WIMP DM Heating in Neutron Stars

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PCF2023-2024
University of Toyama
Jan 16, 2024

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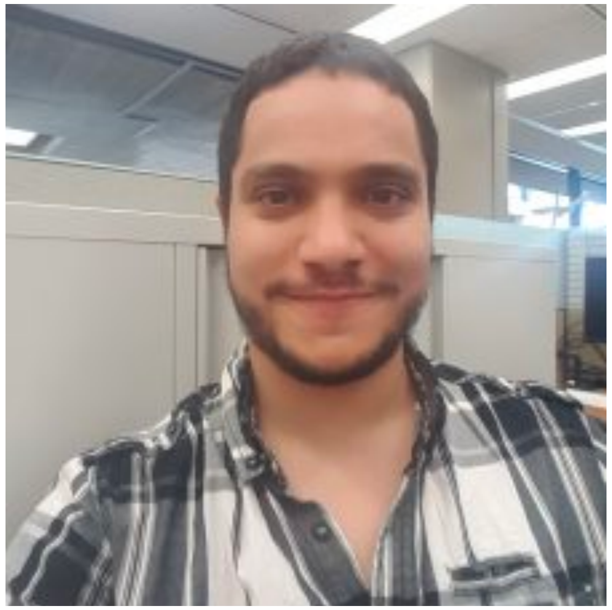

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(6 international students)

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Outline

I. Introduction: Dark Matter

II. DM search on the earth

III. DM heating in neutron stars

IV. Summary

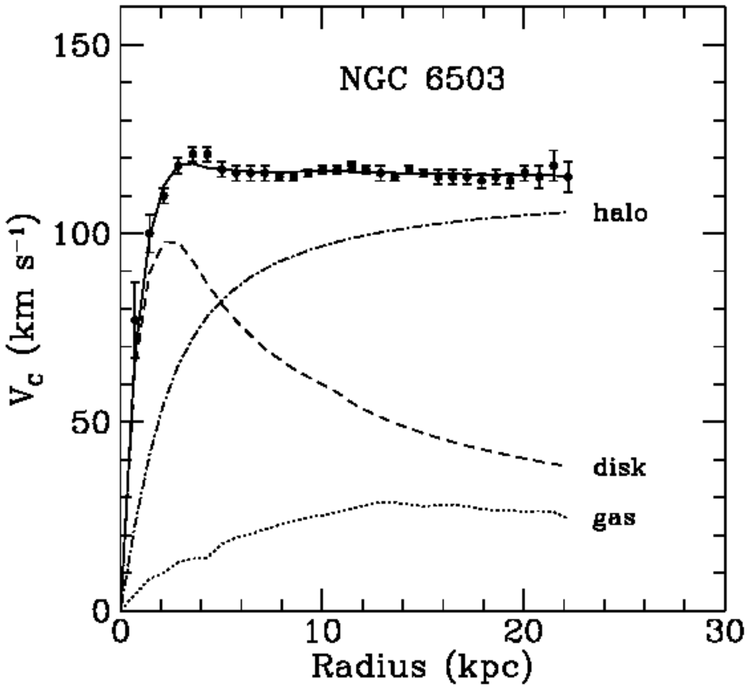
+ Appendix: other heating sources

Introduction: Dark Matter

Evidence for dark matter (DM)

The existence of dark matter has been established by various cosmological observations.

Rotational curves

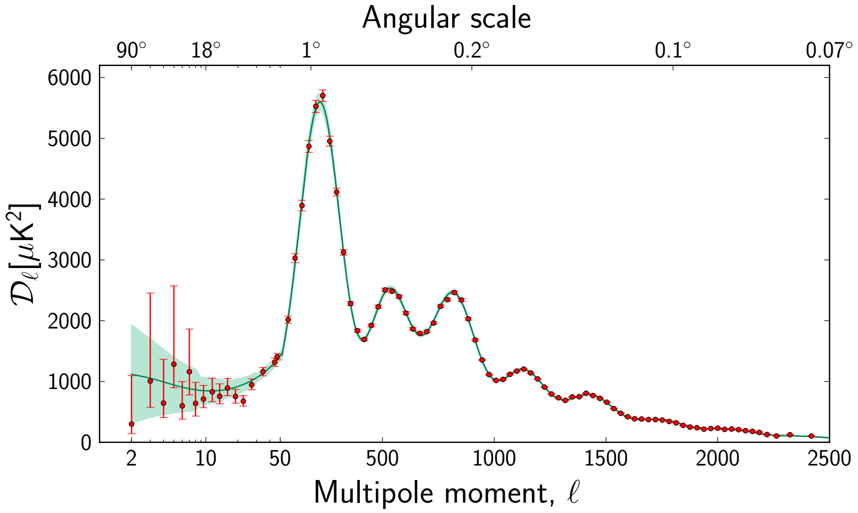


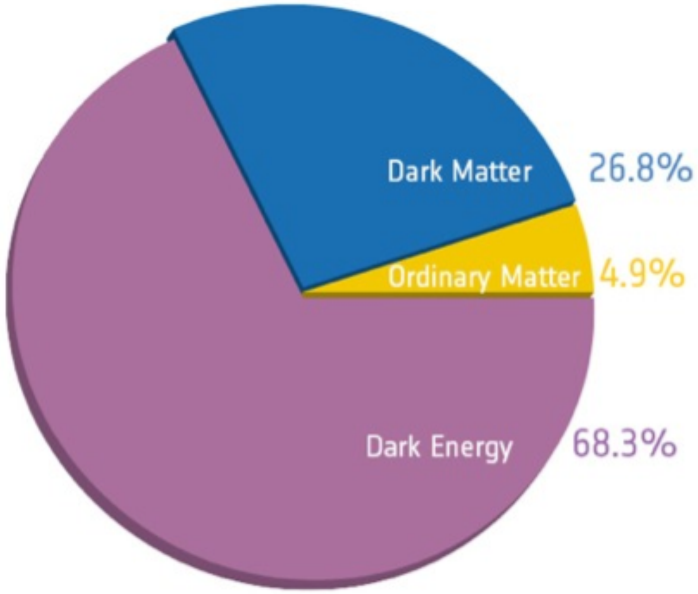
Begeman et. al. (1991)

Bullet cluster

Clowe et. al. (2006)

Cosmic microwave background





Planck (2013)

Nevertheless, the Standard Model of particle physics cannot explain DM.

Properties of Dark Matter

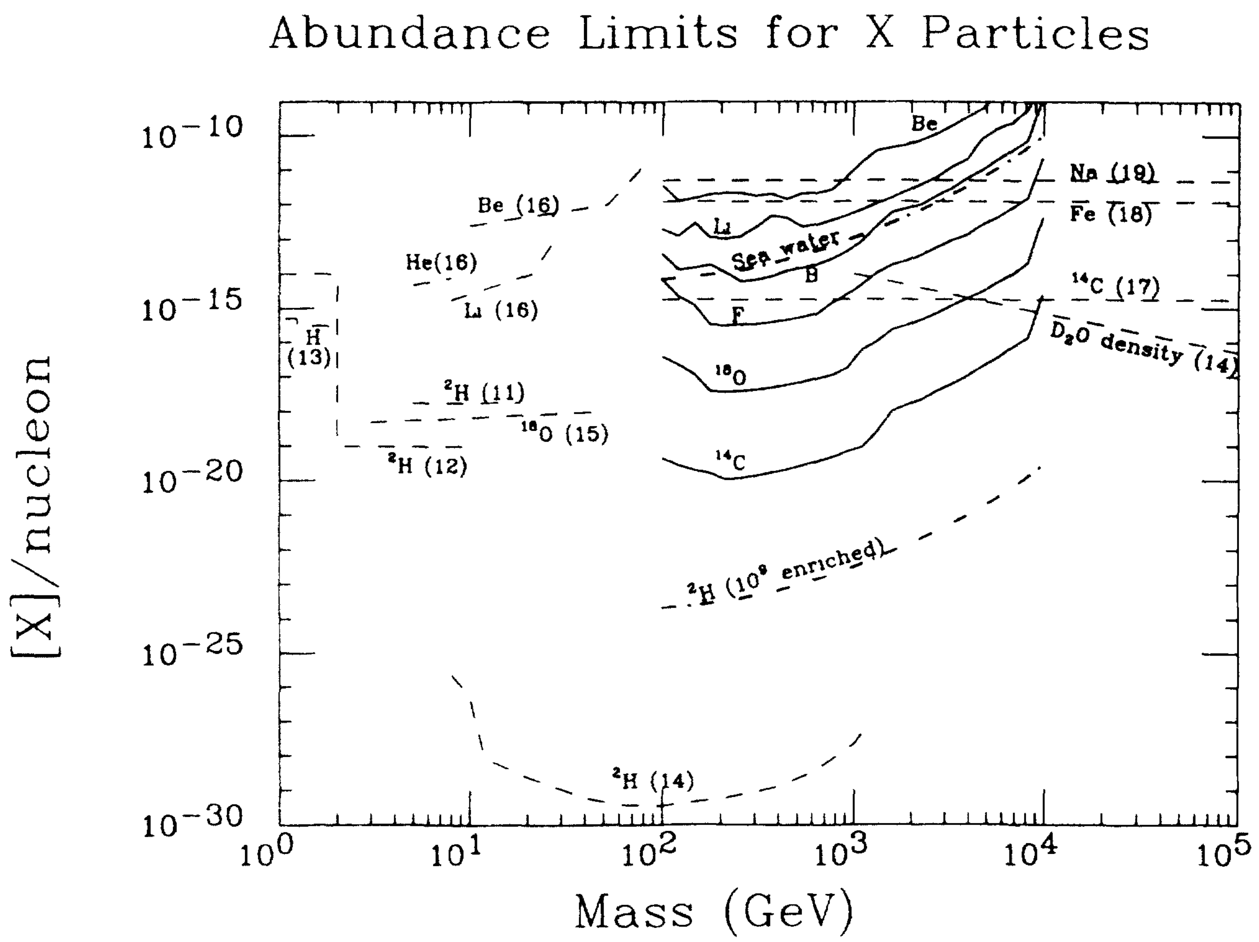
- Stable

  (or has a lifetime much longer than the age of the Universe)

- Cold or warm

- Needs to match the observed density $\Omega_{\rm DM} h^2 \simeq 0.12$

- Electrically neutral and colorless.



Constrained by the searches of anomalously heavy isotopes.

T. K. Hemmick, et. al., Phys. Rev. **D41**, 2074 (1990).

WIMP

Weakly-Interacting Massive Particles (WIMPs)

- Electrically neutral and colorless particles.
- Stable.
- Masses of O(100—1000) GeV.
- Have interactions comparable to EW interactions.

→ Observed Dark Matter (DM) density can be explained by their thermal relic.

Thermal relic scenario (cold DM)

WIMPs were in thermal equilibrium with the SM particles in the early Universe.

For $T \lesssim m_{\rm DM}$

$$n_{\rm DM} \simeq \left(\frac{m_{\rm DM}T}{2\pi}\right)^{\frac{3}{2}} e^{-\frac{m_{\rm DM}}{T}}$$

DM number rapidly decreases.

→ Annihilation rate also rapidly decreases!

Annihilation precess freezes out when

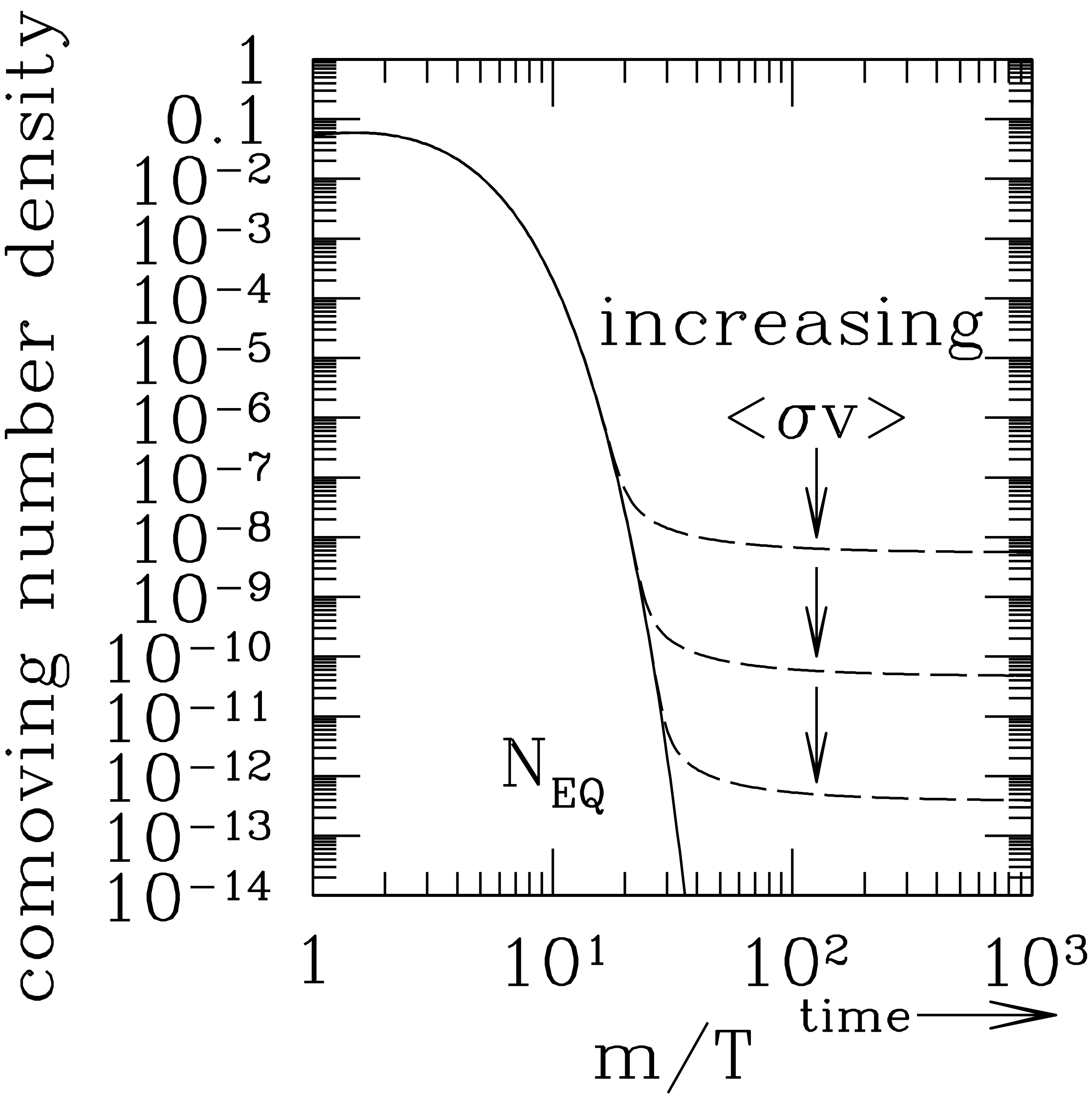
$$n_{\rm DM}(T_{\rm FO}) \cdot \langle \sigma_{\rm ann} v_{\rm rel} \rangle \simeq H(T_{\rm FO}) \quad \Rightarrow \quad \boxed{T_{\rm FO} \simeq \frac{m_{\rm DM}}{25}}$$

↑ Annihilation rate

↑ Hubble expansion rate

Cold DM

Thermal relic scenario (cold DM)



P. Gondolo, astro-ph/0403064

DM thermal relic abundance

$$\Omega_{\rm DM} h^2 \simeq \frac{3\times 10^{-27} {\rm cm}^3 {\rm s}^{-1}}{\langle \sigma_{\rm ann} v_{\rm rel}\rangle}$$

$$\Omega_{\rm DM} h^2 = 0.12$$

→

$$\langle \sigma_{\rm ann} v_{\rm rel}\rangle \simeq 10^{-9}\ {\rm GeV}^{-2}$$

TeV-scale physics and WIMP

Let us discuss the implications of $\langle \sigma_{\rm ann} v_{\rm rel} \rangle \simeq 10^{-9}\ {\rm GeV}^{-2}$

Annihilation cross section is approximately given by

$$\langle \sigma_{\rm ann} v_{\rm rel} \rangle \simeq \frac{\alpha^2}{m_{\rm DM}^2}$$

The above value is then obtained for

$$\alpha \simeq 0.01 \qquad m_{\rm DM} \simeq 300\ {\rm GeV}$$

Weak coupling

Weak scale

Quantum numbers of DM

DM should be electrically neutral and colorless.

→ There still remain many possibilities.

- Spin?
  - Real/complex scalar
  - Majorana/Dirac fermion
  - Vector

etc.

- $\mathrm{SU}(2)_L \otimes \mathrm{U}(1)_Y$ charge?

$$(\mathbf{1},0),\ (\mathbf{2}, \pm 1/2),\ (\mathbf{3},0),\ (\mathbf{3}, \pm 1),\ (\mathbf{4}, \pm 1/2),\ \ldots$$

$$Q = T_3 + Y$$

Singlet scalar DM

V. Silveira and A. Zee (1985);
J. McDonald (1994);
C. P. Burgess, M. Pospelov, and T. ter Veldhuis (2001).

Just add a neutral scalar field to the Standard Model.

Very simple (toy) model

Lagrangian

$$\mathcal{L}_{\text{int}} = -\frac{1}{2}m^2 S^2 - \frac{1}{2}\lambda_{SH} S^2 |H|^2 - \frac{1}{4!}\lambda_S S^4$$

- Stability

Lagrangian has a Z_2 symmetry: S → — S (odd); SM (even).

- Annihilation cross section

$$\sigma_{\text{ann}} v_{\text{rel}} \simeq \frac{\lambda_{sH}^2}{16\pi m_{\text{DM}}^2}$$

(m_{DM} > weak scale)

$m_{\text{DM}} \simeq 3.3\lambda_{SH}$ TeV explains the observed DM density.

Electroweak-Interacting DM

The neutral component of $\mathrm{SU}(2)_L$ $\mathbf{n}$-tuplet, hypercharge Y is regarded as a DM candidate.

Examples:

- Higgsino $(n = \mathbf{2}, Y = 1/2)$
- Wino $(n = \mathbf{3}, Y = 0)$
- Minimal DM $(n = \mathbf{5}, Y = 0)$

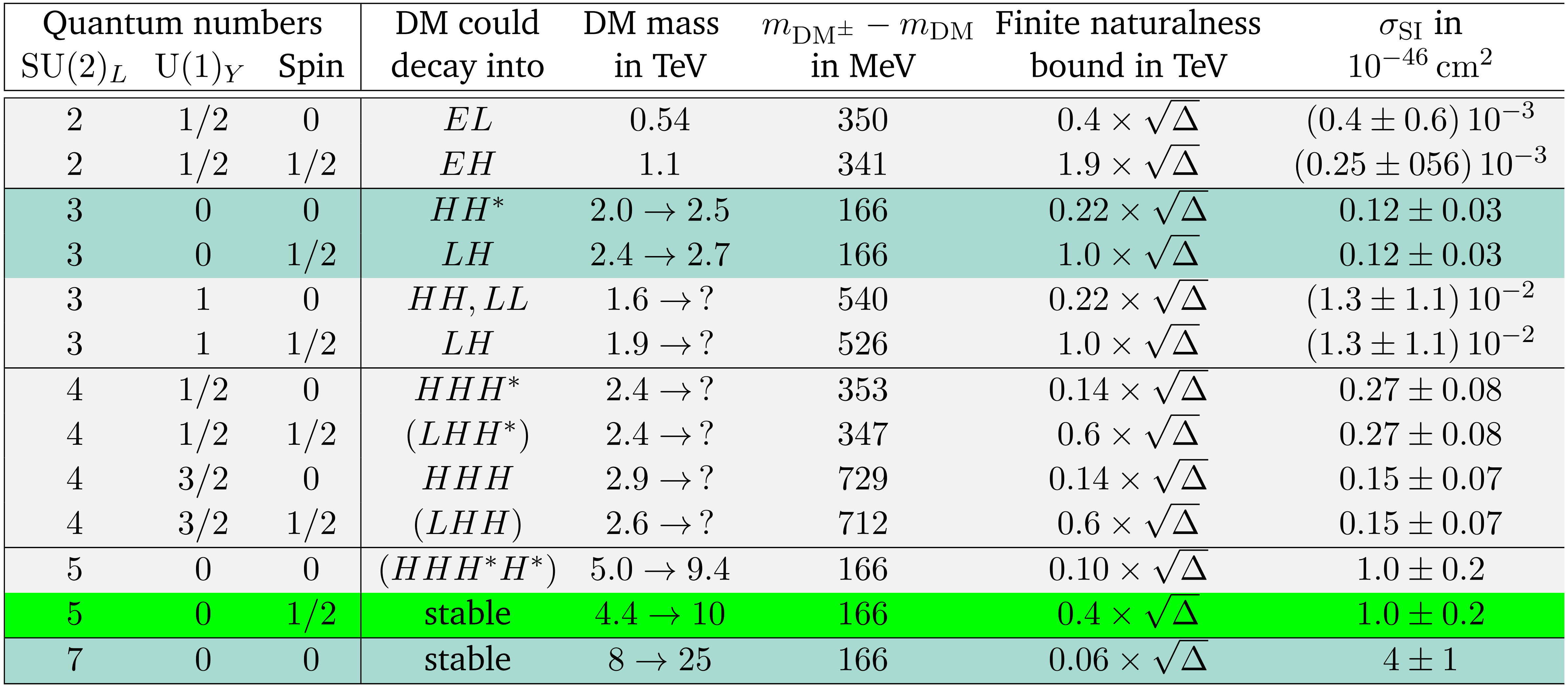
Interactions

$$\begin{aligned}\mathcal{L}_{\mathrm{int}} = &\frac{g_2}{4}\sqrt{n^2-(2Y-1)^2}\;\overline{\chi^+}\not{W}^+\chi^0 + \frac{g_2}{4}\sqrt{n^2-(2Y+1)^2}\;\overline{\chi^0}\not{W}^+\chi^- + \mathrm{h.c.}\\ &+ i g_Z Y \overline{\chi^0}\not{Z}\eta^0 \ .\end{aligned}$$

The DM phenomenology is (almost) completely determined by the gauge interactions.

For scalar DM cases, the DM-Higgs couplings also exist.

Electroweak-Interacting DM



Quantum numbers			DM could	DM mass	$m_{\rm DM^\pm} - m_{\rm DM}$	Finite naturalness	$\sigma_{\rm SI}$ in
$\mathrm{SU}(2)_L$	$\mathrm{U}(1)_Y$	Spin	decay into	in TeV	in MeV	bound in TeV	$10^{-46}\ \mathrm{cm}^2$
2	1/2	0	EL	0.54	350	$0.4 \times \sqrt{\Delta}$	$(0.4 \pm 0.6)\, 10^{-3}$
2	1/2	1/2	EH	1.1	341	$1.9 \times \sqrt{\Delta}$	$(0.25 \pm 056)\, 10^{-3}$
3	0	0	HH^*	$2.0 \to 2.5$	166	$0.22 \times \sqrt{\Delta}$	0.12 ± 0.03
3	0	1/2	LH	$2.4 \to 2.7$	166	$1.0 \times \sqrt{\Delta}$	0.12 ± 0.03
3	1	0	HH, LL	$1.6 \to ?$	540	$0.22 \times \sqrt{\Delta}$	$(1.3 \pm 1.1)\, 10^{-2}$
3	1	1/2	LH	$1.9 \to ?$	526	$1.0 \times \sqrt{\Delta}$	$(1.3 \pm 1.1)\, 10^{-2}$
4	1/2	0	HHH^*	$2.4 \to ?$	353	$0.14 \times \sqrt{\Delta}$	0.27 ± 0.08
4	1/2	1/2	(LHH^*)	$2.4 \to ?$	347	$0.6 \times \sqrt{\Delta}$	0.27 ± 0.08
4	3/2	0	HHH	$2.9 \to ?$	729	$0.14 \times \sqrt{\Delta}$	0.15 ± 0.07
4	3/2	1/2	(LHH)	$2.6 \to ?$	712	$0.6 \times \sqrt{\Delta}$	0.15 ± 0.07
5	0	0	(HHH^*H^*)	$5.0 \to 9.4$	166	$0.10 \times \sqrt{\Delta}$	1.0 ± 0.2
5	0	1/2	stable	$4.4 \to 10$	166	$0.4 \times \sqrt{\Delta}$	1.0 ± 0.2
7	0	0	stable	$8 \to 25$	166	$0.06 \times \sqrt{\Delta}$	4 ± 1

(→: Sommerfeld enhancement)

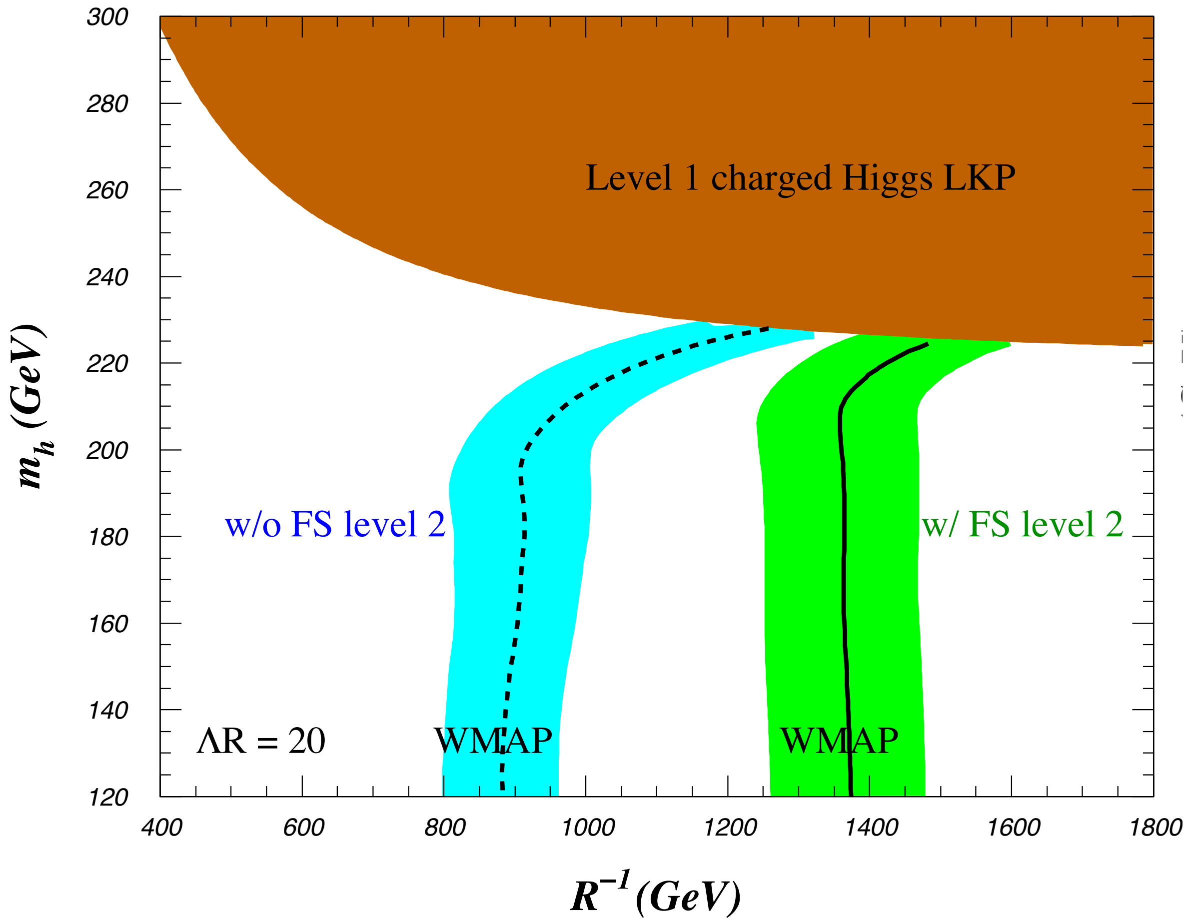
M. Farina, D. Pappadopulo, A. Strumia, JHEP **1308** (2013) 022.

