Compact Stars: a window to new physics

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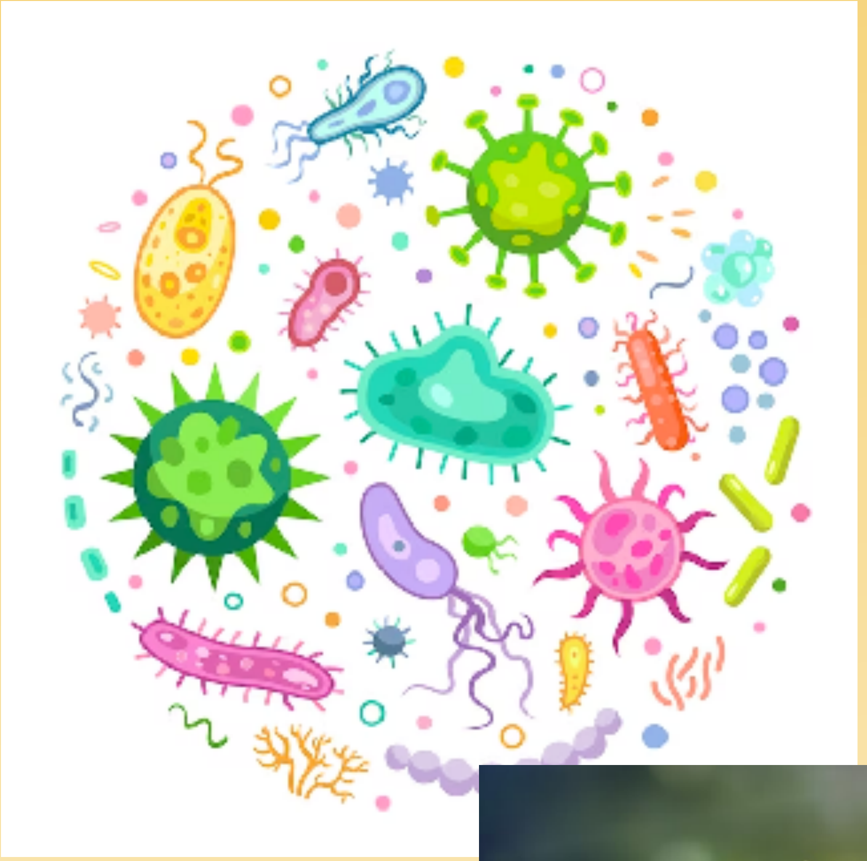
Outline

- Introduction
- Part I: Heating of compact objects
- Part II: Cooling of compact objects
- Summary & conclusions

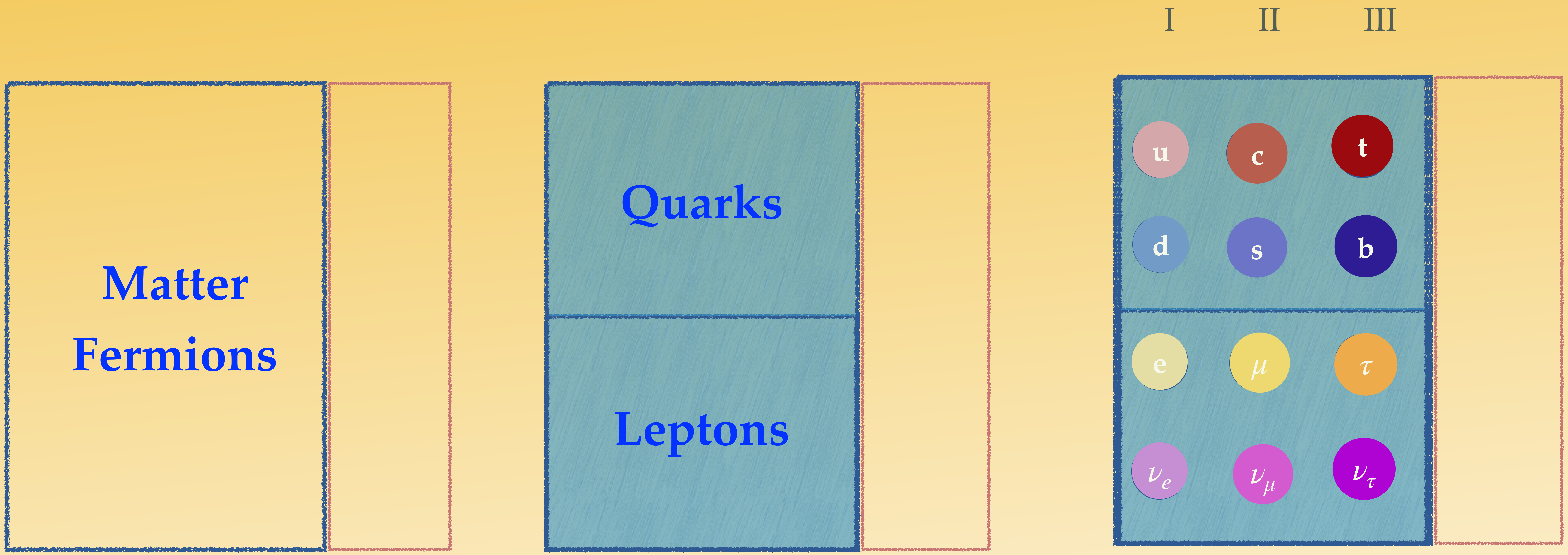
Introduction

Fundamental blocks of the Universe

The Standard Model of particle physics: is a theoretical framework that describes the fundamental particles and their interactions.



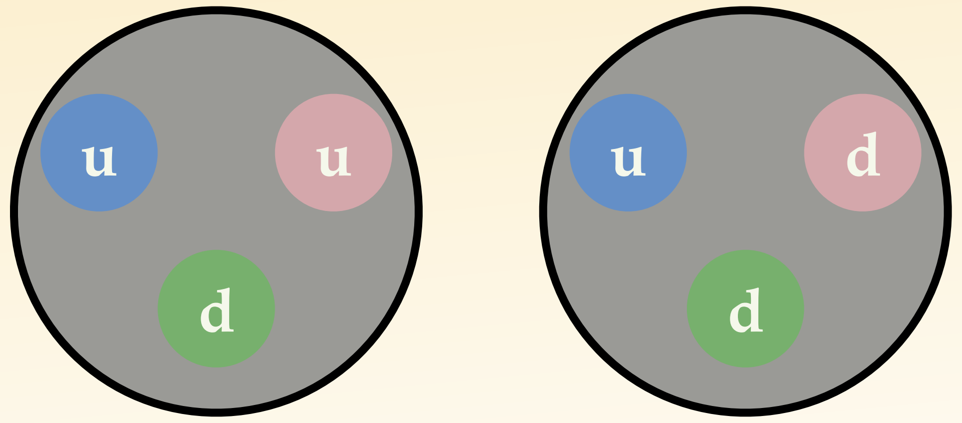
Fundamental blocks of the Universe



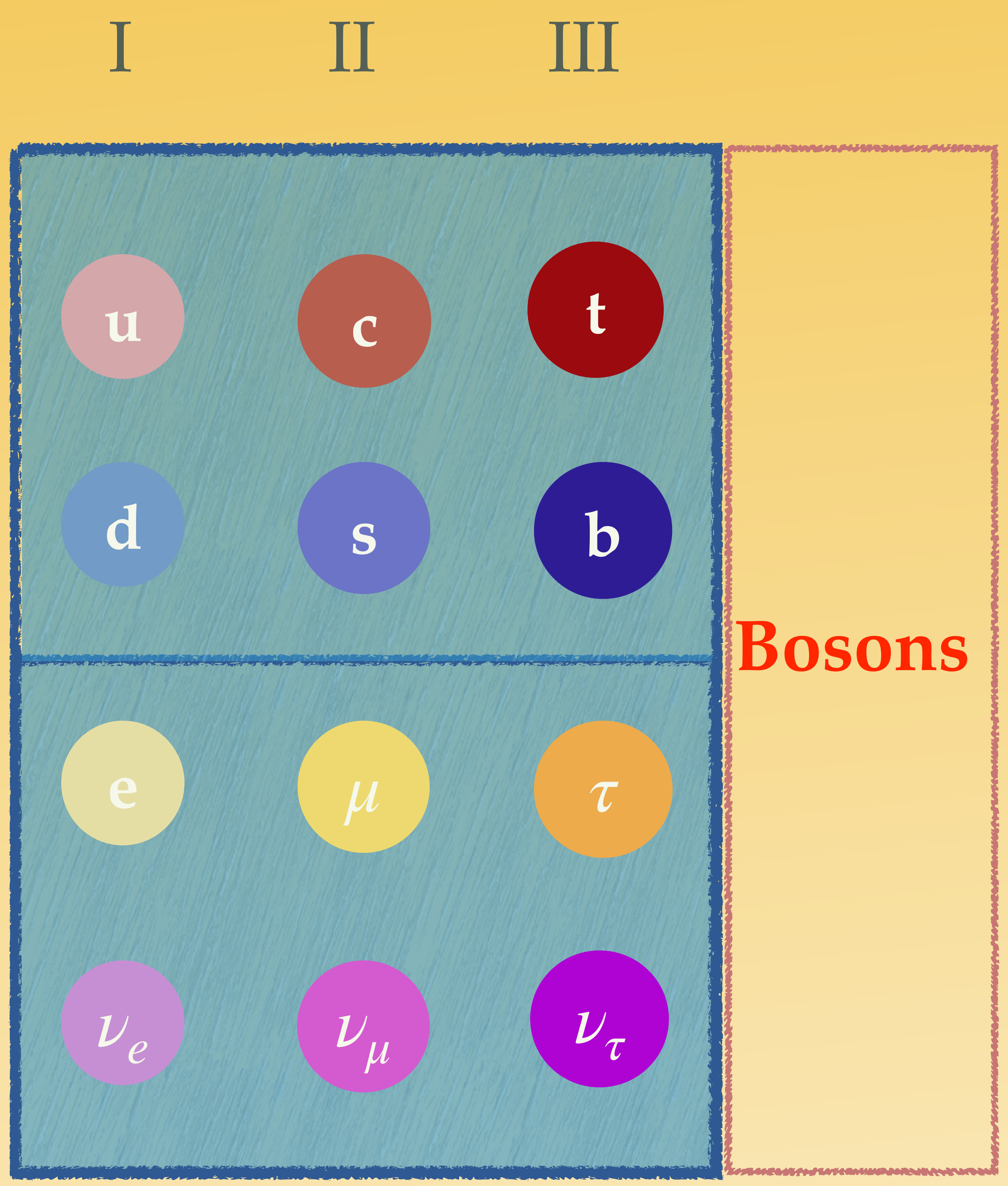
Makes up all the visible matter:
Fermions

