

# 中性子星の内部加熱機構と暗黒物質の探索可能性:

## 渦糸クリープ vs 暗黒物質加熱

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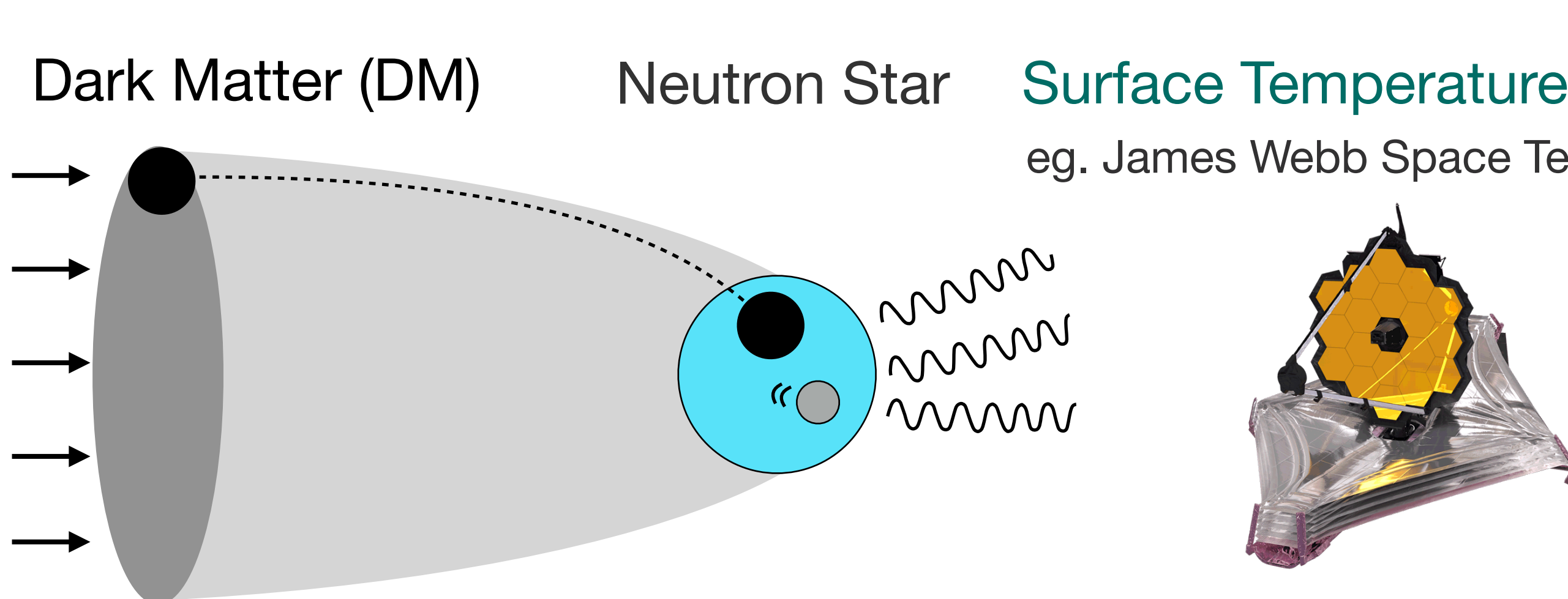
Based on on-going work

PPP2023 @Kyoto, Japan August 28th, 2023

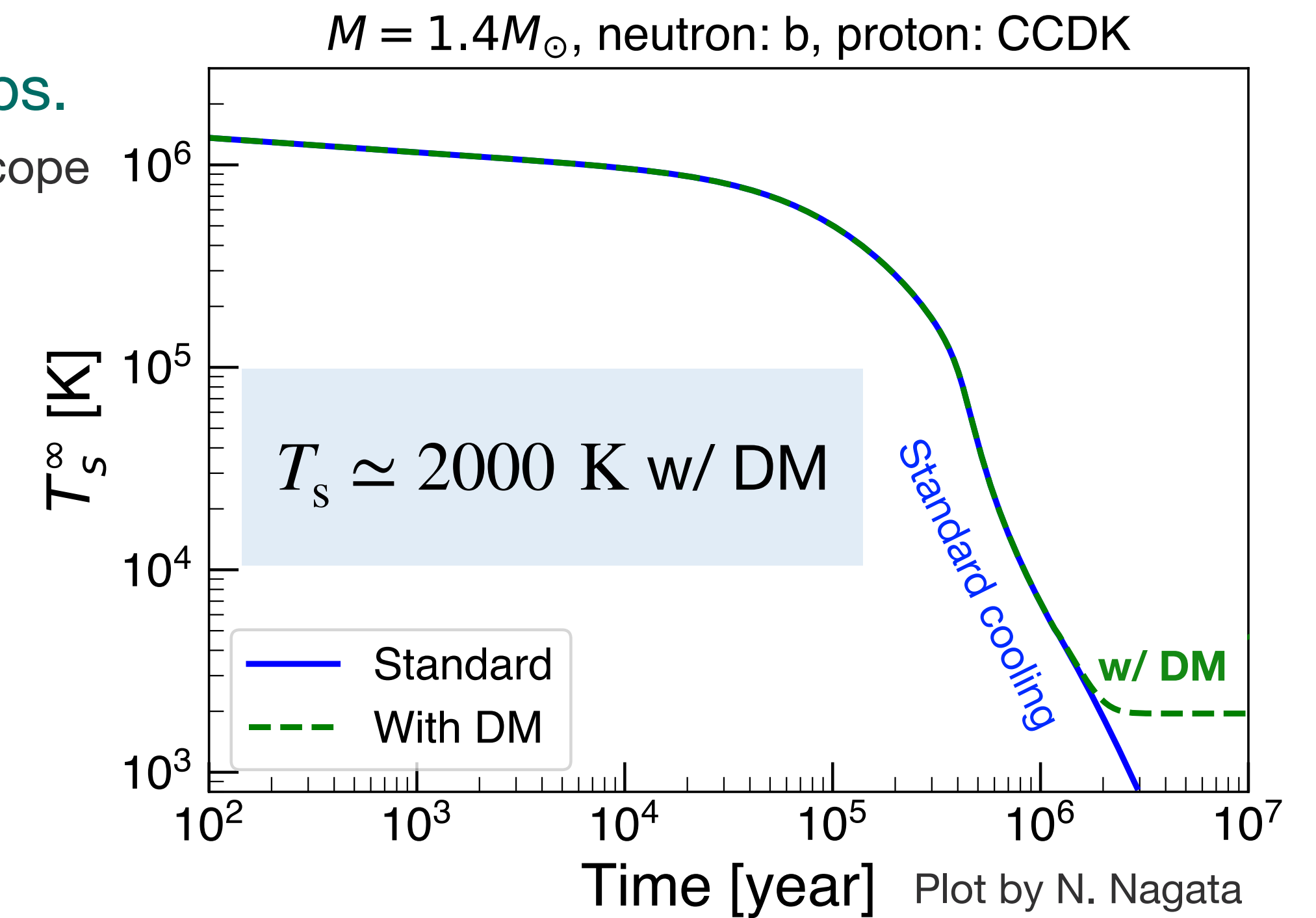


# Neutron Star as target of Dark Matter

[C. Kovaris (2008)]  
[M. Baryakhtar et al. (2017)] ...



$$\frac{dN}{dt} = \sqrt{\frac{6}{\pi}} \cdot \overset{\text{area}}{\pi b_{\text{max}}^2} \cdot \overset{\text{velocity}}{v_{\text{DM}}} \cdot \overset{\text{\# density}}{\frac{\rho_{\text{DM}}}{m_{\text{DM}}}} \simeq 10^{22} \text{ s}^{-1} \left( \frac{m_{\text{DM}}}{1 \text{ TeV}} \right)^{-1}$$



- Neutron Star can be a good target to search for **Weakly Interacting Massive Particle (WIMP)**
- Gravitational capture → Kinetic energy injection/Annihilation → **Anomalous heating source**
- **Universal  $T_s$ -prediction:  $T_s \simeq 2000 \text{ K}$  for wide WIMP parameters ( $1 \text{ GeV} - 1 \text{ PeV}, \sigma_{\chi n} \gtrsim 10^{45} \text{ cm}^2$ )**
- If we observe neutron star w/  $T_s \lesssim 2000 \text{ K}$ , we may constrain **DM-nucleon cross section**

# Possible “Contamination”?

## Old but Still Warm

- We “assume” there is no late time heating source
- Recently, **old but warm stars has been observed** w/  $T_s \simeq 10^4 - 10^6$  K

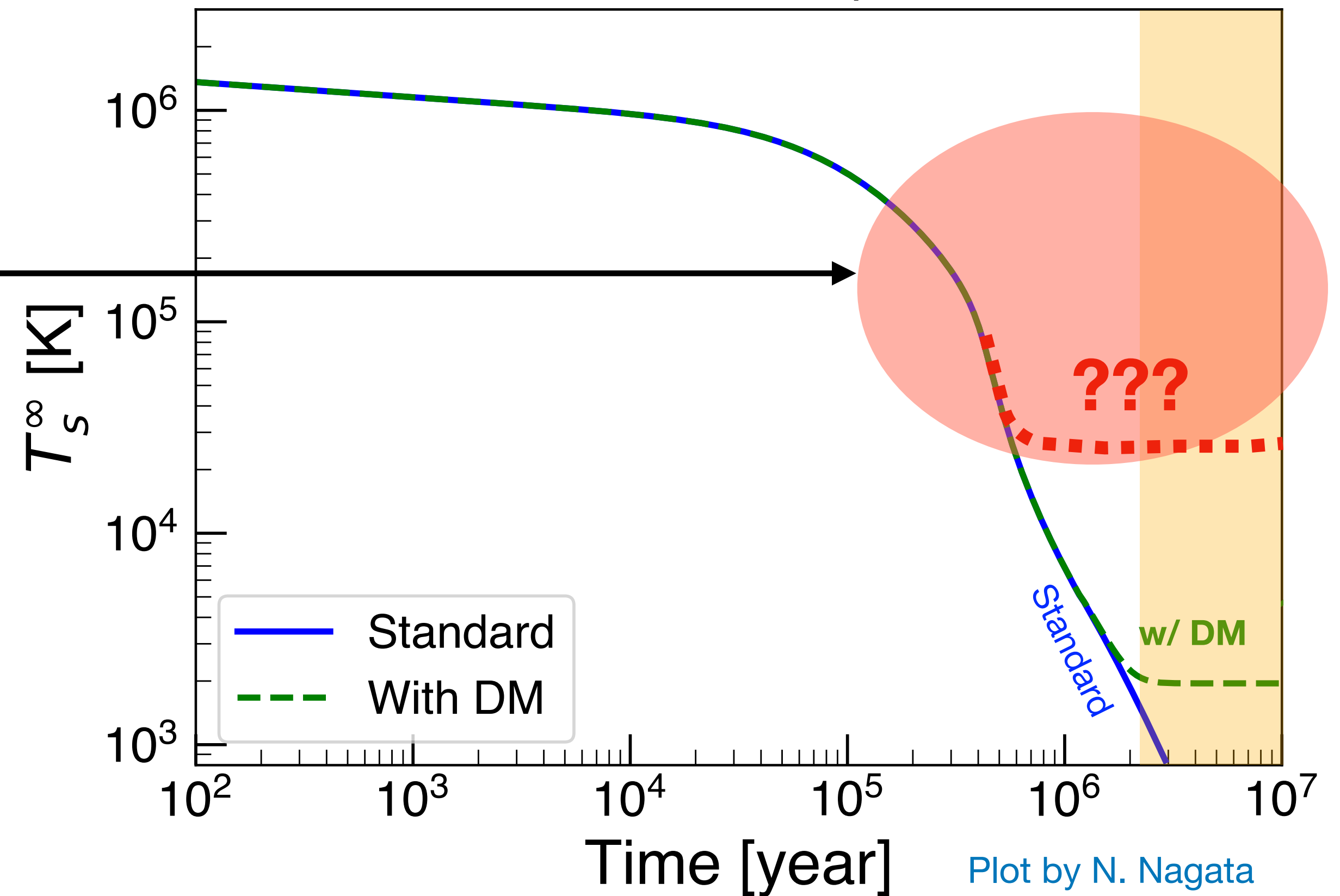
Can we really probe DM heating effects?

- Serious contamination for DM search happens if neutron stars are dominated by the following heating:

- Internal heating
- Universal effects
- Quantitative relevance against DM heating

➔ **Vortex creep heating** (due to creep motion of neutron superfluid vortex lines)

$M = 1.4M_\odot$ , neutron: b, proton: CCDK



[Alpar, Pines, Anderson, Shaham (1984)]

[Shibazaki, Lamb (1989)]

# Vortex lines of neutron superfluid

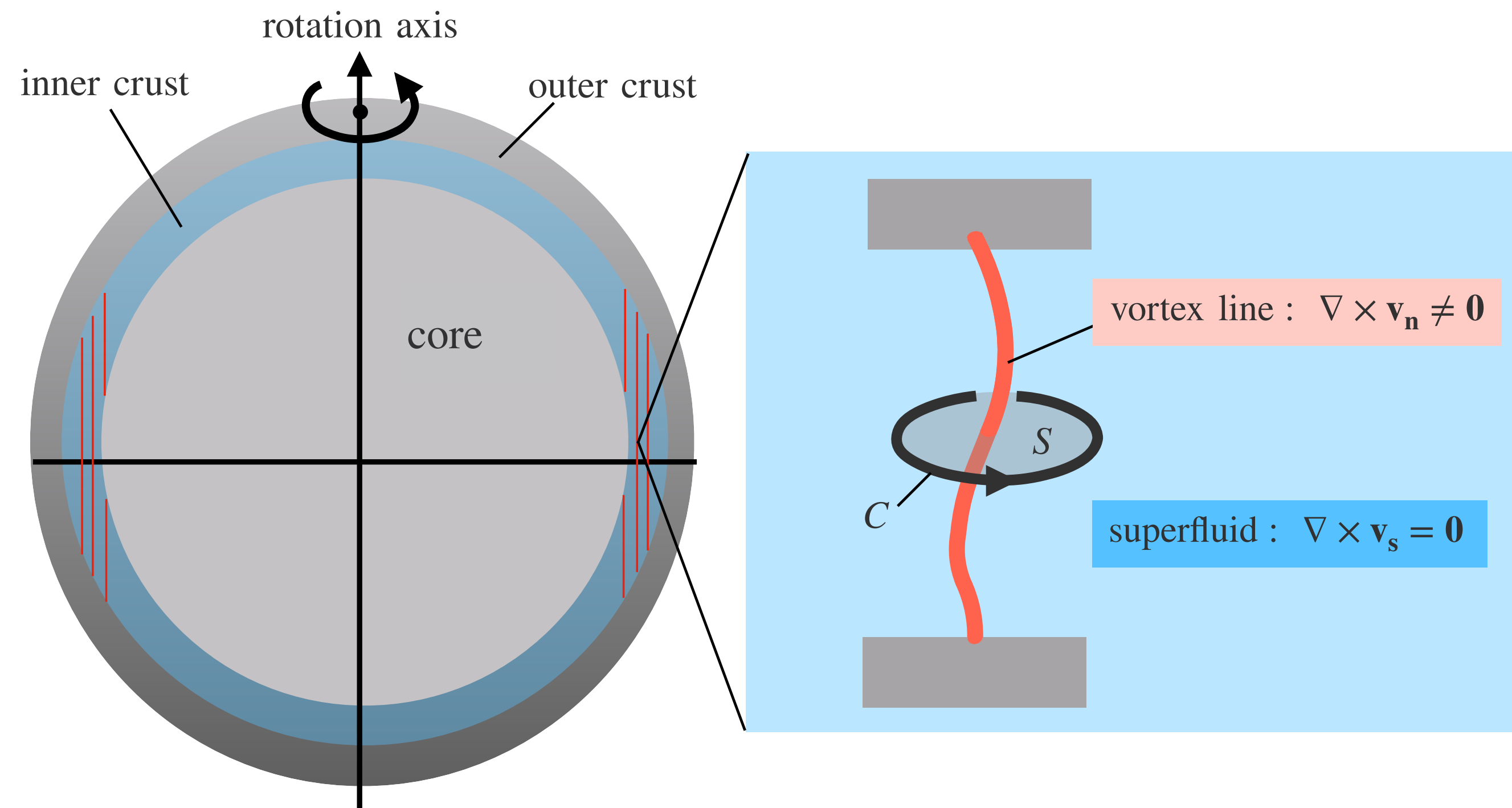
## Neutron superfluid

- Neutron  $^1S_0$  superfluid is expected to exist in inner crust region of a neutron star

$$\nabla \times \mathbf{v}_s = \mathbf{0} \quad (\text{Potential flow condition})$$

↑  
Vorticity : Microscopic measure of rotation

⇒ Is vortex forbidden for superfluid?

