

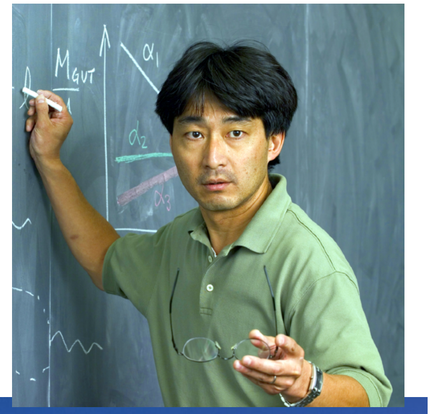
Exploring Data for Heavy QCD Axion From Colliders to the Big Bang

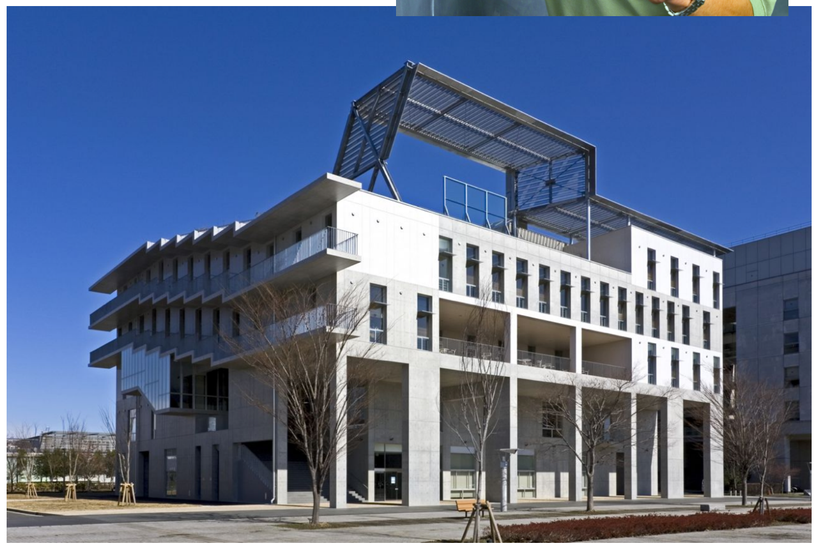
[Hitoshi's Fest, Dec 17, 2024. Kavli IPMU]

Kohsaku Tobioka [Tobi]
Florida State University,
KEK Theory center

My career started from IPMU as a Hitoshi's student

- I was one of the first IPMU graduate students through UTokyo (2009→2014).
- IPMU started in 2007. First anniversary in 2008 (Hitoshi convinced me to join).
- IPMU building, 2009. [LHC started.]
- Hitoshi's the first best seller book, 2010.
- Became "Kavli" IPMU, 2012. [Higgs discovery]





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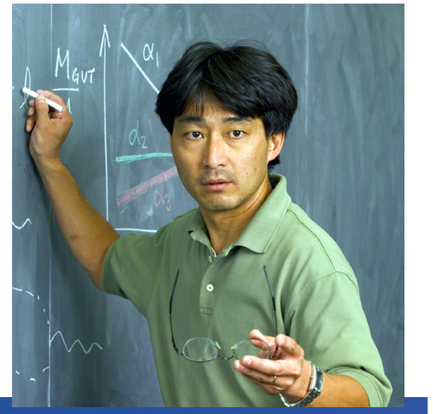


chin-up stand

懸垂機についてのお願い
To: Kohsaku Tobioka,

Admin staff, students, postdocs, in my apartment

Hitoshi’s family from Berkeley (’95-) to IPMU (’09-)

- Hitoshi’s mentorship at IPMU did not start from scratch.

Andre de Gouvea

..R. Harnik,.. M.Buckley

Sourav Mandal

William Klemm

Vikram Rentala

Xiaochuan Lu

Brian Henning

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William Klemm

Lawrence&Hitoshi Fest at P

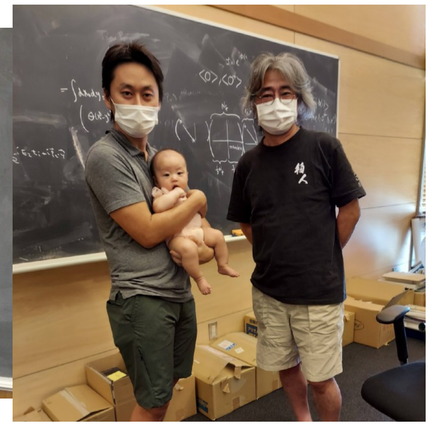
Recent Hitoshi’s group

Working with Hitoshi as a graduate student

- He knows everything, especially for graduate students
- Time was VERY limited!!
  I have to squeeze discussion time between appointments [thanks to Y. Enomoto]

But he knows everything & my 2month ~his 30min

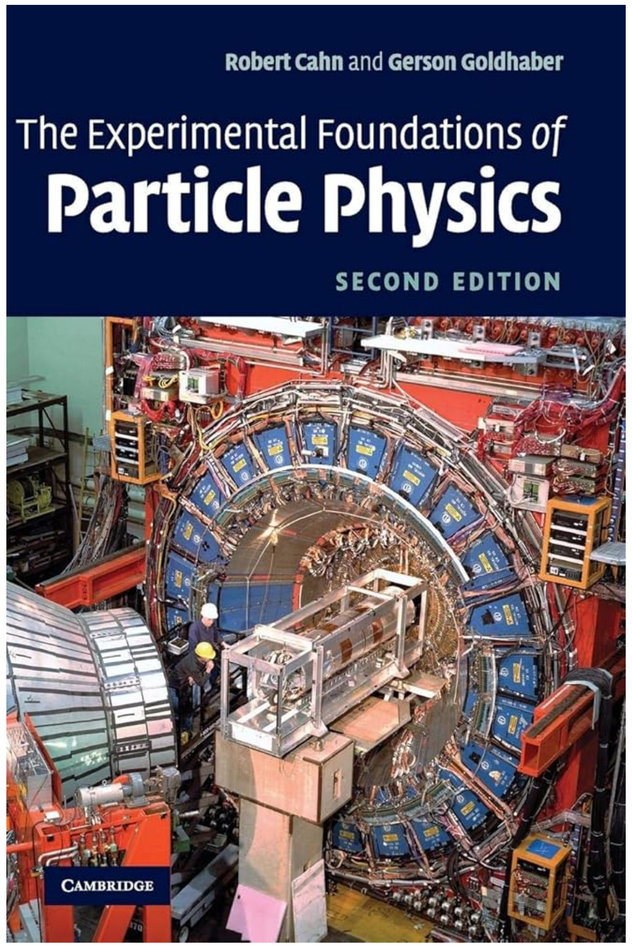
Still I wish I had more time…



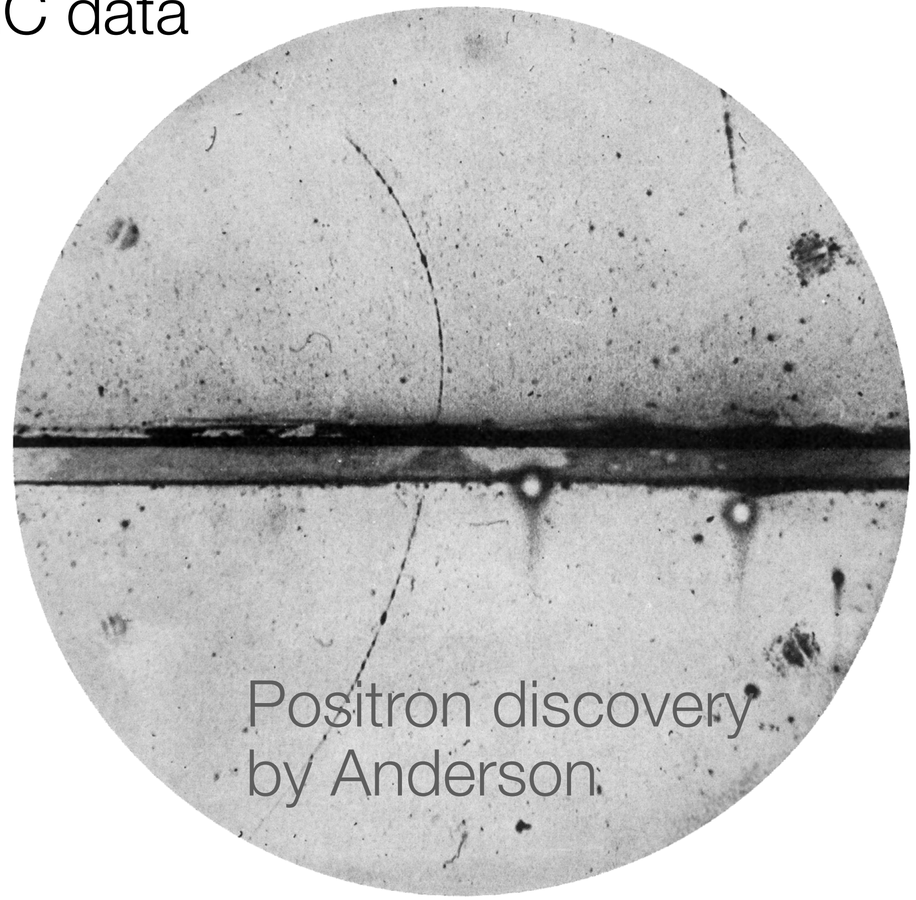
	Me	Hitoshi
Position	Associate Prof.	Prof & Founding Director
Family	2 kids	3 kids
Students	2	2(4)+2
Resut	Overwhelming!!	somehow working.. [**twin Hitoshis**?]

