Title: Warm Baryogenesis

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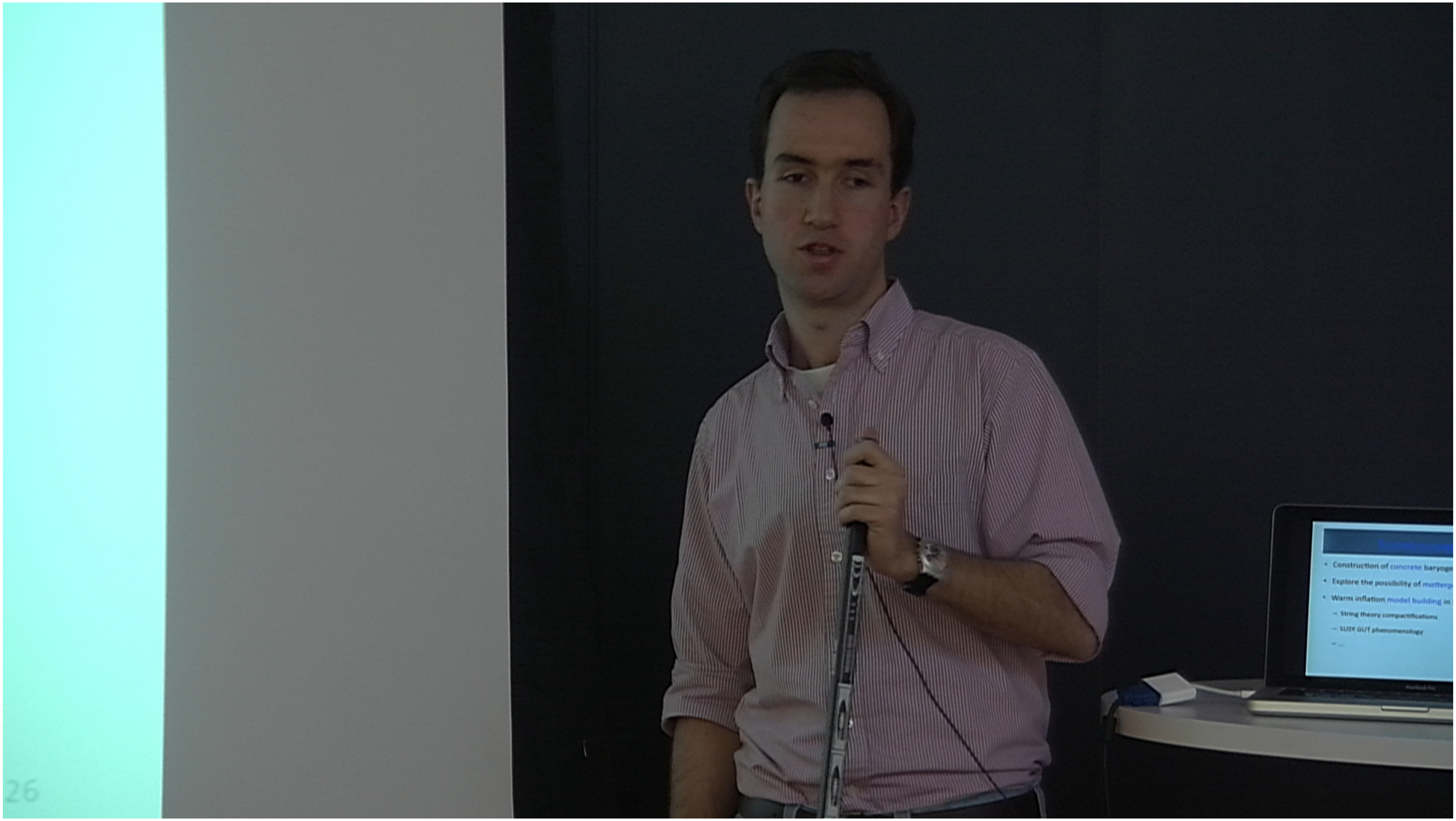
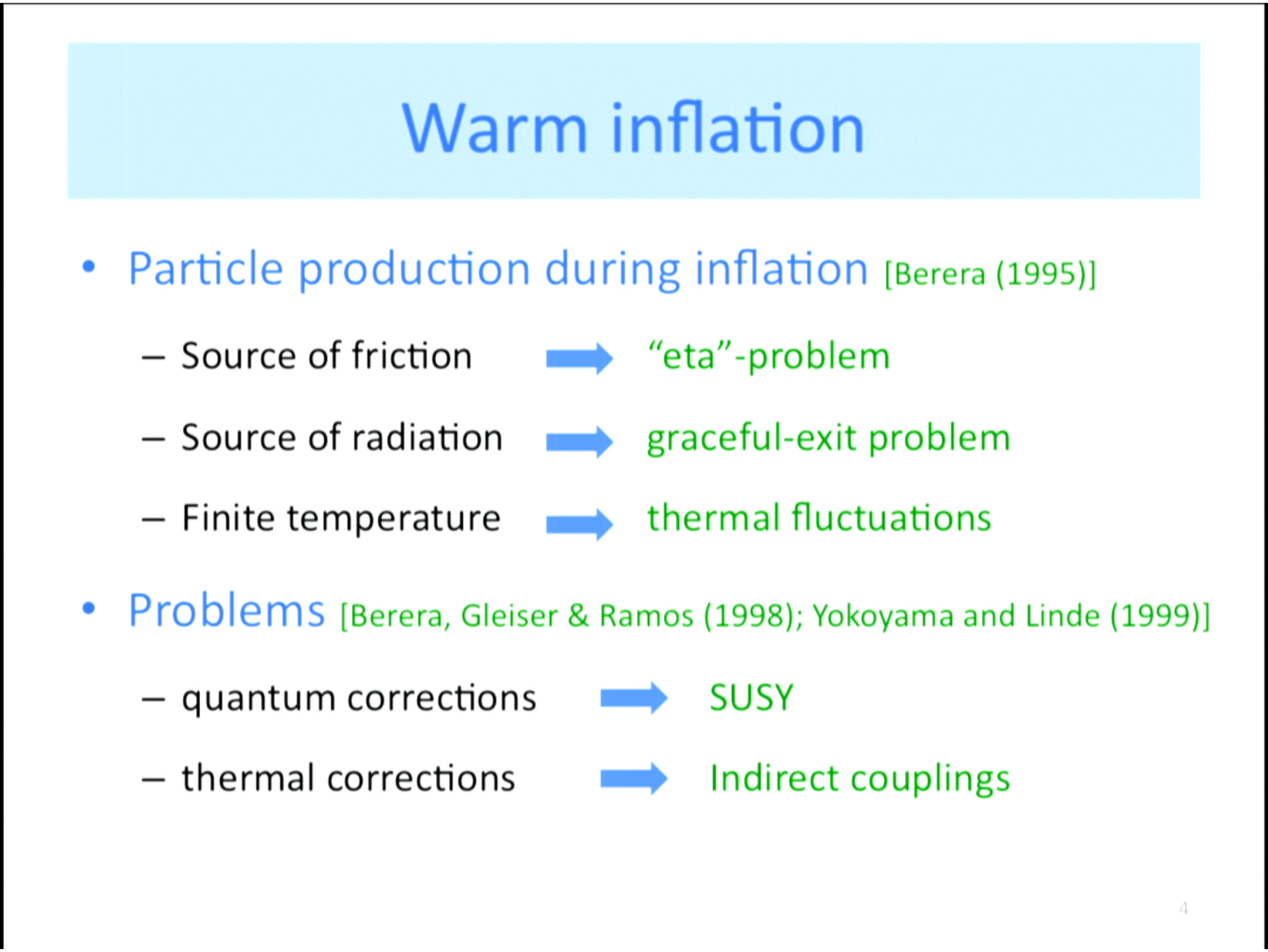
Abstract: We show that a baryon asymmetry can be generated by dissipative effects during warm inflation via a supersymmetric two-stage mechanism, where the inflaton is coupled to heavy mediator fields that then decay into light species through B- and CP-violating interactions. In contrast with thermal GUT baryogenesis models, the temperature during inflation is always below the heavy mass threshold, simultaneously suppressing thermal and quantum corrections to the inflaton potential and the production of dangerous GUT relics. This naturally gives a small baryon asymmetry close to the observed value, although parametrically larger values may be diluted after inflation along with any gravitino overabundance. Furthermore, this process yields baryon isocurvature perturbations within the range of future experiments, making this an attractive and testable model of GUT baryogenesis.



