Flaxion, Axion and Neutron Star.

Koichi Hamaguchi (University of Tokyo)

YuCHE 2019 @ Yonsei Univ. Feb. 26, 2019.

Based on

Y. Ema, KH, T. Moroi, K. Nakayama, [arXiv:1612.05492]
Y. Ema, D. Hagihara, KH, T. Moroi, K. Nakayama, [arXiv:1802.07739]

KH, N. Nagata, K. Yanagi, J. Zheng, [arXiv:1806.07151]

Axion

- Strong CP problem

$$\mathcal{L}_\theta = \frac{\alpha_s}{8\pi}\theta\, F_a^{\mu\nu}\widetilde{F}_{a\mu\nu}, \quad \bar{\theta} = \theta + \arg\det m_q$$

$\underline{|\bar{\theta}| \lesssim 10^{-10}}$ from neutron EDM

Why?

The most serious fine-tuning problem in the SM.

It cannot be explained even by the anthropic discussion.

Axion

- Strong CP problem

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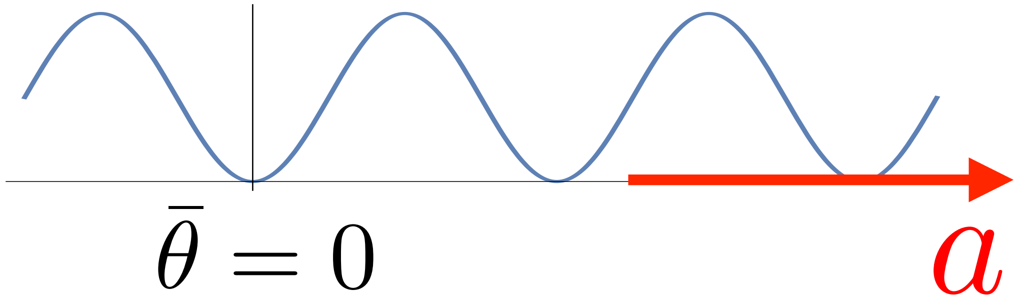
$$\underline{|\bar{\theta}| \lesssim 10^{-10}}$$ from neutron EDM

Why?

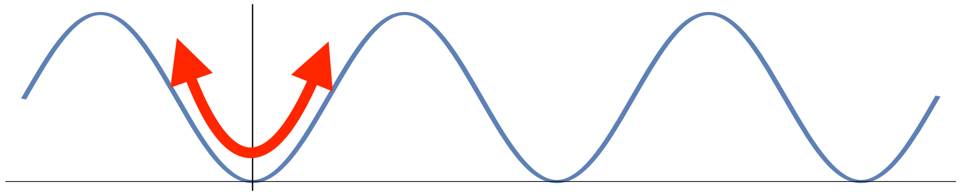
- It can be solved by the PQ mechanism, [Peccei, Quinn,'77]

predicting a very light particle, **Axion**. [Weinberg,'78, Wilczek,'78]

$$\mathcal{L} = \frac{\alpha_s}{8\pi}\frac{a}{f_a}F_a^{\mu\nu}\tilde{F}_{a\mu\nu}$$



- Moreover, **Axion** can be the **Dark Matter.**



$$\Omega_a h^2 = 0.18\,\theta_i^2 \left(\frac{f_a}{10^{12}\,\mathrm{GeV}}\right)^{1.19}.$$

[Turner,'86]

Plan

Part 1. Flaxion

Part 2. Axion and Neutron Star

Part 1. Flaxion

Y. Ema, KH, T. Moroi, K. Nakayama, [arXiv:1612.05492]

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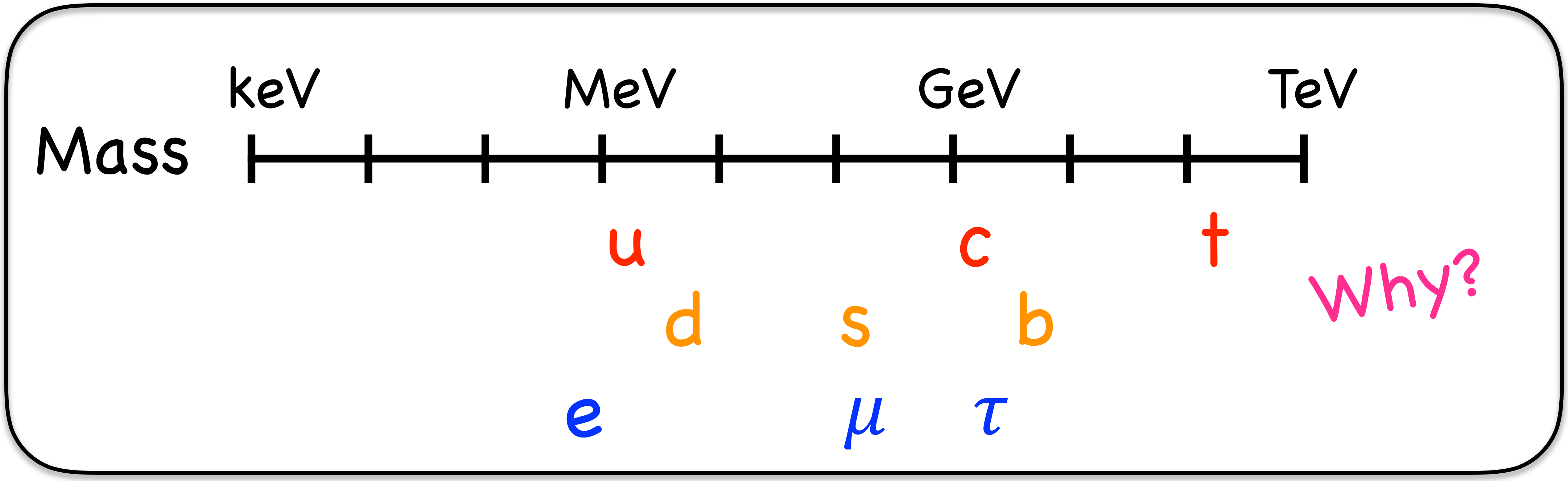
Summary of Part 1: Flaxion

$$U(1)_{FN} = U(1)_{PQ}$$

Summary of Part 1: Flaxion

We proposed a new model (scenario) that explains the hierarchical **flavor** structure of quarks/leptons,



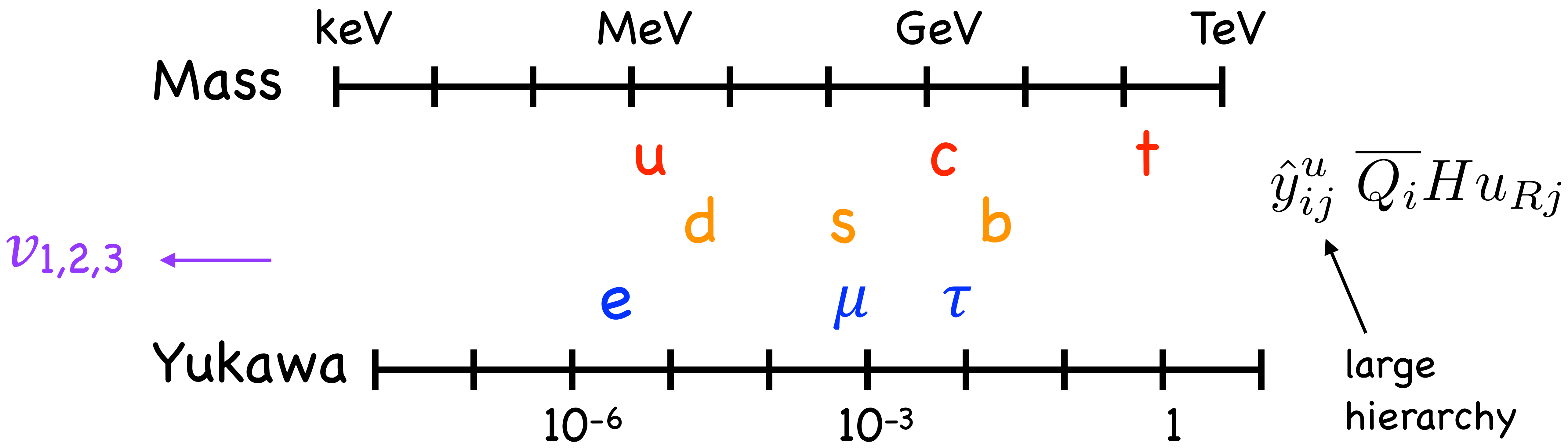
and solves the **strong CP** problem,

$$\mathcal{L}_\theta = \frac{\alpha_s}{8\pi}\theta\, F_a^{\mu\nu}\widetilde{F}_{a\mu\nu}, \quad \bar{\theta} = \theta + \arg\det m_q$$

$\underline{|\bar{\theta}| \lesssim 10^{-10}}$ <u>from neutron EDM</u> Why?

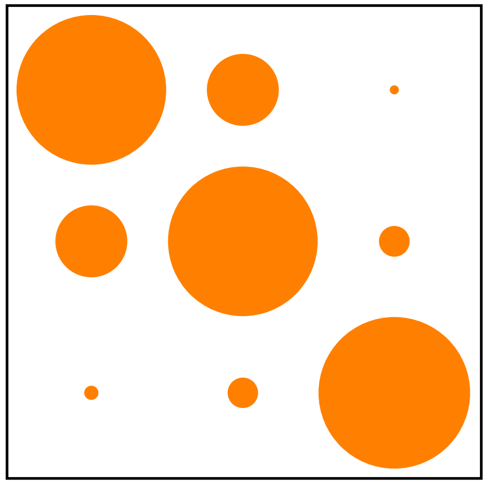
and includes **DM, Leptogenesis**, and **Inflation**.

Q: What's the origin of the quark and lepton mass hierarchy and mixings ??

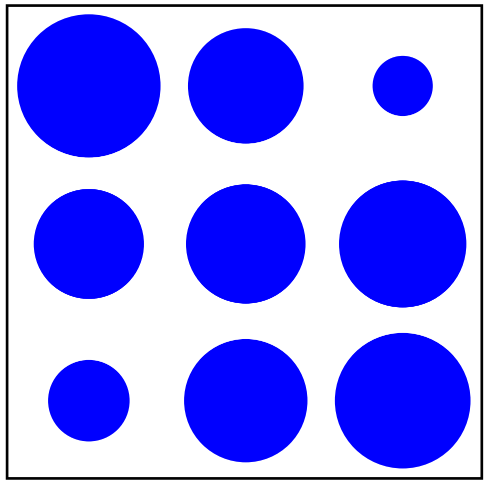


$\hat{y}^u_{ij}\,\overline{Q_i}Hu_{Rj}$

quark mixing



neutrino mixing



A simple possibility:

a spontaneously broken global U(1) symmetry. [Froggatt-Nielsen,'79]

$$\hat{y}^u_{ij}\ \overline{Q_i} H u_{Rj}$$

up-type quark
Yukawa couplings
in the Standard Model

A simple possibility:

a spontaneously broken global U(1) symmetry. [Froggatt-Nielsen,'79]

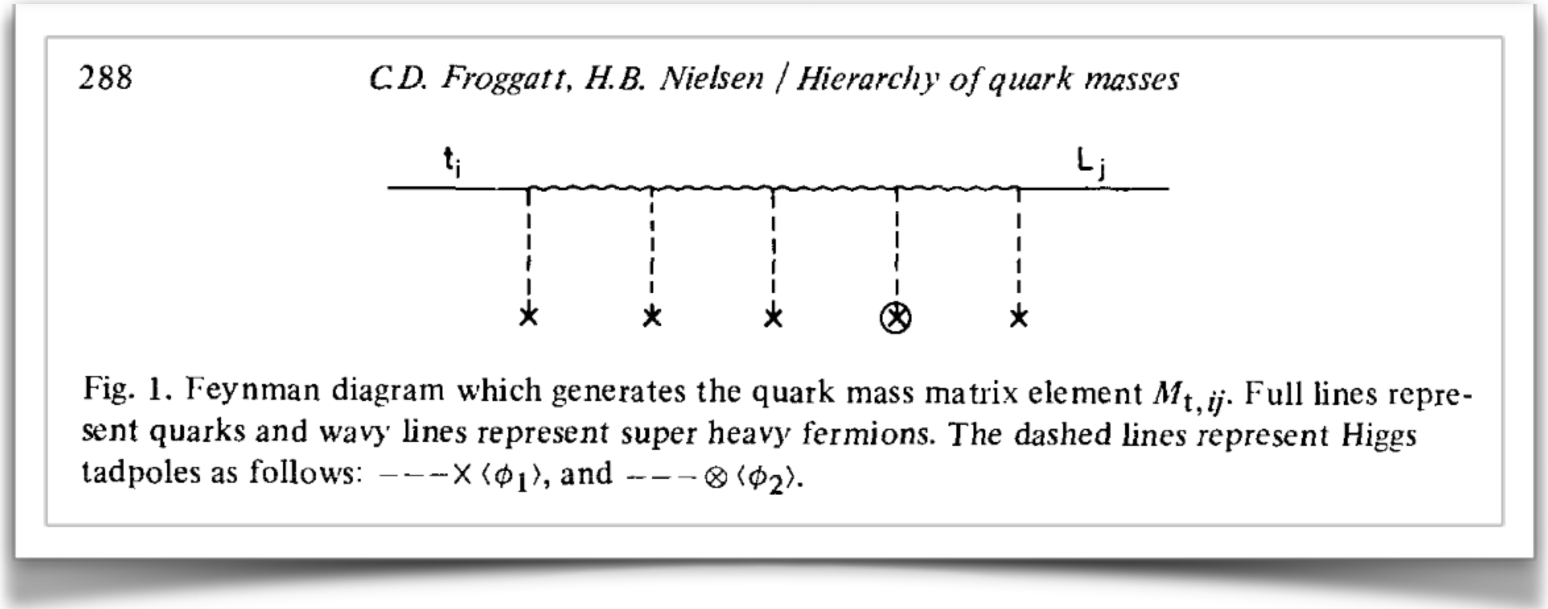
	Q_i	u_{R_j}	H	ϕ
U(1) charge	q_{Q_i}	q_{u_j}	0	$+1$

← New complex scalar: **Flavon**

$$\cancel{\hat{y}^u_{ij}\,\overline{Q}_i H u_{Rj}} \quad \longrightarrow \quad y^u_{ij}\left(\frac{\phi}{M}\right)^{q_{Q_i}-q_{u_j}}\overline{Q}_i H u_{Rj}$$

up-type quark
Yukawa couplings
in the Standard Model

cutoff scale



288 *C.D. Froggatt, H.B. Nielsen / Hierarchy of quark masses*

Fig. 1. Feynman diagram which generates the quark mass matrix element $M_{t,ij}$. Full lines represent quarks and wavy lines represent super heavy fermions. The dashed lines represent Higgs tadpoles as follows: $---\times\ \langle\phi_1\rangle$, and $---\otimes\ \langle\phi_2\rangle$.

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	Q_i	u_{R_j}	H	ϕ
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← New complex scalar: **Flavon**

$$\cancel{\hat{y}^u_{ij}\,\overline{Q}_i H u_{Rj}} \quad \longrightarrow \quad y^u_{ij}\left(\frac{\langle\phi\rangle}{M}\right)^{q_{Q_i}-q_{u_j}} \overline{Q}_i H u_{Rj}$$

→ After U(1) breaking by <ϕ> ≠ 0,

$$m^u_{ij} = y^u_{ij}\,\underbrace{\epsilon^{q_{Q_i}-q_{u_j}}}\,\langle H\rangle$$

O(1)

Mass hierarchy and mixings

where $\frac{\langle\phi\rangle}{M} \equiv \epsilon < 1$

Example:

$q_Q = \{3,2,0\}, q_u = \{-5,-1,0\}$

$$\rightarrow m^u \sim \begin{pmatrix} \epsilon^8 & \epsilon^4 & \epsilon^3 \\ \epsilon^7 & \epsilon^3 & \epsilon^2 \\ \epsilon^5 & \epsilon & 1 \end{pmatrix}$$

up charm top

A simple possibility:
a spontaneously broken global U(1) symmetry. [Froggatt-Nielsen,'79]

Our setup:

$$\mathcal{L} = y^d_{ij}\left(\frac{\phi}{M}\right)^{n^d_{ij}} \overline{Q}_i H d_{Rj} + y^u_{ij}\left(\frac{\phi}{M}\right)^{n^u_{ij}} \overline{Q}_i \widetilde{H} u_{Rj}$$

$$+ y^l_{ij}\left(\frac{\phi}{M}\right)^{n^l_{ij}} \overline{L}_i H l_{Rj} + y^\nu_{i\alpha}\left(\frac{\phi}{M}\right)^{n^\nu_{i\alpha}} \overline{L}_i \widetilde{H} N_{R\alpha}$$

$$+ \frac{1}{2} y^N_{\alpha\beta}\left(\frac{\phi}{M}\right)^{n^N_{\alpha\beta}} M \overline{N^c_{R\alpha}} N_{R\beta} + \text{h.c.}$$

We also introduce
2 or 3 right-handed neutrinos.

where $\frac{\langle\phi\rangle}{M} \equiv \epsilon \simeq 0.2$

$$\begin{cases} n^u_{ij} = q_{Q_i} - q_{u_j}\,, \\ n^d_{ij} = q_{Q_i} - q_{d_j}\,, \\ n^l_{ij} = q_{L_i} - q_{l_j}\,, \\ n^\nu_{i\alpha} = q_{L_i} - q_{N_\alpha} \\ n^N_{\alpha\beta} = -q_{N_\alpha} - q_{N_\beta}\,. \end{cases}$$

A simple possibility:

a spontaneously broken global U(1) symmetry. [Froggatt-Nielsen,'79]

Then, **Quark** mass hierarchy as well as **CKM** angles are naturally explained as e.g.,

$$\begin{cases} q_Q = \{3,2,0\}, \\ q_u = \{-5,-1,0\}, \\ q_d = \{-4,-3,-3\} \end{cases} \rightarrow \begin{cases} m^u_{ij} \sim \begin{pmatrix} \epsilon^8 & \epsilon^4 & \epsilon^3 \\ \epsilon^7 & \epsilon^3 & \epsilon^2 \\ \epsilon^5 & \epsilon & 1 \end{pmatrix} \langle H \rangle, \\ \\ m^d_{ij} \sim \begin{pmatrix} \epsilon^7 & \epsilon^6 & \epsilon^6 \\ \epsilon^6 & \epsilon^5 & \epsilon^5 \\ \epsilon^4 & \epsilon^3 & \epsilon^3 \end{pmatrix} \langle H \rangle, \end{cases} \rightarrow \begin{cases} \mathrm{diag}(m_u) \sim (\epsilon^8, \epsilon^3, 1)\langle H \rangle, & \text{u,c,t} \\ \\ \mathrm{diag}(m_d) \sim (\epsilon^7, \epsilon^5, \epsilon^3)\langle H \rangle, & \text{d,s,b} \\ \\ V_{\mathrm{CKM}} \sim \begin{pmatrix} 1 & \epsilon & \epsilon^3 \\ \epsilon & 1 & \epsilon^2 \\ \epsilon^3 & \epsilon^2 & 1 \end{pmatrix} \end{cases}$$

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Lepton masses and **MNS** angles are also explained as

$$\begin{cases} q_L = \{1,0,0\}, \\ q_e = \{-8,-5,-3\}, \\ q_N = \{q_{N_1}, q_{N_2}, (q_{N_3})\} \end{cases} \to \begin{cases} m^\ell_{ij} \sim \begin{pmatrix} \epsilon^9 & \epsilon^6 & \epsilon^4 \\ \epsilon^8 & \epsilon^5 & \epsilon^3 \\ \epsilon^8 & \epsilon^5 & \epsilon^3 \end{pmatrix} \langle H\rangle, \\ \\ m^\nu_{ij} \sim \begin{pmatrix} \epsilon^2 & \epsilon & \epsilon \\ \epsilon & 1 & 1 \\ \epsilon & 1 & 1 \end{pmatrix} \frac{\langle H\rangle^2}{M}, \end{cases} \to \begin{cases} \mathrm{diag}(m_e) \sim (\epsilon^9, \epsilon^5, \epsilon^3)\langle H\rangle, \quad e,\mu,\tau \\ \\ \mathrm{diag}(m_\nu) \sim (\epsilon^2, 1, 1)\frac{\langle H\rangle^2}{M}, \\ \\ V_{\mathrm{MNS}} \sim \begin{pmatrix} 1 & \epsilon & \epsilon \\ \epsilon & 1 & 1 \\ \epsilon & 1 & 1 \end{pmatrix} \end{cases}$$

q_N-dependence cancels because of the **seesaw** formula.

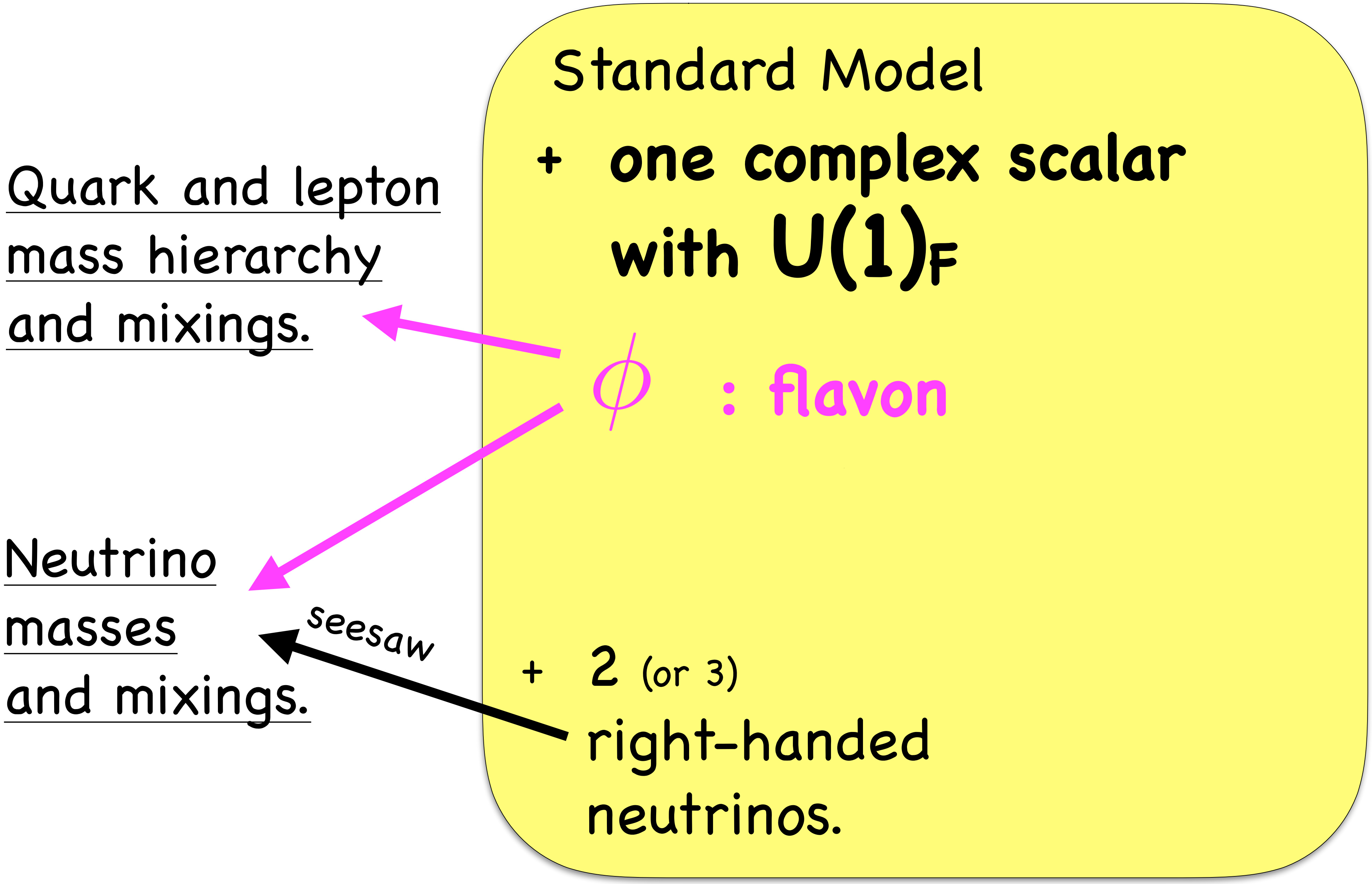
large 2-3 mixing

[cf. Sato-Yanagida,'98, Ramond,'98]

Standard Model

Quark and lepton
mass hierarchy
and mixings.

Neutrino
masses
and mixings.



Standard Model

+ one complex scalar with $U(1)_F$

ϕ : **flavon**

+ 2 (or 3) right-handed neutrinos.

Quark and lepton mass hierarchy and mixings.

Neutrino masses and mixings.

Our setup: $$\begin{aligned}\mathcal{L} = {} & y^d_{ij}\left(\frac{\phi}{M}\right)^{n^d_{ij}}\overline{Q}_i H d_{Rj} + y^u_{ij}\left(\frac{\phi}{M}\right)^{n^u_{ij}}\overline{Q}_i \widetilde{H} u_{Rj} \\ & + y^l_{ij}\left(\frac{\phi}{M}\right)^{n^l_{ij}}\overline{L}_i H l_{Rj} + y^\nu_{i\alpha}\left(\frac{\phi}{M}\right)^{n^\nu_{i\alpha}}\overline{L}_i \widetilde{H} N_{R\alpha} \\ & + \frac{1}{2} y^N_{\alpha\beta}\left(\frac{\phi}{M}\right)^{n^N_{\alpha\beta}} M \overline{N^c_{R\alpha}} N_{R\beta} + \text{h.c.}\end{aligned}$$

can explain the quark and lepton mass hierarchy and mixings.

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$$\mathcal{L} = y^d_{ij}\left(\frac{\phi}{M}\right)^{n^d_{ij}} \overline{Q}_i H d_{Rj} + y^u_{ij}\left(\frac{\phi}{M}\right)^{n^u_{ij}} \overline{Q}_i \widetilde{H} u_{Rj}$$
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can explain the quark and lepton mass hierarchy and mixings.

OK, but………… **What's new?**

Froggatt-Nielsen paper was in 1979……

Our setup:
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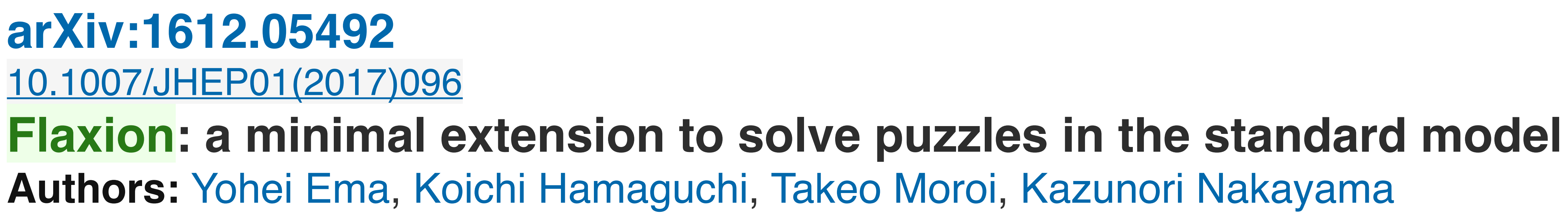
$$+ \frac{1}{2} y^N_{\alpha\beta}\left(\frac{\phi}{M}\right)^{n^N_{\alpha\beta}} M \overline{N^c_{R\alpha}} N_{R\beta} + \text{h.c.}$$

POINT: The global, spontaneously broken U(1) flavor symmetry is **anomalous** under SU(3)$_C$, which means… **the Peccei-Quinn mechanism (to solve the strong CP problem) is automatically included:**

U(1)$_F$ = U(1)$_{PQ}$!! "Flaxion"

* As far as we know, this simple realization has not been studied explicitly before.

cf. **related earlier works**, **Wilczek,'82,** Geng-Ng,'89, Berezhiani-Khlopov,'91, Babu-Barr,'92, Albrecht et.al.,'10, Fong-Nardi,'13, Ahn,'14,'16, Celis et.al.,'14,.....



arXiv:1612.05492

10.1007/JHEP01(2017)096

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* And many related works recently..., including (just showing some of them):

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etc etc…

See the talk by E. J. Chun.

Flaxion

$$\boxed{\phi = \frac{1}{\sqrt{2}}\left(\varphi + i a\right)}$$

flavon

axion

Flaxion

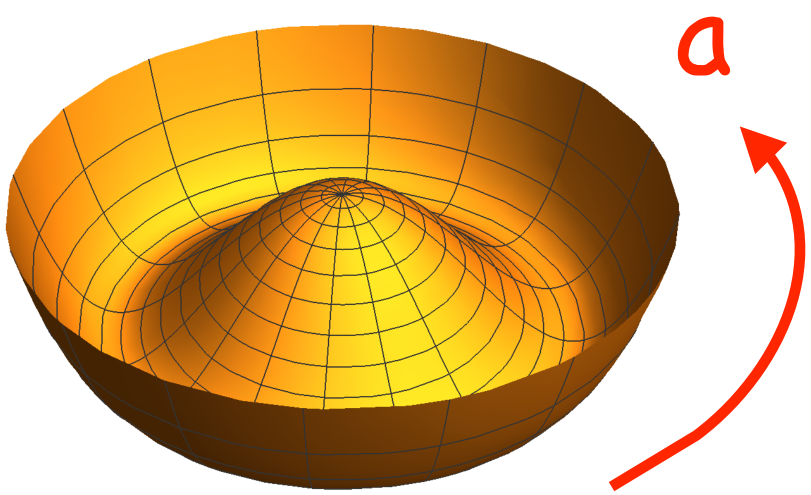
$$\boxed{\underset{\text{flavon}}{\phi} = \frac{1}{\sqrt{2}}(\varphi + i\underset{\text{axion}}{a})}$$

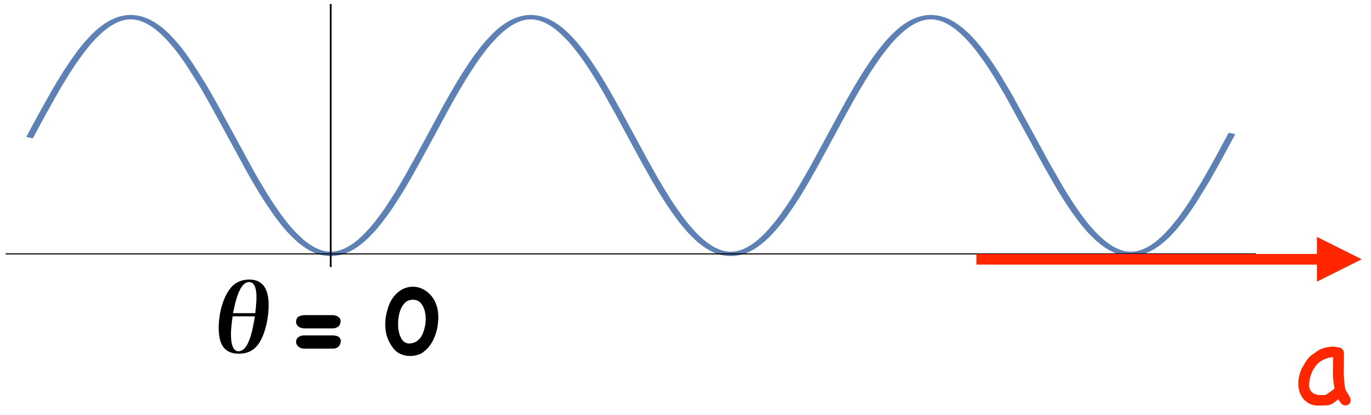
(1) **Strong CP problem is solved** by the PQ mechanism.

[Peccei-Quinn,'77]

$$\mathcal{L} = \frac{g_s^2}{32\pi^2}\frac{a}{f_a}G^a_{\mu\nu}\widetilde{G}^{a\mu\nu} \quad \text{where} \quad f_a = \frac{\sqrt{2}\langle\phi\rangle}{N_{\mathrm{DW}}}, \quad N_{\mathrm{DW}} = \sum_i (2q_{Q_i} - q_{u_i} - q_{d_i})$$

(In the example before, N_{DW} = 26.)





Flaxion

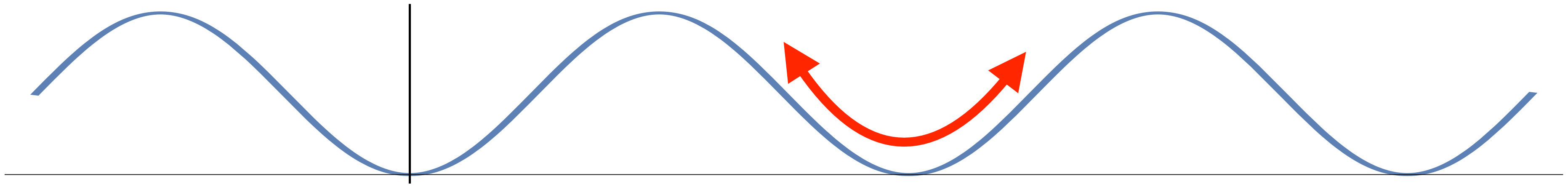
$$\boxed{\phi = \frac{1}{\sqrt{2}}\left(\varphi + i a\right)}$$

flavon

axion

(1) **Strong CP problem is solved** by the PQ mechanism.

