TRANS-PLANCKIAN CENSORSHIP AND *K*-INFLATION

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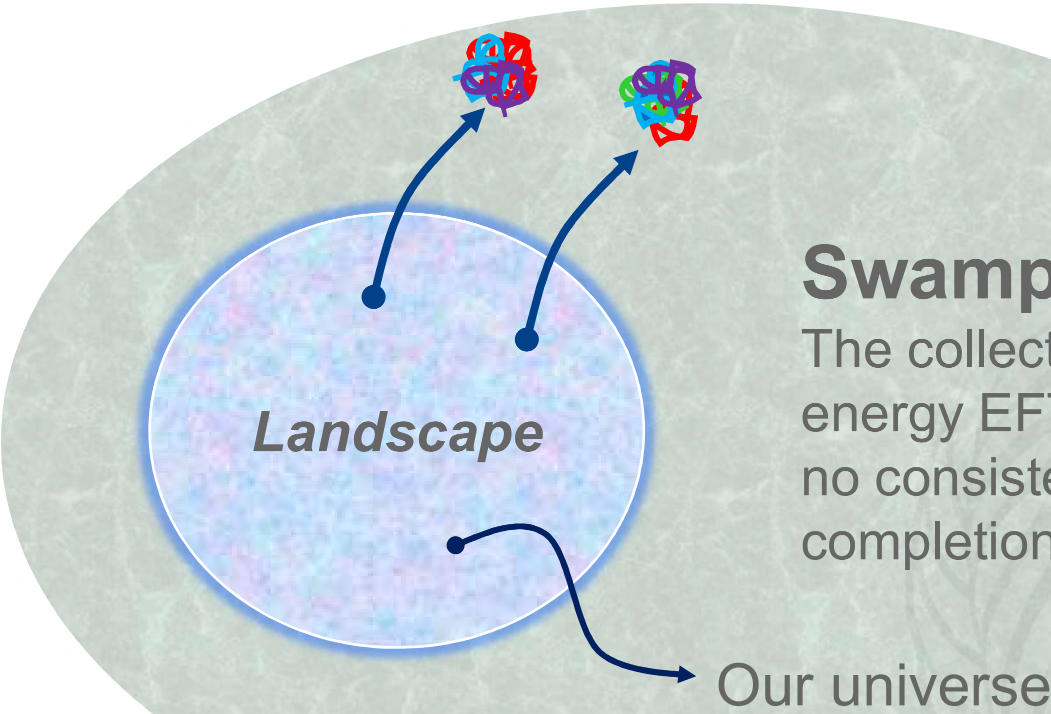
Swampland Conjectures



Swampland:
The collection of low energy EFTs having no consistent UV completion.

Distance conjecture: there is an upper bound on the range traversed by scalar fields in field space

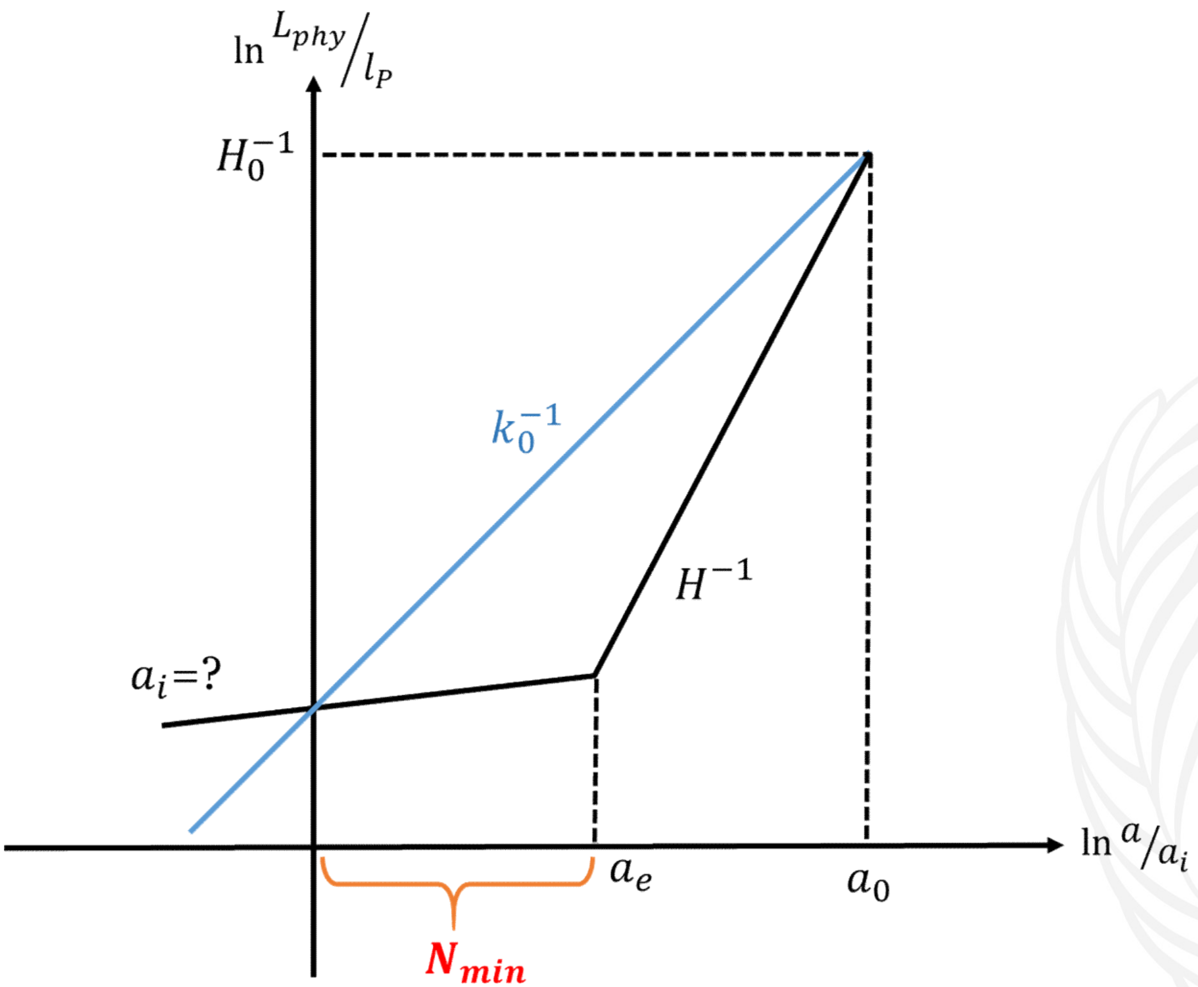
$$\frac{|\Delta\phi|}{M_P} \lesssim \Delta \sim \mathcal{O}(1)$$

Refined de Sitter Conjecture: the potential $V(\phi)$ for scalar fields in a low energy effective theory of any consistent quantum gravity must satisfy either

$$|\nabla V| \geq \frac{c}{M_p} \cdot V \qquad \text{or} \qquad \min\left(\nabla_i \nabla_j V\right) \leq -\frac{c'}{M_p^2} \cdot V$$

[1]C. Vafa, (2005), arXiv:hep-th/0509212 [hep-th].
[2]G. Obied, H. Ooguri, L. Spodyneiko, and C. Vafa, (2018), arXiv:1806.08362 [hep-th].
[3]P. Agrawal, G. Obied, P. J. Steinhardt, and C. Vafa, Phys. Lett. B784, 271 (2018), arXiv:1806.09718 [hep-th].
[4] S. K. Garg and C. Krishnan, (2018), arXiv:1807.05193 [hep-th].
[5] H. Ooguri, E. Palti, G. Shiu, and C. Vafa, (2018), arXiv:1810.05506 [hep-th].

Trans-Planckian problem*



* Some references are listed on the last slide.

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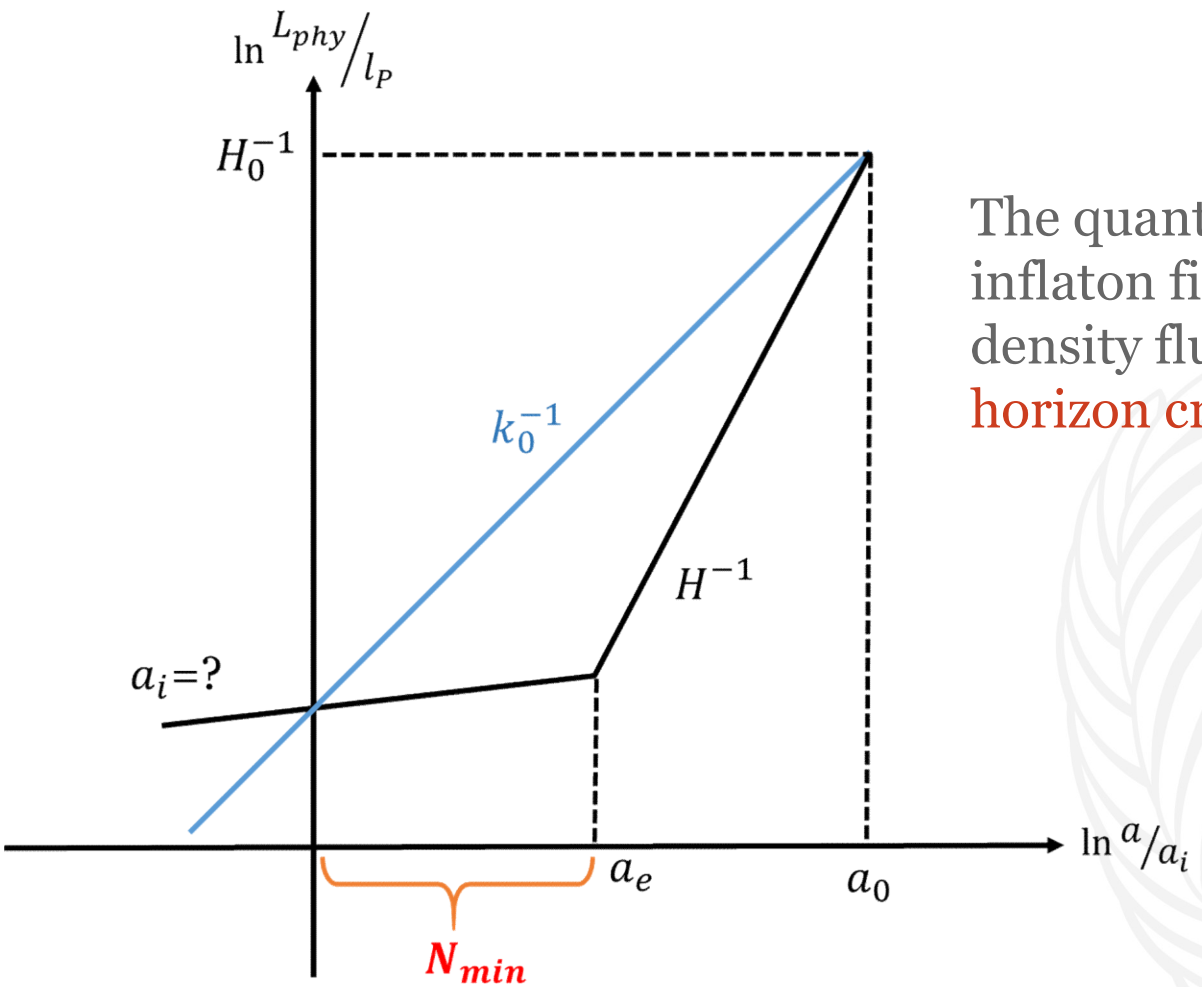

The quantum fluctuations of the inflaton field become classical density fluctuations by the horizon crossing mechanism.