Features

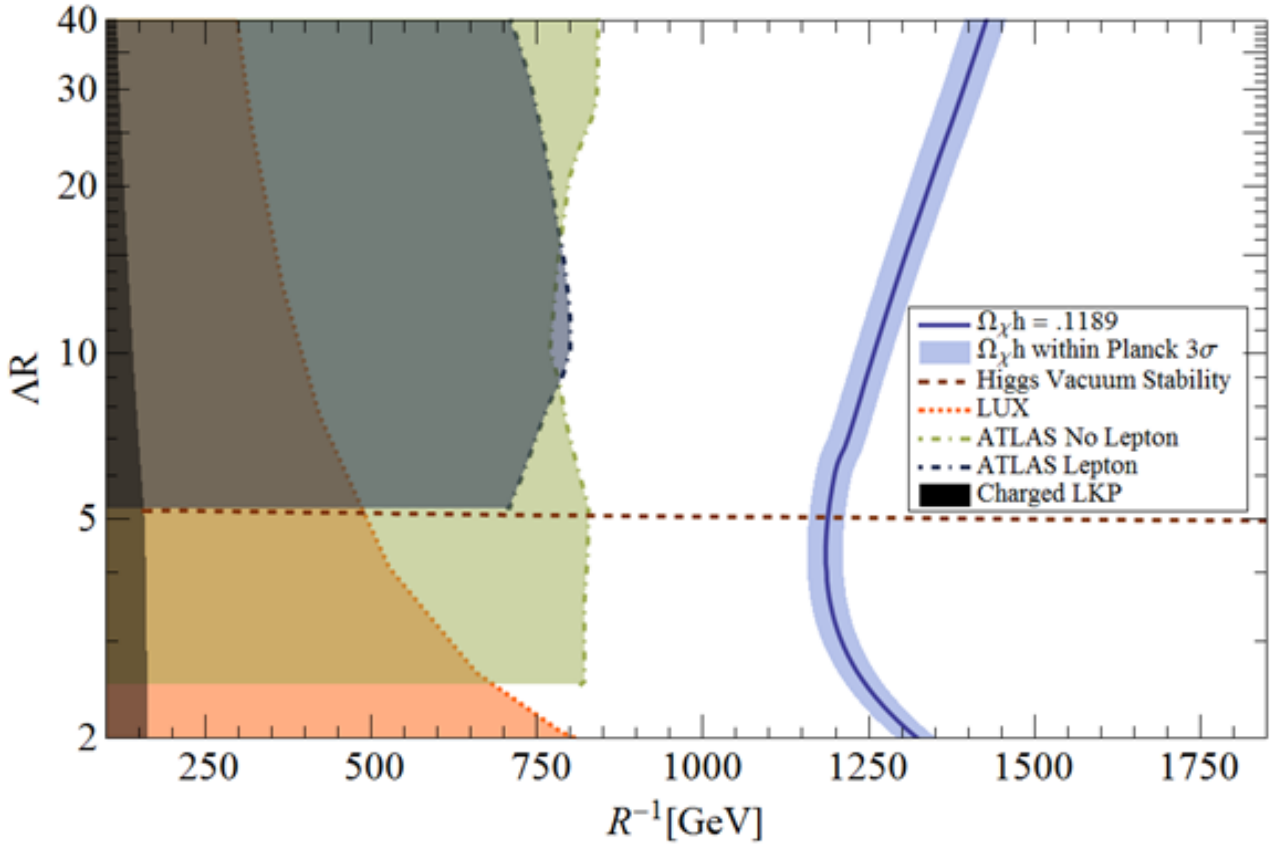
- Relatively heavy mass gives correct DM abundance.
- Small mass difference among the multiplet components.

Vector DM

The first Kaluza-Klein photon DM in the minimal universal extra dimension model.



G. Belanger, M. Kakizaki, A. Pukhov, JCAP **02**, 009 (2011).



J. M. Cornell, S. Profumo, W. Shepherd, Phys. Rev. D**89**, 056005 (2014).

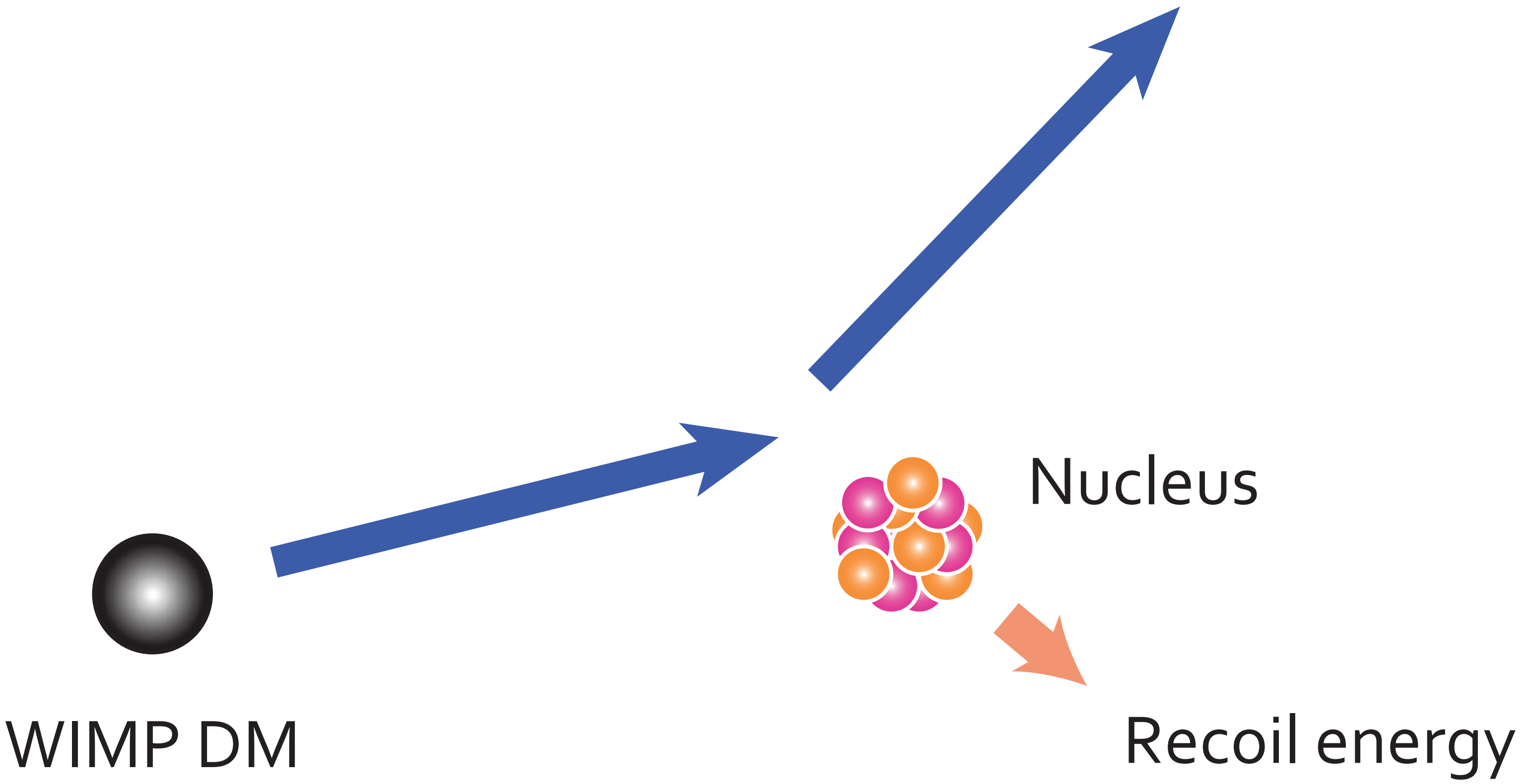
- The model is fully specified by only two parameters:

  R^{-1}: compactification scale, Λ: cut-off scale

- DM mass is predicted to be $1.2\ \mathrm{TeV} \lesssim M_{\mathrm{DM}} \lesssim 1.4\ \mathrm{TeV}$

DM search on the earth

DM Direct Detection experiments



O(10) keV $\sim m_{\text{target}} v_{\text{DM}}^2$

- DM is flying around us.
- If DM interacts with SM particles, this may scatter of matter on the earth.
- We may directly discover DM by detecting the recoil energy.

SI vs SD

In the non-relativistic limit, we can classify the DM-nucleon interactions into two categories:

- Spin-dependent interactions
- Spin-independent interactions

ex.) Majorana fermion DM

- $\mathscr{L}_{\rm SD} = a_N \bar{\chi}\gamma^\mu\gamma_5\chi\bar{N}\gamma_\mu\gamma_5 N$
- $\mathscr{L}_{\rm SI} = f_N \bar{\chi}\chi\bar{N}N$

SI vs SD

The DM-nucleus scattering cross section is given by

$$\sigma = \frac{4}{\pi}\left(\frac{M M_T}{M + M_T}\right)^2 \left[\underline{|Z f_p + (A - Z) f_n|^2} + 4\frac{J+1}{J}|a_p\langle s_p\rangle + a_n\langle s_n\rangle|^2\right]$$

M: DM mass; M_T: nucleus mass; Z: atomic number; A: mass number
J: total spin of nucleus; $\langle s_N\rangle$: expectation value of nucleon spin.

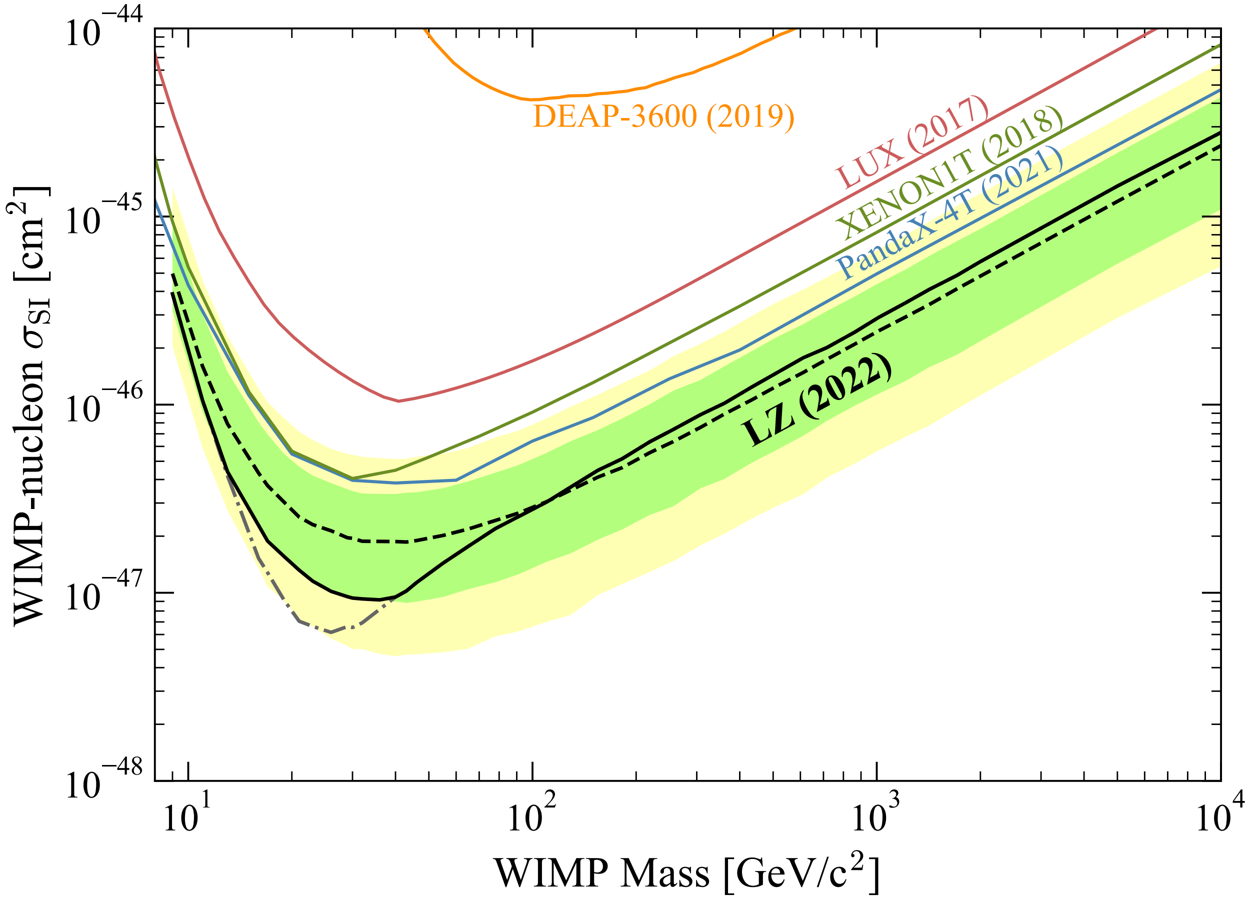
For a large nucleus, this term dominates the second term.

The SI scattering occurs coherently over the target nucleus.

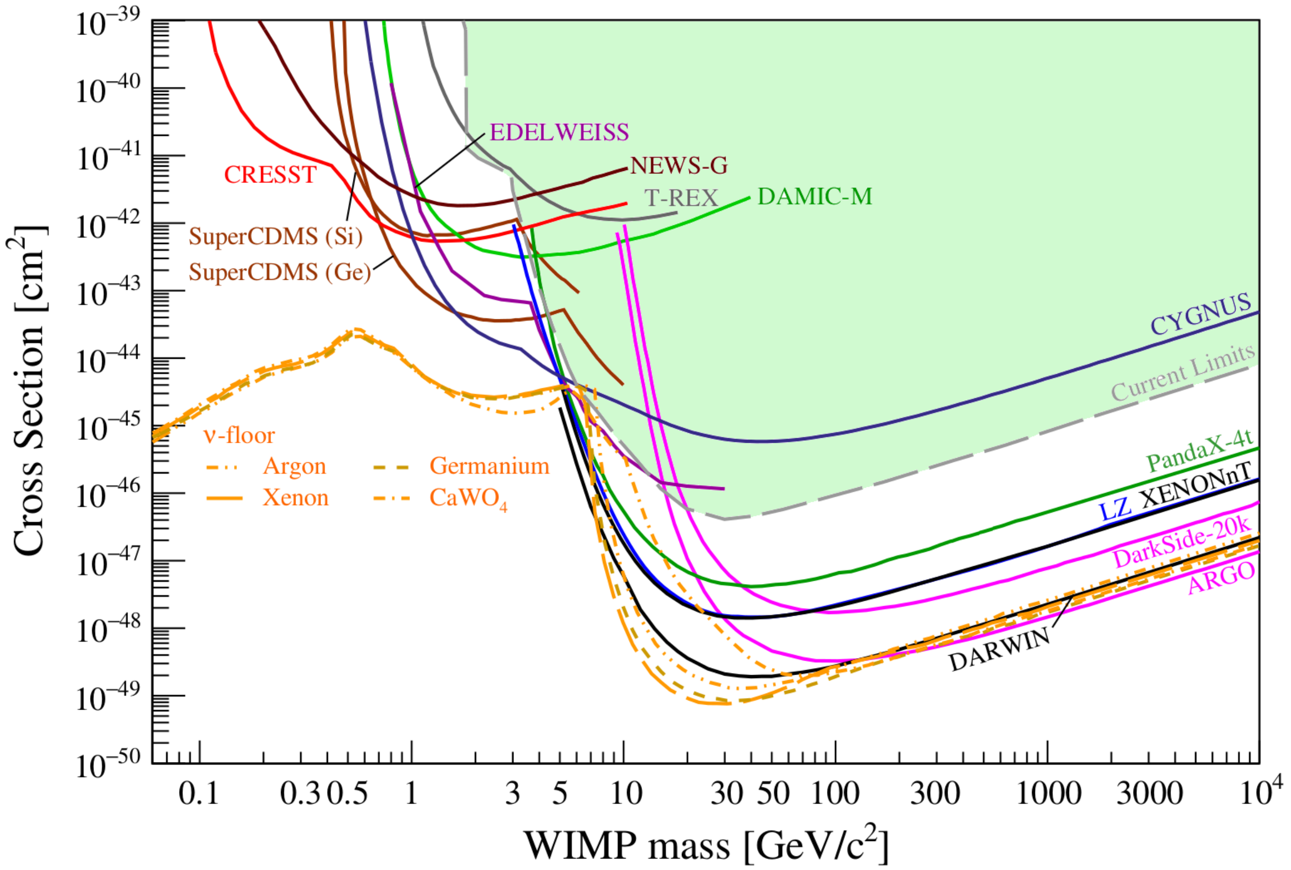
(momentum transfer) × (nucleus size) $\ll 1$

The limits on the SI interactions are much stronger than those on the SD interaction.

DM Direct Detection experiments



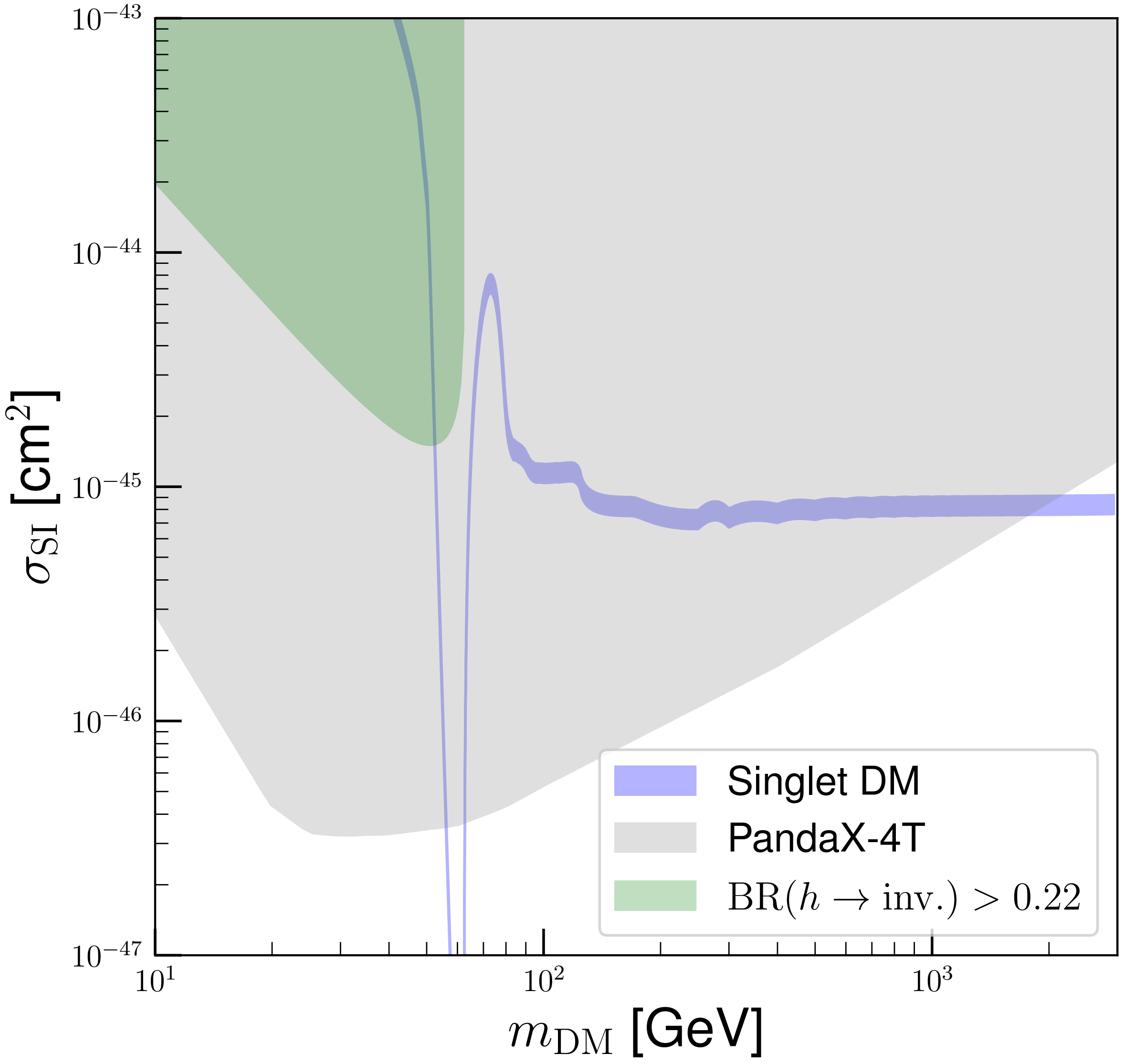
LZ Collaboration, Phys. Rev. Lett. **131**, 041002 (2023).

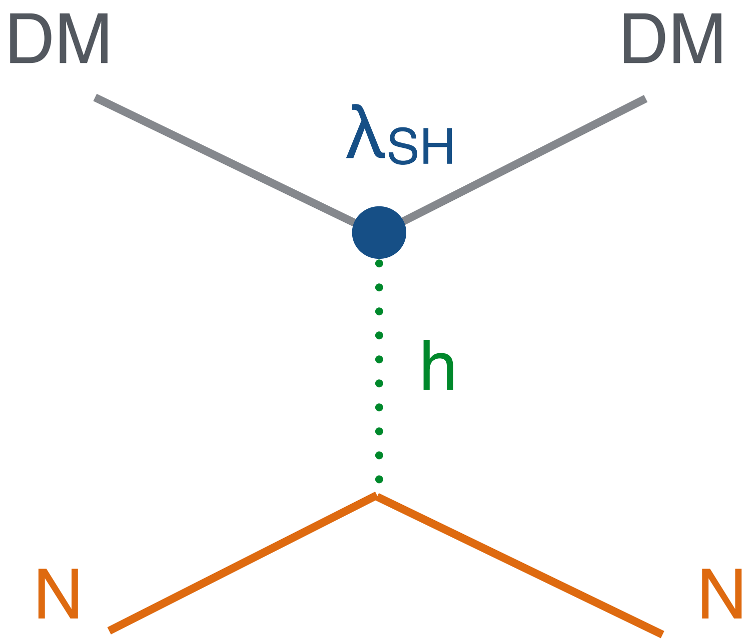


APPEC Committee Report, arXiv:2104.07634.

- DM direct detection experiments have imposed severe limits.
- Improved by orders of magnitude in future experiments.

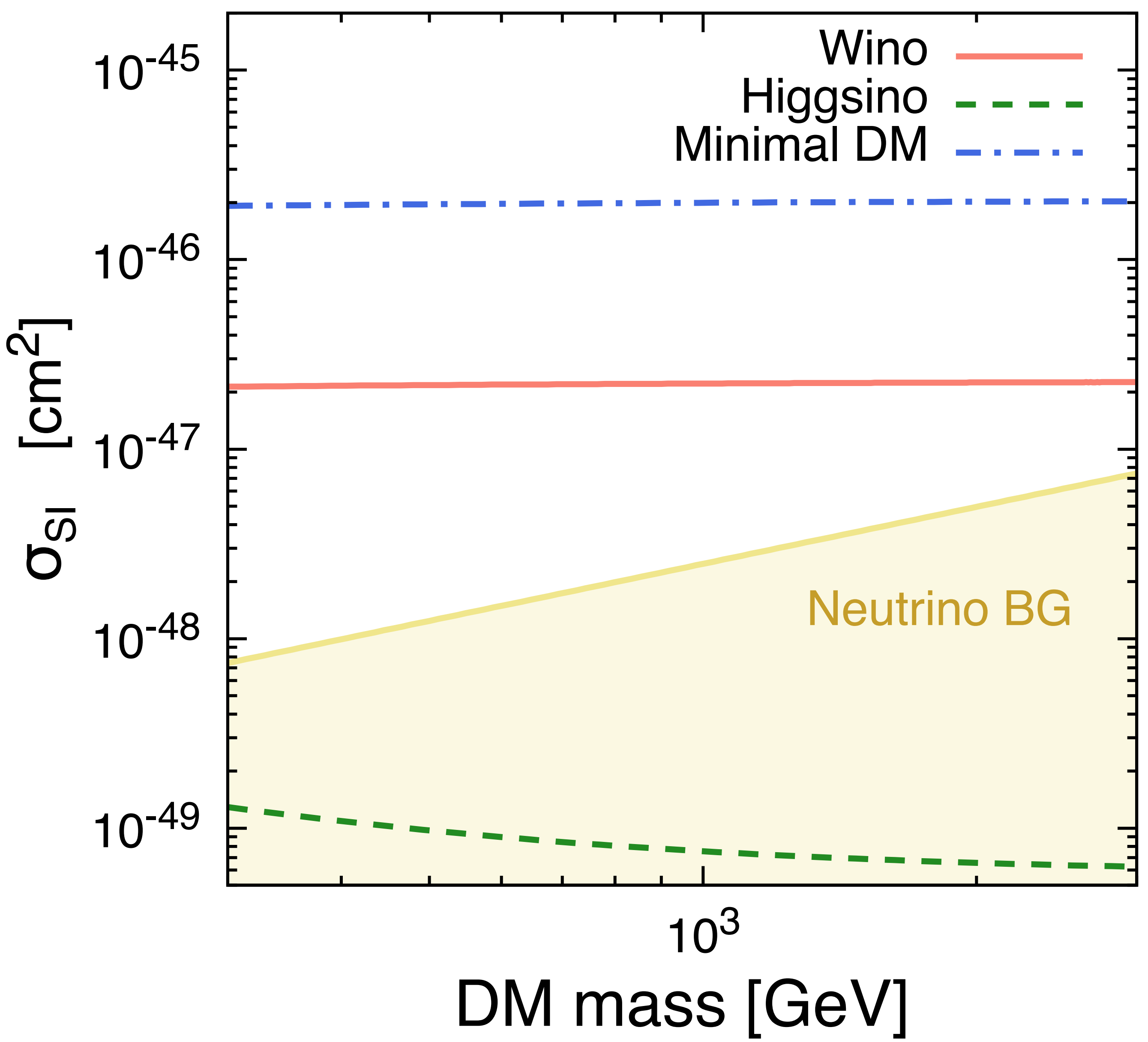
Singlet scalar DM



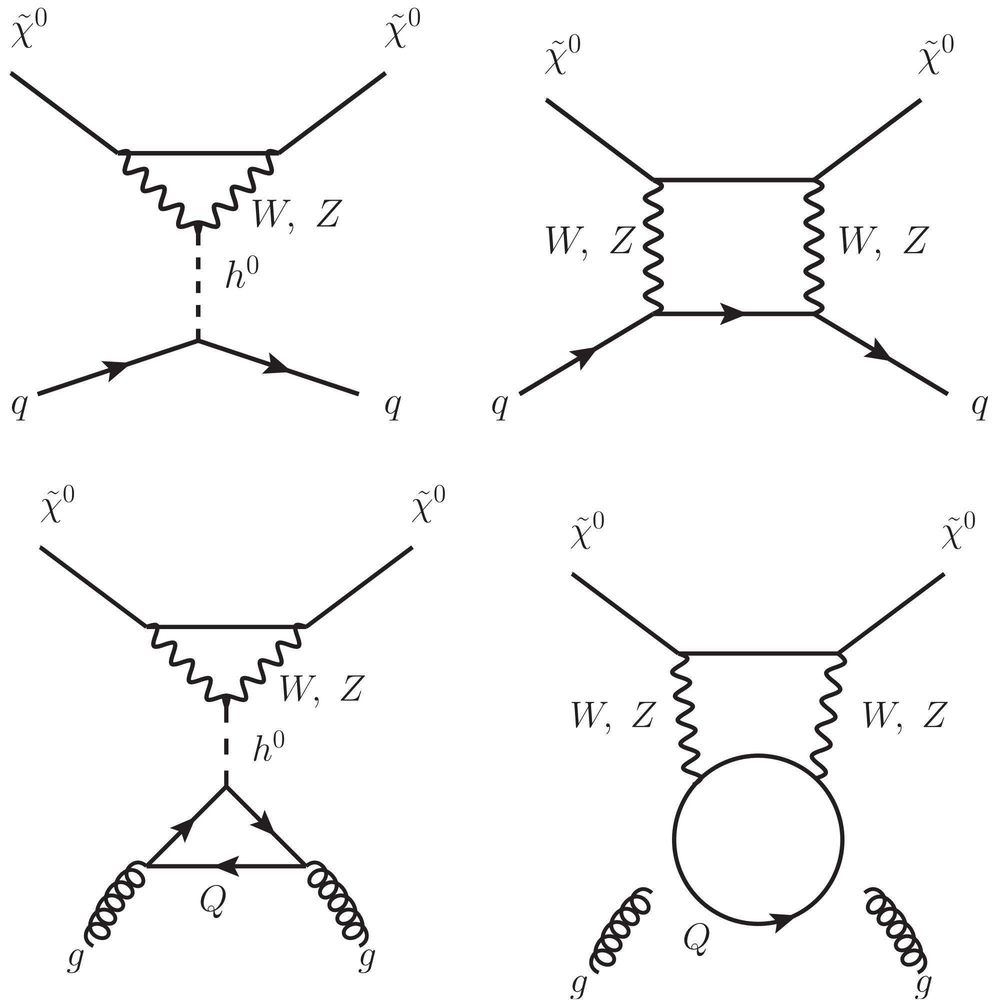


- Cross section is predicted as a function of DM mass.
- DM mass is limited up to a few TeV.

Electroweak interacting DM



Diagrams



- Triplet (pure wino), Minimal DM can be tested.
- Doublet (pure higgsino) is hard to probe.

