The π-axion and π-axiverse of Dark QCD

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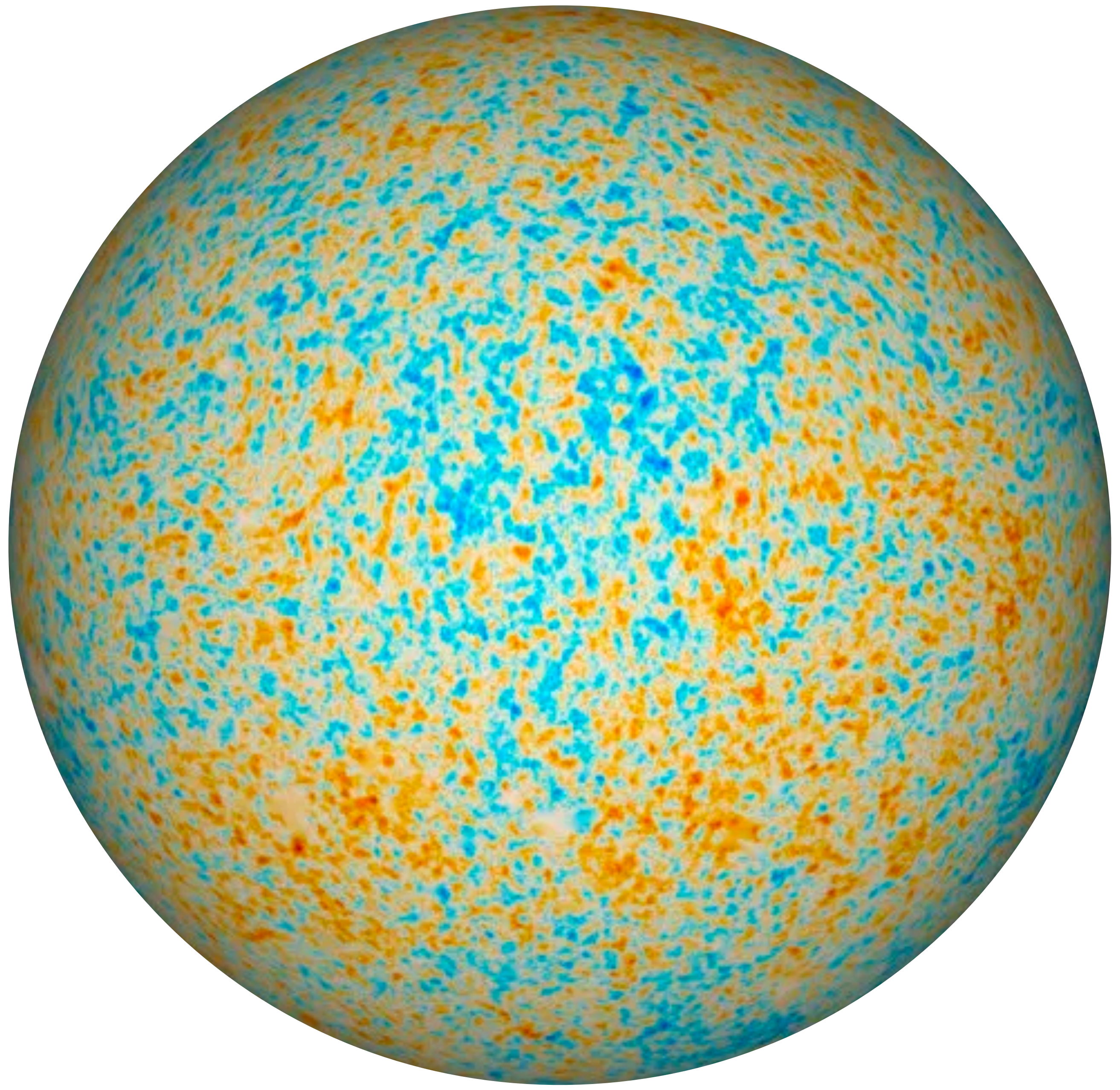
Cosmology from Home 2023

Talk Based on:
Alexander, Gilmer, Manton, EM '23. arXiv:2304.11176
Maleknejad & EM PRD '22

Call for applications:
MSc positions in Theoretical Cosmology



Applications are invited for graduate student positions (MSc) for the 2024-2025 academic year at the University of Manitoba, working in the McDonough Cosmology Group at the nearby University of Winnipeg.

The group uses cutting edge theory to solve problems in cosmology and astrophysics — working on topics ranging from dark matter and dark energy to supergravity and string theory. Students will work in an active and stimulating environment, working closely with collaborators around the world on projects that combine computational and analytical tools at the frontiers of theoretical physics.

Prof. McDonough is an Assistant Professor at the University of Winnipeg, and the Director of the Winnipeg Institute for Theoretical Physics.
As a junior faculty member, McDonough is very invested in the success of students, and works actively and deliberately to support both their professional success and personal happiness. You can find more about Evan, including recordings of research presentations, here: https://www.evanmcdonoughphysics.com/ .

Interested candidates should email a CV and transcript to Evan McDonough at e.mcdonough@uwinnipeg.ca .
The deadline to apply is February 15th.
Applicants are encouraged to reach out at any time.

