Baryogenesis in the presence of thermal inflation

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WIP, JHEP **1007**, 085 (2010)
S. Kim, WIP and E. D. Stewart, JHEP **0901**, 015 (2009)
G. N. Felder, H. Kim, WIP and E. D. Stewart, JCAP **0706**, 005 (2007)
D. -h. Jeong, K. Kadota, WIP and E. D. Stewart, JHEP **0411**, 046 (2004)

See also,
K. Choi, E. J. Chun, H. D. Kim, WIP and C. S. Shin, Phys. Rev. D **83**, 123503 (2011)
K. Choi, K. S. Jeong, WIP and C. S. Shin, JCAP **0911**, 018 (2009)
R. Easther, J. T. Giblin, Jr., E. A. Lim, WIP and E. D. Stewart, JCAP **0805**, 013 (2008)
Y. G. Kim, H. M. Lee and WIP, JHEP **1108**, 126 (2011)

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Outline

- Relic problem in standard cosmology
- Thermal inflation
- Compatibility of known mechanisms of baryogenesis
- Baryogenesis after thermal inflation
- Summary

"In the beginning was inflation"

- The belief(?) of the modern cosmology -

Standard cosmology

- Inflation solves

  - Large scale homogeneity
  - Spatial flatness (or oldness)
  - Relic problem (e.g, monopoles)
  - Small scale inhomogeneity (density perturbation)

- But there is no convincing model yet.

- It can not solve

  - Relic problem occuring after inflation

Relic problem in the standard cosmology

- String theories have many flat directions. They determine

  - internal structure of the compactified extra 6-D
  - the strength of gauge/Yukawa interactions

They should be stabilized at a nearly flat Minkowski vacuum.

- SUSY is broken.
- Moduli potential might be the main source of SUSY-breaking.

$$\left.\begin{array}{l} m_{3/2} \sim F_T/M_{\rm P} \\ m_T \sim \left(\dfrac{\partial^2 V}{\partial T^2}\right)^{1/2} \sim \dfrac{F_T}{T} \end{array}\right\} \Rightarrow m_T \sim m_{3/2} \text{ for } \langle T \rangle \sim M_{\rm P}$$

- Long living particles (gravitinos, moduli)

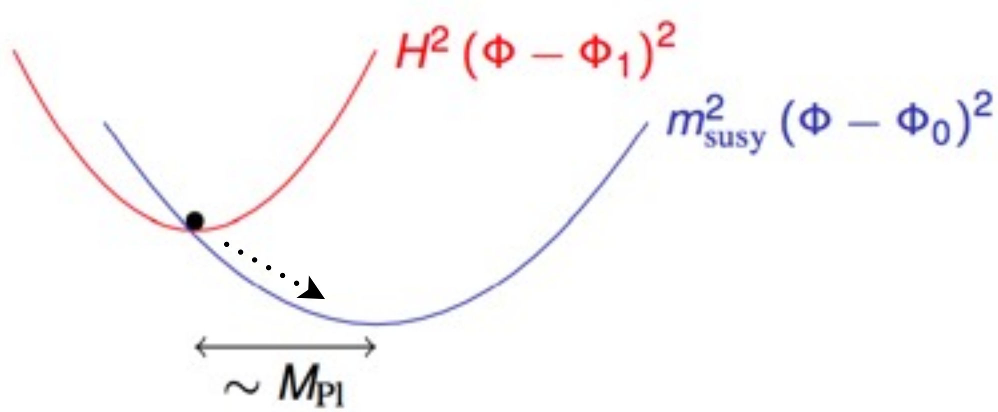
Mass: $m_T = \mathcal{O}(10^{\pm ?}) m_{3/2} = \mathcal{O}(10^{\pm ?}) m_{\rm soft}$

Coupling: $\lambda \propto 1/M_{\rm P} \Rightarrow \Gamma \sim \frac{1}{8\pi} \frac{m_T^3}{M_{\rm P}^2}$

Life-time: $m_T \lesssim \mathcal{O}(10)\,{\rm TeV} \Rightarrow \tau_T \gtrsim 1{\rm sec}$

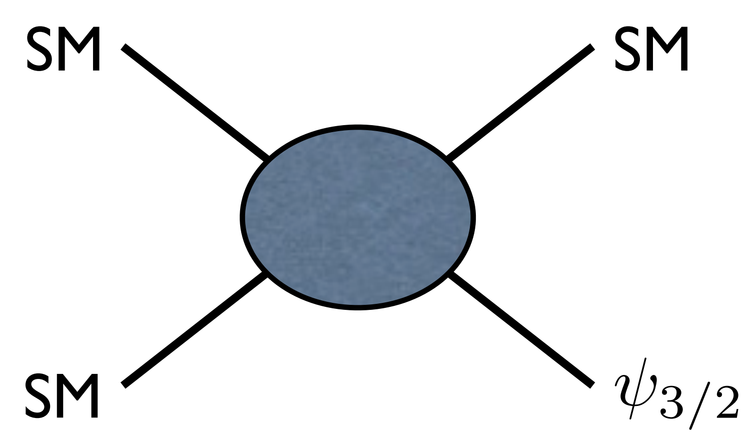
Production:

Coherent oscillation



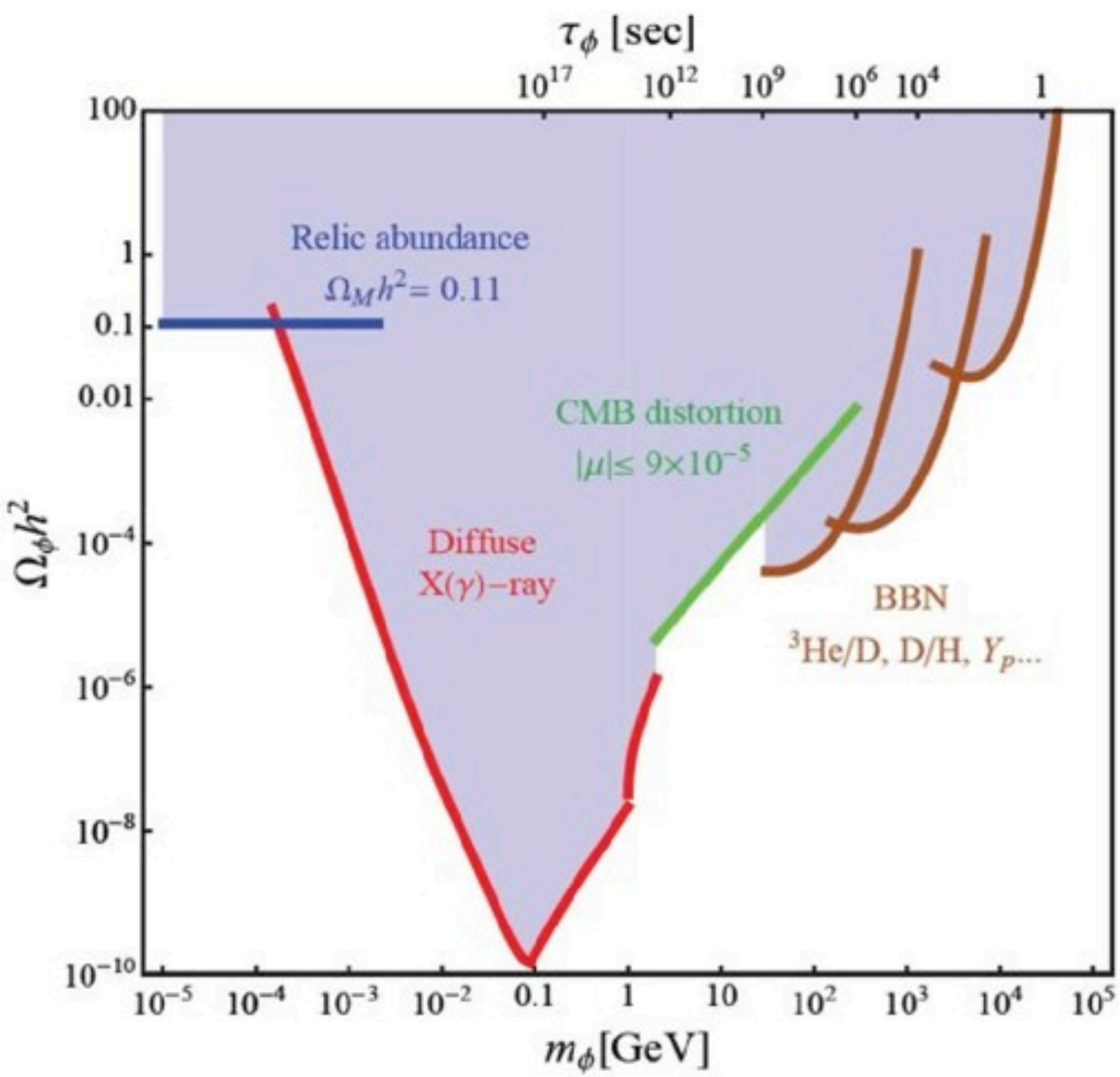
$$\frac{n_\phi}{s} \sim \left(\frac{M_{\rm P}}{m_\phi}\right)^{1/2} \sim 10^{7-8}$$

Thermal scattering



$$\frac{n_{3/2}}{s} \sim \frac{T_{\rm R}}{M_{\rm P}} \left(\frac{m_{\rm soft}}{m_{3/2}}\right)^2$$

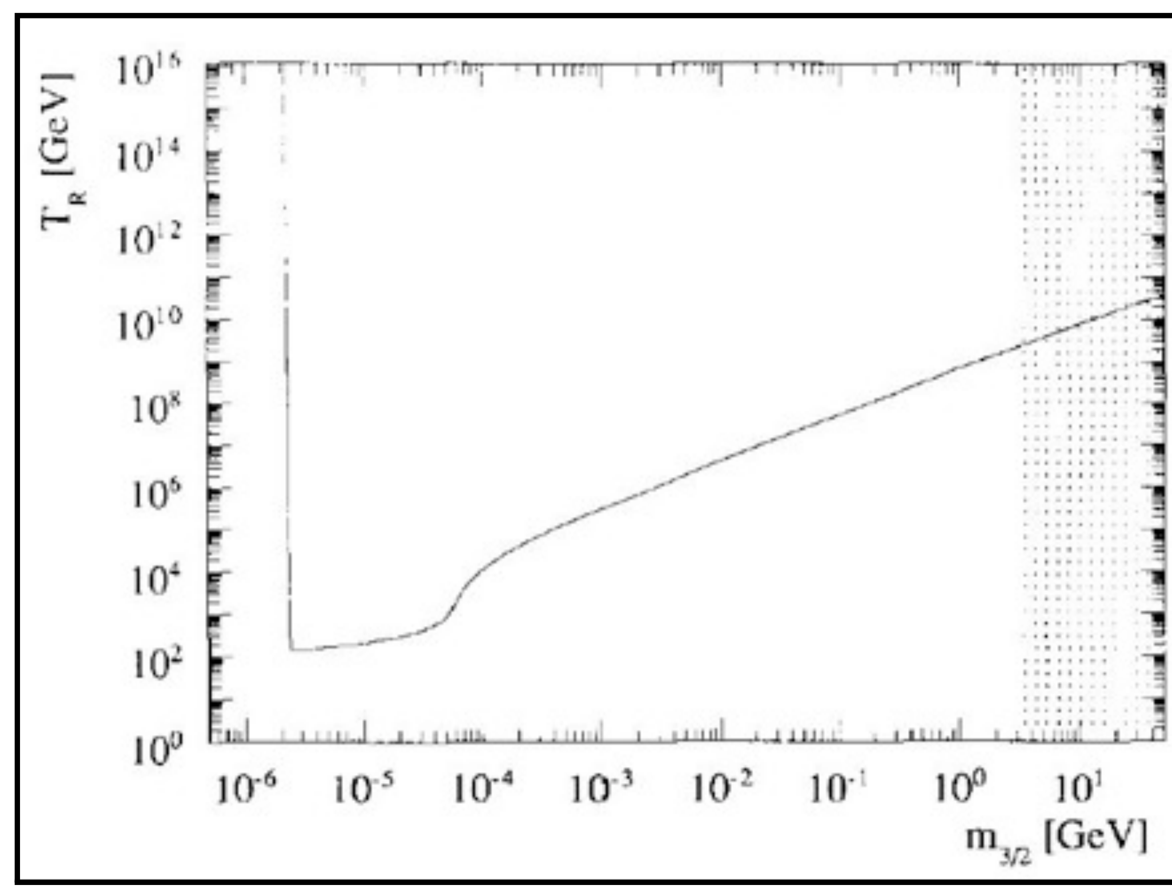
- Constraints



Observational bounds on the abundance of moduli

$$\frac{Y_\phi^{\rm th}}{Y_\phi^{\rm obs}} \sim 10^{23} \text{ if } m_\phi \sim 100\text{GeV}$$