I realize the fact: **Hitoshi actually spent a lot of time for students!!**

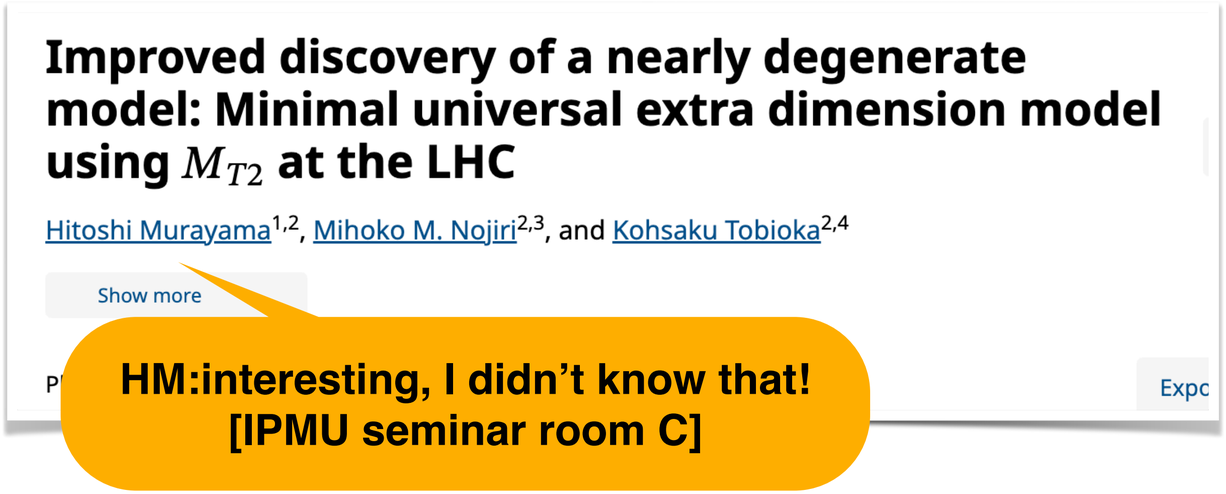
Working with Hitoshi: Listen to experiments



Hitoshi launched a reading group
to prepare for the LHC data



Working with Hitoshi: Listen to experiments



Working with Hitoshi: Listen to experiments

Improved discovery of a nearly degenerate model: Minimal universal extra dimension model using M_{T2} at the LHC

Hitoshi Murayama[1,2], Mihoko M. Nojiri[2,3], and Kohsaku Tobioka[2,4]

Show more

Phys. Rev. D **84**, 094015 – **Published 14 November, 2011**

EDITORS' SUGGESTION

Natural Higgs Mass in Supersymmetry from Nondecoupling Effects

Xiaochuan Lu[1,2,*], Hitoshi Murayama[1,2,3,†], Joshua T. Ruderman[1,2,‡], and Kohsaku Tobioka[3,4,§]

Show more

Phys. Rev. Lett. **112**, 191803 – **Published 14 May, 2014**

Compact supersymmetry

Hitoshi Murayama[1,2,3], Yasunori Nomura[1,2], Satoshi Shirai[1,2], and Kohsaku Tobioka[3,4]

Show more

Phys. Rev. D **86**, 115014 – **Published 7 December, 2012**

Enhanced Higgs mass in Compact Supersymmetry

Regular Article – Theoretical Physics | Open access | Published: 05 April 2016

Volume 2016, article number 25, (2016) Cite this article

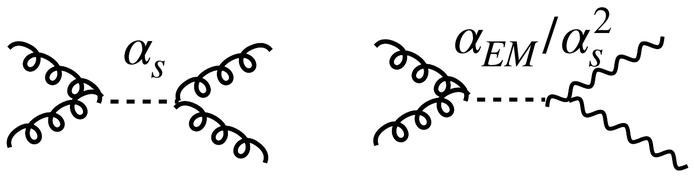
Prepare for the difficult NP signal at LHC such as compressed spectrum

Build a compelling model with SUSY. Try to explain Higgs mass=125GeV.

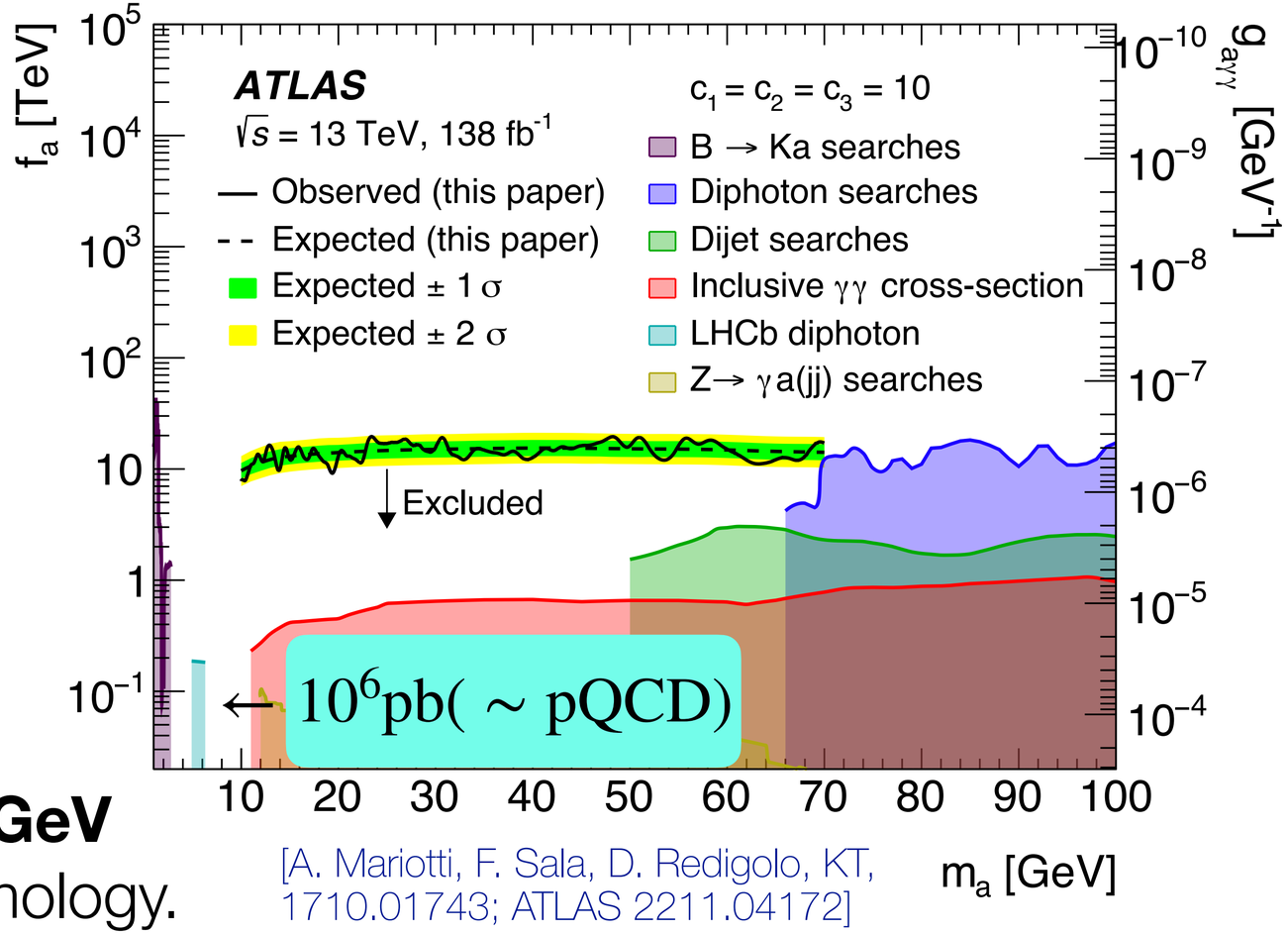
Experimental challenge, measurements→ Pheno work, model, calculation

Exploring Data for Heavy QCD Axion

LHC challenge: low mass resonance below 100GeV



- Typical dijet search at LHC >O(200) GeV
- Dijet with monojet trigger >50GeV
- Typical diphoton resonance >70GeV (Higgs discovery)
- LHC diphoton resonance can be down to ~**10 GeV**



- Challenges in **0.1GeV<m_X<10GeV** ⇒B, Kaon, Beam-dump, Cosmology.

