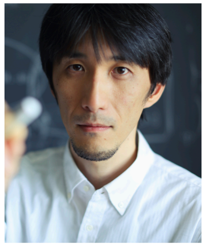
A01: Light Dark Matter

April 24-25. 2025

“What is dark matter? - Comprehensive study of the huge discovery space in dark matter"

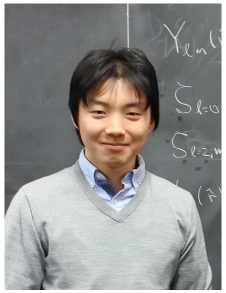
Fuminobu Takahashi (Tohoku)

Members


Fuminobu Takahashi


Naoya Kitajima


Masahiro Kawasaki

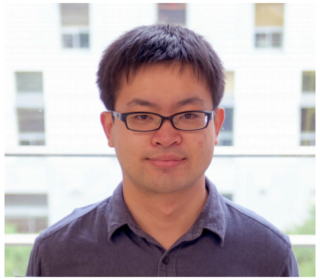

Masaki Yamada


Wen Yin

PI + co-PIs

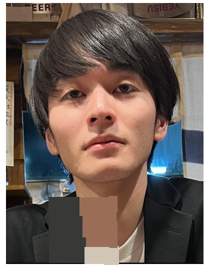

Tatsuya Ogawa

Project assistant professor


Kai Murai


Shota Nakagawa


Junseok Lee


Yuma Narita

PDs + students

- **Promotion**

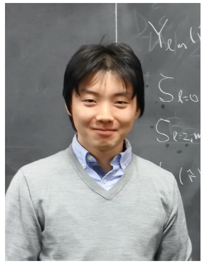
Wen Yin Assistant professor (Tohoku)

→ Associate professor (Tokyo Metropolitan U)

2024 April-

Masaki Yamada Tenure-track assistant professor (Tohoku)

→ Associate professor (Tohoku)



2025 Jan.-

Tatsuya Ogawa Project assistant professor (Tohoku)

→ Lecturer (Tokyo Denki U)

2025 April-

- **6 prizes**

★第12回泉萩会奨励賞 (2020), Wen Yin

★Particle Physics Medal: Young Scientist Award in Theoretical Particle Physics [第17回素粒子メダル奨励賞] (2022), Masaki Yamada

★ The 18th Seitaro Nakamura Prize[第18回中村誠太郎賞](2023), Wen Yin

★ 第15回泉萩会奨励賞 (2023), Masaki Yamada

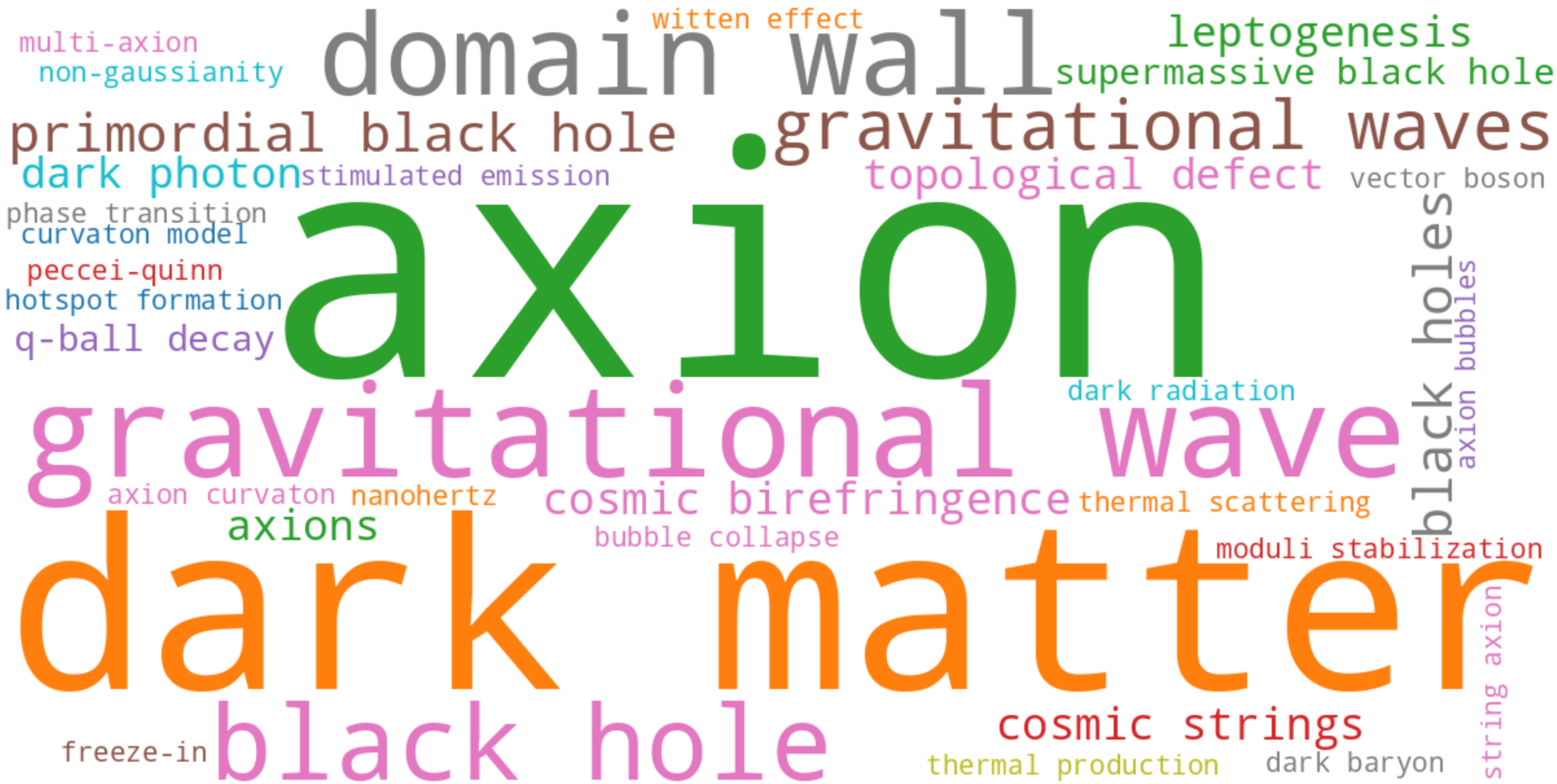
★ Particle Physics Medal: Young Scientist Award in Theoretical Particle Physics [第19回素粒子メダル奨励賞] (2024), Wen Yin

★ Yukawa-Kimura Prize [木村利栄理論物理学賞] (2024) FT

- **4 workshops with A02,B01,B06**

- **Papers**

  ~140 papers since October 2020.