The bound on the reheating temperature of inflation for the gravitino LSP

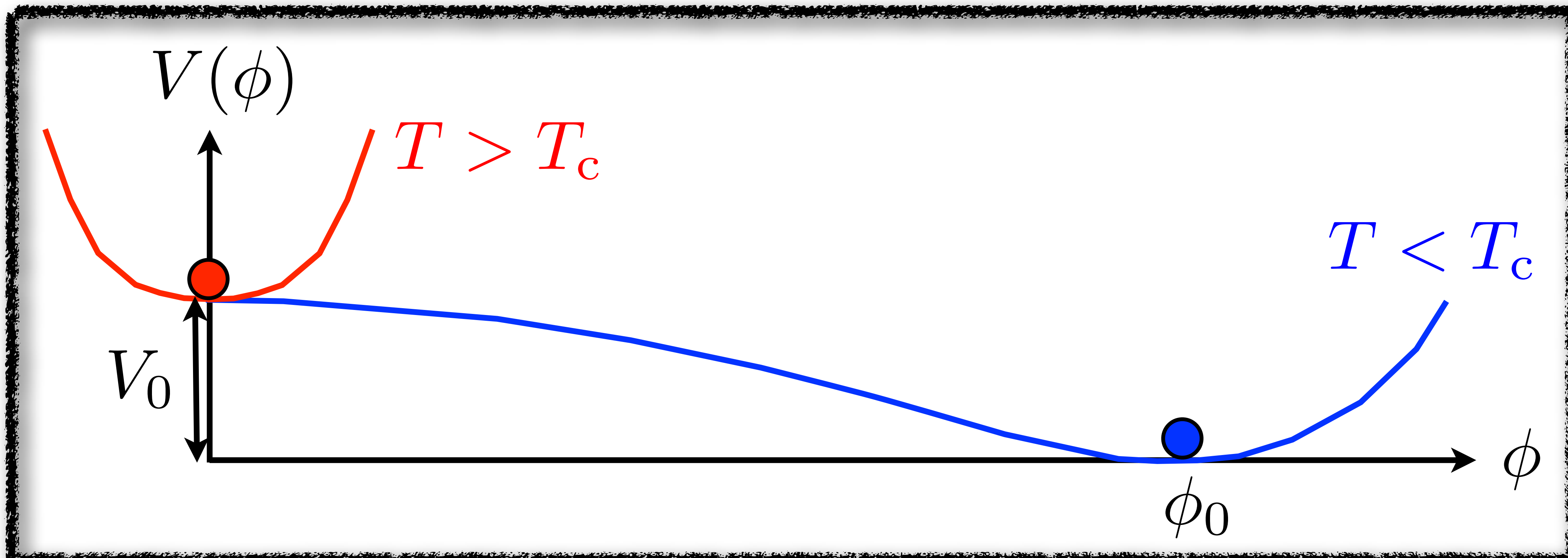


[Moroi, Murayama & Yamaguchi (1993)]

Thermal inflation

[Lyth & stewart, (1995)]

