Cosmology: the String Swampland, Dark Photons, and Moduli Dynamics

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Outline of the talk

In this talk I will briefly discuss a few recent or ongoing, loosely interconnected, projects:

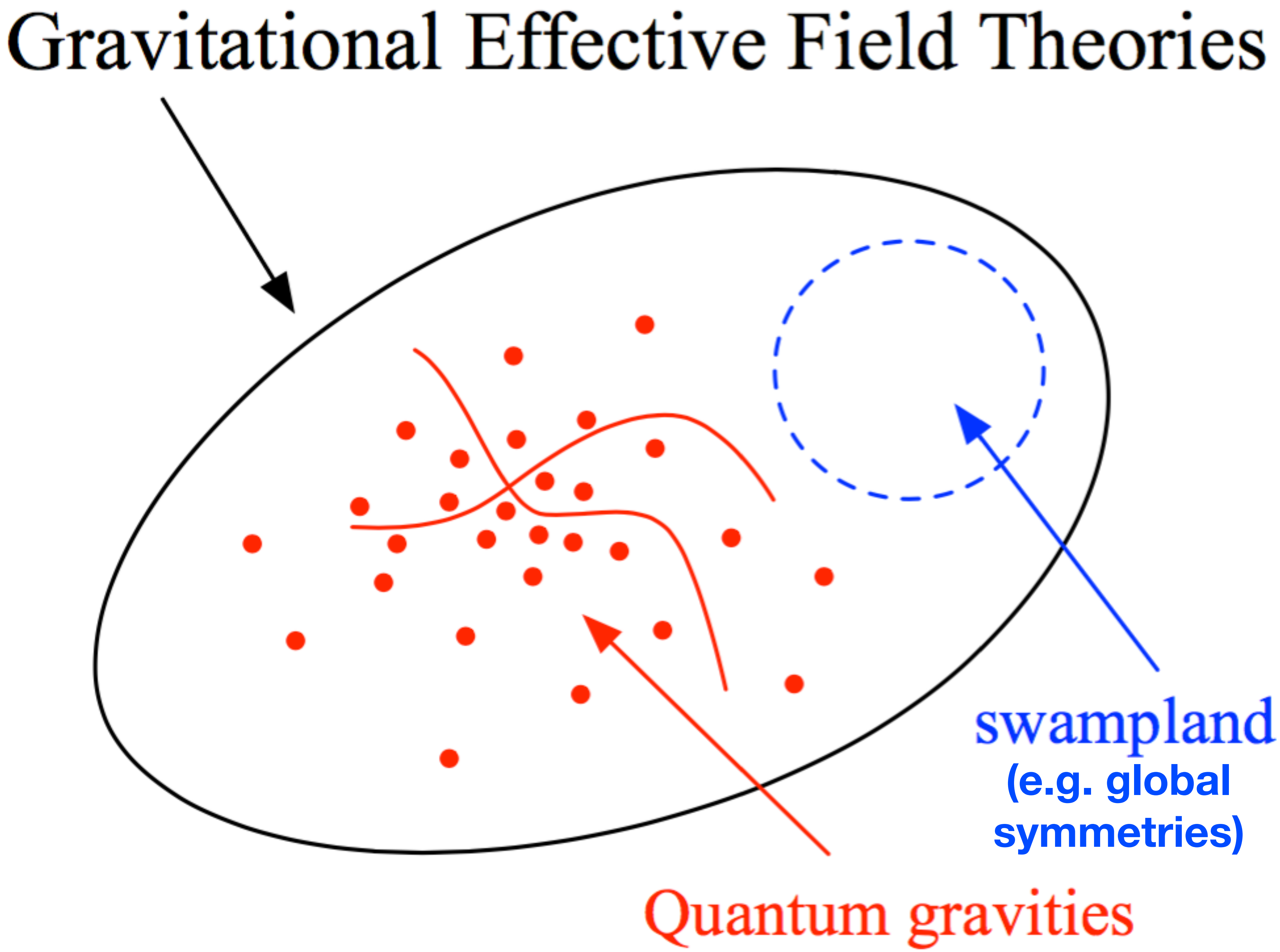
*The Swampland Progra*m. How quantum gravity constrains cosmological models.
[Ben Heidenreich, MR, T. Rudelius, Eur.Phys.J. C78 (2018) no.4, 337; Phys.Rev.Lett. 121 (2018) no.5, 051601]

Tiny *Stückelberg photon masses* are in the Swampland.
[MR, to appear soon]

Dark photon dark matter relic abundance from far-from-equilibrium dynamics in the early universe.
[P. Agrawal, N. Kitajima, MR, T. Sekiguchi, F. Takahashi, to appear soon]

Higgs fine-tuning and far-from-equilibrium dynamics.
[M. Amin, J. Fan, K. Lozanov, MR, arXiv:1802.00444]

The Swampland versus the Landscape



Vafa 2005; Arkani-Hamed, Motl, Nicolis, Vafa 2006; Ooguri, Vafa 2006

Swampland and the Lyth Bound

Lyth: an observable tensor-to-scalar ratio from inflation requires a super-Planckian field distance,

$$\frac{d(\phi)}{M_{\rm Pl}} = \mathcal{O}(1)\sqrt{\frac{r}{0.01}}$$

Ooguri/Vafa: large $d(\phi) \Rightarrow$ breakdown of EFT.

Weak Gravity Conjecture: gauge coupling $g \to 0$ limits in QG at infinite distance, $\Lambda \lesssim g M_{\rm Pl}$. (Charged tower.)

Large field-space distance $d(\phi)$: tower of light modes

$$m \propto \mathrm{e}^{-c\, d(\phi)/M_{\rm Pl}}$$

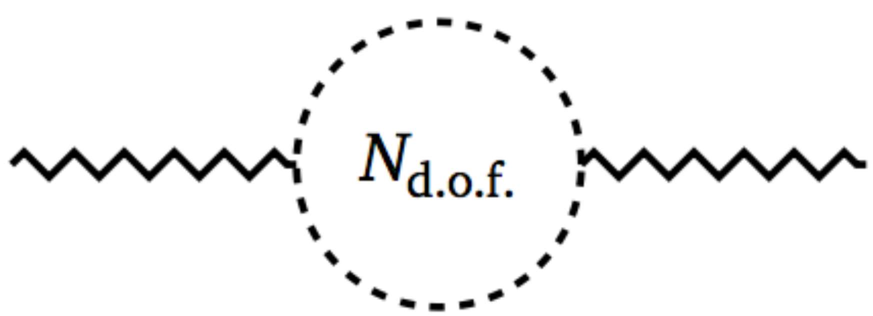
Lesson: must take care regarding QG for cosmology!