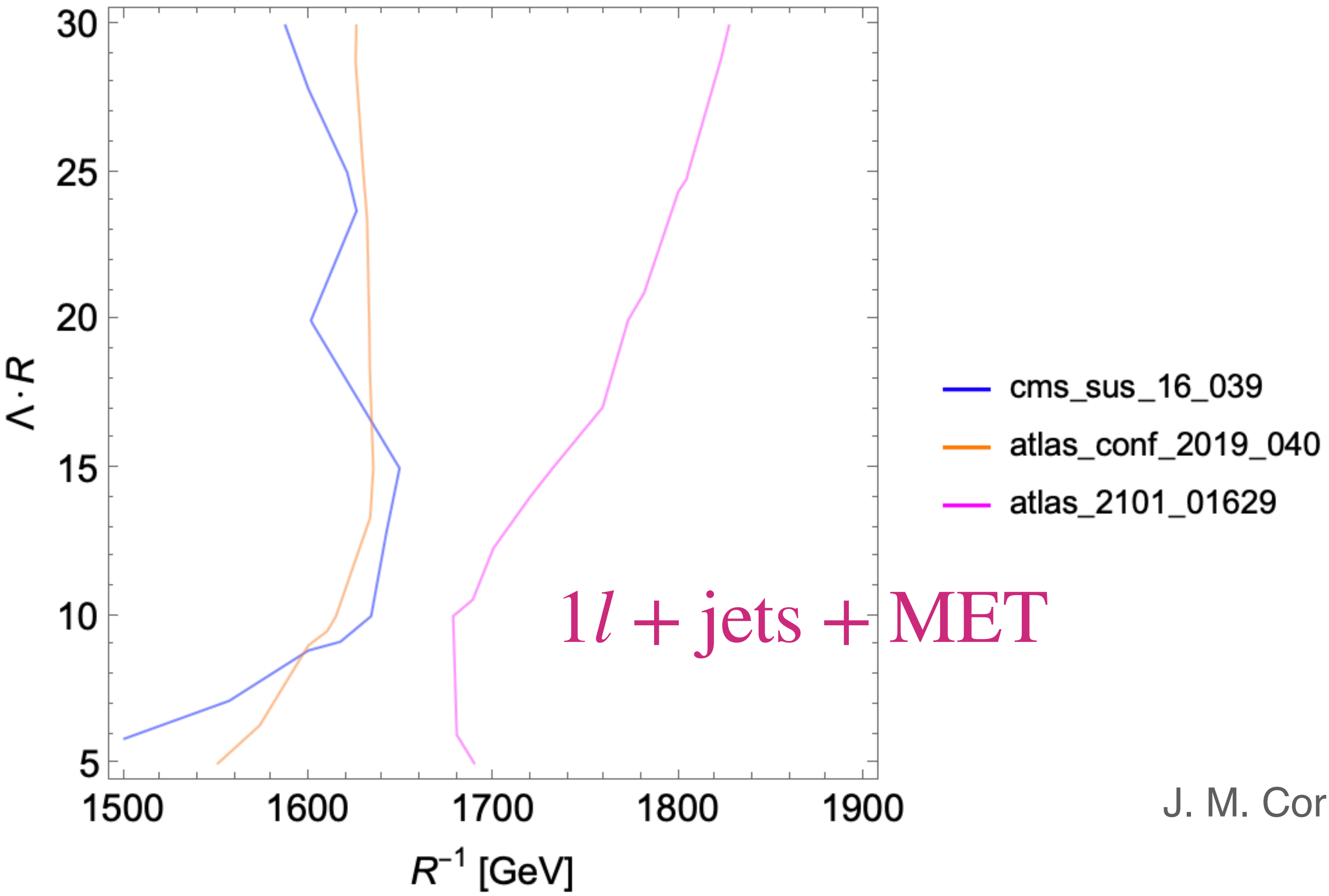
J. Hisano, K. Ishiwata, N. Nagata, JHEP **1506**, 097 (2015).

Caveat

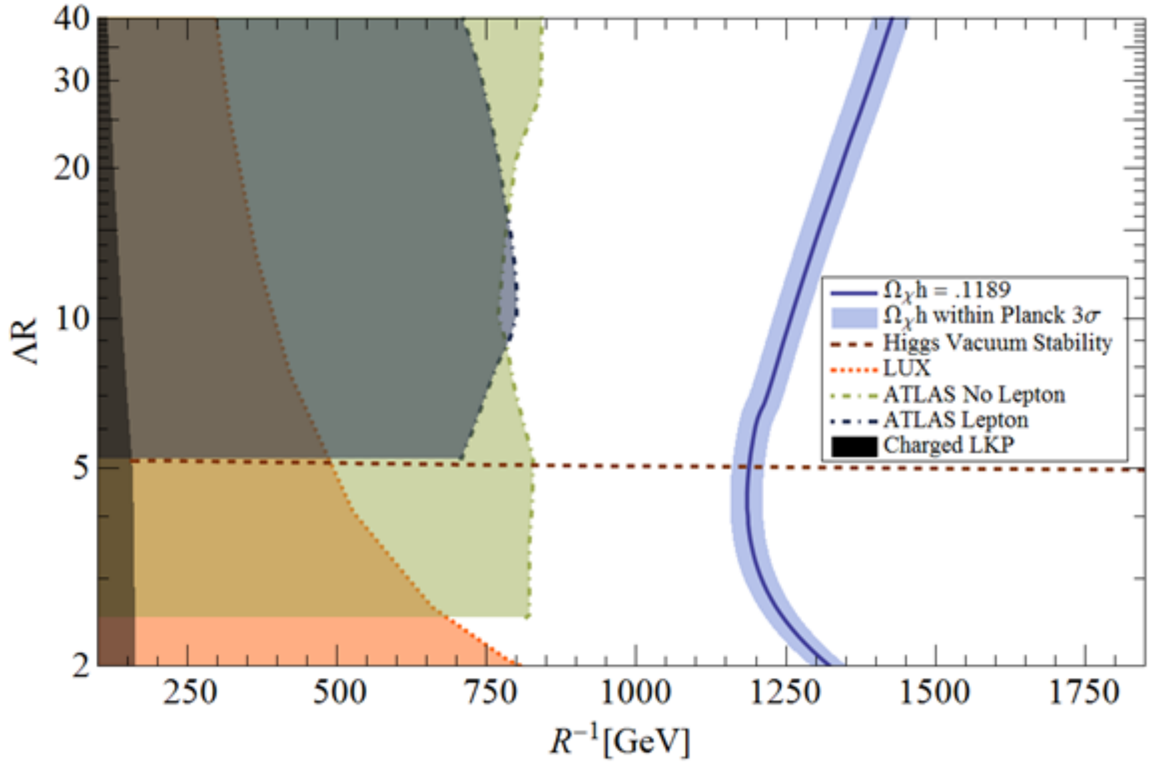
For EW-interacting DM, indirect searches may be more promising.

➡ Ask Hiroshima-san about this!

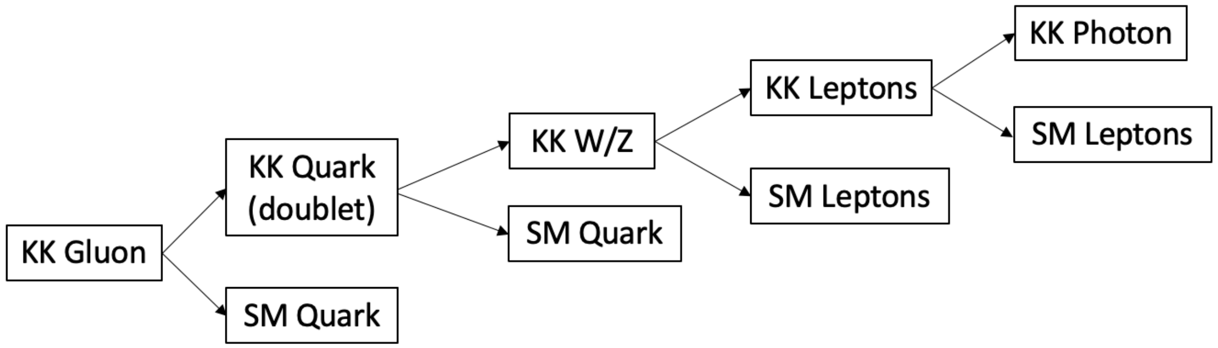
Minimal UED



$1l + \text{jets} + \text{MET}$



J. M. Cornell, S. Profumo, W. Shepherd, Phys. Rev. D**89**, 056005 (2014).


KK Gluon
KK Quark (doublet)
SM Quark
KK W/Z
SM Quark
KK Leptons
SM Leptons
KK Photon
SM Leptons

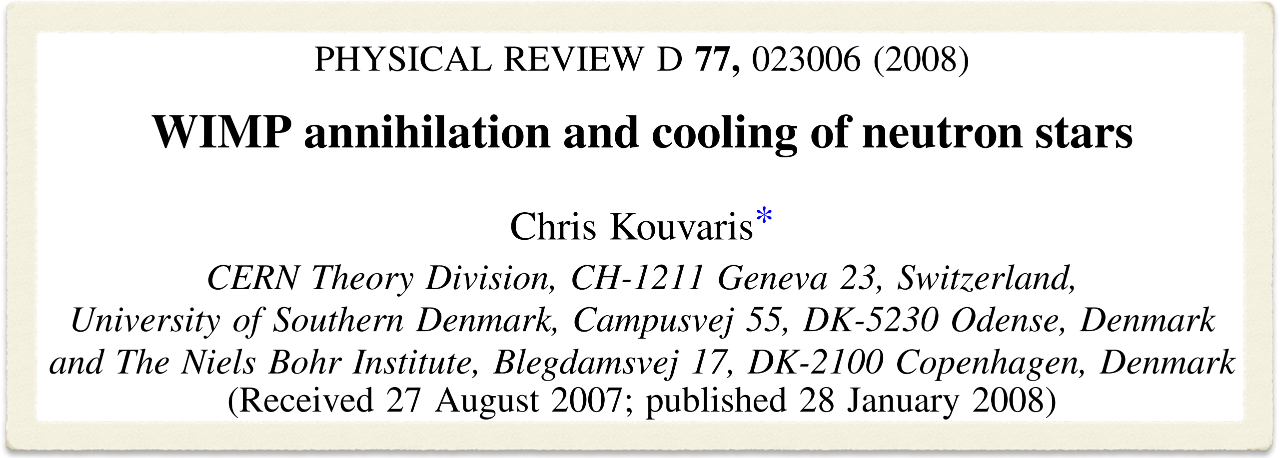
This scenario has been excluded by the LHC Run-2 experiments!

M. M. Flores, J. S. Kim, K. Rolbiecki, R. R. d. Bazan, Int. J. Mod. Phys. A **38**, 2350002 (2023).

DM heating in neutron stars

WIMP dark matter heating in NS

It has been discussed that the signature of WIMP DM may be detected via the neutron star temperature observations.



PHYSICAL REVIEW D **77,** 023006 (2008)

WIMP annihilation and cooling of neutron stars

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CERN Theory Division, CH-1211 Geneva 23, Switzerland,
University of Southern Denmark, Campusvej 55, DK-5230 Odense, Denmark
and The Niels Bohr Institute, Blegdamsvej 17, DK-2100 Copenhagen, Denmark
(Received 27 August 2007; published 28 January 2008)

PHYSICAL REVIEW D **81,** 123521 (2010)

Neutron stars as dark matter probes

Arnaud de Lavallaz* and Malcolm Fairbairn†

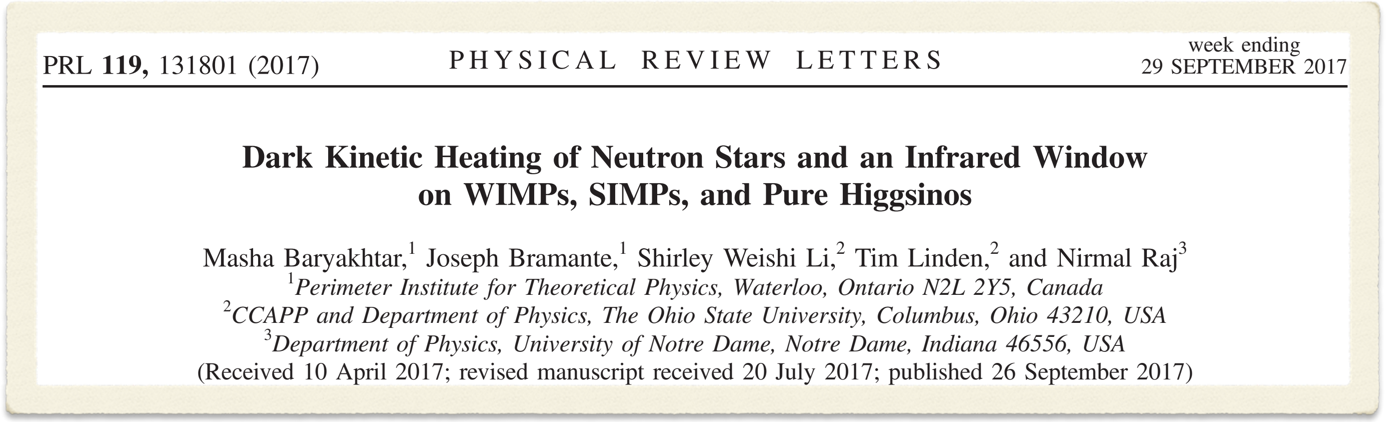
Physics, King's College London, Strand, London WC2R 2LS, United Kingdom
(Received 6 April 2010; published 18 June 2010)

PHYSICAL REVIEW D **82,** 063531 (2010)

Can neutron stars constrain dark matter?

Chris Kouvaris* and Peter Tinyakov†

Service de Physique Théorique, Université Libre de Bruxelles, 1050 Brussels, Belgium
(Received 29 May 2010; published 28 September 2010)



PRL **119,** 131801 (2017) PHYSICAL REVIEW LETTERS week ending 29 SEPTEMBER 2017

Dark Kinetic Heating of Neutron Stars and an Infrared Window on WIMPs, SIMPs, and Pure Higgsinos

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(Received 10 April 2017; revised manuscript received 20 July 2017; published 26 September 2017)

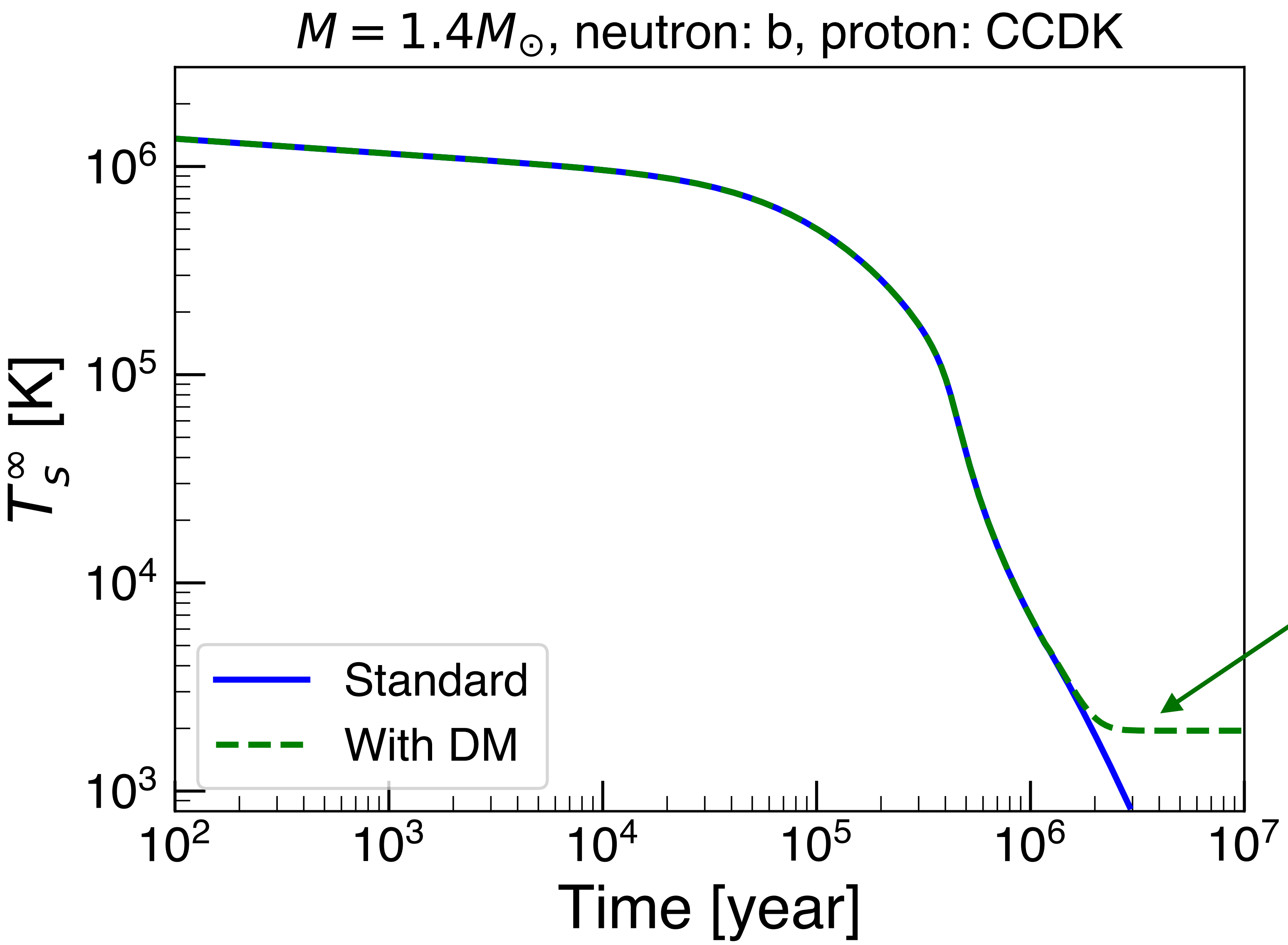
Idea

WIMP DM accretes on a neutron star (NS).

Annihilation of WIMPs in the NS core causes heating effect.

WIMP dark matter heating in NS

Dark matter heating effect may be observed in old NSs.



$\sigma_{\chi N} \gtrsim 10^{-45}\ \mathrm{cm}^2$

- In the standard cooling scenario, temperature becomes very low for $t > 10^7$ years.
- With DM heating effect, $T_s^\infty \to \sim 2 \times 10^3\ \mathrm{K}$ at later times.

Size of neutron star vs Toyama

- Radius: ~10 km
- Mass: $1 - 2\ M_\odot$

As high as nuclear density.

- Neutrons, protons, electrons, muons are Fermi degenerate.
- Neutrons and protons form Cooper parings.

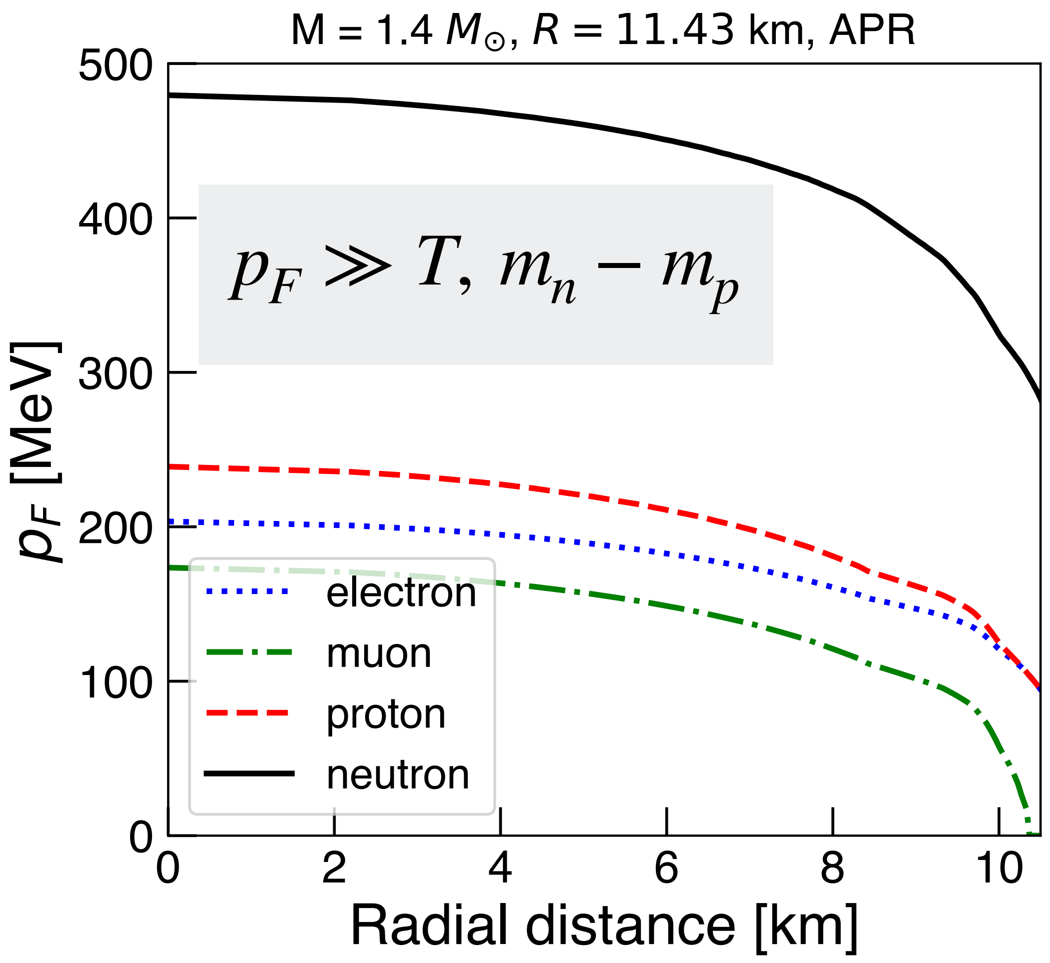
Standard Cooling of NS

D. Pager, J. M. Lattimer, M. Prakash, A. W. Steiner, Astrophys. J. Suppl. **155**, 623 (2004);
M. E. Gusakov, A. D. Kaminker, D. G. Yakovlev, O. Y. Gnedin, Astron. Astrophys. **423**, 1063 (2004).

Consider a NS composed of

- Neutrons
- Protons
- Leptons (e, μ)

- Supposed to be in the β equilibrium.
- In Fermi degenerate states.



$$p_F \gg T,\, m_n - m_p$$

Equation for temperature evolution

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

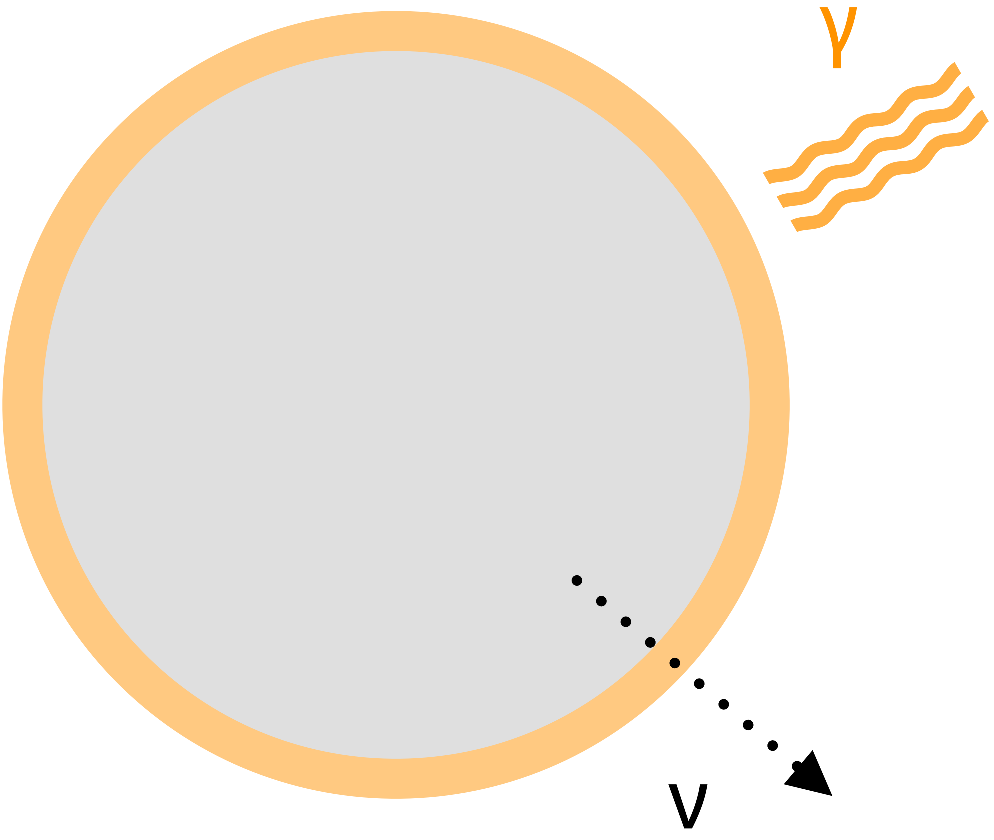
C(T): Stellar heat capacity

L_ν: Luminosity of neutrino emission

L_γ: Luminosity of photon emission

Cooling sources

Two cooling sources:



- Photon emission (from surface)

$$L_\gamma = 4\pi R^2 \sigma_{\rm SB} T_s^4$$

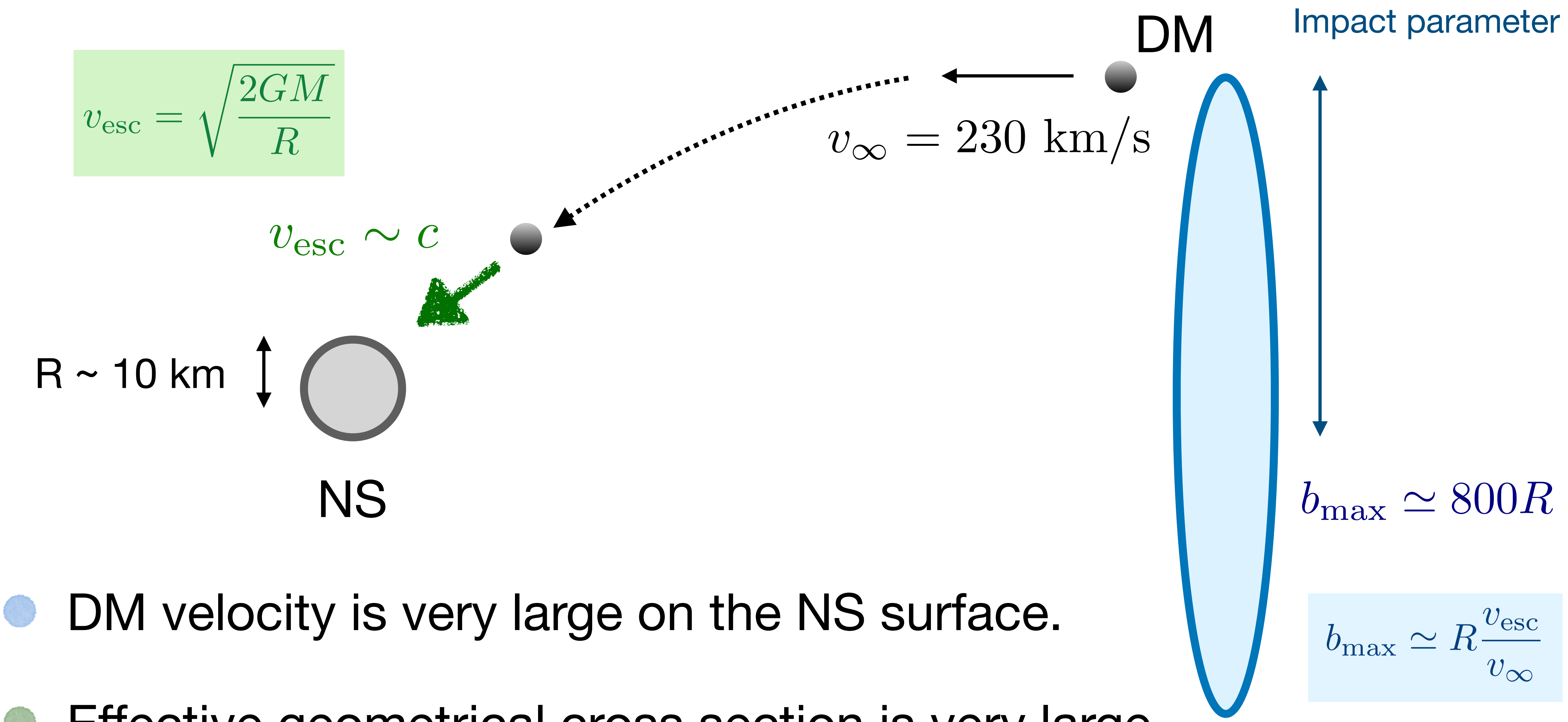
Dominant for $t \gtrsim 10^5$ years

- Neutrino emission (from core)
  - Direct Urca process (DUrca)
  - Modified Urca process (MUrca)
  - Bremsstrahlung
  - PBF process

Occurs when nucleon pairings are formed.

Dominant for $t \lesssim 10^5$ years

Dark matter accretion in NS



- DM velocity is very large on the NS surface.
- Effective geometrical cross section is very large.

