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European Research Council
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ICCUB
Institut de Ciències del Cosmos
UNIVERSITAT DE BARCELONA

EXCELENCIA MARÍA DE MAEZTU 2020-2023

A Cosmology Review for String Theorists

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Cosmology Primer

- Base assumption: FLRW metric

(homogeneity & isotropy at leading order on largest scales)

$$\mathrm{d}s^2 = -\mathrm{d}t^2 + a^2 \mathrm{d}\vec{r}^2$$

$$\vec{d} = a\vec{r}$$

Cosmology Primer

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$$\mathrm{d}s^2 = -\mathrm{d}t^2 + a^2 \mathrm{d}\vec{r}^2$$

$$\vec{d} = a\vec{r}$$

- Also: Perturbations of physical size $k = 1/r_{\mathrm{comoving}}$

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Cosmology Primer

- Expansion rate related to energy content

$$H^2 = \frac{8\pi G}{3}\rho = \frac{1}{3}\rho$$

$$H = \frac{\dot{a}}{a}$$

$$\vec{d} = a\vec{r}$$

Cosmology Primer

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$$H^2 = \frac{8\pi G}{3}\rho = \frac{1}{3}\rho$$

$$H = \frac{\dot{a}}{a}$$

$$\vec{d} = a\vec{r}$$

- This also defines a horizon

$$D_H = 1/H$$

(or in comoving space: $r_H = 1/(aH)$)

Cosmology Primer

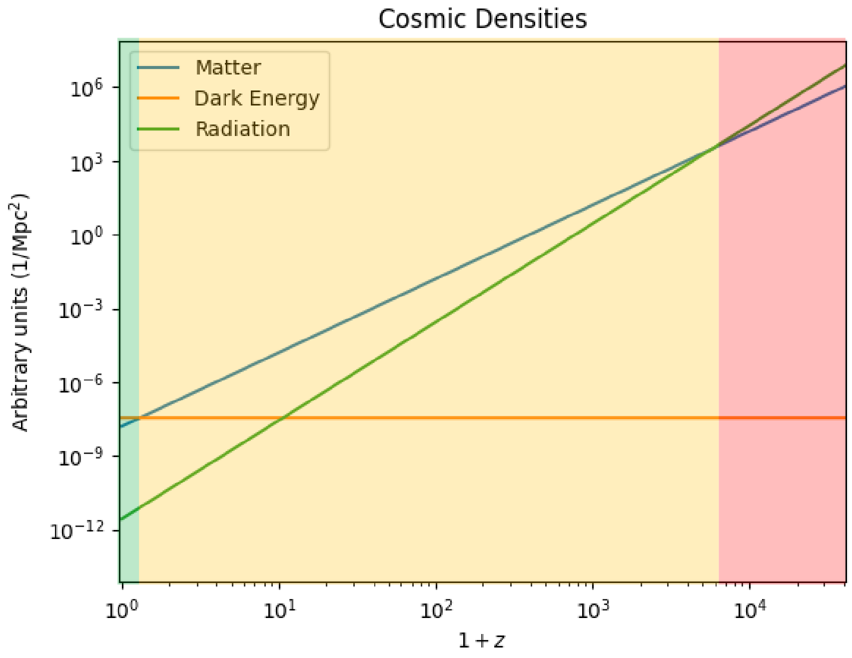
- Energy content:

$$\rho_{\mathrm{rad}} \propto \frac{E}{V} \propto \frac{1}{\lambda V} \propto a^{-4} \qquad \rho_{\mathrm{mat}} \propto \frac{E}{V} \propto \frac{m}{V} \propto a^{-3}$$

$$\rho_\Lambda = \mathrm{const.}$$

Energy content

- The typical ΛCDM energy content:



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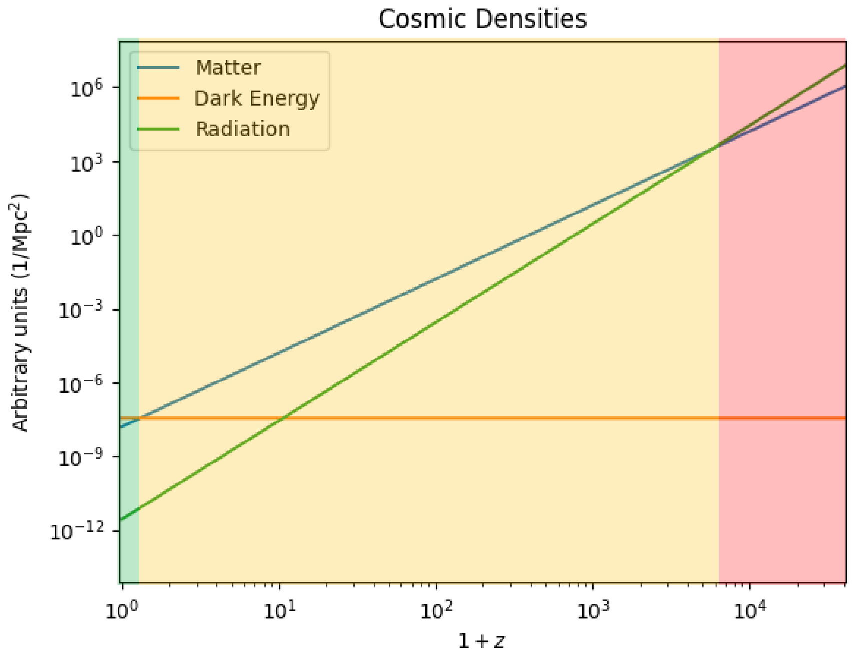

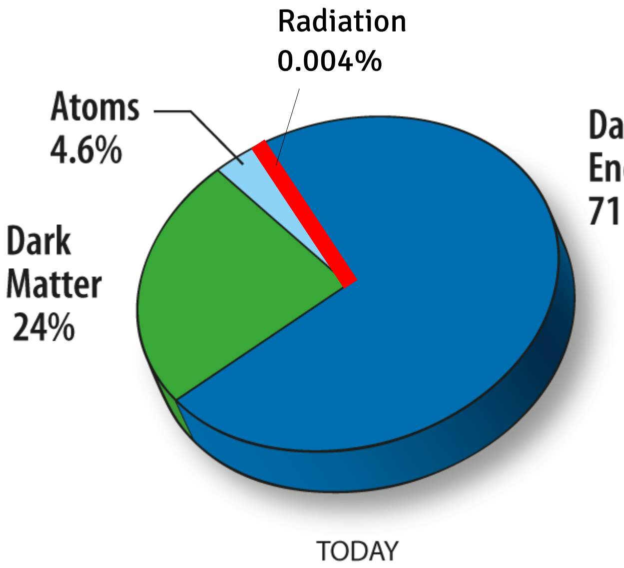

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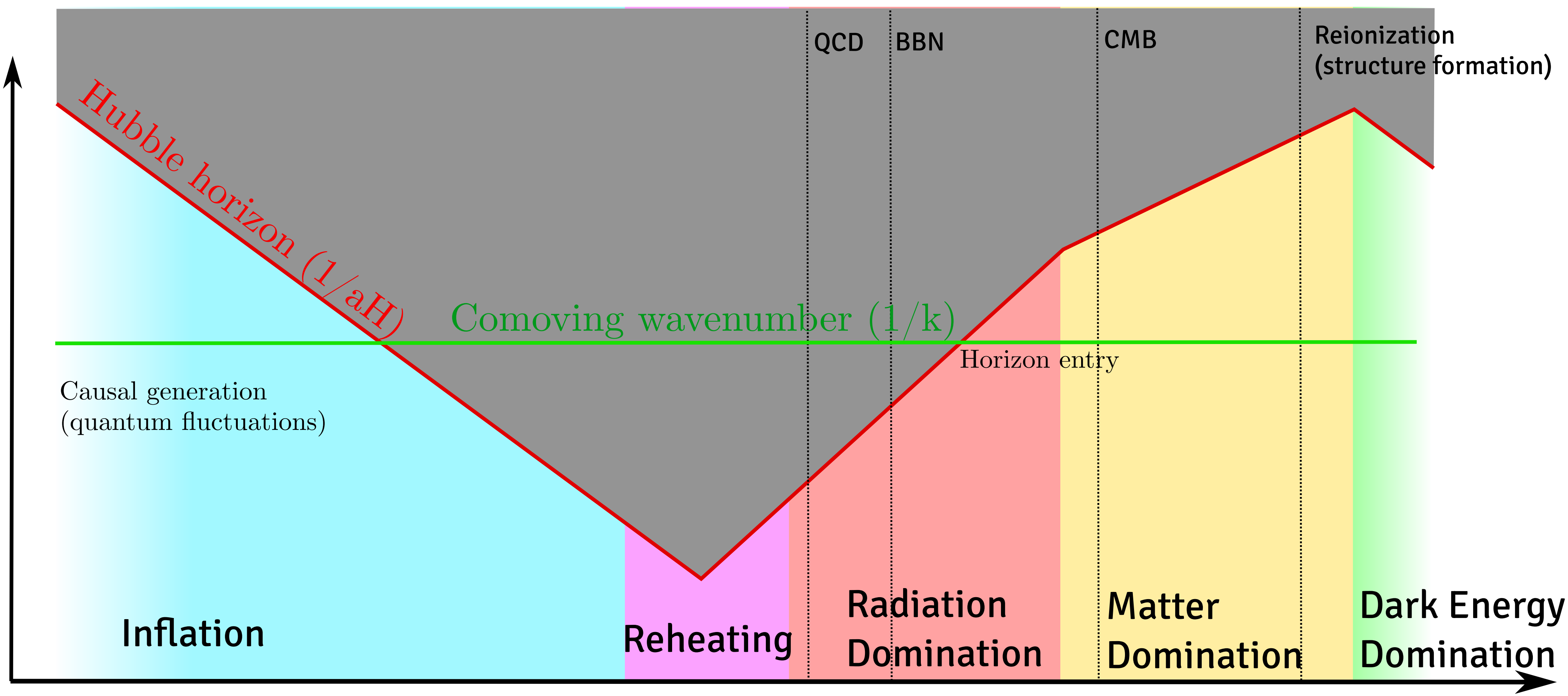
Our cosmic history (so far)



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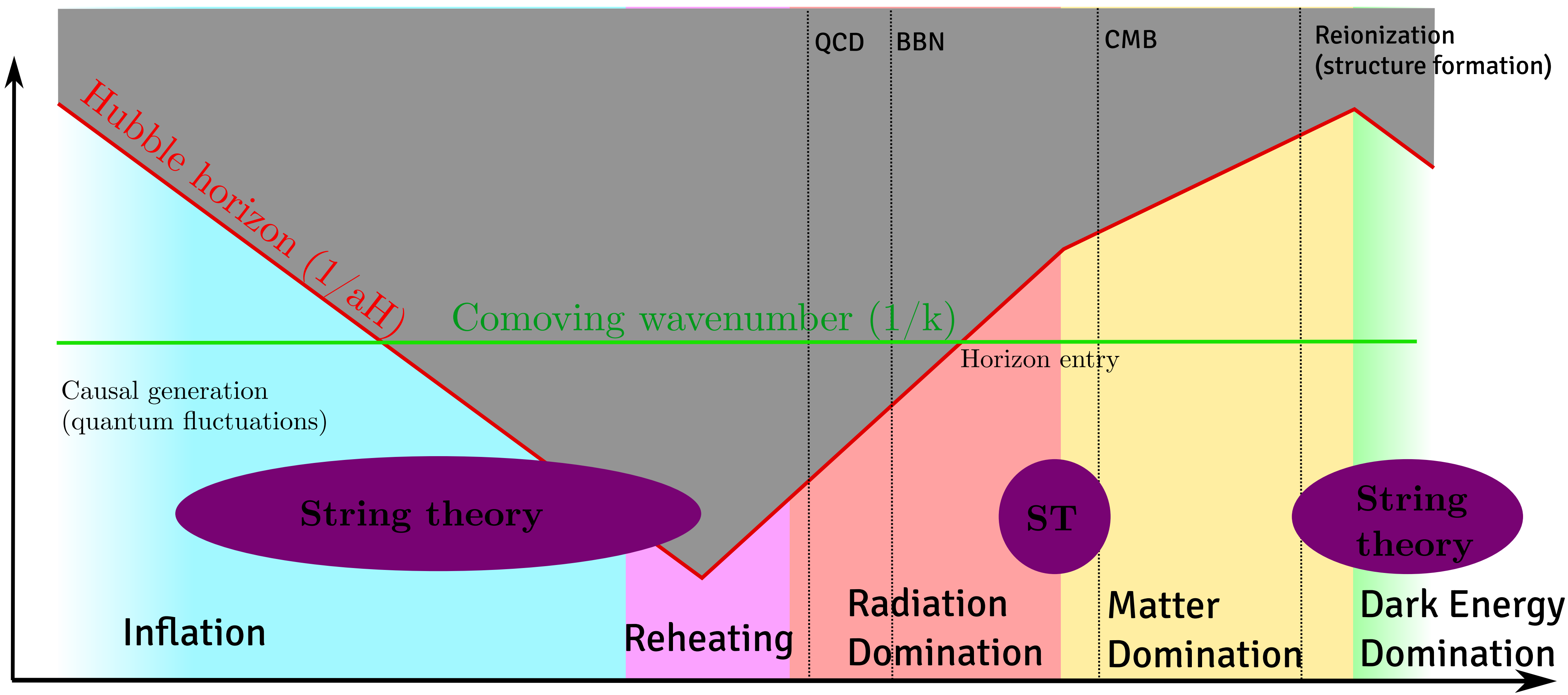

