# Dark Matter Heating vs Vortex Creep Heating in Old Neutron Star

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Based on on-going work

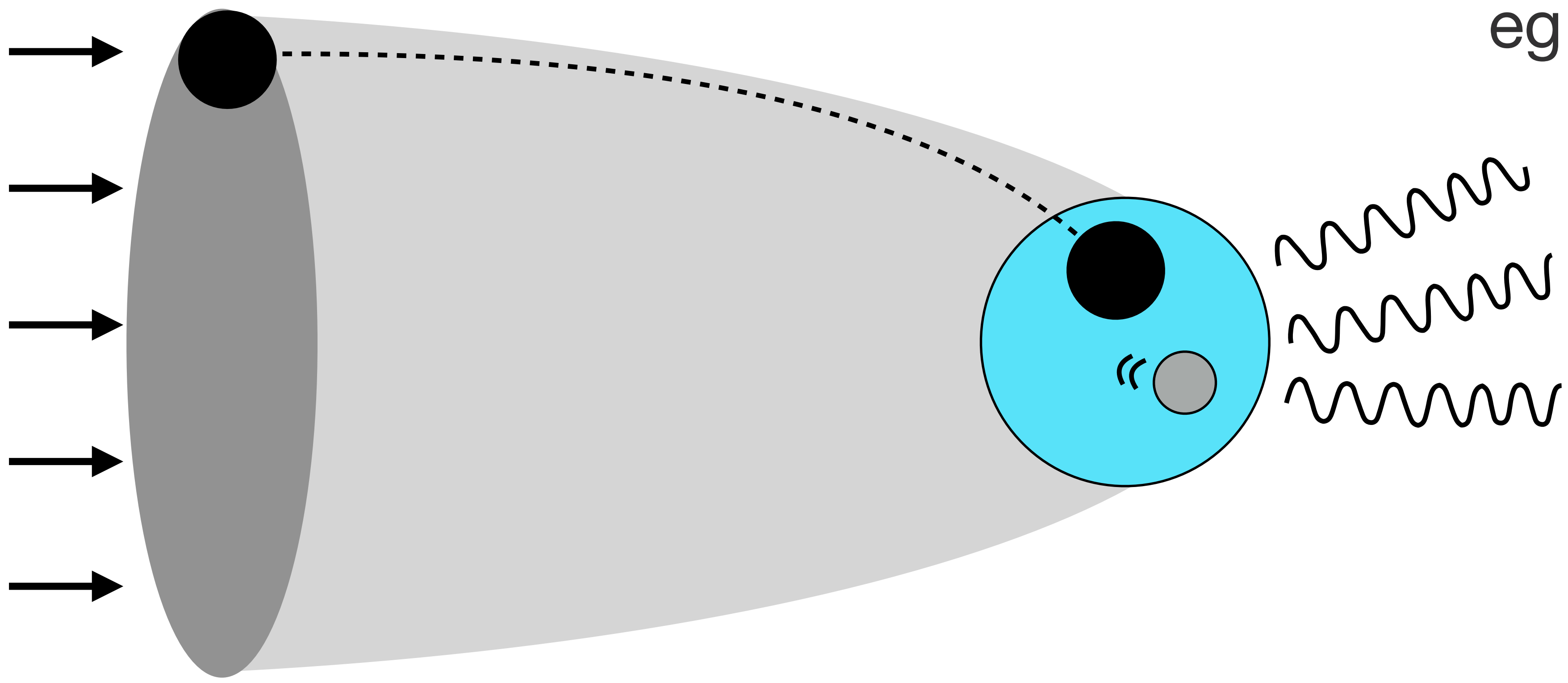
The Dark Side of the Universe @Kigali, Rwanda July 10, 2023

# **Neutron Star** as target of **Dark Matter**

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

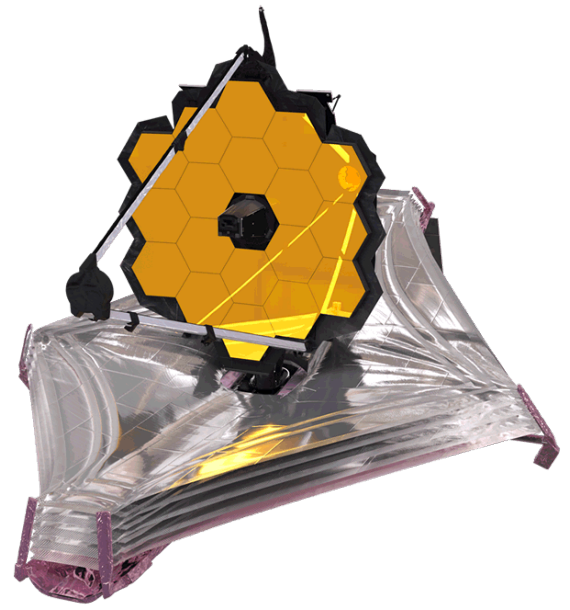
Dark Matter (DM)

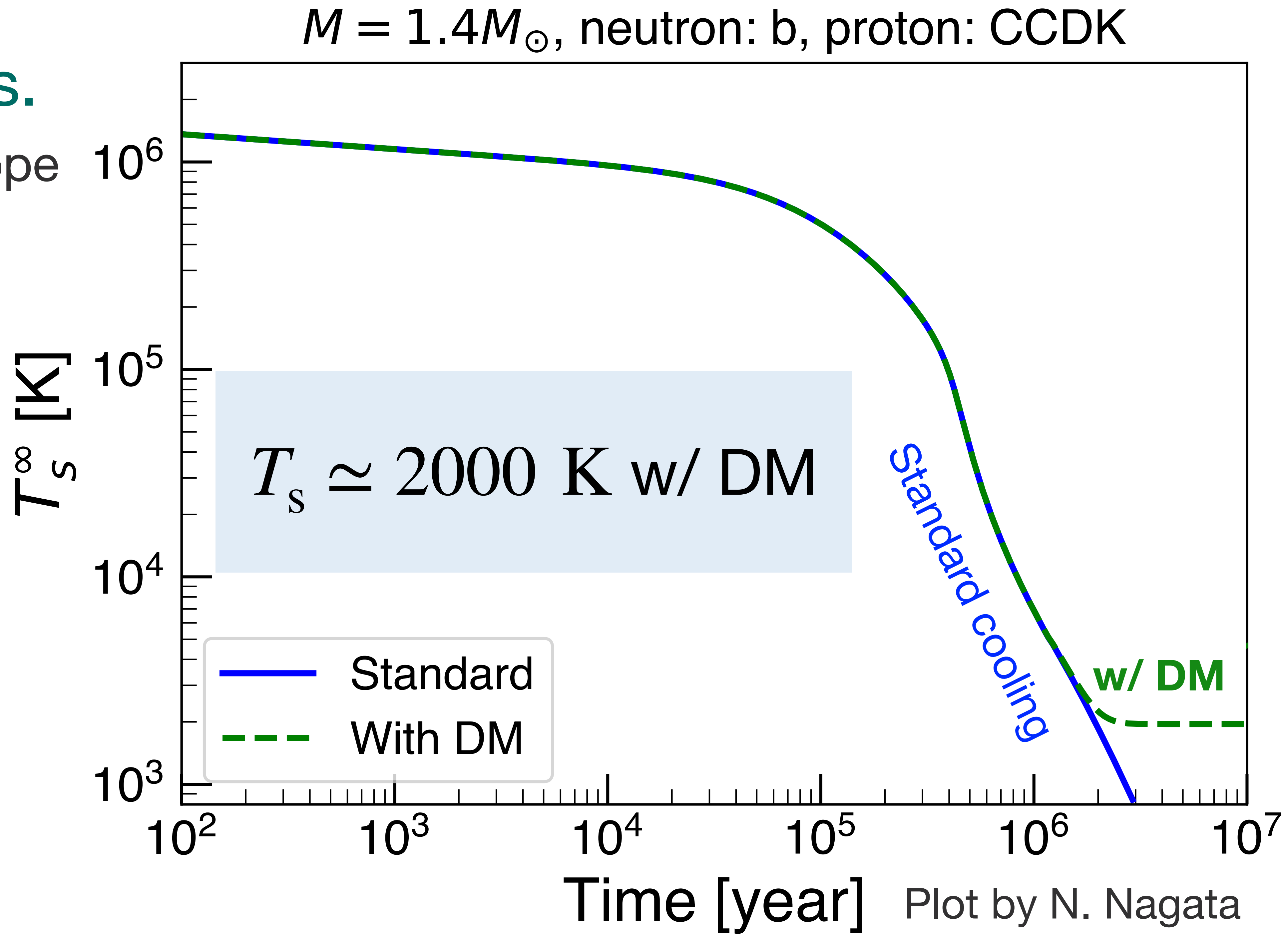
Neutron Star



**Surface Temperature Obs.**

eg. James Webb Space Telescope





Plot by N. Nagata

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

- 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: $T_s \simeq 2000\ {\rm K}$ for wide WIMP parameters** $(1\ {\rm GeV} - 1\ {\rm PeV}, \sigma_{\chi n} \gtrsim 10^{45}\ {\rm cm}^2)$
- If we observe neutron star w/ $T_s \lesssim 2000\ {\rm K}$, **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

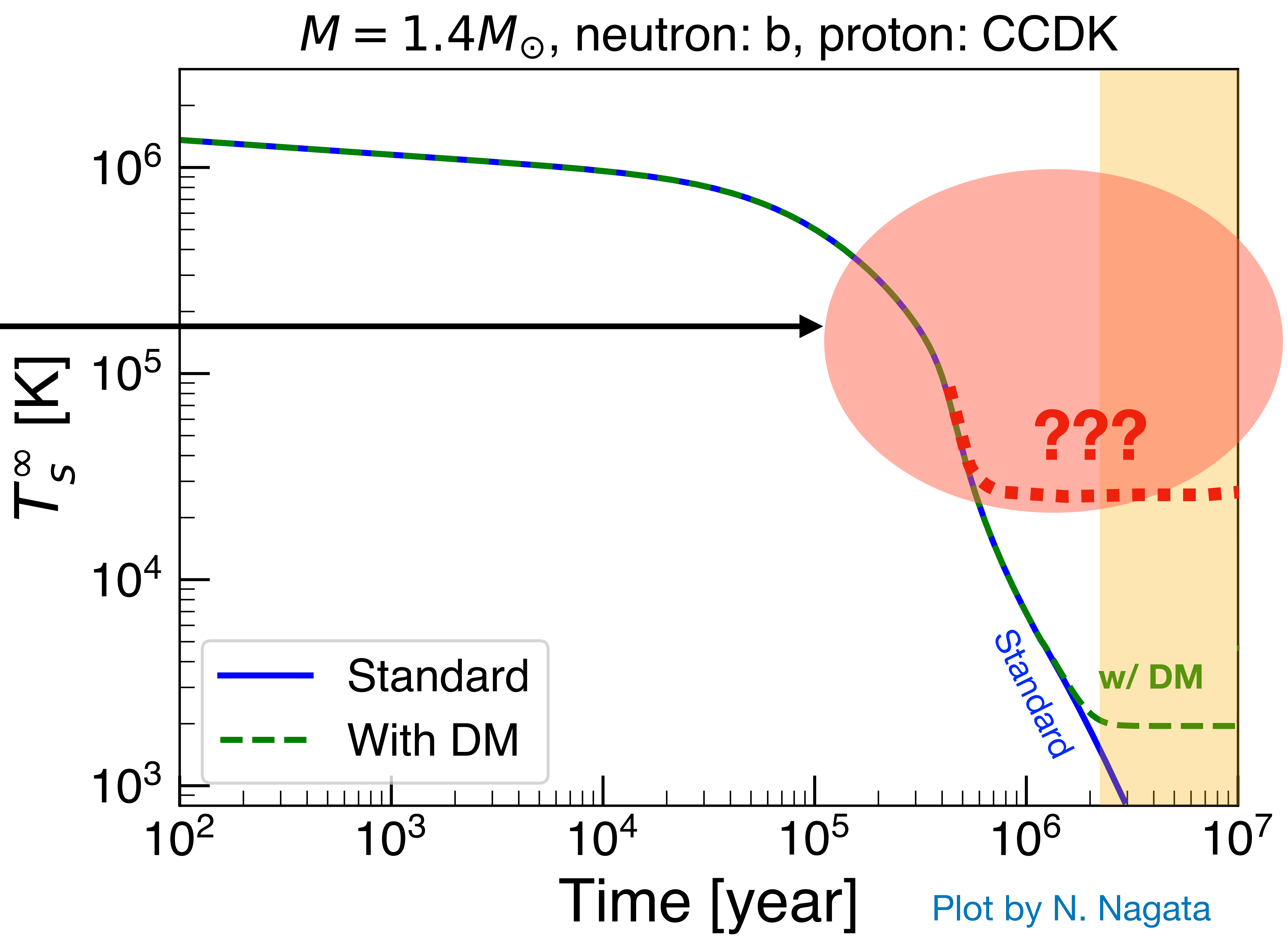
**Can we really probe DM heating effects?**

- 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)

[Alpar, Pines, Anderson, Shaham (1984)]
[Shibazaki, Lamb (1989)]



Plot by N. Nagata

[Lifshitz, Pitaevskii “Statistical Physics Part 2”]

# Vortex lines of neutron superfluid

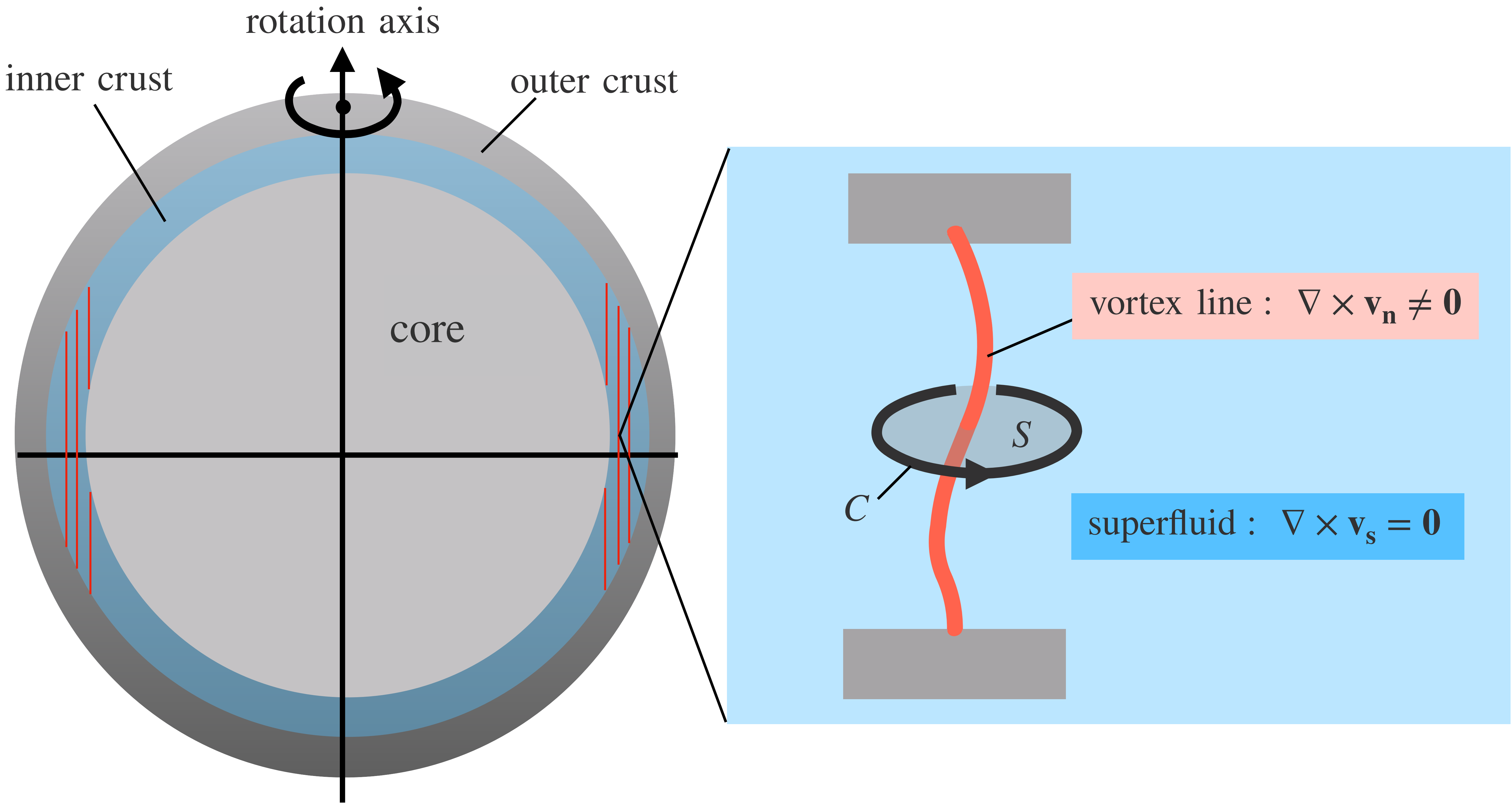
## Neutron superfluid

- 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

$$\Gamma \equiv \iint_S d\mathbf{S} \cdot (\nabla \times \mathbf{v}_s) = \int dr\, 2\pi r\, \underline{\kappa}\, \underline{n(r)}$$