Outline

1. Warm inflation
2. Baryogenesis during warm inflation
    a) SUSY model
    b) Baryon asymmetry
    c) Discussion
    d) Baryon isocurvature perturbations
3. Summary and future prospects



Warm inflation

- Particle production during inflation [Berera (1995)]
  - Source of friction → "eta"-problem
  - Source of radiation → graceful-exit problem
  - Finite temperature → thermal fluctuations
- Problems [Berera, Gleiser & Ramos (1998); Yokoyama and Linde (1999)]
  - quantum corrections → SUSY
  - thermal corrections → Indirect couplings

Warm inflation

- Two-stage mechanism [Berera & Ramos, 2003]
  - Inflaton coupled to heavy fields (mass >> T)
  - Heavy fields decay into light dof (mass << T)
  - Radiation produced by background field dissipation
- Generic superpotential [Bastero-Gil & Berera, 2009]

$$W = g\Phi X^2 + hXY^2$$

$$|F_X|^2 = \underbrace{2g^2|\phi|^2|\chi|^2}_{\text{mass term}} + \underbrace{2gh(\phi\chi y^{\dagger 2} + h.c.)}_{\text{decay}} + h^2|y|^4$$

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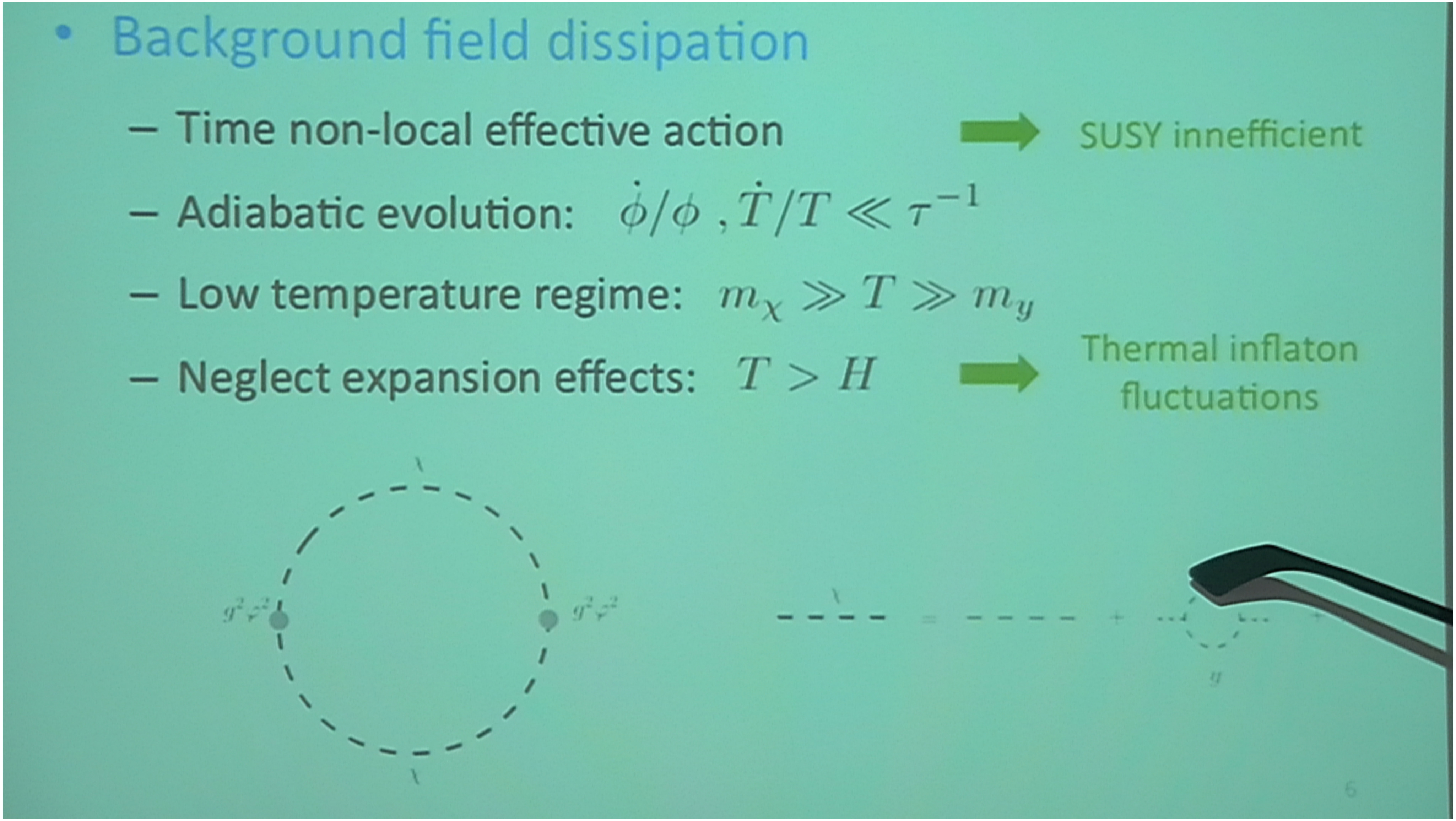
Warm inflation

- Background field dissipation
  - Time non-local effective action ➡ SUSY innefficient
  - Adiabatic evolution: $\dot{\phi}/\phi\ ,\dot{T}/T \ll \tau^{-1}$
  - Low temperature regime: $m_\chi \gg T \gg m_y$
  - Neglect expansion effects: $T > H$ ➡ Thermal inflaton fluctuations



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Warm inflation

- Warm inflation dynamics

$$\ddot{\phi} + (3H + \Upsilon)\dot{\phi} + V'(\phi) = 0$$

$$\dot{\rho}_R + 4H\rho_R = \Upsilon\dot{\phi}^2 \qquad \rho_R = \frac{\pi^2}{30} g_* T^4$$

- Dissipation coefficient

$$\Upsilon = C_\phi \frac{T^3}{\phi^2}\ , \qquad C_\phi = 0.026 h^4 \underbrace{N_\chi N_{decay}^2}$$

Multiplicity enhancement
N>O(10-100)

Warm inflation

- Slow-roll inflation

$$\begin{aligned} 3H(1+Q)\dot{\phi} &\approx -V'(\phi) \\ \rho_R &\approx \frac{3}{4}Q\dot{\phi}^2 \\ H^2 &\approx \frac{V(\phi)}{3M_P^2} \end{aligned} \qquad Q = \frac{\Upsilon}{3H}$$

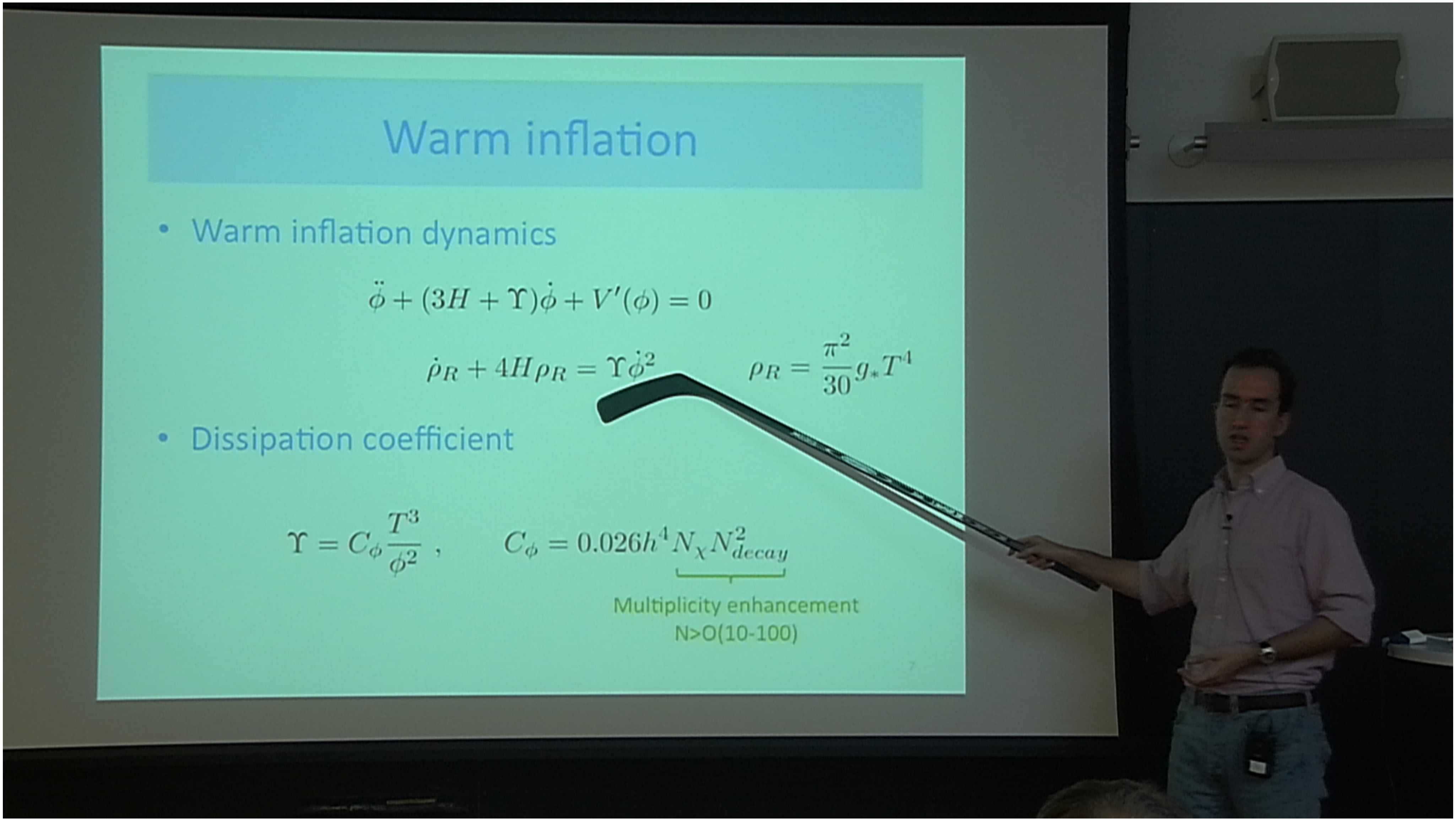
– Inflation ends when:

a) Slow-roll conditions are violated: $\epsilon_\phi \ , \eta_\phi > 1 + Q$

b) Radiation becomes dominant: $\rho_R > V(\phi)$

Warm inflation

- Main features
  - Inflation with steeper potentials
  - Possible smooth transition to radiation era
  - Modified perturbation spectra:
    - suppressed tensor-to-scalar ratio
    - significant non-gaussianity: $f_{NL} = \mathcal{O}(10)$



