# Baryogenesis from Modulus Decay

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based on arXiv:1909.04705 with G. Kane


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# Motivation

- string theory: size and shape of extra dimensions controlled by moduli fields
- typical mass of the lightest modulus

$$m_\phi \sim 10^2 - 10^4 \text{ TeV}$$

- only Planck-suppressed couplings to matter

$$\Gamma_\phi = c\,\frac{m_\phi^3}{M_P^2} \sim \left(\frac{m_\phi}{10 \text{ TeV}}\right)^3 \text{ s}^{-1}$$

- modulus affects cosmology

# Modulus Cosmology

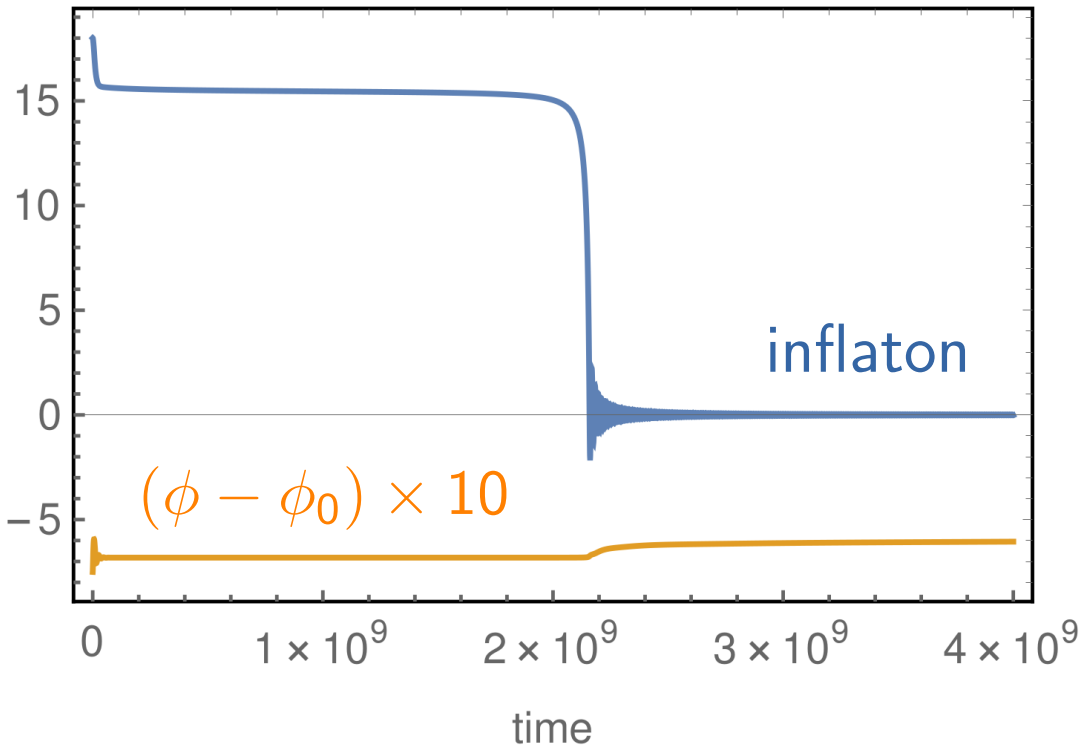
- during inflation modulus gets displaced by linear term

  COUGHLAN ET AL., PLB 131 (1983)

$$V \supset c\,H^2(\phi - \phi_0) \qquad \text{H: Hubble scale}$$

- example: inflation in M-theory

  KANE, WINKLER, PRD 100 (2019)