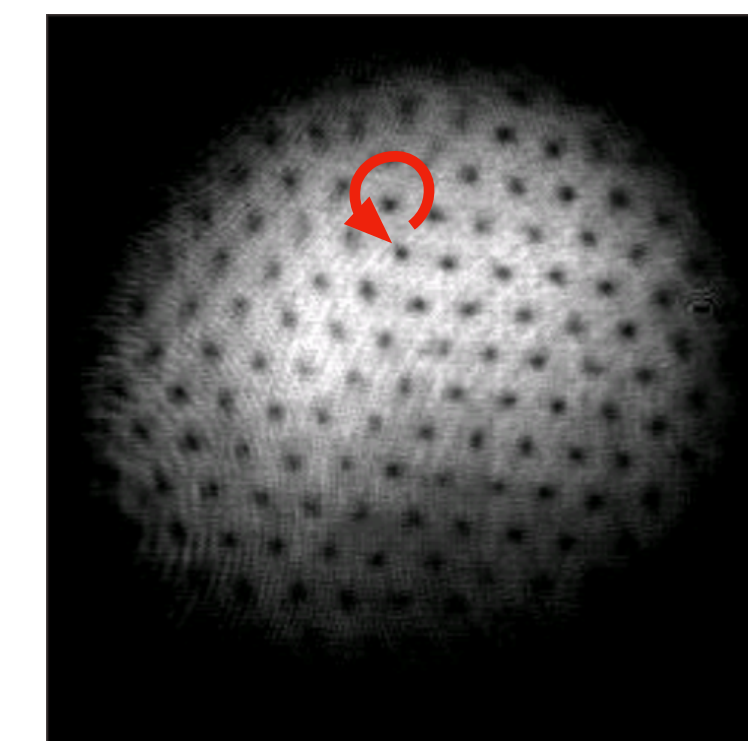


## Vortex Line

$$\Gamma \equiv \iint_S d\mathbf{S} \cdot (\nabla \times \mathbf{v}_s) = \int dr 2\pi r \underbrace{\kappa}_{\text{Vorticity per vortex line}} \underbrace{n(r)}_{\text{\# density of vortex line}}$$

Macroscopic measure of rotation

- (Superfluid angular velocity)  $\Leftrightarrow$  (# of vortex line)  
→ **Radial creep motion of vortex lines are necessary for superfluid to spin-down**



[Abo-Shaeer, Raman, Vogels, Ketterle (2001)]

# Forces on Vortex Line

## (1) Pinning force

- Energy for Nuclear pinning (NP) vs Interstitial pinning (IP)

$$E_{\text{pin}} \equiv E_{\text{NP}} - E_{\text{IP}} \rightarrow f_{\text{pin}} \propto E_{\text{pin}}$$

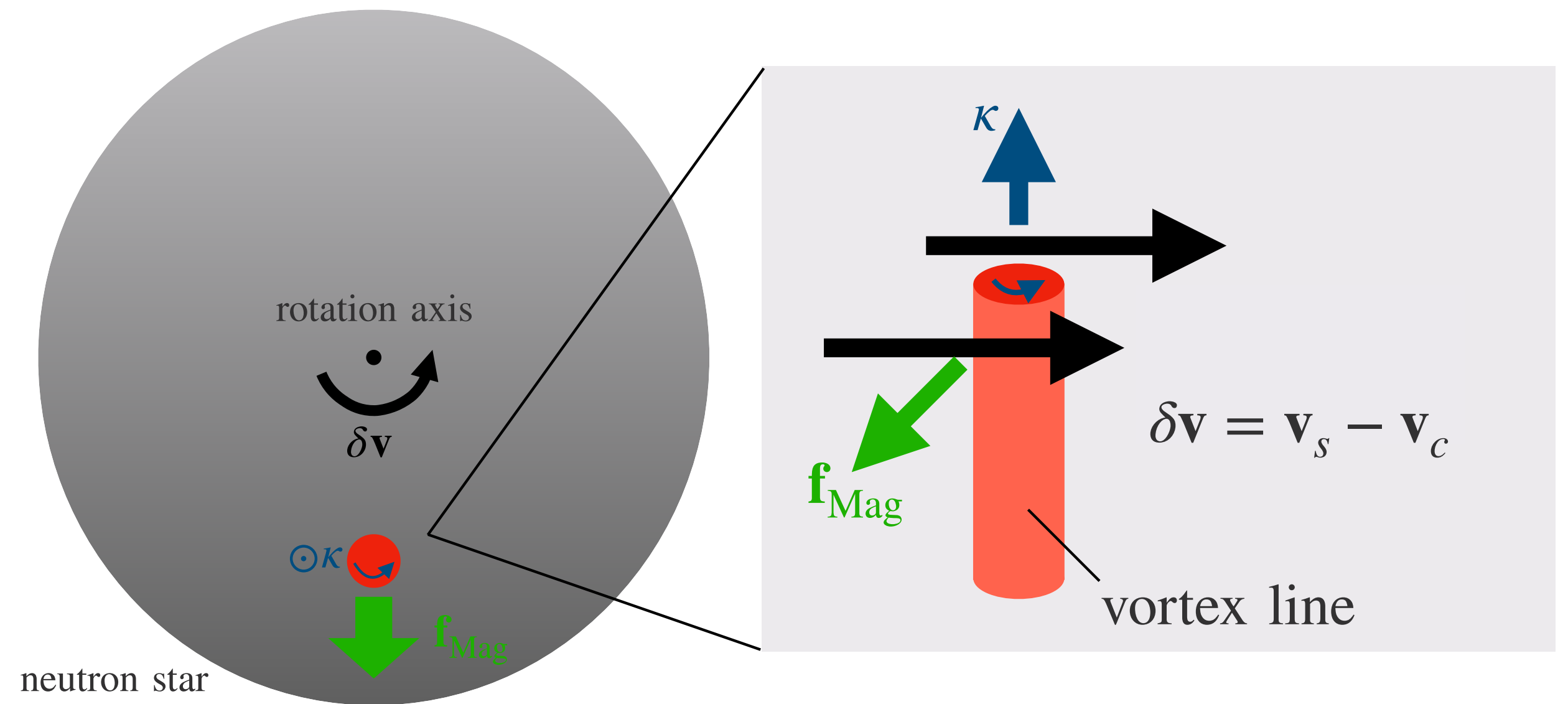
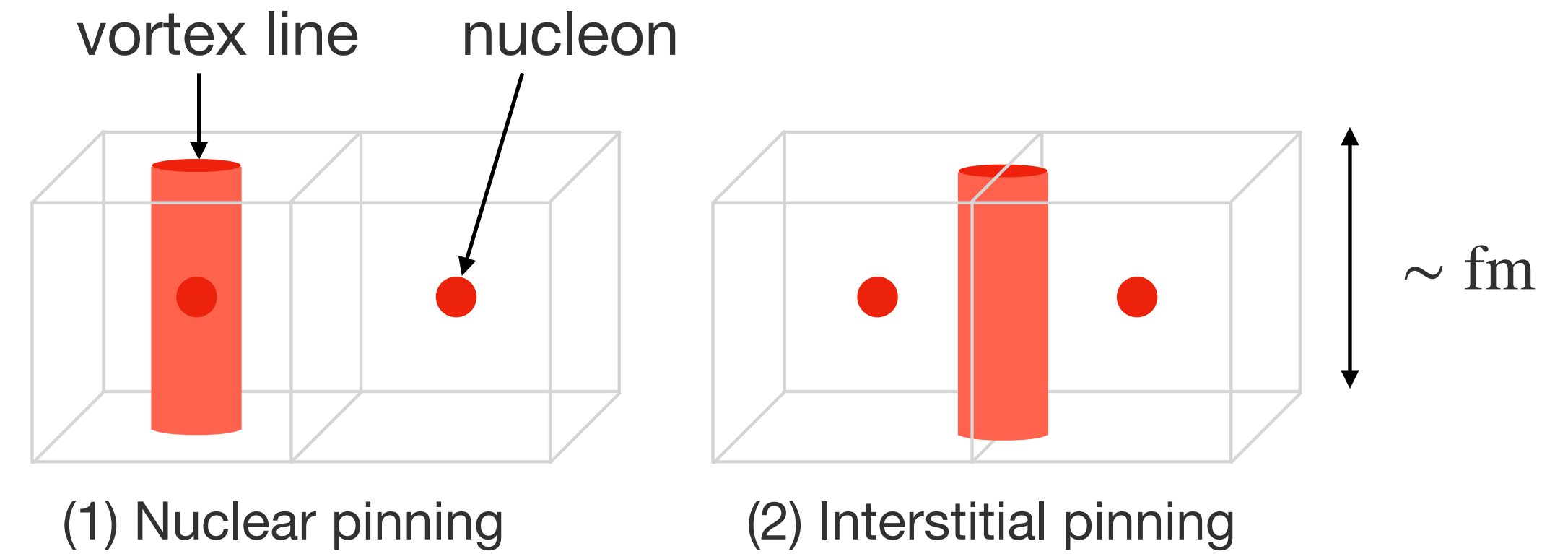
→ Vortex line can be trapped by crust component

→ Relative velocity:  $|\mathbf{v}_s - \mathbf{v}_c| > 0$

## (2) Magnus force

$$f_{\text{Mag}} = \rho(\mathbf{v}_s - \mathbf{v}_c) \times \boldsymbol{\kappa}$$

- Direction of force = Always in outer direction
  - **Vortex creep** happens
  - Decelerate superfluid rotation



$$f_{\text{Mag}} = f_{\text{pin}} \Leftrightarrow (\Omega_s - \Omega_c) |_{\text{cr}} \equiv f_{\text{pin}} / (\rho \kappa r) \simeq (\Omega_s - \Omega_c) |_{\text{steady}}$$

$\rho$  : nucleon density  
 $r$  : distance from rotation axis  
 $\kappa = \hbar / (2m_n)$ : quantized vorticity

# Energy dissipation

$$\dot{E}_{\text{diss}} = |\dot{\Omega}_{\infty}| \cdot \int dI_{\text{pin}}(\Omega_s - \Omega_c) |_{\text{cr}} \equiv J |\dot{\Omega}_{\infty}| \stackrel{!}{=} 4\pi R_{\text{NS}}^2 \sigma_{\text{SB}} T_s^4$$

Proportional const. ↓

We introduce observationally favored value of  $J$  assuming vortex creep dominance

$$\blacktriangleright J_{\text{obs}} \equiv \frac{4\pi R_{\text{NS}}^2 \sigma_{\text{SB}} T_s^4}{|\dot{\Omega}|} \xleftarrow{\text{inputs}} \begin{cases} \dot{\Omega} : \text{Current spin-down rate (observable)} \\ T_s : \text{Surface temperature (observable)} \end{cases}$$

- $J$  is determined by nuclear interaction ( $f_{\text{pin}}$ ) in inner crust region → **Universal value** for all neutron stars
- $J_{\text{obs}}$  **should show the similar values for each neutron stars** (w/ slight  $R_{\text{NS}}$  dependence, up to  $\mathcal{O}(1)$  uncertainty)

We decided to test “**Quasi-Universality of  $J$** ” using neutron star  $T_s$ -observations

# Vortex creep heating vs Observation (1/2)

Young pulsar ( $t_{\text{age}} < 10^5$  yr)

XDINS (w/ strong magnetic field)

Ordinary pulsar

Millisecond pulsar

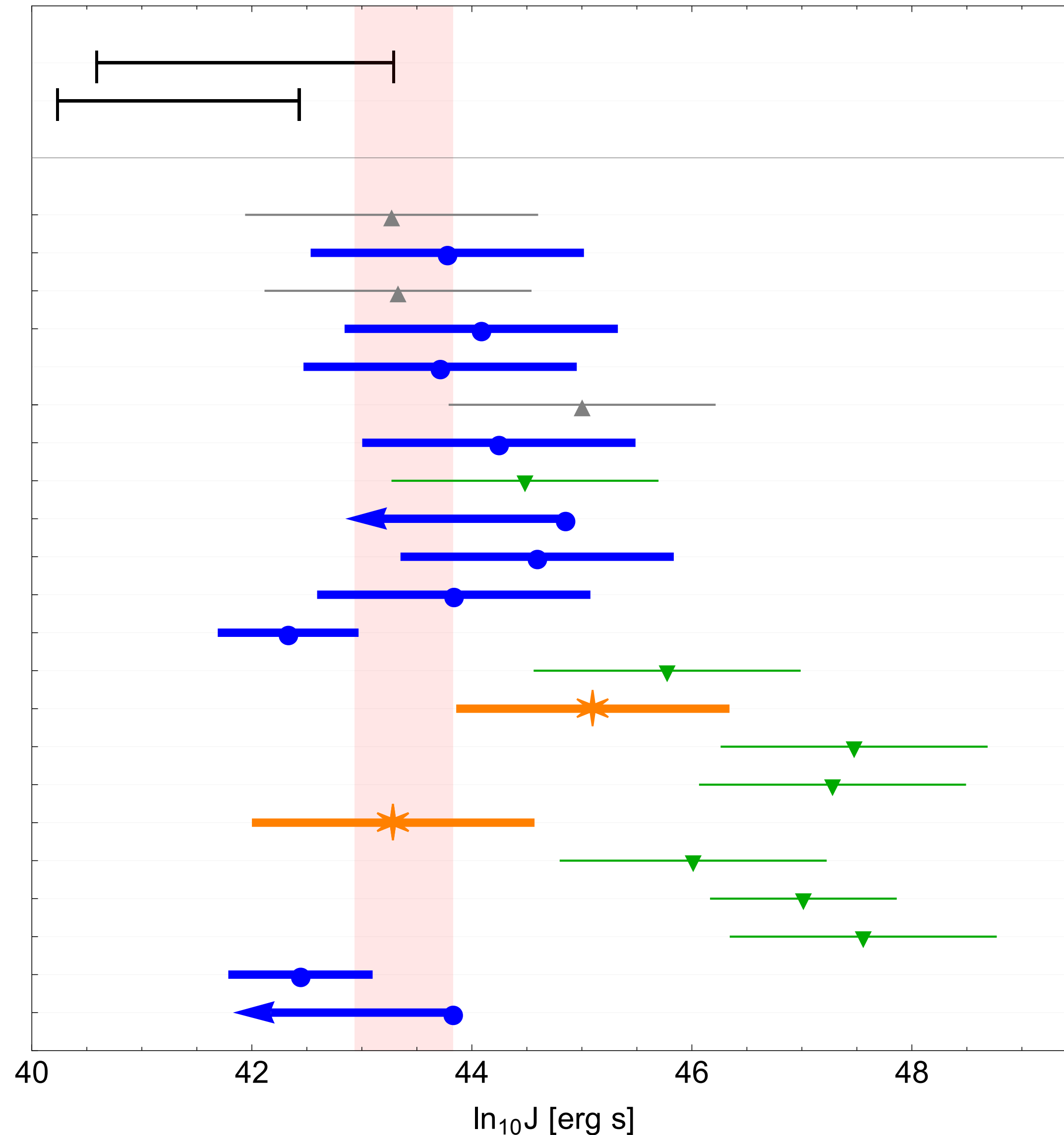
} used to test hypothesis

- We tested quasi-universality of  $J$  in vortex creep hypothesis using NS obs.

$$J_{\text{obs}} \equiv \frac{4\pi R_{\text{NS}}^2 \sigma_{\text{SB}} T_s^4}{|\dot{\Omega}|}$$

Result:  $J_{\text{obs}} \simeq 10^{42.9} - 10^{43.8}$  erg · s  
for  $|\dot{\Omega}| \in [10^{-16}, 10^{-10}] \text{ s}^{-1}$

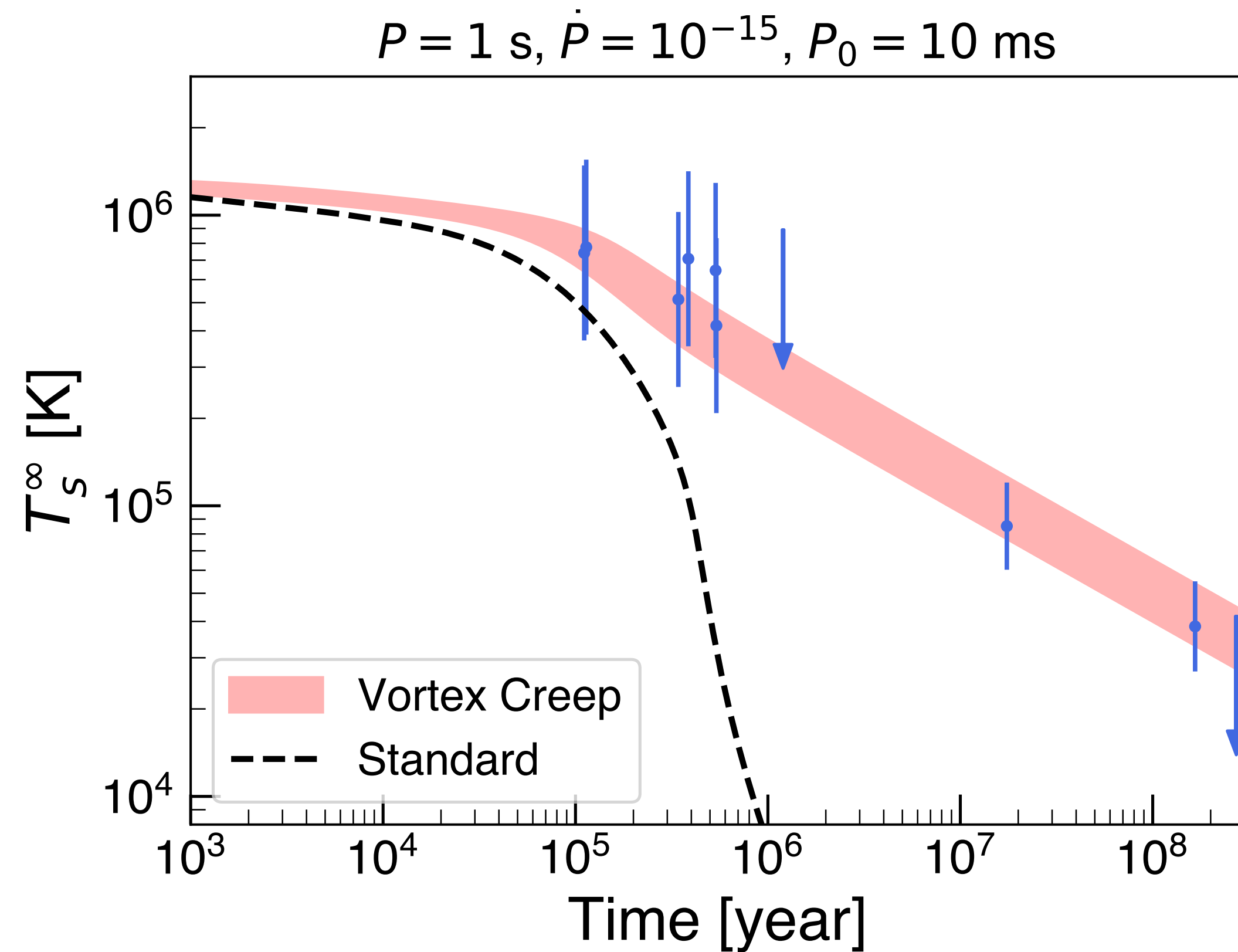
Current obs. shows **similar values of  $J_{\text{obs}}$**  for all neutron stars



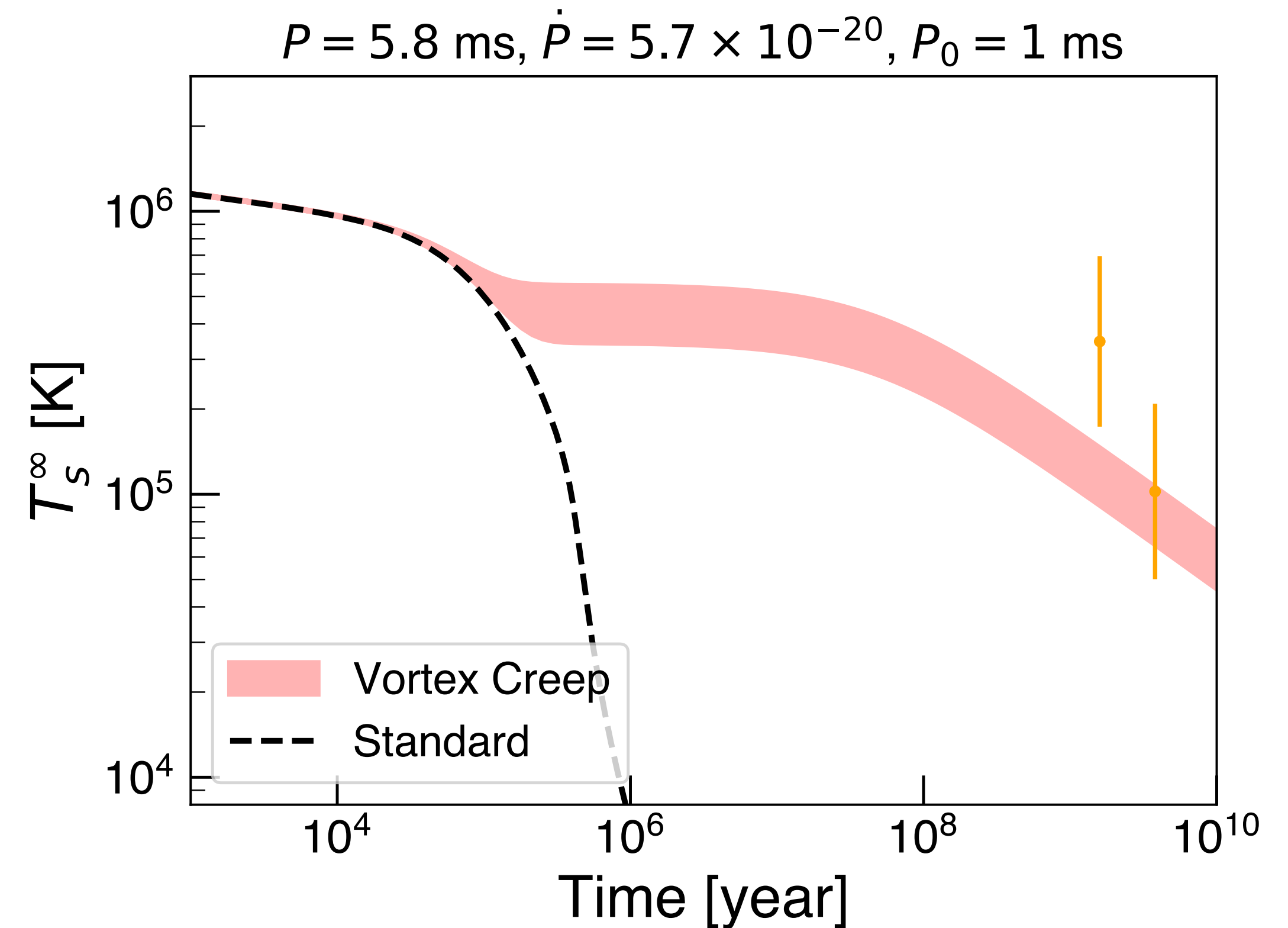
Semi-classical Mesoscopic  
Quantum Mesoscopic

