Moduli at finite temperature

Michael Ratz

15th Rencontres du Vietnam Cosmology 2019

Based on:

- W. Buchmüller, K. Hamaguchi, O. Lebedev & M.R. Nucl. Phys. B699, 292-308 (2004)
- B. Lillard, M.R., T. Tait & S. Trojanowski JCAP 1807 no. 07, 056 (2018)

Diclaimers and apologies

- very little citations
- many cartoons

Overview

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gauge coupling — Yukawa coupling

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moduli (SM singlets)

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e.g. Bauer, Schell & Plehn (2016)

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purpose of this talk:

discuss moduli in the hot early universe

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gravitino mass

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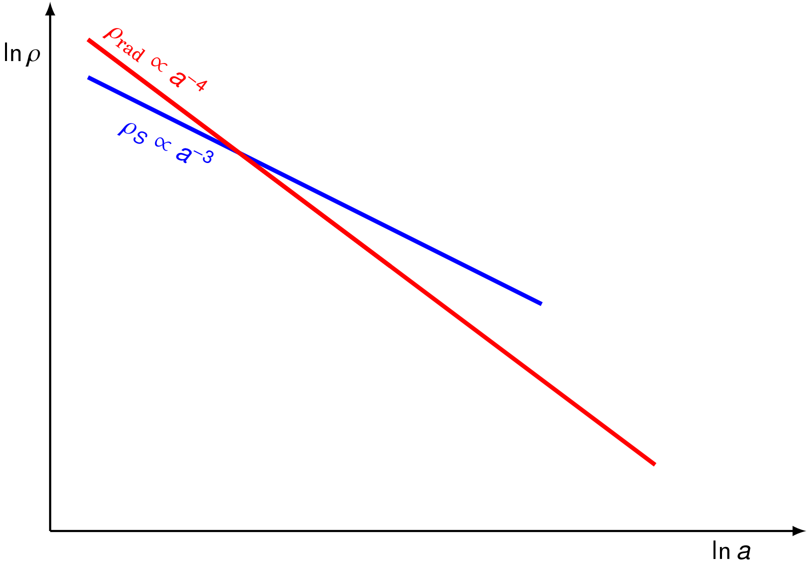
- ☞ moduli problem more model–dependent but also typically more severe

Moduli problems

Coughlan, Fischler, Kolb, Raby & Ross (1983); de Carlos, Casas, Quevedo & Roulet (1993) ,...



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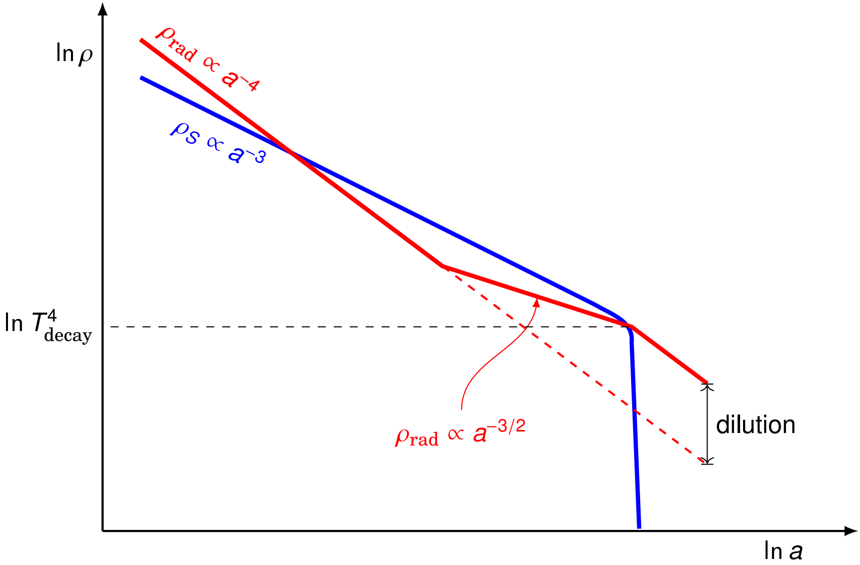

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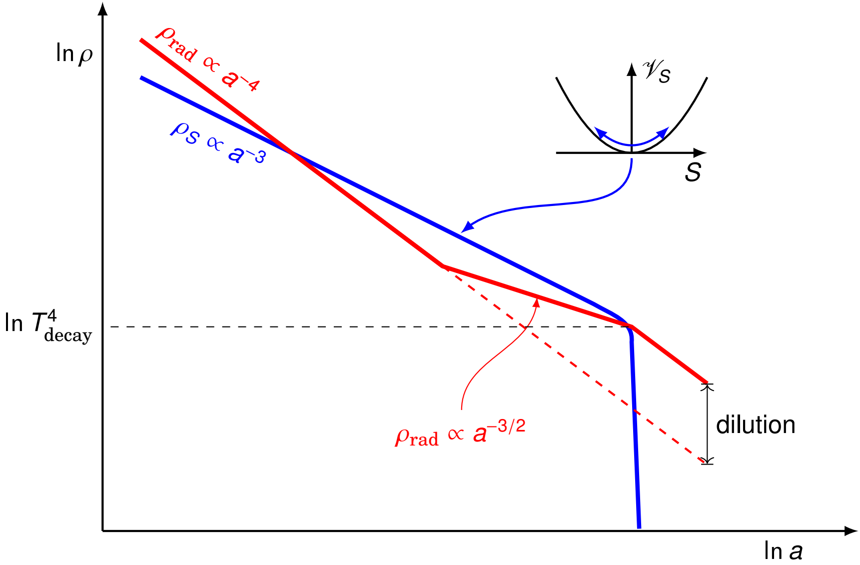

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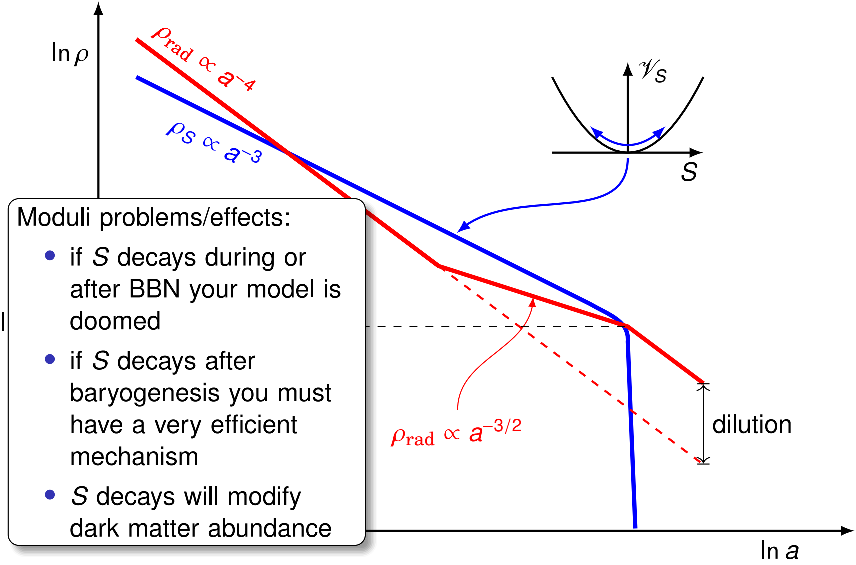

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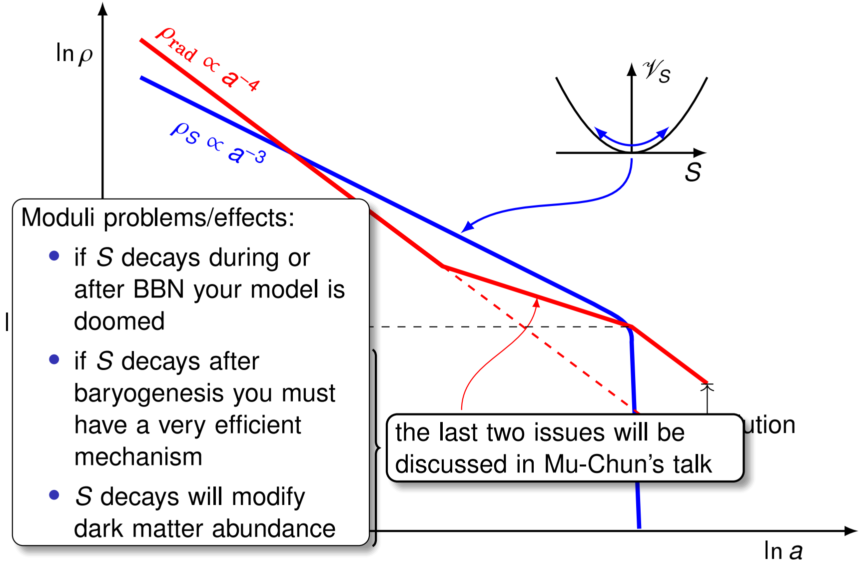

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the last two issues will be discussed in Mu-Chun's talk

Main focus of this talk

☞ will show that moduli move in such a way that couplings *decrease*

$$g \xrightarrow{T\to\text{large}} 0 \quad \text{and} \quad y \xrightarrow{T\to\text{large}} 0$$

temperature

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"modulus decay constant" (Λ)

mass (m_S)

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☞ *briefly* discuss constraints from late–decaying moduli

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- main observation: $\mathscr{V}_{\text{thermal}} = \mathcal{F}$

free energy

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- leading contribution contributions to free energy from gauge and Yukawa interactions

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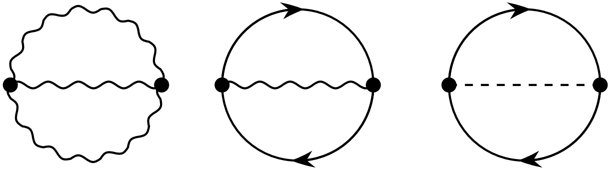

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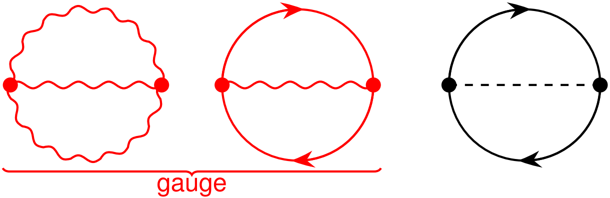

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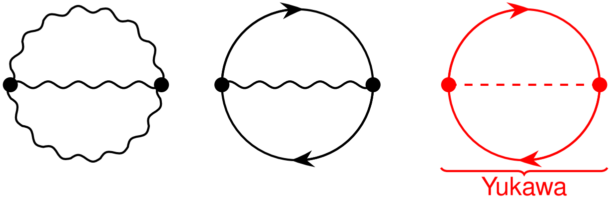

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$$\alpha_2 = \frac{3}{196}(N_C^2 - 1)(N_C + 3N_F) \text{ for } \mathrm{SU}(N_C) \text{ w/ } N_F \text{ fundamentals}$$

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crucial: signs are *positive*

➥ free energy gets minimized for *smaller* couplings y and g

Dilaton destabilization

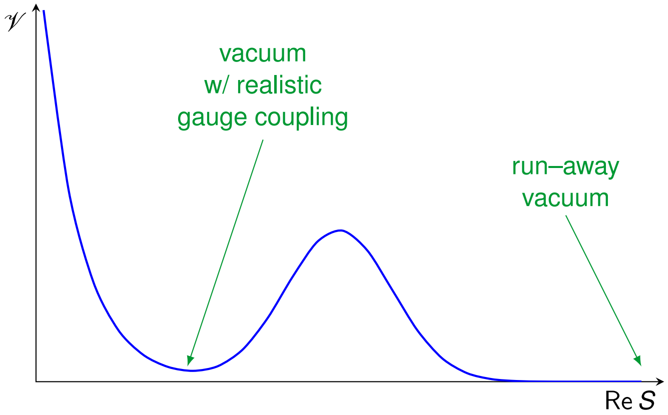
at

high temperature

Application 1: dilaton destabilization at high temperature

Buchmüller, Hamaguchi, Lebedev & M.R. (2004)

☞ typical moduli potential: $g^2 = 1/(\mathrm{Re}\, S)$



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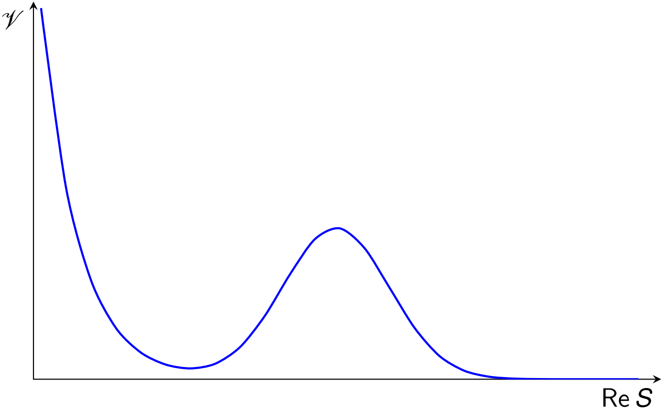

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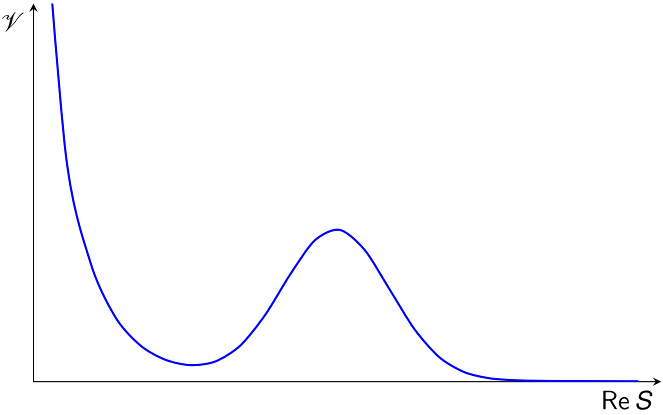

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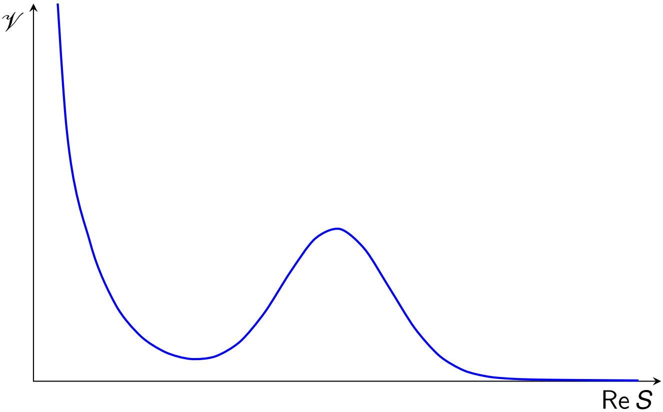

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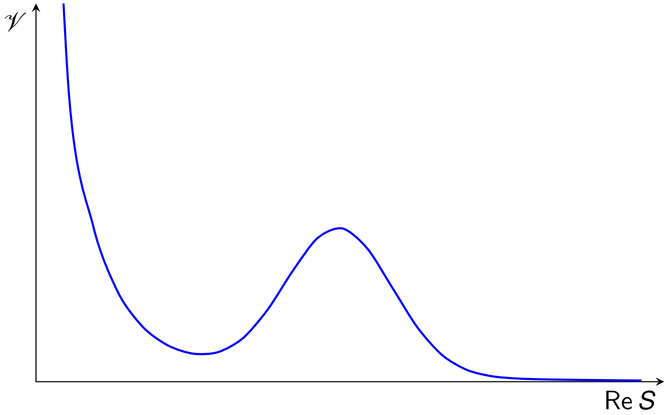