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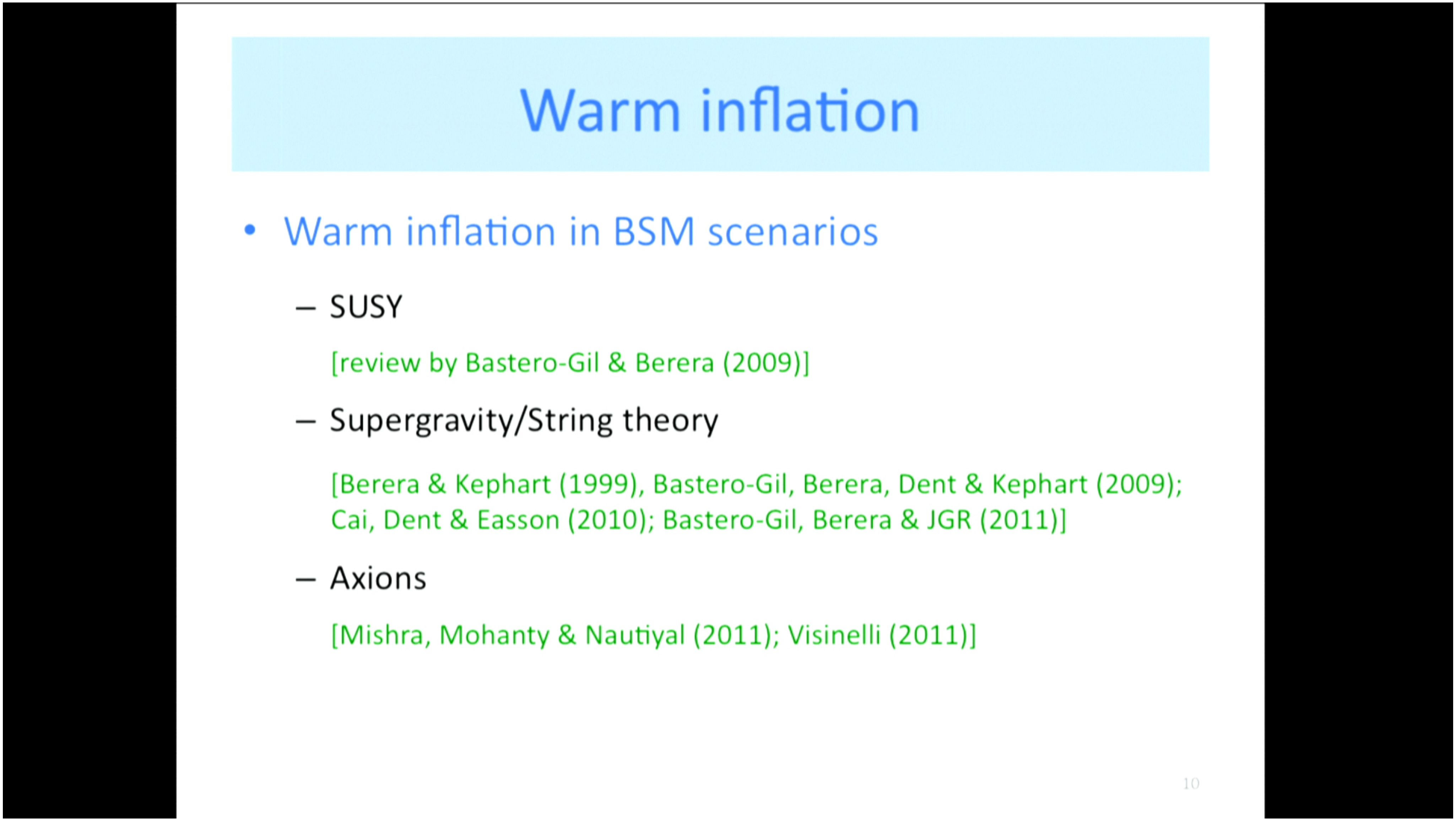

Warm inflation

- Warm inflation in BSM scenarios
  - SUSY

    [review by Bastero-Gil & Berera (2009)]
  - Supergravity/String theory

    [Berera & Kephart (1999), Bastero-Gil, Berera, Dent & Kephart (2009); Cai, Dent & Easson (2010); Bastero-Gil, Berera & JGR (2011)]
  - Axions

    [Mishra, Mohanty & Nautiyal (2011); Visinelli (2011)]

Baryogenesis during warm inflation

- GUT baryogenesis [Nanopoulos & Weinberg (1979)]
  - Heavy GUT bosons decaying into (light) baryons
  - Out-of-equilibrium decays for $T < m_X$
  - B- and CP-violating interactions

  } Sakharov conditions

- Warm inflation:
  - Heavy bosons mediate dissipation and produce light dof
  - Dissipation is naturally out-of-equilibrium
  - Require $T < m_X$ to suppress thermal corrections
  - B- and CP-violating interactions?

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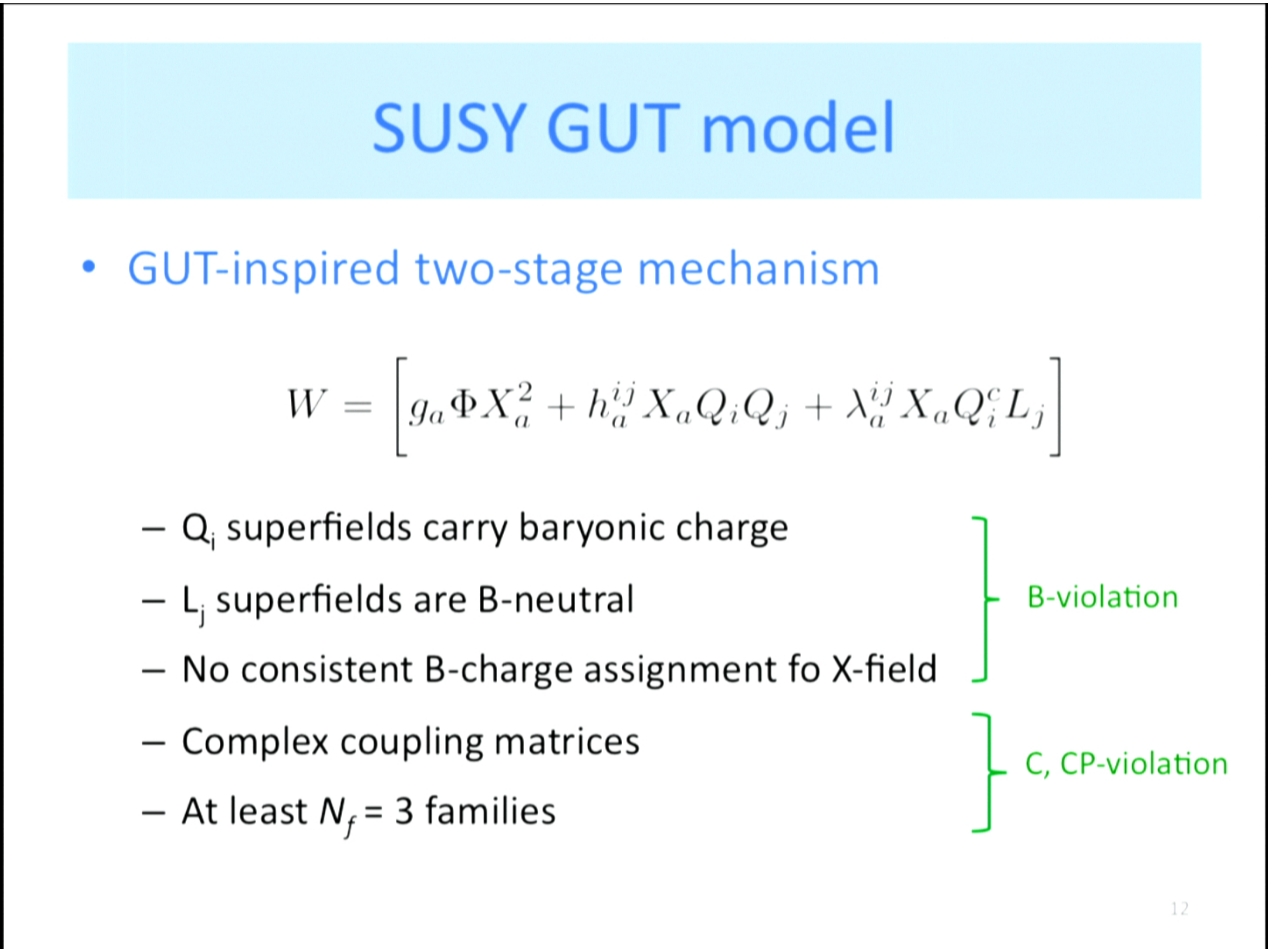