(2) The axion can be **the dark matter.**



$$\Omega_a h^2 = 0.18\,\theta_i^2 \left(\frac{f_a}{10^{12}\,\mathrm{GeV}}\right)^{1.19} .$$

[Turner,'86]

Flaxion

$$\boxed{\phi = \frac{1}{\sqrt{2}}(\varphi + ia)}$$

flavon

axion

(1) **Strong CP problem is solved** by the PQ mechanism.

(2) The axion can be **the dark matter.**

Any new prediction?

Flaxion

$$\boxed{\underset{\text{flavon}}{\phi} = \frac{1}{\sqrt{2}}(\varphi + i\underset{\text{axion}}{a})}$$

(1) **Strong CP problem is solved** by the PQ mechanism.

(2) The axion can be **the dark matter.**

Any new prediction?

……Yes!

(3) **Characteristic flavor-changing signals** are predicted.

[cf. Wilczek,'82]

(3) Characteristic flavor-changing signals.

$$\mathcal{L} = y^d_{ij}\left(\frac{\phi}{M}\right)^{n^d_{ij}} \overline{Q}_i H d_{Rj} + y^u_{ij}\left(\frac{\phi}{M}\right)^{n^u_{ij}} \overline{Q}_i \widetilde{H} u_{Rj}$$

$$+ y^l_{ij}\left(\frac{\phi}{M}\right)^{n^l_{ij}} \overline{L}_i H l_{Rj} + y^\nu_{i\alpha}\left(\frac{\phi}{M}\right)^{n^\nu_{i\alpha}} \overline{L}_i \widetilde{H} N_{R\alpha}$$

$$+ \frac{1}{2} y^N_{\alpha\beta}\left(\frac{\phi}{M}\right)^{n^N_{\alpha\beta}} M\overline{N^c_{R\alpha}} N_{R\beta} + \text{h.c.}$$

$$\longrightarrow \quad -\mathcal{L} = \sum_{f=u,d,l}\left[m^f_{ij}\left(1+\frac{h}{\sqrt{2}\langle H\rangle}\right) + \frac{m^f_{ij}n^f_{ij}(s+ia)}{\sqrt{2}\langle\phi\rangle}\right]\overline{f_{Li}}f_{Rj} + \text{h.c.}$$

They are not simultaneously diagonalized.

-> flavor changing processes.

The most stringent bound comes from **K+ -> π^+ a**.

$$\mathrm{Br}(K^+\to\pi^+ a) \simeq 3\times10^{-10}\left(\frac{10^{10}\,\mathrm{GeV}}{f_a}\right)^2 \underbrace{\left(\frac{26}{N_{\mathrm{DW}}}\right)^2\left|\frac{(\kappa^d_{\mathrm{AH}})_{12}}{m_s-m_d}\right|^2}_{O(1)} < 7.3\times10^{-11}$$

[BNL-E787, E949]

$$\to \quad f_a \gtrsim 2\times10^{10}\mathrm{GeV}$$

CERN **NA62 experiment** can improve the sensitivity !!

Other constraints?

$$\left(\kappa_{\mathrm{H}}^f\right)_{ij} = \frac{1}{2}\left(V^{f\dagger}\widehat{q}_Q V^f - U^{f\dagger}\widehat{q}_f U^f\right)_{ij}\left(m_j^f + m_i^f\right),$$

$$\left(\kappa_{\mathrm{AH}}^f\right)_{ij} = \frac{1}{2}\left(V^{f\dagger}\widehat{q}_Q V^f + U^{f\dagger}\widehat{q}_f U^f\right)_{ij}\left(m_j^f - m_i^f\right).$$

- $K^+ \to \pi^+ a$

$$f_a \gtrsim 2 \times 10^{10}\,\mathrm{GeV}\left(\frac{26}{N_{\mathrm{DW}}}\right)\left|\frac{(\kappa_{\mathrm{AH}}^d)_{12}}{m_s}\right|$$

$$\mathrm{Br}(K^+ \to \pi^+ a) \lesssim 7.3 \times 10^{-11}$$

$$\Gamma(K^+ \to \pi^+ a) = \frac{m_K^3}{32\pi v_\phi^2}\left(1 - \frac{m_\pi^2}{m_K^2}\right)^3\left|\frac{(\kappa_{\mathrm{AH}}^d)_{12}}{m_s - m_d}\right|^2$$

- $\mu \to e\, a\, \gamma$

$$f_a \gtrsim 1 \times 10^{8}\,\mathrm{GeV}\left(\frac{26}{N_{\mathrm{DW}}}\right)\left|\frac{(\kappa_{\mathrm{AH}}^l)_{12}}{m_\mu}\right|$$

$$\mathrm{Br}(\mu \to e a \gamma) \lesssim 1.1 \times 10^{-9},$$

- SN1987A

$$\frac{f_a}{|C_N|} \gtrsim 1 \times 10^{9}\,\mathrm{GeV}$$

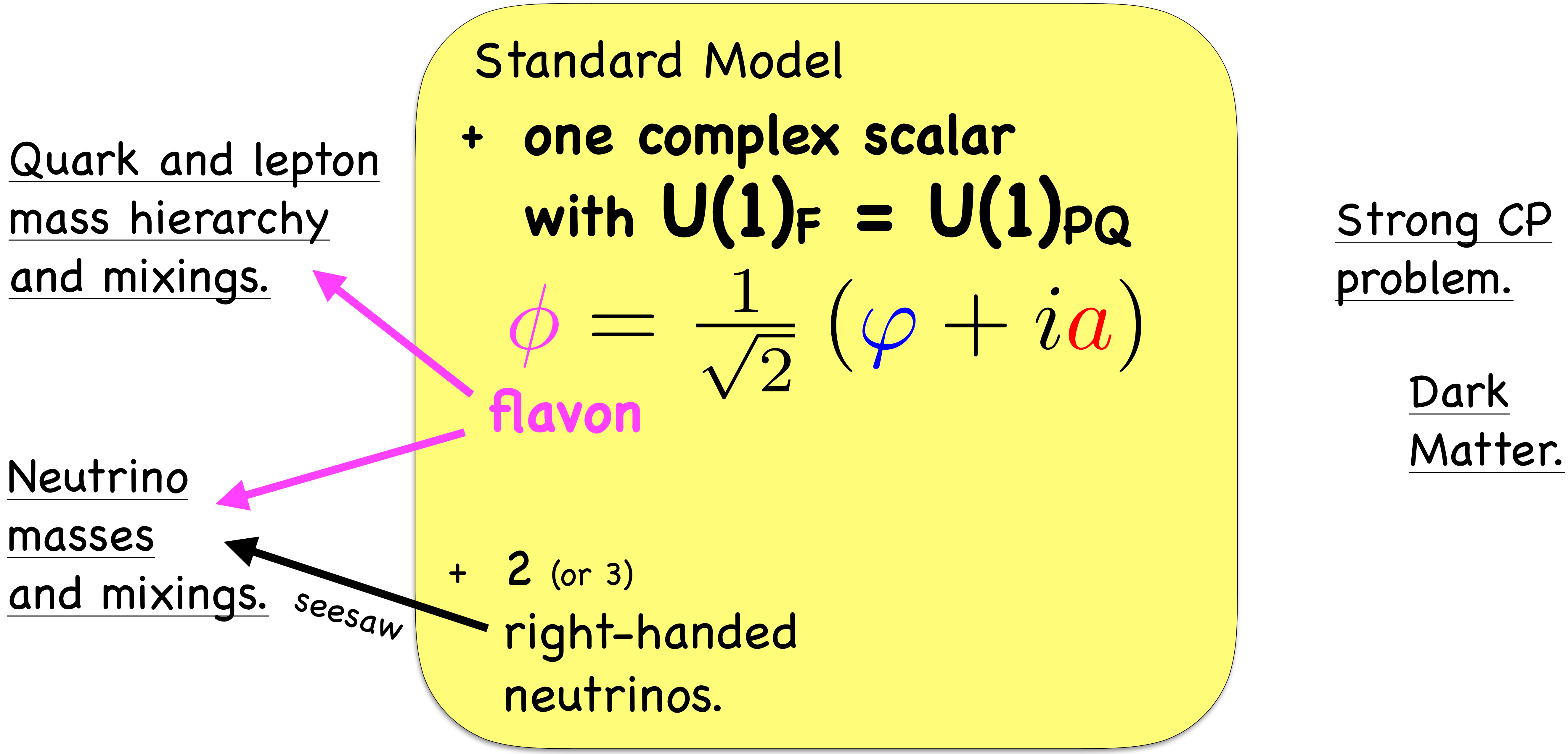
$$\mathcal{L} = \sum_{N=p,n} \frac{C_N m_N}{f_a} i a \overline{N}\gamma_5 N,$$

$C_p \simeq -0.4$ and $|C_n| \ll |C_p|$ for $N_{\mathrm{DW}} \gg 1$.

- cooling of the white dwarf stars. (g_{aee})

$$f_a \gtrsim 7 \times 10^{7}\,\mathrm{GeV}\left(\frac{26}{N_{\mathrm{DW}}}\right)\left|\frac{(\kappa_{\mathrm{H}}^l)_{11}}{m_e}\right|$$

Flaxion Scenario



Standard Model

+ one complex scalar with $U(1)_F = U(1)_{PQ}$

$$\phi = \frac{1}{\sqrt{2}}(\varphi + ia)$$

flavon

+ 2 (or 3) right-handed neutrinos.

Quark and lepton mass hierarchy and mixings.

Neutrino masses and mixings.

seesaw

Strong CP problem.

Dark Matter.

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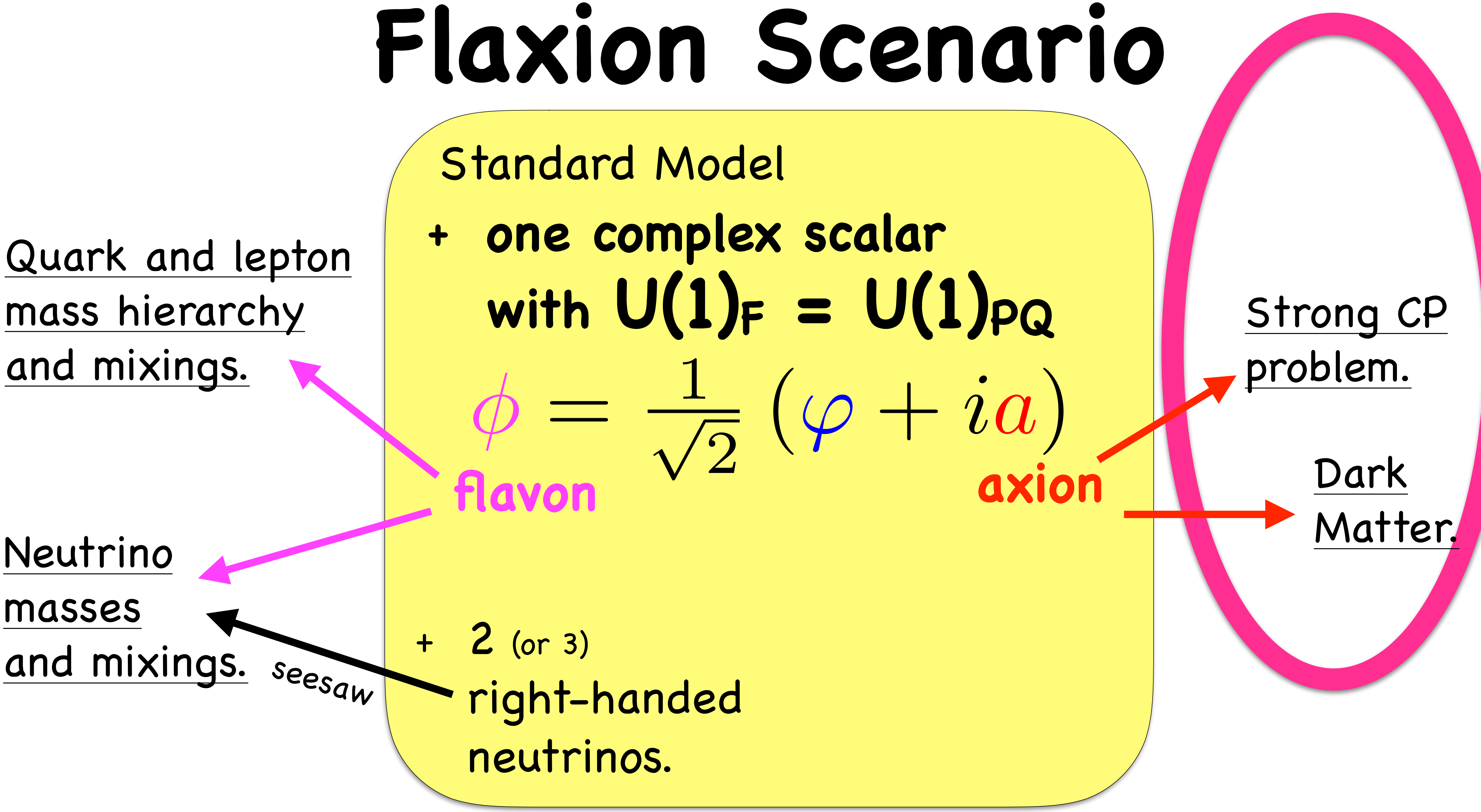

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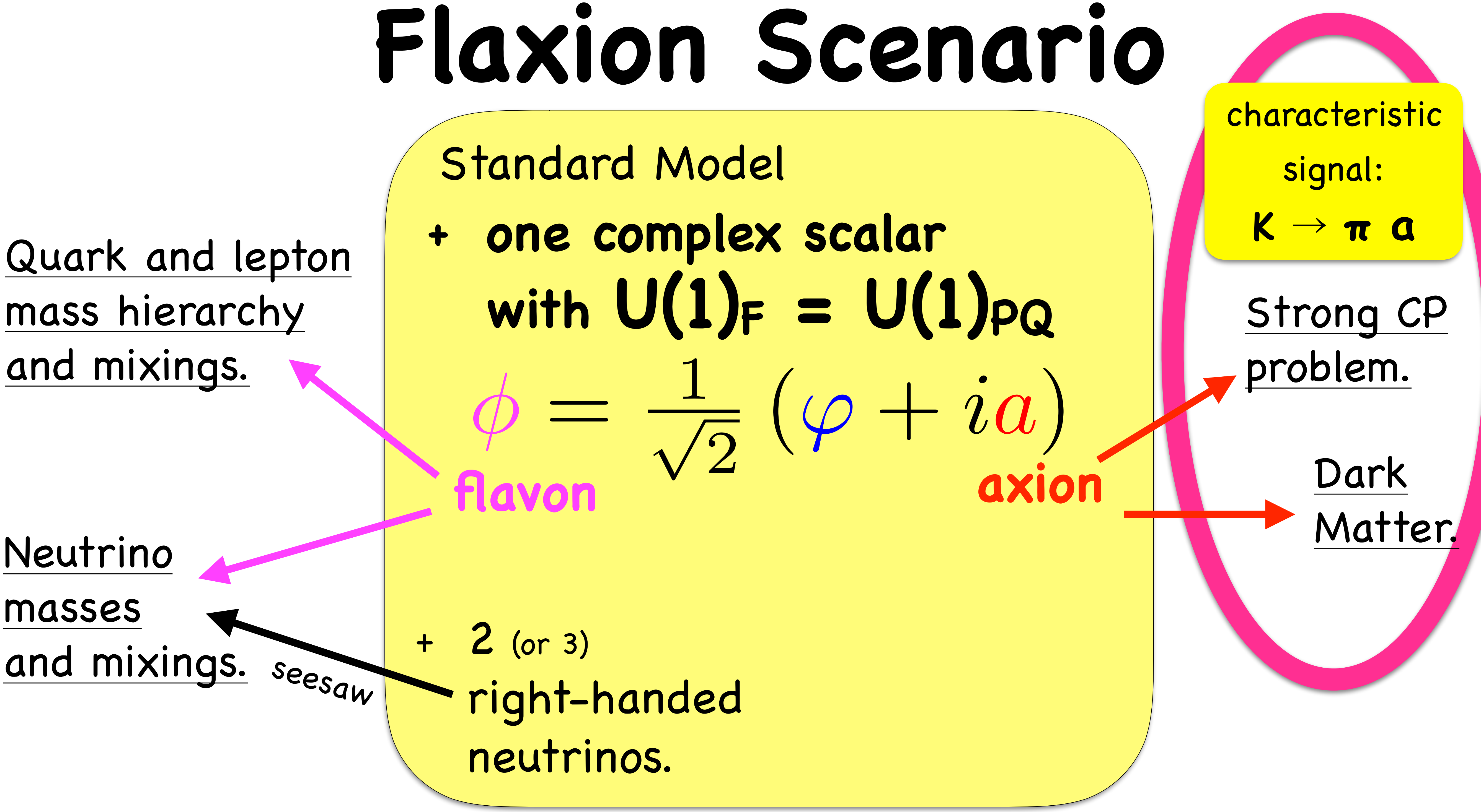

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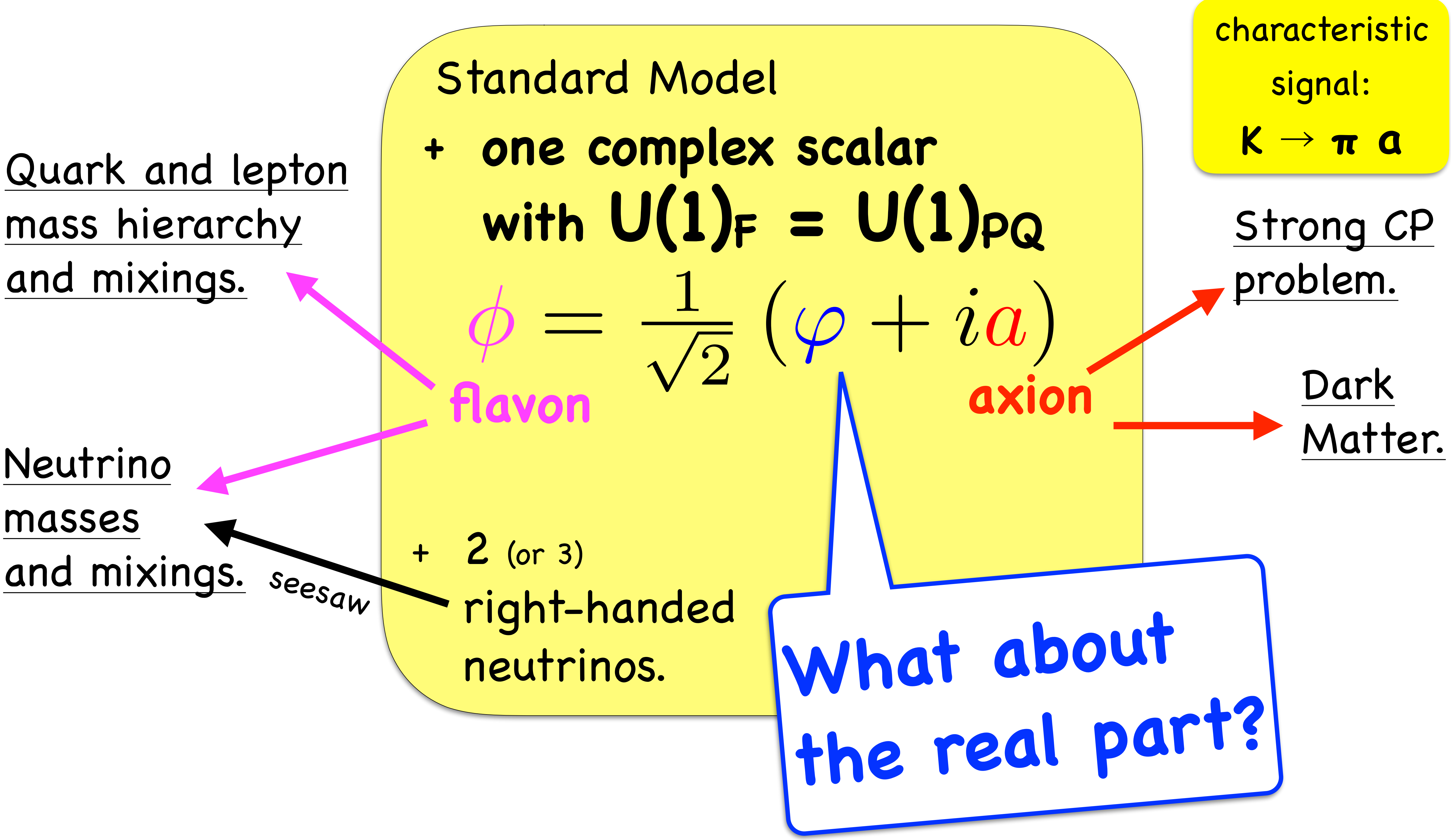

characteristic signal:

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flavon

axion

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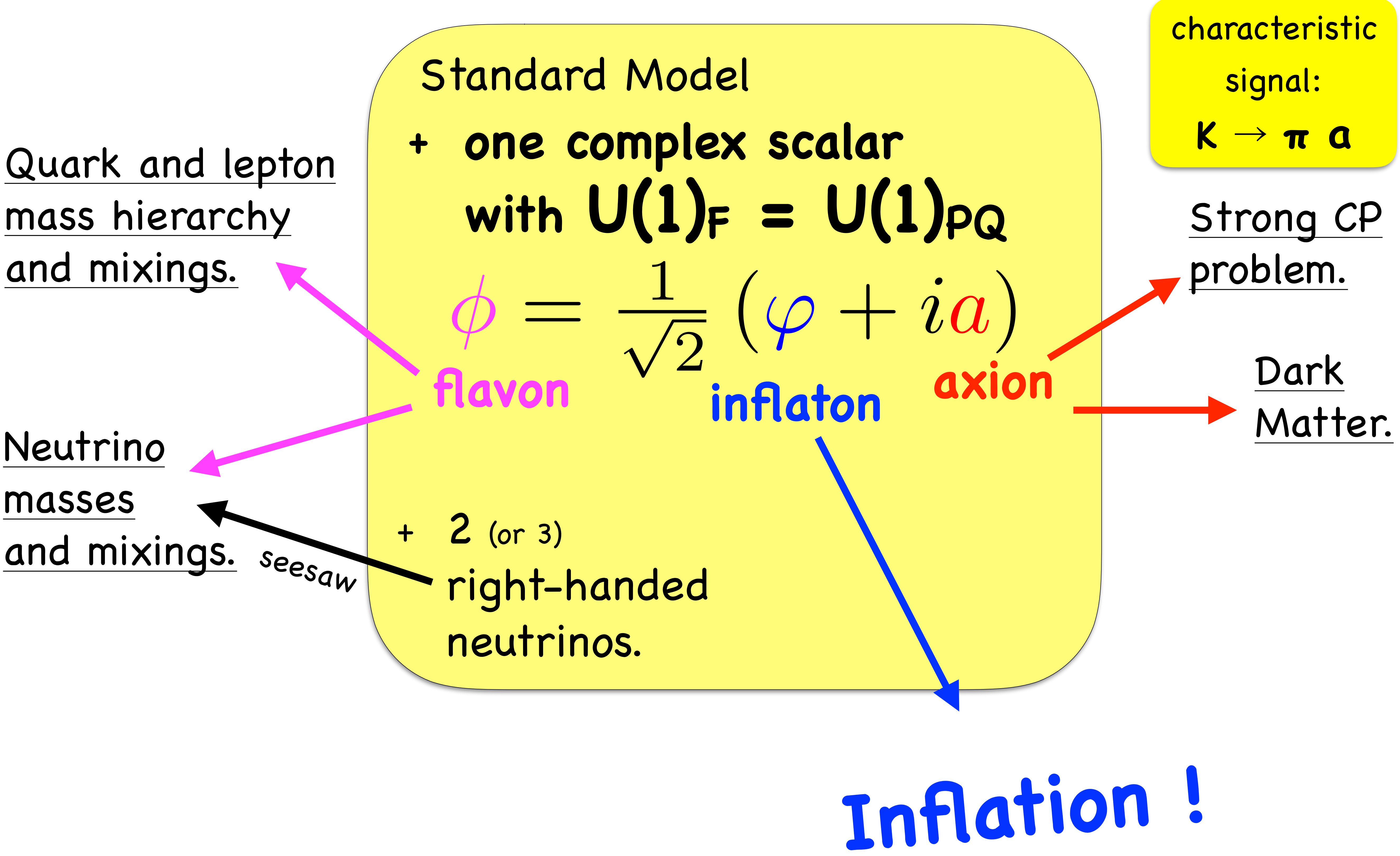
seesaw

What about the real part?

Flaxion Scenario



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seesaw

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Dark Matter.

Inflation !

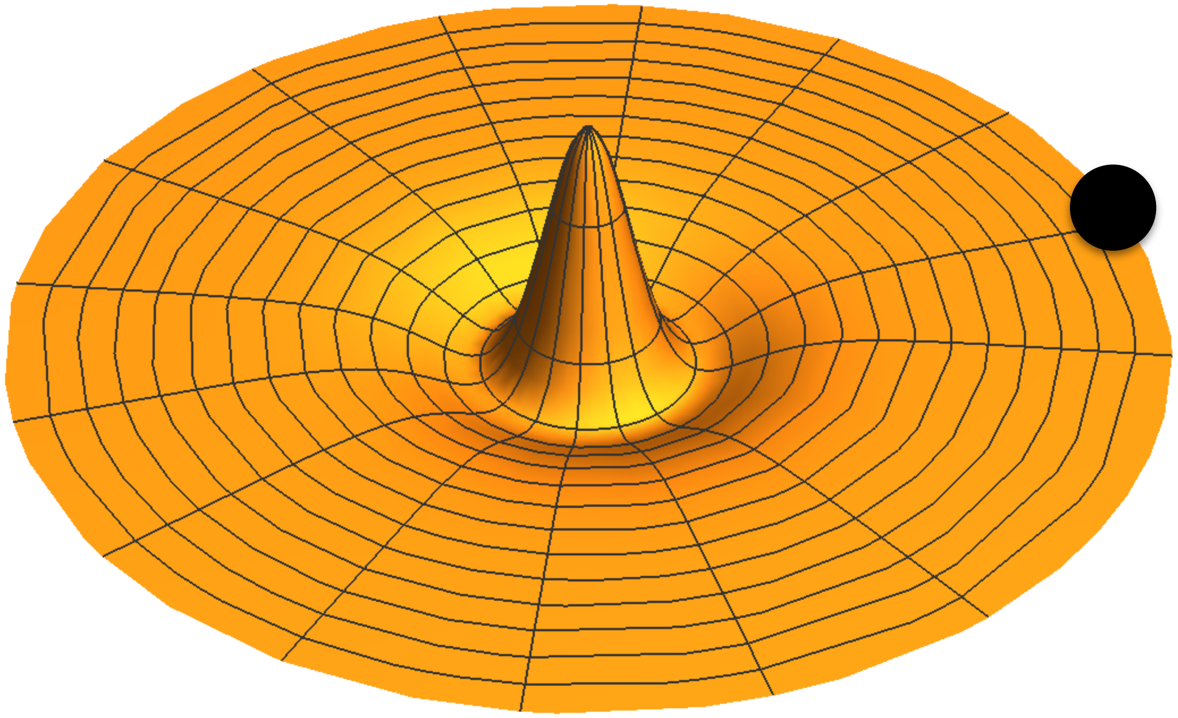
Flaxion Inflation:

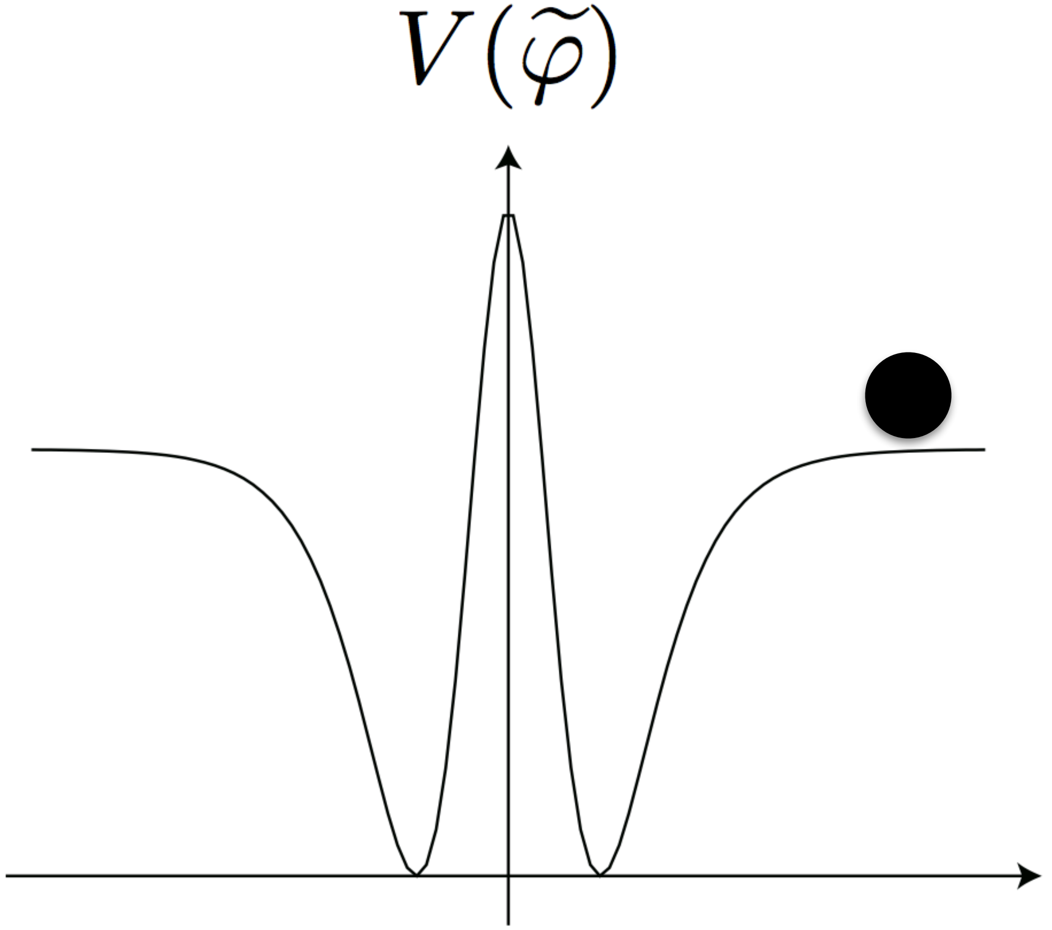
$$v_\phi < \Lambda < \sqrt{2} v_\phi$$

$$\mathcal{L} = -\frac{|\partial\phi|^2}{\left(1 - |\phi|^2/\Lambda^2\right)^2} - \lambda_\phi \left(|\phi|^2 - v_\phi^2\right)^2$$

canonical field $\widetilde{\varphi}$:

$$\frac{\varphi}{\sqrt{2}\Lambda} \equiv \tanh\left(\frac{\widetilde{\varphi}}{\sqrt{2}\Lambda}\right)$$





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☑ Curvature fluctuation:

P_ξ = 2.2 x 10^{-9} [Planck,'15] is reproduced

for $\lambda_\phi \lesssim 1$ and $\Lambda \gtrsim 10^{13}\mathrm{GeV}$ (consistent with flaxion DM.)

