# Simulation of energy transport by dark matter scattering in the Sun

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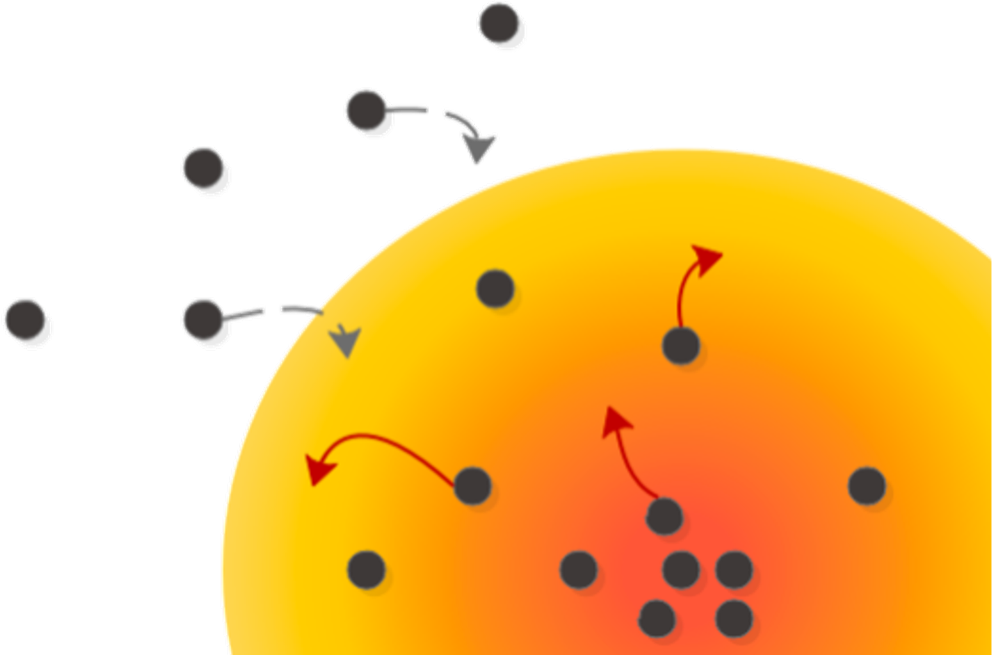
Based on 2111.06895 with S. Ansari, A.C Vincent and P. Scott



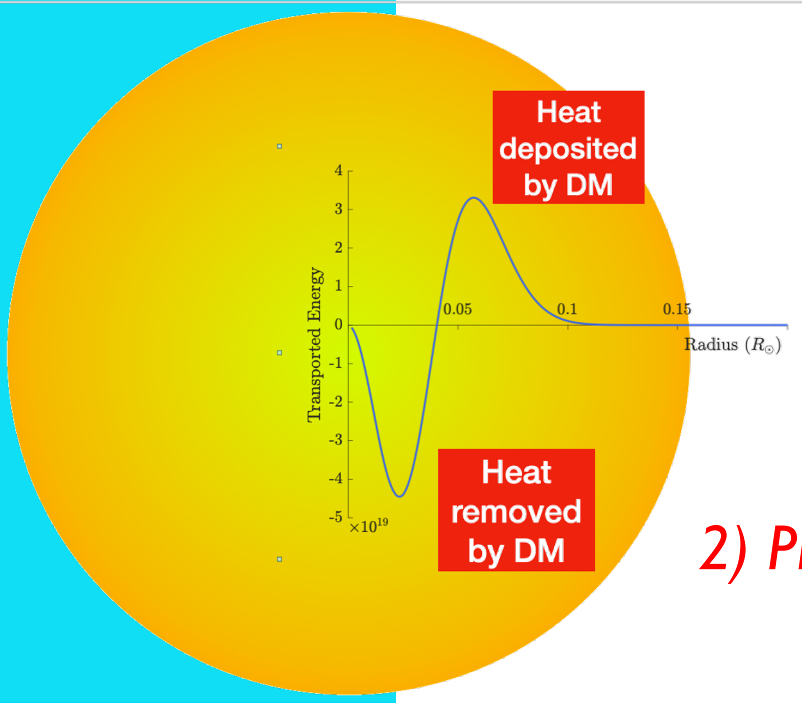
# The Idea

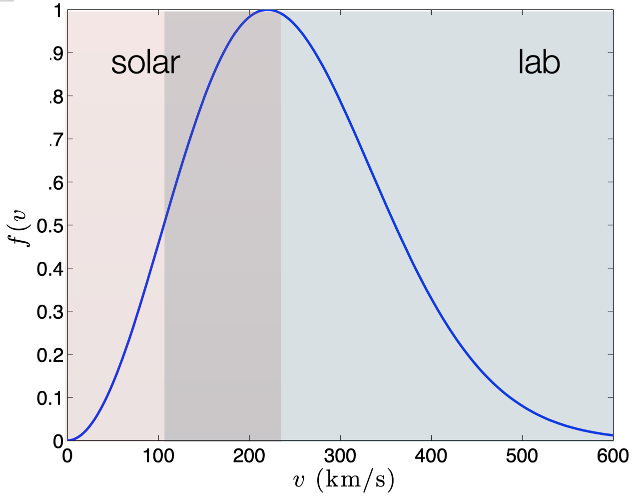
- Can use the Sun as a "direct detection experiment"
- DM particles from the DM halo can become gravitationally trapped in the Sun following collisions
- Subsequent scattering with nuclei can conduct heat, removing from core and depositing in outer layers i.e. changing temperature gradient
- If DM population can accumulate e.g. if Asymmetric, appreciable modifications to the structure and interior properties can be induced

