李政道研究所
TSUNG-DAO LEE INSTITUTE

Dark photon dark matter from flattened axion potentials

Hong-Yi Zhang
Tsung-Dao Lee Institute, Shanghai Jiao Tong University
https://hongyi18.github.io

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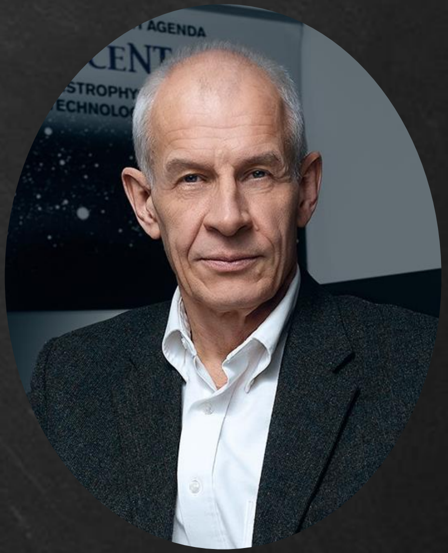
Mainly based on arXiv 2507.20484, with collaborators

Paola Arias

Andrew Cheek

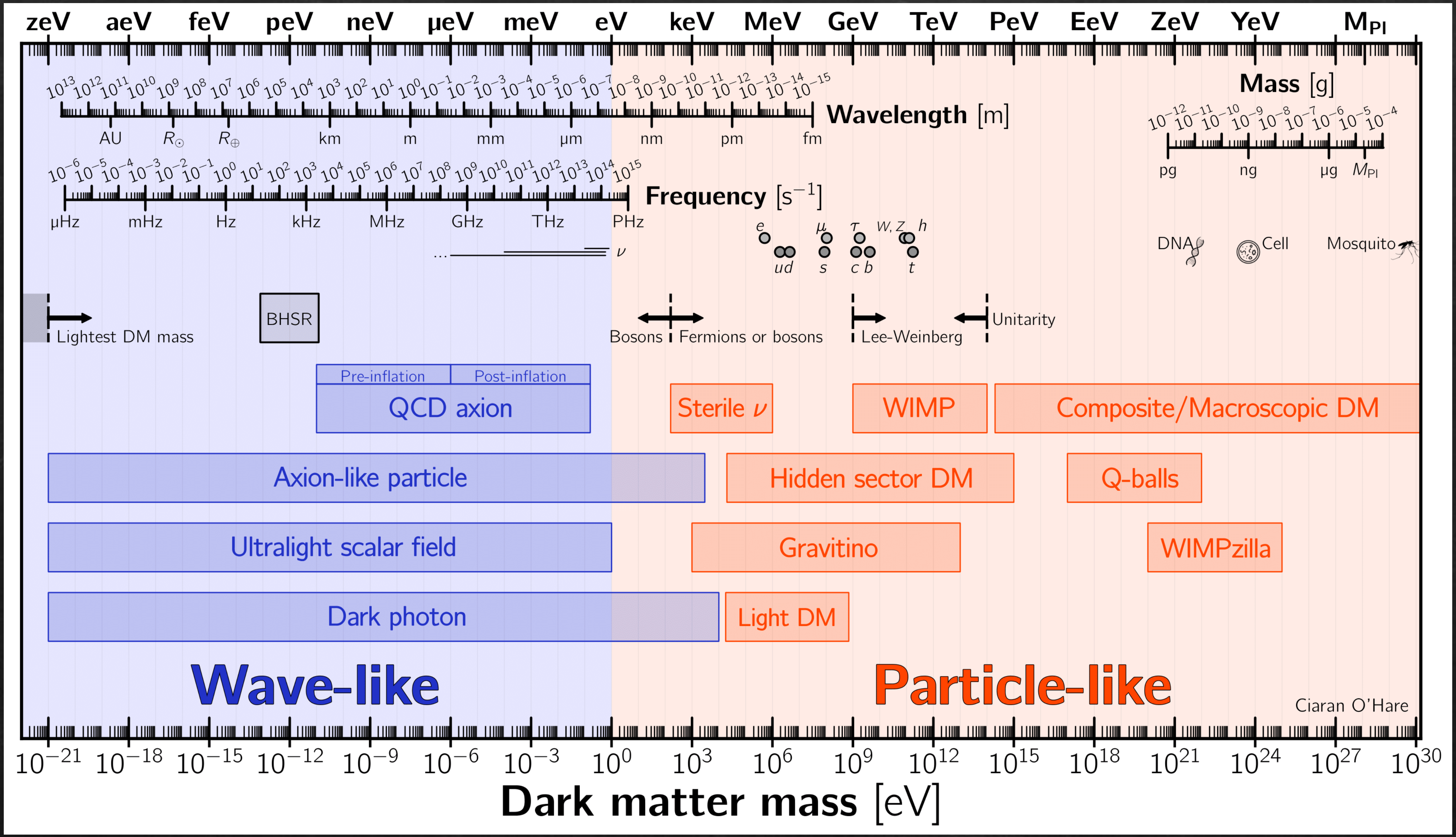
Enrico Schiappacasse

Luca Visinelli



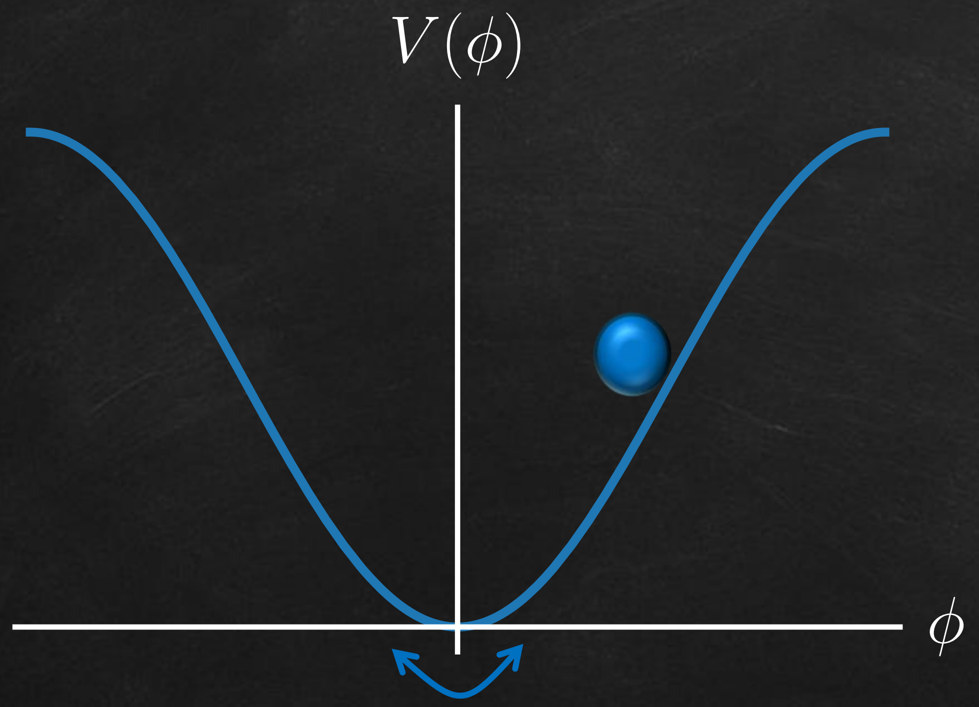
Leszek Roszkowski

Dark matter landscape



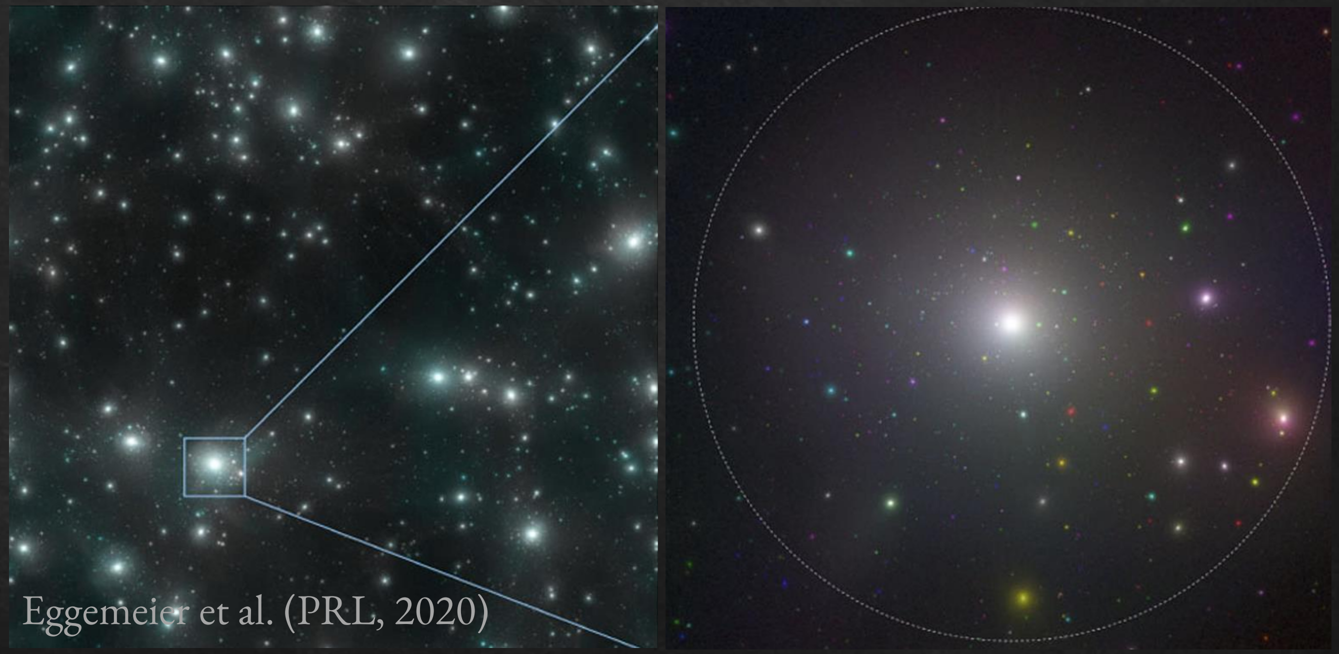
How to produce axions?

Preinflationary axions $f_\phi \gtrsim H_\mathrm{I}$



Misalignment mechanism
Oscillation stars when $3H \simeq m_\phi$

Postinflationary axions



Random field values in each 1/H
Collapse of perturbations → axion miniclusters

How to produce dark photons?