Flaxion Inflation:

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canonical field $\widetilde{\varphi}$:

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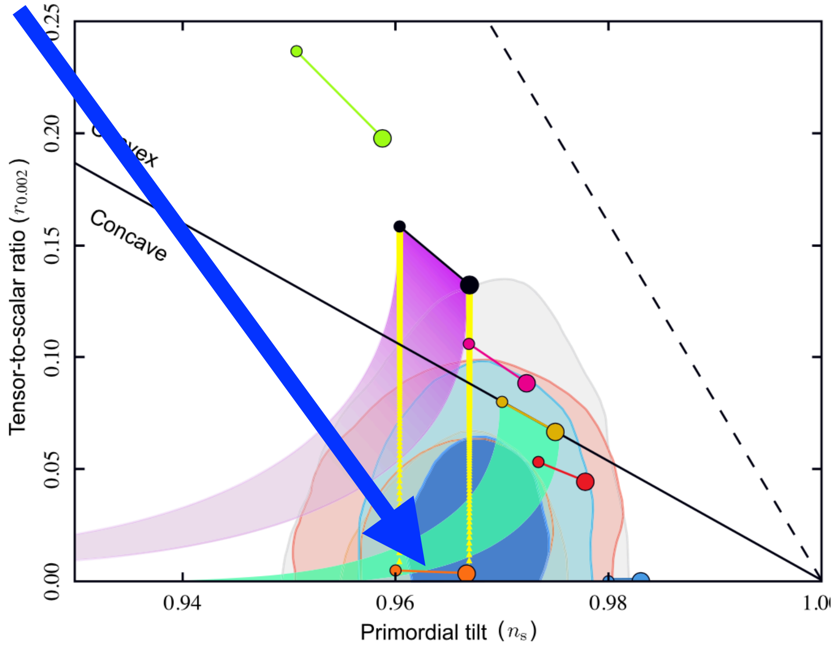
☑ Curvature fluctuation:

☑ (n_s, r) is in the Planck best-fit region.

$$n_s \simeq 1 - \frac{2}{N_e}, \quad r \simeq \frac{4}{N_e^2}\left(\frac{\Lambda}{M_P}\right)^2 .$$



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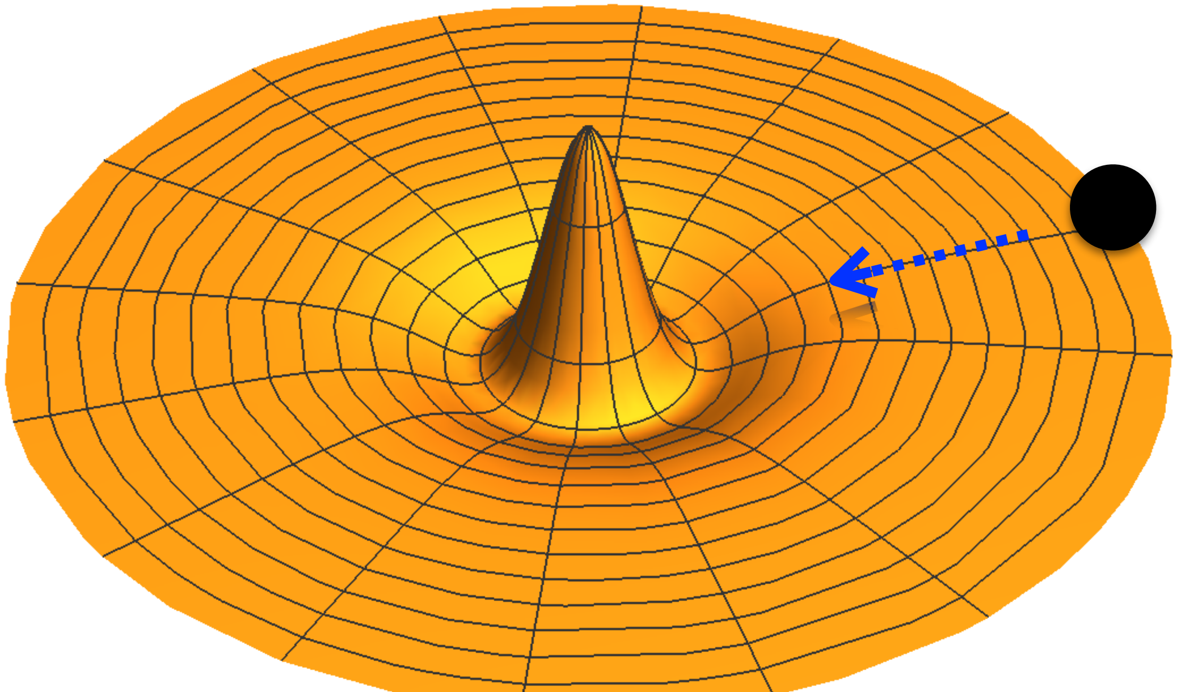
☑ Curvature fluctuation:

☑ (n_s, r) is in the Planck best-fit region.

☑ The U(1) symmetry is never restored -> No Domain wall.



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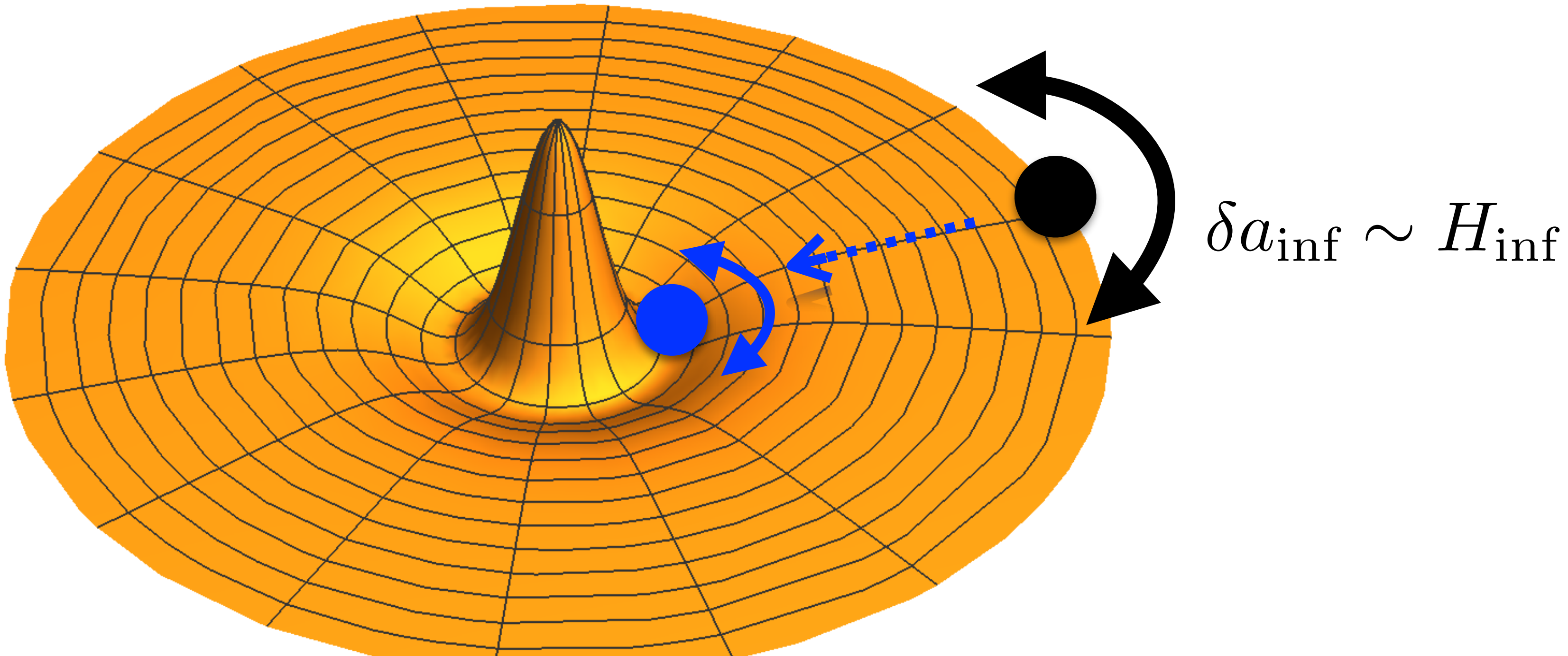

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☑ (n_s, r) is in the Planck best-fit region.

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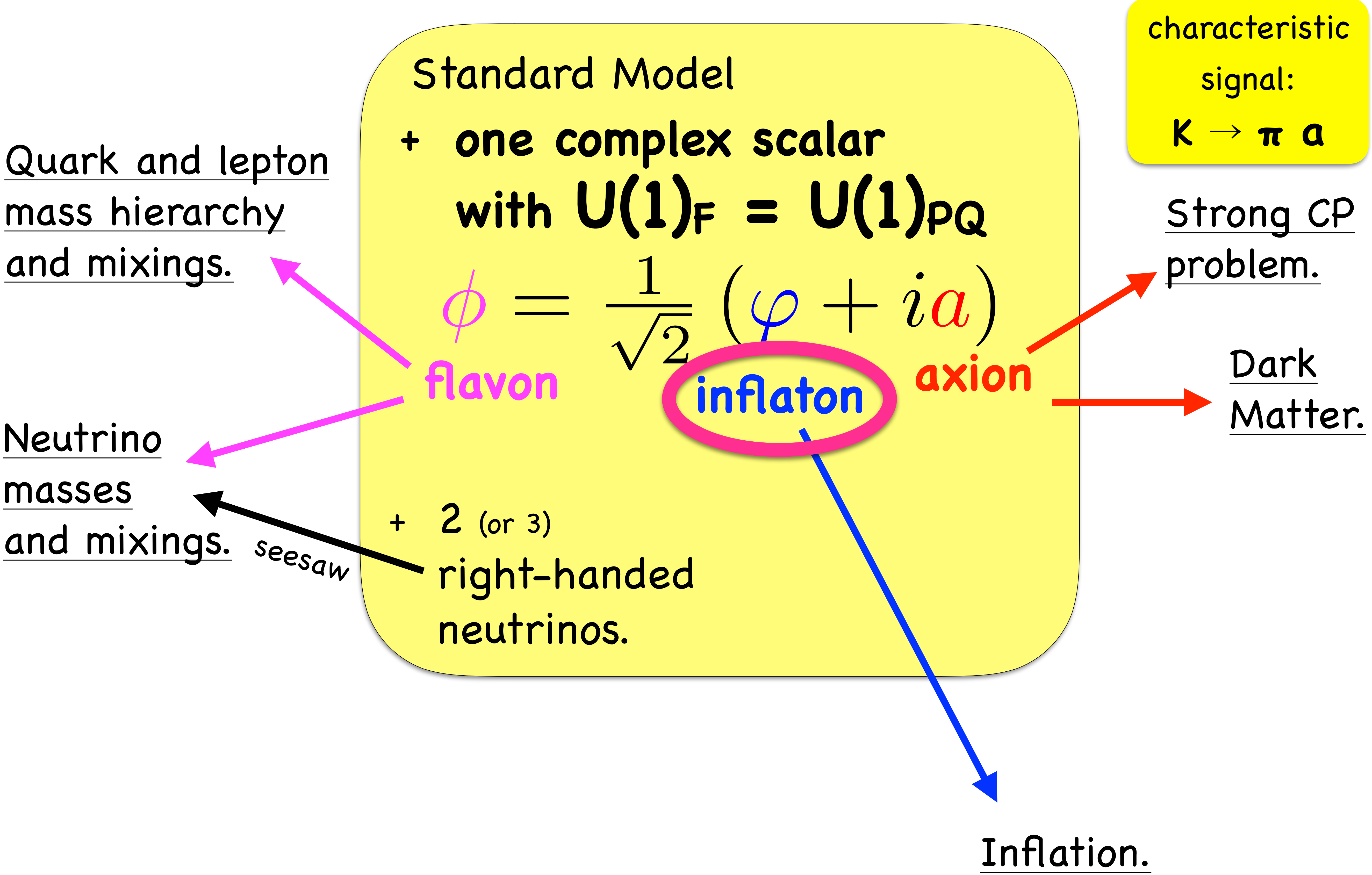
☑ Reheating temperature is high enough for Leptgenesis.

($T_R \simeq 10^{12}$ - 10^{14} GeV) ("strong washout")

More on this later.

Flaxion Scenario



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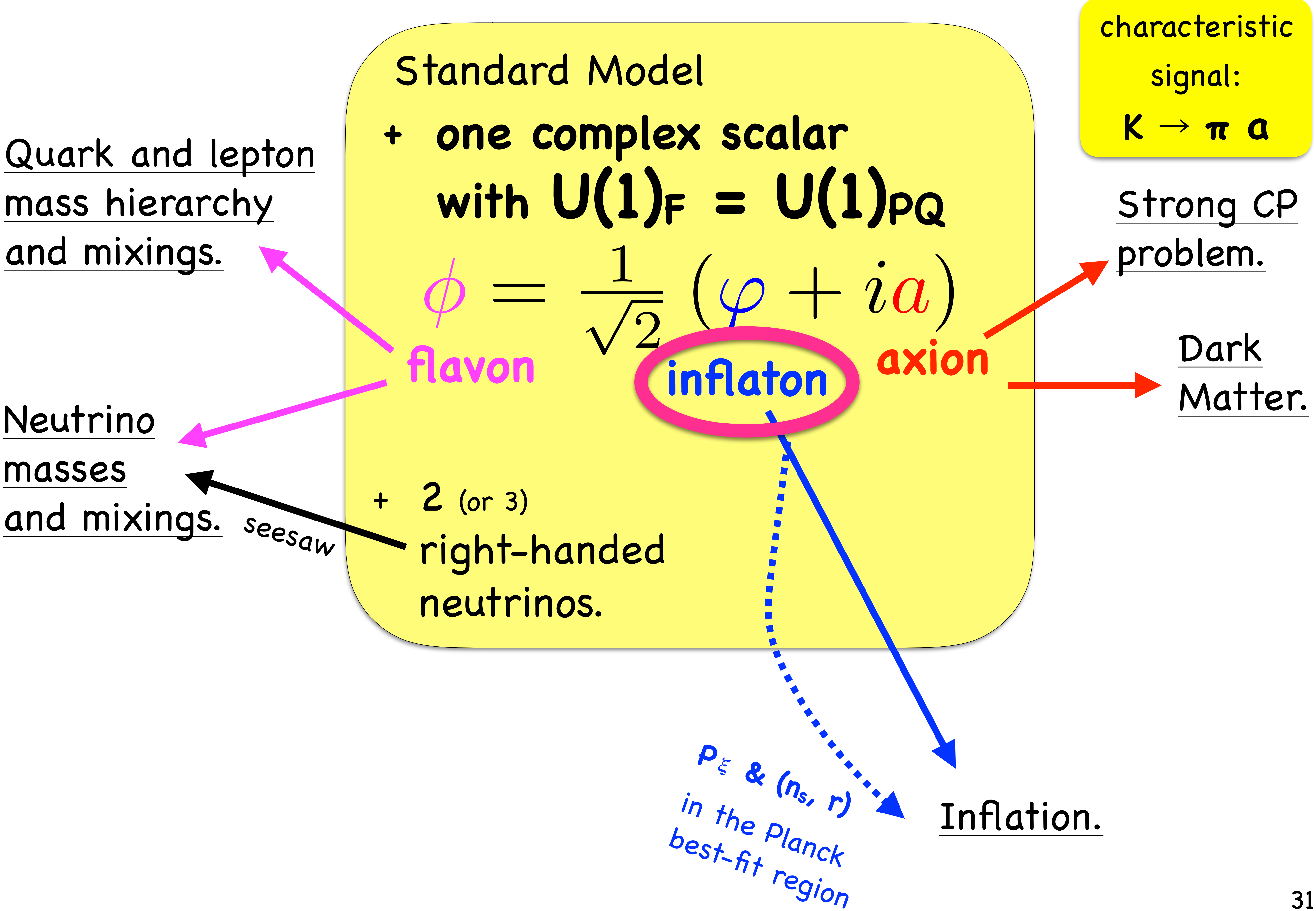

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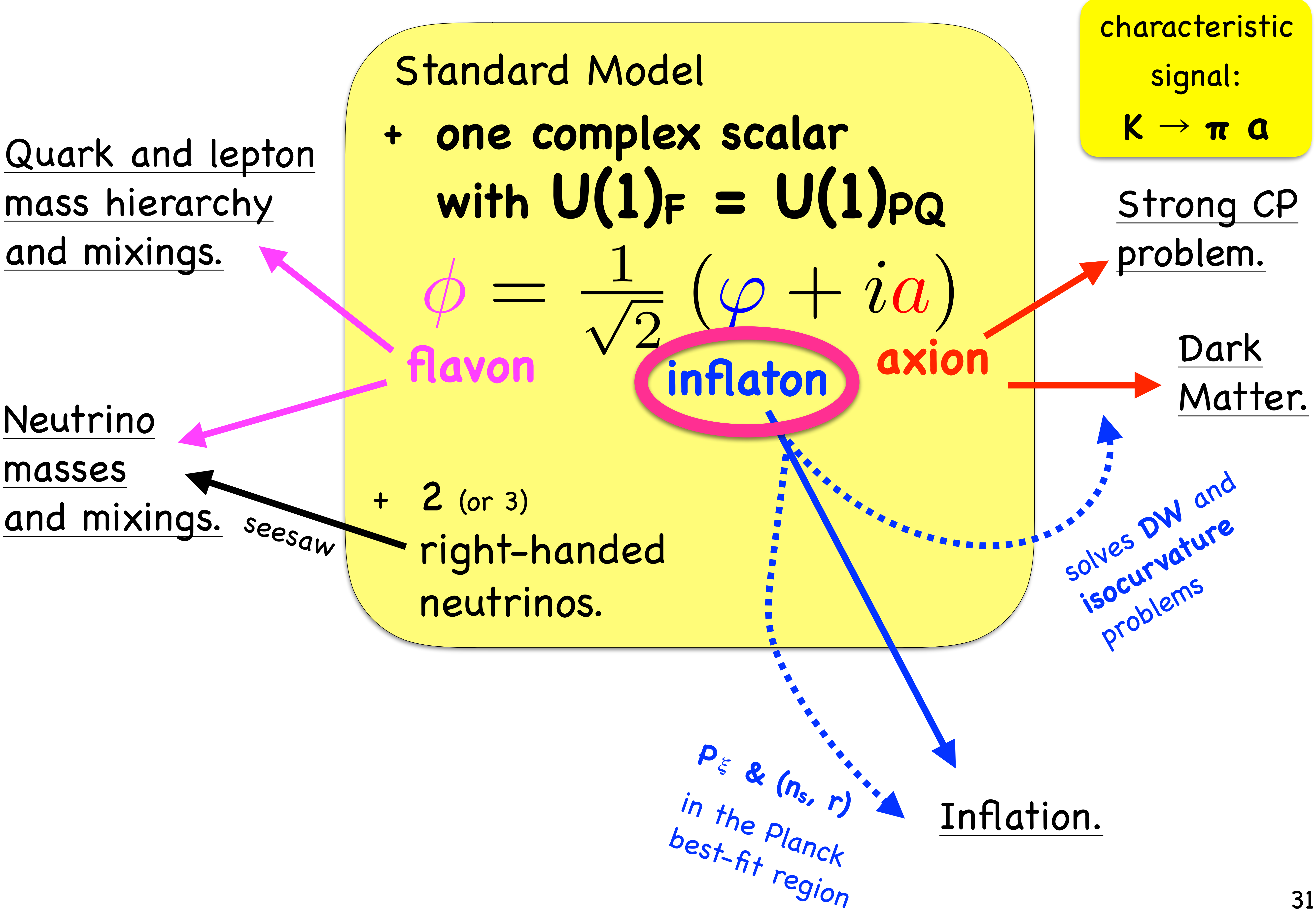
P_ξ & (n_s, r) in the Planck best-fit region

Flaxion Scenario



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Flaxion Inflation: Reheating and Leptogenesis

Inflaton partial decay rate into RHNs,

$$\Gamma(\widetilde{\varphi} \to N_R N_R) \simeq \sum_{\alpha\beta} \frac{|y^N_{\alpha\beta} n^N_{\alpha\beta} \epsilon^{n^N_{\alpha\beta}-1}|^2}{32\pi} \Delta^2 m_\varphi$$

$$\Delta \equiv 1 - v_\phi^2/\Lambda^2$$

$$m_\varphi \sim 3 \times 10^{13}\,\mathrm{GeV}(v_\phi/\Lambda)$$

$$\Downarrow$$

$$H_{\rm inf} \simeq 5 \times 10^8\,\mathrm{GeV} \left(\frac{\Lambda}{10^{14}\,\mathrm{GeV}}\right) .$$

Reheating is completed almost instantaneously.

Reheating temperature

$$T_R \sim 10^{12} - 10^{14}\mathrm{GeV}.$$

Flaxion Inflation: Reheating and Leptogenesis

… and **thermal leptogenesis** [Fukugita-Yanagida,'86]

can work successfully for $m_{N1} \simeq O(10^{12})$ GeV !

In more details,…

Final baryon asymmetry: $\frac{n_B}{s} \simeq \epsilon_1 \kappa_f \frac{28}{79}\left(\frac{n_{N_1}}{s}\right)_{\rm th} \simeq 1.3\times 10^{-3}\epsilon_1\kappa_f$

Asymmetry parameter: $\epsilon_1 = \frac{3}{16\pi}\frac{m_{N_1}m_{\nu 3}}{v_{\rm EW}^2}\delta_{\rm eff} \simeq 1\times 10^{-4}\left(\frac{m_{N_1}}{10^{12}\,{\rm GeV}}\right)\left(\frac{m_{\nu 3}}{0.05\,{\rm eV}}\right)\delta_{\rm eff}$

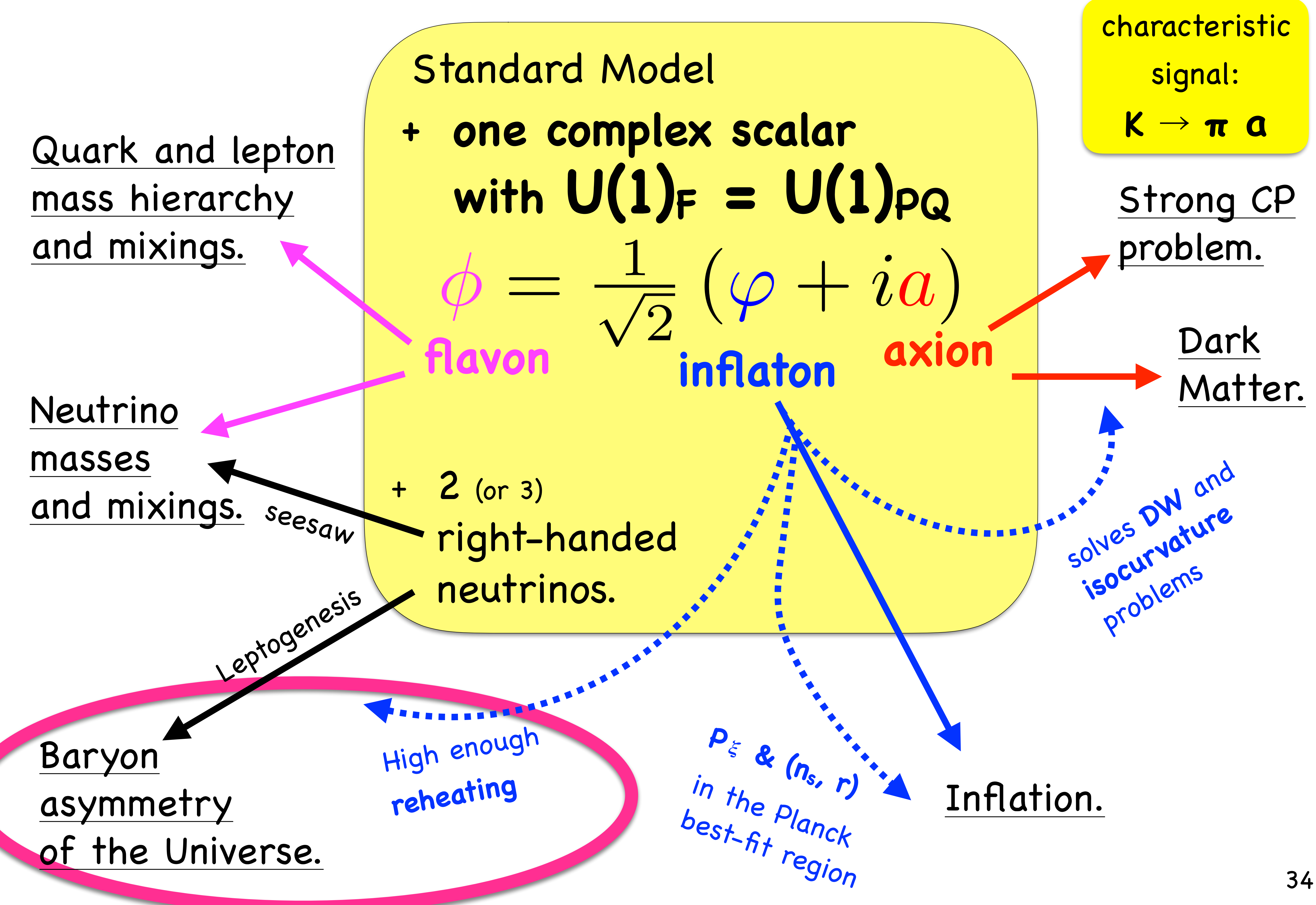
Effective neutrino mass: $\widetilde{m}_{\nu 1} \equiv \sum_k |\epsilon^{n^\nu_{k1}} y^\nu_{k1}|^2 v_{\rm EW}^2/m_{N_1} \ \sim \ m_{\nu_3}$

-> Efficiency factor $\kappa_f \sim 3\times 10^{-3}$ (strong washout region)

Altogether, observed asymmetry $n_B/s \simeq 0.9 \times 10^{-10}$ can be obtained for $m_{N1} \simeq O(10^{12})$ GeV, corresponding to

$q_{N_1} = 1-5$ for $M \sim O(10^{14}\text{–}10^{17})\,{\rm GeV}$

Flaxion Scenario



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Leptogenesis

Baryon asymmetry of the Universe.

Strong CP problem.

Dark Matter.

solves **DW** and **isocurvature** problems

High enough **reheating**

P_ξ & (n_s, r) in the Planck best-fit region

Inflation.

Summary of part 1

Flaxion Scenario

Summary of part 1

Flaxion Scenario

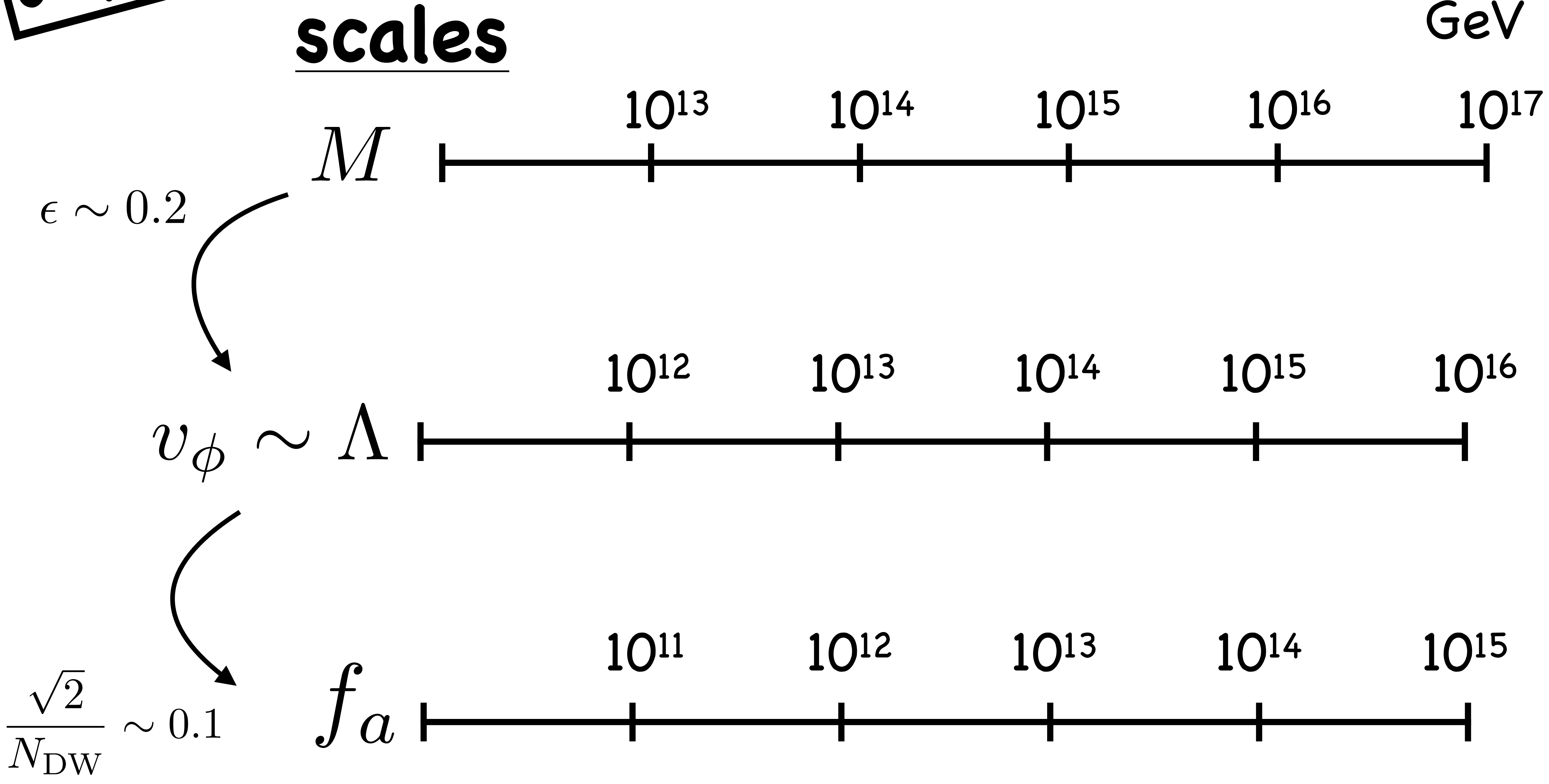
Lagrangian

$$
\begin{aligned}
\mathcal{L} = &-\frac{|\partial\phi|^2}{\left(1-|\phi|^2/\Lambda^2\right)^2} - \lambda_\phi \left(|\phi|^2 - v_\phi^2\right)^2 \\
&+ y_{ij}^d \left(\frac{\phi}{M}\right)^{n_{ij}^d} \overline{Q}_i H d_{Rj} + y_{ij}^u \left(\frac{\phi}{M}\right)^{n_{ij}^u} \overline{Q}_i \widetilde{H} u_{Rj} \\
&+ y_{ij}^l \left(\frac{\phi}{M}\right)^{n_{ij}^l} \overline{L}_i H l_{Rj} + y_{i\alpha}^\nu \left(\frac{\phi}{M}\right)^{n_{i\alpha}^\nu} \overline{L}_i \widetilde{H} N_{R\alpha} \\
&+ \frac{1}{2} y_{\alpha\beta}^N \left(\frac{\phi}{M}\right)^{n_{\alpha\beta}^N} M \overline{N_{R\alpha}^c} N_{R\beta} + \text{h.c.}
\end{aligned}
$$

Flaxion Scenario

Summary of part 1

scales



Flaxion Scenario

Summary of part 1

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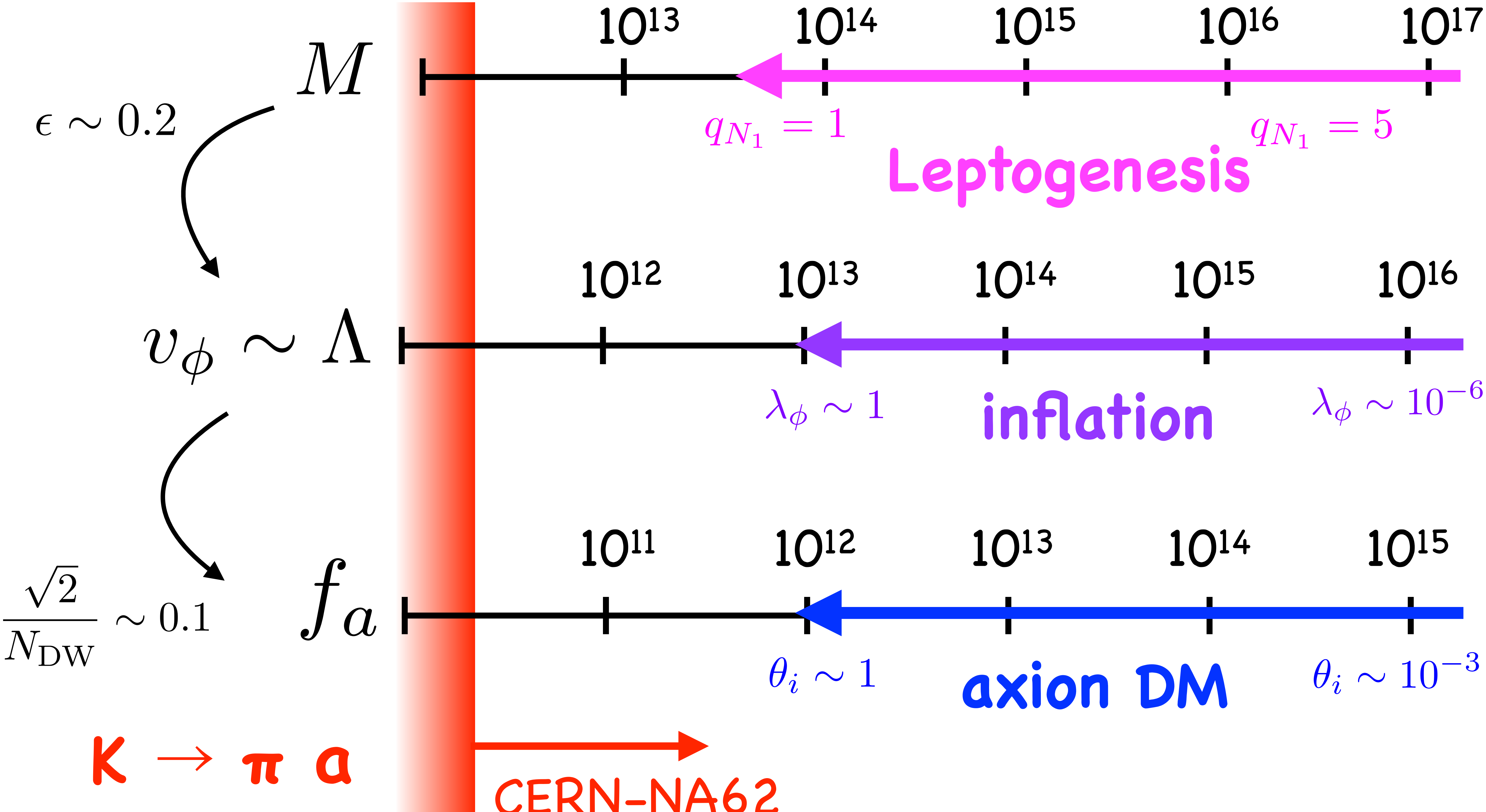
GeV



M

$\epsilon \sim 0.2$

$q_{N_1} = 1$ $q_{N_1} = 5$

Leptogenesis

$v_\phi \sim \Lambda$

$\lambda_\phi \sim 1$ $\lambda_\phi \sim 10^{-6}$

inflation

$\frac{\sqrt{2}}{N_{\rm DW}} \sim 0.1$

f_a

$\theta_i \sim 1$ $\theta_i \sim 10^{-3}$

axion DM

K → π a

[BNL-E787, 949]

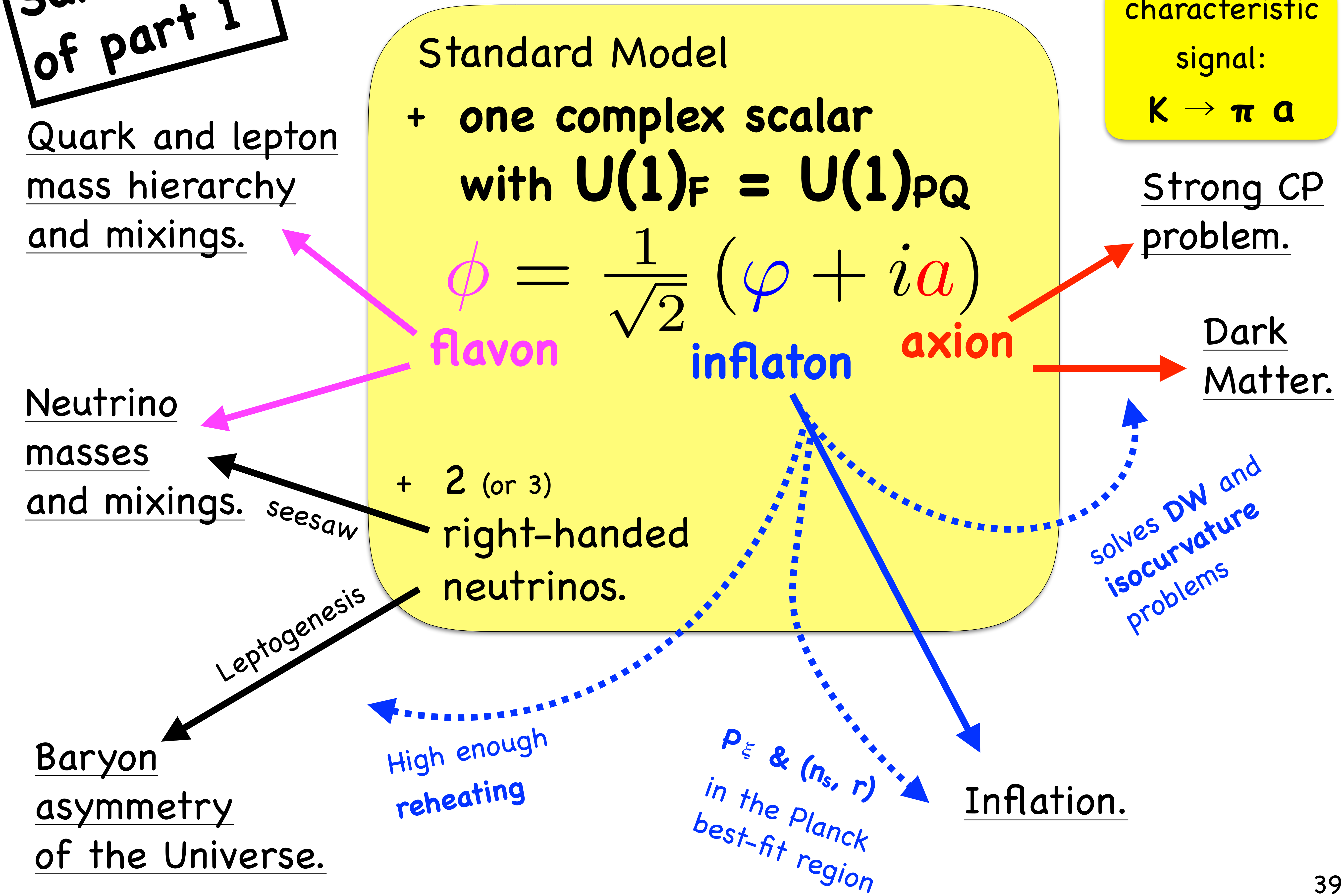
CERN-NA62

Summary of part 1

Flaxion Scenario

characteristic signal:

$K \to \pi\ a$



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Comment

Supersymmetric Flaxion

Y. Ema, D. Hagihara, KH, T. Moroi, K. Nakayama, [arXiv:1802.07739]

Motivation: fine-tuning in Higgs sector.

renormalizable int. $$\mathcal{L} = -\lambda_{\phi H}|\phi|^2|H|^2 \,.$$

-> Higgs mass $$\delta m_H^2 = \lambda_{\phi H}|\langle\phi\rangle|^2 .$$

-> Supersymmetrize it!

