OUT OF THE DARK: WISPS IN STRING THEORY AND THE EARLY UNIVERSE

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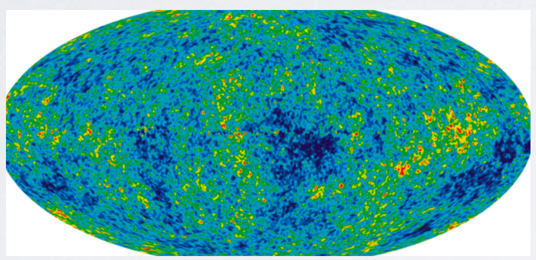
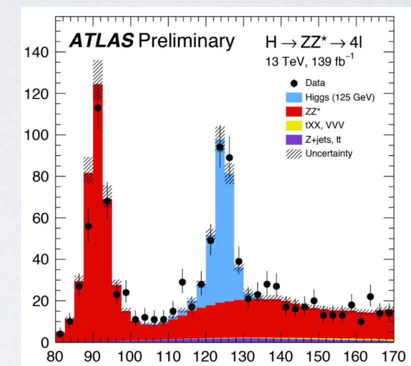
WG1

OUR HOME, THE UNIVERSE

- Our universe is *filled* with hierarchies and small numbers



$$\frac{\Lambda_{EW}}{M_P} \sim 10^{-16}$$



$$\Lambda_{cc} \sim 10^{-120} M_P^4$$

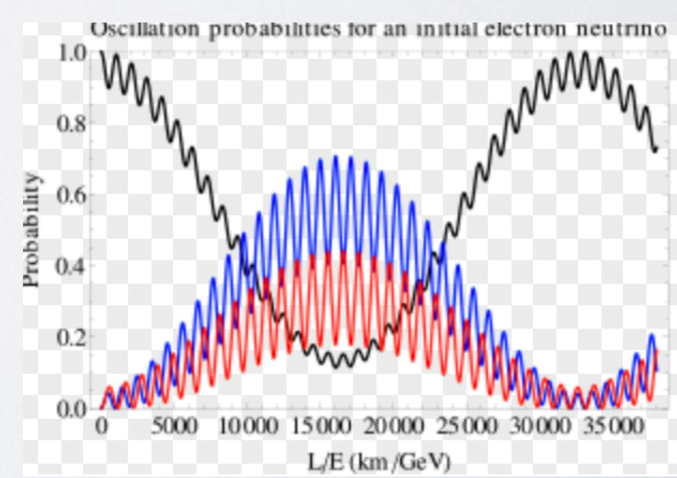
$$\frac{\delta\rho_{CMB}}{\rho} \sim 10^{-5}$$

$$\alpha_{SU(3)} \sim \frac{1}{11}, \alpha_{SU(2)} \sim \frac{1}{30}, \alpha_{U(1)_Y} \sim \frac{1}{60}$$

$$y_e \sim 10^{-5}, y_\mu \sim 10^{-3}, y_\tau \sim 10^{-2}$$

$$\theta_{QCD} \lesssim 10^{-10}$$

$$m_\nu \sim 10^{-3}\text{eV}$$



OUR HOME, THE STRINGY UNIVERSE (?)

- If string theory is true, the true string vacuum is the vacuum of *this* universe
- It must contain a method to generate hierarchies, small couplings and small numbers
- Any particles found in the spectrum of the string theory are also particles of our universe

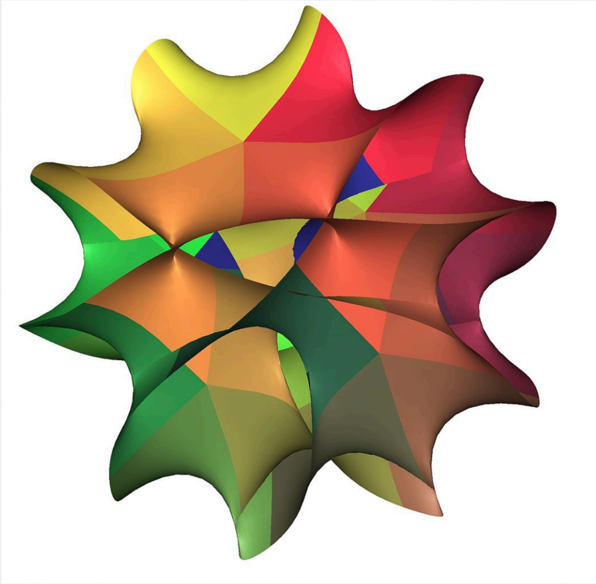
"Our mistake is not that we take our theories too seriously, but that we do not take them seriously enough."