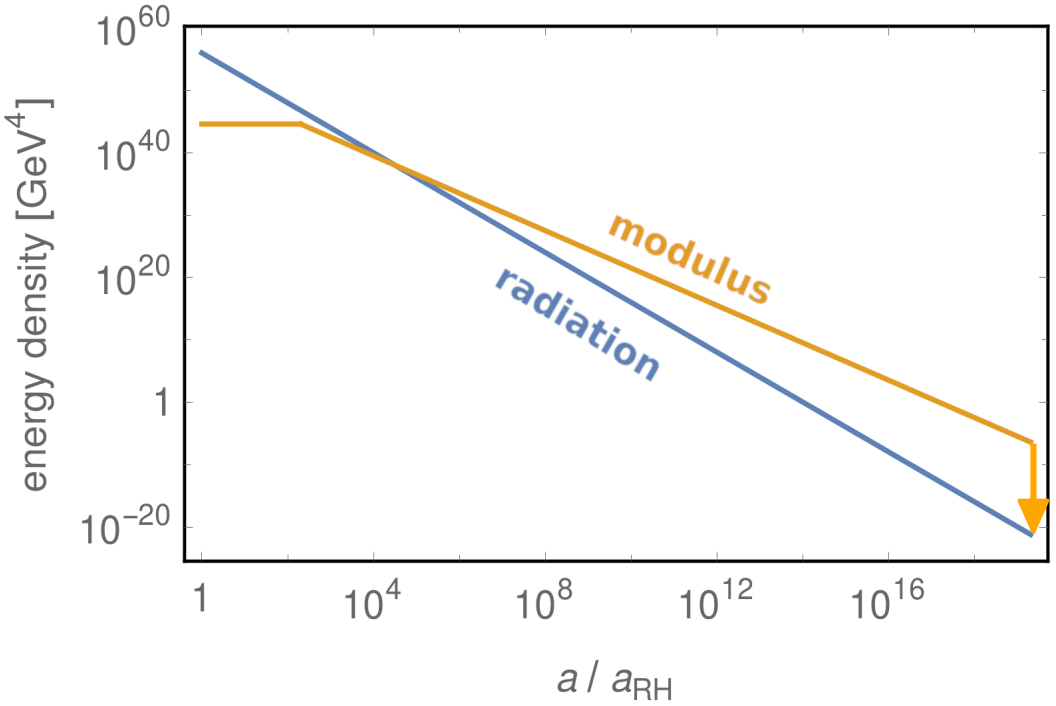


# Modulus Dynamics

- postinflationary evolution: $\ddot{\phi} + 3H\dot{\phi} + m_\phi^2 (\phi - \phi_0) = 0$

$$H > m_\phi \implies \phi \text{ fixed}$$
$$H < m_\phi \implies \phi \text{ oscillates coherently}$$

- energy density




modulus decay inreases entropy by

$$\Delta = \left(\frac{\rho_\phi}{\rho_\gamma}\right)^{3/4} = \mathcal{O}(10^{10})$$

baryon asymmetry washed out!