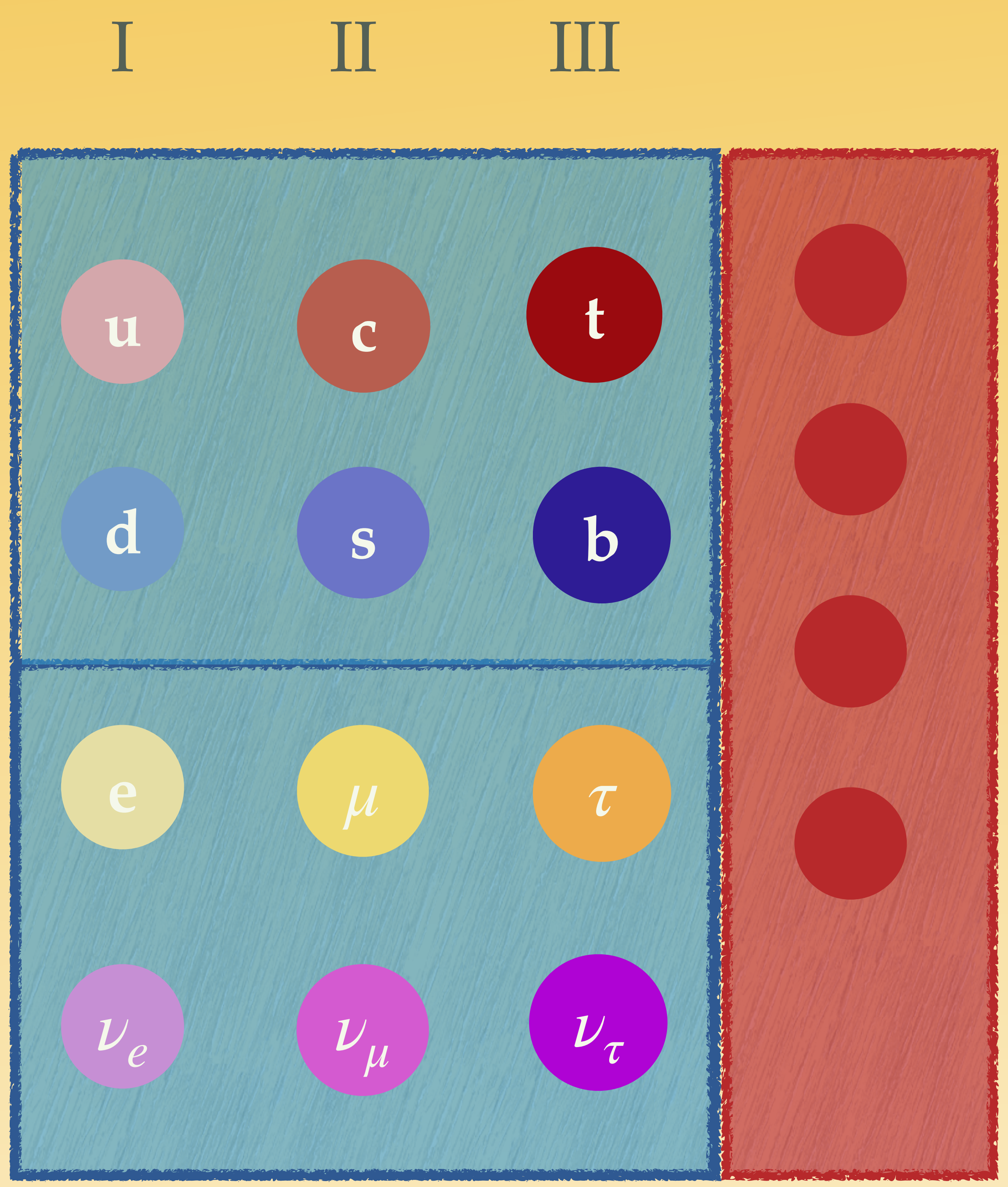
Fermions:
Divided into 2 categories

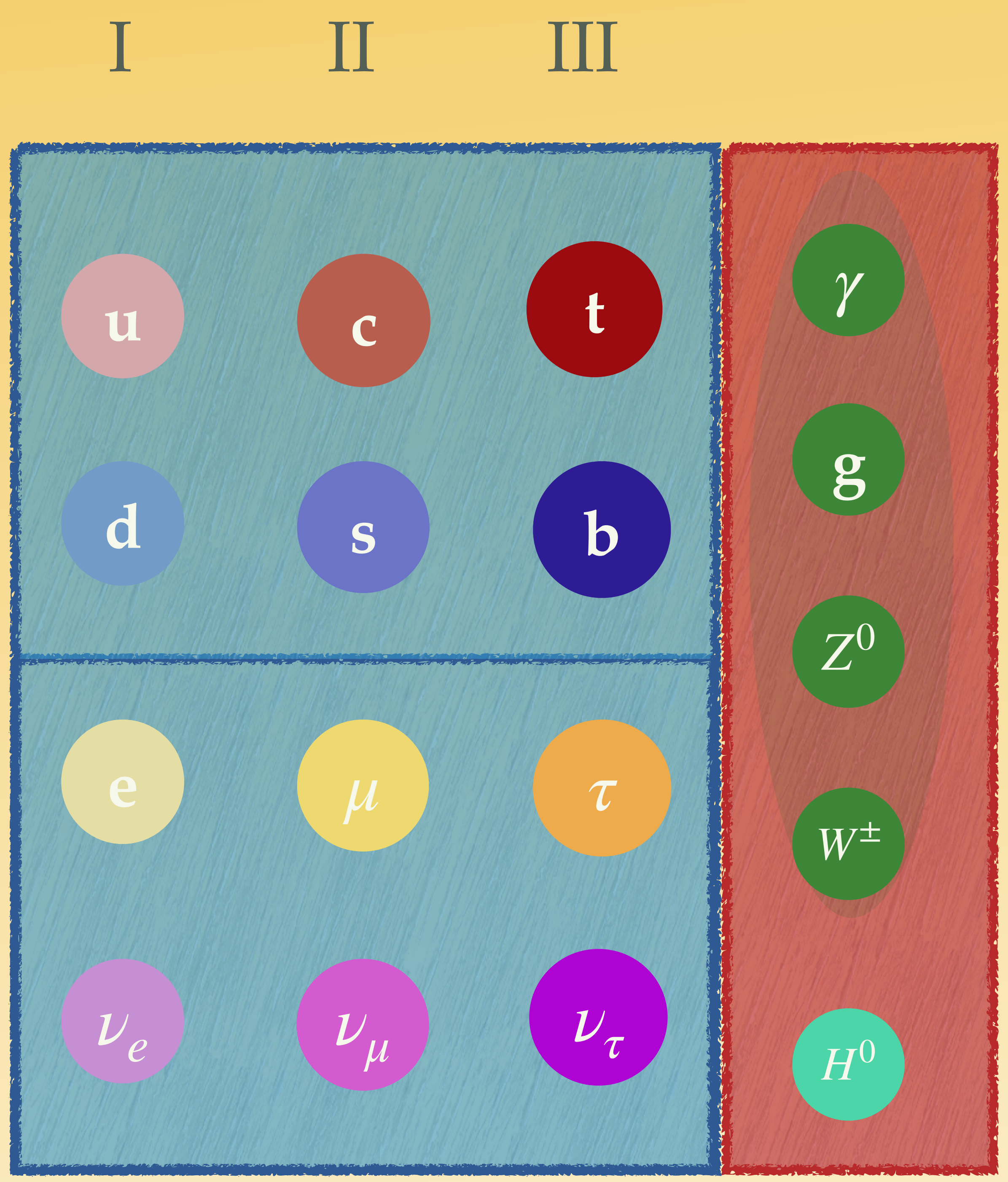
Fermions:
There are 3 generations



Fundamental blocks of the Universe







Bosons:
Mediators of interactions

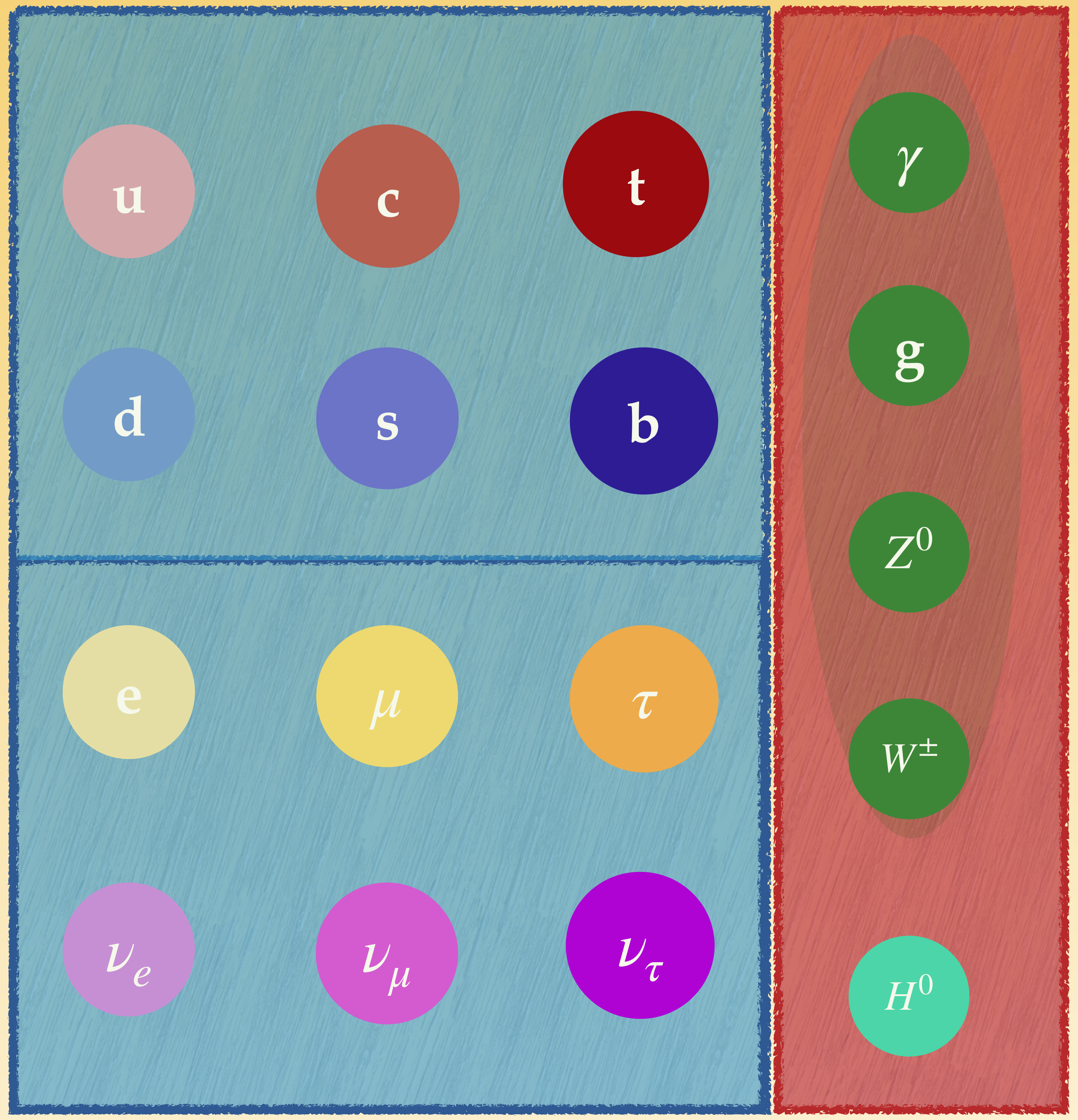
4 Gauge bosons.

1. Photon: Electromagnetic interaction
2. Gluon: Strong interaction
3. Z^0 y $W^{\pm}$: Weak interaction
4. Higgs Boson

Fundamental blocks of the Universe

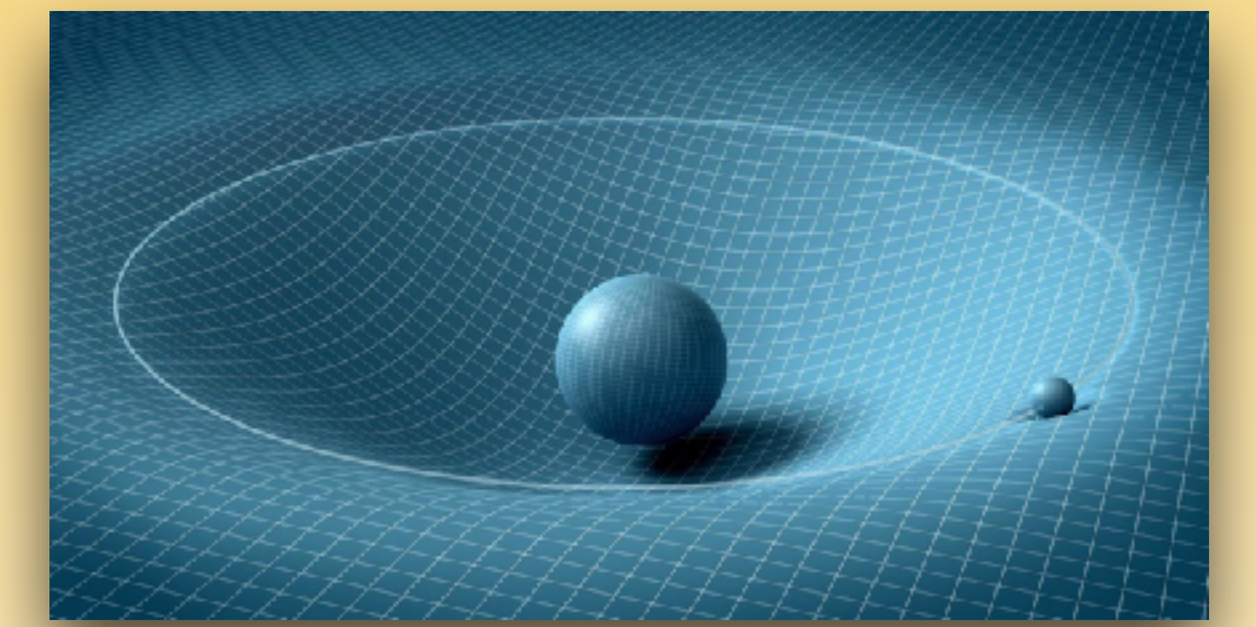
The Standard Model of particle physics

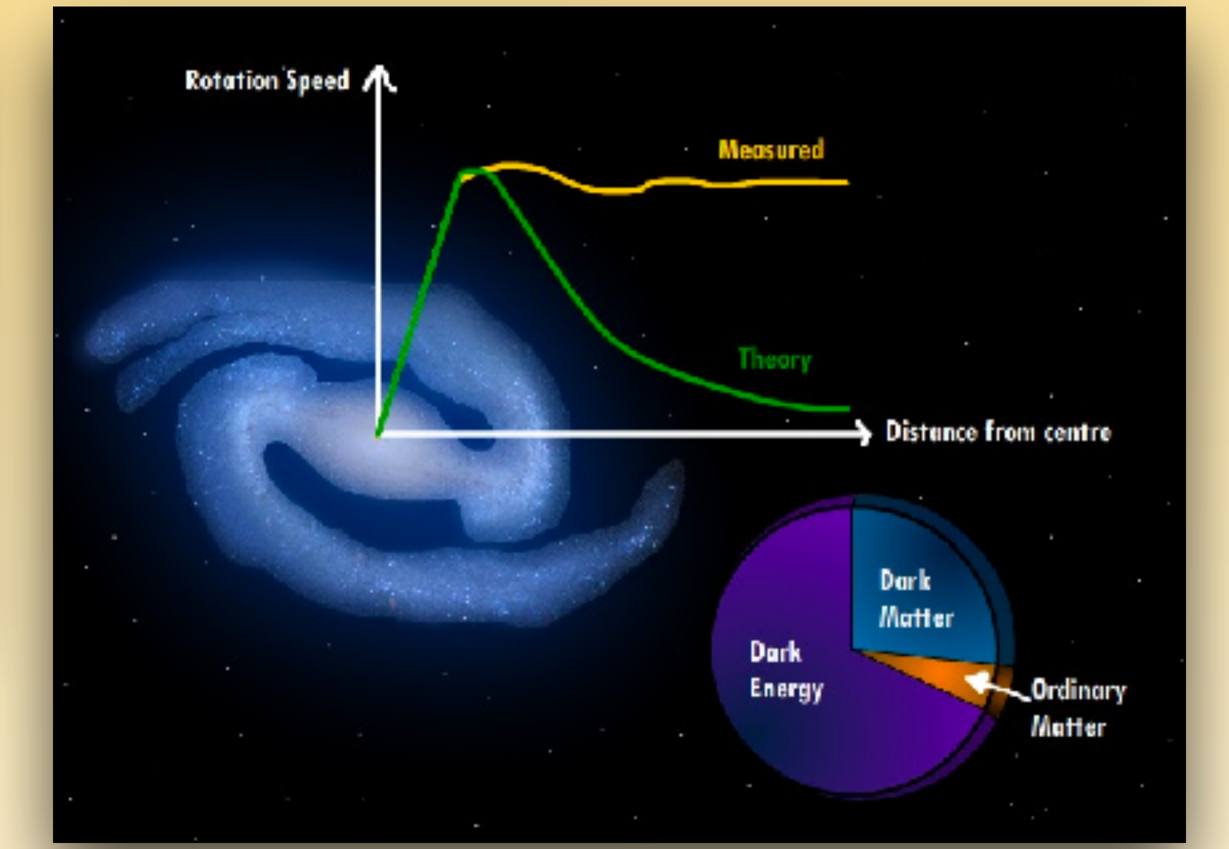
I II III

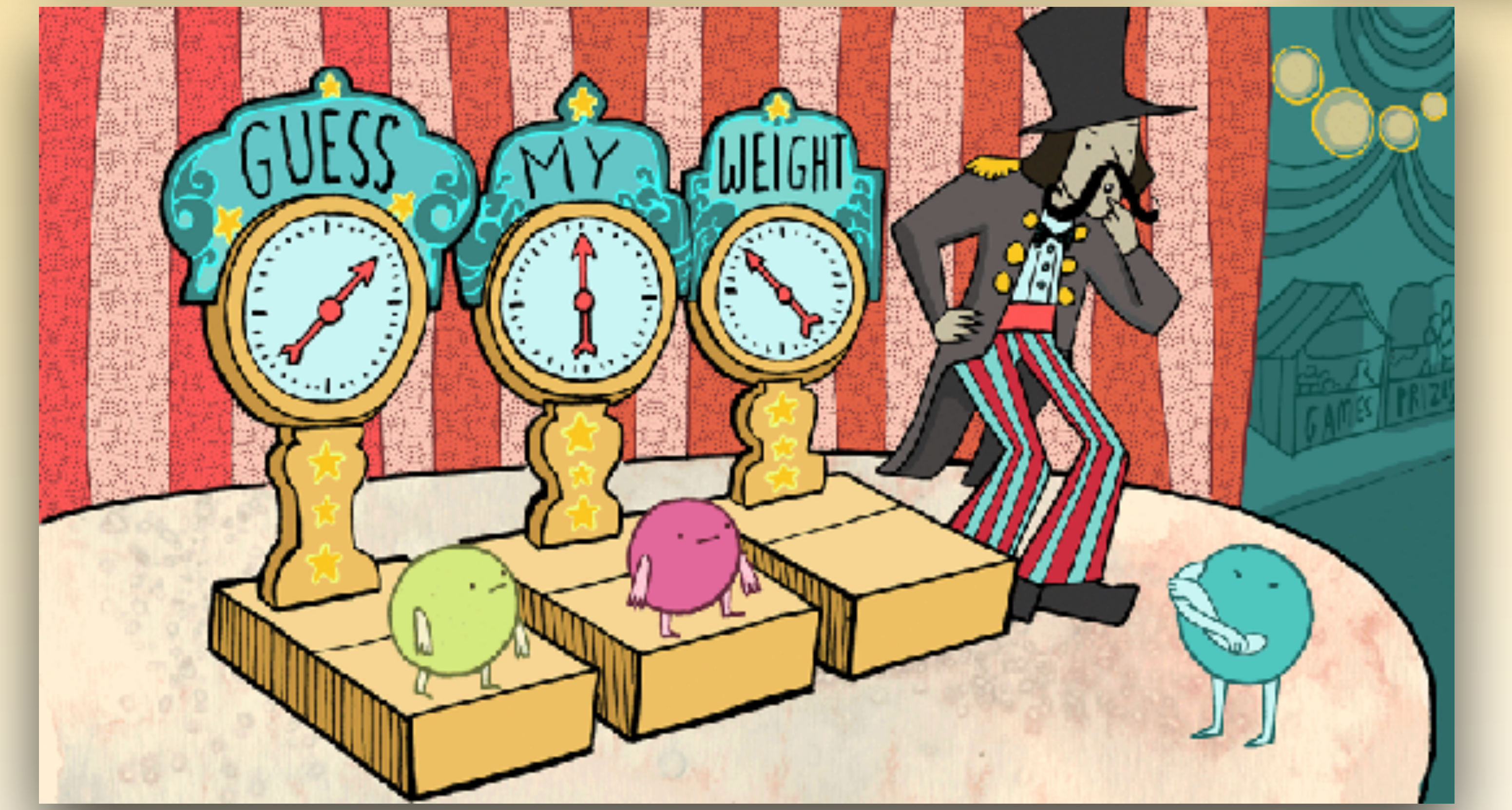


Then.. doest the SM explain everything in our Universe?

While the SM is a remarkably successful theory, there are several phenomena and observations it cannot fully explain.



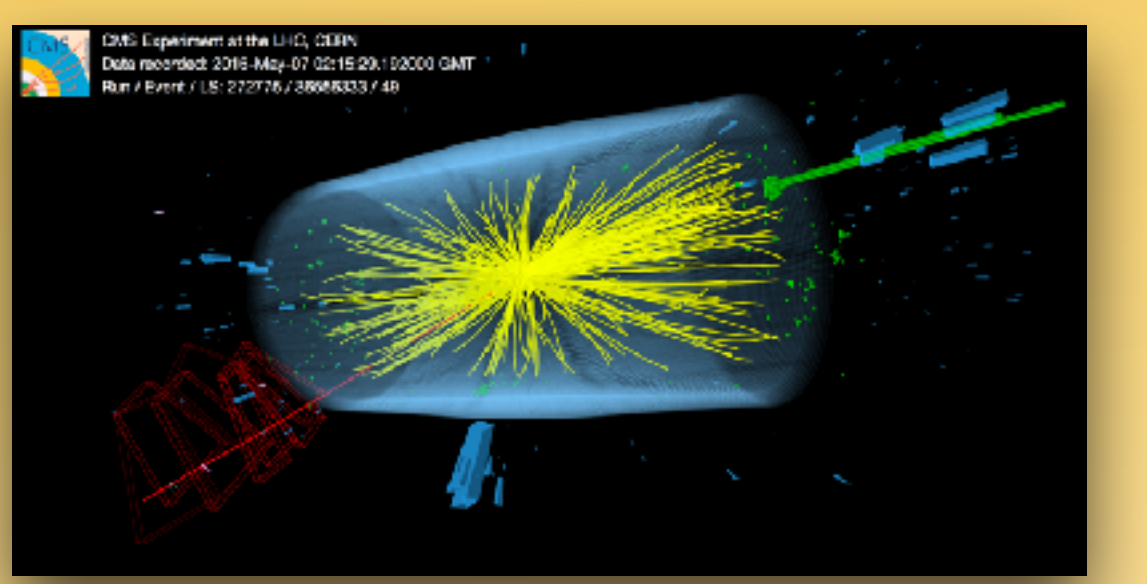




Addressing these limitations requires theories beyond the standard model.