Comment

Supersymmetric Flaxion

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---

supersymmetric version

$$
\begin{aligned}
W_{\mathrm{MSSM}+N} = {} & y^u_{ij}\left(\frac{\phi}{M}\right)^{n^u_{ij}} Q_i \bar{U}_j H_u + y^d_{ij}\left(\frac{\phi}{M}\right)^{n^d_{ij}} Q_i \bar{D}_j H_d \\
& + y^\ell_{ij}\left(\frac{\phi}{M}\right)^{n^\ell_{ij}} L_i \bar{E}_j H_d + y^\nu_{i\alpha}\left(\frac{\phi}{M}\right)^{n^\nu_{i\alpha}} L_i N_\alpha H_u \\
& + \frac{1}{2} y^N_{\alpha\beta}\left(\frac{\phi}{M}\right)^{n^N_{\alpha\beta}} M N_\alpha N_\beta + y^\mu\left(\frac{\phi}{M}\right)^{n^\mu} M H_u H_d
\end{aligned}
$$

μ-term

- Cosmology becomes nontrivial.

  Leptogenesis vs gravitino problem, **sflaxion oscillation**,...

- R-parity violation (controlled by U(1) charges)
- Inflation model vs holomorphy,...

–> Viable scenario is possible. See [arXiv:1802.07739] for details.

Plan

Part 1. Flaxion

Part 2. Axion and Neutron Star

Part 2. Axion and Neutron Star

KH, N. Nagata, K. Yanagi, J. Zheng, [arXiv:1806.07151]

Plan

Part 2. Axion and Neutron Star

2.1. Axion models / constraints
2.2. Cas A NS Cooling
2.3. Cas A NS Cooling with axion
2.4. Summary of Part 2.

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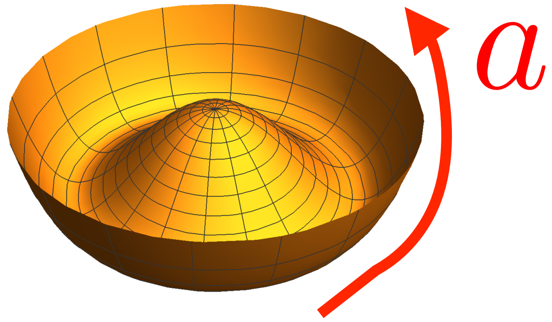
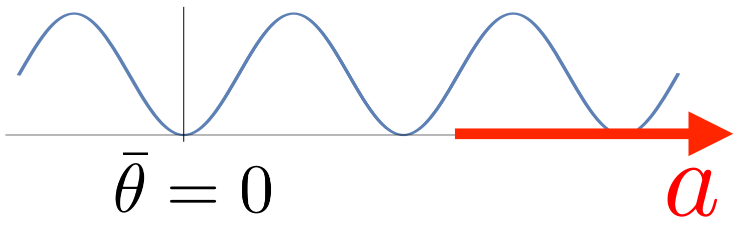
Axion: models





Conventional Models

- KSVZ axion model [Kim,'79, Shifman, Vainshtein, Zakharov,'80]

$$\mathcal{L} = |\partial\phi|^2 + (\lambda\phi\bar{Q}Q + h.c.) - V(|\phi|)$$

  - $Q, \bar{Q}$: heavy vector-like quarks

- DFSZ axion model [Dine, Fischler, Srednicki,'81, Zhitnitski,'80]

$$\mathcal{L} = |\partial\phi|^2 + (\mu\phi H_u H_d + h.c.) - V(|\phi|, H_u, H_d)$$

  - 2 Higgs doublet H_u, H_d

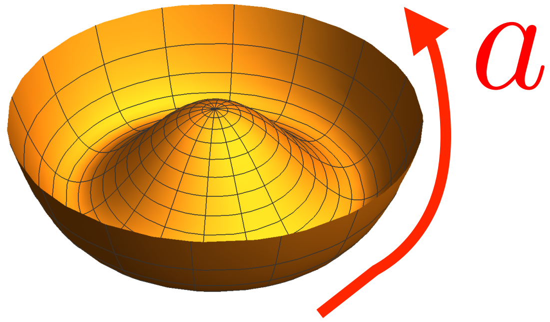
---

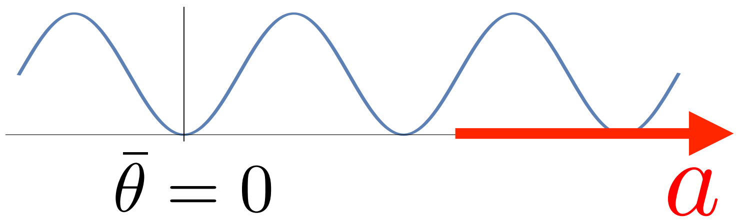
cf. Flaxion model

[Ema, Hamaguchi, Moroi, Nakayama,'16, Calibbi, Goertz, Redigolo, Ziegler, Zupan,'16]

$$\begin{aligned}\mathcal{L} = & \, y_{ij}^d \left(\frac{\phi}{M}\right)^{n_{ij}^d} \overline{Q}_i H d_{Rj} + y_{ij}^u \left(\frac{\phi}{M}\right)^{n_{ij}^u} \overline{Q}_i \widetilde{H} u_{Rj} \\ & + y_{ij}^l \left(\frac{\phi}{M}\right)^{n_{ij}^l} \overline{L}_i H l_{Rj} + y_{i\alpha}^\nu \left(\frac{\phi}{M}\right)^{n_{i\alpha}^\nu} \overline{L}_i \widetilde{H} N_{R\alpha} \\ & + \frac{1}{2} y_{\alpha\beta}^N \left(\frac{\phi}{M}\right)^{n_{\alpha\beta}^N} M \overline{N_{R\alpha}^c} N_{R\beta} + \text{h.c.}\end{aligned}$$

Axion: models





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The following discussion (Part 2) applies to them.

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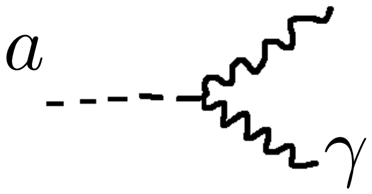
cf. Part 1.
(In this case, K->πa is stronger than NS constraint.)

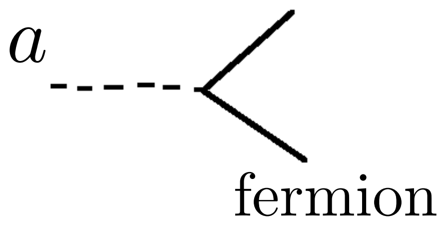
Axion: constraints

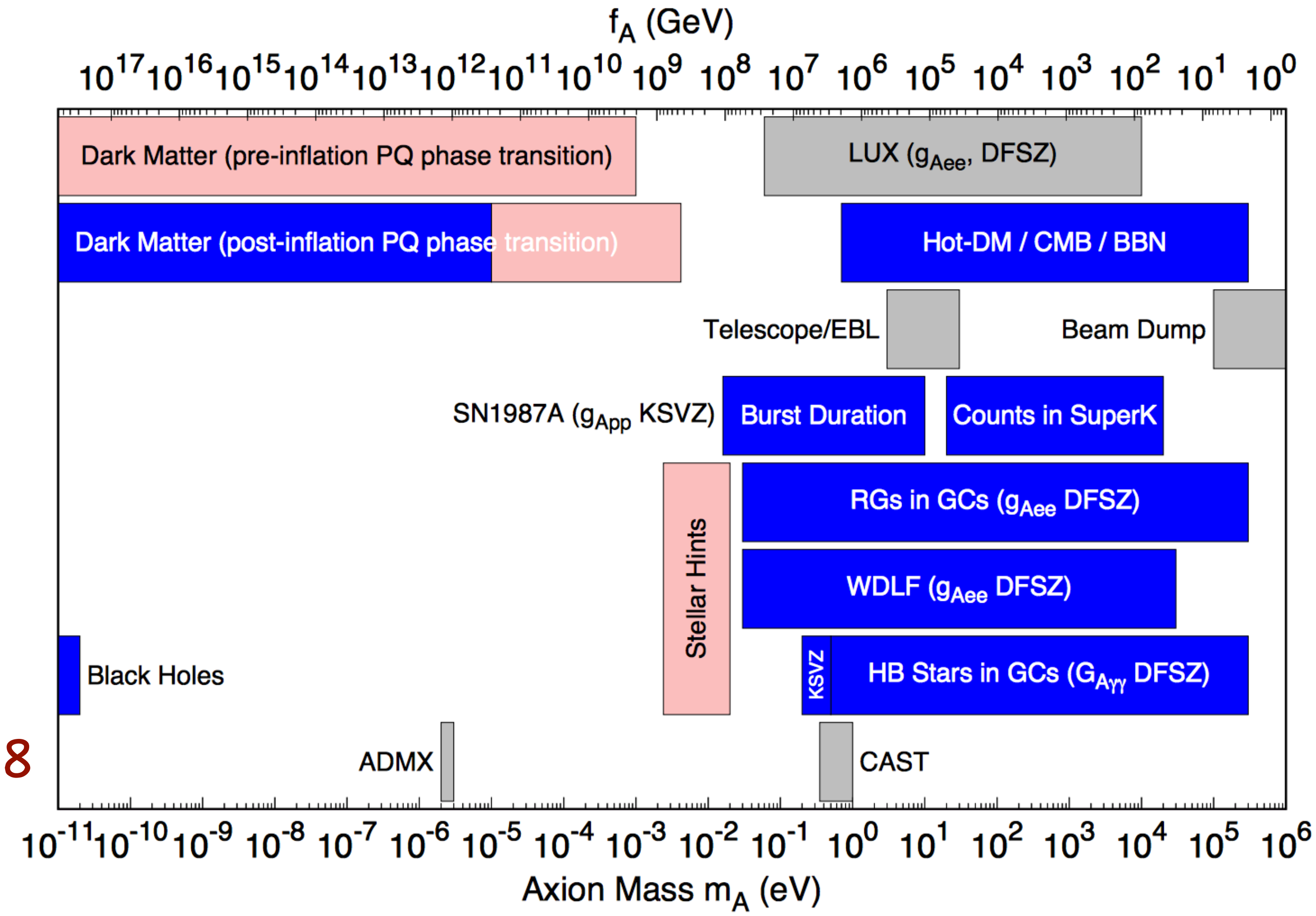
$$\text{interaction} \propto \frac{1}{f_a}$$

$$\boxed{f_a \gtrsim 4 \times 10^8\ \text{GeV (KSVZ)}}$$

from SN1987A [G.G. Raffelt, Lect. Notes Phys. 741, 51 (2008)]







PDG 2018

$$m_a \simeq 6 \times 10^{-6}\,\text{eV} \left(\frac{10^{12}\,\text{GeV}}{f_a}\right)$$

Plan

Part 2. Axion and Neutron Star

2.1. Axion models / constraints

2.2. Cas A NS Cooling

- (1) Cas A
- (2) Cas A NS
- (3) Cas A NS Cooling (observation)
- (4) Cas A NS Cooling (theory)

2.3. Cas A NS Cooling with axion

2.4. Summary of Part 2.

Cassiopeia A

- **What?** Supernova remnant (SNR)

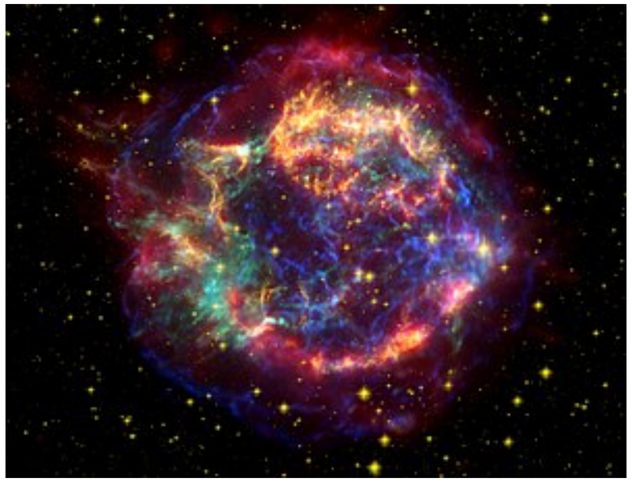


image from Wikipedia

Cassiopeia A

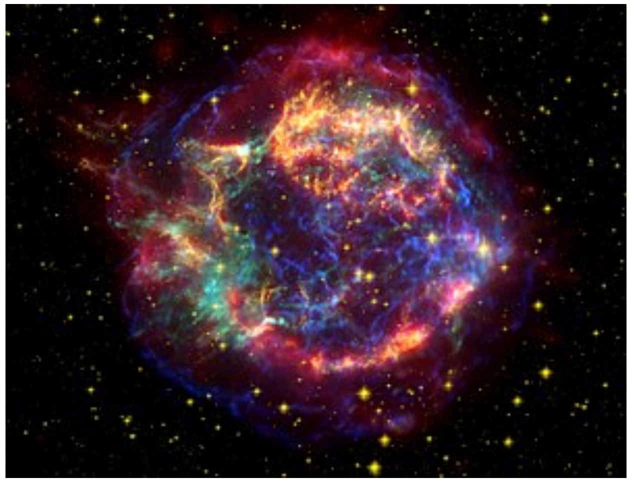
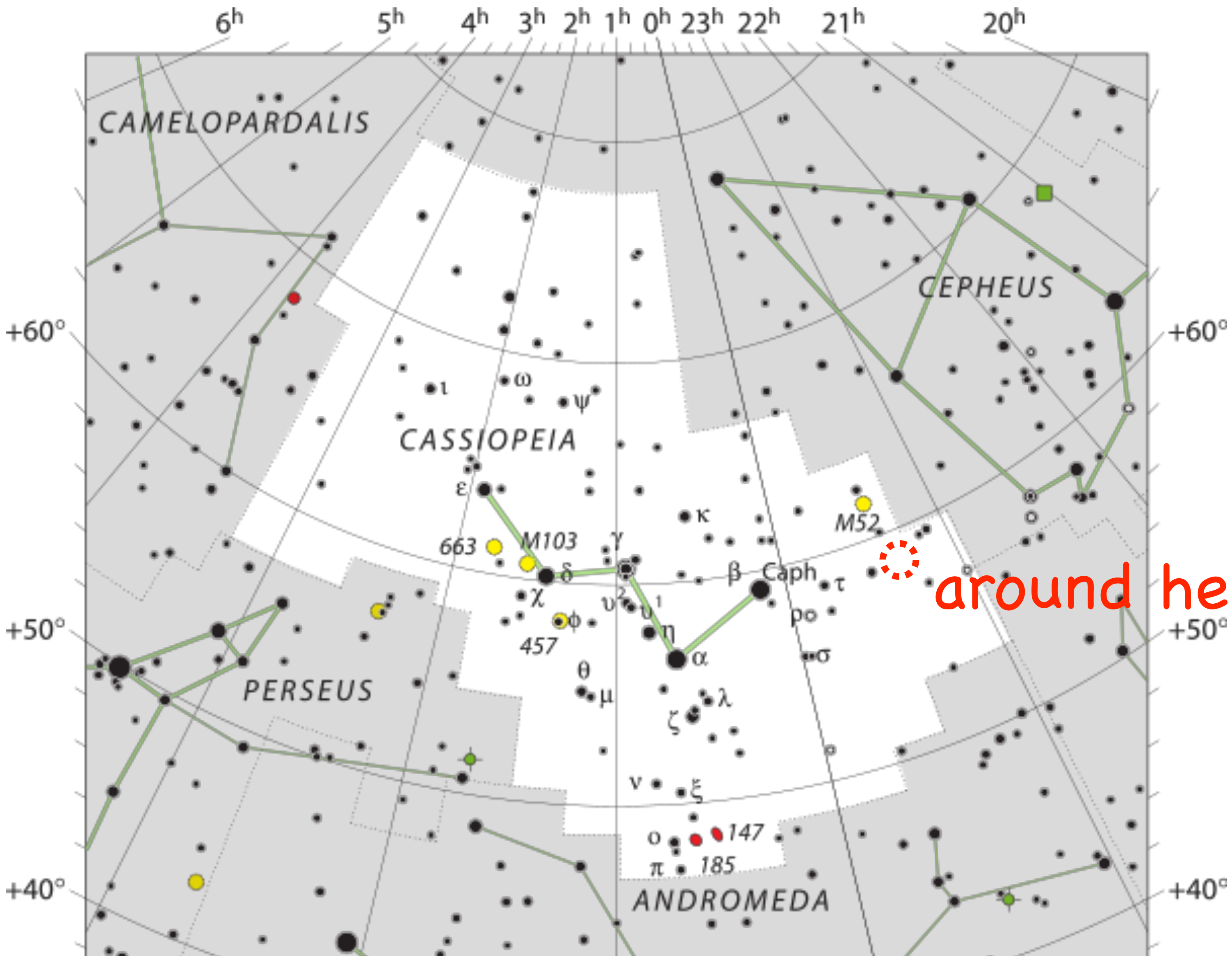


image from Wikipedia

- **What?** Supernova remnant (SNR)
- **Where?**

In the constellation Cassiopeia.
3.4 $^{+0.3}_{-0.1}$ kpc away [J.E.Reed et.al. ’95] , within the Milky Way.



around here

Right ascension
$23^h\ 23^m\ 26^s$
Declination
+58° 48′

Cassiopeia A

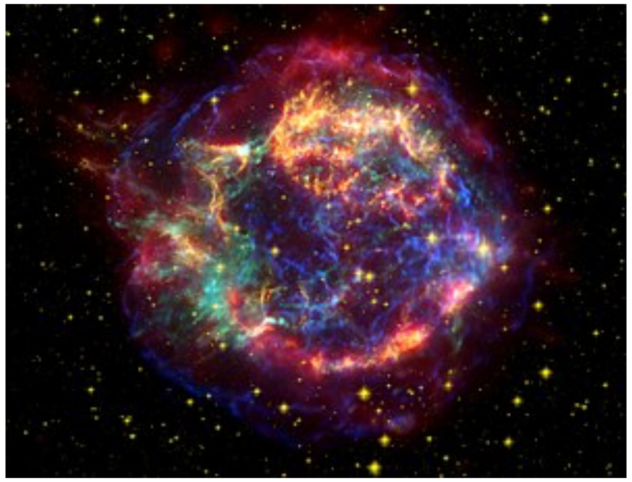


image from Wikipedia

- **What?** Supernova remnant (SNR)
- **Where?**

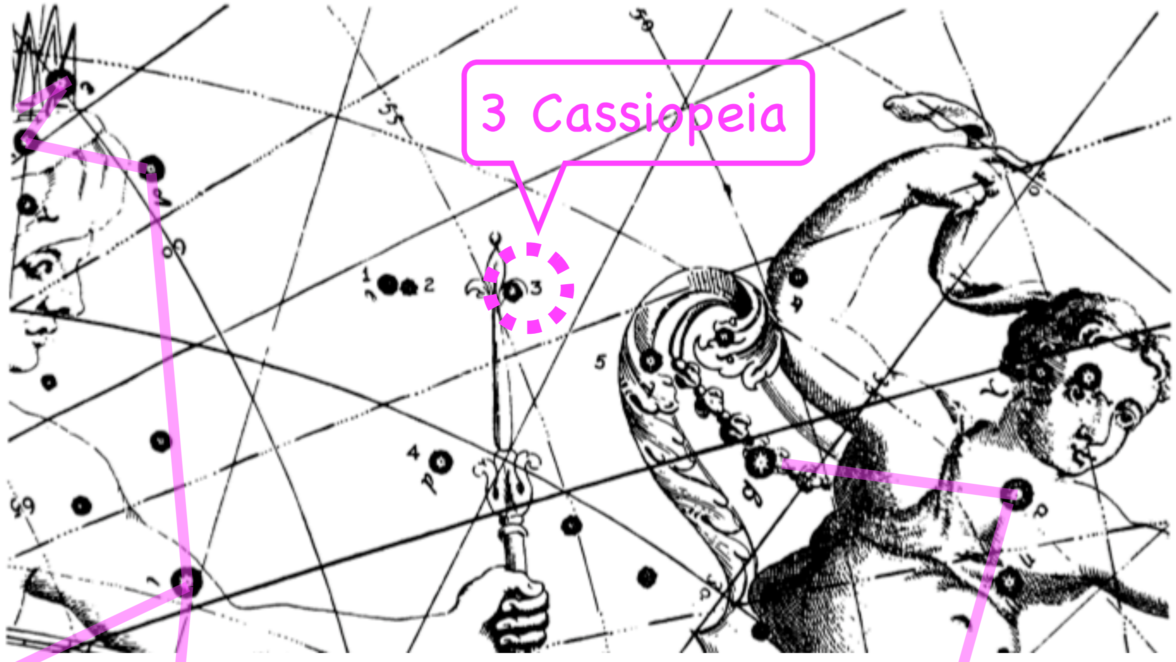
  In the constellation Cassiopeia.
  $3.4\ ^{+0.3}_{-0.1}$ kpc away [J.E.Reed et.al. ’95] , within the Milky Way.

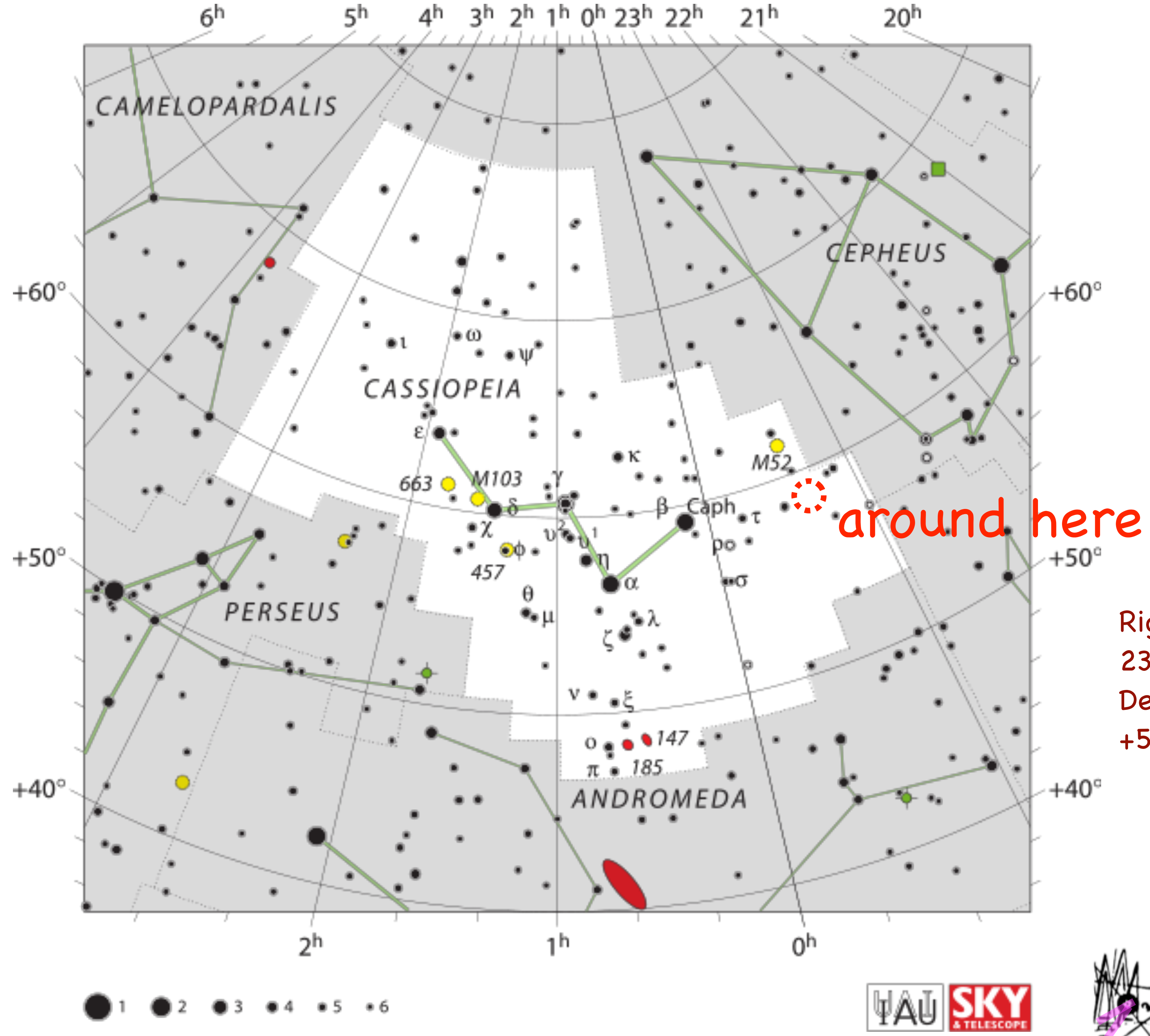
- **When?**

  Explosion (light reached Earth) about 340 years ago.

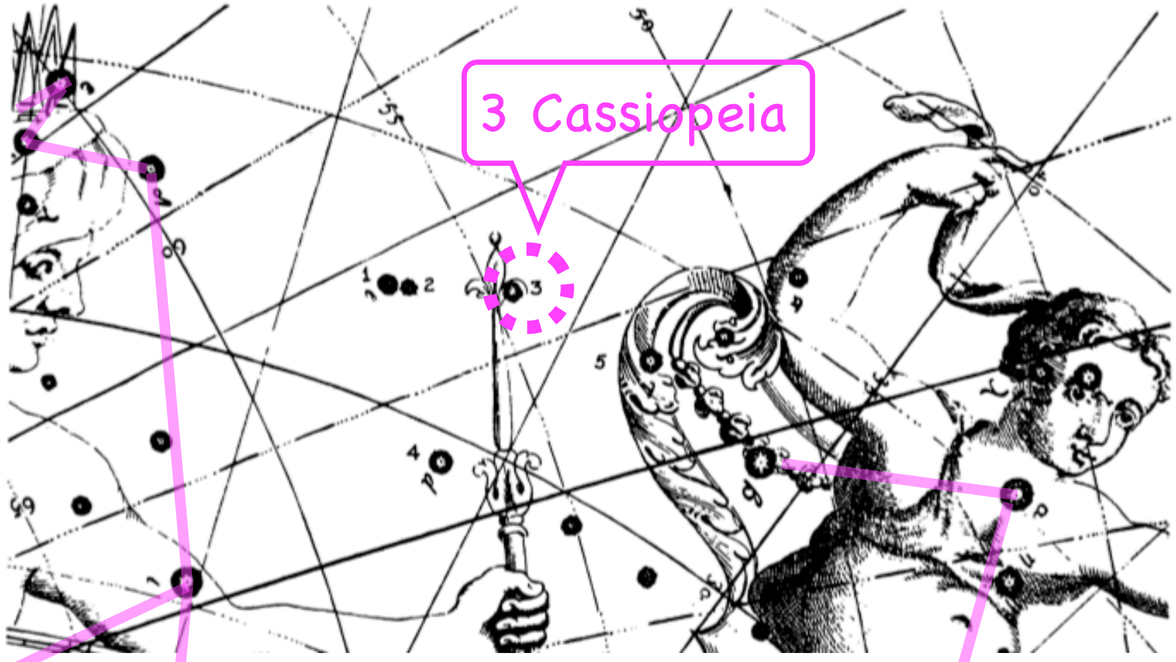
  - Remnant expansion suggests explosion dates of 1681 ± 19. [R.A.Fesen, et.al., ’06]
  - Cas A may be identical to the star 3 Cassiopeia, which was recorded by J. Flamsteed on August 16, 1680 and has been missed since then.

    [W. B. Ashworth, Jr. (1980); K. W. Kamper (1980); D. W. Hughes (1980).]





