Cosmological Varying Kinetic Mixing

arXiv. 2302.03056

Xucheng Gan, DL

27/09/2023, Axion++ workshop

Outline

- Lightning Review
- Dark photon dark matter A' and kinetic mixing ϵ
- Dark photon freeze-in through constant ϵ
- This work
- Scalar-controlled kinetic mixing $\epsilon(\phi)$
- UV model: scalar-photon coupling $d_e^{(1,2)}$
- Signals and constraints on $d_e^{(1,2)}$

Dark Photon and Kinetic Mixing

$$\mathcal{L} = -\frac{1}{4}F^{\mu\nu}F_{\mu\nu} \qquad - \frac{1}{4}F'^{\mu\nu}F'_{\mu\nu} + \frac{m_{A'}^2}{2}A'_\mu A'^\mu - eA_\mu \bar{f}\gamma^\mu f$$

Dark Photon and Kinetic Mixing

$$\mathcal{L} = -\frac{1}{4}F^{\mu\nu}F_{\mu\nu} + \frac{\epsilon}{2}F^{\mu\nu}F'_{\mu\nu} - \frac{1}{4}F'^{\mu\nu}F'_{\mu\nu} + \frac{m_{A'}^2}{2}A'_{\mu}A'^{\mu} - eA_{\mu}\bar{f}\gamma^{\mu}f$$

Dark Photon and Kinetic Mixing

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$$A \to A + \epsilon A' \,, \quad A' \to A'$$

Dark Photon and Kinetic Mixing

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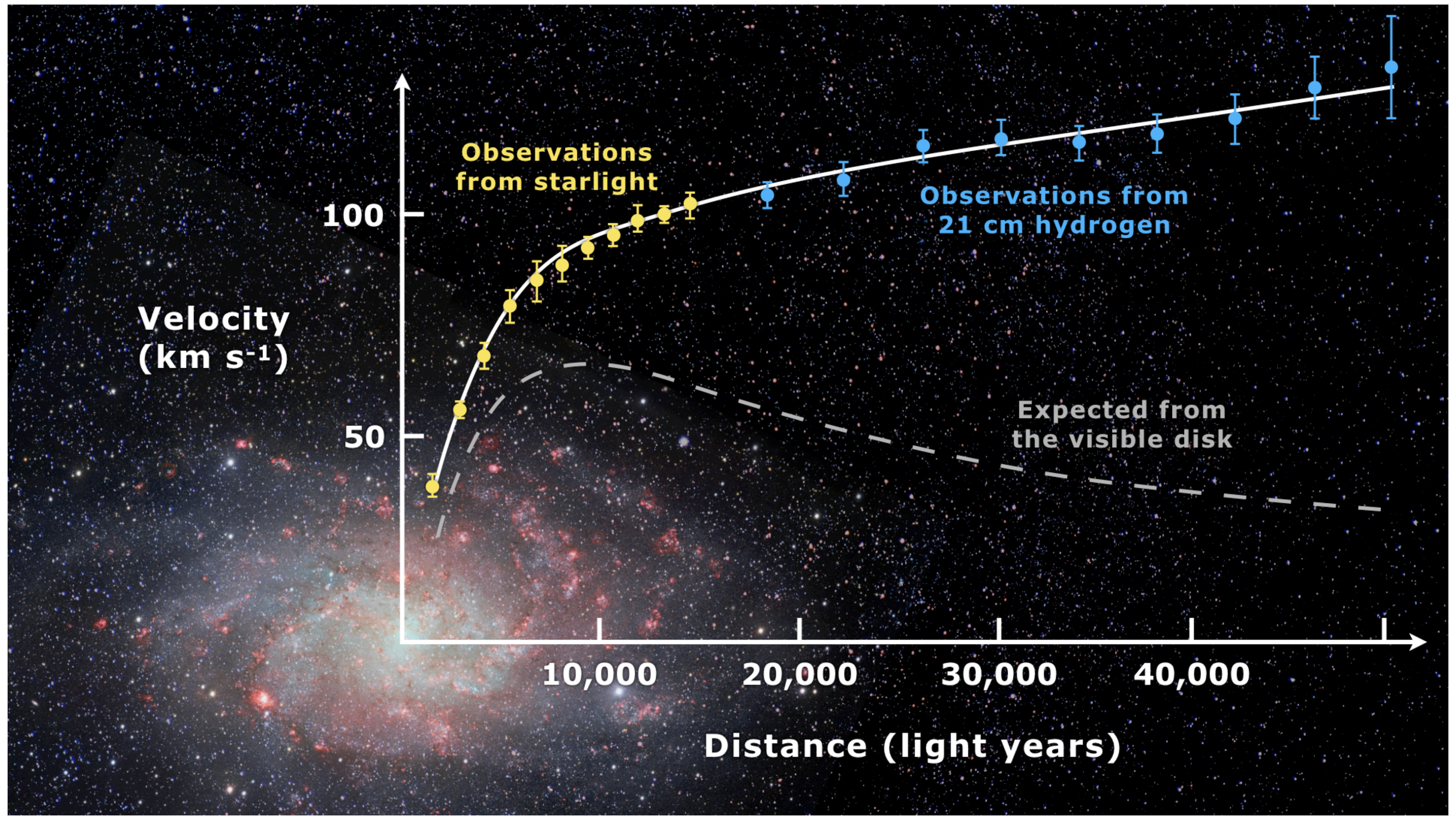
$$A \to A + \epsilon A' , \quad A' \to A'$$

$$\mathscr{L} \supset -\frac{1}{4}F^{\mu\nu}F_{\mu\nu} - \frac{1}{4}F'^{\mu\nu}F'_{\mu\nu} + \frac{1}{2}m^2_{A'}A'_\mu A'^\mu - \epsilon e A'_\mu \bar{f}\gamma^\mu f$$

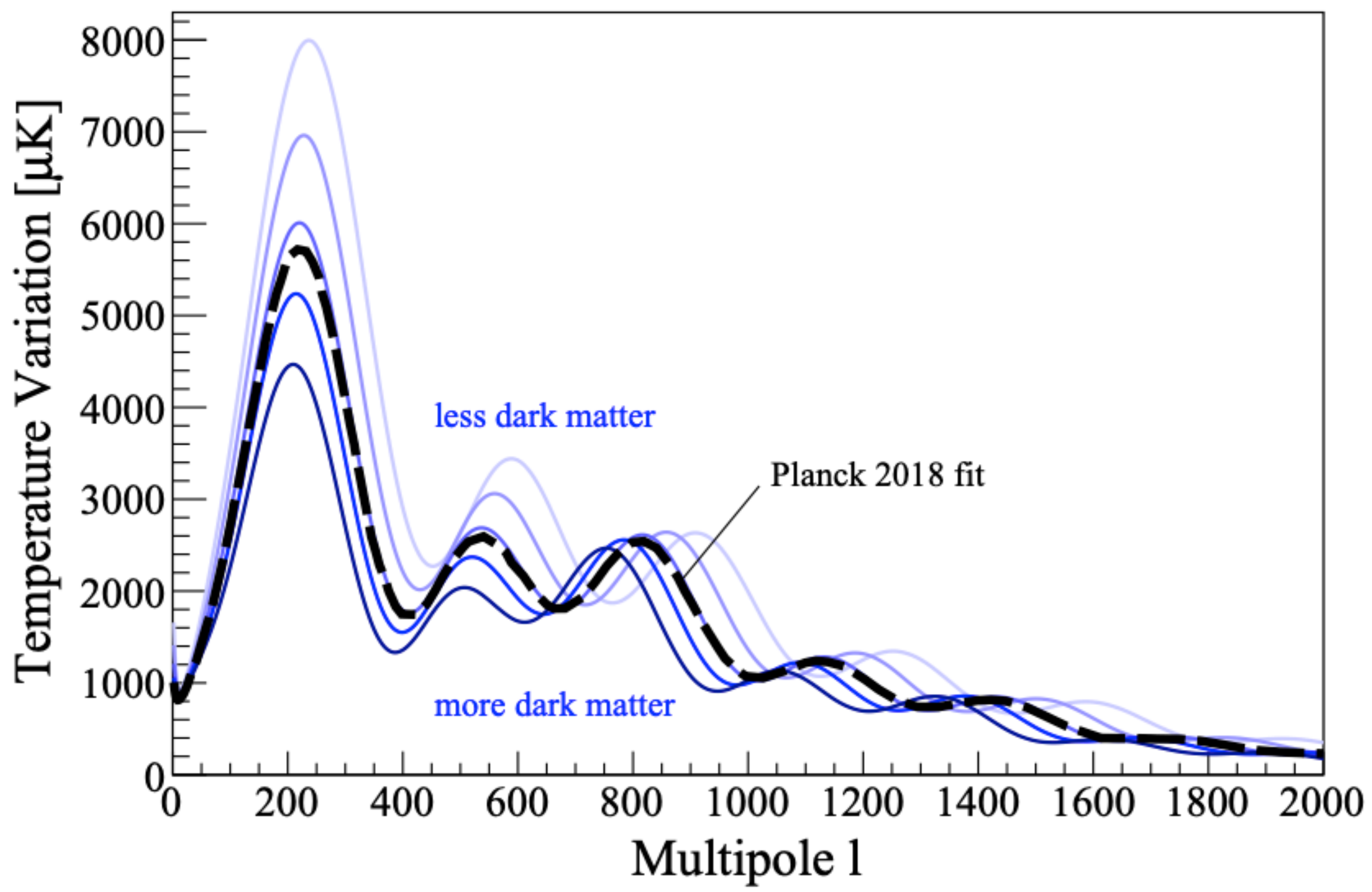
effective coupling:ϵe

Dark Photon Dark Matter

Dark Matter Exists!



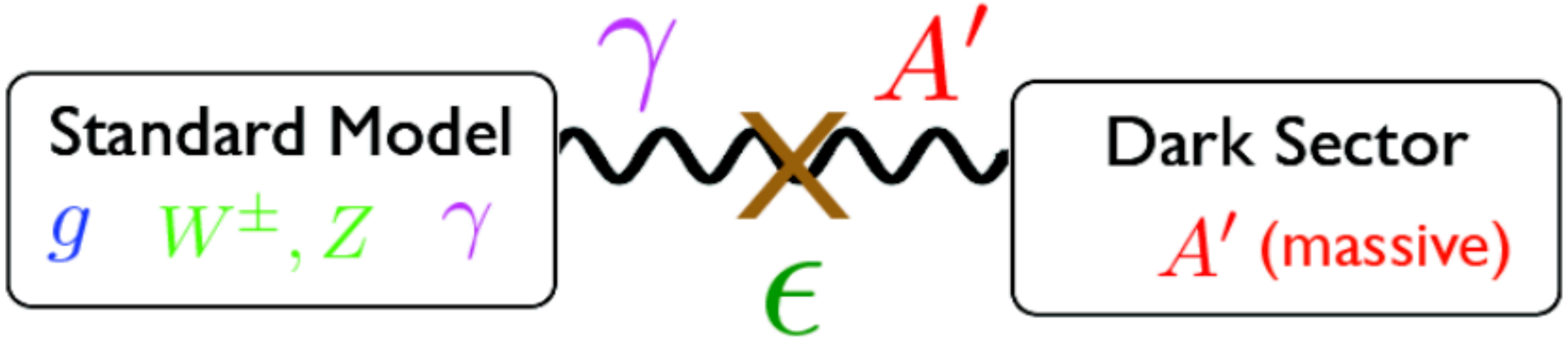
http://background.uchicago.edu/~whu/intermediate/driving2.html



- Dark matter consists 26.8% of the total mass-energy content.
- Dark matter particle interact very weakly with the standard model particles.

Dark Photon Dark Matter

Kinetic mixing as portal to the dark sector



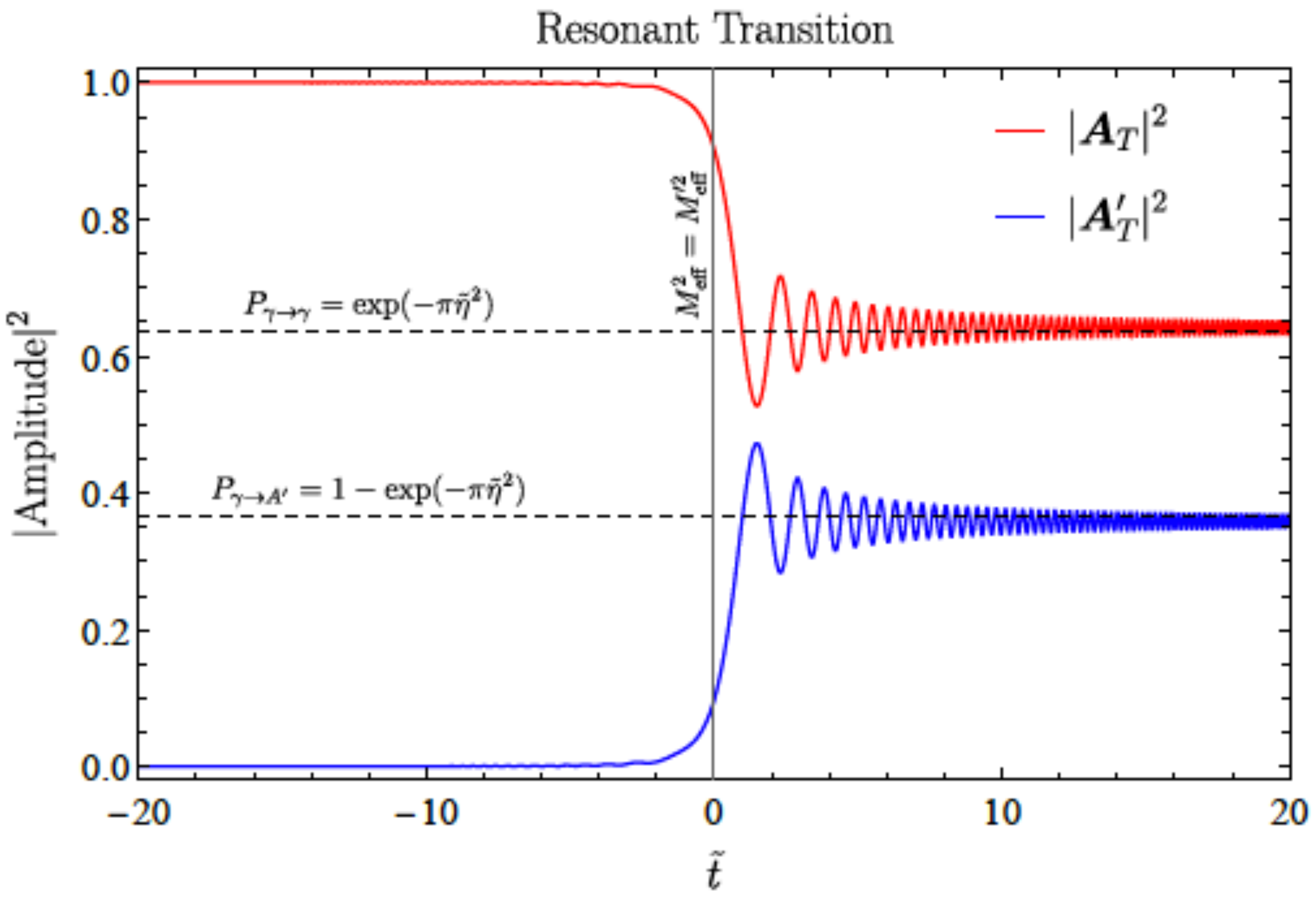
$$\Delta\mathcal{L} = \frac{\epsilon}{2} F^{Y,\mu\nu} F'_{\mu\nu}$$

"Kinetic Mixing" Holdom

Galison, Manohar

Simplest: dark sector consists of just a A'

