Unified Origin of Dark Matter and Baryons

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Based on work in collaboration with Volodymyr Takhistov, JHEP1905 (2019) 101

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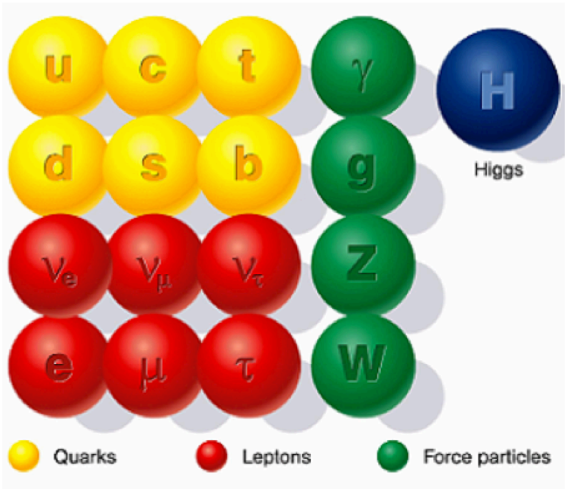
Reasons to go Beyond the Standard Model

- **Observational:**
  - neutrino masses
  - cold dark matter
  - baryon asymmetry of the Universe
- **Theoretical:**
  - in the language of the SM, Quantum Field Theory, it is hard to describe gravitation
- **Aesthetical:** the structure of the SM is very peculiar



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  - neutrino masses
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- **Aesthetical:**
  - flavor puzzle: the structure of the SM is very peculiar
  - gauge hierarchy problem - stability of Higgs mass

MSSM

- Many attractive features
  - partial solution to the gauge hierarchy problem
  - gauge coupling unification
  - dark matter candidate

- Many deficiencies
  - mu problem: $\mu << M_{pl}$
  - proton decay through dim-4, dim-5 operators
    - dim-4 operators: forbidden by imposing R-parity
    - dim-5 operators: severe experimental constraints on the models

