On the WIMP dark matter signature in old neutron stars

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

Introduction

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.

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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(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†

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(Received 6 April 2010; published 18 June 2010)

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

Can neutron stars constrain dark matter?

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(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)

Mechanism

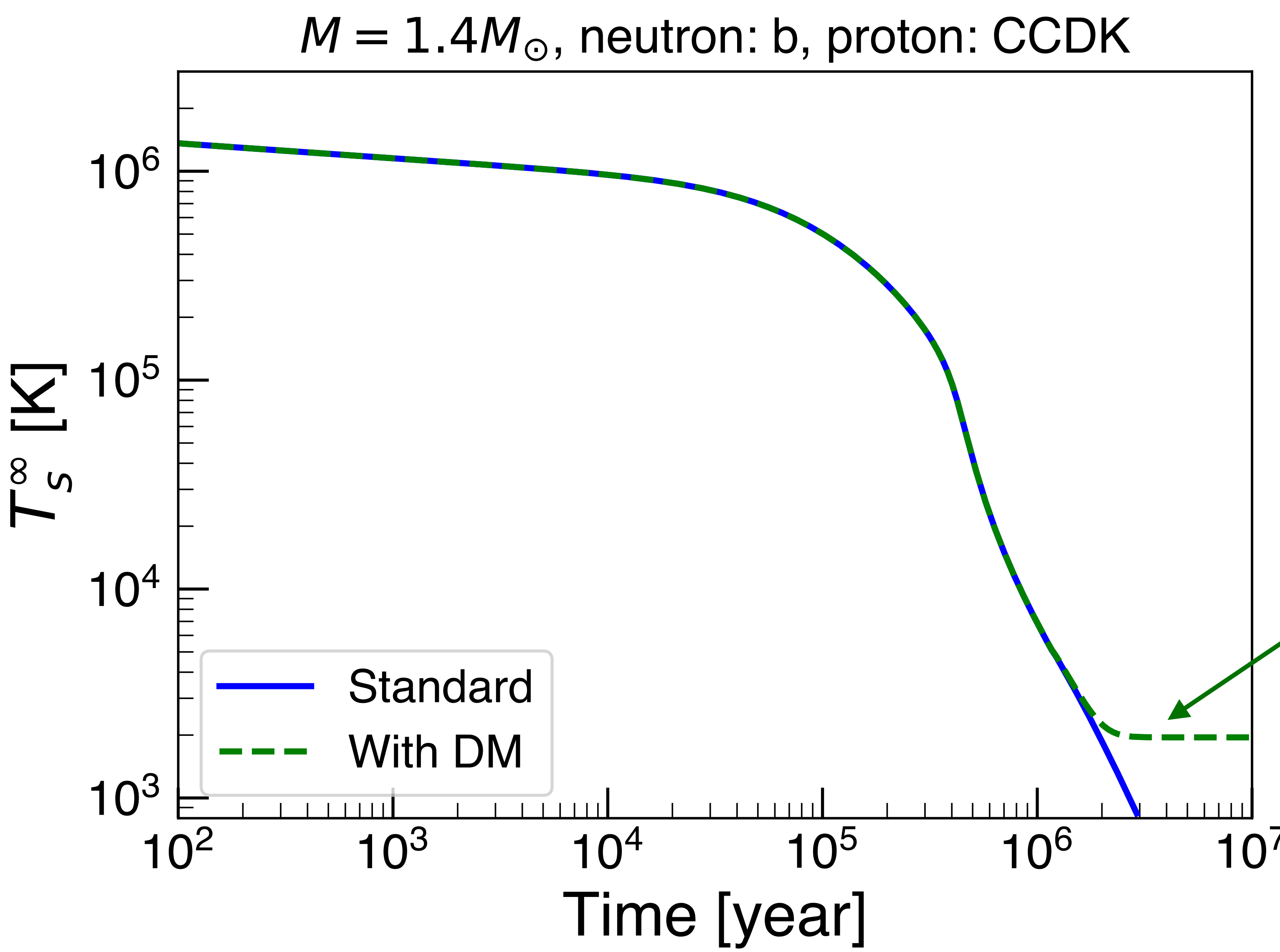
WIMP DM accretes on a neutron star (NS).

→

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.

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, $T_s^\infty = (1.1 - 5.3) \times 10^5$ K

R. P. Mignani, G. G. Pavlov, and O. Kargaltsev, Astron. Astrophys. **488**, 1027 (2008).

- B0950+08: $t_{\rm sd} = 1.75 \times 10^7$ years, $T_s^\infty = (1 - 3) \times 10^5$ K

G. G. Pavlov, *et al.*, Astrophys. J. **850**, 79 (2017).

These observations cannot be explained in the standard cooling.

Topics of this talk

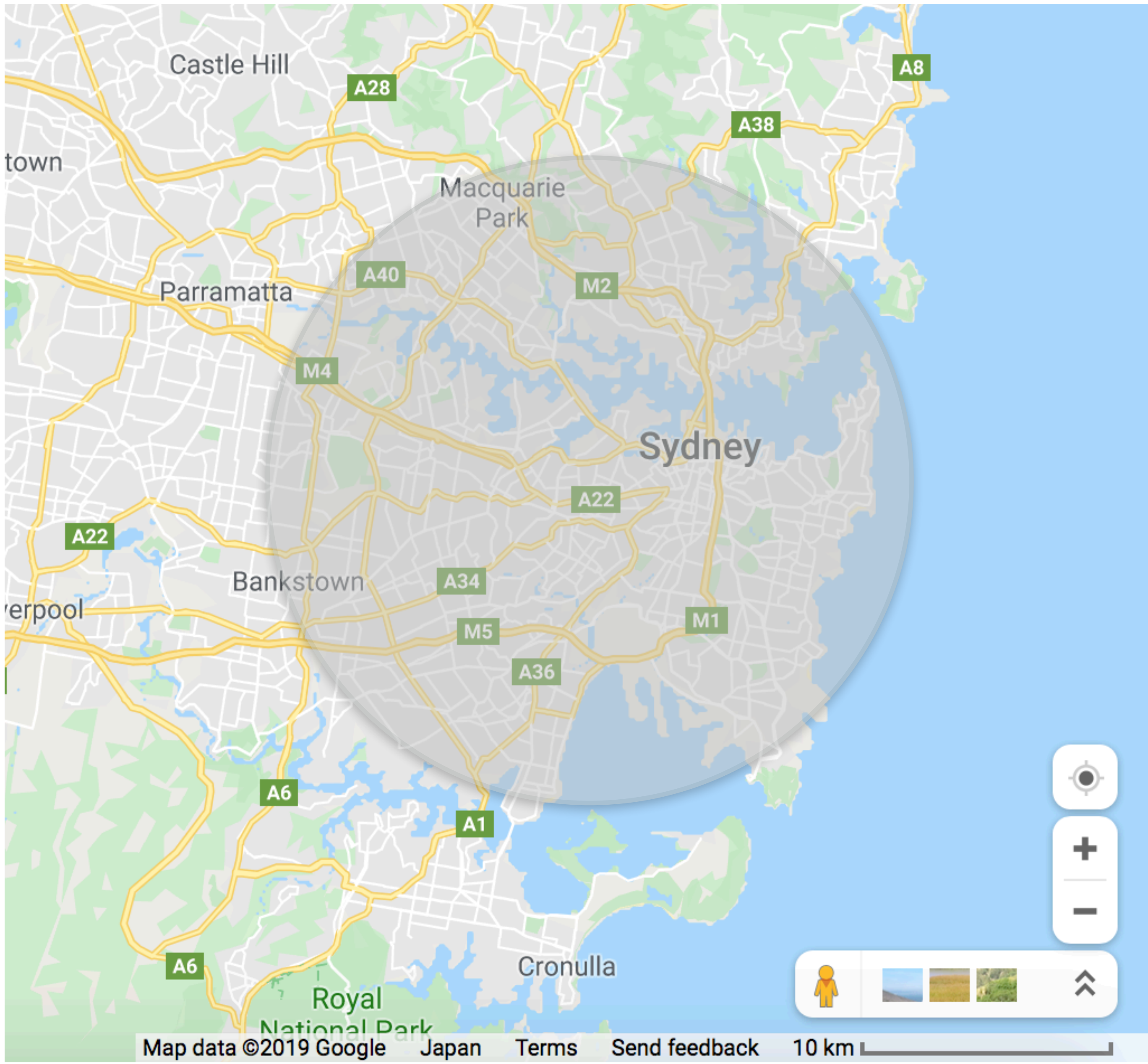
- We need an extra heating source to explain the observations.
    - Out of β equilibrium effect was not included in the standard cooling scenario.
    - This causes late-time heating.
    - The observed data can be explained by this effect.
- Can we still observe the DM heating effect in the presence of this extra heating effect??
- Advantage of DM heating as a WIMP probe??

Outline of this talk

- Introduction
- Standard Cooling Theory
- Dark Matter Heating
- Non-Equilibrium β Process
- Results and implications
- Conclusion

Standard Cooling Theory

Size of neutron star vs Paris



- 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.

Equation for temperature evolution

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

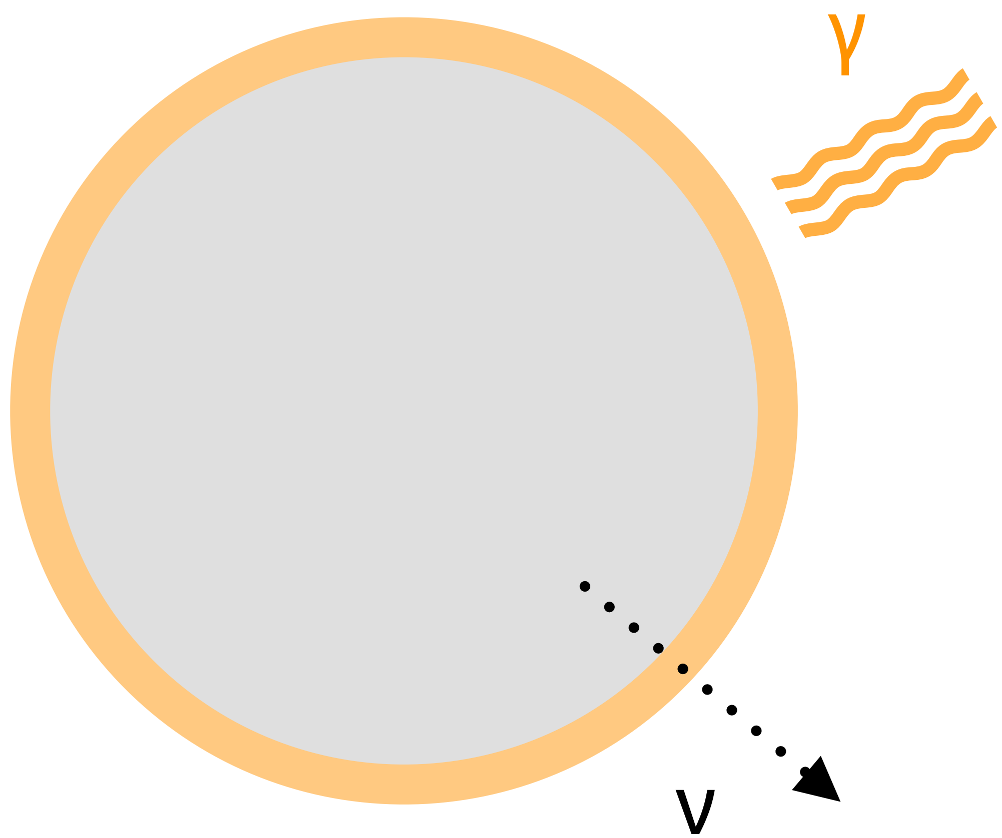
$C(T)$: Stellar heat capacity

L_ν: Luminosity of neutrino emission

L_γ: Luminosity of photon emission

Cooling sources

Two cooling sources:



Dominant for $t \lesssim 10^5$ years

Photon emission (from surface)

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

Dominant for $t \gtrsim 10^5$ years

Neutrino emission (from core)

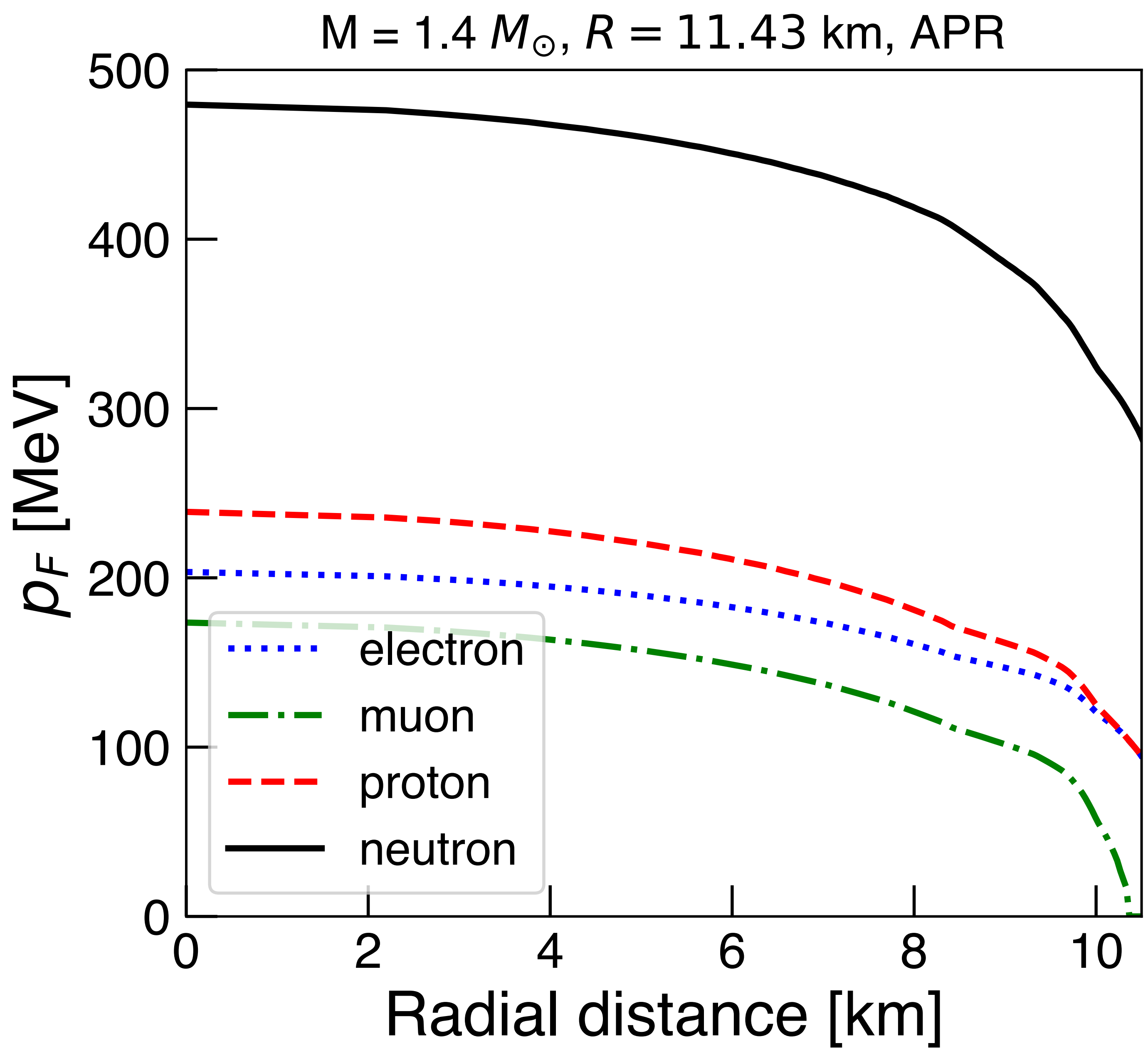
- Direct Urca process (DUrca)
- Modified Urca process (MUrca)
- Bremsstrahlung
- PBF process

PBF process occurs only in the presence of nucleon superfluidity.

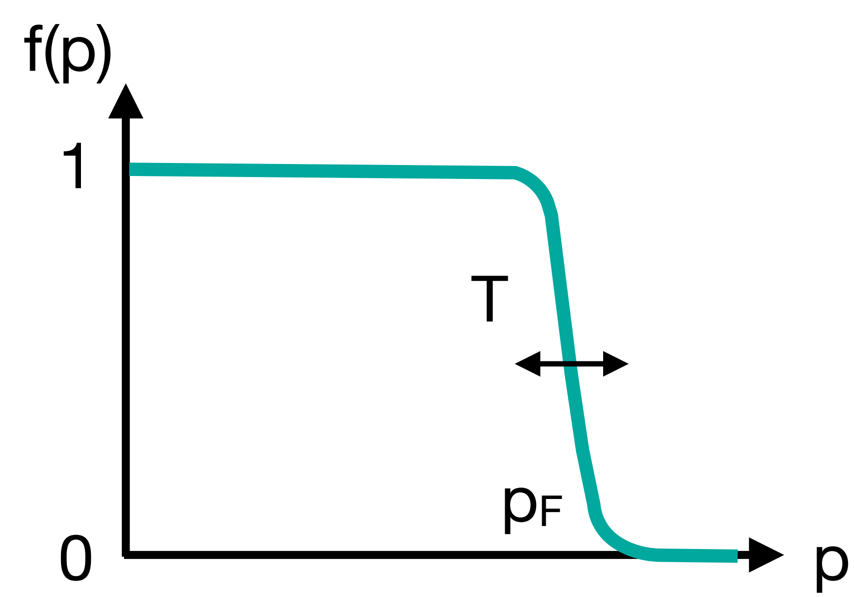
Neutrino emission

Neutrino emission processes occur only near the Fermi surface.

Fermi momenta in neutron star

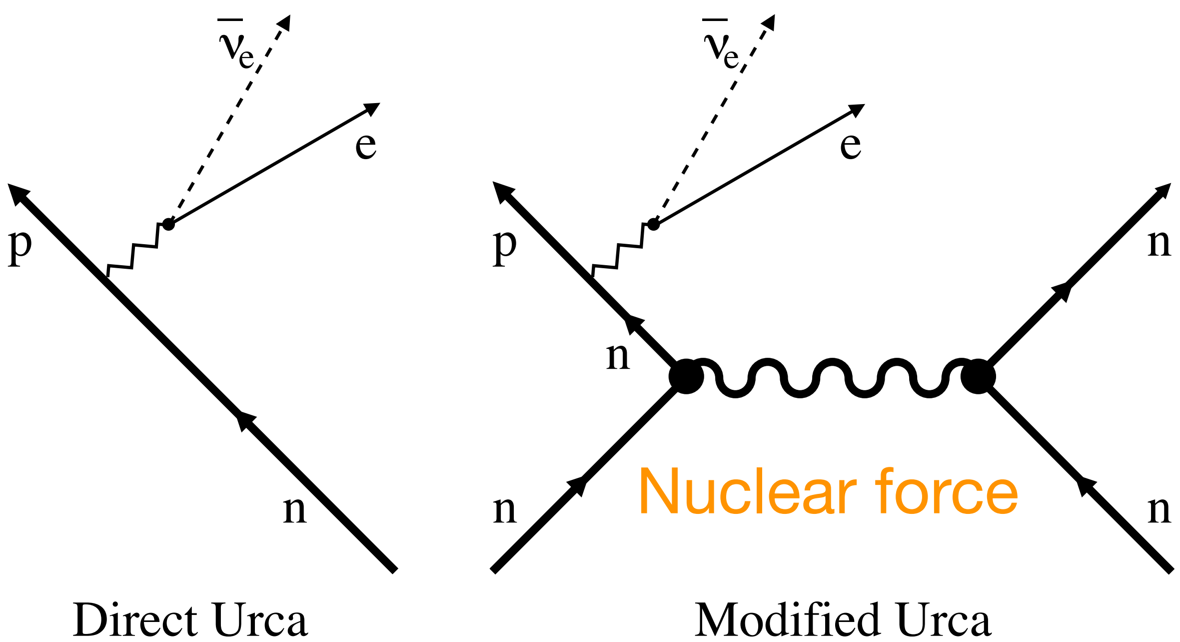


$$p_F \gg T,\ m_n - m_p$$



Urca processes

Urca processes keep NSs into β equilibrium:



Chemical equilibrium

$$\mu_n = \mu_p + \mu_\ell$$

$$n\ (+N) \to p + \ell^- + \bar{\nu}_\ell\ (+N),\ \ \ell^- + p\ (+N) \to n + \bar{\nu}_\ell\ (+N)$$

Rapid Direct Urca process can occur only in heavy stars.

For the APR equation of state, $M \gtrsim 1.97 M_\odot$

Name: Urca

APRIL 1, 1941 PHYSICAL REVIEW VOLUME 59

Neutrino Theory of Stellar Collapse

G. Gamow, *George Washington University, Washington, D. C.*
M. Schoenberg,* *University of São Paulo, São Paulo, Brazil*

(Received February 6, 1941)

of β-particles. In fact, when the temperature and density in the interior of a contracting star reach certain values depending on the kind of nuclei involved, we should expect processes of the type

$$\begin{cases} {}_ZN^A + e^- \rightarrow {}_{Z-1}N^A + \text{antineutrino} \\ {}_{Z-1}N^A \rightarrow {}_ZN^A + e^- + \text{neutrino}, \end{cases} \qquad (3)$$

which we shall call, for brevity, "urca-processes."

Named after a casino in Rio de Janeiro:

Cassino da Urca

- To commemorate the casino where they first met.
- Rapid disappearance of energy (money) of a star (gambler).
- **U**n**R**ecordable **C**ooling **A**gent.
- "Urca" means "thief" in Russian.

Effects of nucleon parings

Nucleons in a NS form Cooper parings.

Energy spectrum

$$\epsilon_N(\boldsymbol{p}) \simeq \sqrt{\Delta_N^2 + v_{F,N}^2(p - p_{F,N})^2}$$

Δ_N: paring gap

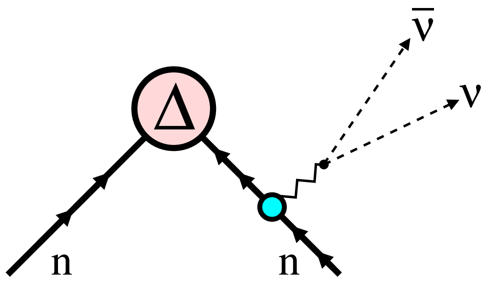
The paring gap introduces a suppression factor to

- Neutrino emission processes
- Heat capacity

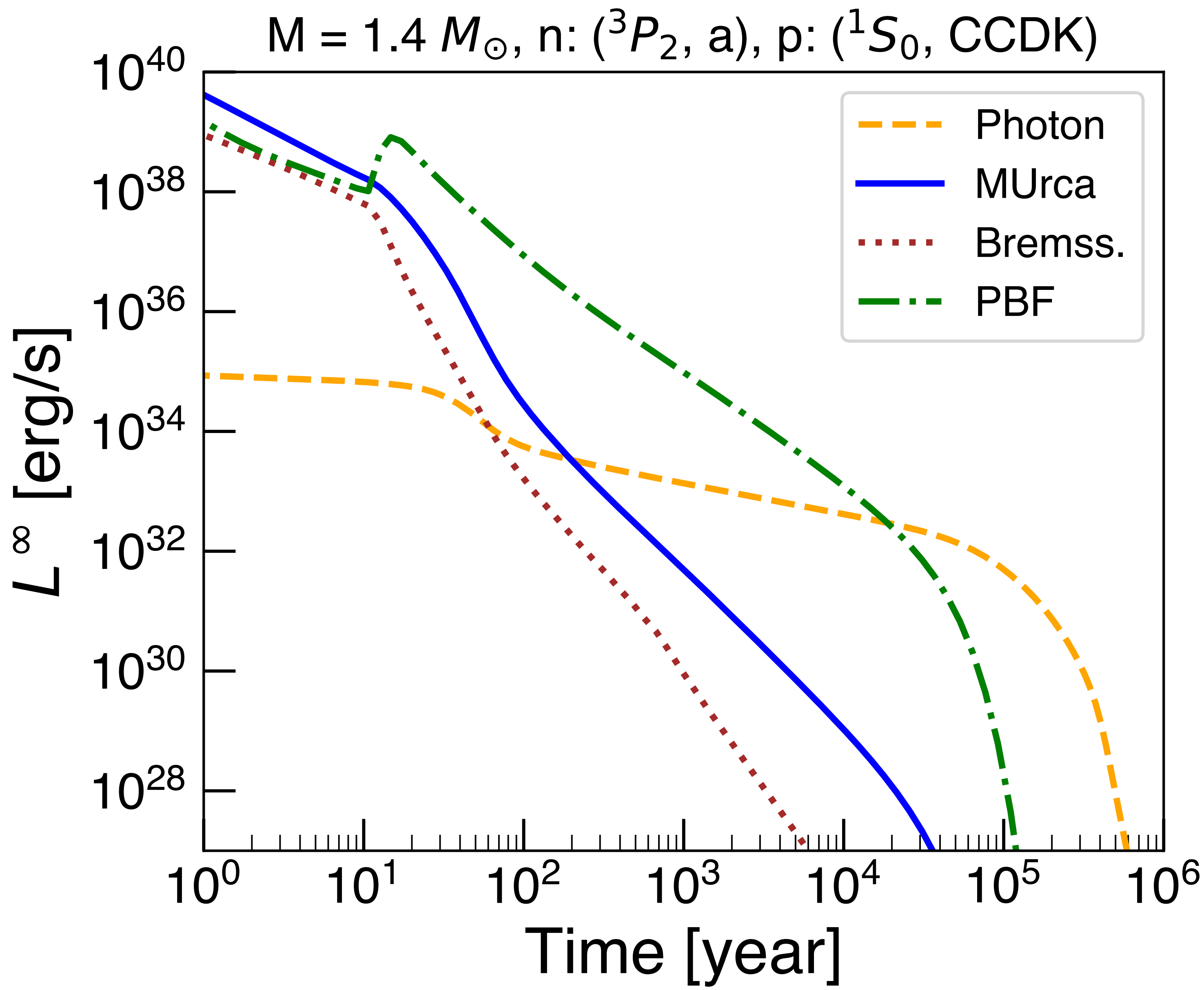
$$\propto e^{-\frac{\Delta_N}{T}}$$

In addition, a new neutrino emission process is turned on:

- Pair-breaking and formation (PBF) process

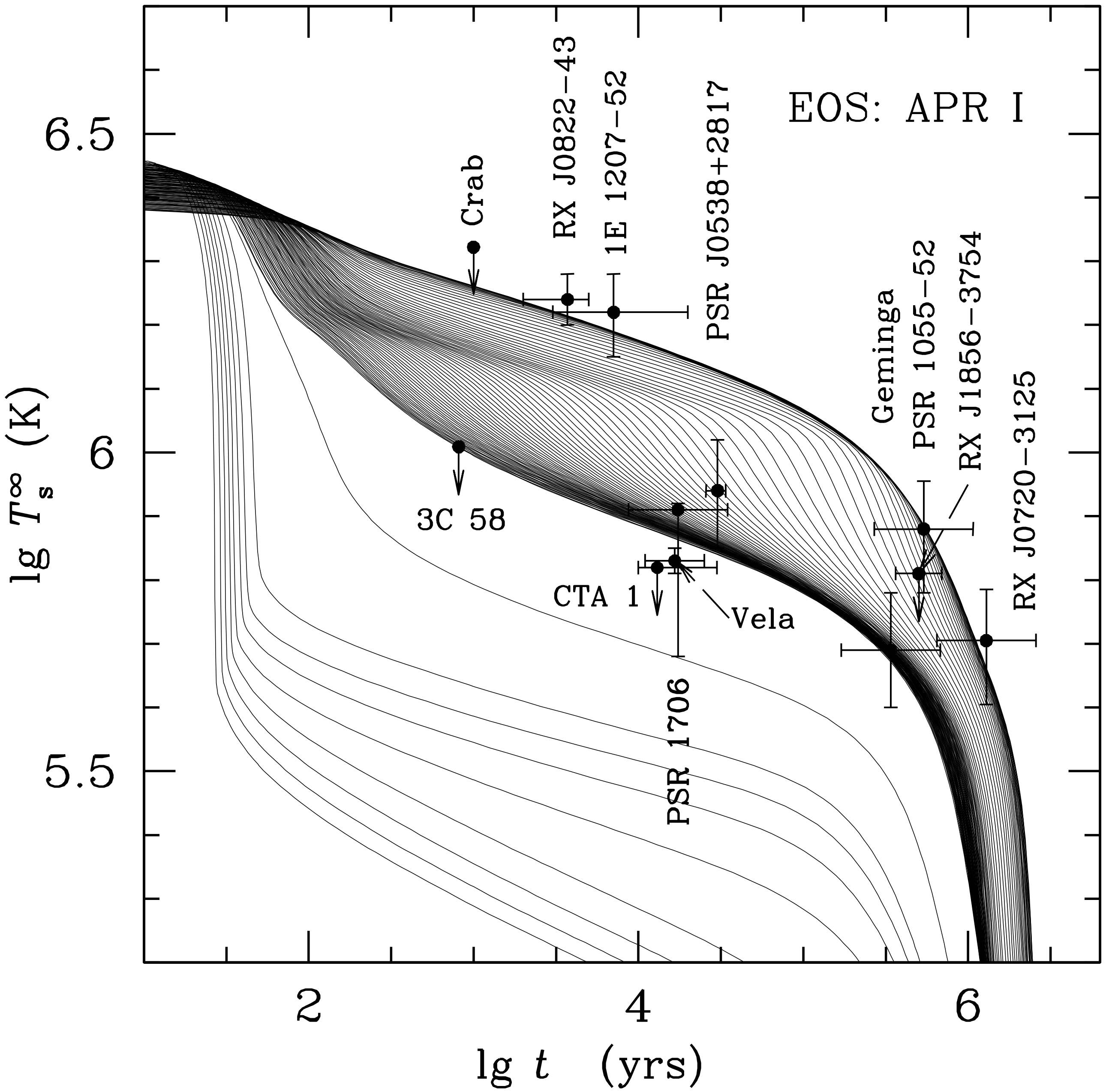


Luminosity



- Photon emission becomes dominant after ~10^5 years.
- Urca process is extremely suppressed at later times.

Success of Standard Cooling



$$M = (1.01 - 1.92)M_\odot$$

O. Y. Gnedin, M. Gusakov, A. Kaminker, D. G. Yakovlev, Mon. Not. Roy. Astron. Soc. **363,** 555 (2005).

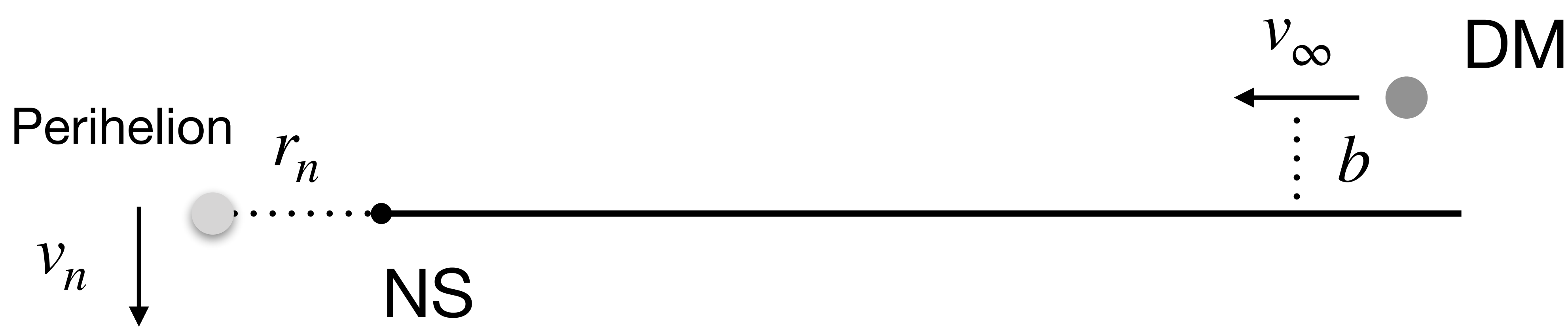
- Temperature gets very low for $t \gtrsim 10^6$ years.
- Consistent with the observations.

Except for those recently observed for old NSs.

Dark Matter Heating

Dark matter accretion in NS

Consider a WIMP with mass m_{DM}, incoming from infinity with speed v_∞ and impact parameter b.



Energy

$$\frac{m_{\rm DM} v_\infty^2}{2} = \frac{m_{\rm DM} v_n^2}{2} - \frac{G m_{\rm DM} M}{r_n}$$

Angular momentum

$$m_{\rm DM} v_\infty b = m_{\rm DM} v_n r_n$$

$$\Rightarrow \quad r_n = \frac{GM}{v_\infty^2}\left[\sqrt{1 + \frac{v_\infty^4 b^2}{G^2 M^2}} - 1\right]$$

Dark matter accretion in NS

For a WIMP to be captured by a NS, $r_n \leq R$ is required.

$$\Rightarrow \quad \boxed{b \leq R\left[1+\frac{v_{\rm esc}^2}{v_\infty^2}\right]^{\frac{1}{2}}}$$

$v_\infty \simeq 230$ km/s

Escape velocity

$$v_{\rm esc} = \sqrt{\frac{2GM}{R}} \simeq 2\times 10^8 \times \left(\frac{M}{1.4M_\odot}\right)^{1/2}\left(\frac{R}{10\ {\rm km}}\right)^{-1/2}\ {\rm m/s}$$

Close to the speed of light!

Maximum impact parameter

$$b_{\rm max} \simeq R\frac{v_{\rm esc}}{v_\infty} \simeq 0.8\times 10^7 \times \left(\frac{M}{1.4M_\odot}\right)^{1/2}\left(\frac{R}{10\ {\rm km}}\right)^{1/2}\ {\rm m}$$

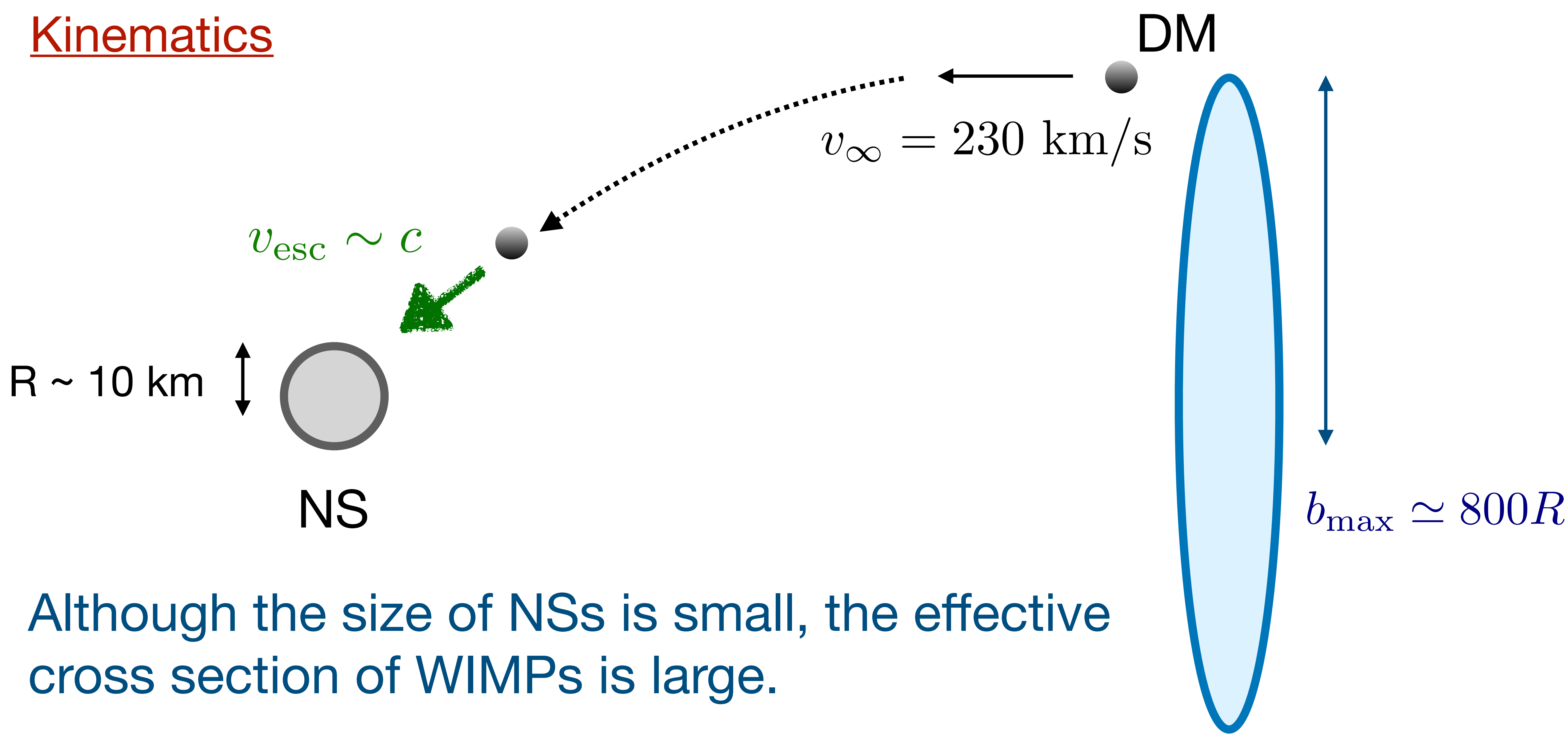
Much larger than the NS radius.

Dark matter accretion in NS

WIMP accretion rate is thus evaluated as

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

<u>Kinematics</u>



Although the size of NSs is small, the effective cross section of WIMPs is large.

Recoil energy

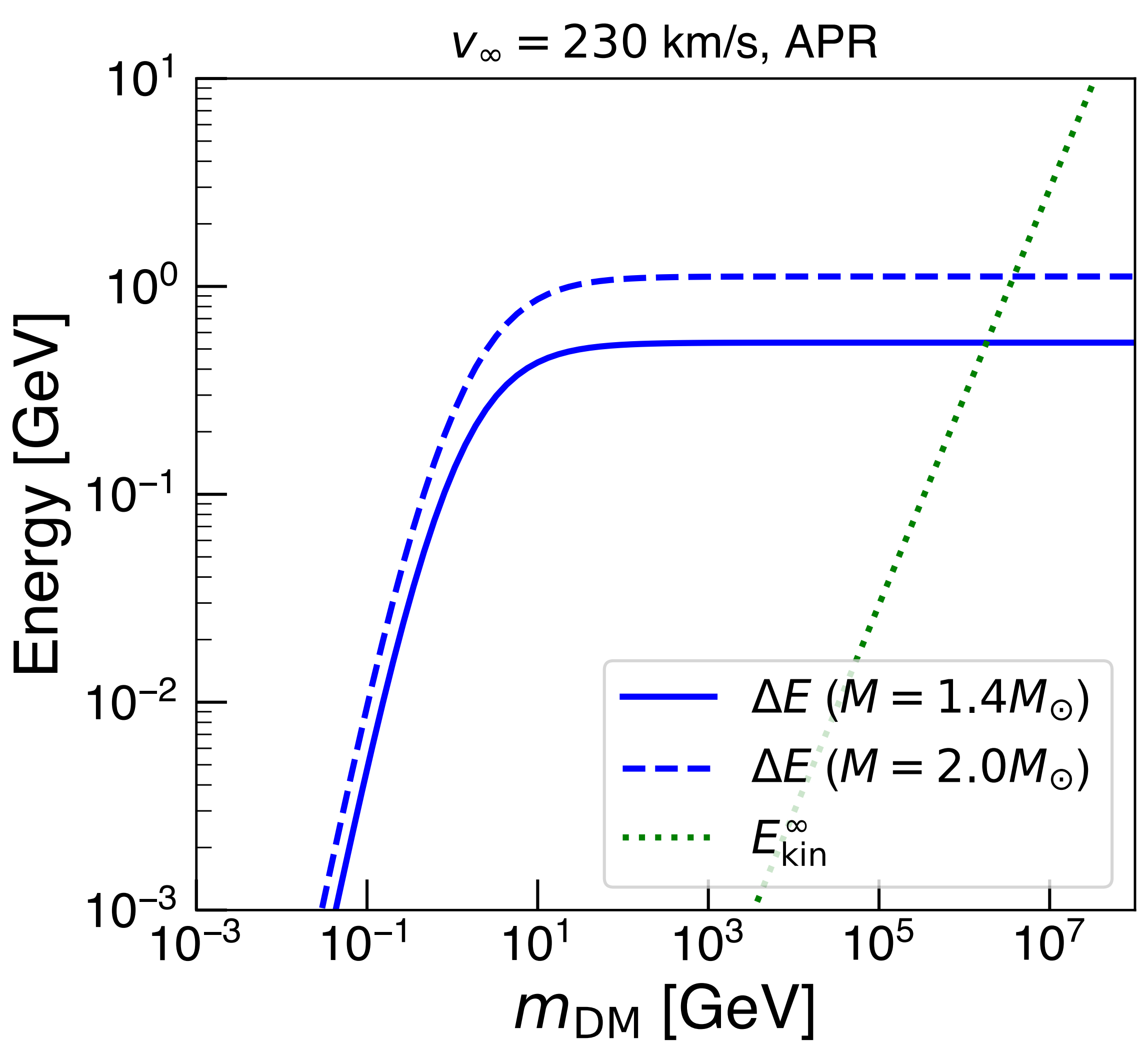
For each DM-nucleon scattering, WIMPs lose energy by

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

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

$$\text{Mean Free Path} \sim (\sigma n)^{-1} \sim \frac{m_N R^3}{\sigma M} < R$$

$$\sigma > \sigma_{\text{crit}} \sim \frac{m_N R^2}{M} \sim 10^{-45}\ \text{cm}^2$$

σ: WIMP-nucleon scattering cross section.

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

If not, capture rate is suppressed by $\sigma/\sigma_{\text{crit}}$.

Dark matter heating

Captured WIMPs eventually annihilate inside the NS core.

For old NSs, we have

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

If all of the accreting WIMPs are captured by the NS,

$$L_H \simeq m_{\mathrm{DM}} \dot{N} \simeq 2\pi G M R \rho_{\mathrm{DM}} / v_\infty$$

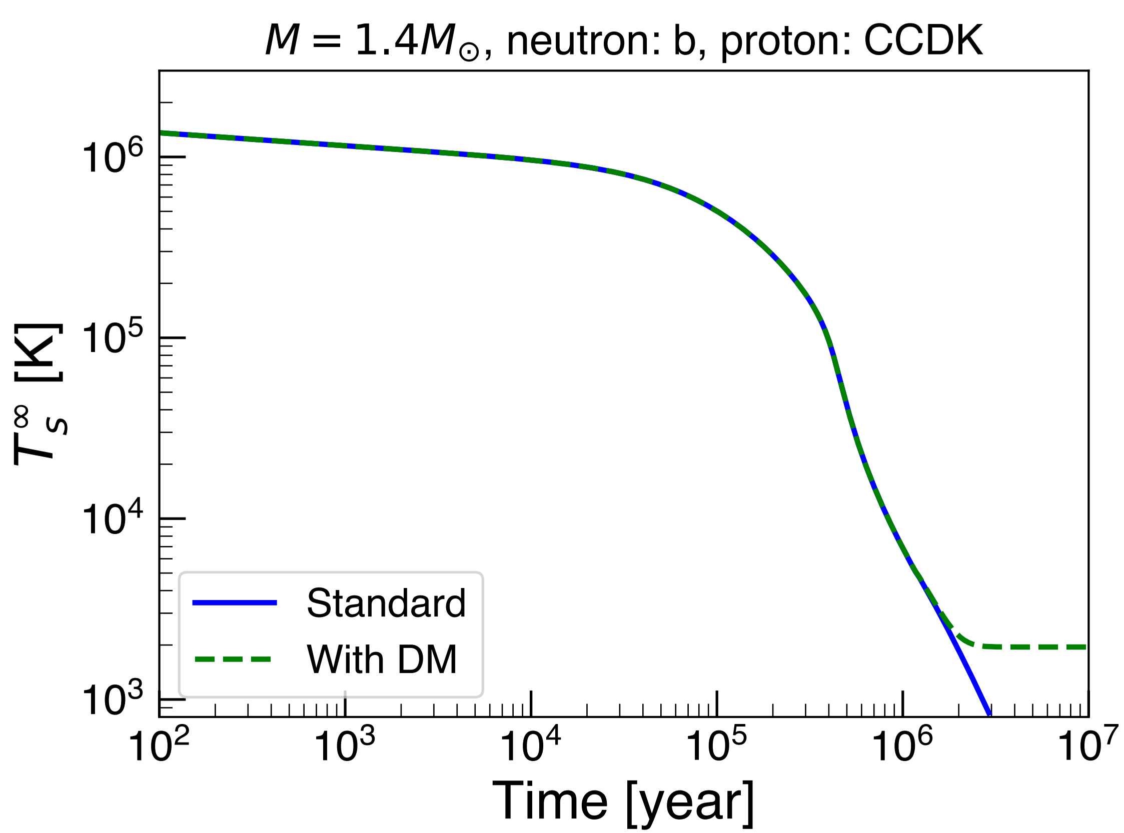
NS temperature with DM heating

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

$$L_H = L_\gamma \quad \Rightarrow \quad 2\pi G M R \rho_{\mathrm{DM}} / v_\infty \simeq 4\pi R^2 \sigma_{\mathrm{SB}} T_s^4$$

(for $\sigma > \sigma_{\mathrm{crit}}$)

$$\Rightarrow \quad T_s \simeq 2500 \text{ K}$$

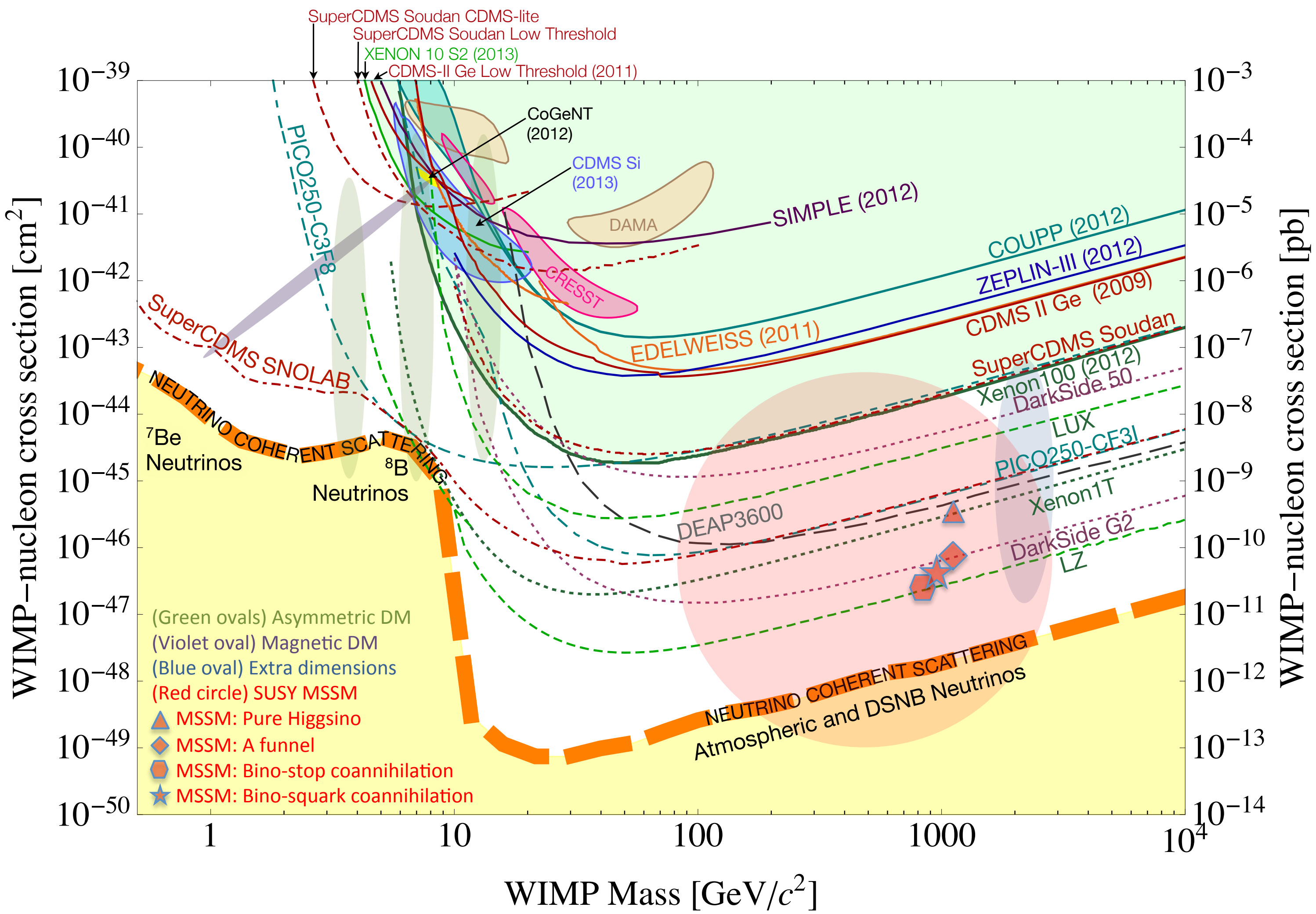


Robust, smoking-gun prediction of DM heating.

DM heating vs direct detection

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

Direct detection



Snowmass, arXiv:1310.8327.

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 $\Delta E \sim O(100)$ MeV.
- WIMP-nucleon scattering is velocity-suppressed.
- Spin-dependent scattering
- Light dark matter
- Heavy dark matter

Electroweak-Interacting DM

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

Examples:

- n = 2, Y = 1/2 (higgsino)
- n = 3, Y = 0 (wino)
- n = 5, Y = 0 (Minimal Dark Matter)

Interactions

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

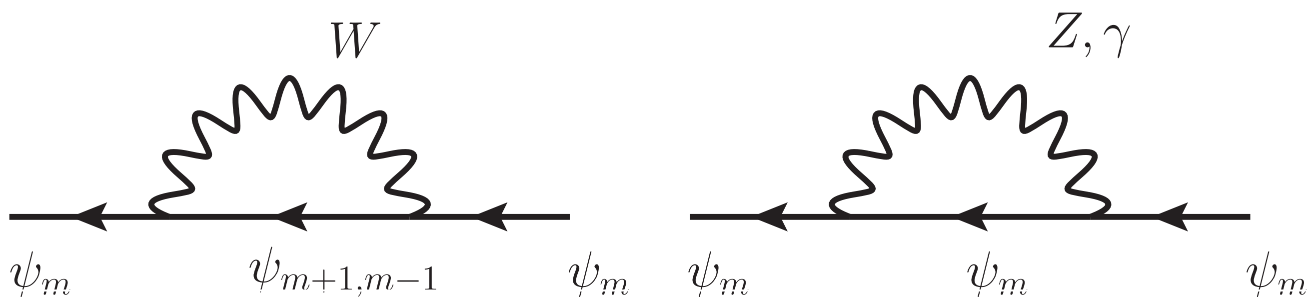
The DM phenomenology is (almost) completely determined by the gauge interactions.

