New insights on light and heavy axions

—From Condensed Matter to Big Bang—

Nov 6, 2024

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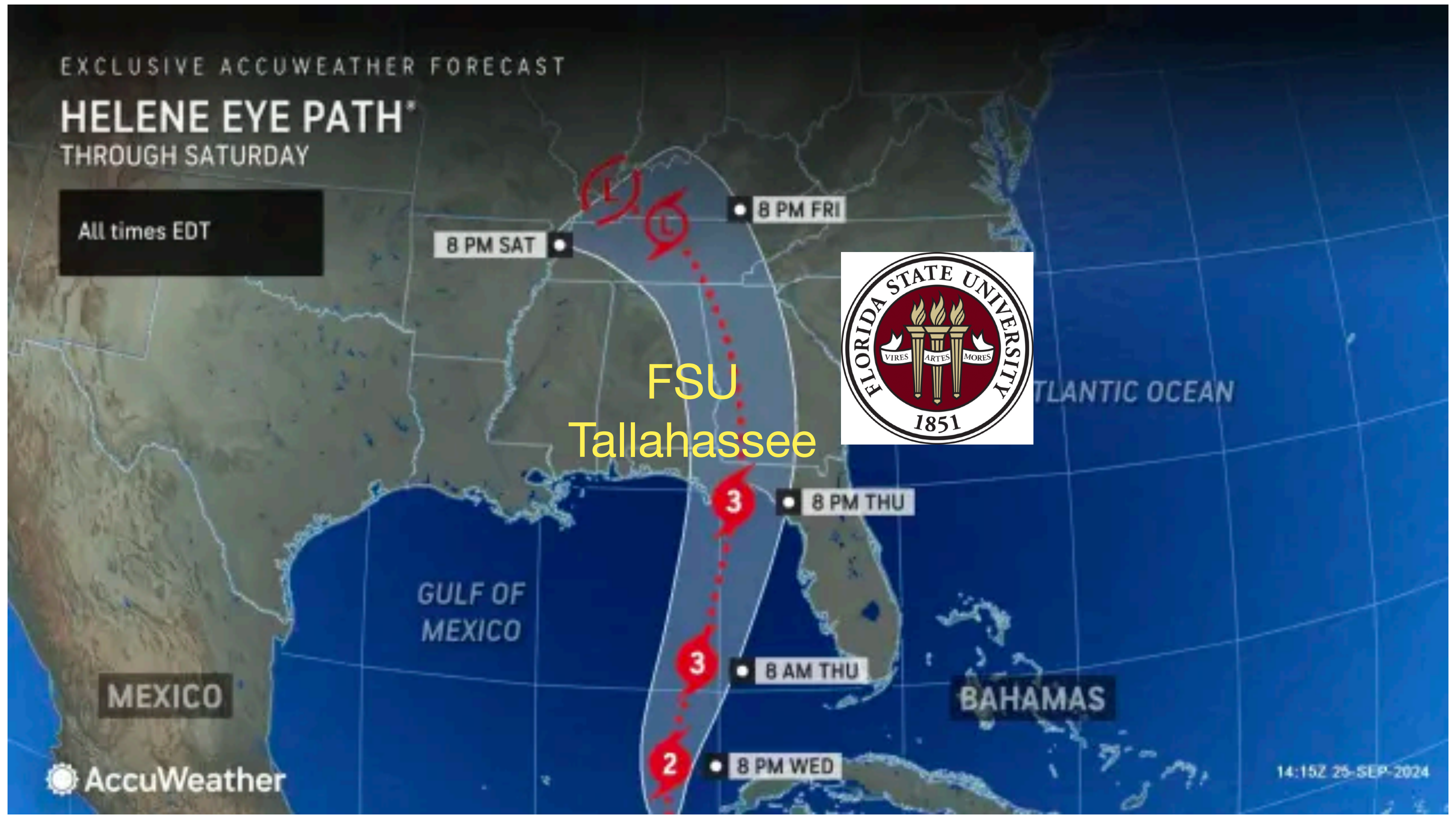
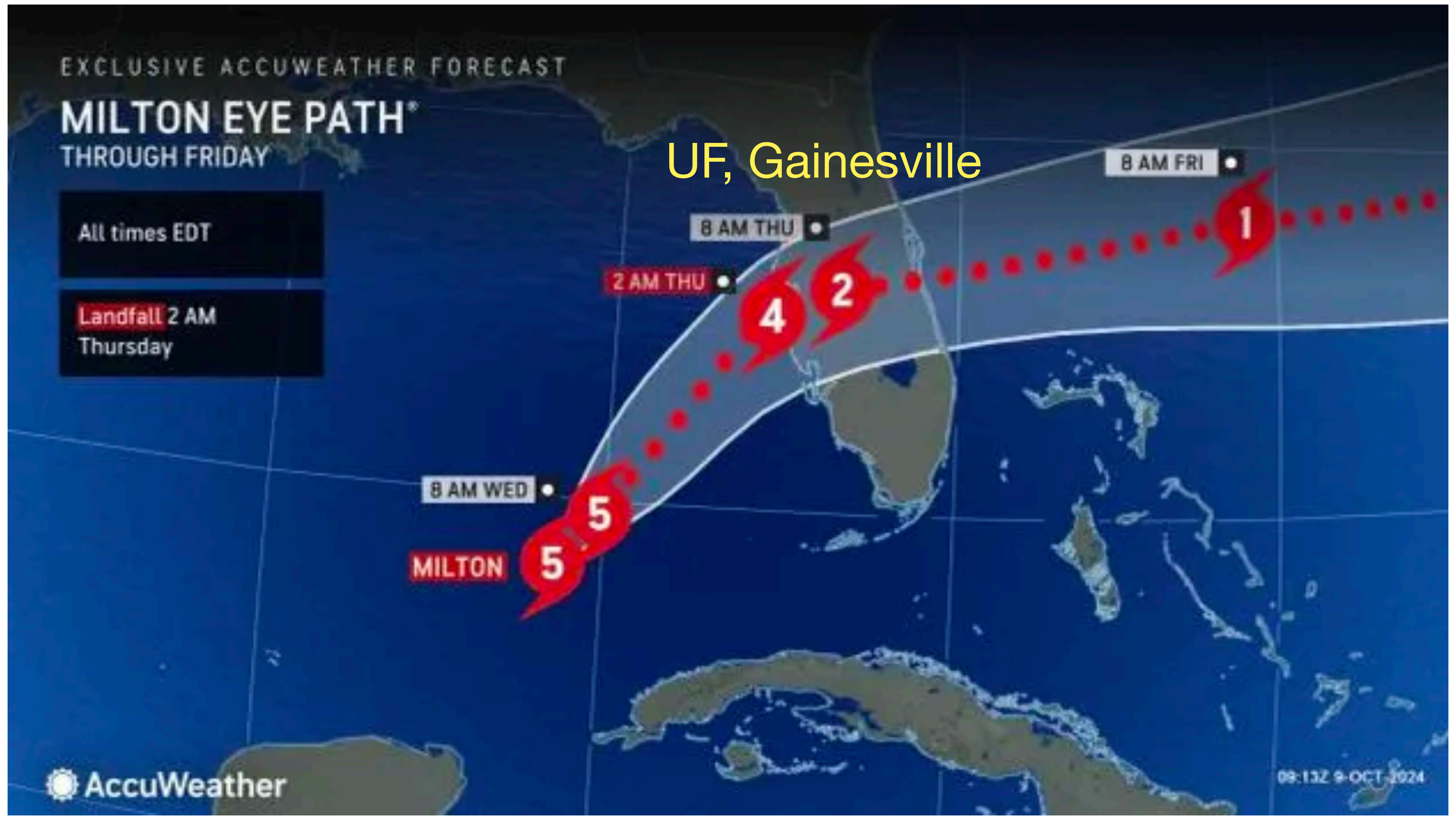
TH Jung, T. Okui, KT, J. Wang (in pareparation)

Before start…

Degeneracy in Florida



State Capital
P. Dirac



P. Sikivie

Strong CP problem and QCD Axion

The strong CP problem

$$\frac{\alpha_s \bar{\theta}}{8\pi} G^{a\mu\nu} \tilde{G}^{a\mu\nu}$$

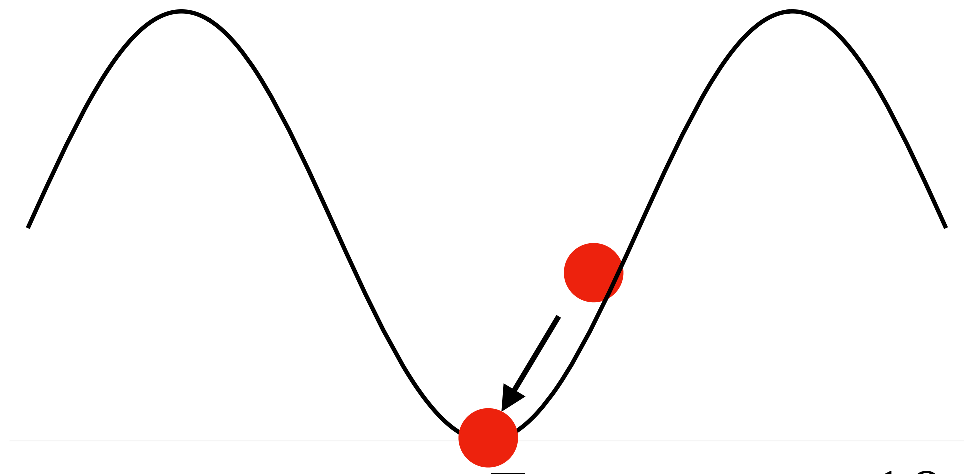
- The unknown of the SM: CP phase in the strong sector
- Neutron EDM sets a very stringent upper bound: $\bar{\theta} \lesssim 10^{-10}$

QCD Axion solution

- Promote $\bar{\theta}$ to a *field* a/f_a *dynamically settles the CP phase to the minimum.*
- *Peccei-Quinn symmetry:* Global U(1) that generates the axion *as* a Nambu-Goldstone boson. **f_a is the breaking scale**.
- Attractive **dark matter** candidate, typically m_a<meV.

$$\frac{\alpha_s}{8\pi} \frac{a}{f_a} G^{a\mu\nu} \tilde{G}^{a\mu\nu}$$

after QCD phase transition



$\langle \bar{\theta} \rangle \lesssim 10^{-10}$

Two topics on axion

- **Light** (dark matter) axion couple to **electrons** [see A.Millar's talk]

  -> Inspired by the superconducting qubit work [T.Moroi's "DarQ" talk]

  -> Systematic connection from HEP to CM systems not established

- **Heavy** axion that decay to **hadrons** (π, K, Baryon→m_a>400MeV), BBN:Neutron decoupling measured by 4He is significantly affected.

  ->The probing lifetime τ_a~**0.02sec** is much shorter than t_{BBN}~1sec,

Axion DM coupling to electrons

Naive thought and confusions for me

If axion or bosonic DM couples to electron (at UV),
it must change CM phenomena, such as Superconductivity at low E.
But how?