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



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

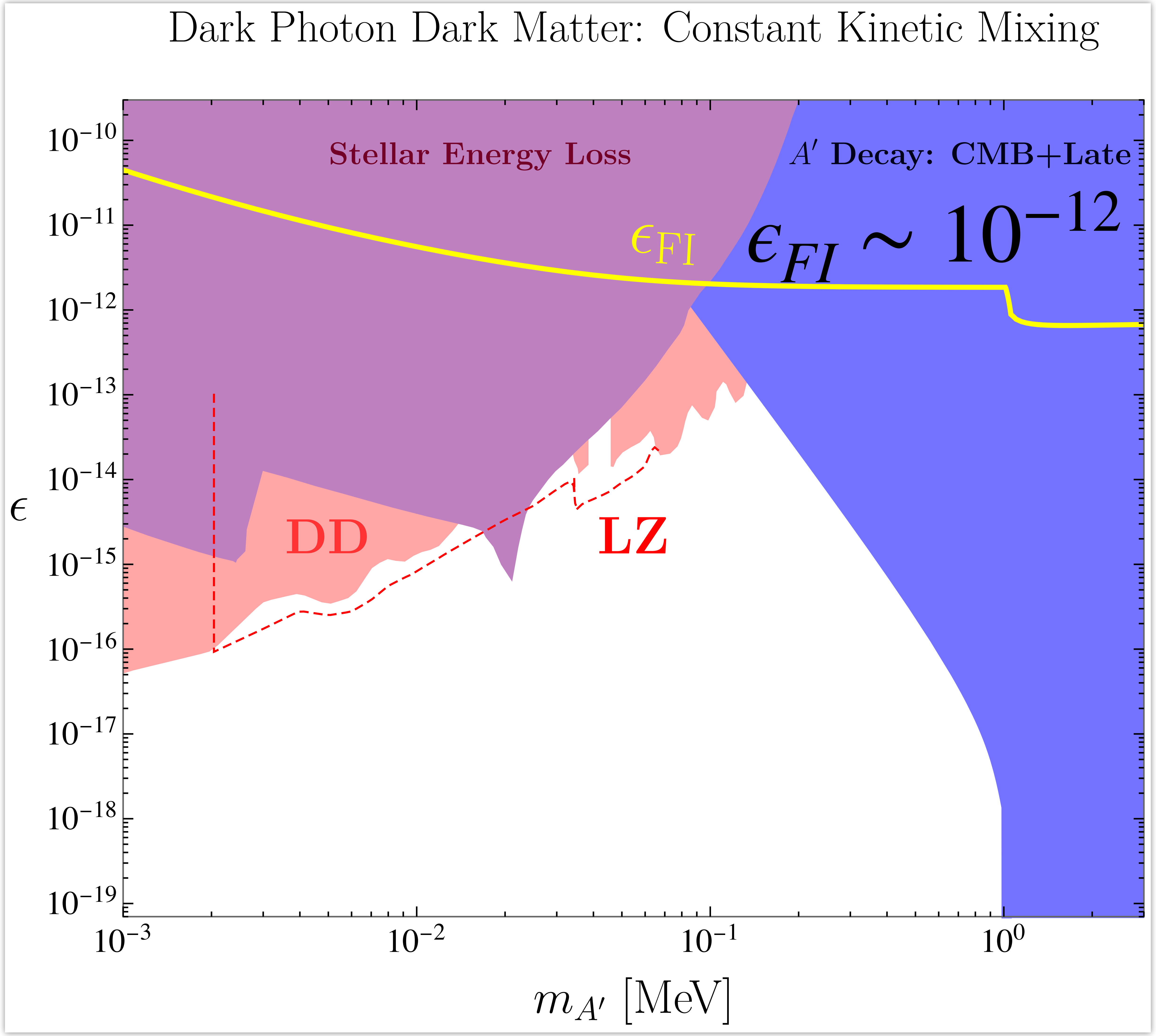
$$\Omega_{A'} \sim 0.1$$

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

$T_{\rm res} : m_\gamma = m_{A'}$

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

Late time constraints $z \ll 1000$

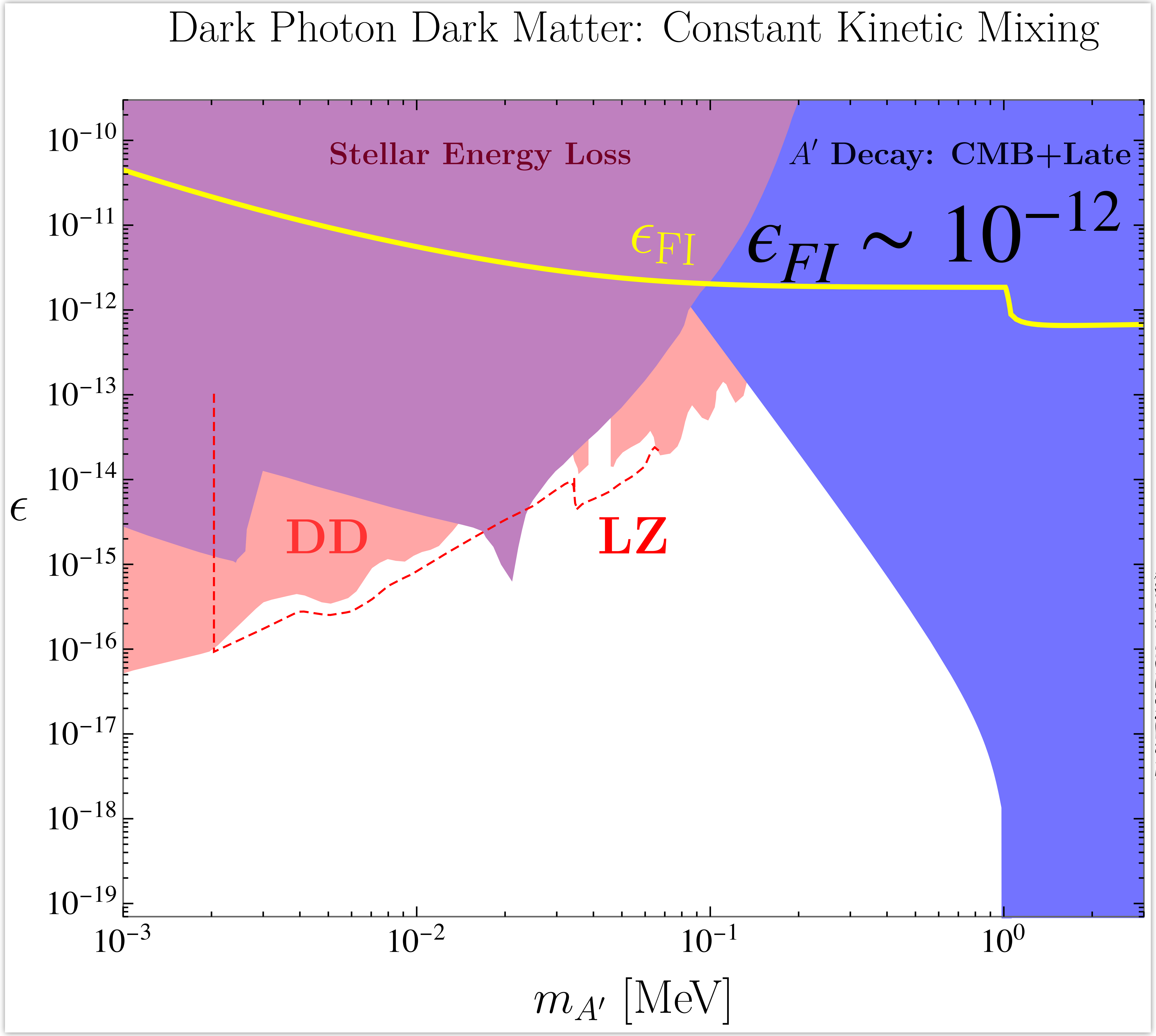


Stellar Energy Loss: $\gamma \to A'$

A' Decay: $A' \to 3\gamma, A' \to e^- e^+$

Redondo, Postma 2005

Late time constraints $z \ll 1000$

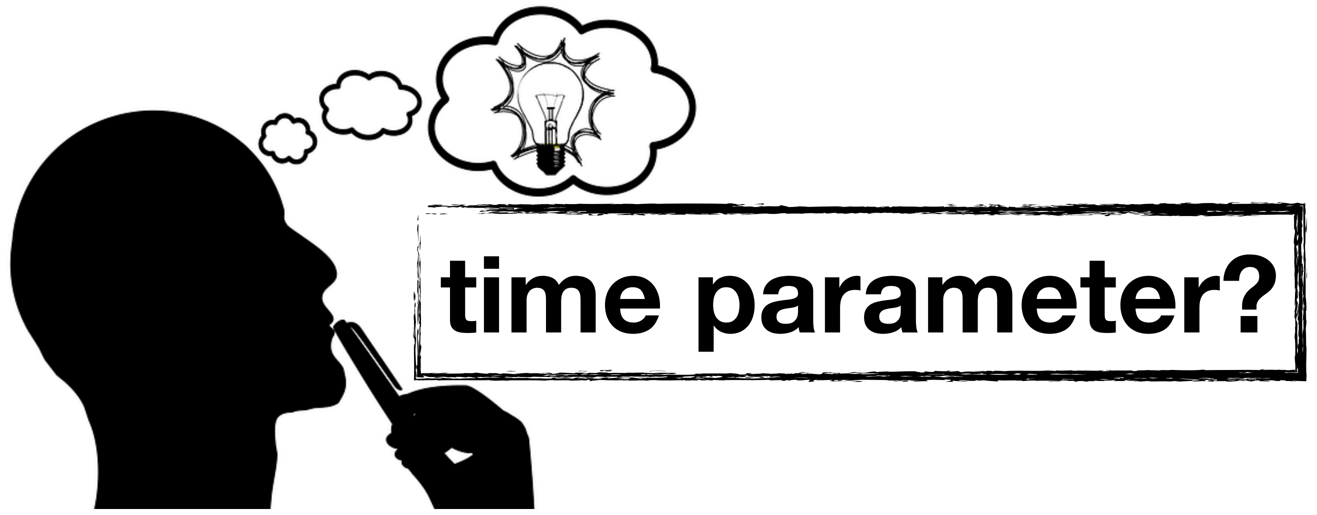


Stellar Energy Loss: $\gamma \to A'$

A' Decay: $A' \to 3\gamma, A' \to e^- e^+$

Redondo, Postma 2005

Simplest DPDM freeze-in through the constant kinetic mixing is ruled out



So… What if we promote ϵ to a field-dependent variable?

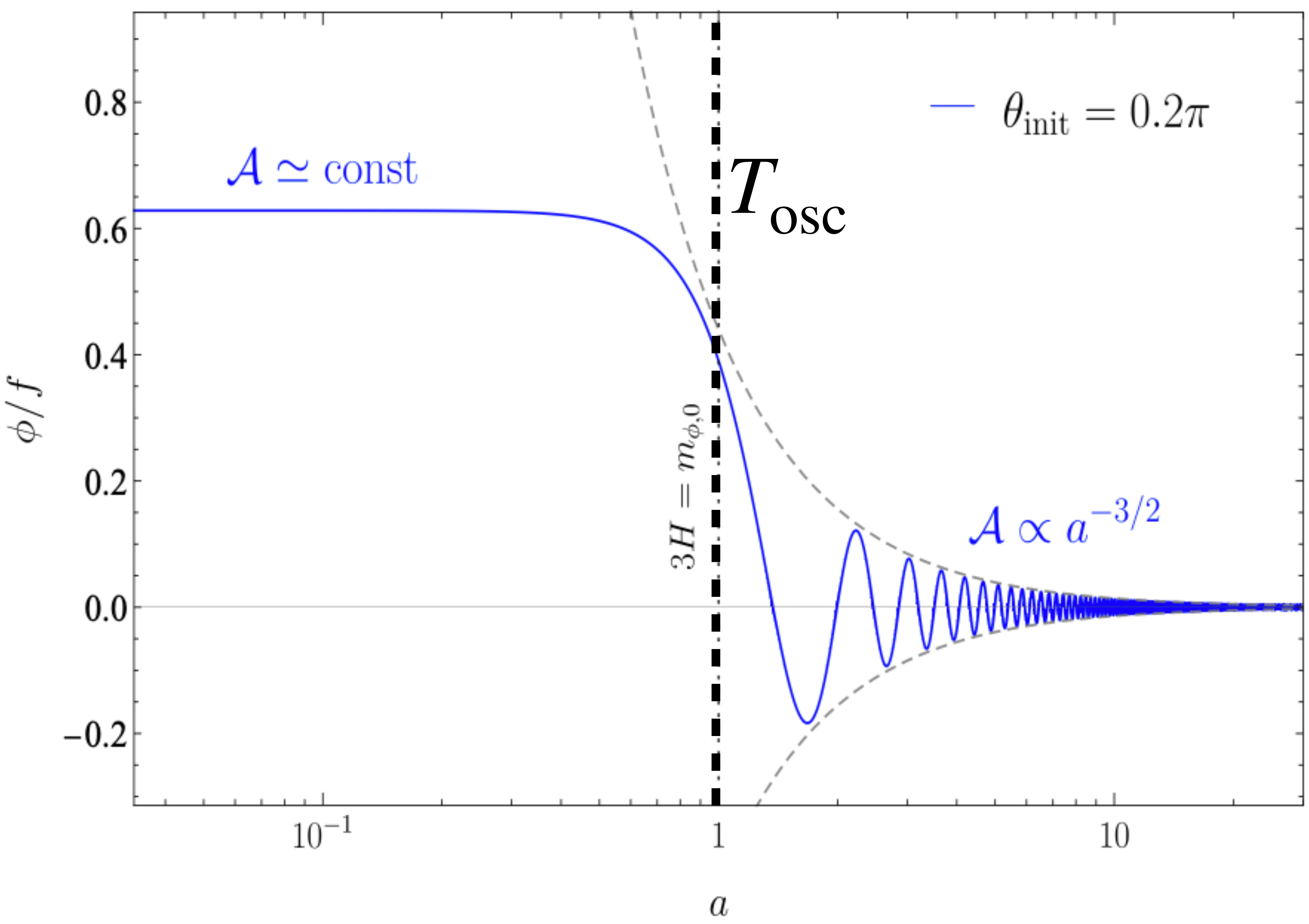
$$\epsilon F^{\mu\nu} F'_{\mu\nu} \rightarrow \frac{\phi}{\Lambda} F^{\mu\nu} F'_{\mu\nu}$$

Time-evolution of homogeneous single scalar field:
KG equation in the FRW metric

$$\ddot{\phi} + 3H\dot{\phi} + m_\phi^2 \phi = 0$$

Misalignment initial condition: $\theta_{\rm ini} = \frac{\phi_{\rm ini}}{f} \sim \mathcal{O}(1)$

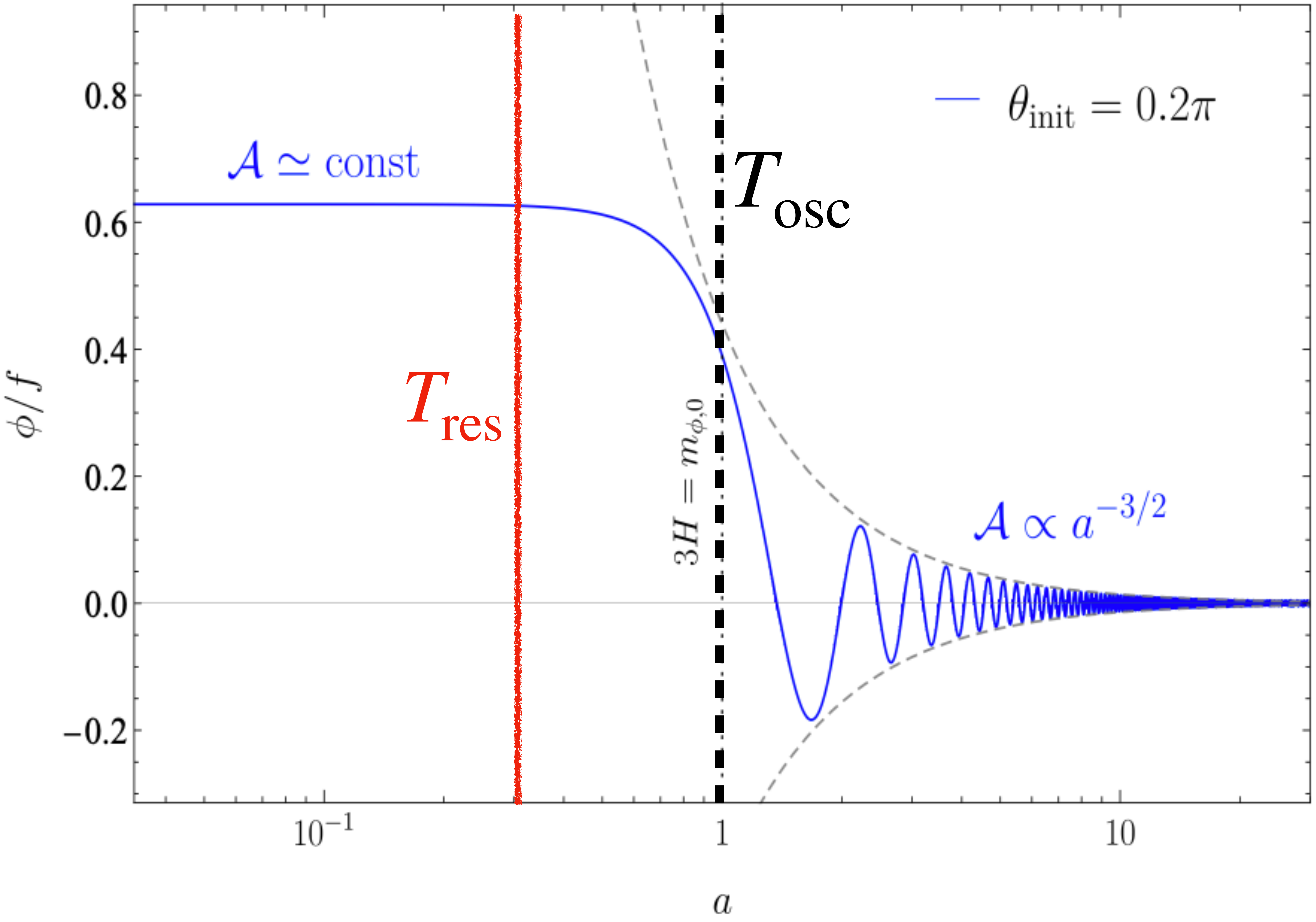
Time-evolution of homogeneous single scalar field



$$\phi = \begin{cases} \phi_{\rm ini}\,, & 3H > m_\phi \\ \dfrac{\sqrt{\rho_\phi}}{m_\phi}\cos\left(m_\phi t\right)\,, & 3H < m_\phi \end{cases}$$

$$T_{\rm osc} \sim \sqrt{m_\phi M_{\rm pl}}$$

Time-evolution of homogeneous single scalar field

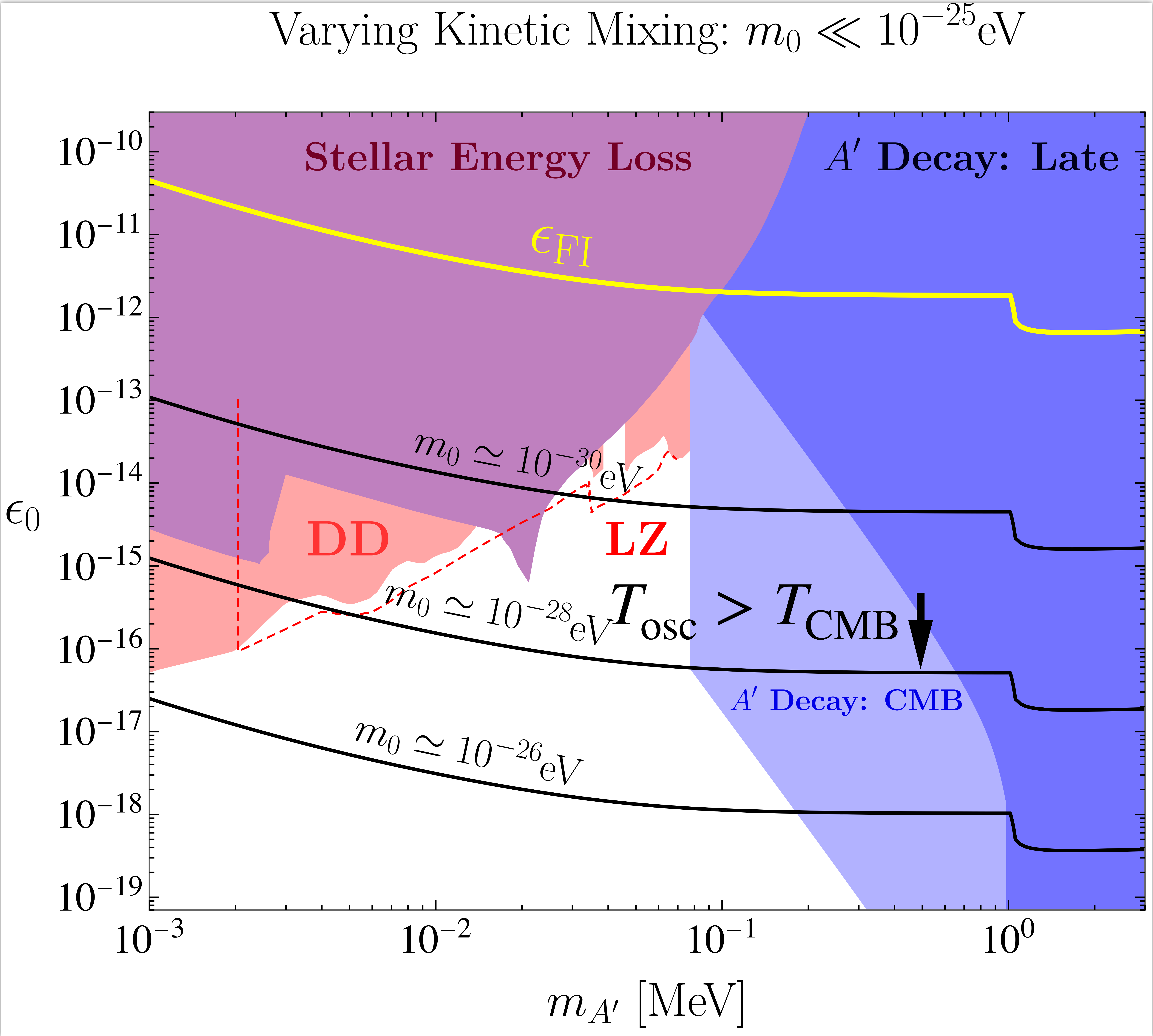


$$\phi = \begin{cases} \phi_{\rm ini}\,, & 3H > m_\phi \\ \dfrac{\sqrt{\rho_\phi}}{m_\phi}\cos\left(m_\phi t\right)\,, & 3H < m_\phi \end{cases}$$

$$T_{\rm osc} \sim \sqrt{m_\phi M_{\rm pl}}$$

ϕ: subcomponent of DM.