Outline

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1. Introduction: Axions past present and future

2. The π-axiverse & π-axion DM

3. Experimental Arenas

4. π-axion vs. axions

Introduction

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Axions circa late 1970's

The Strong CP Problem

$$\mathscr{L} = \frac{g^2}{32\pi^2}\theta G\tilde{G} \qquad \theta < 10^{-10}$$

[PQWW, DFSZ, KSVZ]

$$\mathscr{L}(\Phi \equiv \phi e^{ia/f_a}) = \frac{1}{2}|\partial_\mu \Phi|^2 - \lambda(|\Phi|^2 - f_a^2)^2 - \Lambda^4 \cos(\theta + \frac{a}{f_a}) + \frac{a}{f_a}G\tilde{G}$$

Around the same time: Choi, Kim

Composite (dynamical, colored) axion:

Solve strong CP with:
Dark quarks charged under both dark ("axi-") color and SM color
New heavy quarks; other colored particles

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Axion Dark Matter

$$\Phi = \phi e^{ia/f_a}$$

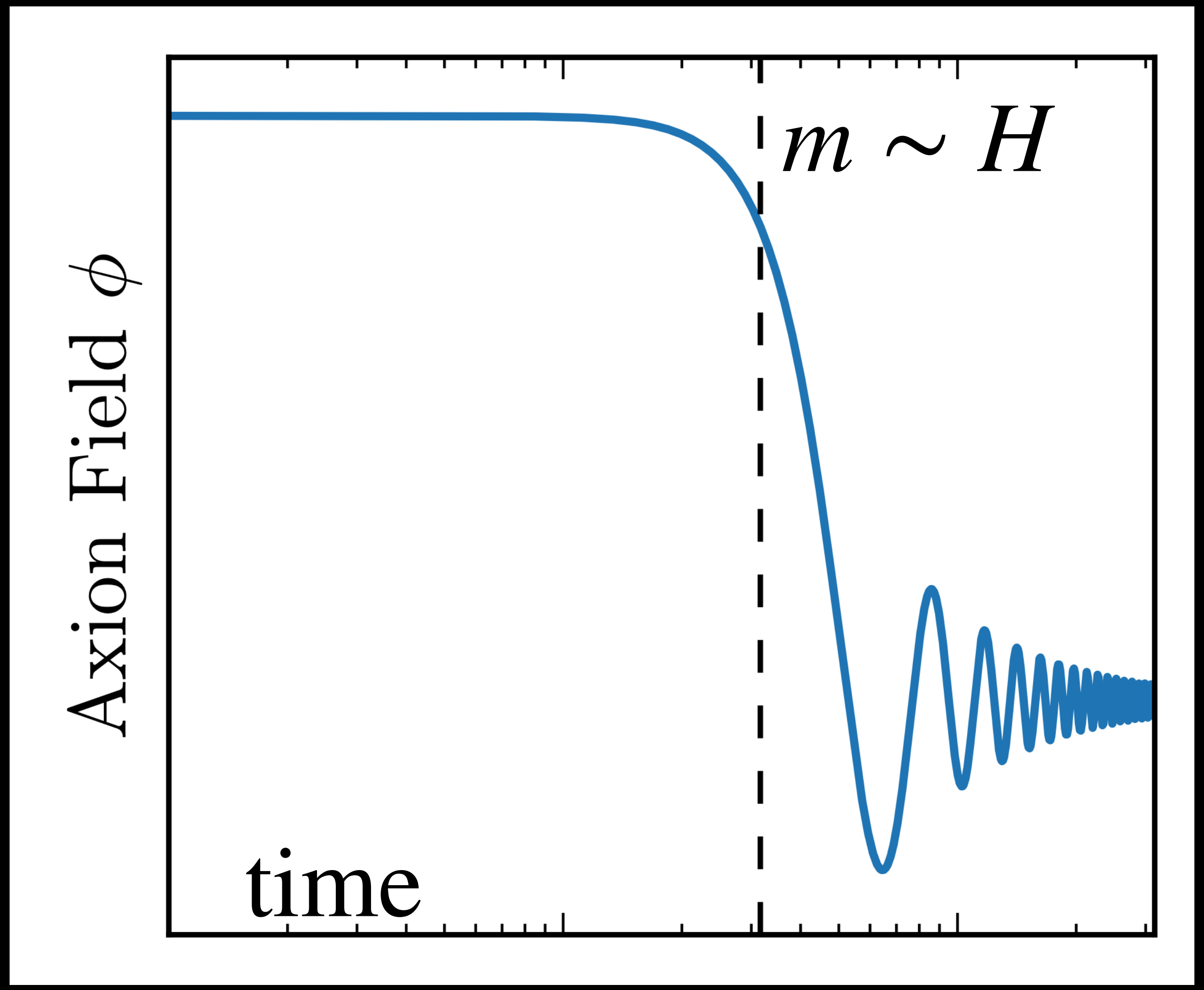
$$\mathscr{L} = |\partial_\mu \Phi|^2 - \lambda(|\Phi|^2 - f^2)^2 - \Lambda^4 \cos(\frac{a}{f_a})$$

ALP: axion-like particle = Goldstone Boson of Spontaneous breaking of global U(1) symmetry

$$\ddot{a} + 3H\dot{a} + m^2 a = 0 \qquad m \ll \mathrm{eV}$$

See e.g. Marsh '15 For a review

$\Omega_{\rm DM}$ set by initial "misalignment" ϕ_i



Lots of neat particle physics:

$$\mathscr{L}_{\rm int} = \frac{a}{f}\epsilon_{\mu\nu\rho\sigma}F^{\mu\nu}F^{\rho\sigma} = \frac{a}{f}E \cdot B$$

Axions (ALPs) from String Theory: The String Axiverse

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Arvanitaki et al ’09
Goodsell, Ringwald ’12

Gauge invariance in 10 dimensions: $B_{\mu\nu} \to B_{\mu\nu} + \partial_{[\mu} f_{\nu]}$

Shift symmetry of scalar in 4 dimensions: $b \to b + c$

Many axions! In type IIB:

Fundamental Axion

$$C_0$$

4-form axions

$$\vartheta = \int_{\Sigma^4} C_4$$

2-form axions

$$c = \int_{\Sigma^2} C_2 \qquad b = \int_{\Sigma^2} B_2$$

Enter the π-axiverse

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Pions: textbook physics — and a lot like axions!