- PSR B1706-44
- PSR J1740+1000
- PSR B2334+61
- PSR B0656+14
- PSR J0633+1748
- PSR J0538+2817
- PSR B1055-52
- RX J1605.3+3249
- PSR J2043+2740
- PSR J1741-2054
- PSR J0357+3205
- PSR B0950+08
- RX J0420.0-5022
- PSR J0437-4715
- RX J1308.6+2127
- RX J0720.4-3125
- PSR J2124-3358
- RX J1856.5-3754
- RX J2143.0+0654
- RX J0806.4-4123
- PSR J0108-1431
- PSR J2144-3933

# Vortex creep heating vs Observation (2/2)



(a) Ordinary pulsars

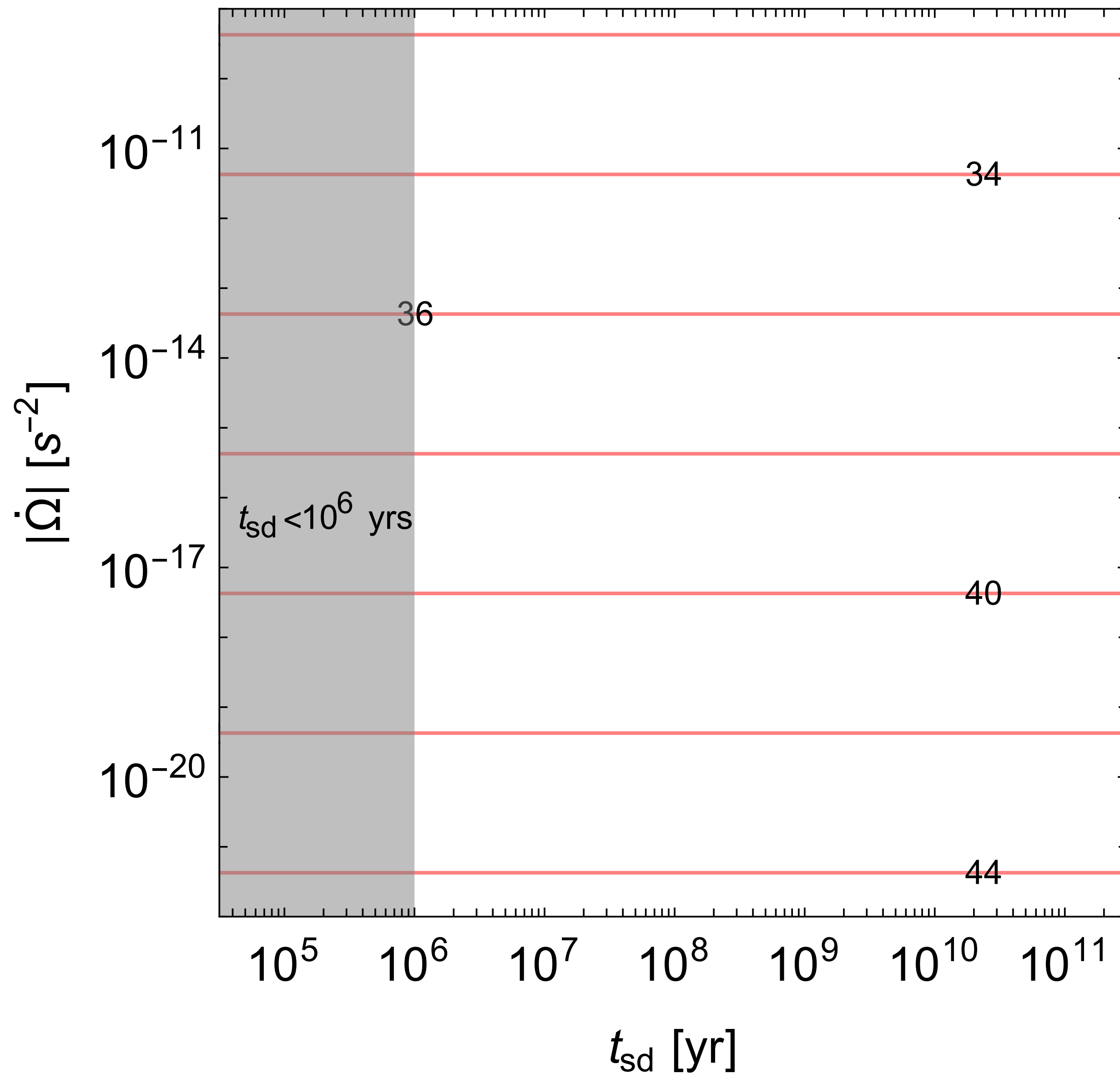


(b) Millisecond pulsars

Current obs. is well-accommodate w/ predicted time evolution of vortex creep heating (despite only one parameter:  $J$ )



# Vortex creep heating vs DM heating



Upper bound on  $J$  (in  $\log_{10}$ ) to probe DM heating

vortex creep heating

DM heating

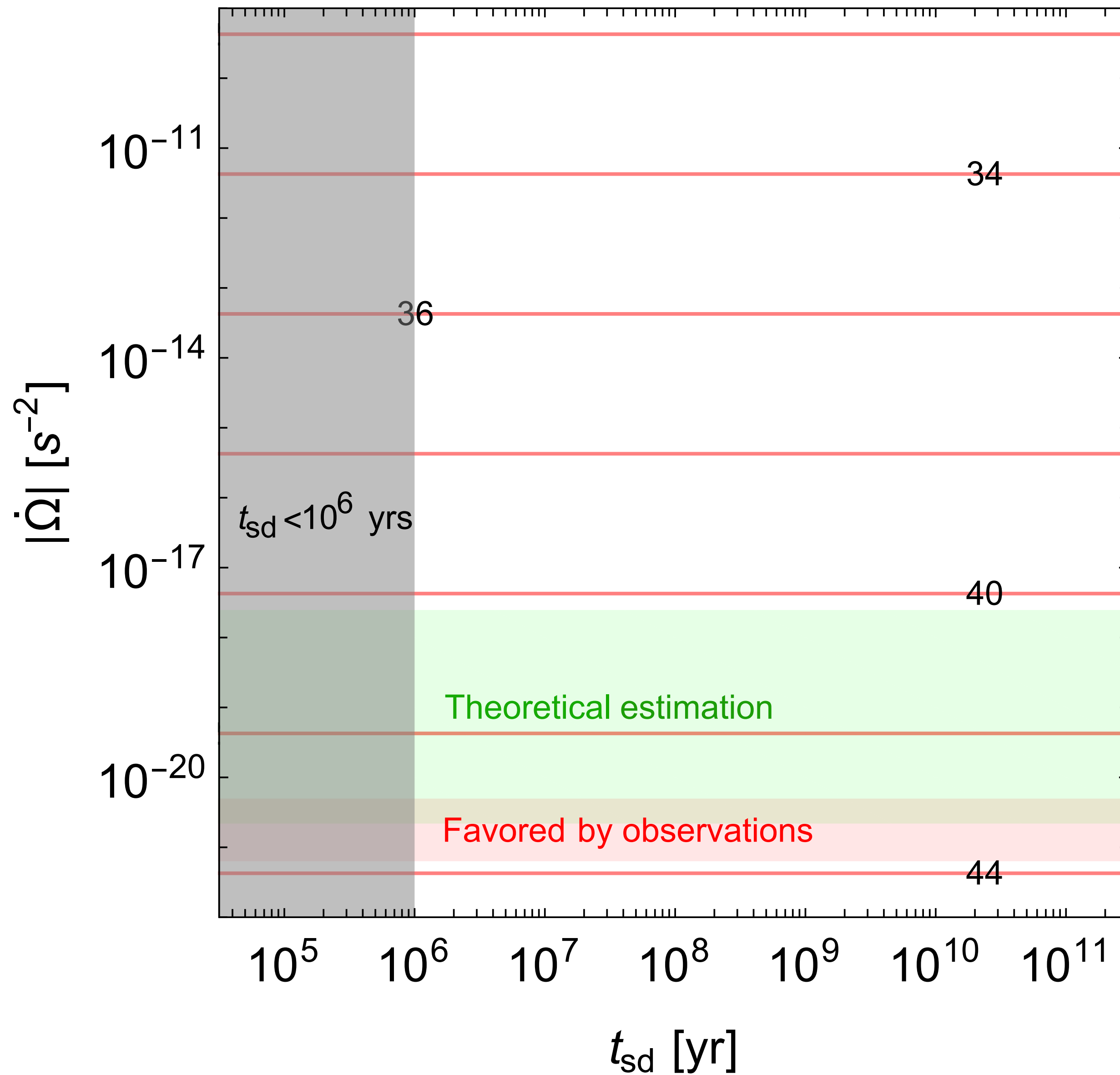
$$J |\dot{\Omega}| < 4\pi\sigma_{SB} R_{NS}^2 (T_s^{DM})^4$$

Optimistic value:

$$T_s^{DM} \lesssim 2600 \text{ K}$$

[Chatterjee, et al. [2205.05048]]

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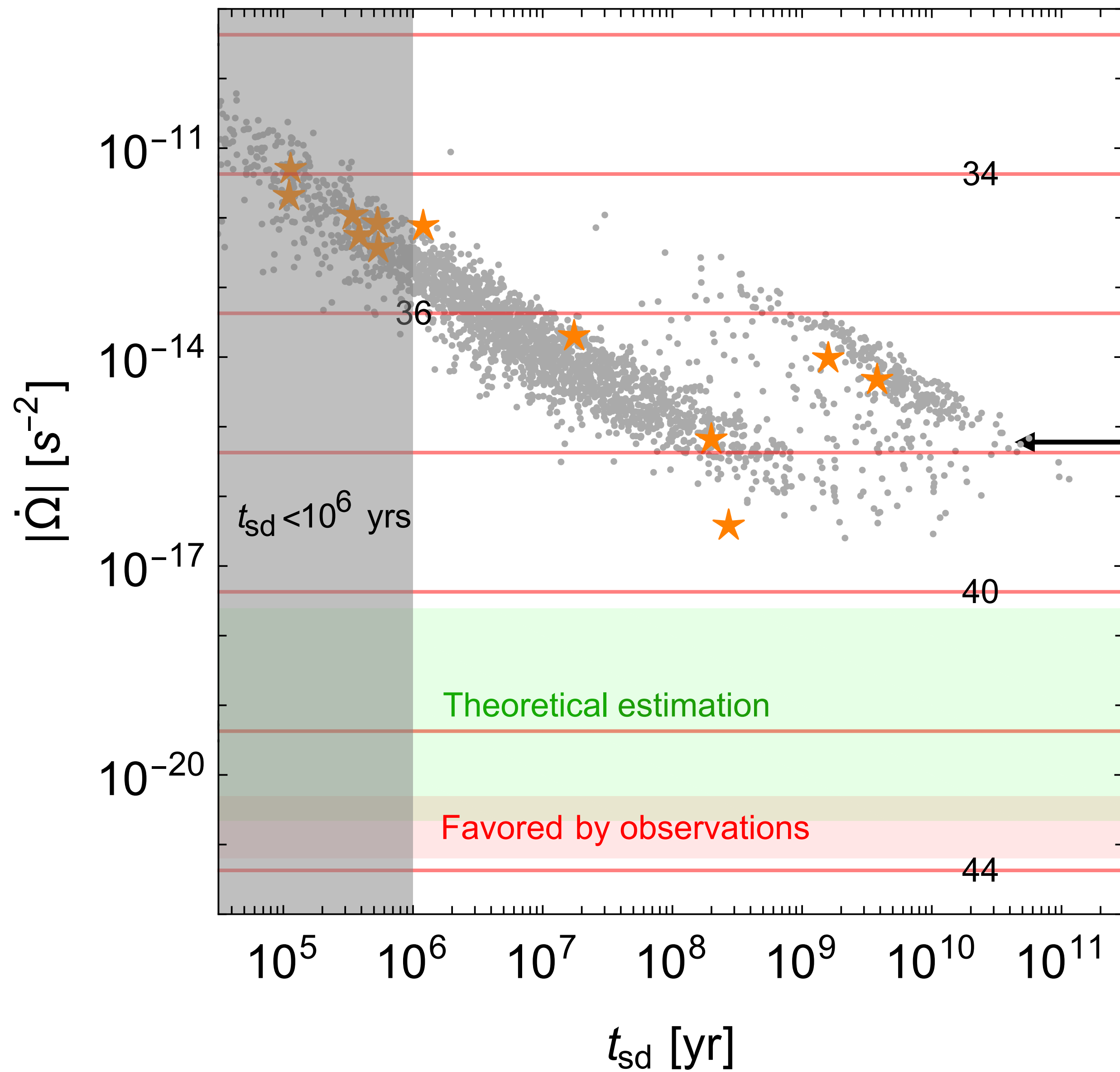
[Chatterjee, et al. [2205.05048]]

**VS**

Observationally favored value of  $J$

$$J_{obs} = 10^{42.9} - 10^{43.8} \text{ erg} \cdot \text{s}$$

# Vortex creep heating vs DM heating



Upper bound on  $J$  (in  $\log_{10}$ ) to probe DM heating

vortex creep heating

DM heating

$$J |\dot{\Omega}| < 4\pi\sigma_{\text{SB}} R_{\text{NS}}^2 (T_s^{\text{DM}})^4$$

Possible values:

- Currently observed data [ATNF catalog]

Optimistic value:

$$T_s^{\text{DM}} \lesssim 2600 \text{ K}$$

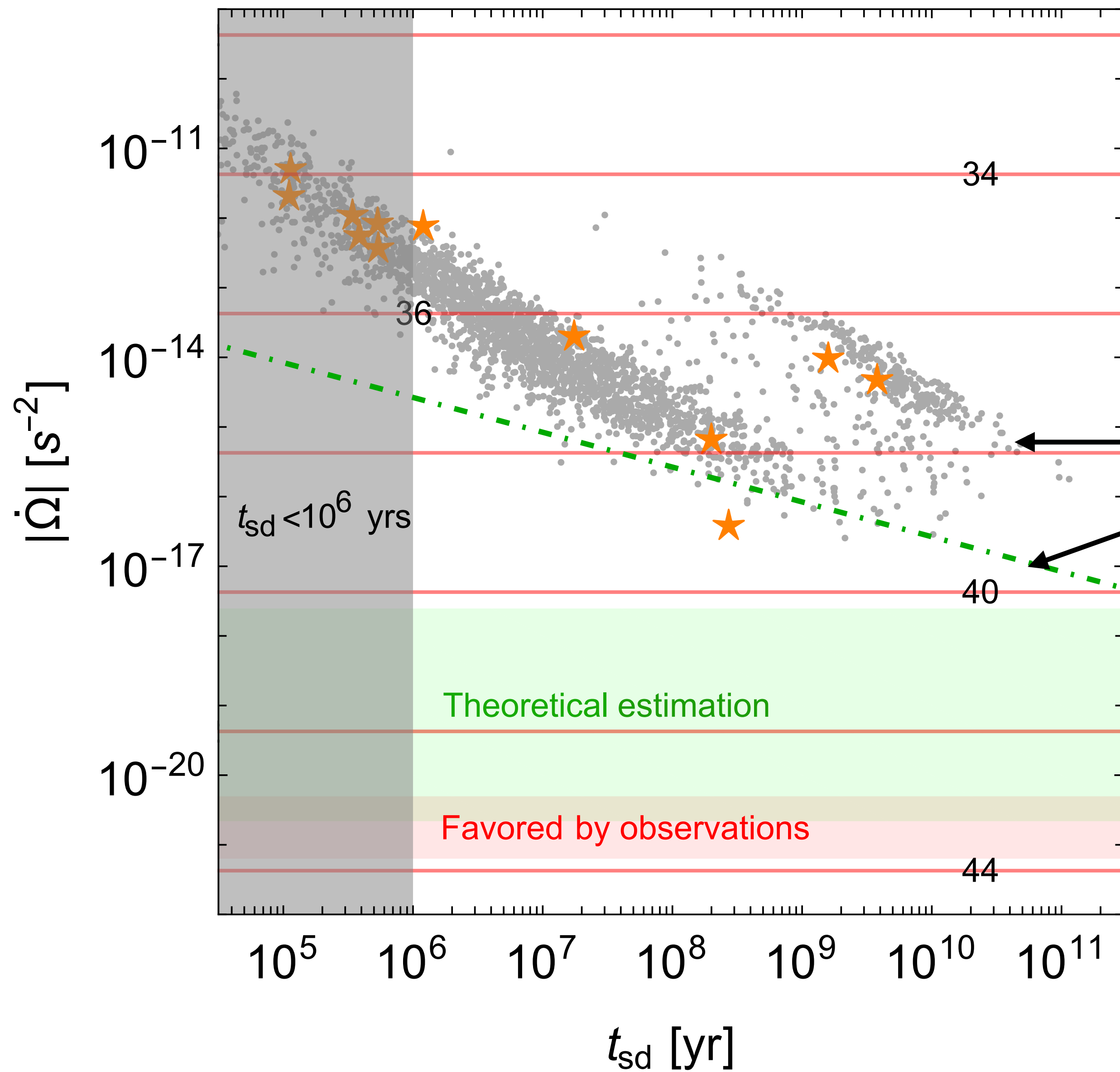
[Chatterjee, et al. [2205.05048]]

