Dark Matter in Extreme Astrophysical Environments

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XIX Mexican Workshop on Particles and Fields, 20-24 October 2025

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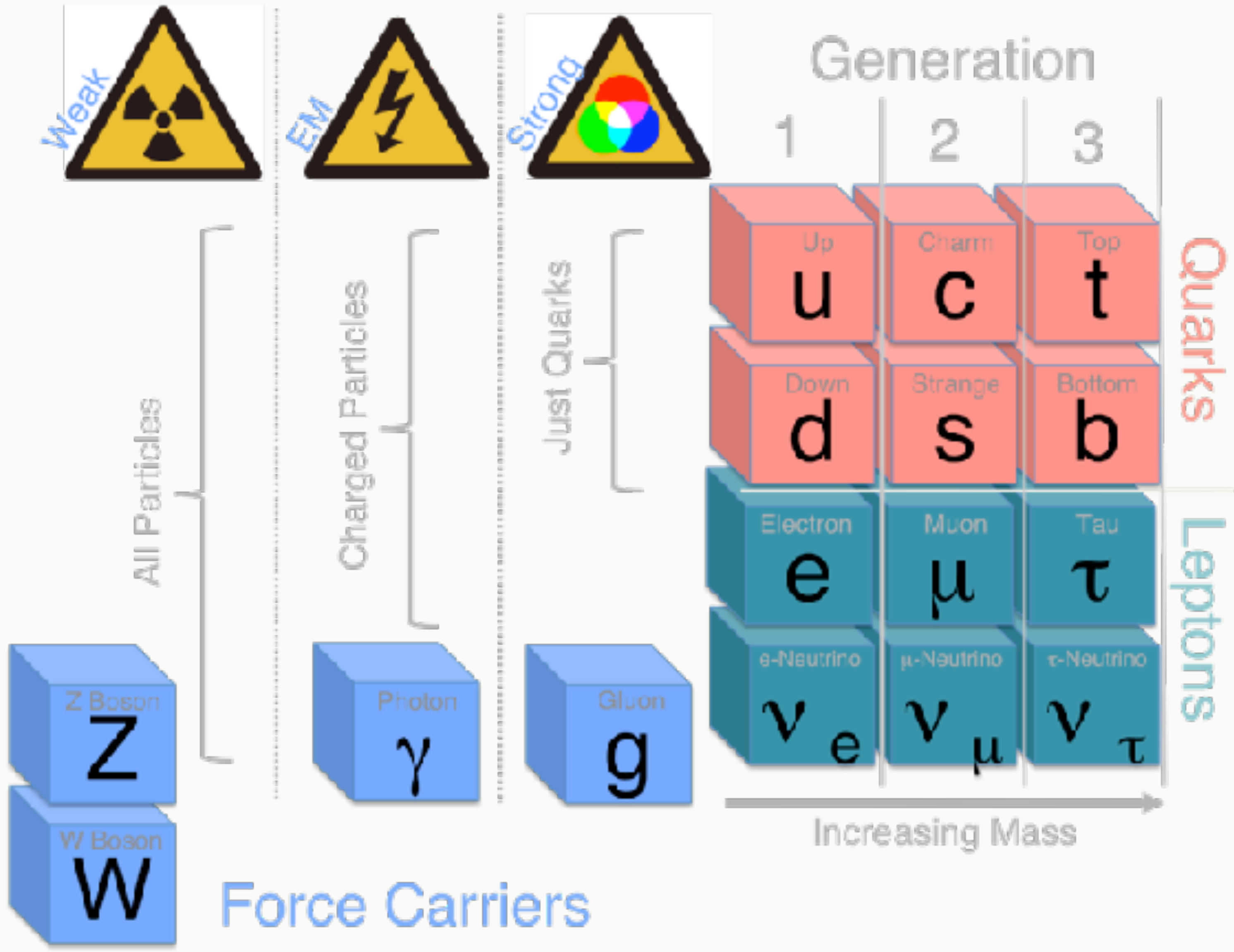
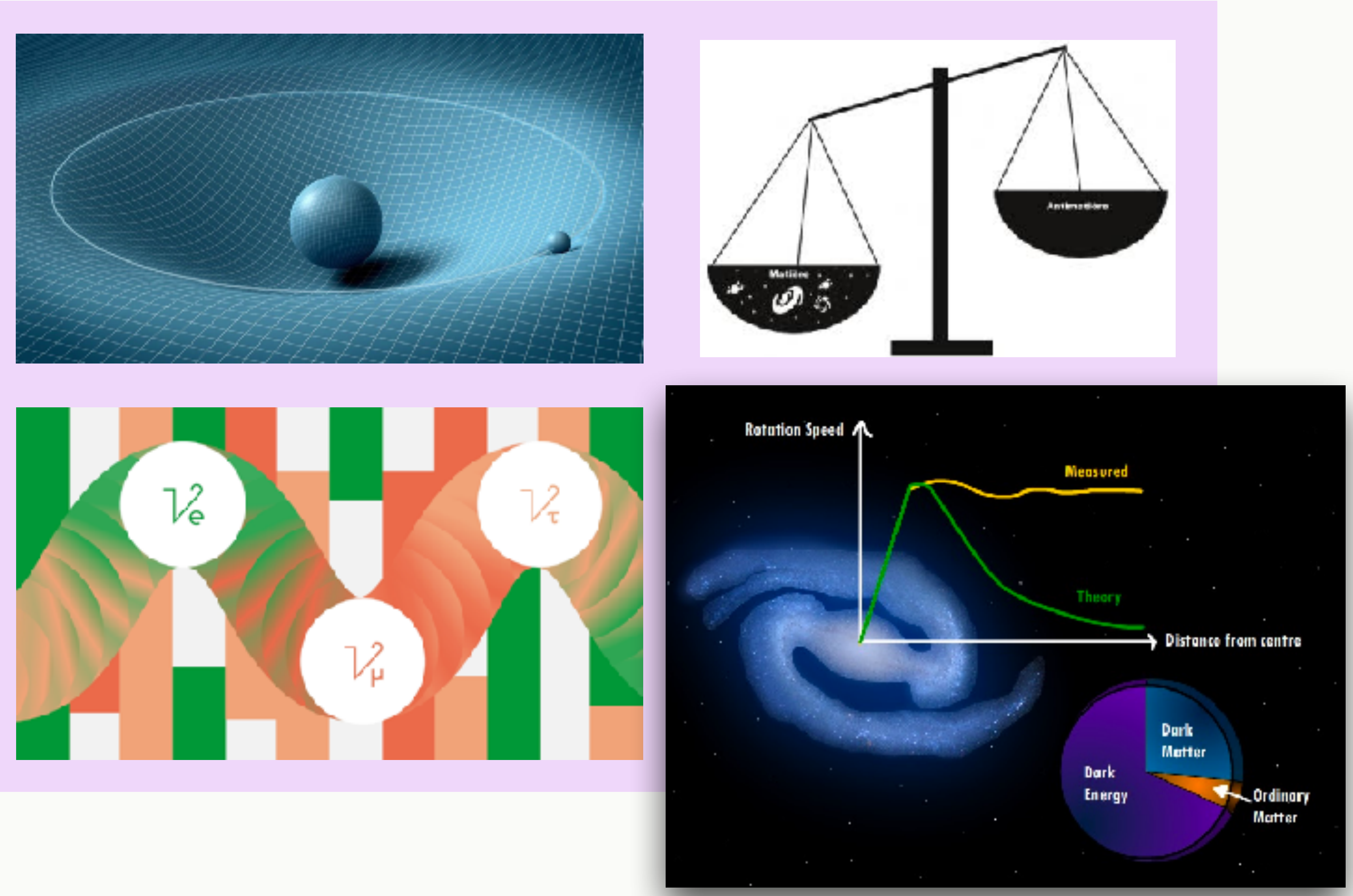
What we know vs. what remains a mystery

Established Physics: The Standard Model.



Open questions



Direct Detection: Current Status and Limitations

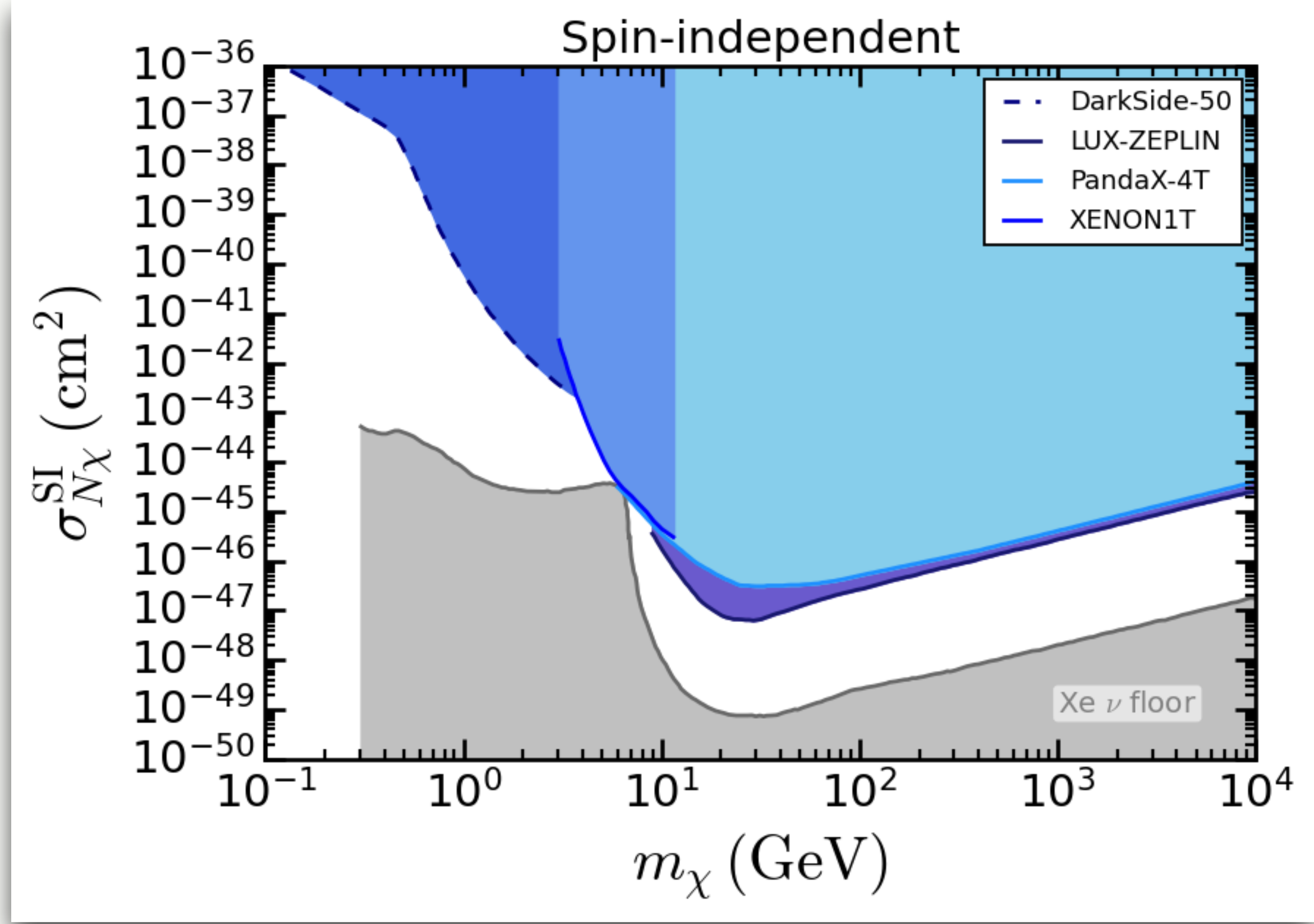
Strong limits on SI interactions

Sensitivity depends on:

Nuclear mass of the target

Recoil threshold

Reduced sensitivity: momentum/velocity-suppressed

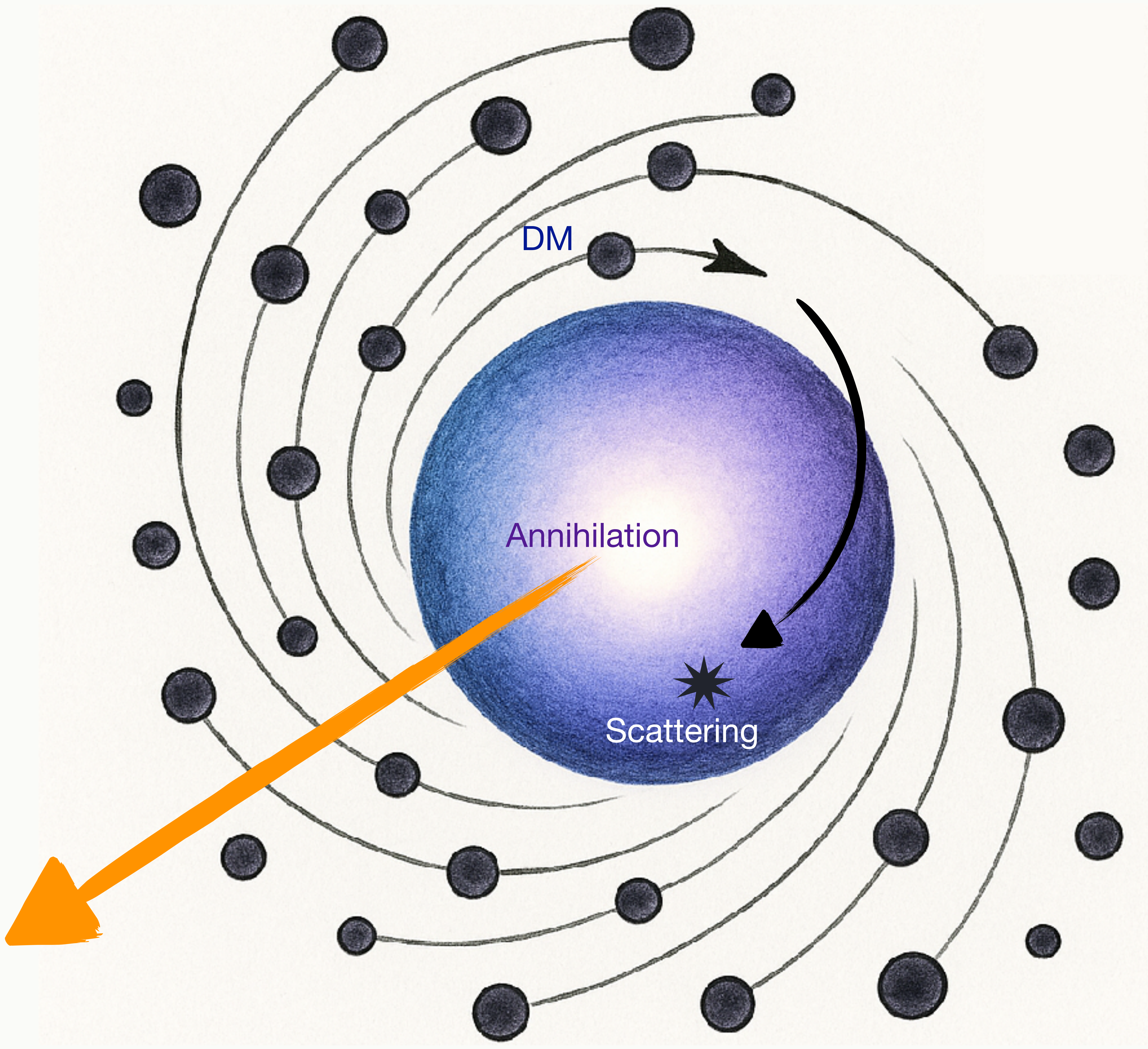


Dark Matter Capture in Stars: the Basic Mechanism

If DM scatters and loses enough energy, becomes gravitationally bound.