[A. Mariotti, F. Sala, D. Redigolo, KT, 1710.01743; ATLAS 2211.04172]

Related to big question: Strong CP& Axion

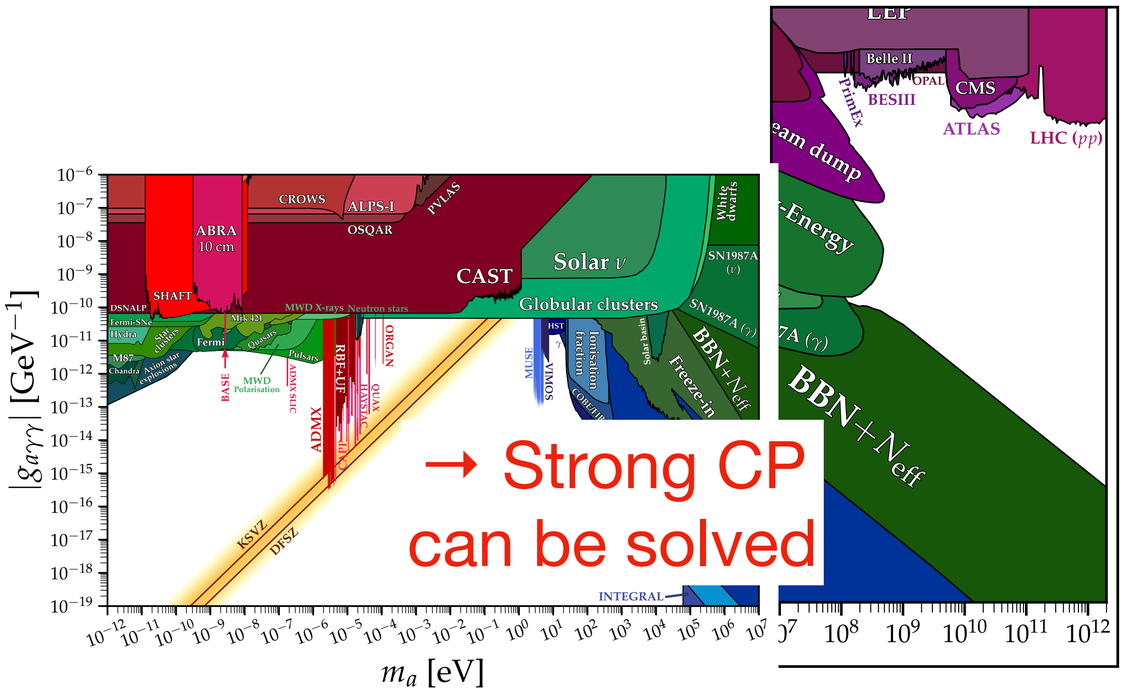
- **Heavy QCD Axion** Must: $\frac{c_g \alpha_s}{8\pi} \frac{a}{f_a} G^{a\mu\nu} \tilde{G}^{a\mu\nu}$ Optional: $aB\tilde{B},\ aW\tilde{W},\ \partial_\mu a \bar{f} \gamma^5 \gamma^\mu f$

to address strong CP

Heavier than standard mass $m_a \gg \frac{m_\pi f_\pi}{f_a}$

$$m_a \sim \frac{m_\pi f_\pi}{f_a} \sim 0.1\mathrm{MeV}\left(\frac{100\mathrm{GeV}}{f_a}\right)$$

Models: additional QCD SU(3)' to raise m_a
Berezhiani et al('01); Hook('04);
Fukuda, Harigaya, Ibe, Yanagida('04).
Dimopoulos et al('16); Hook et al('19); Valenti ('22)…
Another class: Agrawal and Howe ('17)…



→ Strong CP can be solved

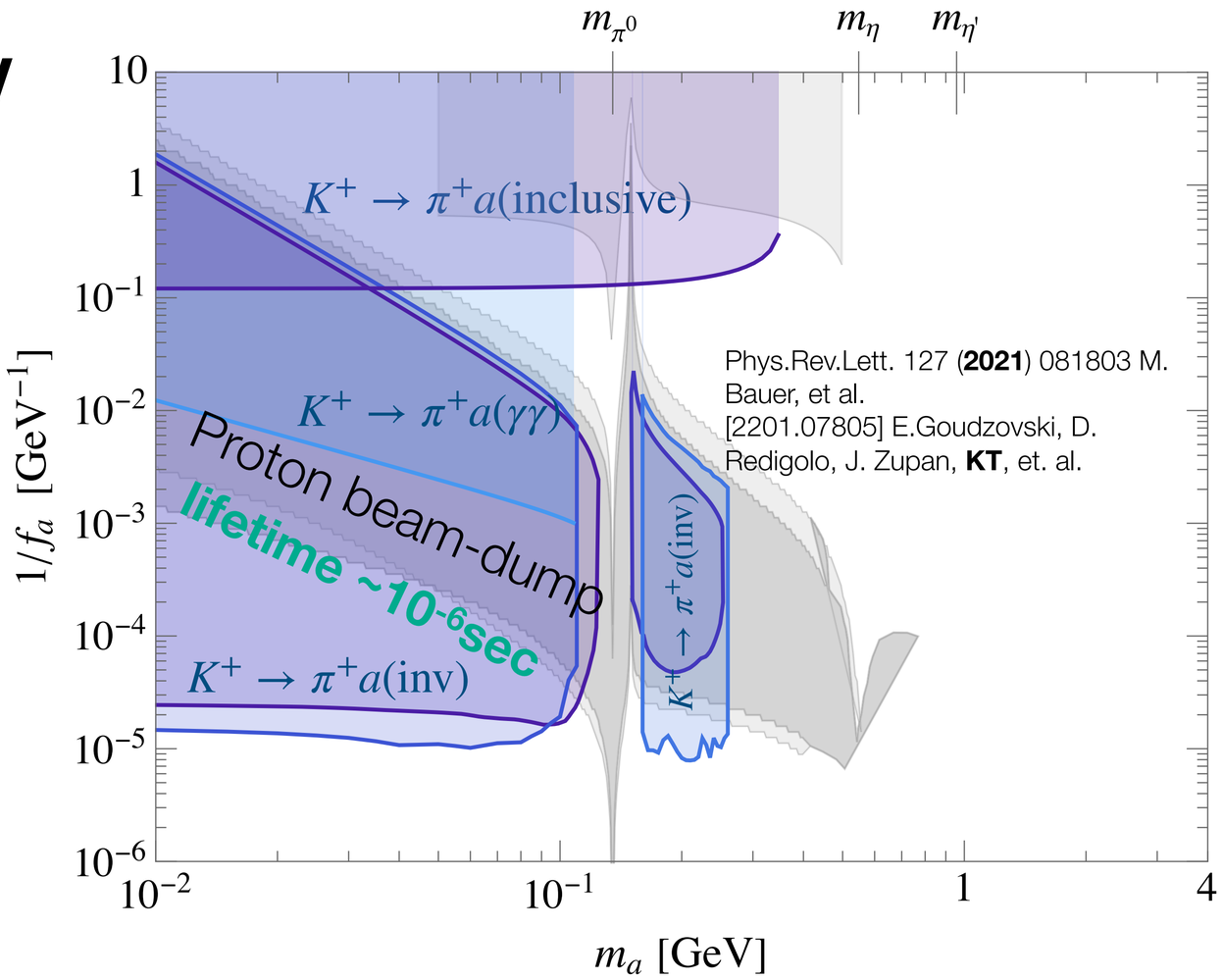
Why interesting?
1. Viable with lower f_a .
2. Lower f_a. better quality of PQ symmetry

Low mass edge: kaon and proton beam-dump

- LHC down to 10GeV. $K^+ \to \pi^+ a$ constraints $m_a < m_K - m_\pi \sim$ **0.35GeV**
- Proton beam-dump search $m_a <$ **0.5GeV** due to shorter lifetime.

- 0.35-4 GeV, B physics

$$B \to Ka$$

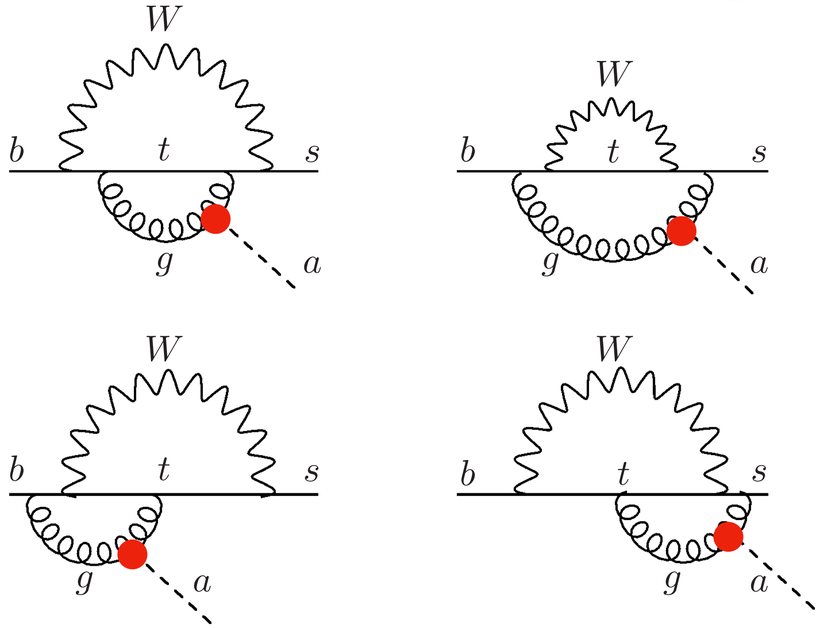


Heavy Axion from B decays

Production rate of $B \to Ka$

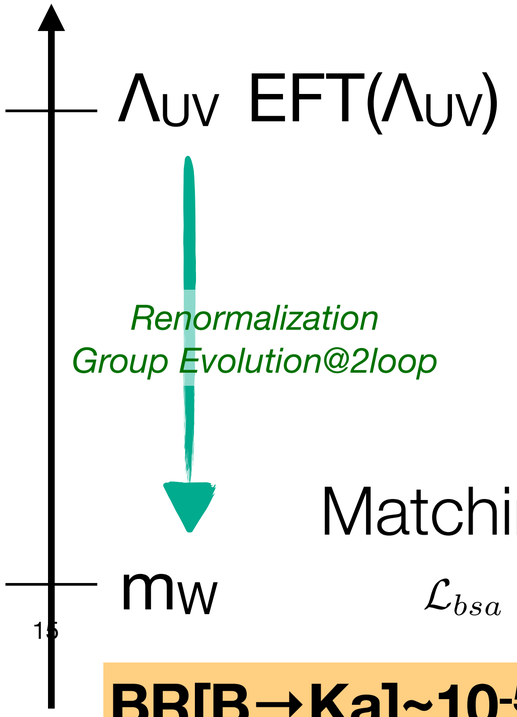
PRD 104 (**2021**) 055036
S. Chakraborty, M. Kraus, V. Loladze, T. Okui, **KT**

- Robust production is from gluon coupling: leading is at 2-loop!