Right ascension
23h 23m 26s
Declination
+58° 48′



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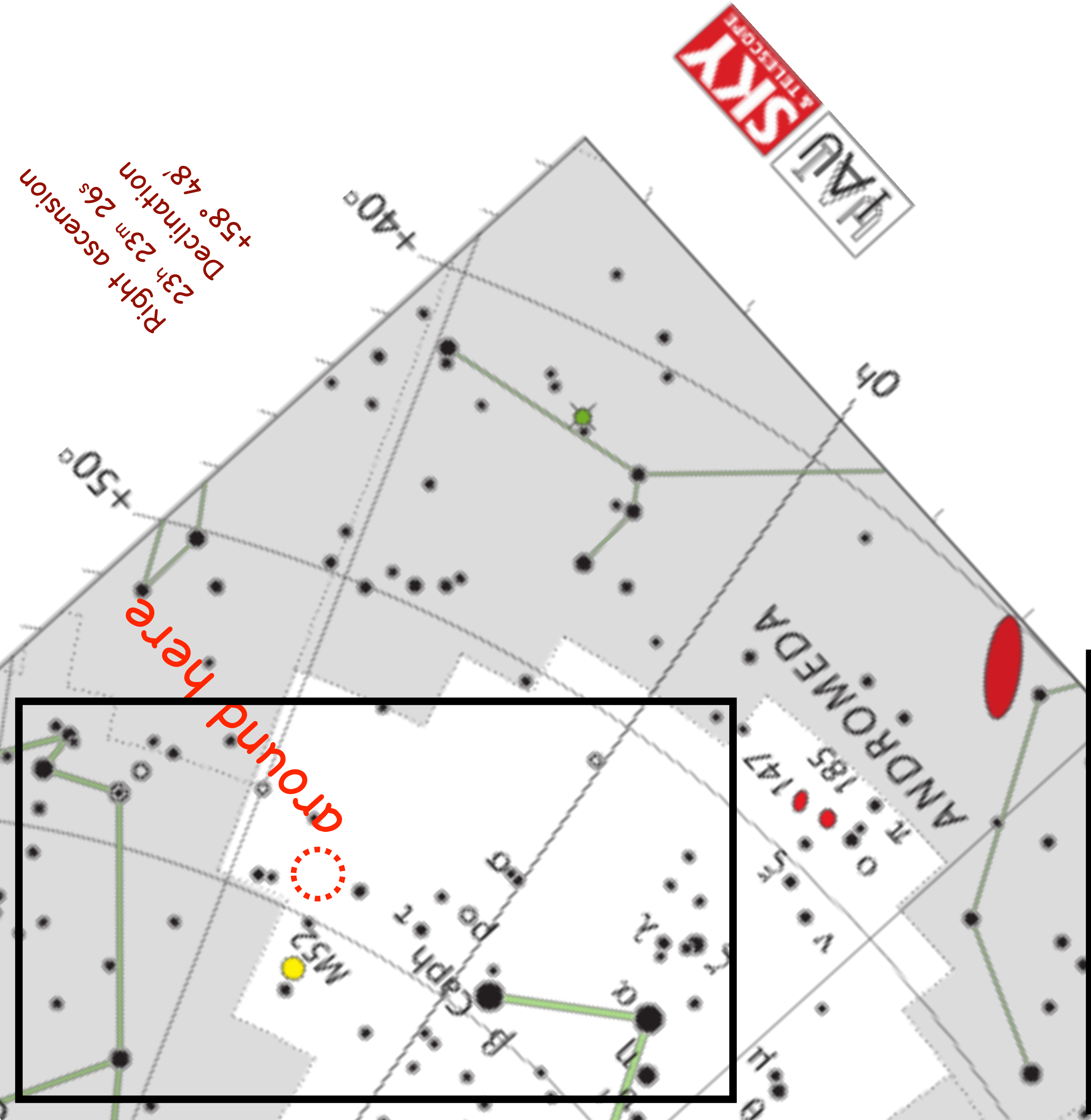
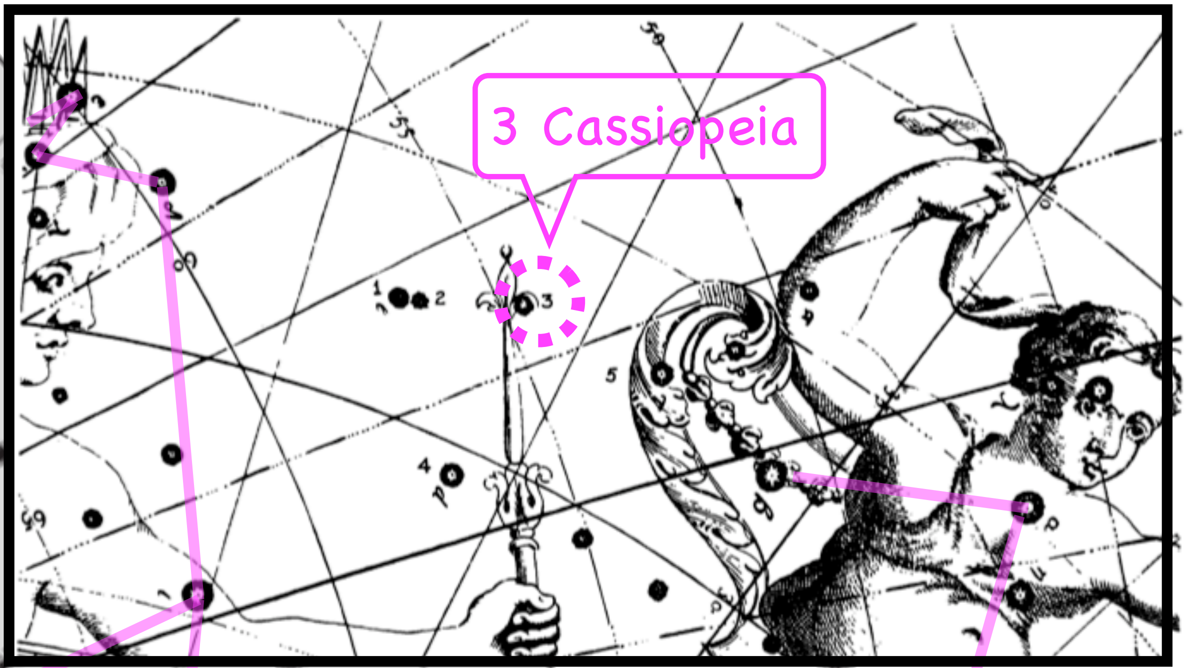
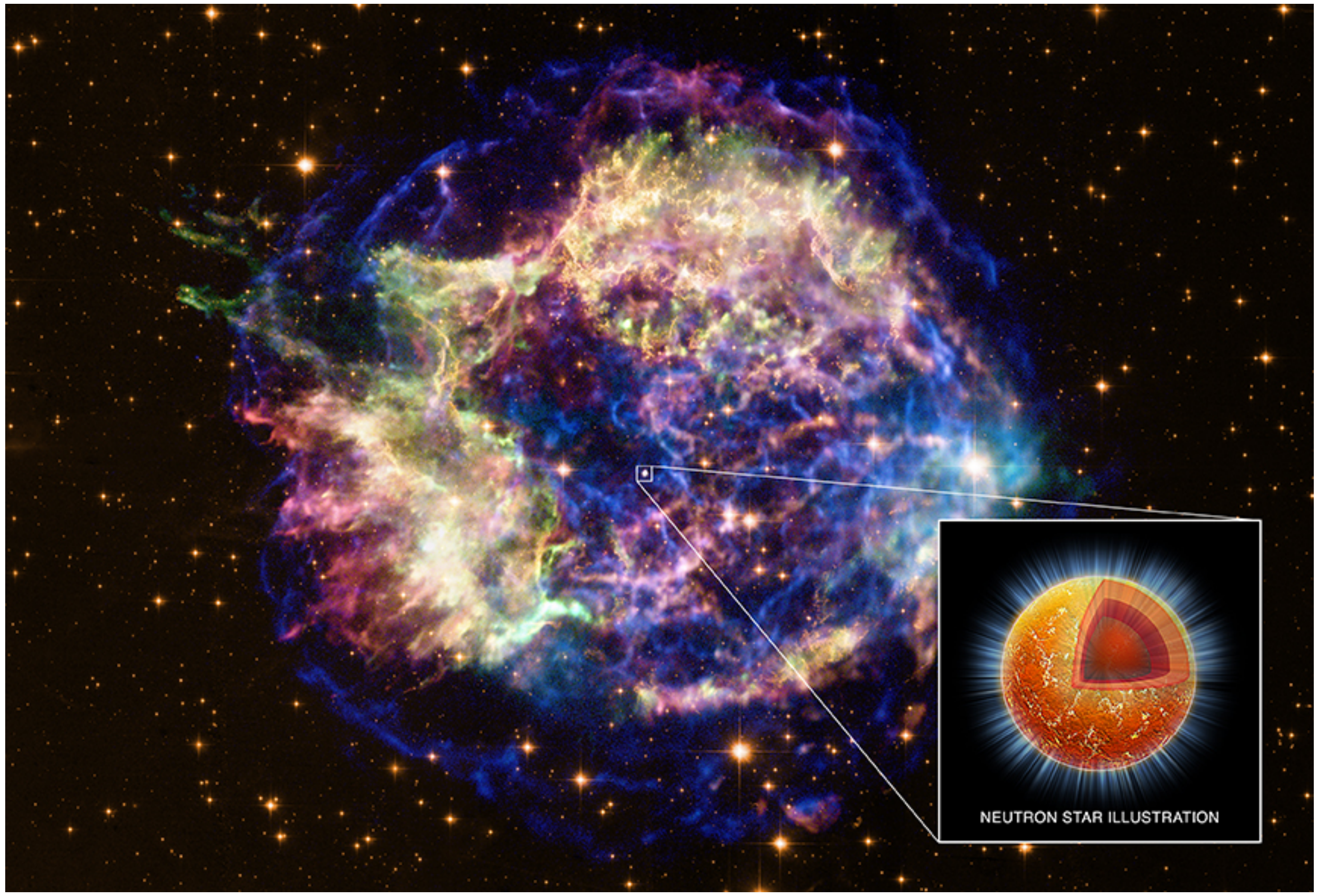
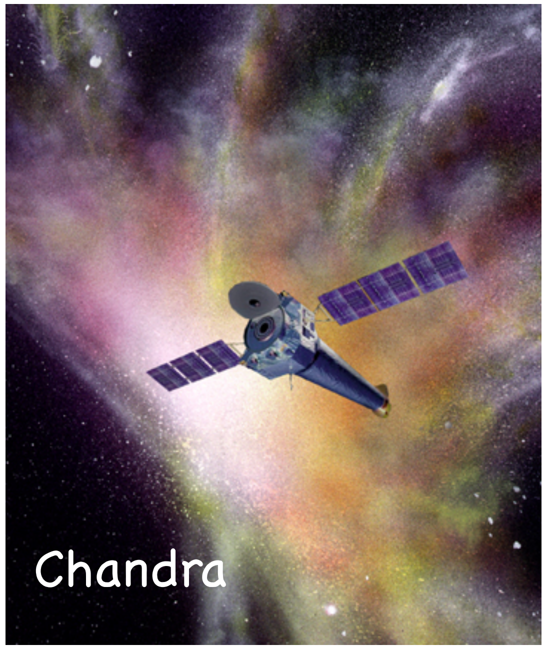




Cas A Neutron Star





images from Chandra's webpage

- In 1999, Chandra found a point source at the center of Cas A.
- X-ray spectrum is consistent with a thermal emission of Neutron Star with a carbon atmosphere, mass M = (1.4±0.3) Msun, and radius R = (11-13) km.

[W.C.G.Ho, C.O.Heinke, '09], [W.C.G.Ho, K.G.Elshamouty, C.O.Heinke, A.Y.Potekhin, '14].

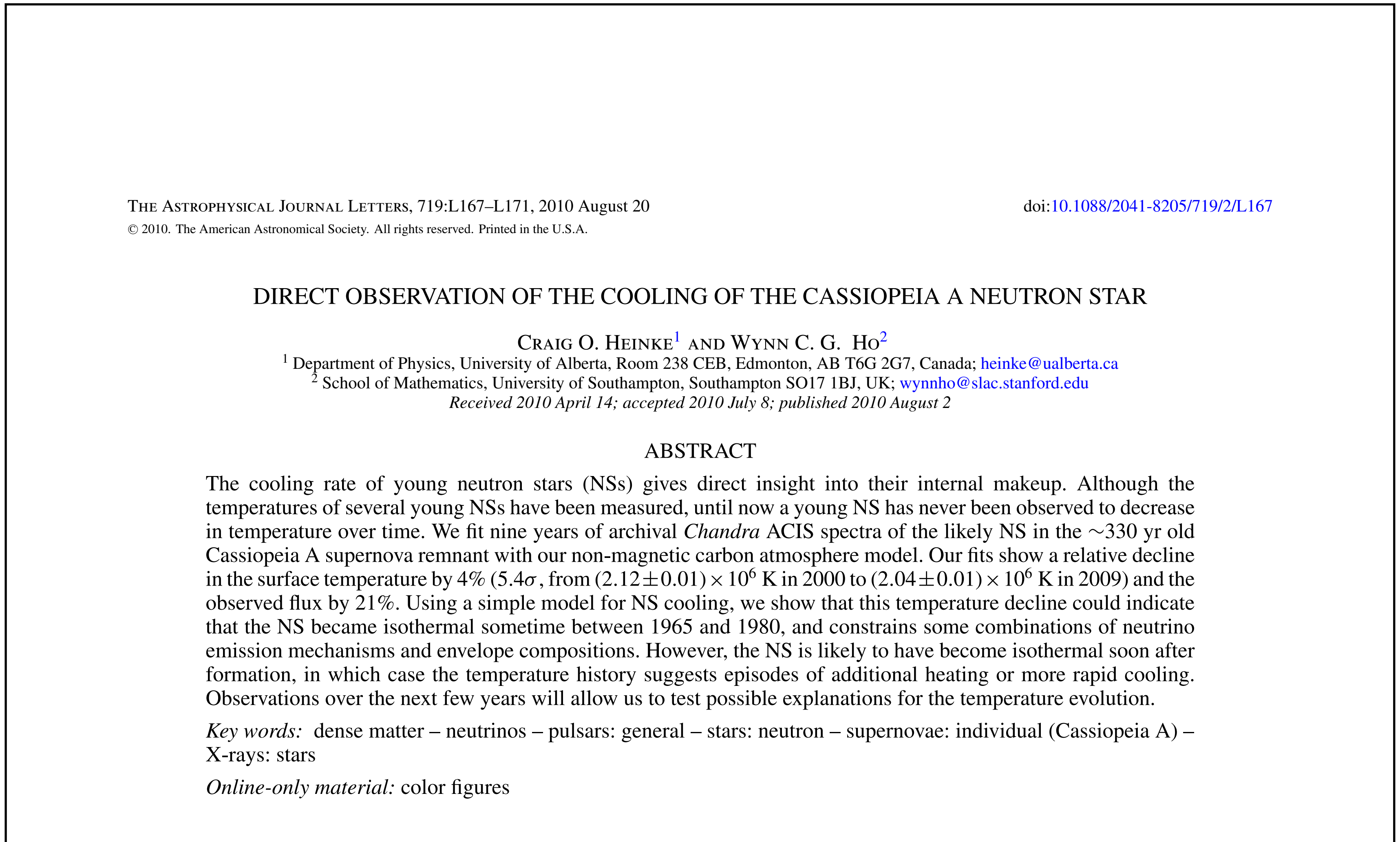
- and,.....

Cas A NS Cooling

- The **Cooling** is directly observed!

Cas A NS is the only isolated NS whose cooling has been observed in real time.

Temperature decreases by (3-4)% in 10 years.



The Astrophysical Journal Letters, 719:L167–L171, 2010 August 20 doi:10.1088/2041-8205/719/2/L167

DIRECT OBSERVATION OF THE COOLING OF THE CASSIOPEIA A NEUTRON STAR

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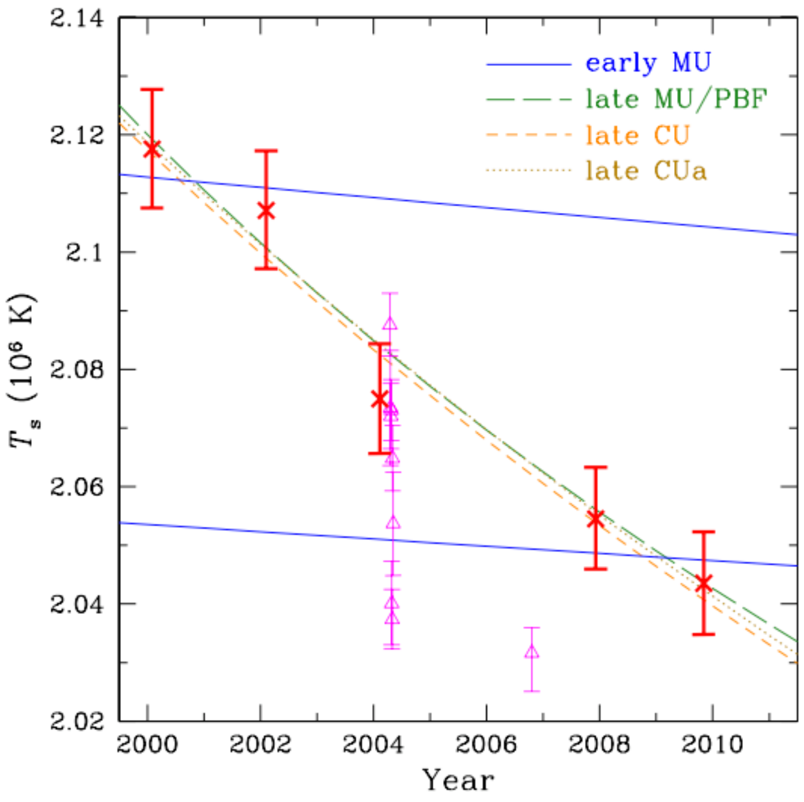
ABSTRACT

The cooling rate of young neutron stars (NSs) gives direct insight into their internal makeup. Although the temperatures of several young NSs have been measured, until now a young NS has never been observed to decrease in temperature over time. We fit nine years of archival *Chandra* ACIS spectra of the likely NS in the ~330 yr old Cassiopeia A supernova remnant with our non-magnetic carbon atmosphere model. Our fits show a relative decline in the surface temperature by 4% (5.4σ, from $(2.12\pm0.01)\times10^6$ K in 2000 to $(2.04\pm0.01)\times10^6$ K in 2009) and the observed flux by 21%. Using a simple model for NS cooling, we show that this temperature decline could indicate that the NS became isothermal sometime between 1965 and 1980, and constrains some combinations of neutrino emission mechanisms and envelope compositions. However, the NS is likely to have become isothermal soon after formation, in which case the temperature history suggests episodes of additional heating or more rapid cooling. Observations over the next few years will allow us to test possible explanations for the temperature evolution.

Key words: dense matter – neutrinos – pulsars: general – stars: neutron – supernovae: individual (Cassiopeia A) – X-rays: stars

Online-only material: color figures



Cas A NS Cooling

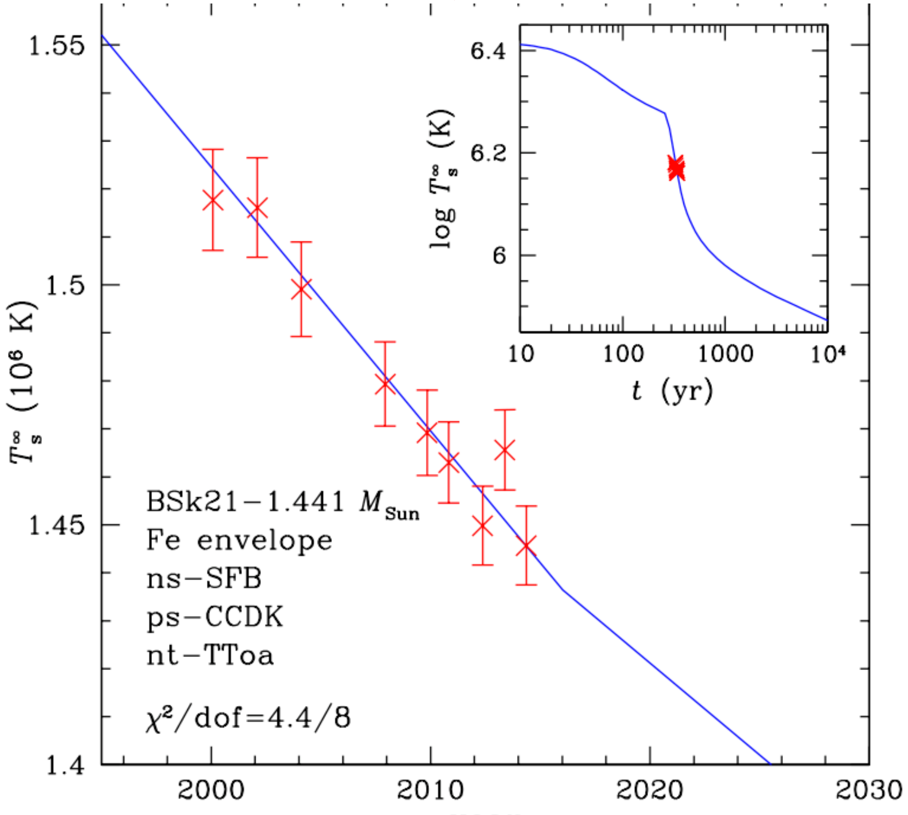
- The **Cooling** is directly observed!

Cas A NS is the only isolated NS whose cooling has been observed in real time.

Temperature decreases by (3-4)% in 10 years.

More Recent data:

W.C.G.Ho, K.G.Elshamouty, C.O.Heinke, A.Y.Potekhin, 1412.7759 (Phys.Rev.C)



14 yrs

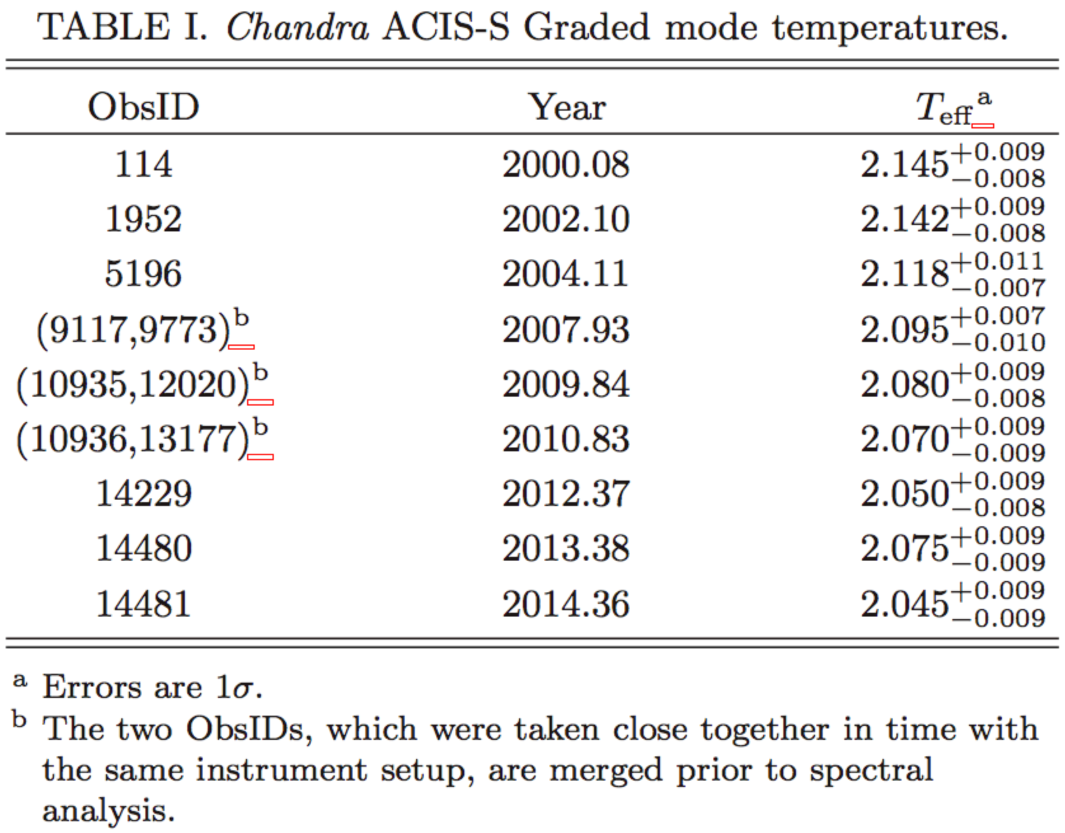


TABLE I. *Chandra* ACIS-S Graded mode temperatures.

ObsID	Year	$T_{\rm eff}$ [a]
114	2000.08	$2.145^{+0.009}_{-0.008}$
1952	2002.10	$2.142^{+0.009}_{-0.008}$
5196	2004.11	$2.118^{+0.011}_{-0.007}$
(9117,9773) [b]	2007.93	$2.095^{+0.007}_{-0.010}$
(10935,12020) [b]	2009.84	$2.080^{+0.009}_{-0.008}$
(10936,13177) [b]	2010.83	$2.070^{+0.009}_{-0.009}$
14229	2012.37	$2.050^{+0.009}_{-0.008}$
14480	2013.38	$2.075^{+0.009}_{-0.009}$
14481	2014.36	$2.045^{+0.009}_{-0.009}$

[a] Errors are 1σ.

[b] The two ObsIDs, which were taken close together in time with the same instrument setup, are merged prior to spectral analysis.

Plan

Part 2. Axion and Neutron Star

2.1. Axion models / constraints

2.2. Cas A NS Cooling

  (1) Cas A

  (2) Cas A NS

  (3) Cas A NS Cooling (observation)

  (4) Cas A NS Cooling (theory)

2.3. Cas A NS Cooling with axion

2.4. Summary of Part 2.

Cas A NS Cooling (theory)

- The observed Cas A NS cooling can be explained within **the standard NS cooling scenario.**

- Neutron **superfluidity** plays a key role. (also proton **superconductivity**)

D. Page, M. Prakash, J. M. Lattimer, A. W. Steiner, 1011.6142 [Phys.Rev.Lett.].
P. S. Shternin, D. G. Yakovlev, C. O. Heinke, W. C. G. Ho, D. J. Patnaude, 1012.0045 [MNRAS].

Cas A NS Cooling (theory)

NS temperature evolution

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

Cas A NS Cooling (theory)

NS temperature evolution

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

Photon emission luminosity. (dE_γ/dt)

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

Neutrino emission luminosity. (dE_ν/dt)

Heat Capacity of the NS.
$C = dE_{\rm thermal}/dT$

※ assuming isothermal state $T(r) \propto e^{-\phi(r)}$ for simplicity.
In the numerical calculation, we followed $T(r,t)$.

Cas A NS Cooling (theory)

NS temperature evolution

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

Photon emission luminosity. (dE_γ/dt)

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

Neutrino emission luminosity. (dE_ν/dt)

$$L_\gamma \ll L_\nu \quad \text{for} \quad t \lesssim 10^6 \text{ years}$$

Negligible for Cas A NS. $t \simeq 300$ years

Heat Capacity of the NS.
$C = dE_{\text{thermal}}/dT$

Cas A NS Cooling (theory)

NS temperature evolution

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

Neutrino emission luminosity. (dE_ν/dt)

Heat Capacity of the NS.
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$$C\frac{dT}{dt} = -L_\nu$$

- Direct Urca
- Modified Urca
- Bremsstrahlung
- PBF

Cas A NS Cooling (theory)

NS temperature evolution

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

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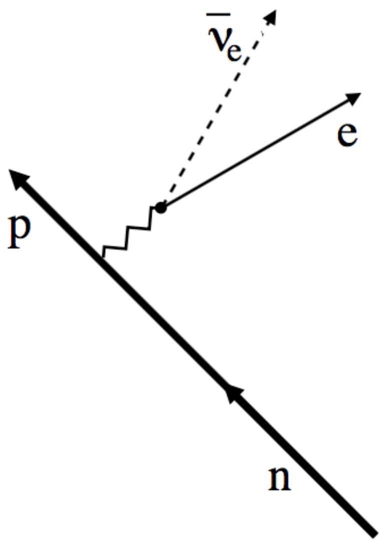
β decay and its inverse:

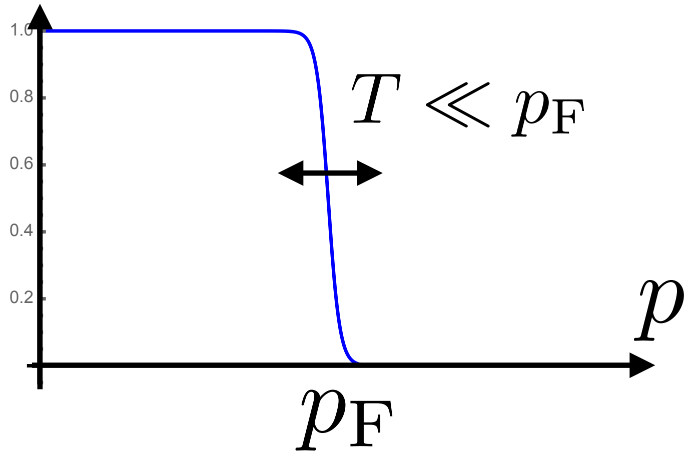
$$\begin{cases} n \;\rightarrow\; p + e^- + \bar{\nu}_e \\ p + e^- \;\rightarrow\; n + \nu_e \end{cases}$$



- It requires $p_p + p_e > p_n$, which works only in very heavy NS and **unlikely** for Cas A NS.

- Even if it happens, the temperature would be T << T(obs.) at ~300 yrs, and **cannot explain the data.**

※ Neutron, proton, electron are all **Fermi degenerate.**



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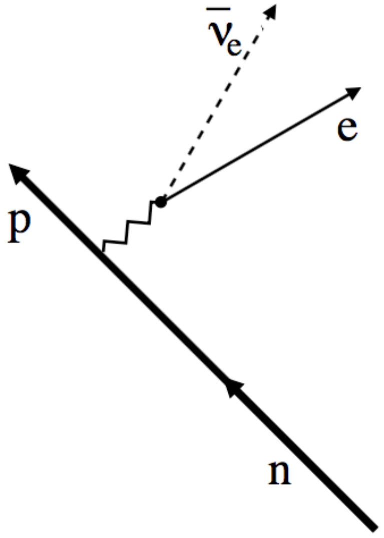

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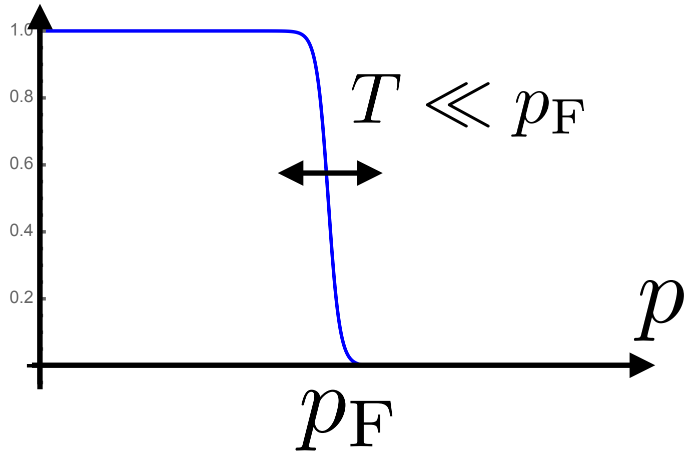


Cas A NS Cooling (theory)

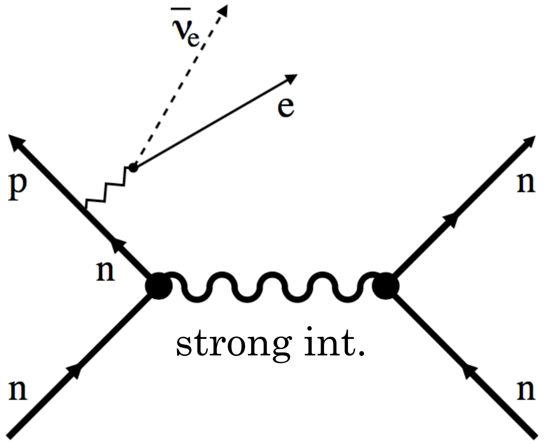
NS temperature evolution

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

- ~~Direct Urca~~
- **Modified Urca**
- Bremsstrahlung
- PBF

$$\begin{cases} n + N \;\rightarrow\; p + N + e^- + \bar{\nu}_e \\ p + N + e^- \;\rightarrow\; n + N + \nu_e \end{cases}$$

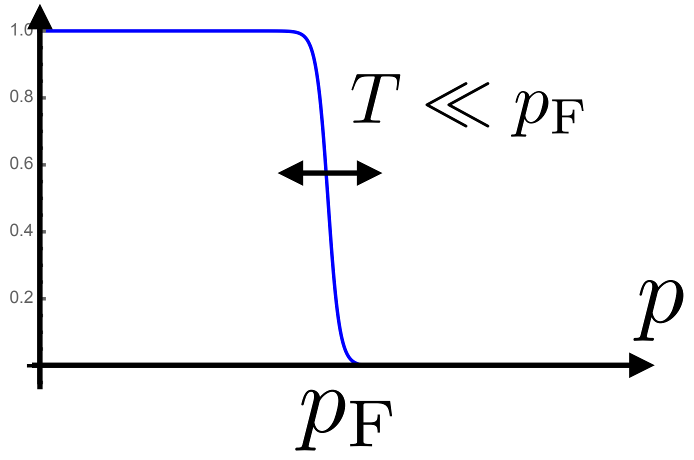
$$(N = n \text{ or } p)$$



- **Dominant process** (before the onset of Cooper pairing)
- $L_\nu^{\text{MU}} \propto T^8$

$$L_\nu^{\text{MU}} \sim \underbrace{\int d^3p_n}_{T}\underbrace{\int d^3p_N}_{T} \cdot \underbrace{\int d^3p_p}_{T}\underbrace{\int d^3p_N}_{T}\underbrace{\int d^3p_e}_{T} \cdot \underbrace{\int d^3p_\nu \delta^4(p_i - p_f)E_\nu}_{T^3}$$

※ Neutron, proton, electron are all **Fermi degenerate.**



Cas A NS Cooling (theory)