DM accretion rate is

$$\dot{N} \simeq \pi b_{\max}^2 v_\infty \cdot \underbrace{\frac{\rho_{\rm DM}}{m_{\rm DM}}}_{\text{DM number density}}$$

Recoil energy

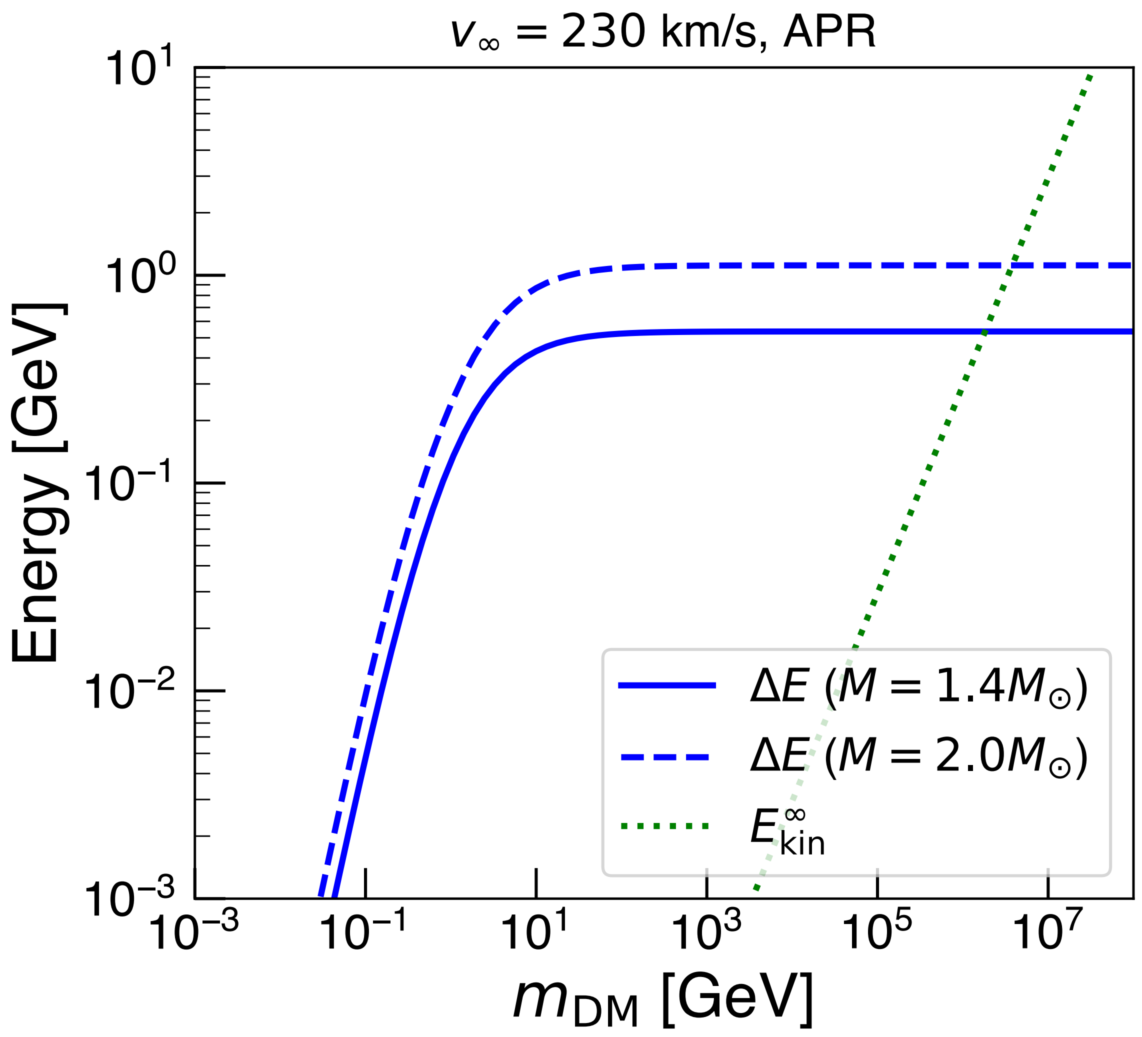
For each DM-nucleon scattering, WIMPs lose energy by

$$\Delta E = \frac{m_N m_{\rm DM}^2 \gamma_{\rm esc}^2 v_{\rm esc}^2}{m_N^2 + m_{\rm DM}^2 + 2\gamma_{\rm esc} m_{\rm DM} m_N}(1 - \cos\theta_c)$$

θ_c : scattering angle in the CM frame.

$\gamma_{\rm esc} \equiv (1 - v_{\rm esc}^2)^{-1/2}$

Let us compare this with the initial kinetic energy: $E_{\rm kin}^{\infty} = m_{\rm DM} v_{\infty}^2/2$



- One scattering is sufficient for WIMPs to lose the initial kinetic energy.
- Energy transfer can be as large as O(100) MeV.

One scattering in NS

WIMP-nucleon scattering occurs at least once if

Mean Free Path $\sim (\sigma_N n)^{-1} \sim \dfrac{m_N R^3}{M \sigma_N} \lesssim R$ ➡ $\sigma_N \gtrsim 10^{-45}\ \mathrm{cm}^2$

σ_N : DM-nucleon scattering cross section

If this is satisfied, then all of the accreted WIMPs are captured.

If not, capture rate is suppressed by $\sigma_N/\sigma_{\mathrm{th}}$.

Captured WIMPs eventually annihilate inside the NS core.

For old NSs, we have

Accretion rate $\underset{\text{equilibrium}}{=}$ Annihilation rate

NS temperature with DM heating

At later times, the DM heating balances with the cooling by photon emission.

$$L_H = L_\gamma$$

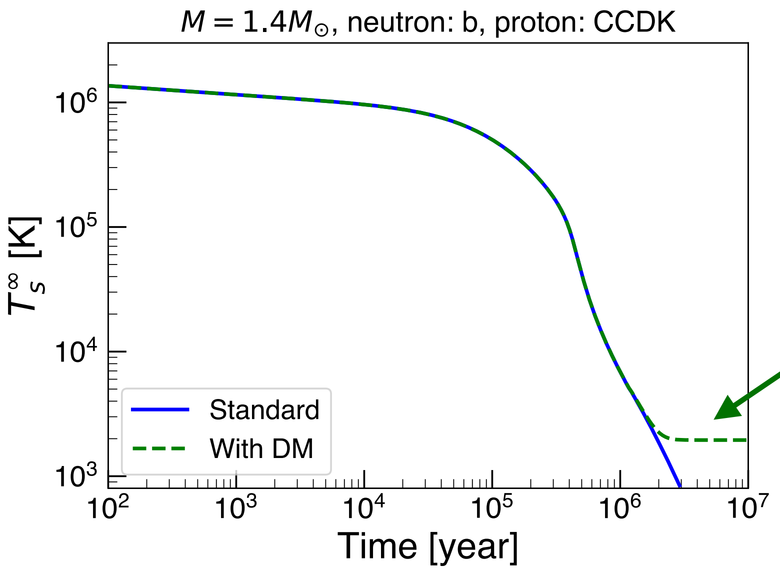
$$L_H \simeq m_{\rm DM}\dot{N} \simeq 2\pi GMR\rho_{\rm DM}/v_\infty$$

Independent of DM mass.

$$\Rightarrow\ 2\pi GMR\rho_{\rm DM}/v_\infty \simeq 4\pi R^2\sigma_{\rm SB}T_s^4$$

(for $\sigma > \sigma_{\rm th}$)

$$\Rightarrow\ T_s \simeq 2500\ {\rm K}$$



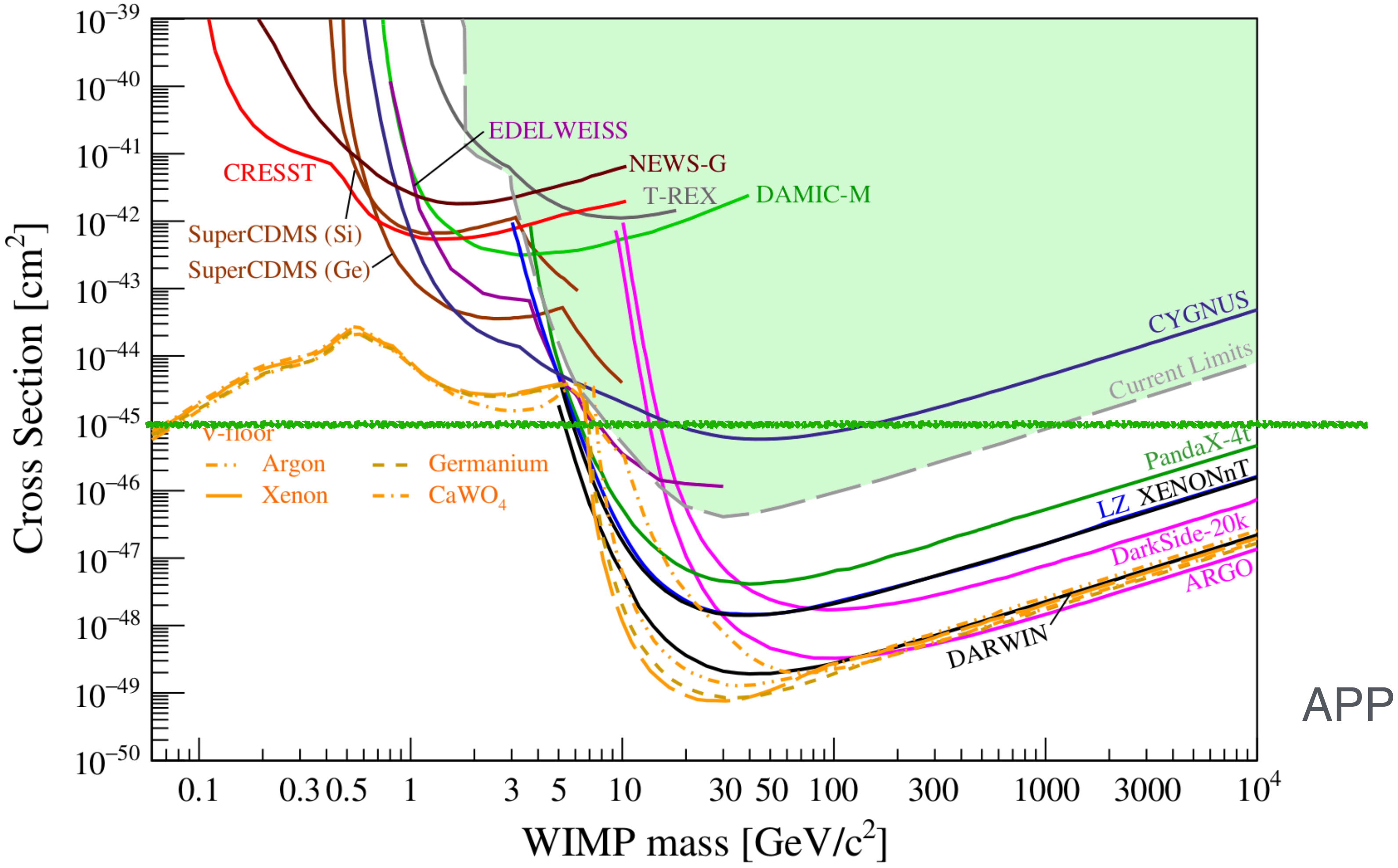
Robust, smoking-gun prediction of DM heating.

Can we observe this??

DM heating vs direct detection

In any case, an observation of a NS with $T_s \lesssim 2 \times 10^3 \text{ K}$ disfavors WIMPs which have $\sigma_N \gtrsim 10^{-45} \text{ cm}^2$.

Prospects for direct detection experiments



$\sigma_N = 10^{-45} \text{ cm}^2$

APPEC Committee Report, arXiv:2104.07634.

Such a large scattering cross section can be probed in direct detection experiments. Why we should care about DM heating??

Advantage of DM heating in NSs

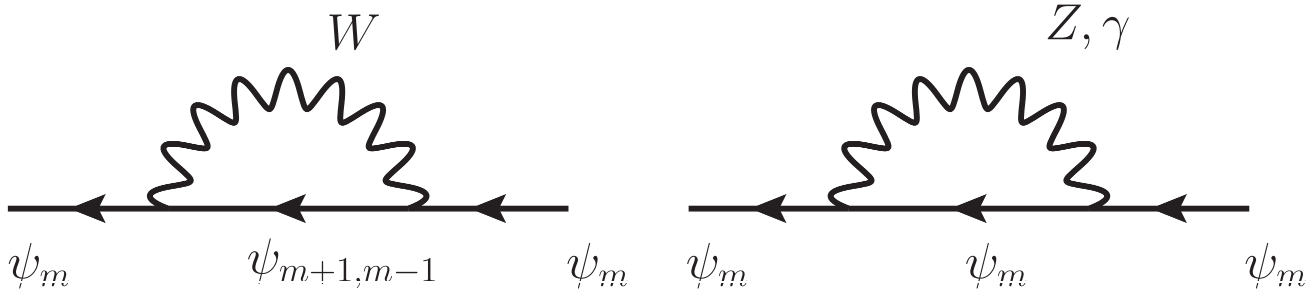
Bound from NS temperature may surpass those from DM direct searches in the following cases:

- Inelastic scattering occurs for $\Delta M \lesssim \mathcal{O}(100)\ \mathrm{MeV}$.
- Dark matter interacts only with leptons.
- WIMP-nucleon scattering is velocity-suppressed.
- Spin-dependent scattering
- Heavy/light dark matter

Electroweak multiplet DM

Electroweak multiplet DM is accompanied by charged particles, which are degenerate in mass.

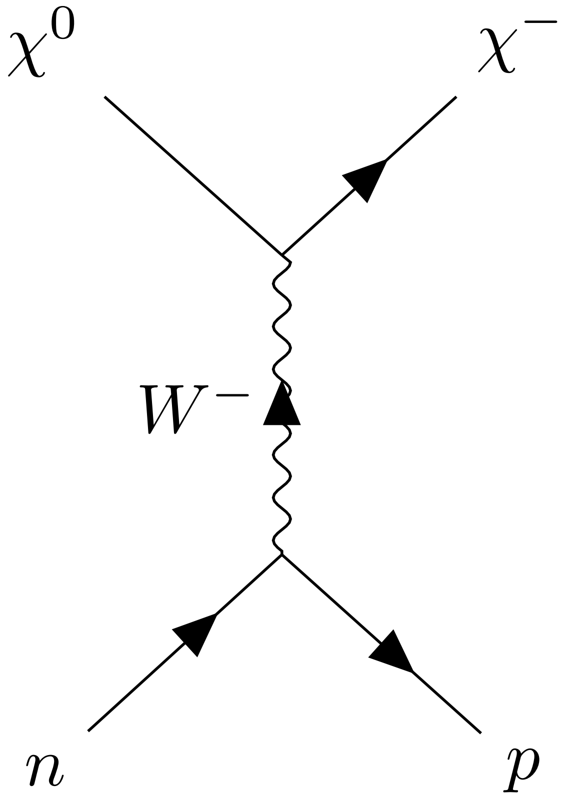
Mass splitting



$$\Delta M \simeq \alpha_2 m_W \sin^2 \frac{\theta_W}{2} + \alpha_2 Y m_W \left(\frac{1}{\cos\theta_W} - 1 \right)$$

O(100) MeV

- Inelastic scattering can occur.
- Cross section is large enough for such a DM to be captured in NS.
- NS can be a promising probe for this class of DM candidates.

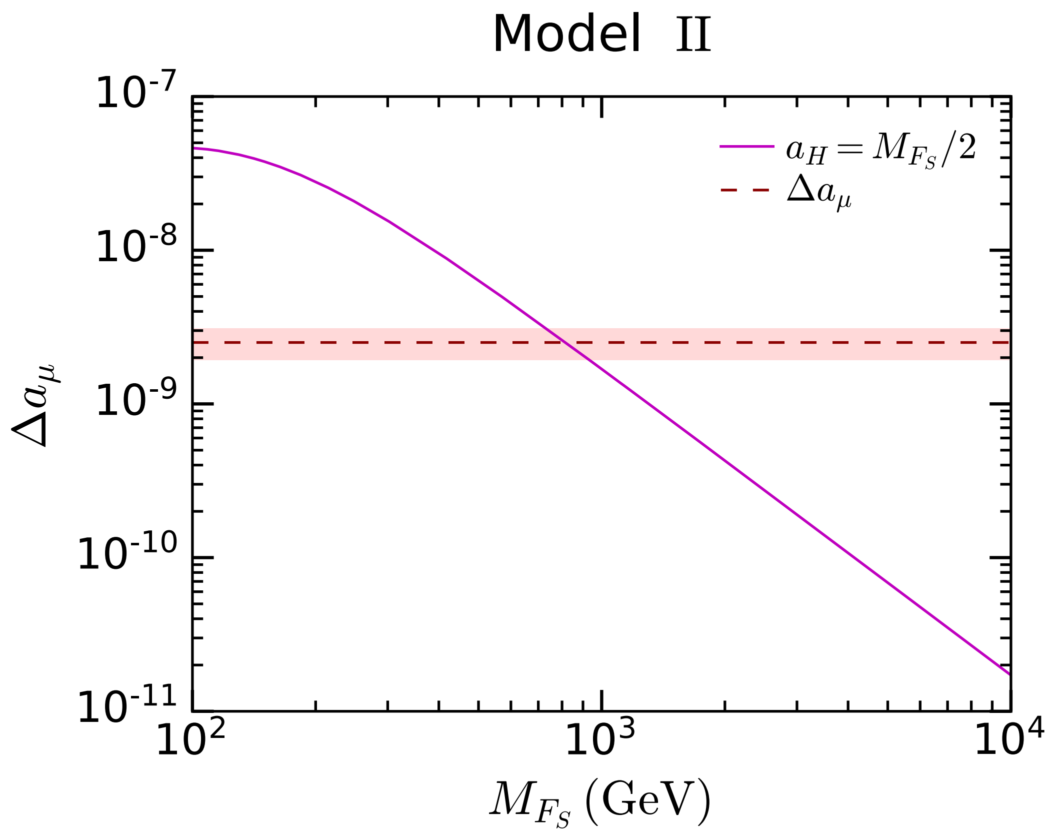


M. Fujiwara, K. Hamaguchi, N. Nagata, J. Zheng, Phys. Rev. D **106**, 055031 (2022).

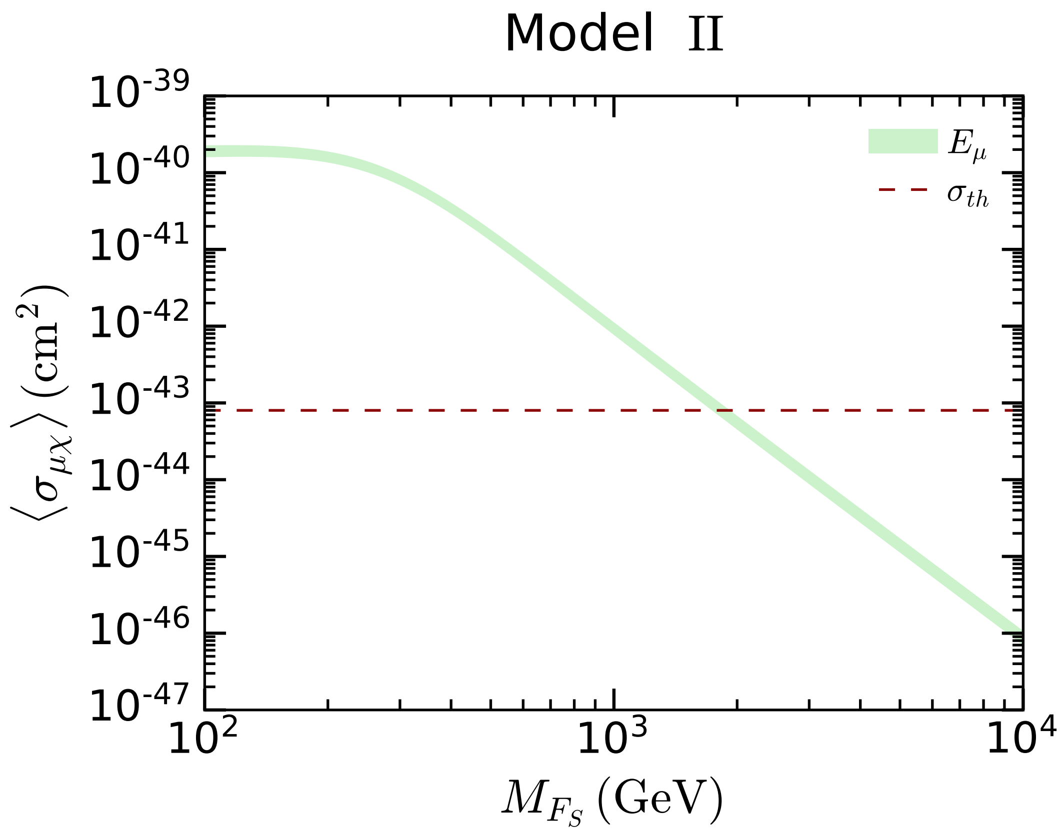
Muon g-2 and DM

NS heating can occur for DM models that couple only to leptons.

Muon g-2



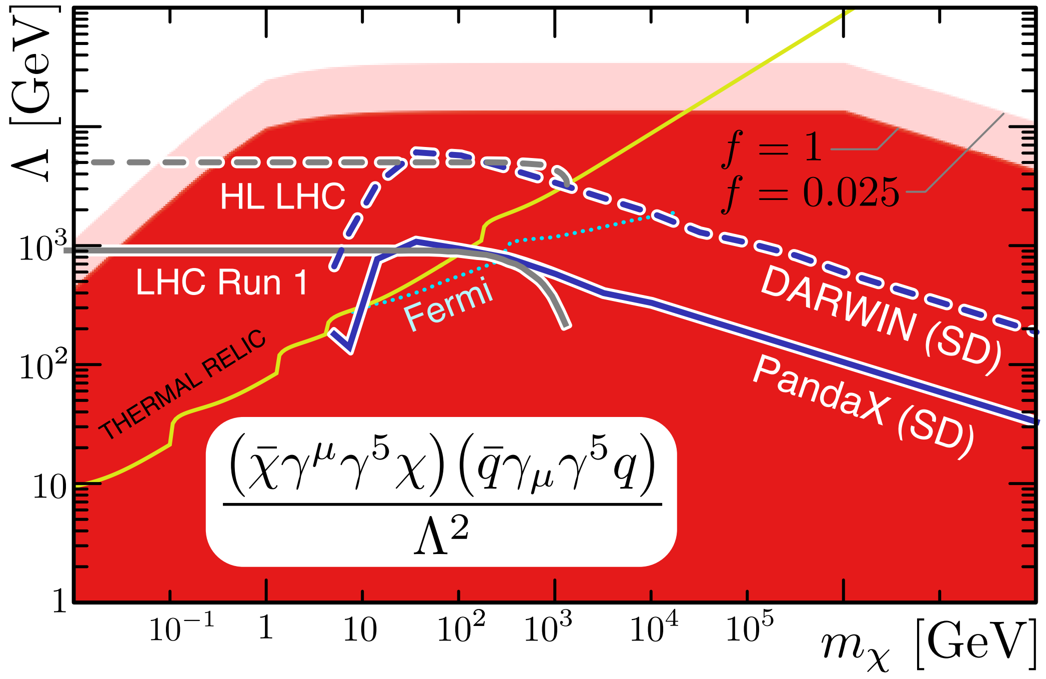
DM-muon scattering cross section

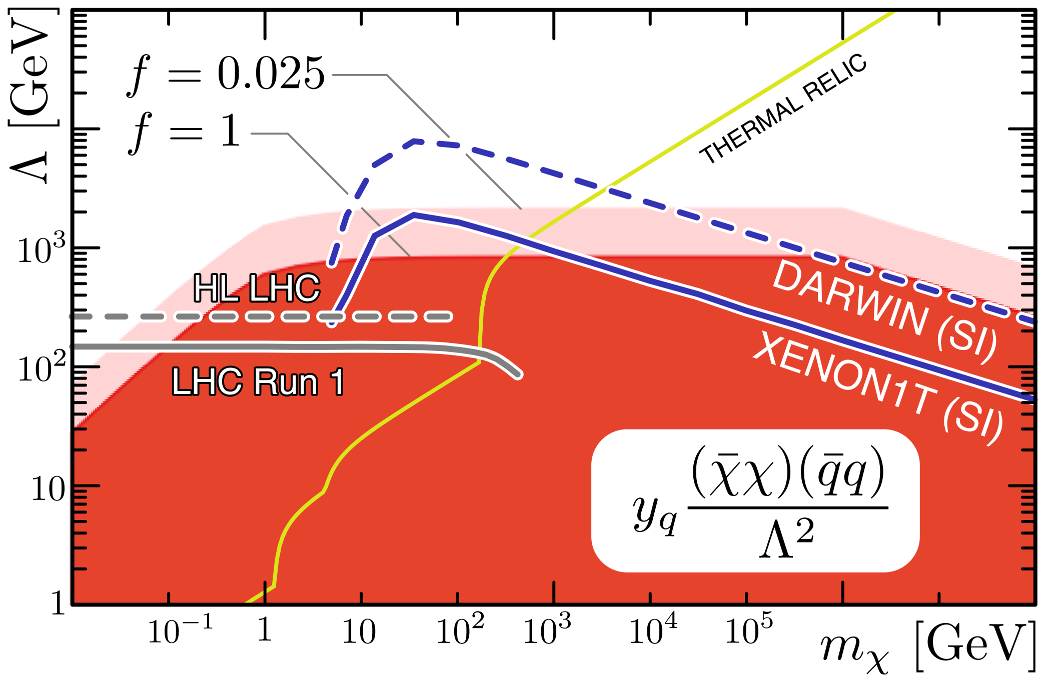


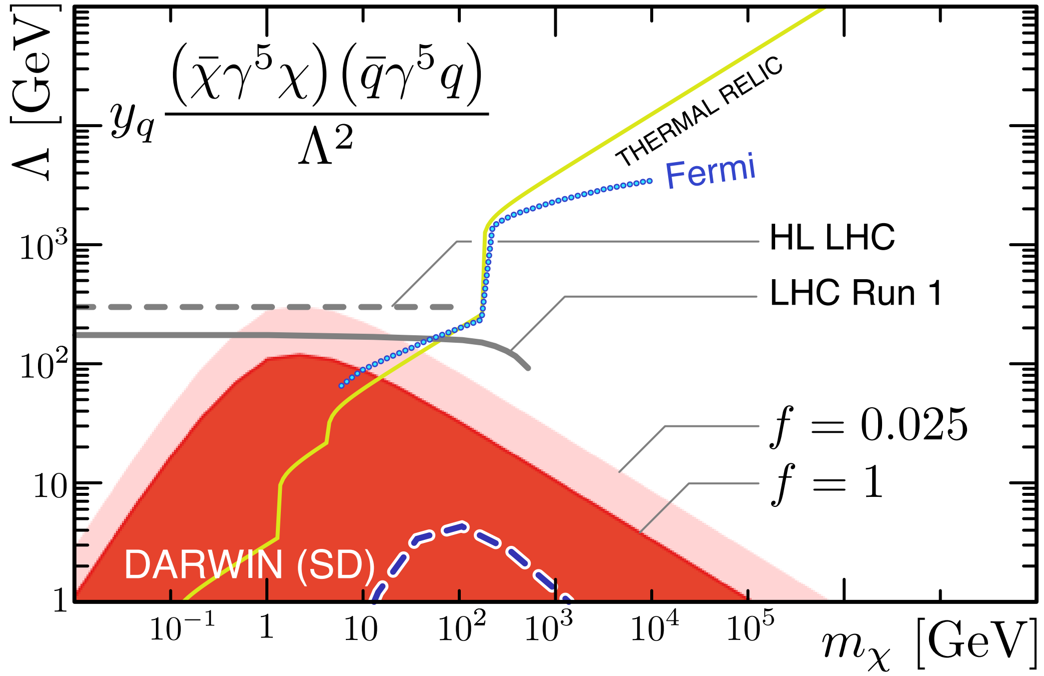
In the parameter regions where the muon g-2 anomaly is explained, DM-muon scattering is sufficiently large.

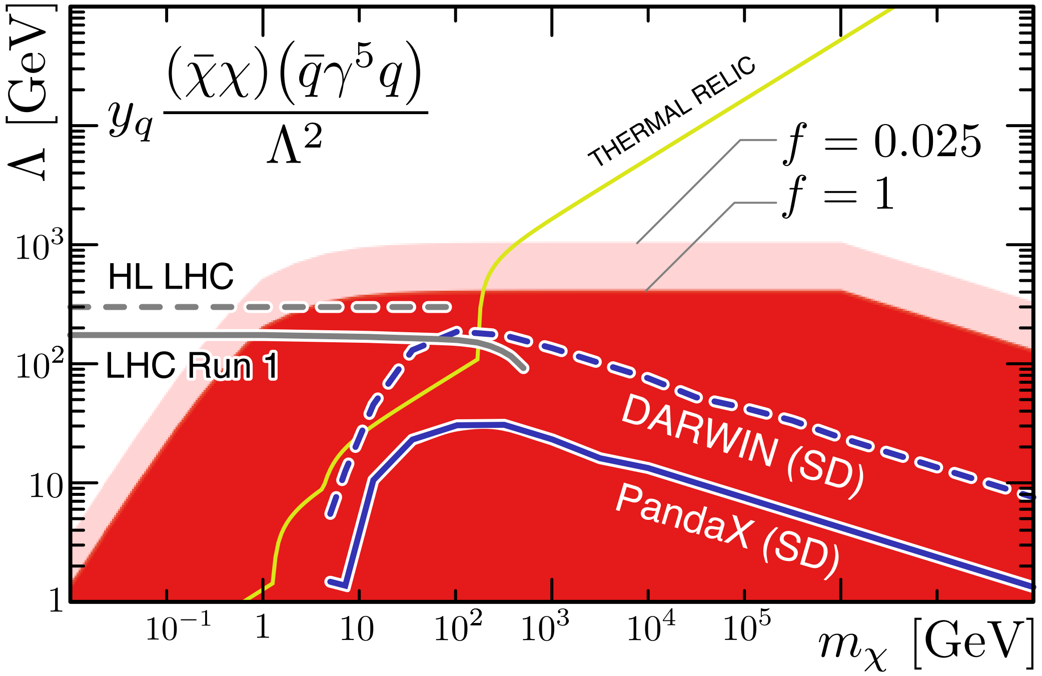
K. Hamaguchi, N. Nagata, M. E. Ramirez-Quezada, JHEP **10**, 088 (2022).