Need 2-loop to generate $b \to sa$ from aGG

- 1-loop QCD for aqq
- 1-loop with W-boson for flavor changing



$$\mathcal{O}_{gg} = \frac{1}{8\pi}\frac{a}{f_a} G^a_{\mu\nu}\tilde{G}^{a\mu\nu} \ ,$$

$$\mathcal{O}_{qq} = \sum_q \frac{\partial_\mu a}{f_a}\, \bar{q}\gamma^\mu\gamma_5 q \ ,$$

$$\mathcal{O}_{bs} = \frac{\partial_\mu a}{f_a}\, \bar{s}_{\rm L}\gamma^\mu\gamma_5 b_{\rm L} + {\rm h.c.} \ .$$

Matching to weak-scale EFT @2loop

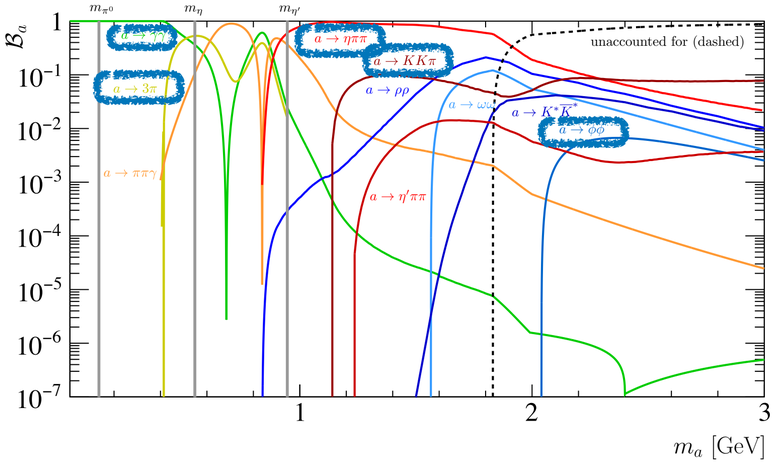
$$\mathcal{L}_{bsa} = C_W \frac{\partial_\mu a}{f_a}\bar{s}_{\rm L}\gamma^\mu\gamma_5 b_{\rm L}$$

BR[B→Ka]~10^{-5} (f_a/100GeV)$^{-2}$

Heavy axion signal in $B \to Ka$

- Various decay modes combined with production rate.

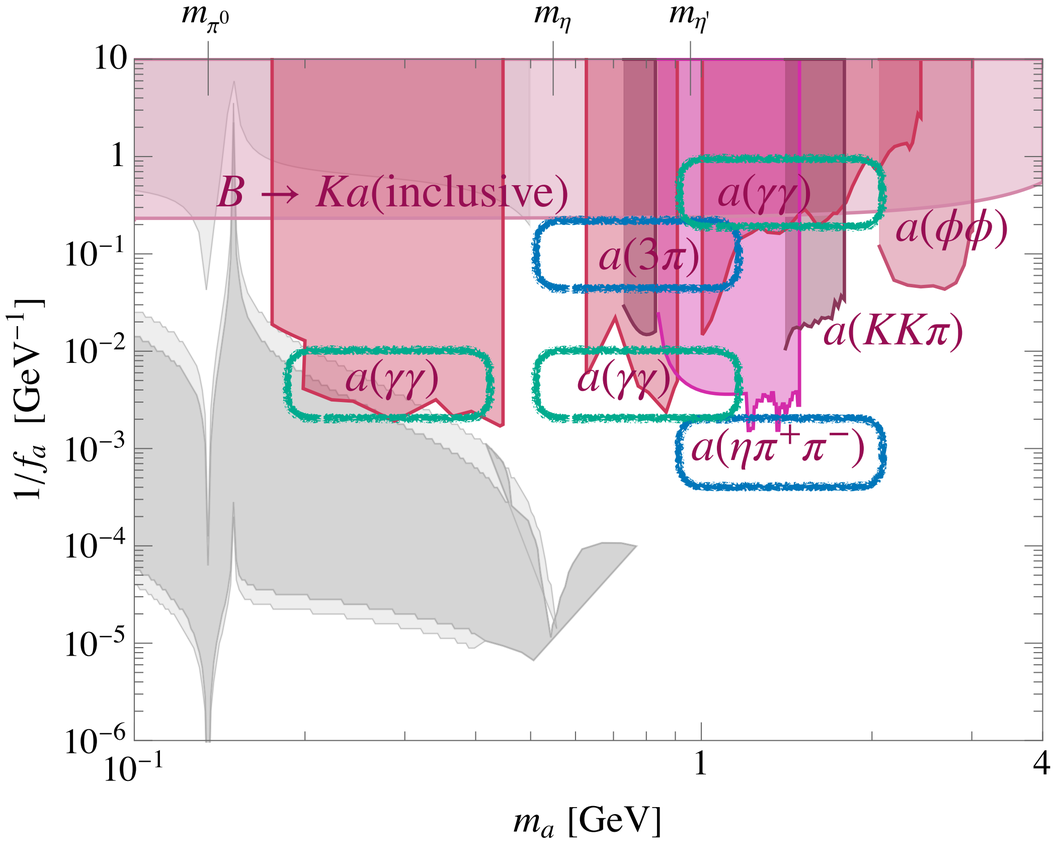
$$a \to (\pi^0\pi^+\pi^-, \eta\pi^+\pi^-, KK\pi, \phi\phi, \gamma\gamma, \ldots),$$



- Recast
  Old (Babar) and new (Belle II) analyses

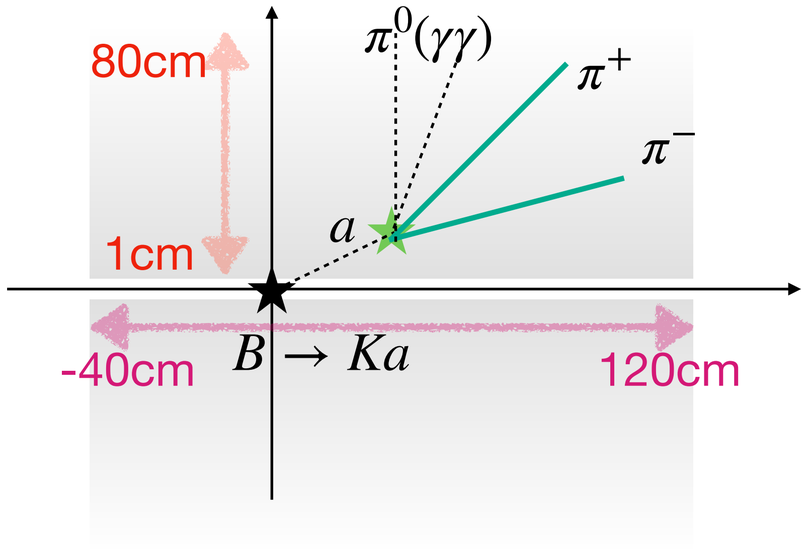
$$B \to KX(\pi^0\pi^+\pi^-, \eta\pi^+\pi^-, KK\pi, \phi\phi, \gamma\gamma),$$

- Need similar/dedicated analyses at Belle II
  Also new searches.

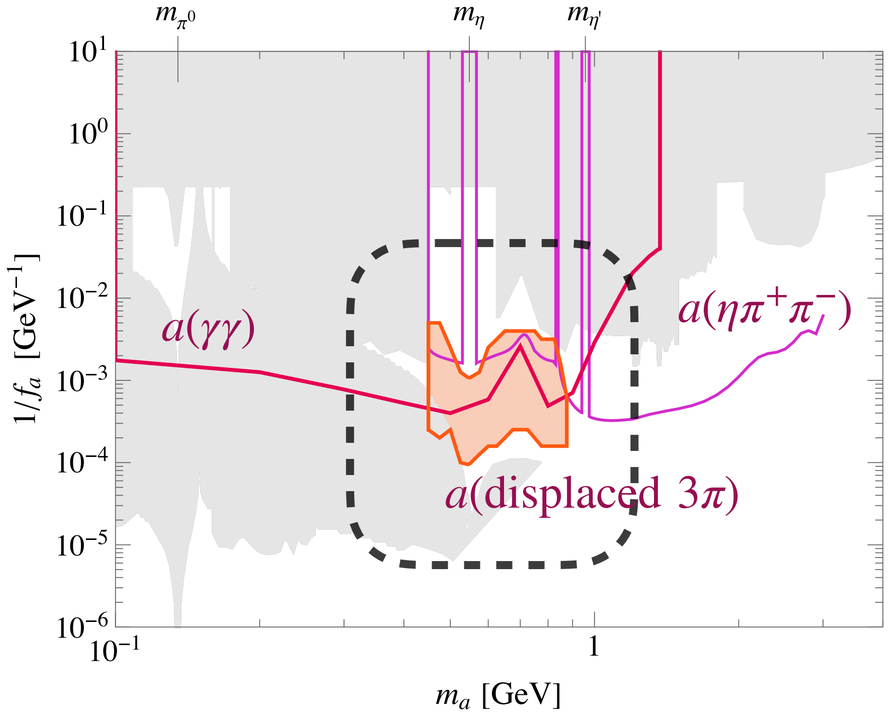


New search $B \to Ka$ *with* displaced $a \to 3\pi$

- **Displaced decay (τ~ns→cτ~cm)** is also possible: 2 π± reconstruct vertex.
- Very low background due to >1cm DV.