Through successive scatterings it sinks to the core, thermalises, accumulates and (eventually) annihilates

Observable signals



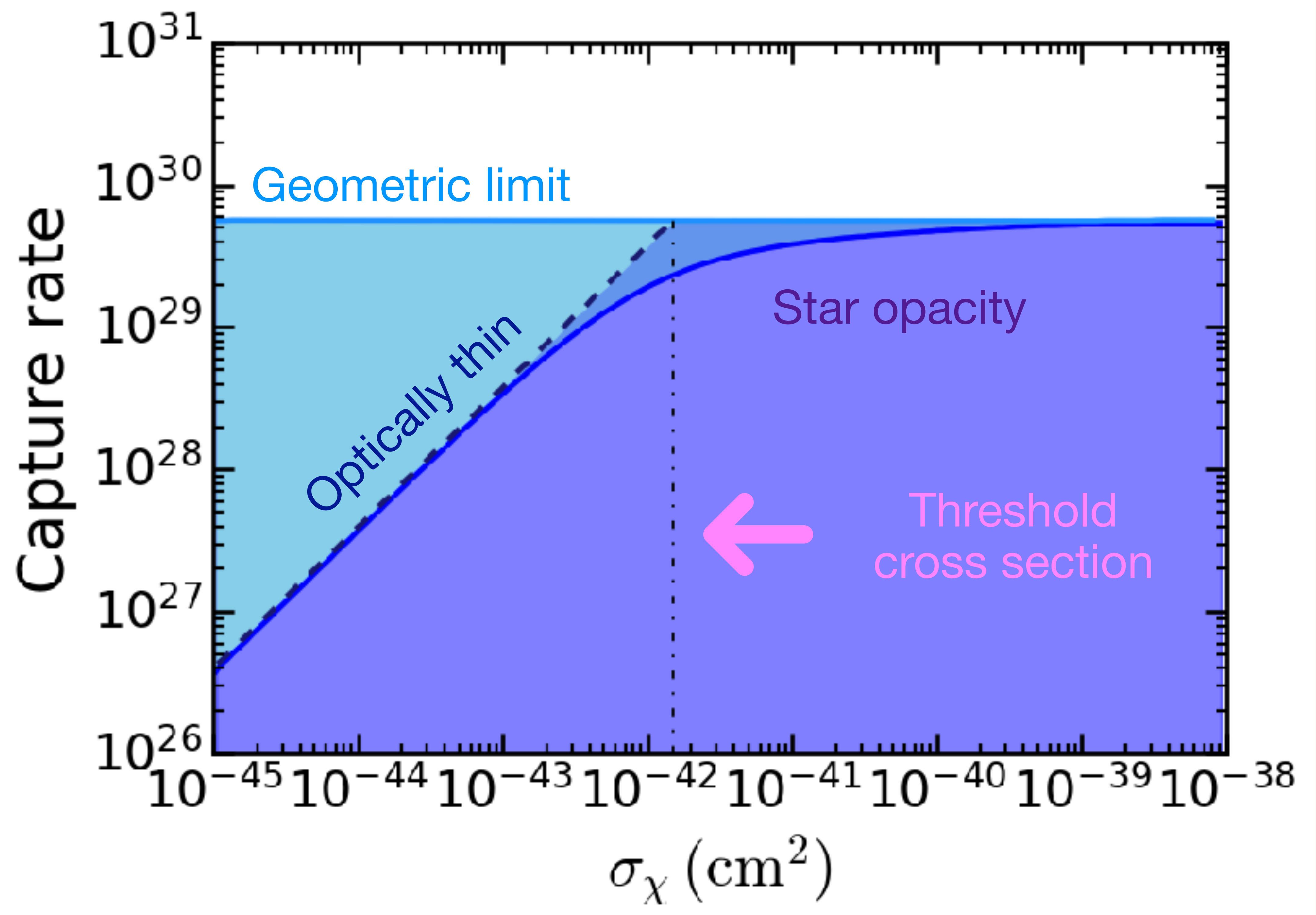
Dark Matter Capture in Stars: Key Ingredients

Capture rate probability $T_\star \to 0$

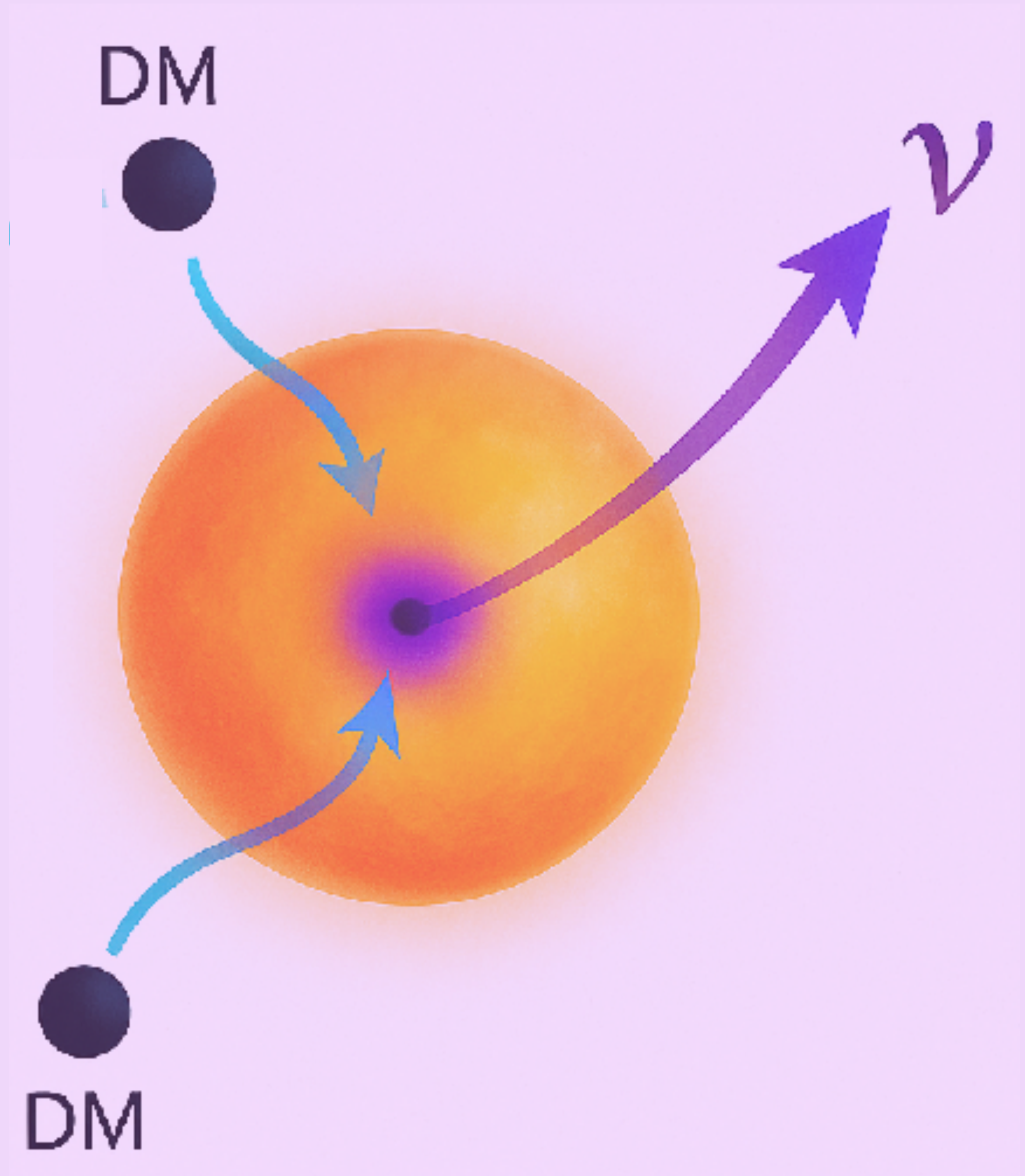
$$C = \frac{\rho_\chi}{m_\chi}\int_0^\infty du_\chi \frac{f_{MB}(u_\chi)}{u_\chi} \times \int_0^{R_\star} 4\pi r^2 \eta(r)\,\omega(r)\,\Omega^-(r)\,dr$$

Requires

- **Star internal structure.**
- **Gravitational focusing**
- **Medium properties**
- **Appropriate interaction model**



The Sun as a Dark Matter Trap



DM plugs into the Sun
Scattering and losing energy.

Captured in the core
thermalise and trapped.

Annihilation ignites
Releasing neutrinos.

Signals reach Earth:
Super-K, Antares, IceCube.

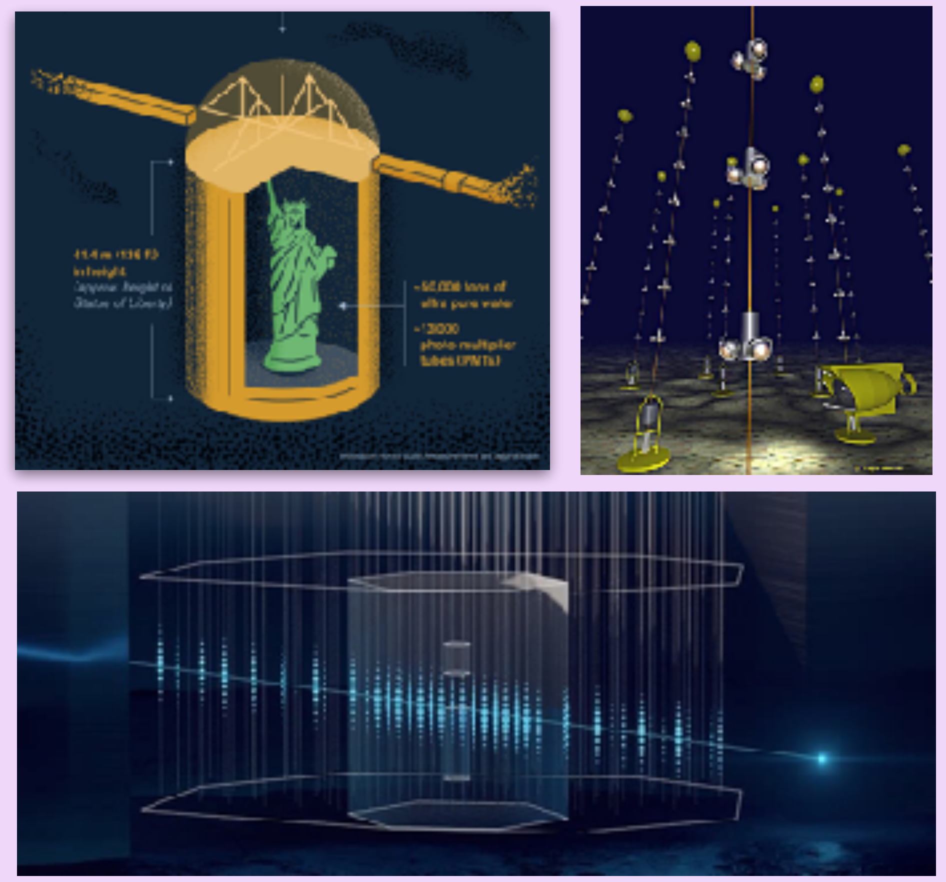
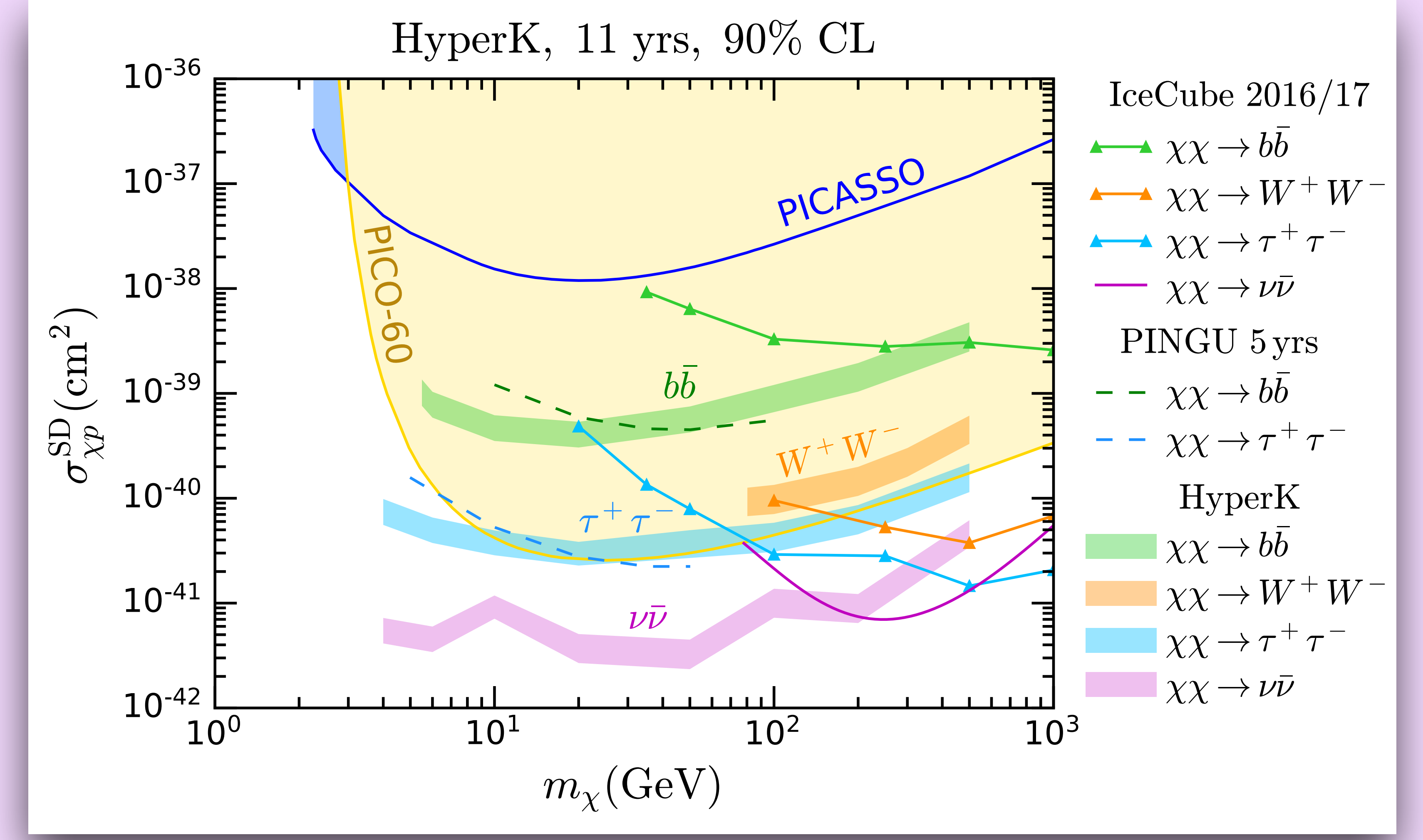