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

Electroweak multiplet DM

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

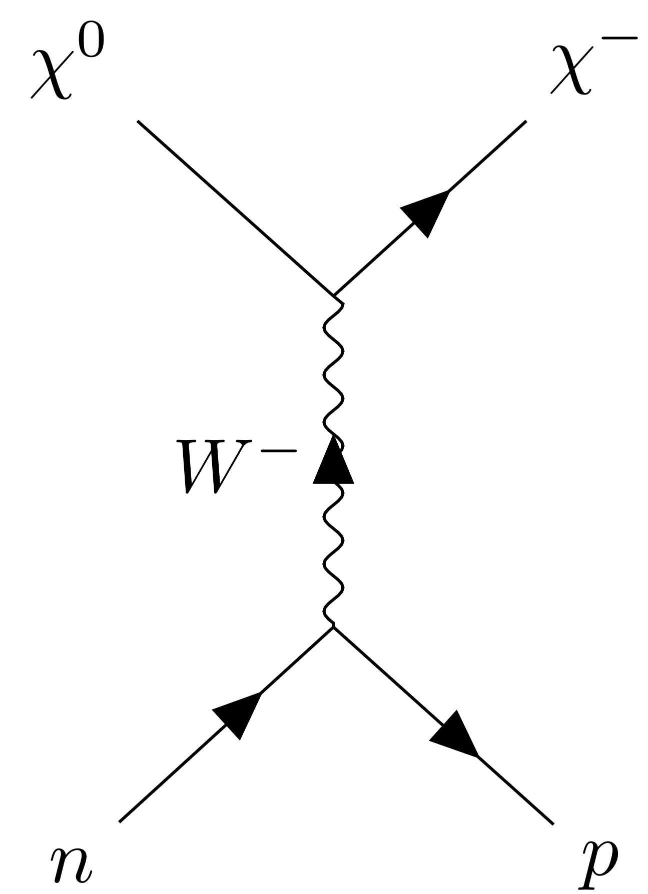
Mass splitting



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

O(100) MeV

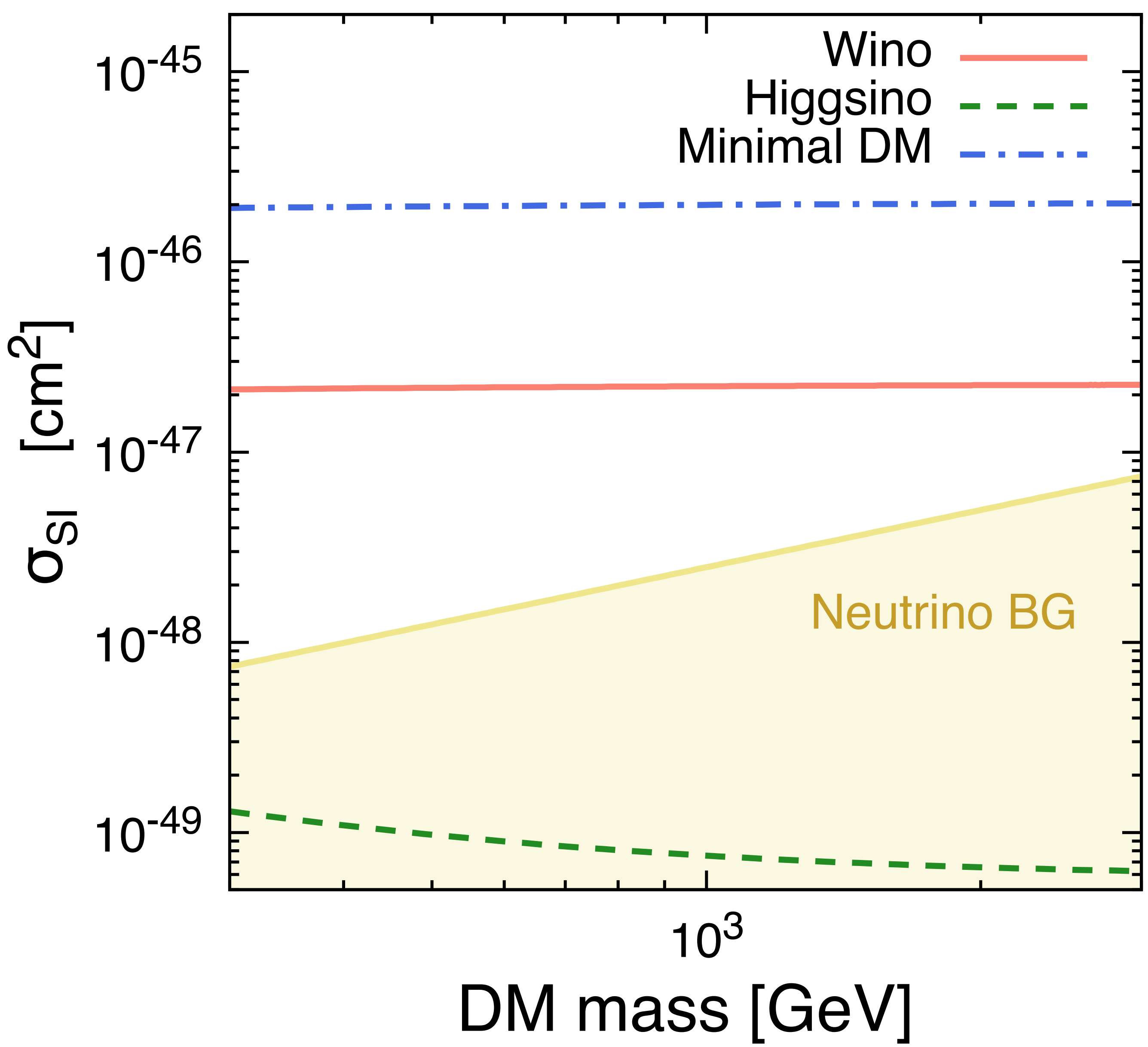
- Inelastic scattering can occur.
- Cross section is large enough for such a DM to be captured in NS.
- NS can be a promising probe for this class of DM candidates.



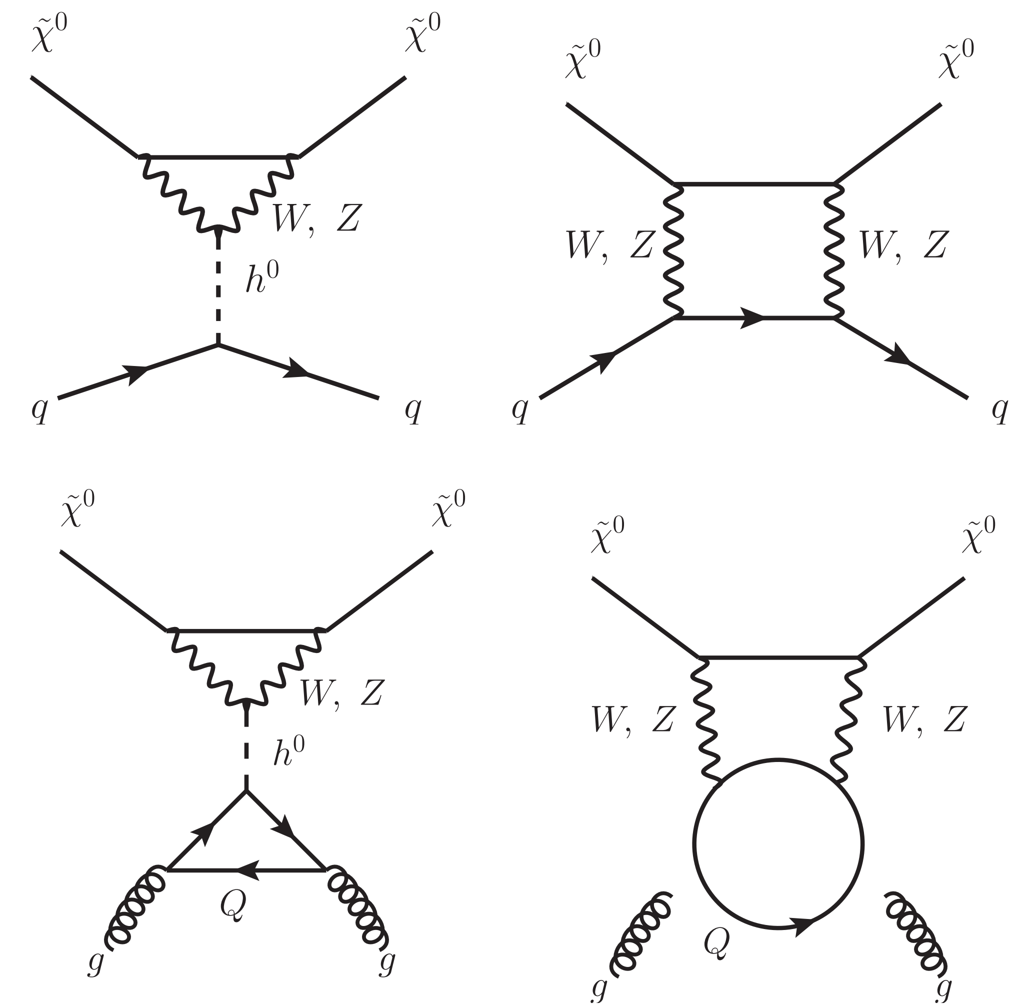
Detailed study ongoing.

Electroweak interacting DM

Elastic scattering cross section



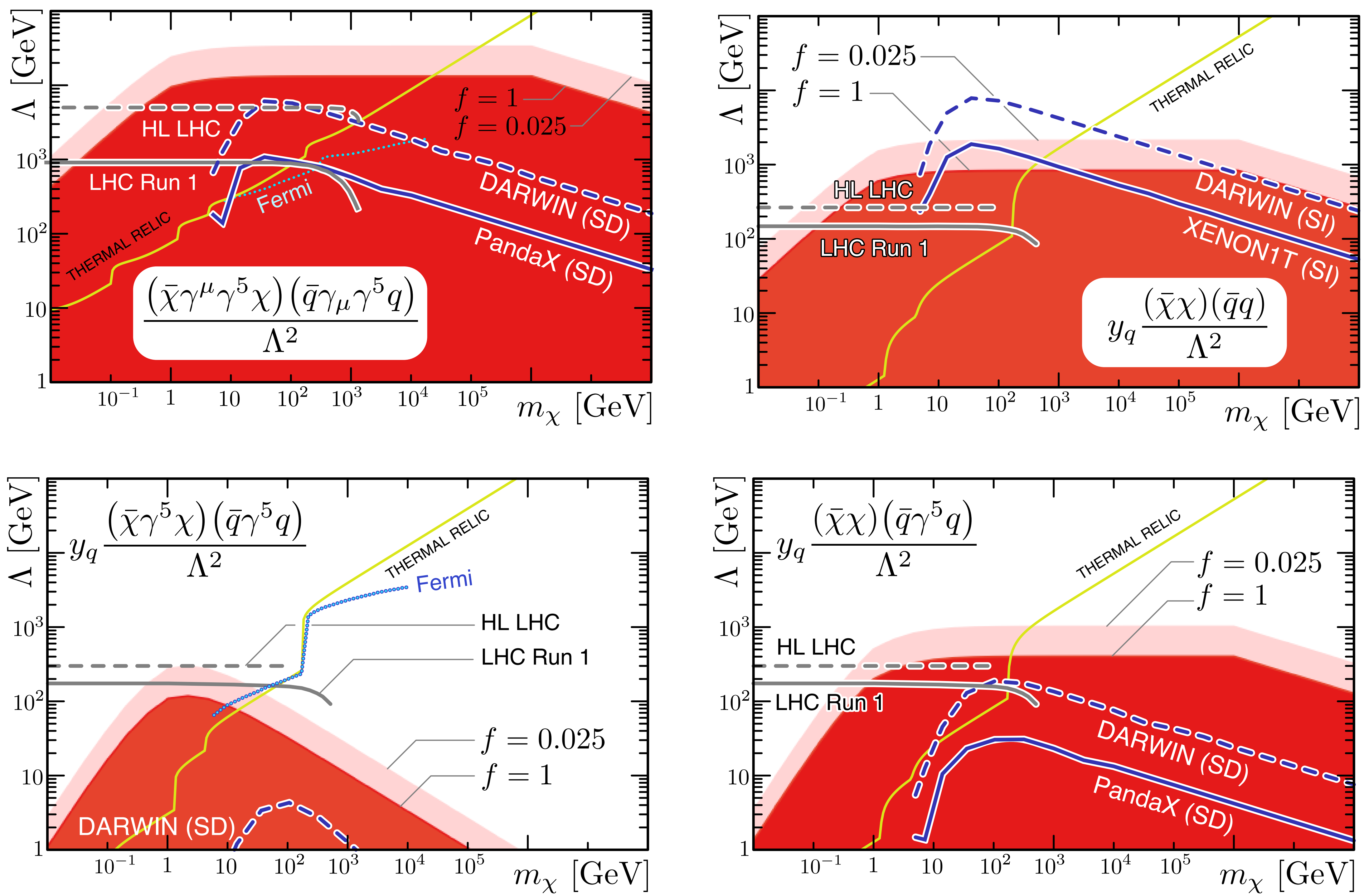
Diagrams



Elastic scattering cross section is generically small.

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

Effective operator analysis



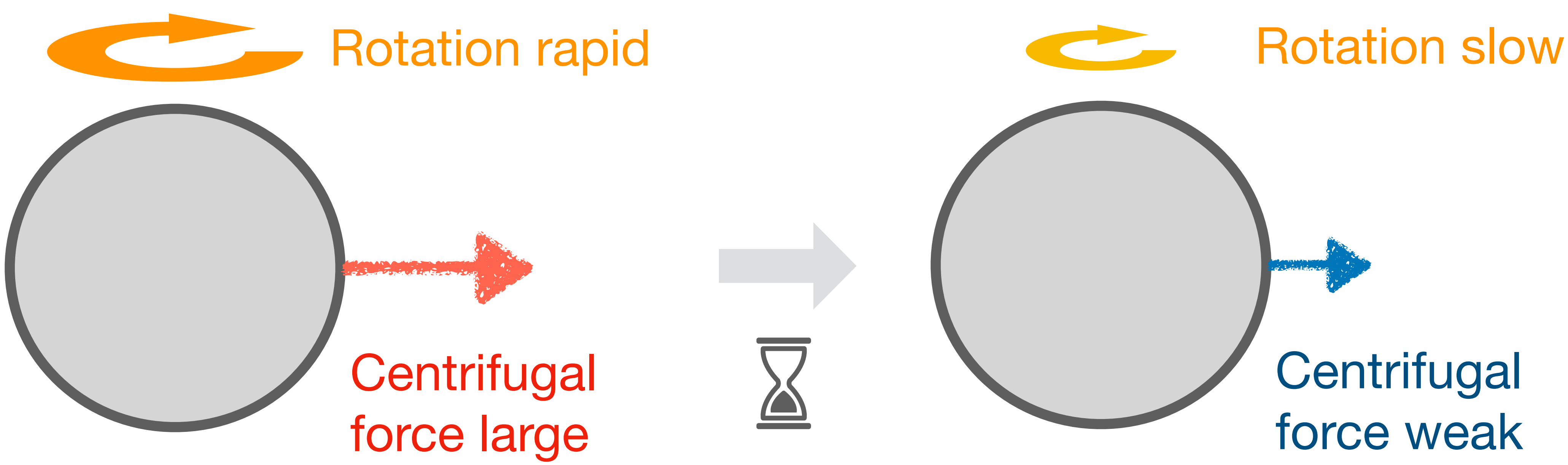
N. Raj, P. Tanedo, H. Yu, Phys. Rev. **D97**, 043006 (2018).

Role of 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.

At low temperatures, the rate of Urca process is fairly suppressed.

➡ Deviation from β equilibrium

Energy excess in chemical potentials.

Out of β equilibrium

Deviation from β equilibrium is quantified by

$$\eta_\ell \equiv \mu_n - \mu_p - \mu_\ell \quad (\ell = e, \mu)$$

<u>At early times</u>

Urca processes are rapid.

➡ NS can follow the change in the equilibrium condition.

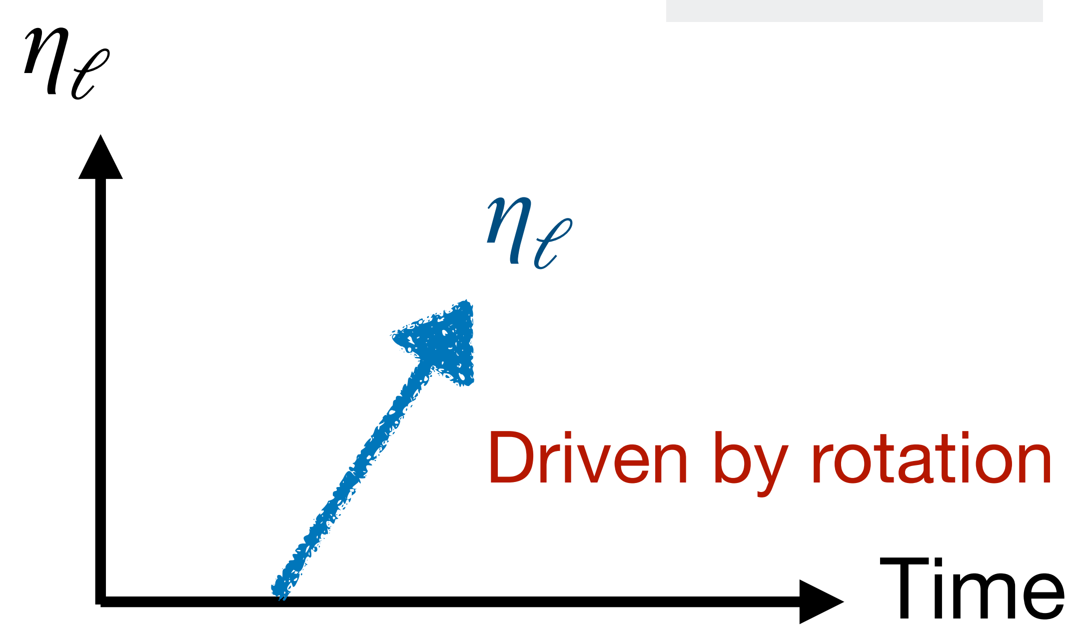
$$\eta_\ell = 0$$

<u>At later times</u>

Urca processes are too slow.

➡ Deviation from β equilibrium

➡ η_ℓ increases!

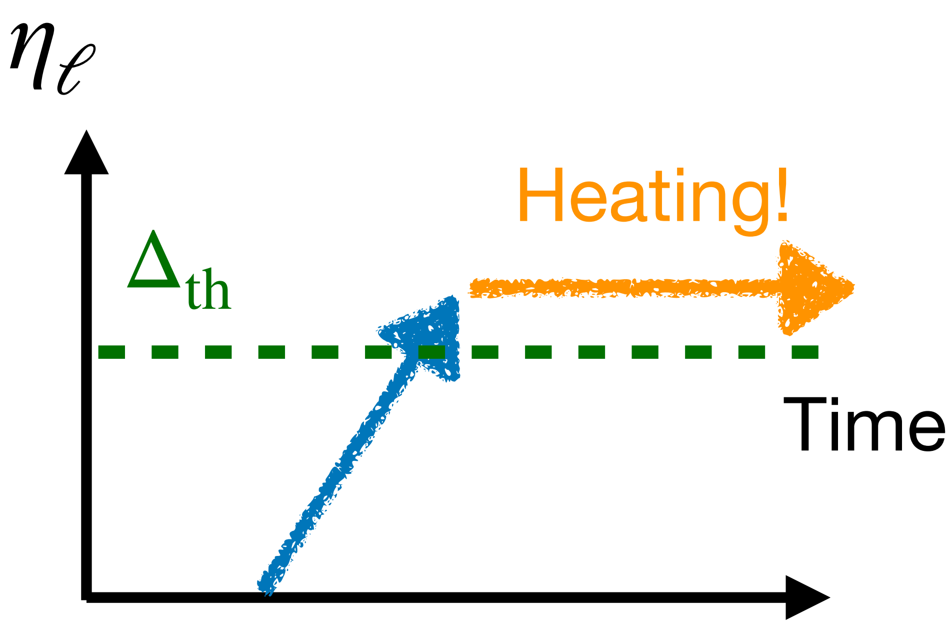


Rotochemical heating

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

Once η_ℓ exceeds a threshold $\Delta_{\rm th}$ determined by nucleon gaps,

$$\Delta_{\rm th} = \min\{3\Delta_n + \Delta_p, \Delta_n + 3\Delta_p\}$$



- Urca processes are enhanced.
- Generation of heat

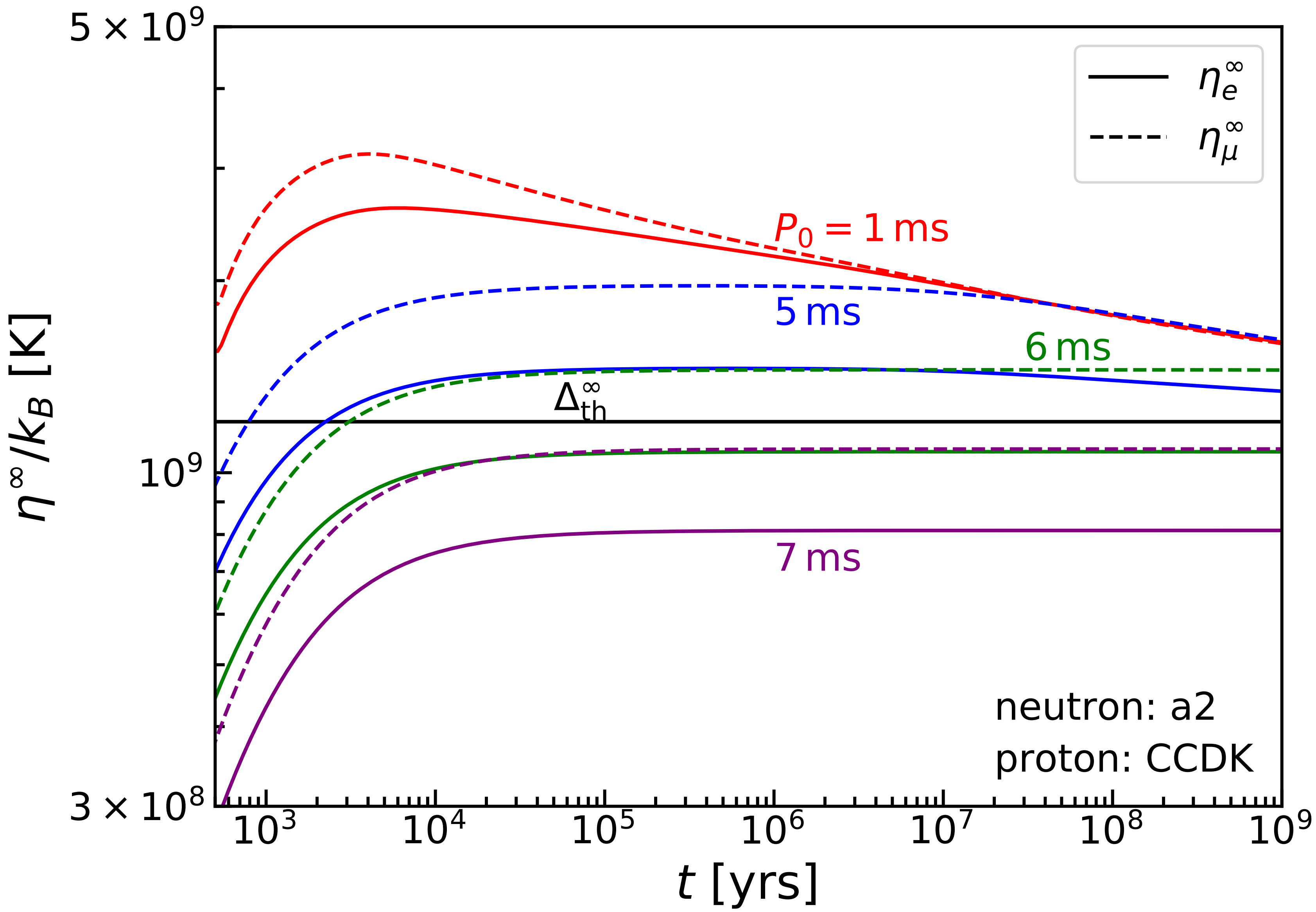
Called the rotochemical heating.

It occurs in the same setup as the standard cooling.