Simple misalignment: $\rho_X \propto X_i X^i \propto a^{-2}$

Exponentially suppressed during inflation even for constant X_i !

Saved by adding nonminimal couplings → UV problems

Arias et al. (JCAP, 2012)

Gravitational production:

$$\frac{\Omega_X}{\Omega_c} \sim \left(\frac{m_X}{10^{-5}\text{eV}}\right)^{1/2} \left(\frac{H_{\text{I}}}{10^{14}\text{GeV}}\right)^2$$

Works for $m_X \gtrsim 10^{-5}\text{eV}$

Graham et al. (PRD, 2016)

Coupling to axions:

$$\frac{\alpha}{4f_\phi} X_{\mu\nu}\widetilde{X}^{\mu\nu}$$

$$\ddot{X}_\pm + H\dot{X}_\pm + \left(\frac{k^2}{a^2} + m_X^2 \mp \frac{\alpha k}{a f_\phi}\dot{\phi}\right) X_\pm = 0$$

(Quasi)periodicity → parametric resonance

Negative sign → tachyonic instability

$X_\pm \propto e^{\mu_k t}$

Parametric resonance

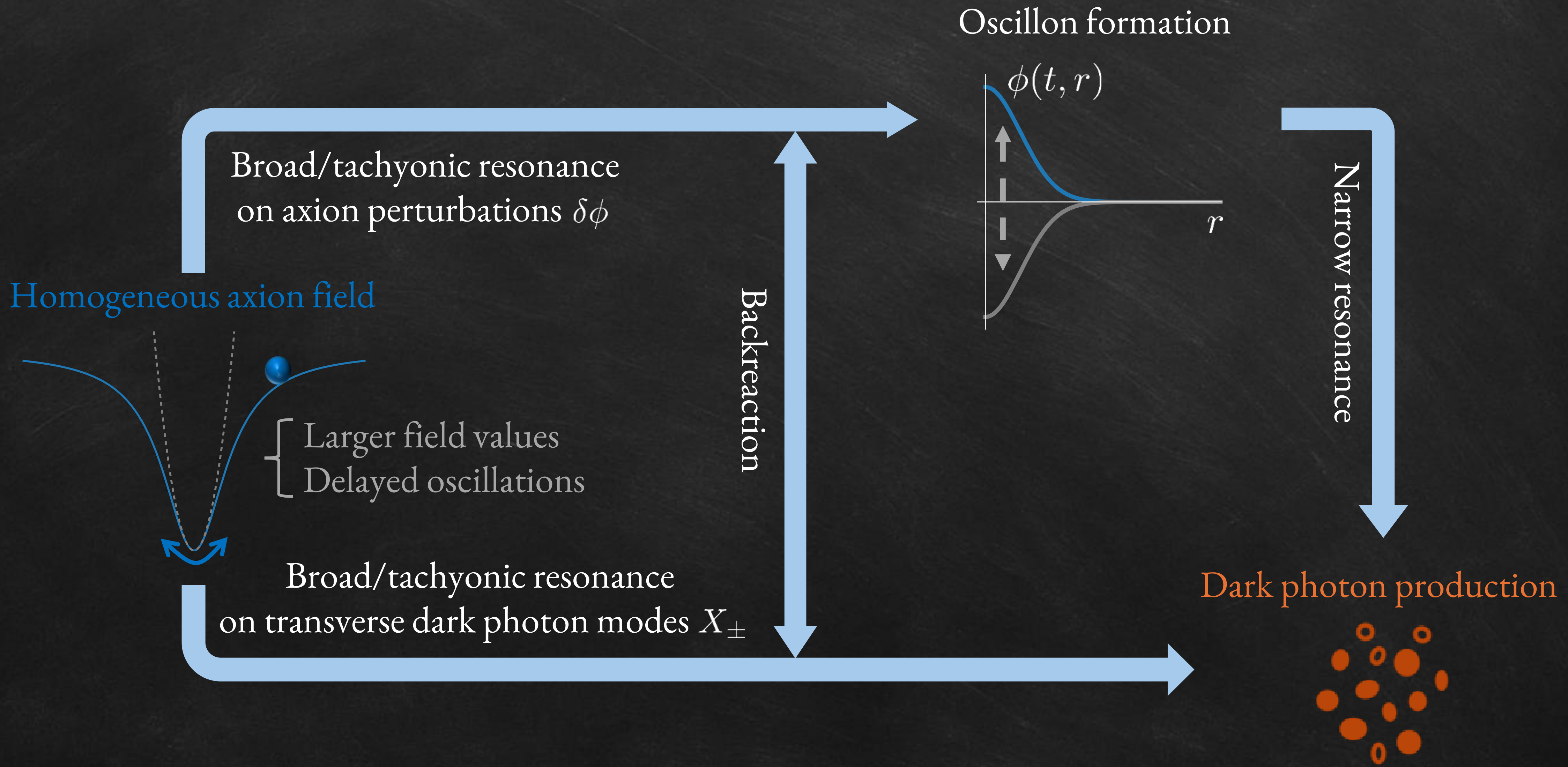
https://www.youtube.com/watch?v=MUJmKl7QfDU

