Dark Matter Heating vs. Vortex Creep Heating of Old Neutron Stars

Maura E. Ramirez Quezada (JGU Mainz)

Based on

arXiv: 2309.02633, 2308.16066, 2204.02413,

In collaboration with/

Motoko Fujiwara, Koichi Hamaguchi & Natsumi Nagata

PPC 2024

JOHANNES GUTENBERG UNIVERSITÄT MAINZ

Indian Institute of Technology Hyderabad

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October 2024

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भारतीय प्रौद्योगिकी संस्थान हैदराबाद
Indian Institute of Technology Hyderabad

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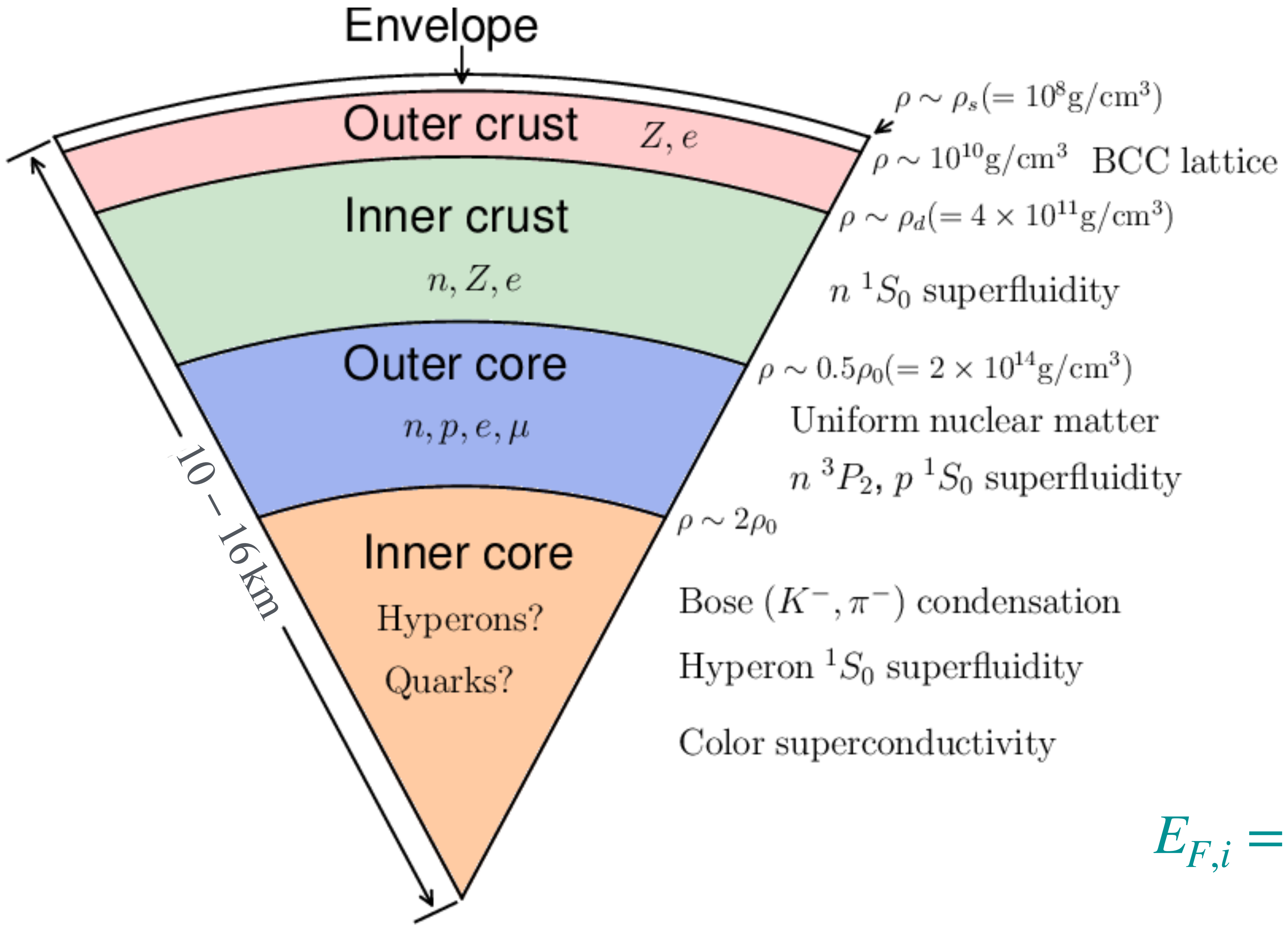
October 2024

Outline

- Neutron Stars
  - Structure
  - Cooling process
- NS as DM laboratories
  - DM heating of NS
  - Vortex creep
- Summary

Neutron Stars: Structure

The upper mass limit depends on the uncertain EOS



Lim, Y., Hyun, C.H., & Lee, C. (2015). Nuclear Equation of State and Neutron Star Cooling. *arXiv: Nuclear Theory*.

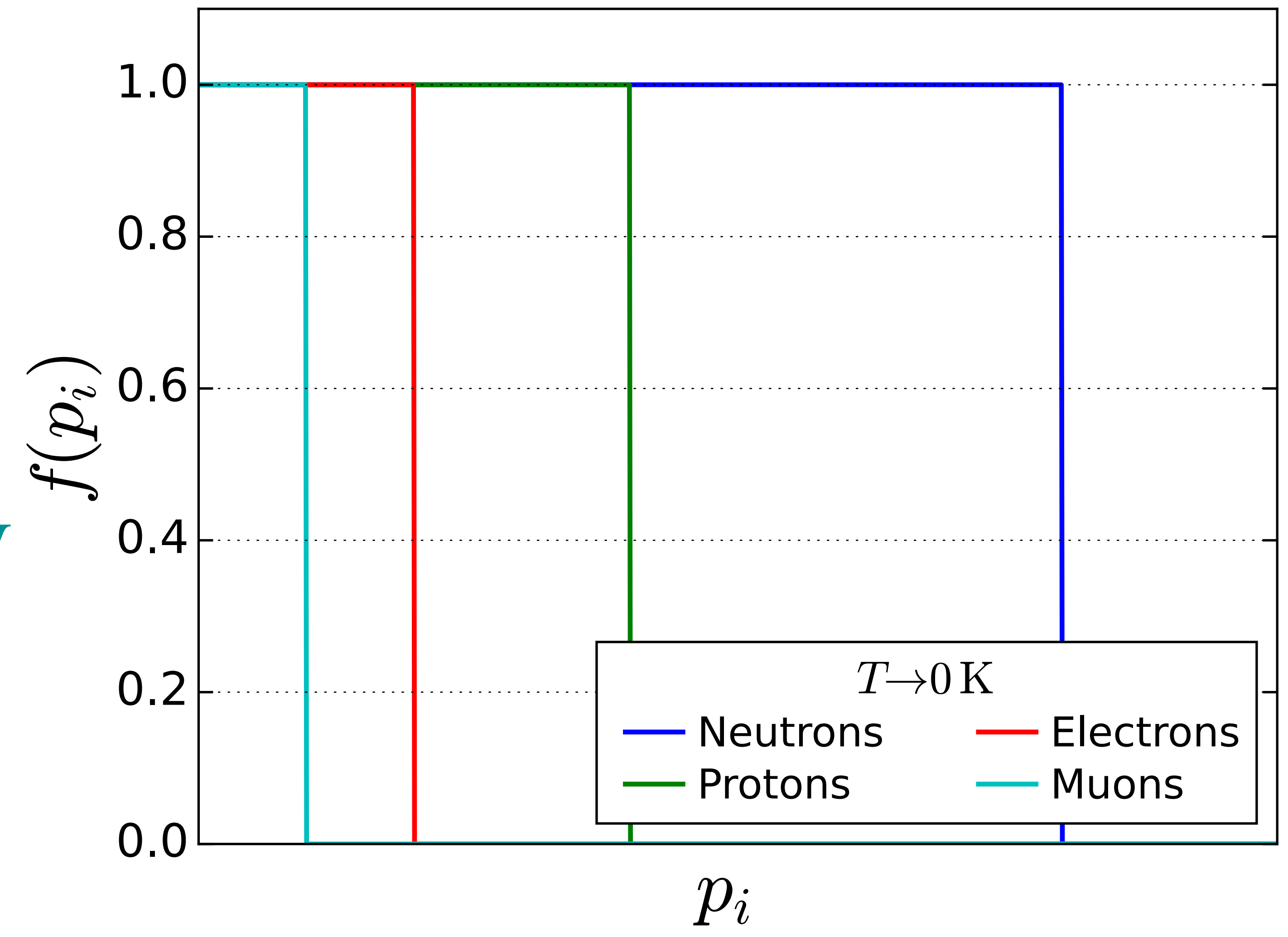
- Extremely compact objects:

$$M_\star \sim (1-2)\ \mathrm{M}_\odot,\quad R_\star \sim (10-16)\,\mathrm{km},\quad \bar{\rho} \sim \mathcal{O}(10^{14})\ \mathrm{g/cm^3}$$

- Their exact composition is still unknown.
- The core accounts for 99% of the mass of the NS
- Mostly composed of neutrons + admixture of protons and electrons + muons (when $E_{F,e} > m_\mu$)
- Neutron, protons and electrons are degenerate

$$E_{F,i} = \frac{\hbar^2 p_{F,i}^2}{2m_i}$$

$$p_{F,n} \sim 300 - 500\,\mathrm{MeV}$$



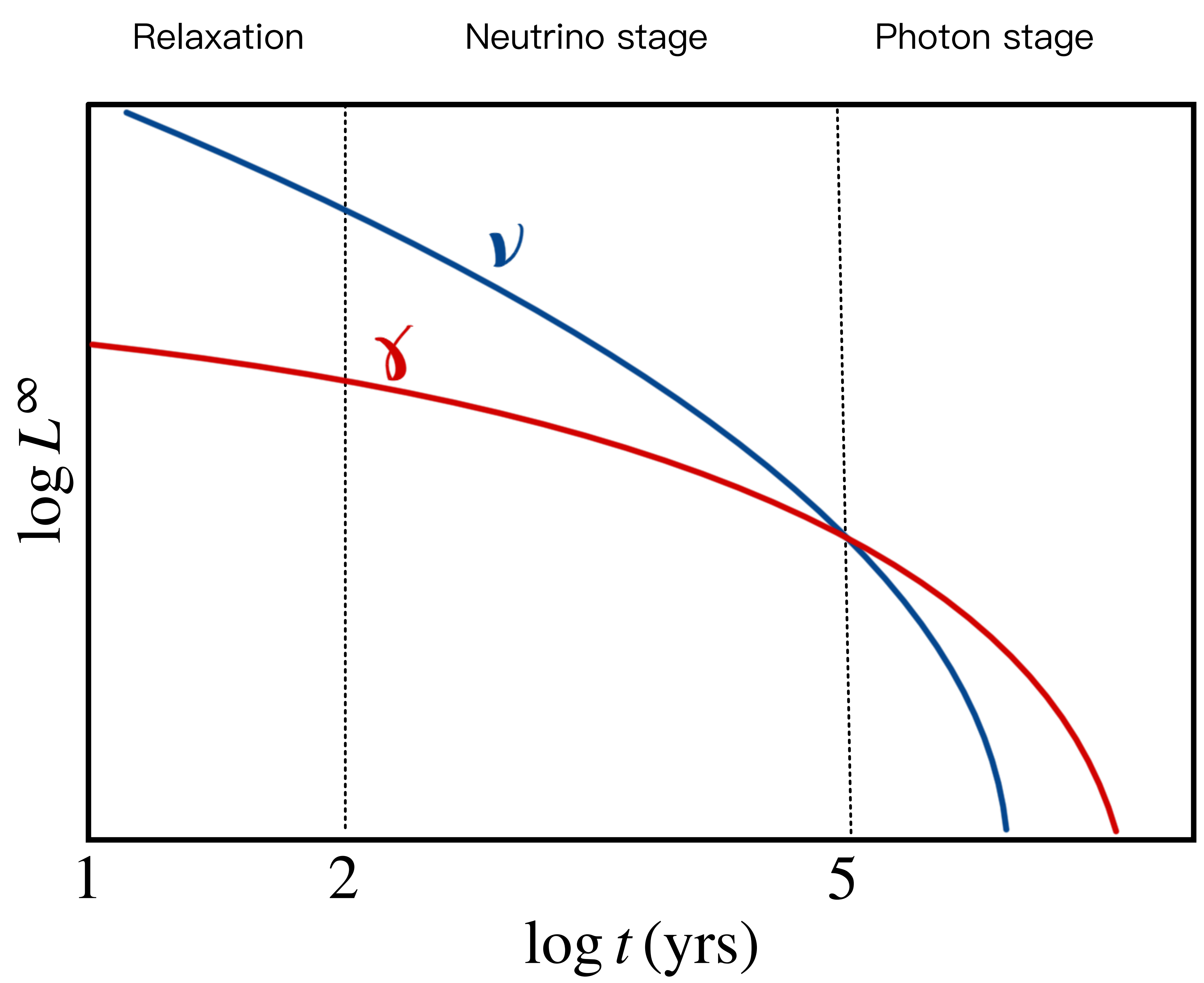
Neutron Stars: Standard Cooling Theory

$$C\frac{dT}{dt} = -L_\nu - L_\gamma$$

- Young NS $(t \lesssim 10^5\ \text{yr})$
  Neutrino emission is the predominant process

