Exploring Physics Beyond the Standard Model via Temperature Observations of Neutron Stars

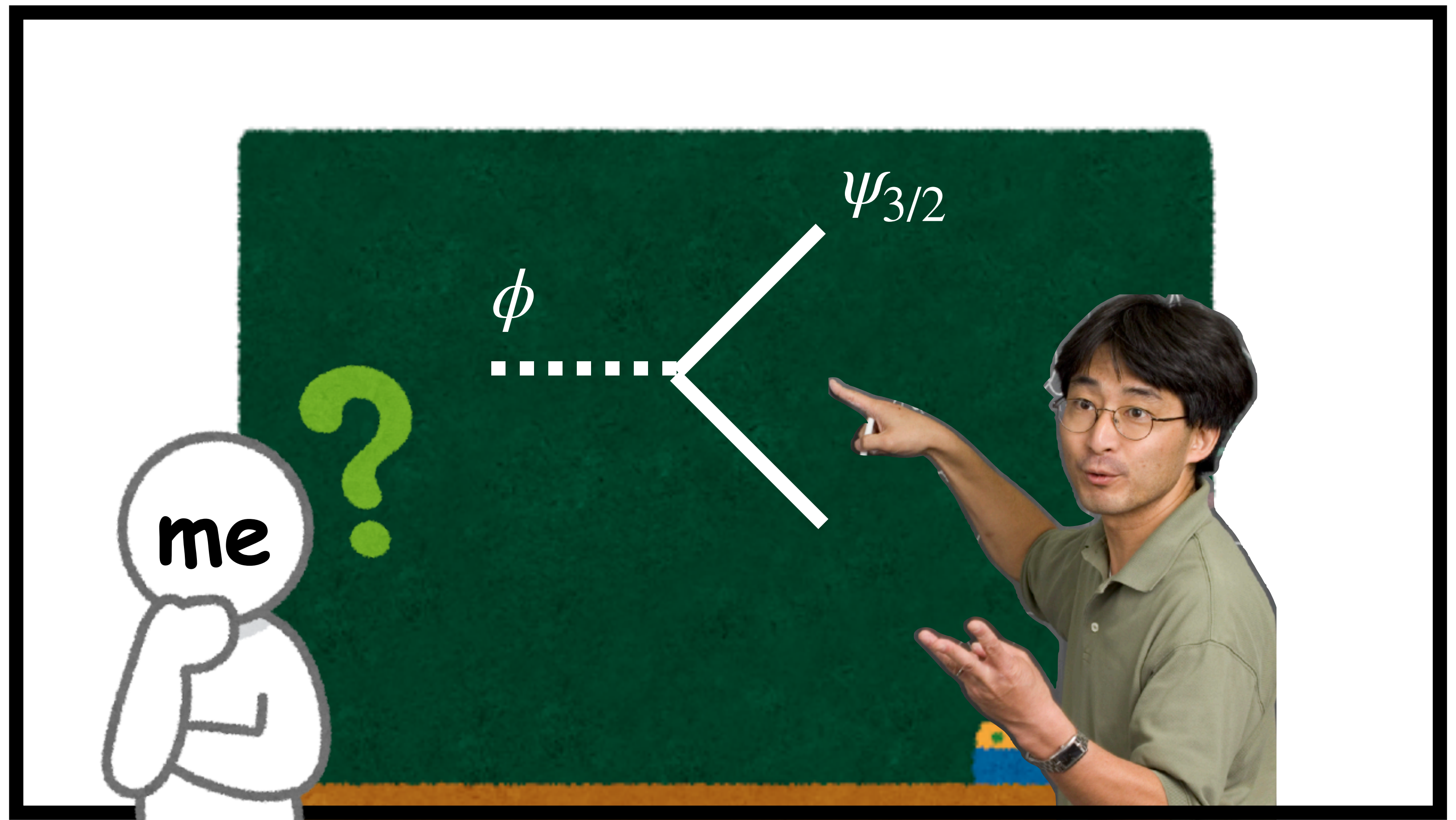
Koichi Hamaguchi (Tokyo U.)

@Hitoshi Fest, Kavli IPMU, Dec. 19, 2024

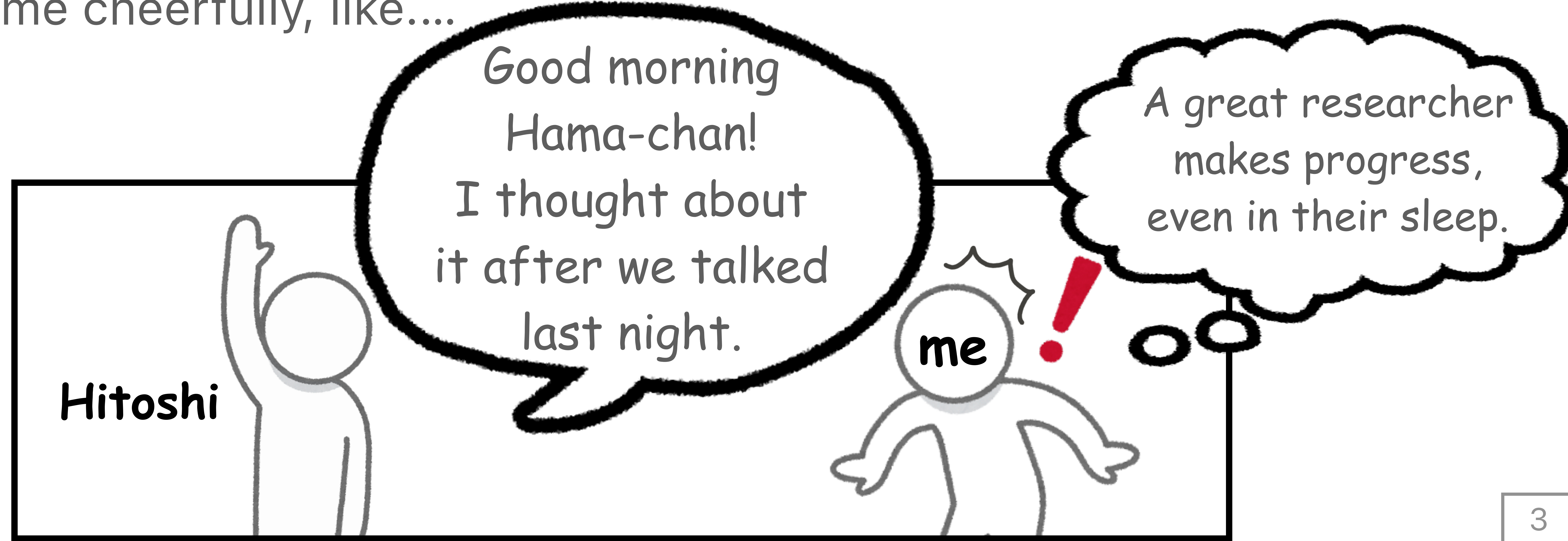
I first met Hitoshi when I was a student. ('97-'02)
He occasionally visited Japan from Berkeley to attend workshops, etc.
He was someone we all looked up to.

At one such workshop (a Summer Institute at Mt. Fuji, if I remember correctly), we had a discussion in the evening,

… followed by a banquet with drinks late into the night.



To my surprise, the next morning,
Hitoshi greeted me cheerfully, like....



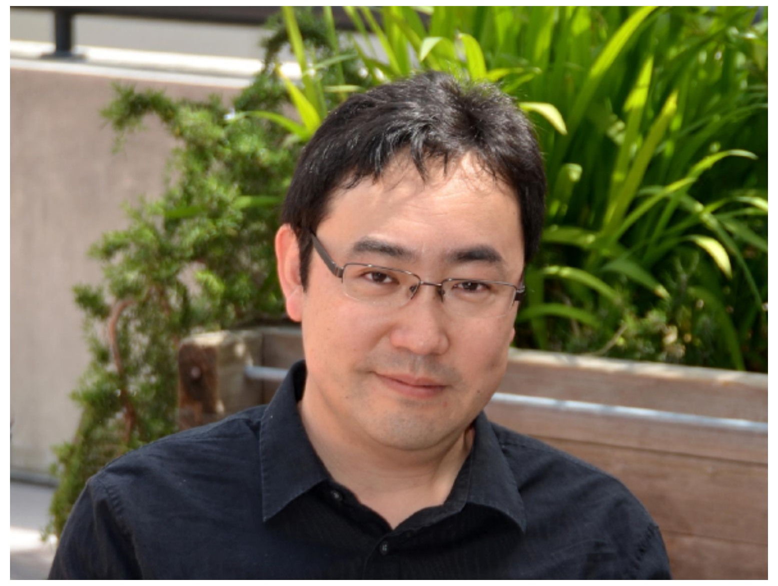
cf. J.Yokoyama-san's talk on Monday.

I have one co-authored paper with Hitoshi.

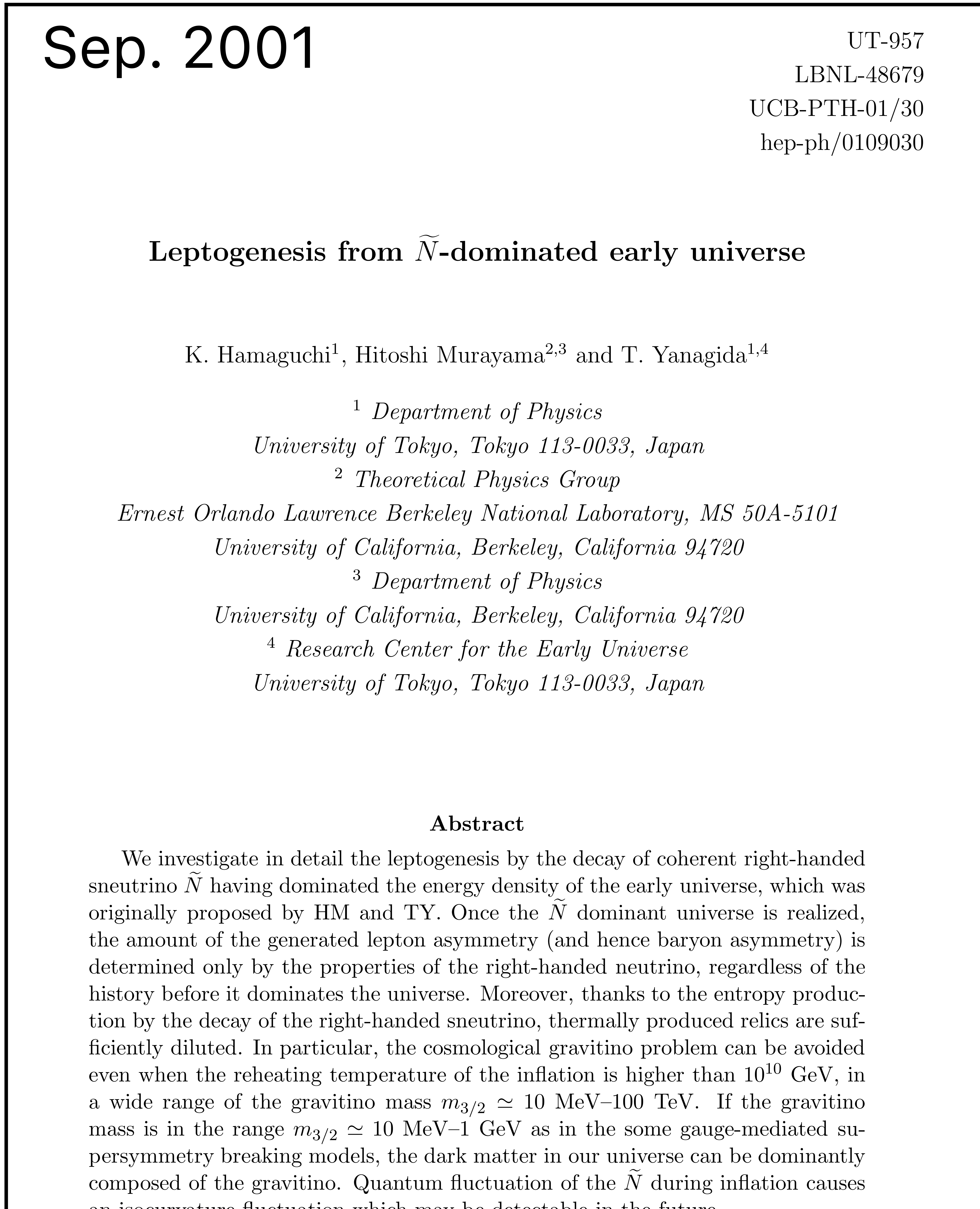
This work was initiated during my visit to Berkeley in February–March 2001.

At that time, I was just a clueless Ph.D. student.

When I arrived, Yasunori kindly picked me up at the airport and showed me around San Francisco.



Thank you very much, Nomura-san!



Sep. 2001

UT-957
LBNL-48679
UCB-PTH-01/30
hep-ph/0109030

Leptogenesis from $\widetilde{N}$-dominated early universe

K. Hamaguchi[1], Hitoshi Murayama[2,3] and T. Yanagida[1,4]

[1] *Department of Physics*
University of Tokyo, Tokyo 113-0033, Japan
[2] *Theoretical Physics Group*
Ernest Orlando Lawrence Berkeley National Laboratory, MS 50A-5101
University of California, Berkeley, California 94720
[3] *Department of Physics*
University of California, Berkeley, California 94720
[4] *Research Center for the Early Universe*
University of Tokyo, Tokyo 113-0033, Japan

Abstract

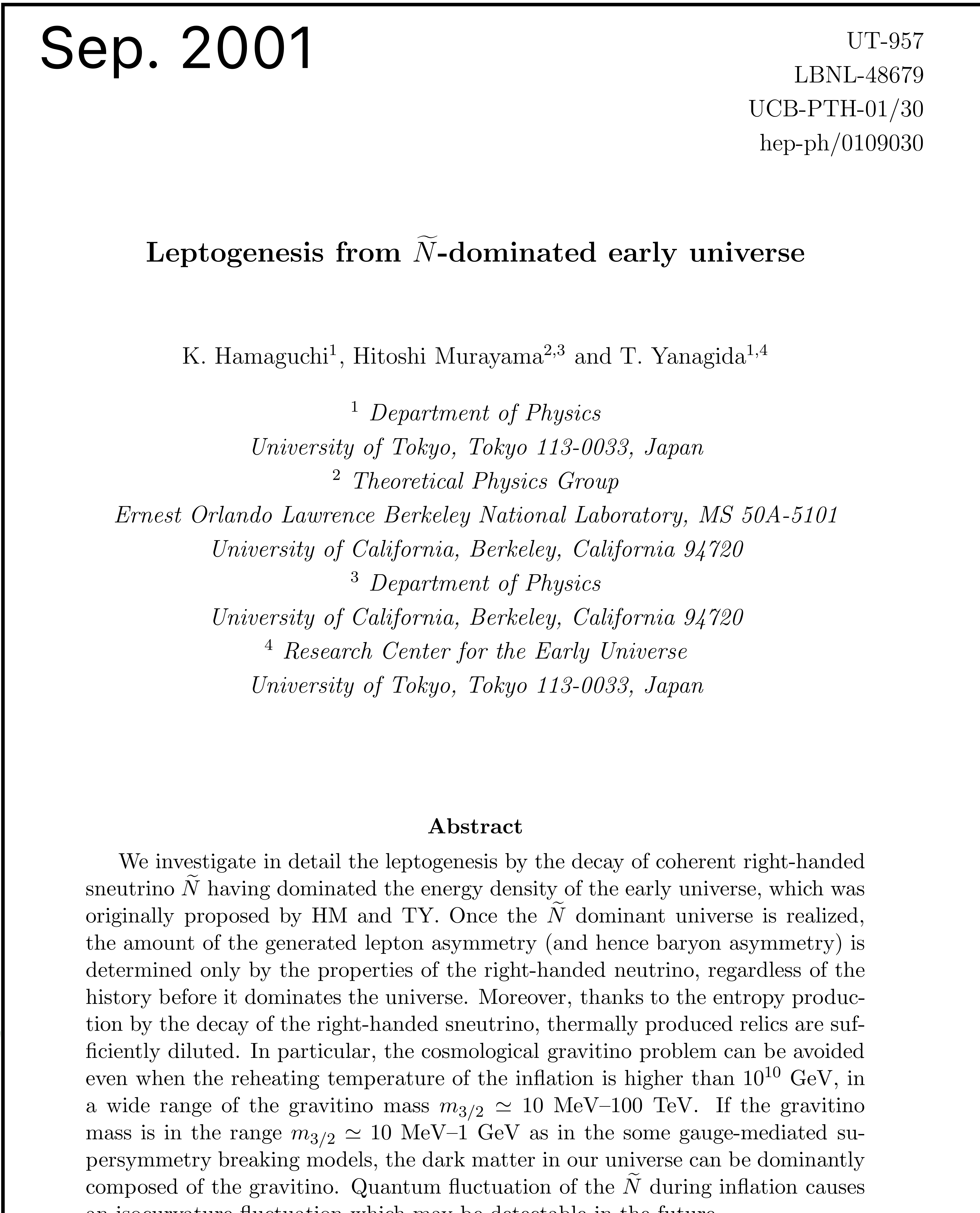
We investigate in detail the leptogenesis by the decay of coherent right-handed sneutrino $\widetilde{N}$ having dominated the energy density of the early universe, which was originally proposed by HM and TY. Once the $\widetilde{N}$ dominant universe is realized, the amount of the generated lepton asymmetry (and hence baryon asymmetry) is determined only by the properties of the right-handed neutrino, regardless of the history before it dominates the universe. Moreover, thanks to the entropy production by the decay of the right-handed sneutrino, thermally produced relics are sufficiently diluted. In particular, the cosmological gravitino problem can be avoided even when the reheating temperature of the inflation is higher than 10^{10} GeV, in a wide range of the gravitino mass $m_{3/2} \simeq 10$ MeV–100 TeV. If the gravitino mass is in the range $m_{3/2} \simeq 10$ MeV–1 GeV as in the some gauge-mediated supersymmetry breaking models, the dark matter in our universe can be dominantly composed of the gravitino. Quantum fluctuation of the $\widetilde{N}$ during inflation causes

cf. J.Yokoyama-san's talk on Monday.

I have one co-authored paper with Hitoshi.

This work was initiated during my visit to Berkeley in February–March 2001.

During the three-week visit, Hitoshi kindly took the time to discuss with me, and we started a collaboration.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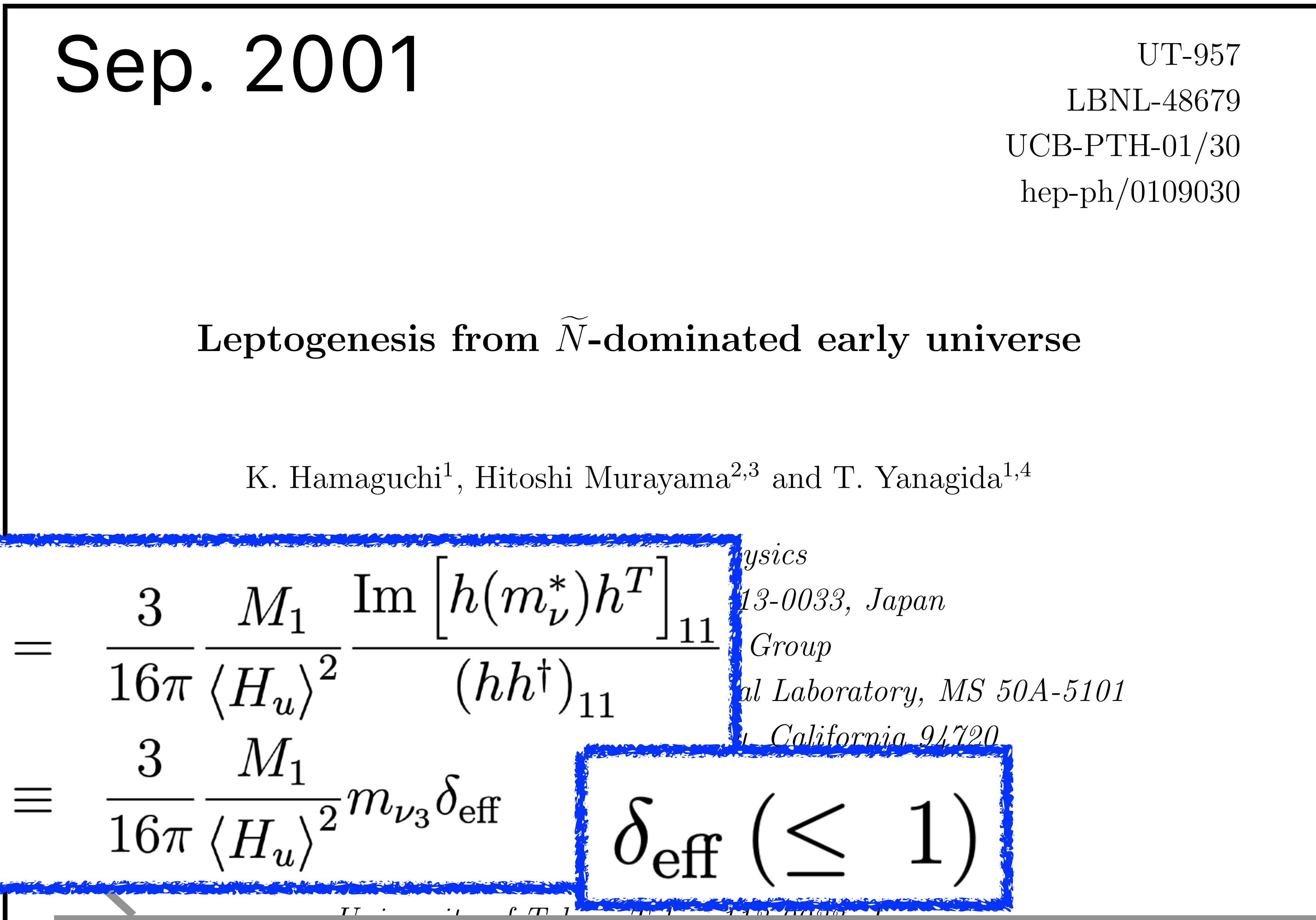
I have one co-authored paper with Hitoshi.

- This paper is one of my favorites and became a main part of my Ph.D. thesis.
- I especially like this paper for pointing out an upper bound on the CP-violating phase in Leptogenesis.
  - While an explicit proof of $\delta_{\mathrm{eff}} \leq 1$ was not included in the HMY paper, it was provided in my Ph.D. thesis. (cf. Davidson-Ibarra, 2002.)