- No exotic physics needed.
- This effect should have been included from the beginning…

Evolution of chemical imbalance

Since the deviation from equilibrium is driven by rotation, it strongly depends on the value of period.



$$M = 1.4 M_\odot$$
$$P = 1 \text{ s}$$
$$\dot{P} = 10^{-15}$$

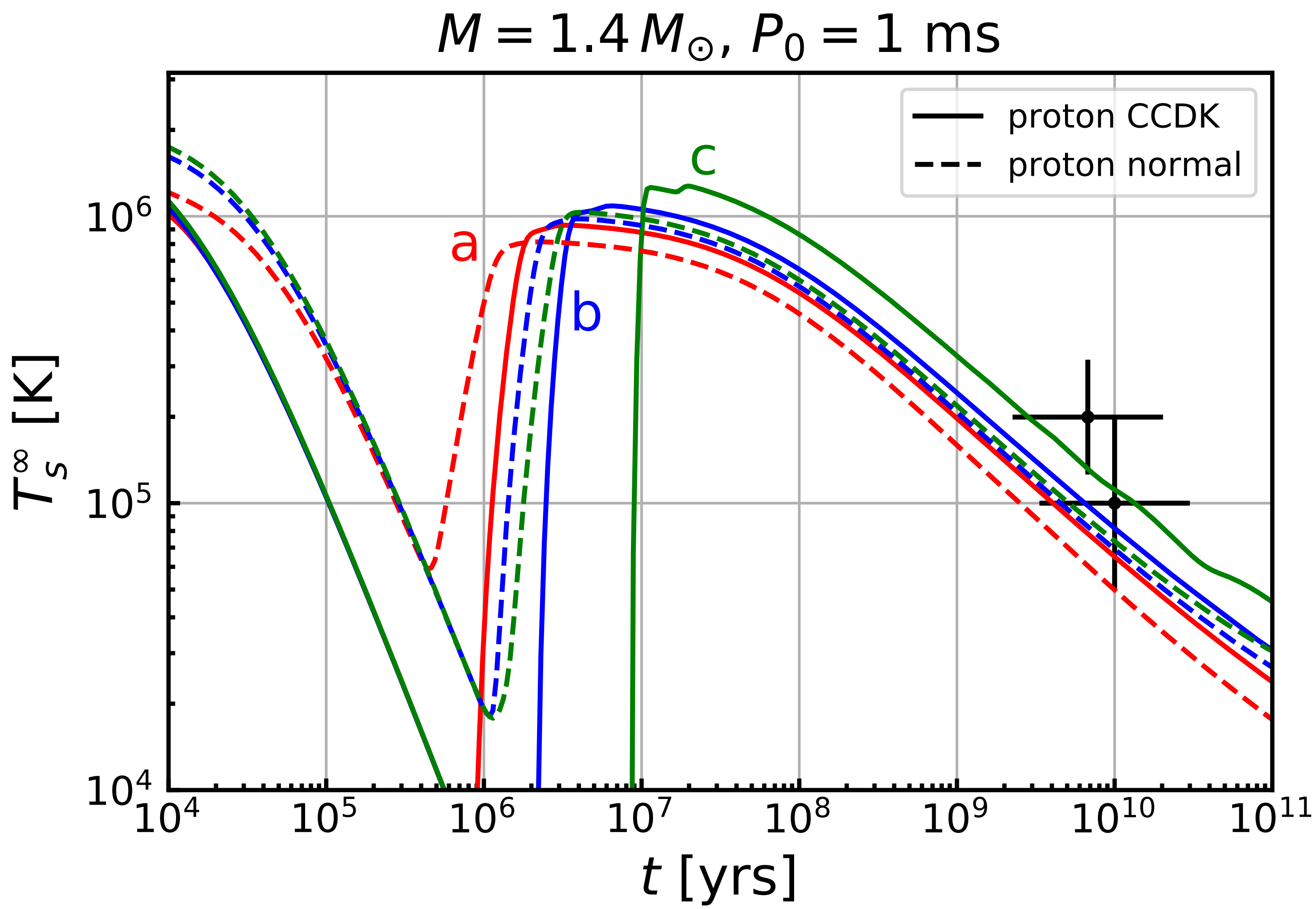
Magnetic dipole radiation

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

Rotochemical heating occurs if the initial period P_0 is small enough.

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

Millisecond pulsars

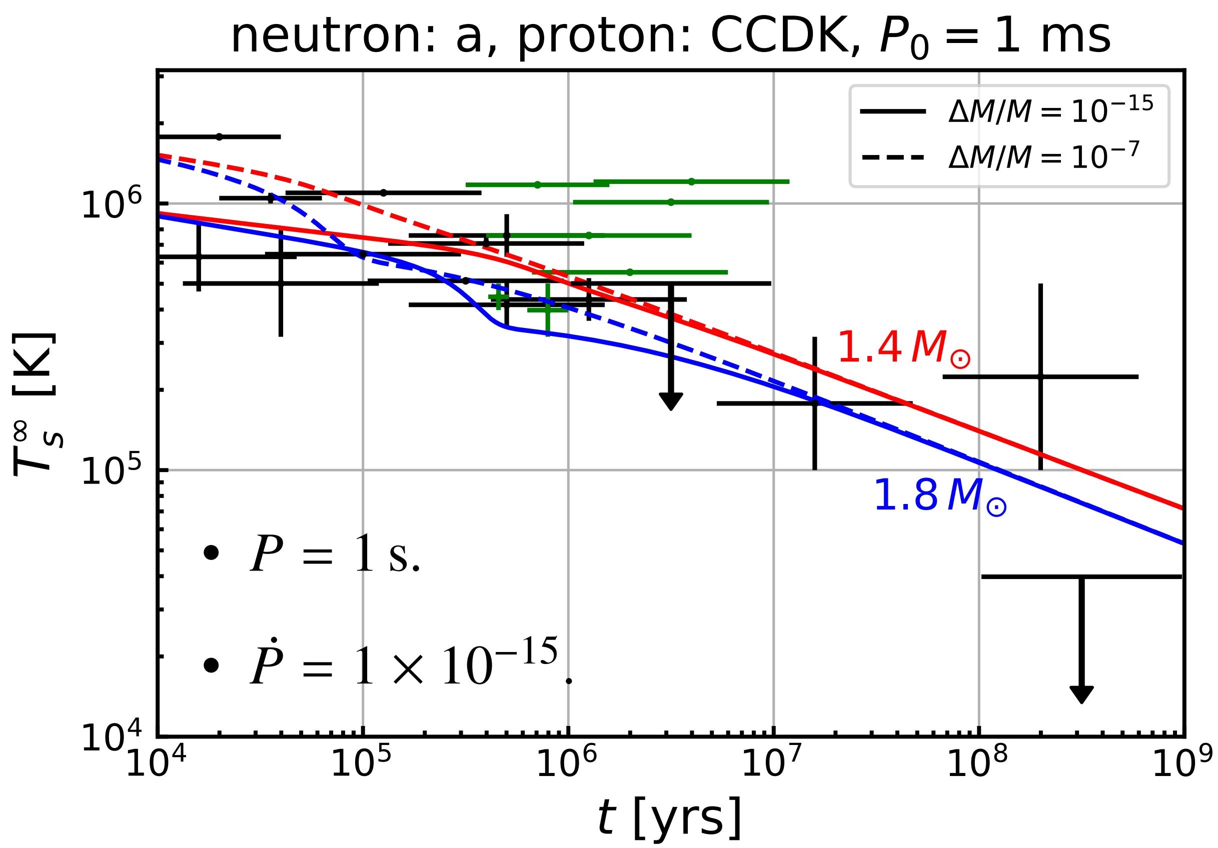


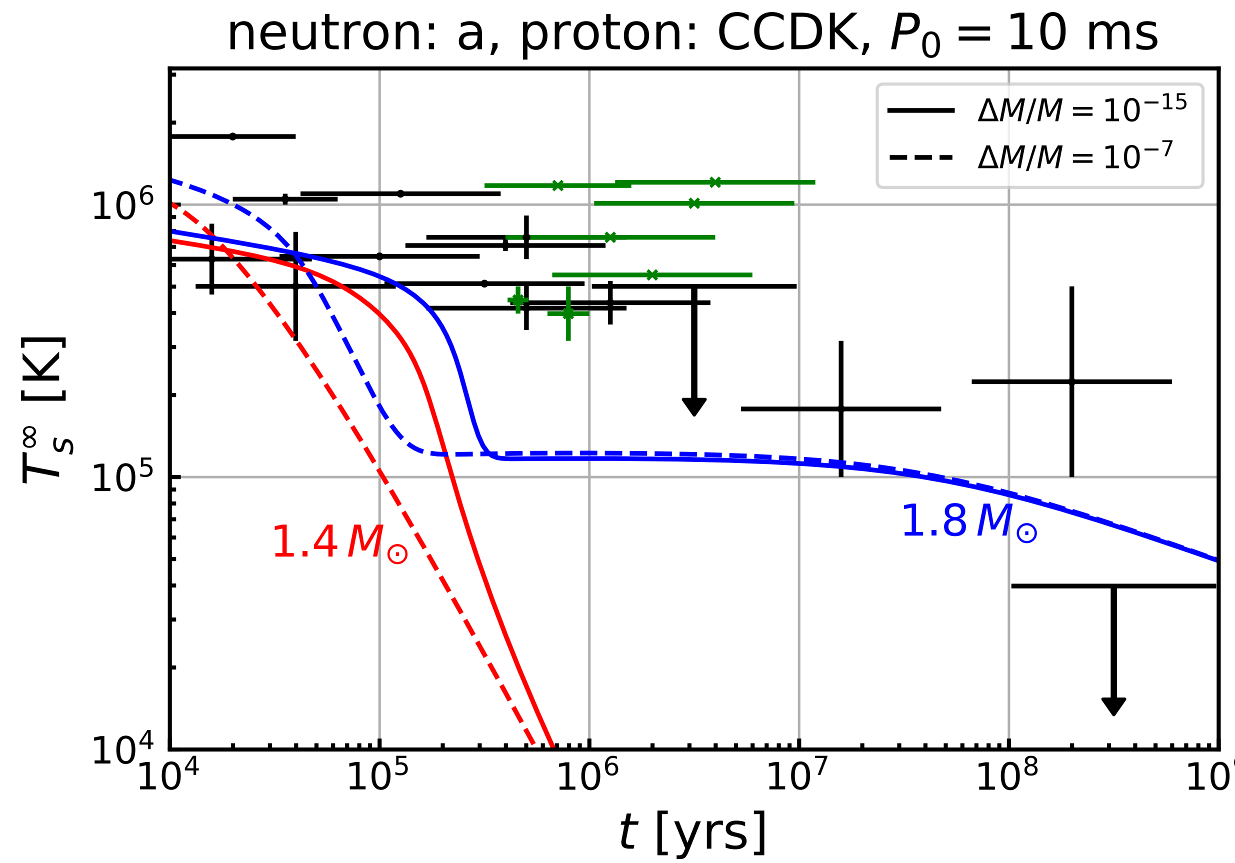
- $M = 1.4\,M_\odot$.
- $P = 5.8\,\mathrm{ms}$.
- $\dot{P} = 5.7 \times 10^{-20}$.
- $\Delta M/M = 10^{-7}$.

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

K. Hamaguchi, N. Nagata, K. Yanagi, arXiv:1904.04667.

Ordinary pulsars





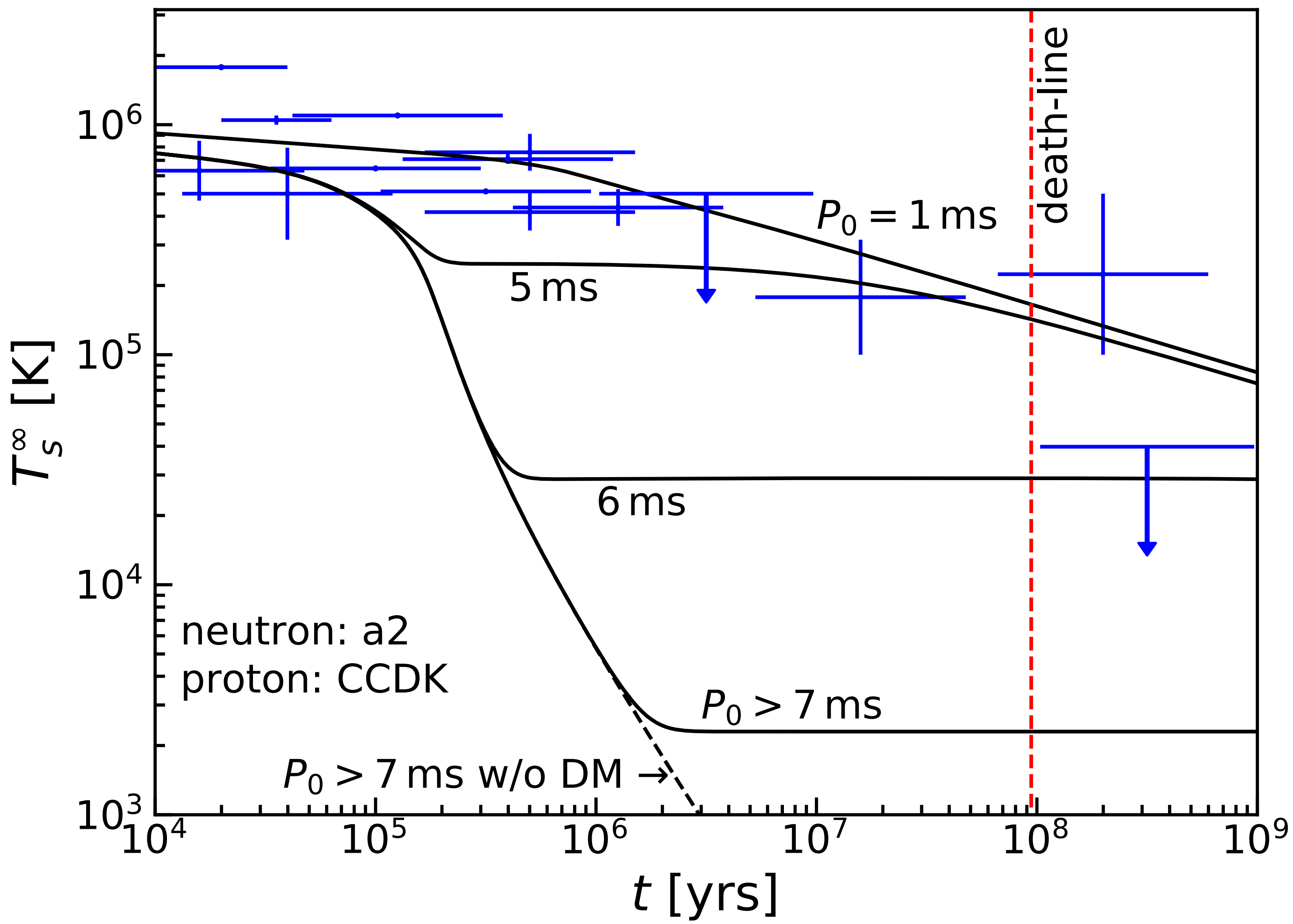
- The temperature revolution highly depends on the initial period of pulsars.
- We can explain all of the observations.
  - Cool star: large initial period → no rotochemical heating.
  - Warm star: small initial period → rotochemical heating effective.

K. Hamaguchi, N. Nagata, K. Yanagi, arXiv:1904.04667.

Results and implications

NS surface temperature evolution

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).

Conclusion

Conclusion

- We studied the NS temperature evolution including both the rotochemical and DM heating effects.

- For ordinary pulsars, DM heating effect can be observed if their initial period is relatively large.

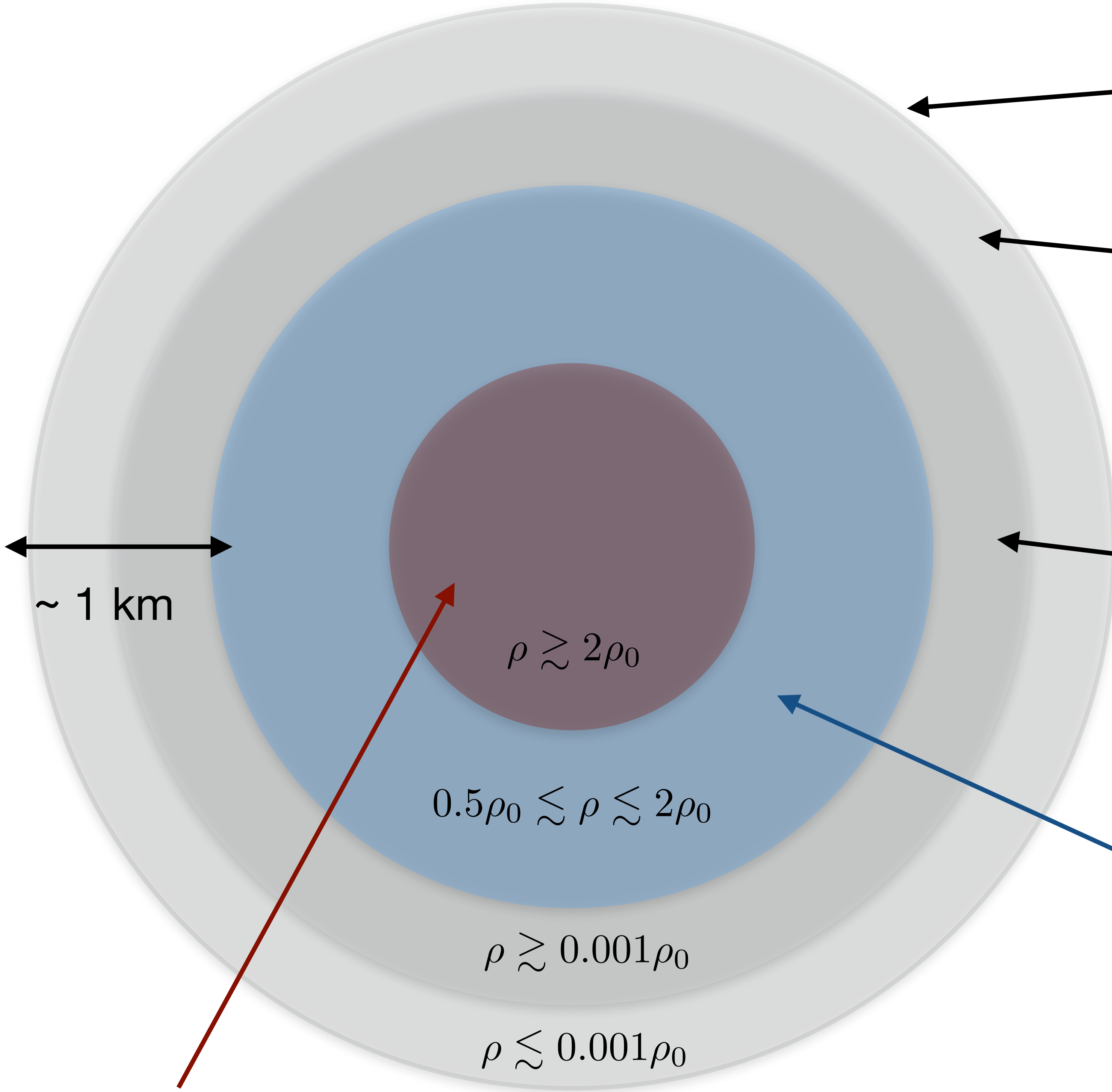
- For millisecond pulsars, DM heating effect is always hidden by the rotochemical heating.

- In any case, an observation of a NS with $T_s^{\infty} \lesssim 10^3$ K can give a stringent constraint on WIMP DM.

Such as electroweak-interacting DM

Backup

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: ${}^1S_0$

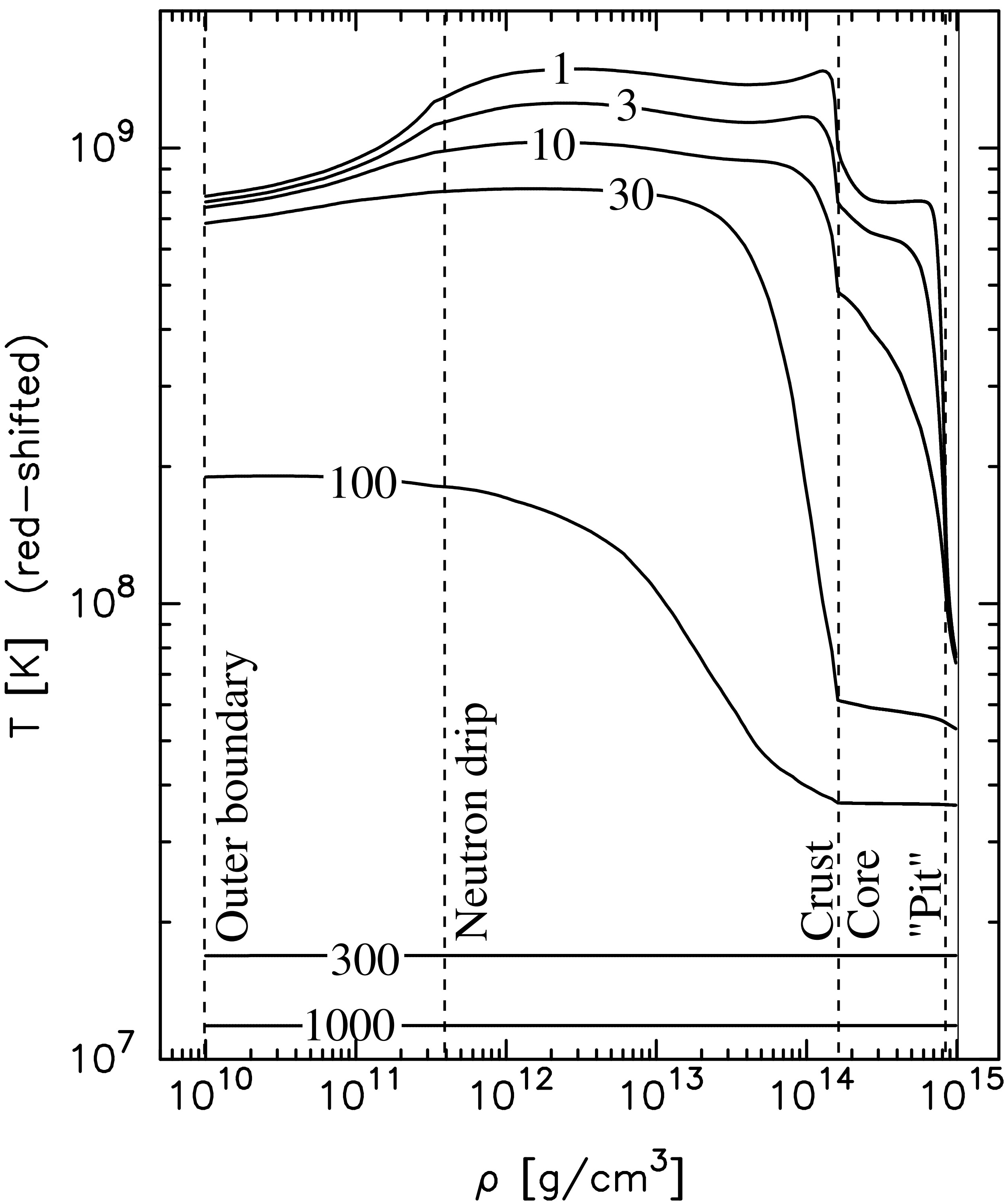
Inner core

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

Neutron superfluid: ${}^3P_2$

~~Hyperons, π/K condensation, quarks (?)~~ We do not consider them in this talk.

Temperature distribution

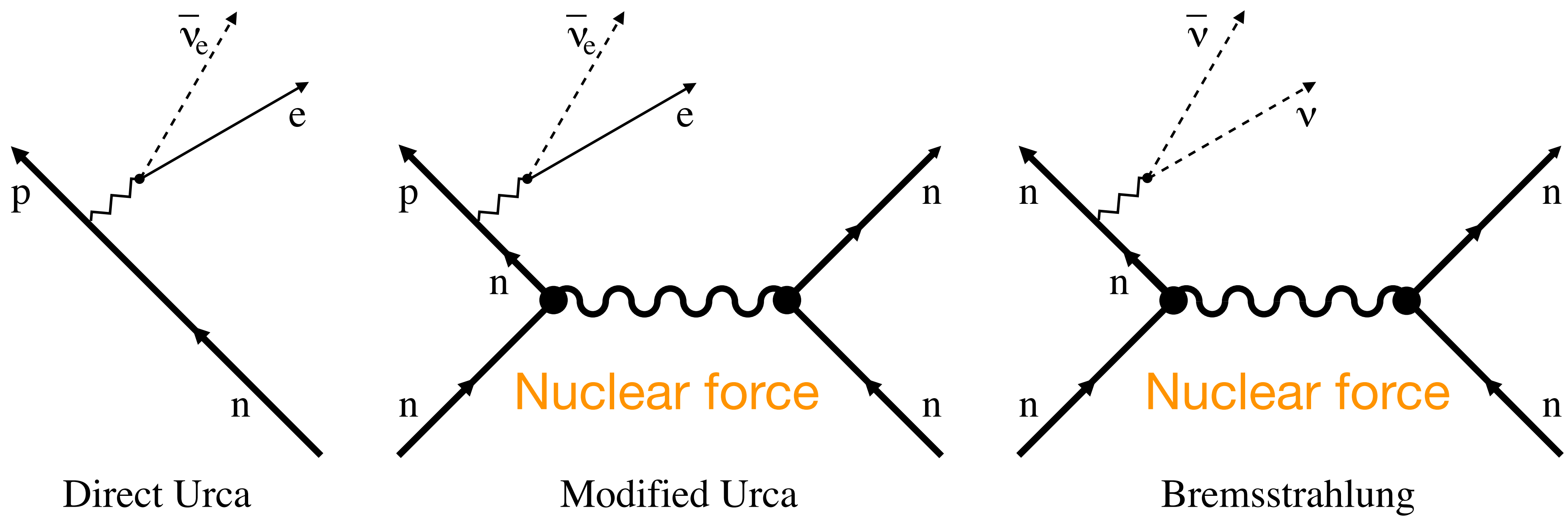


Relaxation in the Core done in ~ 100 years.