Steven Weinberg, 1933 - 2021

(Picture credit Larry Murphy, University of Texas at Austin)

STRING COMPACTIFICATIONS

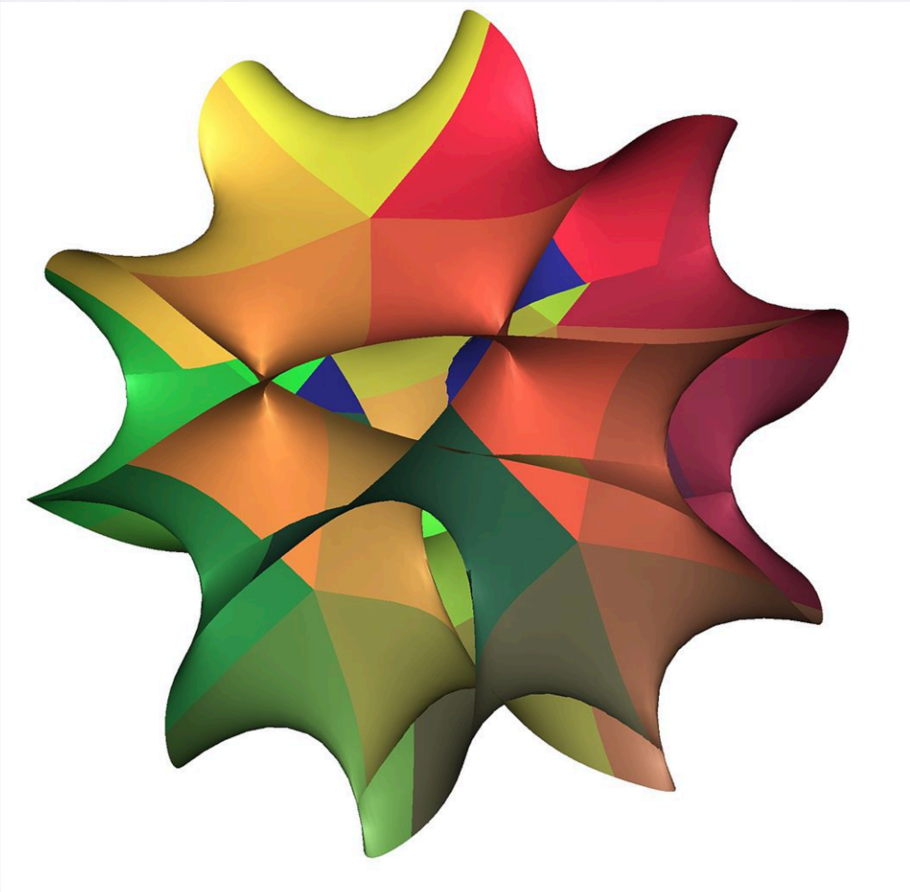
- String theory is consistent in 10 dimensions and 10 > 4.
- For all real-world applications of string theory, six dimensions must be compactified so that they are very small.



- If these dimensions are real, what are their consequences?

STRING COMPACTIFICATIONS

- If extra-dimensional geometry is real, how does it manifest itself in 4 dimensions?



WISP CANDIDATES

- In 4-dimensional field theory there are many viable candidates to be WISPs; some well discussed and others less so.
- Axions
- Dark photons
- Hidden sector chiral fermions (naturally light, but rarely discussed)

WISP CANDIDATES IN STRING THEORY: AXIONS

- Axions in 4d field theory are defined by a topological property

$$a \equiv a + 2\pi f_a$$

- In compact geometries axions arise from topologically non-trivial compact cycles

