The π-axion and π-axiverse of Dark QCD

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

Outline

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1. Introduction: Axions past present and future

2. The π-axiverse

3. π-axion DM

4. Experimental Arenas

5. Summary: π-axions vs axions

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Introduction

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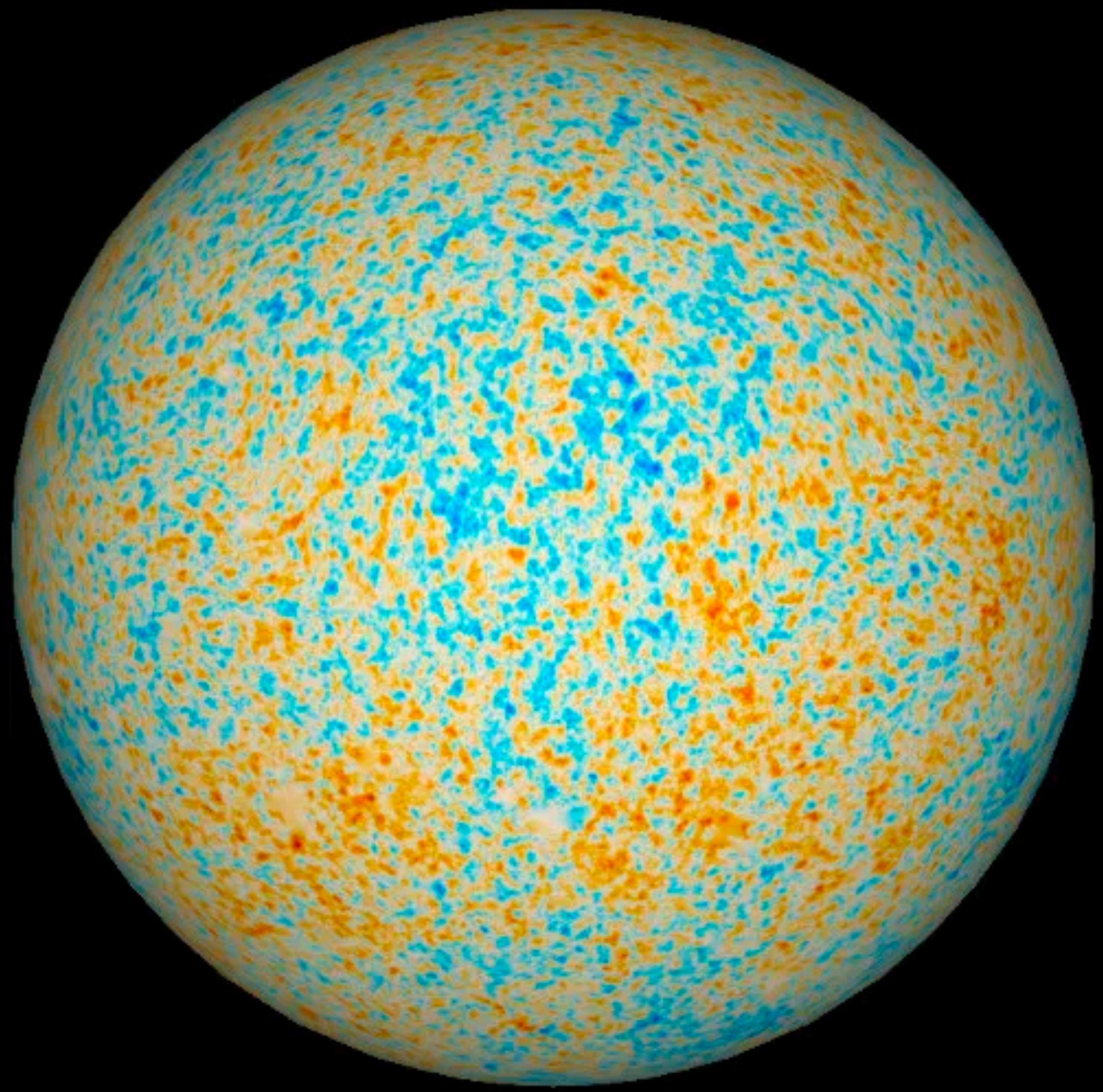
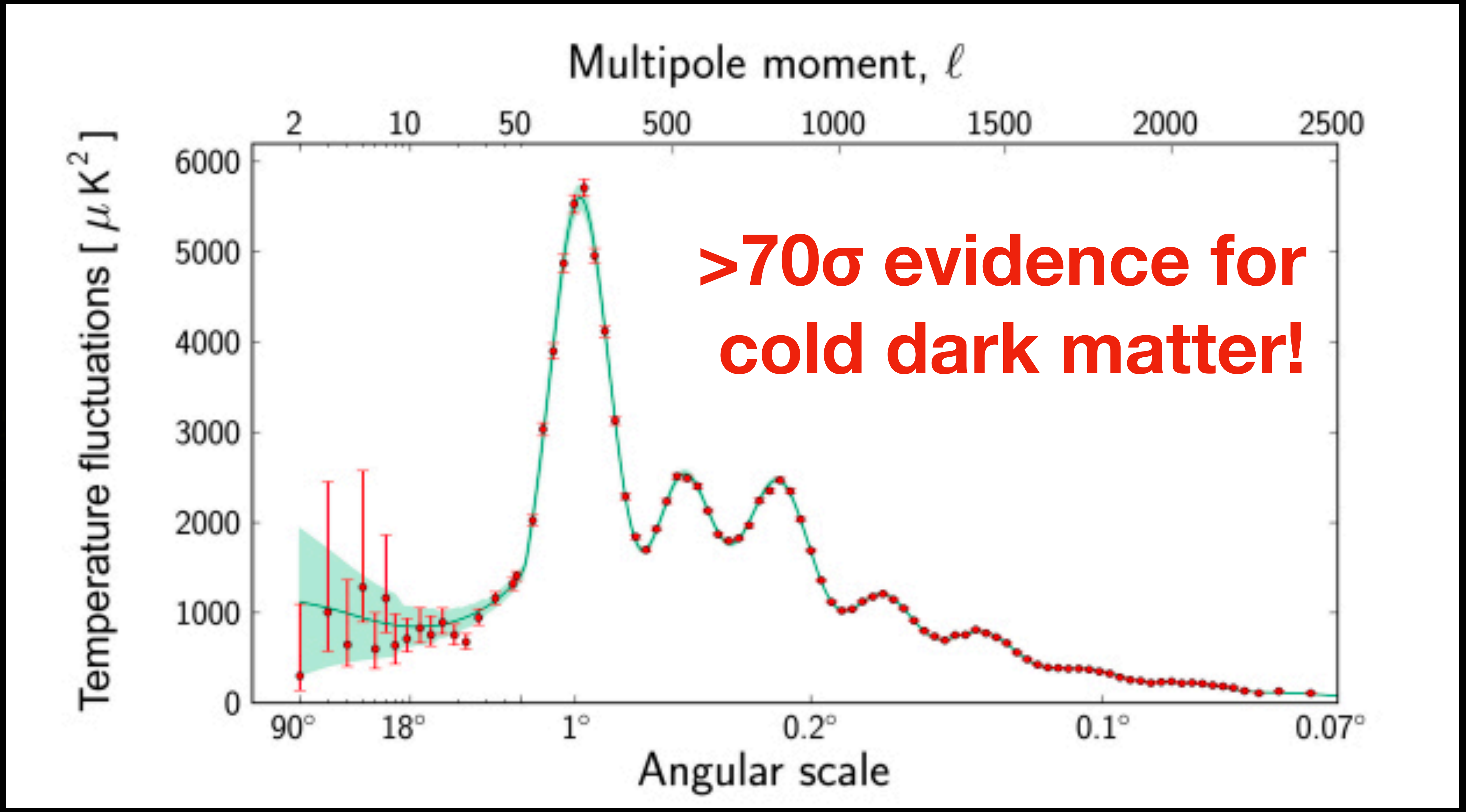
The case for Dark Matter