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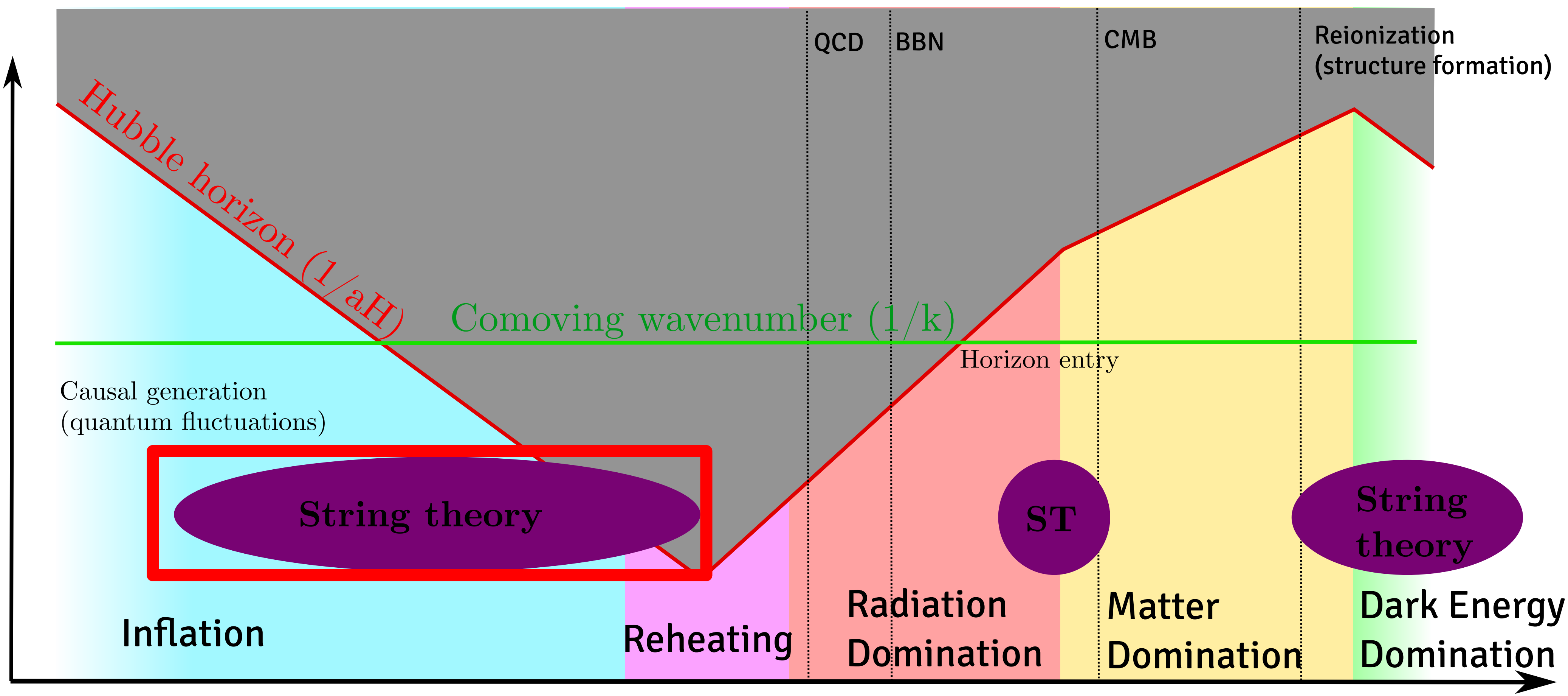

Inflation

- Horizon problem

  → thermal contact before inflation generates isotropy

- Flatness problem

  → inflation expands space, diluting any existing curvature

- Causal perturbations

  → super-horizon perturbations were sourced by sub-horizon quantum fluctuations

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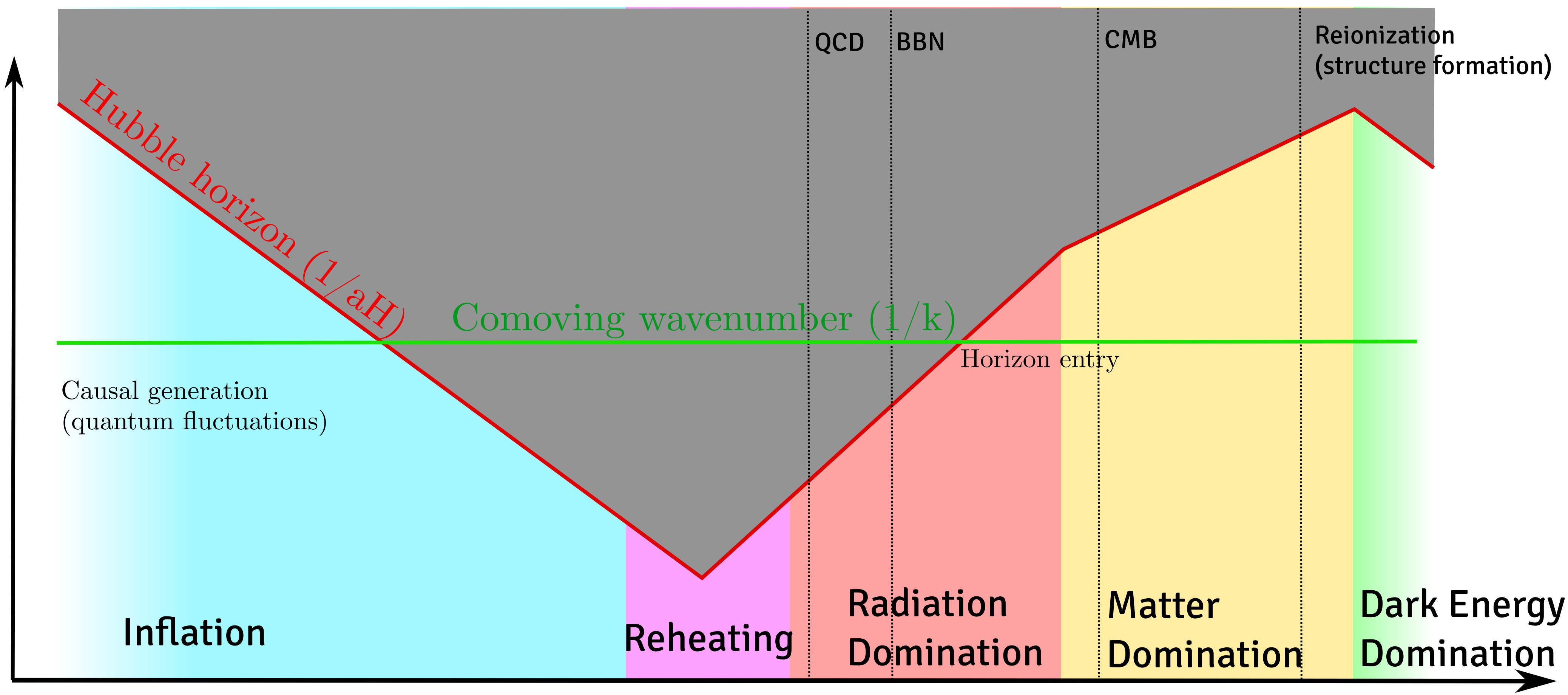

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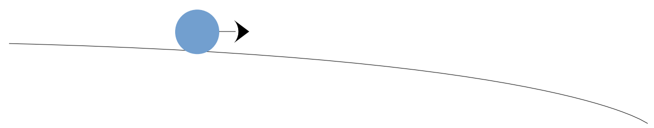
Inflation

Slow roll of scalar field

$$H^2 = \frac{\rho}{3} \approx \frac{1}{3}\left(\frac{\dot{\phi}^2}{2} + V\right) \approx \frac{V}{3}$$



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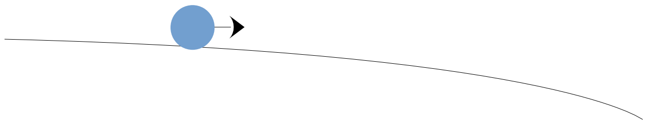

$$\partial_{\ln a}\phi \ll 1$$

$$\partial_\phi V \ll V$$

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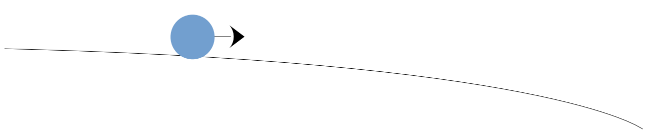

$$\partial_{\ln a}\phi \ll 1$$

$$\partial_\phi V \ll V$$

$$\Rightarrow H^2 \sim V \sim \text{const.}$$

$$\Rightarrow \frac{1}{aH} \propto a^{-1}\text{shrinks}$$

Inflation conditions

- For inflation we need $\partial_\phi V \ll V$
- It needs to last long $\Delta N_{\mathrm{inflation}} \gtrsim \Delta N_{\mathrm{post-inflation}}$

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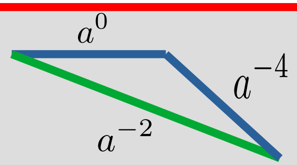

$$\rho_K \propto a^{-2}, \rho_{\rm rest} = \begin{cases} a^0 & \text{inflation} \\ a^{-4} & \text{post} - \text{inflation} \end{cases}$$

$$\frac{1}{aH} = \begin{cases} a^{-1} & \text{inflation} \\ a^{+1} & \text{post} - \text{inflation} \end{cases}$$

$$\Delta N = \Delta \ln a$$

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$\rightarrow$ with $\Delta N_{\mathrm{post-inflation}} = \ln\left(\frac{a_0}{a_{\mathrm{end-infl}}}\right) \approx \ln\left(\frac{T_{\mathrm{end-infl}}}{T_0}\right) \approx \ln\left(\frac{10^{16}\mathrm{GeV}}{0.25\mathrm{meV}}\right) \approx 66$

(more or less, e.g. reheating, different scales)

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- Additional requirement of $\partial_\phi^2 V \ll V$

  $\rightarrow$ Natural result: $|\Delta\phi| \gg 1$

Inflation and strings

- Moduli fields are natural candidates for scalar fields in cosmology

  $\rightarrow$ Can moduli fields do inflation?

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- Moduli fields are natural candidates for scalar fields in cosmology

  → Can moduli fields do inflation?

