Cosmologically Varying Kinetic Mixing

XG, Di Liu
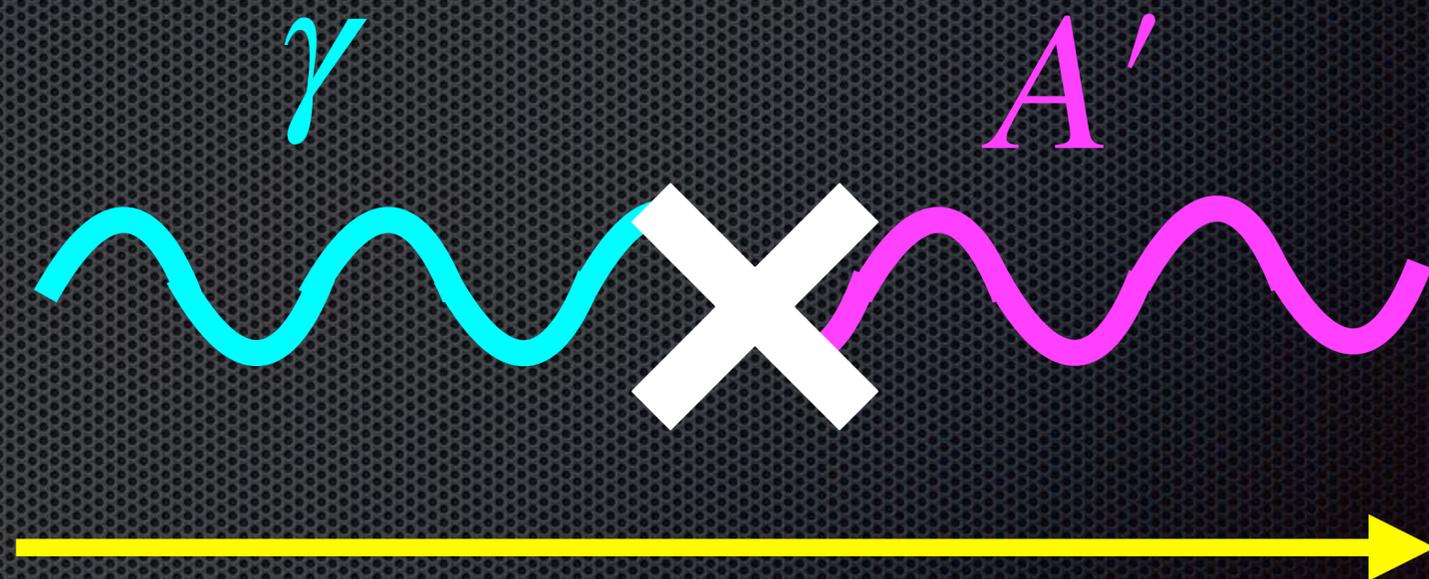
PHENO 2023,
University of Pittsburgh

ϵ

ϕ

Kinetic Mixing

$$\mathcal{L} \supset \frac{\epsilon}{2} F_{\mu\nu} F'^{\mu\nu}$$

Bob Holdom 1985

γ A'
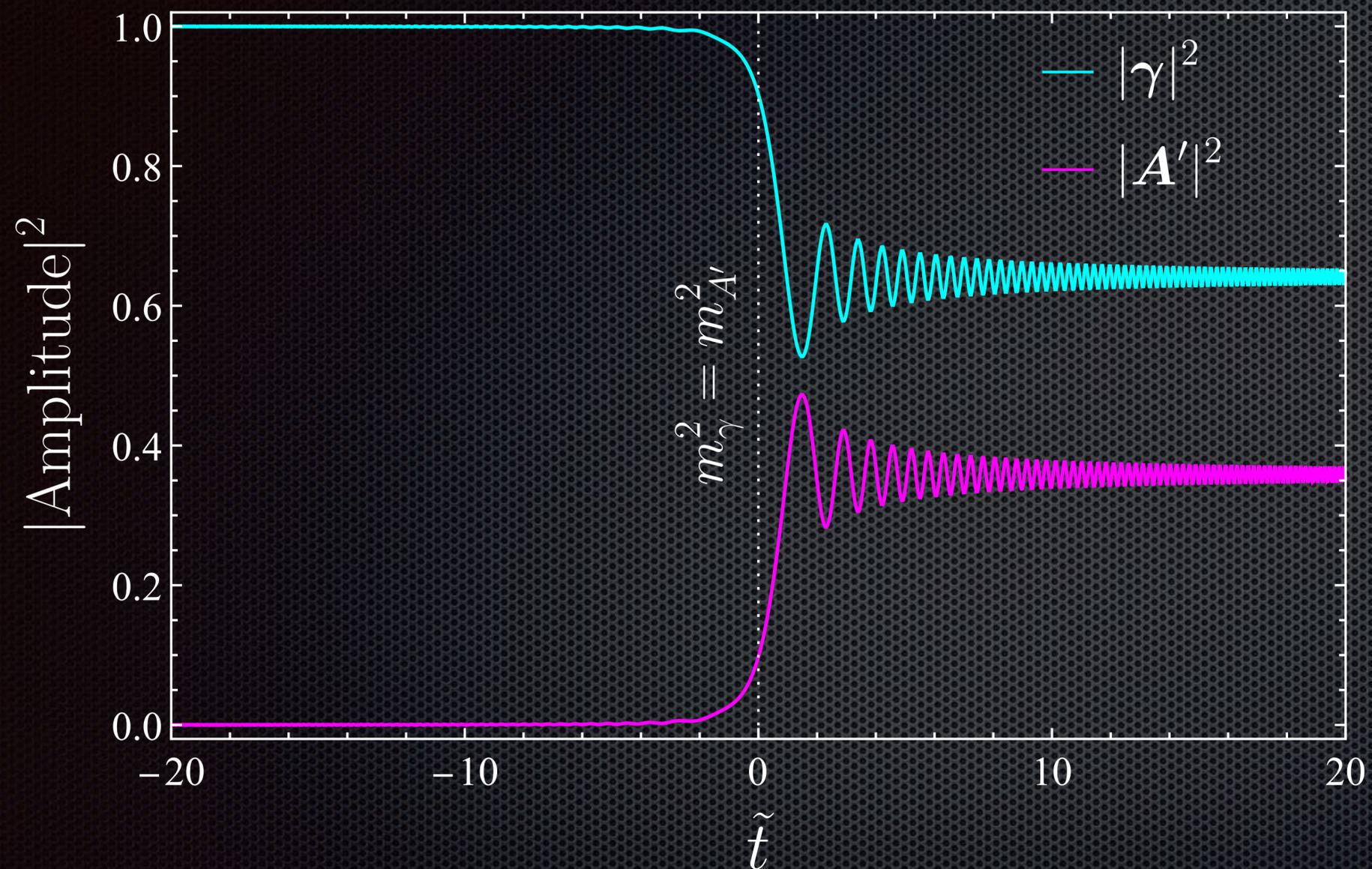
Freeze-in

Hall, Jedamzik, March-Russell, West 2009

A' Freeze-in: $\gamma \rightarrow A'$
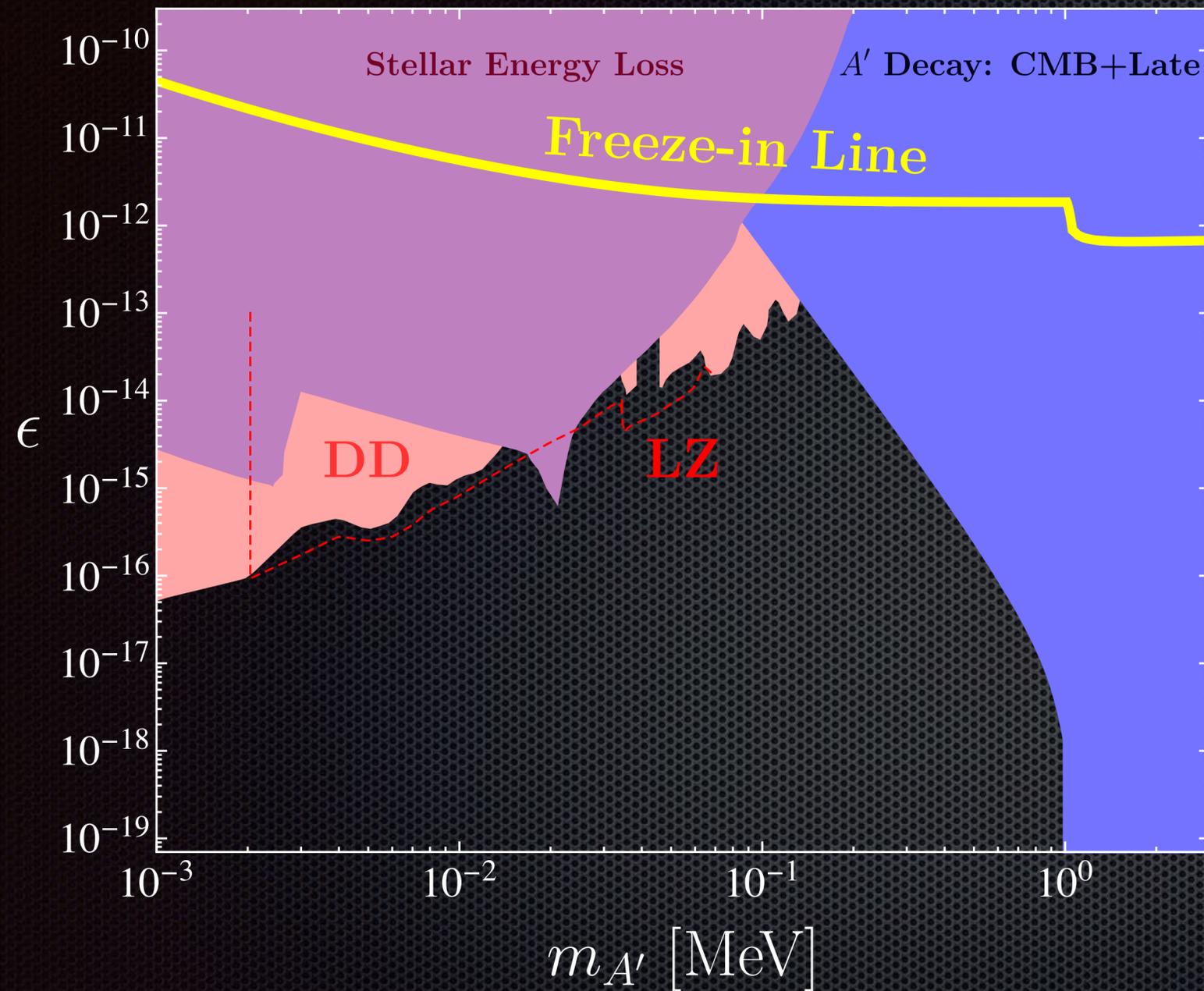
$$\Omega_{A'} \sim \epsilon^2 \alpha^{3/2} \frac{m_{pl}}{T_{eq}}$$

$$\Omega_{A'} \sim 0.1$$

$$\epsilon \sim 10^{-12}$$

Berlin, Dror, **XG**, Ruderman 2022

Dark Photon Dark Matter

Stellar energy loss:

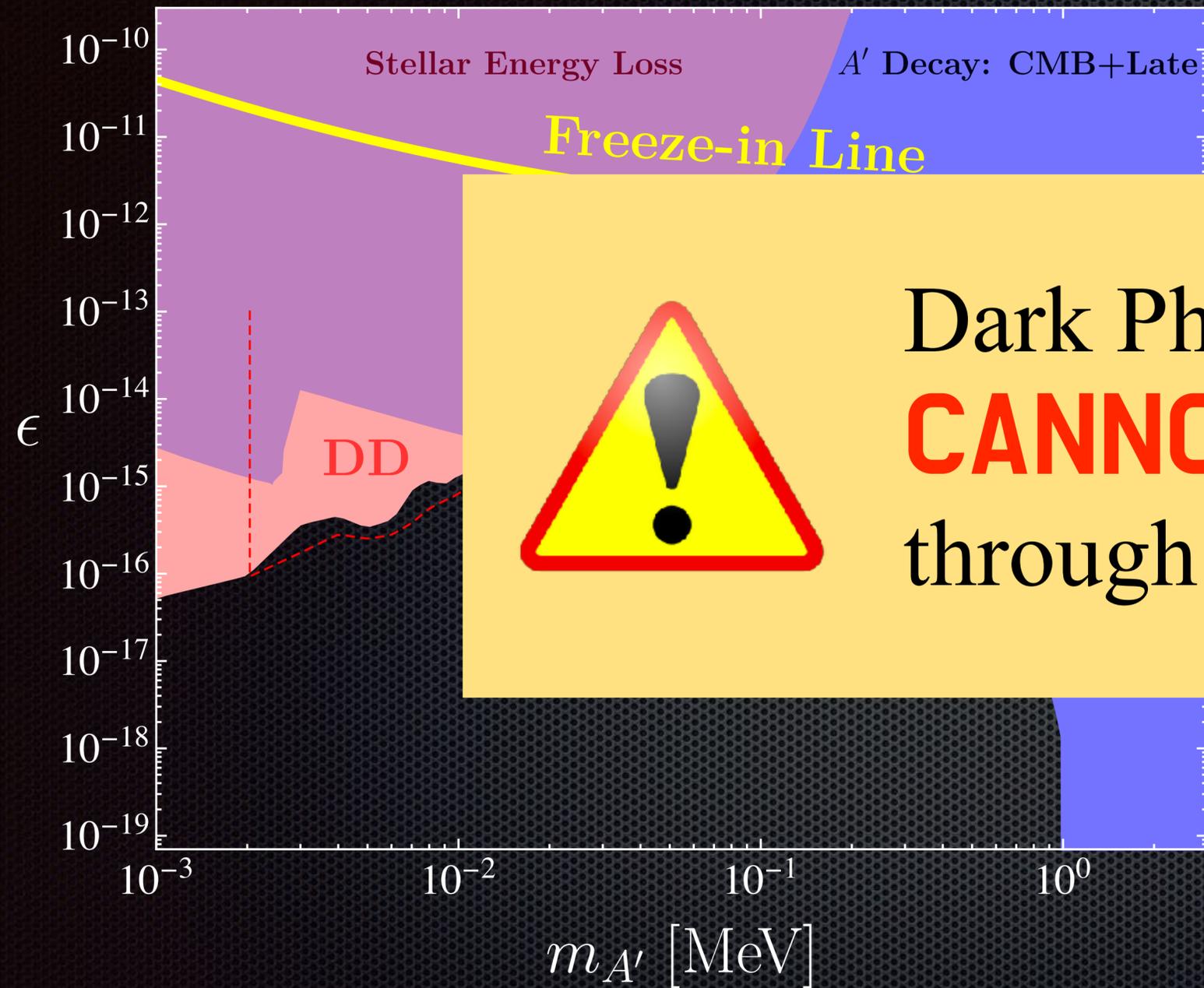$\gamma \rightarrow A'$

Direct Detection:

A' Absorption

A' Decay:

$A' \rightarrow 3\gamma \quad A' \rightarrow e^- e^+$

Redondo, Postma 2005

Dark Photon Dark Matter

Stellar energy loss:

Dark Photon Dark Matter **CANNOT** be frozen in through the kinetic mixing !!!

A' Decay:

$$A' \to 3\gamma \quad A' \to e^- e^+$$

Redondo, Postma 2005

Stellar Energy Loss

A' Decay: CMB+Late

Freeze-in Line

DD

ϵ

$m_{A'}$ [MeV]

Alternative Prodution Mechanisms

Vector Misalignment

1105.2812   1201.5902
1905.09836   1907.06243

Gravitational Production

1504.02102   1903.10973   2005.01766
2009.03828   2203.15452   2204.14274

Production via $aF'\tilde{F}'$

1810.07188   1810.07195   1810.07196
1810.07208   2104.02077   2303.05492

Cosmic String Radiation

1901.03312   2212.13573

Independent of kinetic mixing

UV Freeze-in via $F'_{\mu\nu}\bar{f}\sigma^{\mu\nu}f$

2210.06487   2303.11344

UV sensitive

$\Omega_{A'} \propto T_{rh}$

Alternative Prodution Mechanisms

Vector Mis...

1105.2812
1905.09836

...ependent of
...etic mixing

Production

1810.07188   1810.07...
1810.07208   2104.02...

Dark Photon Dark Matter:

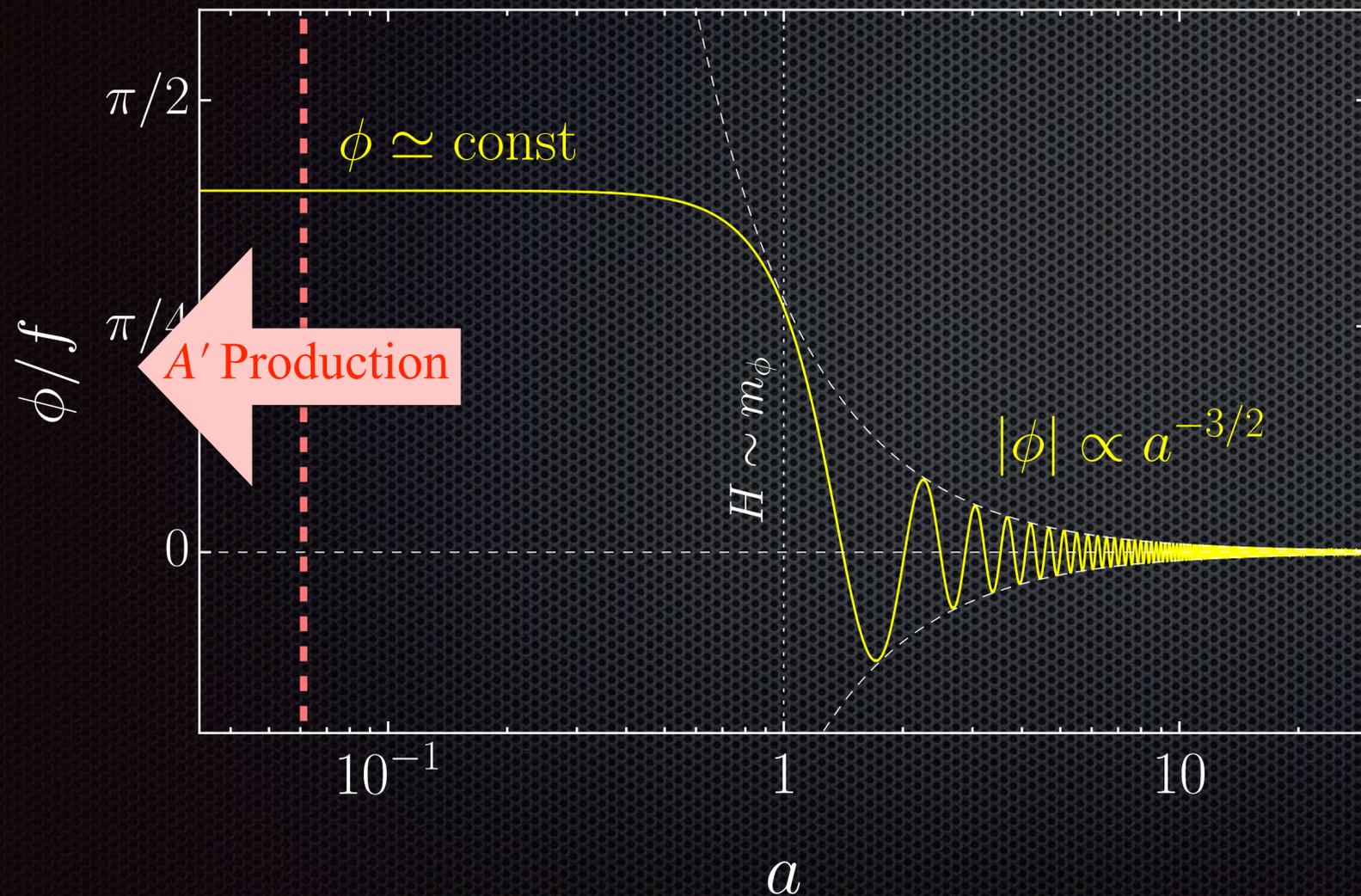**Kinetic Mixing?**
IR Process?