- Old NS $(t > 10^5\ \text{yr})$
  Photon emission is the predominant process

$$L_\gamma = 4\pi R_\star^2 \sigma_{SB} T_s^4$$

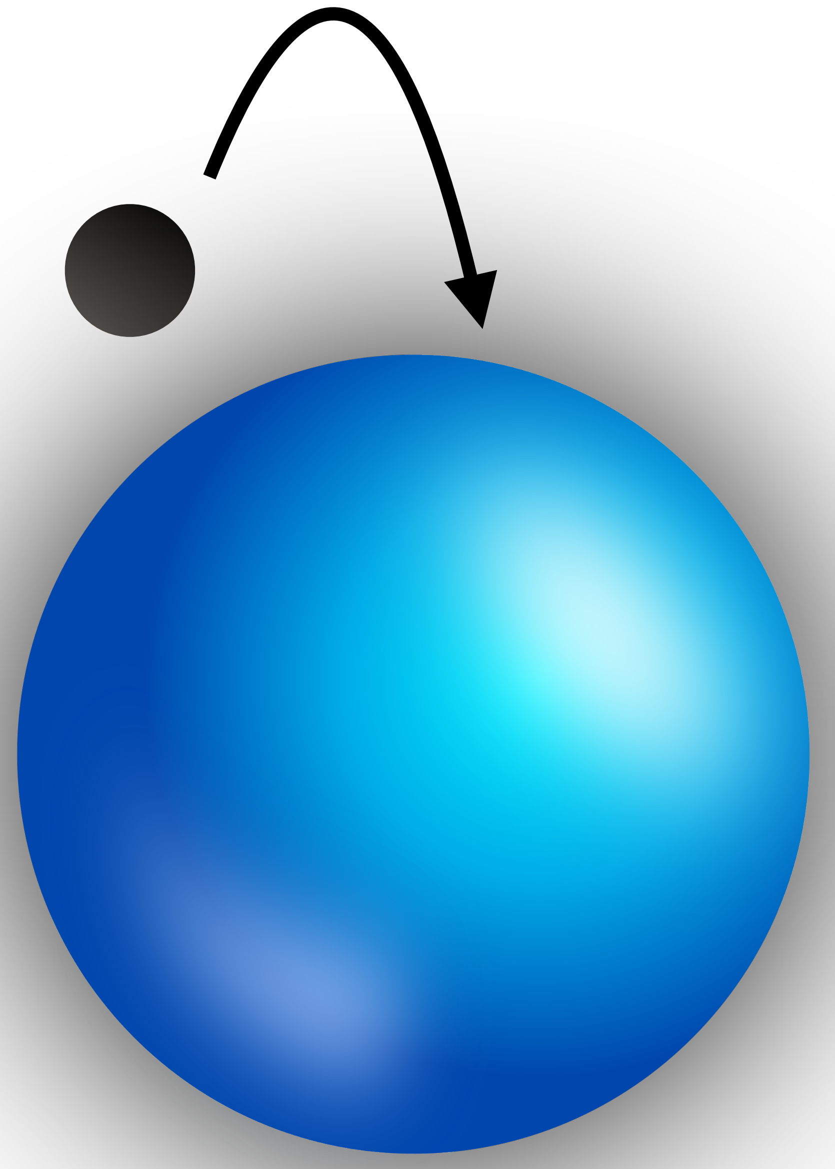


DM heating of NS

$$C\frac{dT}{dt} = -L_\nu - L_\gamma + L_{\mathrm{DM}}$$

DM heating of NS

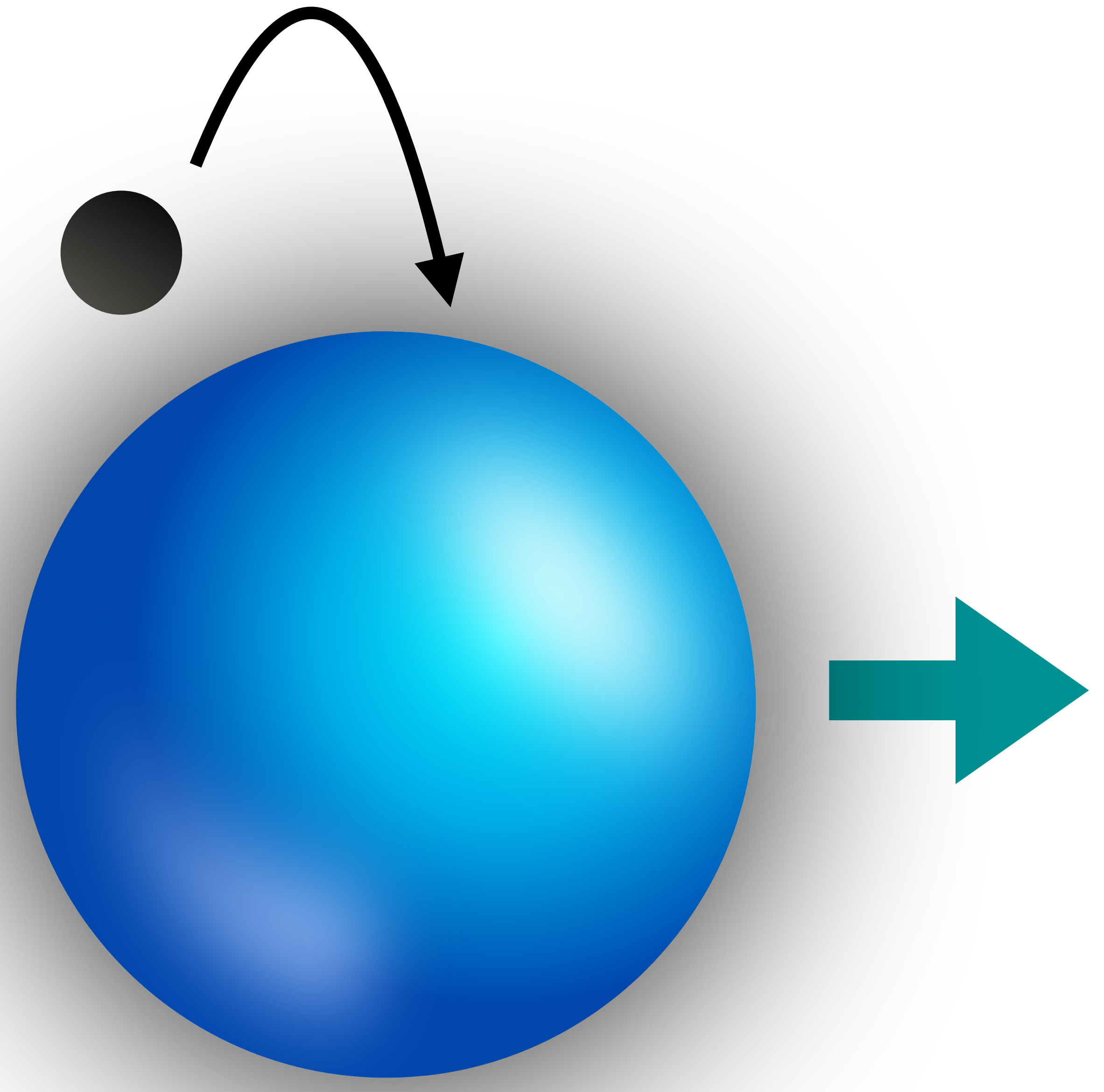
$$C\frac{dT}{dt} = -L_\nu - L_\gamma + L_{\mathrm{DM}}$$



Neutron Stars

DM heating of NS

$$C\frac{dT}{dt} = -L_\nu - L_\gamma + L_{\mathrm{DM}}$$

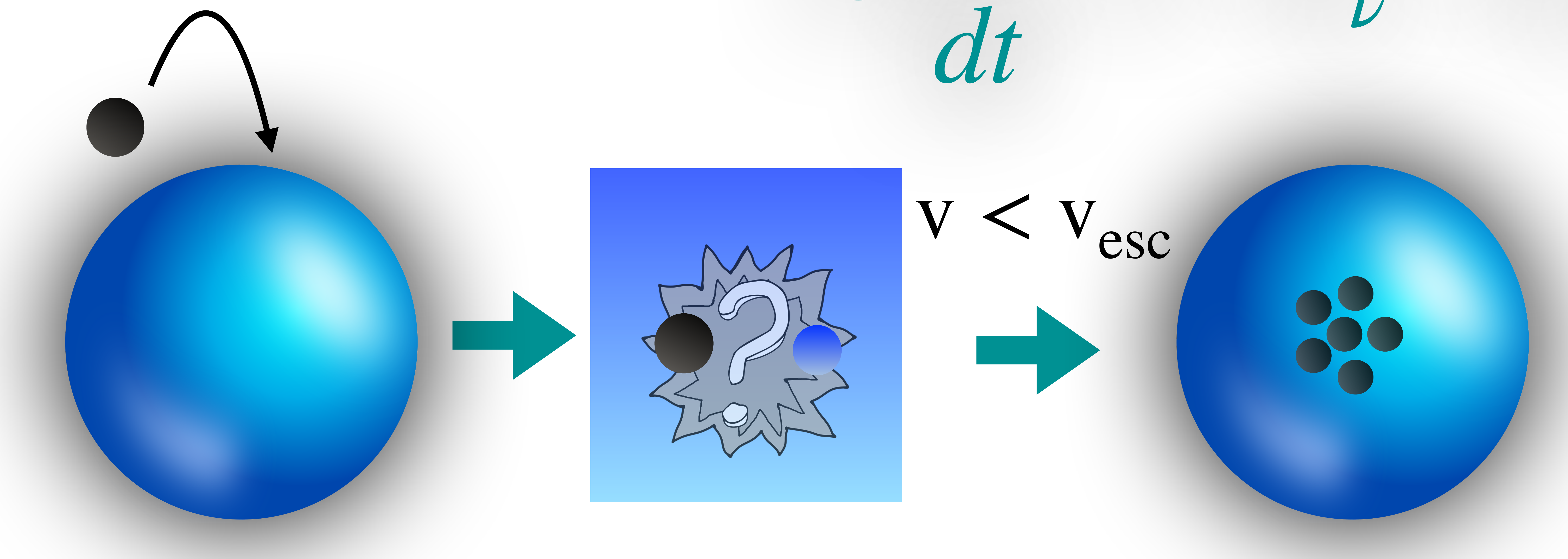


Neutron Stars

Stellar matter

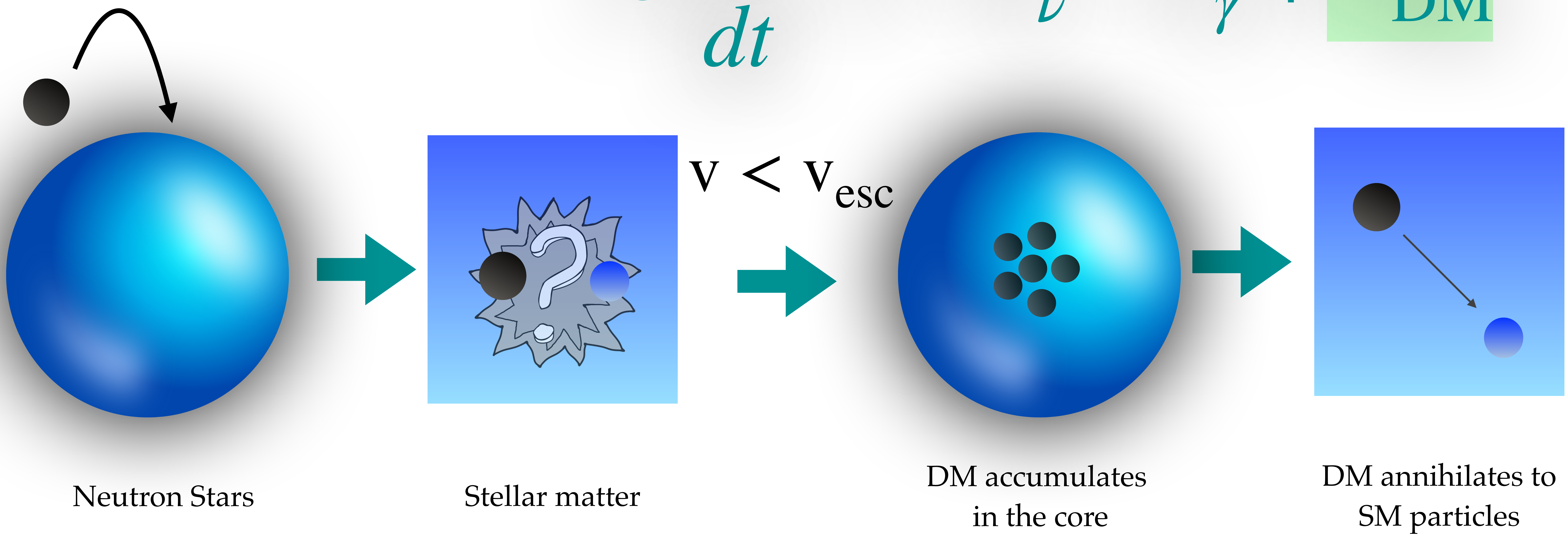
DM heating of NS

$$C\frac{dT}{dt} = -L_\nu - L_\gamma + L_{\mathrm{DM}}$$



DM heating of NS

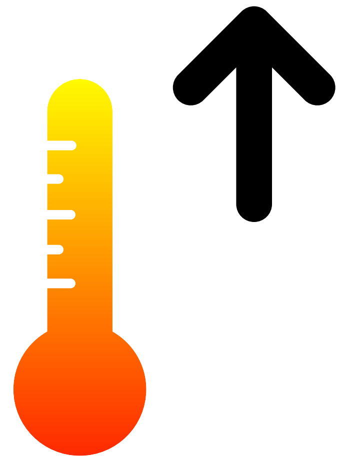
$$C\frac{dT}{dt} = -L_\nu - L_\gamma + L_{\mathrm{DM}}$$