Naively, order parameter modulates with DM e.g. $\Delta \to \Delta\left(1 + \#(a/f_a)^2\right)$

→Josephson energy shift→seen in Qubit?

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→Josephson energy shift→seen in Qubit?

- How to take a NR limit with axion or other DM?
- How the PQ symmetry realized in NR?
  (PQ~Chiral transf, but chiral symmetry is very bad in NR)
- How the BCS theory is understood in particle language?
- How to convert fermion d.o.f. to a scalar dof (Cooper pair)?

Axion-electron coupling down to Cooper pair

Usual relativistic Lagrangian $\mathscr{L}_{\mathrm{UV}}(a, \psi_L, \psi_R)$

Foldy-Wouthuysen method
[half fermion integrated out
systematic 1/me expansion]

Non-relativistic EFT with light field
$\mathscr{L}_{\mathrm{NRQED}}(\psi_l, a)$
(with axion, PQ symmetry?)

➡

BCS theory for particle physicists
$\mathscr{L}_{\mathrm{NRQED}} + \mathscr{L}_{\mathrm{4Fermi}}(\psi_l, a?)$

Hubbard-Stratonovich transformation
[fermion pair→scalar Δ]

Cooper pair scalar theory $\mathscr{L}_{\mathrm{SC}}(\Delta, a?)$
Order parameter (~symm breaking)

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↑This talk

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Cooper pair scalar theory $\mathscr{L}_{\rm SC}(\Delta, a?)$
Order parameter (~symm breaking)

- Methods are not connected from UV to all the way CM

NR limit with systematic $1/m_e$ expansion

Goal: integrate out heavy dof→NR QED

$$\mathscr{L}_{\rm QED} = \overline{\psi}(i\gamma^\mu D_\mu - \gamma^0 m)\psi = \psi^\dagger(iD_t + i\gamma^0\gamma^k D_k - m\gamma^0)\psi$$

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- Take a Dirac representation
  γ^0: **diagonal**, γ^5 γ^i: **off-diagonal**

$$\gamma^0 = \begin{pmatrix} \mathbf{1} & 0 \\ 0 & -\mathbf{1} \end{pmatrix} \qquad \gamma^i = \begin{pmatrix} 0 & \sigma^i \\ -\sigma^i & 0 \end{pmatrix} \quad \gamma^5 = \begin{pmatrix} 0 & \mathbf{1} \\ \mathbf{1} & 0 \end{pmatrix} \qquad \psi \sim \begin{pmatrix} \psi_L + \psi_R \\ \psi_L - \psi_R \end{pmatrix}$$

$$P_+ = \frac{1+\gamma^0}{2} = \begin{pmatrix} \mathbf{1} & 0 \\ 0 & 0 \end{pmatrix}$$

$$P_- = \frac{1-\gamma^0}{2} = \begin{pmatrix} 0 & 0 \\ 0 & \mathbf{1} \end{pmatrix}$$

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- Shift the mass shell: one is massless, the other has mass 2m.

$$\psi \to e^{-imt}\psi$$

$$\psi^\dagger(iD_t + i\gamma^0\gamma^k D_k - \gamma^0 m + m)\psi$$

$$-\gamma^0 m + m = -2mP_-$$

$$= (\psi_1\ \psi_2)^\dagger \begin{pmatrix} iD_t & i\sigma^k D_k \\ i\sigma^k D_k & iD_t - 2m \end{pmatrix} \begin{pmatrix} \psi_1 \\ \psi_2 \end{pmatrix}$$

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NR limit with systematic 1/m_e expansion

- Remove off-diagonal, use **Foldy-Wouthuysen's method**, systematic **1/m_e expansion**

Phys. Rev. 78 (Apr, 1950) and Phys. Rev. 78 (Apr, 1950).

$$\mathscr{L}_{\mathrm{QED}} = \psi^\dagger(iD_t + i\gamma^0\gamma^k D_k - 2P\_m)\psi$$

even — **odd=off-diagonal** — even, **large**

even: commute with γ0
odd: anti-commute with γ0

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even odd=off-diagonal even, **large**

even: commute with γ0
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Order-by-order diagonalization [remove odd terms], odd X_n is introduced.

$$\psi = e^{-iX_0/m}\psi' \ , \quad \psi' = (\psi_l \ \psi_h)^T$$

Expansion generates $[2mP\_, iX_0/m] = 2i\gamma^0 X_0$ to remove $i\gamma^0\gamma^k D_k$

Diagonal at $(1/m)^0$

NR limit with systematic 1/mₑ expansion

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Diagonal at $(1/m)^0$

- [(1/m) order] $e^{-iX_0/m}$ generates odd $D_t X_0/m$ term, which is removed by X_1/m

$$\psi = e^{-iX_0/m}e^{-iX_1/m^2}\psi'$$

X_0^2/m term generates $(\gamma^k D_k)^2/m$
→Schrödinger type theory

FW method plus BSM or axion

2407.14598;
G. Krnjaic, D. Rocha, T. Trickle

- New physics effect $\bar{\psi} g \mathcal{O}_{\text{BSM}} \psi \to \psi'^{\dagger} \gamma^0 g \mathcal{O}_{\text{BSM}} (1 + X_0/m + \ldots) \psi'$

integrate out heavy fermion

$$\to \psi_l^{\dagger} [g \mathcal{O}_{\text{BSM}} (1 + X_0/m + \ldots)][1 + g \mathcal{O}^{\text{odd}}_{\text{BSM}}/(2m) + \ldots] \psi_l$$

due to light-heavy mixing

- Consider general QED+axion where $\theta = a/f_a$

Fridell, Ghosh, Hamada, **KT** (in pareparation)

$$\mathcal{L}_{\text{QED}+a} = \bar{\psi} \left(i \gamma^{\mu} D_{\mu} - m e^{i c_1 \gamma^5 \theta} - \frac{c_2}{2} \partial_{\mu} \theta \gamma^{\mu} \gamma^5 \right) \psi + \frac{\alpha c_3 \theta}{8\pi} F \tilde{F}$$

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- Consider general QED+axion where θ= a/fa

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Since g~**m**, expansion is unclear. We treat **θ~1/m**: (1/m) expansion is not ruined

$$\mathcal{L}_{\rm QED+\it a} = \psi^{\dagger} \left(iD_t + i\gamma^0 \gamma^k D_k - i c_1 m \theta \gamma^0 \gamma^5 - 2P\_m - \frac{c_2}{2} (\partial_\mu \theta) \gamma^0 \gamma^\mu \gamma^5 \right) \psi + O(m\theta^2)$$

Part of X0 — Part of X1 (μ=0)

$$\psi = e^{-iX_0/m} e^{-iX_1/m^2} \psi' \qquad X_0 = \frac{-\gamma^k D_k + c_1 m \theta \gamma^5}{2}, \quad X_1 = \frac{e}{4} \gamma^0 \gamma^k F_{0k} + \frac{i}{4} (c_1 - c_2) m \dot{\theta} \gamma^0 \gamma^5$$

NRQED with axion

Fridell, Ghosh, Hamada, **KT** (in pareparation)

$$\mathscr{L} = \begin{pmatrix} \psi_l \\ \psi_h \end{pmatrix}^\dagger \left(iD_t - 2P\_m - \frac{\gamma^0\gamma^k\gamma^l D_k D_l}{2m} + \frac{c_1 - c_2}{2}(\partial_\mu\theta)\gamma^0\gamma^\mu\gamma^5 - \frac{1}{m^2}[iD_t, iX_1] \right) \begin{pmatrix} \psi_l \\ \psi_h \end{pmatrix}$$

$$\supset \psi_l^\dagger \left(iD_t + \frac{\sigma^k\sigma^l D_k D_l}{2m} + \frac{c_1 - c_2}{2}(\partial_i\theta)\sigma^i \right) \psi_l$$

where $X_0 = \dfrac{-\gamma^k D_k + c_1 m\theta\gamma^5}{2}, \quad X_1 = \dfrac{e}{4}\gamma^0\gamma^k F_{0k} + \dfrac{i}{4}(c_1 - c_2)m\dot{\theta}\gamma^0\gamma^5$

- Naively expected operator $\psi^\dagger(m\theta^2)\psi$ does NOT appear.

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- Naively expected operator $\psi^\dagger(m\theta^2)\psi$ does NOT appear.
- Consistency check with **KSVZ limit** (**c1=c2**), equivalent to only aFF~ coupling
  Surprising cancellations occur at the Lagrangian level.

PQ symmetry in NR

Fridell, Ghosh, Hamada, **KT** (in pareparation)

$$\mathscr{L}_{\mathrm{QED}+a} = \overline{\psi}\left(i\gamma^\mu D_\mu - m e^{ic_1\gamma^5\theta} - \frac{c_2}{2}\partial_\mu\theta\gamma^\mu\gamma^5\right)\psi + \frac{\alpha c_3\theta}{8\pi}F\tilde{F}$$

- Transformation $\theta \to \theta - \alpha,\ \psi \to e^{ic_1\frac{\alpha}{2}\gamma^5}\psi$
- FW method at leading order $\psi = e^{-iX_0/m}\psi'$

$$\psi' = e^{i\frac{X_0}{m}}\psi \to e^{i\frac{X_0}{m} - i\frac{c_1\alpha}{2}\gamma^5}e^{i\frac{c_1\alpha}{2}\gamma^5}\psi = e^{i\frac{X_0}{m} - i\frac{c_1\alpha}{2}\gamma^5}e^{i\frac{c_1\alpha}{2}\gamma^5}e^{-i\frac{X_0}{m}}\psi'$$

After tedious calculation

$$\begin{pmatrix}\psi_l \\ \psi_h\end{pmatrix} \to \begin{pmatrix} 1 + \frac{c_1\alpha}{4m}\sigma^k D_k & O(\alpha^2) \\ O(\alpha^2) & 1 - \frac{c_1\alpha}{4m}\sigma^k D_k \end{pmatrix}\begin{pmatrix}\psi_l \\ \psi_h\end{pmatrix}$$

Leading order trans. is diagonal!!

$$\delta\psi_l = \frac{c_1\alpha}{4m}\sigma^k D_k\psi_l$$

Non-trivial because PQ mixes fermion by γ5

PQ symmetry analysis for low energy operators

Fridell, Ghosh, Hamada, **KT** (in pareparation)

- In CM systems, many operators emerge in low energy.
  E.g. strong coupling via phonon induce effective four-fermi contact term

$$\mathscr{L}_{\rm Cooper} = \frac{1}{\Lambda^2}(\psi_l \sigma_y \psi_l)(\psi_l \sigma_y \psi_l)^*$$

Cooper channel, spin up-down pair

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- **Hubbard-Stratonovich transformation**: auxiliary field Δ added in path integral

$$\mathscr{L}(\psi, \Delta) \supset -\Lambda^2 |\Delta|^2 + (\psi_l \sigma_y \psi_l)\Delta^* + (\psi_l \sigma_y \psi_l)^* \Delta$$

Integrate out fermion, and obtrain the theory of Cooper pair scalar field.

$\mathscr{L}_\Delta(\Delta)$ Theory of conventional superconductivity.