2210.06487   2303.11344

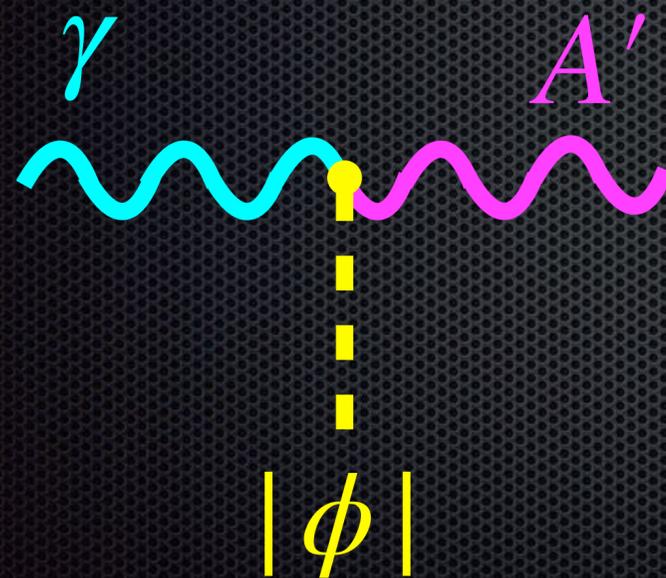V sensitive

$\Omega_{A'} \propto T_{rh}$

Kinetic Mixing Varying Cosmologically

$$\mathcal{L} \supset \frac{\epsilon}{2} F_{\mu\nu} F'^{\mu\nu} \longrightarrow \mathcal{L} \supset \frac{1}{2}\frac{\phi}{\Lambda} F_{\mu\nu} F'^{\mu\nu}$$

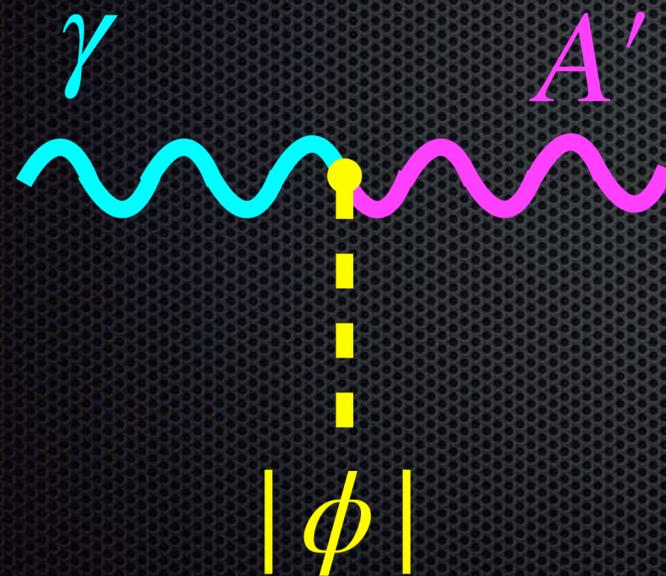When $H \lesssim m_\phi$, ϕ starts the damped oscillation

$$|\phi| \propto a^{-3/2}$$

UV Freeze-in vs IR Freeze-in

γ

A'

ϕ

γ

A'

$|\phi|$

UV Freeze-in vs IR Freeze-in

γ

A'

ϕ

γ

A'

$|\phi|$

$$\frac{\Omega_{\gamma \to A' + \phi}}{\Omega_{\gamma \to A'}} \sim \frac{m_{A'} T_{rh}}{|\phi|^2}$$
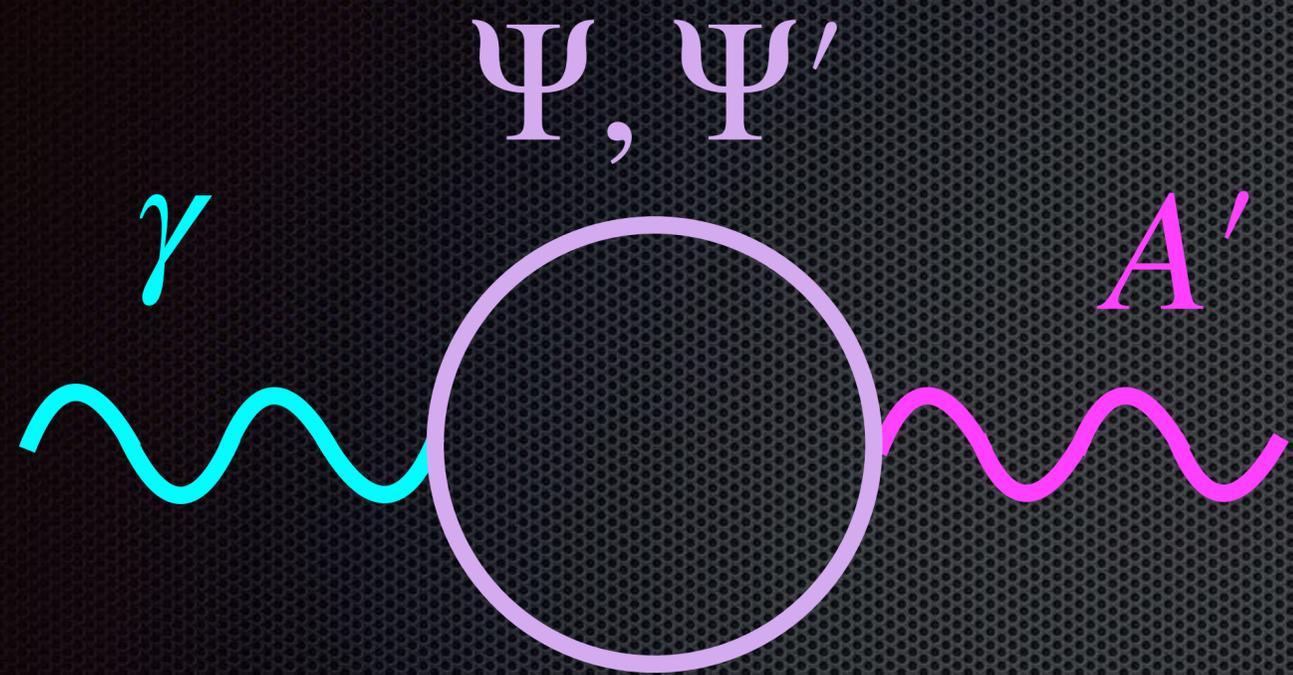
Varying Kinetic Mixing

$$\epsilon_{FI} \sim 10^{-12}$$

$$T_{osc} \sim (m_\phi m_{pl})^{1/2}$$

$$\epsilon_0 \sim \epsilon_{FI} \left(\frac{T_0}{T_{osc}} \right)^{3/2}$$

Aspects of UV Model

Constant Kinetic Mixing

Ψ, Ψ'

γ

A'

$\Psi : (e, e') \quad \Psi' : (e, -e')$

$$\epsilon = \frac{ee'}{6\pi^2} \log\left(\frac{M}{M'}\right)$$

$M = M' : \epsilon$ vanishes

$\mathbb{Z}_2 : \Psi \leftrightarrow \Psi', A \to A, A' \to -A'$

Bob Holdom 1985

Constant Kinetic Mixing

Ψ, Ψ'

γ

A'