Ways to enhance parametric/tachyonic instabilities

$$\ddot{X}_\pm + H\dot{X}_\pm + \left(\frac{k^2}{a^2} + m_X^2 \mp \frac{\alpha k}{a f_\phi}\dot{\phi}\right) X_\pm = 0$$

Large coupling	Generic axions Agrawal et al. (PLB, 2019) Co et al. (PRD, 2019)	Minimal, works for QCD axions Low inflation scale is required $\alpha>40$ is needed, nontrivial model building
Large field velocity	Axion rotation Co et al. (JHEP, 2021)	Naturally arises in several setups, e.g., supersymmetry Massless axions are assumed Disrupted by self-resonance for massive axions?
Delayed oscillation	Trapped axions Kitajima et al. (PRD, 2023)	Explicit PQ breaking, fine tuning for QCD axions Nontrivial model building Disrupted by axion self-resonance?
Large field amplitude	Flattened axion potentials **HYZ** et al. (2025, this talk)	Works for moderate coupling $\alpha\sim1$ Naturally arises in multifield models/string theory Works for QCD axions if fine-tuned

Dark photon dark matter from flattened axion potentials

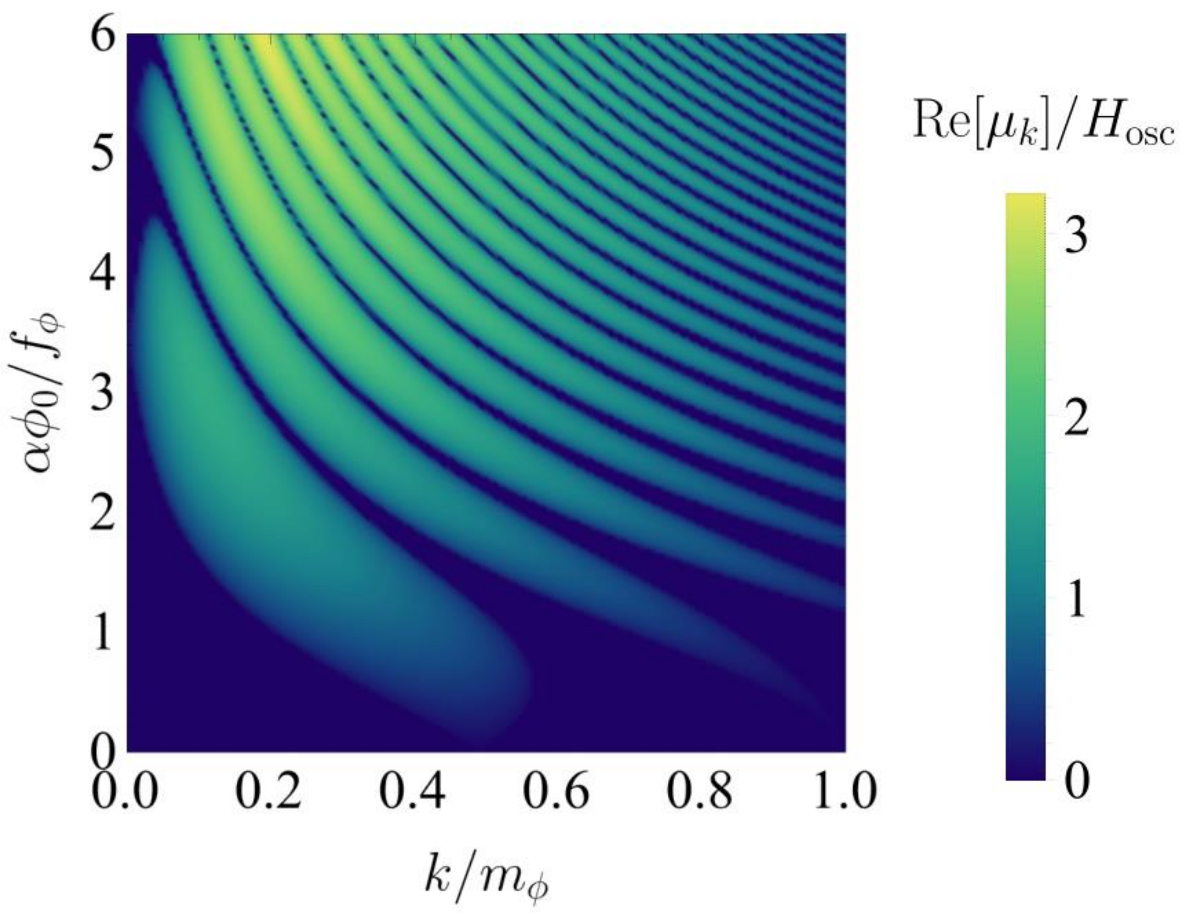


Instabilities of transverse dark photon modes

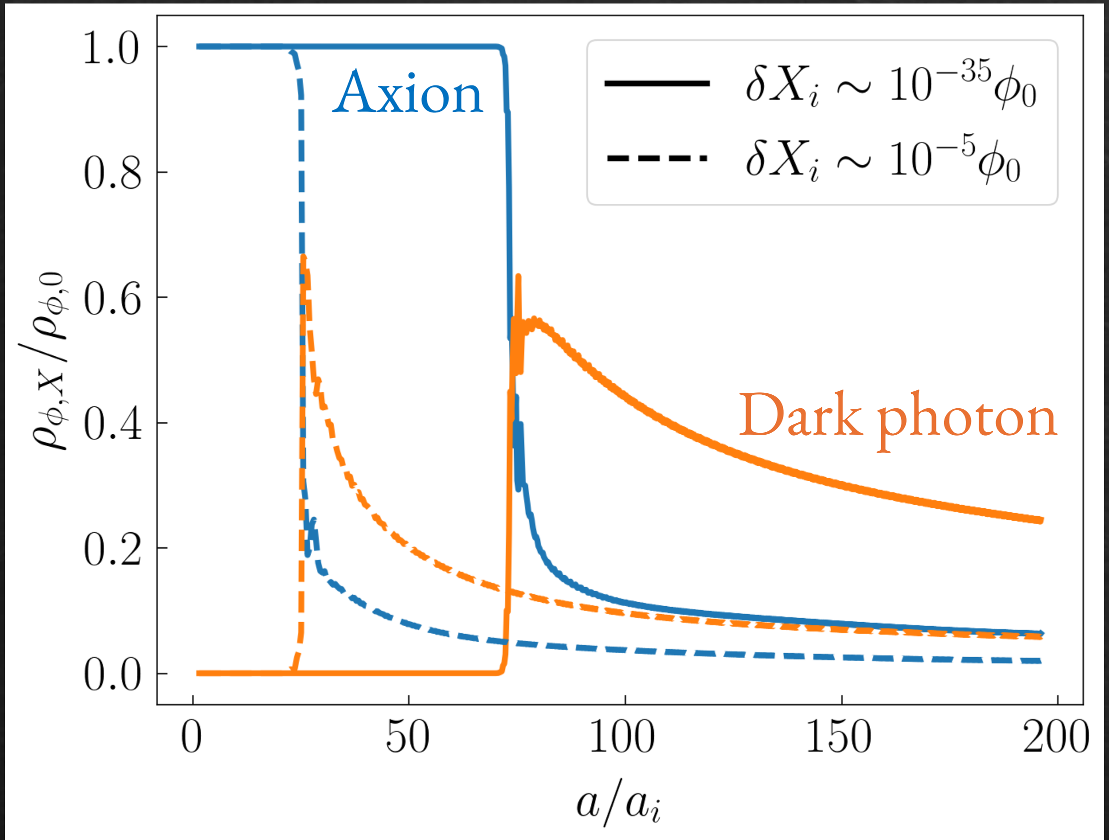
$$\ddot{X}_\pm + H\dot{X}_\pm + \left(\frac{k^2}{a^2} + m_X^2 \mp \frac{\alpha k}{a f_\phi}\dot{\phi}\right) X_\pm = 0$$