*Can be probed to high precision*

***Bonus**: entirely complementary to terrestrial direct detection!*

*1) Sensitive to lower velocities*




*2) Probes lower DM masses*

# Observational Probes

Sun an ideal laboratory:
- High precision measurements
- Well understood physics

**DM changes radial heat transport**

**Change in temperature profile**

**Change to core temperature reduces $^{8}B$ and $^{7}Be$ neutrino fluxes**

*Probed by Helioseismology (oscillations on surface of the Sun)*

**Change to pressure and density alters sound speed, convective zone boundary, surface helium abundance…**

# More Motivation…

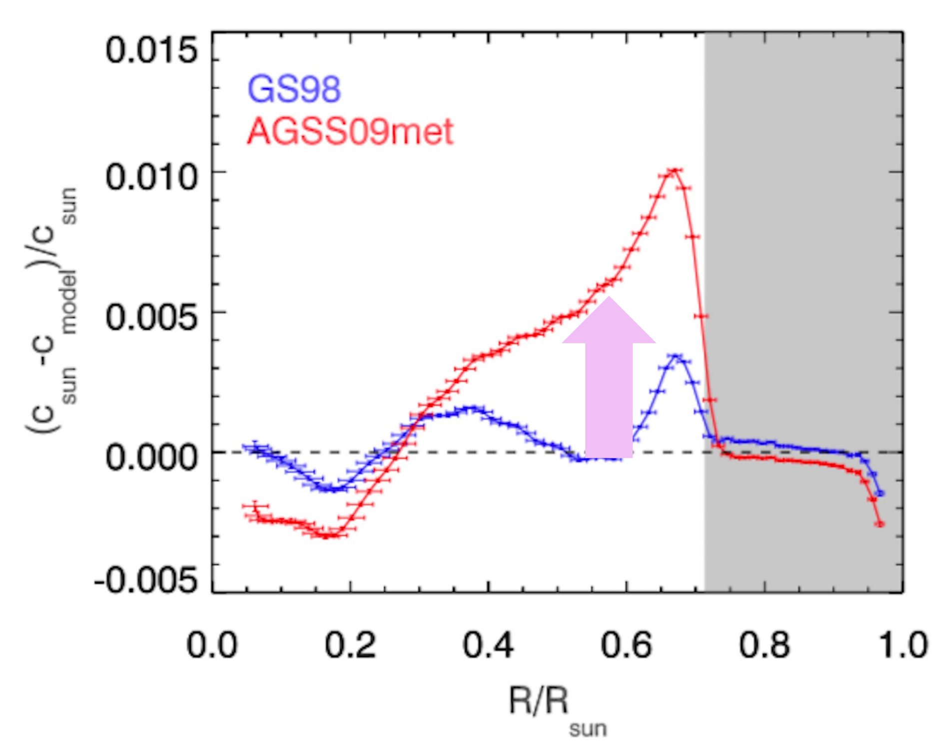
## The Solar Abundance Problem

- Standard Solar models (SSMs) previously in agreement with Helioseismological data (blue line)

- In 2004 models revised to account for improved determination of solar composition

4-5 σ discrepancy

*No resolution to date…… DM conduction?*




Residuals between predicted sound speed profile and helioseismological prediction for pre (blue) and post (red) revision SSMs

# The physics

- To predict observables need to include DM-mediated transport in evolutionary solar simulations
- Thermal behavior fully characterized by DM number density $n_\chi(r)$ and luminosity $L_\chi(r)$ profiles
- Need to consistently solve the BCE at each time-step in stellar evolution – not practical!!

**Require a quantitative parametrisation of thermal behaviour**

Obtain from DM phase space distribution, *F*

*F* governed by a Boltzmann Collision Equation (BCE):

$$\boxed{DF = l_\chi^{-1} C F}$$

$C$ :Collision Operator (microscopic collisions)
$D$ : Diffusion and external forces (gravity)
$l_\chi$ : Typical inter-scattering distance

- *6 dimensional integro-differential equation*
- *not analytically tractable!*

# The transport regimes:

Conveniently characterised by Knudsen number:

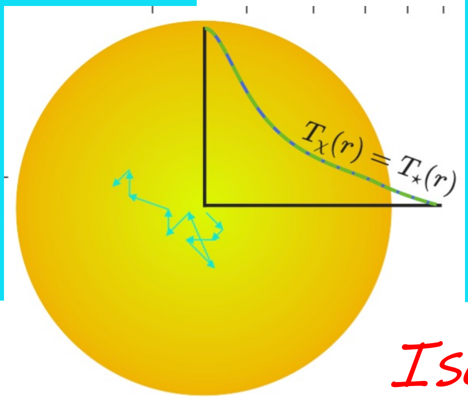
$$\boxed{K = \frac{l_\chi}{r_\chi}}$$

where $r_\chi = \sqrt{\frac{3k_B T_c}{2\pi G \rho_c m_\chi}}$

= scale height of DM distribution

**Low K**

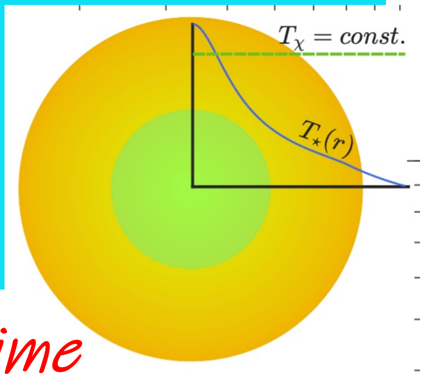
- Strong interactions
- High collision efficiency
- local transport
- DM in LTE with nuclei
- BCE can be solved perturbatively to 1st order dipole expansion