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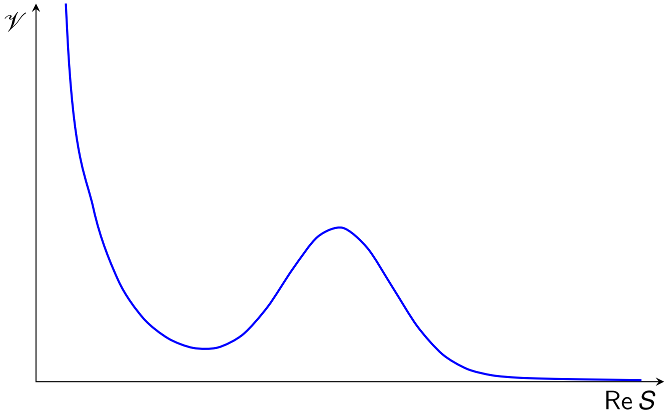

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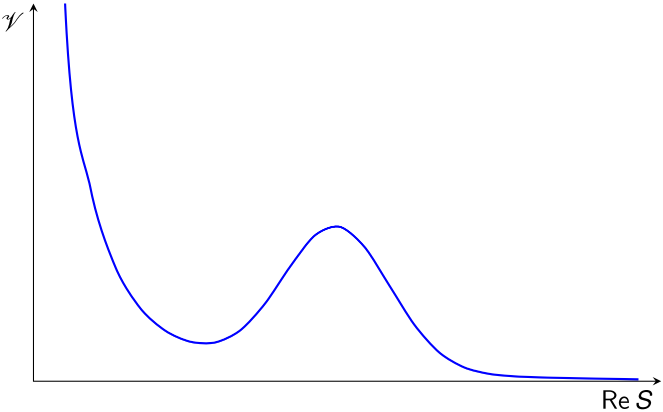

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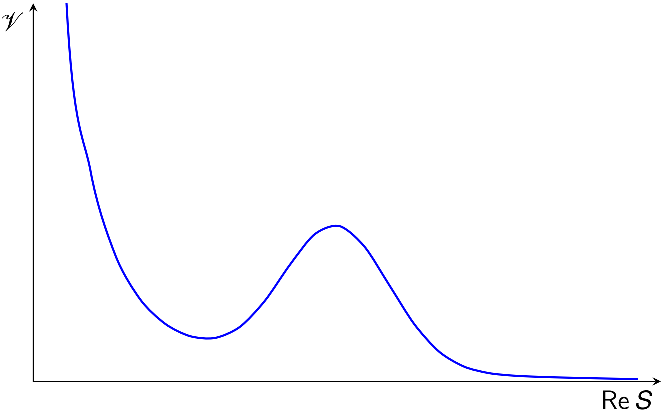

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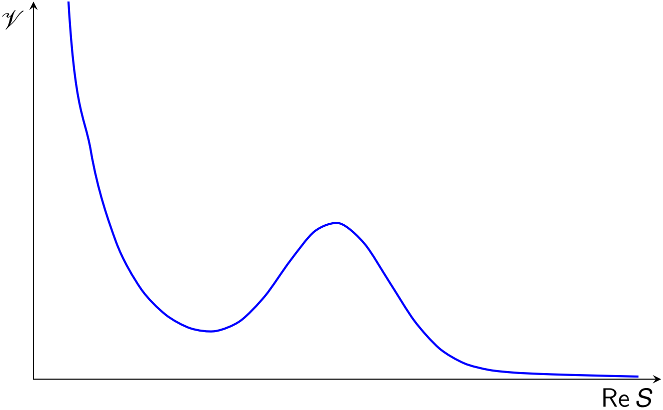

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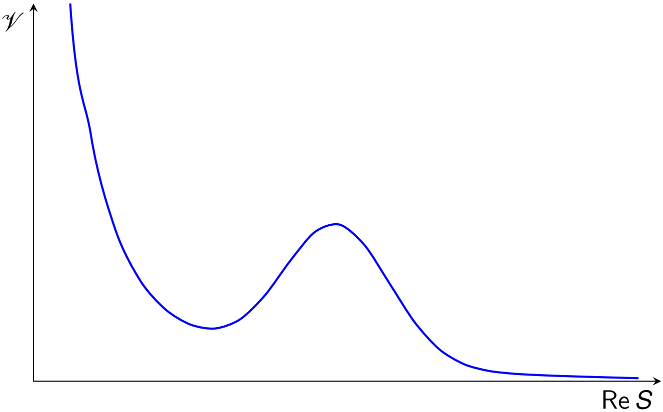

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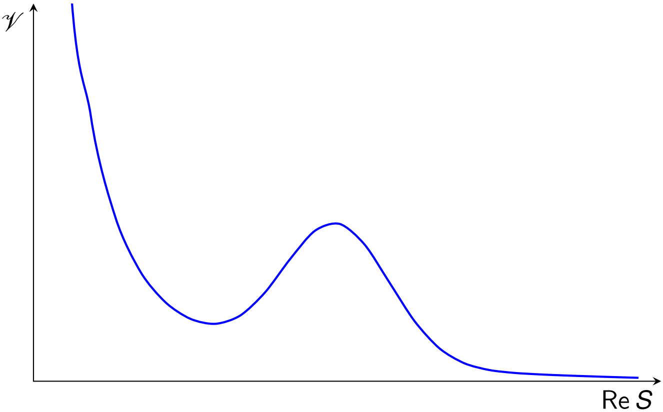

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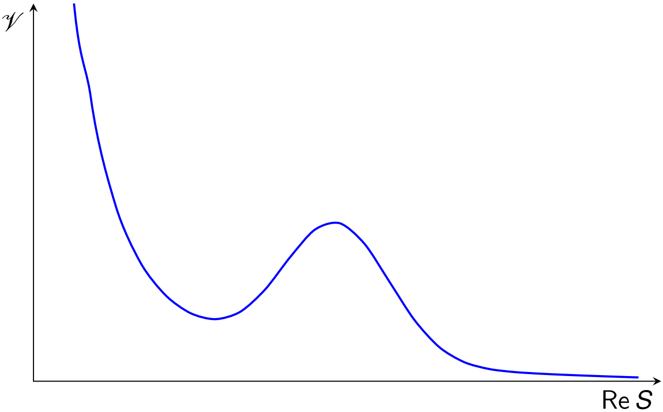

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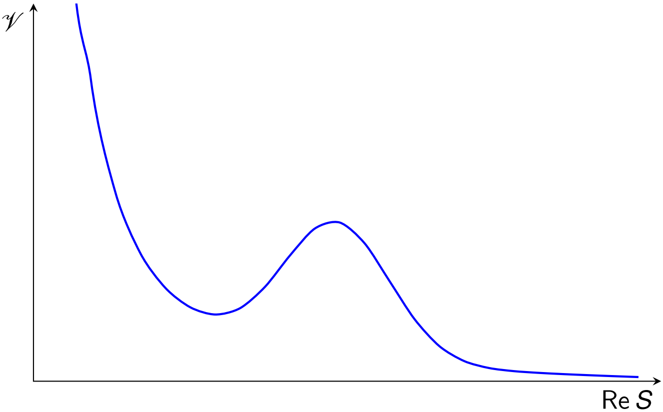

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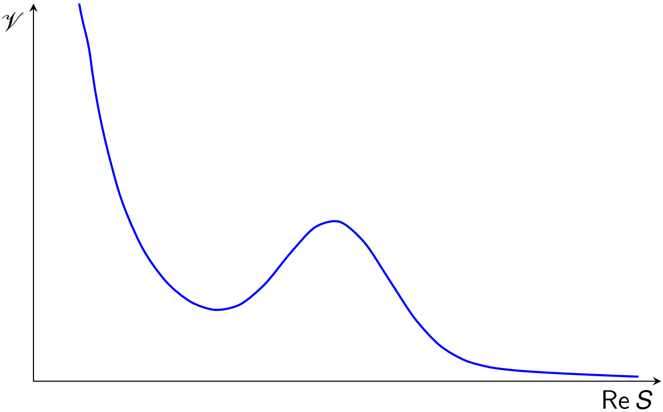

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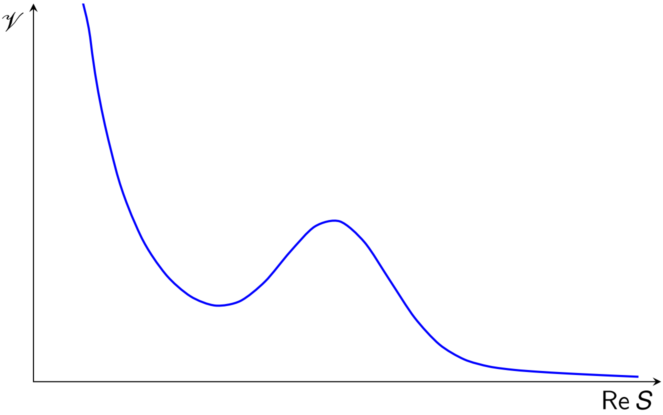

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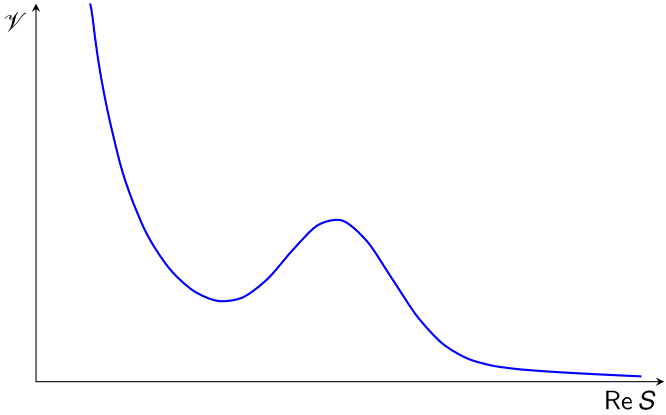

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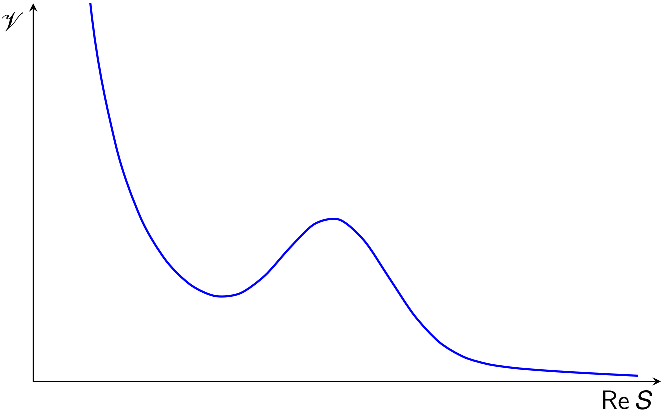

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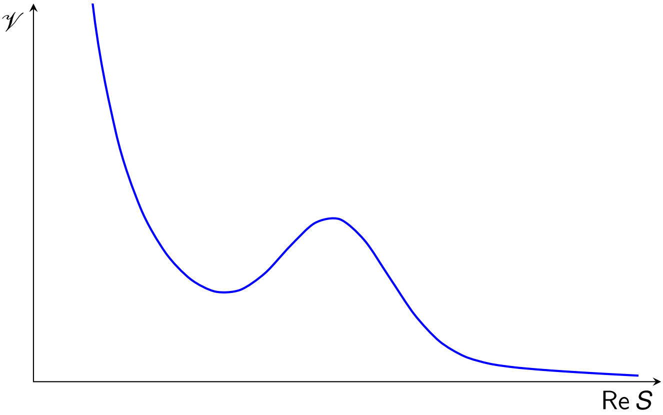

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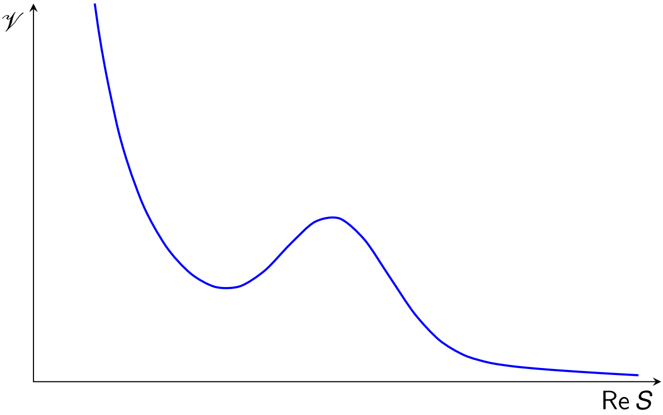

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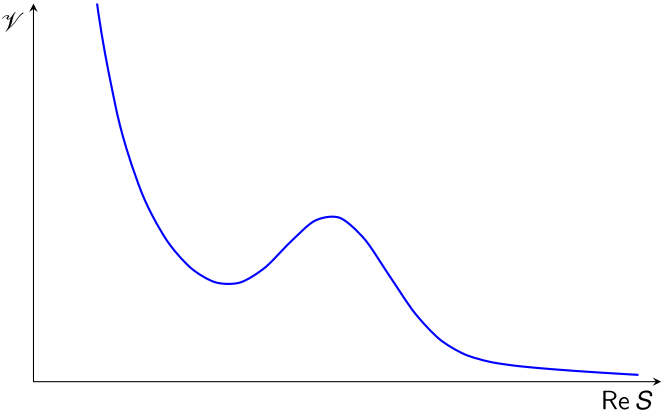

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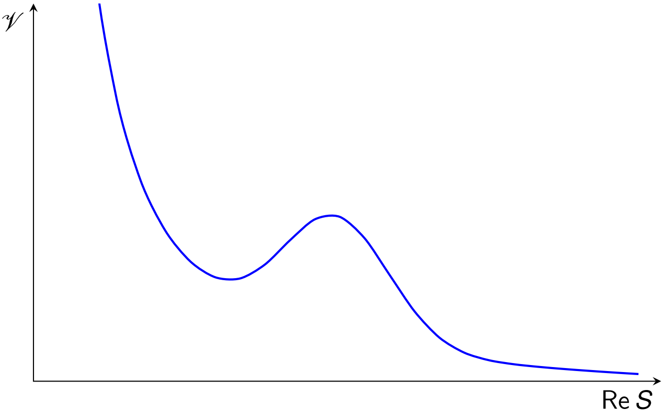

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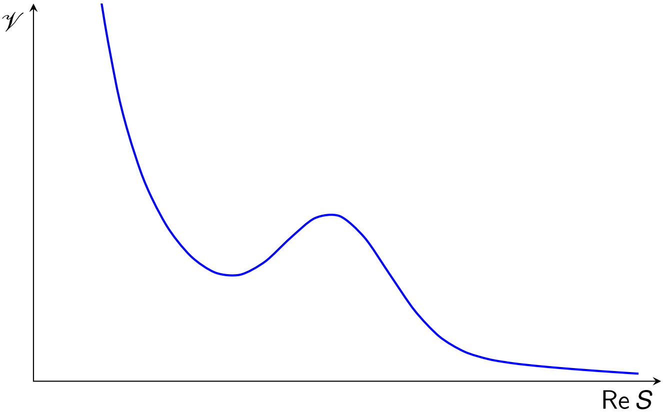

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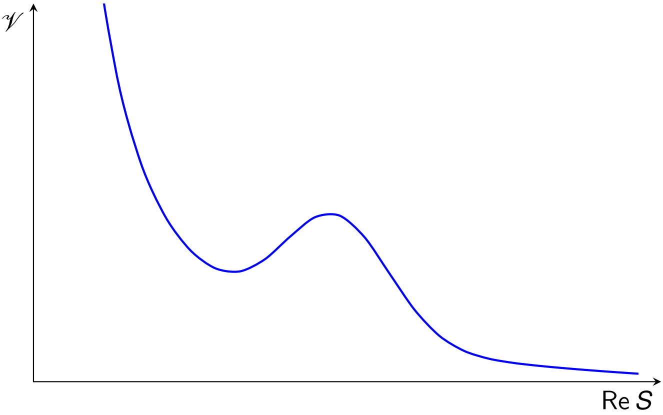