$$\mathscr{F} = 10^{-3}$$



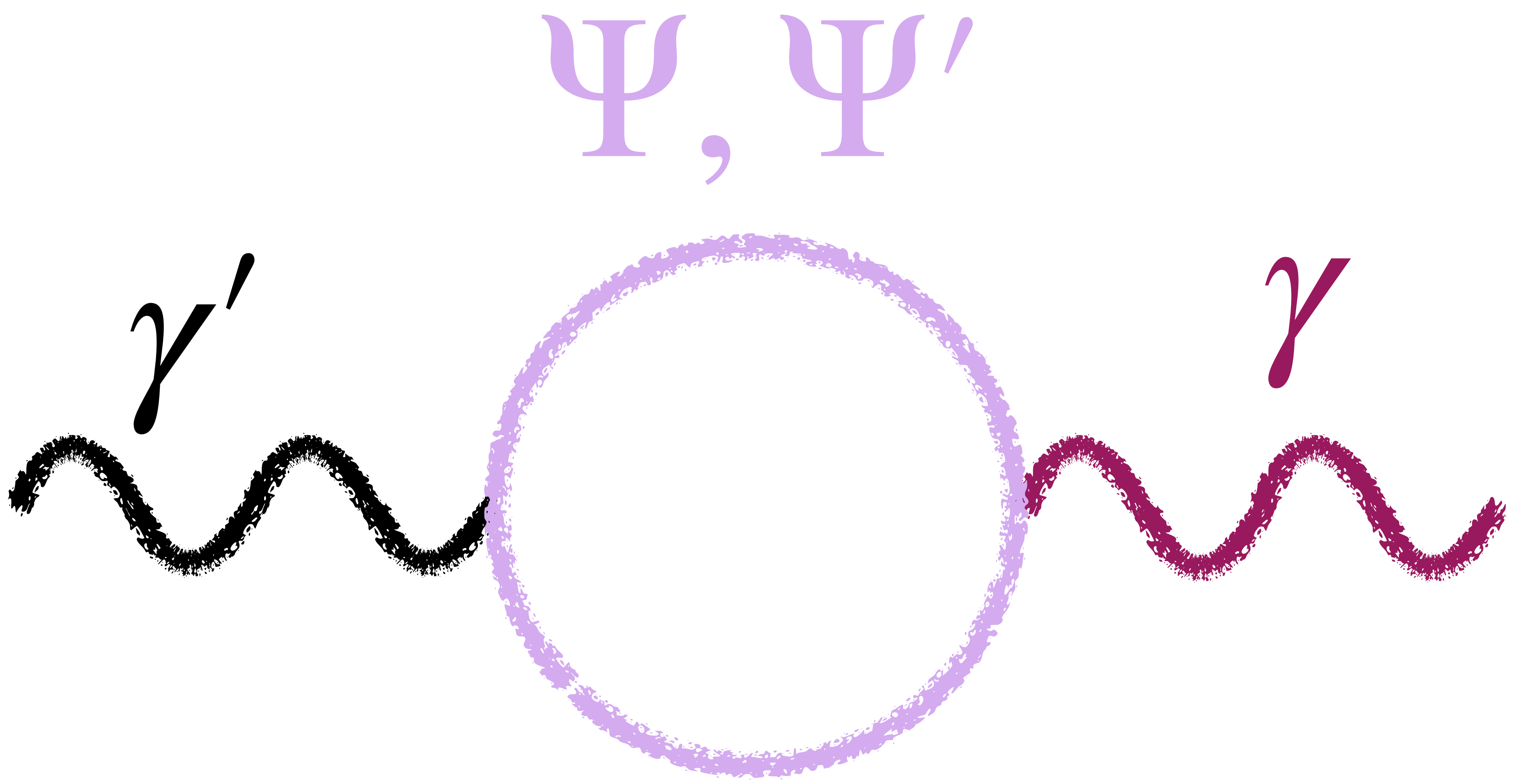
$$m_0 \ll 10^{-25} eV$$

$$T_{\rm osc} < T_{\rm res} \qquad \epsilon_{\rm FI} \sim 10^{-12}$$

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

$$T_{\rm osc} \sim \sqrt{m_\phi M_{\rm pl}}$$

Constant Kinetic Mixing

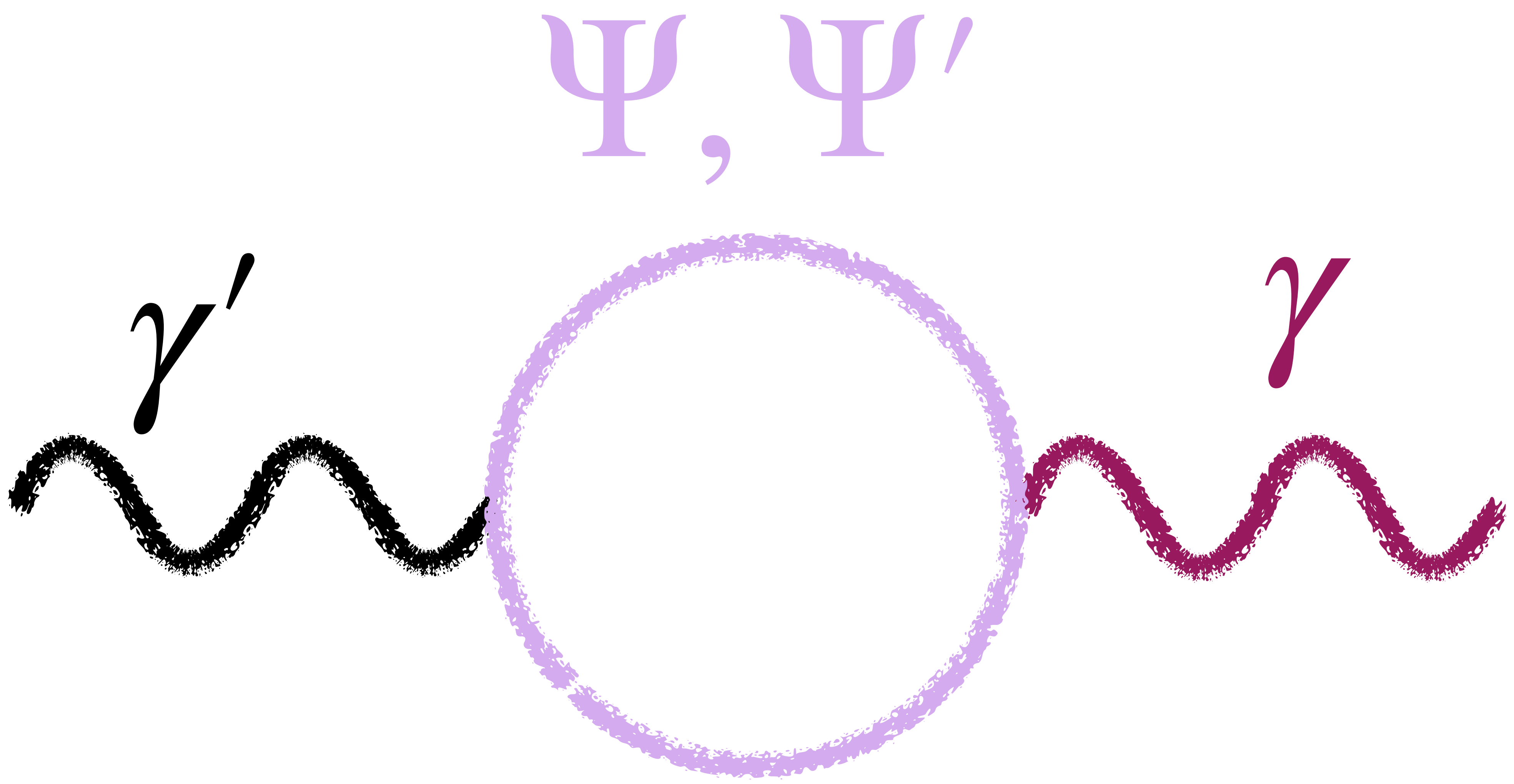


Bob Holdom 1985

$\Psi : (e, e', M) \qquad \Psi' : (e, -e', M')$

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

Constant Kinetic Mixing



Bob Holdom 1985

$\Psi : (e, e', M) \qquad \Psi' : (e, -e', M')$

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

$M = M'$: Constant mixing vanishes

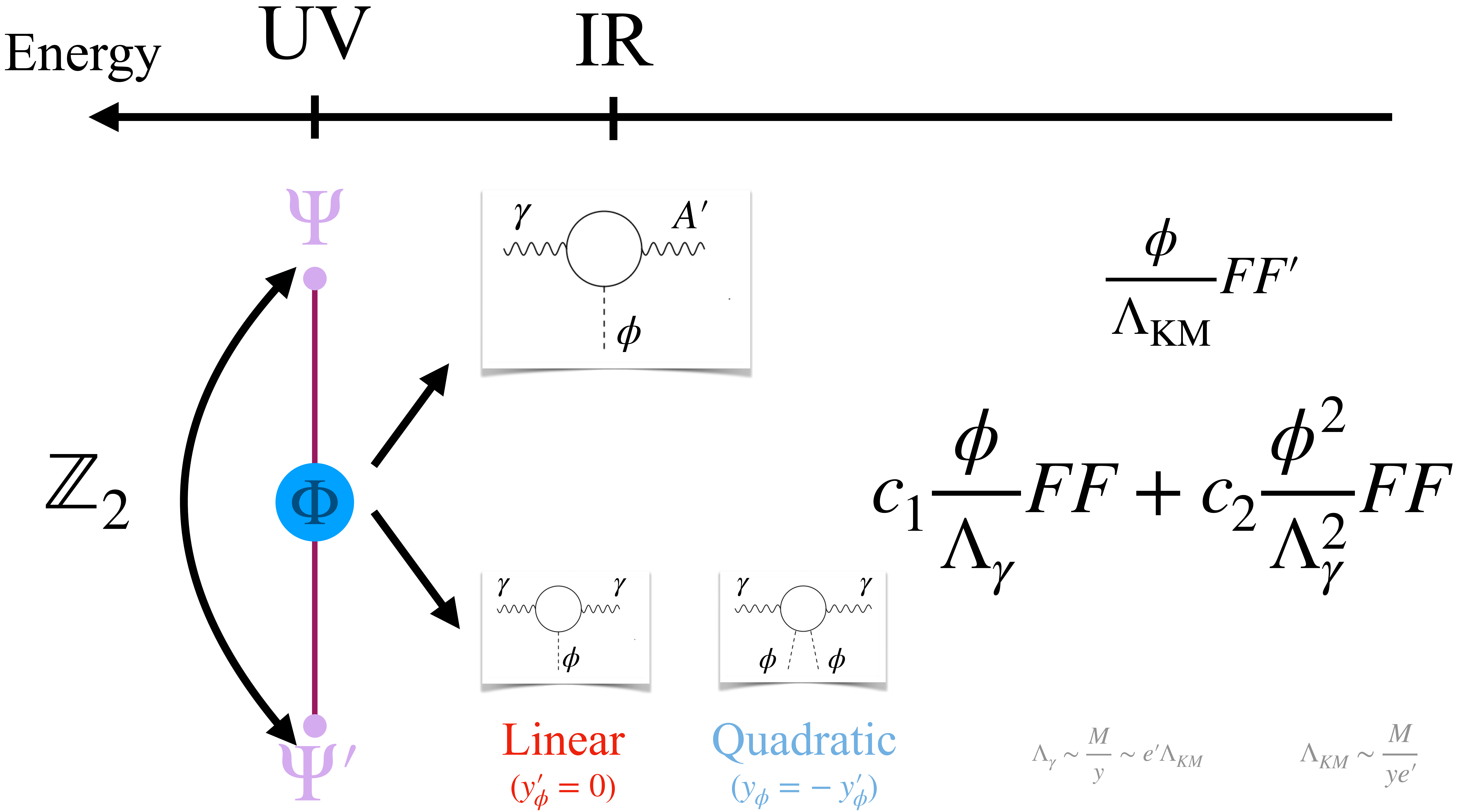
Kinetic mixing is forbidden by $Z_2 : \Psi \leftrightarrow \Psi', A \rightarrow A, A' \rightarrow -A'$

Field-dependent Kinetic Mixing

$$(M, M') \to \left(M + y\phi, M + y'\phi\right)$$

$$\epsilon \to \frac{ee'}{6\pi^2} \log\left(\frac{M + y\phi}{M + y'\phi}\right) \simeq \frac{ee'(y - y')\phi}{6\pi^2 M}$$

Z_2 is broken by ϕ so the kinetic mixing is dependent on ϕ


Energy
UV
IR
Ψ
Ψ'
$\mathbb{Z}_2$
Φ
γ
A'
ϕ
$\frac{\phi}{\Lambda_{\rm KM}} F F'$
$c_1 \frac{\phi}{\Lambda_\gamma} F F + c_2 \frac{\phi^2}{\Lambda_\gamma^2} F F$
Linear
$(y'_\phi = 0)$
Quadratic
$(y_\phi = -y'_\phi)$
$\Lambda_\gamma \sim \frac{M}{y} \sim e' \Lambda_{KM}$
$\Lambda_{KM} \sim \frac{M}{y e'}$

Field dependent fine-structure constant

$$-\frac{1}{16\pi\alpha_{\mathrm{em}}}F^2 + d_{\gamma,n}\left(\frac{\phi}{M_{\mathrm{pl}}}\right)^n F^2 \rightarrow -\frac{1}{16\pi\alpha_{\mathrm{em}}^{\mathrm{eff}}}F^2$$

$$\frac{\Delta\alpha}{\alpha} \propto \begin{cases} d_{\gamma,1}\phi\,, & \text{linear} \\ d_{\gamma,2}\phi^2\,, & \text{quadratic} \end{cases}$$

The fine-structure constant becomes time-dependent

Measurement of the time-varying fine-structure constant

Atomic Clock

$$f_A \propto \alpha^{\xi_A+2}$$

ξ_A **varies for different atoms and transition channels**

$$\frac{\delta(f_A/f_B)}{f_A/f_B} \propto \Delta\xi_{AB} d_\gamma \kappa \phi(t)$$

A. Arvanitaki, J Huang, and K. Van Tilburg, PRD, 2015

Celestial Constraints on $\alpha(t)$

BBN

$$m_{np} = m_n - m_p$$

$$\Delta m_{np} \propto \frac{\Lambda_{\rm QCD}}{M_{\rm pl}} d_\gamma^{(n)} \phi$$