SUSY GUT model

- GUT-inspired two-stage mechanism

$$W = \left[g_a \Phi X_a^2 + h_a^{ij} X_a Q_i Q_j + \lambda_a^{ij} X_a Q_i^c L_j \right]$$

  - Q_i superfields carry baryonic charge
  - L_j superfields are B-neutral
  - No consistent B-charge assignment fo X-field

B-violation

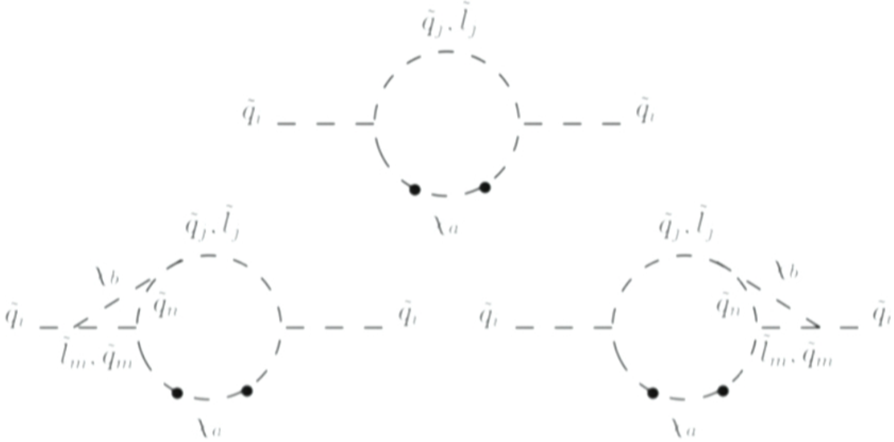
  - Complex coupling matrices
  - At least $N_f = 3$ families

C, CP-violation

Baryon asymmetry

- Particle production rate [Graham & Moss (2008)]

$$\dot{\rho}_i^{(d)} = \int \frac{d^3p}{(2\pi)^3}\,\omega_p \mathrm{Im}\left[2\int_{-\infty}^{t} dt' \,\frac{e^{-i\omega_p(t-t')}}{2\omega_p}\,\Sigma_{21}(p,t,t')\right]$$



cf. Nanopoulos & Weinberg (1979)

Baryon asymmetry

- Self-energy difference

$$\Delta\Sigma^B_{21} = 8\sum_{a,b=1}^{N_X}\int d^3k\; \underbrace{f_a}_{\text{main loop}} m_b^2 I_{ab}\,\mathrm{Im}\big(\mathrm{Tr}[\lambda_b^*\lambda_a^T h_b h_a^\dagger]\big)$$

  - Triangle loop imaginary part (low-T):

$$m_b^2 I_{ab}(p,k) \simeq -\frac{1}{16\pi}\left(1-\frac{1}{2}\frac{k^2-(p-k)^2}{m_b^2}\right)$$

  - Additional T-dependence: $p,\ k \lesssim T$
  - Need at least two distinct heavy fields

Baryon asymmetry

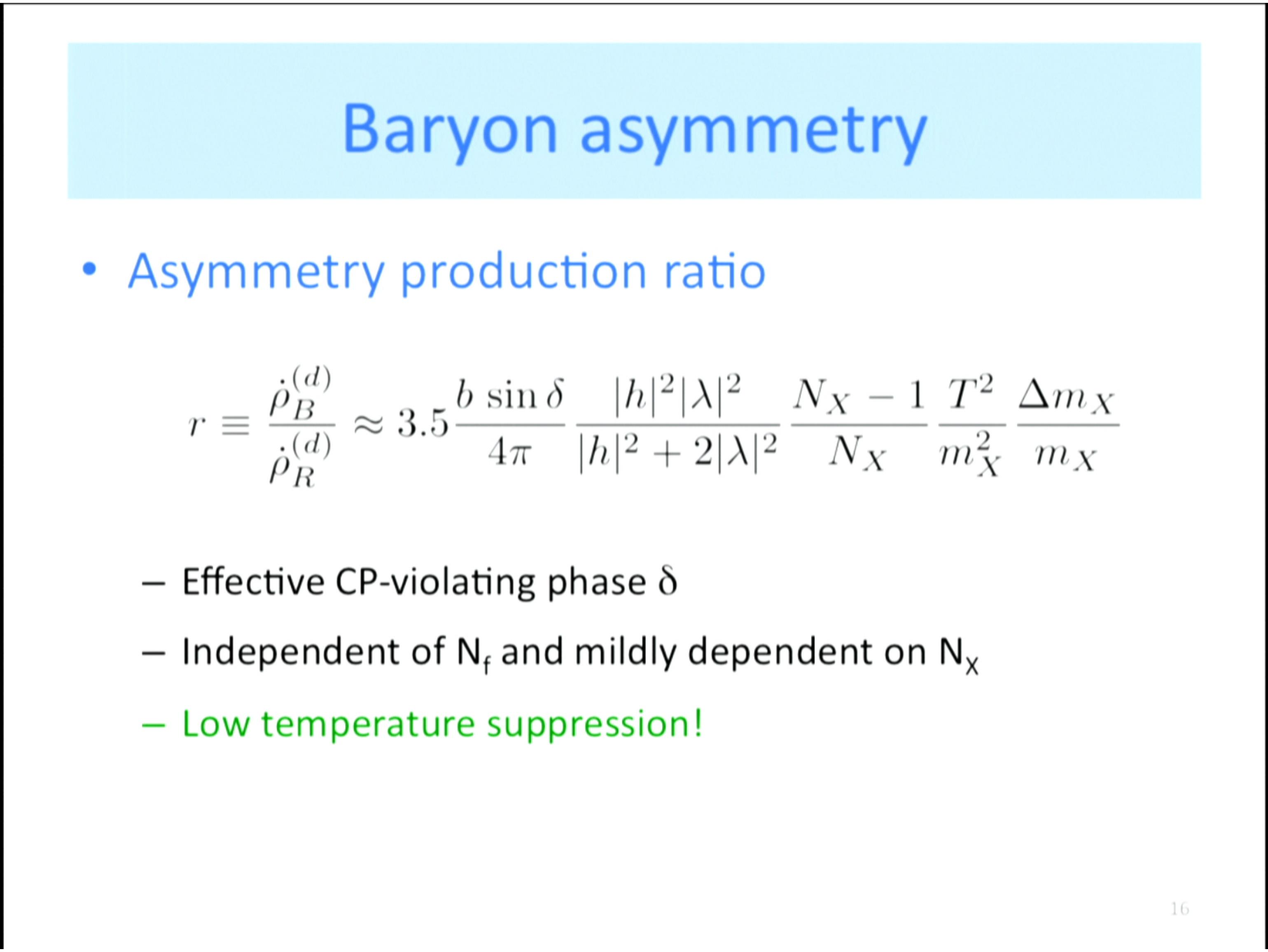
- Total self-energy

$$\Sigma_{21}^{R} = 2 \sum_{a=1}^{N_X} \int d^3k \; f_a \left[\mathrm{Tr}[h_a h_a^\dagger] + \mathrm{Tr}[\lambda_a^* \lambda_a^T] + \mathrm{Tr}[\lambda_a \lambda_a^\dagger] \right]$$

- Example
  - N_X-*1* degenerate mediators
  - additional X-multiplet with small mass splitting
  - Yukawa couplings differing by a phase:

$$h_a = |h| V e^{i\theta_a} \;, \quad \lambda_a = |\lambda| U e^{i\alpha_a}$$

  - Common baryonic charge *b*

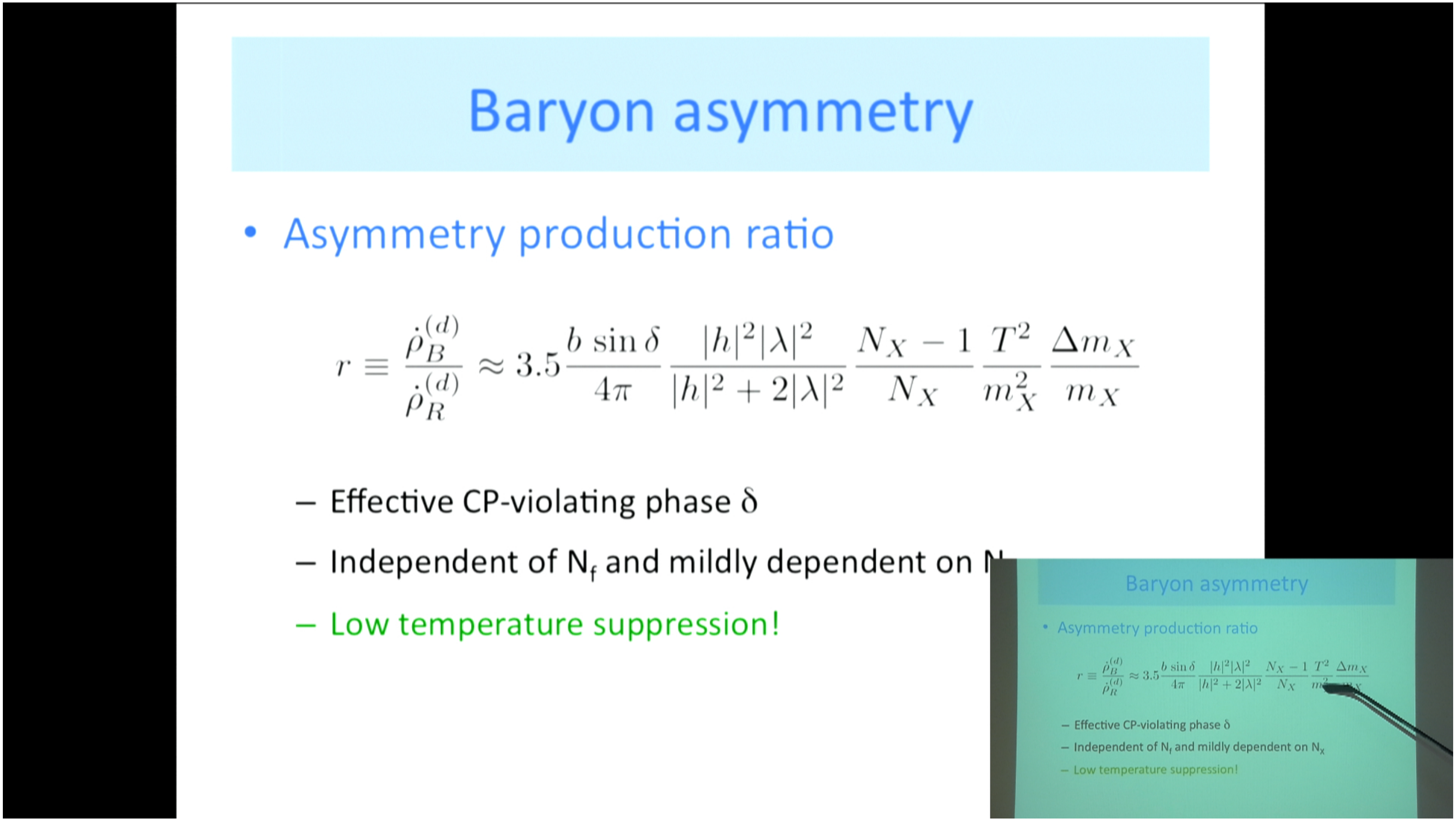


Baryon asymmetry

- Asymmetry production ratio

$$r \equiv \frac{\dot{\rho}_B^{(d)}}{\dot{\rho}_R^{(d)}} \approx 3.5 \frac{b \sin\delta}{4\pi} \frac{|h|^2|\lambda|^2}{|h|^2 + 2|\lambda|^2} \frac{N_X - 1}{N_X} \frac{T^2}{m_X^2} \frac{\Delta m_X}{m_X}$$

  - Effective CP-violating phase δ
  - Independent of N_f and mildly dependent on N_X
  - Low temperature suppression!



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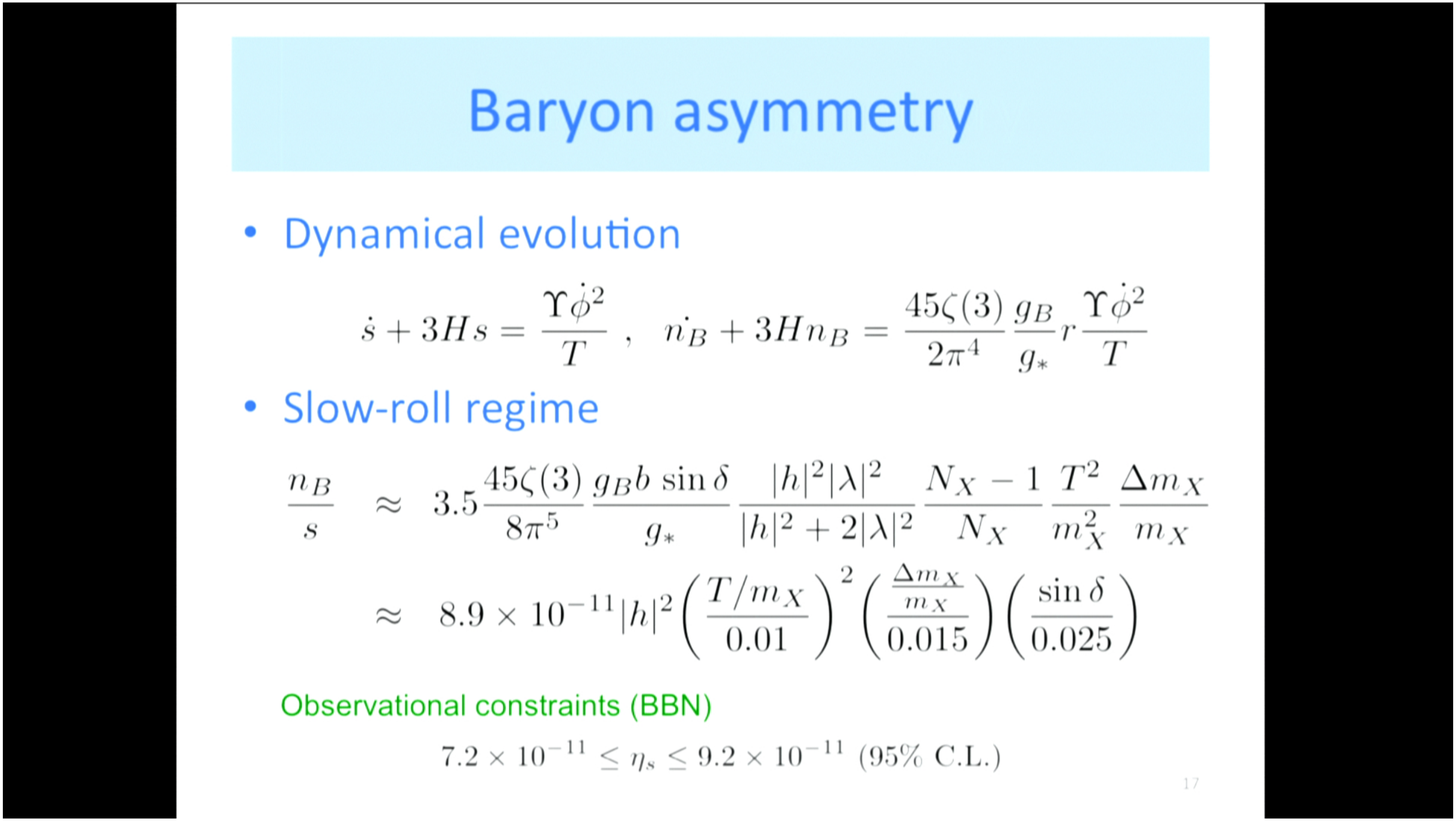


Baryon asymmetry

- Dynamical evolution

$$\dot{s} + 3Hs = \frac{\Upsilon\dot{\phi}^2}{T} \;, \quad \dot{n}_B + 3Hn_B = \frac{45\zeta(3)}{2\pi^4}\frac{g_B}{g_*}r\frac{\Upsilon\dot{\phi}^2}{T}$$