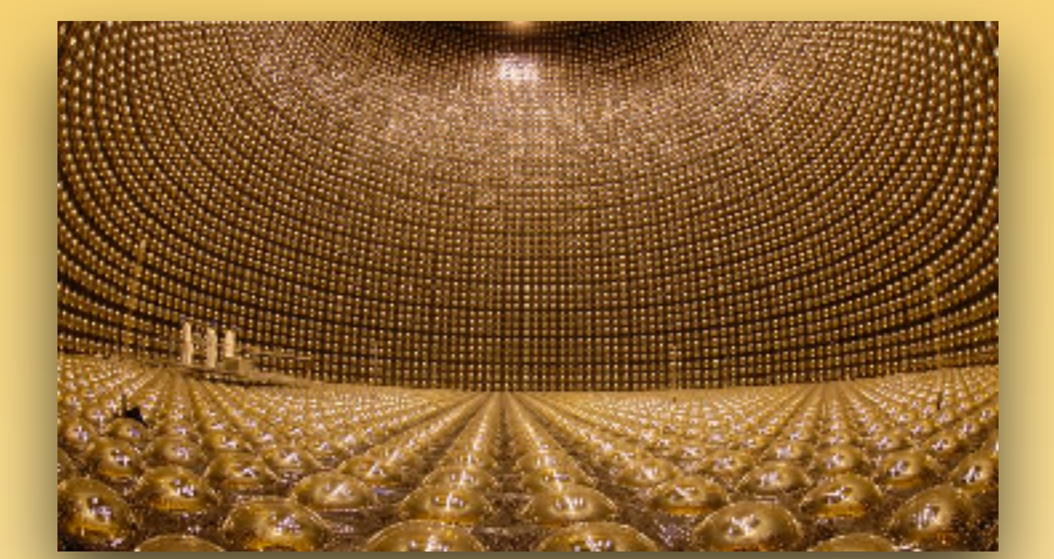
Searches for new physics

Particle Collider Experiments



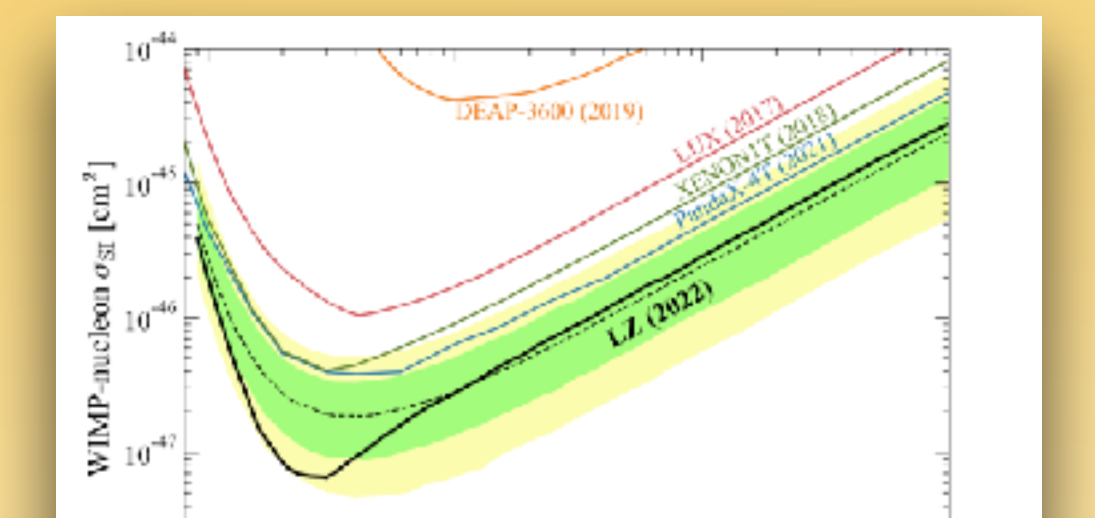
- Energy limitations
- Cost and technical challenges
- Background
- Limited access to certain processes.

Neutrino Experiments



- Neutrino detection efficiency
- Neutrino flavor and energy measurements
- Background

Dark Matter Experiments



LUX-ZEPLIN Experiment. arXiv:2207.03764

- Low interaction rates
- Background noise
- Threshold energy and resolution
- Non-relativistic regimen

Compact Objects as Cosmic Laboratories

$M_\odot = 2 \times 10^{30}\,\mathrm{kg}$

333,333 times the mas of the Earth!!

Searches for new physics: Compact objects

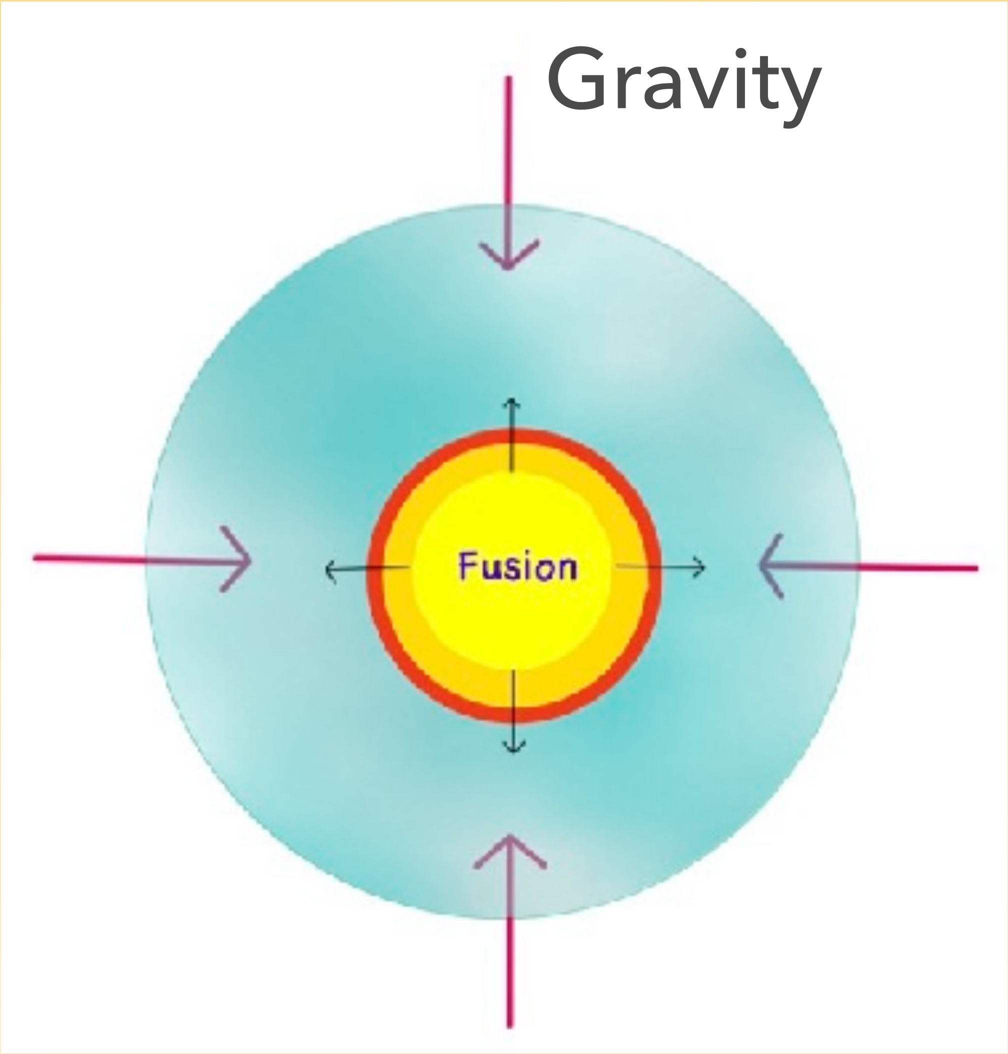
There are many ways to search for new interactions by observing & studying compact stars. Here we focus on:

- Capture of particles in their core
- Production of new particles in their core

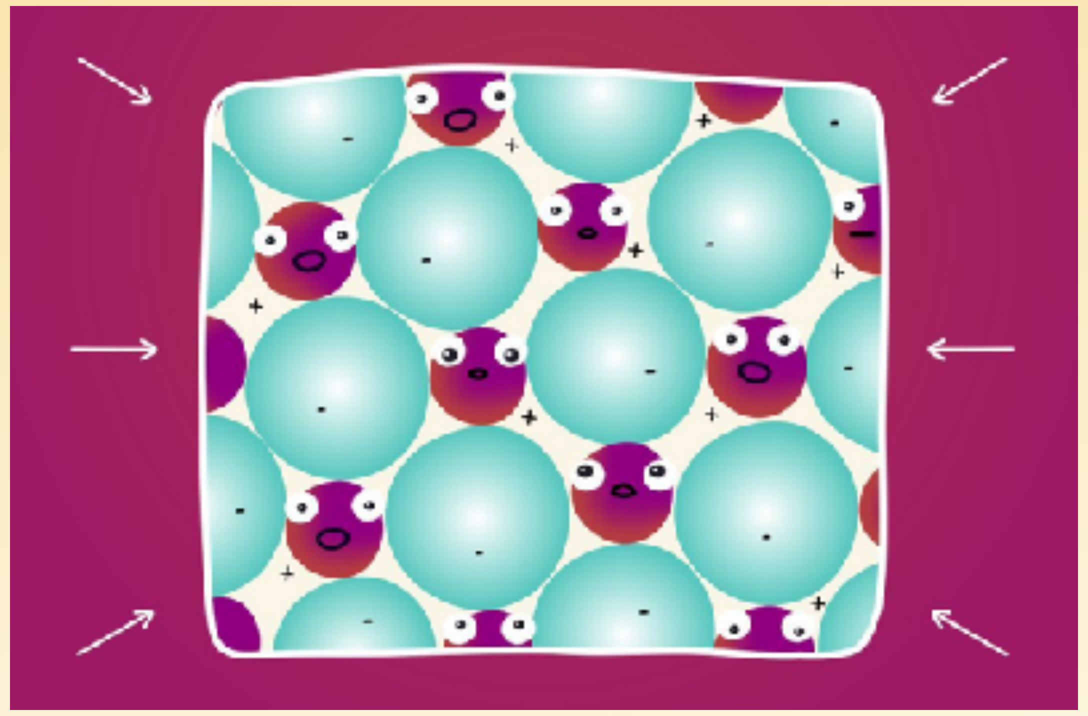
→ **The presence of new physics can modify the evolution of the star.**

But.. why compact stars?

- Compact starts are the final state of massive stars after collapsing gravitationally.



- There is no fusion: the only support against gravitational collapse is the electron degeneracy pressure



- Compact stars cool down in two stages:
  - Neutrino cooling stage
  - Photon cooling stage

If there is no other standard heating/cooling mechanisms, observing hotter/cooler compacts stars may indicate the presence of new physics!

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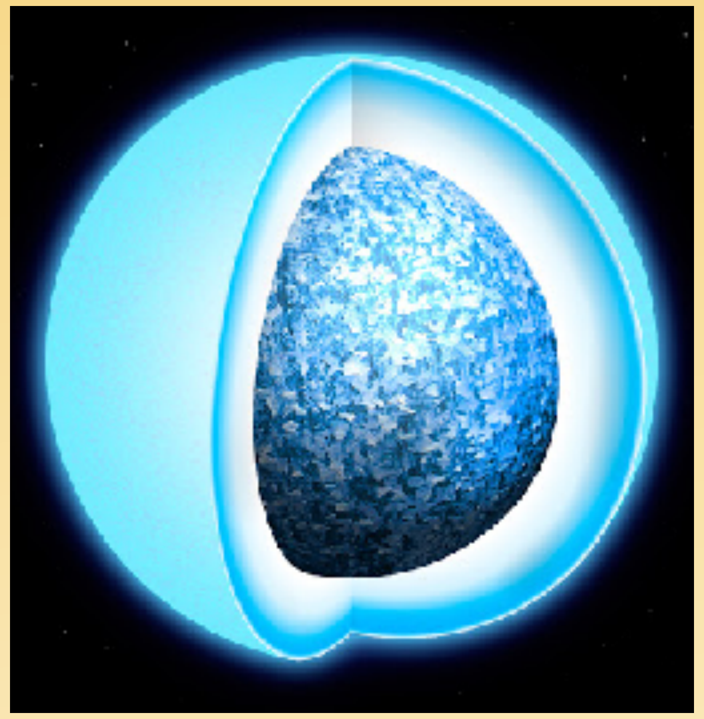
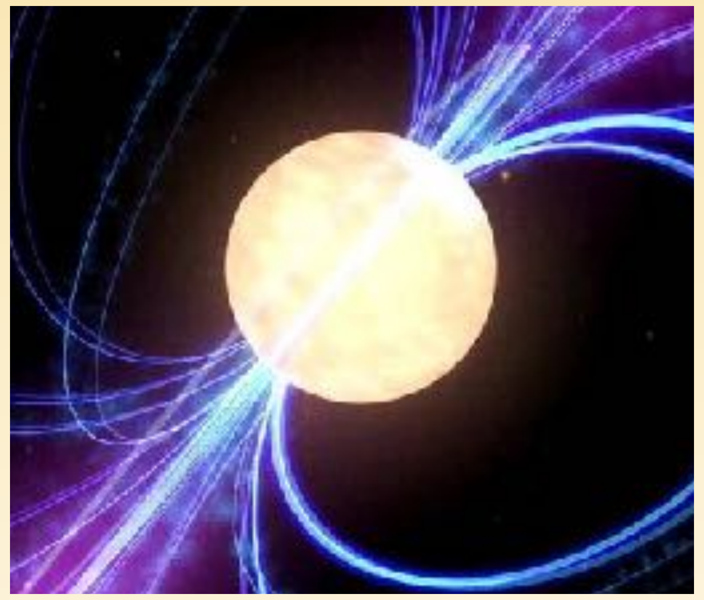
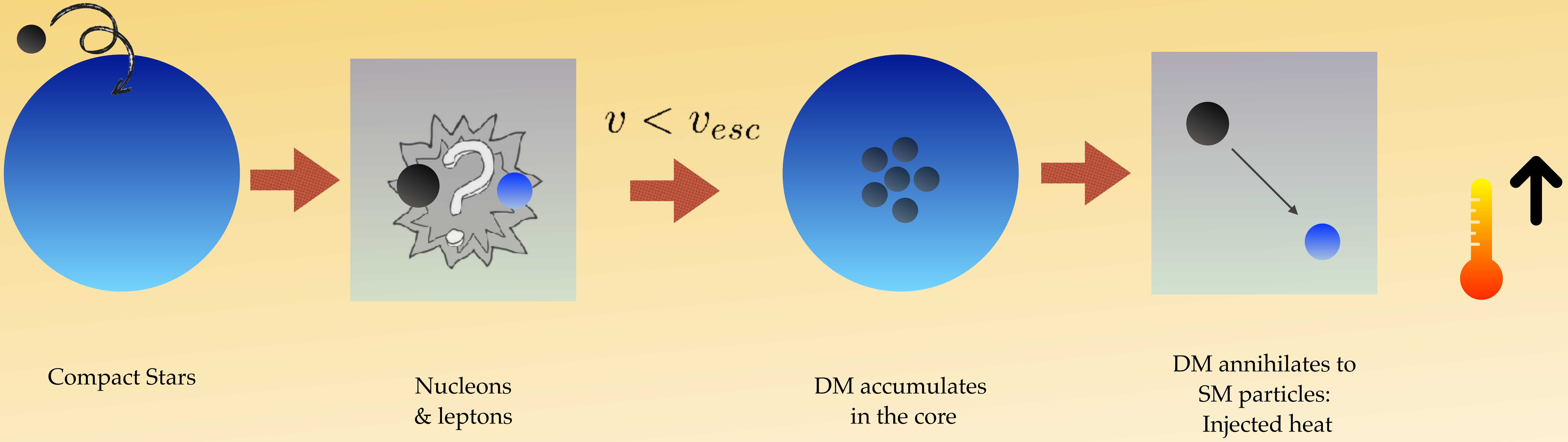