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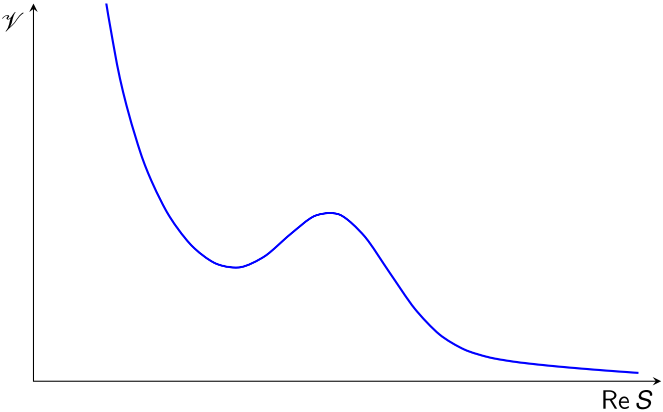

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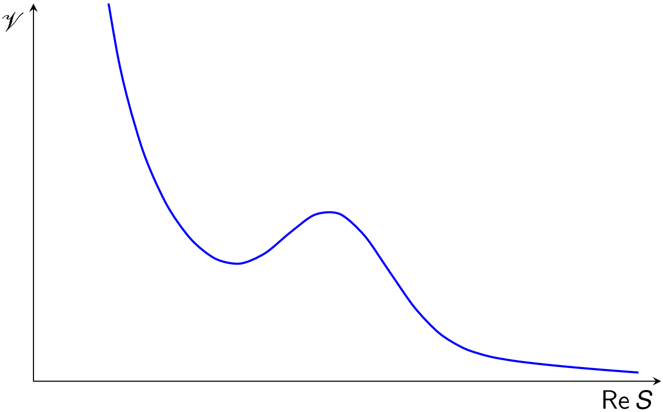

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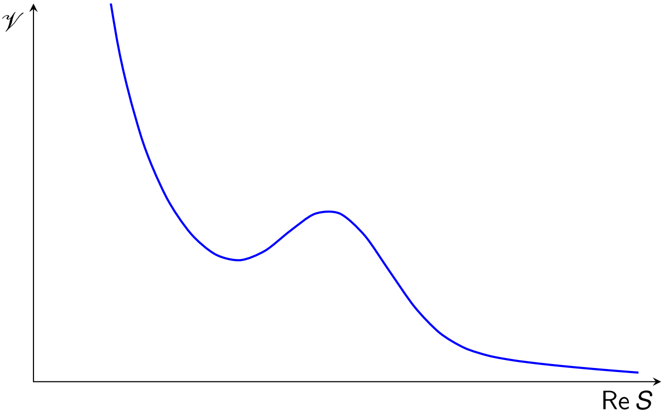

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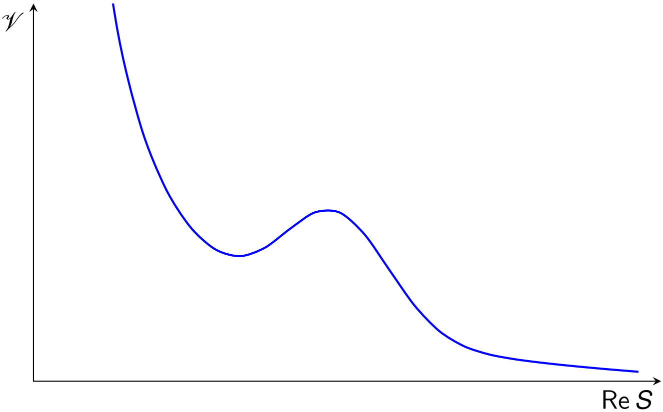

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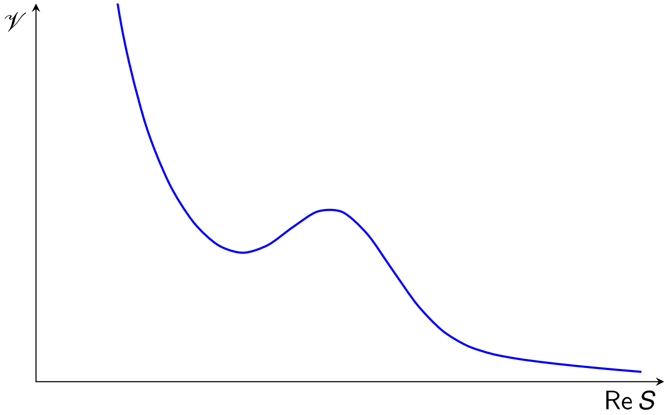

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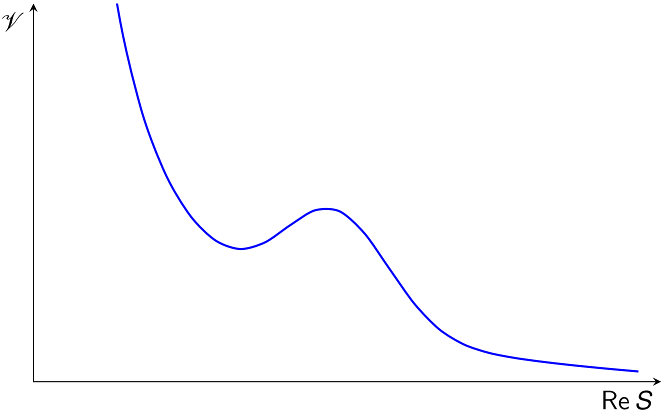

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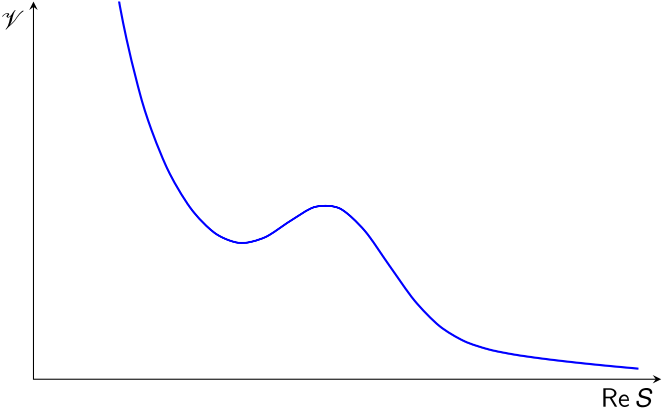

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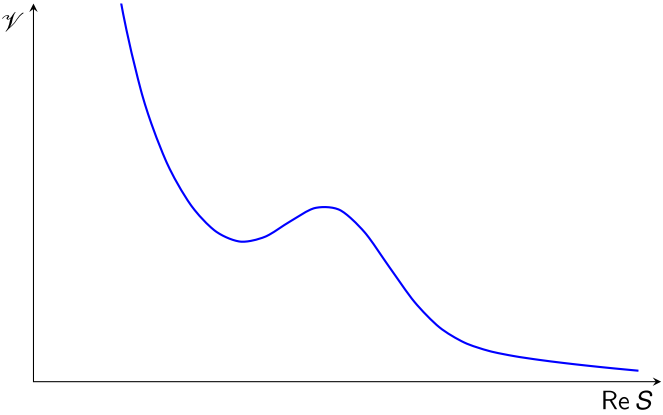

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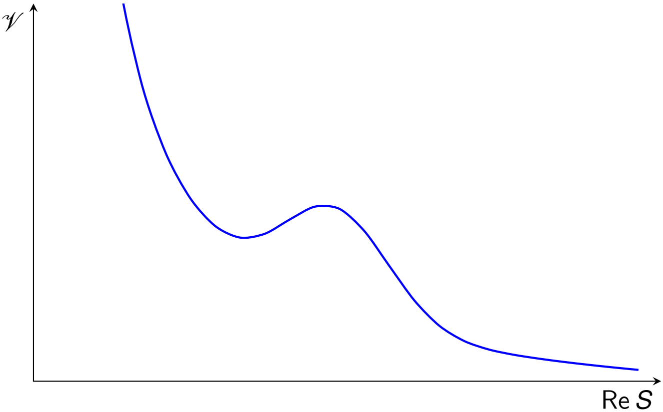

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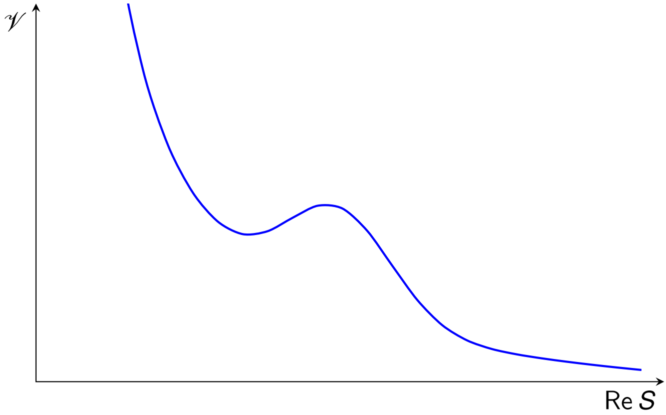

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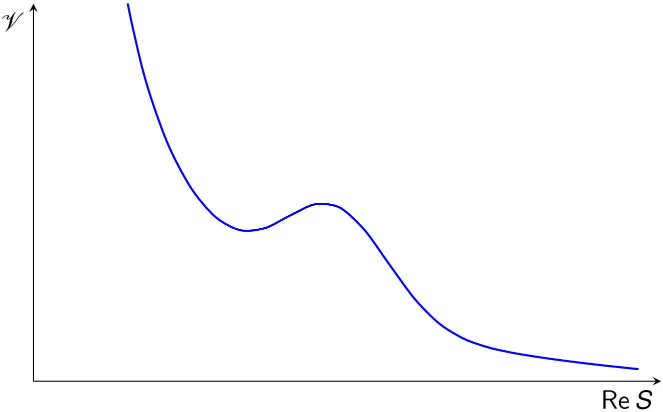

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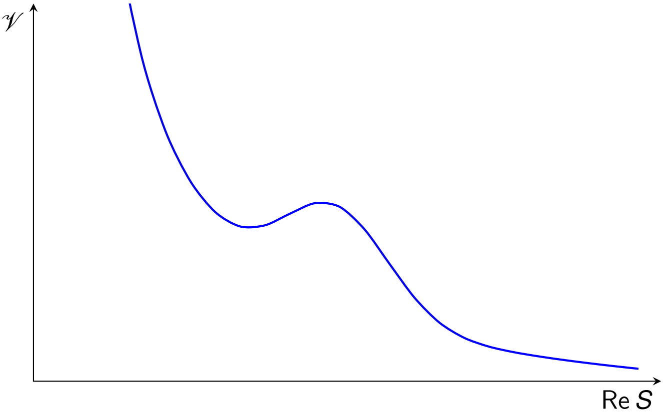

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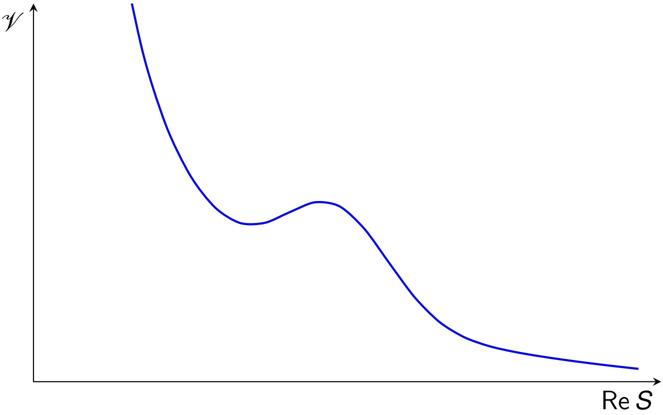

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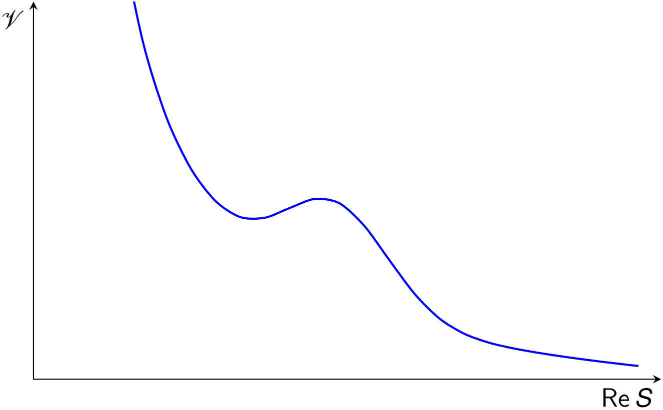

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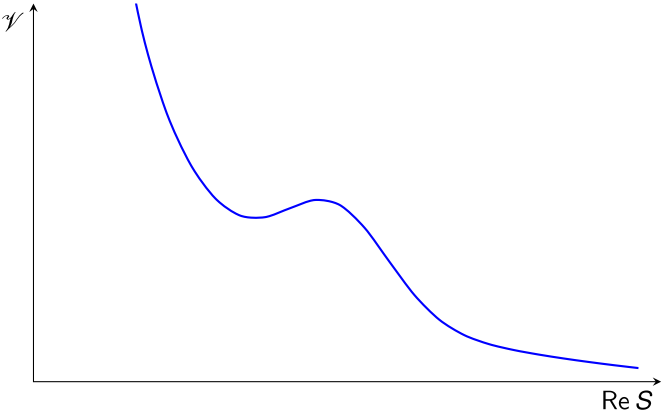

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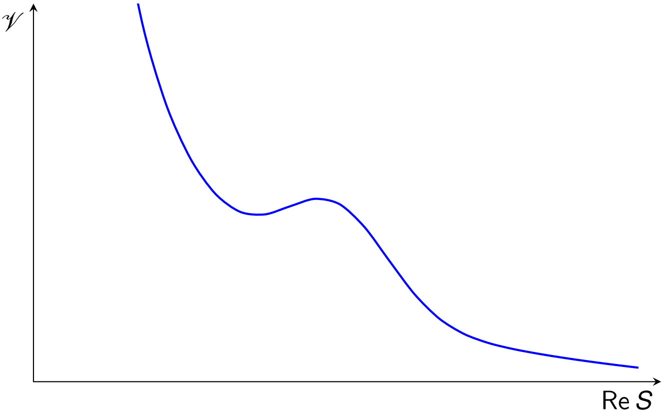

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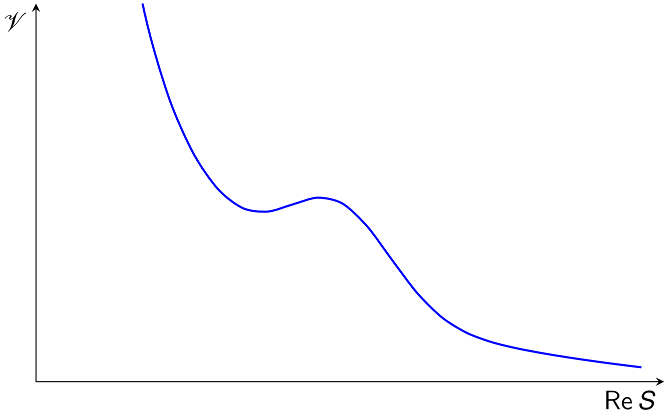

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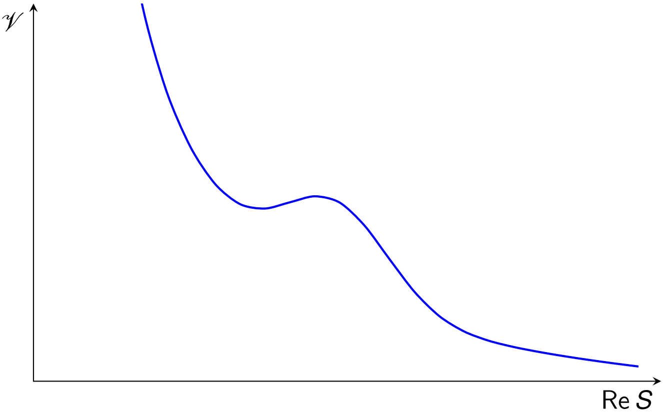