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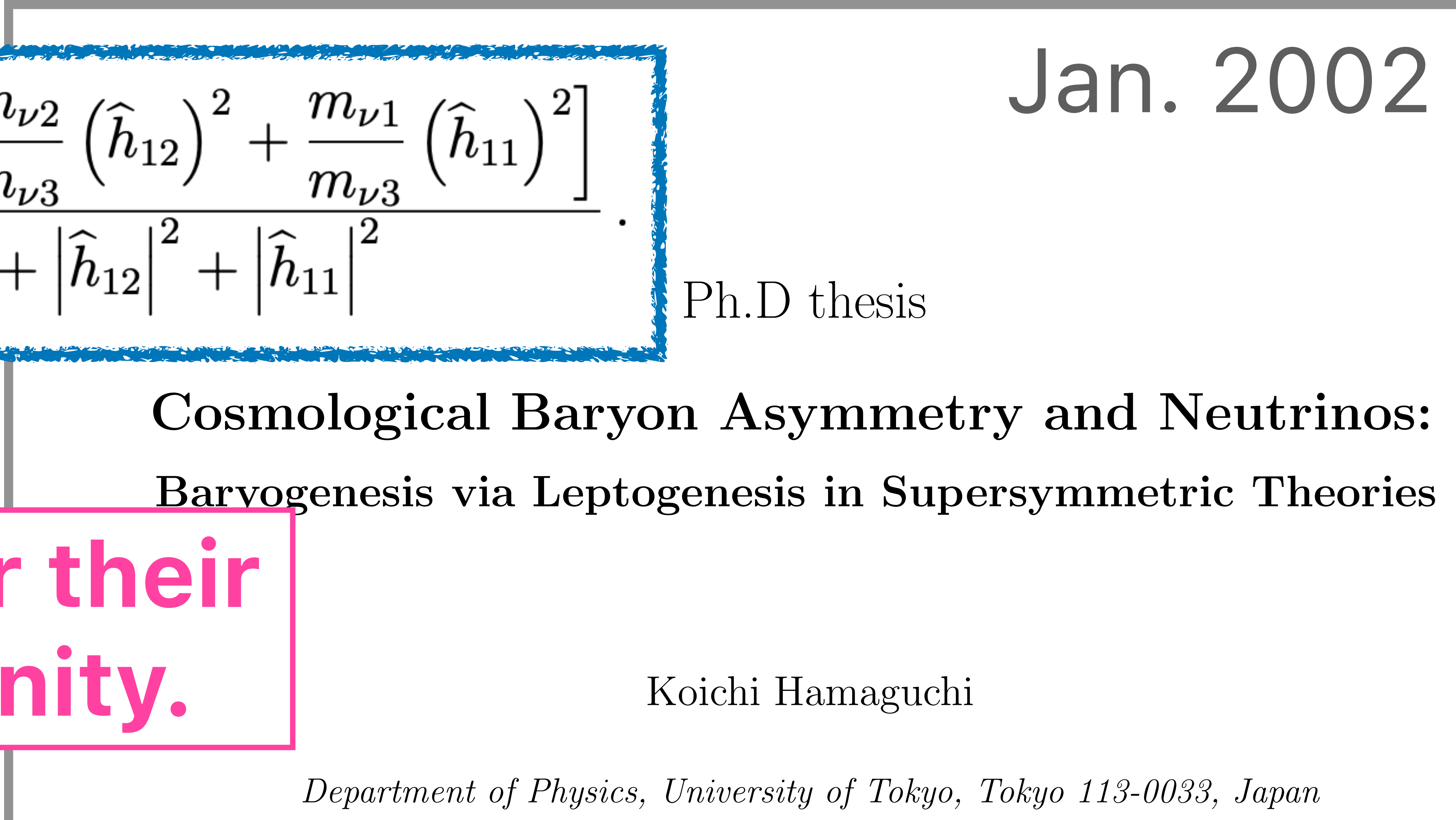
ysics
13-0033, Japan
Group
al Laboratory, MS 50A-5101
California 94720

$$\epsilon_1 = \frac{3}{16\pi}\frac{M_1}{\langle H_u\rangle^2}\frac{\mathrm{Im}\left[h(m_\nu^*)h^T\right]_{11}}{(hh^\dagger)_{11}} \equiv \frac{3}{16\pi}\frac{M_1}{\langle H_u\rangle^2}m_{\nu_3}\delta_{\mathrm{eff}}$$

$$\delta_{\mathrm{eff}}\ (\leq\ 1)$$

$$\delta_{\mathrm{eff}} \equiv \frac{\mathrm{Im}\left[\left(\widehat{h}_{13}\right)^2 + \frac{m_{\nu 2}}{m_{\nu 3}}\left(\widehat{h}_{12}\right)^2 + \frac{m_{\nu 1}}{m_{\nu 3}}\left(\widehat{h}_{11}\right)^2\right]}{\left|\widehat{h}_{13}\right|^2 + \left|\widehat{h}_{12}\right|^2 + \left|\widehat{h}_{11}\right|^2}.$$



Jan. 2002

Ph.D thesis

Cosmological Baryon Asymmetry and Neutrinos:

Baryogenesis via Leptogenesis in Supersymmetric Theories

Koichi Hamaguchi

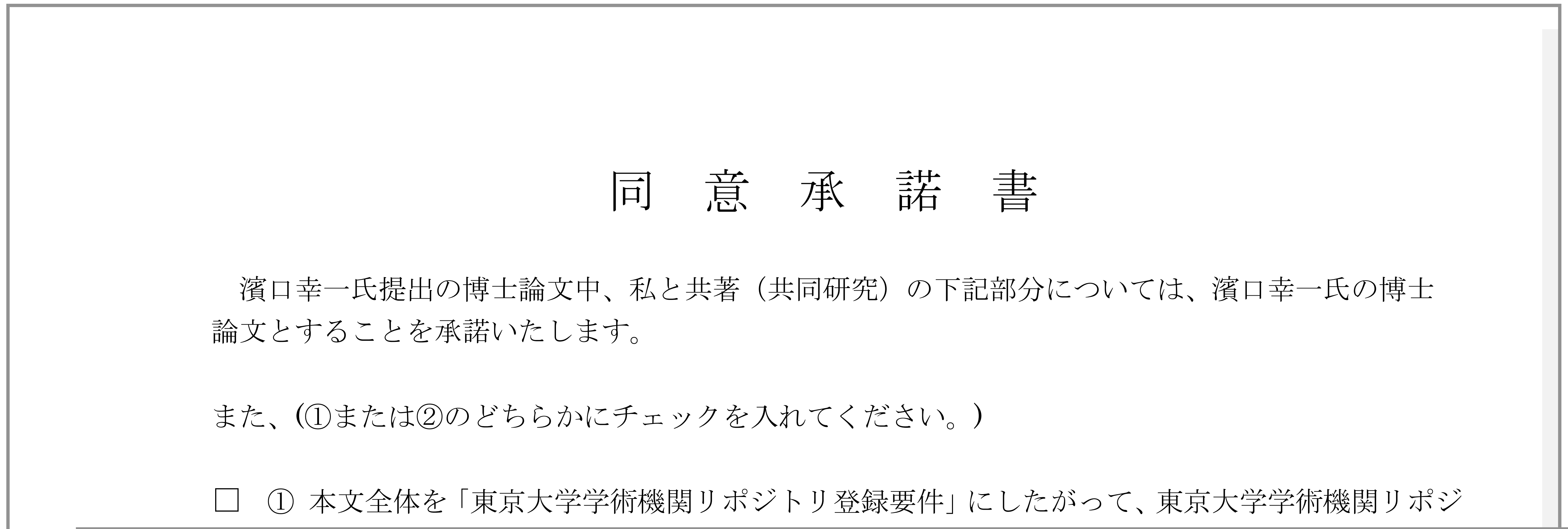
Department of Physics, University of Tokyo, Tokyo 113-0033, Japan

I truly appreciate Hitoshi and Tsutomu for their collaboration and this invaluable opportunity.

About my Ph.D. thesis,…

I needed co-authors' approval.

T. Asaka,
M. Fujii,
M. Kawasaki,
H. Murayama,
T. Yanagida.

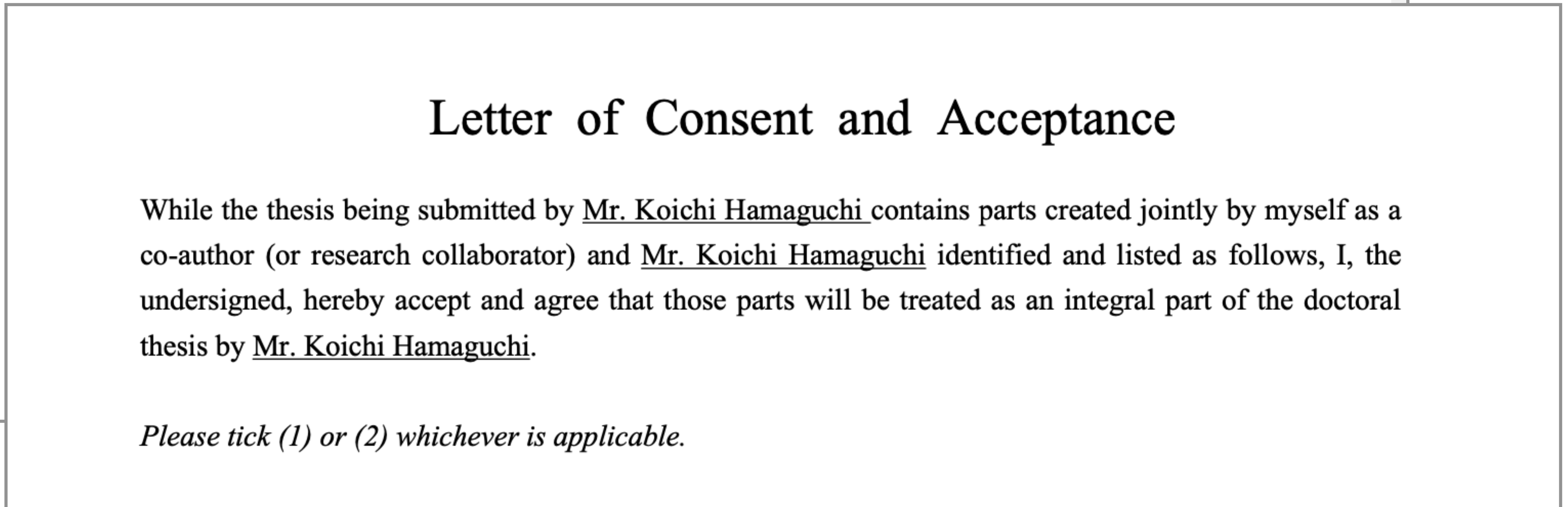


同意承諾書

濱口幸一氏提出の博士論文中、私と共著（共同研究）の下記部分については、濱口幸一氏の博士論文とすることを承諾いたします。

また、(①または②のどちらかにチェックを入れてください。)

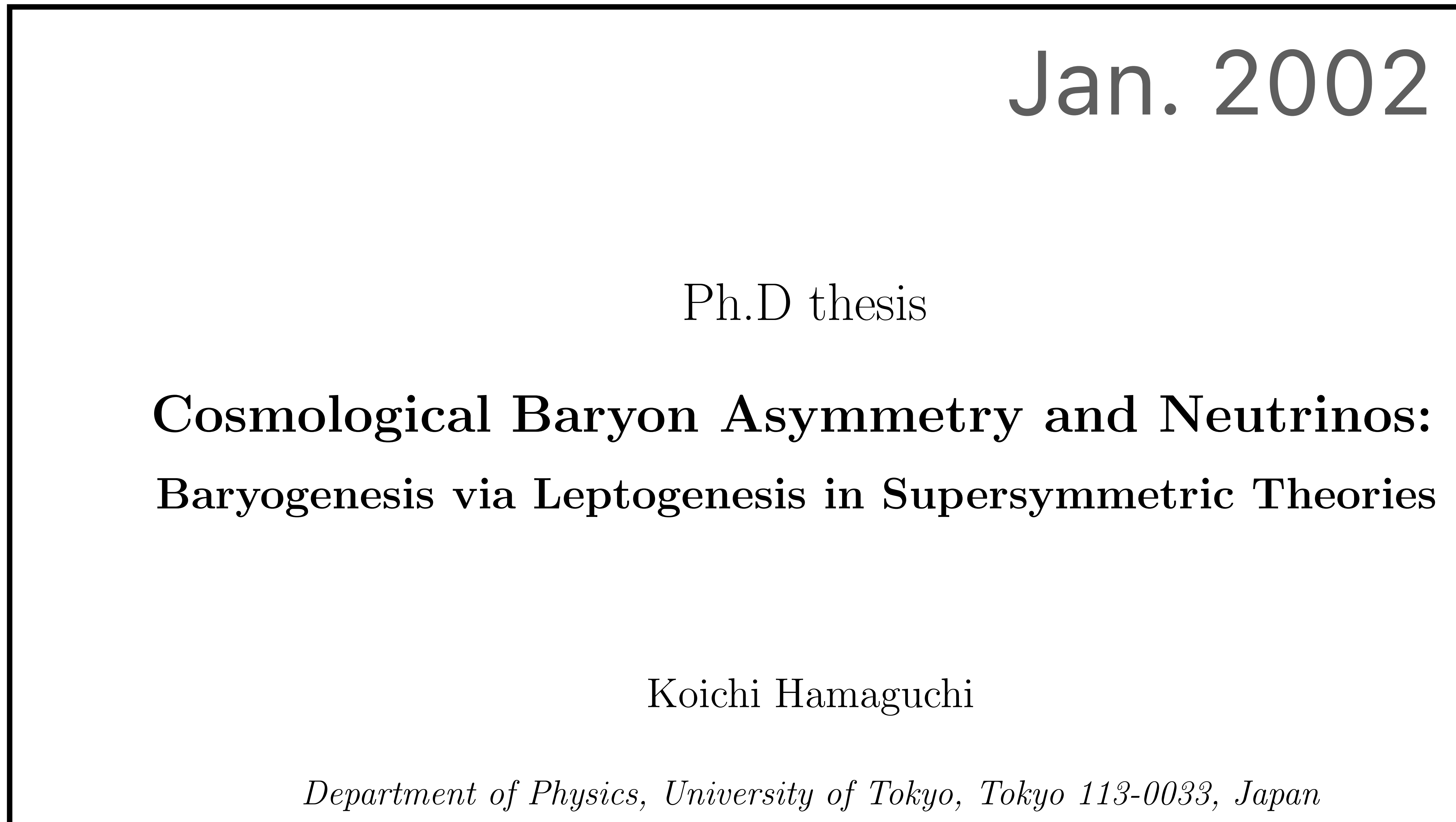
□ ① 本文全体を「東京大学学術機関リポジトリ登録要件」にしたがって、東京大学学術機関リポジ



Letter of Consent and Acceptance

While the thesis being submitted by Mr. Koichi Hamaguchi contains parts created jointly by myself as a co-author (or research collaborator) and Mr. Koichi Hamaguchi identified and listed as follows, I, the undersigned, hereby accept and agree that those parts will be treated as an integral part of the doctoral thesis by Mr. Koichi Hamaguchi.

Please tick (1) or (2) whichever is applicable.



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Ph.D thesis

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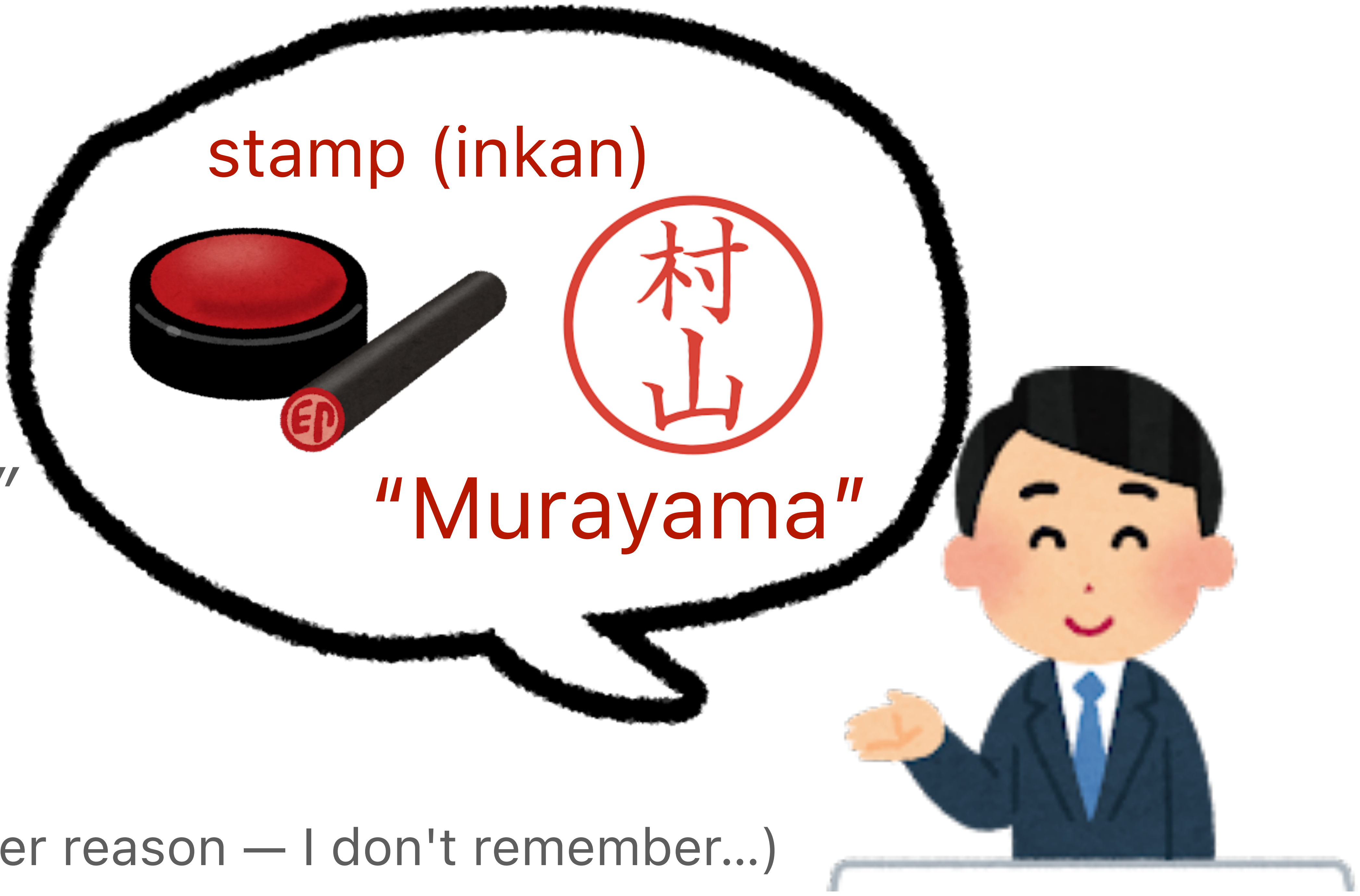
Koichi Hamaguchi

Department of Physics, University of Tokyo, Tokyo 113-0033, Japan

About my Ph.D. thesis,...

I needed co-authors' approval.

The rule back then:
"Non-Japanese sign, Japanese use a stamp (inkan)."



I emailed Hitoshi.
But somehow the stamp wasn't an option.
(I asked too late, or he didn't have his stamp with him, or for some other reason — I don't remember...)

The office insisted:
"You need a stamp from him. By the deadline."

I was stuck.

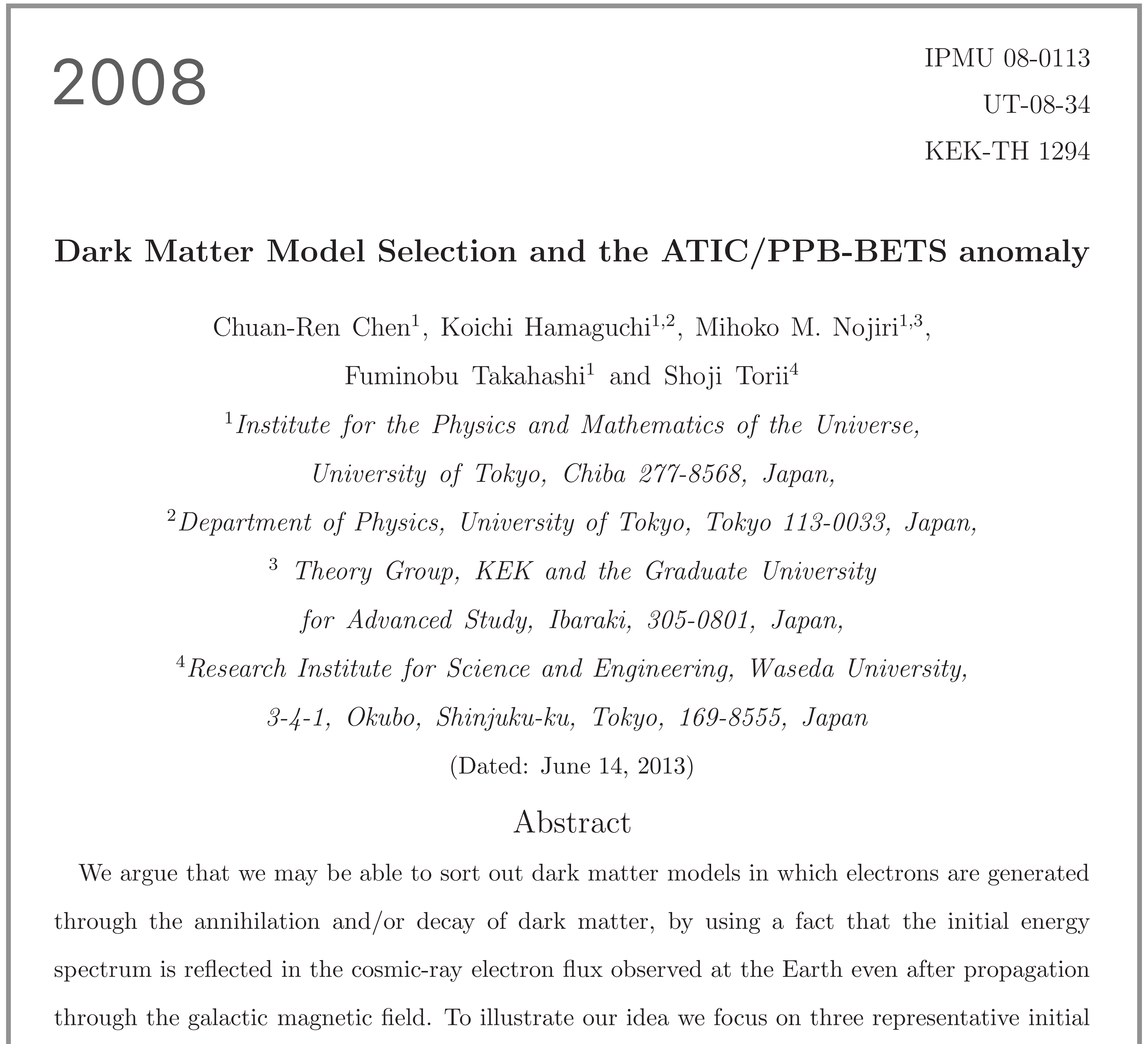
I went back to the office, and (if I remember right...)
they told me,...
"By the way, there's a stamp shop in front of the university..."

(You can guess the rest. Fortunately, my thesis was accepted, and here I am today...)

2007, IPMU launched! (2006, I joined Physics Department)

In the early days,…

- I occasionally (or maybe fairly often?) came to IPMU.
- I also collaborated with IPMU members and wrote papers.



2008

IPMU 08-0113
UT-08-34
KEK-TH 1294

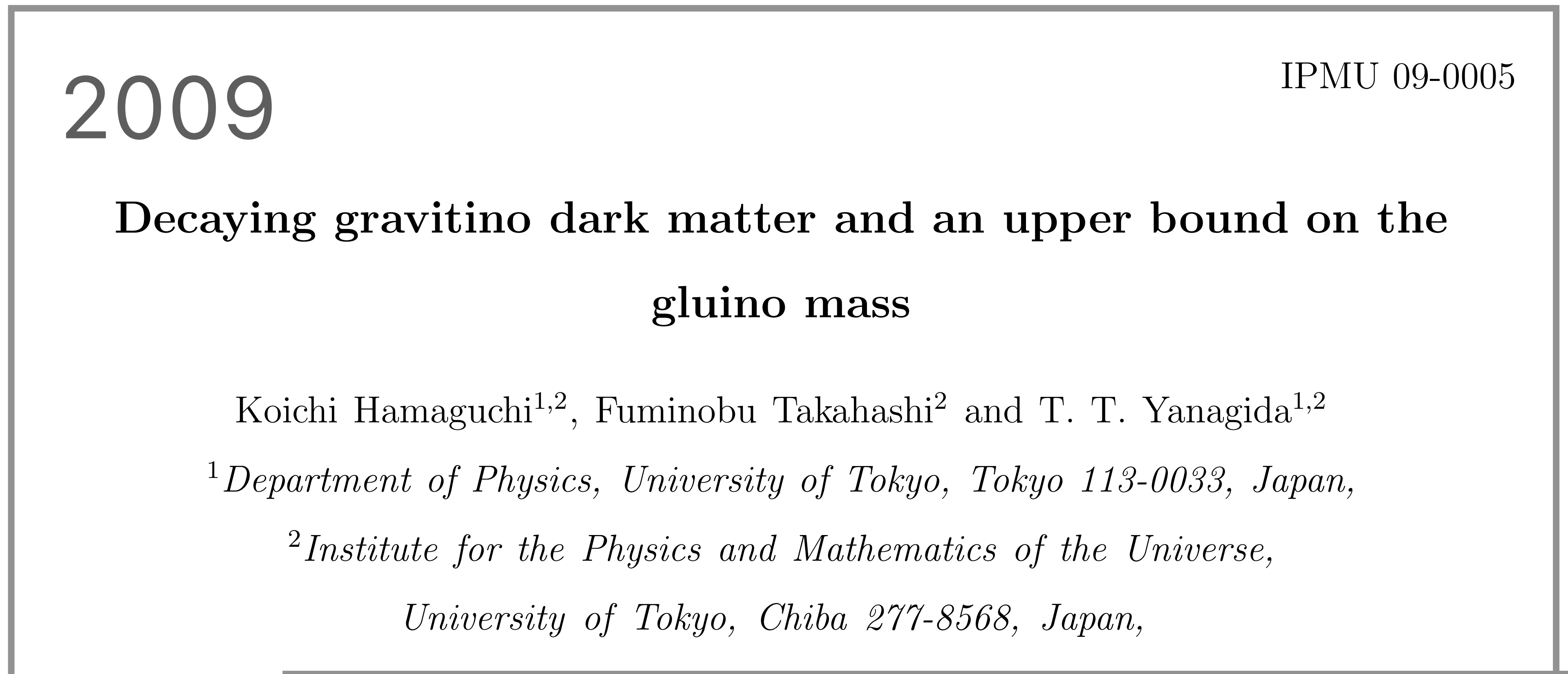
Dark Matter Model Selection and the ATIC/PPB-BETS anomaly

Chuan-Ren Chen[1], Koichi Hamaguchi[1,2], Mihoko M. Nojiri[1,3],
Fuminobu Takahashi[1] and Shoji Torii[4]
[1] *Institute for the Physics and Mathematics of the Universe,*
University of Tokyo, Chiba 277-8568, Japan,
[2] *Department of Physics, University of Tokyo, Tokyo 113-0033, Japan,*
[3] *Theory Group, KEK and the Graduate University*
for Advanced Study, Ibaraki, 305-0801, Japan,
[4] *Research Institute for Science and Engineering, Waseda University,*
3-4-1, Okubo, Shinjuku-ku, Tokyo, 169-8555, Japan

(Dated: June 14, 2013)

Abstract

We argue that we may be able to sort out dark matter models in which electrons are generated through the annihilation and/or decay of dark matter, by using a fact that the initial energy spectrum is reflected in the cosmic-ray electron flux observed at the Earth even after propagation through the galactic magnetic field. To illustrate our idea we focus on three representative initial