	Simple structure	Equation of state	Observations	New physics?	Constraints
Stars: Sun	✗	✓	✓	△	△
White dwarfs	✓	✓	✓	✓	✓
Neutron stars	△	✗	△	✓	✓

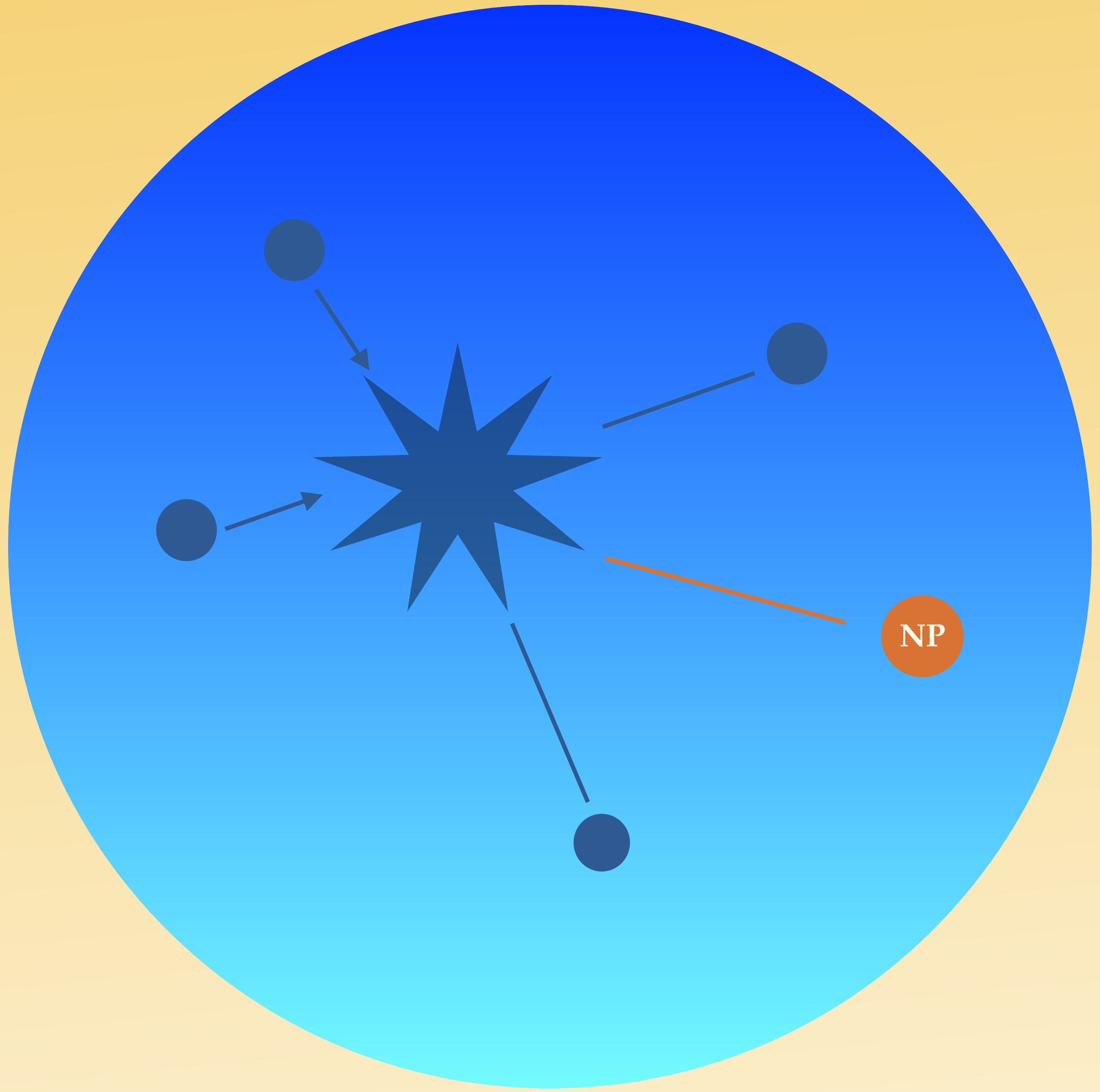
Searches for new physics: Compact objects

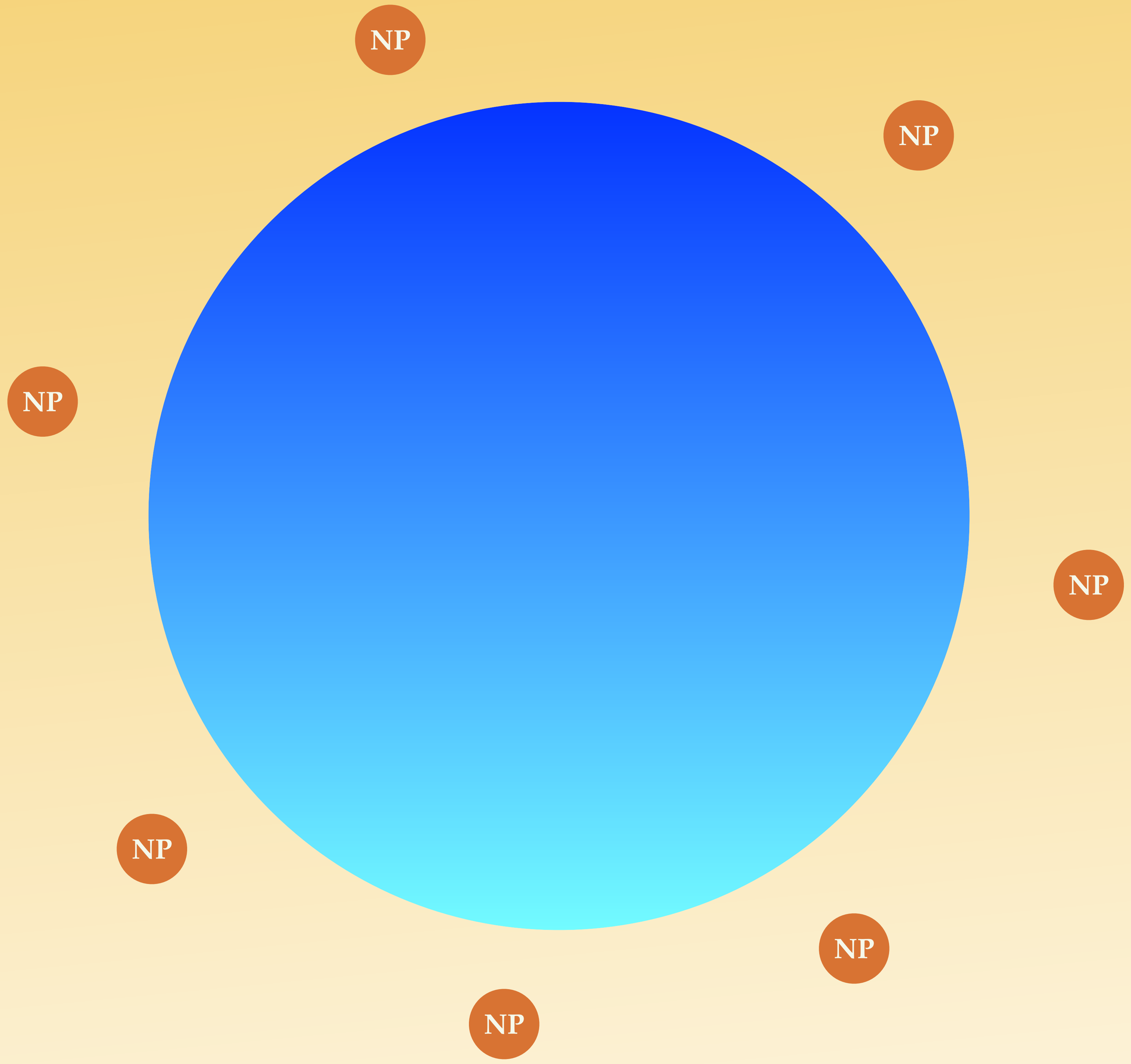
Heating of compact objects: Dark matter can accumulate in the core of compact stars, heat them up and hence and generate an observable signal.



Searches for new physics: Compact objects

Cooling of compact objects: Light new particles can be produced in the core of compact stars and

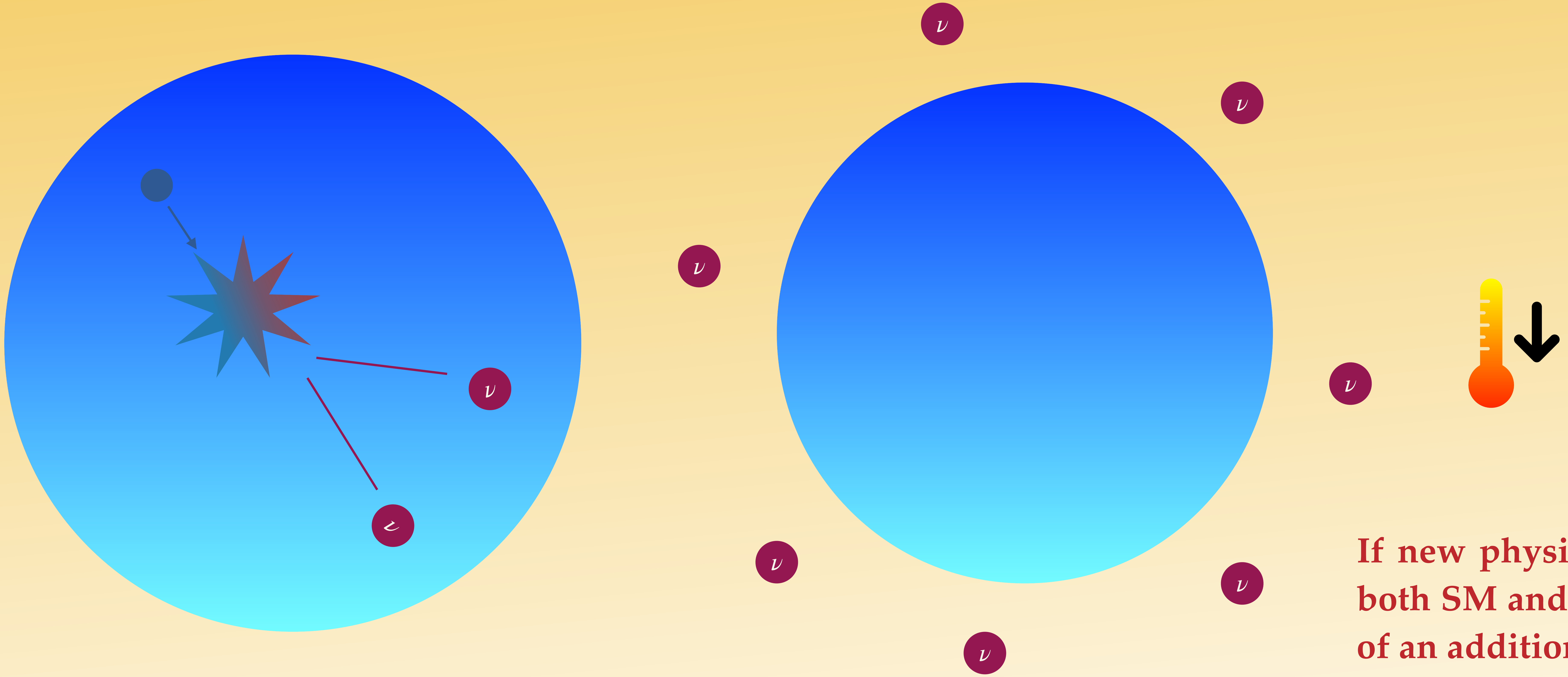




- How many are produced?
- How many get re-absorbed?
- How many escape, taking off energy?

Searches for new physics: Compact objects

Cooling of compact objects: Photon & plasmon decay



If new physics is present and interact with both SM and NP, it introduces the possibility of an additional way to produce neutrinos.

SM + NP

Heating of Compact Stars

Star Opacity

Interaction rate

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

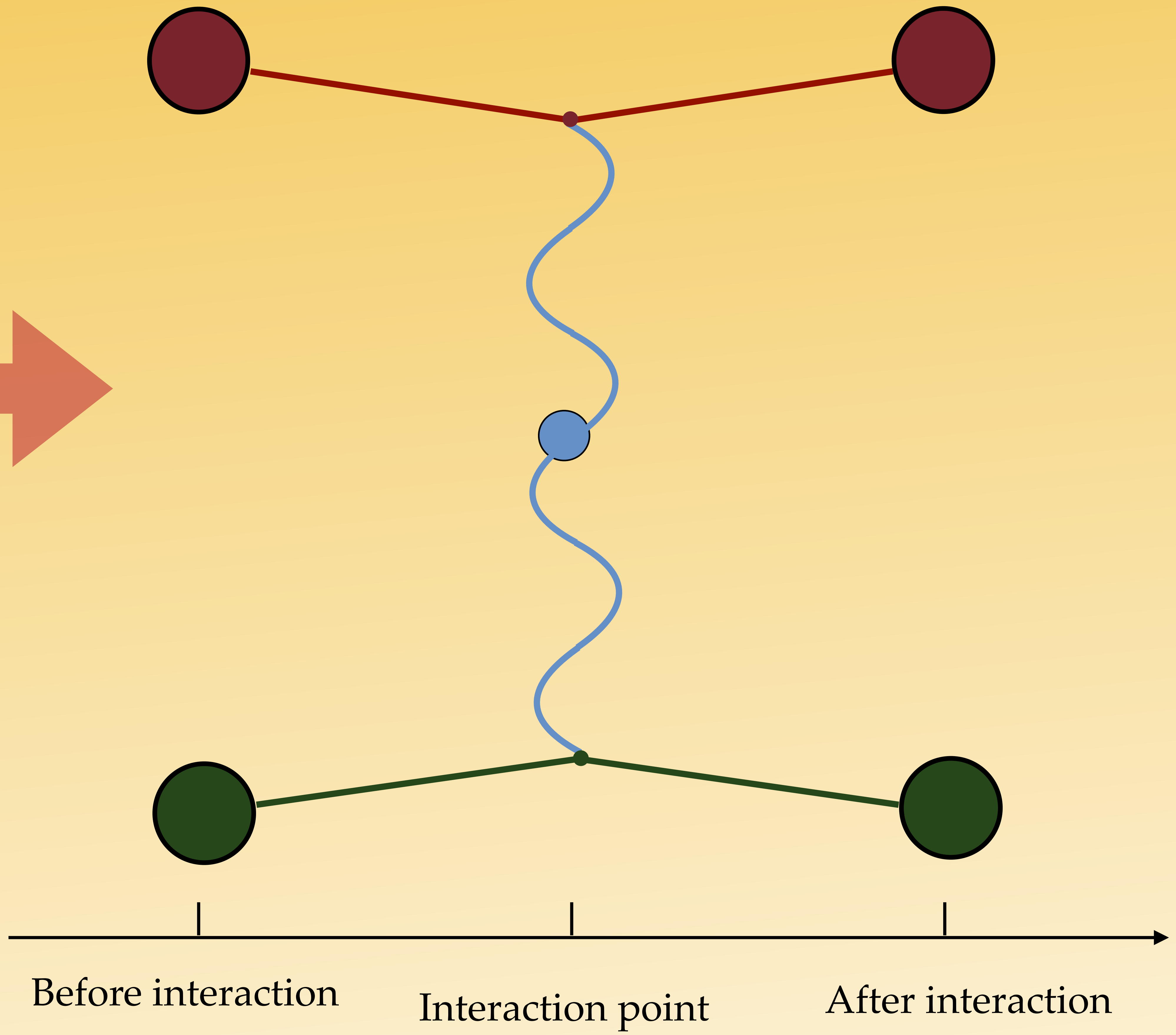
Dark matter flux

- Maximum capture: Geometric limit $\Omega^-(\omega) \to 1$
- Optically thin limit: $\eta(r) \to 1$