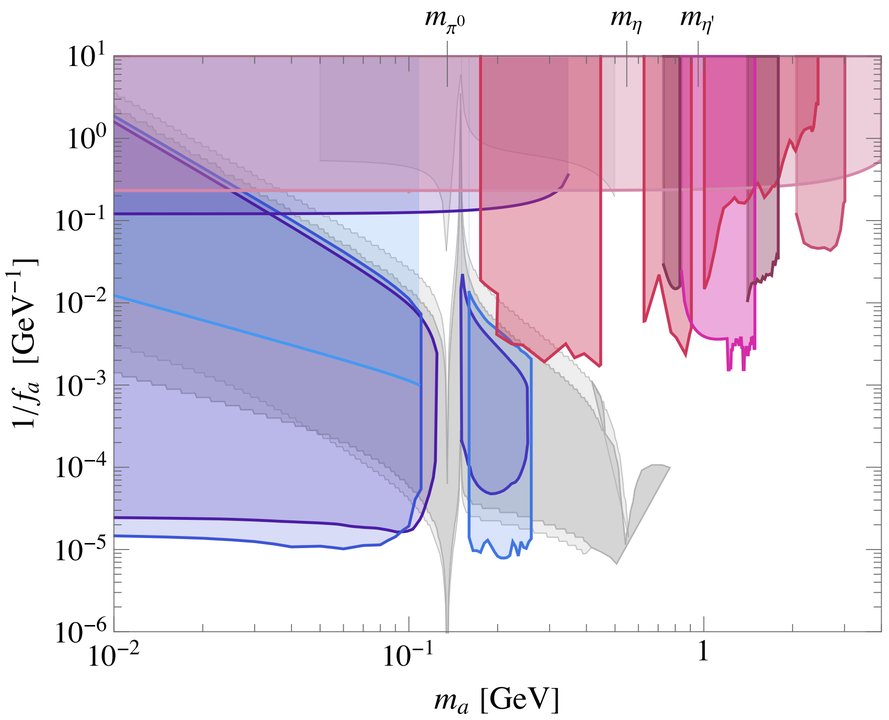


Phys.Rev.D 105 (2022) L071701
E. Bertholet, S. Chakraborty, V. Loladze, T. Okui, A. Soffer, **KT**



- **Can be done at LHCb**

Future Proton Beam Dump Exp and KOTO detector

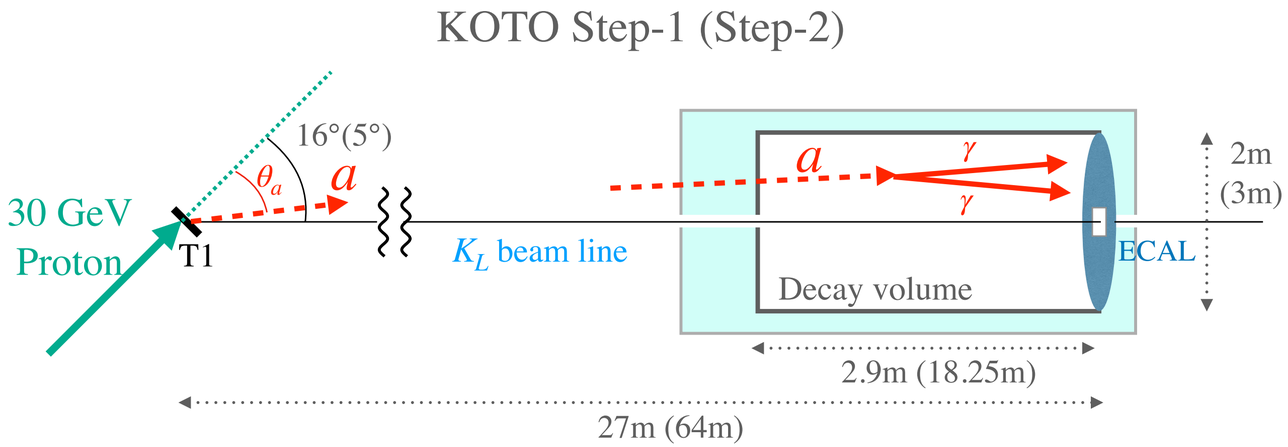


Next proton beam dump experiments

for long-lived axion with lifetime of microsecond.

- Proton beam on fixed target + distant detector
- Last proton beam dump experiment was in ‘90s. CHARM/NuCal

High intensity GeV+ proton source is at limited labs: CERN, Fermilab, J-PARC, Oak Ridge?



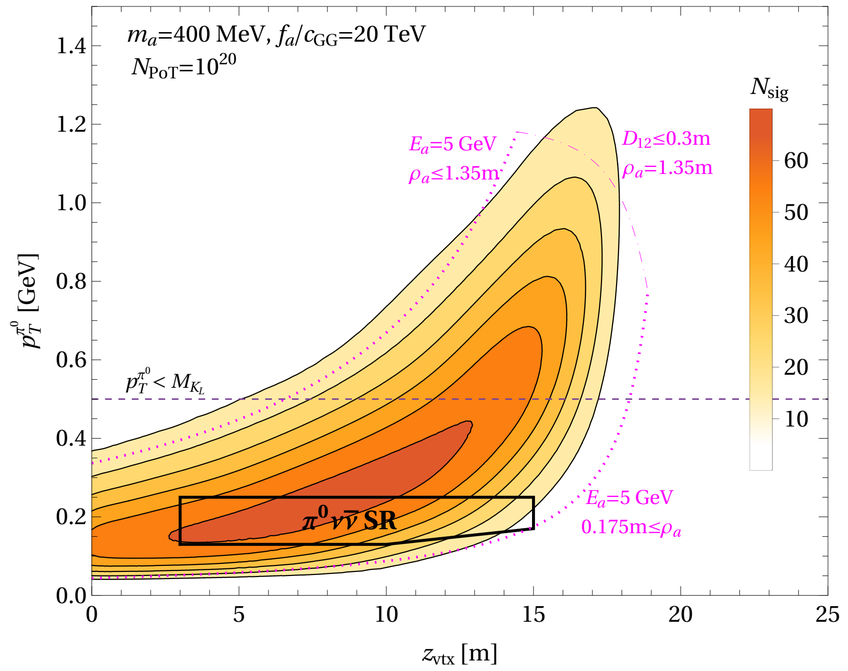
Proton beam: J-PARC, Fermilab, CERN

Detector: **KOTO**, T2K Near-Detector, DUNE Near-Detector, FASER, MATHUSLA, **SHiP**

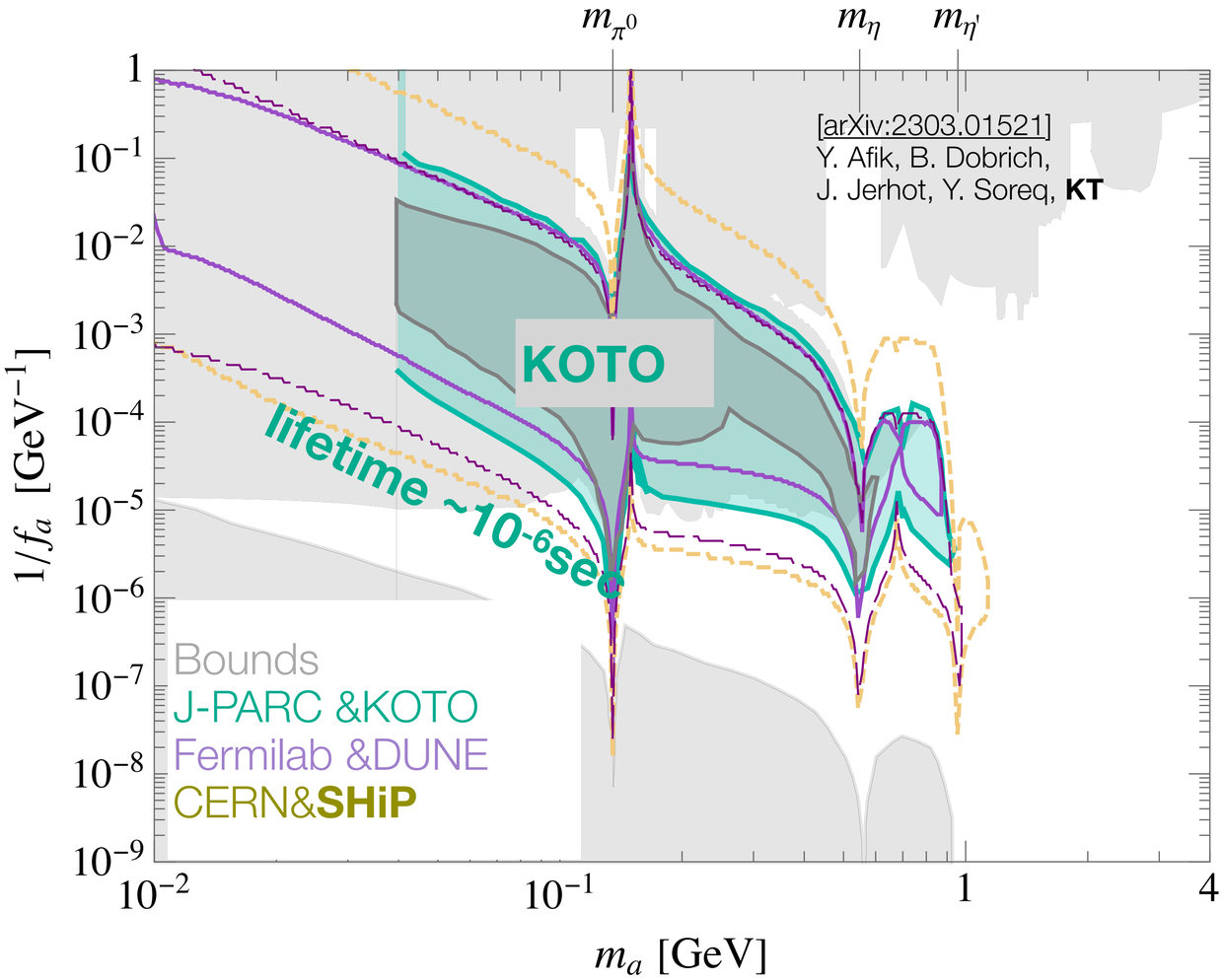
Next proton beam dump experiments

for long-lived axion with lifetime of microsecond.