**VS**

Observationally favored value of  $J$  (using ★)

$$J_{\text{obs}} = 10^{42.9} - 10^{43.8} \text{ erg} \cdot \text{s}$$

# Vortex creep heating vs DM heating



Upper bound on  $J$  (in  $\log_{10}$ ) to probe DM heating

vortex creep heating

DM heating

$$J |\dot{\Omega}| < 4\pi\sigma_{\text{SB}} R_{\text{NS}}^2 (T_s^{\text{DM}})^4$$

Possible values:

- Currently observed data [ATNF catalog]
- Pulsar death line [Ruderman, et al. (1975)]

Optimistic value:

$$T_s^{\text{DM}} \lesssim 2600 \text{ K}$$

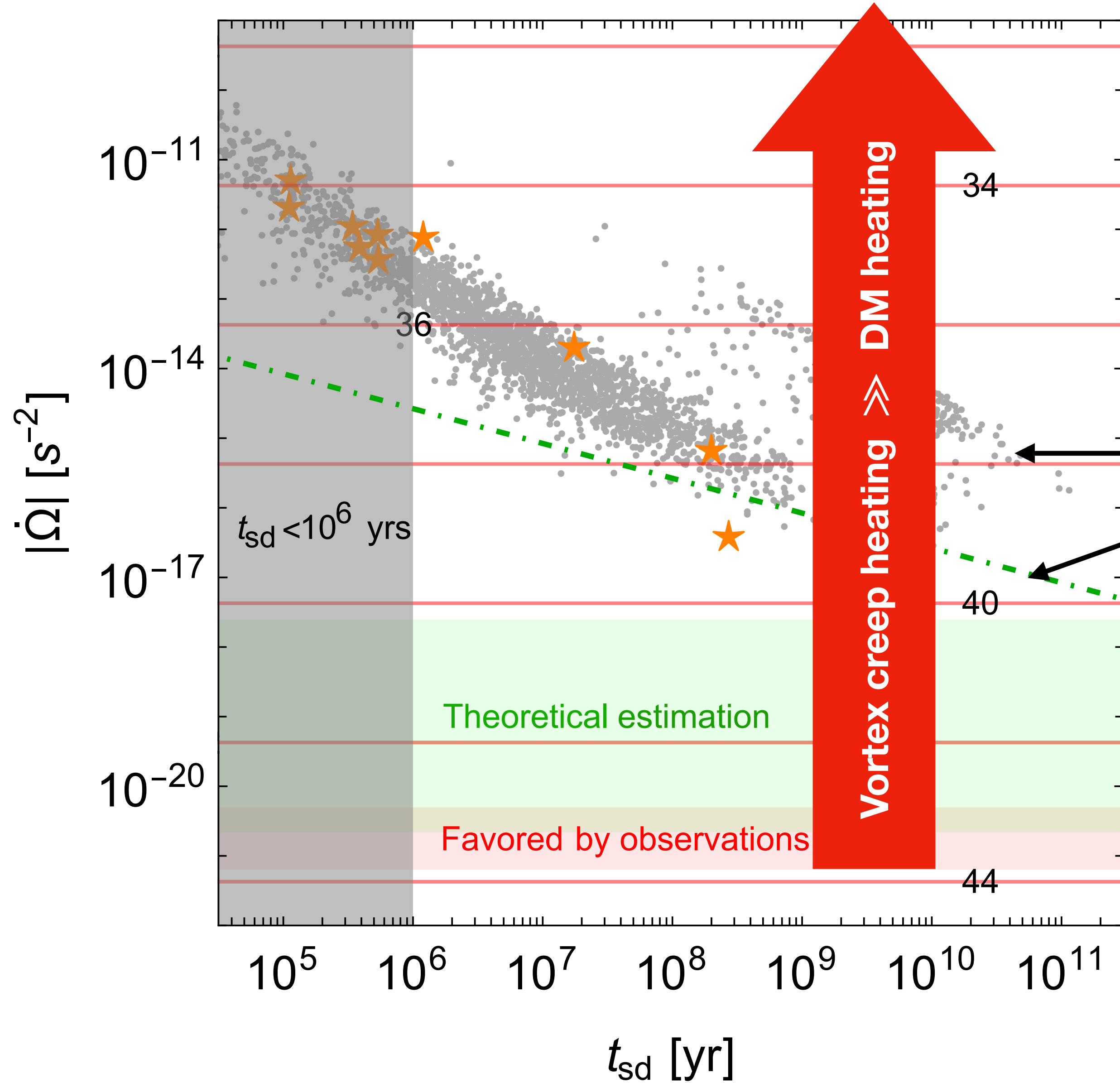
[Chatterjee, et al. [2205.05048]]

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[Chatterjee, et al. [2205.05048]]

**VS**

Observationally favored value of  $J$  (using ★)

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# Summary

We study **vortex creep heating** as possible contamination to probe for **DM heating** ( $T_s^{\text{DM}} \sim 2000$  K) in old NSs

- ✓ **Internal heating** → associated by superfluid spin-down
- ✓ **Universal effects** → controlled by  $J$
- ✓ **Quantitative relevance against DM heating**

$$J |\dot{\Omega}_\infty| \stackrel{!}{=} 4\pi R_{\text{NS}}^2 \sigma_{\text{SB}} T_s^4$$

## Vortex creep heating vs Observation

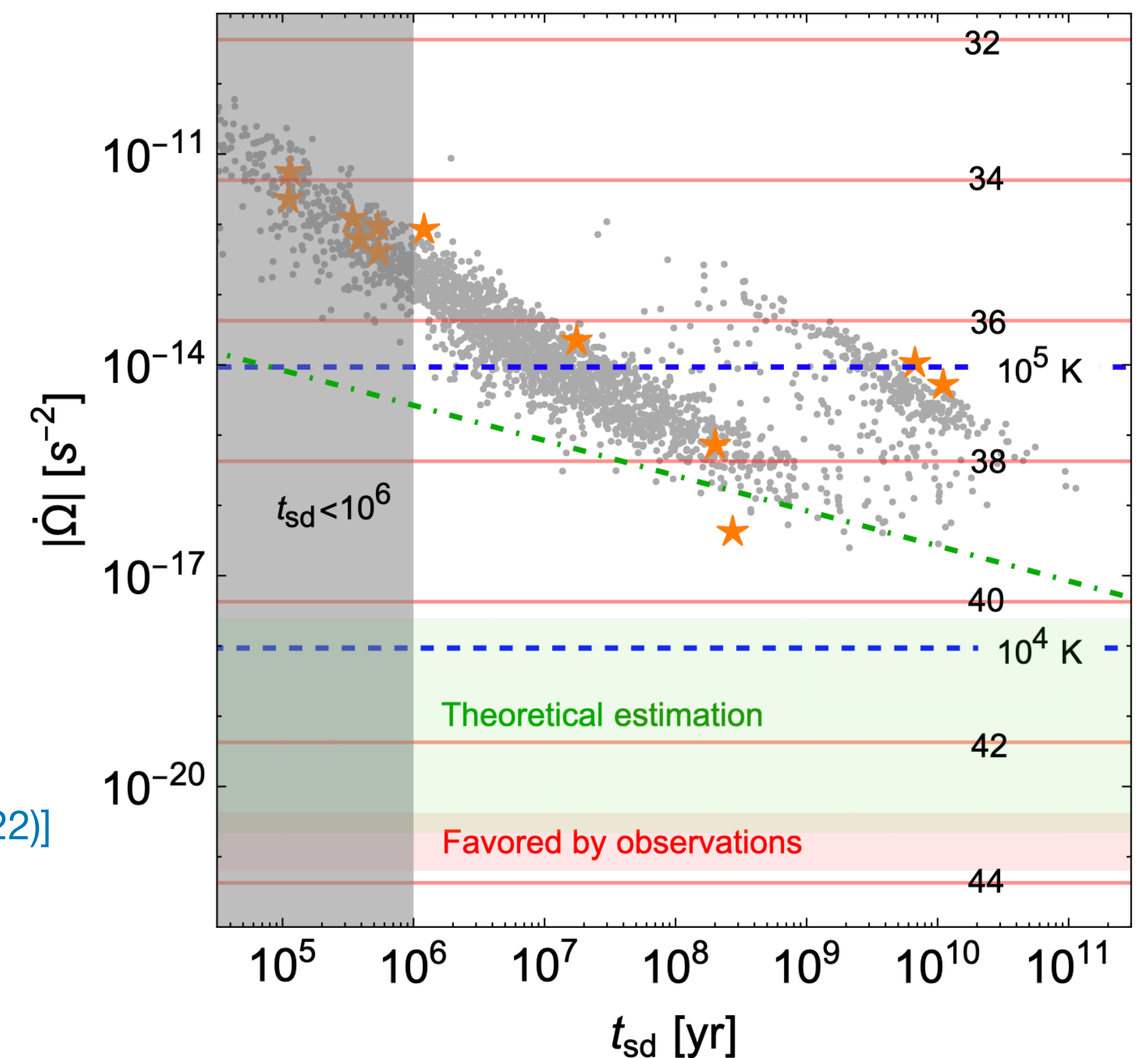
- Quasi-universal  $J$  is obtained from obs:  $J_{\text{obs}} \simeq 10^{43.0-43.8}$  erg s  
→ Consistent with vortex creep heating

## Vortex creep heating vs DM heating

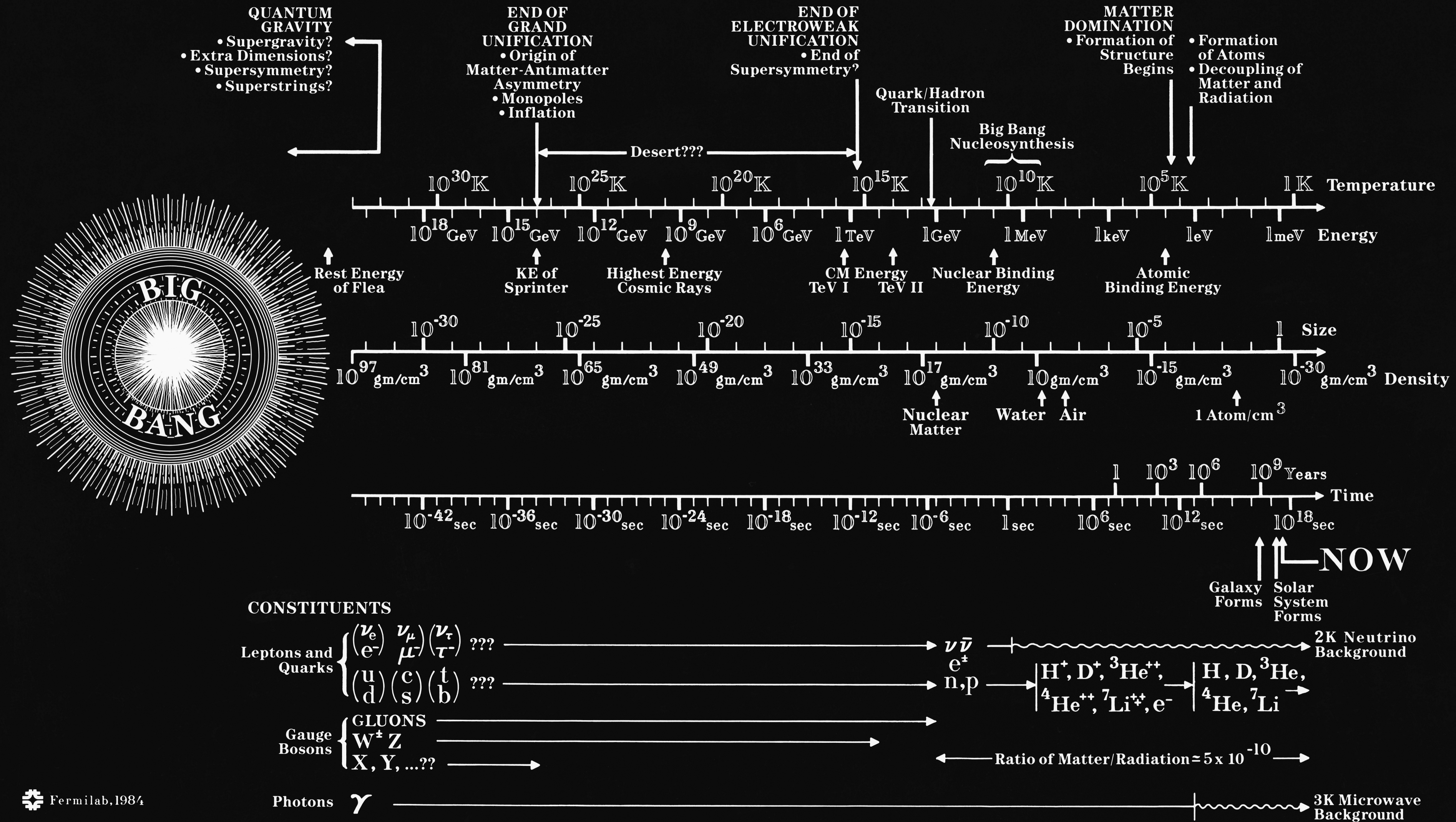
- Vortex creep heating seems to dominate DM heating

## Future direction?

- Accumulation of NS obs. may further test vortex creep hypothesis  
cf. wide area optical survey may observe  $T_s \sim 5 \times 10^5$  K [Toyouchi, et al. (2022)]
- Be more creative to come up with brand-new DM search directions!



# Backup



# Pinning force (1/2)

$R$ : distance from rotational axis

$$J_{\text{pin}} \simeq \int_{R_{\text{in}}}^{R_{\text{out}}} dR d\theta d\phi R^3 \sin^2 \theta \cdot \frac{f_{\text{pin}}(R)}{\mathcal{K}}$$

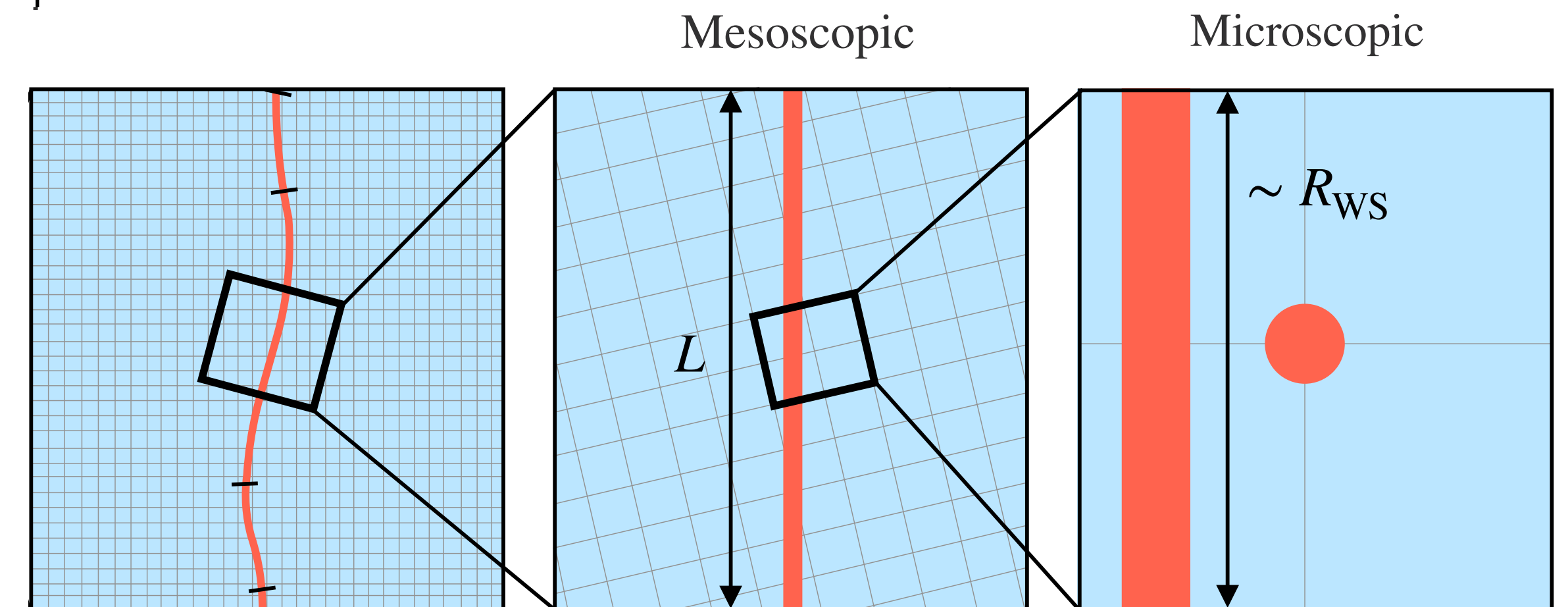
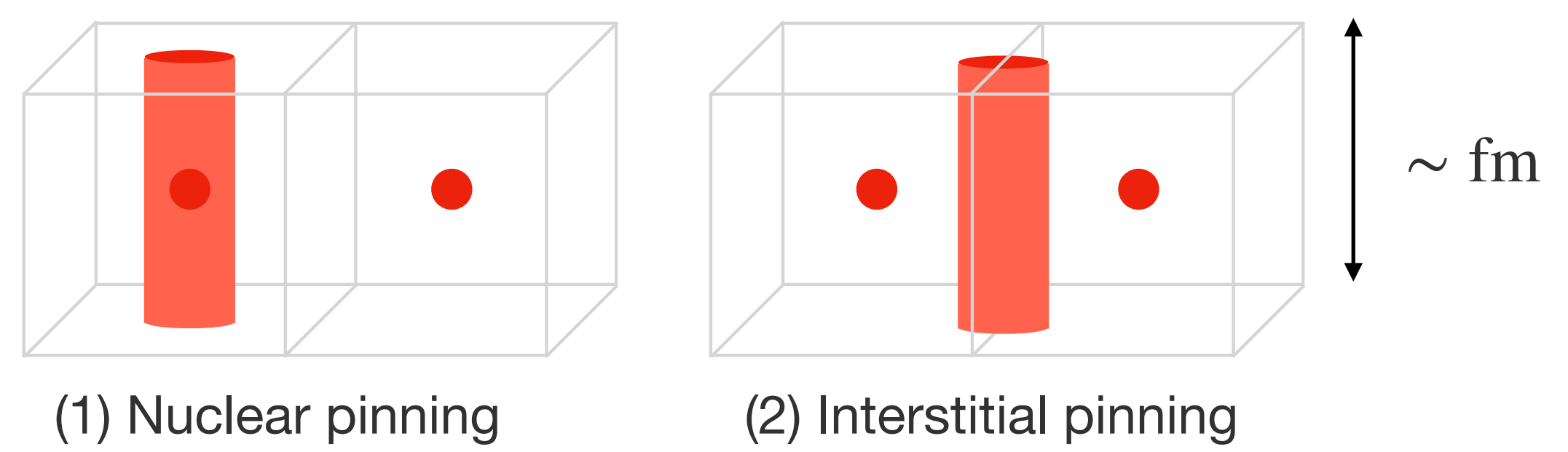
→ We need to specify  $\left\{ \begin{array}{l} \bullet [R_{\text{in}}, R_{\text{out}}] \\ \bullet f_{\text{pin}} \text{ for each region} \end{array} \right.$