$\Psi : (e, e') \quad \Psi' : (e, -e')$

$$\epsilon = \frac{ee'}{6\pi^2} \log\left(\frac{M}{M'}\right)$$

$M = M' : \epsilon$ vanishes

$\mathbb{Z}_2 : \Psi \leftrightarrow \Psi', A \to A, A' \to -A'$

$\phi \to -\phi \quad \phi F F'$ survives

Bob Holdom 1985

Introduce $y\phi\bar{\Psi}\Psi$ and $y'\phi\bar{\Psi}'\Psi'$

Time-varying ϵ
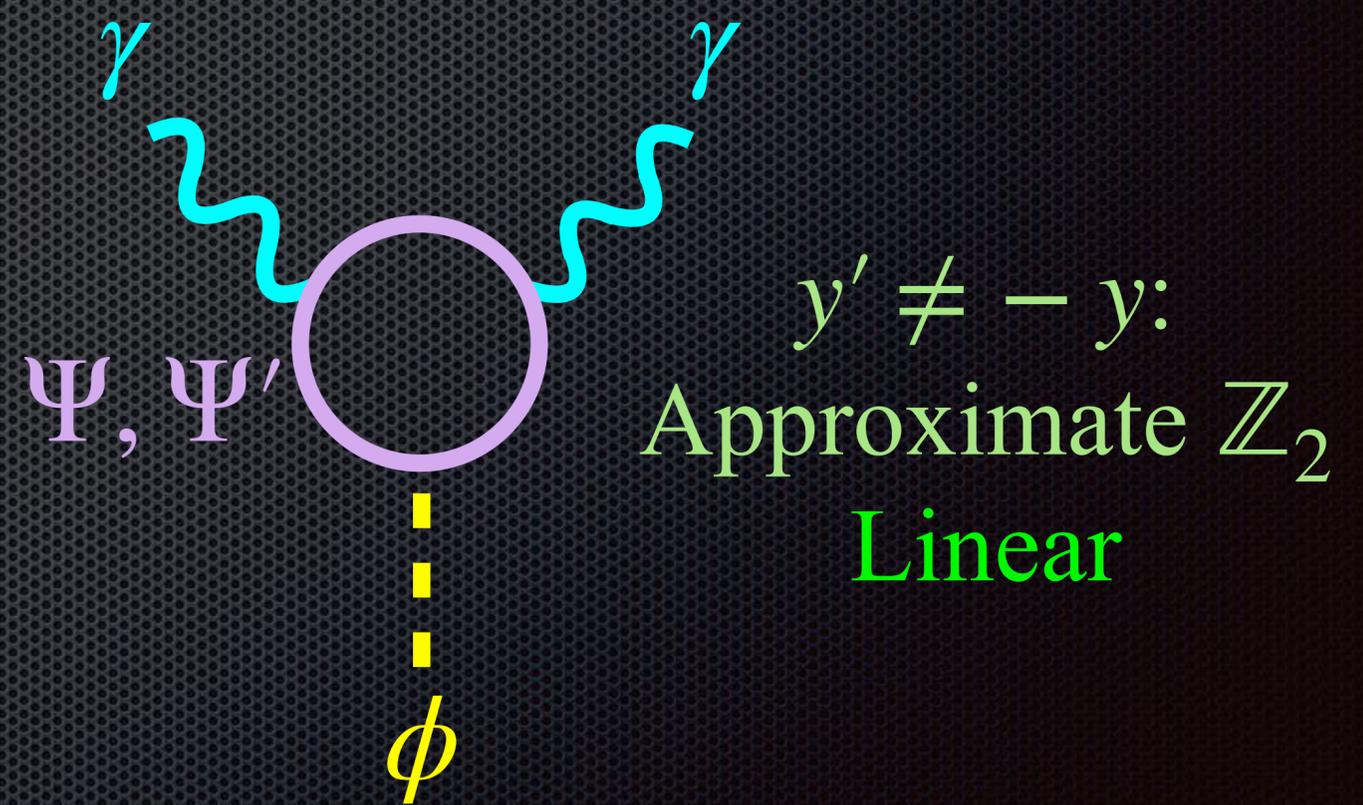

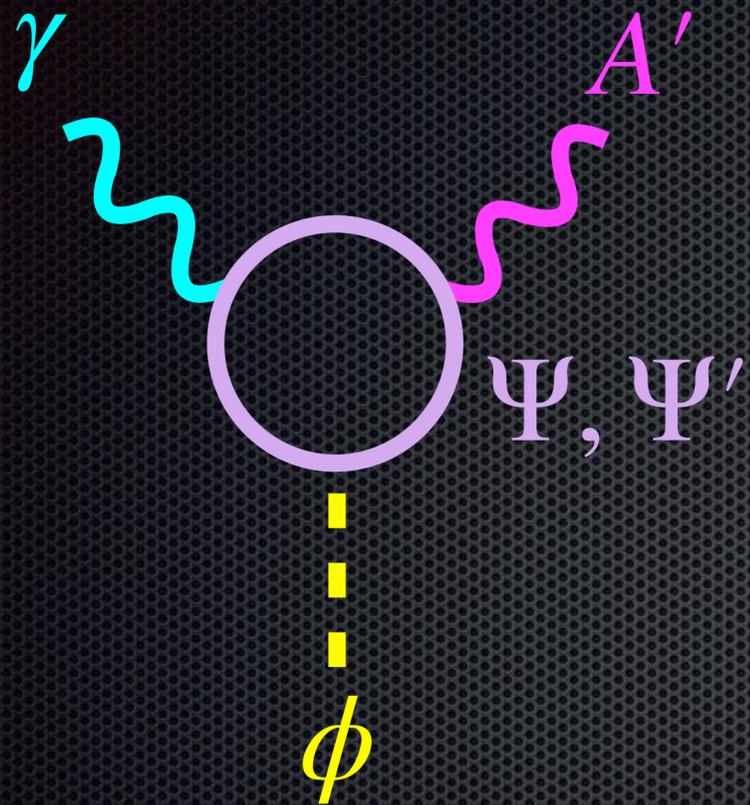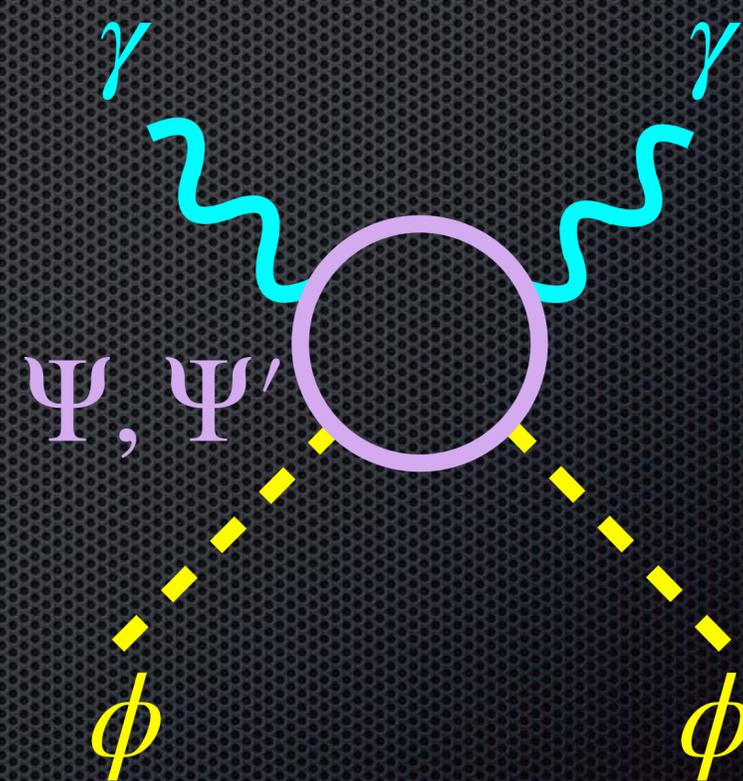$$\mathcal{L} \supset \frac{1}{2}\frac{\phi}{\Lambda_{KM}}FF'$$

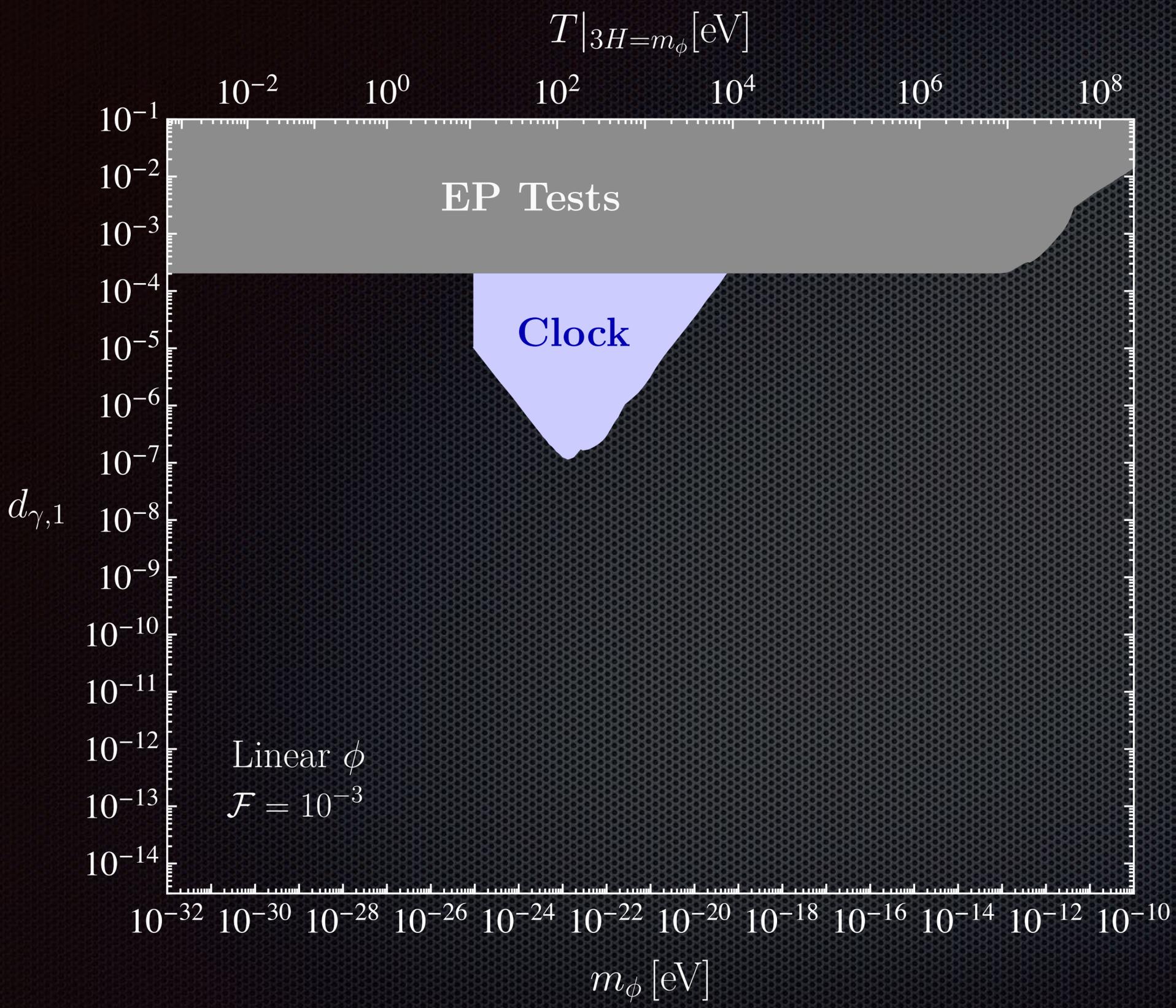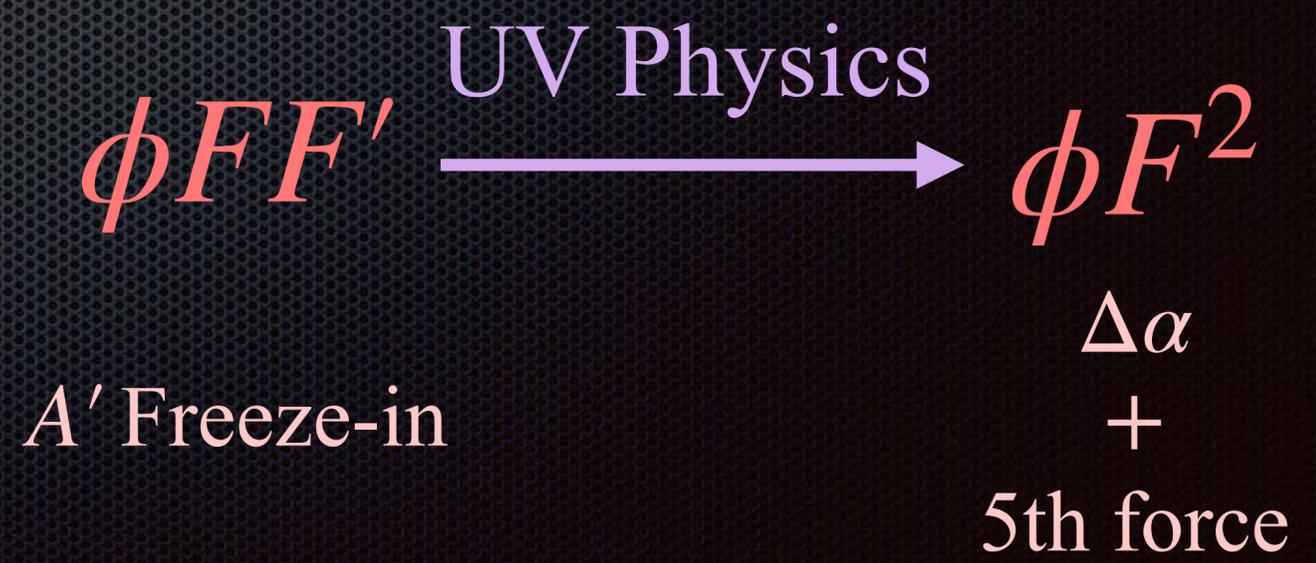# Introduce $y\phi\bar{\Psi}\Psi$ and $y'\phi\bar{\Psi}'\Psi'$