The Species Bound: Low Cutoffs from Many Weakly-Coupled Particles

In a theory with many light, weakly-coupled degrees of freedom, the UV cutoff at which gravity becomes strong is:

$$\Lambda_{\rm QG} \lesssim \frac{M_{\rm Pl}}{(N_{\rm d.o.f.}(\Lambda_{\rm QG}))^{1/(D-2)}}$$

The simplest argument for this is perturbative. Loops



renormalize the graviton kinetic term:

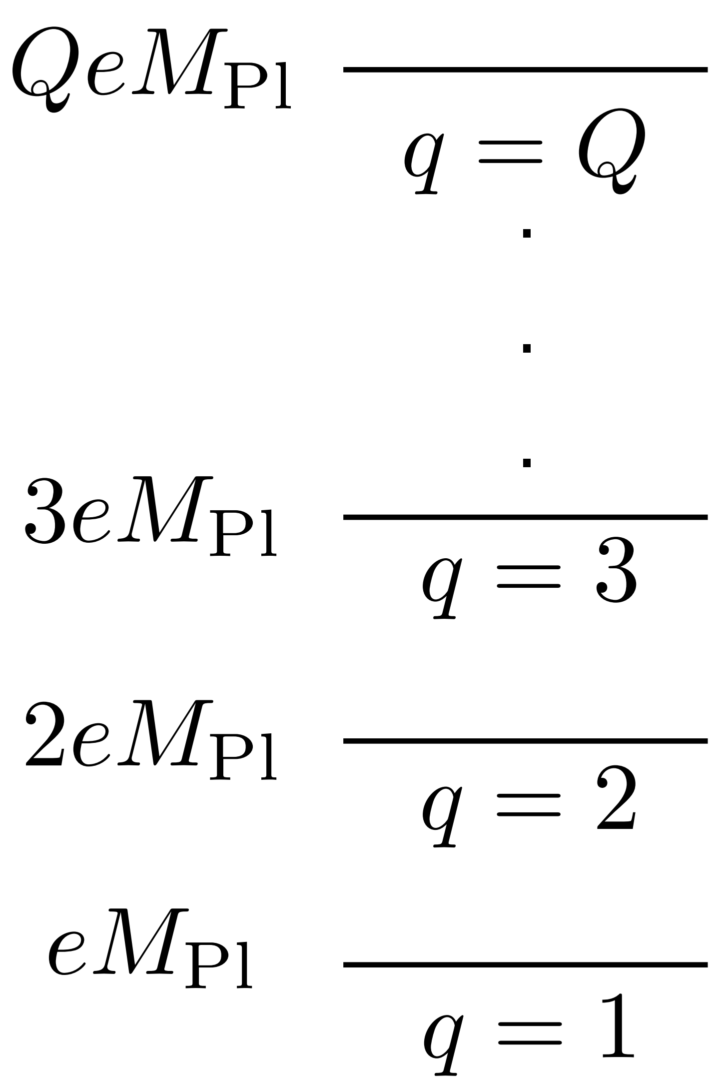
$$\delta M_{\rm Pl}^{D-2} \sim N_{\rm d.o.f} \Lambda_{\rm QG}^{D-2}$$

e.g. G. Dvali, 0706.2050 and G. Dvali & M. Redi, 0710.4344

Tower of States and Cutoffs

(in 4d for concreteness)

Single U(1):



Lattice versions of the WGC imply the existence of a tower of charged particles.

$$N_{\rm d.o.f}(\Lambda) \gtrsim \frac{\Lambda}{eM_{\rm Pl}}$$

(A sparse sublattice could change this, but we know no examples.)

$$\Lambda_{QG}^2 \lesssim \frac{1}{N_{\rm d.o.f}(\Lambda_{\rm QG})} M_{\rm Pl}^2$$

$$\Rightarrow \Lambda_{\rm QG} \lesssim e^{1/3} M_{\rm Pl}$$

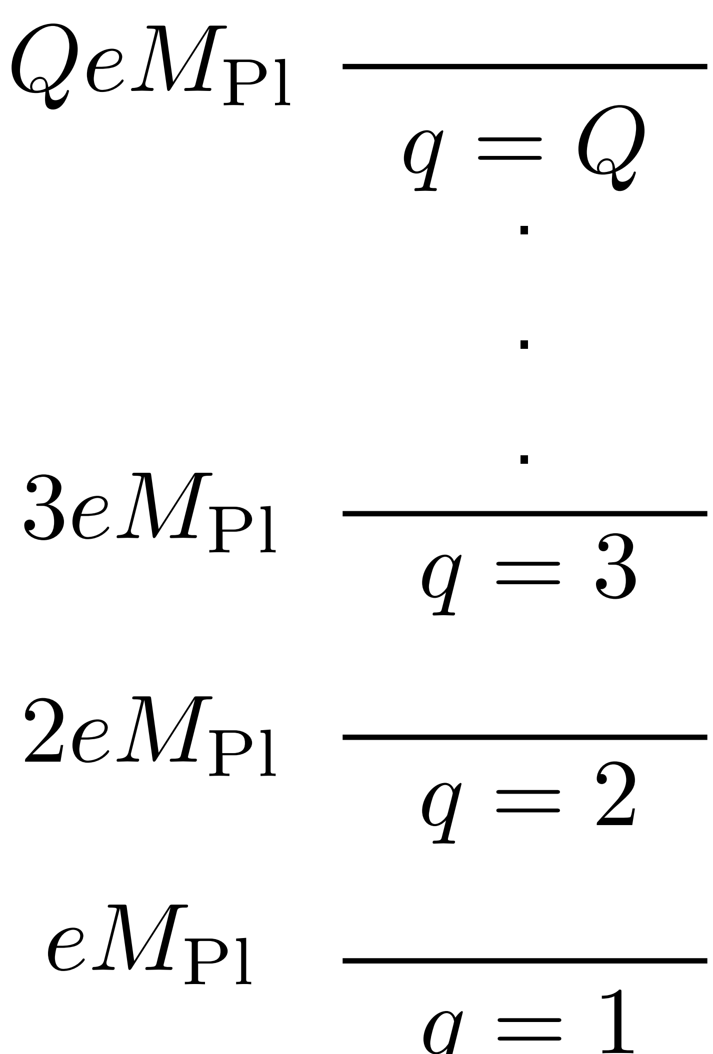
Heidenreich, MR, Rudelius '17

Emergent Gauge Fields?

(in 4d for concreteness)

Single U(1):

$$N_{\mathrm{d.o.f}}(\Lambda) \gtrsim \frac{\Lambda}{eM_{\mathrm{Pl}}} \Rightarrow \Lambda_{\mathrm{QG}} \lesssim e^{1/3} M_{\mathrm{Pl}}$$



This suggests the tower hits strong coupling at level

$$Q \sim e^{-2/3}$$

Integrating out charged degrees of freedom:

$$\frac{1}{e^2} = \frac{1}{e_{\mathrm{UV}}^2} + \sum_{q=1}^{Q} \frac{q^2}{12\pi^2} \log \frac{\Lambda}{eqM_{\mathrm{Pl}}}$$

Ignoring logs and constants, the sum is:

$$Q^3 \sim \frac{1}{e^2}$$

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Emergent Gauge Fields?

Single U(1):

QeM_{Pl} ——— $q = Q$

⋮

$3eM_{\mathrm{Pl}}$ ——— $q = 3$

$2eM_{\mathrm{Pl}}$ ——— $q = 2$

eM_{Pl} ——— $q = 1$

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Put differently: a tower of states of different charges leads to a Landau pole for the U(1) coupling in the UV.

It also renormalizes the Planck scale, leading to a low gravitational cutoff.

A Lattice WGC tower is one for which these are (at least up to constant factors) the *same* scale!