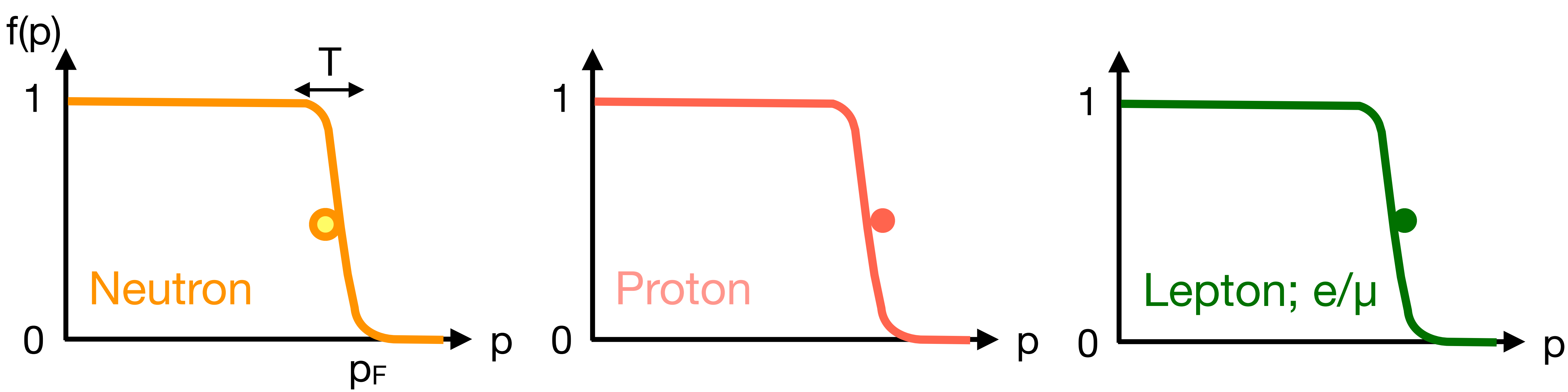
D. Page, J. M. Lattimer, M. Prakash, A. W. Steiner [arXiv: 1302.6626].

Neutrino emission

First we consider the processes that occur without superfluidity.



These processes occur only near the Fermi surface.



β equilibrium

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

<u>Chemical equilibrium</u>

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

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

<u>Charge neutrality</u>

$$n_p = n_e$$

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

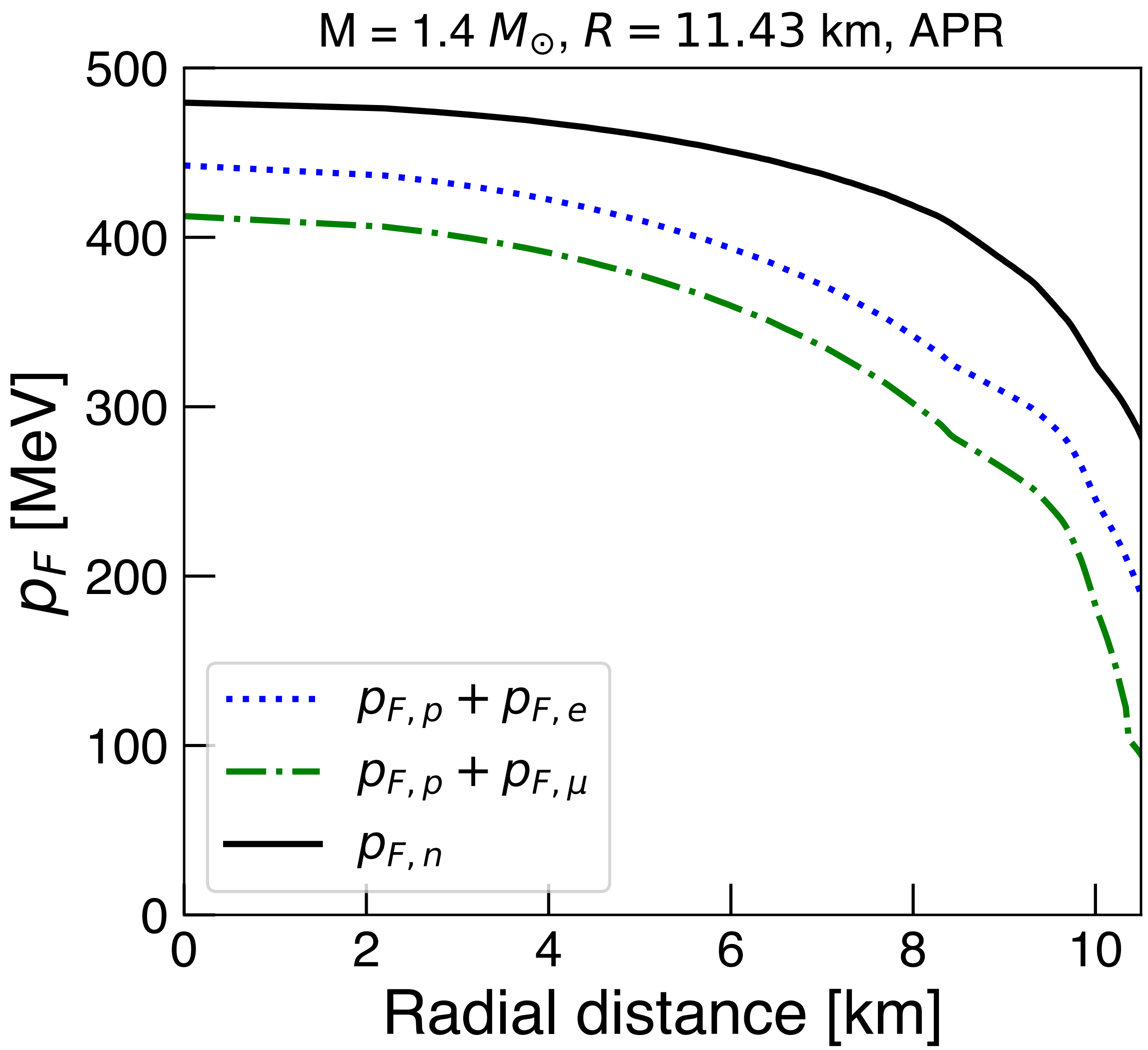
<u>Chemical equilibrium</u>

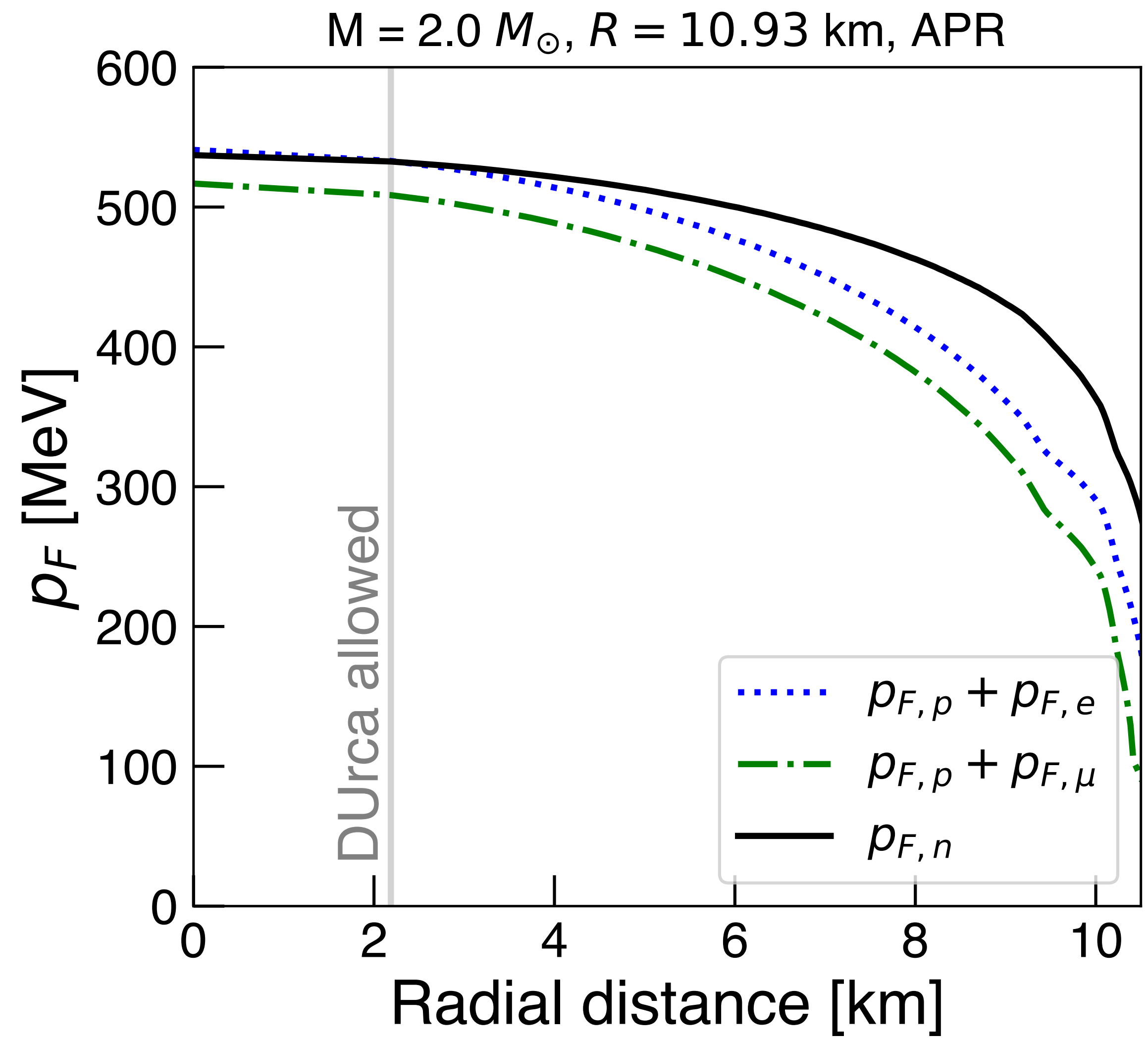
$$\mu_e = \mu_\mu \qquad (\mu_\mu + \mu_p = \mu_n)$$

<u>Charge neutrality</u>

$$n_p = n_e + n_\mu$$

Direct Urca condition





- Direct Urca can occur only in the high density region.
- It can occur only in relatively heavy stars.

For the APR equation of state, $M \gtrsim 1.97 M_\odot$

Direct Urca

Emissivity ≡ energy loss per volume per time.

of the direct Urca process is given by

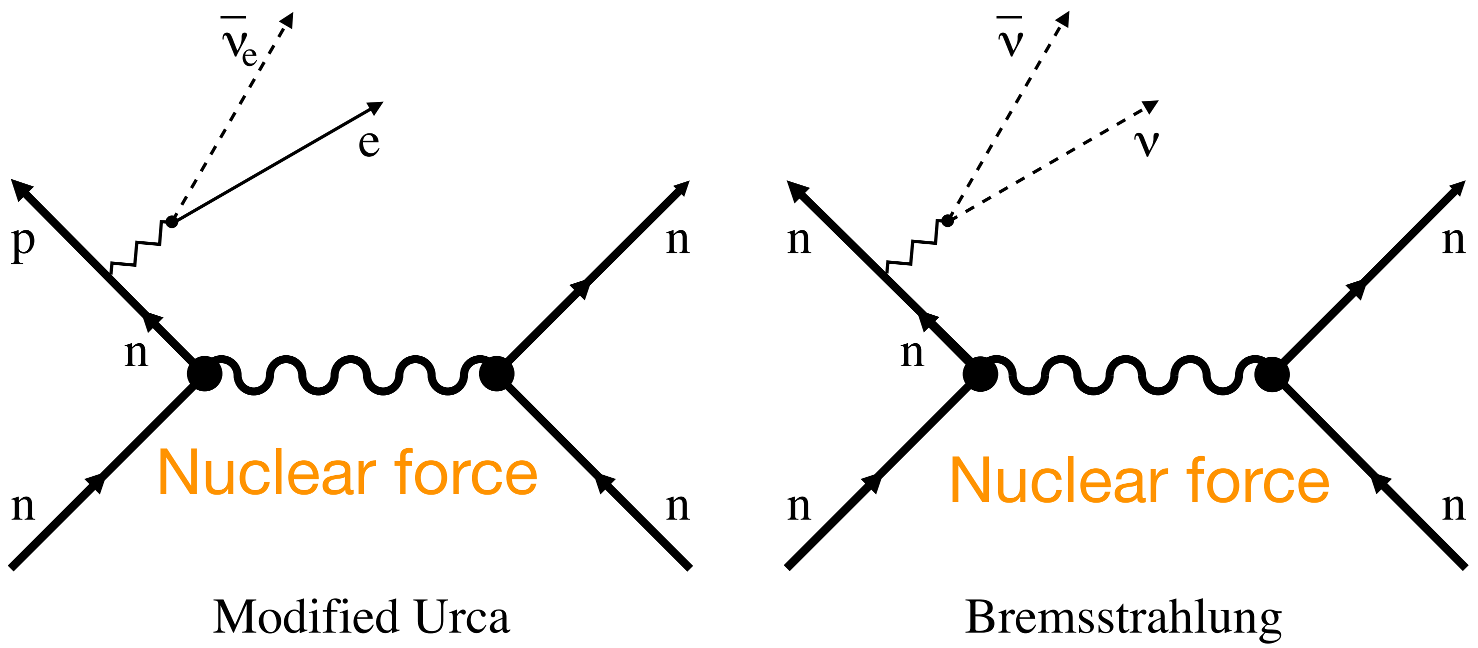
$$Q_D = \frac{457\pi}{10080} G_F^2 V_{ud}^2 (1+3g_A^2) m_{*,n} m_{*,p} m_{*,e} T^6 \Theta(p_{F,p} + p_{F,e} - p_{F,n})$$
$$\simeq 4 \times 10^{27} \times \left(\frac{T}{10^9\ \mathrm{K}}\right)^6 \Theta(p_{F,p} + p_{F,e} - p_{F,n})\ \mathrm{erg} \cdot \mathrm{cm}^{-3} \cdot \mathrm{s}^{-1}$$

- The step function comes from the momentum conservation.

$$p_{F,p} + p_{F,e} > p_{F,n}$$

- Direct Urca is the dominant process, if it occurs.

Modified Urca/bremsstrahlung



If Direct Urca does not operate, Modified Urca/bremsstrahlung processes become dominant.

Momentum exchange with a spectator allows these processes to satisfy the momentum conservation.

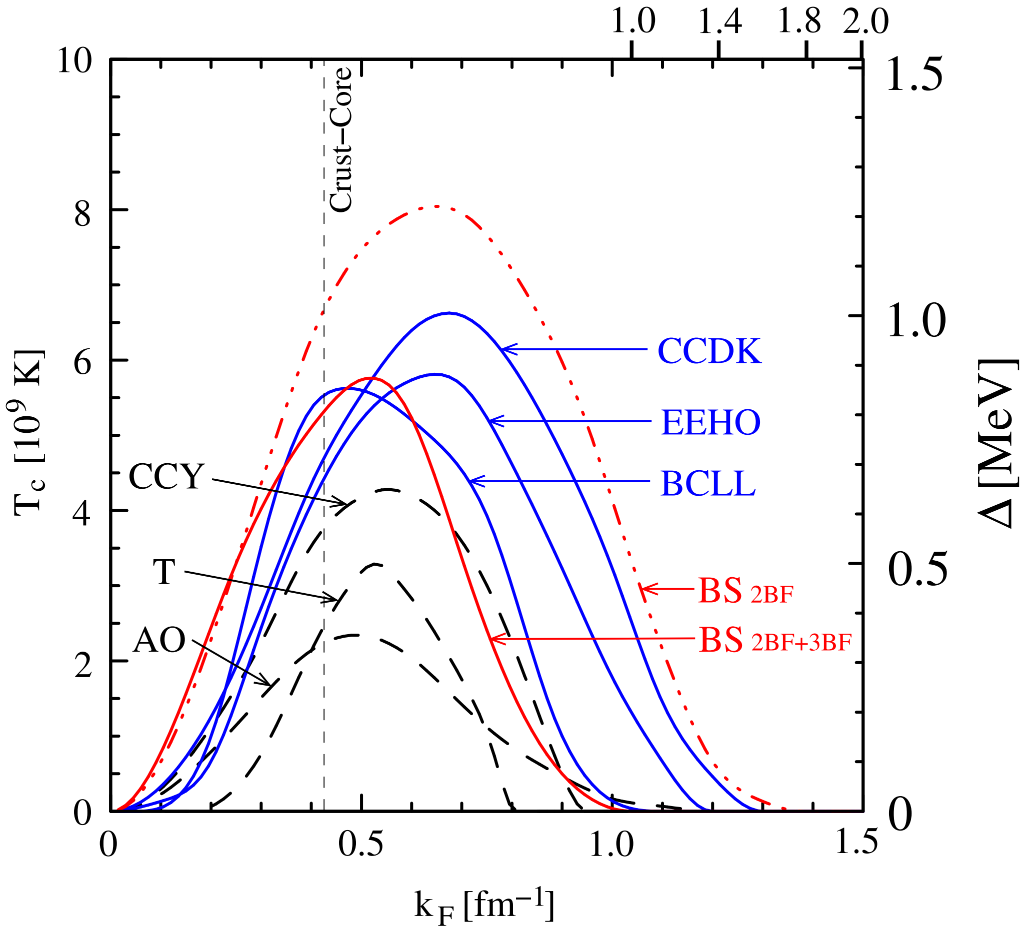
Nucleon pairing

Nucleons in a NS form pairings below their critical temperatures:

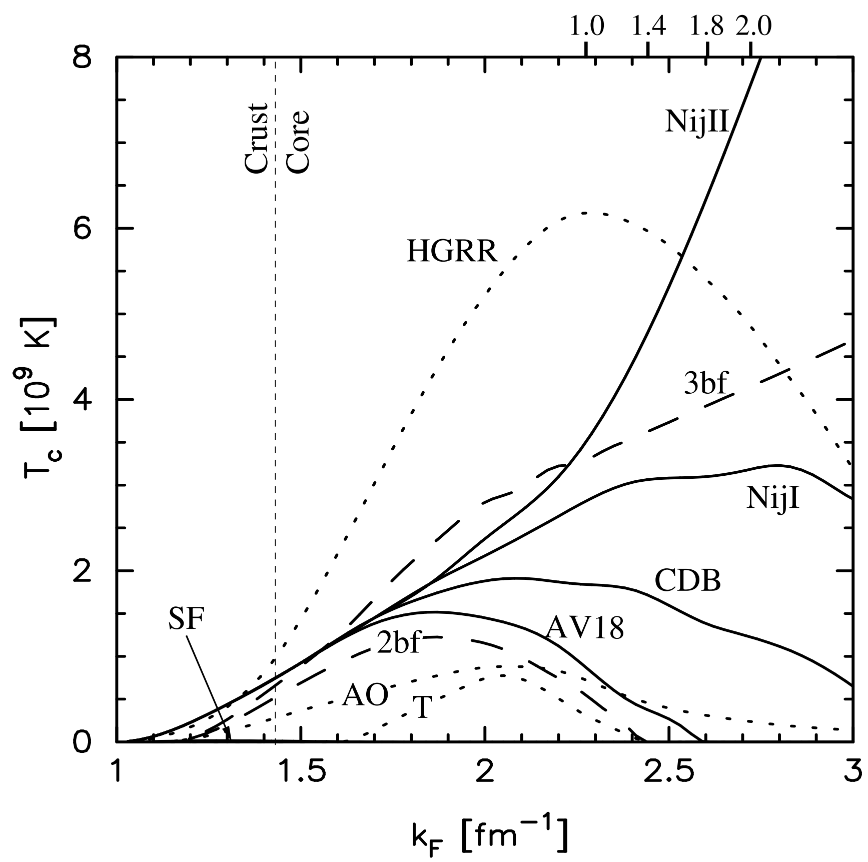
- Neutron singlet $^1S_0$ ⟵ Only in the crust. Less important.
- Proton singlet $^1S_0$
- Neutron triplet $^3P_2$

} ⟵ 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

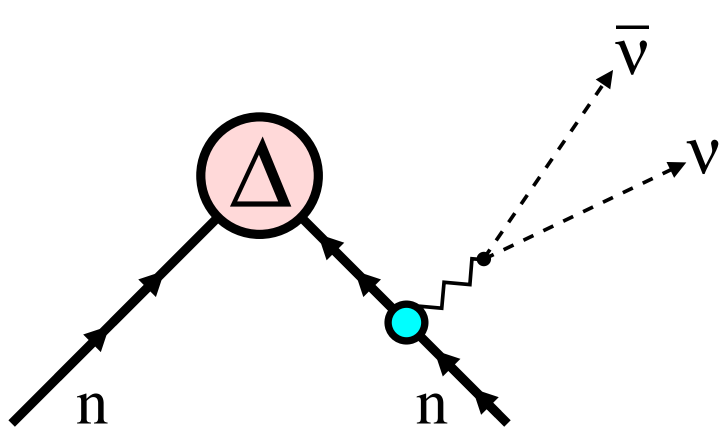
Thermal disturbance induces the breaking of nucleon pairs.

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.



Summary for standard cooling

- Photon emission

  Emitted from the surface. Dominant for $t \gtrsim 10^5$ years.

- Direct Urca process

  Occurs only in heavy stars.

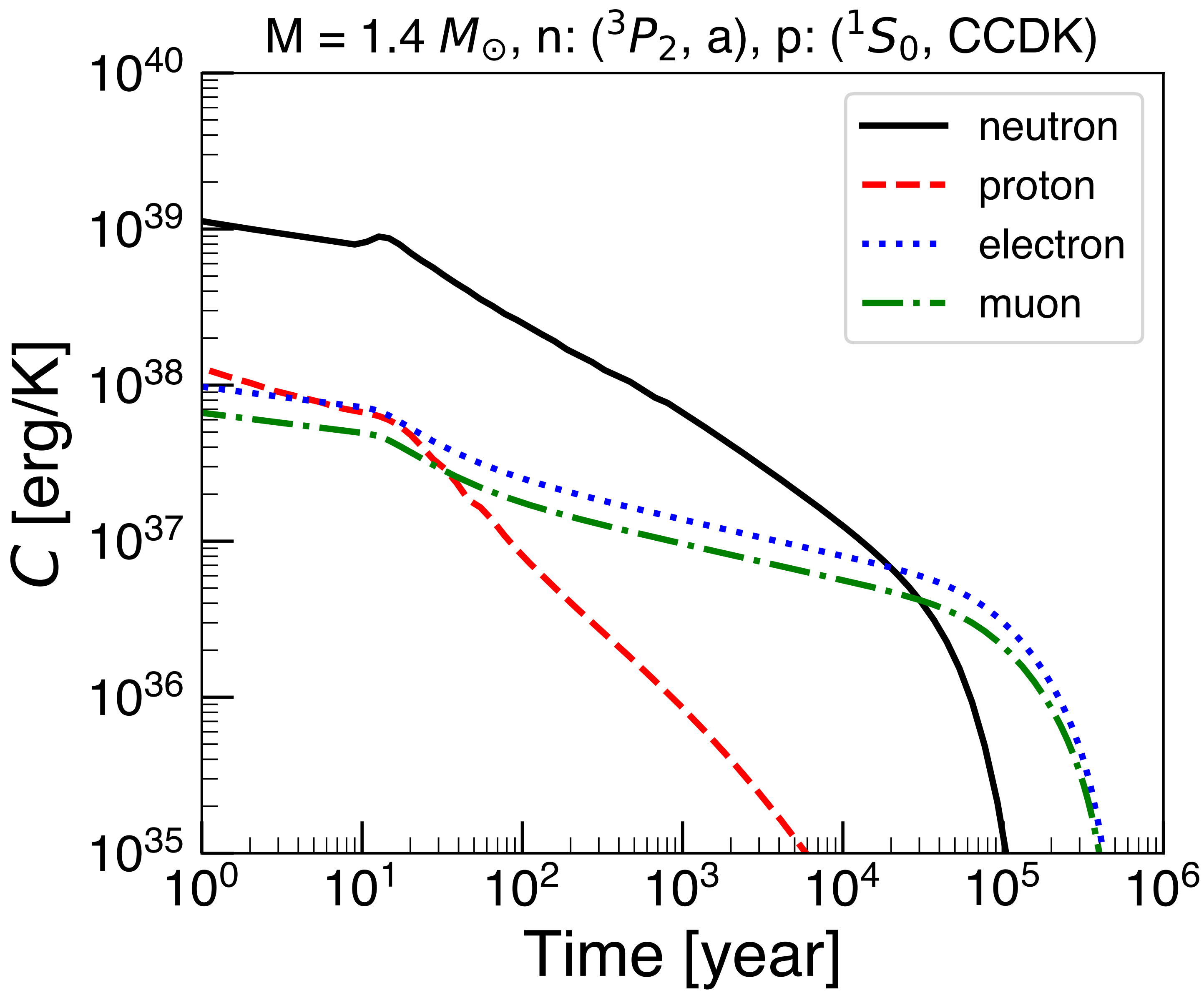
- Modified Urca & bremsstrahlung

  Always occur, but the emission is weaker.