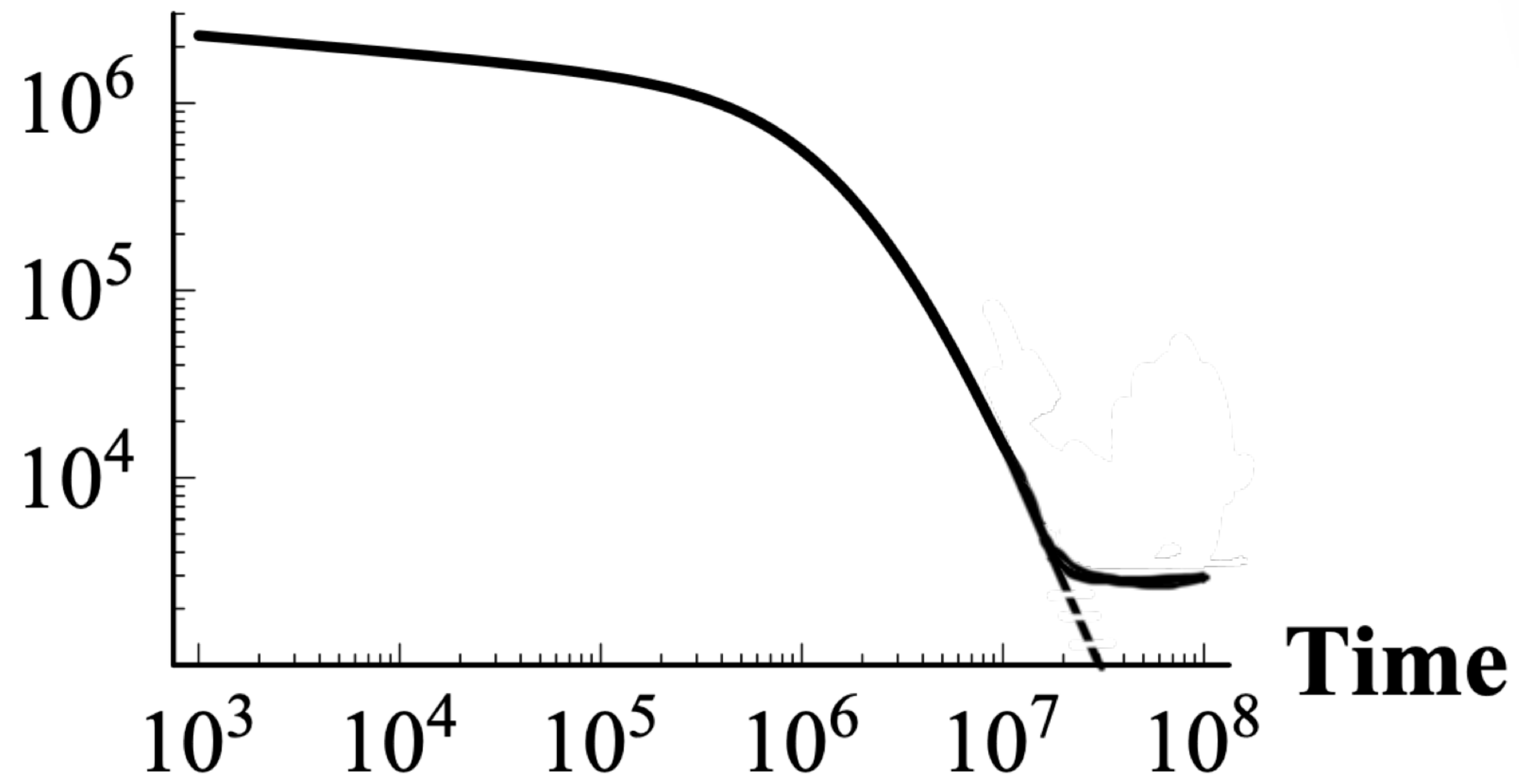
DM heating of NS

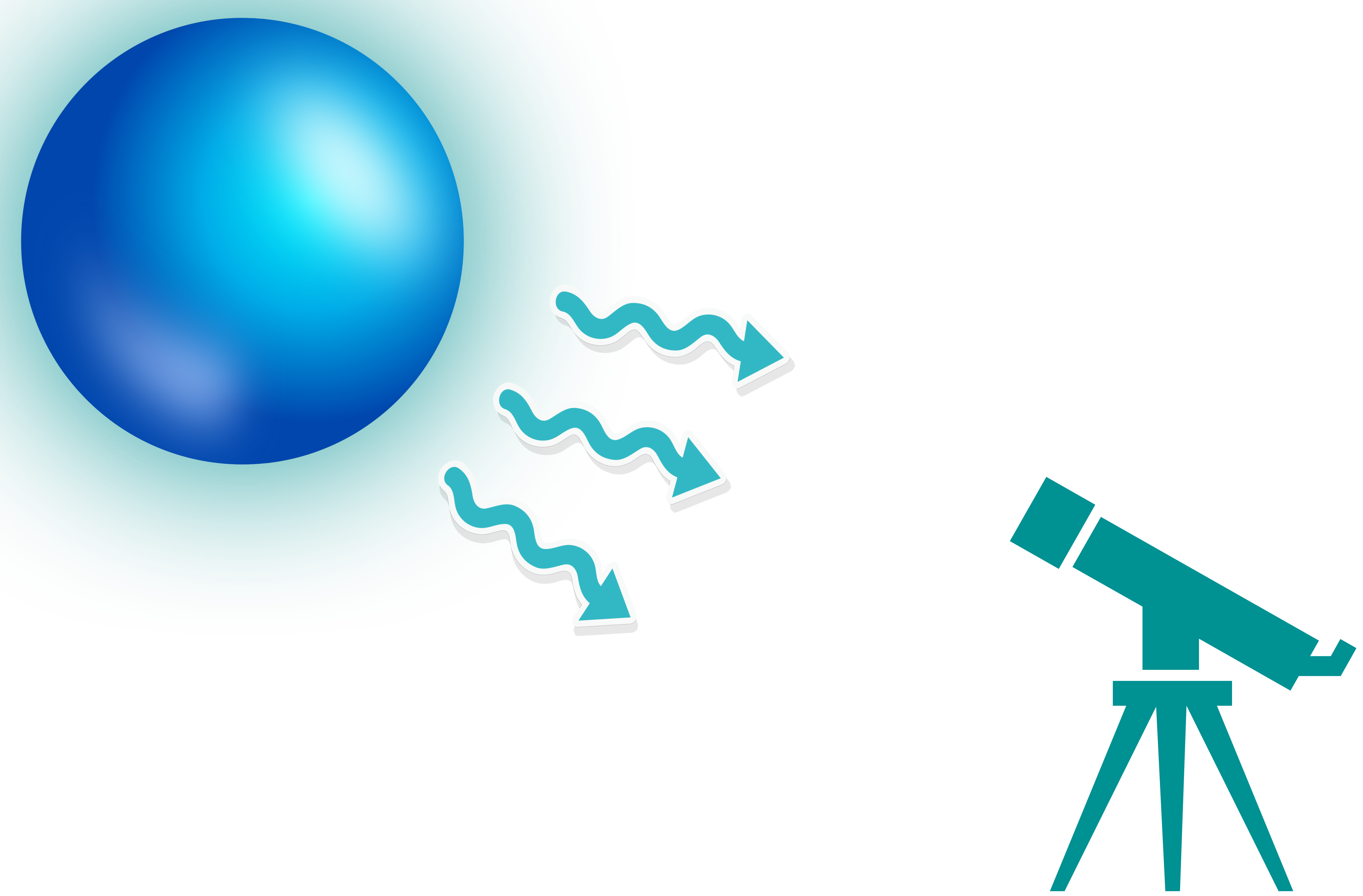
$$C\frac{dT}{dt} = -L_\nu - L_\gamma + L_{\mathrm{DM}}$$

Heating of the star to temperatures of the order of $\sim 2000\,\mathrm{K}$



Surface Temperature

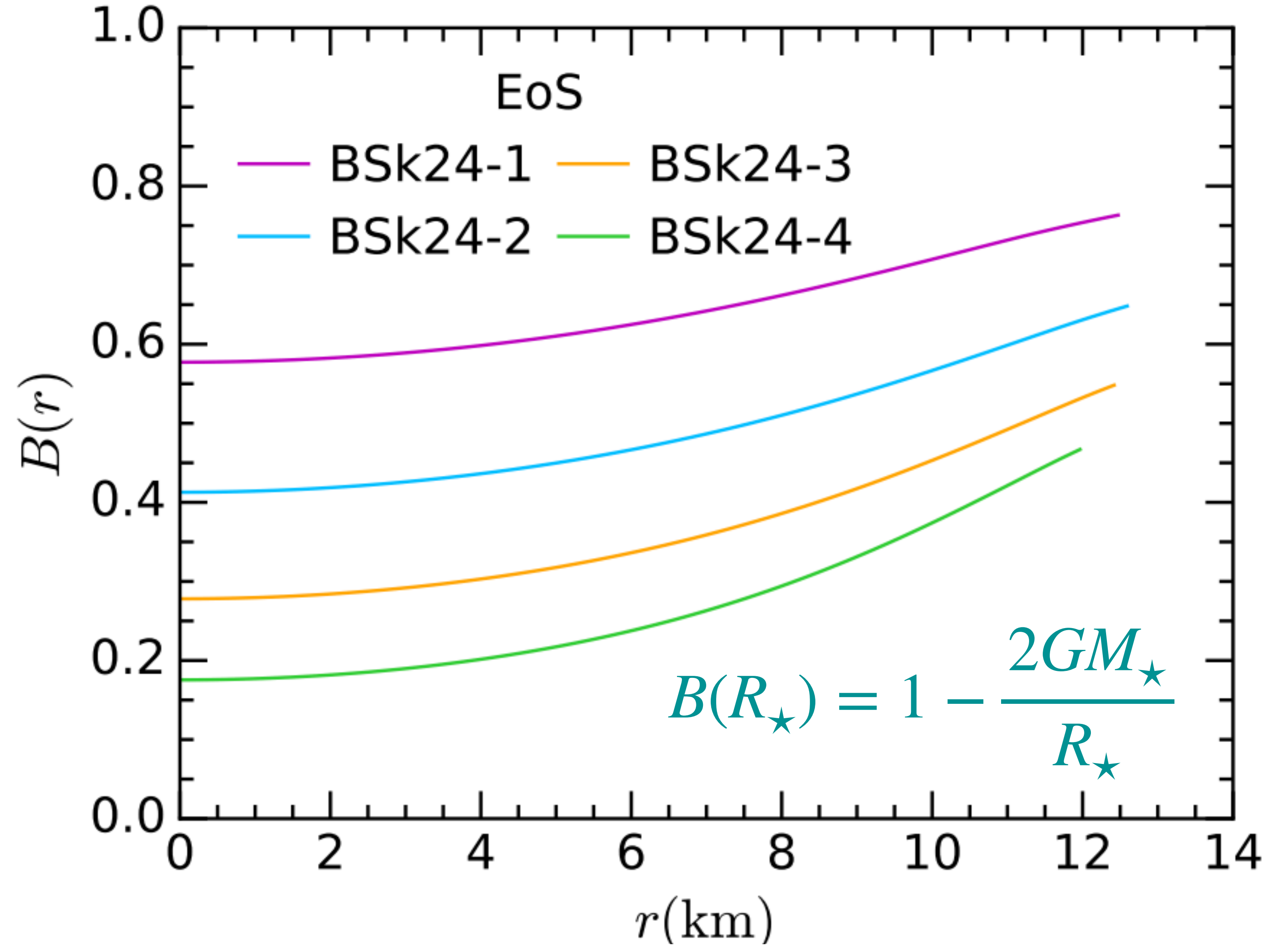




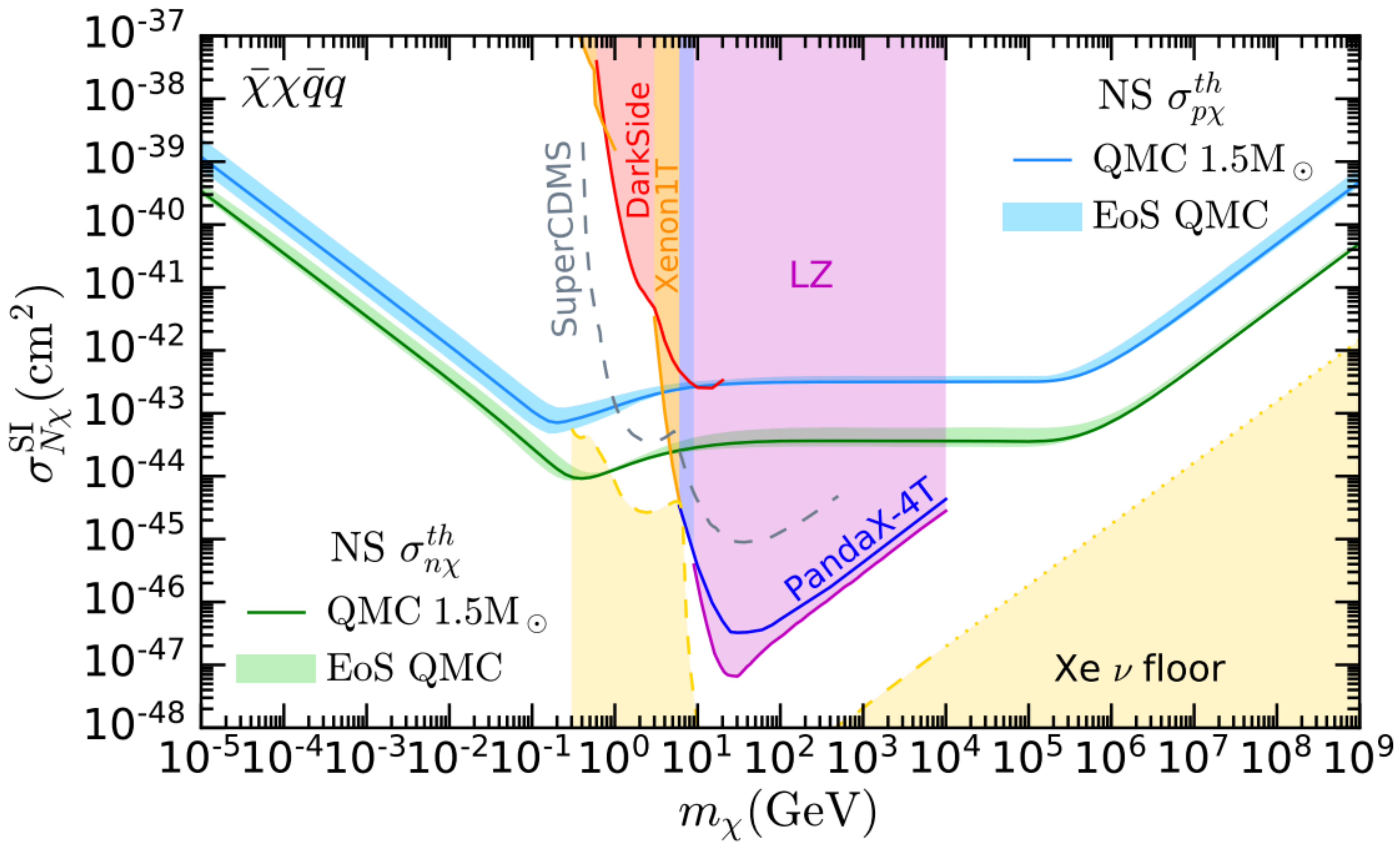
- **Observations of an old/cold NS potentially leads to a DM signal.**

NS as DM laboratories

- No detector threshold for light DM: Sub-GeV regime, down to $\mathcal{O}(10)\,\mathrm{keV}$
- DM particles become mildly relativistic when approaching the NS
  - $v_{esc}^2(r) = 1 - B(r)$ ($v \sim (0.5 - 0.7)\,c$ at the NS surface)
  - Velocity/momentum suppressed scattering
- Threshold cross sections:
  - Nucleons: $\sigma_{th}^{N} \sim [10^{-45} - 10^{-44}]\,\mathrm{cm}^2$
  - Leptons: $\sigma_{th}^{\mu} \sim 8 \times 10^{-44}\,\mathrm{cm}^2$
- No limitation from neutrino floor



Anzuini, Bell, Busoni, Motta, Robles, Thomas and Virgato 2108.02525



NS as DM laboratories

- Multiple targets: e, μ, p, n
  - **DM coupled only to muon**
    K. Hamaguchi, N. Nagata,MRQ [2204.02413]

A large parameter space will remain unexplored in the LHC and DM direct searches.