## Evaluation of $E_{\text{pin}}$

- **Semi-classical approach** [Donati, Pizzochero (2004)]  
[Seveso, Pizzochero, Grill, Haskell (2015)]  
 Thomas-Fermi approx. (nucleons  $\simeq$  interacting Fermi gas)  
 → Total energy = functional of local density
- **Quantum approach** [Avogadro, Barranco, Broglia, Vigezzi (2008)]  
[Klausner, et al. [2303.18151]]  
 Hartree-Fock-Bogoliubov approx.  
 → We can naturally include quantum & pairing effects

## Evaluation of $f_{\text{pin}}$

- **“Microscopic” evaluation**  
 Estimation using  $E_{\text{pin}}$  derived in fm-size box
- **“Mesoscopic” evaluation**  
 Averaging  $f_{\text{pin}}$  along mesoscopic length  $L \simeq (10^3 - 10^4)$  fm



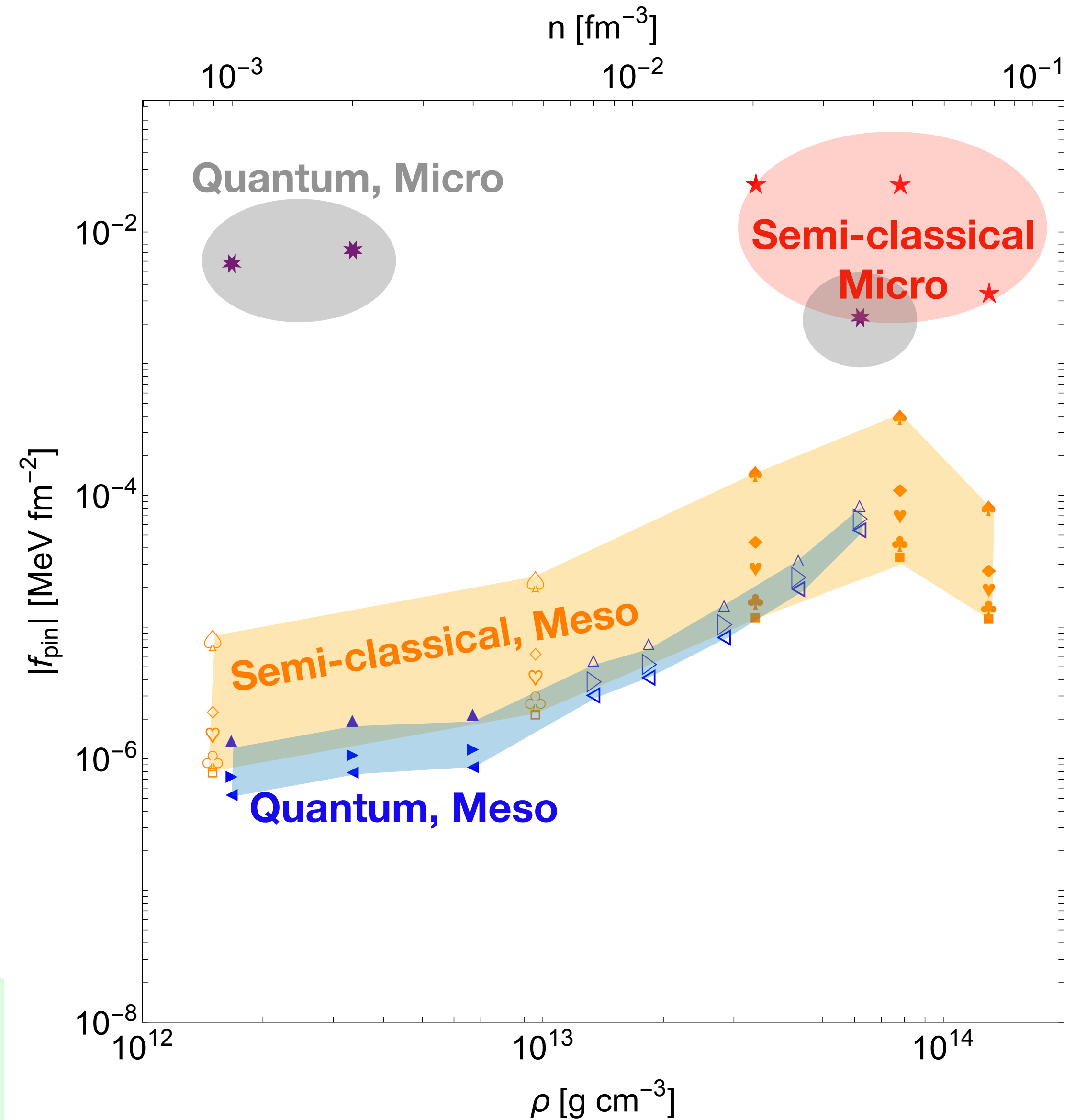


# Pinning force (2/2)

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

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

Each many-body calculation implies different  $f_{\text{pin}}(\rho)$   
 EoS uncertainty enters to connect  $\rho \rightarrow R$  (radial distance)

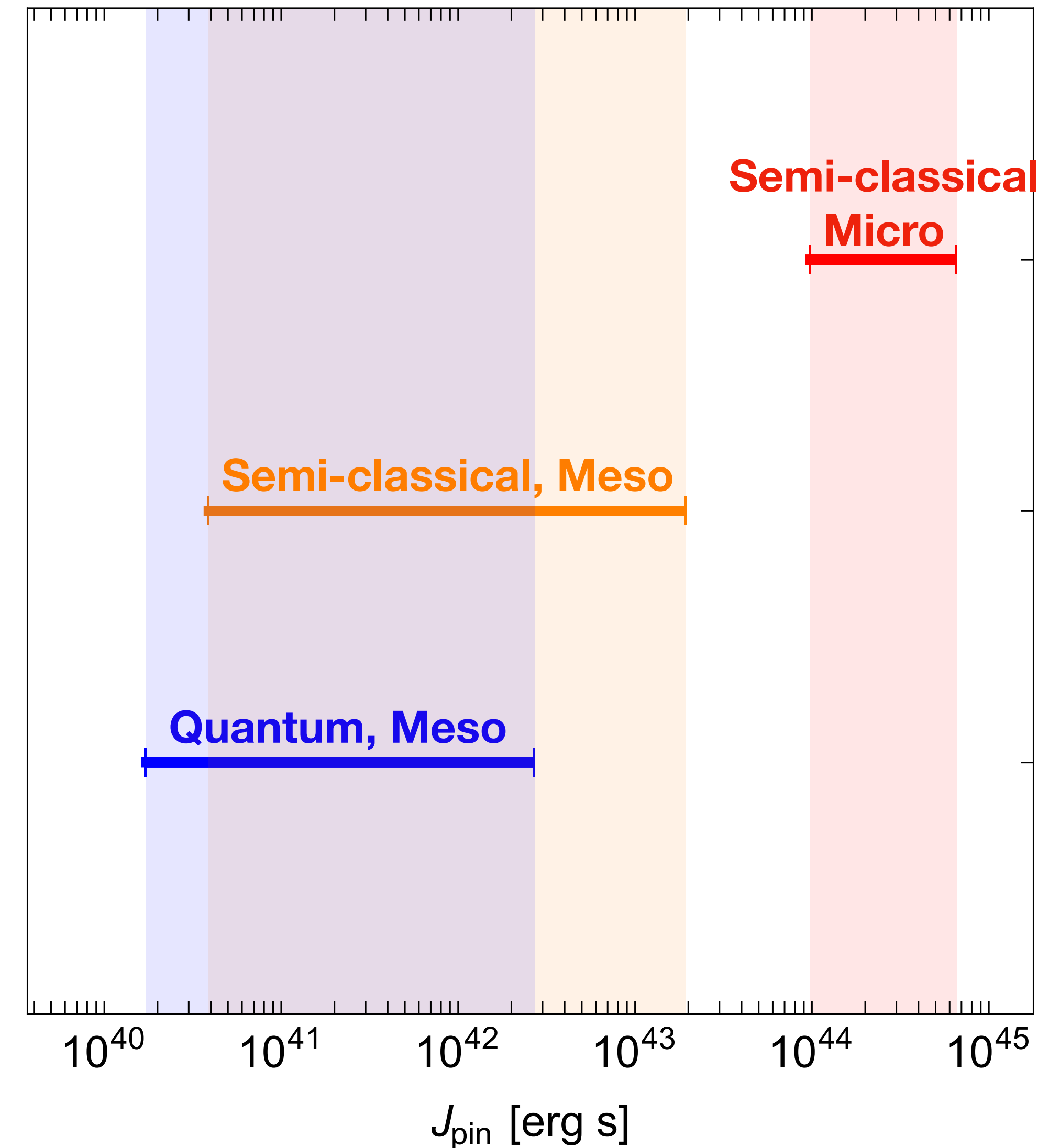


# Evaluation of $J_{\text{pin}}$

$$J_{\text{pin}} \simeq \int_{R_{\text{in}}}^{R_{\text{out}}} dR d\theta d\phi R^3 \sin^2 \theta \cdot \frac{f_{\text{pin}}(R)}{K} \Big|_{\text{min}}^{\text{max}}$$

Input evaluations of  $f_{\text{pin}}$

$$J_{\text{pin}} = \begin{cases} [9.8 \times 10^{43}, 6.6 \times 10^{45}] \text{ erg s} \\ \text{(Semi-classical, Micro.)} \\ [1.7 \times 10^{40}, 1.9 \times 10^{43}] \text{ erg s} \\ \text{(Semi-classic/Quantum, Meso.)} \end{cases}$$



We evaluated range of  $J_{\text{pin}}$  w/ conservative error

$$\rightarrow \text{well-accommodate w/ } T_s \simeq (10^4 - 10^6) \text{ K} \left( \frac{J}{(10^{40} - 10^{46}) \text{ erg s}} \right)^{\frac{1}{4}}$$

# Temperature observation: B1706-44 as eg.

## Profile

- Mass: unknown → Fixed as  $M = 1.4 M_{\odot}$
- Radius: unknown → Fixed as  $R = 10$  km
- Distance: unknown → Fitted to be  $d = 1.7 \pm 0.3$  kpc

## Fitting

- Data: XMM-Newton (soft X-ray)
- Model: BB, BB+PL, atomos + PL
- Result: Acceptable  $\chi^2$  is obtained for BB+PL & atomos+PL models  
BB + PL also works but w/ small radii ( $R \sim 1 - 3$  km)  
atomos + PL model tend to predict lower  $T_s$  & larger  $R$
- Uncertainty:  $T_s = (0.72 - 3.45) \times 10^6$  K (BB+PL & atomos+PL)

Uncertainty comes from  $\{M_{\text{NS}}, R_{\text{NS}}, d\}$  & fitting models  
→ We choose a conservative range of  $T_s^{\text{obs}}$

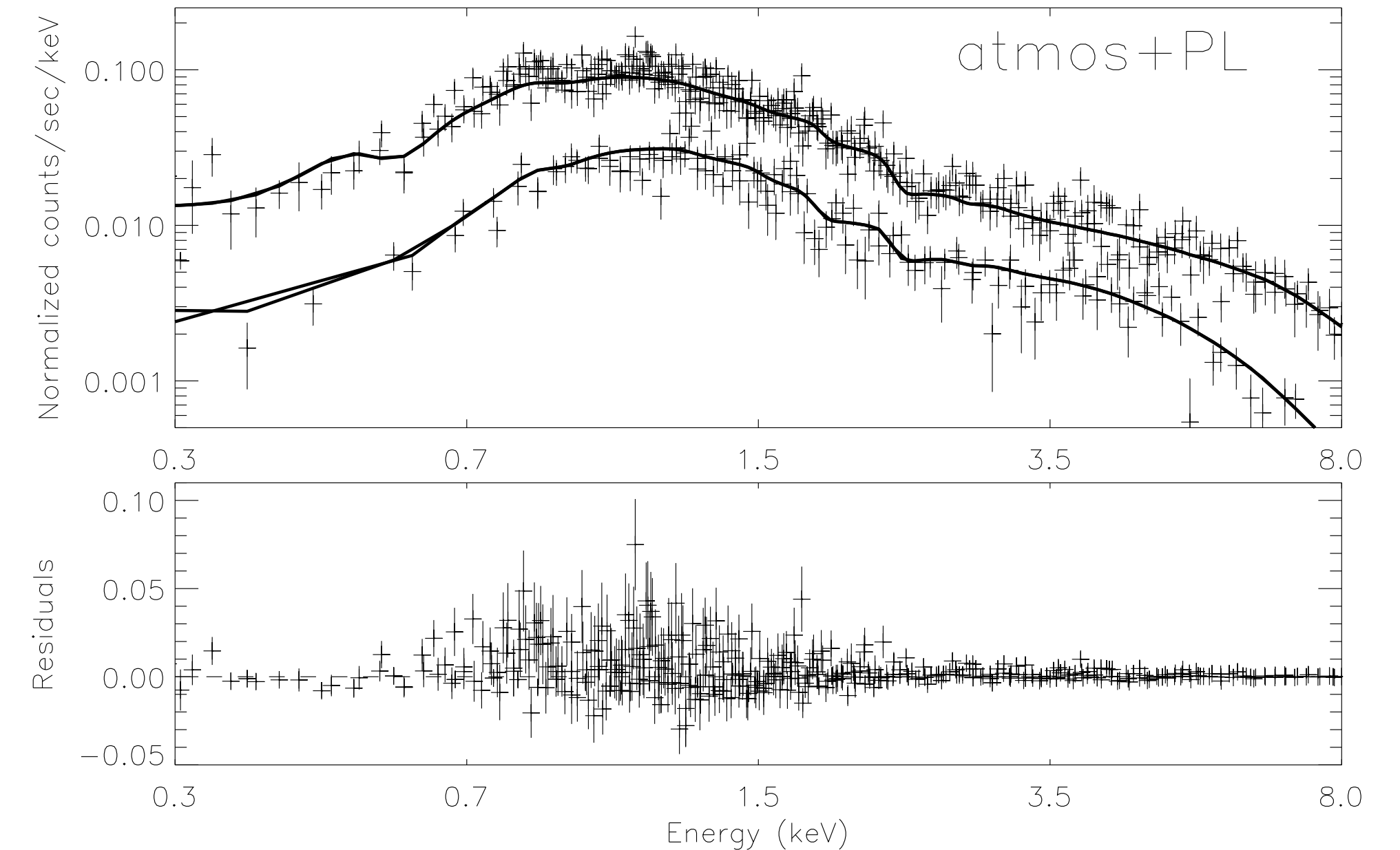


Table 1. Spectral fits to PSR B1706-44

Model	$N_H$ $\times 10^{21} \text{ cm}^{-2}$	$\Gamma$	$R$ km	$T^\infty$ $\times 10^6$ K	$D$ kpc	$\chi^2_\nu$ [dof]
BB	5.5 (fixed)	...	$0.75^{+0.06, a}_{-0.04}$	$3.28^{+0.08}_{-0.12}$	$2.3 \pm 0.3$ (fixed)	4.88 [661]
BB	$0.001^{+0.058}_{-0.001}$	...	$0.10^{+0.04, a}_{-0.02}$	$8.14^{+1.14}_{-1.18}$	$2.3 \pm 0.3$ (fixed)	2.92 [660]
PL	5.5 (fixed)	$2.45^{+0.05}_{-0.05}$	...	...	$2.3 \pm 0.3$ (fixed)	1.82 [661]
PL	$2.9^{+0.2}_{-0.2}$	$1.83^{+0.05}_{-0.05}$	...	...	$2.3 \pm 0.3$ (fixed)	1.17 [660]
BB+PL	5.5 (fixed)	$1.57^{+0.07}_{-0.06}$	$3.23^{+0.22, a}_{-0.20}$	$1.76^{+0.06}_{-0.06}$	$2.3 \pm 0.3$ (fixed)	0.84 [659]
BB+PL	$4.5^{+0.7}_{-0.4}$	$1.49^{+0.09}_{-0.08}$	$1.81^{+0.43, a}_{-0.29}$	$2.01^{+0.18}_{-0.20}$	$2.3 \pm 0.3$ (fixed)	0.84 [658]
atmos+PL	$5.2^{+0.1}_{-0.1}$	$1.45^{+0.14}_{-0.01}$	10 (fixed)	$0.79^{+0.07}_{-0.31}$	$1.7 \pm 0.3$	0.84 [658]
atmos+PL	$5.1^{+0.2}_{-0.1}$	$1.43^{+0.20}_{-0.05}$	12 (fixed)	$0.82^{+0.01}_{-0.34}$	$2.1 \pm 0.2$	0.84 [658]

# Neutron Star obs. vs Direct detection

\*  $N = n, p$

## Sensitivity as target

$$\sigma_{\text{th}} \equiv \frac{\pi R_{\text{NS}}^2 m_n}{M_{\text{NS}}} \simeq 2.5 \times 10^{-45} \text{ cm}^2$$

$$\Delta M_{\text{NS}} \simeq m_n \left( 1 - \frac{2GM_{\text{NS}}}{R_{\text{NS}}} \right)^{-\frac{1}{2}} \simeq 300 \text{ MeV}$$

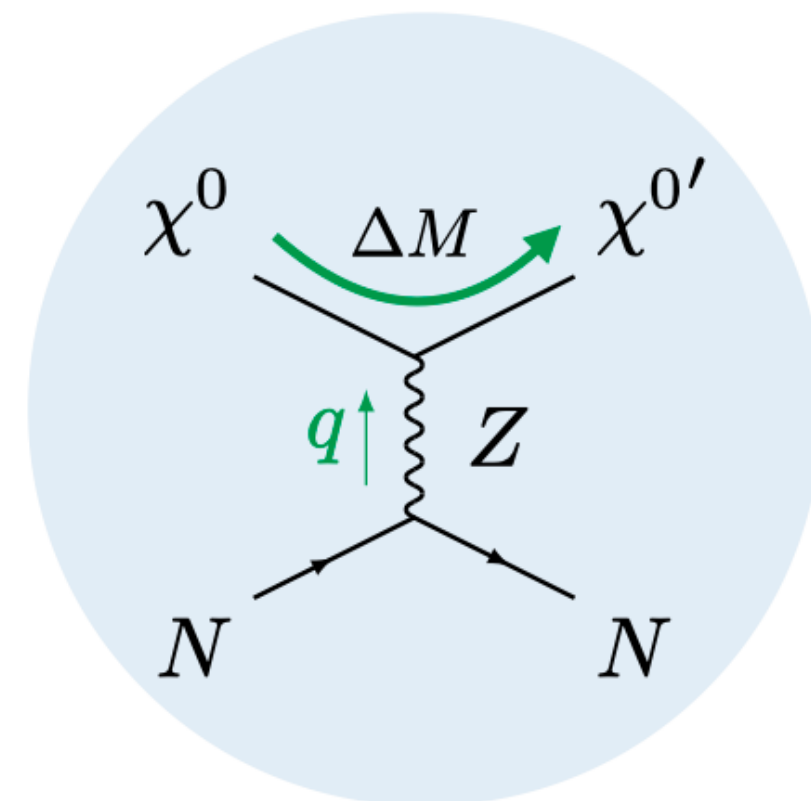
		Direct detection	NS observation
Elastic	SI	$\sigma_{\text{SI}}^{(N), \text{upper}} \simeq 10^{-45} \text{ cm}^2$	$\sigma_{\text{th}}^{(N)} \simeq 10^{-45} \text{ cm}^2$
	SD	$\sigma_{\text{SD}}^{(N), \text{upper}} \simeq 10^{-40} \text{ cm}^2$	
Inelastic	SI	$\Delta M_0, \Delta M_{\pm} \lesssim \mathcal{O}(100) \text{ keV}$	$\Delta M_0, \Delta M_{\pm} \lesssim \mathcal{O}(100) \text{ MeV}$
	SD		