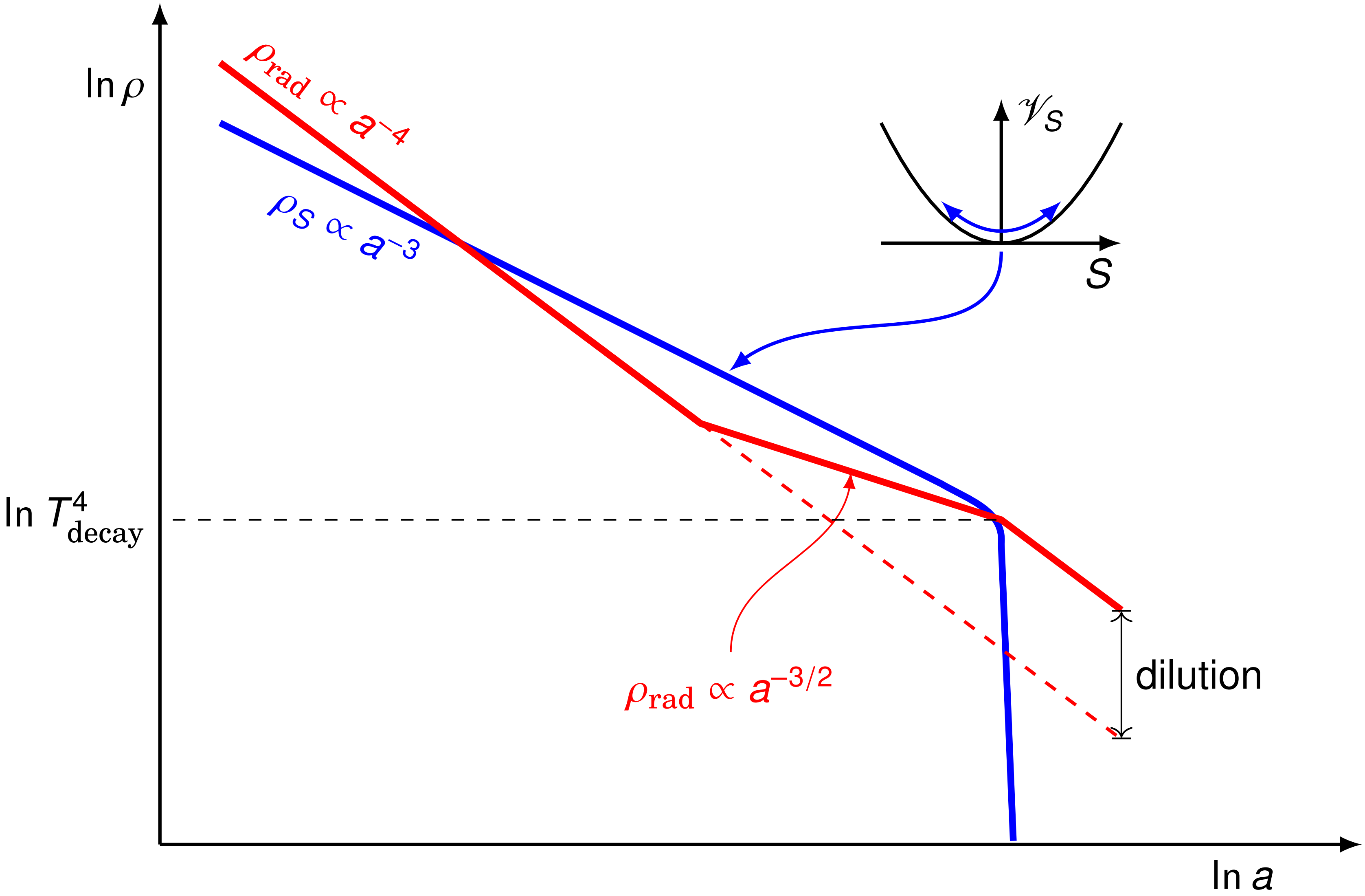
Cosmological Moduli Problems

- SUSY: predict many scalars
  - concrete models have many flat directions before SUSY breaking
  - moduli mass ~ SUSY breaking scale
  - Planck suppressed interactions ⇒ never thermalized
  - EW scale moduli: decay after BBN
    - destroy light elements
    - entropy productions: dilute n_B/s ⇒ no baryogenesis
- gravity-mediated SUSY breaking $m_{3/2} \sim 10^{2-3}$ GeV
  - neutralino dark matter
  - late time moduli decay
  - dilute n_B/s by large order of magnitude

Cosmological Moduli Problems

recall talk by on Thursday

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



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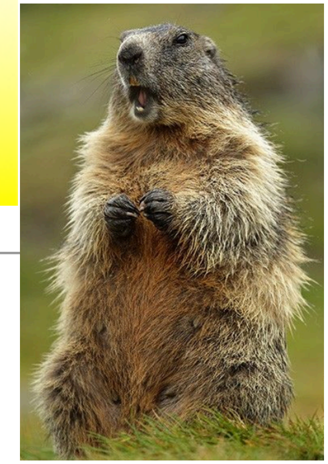