- Many potentials can be realized in string theory

Inflation and strings

- Moduli fields are natural candidates for scalar fields in cosmology

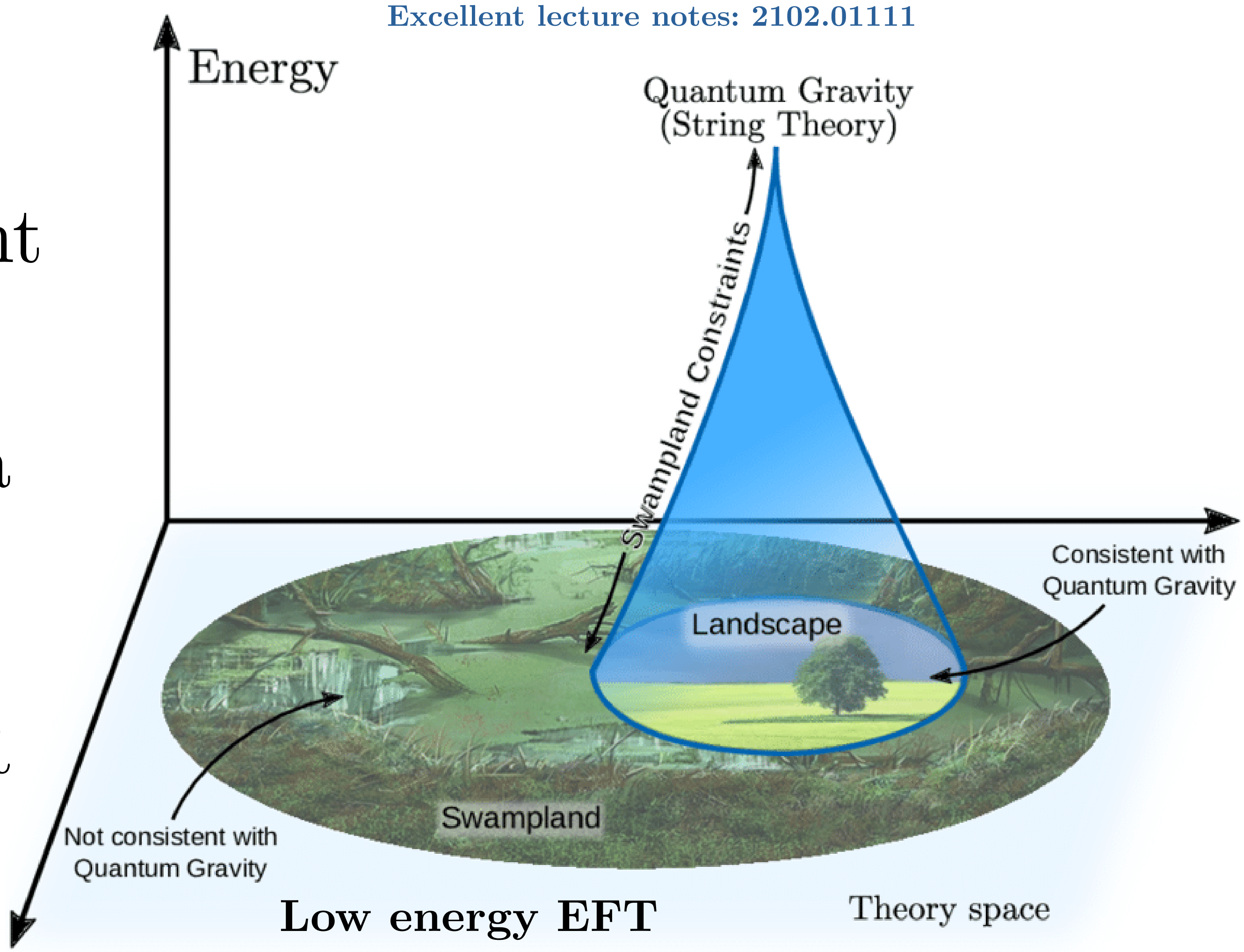
  → Can moduli fields do inflation?

- Many potentials can be realized in string theory
- BUT there might be problems lurking:

  → **Swampland criteria**

Swampland Criteria

- Which EFTs have consistent UV theories?
- Define criteria in UV that need to be kept in the IR



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Swampland Criteria

Excellent lecture notes: 2102.01111

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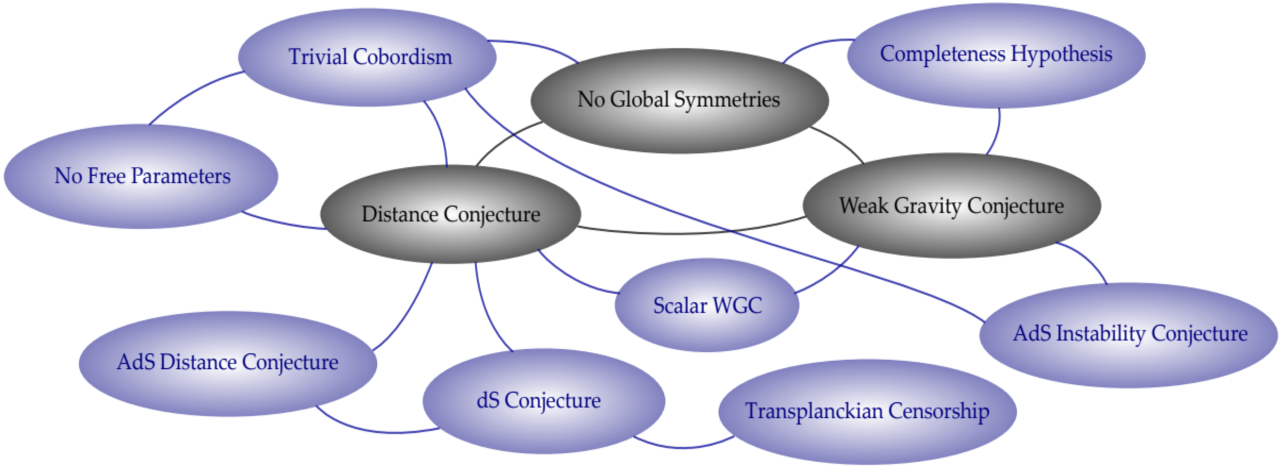

Figure 4: Map of the Swampland conjectures. The conjectures in black are at the core of the Swampland program, and we will discuss them in detail in the following. The conjectures in purple will also be discussed throughout the lectures, but sometimes in less detail.

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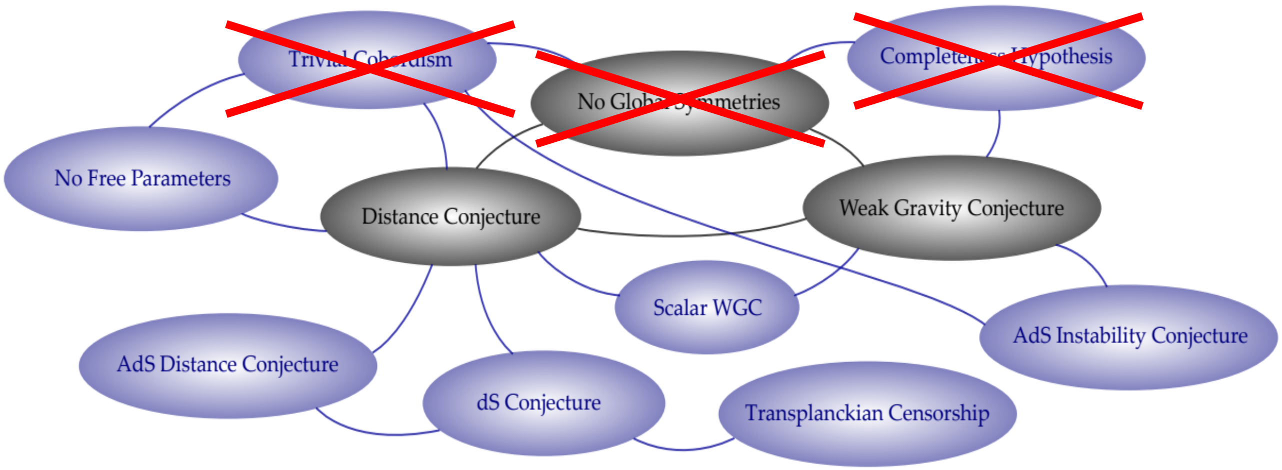
No *direct* cosmology impact



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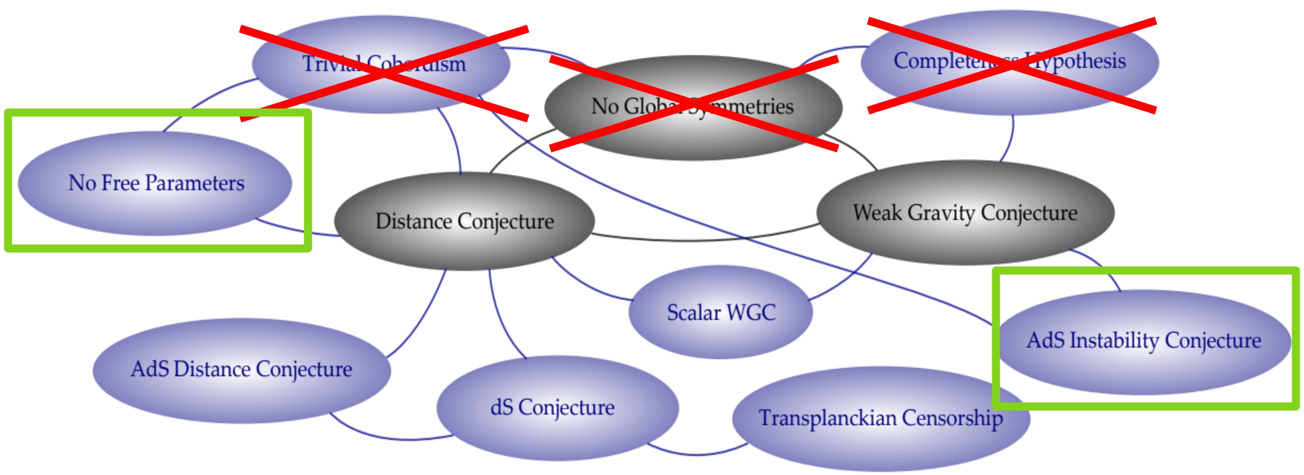

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Boundary conditions

Swampland Criteria

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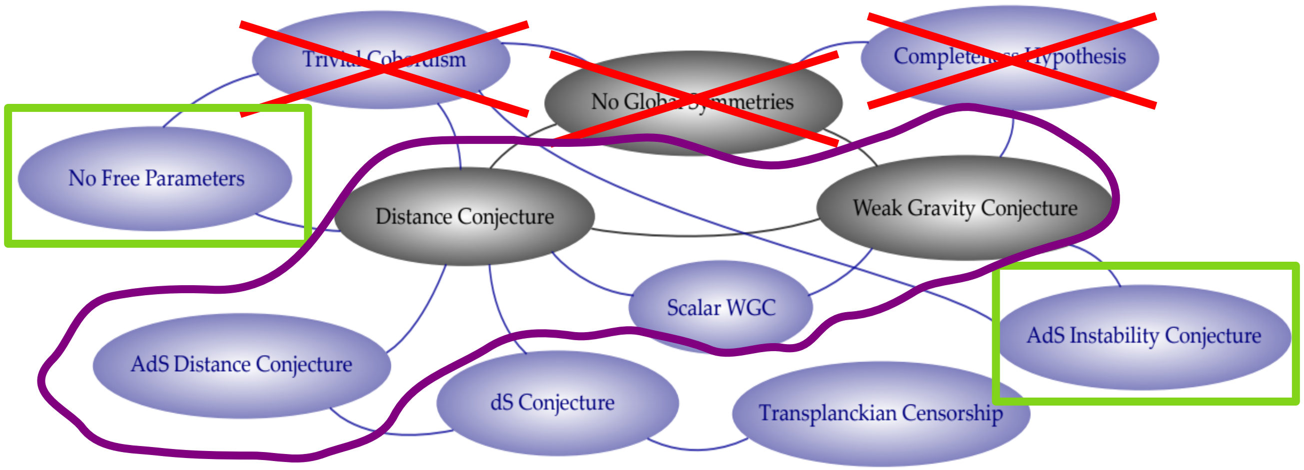