$$c_i = \int_{\Sigma_{4,i}} C_4$$

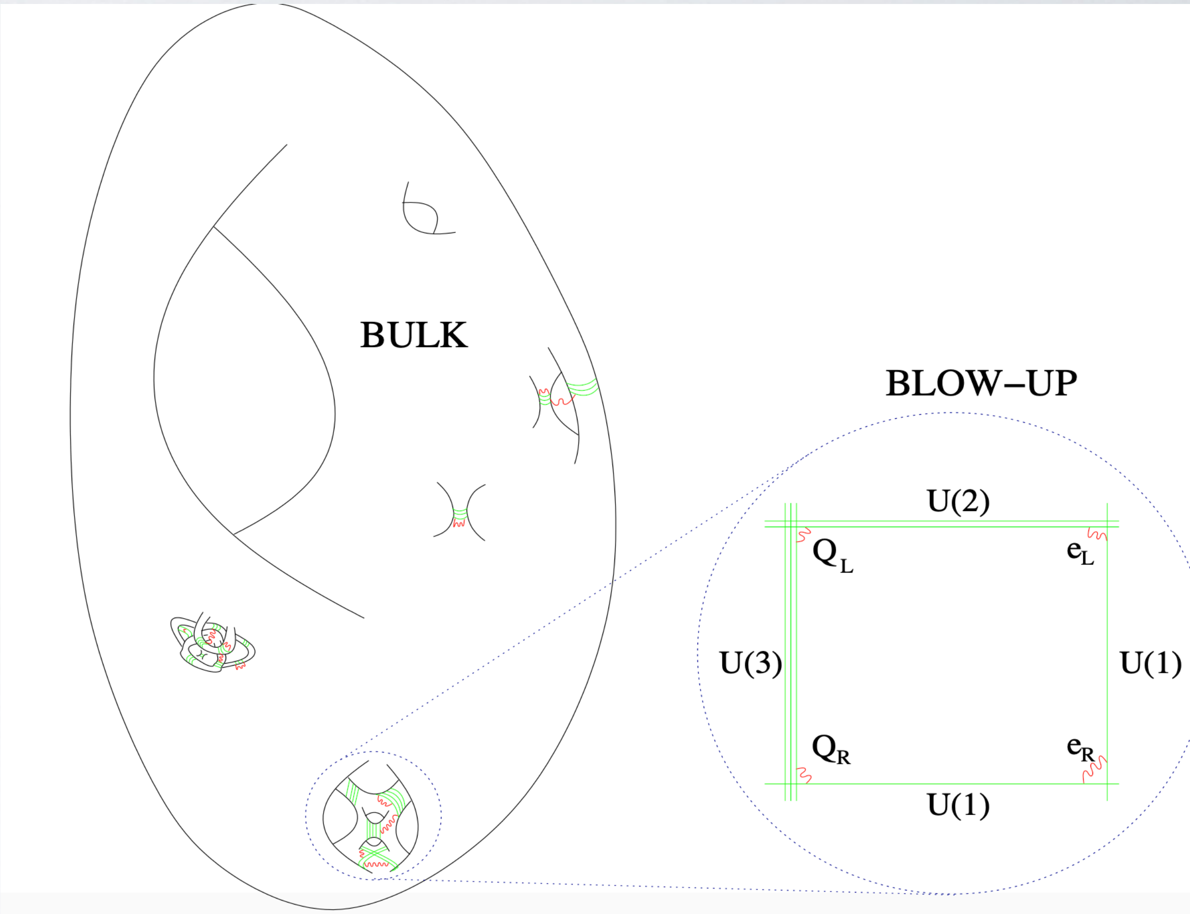
- Axions and axion-like particles extremely well motivated in string theory

- For QCD string axion, what sets decay constant?

WISP CANDIDATES IN STRING THEORY: AXIONS

- `Natural' axion decay constant is either M_P or $M_{string} \sim \frac{g_s M_P}{\sqrt{\mathcal{V}}}$

  (in dimensionless units)



- So decay constants $f_a \ll M_P$ can be achieved through e.g. large compactification volumes and local realisations of the Standard Model

WISP CANDIDATES IN STRING THEORY: AXIONS

- What are axion or ALP masses in string theory?
- Axions partner Saxions due to underlying supersymmetric structure
  Effects can give mass to both Saxion and axion, e.g.

$$W = W_0 + \sum A_i e^{-a_i T_i} = W_0 + \sum A_i e^{-a_i(\tau_i + i a_i)}$$

- Axions only get mass non-perturbatively, and mass is exponential in saxion.
- Large cycle volumes in compactification mean axion partner will be (effectively) massless, as effects non-perturbative in volume

WISP CANDIDATES IN STRING THEORY: DARK PHOTONS

- Hidden U(1) dark photons can arise in string theory from both open string sectors and closed string sectors