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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

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

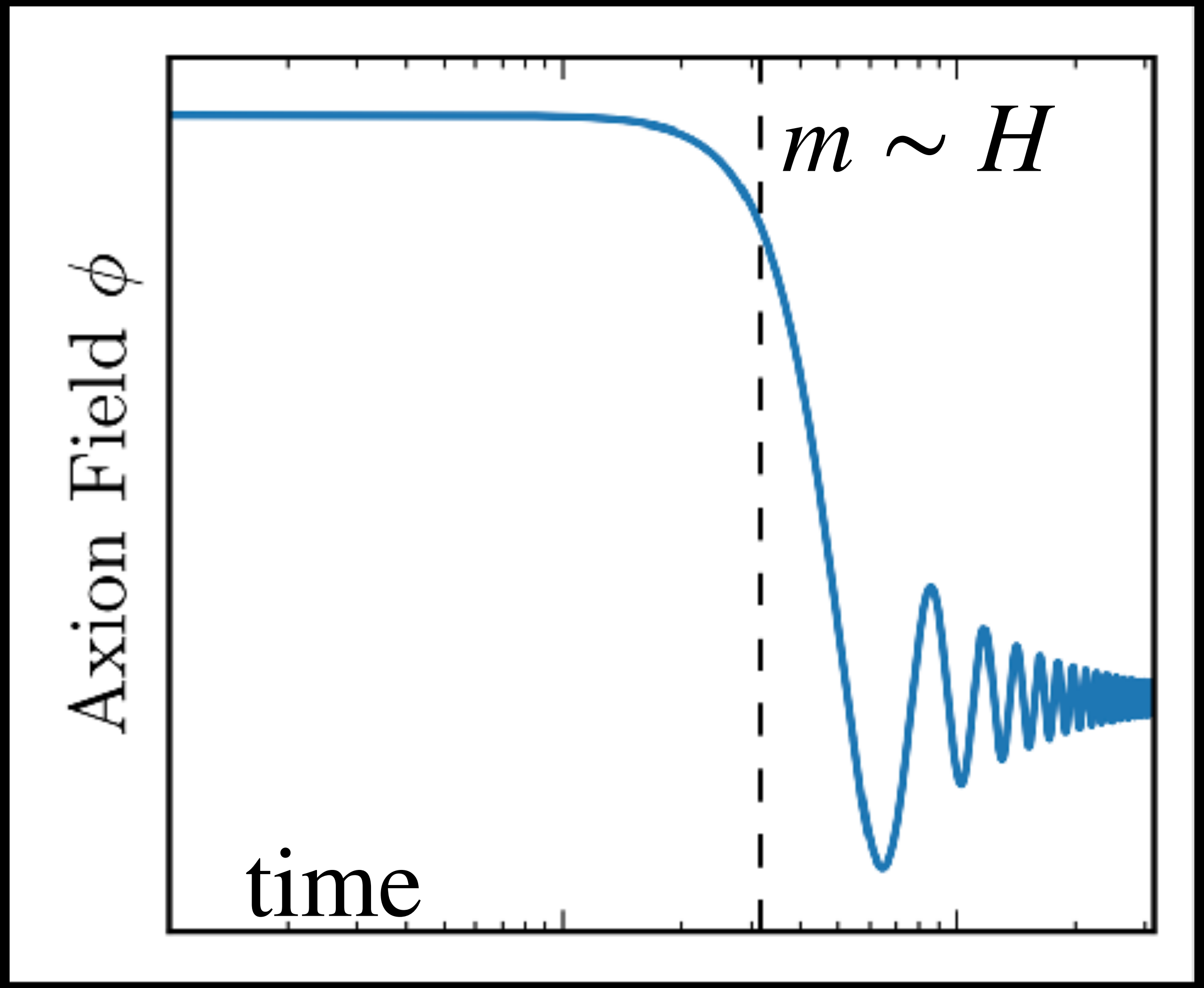
$$\mathscr{L} = |\partial_\mu \Phi|^2 - \lambda(|\Phi|^2 - f^2)^2 - \Lambda^4 \cos(\frac{a}{f_a})$$

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

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

See e.g. Marsh '15
For a review

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



Lots of neat particle physics:

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

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Axions (ALPs) from String Theory: The String Axiverse

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	4-form axions	2-form axions	
C_0	$\vartheta = \int_{\Sigma^4} C_4$	$c = \int_{\Sigma^2} C_2$	$b = \int_{\Sigma^2} B_2$

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Enter the π-axiverse

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Pions: textbook physics — and a lot like axions!