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- Now we can check the low energy operators attached with axion by PQ transf.

$$(\psi_l \sigma_y \psi_l) \to (\psi_l \sigma_y \psi_l)$$

PQ invariant without axion (rare)

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- How about something like $(\overline{\psi}\psi)^n$?

$$\psi_l^\dagger \psi_l \to \psi_l^\dagger \psi_l + \frac{c_1 \alpha}{4m} D_k(\psi_l^\dagger \sigma^k \psi_l)$$

not invariant

This suggests how axion should couple.
[assuming PQ is still robust]

$$\left(\psi_l^\dagger \psi_l + \frac{c_1 \theta}{4m} D_k(\psi_l^\dagger \sigma^k \psi_l)\right)^n$$

PQ invariant

Heavy Axion coupling to hadrons

Axion to hadron decays

- If it's heavier than the standard QCD axion, $\mathbf{m_a > m_\pi f_\pi / f_a}$
  unexplored possibility of axion for m_a>MeV [B,K physics, beam-dump if f_a<10TeV]

e.g. Y. Afik, B. Dobrich, J. Jerhot, Y. Soreq, KT;
S. Chakraborty, M. Kraus, V. Loladze, T. Okui, KT

For fa>>TeV, difficult in the ground experiments, but in cosmology.

- Big Bang Nucleosynthesis probes long-lived particles decaying to **hadrons.**
  In particular **^{4}He** which is determined by **neutron abundance**.

Past relevant works	Gravitino	M. Kawasaki, K. Kohri, T. Moroi [astro-ph/0408426]; K. Kohr i[astro-ph/0103411]
	Dark photon	A. Fradette, M. Pospelov, J. Pradler, A. Ritz 1407.0993
	Higgs portal scalar	A. Fradette, M. Pospelov 1706.01920
	Sterile neutrinos	A. Boyarsky, M. Ovchynnikov, O. Ruchayskiy, V. Syvolap 2008.00749

Standard neutron decoupling (→^{4}He)

- Neutron **weak interaction** decouples from the bath at T~0.7MeV (t~1sec).

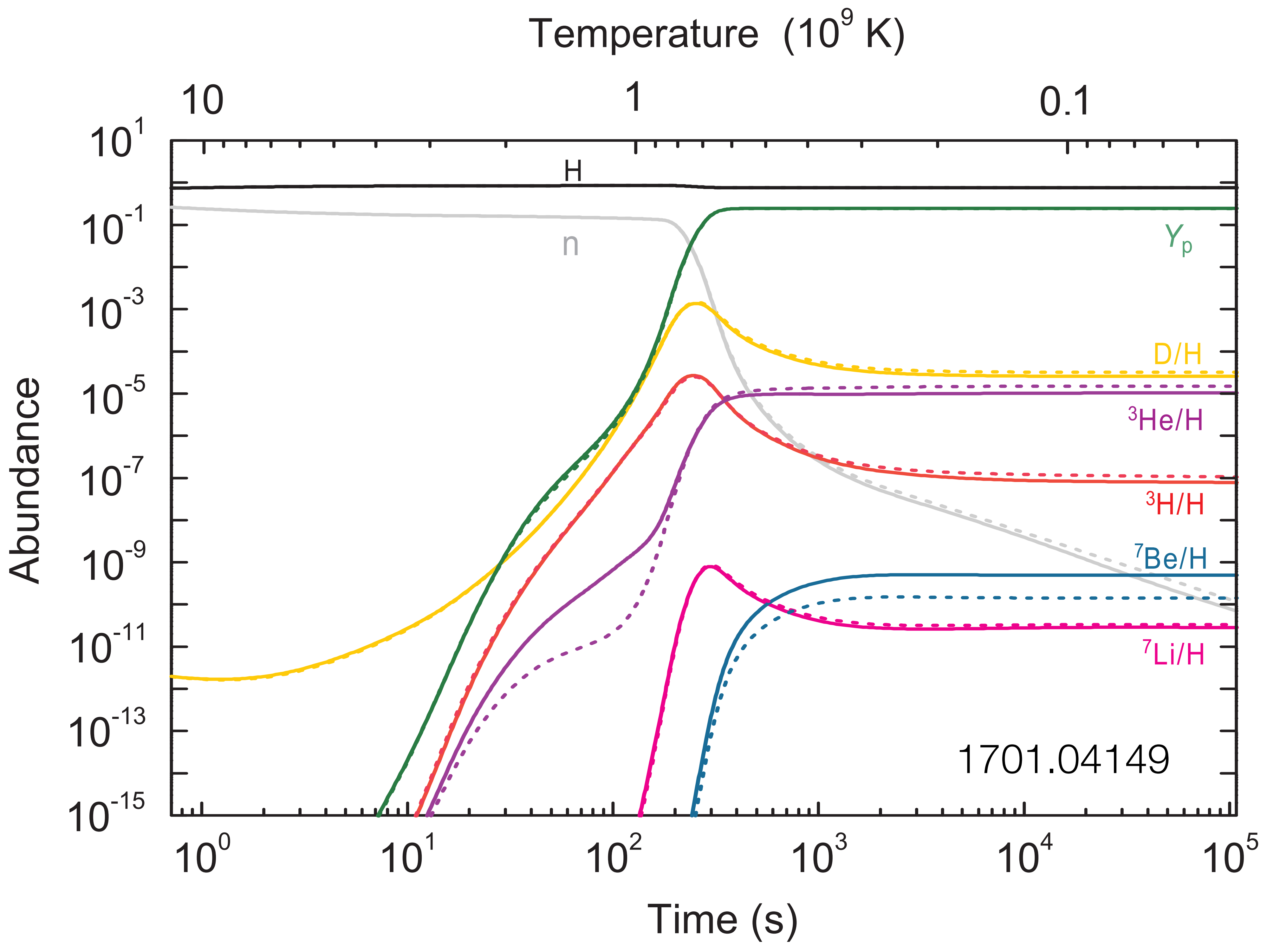
$$p + e^- \leftrightarrow n + \nu_e$$

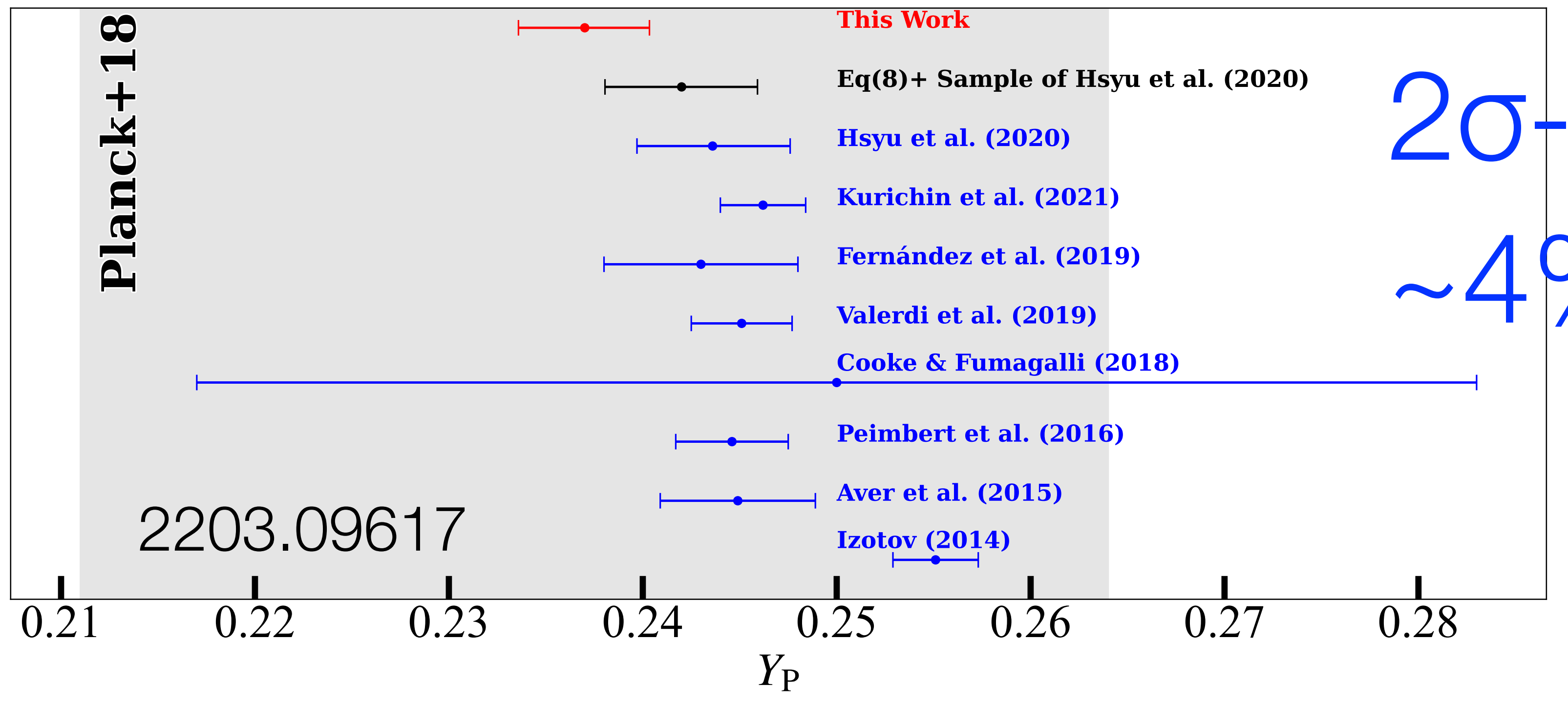
Rate is tiny: $n_{\nu,e}\sigma v \sim T^5 G_F^2$

neutron to proton ration: $n_n/n_p \simeq 1/6$

- After some decays, $n_n/n_p \simeq 1/7$ neutrons convert to ^{4}He at T~70keV

$$Y_P = \frac{\rho_{^4\mathrm{He}}}{\rho_{\mathrm{baryon}}} \simeq \frac{2(n_n/n_p)}{1+n_n/n_p} \simeq 0.25$$





