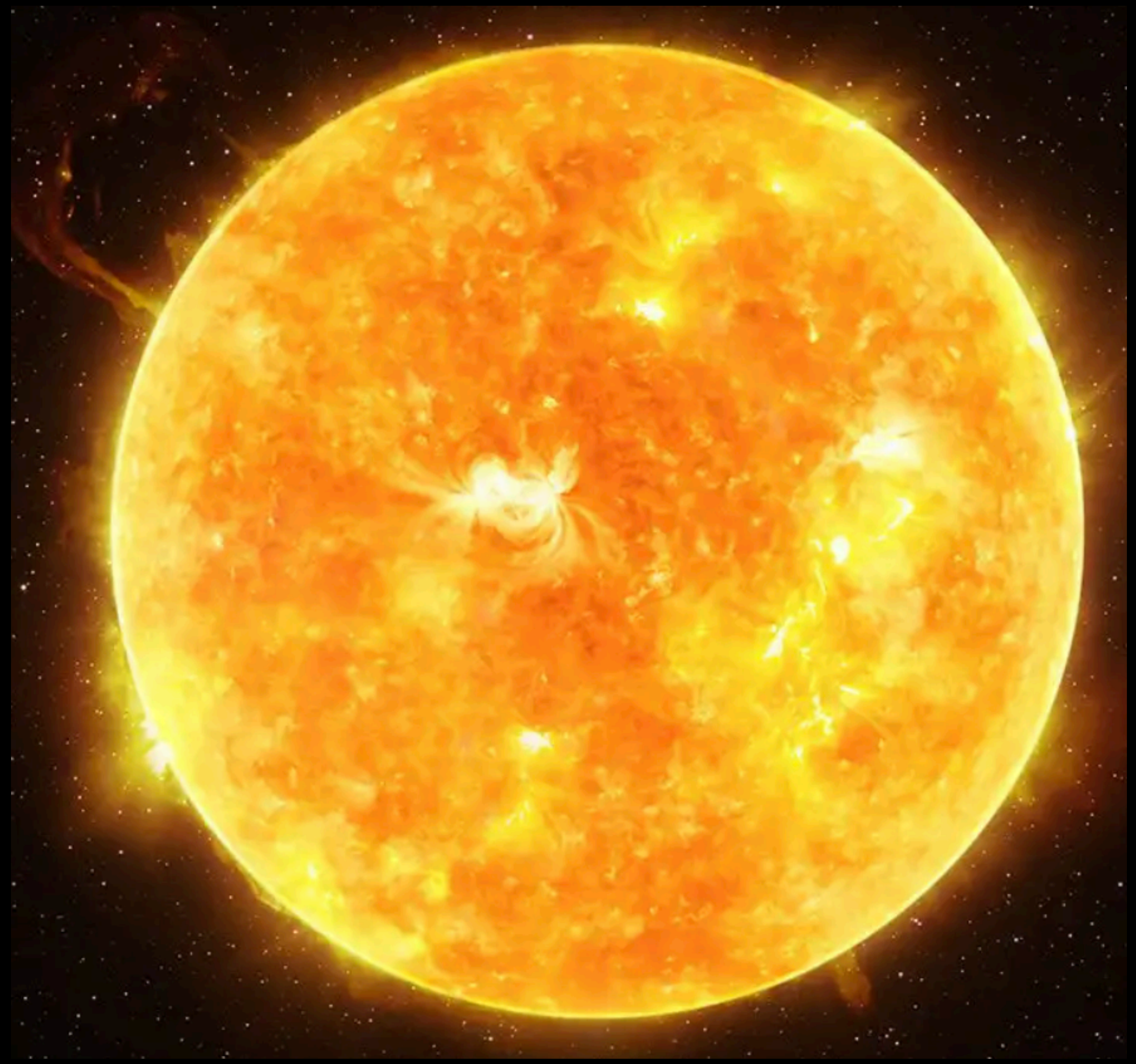
The Sun as Dark Matter Detectors

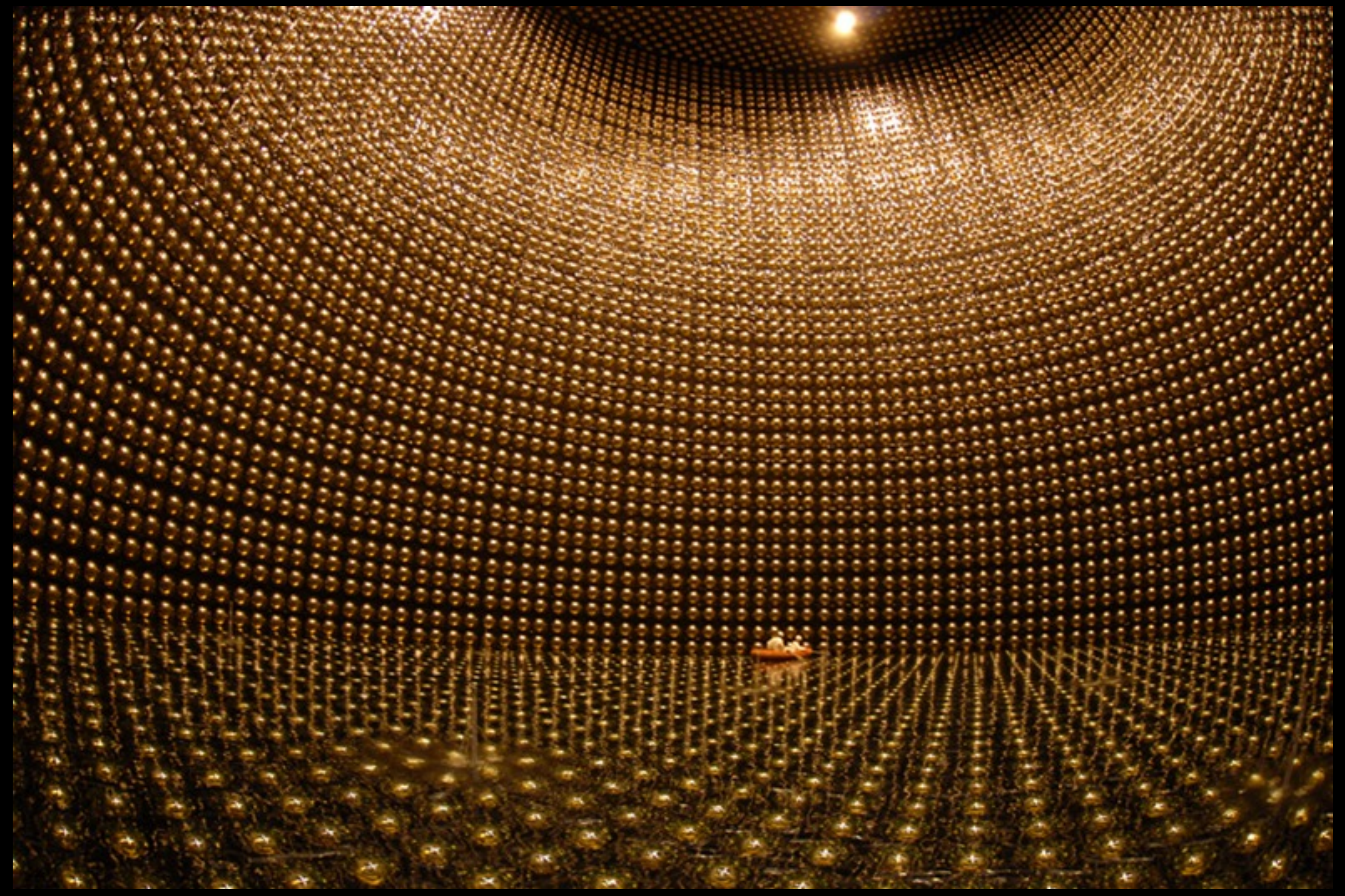
A budget-free solution?



The Sun as Dark Matter Detectors

A budget-free solution?





The Sun is there already!

Super-K is built already!

The Sun as Dark Matter Detectors

Large Exposure from the Heaven!

The Sun as Dark Matter Detectors

Large Exposure from the Heaven!

XENONnT:

- 7000 kg
- 700 days

5×10^6 kg day

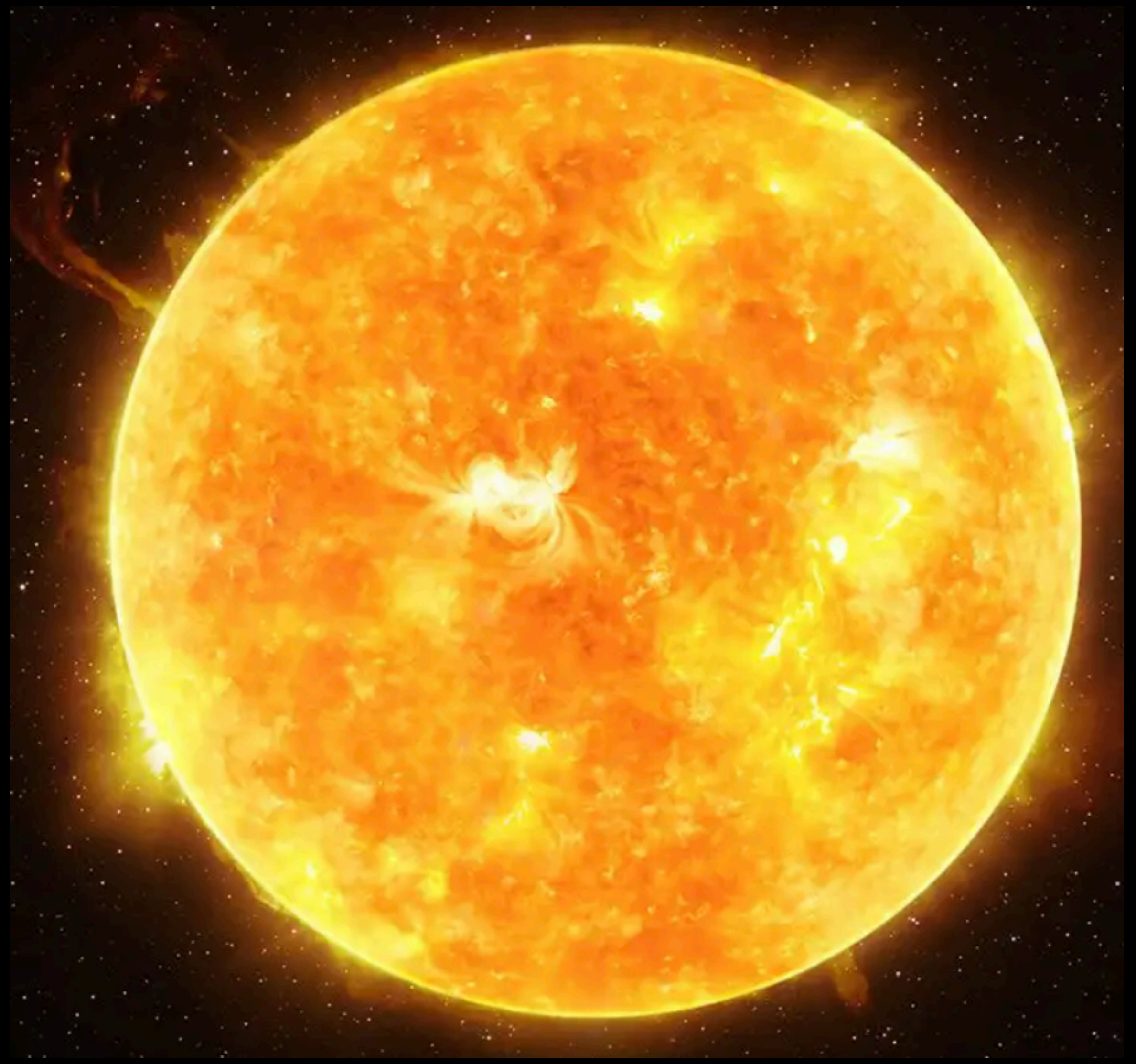
The Sun as Dark Matter Detectors

Large Exposure from the Heaven!

XENONnT:

- 7000 kg
- 700 days

5×10^{6} kg day



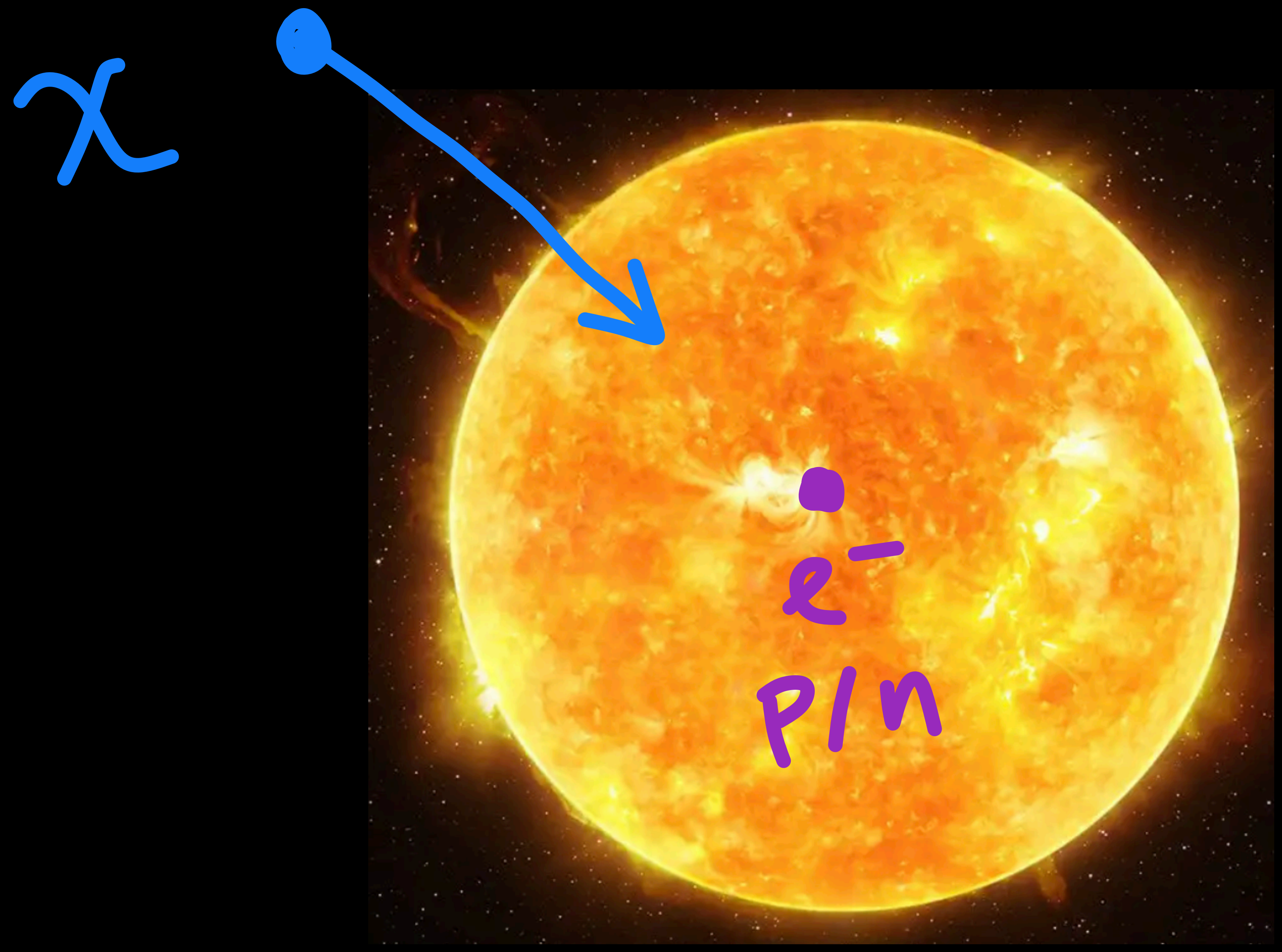
The Sun:

- 3×10^{30} kg
- 2×10^{10} days

6×10^{40} kg day

Leptophilic Dark Matter in the Sun

Dark Matter Capture by scattering with SM

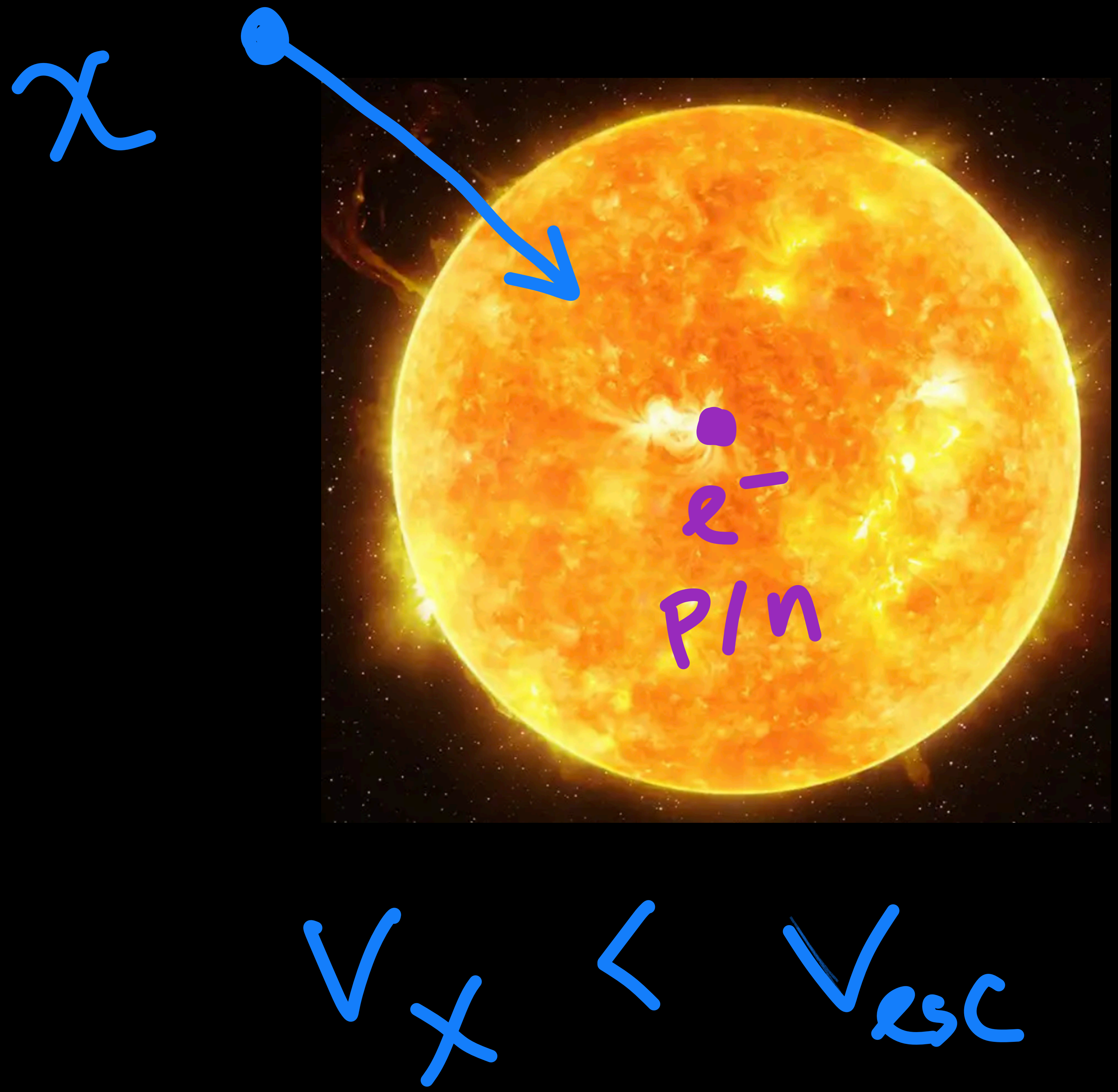


$v_\chi < v_{esc}$

Gould, ApJ (1987), Garani and Palomares-Ruiz, JCAP (1702.02768)

Leptophilic Dark Matter in the Sun

Dark Matter Capture by scattering with SM



Capture Rate:

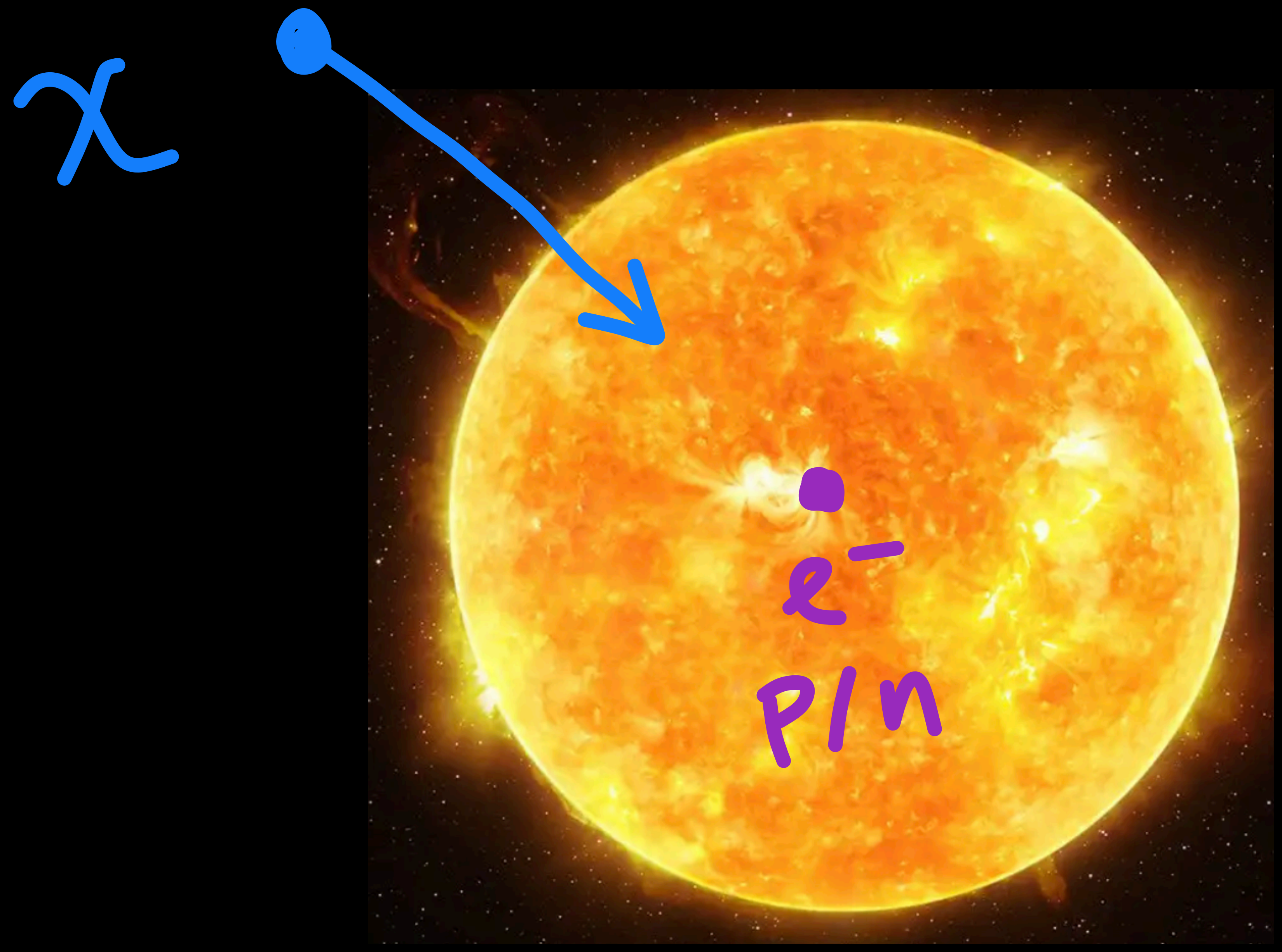
$$C_\odot^{\text{weak}} = \int_0^{R_\odot} \mathrm{d}r 4\pi r^2 \frac{\rho_\chi}{m_\chi} \int_0^\infty \mathrm{d}u_\chi \frac{f_{v_\odot}(u_\chi)}{u_\chi} \times \int_0^{v_{\text{esc}}(r)} \mathrm{d}v \times w(r) R_e^-(w \to v)$$

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

Gould, ApJ (1987), Garani and Palomares-Ruiz, JCAP (1702.02768)

Leptophilic Dark Matter in the Sun

Dark Matter Capture by scattering with SM



$V_\chi < V_{esc}$

DM Halo velocity distribution

$0.3\,\mathrm{GeV/cm^3}$

Capture Rate:

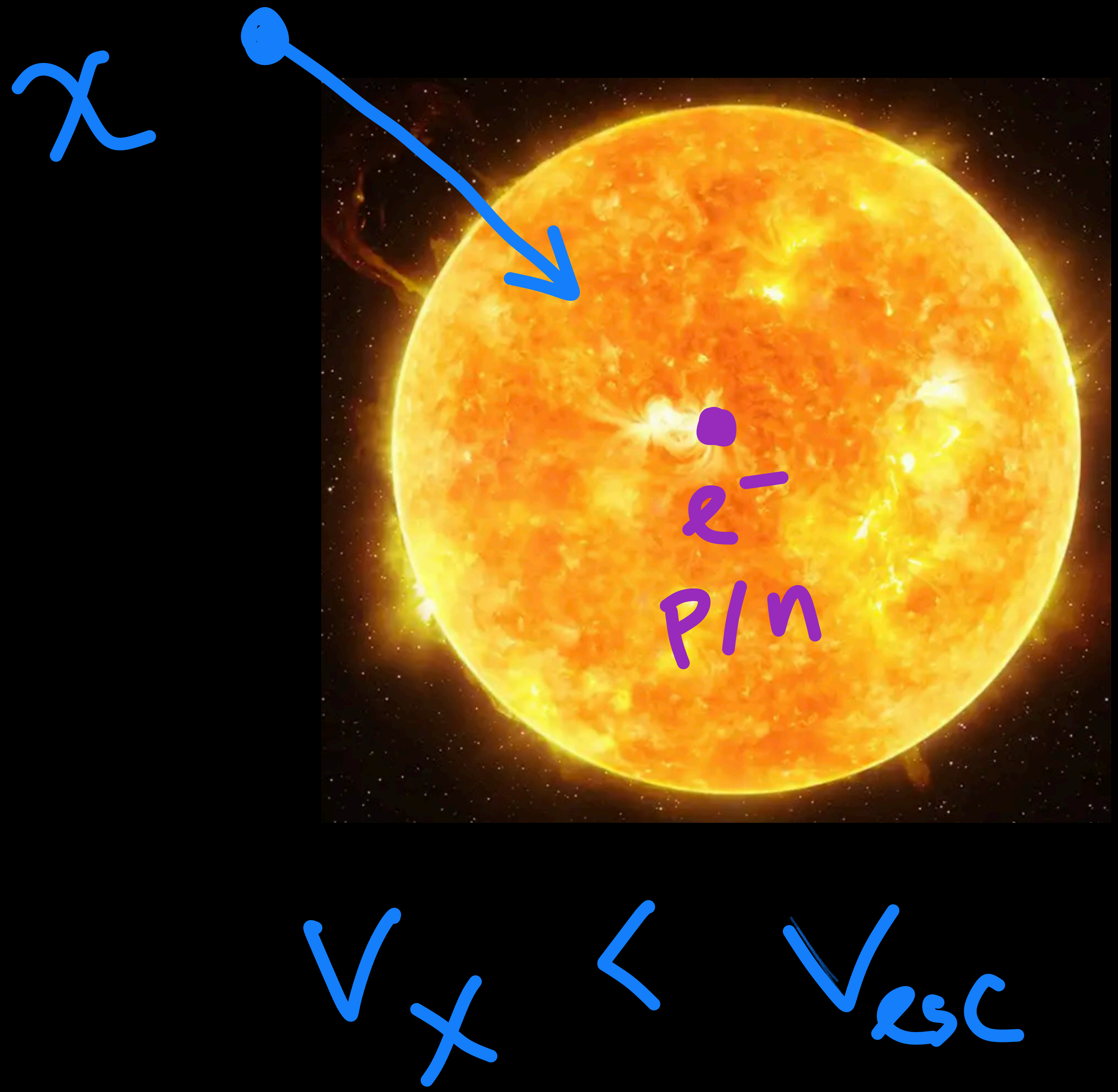
$$C_\odot^{\mathrm{weak}} = \int_0^{R_\odot} \mathrm{d}r\, 4\pi r^2 \frac{\rho_\chi}{m_\chi} \int_0^{\infty} \mathrm{d}u_\chi \frac{f_{v_\odot}(u_\chi)}{u_\chi} \times \int_0^{v_{\mathrm{esc}}(r)} \mathrm{d}v \times w(r) R_e^-(w \to v)$$

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

Gould, ApJ (1987), Garani and Palomares-Ruiz, JCAP (1702.02768)

Leptophilic Dark Matter in the Sun

Dark Matter Capture by scattering with SM



DM Halo
velocity distribution

$0.3 \mathrm{GeV}/\mathrm{cm}^3$

Capture Rate:

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

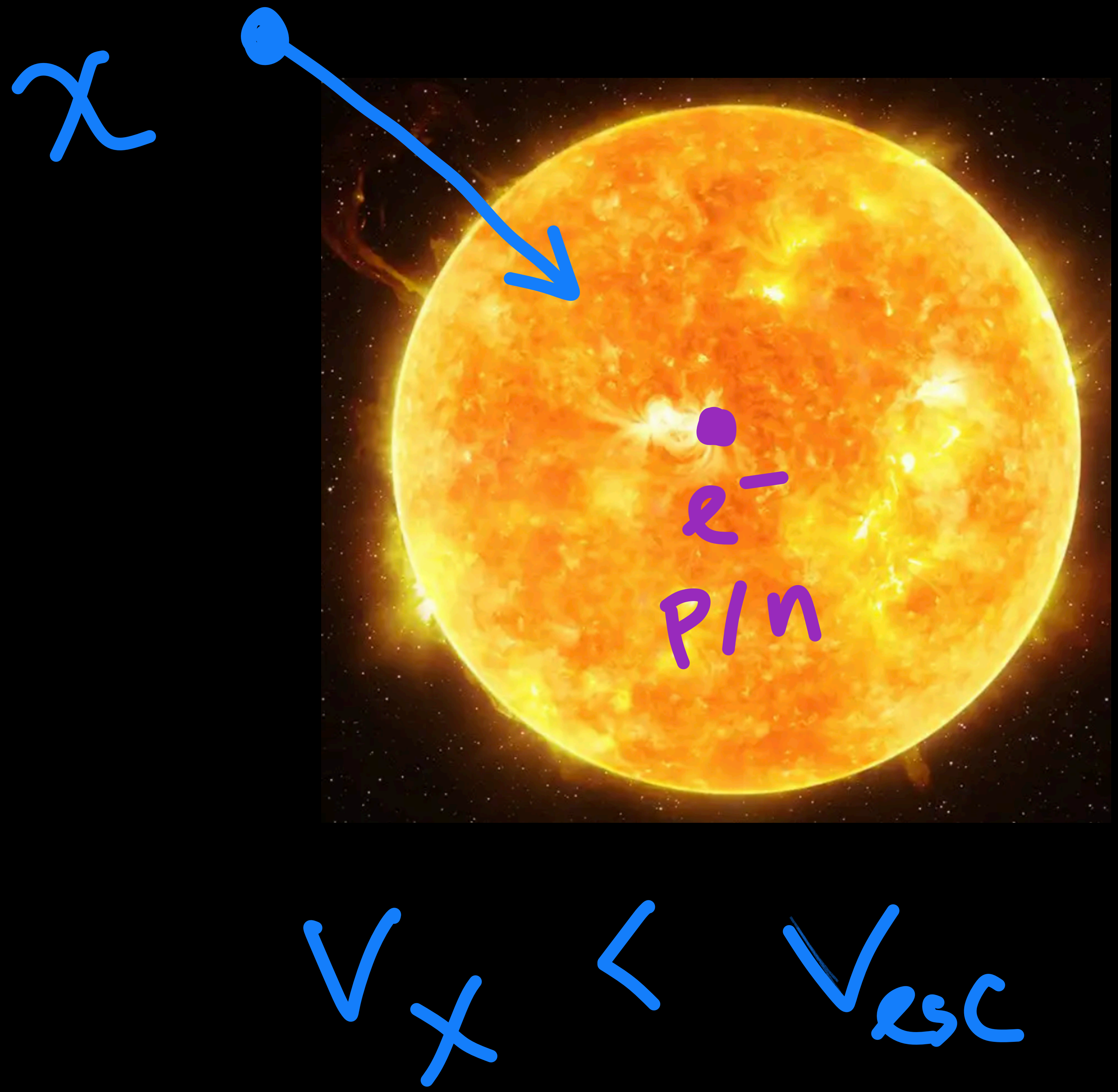
$[\mathrm{s}^{-1}]$

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

Gould, ApJ (1987), Garani and Palomares-Ruiz, JCAP (1702.02768)

Leptophilic Dark Matter in the Sun

Dark Matter Capture by scattering with SM



DM Halo velocity distribution

$0.3\,\mathrm{GeV/cm^3}$

Capture Rate:

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

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

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

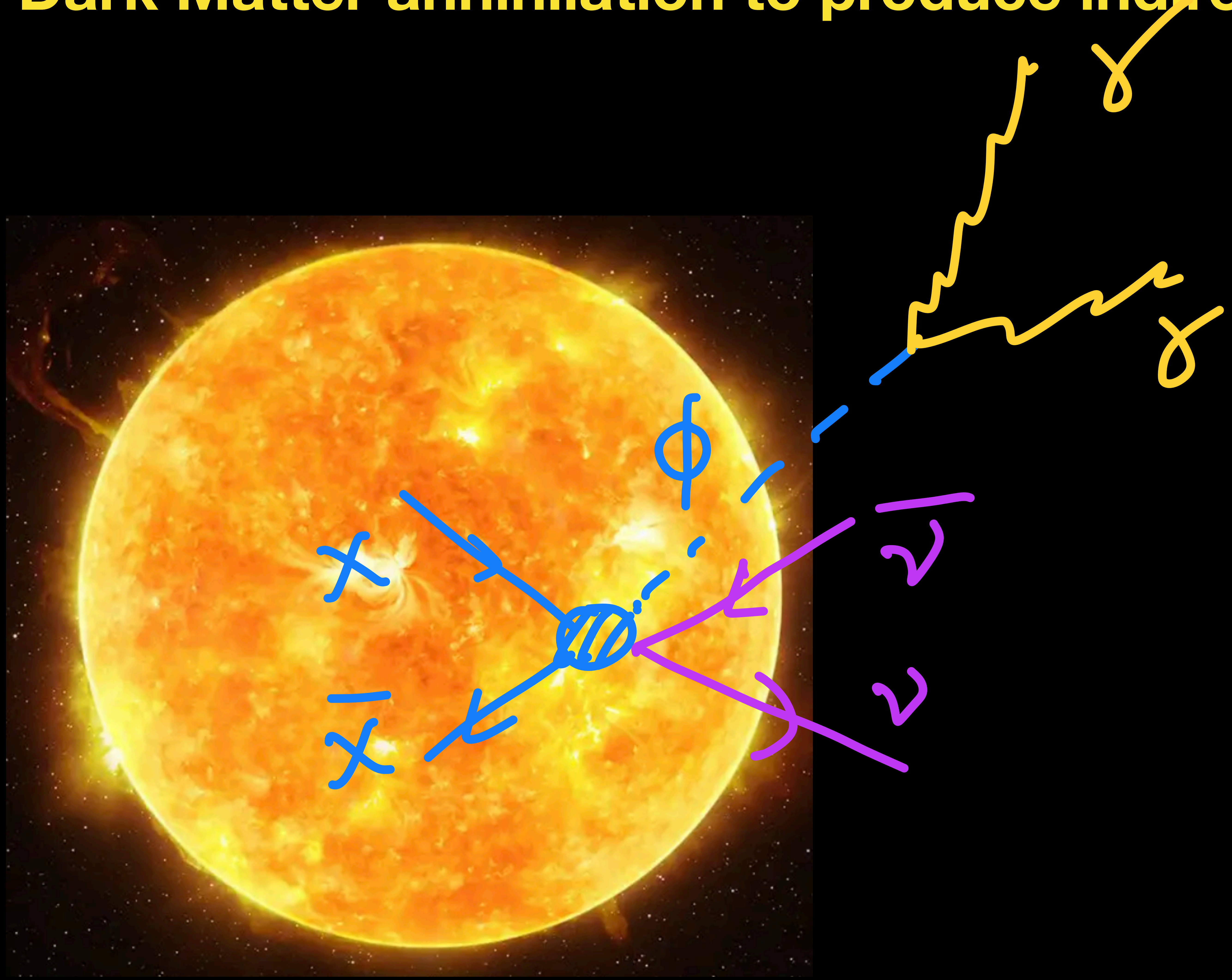
Scattering Rate

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

Gould, ApJ (1987), Garani and Palomares-Ruiz, JCAP (1702.02768)

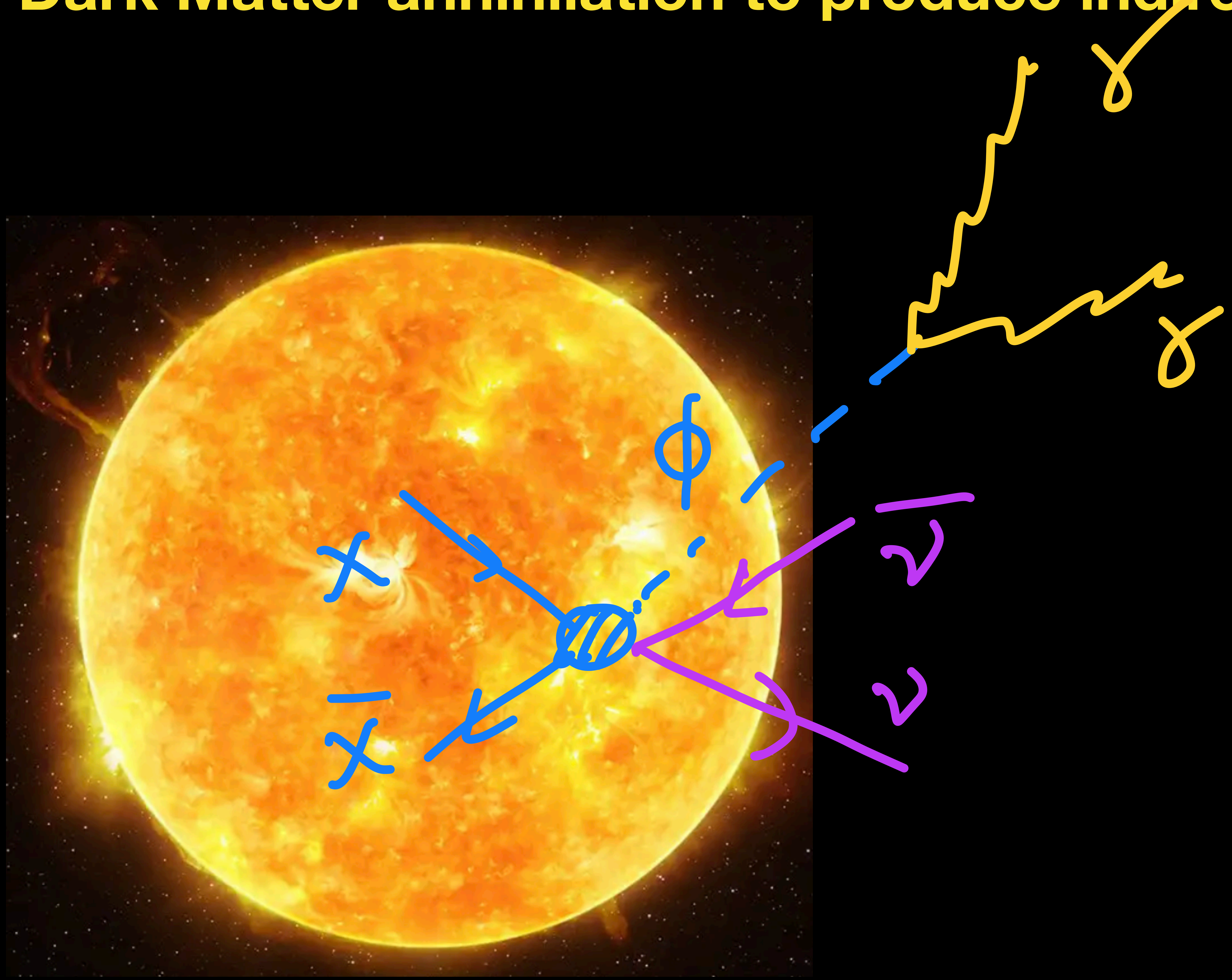
Leptophilic Dark Matter in the Sun

Dark Matter annihilation to produce indirect detection signal



Leptophilic Dark Matter in the Sun

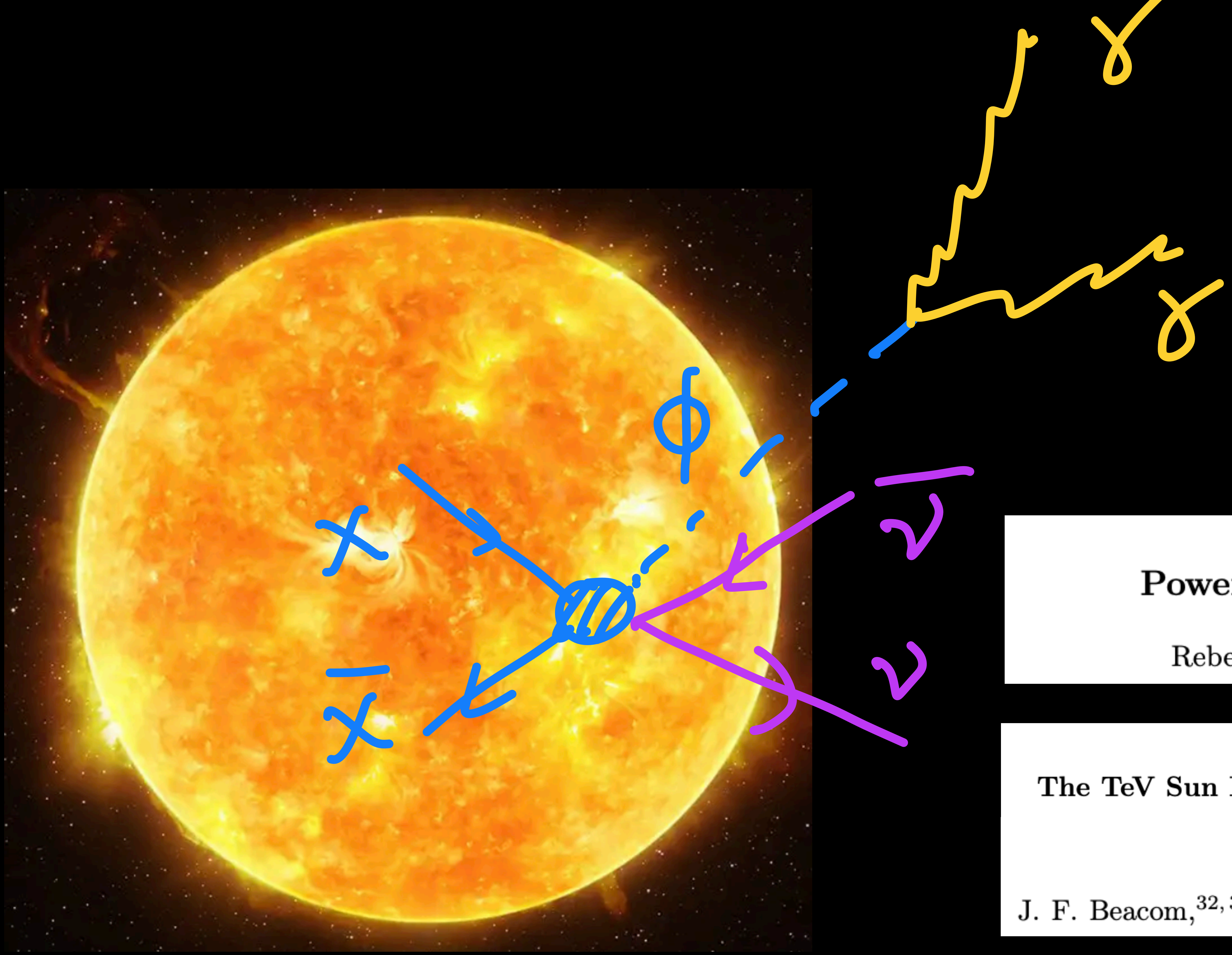
Dark Matter annihilation to produce indirect detection signal



HAWC

Leptophilic Dark Matter in the Sun

Dark Matter annihilation to produce indirect detection signal



(1703.04629)

HAWC

(2212.00815)

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]

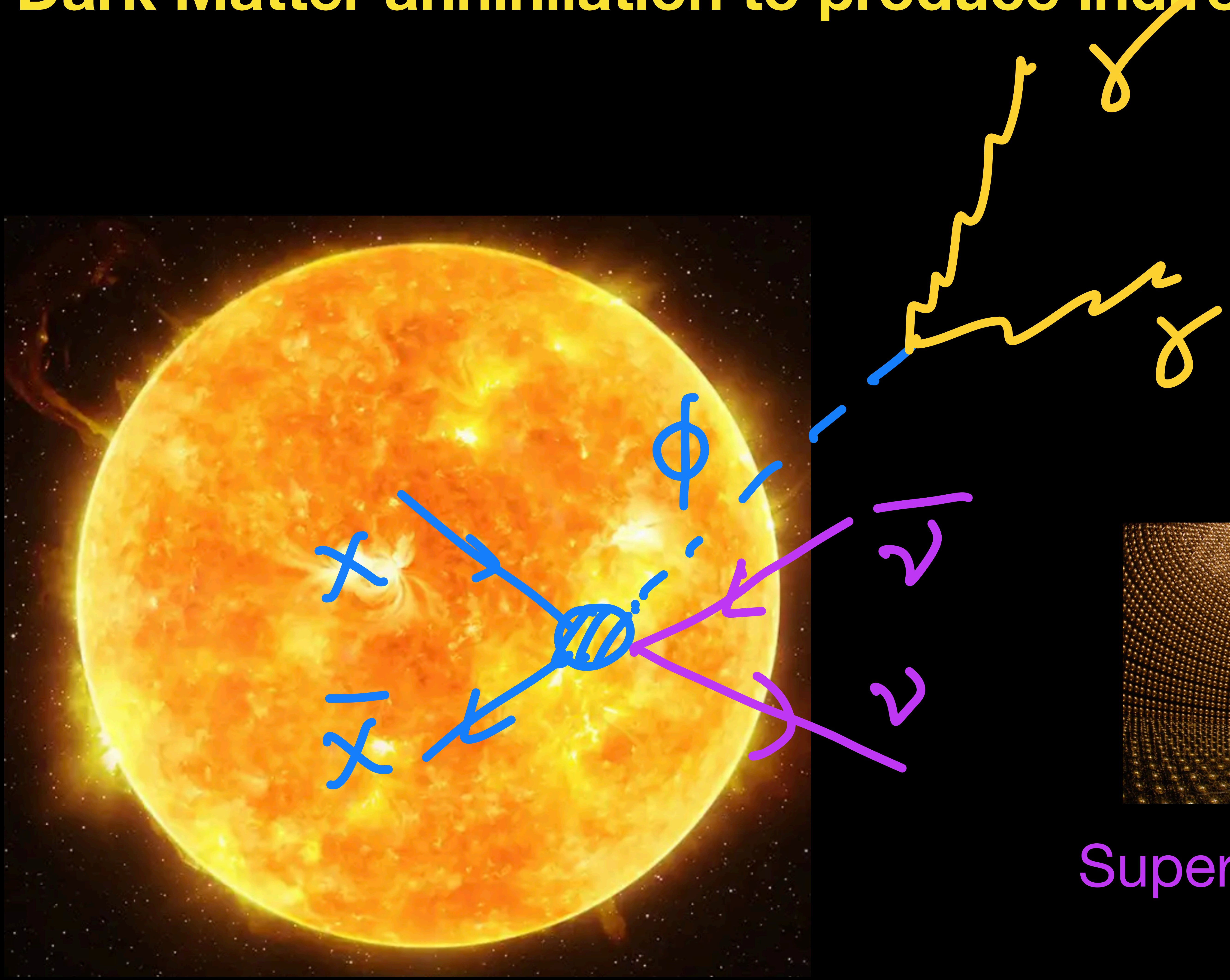
The TeV Sun Rises: Discovery of Gamma rays from the Quiescent Sun with HAWC

(HAWC Collaboration)

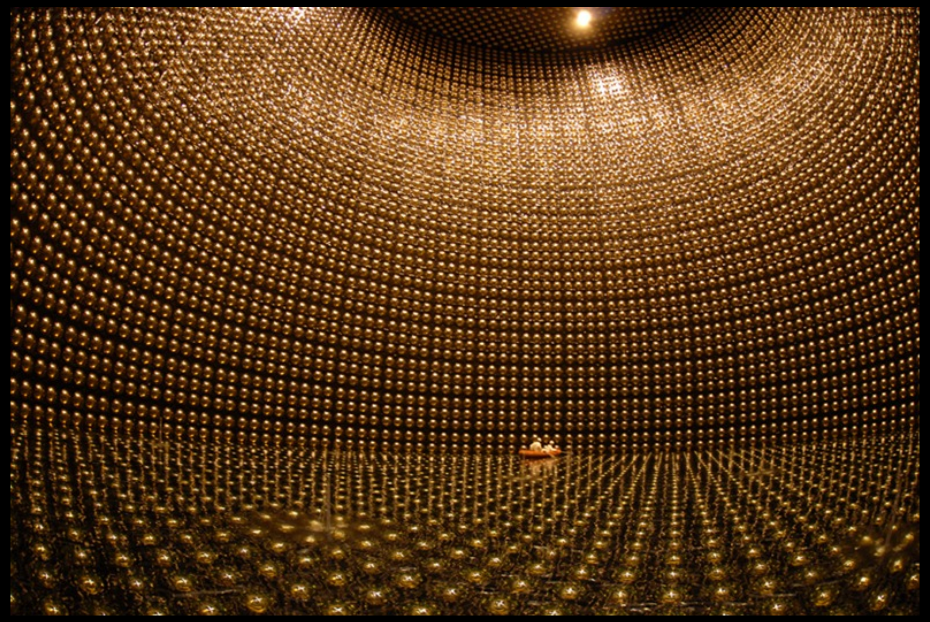
J. F. Beacom,[32,33,34] T. Linden,[35] K. C. Y. Ng,[36] A. H. G. Peter,[32,33,34,37] and B. Zhou [38]