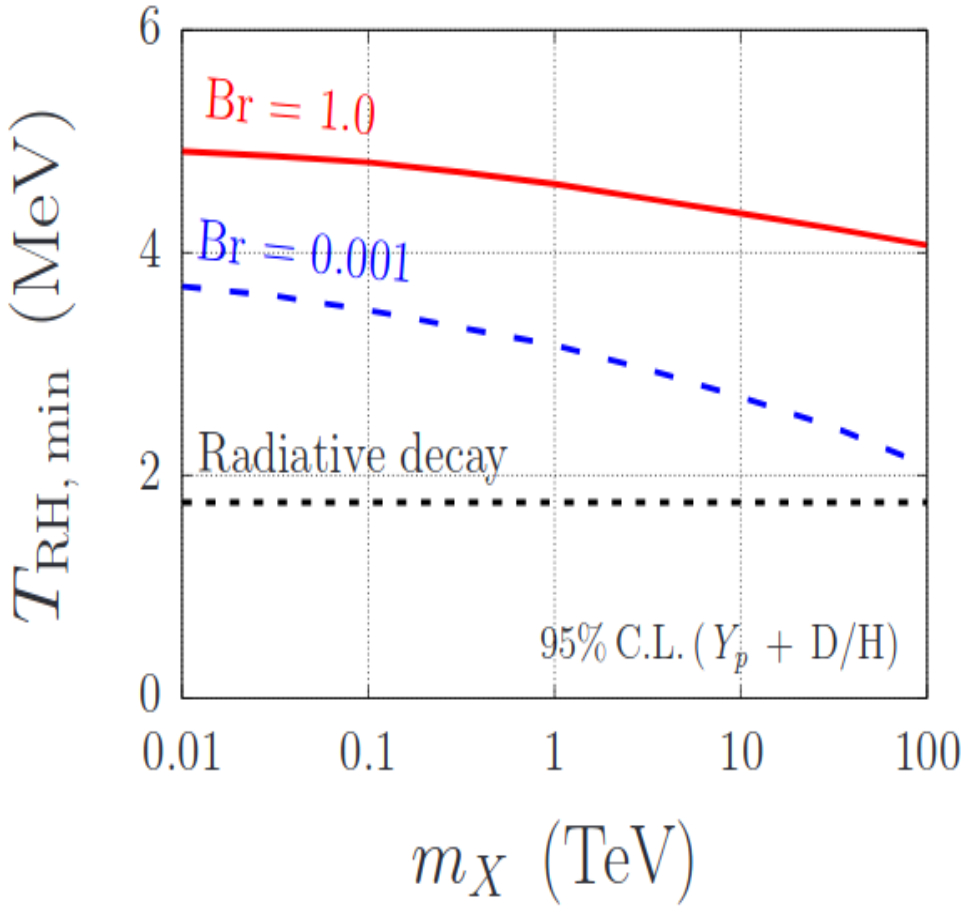
# Big Bang II

- reheating from modulus decay: $T_\phi \simeq 20\,\text{MeV}\,\sqrt{c}\left(\frac{m_\phi}{100\,\text{TeV}}\right)^{3/2}$
- consistent with BBN for

  DE SALAS ET AL., PRD 92 (2015), HASEGAWA ET AL., ARXIV:1908.10189

  $$T_\phi \gtrsim 4\,\text{MeV}$$

- **but**: too cold for most prominent baryogenesis mechanisms (leptogenesis, EW baryogenesis)



# Baryon Abundance vs. Modulus Abundance

- modulus abundance (before decay)

$$Y_\phi \sim \sqrt{\frac{c\, m_\phi}{M_P}} \sim 10^{-7}$$

baryon abundance

$$Y_b = 0.8 \times 10^{-10}$$

- observation: $Y_b \sim (\text{loop factor}) \times Y_\phi$

- idea: generate baryon asymmetry by modulus decay

  SEE ALSO: KITANO, MURAYAMA, RATZ, PLB 669 (2008), ALLAHVERDI, DUTTA, SINHA, PRD 82 (2010), ISHIWATA, JEONG, TAKAHASHI, JHEP 02 (2014)

- smallness of asymmetry would follow from hierarchy between Planck and weak scale (which sets $m_\phi$)

# Modulus Decay pattern

- in UV theories $m_\phi \propto M_{\cancel{SUSY}} \Rightarrow$ observed Higgs mass constrains $m_\phi$
- moduli decay into SM particles, superpartners, gravitinos, axions.

  example: decay to gauge bosons:

$$\mathcal{L} \supset -\frac{\mathrm{Re}\, f(\phi)}{4} F^a_{\mu\nu} F^{a\,\mu\nu} + K_{\bar\phi\phi}\partial_\mu\bar\phi\partial^\mu\phi \quad \Longrightarrow \quad \Gamma_{gg} = \frac{3\, m_\phi^3}{32\pi\, M_P^2} \frac{|\partial_\phi f|^2}{K_{\bar\phi\phi}\,(\mathrm{Re}\, f)^2}$$

predicted in UV theory

| model | $m_\phi$ | $\mathrm{Br}_{gg}$ | $\mathrm{Br}_{\tilde\lambda\tilde\lambda}$ | $\mathrm{Br}_{HH}$ | $\mathrm{Br}_{\tilde h\tilde h}$ | $\mathrm{Br}_{\tilde\Psi\tilde\Psi}$ | $Y_\phi$ |
|---|---|---|---|---|---|---|---|
| type IIb | $(1000-8000)$ TeV | $0.3-0.4$ | $0.3-0.4$ | $<0.1$ | $<0.1$ | $0.2-0.3$ | $(2-5)\times10^{-7}$ |
| heterotic | $(2000-6000)$ TeV | 0.5 | 0.5 | – | – | 0.05 | $(3-5)\times10^{-7}$ |
| M-theory | $(60-160)$ TeV | – | $0.01-1$ | $<1$ | $<1$ | – | $(0.4-10)\times10^{-7}$ |