Capture rate in WDs: ions

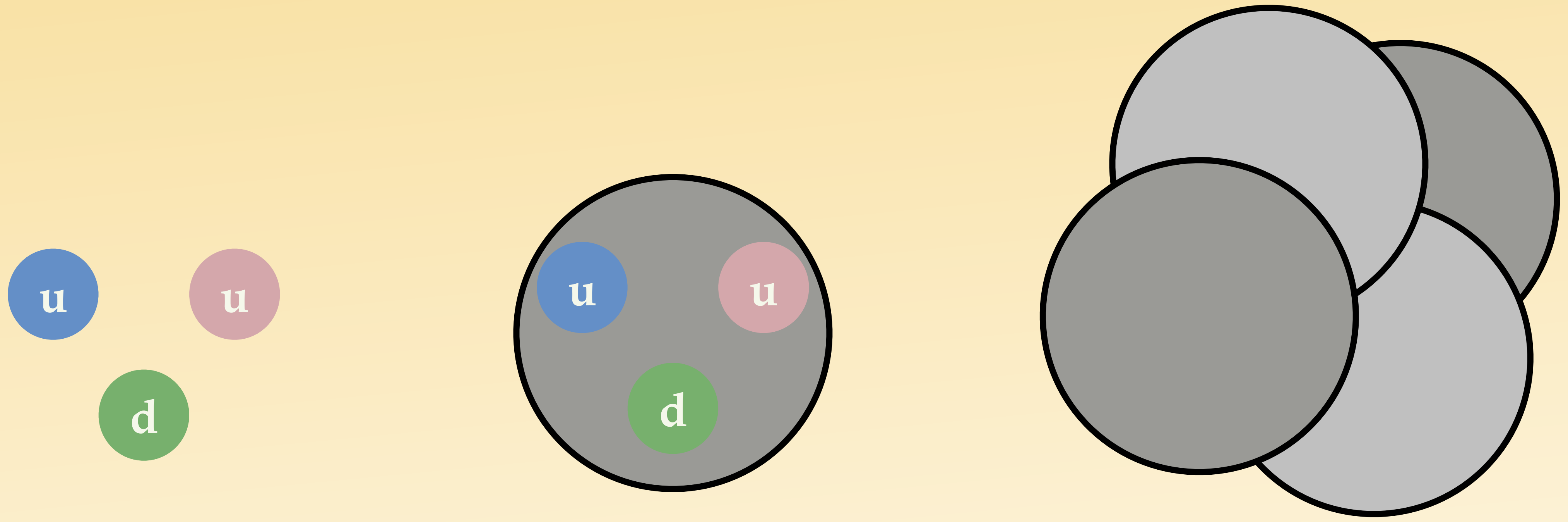
We calculate bounds on the cut off scale of the dimension 6 EFT operators that describe DM interactions with WD targets: ions and electrons.

$$\frac{d\sigma_{T\chi}}{d\cos\theta} = \frac{1}{32\pi}\frac{|\overline{M}_T|^2}{(m_\chi + m_T)^2}$$



Assuming the WD if made solely of carbon: we have introduced the nuclear response function for carbon–12

Basically, we have to go from

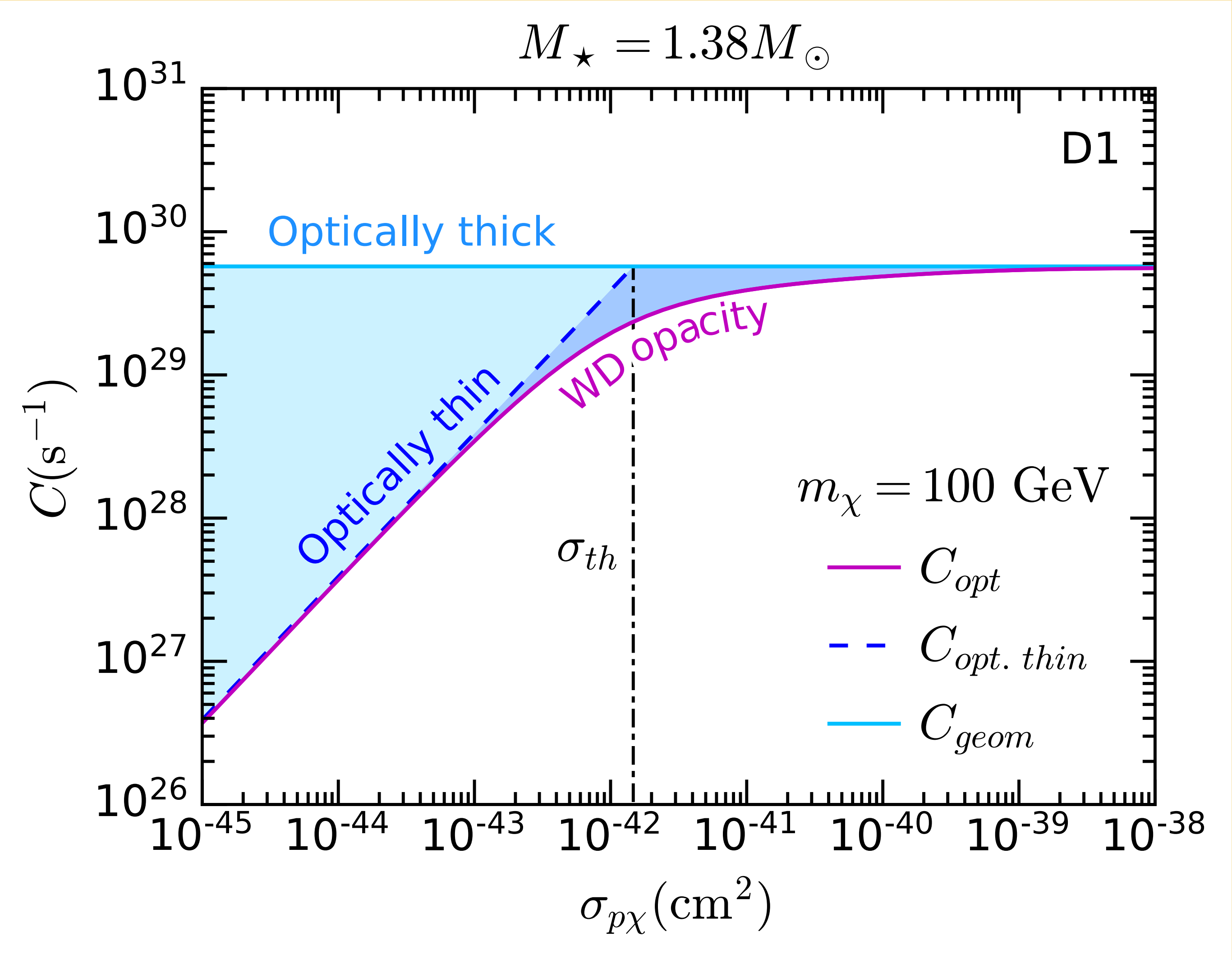


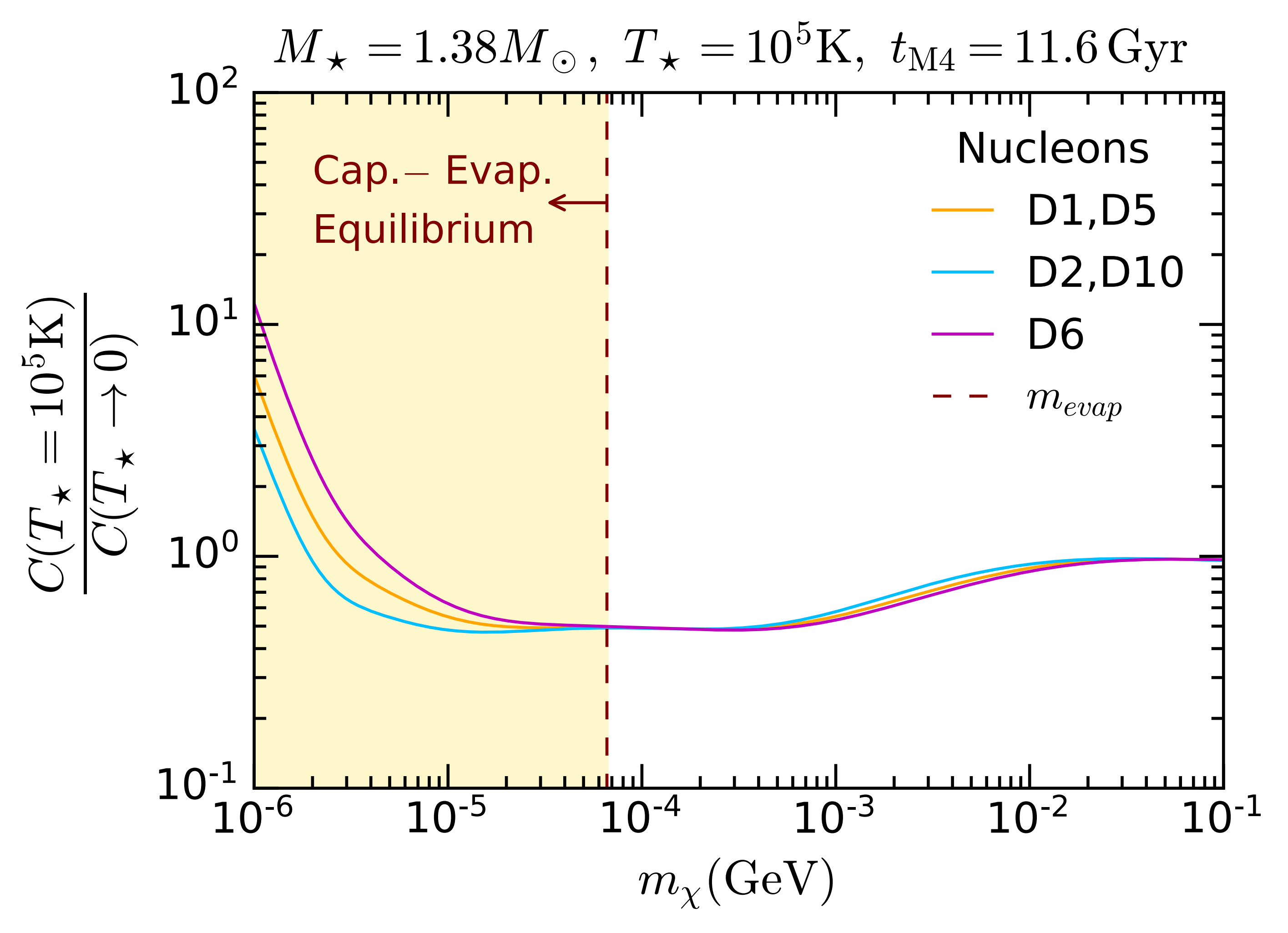
DM-quarks → DM-nucleons. → DM-nuclei.

Capture rate in WDs: ions

In the $T_\star \to 0$ limit,

- Maximum capture: Geometric limit $\Omega^-(\omega) \to 1$
- Optically thin limit: $\eta(r) \to 1$
- The complete treatment includes the inner structure of the WD as well as its opacity





Finite temperature ($T_\star = const$)

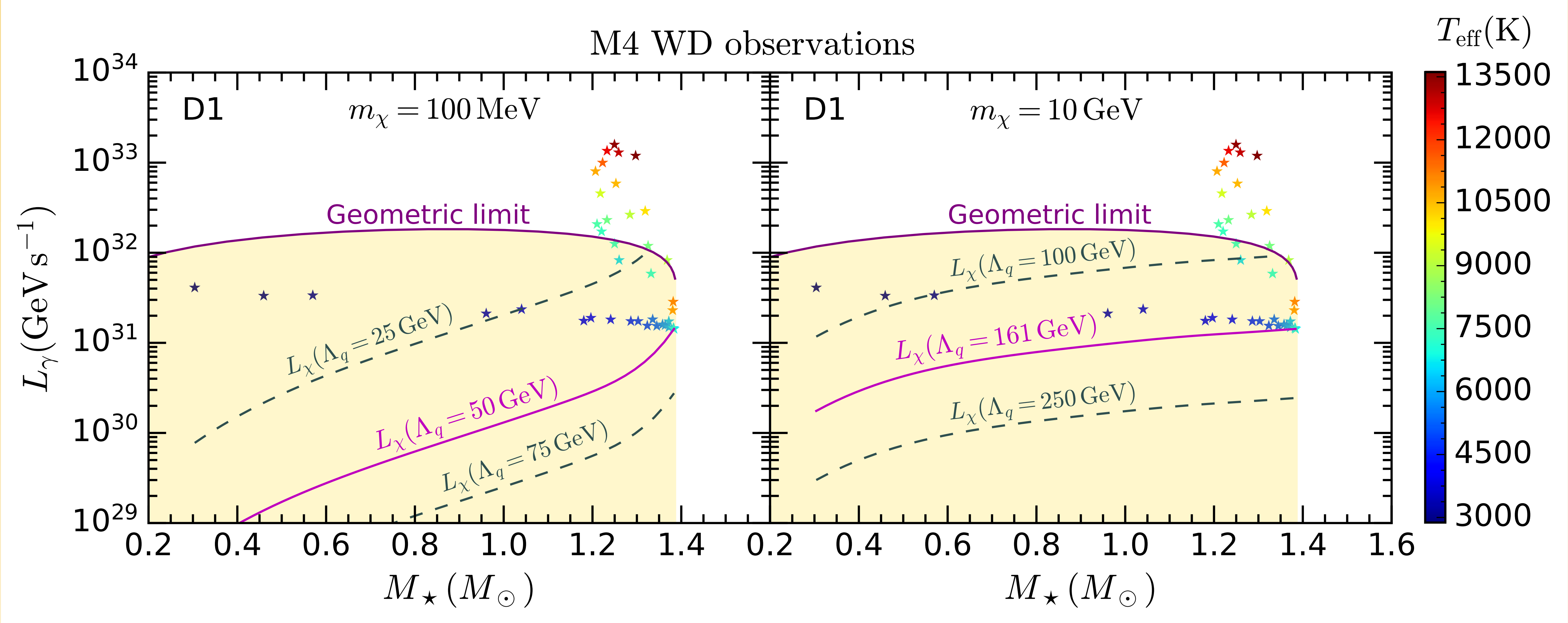
- For the oldest and heaviest WDs in M4, $T_\star = 10^5$ K
- Ratio starts to deviate from 1 at $m_\chi \sim 10$ MeV
- Evaporation mass $m_{evap} \sim 70$ keV

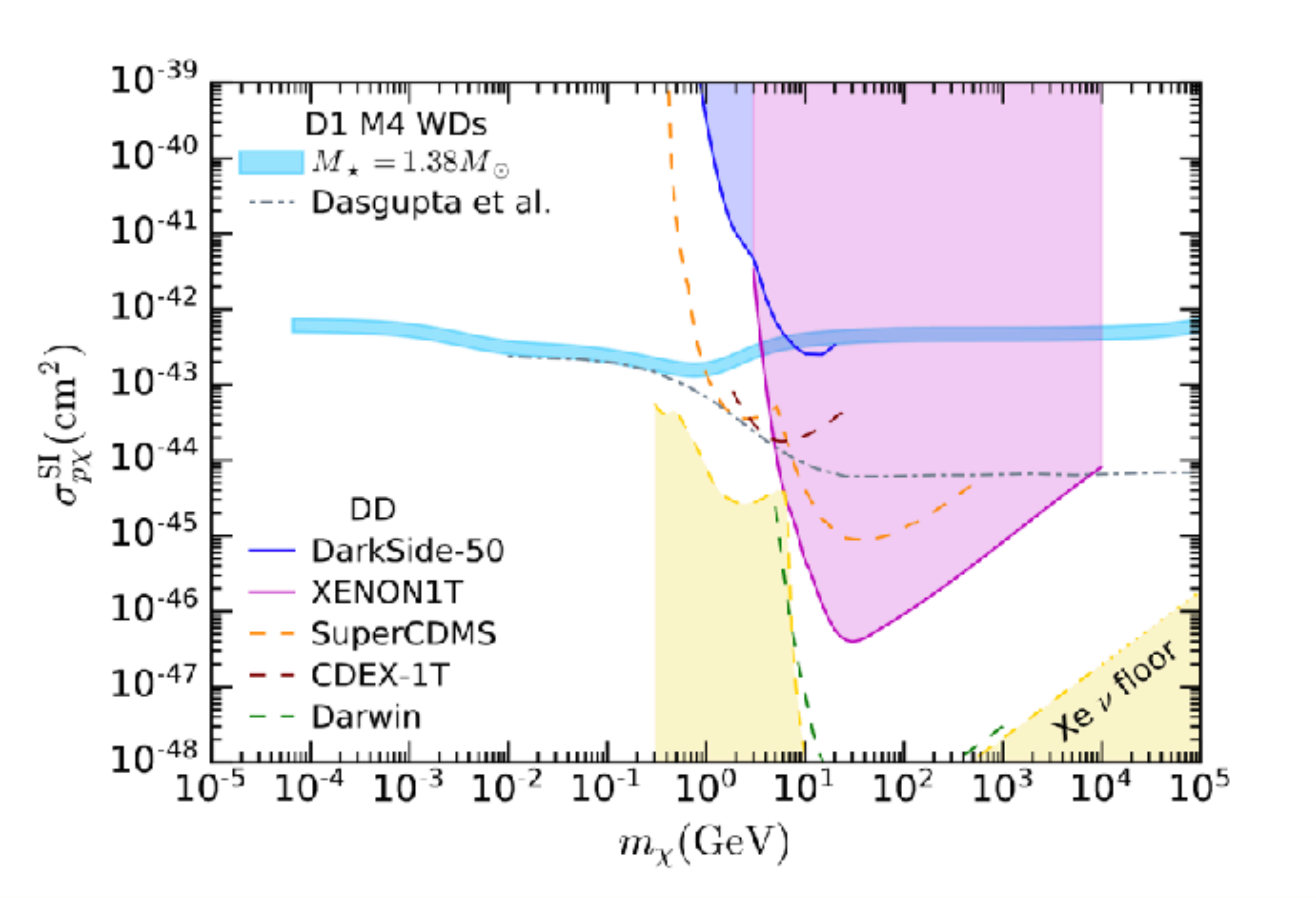
Capture rate in WDs: ions

- Observed luminosity of the faintest WD: Assumed to be composed of Carbon
- Since DM capture and annihilation processes are in equilibrium, the star luminosity due to DM is

$$L_\chi = m_\chi C(m_\chi, \Lambda_f)$$

- We compare the WD observed luminosity L_γ to L_χ
- L_γ should be at least equal to the luminosity from DM contribution.