Effective operator analysis







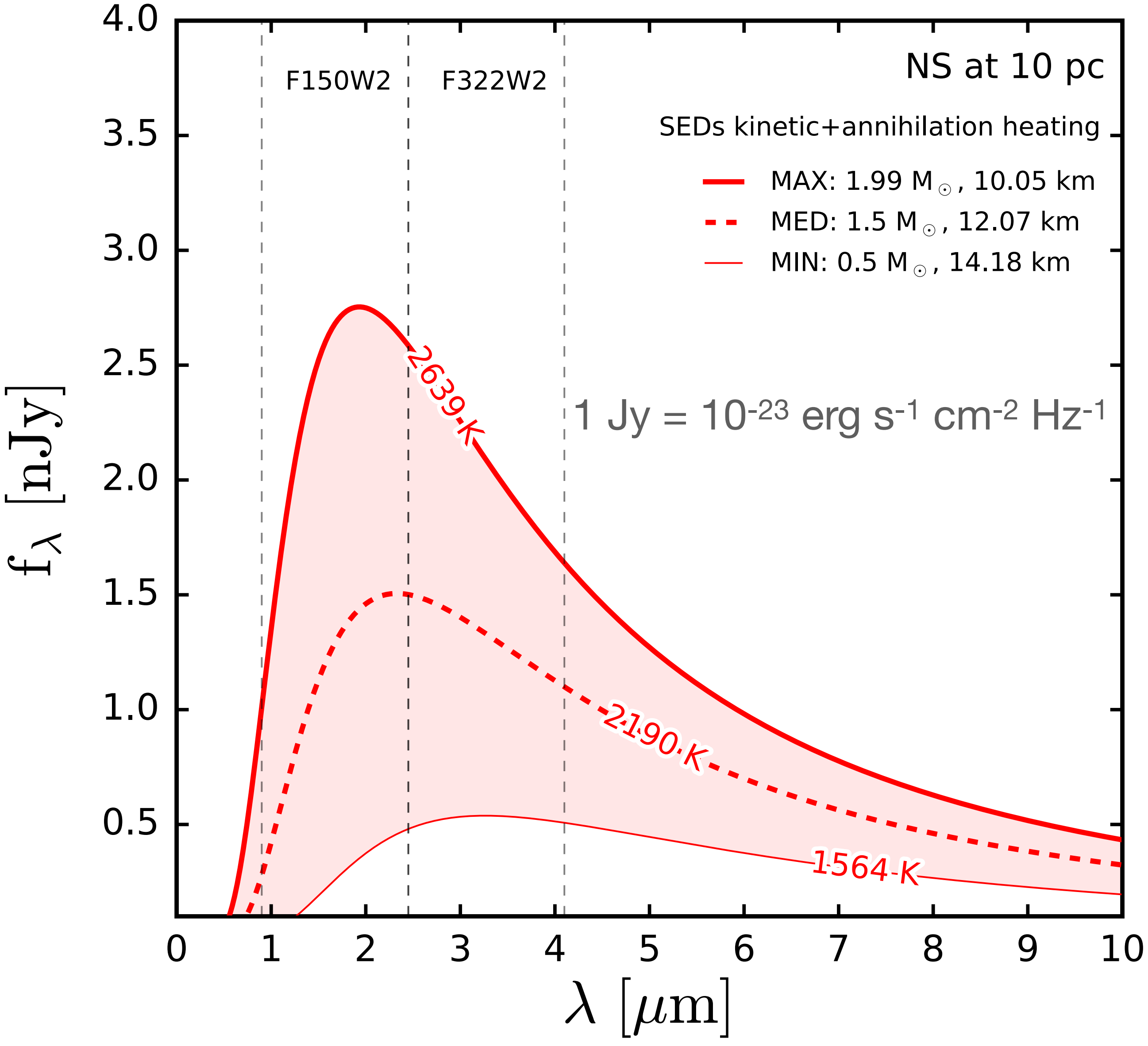


N. Raj, P. Tanedo, H. Yu, Phys. Rev. **D97**, 043006 (2018).

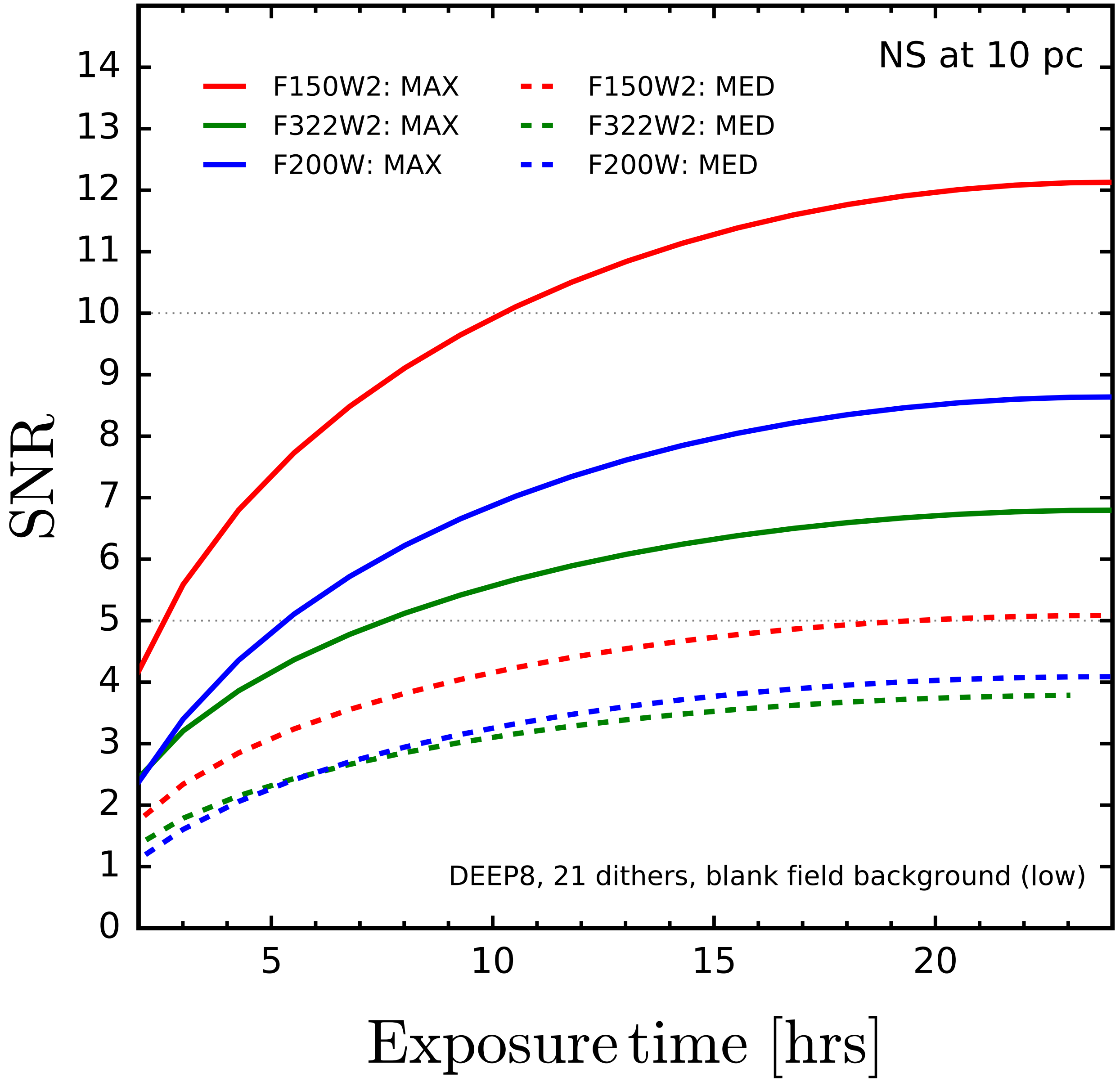
Challenges: observation

arXiv:2205.05048

Spectral distributions



Signal-to-noise ratio



- $\lambda \sim 2\ \mu m$ → Near-Infrared Camera (NIRCam) on JWST
- With the F150W2 filter, SNR $\gtrsim 5$ is obtained for 24 hours.

Challenges: other heating sources

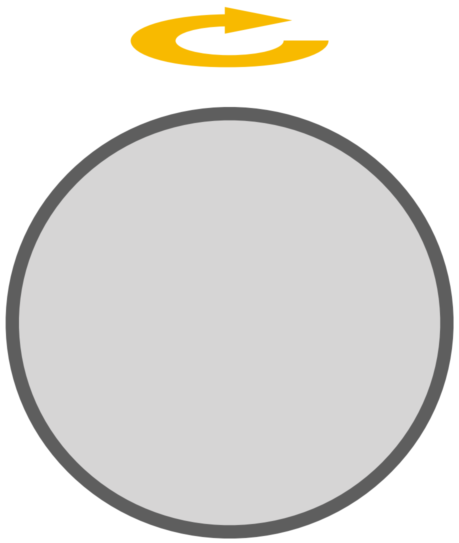
In actual NSs, the following heating mechanisms due to the slowdown of NS rotation may operate:

- Non-equilibrium beta processes

K. Hamaguchi, N. Nagata, K. Yanagi, Phys. Lett. **B795**, 484 (2019);
K. Hamaguchi, N. Nagata, K. Yanagi, MNRS **492**, 5508 (2020).

- Friction caused by vortex creep

M. Fujiwara, K. Hamaguchi, N. Nagata, M. E. Ramirez-Quezada, arXiv:2308.16066, 2309.02633.



These heating may conceal the DM heating.

Summary

Conclusion

- DM heating predicts NS surface temperature of ~ a few thousand K at later times.
- This may be detectable.
- An observation of a NS with $T_s^\infty \lesssim 10^3$ K can give a stringent constraint on WIMP DM models.
    - Electroweak multiplet dark matter
    - Muon g-2 motivated dark matter models

Appendix: other heating mechanisms

Other heating sources?

If there are other heating sources in NSs, DM heating effect may be concealed.

- There is no heating source in Standard NS cooling theory.

- Is it possible to have extra heating sources?

Or, even motivated?

Old warm neutron stars?

Recently, “old but warm neutron stars” have been observed.

Milli-second pulsars

- J0437-4715: $t_{\rm sd} = (6.7 \pm 0.2) \times 10^9$ years, $T_s^\infty = (1.25 - 3.5) \times 10^5$ K

O. Kargaltsev, G. G. Pavlov, and R. W. Romani, Astrophys. J. **602**, 327 (2004);
M. Durant, *et al.*, Astrophys. J. **746**, 6 (2012).

- J2124-3358: $t_{\rm sd} = 11^{+6}_{-3} \times 10^9$ years, $T_s^\infty = (0.5 - 2.1) \times 10^5$ K

B. Rangelov, *et al.*, Astrophys. J. **835**, 264 (2017).

Ordinary pulsars

- J0108-1431: $t_{\rm sd} = 2.0 \times 10^8$ years, $T_s^\infty = (2.7 - 5.5) \times 10^4$ K

V. Abramkin, Y. Shibanov, R. P. Mignani, and G. G. Pavlov, Astrophys. J. **911**, 1 (2021).

- B0950+08: $t_{\rm sd} = 1.75 \times 10^7$ years, $T_s^\infty = (6 - 12) \times 10^4$ K

V. Abramkin, G. G. Pavlov, Y. Shibanov, and O. Kargaltsev, Astrophys. J. **924**, 128 (2022).

These observations cannot be explained in the standard cooling.

Topics of this Appendix

- We need an extra heating source to explain those observations.

Candidates for the heating mechanism

  - Non-equilibrium beta processes
  - Friction caused by vortex creep

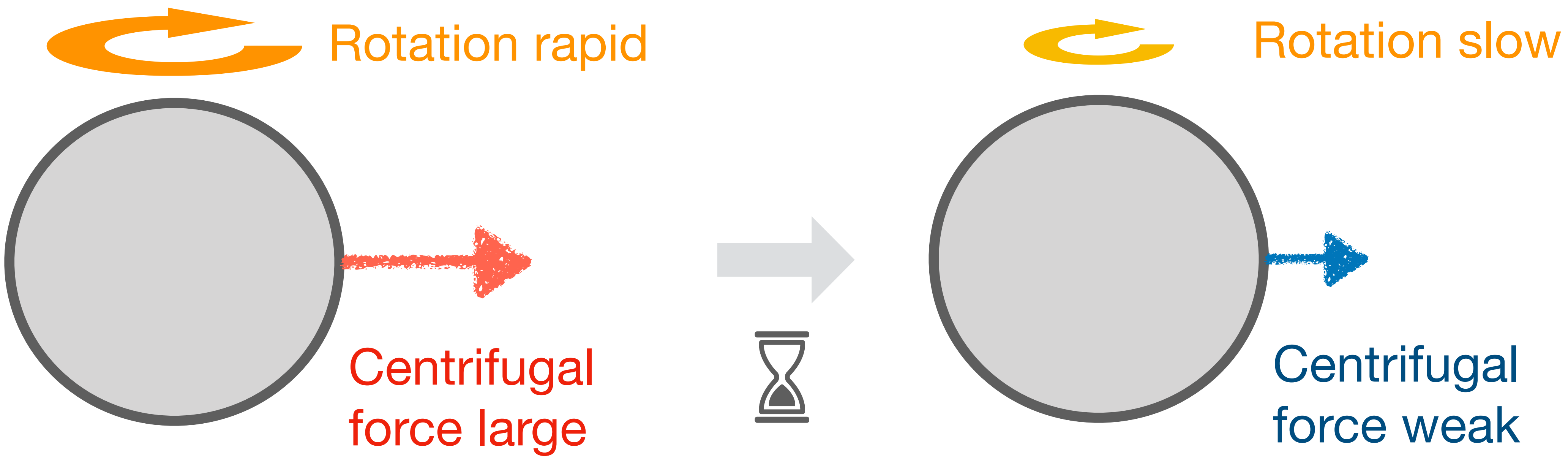
- Can we still observe the DM heating effect in the presence of this extra heating effect??

Non-equilibrium β processes

Loop hole in standard cooling

In the standard cooling, β equilibrium is assumed.

In a real pulsar

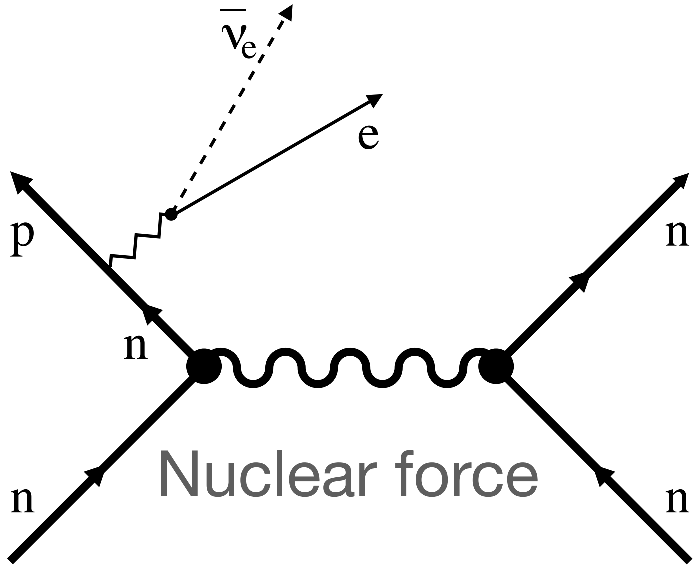


Local pressure changes. Chemical equilibrium condition changes.

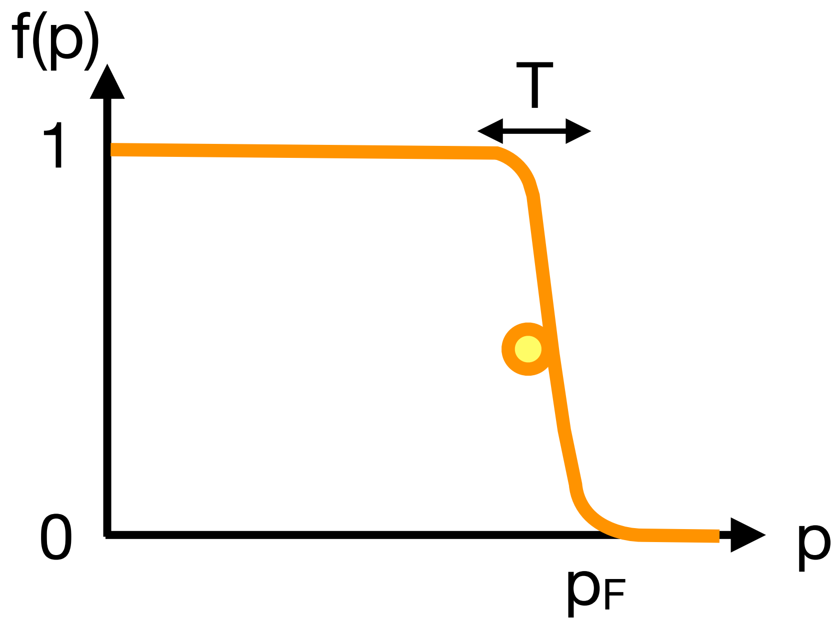
If the beta processes are rapid enough, the system can follow the change in the equilibrium condition. But…

Neutrino emission

The beta processes are highly suppressed at later times, i.e., for low temperatures.



Modified Urca



Only the particles near the Fermi surface can participate in the processes.

➡ Deviation from β equilibrium

A. Reisenegger, Astrophys. J. **442**, 749 (1995).

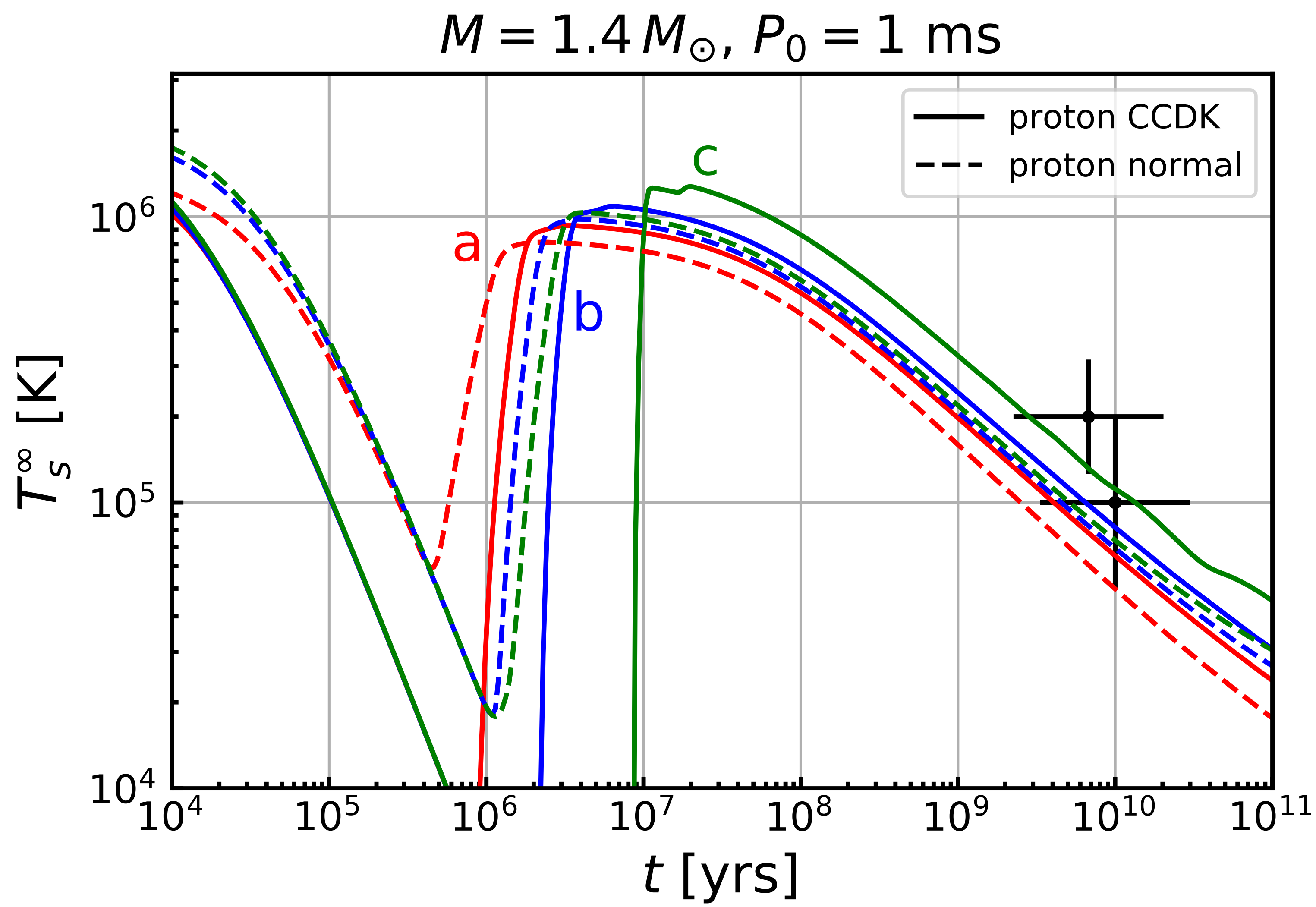
The imbalance in chemical potentials is dissipated as heat.

➡ Rotochemical heating

R. Fernandez and A. Reisenegger, Astrophys. J. **625**, 291 (2005);
C. Petrovich, A. Reisenegger, Astron. Astrophys. **521**, A77 (2010).

Millisecond pulsars

We take account of the effect of non-equilibrium β processes.



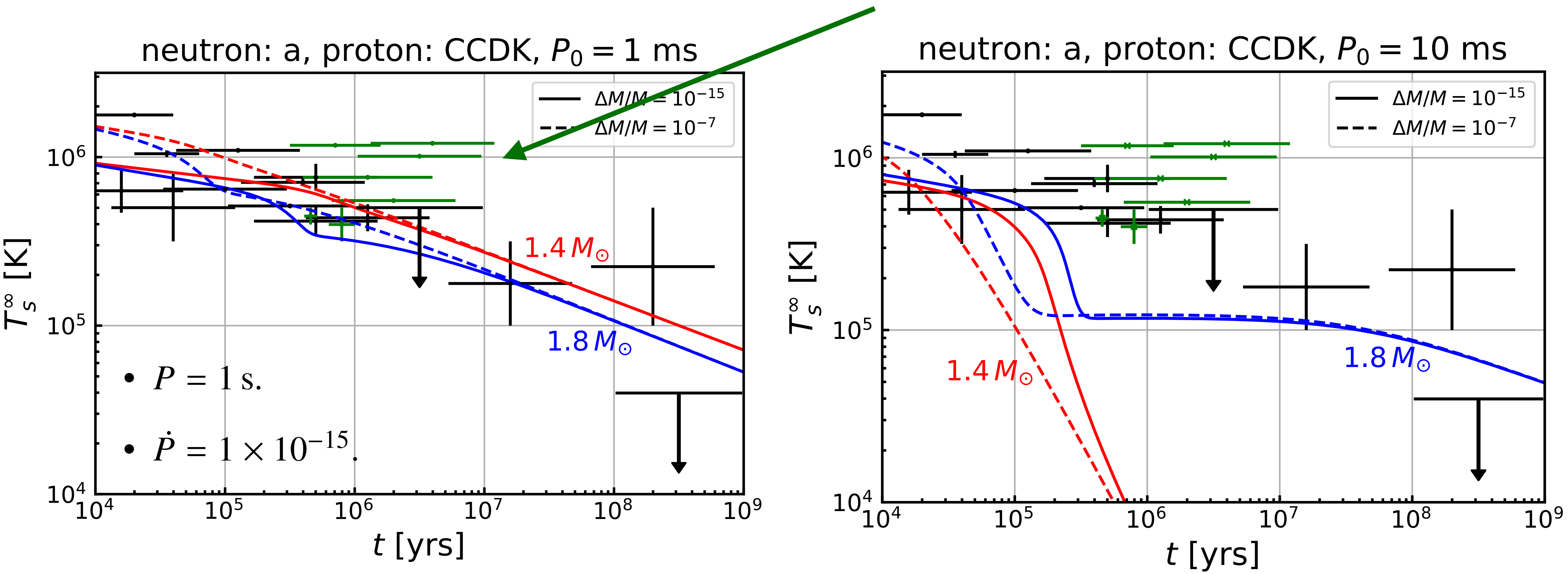
- $M = 1.4\,M_\odot$.
- $P = 5.8\,\mathrm{ms}$.
- $\dot{P} = 5.7 \times 10^{-20}$.

- Rotochemical heating always occurs in MSPs.
- We can explain the observations.

K. Hamaguchi, N. Nagata, K. Yanagi, MNRS **492**, 5508 (2020).

Ordinary pulsars

Heating due to magnetic field decay may occur.

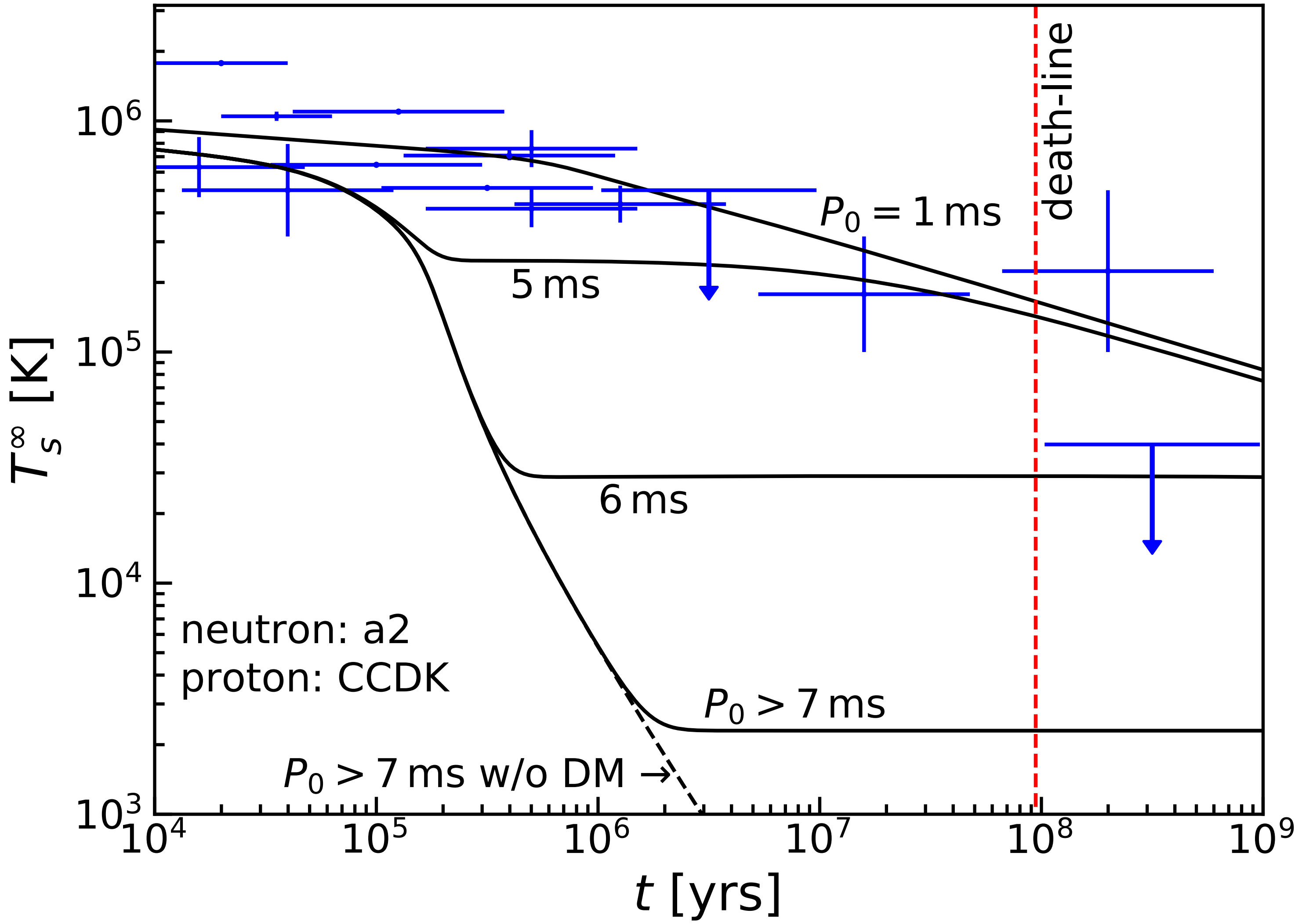


- The temperature evolution highly depends on the initial period P_0 of pulsars.
- We can explain all of the observations.
  - Cool star: large initial period → no rotochemical heating.
  - Warm star: small initial period → rotochemical heating effective.