MODESLS: KACHRU ET AL., PRD 68 (2003), ACHARYA ET AL., PRD 76 (2007), LOWEN, NILLES, PRD 77 (2008)

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**large branching to gauginos**

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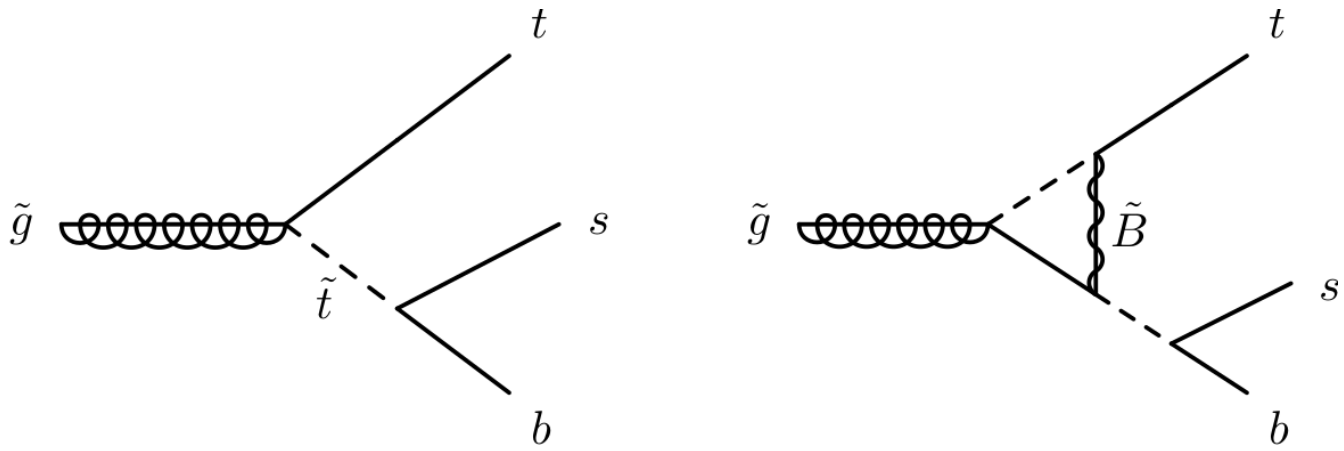
# Baryogenesis

- idea: modulus $\rightarrow$ gluinos $\rightarrow$ baryons




SEE ALSO: CUI, JHEP 12 (2013), ARCADI, COVI, NARDECCHIA, PRD 92 (2015)

- gluionos are **out of thermal equilibrium** (produced by decay)
- ~~CP~~ due to phase in the gaugino mass matrix
- ~~R~~ by R-parity violating operator $W \supset t^c\, b^c\, s^c$

# Baryogenesis

- baryon asymmetry

$$Y_b = Y_\phi \times 2\,\mathrm{Br}(\phi \to \tilde{g}\tilde{g}) \times \epsilon_{CP}$$

- CP asymmetry

$$\epsilon_{CP} \simeq 2 \cdot 10^{-4} \left(\frac{m_{\tilde{g}}}{5\ \mathrm{TeV}}\right) \left(\frac{m_{\tilde{B}}}{1\ \mathrm{TeV}}\right) \left(\frac{8\ \mathrm{TeV}}{m_{\tilde{t}}}\right)^2 f_2\left(\frac{m_{\tilde{B}}^2}{m_{\tilde{g}}^2}\right) \sin(2\varphi_{12})$$

phase gluino-bino

- wino contribution may enhance $\epsilon_{CP}$ by factor $\sim 2$, hidden sector by $\sim 10$

