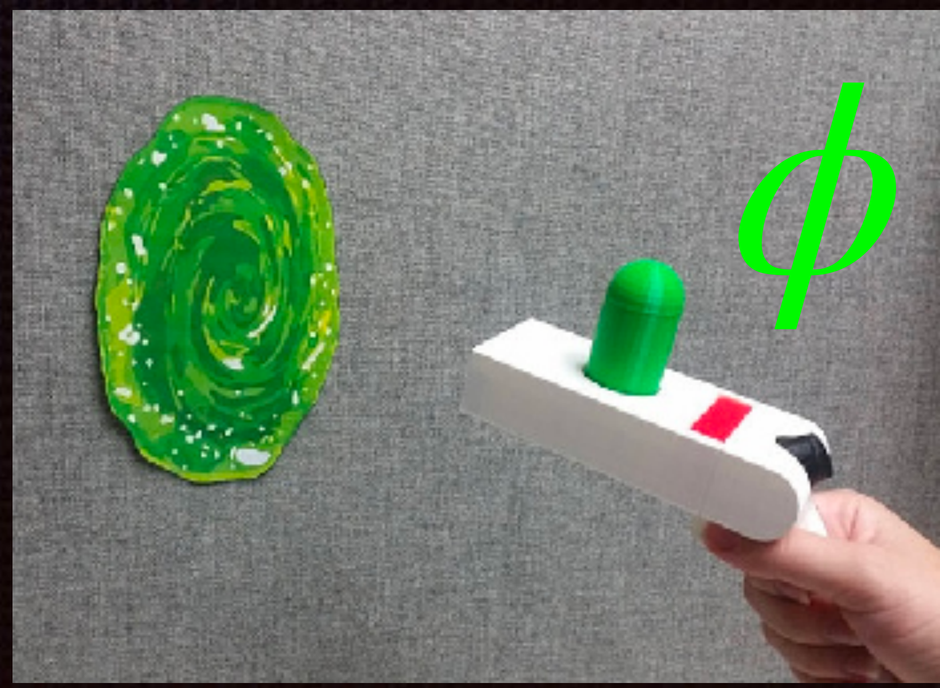
Cosmologically Varying Kinetic Mixing

Xucheng Gan, Di Liu

arXiv. 2302.03056

PASCOS 2023,
University of California Irvine

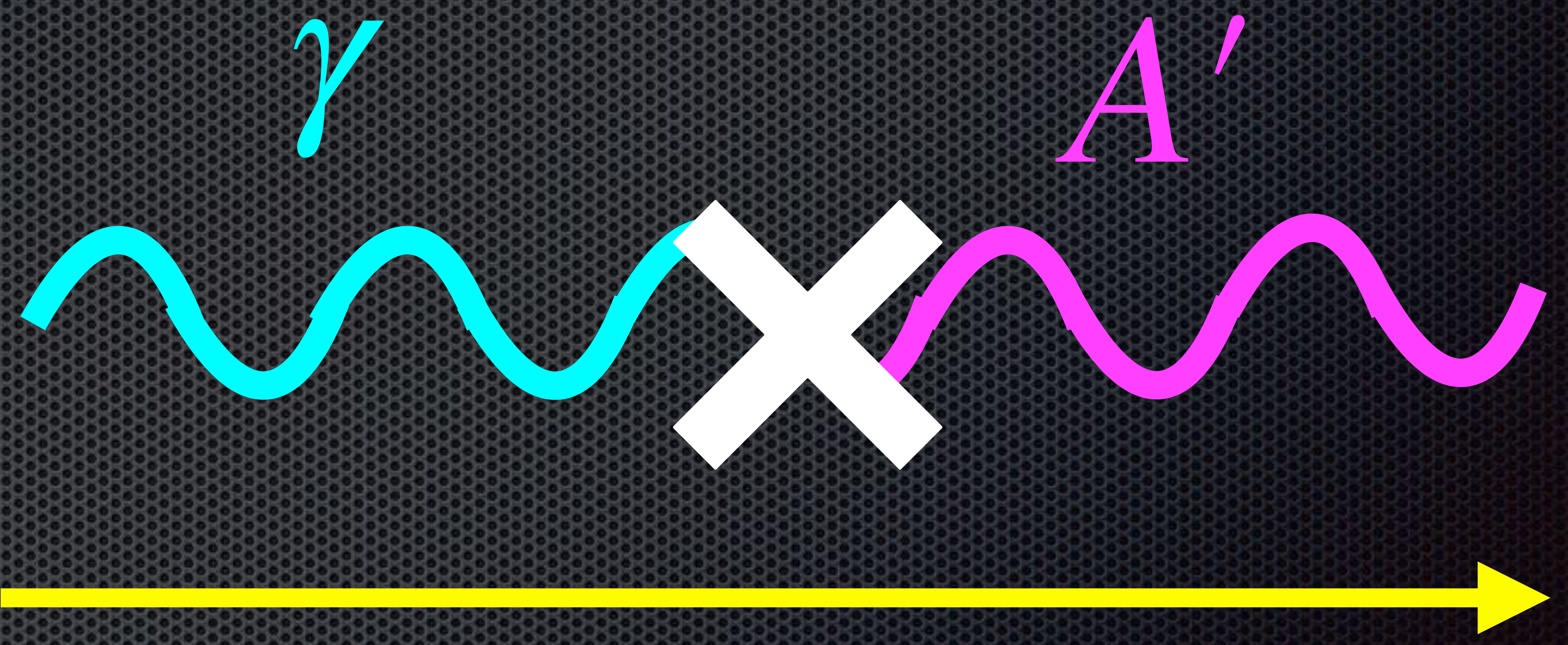
ϵ



Kinetic Mixing

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

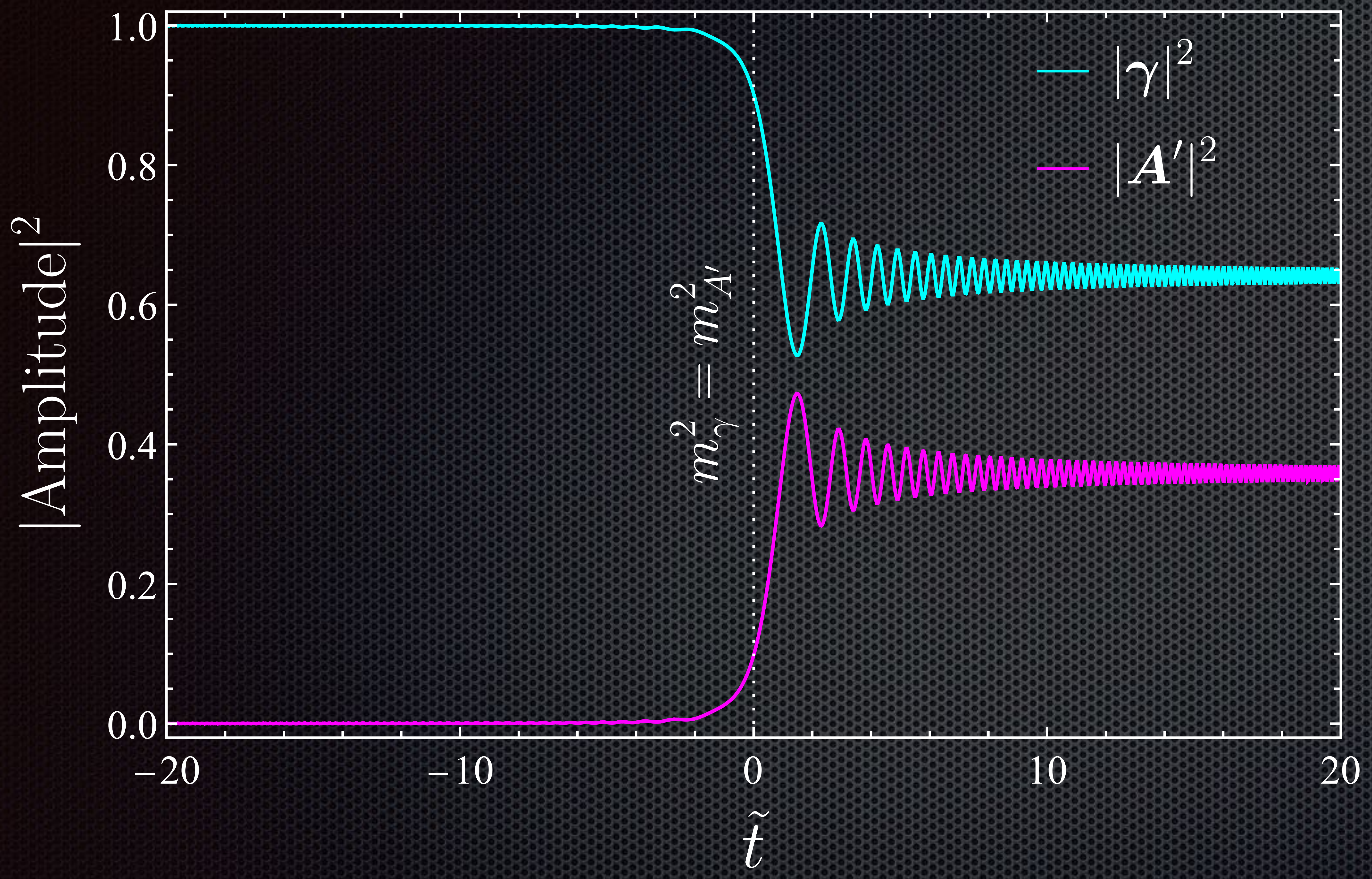
Bob Holdom 1985



Freeze-in

Hall, Jedamzik, March-Russell, West 2009

A' Freeze-in: $\gamma \to A'$



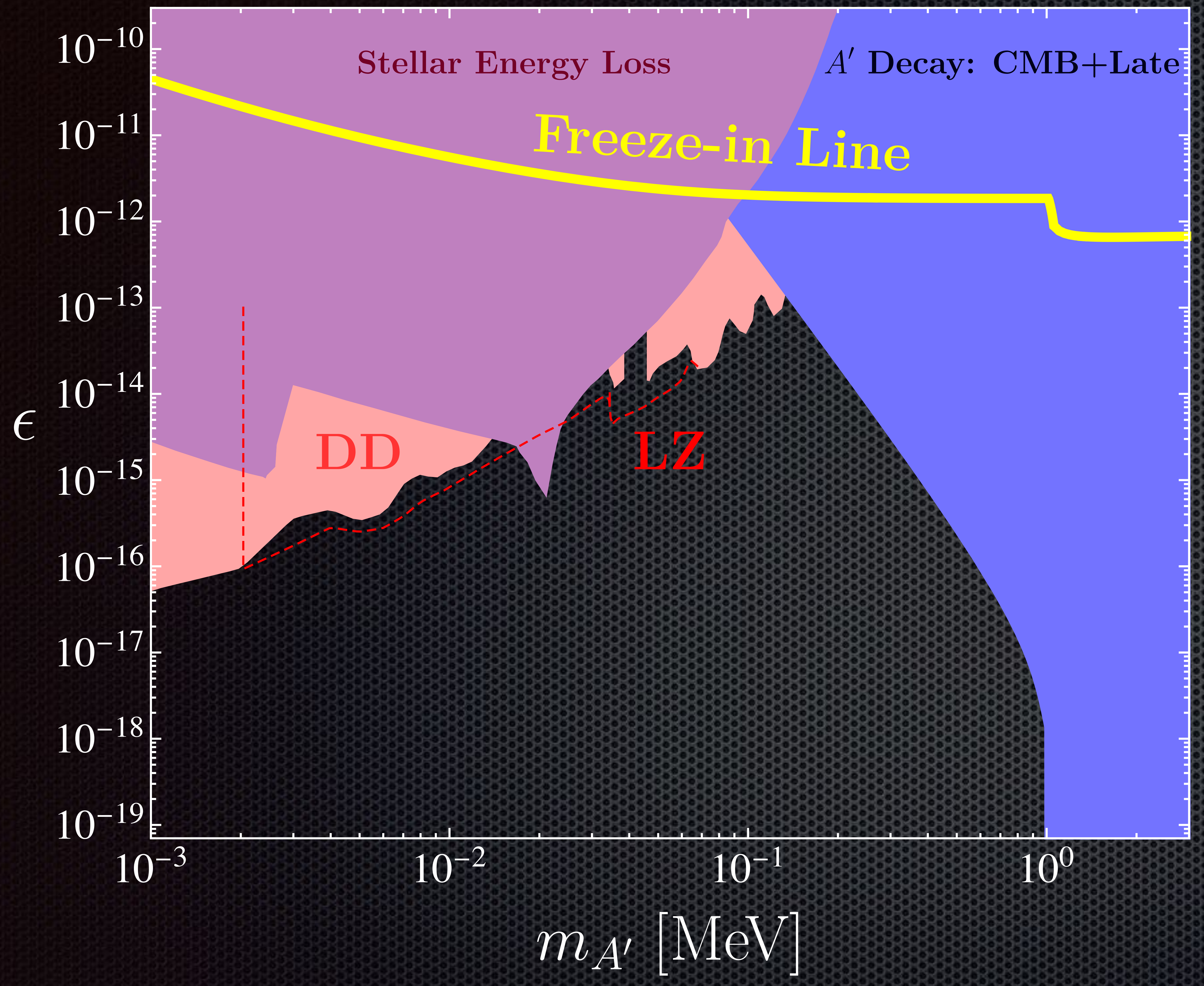
$$\Omega_{A'} \sim \epsilon^2 \alpha^{3/2} \frac{m_{pl}}{T_{eq}}$$

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

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

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

Dark Photon Dark Matter



Redondo, Postma 2005

Stellar energy loss:

$\gamma \rightarrow A'$

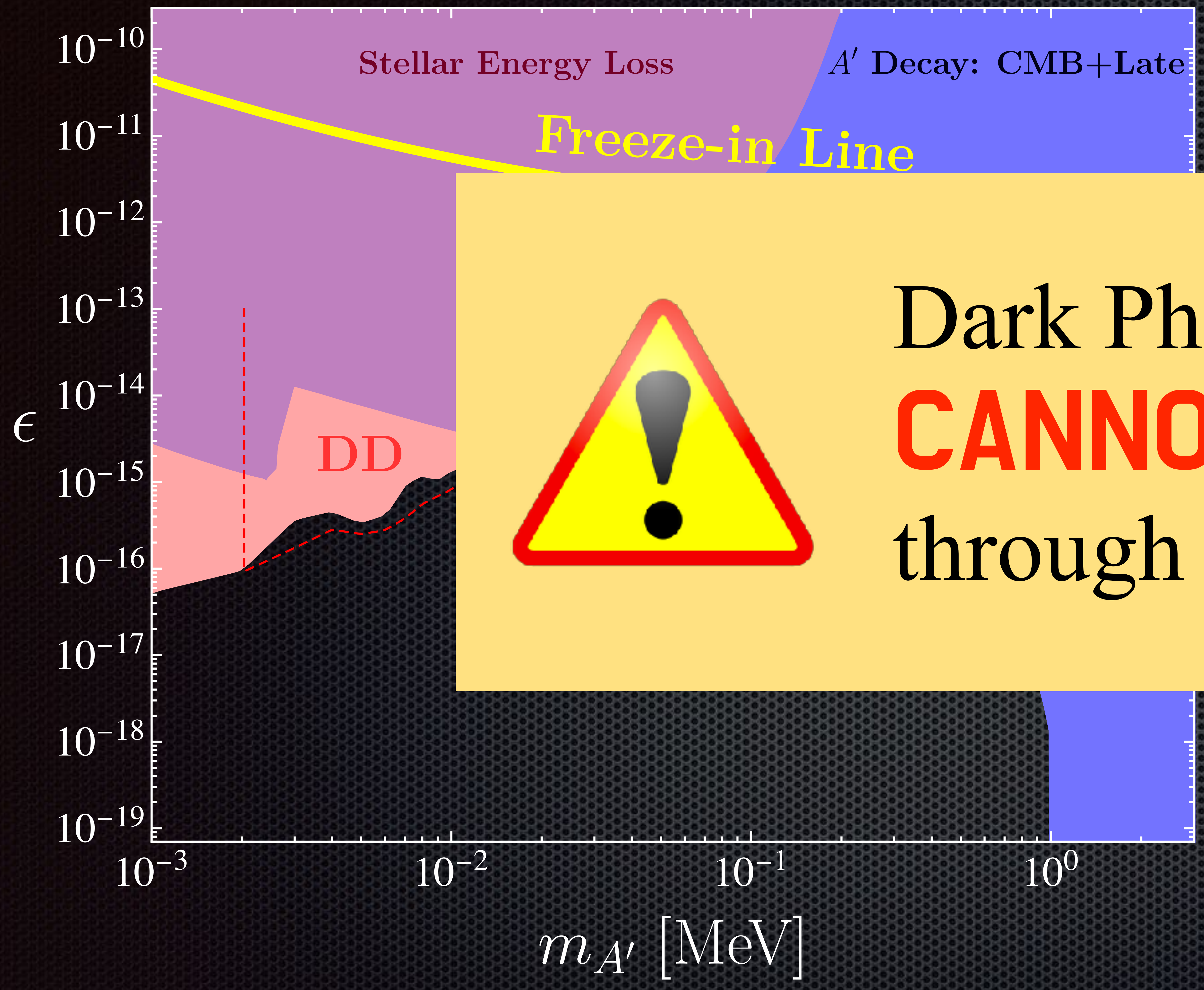
Direct Detection:

A' Absorption

A' Decay:

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

Dark Photon Dark Matter



Redondo, Postma 2005

Stellar energy loss:

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

A' Decay:

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

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 1
1905.09836 1

Production

1810.07188 1810.07
1810.07208 2104.02

ependent of
etic mixing

Dark Photon Dark Matter:

Kinetic Mixing?
IR Process?