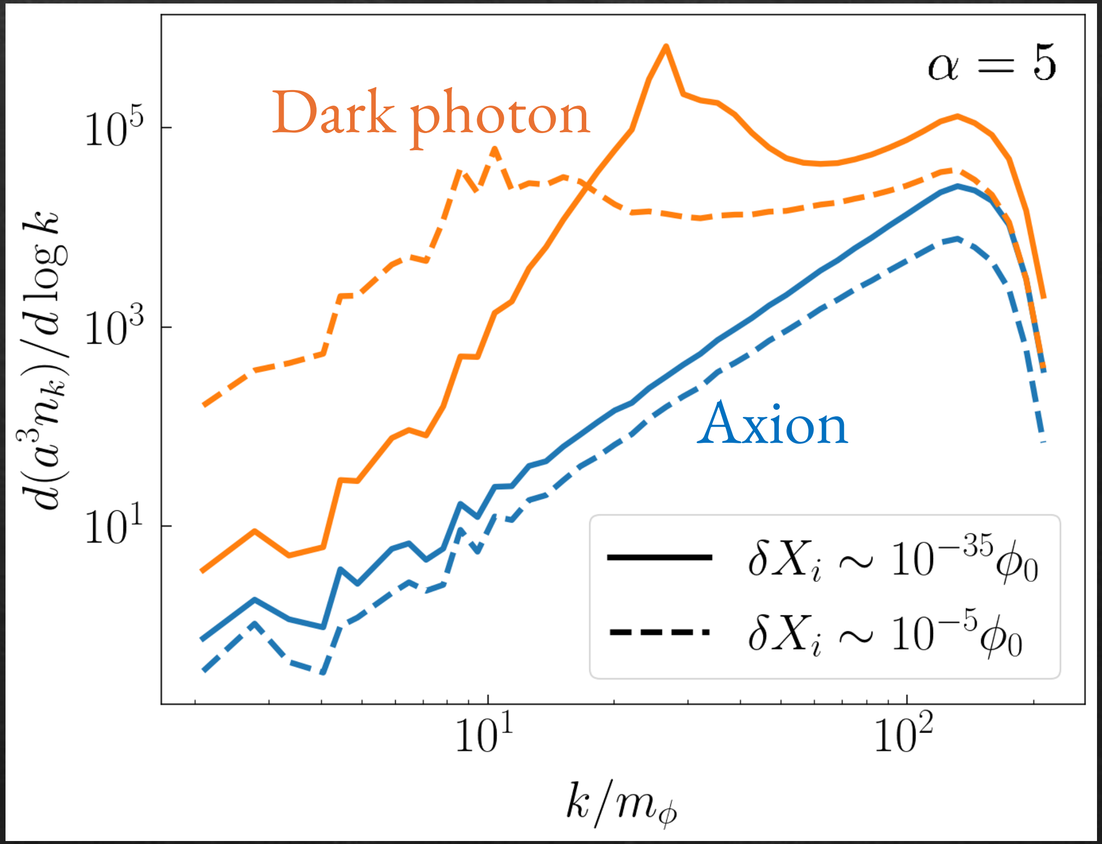
In flat spacetime: $X_\pm \propto e^{\mu_k t}$

In an expanding universe:
efficient instabilities occur if $\mathrm{Re}[\mu_k] > H$



Lattice simulations





Initial conditions: $\phi_0 = 5f_\phi, \delta\phi = 0$

Turn off axion self-resonance

Typically, $k_{\rm phys} \sim 0.2 m_\phi$

Spectrum is flatter if resonance remains efficient

Relic abundance

Time at onset of oscillations

$$\frac{\rho_X}{s} \sim \frac{m_X}{0.2 m_\phi} r_X \frac{\rho_\phi}{s}\bigg|_{H=H_{\rm osc}}$$

Redshift factor

Fraction of transferred density

For efficient dark photon production, $r_X \sim 1$

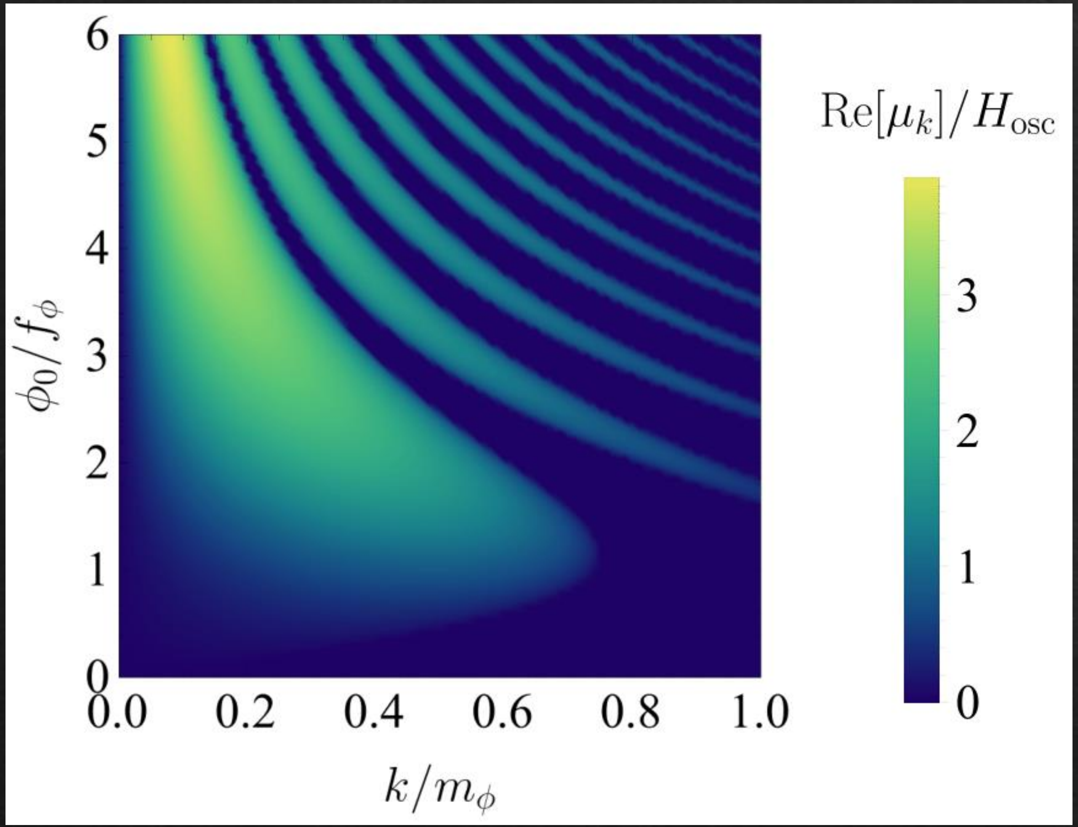
$$\Omega_X h^2 \sim 0.1 r_X \left(\frac{m_X}{0.1 m_\phi}\right)\left(\frac{m_\phi}{10^{-17}\mathrm{eV}}\right)^{1/2}\left(\frac{f_\phi}{3\times 10^{14}\mathrm{GeV}}\right)^2\left(\frac{4}{g_*(T_{\rm osc})}\right)^{1/4}\left(\frac{0.01 m_\phi}{H_{\rm osc}}\right)^{3/2}$$