- Symmetry breaking flat direction

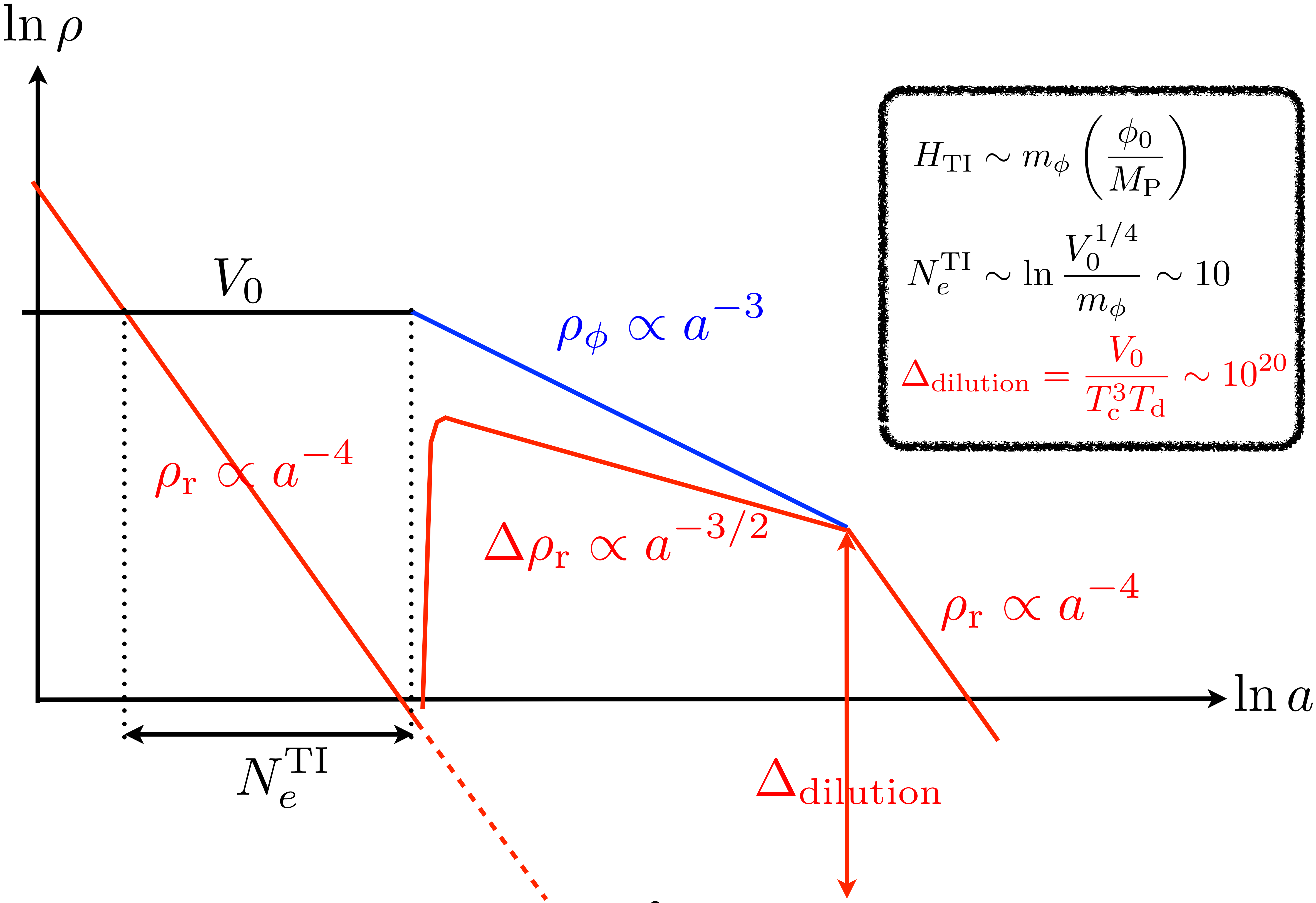


$$V(\phi) = V_0 + \frac{1}{2}\left(g^2 T^2 - m_\phi^2\right)\phi^2 + \dots$$

$T > m_\phi/g$: V_0 can dominate the universe $\Rightarrow$ Inflation!

$T < m_\phi/g$: ϕ rolls down $\Rightarrow$ Inflation ends.

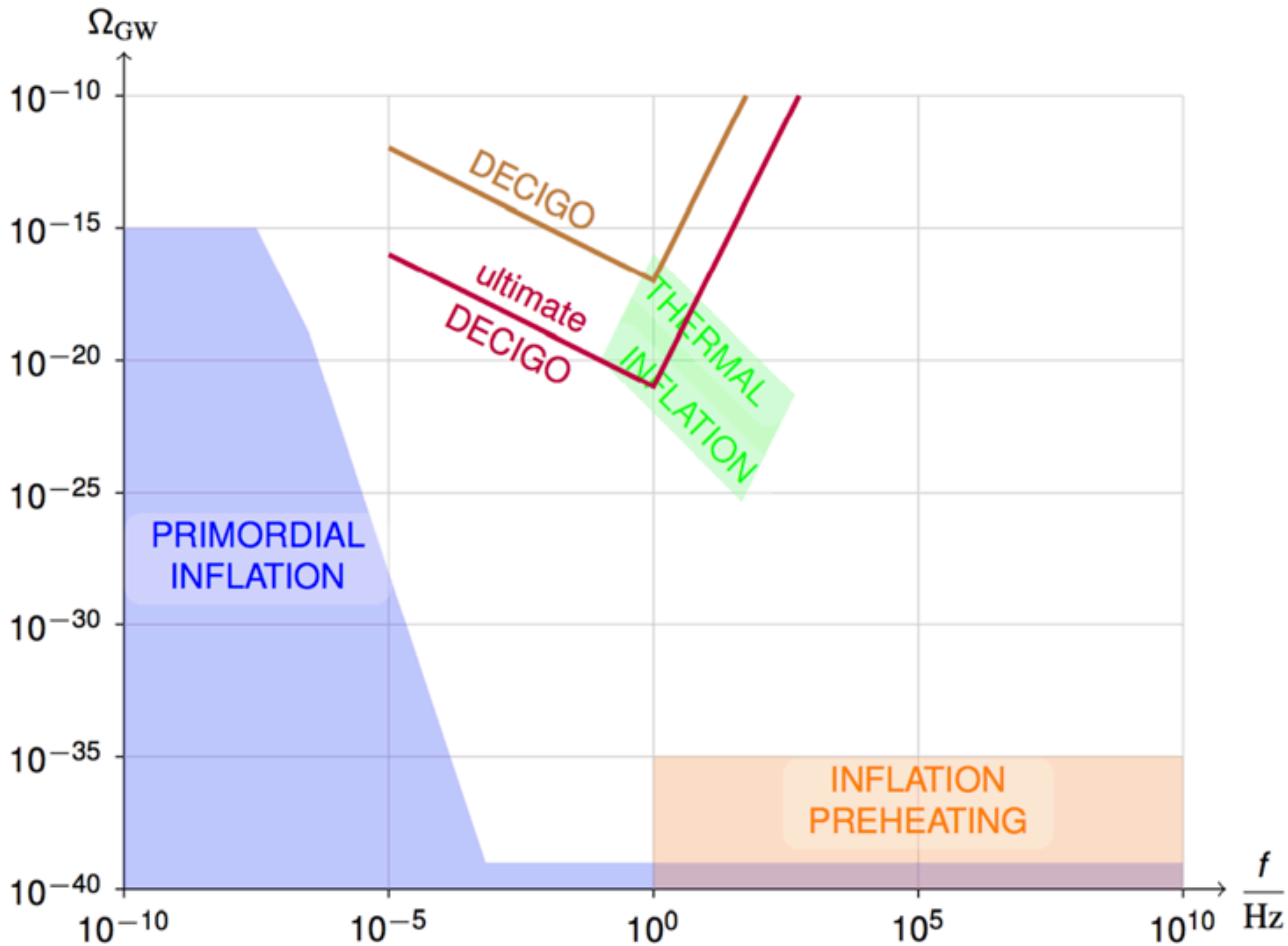
- Properties of thermal inflation



- An observable of thermal inflation

R. Easther, J. T. Giblin, Jr., E. A. Lim, WIP and E. D. Stewart, JCAP **0805**, 013 (2008)

Gravitational wave background from bubble-collision



"..., and there may be other observables."

(work in progress)

Thermal inflation is quite natural in SUSY.

- Negative curvature around the origin:
  an order unity Yukawa coupling provides a strong RG-running like the MSSM up-type Higgs direction.