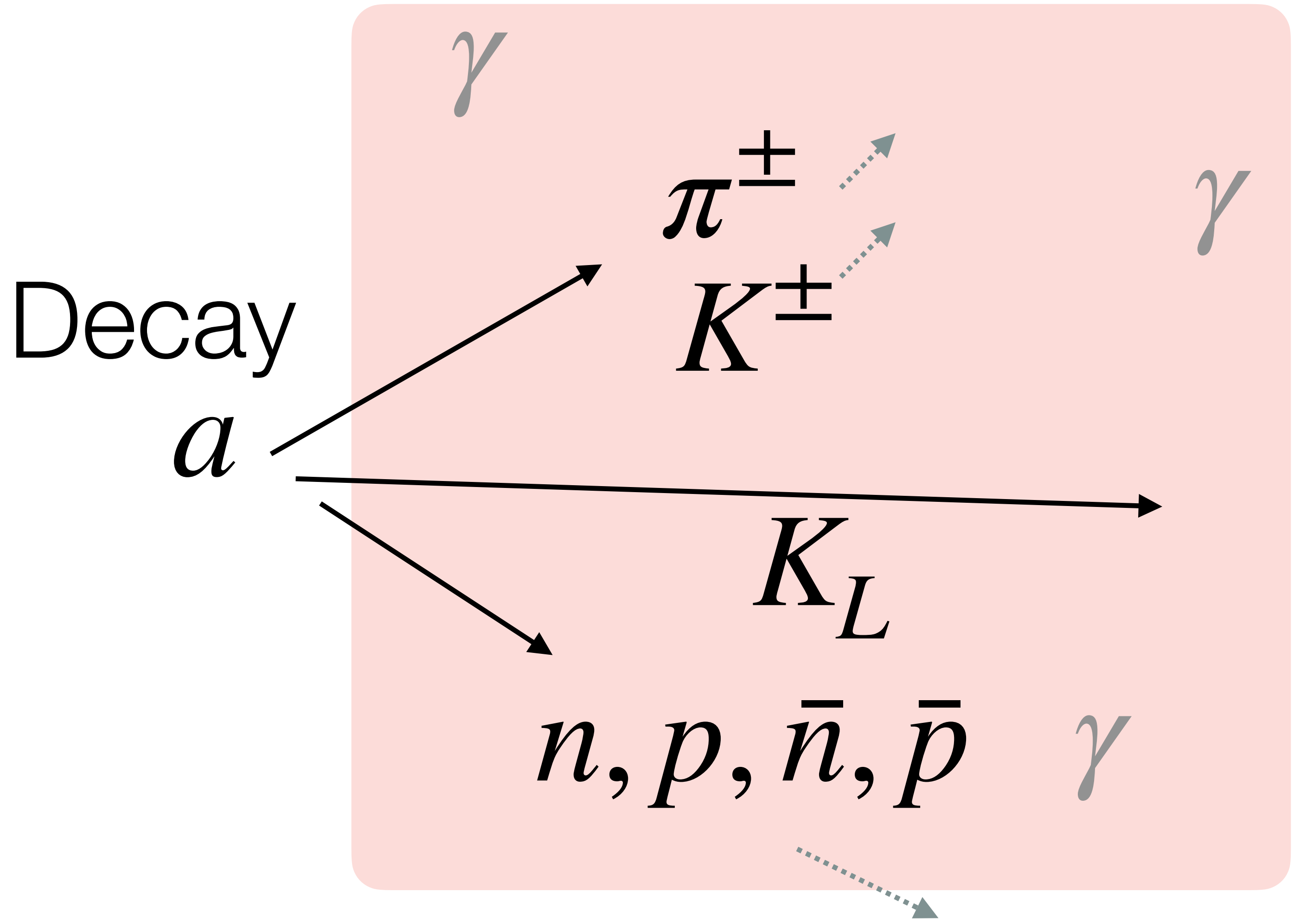
2σ-band: ~4%

a→hadrons alters neutron decoupling

TH Jung, T. Okui, **KT,** J. Wang (in pareparation)

- Standard process $p + e^- \leftrightarrow n + \nu_e$

  New process $n + \pi^+ \to p + \pi^0$



$n + \pi^+ \to p + \pi^0$

$p + \pi^- \to n + \pi^0$ ~1mb

$p + K^- \to n + X$ ~30mb

$p(n) + K_L \to n(p)$ ~10mb

$p, n + \bar{p}(\bar{n}) \to X$ ~40mb

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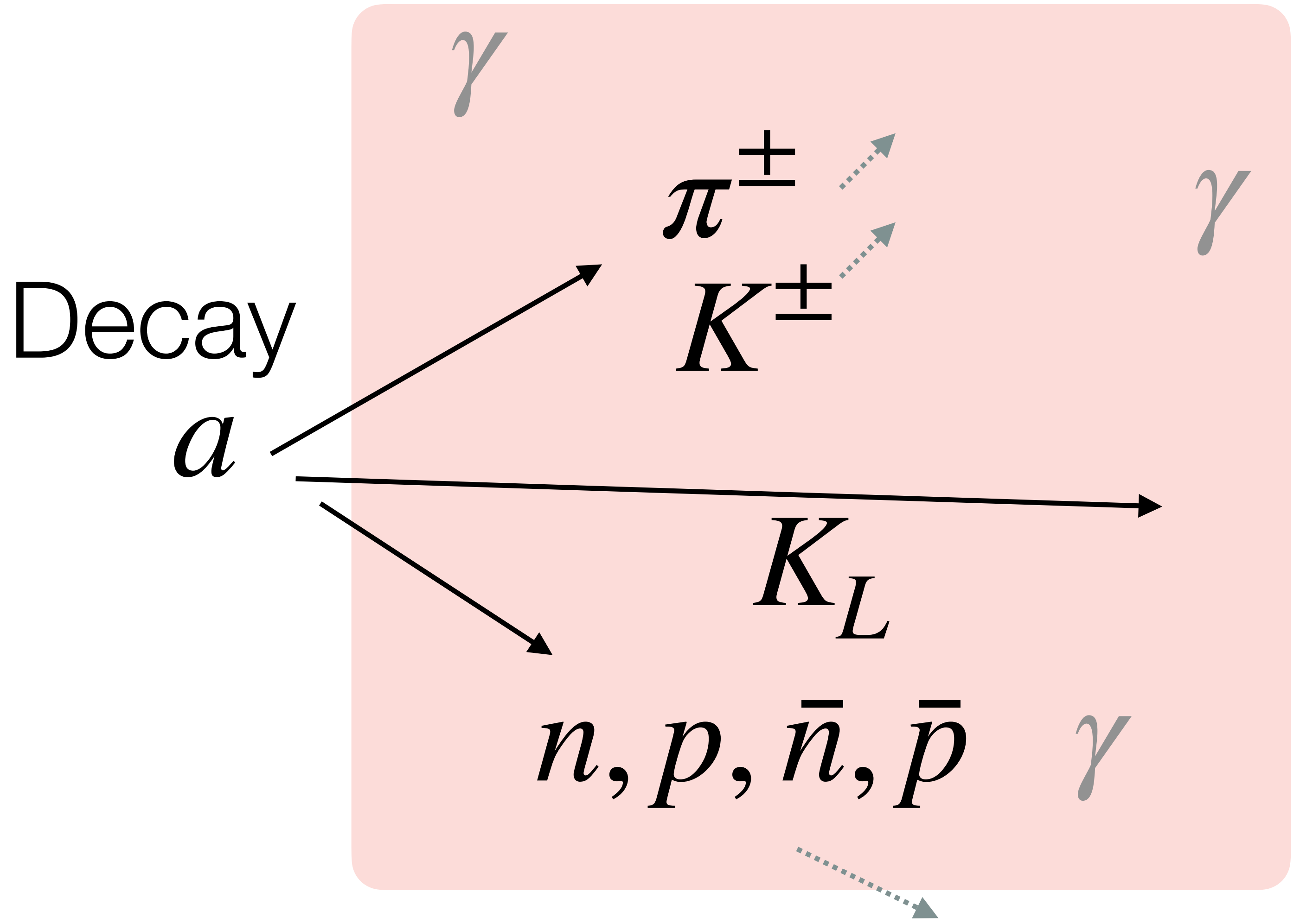
  New process $n + \pi^+ \rightarrow p + \pi^0$
- Thermally produced axion $Y_a \sim 1/g_*(T_{FO})$.
  Hadrons from axion decays participates in $p \leftrightarrow n$ by much higher rate ($\sigma \sim f_\pi^{-2} \sim 4$**mb**).



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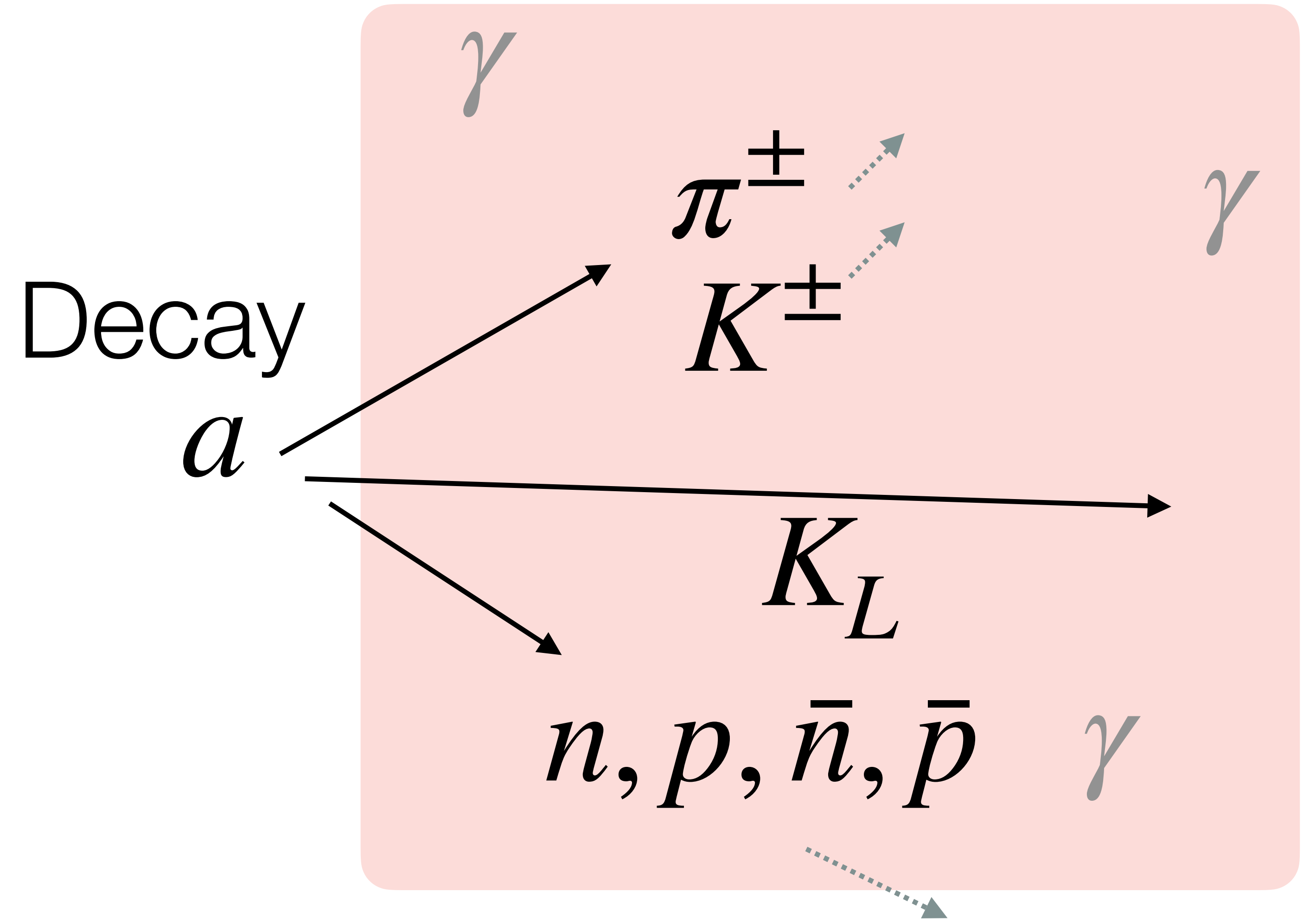
- Hadrons except K_L immediately slow down