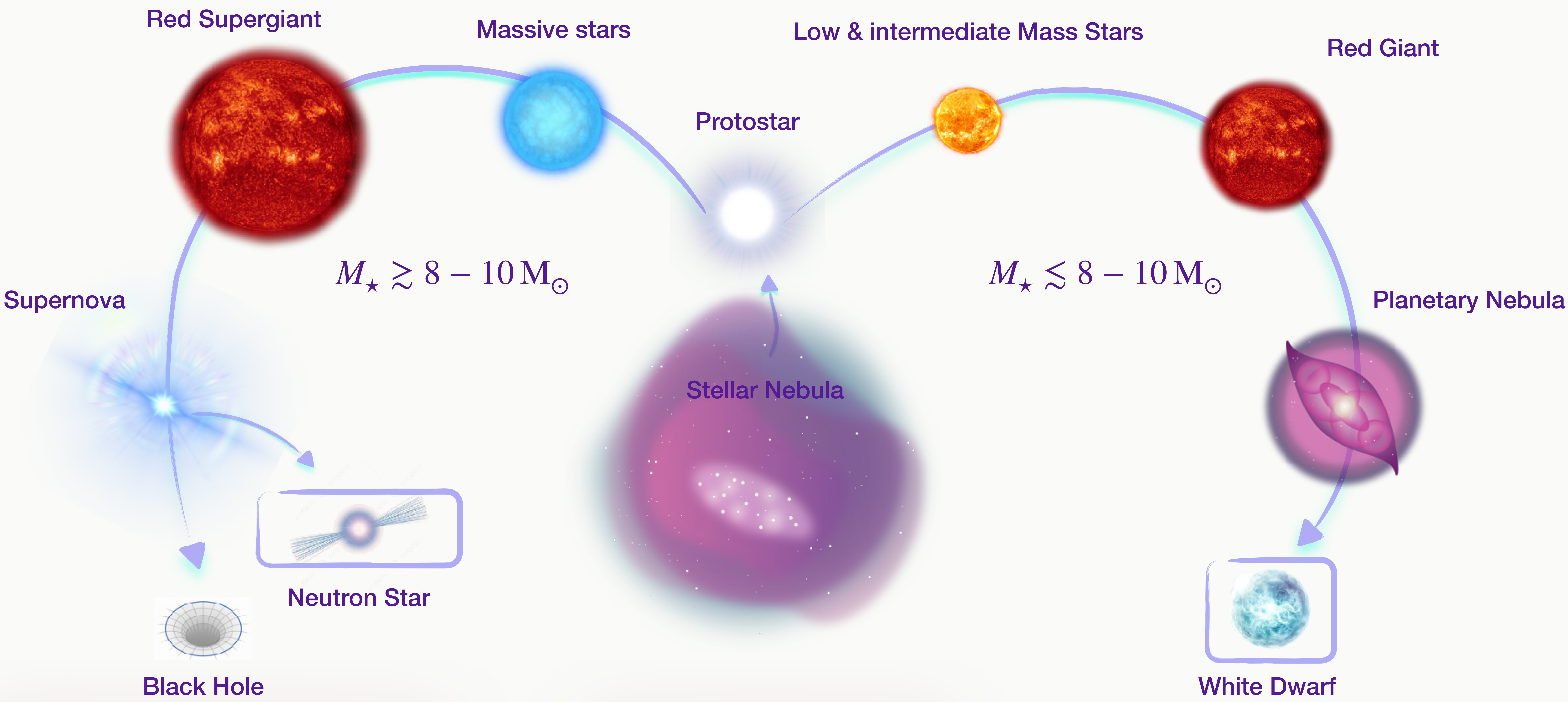
Image credit:
Sandbox Studio, Chicago with Steve Shanabruch
François Montanet
DESY, Science Communication Lab

N. F. Bell, M. J. Dolan, S. Robles JCAP 11 (2021), 004

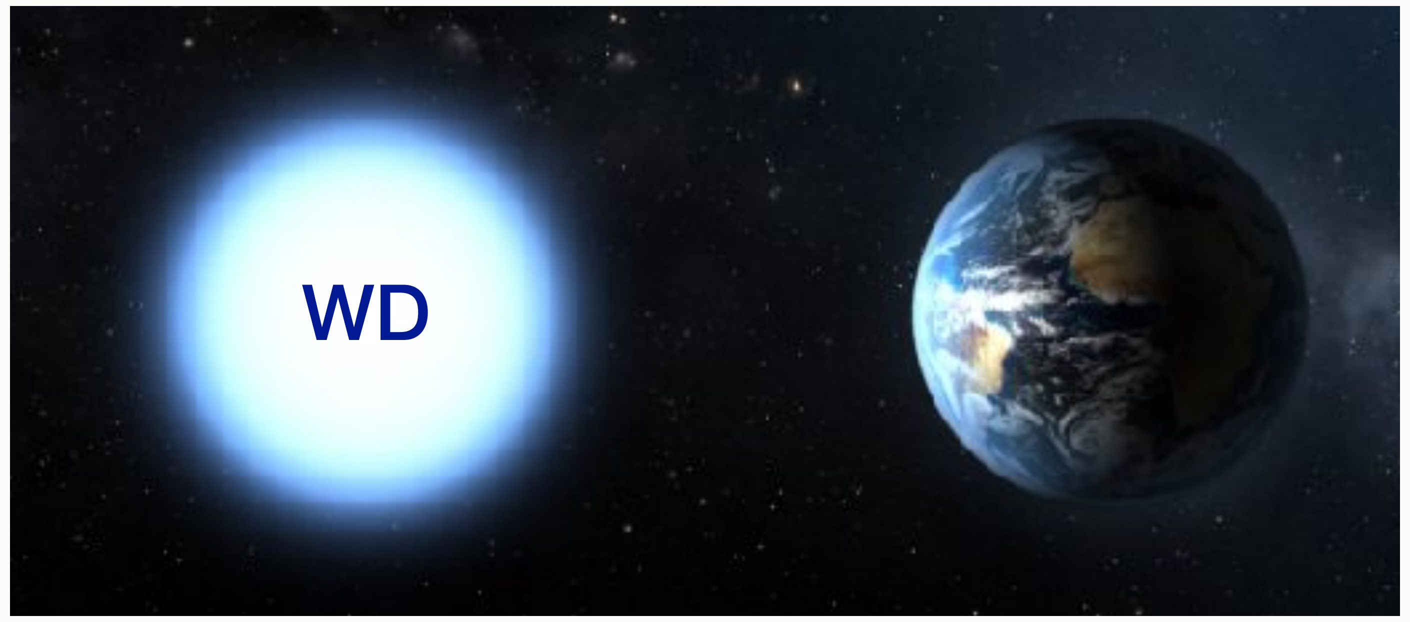


Evaporation sets lower bound ($m_\chi \geq$ GeV)
Limits **weaker** that DD (but complementary)

