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# Transport by Dark Matter and Stellar Evolution

Diogo Capelo  
CENTRA, Técnico, U. Lisboa

In collaboration with Ilídio Lopes

**International Conference on Dark Matter and Stars (2025)**  
Kingston, Queen's University

July 15<sup>th</sup>, 2025



# Intro

Stars as Dark Matter Laboratories  
Capture and Transport in Stars  
A Tale of Two Scenarios

# Results

Photometry and Asteroseismology  
Testing the Transport Models  
Comparing the Transport Models

# Conclusion

Summary  
The Future

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# Results

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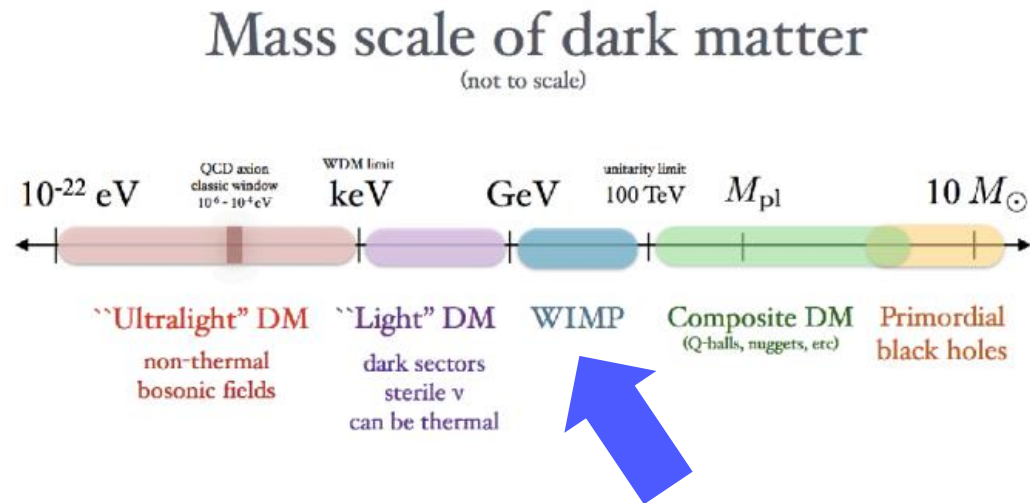
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# Dark Matter (DM), but what kind?

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Weakly Interacting **M**assive **P**articles



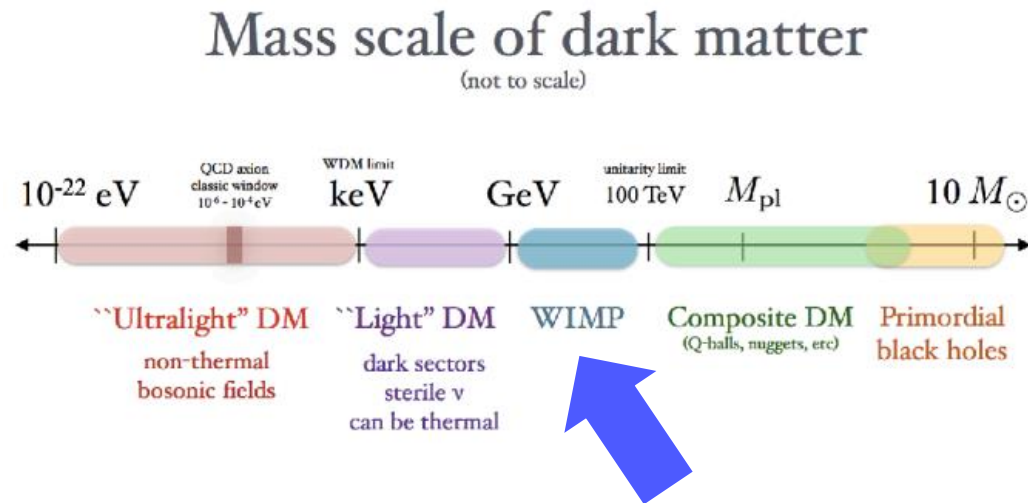
**FIG 1** The mass scale of different DM models. WIMPs occupy the range in the GeV to TeV. From **Lin 2019**.

# Dark Matter (DM), but what kind?

Weakly Interacting **M**assive **P**articles

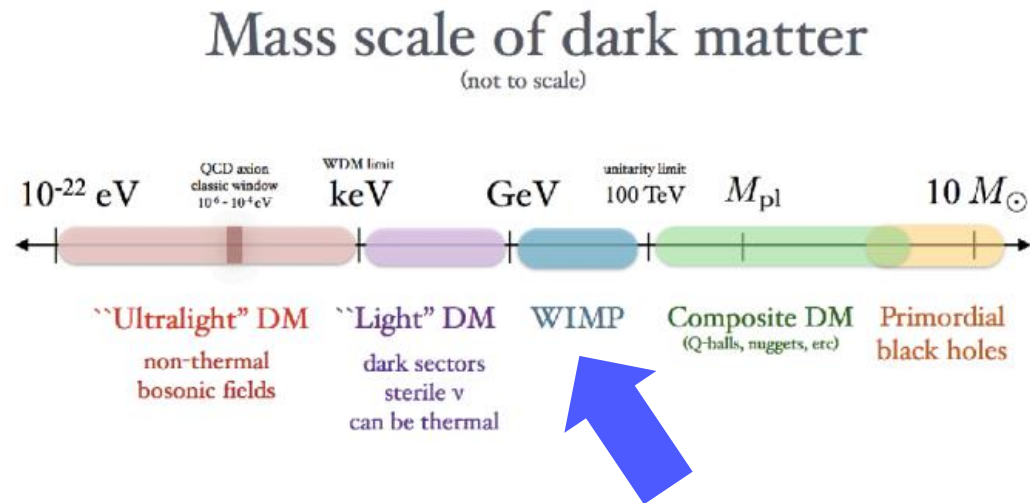
**Weakly**

$$\sigma \sim 10^{-30} - 10^{-50} \text{ cm}^2$$



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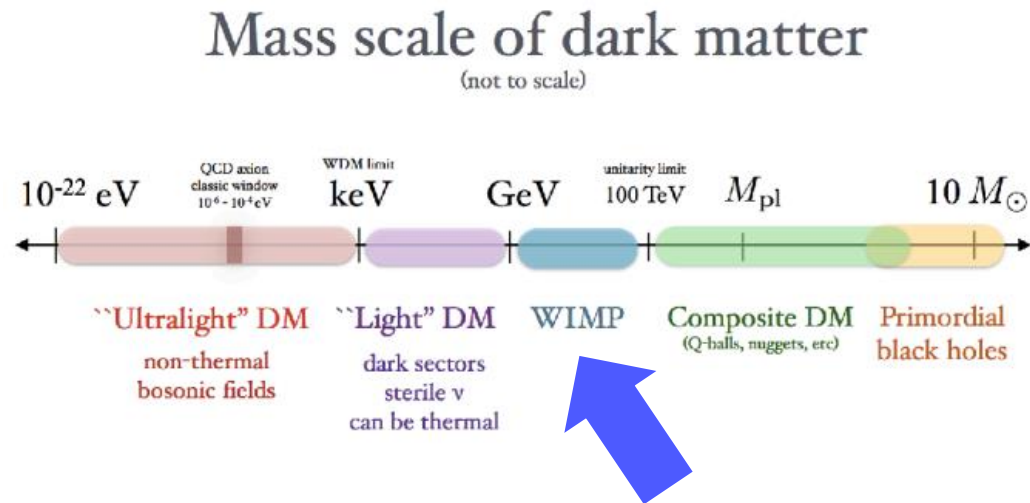
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**I**nteracting

spin-dependent (**SD**): hydrogen only  
spin-independent (**SI**): all elements

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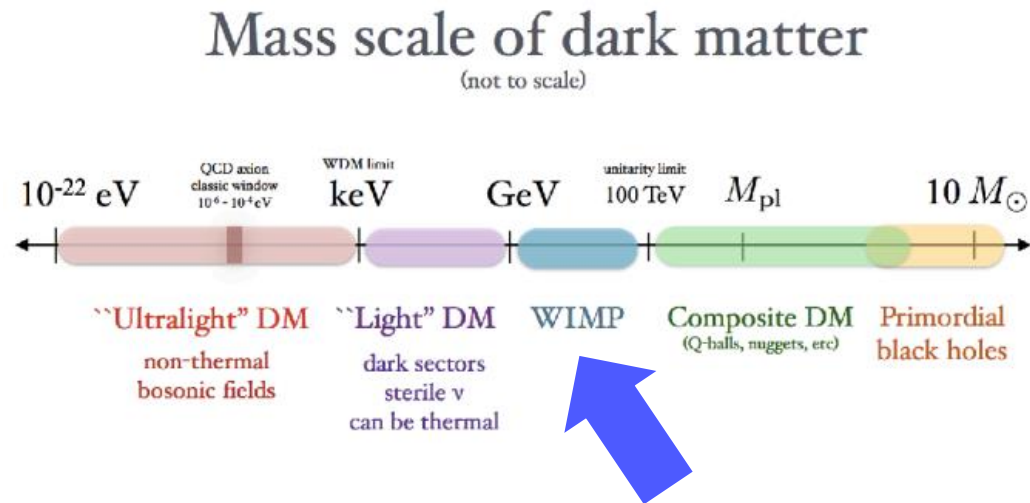
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**Massive**

GeV – TeV mass range

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**Weakly Interacting Massive Particles**