Goldstone Bosons of Chiral Symmetry Breaking: $SU(N_f)_L \times SU(N_f)_R \rightarrow SU(N_f)$

$$\Phi = \phi e^{ia/f_a} \Rightarrow \phi e^{\frac{2i\pi^a(x)\tau_a}{F_\pi}}$$

Pion Potential: $V(\pi) \propto \mathrm{Tr}[M\Phi + M^\dagger \Phi^\dagger] \rightarrow \cos(\frac{\pi}{F_\pi})$ $(M_{ij} = m_\pi \delta_{ij})$

Energy scales: $m_\pi^2 \sim \Lambda m_q \; , \; F_\pi \sim \Lambda$

ALP-DM-like cosmological evolution:

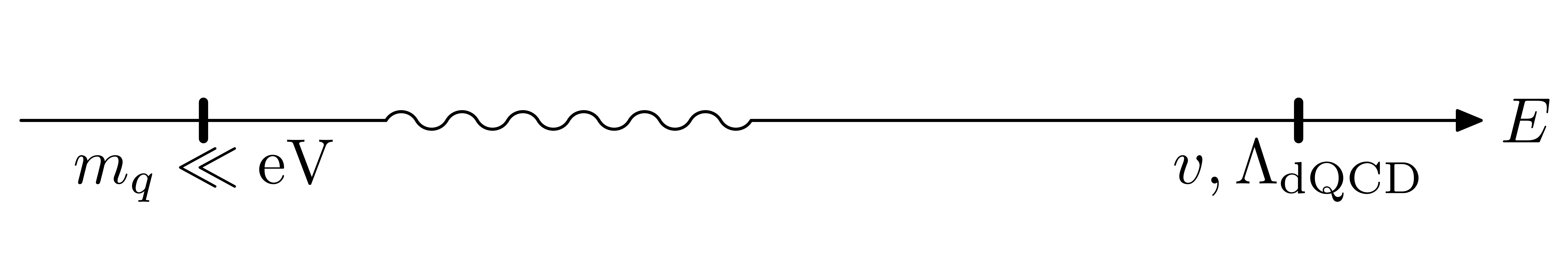
$$m_{\pi_0} < \mathrm{eV} \; , \; F_\pi \gtrsim 10^{10}\mathrm{GeV}$$

“π-axions” $\Rightarrow m_q < 10^{-19}\mathrm{eV} \; , \; \Lambda \gtrsim 10^{10}\mathrm{GeV}$