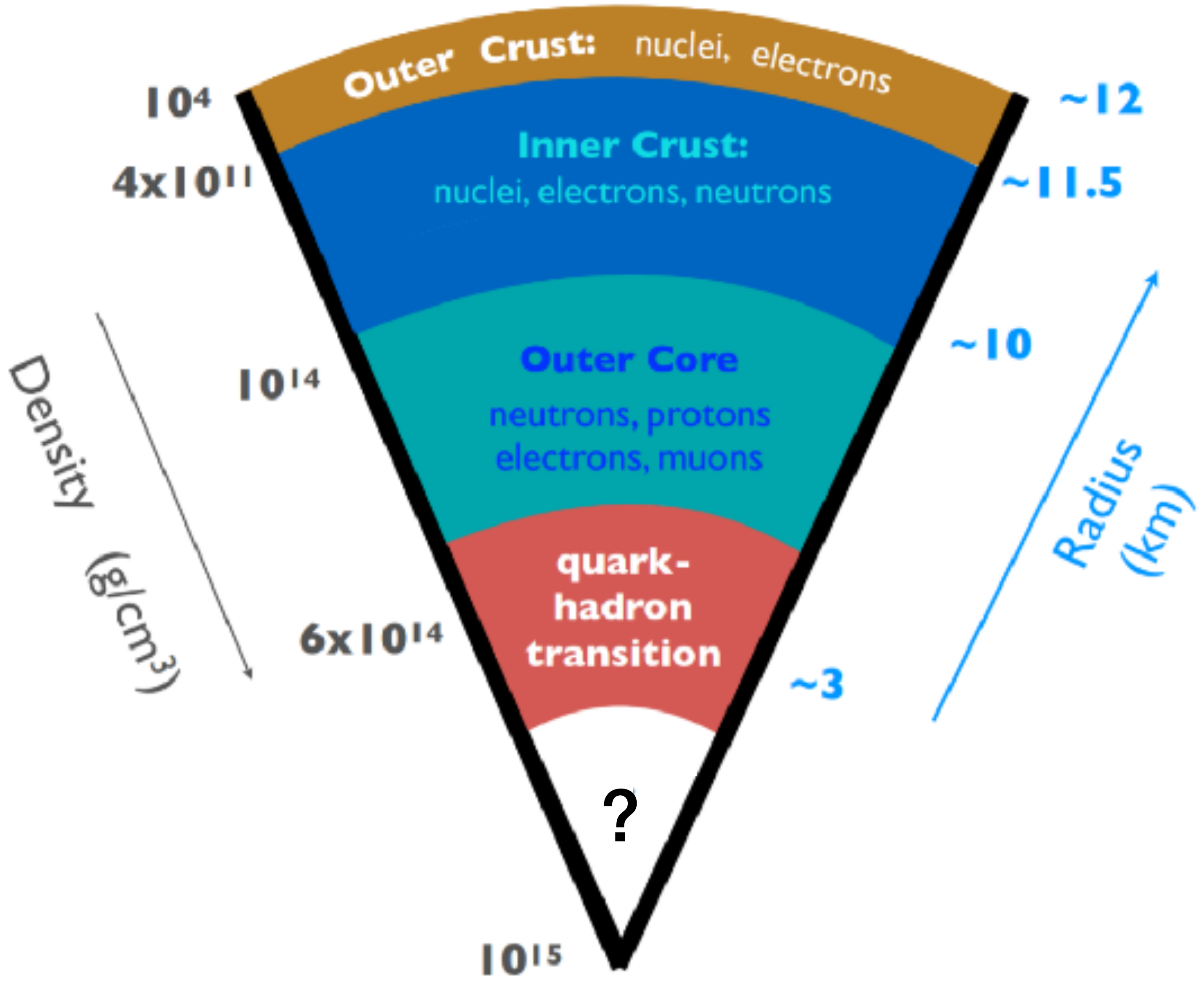
Compact Stars



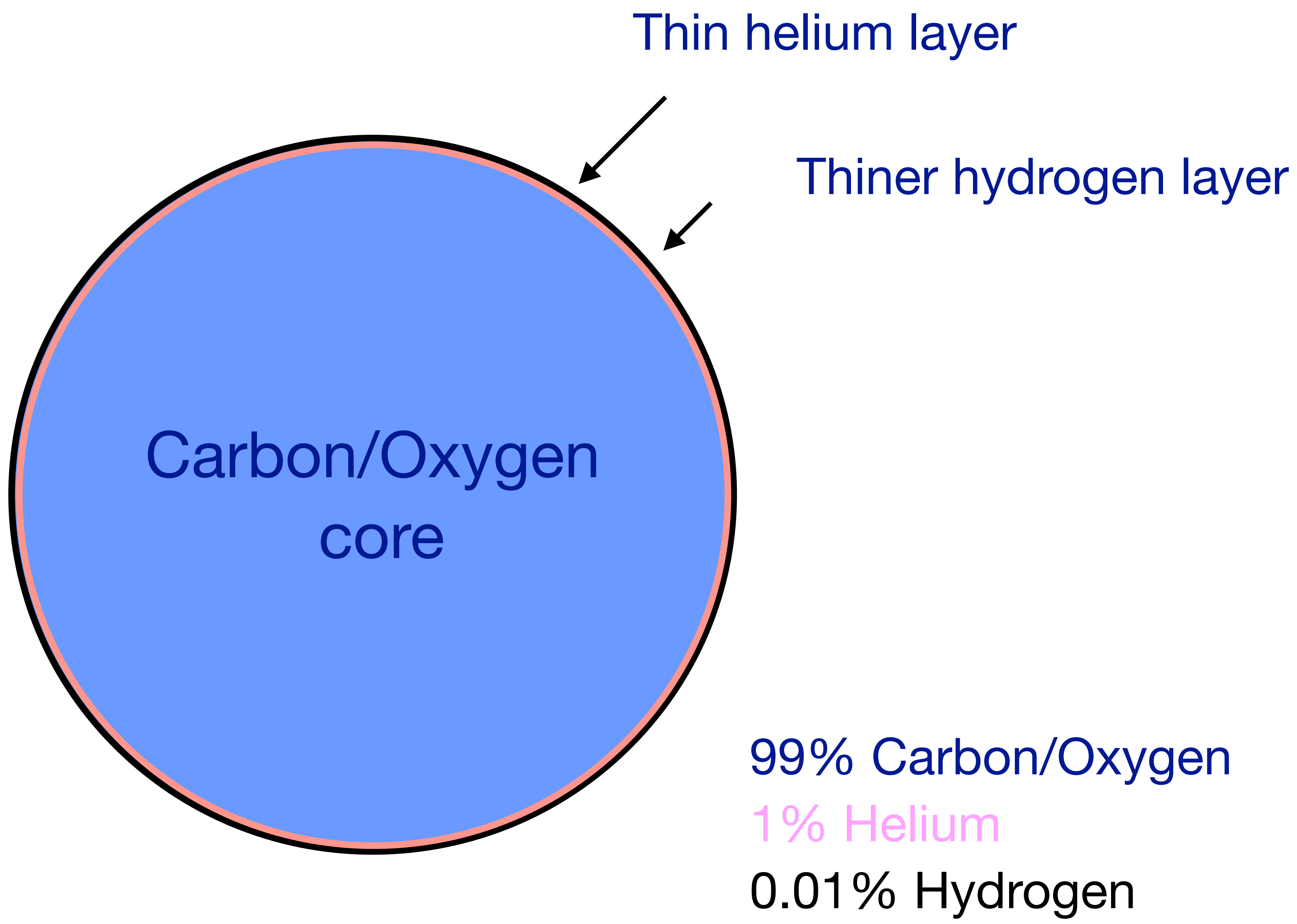
Compact stars as cosmic laboratories



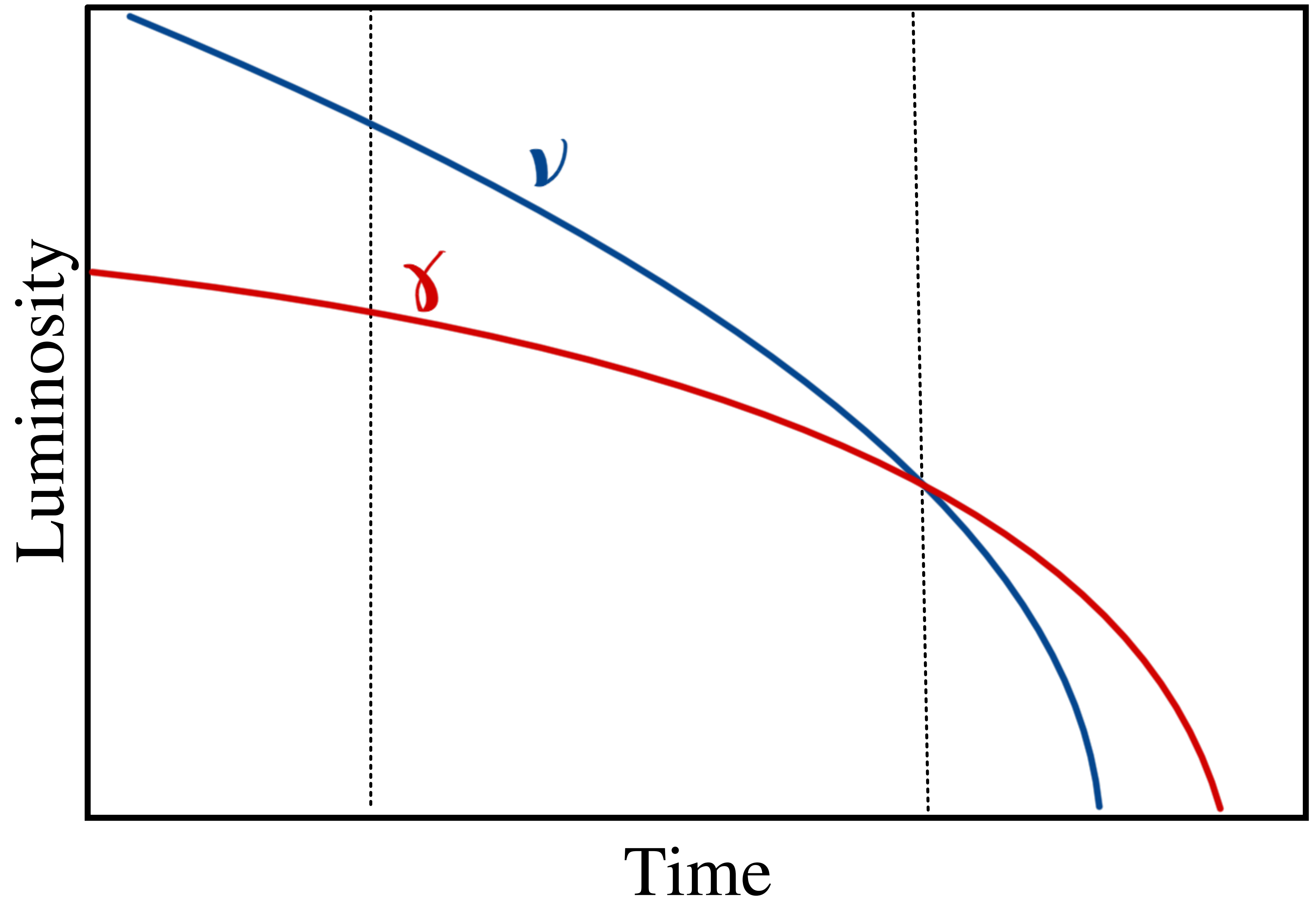
Neutron Star



White Dwarf

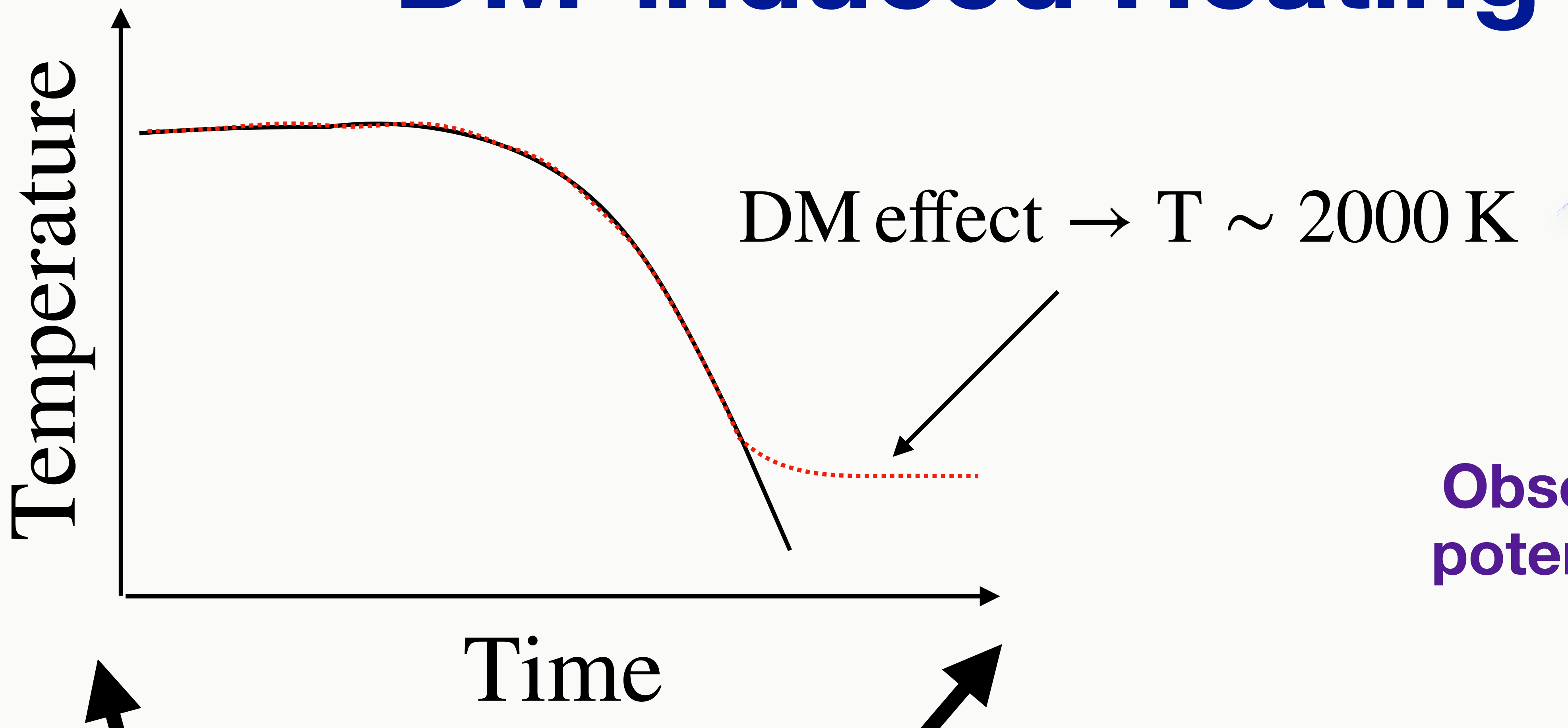


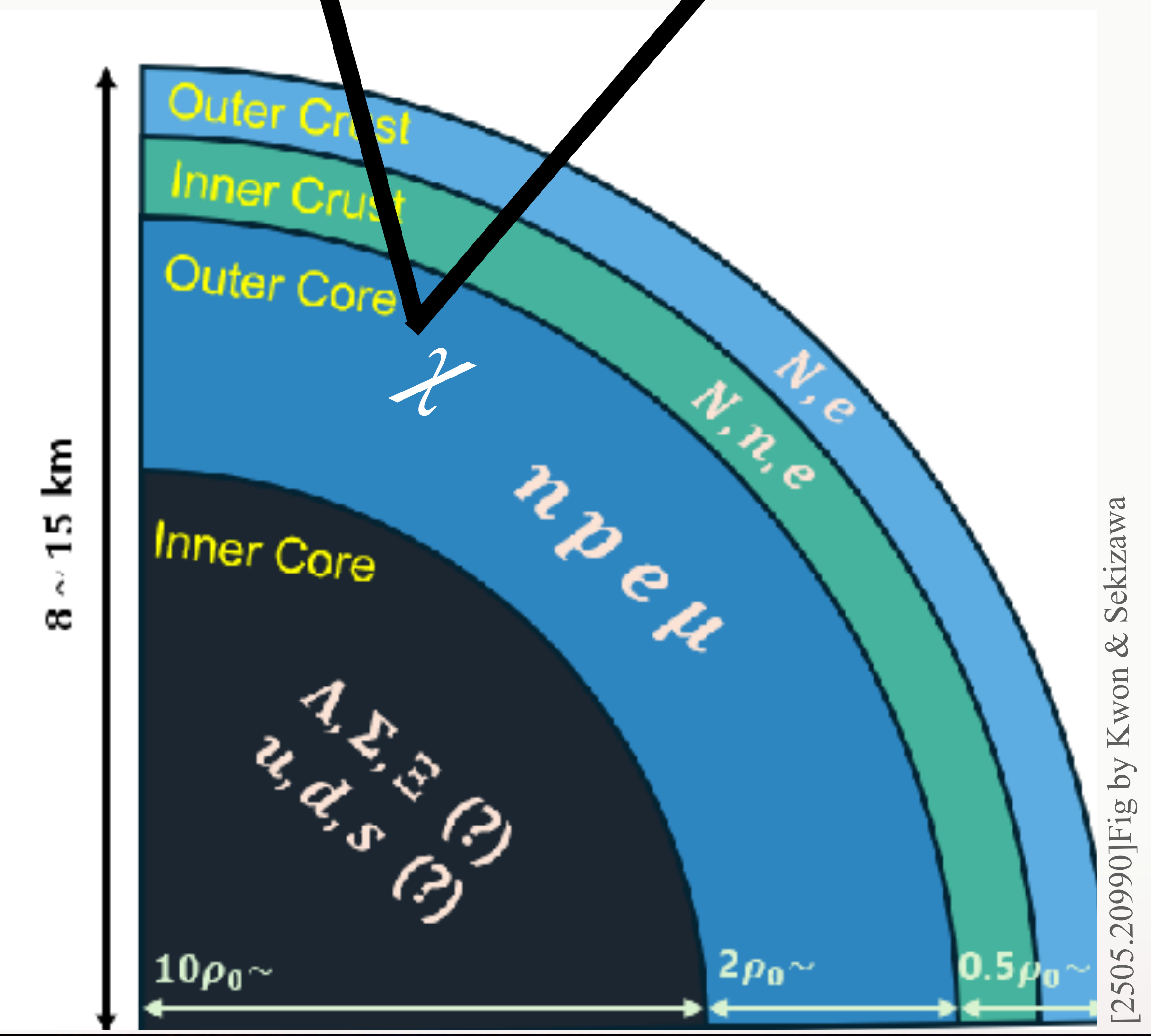
Standard cooling (schematic)



Compact stars are born hot and cool over time — but new physics can alter their thermal evolution.

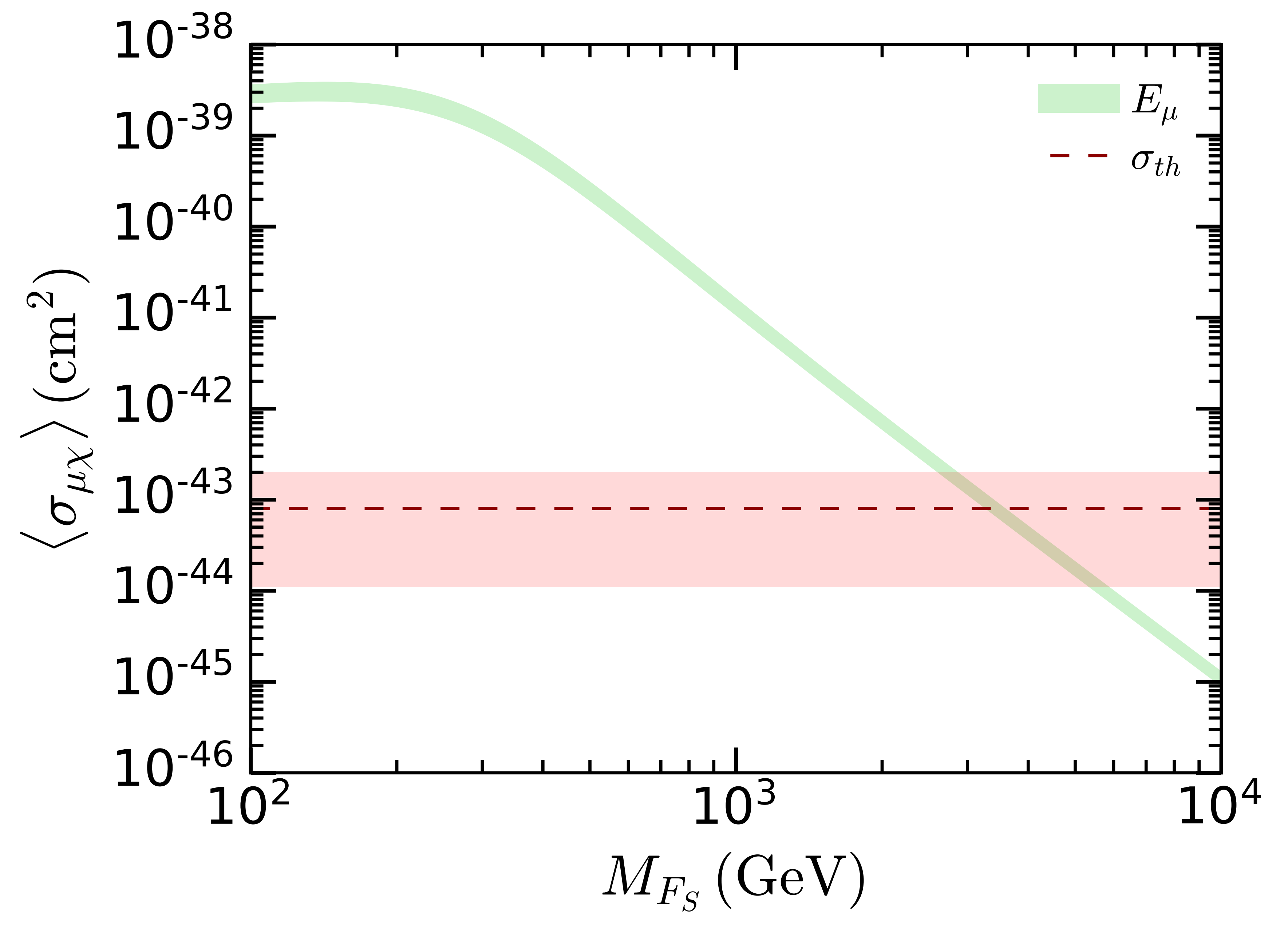
DM-induced Heating in NSs



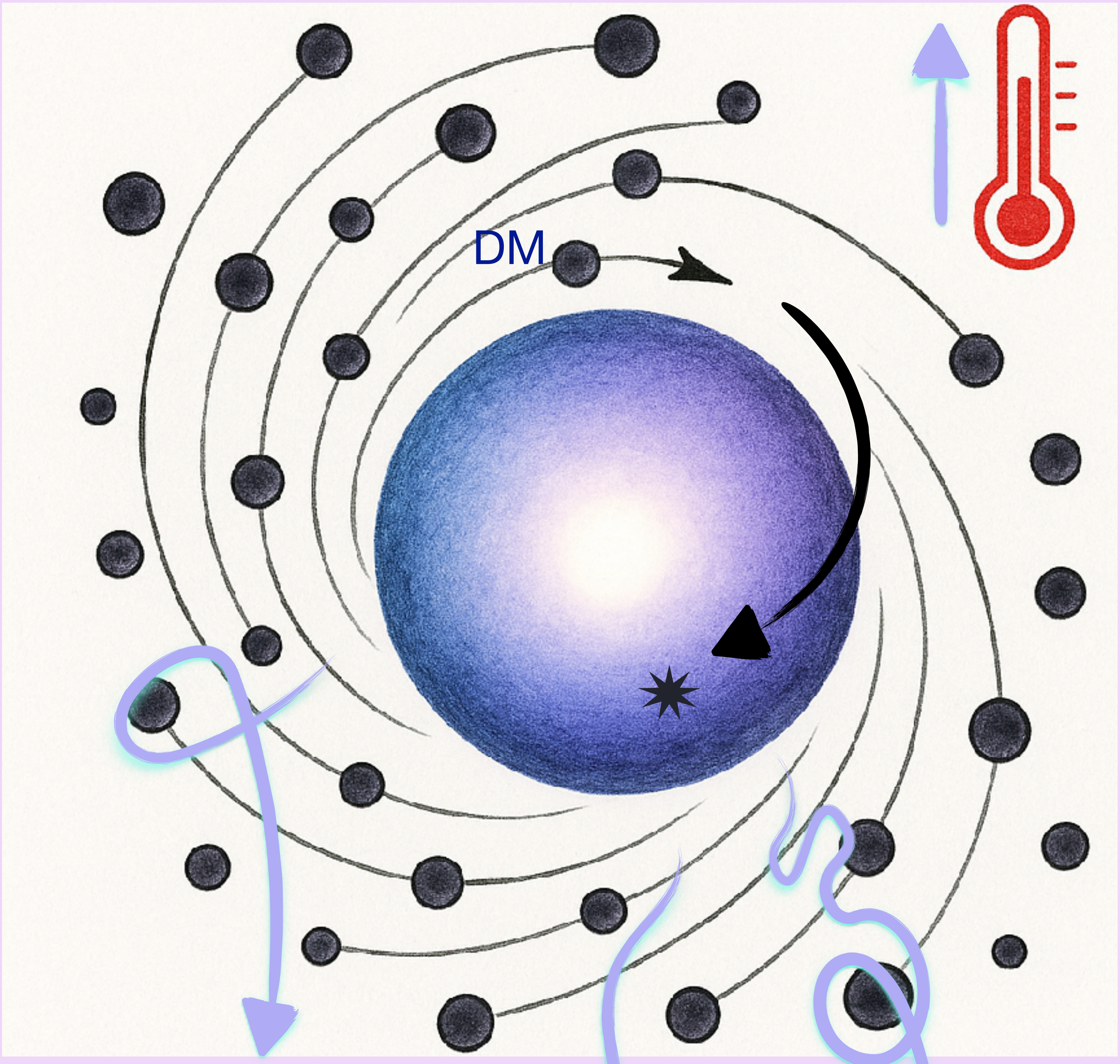


Observations of an old/cold NS potentially leads to a DM signal.