Macroscopic measure of rotation

Vorticity per vortex line

# density of vortex line

- (Superfluid angular velocity) ⇔ (# of vortex line)

  → **Radial creep motion of vortex lines are necessary for superfluid to spin-down**

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

# Forces on Vortex Line

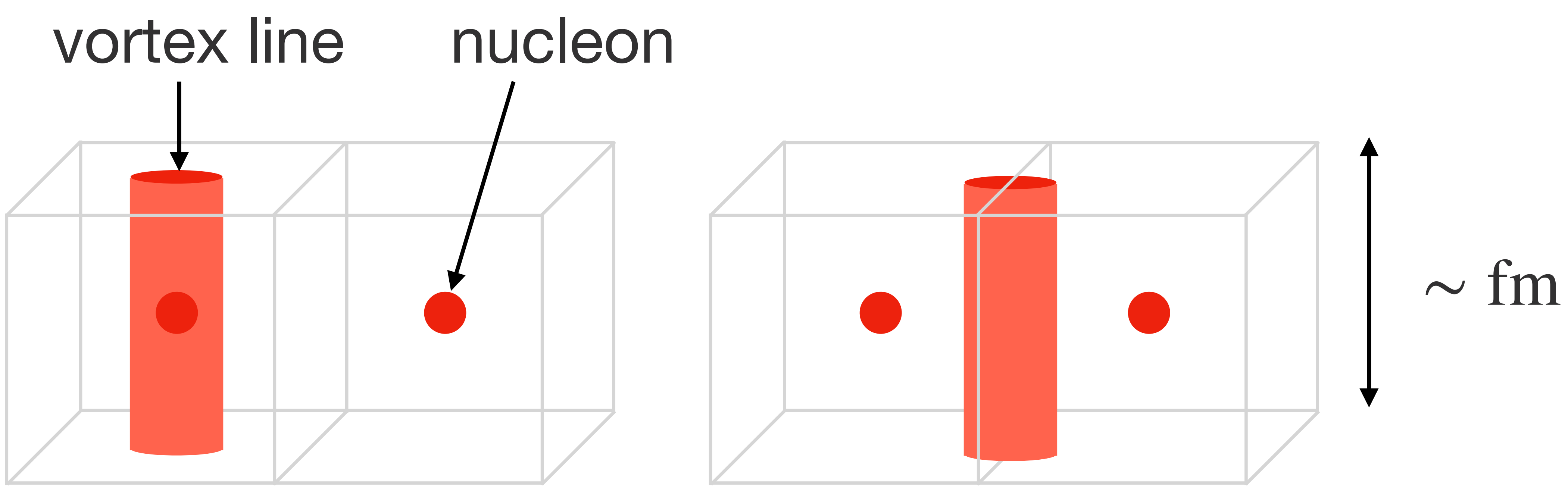
## (1) Pinning force

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

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

→ Vortex line can be trapped by crust component

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

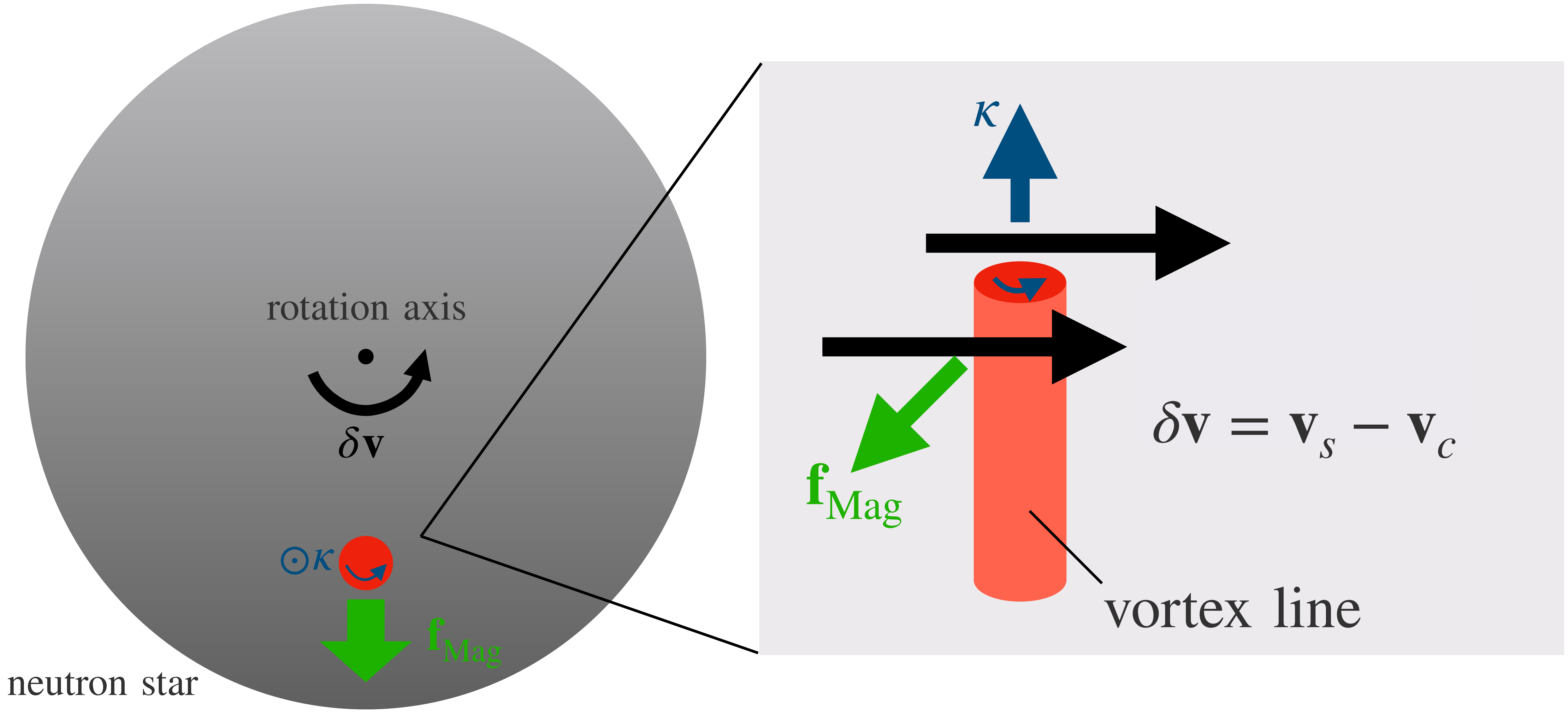


(1) Nuclear pinning (2) Interstitial pinning

## (2) Magnus force

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

- 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

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

# Energy dissipation

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

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

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

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

**We decided to test "Quasi-Universality of $J$" using neutron star $T_{\rm s}$-observations**

# Vortex creep heating vs Observations cf. $T_s \propto J^{1/4}$

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

XDINS (w/ strong magnetic field)

**Ordinary pulsar**
**Millisecond pulsar** } used to test hypothesis

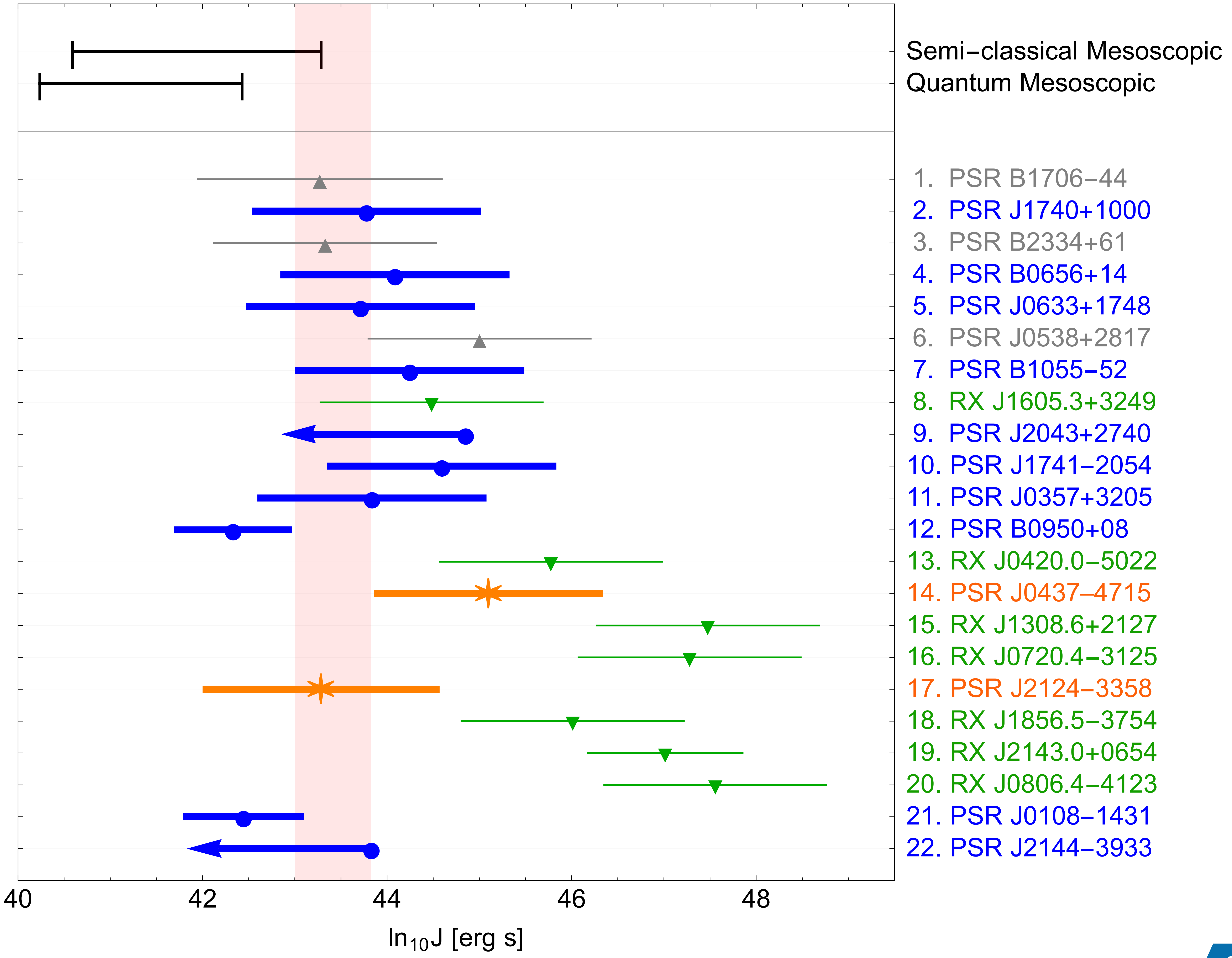
- We tested quasi-universality of $J$ in vortex creep hypothesis using NS obs.

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

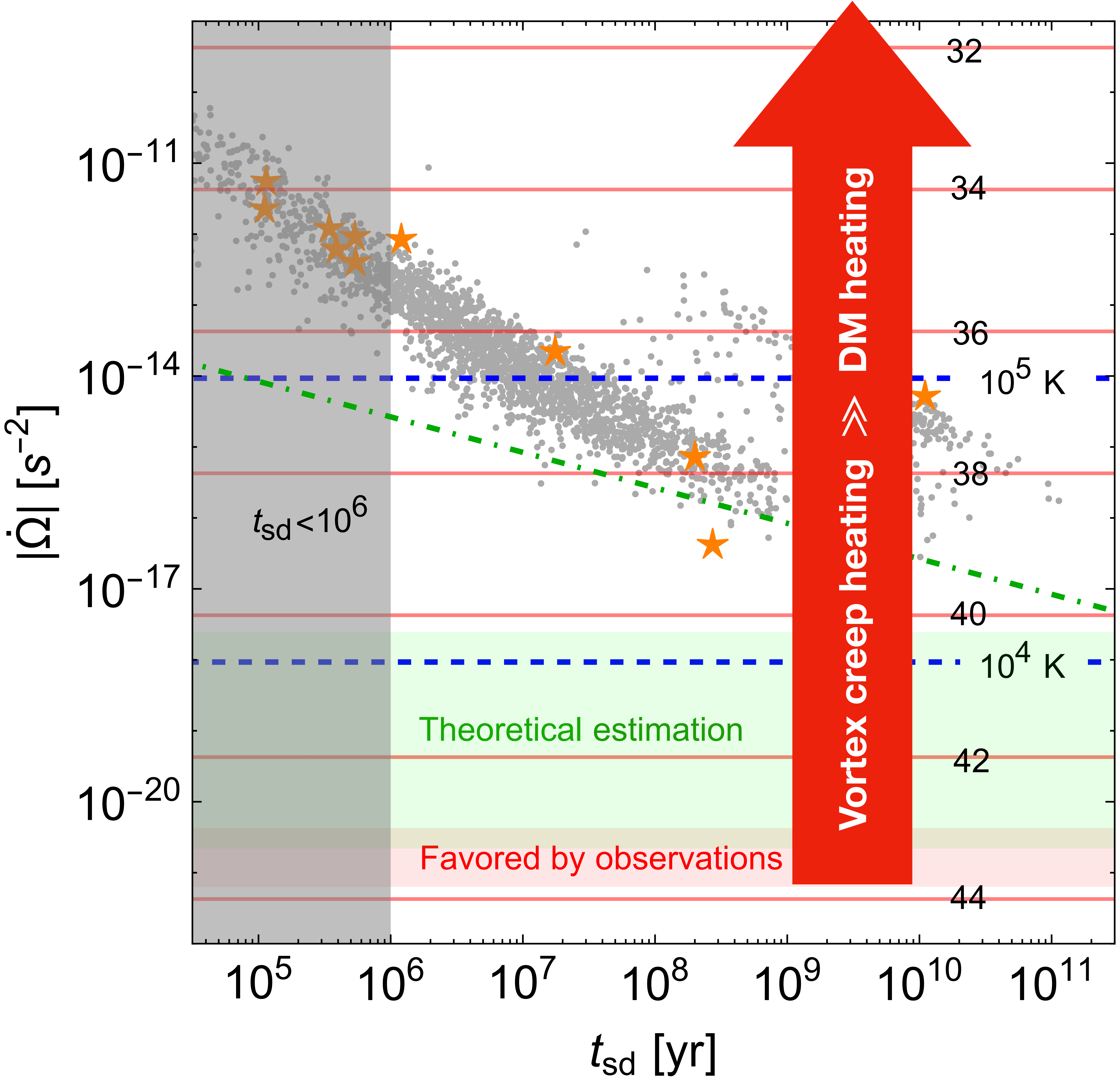
Result: $J_{\rm obs} \simeq 10^{43.0} - 10^{43.8}\ {\rm erg \cdot s}$

for $|\dot{\Omega}| \in [10^{-16}, 10^{-10}]\ s^{-1}$

**Vortex creep heating is consistent w/ current NS obs.**



# Vortex creep heating vs DM heating



● Currently discovered neutron stars

★ NS used to test vortex creep hypothesis

— Necessary value of $J$ to detect DM (in $\log_{10}$)
($T_s^{\rm DM} \simeq 2600$ K) [Chatterjee, et al.[arXiv:2205.05048]]

🟥 Observationally favored value of $J$ (in $\log_{10}$)

🟩 Theoretically favored value of $J$ (in $\log_{10}$)

- - - $T_s$ predicted by vortex creep heating ($J = 10^{43}$ erg · K)

- - - Pulsar death line [Ruderman, et al. (1975)]

Implication on DM heating?