**Weakly**

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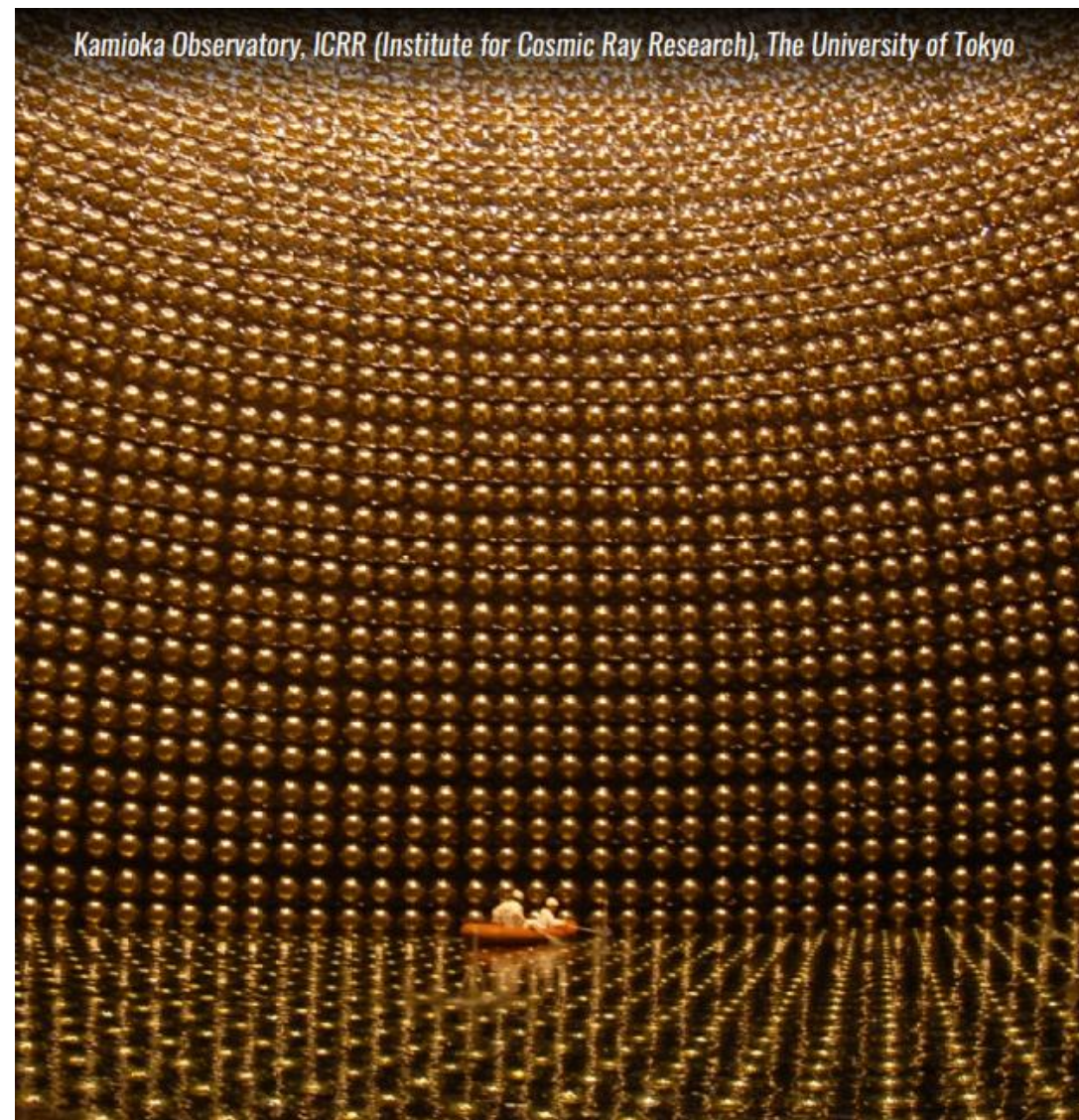
**Particles**