Change He abundance

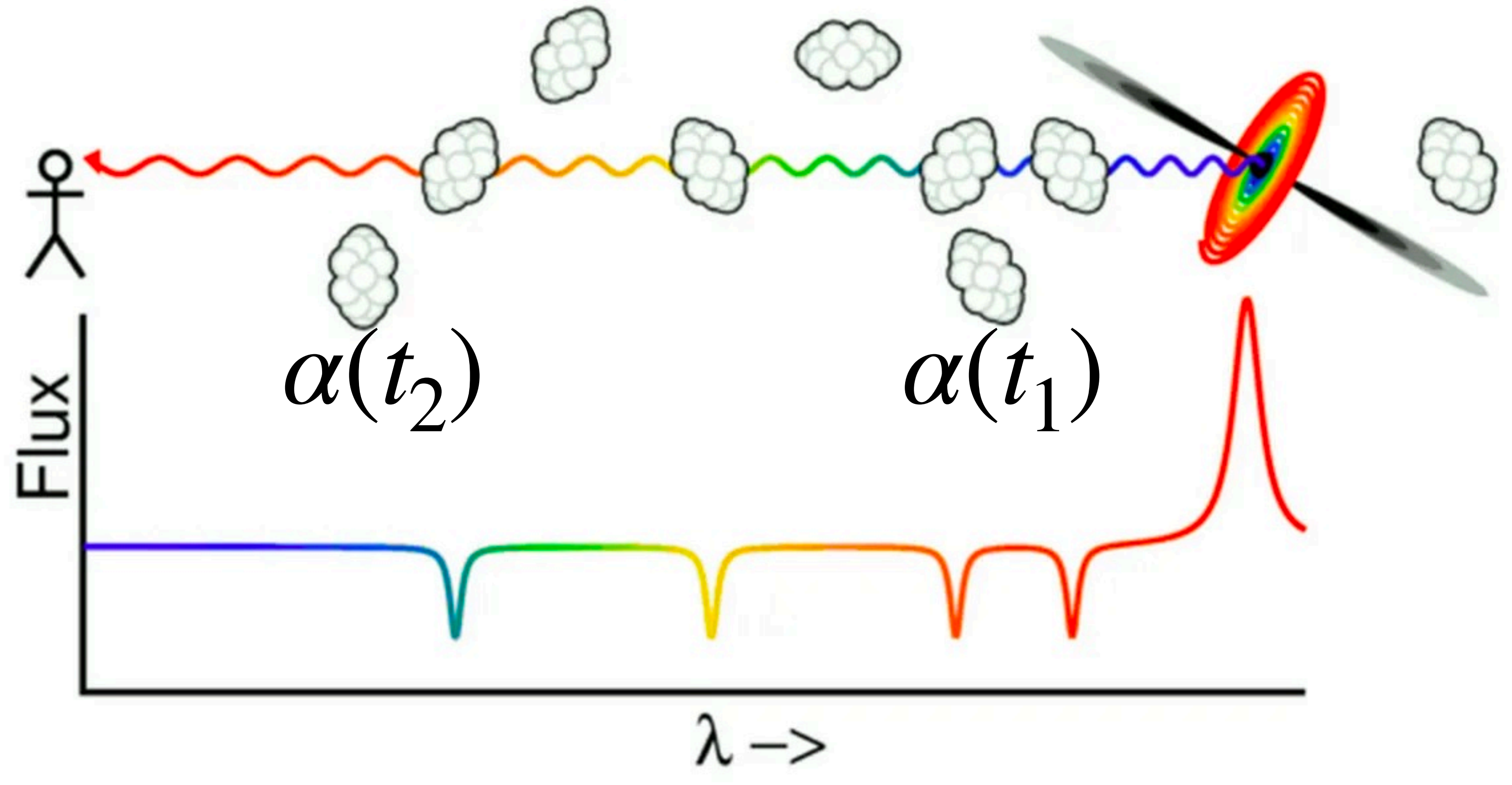
Y. V. Stadnik, V. V. Flambaum PRL 2015

Lyman-α

$$10 \mathrm{Mpc}^{-1} \sim 10^{-28} \mathrm{eV}$$

$$d_{\rm quasar} \sim m_\phi^{-1}$$

$$\Delta E_{{\rm Ly}\alpha} \sim m_e \alpha_{\rm em}$$



L. Hamaide, H. Muller, and D. J. E. Marsh, PRD 2022

Equivalence Principle Test

Ultralight ϕ provides the 5th force and modifies the Newtonian interaction

$$V_{ij}(r) = -\frac{G m_i m_j}{r}\left(1 + \alpha_{ij} e^{-r/\lambda}\right)$$

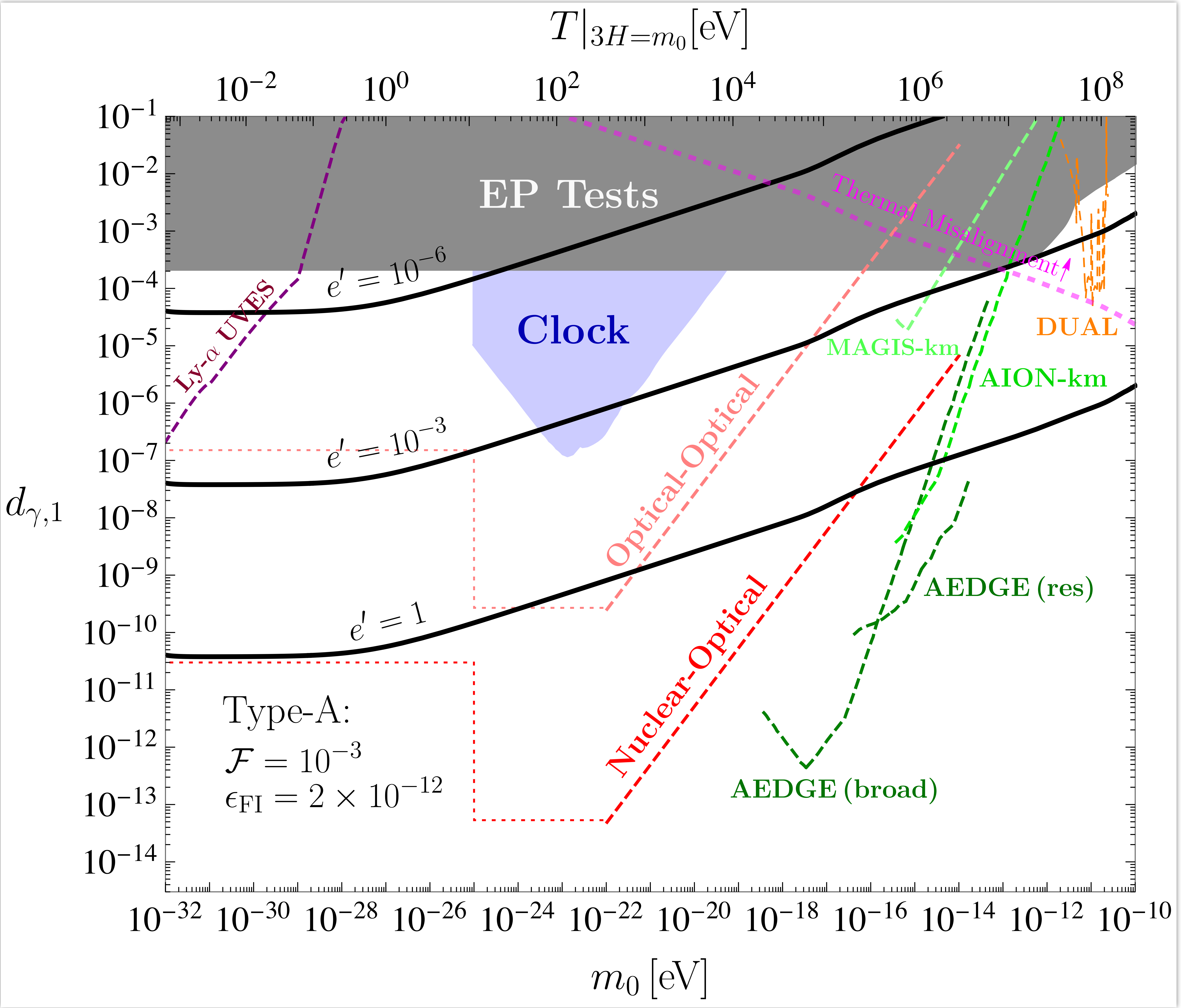
E$\ddot{o}$tv$\ddot{o}$s parameter

$$\eta = \left(\frac{\Delta a}{a}\right)_{ij} = \frac{|\vec{a}_i - \vec{a}_j|}{|\vec{a}_i + \vec{a}_j|} = (-1 \pm 27) \times 10^{-15}$$

$$\eta \propto \begin{cases} \left(d_e^{(1)}\right)^2 , & \text{linear} \\ \left(d_e^{(2)}\right)^2 \rho_\phi , & \text{quadratic} \end{cases}$$

Joel Bergé, Philippe Brax, Gilles Métris, et.al. PRL 2018

pheno of d_γ from $\epsilon(\phi)$ UV model



Linear Coupling

$$d_{\gamma,1} \sim \frac{m_{pl}\epsilon_{FI}}{e'|\phi|_{osc}}$$

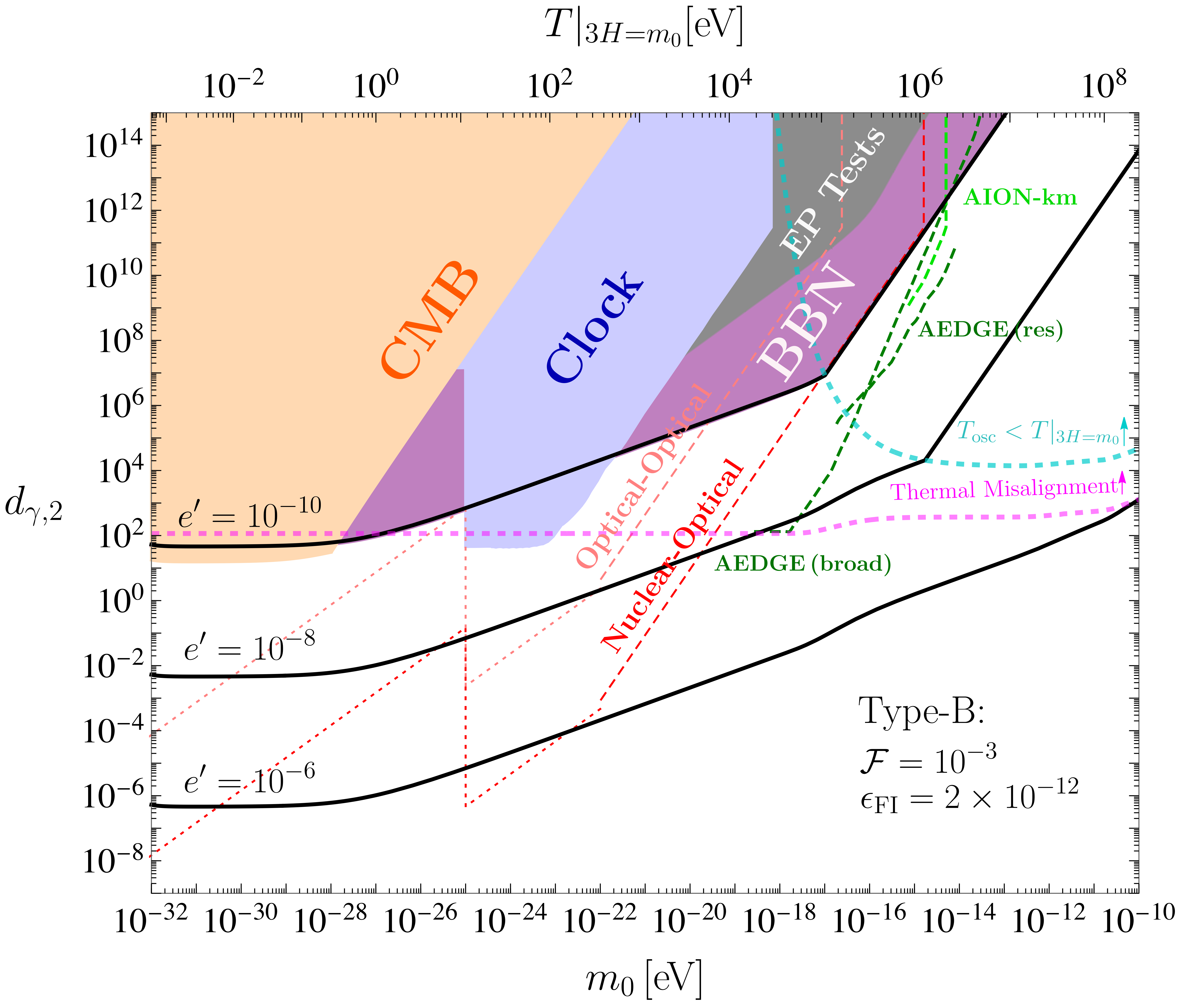
$$\epsilon_{FI} \sim 10^{-12}$$

$$m_0 \sim 10^{-28}\text{eV}$$

$$|\phi|_{osc} \sim 10^{16}\text{GeV}$$

$$e' \sim 1 \rightarrow d_{\gamma,1} \sim 10^{-10}$$

Quadratic Coupling



$$d_{\gamma,2} \sim \left(\frac{m_{pl}\epsilon_{FI}}{e'|\phi|_{osc}} \right)^2$$

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

$$m_0 \sim 10^{-28}\text{eV}$$

$$|\phi|_{osc} \sim 10^{16}\text{GeV}$$

$$e' \sim 10^{-6} \rightarrow d_{\gamma,2} \sim 10^{-6}$$

Conclusion:

- DPDM and photon are connected by the kinetic mixing.
- ϕ dependent kinetic mixing relieves $\epsilon_{\rm FI}$ tension.
- The ultralight scalar to photon coupling modifies $\alpha_{\rm em}$.
- Signals and constraints from varies experiments/observations.


Thanks For
Your
Attention!

Suppress UV Freeze-in

We want

$$\frac{\Omega_{\gamma \to \gamma' + \phi}}{\Omega_{\gamma \to \gamma'}} \ll 1$$

$\delta\phi F F'$

$\phi_{\rm osc} F F'$

Suppress UV Freeze-in

$$\frac{\Omega_{\gamma\to\gamma'+\phi}}{\Omega_{\gamma\to\gamma'}} \sim \frac{m_{DM}T_{rh}}{|\phi|^2_{osc}} \ll 1 \qquad \phi_{\rm osc} = \phi(T_{\rm osc})$$

GUT 10^{16}GeV

NR Ultralight Boson: $|\phi|_{osc} = \sqrt{2\rho_\phi}/m_\phi$

$m_\phi \sim 10^{-20}$eV ⟷ $|\phi|_{osc} \sim 10^{15}$GeV

Ultralight ϕ suppresses UV FI

1. Schrödinger Equation

We begin with the traditional time domain method which was first developed by Landau and Zener [75, 76], and later used within the context of neutrino physics [77, 78] (see also the discussion in Ref. [18]). Working in the ultrarelativistic and collisionless limit, the dispersion relation of Eq. (2) corresponds to (up to an arbitrary phase) the following Schrödinger-type time-dependent equation

$$i\partial_t \begin{pmatrix} \boldsymbol{A}_T \\ \boldsymbol{A}'_T \end{pmatrix} \simeq \begin{pmatrix} \xi & \eta \\ \eta & -\xi \end{pmatrix} \begin{pmatrix} \boldsymbol{A}_T \\ \boldsymbol{A}'_T \end{pmatrix} , \tag{B1}$$

where $\xi = (M_{\rm eff} - M'_{\rm eff})/4\omega$ and $\eta = \epsilon\, M_{\rm eff}/2\omega$ (we remind the reader that we have shortened our notation such that only the real part is included in $M^2_{\rm eff}$ and $M'^2_{\rm eff}$). Now, expanding $\boldsymbol{A}_T$ and $\boldsymbol{A}'_T$ in terms of the instantaneous basis of the $\mathcal{O}(\epsilon^0)$ Hamiltonian, we have

$$\boldsymbol{A}_T = c_\gamma(t)\, e^{-i\int_{-\infty}^{t} dt'\,\xi(t')} \, , \;\; \boldsymbol{A}'_T = c_{A'}(t)\, e^{i\int_{-\infty}^{t} dt'\,\xi(t')} \, . \tag{B2}$$

To determine the time-dependent coefficients c_γ and $c_{A'}$, we substitute Eq. (B2) into Eq. (B1), which yields the following differential equations,

$$i\partial_t c_\gamma = \eta\, c_{A'}\, e^{2i\int_{-\infty}^{t} dt'\xi(t')} \, , \;\; i\partial_t c_{A'} = \eta\, c_\gamma\, e^{-2i\int_{-\infty}^{t} dt'\xi(t')} \, . \tag{B3}$$

Since Eq. (B3) is symmetric under $c_\gamma \leftrightarrow c_{A'}$, it follows that conversion probability satisfies $P_{\gamma\to A'} = P_{A'\to\gamma}$. Assuming an initially negligible dark photon density, $\gamma \to A'$ dominates over the inverse process, corresponding to the initial condition $c_\gamma(-\infty) = 1$, $c_{A'}(-\infty) = 0$. For $\epsilon \ll 1$, $c_\gamma(t) \simeq 1$ and the $\gamma \to A'$ transition probability at $t = \infty$ (to leading order in ϵ) is approximately

$$P_{\gamma\to A'} \simeq |c_{A'}(\infty)|^2 \simeq \left| \eta \int_{-\infty}^{+\infty} dt' e^{-2i\int_{-\infty}^{t'} dt''\xi(t'')} \right|^2 . \tag{B4}$$

This integral can be evaluated using the saddle point approximation, which gives

$$P_{\gamma\to A'} \simeq \sum_{t_{\rm res}} \pi\, \eta^2 \left| \frac{d\xi}{dt} \right|^{-1} \Bigg|_{t_{\rm res}} , \tag{B5}$$

This integral can be evaluated using the saddle point approximation, which gives

$$P_{\gamma\to A'} \simeq \sum_{t_{\rm res}} \pi\,\eta^2 \left|\frac{d\xi}{dt}\right|^{-1}\Bigg|_{t_{\rm res}} , \tag{B5}$$

where the sum includes all times $t_{\rm res}$ at which $\xi(t_{\rm res}) = 0$. Using the definitions of η and ξ, we find that Eq. (B5) gives $P_{\gamma\to A'}$ agrees with $-\Delta f_\gamma/f_\gamma$, where $\Delta f_\gamma/f_\gamma$ is given by integrating Eq. (8) over time.

In order to calculate $P_{\gamma\to A'}$ to the all orders in ϵ, we utilize the Dykhne-Davis-Pechukas (DDP) method [79–83]. This gives

$$P_{\gamma\to A'} = 1 - \prod_{t_{\rm res}} e^{-\frac{1}{\omega}\,{\rm Im}\int_0^{t_c} dt\ (\Pi_+ - \Pi_-)} , \tag{B6}$$

where

$$\Pi_\pm = \frac{M_{\rm eff}^2 + M_{\rm eff}'^2}{2} \pm \frac{1}{2}\sqrt{\left(\frac{d\,(M_{\rm eff}^2 - M_{\rm eff}'^2)}{dt}\bigg|_{t_{\rm res}}\right)^2 t^2 + 4\,\epsilon^2 M_{\rm eff}^4} \tag{B7}$$

and

$$t_c = 2i\,\epsilon\, M_{\rm eff}^2 \left|\frac{d\,(M_{\rm eff}^2 - M_{\rm eff}'^2)}{dt}\right|^{-1}\Bigg|_{t_{\rm res}} . \tag{B8}$$

Performing the time integral in Eq. (B6) from $t = 0$ to $t = t_c$, we find that the transition probability to all orders in

FIG. 6. The time evolution (in terms of the dimensionless time variable $\tilde{t}$) of the transverse field components $\boldsymbol{A}_T$ and $\boldsymbol{A}'_T$, as described by the two-level system of Eq. (B1). Numerical solutions of Eq. (B1) are shown as red and blue lines, for the SM-like and dark-like photon states, respectively. Along the dashed gray lines, we show the late-time semi-analytic estimate, provided by Eq. (B9). Resonant enhancement occurs at $\tilde{t} = 0$, corresponding to $M_{\rm eff} \simeq M'_{\rm eff}$ near the vertical gray line.

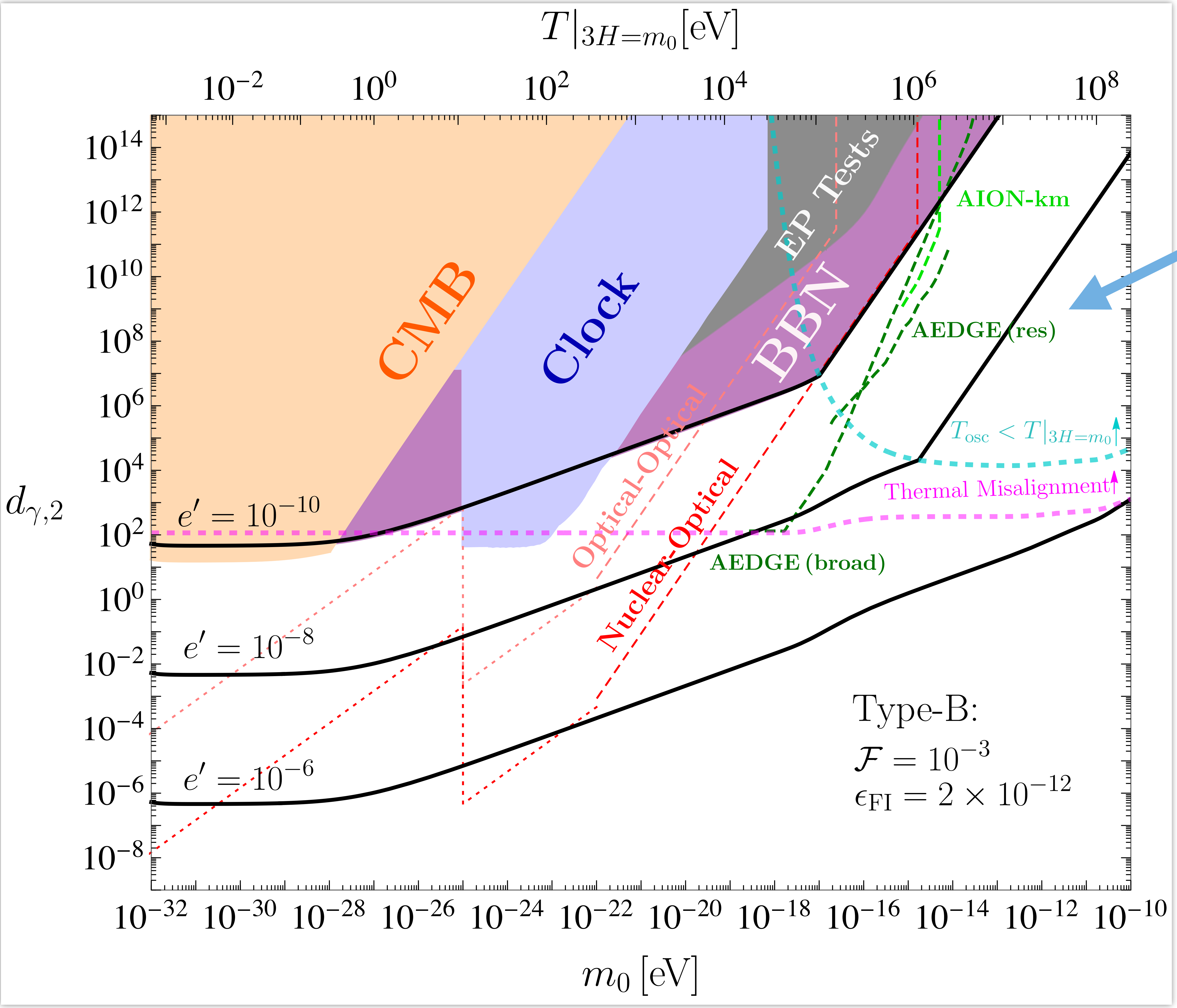
ϵ is

$$P_{\gamma \to A'} \simeq 1 - \exp\left(\sum_{t_{\rm res}} \pi \, \eta^2 \left| \frac{d\xi}{dt} \right|^{-1} \Bigg|_{t_{\rm res}} \right) . \tag{B9}$$