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$$\Delta\phi < \frac{1}{\lambda} \ln\left(\frac{1}{M}\right)$$

Distance conditions

Boundary conditions

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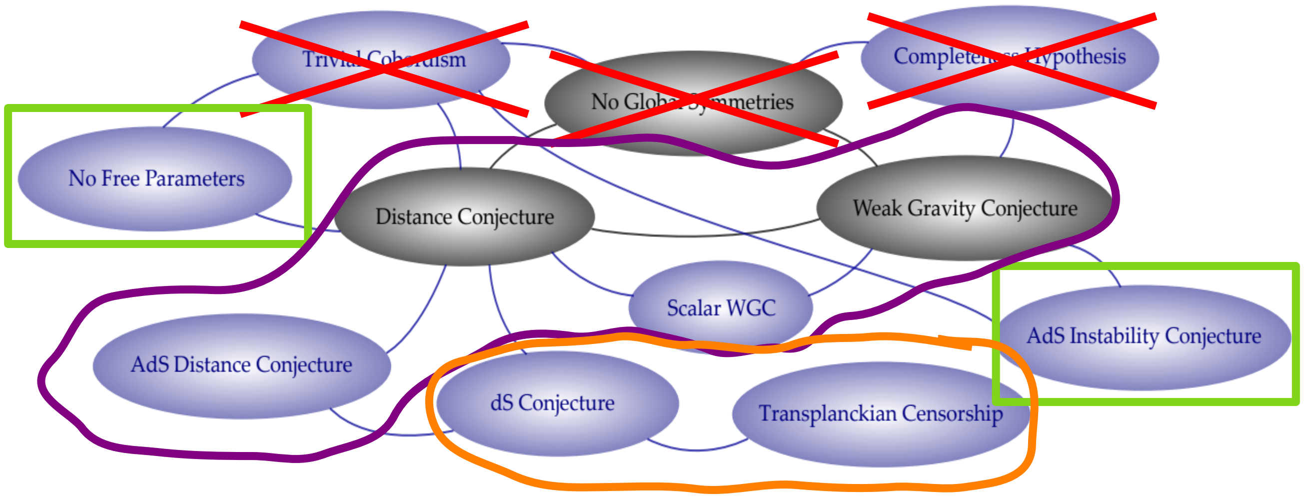

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$$\Delta\phi < \frac{1}{\lambda}\ln\left(\frac{1}{M}\right)$$

Distance conditions

Boundary conditions

Potential conditions

$$\partial_\phi V/V > 1$$

Simplified SWAMPLAND

- Field shall not move too much

$$\Delta\phi < \frac{1}{\lambda} \ln\left(\frac{1}{M}\right) \sim \mathcal{O}(1)$$

- Potential should be curved enough

$$\partial_\phi V/V \gtrsim \mathcal{O}(1)$$

or

$$-\partial_\phi^2 V/V \gtrsim \mathcal{O}(1)$$

Contested!

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Simplified Inflation

- Slow roll requires $\partial_\phi V \ll V$
- Long inflation + slow roll requires $\partial_\phi^2 V \ll V$

  $|\Delta\phi| \gg 1$

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Simplified Inflation

- Slow roll requires $\partial_\phi V \ll V$
- Long inflation + slow roll requires $\partial_\phi^2 V \ll V$
  $|\Delta\phi| \gg 1$

$\Rightarrow$ Obviously in tension!

$$\Delta\phi \lesssim \mathcal{O}(1)$$

$$\partial_\phi V/V \gtrsim \mathcal{O}(1)$$

or

$$-\partial_\phi^2 V/V \gtrsim \mathcal{O}(1)$$

(single-field slow-roll is incompatible)

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What Gives?

- Swampland:
  - Wrong conjectures
  - Wrong application of conjectures to EFT
- Inflation:
  - More complicated models!

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$$\ddot{\phi} + 3H(1+Q)\dot{\phi} + \partial_\phi V = 0$$

e.g. warm inflation: Dissipative equation of motion

Multifield, warm, eternal, natural/Starobinsky, modified gravity, ...

Multifield	Warm	Eternal	Natural/Starobinsky	Modified gravity	...
1807.04390, 1807.05193, 1807.09698, 1808.01615, 2204.13794...	1809.03962, 1108.2166, 1910.06796, 1911.00323, 2001.10042, 2002.04925, 2101.00638, 2209.06153	1807.11938, 1811.11698, 1907.08943, 1912.00749,	1810.06532, 2101.08882	1902.02849, 1902.03939, 1905.05654, 1910.11676, 2105.11935, 2108.01448, 2111.15477, 2207.09793	1809.01277, 1810.04001, 2106.03578, 2002.02941

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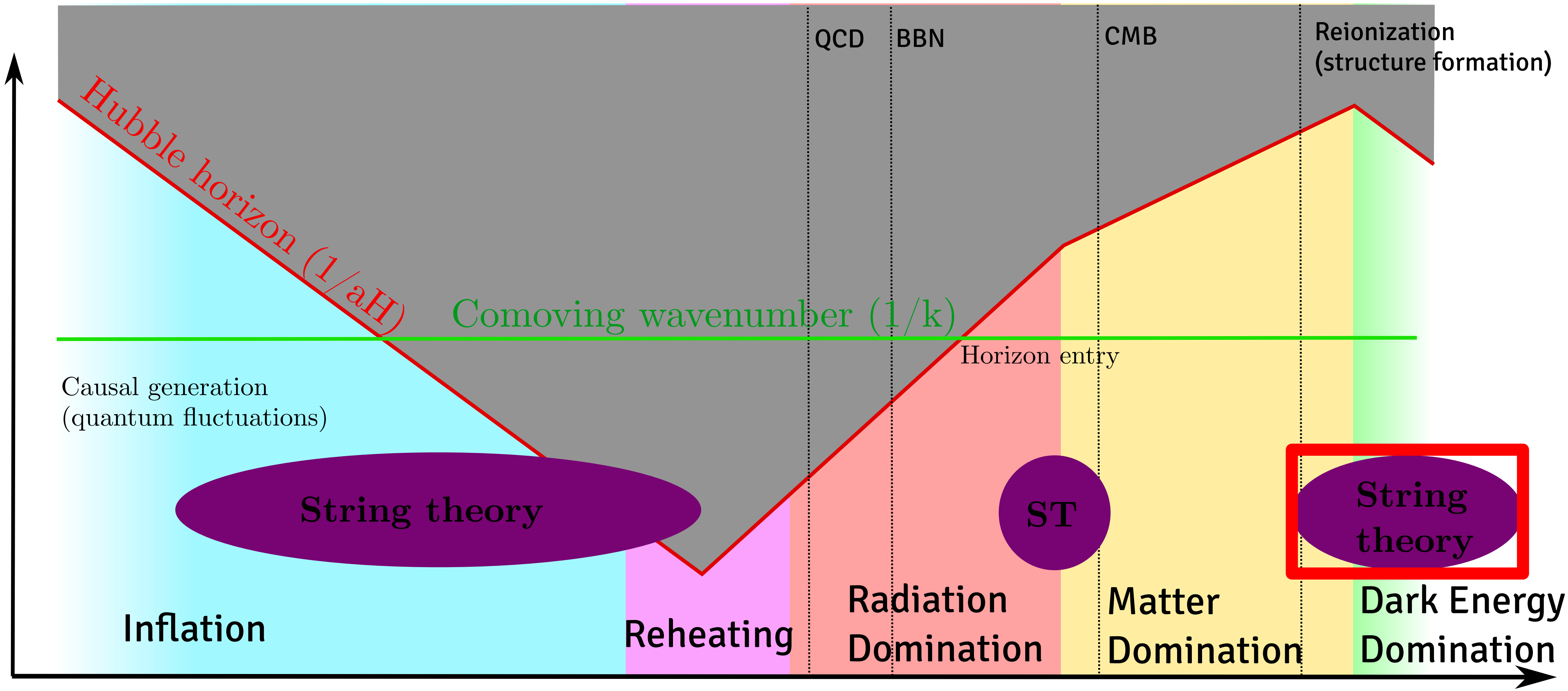
Our cosmic history (so far)



String theory and dark energy

- No constants/no free parameter

  $\rightarrow$ no cosmological constant!

- We need dynamical dark energy!

  $\rightarrow$ Can we realize it?

$\Rightarrow$ Quintessence

News from the Swampland

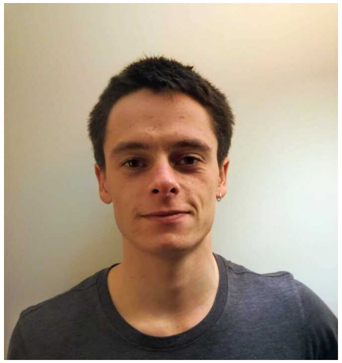
- Nils Schöneberg
- Léo Vacher
- J. D. F. Dias
- Martim M. C. D. Carvalho
- C. J. A. P. Martins

Leo Vacher

Carlos Martins

João Dias

Martim Carvalho



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Quintessence 101

- Scalar field Dark Energy

$$\ddot{\phi} + 3H\dot{\phi} + \partial_\phi V = 0$$
$$\ddot{\delta\phi} + 3H\dot{\delta\phi} + \dot{h}\dot{\phi}/2 + [k^2/a^2 + \partial_\phi^2 V]\delta\phi = 0$$

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$$\delta\ddot{\phi} + 3H\delta\dot{\phi} + \dot{h}\dot{\phi}/2 + [k^2/a^2 + \partial_\phi^2 V]\delta\phi = 0$$

$$\ddot{a} = -\frac{1}{2}aH^2(1+3w_{\mathrm{eff}}) > 0$$

$$w_{\mathrm{eff}} = f_\phi w_\phi + (1-f_\phi)w_{\mathrm{rest}} \approx f_\phi w_\phi < -\frac{1}{3}$$

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$$\frac{1}{2}\dot{\phi}^2 < V$$

Similar to SR, but less restrictive

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Quintessence 101

- Scalar field Dark Energy

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Dynamical system analysis
(is it at all possible?)