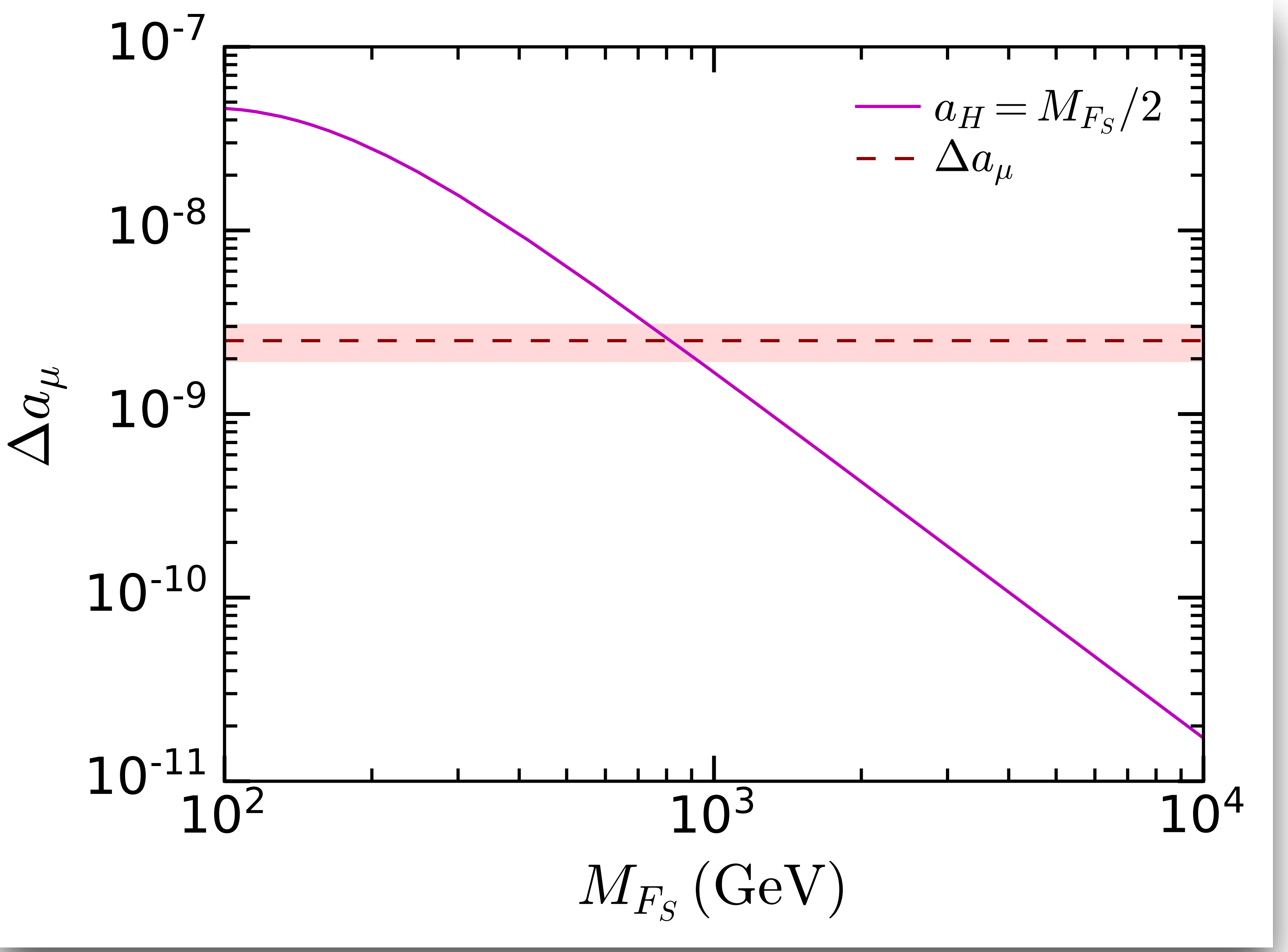
Field	Spin	$SU(3)_C$	$SU(2)_L$	$U(1)_Y$	$\mathbb{Z}_2$
χ_S	1/2	**1**	**1**	0	−
$\tilde{L}$	0	**1**	**2**	−1/2	−
$\tilde{\bar{e}}$	0	**1**	**1**	1	−

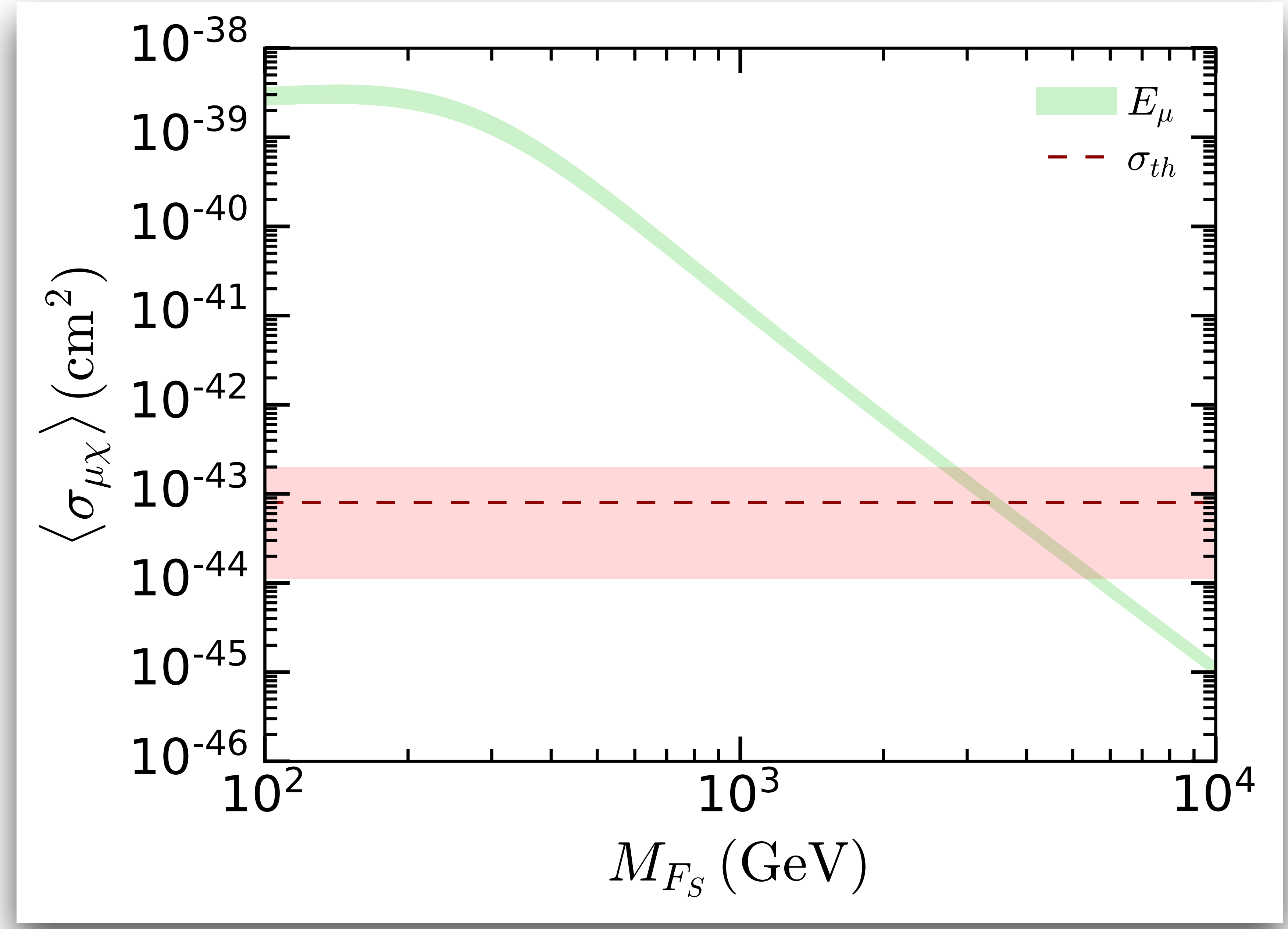
$$\mathcal{L}_{\rm mass} = -\left(\frac{1}{2}M_{F_S}\chi_S\chi_S + \text{h.c.}\right) - M_{\tilde{L}}^2|\tilde{L}|^2 - M_{\tilde{\bar{e}}}^2|\tilde{\bar{e}}|^2 ,$$

$$\mathcal{L}_{\rm Yukawa} = -y_1\,\chi_S L_\mu \tilde{L}^\dagger - y_2\,\chi_S \mu_R^c \tilde{\bar{e}}^\dagger + \text{h.c.} ,$$

$$\mathcal{L}_{\rm tri} = -a_H\,\tilde{\bar{e}}\tilde{L}H^\dagger + \text{h.c.} ,$$

$$\mathcal{L}_{\rm quart} = -\sum_{f=L,\bar{e}} \lambda_f|\tilde{f}|^2|H|^2 - \lambda'_L\tilde{L}^\dagger\tau_a\tilde{L}H^\dagger\tau_a H + \dots .$$