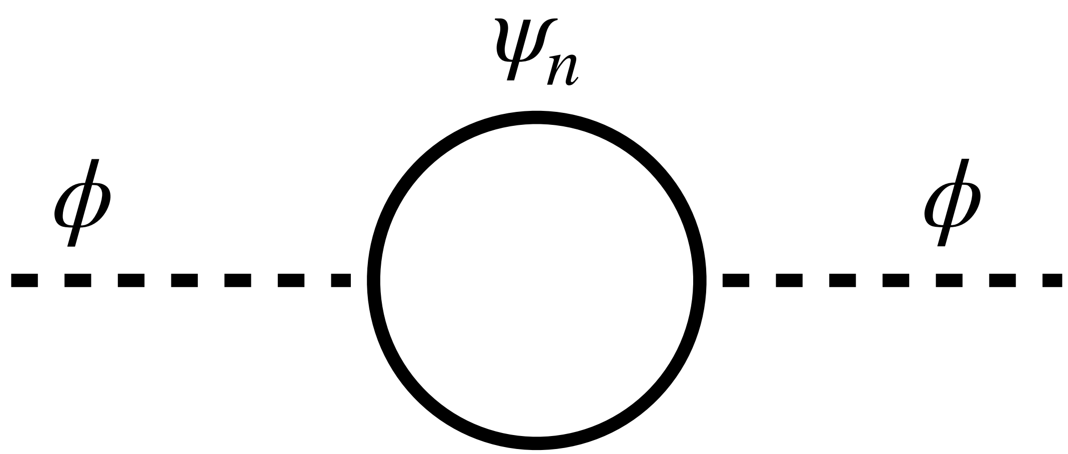
Extends to general gauge groups!

Moduli and the Quantum Gravity Scale

Assume fields becoming light at a special point $\phi = 0$.

$$\mathcal{L} = \frac{1}{2}K(\phi)(\partial\phi)^2 + \sum_n \bar{\psi}_n(\mathrm{i}\partial\!\!\!/ - m_n(\phi))\psi_n$$

Loops:



$$\sim \frac{1}{K(\phi_0)}\left(\frac{\partial m_n}{\partial\phi}\right)^2$$

Strong coupling at same scale as species bound:

$$K(\phi_0) \sim \sum_{m_n < \Lambda_{\mathrm{QG}}} \left(\frac{\partial m_n}{\partial\phi}\right)^2 \sim \frac{1}{\phi_0^2}\sum_{m_n < \Lambda_{\mathrm{QG}}} m_n^2 \sim \frac{1}{\phi_0^2}N\Lambda_{\mathrm{QG}}^2 \sim \frac{M_{\mathrm{Pl}}^2}{\phi_0^2}$$

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Moduli and the Quantum Gravity Scale

Ooguri/Vafa 2006 *conjectured* towers become light at a rate exponential in field space distance.

Here we see it is an *output* of assuming a universal strong-coupling scale, implying a kinetic term:

$$\mathscr{L} \sim \frac{M_{\rm Pl}^2}{\phi^2}\partial_\mu\phi\partial^\mu\phi$$

Applying a similar argument to *axion* fields:

$$\left\langle (\Delta m)^2 \right\rangle \sim \Lambda_{\rm QG}^2 \frac{d(\phi)^2}{M_{\rm Pl}^2}$$

Super-Planckian field traversals require O(1) fraction of modes to pass through QG cutoff!

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Moduli and the Quantum Gravity Scale

This is not a sharp no-go theorem, but it does suggest that one should be very careful trusting the validity of EFTs over super-Planckian field ranges in quantum gravity.

One loophole: this refers to the *field-space distance* (geodesic distance), while the *potential* might steer fields along non-geodesic paths.

(See: Hebecker, Henkenjohann, Witkowski '17; Landete, Shiu '18)

Super-Planckian field traversals require O(1) fraction of modes to pass through QG cutoff!

Stückelberg in the Swampland

We can view a photon mass as a *Stückelberg* mass, introducing a Goldstone boson that shifts:

$$\frac{1}{2} f^2 (\partial_\mu \theta - e\hat{A}_\mu)^2$$

Dualize the eaten Goldstone boson to a 2-form gauge field *B*:

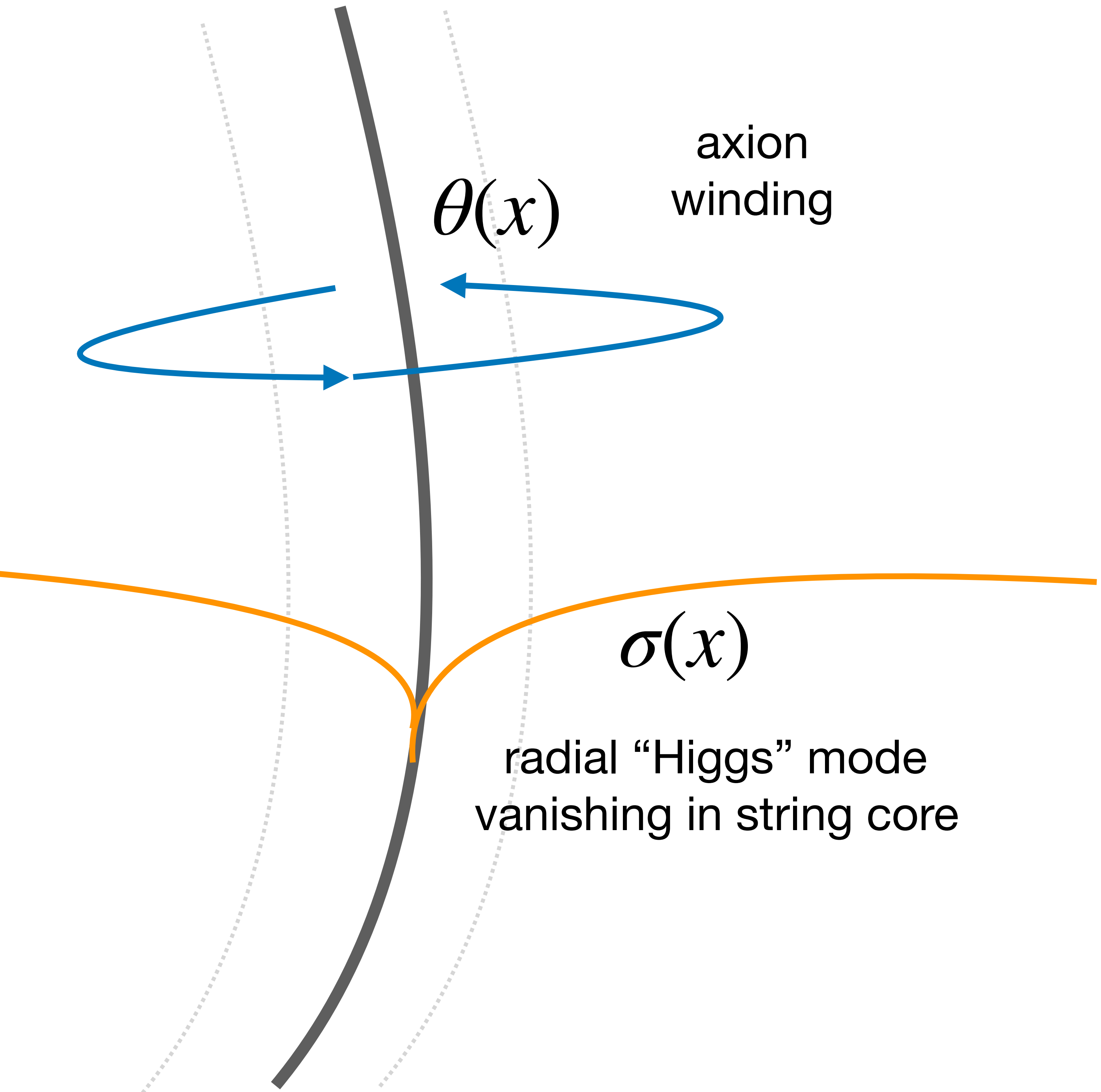
$$\epsilon^{\mu\nu\rho\lambda}\partial_{[\mu}B_{\nu\rho]} = f^2 \partial^\lambda \theta$$