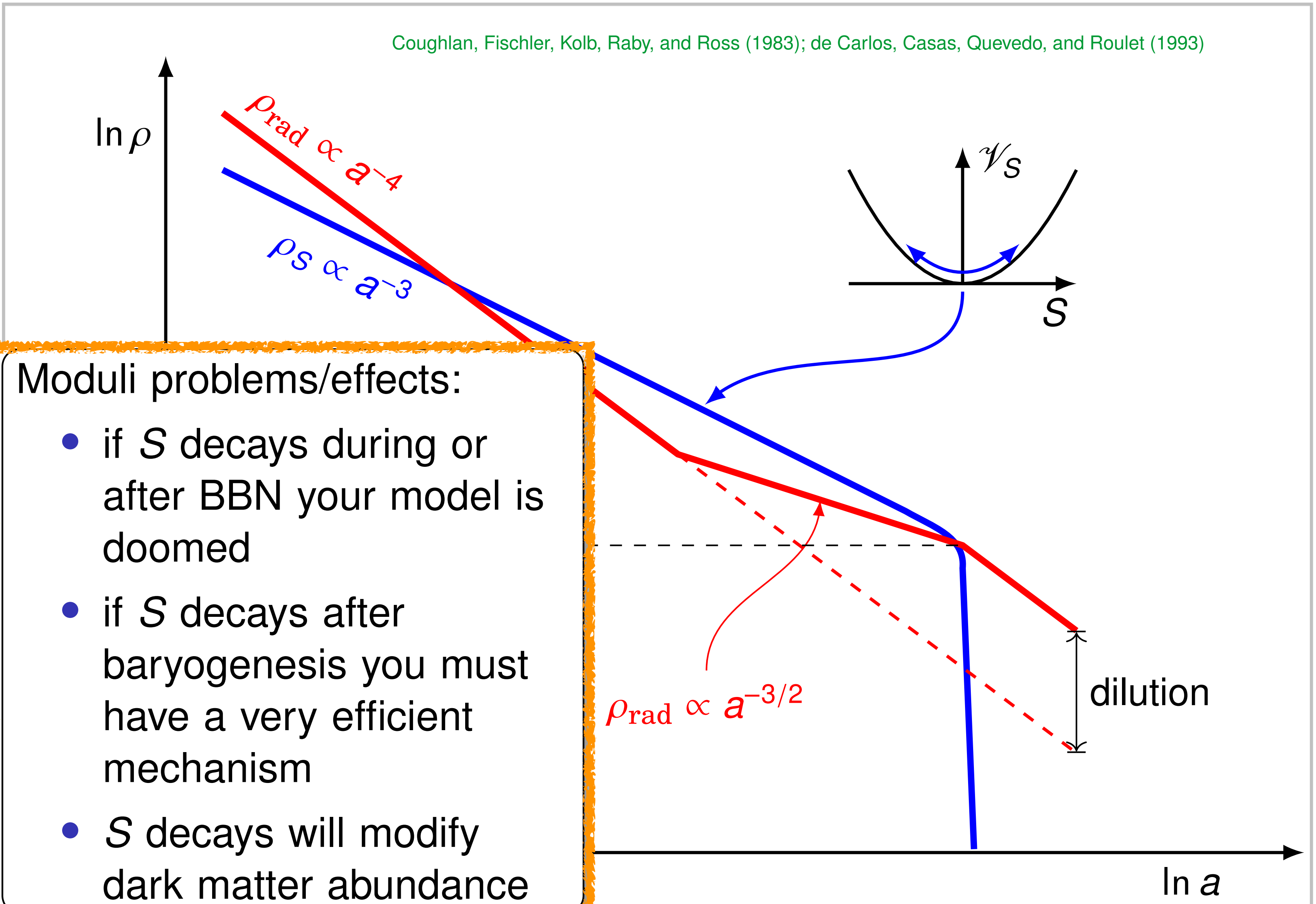

Moduli problems/effects:

- if S decays during or after BBN your model is doomed
- if S decays after baryogenesis you must have a very efficient mechanism
- S decays will modify dark matter abundance

Avoiding Cosmological Moduli Problems

- **raising moduli mass:** Anomaly/Mirage-mediated SUSY breaking

  $m_{3/2} > (10 - 100)$ TeV ⇒ moduli decay before BBN

  - LSP: Wino or Higgsino ⇒ too small dark matter thermal abundance

  - entropy production diluting produced baryon asymmetry

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    non-thermal abundance due to moduli decay

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    baryogenesis due to moduli decay