$M_\star \sim 1.38\,\mathrm{M}_\odot$

How about DM capture in neutron stars?

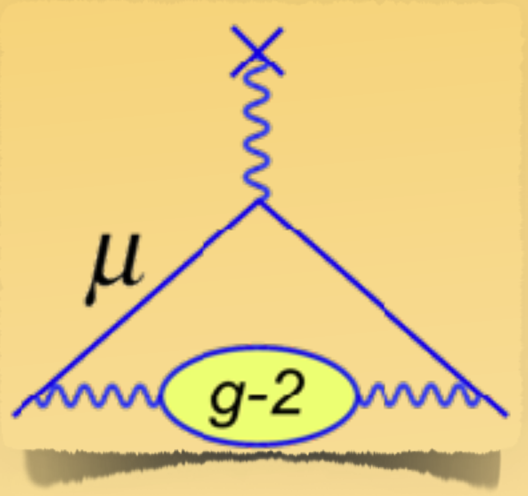
- DM can heat NS up to $\sim$ a few $\times 10^3$ K

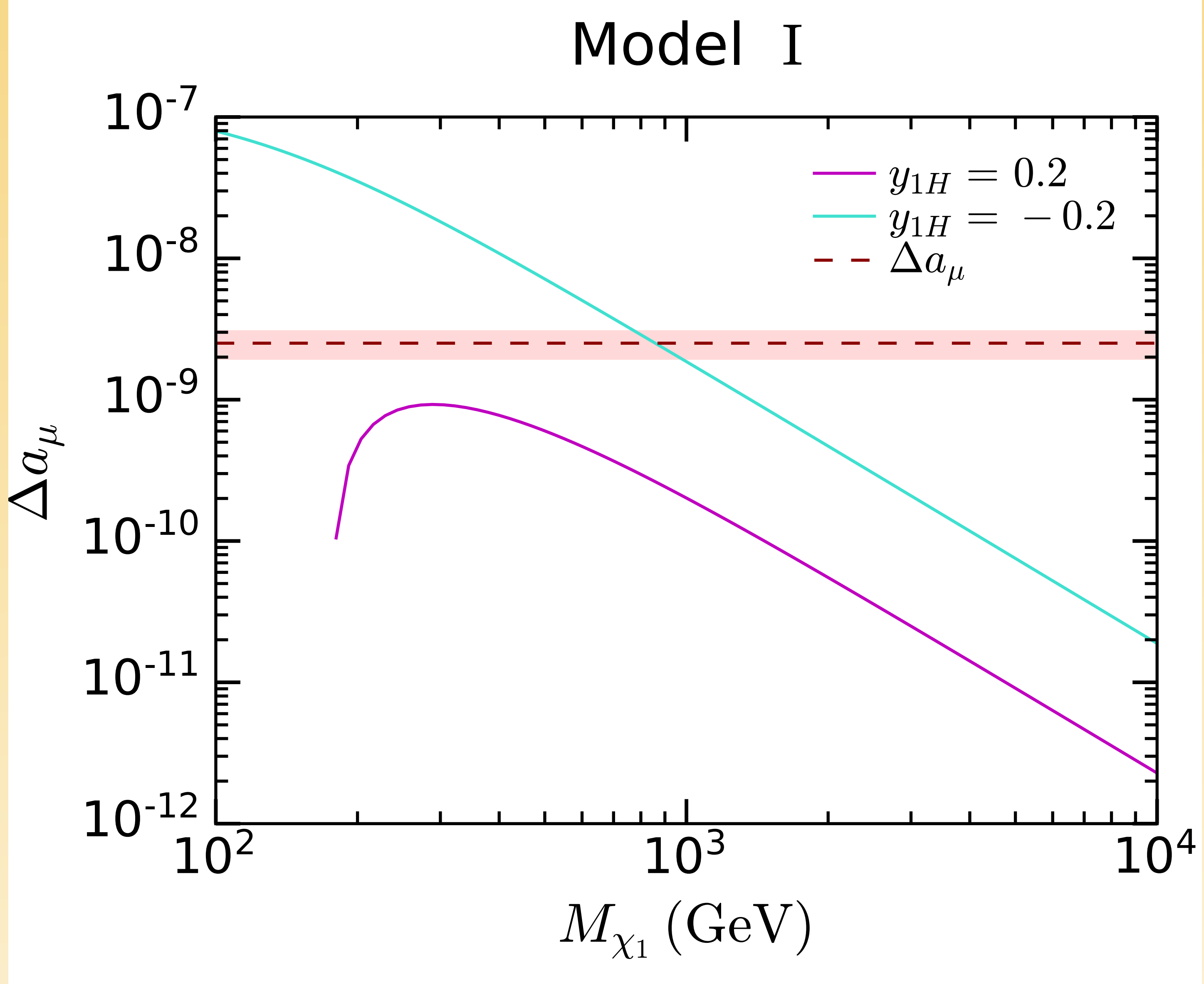
- NS efficiently capture DM particles $m_\chi \sim 10^2$ TeV after a single scattering

The temperature observation of neutron stars offers a promising way to probe new physics through DM accretion and annihilation in their core.

How about DM capture in neutron stars?

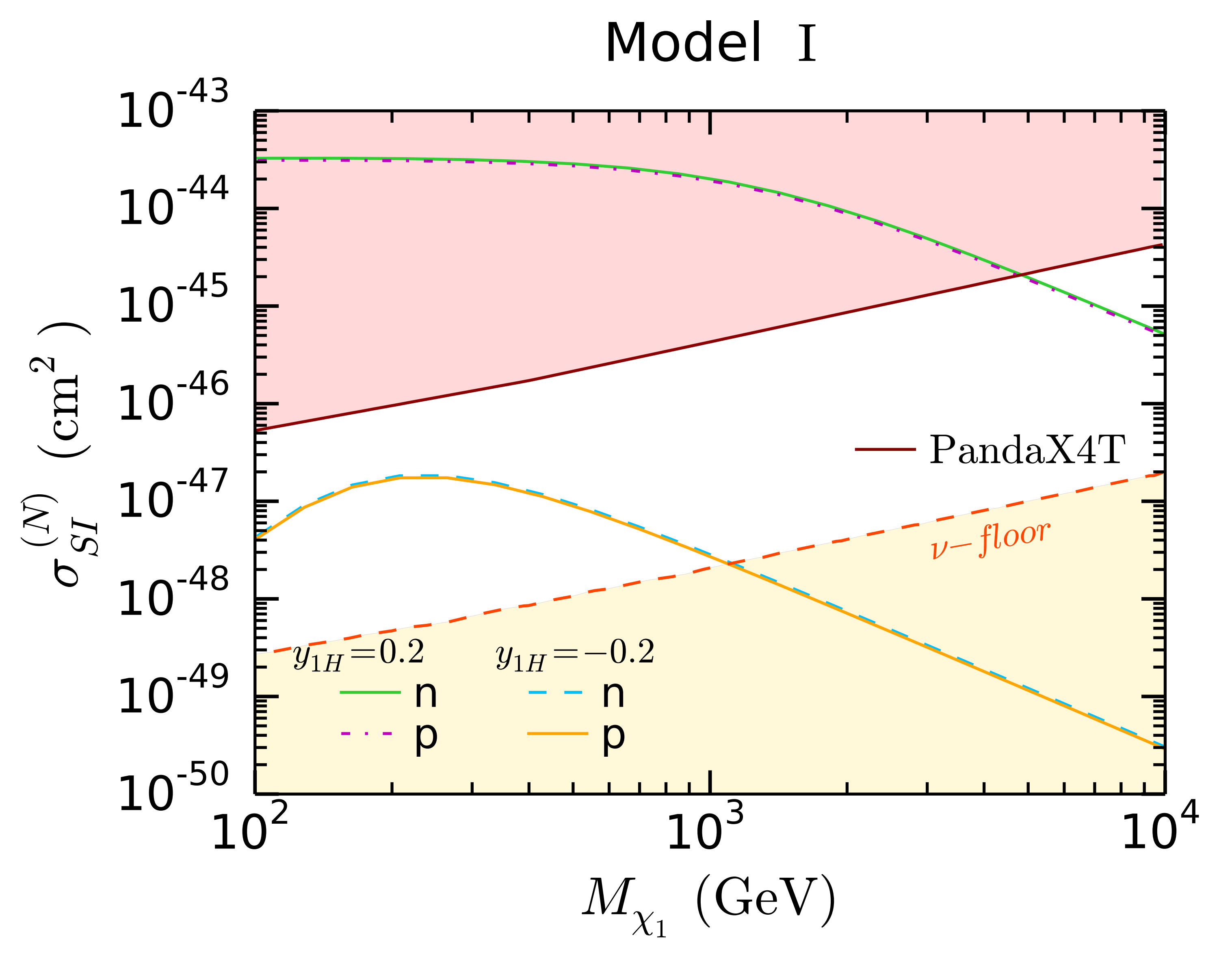
- For example: Several models have been proposed in order to explain the $(g-2)_\mu$ discrepancy





This model could explain the observed discrepancy in the $(g-2)_\mu$ if the DM mass is

$$M_{\chi_1} \simeq 1\,\text{TeV}$$



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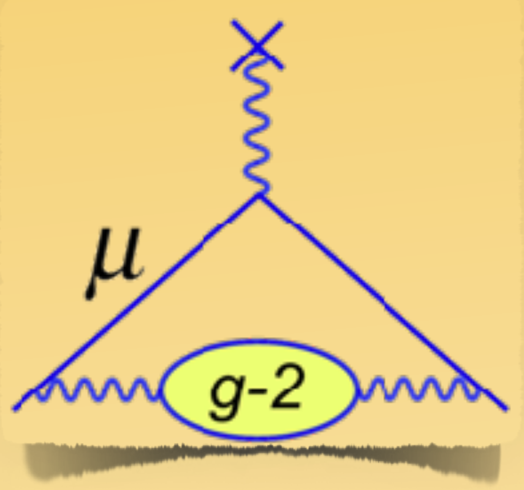