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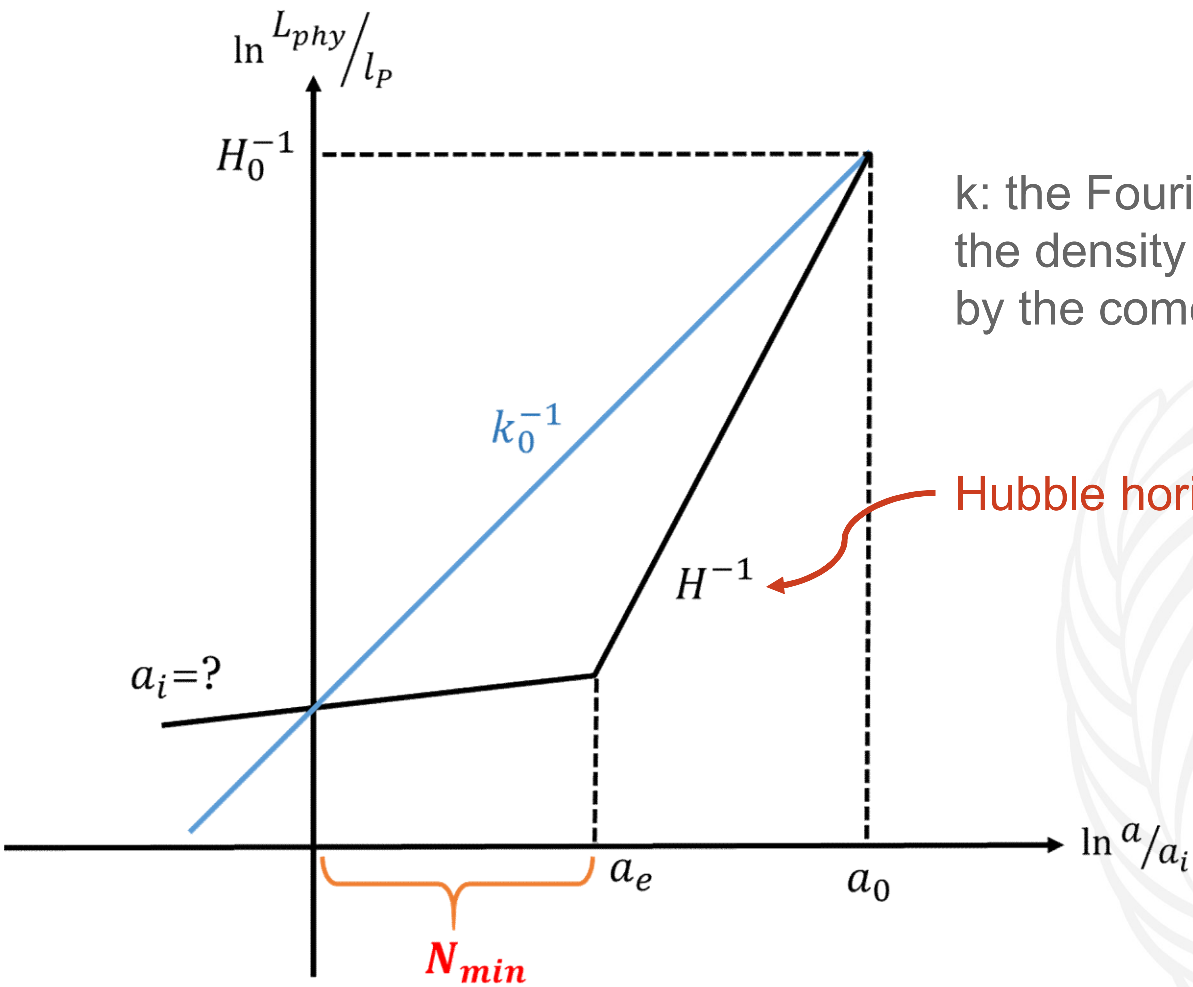
Trans-Planckian problem*



k: the Fourier transformation of the density fluctuations specified by the comoving wavenumber

Hubble horizon (radius)

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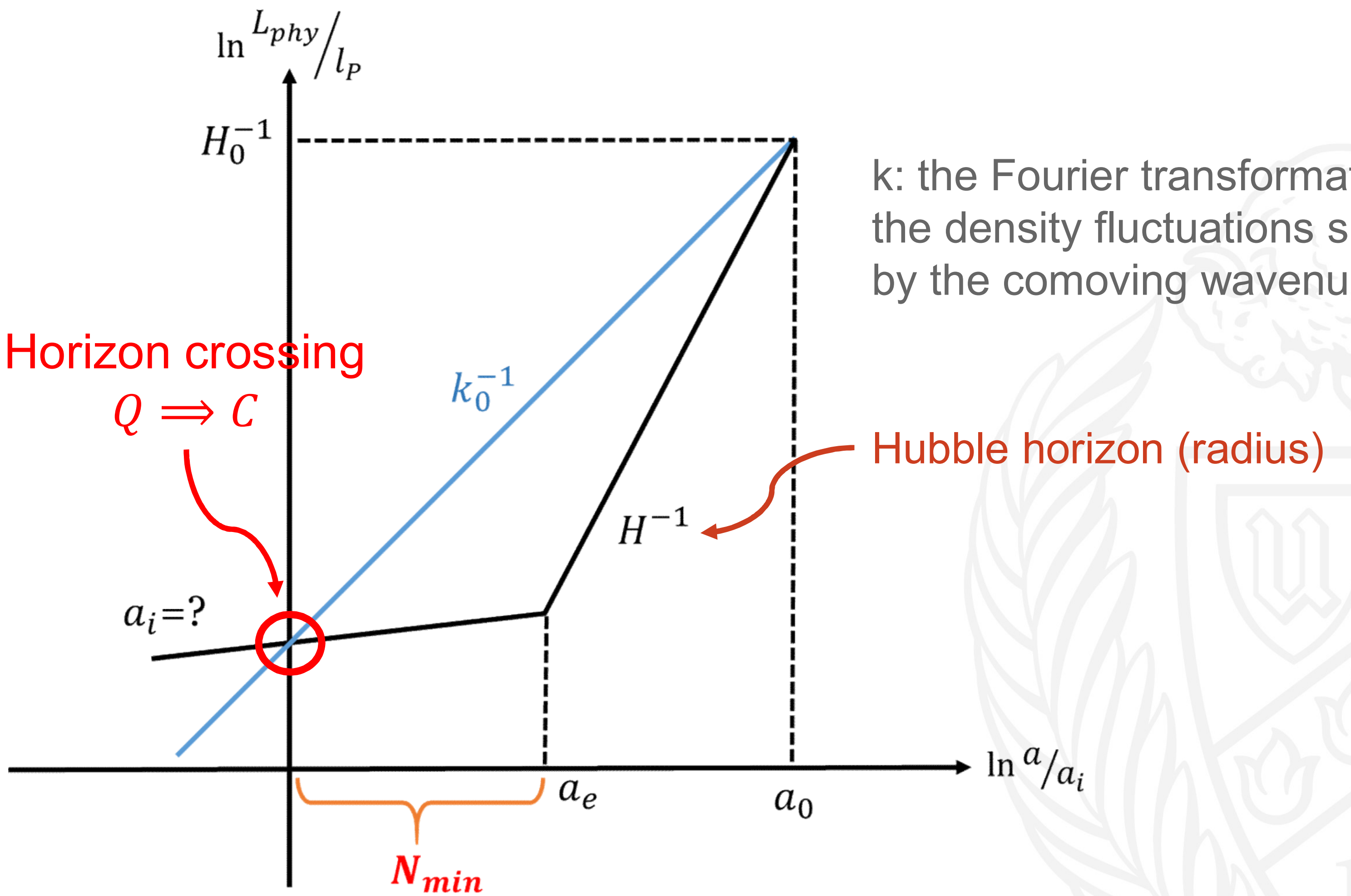