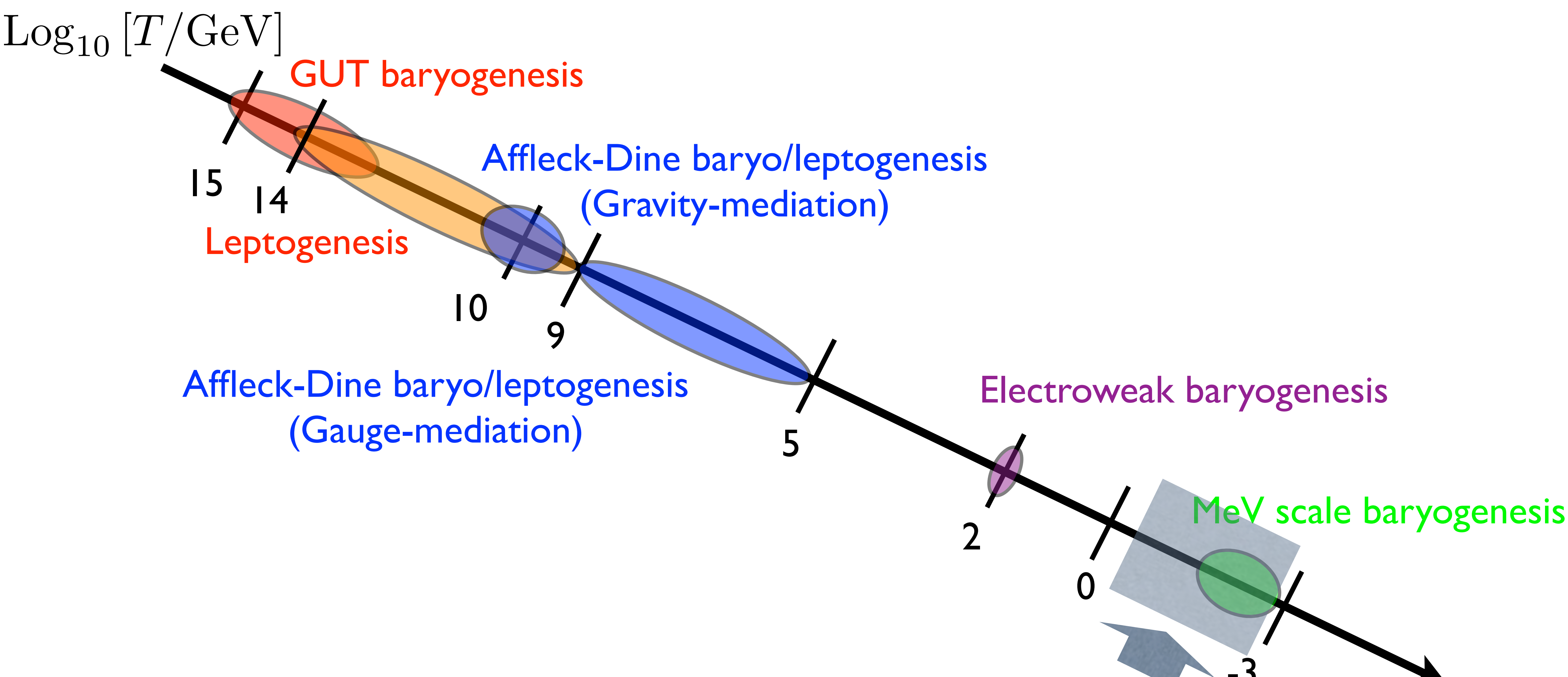
- Many flat directions guaranteed by some symmetry

- There is a well-motivated flaton candidate, $U(1)_{PQ}$ field.

It is quite plausible, and may be indispensable for a consistent string theory.

Compatibility of known baryogenesis

- Baryogenesis mechanisms



$$\text{For } m_{\text{moduli}} \lesssim 10\text{TeV}, \text{ we need } T_{\text{decay}} \ll 1\text{GeV}$$

Most of the known mechanisms can not endure the huge dilution effect of thermal inflation.

- Is AD baryo/leptogenesis viable ?

$$\frac{n_B}{s} \sim \delta_{\rm CP} \left(\frac{\phi^i_{\rm AD}}{M_{\rm P}}\right)^{1/2} \frac{n_{\rm moduli}}{s}$$

$$\Rightarrow \Omega_B \sim \delta_{\rm CP} \left(\frac{\phi^i_{\rm AD}}{M_{\rm P}}\right)^{1/2} \left(\frac{m_B}{m_{\rm moduli}}\right) \Omega_{\rm moduli}$$

For $m_{\rm moduli} \gtrsim 1{\rm MeV}, \Omega_{\rm moduli} \ll 0.1.$

AD mechanism working before TI is not viable too
if $m_{moduli} \gtrsim m_B$.

Baryogenesis after TI

- Only AD mechanism is viable

$$\frac{n_B}{s} \sim \epsilon \delta_{\rm CP} \frac{n_{\rm AD}}{s} \frac{1}{\Delta_{\rm dilution}}$$
$$\sim \epsilon \delta_{\rm CP} \frac{T_{\rm decay}}{m_{\rm AD}} \frac{\rho^i_{\rm AD}}{V_0}$$

$$\delta_{\rm CP} = \mathcal{O}(0.1),$$
$$\frac{T_{\rm decay}}{m_{\rm AD}} = \mathcal{O}(10^{-6} - 10^{-4}),$$
$$\frac{\rho^i_{\rm AD}}{V_0} \lesssim \mathcal{O}(0.1)$$

$$\left.\frac{n_B}{s}\right|_{\rm obs} \sim 10^{-10} \Rightarrow \epsilon = \mathcal{O}(10^{-4} - 10^{-2})$$

(Efficiency factor)

AD mechanism working after TI can match observed matter-antimatter asymmetry.