## Inelastic DM scattering

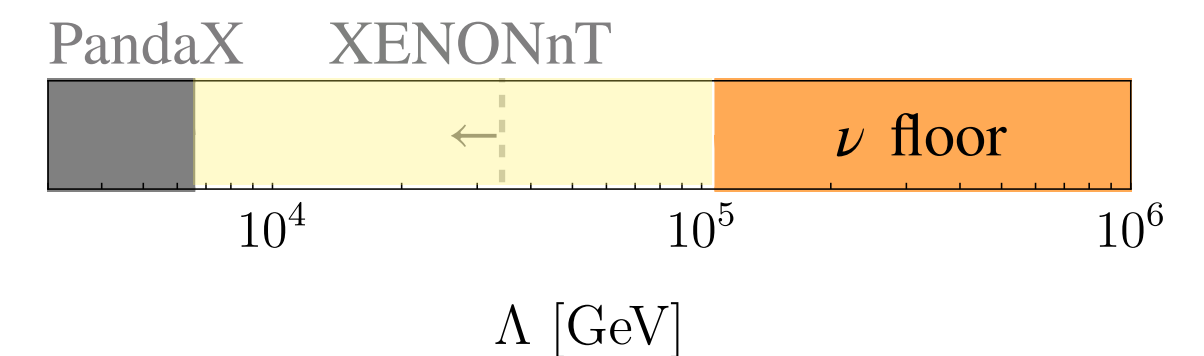
[N. F. Bell, G. Busoni, S. Robles (2018)]  
 [MF, K. Hamaguchi, N. Nagata, J. Zheng (2022)]

- Large energy injection due to gravitational acceleration
- DM may be excited
- eg. Electroweak multiplet DM

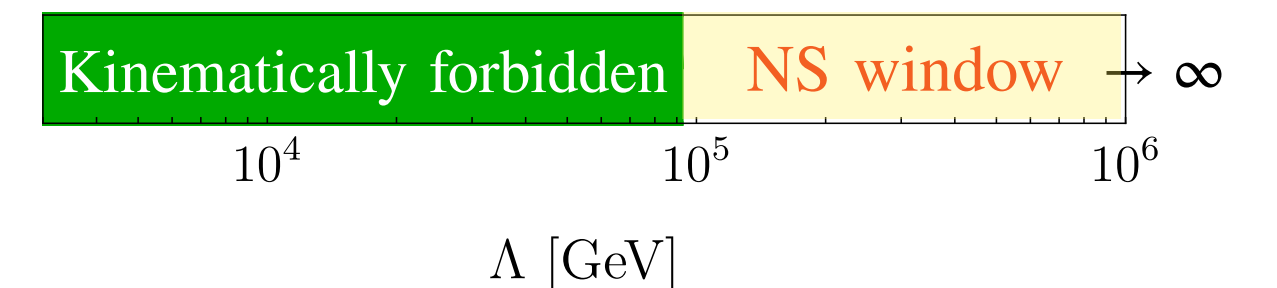
$$\Delta M_{\text{EW}} \simeq \alpha_2 m_W \simeq \mathcal{O}(100) \text{ MeV}$$



Direct detection, Elastic (SI)



NS capture, Inelastic (NC)



Direct detection & Neutron Star observation  
 will be a **complimentary probe** for **EW Multiplet DM**

# Is Neutron Star Obs. Promising?

## Can we really detect such inflated signatures?

- Recently, study of JWST sensitivity on DM heating is released [[S. Chatterjee et al. \[arXiv:2205.05048\]](#)]
- Neutron Star w/ (1)  $T_s \gtrsim 2600$  K & (2) 10 pc distance may be detectable in JWST (through NIRCAM filter)

## Can we discriminate DM heating effects against other Neutron Star internal heating mechanisms?

- eg. Rotochemical heating → Irrelevant if initial rotational period:  $P_0$  is sufficiently large [[K. Hamaguchi et al. \(2019\)](#)]
- We need to study other internal heating mechanisms to conclude whether or not we can really detect DM heating
- If we observe Neutron Star w/  $T_s \lesssim 10^3$  K, **DM w/ nucleon int. can be widely constrained** for GeV-PeV range

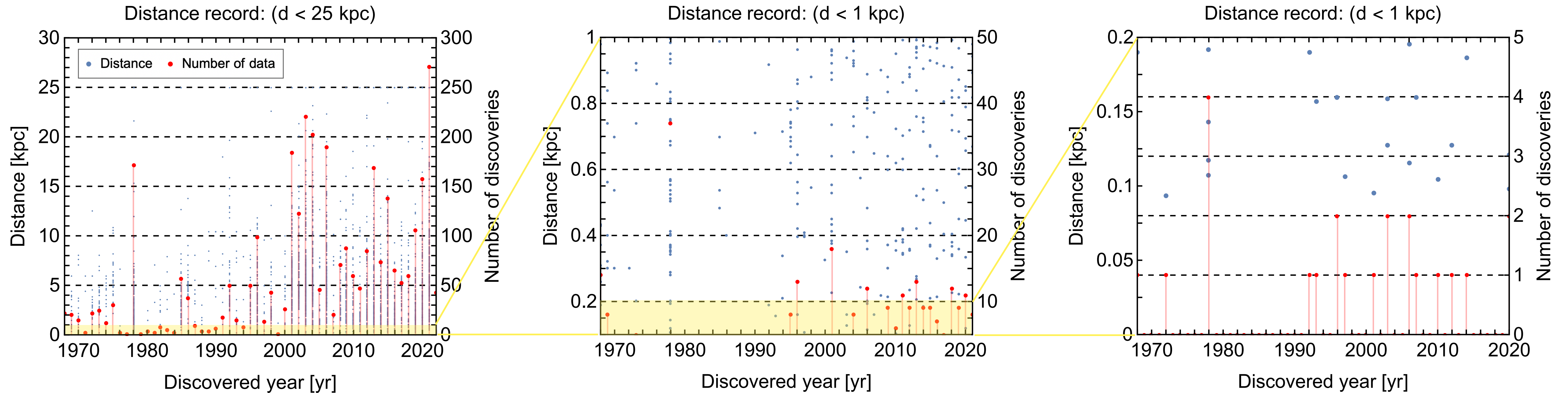
## Can we control uncertainty in Neutron Star (astro obs.) compared w/ Direct Detection (Underground exp.)?

- We do have uncertainty from  $\left\{ \begin{array}{l} \text{Astrophysics (eg. Internal unknown structure of compact star, initial condition)} \\ \text{Nuclear Physics (eg. Nuclear force model under high density)} \end{array} \right.$
- Still, we may overcome some disadvantages in Direct Detection by combining Neutron Star obs.

To establish this new direction, **continuous efforts to form fundamental phys. is mandatory**

# Pulsar Catalogue

[ATNF pulsar catalogue: <https://www.atnf.csiro.au/research/pulsar/psrcat/>]



## Discovered Year vs Distance

- Recently, the number of pulsar data is increasing rapidly (eg. **248 pulsar data** is added by FAST exp.)
- Nearest pulsar data: (Distance)  $\sim 100$  pc  
Pulsar within  $\sim 100$  pc is discovered recently  
(Note: we have to point telescope into pulsar direction )

Distance	Discovery
93 pc	1972
95 pc	2001
98 pc	2020

# JWST Sensitivity

## Targets

- Our targets: Isolated & old Neutron Stars near close to us
- Spatial distribution of stars are predicted by Monte-Carlo orbital simulations
  - 1-2 (100-200) old isolated Neutron Stars within 10 (50) pc are expected

## DM capture rate

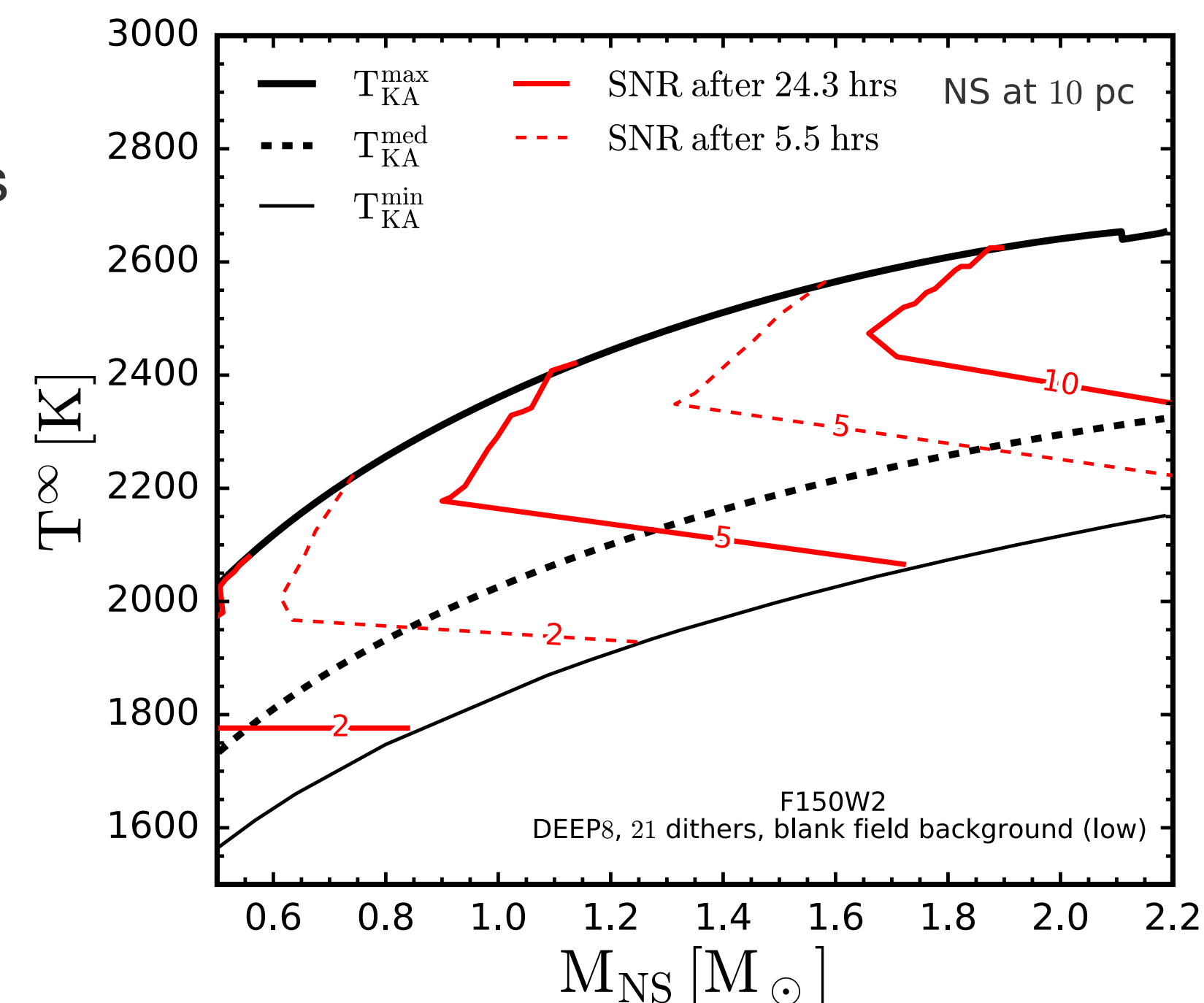
- Maximum surface temperature is derived by considering uncertainties:
  - EoS allowed region (on radius-mass plots)
  - Neutron Star-DM phase space distribution
- $T_s \simeq 2600$  K (w/ 40 % validation)

## JWST Sensitivity for DM heating

- Wave length of DM black body radiation :  $\lambda \simeq 2 \mu\text{m}$
- NIRCAM filter F150W2 provides the best sensitivity
  - Detection w/ Signal to Noise Ratio (SNR)  $\gtrsim 10$  within 24 hours of exposure time (using [Exposure Time Calculator](#))

### Faint light of old neutron stars from dark matter capture and detectability at the James Webb Space Telescope

Shiuli Chatterjee<sup>1,\*</sup>, Raghuvver Garani<sup>2,†</sup>, Rajeev Kumar Jain<sup>3,‡</sup>,  
Brijesh Kanodia<sup>1,3,§</sup>, M. S. N. Kumar<sup>4,¶</sup> and Sudhir K. Vempati<sup>1,\*\*</sup>  
<sup>1</sup>Centre for High Energy Physics, Indian Institute of Science, Bangalore 560012, India  
<sup>2</sup>INFN Sezione di Firenze, Via G. Sansone 1, I-50019 Sesto Fiorentino, Italy  
<sup>3</sup>Department of Physics, Indian Institute of Science, Bangalore 560012, India  
<sup>4</sup>Instituto de Astrofísica e Ciências do Espaço, Porto,  
Rua das Estrelas, s/n, 4150-762, Porto, Portugal



※ After releasing the first scientific data on July 12, 2022, JWST will start scientific works

# JWST Sensitivity (2/3)

## Wavelength vs Flux

- Spectral energy distribution assuming black body

$$f_{\lambda}(M, R) = \frac{4\pi^2}{\lambda^3} \left( e^{\frac{2\pi}{\lambda T^{\infty}}} - 1 \right)^{-1} \left( \frac{R\gamma}{d} \right)^2$$

- Uncertainty source

- $v_{\star}$ : velocity
- $\rho_{\chi}$ : DM density around the target
- $v_d$ : DM dispersion velocity
- Neutron star Equation of State (NS EoS)

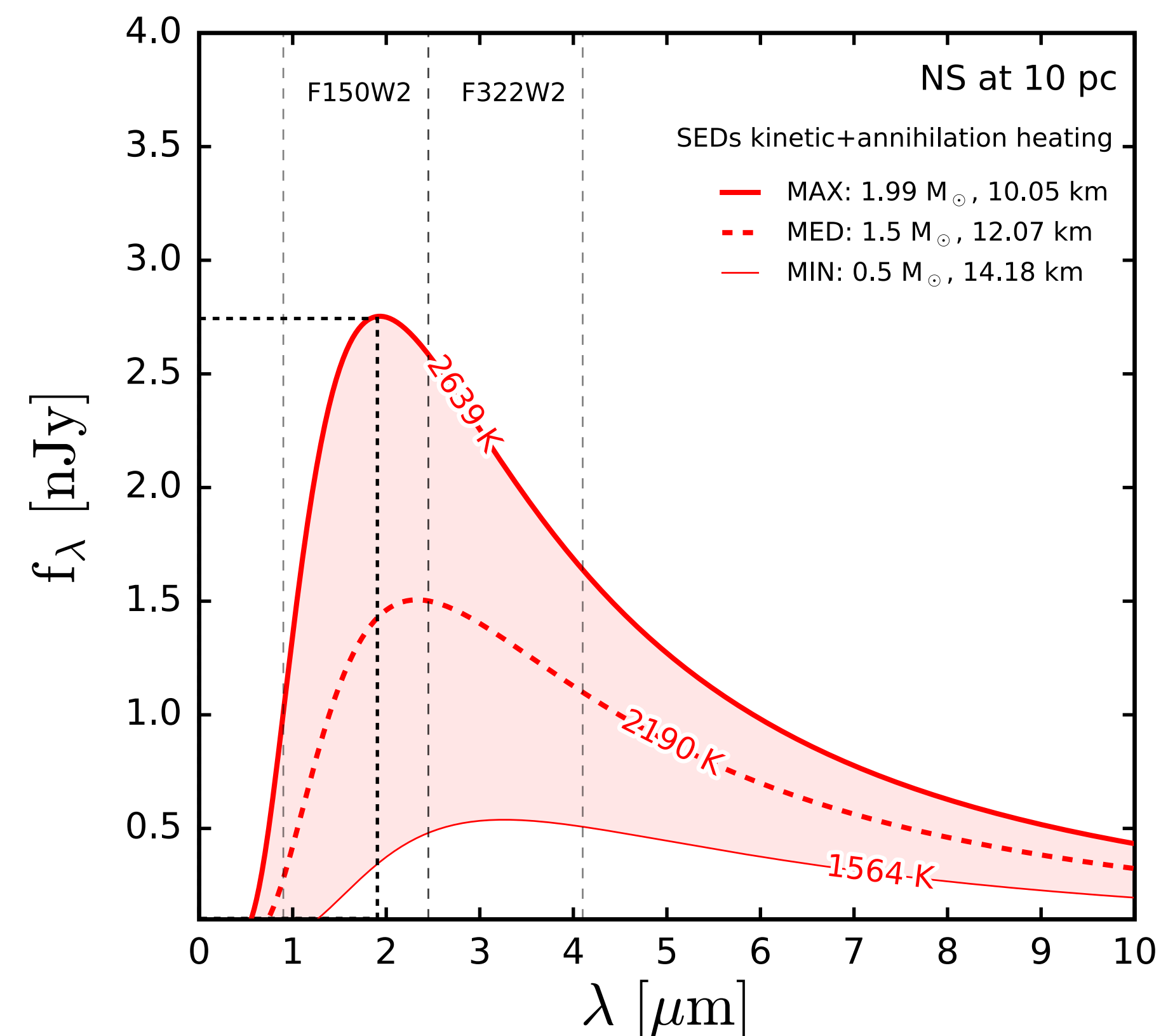
- Prediction band is specified

- MAX: EoS WFF-1 & 1E velocity PDF
- MED: Averaged
- MIN: EoS PAL-1 & bimodal velocity PDF

- Maximum flux:  $f_{\lambda} \in [0.5, 2] \text{ nJy @ } \lambda \sim 2 \mu\text{m}$

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# JWST Sensitivity (3/3)

## Exposure time vs SNR

- Input: {MAX, MED} black body prediction in DM heating scenario
- Tool: JWST exposure time calculator [Pandeia]
- Setup: NIRCAM is assumed
- To do: Prediction vs Background model → Expected SNR