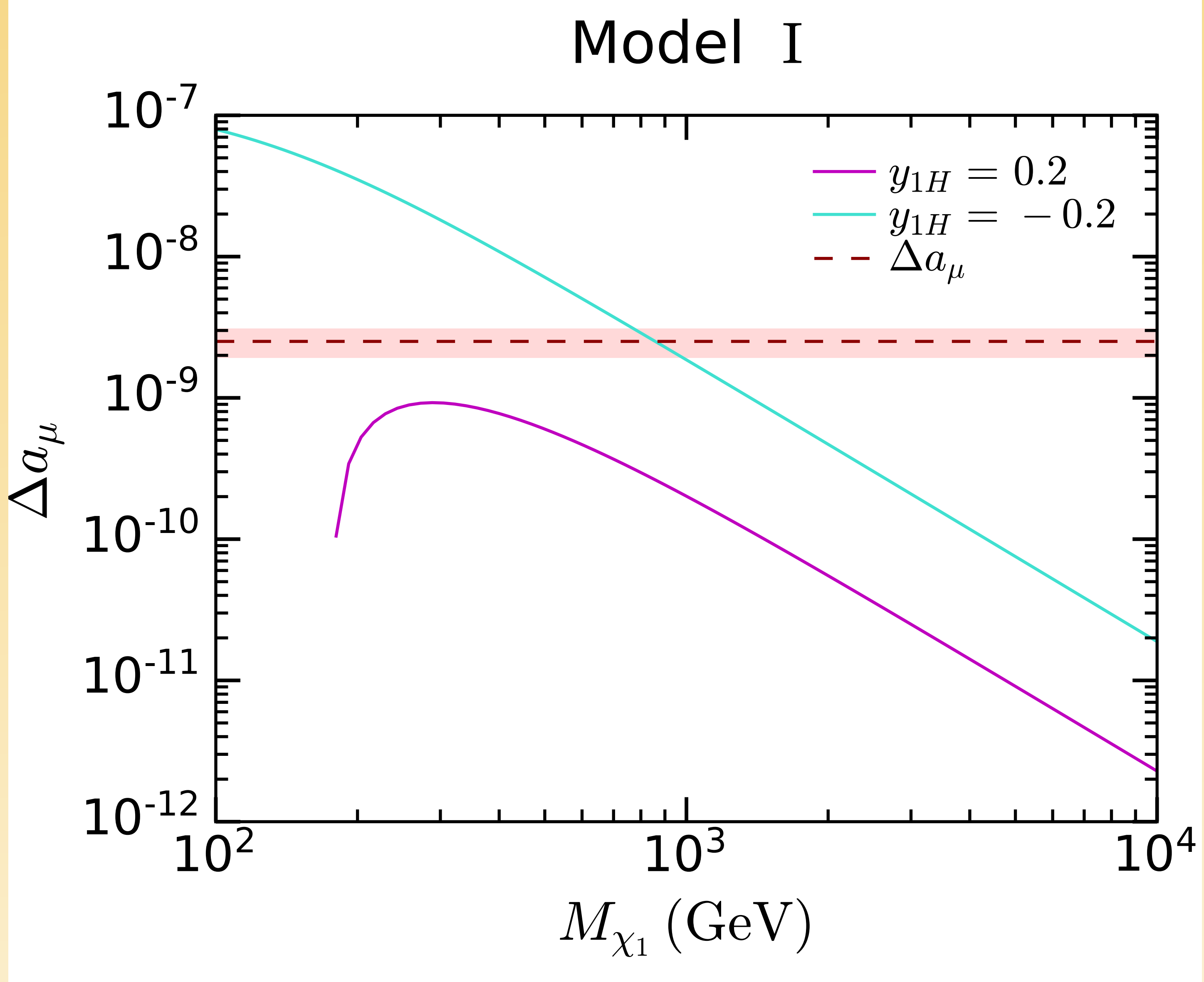

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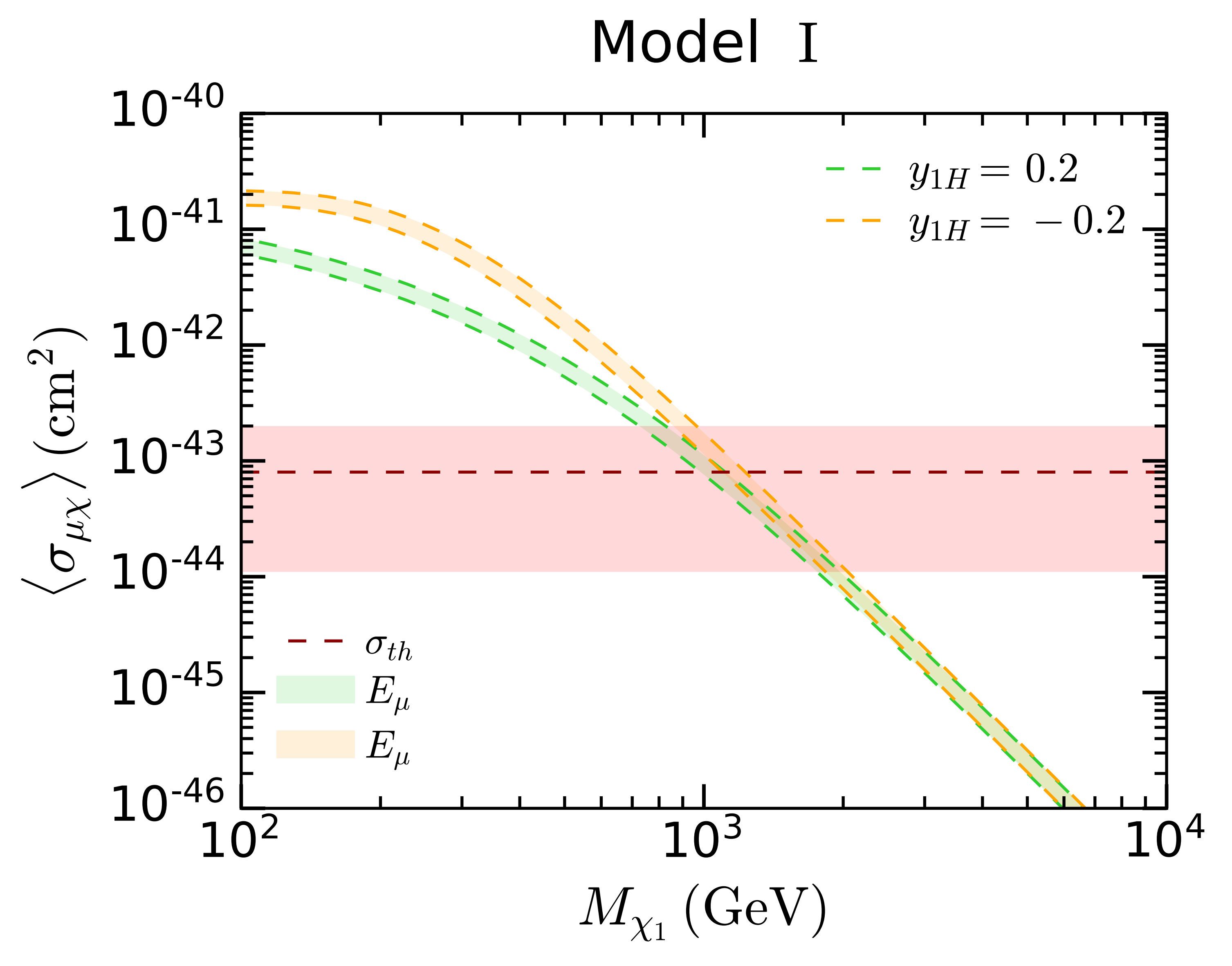
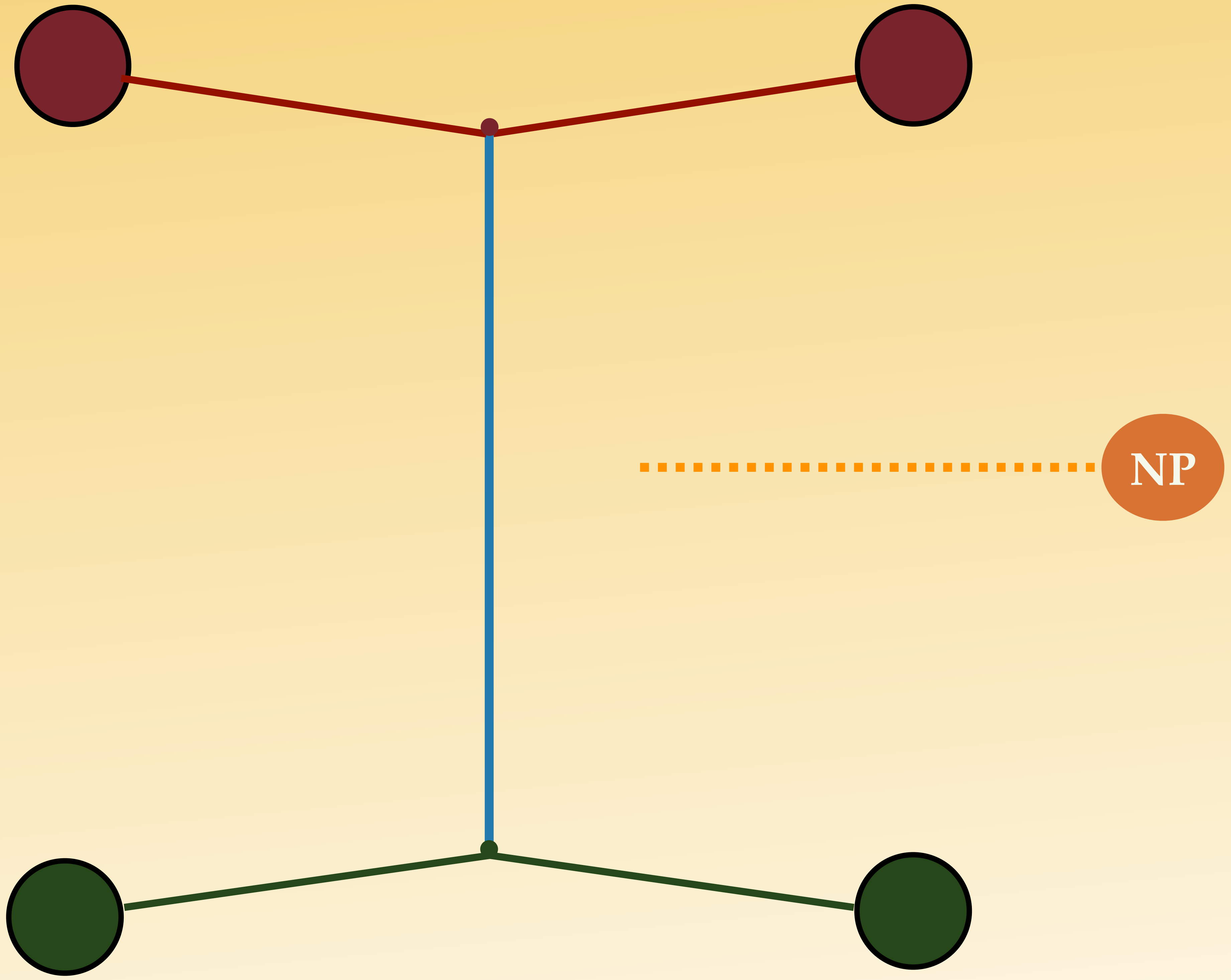


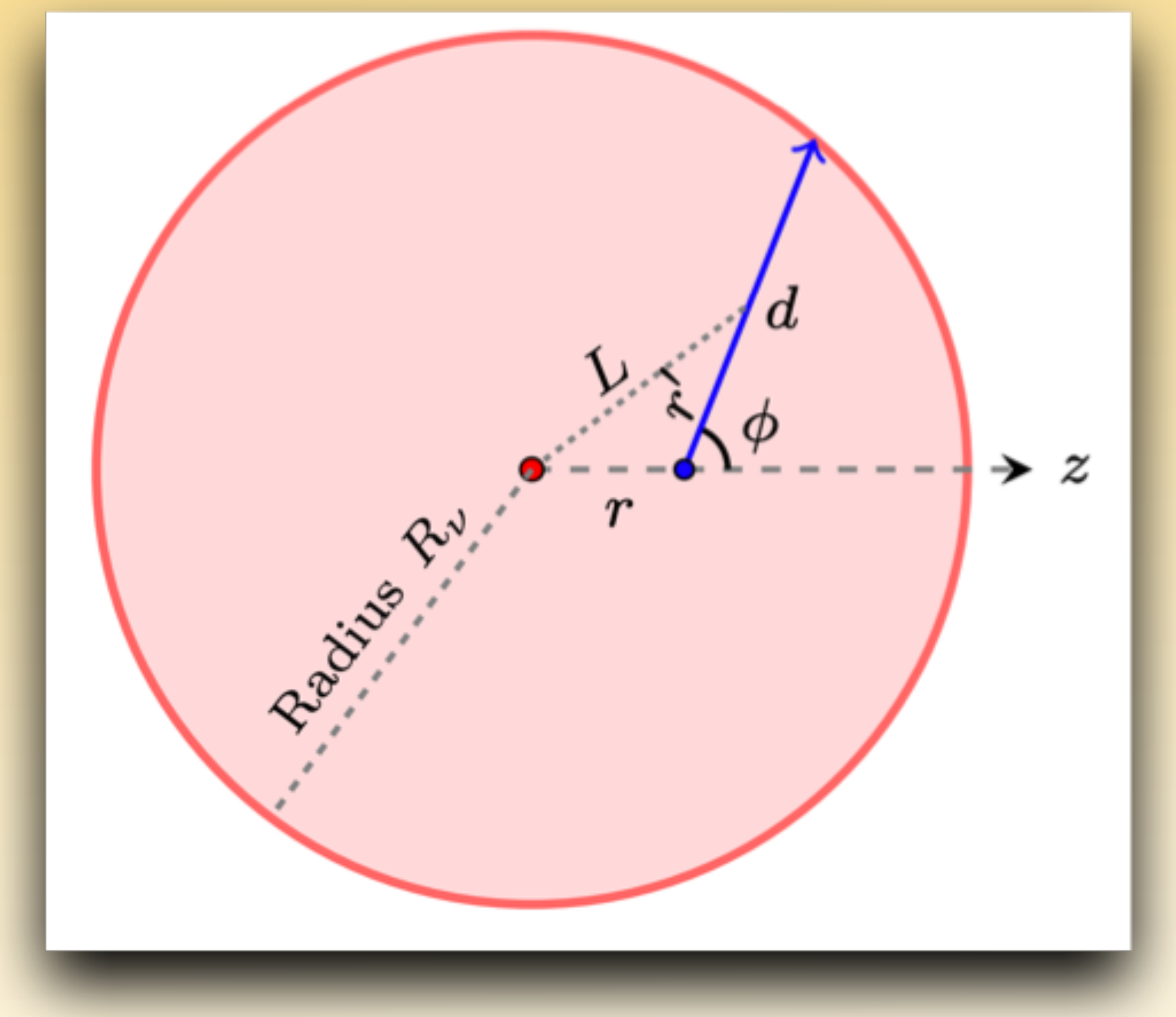
Cooling of Compact Stars

Decay probability

$$\mathcal{Q}(r,\,\phi) = \int \mathrm{d}\Pi_5 \mathcal{S} \sum_{\text{spins}} |\mathcal{M}|^2 (2\pi)^4 \delta^4(p_1 + p_2 - p_3 - p_4 - k_S) E_S f_1 f_2 P_{\text{decay}} P_{\text{abs}}$$

Absorption probability





- The probabilities will depend on where is the particle produced in the star.
- The production mechanism depends on the type of compact object.

Production of new particles

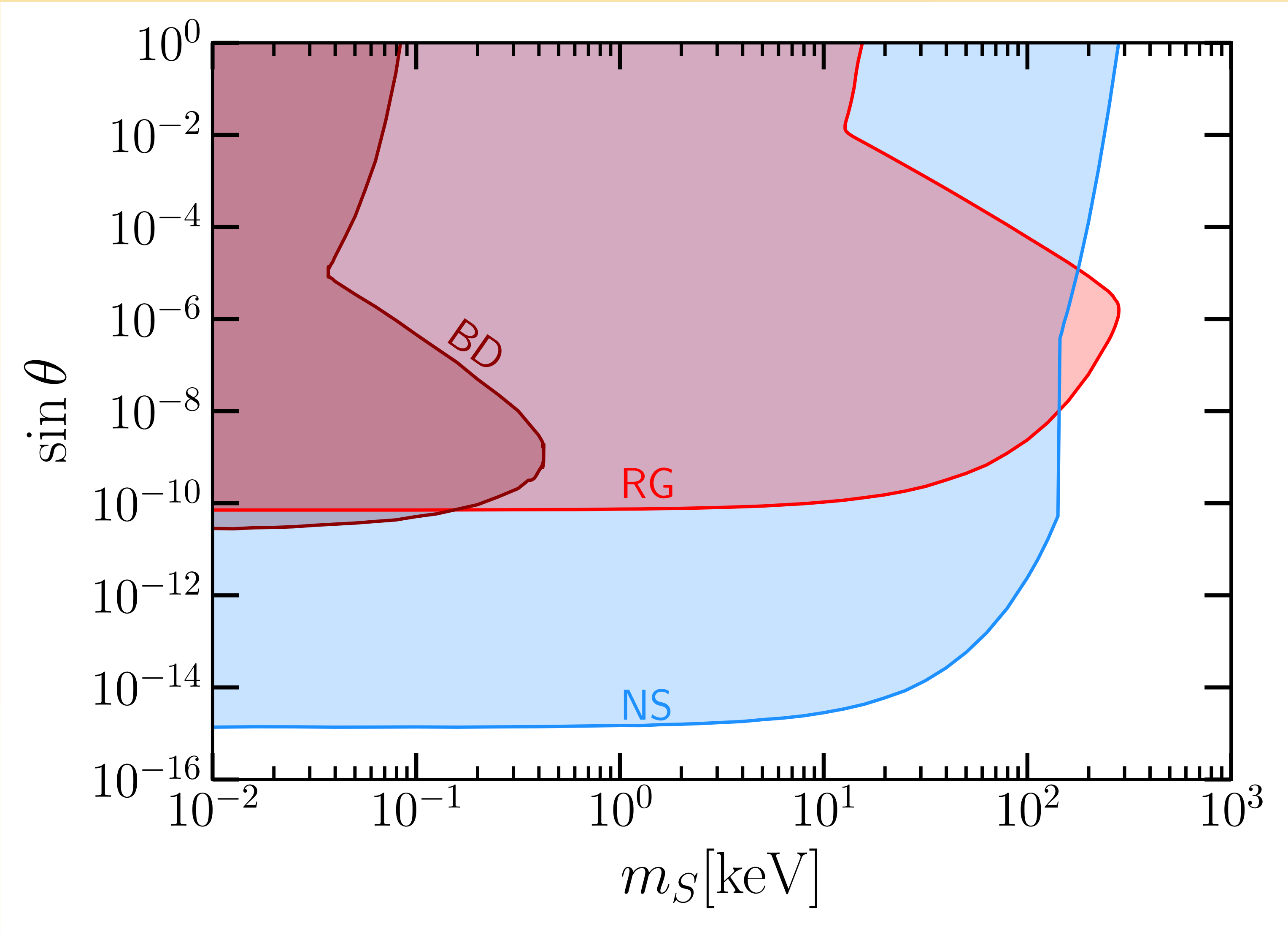
$$\mathcal{L}_S = \int \mathcal{Q}(r,\phi)\mathrm{d}V = 2\pi \int_0^{R_\nu} \mathrm{d}r\, r^2 \int_0^{\pi} \mathrm{d}\phi \sin\phi\, \mathcal{Q}(r,\phi)\,.$$

PRELIMINAR

We can obtain limits by requiring that the luminosity due to the new particles is less than 10% the luminosity of the observed compact star

$$\mathcal{L}_S \lesssim \mathcal{L}_\gamma$$

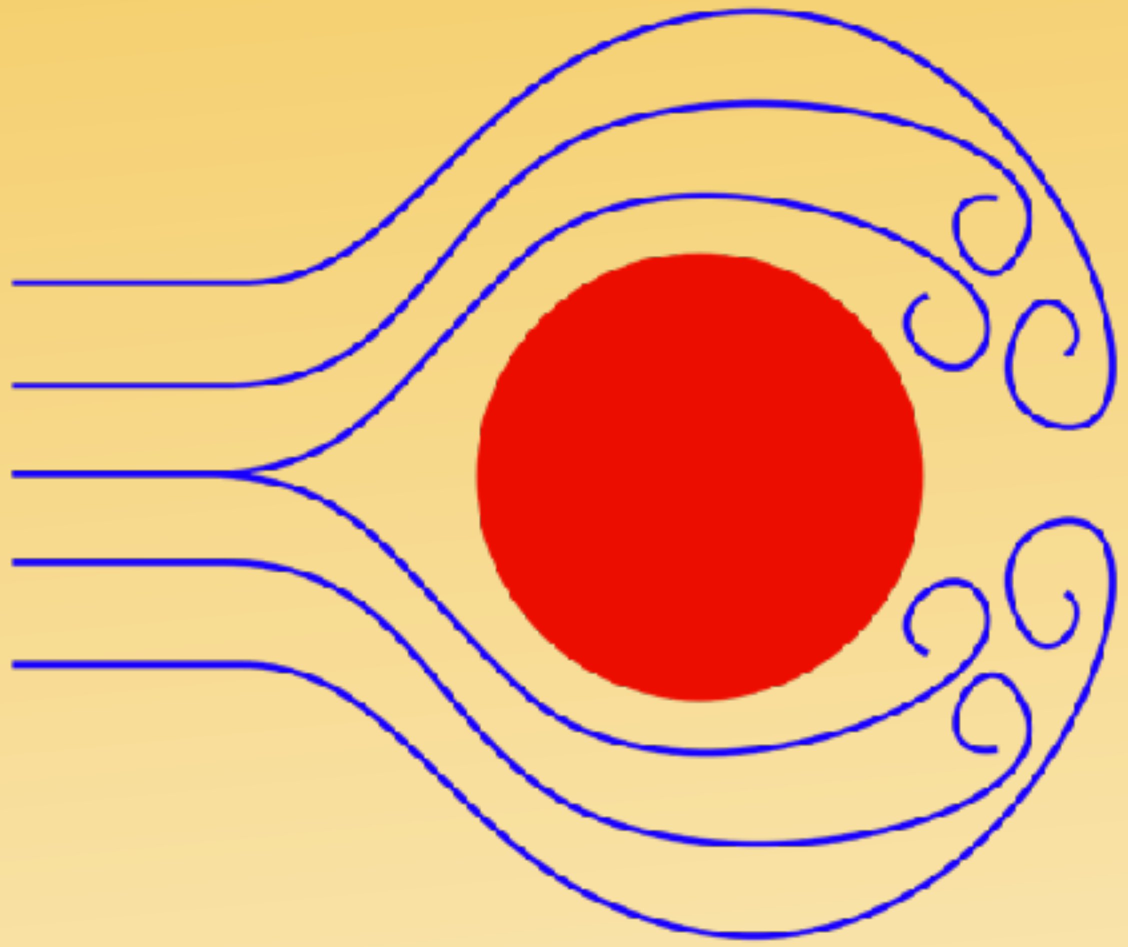
$$\mathcal{L} = \sin\theta S \left[y_{hNN}\overline{N}N + A_\pi(\pi^0\pi^0 + \pi^+\pi^-)\right]$$