not macroscopic

# Stars as DM Labs

## Big and Plentiful

Large numbers, volumes, unique conditions



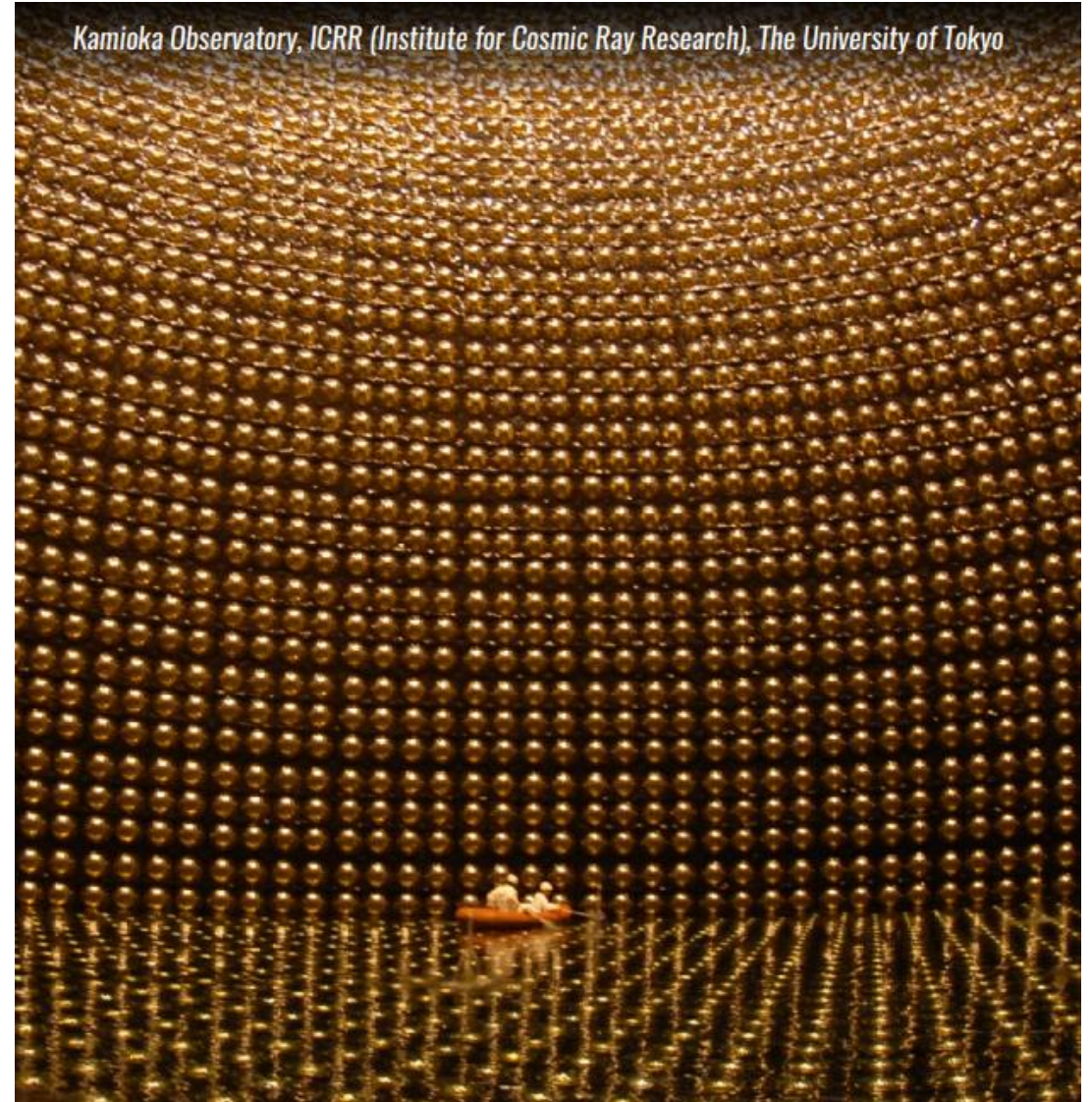
# Stars as DM Labs

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## Everywhere

Affected by different extrinsic conditions



# Stars as DM Labs

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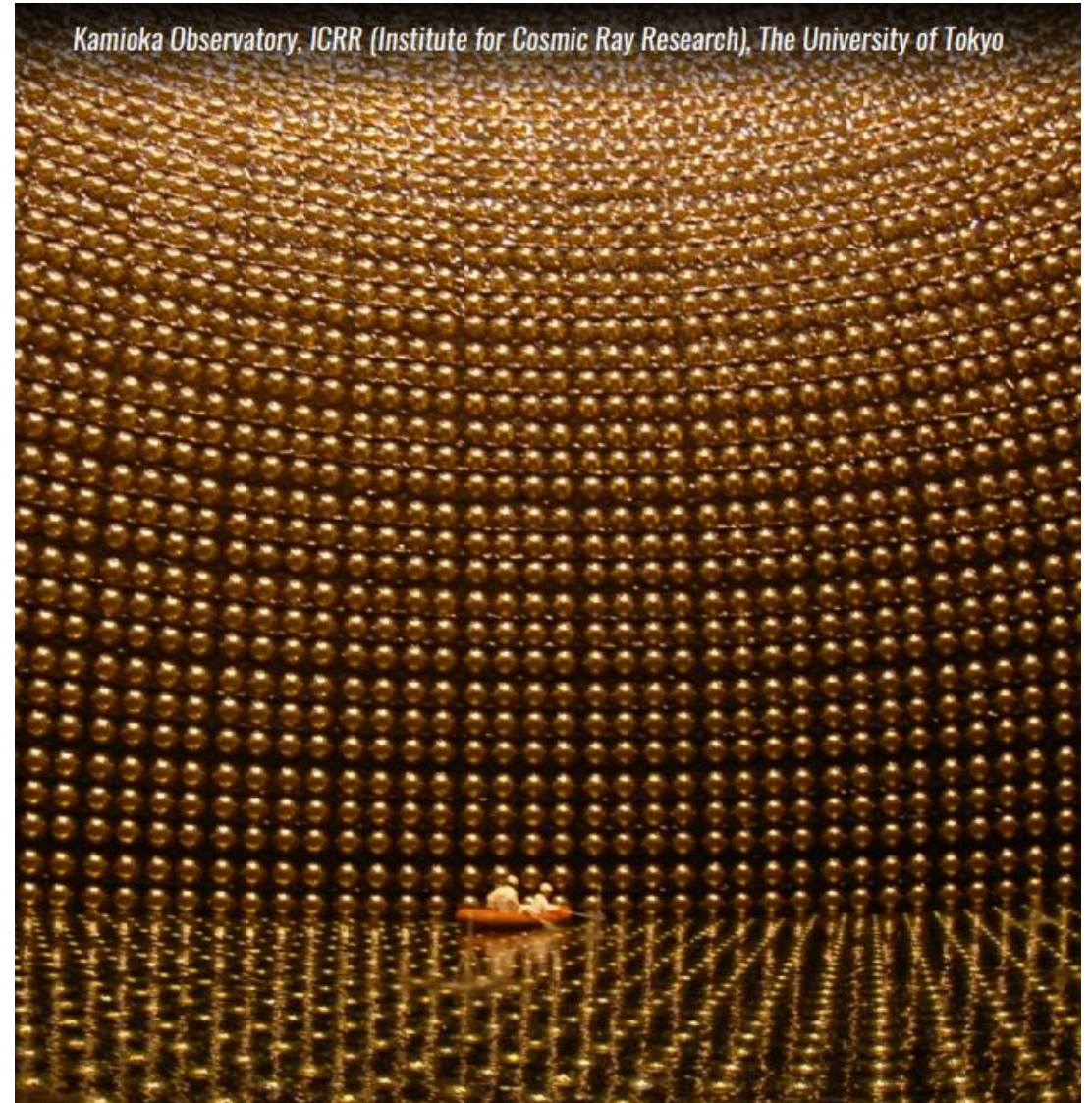
## Everywhere

Affected by different extrinsic conditions

## Catch-All

Accumulate DM regardless of model\*

\* limits may apply (but fewer than you may think)



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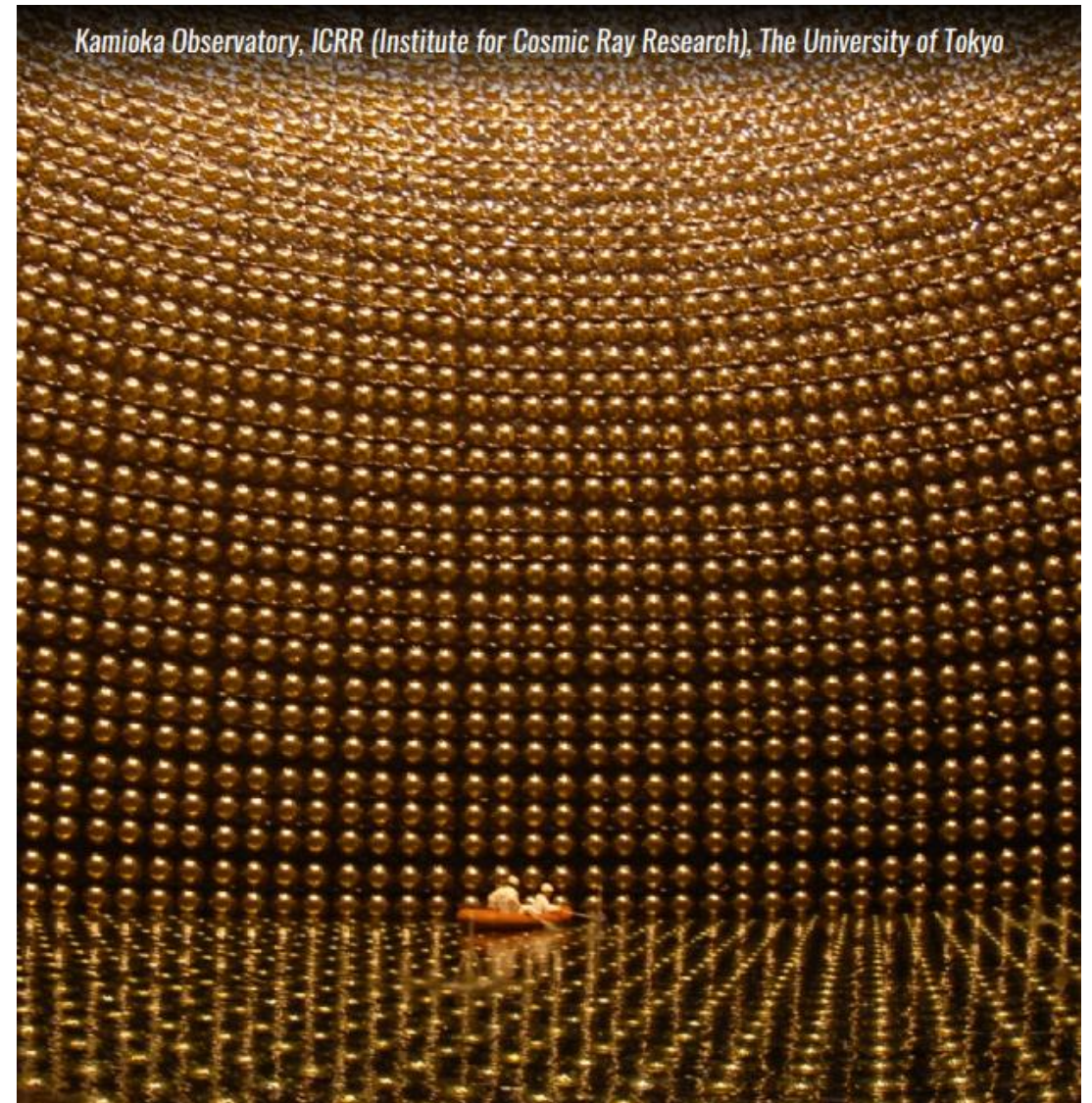
## Catch-All

Accumulate DM regardless of model\*

*Search for signatures of DM interactions changing stellar structure or evolution*

**Spergel & Press 1985; Lopes & Silk 2002;  
Moskalenko & Wai 2007**

\* limits may apply (but fewer than you may think)



# Dark Matter in Stars

$$\frac{dN_\chi}{dt} = C(t) - E(t)N_\chi - A(t)N_\chi^2$$

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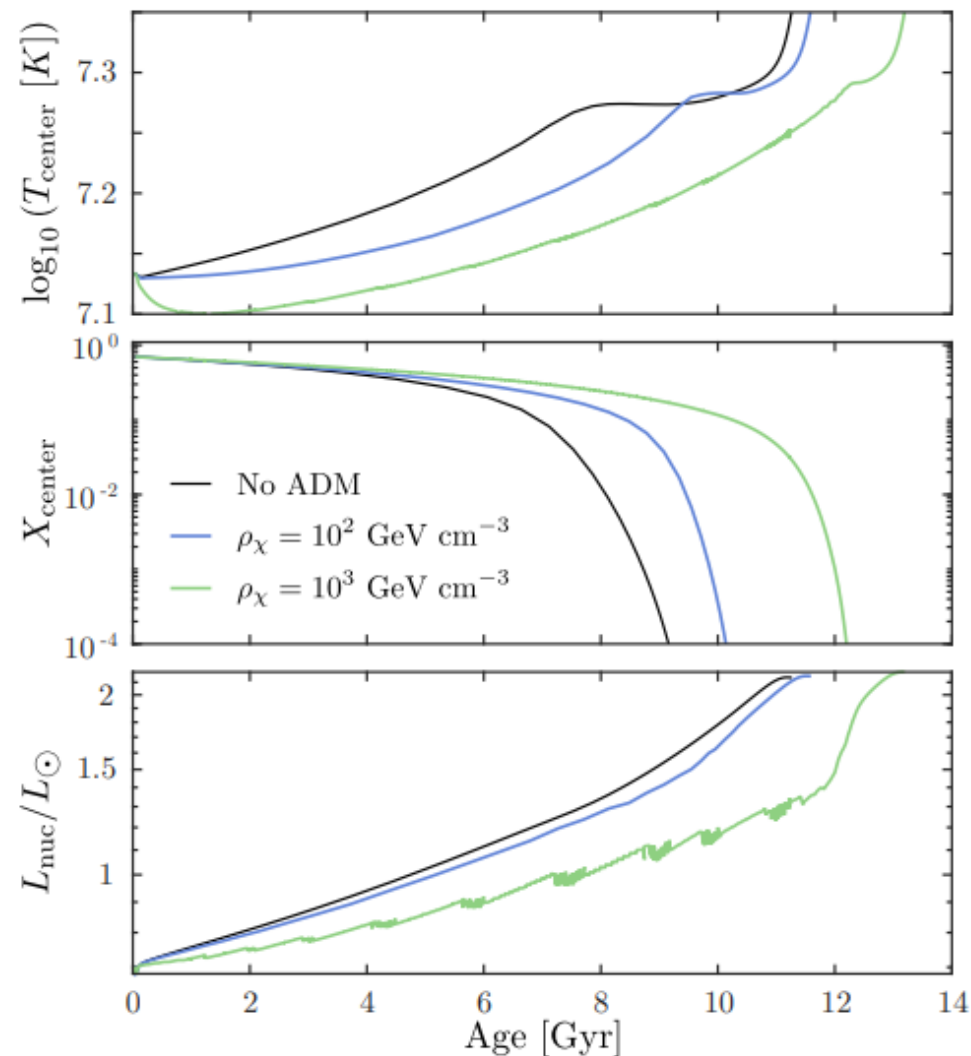
# Dark Matter in Stars