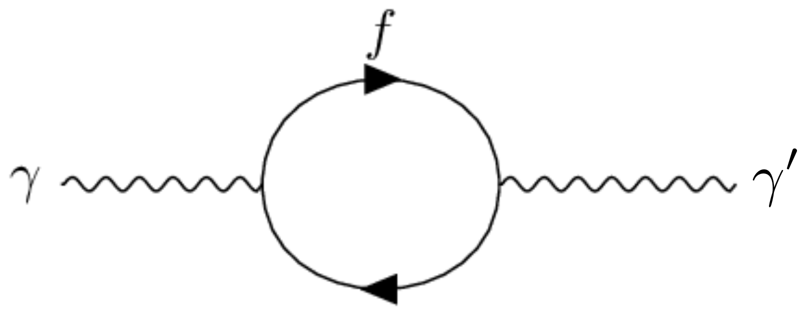
Highlights

- First result for dark matter search by WINERED — See talk by Yin
  Wen Yin, Taiki Bessho, Yuji Ikeda, Hitomi Kobayashi, Daisuke Taniguchi et al. 2402.07976
- Dark photon dark matter production — See talk by Kitajima
  Naoya Kitajima and Kazunori Nakayama 2303.04287, FT, Naoya Kitajima, 2303.05492
- Axion topological defects Junseok Lee, Kai Murai, FT, and Wen Yin 2407.09478 2409.09749 — See talk by Murai
- KiloByte cosmic birefringence FT and Wen Yin 2012.11576
- A general bound on dark photon dark matter
  Naoya Kitajima, Shota Nakagawa, FT and Wen Yin, 2410.17964
- Axion dark matter from FOPT, bubble nucleation, and small PQ breaking
  Shota Nakagawa, FT, Masaki Yamada, and Wen Yin 2210.10022 Junseok Lee, Kai Miurai, FT, and Wen Yin 2402.09501
- Gravitational waves from domain walls
  Naoya Kitajima, Junseok Lee, Kai Murai, FT, and Wen Yin 2306.17146 Naoya Kitajima, Junseok Lee, FT, and Wen Yin 2311.14590
- Thermal production of DFSZ axions, and cosmology of anomaly-free axions
  Kodai Sakurai, FT 2203.17212, 2411.06457
- CMB constraints on DM annihilation Kawasaki Nalatsuka Nakayama Sekiguchi arXiv:2105.08334
  Kawasaki Nalatsuka Nakayama arXiv:2110.12620

Dark Photon Dark Matter (DPDM)

Dark photons interact with ordinary photons via the kinetic mixing,

$$\mathcal{L} = -\frac{1}{4}F'_{\mu\nu}F'^{\mu\nu} + \frac{1}{2}m^2_{\gamma'}A'_{\mu}A'^{\mu} - \frac{\chi}{2}F'_{\mu\nu}F^{\mu\nu}$$



$$\chi \sim \frac{ee_h}{6\pi^2}$$

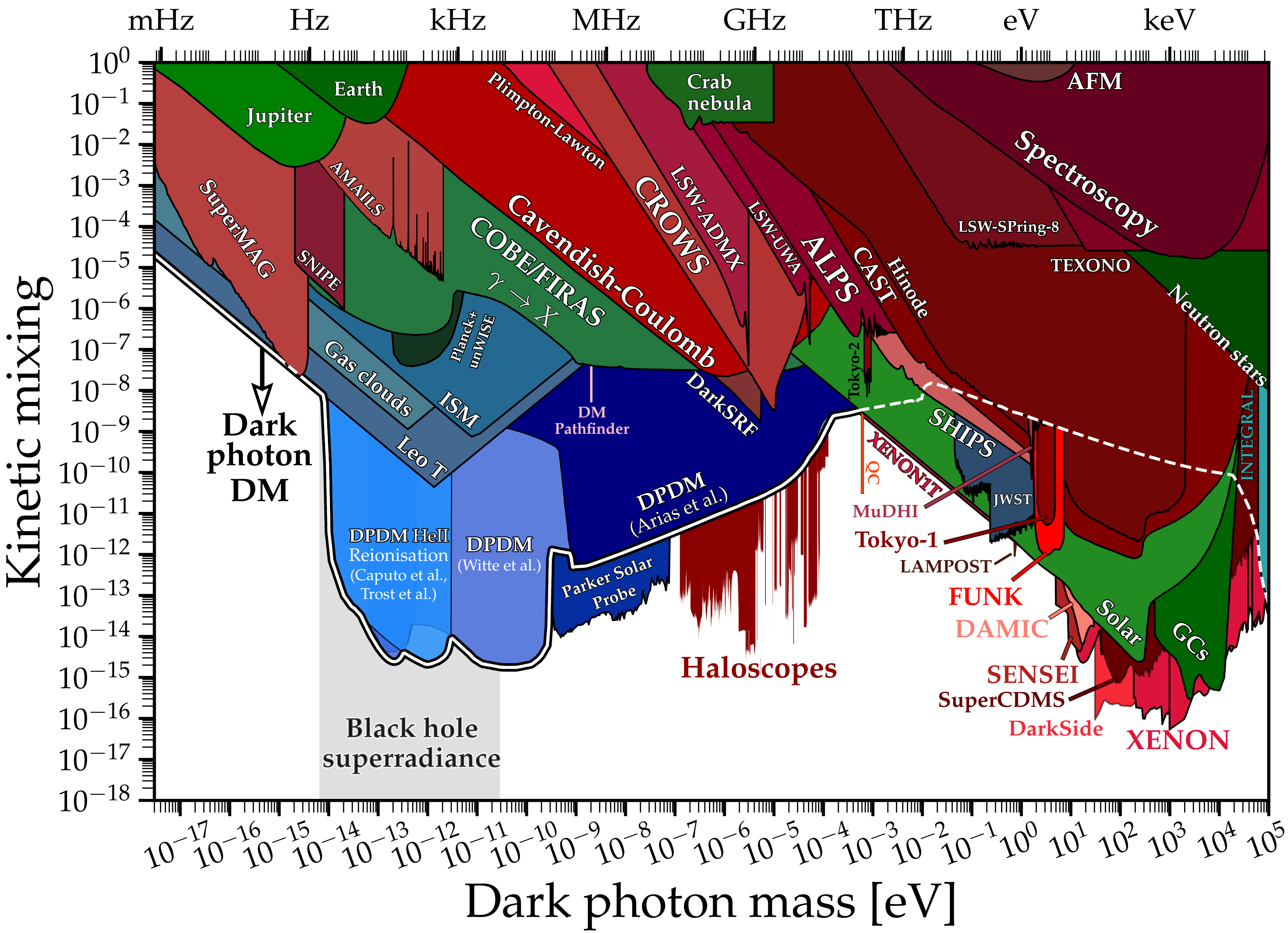
The mass is generated via either the Higgs or Stueckelberg mechanism.

If lighter than twice the electron mass, the dark photon is effectively stable and a good dark matter candidate.

Production of DPDM is non-trivial...

See talk by Naoya Kitajima

- Inflationary fluctuations Graham, Mardon, Rajendran 1504.02102 [Stuekelberg], Sato, FT, Yamada 2204.11896 [Higgs]
- Gravitational production Ema, Nakayama, and Tang 1804.07471, Ahmed, Grzadkowski, and Socha 2005.01766, Kolb and Long 2009.03828
- Tachyonic production from axions
  Agrawal, Kitajima, Reece, Sekiguchi, and FT, 1810.07188, Co et al, 1810.07196, Bastero-Gil et al 1810.07208
  Kitajima and FT, 2303.05492
- Cosmic strings Long and Wang 1901.03312, Kitajima and Nakayama 2212.13573
- Dark Higgs dynamics Dror, Harigaya, Narayan, 1810.07195, Nakayama and Yin 2105.14549
- Coherent oscillations Nelson and Scholtz 1105.2812, Adias et al 1201.5902, Nakayama 1907.06243, 2004.10036,
  Kitajima and Nakayama 2303.04287
- Kinetic coupling Salehian et al, 2010.04491, Firouzjahi et al 2011.06324