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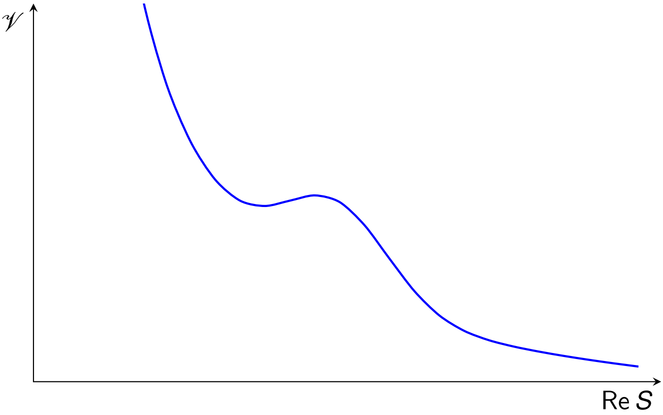

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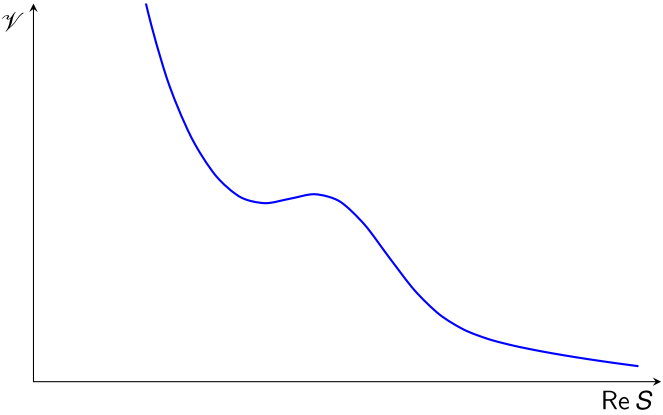

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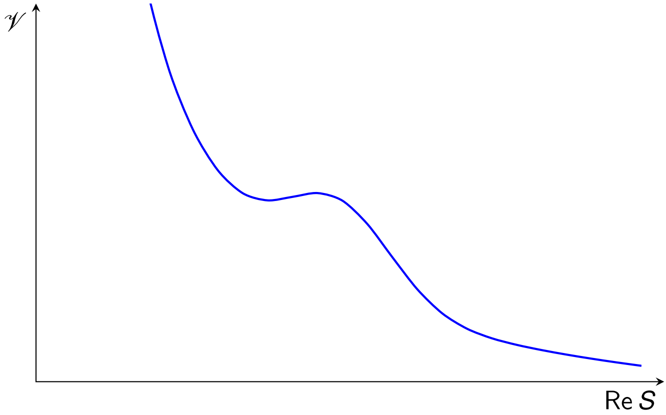

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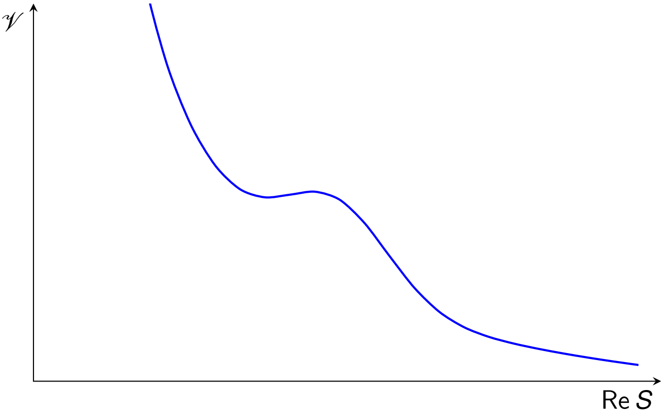

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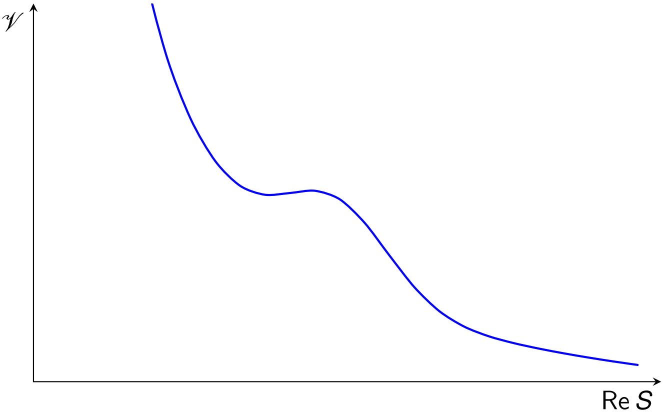

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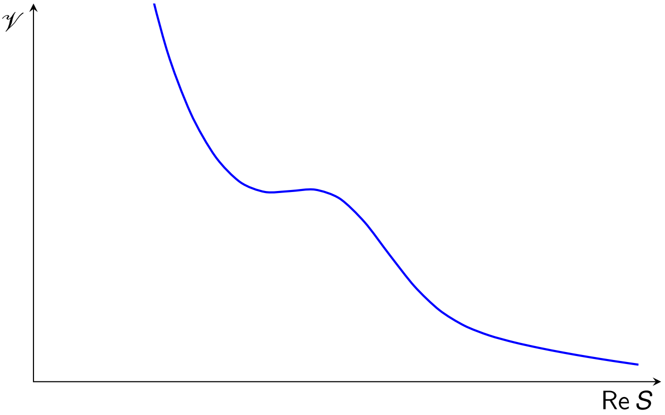

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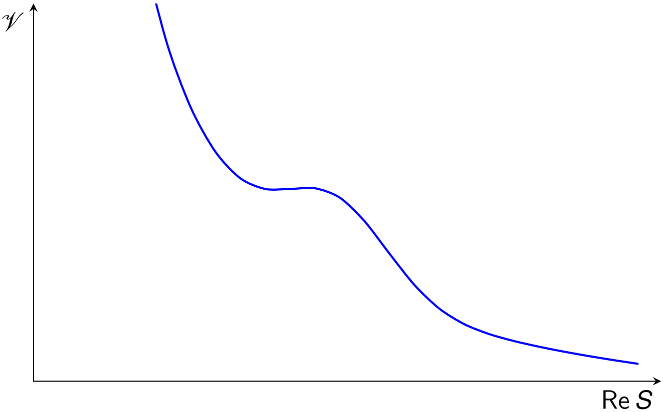

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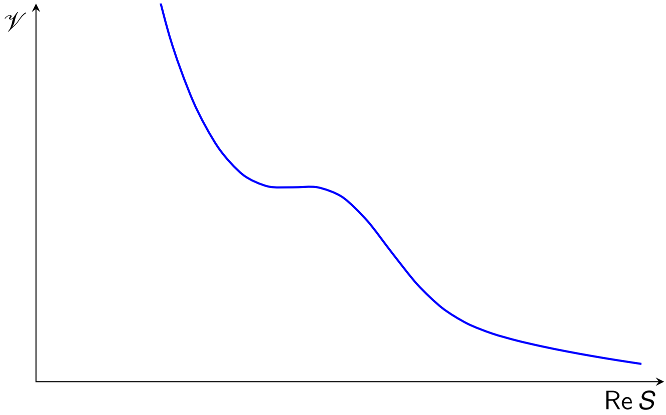

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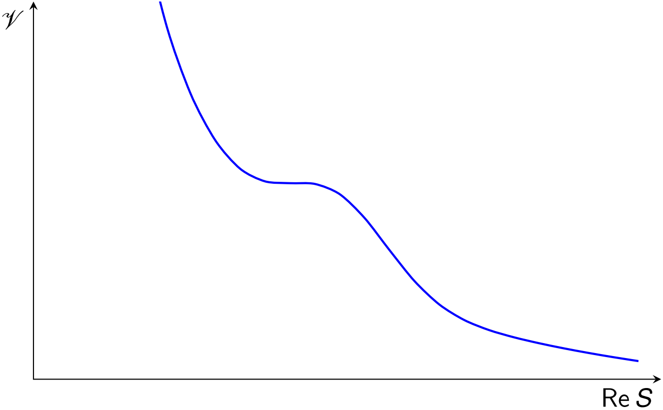

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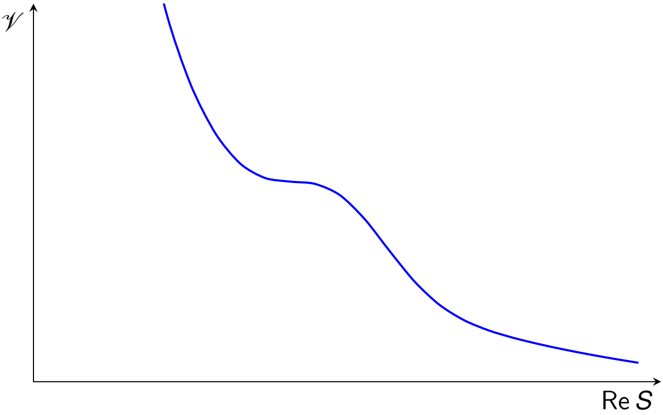

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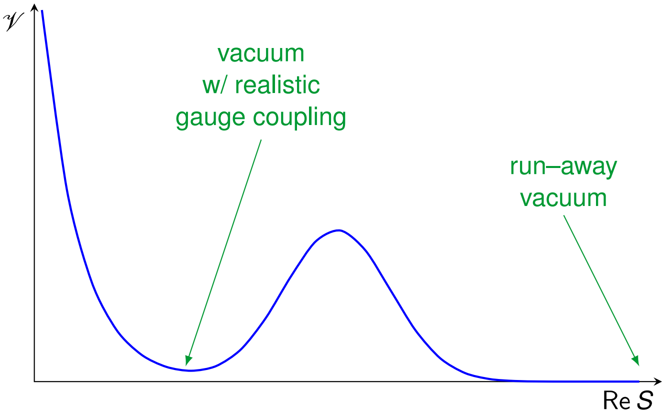
Critical temperature



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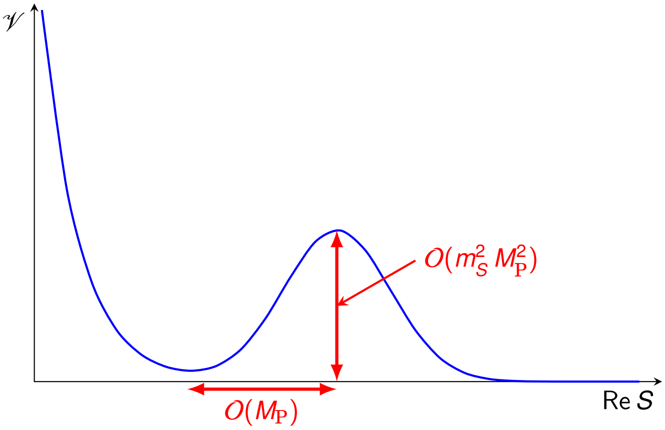

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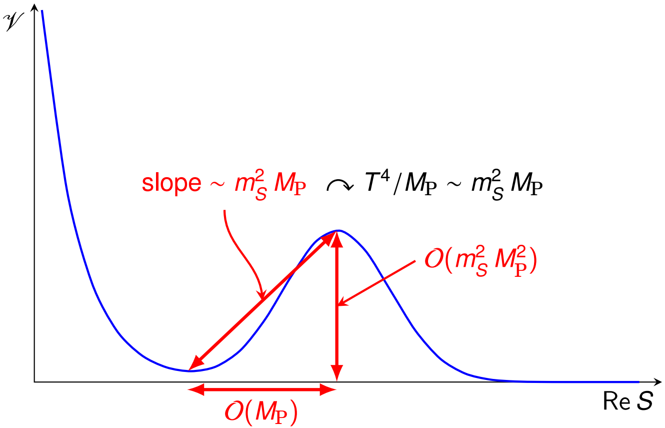

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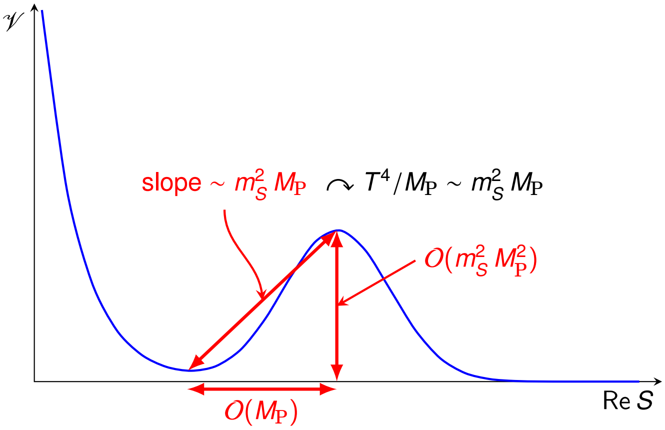

bottom–line:

critical temperature $T_* \sim \sqrt{m_S\, M_{\mathrm{P}}}$

Discussion

- ☞ if the dilaton has been destabilized, it will run away and cannot come back

model–independent contraint:

$$T_R \lesssim T_* \sim \sqrt{m_S M_\mathrm{P}}$$

reheating temperature (maximal temperature of the radiation dominated universe)

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Kallosh & Linde (2004)

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model–independent contraint:

$$T_R \lesssim T_* \sim \sqrt{m_S M_\mathrm{P}}$$

- model–dependent bounds on the energy density of the universe during inflation Kallosh & Linde (2004)
- the bounds can be circumvented by stabilizing the field combination that fixes the gauge coupling in a different way (i.e. w/ an infinite barrier) Kane & Winkler (2019)

Constraints

on

flavons

Field–dependent fermion masses

☞ e.g. Froggatt–Nielsen mechanism

Froggatt & Nielsen (1979)

$$\mathscr{L}_{\mathrm{FN}} = \sum_{i,j=1}^{3} y_{ij}^{u} \left(\frac{S}{\Lambda}\right)^{n_{ij}^{u}} \overline{Q}_i \, \widetilde{\Phi} \, u_j + \sum_{i,j=1}^{3} y_{ij}^{d} \left(\frac{S}{\Lambda}\right)^{n_{ij}^{d}} \overline{Q}_i \, \Phi \, d_j + \text{h.c.}$$

flavon

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$$\mathscr{V}_S = -\mu_S^2 |S|^2 + \lambda_S |S|^4 + \lambda_{S\Phi} |S|^2 |\Phi|^2 + \mathrm{U}(1)_{\mathrm{FN}} \text{ breaking terms}$$

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$$S = \frac{1}{\sqrt{2}} (v_S + \sigma + \mathrm{i}\,\rho)$$

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➥ VEV at $T = 0$

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- effective potential

$$\alpha = \gamma \frac{\partial T_Y}{\partial \varepsilon} \sim 10^{-2}$$

$$\mathscr{V}_{\mathrm{eff}}(\sigma, T) = \gamma\, T_Y\, T^4 + \alpha\, T^4 \frac{\sigma}{\Lambda} + \frac{m_\sigma^2(T)}{2} \sigma^2 + \frac{\kappa}{3!} \sigma^3 + \frac{\lambda_S}{4} \sigma^4 + \ldots$$

Flavon dynamics

Lillard, M.R., Tait & Trojanowski (2018)

☞ the flavon gets driven away from its $T = 0$ minimum until it gets stopped by the mass term or Hubble friction

$$\Delta\sigma \simeq -\alpha \frac{T^4}{\Lambda\, m_{\mathrm{eff}}^2} \qquad \text{where } m_{\mathrm{eff}}^2 = 6H^2 + m_\sigma^2$$

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- as the temperature decreases, the flavon undergoes oscillations around the $T = 0$ minimum, which behave like nonrelativistic matter