- Closed string U(1) dark photons can arise (similar to axions) from integrating form fields over cycles,

$$A_{\mu,i} = \int_{\Sigma_{3,i}} C_4$$

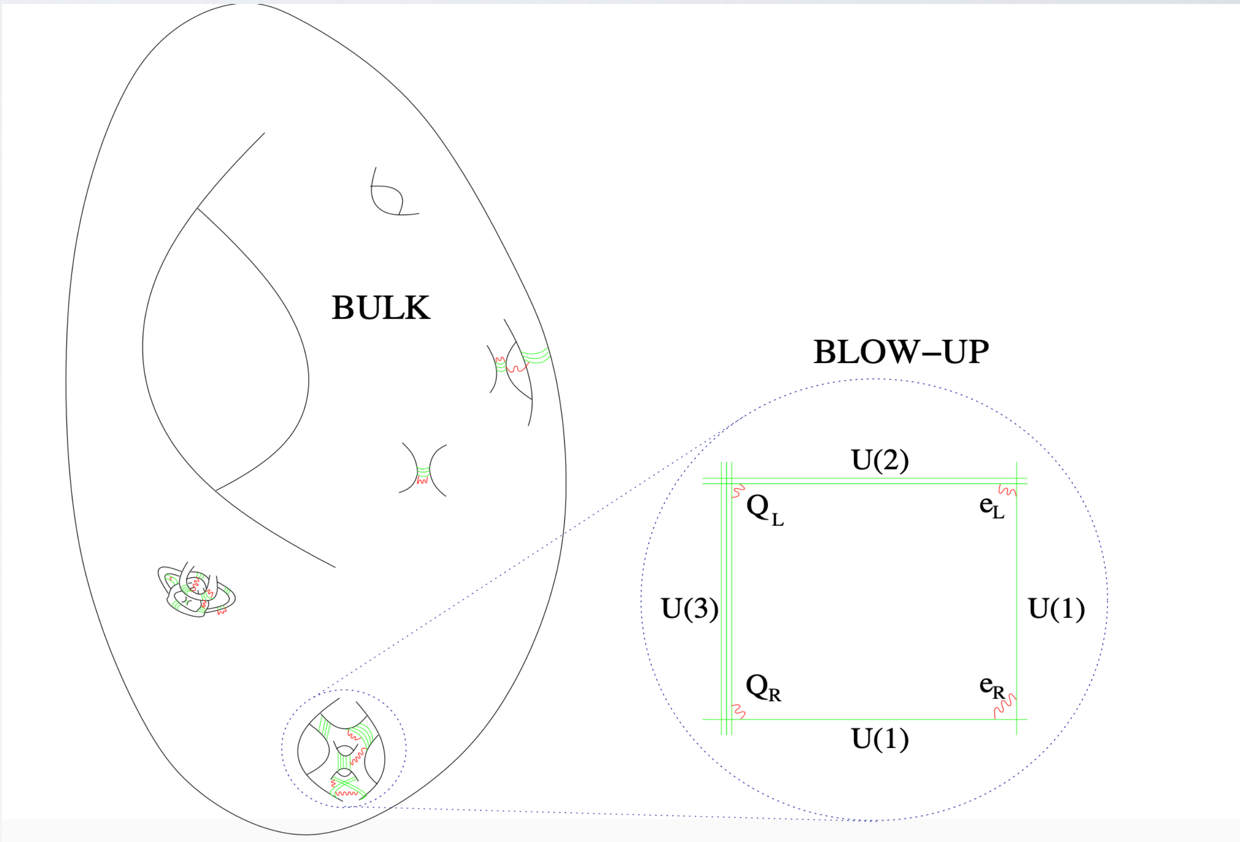
  These have no light charged states (only D-brane states are charged under these)

- Open string U(1) dark photons can arise from local D-brane models far from the Standard Model sector