NS temperature evolution

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

- ~~Direct Urca~~
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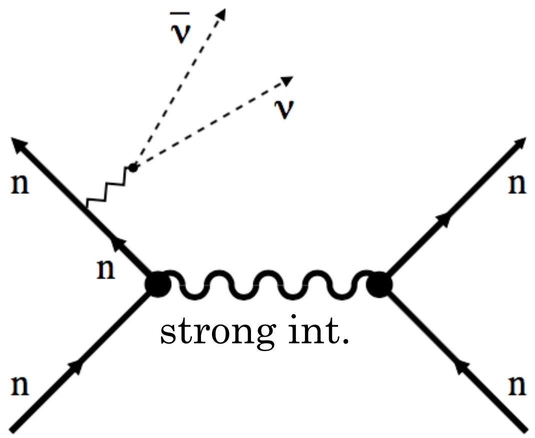
- PBF

$$N + N' \;\to\; N + N' + \nu + \bar{\nu}$$

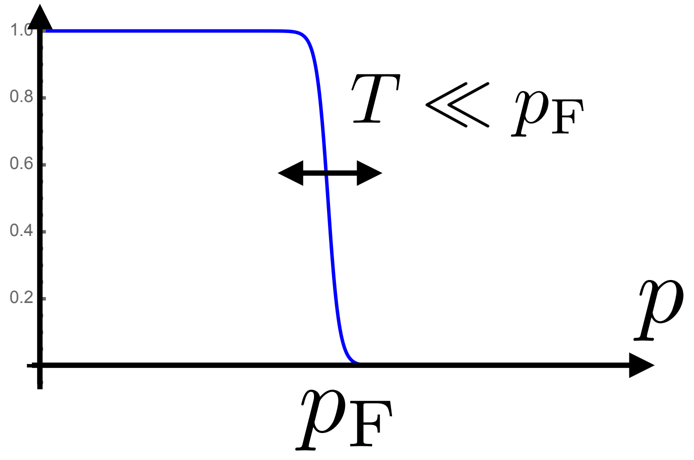
$$(N, N' = n \text{ or } p)$$



- similarly, $L_\nu^{\rm Brems} \propto T^8$

but **subdominant**, $L_\nu^{\rm Brems} \sim \mathcal{O}(0.01) L_\nu^{\rm MU}$

※ Neutron, proton, electron are all **Fermi degenerate.**



Cas A NS Cooling (theory)

NS temperature evolution

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

- ~~Direct Urca~~
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- (PBF)

We neglect it for the moment.
(more on this later)

Cas A NS Cooling (theory)

NS temperature evolution

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

- ~~Direct Urca~~
- **Modified Urca**
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Cas A NS Cooling (theory)

NS temperature evolution

$$C\frac{dT}{dt} = -L_\nu \propto T^8$$

$$\boxed{\propto T}$$

- ~~Direct Urca~~
- **Modified Urca**
- **Bremsstrahlung**
- (PBF)

Cas A NS Cooling (theory)

NS temperature evolution

$$\underset{\propto T}{C}\frac{dT}{dt} = -L_\nu \propto T^8 \Longrightarrow \boxed{T \propto t^{-1/6}}$$

- ~~Direct Urca~~
- **Modified Urca**
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Cas A NS Cooling (theory)

NS temperature evolution

$$\underset{\boxed{\propto T}}{C}\frac{dT}{dt} = -L_\nu \propto T^8 \Longrightarrow \boxed{T \propto t^{-1/6}}$$

- ~~Direct Urca~~
- **Modified Urca**
- **Bremsstrahlung**
- (PBF)

For Cas A NS observation,

$$\begin{cases} t \simeq 330 \text{ yrs} \\ \Delta t \simeq 10 \text{ yrs} \end{cases}$$

$$\Longrightarrow \left.\frac{\Delta T}{T}\right|_{10\text{yrs}} \sim -\frac{1}{6}\cdot\frac{\Delta t}{t} \sim 0.5\%$$

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surface temperature

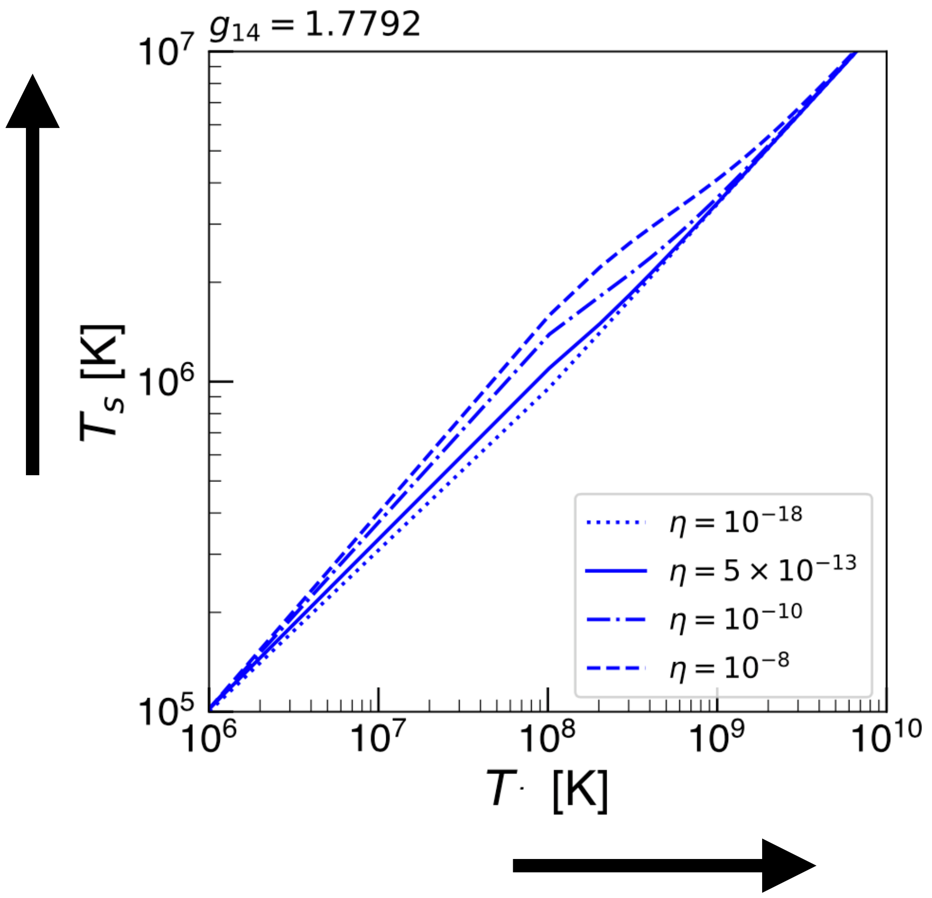
$$\Longrightarrow \boxed{\left.\frac{\Delta T_s}{T_s}\right|_{10\text{yrs}} \sim 0.3\% \text{ !!}}$$

Cas A NS Cooling (theory)

NS surface is insulated from the hot interior by its envelope.

surface temperature (observed)

$$T_s \sim T^{\alpha} \ (\alpha \sim 0.5)$$



internal temperature

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

ΔM : mass of light elements

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

$$\Longrightarrow \boxed{T \propto t^{-1/6}}$$

For Cas A NS observation,

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Cas A NS Cooling (theory)

NS temperature evolution

$$\underset{\boxed{\propto T}}{C}\frac{dT}{dt} = -L_\nu \propto T^8 \implies \boxed{T \propto t^{-1/6}}$$

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For Cas A NS observation,

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surface temperature

$$\implies \boxed{\left.\frac{\Delta T_s}{T_s}\right|_{10\text{yrs}} \sim 0.3\% \;!!}$$

much smaller than the observation, $\Delta T_s/T_s \sim$ (3-4)%.

Cas A NS Cooling (theory)

NS temperature evolution

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

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Cas A NS Cooling (theory)

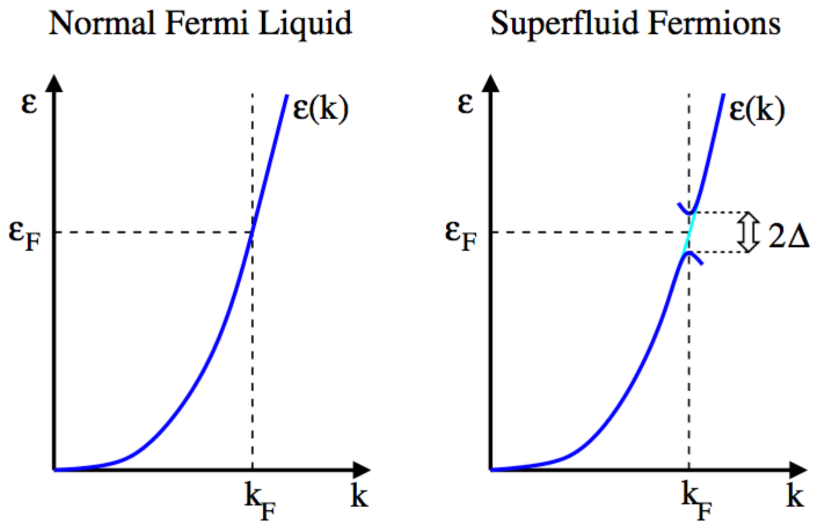
NS temperature evolution

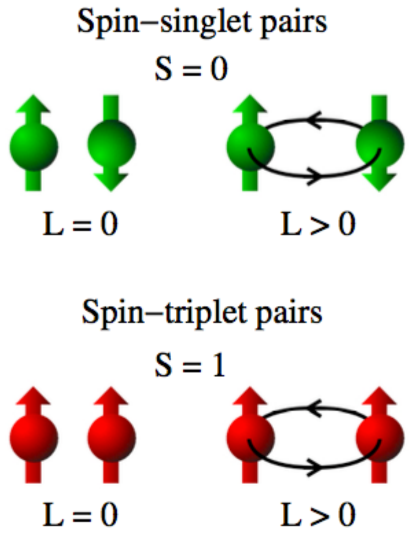
$$C\frac{dT}{dt} = -L_{\nu}$$

- ~~Direct Urca~~
- Modified Urca
- Bremsstrahlung
- **PBF**

- At T < Tc, Cooper pairing occurs.

T > Tc T < Tc





neutron singlet ($^1S_0$)
neutron triplet ($^3P_2$)
proton singlet ($^1S_0$)

- M.Urca and Brems. are suppressed then.
- On the other hand, a new process, Cooper pair breaking and formation (PBF), is enhanced.

Figs. from Page et.al. 1302.6626

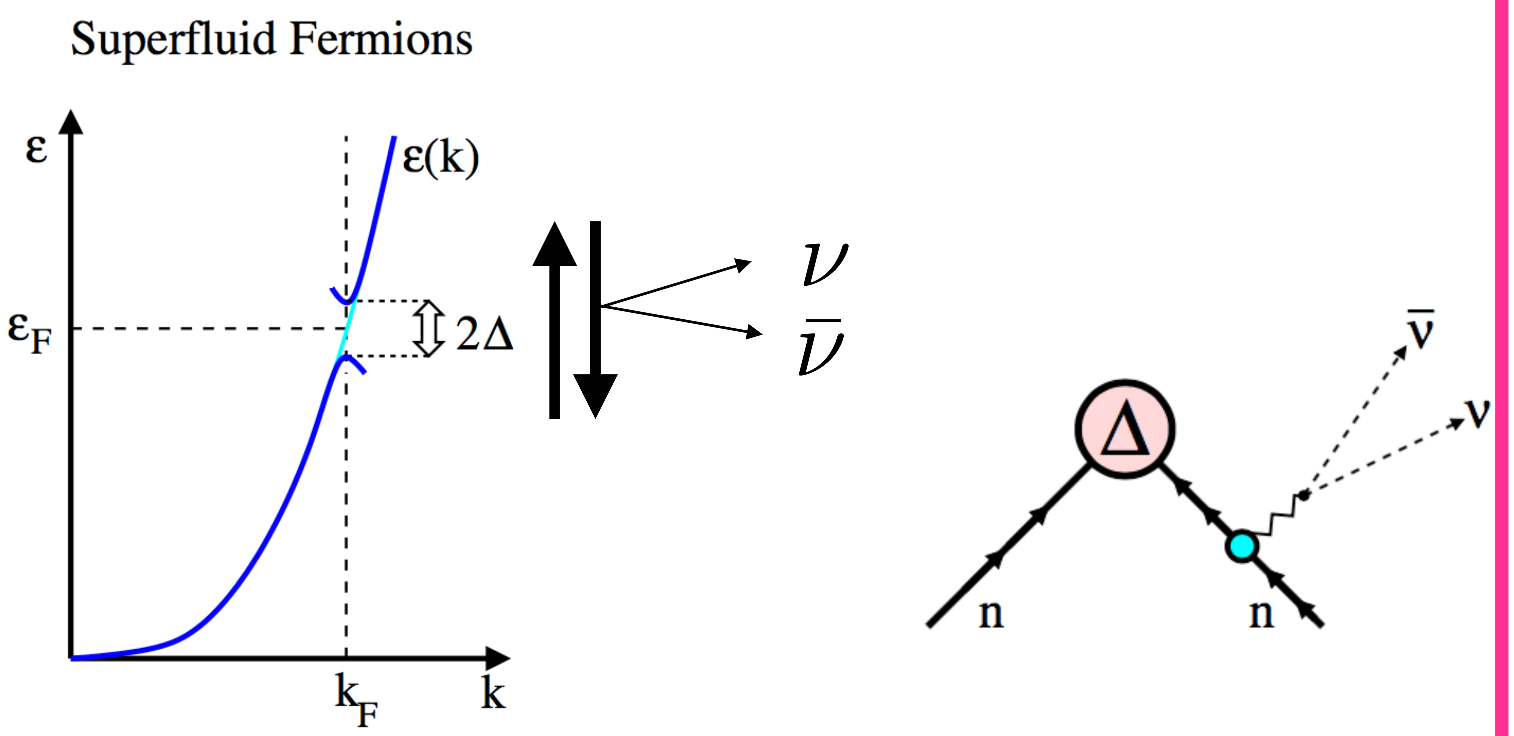
Cas A NS Cooling (theory)

NS temperature evolution

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

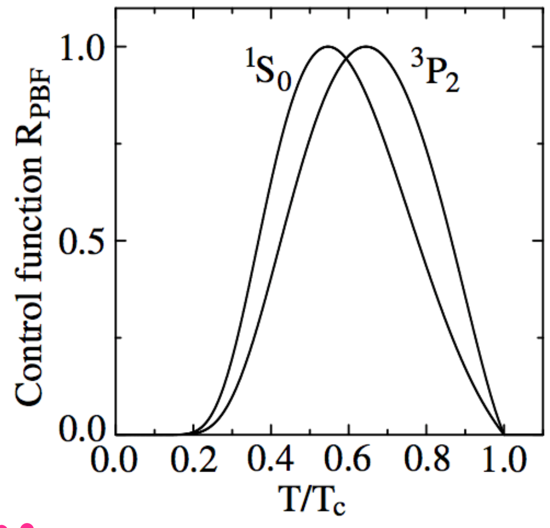
- ~~Direct Urca~~
- Modified Urca
- Bremsstrahlung
- **PBF**

Cooper pair breaking and formation (PBF)



Effective only in a short period

- At T > Tc, no paring.
- At T << Tc, no pair breaking.



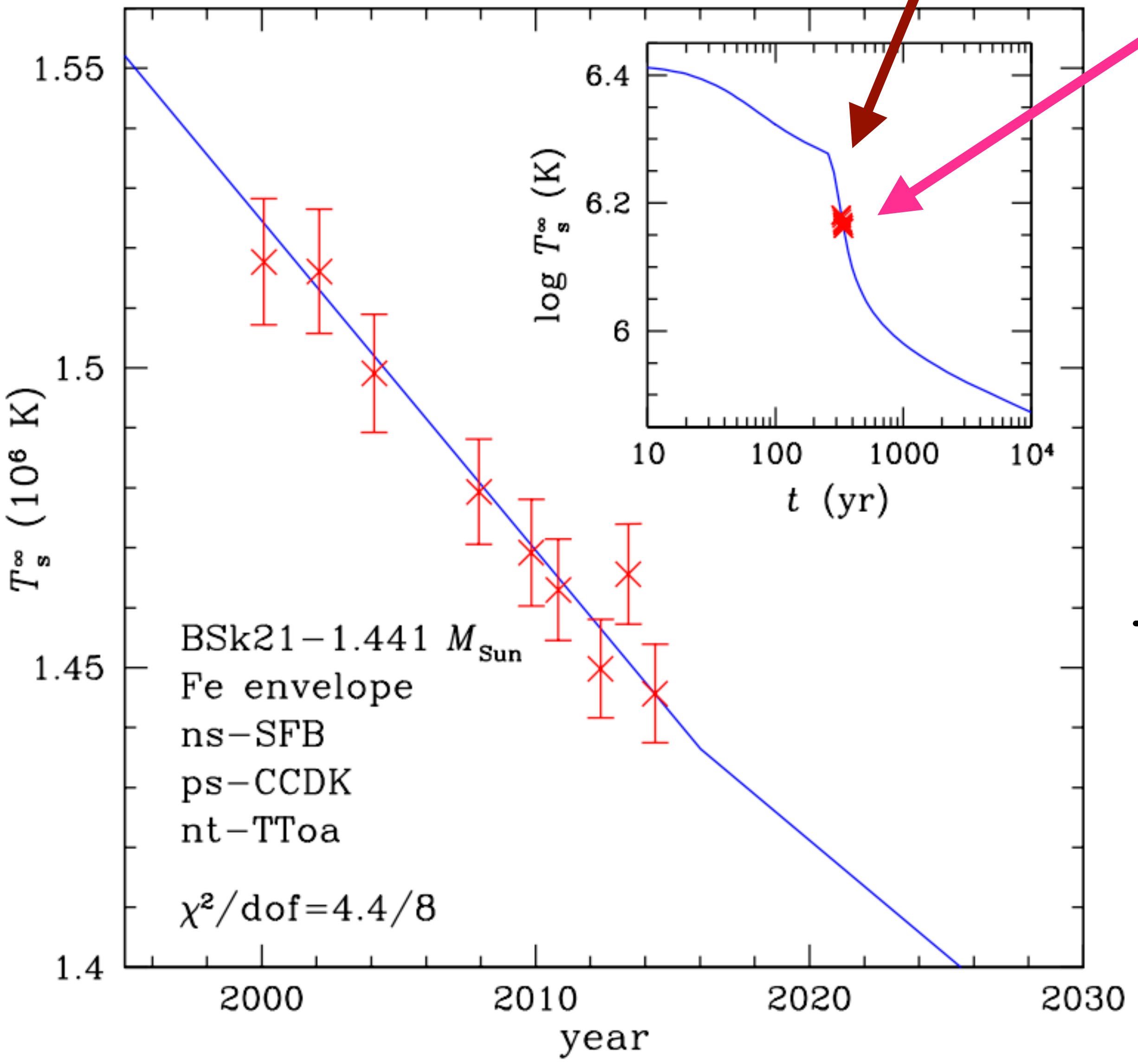
It triggers a **sudden cooling** at around T = Tc.

Figs. from Page et.al. 1302.6626

Cas A NS Cooling (theory)

phase transition
T = Tc

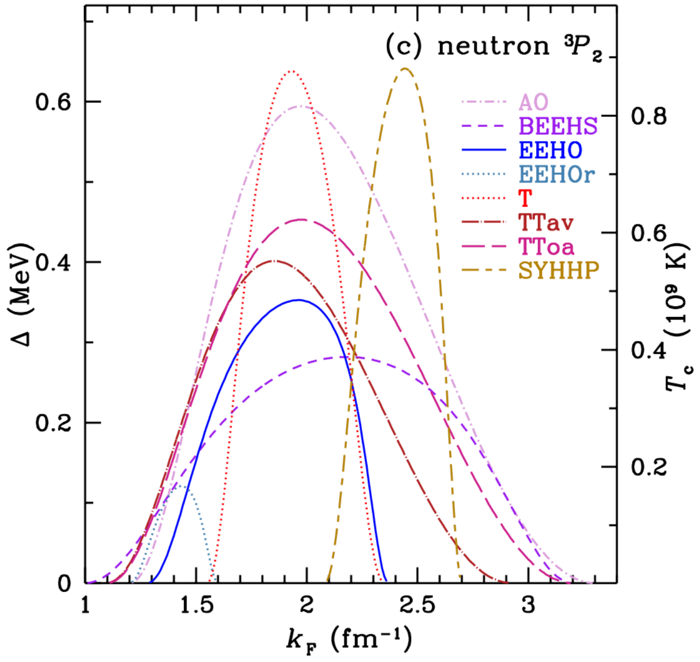
sudden, rapid cooling by PBF process.



W.C.G.Ho, K.G.Elshamouty, C.O.Heinke, A.Y.Potekhin, 1412.7759

- Neutron triplet (n-$^3P_2$) PBF is dominant.
- Large uncertainty in n-$^3P_2$ gap.

-> Parameters
(in particular, Tc)
are adjusted
to fit the data.



Cas A NS Cooling (theory)

- The observed Cas A NS cooling can be explained within **the standard NS Cooling.**
- Neutron **superfluidity** (and proton **superconductivity**) play key roles.

D. Page, M. Prakash, J. M. Lattimer, A. W. Steiner, 1011.6142 [Phys.Rev.Lett.].
P. S. Shternin, D. G. Yakovlev, C. O. Heinke, W. C. G. Ho, D. J. Patnaude, 1012.0045 [MNRAS].

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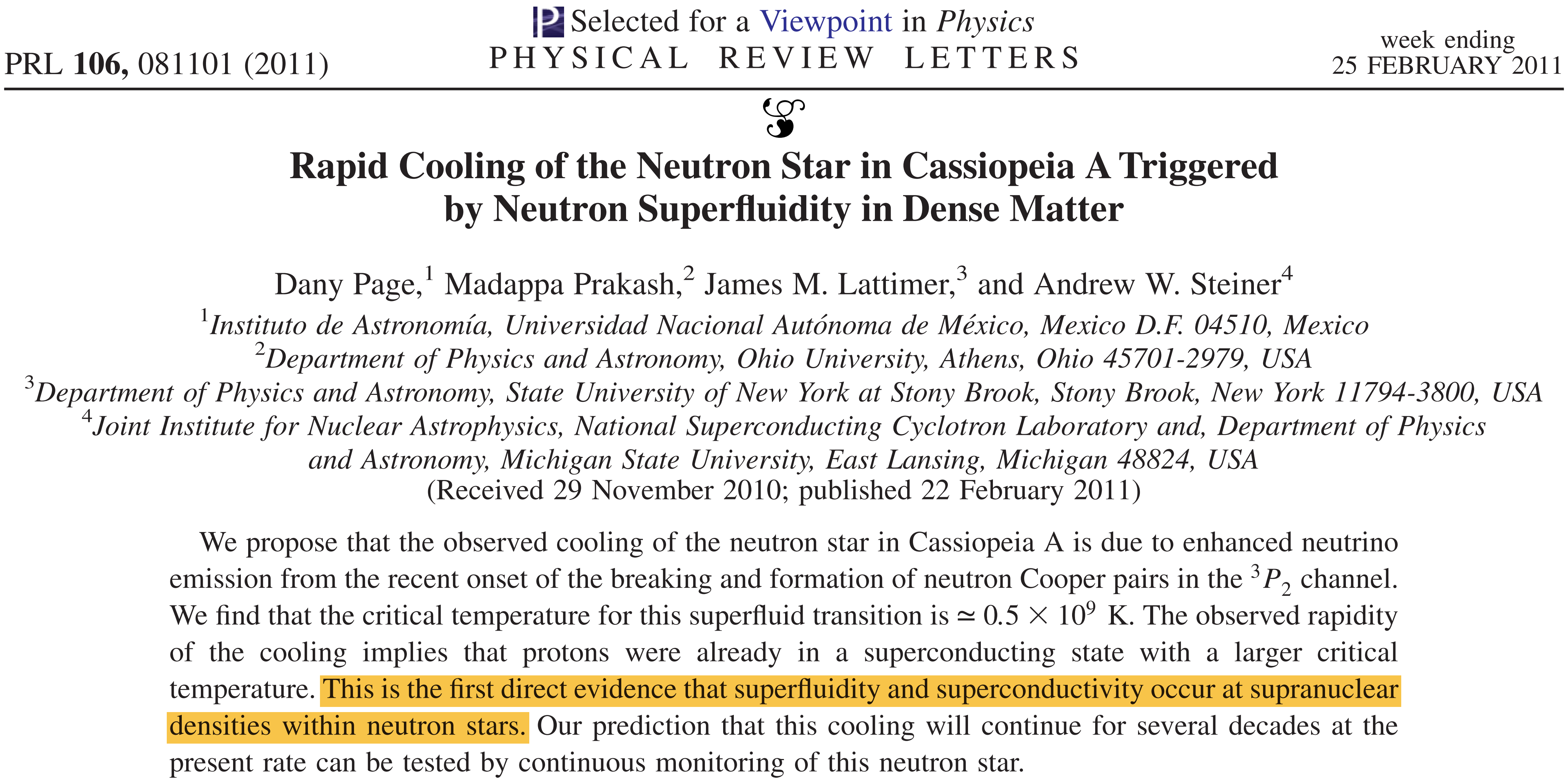


Selected for a Viewpoint in *Physics*
PRL **106,** 081101 (2011) PHYSICAL REVIEW LETTERS week ending 25 FEBRUARY 2011

Rapid Cooling of the Neutron Star in Cassiopeia A Triggered by Neutron Superfluidity in Dense Matter

Dany Page,[1] Madappa Prakash,[2] James M. Lattimer,[3] and Andrew W. Steiner[4]
[1]*Instituto de Astronomía, Universidad Nacional Autónoma de México, Mexico D.F. 04510, Mexico*
[2]*Department of Physics and Astronomy, Ohio University, Athens, Ohio 45701-2979, USA*
[3]*Department of Physics and Astronomy, State University of New York at Stony Brook, Stony Brook, New York 11794-3800, USA*
[4]*Joint Institute for Nuclear Astrophysics, National Superconducting Cyclotron Laboratory and, Department of Physics and Astronomy, Michigan State University, East Lansing, Michigan 48824, USA*

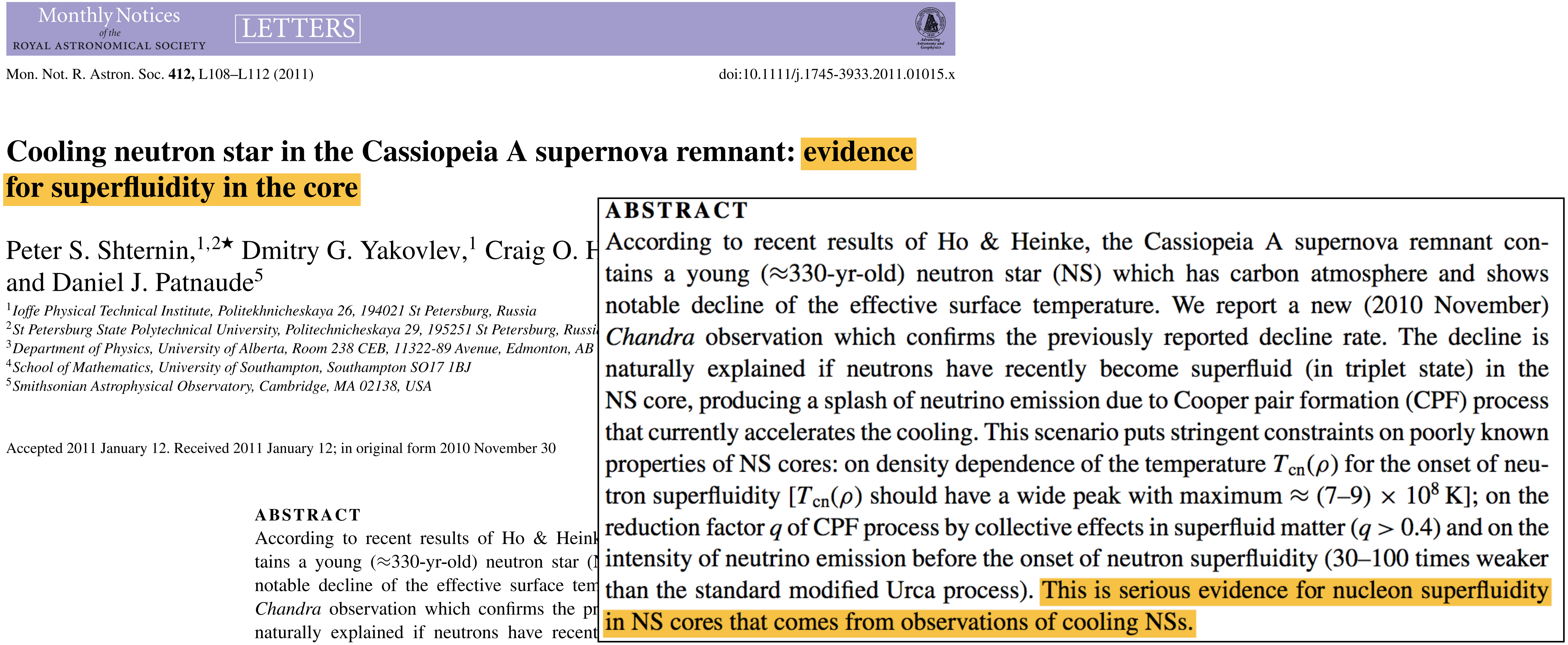
(Received 29 November 2010; published 22 February 2011)

We propose that the observed cooling of the neutron star in Cassiopeia A is due to enhanced neutrino emission from the recent onset of the breaking and formation of neutron Cooper pairs in the $^3P_2$ channel. We find that the critical temperature for this superfluid transition is $\simeq 0.5 \times 10^9$ K. The observed rapidity of the cooling implies that protons were already in a superconducting state with a larger critical temperature. This is the first direct evidence that superfluidity and superconductivity occur at supranuclear densities within neutron stars. Our prediction that this cooling will continue for several decades at the present rate can be tested by continuous monitoring of this neutron star.

Cas A NS Cooling (theory)

- The observed Cas A NS cooling can be explained within **the standard NS Cooling.**
- Neutron **superfluidity** (and proton **superconductivity**) play key roles.

D. Page, M. Prakash, J. M. Lattimer, A. W. Steiner, 1011.6142 [Phys.Rev.Lett.].
P. S. Shternin, D. G. Yakovlev, C. O. Heinke, W. C. G. Ho, D. J. Patnaude, 1012.0045 [MNRAS].



Monthly Notices of the ROYAL ASTRONOMICAL SOCIETY LETTERS

Mon. Not. R. Astron. Soc. **412,** L108–L112 (2011) doi:10.1111/j.1745-3933.2011.01015.x

Cooling neutron star in the Cassiopeia A supernova remnant: evidence for superfluidity in the core

Peter S. Shternin,[1,2]★ Dmitry G. Yakovlev,[1] Craig O. H
and Daniel J. Patnaude[5]

[1] *Ioffe Physical Technical Institute, Politekhnicheskaya 26, 194021 St Petersburg, Russia*
[2] *St Petersburg State Polytechnical University, Politechnicheskaya 29, 195251 St Petersburg, Russi*
[3] *Department of Physics, University of Alberta, Room 238 CEB, 11322-89 Avenue, Edmonton, AB*
[4] *School of Mathematics, University of Southampton, Southampton SO17 1BJ*
[5] *Smithsonian Astrophysical Observatory, Cambridge, MA 02138, USA*

Accepted 2011 January 12. Received 2011 January 12; in original form 2010 November 30

ABSTRACT
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ABSTRACT

According to recent results of Ho & Heinke, the Cassiopeia A supernova remnant contains a young (≈330-yr-old) neutron star (NS) which has carbon atmosphere and shows notable decline of the effective surface temperature. We report a new (2010 November) *Chandra* observation which confirms the previously reported decline rate. The decline is naturally explained if neutrons have recently become superfluid (in triplet state) in the NS core, producing a splash of neutrino emission due to Cooper pair formation (CPF) process that currently accelerates the cooling. This scenario puts stringent constraints on poorly known properties of NS cores: on density dependence of the temperature $T_{\rm cn}(\rho)$ for the onset of neutron superfluidity [$T_{\rm cn}(\rho)$ should have a wide peak with maximum $\approx (7–9) \times 10^8$ K]; on the reduction factor q of CPF process by collective effects in superfluid matter ($q > 0.4$) and on the intensity of neutrino emission before the onset of neutron superfluidity (30–100 times weaker than the standard modified Urca process). This is serious evidence for nucleon superfluidity in NS cores that comes from observations of cooling NSs.