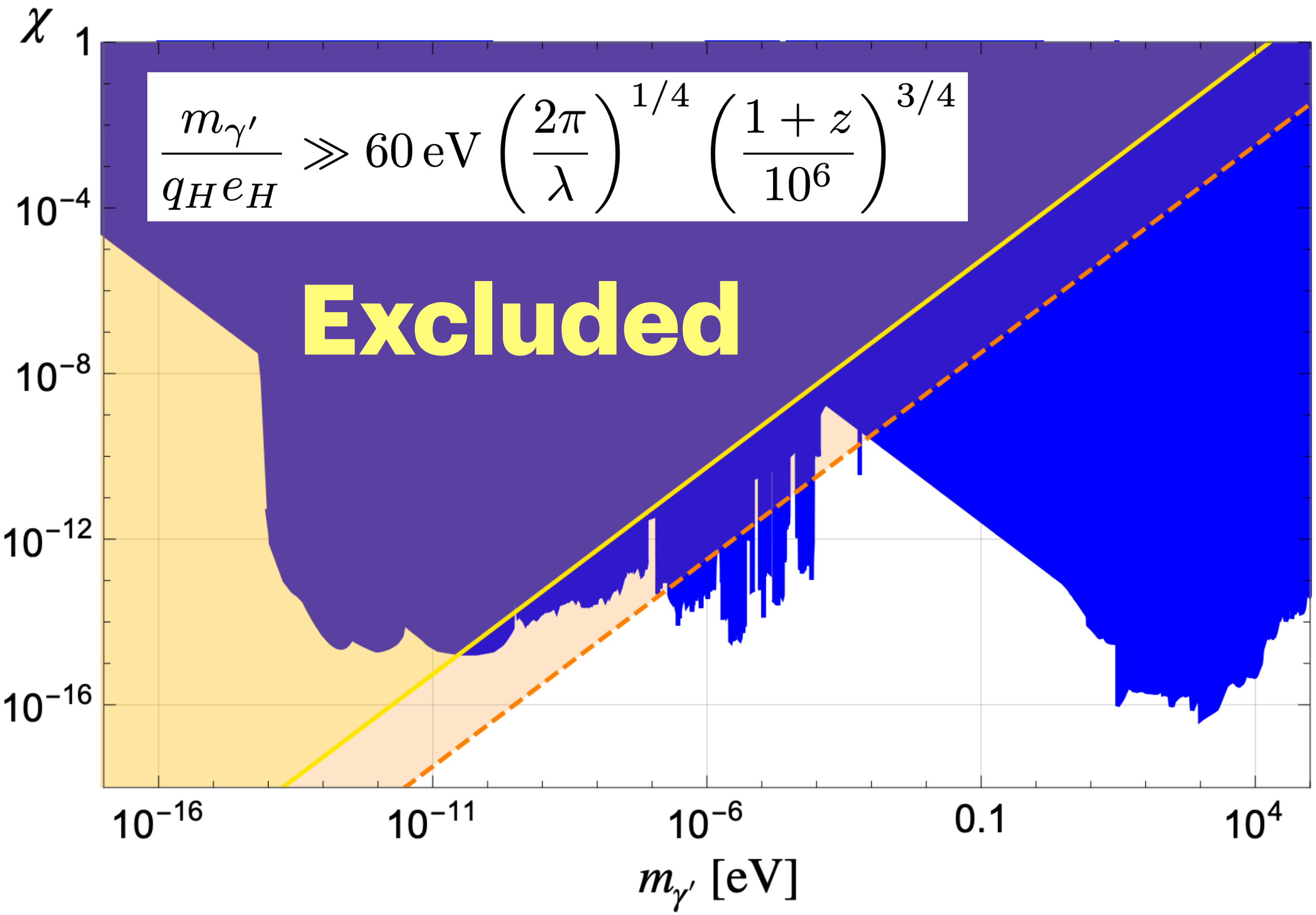


Taken from https://cajohare.github.io/AxionLimits/

A general bound on DPDM with a Higgs mass

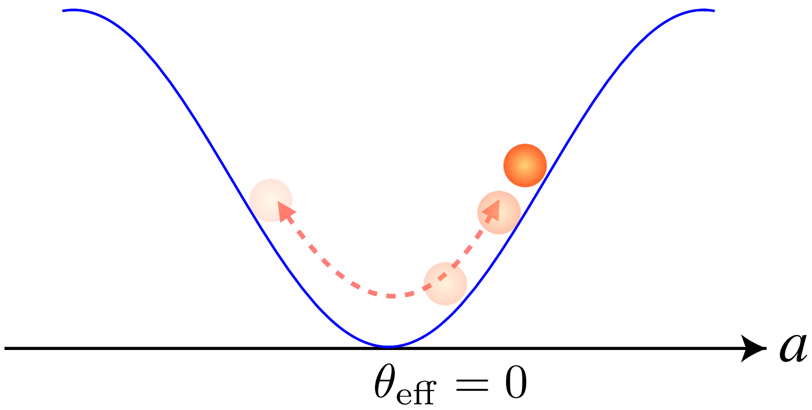
Kitajima, Nakagawa, FT, Yin 2410.17964

$\chi = e e_H / 6\pi^2$



Axion dark matter

Pre-inflationary scenario

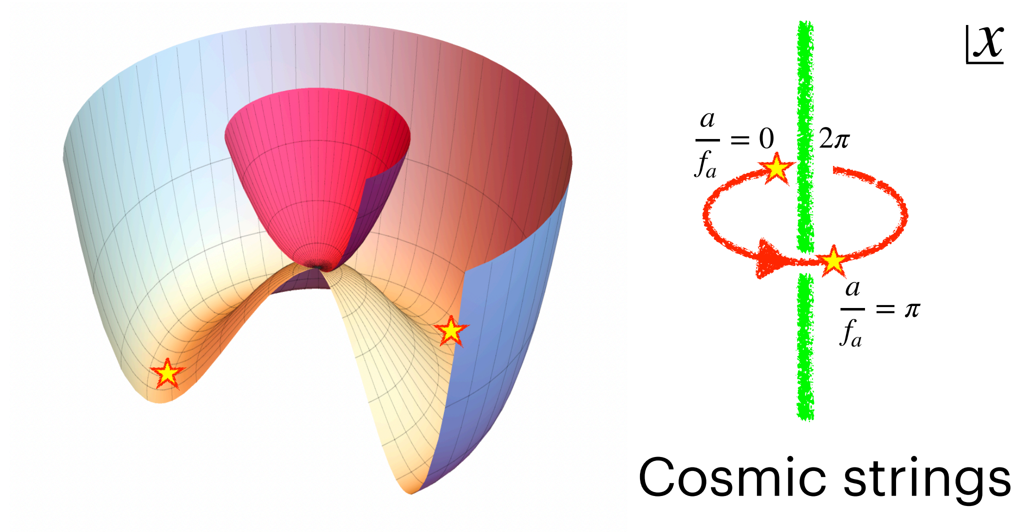


The axion is produced via the misalignment mechanism.