• Model(s)

WIP, JHEP **1007**, 085 (2010)
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The (simplest) model:

[WIP ('10)]

$$W = \lambda_u Q H_u \bar{u} + \lambda_d Q H_d \bar{d} + \lambda_e L H_d \bar{e} + \lambda_N L H_u N + \frac{1}{2}\lambda_\Phi \Phi N^2 + \frac{1}{2}\lambda_\mu \Phi^2 \frac{H_u H_d}{M_{\rm P}}$$

Organizing principle:

- SM guage symmetries
- R-parity (LSP is stable)
- $U(1)_{\rm PQ}$ with charges assigned as

Field	H_u	H_d	Qu^c	Qd^c	Le^c	LN	N^2
PQ charge	-1	-1	1	1	1	1	1

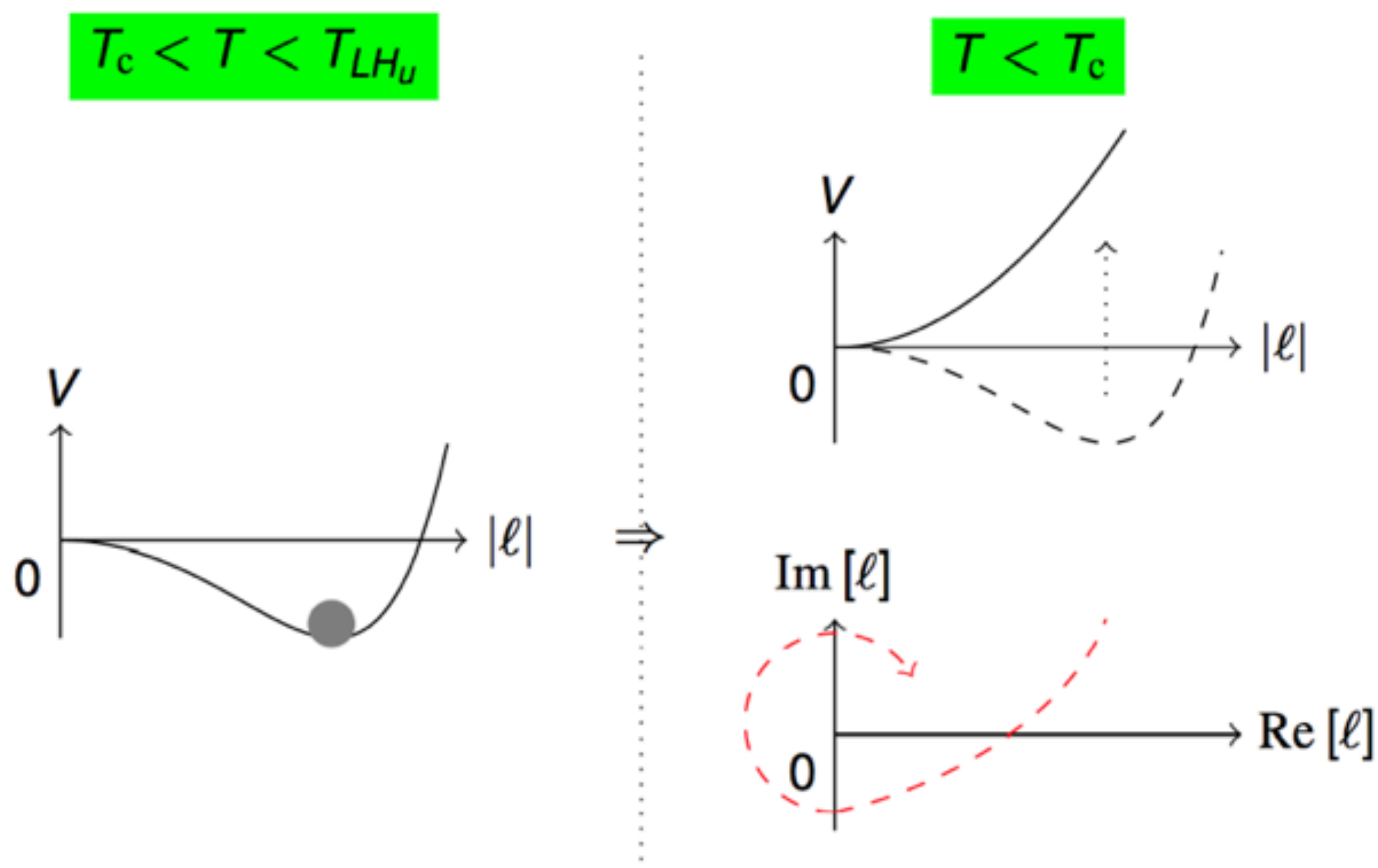
Flaton potential for thermal inflation:

$$V(|\phi|) = V_0 + \lambda_\Phi^2 T^2 |\phi|^2 - m_\phi^2 \left[1 - \alpha \ln\left(\frac{|\lambda_\Phi \phi|}{m_{\rm soft}}\right)\right] |\phi|^2$$

Late-time Affleck-Dine leptogenesis:

[Jeong,Kadota,WIP & Stewart ('04)]