Plan

Part 2. Axion and Neutron Star

2.1. Axion models / constraints

2.2. Cas A NS Cooling
  - (1) Cas A
  - (2) Cas A NS
  - (3) Cas A NS Cooling (observation)
  - (4) Cas A NS Cooling (theory)

2.3. Cas A NS Cooling with axion

2.4. Summary of Part 2.

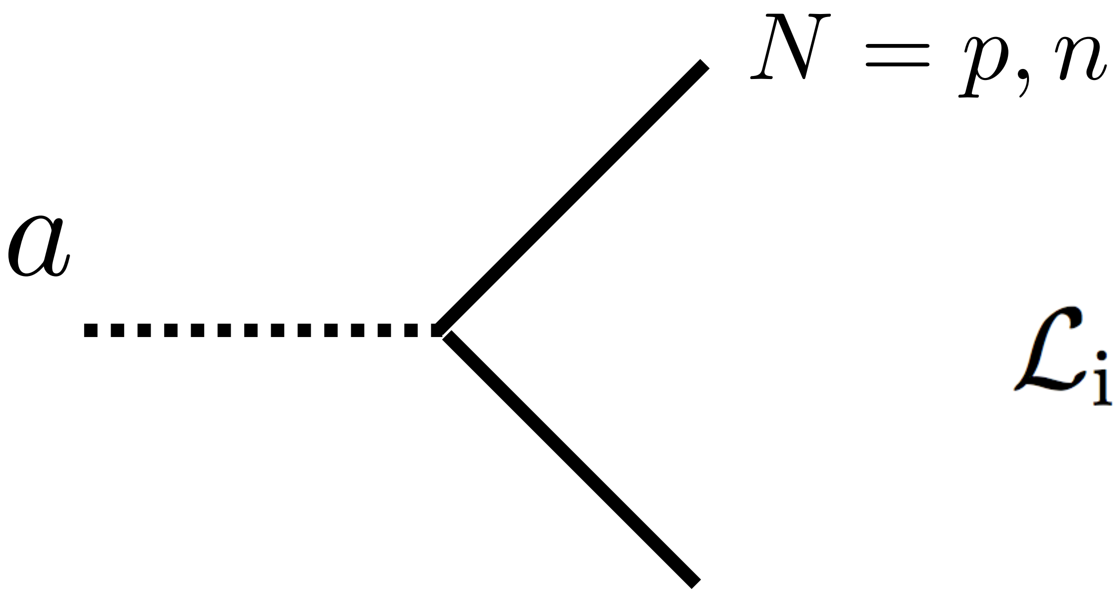
Cas A NS Cooling with axion

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

Cas A NS Cooling with axion

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

axion emission



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

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

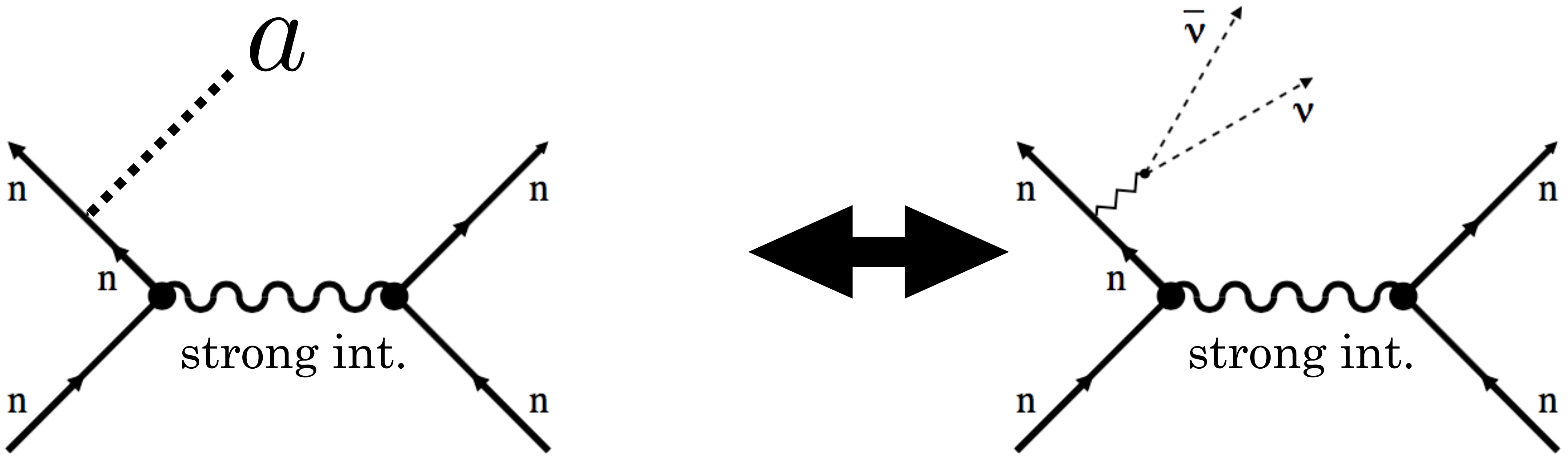
$$\text{DFSZ:} \begin{cases} C_p = -0.182(25) - 0.435\sin^2\beta \\ C_n = -0.160(25) - 0.414\sin^2\beta \end{cases}$$

Cas A NS Cooling with axion

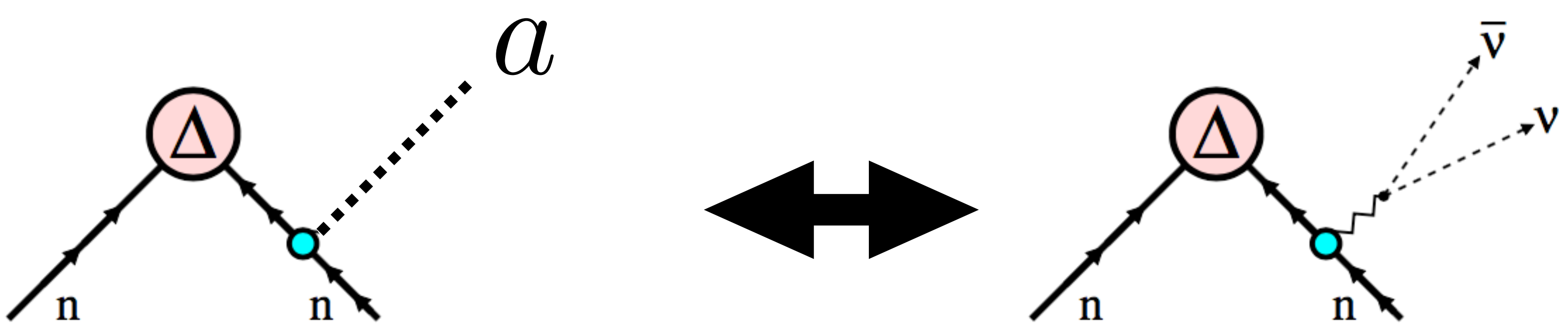
$$\boxed{C\frac{dT}{dt} = -L_\nu - L_a}$$

axion emission

Bremsstrahlung
axion emission



PBF
axion emission



Brems.: N. Iwamoto, Phys. Rev. Lett. 53, 1198 (1984);   N. Iwamoto,'89, '01.

PBF: A. Sedrakian, 1512.07828 [PRD];   J. Keller, A. Sedrakian,'12.

Cas A NS Cooling with axion

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

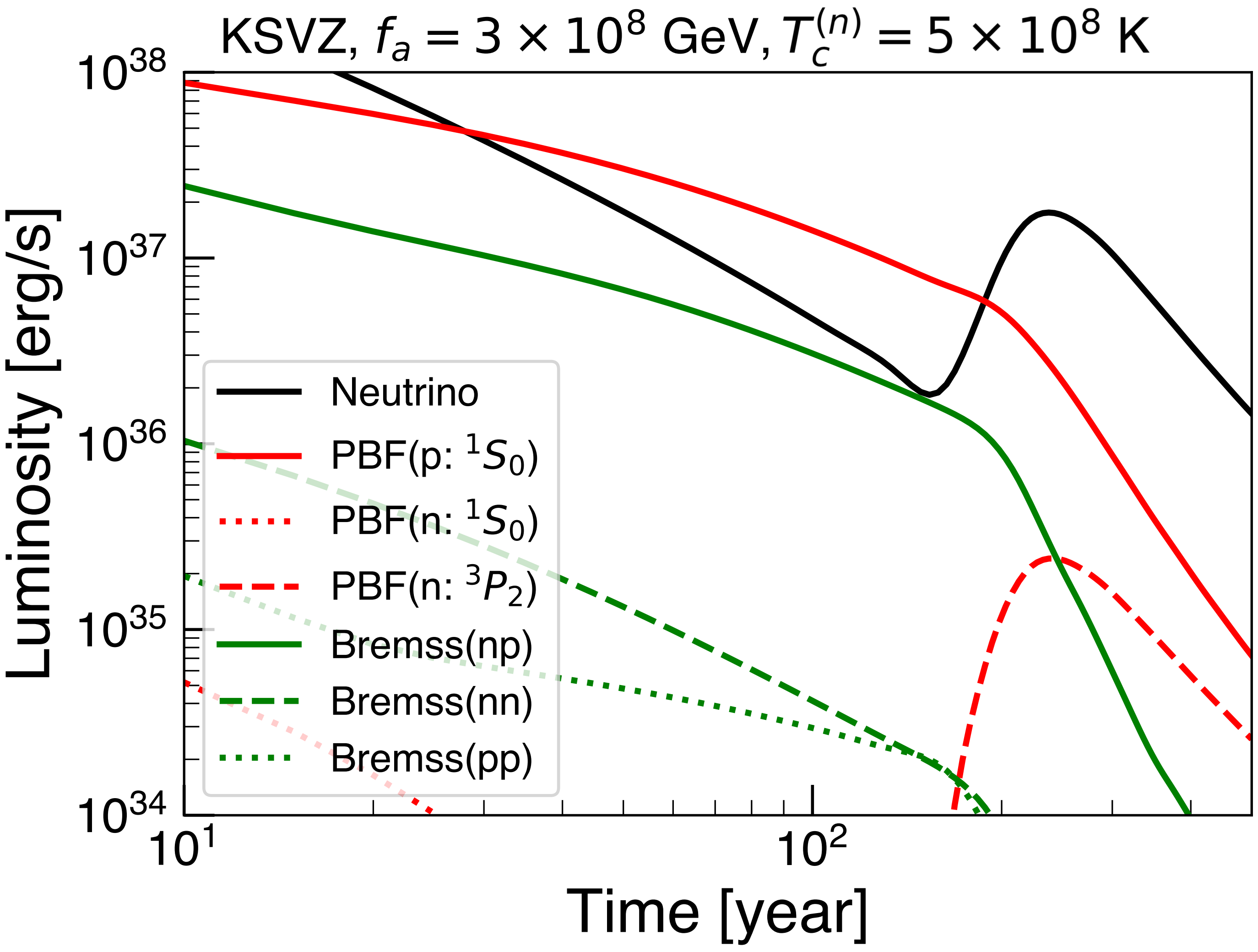
axion emission

What we did:

- followed NS cooling **with axion emission** (Brems. and PBF). by modifying a public code NSCool.
- APR EoS.
- NS mass M = 1.4 Msun.
- gap models:
  - n-$^1S_0$ gap: SFB (doesn't matter)
  - p-$^1S_0$ gap: CCDK (doesn't matter as far as large enough)
  - n-$^3P_2$ gap: gap height $\Delta \propto T_c$ and width: free parameter.

Cas A NS Cooling with axion

Results



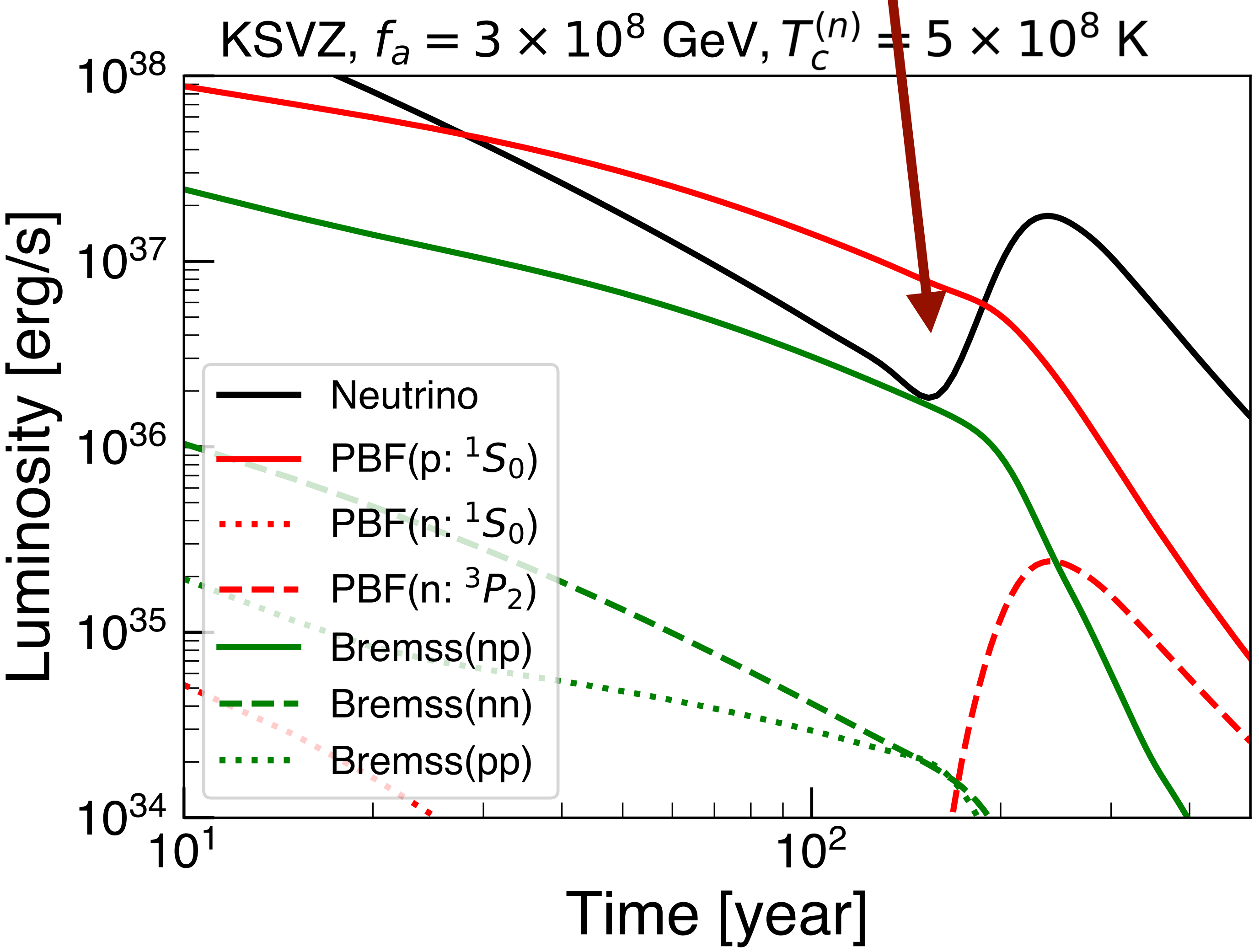
K. Hamaguchi,
N. Nagata,
K. Yanagi,
J. Zheng,
1806.07151

Axion emission can be as strong as neutrino emission.

Cas A NS Cooling with axion

Results

phase transition
T = Tc



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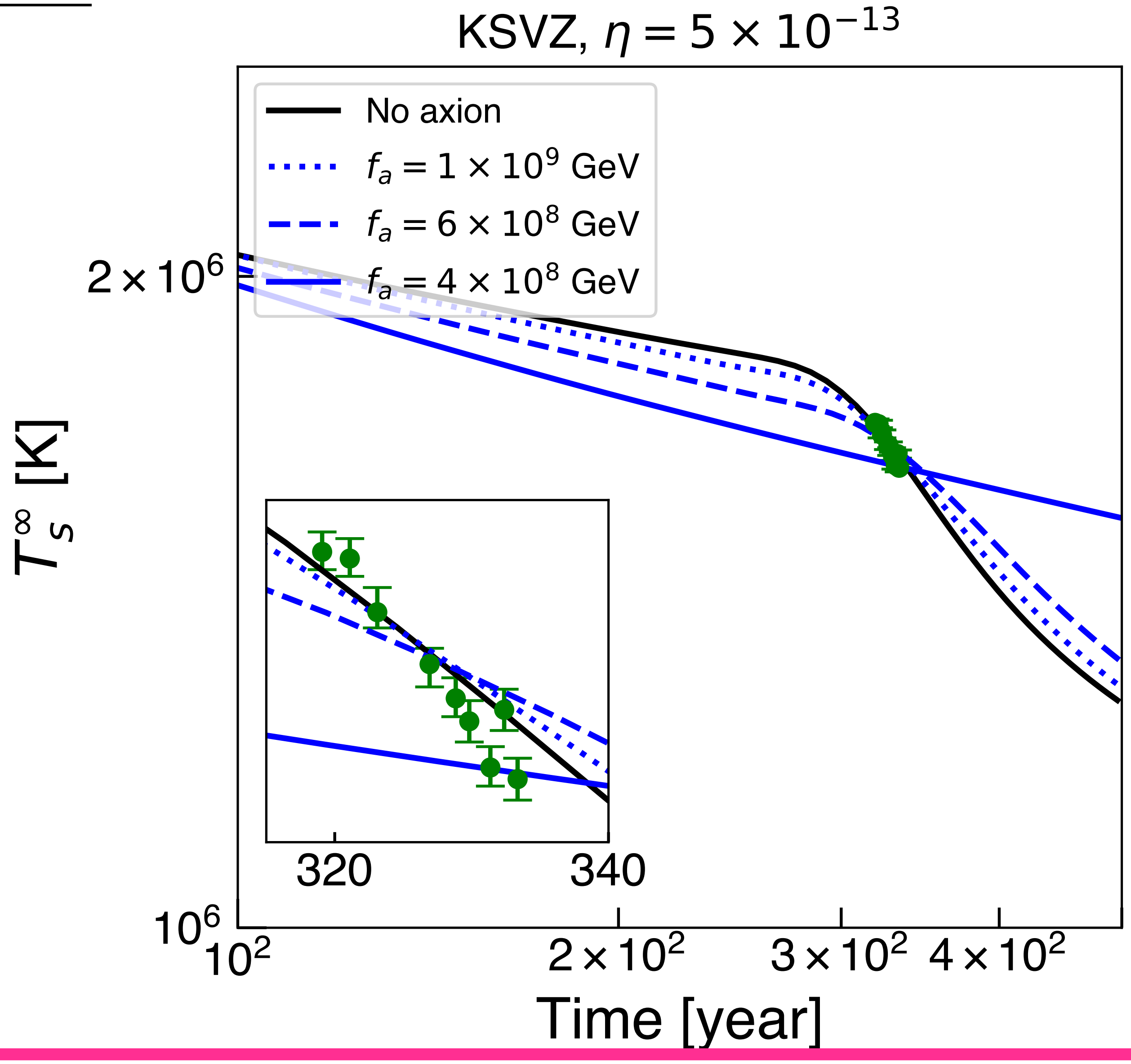


K. Hamaguchi,
N. Nagata,
K. Yanagi,
J. Zheng,
1806.07151

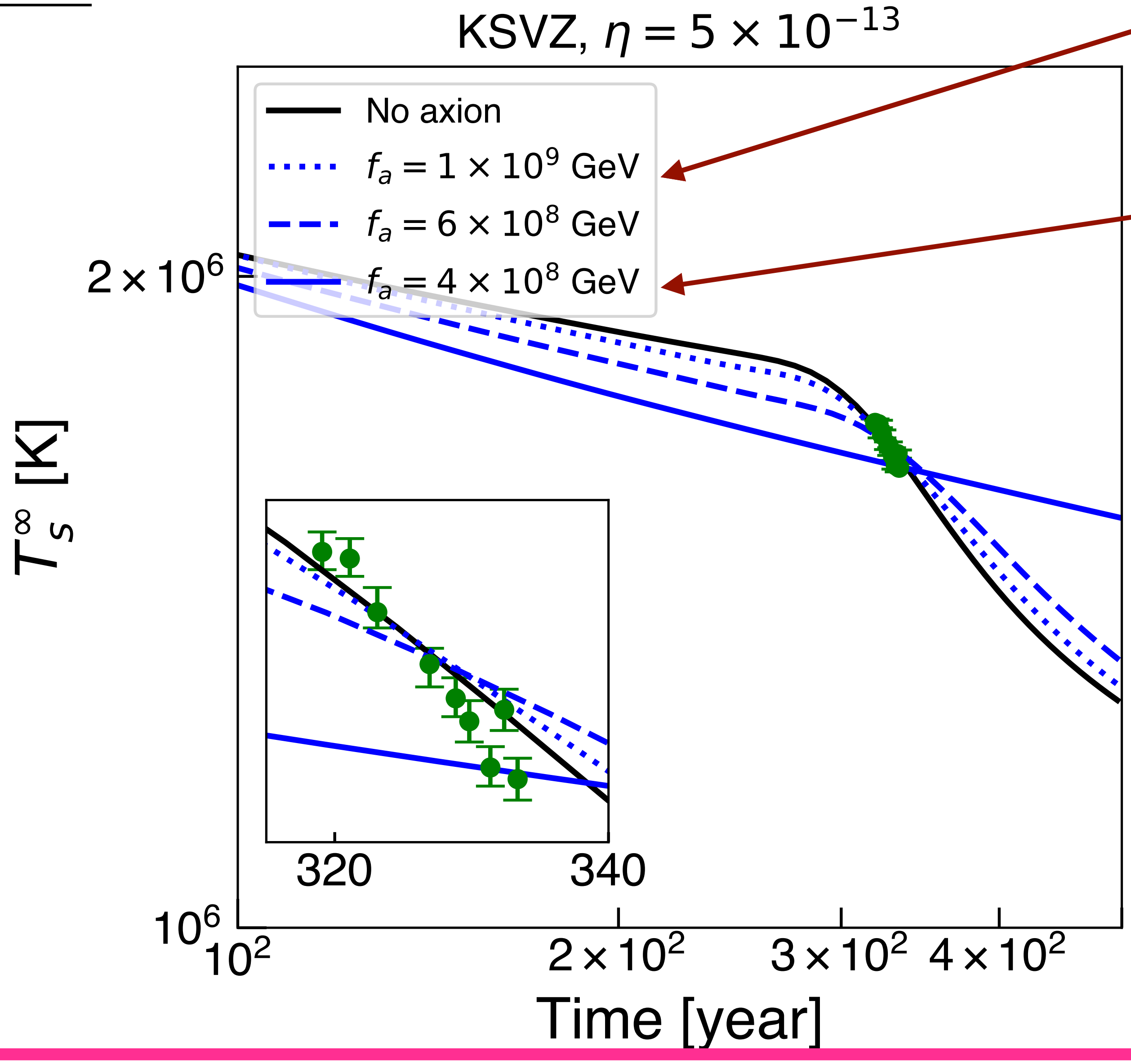
obtained a new bound: $f_a \gtrsim 5 \times 10^8$ GeV (KSVZ)

(for an envelope with a thin carbon layer)

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

Cas A NS Cooling with axion

Results



fa = 1 x 10^9 GeV: can fit the data.

fa = 4 x 10^8 GeV: difficult to fit the data even by adjusting gap parameters.

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

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

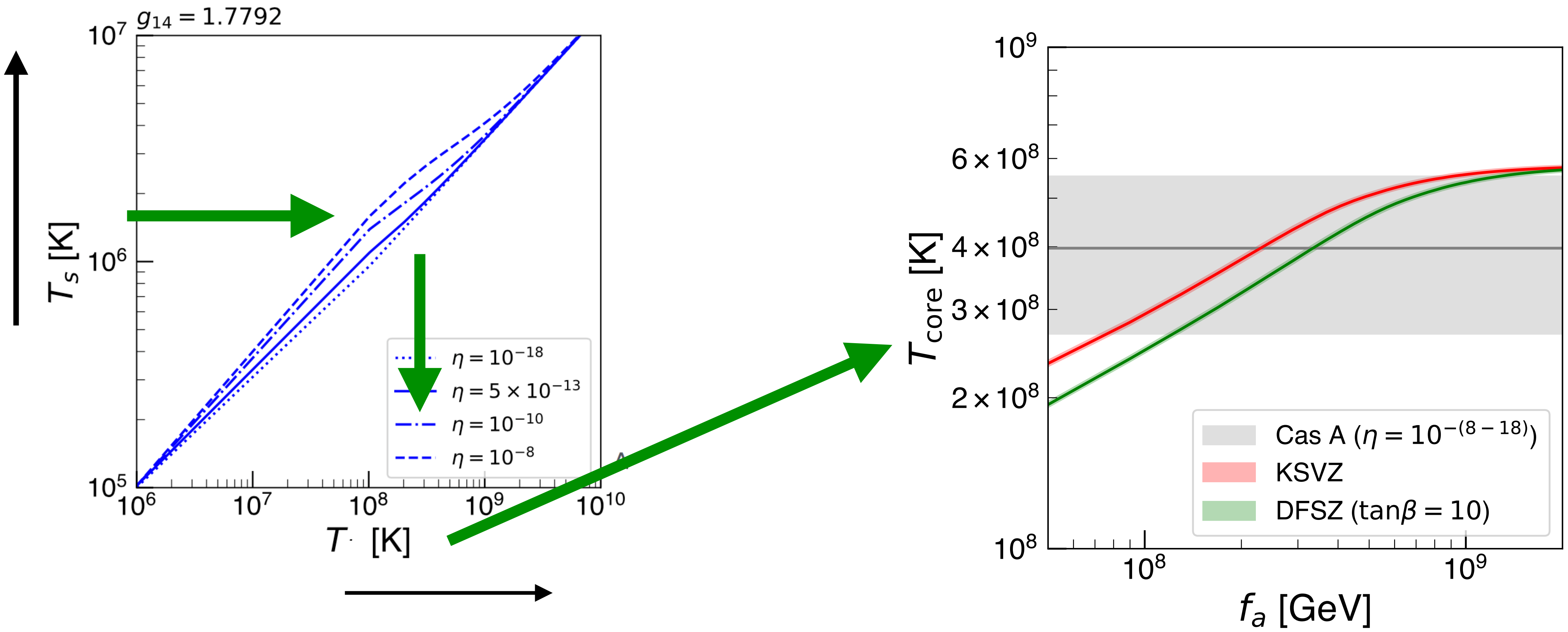
(for an envelope with a thin carbon layer)

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

Cas A NS Cooling with axion

Remark: uncertainty from envelope

surface
temperature
(observed)

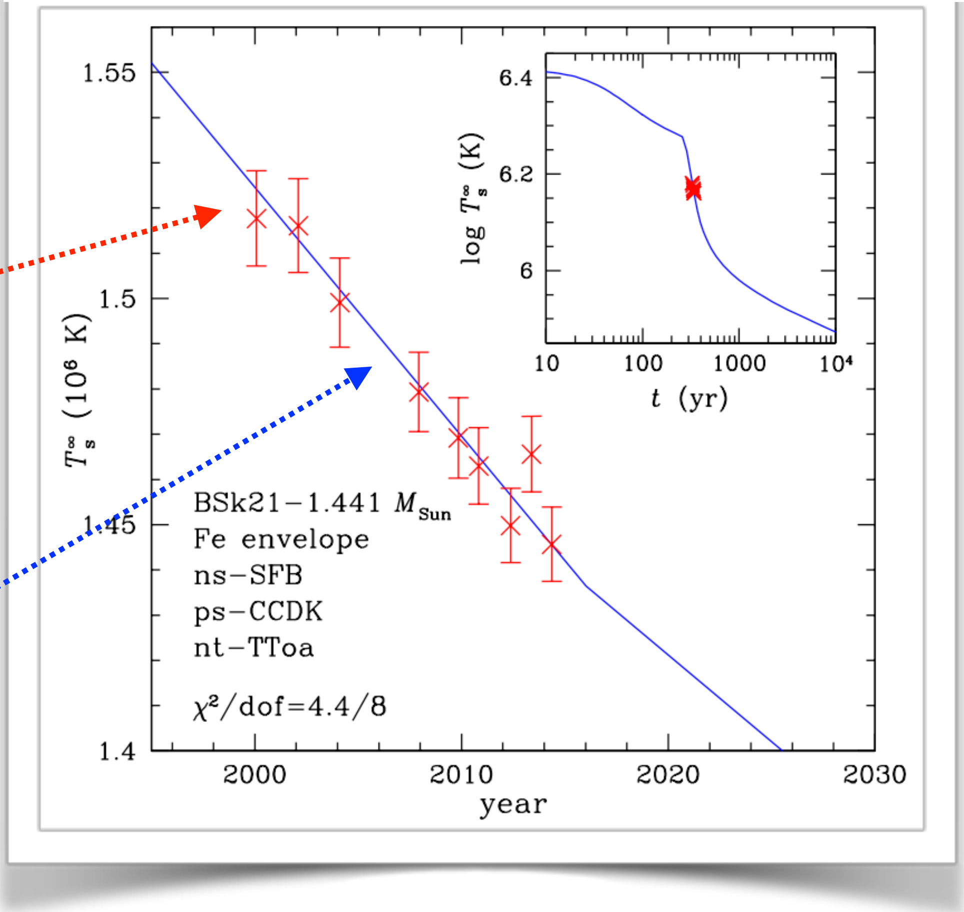


internal temperature

==> O(1) uncertainty in f_a bound.

Summary of part 2

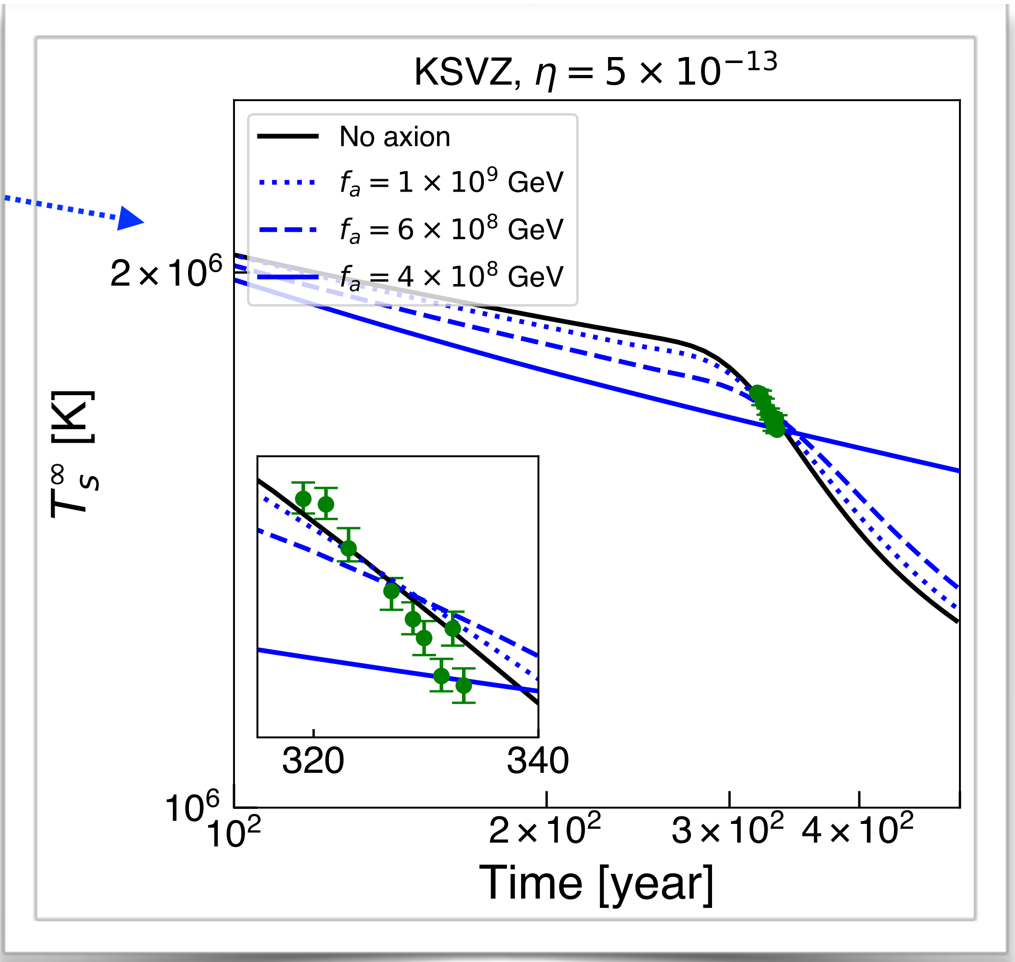
W.C.G.Ho, K.G.Elshamouty, C.O.Heinke, A.Y.Potekhin, 1412.7759



A rapid cooling of Cas A Neutron Star (NS) has been observed.

It can be explained within the standard NS cooling scenario. (i.e., without physics beyond the Standard Model)

If there is an extra cooling, such as an axion emission, the cooling is modified.