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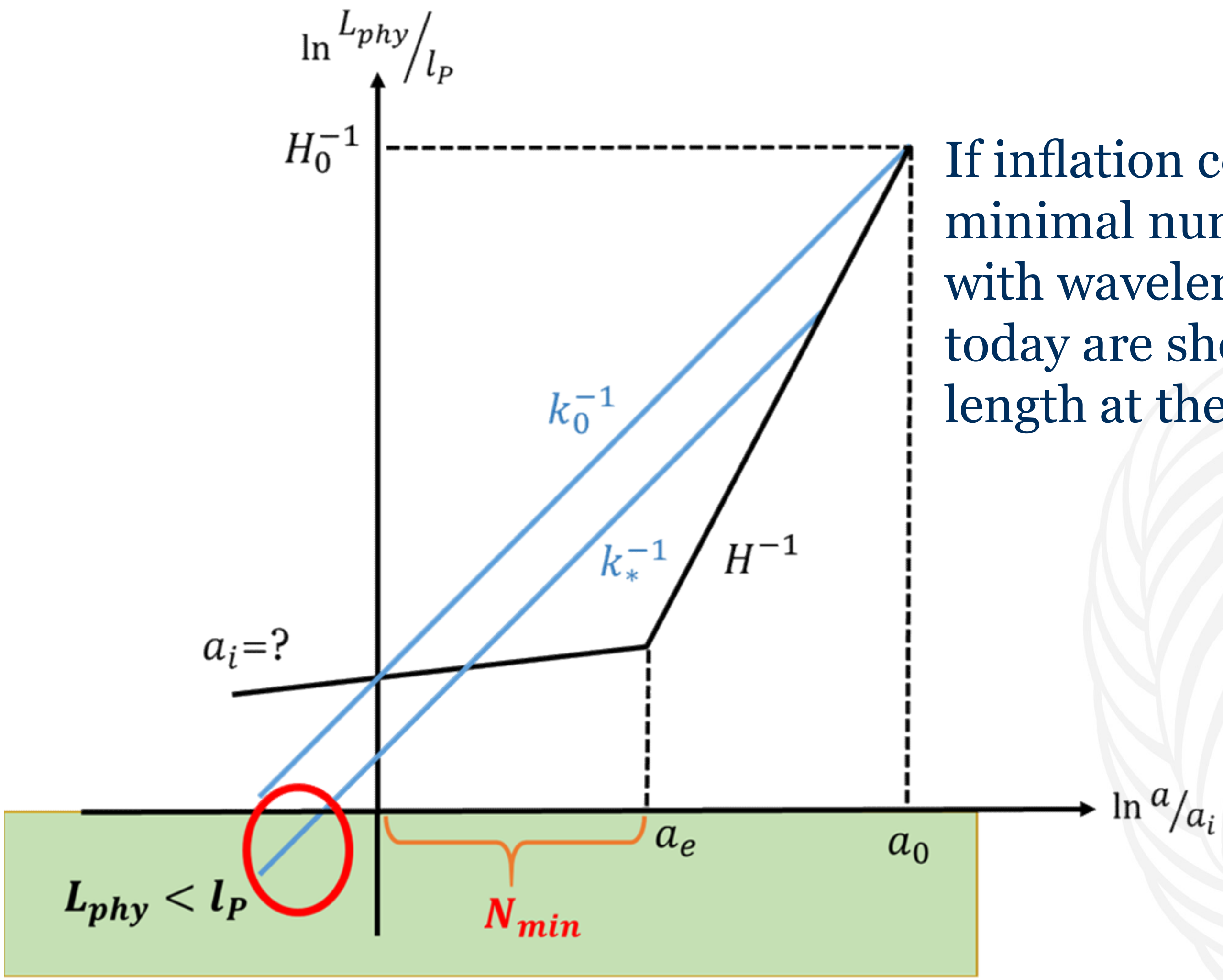
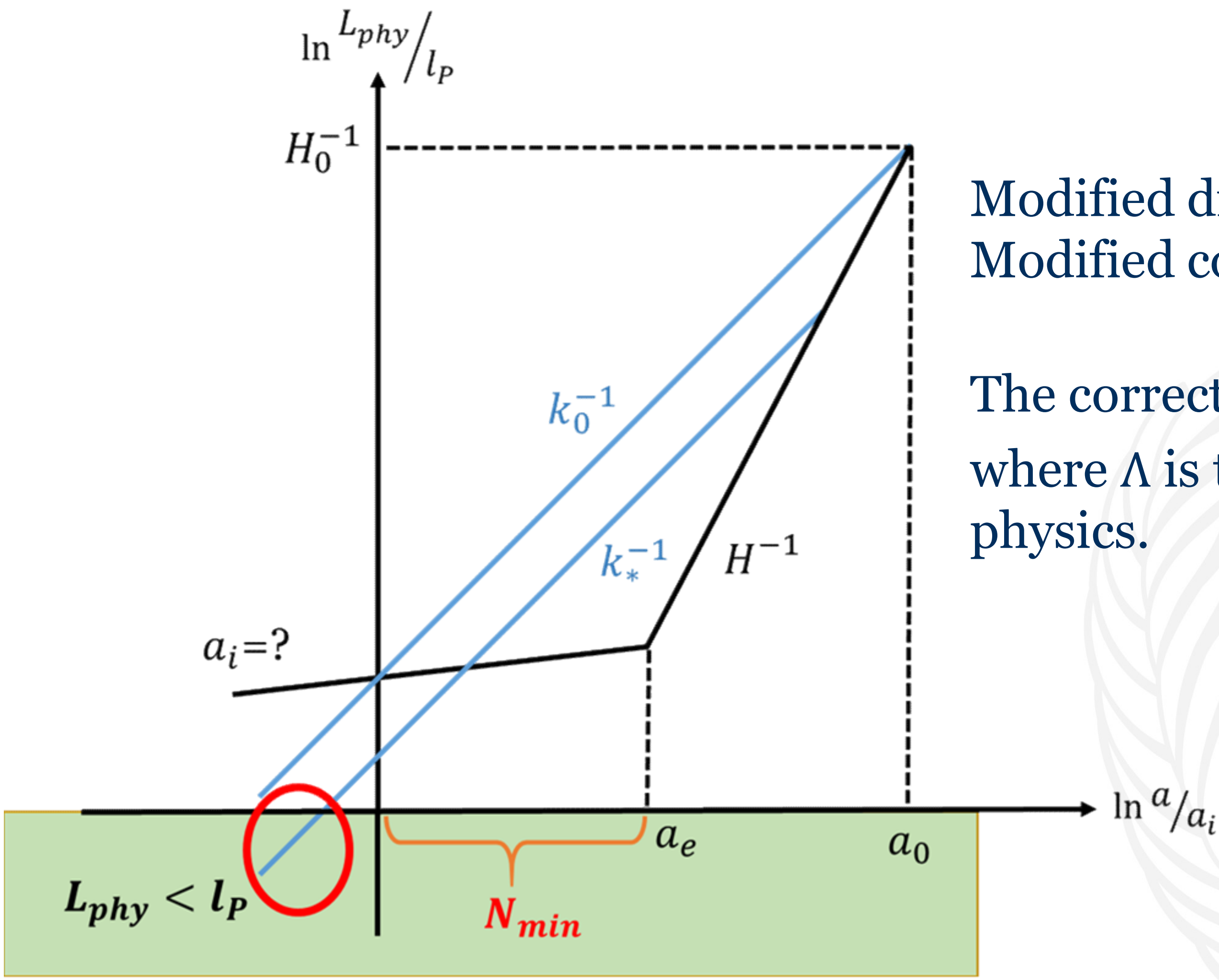
Trans-Planckian problem



If inflation continues beyond the minimal number of e-folds, modes with wavelengths on observable scales today are shorter than the Planck length at the beginning of inflation.

Trans-Planckian problem



Modified dispersion relations,
Modified commutation relation…

The corrections can be of order of $\frac{H}{\Lambda}$, where Λ is the energy scale of the new physics.

Trans-Planckian Censorship Conjecture (TCC)

"trans-Planckian problem can never arise in a consistent theory of quantum gravity and that all the models which would lead to such issues are inconsistent and belong to the Swampland."

--- quoted from[2]

[1] A. Bedroya and C. Vafa, (2019), arXiv:1909.11063 [hep-th].
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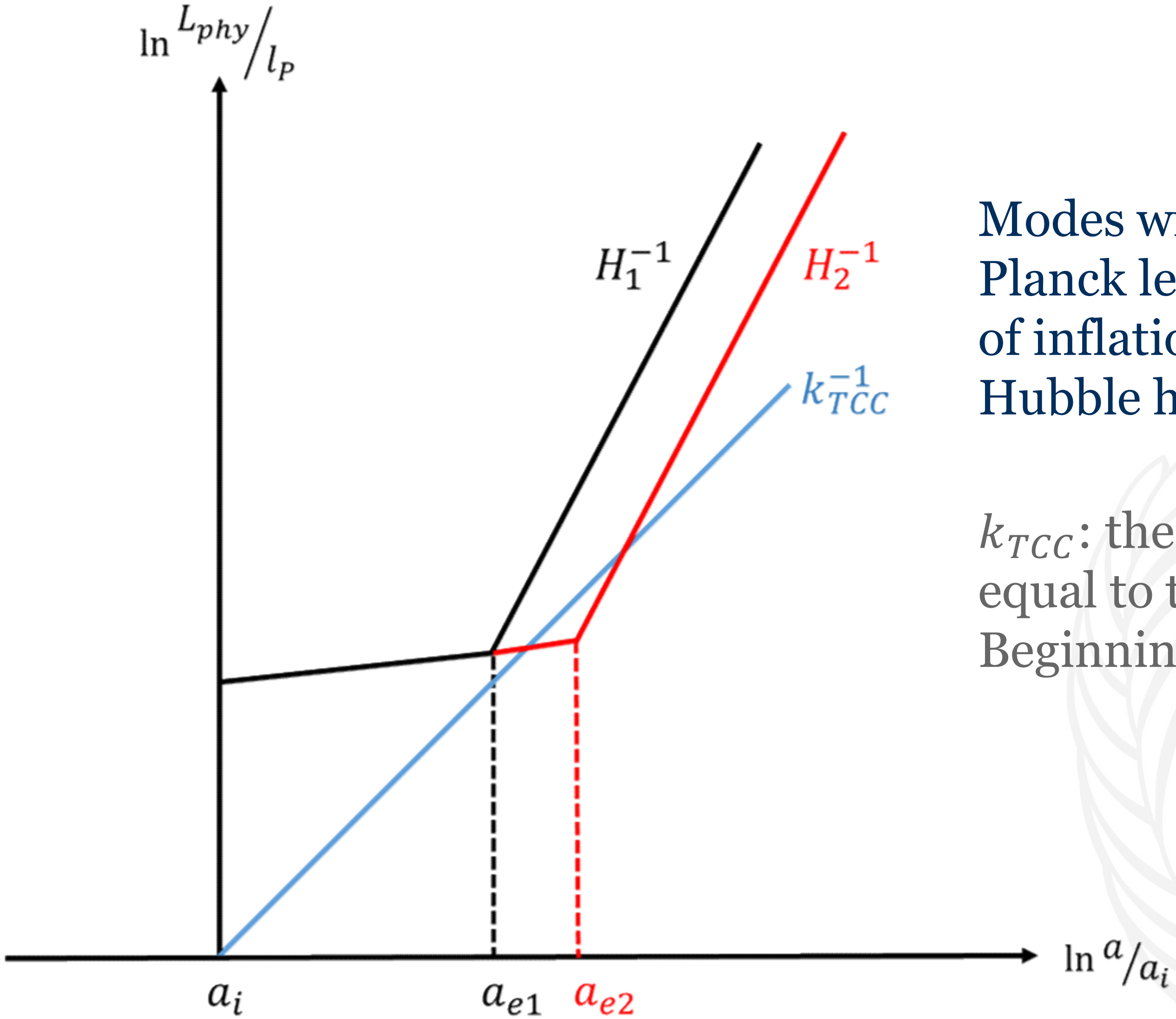
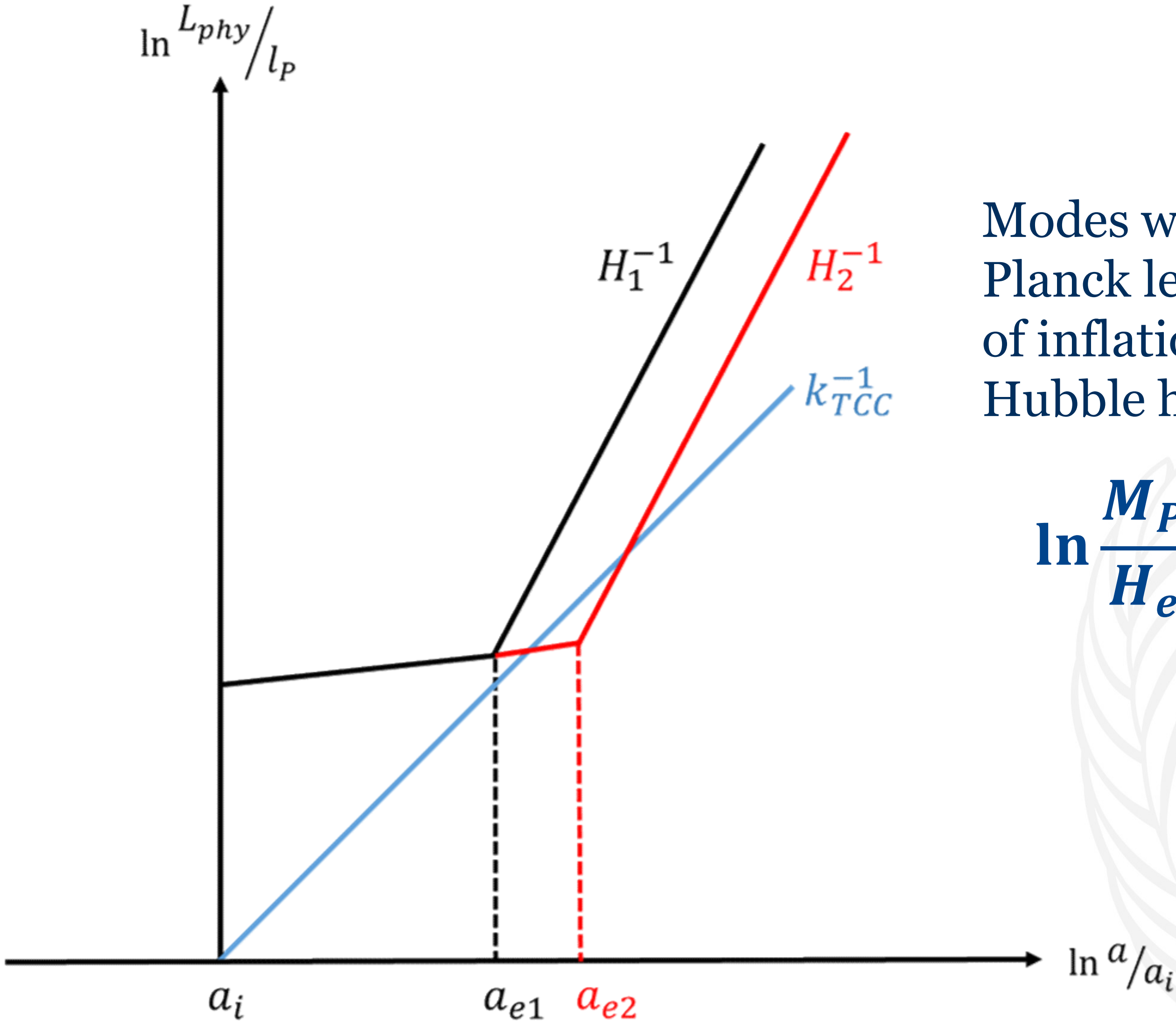