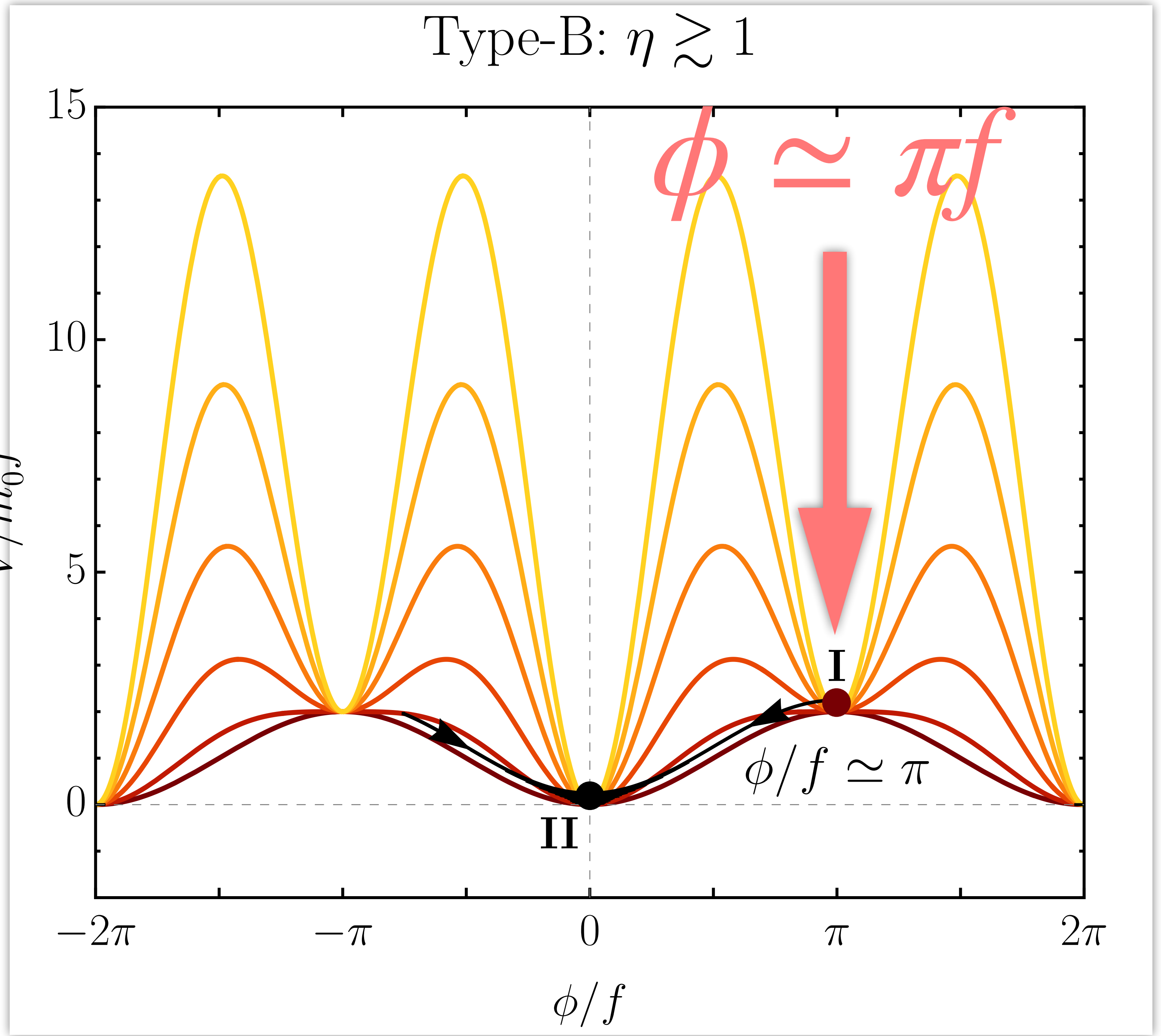
The probability for $\gamma \to \gamma$ is given by $P_{\gamma \to \gamma} = 1 - P_{\gamma \to A'}$.

In Fig. 6, we compare the numerical solution of Eq. (B1) ($|c_\gamma|^2$ in red and $|c_{A'}|^2$ in blue) to the semi-analytic approximation of Eq. (B9) (dashed gray lines). In the figure, we have defined the dimensionless quantities $\tilde{t} \equiv t\,|d\xi(t_{\rm res})/dt|^{-1/2}$ and $\tilde{\eta} \equiv \eta\,|d\xi(t_{\rm res})/dt|^{-1/2}$. The resonantly enhanced transitions occurs when $M_{\rm eff}^2 \simeq M'^2_{\rm eff}$, denoted as $\tilde{t} \simeq 0$ near the vertical gray line. Before this time, $|c_\gamma| \simeq 1$ and $|c_{A'}| \simeq 0$. Near the resonance, photons convert to the dark photons. After the resonance, c_γ and $c_{A'}$ oscillate around the asymptotic value given in Eq. (B9).

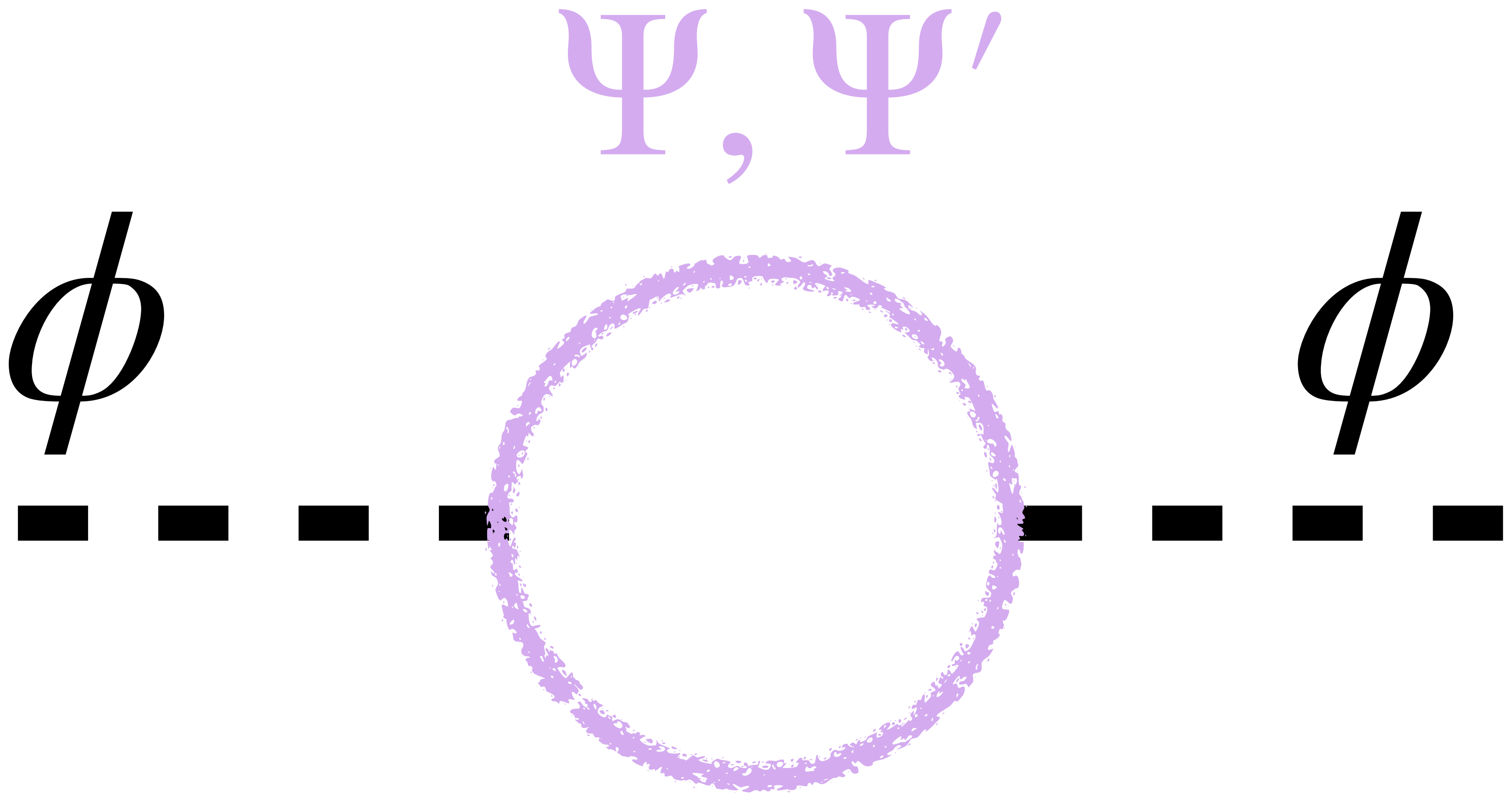
Scalar-Photon Coupling： Quadratic

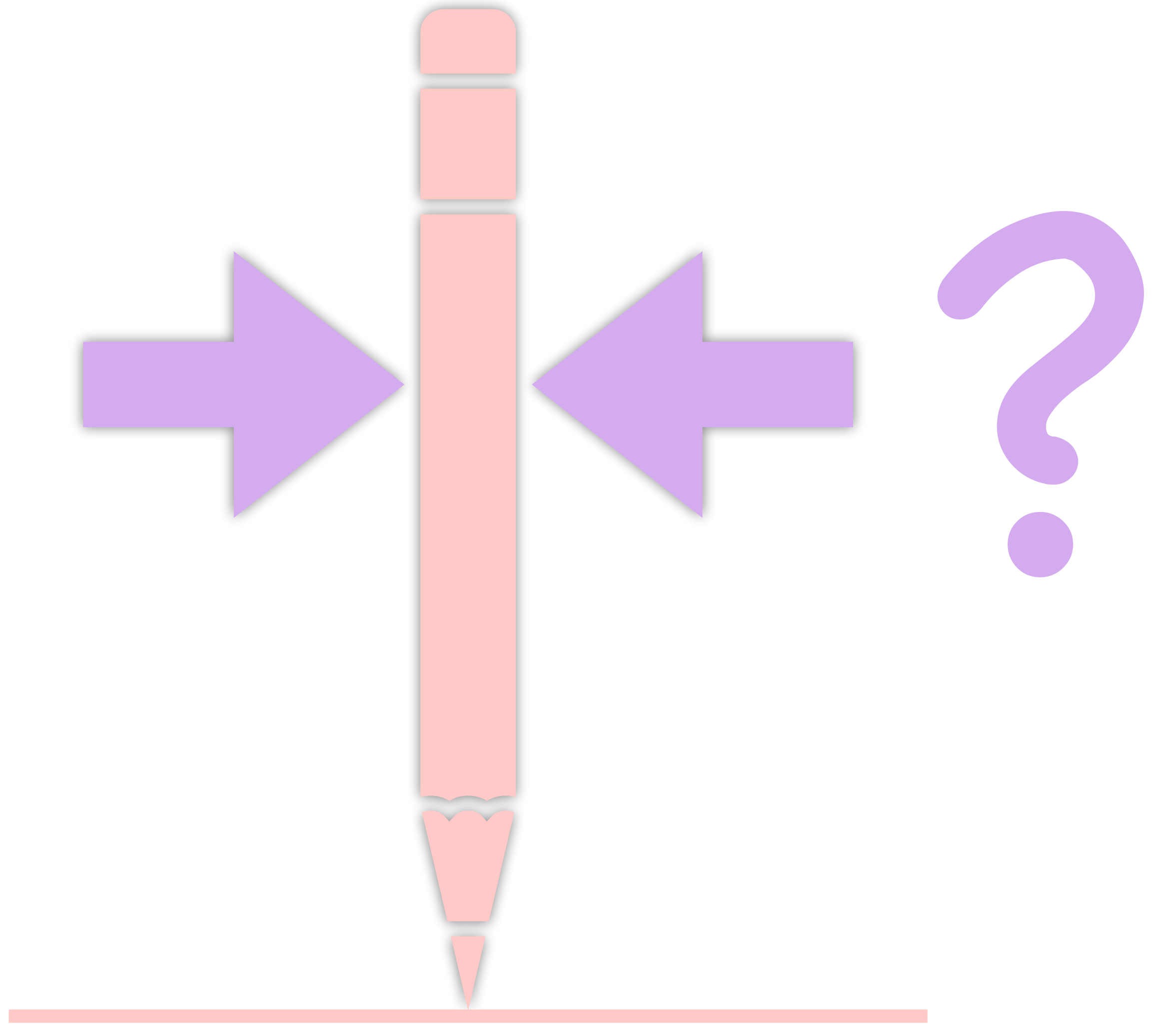


Trapped Misalignment



Protect Scalar Naturalness

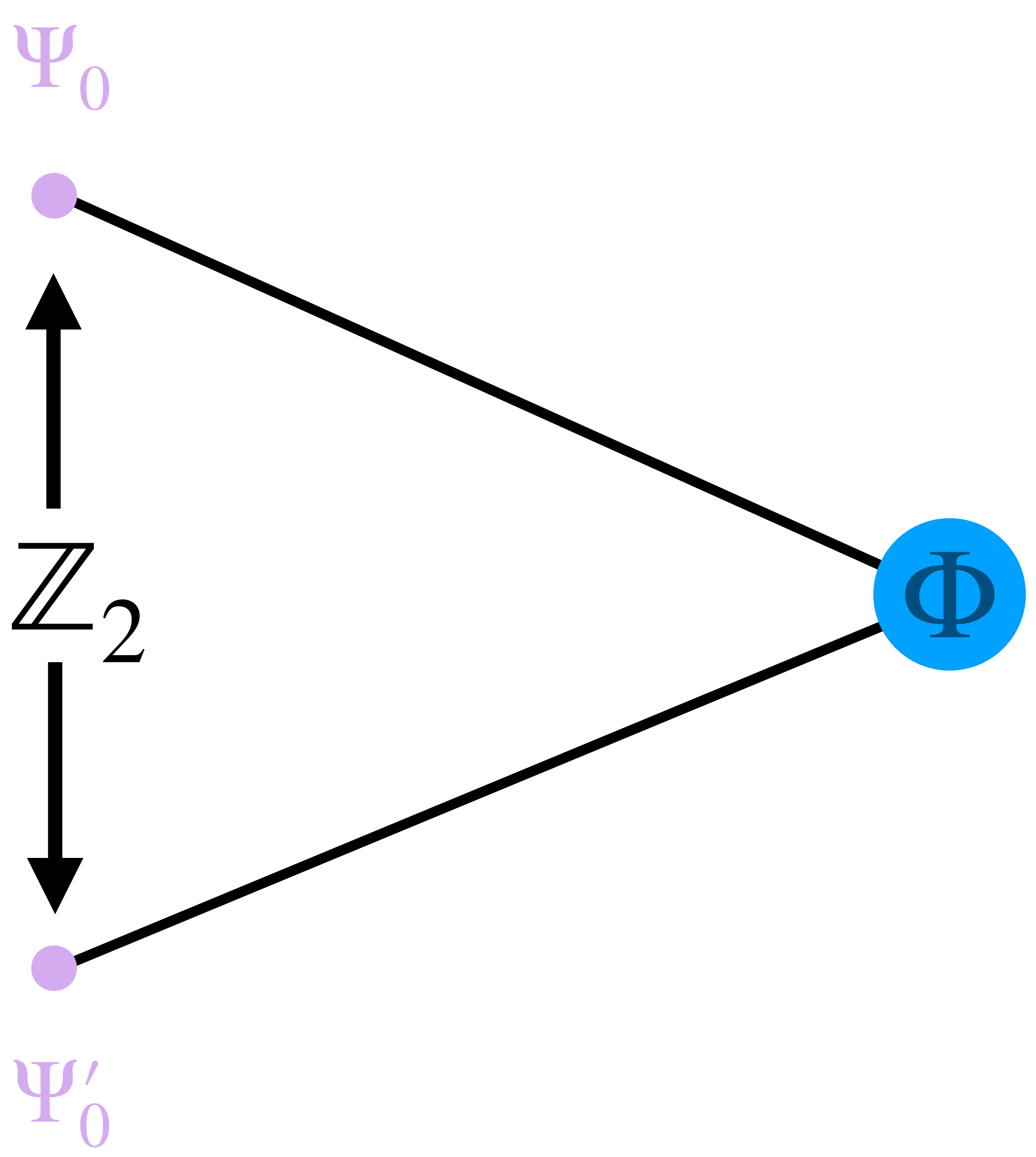




$$\Delta m_\phi \simeq 10^{-11}\mathrm{eV}\left(\frac{\epsilon_{\rm FI}}{10^{-12}}\right)\left(\frac{M}{10\mathrm{TeV}}\right)^2\left(\frac{10^{17}\mathrm{GeV}}{|\phi|_{osc}}\right)\left(\frac{1}{e'}\right)$$