Time-varying ϵ

Time-varying α + 5th force

γ

A'

γ

γ

Ψ, Ψ'

Ψ, Ψ'

$y' \neq -y$:

Approximate $\mathbb{Z}_2$

Linear

ϕ

ϕ

$$\mathcal{L} \supset \frac{1}{2}\frac{\phi}{\Lambda_{KM}}FF'$$

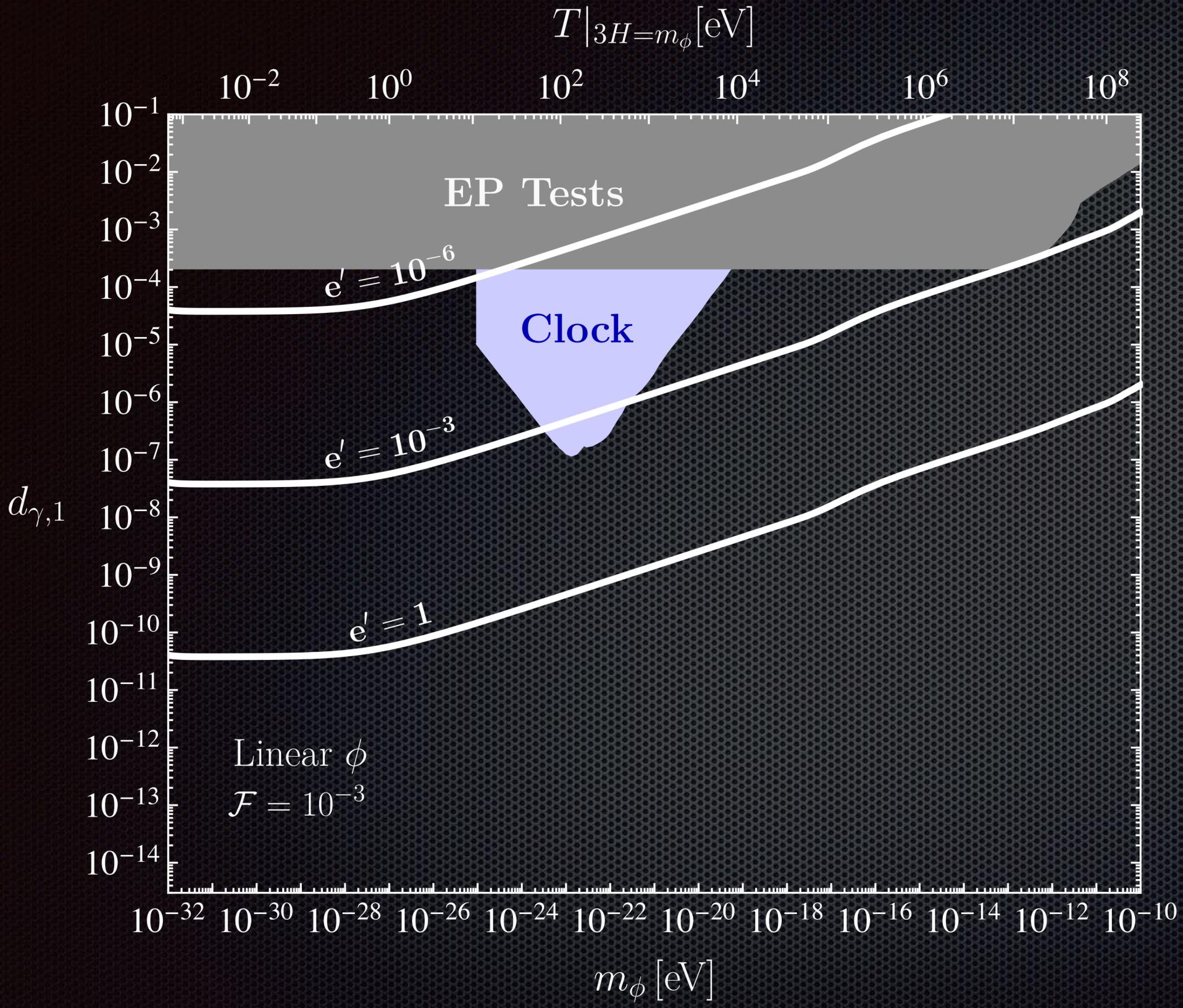$$\mathcal{L} \supset \frac{1}{2}\frac{\phi}{\Lambda_{\gamma}}F^2$$

Introduce $y\phi\bar{\Psi}\Psi$ and $y'\phi\bar{\Psi'}\Psi'$

Time-varying ϵ

Time-varying α + 5th force

$$\mathcal{L} \supset \frac{1}{2}\frac{\phi}{\Lambda_{KM}}FF'$$

$y' = -y$:
Exact $\mathbb{Z}_2$
Quadratic

$$\mathcal{L} \supset \frac{1}{2}\frac{\phi^2}{\Lambda_\gamma^2}F^2$$

Linear Coupling

$$\mathscr{L} \sim d_{\gamma,1} \frac{\phi}{m_{pl}} F^2$$

UV Physics

$$\phi FF' \xrightarrow{\quad\quad} \phi F^2$$

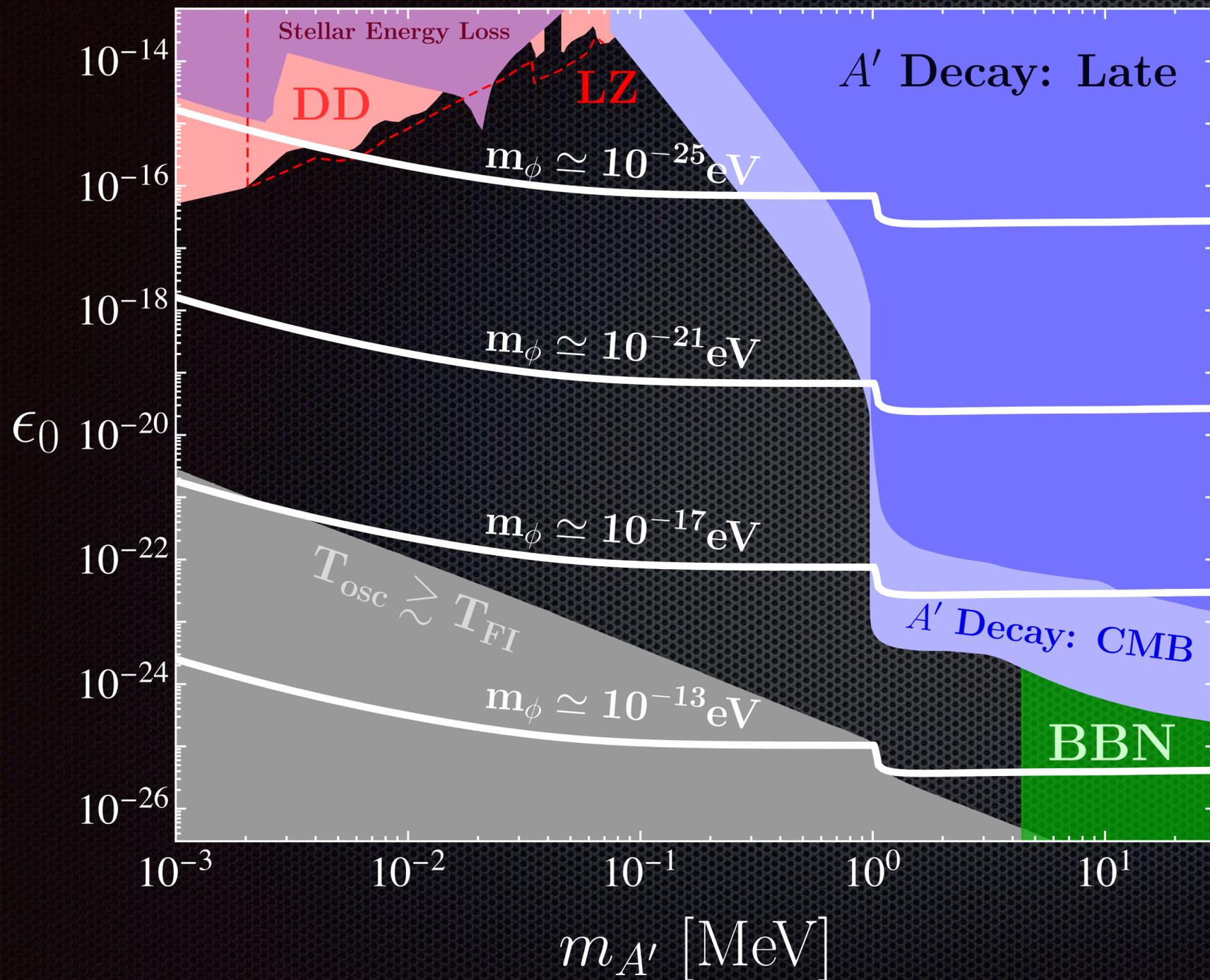A' Freeze-in

$\Delta\alpha$
+
5th force

Conclusion

- The freeze-in of dark photon dark matter through the kinetic mixing is entirely ruled out by current constraints. Other dark photon production mechanisms are either independent of the kinetic mixing or UV sensitive.

- Noticing that all the constraints are imposed in the late universe, in our model, we promote the kinetic mixing to be a dynamical variable controlled by the cosmological evolution of the ultralight scalar ϕ. In this case, the dark photon is produced through effective mixing, and this is the IR process.

- Based on UV physics, the varying kinetic mixing is always accompanied by scalar-photon coupling, which changes the fine-structure constant and induces the 5th force between objects. Table-top experiments and cosmological observations detecting the fine-structure constant variation and the equivalence principle violation can also be used to test the dark photon dark matter freeze-in through the varying kinetic mixing.