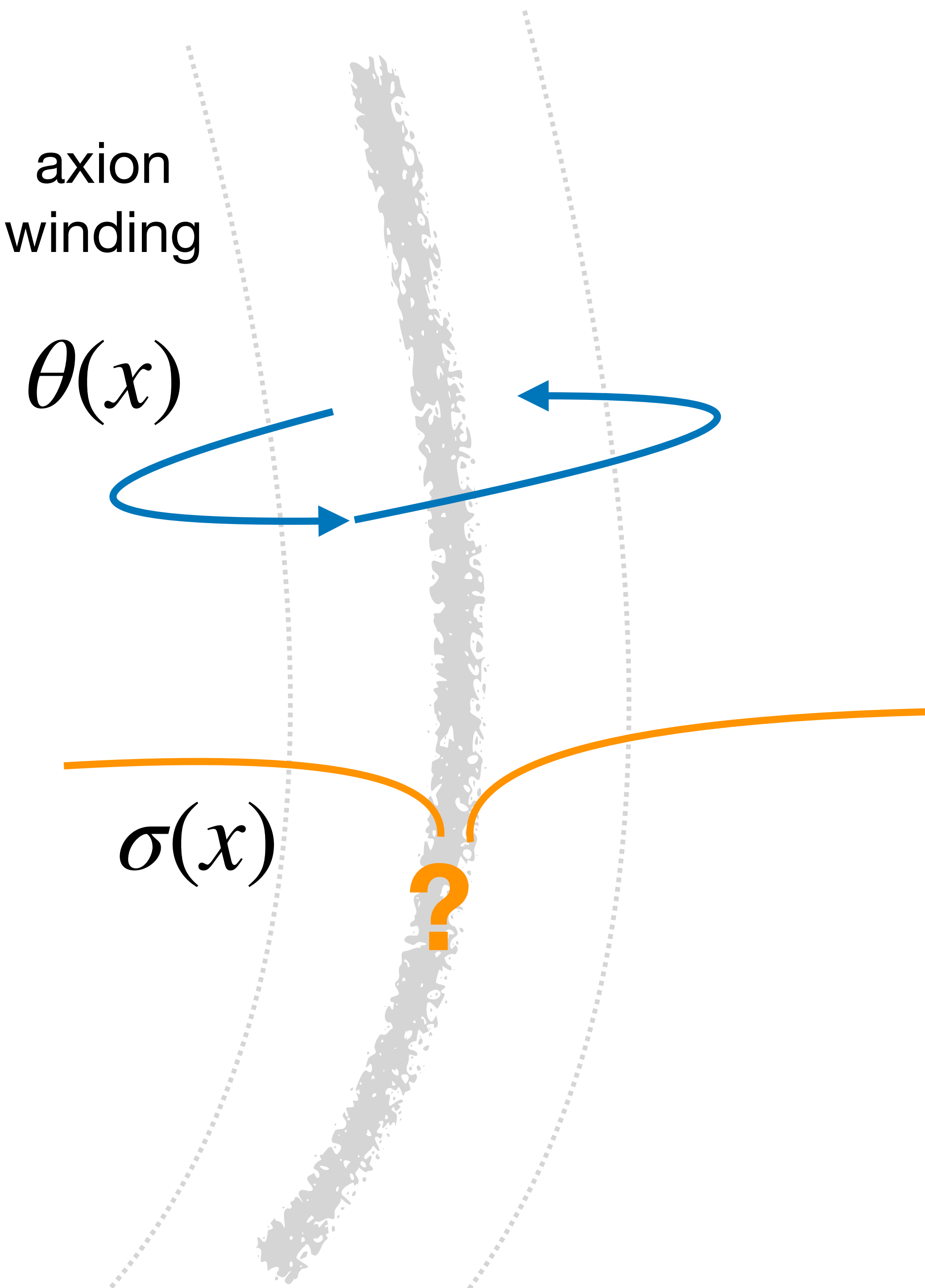
Now apply the **WGC** to the *B*-field: charged strings exist with tension $T \lesssim f\, M_{\rm Pl}$. (see Hebecker, Soler ’17)

For Stückelberg masses—unlike the Higgs mechanism—these are *fundamental* strings.

MR, ’18

Abelian Higgs strings versus fundamental (Stückelberg) strings





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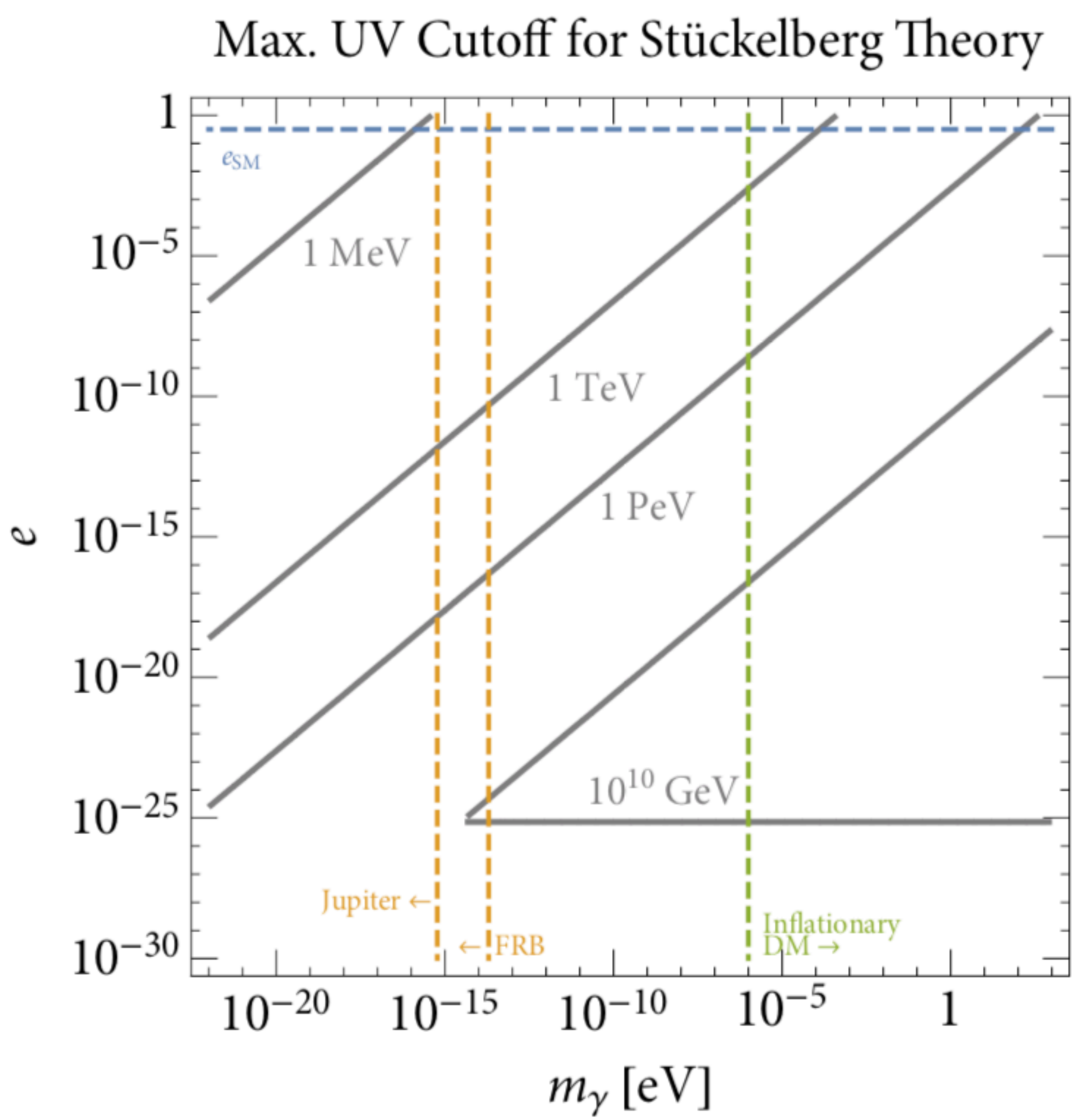
Ultraviolet cutoffs on Stückelberg photons



$$m_\gamma = ef$$

$e \to 0 : A_\mu$ weakly coupled

$f \to 0 : B_{\mu\nu}$ weakly coupled

$$\Lambda_{QG} \lesssim \min(e^{1/3}M_{Pl}, \sqrt{m_\gamma M_{Pl}/e})$$

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Can the photon have a mass?