NS as DM laboratories

Internal heating: Vortex creep

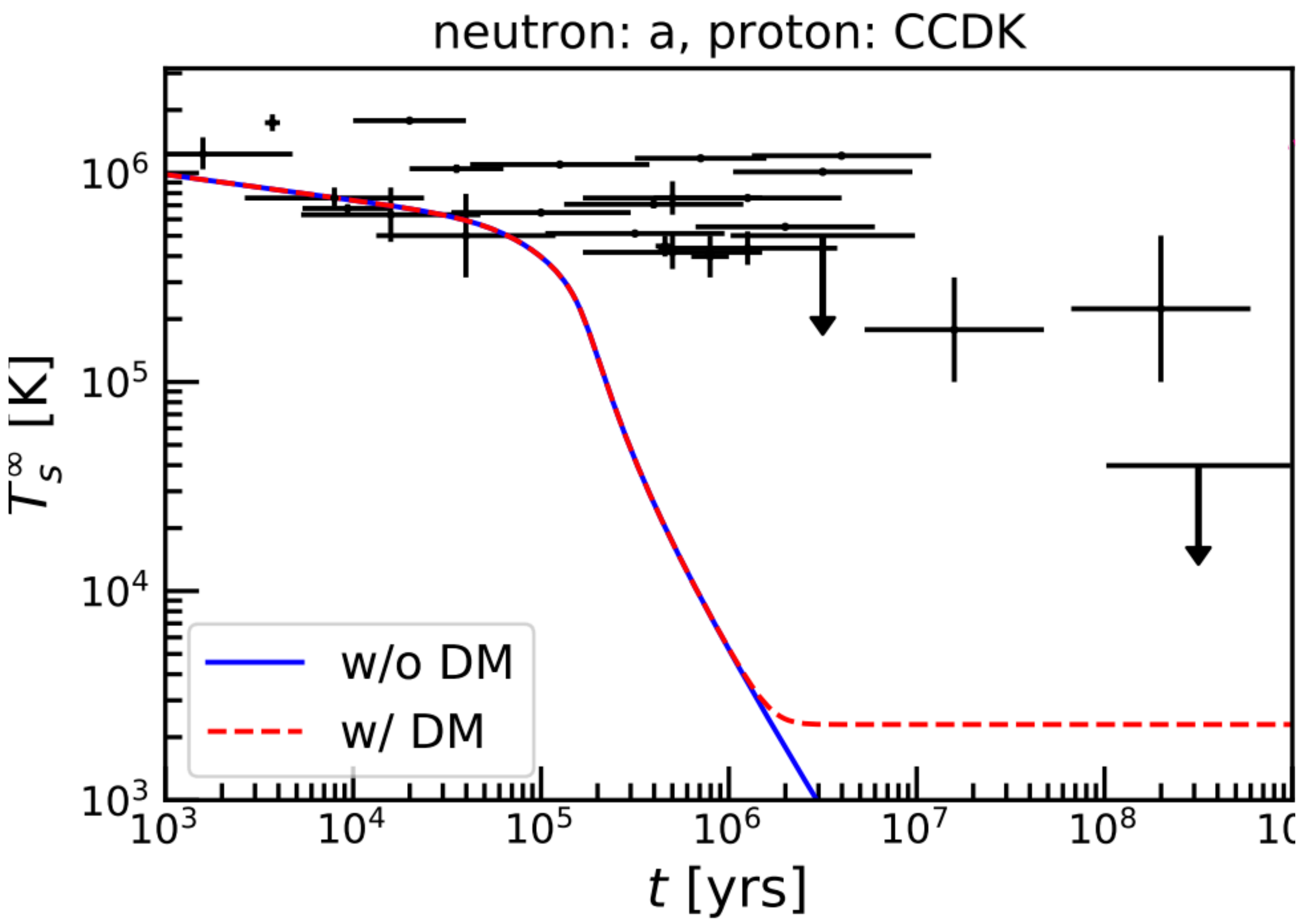
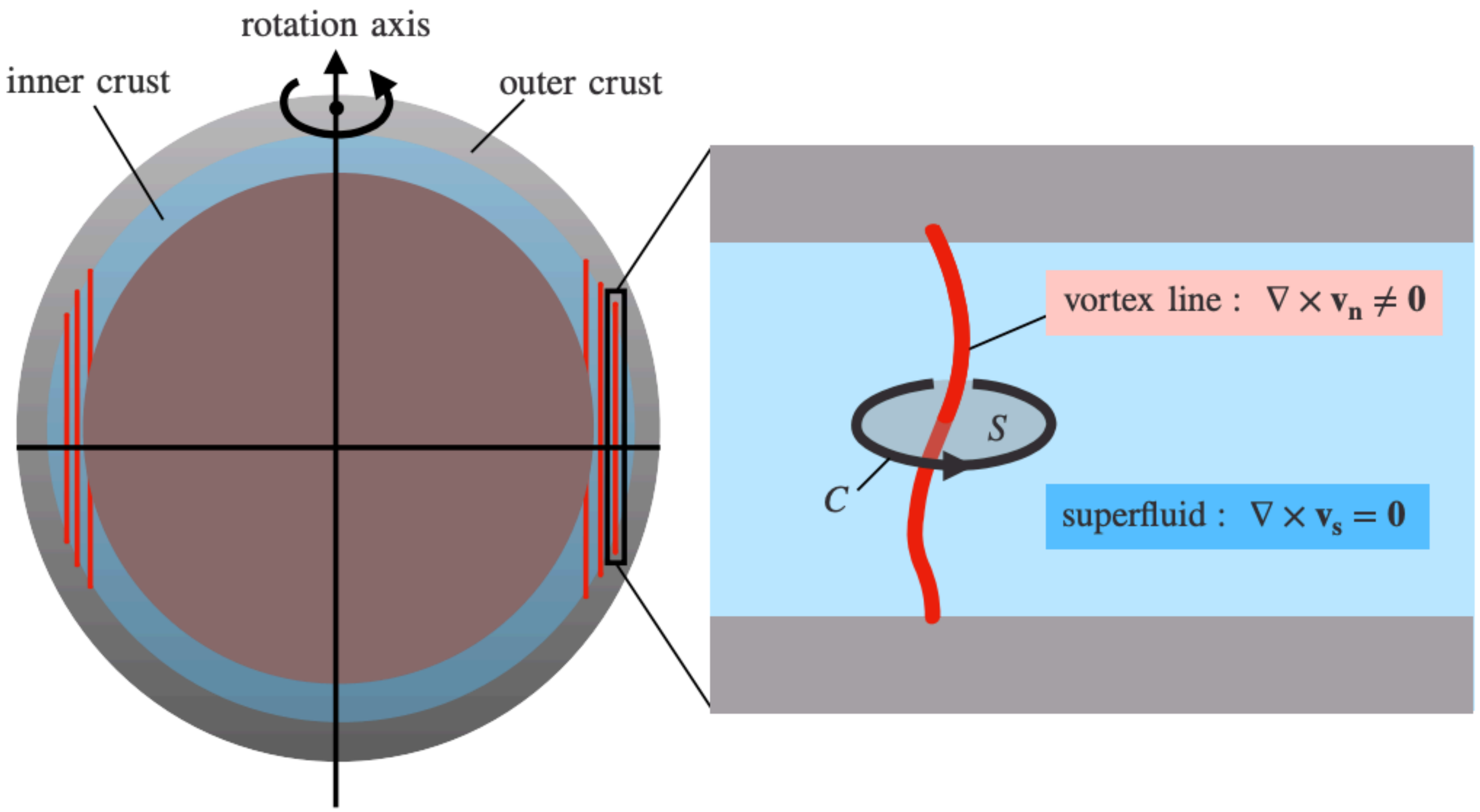


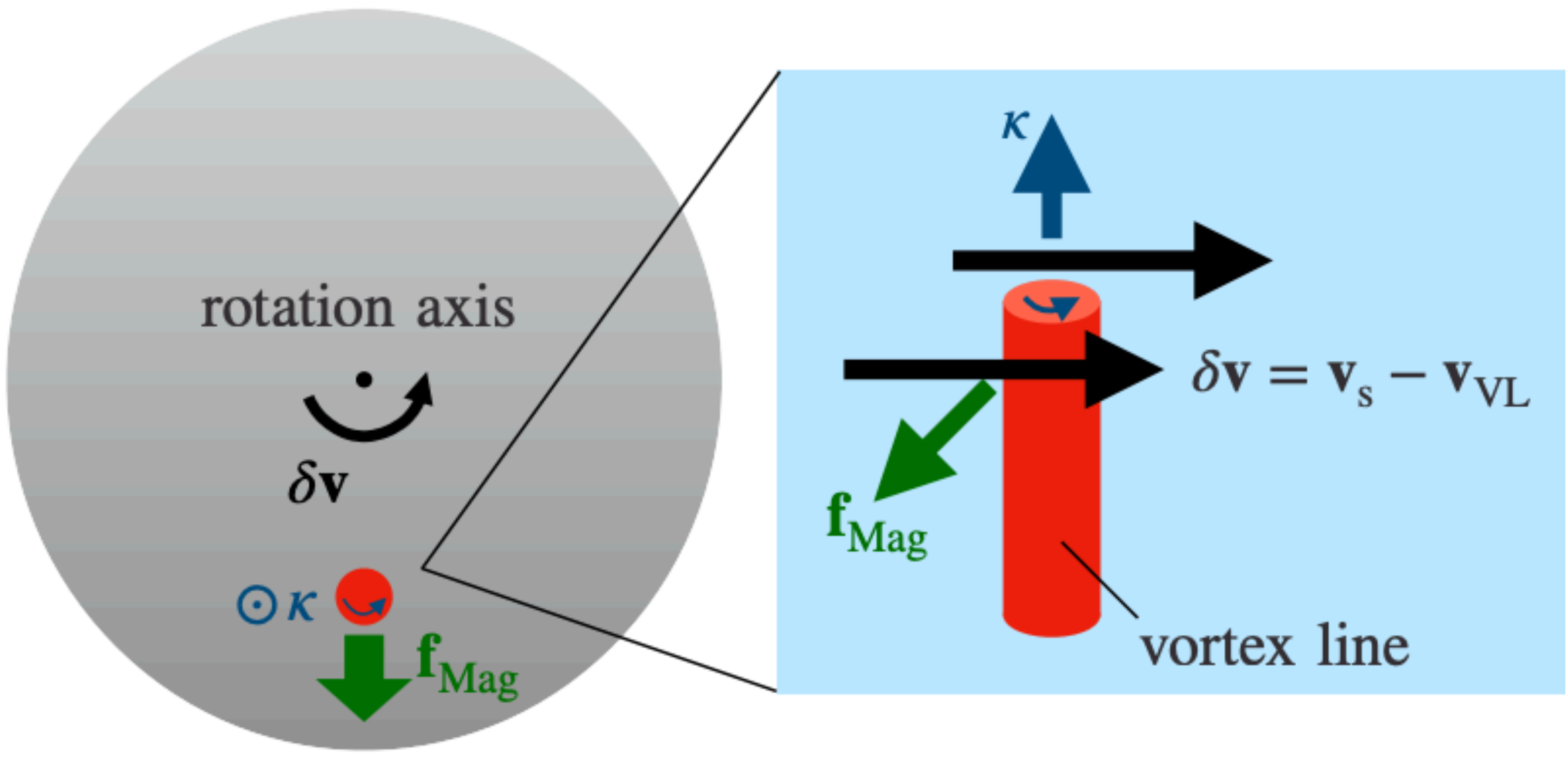
Figure taken from K. Yanagi's

- Some old and warmer NSs have been observed ($T \gg 2000\,\mathrm{K}$)
- Neither standard cooling nor DM heating can explain those old warm NSs.
- Some internal heating could be the reason/explanation for such NS temperatures:
  - **Vortex creep Heating.** M. Fujiwara, K. Hamaguchi, N. Nagata, MRQ [arXiv: 2308.16066, 2309.02633]

NS as DM laboratories

Internal heating: Vortex creep





Vortex lines are formed in a rotating NS → Vortex creep: Vortex lines start to move outwards → Vortex creep heating: total energy stored in the superfluid component is dissipated as heat

NS as DM laboratories

Internal heating: Vortex creep

$$C\frac{dT}{dt} = -L_\nu - L_\gamma + L_{\rm VC}$$

$$L_{\rm VC} = J|\dot{\Omega}|$$

Phenomenological approach of J

$$T_s^{\rm eq} = \left(\frac{J|\dot{\Omega}|}{4\pi R_\star^2 \sigma_{\rm SB}}\right)^{1/4}$$

Steady vortex creep scenario: The crust and superfluid component decelerate at the same time

VC heating mechanism balanced with the photon luminosity $L_\gamma = L_{\rm VC}$

NS as DM laboratories

Internal heating: Vortex creep

$$J_{\rm obs} = \frac{4\pi R_\star^2 \sigma_{\rm SB} T_s^4}{|\dot{\Omega}|}$$

Young pulsars

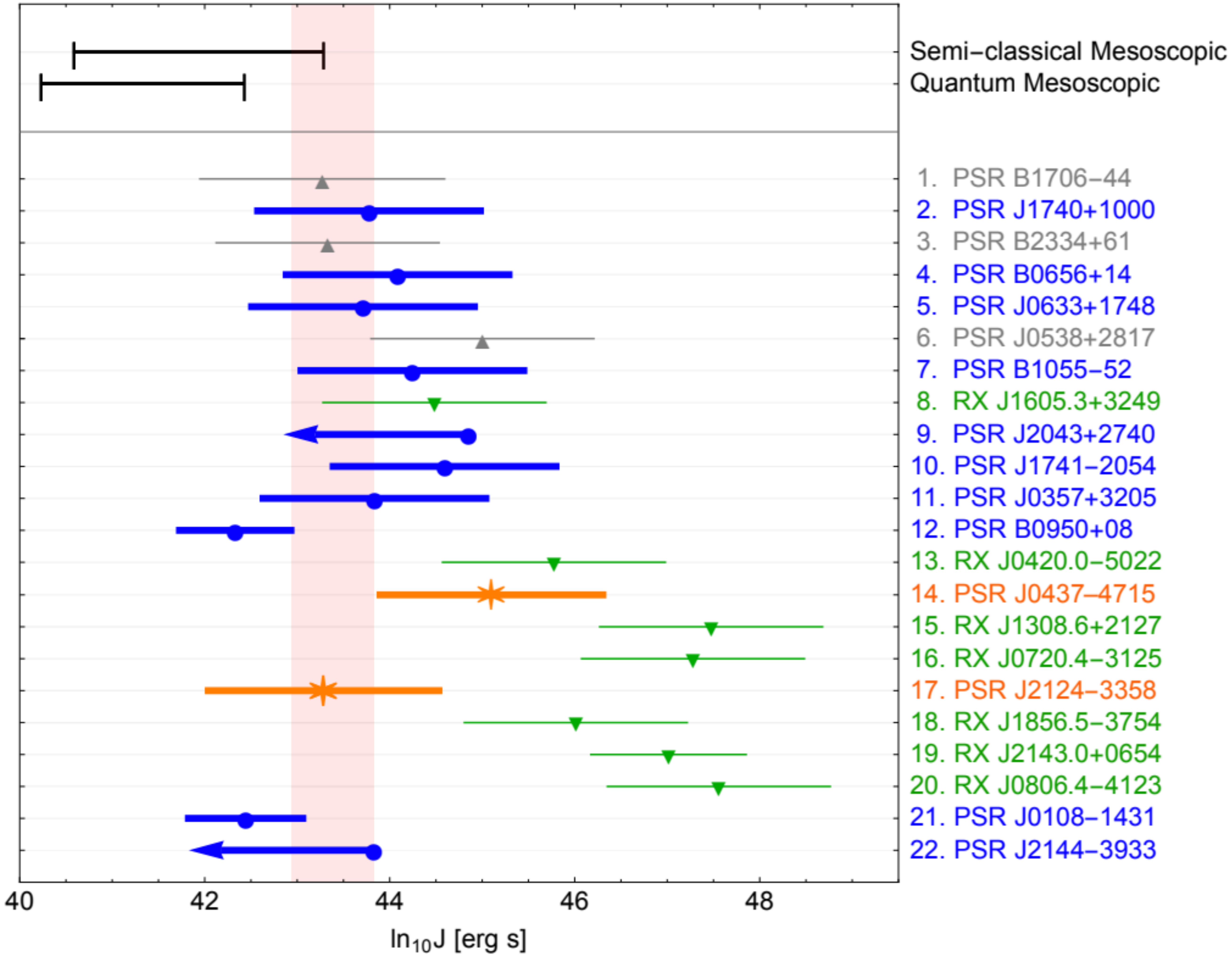
XDINS (strong magnetic fields)