2009

IPMU 09-0005

Decaying gravitino dark matter and an upper bound on the gluino mass

Koichi Hamaguchi[1,2], Fuminobu Takahashi[2] and T. T. Yanagida[1,2]
[1] *Department of Physics, University of Tokyo, Tokyo 113-0033, Japan,*
[2] *Institute for the Physics and Mathematics of the Universe,*
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We show that
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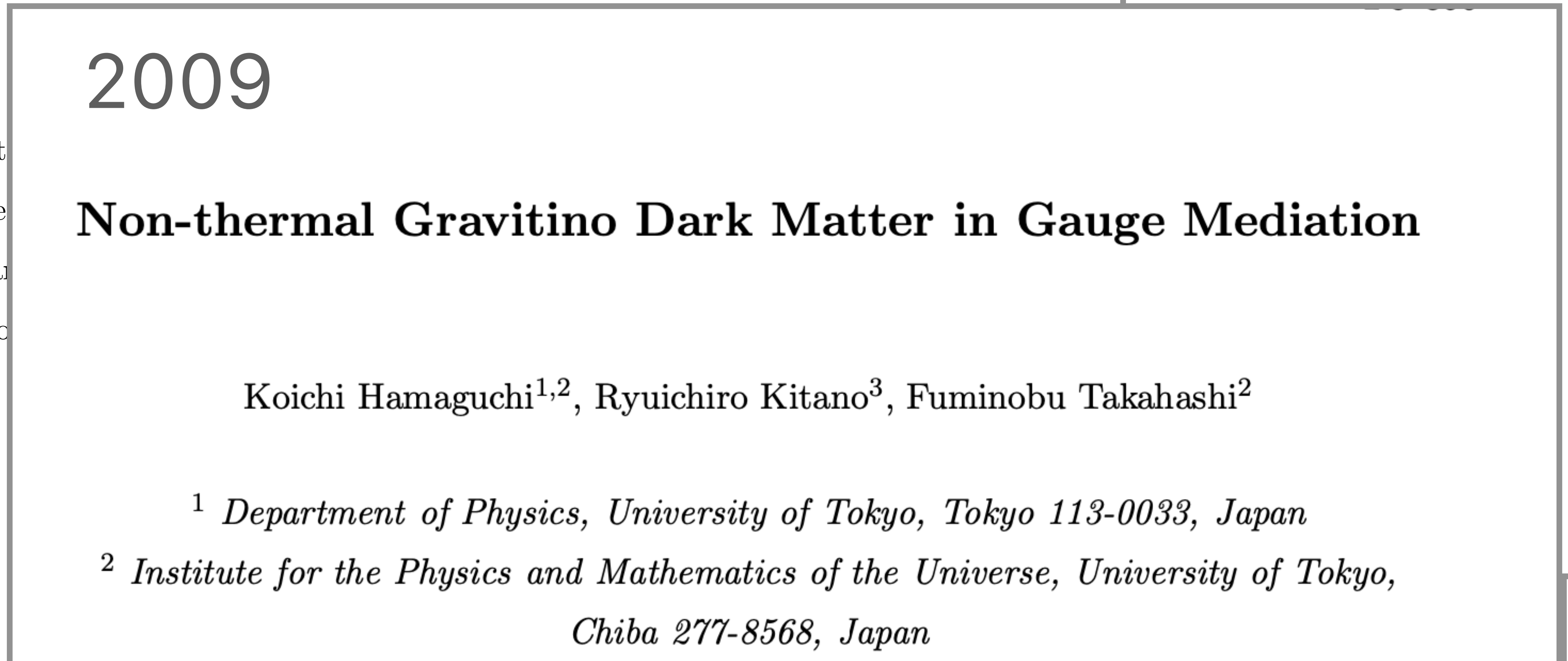

2009

Non-thermal Gravitino Dark Matter in Gauge Mediation

Koichi Hamaguchi[1,2], Ryuichiro Kitano[3], Fuminobu Takahashi[2]

[1] *Department of Physics, University of Tokyo, Tokyo 113-0033, Japan*
[2] *Institute for the Physics and Mathematics of the Universe, University of Tokyo, Chiba 277-8568, Japan*

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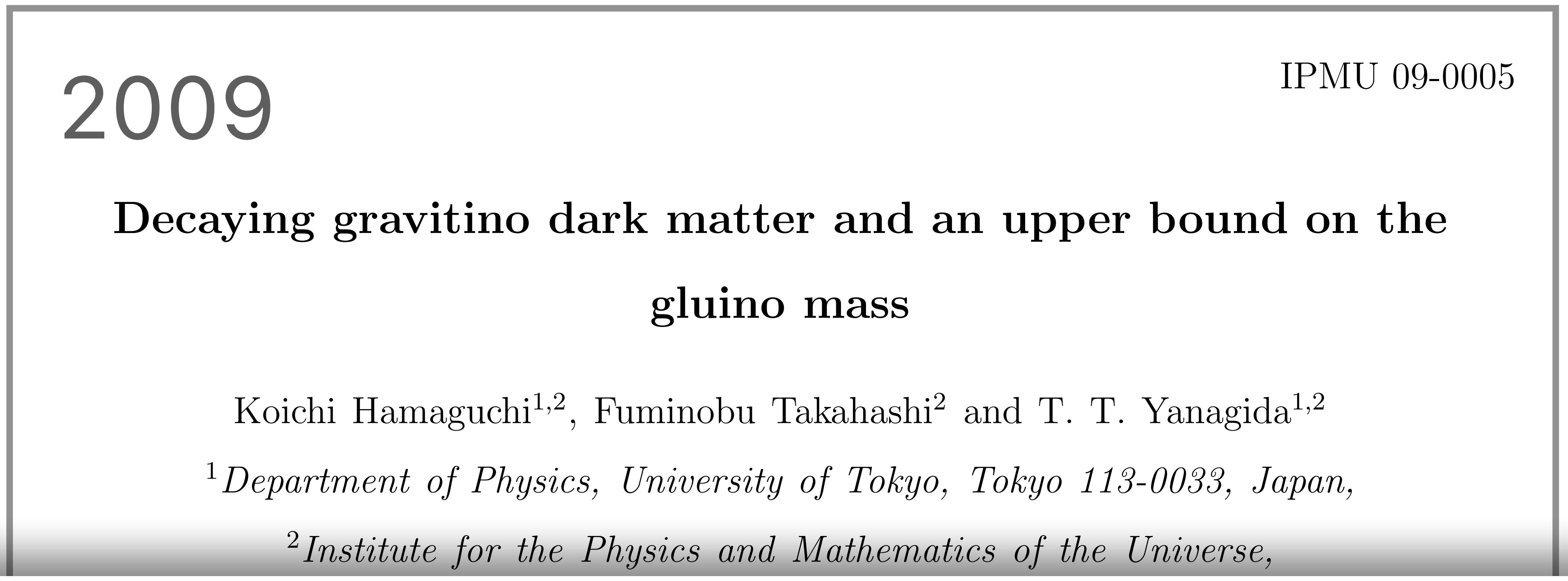

2009

IPMU 09-0005

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[1]*Department of Physics, University of Tokyo, Tokyo 113-0033, Japan,*
[2]*Institute for the Physics and Mathematics of the Universe,*

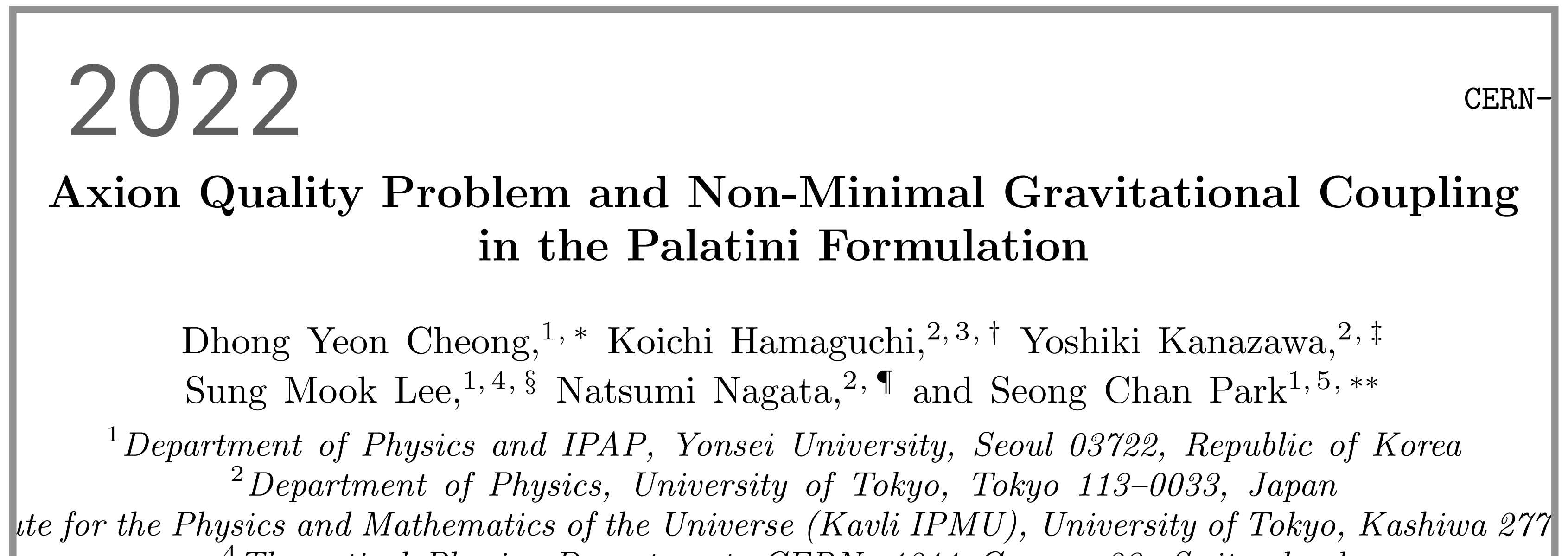
… and we remain great friends and occasional collaborators.

2016

From the 750 GeV Diphoton Resonance to Multilepton Excesses

Kyu Jung Bae[a], Chuan-Ren Chen[b], Koichi Hamaguchi[a,c] and Ian Low[d,e]

[a]*Department of Physics, University of Tokyo, Bunkyo-ku, Tokyo 113–0033, Japan*

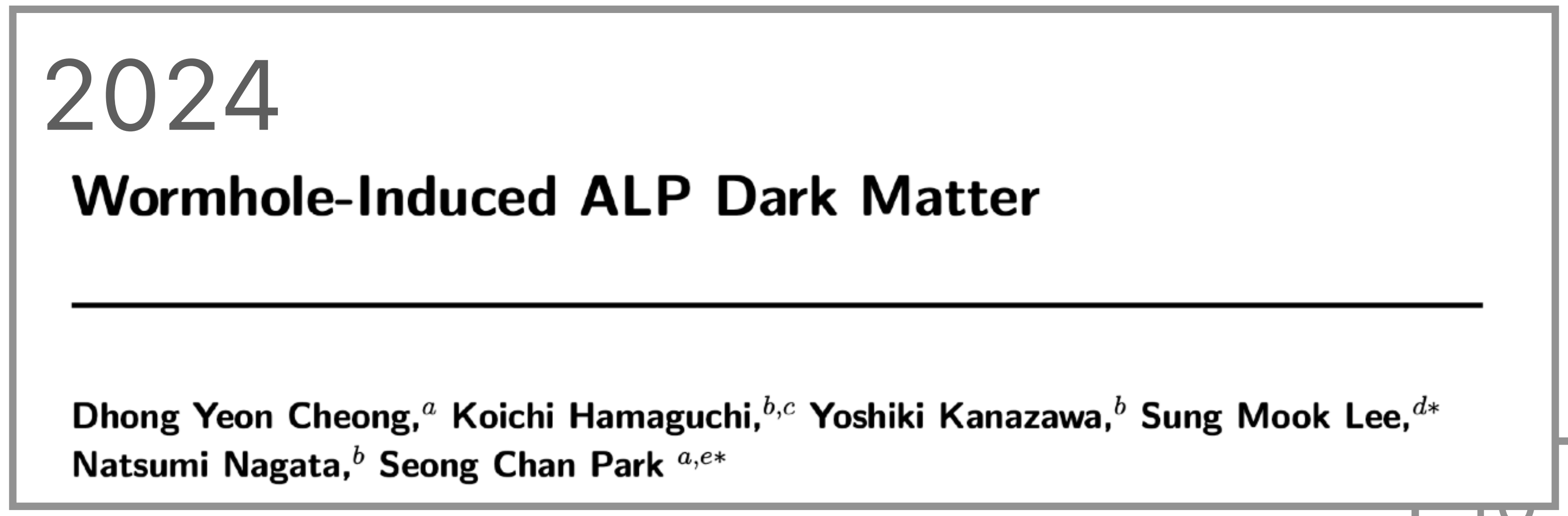


2022

CERN-

Axion Quality Problem and Non-Minimal Gravitational Coupling in the Palatini Formulation

Dhong Yeon Cheong,[1, *] Koichi Hamaguchi,[2, 3, †] Yoshiki Kanazawa,[2, ‡]
Sung Mook Lee,[1, 4, §] Natsumi Nagata,[2, ¶] and Seong Chan Park[1, 5, **]
[1]*Department of Physics and IPAP, Yonsei University, Seoul 03722, Republic of Korea*
[2]*Department of Physics, University of Tokyo, Tokyo 113–0033, Japan*
ute for the Physics and Mathematics of the Universe (Kavli IPMU), University of Tokyo, Kashiwa 277



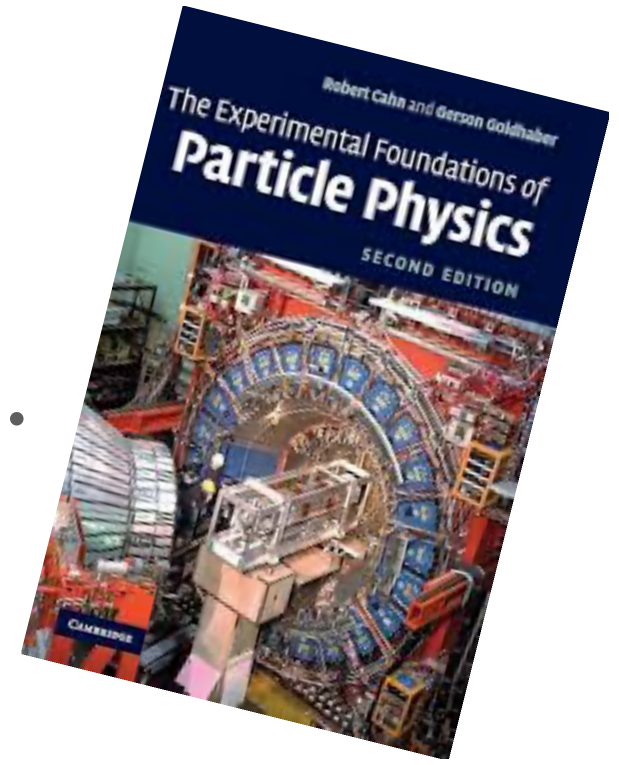
2024

Wormhole-Induced ALP Dark Matter

Dhong Yeon Cheong,[a] Koichi Hamaguchi,[b,c] Yoshiki Kanazawa,[b] Sung Mook Lee,[d*]
Natsumi Nagata,[b] Seong Chan Park [a,e*]

Hitoshi has also been deeply involved in the **Physics Department**, contributing in various ways, e.g.:

- Organized joint reading courses for students in Kashiwa and Hongo.



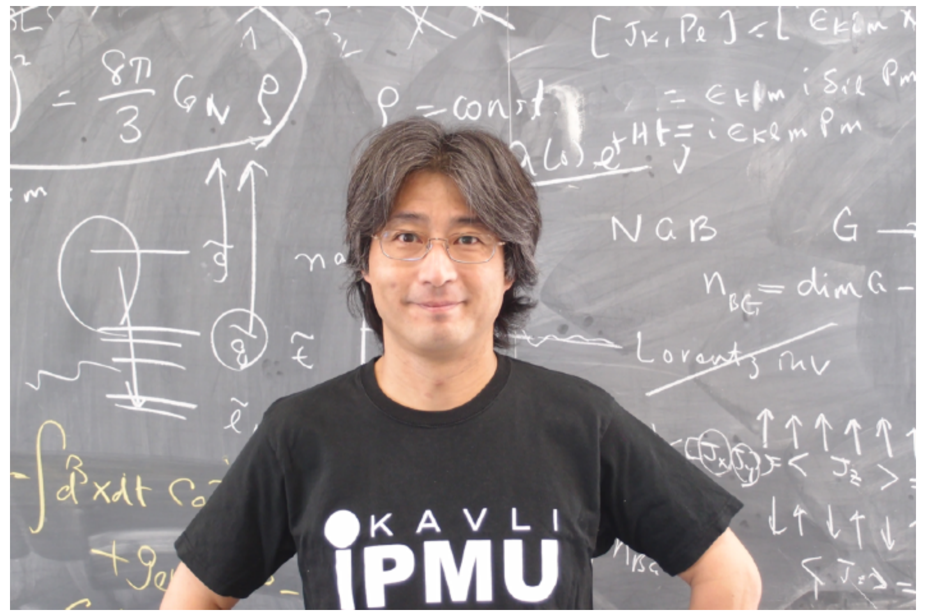
cf. K.Tobioka-san's talk on Tuesday.

- Led 'Berkeley Week' — joint workshops with Berkeley members.

cf. H.Fukuda-san's talk today.

- Launched **FoPM** (=The Forefront Physics and Mathematics Program to Drive Transformation) as the Program Coordinator. cf. H.Yokoyama-san's talk on Monday.
    - **Financial support from master's course. (cf. JSPS.)**
    - Various features: Lab rotation, second supervisor, etc.
- etc., etc.

FoPM



We are truly grateful for Hitoshi's leadership and continued support.

Exploring Physics Beyond the Standard Model via Temperature Observations of Neutron Stars

Koichi Hamaguchi (Tokyo U.)

@Hitoshi Fest, Kavli IPMU, Dec. 19, 2024

Based on the works with

Motoko Fujiwara, Natsumi Nagata, Maura E. Ramirez-Quezada, Keisuke Yanagi, Jiaming Zheng

(+ Shao-Feng Ge, Yoshiki Kanazawa, Koichi Ichimura, Koji Ishidoshiro, Yasuhiro Kishimoto, for the work on SN axion)

references

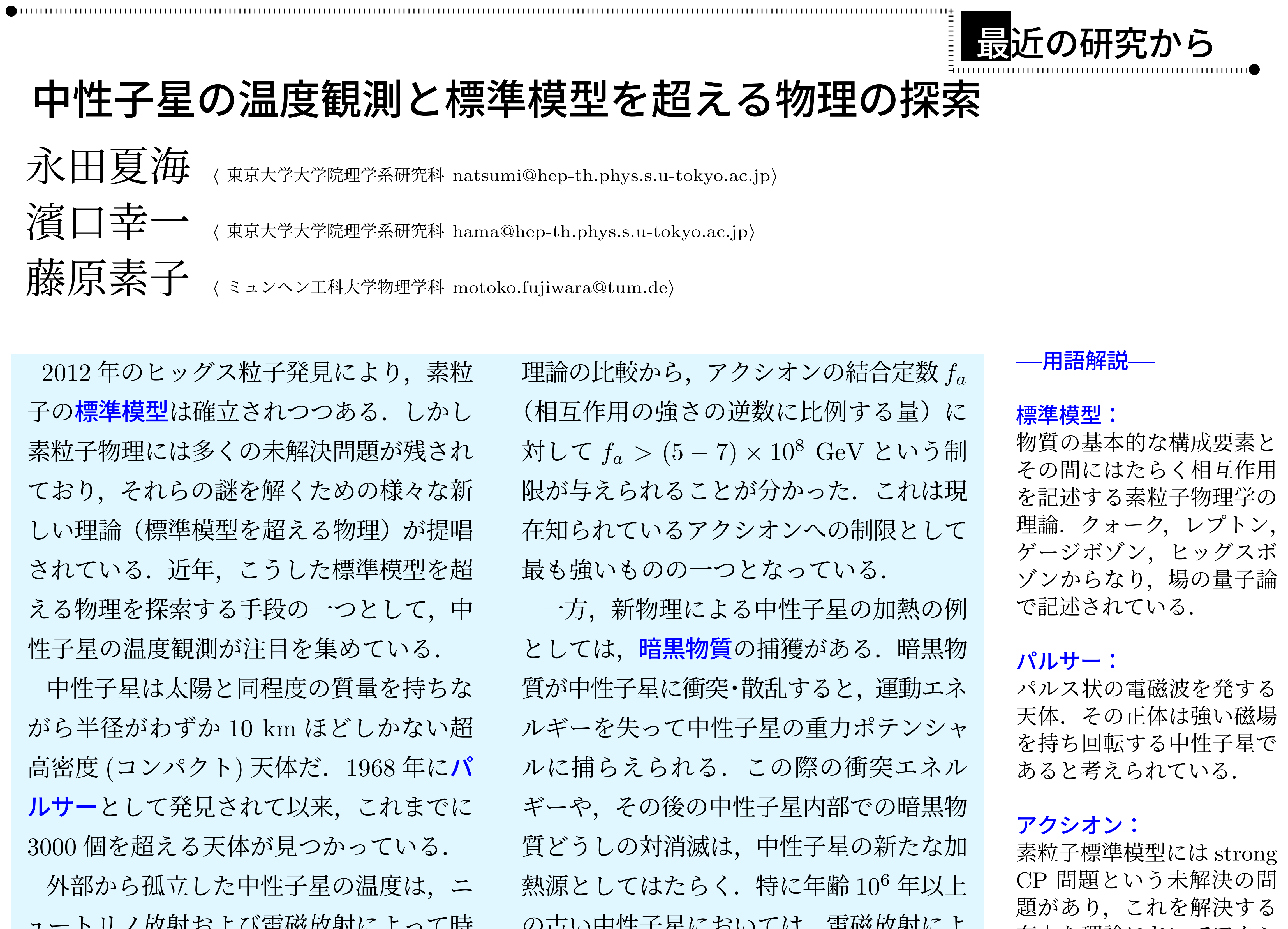
NS heating by DM: arXiv 2309.02633, 2308.16066, 2204.02413, 2204.02238, 1905.02991, 1904.04667.

NS cooling by axion: 1806.07151.

SN axion: 2008.03924.