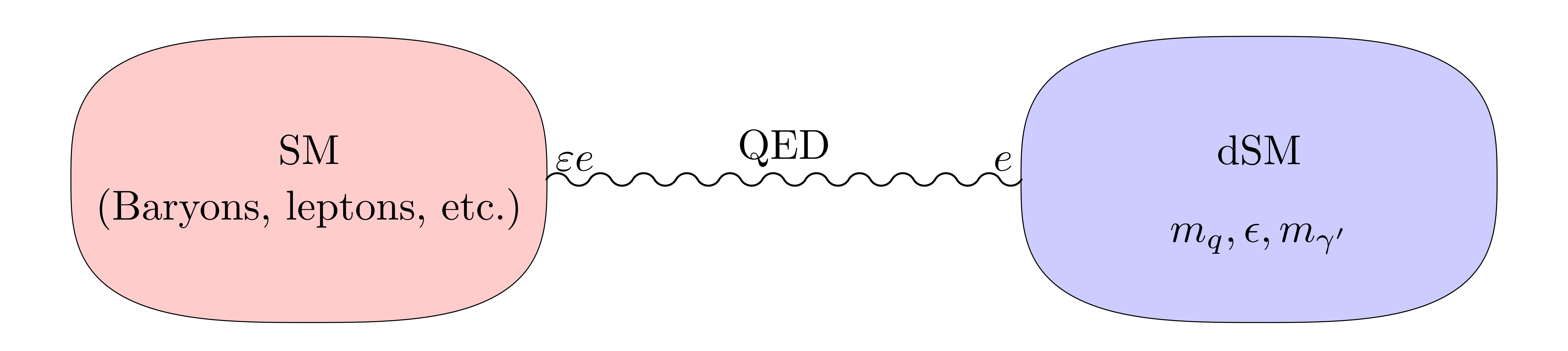
The Dark Standard Model

Key points

1. Two energy scales



2. SM portal: photon kinetic mixing (millicharges)



Dark Pions

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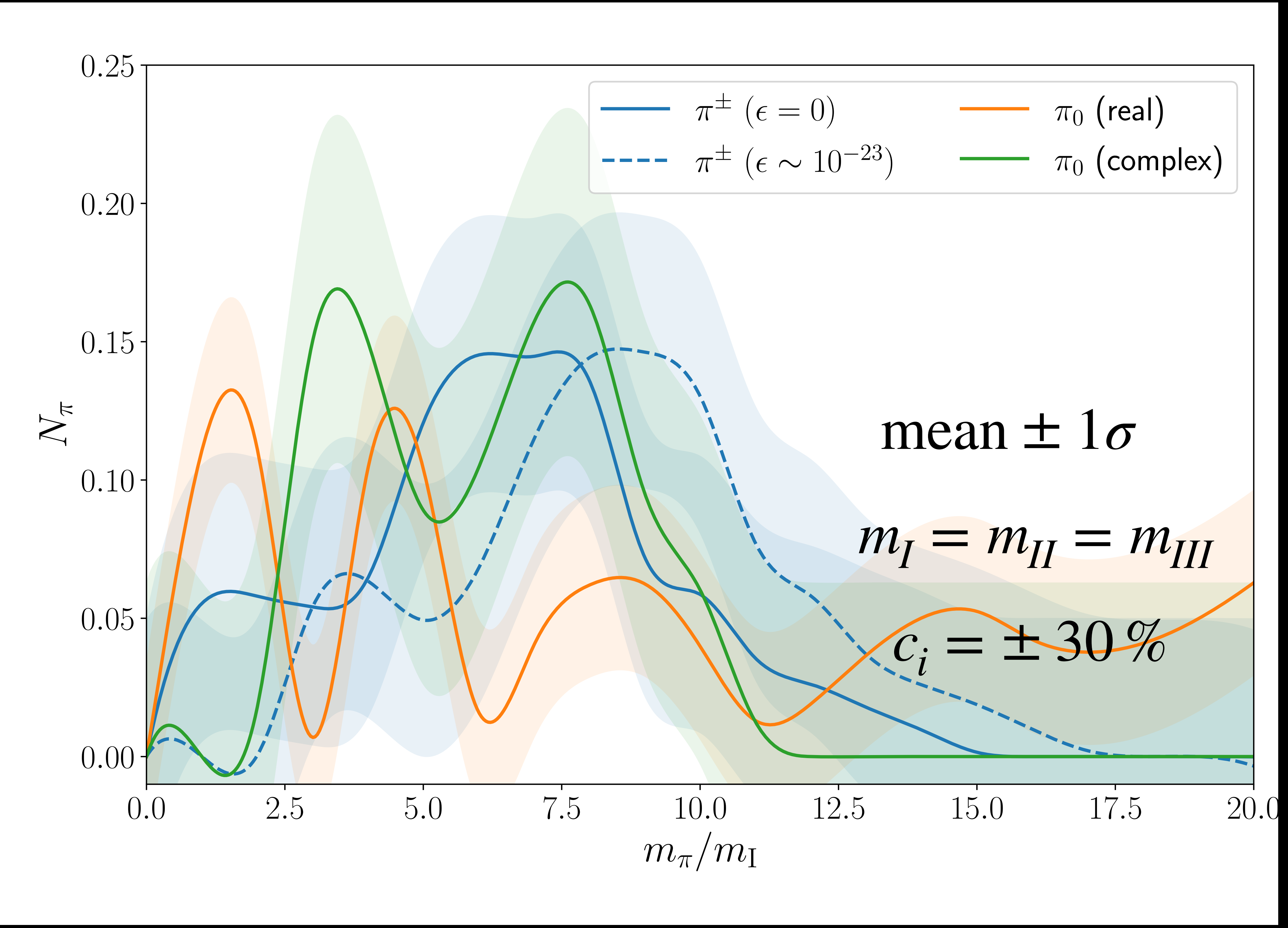
$$m_\pi^2 \simeq \frac{\langle q\bar q\rangle}{F_\pi^2}\sum_i m_{q_i} \quad \Delta m^2_{\pi_i^\pm} \simeq \begin{cases} \alpha'_e F_\pi^2 & , \; m_{\gamma'} < F_\pi \\ \alpha_e \varepsilon^2 F_\pi^2 & , \; m_{\gamma'} > F_\pi, \end{cases}$$

Spectrum of π-axions in Dark QCD

# π-axion	quark content	mass squared $(m^2_{\pi^i})$	charge $[\varepsilon]$
5 Real Neutral:			
π_3	$u\bar u - d\bar d$	$(c_1+c_2)m_{\rm I}F_\pi$	0
π_8	$u\bar u + d\bar d - 2s\bar s$	$((c_1+c_2)m_{\rm I} + c_3 m_{\rm II})\,F_\pi$	0
π_{29}	$c\bar c - b\bar b$	$(c_4 m_{\rm II} + c_5 m_{\rm III})\,F_\pi$	0
π_{34}	$c\bar c + b\bar b - 2t\bar t$	$(c_4 m_{\rm II} + (c_5+c_6)m_{\rm III})\,F_\pi$	0
π_{35}	$-u\bar u - d\bar d - s\bar s + c\bar c + b\bar b + t\bar t$	$((c_1+c_2)m_{\rm I} + (c_3+c_4)m_{\rm II} + (c_5+c_6)m_{\rm III})\,F_\pi$	0
6 Complex Neutral:			
$\pi_6 \pm i\pi_7$	$d\bar s/\bar d s$	$(c_2 m_{\rm I} + c_3 m_{\rm II})\,F_\pi$	0
$\pi_9 \pm i\pi_{10}$	$u\bar c/\bar u c$	$(c_1 m_{\rm I} + c_4 m_{\rm II})\,F_\pi$	0
$\pi_{17} \pm i\pi_{18}$	$d\bar b/\bar d b$	$(c_2 m_{\rm I} + c_5 m_{\rm III})\,F_\pi$	0
$\pi_{19} \pm i\pi_{20}$	$s\bar b/\bar s b$	$(c_3 m_{\rm II} + c_5 m_{\rm III})\,F_\pi$	0
$\pi_{21} \pm i\pi_{22}$	$u\bar t/\bar u t$	$(c_1 m_{\rm I} + c_6 m_{\rm III})\,F_\pi$	0
$\pi_{30} \pm i\pi_{31}$	$c\bar t/\bar c t$	$(c_4 m_{\rm II} + c_6 m_{\rm III})\,F_\pi$	0
9 Charged:			
$\pi_1 \pm i\pi_2$	$u\bar d/\bar u d$	$(c_1+c_2)m_{\rm I}F_\pi + 2\xi_1(e\varepsilon F_\pi)^2$	±1
$\pi_4 \pm i\pi_5$	$u\bar s/\bar u s$	$(c_1 m_{\rm I} + c_3 m_{\rm II})F_\pi + 2\xi_2(e\varepsilon F_\pi)^2$	±1
$\pi_{15} \pm i\pi_{16}$	$u\bar b/\bar u b$	$(c_1 m_{\rm I} + c_5 m_{\rm III})F_\pi + 2\xi_3(e\varepsilon F_\pi)^2$	±1
$\pi_{11} \pm i\pi_{12}$	$d\bar c/\bar d c$	$(c_2 m_{\rm I} + c_4 m_{\rm III})F_\pi + 2\xi_4(e\varepsilon F_\pi)^2$	∓1
$\pi_{23} \pm i\pi_{24}$	$d\bar t/\bar d t$	$(c_2 m_{\rm I} + c_6 m_{\rm III})F_\pi + 2\xi_5(e\varepsilon F_\pi)^2$	∓1
$\pi_{13} \pm i\pi_{14}$	$s\bar c/\bar s c$	$(c_3+c_4)m_{\rm II}F_\pi + 2\xi_6(e\varepsilon F_\pi)^2$	∓1
$\pi_{25} \pm i\pi_{26}$	$s\bar t/\bar s t$	$(c_3 m_{\rm II} + c_6 m_{\rm III})F_\pi + 2\xi_7(e\varepsilon F_\pi)$	∓1
$\pi_{27} \pm i\pi_{28}$	$c\bar b/\bar c b$	$(c_4 m_{\rm II} + c_5 m_{\rm III})F_\pi + 2\xi_8(e\varepsilon F_\pi)^2$	±1
$\pi_{32} \pm i\pi_{33}$	$b\bar t/\bar b t$	$(c_5+c_6)m_{\rm III}F_\pi + 2\xi_9(e\varepsilon F_\pi)^2$	∓1