WISP CANDIDATES IN STRING THEORY: DARK PHOTONS

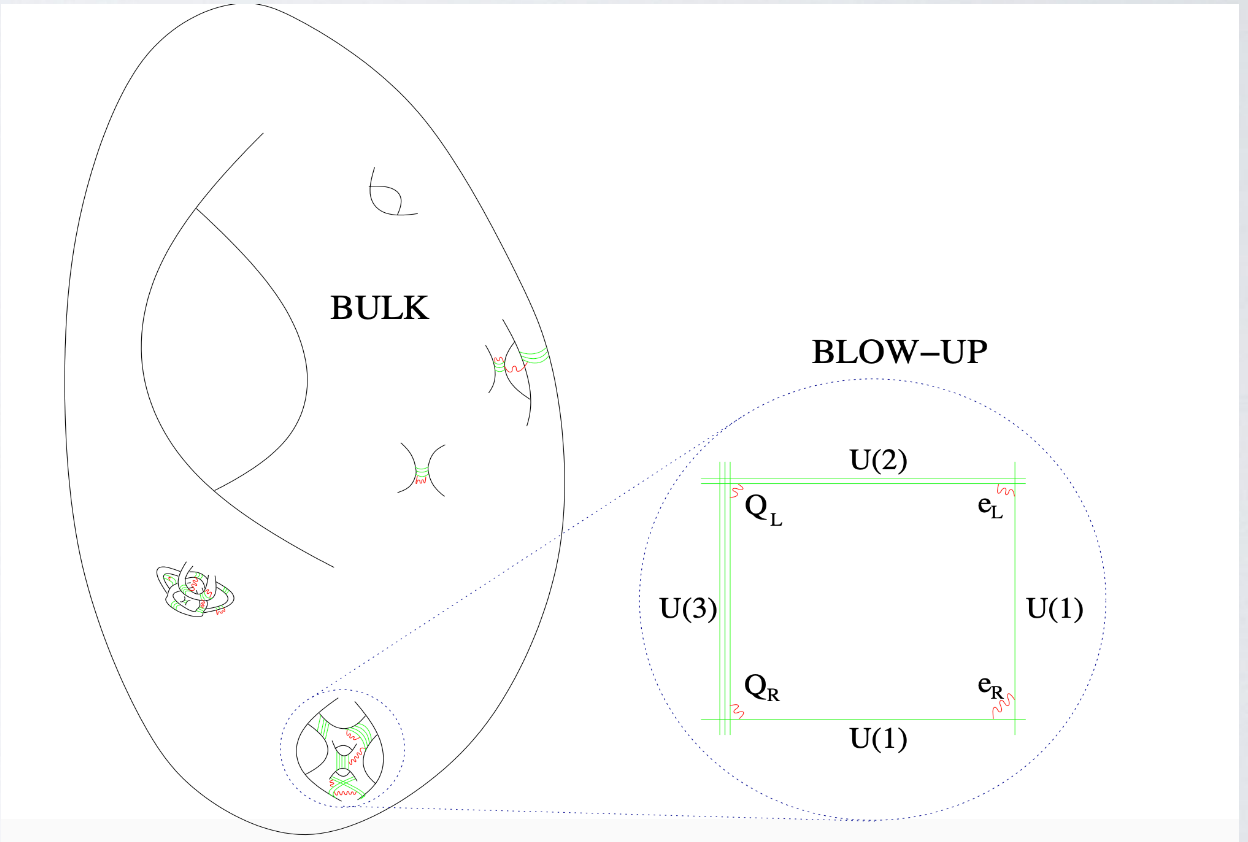
- Large compact spaces could have many different gauge sectors

- Brane stacks far from the Standard Model could also host chiral matter sectors and gauge groups



WISP CANDIDATES IN STRING THEORY: CHIRAL FERMIONS

- Large compact spaces could have many different gauge sectors



- Brane stacks far from the Standard Model could also host chiral matter sectors and gauge groups including hidden chiral fermions

MOTIVATION

- UV Theory (String theory) gives strong *motivation* for the existence of WISPs in the low-energy effective field theory of our universe ✓
- Can it *constrain* the properties of such WISPs? ?
- Can it *suggest new scenarios* to look for them? ?

WISP CONSTRAINTS

- UV Theory (String theory) can also ***constrain*** the properties of WISPs via the Swampland Program:

  What features of low-energy theories are *incompatible with any quantum gravity theory*

- Features that appear valid in effective field theory *may be incompatible with quantum gravity*

- Swampland program contains results with varying level of support; some much more conjectural than others.

WISP CONSTRAINTS

- QCD axion is one of the paradigmatic targets for WISP searches; much phenomenology set by f_a

- Strong evidence from string theory that

$$f_a < M_P$$

  and no transPlanckian axion decay constants allowed.