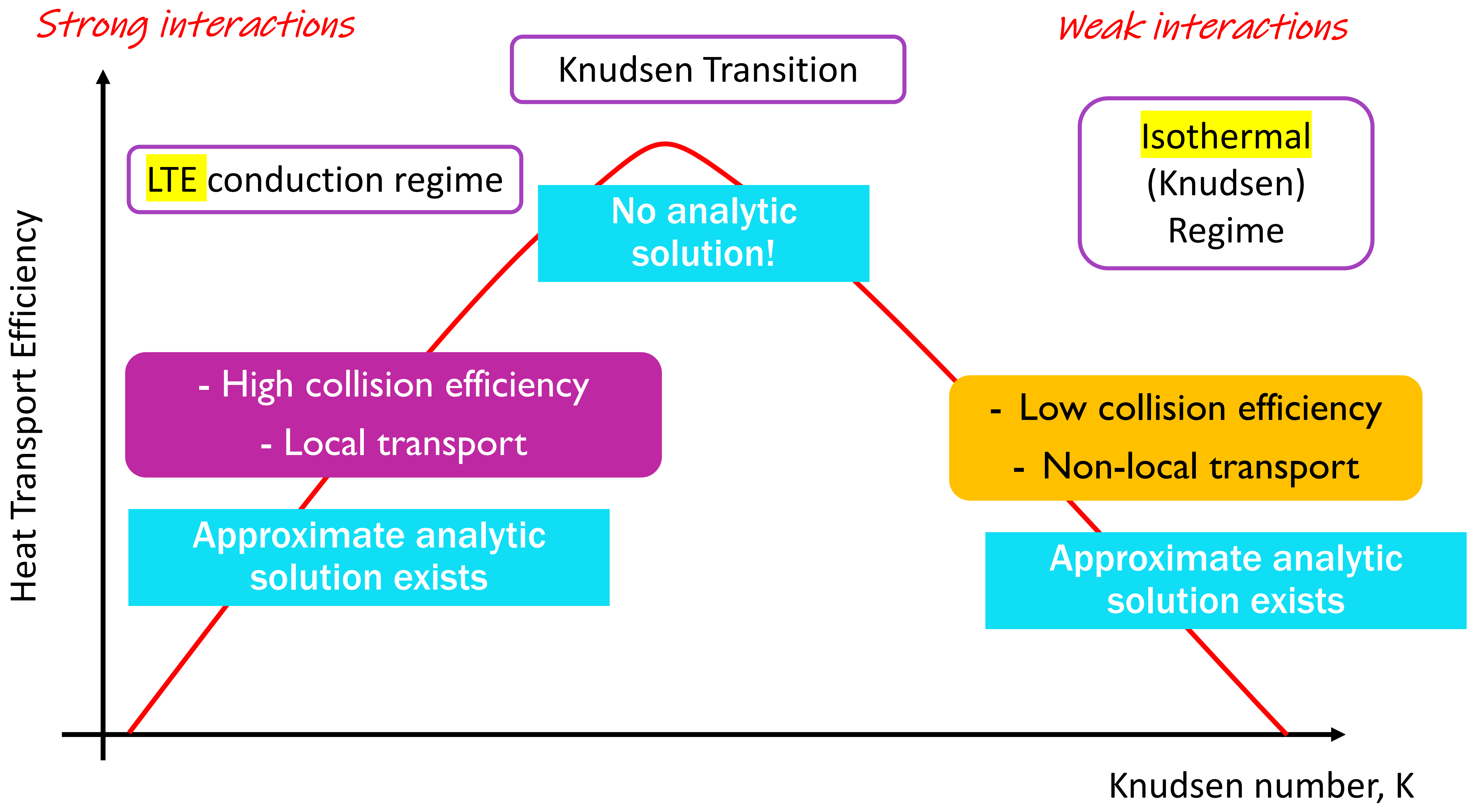

*LTE conduction regime*

**High K**

- Weak interactions
- Low collision efficiency
- Non-local transport
- DM isothermal
- BCE can be solved analytically




*Isothermal or "Knudsen" regime*


Strong interactions
Weak interactions
Knudsen Transition
LTE conduction regime
Isothermal (Knudsen) Regime
No analytic solution!
- High collision efficiency
- Local transport
- Low collision efficiency
- Non-local transport
Approximate analytic solution exists
Approximate analytic solution exists
Heat Transport Efficiency
Knudsen number, K

Known to only hold in 1 regime.... But numerically stable

# The existing formalisms:

Believed to be "correct"

## Spergel & Press

Based on Isothermal "solutions"

VS

## Gould & Raffelt

Based on *corrected* LTE "solutions"

Modified by a "Knudsen" correction at high K fitted from simulation

1. Use assumptions only valid for one regime
2. Calibrated using a single, simplified simulation done > 30 years ago
3. Only tested numerically for constant interactions

How do they hold up? Do they work for other interaction types?