Exploring Physics Beyond the Standard Model via Temperature Observations of Neutron Stars

review article in 日本物理学会誌 (JPS, 2024)



最近の研究から

中性子星の温度観測と標準模型を超える物理の探索

永田夏海 〈東京大学大学院理学系研究科 natsumi@hep-th.phys.s.u-tokyo.ac.jp〉
濱口幸一 〈東京大学大学院理学系研究科 hama@hep-th.phys.s.u-tokyo.ac.jp〉
藤原素子 〈ミュンヘン工科大学物理学科 motoko.fujiwara@tum.de〉

2012年のヒッグス粒子発見により，素粒子の**標準模型**は確立されつつある．しかし素粒子物理には多くの未解決問題が残されており，それらの謎を解くための様々な新しい理論（標準模型を超える物理）が提唱されている．近年，こうした標準模型を超える物理を探索する手段の一つとして，中性子星の温度観測が注目を集めている．

中性子星は太陽と同程度の質量を持ちながら半径がわずか10 kmほどしかない超高密度(コンパクト)天体だ．1968年に**パルサー**として発見されて以来，これまでに3000個を超える天体が見つかっている．

外部から孤立した中性子星の温度は，ニュートリノ放射および電磁放射によって時

理論の比較から，アクシオンの結合定数f_a（相互作用の強さの逆数に比例する量）に対して$f_a > (5-7) \times 10^8$ GeVという制限が与えられることが分かった．これは現在知られているアクシオンへの制限として最も強いものの一つとなっている．

一方，新物理による中性子星の加熱の例としては，**暗黒物質**の捕獲がある．暗黒物質が中性子星に衝突･散乱すると，運動エネルギーを失って中性子星の重力ポテンシャルに捕らえられる．この際の衝突エネルギーや，その後の中性子星内部での暗黒物質どうしの対消滅は，中性子星の新たな加熱源としてはたらく．特に年齢10^6年以上の古い中性子星においては，電磁放射によ

―用語解説―

標準模型：
物質の基本的な構成要素とその間にはたらく相互作用を記述する素粒子物理学の理論．クォーク，レプトン，ゲージボゾン，ヒッグスボゾンからなり，場の量子論で記述されている．

パルサー：
パルス状の電磁波を発する天体．その正体は強い磁場を持ち回転する中性子星であると考えられている．

アクシオン：
素粒子標準模型にはstrong CP問題という未解決の問題があり，これを解決する

Natsumi Nagata
(Tokyo)

🏆 **2024 AAPPS-JPS Award**

Motoko Fujiwara
(Tokyo → TUM → Toyama)

🏆 **2025 JPS Young Scientist Award**

Neutron Star

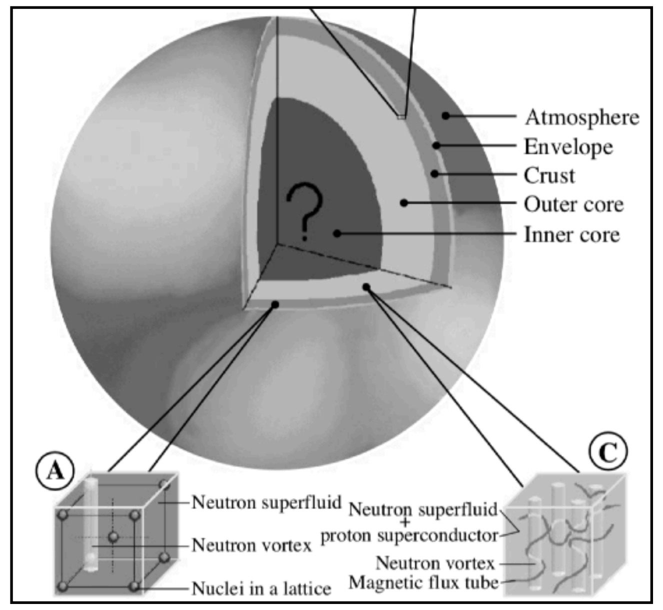


fig. from 1302.6626

- **Mass** : $M \sim (1-2)M_\odot$ ($M_\odot$ = solar mass)

  heaviest one found so far: $M \simeq 2.35 M_\odot$ (pulsar PSR J0952-0607 [arXiv:2207.05124])

- **Radius** : $R \sim 10$ km
- **Density** : $\bar{\rho} = \dfrac{M}{(4\pi/3)R^3} \simeq 7 \times 10^{14} \mathrm{g/cm^3}$ cf. nuclear density $\sim 3 \times 10^{14} \mathrm{g/cm^3}$
- mostly composed of **neutrons**, + O(10%) protons, electrons, muons.
- Most of NSs are found as **pulsars.**

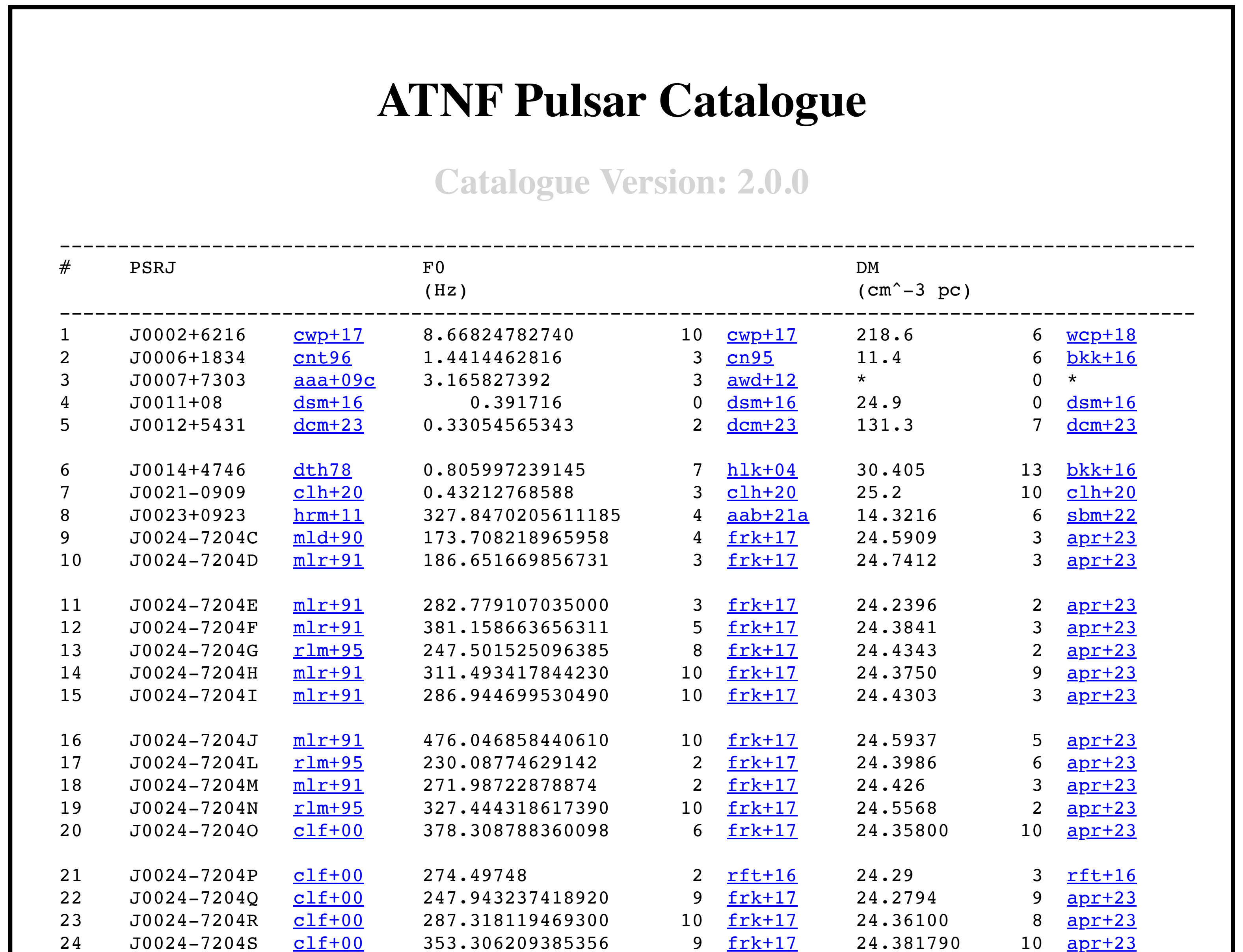
  > **3400 pulsars found** so far.

  ATNF pulsar catalogue 👉

PLEASE NOTE: We are currently transitioning to PSRCAT v2.0. Please contact us if you experience any issues.

ATNF Pulsar Catalogue

Catalogue version: 2.0.0



ATNF Pulsar Catalogue

Catalogue Version: 2.0.0

#	PSRJ		F0 (Hz)			DM (cm^-3 pc)		
1	J0002+6216	cwp+17	8.66824782740	10	cwp+17	218.6	6	wcp+18
2	J0006+1834	cnt96	1.4414462816	3	cn95	11.4	6	bkk+16
3	J0007+7303	aaa+09c	3.165827392	3	awd+12	*	0	*
4	J0011+08	dsm+16	0.391716	0	dsm+16	24.9	0	dsm+16
5	J0012+5431	dcm+23	0.33054565343	2	dcm+23	131.3	7	dcm+23
6	J0014+4746	dth78	0.805997239145	7	hlk+04	30.405	13	bkk+16
7	J0021-0909	clh+20	0.43212768588	3	clh+20	25.2	10	clh+20
8	J0023+0923	hrm+11	327.8470205611185	4	aab+21a	14.3216	6	sbm+22
9	J0024-7204C	mld+90	173.708218965958	4	frk+17	24.5909	3	apr+23
10	J0024-7204D	mlr+91	186.651669856731	3	frk+17	24.7412	3	apr+23
11	J0024-7204E	mlr+91	282.779107035000	3	frk+17	24.2396	2	apr+23
12	J0024-7204F	mlr+91	381.158663656311	5	frk+17	24.3841	3	apr+23
13	J0024-7204G	rlm+95	247.501525096385	8	frk+17	24.4343	2	apr+23
14	J0024-7204H	mlr+91	311.493417844230	10	frk+17	24.3750	9	apr+23
15	J0024-7204I	mlr+91	286.944699530490	10	frk+17	24.4303	3	apr+23
16	J0024-7204J	mlr+91	476.046858440610	10	frk+17	24.5937	5	apr+23
17	J0024-7204L	rlm+95	230.08774629142	2	frk+17	24.3986	6	apr+23
18	J0024-7204M	mlr+91	271.98722878874	2	frk+17	24.426	3	apr+23
19	J0024-7204N	rlm+95	327.444318617390	10	frk+17	24.5568	2	apr+23
20	J0024-7204O	clf+00	378.308788360098	6	frk+17	24.35800	10	apr+23
21	J0024-7204P	clf+00	274.49748	2	rft+16	24.29	3	rft+16
22	J0024-7204Q	clf+00	247.943237418920	9	frk+17	24.2794	9	apr+23
23	J0024-7204R	clf+00	287.318119469300	10	frk+17	24.36100	8	apr+23
24	J0024-7204S	clf+00	353.306209385356	9	frk+17	24.381790	10	apr+23

NS Cooling

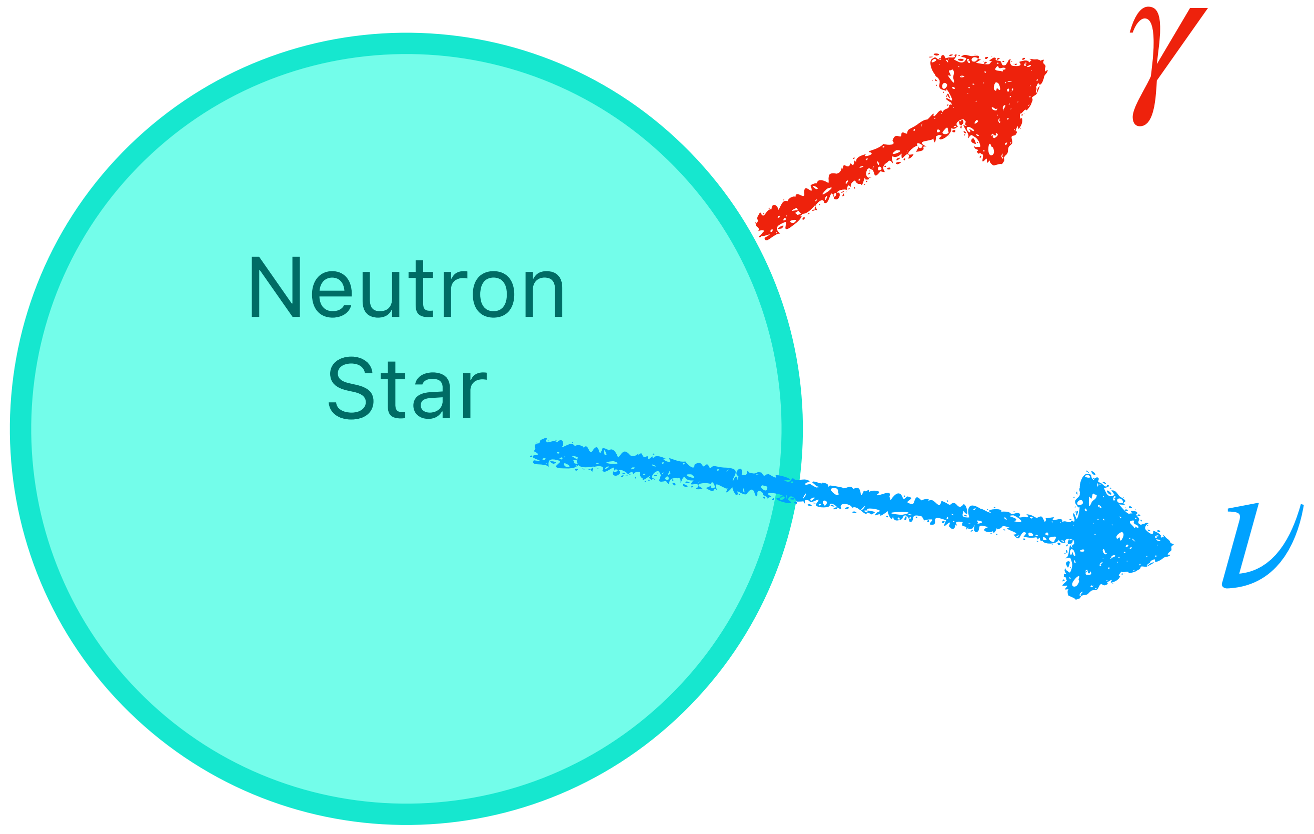
For reviews, e.g., D.G.Yakovlev+, astro-ph/0402143,
D.Page+, astro-ph/0508056, 1302.6626

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

Temperature Evolution.

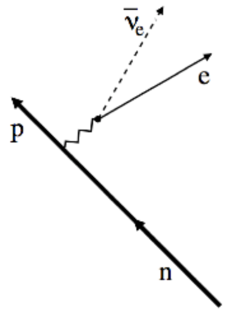
$C = \frac{dE_{\text{thermal}}}{dT}$ (heat capacity)

$C = C_n + C_p + C_e + C_\mu$

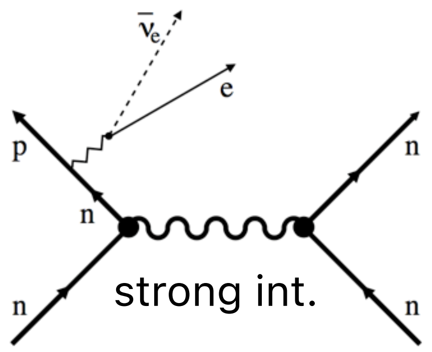


Neutrino emission
dominant for a **young** NS ($\tau \lesssim 10^5$ yrs)

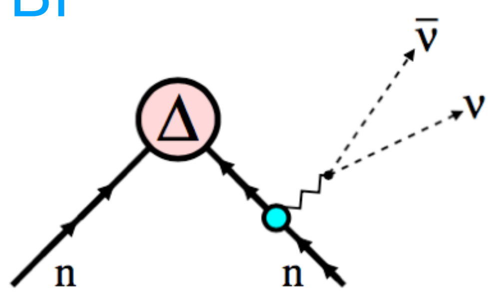
- Direct Urca



- Modified Urca (& Bremsstrahlung)



- PBF



Photon emission
dominant process for an **old** NS ($\tau \gtrsim 10^5$ yrs).

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

※ assuming isothermal state $T(r) \propto e^{-\Phi(r)}$ for simplicity (valid for $t \gtrsim 100$ sec).

NS Cooling

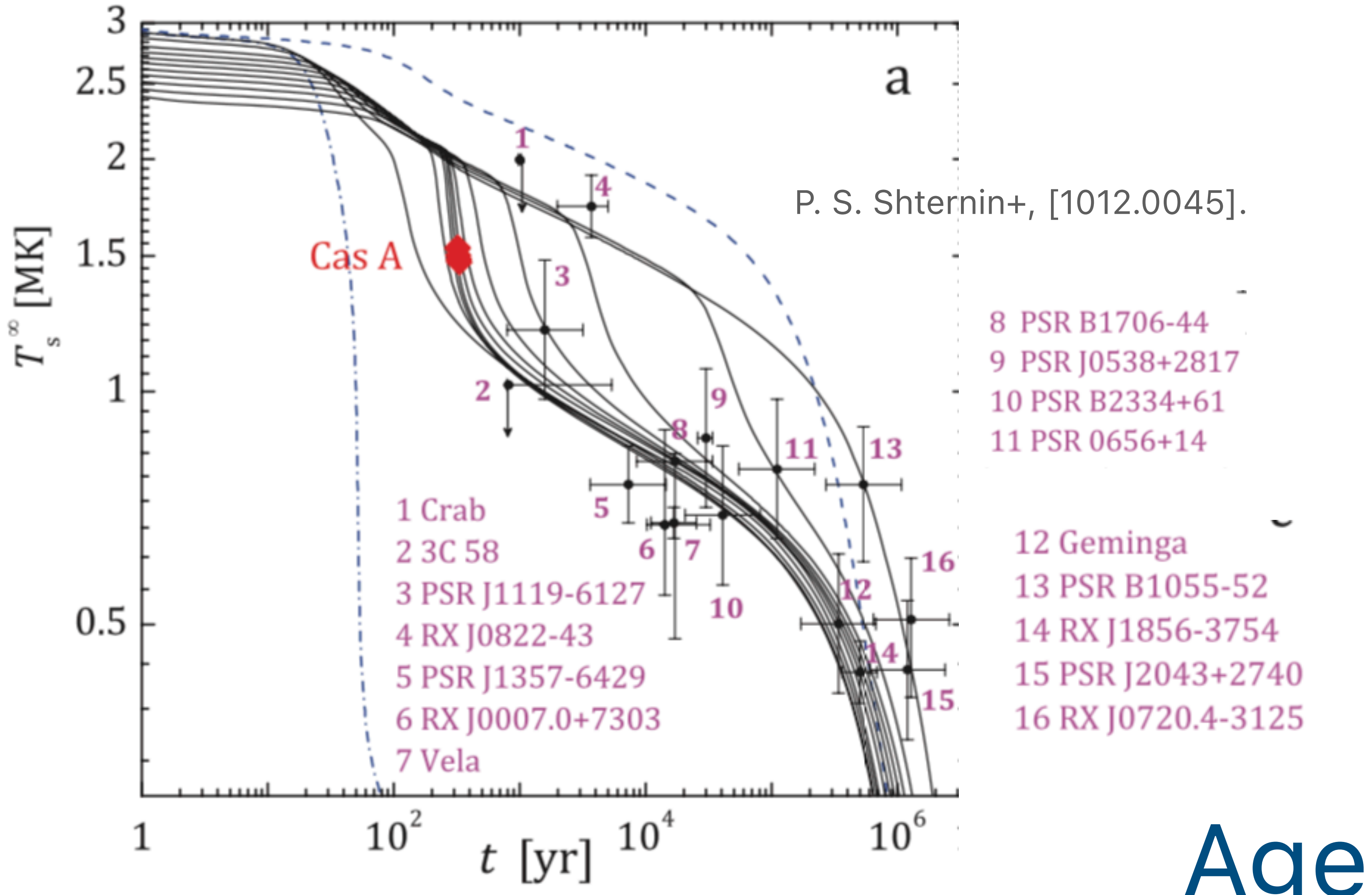
For reviews, e.g., D.G.Yakovlev+, astro-ph/0402143,
D.Page+, astro-ph/0508056, 1302.6626

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

The standard cooling scenario can successfully explain many NS temperature observations.

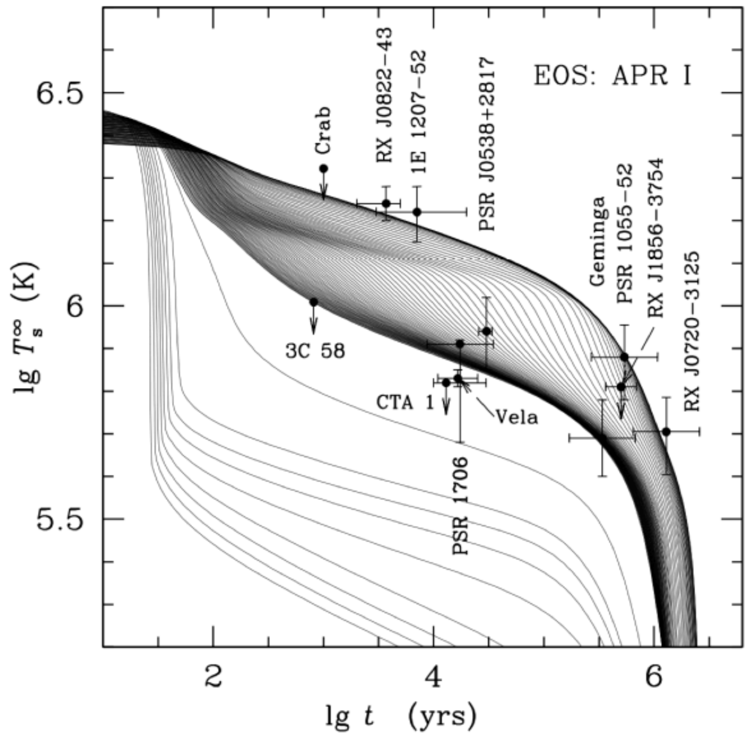
D.Page+, astro-ph/0403657,
M.E.Gusakov+, astro-ph/0404002,
D.Page+, 0906.1621

Surface Temperature

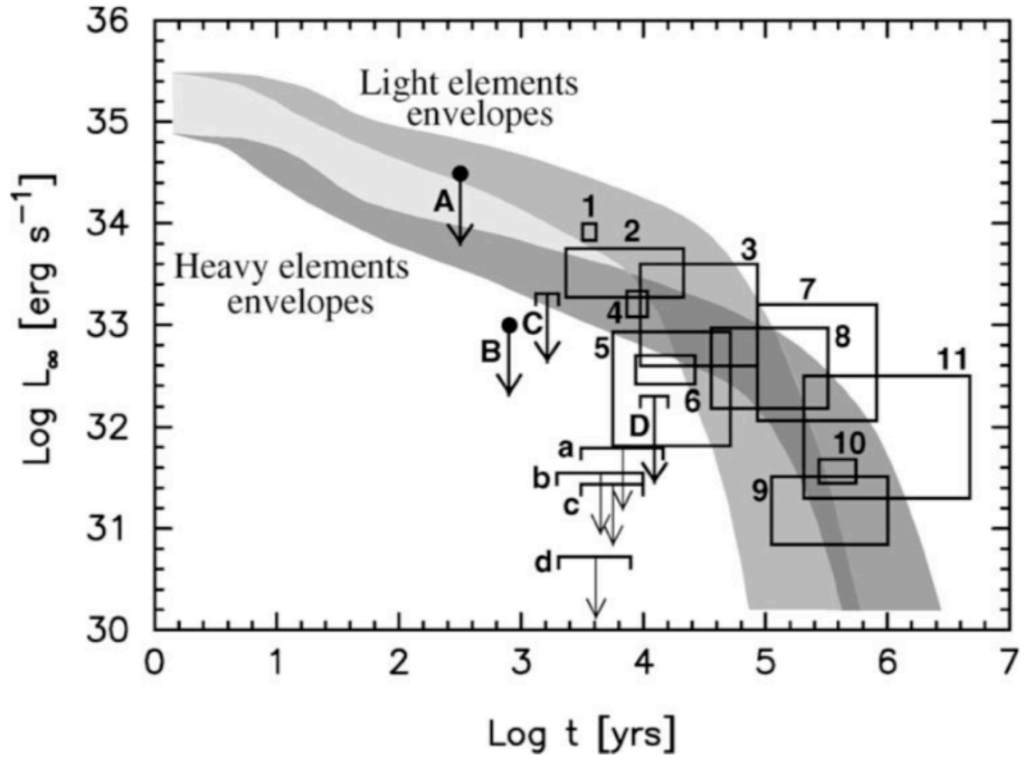


P. S. Shternin+, [1012.0045].

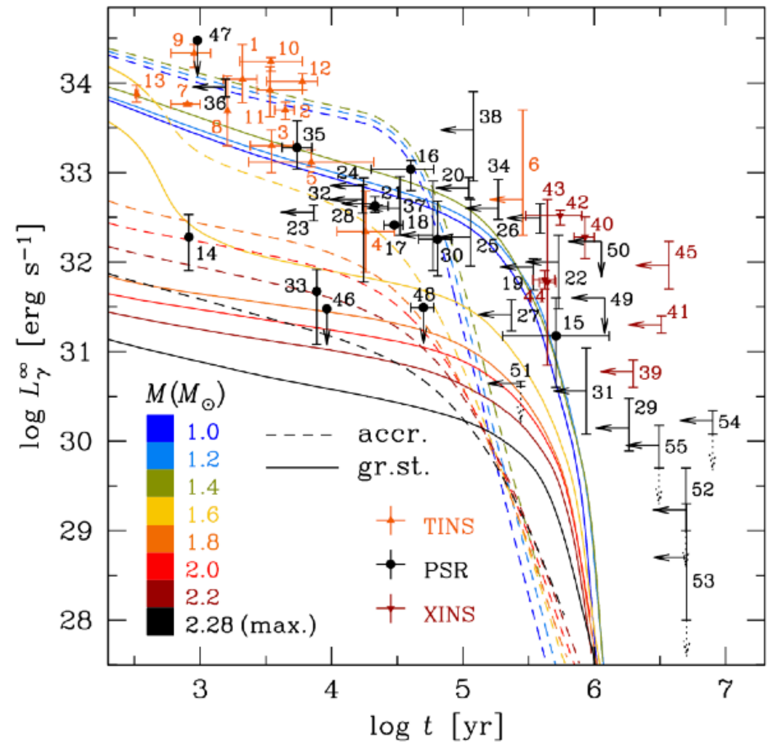
M. E. Gusakov, A. D. Kaminker, D. G. Yakovlev, O. Y. Gnedin
Mon.Not.Roy.Astron.Soc. **363** (2005) 555-562



D. Page et al. / Nuclear Physics A 777 (2006) 497–530



A. Y. Potekhin+,2006.15004

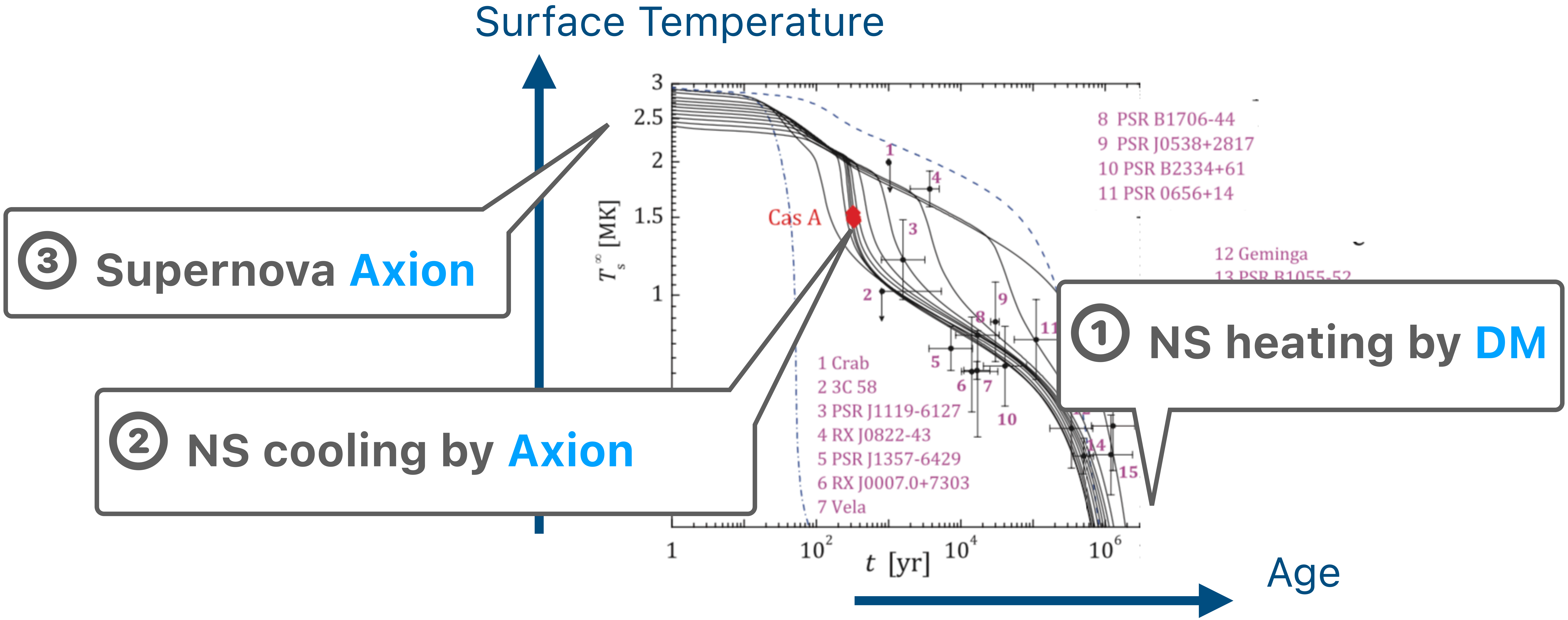


Ages of Neutron Stars

estimated by spin-down age $\tau_{\rm sd} = P/(2\dot{P})$ or kinematics.