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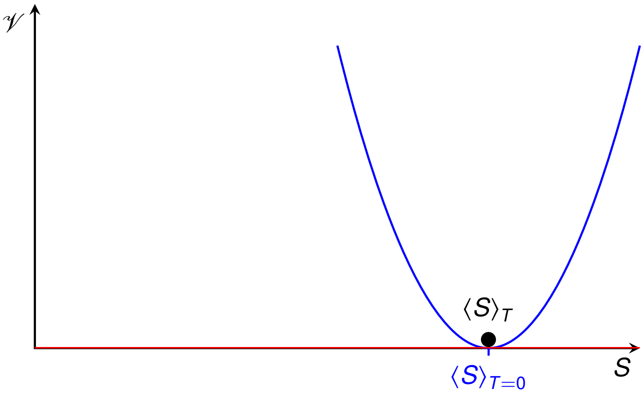

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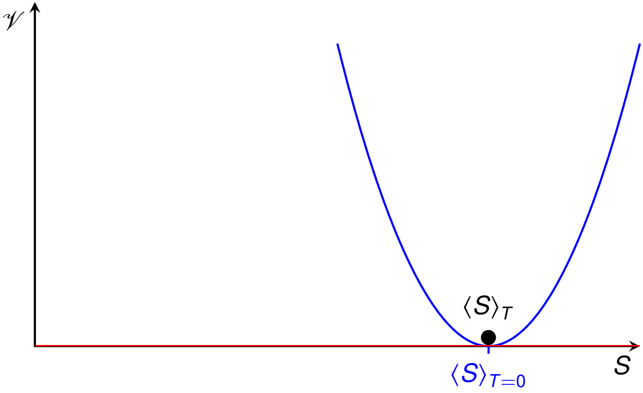

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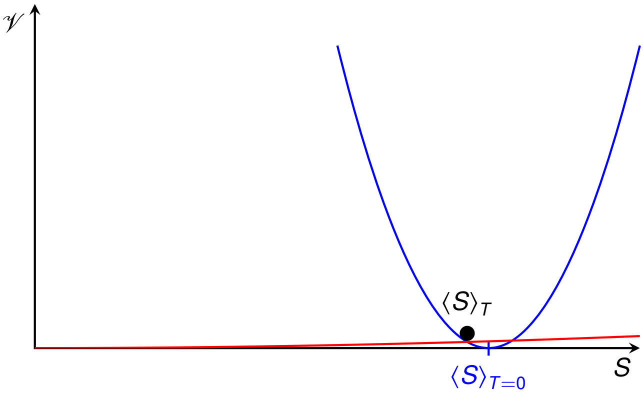

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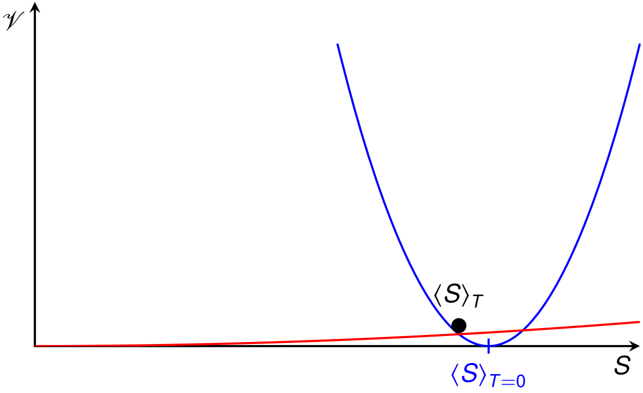

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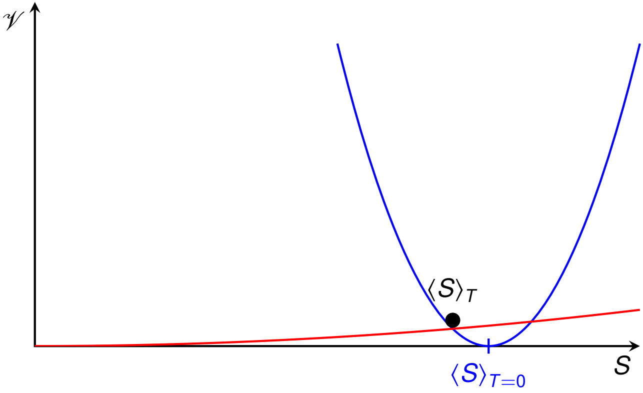

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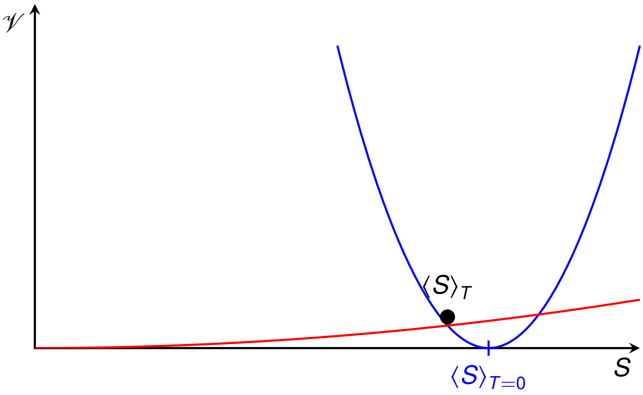

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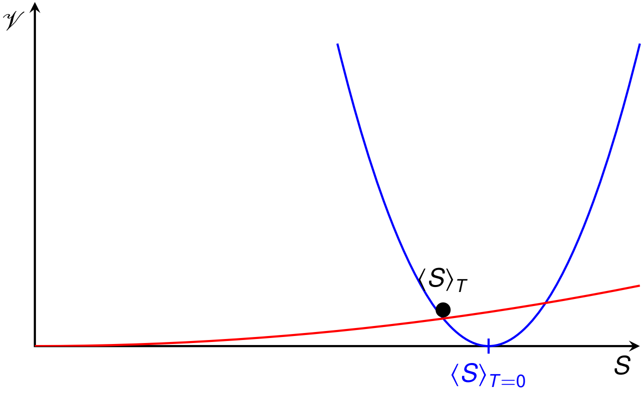

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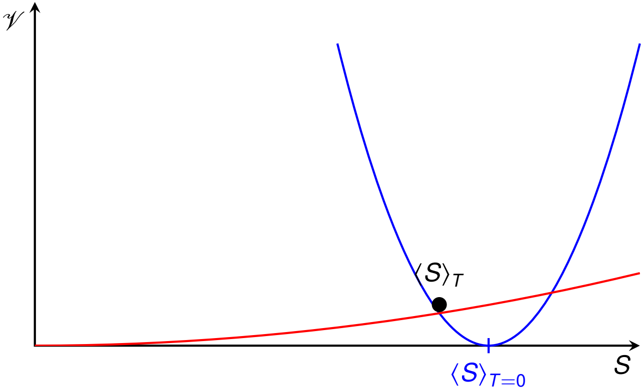

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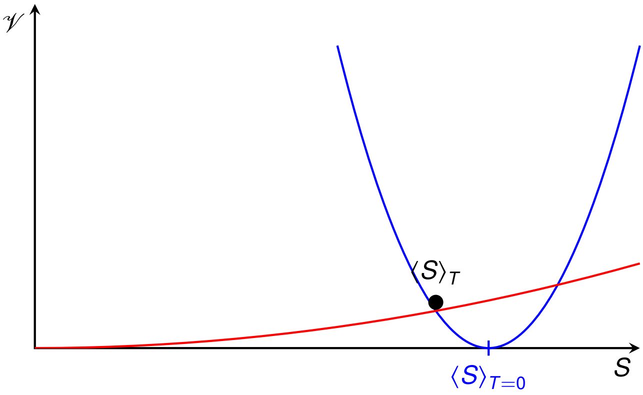

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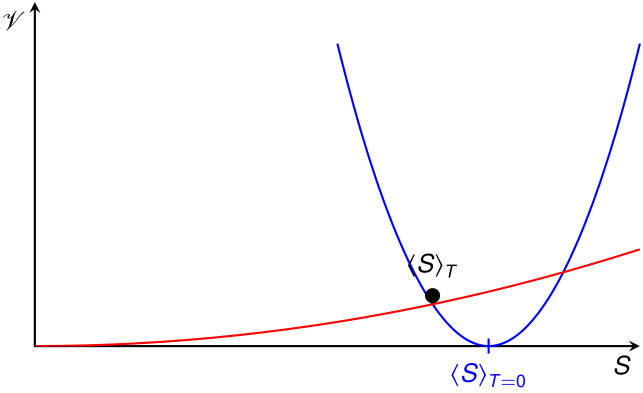

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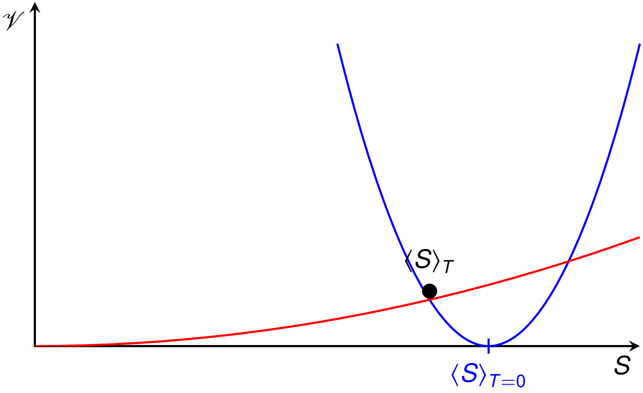

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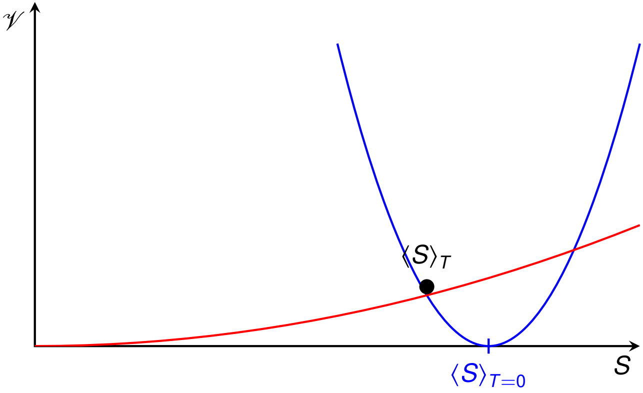

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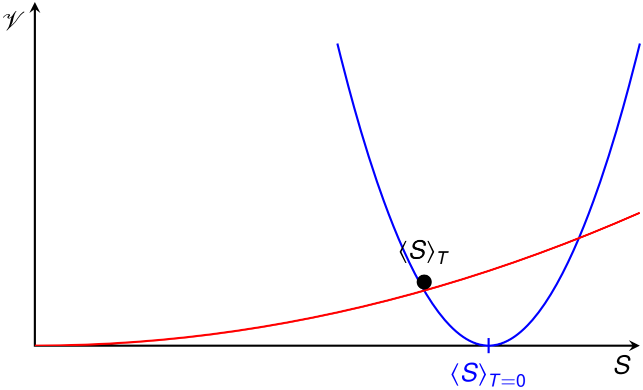

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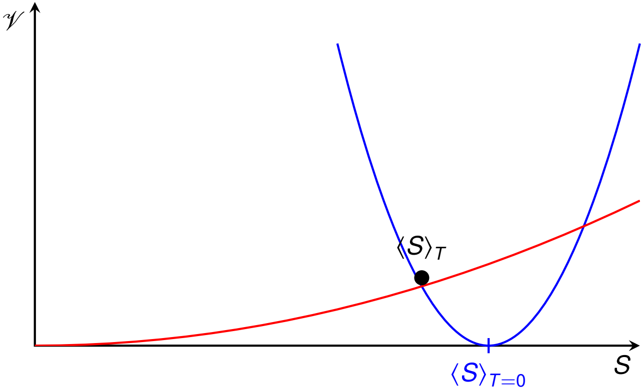

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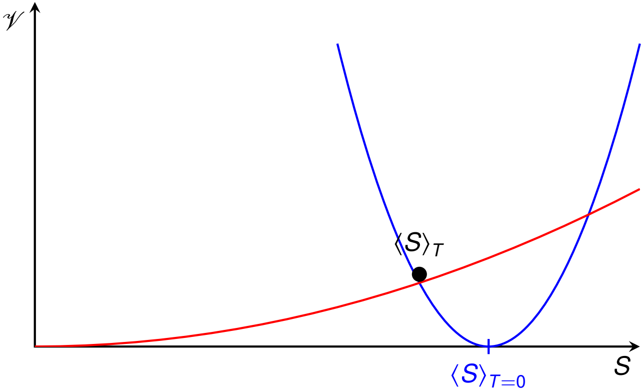

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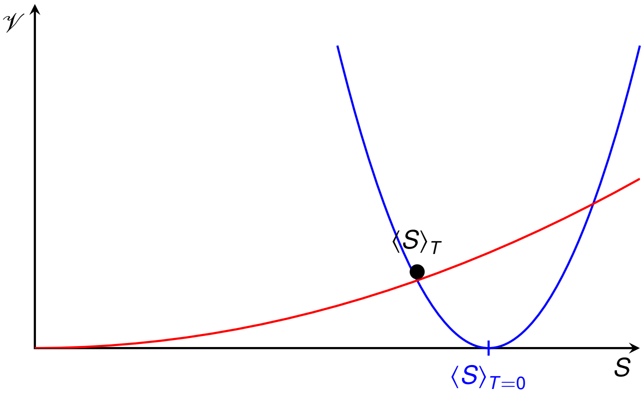

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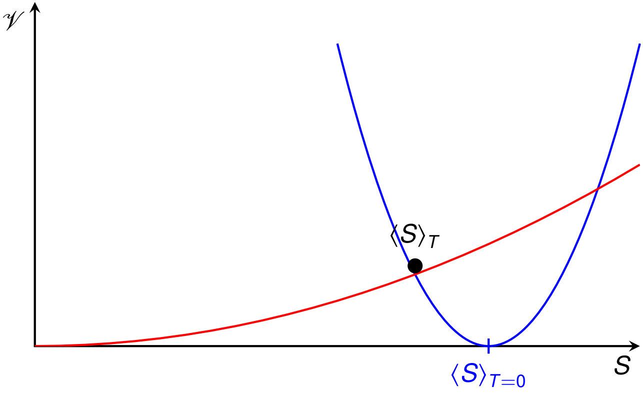

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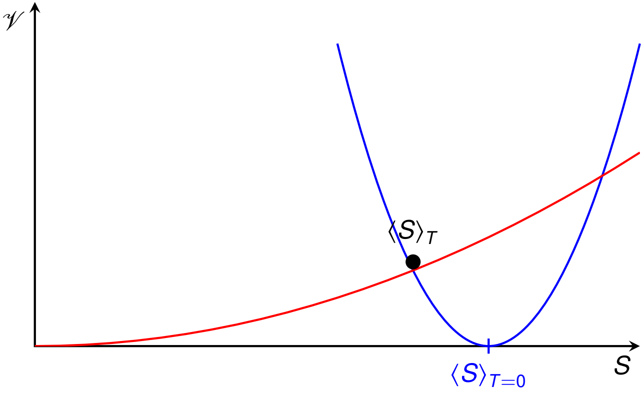

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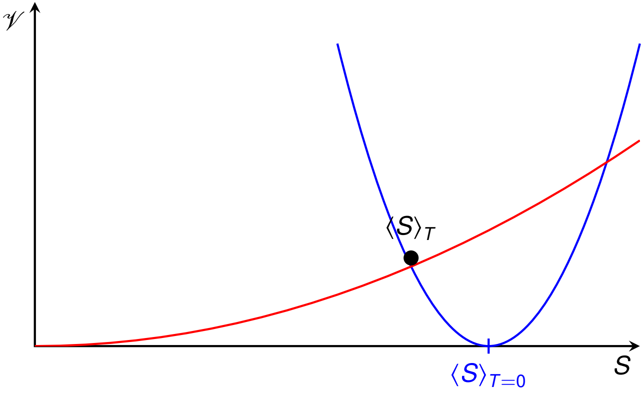