**If we use $J_{\rm obs} \simeq 10^{43.0} - 10^{43.8}$ erg · s ,**

**(Vortex creep heating) $\gg$ (DM heating)**

# Summary

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

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

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

## Vortex creep heating vs Observation

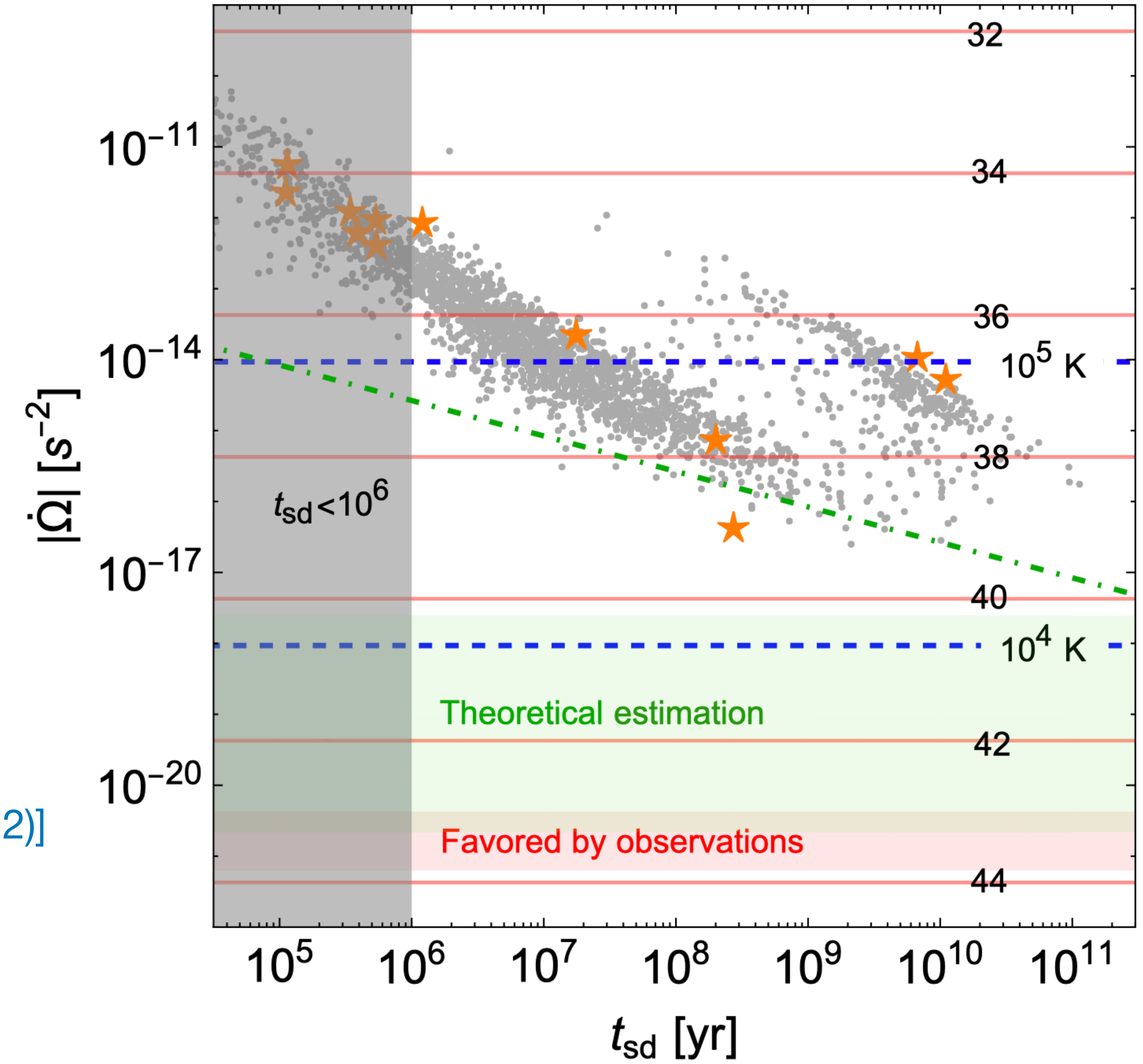
- Quasi-universal $J$ is obtained from obs: $J_{\mathrm{obs}} \simeq 10^{43.0-43.8}\ \mathrm{erg\ s}$
  → Consistent with vortex creep heating

## Vortex creep heating vs DM heating

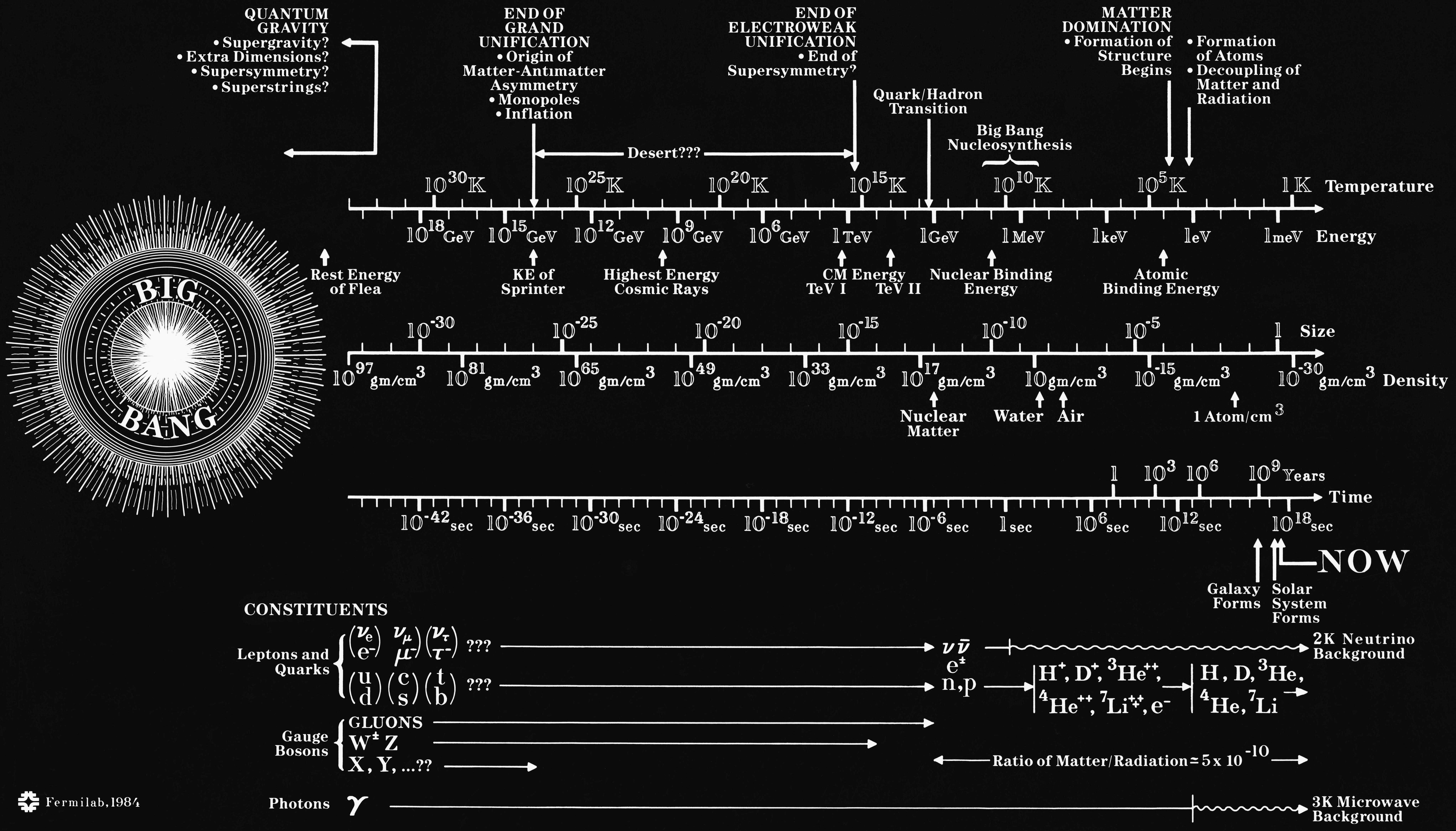
- Vortex creep heating seems to dominate DM heating

## Future direction?

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



# Backup



QUANTUM GRAVITY
- Supergravity?
- Extra Dimensions?
- Supersymmetry?
- Superstrings?

END OF GRAND UNIFICATION
- Origin of Matter-Antimatter Asymmetry
- Monopoles
- Inflation

Desert???

END OF ELECTROWEAK UNIFICATION
- End of Supersymmetry?

Quark/Hadron Transition

Big Bang Nucleosynthesis

MATTER DOMINATION
- Formation of Structure Begins

- Formation of Atoms
- Decoupling of Matter and Radiation

$10^{30}$K $10^{25}$K $10^{20}$K $10^{15}$K $10^{10}$K $10^{5}$K 1 K Temperature

$10^{18}$GeV $10^{15}$GeV $10^{12}$GeV $10^{9}$GeV $10^{6}$GeV 1 TeV 1GeV 1 MeV 1keV 1eV 1meV Energy

Rest Energy of Flea

KE of Sprinter

Highest Energy Cosmic Rays

CM Energy TeV I TeV II

Nuclear Binding Energy

Atomic Binding Energy

BIG BANG

$10^{-30}$ $10^{-25}$ $10^{-20}$ $10^{-15}$ $10^{-10}$ $10^{-5}$ 1 Size

$10^{97}$gm/cm$^3$ $10^{81}$gm/cm$^3$ $10^{65}$gm/cm$^3$ $10^{49}$gm/cm$^3$ $10^{33}$gm/cm$^3$ $10^{17}$gm/cm$^3$ 10gm/cm$^3$ $10^{-15}$gm/cm$^3$ $10^{-30}$gm/cm$^3$ Density

Nuclear Matter

Water

Air

1 Atom/cm$^3$

1 $10^{3}$ $10^{6}$ $10^{9}$ Years

$10^{-42}$sec $10^{-36}$sec $10^{-30}$sec $10^{-24}$sec $10^{-18}$sec $10^{-12}$sec $10^{-6}$sec 1 sec $10^{6}$sec $10^{12}$sec $10^{18}$sec Time

Galaxy Forms

Solar System Forms

NOW

**CONSTITUENTS**

Leaptons and Quarks $\begin{pmatrix}\nu_e\\ e^-\end{pmatrix} \begin{pmatrix}\nu_\mu\\ \mu^-\end{pmatrix} \begin{pmatrix}\nu_\tau\\ \tau^-\end{pmatrix}$ ??? $\rightarrow$ $\nu\bar{\nu}$ $\rightsquigarrow$ 2K Neutrino Background

$\begin{pmatrix}u\\ d\end{pmatrix} \begin{pmatrix}c\\ s\end{pmatrix} \begin{pmatrix}t\\ b\end{pmatrix}$ ??? $\rightarrow$ $e^\pm$ n,p $\rightarrow$ $H^+, D^+, {}^3He^{++}, {}^4He^{++}, {}^7Li^{+++}, e^-$ $\rightarrow$ $H, D, {}^3He, {}^4He, {}^7Li$ $\rightarrow$

Gauge Bosons
GLUONS $\rightarrow$
$W^\pm$ Z $\rightarrow$
X, Y, ...?? $\rightarrow$

Ratio of Matter/Radiation ≈ 5 x $10^{-10}$

Photons $\gamma$ $\rightarrow$ $\rightsquigarrow$ 3K Microwave Background

Fermilab,1984

# Pinning force (1/2)

$R$: distance from rotational axis

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

→ We need to specify
- $[R_{\rm in}, R_{\rm out}]$
- $f_{\rm pin}$ for each region

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

- **Semi-classical approach** [Donati, Pizzochero (2004)] [Seveso, Pizzochero, Grill, Haskell (2015)]

  Thomas-Fermi approx. (nucleons ≃ 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

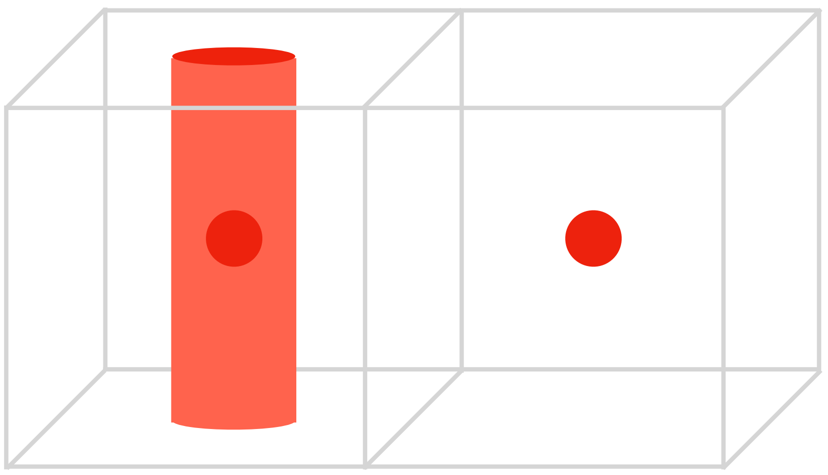
## Evaluation of $f_{\rm pin}$

- **“Microscopic” evaluation**

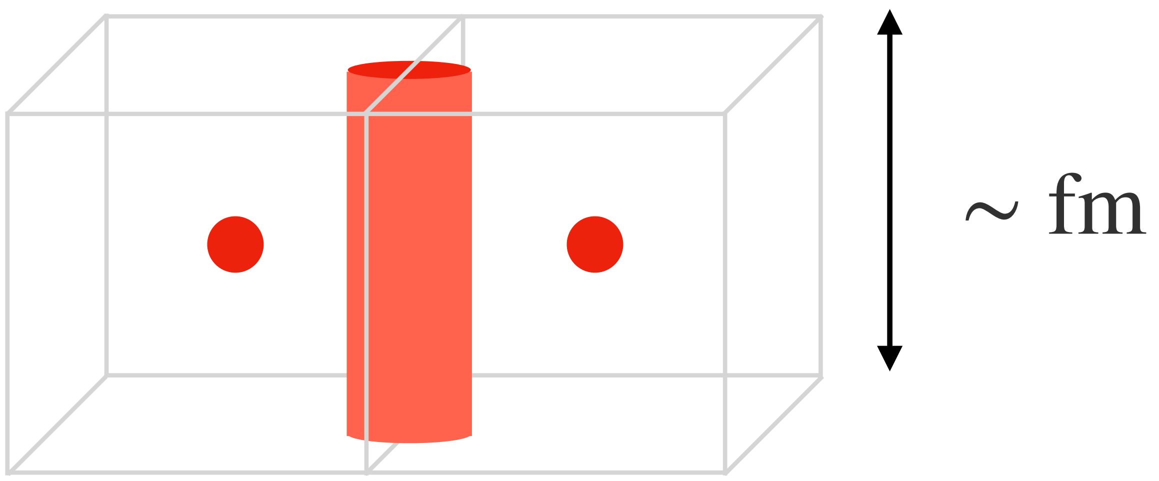
  Estimation using $E_{\rm pin}$ derived in $\rm fm$-size box