- observed baryon asymmetry can be generated for $\varphi_{12} \gtrsim 10^\circ$

# Baryogenesis

- baryon asymmetry

$10^{-7}$ - $10^{-6}$

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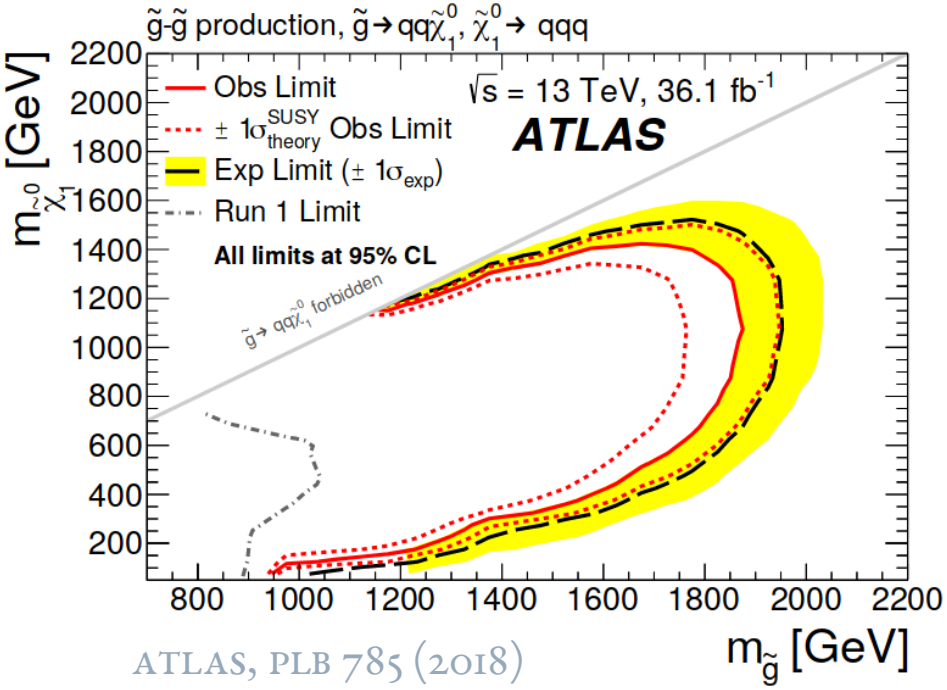
# Experimental Probes

- early matter domination affects small scale structure (perturbations grow linear with scale factor in this time)

  → axion miniclusters, boost of dark matter signals ...

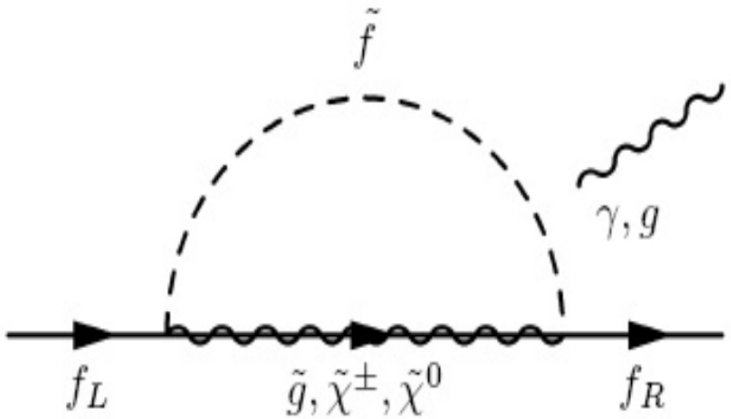
  KHLOPOV, POLNAREV, NUF. W. (1982), ERICKCEK, PRD 92 (2015), NELSON, XIAO, PRD 98 (2018)

- LHC superpartner searches




ATLAS, PLB 785 (2018)

- EDMs probe gaugino phases



# Summary

- string/ supergravity models generically predict superweakly coupled modulus field with mass $m_\phi \sim 10^2 - 10^4$ TeV
- modulus alters the cosmological history by late time entropy production, washes out the baryon asymmetry
- baryon asymmetry (re)generated by the modulus decay into quarks via intermediate gluinos
- size of the asymmetry $Y_b \sim (\text{loop factor}) \times \sqrt{m_\phi / M_P}$