Modes with size shorter than Planck length at the onset of inflation **never** crossed the Hubble horizon.

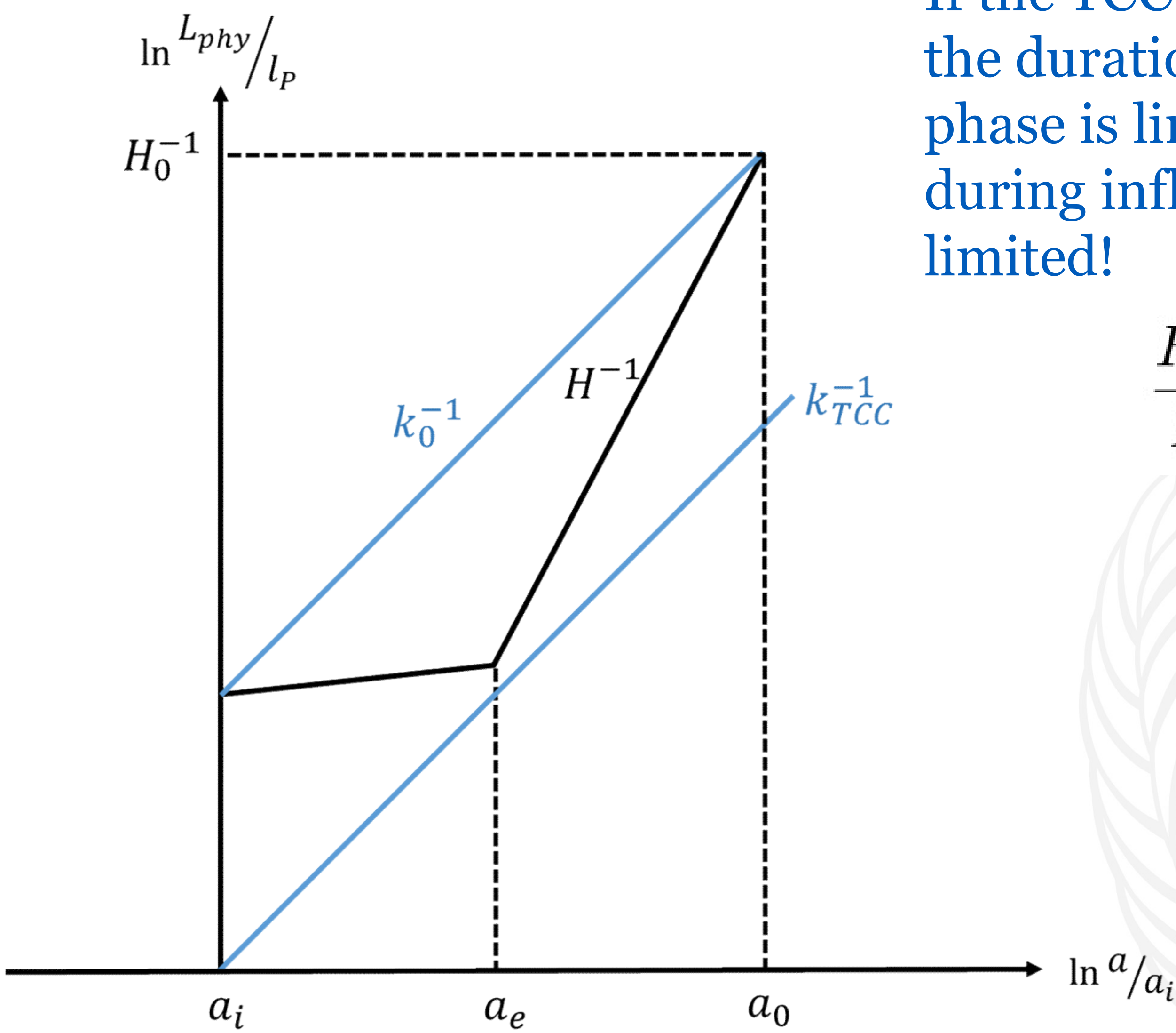
k_{TCC}: the mode having wavelength equal to the Planck length at the Beginning of inflation

Trans-Planckian Censorship Conjecture (TCC)



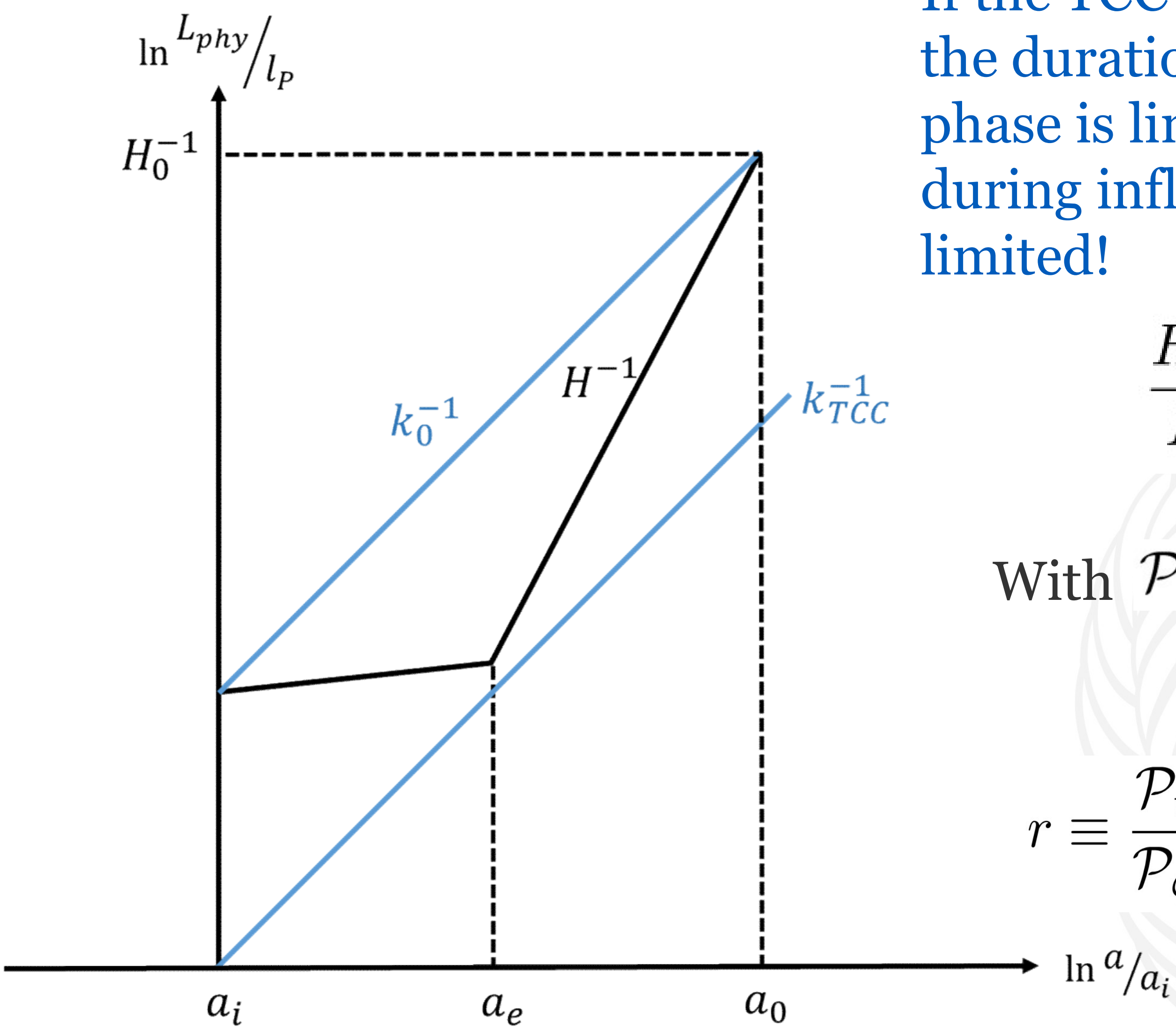
Modes with size shorter than Planck length at the onset of inflation **never** crossed the Hubble horizon.

$$\ln \frac{M_P}{H_e} > \ln \frac{a_e}{a_i} = N_{tot}$$



If the TCC is true, then not only the duration of the inflationary phase is limited, the energy scale during inflation is also strongly limited!