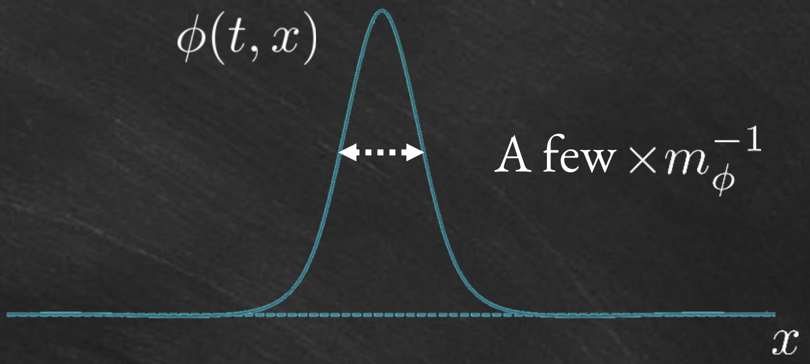
Condition for $\frac{\Omega_X}{\Omega_X + \Omega_\phi} \gtrsim 10\%$ and parametric resonance : $\frac{m_X}{m_\phi} \sim \mathcal{O}(10^{-3}\text{–}1)$

Works for a vast range of dark photon mass!

Axion self-interactions → self-resonance & oscillon

$$\ddot{\delta\phi} + 3H\dot{\delta\phi} + \left[\frac{k^2}{a^2} + \partial_{\bar\phi}^2 V(\bar\phi)\right]\delta\phi = 0$$