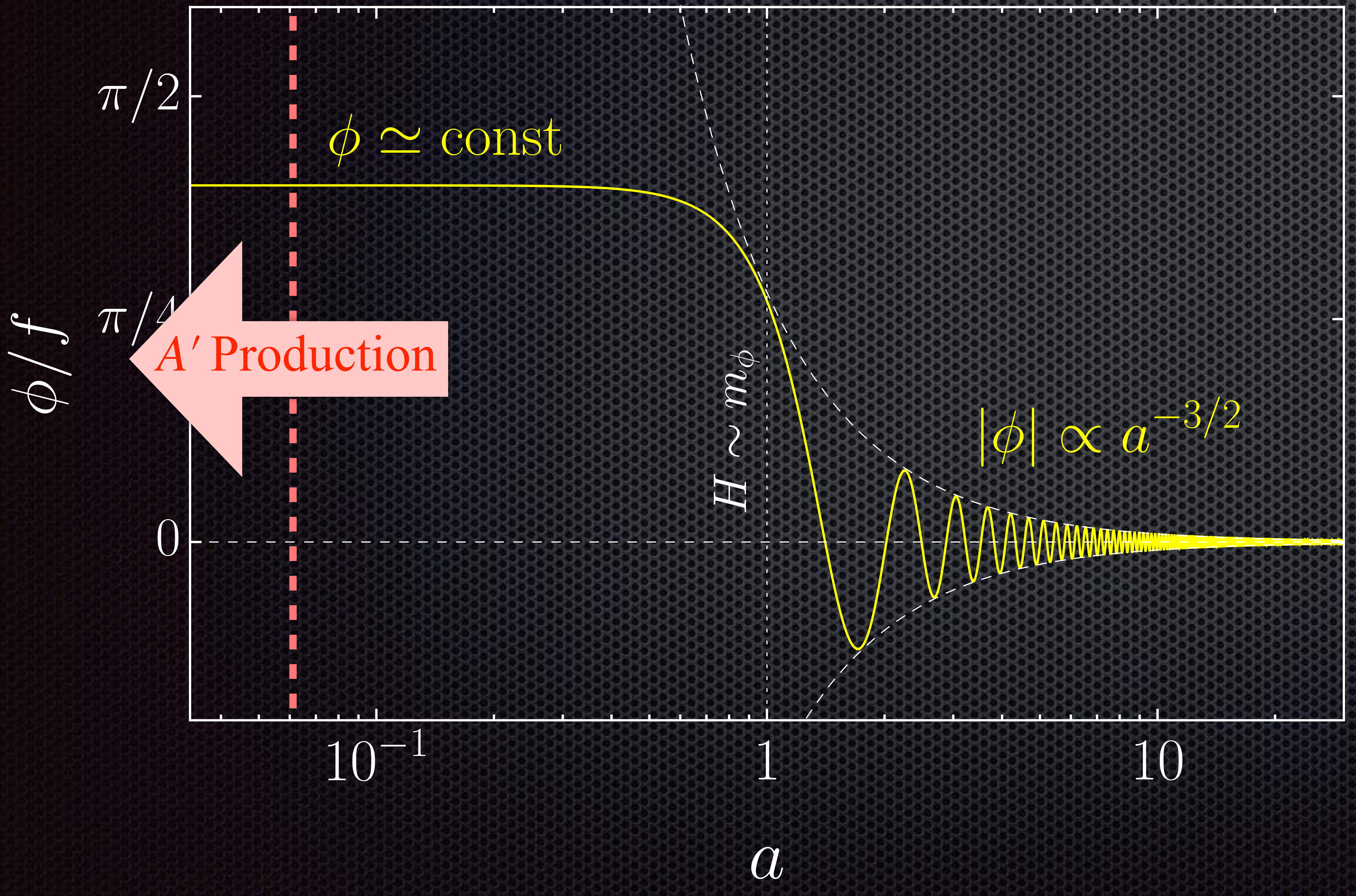
V sensitive

2210.06487 2303.11344

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

Kinetic Mixing Varying Cosmologically

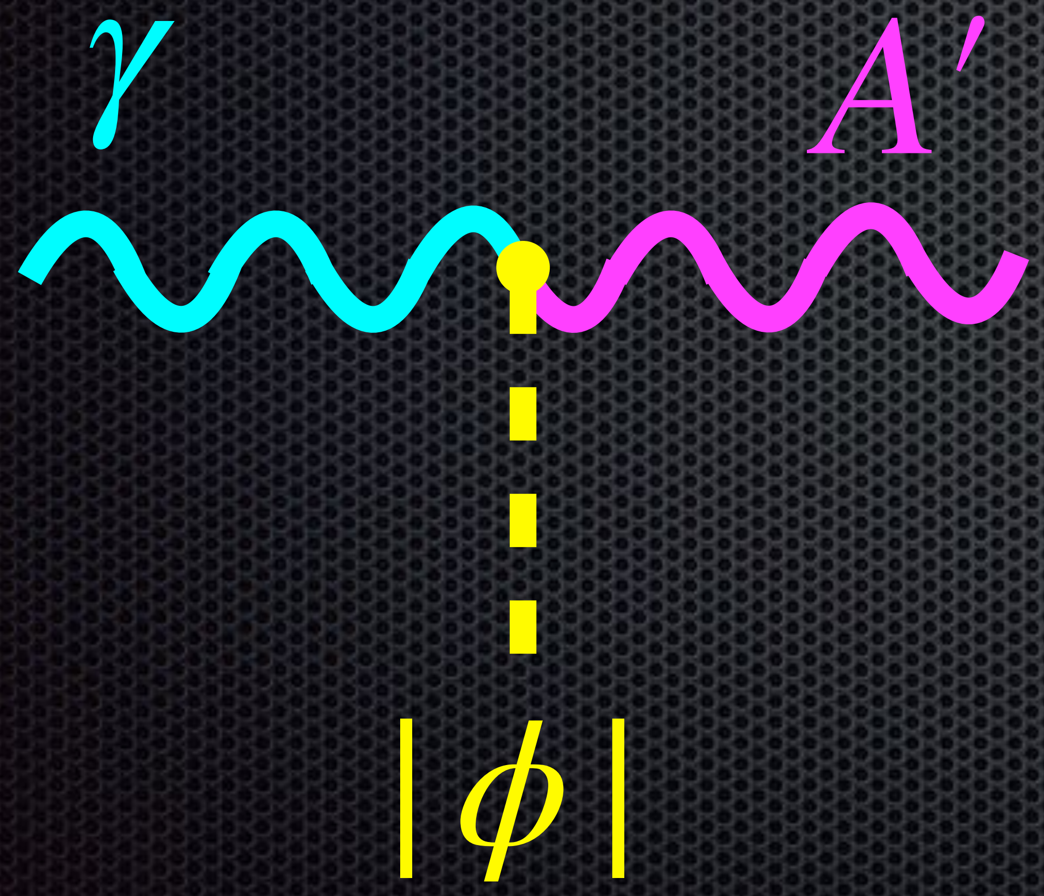
$$\mathscr{L} \supset \frac{\epsilon}{2} F_{\mu\nu} F'^{\mu\nu} \longrightarrow \mathscr{L} \supset \frac{1}{2}\frac{\phi}{\Lambda} F_{\mu\nu} F'^{\mu\nu}$$



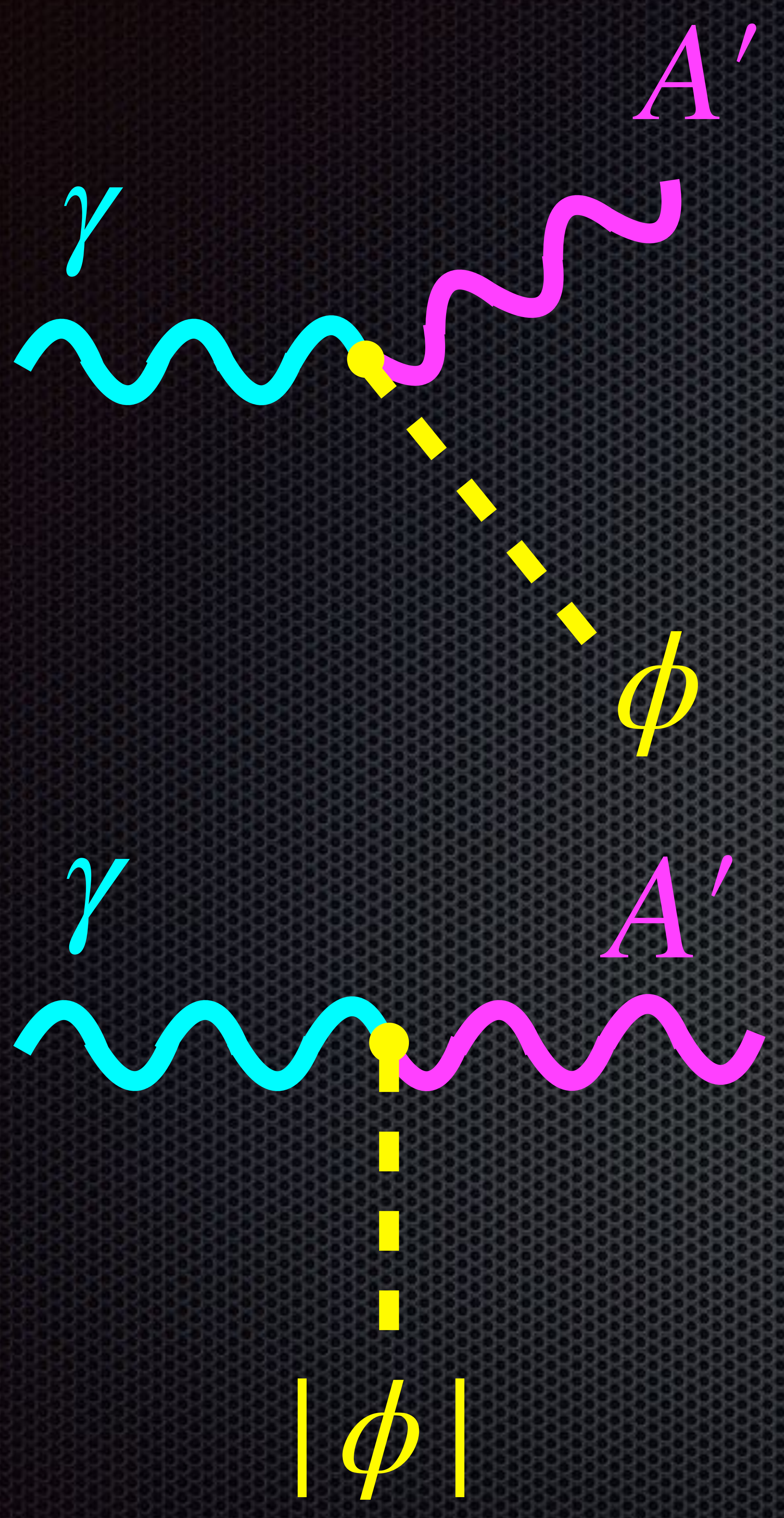
When $H \lesssim m_\phi$, ϕ starts the damped oscillation