- Swampland distance conjecture: when a field moves through a parametrically transPlanckian distance D in field space, a tower of states comes down with mass scale set by

$$m_i \sim e^{-\lambda D/M_P}$$

WISP CONSTRAINTS

- Chiral fermions charged under hidden sector gauge groups are motivated WISP candidates

- Festina lente conjecture in string theory would imply
$$m > gqM_P H$$
and so no exactly massless charged chiral fermions would exist (cf Gerben Venken talk)

- More conjectural than constraints on axion decay constant; example of how UV Swampland constraints on quantum gravity could bound allowed WISP candidates

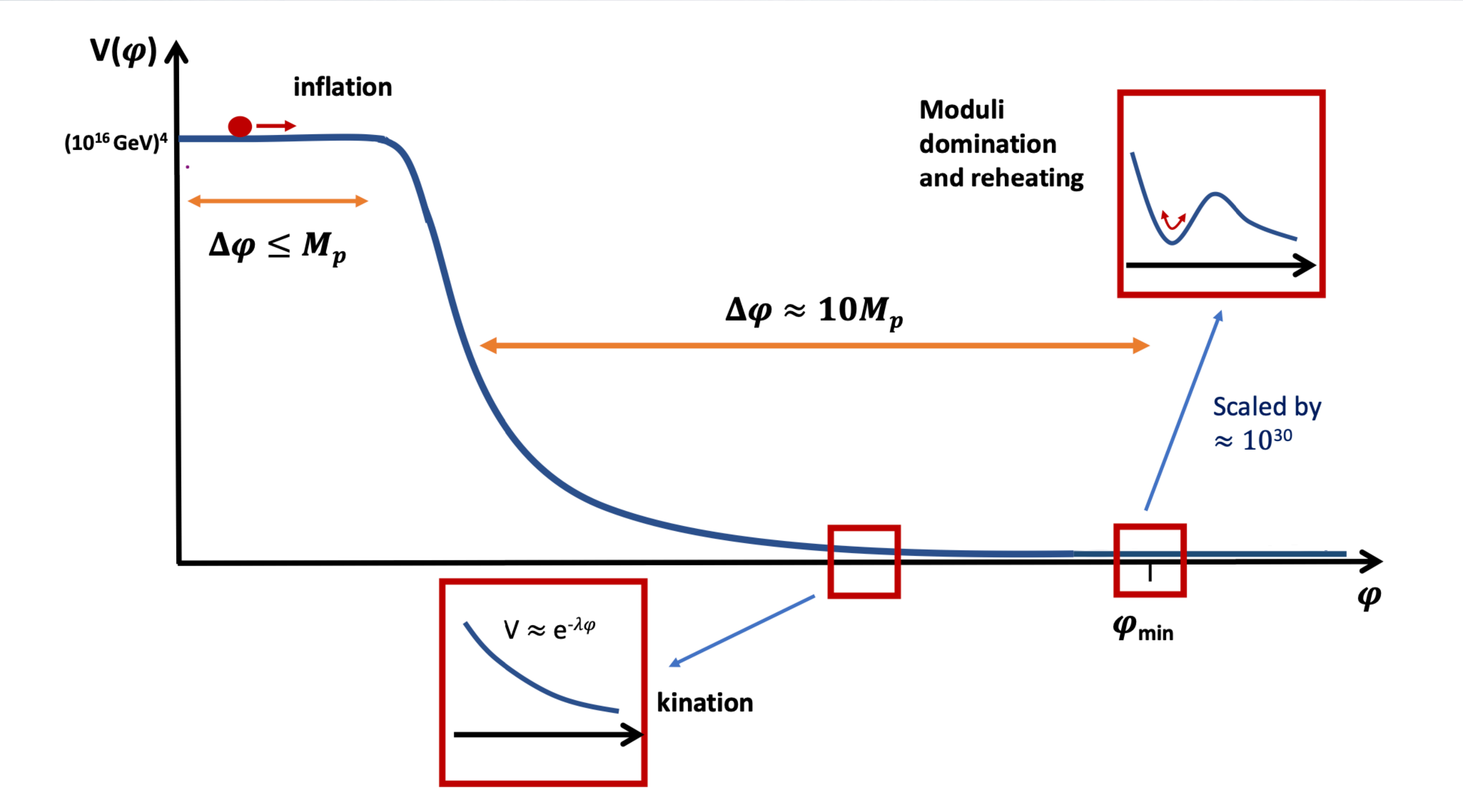
CONSTRAINTS

- UV Theory (String theory) gives strong *motivation* for the existence of WISPs in the low-energy effective field theory of our universe