Multiple targets:
DM coupled only to muon
K. Hamaguchi, N. Nagata, MERQ JHEP 2022



Heating process:
Capture + Thermalisation + Annihilation



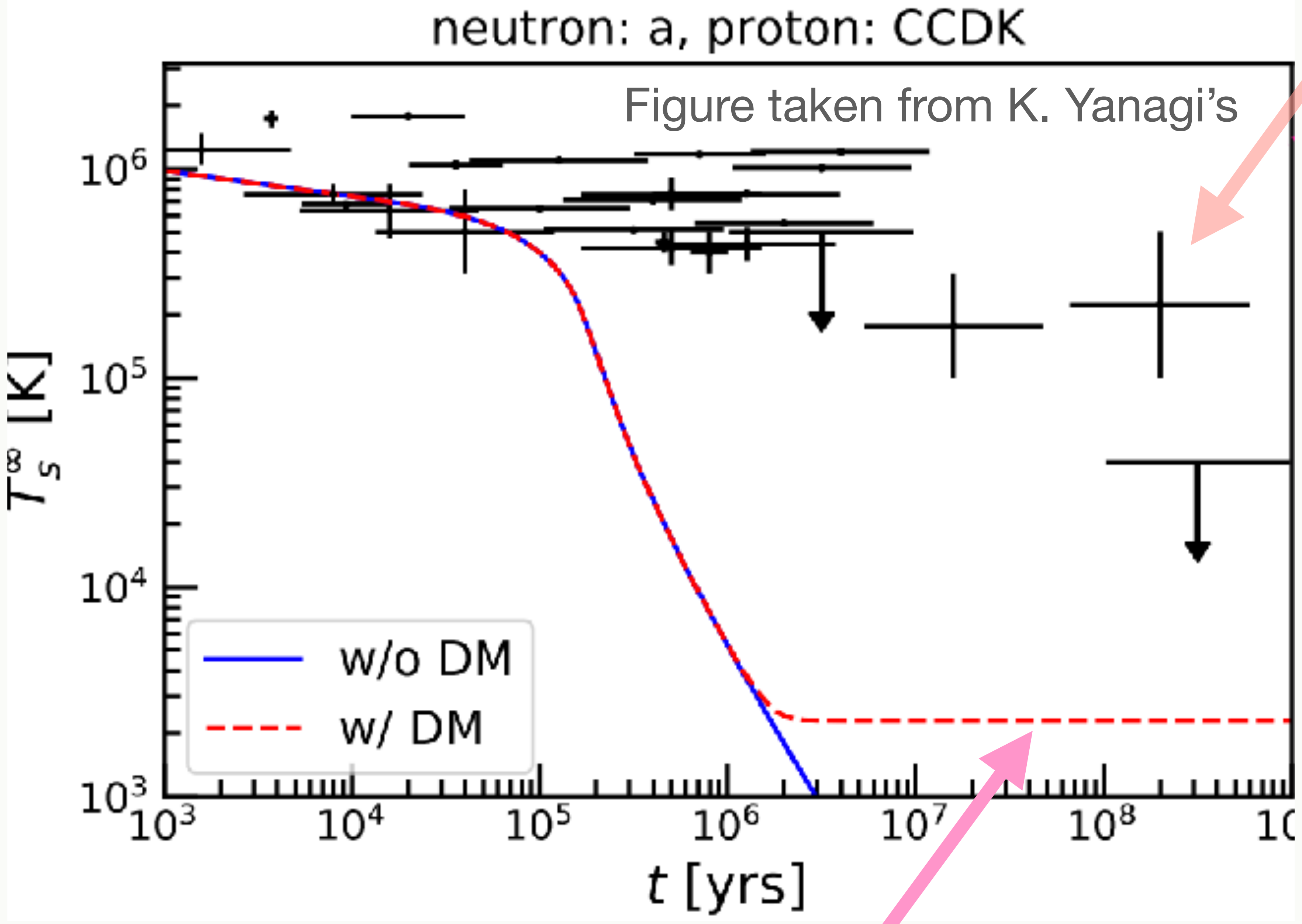
Sub-GeV regime, down to $\mathcal{O}(10)$ keV

No limitation from neutrino floor

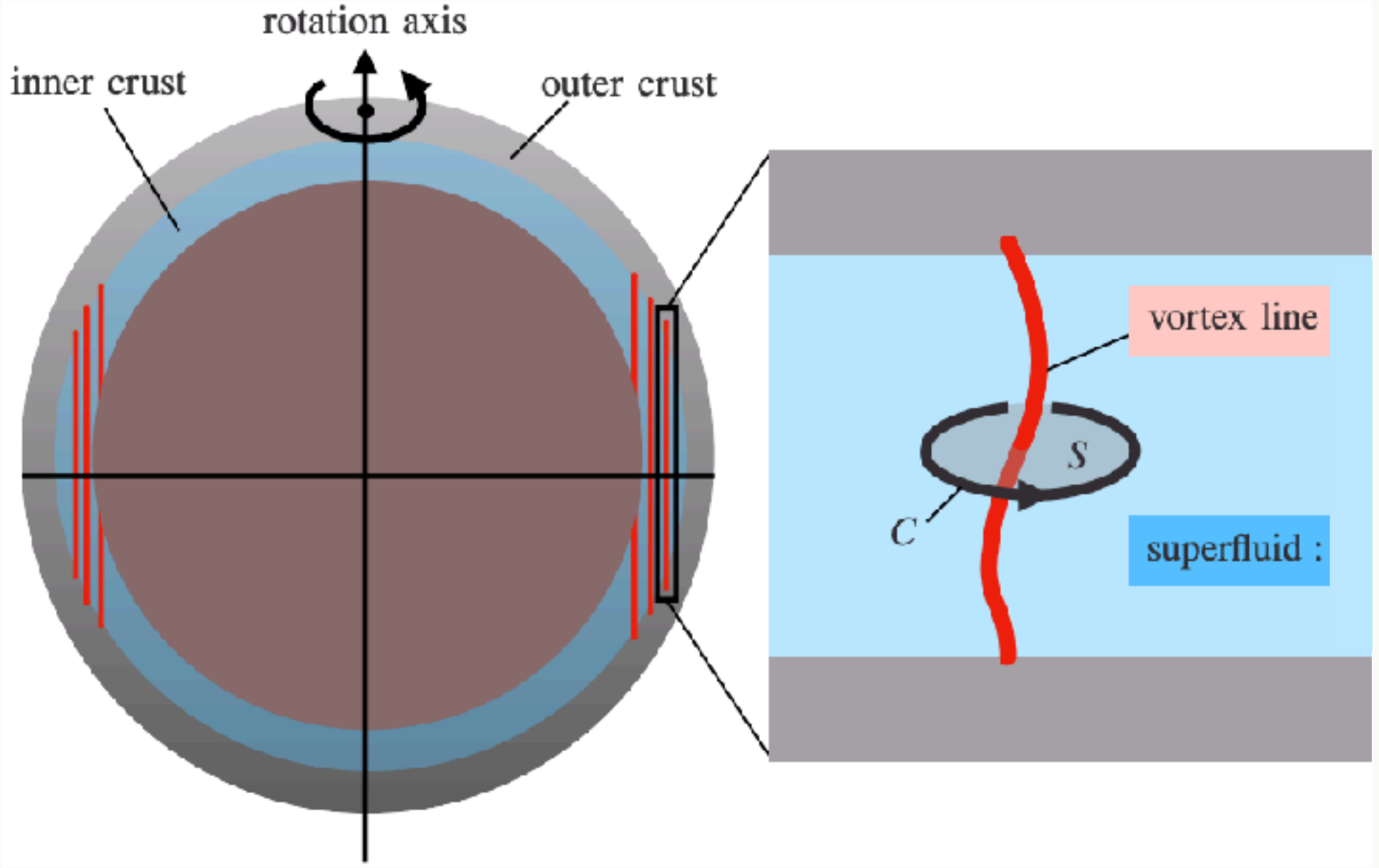
DM particles become mildly relativistic

DM-induced Heating in NSs: Comparison with Vortex Creep

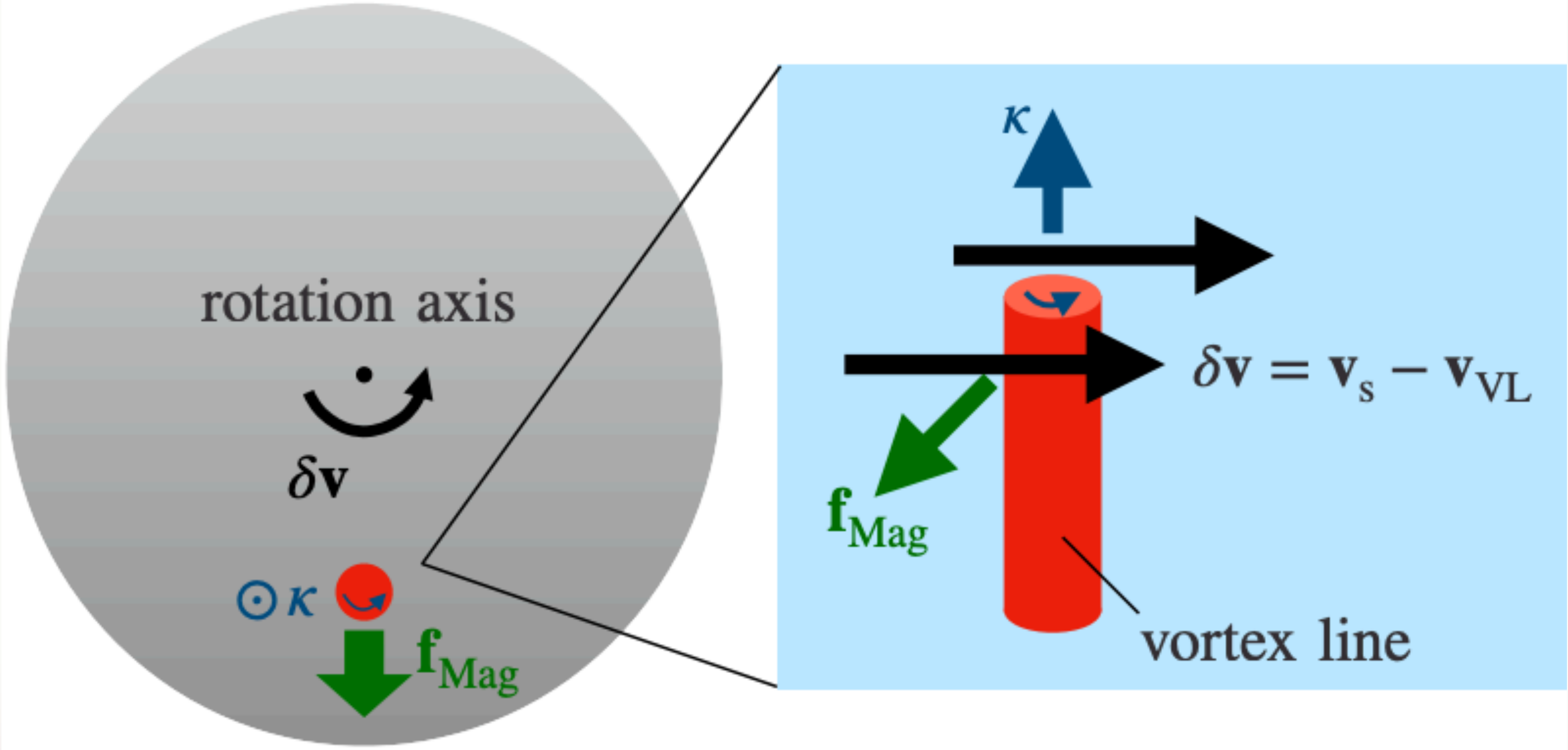
Old NS hotter than expected ($T_\star \gg 2000\,\mathrm{K}$)



DM heating alone is not sufficient



Fujiwara, Hamaguchi, Nagata, MERQ, JCAP 2024

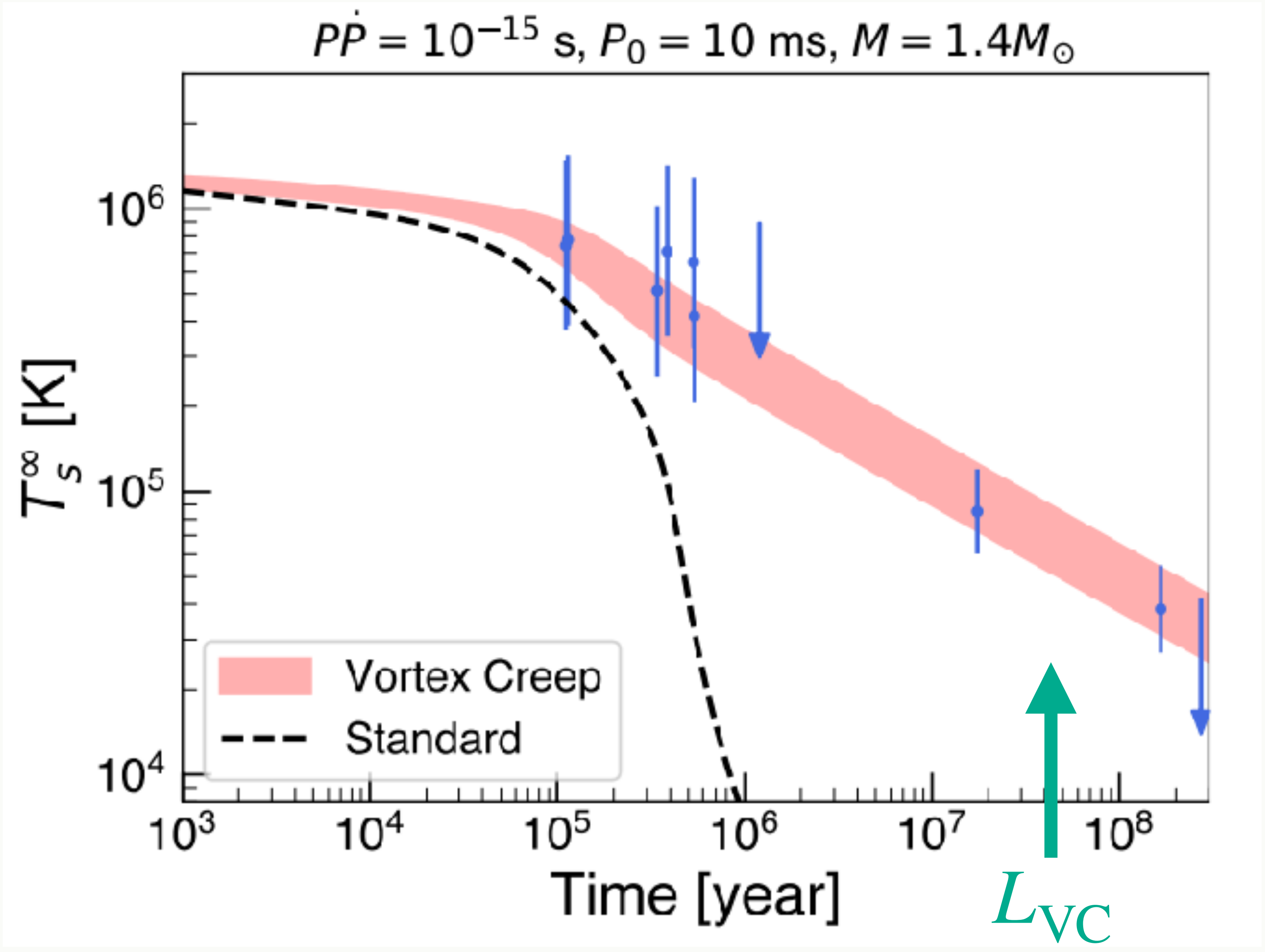


Vortex creep gradually transfers angular momentum from the superfluid core to the crust, releasing heat through internal friction.