Statistical Distribution of masses



Quark masses: $c_1 m_I$, $c_2 m_I$ $c_3 m_{II}$, $c_4 m_{II}$ $c_5 m_{III}$, $c_6 m_{III}$

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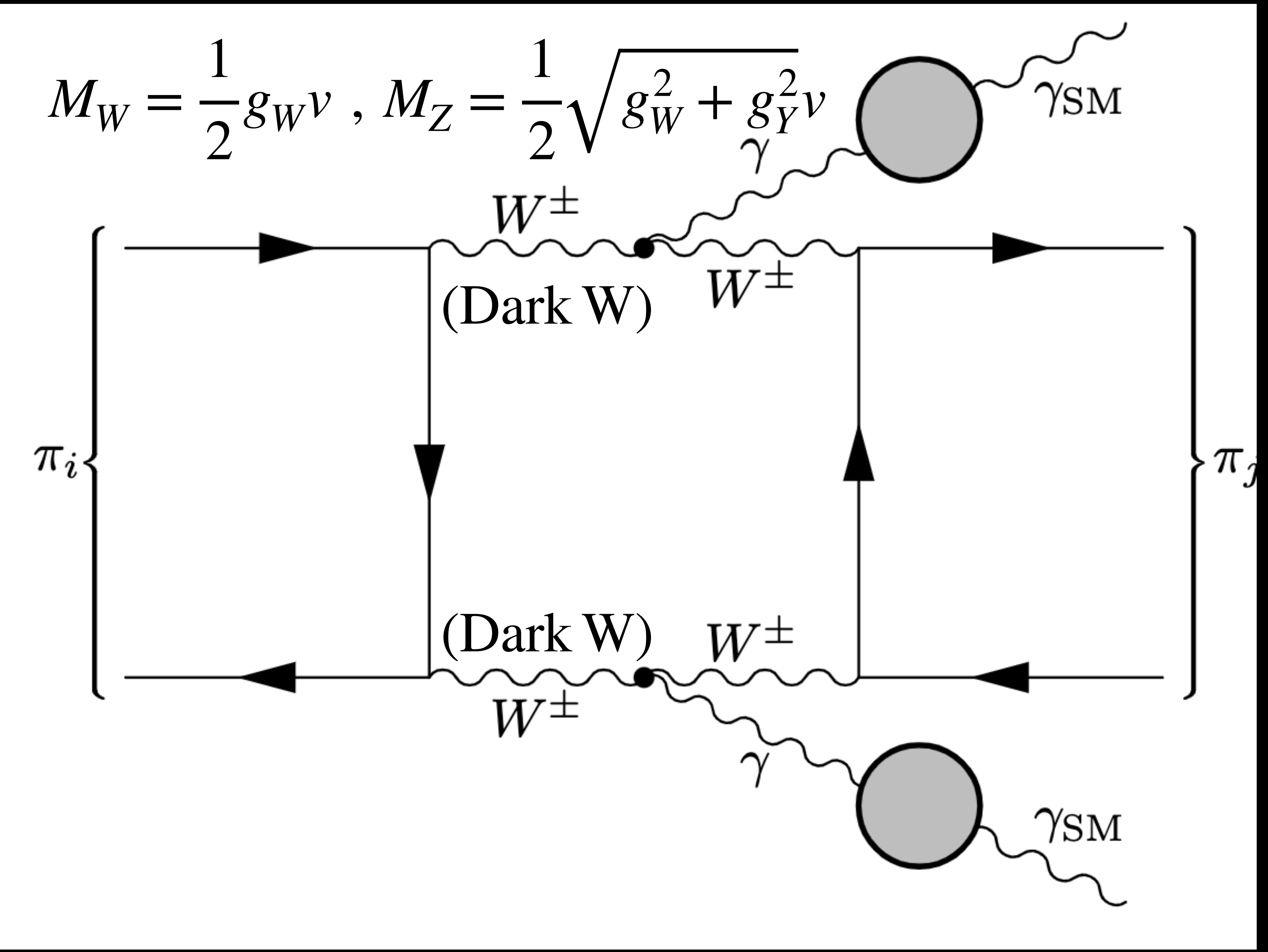
Photon Portal to the SM:

$\varepsilon F_{\mu\nu}\tilde{F}^{\mu\nu} \Rightarrow \text{millicharges},$ π-axion—photon couplings

1. Neutral scalar pion: $\mathscr{L} = \lambda_1 \frac{\varepsilon^2}{F_\pi}\pi^0 F\tilde{F}$
2. Charged pion: $\mathscr{L} \sim \varepsilon^2 \pi^+\pi^- A_\mu A^\mu$
3. Flavor violating:

$$\mathscr{L} = \lambda \frac{\varepsilon^2}{M^2}\pi_i \pi_j^* F_{\mu\nu}F^{\mu\nu} + h.c.$$



π-axion Lifetime:

$$\tau_{\pi^0} \sim H_0^{-1}\left(\frac{F_\pi}{\text{TeV}}\right)^2\left(\frac{0.3\text{eV}}{m_{\pi^0}}\right)^3\frac{1}{\varepsilon^4}$$