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Asymmetric Dark Matter (ADM)  $\Rightarrow A(t) \approx 0$   
**Kaplan et al. 2019**

**FIG III** Evolution of central temperature, hydrogen mass fraction and nuclear luminosity of a  $1 M_\odot$  star in different ADM density scenarios, showing prolonged Main Sequence life, in **Lopes & Lopes 2019 (i)**



# Capture

DM particles in the halo can get gravitationally bound inside a star (**Gould 1987**)

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*Single scattering capture promoted by baryonic nuclei at non-relativistic speeds*

$$C = \sum_i \int_0^R dr 4\pi r^2 \int_0^{u_{max,i}(r)} du \frac{\rho_\chi}{m_\chi} \frac{f(u)}{u} w \Omega_i(0, v_{esc}; w)$$

$$w \equiv w(r) = \sqrt{u^2 + v_{esc}(r)^2}$$

$$u_{max,i}(r) = \frac{2\sqrt{m_\chi m_i}}{|m_\chi - m_i|} v_{esc}^2$$

\*Computing clusters really hate this one task

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# Capture

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Single scattering approximation is not a universal prescription: **breaks down** at high masses or cross-sections

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# Capture

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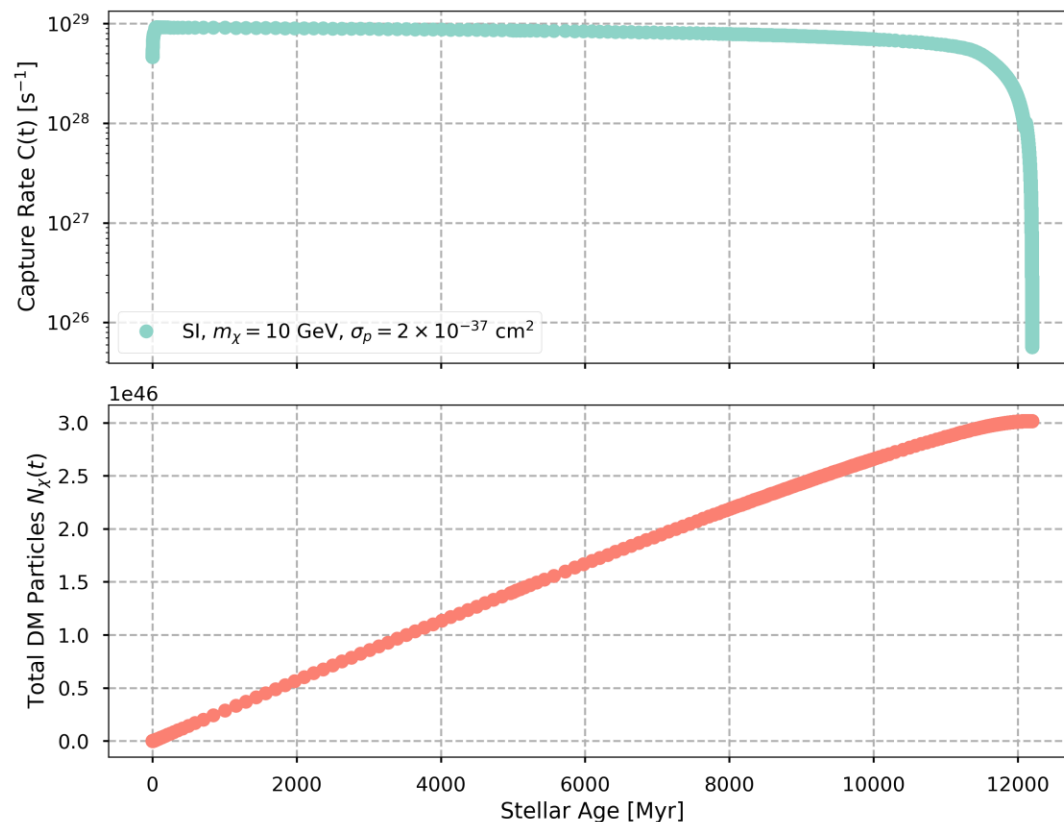
Scaling relation (**Zentner & Hearin 2011**) holds up to  $m_\chi \approx 15$  GeV \*

$$C = C_{\odot}^{SI,SD} \left( \frac{\rho_\chi}{0.4 \text{ GeV cm}^{-3}} \right) \left( \frac{\sigma_p}{10^{-43} \text{ cm}^2} \right) \times \left( \frac{v_{esc}}{618 \text{ km s}^{-1}} \right) \left( \frac{270 \text{ km s}^{-1}}{\bar{v}} \right)$$

$$C_{\odot}^{SI} = 7 \times 10^{22} \text{ s}^{-1}$$

$$C_{\odot}^{SD} = 5 \times 10^{21} \left( \frac{5 \text{ GeV}}{m_\chi} \right) \text{ s}^{-1}$$

\* it holds remarkably well at higher masses (depending on composition). In Sun-like the monoscattering assumption breaks down only slightly after this relation stops holding.



**FIG IV** Evolution of capture rate and total particle number of SI ADM with  $m_\chi = 10$  GeV and  $\sigma_p = 2 \times 10^{-37} \text{ cm}^2$  in a  $1 M_{\odot}$  star in the conditions of the solar system using the full multiscatter approach of **Leane & Smirnov 2023**

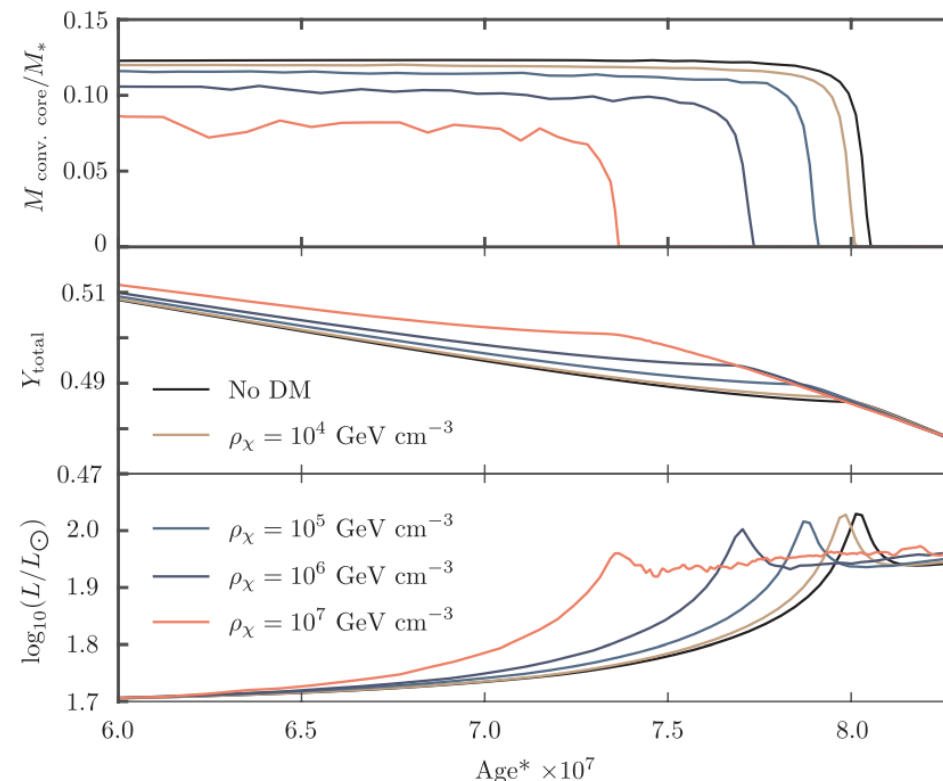
# DM phenomenology in MESA: **dmEFT**

Computes constant cross-section DM phenomenology and models **robustly** (implicitly or explicitly) its impact in the evolution of stars

Designed for use with **MESA**, a popular, open-source, 1D stellar evolution software in constant development