Ordinary pulsars

Millisecond pulsars

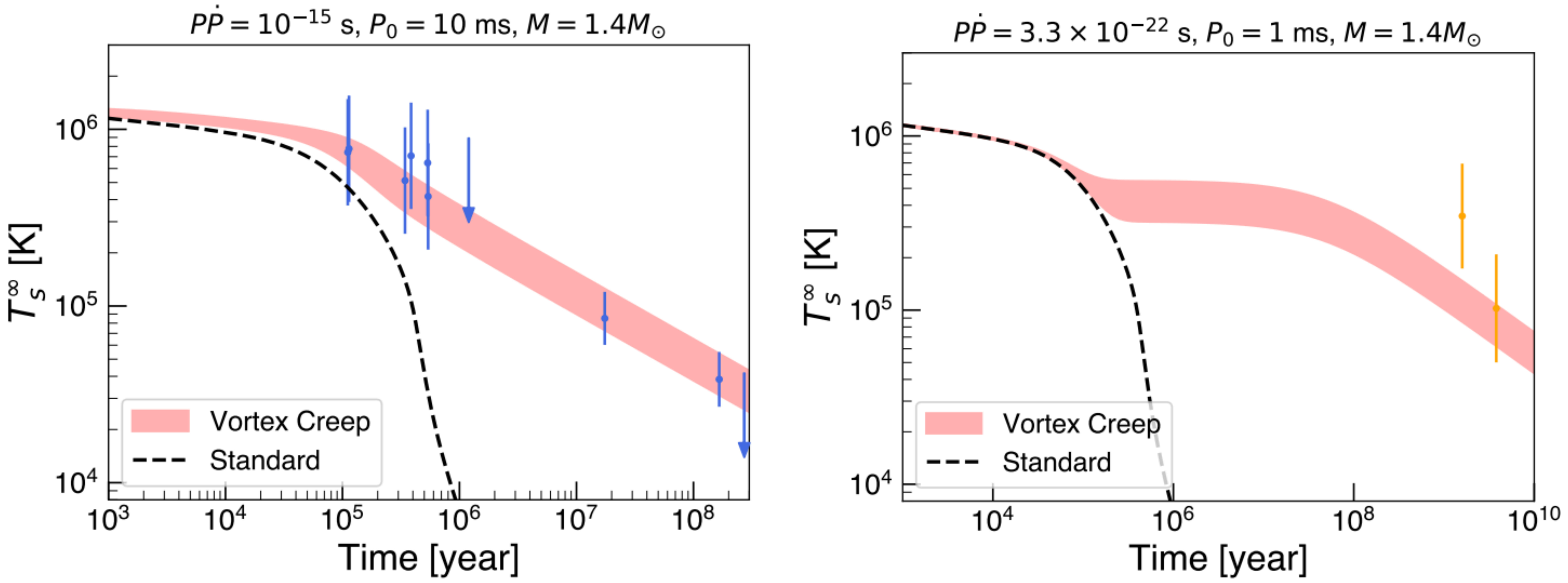
$J_{\rm obs} \sim 10^{43} - 10^{44}\,{\rm erg \cdot s}$

For $|\dot{\Omega}| = [10^{-16}, 10^{-10}]\,{\rm s}^{-2}$



NS as DM laboratories

Internal heating: Vortex creep



(a) Ordinary pulsars (b) Millisecond pulsars

NS as DM laboratories

Vortex creep heating + DM heating

$$C\frac{dT}{dt} = -L_\nu - L_\gamma + L_{\rm heat}$$

$$L_{\rm heat} \simeq L_\gamma = B(R_\star) \times 4\pi R_\star^2 \sigma_{\rm SB} T_s^4$$

After capture and annihilation of DM

$$L_{\rm DM} \simeq B(R_\star) \times [X + (B(R_\star)^{-1/2} - 1)]\, m_\chi C(m_\chi)$$

Assuming the heating luminosity is dominated by the DM effects:

$$T_{s|\rm DM} = \left(\frac{[X + (B(R_\star)^{-1/2} - 1)]\, m_\chi C(m_\chi)}{4\pi R_\star^2 \sigma_{\rm SB}} \right)^{1/4}$$

$$T_s^{\rm Max} = 2600\,\rm K$$

- The predicted surface temperature dominated by DM effects is quite universal for a wide range of DM mass

$$1\,{\rm GeV} \lesssim {\rm m}_\chi \lesssim 1\,{\rm PeV}$$

NS as DM laboratories

Vortex creep heating + DM heating

$$C\frac{dT}{dt} = -L_\nu - L_\gamma + L_{\rm heat}$$

$$L_{\rm VC} + L_{\rm DM}$$

$$L_{\rm heat} \simeq L_\gamma = B(R_\star) \times 4\pi R_\star^2 \sigma_{\rm SB} T_s^4$$

After capture and annihilation of DM

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M. Fujiwara, K. Hamaguchi, N. Nagata, MRQ [arXiv: 2308.16066, 2309.02633]

NS as DM laboratories

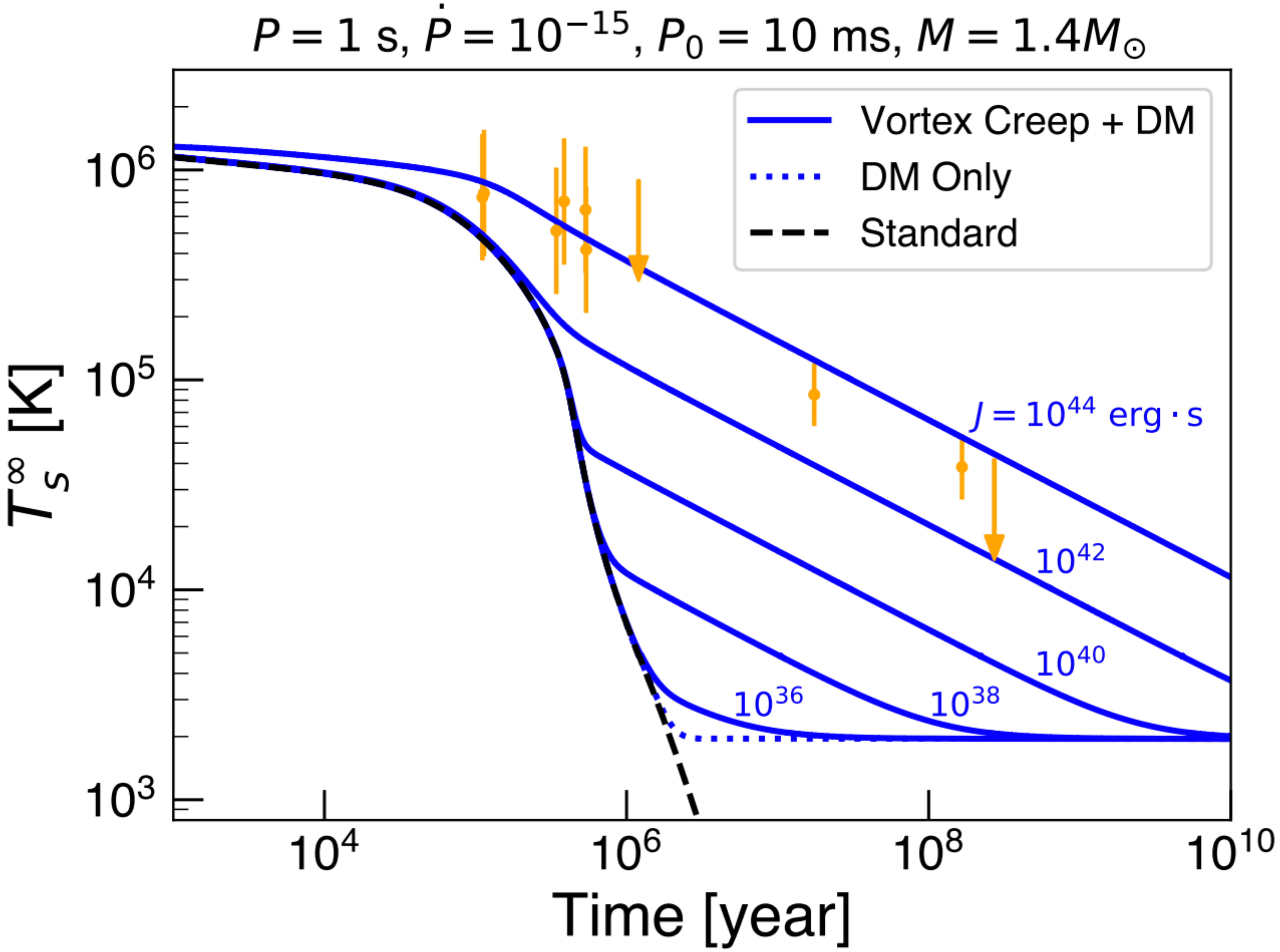
Vortex creep heating + DM heating

To observe DM heating effects:

$$L_{VC} \ll L_{DM}$$

The DM heating is concealed by the vortex creep heating unless $J \lesssim 10^{38}\,\mathrm{erg \cdot s}$

- Akmal-Pandaharipande-Ravenhall (APR) EOS. [arXiv:nucl-th/9804027]
- $M_\star = 1.4\,\mathrm{M}_\odot$
- $R_\star = 12\,\mathrm{km}$



NS as DM laboratories

Vortex creep heating + DM heating

To observe DM heating effects:

$$L_{VC} \ll L_{DM}$$ ✗

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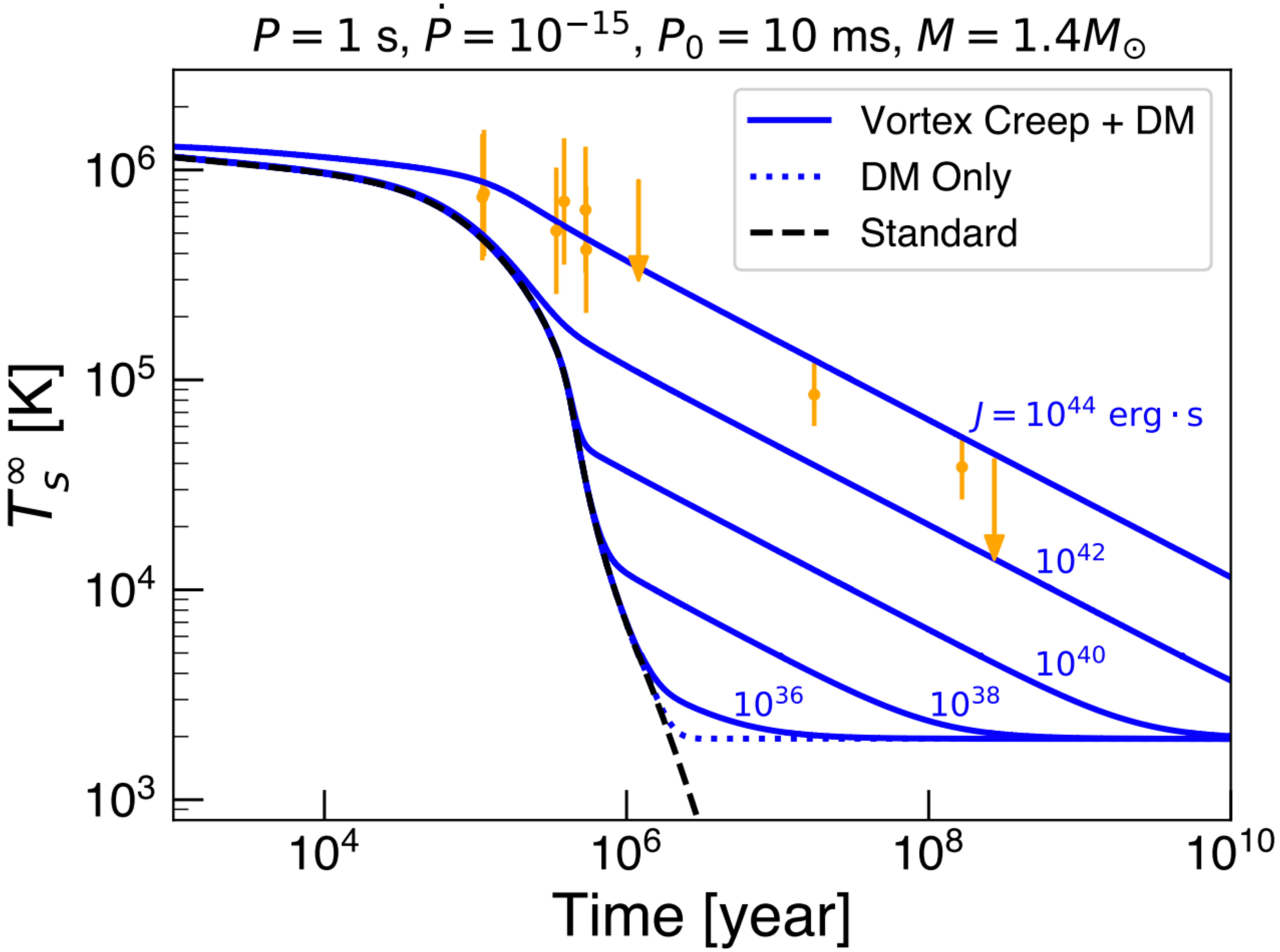


M. Fujiwara, K. Hamaguchi, N. Nagata, MRQ [arXiv: 2308.16066, 2309.02633]

NS as DM laboratories

Vortex creep heating + DM heating

To observe DM heating effects:

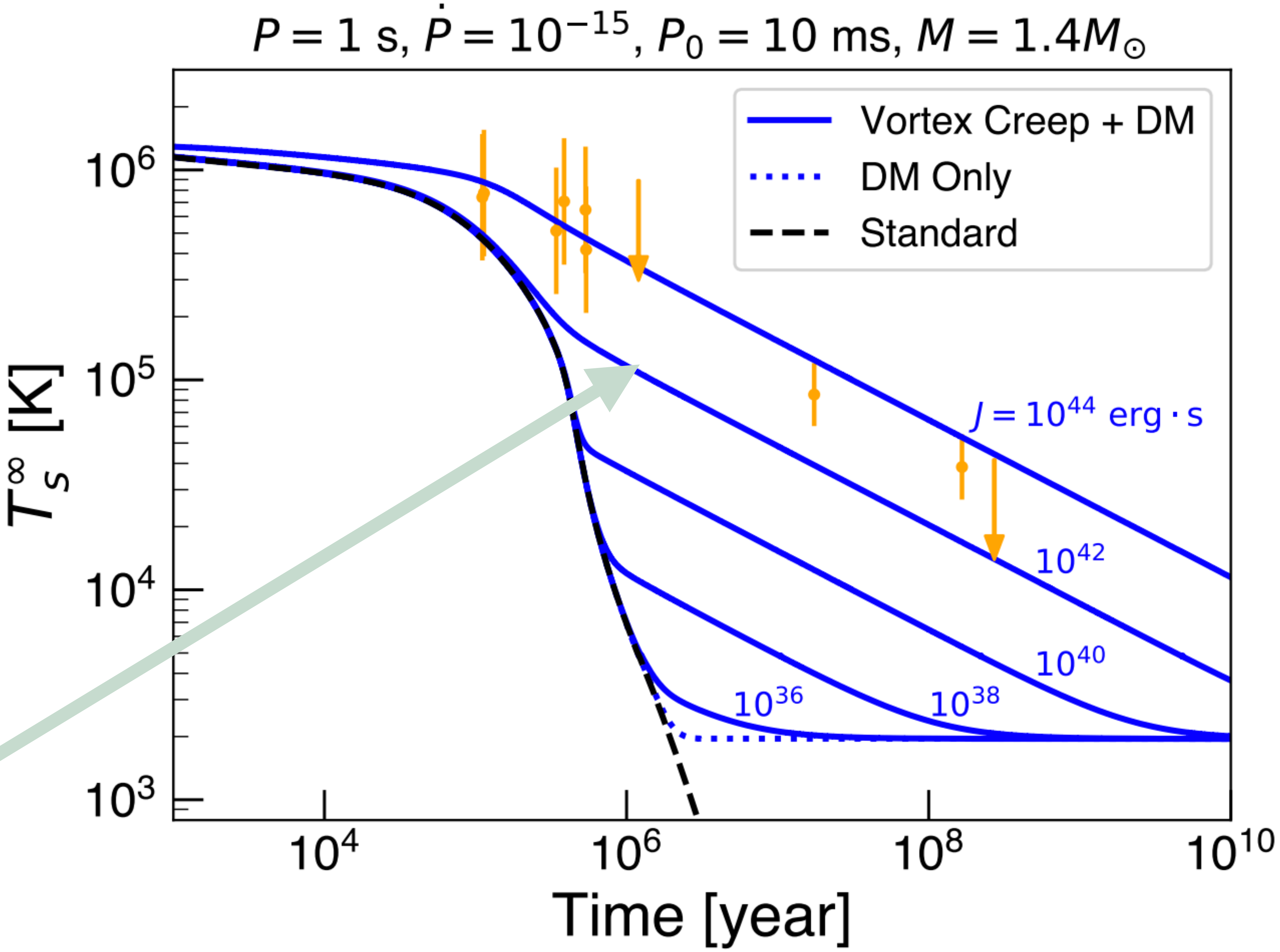
$$L_{VC} \ll L_{DM}$$ ✗

The DM heating is concealed by the vortex creep heating unless $J \lesssim 10^{38}\,\mathrm{erg \cdot s}$

Seems to be challenging

$J \sim 10^{44}\,\mathrm{erg \cdot s}$ can explain old & warm NS

- Akmal-Pandaharipande-Ravenhall (APR) EOS. [arXiv:nucl-th/9804027]
- $M_\star = 1.4\,\mathrm{M_\odot}$
- $R_\star = 12\,\mathrm{km}$



Summary

- NS Heating is a promising alternative/complementary method to test Dark Matter.
  - Allows access to velocity- and momentum-dependent interactions
  - Probes the Sub-GeV DM mass regime
  - Multiple targets make it ideal for testing DM-lepton interactions
- Some old and warm NSs have been observed suggesting an internal heating mechanism
  - Vortex creep heating: If this is the dominant mechanism, DM effects could be difficult to detect or observe.

Thank you

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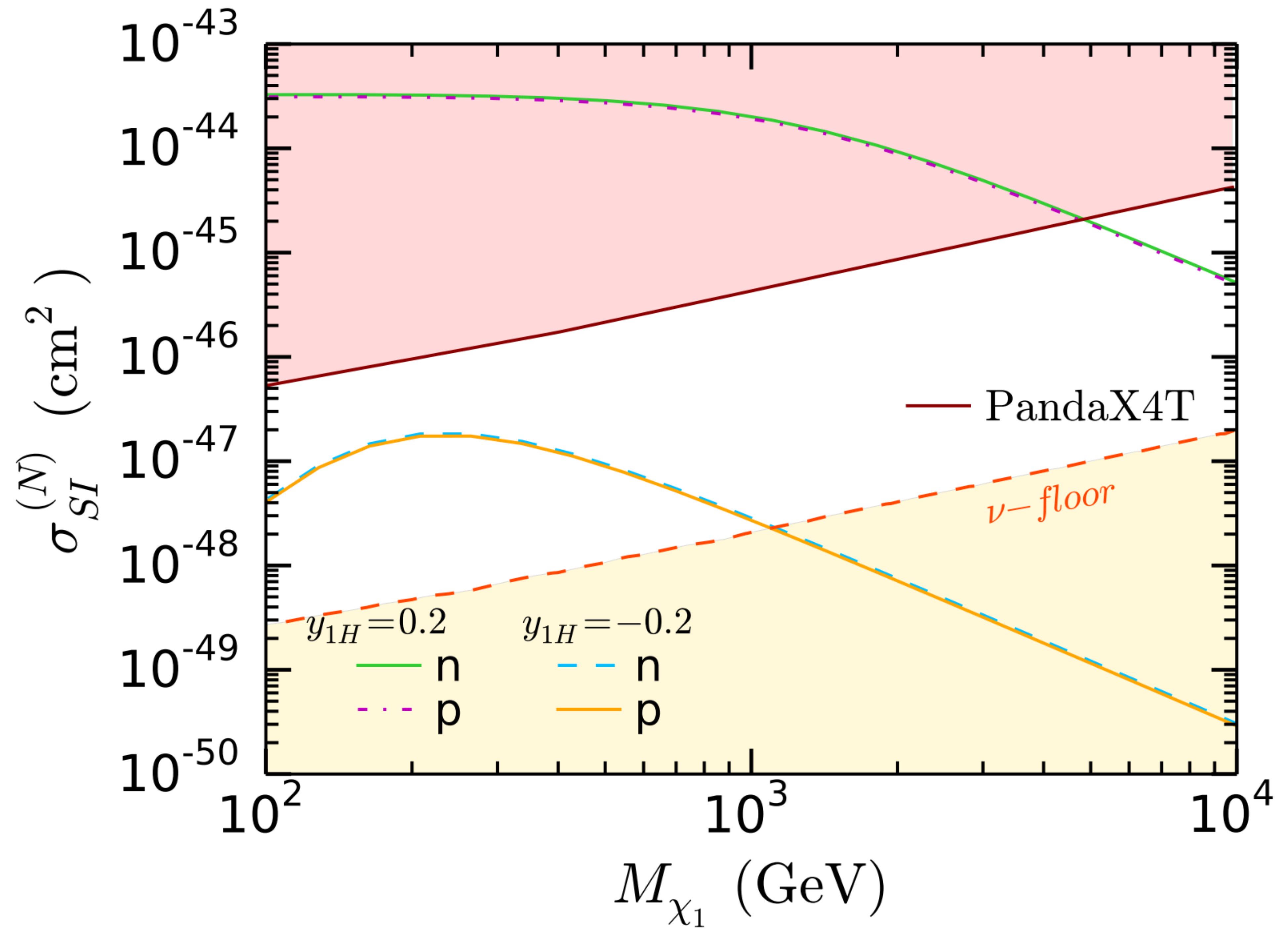
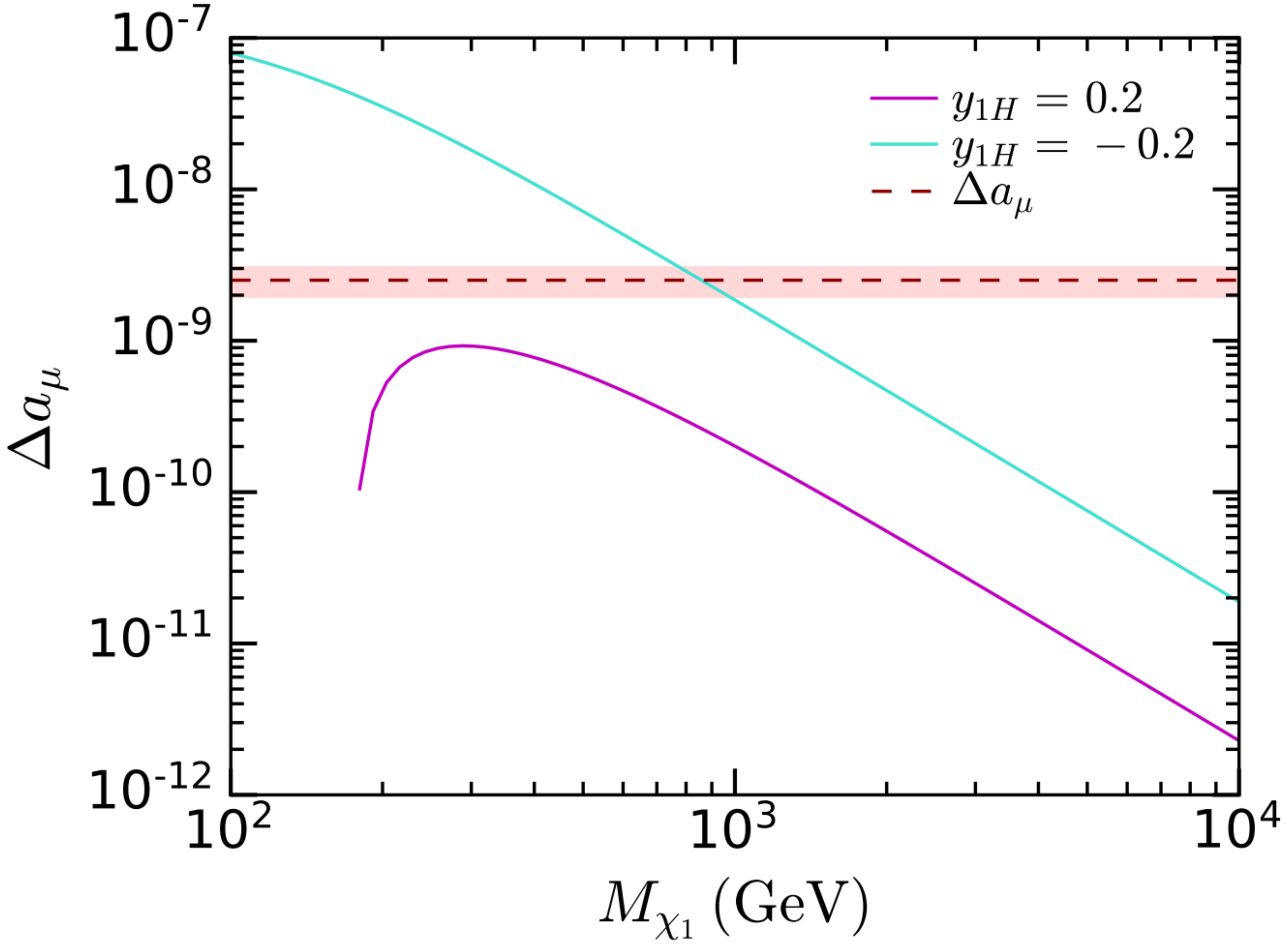
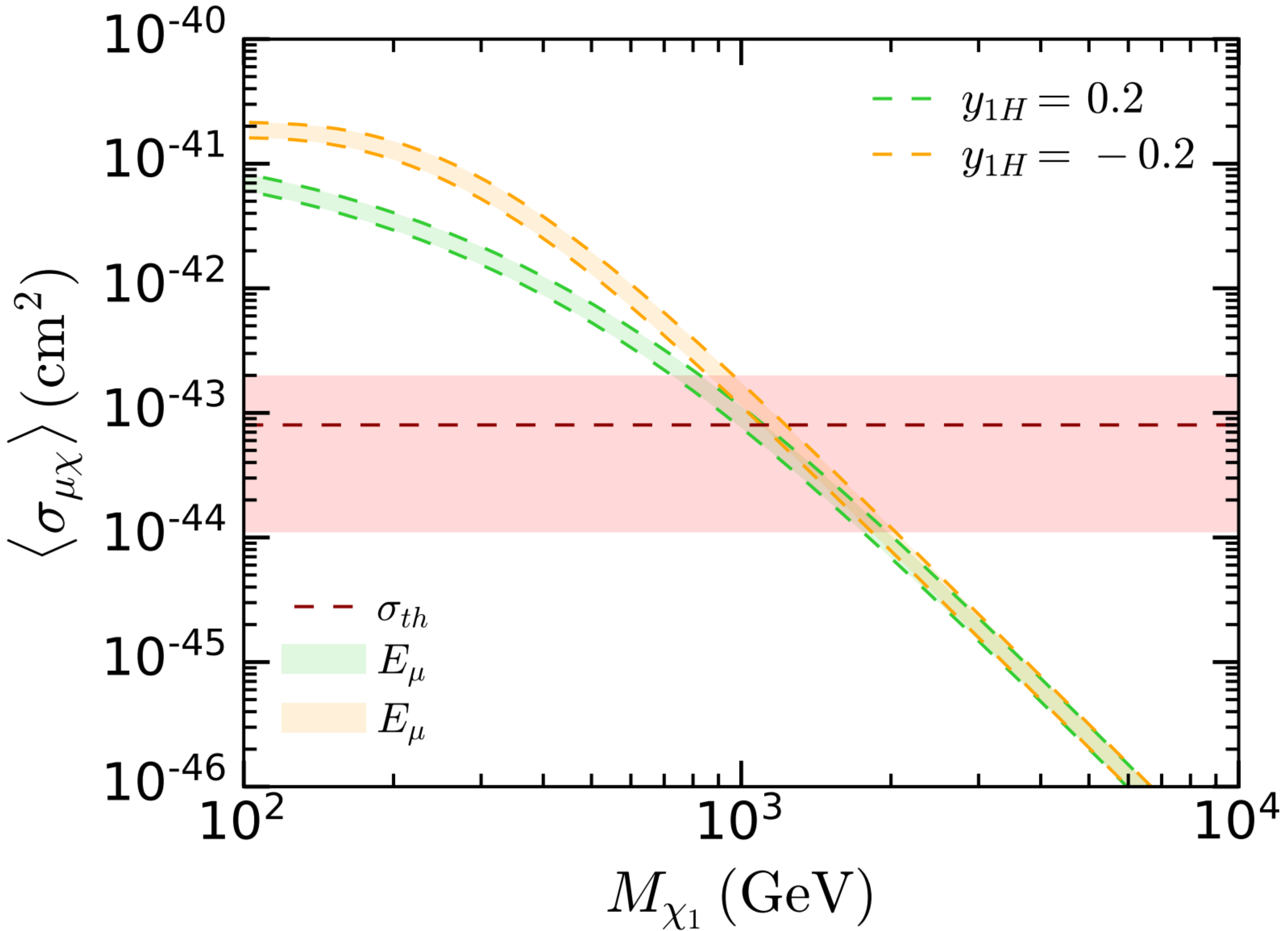
Back up slides