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Standard

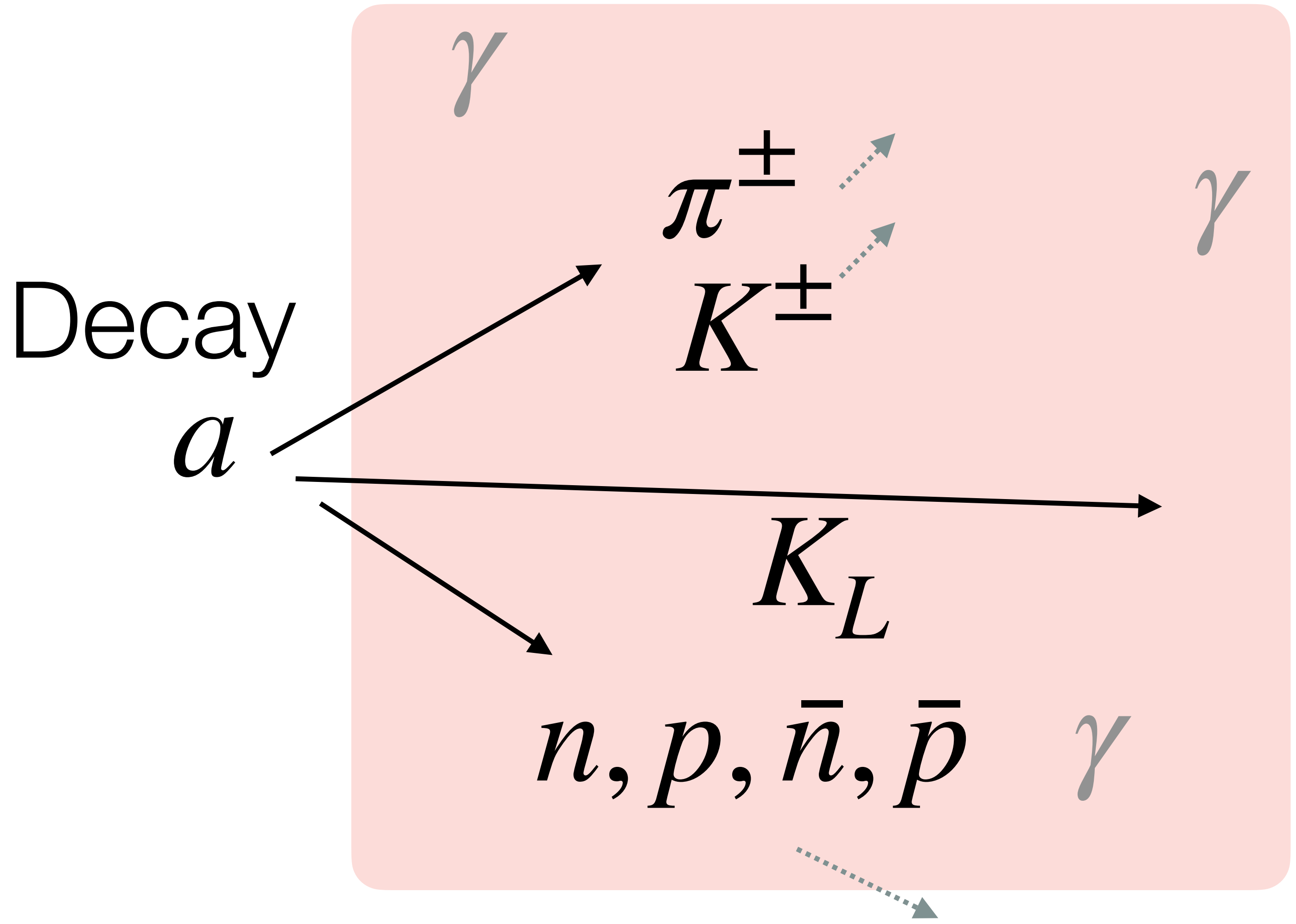
Rate: $n_{\nu,e}\sigma v \sim T^5 G_F^2 \sim 10^{-26}\mathrm{GeV}$

NP Rate:

$$n_{a\to K}\sigma v \sim (\mathrm{BR}e^{-t_{\mathrm{BBN}}/\tau_a})T^3 10\mathrm{mb}$$

$$\sim 10^{-10}\mathrm{GeV}(\mathrm{BR}e^{-1\mathrm{s}/\tau_a})$$

16 orders larger!



$n + \pi^+ \rightarrow p + \pi^0$

$p + \pi^- \rightarrow n + \pi^0$ ~1mb

$p + K^- \rightarrow n + X$ ~30mb

$p(n) + K_L \rightarrow n(p)$ ~10mb

$p, n + \bar{p}(\bar{n}) \rightarrow X$ ~40mb

a→hadrons alters neutron decoupling

TH Jung, T. Okui, **KT,** J. Wang (in pareparation)

- Standard process $p + e^- \leftrightarrow n + \nu_e$
  New process $n + \pi^+ \to p + \pi^0$
- Thermally produced axion $Y_a \sim 1/g_*(T_{FO})$.
  Hadrons from axion decays participates in $p \leftrightarrow n$ by much higher rate ($\sigma \sim f_\pi^{-2} \sim 4$**mb**).
- Hadrons except K_L immediately slow down

Standard

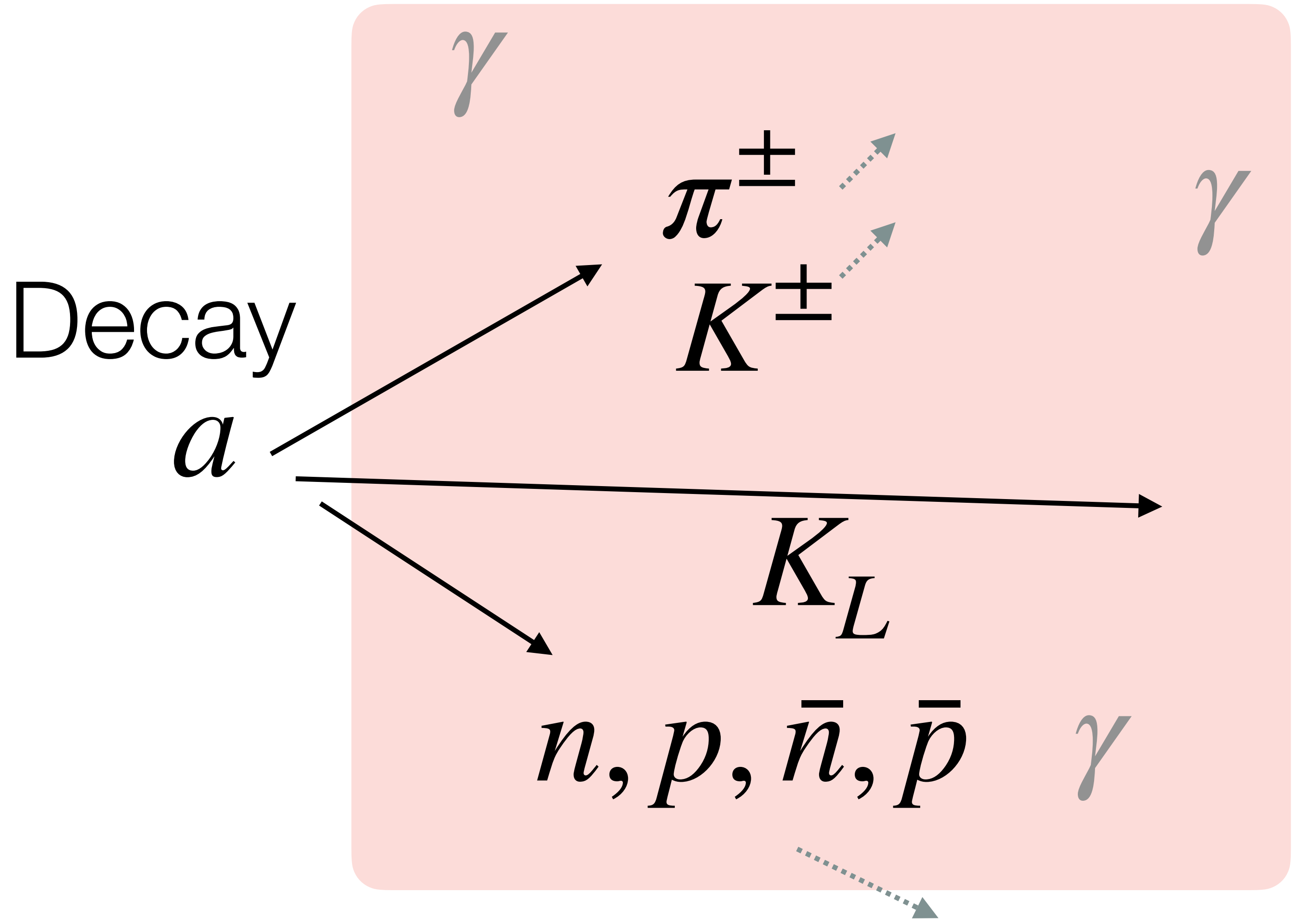
Rate: $n_{\nu,e}\sigma v \sim T^5 G_F^2 \sim 10^{-26}\mathrm{GeV}$

NP Rate:

$$n_{a\to K}\sigma v \sim (\mathrm{BR}e^{-t_{\mathrm{BBN}}/\tau_a})T^3 10\mathrm{mb}$$

$$\sim 10^{-10}\mathrm{GeV}(\mathrm{BR}e^{-1\mathrm{s}/\tau_a})$$

16 orders larger!