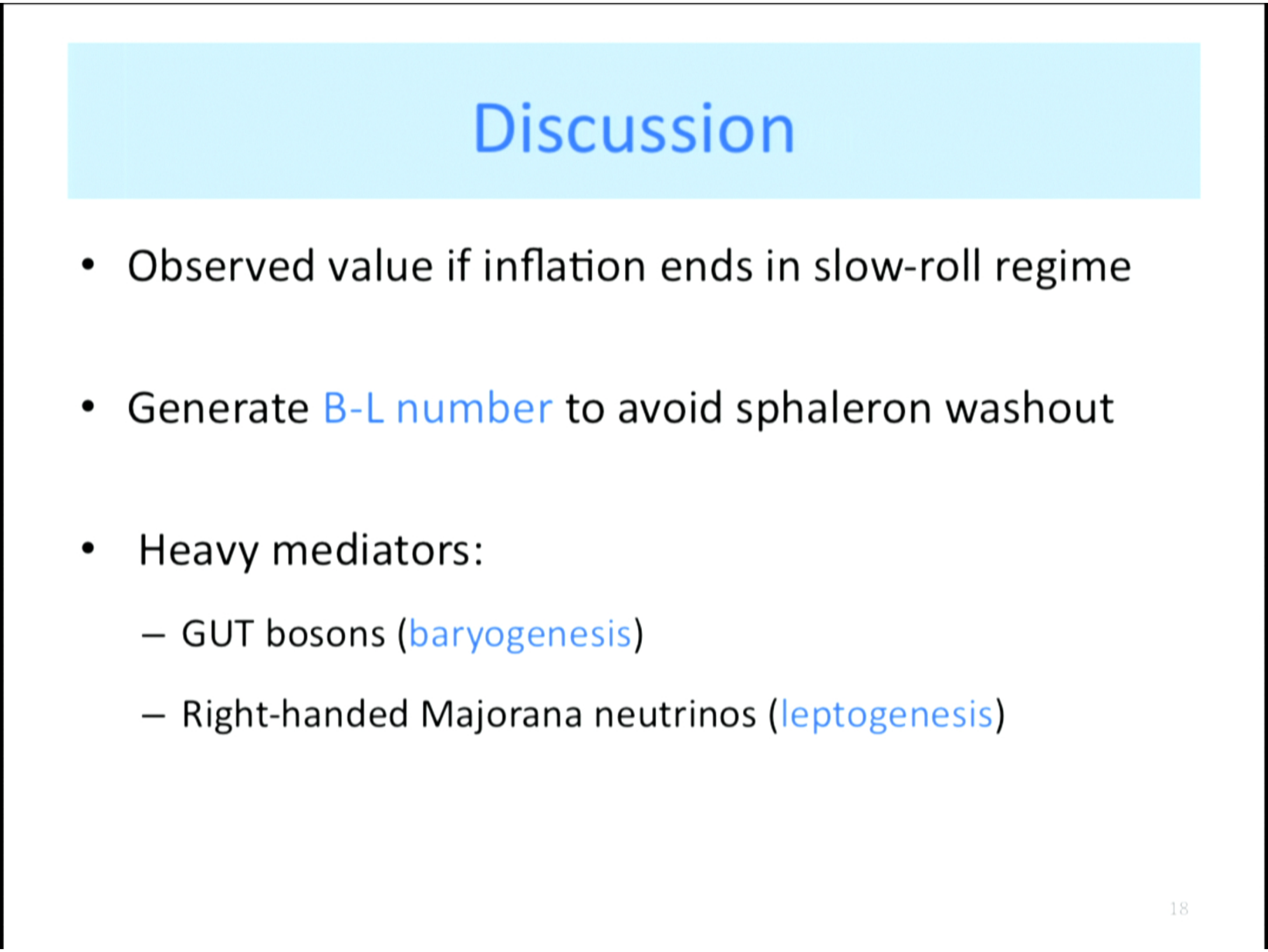
- Slow-roll regime

$$\frac{n_B}{s} \approx 3.5\frac{45\zeta(3)}{8\pi^5}\frac{g_B b\sin\delta}{g_*}\frac{|h|^2|\lambda|^2}{|h|^2+2|\lambda|^2}\frac{N_X-1}{N_X}\frac{T^2}{m_X^2}\frac{\Delta m_X}{m_X}$$

$$\approx 8.9\times 10^{-11}|h|^2\left(\frac{T/m_X}{0.01}\right)^2\left(\frac{\frac{\Delta m_X}{m_X}}{0.015}\right)\left(\frac{\sin\delta}{0.025}\right)$$

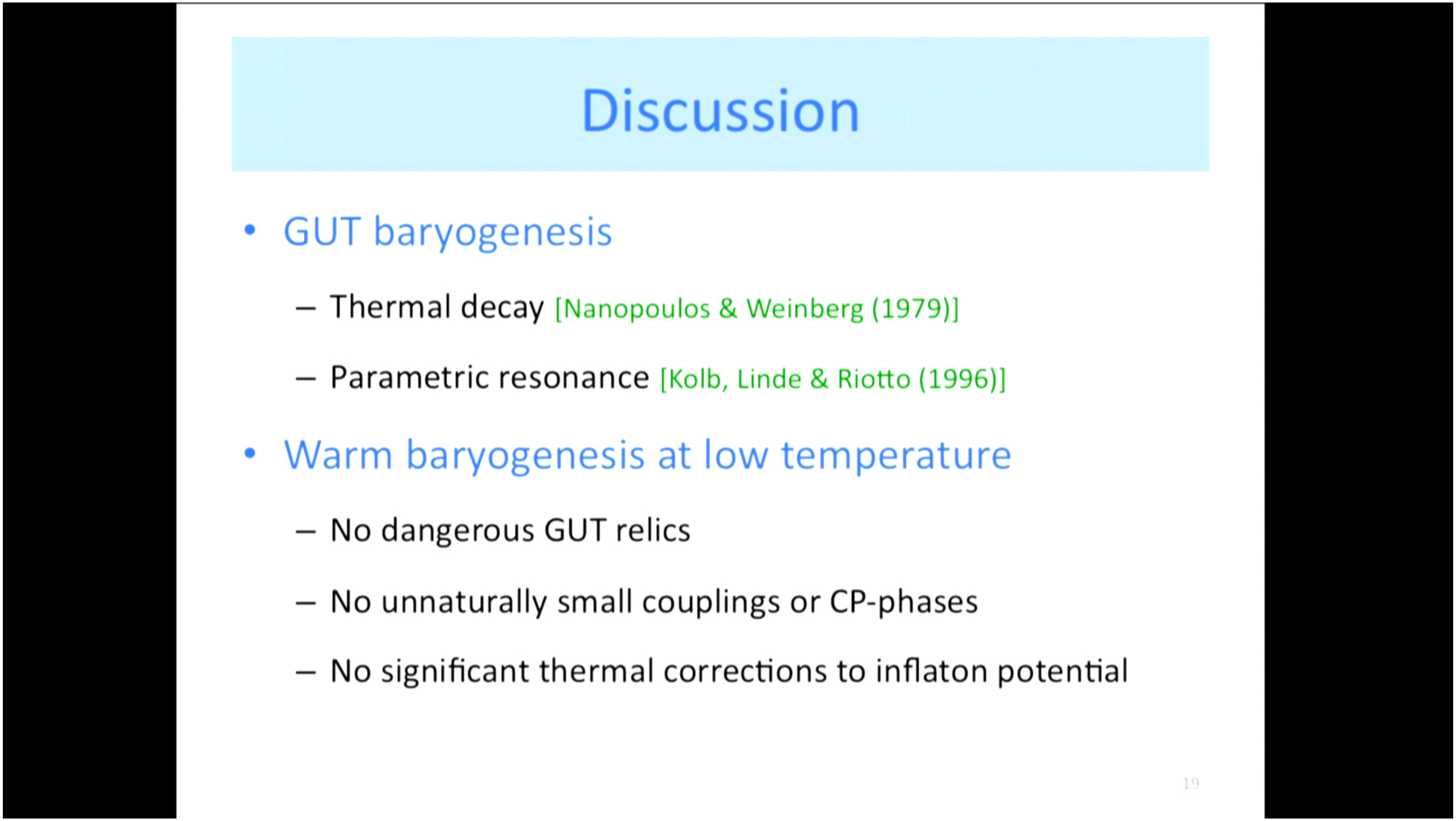
Observational constraints (BBN)

$$7.2\times 10^{-11} \leq \eta_s \leq 9.2\times 10^{-11} \;\; (95\%\ \text{C.L.})$$