Projection at KOTO Step-2



Main target at KOTO is inside the solid
Long-lived axion signal is colored (pT>mK)



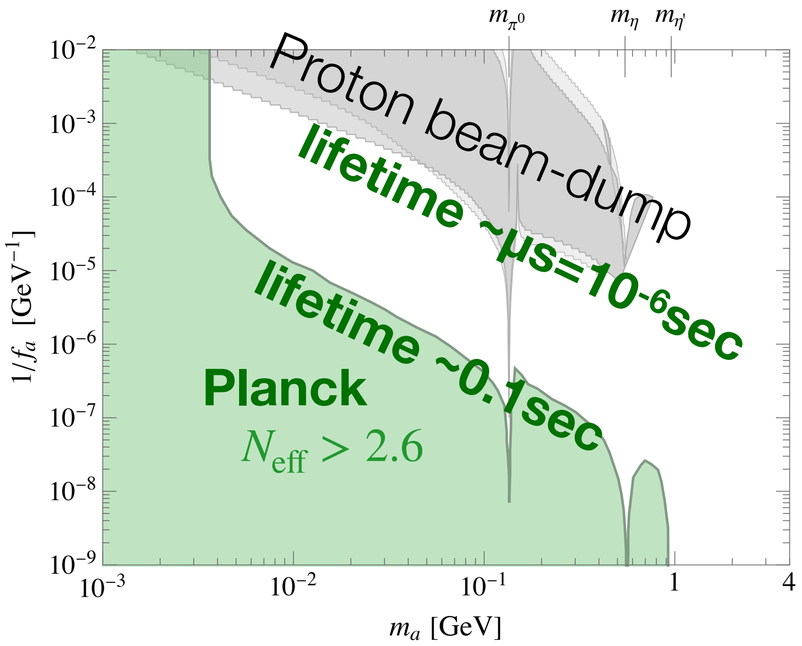
Pushing the lifetime limit with CMB and BBN

Axion to hadron decays: N_{eff}, BBN and ^{4}He

- Neff using CMB bound covers the large mass range. Lifetime >**0.1sec** [Planck]

[2205.11540] D. I. Dunsky, L. J. Hall, **K. Harigaya**

- 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], +Y. Takaesu [1709.01211]

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).

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

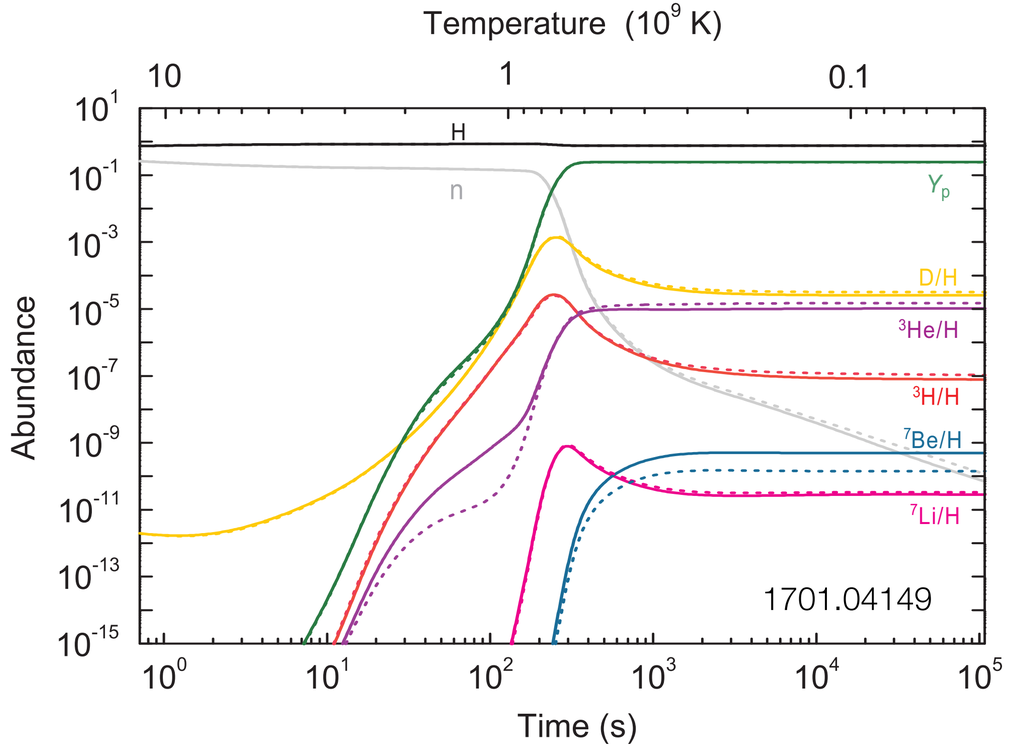
Rate is tiny: $n_{\nu,e}\sigma v \sim T^5 G_F^2$

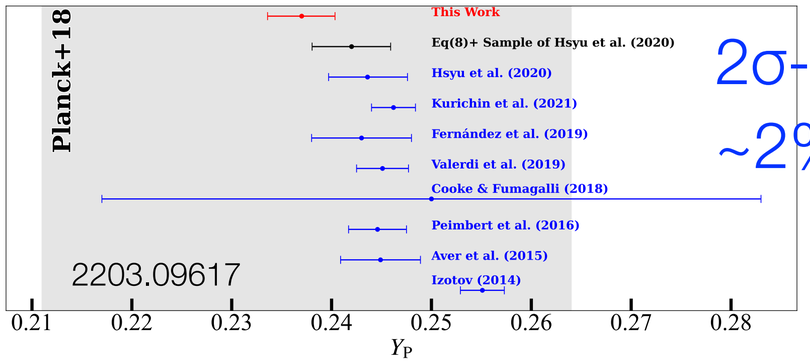
neutron to proton ratio: $n_n/n_p \simeq 1/6$

- Some neutron decays, $n_n/n_p \simeq 1/7$

Neutrons convert to ^{4}He at T~70keV

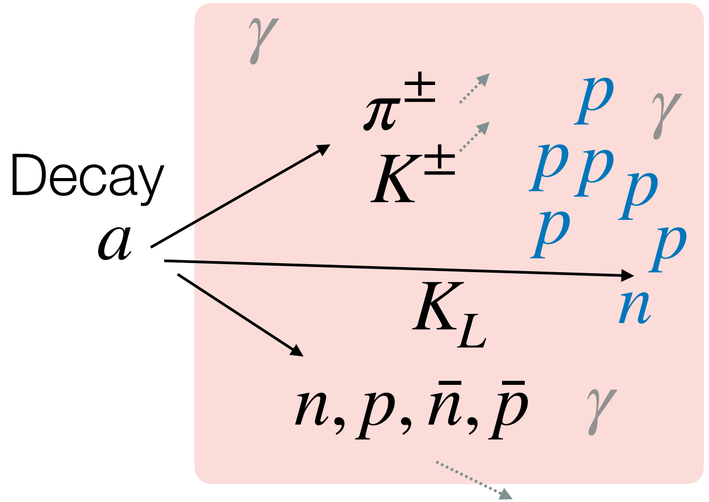
$$Y_P = \frac{\rho_{^4\mathrm{He}}}{\rho_{\mathrm{baryon}}} \simeq \frac{2(n_n/n_p)}{1 + n_n/n_p} \simeq 0.25$$





2σ-band: ~2%

Neutron decoupling with Hadron injection



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

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

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

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

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

Hadrons immediately slow down in the plasma except **K_L**

- Hadrons from axion decays participates in $p \leftrightarrow n$ with high rate ($\sigma \sim f_\pi^{-2} \sim 4$**mb**).

Standard Rate:

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

NP Rate:

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

$$\sim 10^{-12}\text{GeV}(\text{BR}e^{-1\text{s}/\tau_a})$$

14 orders larger!