$$\frac{H_{inf}}{M_P} \lesssim 10^{-20}$$



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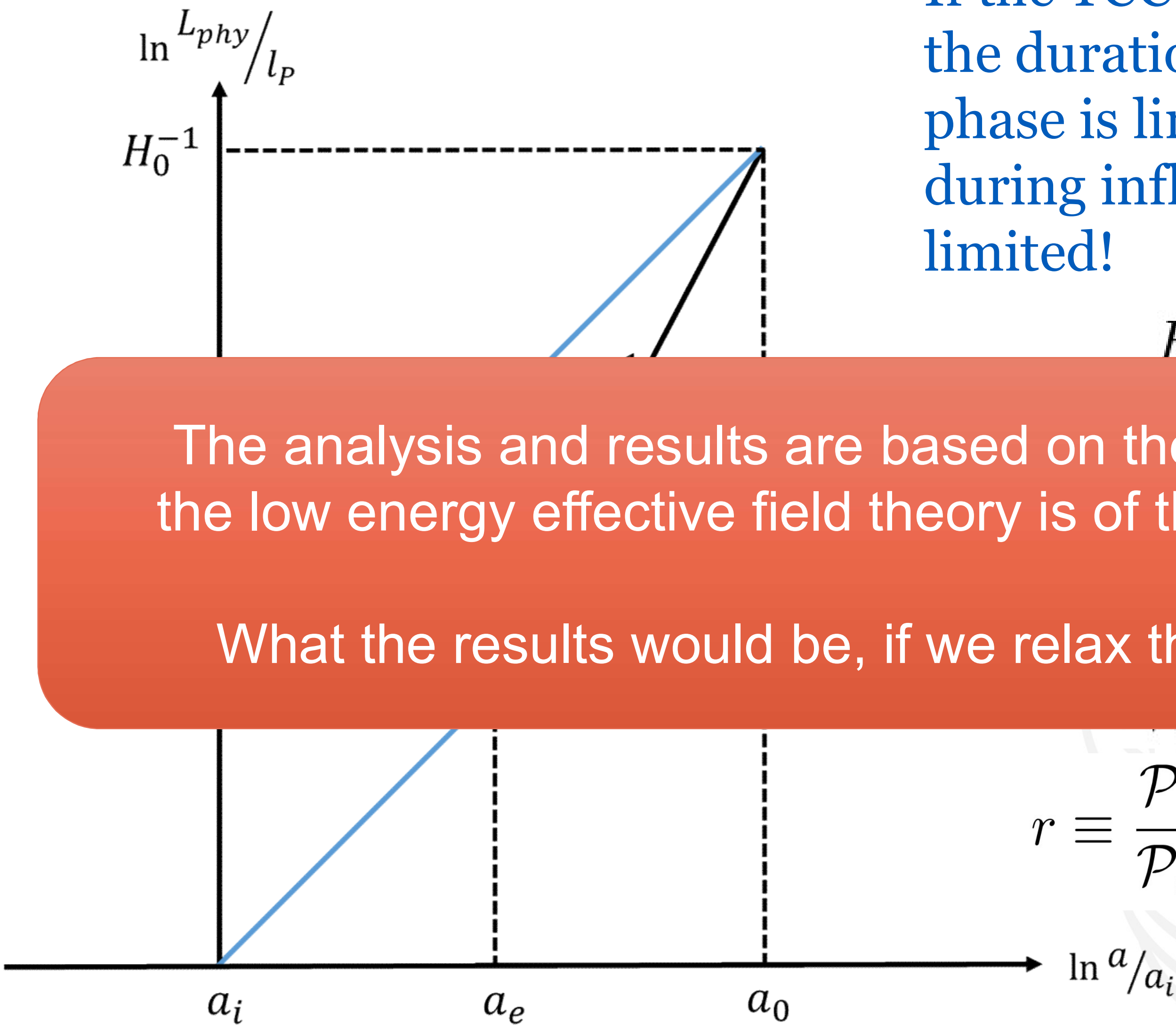
$$\frac{H_{inf}}{M_P} \lesssim 10^{-20}$$

With $\mathcal{P}_\zeta(k_*) \sim 10^{-9}$

$$\epsilon \lesssim 10^{-32}$$

$$r \equiv \frac{\mathcal{P}_t(k_*)}{\mathcal{P}_\zeta(k_*)} = 16\epsilon \lesssim 10^{-31}$$



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The analysis and results are based on the assumption that the low energy effective field theory is of the canonical form.

What the results would be, if we relax this assumption?

k-inflation

$$\mathcal{L} = \mathcal{L}[X, \phi]$$

$$X = \frac{1}{2} g^{\mu\nu} \partial_\mu \phi \partial_\nu \phi$$

$$c_S^2 \equiv \frac{p_X}{\rho_X} = \left(1 + 2X \frac{\mathcal{L}_{XX}}{\mathcal{L}_X}\right)^{-1}$$

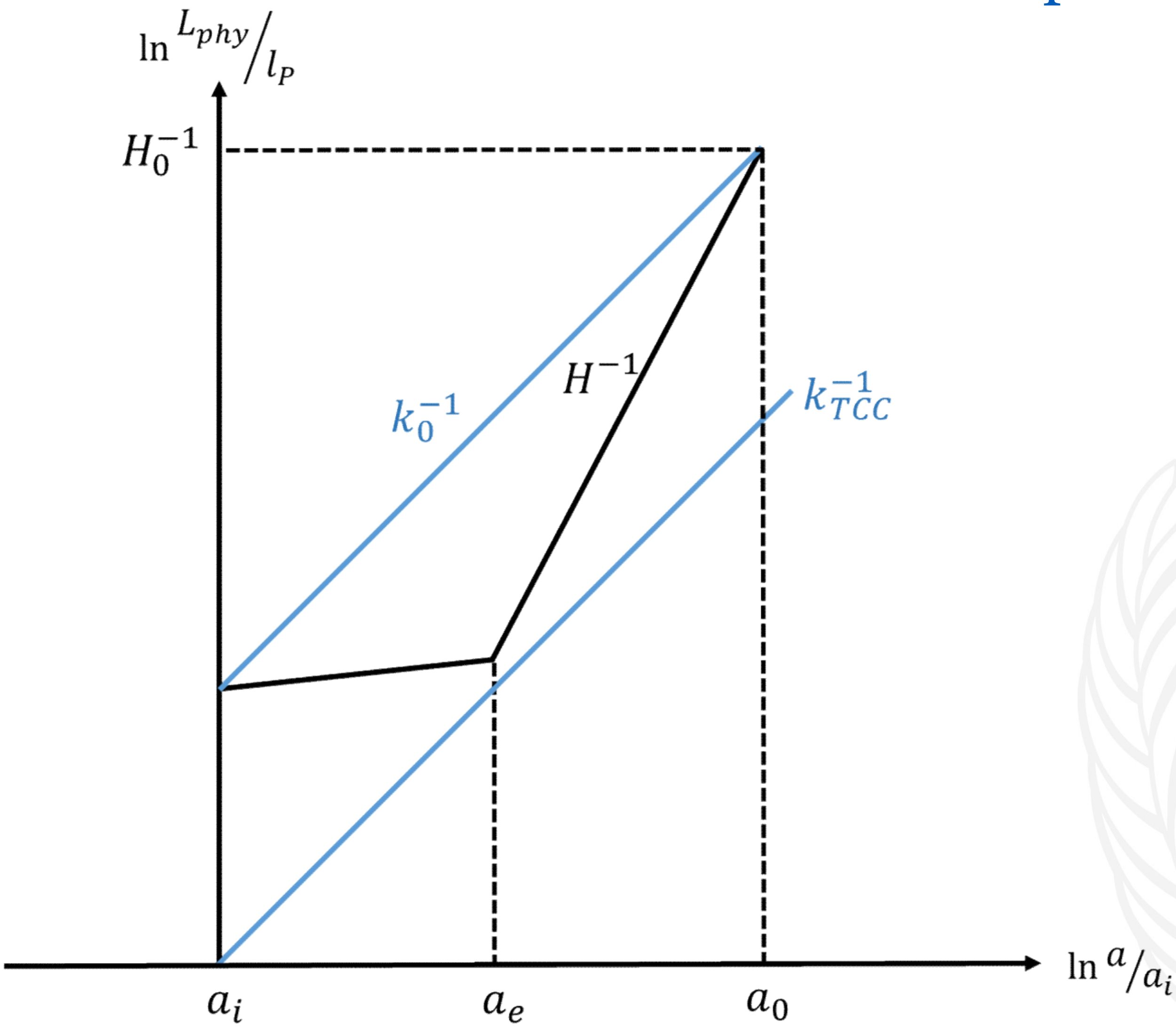
acoustic horizon: $\frac{c_S}{H}$

$$\mathcal{P}_\zeta(k) = \frac{1}{8\pi M_P^2} \frac{H^2}{c_S \epsilon}\bigg|_{kc_S = H} \qquad \mathcal{P}_t(k) = \frac{2}{\pi M_P^2} H^2\bigg|_{k=H}$$

$$r \equiv \frac{\mathcal{P}_t(k_*)}{\mathcal{P}_\zeta(k_*)} = 16\epsilon c_S^{(1+\epsilon)/(1-\epsilon)} \simeq 16 c_S \epsilon$$

[1] C. Armendariz-Picon, T. Damour, and V. F. Mukhanov, arXiv:hep-th/9904075 [hep-th].