Avoiding Cosmological Moduli Problems

Kitano, Murayama, Ratz (2008)

- **Basic idea:** chiral superfield $\Phi = (\phi, \widetilde{\phi}, F_\phi)$

  ϕ-number asymmetry $q_\phi := \mathrm{i}\left(\dot{\phi}^*\phi - \phi^*\dot{\phi}\right)$

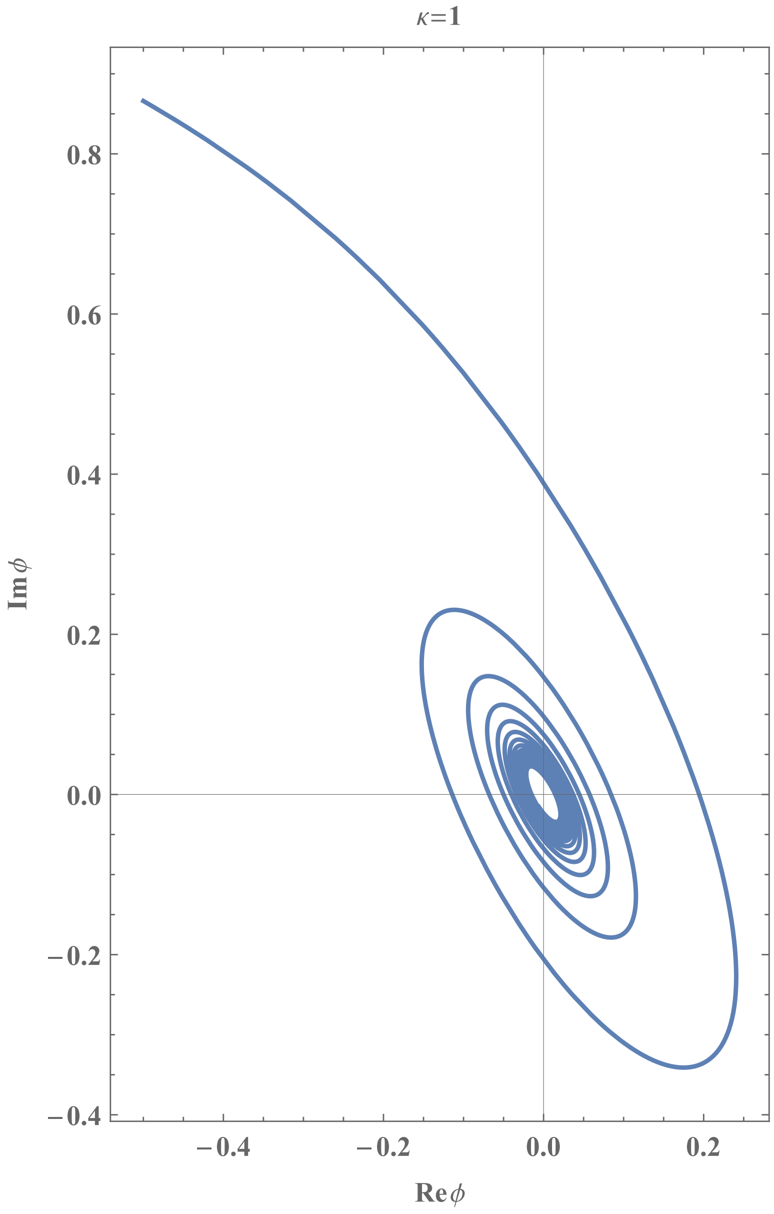
- Evolution of the moduli field

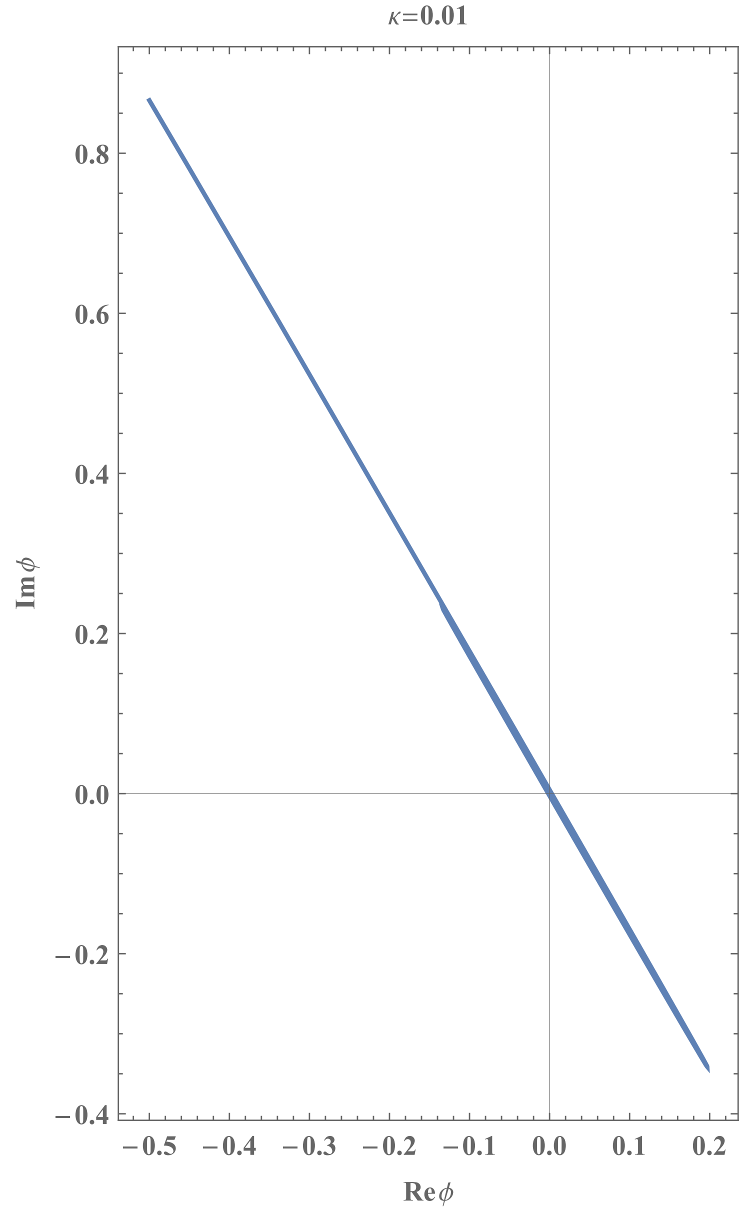
$$\ddot{\phi} + (3H + \Gamma_\phi)\,\dot{\phi} + \frac{\partial V}{\partial \phi^*} = 0$$

$$\dot{q}_\phi + 3H\,q_\phi = -\mathrm{i}\left(\phi\frac{\partial V}{\partial \phi} - \phi^*\frac{\partial V}{\partial \phi^*}\right)$$

Moduli Number Asymmetry

$$q_\phi := \mathrm{i}\left(\dot{\phi}^*\phi - \phi^*\dot{\phi}\right)$$





Avoiding Cosmological Moduli Problems

Kitano, Murayama, Ratz (2008)

- Evolution of moduli field

$$\dot{q}_\phi + 3H\, q_\phi \;=\; -\,\mathrm{i}\left(\phi\frac{\partial V}{\partial \phi} - \phi^*\frac{\partial V}{\partial \phi^*}\right)$$

$V(\phi, \phi^*)$ such that $\underbrace{}$ $\neq 0$

with suppressed ϕ-number violation interactions

- Early Era (after inflation): H $\gg$ m_ϕ oscillation unimportant
  - generation of moduli asymmetry through evolution
- Coherent oscillation of moduli: (@T ~ T* = $(M_{pl} \times m_\phi)^{1/2}$: H ~ m_ϕ)
  - ϕ-number approximately conserved ⇒ asymmetry preserved
  - dominate energy density of Universe
- Moduli decay (H~Γ_ϕ) ⇒ Baryogenesis:

  ϕ-number asymmetry → B-number asymmetry

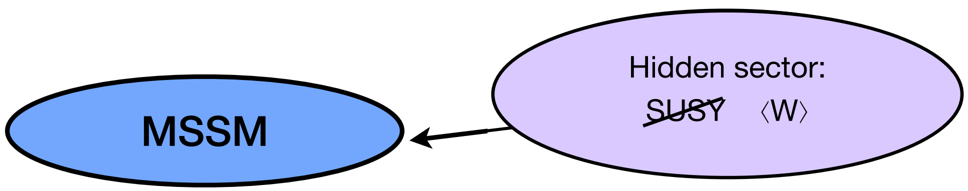
The μ Term and Dirac Neutrino Mass

- naturally small μ Term and Dirac neutrino masses?
- before SUSY breaking: absence of μ term & Dirac neutrino masses (as well as Weinberg operator)

- after SUSY breaking

Giudice, Masiero (1988)

$$\mu \sim \langle \mathscr{W} \rangle / M_{\mathrm{P}}^2 \sim m_{3/2}$$



- realistic effective Dirac neutrino masses generated

Arkani-Hamed, Hall, Murayama, Tucker-Smith, Weiner (2001)

$$Y_\nu \sim \frac{m_{3/2}}{M_{\mathrm{P}}} \sim \frac{\mu}{M_{\mathrm{P}}}$$

- need a symmetry reason for the absence of these operators before SUSY breaking

The μ Term and Dirac Neutrino Mass

- Requiring Symmetries
  - to forbid mu term
  - be anomaly-free
  - be consistent with SU(5)
- continuous R symmetries not available

A.H. Chamseddine, H.K. Dreiner (1996)

→ R Symmetries

H.M. Lee, S. Raby M. Ratz, G.G. Ross, R. Schieren, K. Schmidt-Hoberg, P.K. Vaudrevange, (2011);

→ Discrete R Symmetries

- Exist classes of Abelian discrete R symmetries, $\mathbb{Z}_M^R$, that satisfy
  - Dirac neutrino case for q_θ = integer:
    - anomaly freedom (a la Green-Schwarz)
    - forbidding mu term perturbatively
    - consistent with SU(5)
    - allowing usual Yukawa
    - Weinberg operators forbidden perturbatively

M.-C. C., Michael Ratz, Christian Staudt, Patrick Vaudrevange (2012)