K. Hamaguchi, N. Nagata, K. Yanagi, MNRS **492**, 5508 (2020).

Rotochemical heating vs DM heating

Now we include both the DM and rotochemical heating effects.



Simulations show that P_0 can be as large as O(100) ms.

See, *e.g.*, 1811.05483.

- If P_0 is large enough, DM heating effect can be observed.
- It is always concealed in millisecond pulsars.

K. Hamaguchi, N. Nagata, K. Yanagi, Phys. Lett. **B795**, 484 (2019).

Vortex Creep Heating

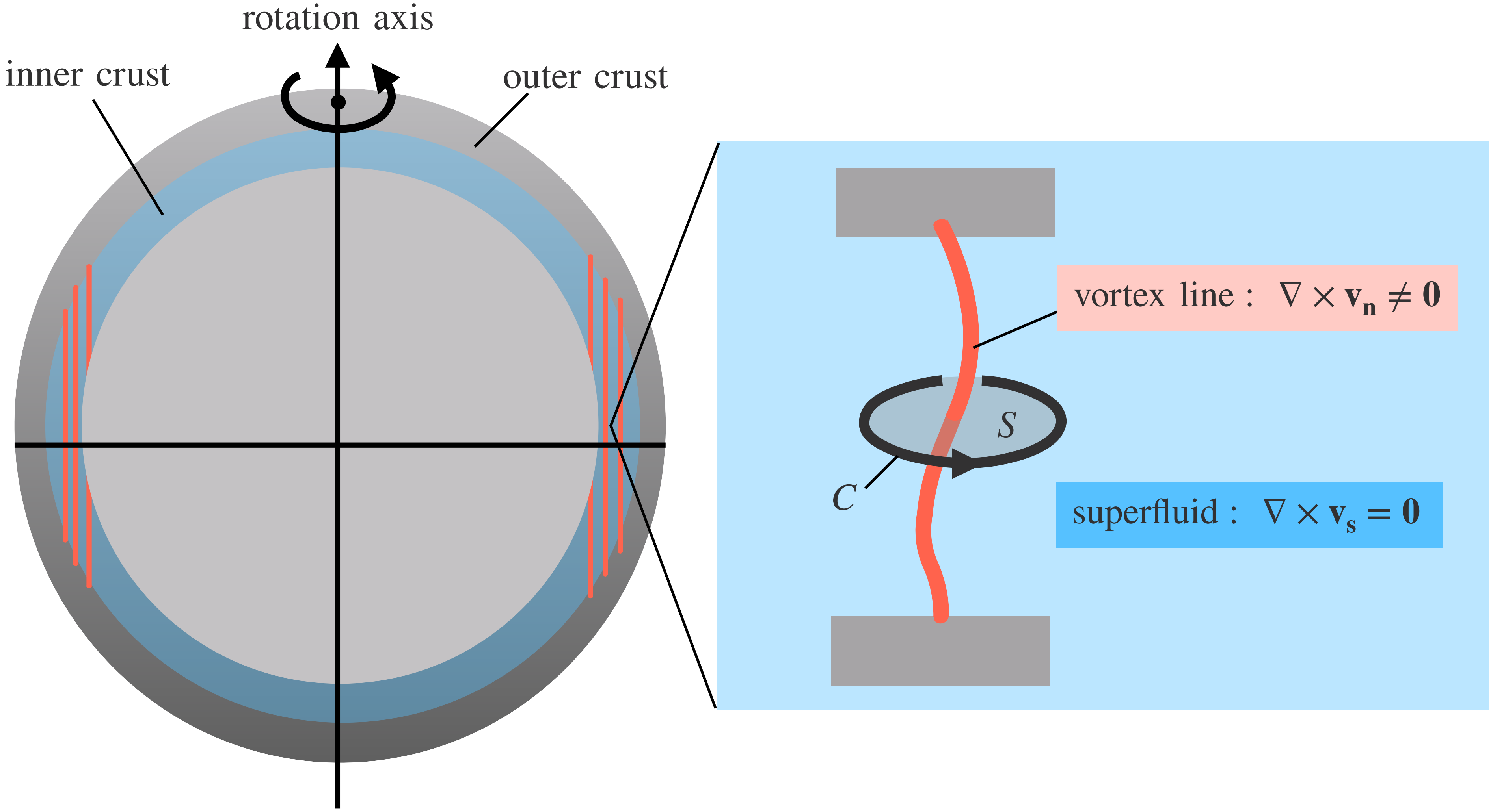
Neutron superfluid vortex lines

Neutrons form Cooper pairs in NSs. ➡ Neutron superfluidity

In a rotating NS, superfluid vortex lines are formed.

The vortex lines are fixed to the crust by nuclear interactions.

P. W. Anderson and N. Itoh, Nature **256**, 25 (1975).



Vortex creep

Due to the pulsar radiation, the crust component slows down.

But the superfluid component does not.

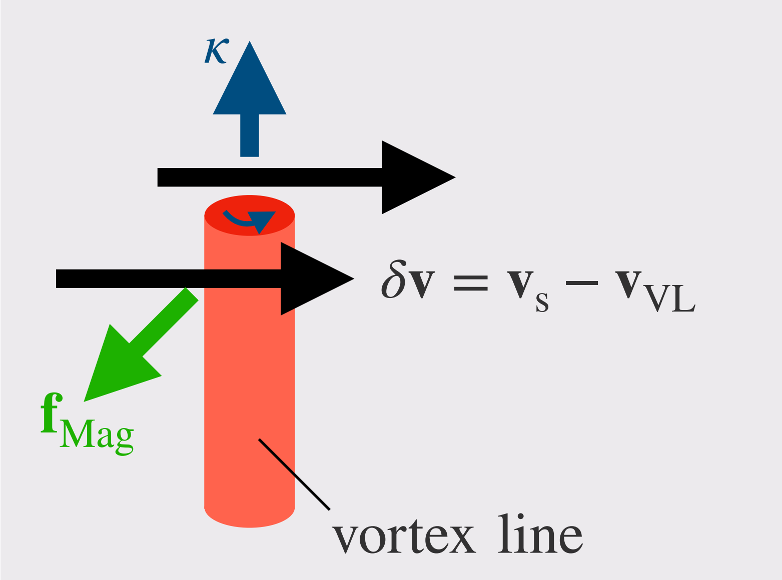
➡ The rotational speed difference developed.

This induces Magnus force.

When it gets large enough, vortex lines start to move outwards.

Vortex creep

➡ Speed difference decreases.



The vortex creep keeps the speed difference constant.

$$\Omega_{SF} - \Omega_{crust} = \text{const.}$$

Determined by the pinning force.

Vortex creep heating

M. A. Alpar, et.al., Astrophys. J. **276**, 325 (1984);
M. Shibazaki and F. K. Lamb, Astrophys. J. **346**, 808 (1989).

The rotational energy stored in the superfluid component is dissipated as heat:

$$L_{\mathrm{H}} = \int \underbrace{dI_{\mathrm{crust}}}_{\text{Moment of inertia}} \underbrace{(\Omega_{\mathrm{SF}} - \Omega_{\mathrm{crust}})}_{\text{Determined by the pinning force.}} |\dot{\Omega}| \equiv \boxed{J|\dot{\Omega}|}$$

All NSs have similar values of J.

In old NSs, this heating balances with the photon cooling:

$$L_{\mathrm{H}} = L_{\gamma} = 4\pi R^2 \sigma_{\mathrm{SB}} T_s^4$$

$$\Rightarrow \quad \boxed{J_{\mathrm{obs}} = 4\pi R^2 \sigma_{\mathrm{SB}} T_s^4 / |\dot{\Omega}|}$$

Can be determined by observation.

The vortex heating mechanism predicts this to be almost universal.

Vortex creep heating

M. A. Alpar, et.al., Astrophys. J. **276**, 325 (1984);
M. Shibazaki and F. K. Lamb, Astrophys. J. **346**, 808 (1989).

The rotational energy stored in the superfluid component is dissipated as heat:

$$L_{\mathrm{H}} = \int \underline{dI_{\mathrm{crust}}}\,\underline{(\Omega_{\mathrm{SF}} - \Omega_{\mathrm{crust}})}|\dot{\Omega}| \equiv J|\dot{\Omega}|$$

Moment of inertia

Determined by the pinning force.

All NSs have similar values of J.

In old NSs, this heating balances with the photon cooling:

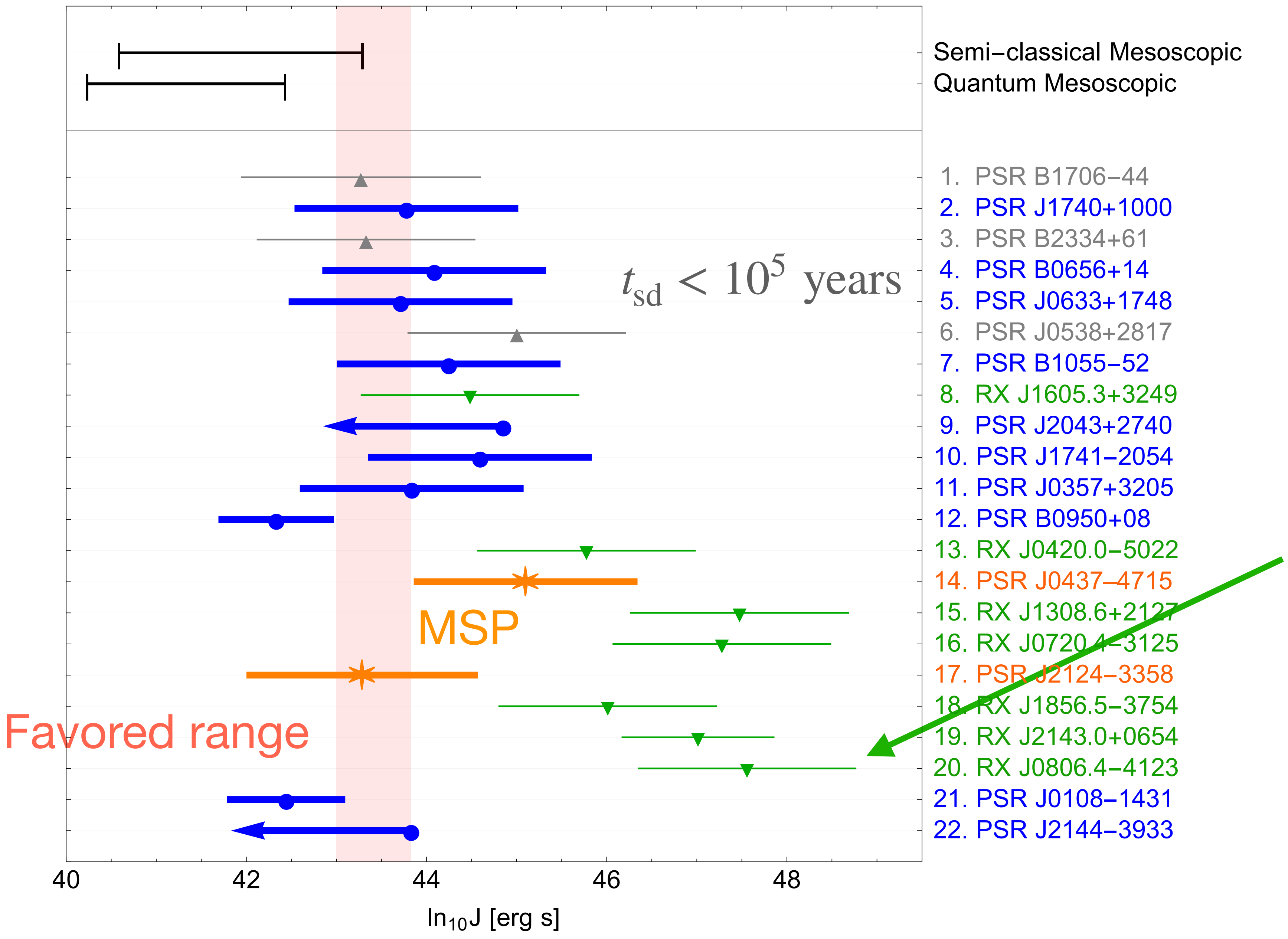
$$L_{\mathrm{H}} = L_{\gamma} = 4\pi R^2 \sigma_{\mathrm{SB}} T_s^4$$

⇒ $J_{\mathrm{obs}} = 4\pi R^2 \sigma_{\mathrm{SB}} T_s^4 / |\dot{\Omega}|$

Can be determined by observation.

The vortex heating mechanism predicts this to be almost universal.

Vortex creep heating vs observations



Theoretical estimations.

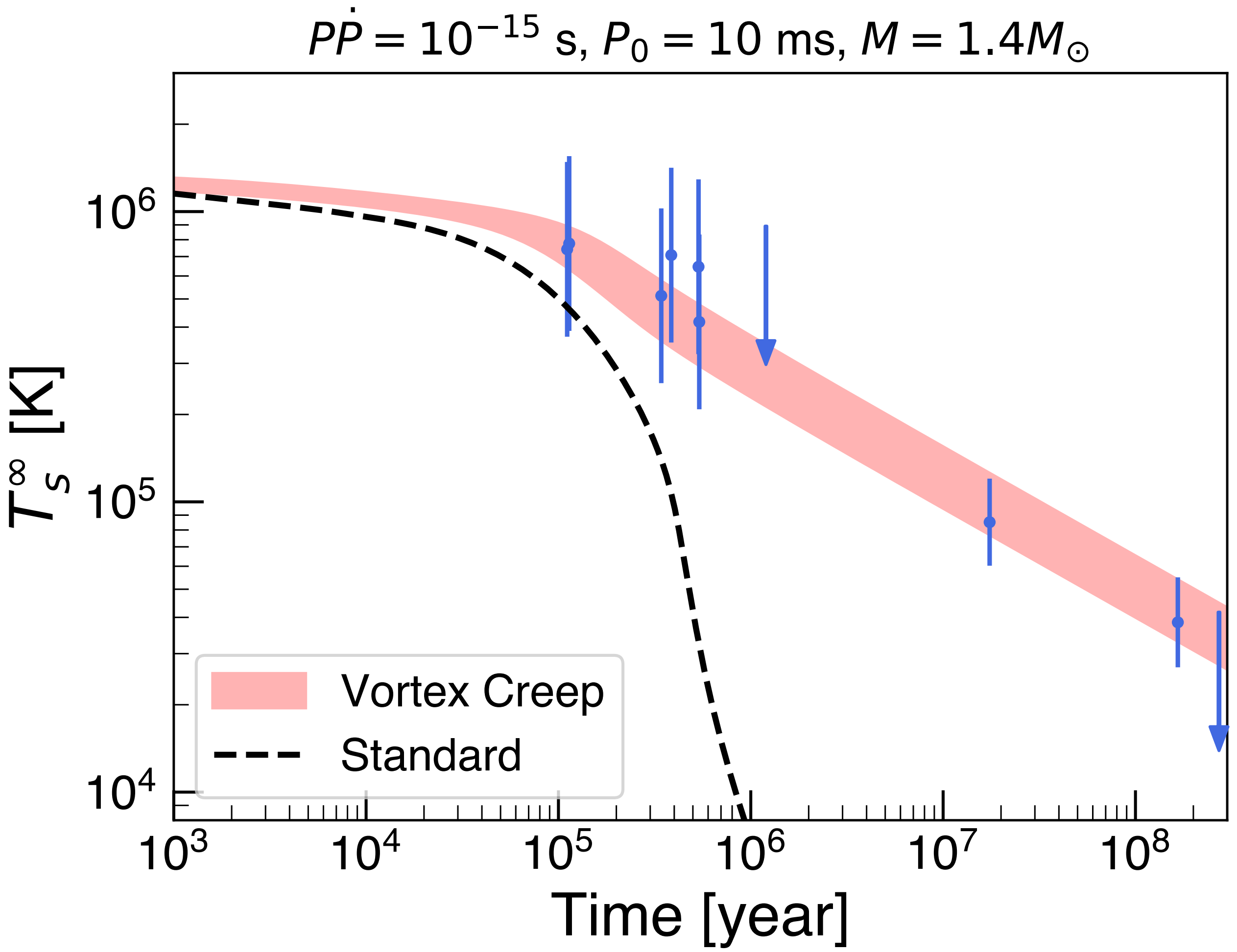
Magnetic heating suspected

- Observations find similar values of J.
- Theoretical calculations are in the same ballpark.

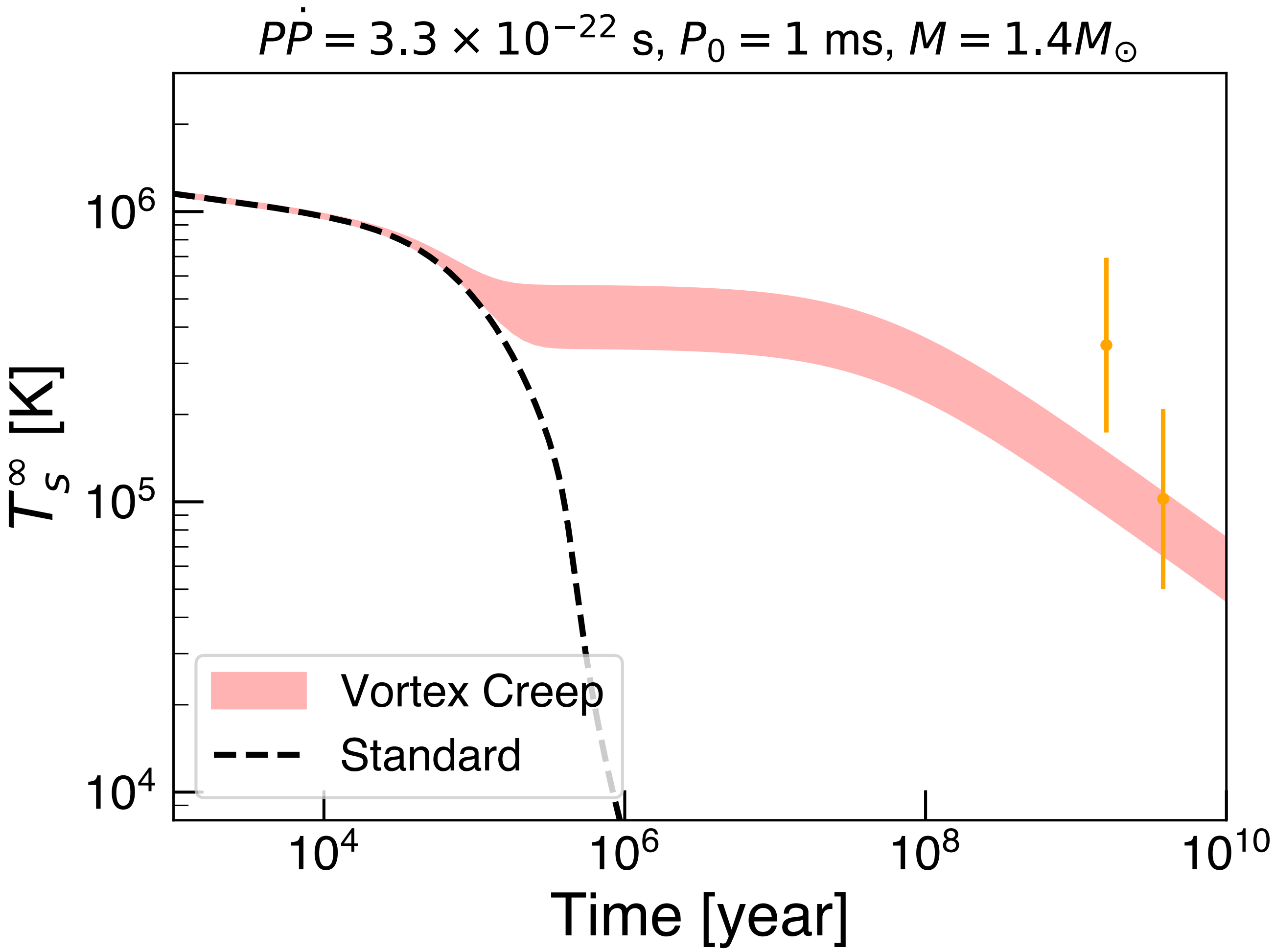
M. Fujiwara, K. Hamaguchi, N. Nagata, M. E. Ramirez-Quezada, arXiv:2308.16066

Vortex creep heating vs observations

Ordinary pulsars



Millisecond pulsars

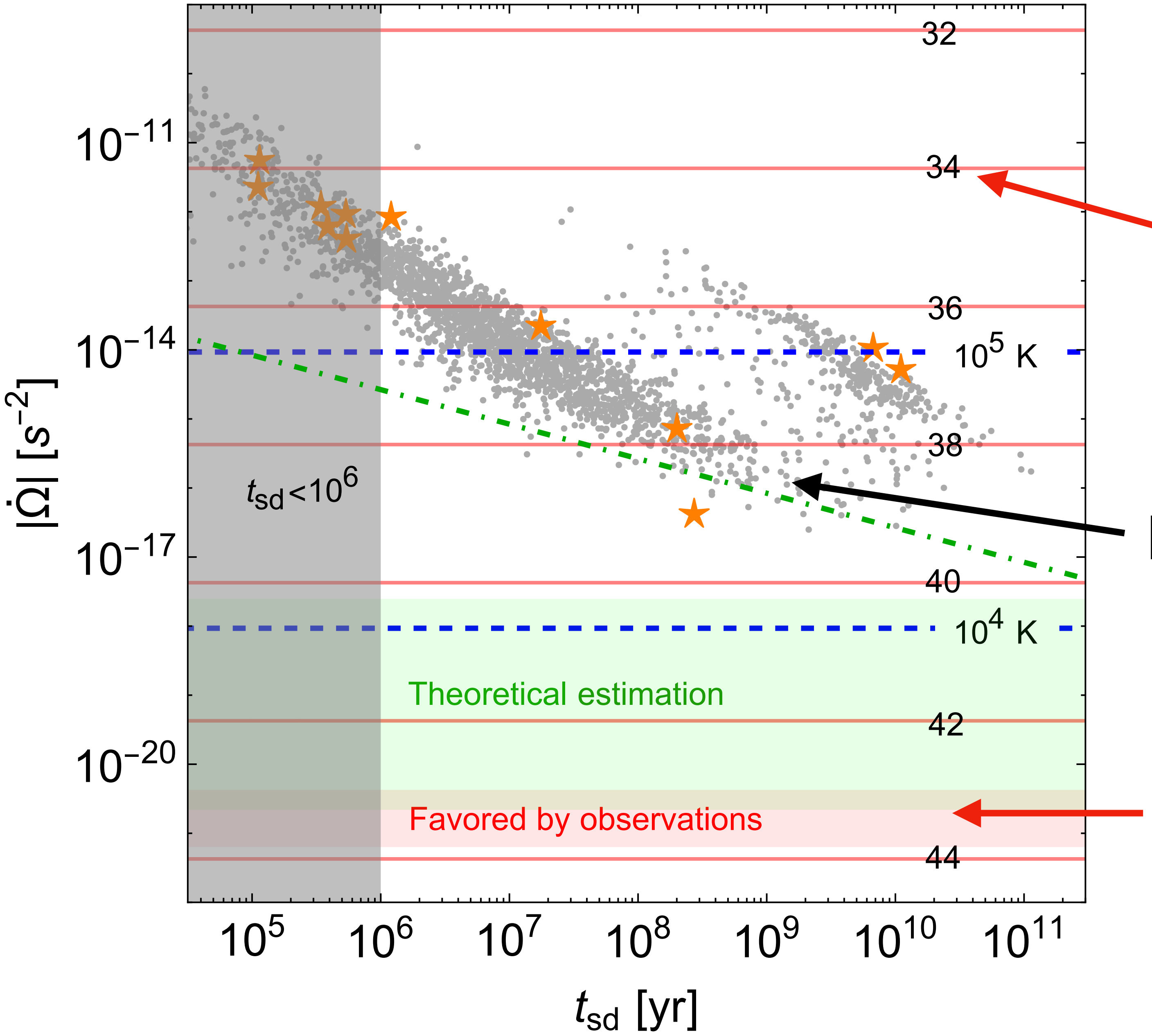


- Temperature evolution deviates at $t \gtrsim 10^5$ years.
- Even for very old NSs, $T_s \gtrsim 10^4$ K.

M. Fujiwara, K. Hamaguchi, N. Nagata, M. E. Ramirez-Quezada, arXiv:2308.16066

Vortex creep heating vs DM heating

To see the DM heating effect, we want $L_{\mathrm{vortex}} < L_{\mathrm{DM}}$.



Upper limit on $J|\dot{\Omega}|$

Limit on J (log J [erg s])

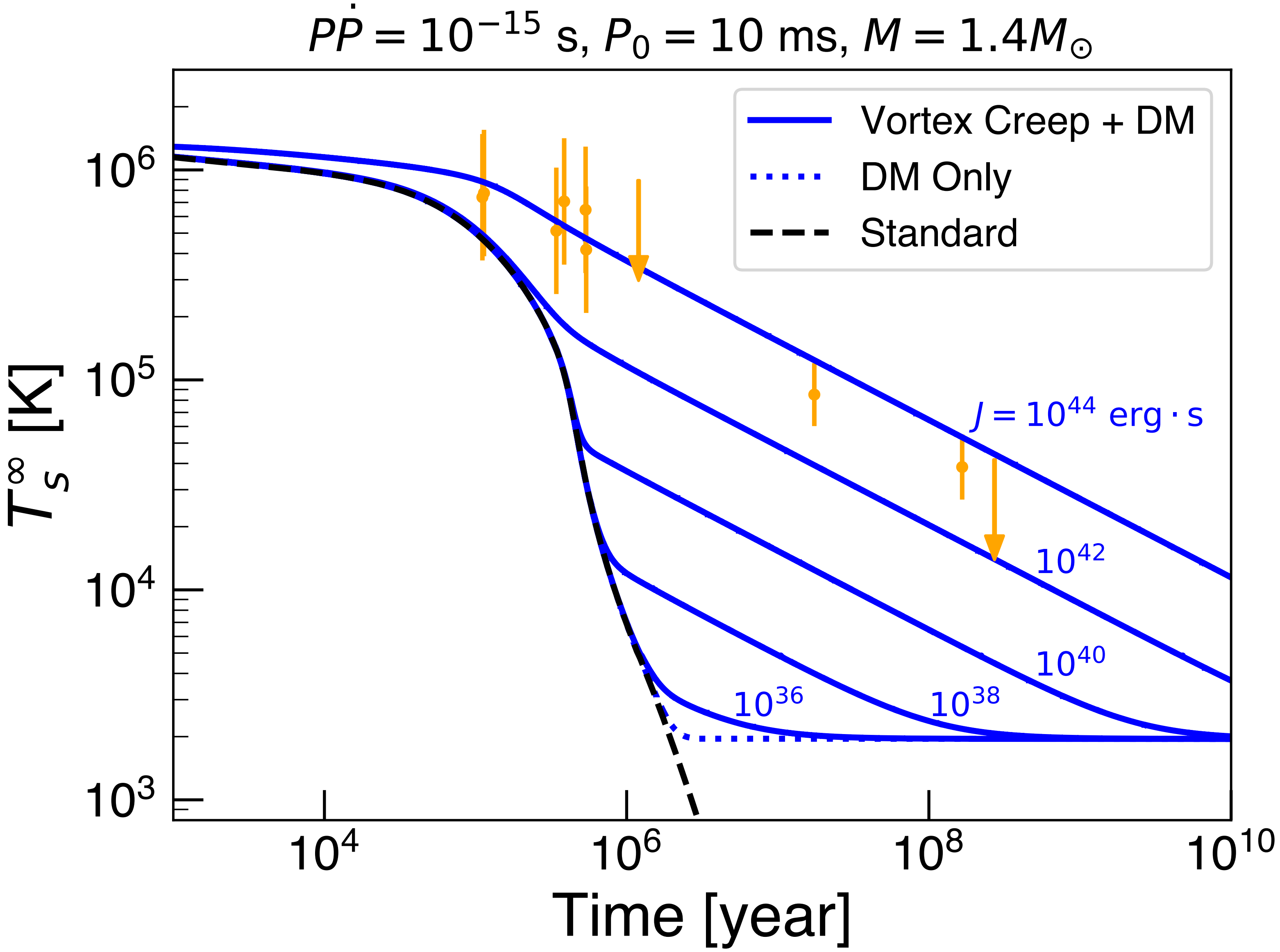
Distribution of known pulsars

For observationally favored value of J, we need this size of $|\dot{\Omega}|$

J must be much smaller than the values favored by obs. and theor.

M. Fujiwara, K. Hamaguchi, N. Nagata, M. E. Ramirez-Quezada, arXiv:2309.02633.

Vortex creep heating vs DM heating



The DM heating is buried under the vortex creep heating unless

$$J \lesssim 10^{38} \text{ erg} \cdot \text{s}$$

Much smaller than the values favored by obs. and theor.