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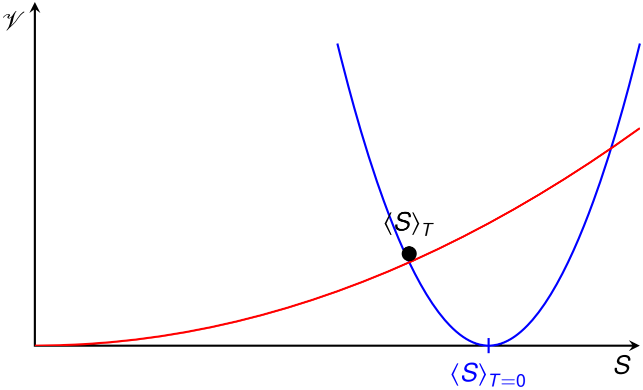

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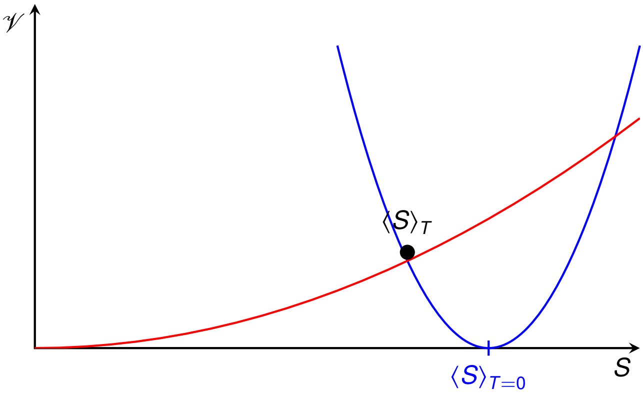

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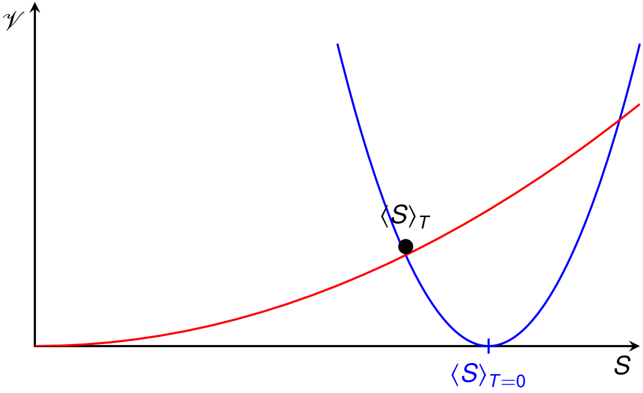

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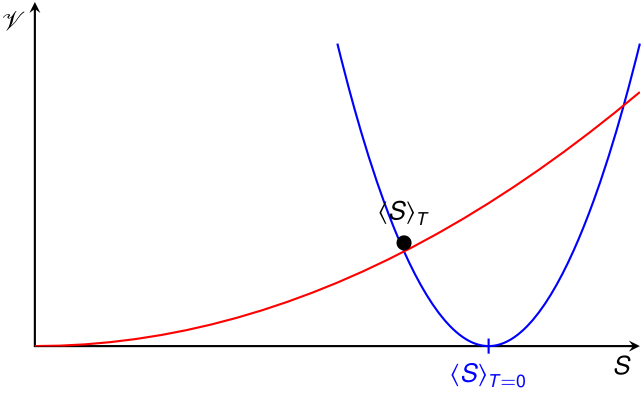

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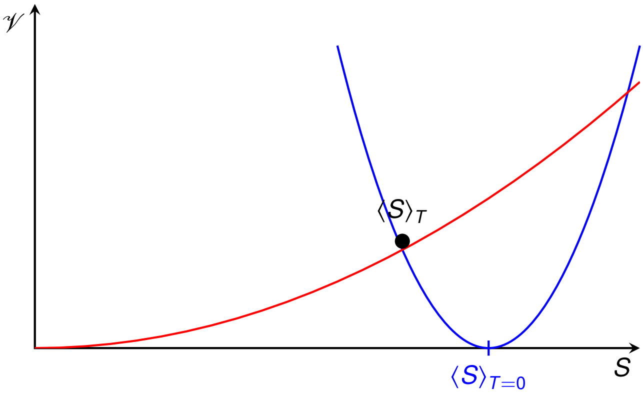

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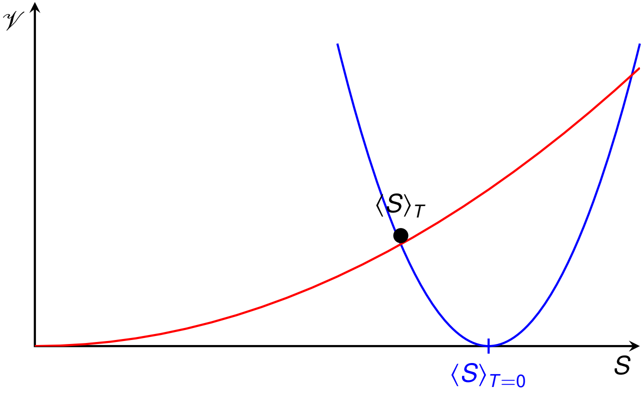

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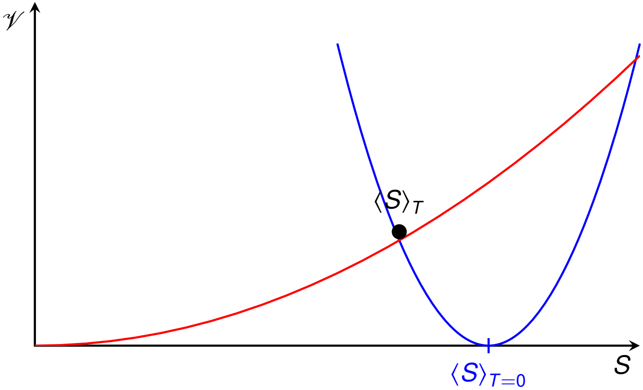

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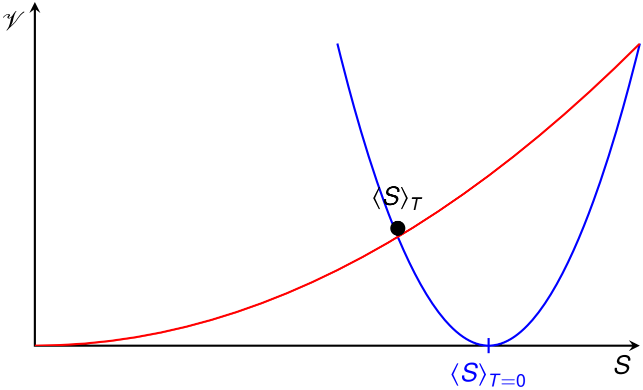

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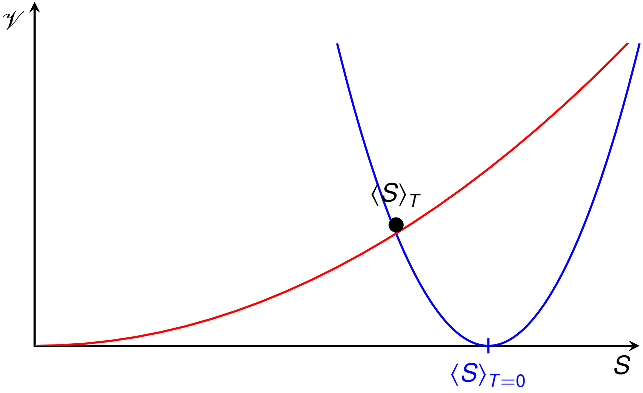

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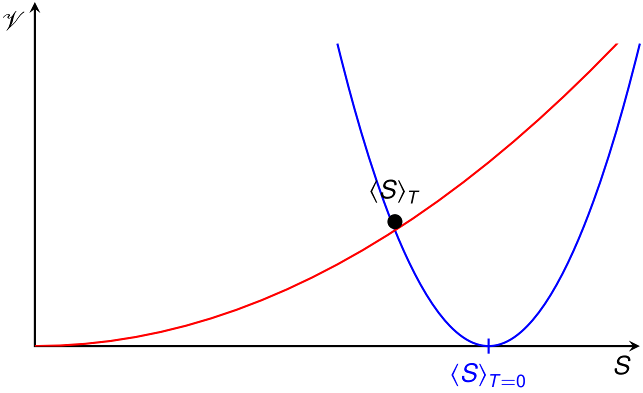

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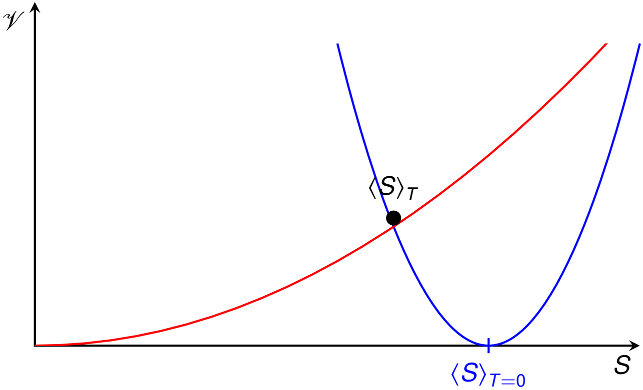

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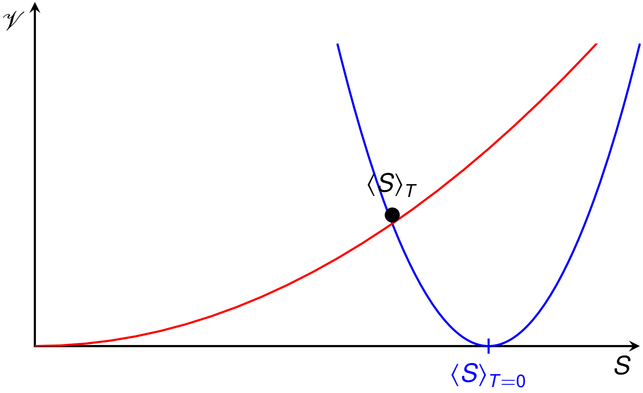

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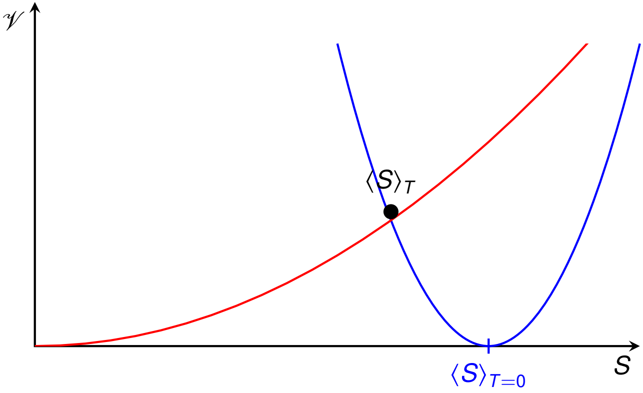

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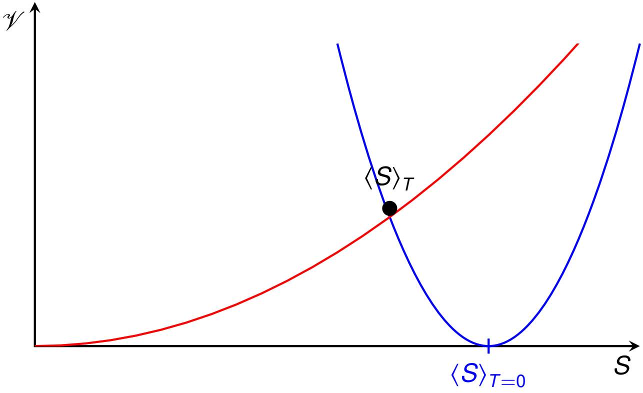

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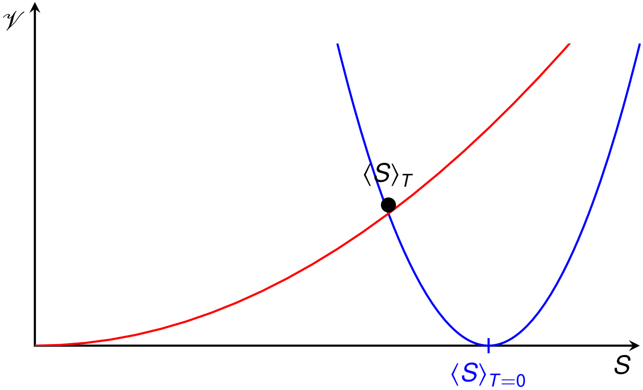

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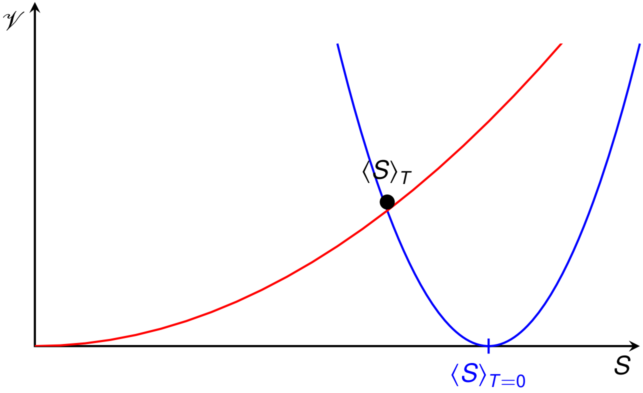

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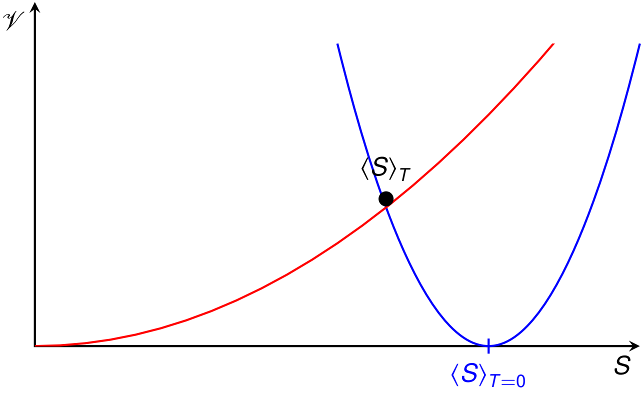

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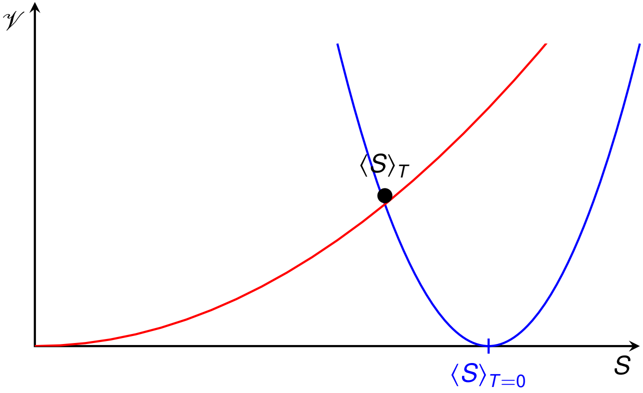

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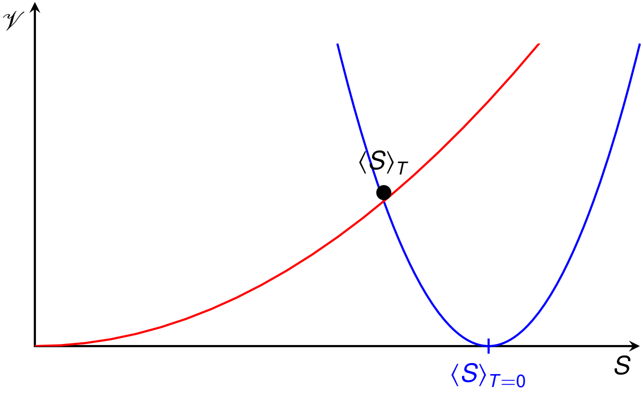