Leptophilic Dark Matter in the Sun

Dark Matter annihilation to produce indirect detection signal



HAWC

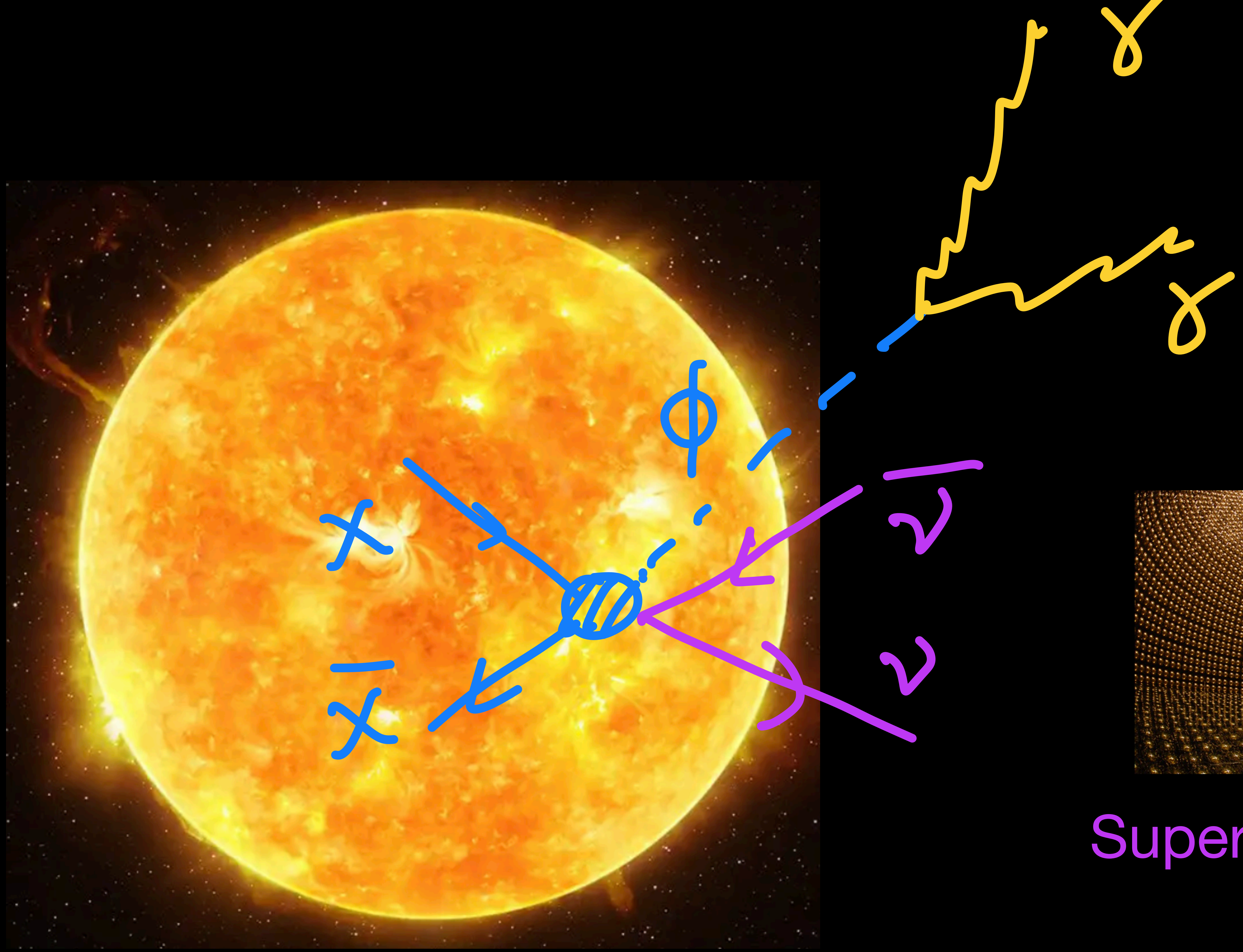


Super-Kamiokande

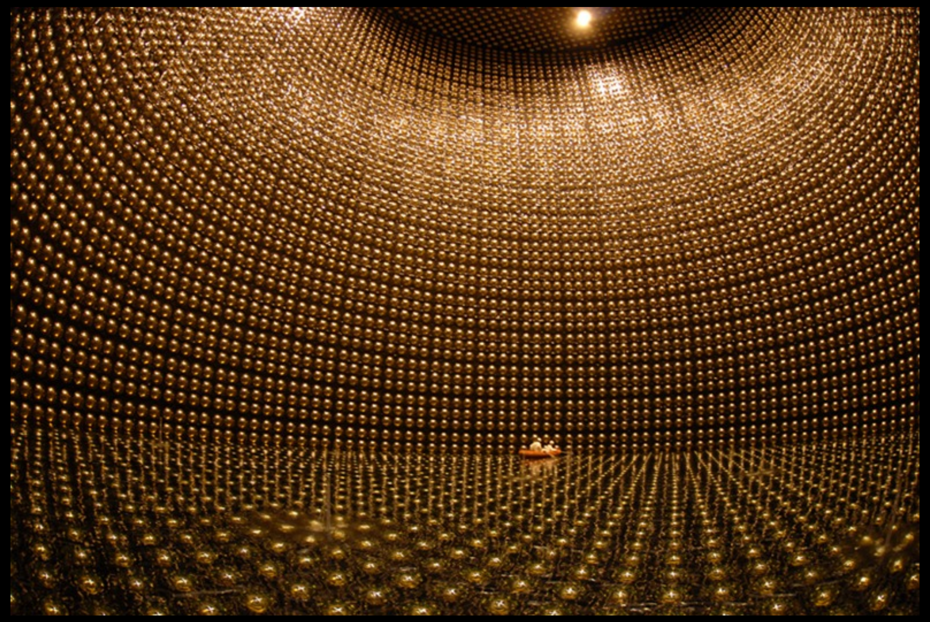
IceCube

Leptophilic Dark Matter in the Sun

Dark Matter annihilation to produce indirect detection signal



HAWC

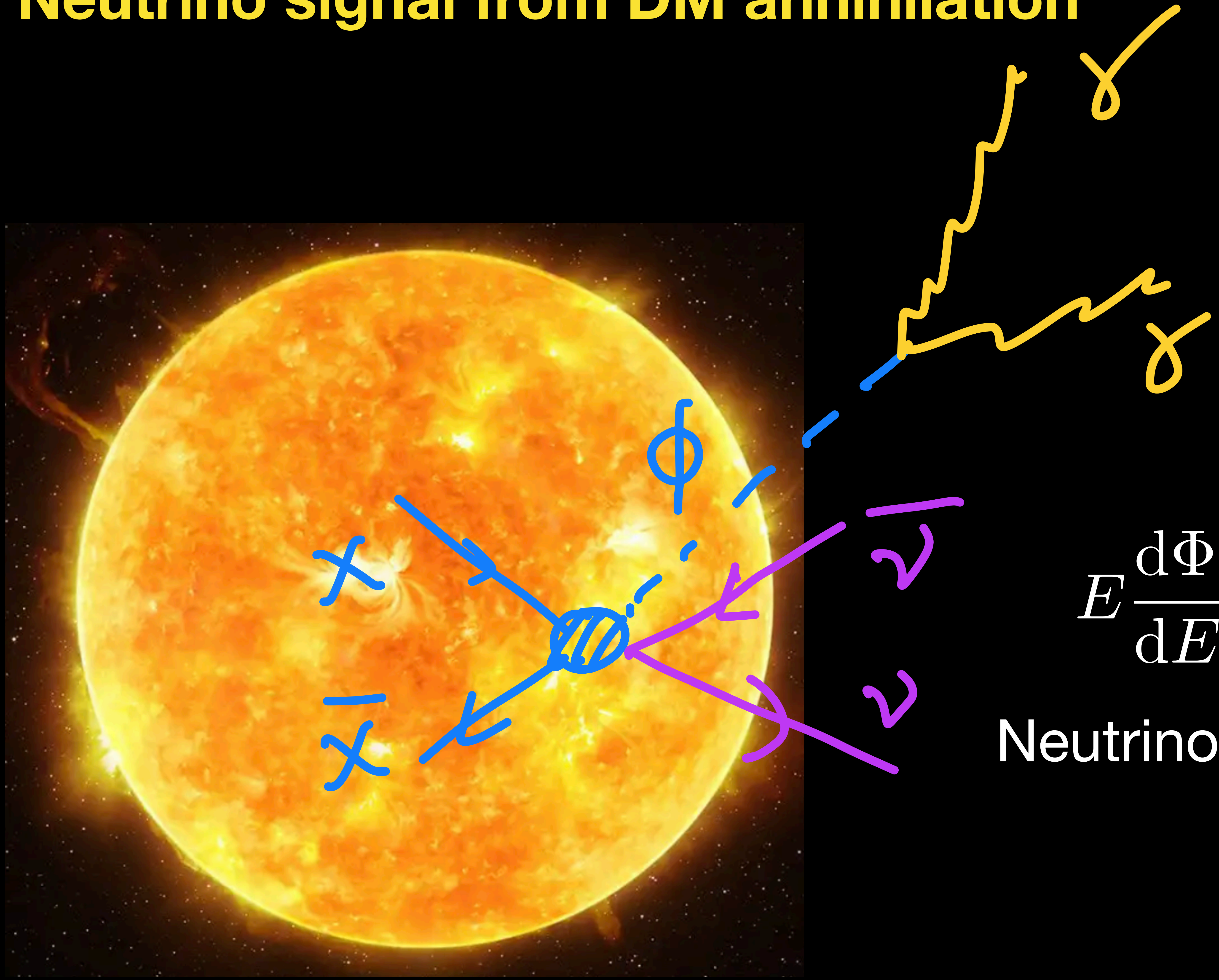


Super-Kamiokande

IceCube

Leptophilic Dark Matter in the Sun

Neutrino signal from DM annihilation

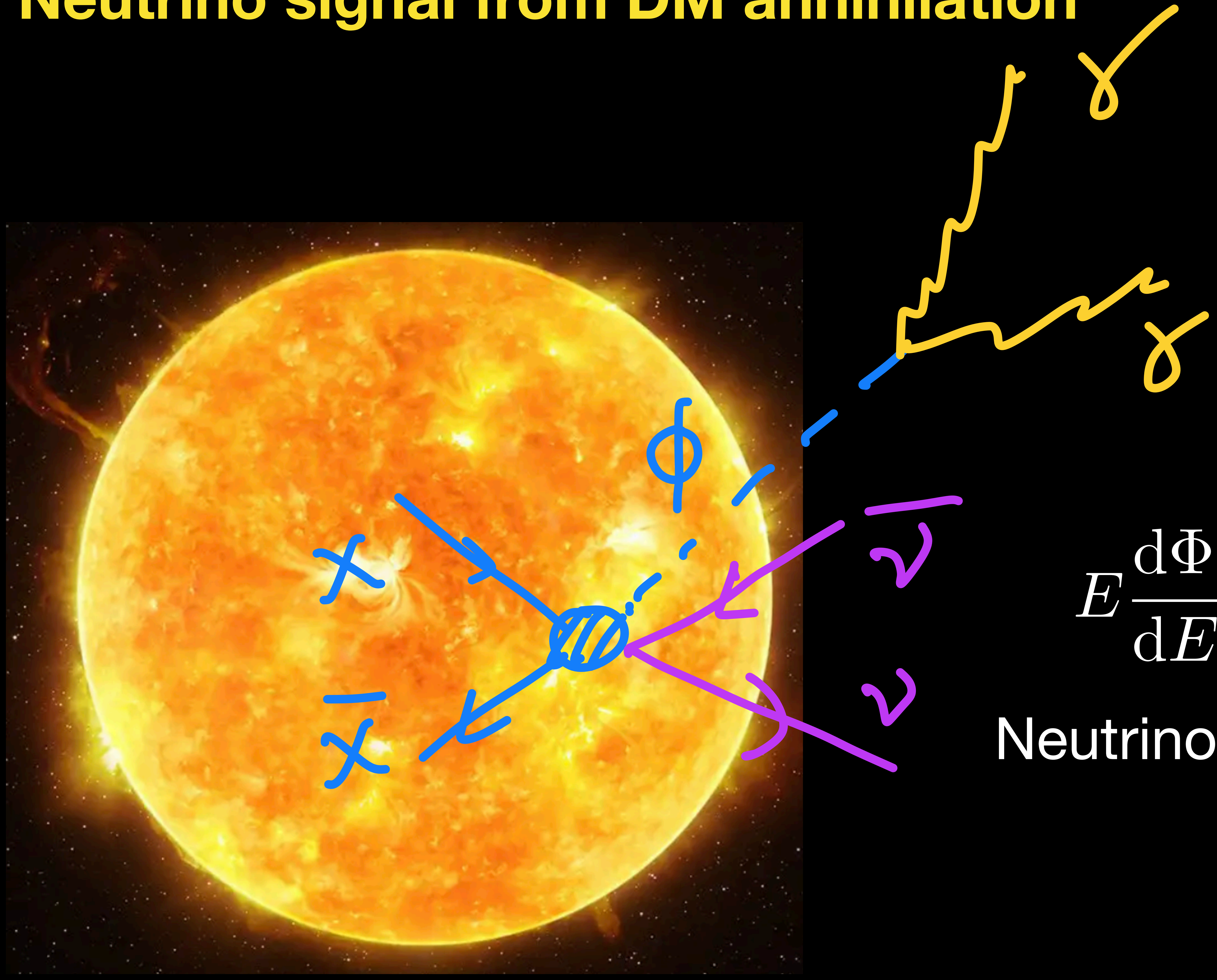


$$E\frac{\mathrm{d}\Phi_\nu}{\mathrm{d}E_\nu} = \frac{\Gamma_{\chi\chi\to\nu\bar{\nu}}}{4\pi D^2} \times E_\nu \frac{\mathrm{d}N_\nu}{\mathrm{d}E_\nu} \times P_{\mathrm{surv}}$$

Neutrino Flux

Leptophilic Dark Matter in the Sun

Neutrino signal from DM annihilation



Annihilation Rate:

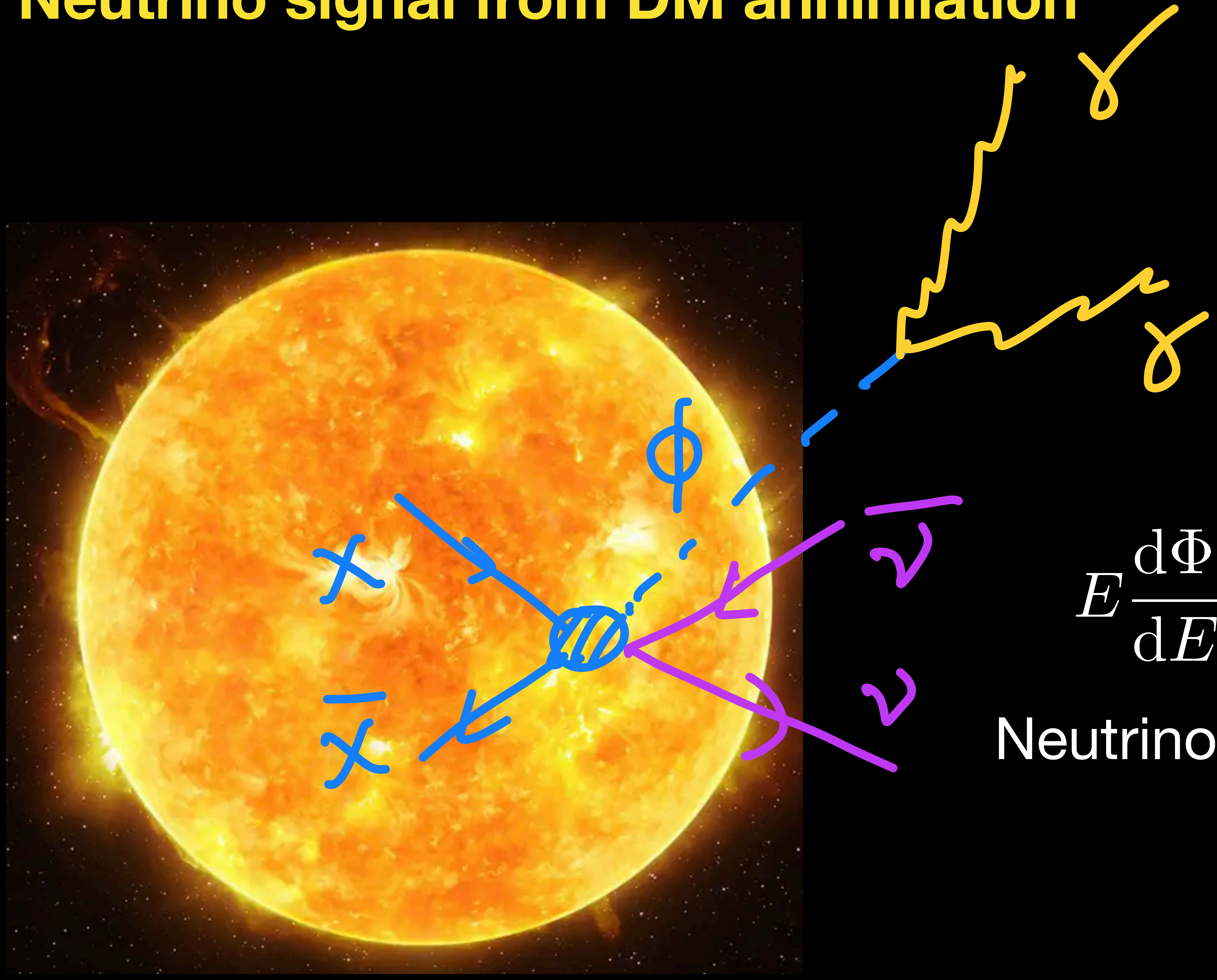
$$\Gamma = \frac{C}{2}$$

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

Neutrino Flux

Leptophilic Dark Matter in the Sun

Neutrino signal from DM annihilation



Annihilation Rate:

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Neutrino Flux

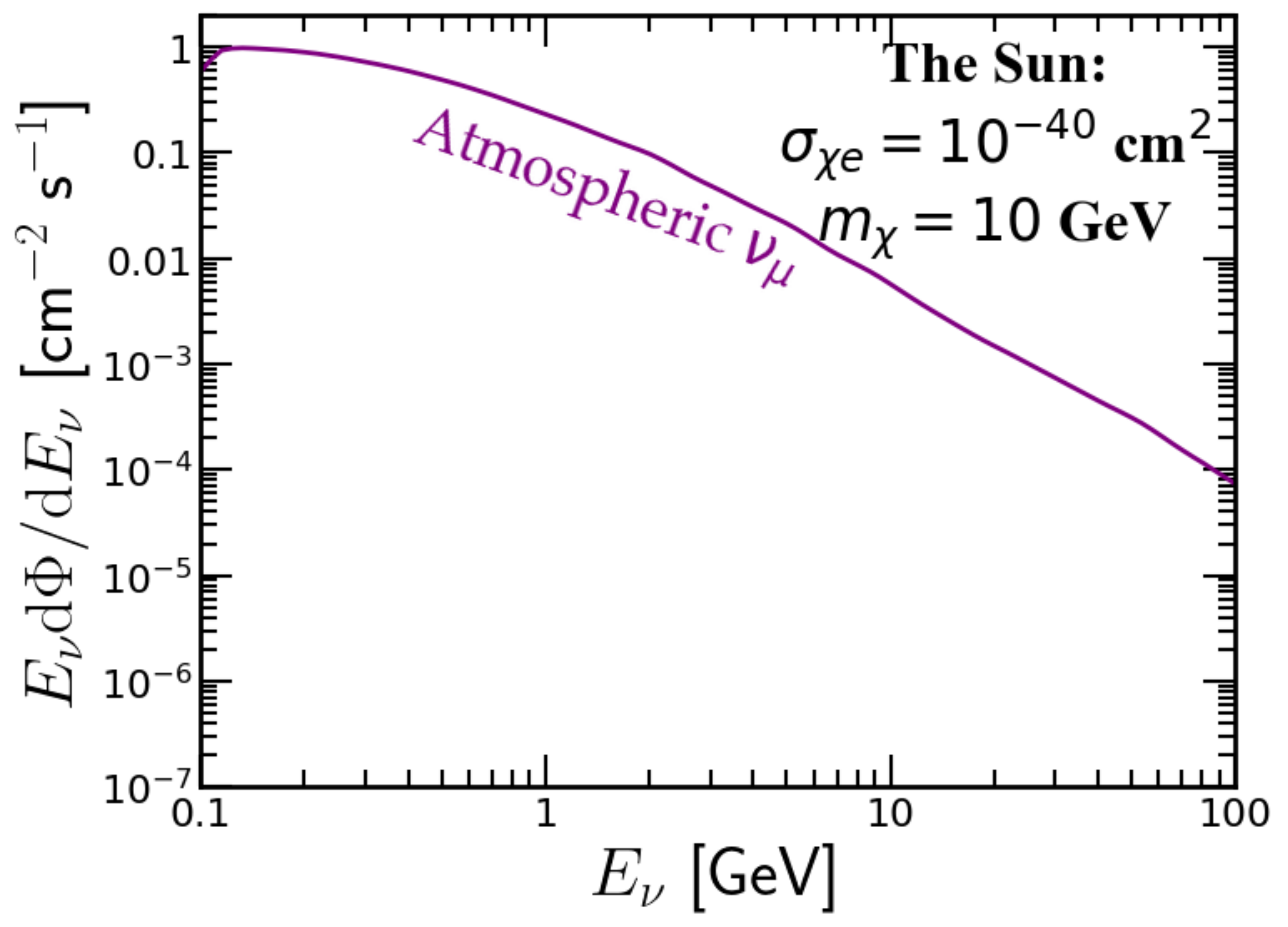
Neutrino Spectrum

Leptophilic dark matter cross section constraint

Using the Sun and 10-year Super-Kamiokande observation

Leptophilic dark matter cross section constraint

Using the Sun and 10-year Super-Kamiokande observation

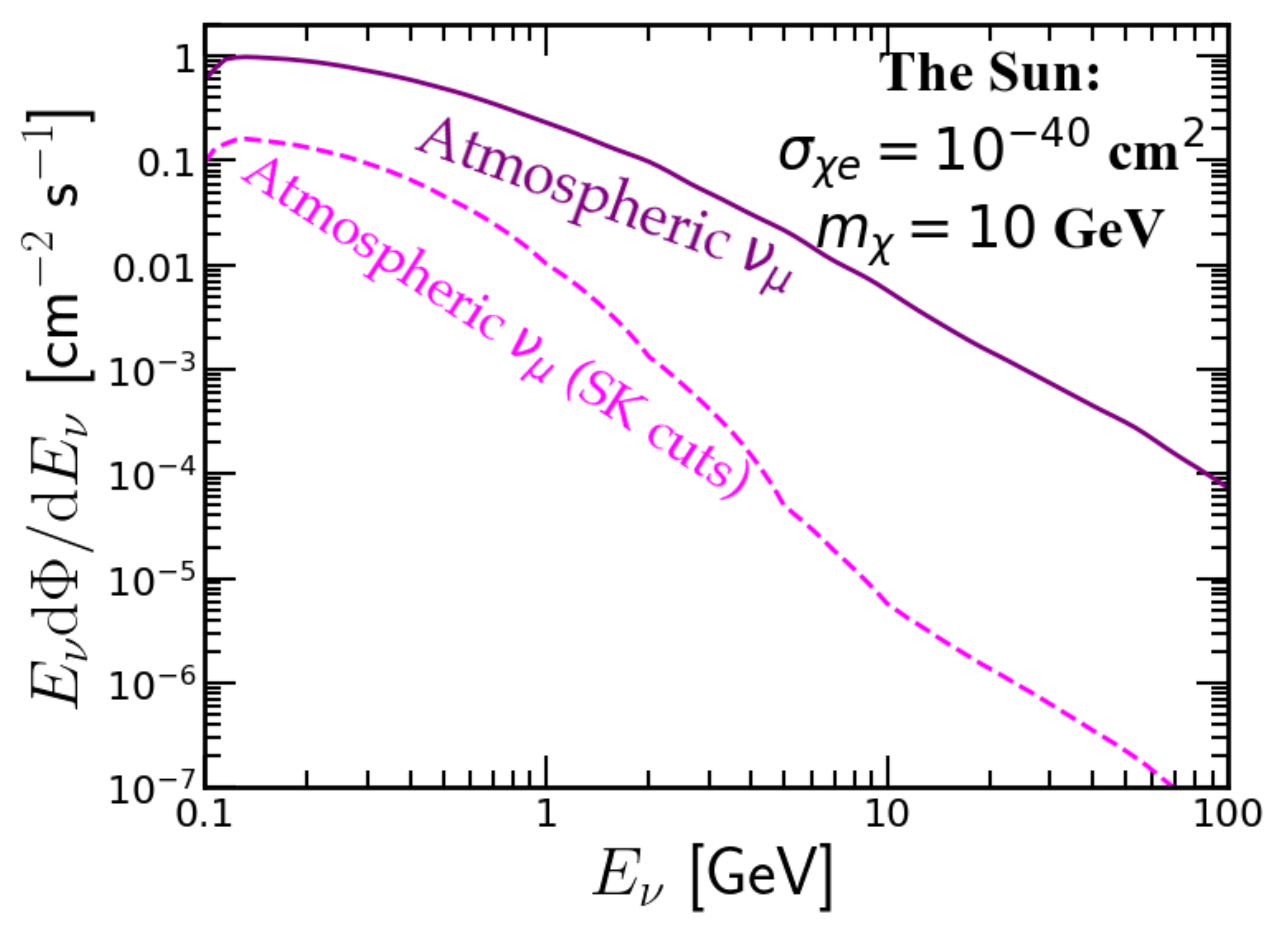


- The background is less than 1 event!

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

Leptophilic dark matter cross section constraint

Using the Sun and 10-year Super-Kamiokande observation

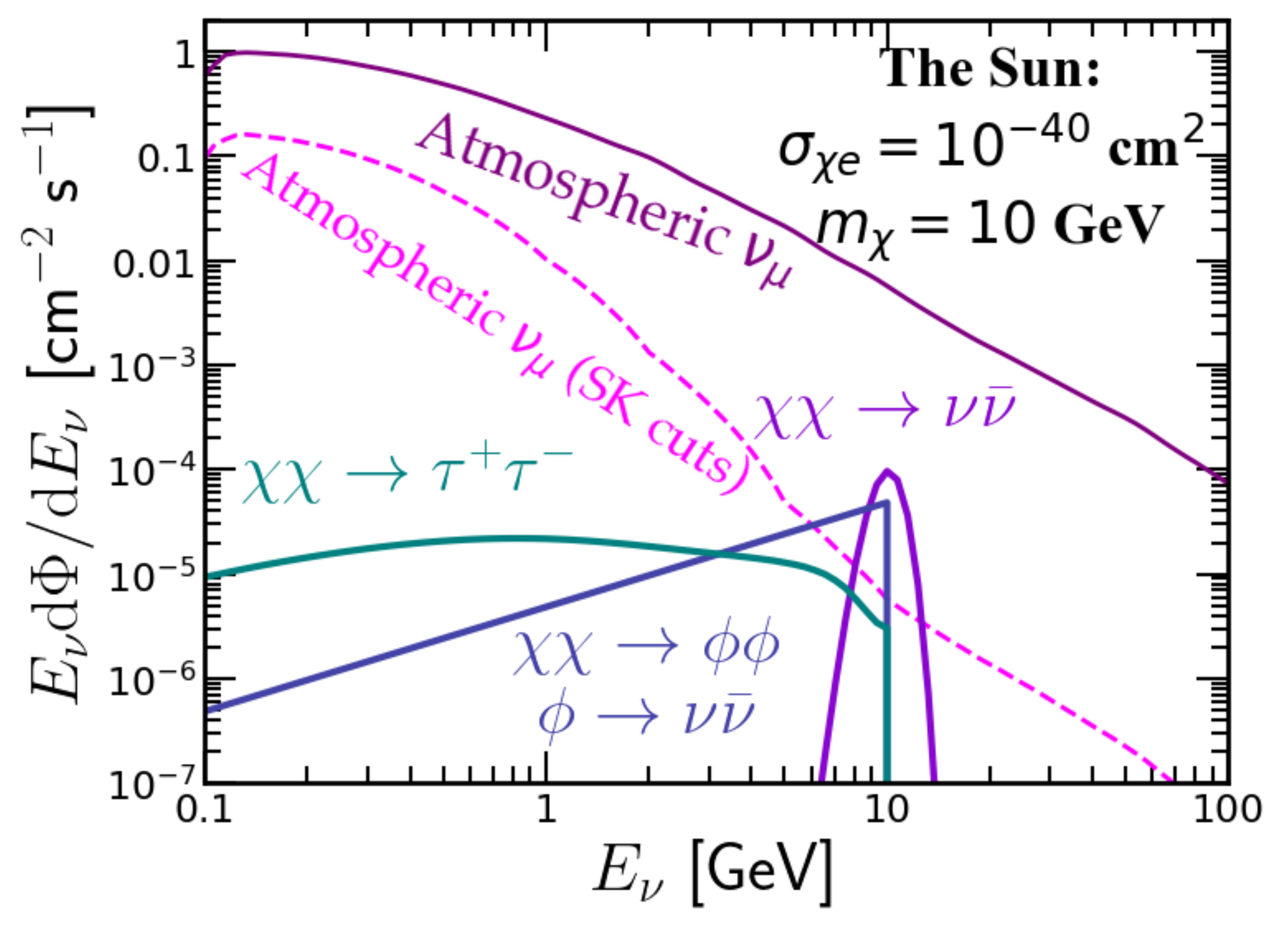


- The background is less than 1 event!
- Reducing Atmospheric background with Super-K angular resolution.

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

Leptophilic dark matter cross section constraint

Using the Sun and 10-year Super-Kamiokande observation



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Leptophilic dark matter cross section constraint

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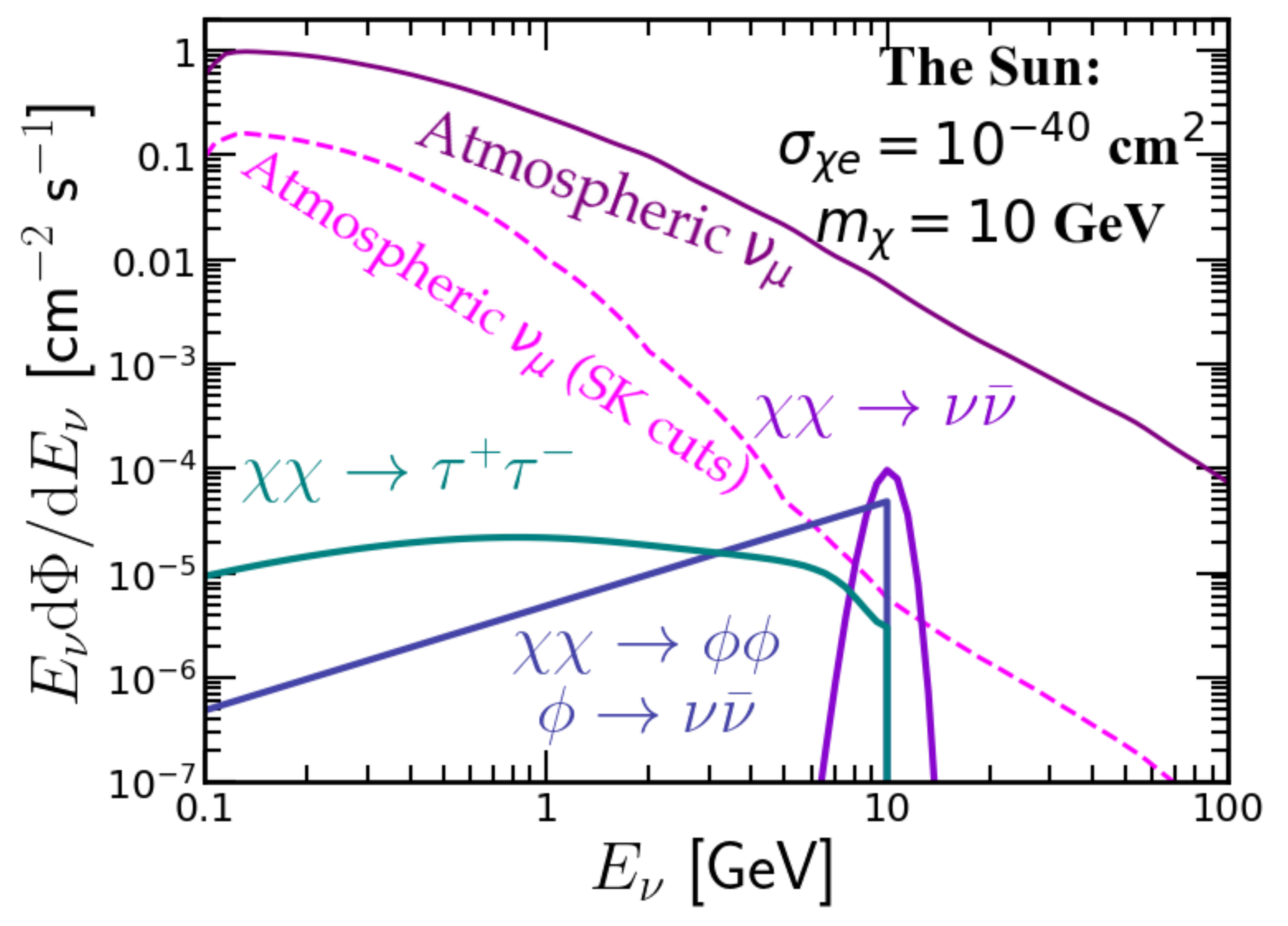