Bubble misalignment, trapped misalignment

Lee, Murai, FT and Yin 2402.09501, Jeong, Matsukawa, Nakagawa and FT 2201.00681
Higaki, Jeong, Kitajima and FT 1603.02090

Post-inflationary scenario



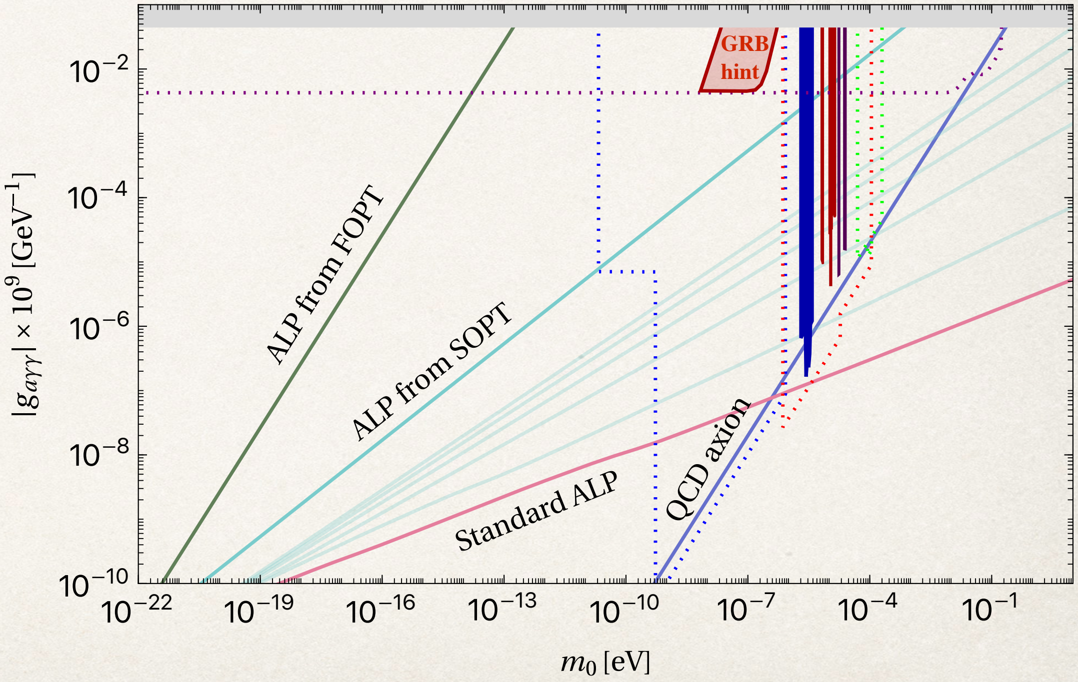
Topological defects like strings and domain walls produce axions

Axion dark matter from first-order phase transition

S. Nakagawa, FT, M.Yamada., Wen Yin, 2210.10022

- Axion-like particles are typically assumed to have a constant potential, possibly originating from non-perturbative effects in the dark sector.

But what if the axion potential emerges suddenly, for example, due to a phase transition in the dark sector?

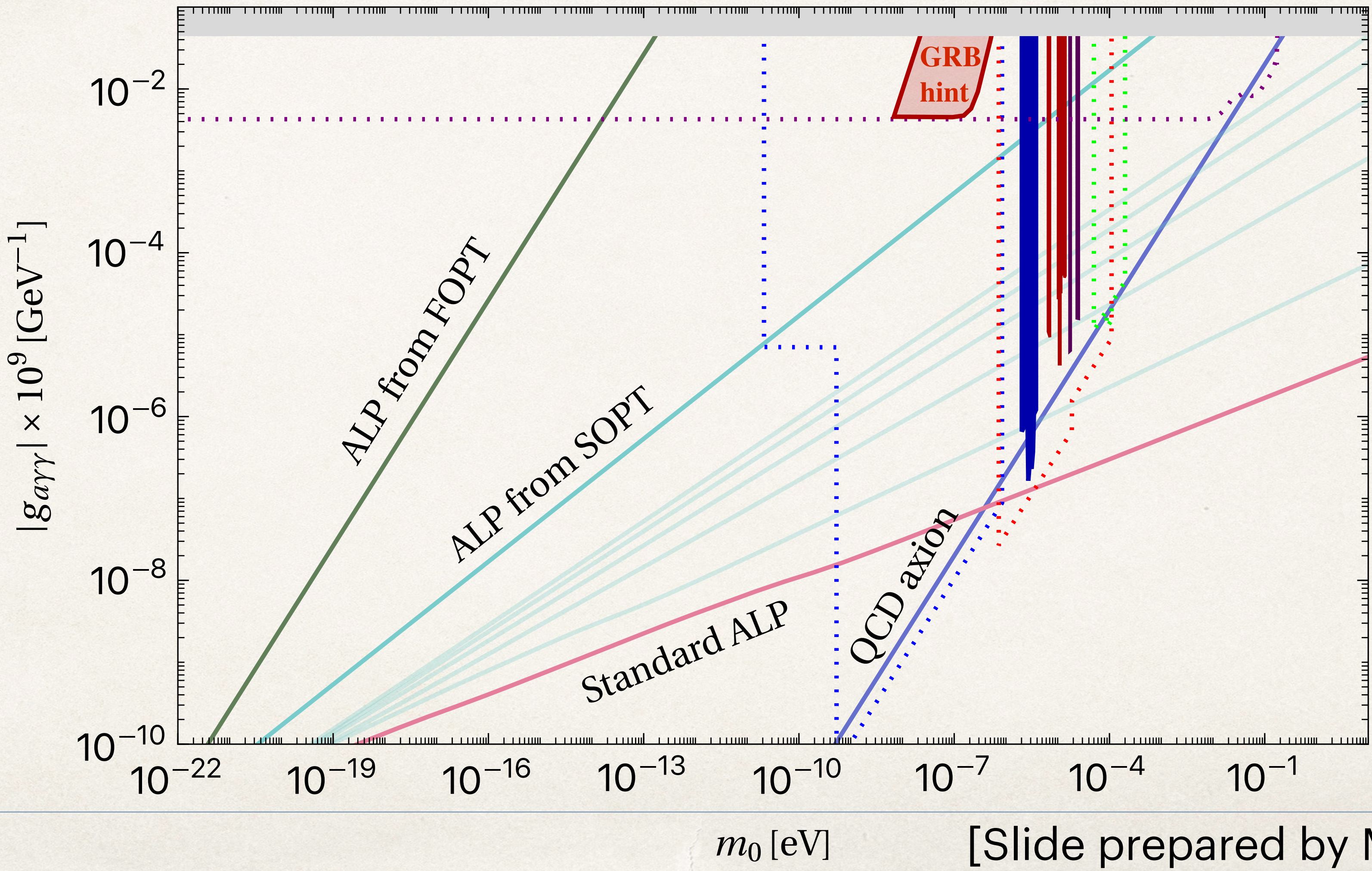


- A relatively light axion-like particle can account for the observed dark matter abundance.
- The viable parameter space includes regions suggested by extremely bright gamma-ray burst observations.

[Slide prepared by M.Yamada]

Axion dark matter from first-order phase transition

S. Nakagawa, FT, M.Yamada., Wen Yin, 2210.10022

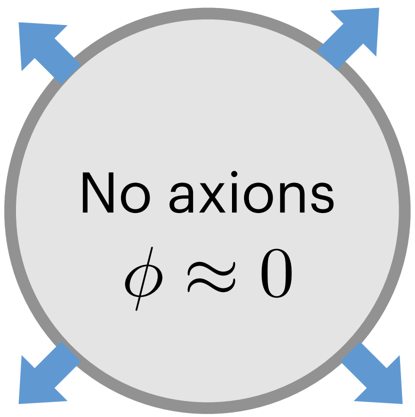


[Slide prepared by M.Yamada]

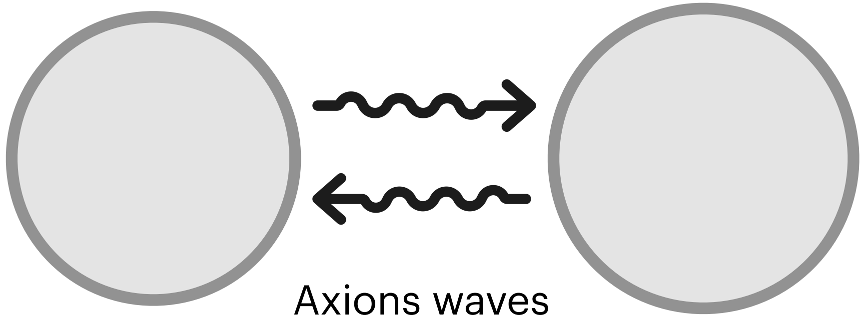
Bubble Misalignment Mechanism

Lee, Murai, FT and Yin 2402.09501

① Axions are expelled from the inside of bubbles.