$$x = \frac{\dot{\phi}}{\sqrt{6}H} \quad y = \frac{\sqrt{V}}{\sqrt{3}H} \quad f_\phi = x^2 + y^2$$

$$\partial_{\ln a} x = -3x + \frac{\sqrt{6}}{2} L y^2 - x \frac{d \ln H}{d \ln a}$$
$$\partial_{\ln a} y = -\frac{\sqrt{6}}{2} L x y - y \frac{d \ln H}{d \ln a}$$

$$L = -\partial_\phi V / V$$

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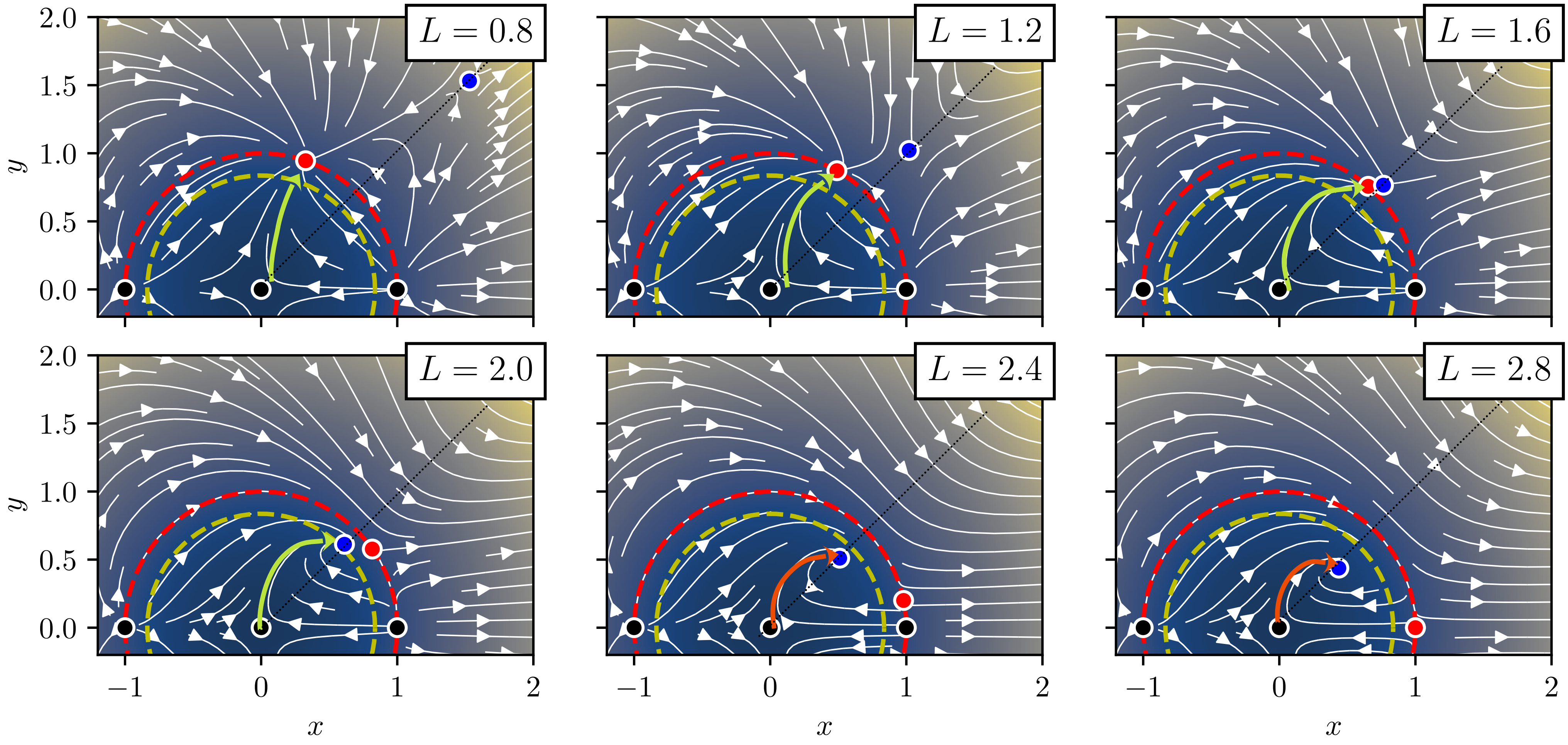
Dynamical System Analysis



Red circle = dark energy domination

Yellow circle = current observed accel.

Points = critical points

Dynamical System analysis

- Location of blue attractor:

$$x^2 + y^2 = 3/L^2 \overset{!}{=} (1 - \Omega_m) \approx 0.7$$

- Corresponding bound on potential:

$$L = -\partial_\phi V/V \leq 2.1$$

BUT: No need to last long, so maybe $\begin{array}{c} |\Delta\phi| \ll 1 \\ -\partial_\phi^2 V \gg V \end{array}$ are fine

Quintessence and Swampland

- The equation for L:

$$\frac{\mathrm{d}L}{\mathrm{d}\ln a} = \sqrt{6}x(L^2 + g) \qquad g = -\partial_\phi^2 V/V$$

Quintessence and Swampland

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$$\frac{\mathrm{d}L}{\mathrm{d}\ln a} = \sqrt{6}x(L^2 + g) \qquad g = -\partial_\phi^2 V/V$$

$\Rightarrow$ For large g, we have strong acceleration of L (either positive or negative) ✗

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$$\Delta\phi = \int \frac{\mathrm{d}\phi}{\mathrm{d}t}\mathrm{d}t = \sqrt{6}\int x \mathrm{d}\ln a \sim 1.2 \Delta \ln a \sim 0.3$$ ✓

$$x \sim 0.5$$

From Theory to Practice

- Let's investigate a few models and see what's happening!

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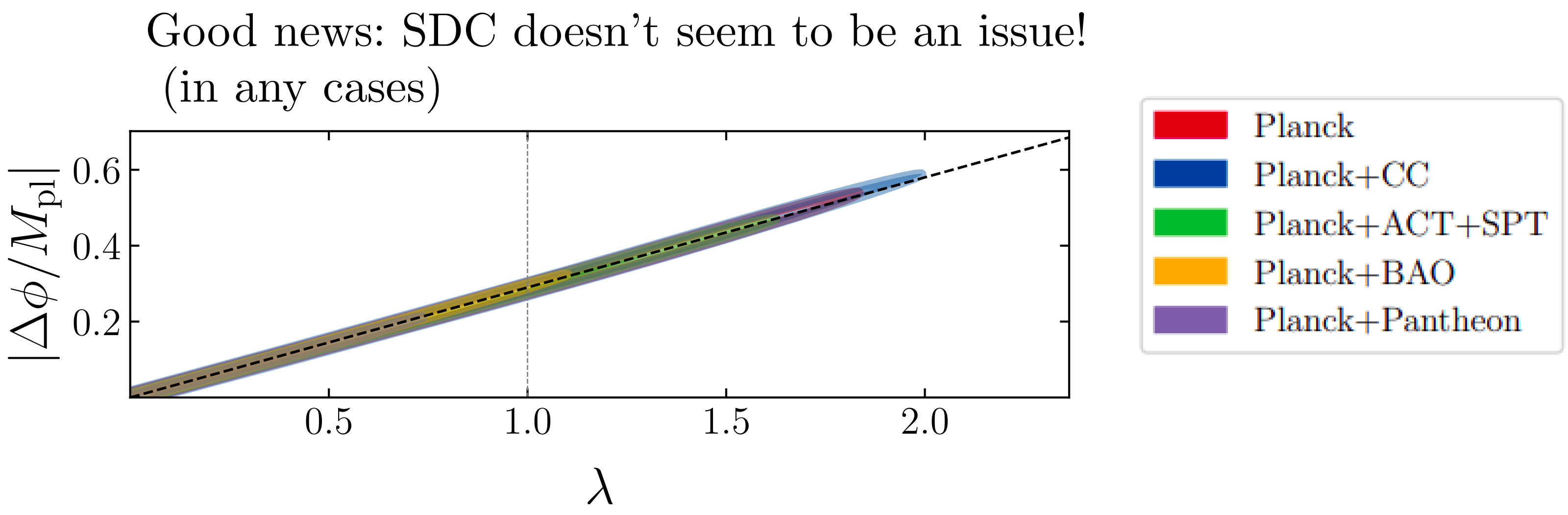
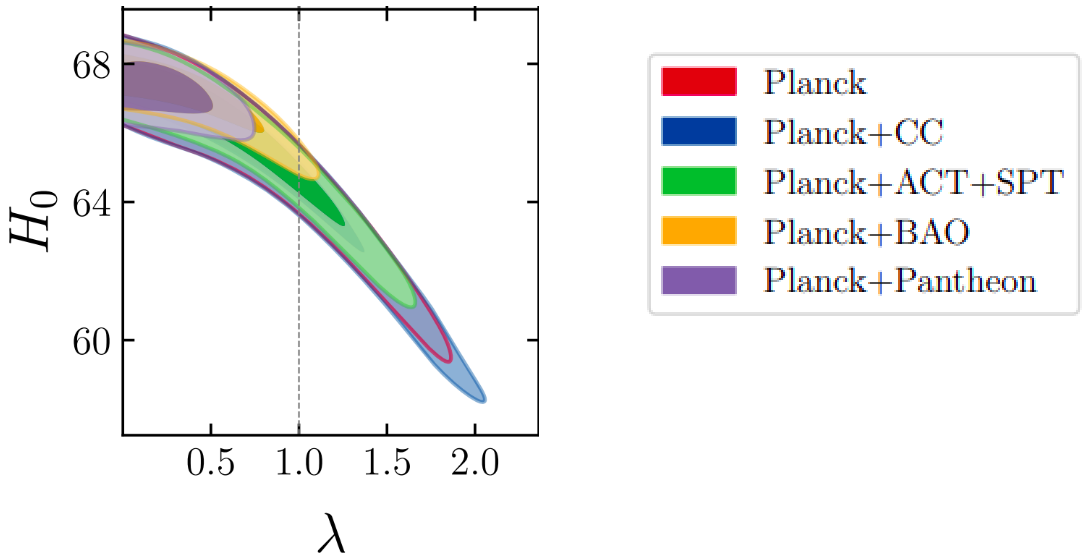


From Theory to Practice

- Exponential:

$$V(\phi) = V_0 \exp(-\lambda\phi)$$



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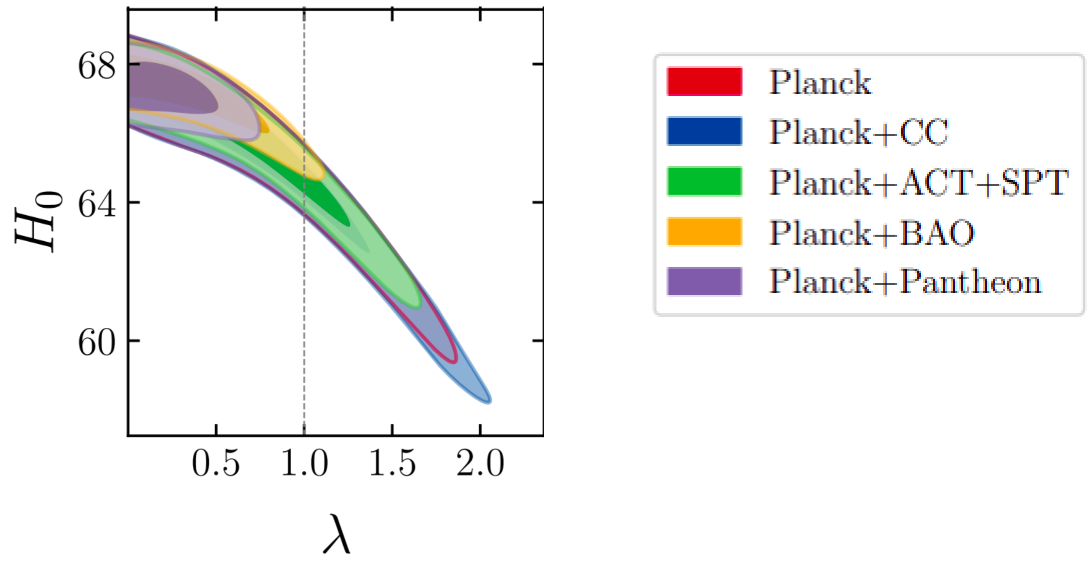

- Swampland very much in tension with observations! $\lambda = |\partial_\phi V/V| \gg 1$ ✗

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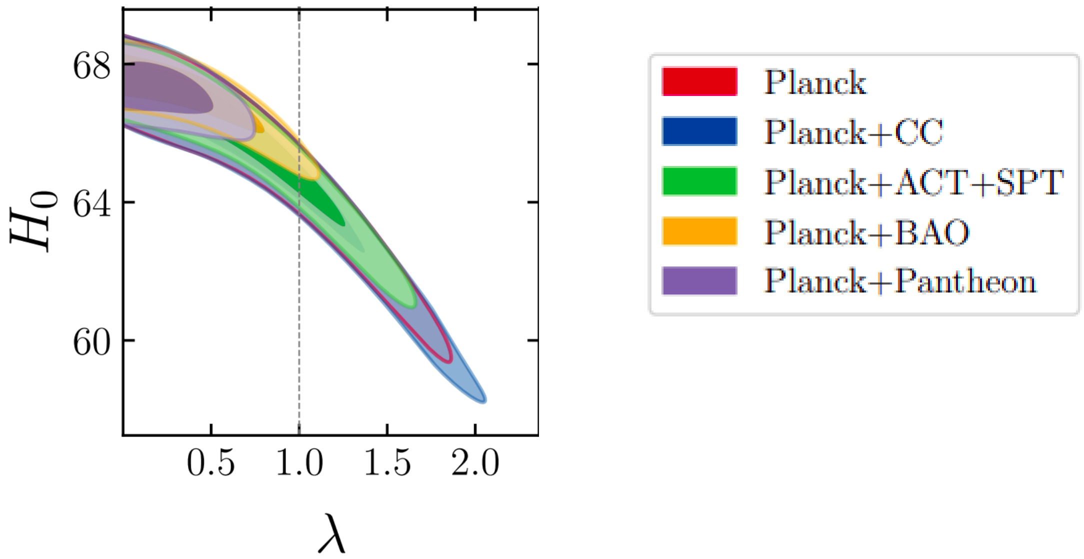

- Swampland very much in tension with observations! $\lambda = |\partial_\phi V/V| \gg 1$ ✗

$$P(\lambda > 1) \approx \begin{cases} 24\% & \text{Planck} \\ 0.24\% & \text{Planck + Pantheon+} \\ < 0.001\% & \text{Planck + Pantheon} \\ < 0.001\% & \text{Planck+H}_0 \end{cases}$$

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From Theory to Practice

- Constant $L = -\partial_\phi V/V$ does not work...