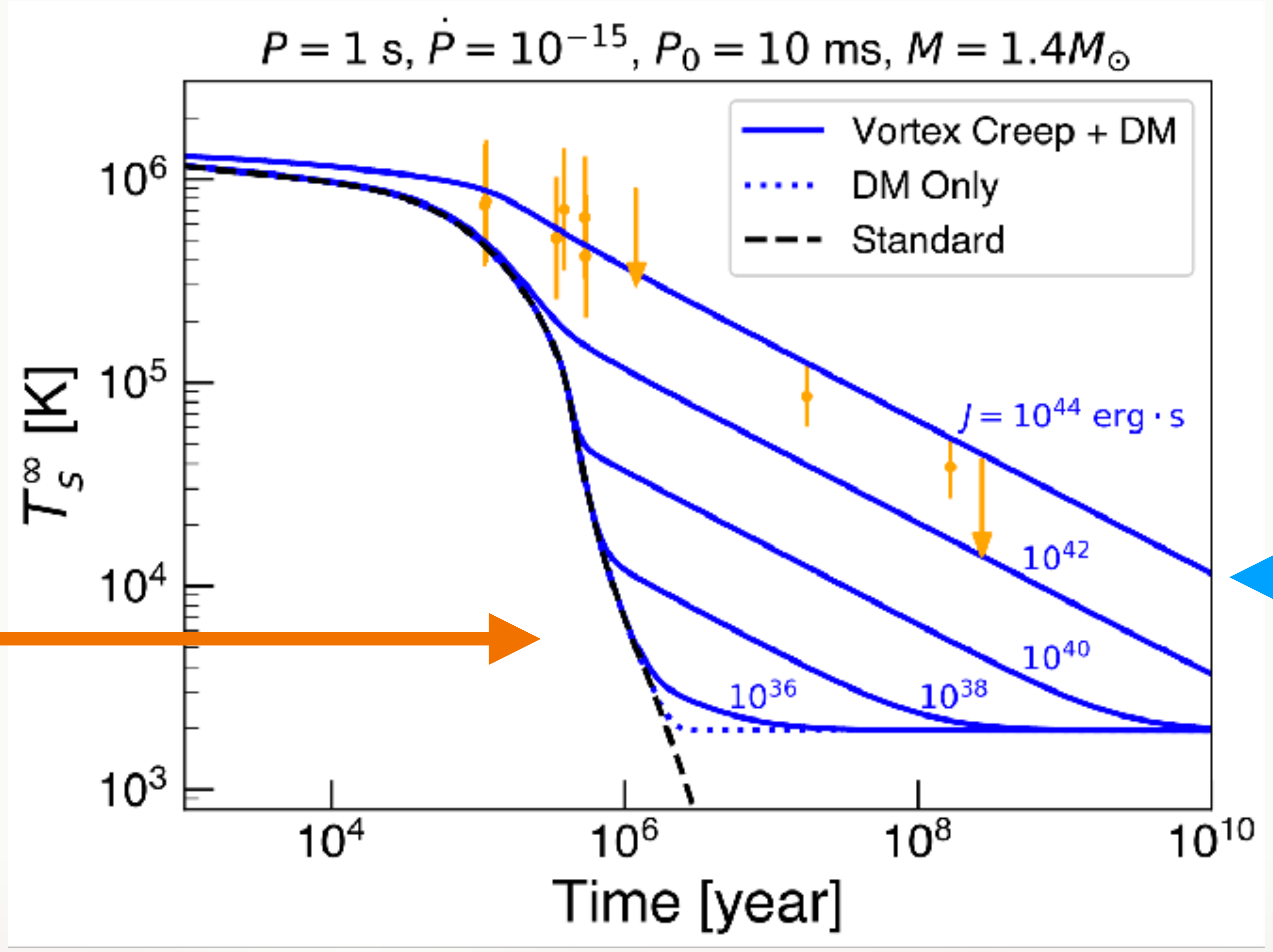
DM-induced Heating in NSs: Comparison with Vortex Creep

$L_{VC} = J|\dot{\omega}| \rightarrow$ predicts quasi universal thermal floor

Observed warm NS reproduced for $J \sim 10^{43} - 10^{44}\,\mathrm{erg\,s}$.



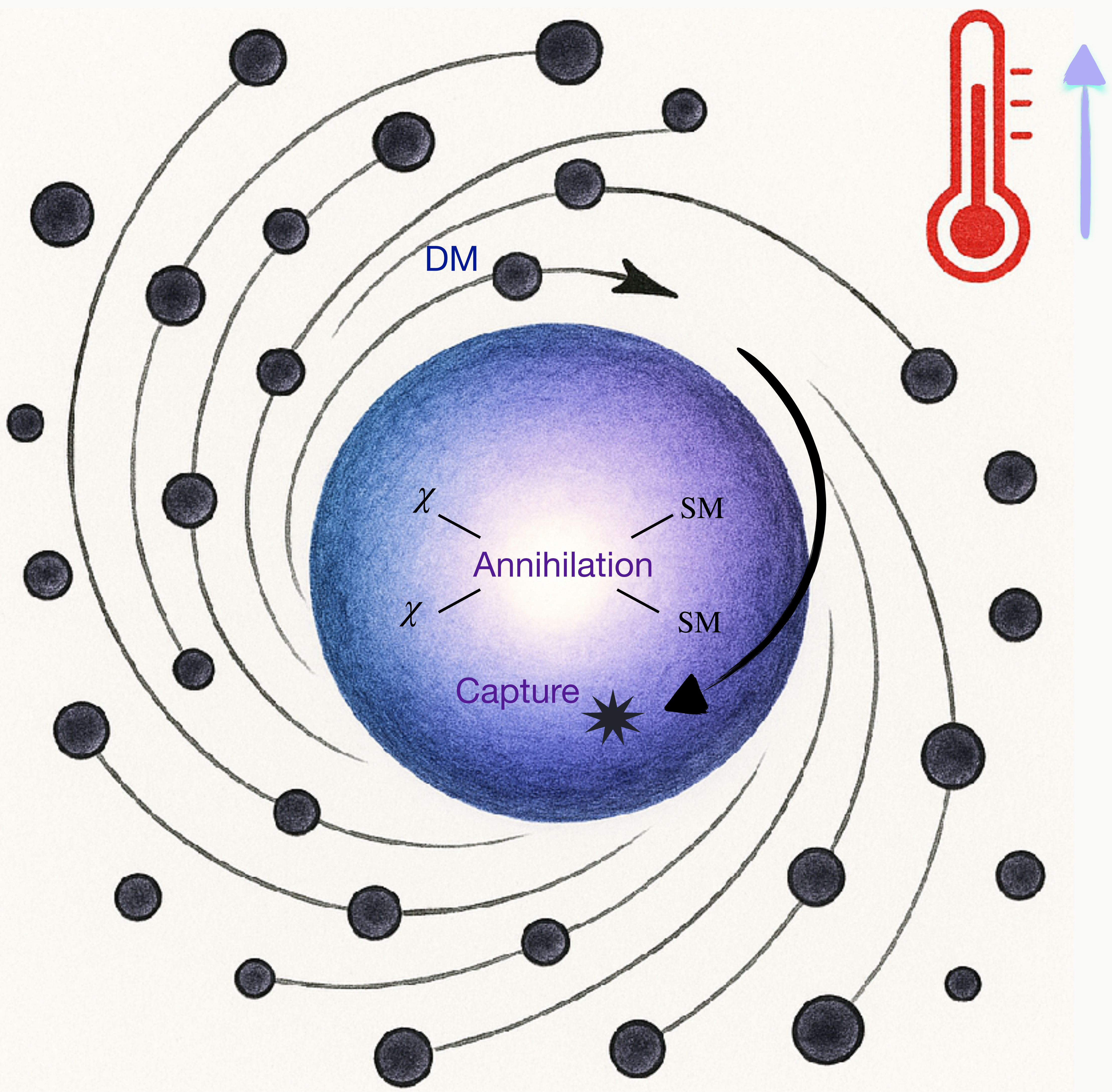
DM heating hidden unless $J \lesssim 10^{38}\,\mathrm{erg\,s}$

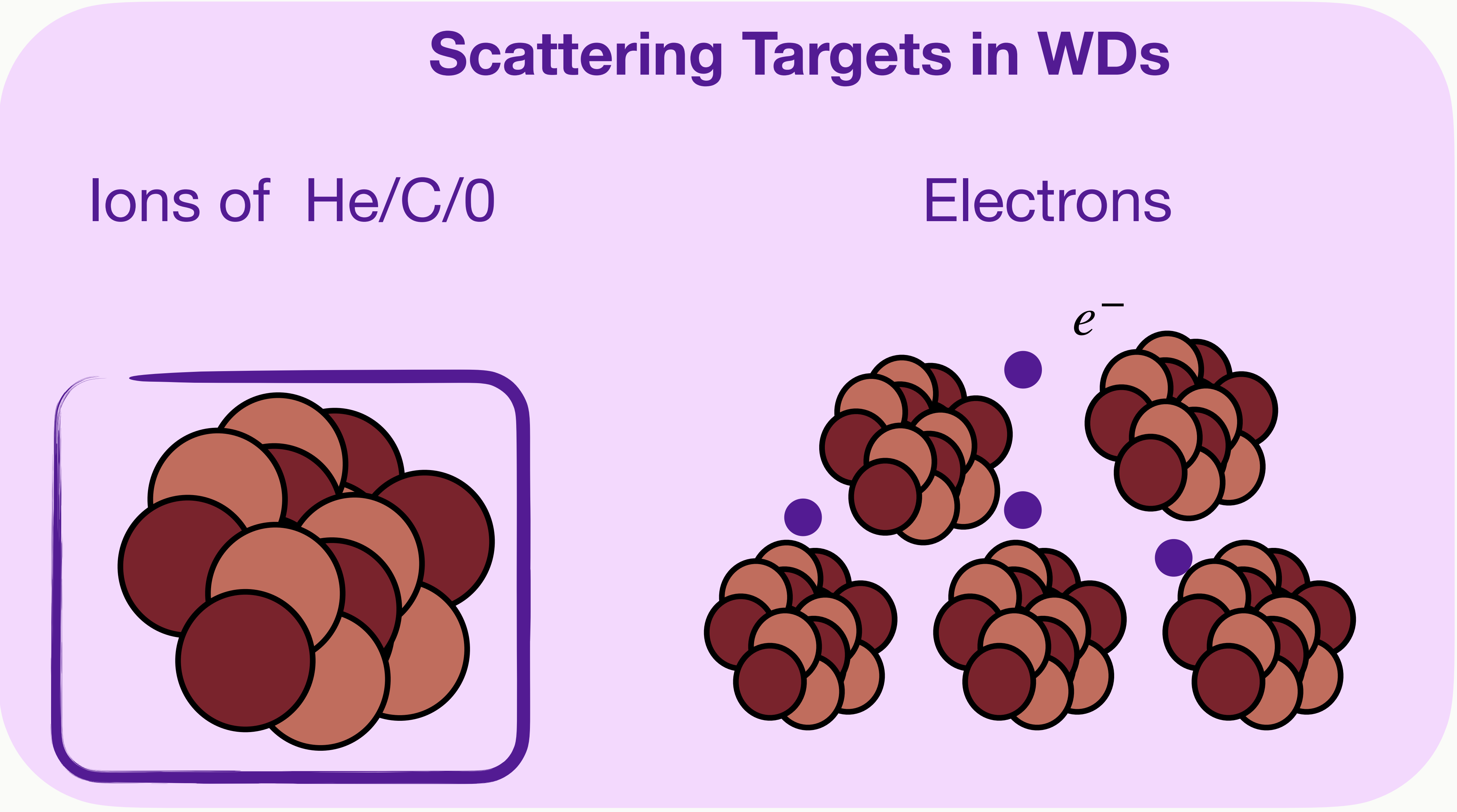


$L_{VC} + L_\chi$

Vortex creep sets a natural thermal floor in old NSs, and we must account for it before claiming DM heating.

DM-induced Heating in WDs

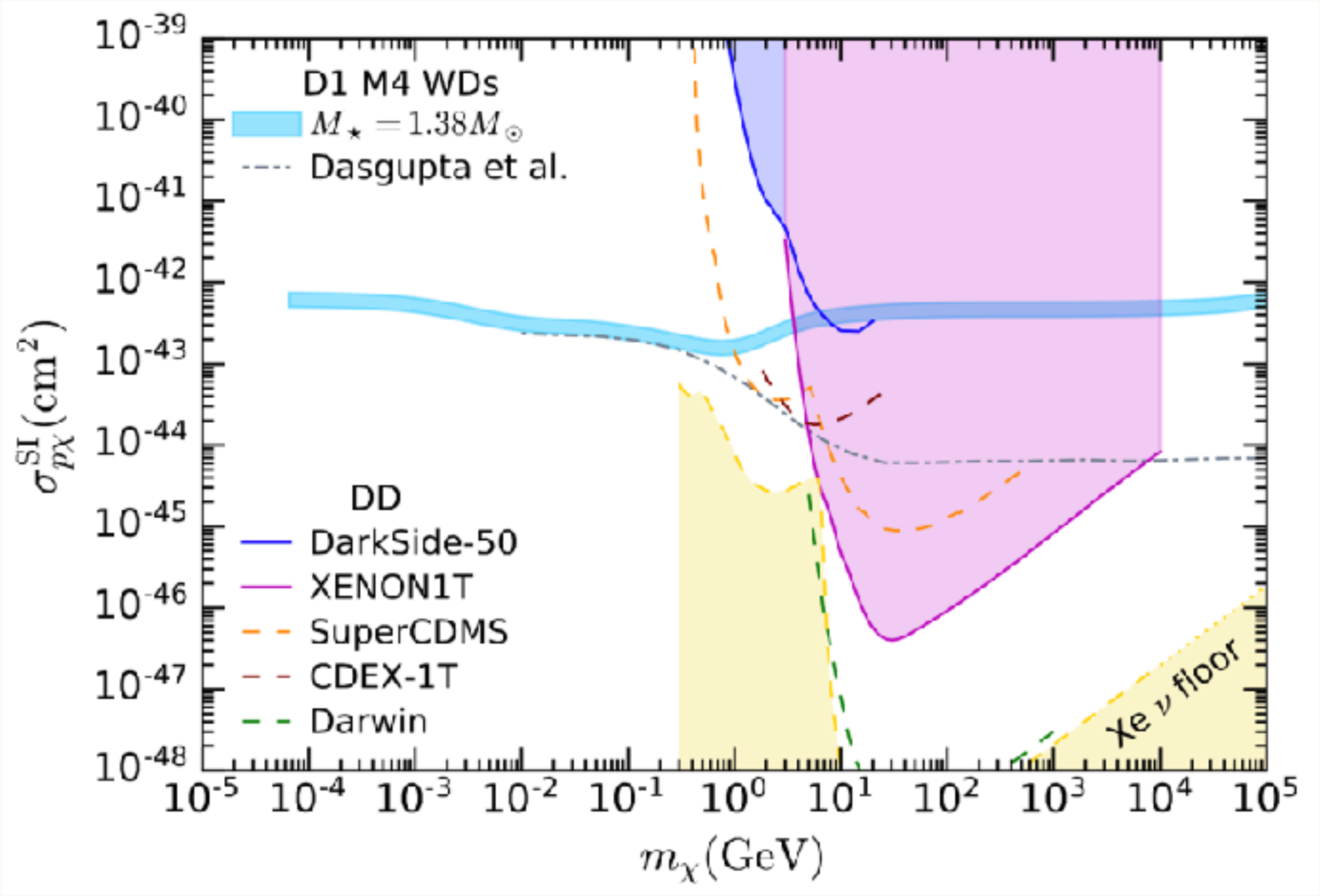




Name	Operator	Coupling
D1	$\bar{\chi}\chi\bar{f}f$	y_f/Λ_q^2
D2	$\bar{\chi}\gamma^5\chi\bar{f}f$	iy_f/Λ_q^2
D5	$\bar{\chi}\gamma_\mu\chi\bar{f}\gamma^\mu f$	$1/\Lambda_q^2$
D6	$\bar{\chi}\gamma_\mu\gamma^5\chi\bar{f}\gamma^\mu f$	$1/\Lambda_q^2$
D10	$\bar{\chi}\sigma_{\mu\nu}\gamma^5\chi\bar{f}\sigma^{\mu\nu}f$	i/Λ_q^2