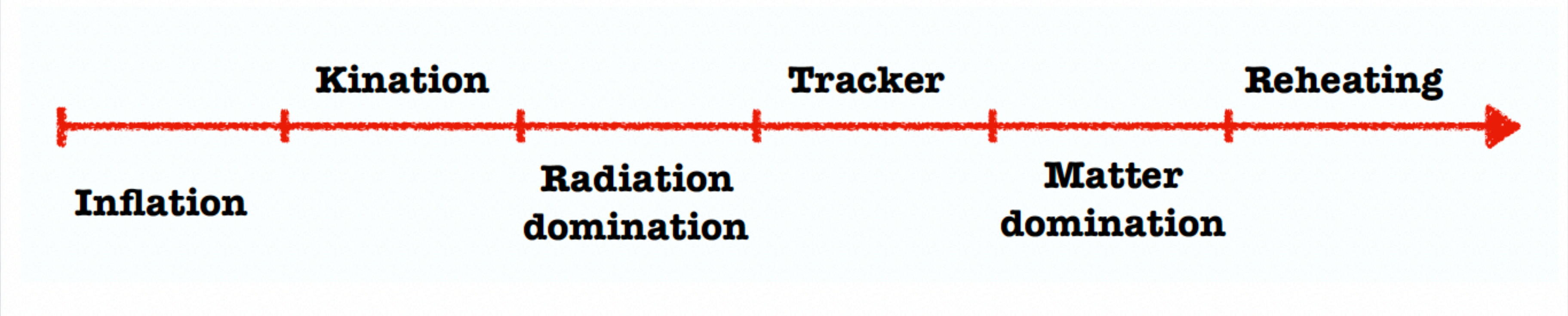
- Can it *constrain* the properties of such WISPs?

- Can it *suggest new scenarios* to look for them?

UV SCENARIOS: NON-STANDARD COSMOLOGIES



String theory motivates a distinctive ‘stringy’ cosmological history quite distinct from the normal assumption of radiation domination after inflation



From review 2303.04819 Cicoli, JC, Maharana, Parameswaran, Quevedo, Zavala

UV SCENARIOS: CONTROLLED TRANS-PLANCKIAN FIELD EXCURSIONS

- During roll, with universe in kination epoch, field evolves as

$$\Phi(t) = \Phi_0 + \sqrt{\frac{2}{3}} M_P \ln\left(\frac{t}{t_0}\right)$$

- Field moves through $\sim M_P$ in field space each Hubble time

  Long kination epoch implies large transPlanckian field excursions

- String theorists should **care!** - lots of work on problems and backreactions with trans-Planckian field excursions $\Delta\Phi \gg M_P$ during inflation.