DM models: tree-level coupling

Field	Spin	$SU(3)_C$	$SU(2)_L$	$U(1)_Y$	$\mathbb{Z}_2$
χ_S	1/2	**1**	**1**	0	−
ξ_D	1/2	**1**	**2**	−1/2	−
η_D	1/2	**1**	**2**	1/2	−
$\widetilde{L}$	0	**1**	**2**	−1/2	−





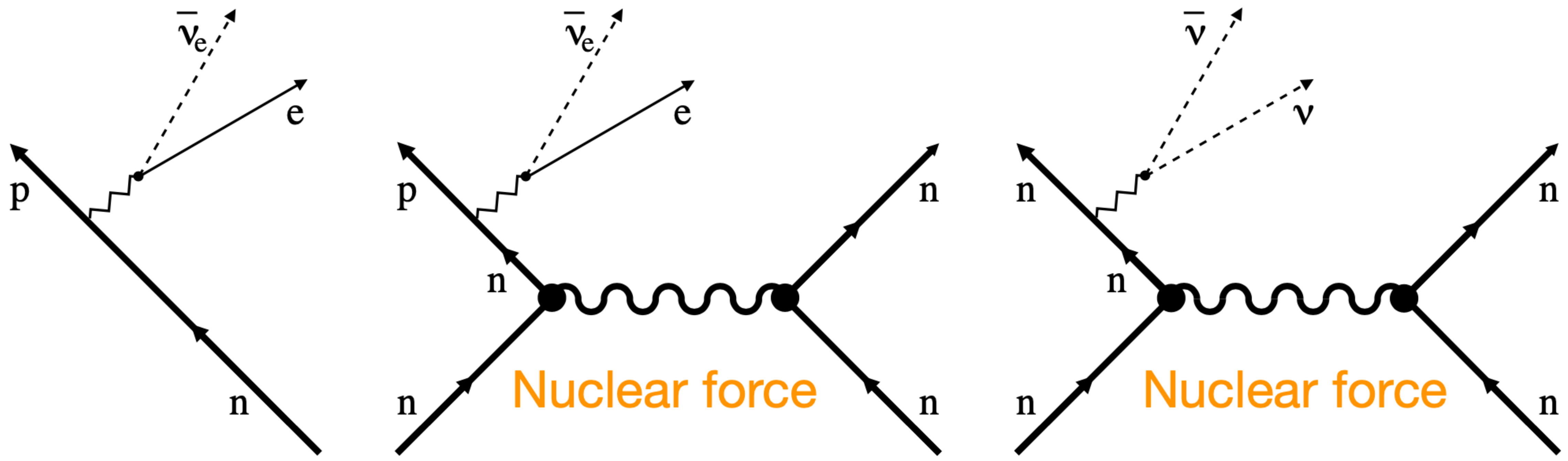


Neutron star

- Neutron star of $M_\star = 1.4\,\mathrm{M}_\odot$, And radius of $R_\star \sim 12\,\mathrm{km}$
- EOS: APR- EOS (A. Akmal, V.R. Pandharipande, D.G. Ravenhall) Phys.Rev.C58:1804-1828,1998
- pion condensation

A lot of uncertainty: Many different Equations of state!

Neutron star cooling: Neutrino emission



Direct Urca Modified Urca Bremsstrahlung

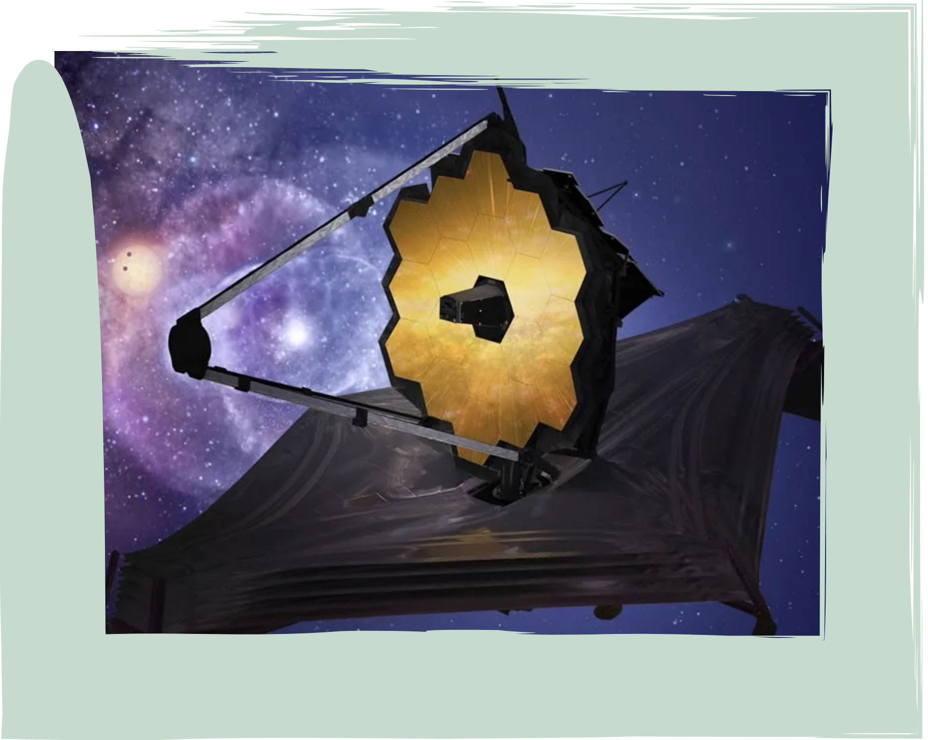
Figure taken from Natsumi Nagata

Yet, a lot to do!

Possible observations

- Sensitivity at James Webb Space Telescope. For this we need
  - Exposure time ~ 1 day
  - Distance ~ 10 pc

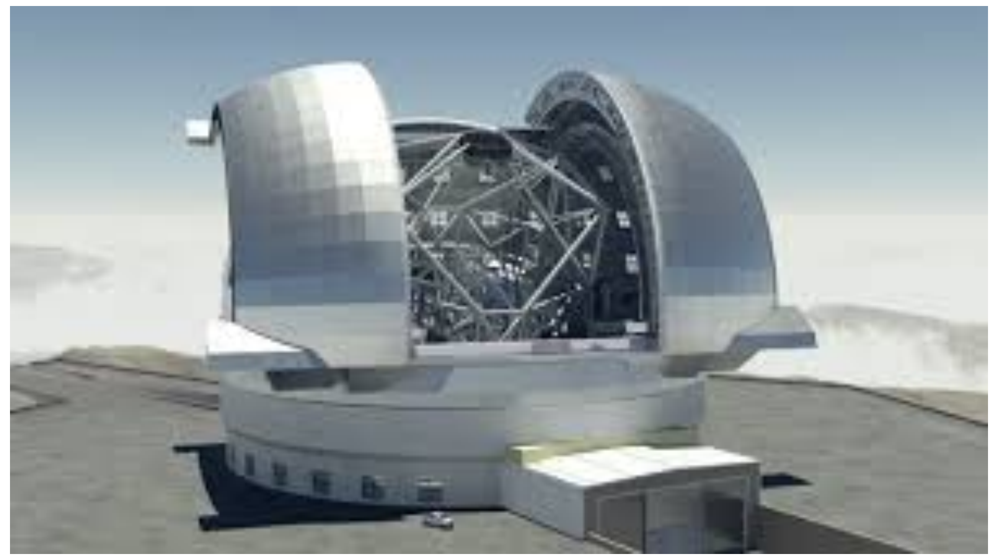
Nearest NS is discovered at 100 pc (!)



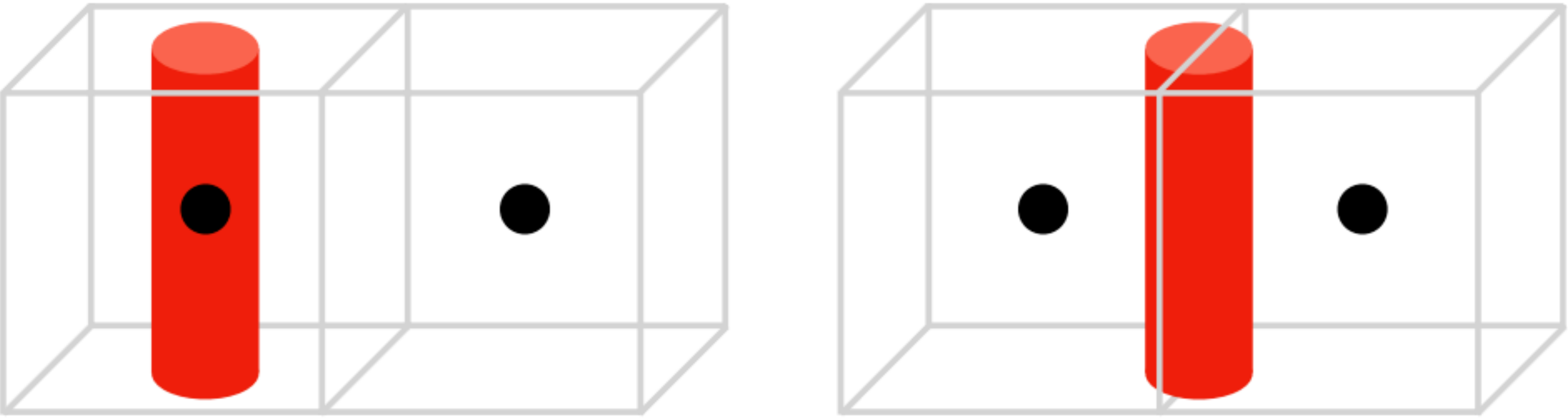
Future possibilities

FAST (radio telescope)

Thirty Meter Telescope



Extremely Large Telescope

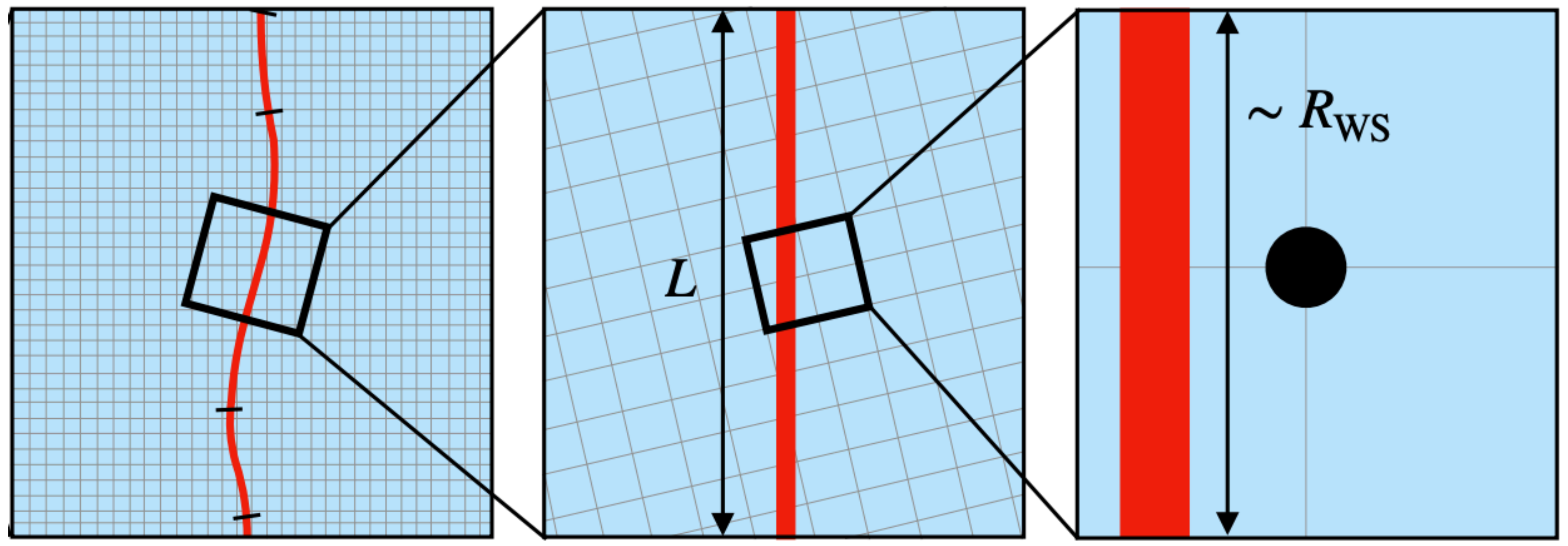


Evaluation of $E_{\rm pin}$

- Semi-classical approach [Donati, Pizzochero (2004)] [Seveso, Pizzochero, Grill, Haskell (2015)]
  Thomas-Fermi approx. (Interacting fermi gas of nucleons)
- Quantum approach [Avogadro, Barranco, Broglia, Vigezzi (2008)] [Klausner, et al. [2303.18151]]
  Hartree-Fock-Bogoliubov approx

Evaluation of $f_{\rm pin}$

- Microscopic
  Estimation using $E_{\rm pin}$ derived from fm-size box
- Mesoscopic
  Average $f_{\rm pin}$ along a mesoscopic length $L \simeq (10^3 - 10^4)$ fm



Theoretical approaches for Vortex creep

Table from Motoko's

		$E_{\rm pin}$-evaluation	
		Semi-classical	Quantum
$f_{\rm pin}$-evaluation	Micro.	Donati, et al. (2004)	Avogadro, et al. (2008)
	Meso.	Seveso, et al. (2015)	Klausner, et al [2303.18151]

$$J_{\rm pin} \simeq \int_{R_{\rm in}}^{R_{\rm out}} dR\, d\theta\, d\phi\, R^3 \sin^2\theta \cdot \frac{f_{\rm pin}}{\kappa}$$

$$f_{\rm pin}\big|_{\rm NP} \simeq \frac{|E_{\rm pin}|}{\Delta r \Delta L}$$