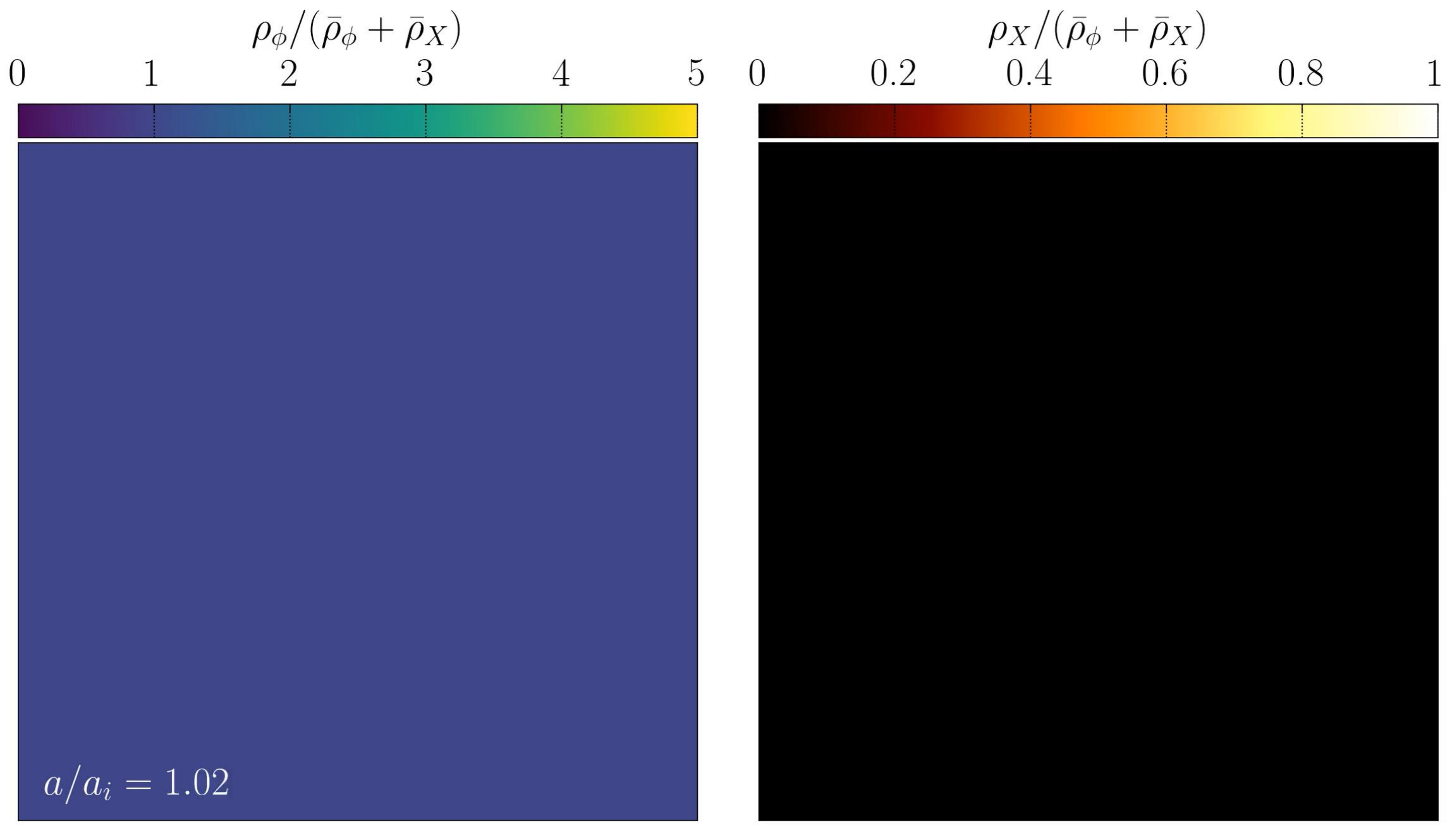


(Initial) curvature perturbations $\delta\phi \sim 10^{-5}\phi_0$

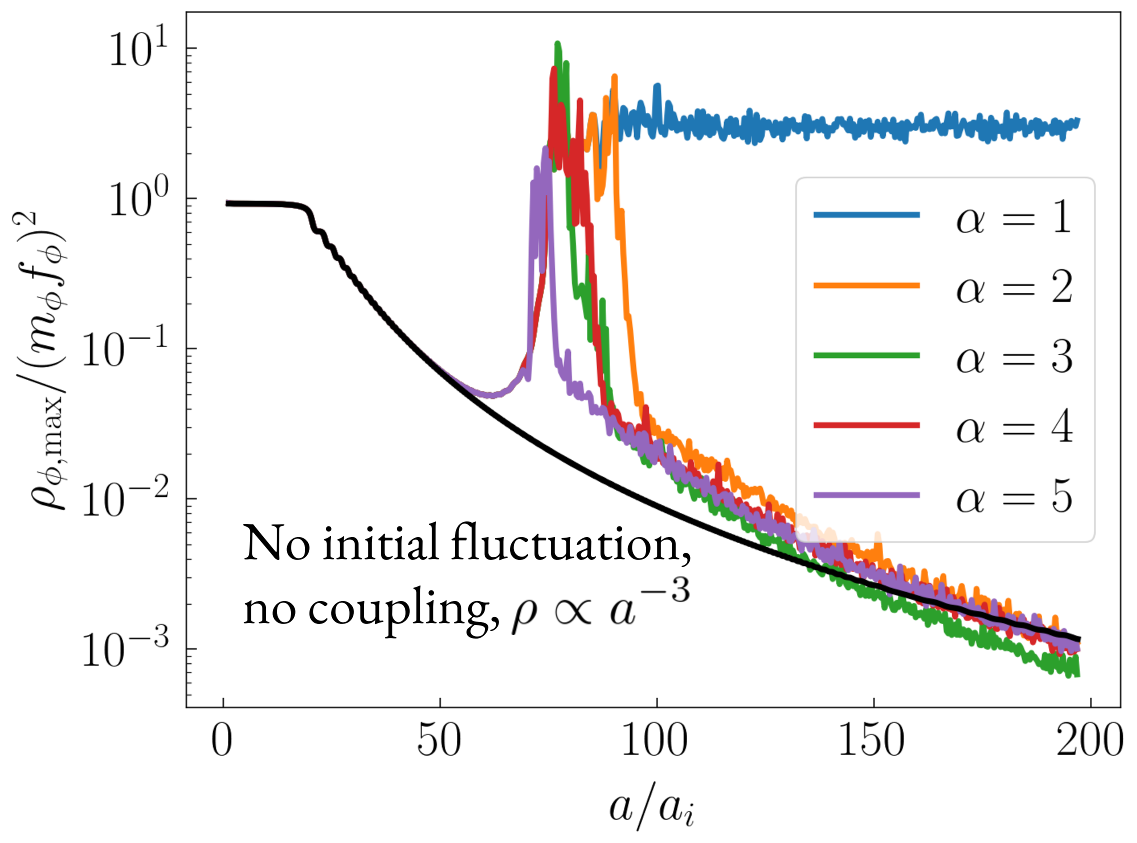
Vacuum fluctuations of dark photons $\delta X_\pm \ll \delta\phi$

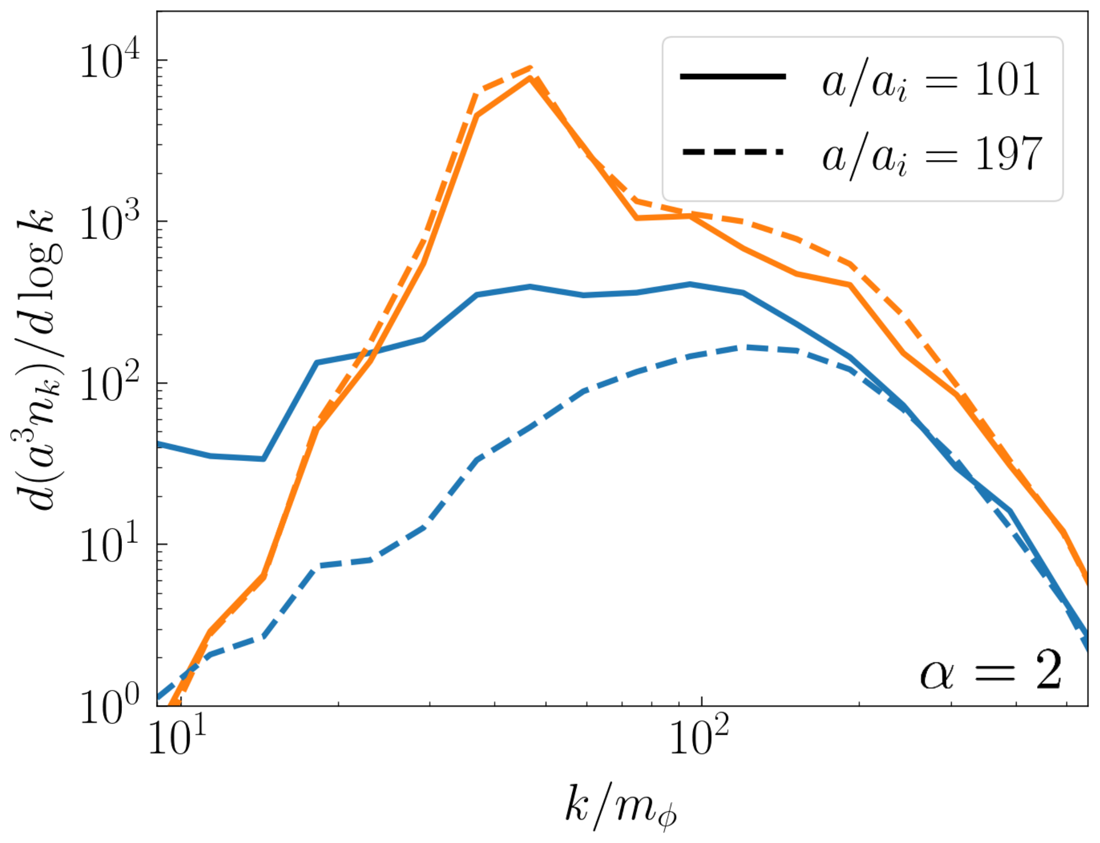
Generic: attractor solutions
Nonlinear: field amplitude $\gtrsim f_\phi$
Stable: long-lived, small radiation
Localized: decoupled from expansion
Useful: local sources of dark photons