$\Rightarrow$ Maybe if we use other criterion!

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- Try large second criterion:

$$V(\phi) = A\cos(c\phi) \qquad -\partial_\phi^2 V/V = c^2 \gg 1$$

From Theory to Practice

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  $\Rightarrow$ Maybe if we use other criterion!
- Try large second criterion:

$$V(\phi) = A\cos(c\phi) \qquad -\partial_\phi^2 V/V = c^2 \gg 1$$

We even get for free: $|\partial_\phi V/V| = c\tanh(c\phi) \to \infty \quad \text{for} \quad c\phi \to \frac{\pi}{2}$

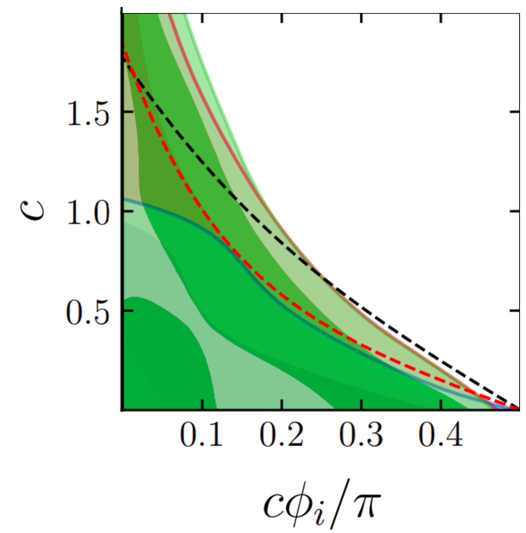
From Theory to Practice

- Cosine potential:

$$V(\phi) = A\cos(c\phi)$$

$$-\partial_\phi^2 V/V = c^2 \gg 1$$

$$|\partial_\phi V/V| = c\tan(c\phi) \to \infty \quad \text{for} \quad c\phi \to \frac{\pi}{2}$$



- Conclusions:

From Theory to Practice

- Cosine potential:

$V(\phi) = A\cos(c\phi)$

$-\partial_\phi^2 V/V = c^2 \gg 1$

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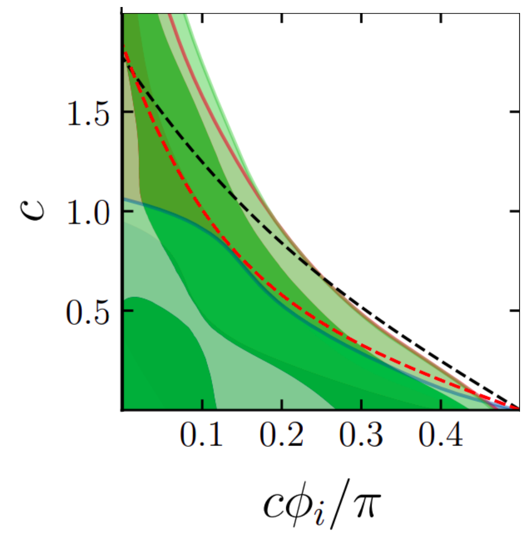

- Conclusions:
  - $c > 1$ is possible! (though disfavored by large H_0)

From Theory to Practice

- Cosine potential:

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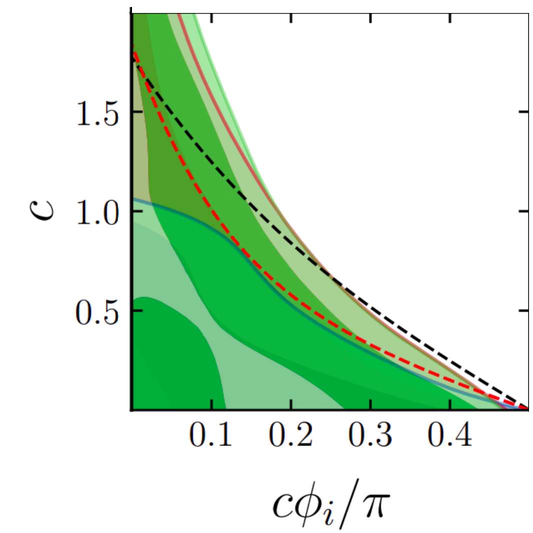

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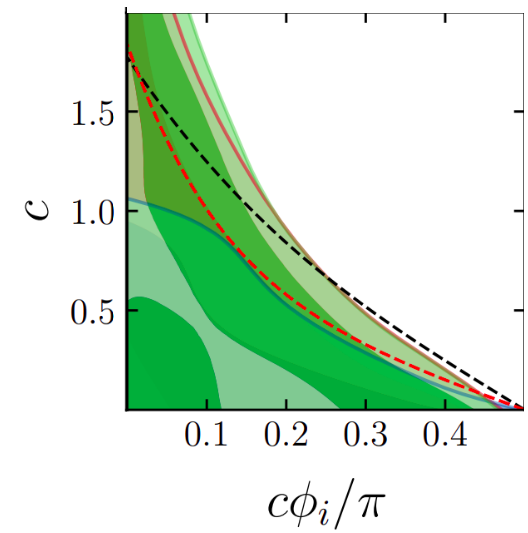

- Conclusions:
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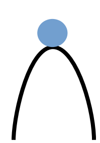
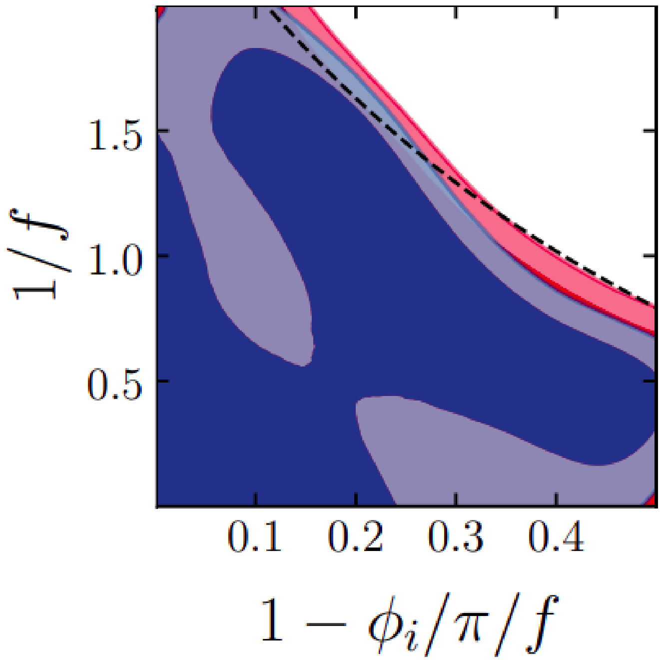
  - Fine tuning  (but only very mildly!)

Other possibilities

- Axionic potential $V(\phi) = m^2 f^2 [1 - \cos(\phi/f)]$
  - Similar to cosine potential, just more permissive



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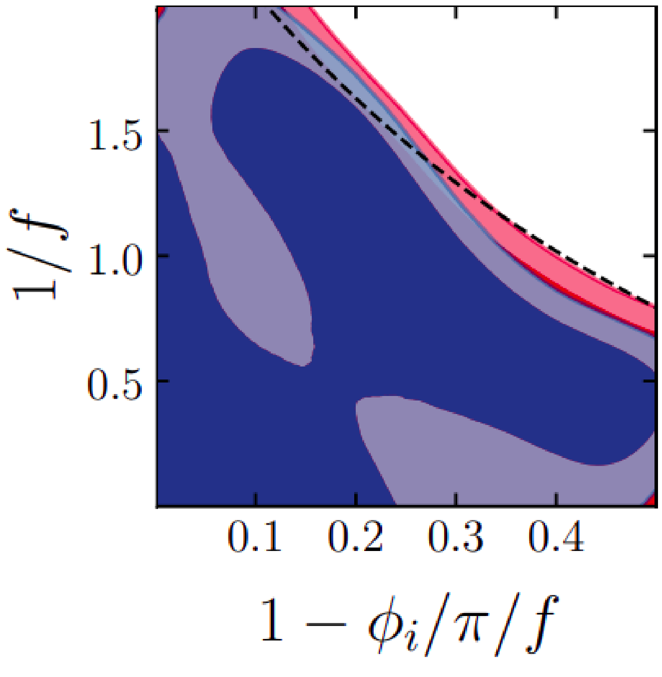
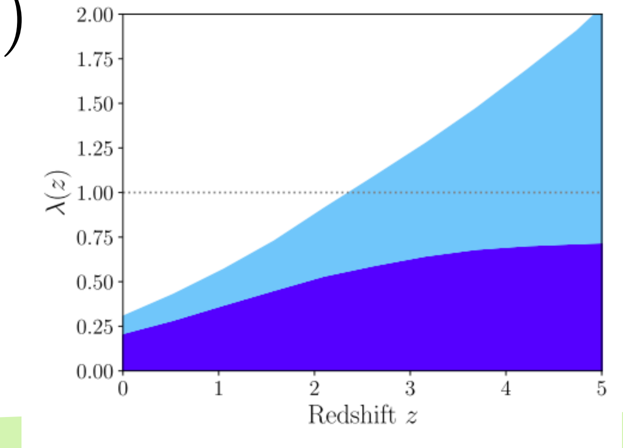


- Inverse exponential

$V(\phi) = A\exp(\sigma/\phi)$

  - Not great



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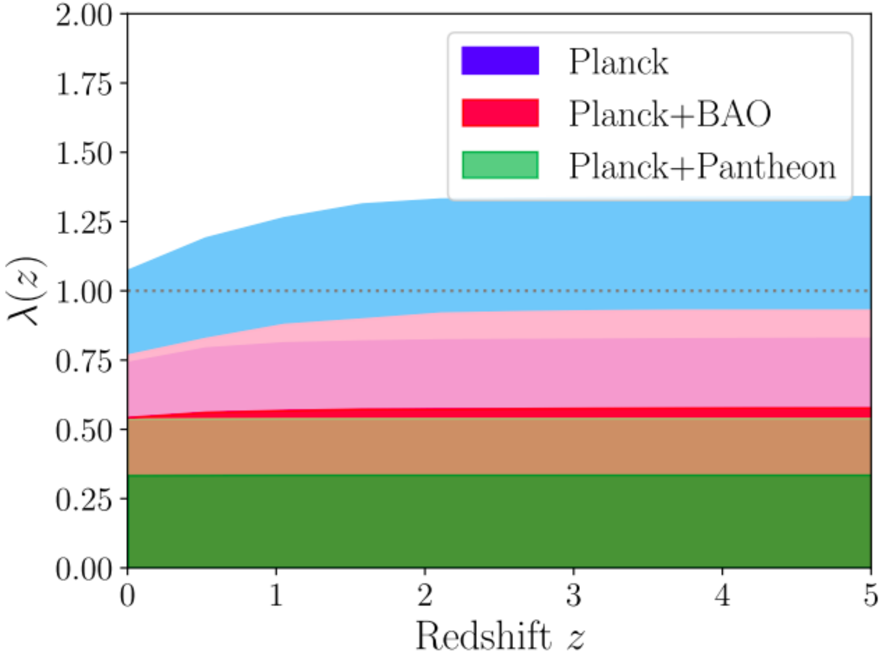
Other possibilities