- PBF

  Strongly enhances the neutrino emission at $T \lesssim T_C$

Heat capacity



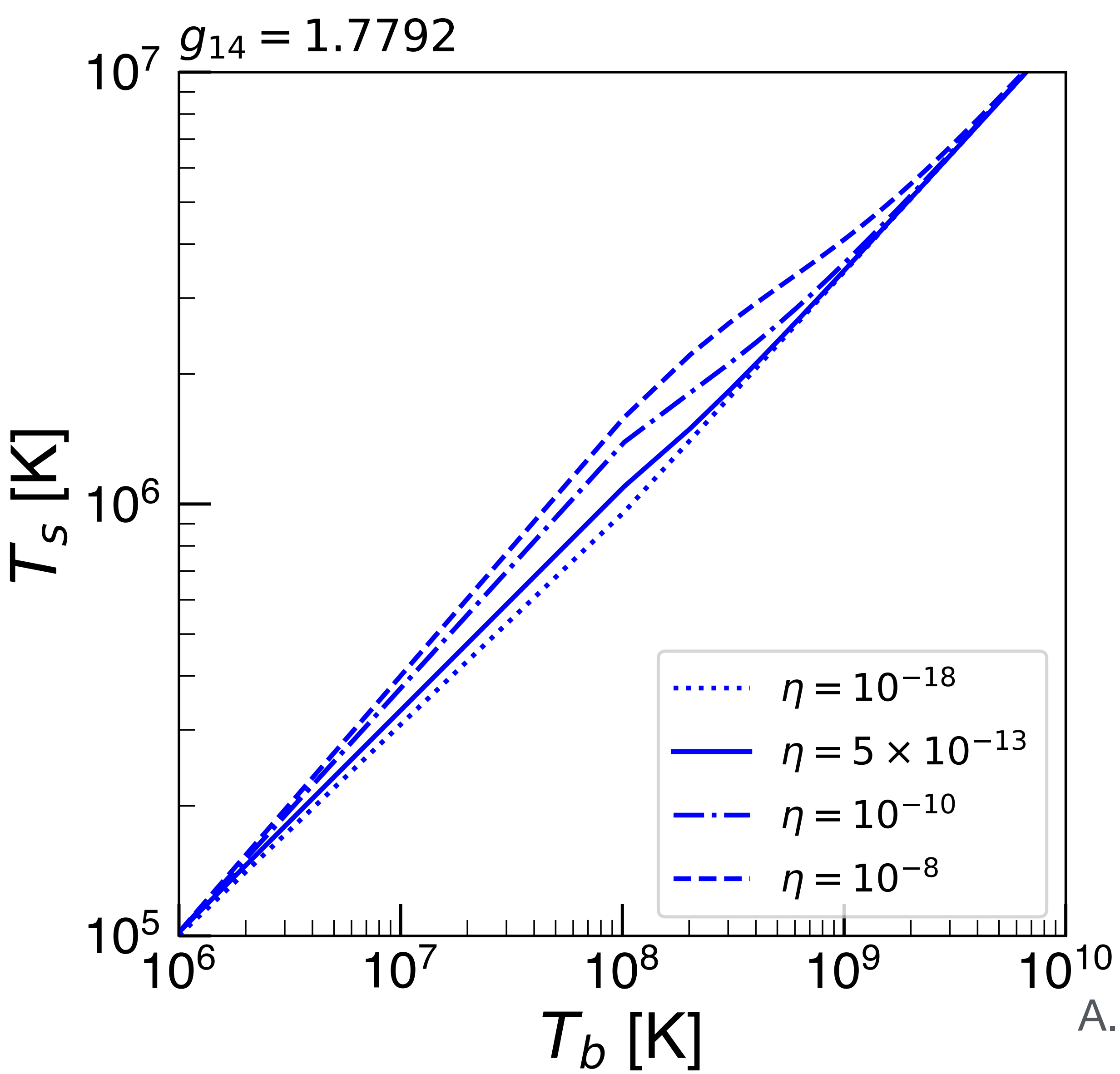
Specific heat per particle without superfluidity:

$$c_i = \frac{1}{3} m_{*,i} p_{F,i} T$$

Nucleon specific heat gets suppressed at low temperatures due to the paring gaps.

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.

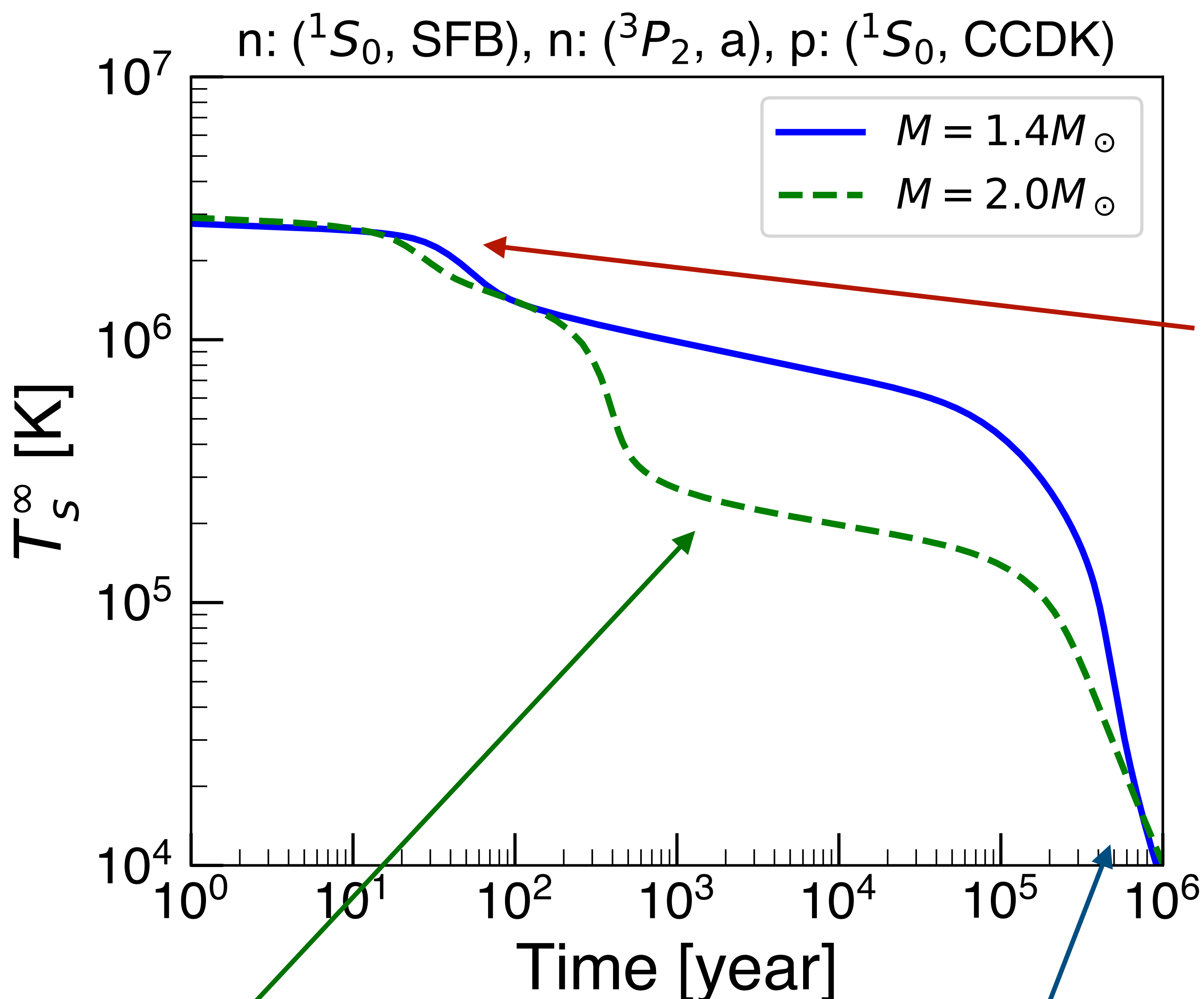
A. Y. Potekhin, G. Chabrier, and D. G. Yakovlev, A&A **323,** 415 (1997).

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:

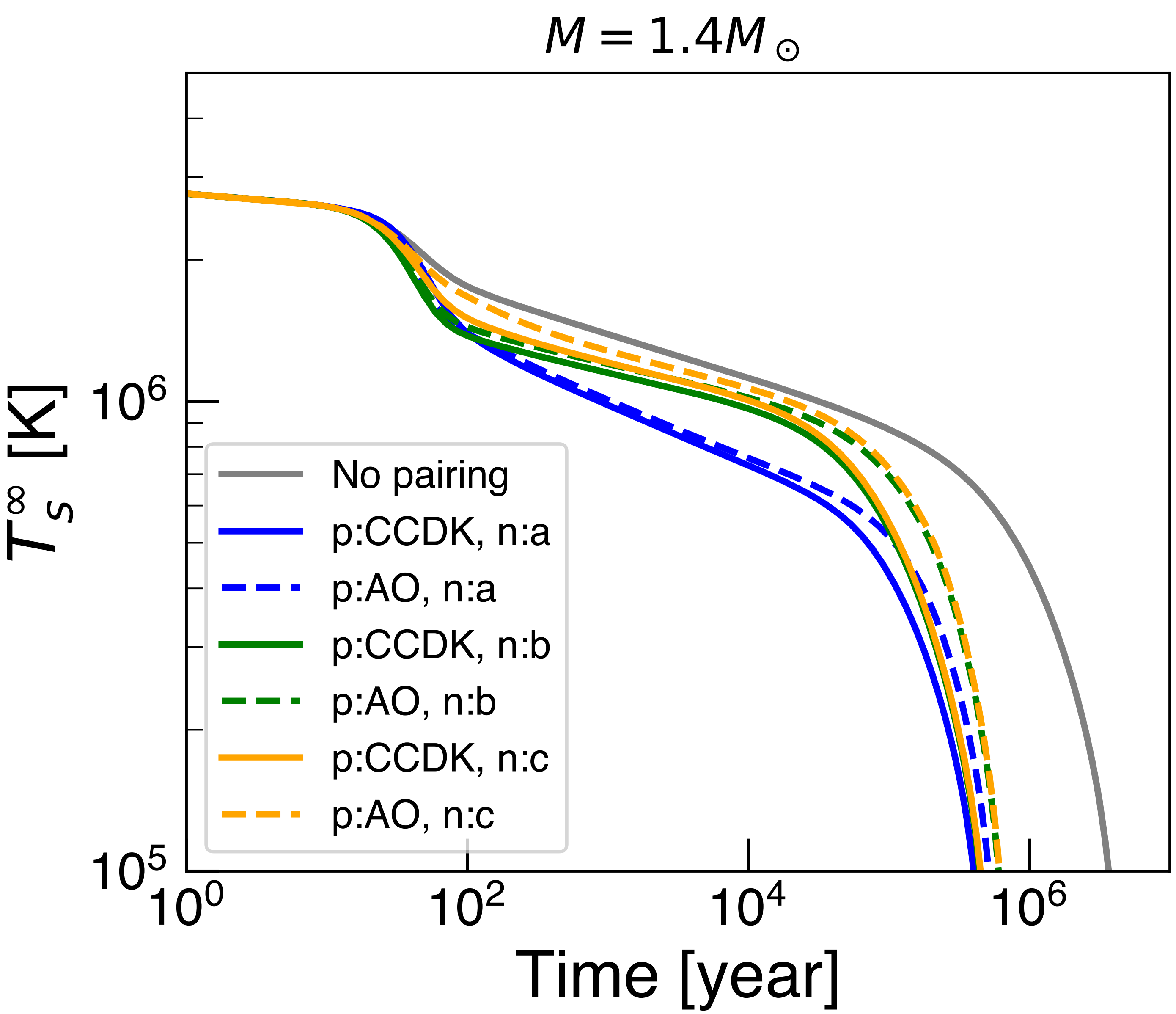


Before the thermal relaxation completed, the surface temperature does not follow the internal temperature.

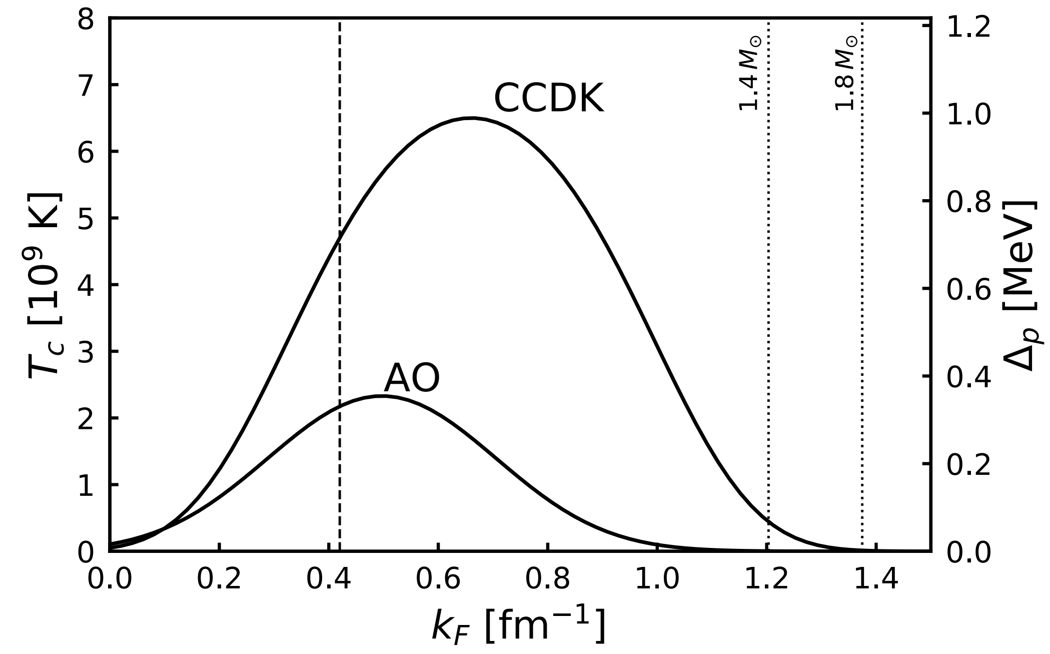
If Direct Urca occurs, the neutron star cools down rapidly.

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

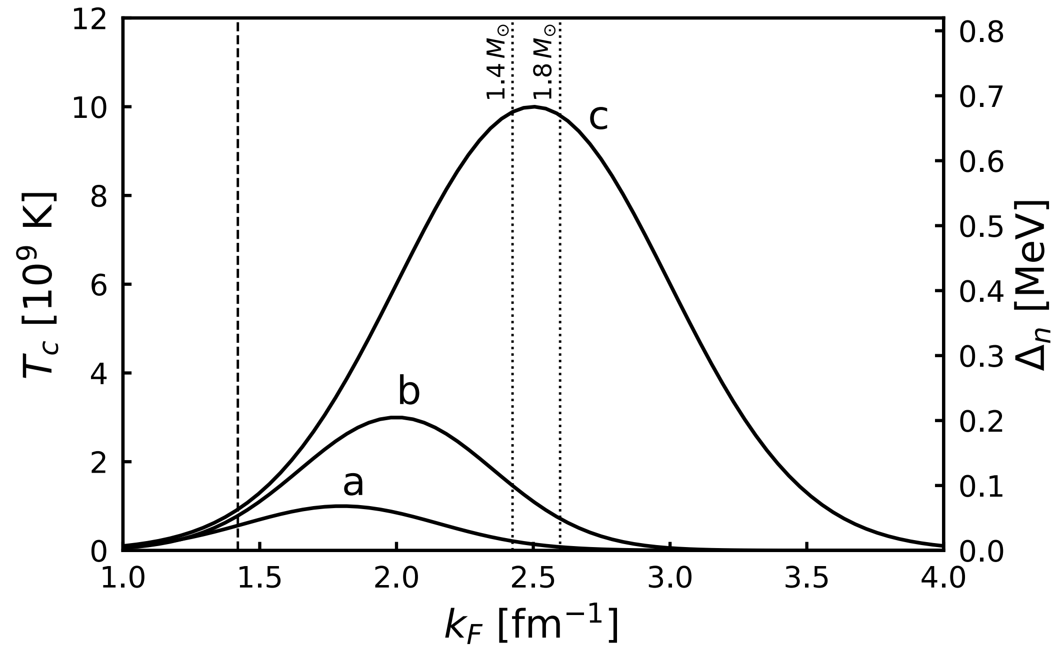
Temperature evolution (gap dependence)



Proton singlet gap



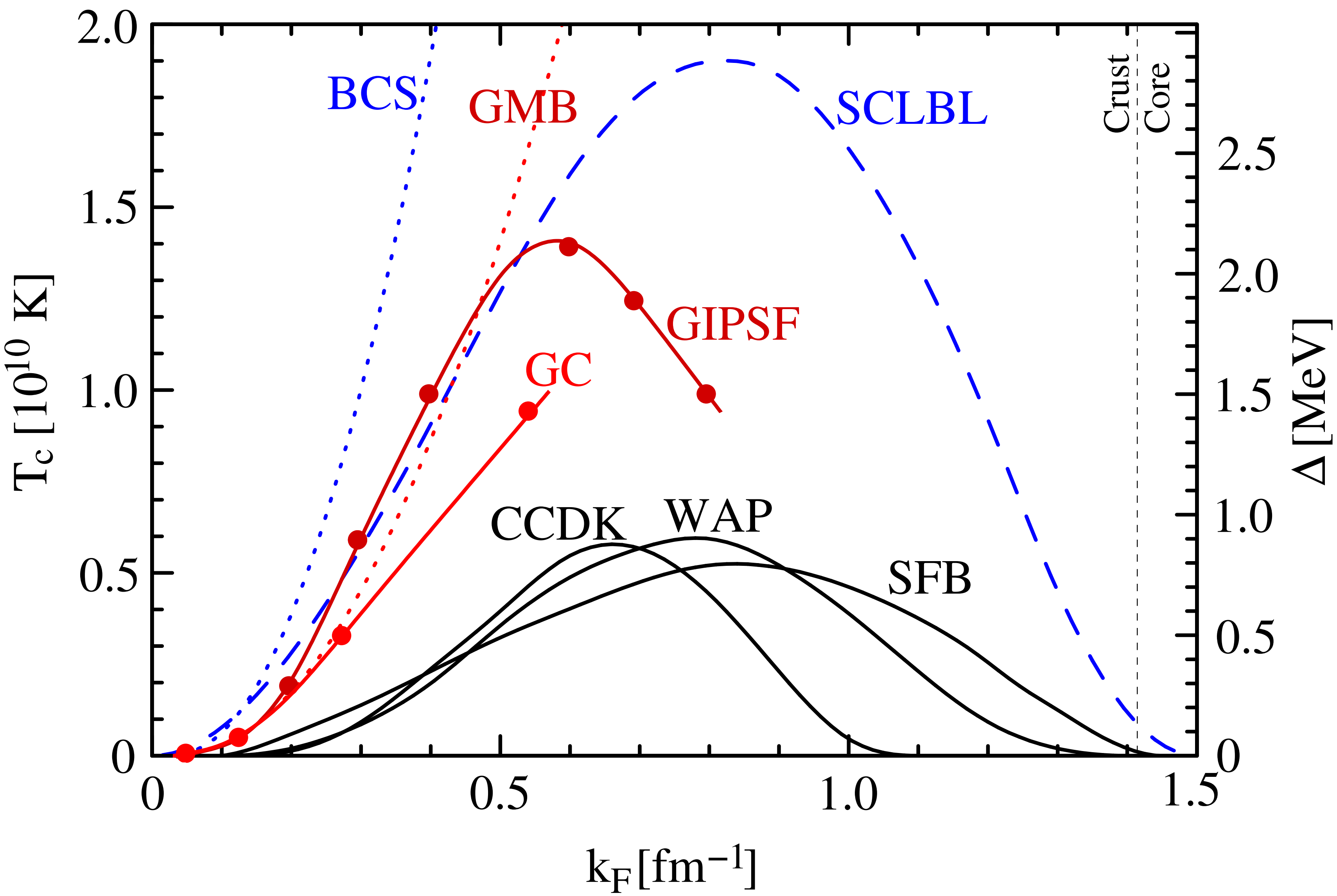
Neutron triplet gap



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

$^1S_0$ neutron gap

Neutron singlet gap vs. Fermi momentum

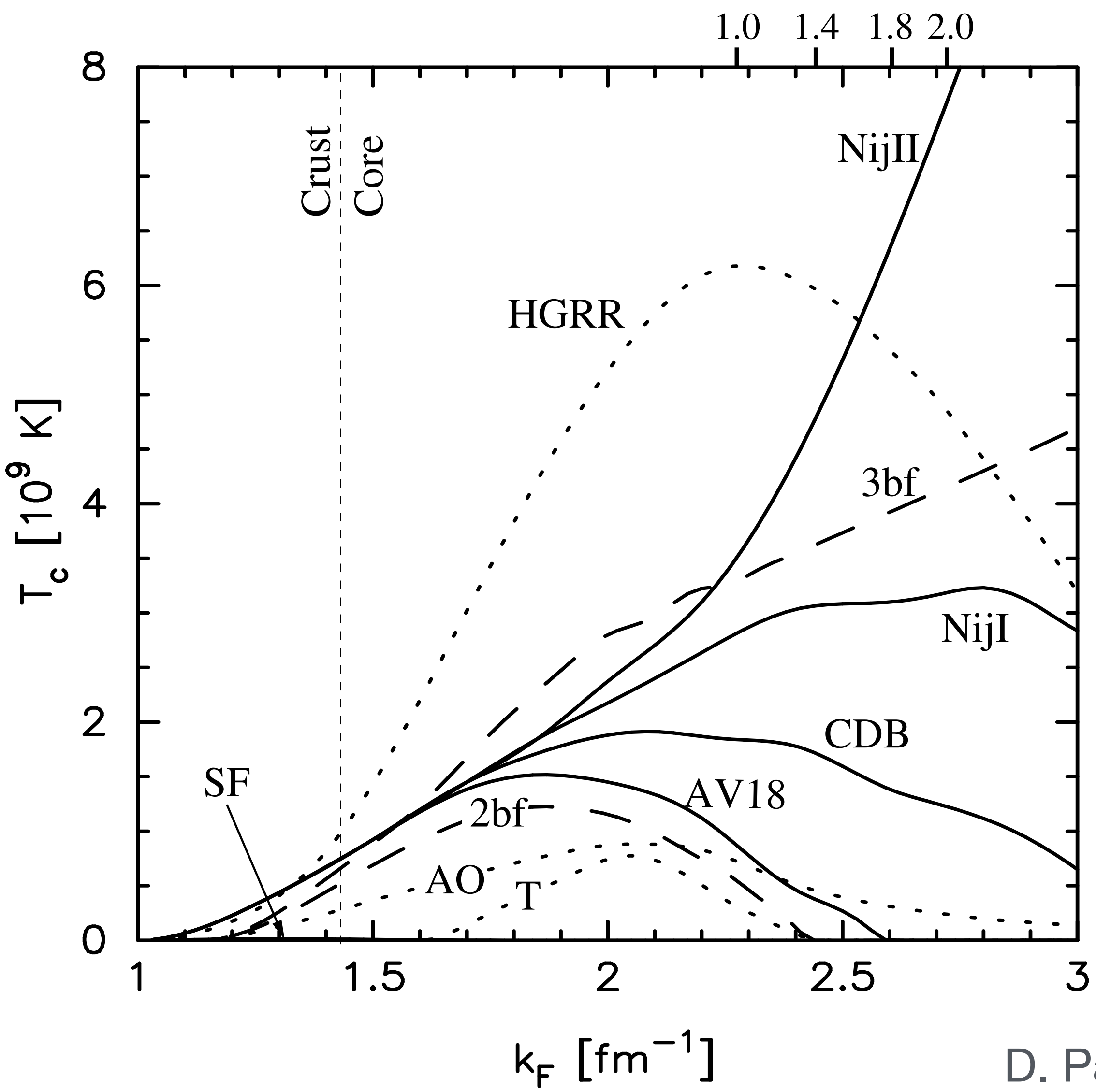


D. Page, J. M. Lattimer, M. Prakash, A. W. Steiner [arXiv: 1302.6626].

Non-zero gap is obtained for a relatively small momentum, i.e., a low density.