The WIMPZilla Connection: Dark Baryons

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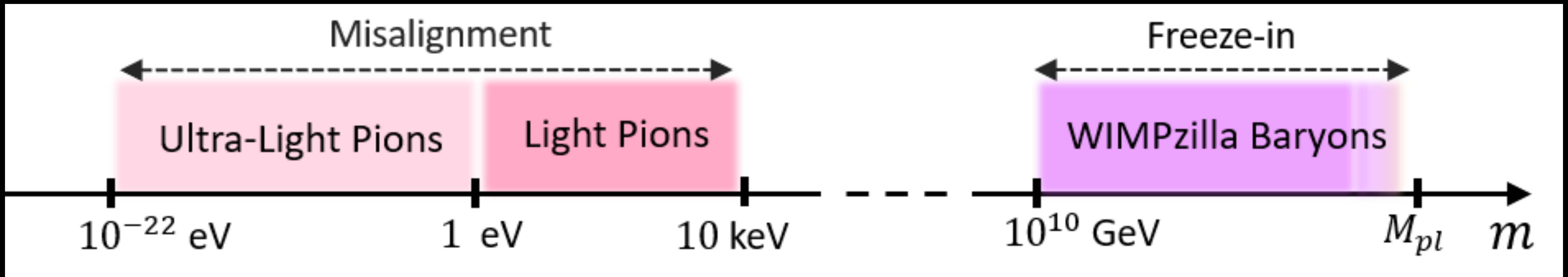
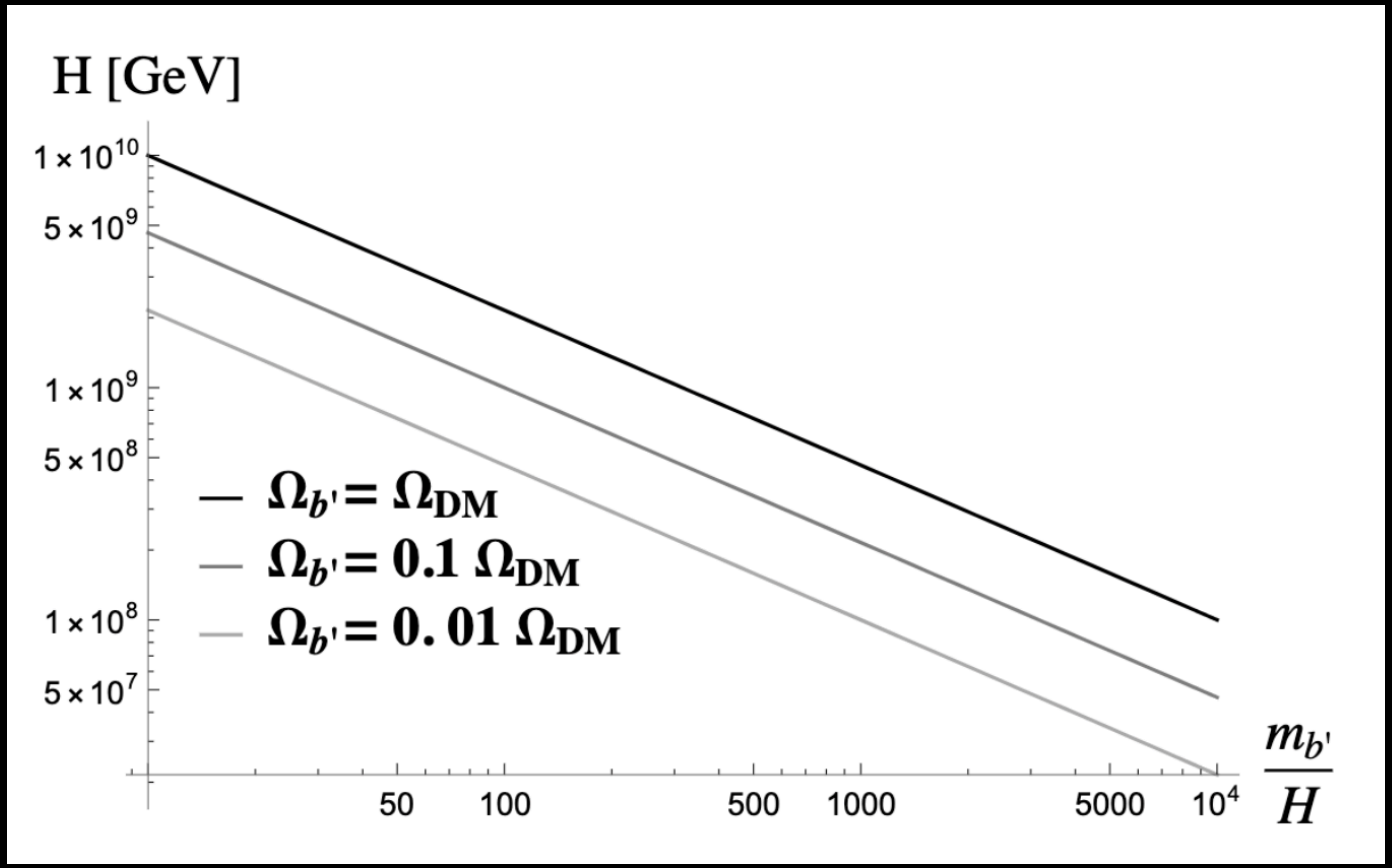
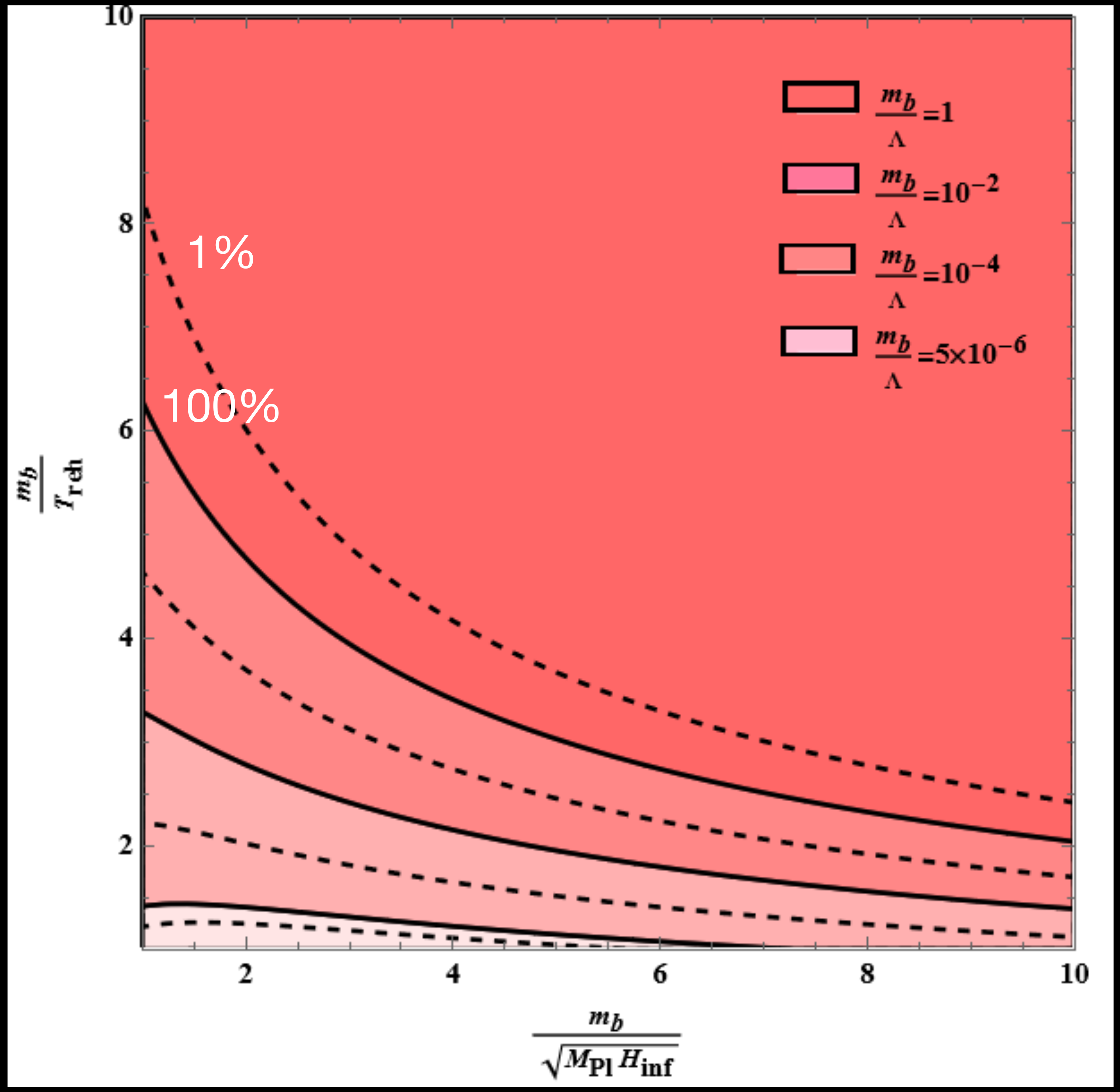
Maleknejad, EM '22