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

UV Freeze-in vs IR Freeze-in

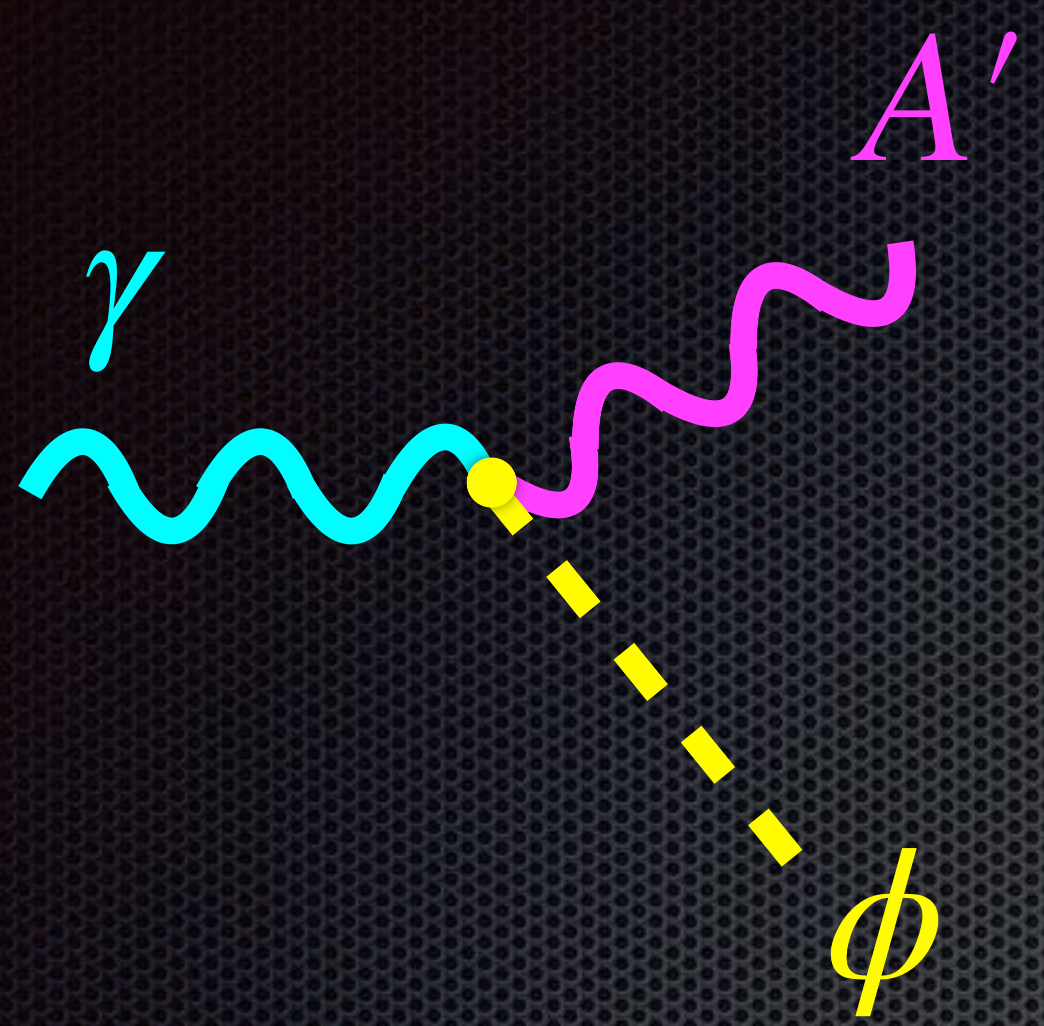


UV Freeze-in vs IR Freeze-in

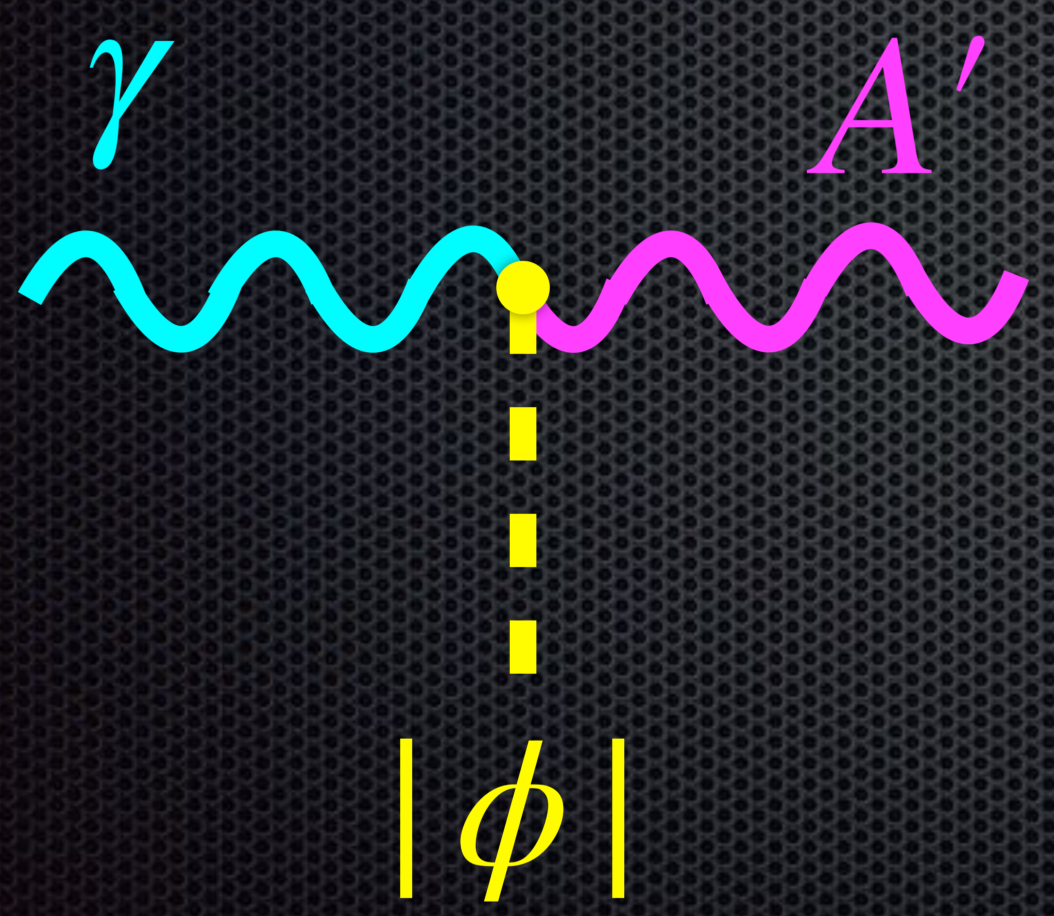


$$\frac{\Omega_{\gamma \to A' + \phi}}{\Omega_{\gamma \to A'}} \sim \frac{m_{A'} T_{rh}}{|\phi|^2}$$

UV Freeze-in vs IR Freeze-in



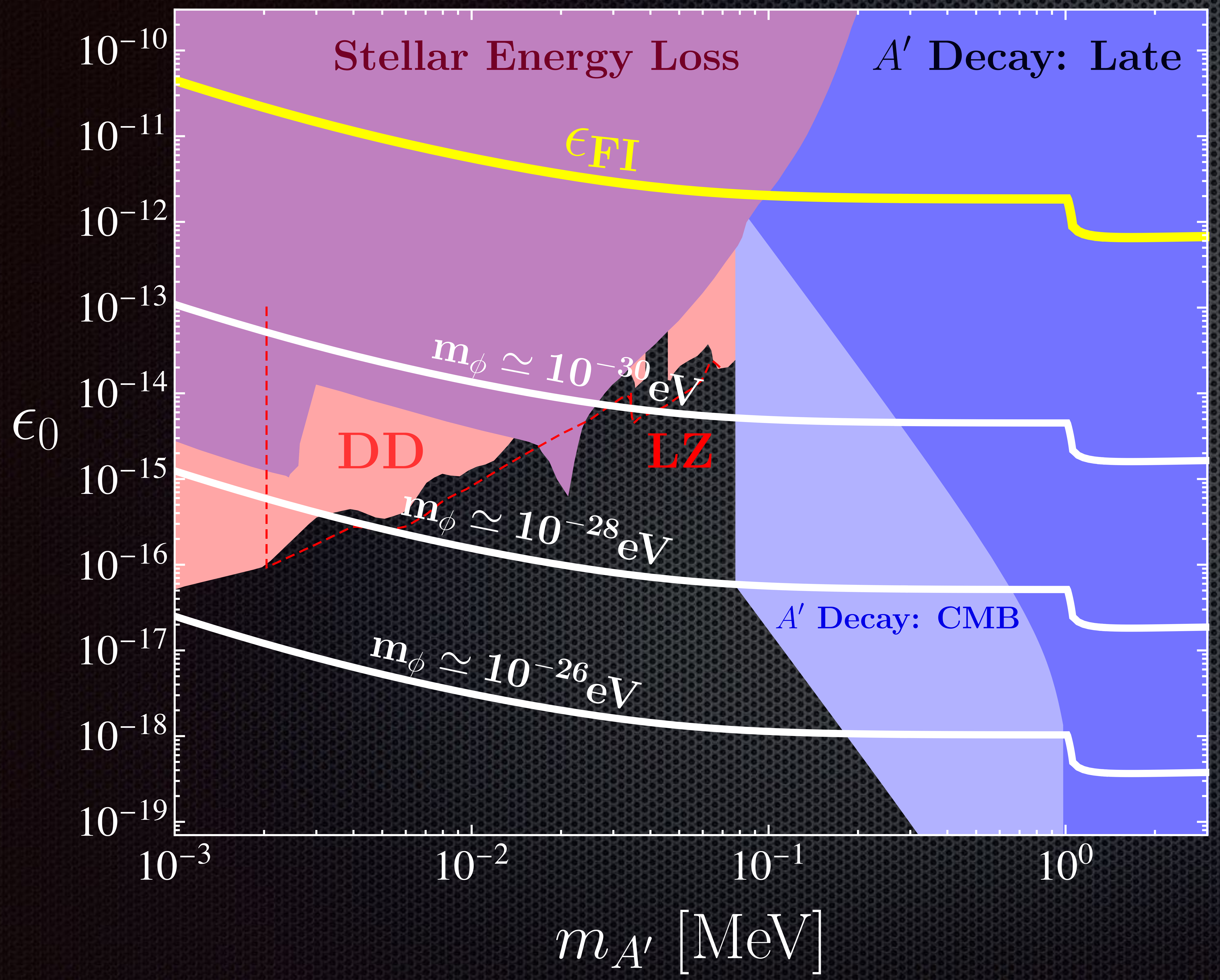
$$\frac{\Omega_{\gamma\to A'+\phi}}{\Omega_{\gamma\to A'}} \sim \frac{m_{A'}T_{rh}}{|\phi|^2} \ll 1$$



$$|\phi| = \sqrt{2\rho_\phi / m_\phi}$$

$$m_\phi \sim 10^{-20} eV \Longleftrightarrow |\phi| \sim 10^{15} GeV$$

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

Bob Holdom 1985

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

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

$M = M'$: ϵ vanishes

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

Constant Kinetic Mixing

Bob Holdom 1985

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

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

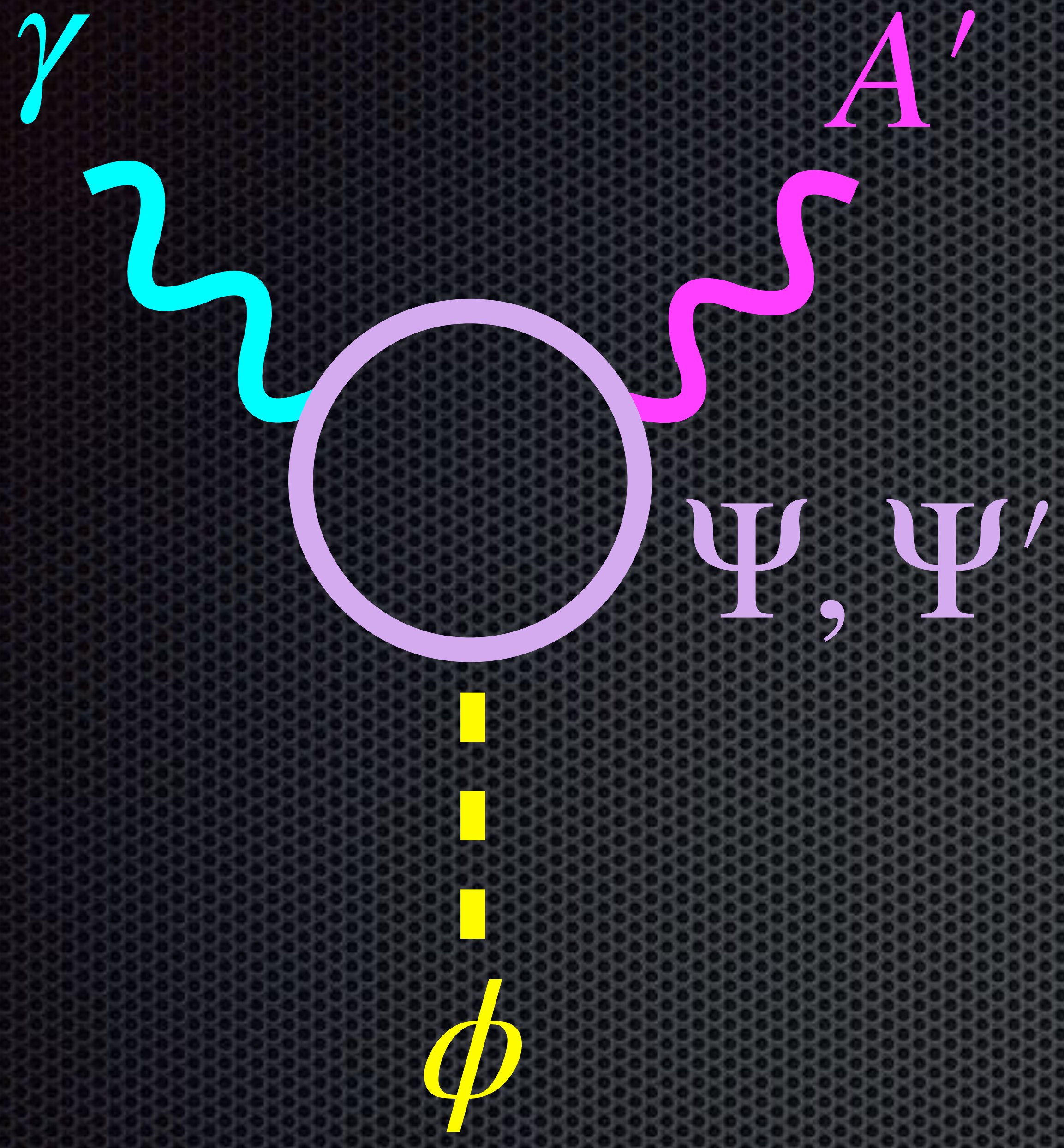
$M = M'$: ϵ vanishes

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

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

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

Time-varying ϵ

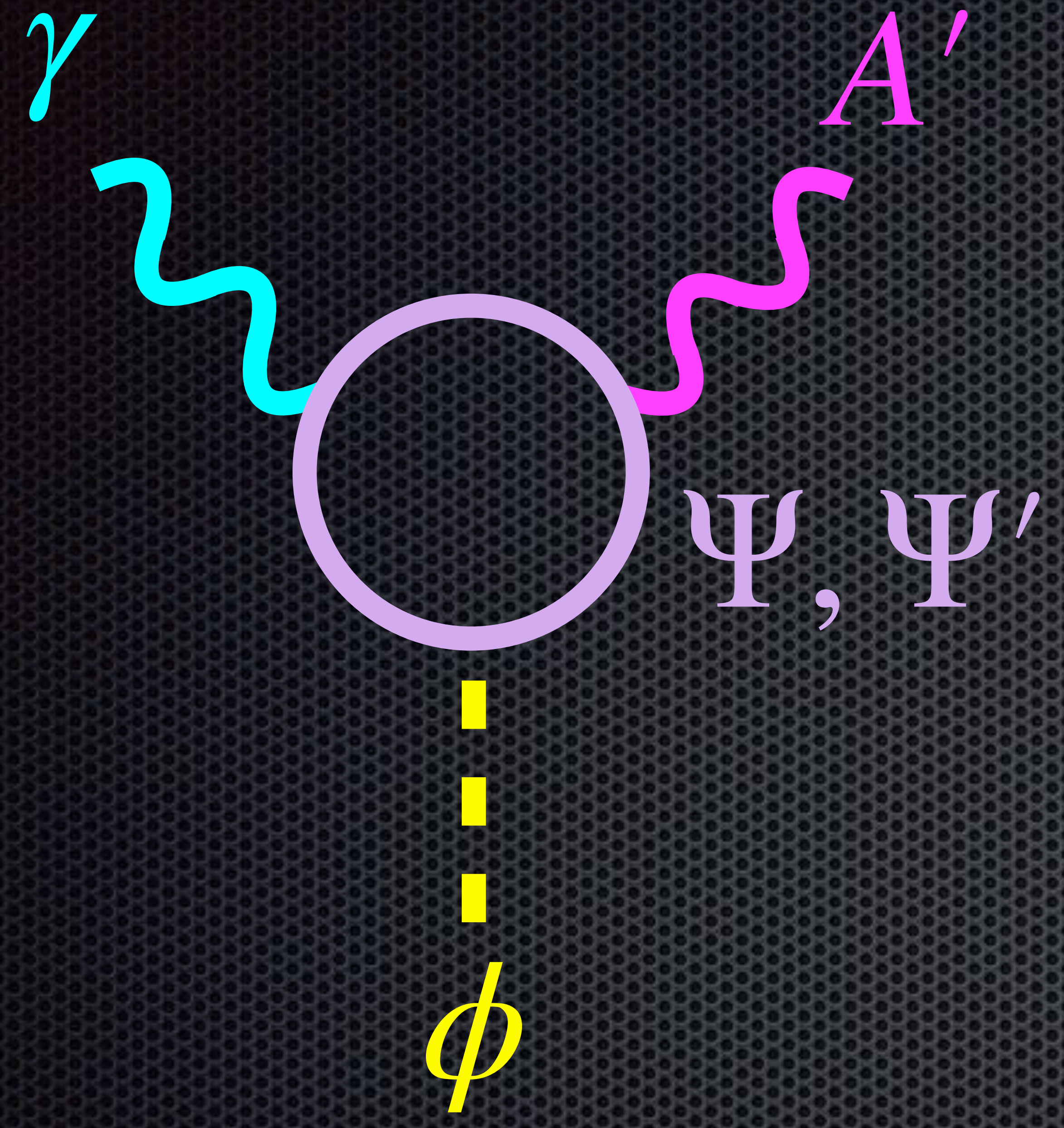


$$\mathscr{L} \supset \frac{1}{2}\frac{\phi}{\Lambda_{KM}}FF'$$

?