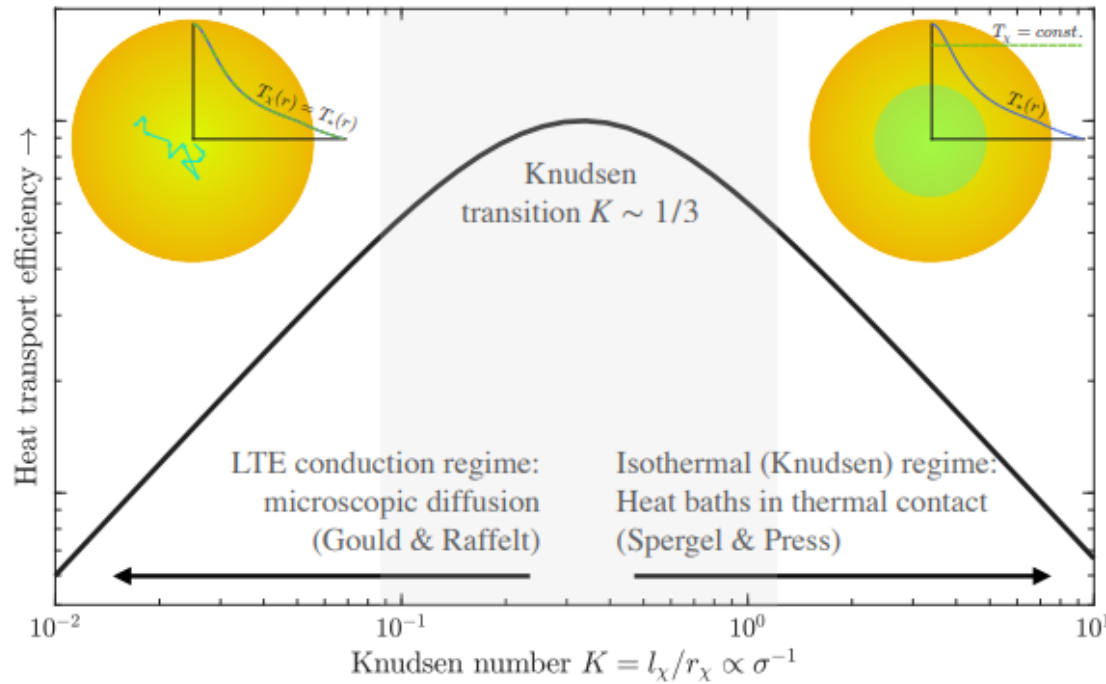
**Paxton et al. 2011; 2013; 2015; 2018; 2019**  
**Jermyn et al. 2023**

Its **modularity** facilitates adding features, or changing DM models



**FIG V** Mass of the convective core, total helium content and total luminosity of a  $1 M_{\odot}$  core Helium-burning star for different densities of dark matter and  $m_{\chi} = 4$  GeV. From **Lopes & Lopes 2019 (ii)**

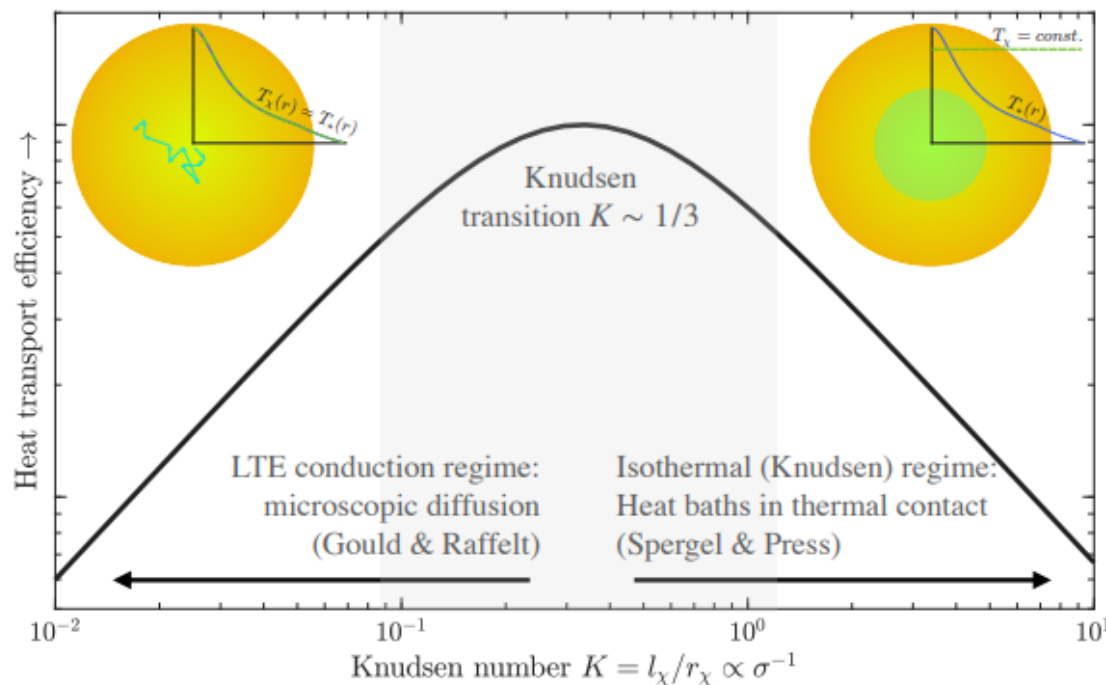
# A Tale of Two Scenarios



$$K \equiv \frac{l_\chi(0)}{r_\chi} = \frac{1}{\langle \sigma \rangle n(0)} \frac{1}{\sqrt{\frac{3k_B T_c}{2\pi G m_\chi \rho_c}}}$$

**FIG VI** Schematic diagram showing the efficiency of heat transport in stars by a weakly interacting particle, as a function of the Knudsen number,  $K$ , from **Banks et al. 2022**

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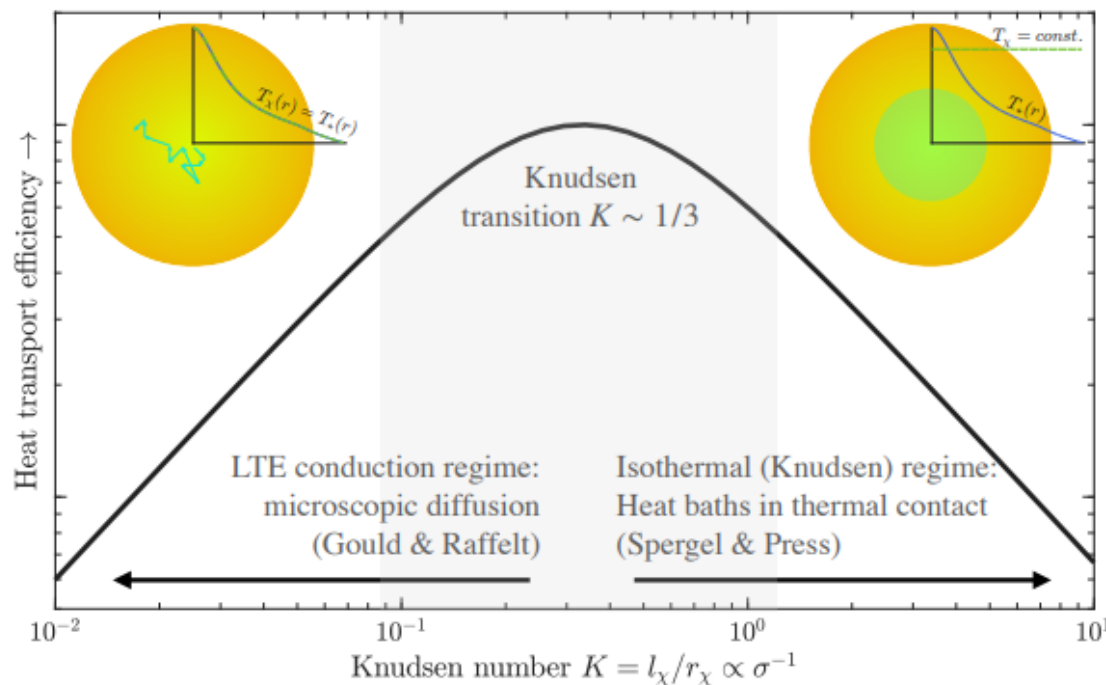
**Spergel & Press 1985**

longer distance between scatters  
less scatters  
less energy deposition

$$\epsilon_{\text{SP}} = \frac{8}{\rho(r)} \sqrt{\frac{2}{\pi}} \frac{m_\chi m_N}{(m_\chi + m_N)^2} n_\chi(r) n_N(r) \sigma_{\text{tot}} k_B (T_\chi - T(r)) \left( \frac{k_B T(r)}{m_N} + \frac{k_B T_\chi}{m_\chi} \right)^{\frac{1}{2}}$$

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**Spergel & Press 1985**

longer distance between scatters  
less scatters  
less energy deposition

**Gould & Raffelt 1990**

many scatters  
more energy deposition  
interactions are local only

**FIG VI** Schematic diagram showing the efficiency of heat transport in stars by a weakly interacting particle, as a function of the Knudsen number,  $K$ , from **Banks et al. 2022**

$$L_\chi(r) = 4\pi r^2 \kappa(r) n_\chi(r) \ell(r) \left( \frac{k_B T(r)}{m_\chi} \right)^{1/2} k_B \frac{dT(r)}{dr}$$

# The calibrated Spergel & Press model

## Simulation of thermal conduction by asymmetric dark matter in realistic stars and planets

Hannah Banks,<sup>1,\*</sup> Stephanie Beram,<sup>2,3,†</sup> Rashaad Reid,<sup>4,2,‡</sup> and Aaron C. Vincent<sup>2,3,5,§</sup>

<sup>1</sup>Department of Applied Mathematics and Theoretical Physics,  
University of Cambridge, Wilberforce Road, Cambridge, CB3 0WA, UK

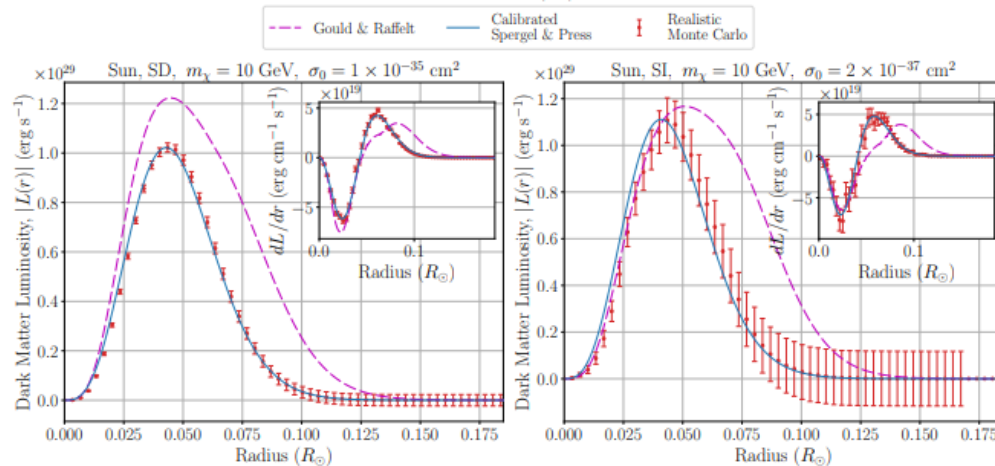
<sup>2</sup>Department of Physics, Engineering Physics and Astronomy,  
Queen's University, Kingston ON K7L 3N6, Canada