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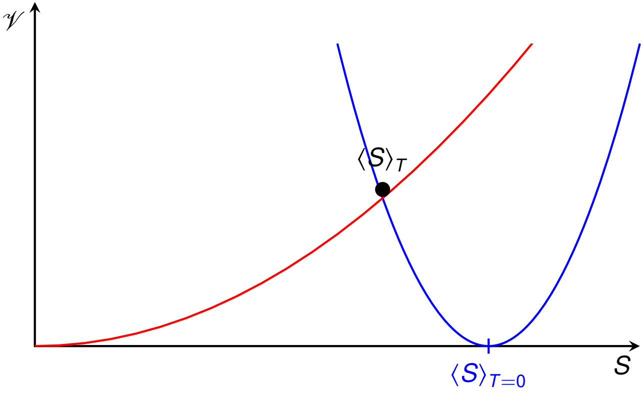

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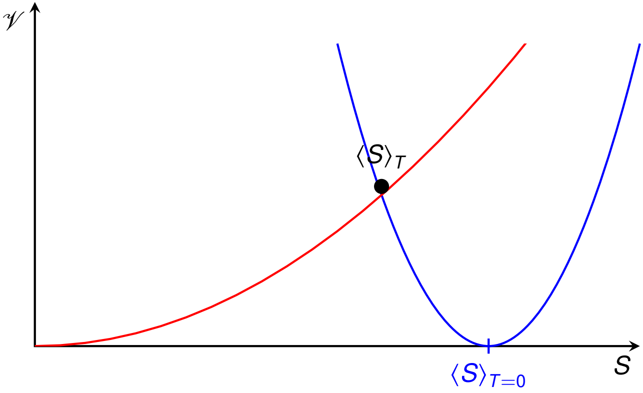

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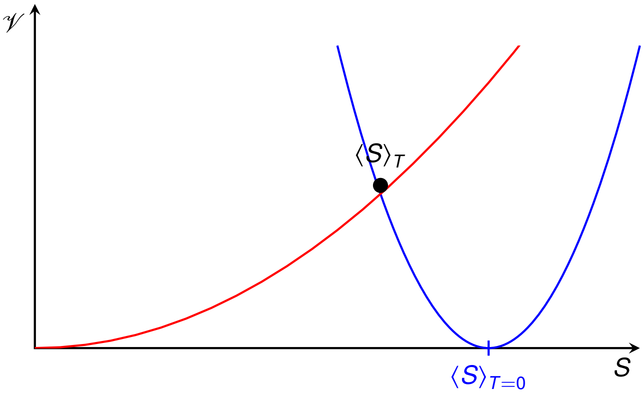

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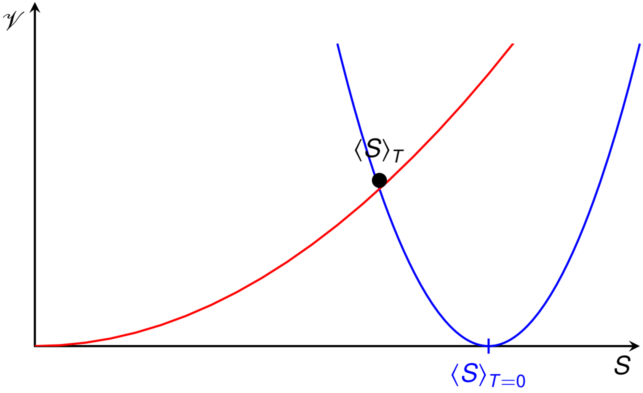

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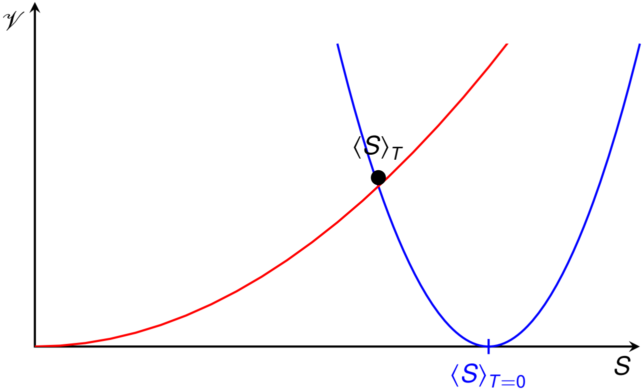

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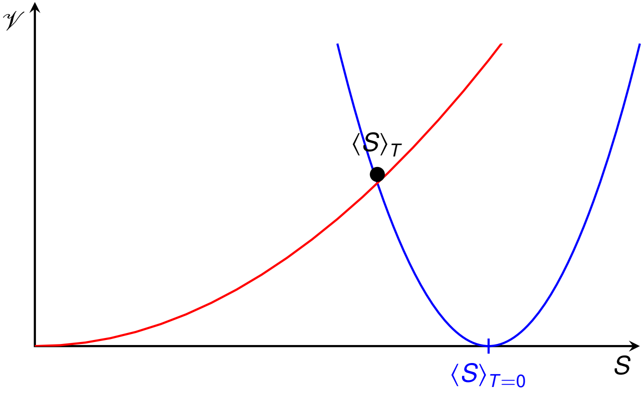

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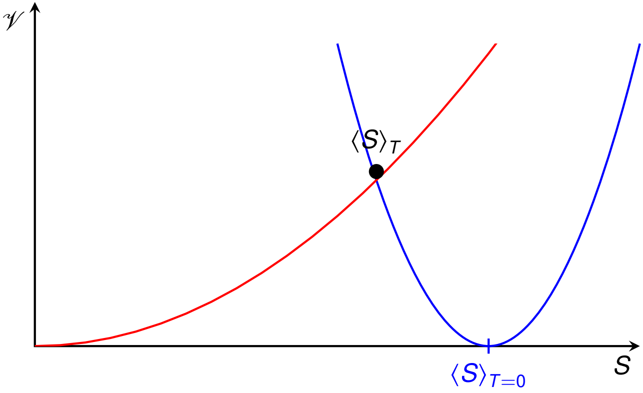

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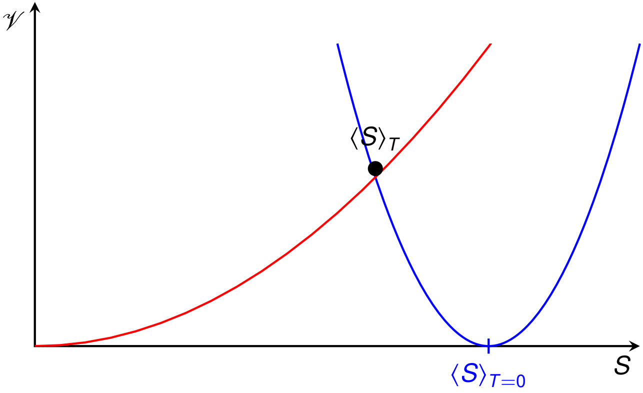

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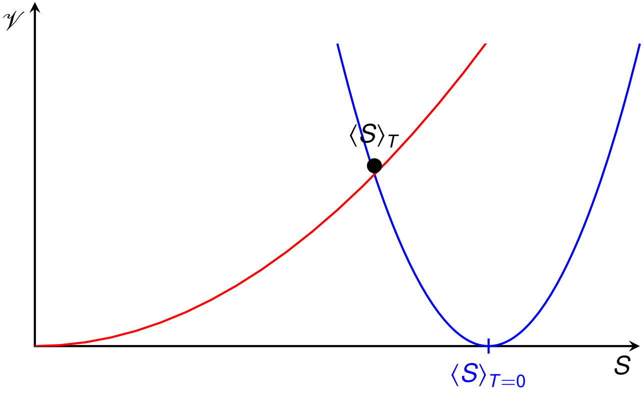

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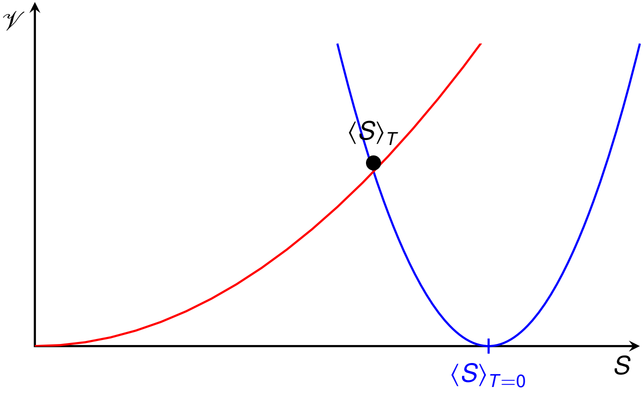

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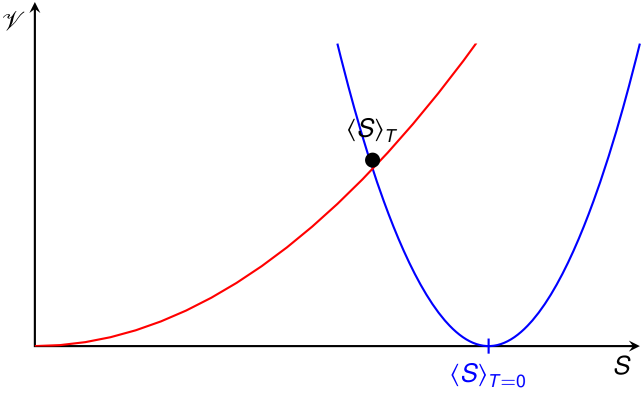

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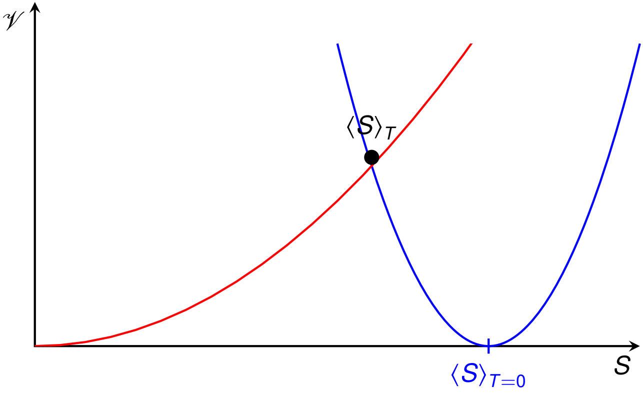

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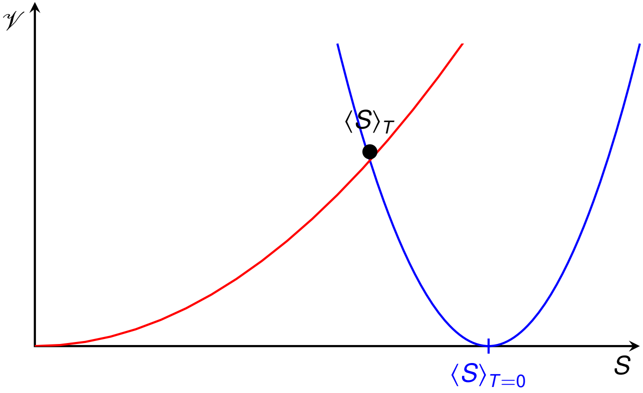
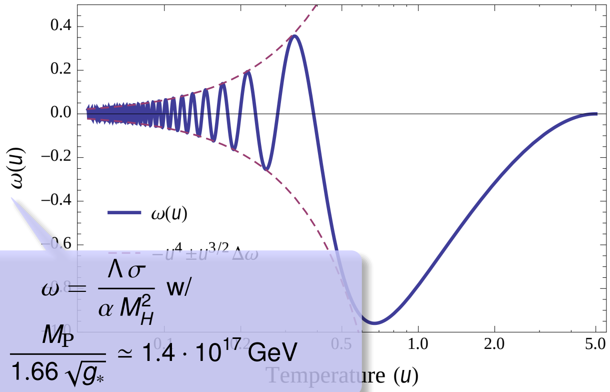


Flavon oscillations



$$\omega = \frac{\Lambda\,\sigma}{\alpha\, M_H^2} \text{ w/}$$

$$M_H = \frac{M_\mathrm{P}}{1.66\,\sqrt{g_*}} \simeq 1.4\cdot 10^{17}\,\mathrm{GeV}$$

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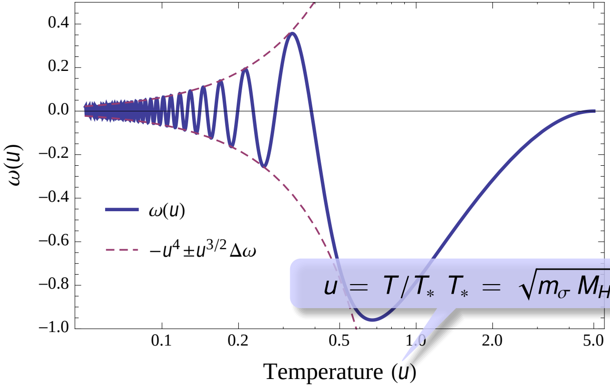

$u = T/T_*$ $T_* = \sqrt{m_\sigma M_H}$

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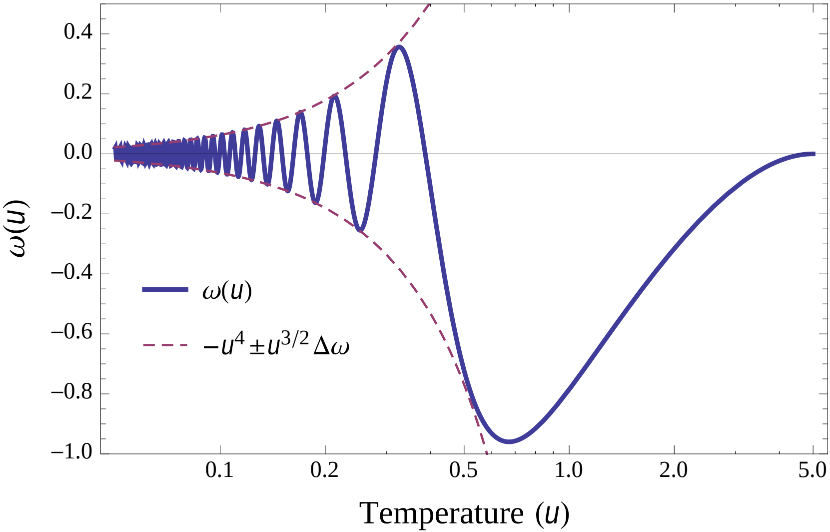

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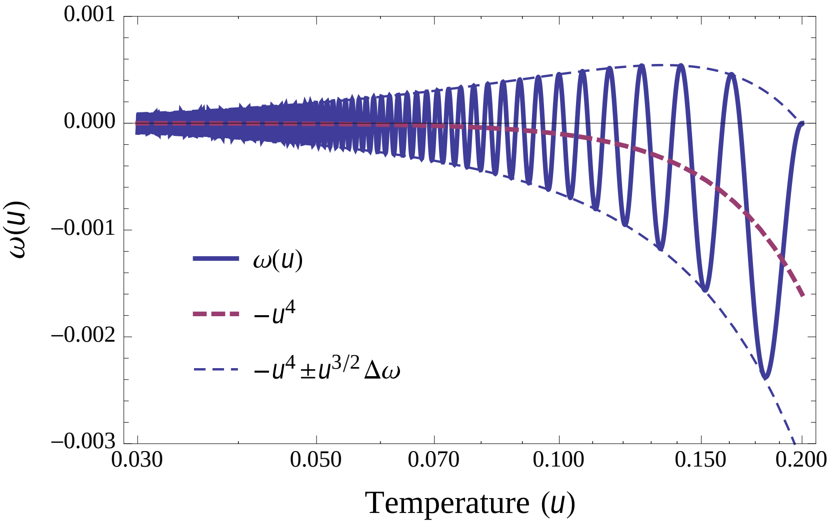