Trans-Planckian Censorship in k-inflation



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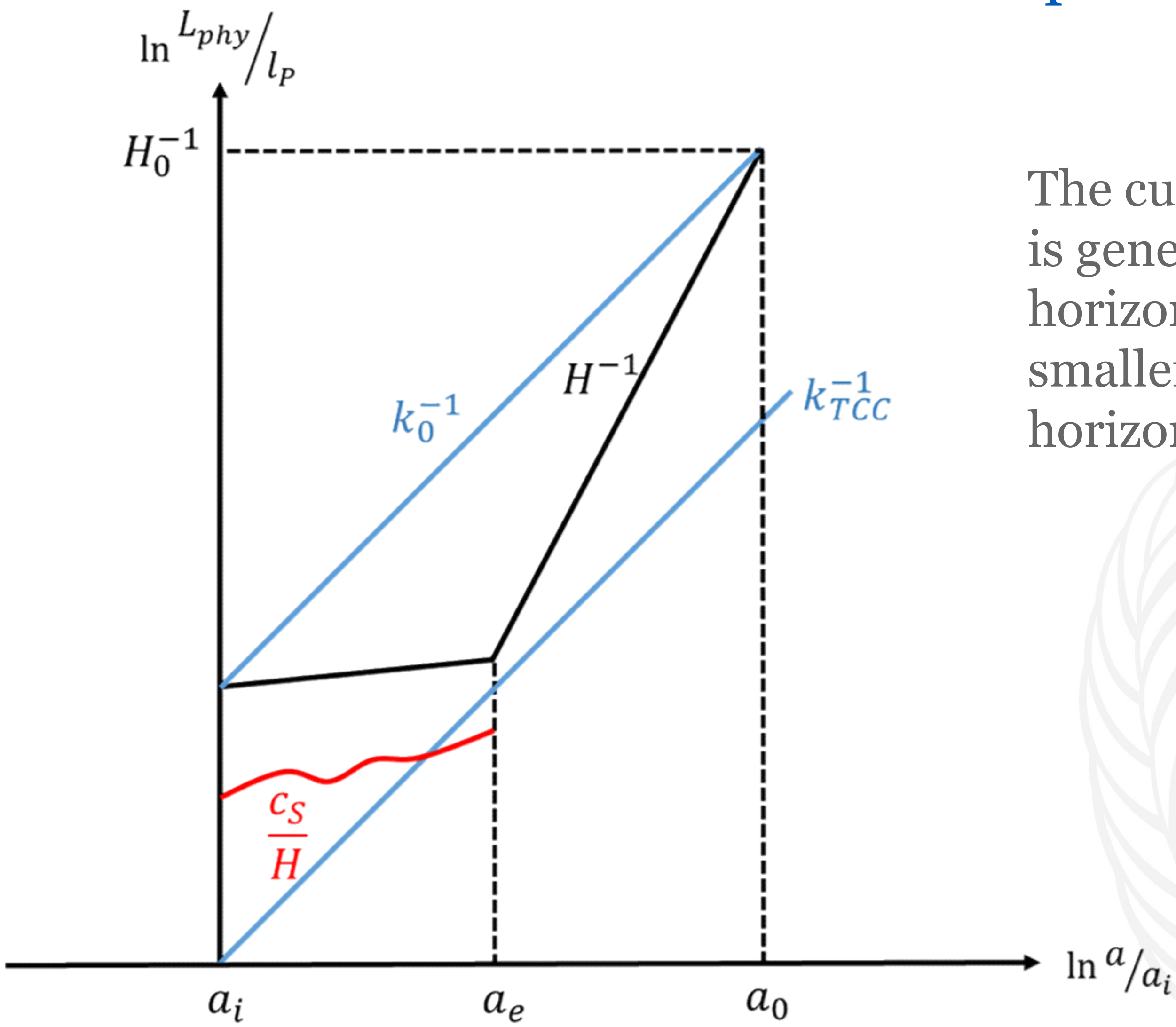
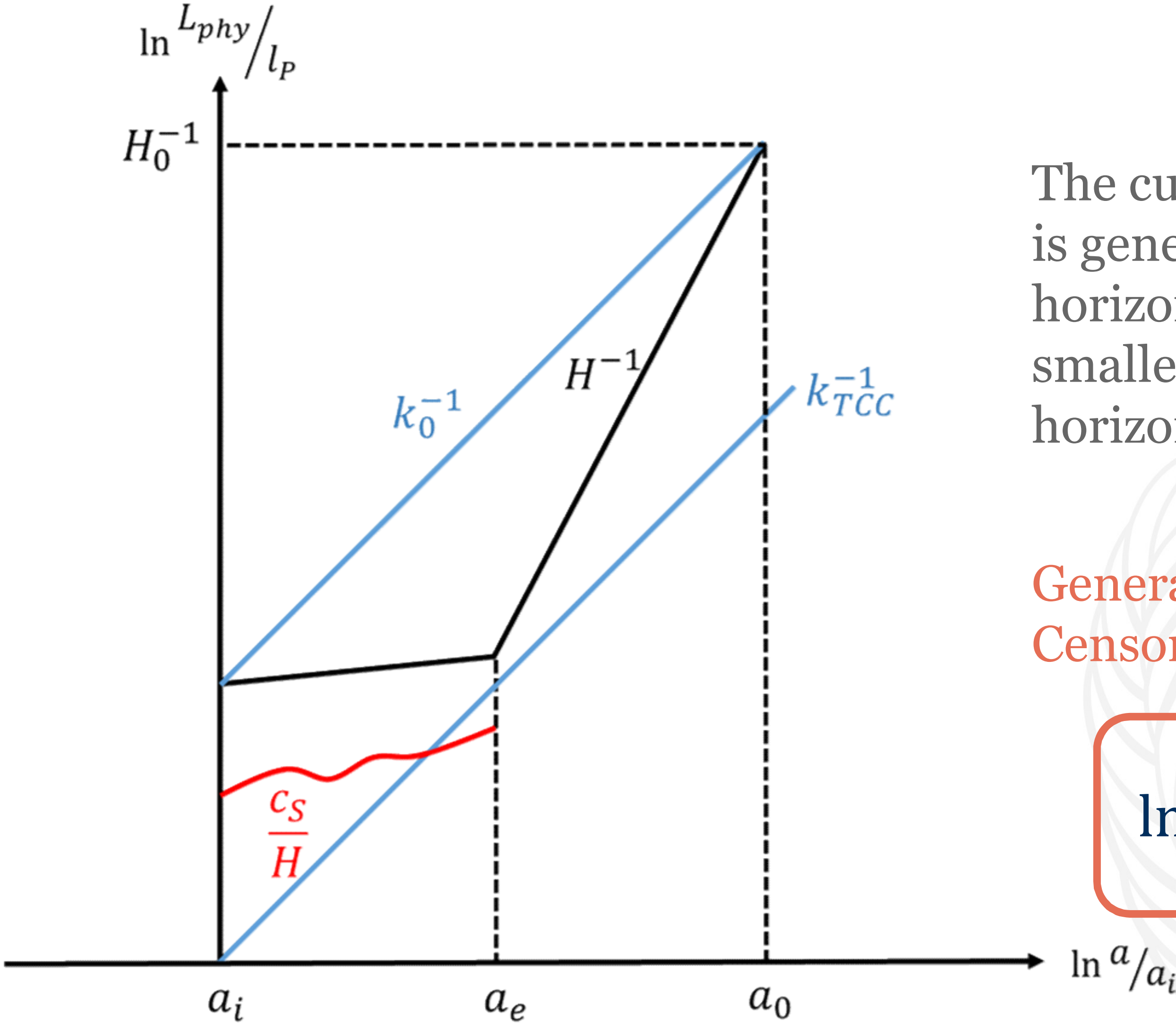


The curvature perturbation is generated at the acoustic horizon c_S/H, which is smaller than the Hubble horizon H^{-1} when $c_S < 1$.

Trans-Planckian Censorship in k-inflation

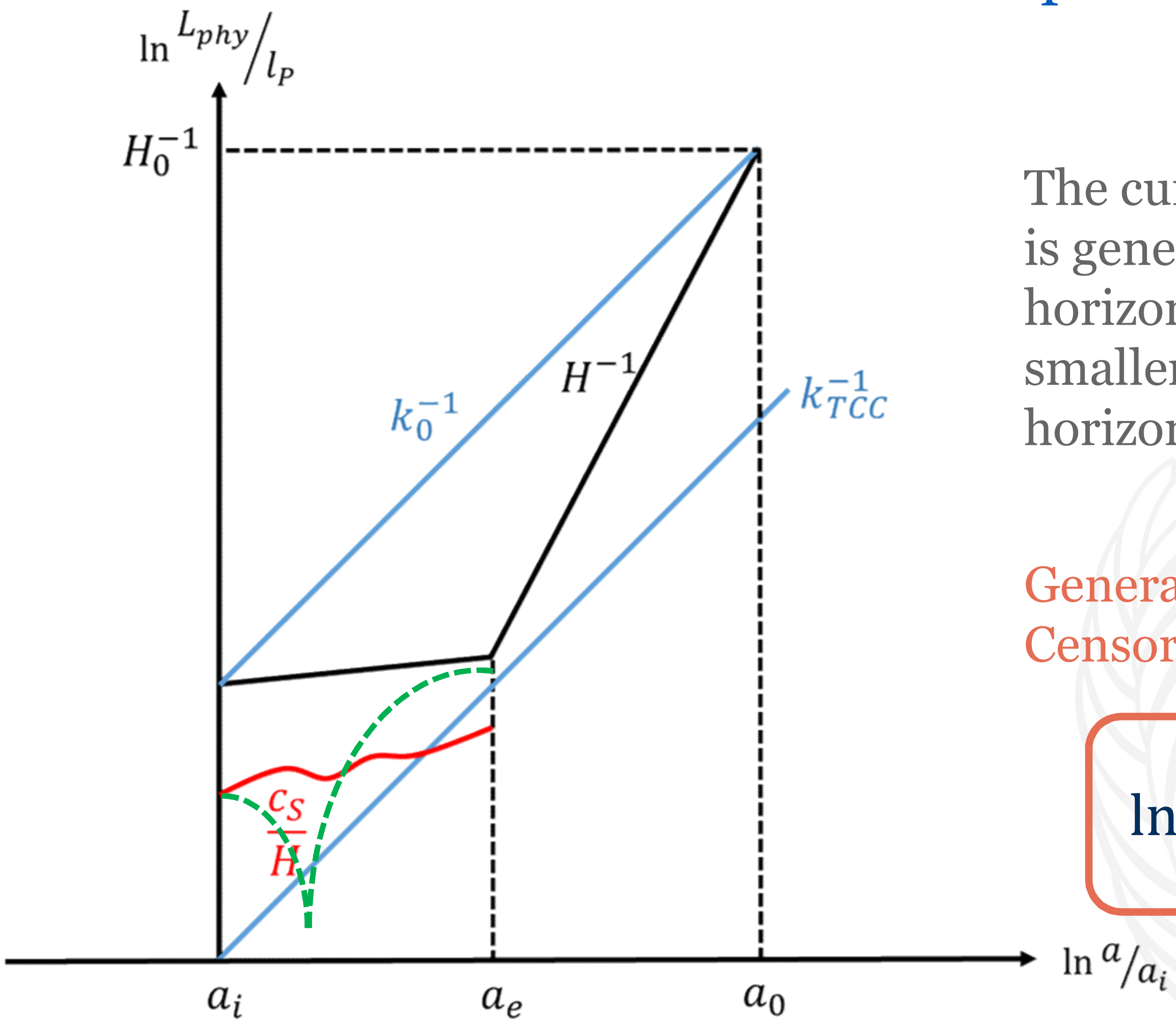


The curvature perturbation is generated at the acoustic horizon c_S/H, which is smaller than the Hubble horizon H^{-1} when $c_S < 1$.

Generalized Trans-Planckian Censorship Conjecture (GTCC)