## Simulate the "random walk" of a DM interacting with solar nuclei

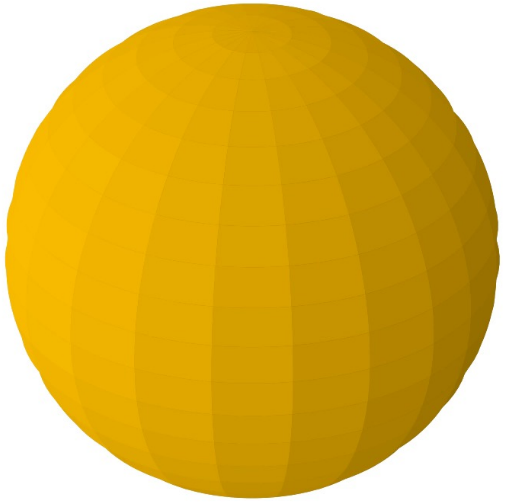
1) Specify DM mass, cross-section, interaction type
2) Initialize DM particle in solar environment
3) Let it scatter $10^7 - 10^8$ times
4) Keep track DM velocity, position and energy transfer at collision points
5) Extract number density and luminosity distributions

Consider cross sections that depend on relative velocity of DM and nucleon, $v_{rel}$ or momentum transferred, q:

$$\boxed{\sigma = \sigma_0 \left(\frac{v_{\mathrm{rel}}}{v_0}\right)^{2n} \qquad \sigma = \sigma_0 \left(\frac{q}{q_0}\right)^{2n}}$$

## ... Monte Carlo!

Billions of CPU hrs later....



# Constant interactions

## LTE regime (Low K)

**G&R works well (as expected)**

**S&P very wrong! (wrong regime!)**

## Isothermal (High K)

= S&P

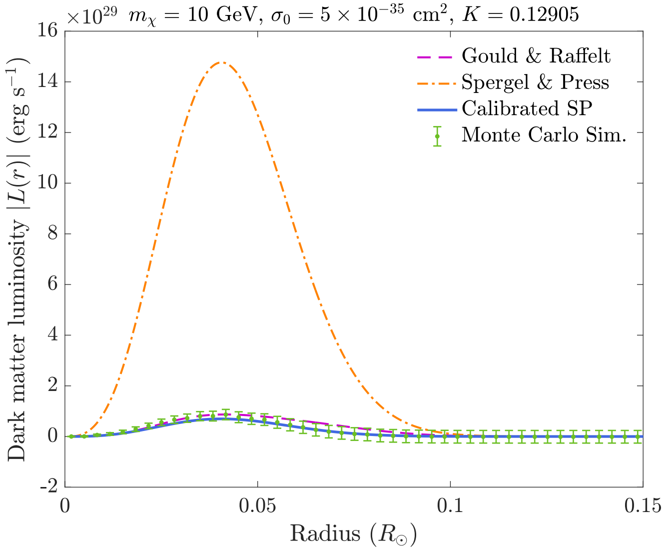
= Monte Carlo

= G&R

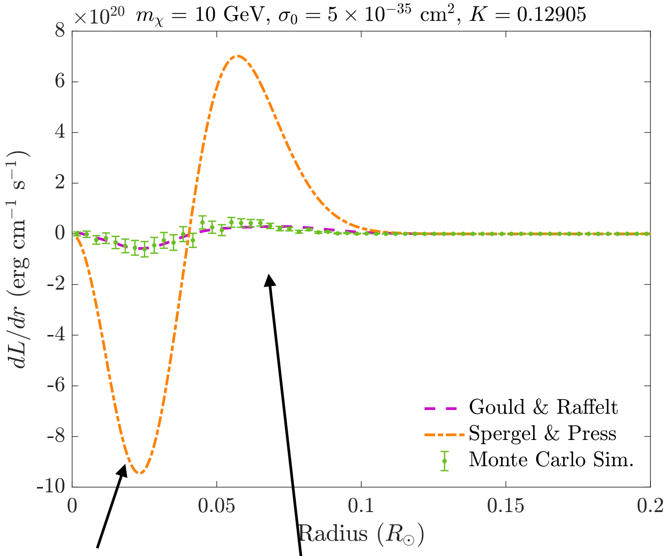
**S&P has better shape – but off by a factor of 2**