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$p, n + \bar{p}(\bar{n}) \to X$ ~40mb

e.g. two rates are comparable
if BR~0.1, τ_a~**0.03sec**

Much stronger
than naive bound $\tau_a \sim t_{\mathrm{BBN}} \sim$ **1sec**

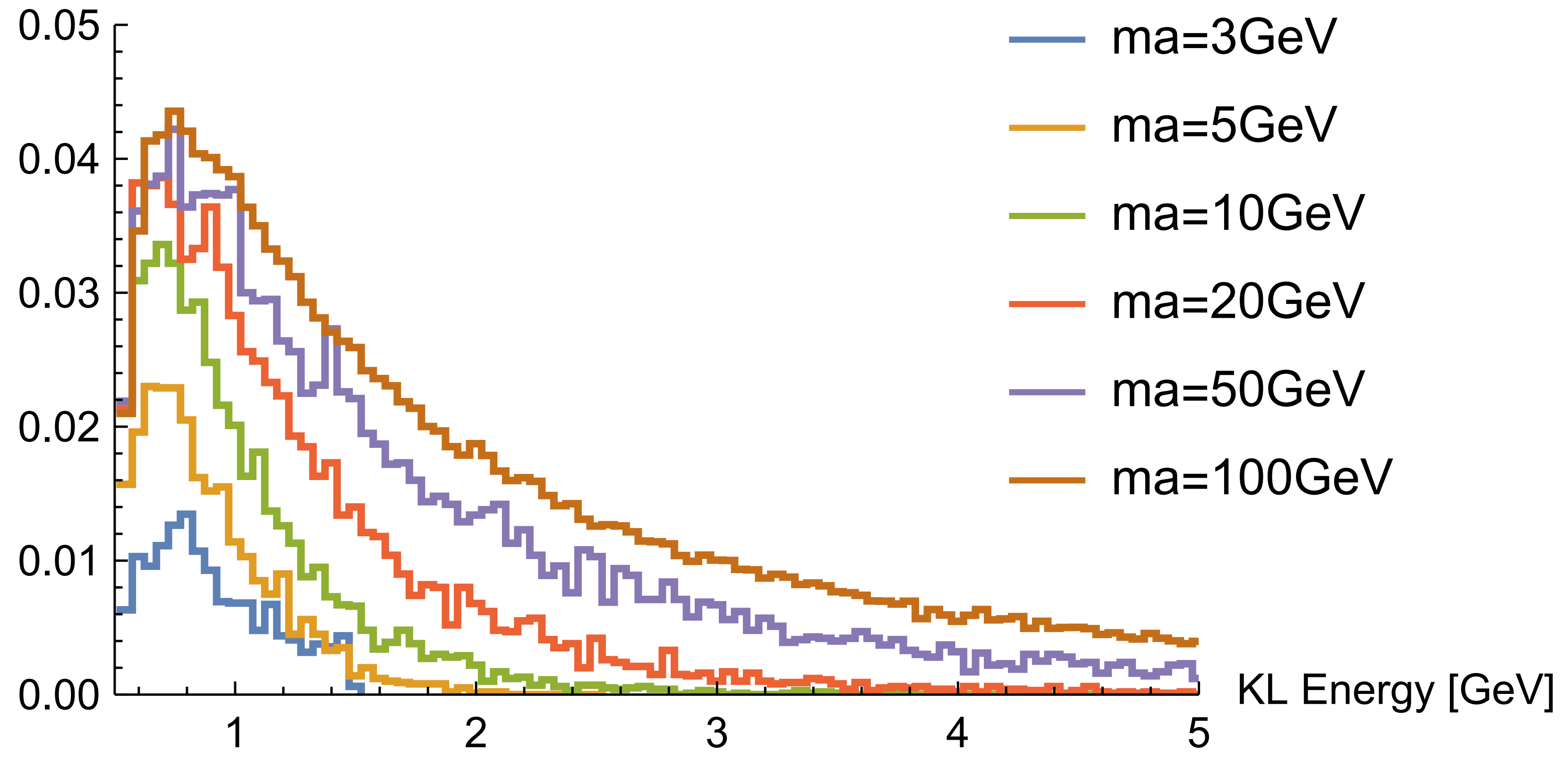
Updates from previous works

TH Jung, T. Okui, **KT,** J. Wang (in pareparation)

- Many hadronic cross sections updated.
  Proper partial wave analysis, Coulomb correction, tedious isospin analysis

  [thanks to Taehyun]

- **K_L** was not included or assumed to be thermal.
  Account K_L mom. spectrum from axion decay.
  Cross section weighted by momentum.



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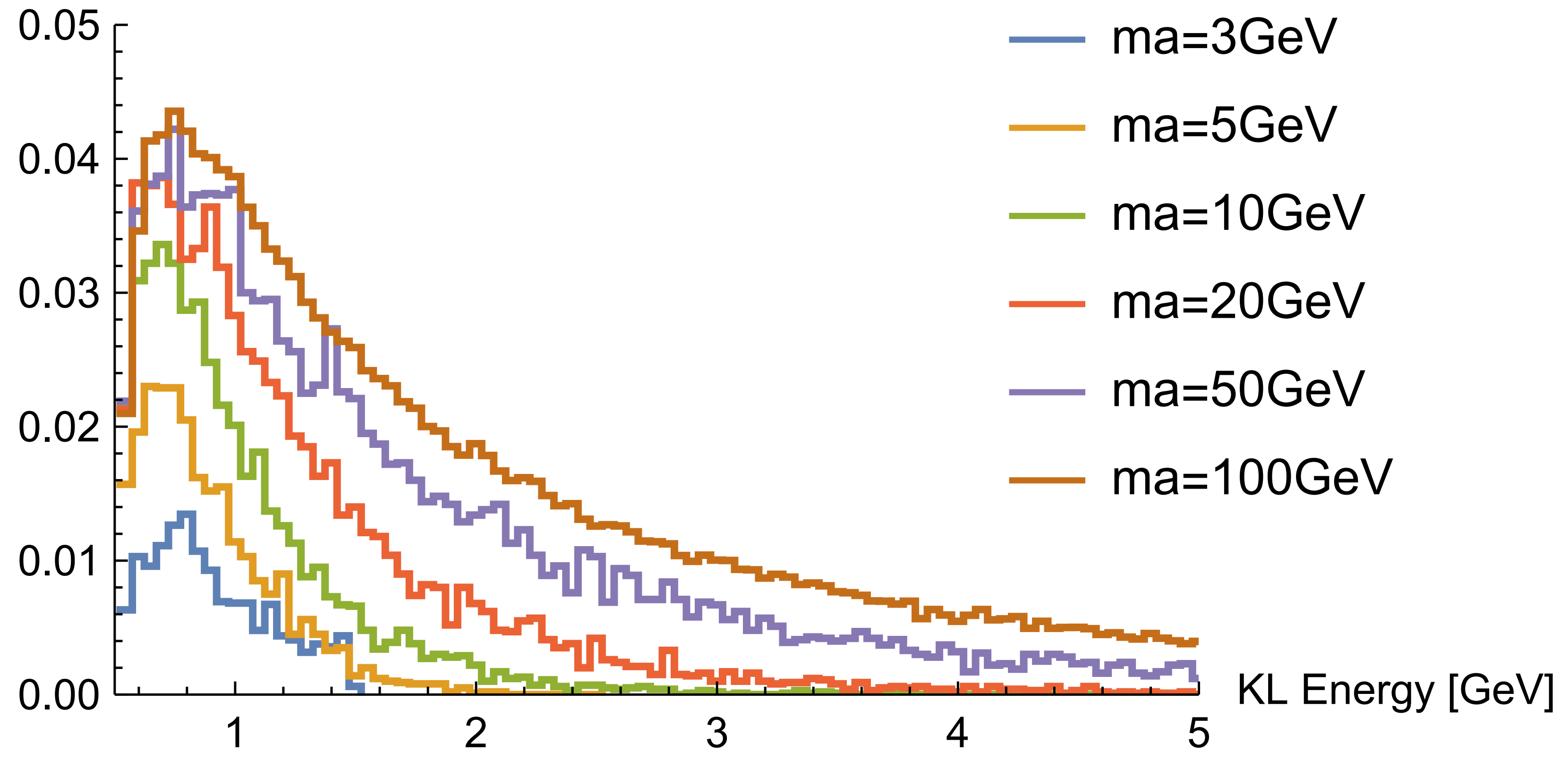


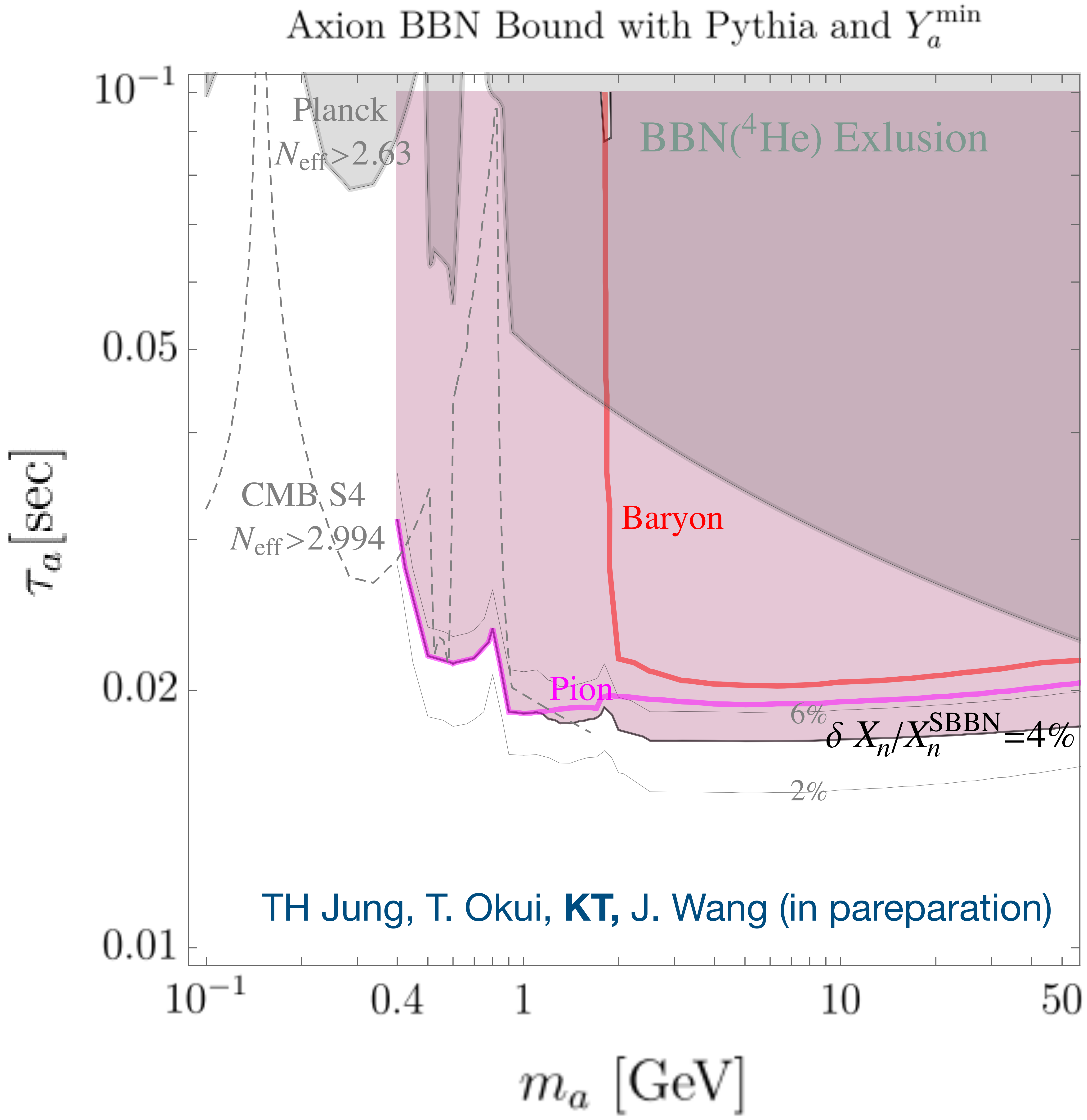
- As new particles heavy >GeV, the decay products are **extra radiation**→N_{eff} bound
  background cosmology modified (expansion rate is larger)

Dunsky, Hall, Harigaya [2205.11540]

Preliminary Results

- First study for axion hadronic decays.
- Require ΔYp/Yp<4% (conservative)
- m_a threshold is $3m_\pi$~400MeV,
  Kaon matters for m_a>1GeV.
- Better than Neff bound,
  comparable to CMB-S4 projection.
  Dunsky, Hall, Harigaya [2205.11540]

✴the updates can be implemented to other particles
(sterile ν, dark γ, Higgs portal)



Outlook

- **Axion** predominantly couple to **electrons**

Fridell, Ghosh, Hamada, **KT** (in pareparation)

We improved FW method to accommodate axion effect.