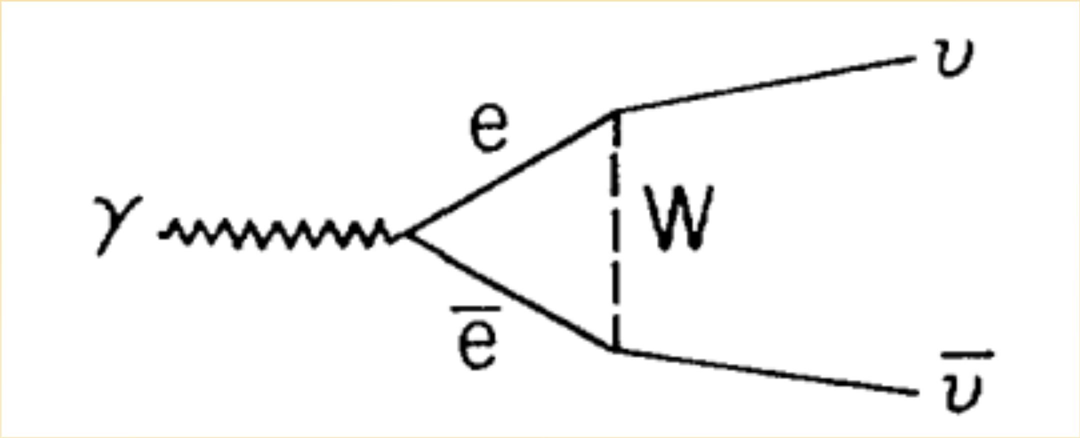
New particles as mediators: ν emission rate

Ingredients to compute the emission rate:

- Thermal photon-self energy: the originally massless photon acquire an effective mass caused by the interactions with the other particles of the system.

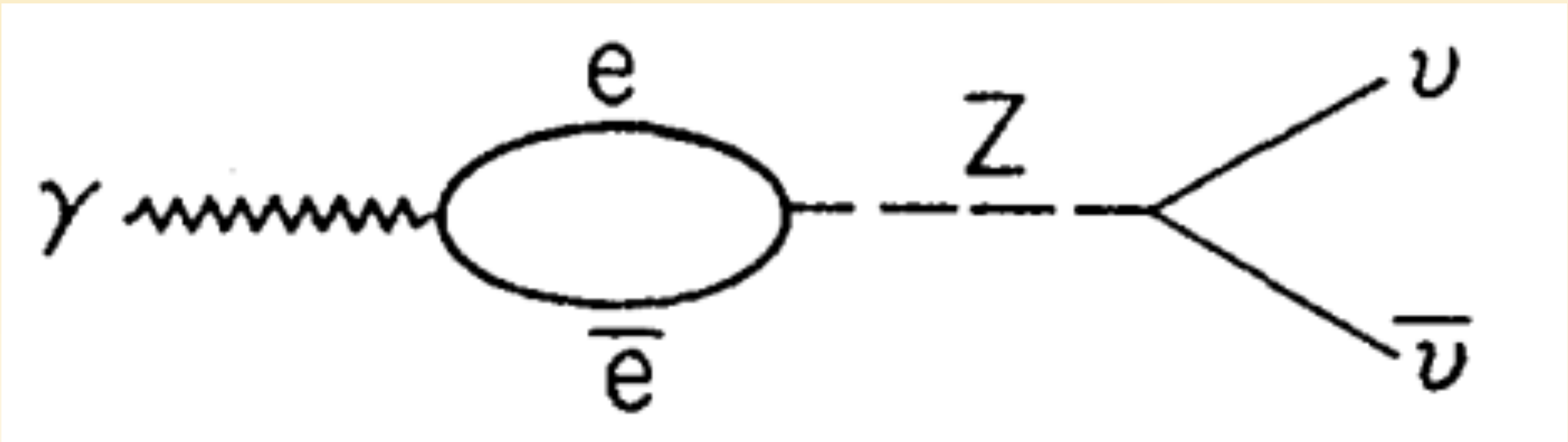


$$\Pi^{\mu\nu} = 4e^2 \int \frac{d^3K}{(2\pi)^3} \frac{f_e(E_K) + f_{\bar{e}}(E_K)}{2E_K}$$
$$\times \frac{Q\cdot K(K^\mu Q^\nu + K^\nu Q^\mu) - Q^2 K^\mu K^\nu - (Q\cdot K)^2 g^{\mu\nu}}{(Q\cdot K)^2 - Q^4/4}$$



- This modifies the polarisation 4-vector: we account for the temperature effects. The expression of these factors depend on the photon self-energy.

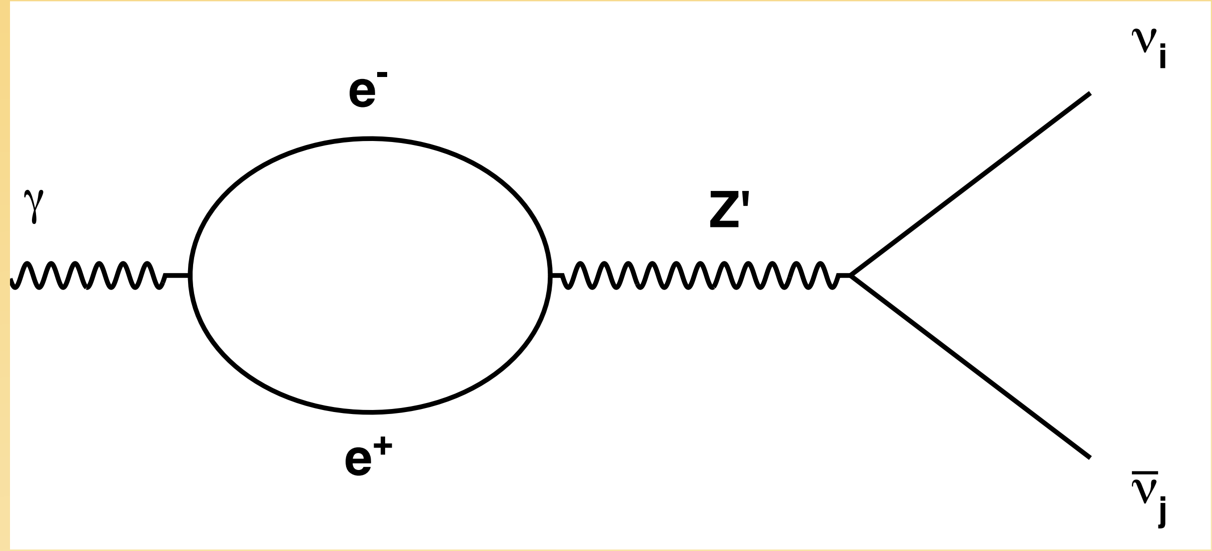
$$\epsilon_l \text{ and } \epsilon_t$$



New particles as mediators: ν emission rate

PRELIMINAR

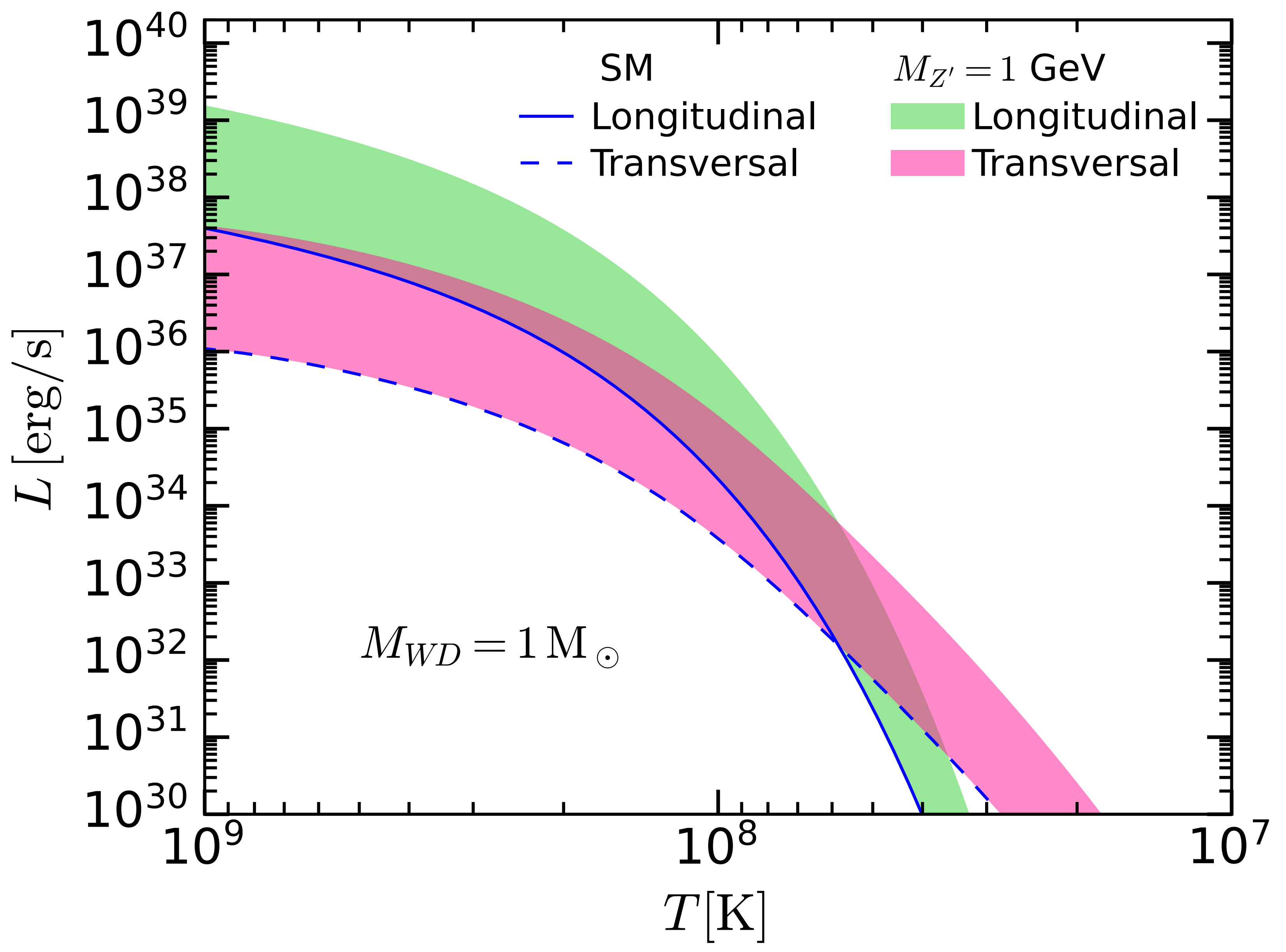
Presence of new physics that couples to both, SM and new forces, introduces the possibility of an additional way to produce neutrinos.

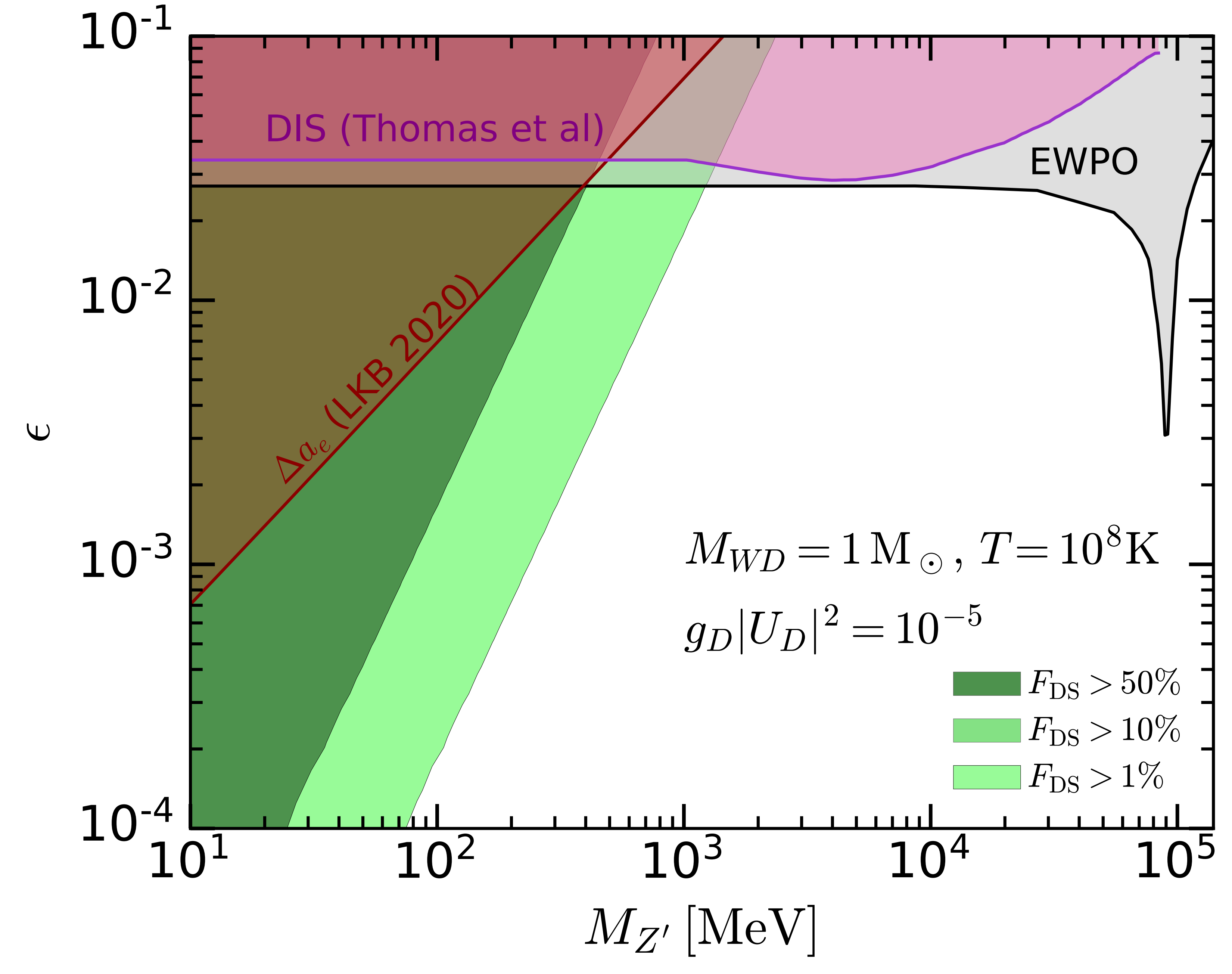


We express the contribution of the new physics as a fraction of the total SM luminosity,

$$F_{\mathrm{DS}} = \frac{\mathscr{L}_{\mathrm{DS+SM}} - \mathscr{L}_{\mathrm{SM}}}{\mathscr{L}_{\mathrm{SM}}} \times 100\,\%\,.$$

Therefore, we can perform estimations and projections of the allowed parameter space regarding the cooling of WD mediated by new physics.





Summary

- There are some limitations of the standard model - it cannot fully explain several phenomena. Addressing these limitations requires theories beyond the standard model.
- Scientists and researchers are actively working on various fronts to explore explanations. These efforts involve collaborations between experimentalists, theorists, and cosmologists worldwide.
- Compact stars, provide unique environments that can be utilized to probe for new physics beyond the standard model.
- We have explored the heating (accumulation of new particles) and cooling (production of new particles) mechanisms: both providing improved constrains compared to earth based experiments.
- Deviations from theoretical predictions, unexpected phenomena, or anomalous observations in compact stars and white dwarfs could indicate the presence of new physics and guide further investigations.

Thank you!