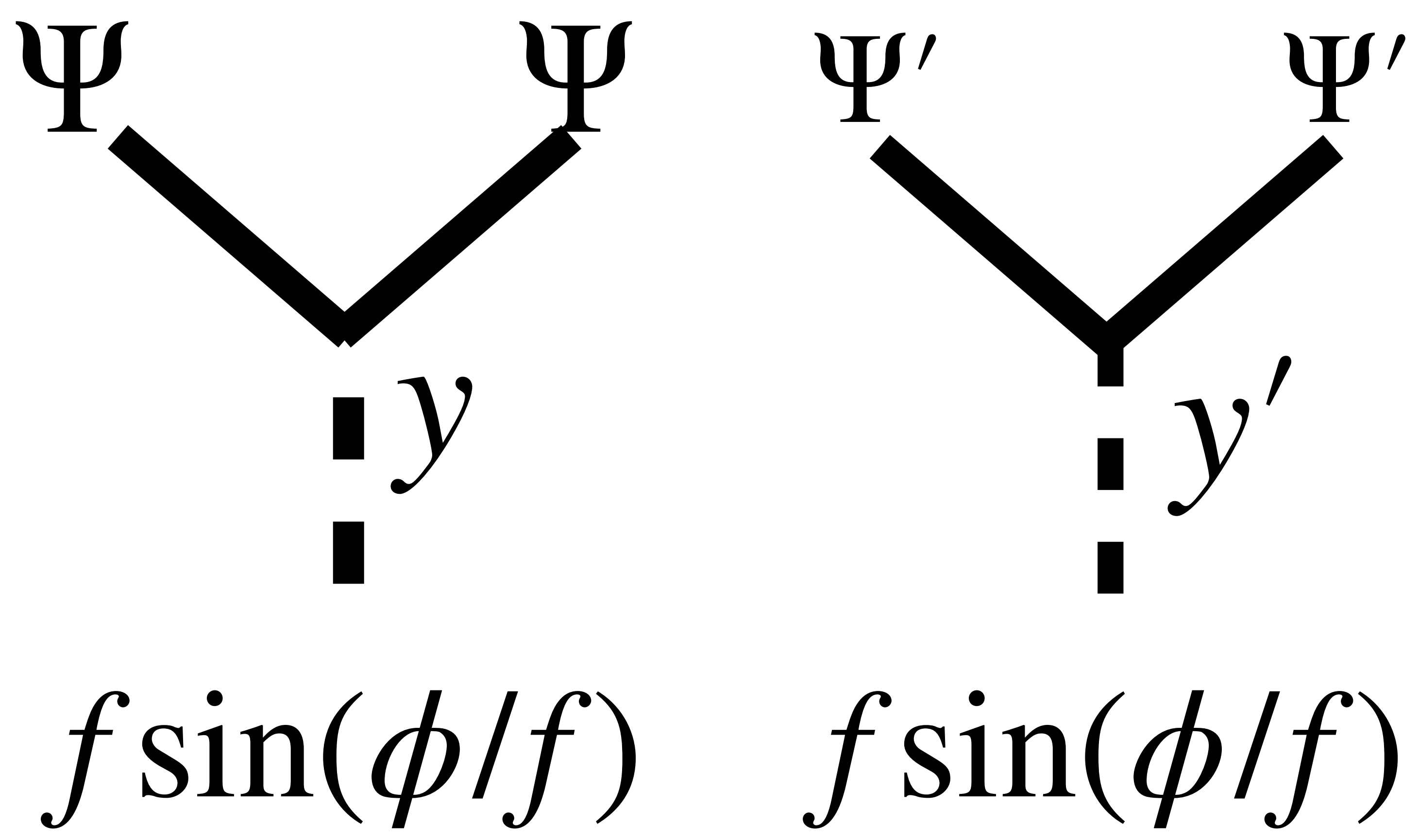
$$\gg 10^{-20}\mathrm{eV}$$

$\mathbb{Z}_2$

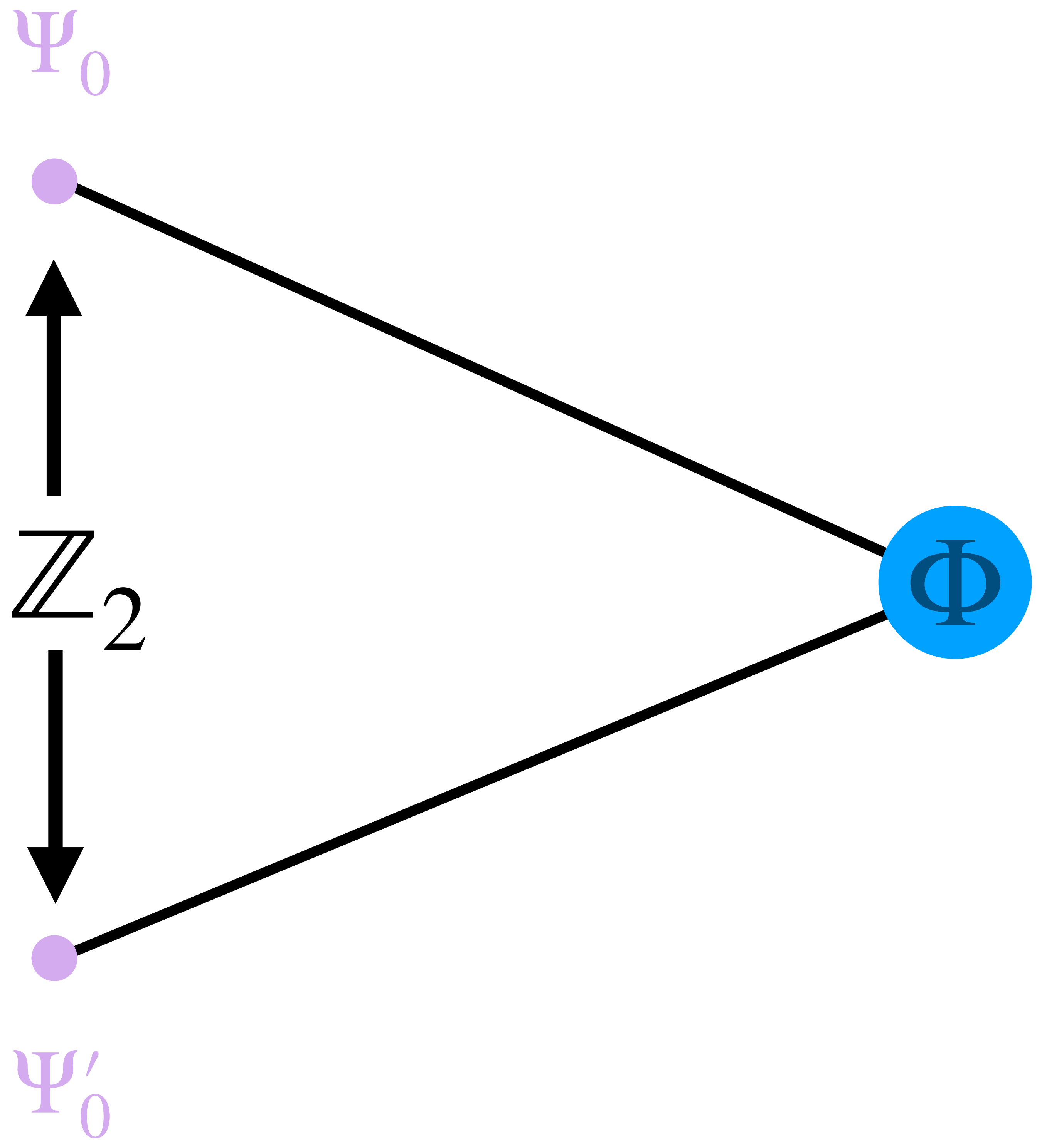


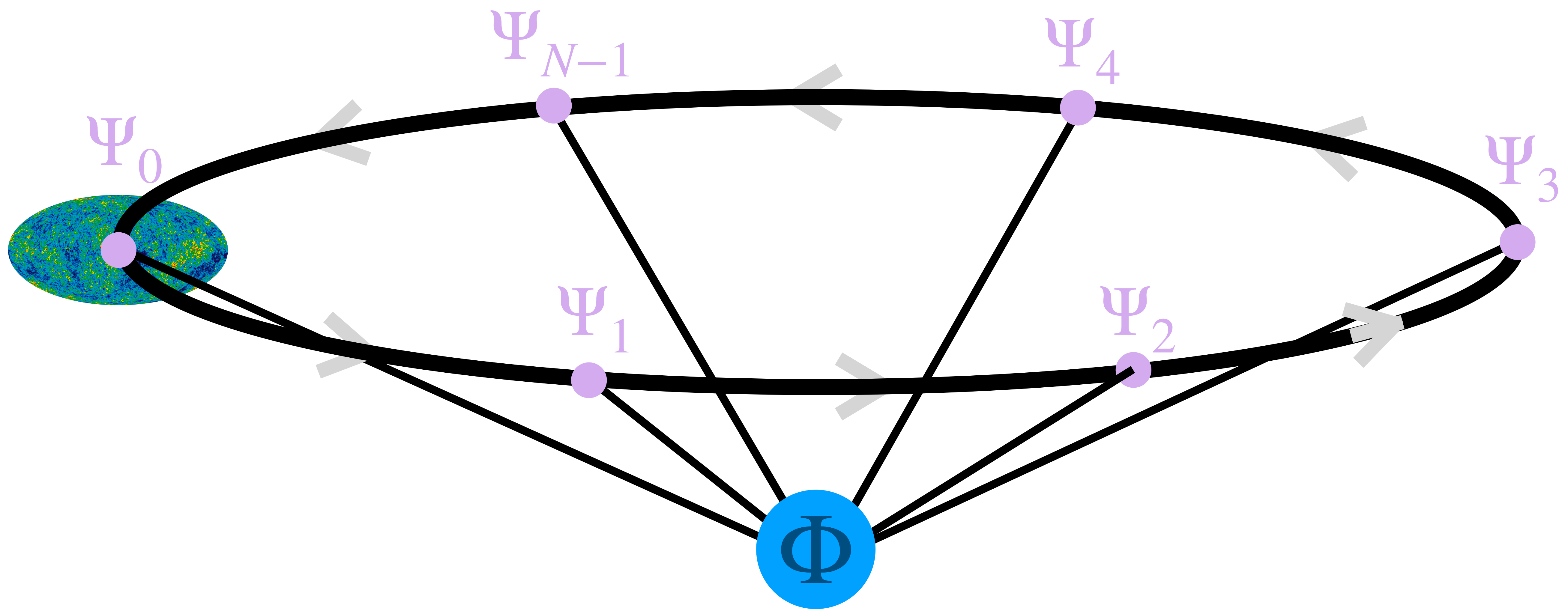
$$\mathscr{L}_{UV} \supset M\left(\bar{\Psi}\Psi + \bar{\Psi}'\Psi'\right) + y\Phi\bar{\Psi}\Psi + y'\Phi\bar{\Psi}'\Psi' + \text{h.c.}$$

$$\Phi = \frac{if}{\sqrt{2}}\exp\left(i\frac{\phi}{f}\right)$$



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





Hill et. al. 1995

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

Dror et. al. , 2020

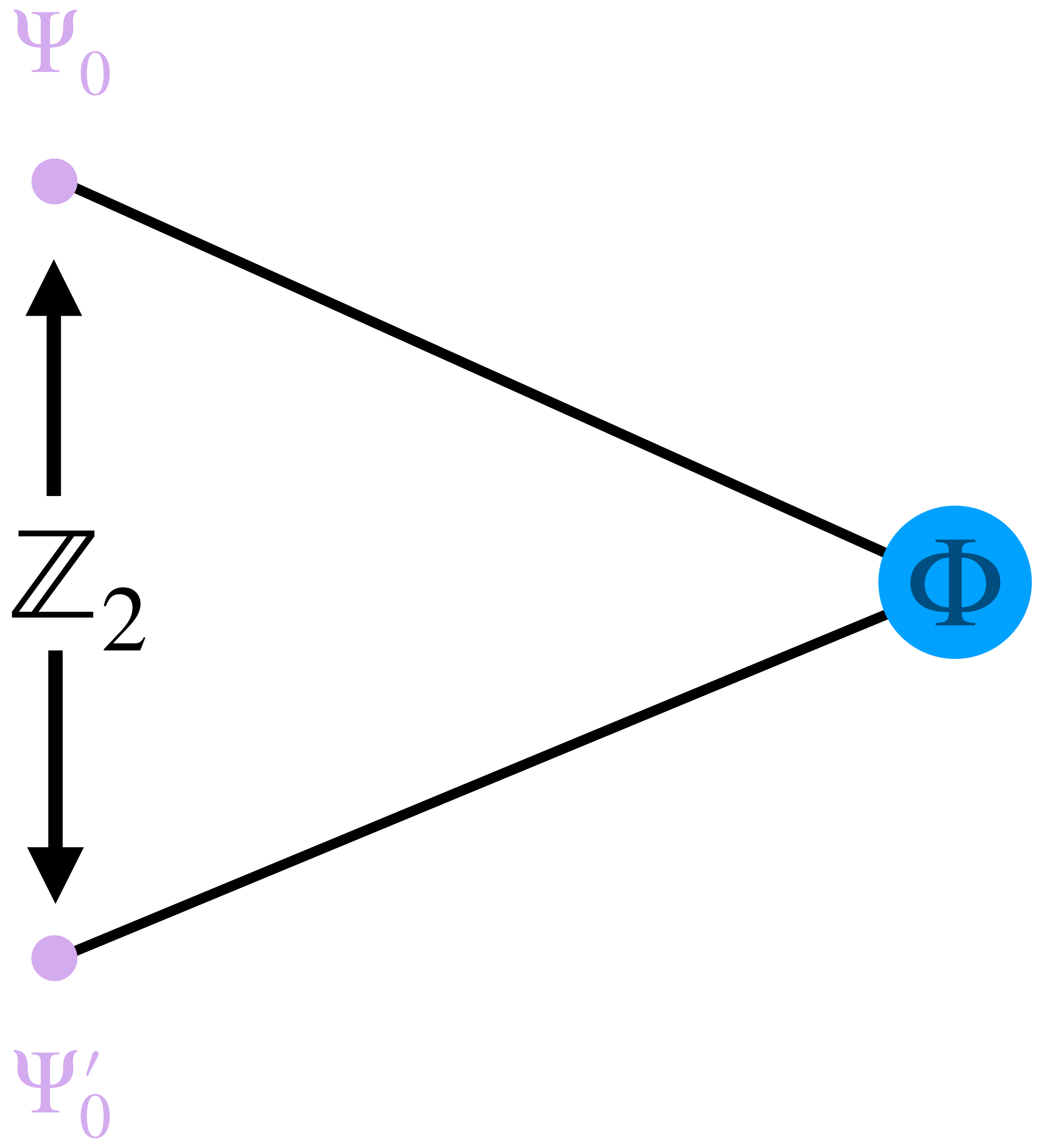
Ringwald et. al. , 2021

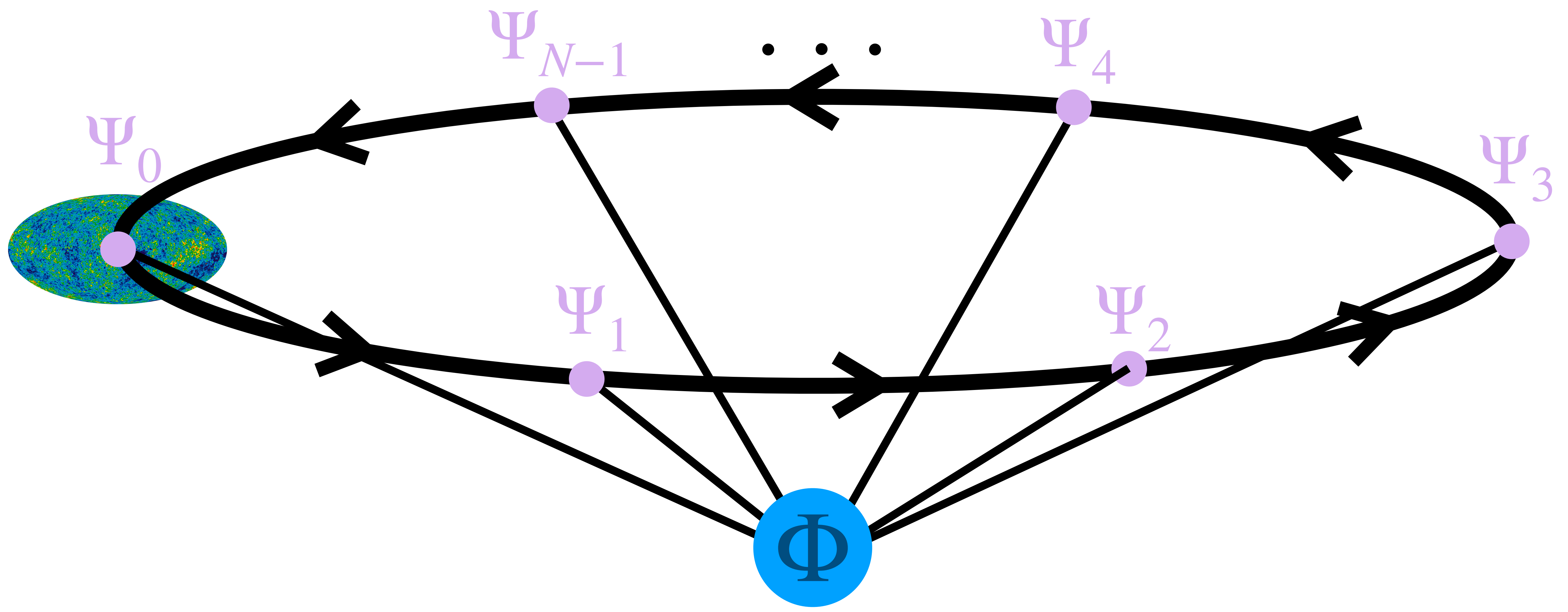
Perez et. al. , 2021

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

$$(\Psi, \Psi', A')_k \to (\Psi, \Psi', A')_{k+1}$$

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





Z_N as discretized $U(1)$

$$\mathscr{L}_{Z_N} \sim \frac{\Phi^N}{M^{N-4}} + h.c.$$

Backup

Suppress UV Freeze-in

We want

$$\frac{\Omega_{\gamma\to\gamma'+\phi}}{\Omega_{\gamma\to\gamma'}} \ll 1$$

$\delta\phi FF'$

$\phi_{\rm osc}FF'$

Suppress UV Freeze-in

GUT 10^{16}GeV

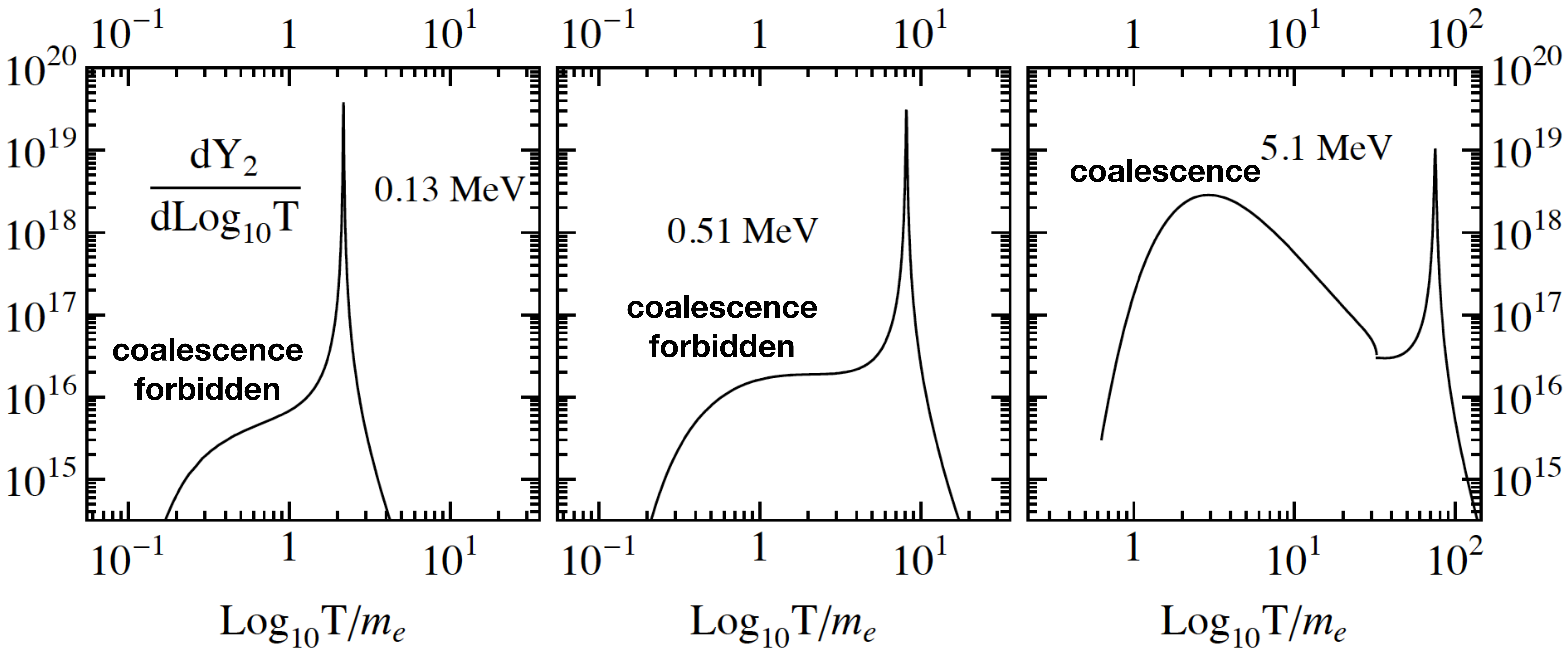
$$\frac{\Omega_{\gamma\to\gamma'+\phi}}{\Omega_{\gamma\to\gamma'}} \sim \frac{m_{DM}T_{rh}}{|\phi|^2_{osc}} \ll 1 \qquad \phi_{\rm osc} = \phi(T_{\rm osc})$$