This talk

$$C\frac{dT}{dt} = -L_{\nu} - L_{\gamma} \pm L_{\text{new physics}}$$



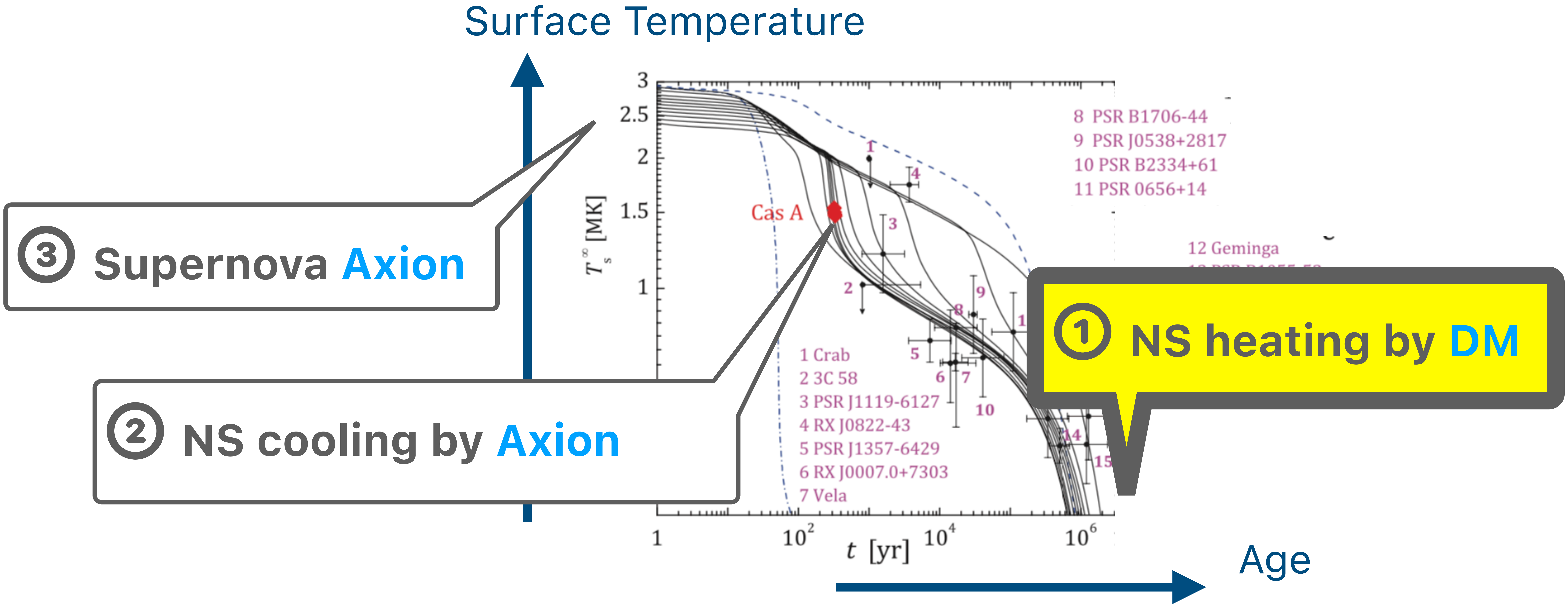
③ **Supernova Axion**

② **NS cooling by Axion**

① **NS heating by DM**

This talk

$$C\frac{dT}{dt} = -L_\nu - L_\gamma \pm L_{\text{new physics}}$$



③ Supernova **Axion**

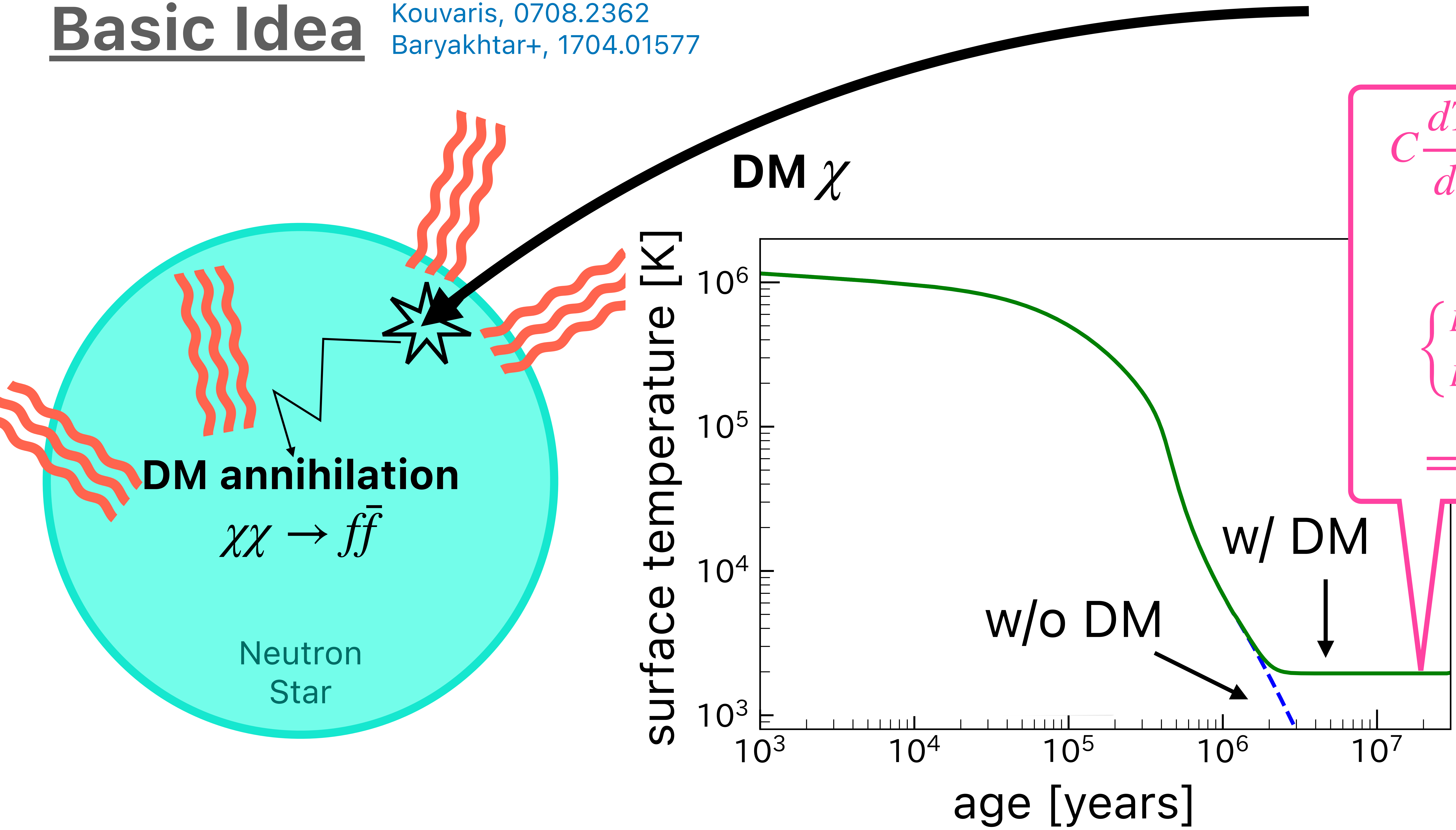
② NS cooling by **Axion**

① NS heating by **DM**

① NS heating by DM

Basic Idea

Kouvaris, 0708.2362
Baryakhtar+, 1704.01577



$$C\frac{dT}{dt} = \underbrace{-L_\nu}_{\ll L_\gamma} \underbrace{-L_\gamma + L_{\text{DM heating}}}_{\simeq 0}$$

$$\begin{cases} L_\gamma = 4\pi R_{\text{NS}}^2 \sigma_{\text{SB}} T^4 \\ L_{\text{DM}} = \pi b^2 \rho_{\text{DM}} v_{\text{DM}} \quad (b \simeq 10^3 R_{\text{NS}}) \end{cases}$$

$$\Longrightarrow T \sim \text{a few } 1000 \text{ K}$$

Old and warm NS = DM signal ?!

① NS heating by DM

Example

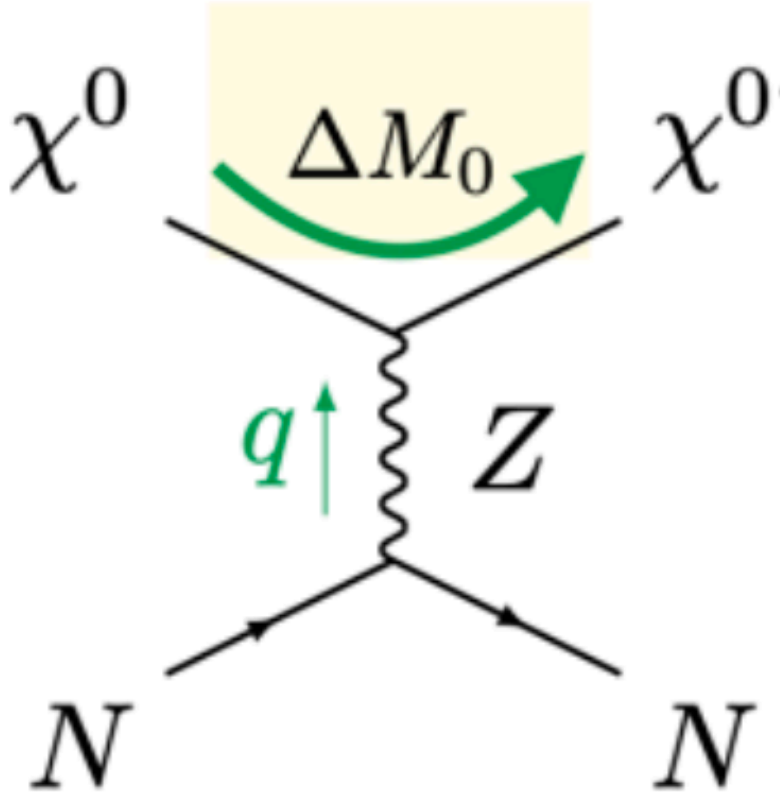
- **Electroweak multiplet DM** Fujiwara, KH, Nagata, Zheng [2204.02238]

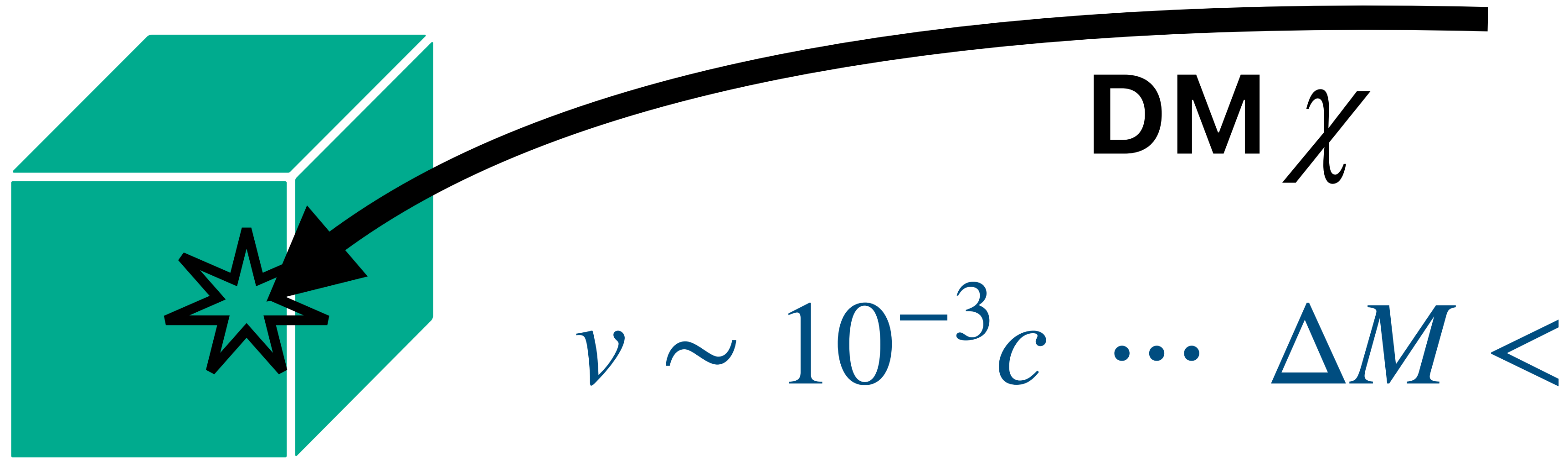
  e.g., Wino and Higgsino in SUSY

  The masses of the DM χ and its partner χ' are degenerate, $\Delta M \ll M_\chi$.

→ Inelastic scattering is important.

inelastic scattering





direct detection experiments

$v \sim 10^{-3}c \;\cdots\; \Delta M < \mathcal{O}(100)$ keV is necessary for inelastic scattering.

NS

$v \sim c \;\cdots\; \Delta M < \mathcal{O}(100)$ MeV is necessary for inelastic scattering.

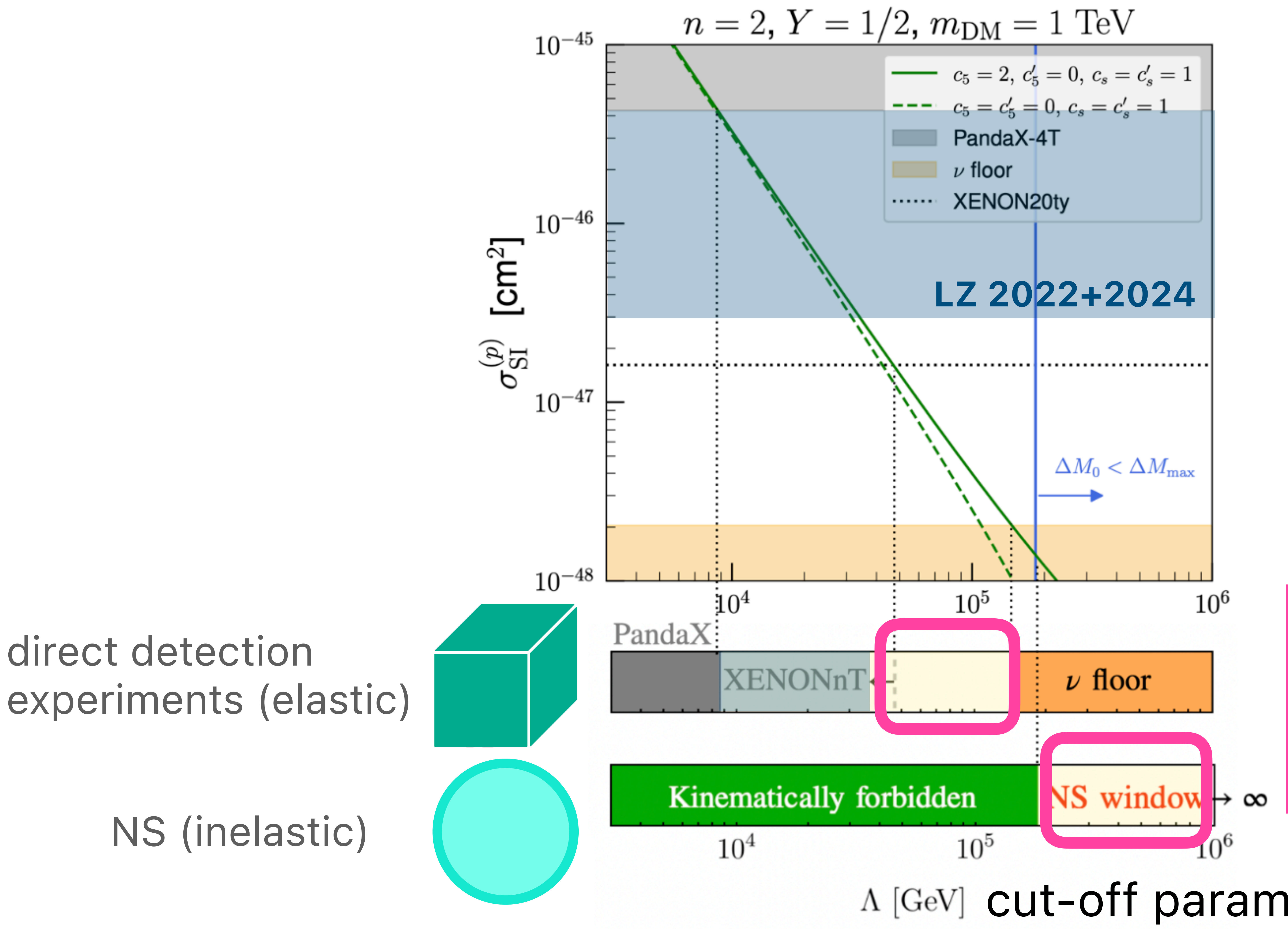
NS is much more sensitive to inelastic scattering.

① NS heating by DM

Example

- **Electroweak multiplet DM**

Fujiwara, KH, Nagata, Zheng [2204.02238]



cut-off parameter

Direct detection and NS heating can play complementary roles.

① NS heating by DM

Challenge

$$C\frac{dT}{dt} \simeq -L_\gamma + L_{\text{DM heating}} + \underline{L_{\text{internal heating}}}$$

There may be some **internal NS heating mechanisms.**

(...motivated by observations of old and warm NSs.)

We studied two kinds of such internal heatings and their effects on DM probe.

Rotochemical heating vs DM heating

KH, N. Nagata, K. Yanagi

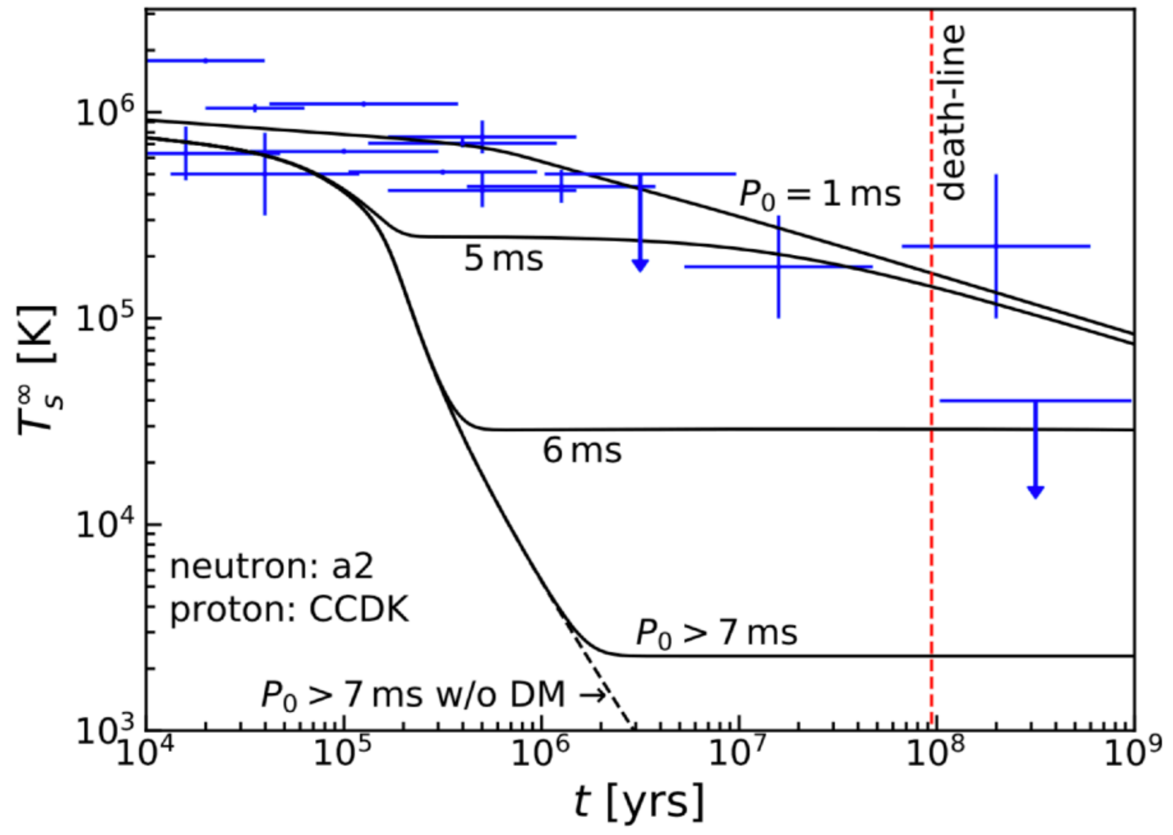
[1904.04667] +[1905.02991]

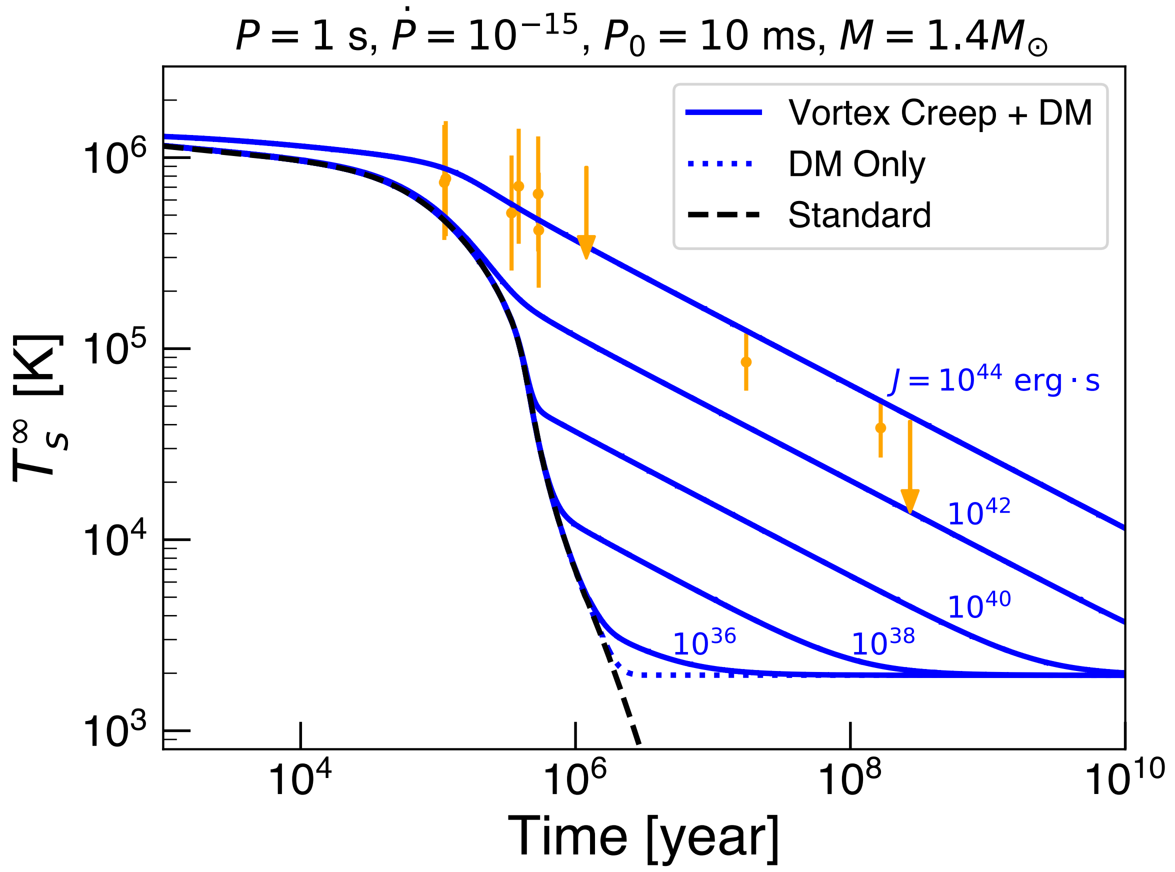
Vortex Creep heating vs DM heating

M. Fujiwara, KH, N. Nagata, M. Ramirez-Quezada

[2308.16066] + [2309.02633]

👉 (more details in backup slides..)