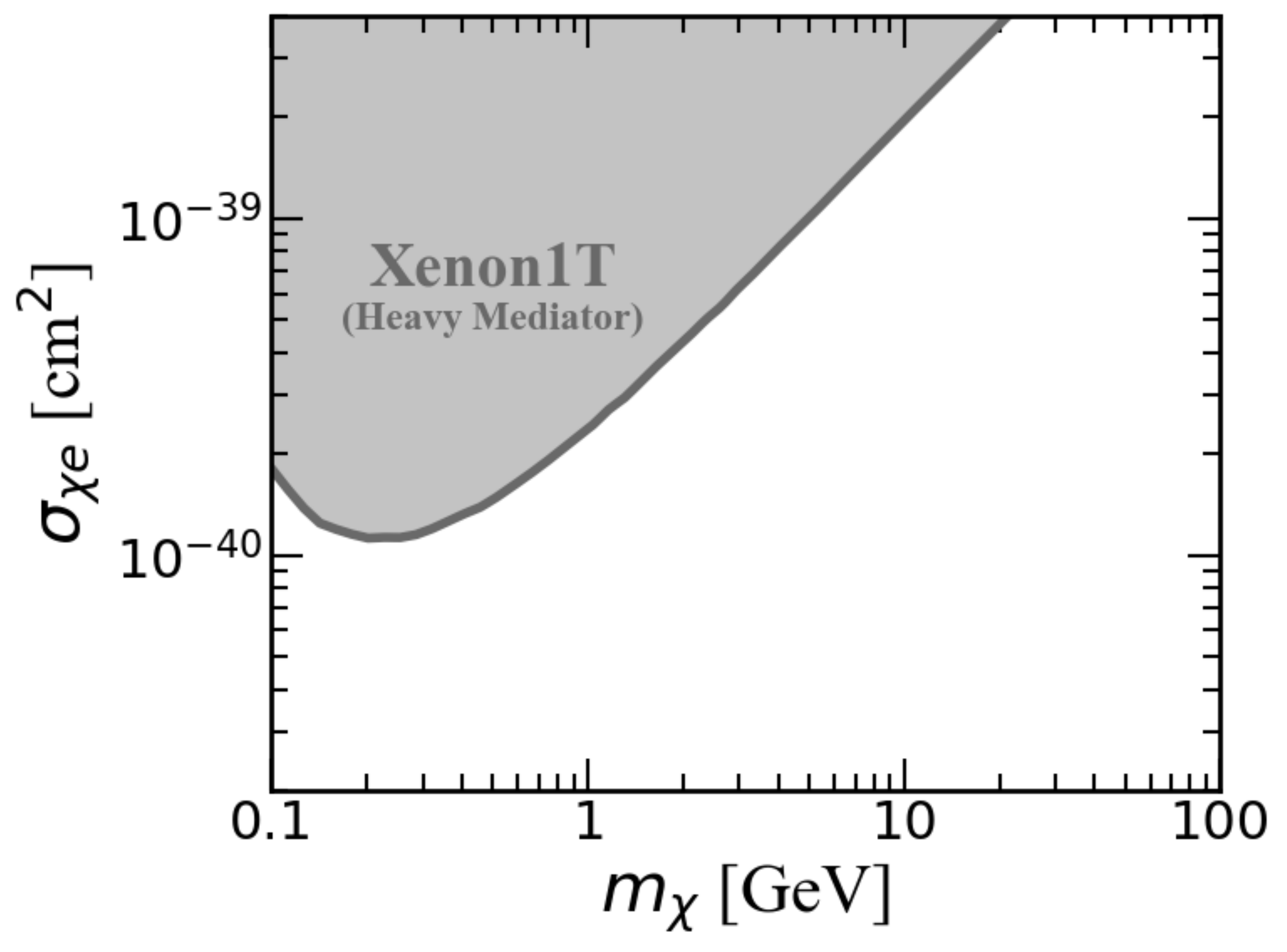

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Leptophilic dark matter cross section constraint

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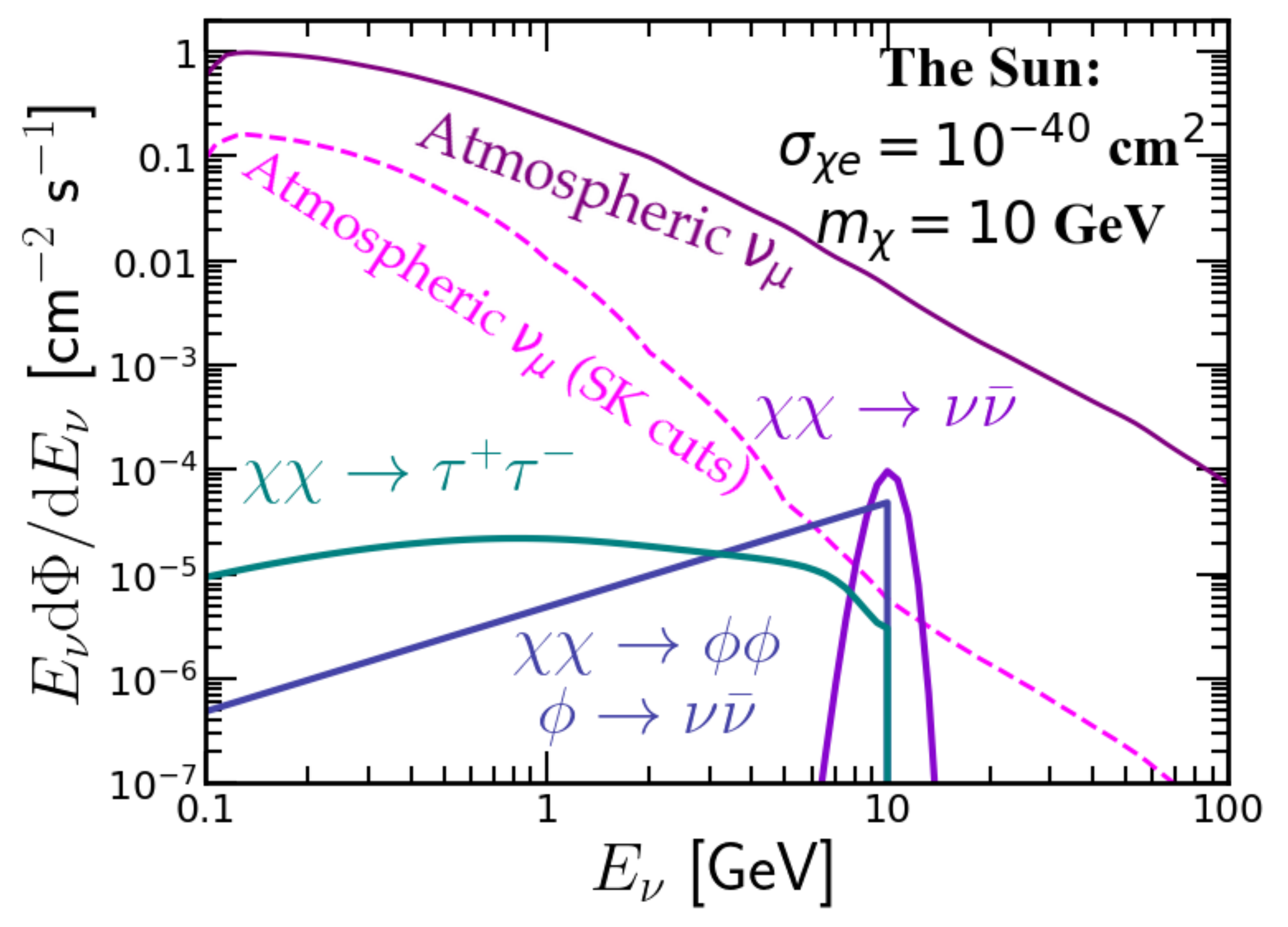
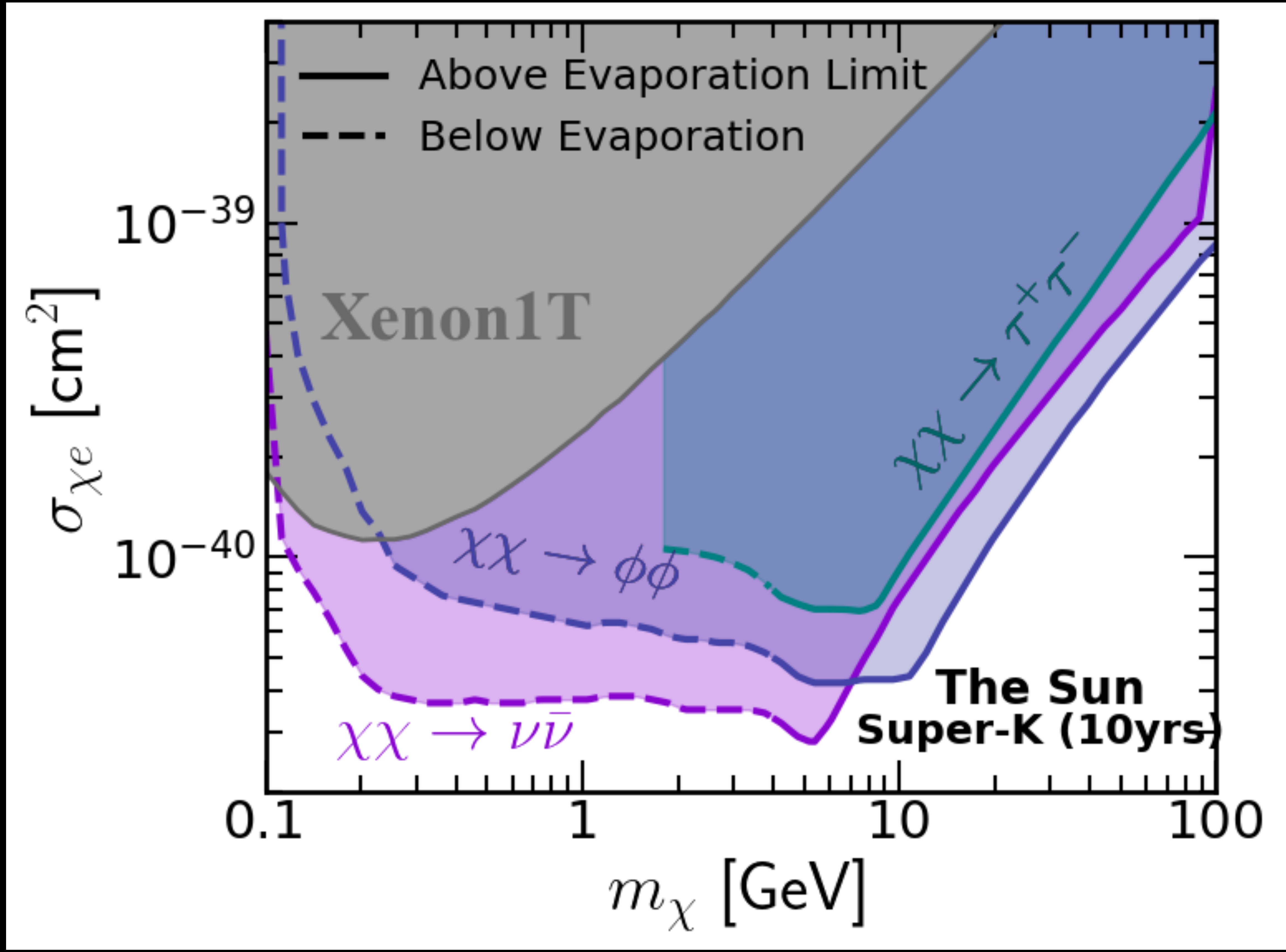




TTQN, Tim Linden, Pierluca Carenza, Axel Widmark (arXiv:2501.14864)

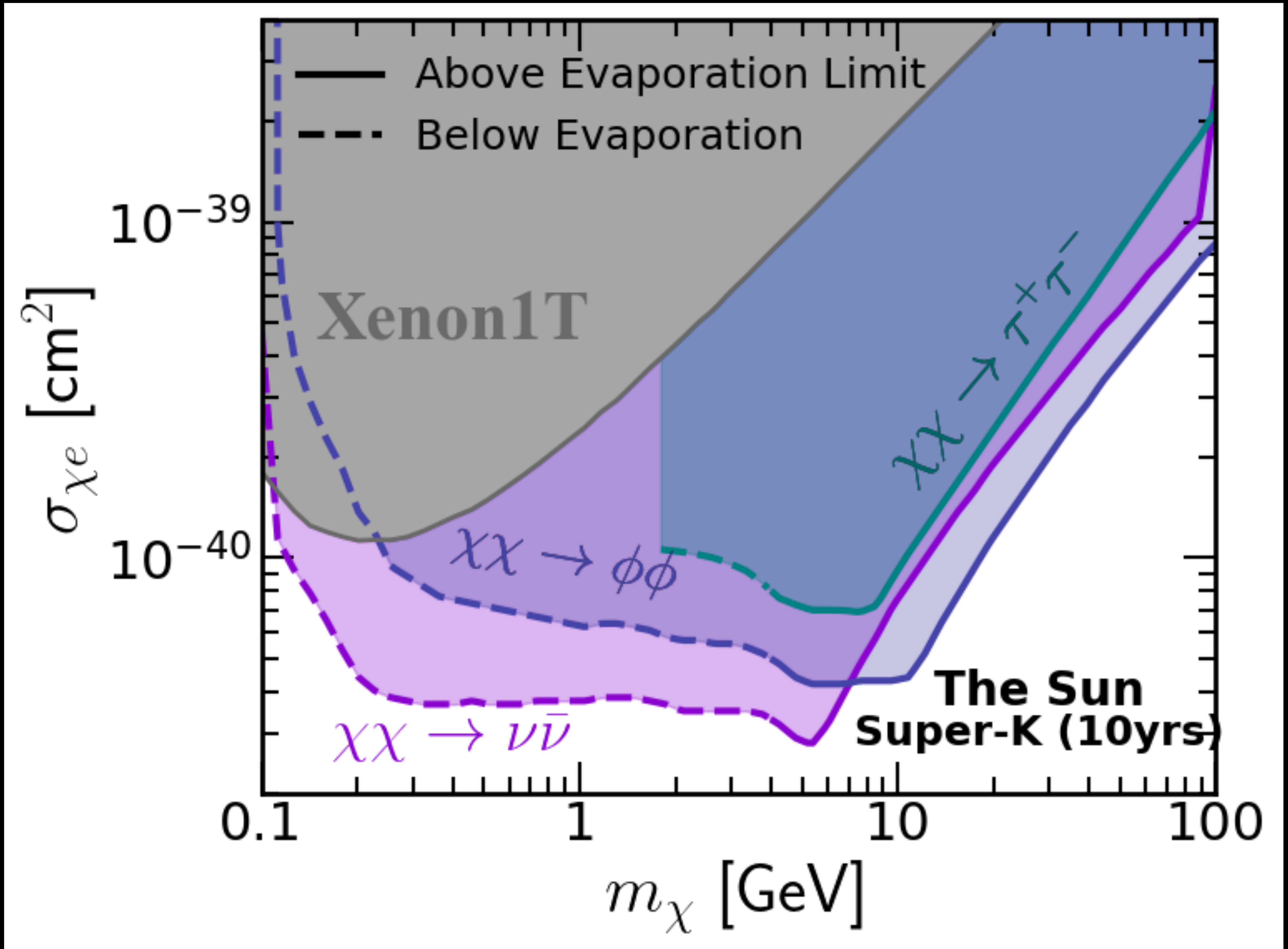
Conclusion 1

- We provide the strongest constraints for DM-electron cross section, from 4-100 GeV Leptophilic DM.
- For Hyper-K, we provide the projection that is an order of magnitude improvement.
- We also have the results for DM models with momentum-dependence cross section (check our 2501.14864 paper)