NR Ultralight Boson: $|\phi|_{osc} = \sqrt{2\rho_\phi}/m_\phi$

$m_\phi \sim 10^{-20}eV$ ⟷ $|\phi|_{osc} \sim 10^{15}GeV$

Ultralight ϕ suppresses UV FI

Dark photon dark matter freeze-in through the kinetic mixing

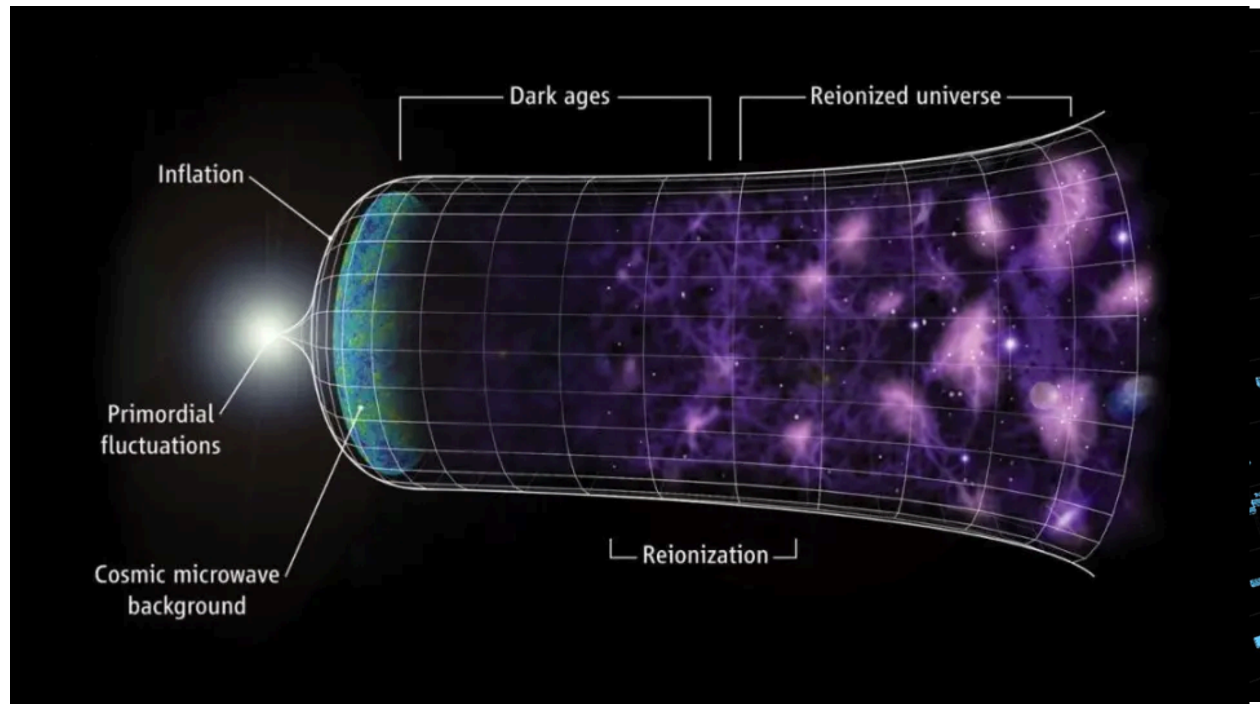


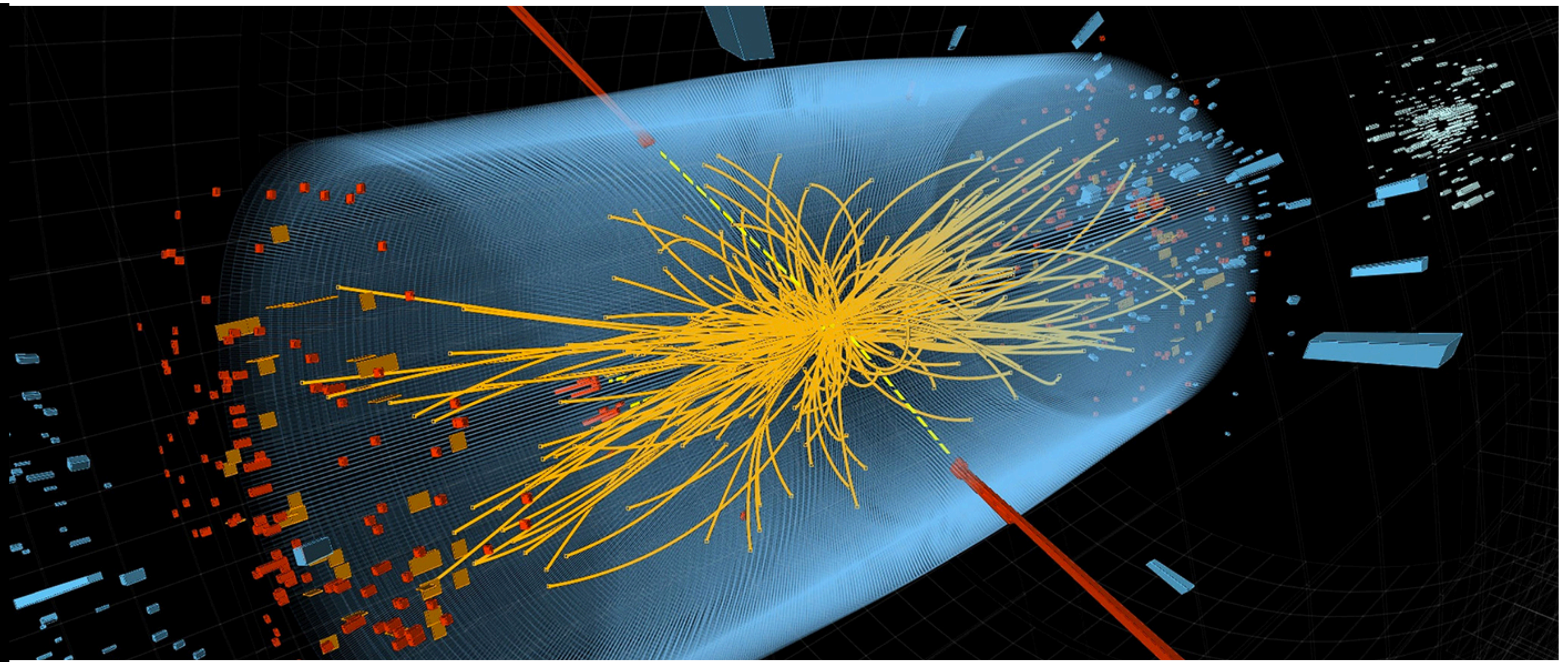
Redondo, Postma 2005

Freeze-in happens: $T \approx T_{\rm res} \sim 10 m_{A'}$

$$\Omega_{A'} = 0.12 \quad \Rightarrow \epsilon_{FI} \sim 10^{-12}$$

Dark photon freeze-in from the early Universe





$$m_\gamma^2 = \begin{cases} \omega_p^2 = 4\pi\alpha(n_e/m_e), & (T \ll m_e) \\ \frac{3}{2}\omega_p^2 = (2/3)\alpha\pi T^2, & (T \gg m_e) \end{cases}$$

Dominant:	$\gamma \to \gamma'$ @ $T_{\rm res} = m_{\gamma'}\sqrt{\frac{3}{2\pi\alpha}}$ **resonant conversion:** $m_\gamma = m_{\gamma'}$	$e^- e^+ \to \gamma'$ **coalescence:** $m_{\gamma'} > 2m_e$
Sub-dominant:	$\gamma e \to \gamma' e$ **Compton-like**	$e^+ e^- \to \gamma\gamma'$ **pair annihilation**

Measurement of the time-varying fine-structure constant

Atomic Clock

$$f_A \propto \left(\frac{\mu_A}{\mu_b}\right)^{\zeta_A} (\alpha)^{\xi_A+2} \qquad \frac{\delta(f_A/f_B)}{f_A/f_B} \simeq \left[\zeta_A\left(d_{m_e} - d_g + M_A d_{\hat{m}}\right) + \Delta\xi_{AB} d_e\right]\kappa\phi(t),$$

Species	Transition	ξ_A
$^{171}Yb^+$ [22]	$4f^{14}6s\ ^2S_{\frac{1}{2}} \leftrightarrow 4f^{13}6s^2\ ^2F_{\frac{7}{2}}$	-5.30
$^{27}Al^+$ [23]	$3s^2\ ^1S_0 \leftrightarrow 3s3p\ ^3P_0$	0.008
$^{88}Sr^+$ [24]	$5s\ ^2S_{\frac{1}{2}} \leftrightarrow 4d\ ^2D_{\frac{5}{2}}$	0.43
^{171}Yb [12]	$6s^2\ ^1S_0 \leftrightarrow 6s6p\ ^3P_0$	0.31
^{87}Sr [13]	$5s^2\ ^1S_0 \leftrightarrow 5s5p\ ^3P_0$	0.06

A. Arvanitaki, J. Huang, and K. Van Tilburg, **PRD, 2015**

Celestial Constraints on $\alpha(t)$

BBN

$$X_n^{\rm eq} = \frac{1}{1 + e^{m_{np}/T}}$$

$$Y_p \approx 2X_{n,\rm BBN}$$

$$m_{np} = m_n - m_p$$

$$\Delta m_{np} \propto \frac{\Lambda_{\rm QCD}}{M_{\rm pl}} d_\gamma^{(n)} \phi$$

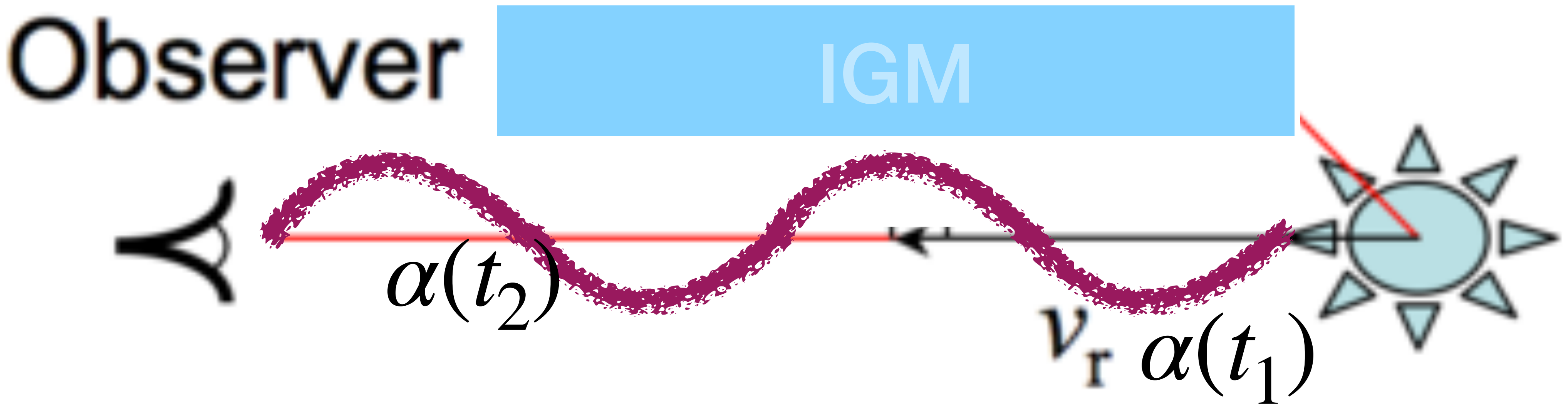
Y. V. Stadnik, V. V. Flambaum PRL 2015

Lyman-α

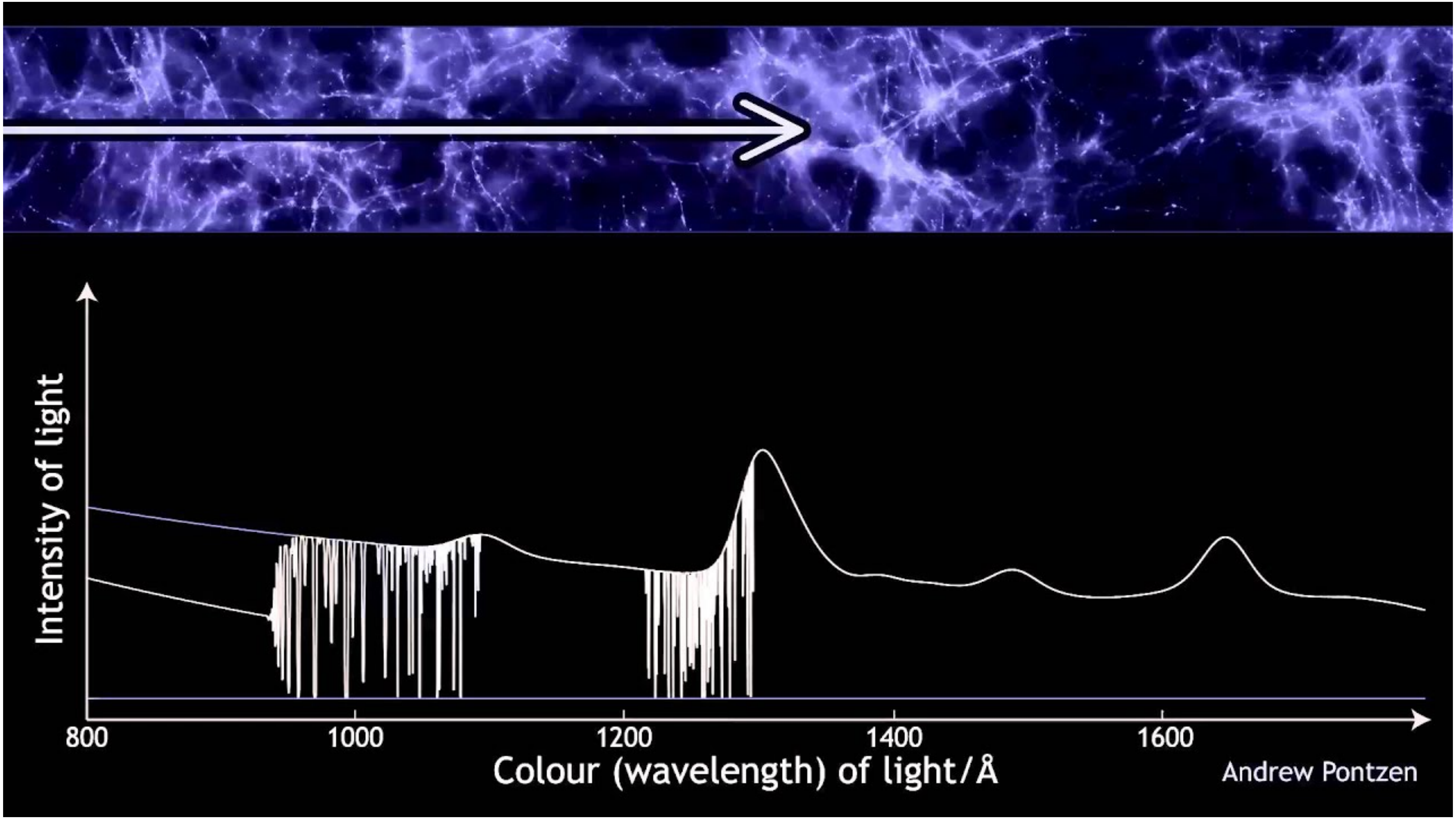
$$10{\rm Mpc}^{-1} \sim 10^{-28}{\rm eV}$$

$$d_{\rm pulsar} \sim m_\phi^{-1}$$

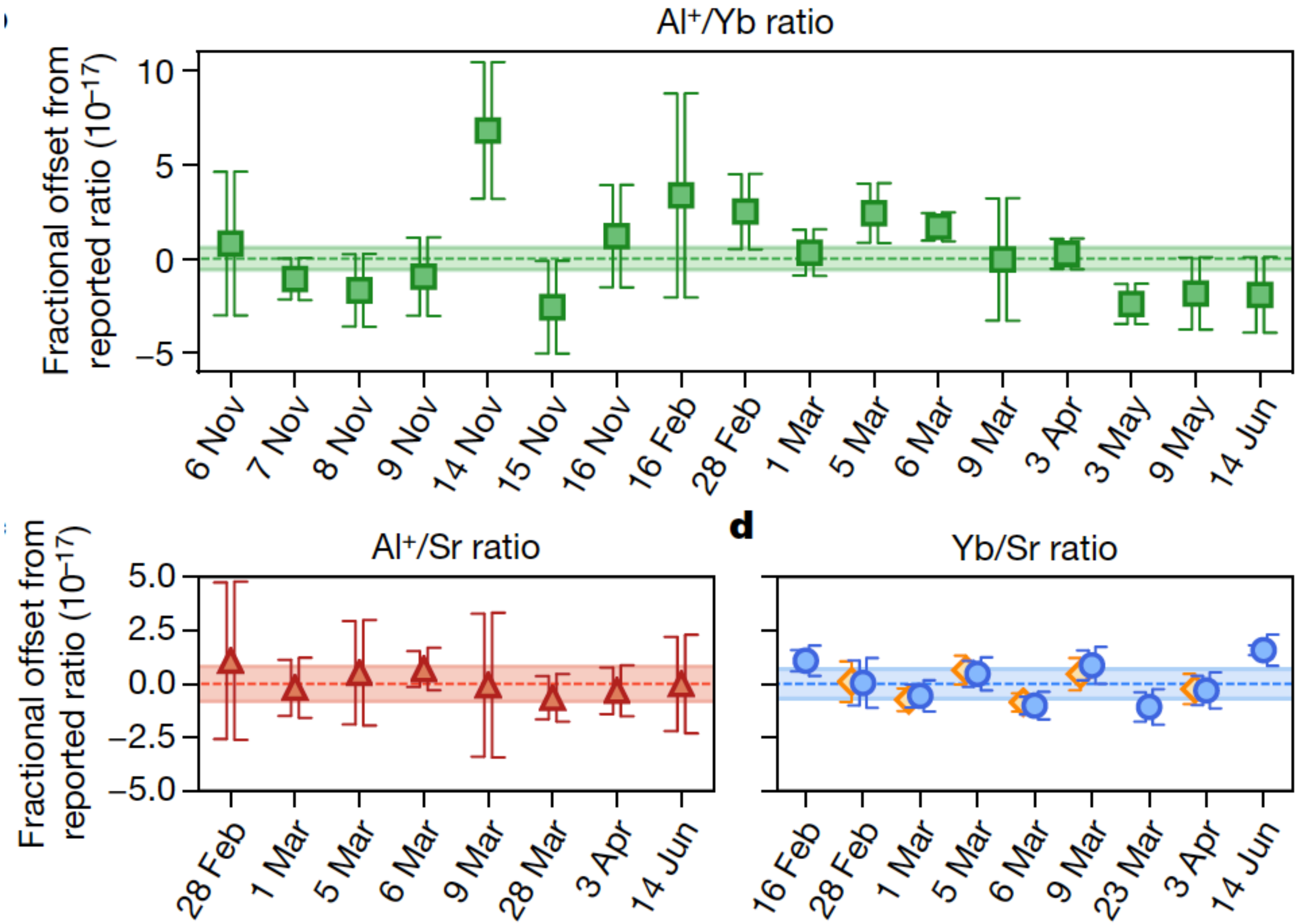
$$\Delta E_{{\rm Ly}\alpha} \sim m_e \alpha_{\rm em}$$