Goldstone Bosons of Chiral Symmetry Breaking:

$$SU(N_f)_L \times SU(N_f)_R \to SU(N_f) \qquad \Phi = \phi e^{\frac{2i\pi^a(x)\tau_a}{F_\pi}}$$

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

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" $\quad \Rightarrow m_q < 10^{-19}\mathrm{eV} \ , \ \Lambda \gtrsim 10^{10}\mathrm{GeV}$

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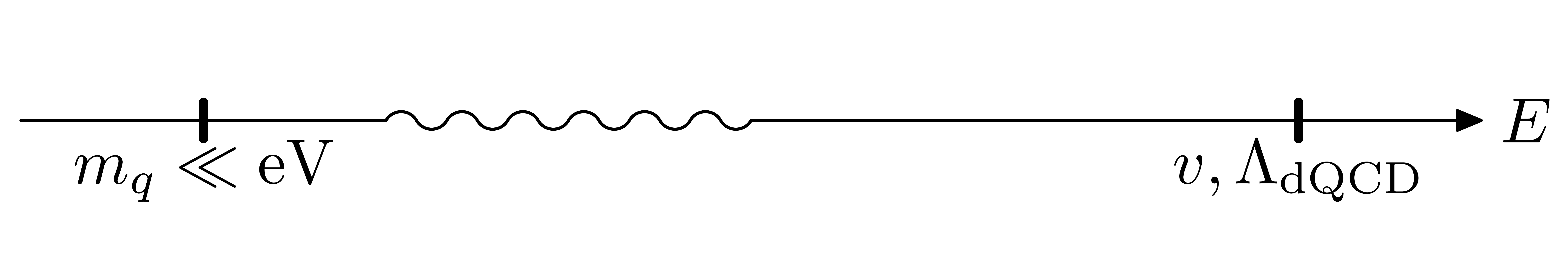
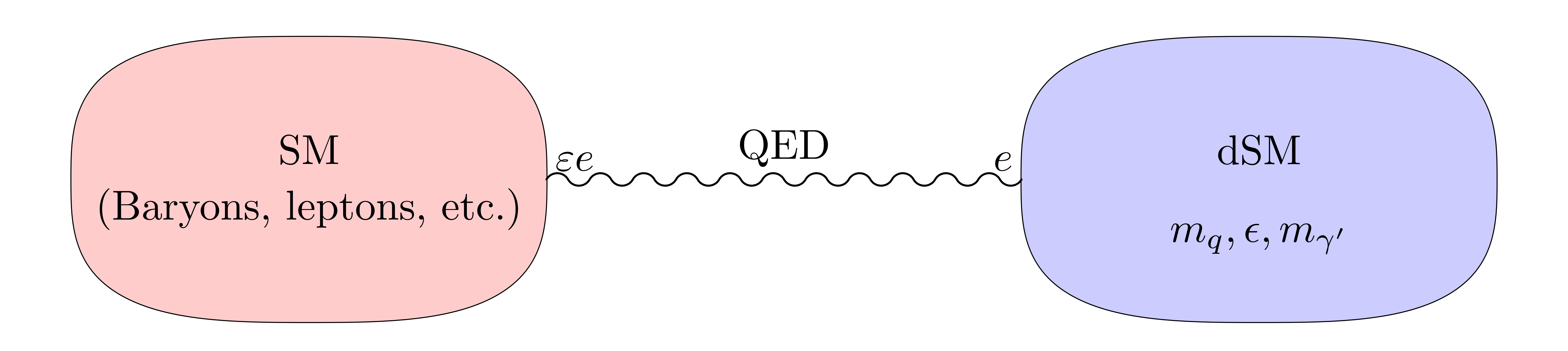
The Dark Standard Model