<sup>3</sup>Arthur B. McDonald Canadian Astroparticle Physics Research Institute, Kingston ON K7L 3N6, Canada

<sup>4</sup>Department of Physics and Astronomy, University of Waterloo, Waterloo ON N2L 3G1, Canada

<sup>5</sup>Perimeter Institute for Theoretical Physics, Waterloo ON N2L 2Y5, Canada

Dark matter captured in stars can act as an additional heat transport mechanism, modifying fusion rates and asteroseismological observables. Calculations of heat transport rates rely on approximate solutions to the Boltzmann equation, which have never been verified in realistic stars. Here, we simulate heat transport in the Sun, the Earth, and a brown dwarf model, using realistic radial temperature, density, composition and gravitational potential profiles. We show that the formalism developed in Ref. [1] remains accurate across all celestial objects considered, across a wide range of kinematic regimes, for both spin-dependent and spin-independent interactions where scattering with multiple species becomes important. We further investigate evaporation rates of dark matter from the Sun, finding that previous calculations appear robust. Our Monte Carlo simulation software *cosmion* is publicly available. [🔗](#)



**FIG VII** Luminosity  $|L(r)|$  and transported energy  $dL/dr$  (insets) in the Sun, along with the Gould & Raffelt prediction and the calibrated Spergel & Press model in **Banks et al. 2024**

$$L(r) = \frac{A}{1 + \left(\frac{K_0}{K}\right)^2} L_{SP}$$

$$A \approx 0.5$$

$$K_0 \approx 0.4$$

*arXiv:2412.14342v1*

# Asking Questions

How do the different transport methods affect stellar evolution (and stellar internal structure)?

Does the Banks et al. (2024) prescription for K-suppressed Spiegel & Press transport hold throughout evolution?

How do variations of the DM model parameters affect the results?

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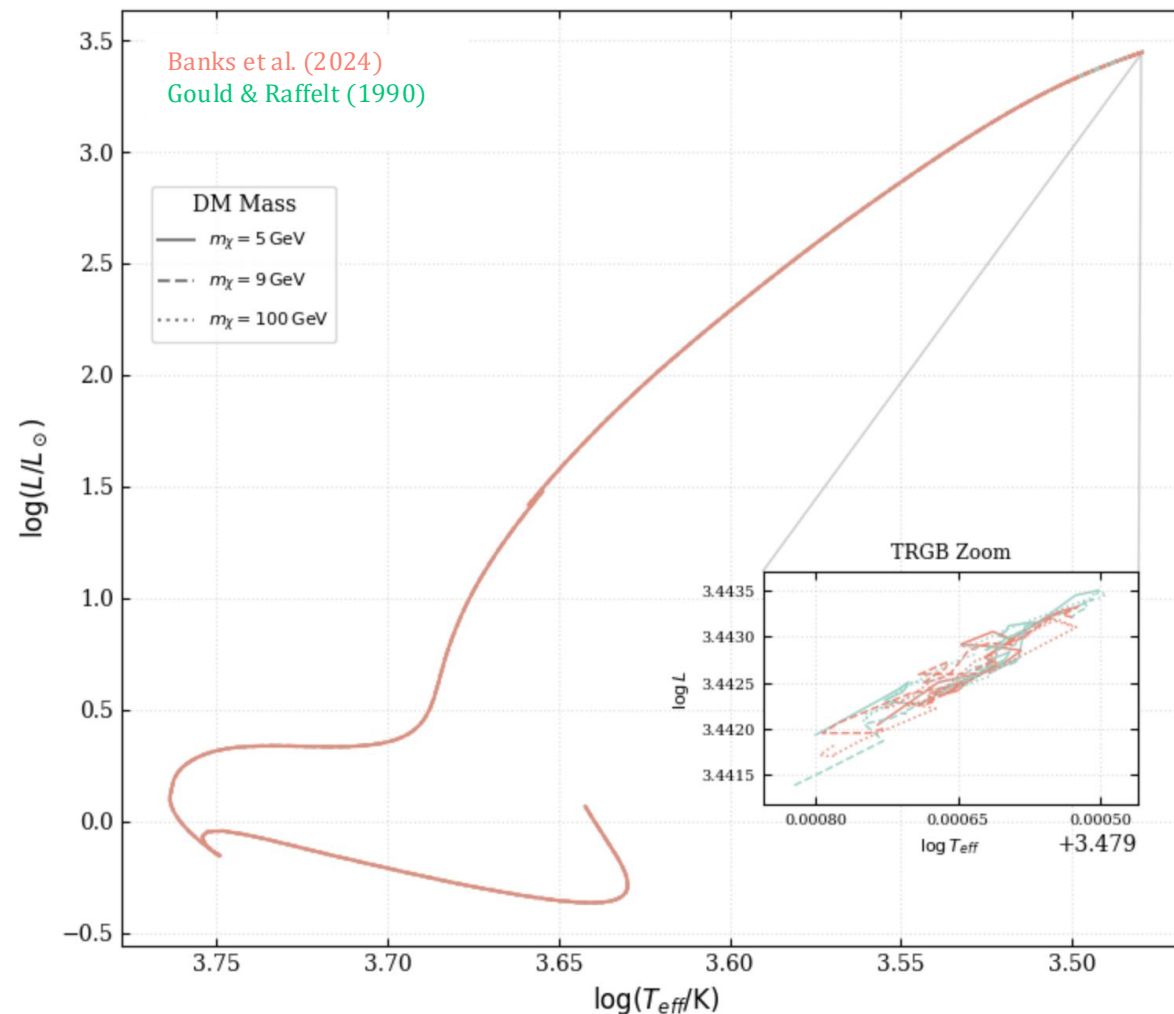
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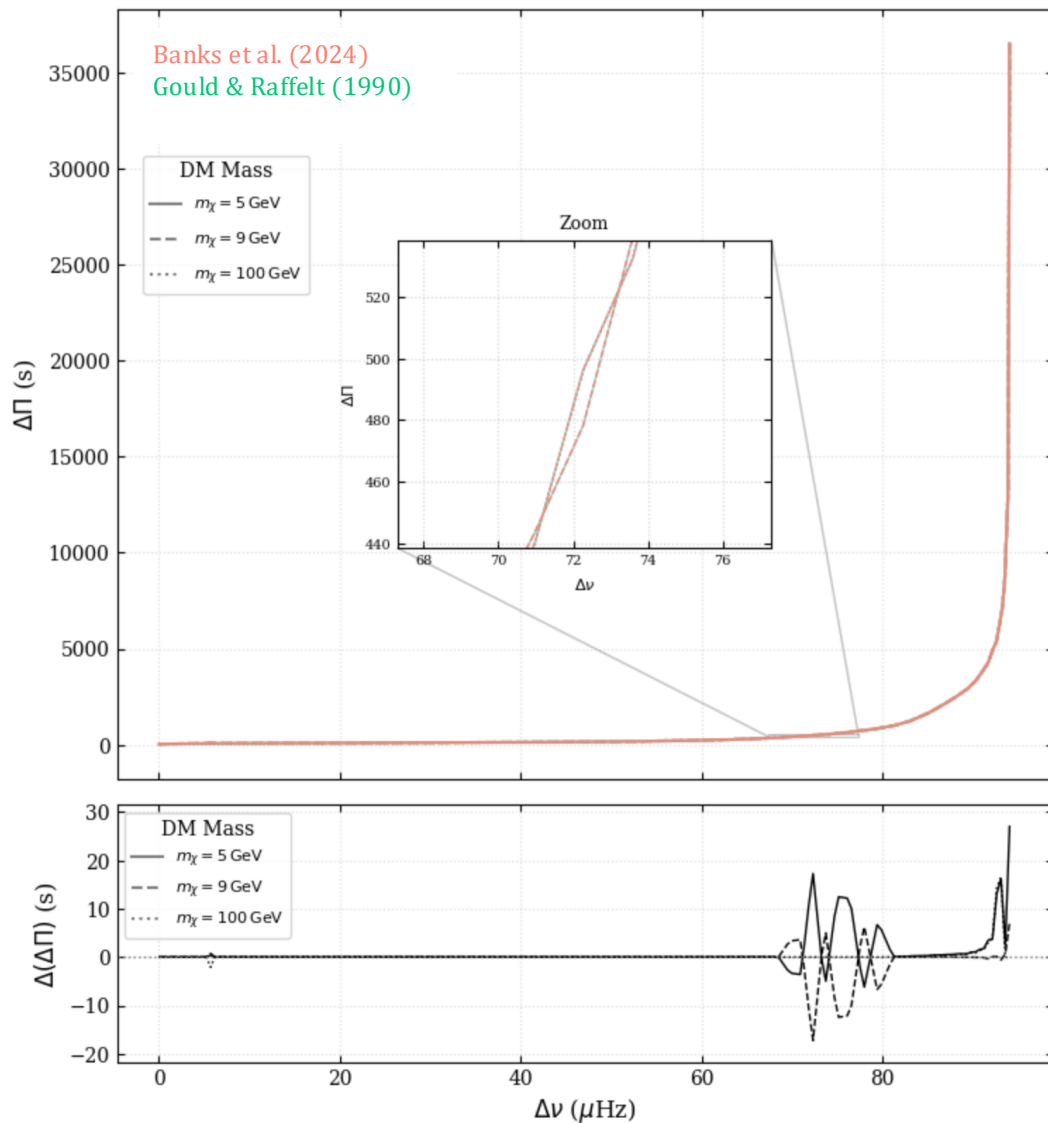
From this point on, everything should be considered  
**preliminary**

# Photometry

Consistent difference of  $\sim 2 L_{\odot}$  at the TRGB  
( $\sim 0.07\%$ )

**FIG VIII** HR diagram for  $1 M_{\odot}$  models with  $m_{\chi} = 5, 9, 100$  GeV using the **Ba24** and **G&R90** transport methods for SI interaction with  $\sigma = 10^{-38} \text{ cm}^2$  and solar system-like DM halo density.