Appendix

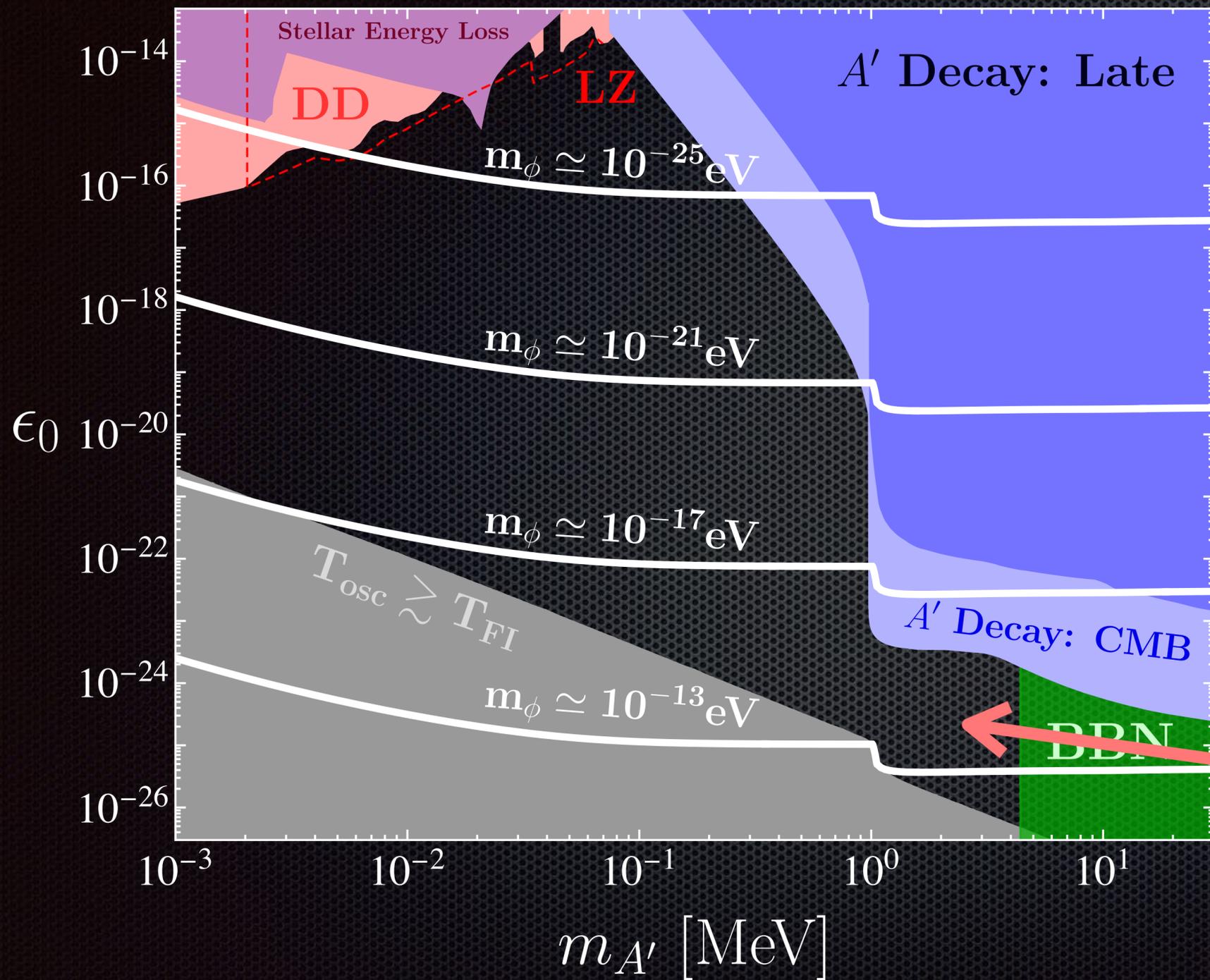$$m_\phi \gg 10^{-25} eV$$

$$\epsilon_{FI} \sim 10^{-12}$$

$$T_{osc} \sim (m_0 m_{pl})^{1/2}$$

$$\epsilon_0 \sim \epsilon_{FI} \left(\frac{T_0}{T_{osc}} \right)^{3/2} \times \mathscr{F}$$

$$m_{A'} > 2m_e$$

Linear Coupling

$$d_{\gamma,1} \sim \frac{m_{pl}}{\Lambda_\gamma}$$

UV Physics: $\Lambda_\gamma \sim e'\Lambda_{KM}$

A' Freeze-in: $\epsilon_{FI} \sim |\phi|/\Lambda_{KM}$

$$\epsilon_{FI} \rightarrow d_{\gamma,1}$$

Quadratic Coupling

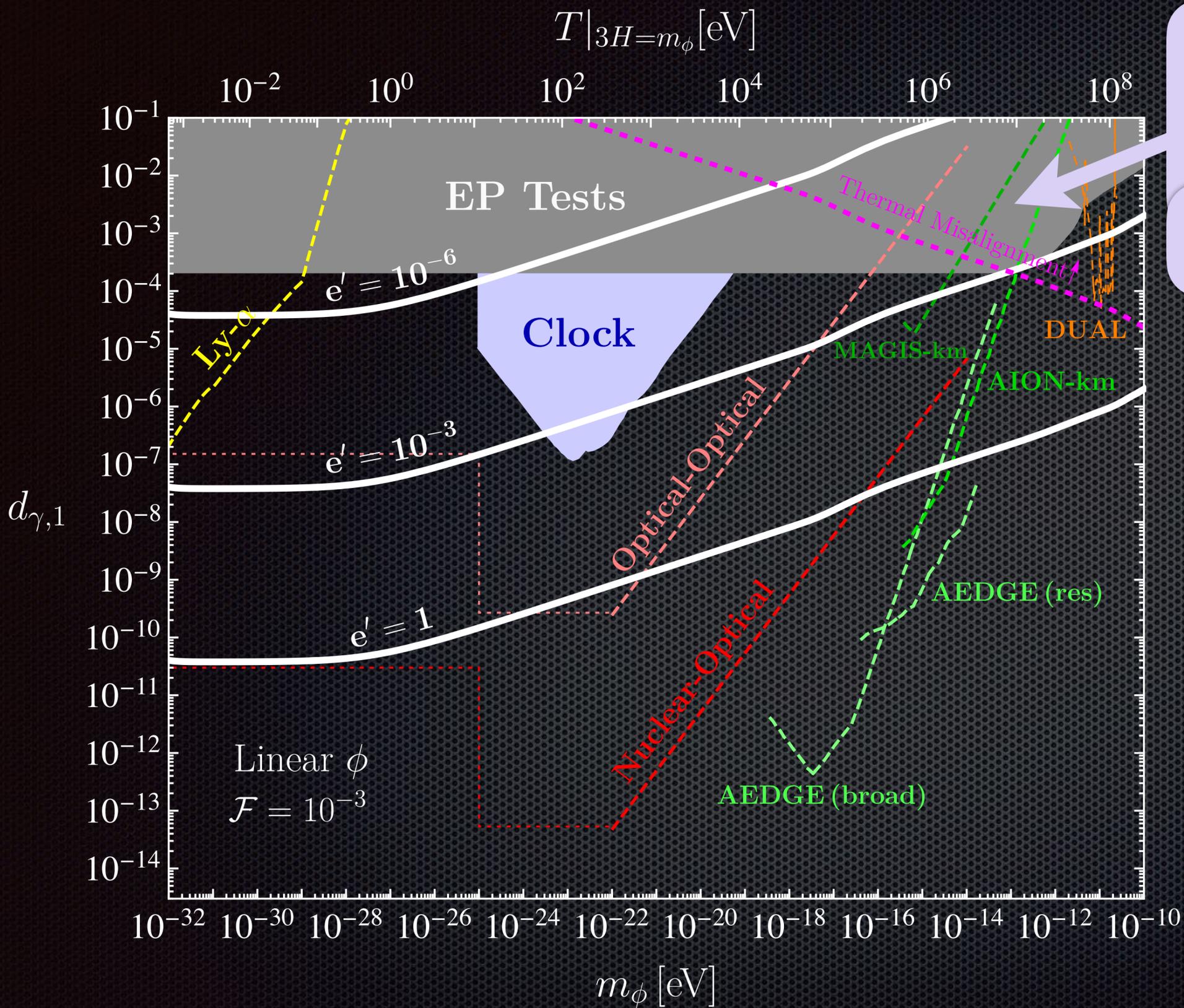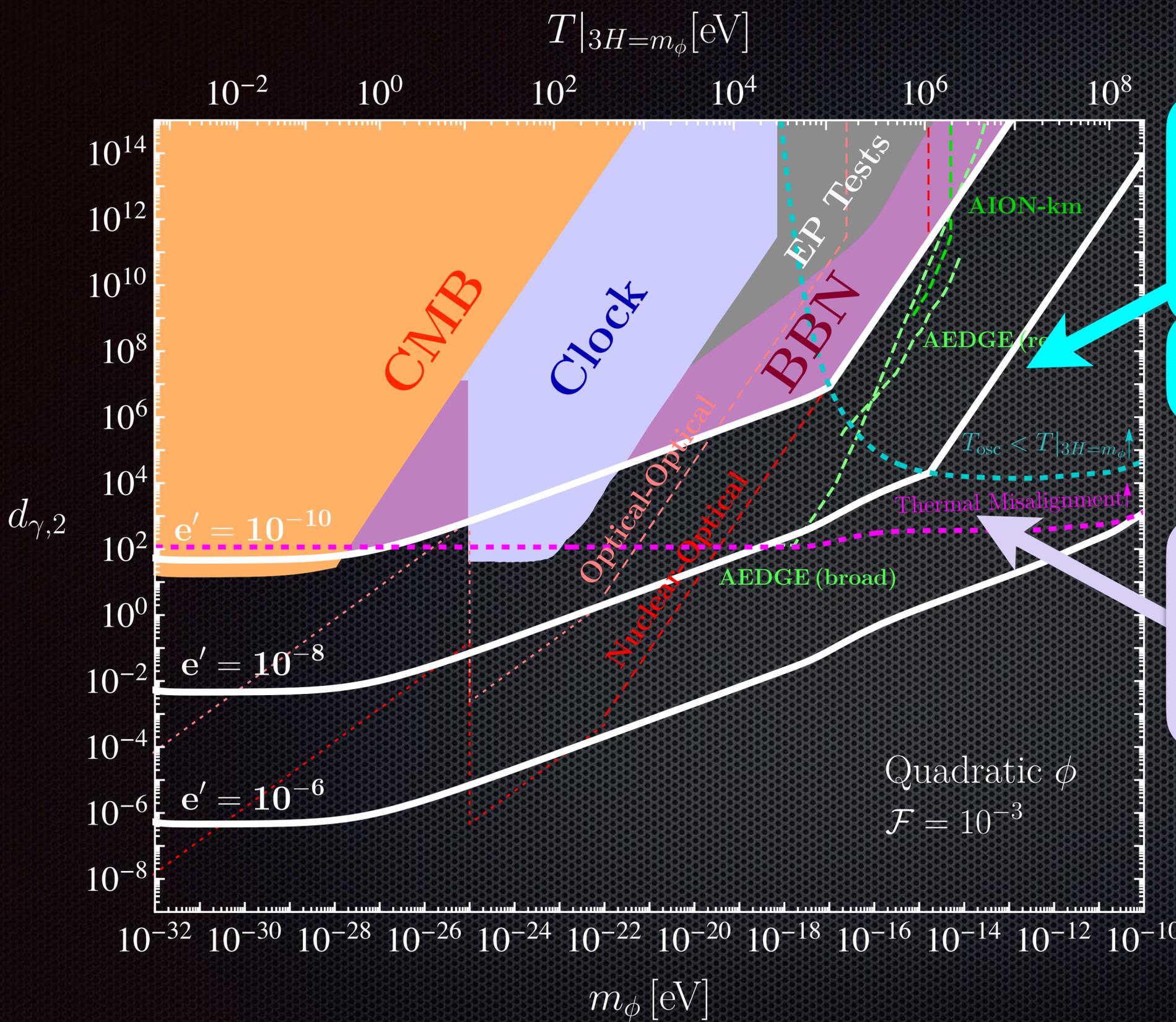$$d_{\gamma,2} \sim \left(\frac{m_{pl}}{\Lambda_\gamma}\right)^2$$