- **“Mesoscopic” evaluation**

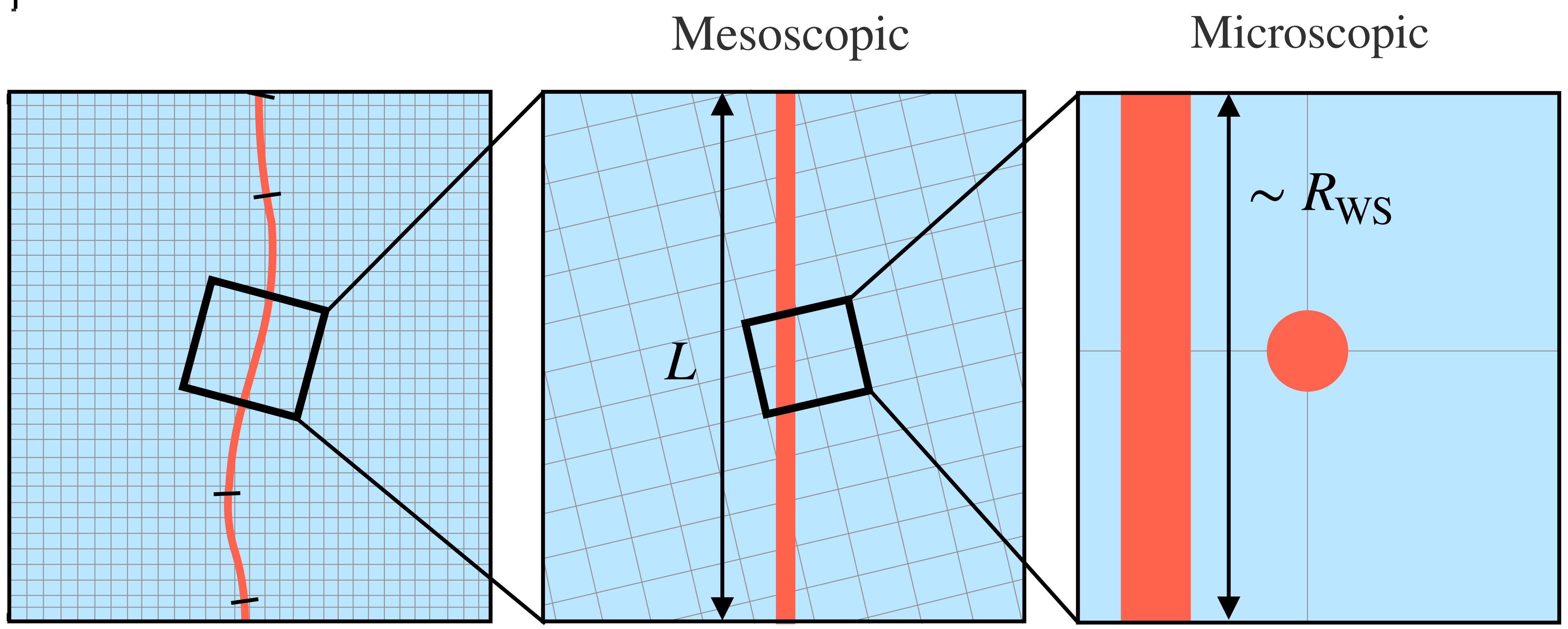
  Averaging $f_{\rm pin}$ along mesoscopic length $L \simeq (10^3 - 10^4)\ \rm fm$



(1) Nuclear pinning



(2) Interstitial pinning



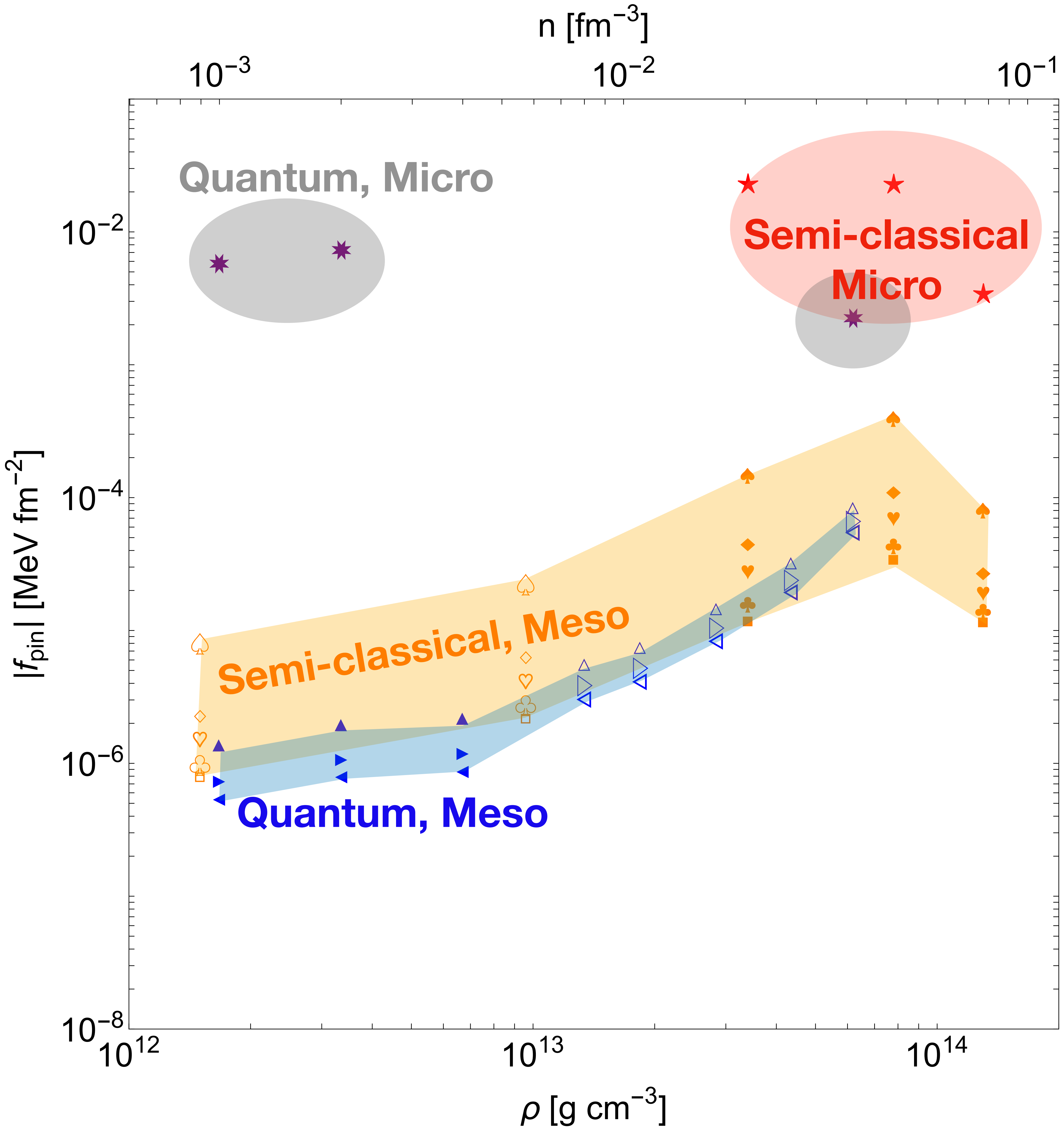
# Pinning force (2/2)

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

| | | $E_{\rm pin}$-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] |

**Each many-body calculation implies different $f_{\rm pin}(\rho)$**

**EoS uncertainty enters to connect $\rho \to R$** (radial distance)



# Evaluation of $J_{\rm pin}$

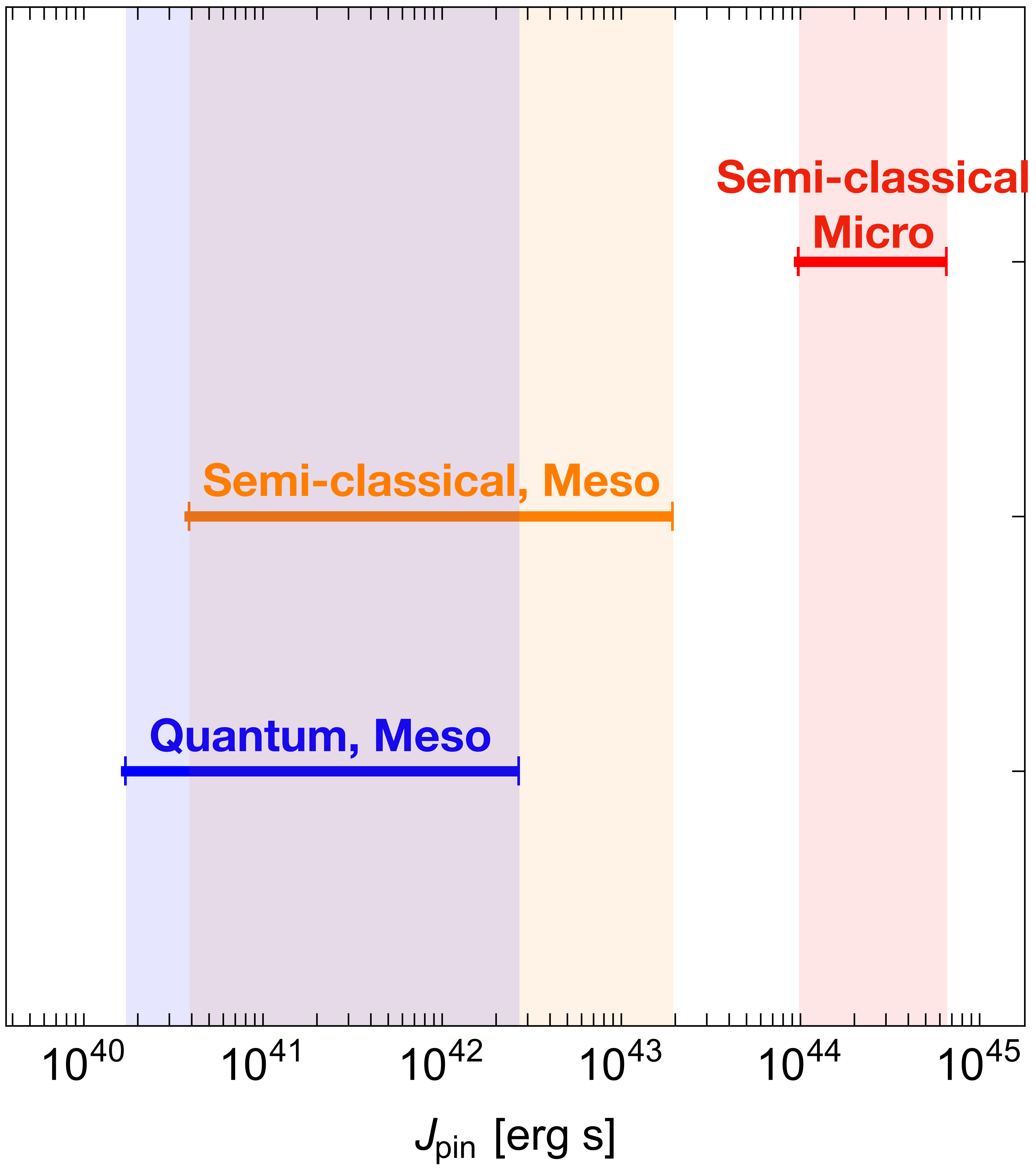
$$J_{\rm pin} \simeq \int_{R_{\rm in}}^{R_{\rm out}} dR\,d\theta\,d\phi\; R^3 \sin^2\theta \cdot \frac{f_{\rm pin}(\cancel{R})}{\kappa}\Bigg|_{\rm min}^{\rm max}$$

Input evaluations of $f_{\rm pin}$

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

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

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



[McGowan et al. (2004)]

# Temperature observation: B1706-44 as eg.

## Profile

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

## Fitting

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

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

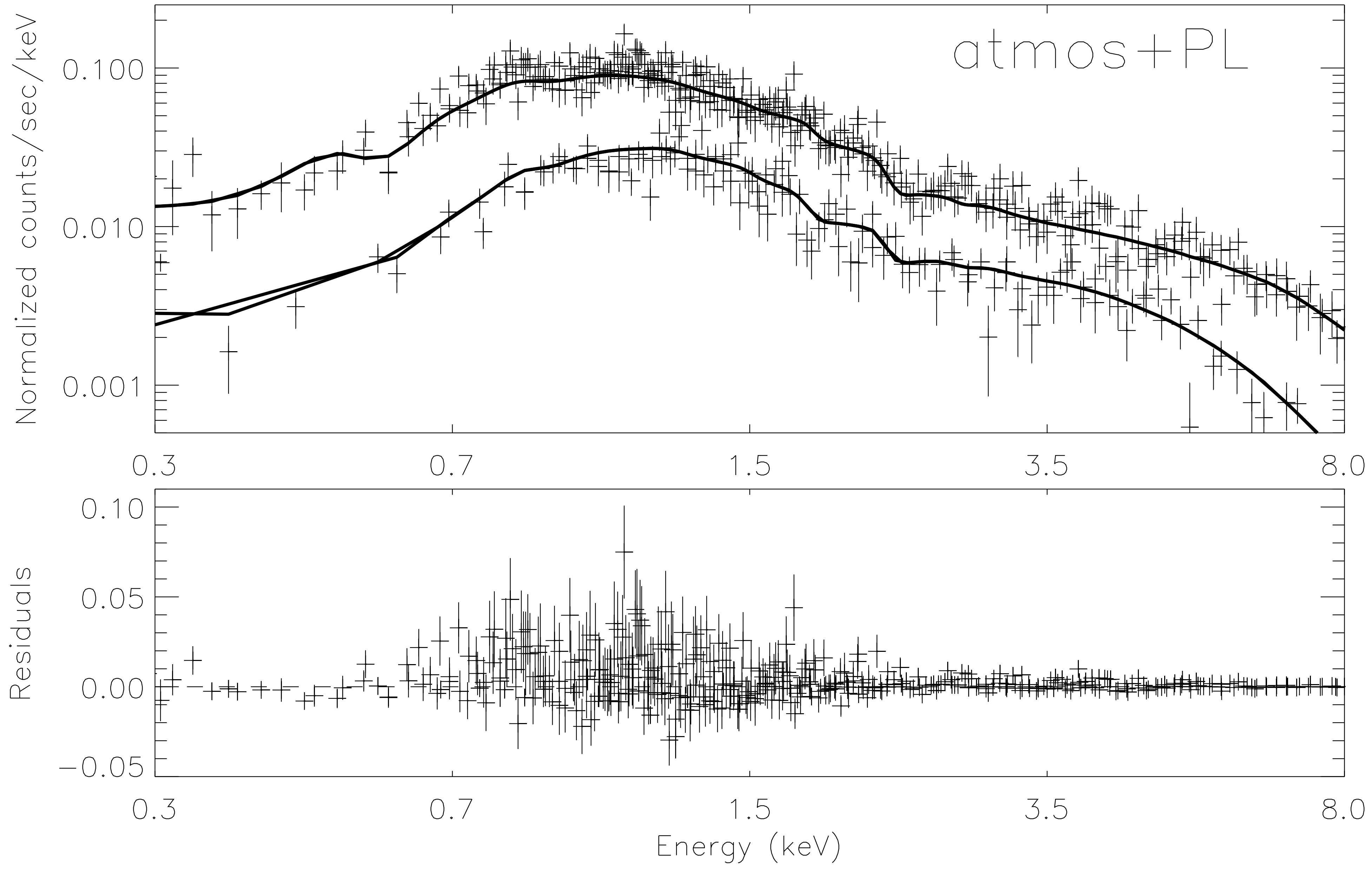
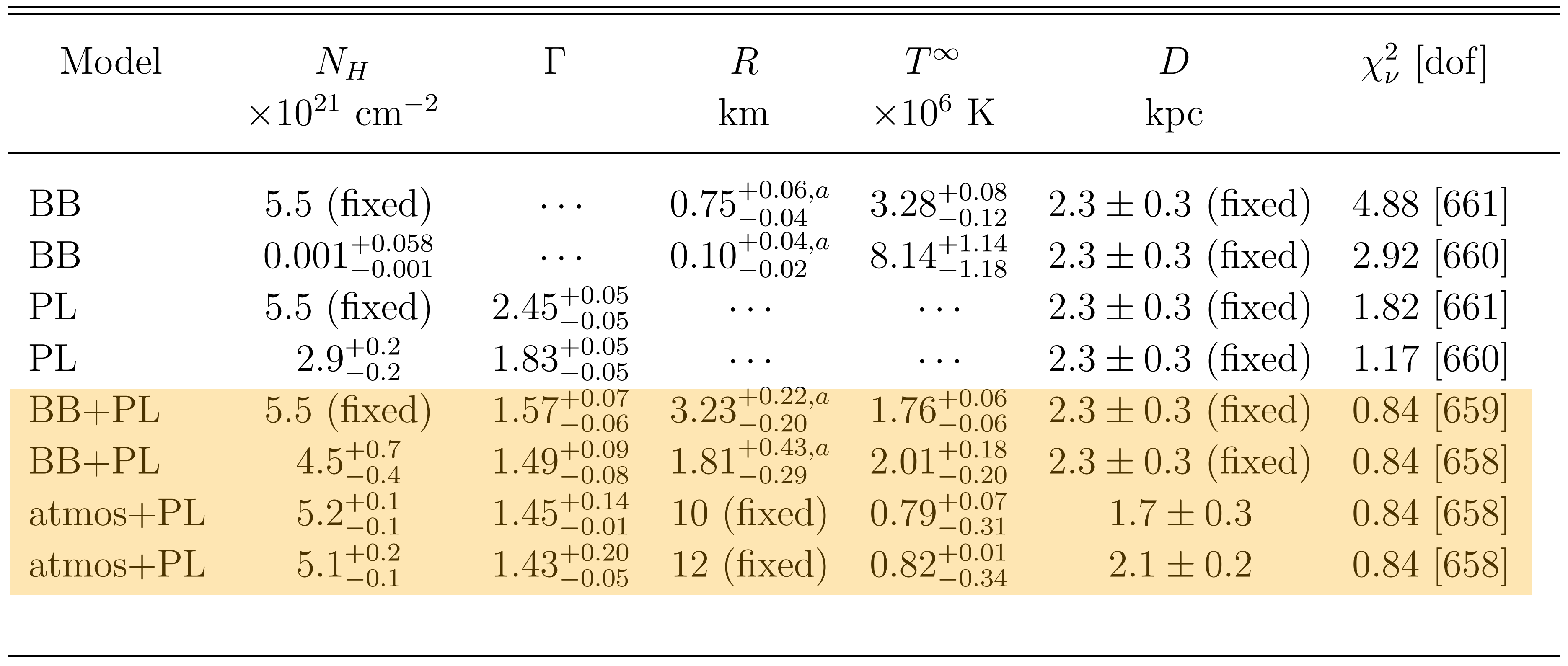