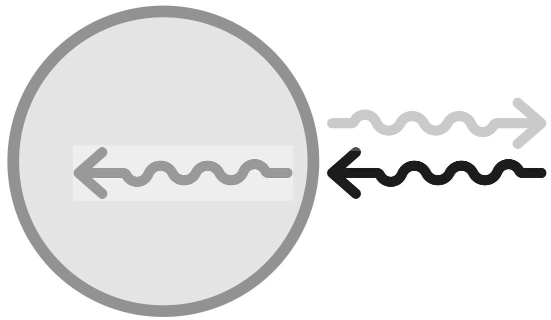


② Axions waves are accumulated outside the bubbles and repeatedly scatter off bubble walls.



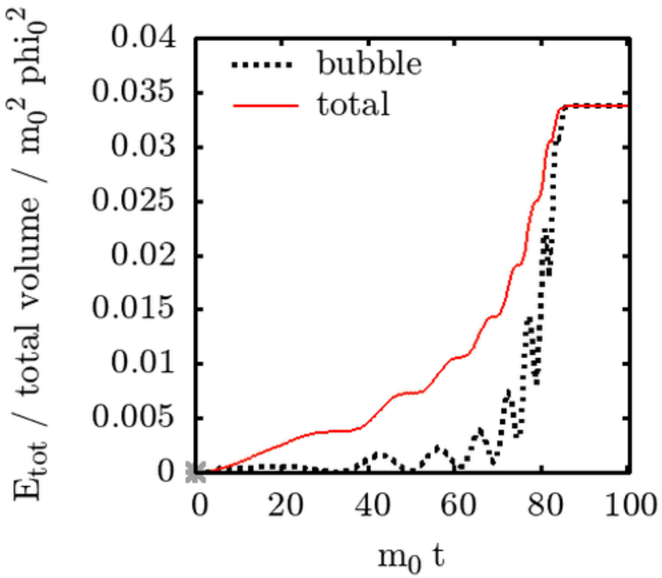
$\sim$ **Fermi acceleration**

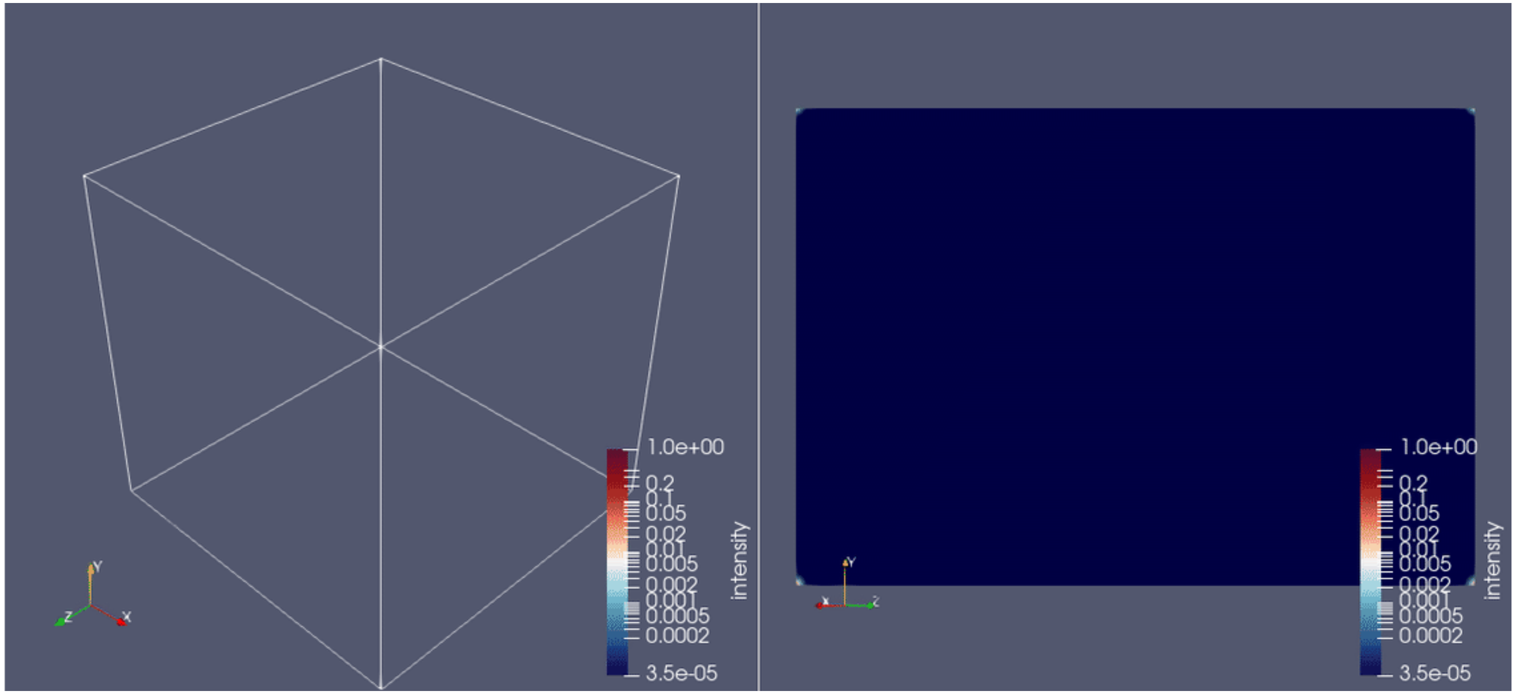
③ Axions waves enter the bubbles if they acquire enough energy.