M. Fujiwara, K. Hamaguchi, N. Nagata, M. E. Ramirez-Quezada, arXiv:2309.02633.

Conclusion

- We studied potential heating mechanisms in NSs.
- Non-equilibrium β processes.
  - For ordinary pulsars, DM heating effect can be observed if their initial period is relatively large.
  - For millisecond pulsars, DM heating effect is always hidden by the rotochemical heating.
- Vortex creep heating

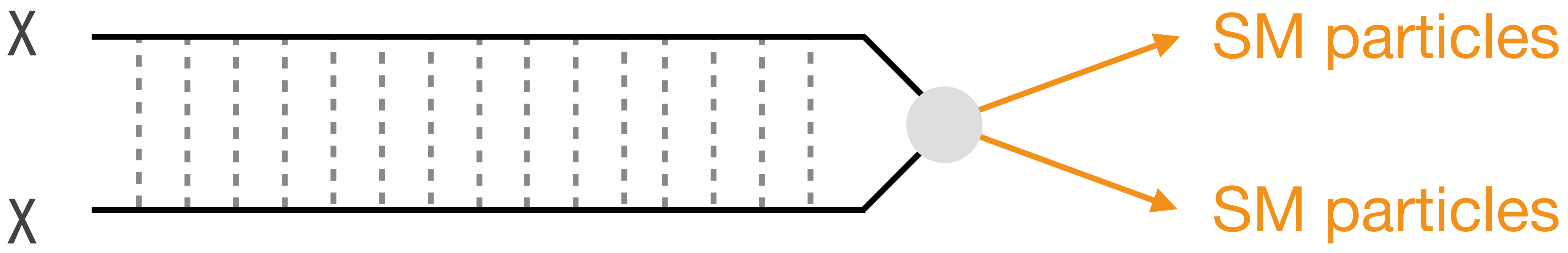
This heating effect seems to dominate the DM heating.

Backup

Sommerfeld effects

J. Hisano, S. Matsumoto, and M. M. Nojiri, Phys. Rev. Lett. **92**, 031303 (2004).

Electroweak-interacting DM has self-interactions via EW interactions.



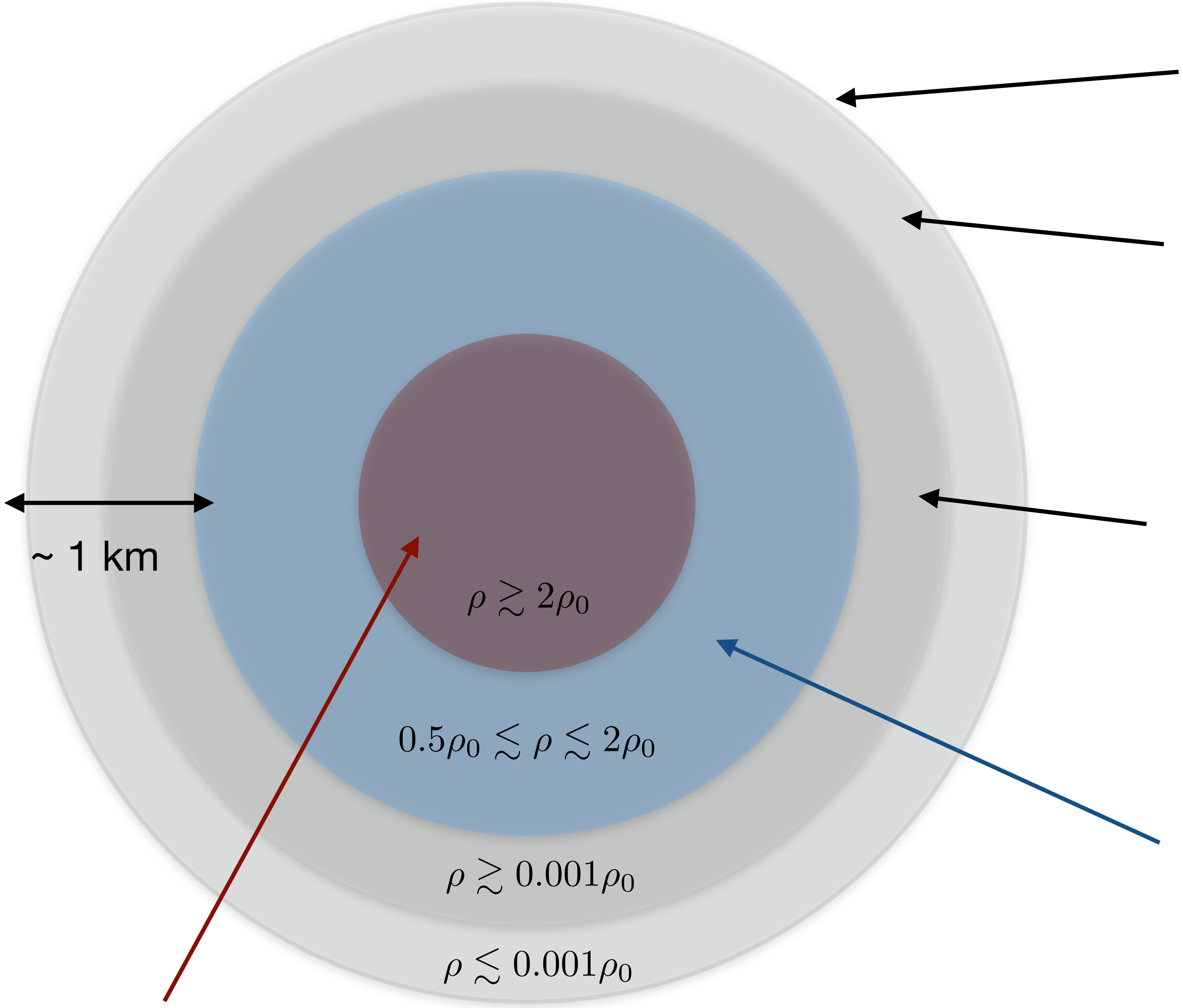
Incoming wave-functions deviate from plane waves due to long-distance self-interactions.

➡ Sommerfeld effect

This effect becomes important when the interaction range becomes longer than the Bohr radius of the two-body system.

$$\frac{1}{m_W} \gtrsim \frac{1}{\alpha_2 m_{\rm DM}}$$

Neutron star structure



Envelope, atmosphere

Outer crust

Neutron-rich nucleus (crystal)

Electron

Inner crust

Neutron-rich nucleus, electron

Neutron superfluid: $^1S_0$

Outer core

Electron, muon

Neutron superfluid: $^3P_2$

Proton superconductor: $^1S_0$

Inner core

$$\rho_0 = 2.8 \times 10^{14} \ \mathrm{g \cdot cm^{-3}}$$

Neutron superfluid: $^3P_2$

~~Hyperons, π/K condensation, quarks (?)~~

We do not consider them in this talk.

Early stage of neutron star

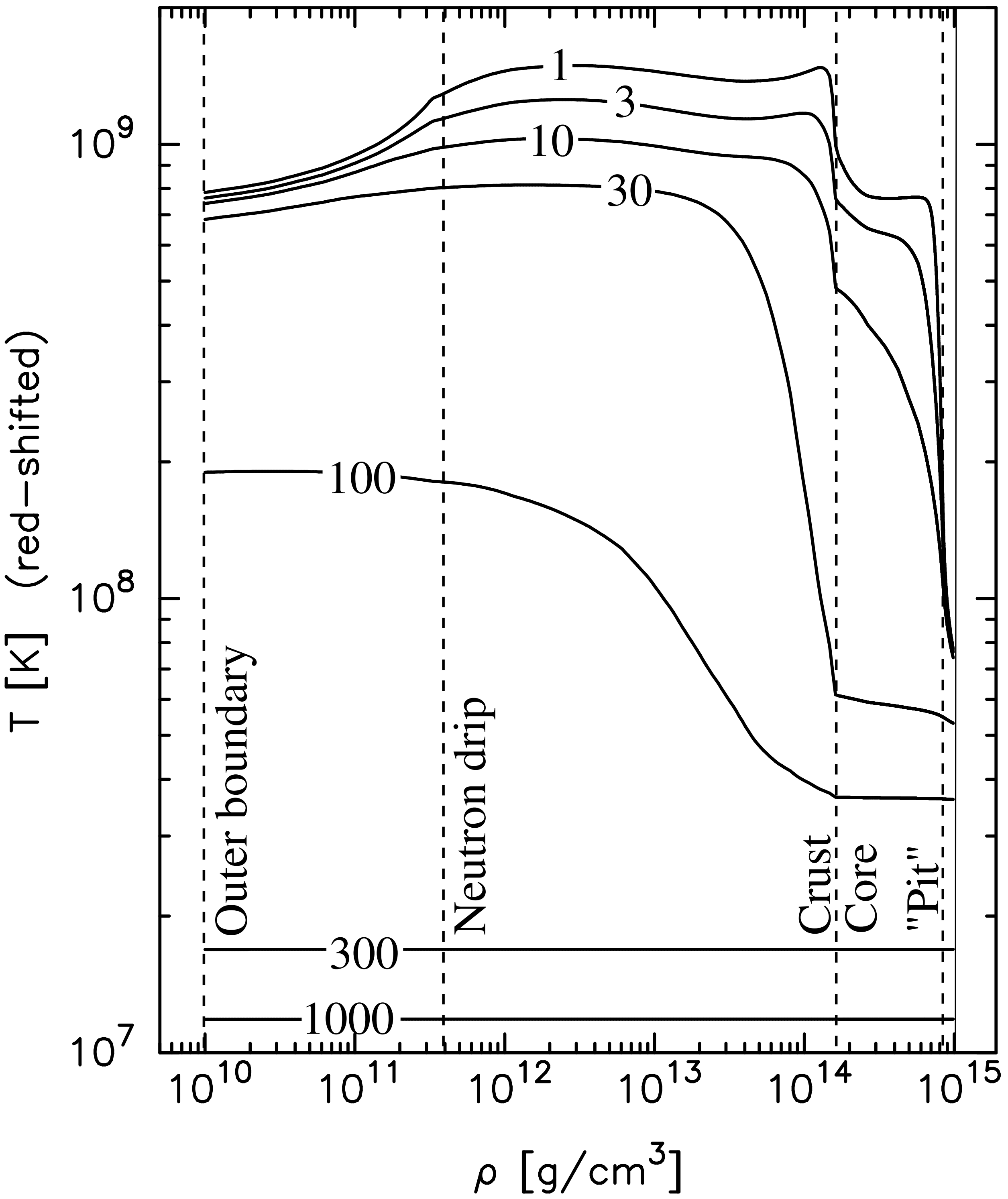
- Right after SN explosion, a NS is in a very high-temperature state with $T \sim 10^{11}$ K.

- After ~ 20s, the temperature gets low enough for neutrinos to escape from the neutron star.

- Thermal relaxation completed after 10—100 years, and the temperature becomes constant inside the neutron star.
  - We focus on this case in what follows.
  - To follow the temperature evolution within 100 years, we must solve the heat conduction equations.
  - The following results rarely depend on the initial conditions.

Temperature decreases very rapidly in the first moments.

Temperature distribution



Relaxation in the Core done in ~ 100 years.

D. Page, J. M. Lattimer, M. Prakash, A. W. Steiner [arXiv: 1302.6626].

β equilibrium

Inside neutron stars, β equilibrium is achieved via the direct/modified Urca reactions

Chemical equilibrium

$$\mu_e + \mu_p = \mu_n$$

Chemical potential of neutrino is zero since it can escape from neutron star.

Charge neutrality

$$n_p = n_e$$

Muons also appear in the region where $\mu_e > m_\mu$.

Chemical equilibrium

$$\mu_e = \mu_\mu \qquad (\mu_\mu + \mu_p = \mu_n)$$

Charge neutrality

$$n_p = n_e + n_\mu$$

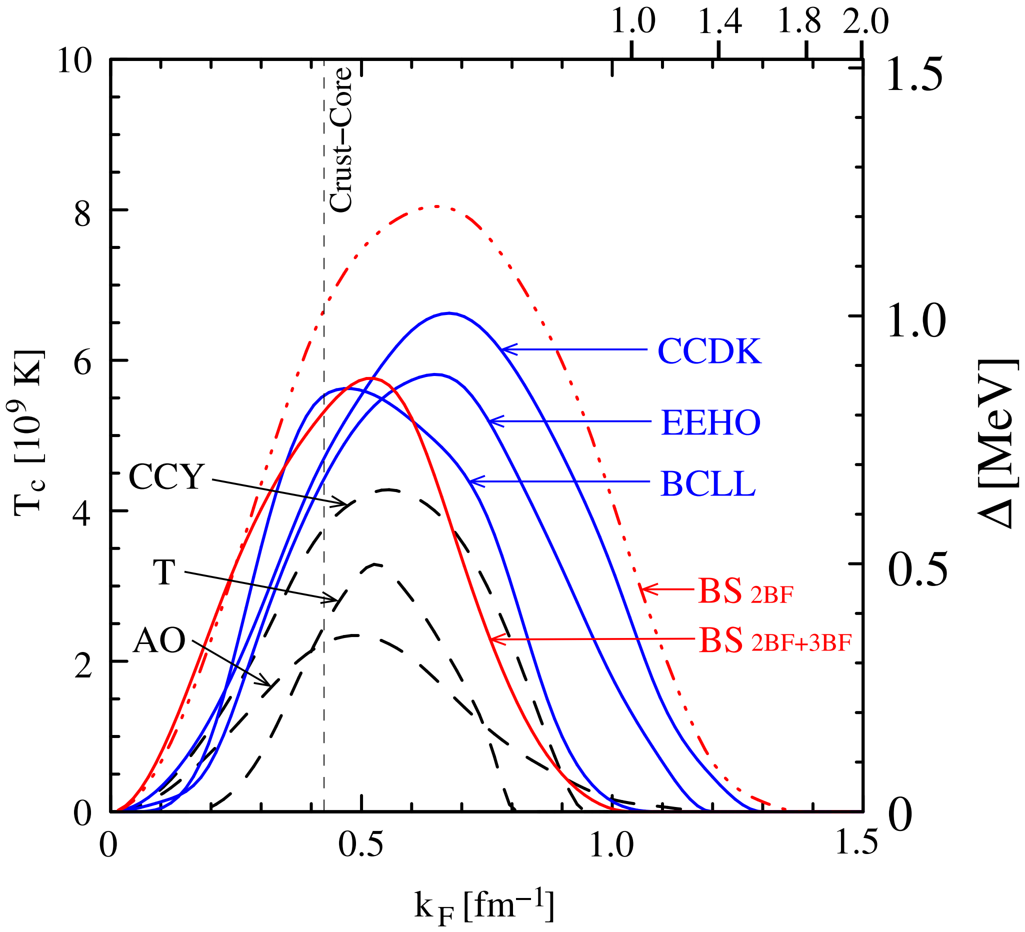
Nucleon pairing

Nucleons in a NS form pairings below their critical temperatures:

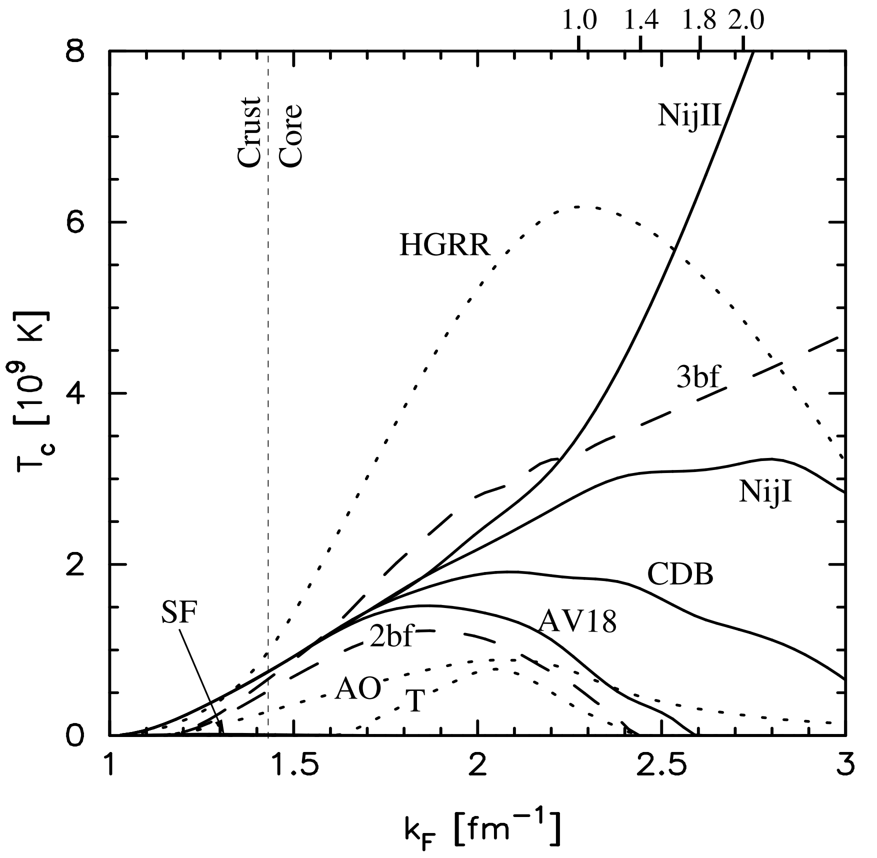
- Neutron singlet $^1S_0$ ← Only in the crust. Less important.
- Proton singlet $^1S_0$
- Neutron triplet $^3P_2$

} ← Form in the core. Important.

Proton singlet pairing gap



Neutron triplet pairing gap



D. Page, J. M. Lattimer, M. Prakash, A. W. Steiner [arXiv: 1302.6626].

PBF process

Thermal disturbance induces the breaking of nucleon pairs.

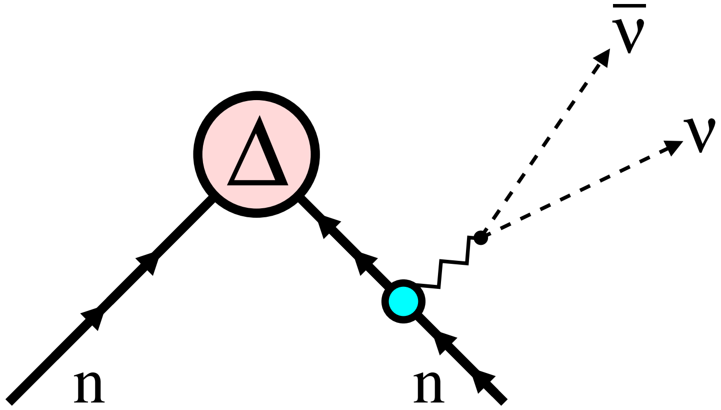
↓

During the reformation of cooper pairs, the gap energy is released via neutrino emission.

This process significantly enhances the neutrino emission only when

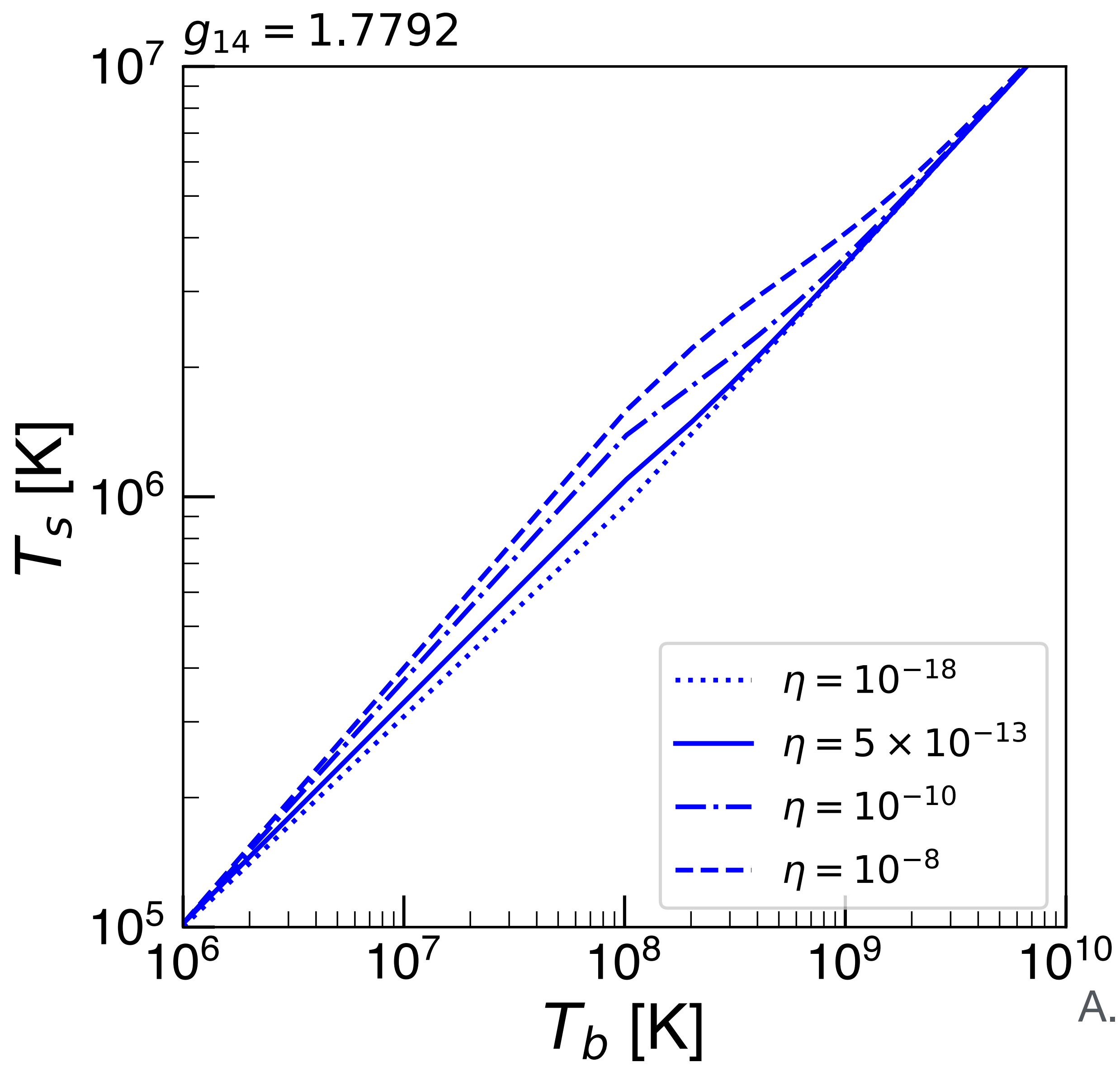
$$T \lesssim T_C$$

- If T > T_C, this process does not occur.
- If T << T_C, pair breaking rarely occurs.



Surface temperature

It is the surface temperature that we observe, so we need to relate it to the internal temperature.



This relation depends on the amount of light elements in the envelope.

$$\eta \equiv g_{14}^2 \Delta M/M$$

g_{14}: surface gravity in units of 10^{14} cm s^{-2}.

ΔM: mass of light elements.

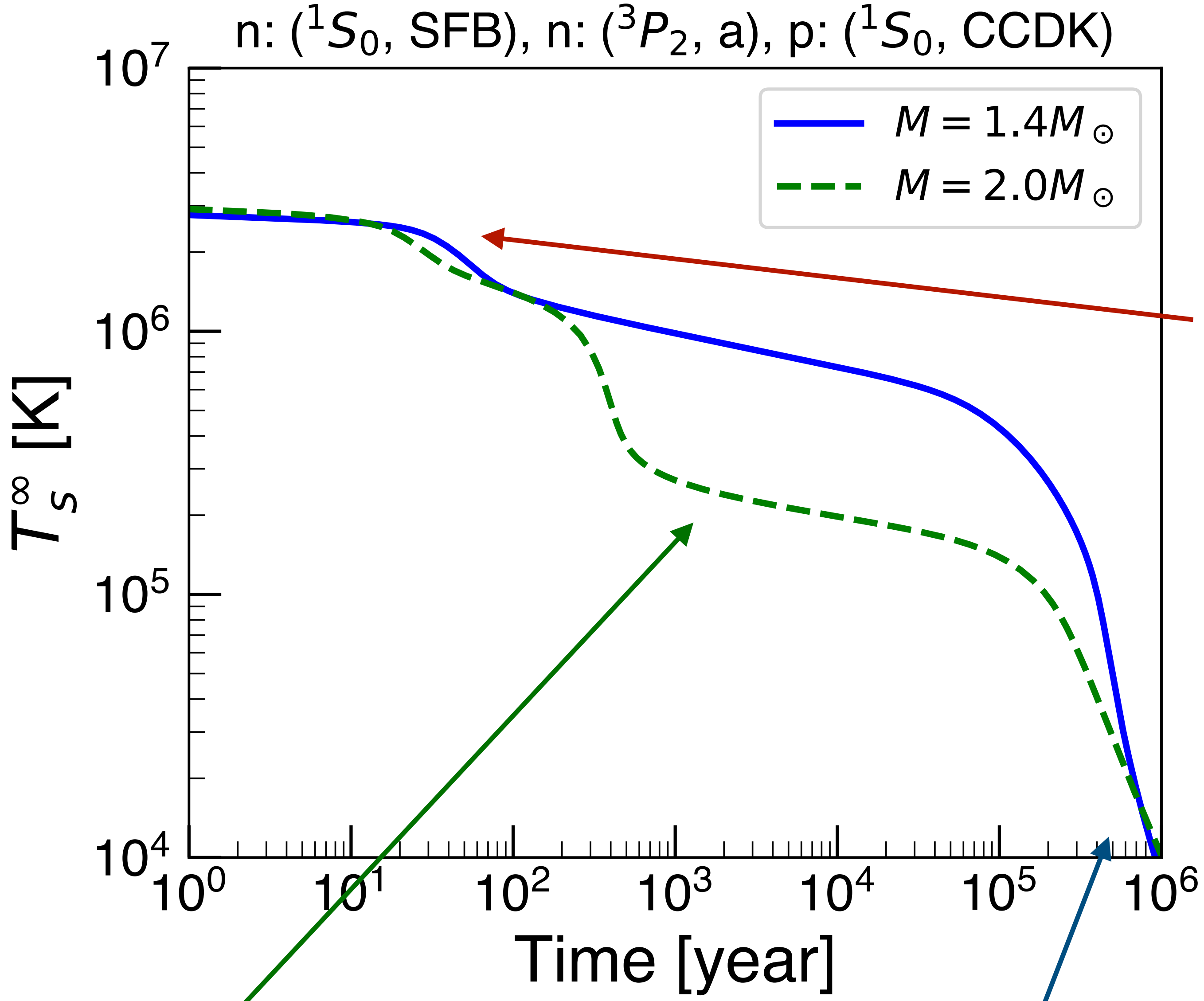
A. Y. Potekhin, G. Chabrier, and D. G. Yakovlev, A&A **323,** 415 (1997).

As the amount of light elements gets increased, the surface temperature becomes larger.

Light elements have large thermal conductivities.

Temperature evolution

We can now solve the equation for temperature evolution:

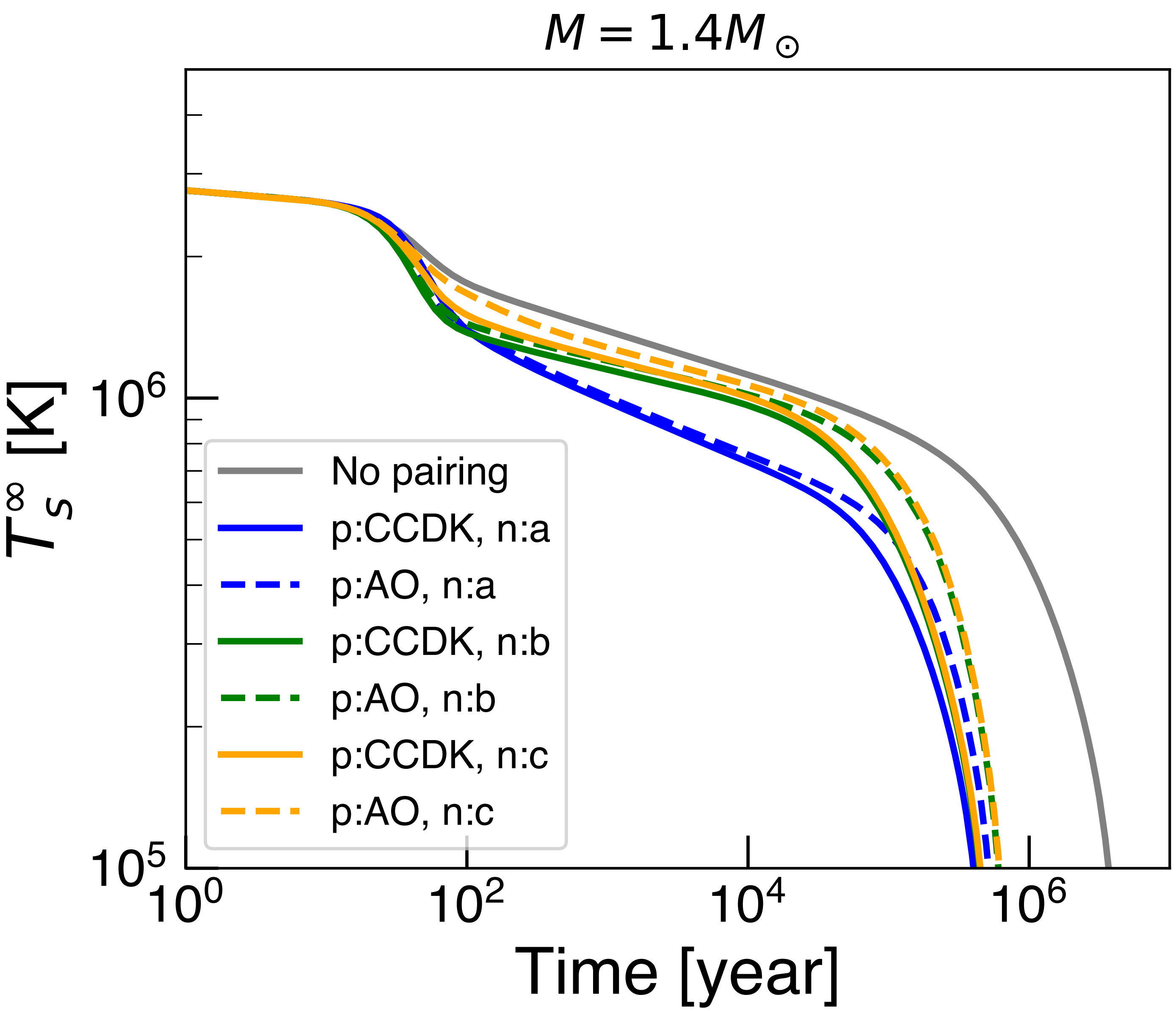


Before the thermal relaxation completed, the surface temperature does not follow the internal temperature.