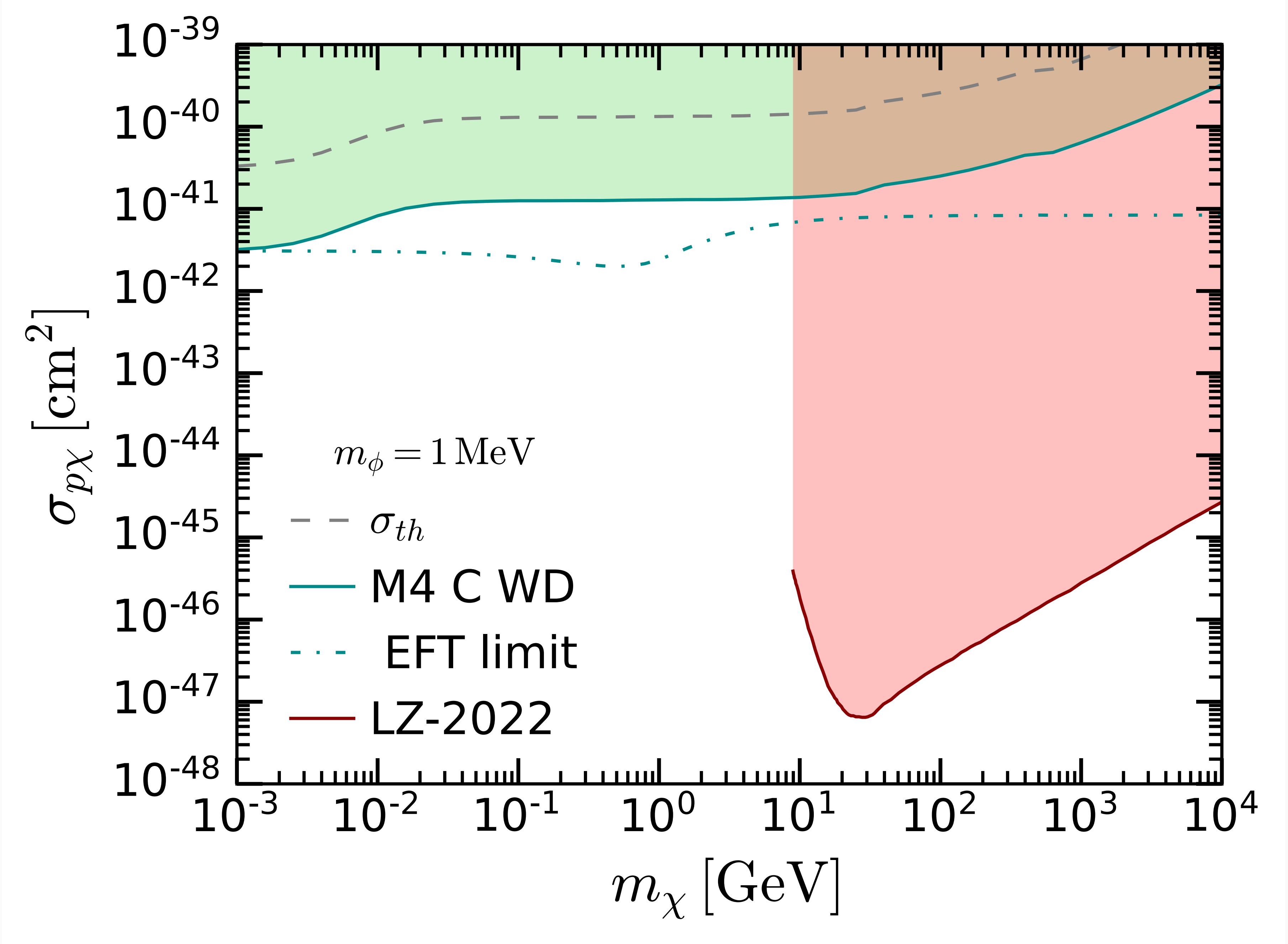
Reaching New Regimes with WD observations

Bell, Busoni, Robles, MERQ, Virgato *JCAP 2021* & MERQ, Phys.Rev.D (2023)

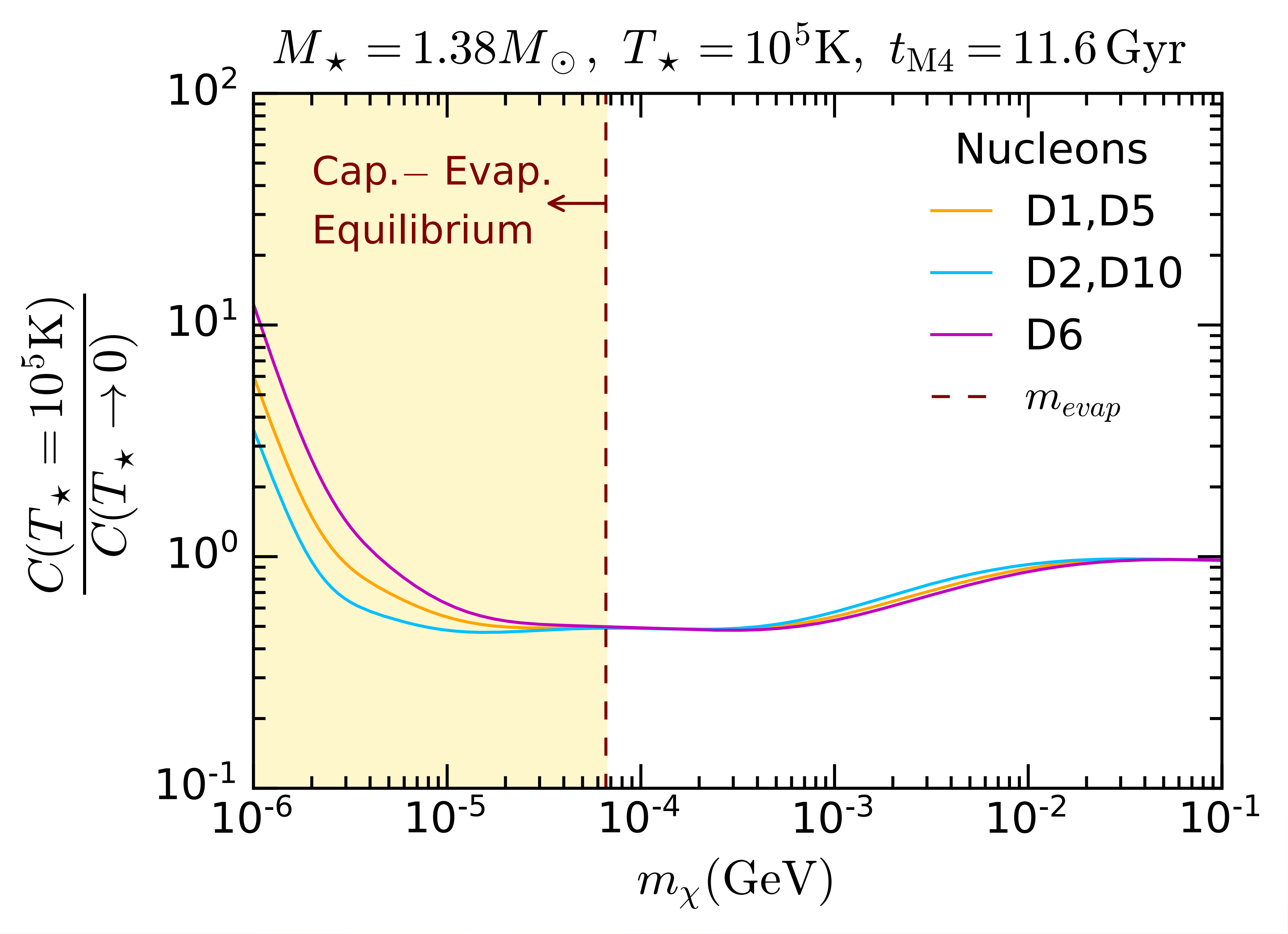


Beyond EFT

$$\frac{1}{\Lambda_q^2} \rightarrow \frac{1}{(q^2 - m^2)}$$



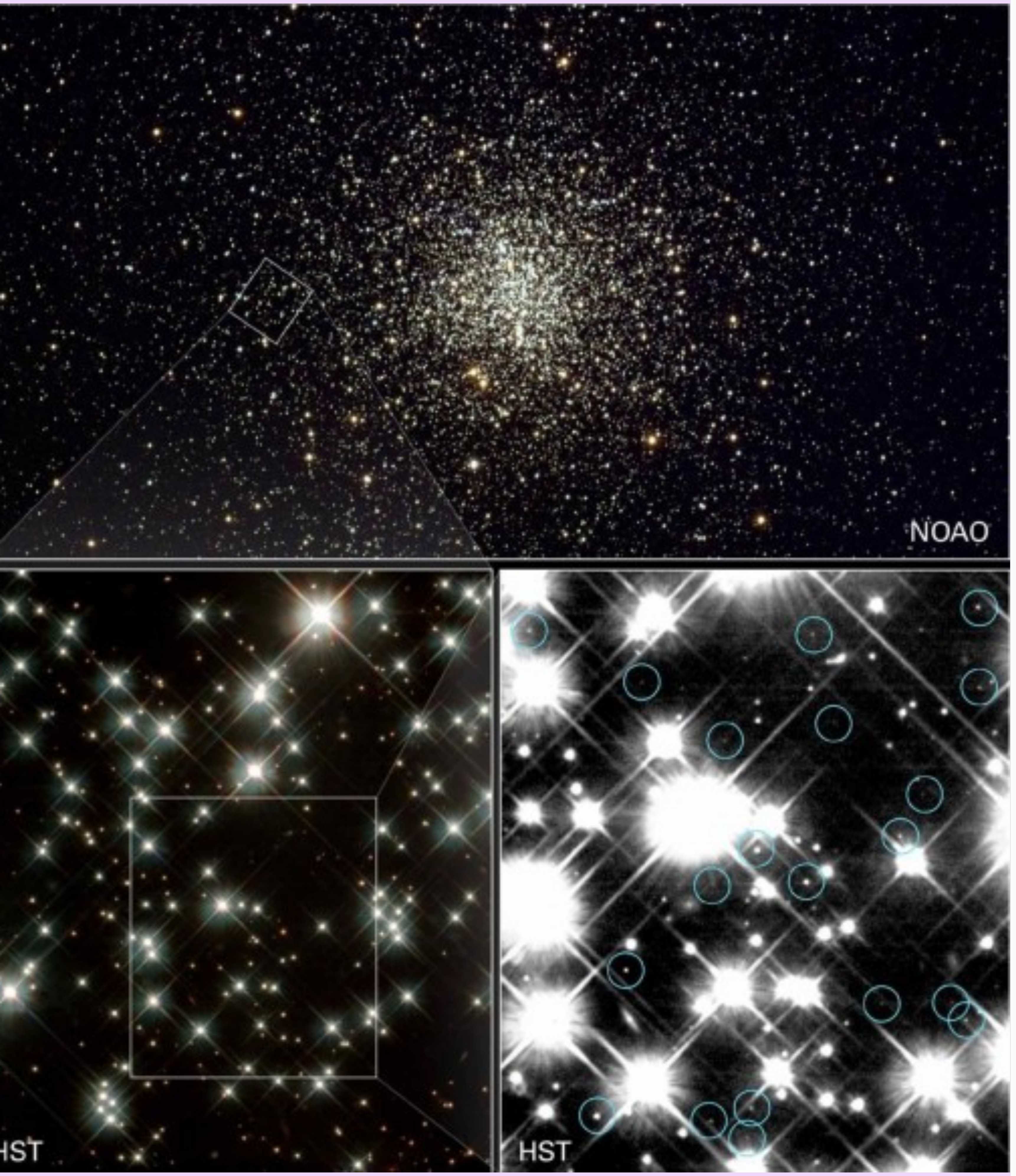
Thermal effects



With old, cold WDs, we obtain bounds competitive with direct detection — reaching the sub-GeV regime.

White Dwarf Observations

Messier 4 (M4) – the NGC 6121 globular cluster



Credit: NASA/JPL/NOAO/HST

Observation of old/cold white dwarfs in M4:
Hubble Space Telescope

Distance from Earth ~$(1.9\,\mathrm{kpc})$
Age of M4 $t_{M4} \sim 11.6\,\mathrm{Gyr}$
If formed in a DM sub-halo:

$\rho_\chi = 798\,\mathrm{GeV cm^{-3}}$

McCullough, Fairbairn, Phys.Rev.D 2010

Largest astrophysical uncertainty

DM density in M4 was found to be of the order of few $\mathrm{GeV/cm^3}$ in Hooper et al Phys. Rev. D 2010

Beyond traditional capture: Multi-energy mechanism in WDs

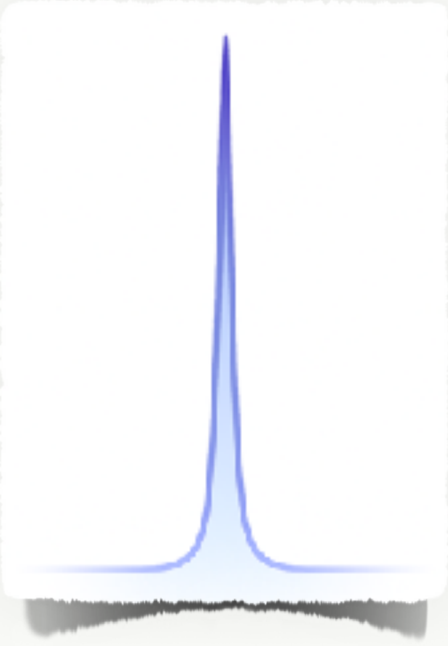
Elastic scattering — Deep inelastic

T_χ

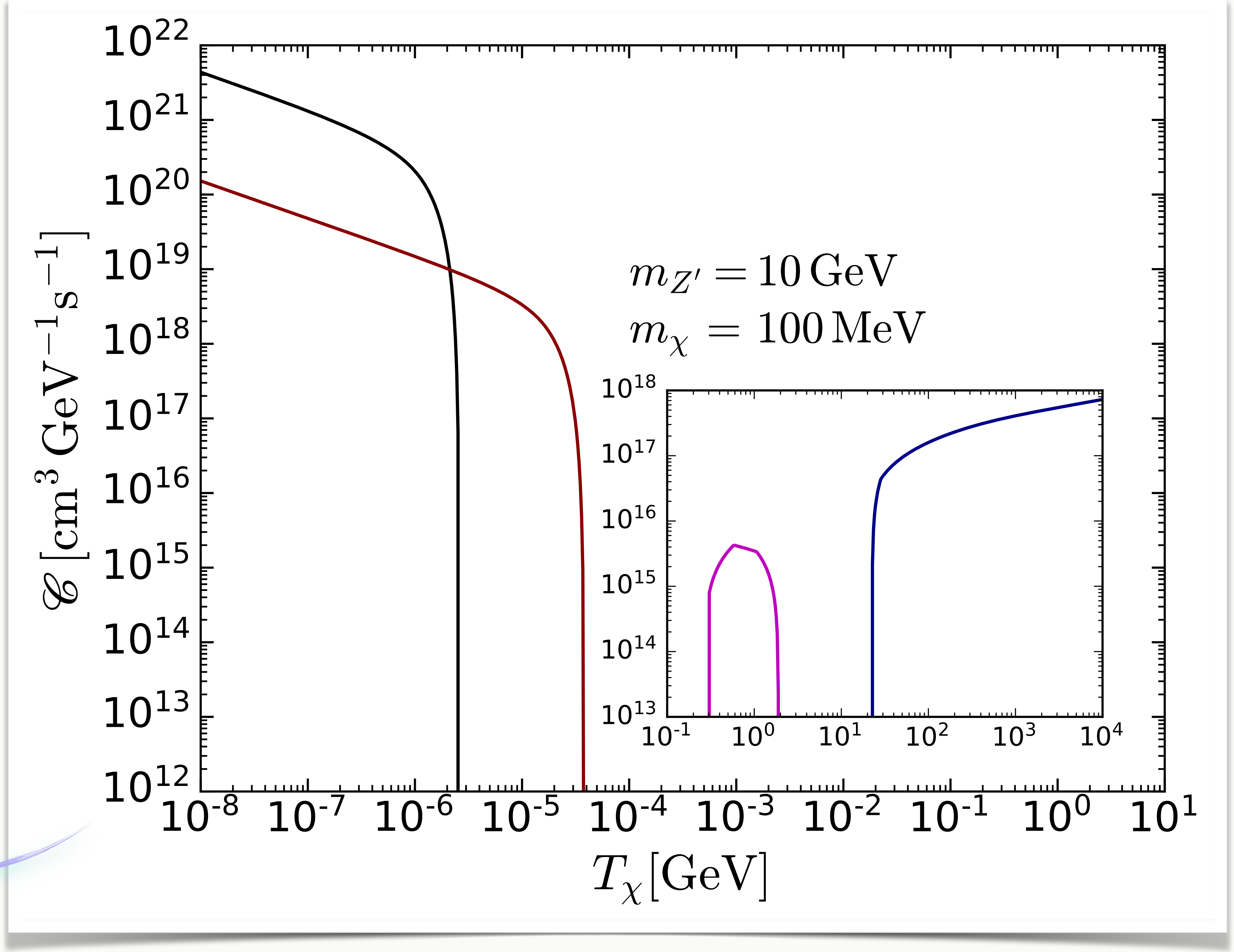
Low — High

Is it possible to capture DM with these high energies?