- Double exponential:

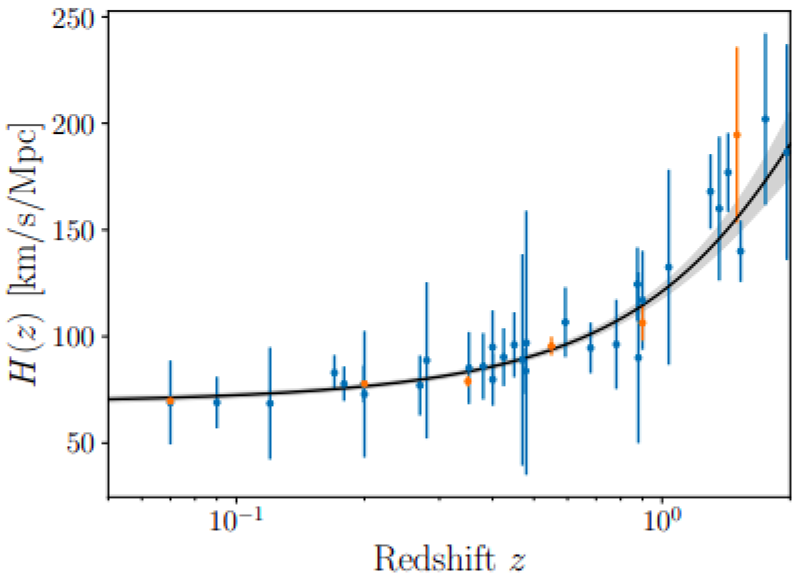
$$V(\phi) = A[\exp(\lambda\phi) + r\exp(\kappa\phi)]$$

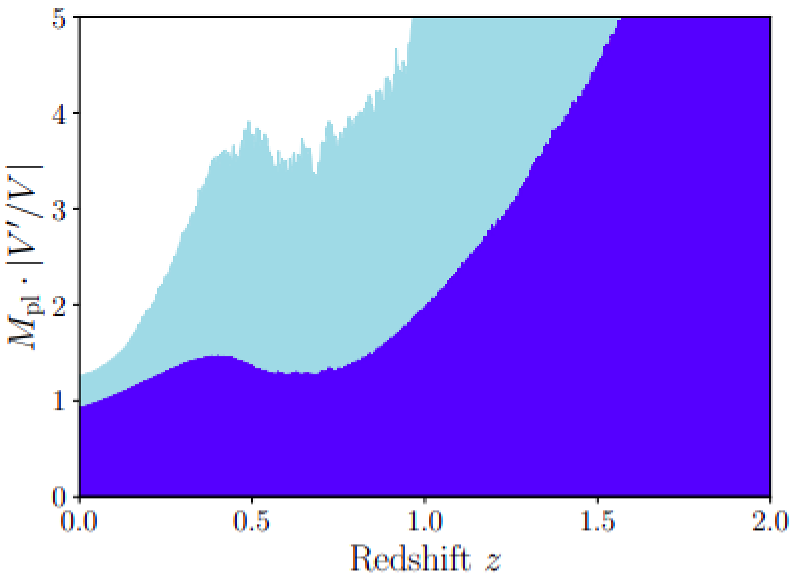
  - Basically the same as exponential case



Can we do better?

- Model-independent construction, right?!
  (e.g. cosmic chronometers + BAO)





Devil in the Detail

- Have to convert

$$\text{Data} \to H(z) \to H(z), H'(z) \to \rho_\phi, \mathrm{d}\rho_\phi/\mathrm{d}z \to \dot{\phi}, V(z) \to V, \partial_\phi V \to \lambda = |\partial_\phi V/V|$$

Except for CC, The data require other cosmo params to convert to H(z), e.g. r_s or H_0

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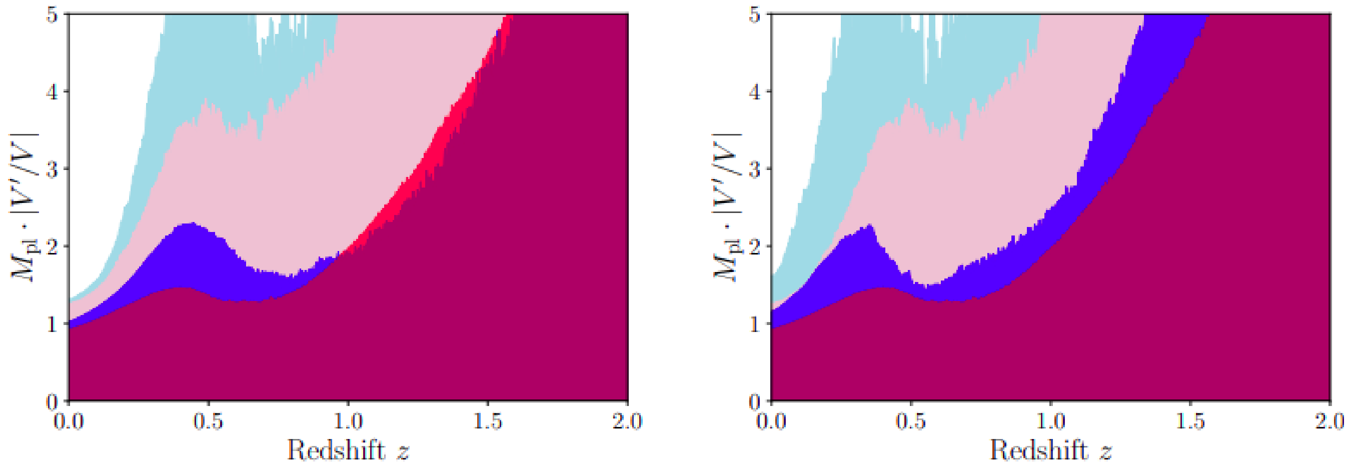

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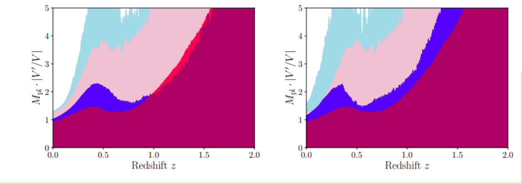

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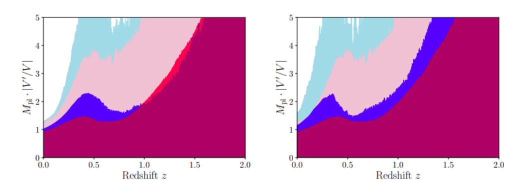

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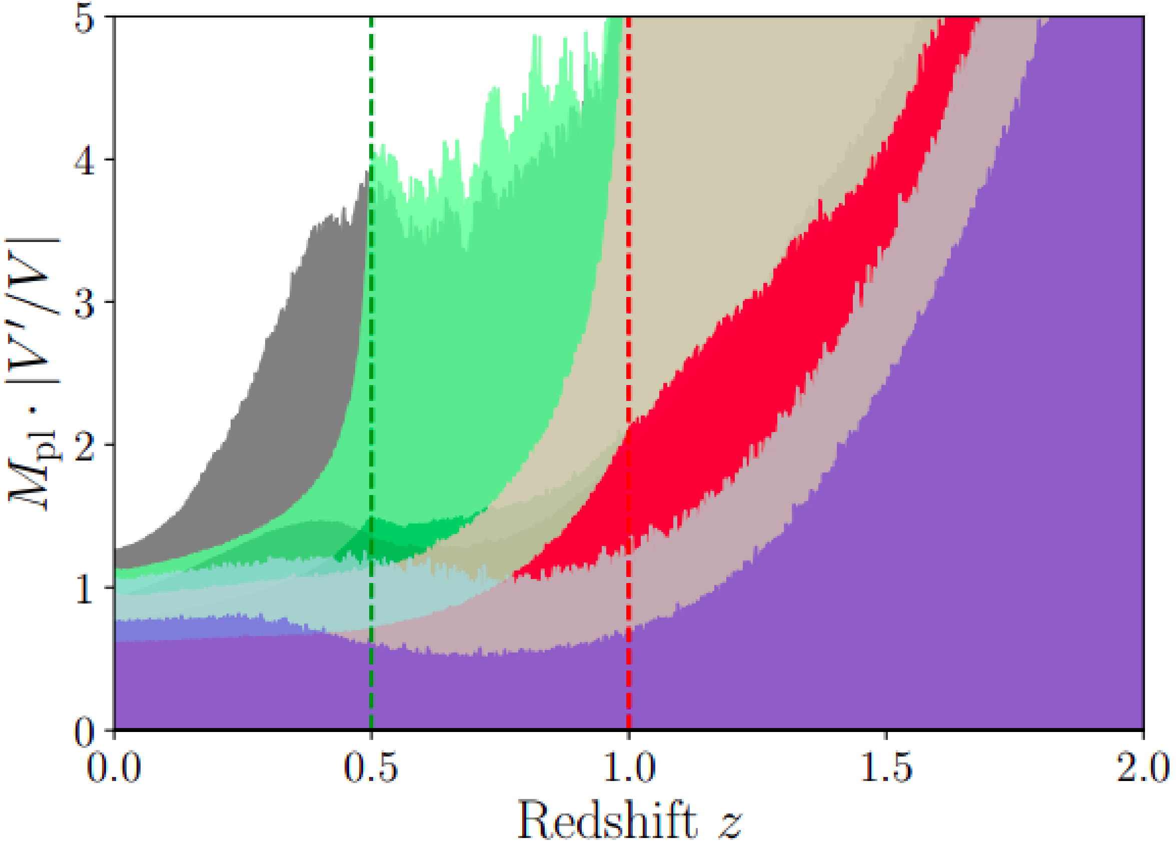

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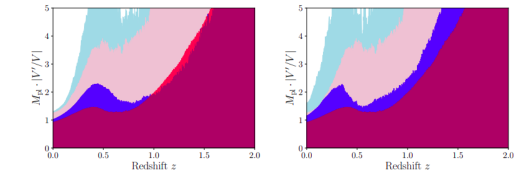

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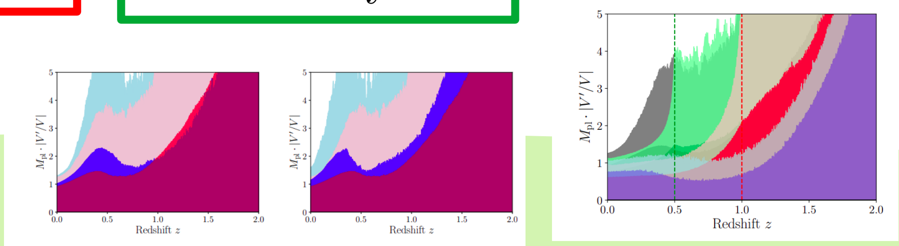

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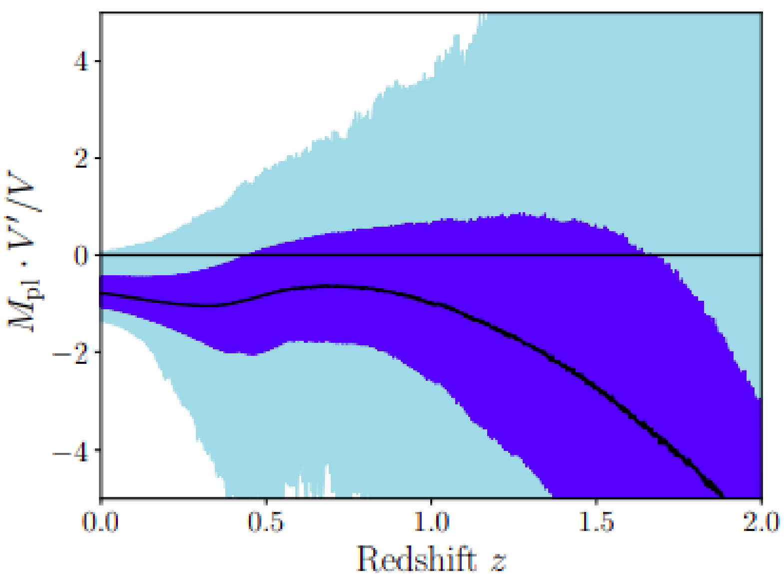