Table 1. Spectral fits to PSR B1706-44



| Model | $N_H$ $\times 10^{21}$ 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

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

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

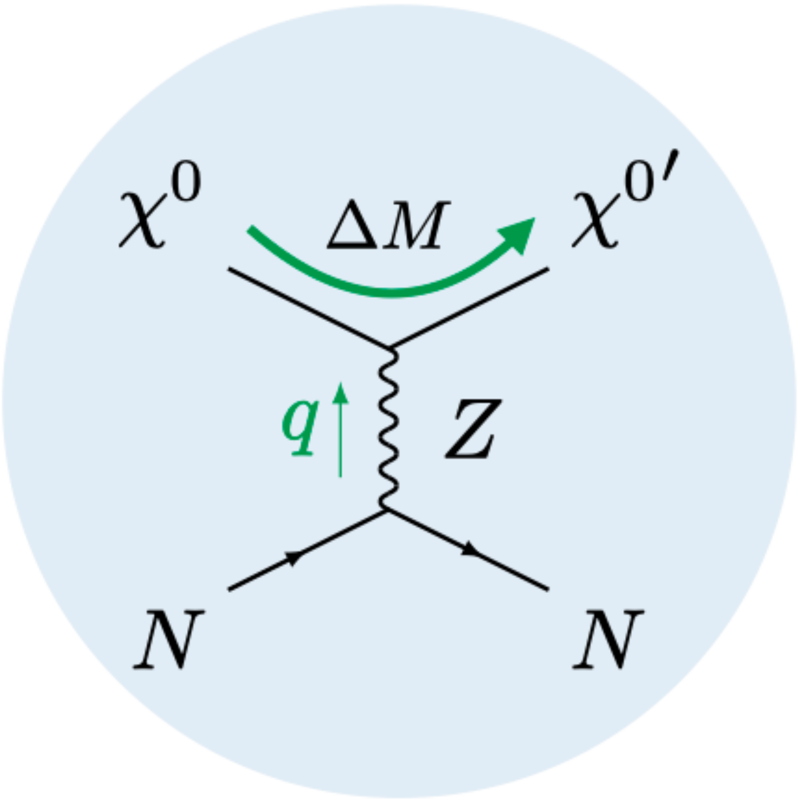
| | | Direct detection | NS observation |
|---|---|---|---|
| Elastic | SI | $\sigma_{\rm SI}^{(N),{\rm upper}} \simeq 10^{-45}\ {\rm cm}^2$ $\simeq$ | $\sigma_{\rm th}^{(N)} \simeq 10^{-45}\ {\rm cm}^2$ |
| | SD | $\sigma_{\rm SD}^{(N),{\rm upper}} \simeq 10^{-40}\ {\rm cm}^2$ $\gg$ | |
| Inelastic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

## Inelastic DM scattering

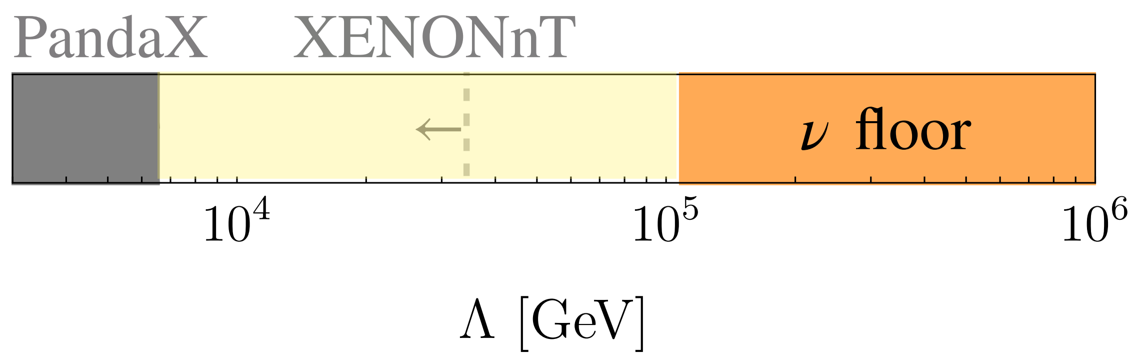
[N. F. Bell, G. Busoni, S. Robles (2018)]
[MF, K. Hamaguchi, N. Nagata, J. Zheng (2022)]

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

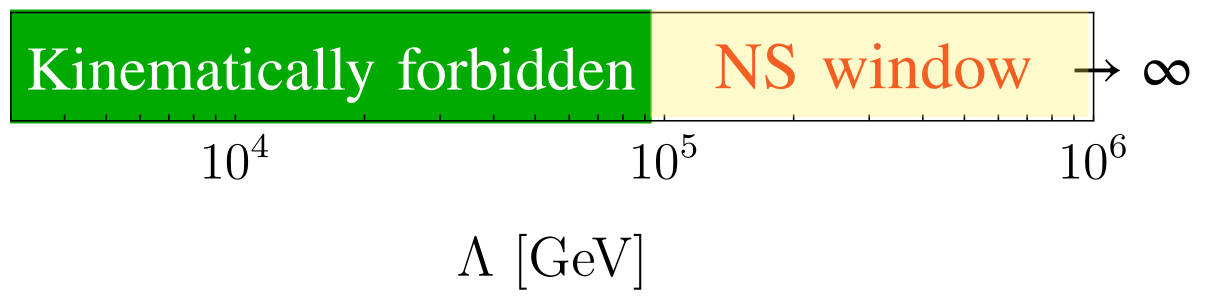
$$\Delta M_{\rm EW} \simeq \alpha_2 m_W \simeq \mathcal{O}(100)\ {\rm MeV}$$



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) $T_s \gtrsim 2600\ \mathrm{K}$ & (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/ $T_s \lesssim 10^3\ \mathrm{K}$, **DM w/ nucleon int. can be widely constrained** for $\mathrm{GeV}$-$\mathrm{PeV}$ range

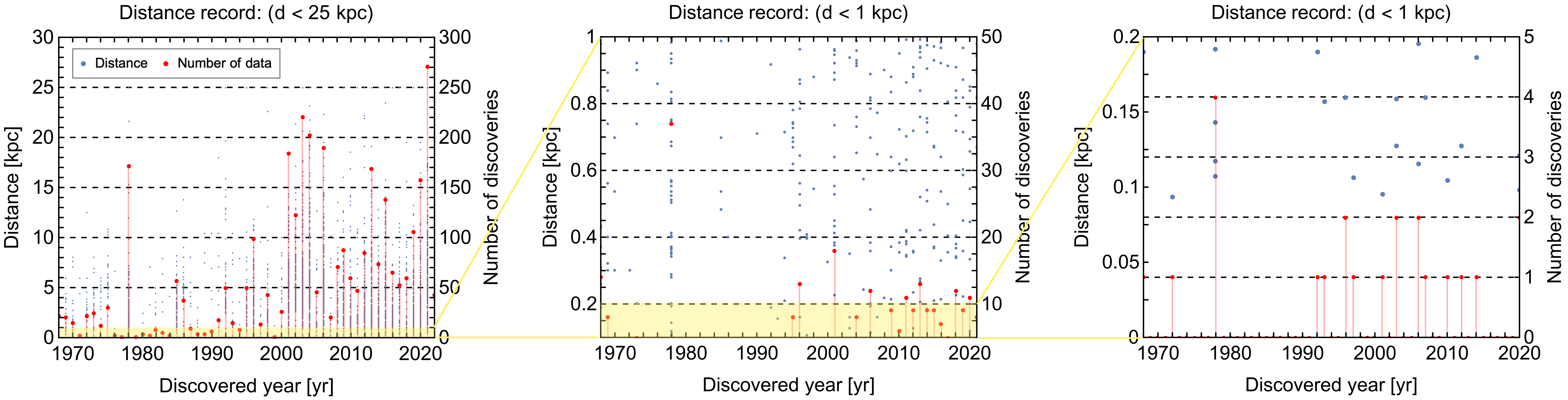
**Can we control uncertainty in Neutron Star (astro obs.) compared w/ Direct Detection (Underground exp.)?**

- We do have uncertainty from {
  - Astrophysics (eg. Internal unknown structure of compact star, initial condition)
  - Nuclear Physics (eg. Nuclear force model under high density )
- 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/]



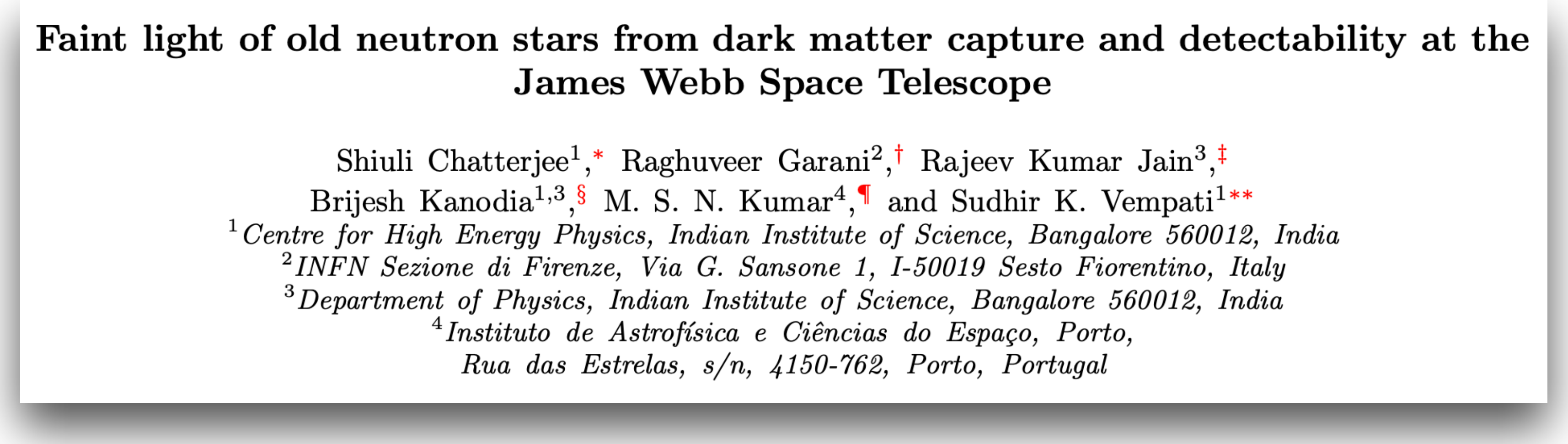
## Discovered Year vs Distance

- Recently, the number of pulsar data is increasing rapidly
  (eg. **248 pulsar data** is added by FAST exp.)
- Nearest pulsar data: (Distance) ~ 100 pc
  Pulsar within ~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 |

[Chatterjee, Garani, Kumar Jain, Konadia, Kumar, Vempati [2205.05048]]

# JWST Sensitivity



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

Shiuli Chatterjee[1,*] Raghuveer Garani[2,†] Rajeev Kumar Jain[3,‡]
Brijesh Kanodia[1,3,§] M. S. N. Kumar[4,¶] and Sudhir K. Vempati[1**]
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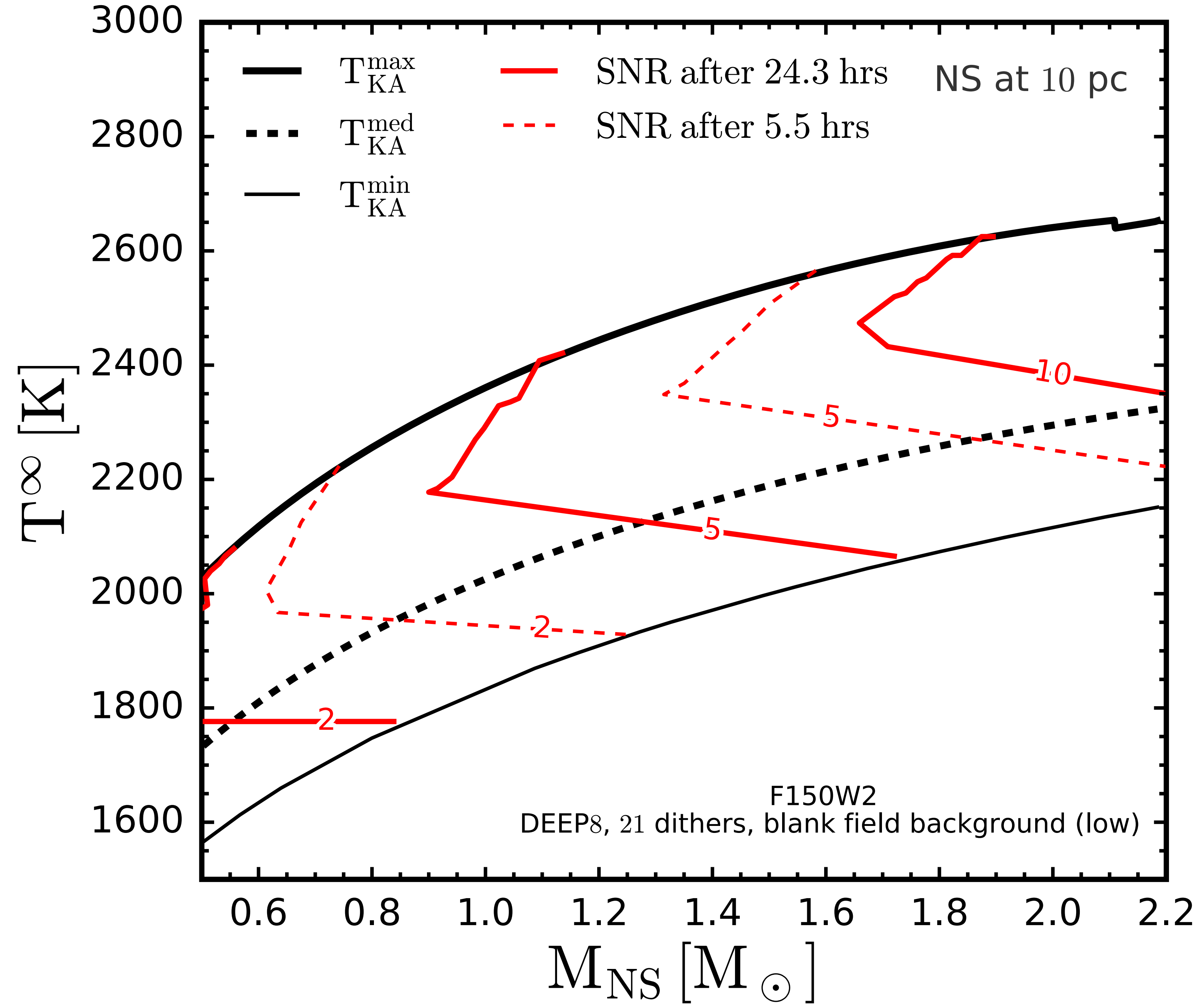
## Targets