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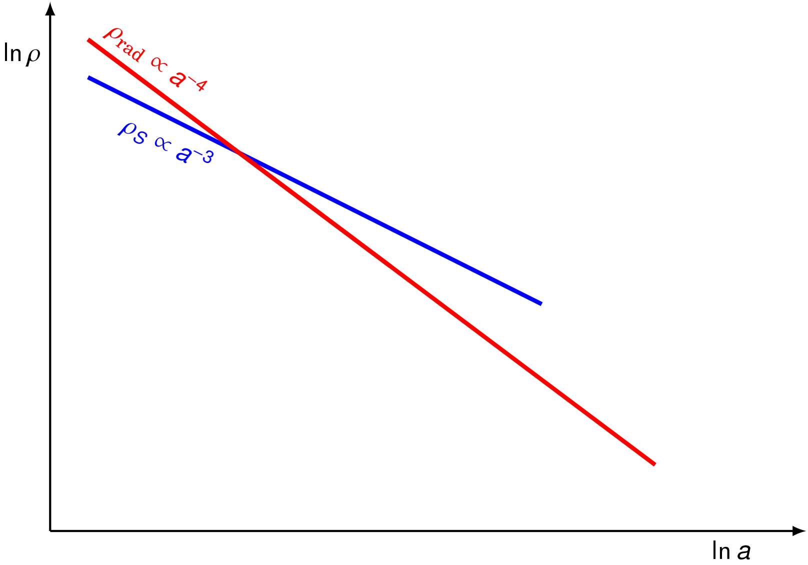

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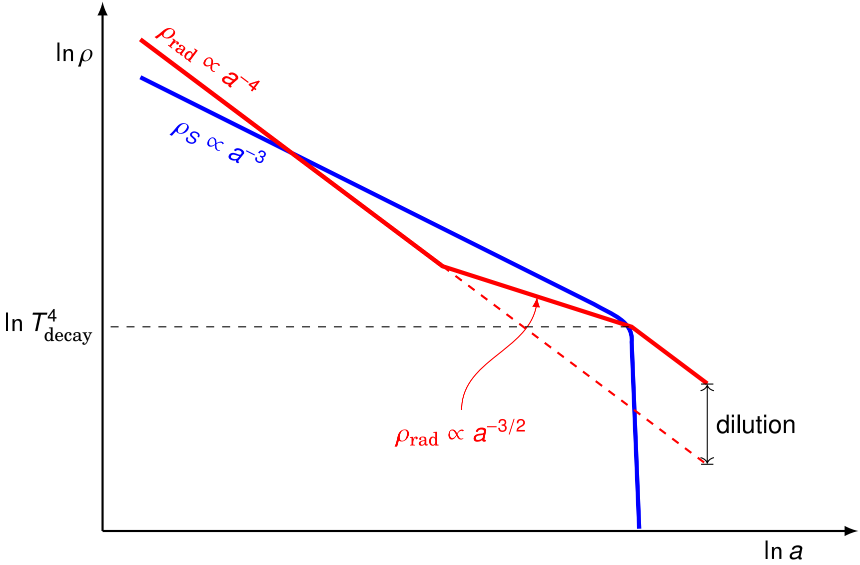

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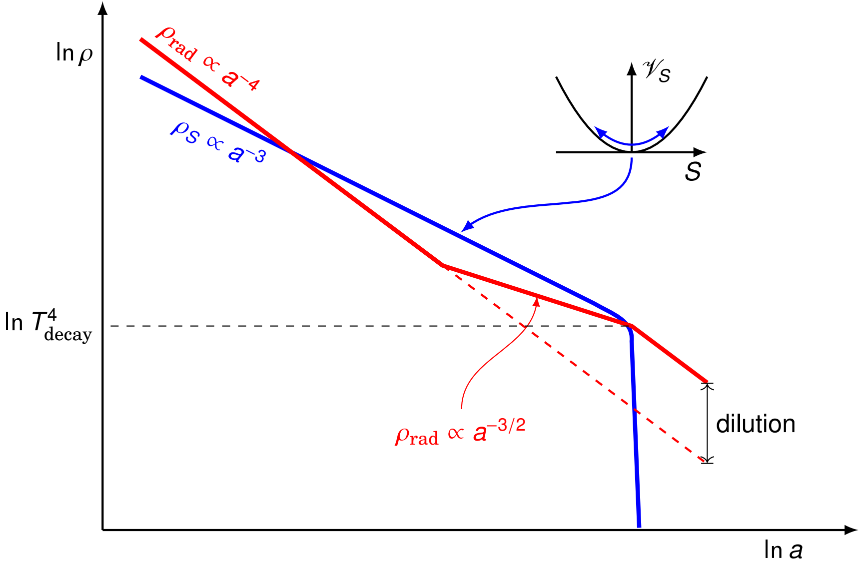

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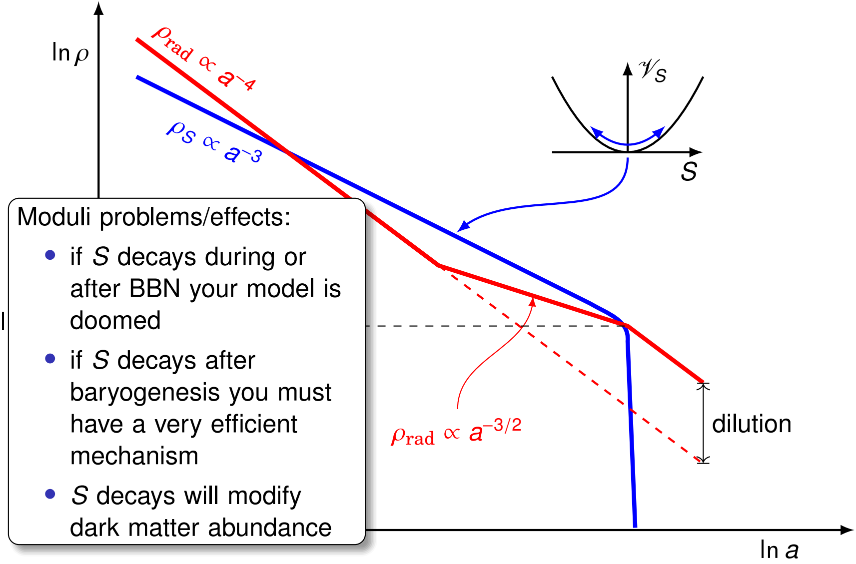

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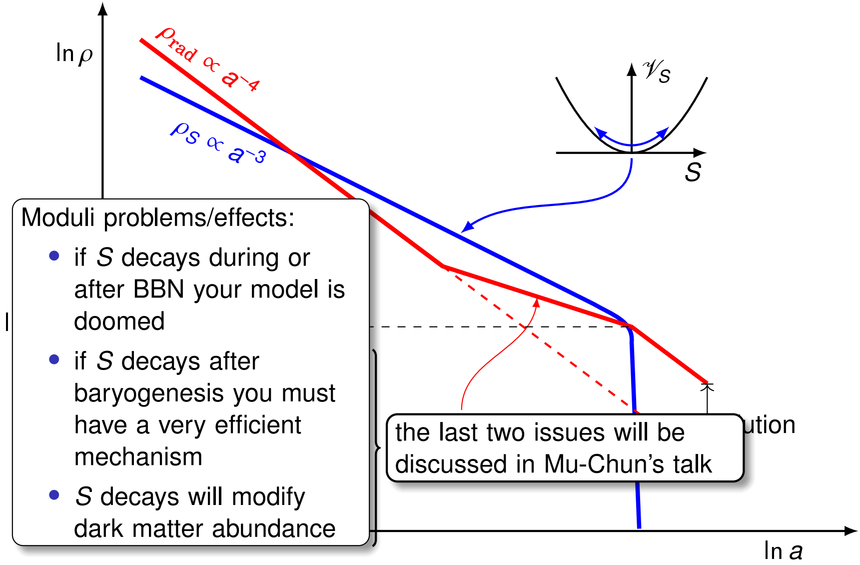

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the last two issues will be discussed in Mu-Chun's talk

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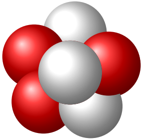

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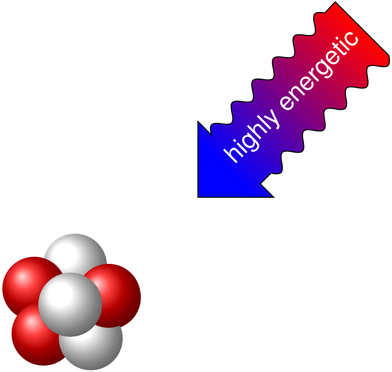

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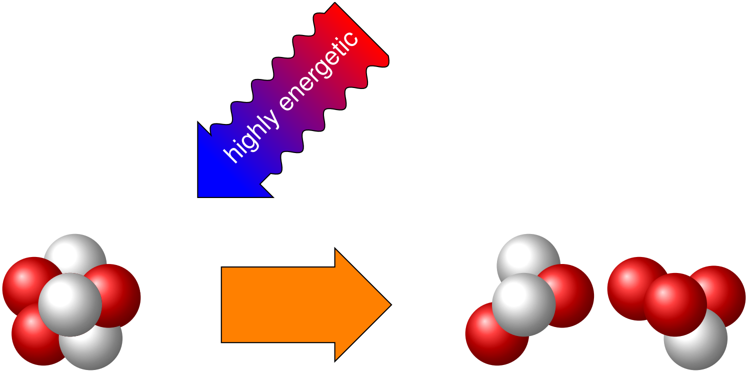

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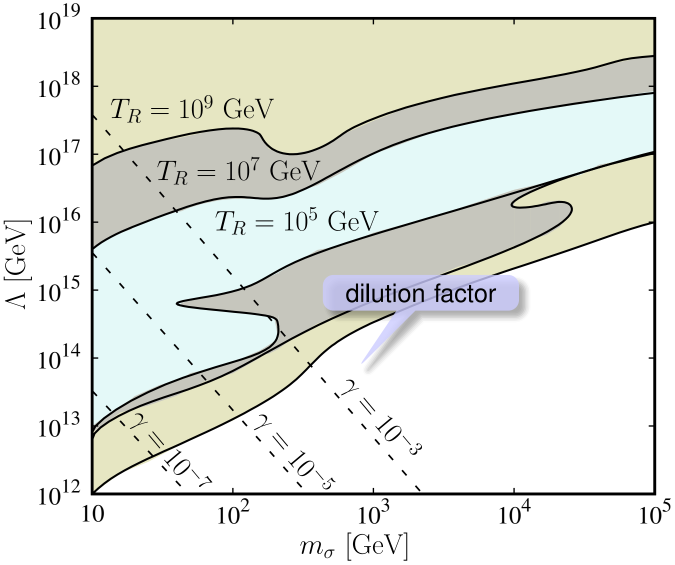

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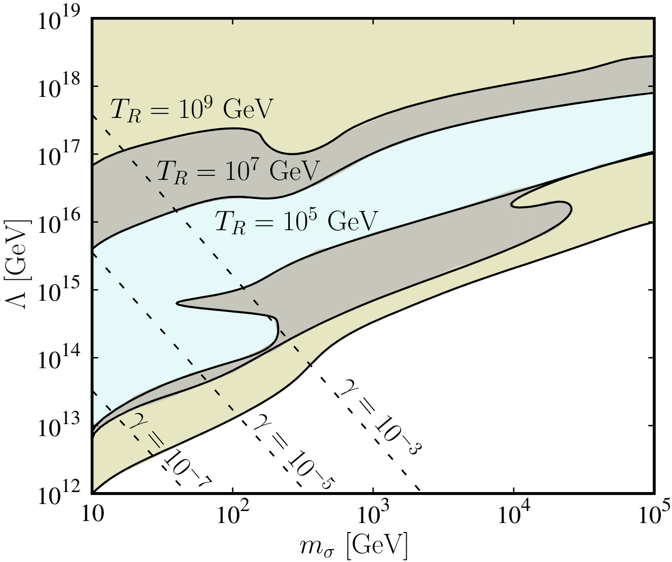

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bottom–line:

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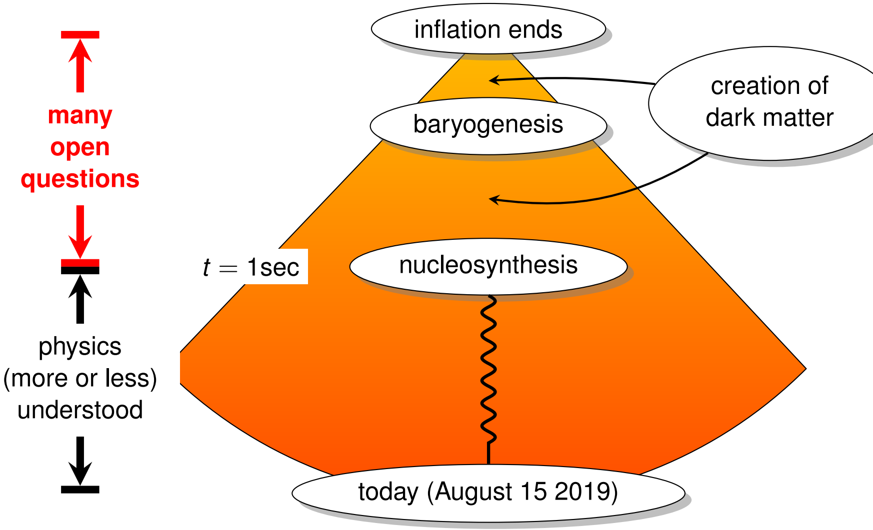
many
open
questions
physics
(more or less)
understood
inflation ends
creation of
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$t = 1\text{sec}$
nucleosynthesis
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Thanks a lot!

References I

Martin Bauer, Torben Schell & Tilman Plehn. Hunting the Flavon. *Phys. Rev.*, D94(5):056003, 2016. doi: 10.1103/PhysRevD.94.056003.

Wilfried Buchmüller, Koichi Hamaguchi, Oleg Lebedev & Michael Ratz. Dilaton destabilization at high temperature. *Nucl. Phys.*, B699: 292–308, 2004.

G. D. Coughlan, W. Fischler, Edward W. Kolb, S. Raby & Graham G. Ross. Cosmological Problems for the Polonyi Potential. *Phys. Lett.*, B131:59, 1983. doi: 10.1016/0370-2693(83)91091-2.

B. de Carlos, J.A. Casas, F. Quevedo & E. Roulet. Model independent properties & cosmological implications of the dilaton & moduli sectors of 4-d strings. *Phys. Lett.*, B318:447–456, 1993. doi: 10.1016/0370-2693(93)91538-X.

C.D. Froggatt & Holger Bech Nielsen. Hierarchy of Quark Masses, Cabibbo Angles & CP Violation. *Nucl. Phys.*, B147:277, 1979. doi: 10.1016/0550-3213(79)90316-X.

References II

Renata Kallosh & Andrei D. Linde. Landscape, the scale of SUSY breaking & inflation. *JHEP*, 0412:004, 2004. doi: 10.1088/1126-6708/2004/12/004.

Gordon Kane & Martin Wolfgang Winkler. Deriving the Inflaton in Compactified M-theory with a De Sitter Vacuum. 2019.

M. Yu. Khlopov & Andrei D. Linde. Is It Easy to Save the Gravitino? *Phys. Lett.*, 138B:265–268, 1984. doi: 10.1016/0370-2693(84)91656-3.

Lev Kofman, Andrei D. Linde, Xiao Liu, Alexander Maloney, Liam McAllister & Eva Silverstein. Beauty is attractive: Moduli trapping at enhanced symmetry points. *JHEP*, 05:030, 2004. doi: 10.1088/1126-6708/2004/05/030.

Benjamin Lillard, Michael Ratz, M. P. Tait, Tim & Sebastian Trojanowski. The Flavor of Cosmology. *JCAP*, 1807(07):056, 2018. doi: 10.1088/1475-7516/2018/07/056.