Key points

1. Two energy scales



2. SM portal: photon kinetic mixing (millicharges)



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Dark Pions

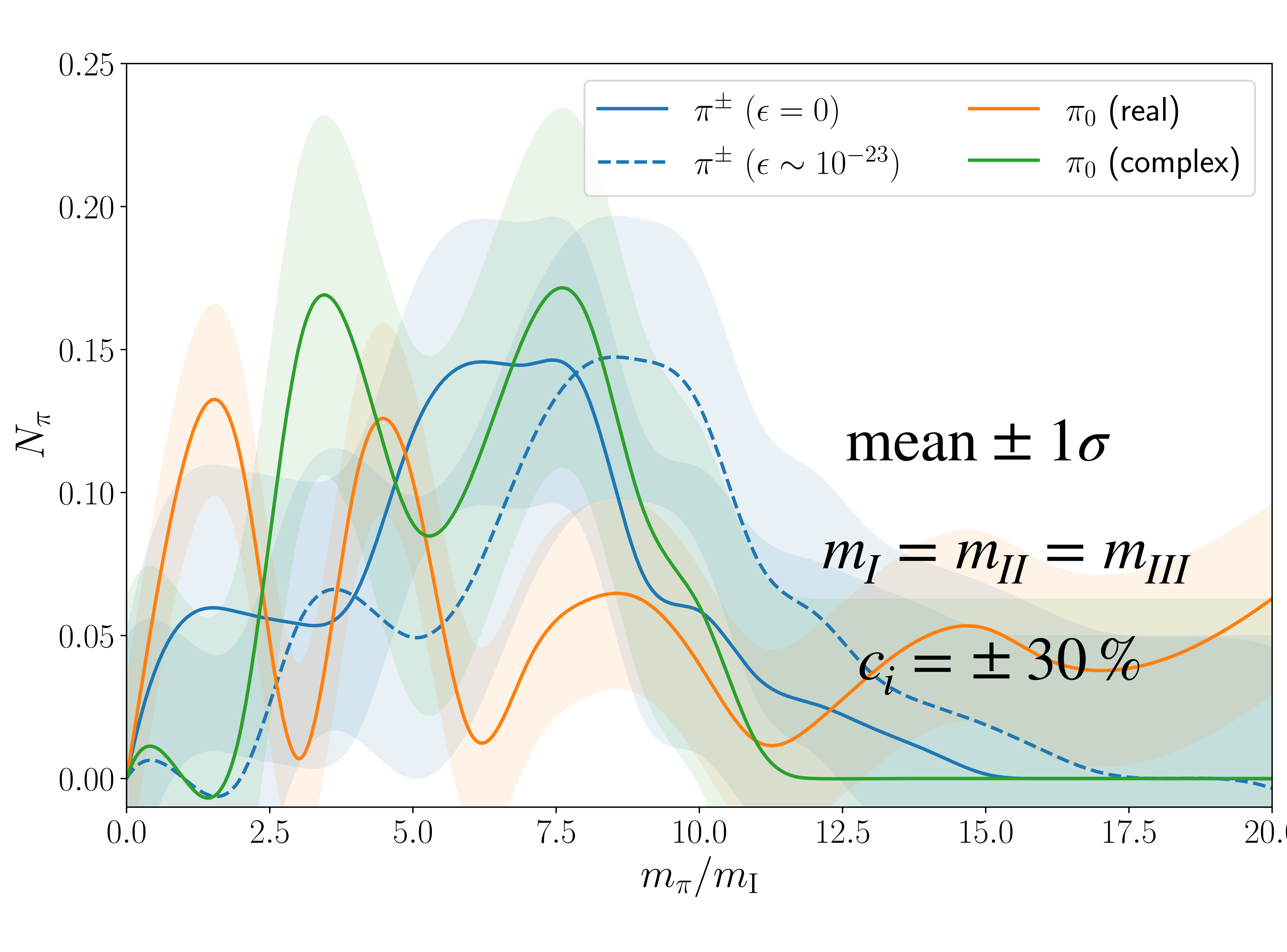
$$m_\pi^2 \simeq \frac{\langle q\bar{q}\rangle}{F_\pi^2}\sum_i m_{q_i}$$

$$\Delta m^2_{\pi_i^\pm} \simeq \begin{cases} \alpha'_e F_\pi^2 & , \; m_{\gamma'} < F_\pi \\ \alpha_e \varepsilon^2 F_\pi^2 & , \; m_{\gamma'} > F_\pi, \end{cases}$$