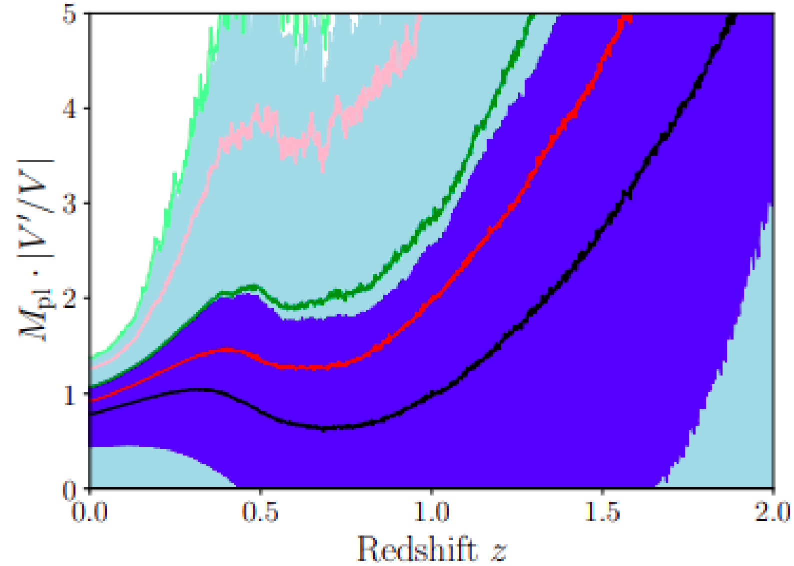

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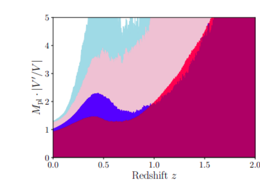

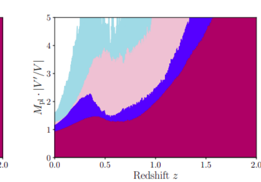

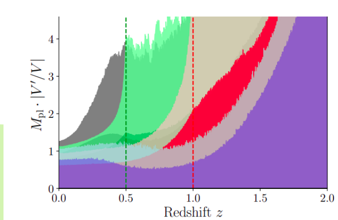

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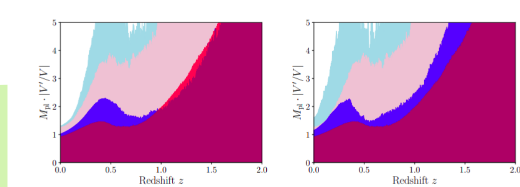

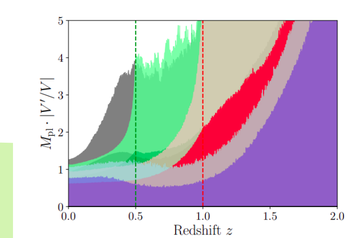

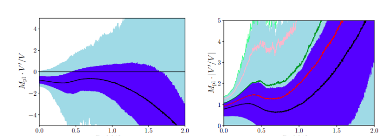

Final Nail

- Any modulus field could in principle interact with SM fields through coupling ζ

$$\Delta\alpha/\alpha_0 = \zeta\Delta\phi$$

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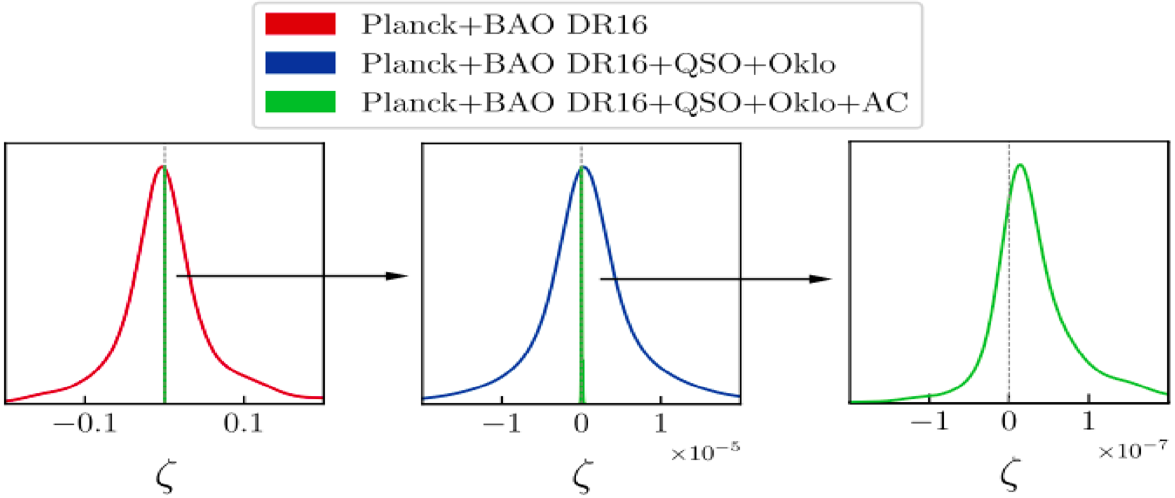

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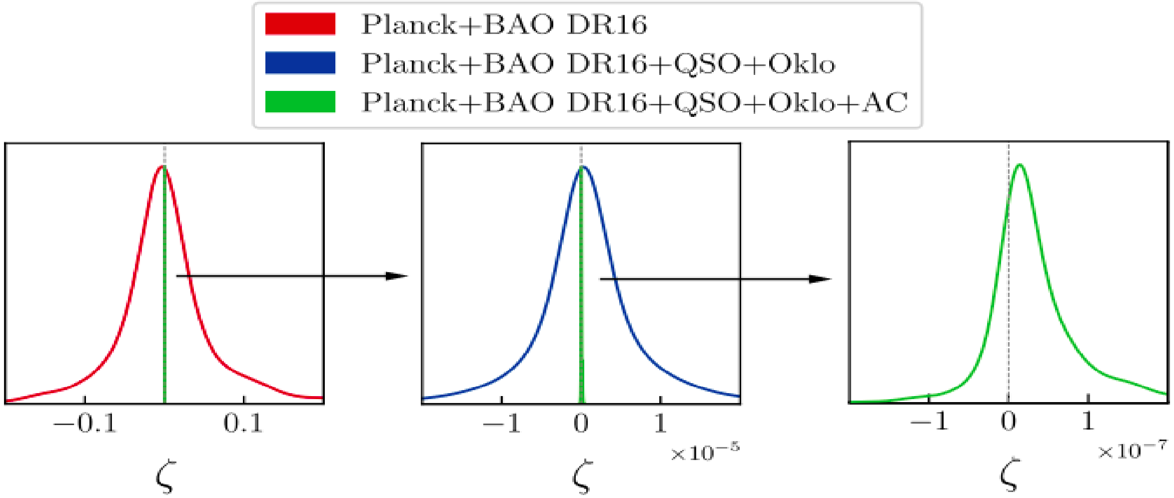

As such, almost any natural order coupling of the quintessence with electromagnetic fields expected from most unified theories has to face either the large hurdle of constructing a theoretical reason to effectively forbid such a coupling or has to face problems of extreme fine-tuning.

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Quintessence Takeaways

- Typically the potential needs to be locally flat to agree with observations $\partial_\phi V \ll V$

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- Additional fine-tuning argument if no reason to prevent coupling to EM fields
- Be careful about model-independent reconstructions

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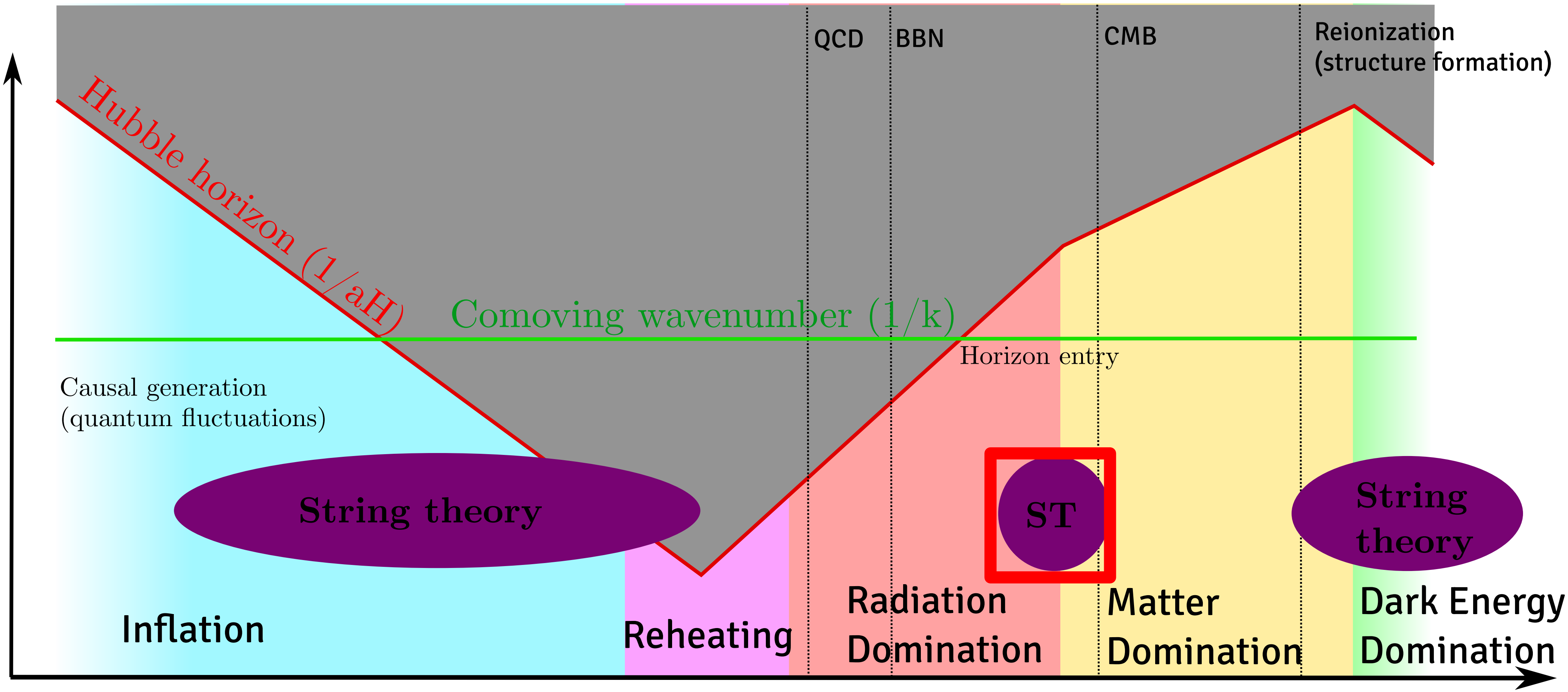
Our cosmic history (so far)



Things I did not touch upon

- Hubble tension in cosmology:
  - Local data measuring high $H_0 \sim 73\text{km/s/Mpc}$
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- Model solutions involve recombination-time dynamics
  - Early dark energy can be motivated with a string-motivated axionic potential

Summary

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  $\rightarrow$ modified inflationary models can come to the rescue

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  $\rightarrow$ modified inflationary models can come to the rescue

- Dynamical dark energy is in peril from swampland criteria

  $\rightarrow$ currently no better solution than to put DE on an unstable maximum