UV Physics: $\Lambda_\gamma \sim e'\Lambda_{KM}$

A' Freeze-in: $\epsilon_{FI} \sim |\phi|/\Lambda_{KM}$

$$\epsilon_{FI} \rightarrow d_{\gamma,2}$$

Thermal Misalignment

Brzeminski, Chacko, Dev, Hook 2021
Batell, Ghalsasi 2021

$$\mathscr{L} \sim d_{\gamma,1} \frac{\phi}{m_{pl}} F^2$$
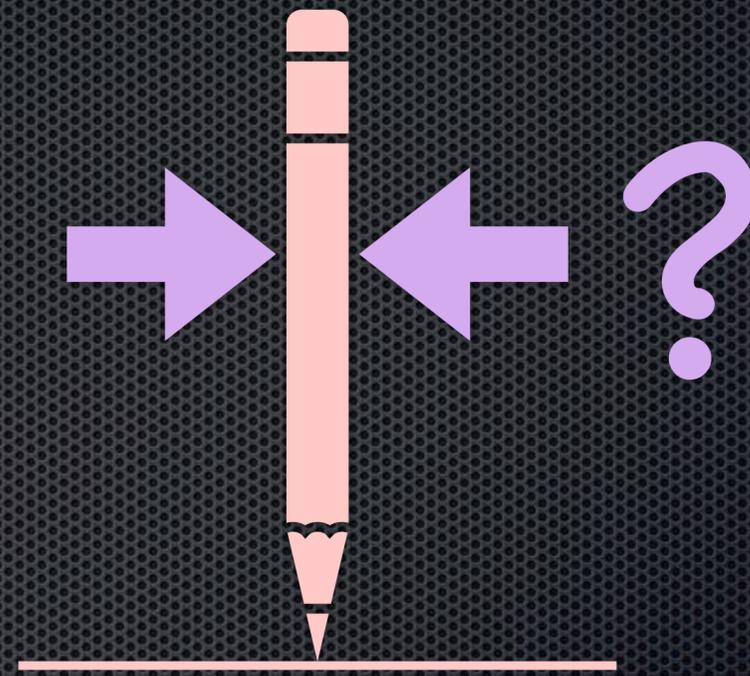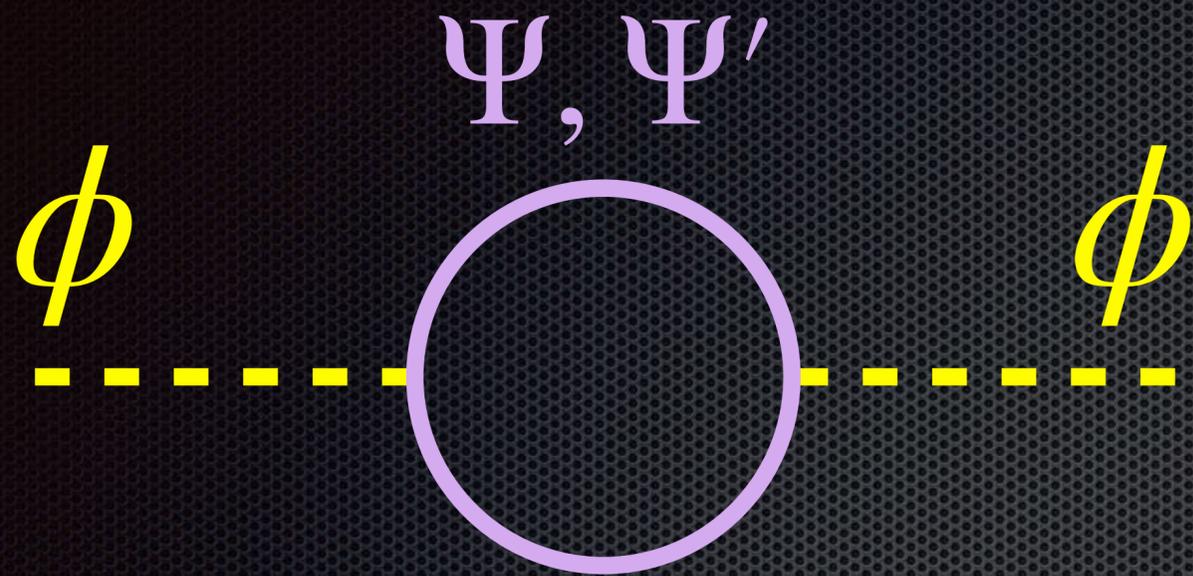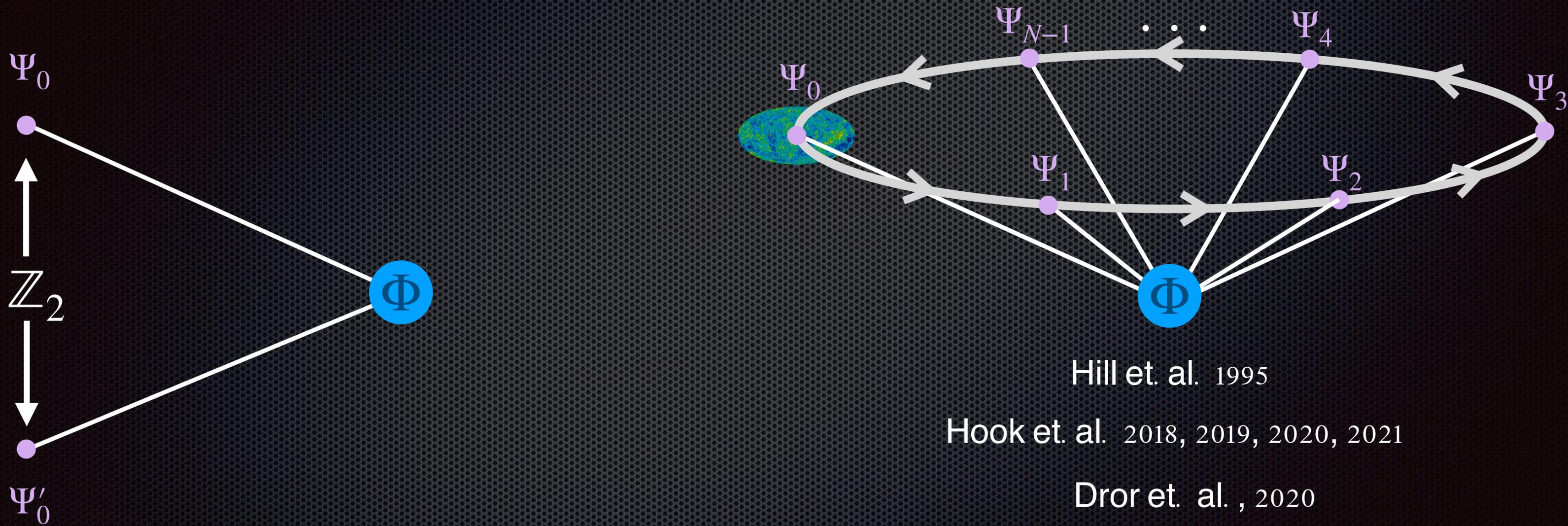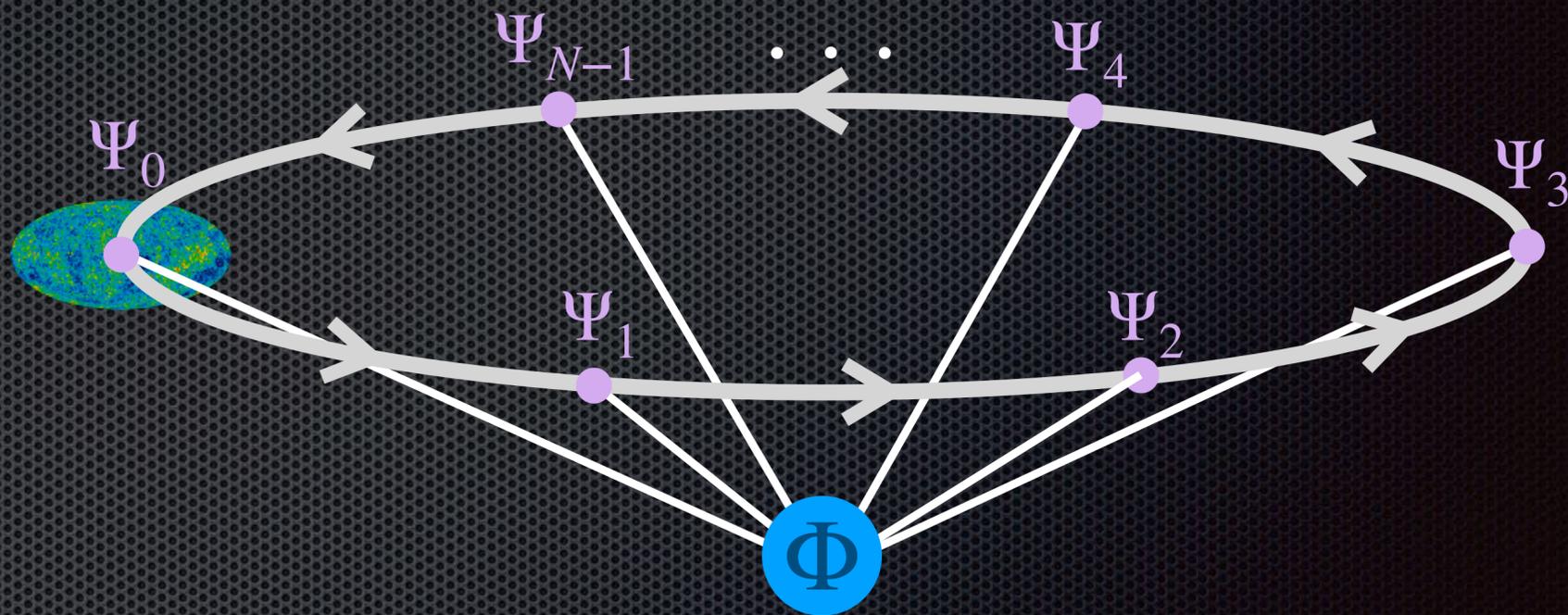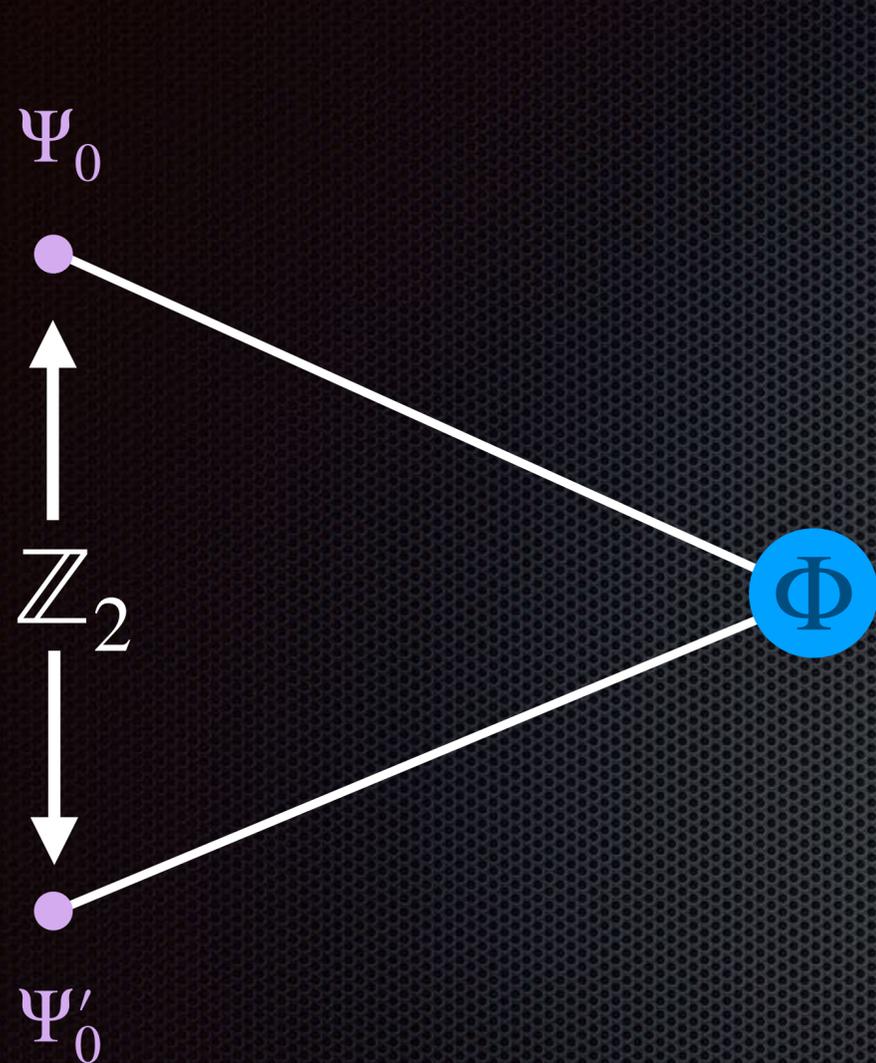
UV Physics