$^3P_2$ neutron gap

Neutron triplet gap vs. Fermi momentum



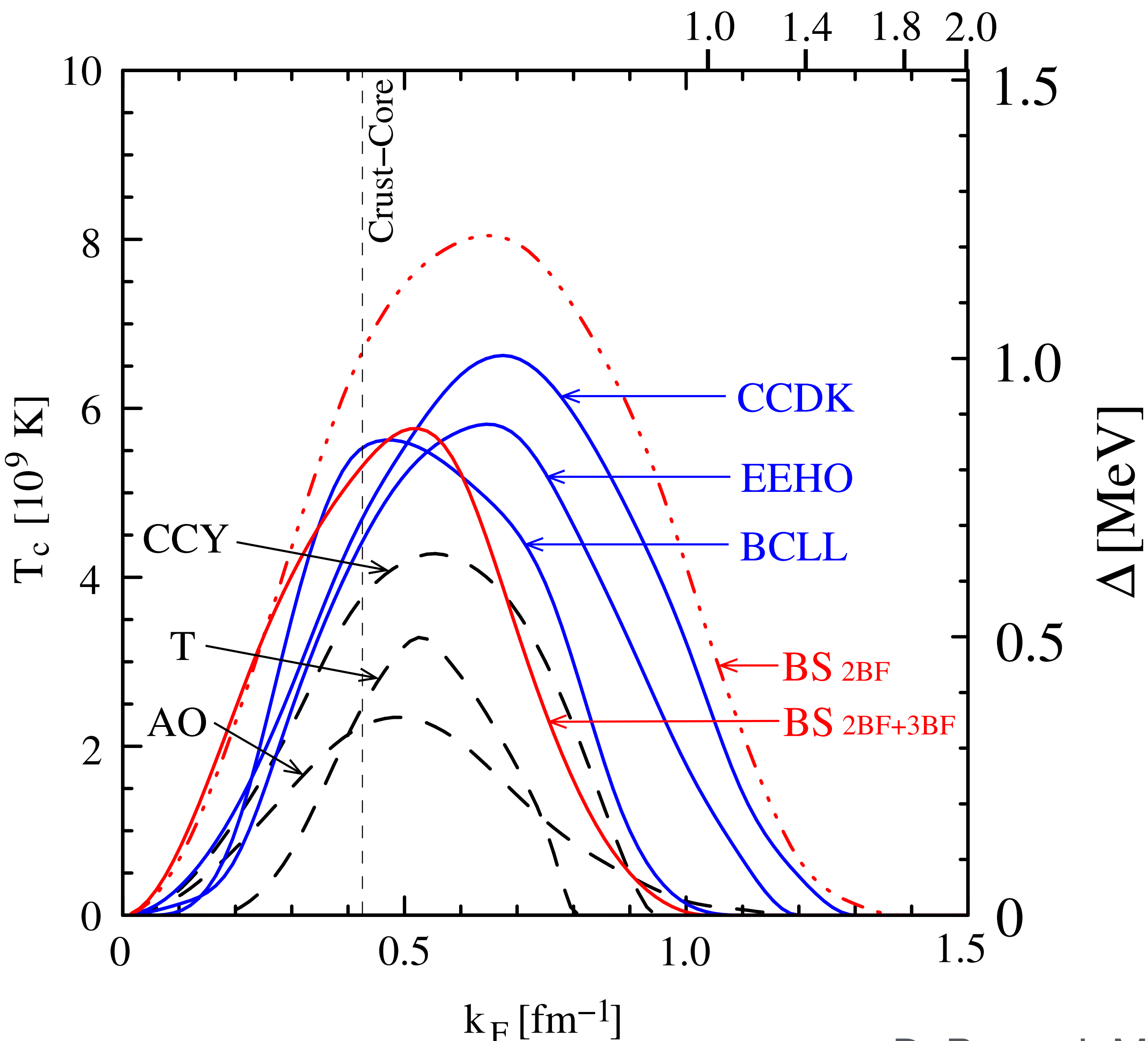
D. Page, J. M. Lattimer, M. Prakash, A. W. Steiner [arXiv: 1302.6626].

- Paring forms for a large momentum, high density.
- Theoretical uncertainty is huge.

Because there is no nuclear potential model that can explain the observed phase shift.

$^1S_0$ proton gap

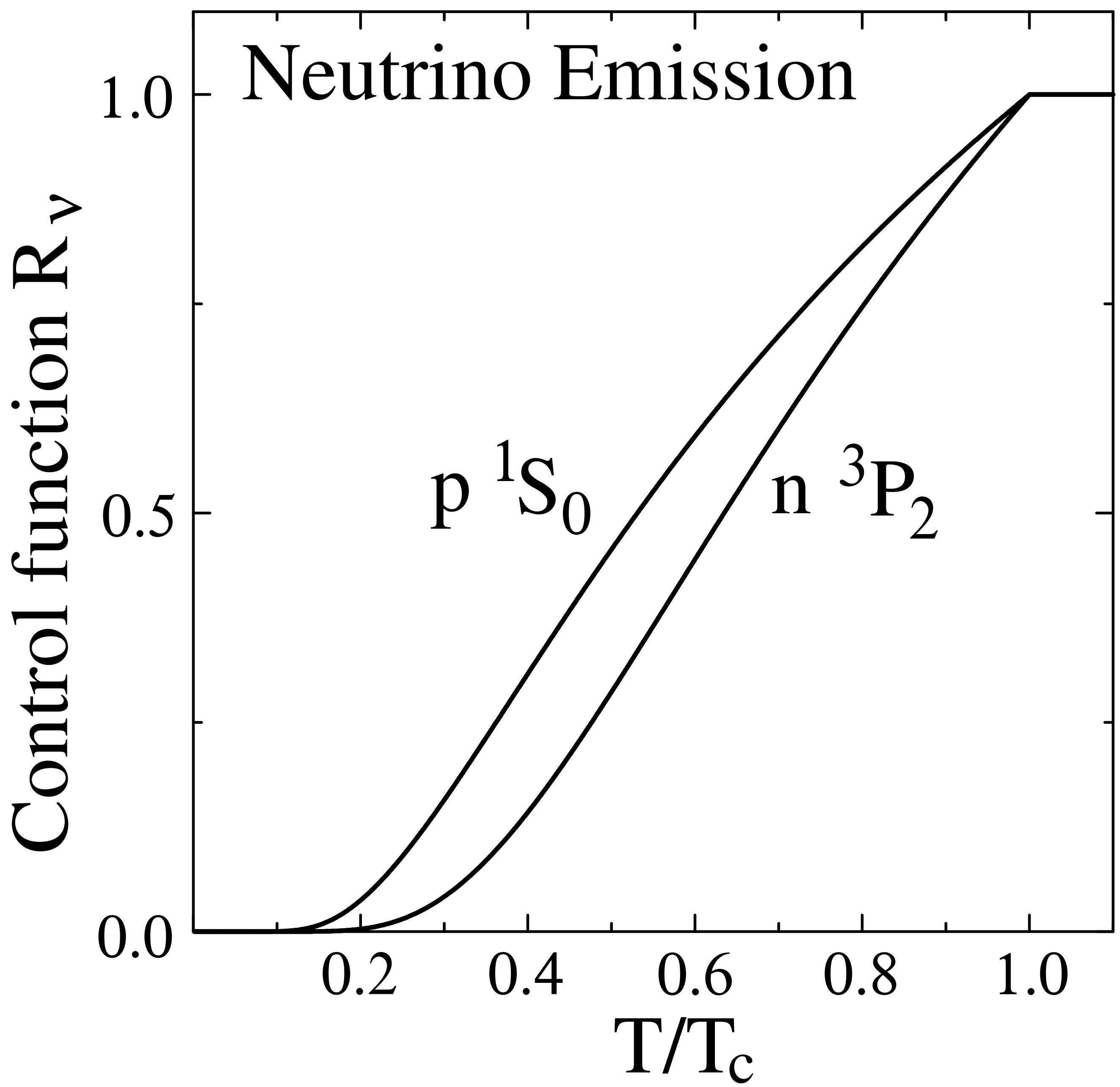
Proton singlet gap vs. Fermi momentum



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

Proton singlet pairing can form deep insider the neutron star since the proton density is smaller than the neutron density.

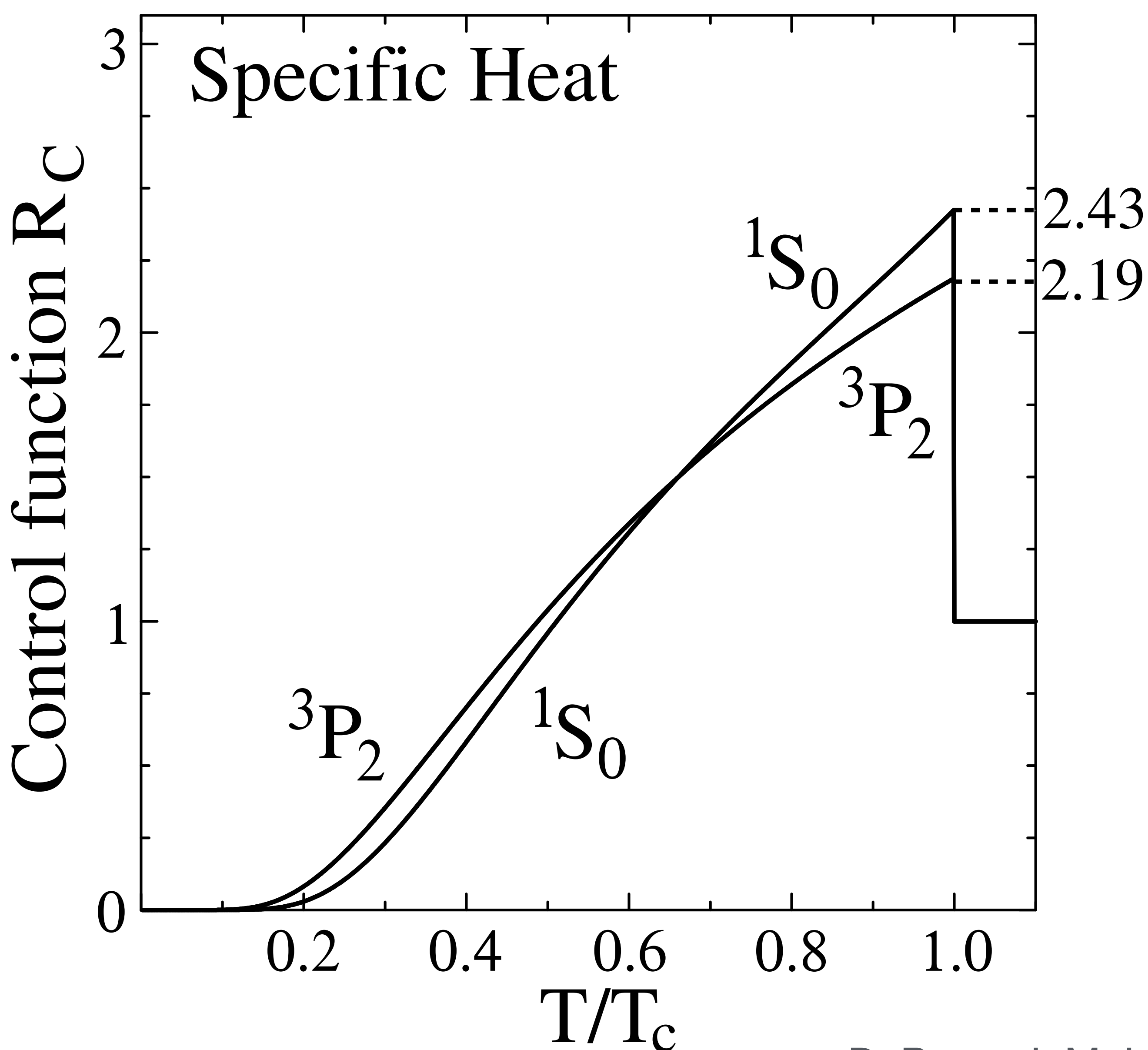
Pairing effects on neutron emission



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

Neutrino emission is suppressed due to the energy gap.

Pairing effects on specific heat



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

- Specific heat jumps at the critical temperature.
- Specific heat is fairly suppressed at low temperatures.

Challenge for standard cooling

On the other hand, there is an example of old cool neutron star.

Ordinary pulsar

- J2144-3933: $t_{\rm sd} = 3.33 \times 10^8$ years, $T_s^\infty < 4.2 \times 10^4$ K

S. Guillot, *et al.*, Astrophys. J. **874**, 175 (2019).

Is there any theory that can explain these observations on the equal footing??

Spin-down age

For magnetic dipole radiation,

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

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

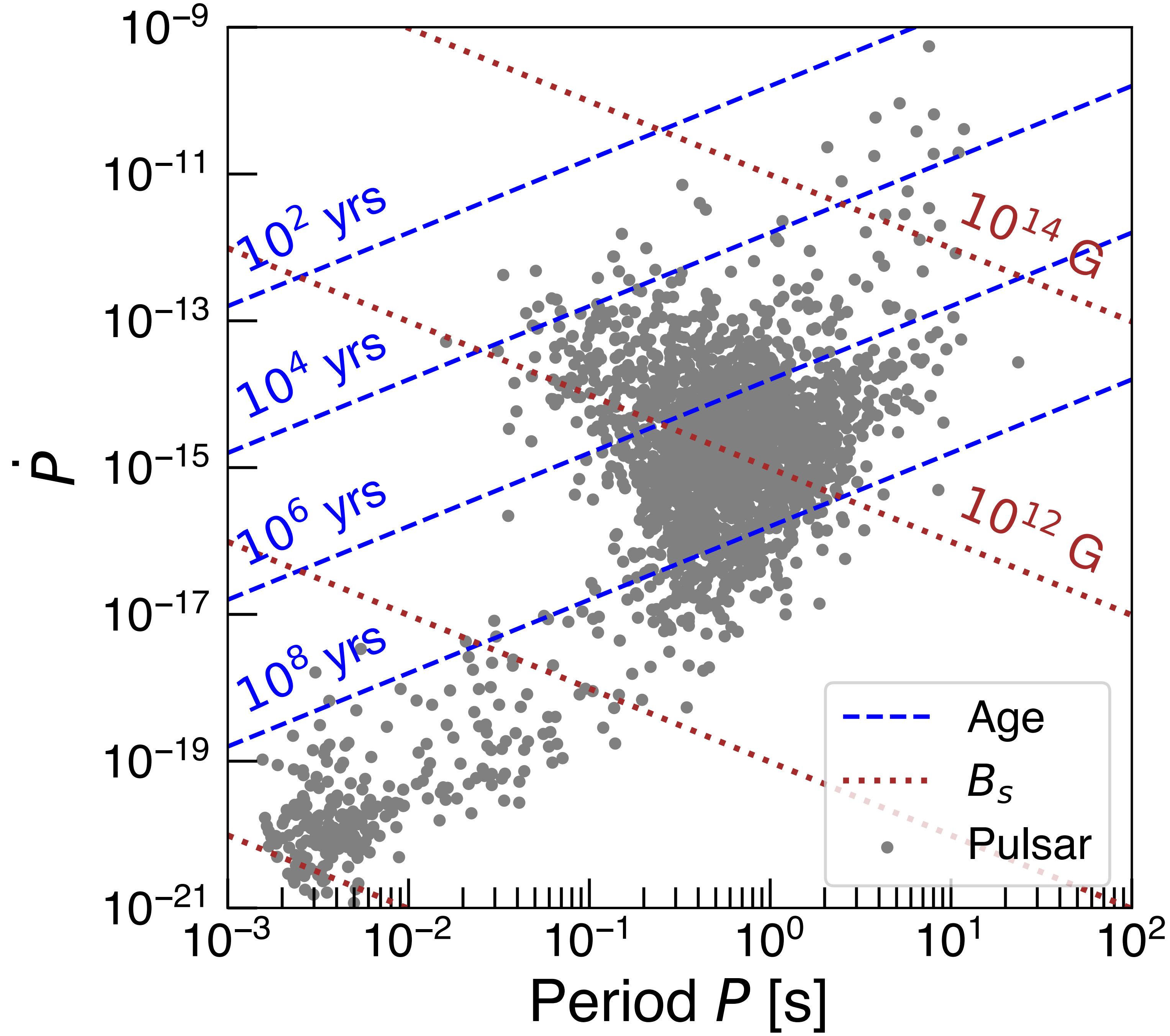
$$P = 0.033392 \text{ s}, \quad \dot{P} = 4.21 \times 10^{-13}$$

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

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.



Out of β equilibrium

The excess of energy is dissipated by

- Increase of neutrino emission
- Generation of heat

P. Haensel, Astron. Astrophys. **262**, 131 (1992);
A. Reisenegger, Astrophys. J. **442**, 749 (1995).

Deviation from β equilibrium is quantified by

$$\eta_\ell \equiv \mu_n - \mu_p - \mu_\ell \quad (\ell = e, \mu)$$

<u>Heating luminosity</u>

$$L_H = \sum_{\ell=e,\mu} \sum_{N=n,p} \int dV \, \eta_\ell \cdot \Delta\Gamma_{M,N\ell}$$

where

$$\Delta\Gamma_{M,N\ell} \equiv \Gamma(n + N \to p + N + \ell + \bar{\nu}_\ell) - \Gamma(p + N + \ell \to n + N + \nu_\ell)$$

Evolution of chemical imbalance

The time evolution off η_ℓ is determined by

$$\frac{d\eta_e}{dt} = -\sum_{N=n,p} \int dV \, (Z_{npe}\Delta\Gamma_{M,Ne} + Z_{np}\Delta\Gamma_{M,N\mu}) + 2W_{npe}\Omega\dot{\Omega}$$

Bring the system back to equilibrium.

Drive the system out of equilibrium.

W < 0, Z > 0: coefficients which depend on NS structure.

R. Fernandez and A. Reisenegger, Astrophys. J. **625**, 291 (2005).

Once the second term wins, the imbalance increases.

Magnetic dipole radiation

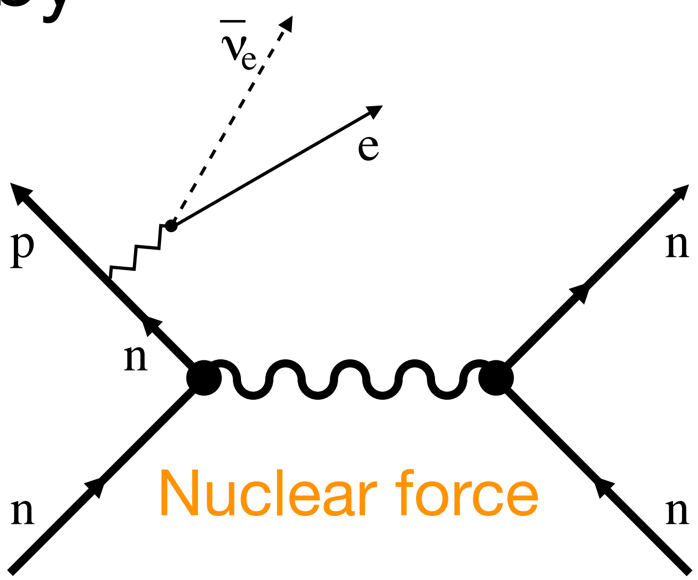
$$\dot{\Omega} = -k\Omega^3 \quad \Rightarrow \quad \Omega\dot{\Omega} = -\frac{4\pi^2 P_{\rm now}\dot{P}_{\rm now}}{(P_0^2 + 2P_{\rm now}\dot{P}_{\rm now}t)^2}$$

(P_0: initial period)

Rotochemical heating

If the imbalance overcomes the threshold given by

$$\Delta_{\mathrm{th}} = \min\left\{3\Delta_n + \Delta_p, \Delta_n + 3\Delta_p\right\}$$



Modified Urca

Pauli blocking is overcame by the chemical imbalance.

Heating becomes effective.

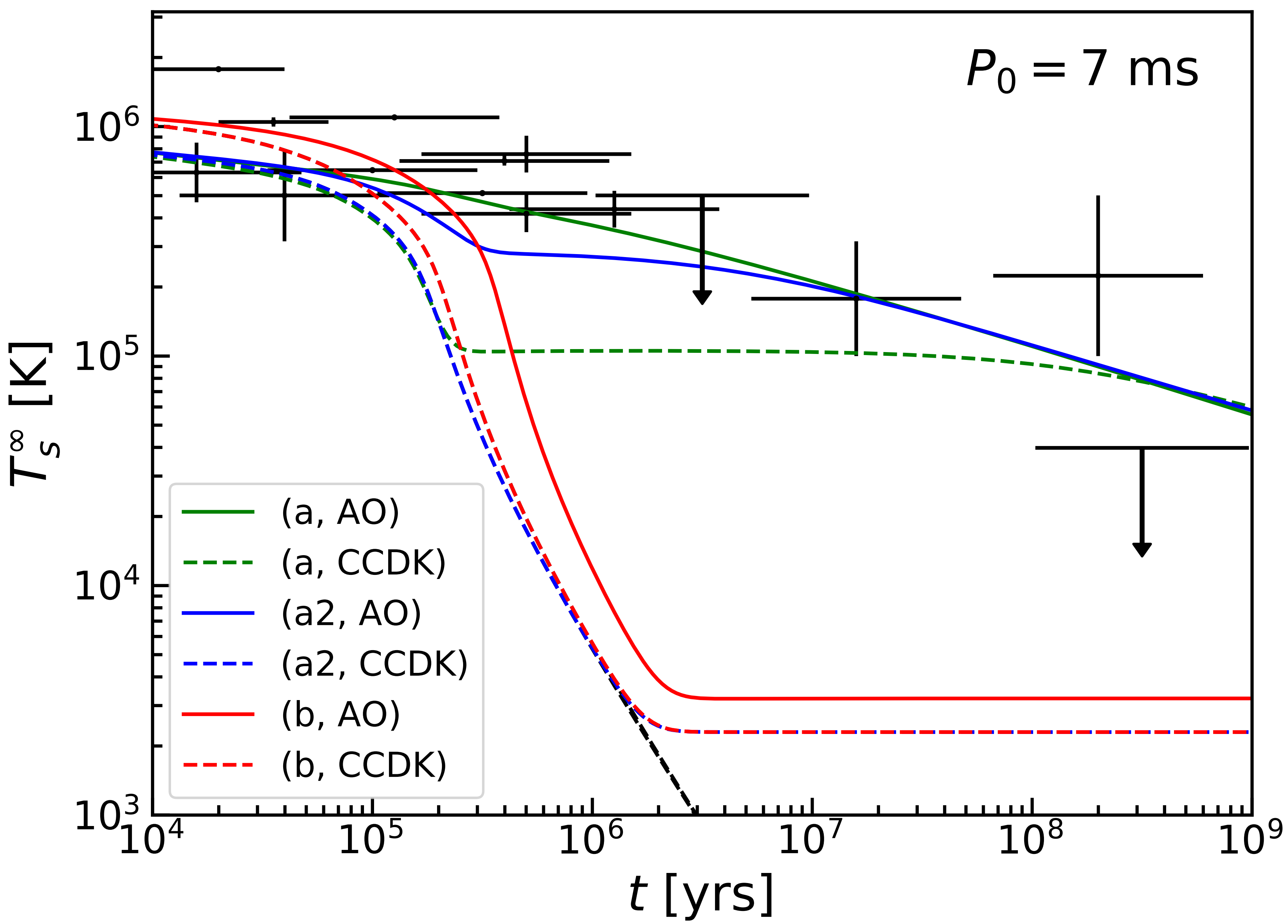
This mechanism is called the rotochemical heating.

A. Reisenegger, Astrophys. J. **442**, 749 (1995);
R. Fernandez and A. Reisenegger, Astrophys. J. **625**, 291 (2005).

It occurs in the same setup as the standard cooling.

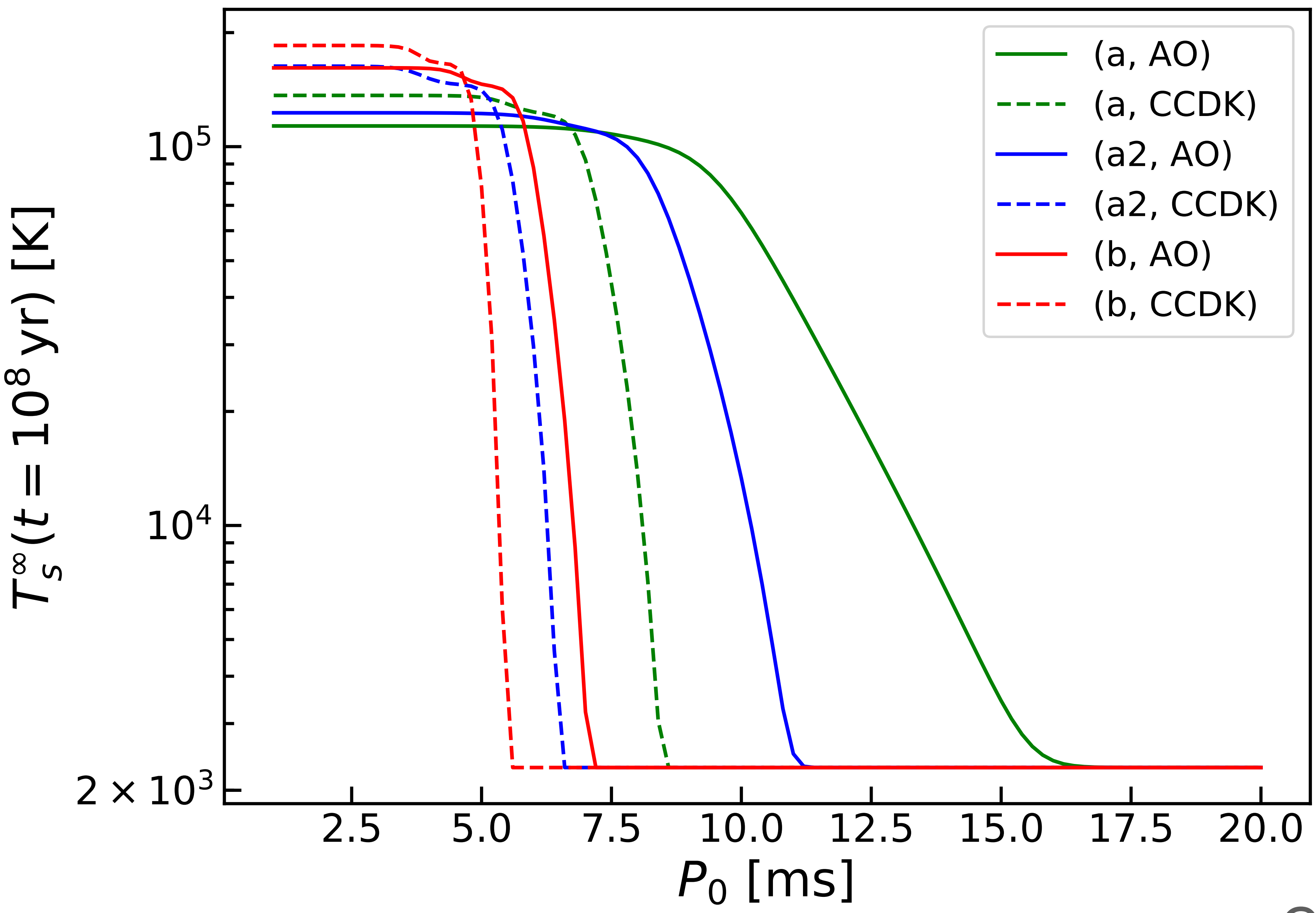
No exotic effects are needed.