For the SM photon, very simple kinematic bounds (from fast radio bursts) tell us

$$m_\gamma \lesssim 10^{-14}\ \mathrm{eV}$$

A mass at this scale leads to local EFT breaking down at low energies:

$$\Lambda_{\mathrm{QG}} \lesssim \sqrt{m_\gamma M_{\mathrm{Pl}}/e} \lesssim 10\ \mathrm{MeV}$$

So the SM photon can't have a Stückelberg mass.
Loophole is the unit of charge: suppose the electron charge is N, i.e. what we know as e is really $e_0 N$ for $N >> 1$.

We can push the UV cutoff above a TeV if $N \sim 10^{12}$.
(Or Higgs mechanism: Higgs is millicharged, similarly huge N.)

Not very *plausible*, but not logically inconsistent?

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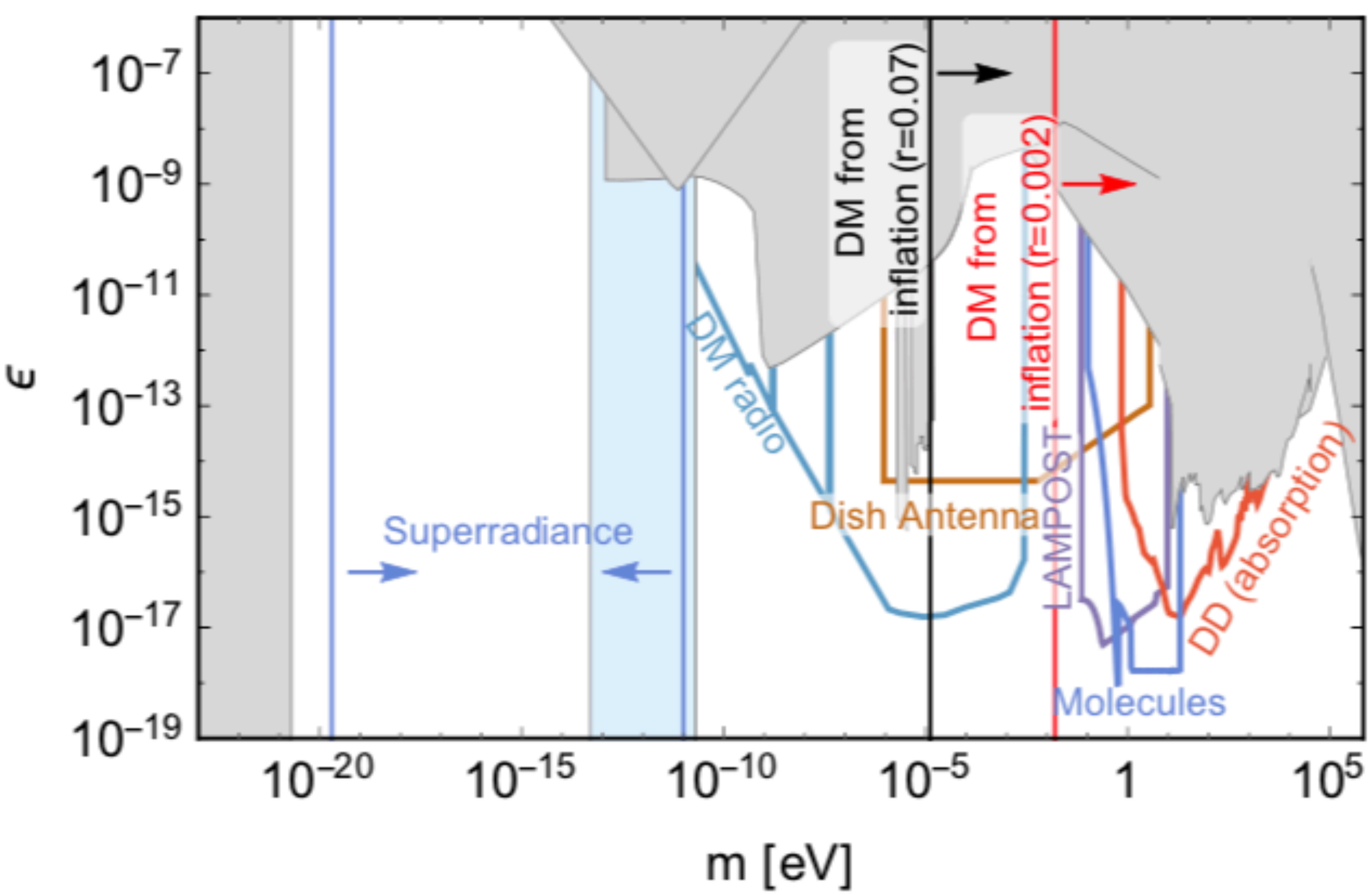
Light dark photon dark matter

Very light dark photons are an interesting dark matter candidate, with many proposed experiments searching for them.



Relic abundance? Inflationary fluctuations give

$$\Omega_{\gamma'} = \Omega_m \sqrt{\frac{m_{\gamma'}}{6\,\mu\text{eV}}} \left(\frac{H_I}{10^{14}\ \text{GeV}}\right)^2$$

for Stückelberg masses (Graham, Mardon, Rajendran '15).

Tension with Swampland bound at $m_\gamma \lesssim 0.1$eV! Find $\Lambda_{QG} \lesssim H_I$.

In fact, generally expect self-interactions ~ e_D^4, so mechanisms to populate very large occupation numbers probably always require $e_D << 1$. Is there a mechanism populating DM at lower mass?

Figure from P. Agrawal, N. Kitajima, MR, T. Sekiguchi, F. Takahashi, to appear soon

Dark Photon DM from Axion Oscillations

Consider an axion field ϕ coupled to a massive photon field A_μ.

$$S = \int d^4x \sqrt{-g} \left(\frac{1}{2}(\partial\phi)^2 - V(\phi) - \frac{1}{4}F_{\mu\nu}^2 + \frac{1}{2}m_{\gamma'}^2 A_\mu^2 - \frac{\beta}{4f_a}\phi F_{\mu\nu}\widetilde{F}^{\mu\nu} \right)$$