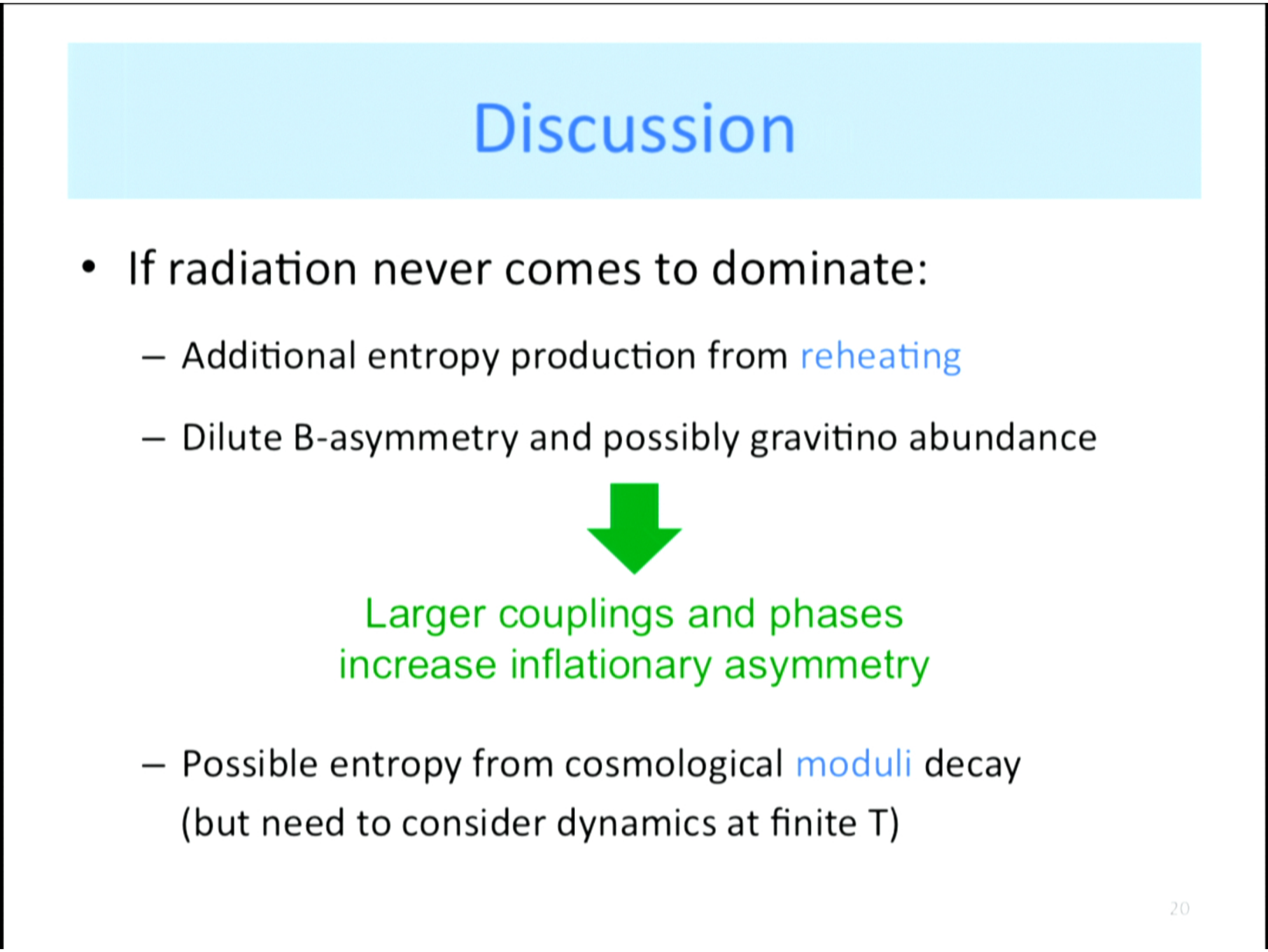
Discussion

- Observed value if inflation ends in slow-roll regime
- Generate B-L number to avoid sphaleron washout
- Heavy mediators:
  - GUT bosons (baryogenesis)
  - Right-handed Majorana neutrinos (leptogenesis)



Discussion

- GUT baryogenesis
  - Thermal decay [Nanopoulos & Weinberg (1979)]
  - Parametric resonance [Kolb, Linde & Riotto (1996)]
- Warm baryogenesis at low temperature
  - No dangerous GUT relics
  - No unnaturally small couplings or CP-phases
  - No significant thermal corrections to inflaton potential



Discussion

- If radiation never comes to dominate:
  - Additional entropy production from reheating
  - Dilute B-asymmetry and possibly gravitino abundance

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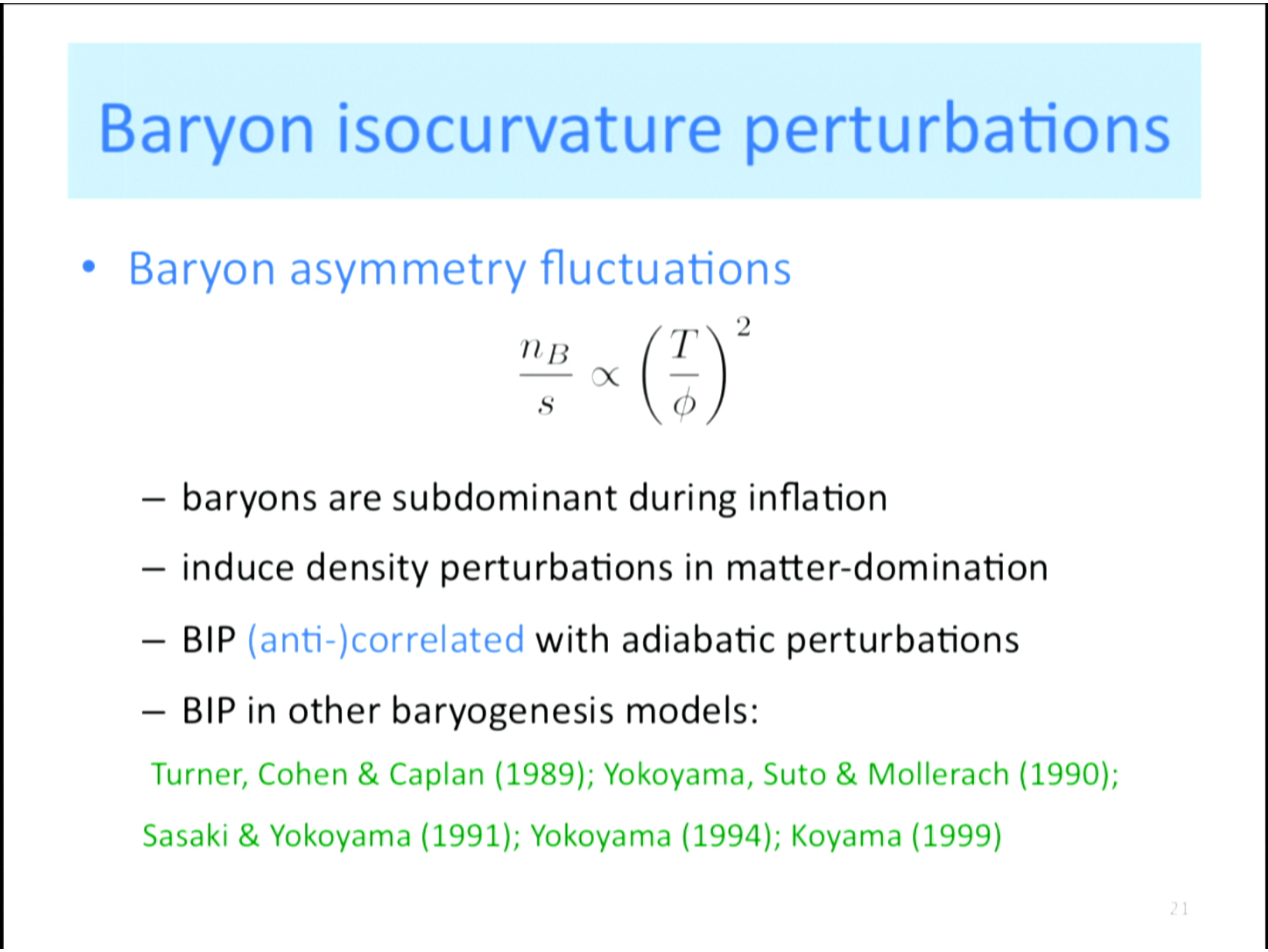
Larger couplings and phases
increase inflationary asymmetry

  - Possible entropy from cosmological moduli decay (but need to consider dynamics at finite T)