# Asteroseismology

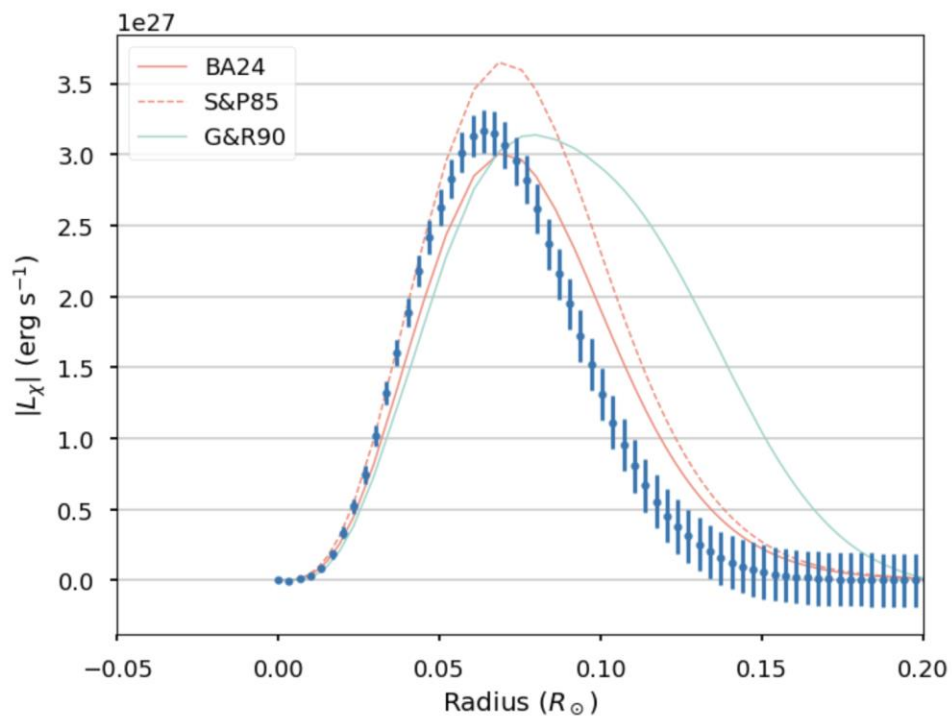
$$\Delta\nu = \nu_{n+1,l} - \nu_{n,l} = \left( 2 \int_0^R \frac{dr}{c_s(r)} \right)^{-1}$$

$$\Delta\Pi_\ell = \frac{2\pi^2}{\sqrt{\ell(\ell+1)}} \left( \int_{r_1}^{r_2} N \frac{dr}{r} \right)^{-1}$$

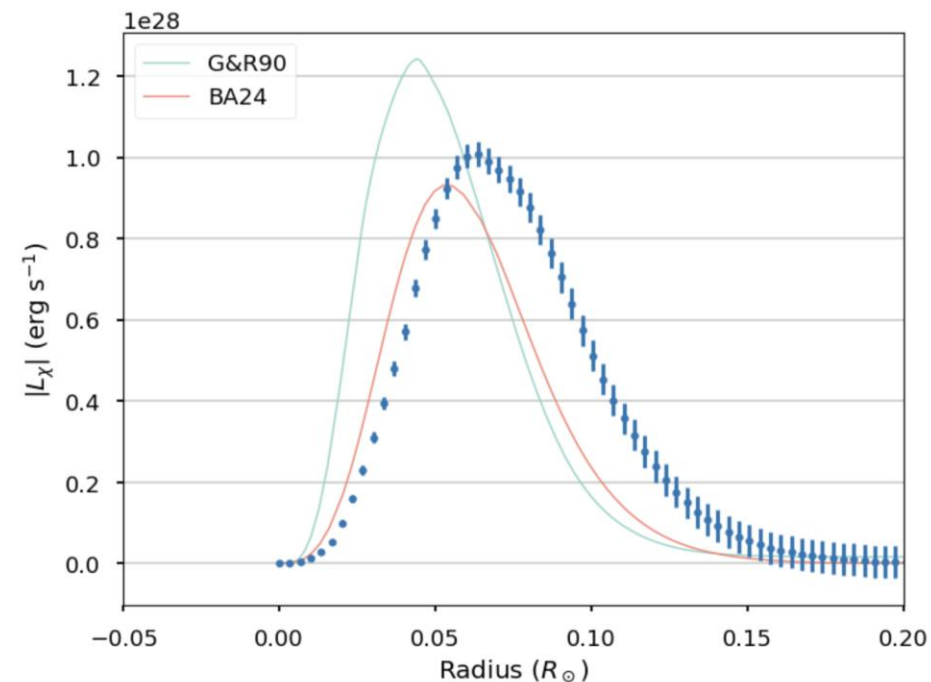
This picture should change dramatically at higher stellar masses due to suppression of convection in the core

**FIG IX** Asteroseismic evolution plot for  $m_\chi = 5, 9, 100$  GeV superimposed on dmEFT **Ba24** and **G&R90** predictions. Model includes SD+SI interaction at  $\sigma_p^{(SD,SI)} = (10^{-38}, 10^{-44}) \text{ cm}^2$  in the DM halo density of the solar system

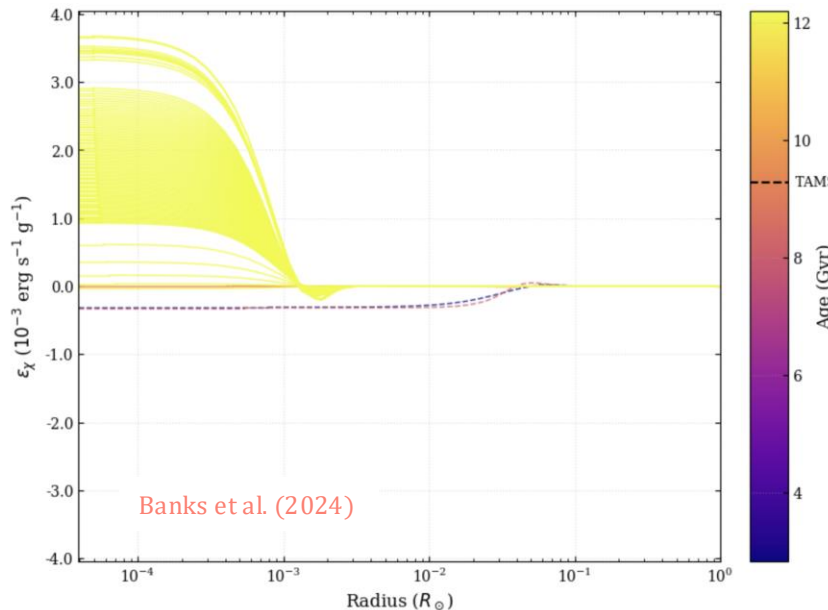
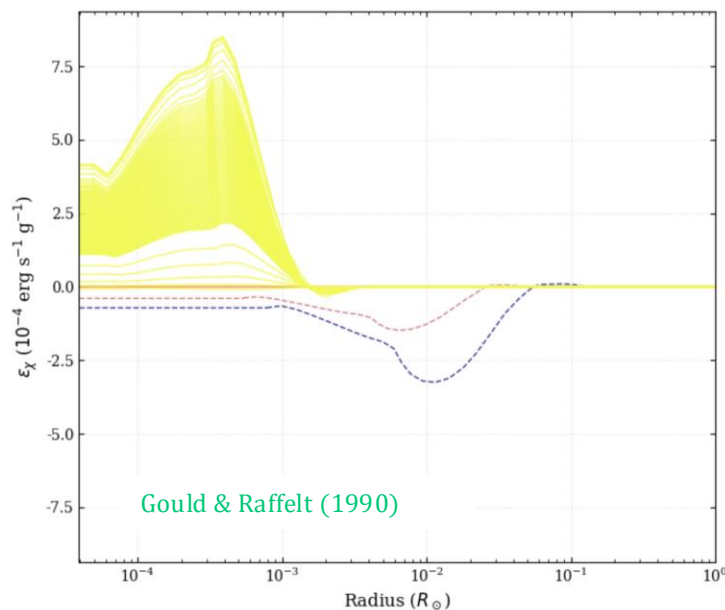
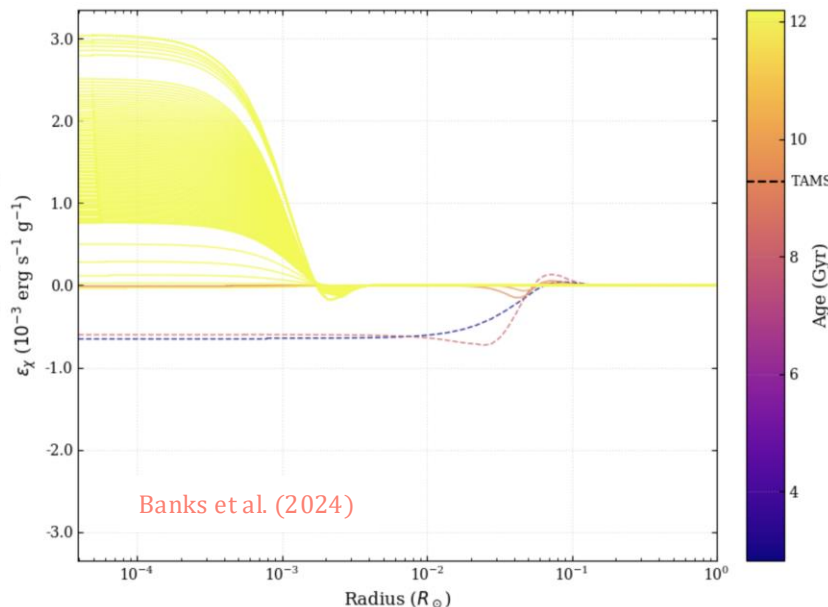
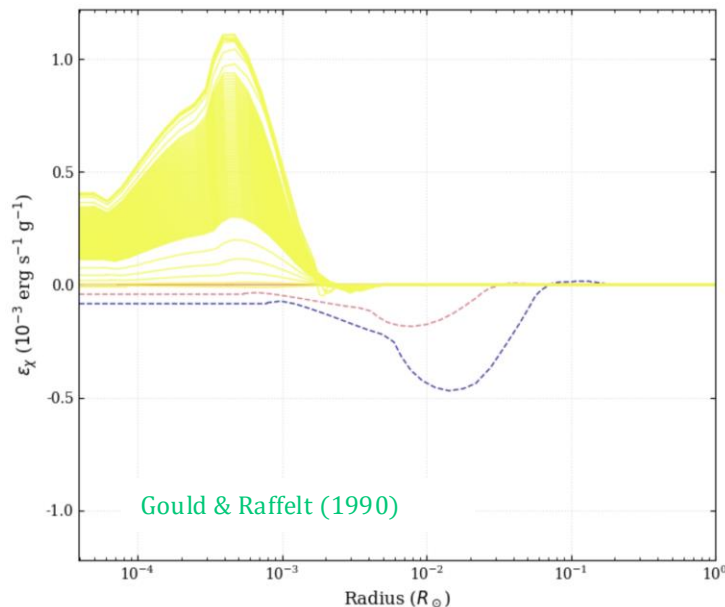
# Testing models against simulations