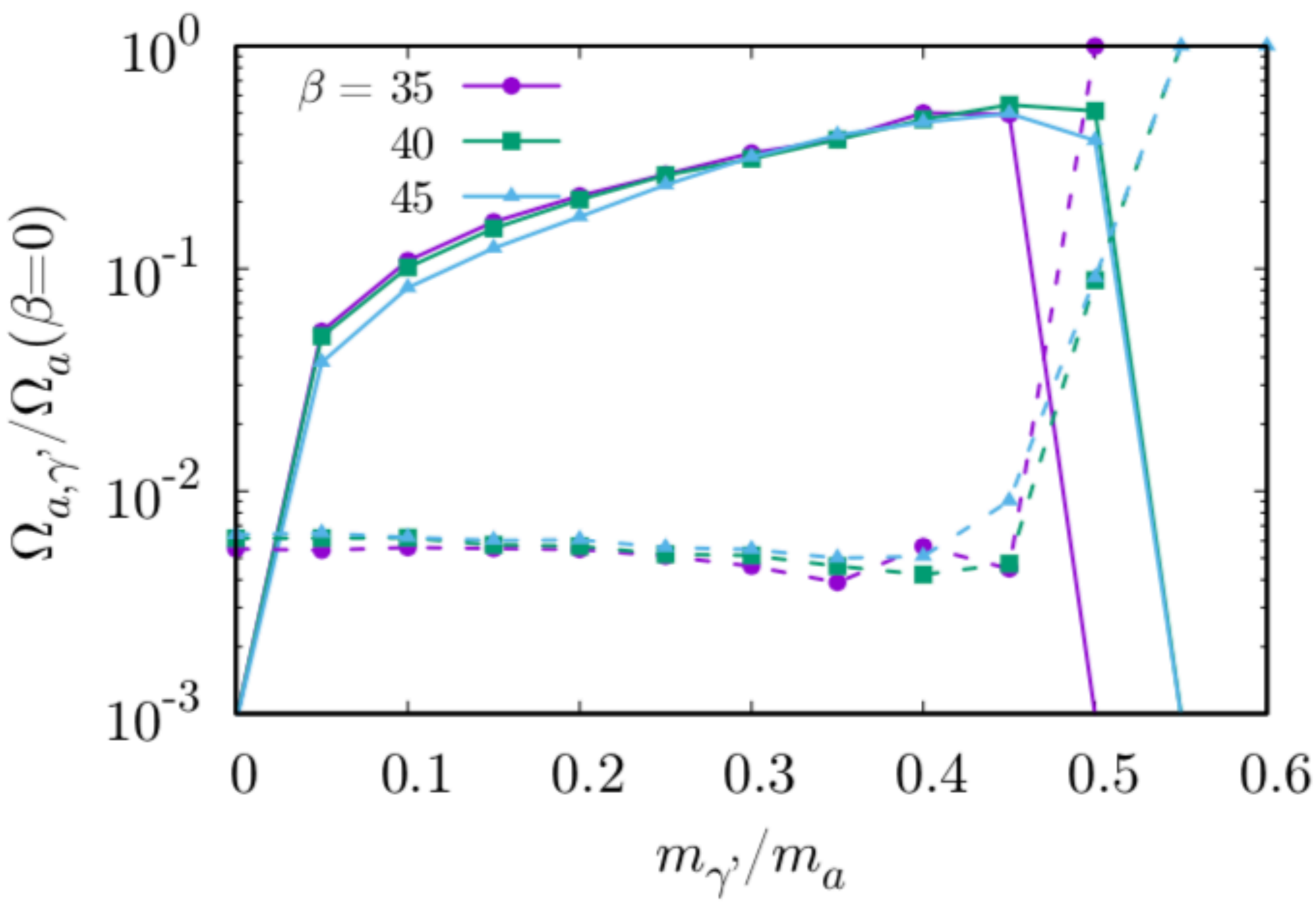
As ϕ oscillates, some Fourier modes of A become tachyonic:

$$\ddot{\mathbf{A}}_{\mathbf{k},\pm} + H\dot{\mathbf{A}}_{\mathbf{k},\pm} + \left(m_{\gamma'}^2 + \frac{k^2}{a^2} \mp \frac{k}{a}\frac{\beta\dot{\phi}}{f_a} \right) \mathbf{A}_{\mathbf{k},\pm} = 0$$

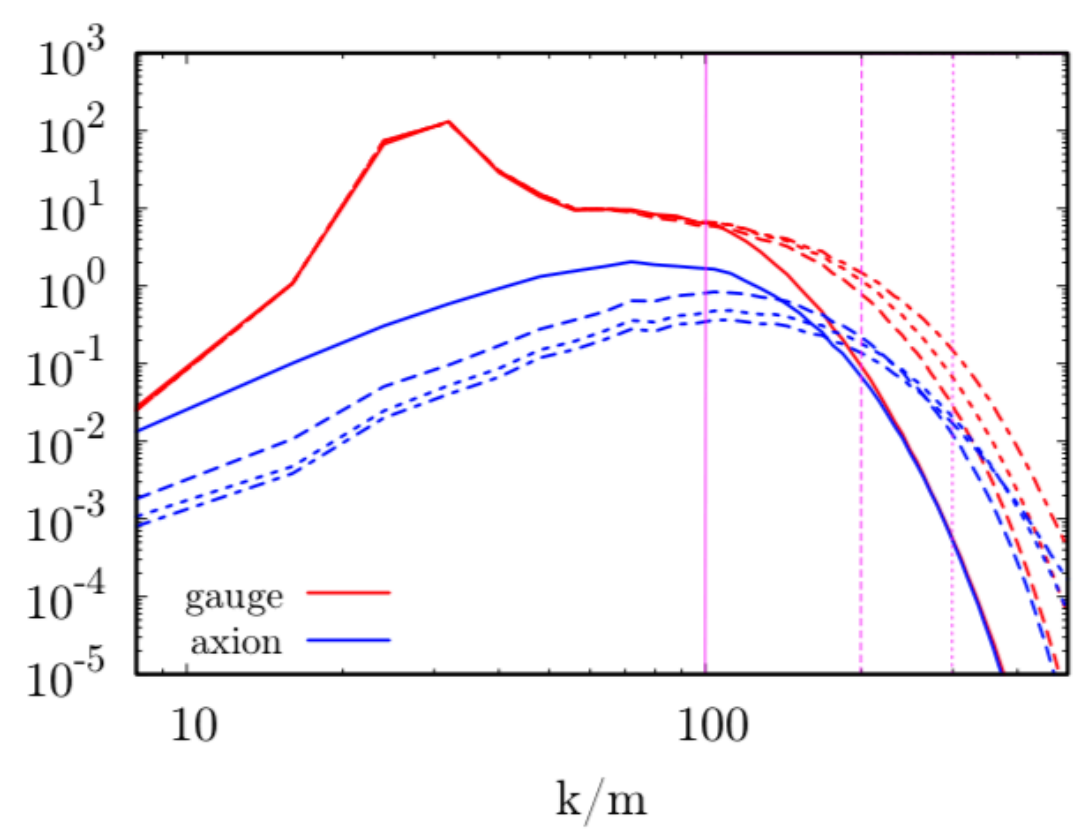
For $\beta \sim 100$, an initial axion abundance can be almost fully converted into a population of dark photons. The misalignment mechanism stores energy later converted to dark photons.

P. Agrawal, N. Kitajima, MR, T. Sekiguchi, F. Takahashi, to appear soon

Dark Photon Dark Matter



Final dark photon DM relic abundance compared to the would-be axion relic abundance with no axion/ dark photon coupling.