$$\phi F F' \longrightarrow \phi F^2$$

Scalar Naturalness

$$\Delta m_\phi \simeq 10^{-11} eV \left(\frac{\epsilon_{FI}}{10^{-12}} \right) \left(\frac{M}{10 TeV} \right)^2 \left(\frac{10^{17} GeV}{|\phi|_{osc}} \right) \left(\frac{1}{e'} \right)$$

$$\gg 10^{-20} eV$$
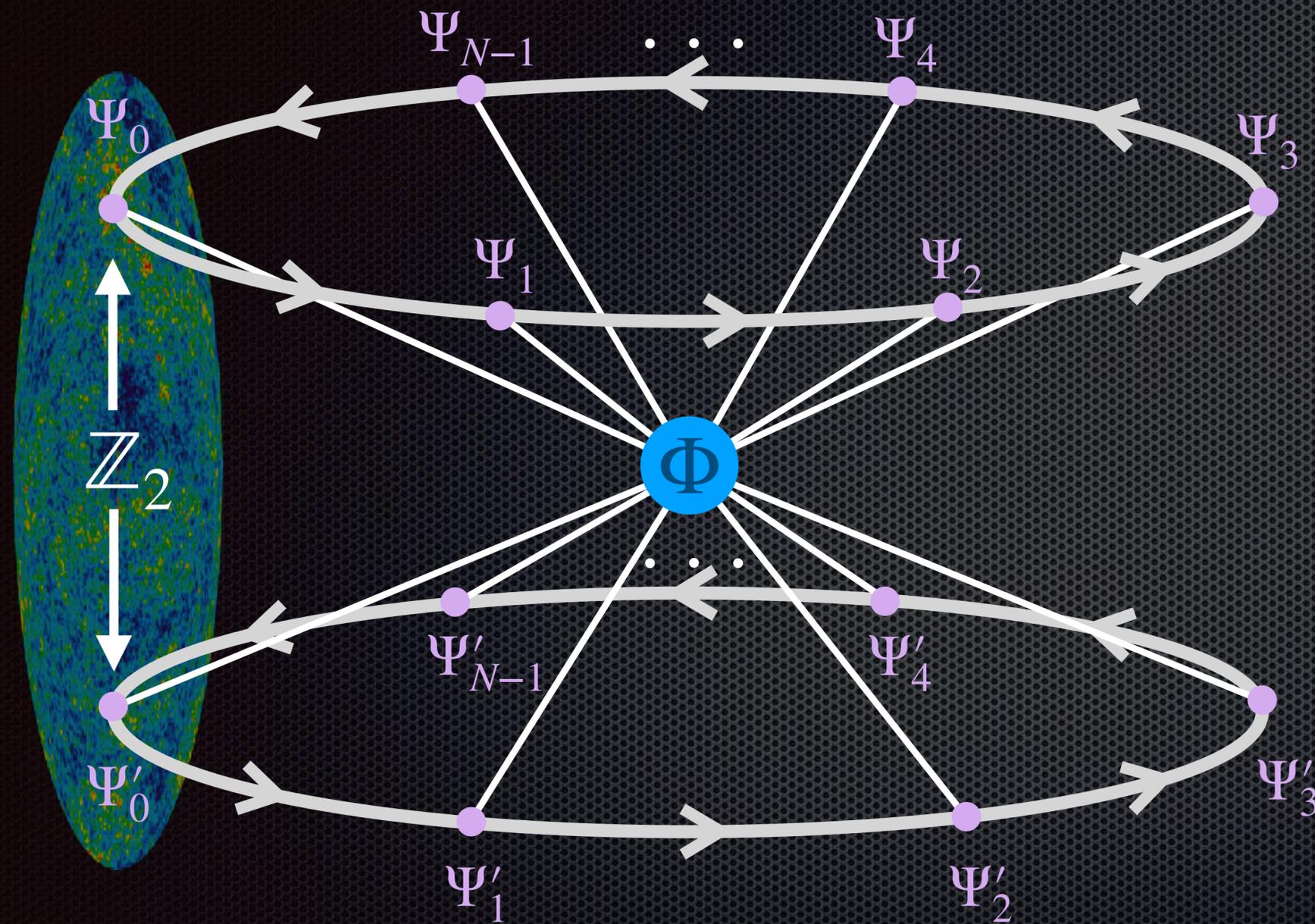
$\mathbb{Z}_2$ $\times$ $\mathbb{Z}_N$

Ψ_0

$\mathbb{Z}_2$

Φ

Ψ_0'

Ψ_{N-1} $\cdots$ Ψ_4

Ψ_0

Ψ_3

Ψ_1 Ψ_2

Φ

Hill et. al. 1995

Hook et. al. 2018, 2019, 2020, 2021

Dror et. al. , 2020

Ringwald et. al. , 2021

Perez et. al. , 2021

$$\mathbb{Z}_2 \quad \times \quad \mathbb{Z}_N$$

$$\Psi_0$$

$$\mathbb{Z}_2$$

$$\Psi_0'$$

$$\Phi$$

$$\Psi_{N-1} \quad \cdots \quad \Psi_4$$

$$\Psi_0$$

$$\Psi_3$$

$$\Psi_1$$

$$\Psi_2$$

$$\Phi$$

$$\Phi \rightarrow \Phi \exp\left(i\frac{2\pi}{N}\right)$$

$$(SM + \mathcal{O}_P + DS)_k \rightarrow (SM + \mathcal{O}_P + DS)_{k+1}$$

$$\mathscr{L}_{U(1)} \sim \frac{\Phi^N}{\Lambda_1^{N-4}} + h.c.$$