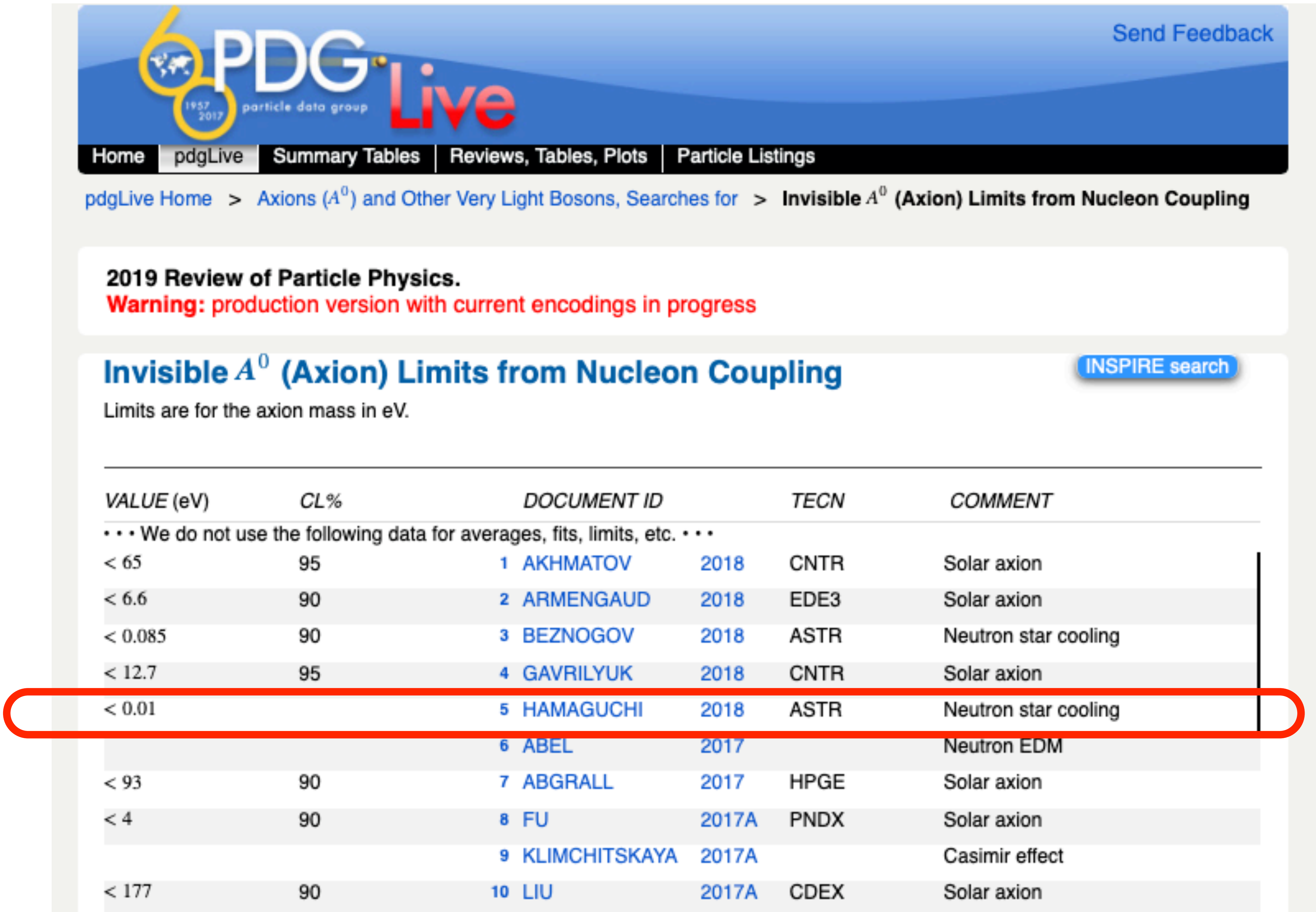
We studied the Cas A NS cooling with an axion emission, and obtained a new bound on the axion decay constant,

$f_a > O(10^8)$ GeV.

(comparable to the existing SN1987A bound)

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

Summary of part 2



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

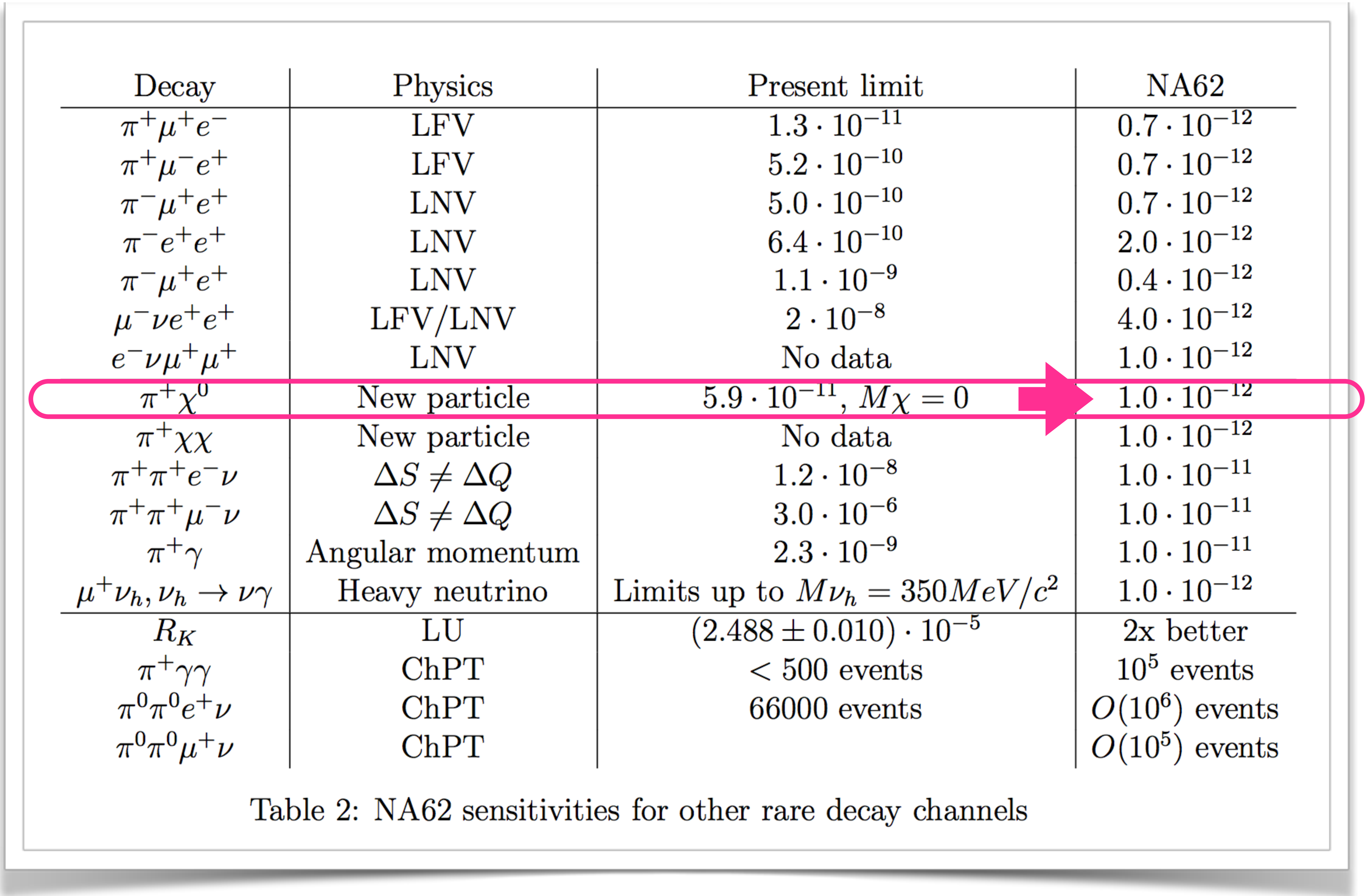
2019 Review of Particle Physics.
Warning: production version with current encodings in progress

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

Backup for Part 1



Decay	Physics	Present limit	NA62
$\pi^+\mu^+e^-$	LFV	$1.3 \cdot 10^{-11}$	$0.7 \cdot 10^{-12}$
$\pi^+\mu^-e^+$	LFV	$5.2 \cdot 10^{-10}$	$0.7 \cdot 10^{-12}$
$\pi^-\mu^+e^+$	LNV	$5.0 \cdot 10^{-10}$	$0.7 \cdot 10^{-12}$
$\pi^-e^+e^+$	LNV	$6.4 \cdot 10^{-10}$	$2.0 \cdot 10^{-12}$
$\pi^-\mu^+e^+$	LNV	$1.1 \cdot 10^{-9}$	$0.4 \cdot 10^{-12}$
$\mu^-\nu e^+e^+$	LFV/LNV	$2 \cdot 10^{-8}$	$4.0 \cdot 10^{-12}$
$e^-\nu\mu^+\mu^+$	LNV	No data	$1.0 \cdot 10^{-12}$
$\pi^+\chi^0$	New particle	$5.9 \cdot 10^{-11}$, $M\chi = 0$	$1.0 \cdot 10^{-12}$
$\pi^+\chi\chi$	New particle	No data	$1.0 \cdot 10^{-12}$
$\pi^+\pi^+e^-\nu$	$\Delta S \neq \Delta Q$	$1.2 \cdot 10^{-8}$	$1.0 \cdot 10^{-11}$
$\pi^+\pi^+\mu^-\nu$	$\Delta S \neq \Delta Q$	$3.0 \cdot 10^{-6}$	$1.0 \cdot 10^{-11}$
$\pi^+\gamma$	Angular momentum	$2.3 \cdot 10^{-9}$	$1.0 \cdot 10^{-11}$
$\mu^+\nu_h, \nu_h \rightarrow \nu\gamma$	Heavy neutrino	Limits up to $M\nu_h = 350MeV/c^2$	$1.0 \cdot 10^{-12}$
R_K	LU	$(2.488 \pm 0.010) \cdot 10^{-5}$	2x better
$\pi^+\gamma\gamma$	ChPT	< 500 events	10^5 events
$\pi^0\pi^0e^+\nu$	ChPT	66000 events	$O(10^6)$ events
$\pi^0\pi^0\mu^+\nu$	ChPT		$O(10^5)$ events

Table 2: NA62 sensitivities for other rare decay channels

[arXiv:1407.8213]

The NA62 experiment at CERN: status and perspectives

NA62 Collaboration

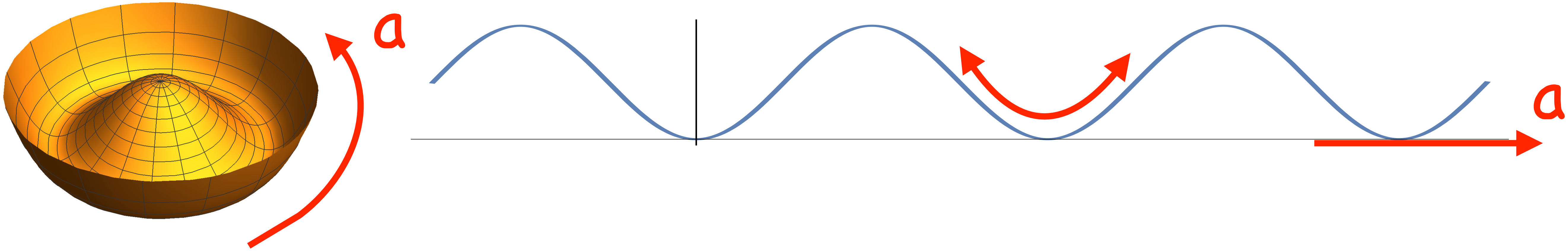
$B^+ \to K^+ a$??

[arXiv:1612.08040] Phys.Rev. **D95** (2017) 095009
The Axiflavon
L. Calibbi, F. Goertz, D. Redigolo, R. Ziegler, J. Zupan

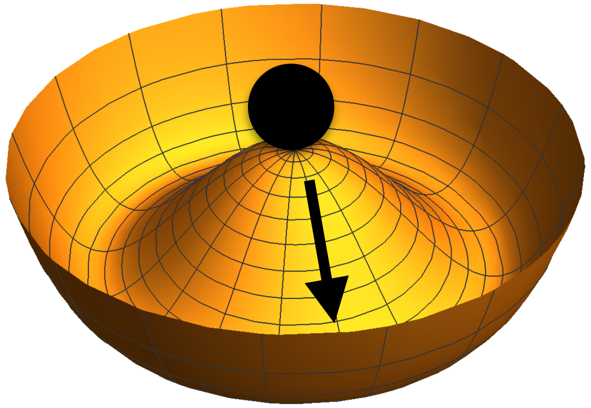
$$\mathrm{BR}(B^+ \to K^+ a) \simeq 1.4{\cdot}10^{-12} \left(\frac{m_a}{\underbrace{0.1\,\mathrm{meV}}_{\simeq \left(\frac{6\times 10^9\ \mathrm{GeV}}{f_a}\right)}} \times \frac{\kappa_{bs}}{N} \right)^2$$

. $\kappa_{bs}/N \sim \mathcal{O}(1)$.

Flaxion Dark Matter:



Case 1: U(1) is broken after inflation.

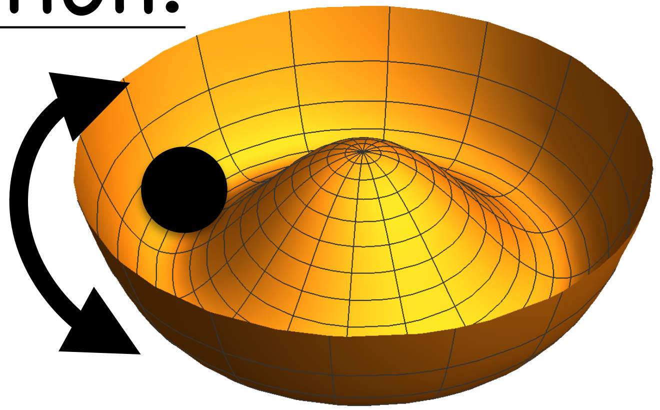


-> **Domain Wall !**

In the flaxion scenario, typically $N_{DW} \neq 1$,

and this possibility is **excluded**.

Case 2: U(1) was already broken during inflation.



$$\delta a \sim H_{\rm inf}$$

Quantum fluctuation during inflation

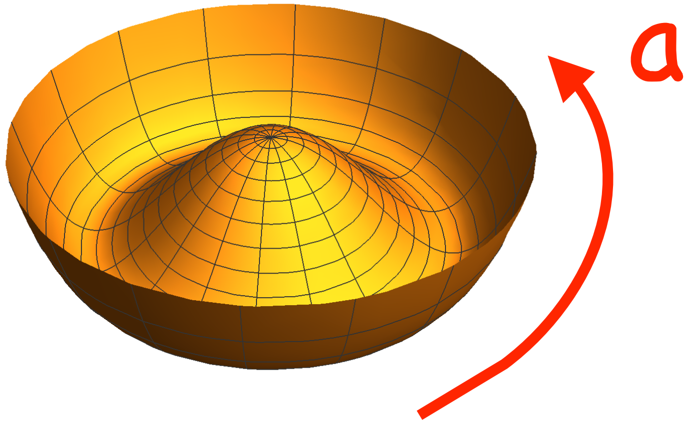
leads to **DM isocurvature** perturbation,

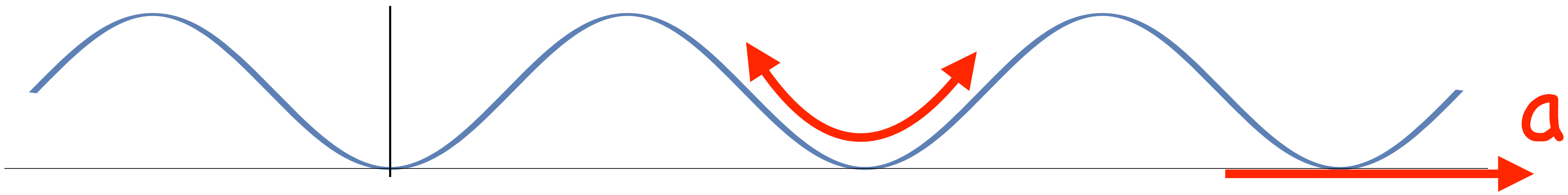
which is severely constrained [Planck,'15].

-> Strong bound on inflation scale.

$$H_{\rm inf} \lesssim 3 \times 10^{7}\,{\rm GeV}\,\theta_i^{-1}\left(\frac{10^{12}\,{\rm GeV}}{f_a}\right)^{0.19}\,.$$

Flaxion Dark Matter:





Case 1: U(1) is broken after inflation.

-> **Domain Wall !**

In the flaxion scenario, typically N_{DW} ≠ 1,

and this possibility is **excluded**.

$\delta a \sim H_{\rm inf}$

Case 2: U

Quantum flu

leads to **DM**

which is seve

-> **Strong bou ion scale.**

$$H_{\rm inf} \lesssim 3 \times 10^7\,{\rm GeV}\,\theta_i^{-1}\left(\frac{10^{12}\,{\rm GeV}}{f_a}\right)^{0.19} .$$

No problem in "flaxion-inflation" scenario !

Proton decay ?

$$\mathcal{L} \sim \frac{QQQL}{M^2}, \quad \frac{uude}{M^2}, \quad \frac{QQue}{M^2}, \quad \frac{QLud}{M^2}$$

—> In the case of example charge assignments, the most dangerous one is the last one.
With O(1) coefficients,

$$M > 5 \times 10^{14} \text{ GeV}$$

is sufficient to suppress it.

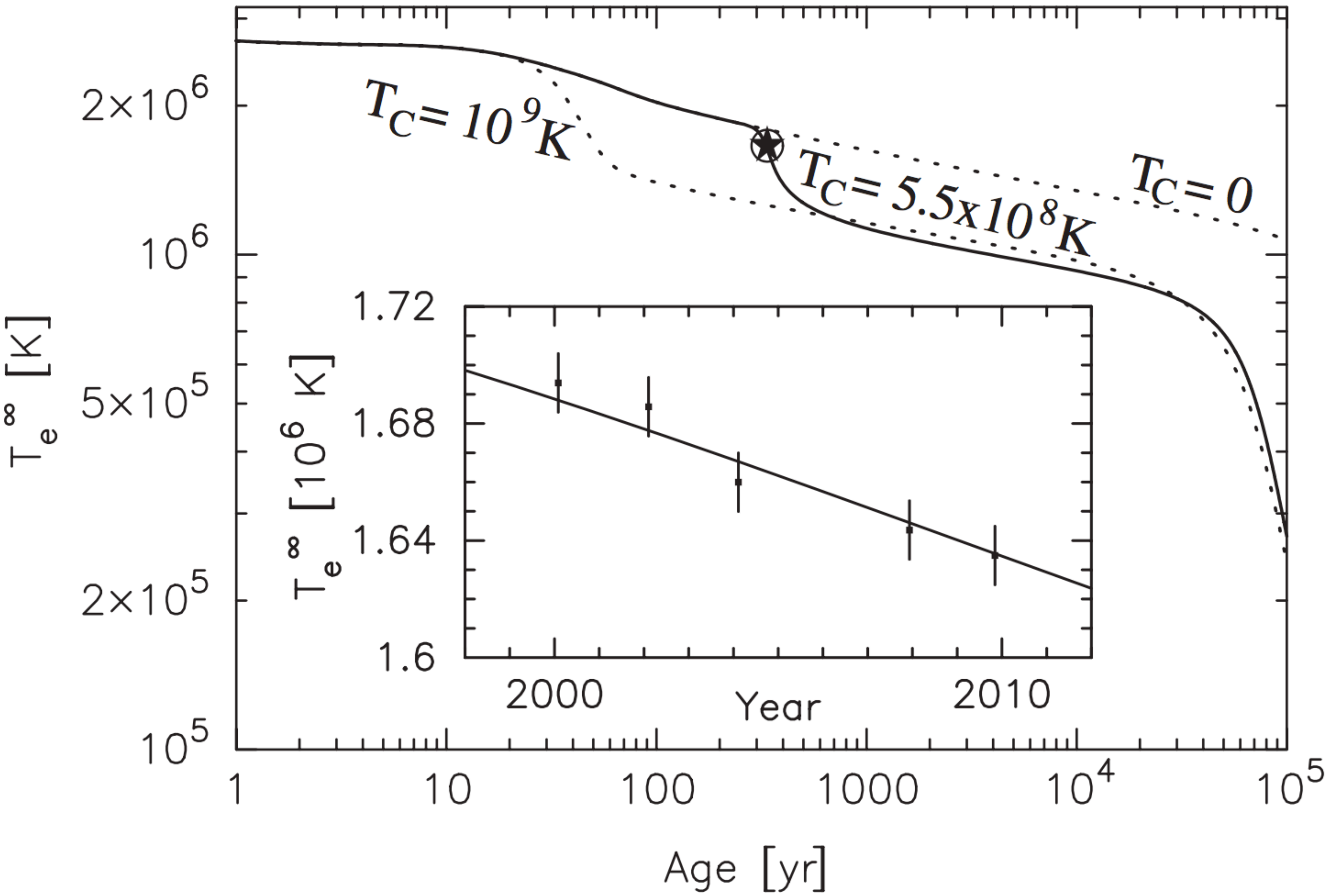
Backup for Part 2

Alternative scenario to explain Cas A cooling

- longer thermal relaxation timescale in the crust or core
- etc

S.-H. Yang, C.-M. Pi, and X.-P. Zheng, arXiv:1103.1092;
R. Negreiros, S. Schramm, and F. Weber, arXiv:1103.3870;
D. Blaschke, H. Grigorian, D. N. Voskresensky, and F. Weber, arXiv:1108.4125;
T. Noda, M.-A. Hashimoto, N. Yasutake, T. Maruyama, T. Tatsumi, and M. Fujimoto, arXiv:1109.1080;
A. Sedrakian, arXiv:1303.5380;
D. Blaschke, H. Grigorian, and D. N. Voskresensky, arXiv:1308.4093;
A. Bonanno, M. Baldo, G. F. Burgio, and V. Urpin, arXiv:1311.2153;
L. B. Leinson, arXiv:1411.6833;
G. Taranto, G. F. Burgio, and H. J. Schulze, arXiv:1511.04243;
T. Noda, N. Yasutake, M.-a. Hashimoto, T. Maruyama, T. Tatsumi, and M. Y. Fujimoto, arXiv:1512.05468;
H. Grigorian, D. N. Voskresensky, and D. Blaschke, arXiv:1603.02634.

Minimal Cooling vs Cas A NS



D. Page, M. Prakash, J. M. Lattimer, A. W. Steiner, 1011.6142 [Phys.Rev.Lett.].

Other NS temperature observations

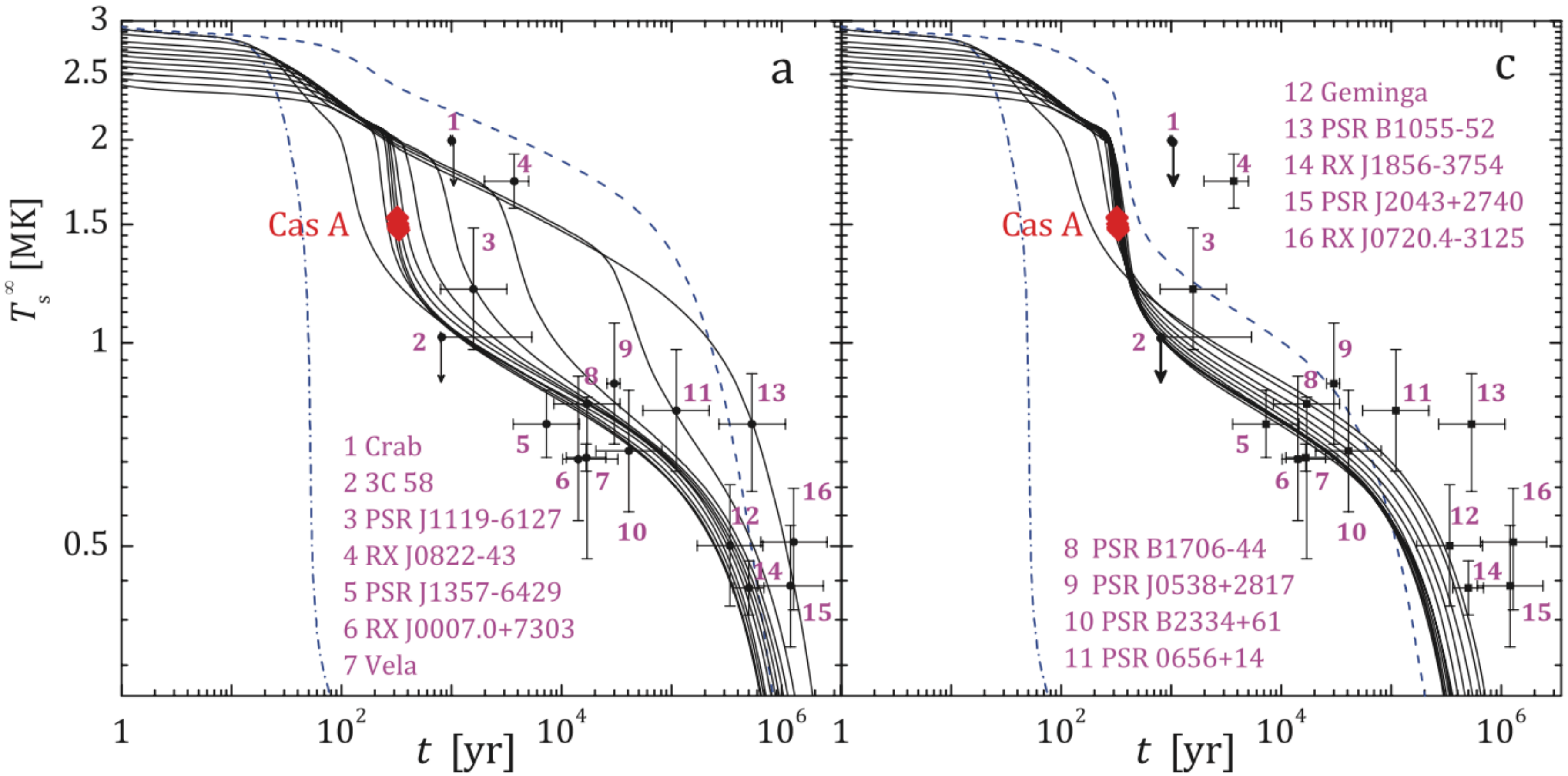


Figure 2. Sequences of (solid) cooling curves for NSs of masses from 1 $M_\odot$ to $M_{\max}$ (through 0.1 $M_\odot$) with strong proton superfluidity and moderate neutron superfluidity (a) (left-hand panel) or (c) (right-hand panel) in the core ($q = 0.76$) compared with observations of isolated NSs. Dashed lines refer to warmest stars of these types – 1 $M_\odot$ stars with the carbon surface layer of mass 10^{-8} $M_\odot$. Dot–dashed lines refer to coolest $M_{\max}$ stars without proton superfluidity in the inner core.

P. S. Shternin, D. G. Yakovlev, C. O. Heinke, W. C. G. Ho, D. J. Patnaude, 1012.0045 [MNRAS].

KSVZ and DFSZ

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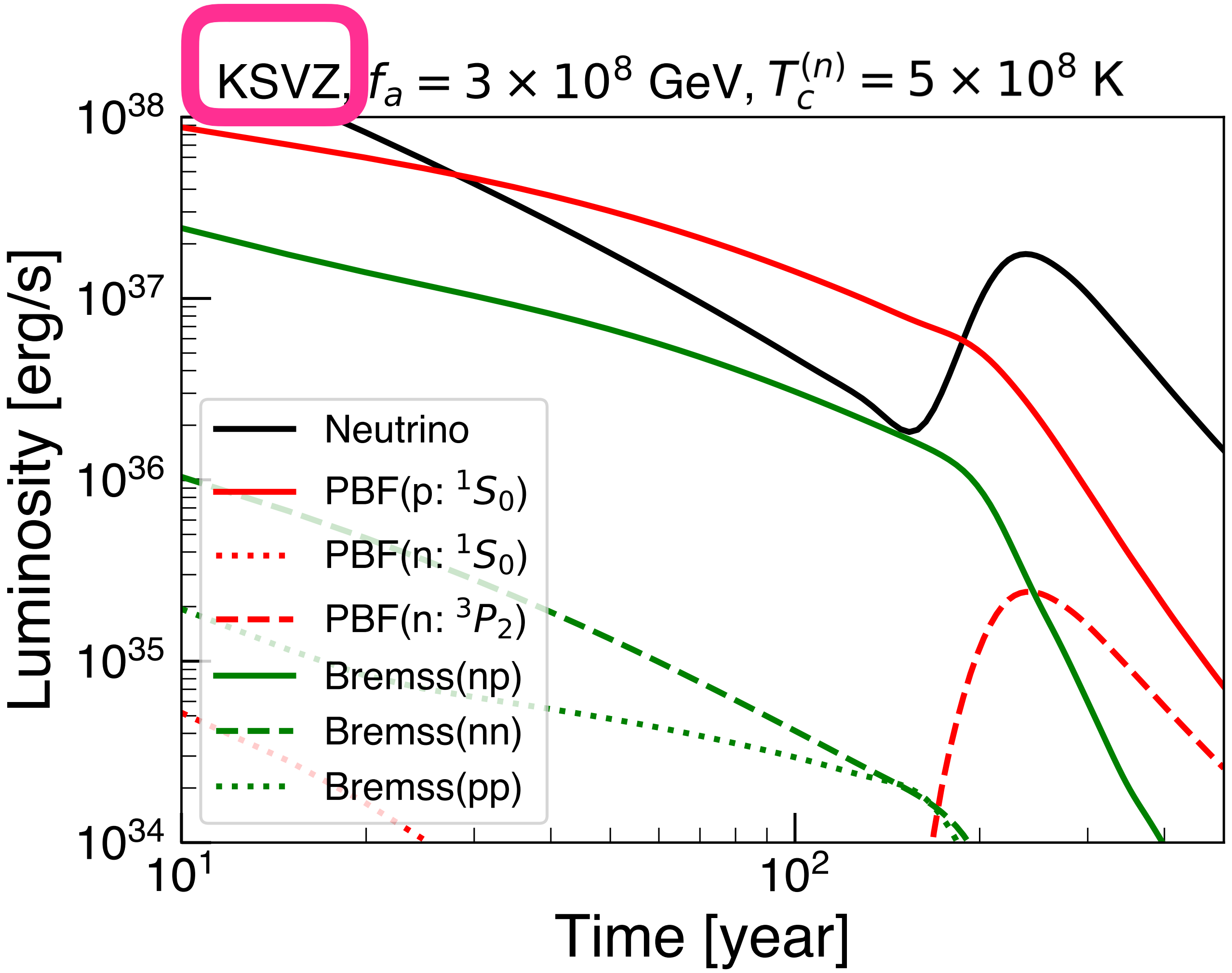
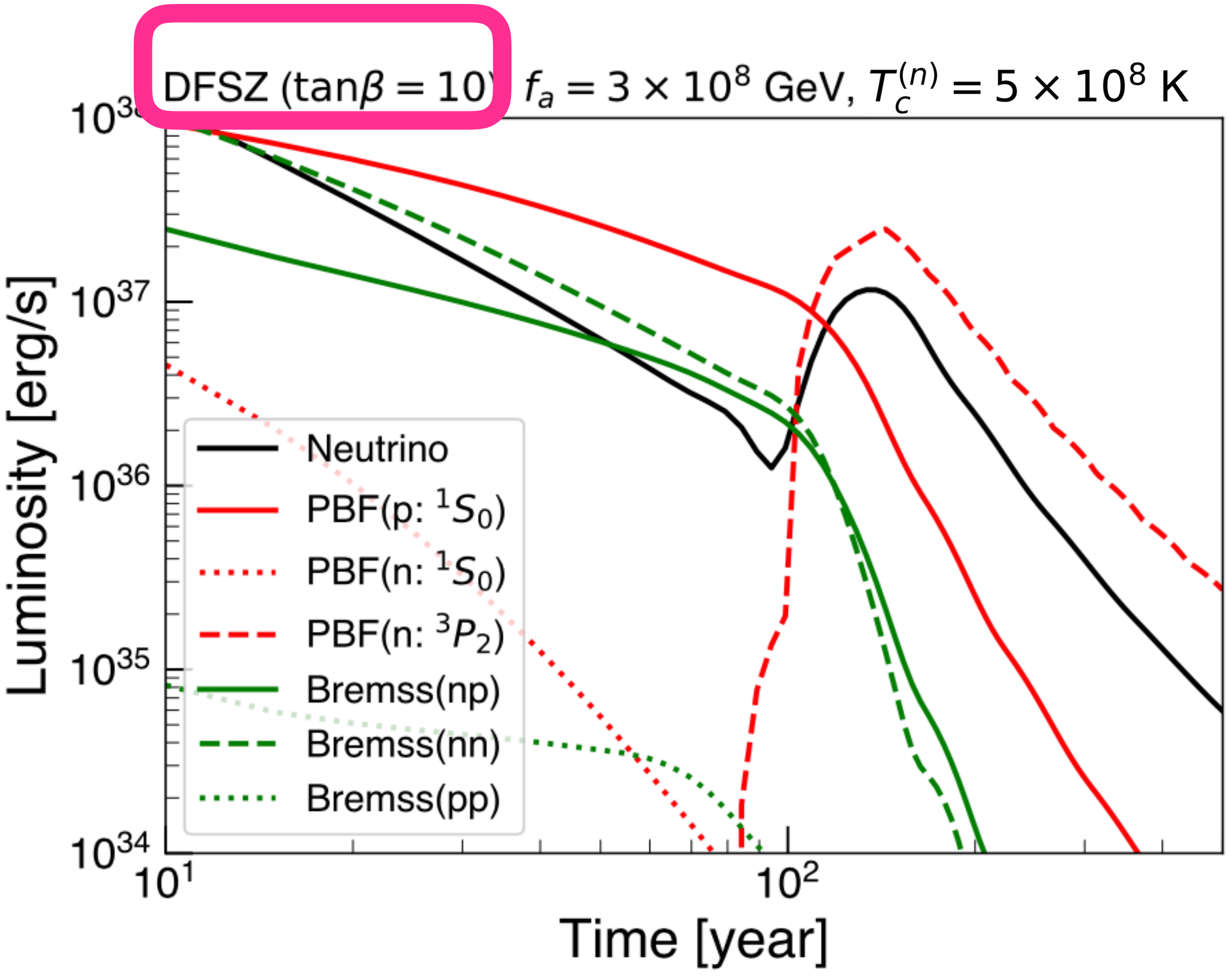
$$\text{DFSZ:}\begin{cases} C_p = -0.182(25) - 0.435\sin^2\beta \\ C_n = -0.160(25) - 0.414\sin^2\beta \end{cases}$$





$$\boxed{\begin{array}{l} f_a \gtrsim 5 \times 10^8 \ \mathrm{GeV} \ (\mathrm{KSVZ}) \\ f_a \gtrsim 7 \times 10^8 \ \mathrm{GeV} \ (\mathrm{DFSZ}, \tan\beta = 10) \end{array}}$$

(larger uncertainty from envelope for DFSZ)

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