$$f(u_\chi) \propto \delta(u_\chi - u_{\chi,0})$$



Mono-energetic flux

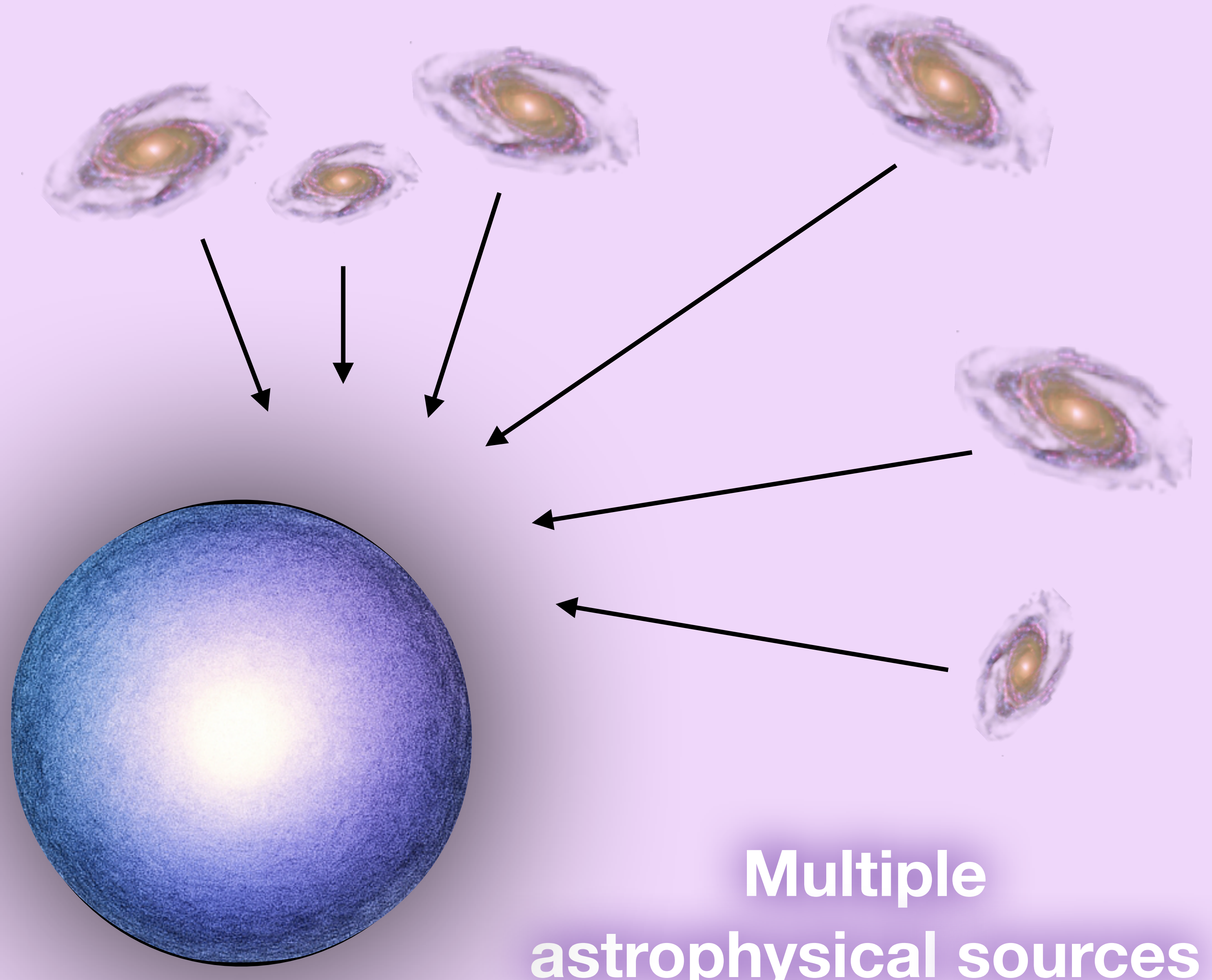


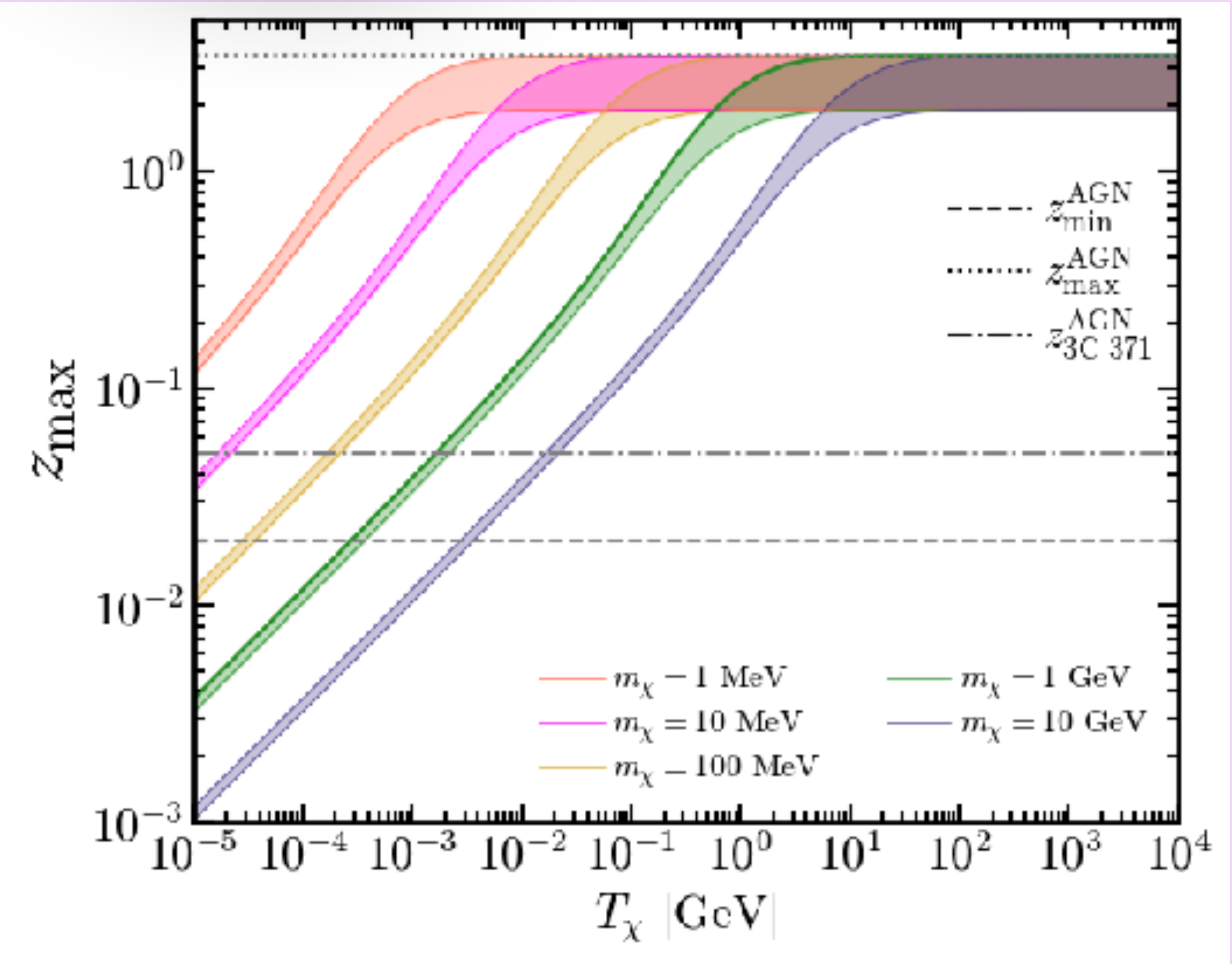
Resonant and deep-inelastic channels open an additional capture window at high energies.

Hoefken-Zink, Hor, MERQ, JHEP 2025 & Hoefken-Zink & MERQ Phys.Rev.D 111 2025

Beyond traditional capture: Toward a Realistic Multi-source Flux in WDs

325 AGNs — Healey, Romani, Cotter, Michelson, Schafly Astrophys.J.Suppl. (2008)

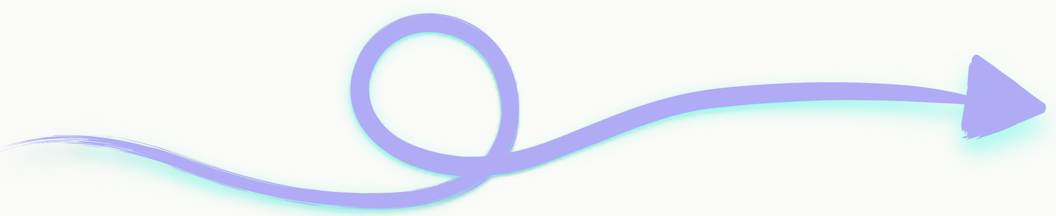


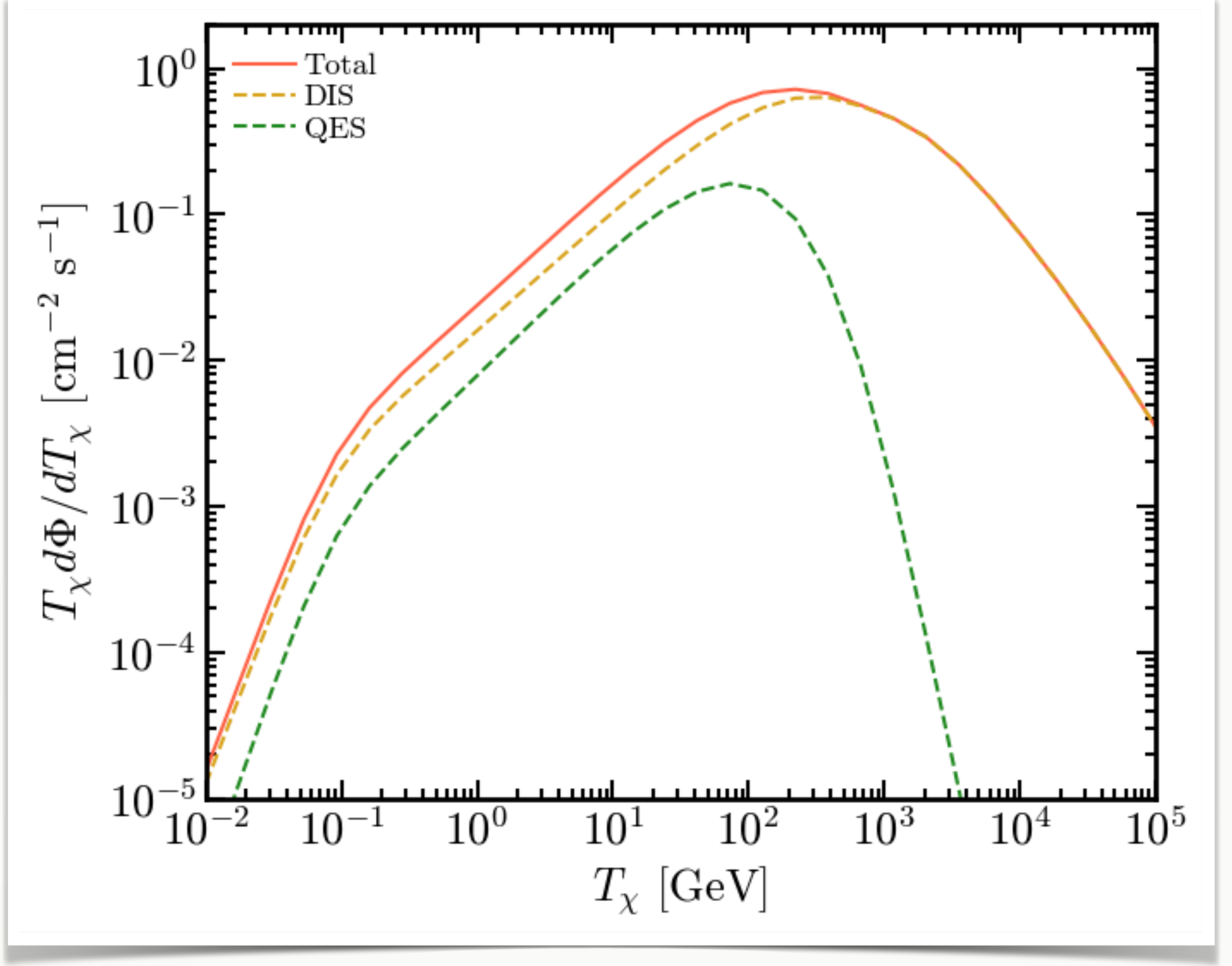


Soon → Hoefken, Hor, MERQ

$$\frac{d\Phi_\chi}{dT_\chi}(T_\chi; m_\chi) = \sum_{j=1}^{N} \Theta\big(z_{\rm max}(T_\chi; m_\chi) - z_j\big)\left(\left.\frac{d\Phi_{\rm EL}}{dT_\chi}\right|_j + \left.\frac{d\Phi_{\rm RES}}{dT_\chi}\right|_j + \left.\frac{d\Phi_{\rm DIS}}{dT_\chi}\right|_j\right)$$

Work in progress: building the full flux from 325 AGNs, weighted by distance and luminosity





Summary

DD

Strong limits, but low-energy sensitivity

Complementary

DM in Extreme Astrophysical Environments

Neutron Stars:
DM heating & vortex dynamics

White Dwarfs:
DM heating &
Multi-energy capture/
realistic flux from AGNs (status)

*-Together, compact stars establish a **framework** to test DM interactions across energies and environments, complementary to lab experiments*

Thank you!