Bubble Misalignment Mechanism

Lee, Murai, FT and Yin 2402.09501





[GIF prepared by J. Lee]

Isotropic CB from ALP DWs

FT and Yin 2012.11576

The ALP DWs predict

$$\beta \simeq 0.21\, c_\gamma \,\mathrm{deg}$$

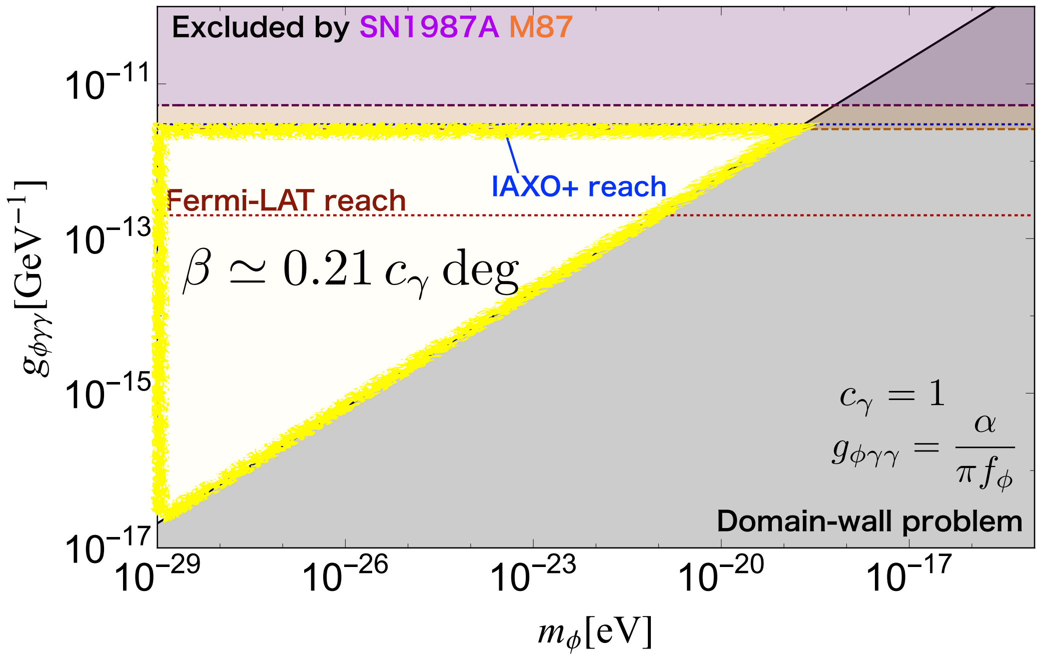
independent of m_ϕ and f_ϕ, explaing

$\beta_{\rm obs} = 0.342^{+0.094}_{-0.091}$ deg for $c_\gamma = O(1)$.

(Recall the rotation angle $\Phi = 0$ or $0.42 c_\gamma$ deg)

Thus, this naturally explains the alpha-beta coincidence,

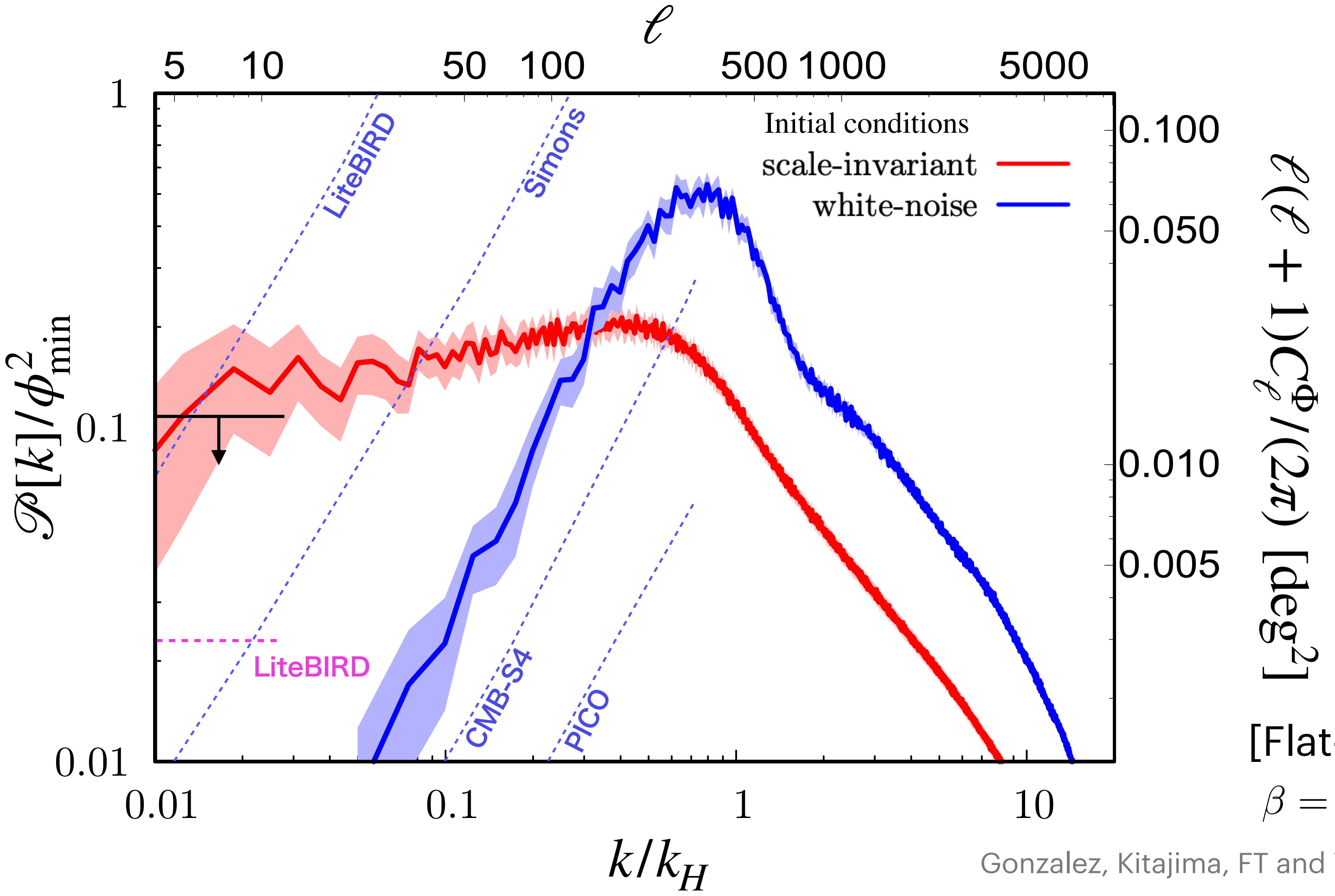
$$\alpha \sim \beta \qquad \alpha = \frac{1}{137}[\mathrm{rad}] = 0.42[\mathrm{deg}]$$

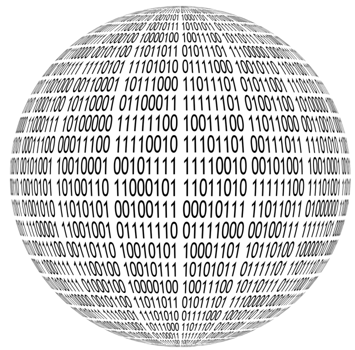


Note that the mass is heavier than $H_{\rm LSS} \sim 3\times 10^{-29}$eV.

Anisotropic CB from ALP DWs

The typical size of the anisotropic CB is of order the isotropic CB.





[Flat-sky approx.]