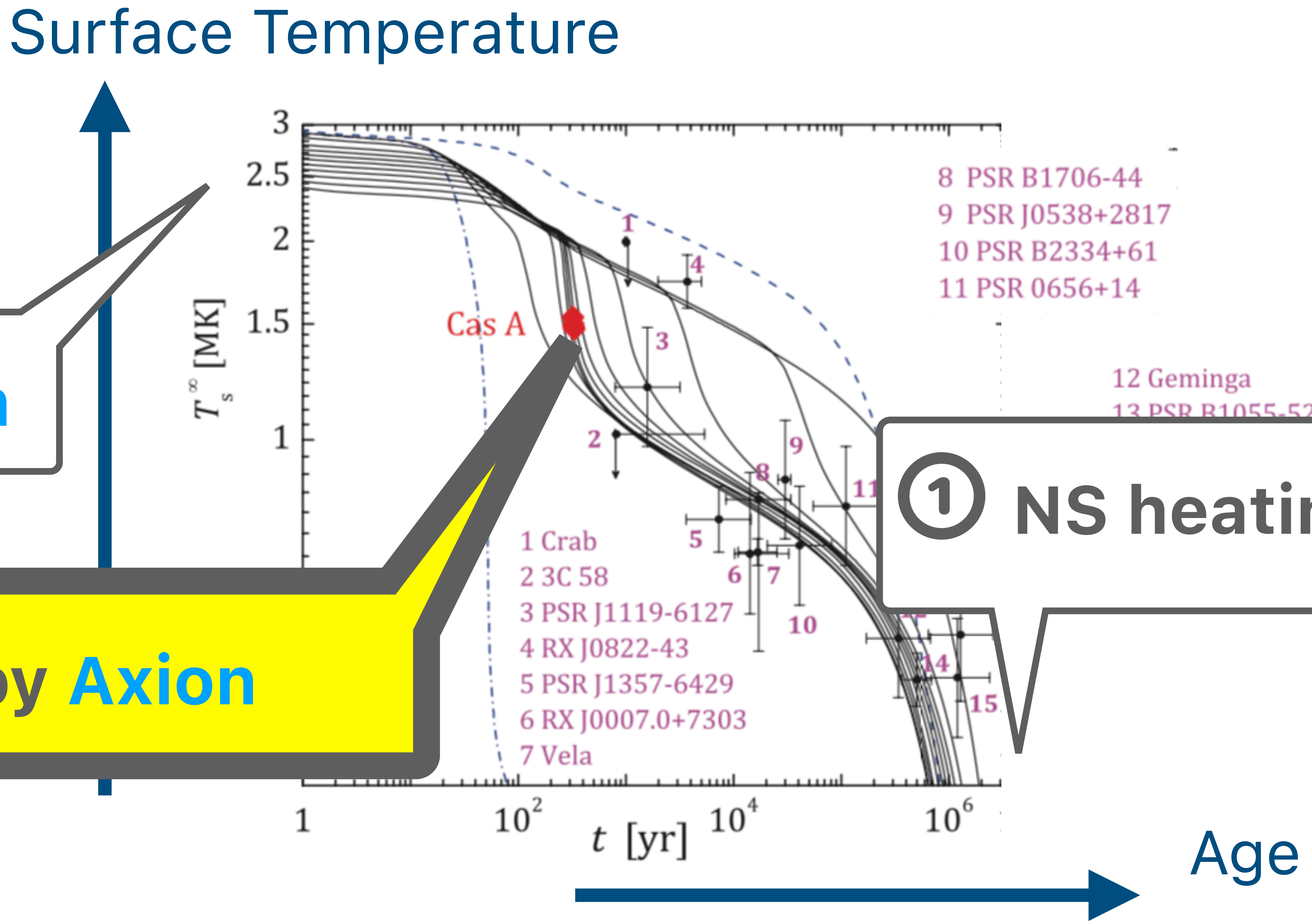


DM signal may be masked depending on the scenario and parameters.

→ Further studies of NSs, both theoretical and observational, are crucial for verification.

This talk

$$C\frac{dT}{dt} = -L_\nu - L_\gamma \pm L_{\text{new physics}}$$



③ **Supernova Axion**

② **NS cooling by Axion**

① **NS heating by DM**

② NS cooling by axion

KH, Nagata, Yanagi, Zheng, [1806.07151]

Cas A NS

- At the centre of the Cassiopeia A supernova remnant.
- ～ 340 yrs old. (A young NS.)
- The only isolated NS whose **cooling has been observed in real time.**

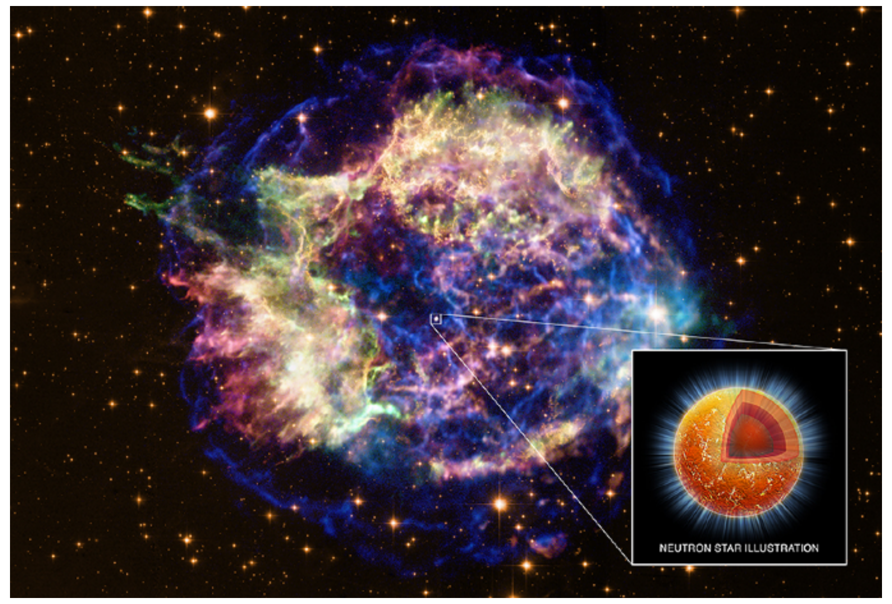
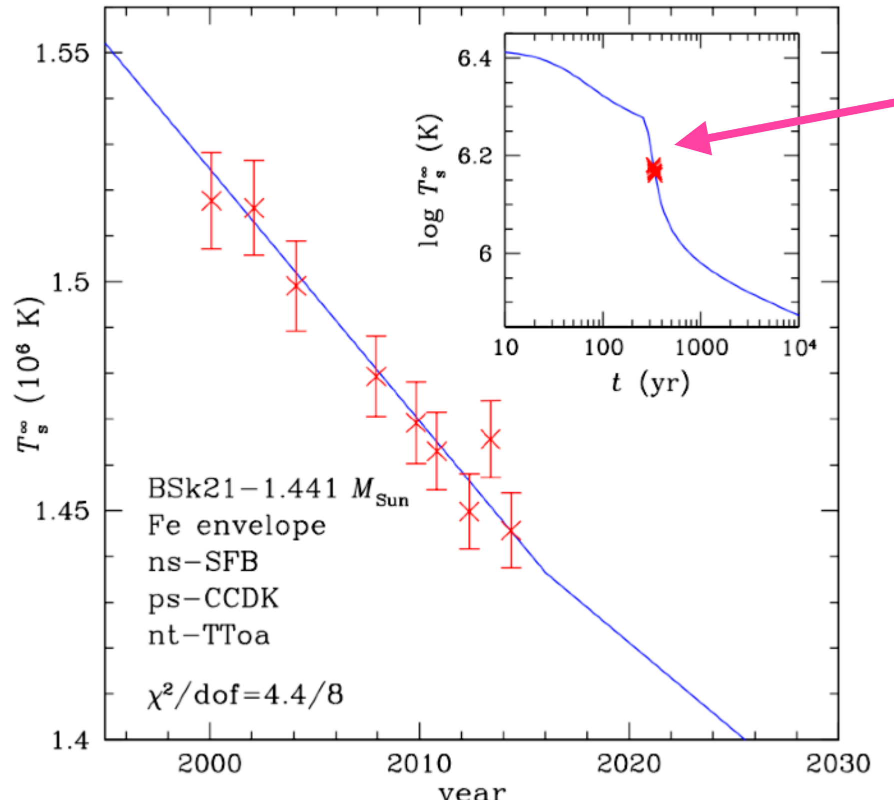


image from Wikipedia

- Temperature decreases by (3-4)% in 10 years.
- This rapid cooling is difficult to explain with M.Urca.
- It can be explained by the PBF process.
- **"Evidence of superfluidity in NS".**

D. Page +, 1011.6142 [Phys.Rev.Lett.].
P. S. Shternin +, 1012.0045 [MNRAS].
See also: Posselt+, 1311.0888, Posselt and G.G.Pavlov, 1808.00531, 2205.06552, W.C.G.Ho+. 1904.07505, Shternin+, 2211.02526.



phase transition $T = T_C$
sudden, rapid cooling by PBF neutrino emission.

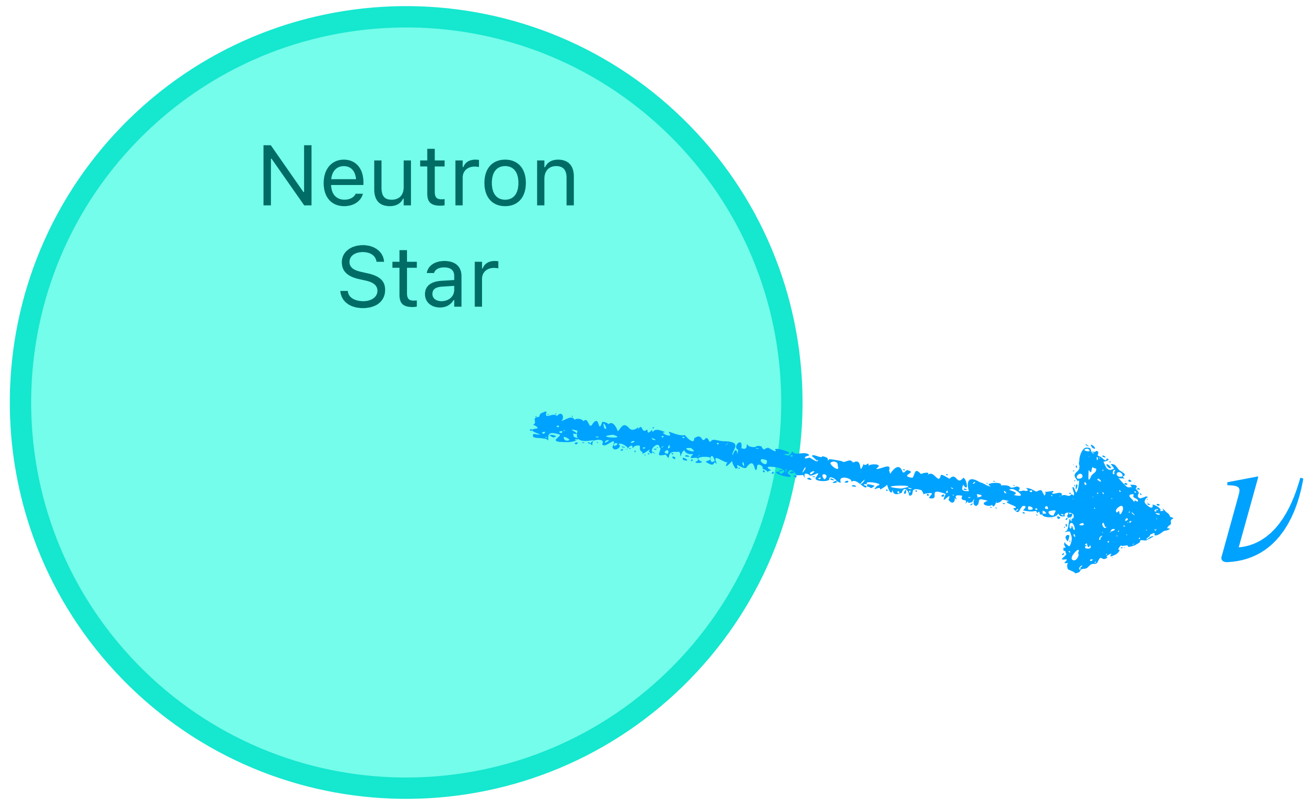
Fig. from W.C.G.Ho+, 1412.7759.

② NS cooling by axion

KH, Nagata, Yanagi, Zheng, [1806.07151]

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

negligible for $\tau \sim 300$ yrs

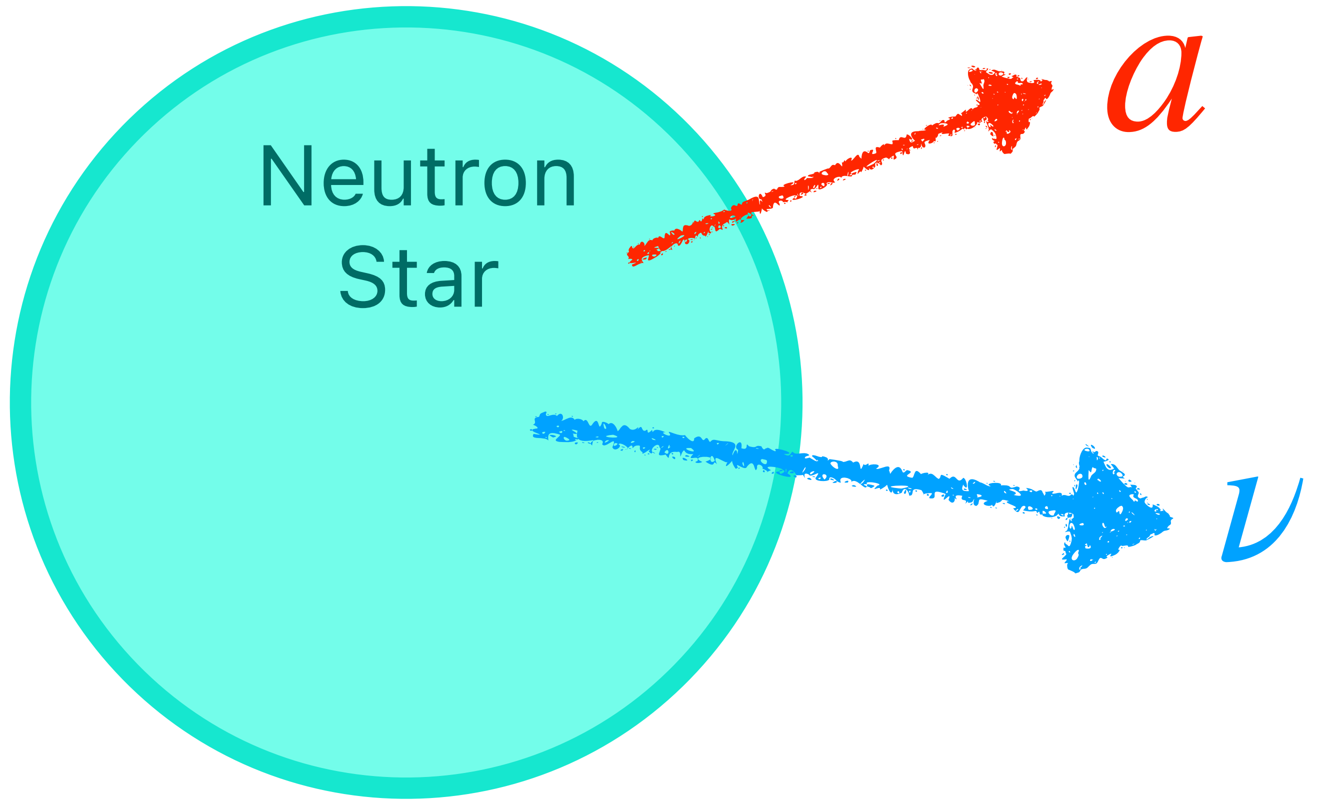


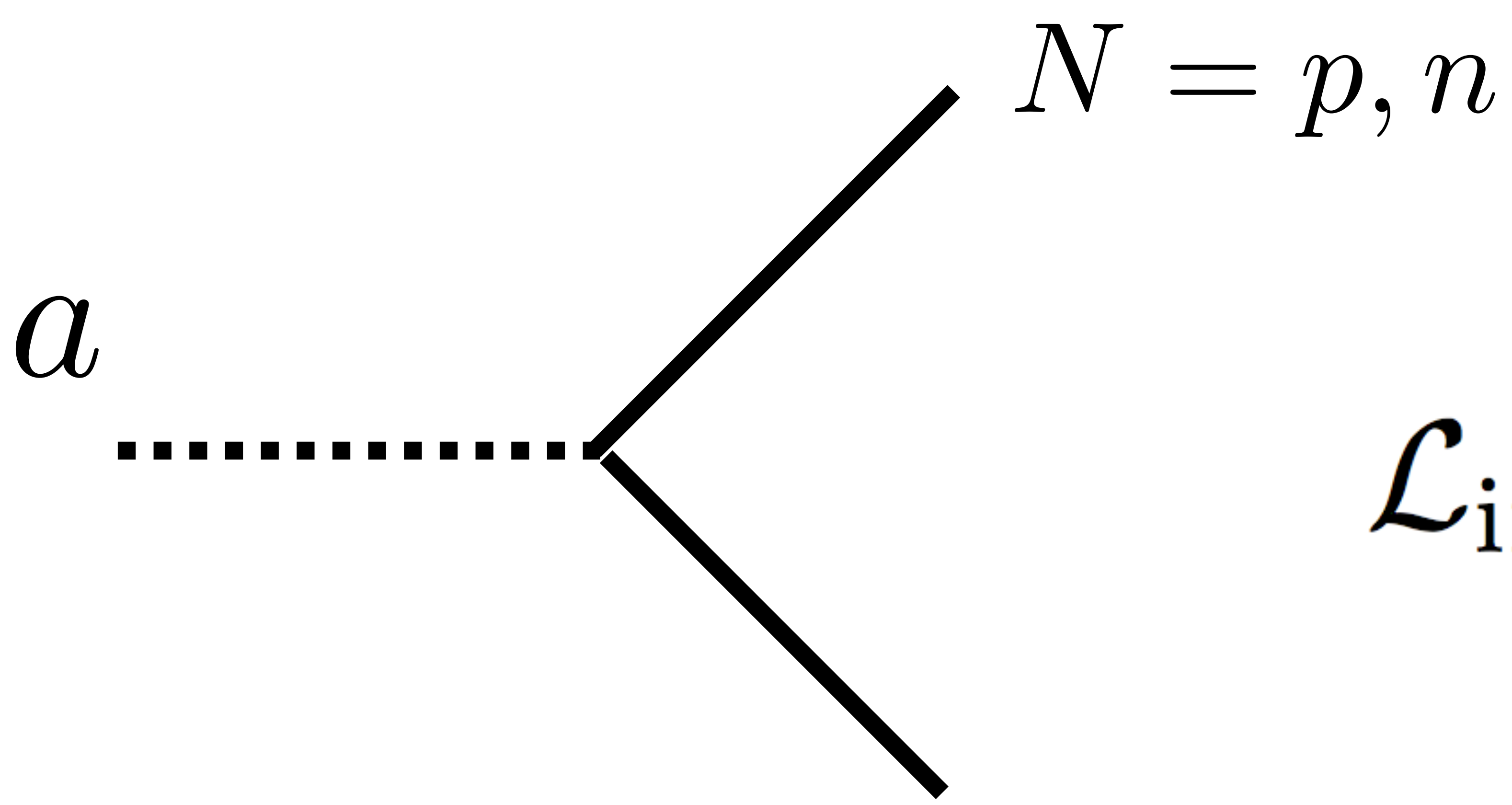
② NS cooling by axion

KH, Nagata, Yanagi, Zheng, [1806.07151]

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

axion emission





$$\mathcal{L}_{\text{int}} = \sum_{N=p,n} \frac{C_N}{2f_a} \bar{N}\gamma^\mu\gamma_5 N\partial_\mu a$$

$$\text{interaction} \propto \frac{1}{f_a}$$

C_N : model−dependent parameter

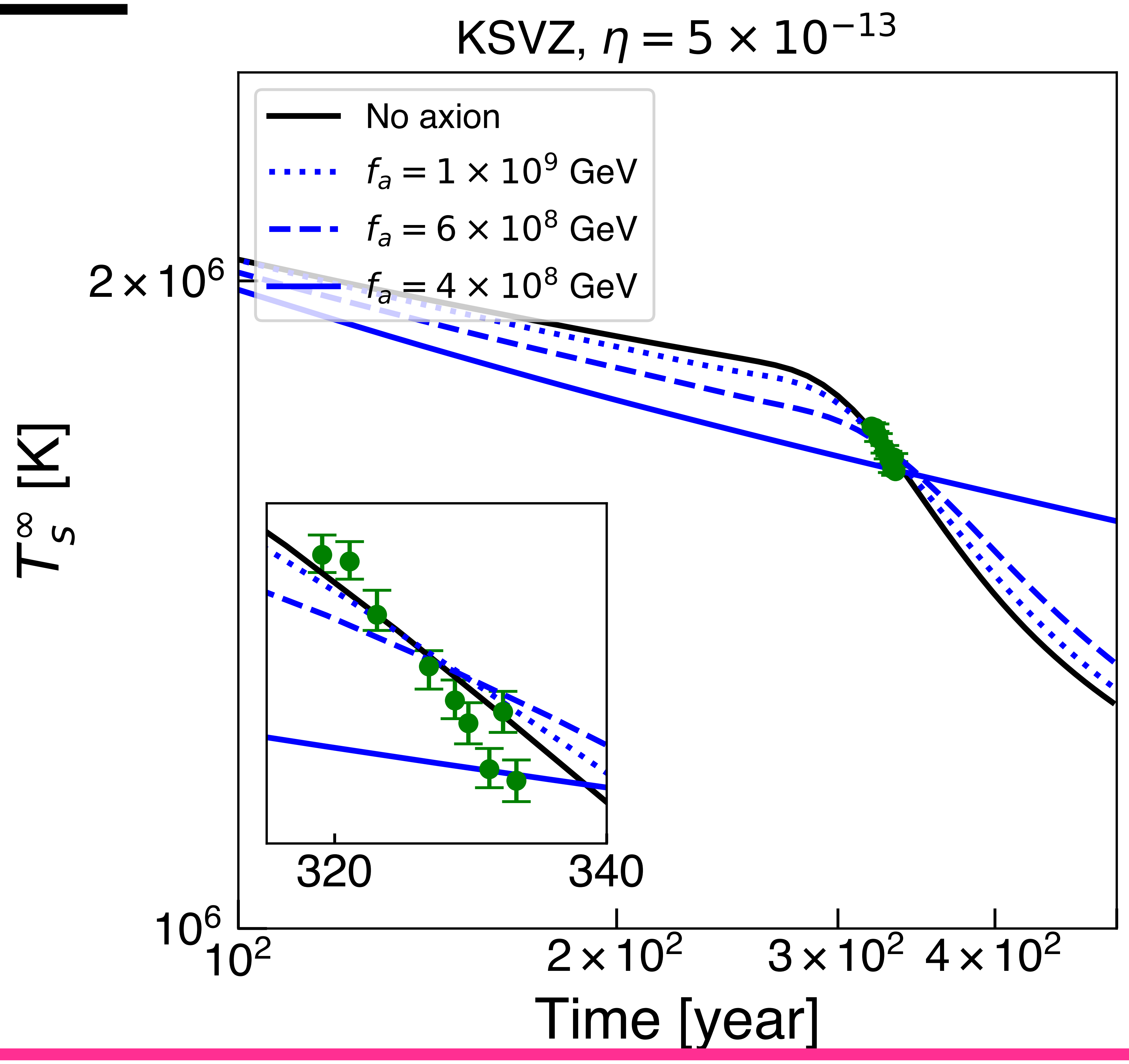
$$\text{KSVZ: } \begin{cases} C_p = -0.47(3) \\ C_n = -0.02(3) \end{cases}$$

$$\text{DFSZ: } \begin{cases} C_p = -0.182(25) - 0.435\sin^2\beta \\ C_n = -0.160(25) - 0.414\sin^2\beta \end{cases}$$

② NS cooling by axion

KH, Nagata, Yanagi, Zheng, [1806.07151]