$$\ln \frac{c_S(a) M_P}{H(a)} > \ln \frac{a}{a_i}$$

Trans-Planckian Censorship in k-inflation



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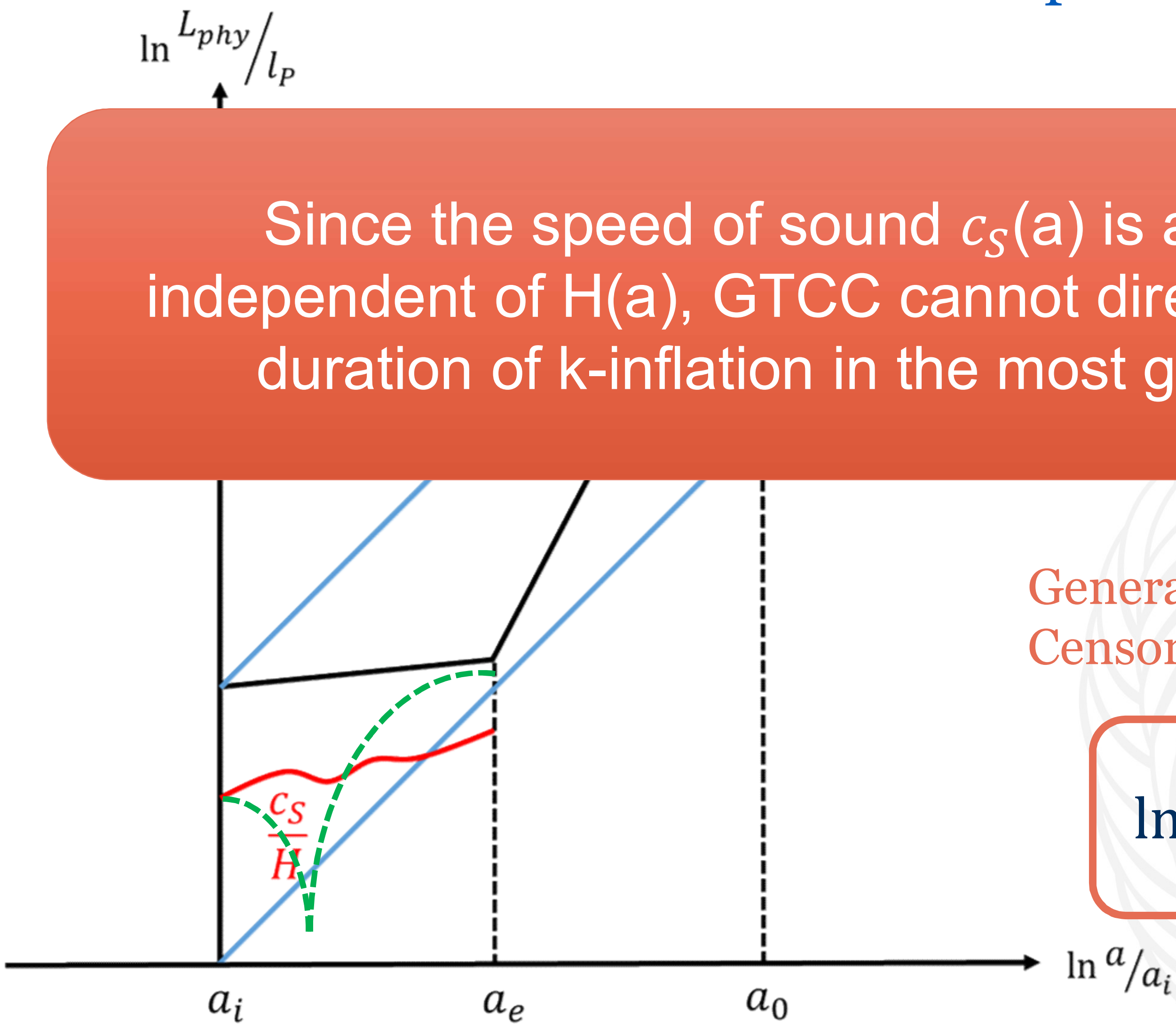

Since the speed of sound c_S(a) is an extra factor independent of H(a), GTCC cannot directly constrain the duration of k-inflation in the most general sense.

Generalized Trans-Planckian Censorship Conjecture (GTCC)

$$\ln \frac{c_S(a) M_P}{H(a)} > \ln \frac{a}{a_i}$$

Consider only the k-inflation models satisfying one of the following two conditions:

- The acoustic horizon decreases monotonically.
- The acoustic horizon grows monotonically and at most as quickly as the wavelength of comoving wave modes.

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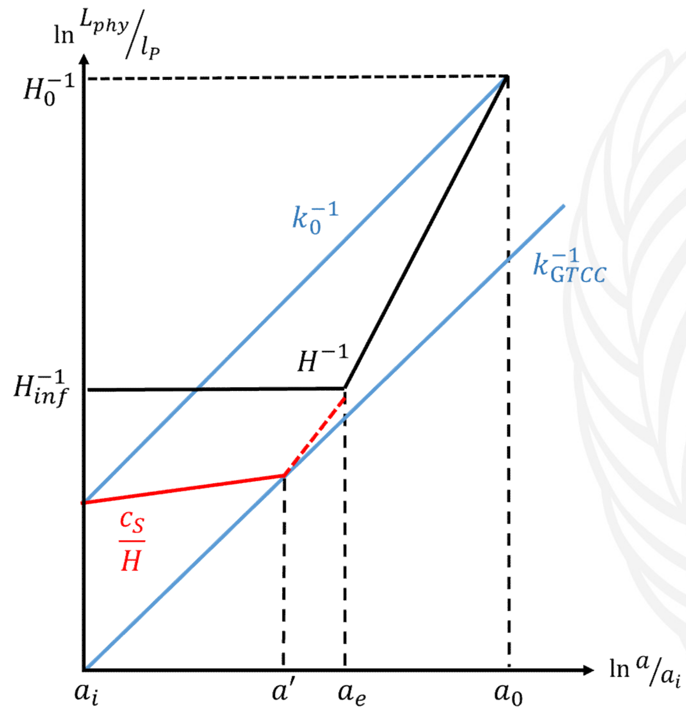

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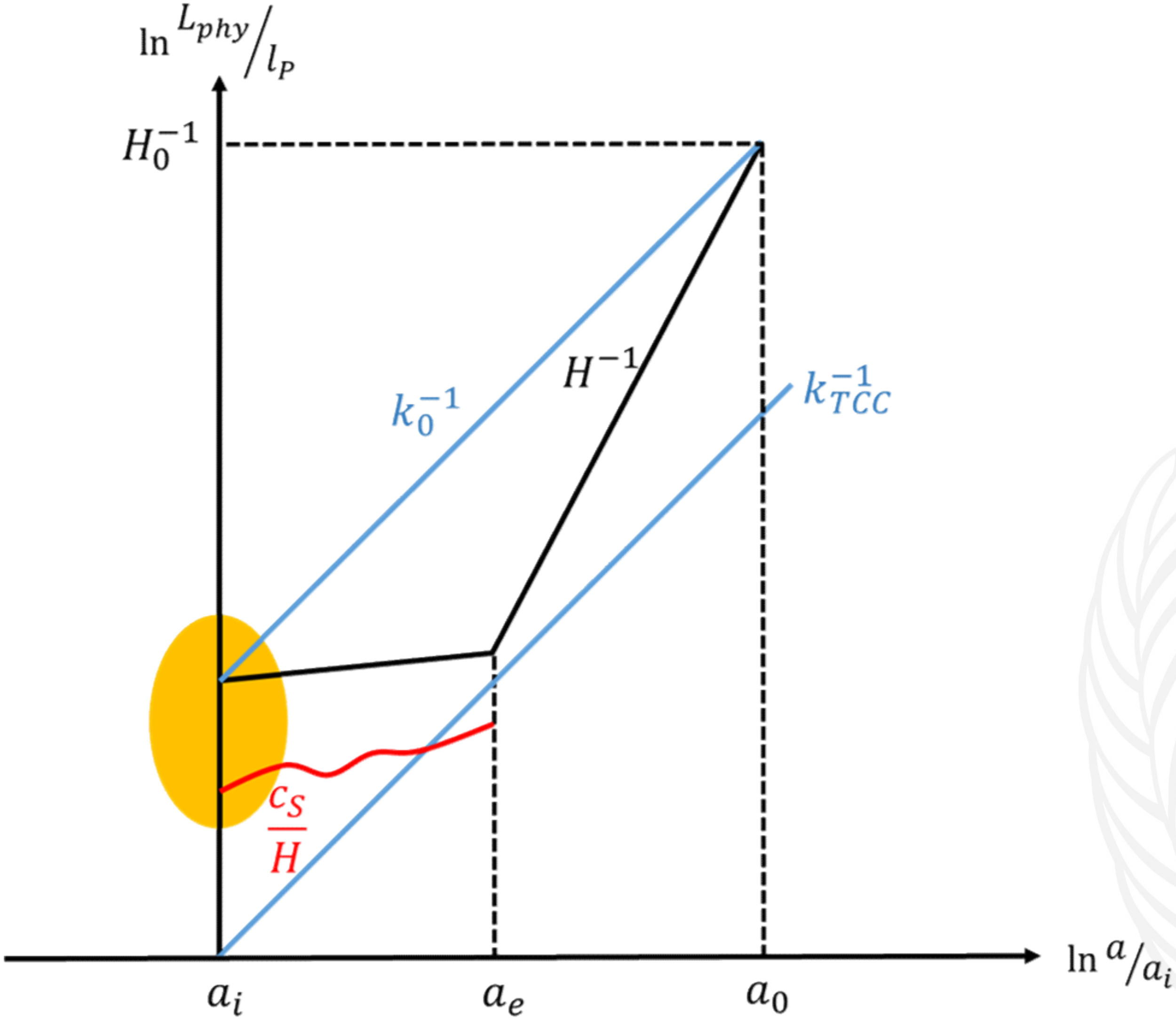
By taking the end of inflation to be
the earliest time at which the GTCC is saturated

$$\ln\frac{c_S(a)M_P}{H(a)} > \ln\frac{a}{a_i} \quad \Longrightarrow \quad \ln\frac{c_S(a_e)M_P}{H_e} > N_{tot}$$