**FIG X.1** `cosmion` results superimposed on dmEFT **G&R90** and **Ba24** transport absolute luminosities for a model with SD interaction,  $m_\chi = 5\text{GeV}$ ,  $\sigma_p = 10^{-38}\text{cm}^2$ , and  $\frac{N_\chi}{N_b} = 10^{-14}$  at a stellar age of 1.45 Gyrs.



**FIG X.2** `cosmion` results superimposed on dmEFT **G&R90** and **Ba24** transport absolute luminosities for a model with SD interaction,  $m_\chi = 5\text{GeV}$ ,  $\sigma_p = 10^{-38}\text{cm}^2$ , and  $\frac{N_\chi}{N_b} = 10^{-14}$  at a stellar age of 8.00 Gyrs.



**Fl  $\chi$**  Evolution of  $\epsilon_\chi$  from the ZAMS to the TRGB for  $1 M_\odot$  models considering SD+SI interactions with  $m_\chi = 5, 9, 100$  GeV using the **Ba24** and **G&R90** transport methods for solar system-like DM halo densities,  $\sigma_p^{SD} = 10^{-38} \text{ cm}^2$  and  $\sigma_p^{SI} = 10^{-44} \text{ cm}^2$ .

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# Summary

Implemented K-suppressed Spergel & Press transport formalism of **Banks et al. 2024**

**(Banks24)**

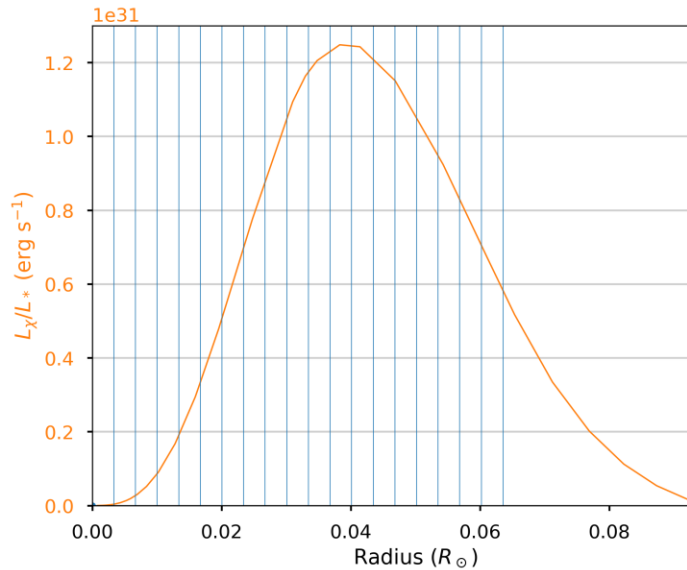
Tested the evolution of **Banks24** transport outside the evolutionary region it was calibrated for (solar case): through the TAMS and to the TRGB

Compared **Banks24** and **Gould & Raffelt 1990** (**G&R90**) prescriptions across DM parameters:

$m_\chi, \rho_\chi, \sigma_p$

Agreement with simulation results is improved in the Main Sequence, more work is needed to verify validity in other stages

Inversion of the energy deposition profile in the RGB could be important for core-sensitive phenomena (convection and neutrinos)



# The Future

Test both **G&R90** and **Ba24** transport results against simulations of a realistic solution of the Boltzmann collision equation (correctly)

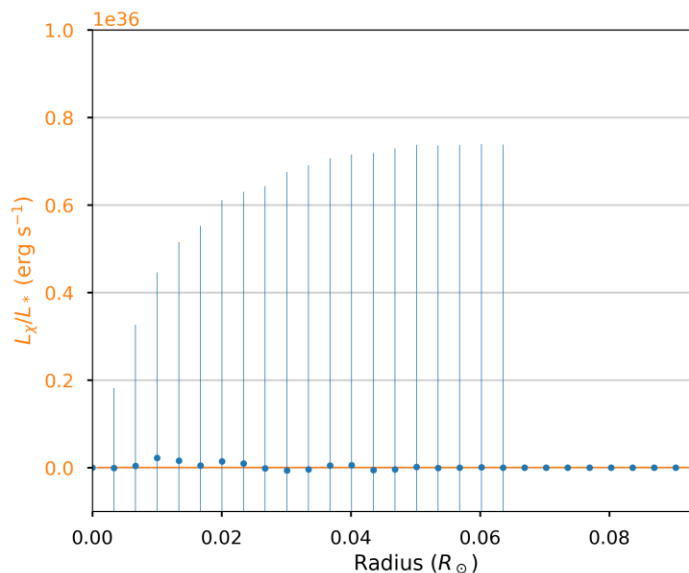
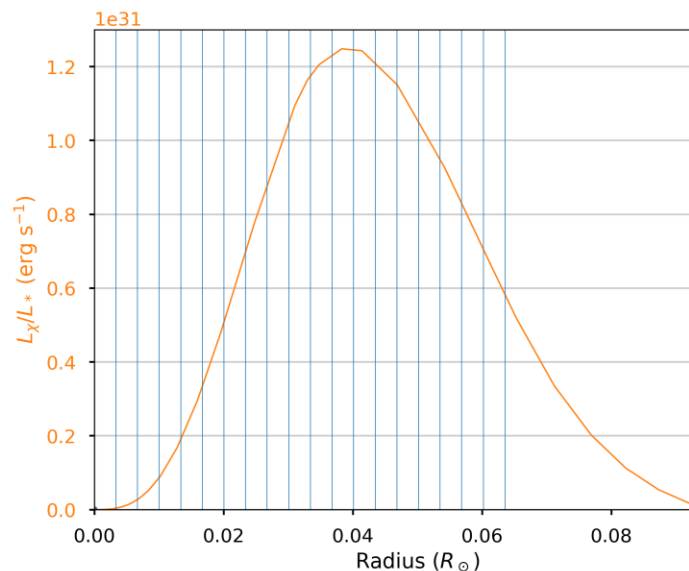
Explore other stellar masses where structure is more sensitive to changes in the core ( $> 1.2 M_{\odot}$ )

Carefully model evolutionary stages that are sensitive to energy transfer (like the **helium flash**)

Investigate how **composition changes** can subtly alter SI transport and be sensitive to different DM masses (sdB stars)

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**FI XII** Attempted simulation of realistic transport at the TRGB with the cosmion code (**Banks et al. 2022; 2024**) superimposed on dmEFT **Ba24** results. Result is for  $> 10^7$  simulated collisions. Model included SI interaction at  $\sigma_p = 10^{-38} \text{ cm}^2$  for  $m_{\chi} = 10 \text{ GeV}$  and  $n_{\chi}/n_b \sim 10^{-13}$ .



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# Thank you.

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