Gravitational Production from Inflation:



Freeze-In Production: Higgs-, QED-,or inflaton- portal



$\Lambda \equiv \Lambda_H/y\ ,\ \Lambda_\phi/\lambda\ ,\ m_{b'}/\epsilon$

Experimental Arenas

Parity-odd portal: $\mathscr{L} \sim g_{\pi\gamma\gamma}\pi F\tilde{F}$

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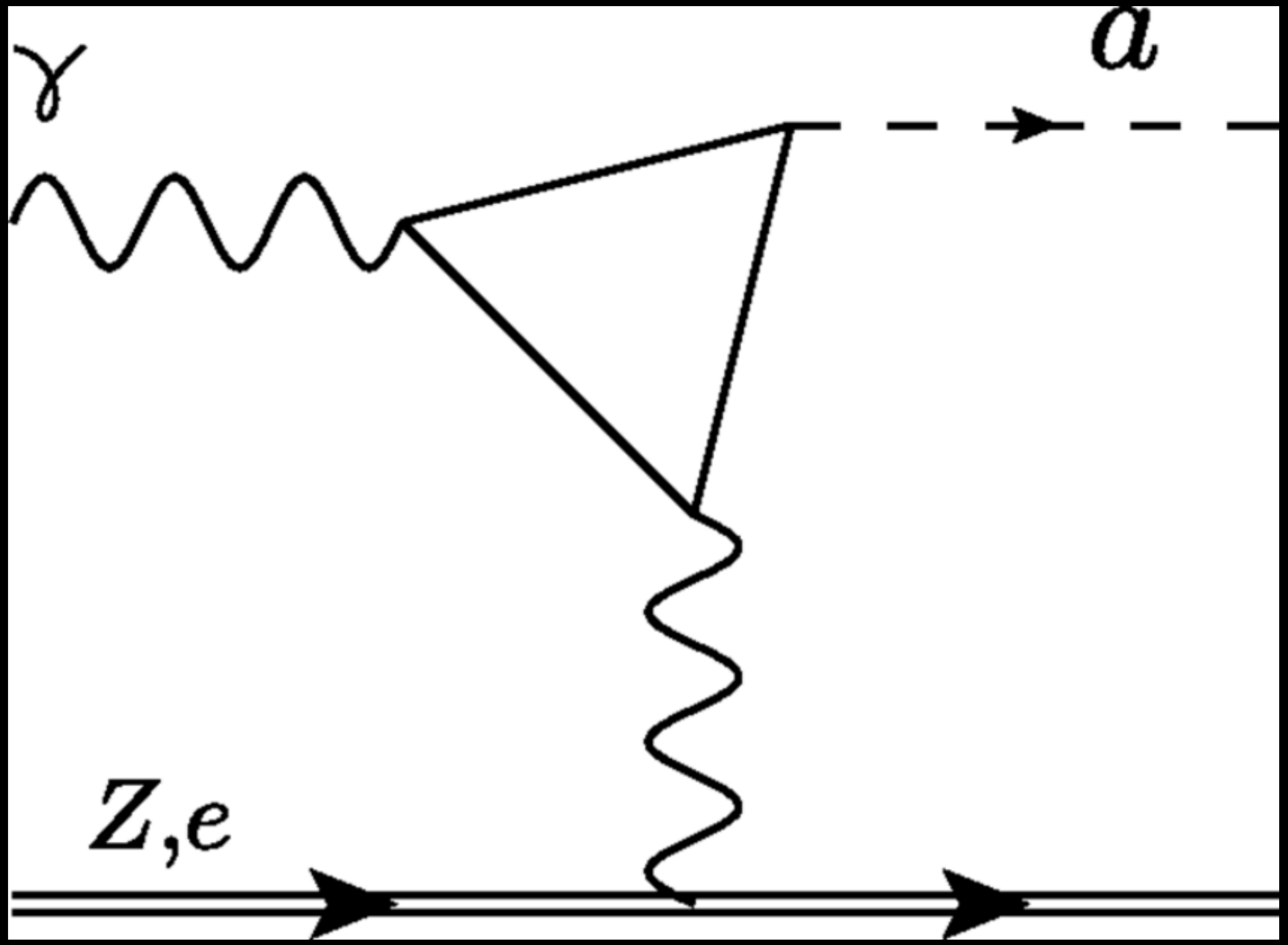
Recent review:
Adams et al Axion DM Snowmass