15 July 2016

### Pandeia: a multi-mission exposure time calculator for JWST and WFIRST

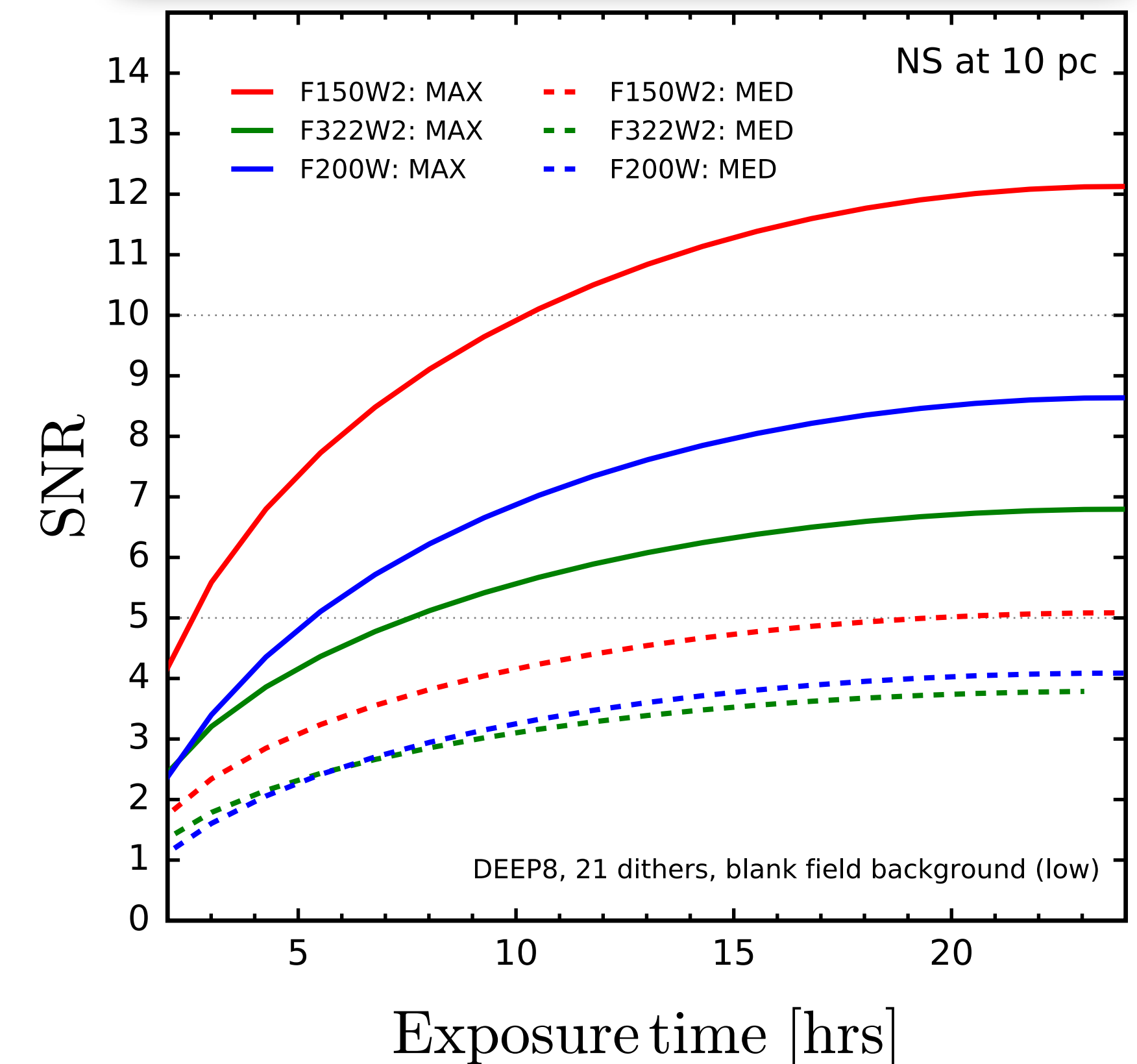
*Klaus M. Pontoppidan, Timothy E. Pickering, Victoria G. Laidler, Karoline Gilbert, Christopher D. Sontag, Christine Slocum, Mark J. Sienkiewicz Jr., Christopher Hanley, Nicholas M. Earl, Laurent Pueyo, Swara Ravindranath, Diane M. Karakla, Massimo Robberto, Alberto Noriega-Crespo, Elizabeth A. Barker*

RAA 2015 Vol. 15 No. 12, 1945–2140 doi: 10.1088/1674-4527/15/12/001  
<http://www.raa-journal.org> <http://www.iop.org/journals/raa>

Research in  
Astronomy and  
Astrophysics

### Thirty Meter Telescope Detailed Science Case: 2015 \*

Warren Skidmore on behalf of the TMT International Science Development Teams & TMT Science Advisory Committee



# Vela Rubin Surveys

## “Deep survey over an enormous area of sky”

Design: [[https://www.lsst.org/about/tel-site/optical\\_design](https://www.lsst.org/about/tel-site/optical_design)]

- Targeted goal: 10 yrs observation using Legacy Survey of Space and Time (LSST)
- Location: Cerro Pachón ridge (in north-central Chile)
- Conducting frequency survey
  - Obtaining **images of every part of the visible sky** (/every few nights) for 10 yrs
  - Achieve huge astronomical catalog (×1000 larger size than that is previously achieved)
- Optical imaging telescope: A gigapixel camera & a data management system (to store data)

## Aim

- Probing Dark energy & Dark matter
- Taking an inventory of the solar system
- Exploring the transient optical sky
- Mapping the Milky Way



WebCam: [<https://www.lsst.org/news/see-whats-happening-cerro-pachon>]

# DM Annihilation into Neutrino

## Standard Scenario: Neutron Star Heating by DM Annihilation

- (1) DM is captured by Neutron Star if DM-nucleon cross section exceeds threshold value
- (2) DM annihilates into **the SM particles**, which is thermalized and release its energy ( $\simeq$  DM mass) into Neutron Star  
\* If DM annihilates into non-SM particles, final state particles may escape from stars (cf. “Secluded DM” scenario)
- (3) Neutron Star Surface Temperature will be increased to reach JWST-sensitivity:  $T_s \simeq \mathcal{O}(1000)$  K

Question: Can we apply this standard scenario to **DM annihilation channel into neutrino**?

Answer: **Yes**, neutrino lose its energy before escaping from Neutron Star

$$L_\nu \simeq \frac{1}{\bar{n}_n \sigma_{n\nu}} \sim \frac{1}{\bar{n}_n \times G_F^2 E_\nu^2} = 2.5 \text{ m} \left( \frac{100 \text{ MeV}}{E_\nu} \right)^2$$

Neutrino mean free path :  $L_\nu$   
Neutron averaged density :  $\bar{n}_n = 10^{37} \text{ cm}^{-3}$   
Neutron-neutrino cross section :  $\sigma_{n\nu} \propto G_F^2 E_\nu^2$

Initially, neutrino from DM pair annihilation has  $E_\nu \simeq m_{\text{DM}}$

→ Neutrino should lose its energy (to reach  $E_\nu \ll 100 \text{ MeV}$ ) to escape from star

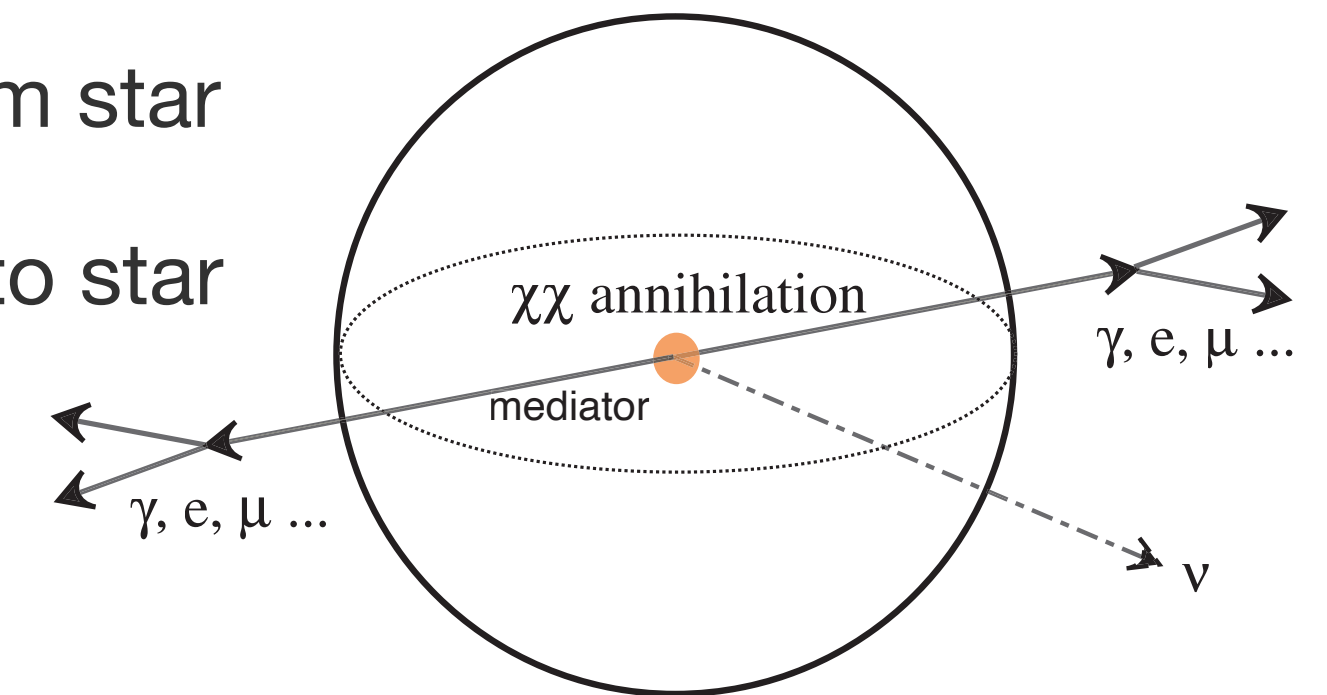
cf. Neutrino trapping in Supernova:  $\nu$  ( $E_\nu \gtrsim 10 \text{ MeV}$ ) is trapped in core of Supernova core ( $\rho \sim 10^{11} \text{ g/cm}^3$ )

→ **Neutrino may inject almost all its energy into Neutron Star before escaping**

# Indirect Detection @Compact Star

## Escape from Star: “Secluded DM” [B. Batell, M. Pospelov, A. Ritz, Y. Shang (2010)]

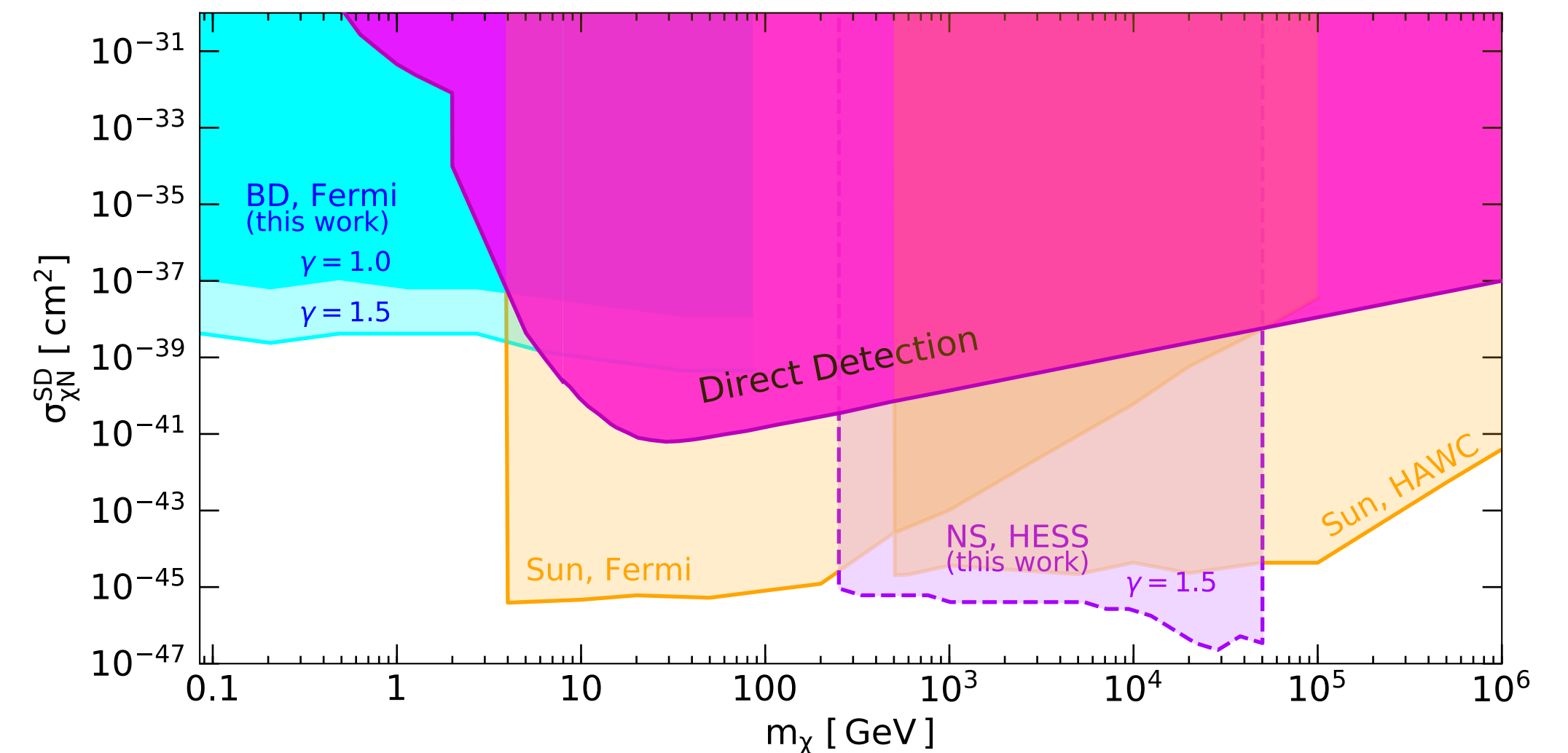
- Secluded DM: DM mainly annihilates into non-SM mediator first (which finally decay into the SM particles)
- If (mean free path of annihilation final state)  $>$  (star radius), mediator may escape from star
- Mediator decays outside of star, which may bring astro-signatures of DM capture into star  
This scenario is studied in the context of indirect detection



## Indirect Detection @Neutron Star

- Target: **Neutron Star**
- Region: **Galactic Center & Globular Cluster**
- Channel:  $\gamma$ -ray (H.E.S.S. data is used)
- Result: DM-nucleon cross section is constrained  
(Constrained region scales as the product of DM & celestial body densities )

[R. K. Leane et al. (2021)]



# Evaluation of Threshold $\sigma_{\text{th}}$ (Improved Treatment)

Question: **Robust evaluation of threshold  $\sigma_{\text{th}}$ ?**

- Most “Naive” treatment of Neutron Star  
→ Regarding Star as **bunch of individual neutrons**
- Conservative approach  
→ Considering DM scattering **other than** core region  
(Core is less understood compared other regions)

**Atmosphere**

**Outer crust:**

neutron-rich nuclei (crystalline lattice)  
in degenerated electron sea

**Inner crust:**

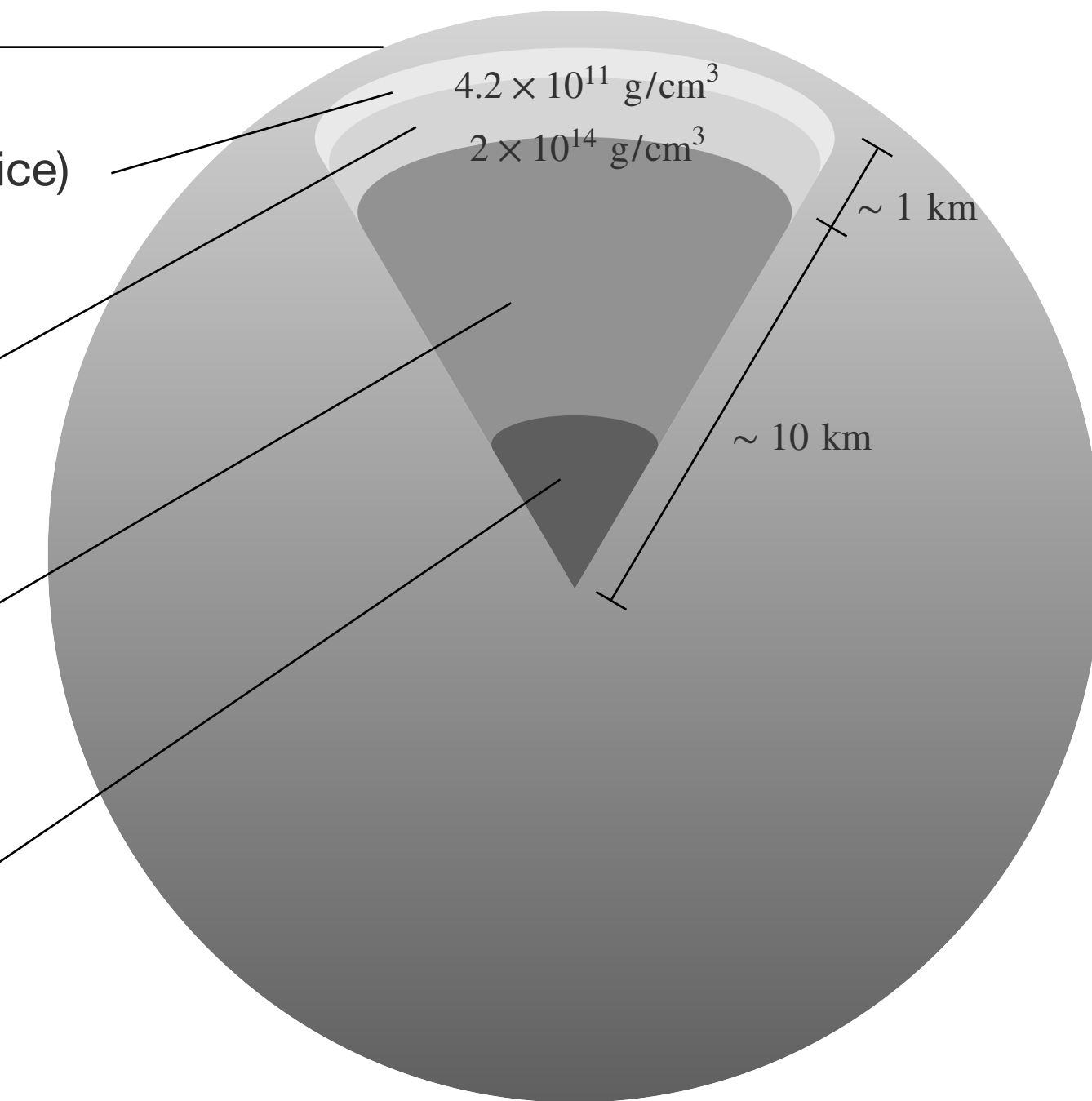
neutron-rich nuclei, electron  
neutron (superfluid:  $^1S_0$ )

**Outer core:**

electron, muon  
neutron (superfluid:  $^3P_2$ )  
proton (supercond.:  $^1S_0$ )

**Inner core:**

unknown



## Outer Crust: DM-Nucleon Scatt.

- Physics of the outer crust is best-understood of all the layers  
\* Coherent effects are irrelevant for all the DM mass range

$$\sigma_{\text{th}}^{\text{outer}} \simeq 10^{-40} \text{ cm}^2 \quad (\text{for } 10 \text{ MeV} - 1 \text{ PeV})$$

## Inner Crust: DM-Pasta Scatt.

- DM-nucleon scatt. dominates in outer region of inner crust
- Relatively light DM may excite phonon in superfluid of inner crust
- “Nuclear pasta” phase is predicted in innermost region of inner crust

$$\sigma_{\text{th}}^{\text{nucleon}} \simeq 10^{-41} \text{ cm}^2 \quad (\text{for } 10 \text{ MeV} - 1 \text{ PeV})$$

$$\sigma_{\text{th}}^{\text{phonon}} \simeq 10^{-39} - 10^{-34} \text{ cm}^2 \quad (\text{for } 10 \text{ eV} - 1 \text{ MeV})$$

$$\sigma_{\text{th}}^{\text{pasta}} \simeq 10^{-43} - 10^{-41} \text{ cm}^2 \quad (\text{for } 10 \text{ MeV} - 1 \text{ PeV})$$