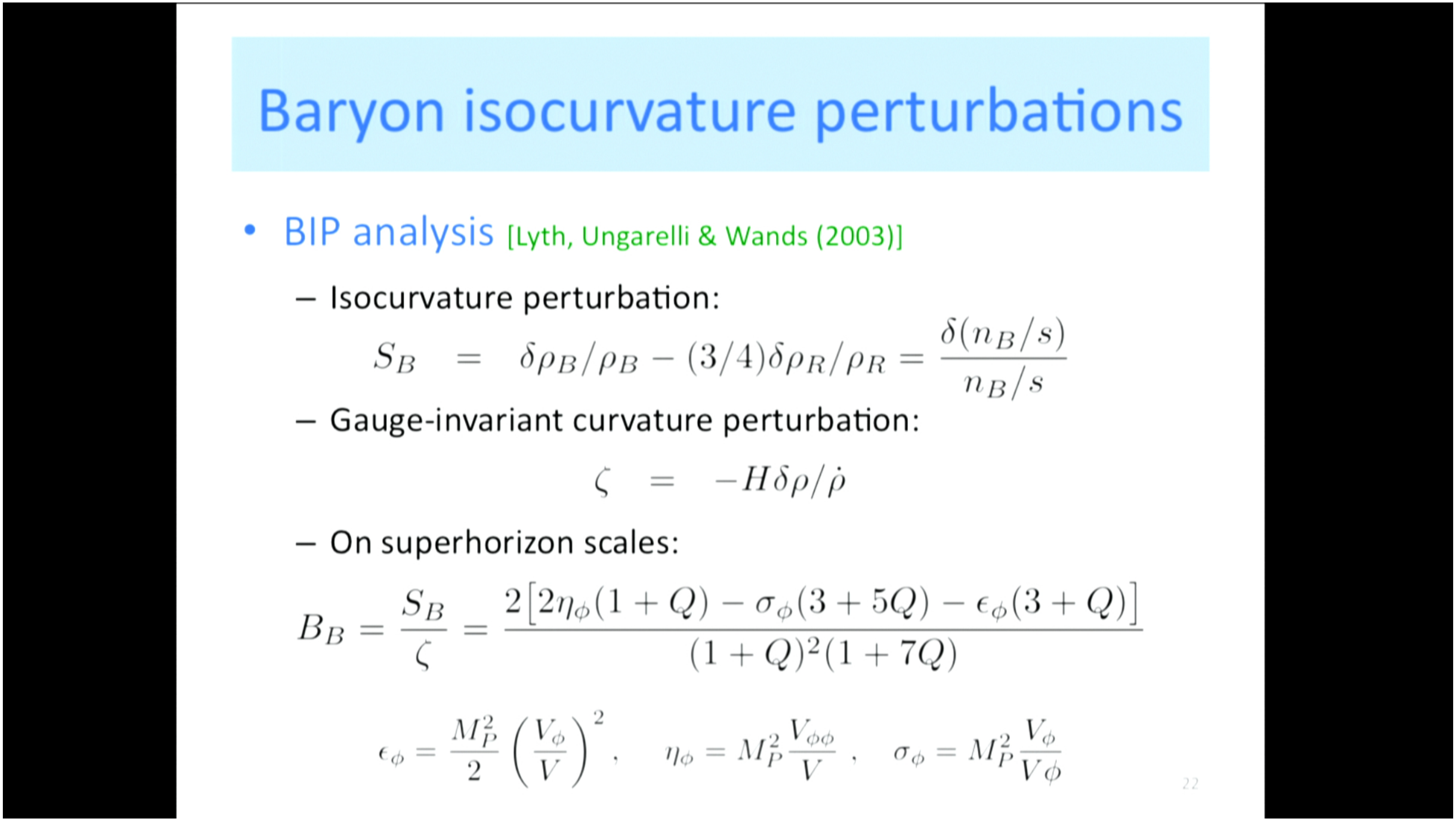
Baryon isocurvature perturbations

- Baryon asymmetry fluctuations

$$\frac{n_B}{s} \propto \left(\frac{T}{\phi}\right)^2$$

  - baryons are subdominant during inflation
  - induce density perturbations in matter-domination
  - BIP (anti-)correlated with adiabatic perturbations
  - BIP in other baryogenesis models:

Turner, Cohen & Caplan (1989); Yokoyama, Suto & Mollerach (1990); Sasaki & Yokoyama (1991); Yokoyama (1994); Koyama (1999)



Baryon isocurvature perturbations

- BIP analysis [Lyth, Ungarelli & Wands (2003)]
  - Isocurvature perturbation:

$$S_B \quad = \quad \delta\rho_B/\rho_B - (3/4)\delta\rho_R/\rho_R = \frac{\delta(n_B/s)}{n_B/s}$$

  - Gauge-invariant curvature perturbation:

$$\zeta \quad = \quad -H\delta\rho/\dot{\rho}$$

  - On superhorizon scales:

$$B_B = \frac{S_B}{\zeta} = \frac{2\left[2\eta_\phi(1+Q) - \sigma_\phi(3+5Q) - \epsilon_\phi(3+Q)\right]}{(1+Q)^2(1+7Q)}$$

$$\epsilon_\phi = \frac{M_P^2}{2}\left(\frac{V_\phi}{V}\right)^2, \quad \eta_\phi = M_P^2\frac{V_{\phi\phi}}{V}, \quad \sigma_\phi = M_P^2\frac{V_\phi}{V\phi}$$

Baryon isocurvature perturbations

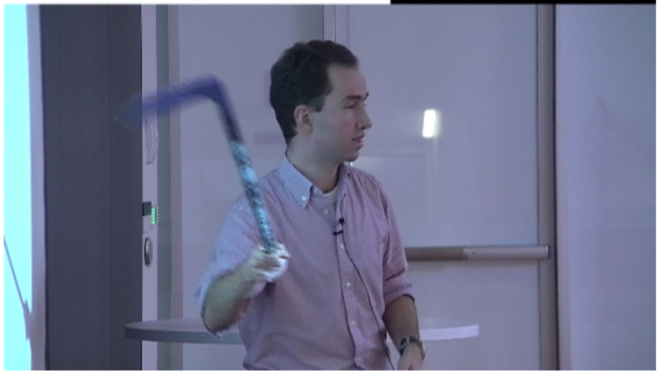
- Relation to spectral index

$$\frac{B_B}{n_S - 1} \simeq \begin{cases} \frac{3\epsilon_\phi - 2\eta_\phi + 3\sigma_\phi}{\epsilon_\phi - \sigma_\phi} , & Q \ll 1 \\ \frac{2}{3Q} \frac{\epsilon_\phi - 2\eta_\phi + 5\sigma_\phi}{3\epsilon_\phi + \eta_\phi - 6\sigma_\phi} , & Q \gg 1 \end{cases}$$

$n_S = 0.968 \pm 0.012$ (68% C.L.) [Komatsu *et al.* (2011)]

– Quartic potential:

$$B_B \simeq \begin{cases} -0.096 , & Q \ll 1 \\ -0.007/Q , & Q \gg 1 \end{cases}$$



Baryon isocurvature perturbations

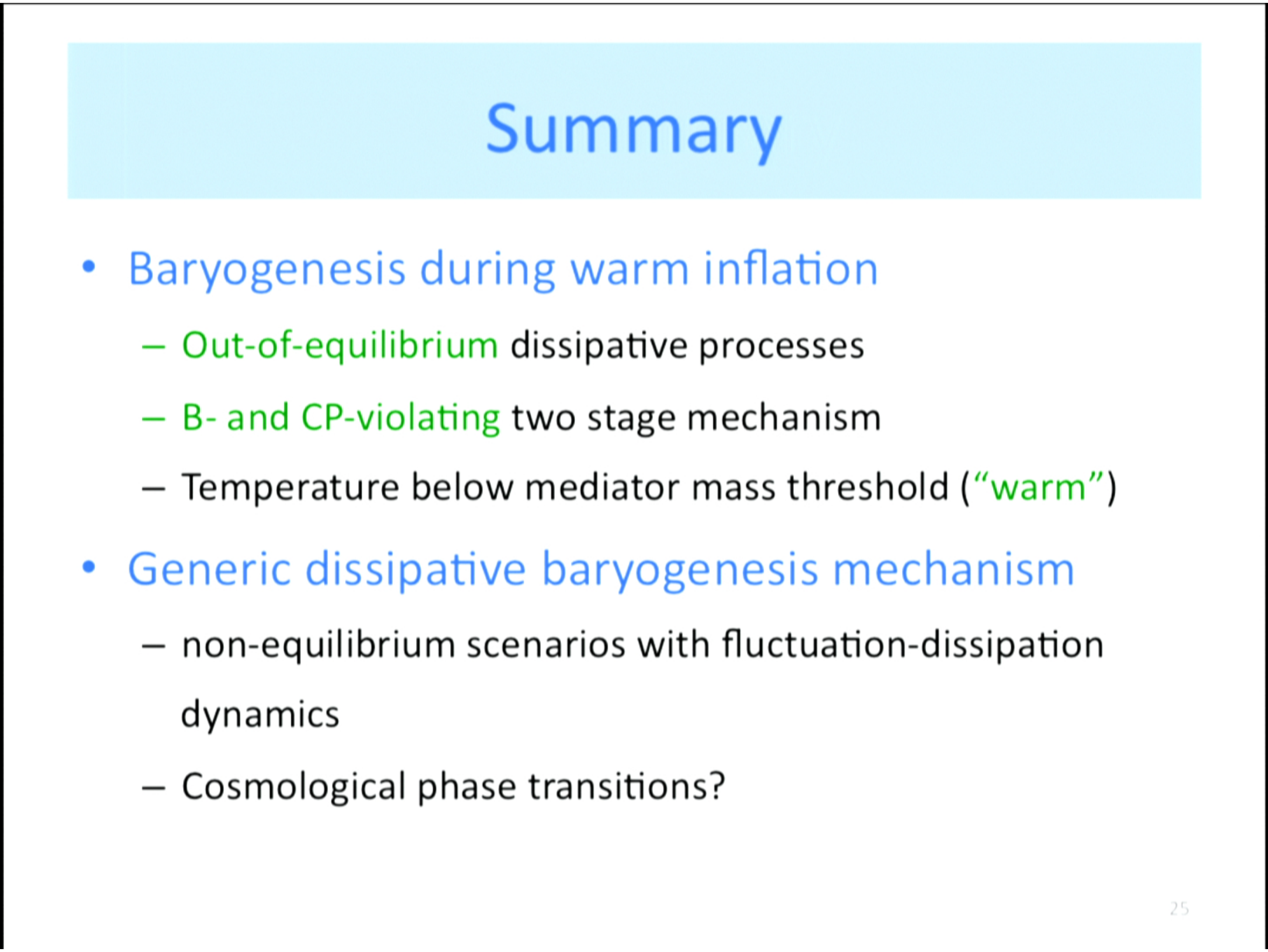
- Observational constraints
  - Early WMAP [Gordon & Lewis (2003)]

$$-0.53 < B_B < 0.43 \ (95\% \ \mathrm{C.L.})$$

  - WMAP7 [Komatsu *et al.* (2011)]

$$|B_B| < 0.34 \ (95\% \ \mathrm{C.L.}), \ B_B < 0$$

  - Planck should improve these bounds by one order of magnitude!



Summary

- Baryogenesis during warm inflation
  - Out-of-equilibrium dissipative processes
  - B- and CP-violating two stage mechanism
  - Temperature below mediator mass threshold (“warm”)
- Generic dissipative baryogenesis mechanism
  - non-equilibrium scenarios with fluctuation-dissipation dynamics
  - Cosmological phase transitions?

Future prospects

- Construction of concrete baryogenesis models
- Explore the possibility of *mattergenesis*
- Warm inflation model building in BSM constructions
  - String theory compactifications
  - SUSY GUT phenomenology
  - ...