Results



K. Hamaguchi,
N. Nagata,
K. Yanagi,
J. Zheng,
1806.07151

$$\text{interaction} \propto \frac{1}{f_a}$$

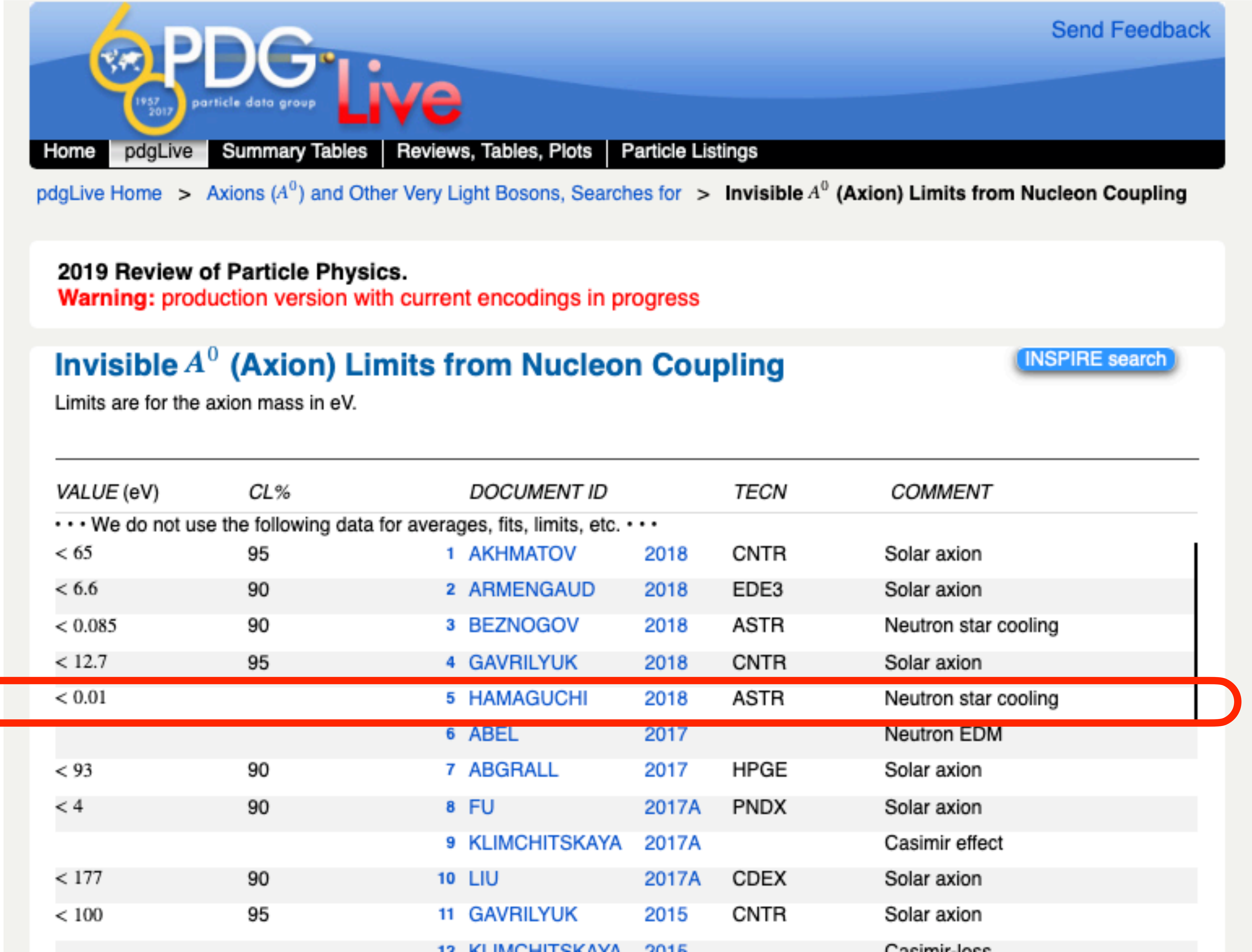
obtained a new bound: $f_a \gtrsim 5 \times 10^8 \text{ GeV (KSVZ)}$

(for an envelope with a thin carbon layer)

cf. SN1987A bound: $f_a \gtrsim 4 \times 10^8$ GeV

② NS cooling by axion

KH, Nagata, Yanagi, Zheng, [1806.07151]



pdgLive Home > Axions (A^0) and Other Very Light Bosons, Searches for > **Invisible A^0 (Axion) Limits from Nucleon Coupling**

2019 Review of Particle Physics.
Warning: production version with current encodings in progress

Invisible A^0 (Axion) Limits from Nucleon Coupling

Limits are for the axion mass in eV.

VALUE (eV)	*CL%*	*DOCUMENT ID*			*TECN*	*COMMENT*
• • • We do not use the following data for averages, fits, limits, etc. • • •						
< 65	95	1	AKHMATOV	2018	CNTR	Solar axion
< 6.6	90	2	ARMENGAUD	2018	EDE3	Solar axion
< 0.085	90	3	BEZNOGOV	2018	ASTR	Neutron star cooling
< 12.7	95	4	GAVRILYUK	2018	CNTR	Solar axion
< 0.01		5	HAMAGUCHI	2018	ASTR	Neutron star cooling
		6	ABEL	2017		Neutron EDM
< 93	90	7	ABGRALL	2017	HPGE	Solar axion
< 4	90	8	FU	2017A	PNDX	Solar axion
		9	KLIMCHITSKAYA	2017A		Casimir effect
< 177	90	10	LIU	2017A	CDEX	Solar axion
< 100	95	11	GAVRILYUK	2015	CNTR	Solar axion
		12	KLIMCHITSKAYA	2015		Casimir-less

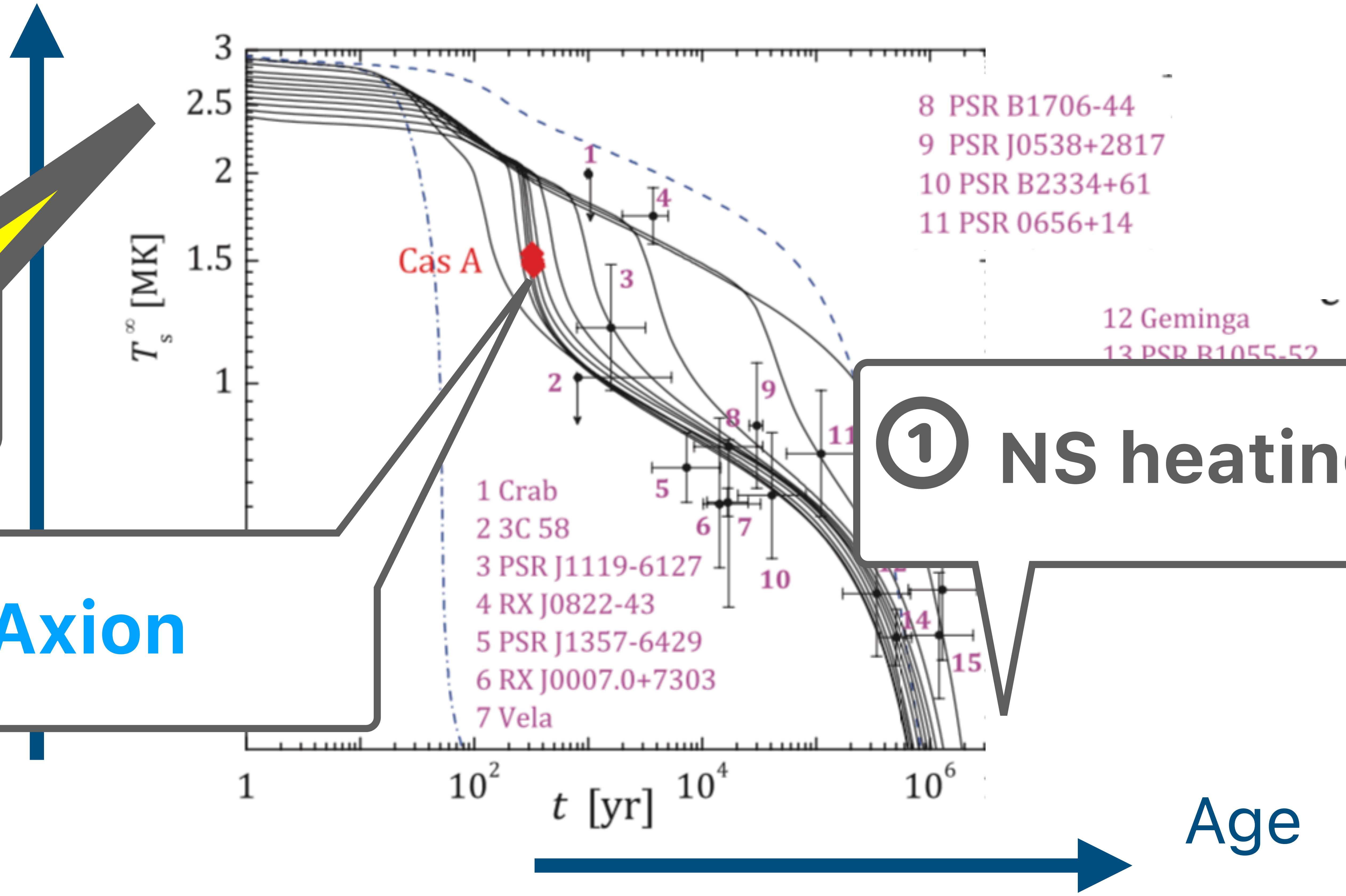
K. Hamaguchi, N. Nagata, K. Yanagi, J. Zheng, 1806.07151

See also:
- M. V. Beznogov+ [1806.07991].
- L. B. Leinson, [1909.03941] [2105.14745].
- Buschmann+, [2111.09892]

+ K. Hamaguchi, N. Nagata, J. Zheng, work in progress

This talk

$$C\frac{dT}{dt} = -L_\nu - L_\gamma \pm L_{\text{new physics}}$$



Surface Temperature

Age

① NS heating by **DM**

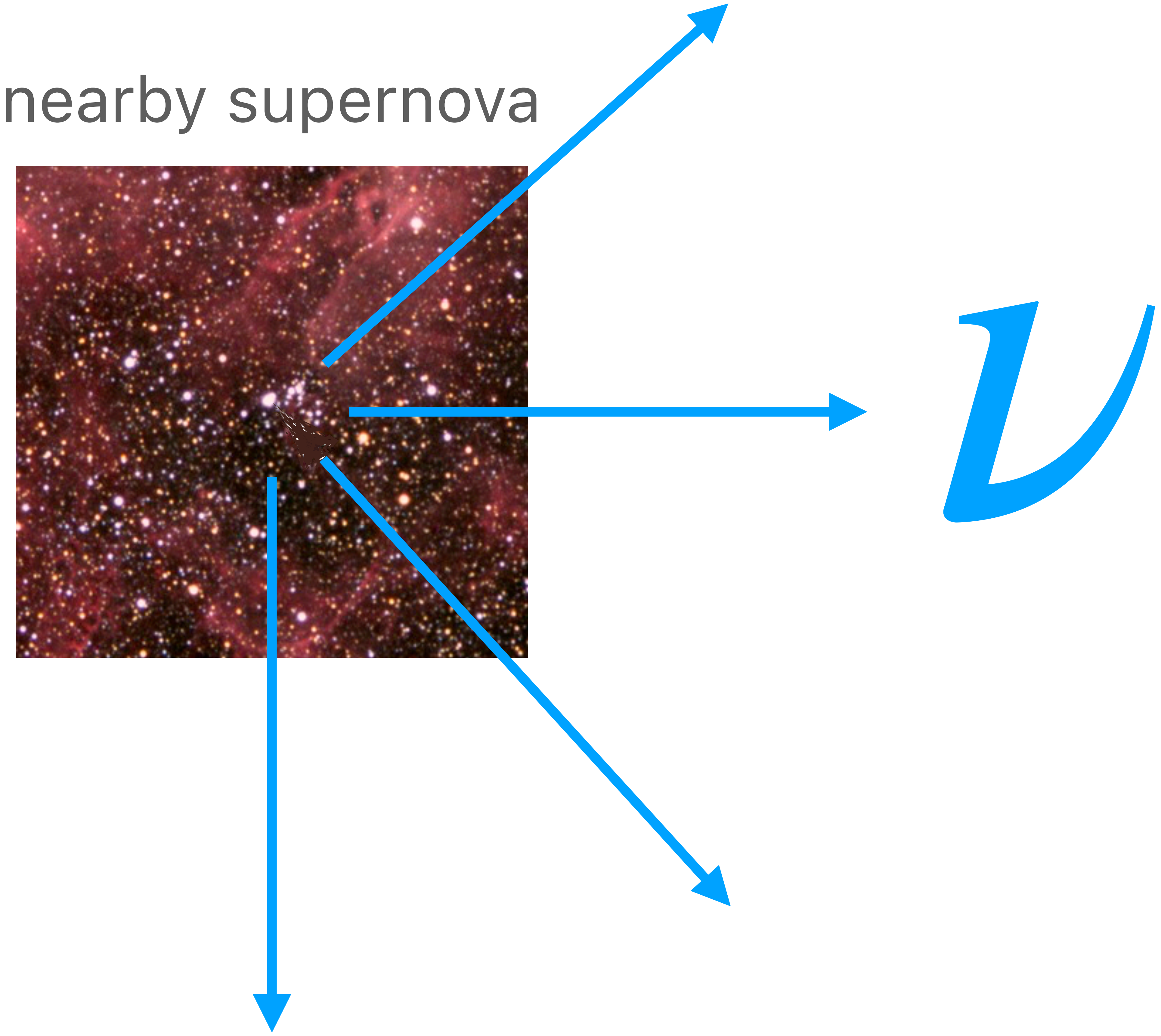
② NS cooling by **Axion**

③ Supernova **Axion**

③ Supernova **Axion**

- What if **a nearby supernova** occurs in near future?

nearby supernova

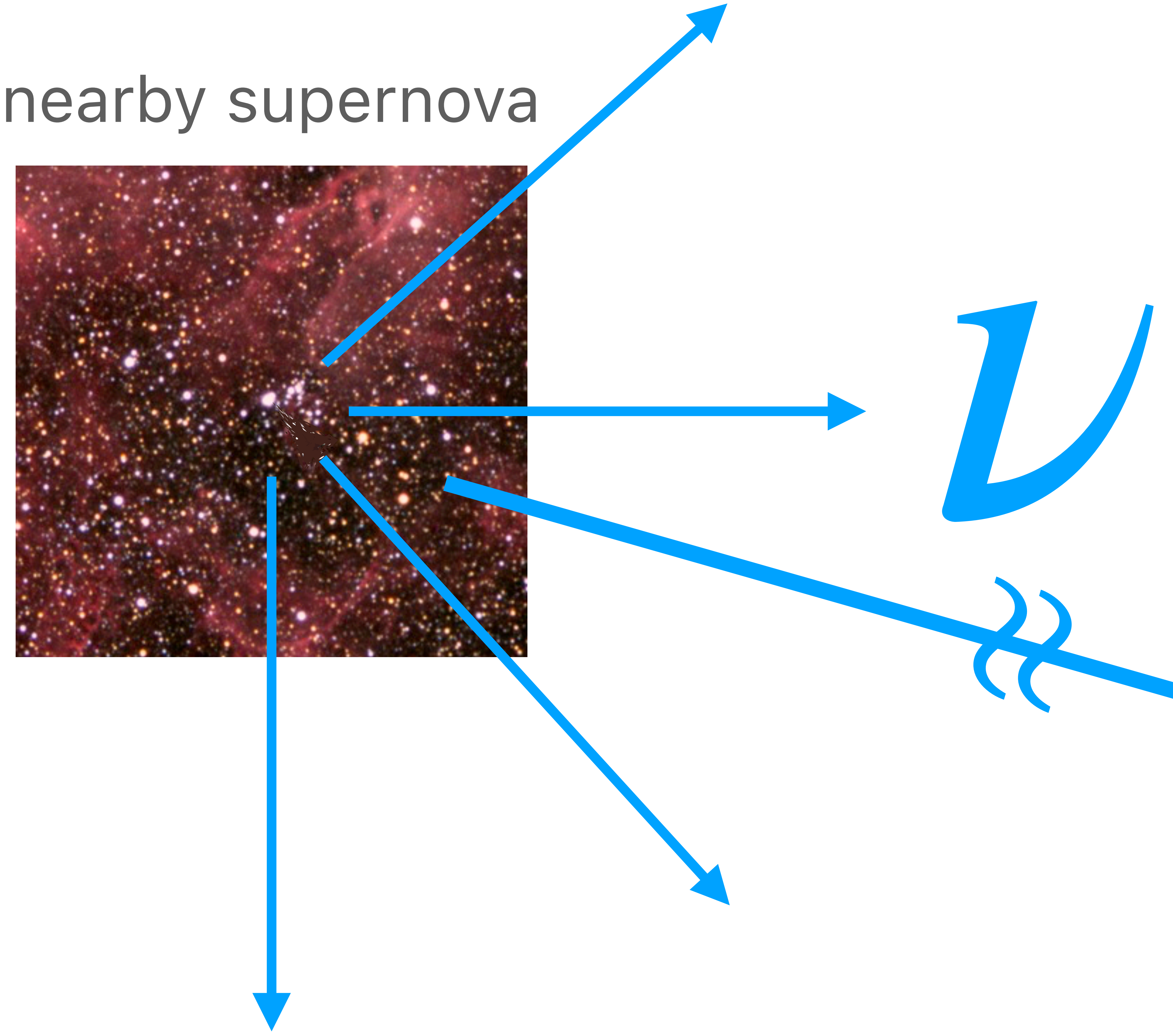


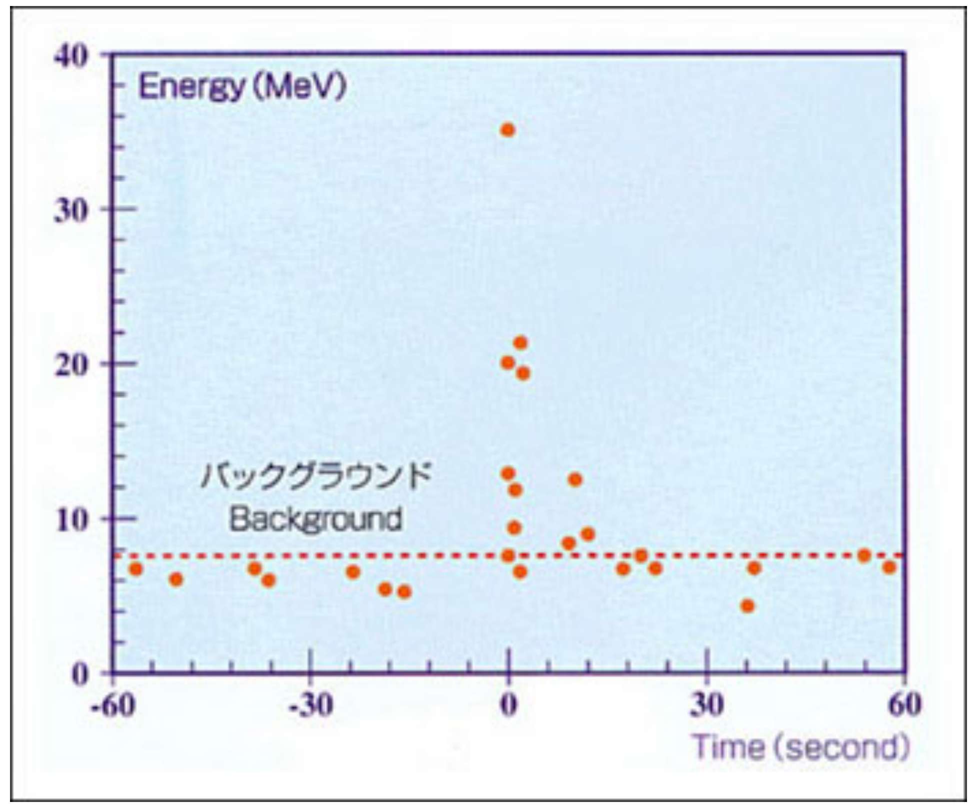
③ Supernova Axion

- What if **a nearby supernova** occurs in near future?

cf. Mark Vagins-san's talk on yesterday.

nearby supernova





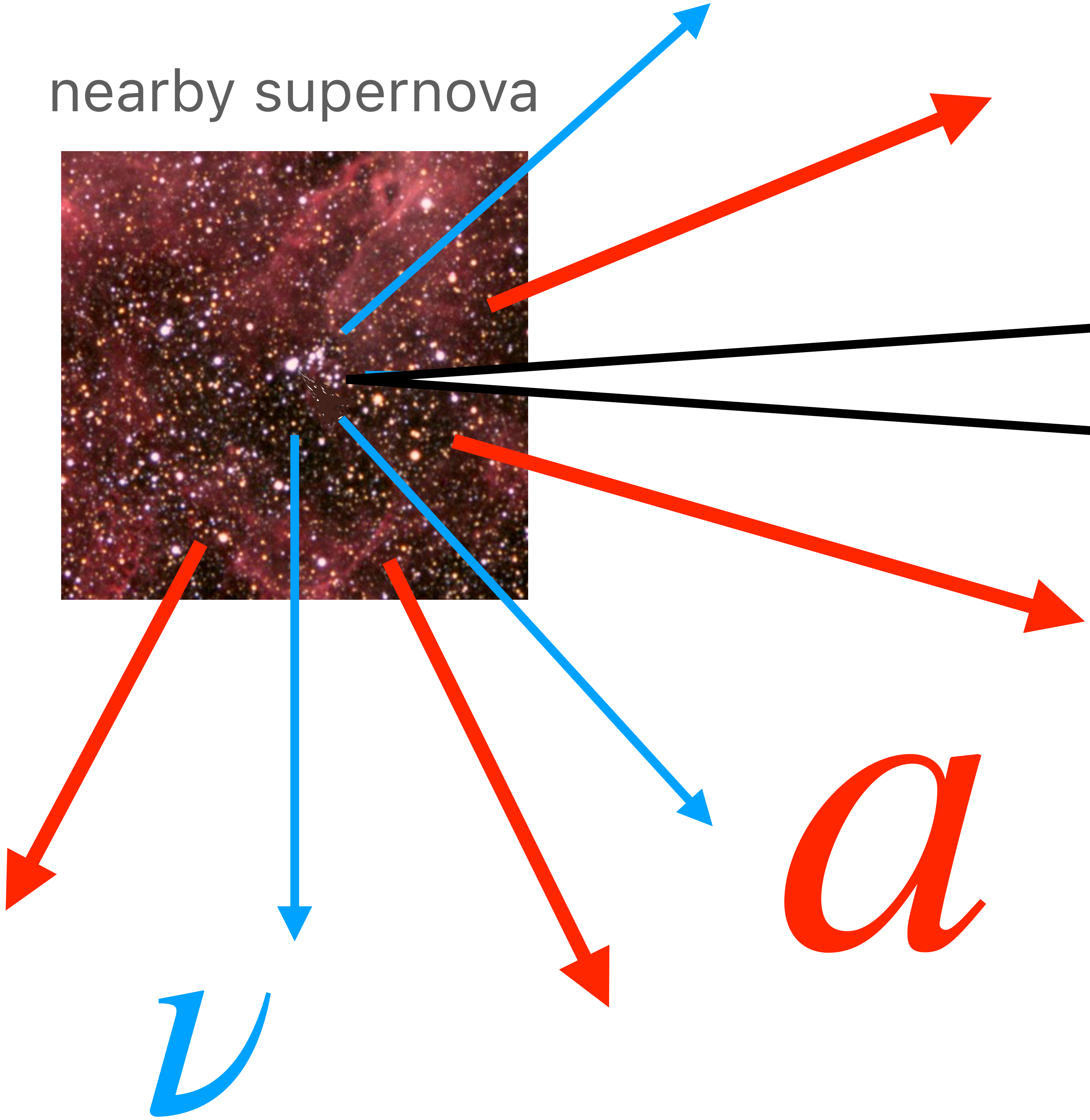
- SN1987A

neutrino burst within $\Delta t \simeq 10$ sec.

- Future: various neutrino detectors

③ Supernova Axion

- What if **a nearby supernova** occurs in near future?