What next?
Probing the sub-GeV DM regime with Jupiter

Dark Matter Evaporation

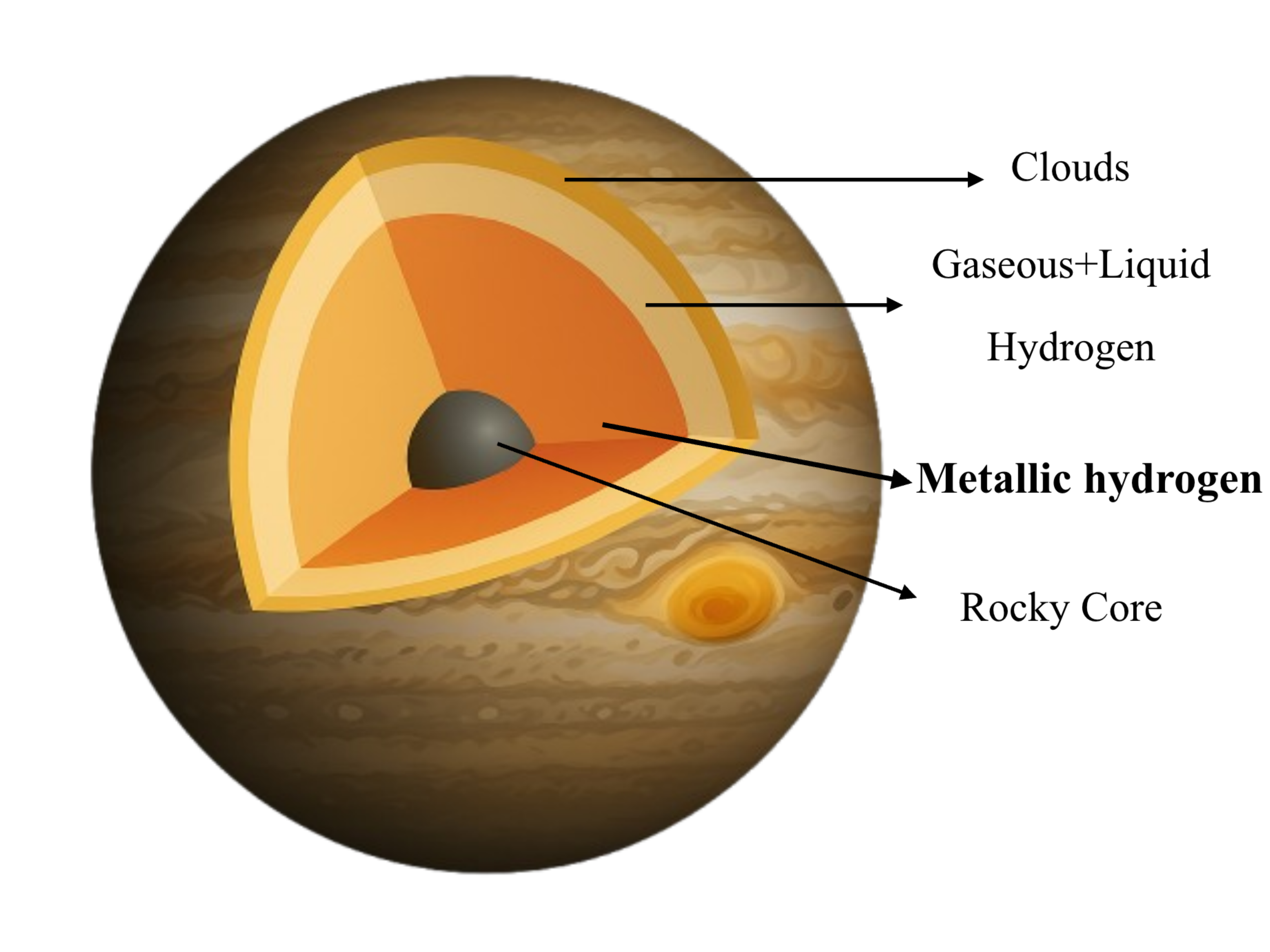
A challenge in this direction



- The Sun evaporates DM below 4 GeV!!!
- Require other DM detection strategies (See Rebecca Leane's talk on Thursday!)

Jupiter with Metallic Hydrogen

Acting as Dark Matter Refrigerator!!!



Electrons in Metallic Hydrogen are cold and follow Fermi-Dirac Distribution!

Cannot transfer enough energy to DM to evaporate them!

Jupiter with Metallic Hydrogen

Acting as Dark Matter Refrigerator!!!

Jupiter Metallic Hydrogen as Dark Matter Refrigerator: Probing sub-GeV Dark Matter-Electron Theory target with the Jovian Airglow

Thong T.Q. Nguyen,[1,*] Carlos Blanco,[2,3,4,*] and Tim Linden[1,5,†]

[1] *Stockholm University and The Oskar Klein Centre for Cosmoparticle Physics, Alba Nova, 10691 Stockholm, Sweden*
[2] *Department of Physics, The Pennsylvania State University, University Park, PA 16802, USA*
[3] *Institute for Gravitation and the Cosmos, The Pennsylvania State University, University Park, PA 16802, USA*
[4] *Institute for Computational and Data Sciences, The Pennsylvania State University, University Park, PA 16802, USA*
[5] *Erlangen Centre for Astroparticle Physics (ECAP), Friedrich-Alexander-Universität Erlangen-Nürnberg, Nikolaus-Fiebiger-Str. 2, 91058 Erlangen, Germany*

Carlos Blanco

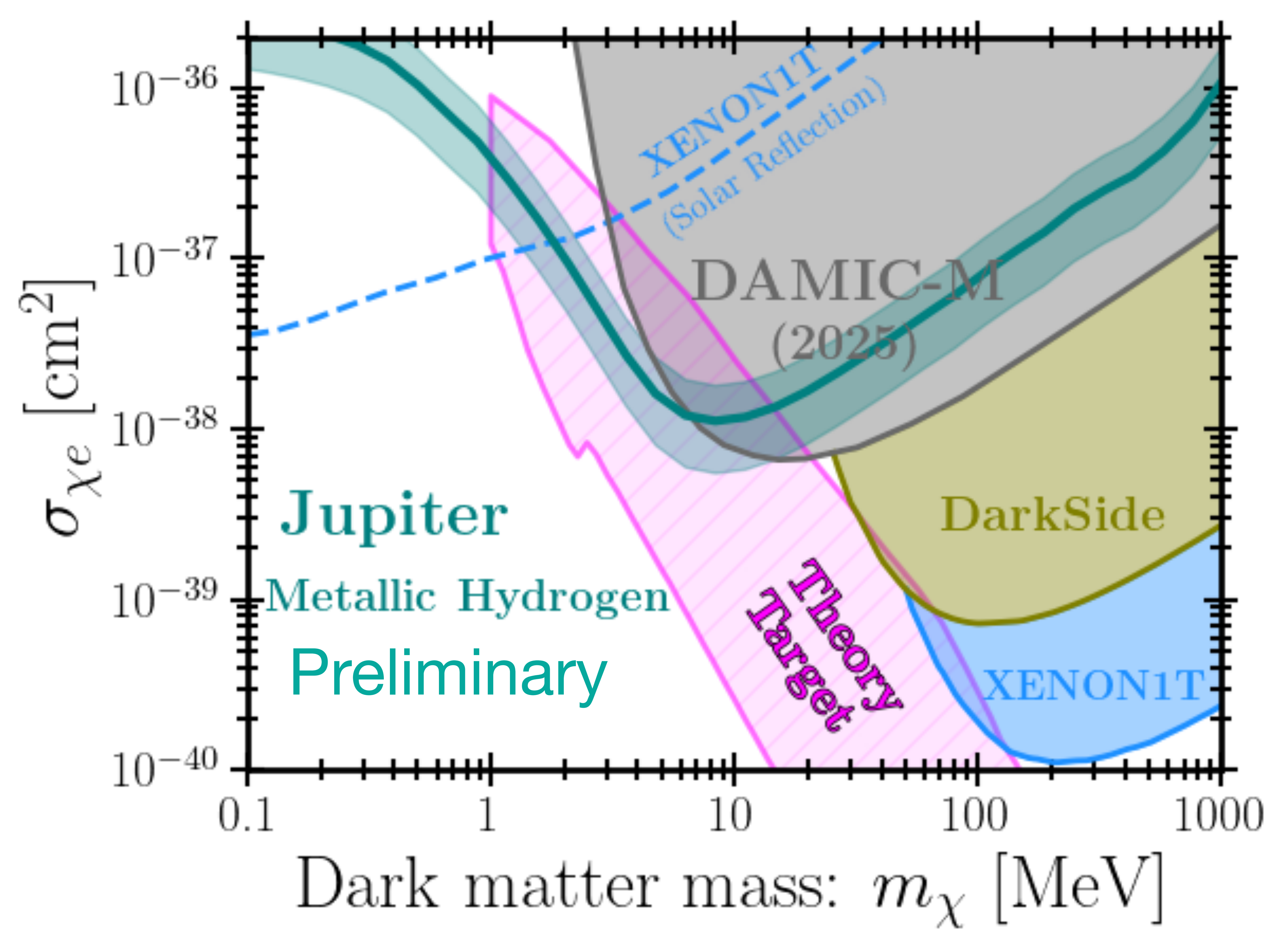
Penn State U.

Other References:

- Blanco, Leane, Moore, Tong (2408.15318)
- Blanco and Leane, PRL (2312.06758)

Jupiter with Metallic Hydrogen

Acting as Dark Matter Refrigerator!!!



TTQN, Carlos Blanco, Tim Linden, in preparation!

Conclusion 2

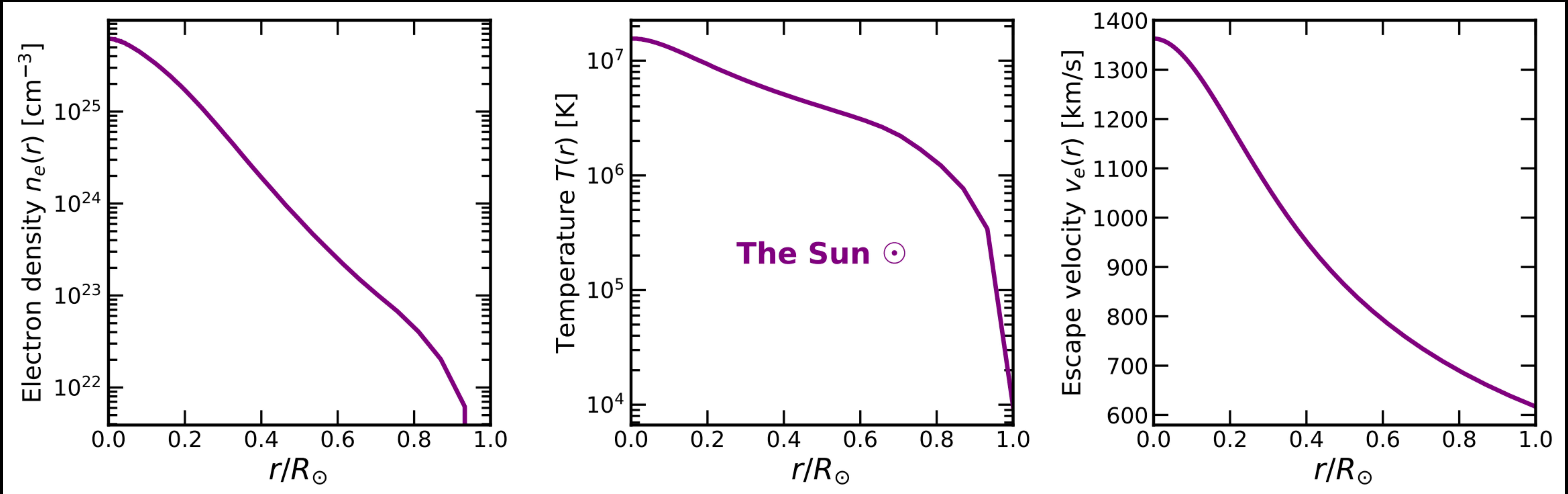
More like an advertisement!

- Jupiter is a promising detector for sub-GeV leptophilic DM.
- We provide the strongest constraints that can probe a large portion of theory-target parameter space.
- Stay tuned for our work!!


Thank you for listening!
Chiao is searching for Dog-matter too!

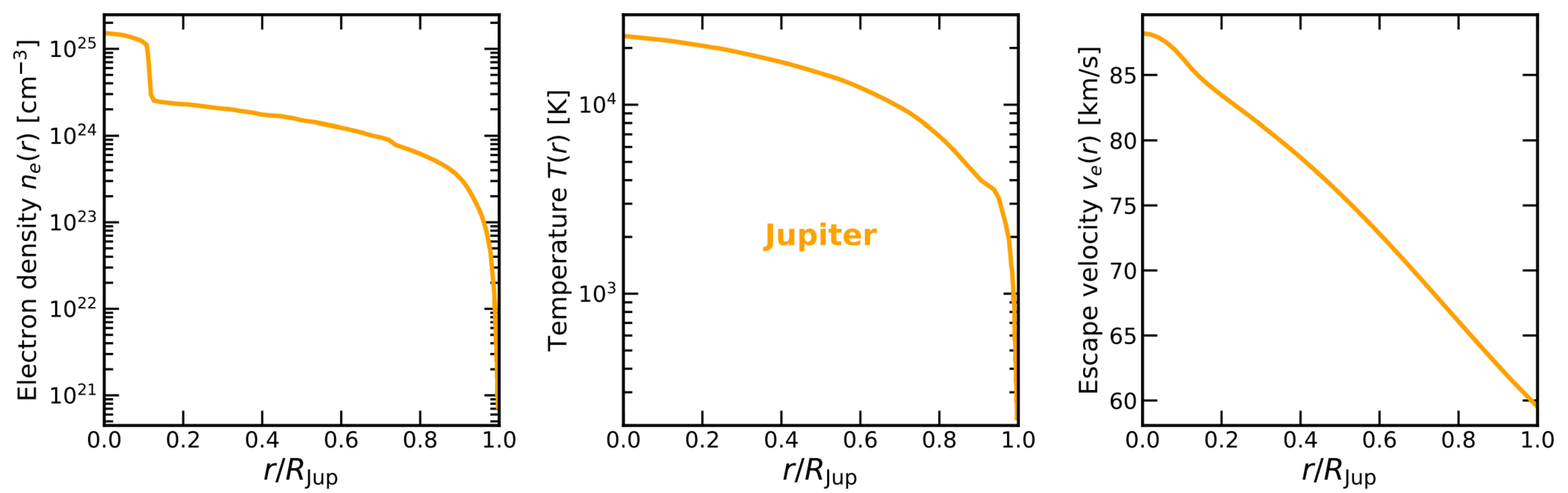
Backup Slide

The Solar model



Jupiter model

Jovian J11-4a



Metallic Hydrogen

Inside Jupiter

Metallic hydrogen

38 languages

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From Wikipedia, the free encyclopedia

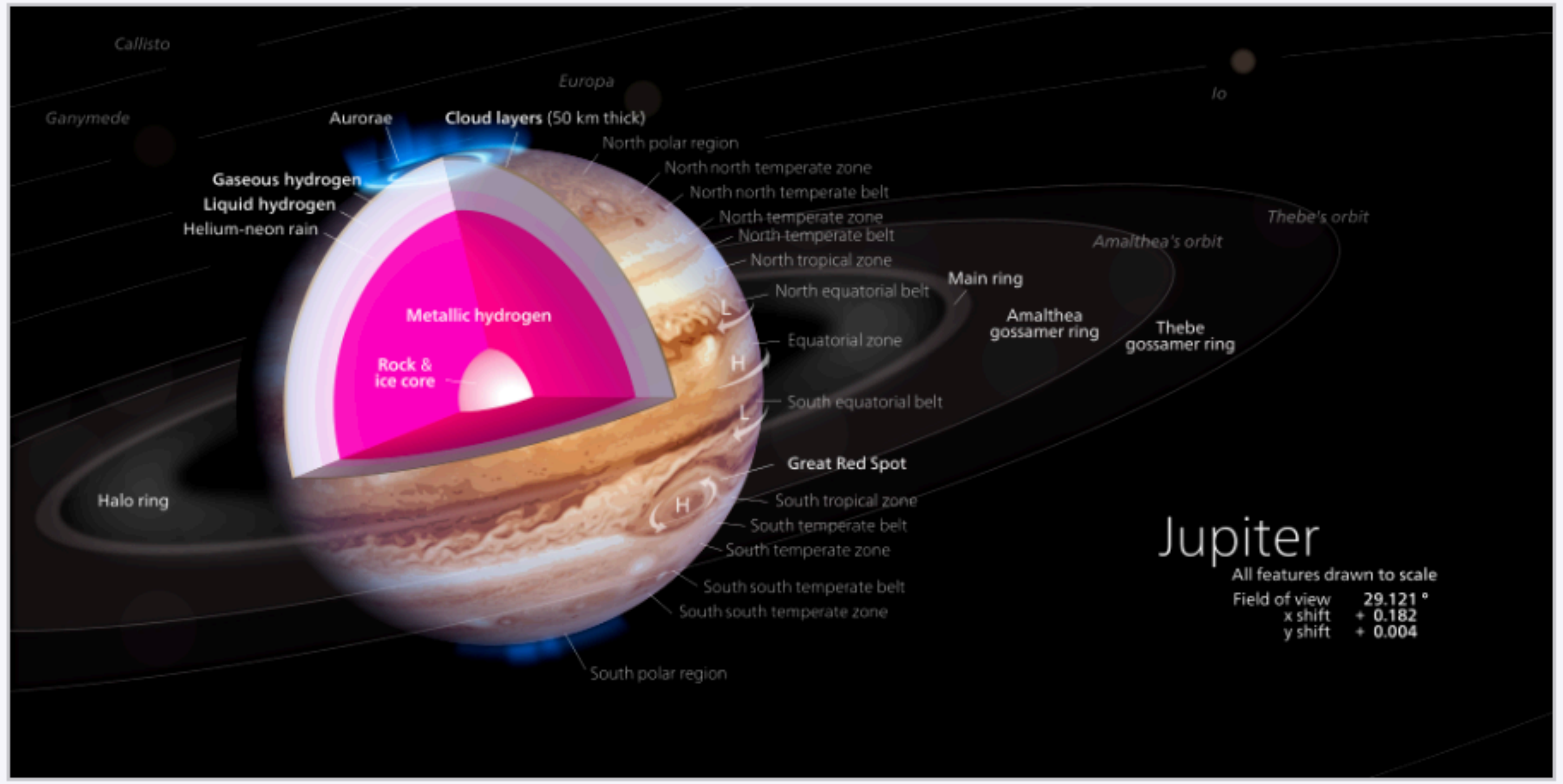
Metallic hydrogen is a phase of hydrogen in which it behaves like an electrical conductor. This phase was predicted in 1935 on theoretical grounds by Eugene Wigner and Hillard Bell Huntington.[1]