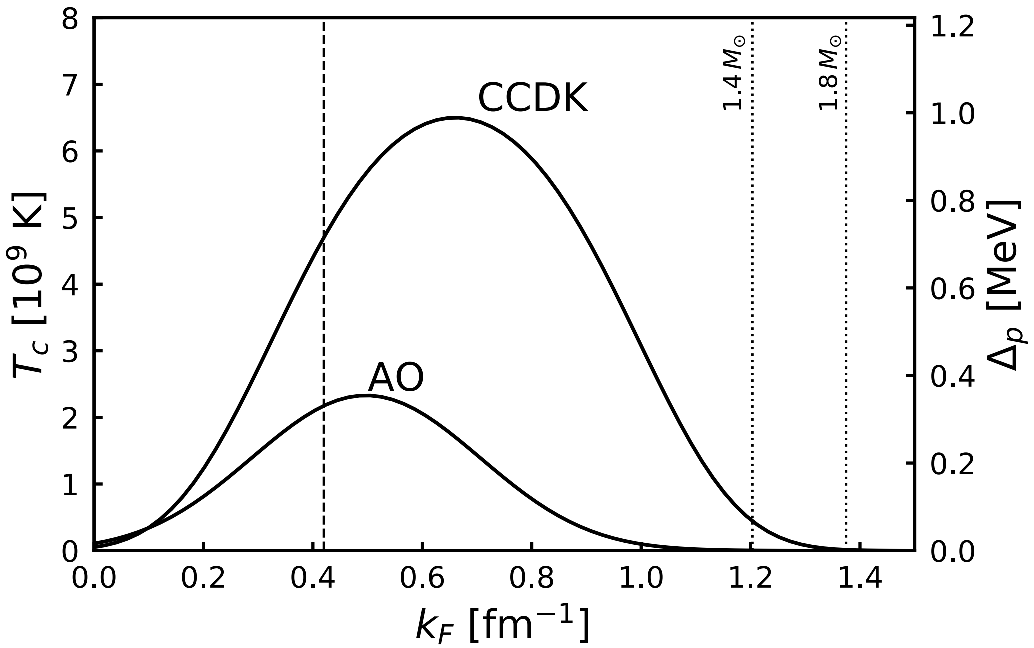
If Direct Urca occurs, the neutron star cools down rapidly.

Temperature of NSs (older than 10^6 years) is very low.

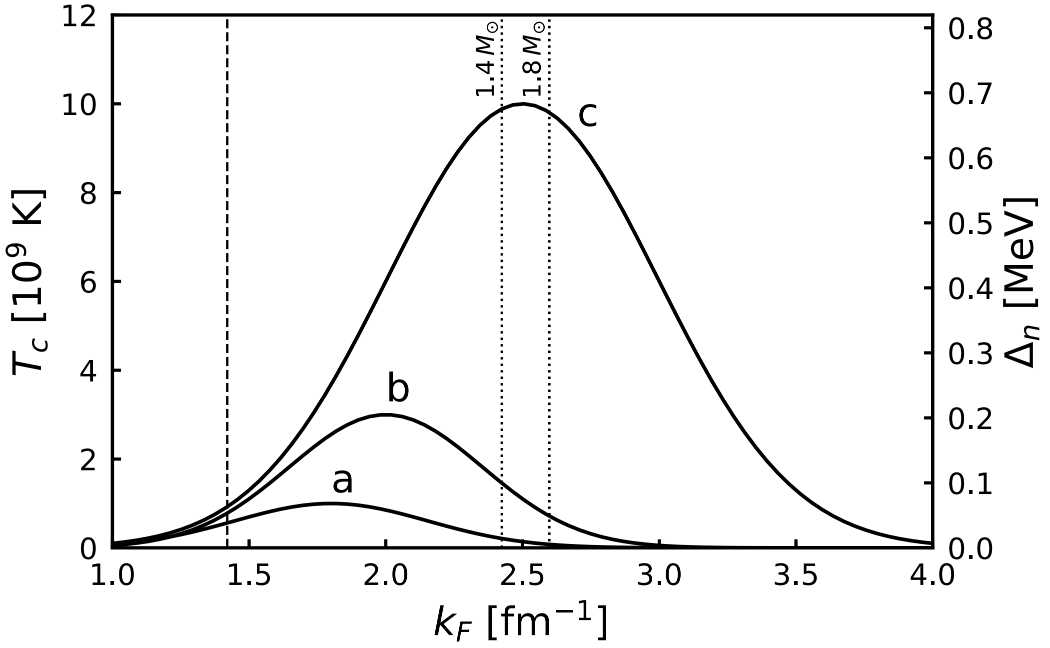
Temperature evolution (gap dependence)



Proton singlet gap



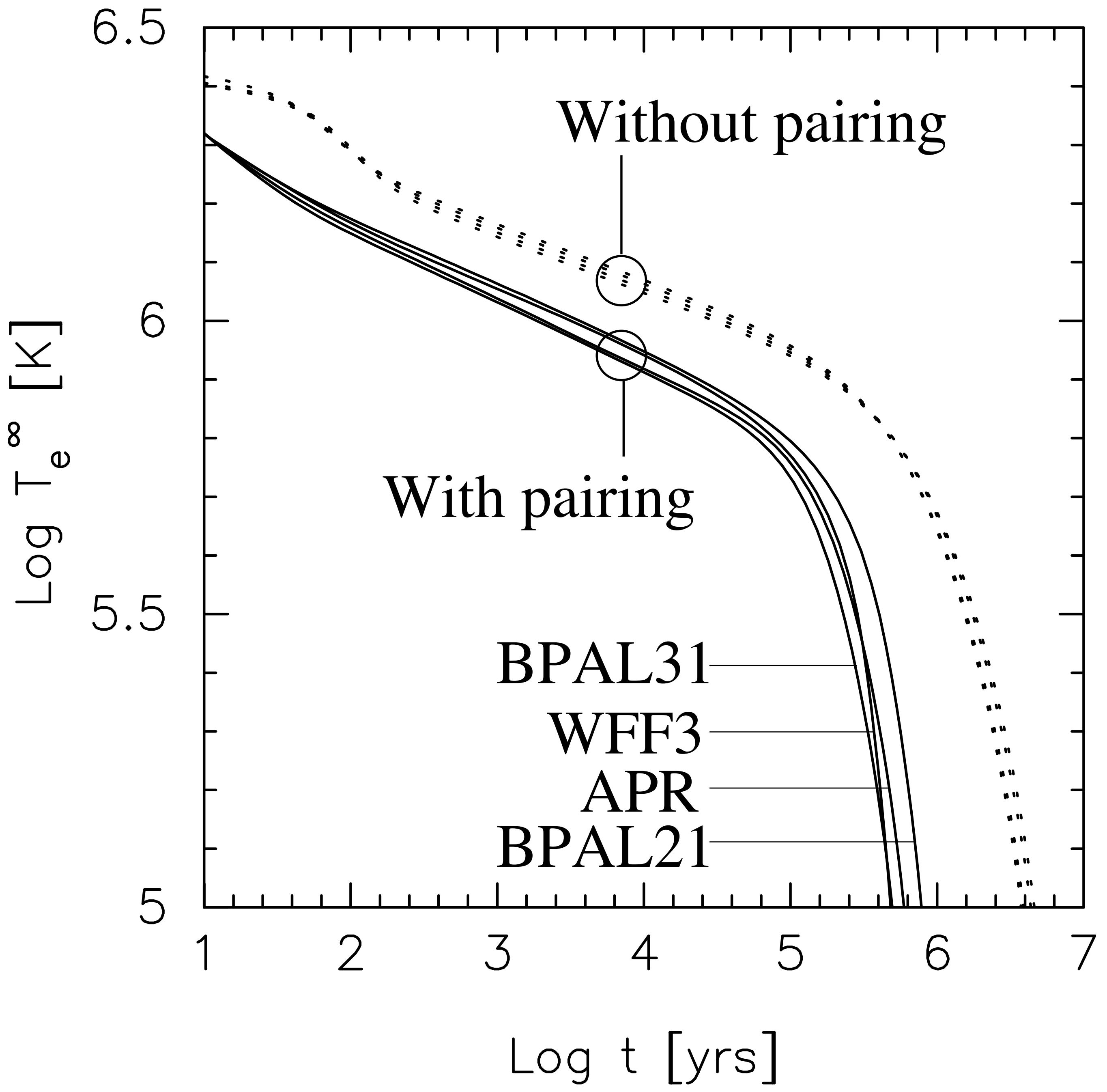
Neutron triplet gap



Uncertainty in nucleon gap models lead to the theoretical errors in the cooling calculation.

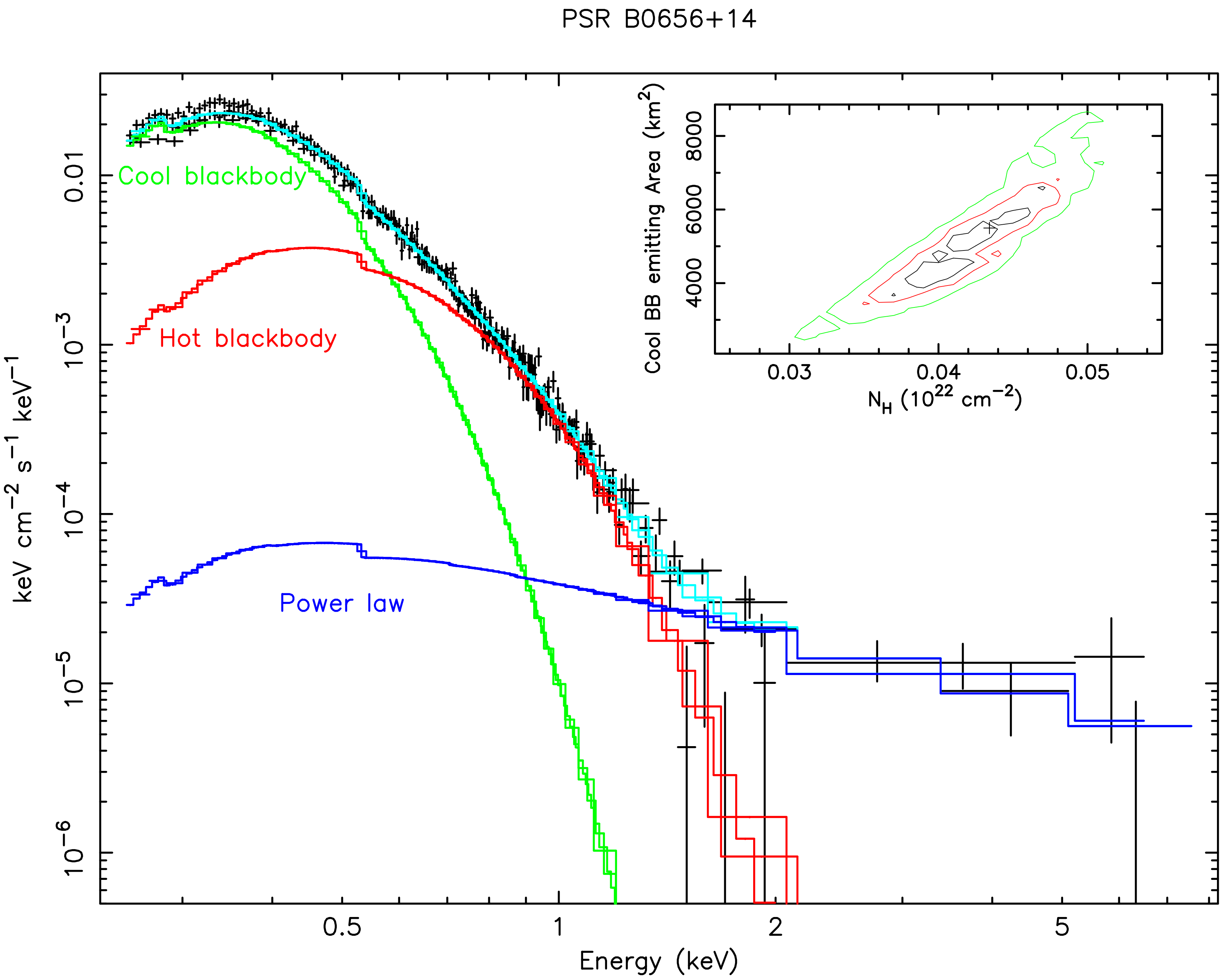
EOS dependence

EOS dependence of the temperature evolution



J. M. Lattimer, D. Page, M. Prakash, A. W. Steiner, Astrophys. J. Suppl. **155**, 623 (2004).

PSR B0656+14



$$T_{\rm cool} = (6.5 \pm 0.1) \times 10^5\ {\rm K}$$

$$R_{\rm cool} = 20.9^{+2.7}_{-3.8}\ {\rm km}$$

$$T_{\rm hot} = (1.25 \pm 0.03) \times 10^6\ {\rm K}$$

$$R_{\rm hot} = 1.8 \pm 0.15\ {\rm km}$$

2 Black body components + power low fit

G. Bignami, P. Caraveo, A. de Luca, S. Mereghetti, M. Negroni, Astrophys. J. **623**, 1051 (2005).

FAST

Many pulsars are expected to be discovered by

Five-hundred-meter Aperture Spherical radio Telescope (FAST)

（五百米口径球面射电望远镜）

in China in the near future.

- About 5000 (4000 new) pulsars are expected to be discovered.

arXiv: 1105.3794

- A lot of pulsars have already been discovered.

See J. L. Han *et al.*, arXiv:2105.08460

eROSITA

- X-ray instrument on the SRG space observatory.
- Launched on July 13, 2019.
- Started an all-sky survey on Dec. 13, 2019.
- Eight full-sky surveys are planned.

P. Predehl, et.al., A&A **647**, A1 (2021).

85—95 thermally emitting isolated NSs are expected to be detected.

A. M. Pires, A. D. Schwope, C. Motch, Astron. Nachr., **338**, 213 (2017).

Vera C. Rubin Observatory, LSST

- Deep optical survey
- Under construction in Chile
- Full survey operations are aimed to begin in Oct. 2024

By using this, we can search for thermally emitting NSs.

D. Toyouchi, K. Hotokezaka, M. Takada, MNRAS **510**, 611 (2021).

- Nearby (~ 100 pc) NSs with with a large kick velocity ($\mathcal{O}(100)$ km/s) can be detected.

Caused by anisotropic SN explosion

- O(1) NSs are expected to be detected for a 10-yr monitoring.

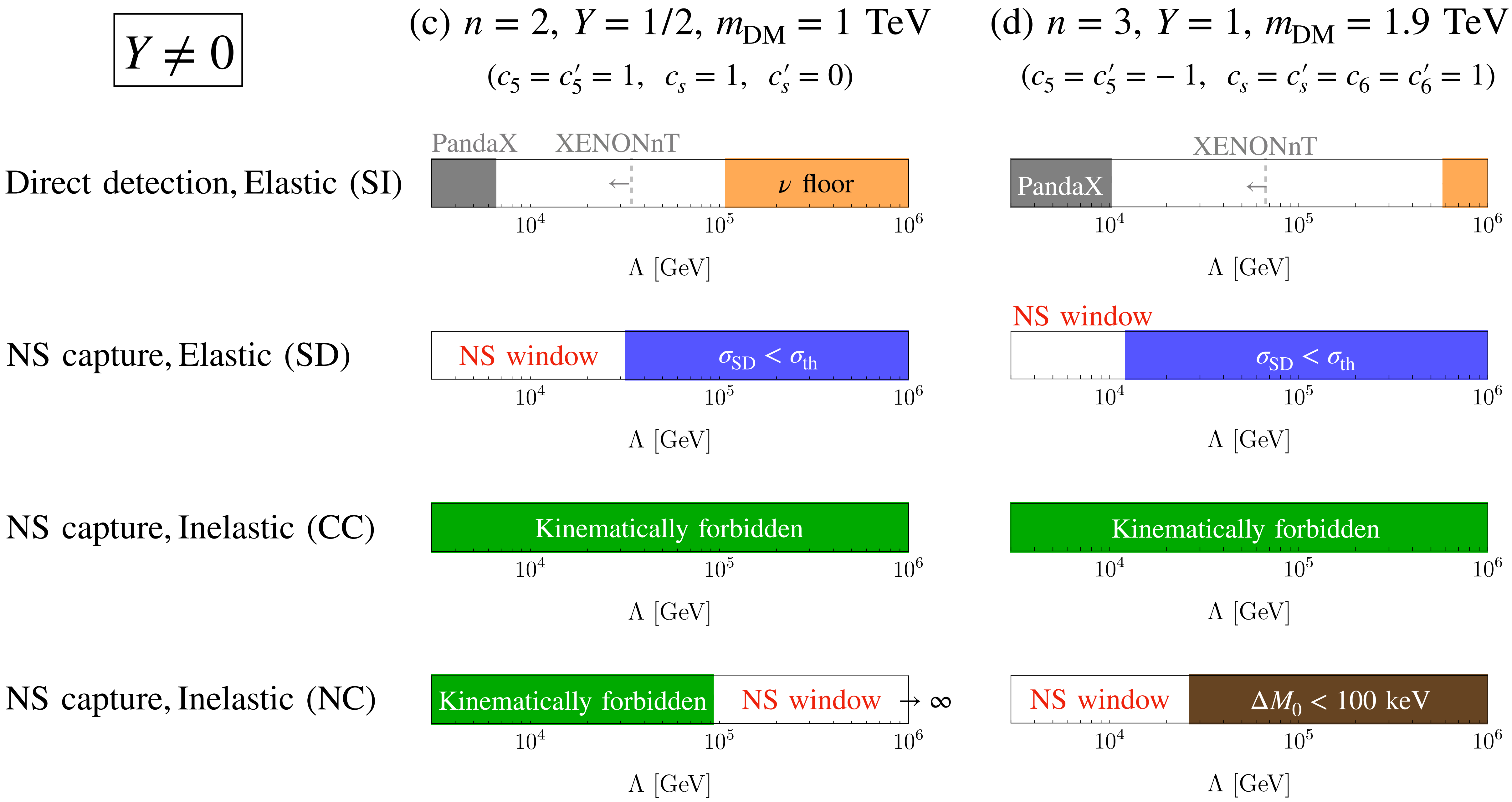
Pulsar searches with SKA

The Square Kilometer Array is expected to discover

- ~ 9000 ordinary pulsars
- ~ 1200 MSPs

L. Levin, et.al., arXiv:1712.01008

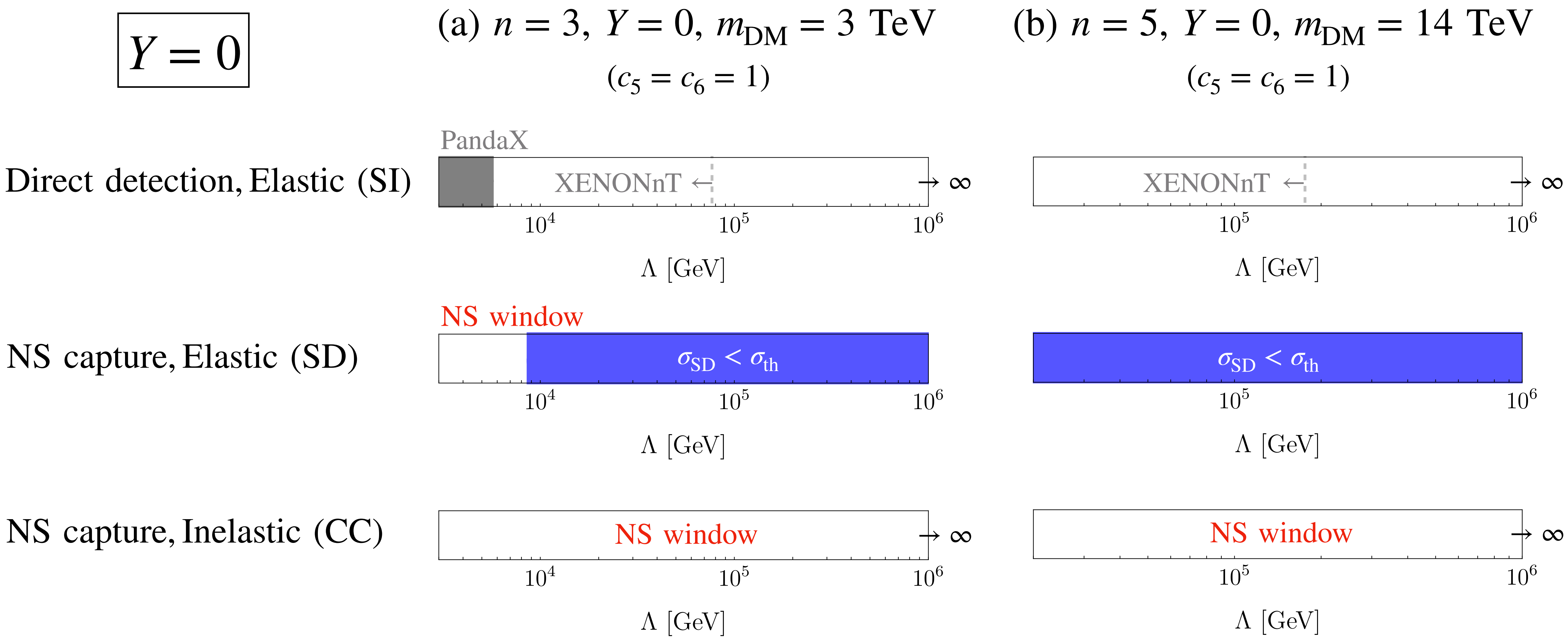
$Y \neq 0$



DM capture in NSs and direct detection experiments play complementary roles.

M. Fujiwara, K. Hamaguchi, N. Nagata, J. Zheng, arXiv:2204.02238.

$Y = 0$



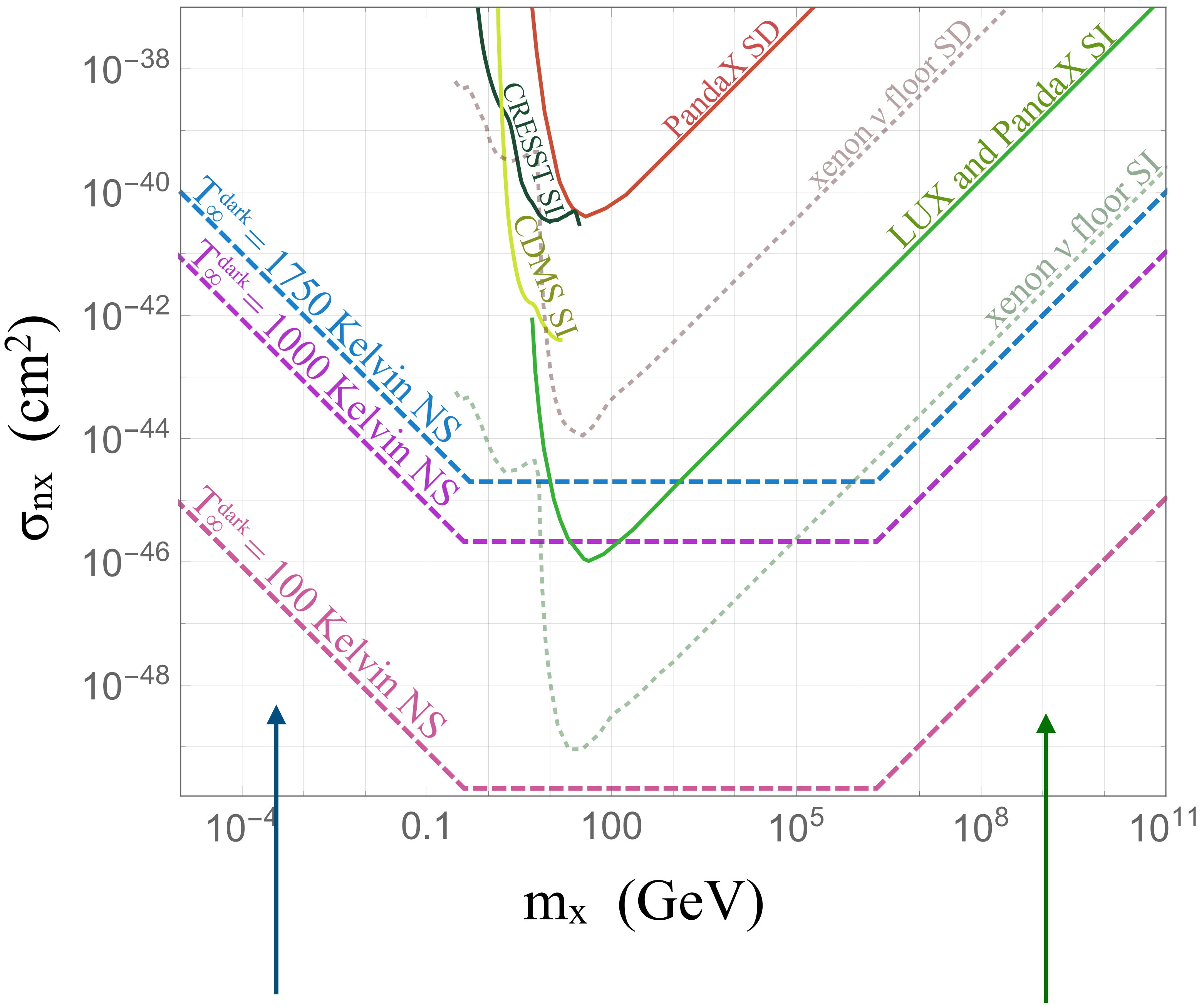
DM is always captured by NSs since the neutral-charged mass difference is very small.

$$\mathcal{L}_7 = -\frac{c_7}{2\Lambda^3} \sum_{m,n} (-1)^m \chi_{-m} (T_a T_b)_{mn} \chi_n \, (H^\dagger \tau_a H)(H^\dagger \tau_b H) + \text{h.c.}$$

Dim.7

M. Fujiwara, K. Hamaguchi, N. Nagata, J. Zheng, arXiv:2204.02238.

Dark kinetic heating



Effect of Pauli blocking

Multiple scattering required

M. Baryakhtar, J. Bramante, S. W. Li, T. Linden, N. Raj, Phys. Rev. Lett. **119**, 131801 (2017).

Spin-down age

For magnetic dipole radiation,

$$\dot{\Omega} = -k\Omega^3$$

$$k = \frac{2B_s^2 \sin^2 \alpha\, R^6}{3c^3 I} = -\frac{\dot{\Omega}_{\rm now}}{\Omega_{\rm now}^3} = \frac{P_{\rm now}\dot{P}_{\rm now}}{4\pi^2}$$

By solving this, we have

$$P(t) = \sqrt{P_0^2 + 2P_{\rm now}\dot{P}_{\rm now}t}$$

(P_0: initial period)

In particular, for $P_0 \ll P_{\rm now}$, we can estimate the neutron star age

$$t_{\rm sd} = \frac{P_{\rm now}}{2\dot{P}_{\rm now}}$$

$t_{\rm sd}$ is called spin-down age or characteristic age.

Pulsar age

Let us compare the spin-down age with the actual age in the case of the Crab pulsar.

Actual age

It was born in 1054, so its age is 965 years old.

Spin-down age

$$P = 0.033392 \text{ s}, \quad \dot{P} = 4.21 \times 10^{-13}$$

➡ $$\boxed{t_{\rm sd} = \frac{P}{2\dot{P}} = 1.26 \times 10^3 \text{ yrs}}$$

Agrees within ~ 30%.

$P - \dot{P}$ diagram

It is useful to show pulsars in the $P - \dot{P}$ plane, since we can see the distribution of their age and magnetic field.