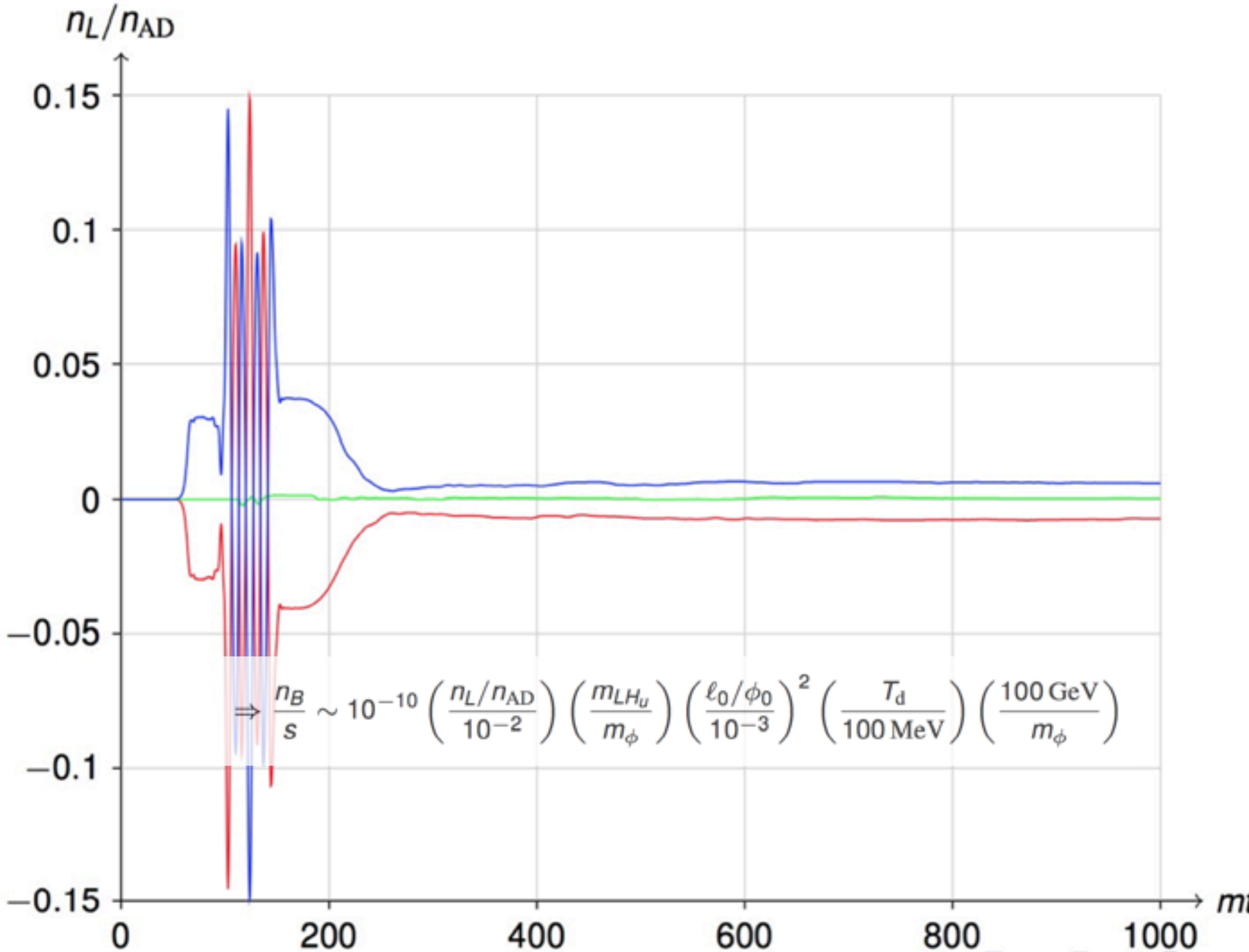
$$V = \mu^2(|\phi|)|\ell|^2 - m^2_{LH_u}|\ell|^2 + \left[\left(1 + 2\frac{h_d^*}{h_u}\frac{\mu(|\phi|)}{A_\nu}\right)\frac{A_\nu \lambda_\nu \ell^4}{4M_\nu} + \text{c.c.}\right] + \left|\frac{\lambda_\nu \ell^3}{M_\nu}\right|^2$$



angular momentum = charge asymmetry

Present baryon number asymmetry:

$$\frac{n_B}{s} \sim \frac{n_B}{n_\phi}\frac{T_{\rm d}}{m_\phi} \sim \frac{n_L}{n_{\rm AD}}\frac{m_{L_i H_u}}{m_\phi}\left(\frac{|l_0|}{\phi_0}\right)^2\frac{T_{\rm d}}{m_\phi}$$



$$\Rightarrow \frac{n_B}{s} \sim 10^{-10}\left(\frac{n_L/n_{\rm AD}}{10^{-2}}\right)\left(\frac{m_{LH_u}}{m_\phi}\right)\left(\frac{\ell_0/\phi_0}{10^{-3}}\right)^2\left(\frac{T_{\rm d}}{100\,{\rm MeV}}\right)\left(\frac{100\,{\rm GeV}}{m_\phi}\right)$$