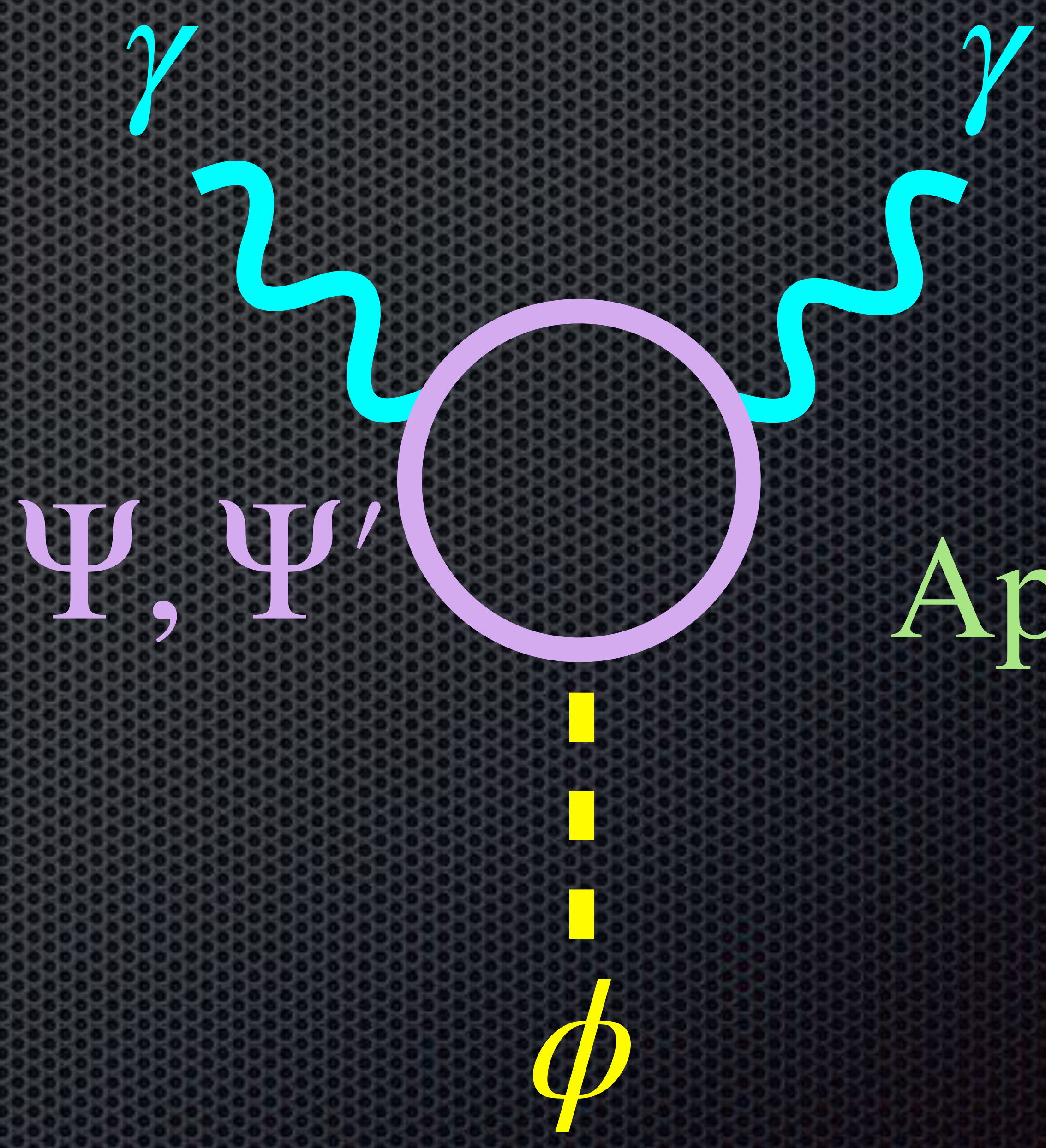
Introduce $y\phi\bar{\Psi}\Psi$ and $y'\phi\bar{\Psi}'\Psi'$

Time-varying ϵ



$$\mathscr{L} \supset \frac{1}{2}\frac{\phi}{\Lambda_{KM}} F F'$$

Time-varying α + 5th force



$y' \neq -y$:

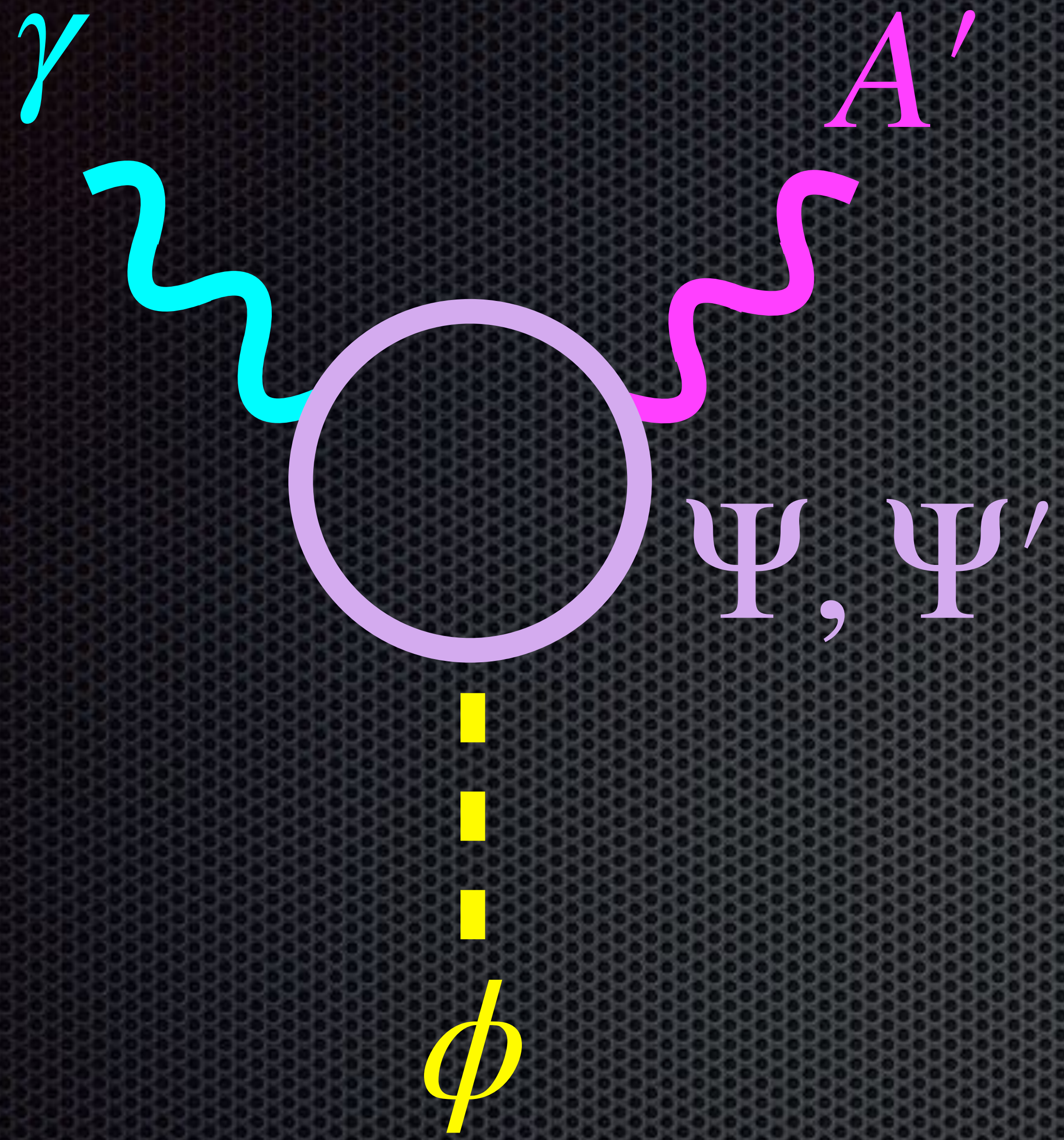
Approximate $\mathbb{Z}_2$

Linear

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

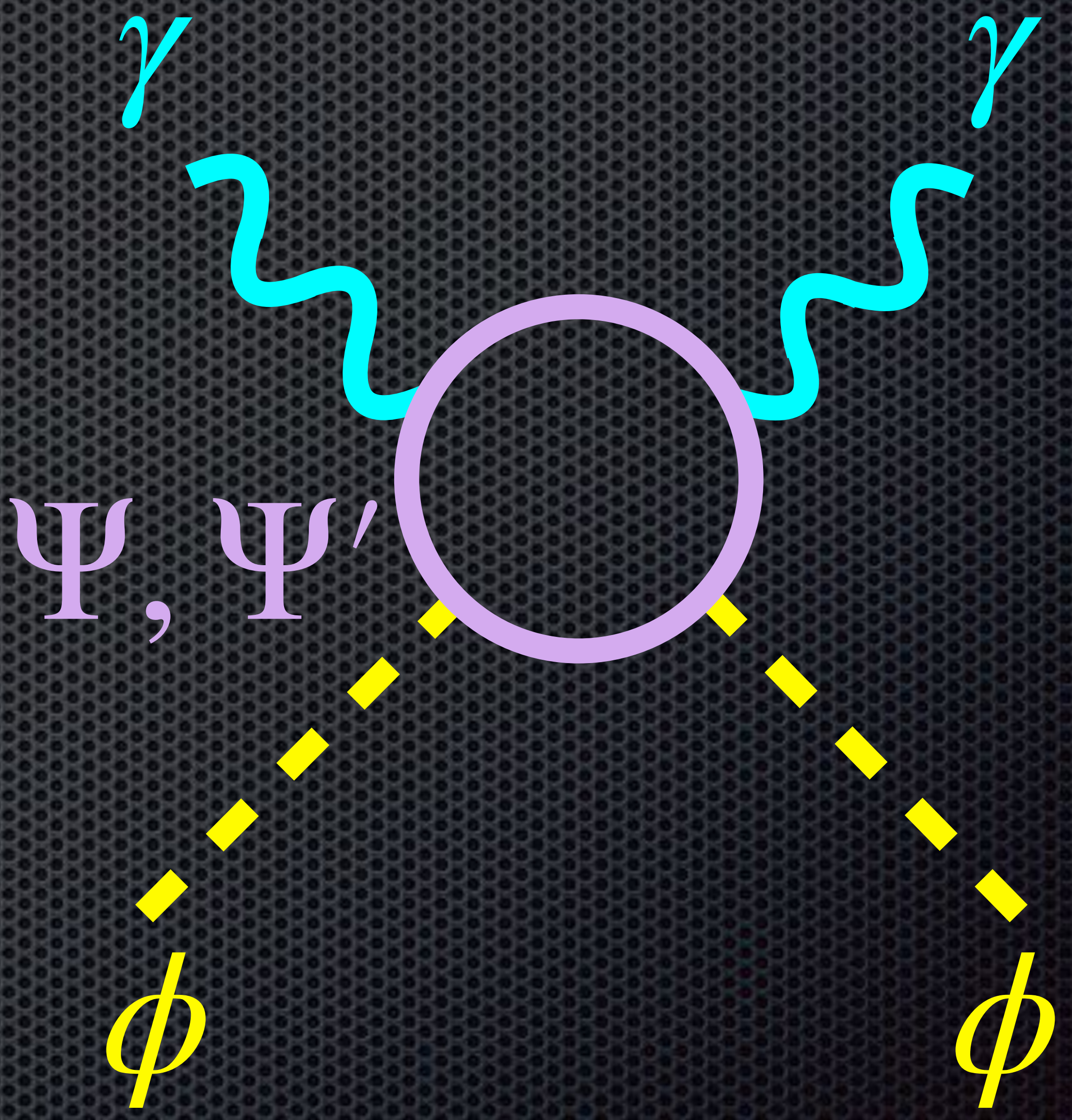
Introduce $y\phi\bar{\Psi}\Psi$ and $y'\phi\bar{\Psi}'\Psi'$