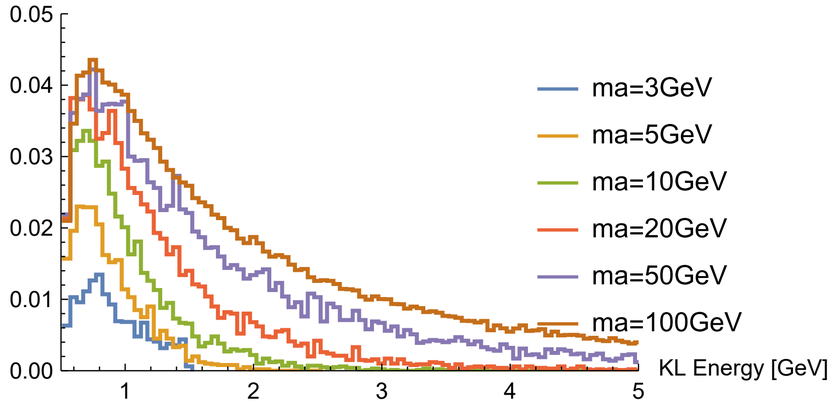
- Probe down to **0.02sec**

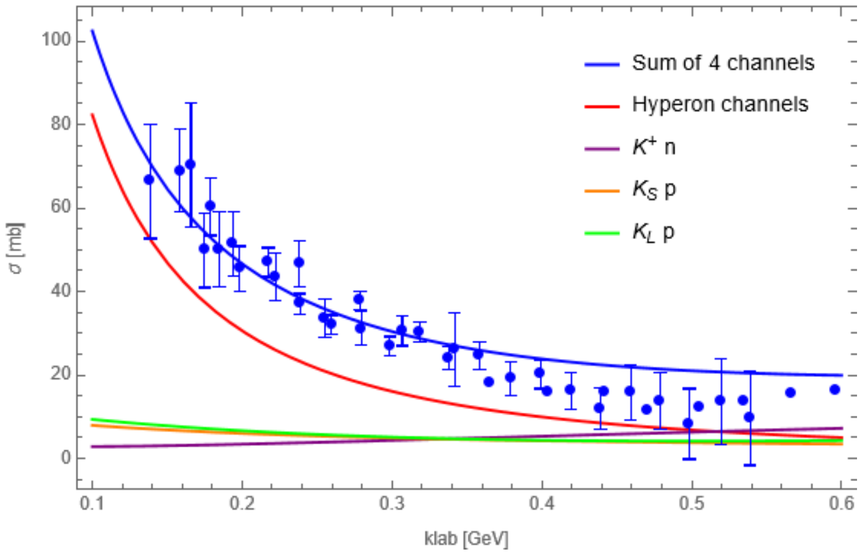
Importance of KL

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

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

- **K_L** was not included or assumed to be thermal.
  Account K_L mom. spectrum from axion decay.

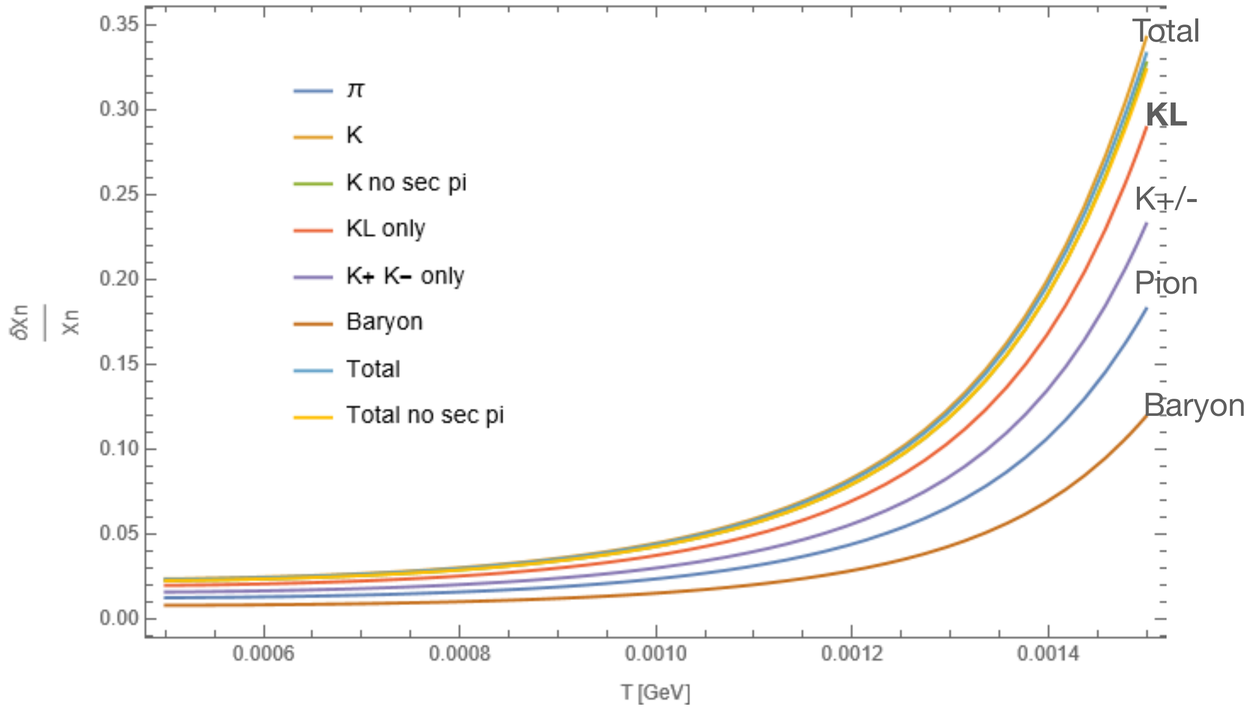


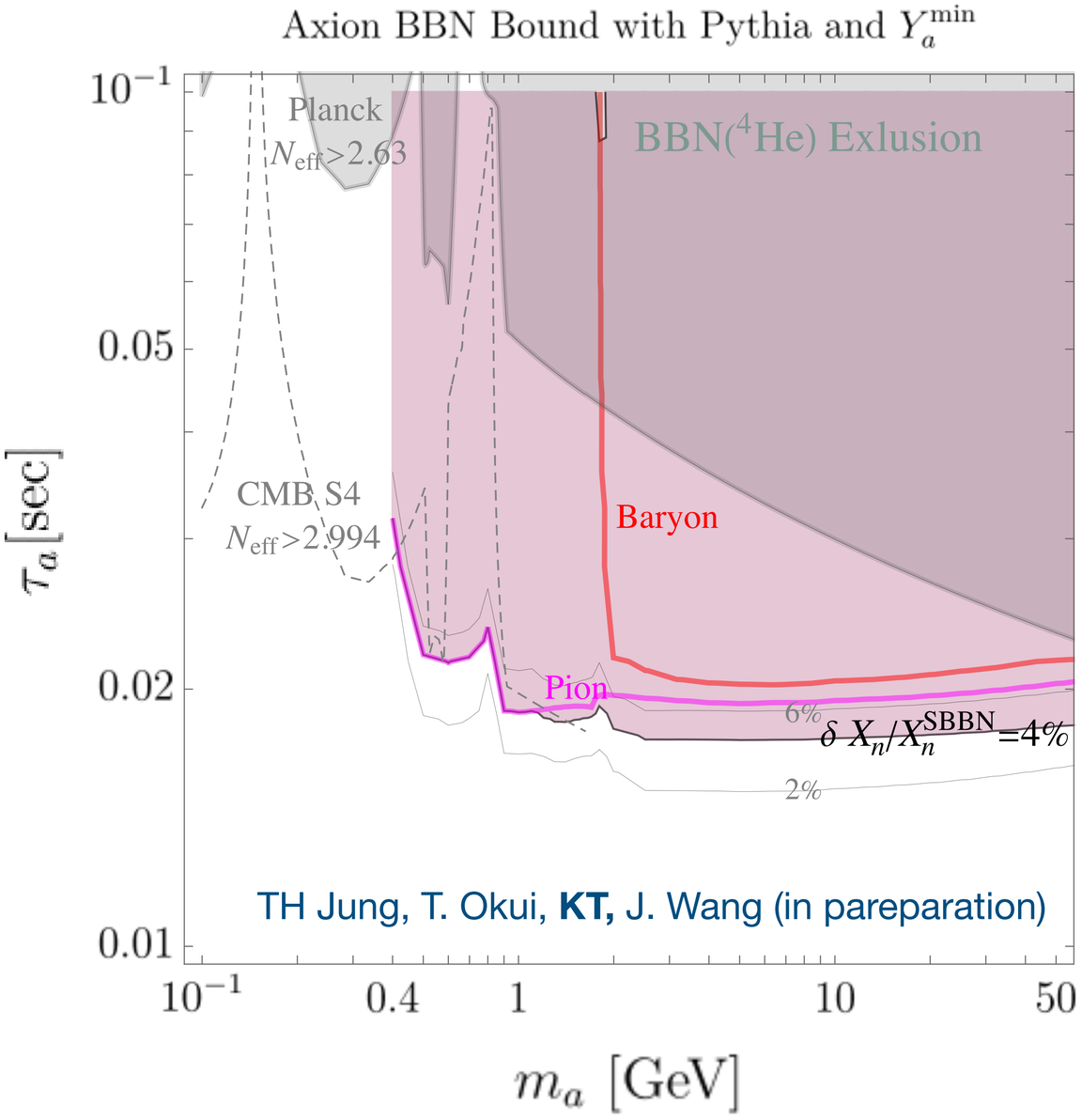


- Known (old) kaon data to obtain the relevant KL n/p scattering cross sections. Validated!

Preliminary Results

- First study for axion hadronic decays.
- Dominant effect is from K_L due to long lifetime, and boost factor.