UV SCENARIOS: MODIFED COSMOLOGIES

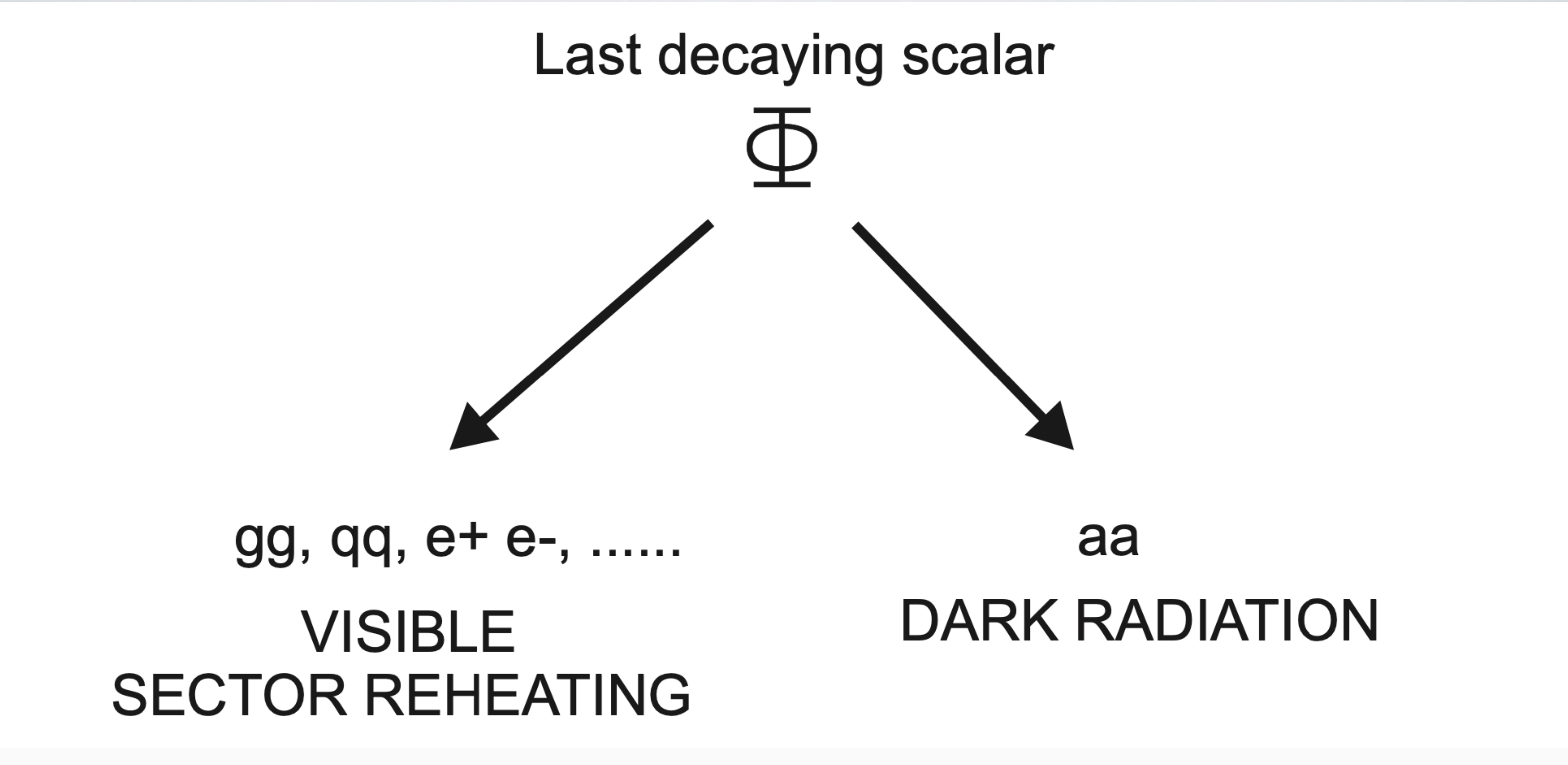
- Moduli behave as matter and live for ages

$$\Gamma_\Phi \sim \frac{1}{8\pi}\frac{M_\phi^3}{M_P^2}$$

$$\tau_\Phi \sim 8\pi\frac{M_P^2}{m_\Phi^3} \sim 10^{-6}\mathrm{s}\left(\frac{10^6\mathrm{GeV}}{m_\Phi}\right)^3$$

- In string theory, reheating is expected to proceed via moduli decays

UV SCENARIOS: MODIFED COSMOLOGIES



Gravitationally coupled particles such as moduli can decay to hidden WISPy sectors and so can lead to a dark radiation Cosmic Axion (WISP) Background that survives from the time of reheating

CHALLENGES FROM THEORY (OR, WHAT HAS WG1 EVER DONE FOR ME?)

- Easy to obtain and motivate WISP candidates (axions, dark photons, etc) from string compactifications
- Moderate to find string-motivated signatures describable in effective field theory (e.g Cosmic Axion Background, superradiance)
- Hard to find signatures that would be convincing evidence of string theory (i.e. more than BSM)

CHALLENGES FROM THEORY (OR, WHAT HAS WG1 EVER DONE FOR ME?)

- String compactifications are topologically complex and can produce $\mathcal{O}(100 - 1000)$ WISPs in the effective field theory (depends on $h^{2,1}$ or $h^{1,1}$)

- This is something truly stringy, a real sign of compactification structure: $N \gg 1$ WISPs in the low energy theory

- There are effects whose observability scales with occupation number, e.g. $\propto n^2$

- Are there observables that scale with number of species, $\propto N^2, e^N$, etc? In such effects would lie something uniquely stringy.

CONCLUSIONS

- String theory ***motivates the existence of WISPs*** in the low-energy effective field theory ✓
- String theory ***can provide UV constraints*** on allowed properties of WISPs in the low-energy theory ✓
- String theory can ***suggest new scenarios*** and ways in which WISPs can appear ✓