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	$u\bar{u}+d\bar{d}-2s\bar{s}$	$((c_1+c_2)m_{\rm I}+c_3m_{\rm II})\,F_\pi$	0
π_{29}	$c\bar{c}-b\bar{b}$	$(c_4m_{\rm II}+c_5m_{\rm III})\,F_\pi$	0
π_{34}	$c\bar{c}+b\bar{b}-2t\bar{t}$	$(c_4m_{\rm II}+(c_5+c_6)m_{\rm III})\,F_\pi$	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:			
$\pi_6\pm i\pi_7$	$d\bar{s}/\bar{d}s$	$(c_2m_{\rm I}+c_3m_{\rm II})\,F_\pi$	0
$\pi_9\pm i\pi_{10}$	$u\bar{c}/\bar{u}c$	$(c_1m_{\rm I}+c_4m_{\rm II})\,F_\pi$	0
$\pi_{17}\pm i\pi_{18}$	$d\bar{b}/\bar{d}b$	$(c_2m_{\rm I}+c_5m_{\rm III})\,F_\pi$	0
$\pi_{19}\pm i\pi_{20}$	$s\bar{b}/\bar{s}b$	$(c_3m_{\rm II}+c_5m_{\rm III})\,F_\pi$	0
$\pi_{21}\pm i\pi_{22}$	$u\bar{t}/\bar{u}t$	$(c_1m_{\rm I}+c_6m_{\rm III})\,F_\pi$	0
$\pi_{30}\pm i\pi_{31}$	$c\bar{t}/\bar{c}t$	$(c_4m_{\rm II}+c_6m_{\rm III})\,F_\pi$	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
$\pi_4\pm i\pi_5$	$u\bar{s}/\bar{u}s$	$(c_1m_{\rm I}+c_3m_{\rm II})F_\pi+2\xi_2(e\varepsilon F_\pi)^2$	±1
$\pi_{15}\pm i\pi_{16}$	$u\bar{b}/\bar{u}b$	$(c_1m_{\rm I}+c_5m_{\rm III})F_\pi+2\xi_3(e\varepsilon F_\pi)^2$	±1
$\pi_{11}\pm i\pi_{12}$	$d\bar{c}/\bar{d}c$	$(c_2m_{\rm I}+c_4m_{\rm III})F_\pi+2\xi_4(e\varepsilon F_\pi)^2$	∓1
$\pi_{23}\pm i\pi_{24}$	$d\bar{t}/\bar{d}t$	$(c_2m_{\rm I}+c_6m_{\rm III})F_\pi+2\xi_5(e\varepsilon F_\pi)^2$	∓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
$\pi_{25}\pm i\pi_{26}$	$s\bar{t}/\bar{s}t$	$(c_3m_{\rm II}+c_6m_{\rm III})F_\pi+2\xi_7(e\varepsilon F_\pi)$	∓1
$\pi_{27}\pm i\pi_{28}$	$c\bar{b}/\bar{c}b$	$(c_4m_{\rm II}+c_5m_{\rm III})F_\pi+2\xi_8(e\varepsilon F_\pi)^2$	±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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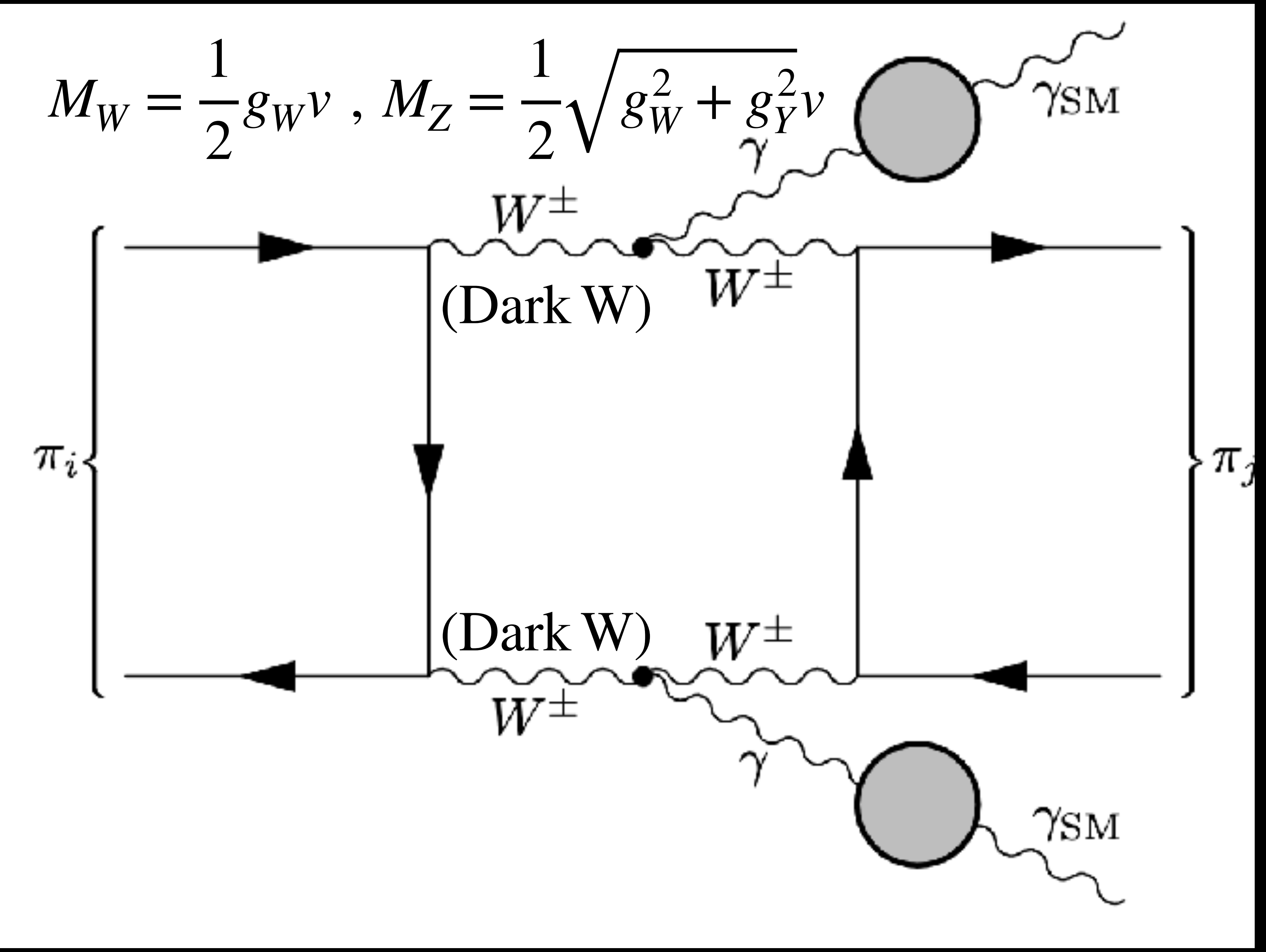
Photon Portal to the SM:

$\varepsilon F_{\mu\nu}\tilde{F}^{\mu\nu} \Rightarrow$ 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:

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

π-axion DM

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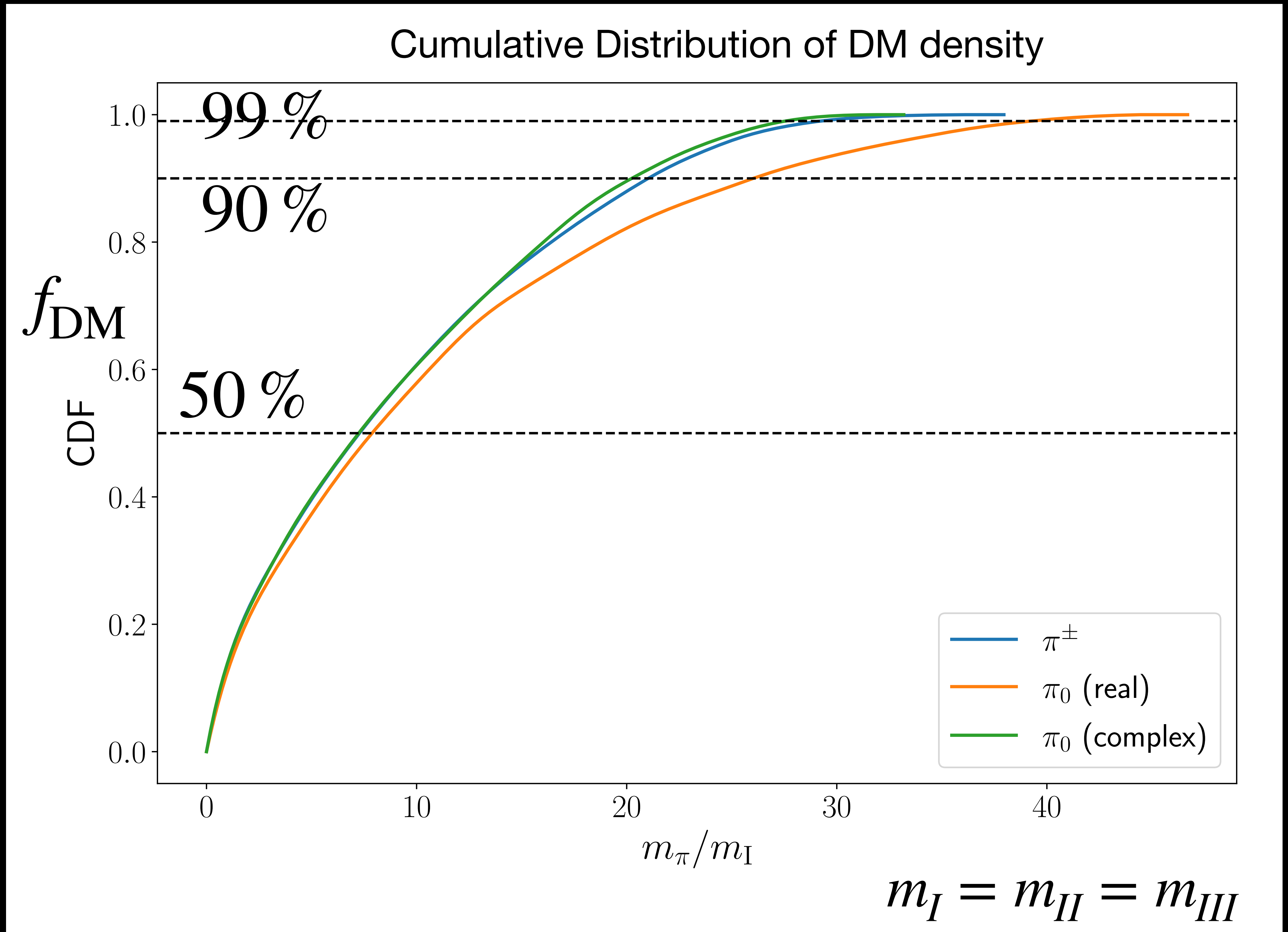
Misalignment Relic Density

Scenario:

- Symmetry breaking before inflation
- CMB Isocurvature: $H_{\rm inf} \lesssim 10^{10}(F_\pi/M_P)\,\text{GeV}$
- Cosmological stability: $\tau_{\pi^0} \sim H_0^{-1}\left(\frac{F_\pi}{\text{TeV}}\right)^2\left(\frac{0.3\text{eV}}{m_{\pi^0}}\right)^3\frac{1}{\varepsilon^4}$
- Heavy Dark Photon: $m_{\gamma'} > F_\pi$
- Late-time relic density produced by misalignment:

$$\Omega_{\pi_i} = \frac{1}{6}(9\Omega_r)^{\frac{3}{4}}\frac{F_\pi^2}{M_p^2}\sqrt{\frac{m_i}{H_0}}\theta_i^2$$