Interesting cancellation in KSVZ limit. Checking with higher dim operators.

(First?) obtained PQ transformation in NR.
Powerful tool to find the axion coupling in various CM systems.

- **Heavy** axion that decay to **hadrons** (π, K, baryon→m_a>400MeV)

TH Jung, T. Okui, **KT,** J. Wang (in pareparation)

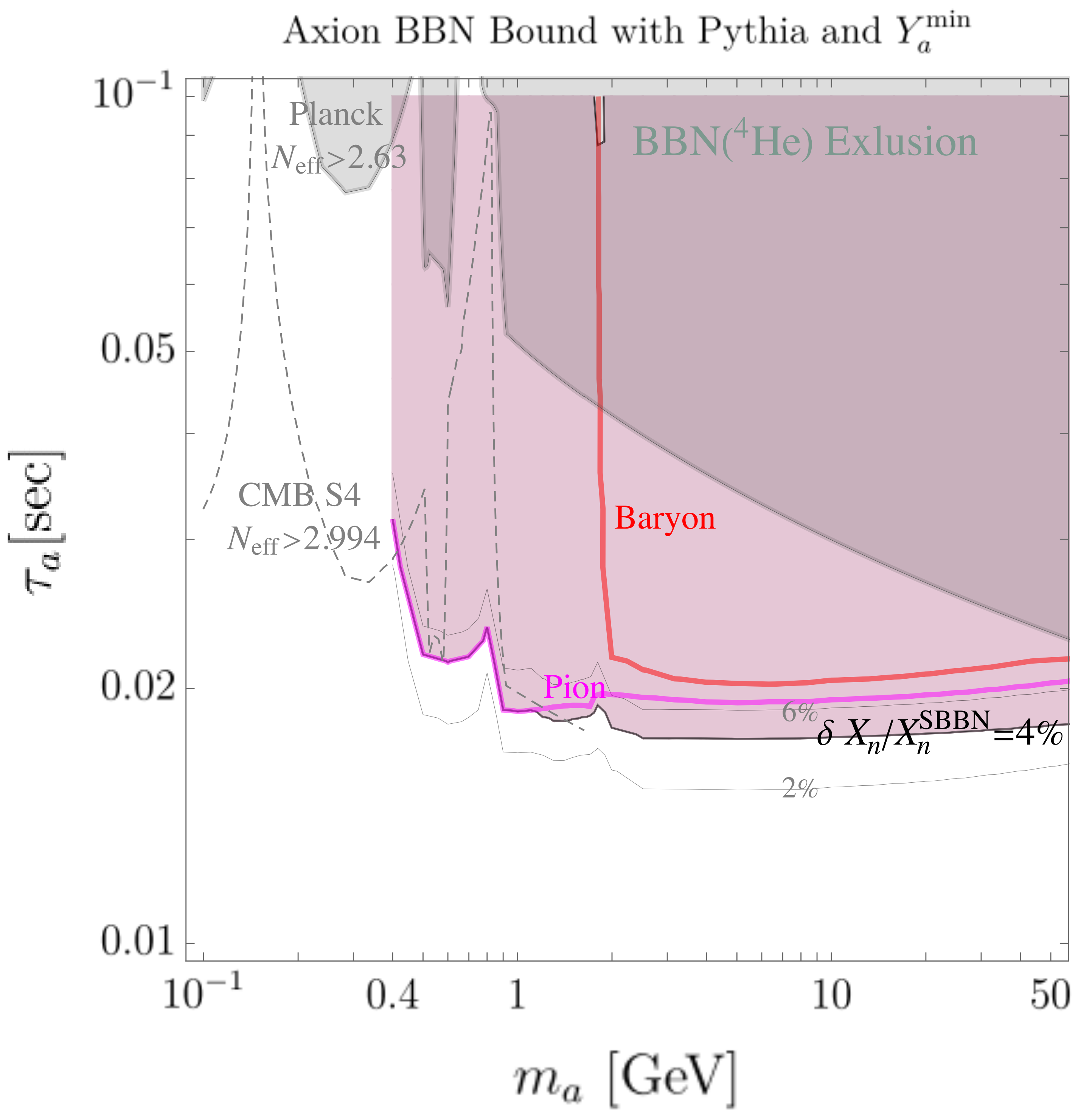
Adopting earlier works for other long-lived particles in BBN,
we update the methods, for KL and background cosmology.

First study on the axion→hadrons. Lifetime bound ~0.02sec (f_a~$10^{9\text{-}11}$GeV).

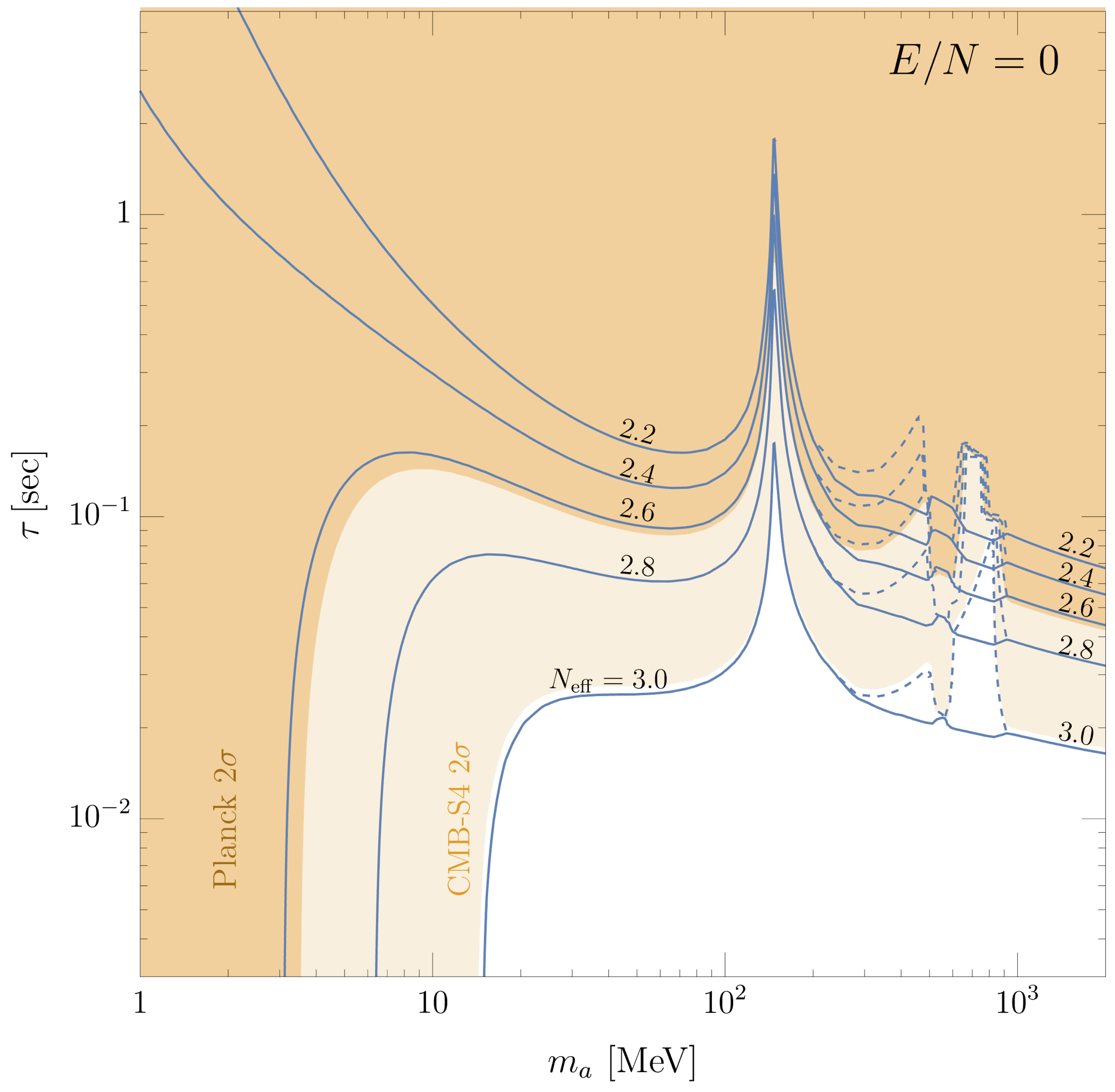
Thank you!