Experiments such as ADMX

- Axion-photon couplings in strong B-field background



Neutral pseudo-scalar pions have coupling:

$$g_{\pi\gamma\gamma} \sim c\frac{\alpha_e \varepsilon^2}{F_\pi}$$

Five neutral π-axions

$\Rightarrow$ Multiple distinct resonances

But $\varepsilon-$suppressed
relative to conventional axion

Note: $\tau_{\pi^0} \sim H_0^{-1}\left(\frac{F_\pi}{\mathrm{TeV}}\right)^2\left(\frac{0.3\mathrm{eV}}{m_{\pi^0}}\right)^3\frac{1}{\varepsilon^4}$ $\Rightarrow$ **Can have $\varepsilon = \mathcal{O}(1)$!**

$m_\pm \sim \varepsilon F_\pi$

Parity-even portal

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Experiments such as Atomic Clocks **Arvanitaki, Huang, Tilburg '15**

$$\mathcal{L} = \lambda \frac{\varepsilon^2}{M^2} |\pi_i|^2 F_{\mu\nu} F^{\mu\nu} + h.c.$$

$$\pi \sim \pi_0 \cos(mt + \delta) \qquad \Rightarrow \alpha_e(t) = \alpha_e \left(1 + \frac{2\lambda e^2}{\Lambda^2} \varepsilon^2 \sum_i |\pi_{i,0}|^2 \cos^2(m_i t + \delta_i) \right)$$

- Multiple (light) fields $\Rightarrow$ multiple incoherent contributions
- Benchmark needed for detection:

$$\frac{\rho^i_{\text{DM}} \varepsilon^2}{M^2 m^2_{\pi_i}} \gtrsim 10^{-15}$$

Example: Fuzzy π-axion, and $M = M_W = gv$,
If $v \sim \Lambda$, need tiny gauge coupling: $g < 10^{-8} \varepsilon$

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π-axion Star Explosions (Via Parametric Resonance)

Amin, Mou '20
Amin, Mou, Saffin 21
Du et al. '23 ("Axion Star Explosions")
Chung-Jukko et al. '23

$$A''_\pm + \left(k^2 + B_\pm(t)k + C(t)\right) A_\pm = 0$$

$$B_\pm(t) = \frac{\lambda_2}{\Lambda_2^2}\varepsilon^2 \sum_{i,j}^{9} \pi^c_{i,0}\pi^c_{j,0}(2\cos(\theta_i - \theta_j))\Big[m_i \cos\varphi_i(t)\sin\varphi_j(t) + m_j \sin\varphi_i(t)\cos\varphi_j(t)\Big]$$

$$+\frac{\lambda_4}{\Lambda_4^2}\varepsilon^2\Big\{\sum_{i,j}^{6} \pi^c_{i,0}\pi^c_{j,0}(2\cos(\theta_i - \theta_j)) + \sum_{i,j}^{5} \pi^r_{i,0}\pi^r_{j,0}\Big\}\Big[m_i \cos\varphi_i(t)\sin\varphi_j(t) + m_j \sin\varphi_i(t)\cos\varphi_j(t)\Big]$$

$$\pm\frac{\lambda_3}{F_\pi}\varepsilon^2 \sum_{i}^{5} \pi^r_{i,0} m_i \cos\varphi_i(t),$$

$$[\varphi_i \equiv m_i t + \delta_i]$$

$$C(t) = \lambda_1 \varepsilon^2 e^2 \sum_{i,j}^{9} \pi^c_{i,0}\pi^c_{j,0}\cos(\theta_i - \theta_j)\sin\varphi_i(t)\sin\varphi_j(t)$$

Even just the simple charged-pion coupling, $|\pi^\pm|^2 A_\mu A^\mu$ can dramatically enhance parameter resonance

Jaeckel, Schenk '21

Summary

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π-Axion	Axion
confining gauge theory, Chiral symmetry breaking	complex scalar, spontaneously broken global U(1) symmetry
Many pions, mass splitting due to charges	1 axion per complex scalar
WIMPZilla: dark baryons	WIMPZilla: radial field
Real and complex neutral, and charged	Real neutral
Other degrees of freedom: dark Electroweak , glueballs . . .	Other degrees of freedom: Model dependent
Interactions: Parity-odd and parity-even	Parity-odd couplings

$(\text{e.g.}\, |\pi^{\pm}|^2 A_\mu A^\mu)$

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Q: Smoking guns of π-axions?

A:

- Combination of parity-odd and parity even couplings, each benchmarked to the millicharge and decay constant
- Heavy dark baryons with mass $\sim$ π-axion decay constant
- The spectrum of π-axions: tightly packed discretum (e.g. 5 neutral pi-axions); combination of real scalars,

Thanks!

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