The WIMPZilla Connection: Dark Baryons

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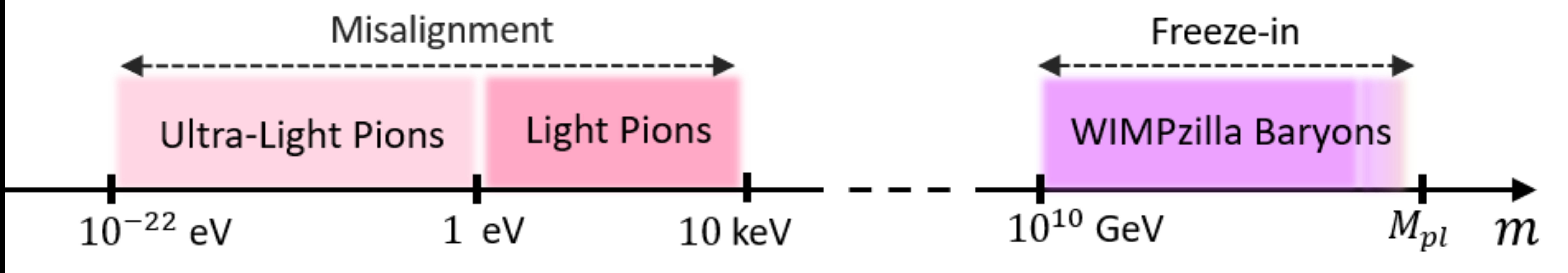
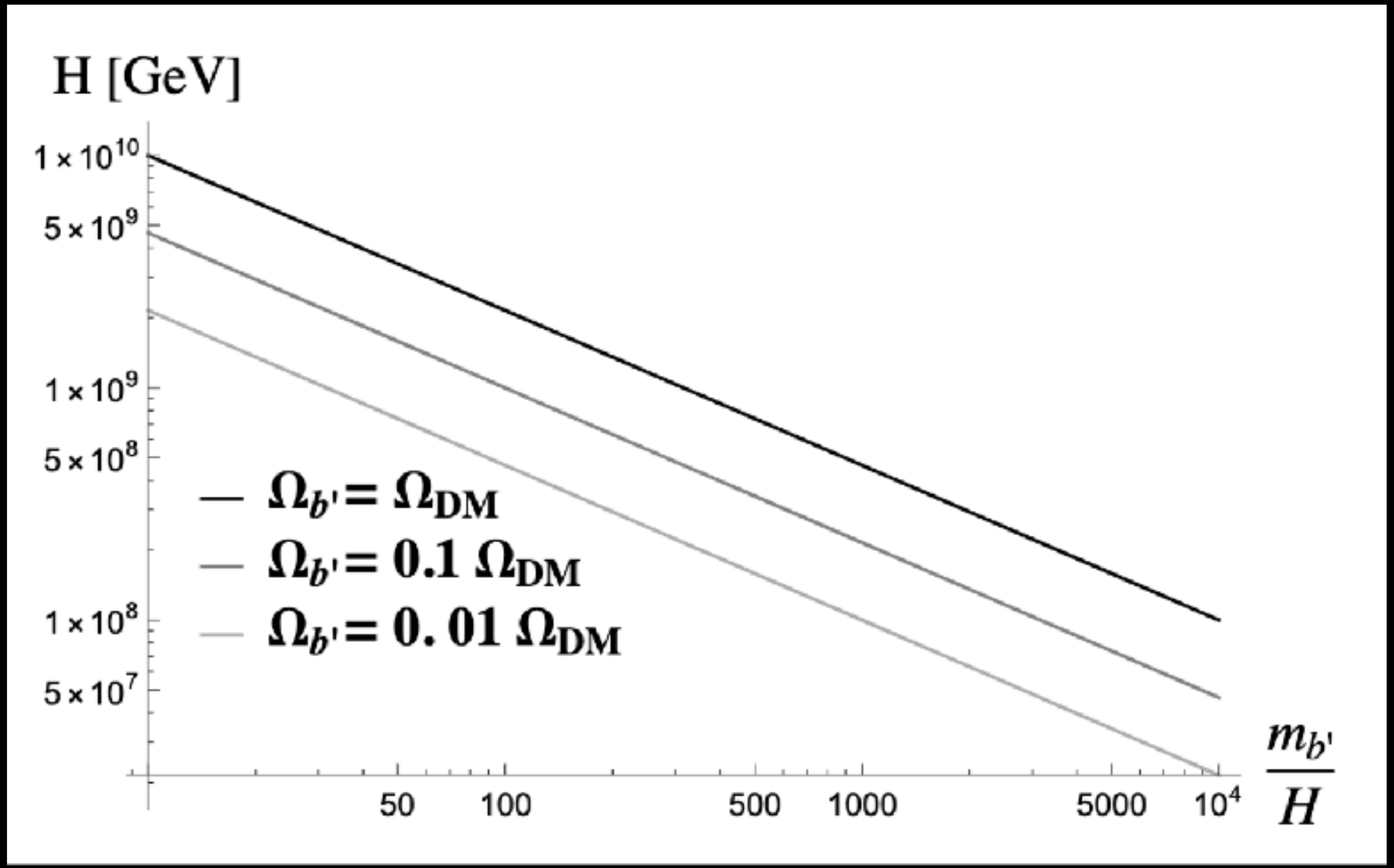
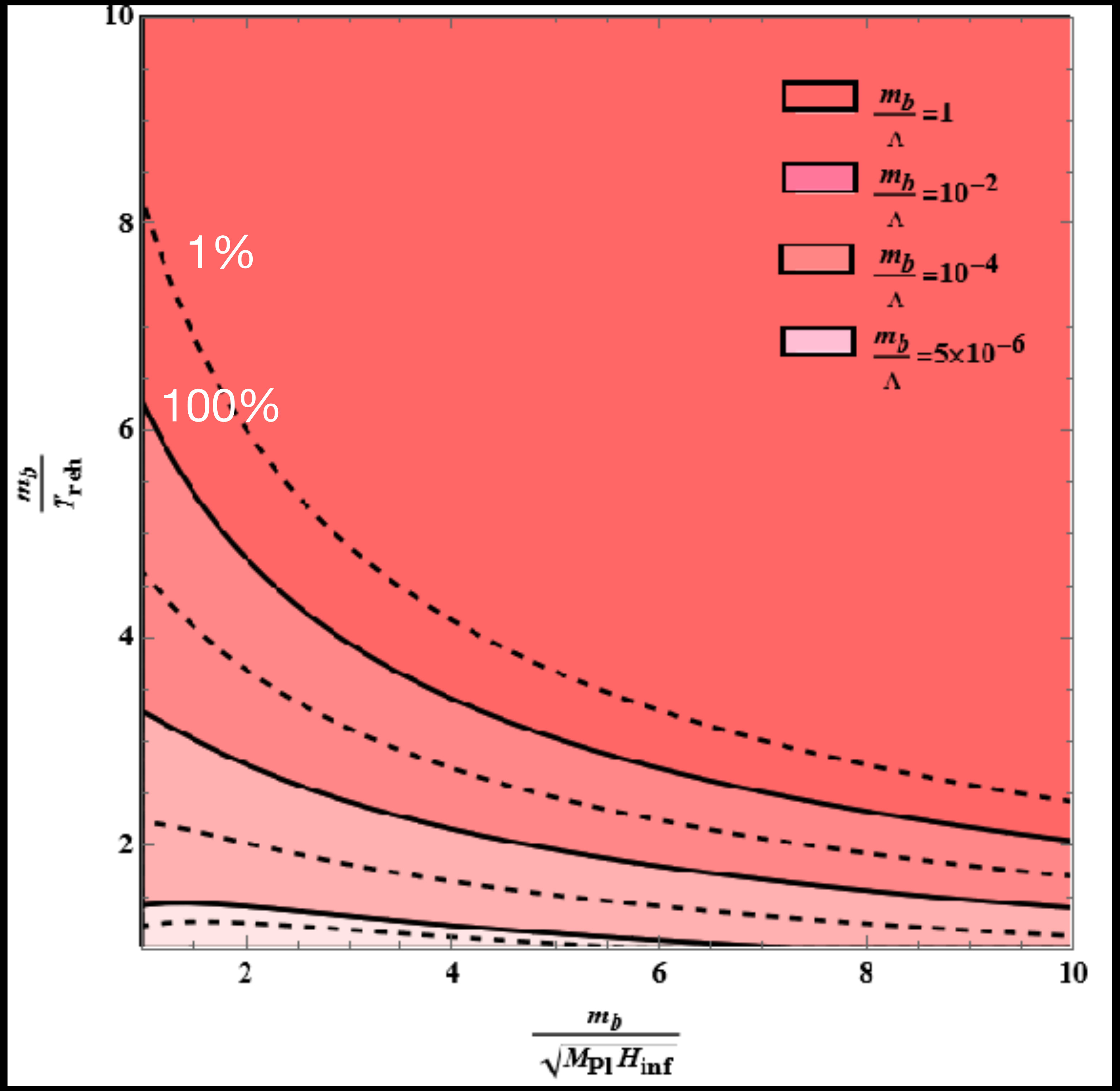
Maleknejad, EM '22