Backup

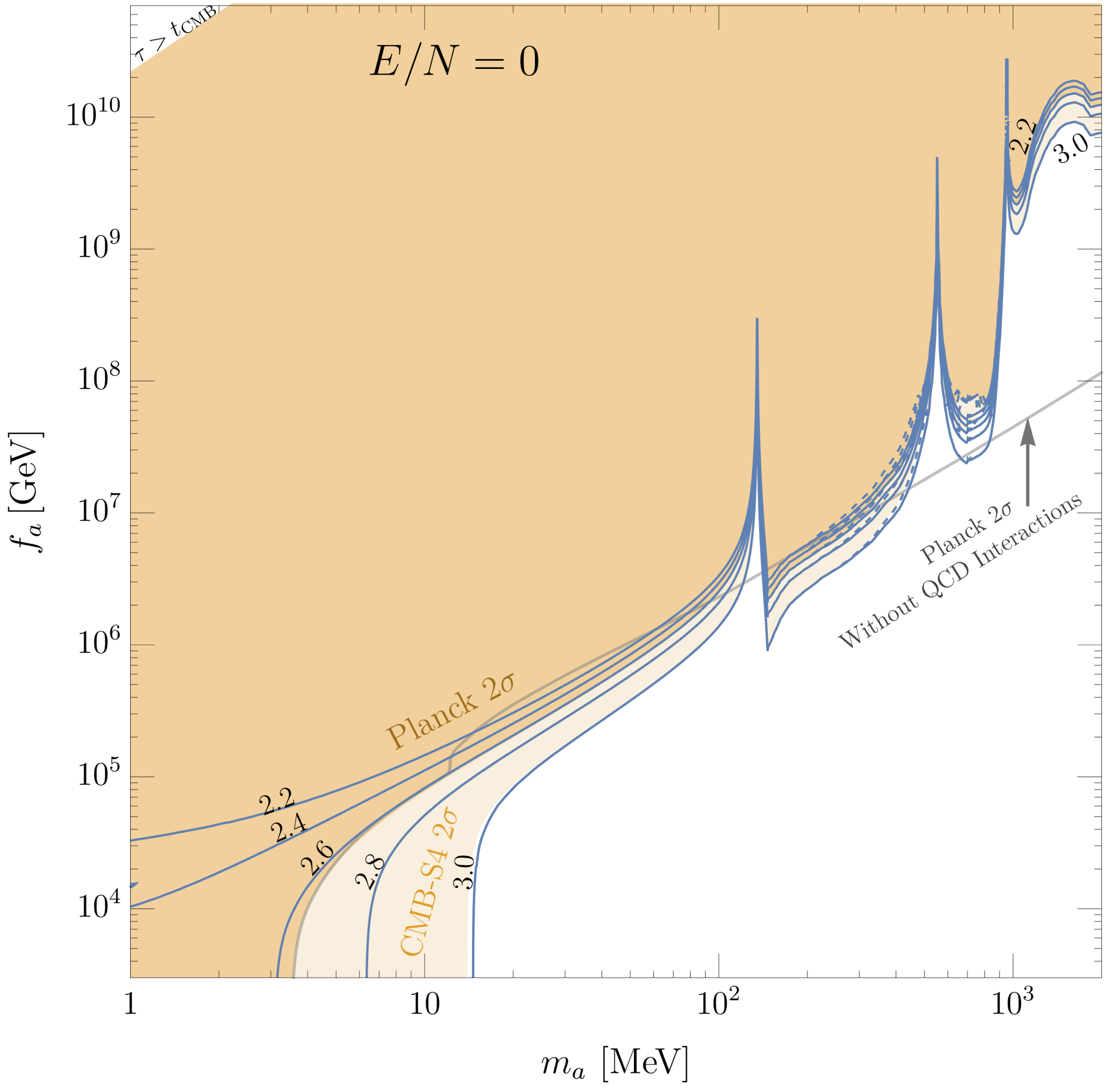
Results



Axion BBN Bound with Pythia and $Y_a^{\rm min}$
Planck
$N_{\rm eff}$>2.63
BBN(^{4}He) Exlusion
CMB S4
$N_{\rm eff}$>2.994
Baryon
Pion
6%
$\delta X_n/X_n^{\rm SBBN}$=4%
2%
τ_a [sec]
m_a [GeV]

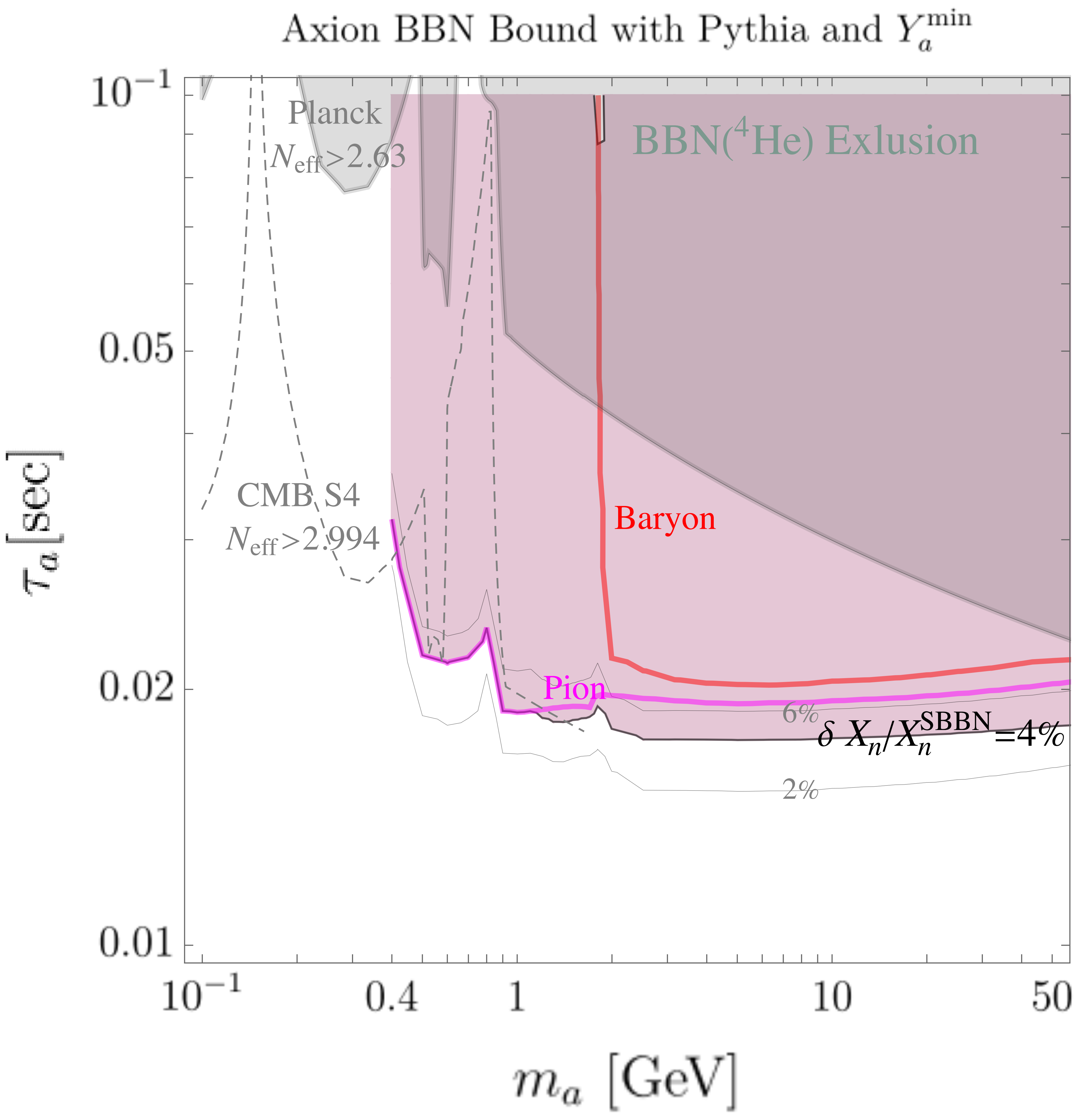


$E/N = 0$
2.2
2.4
2.6
2.8
$N_{\rm eff}$ = 3.0
3.0
Planck 2σ
CMB-S4 2σ
τ [sec]
m_a [MeV]

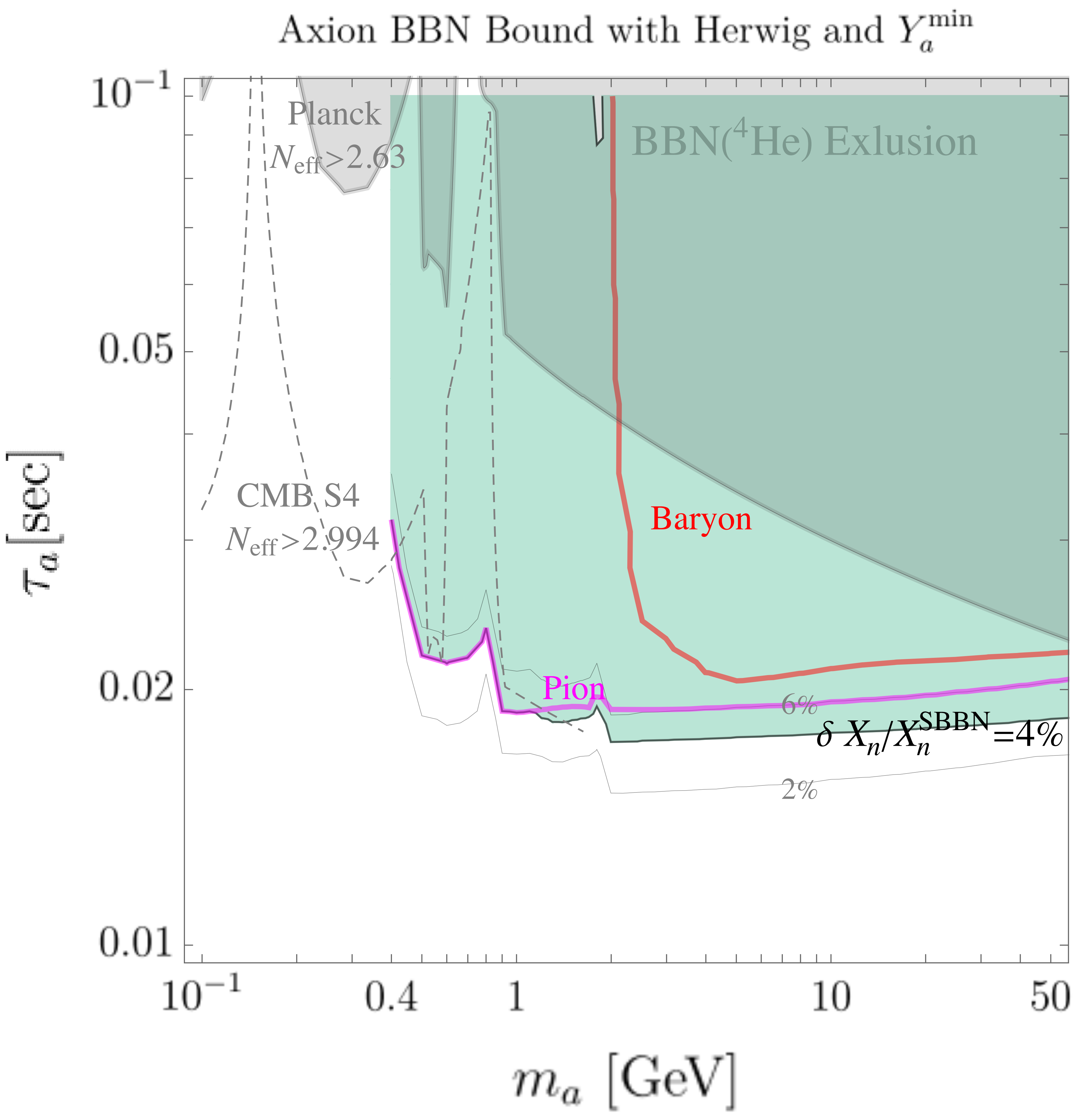


$E/N = 0$
2.2
3.0
2.4
2.6
2.8
Planck 2σ
CMB-S4 2σ
Planck 2σ
Without QCD Interactions
f_a [GeV]
m_a [MeV]

Results


Axion BBN Bound with Pythia and $Y_a^{\min}$
Planck
N_{eff}>2.63
BBN(^{4}He) Exlusion
CMB S4
N_{eff}>2.994
Baryon
Pion
6%
$\delta X_n/X_n^{\text{SBBN}}$=4%
2%
τ_a [sec]
m_a [GeV]
10^{-1}
0.05
0.02
0.01
10^{-1}
0.4
1
10
50

Results



Axion BBN Bound with Herwig and Y_a^{min}
Planck
N_{eff}>2.63
BBN(^{4}He) Exlusion
CMB S4
N_{eff}>2.994
Baryon
Pion
6%
$\delta X_n/X_n^{SBBN}$=4%
2%
10^{-1}
0.05
0.02
0.01
τ_a [sec]
10^{-1}
0.4
1
10
50
m_a [GeV]