**G&R not too bad (thanks to Knudsen correction)**

Luminosity

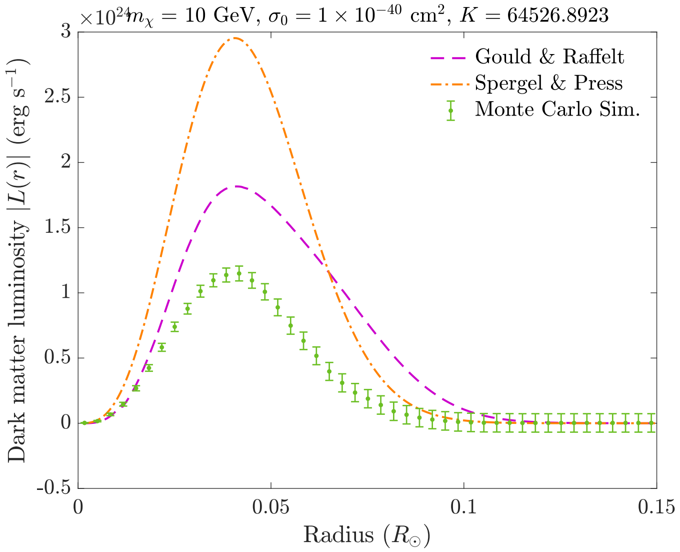


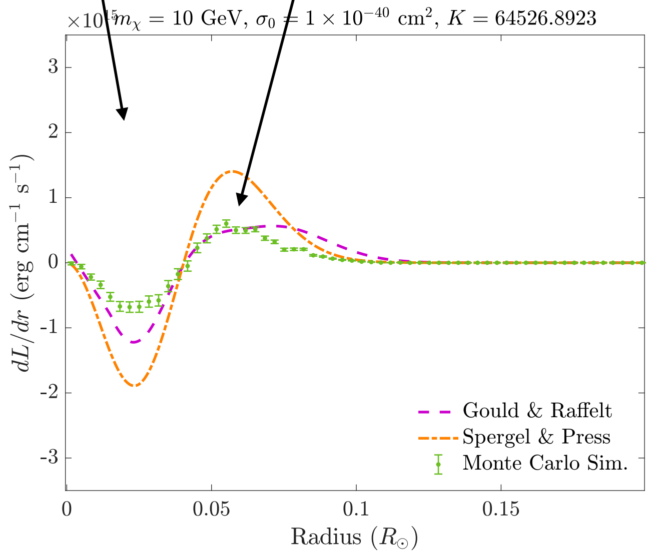

Transported energy




E removed from core

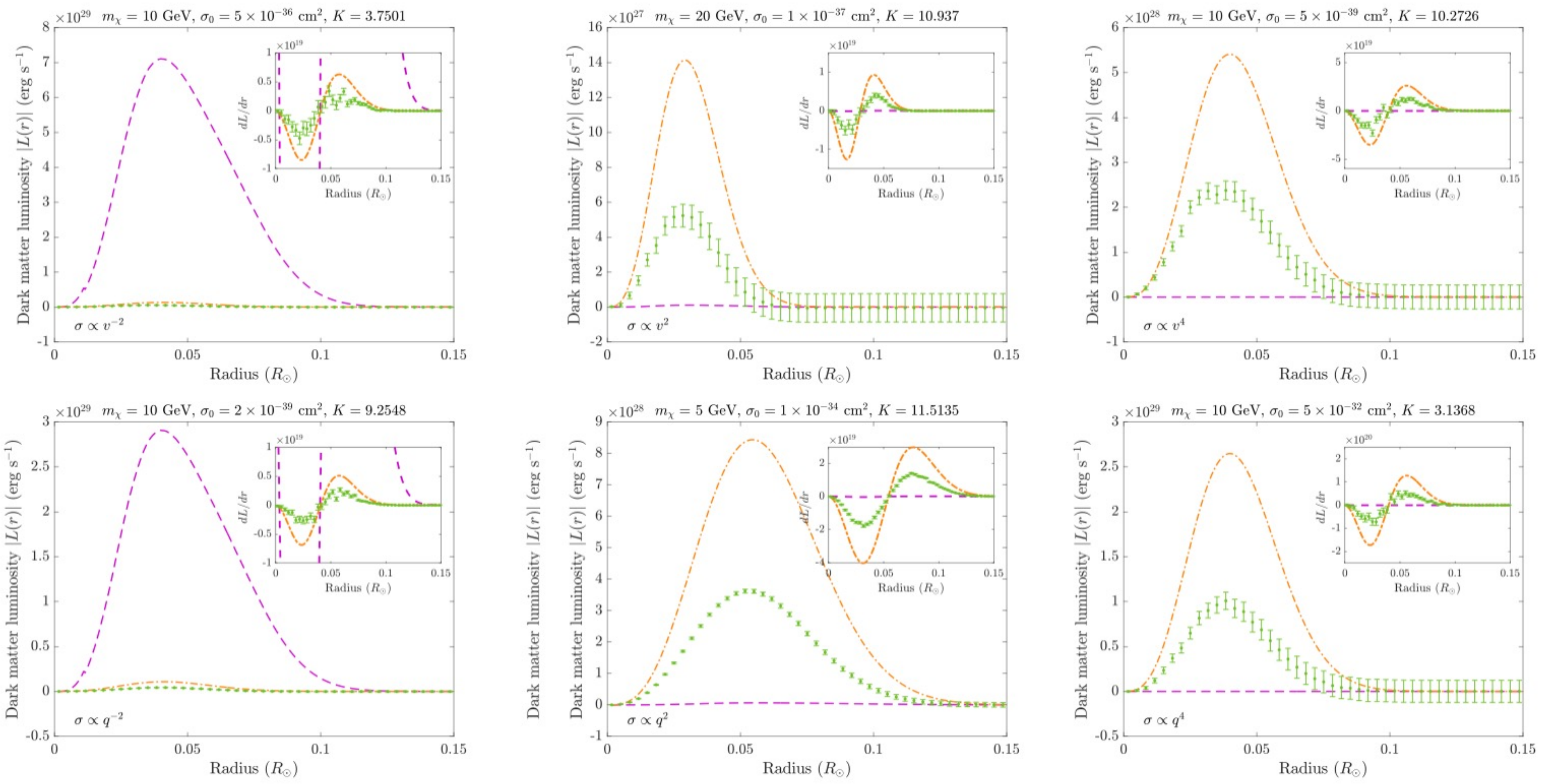
Deposited



# Non-Constant interactions – terrible!

DM Luminosity and Energy Transport (inset) distributions for various interaction types and strengths:




= S & P

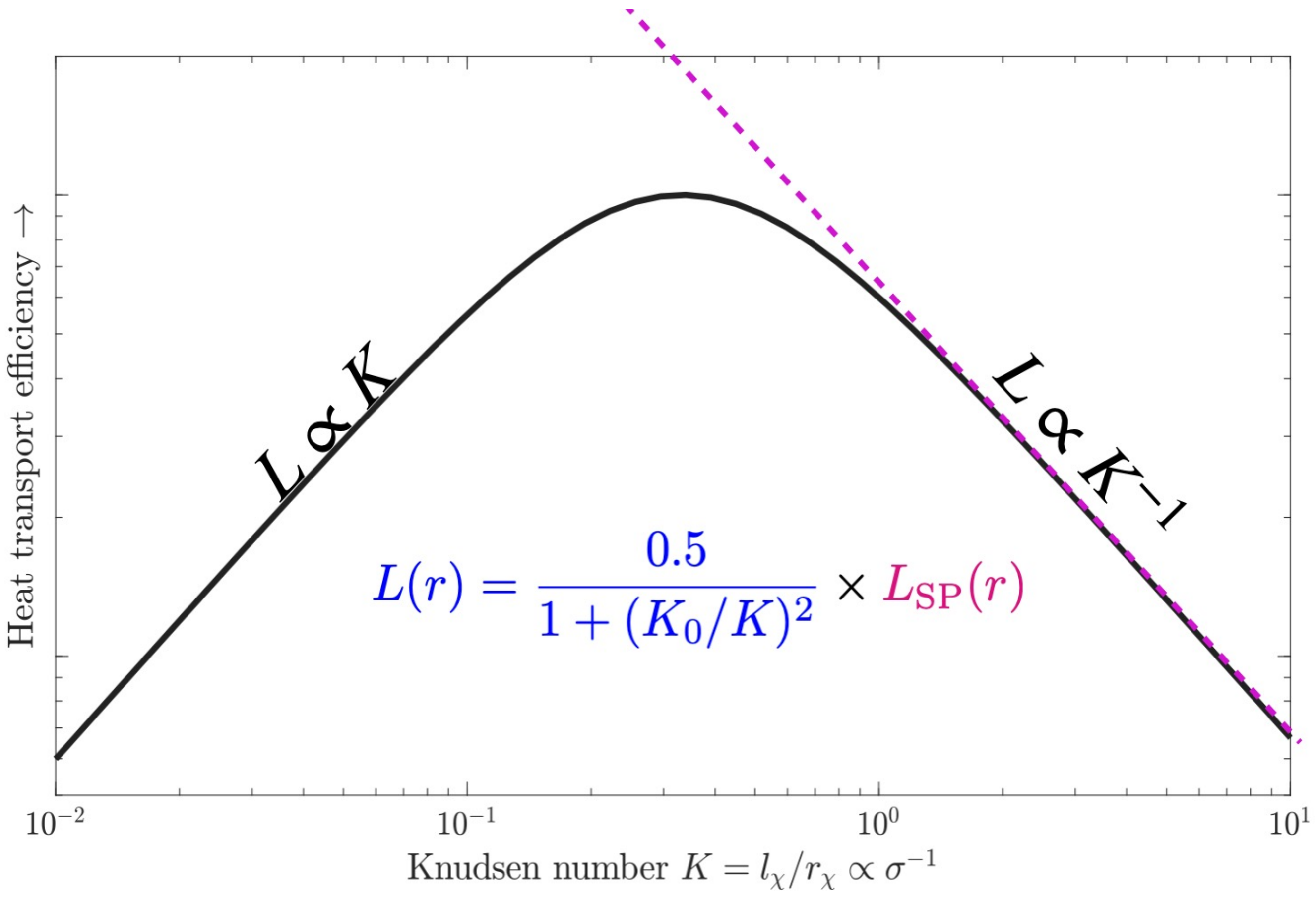
= Monte-Carlo

= G&R

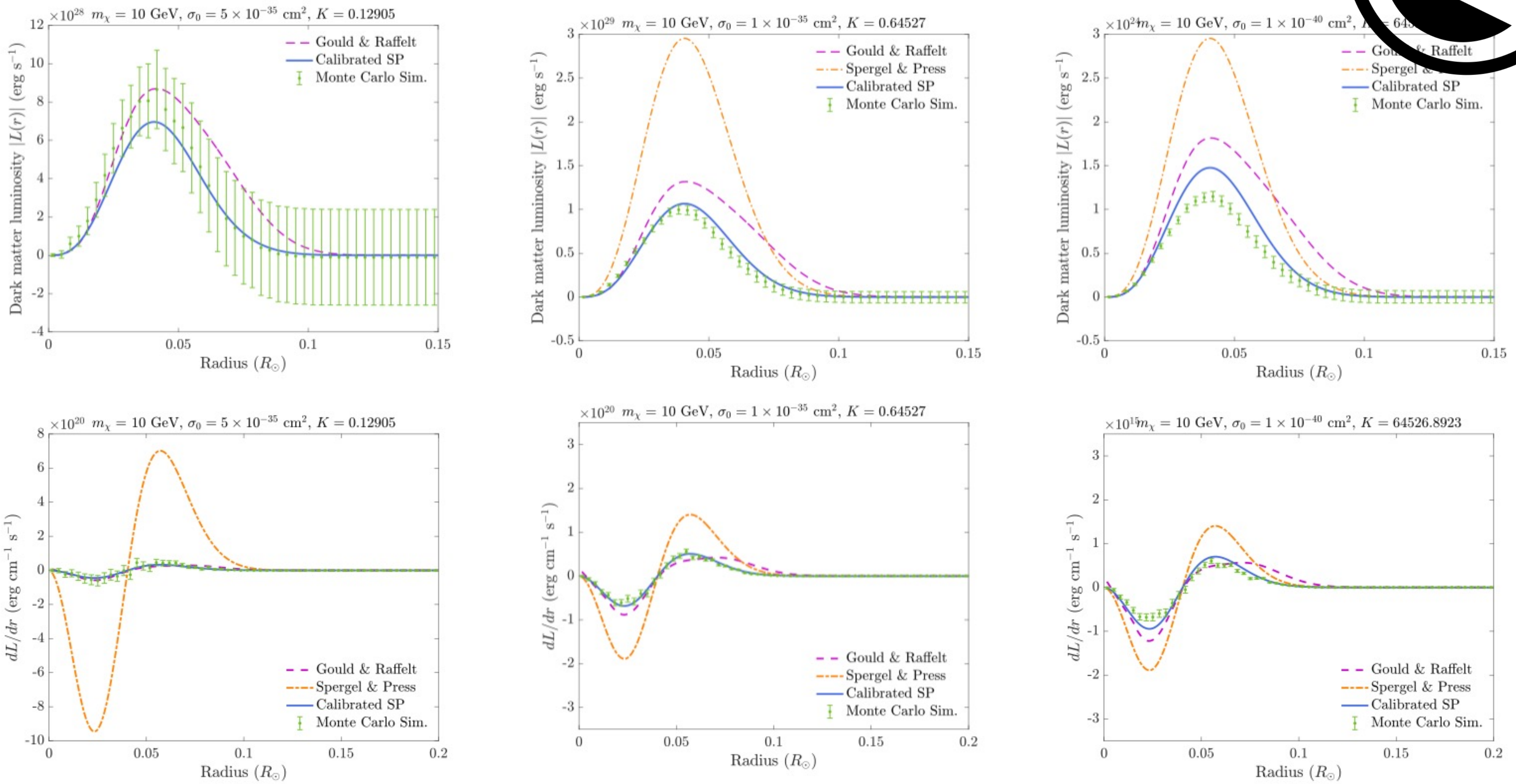
# What we know…

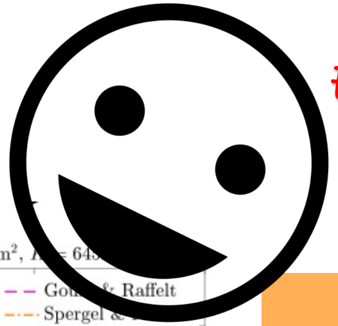
- **S&P** has better shape than **G&R**
- **G&R** off by several orders of magnitude for non-constant interactions (but works ok for constant interactions)
- For all interaction types, **S&P** "*only*" off by factor of 2 in isothermal regime
- **Idea**: correct **S&P** scheme for small K (similar way to how Knudsen correction in G&R corrects at high K)

# Possible Solution?



# Constant interactions – all regimes



Even better!!