Time-varying ϵ



$$\mathscr{L} \supset \frac{1}{2}\frac{\phi}{\Lambda_{KM}} F F'$$

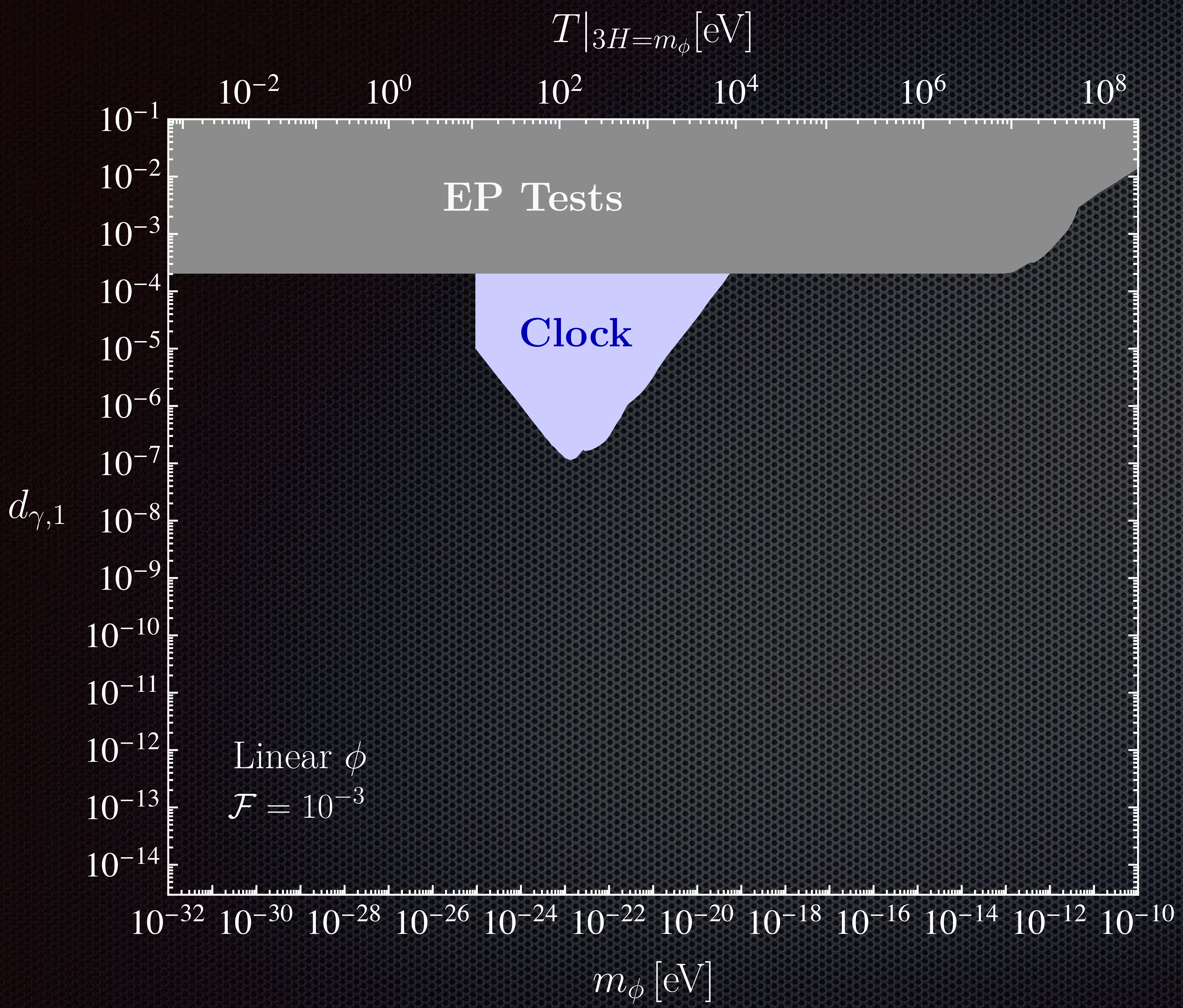
Time-varying α + 5th force



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

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

Linear Coupling

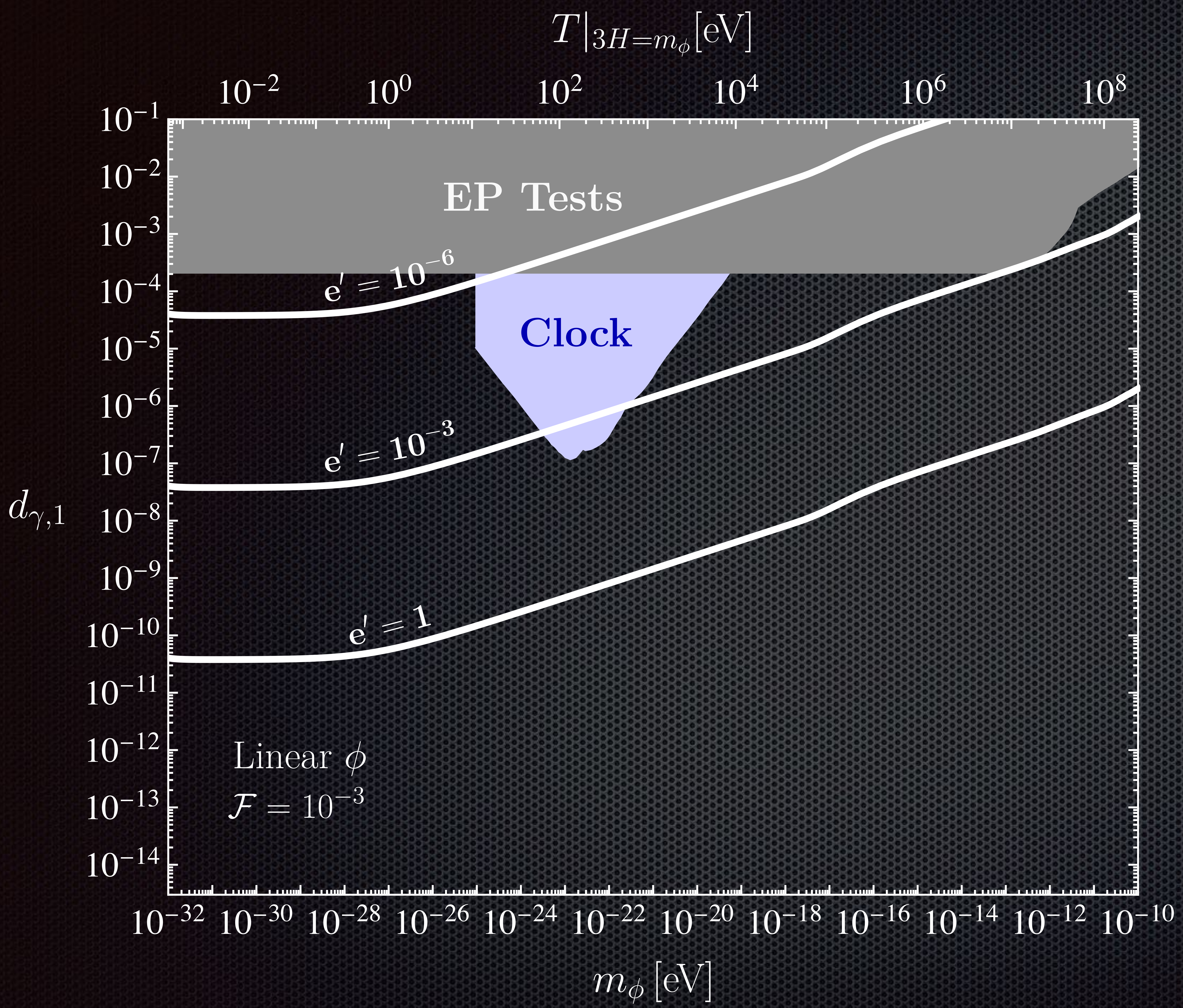


$$\mathscr{L} \sim d_{\gamma,1} \frac{\phi}{m_{pl}} F^2$$

$$\phi F F' \xrightarrow{\text{UV Physics}} \phi F^2$$

A' Freeze-in

$\Delta\alpha$
+
5th force



Linear Coupling

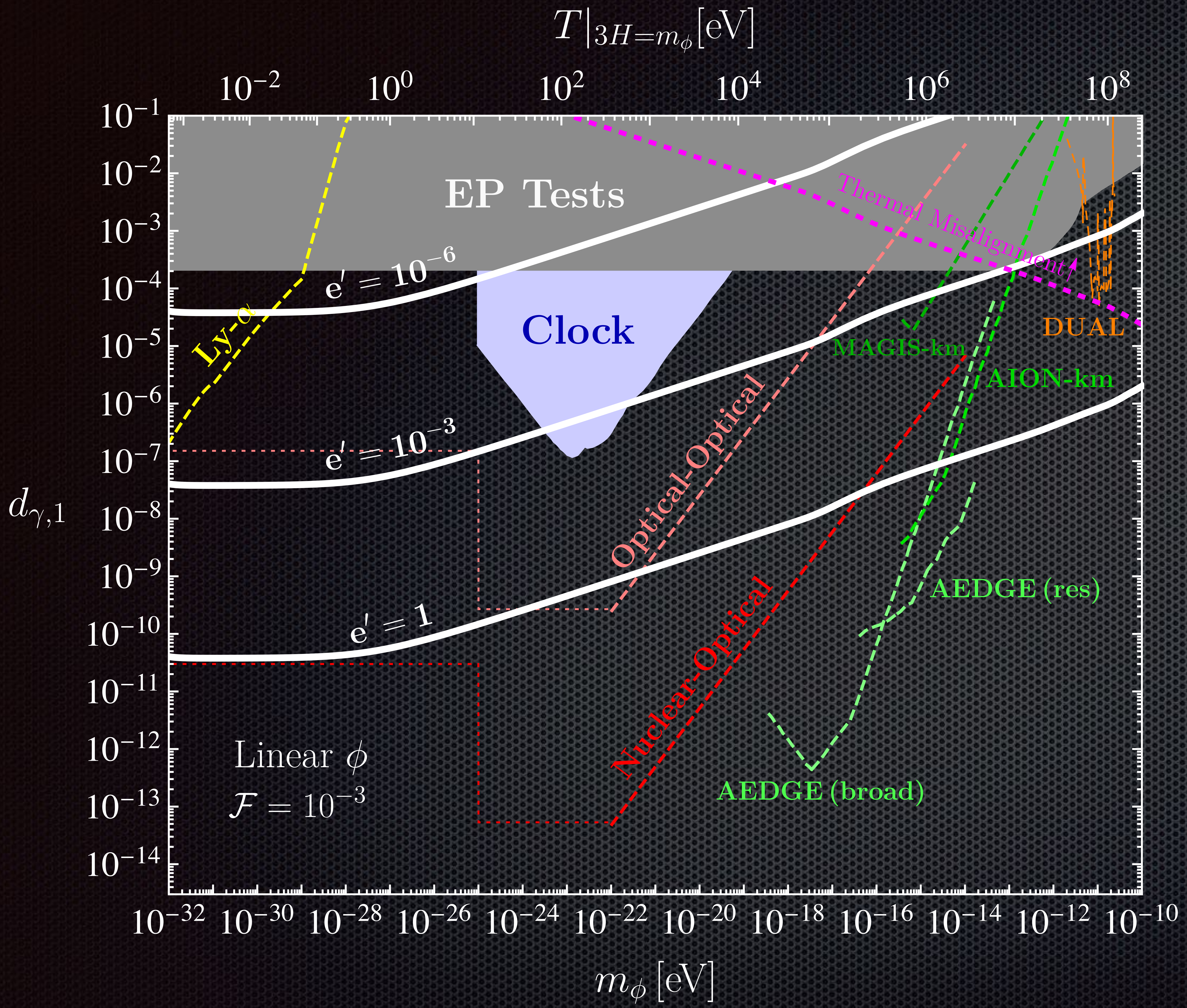
$$\mathscr{L} \sim d_{\gamma,1} \frac{\phi}{m_{pl}} F^2$$

$$\phi F F' \xrightarrow{\text{UV Physics}} \phi F^2$$

A' Freeze-in

$\Delta\alpha$
+
5th force

Linear Coupling

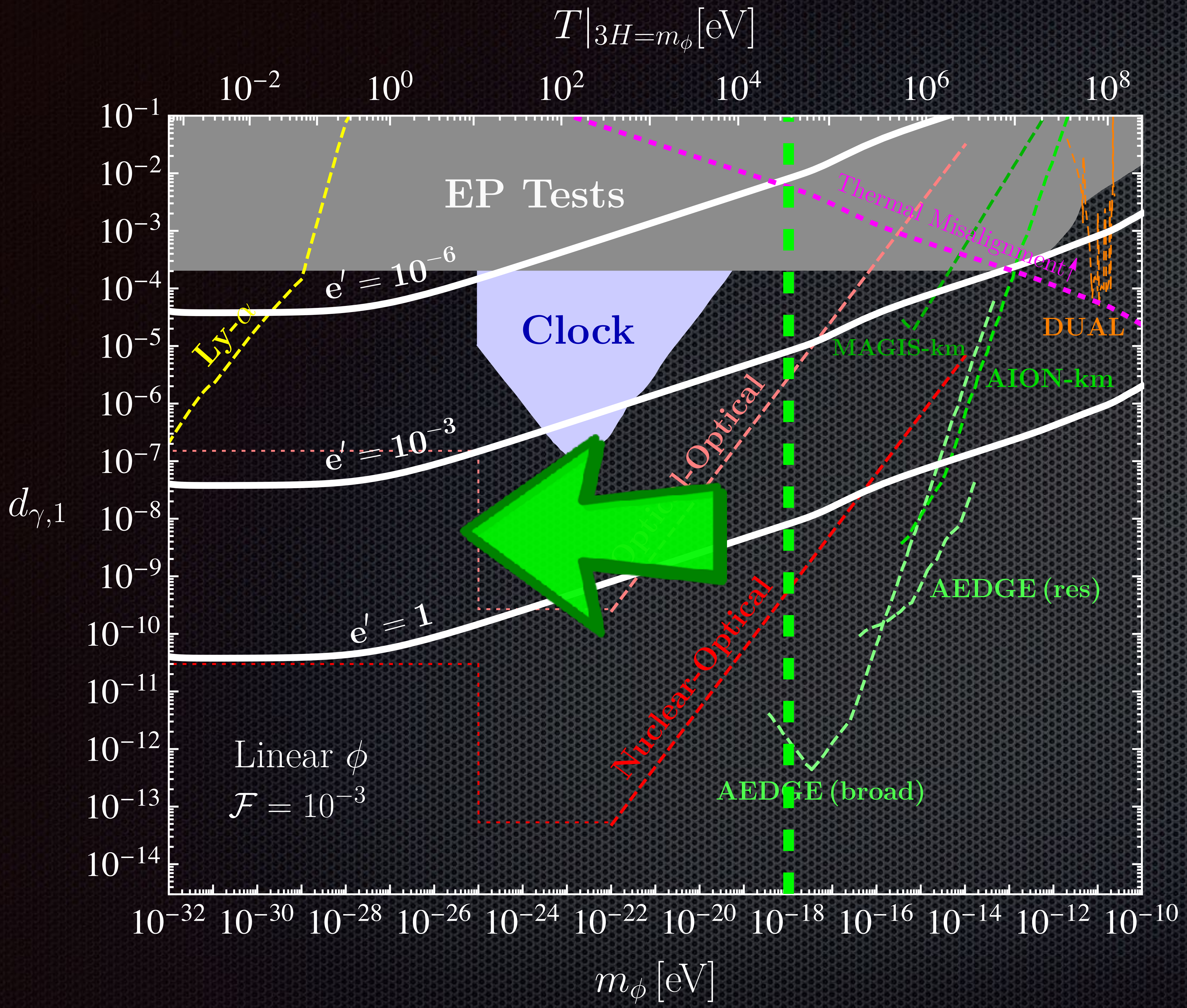


$$\mathscr{L} \sim d_{\gamma,1} \frac{\phi}{m_{pl}} F^2$$

$$\phi F F' \xrightarrow{\text{UV Physics}} \phi F^2$$

A' Freeze-in

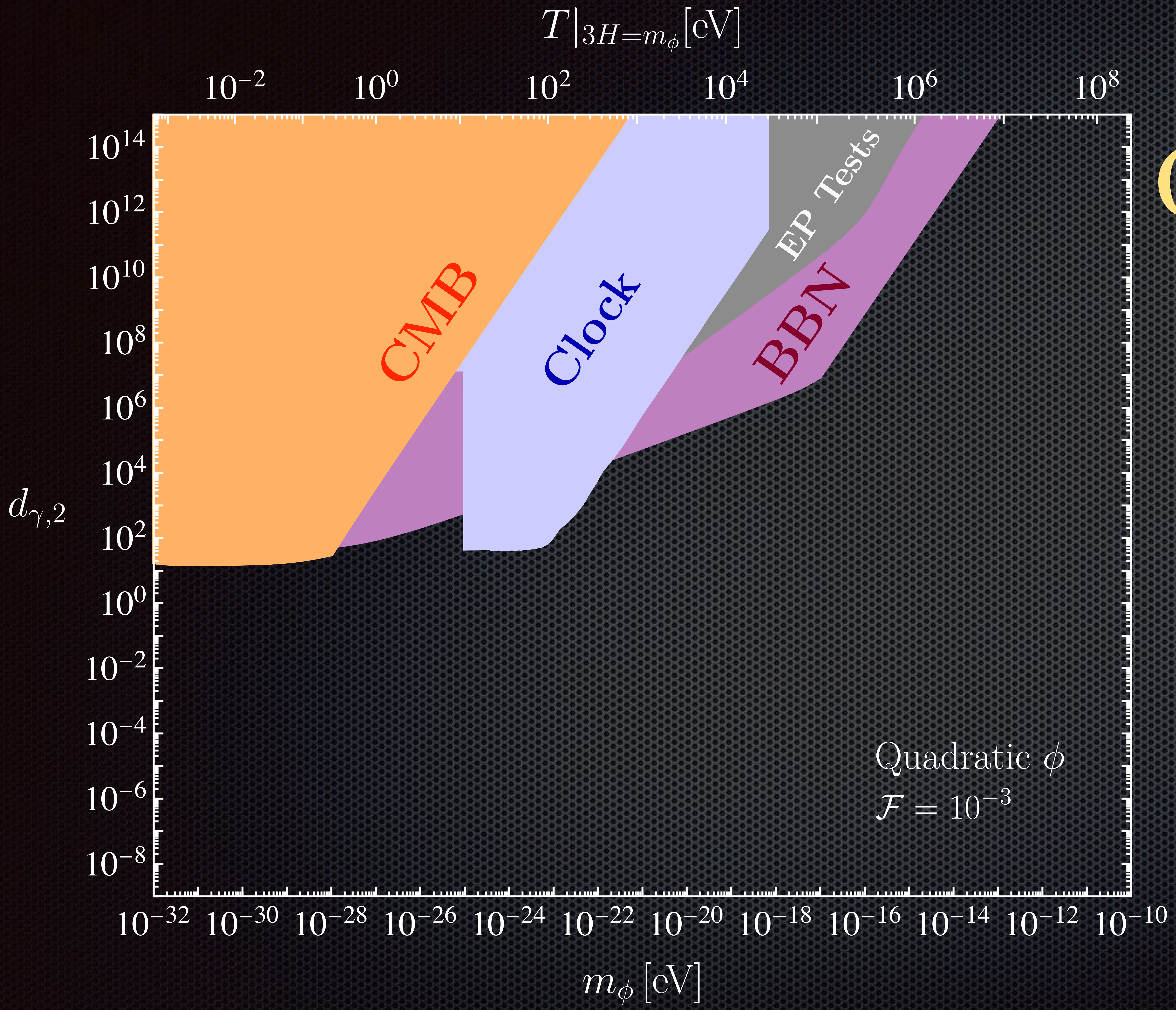
$\Delta\alpha$
+
5th force



Motivates the region excluded by fuzzy DM bound and black hole super-radiance.

$$m_\phi \lesssim 10^{-18}\text{eV}$$

Quadratic Coupling



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

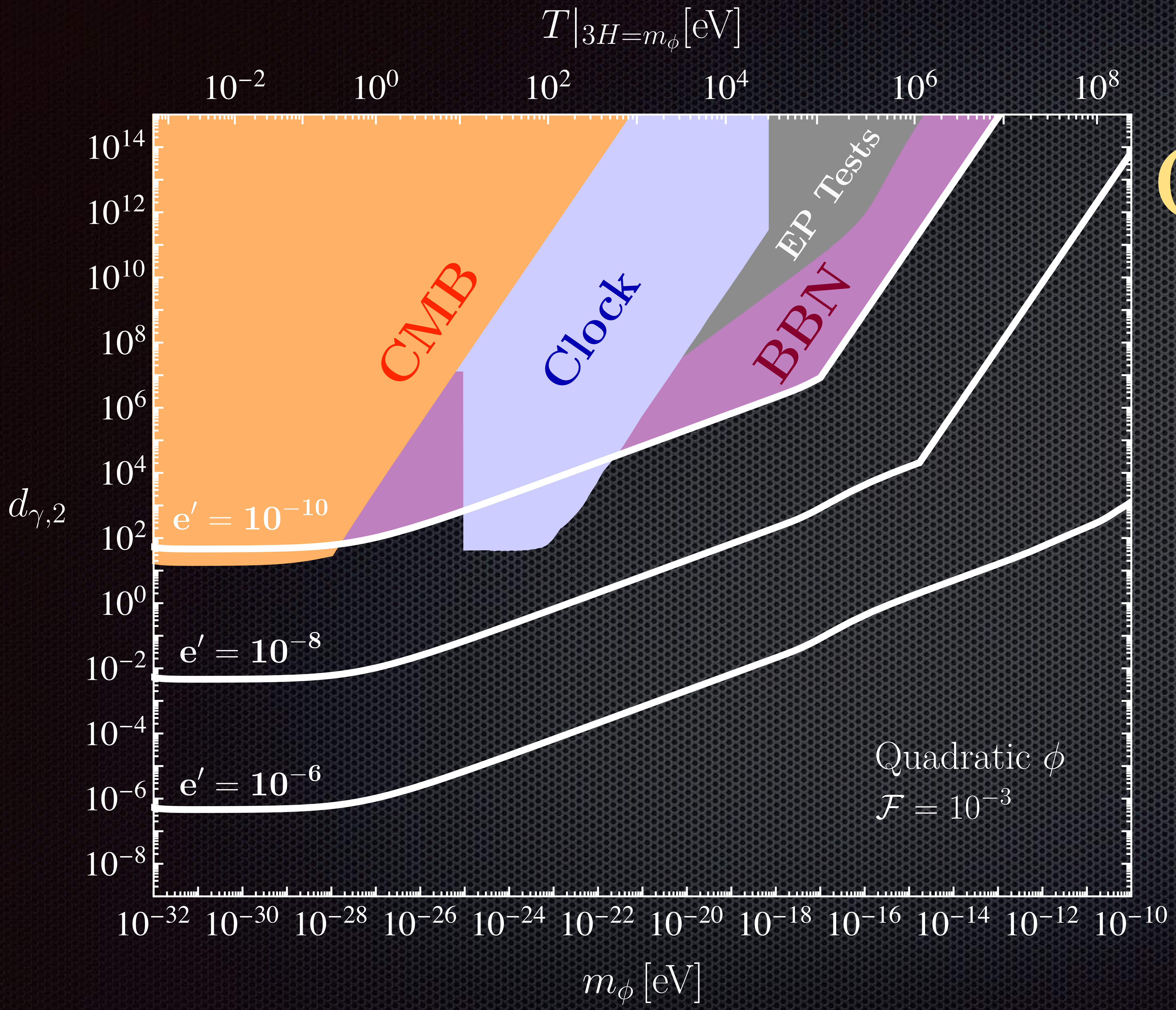
$$\phi F F' \xrightarrow{\text{UV Physics}} \phi^2 F^2$$