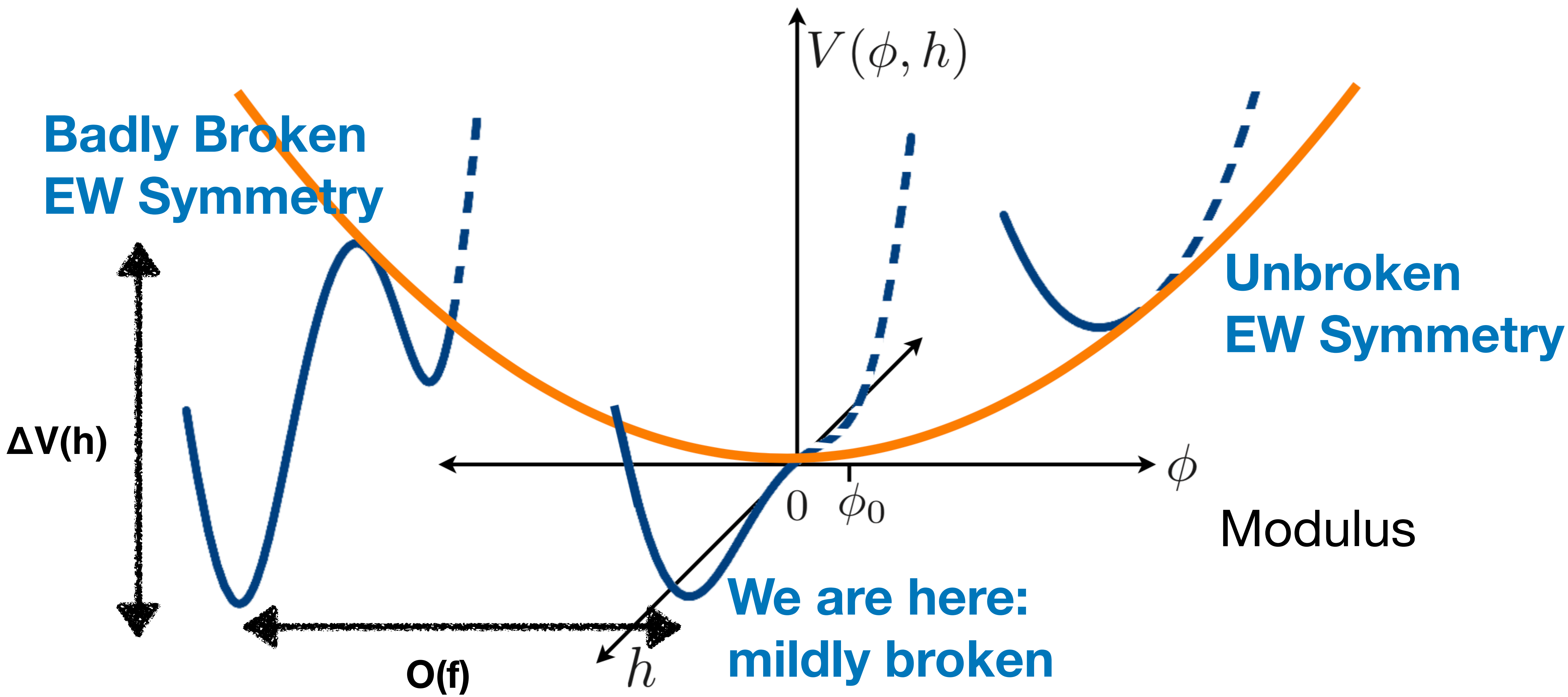


Produce modestly relativistic photons which then redshift to become CDM.

Important that photons not thermalize!

P. Agrawal, N. Kitajima, MR, T. Sekiguchi, F. Takahashi, to appear soon

Cosmological Signals of a Fine-Tuned Higgs: Coupled Modulus-Higgs Dynamics

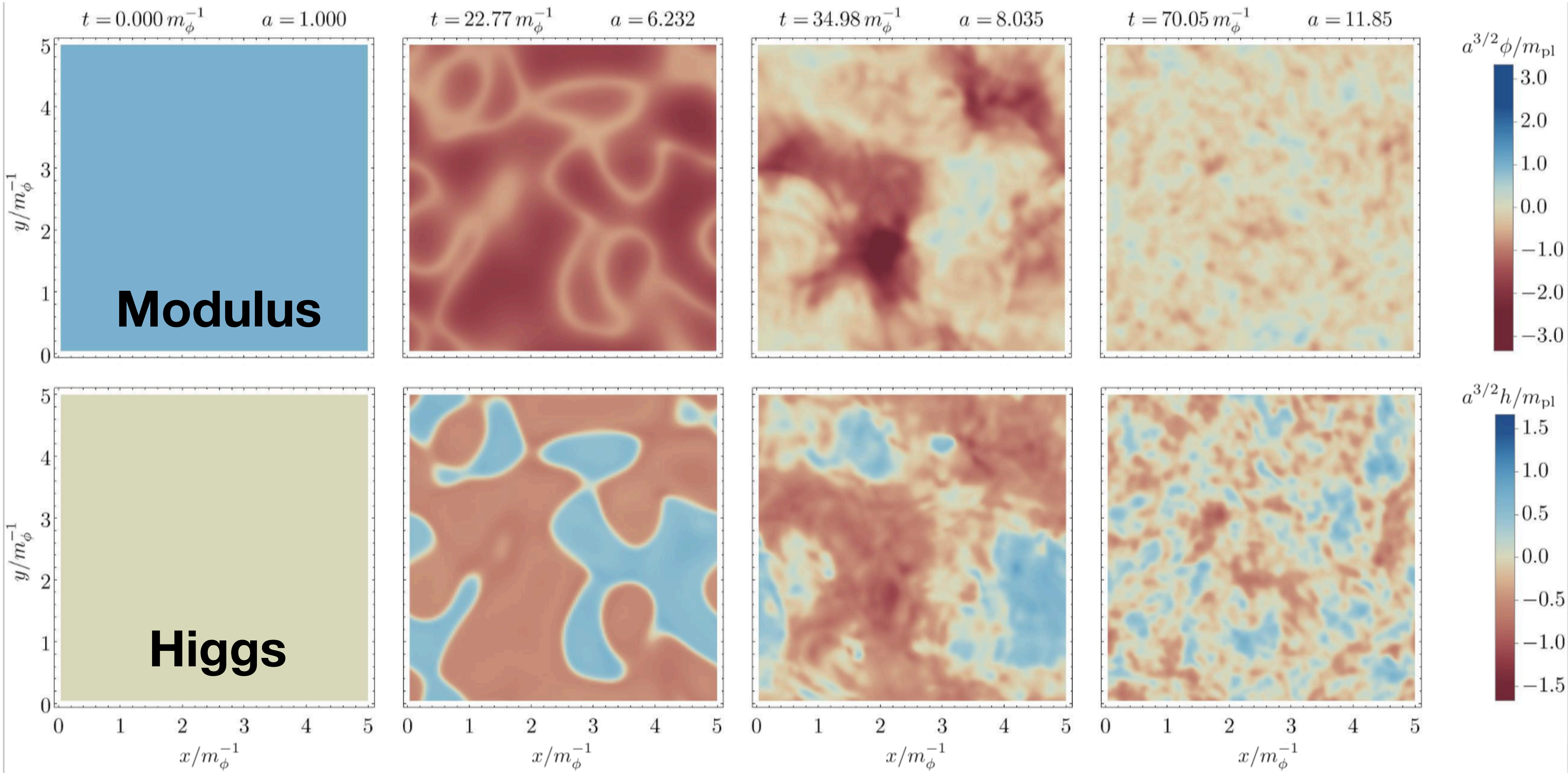


$$\frac{1}{2}m_\phi^2\phi^2 + M^2\frac{\phi - \phi_0}{f}h^\dagger h + \lambda(h^\dagger h)^2 + V_0$$

Fine tuning is the coincidence between the minimum of the ϕ potential and the point of marginal EWSB.