At high pressure and temperatures, metallic hydrogen can exist as a partial liquid rather than a solid, and researchers think it might be present in large quantities in the hot and gravitationally compressed interiors of Jupiter and Saturn, as well as in some exoplanets.[2]

Theoretical predictions [edit]

Hydrogen under pressure [edit]

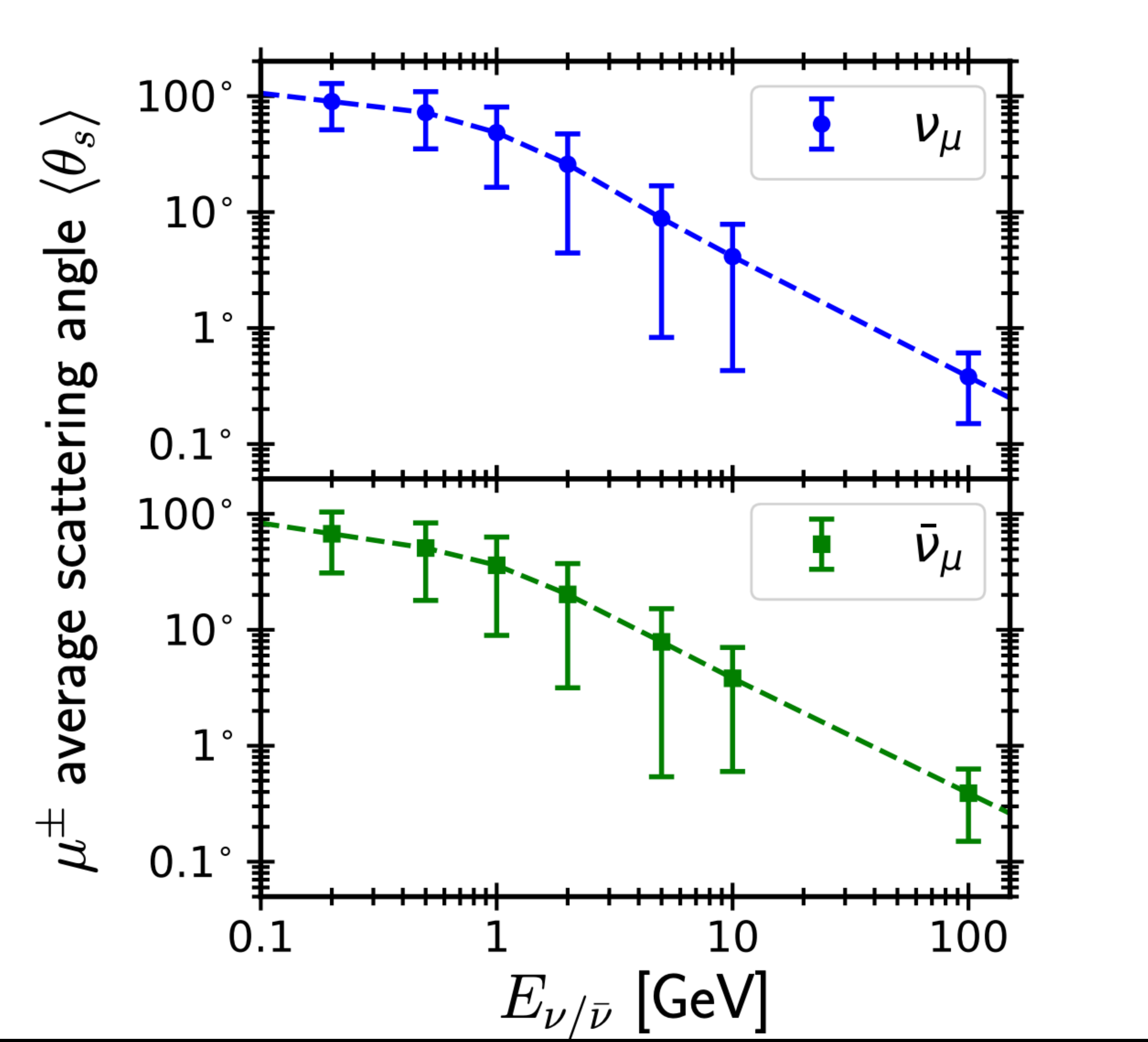
Though often placed at the top of the alkali metal column in the periodic table, hydrogen does not, under ordinary conditions, exhibit the properties of an alkali metal. Instead, it forms diatomic H_2 molecules, similar to halogens and some nonmetals in the second period of the periodic table, such as nitrogen and oxygen. Diatomic hydrogen is a gas that, at atmospheric pressure, liquefies and solidifies only at very low temperature (20 K and 14 K respectively).



A diagram of Jupiter showing a model of the planet's interior, with a rocky core overlaid by a deep layer of liquid metallic hydrogen (shown as magenta) and an outer layer predominantly of molecular hydrogen.

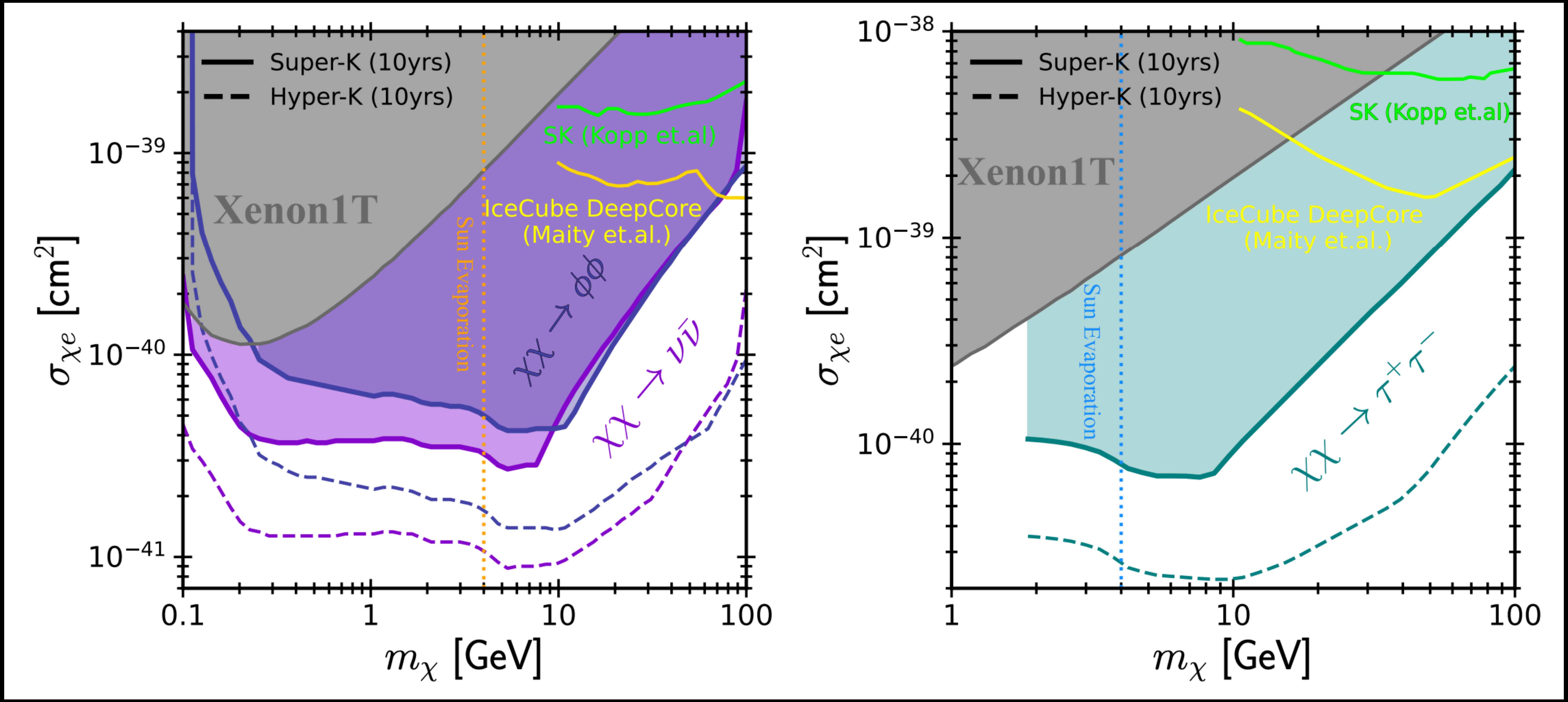
In 1935, physicists Eugene Wigner and Hillard Bell Huntington

Super-K angular resolution



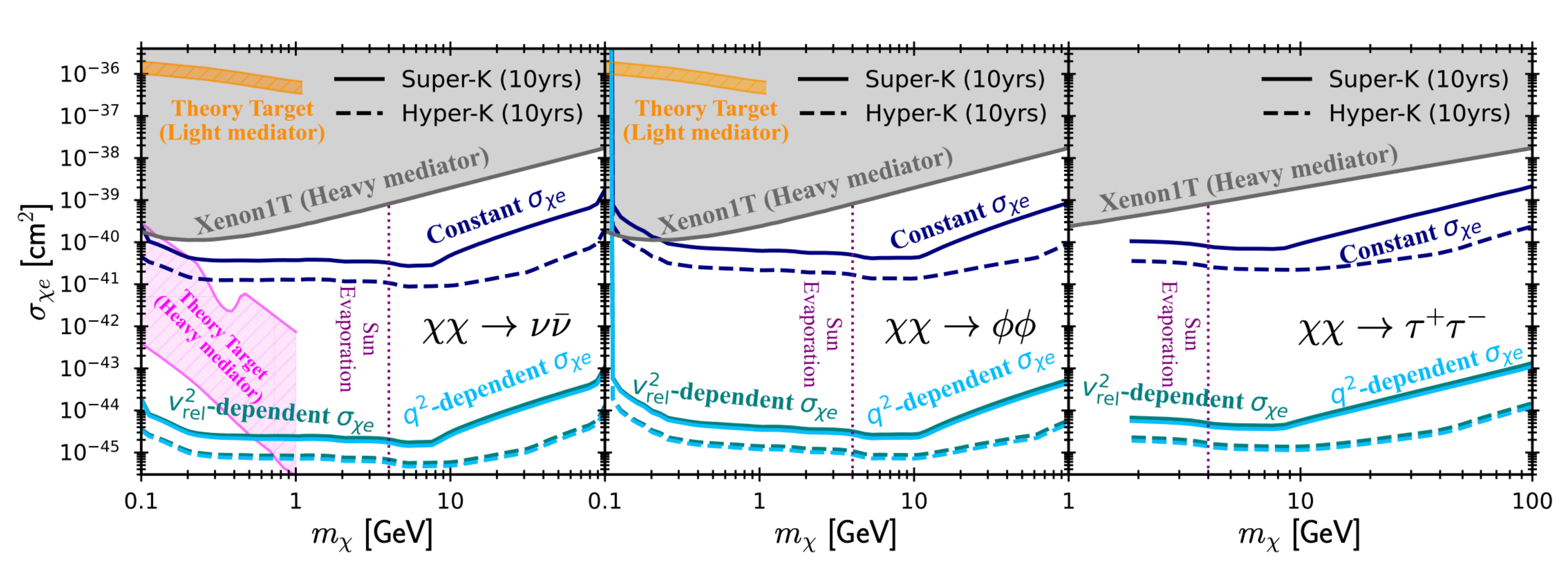
Super-K and Hyper-K

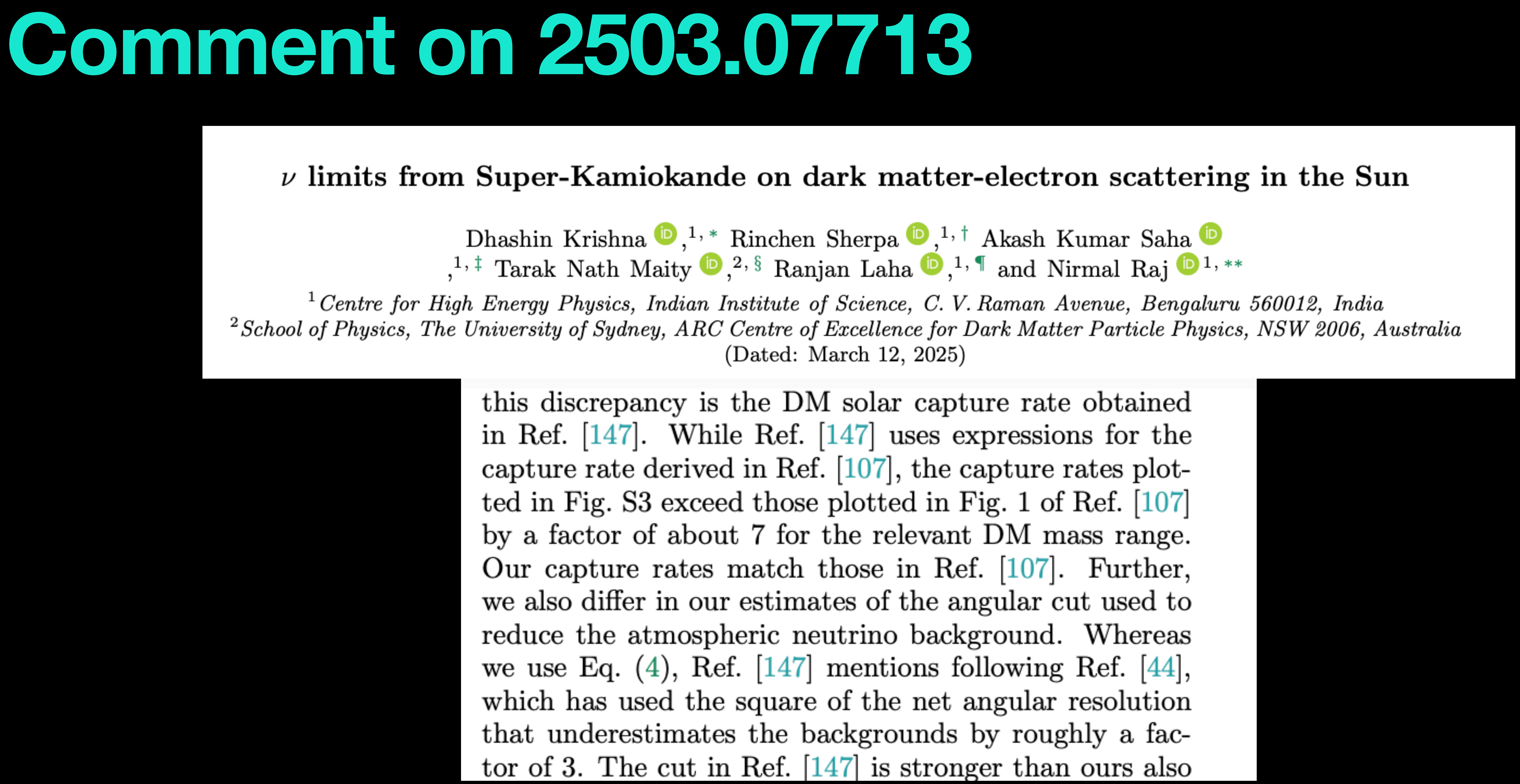
Maybe Super-Duper-Kamiokande in the future?



Velocity and Momentum-dependent cross sections

Too fast too furious!




Comment on 2503.07713
ν limits from Super-Kamiokande on dark matter-electron scattering in the Sun
Dhashin Krishna [1,*] Rinchen Sherpa [1,†] Akash Kumar Saha [1,‡] Tarak Nath Maity [2,§] Ranjan Laha [1,¶] and Nirmal Raj [1,**]
[1] Centre for High Energy Physics, Indian Institute of Science, C. V. Raman Avenue, Bengaluru 560012, India
[2] School of Physics, The University of Sydney, ARC Centre of Excellence for Dark Matter Particle Physics, NSW 2006, Australia
(Dated: March 12, 2025)
this discrepancy is the DM solar capture rate obtained in Ref. [147]. While Ref. [147] uses expressions for the capture rate derived in Ref. [107], the capture rates plotted in Fig. S3 exceed those plotted in Fig. 1 of Ref. [107] by a factor of about 7 for the relevant DM mass range. Our capture rates match those in Ref. [107]. Further, we also differ in our estimates of the angular cut used to reduce the atmospheric neutrino background. Whereas we use Eq. (4), Ref. [147] mentions following Ref. [44], which has used the square of the net angular resolution that underestimates the backgrounds by roughly a factor of 3. The cut in Ref. [147] is stronger than ours also

Compare with previous capture rate results

We are confident that we have obtained the correct finite-temperature capture rate!