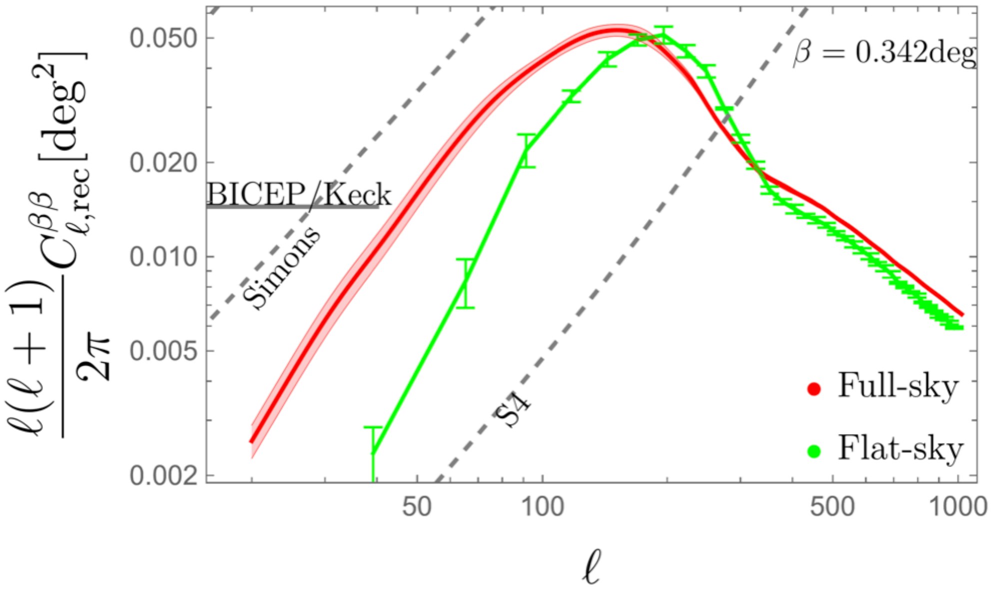
$\beta = 0.36$ deg

Gonzalez, Kitajima, FT and Yin 2211.06849

Anisotropic CB from ALP DWs

White noise

[recombination]



[reionization]

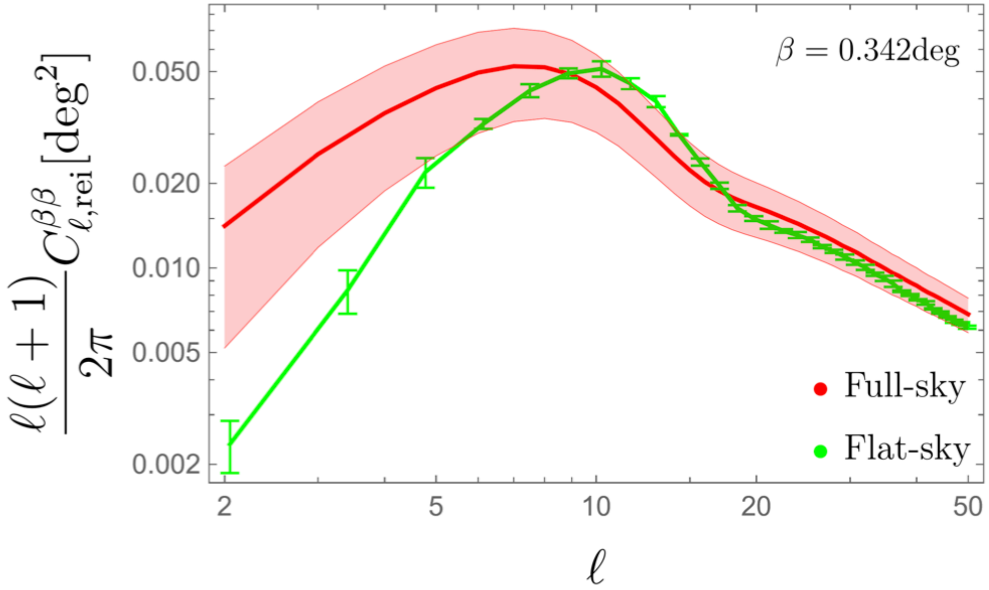
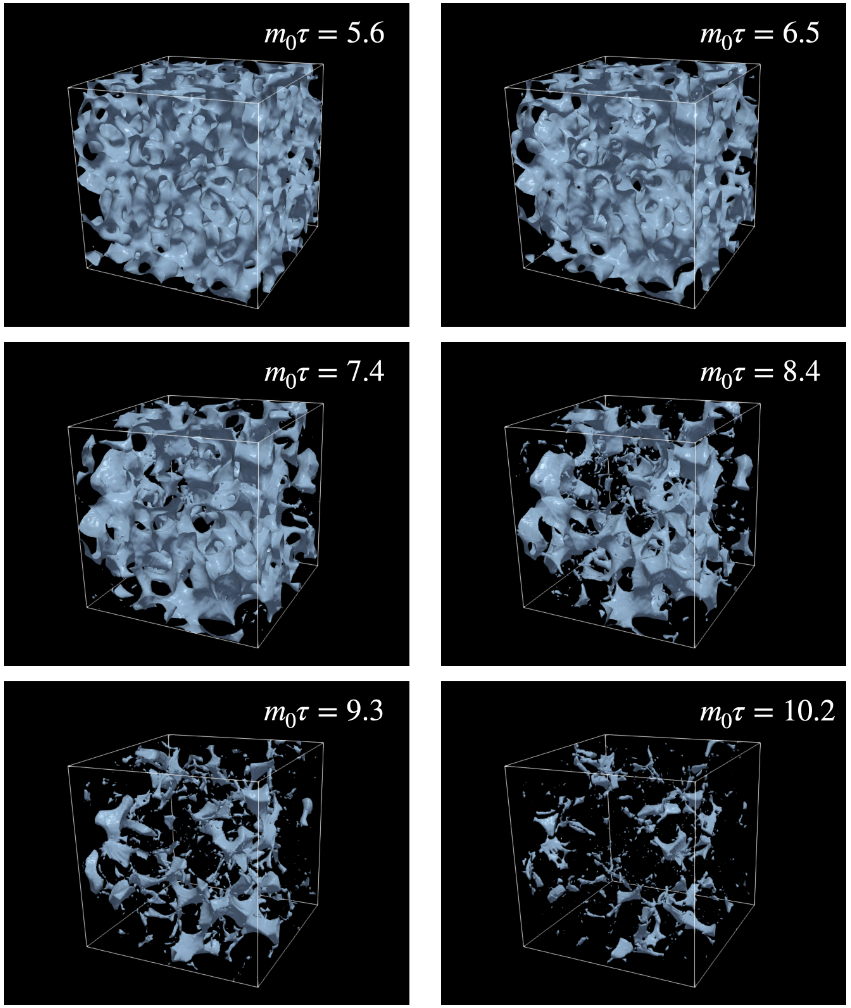