# Accretion of Normal Matter

## Interstellar matter (ISM) heating effects

Some “expectation” for neglecting ISM effects

- Deflection by magnetic fields
- “Local bubble” structure near us  
ISM is relatively low within  $\sim 100$  pc

## Dedicated treatment

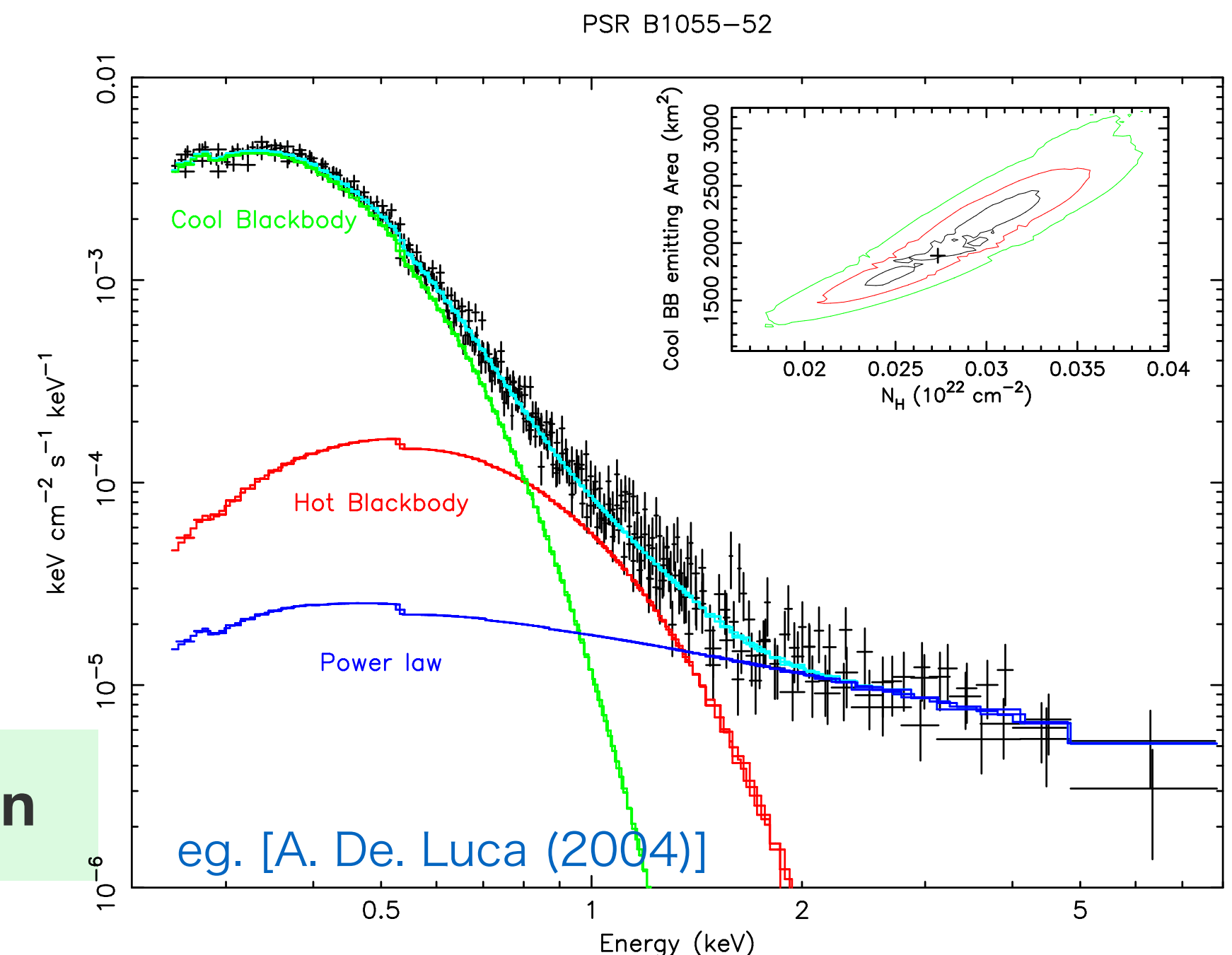
Key: Separating “Heating on magnetic pole” & “Surface temperature”

- Temperature observation = spectral fit w/ two blackbody component
- Hot blackbody ( $T_{hot}$ ): Coming from normal matter accretion on pole
- Cool blackbody ( $T_{cool}$ ): Corresponding to surface temperature

Separating  $T_{hot}$  &  $T_{cool}$  → We can overcome ISM heating contamination

Comment in [M. Baryakhtar et al. (2017)]

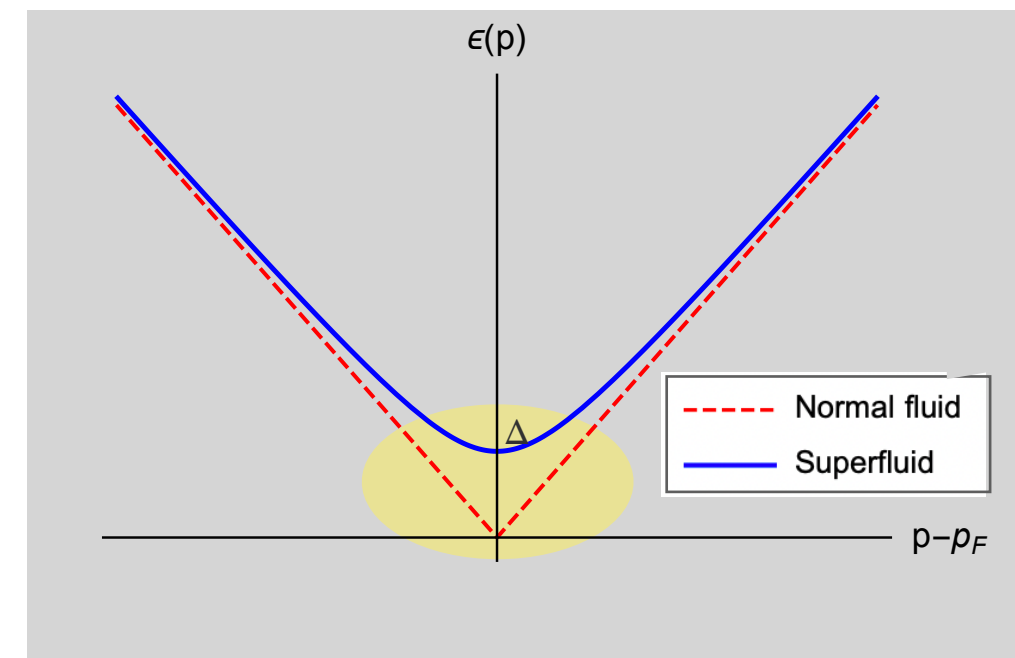
Another possible background to dark kinetic heating is **interstellar medium accretion onto neutron stars**, which depends on their **historic paths through the Milky Way disk and halo** [30, 31]. Present-day ISM heating can potentially be discerned from dark kinetic heating, because **accreted ions preferentially warm the poles of the neutron star and emit some X-ray photons** [32, 33]. In practice, **neutron star magnetic fields may deflect all but a fraction of incident ISM** [34]. Fortunately, the local 100 parsecs of ISM (the “Local Bubble” [35]) is relatively underdense, with ISM densities as low as  $\sim 10^{-3} \text{ GeV cm}^{-3}$ , making the present-day dark matter heating contribution predominant in this region.



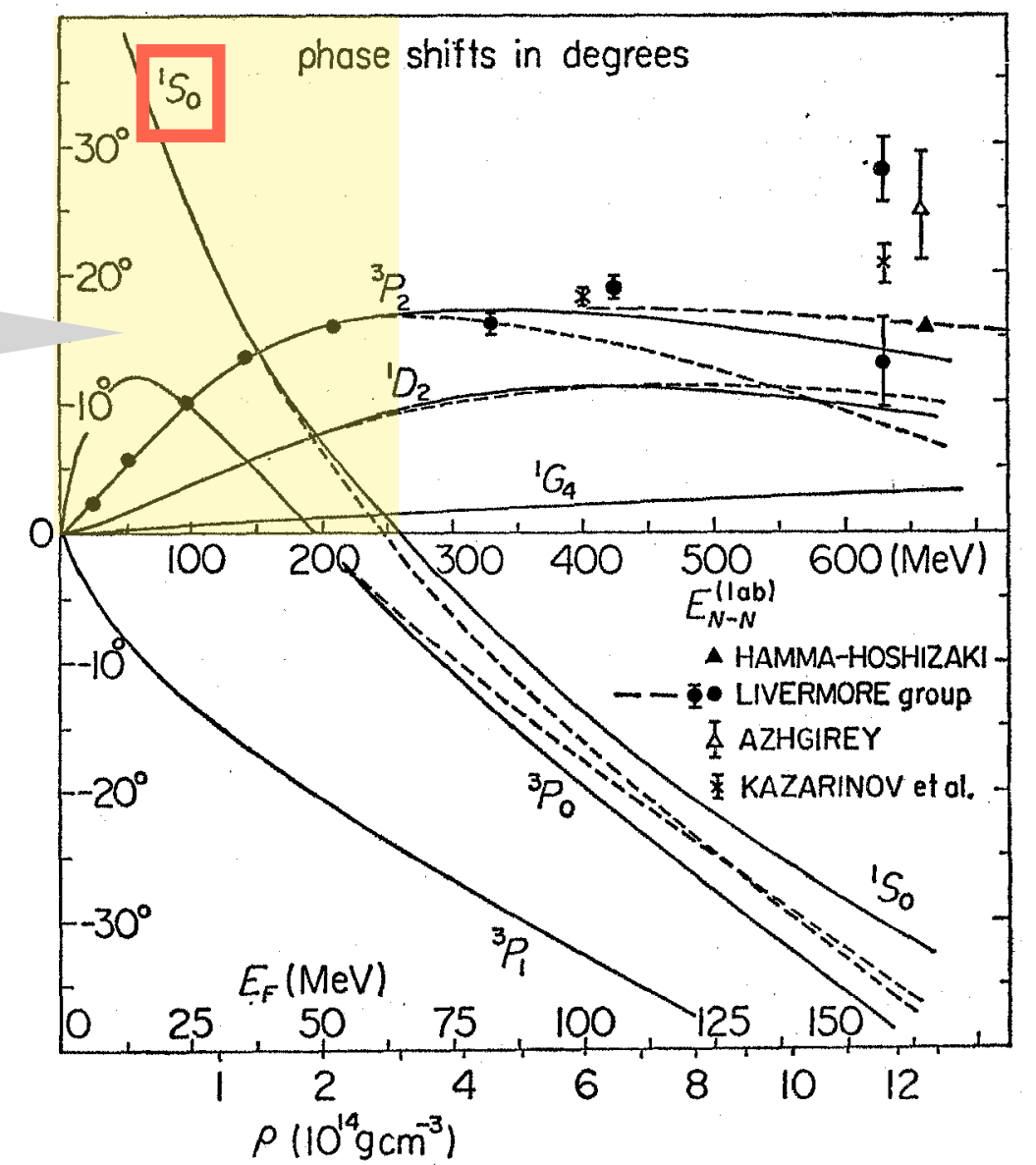
# Superfluidity in Neutron Star

## Condition for superfluidity appear

- Transport w/o dissipation effect
- $\Leftrightarrow$  Nonzero gap for the energy spectrum (to forbid dissipation)
- $\Leftrightarrow$  **Attractive force** (to have nonzero gap)
  - Can be read out from phase shift in nuclear scattering
    - Positive : attractive
    - Negative : repulsive



[R. Tamagaki (1970)]

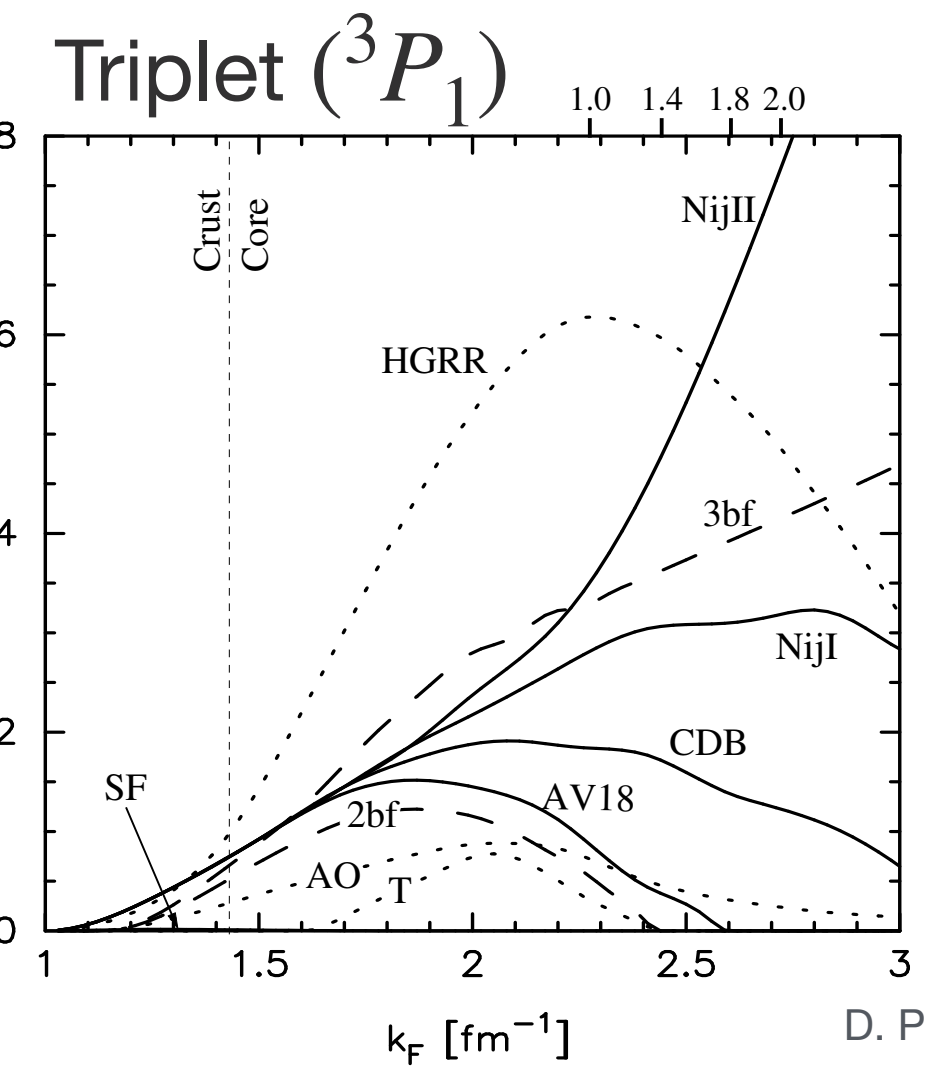
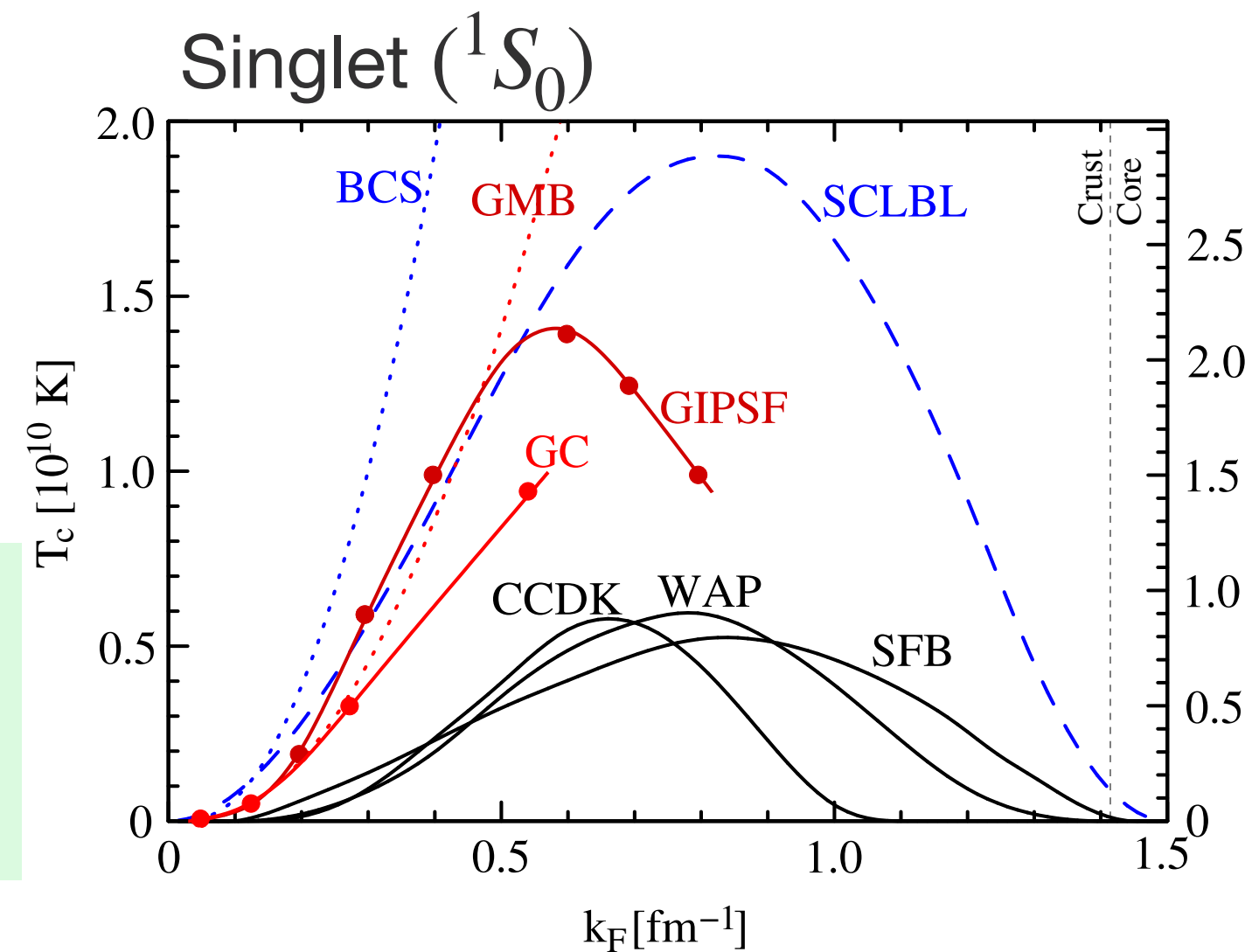


## Region for super fluidity to appear

- Two possibilities: singlet vs triplet
- Energy gap depends on Fermi momentum

Singlet ( $^1S_0$ ) : low momentum  $\rightarrow$  inner crust  
 Triplet ( $^3P_1$ ) : low momentum  $\rightarrow$  core

[D. Page+ [1302.6626]]



# Our Scales