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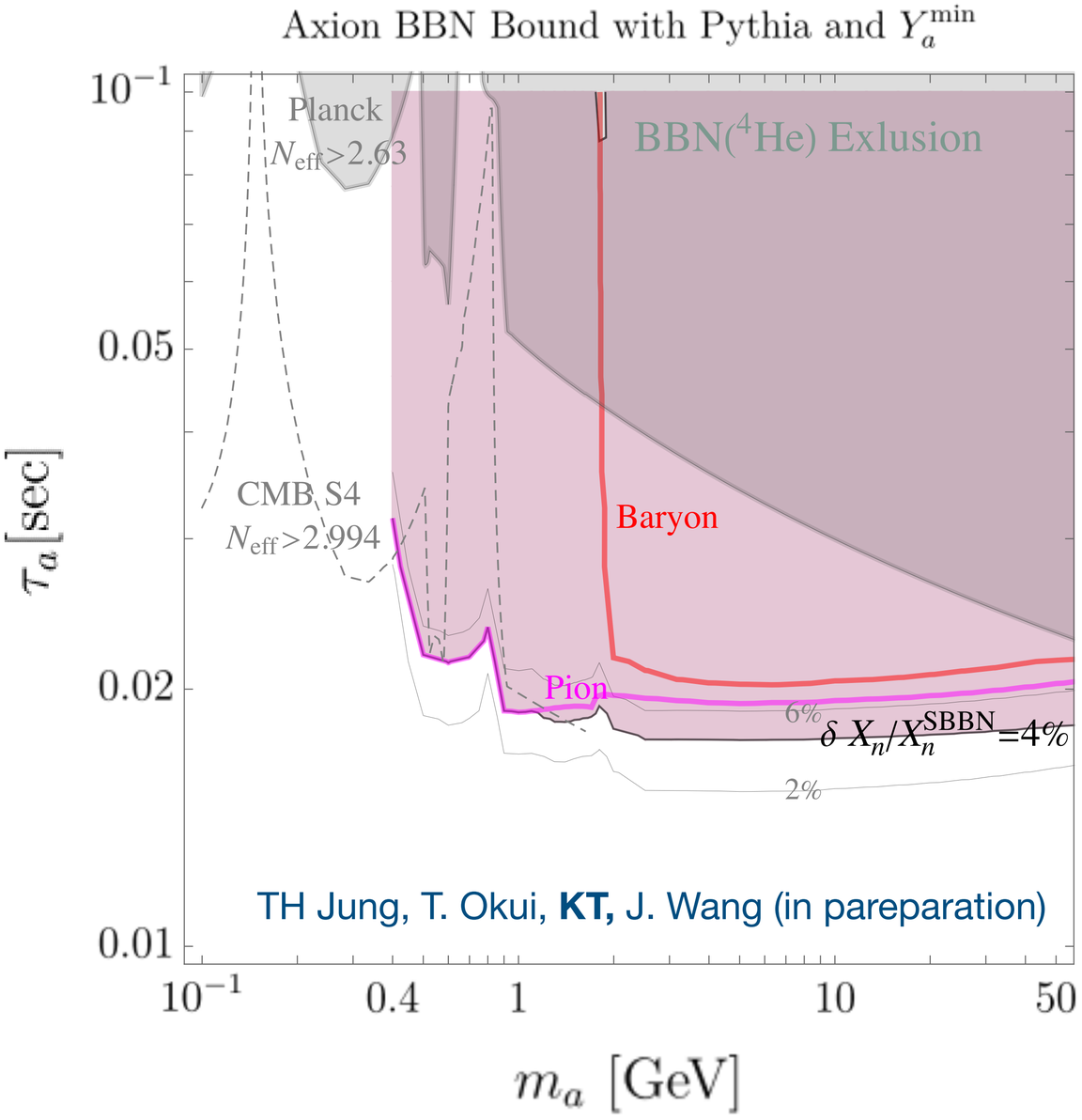
- Better than Neff bound,
  comparable to CMB-S4 projection.

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



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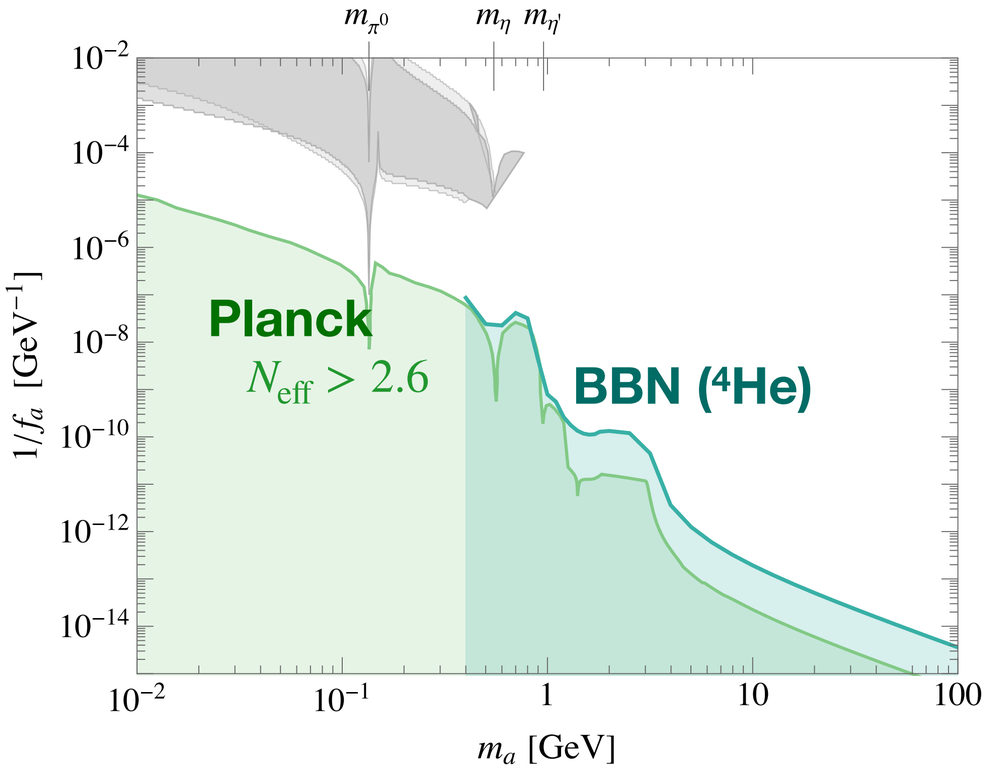
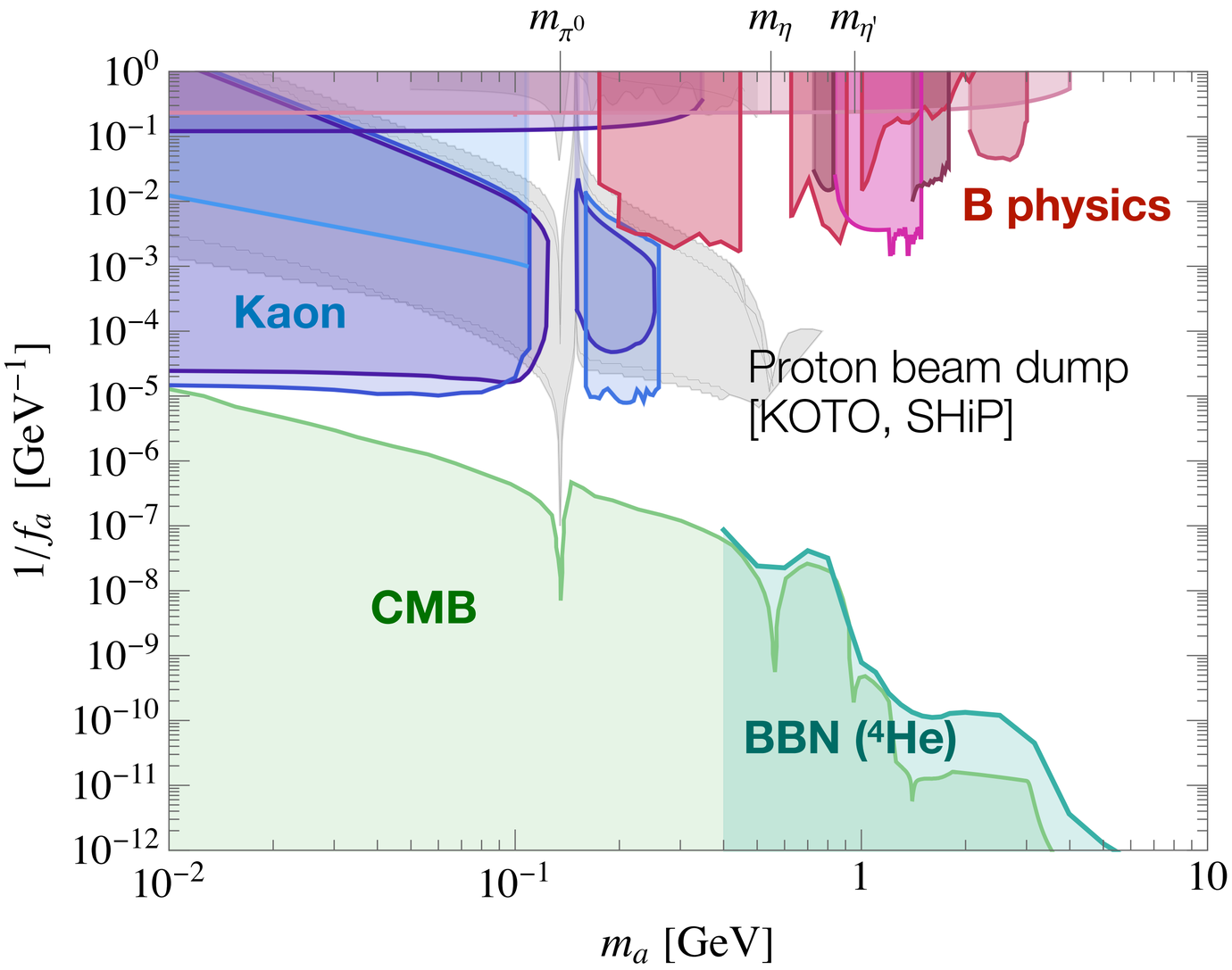


TH Jung, T. Okui, **KT,** J. Wang (in pareparation)

Landscape of heavy axion searches



Hitoshi, Happy 60th Birthday!!

- IPMU started in 2007.
- …
- Stepped down in 2018.
- 2022- Leading P5!
- 2024 Elected DPF Vice chair, to be the DPF chair (2027)

- In **203x, Hitoshi is ??** [Of course something great and unexpected!]

Thank you for your hard work for the community and for mentoring the younger generation!