= S & P

= Monte-Carlo

= G&R

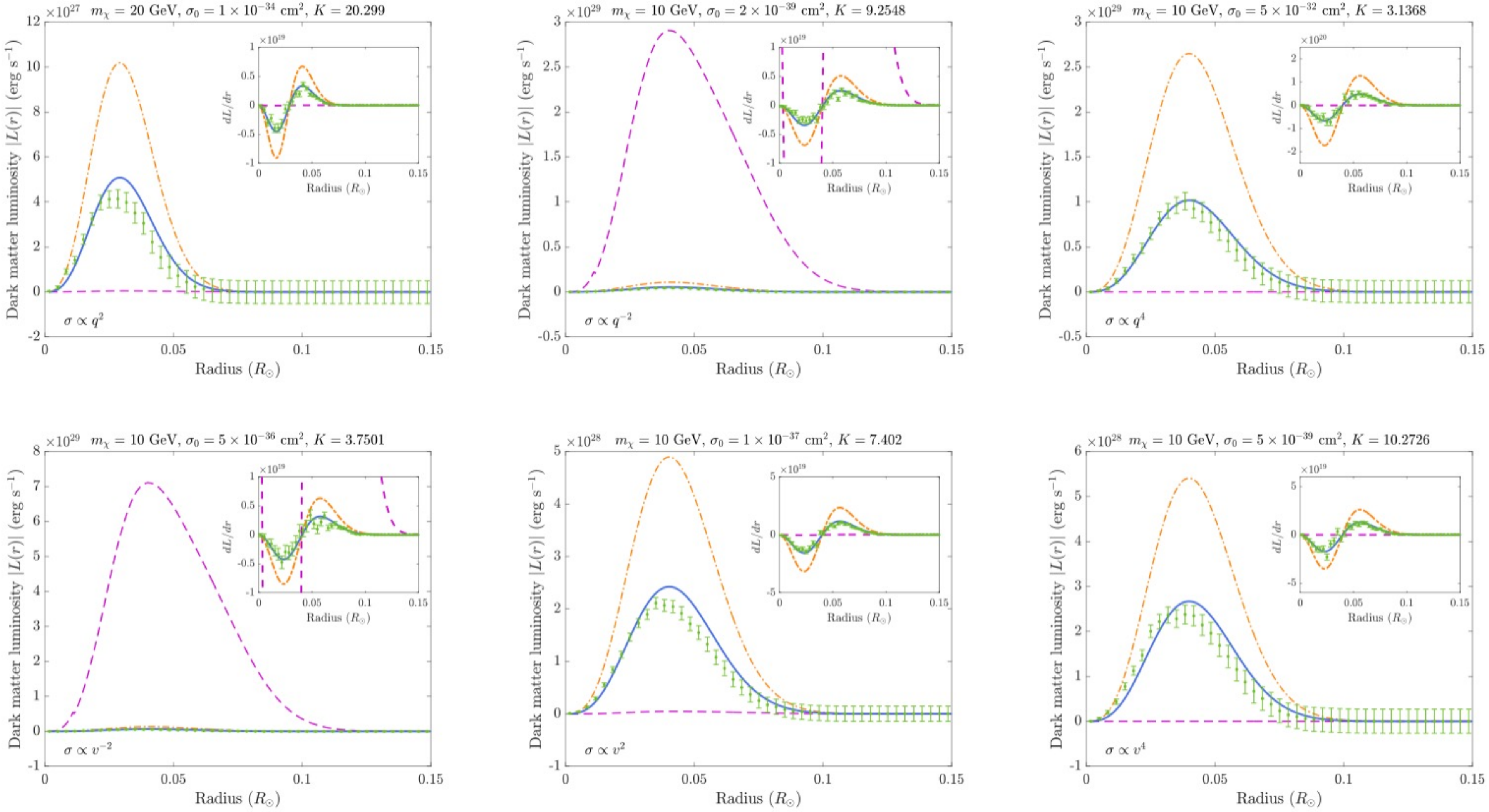
= Our scheme

$K$

Strong interactions

Weak interactions

# Non-Constant interactions



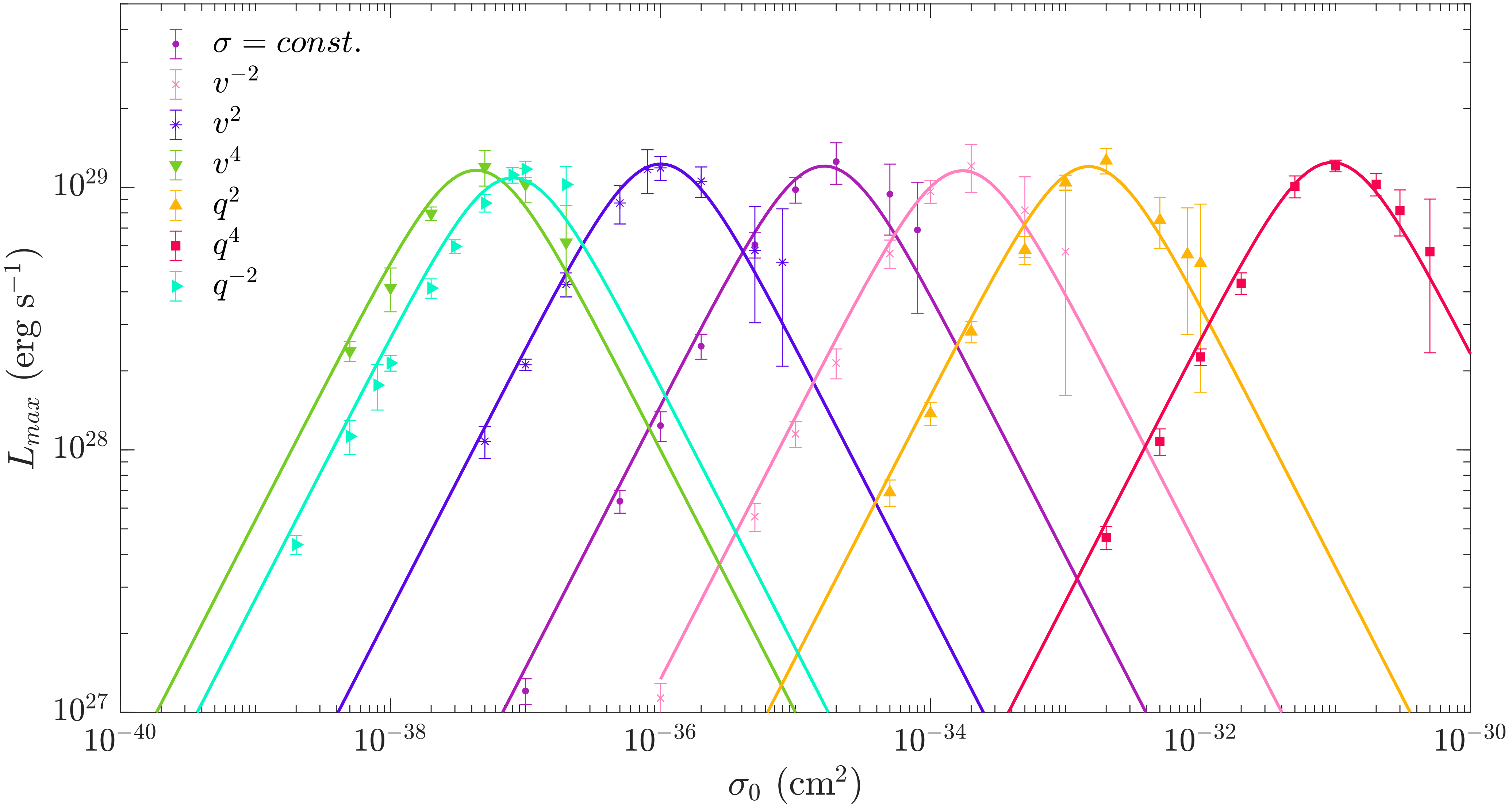

= S & P

= Monte-Carlo

= G&R

= Our scheme

# But a simple universal rescaling of S&P scheme works for all interaction types and across all regimes!



# Summary

- **First direct simulation of DM mediated energy transport in stars performed in realistic models of the Sun for non-constant cross-sections**

- **Neither of the conventional approaches accurately describe DM mediated conduction in realistic simulations**

- **Simple, universal, rescaling of Spergel & Press formalism accurate for all interaction types and regimes**

Can now find new bounds on properties of DM!