- 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
  → $T_s \simeq 2600~\mathrm{K}$ (w/ $40~\%$ validation)



## JWST Sensitivity for DM heating

- Wave length of DM black body radiation : $\lambda \simeq 2~\mu\mathrm{m}$
- 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)

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

[Chatterjee, Garani, Kumar Jain, Konadia, Kumar, Vempati [2205.05048]]

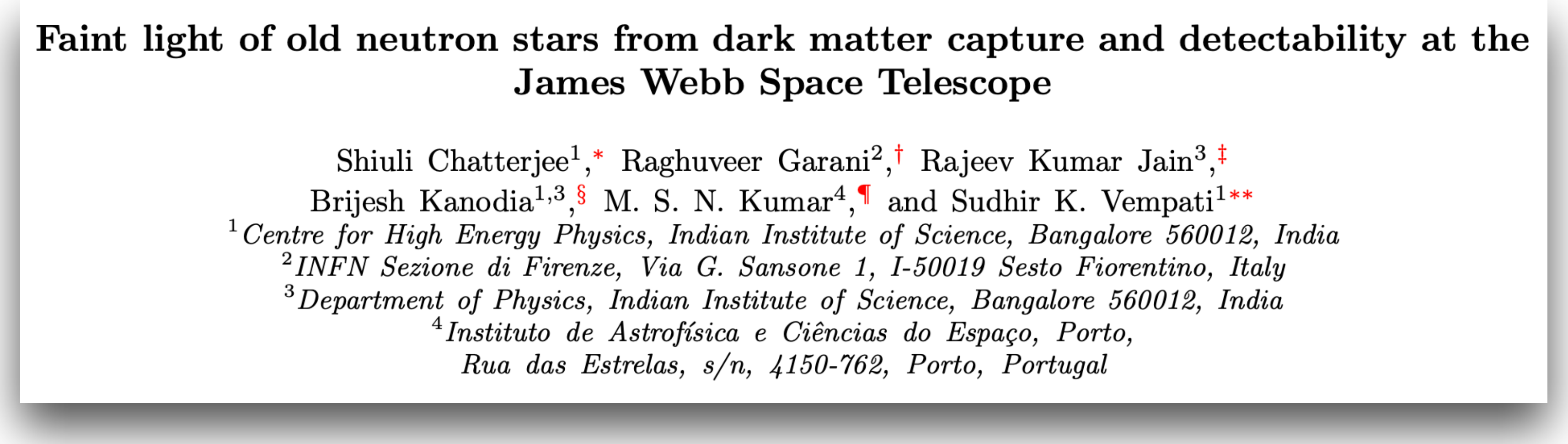
# JWST Sensitivity (2/3)

## 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: $f_\lambda \in [0.5,2]$ nJy $@\lambda \sim 2\ \mu$m



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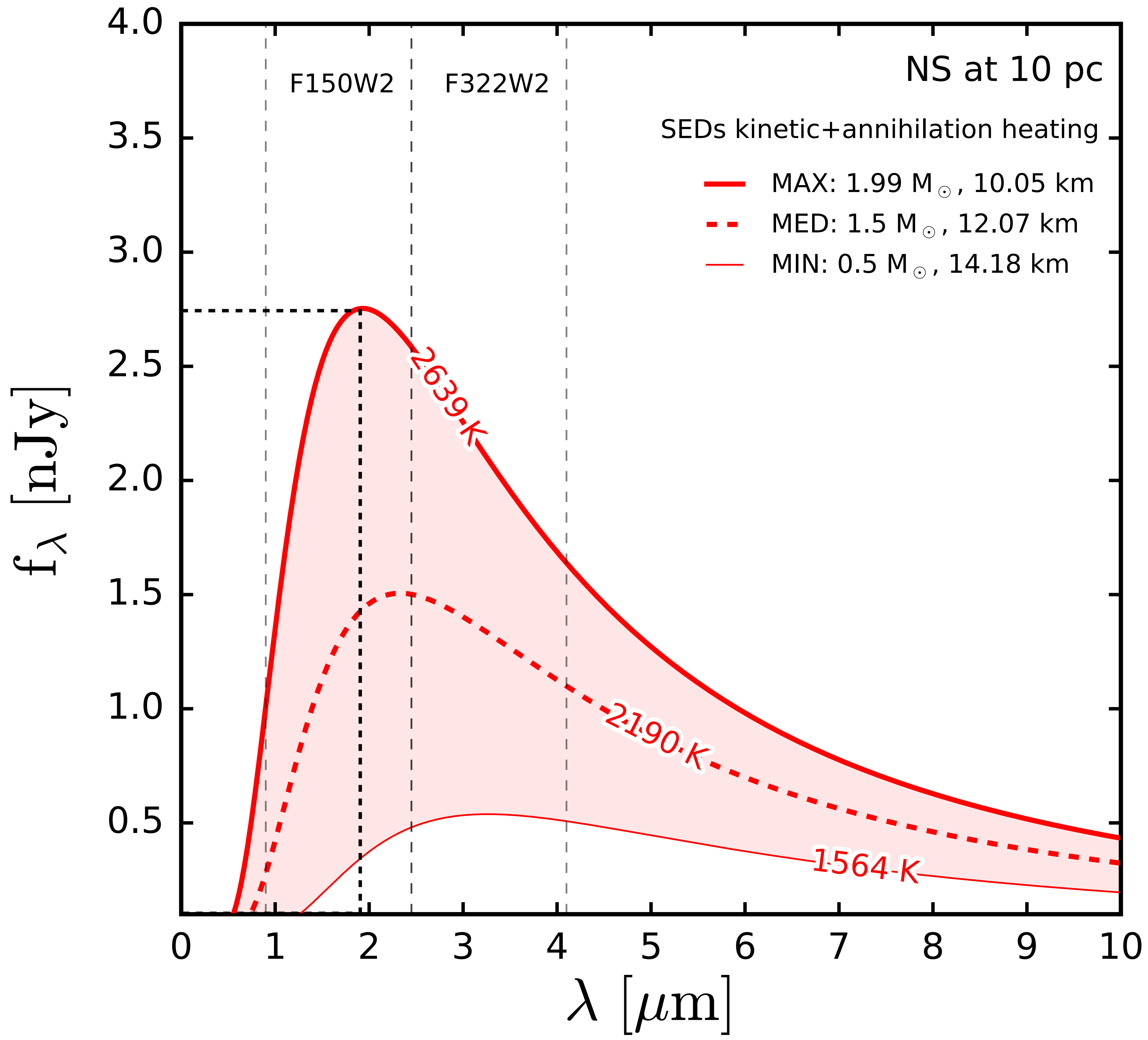


[Chatterjee, Garani, Kumar Jain, Konadia, Kumar, Vempati [2205.05048]]

# JWST Sensitivity (3/3)

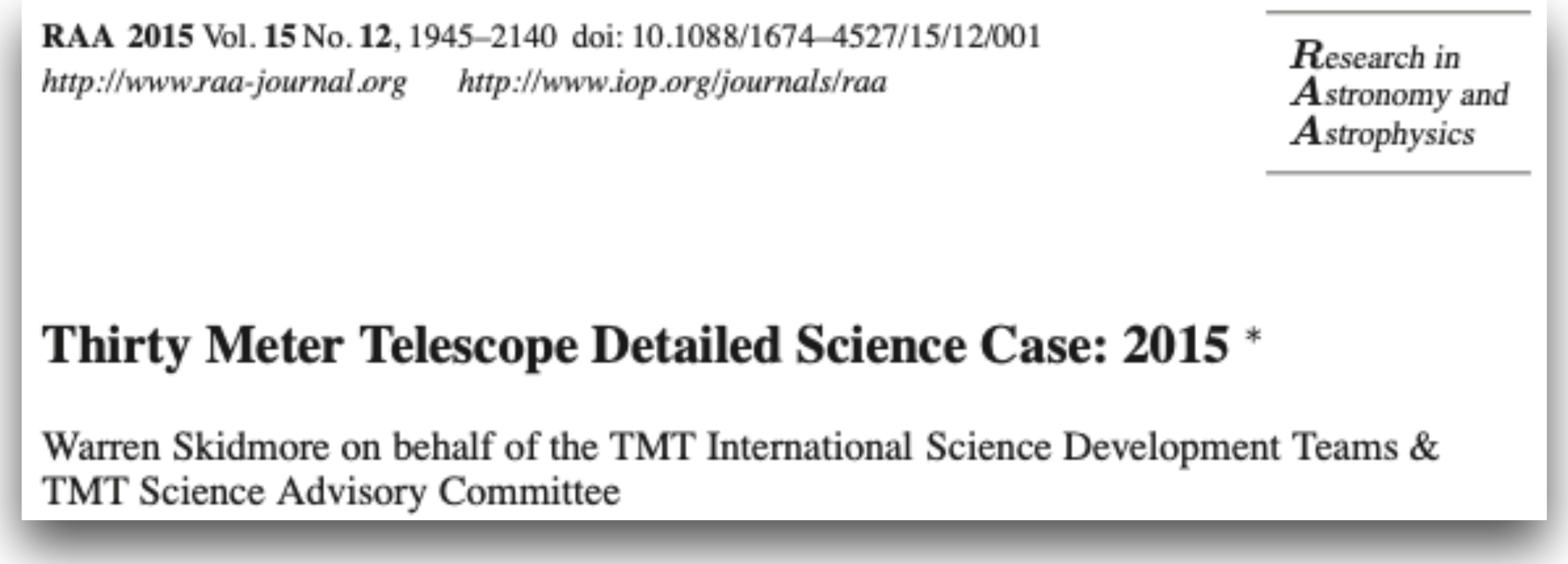
## Exposure time vs SNR

- 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

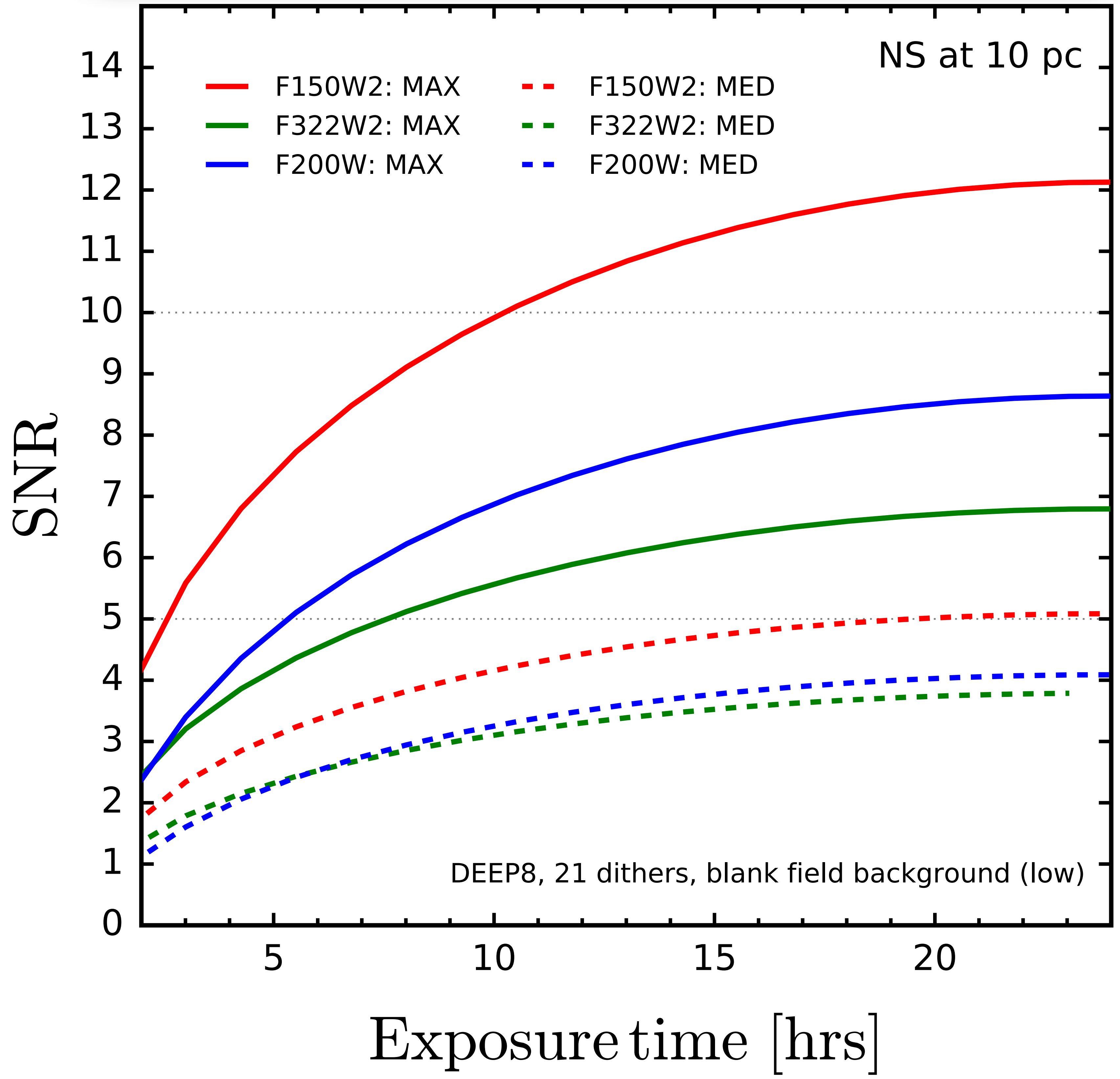


**RAA 2015** Vol. **15** No. **12**, 1945–2140 doi: 10.1088/1674–4527/15/12/001
*http://www.raa-journal.org* *http://www.iop.org/journals/raa*

*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]

- 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: $T_s \simeq \mathcal{O}(1000)\ \mathrm{K}$

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

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

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

Neutrino mean free path : $L_\nu$

Neutron averaged density : $\bar{n}_n = 10^{37}\ \mathrm{cm}^{-3}$

Neutron-neutrino cross section : $\sigma_{n\nu} \propto G_{\mathrm{F}}^2 E_\nu^2$