A' Freeze-in

$\Delta\alpha$

+

5th force



Quadratic Coupling

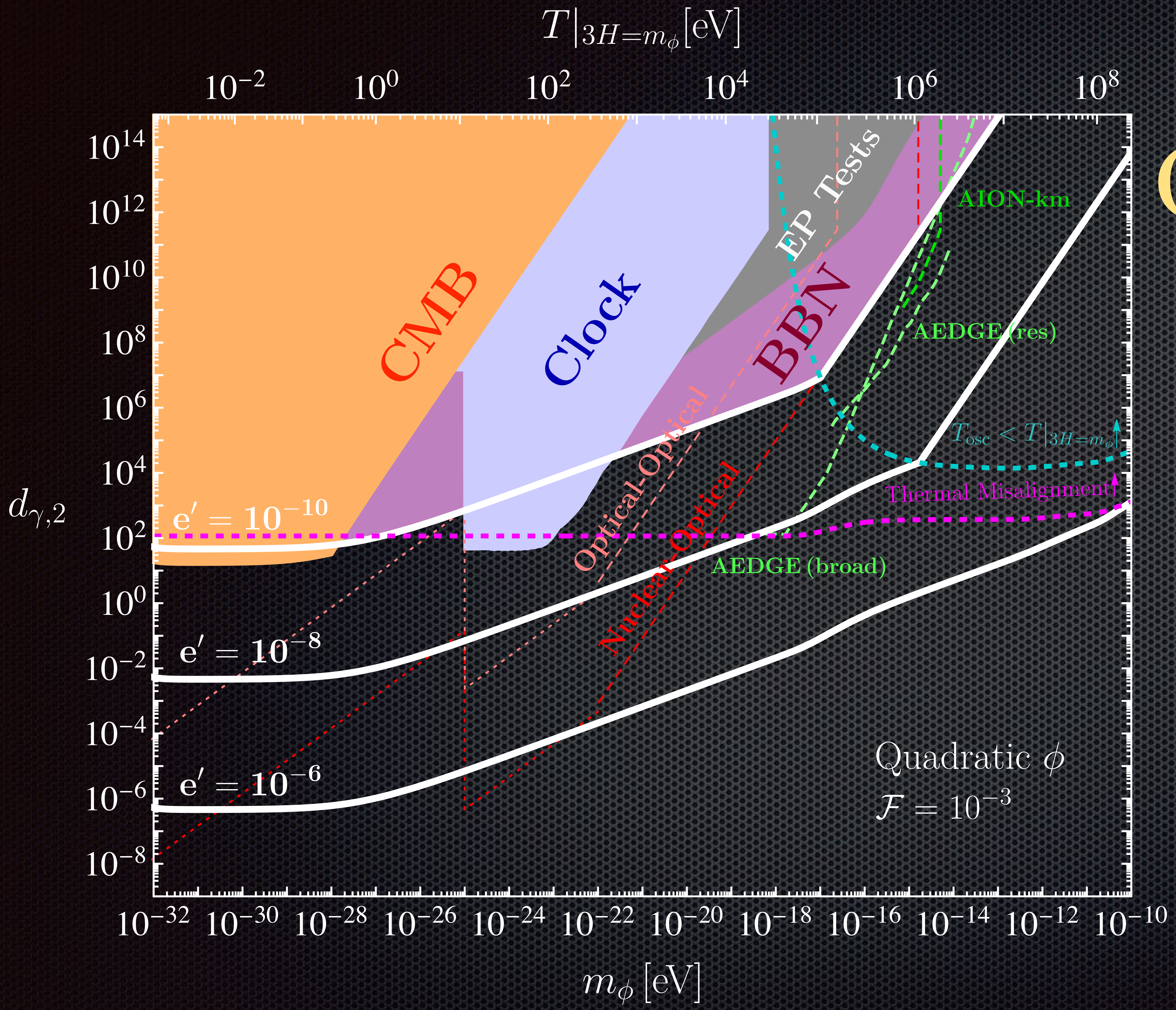
$$\mathscr{L} \sim d_{\gamma,2} \frac{\phi^2}{m_{pl}^2} F^2$$

$$\phi F F' \xrightarrow{\text{UV Physics}} \phi^2 F^2$$

A' Freeze-in

$\Delta\alpha$
+
5th force

Quadratic Coupling



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

$$\phi F F' \xrightarrow{\text{UV Physics}} \phi^2 F^2$$

A' Freeze-in

$\Delta\alpha$
+
5th force

Conclusion

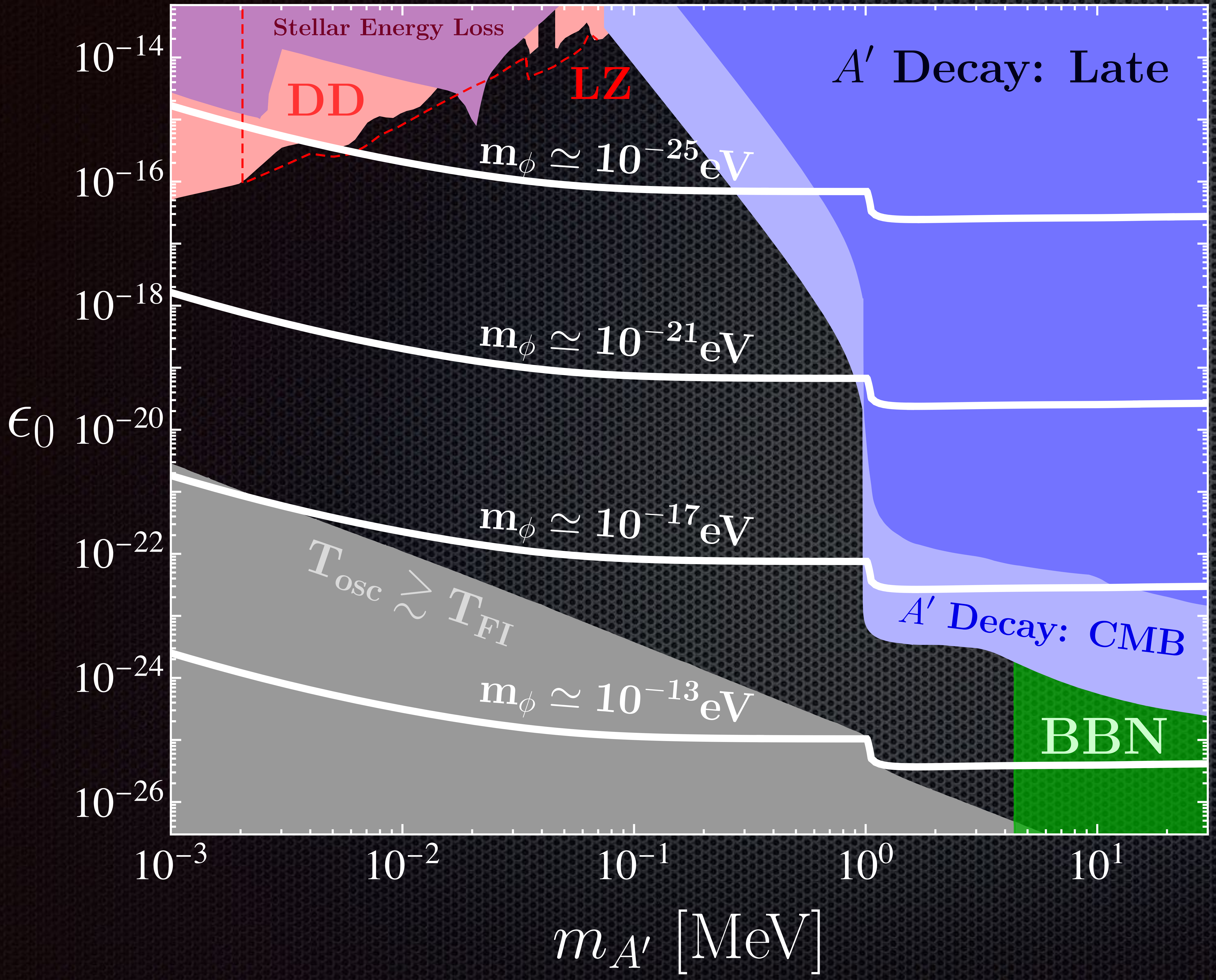
- The freeze-in of dark photon dark matter through the kinetic mixing is entirely ruled out by current constraints. Other dark photon production mechanisms are either independent of the kinetic mixing or UV sensitive.

- 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, which 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

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



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

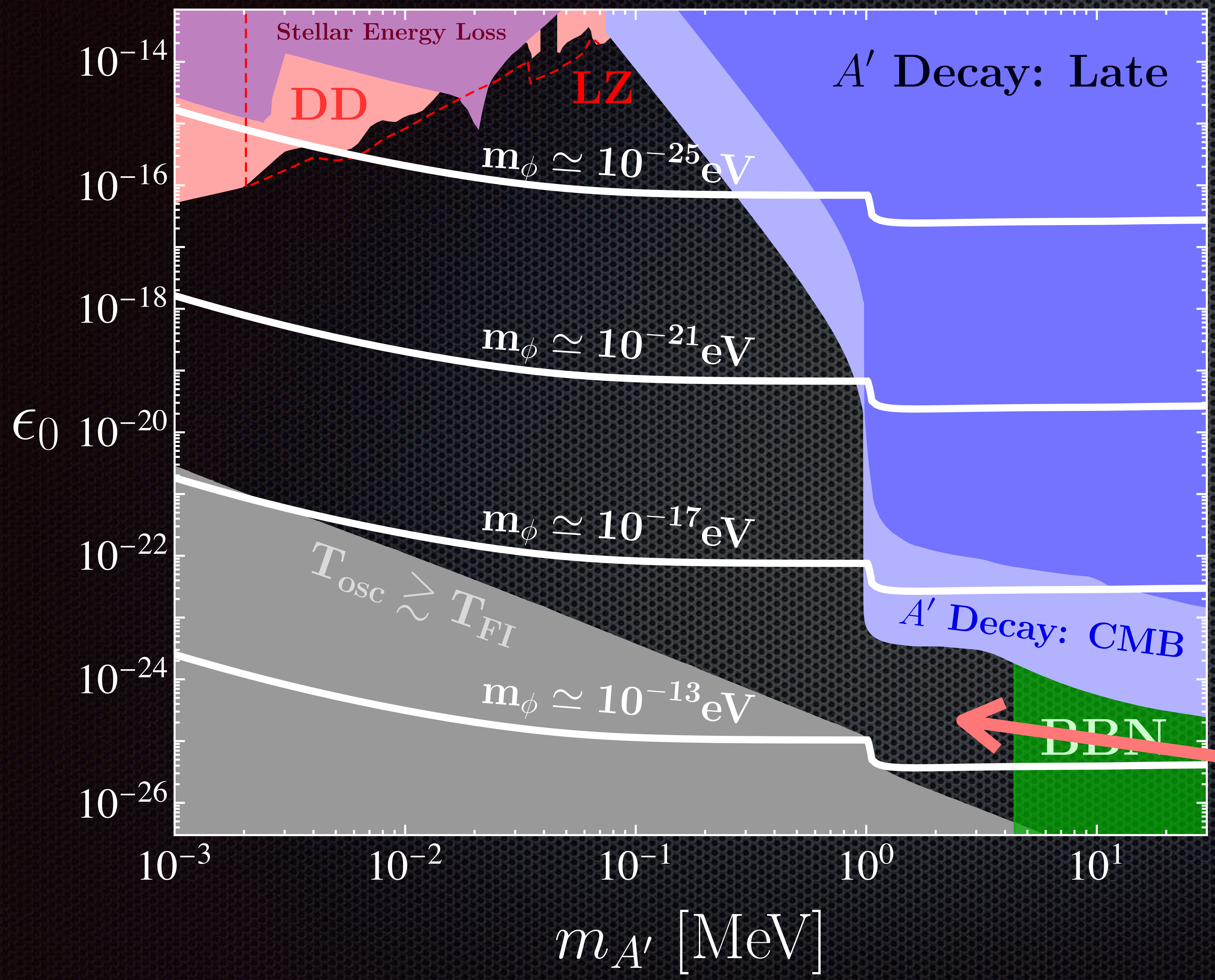
$$T_{osc} \sim (m_0 m_{pl})^{1/2}$$

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

Structure Formation:

$$\mathscr{F} \sim 600$$

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



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

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

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

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

Linear Coupling

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

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

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

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

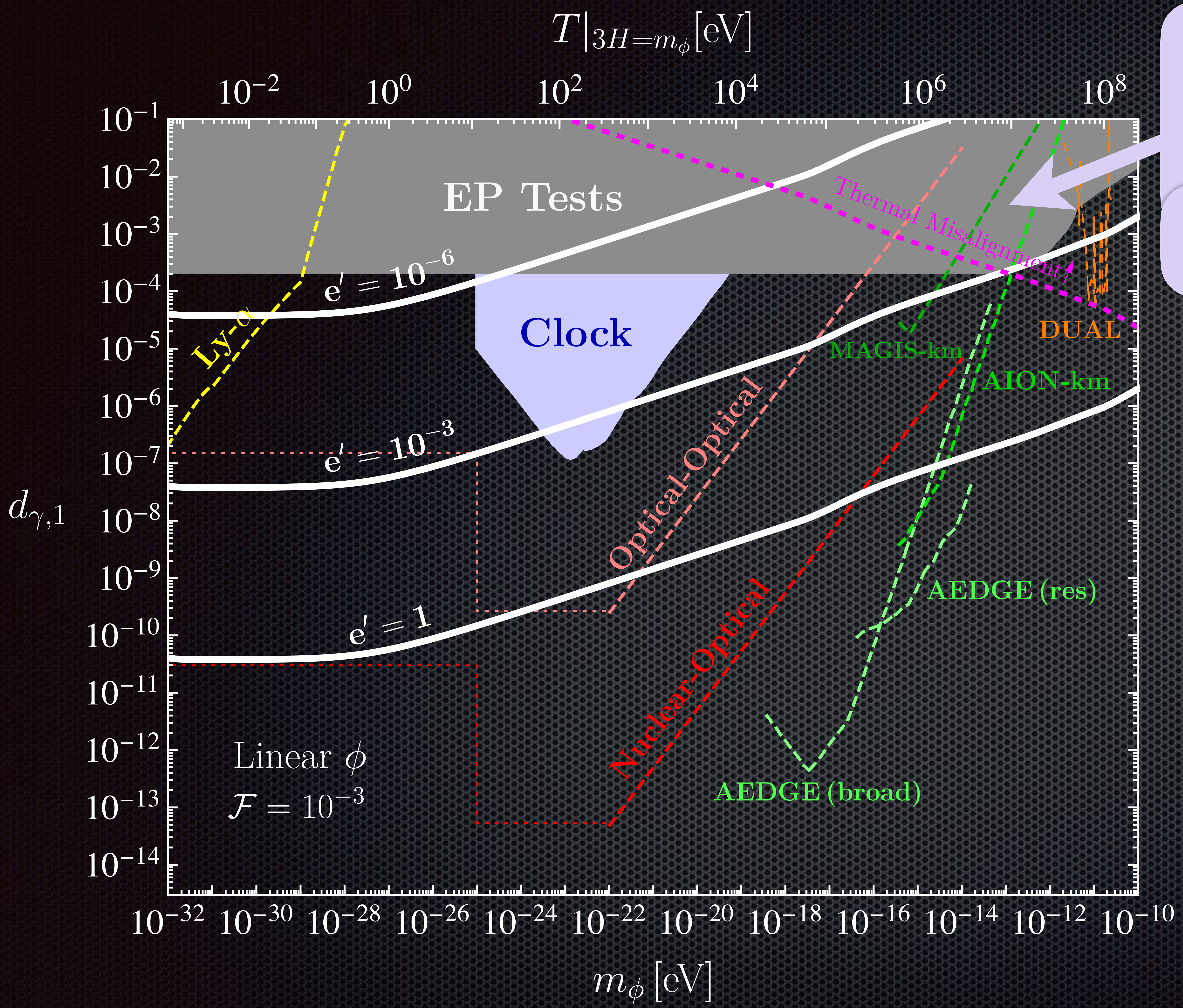
Quadratic Coupling

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

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

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

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

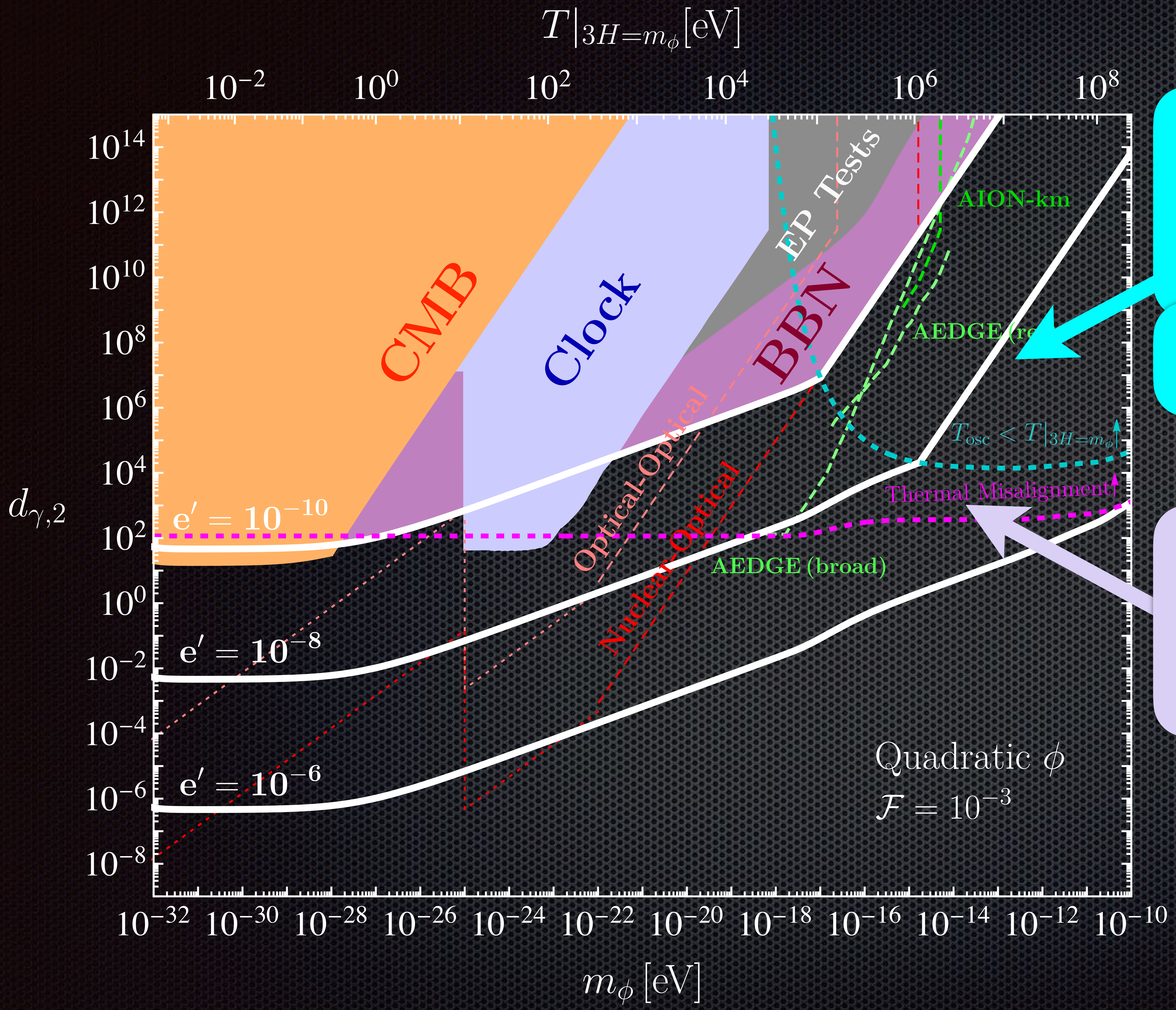


Thermal Misalignment

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

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

$$\phi F F' \xrightarrow{\text{UV Physics}} \phi F^2$$



Trapped Misalignment

$$T_{osc} < T|_{3H=m_\phi}$$

Nakagawa, Takahashi, Yamada 2020
Luzio, Gavela, Quilez, Ringwald 2021

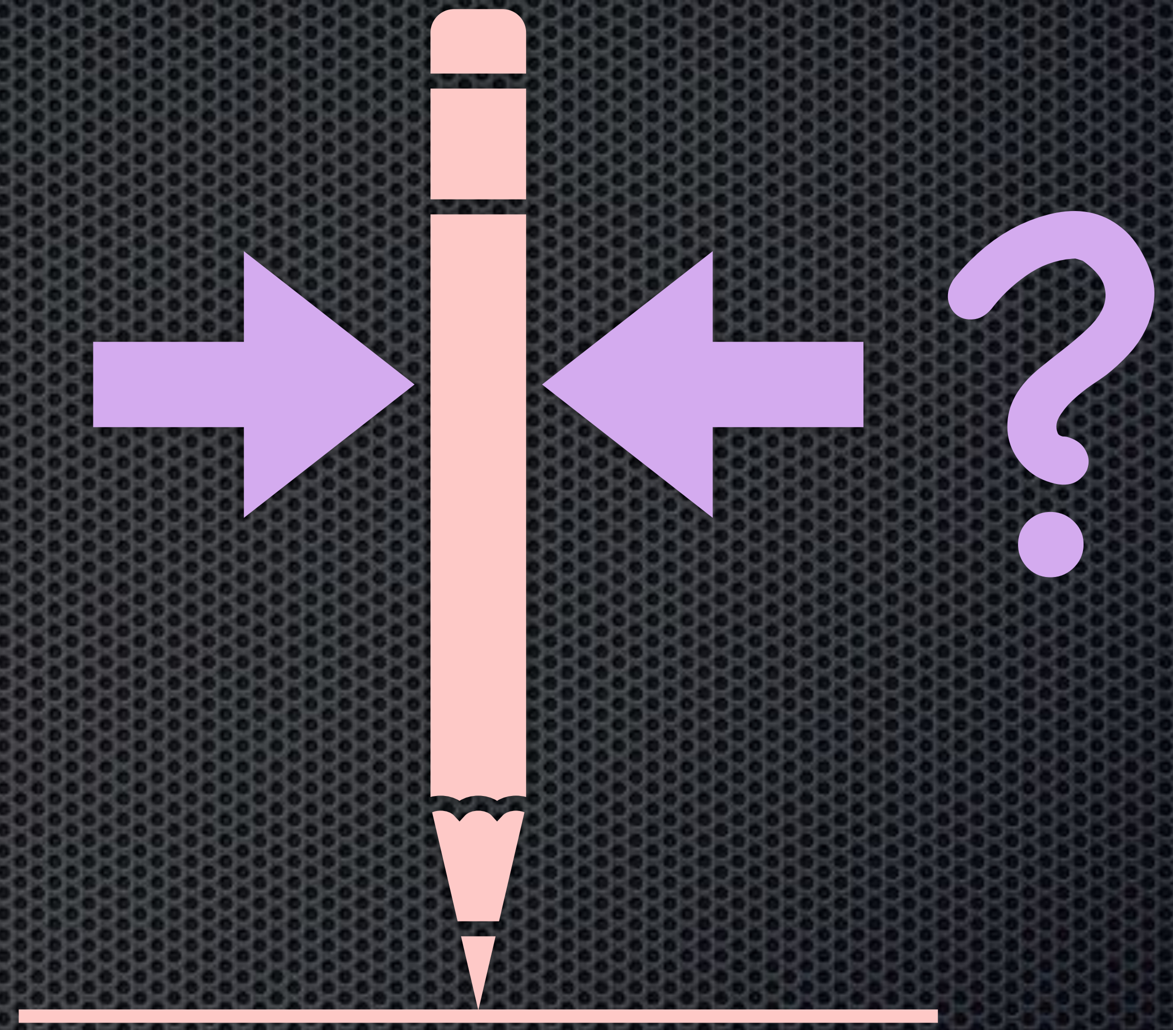
axion models

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

Thermal Misalignment

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

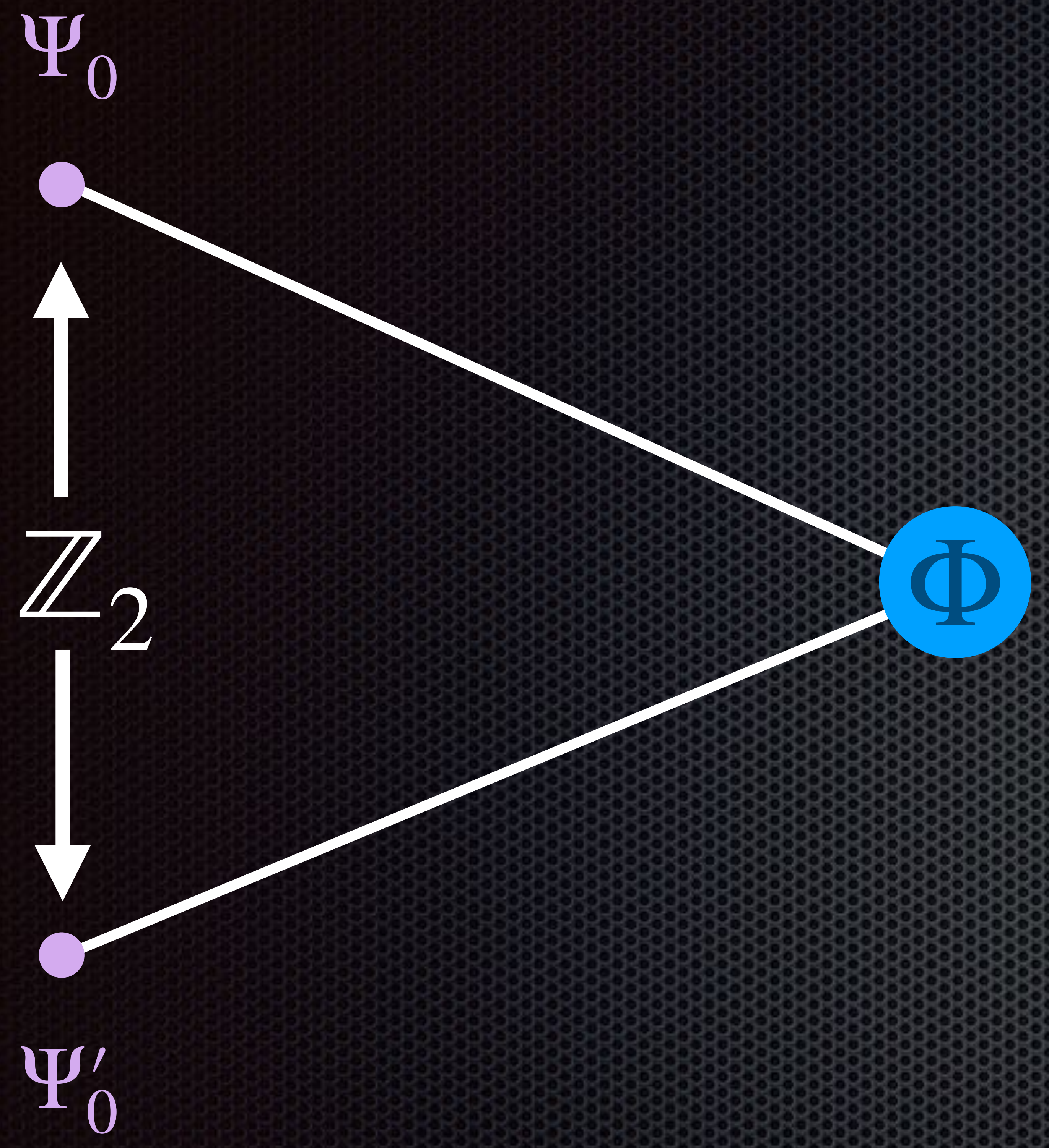
Scalar Naturalness

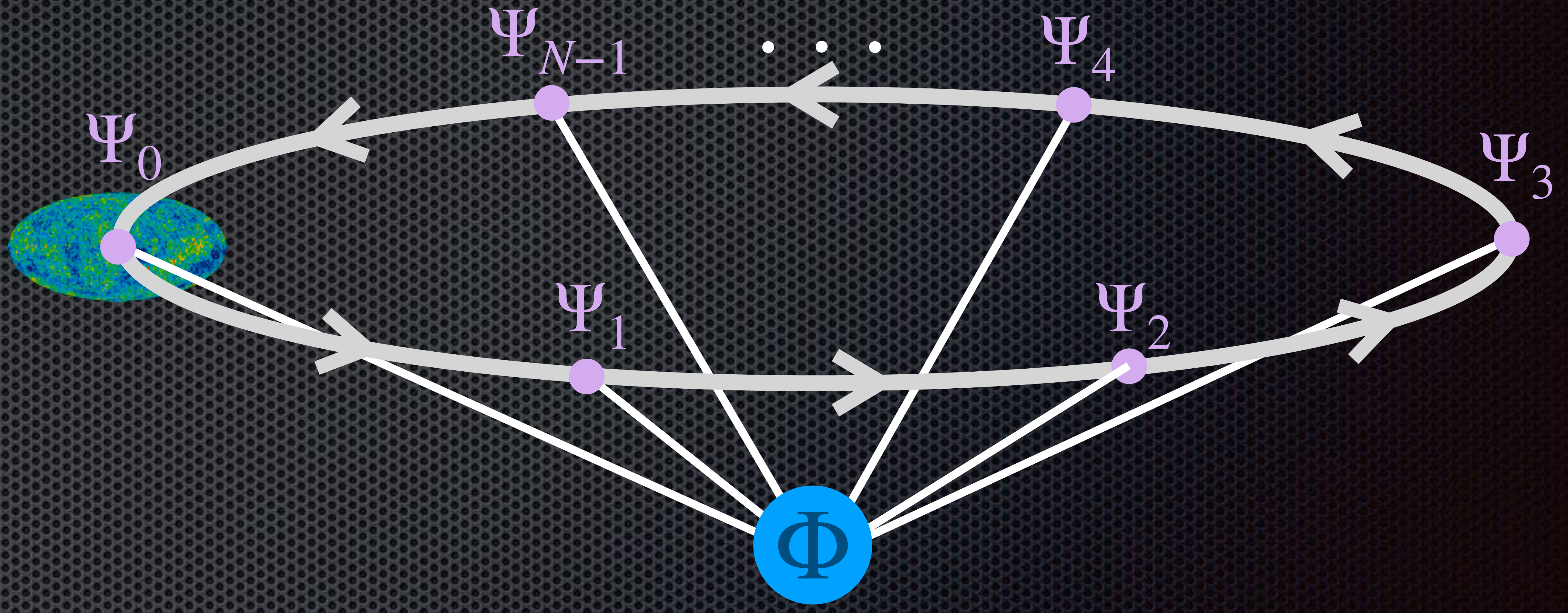


$$\Delta m_\phi \simeq 10^{-11} eV \left(\frac{\epsilon_{FI}}{10^{-12}}\right)\left(\frac{M}{10TeV}\right)^2\left(\frac{10^{17}GeV}{|\phi|_{osc}}\right)\left(\frac{1}{e'}\right)$$