Dark photon production from oscillons



Dark photon production from oscillons





Resonance threshold: $\alpha \gtrsim 2$

Narrow resonance → $k_{\rm phys} \simeq 0.5 m_\phi$

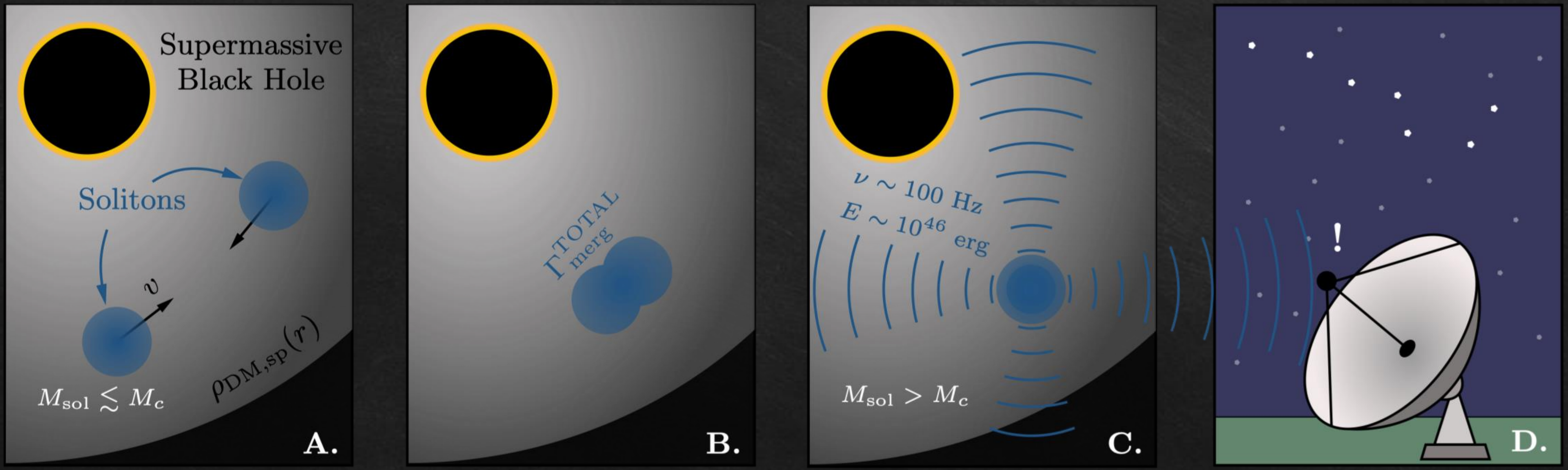
Constraining dark photon solitons from radio silence

Spiky profile around supermassive black holes $\rho_{\mathrm{DM,sp}} \propto r^{-\omega}$

Lower velocity + larger number density → more mergers

Dorian Amaral

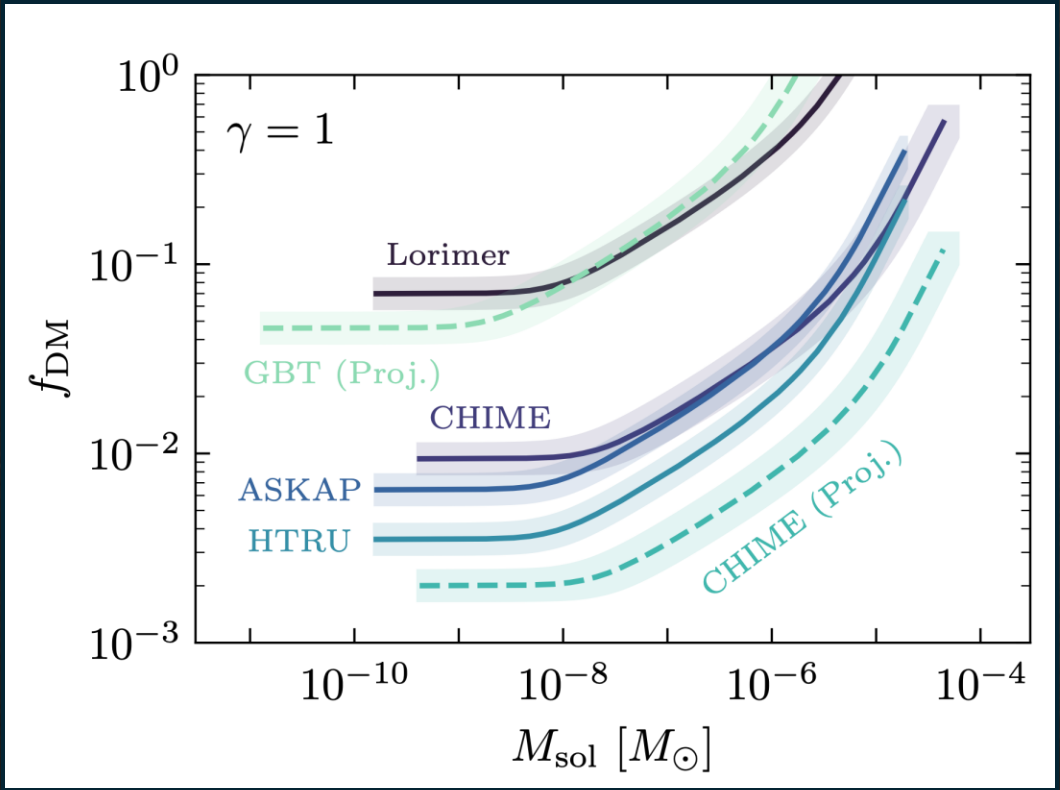
Enrico Schiappacasse

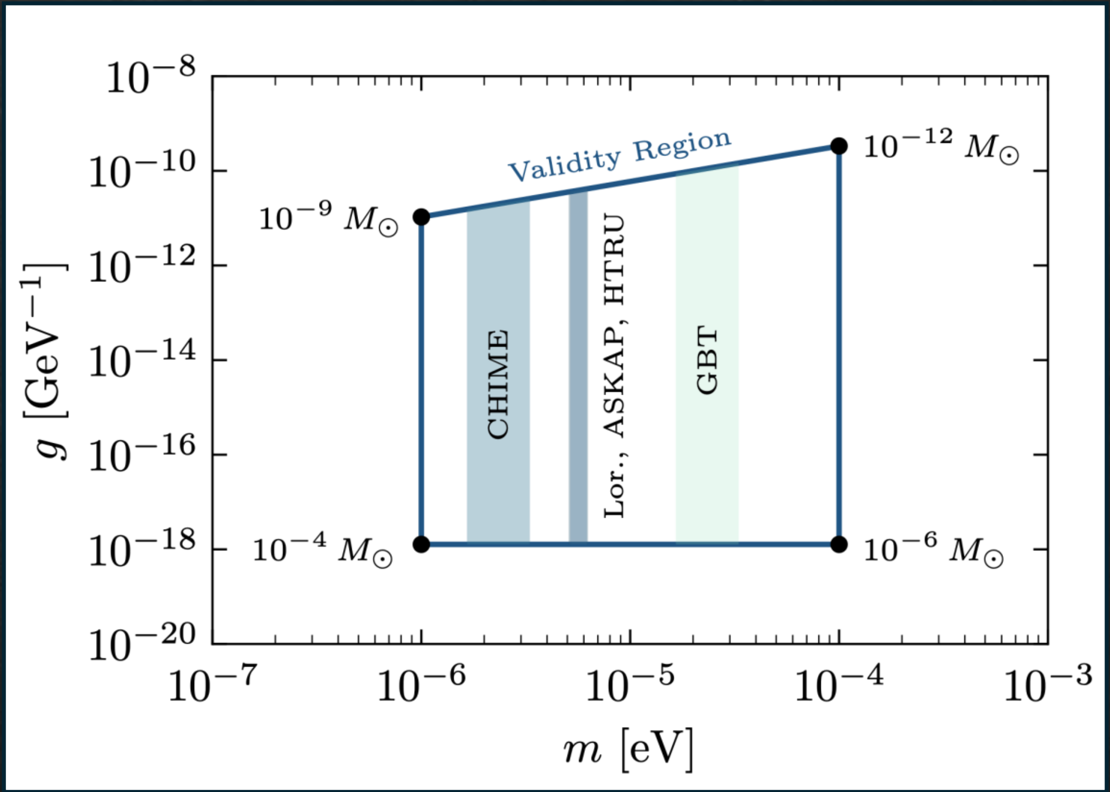


Before major merger | Major merger | Parametric resonance | Detection

Amaral, Schiappacasse, and **HYZ** (to be released in O(1) week).