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

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

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

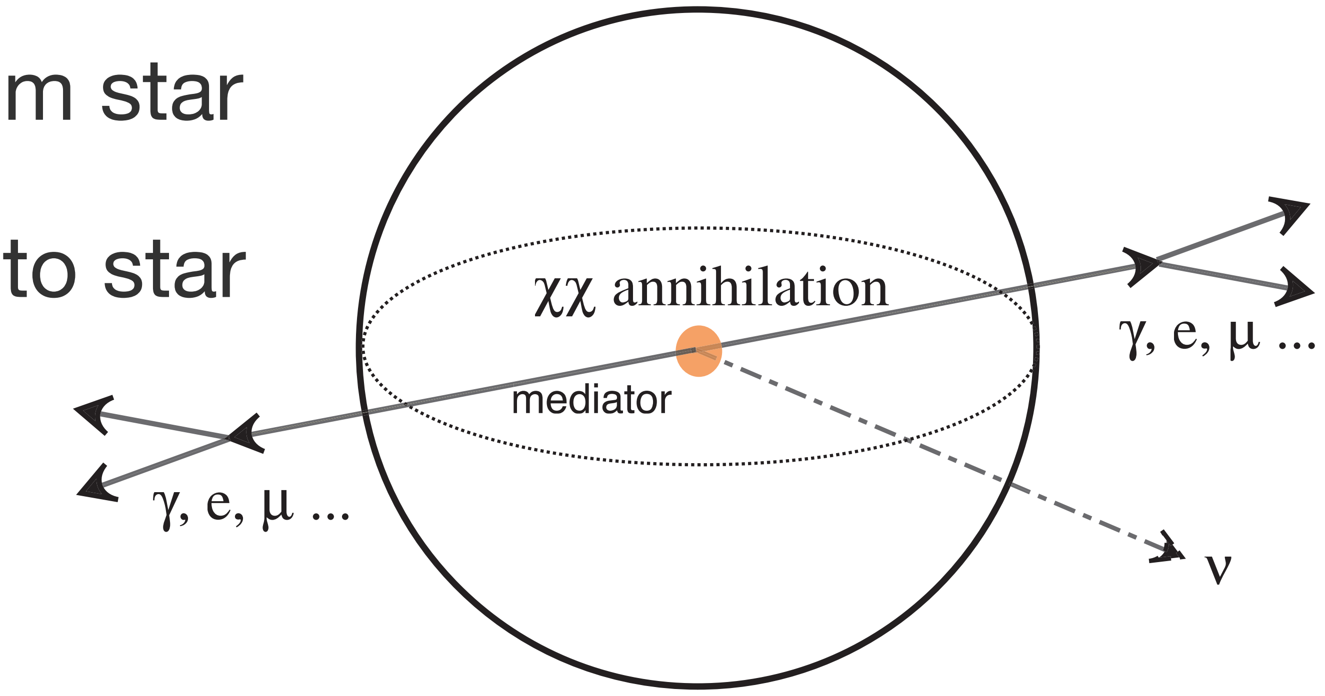
→ **Neutrino may inject almost all its energy into Neutron Star before escaping**

# Indirect Detection @Compact Star

## Escape from Star: “Secluded DM”

[B. Batell, M. Pospelov, A. Ritz, Y. Shang (2010)]

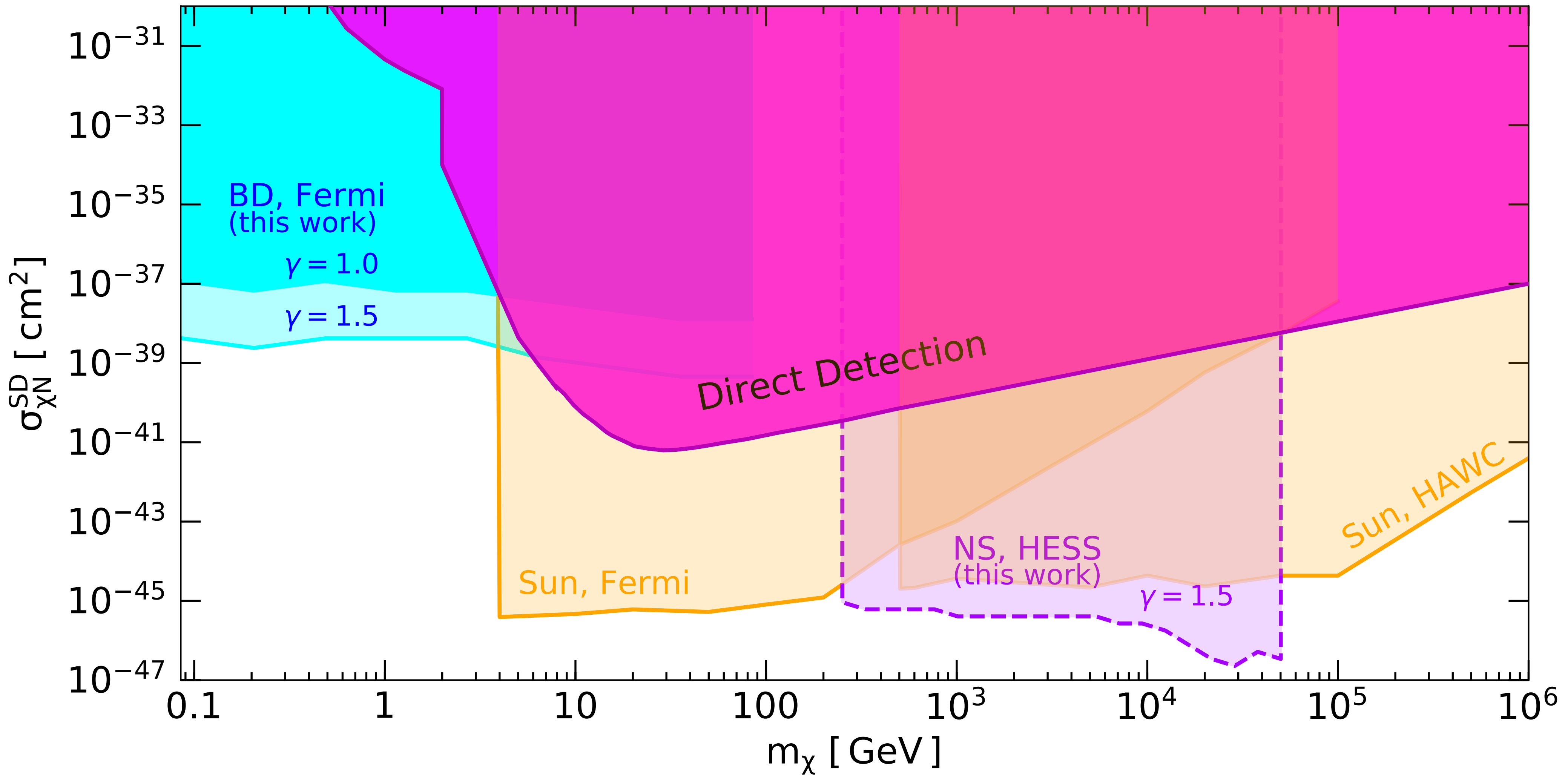
- Secluded DM: DM mainly annihilates into non-SM mediator first (which finally decay into the SM particles)
- If (mean free path of annihilation final state) > (star radius), mediator may escape from star
- Mediator decays outside of star, which may bring astro-signatures of DM capture into star
  This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

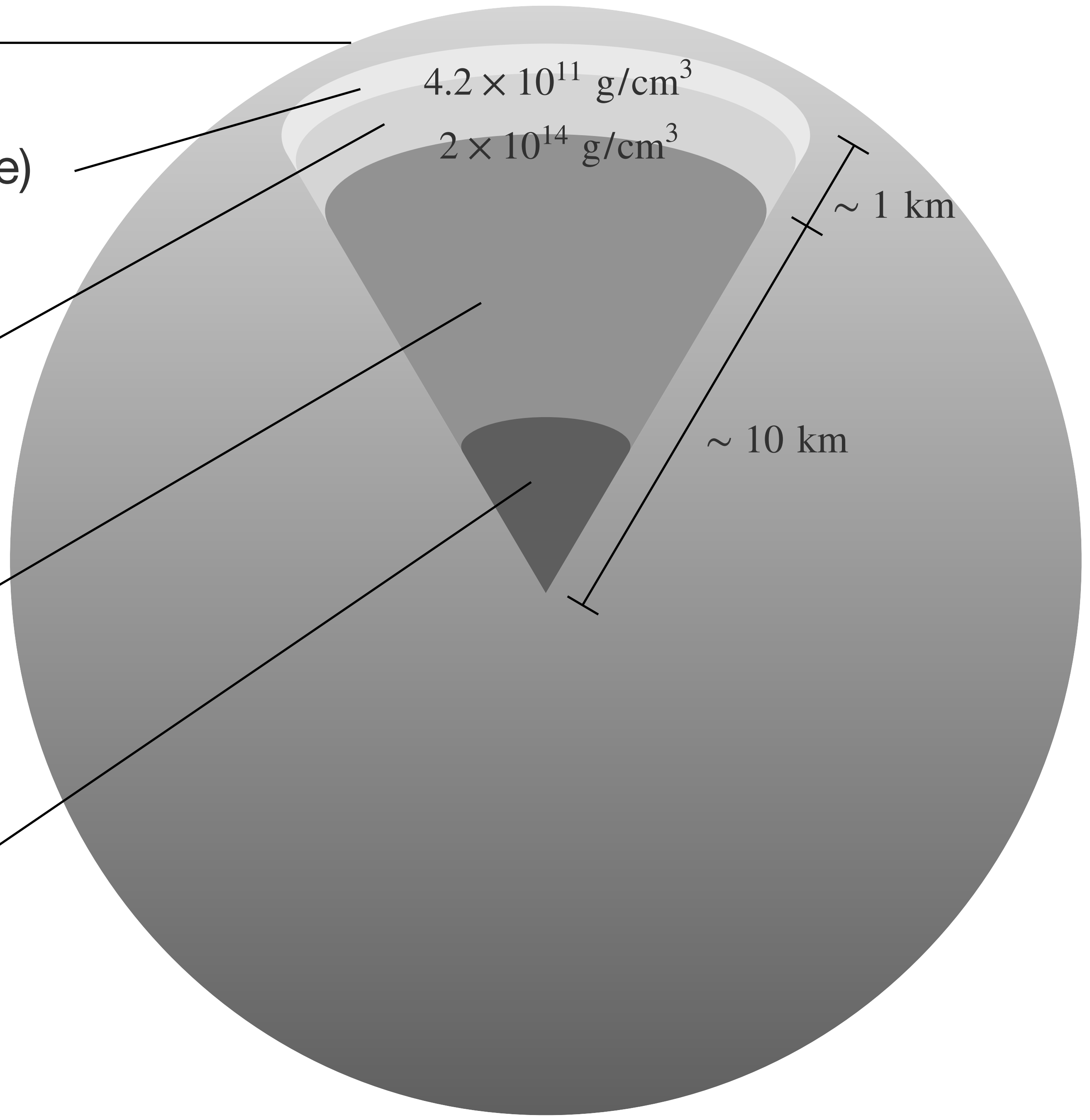


[J. F. Acevedo, J. Bramante, R. K. Leane, N. Raj (2020)]

# Evaluation of Threshold xsec (Improved Treatment)

Question: **Robust evaluation of threshold xsec?**

- 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

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

## 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

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

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

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

# 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 $\sim 100\ \mathrm{pc}$

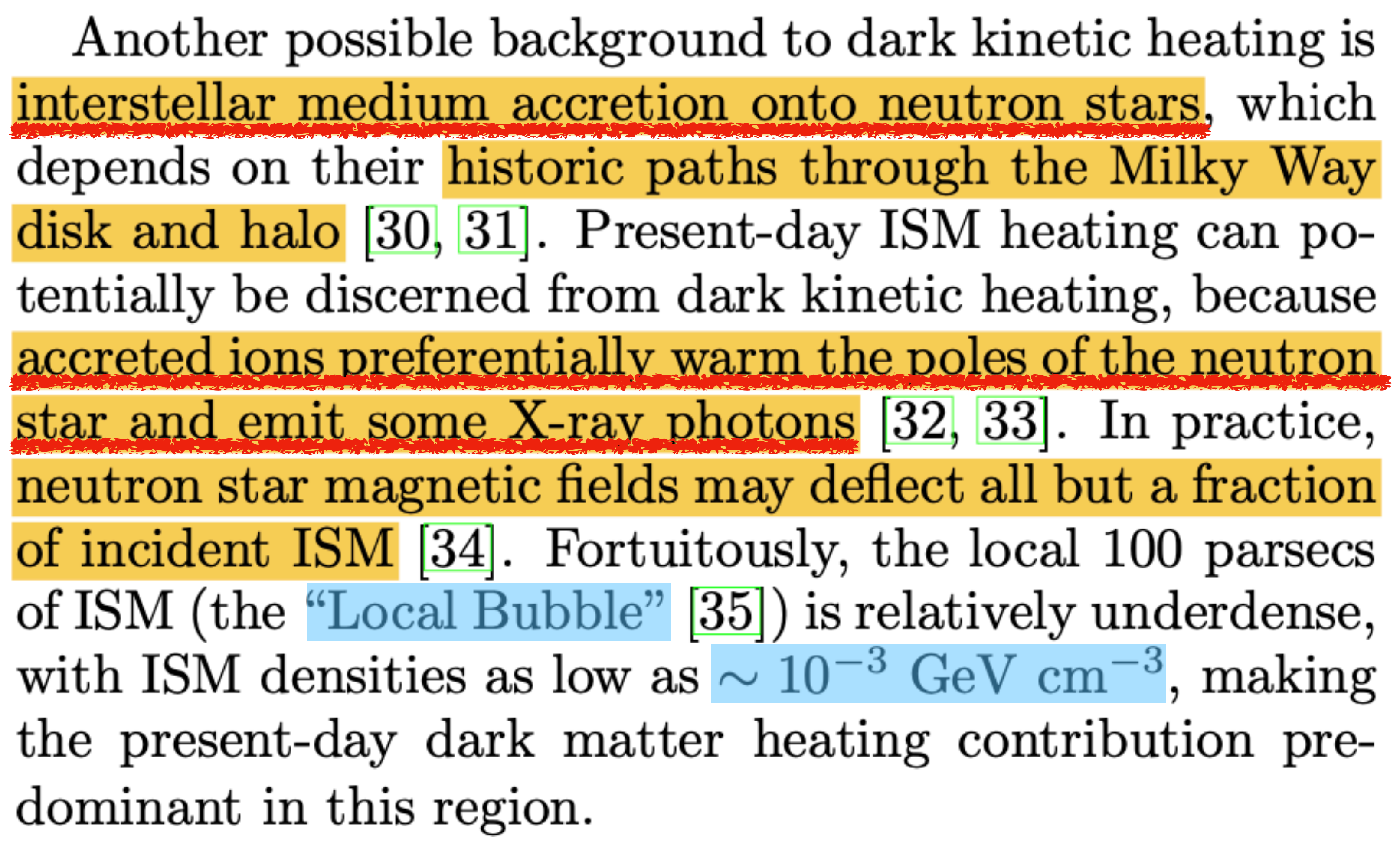
## Dedicated treatment

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

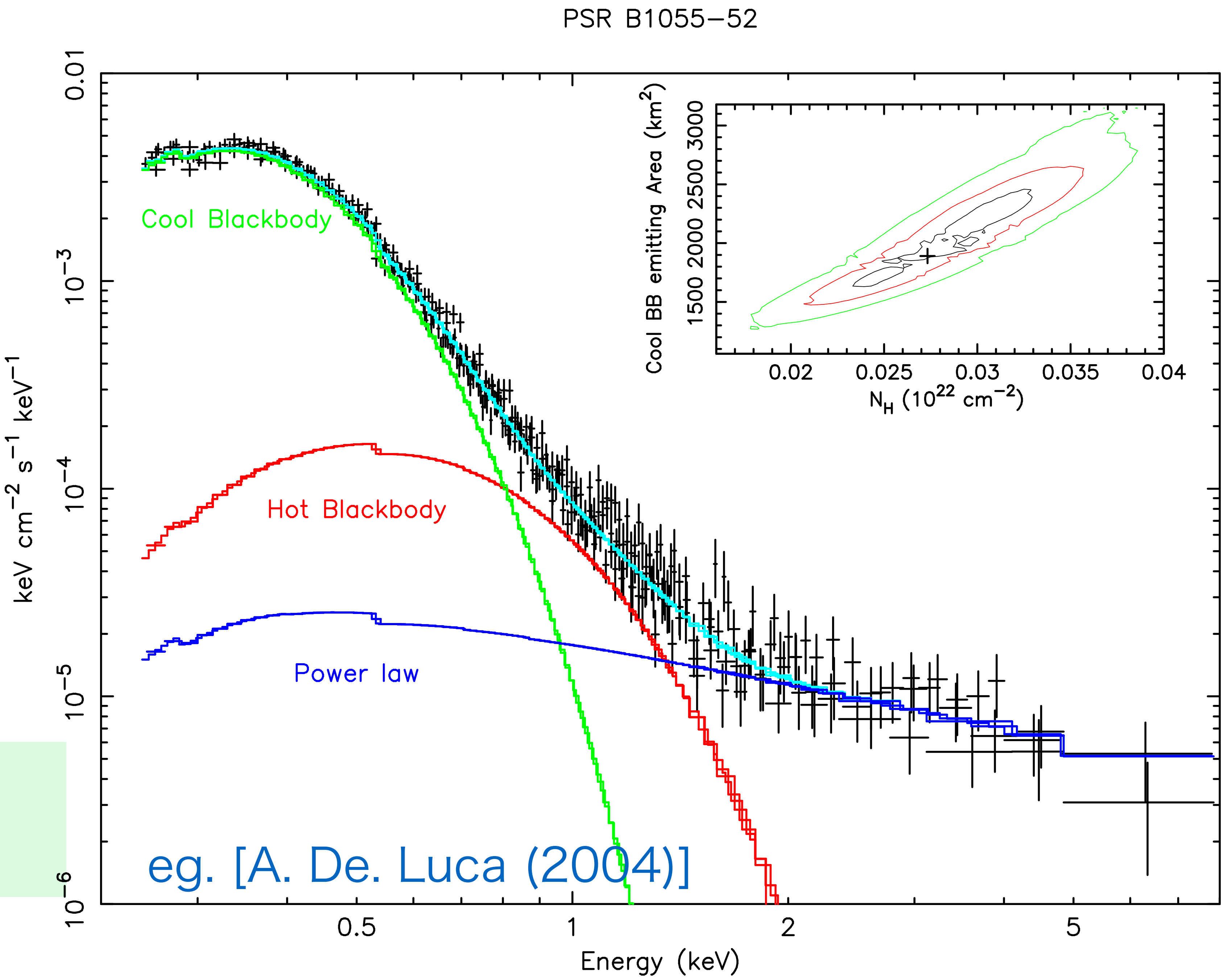
- Temperature observation = spectral fit w/ two blackbody component
  - Hot blackbody ($T_{hot}$): Coming from normal matter accretion on pole
  - Cool blackbody ($T_{cool}$): Corresponding to surface temperature

**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]. Fortuitously, the local 100 parsecs of ISM (the “Local Bubble” [35]) is relatively underdense, with ISM densities as low as $\sim 10^{-3}$ GeV cm$^{-3}$, making the present-day dark matter heating contribution predominant in this region.