$$\gg 10^{-20} eV$$

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





Hill et. al. 1995

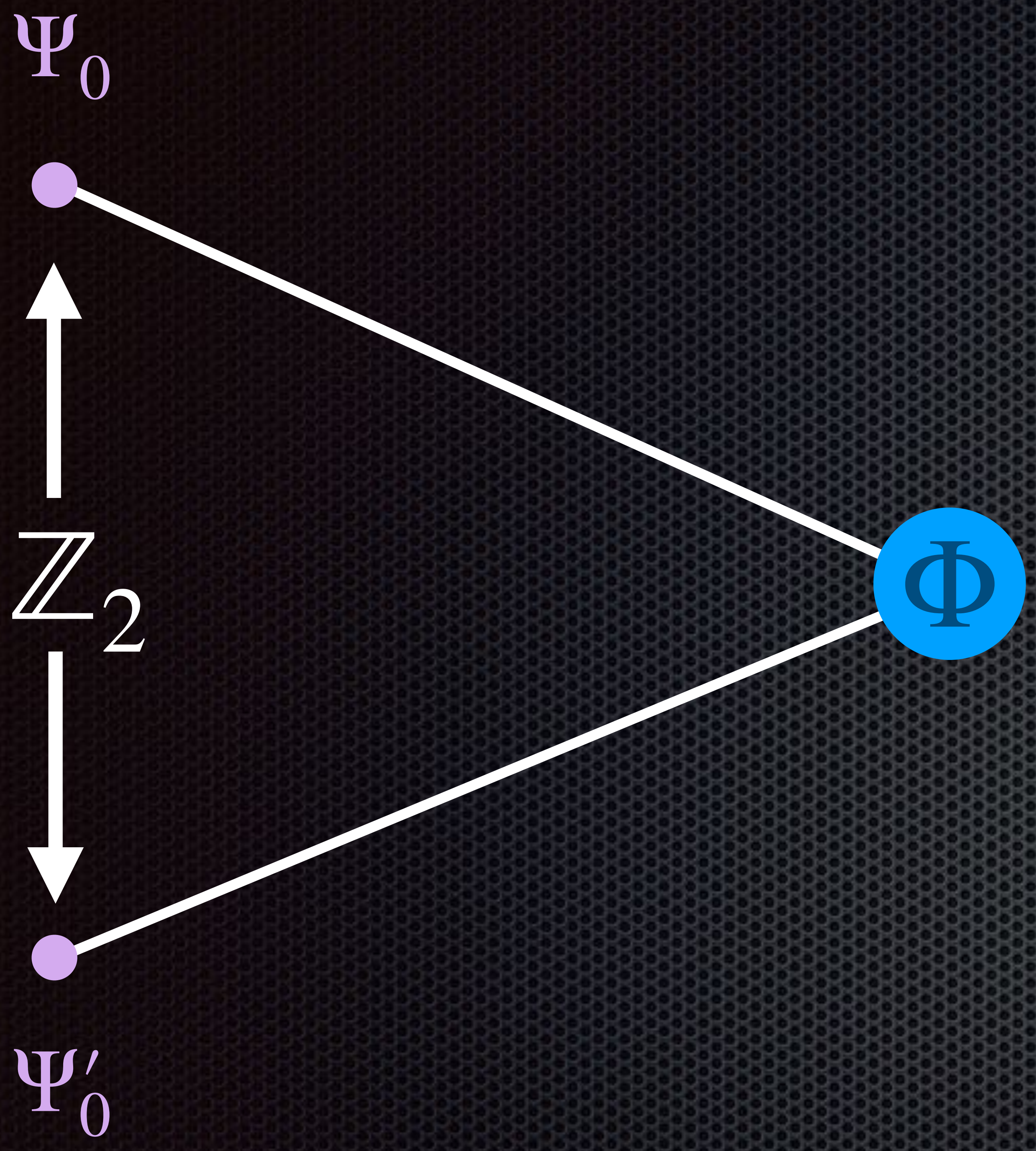
Hook et. al. 2018, 2019, 2020, 2021

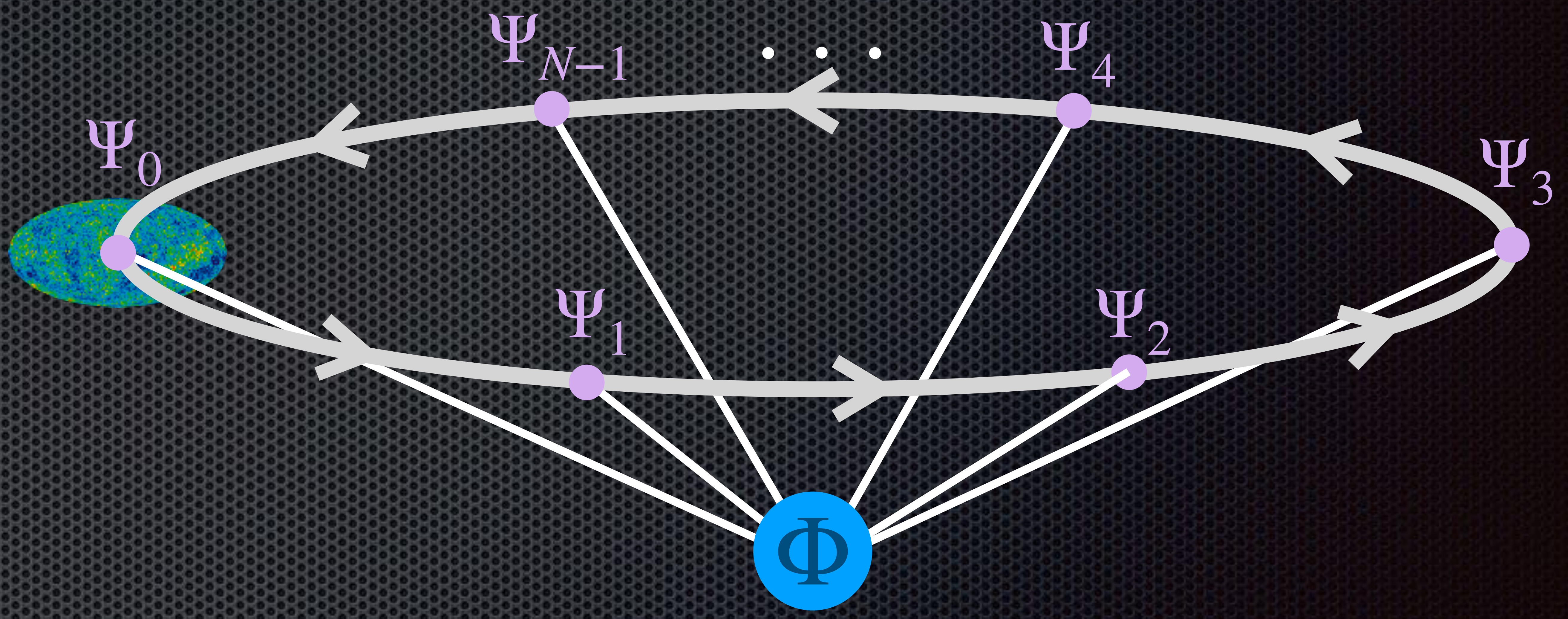
Dror et. al. , 2020

Ringwald et. al. , 2021

Perez et. al. , 2021

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



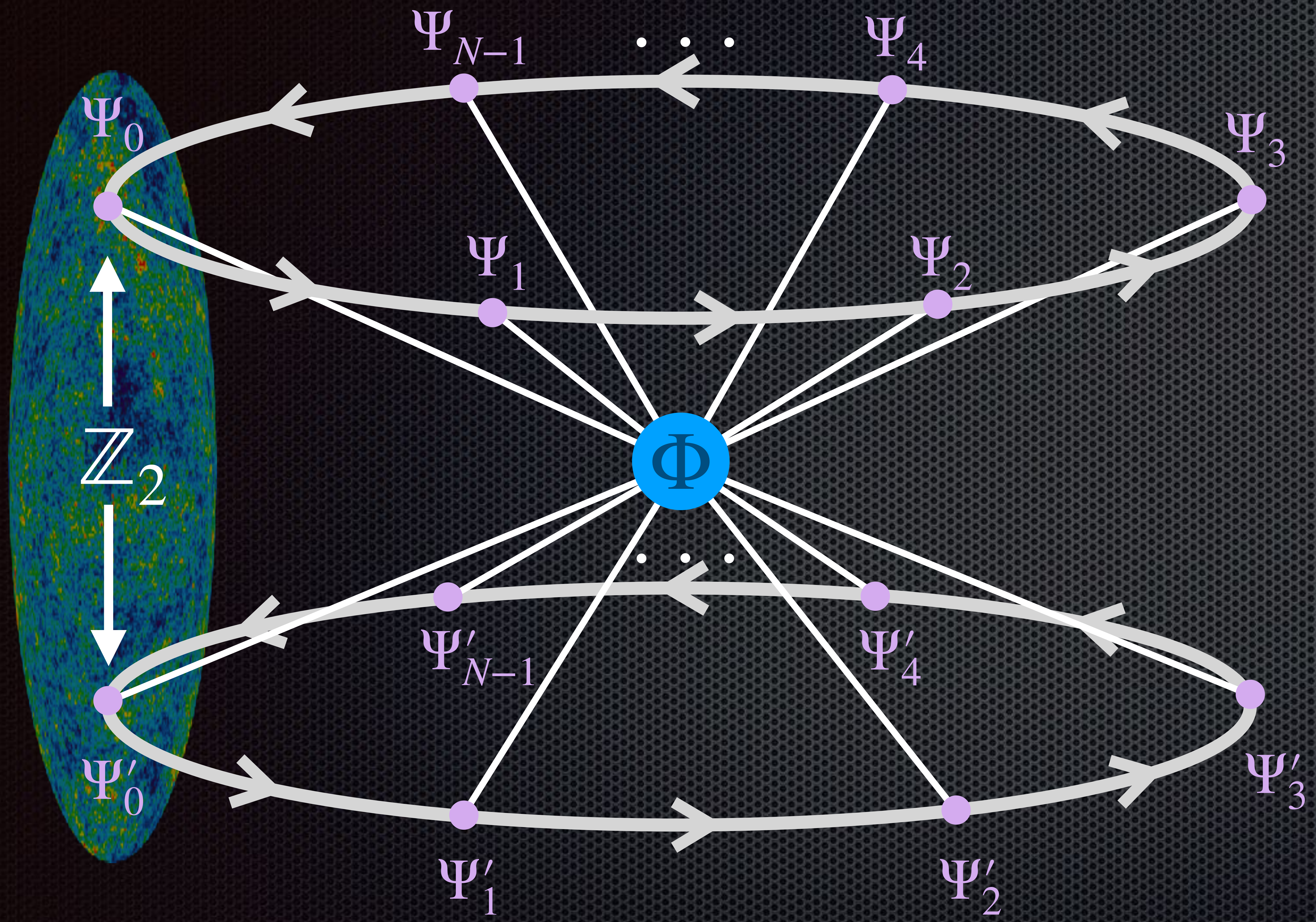


$$\Phi \to \Phi \exp\left(i\frac{2\pi}{N}\right)$$

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

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

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



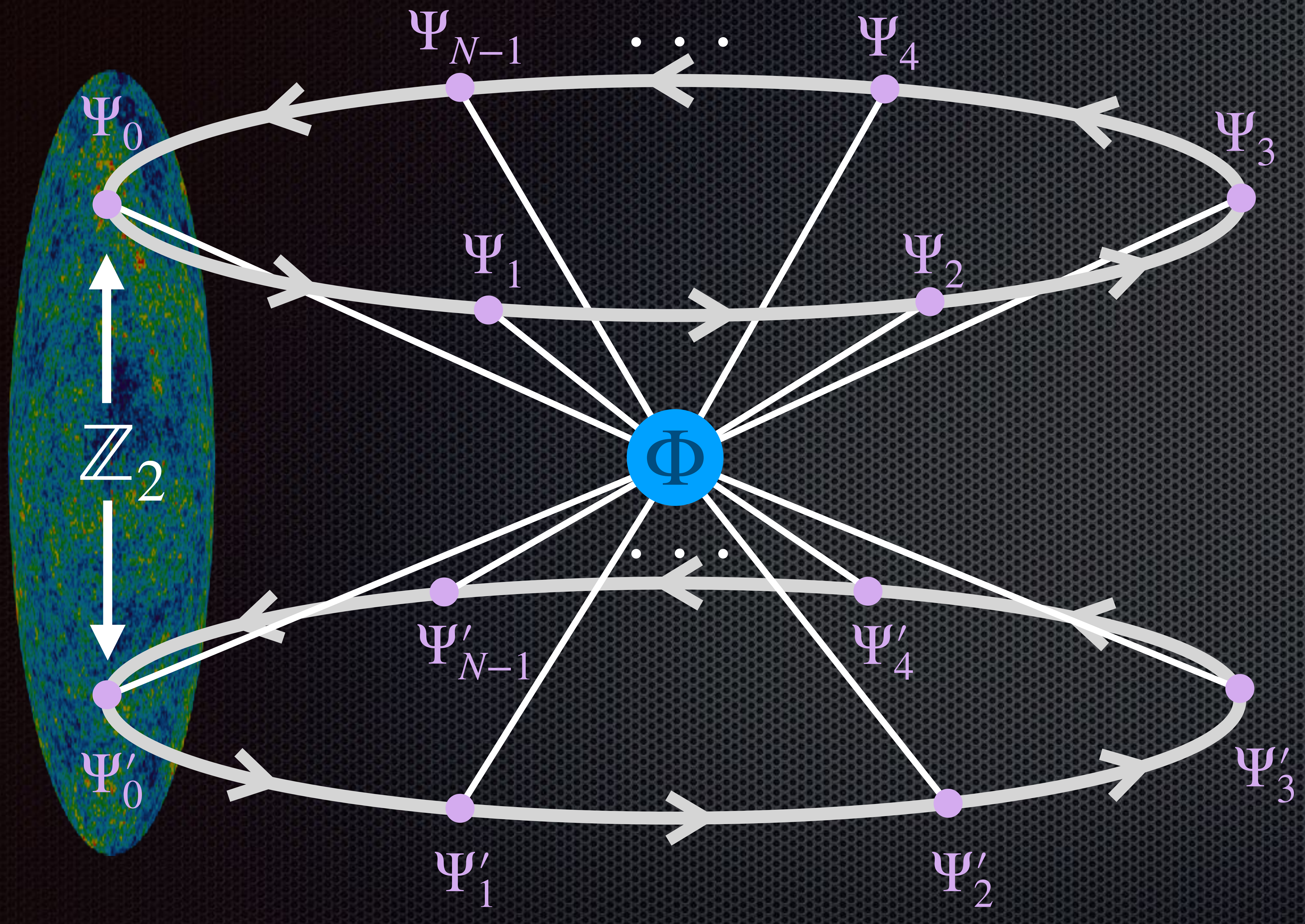
$$\epsilon_k \sim \frac{1}{\Lambda_{KM}} f \sin\left(\frac{\phi}{f} + \frac{2\pi k}{N}\right)$$

$$\left(\frac{\Delta\alpha_{em}}{\alpha_{em}}\right)_k \sim \left(\frac{1}{\Lambda_\gamma} f \sin\left(\frac{\phi}{f} + \frac{2\pi k}{N}\right)\right)^i$$

Type-A: i=1 Type-B: i=2

k=0: Our universe

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



Quantum Correction

$$V_{tot}(\phi) = \sum_{i=0}^{N-1} V\left(\phi + \frac{2\pi i}{N}\right)$$

$$\Delta m_\phi^2 \propto r^{N-2}$$

$$r \sim 10^{-10}\left(\frac{\epsilon_{FI}}{10^{-12}}\right)\left(\frac{1}{e'}\right)$$

$$N \sim 7 \quad \Delta m_\phi \ll 10^{-33} eV$$