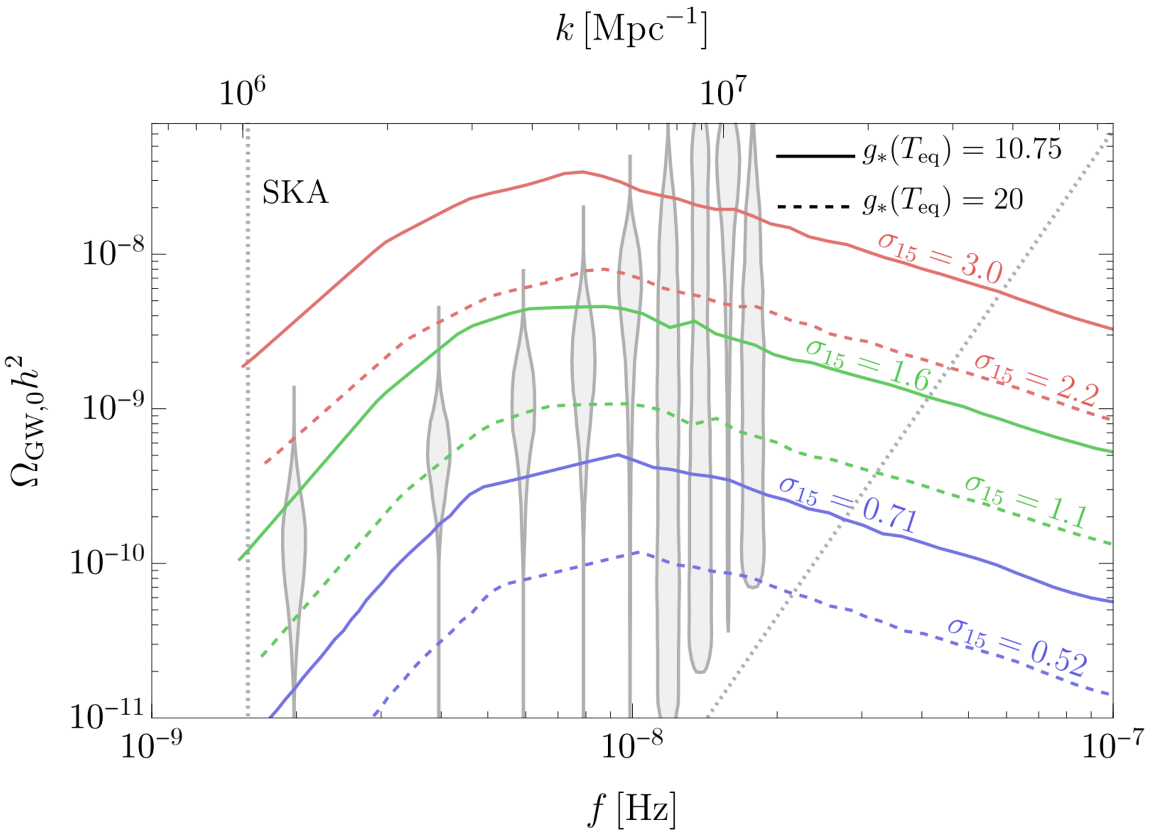
Figure taken from Ferreira, Gasparotto, Hiramatsu, Obata, Pujolas 2312.14104

Gravitational Waves from Domain Wall Annihilation

Lee, Murai, FT, Yin 2306.17146



First GW calculation from biased domain wall collapse, showing enhancement over previous estimates.

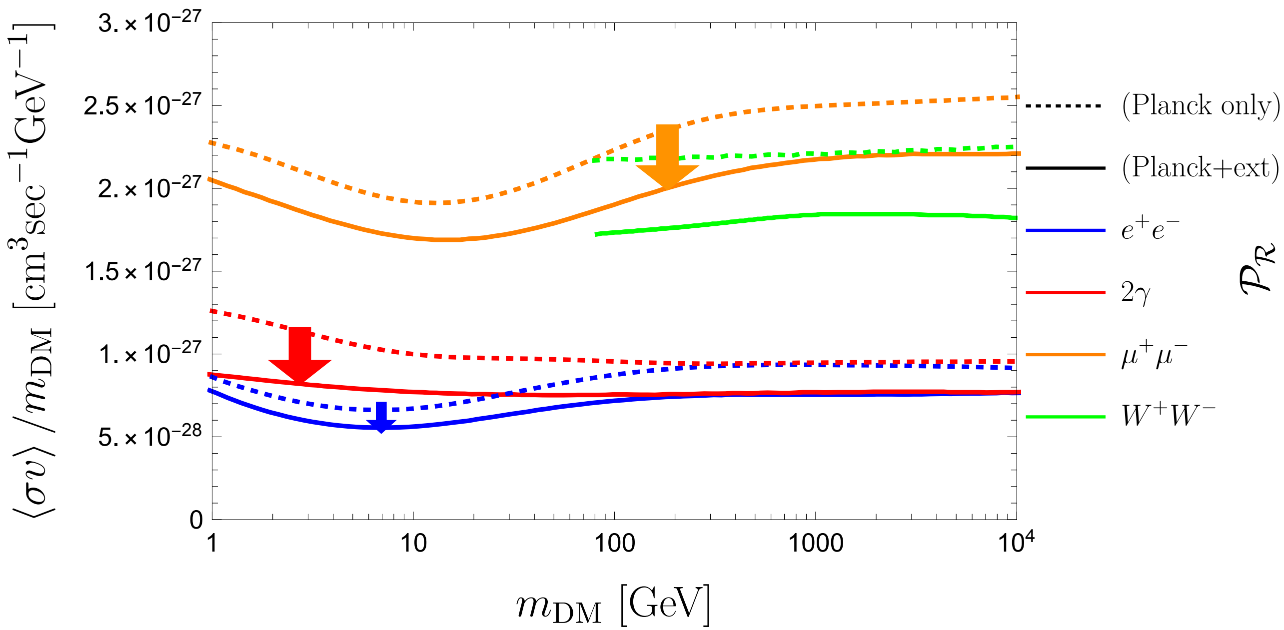


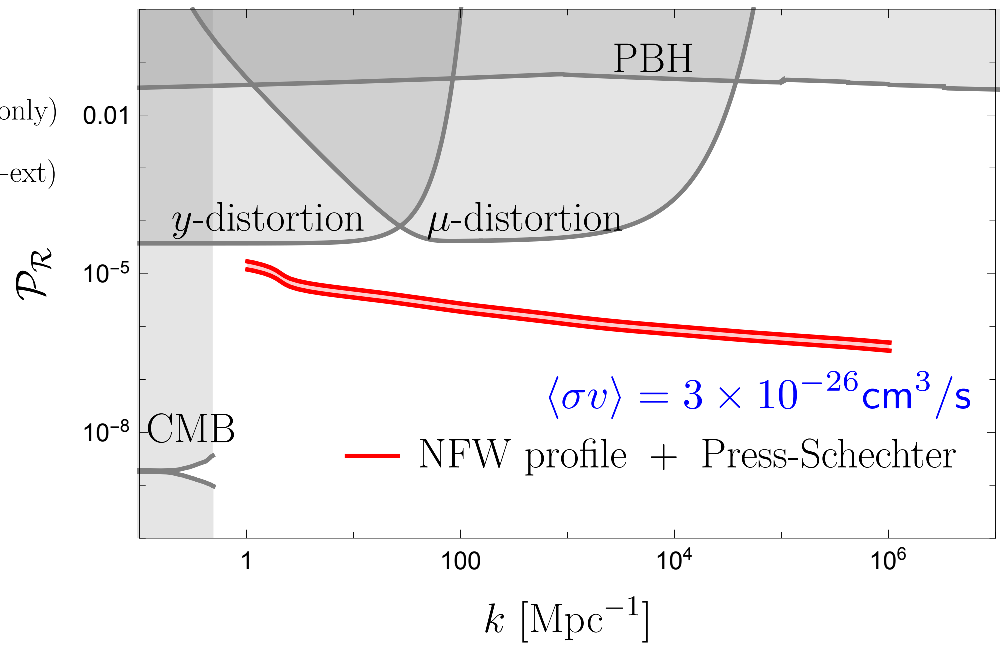
[Slide prepared by M.Kawasaki]

CMB constraints on dark matter annihilation

- We updated simulation code for calculating ionization history with an electromagnetic injection by annihilation of dark matter particles
  Kawasaki Nalatsuka Nakayama Sekiguchi   arXiv:2105.08334
  - Including He interactions and improved precision
  - Constraints on the annihilation cross sections
- Large small-scale density fluctuations → Minihalos at high redshifts
  - Enhanced DM annihilation → Constraint on density fluctuations

Kawasaki Nalatsuka Nakayama   arXiv:2110.12620





Summary

We explored light dark matter candidates such as axions and dark photons, and revealed their cosmological signatures and deriving new constraints from X-rays, gravitational waves, CMB etc, expanding the viable parameter space.