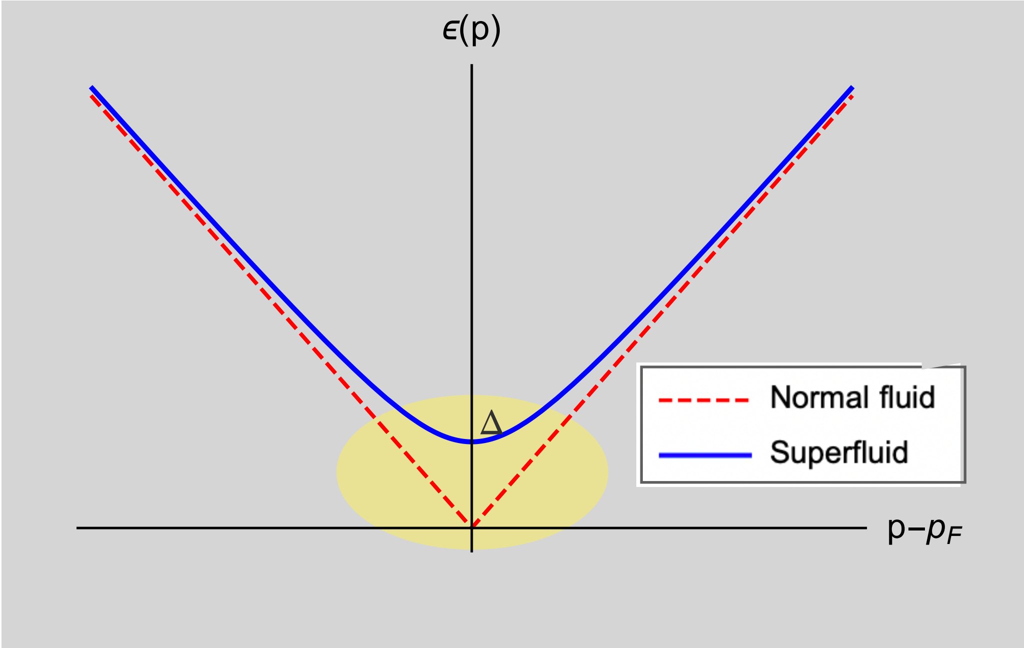
eg. [A. De. Luca (2004)]

# Superfluidity in Neutron Star

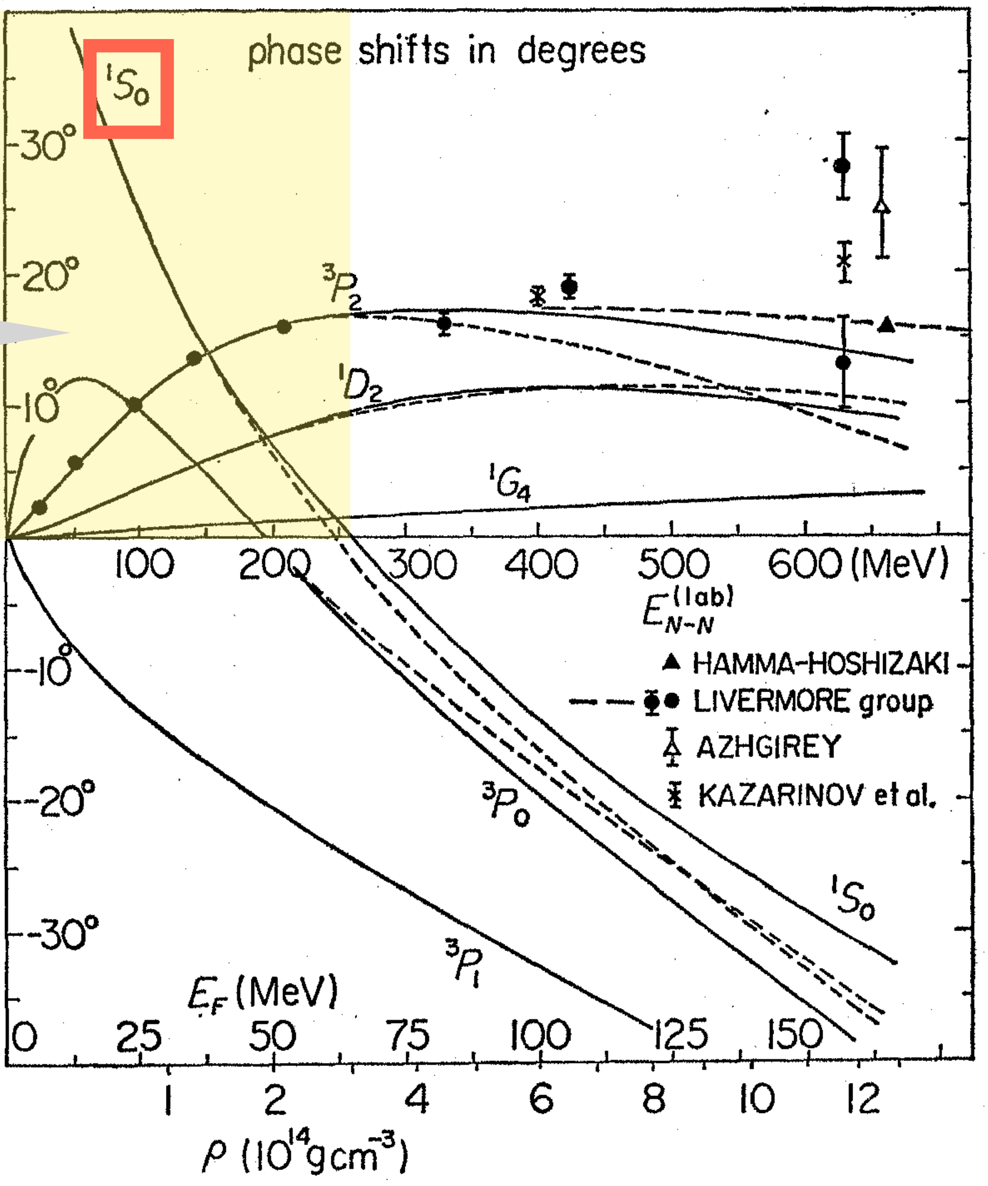
## Condition for superfluidity appear

- Transport w/o dissipation effect
- ⇔ Nonzero gap for the energy spectrum (to forbid dissipation)
- ⇔ **Attractive force** (to have nonzero gap)

  → Can be read out from phase shift in nuclear scattering
  - Positive : attractive
  - Negative : repulsive



[R. Tamagaki (1970)]



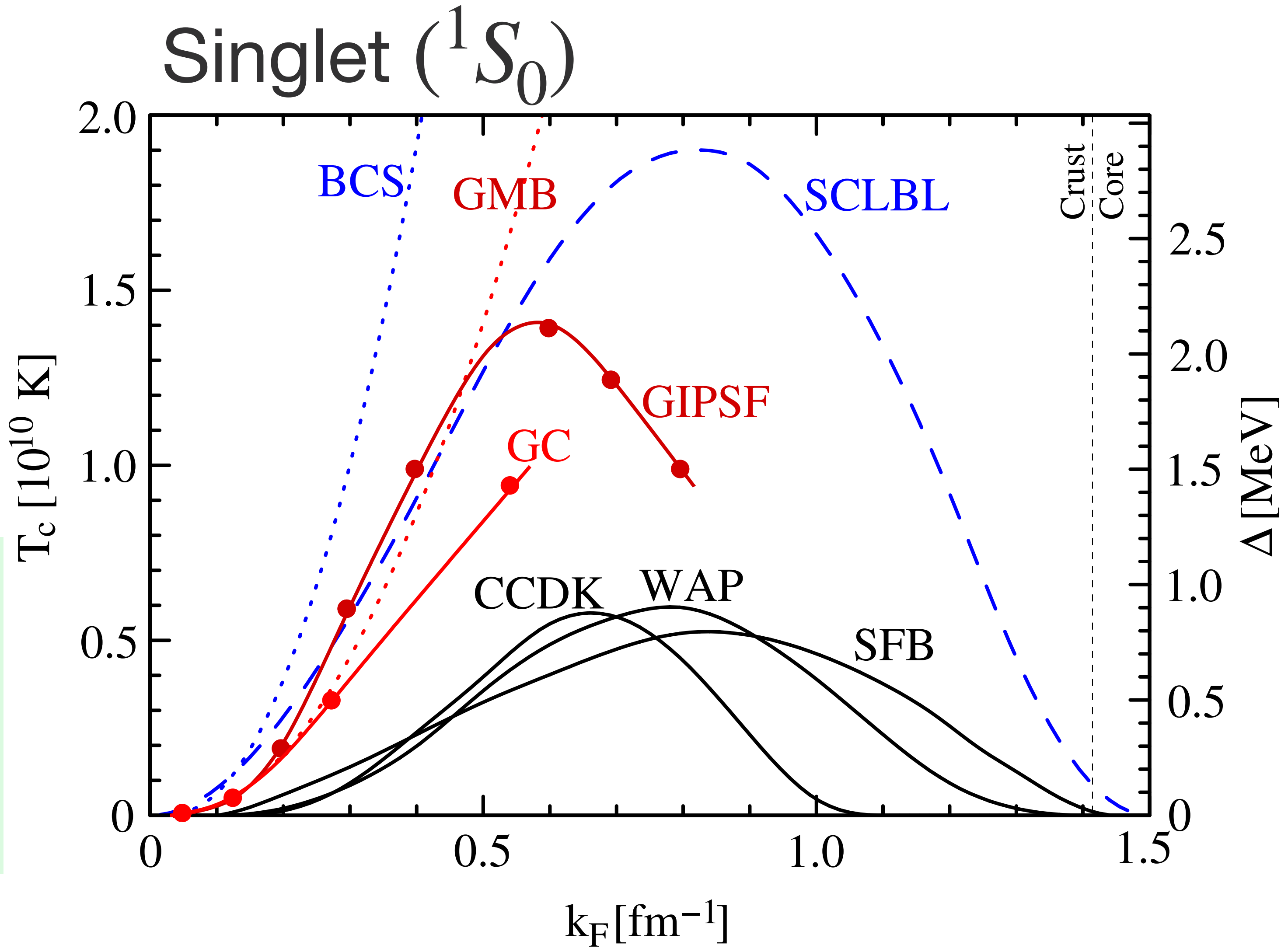
## Region for super fluidity to appear

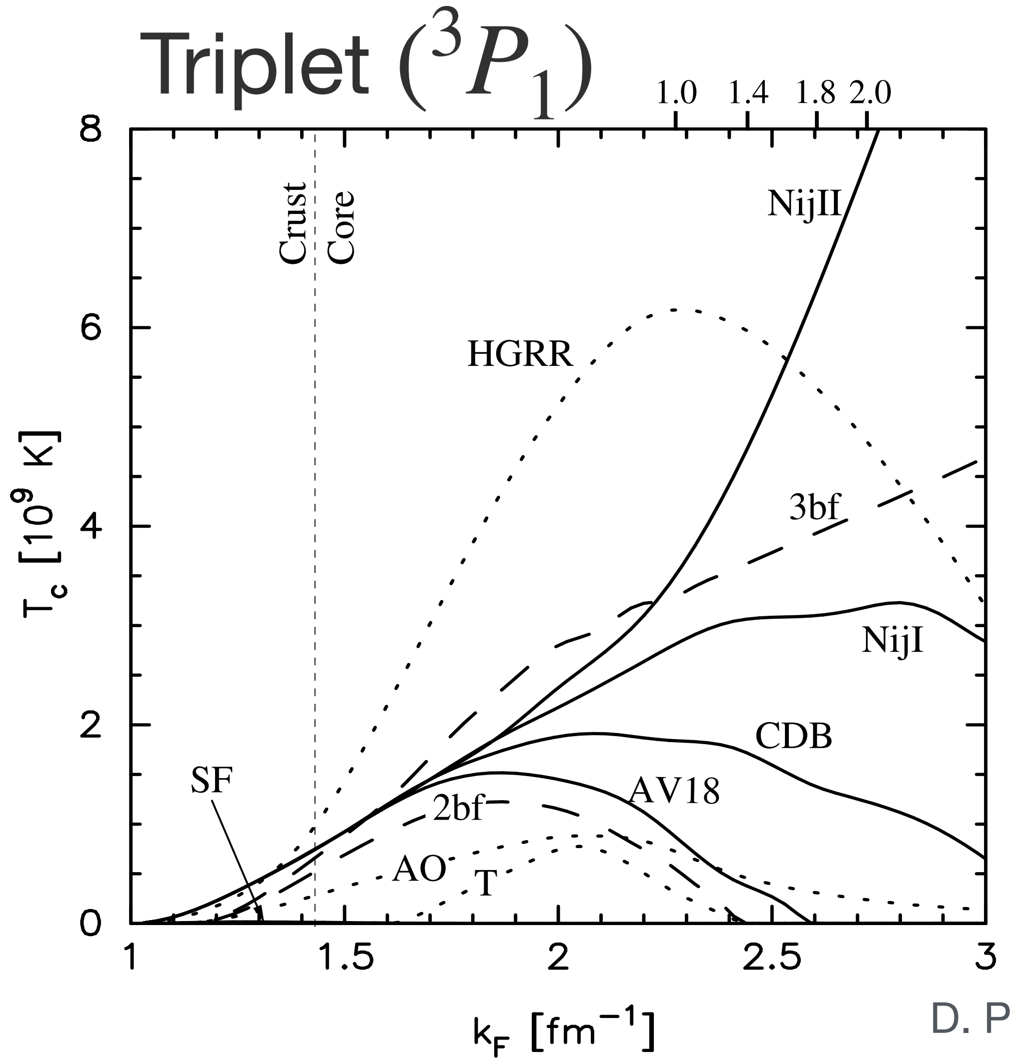
- Two possibilities: singlet vs triplet
- Energy gap depends on Fermi momentum

Singlet ($({}^1S_0)$) : low momentum → inner crust

Triplet ($({}^3P_1)$) : low momentum → core

[D. Page+ [1302.6626]]


Singlet $({}^1S_0)$


Triplet $({}^3P_1)$