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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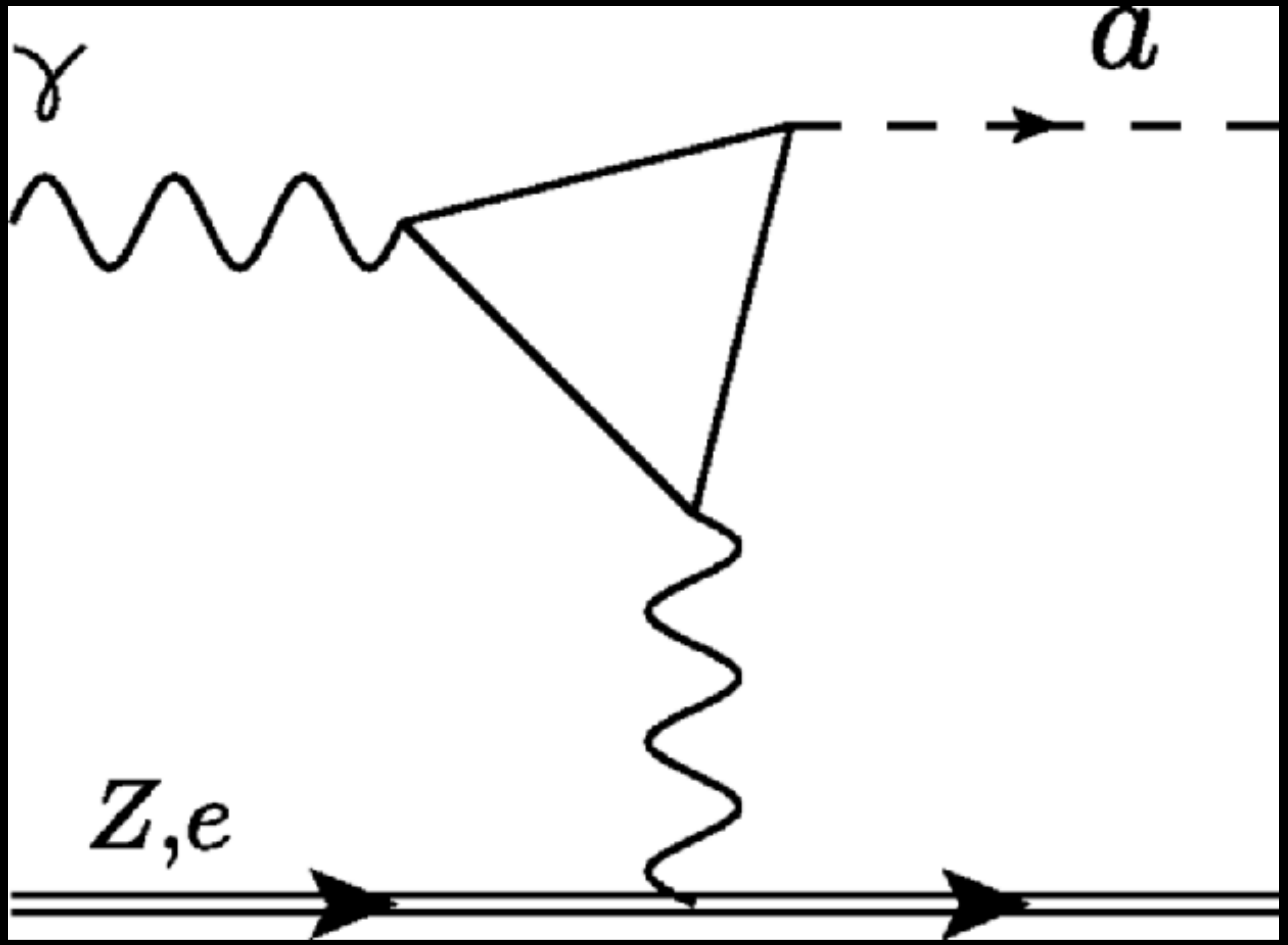
Recent review:
Adams et al Axion DM Snowmass

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

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

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

- Multiple (light) fields ⇒ multiple incoherent contributions
- Benchmark needed for detection:

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

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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: $\text{dark Electroweak}\ ,\text{glueballs}\ldots$	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,

Take-Home Messages

- SM Physics can provide an ‘axiverse’: the π-axiverse of a dark SM
    - Dark SM gets you the millicharges, flavor violation, etc.
- DM candidate: π-axion DM
    - DM can be mixture of real scalar, neutral complex scalars, and millicharged complex scalars
    - Natural theory expectation is tightly packed discretum of masses
- Detection: mixture of parity-odd and parity-even signals

Lots to do!

1. Constraints Plot! Statistical distribution of predictions
2. Millicharge signatures
3. Imprint on CMB and Large Scale Structure

Thanks!

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