Constraining dark photon solitons from radio silence



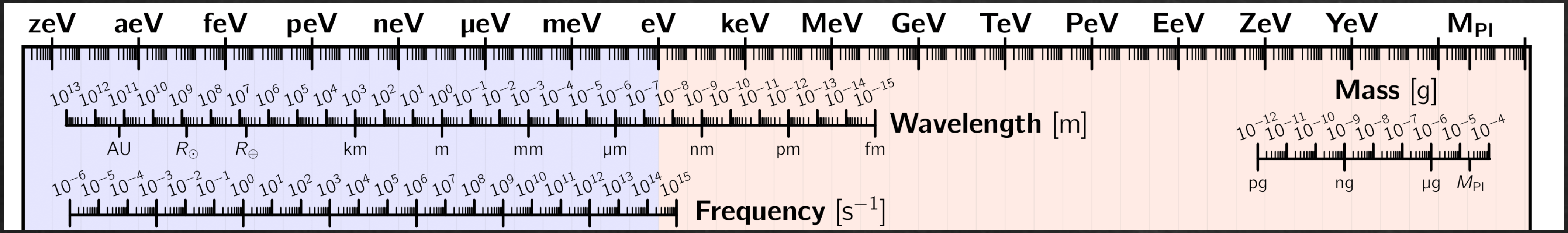


Amaral, Schiappacasse, and **HYZ** (to be released in O(1) week).

Summary

- Dark photon dark matter from flattened axion potentials
  - Three key effects:
    large amplitudes, delayed oscillations, oscillon formation
  - Homogeneous axion mode → dark photons
    (broad resonance, only for large couplings)
  - Homogeneous axion mode → oscillons → dark photons
  - Isocurvature constraints can be naturally evaded
- Constraining dark photon dark matter with soliton mergers
  (Stay tuned!)

Why study ultralight dark matter?



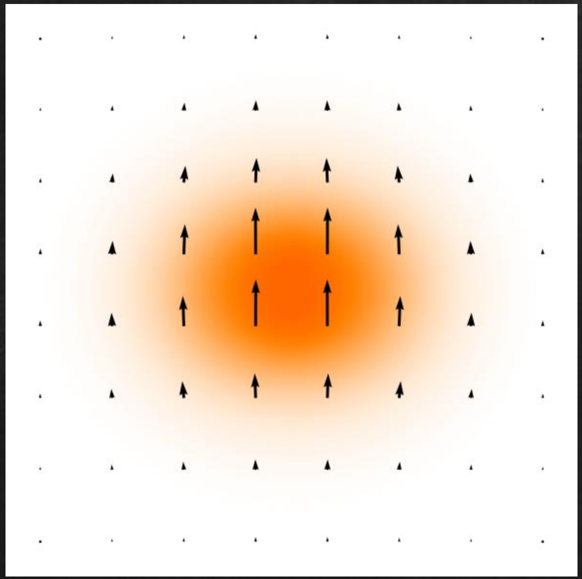
Simple: one or a few new fields
Bounded: a few leading interactions
Generic: presence in many models
Kaleidoscopic: rich phenomenology
Accessible: relatively low experimental costs

$$n\lambda_{\mathrm{dB}}^3 \sim \left(\frac{40\ \mathrm{eV}}{m}\right)^4 \sim 3 \times 10^{82} \left(\frac{10^{-19}\ \mathrm{eV}}{m}\right)^4$$

$$\lambda_{\mathrm{dB}} \sim 50\ \mu\mathrm{m} \left(\frac{40\ \mathrm{eV}}{m}\right) \sim 0.6\ \mathrm{pc} \left(\frac{10^{-19}\ \mathrm{eV}}{m}\right)$$

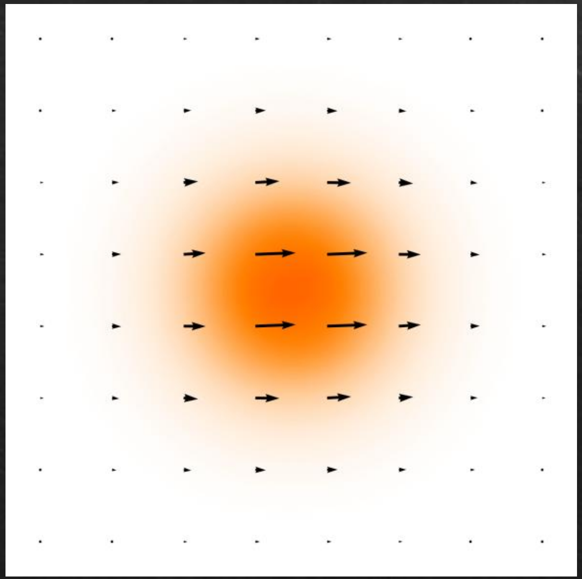
Dark photon solitons

$$X_i \approx \sqrt{\frac{2}{m}} f(r) \begin{pmatrix} 0 \\ 0 \\ \cos(\omega t) \end{pmatrix}$$



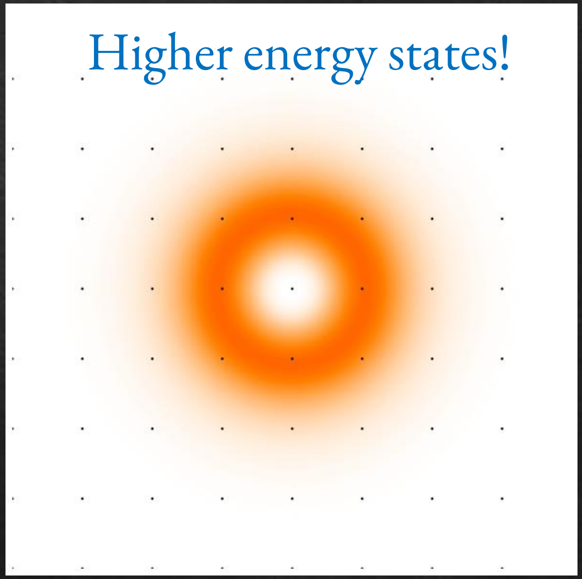
Linearly polarized

$$X_i \approx \frac{1}{\sqrt{m}} f(r) \begin{pmatrix} \cos(\omega t) \\ \sin(\omega t) \\ 0 \end{pmatrix}$$



Circularly polarized

$$X_i \propto g(r) \cos(\omega t) \hat{\boldsymbol{r}}$$



Spherically symmetric
(Solutions with a node)

Jain and Amin (PRD, 2022)
HYZ, Jain, and Amin (PRD, 2022)

Isocurvature perturbations and free-streaming lengths

CMB constraint: $\delta_{\mathrm{iso}} = \frac{\delta\rho_\phi}{\rho_\phi} \lesssim 9 \times 10^{-6}$ at $k_0 = 0.05\mathrm{Mpc}^{-1}$

Inflationary isocurvature fluctuations: $\delta_{\mathrm{iso}} \sim \frac{nH_{\mathrm{I}}}{2\pi\phi_0}$ for $V(\phi) \propto \phi^n$

Suppressed if n $\rightarrow$ 0

Lyman-α constraint: $\lambda_{\mathrm{fs}} = \int_0^{z_{\mathrm{prod}}} \frac{v(z)}{H(z)} dz \lesssim 0.1\mathrm{Mpc}$

Satisfied for $m_X \gtrsim 10^{-18}\mathrm{eV}$