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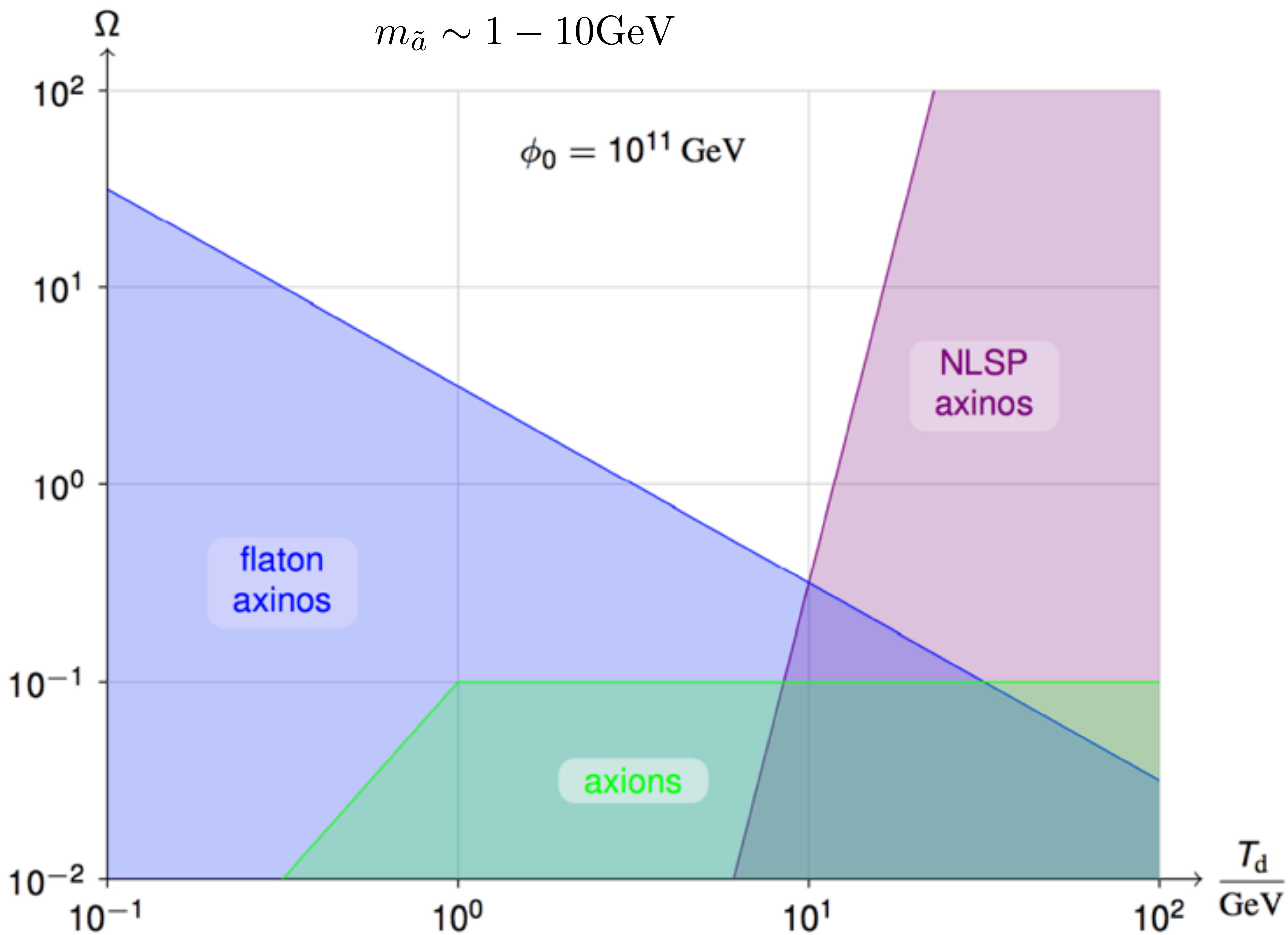
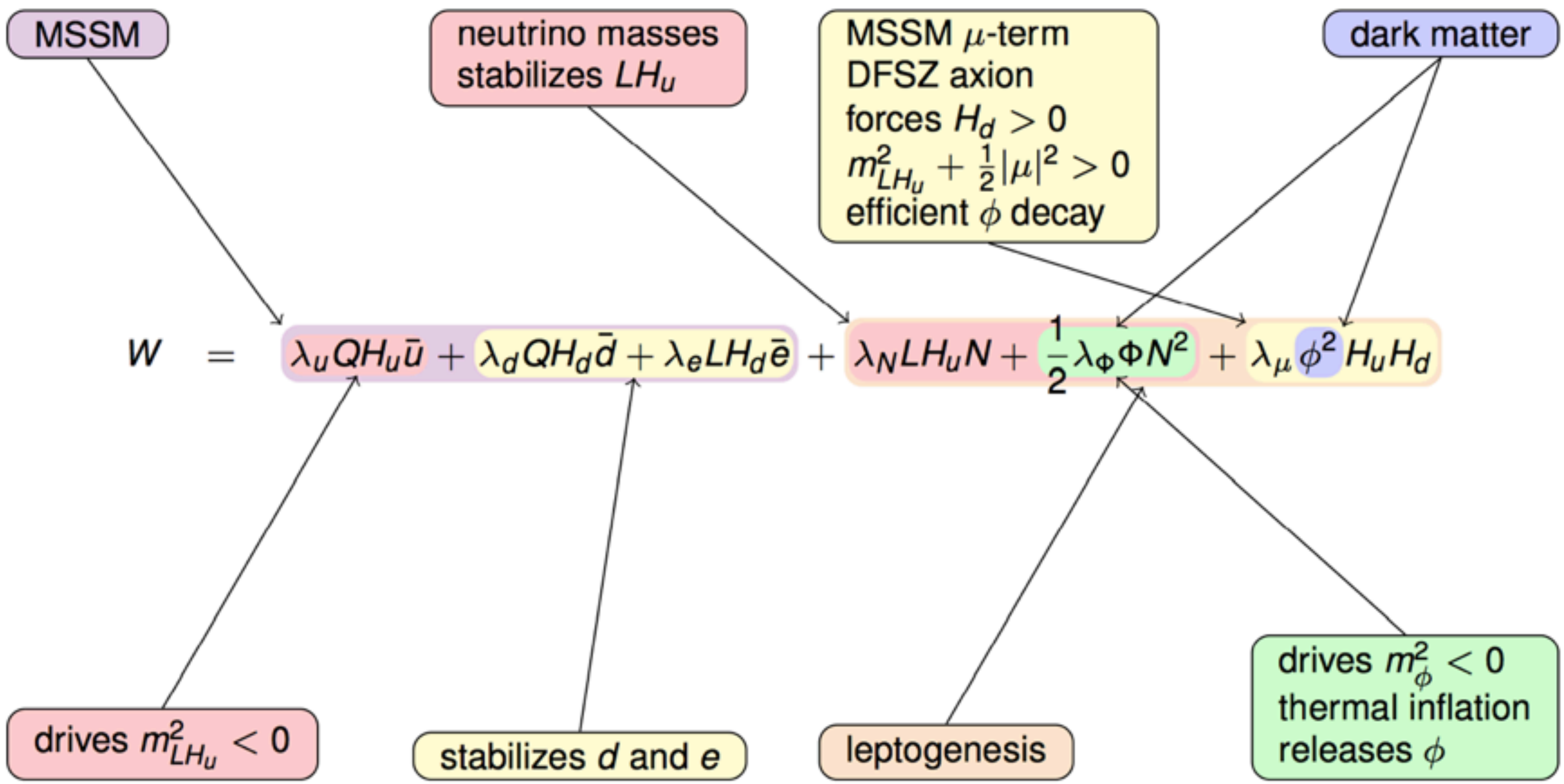
Dark matter (axion + axino)

$$m_a \simeq 6 \times 10^{-5}\text{eV}\left(\frac{10^{11}\text{GeV}}{\phi_0}\right)$$

$$m_{\tilde{a}} \sim 1 - 10\text{GeV}$$



Model summary



The model has

- no supersymmetric dimensionful parameter
- only one singlet(modulo RHN) is introduced

It can address following issues very economically.

- Thermal inflation as the solution to the cosmological moduli problem
- Baryogenesis(late-time AD leptogenesis) and dark matter (axion+axino)
- The origin of the heavy/light neutrino masses
- The origin of the MSSM μ-term
- Axion as the solution to the strong CP-problem

Summary

- String theories has flat directions, called moduli
- If the mass of moduli is similar to the soft SUSY-breaking scale or smaller, generically they are problematic due to its long life time and huge abundance.
- Inflation can not solve the cosmological moduli problem, unless it works after the moduli production.
- The most compelling solution to the problem is thermal inflation.
- Generically, baryo/leptogenesis mechanisms working before thermal inflation are invalidated because of the huge dilution caused by enormous entropy release after thermal inflation.
- Late-time AD mechanism along LH_u flat direction after thermal inflation provides a (or the ?) solution to this problem.
- A right amount of dark matter can also be obtained from PQ-sector.