Amin, Fan, Lozanov, MR, '18

Higgscitement: Evolution of the Fields



Fine-tuned Higgs ⇒ Violent dynamics fragment the modulus

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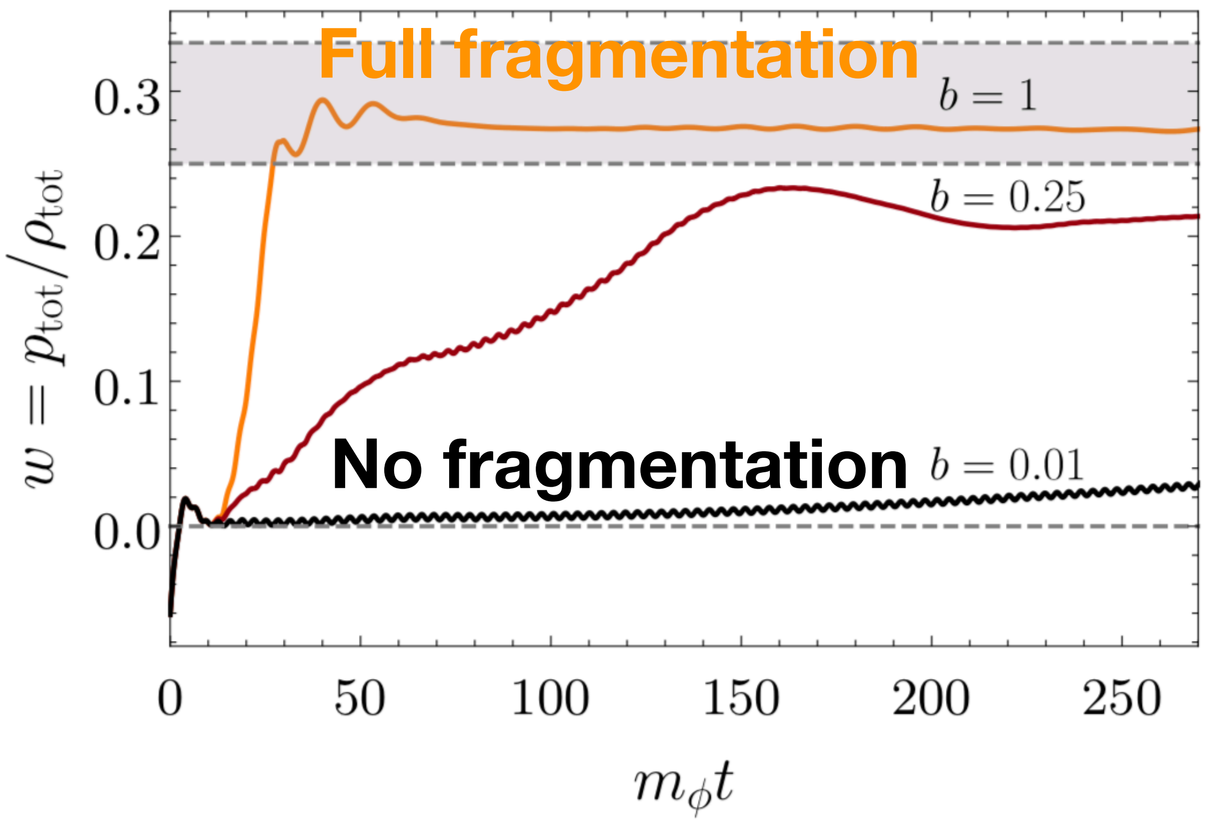
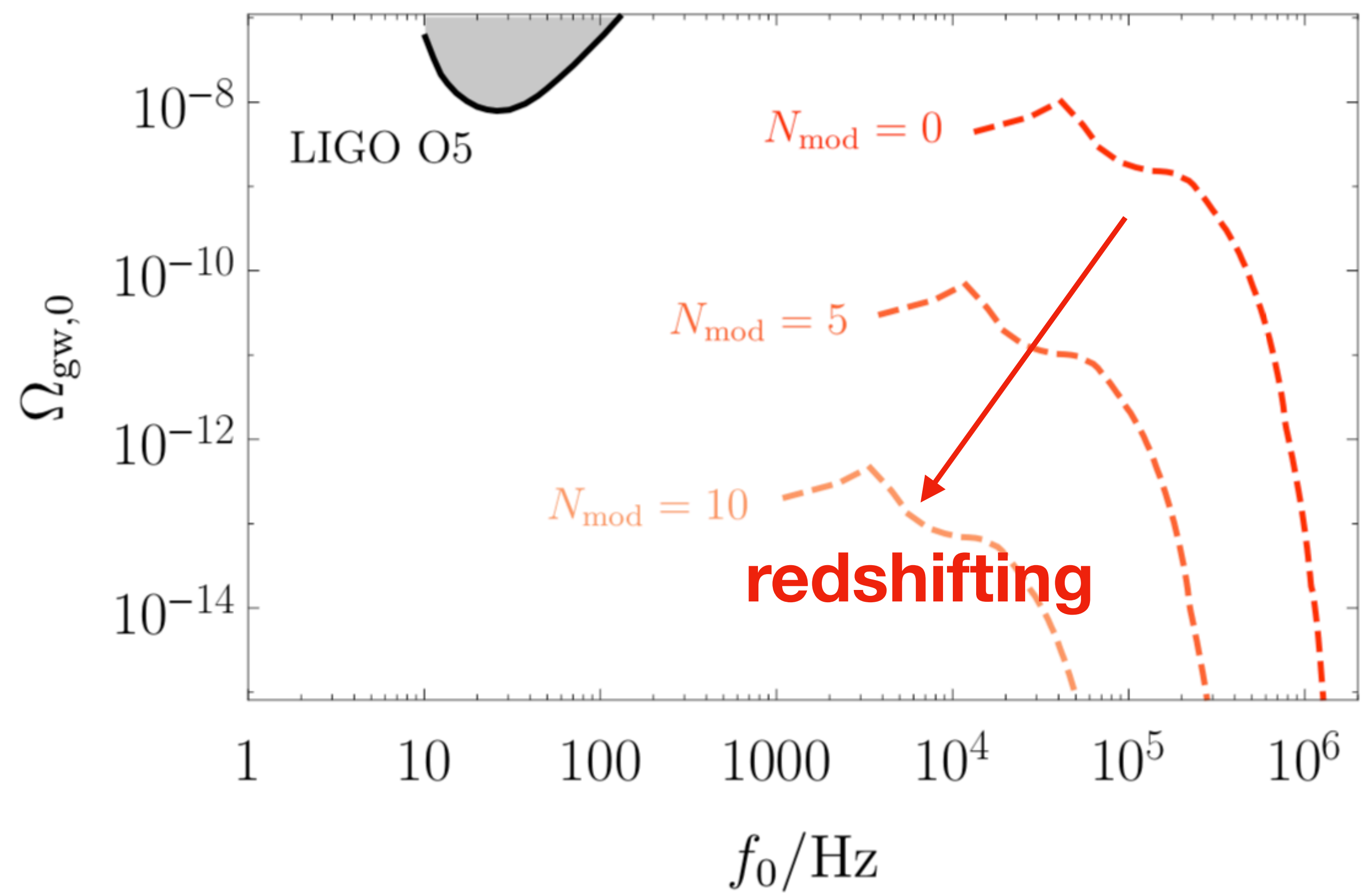
Higgscitement: Cosmological Consequences

nontrivial equation of state



stochastic gravitational waves



Fine-tuned dynamics *and* SUSY flat directions: far from a quiescent, modulus-dominated phase with equation of state $w = 0$.

Amin, Fan, Lozanov, MR, '18

Conclusions

Quantum gravity can provide interesting hints for cosmology, for instance: moduli fields (scalars with gravitational strength couplings) likely exist; field ranges above the Planck scale may be problematic.

In particular, very light Stückelberg dark photons likely do not exist, but dark photon masses from Higgsing / dynamical symmetry breaking are viable.

New mechanism for dark photon dark matter populated by an oscillating axion field.

More generally, far-from-equilibrium dynamics in the early universe can have interesting links to particle physics problems, e.g. the fine-tuned weak scale.