L. Hamaide, H. Muller, and D. J. E. Marsh, PRD 2022


Intensity of light
800
1000
1200
1400
1600
Colour (wavelength) of light/Å
Andrew Pontzen

Frequency ratio measurements at 18-digit accuracy using an optical clock network



$$\nu_{Al^+}/\nu_{Yb} = 2.162887127516663703(13),$$

$$\nu_{Al^+}/\nu_{Sr} = 2.611701431781463025(21),$$

$$\nu_{Yb}/\nu_{Sr} = 1.2075070393433378482(82).$$

Boulder Atomic Clock Optical Network (BACON) Collaboration*

Celestial Constraints on $\alpha(t)$

BBN

$$m_{np} = m_n - m_p$$

$$\Delta m_{np} \propto \frac{\Lambda_{\rm QCD}}{M_{\rm pl}} d_\gamma^{(n)} \phi$$

Change He abundance

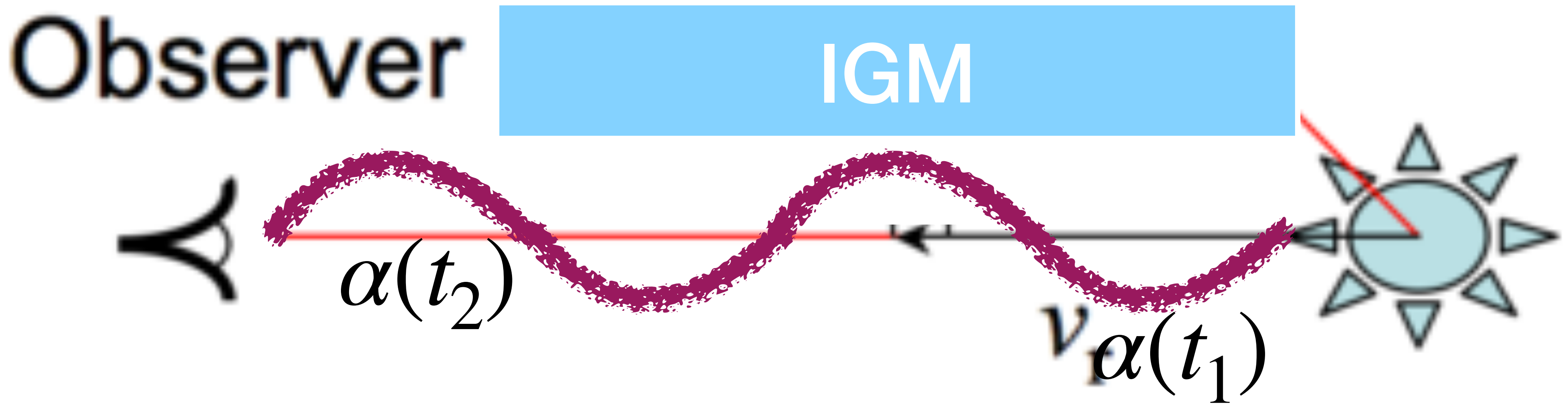
Y. V. Stadnik, V. V. Flambaum PRL 2015

Lyman-α

$$10{\rm Mpc}^{-1} \sim 10^{-28}{\rm eV}$$

$$d_{\rm quasar} \sim m_\phi^{-1}$$

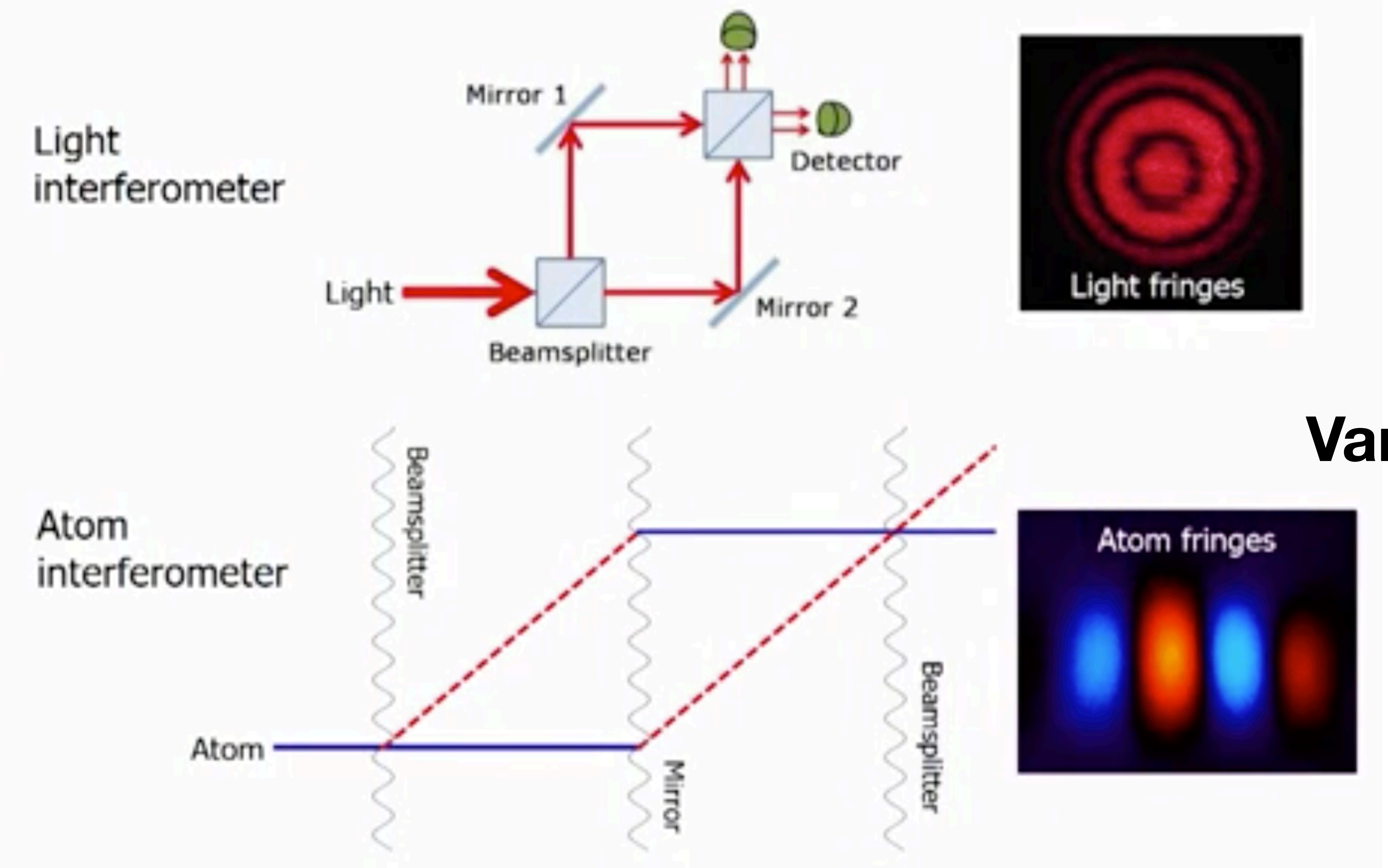
$$\Delta E_{{\rm Ly}\alpha} \sim m_e \alpha_{\rm em}$$

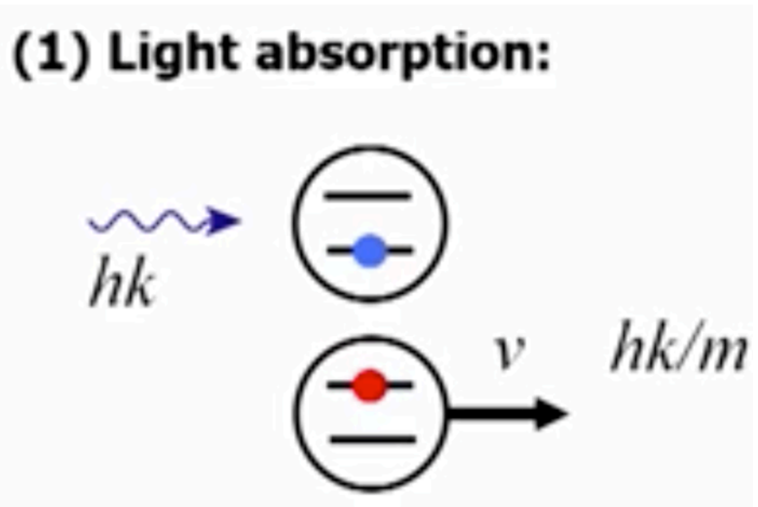


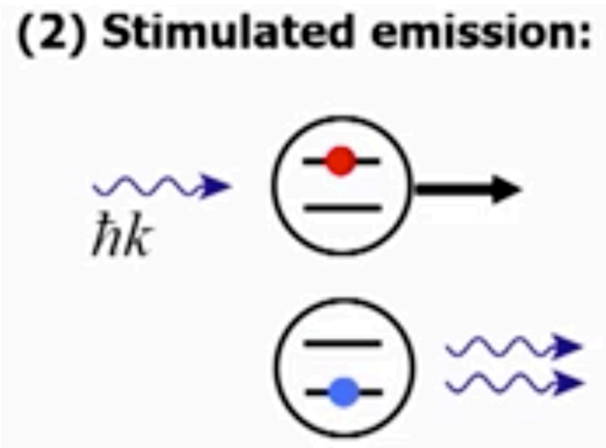
L. Hamaide, H. Muller, and D. J. E. Marsh, PRD 2022

Celestial and Terrestrial Constraints

Cold-atom Interferometer







Laser: Excite and de-excite the atoms. Generate a quantum superposition of two paths and then recombining

Measurement: accumulated phase between the two paths

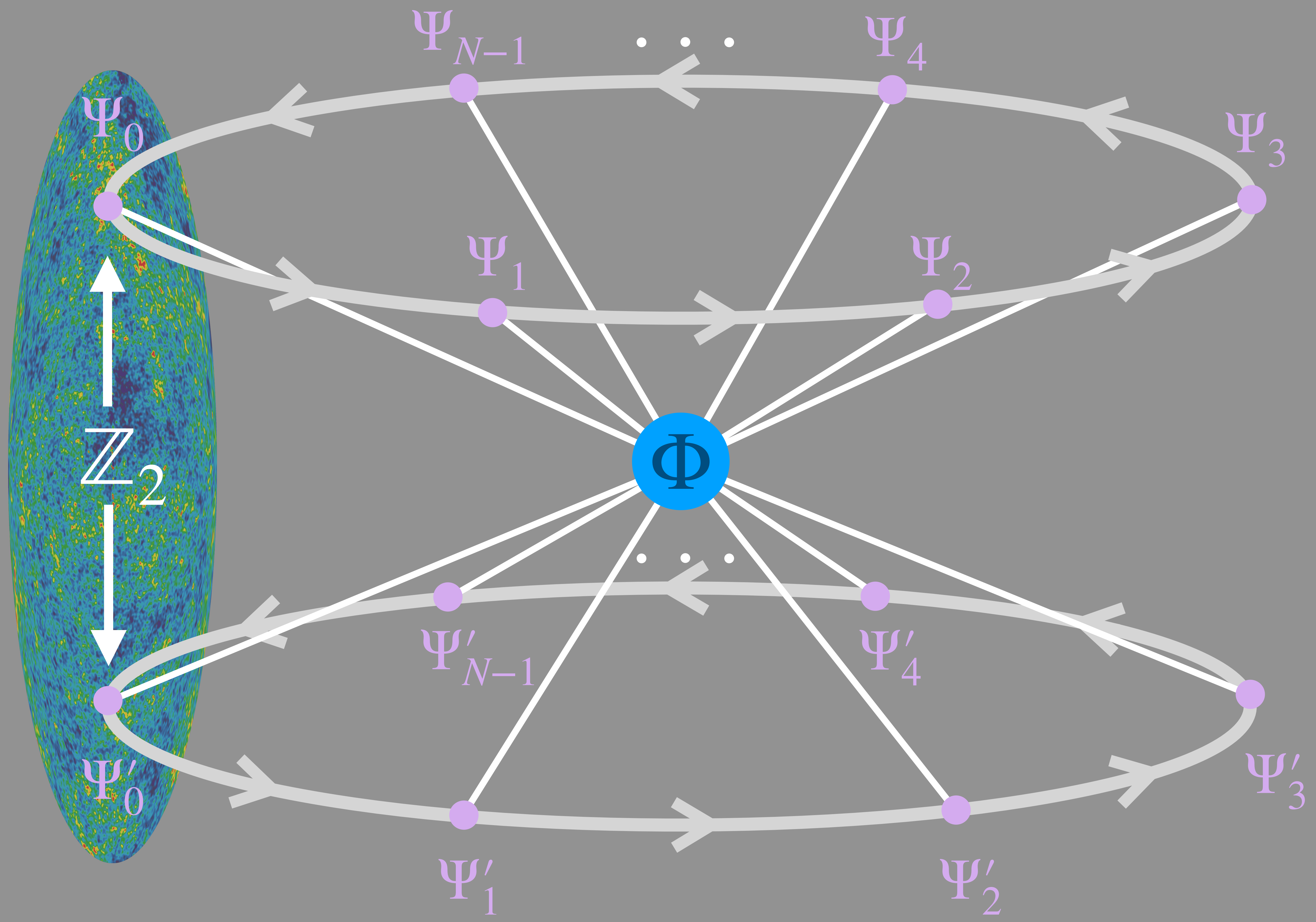
Varying $\alpha_{\rm em}$ modifies transition frequency

$$\frac{\Delta\omega_A}{\omega_A} \propto \sqrt{\rho_\phi}\,\xi_A d_e^{(1)}$$

Signal of ultralight scalar:

$$\bar{\Phi}_s = 8\frac{\Delta\omega_A}{m_\phi}\left|\sin\left[\frac{m_\phi n L}{2}\right]\sin\left[\frac{m_\phi(T-(n-1)L)}{2}\right]\sin\left[\frac{m_\phi T}{2}\right]\right|$$

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



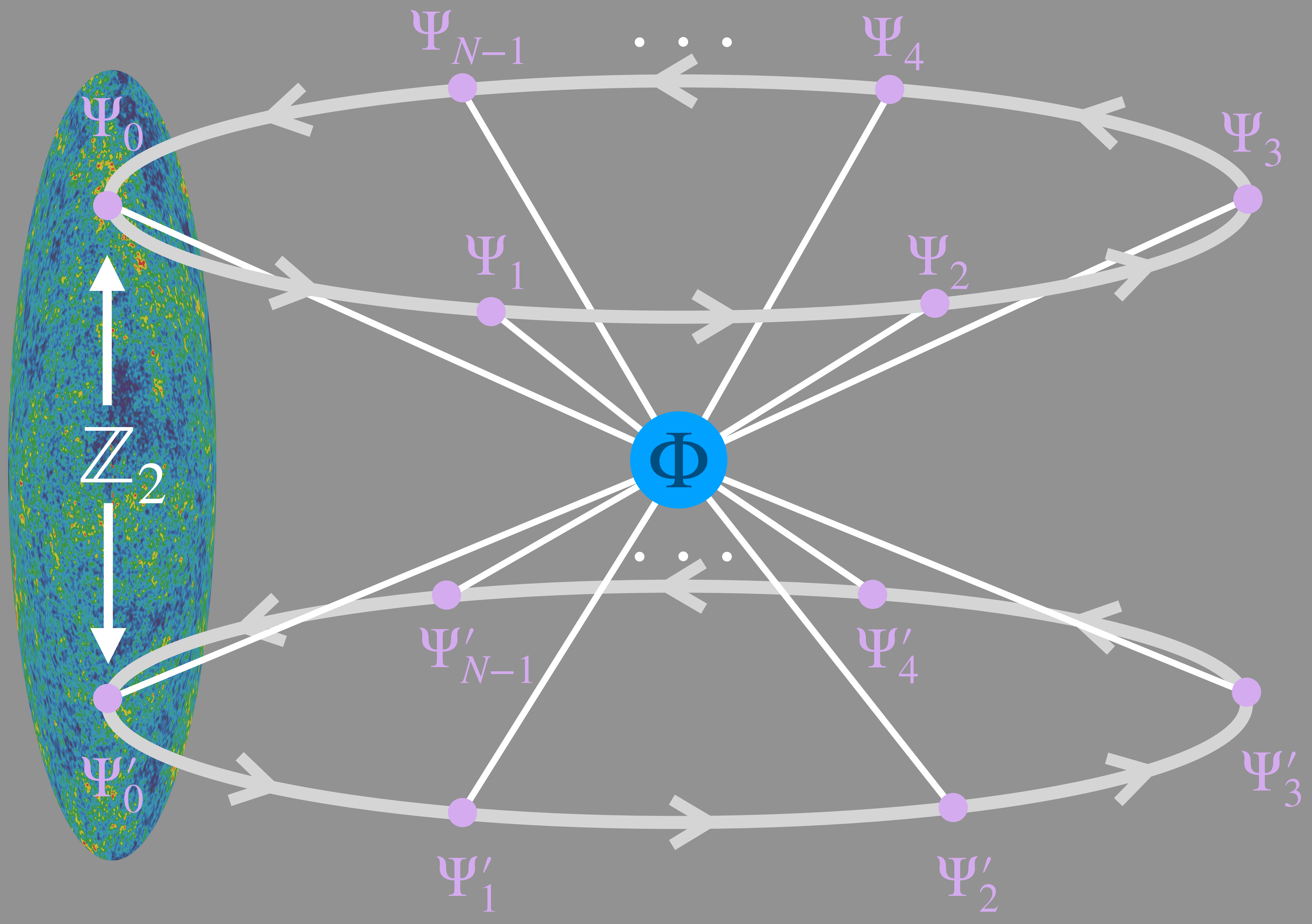
$$\epsilon_k \sim \frac{1}{\Lambda_{KM}} f \sin\left(\frac{\phi}{f} + \frac{2\pi k}{N}\right)$$

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

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

k=0: Our universe

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



Quantum Correction

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

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

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

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