Trans-Planckian Censorship in k-inflation



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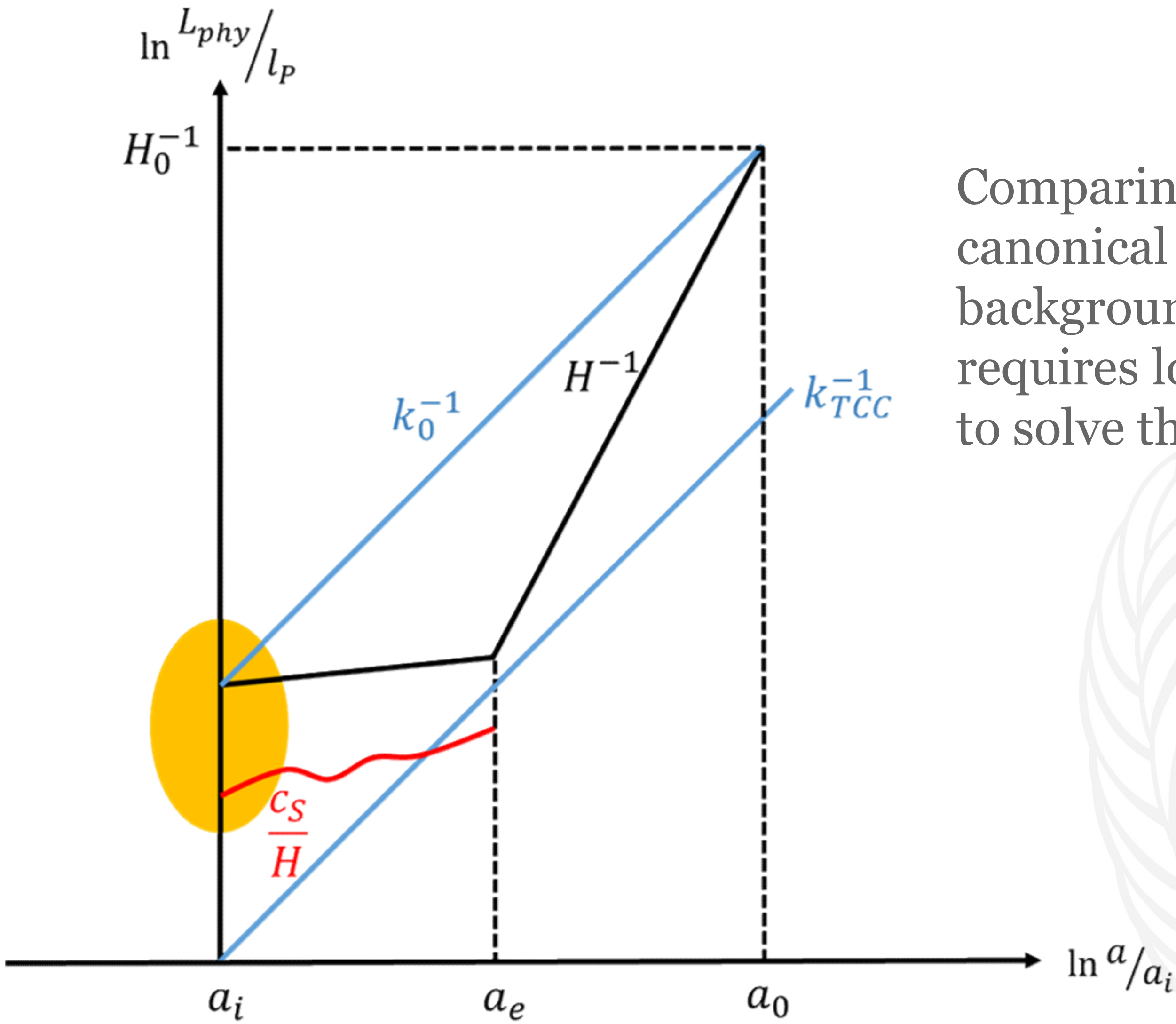
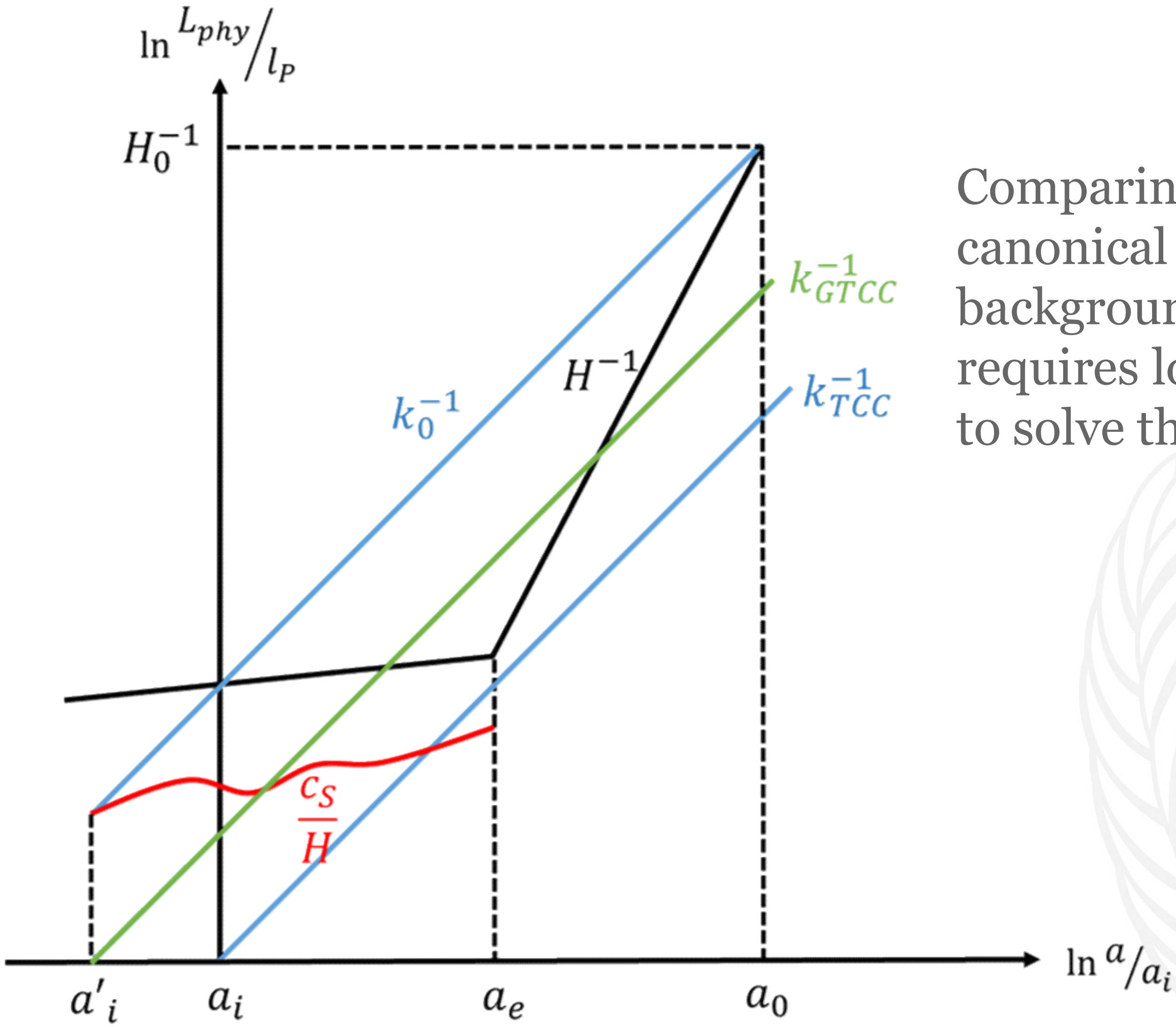


Comparing a k-inflation to a canonical model with the same background evolution, the k-inflation requires longer inflationary phase to solve the horizon problem.

Trans-Planckian Censorship in k-inflation



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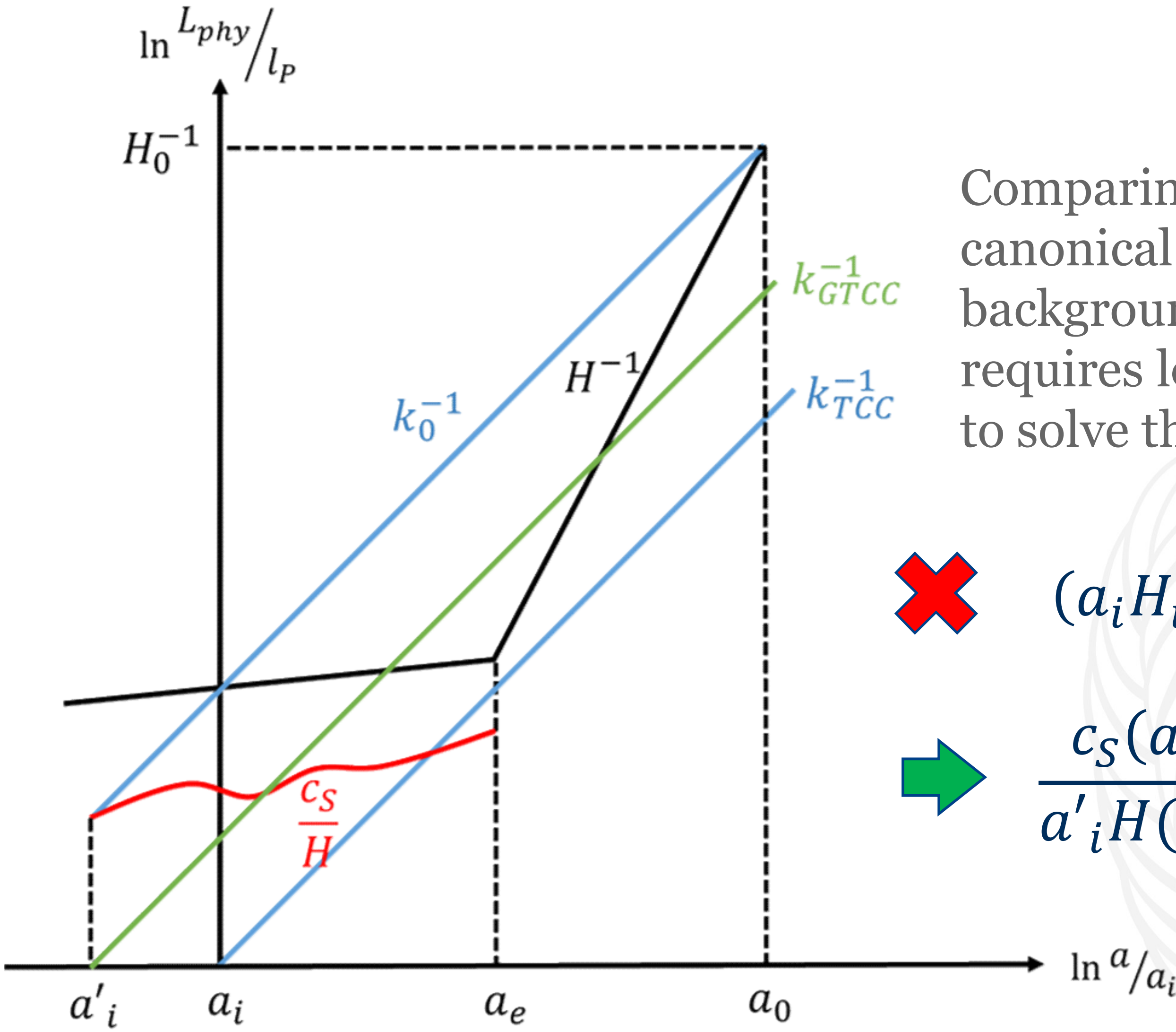

Comparing a k-inflation to a canonical model with the same background evolution, the k-inflation requires longer inflationary phase to solve the horizon problem.

✗ $$(a_i H_i)^{-1} \geq (a_0 H_0)^{-1}$$

➡ $$\frac{c_S(a'_i)}{a'_i H(a'_i)} \geq (a_0 H_0)^{-1}$$

For the k-inflation models satisfying one of the following two conditions:

- The acoustic horizon decreases monotonically.
- The acoustic horizon grows monotonically and at most as quickly as the wavelength of comoving wave modes.

$$\frac{H_{inf}}{M_P} \lesssim 10^{-20}(c_S(a_e)c_S(a_i))^{2/3}$$

$$r \lesssim 10^{-31}(c_S(a_e)c_S(a_i))^{4/3}$$

Conclusions

- For k-inflation, in principle the Trans-Planckian Censorship conjecture (TCC) should be replaced by the Generalized Trans-Planckian Censorship conjecture (GTCC) as

$$\ln \frac{c_S(a) M_P}{H(a)} > \ln \frac{a}{a_i}$$

which is genuinely a stronger condition than the canonical counterpart.

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- For k-inflation, in principle the Trans-Planckian Censorship conjecture (TCC) should be replaced by the Generalized Trans-Planckian Censorship conjecture (GTCC) as

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which is genuinely a stronger condition than the canonical counterpart.

- If the speed of sound satisfying certain monotonic behaviors, GTCC gives the following bounds on the energy scale during the inflationary phase and the tensor-to-scalar ratio as

$$\frac{H_{inf}}{M_P} \lesssim 10^{-20} (c_S(a_e) c_S(a_i))^{2/3}$$
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Thank you!

- Some references of the Trans-Planckian problem

[1] J. Martin and R. H. Brandenberger, Phys. Rev. D63, 123501 (2001), arXiv:hep-th/0005209 [hep-th].

[2] R. H. Brandenberger and J. Martin, Mod. Phys. Lett. A16, 999 (2001), arXiv:astro-ph/0005432 [astro-ph].

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[7] R. Easther, B. R. Greene, W. H. Kinney, and G. Shiu, Phys. Rev. D66, 023518 (2002), arXiv:hep-th/0204129 [hep-th].

[8] U. Danielsson, Phys. Rev.D 66 (2002) 023511, arXiv:hep-th/0203198 [hep-th]