Gap dependence



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

Gap dependence



Courtesy of K. Yanagi.

Electroweak-Interacting DM

Quantum numbers $SU(2)_L$	$U(1)_Y$	Spin	DM could decay into	DM mass in TeV	$m_{DM^\pm} - m_{DM}$ in MeV	Finite naturalness bound in TeV	σ_{SI} in $10^{-46}\,\text{cm}^2$
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

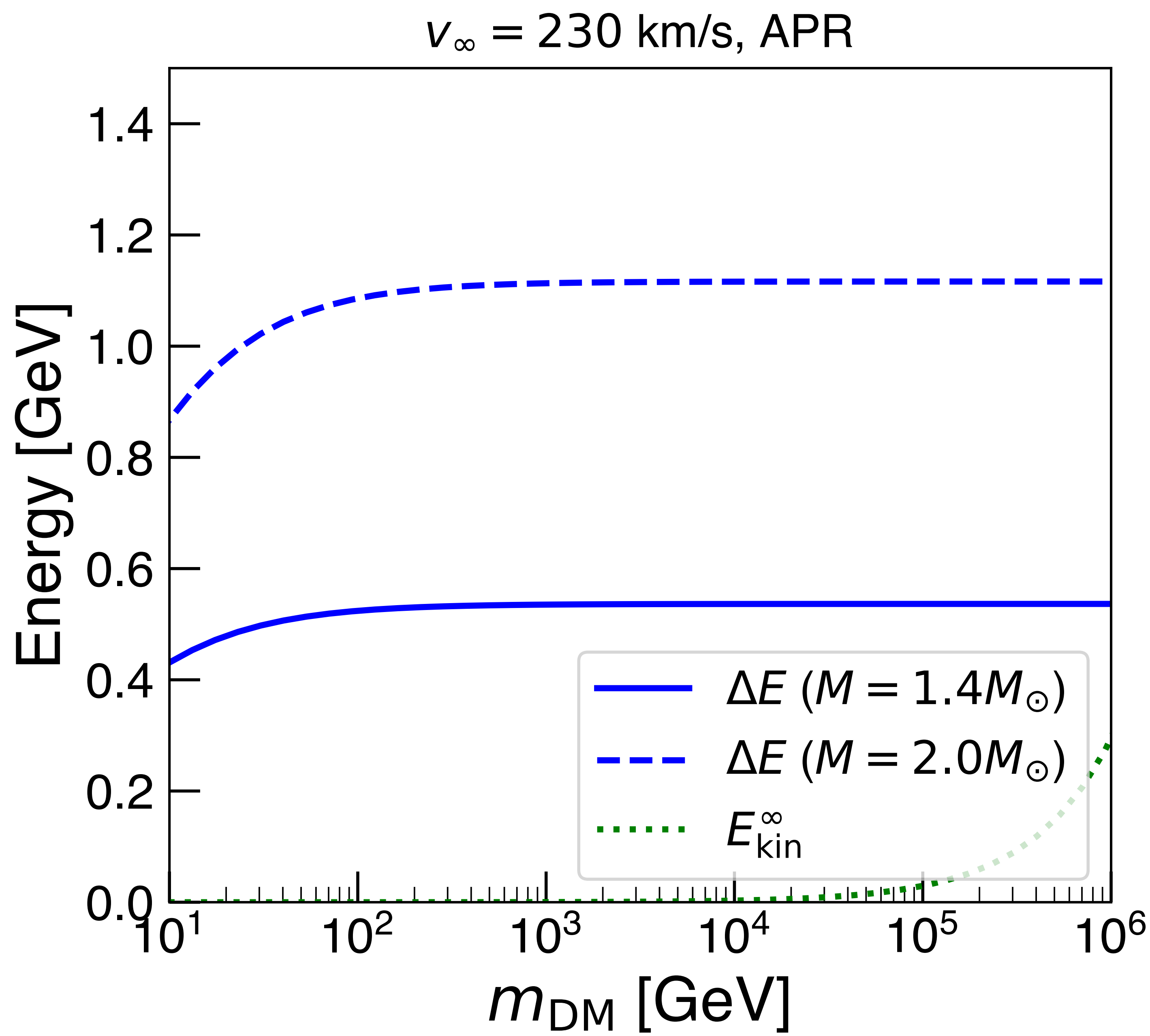
($\to$: Sommerfeld enhancement)

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

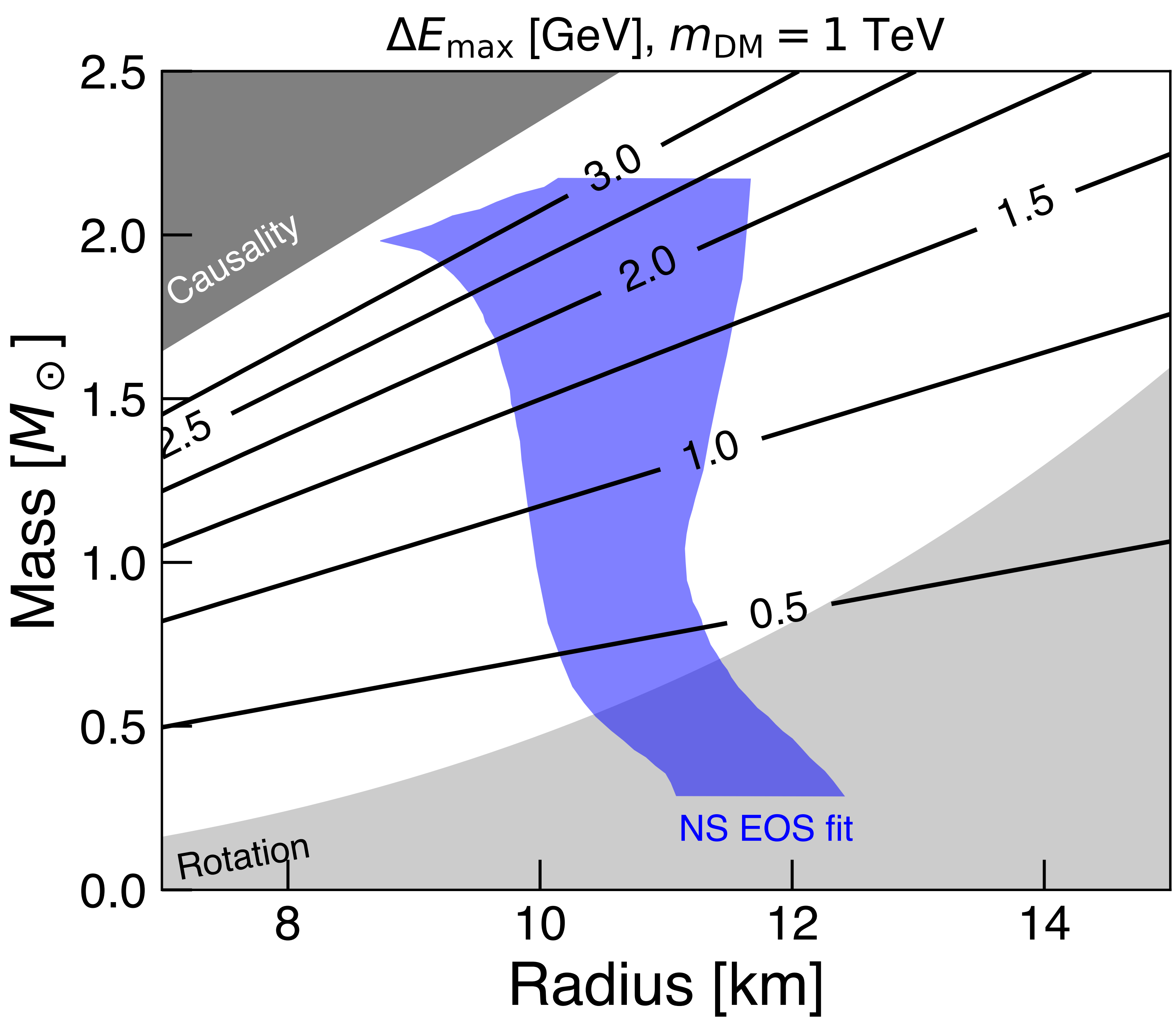
Features

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

Recoil energy



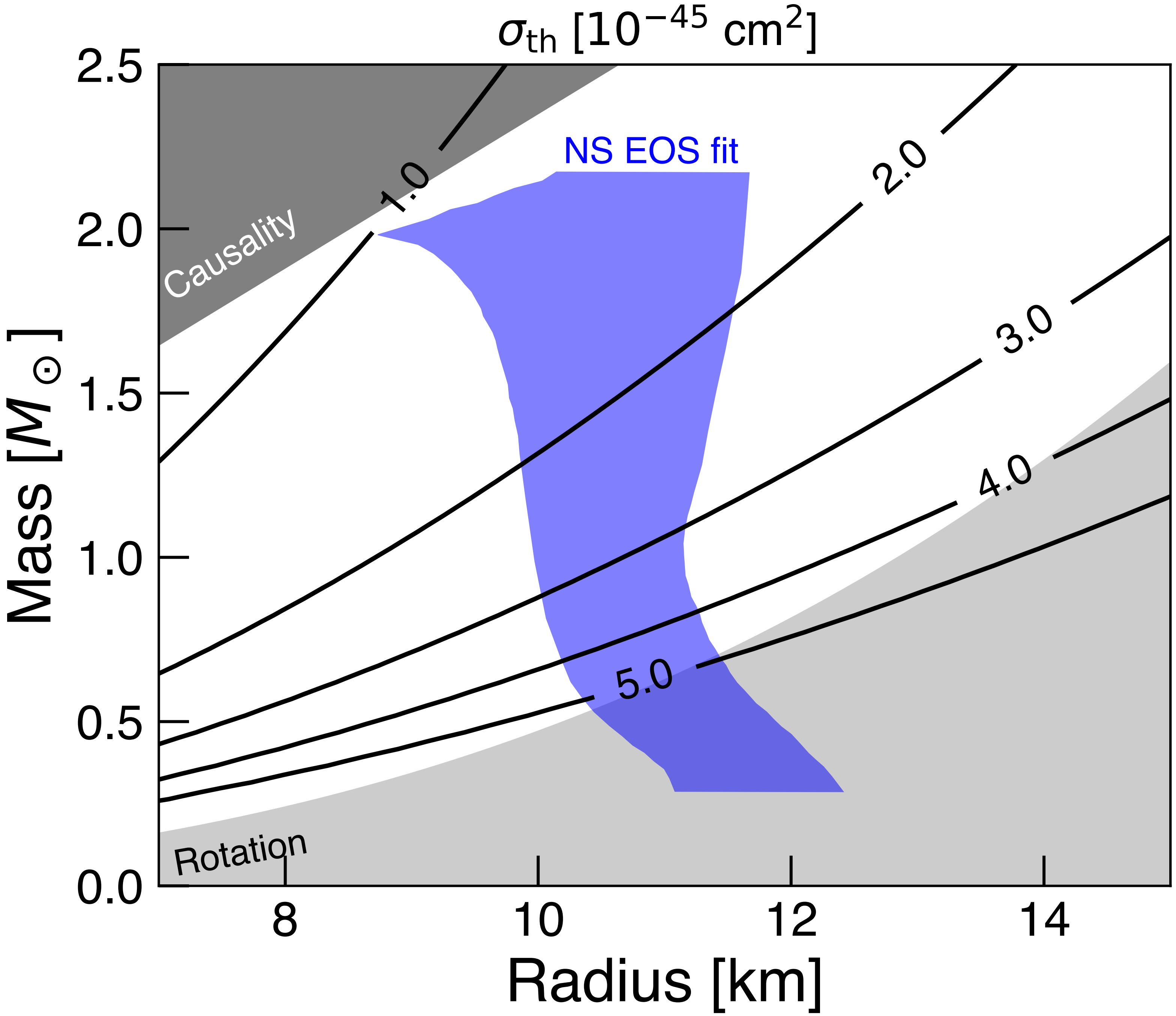
Maximum energy transfer



NS EOS:
1505.05155

Energy transfer can be as large as a few GeV.

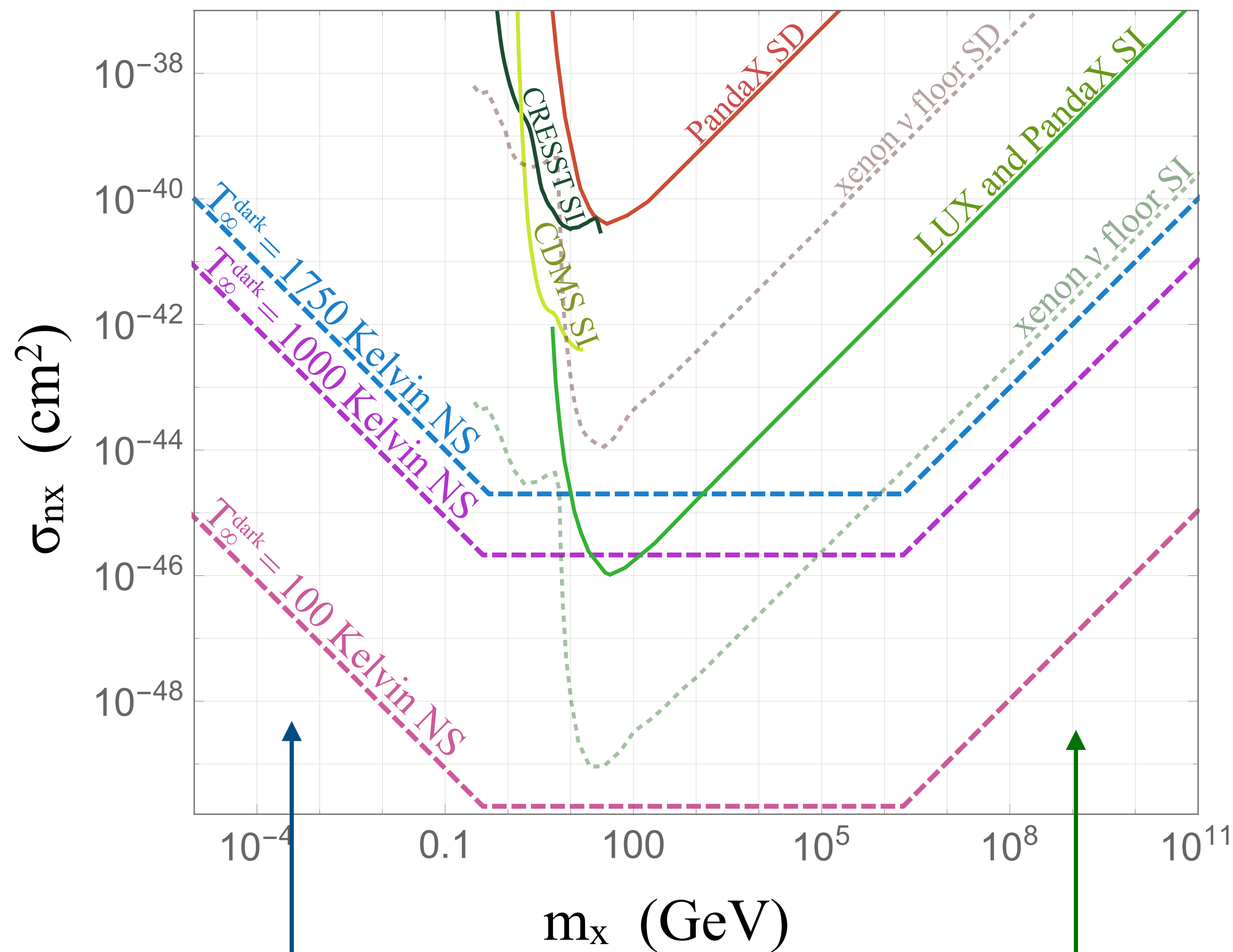
σ_{th}



NS EOS:
1505.05155

DM is efficiently captured for $\sigma_{th} \gtrsim (2-3) \times 10^{-45}$ cm^2.

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).

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.

- Largest radio telescope
- Started on Sep. 25, 2016.

About 5000 (4000 new discovery) pulsars will be observed.

Temperature measurement

Can we actually observe a NS temperature of a few thousand K?

2—3000 K ➡ $\lambda \sim 2\ \mu m$ ➡ IR telescope

e.g.) NS at the distance of 10 pc emitting radiation with $\lambda = 2\ \mu m$:

➡ O(1) nanoJansky (nJy) flux density:

1 Jy = 10^{-23} erg s^{-1} cm^{-2} Hz^{-1}

1—5 NSs are expected in this range.

O. Blaes and P. Madau, Astrophys. J. **403**, 690 (1993).

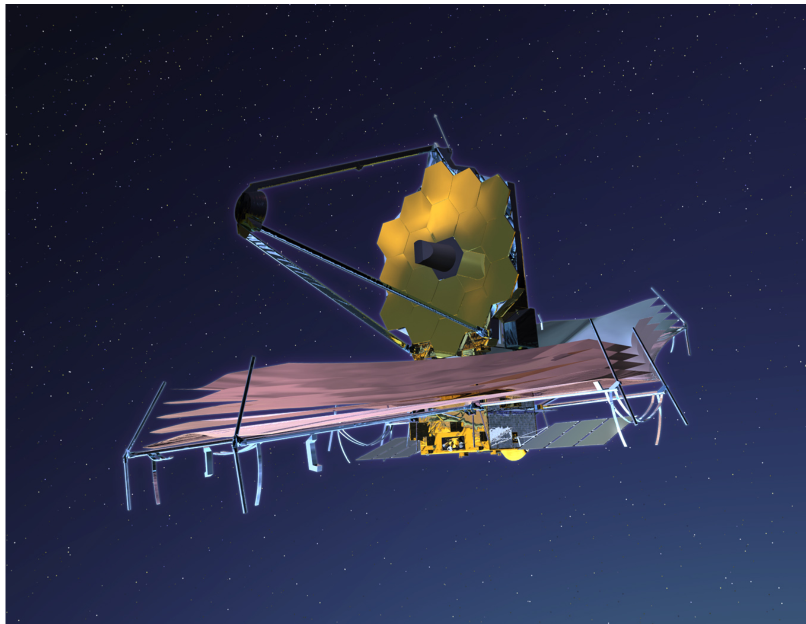
Candidate observatories:

- James Webb Space Telescope (JWST)
- Thirty Meter Telescope (TMT)
- European Extremely Large Telescope (E-ELT)

JWST

- Infrared space telescope run by NASA.
- Successor to the Hubble Space Telescope.
- Construction completed in Aug. 28, 2019.
- Launch is scheduled for Mar. 30, 2021.

Near Infrared Camera (NIRCam) has sensitivities to ~μm.



NIRCam

Sensitive to ~μm.

For 7.9 nJy, S/N = 10 for 10^4 s.

At a Glance:	Short Wavelength Channel	Long Wavelength Channel
Wavelength Range	0.6 – 2.3 μm	2.4 – 5.0 μm
Nyquist Wavelength *	2.0 μm	4.0 μm
Fields of View **	2 × 2.2' × 2.2' (with 4-5" gaps)	2 × 2.2' × 2.2'
Imaging Pixels	8 × 2040 × 2040 pixels	2 × 2040 × 2040 pixels
Pixel Scale	0.032" / pixel	0.065" / pixel
Grism Slitless Spectroscopy	(wavefront sensing across mirror edges)	R = 1200 – 1550
Coronagraphy occulters + Lyot stops	round: 2.1 μm bar: 1.7 – 2.2 μm	round: 3.35, 4.3 μm bar: 2.4 – 5.0 μm

* PSF FWHM ~ 2 pixels; undersampled at lower wavelengths.
** Two modules image adjacent fields in both channels simultaneously.

Filter	Sensitivity Point source S/N=10 in 10 ks	Saturation G2V star 80% full well 2 reads of 64x64 subarray
F090W	13.1 nJy	K ~ 9.5 Vega
F115W	11.8 nJy	K ~ 9.6 Vega
F150W	9.6 nJy	K ~ 9.8 Vega
F200W	7.9 nJy	K ~ 9.3 Vega
F277W	11.5 nJy	K ~ 9.6 Vega
F356W	11.0 nJy	K ~ 8.9 Vega
F410M	20.6 nJy	K ~ 7.4 Vega
F444W	17.6 nJy	K ~ 8.0 Vega

Preliminary ETC sensitivity estimates assume:
low zodiacal background (UDF in November)
0.08" radius aperture for short wavelength filters
0.16" radius aperture for long wavelength filters
large annuli for background subtraction

O(10^5) s observation time can give S/N = 4—5 for O(1) nJy.

https://jwst.stsci.edu/files/live/sites/jwst/files/home/science%20planning/Technical%20documents/JWST-PocketBooklet_January17.pdf

Thirty Meter Telescope (TMT)

Planned to be located on Mauna Kea on Hawaii.

CNN US Crime + Justice Energy + Environment Extreme Weather Space + Science Edition

Protesters arrested at Hawaii's Mauna Kea for blocking construction of the Thirty-Meter Telescope

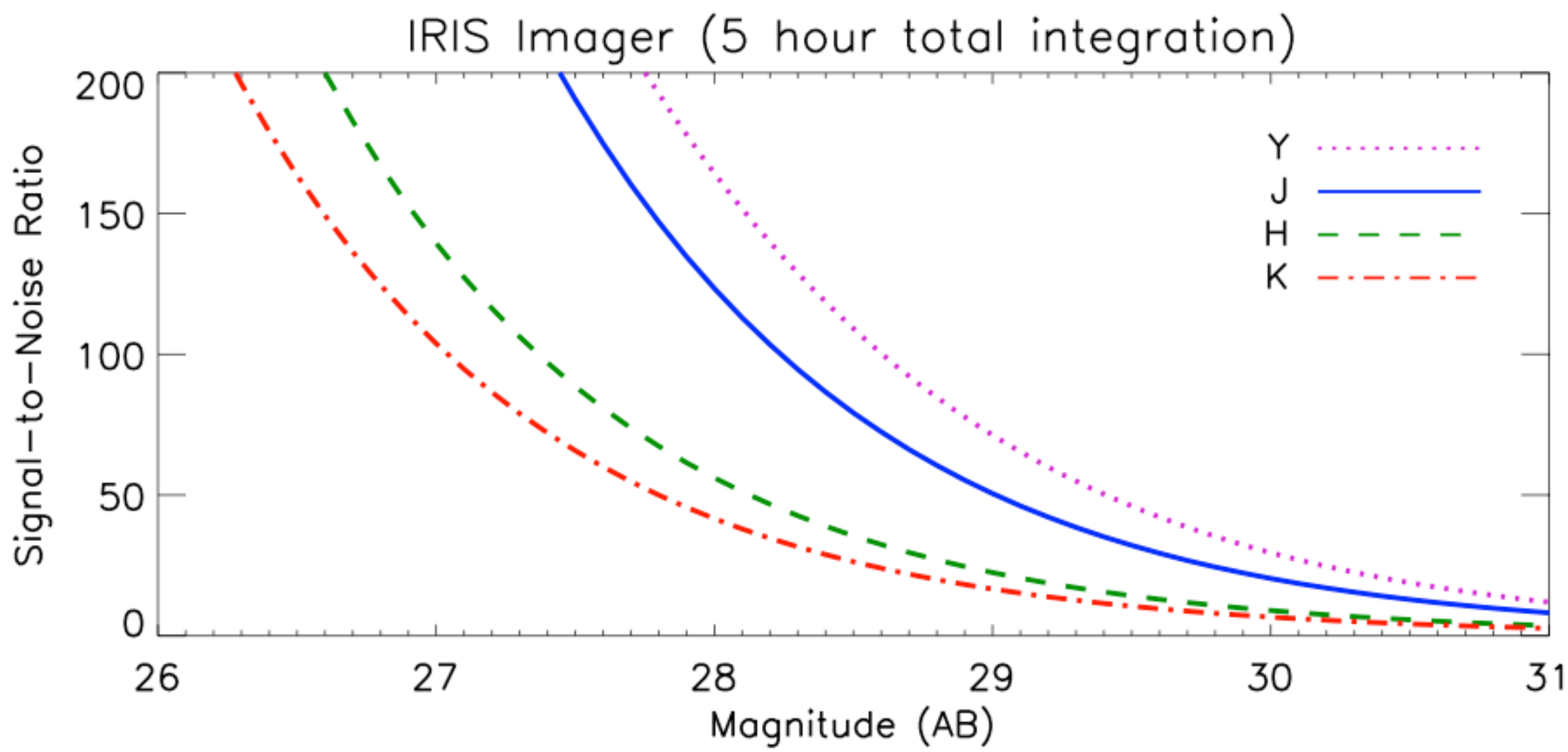
By Ryan Prior and Chris Boyette, CNN
Updated 0347 GMT (1147 HKT) July 18, 2019

https://edition.cnn.com/2019/07/17/us/mauna-kea-arrests-telescope-protests-trnd/index.html

Native Hawaiians strongly protest the construction of TMT.

IRIS

InfraRed Imaging Spectrograph (IRIS) has sensitivities to ~ μm.



[arXiv: 1007.1975]

$$Y: \ \lambda = 1.09\ \mu\text{m}; \ \ J: \ \lambda = 1.27\ \mu\text{m}; \ \ H: \ \lambda = 1.63\ \mu\text{m}; \ \ K: \ \lambda = 2.18\ \mu\text{m}$$

$$m_{\rm AB} = 31.4 - \frac{5}{2}\log_{10}\left(\frac{f_\nu}{1\ \text{nJy}}\right)$$

5-10 hour observation time seems sufficient.