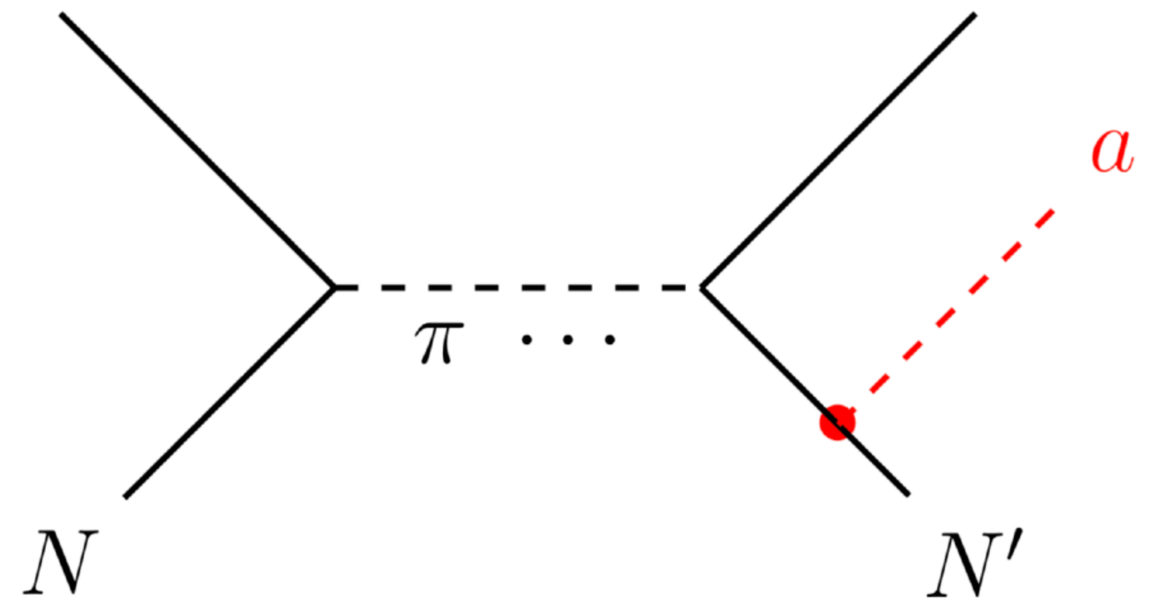


If the axion exists,...

$$NN' \to NN' + a$$

$$(N, N' = n, p)$$

$$\mathcal{L}_{aNN} = \sum_{N=n,p} \frac{C_N}{f_a}\bar{N}\gamma^\mu\gamma^5 N\partial_\mu a$$



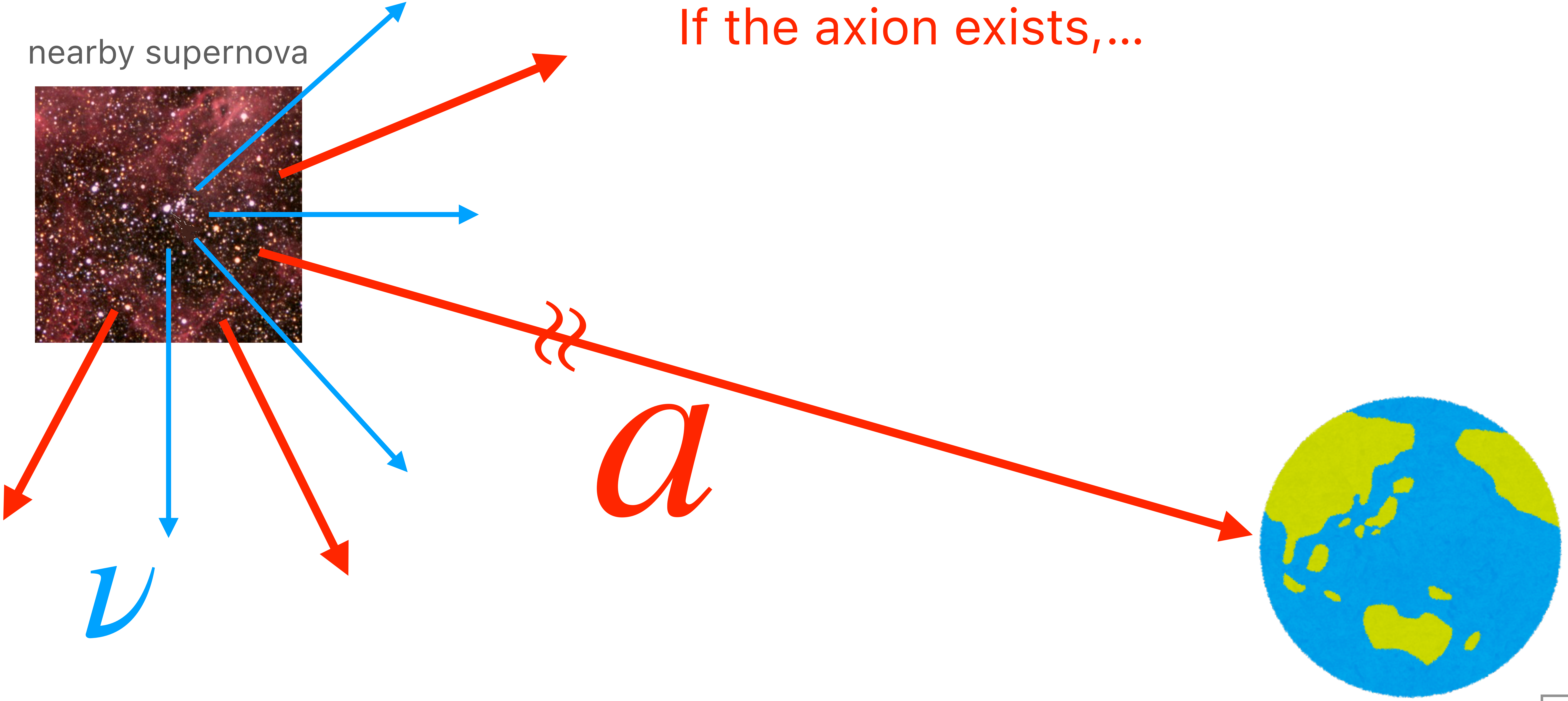
$$\begin{cases} C_p = -0.47 \\ C_n = -0.02 \end{cases} \quad \text{(KSVZ)}$$

$$\begin{cases} C_p = -0.182 - 0.435\sin^2\beta \\ C_n = -0.160 + 0.414\sin^2\beta \end{cases} \quad \text{(DFSZ)}$$

③ Supernova Axion

- What if **a nearby supernova** occurs in near future?

If the axion exists,…



③ Supernova Axion

- What if **a nearby supernova** occurs in near future?

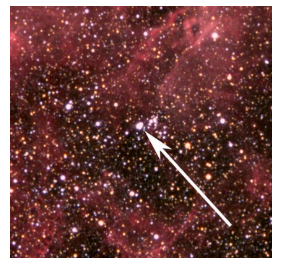
$$\mathscr{L}_{a\gamma\gamma} = \frac{1}{4}\frac{C_{a\gamma\gamma}}{f_a} a F_{\mu\nu}\widetilde{F}^{\mu\nu}$$

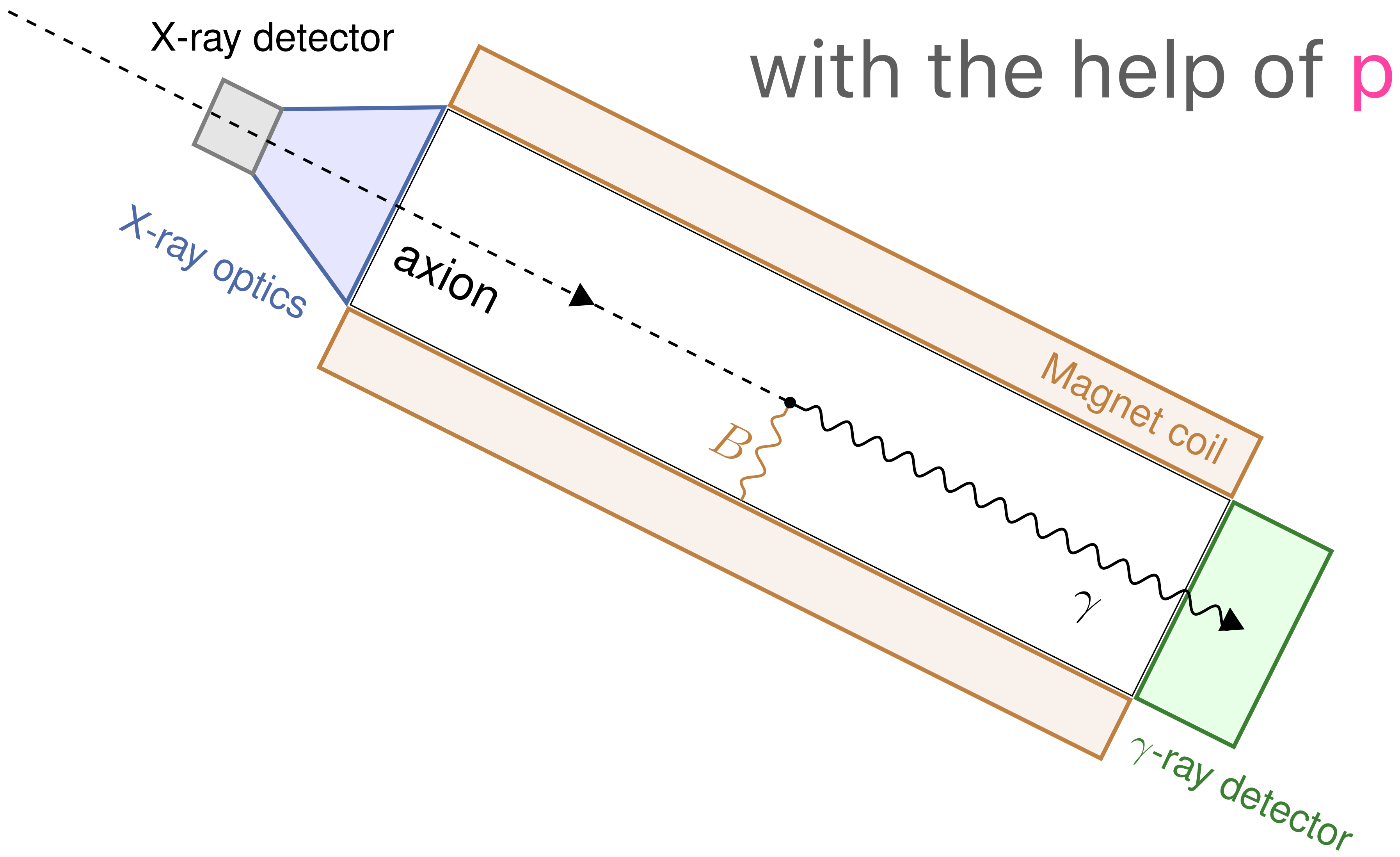
③ Supernova Axion

- What if **a nearby supernova** occurs in near future?

※ extremely rare!
cf. Mark Vagins-san's talk yesterday.

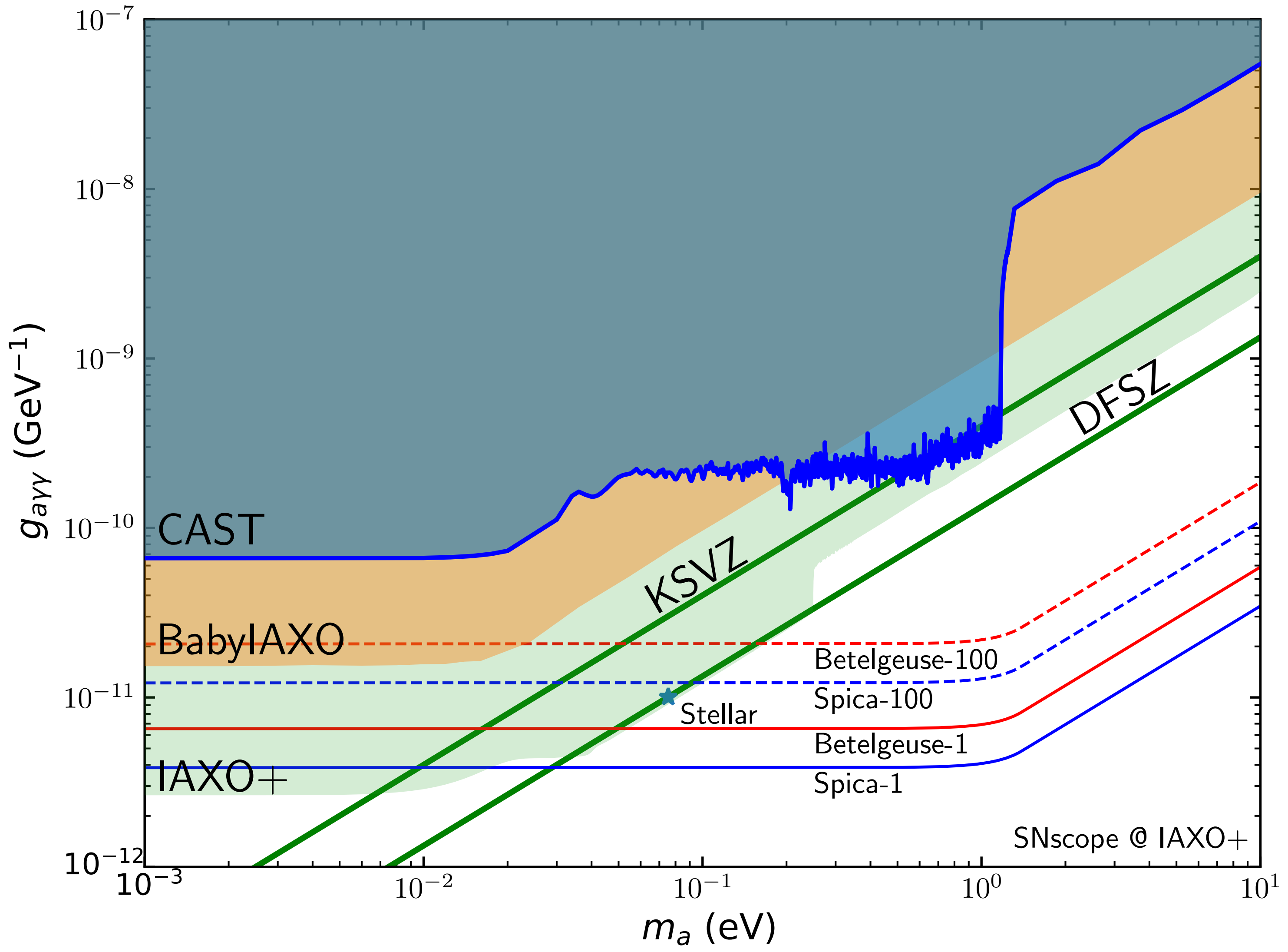
We have shown that, if a nearby (< a few 100pc) supernova (SN), such as Betelgeuse, occurs,..





...by using a "axion Supernova scope",
with the help of pre-SN neutrino alert,...

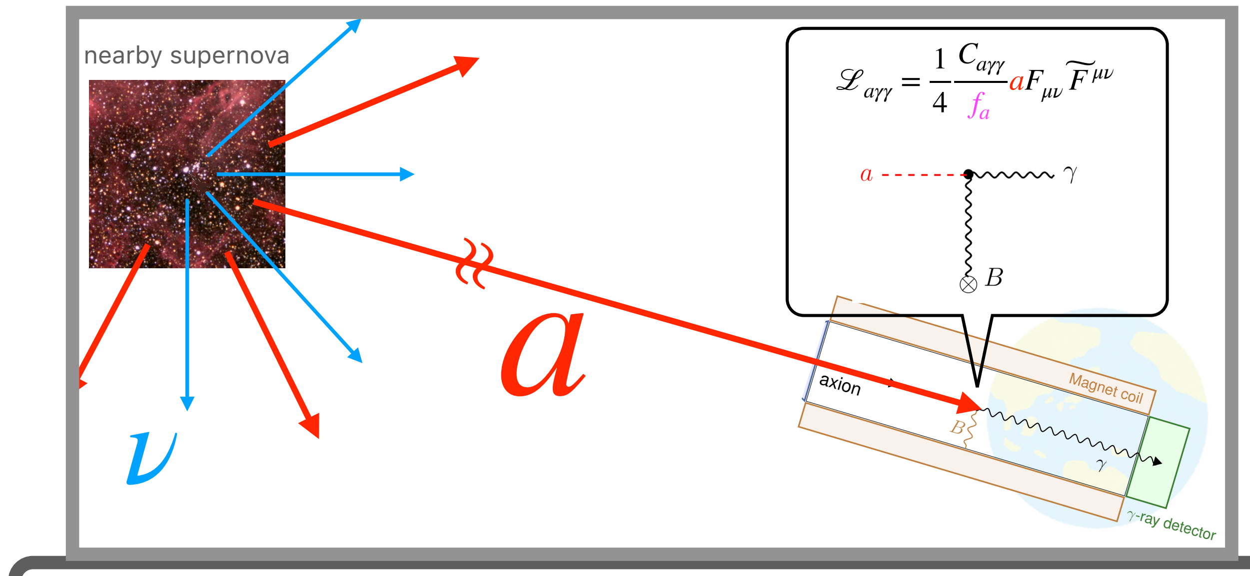
...O(1-10) SN axions may be detected!



"Supernova-scope for the Direct Search of Supernova Axions"
S.Ge, KH, K.Ichimura, K.Ishidoshiro, Y.Kanazawa, Y.Kishimoto, N.Nagata, J.Zheng, [arXiv:2008.03924]

Summary

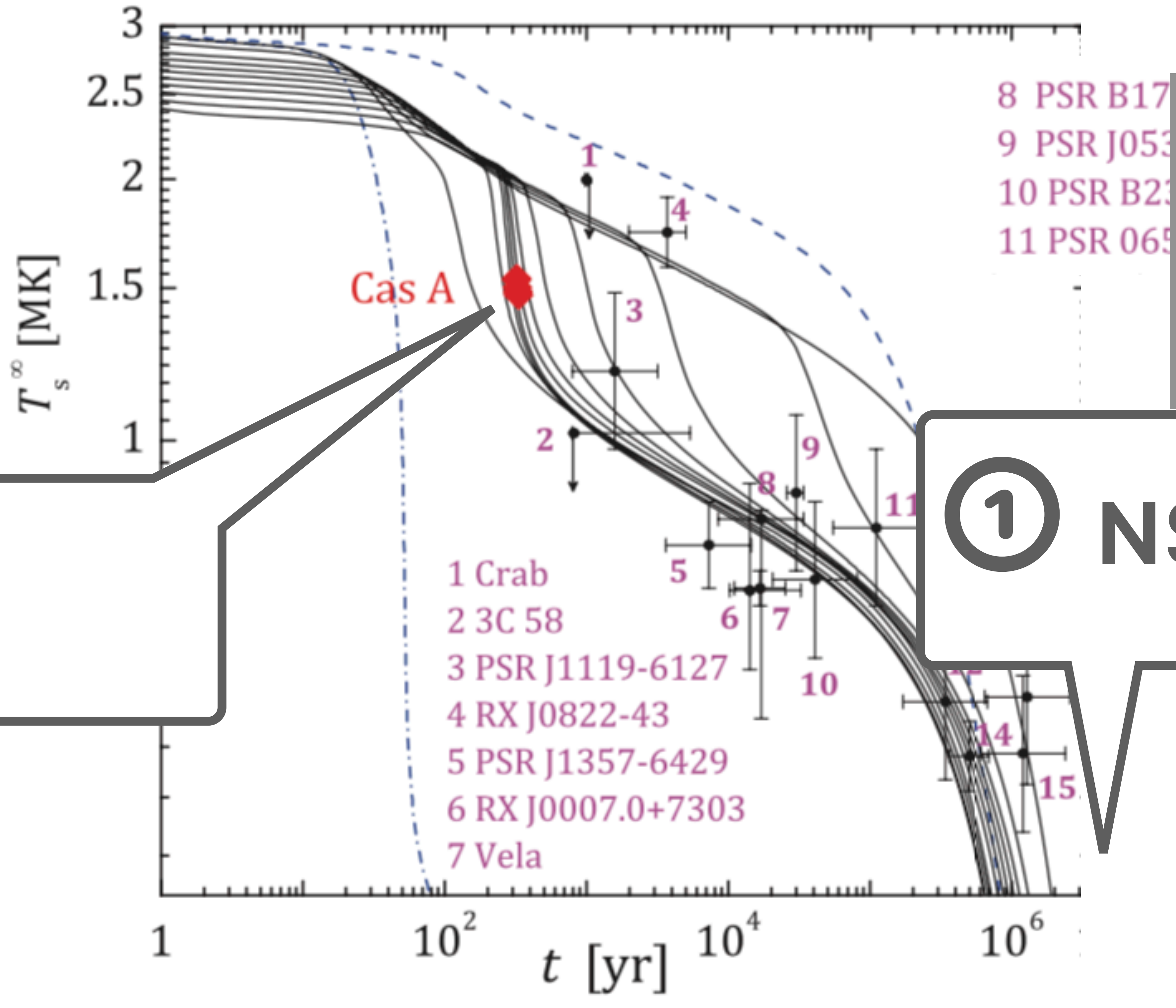
$$C\frac{dT}{dt} = -L_\nu - L_\gamma \pm L_{\text{new physics}}$$

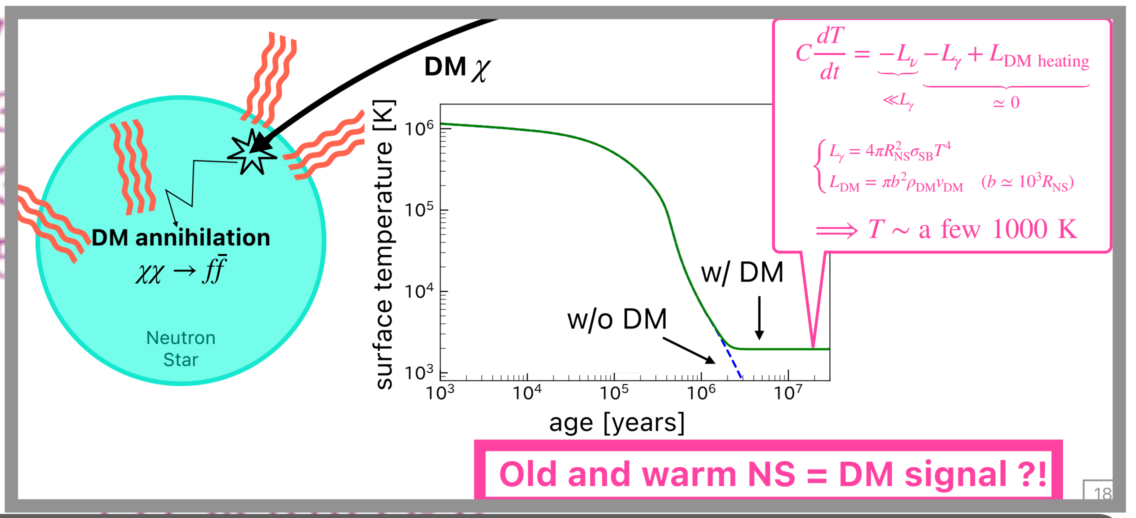


$$\mathscr{L}_{a\gamma\gamma} = \frac{1}{4}\frac{C_{a\gamma\gamma}}{f_a} a F_{\mu\nu}\widetilde{F}^{\mu\nu}$$

③ **Supernova Axion**

Surface Temperature





$$C\frac{dT}{dt} = \underbrace{-L_\nu}_{\ll L_\gamma} \underbrace{-L_\gamma + L_{\text{DM heating}}}_{\simeq 0}$$

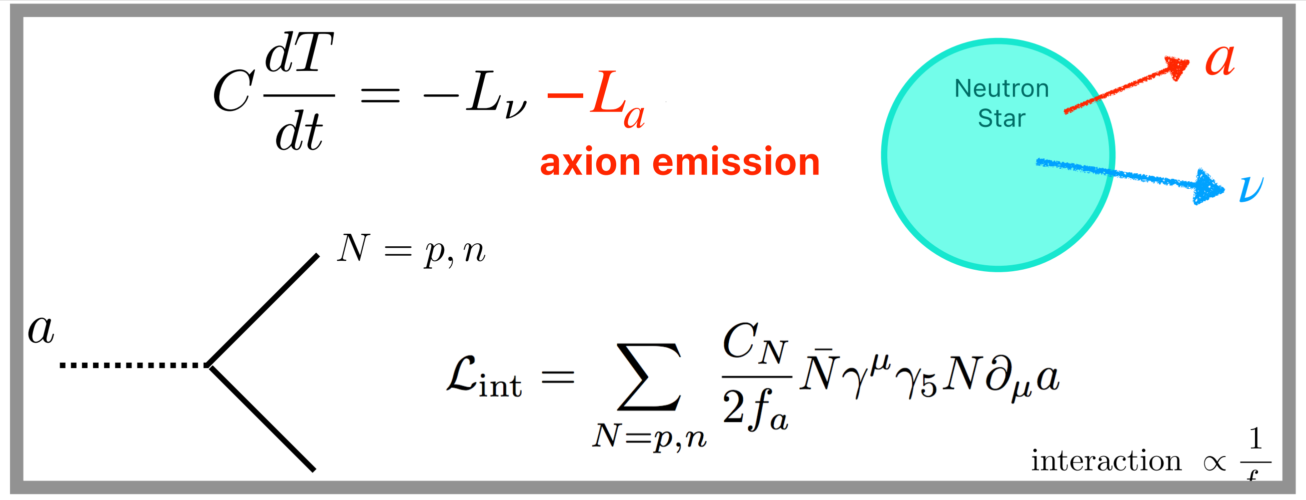
$$\begin{cases} L_\gamma = 4\pi R_{\text{NS}}^2 \sigma_{\text{SB}} T^4 \\ L_{\text{DM}} = \pi b^2 \rho_{\text{DM}} v_{\text{DM}} \quad (b \simeq 10^3 R_{\text{NS}}) \end{cases}$$

$\Longrightarrow T \sim$ a few 1000 K

Old and warm NS = DM signal ?!

① **NS heating by DM**

② **NS cooling by Axion**



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

axion emission

$$\mathcal{L}_{\text{int}} = \sum_{N=p,n} \frac{C_N}{2f_a} \bar{N}\gamma^\mu\gamma_5 N \partial_\mu a$$

interaction $\propto \frac{1}{f}$

Age

Murayama-san,
Thank you very much!
and Happy 60th Birthday!! 🎉🎉🎉