Structure of the Model

MSSM with

anomaly-free discrete R symmetry Z_{12}^R

- μ-term
- nucleon stability
- moduli potential $V(\phi, \phi^*)$

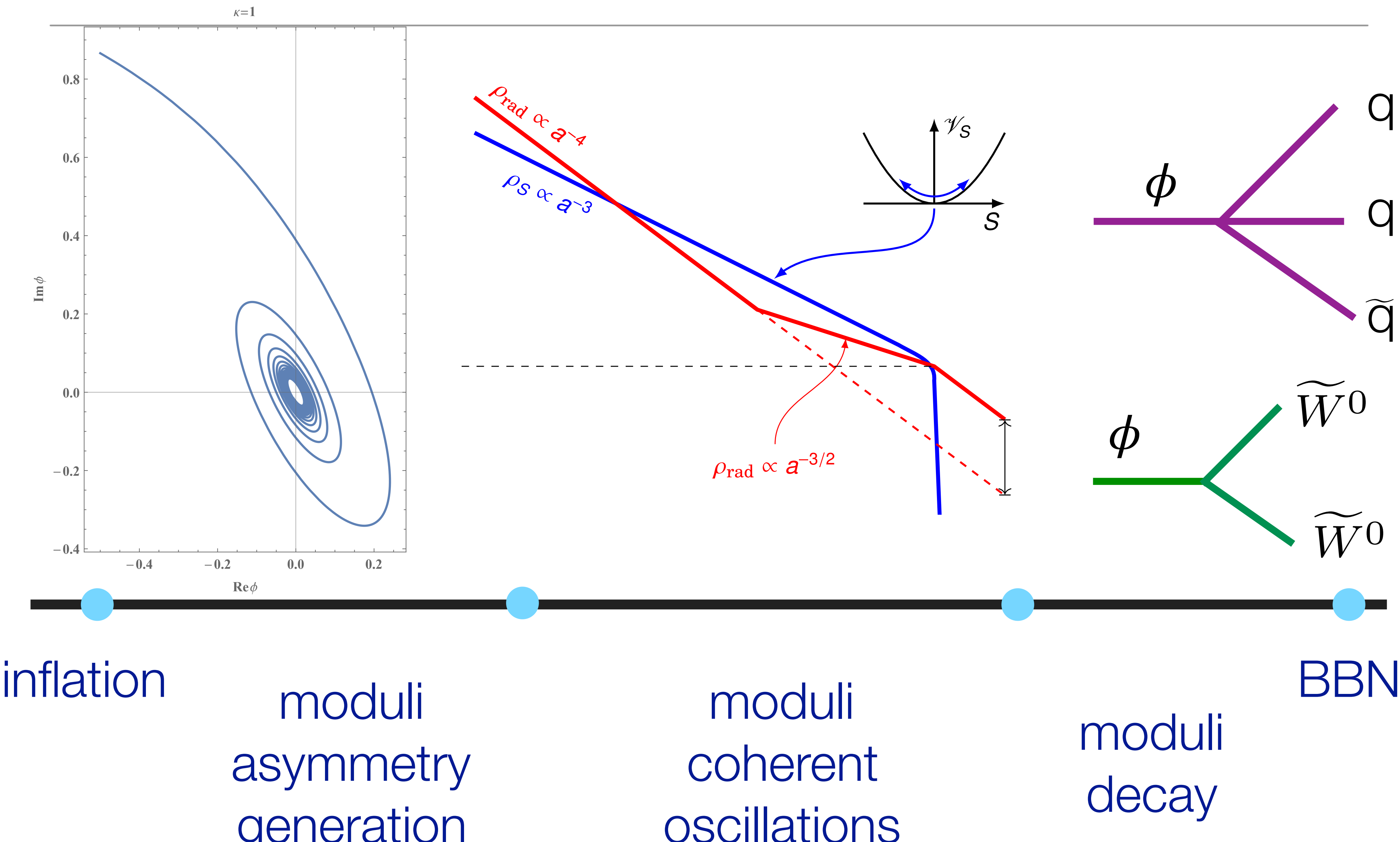
anomalous $U(1)_A$

- flavor structure a lá Froggatt-Nielsen
- Dirac neutrino masses

moduli potential → baryogengesis, dark matter (wino)

$$\frac{\Omega_{DM}}{\Omega_b} \sim 5$$

Avoiding Cosmological Moduli Problems



The Model

Particle Content: SU(5) compatible

	SU(5) $\mathbf{10}$			SU(5) $\overline{\mathbf{5}}$								$\mathscr{W}_{\text{hid}}$		
	Q	$\overline{U}$	$\overline{E}$	$\overline{D}$	L	H_u	H_d	$\overline{\nu}$	Φ	$\overline{\Phi}$	σ	e^{-bS}	X	θ
$\mathbb{Z}_{12}^R$	2	2	2	6	6	2	10	10	4	8	0	6	r_X	3
$\to \mathbb{Z}_3$	2	2	2	0	0	1	2	1	2	1	0	0	$r_{X'}$	-
$\mathbb{Z}_2^M$	1	1	1	1	1	0	0	1	1	1	0	0	0	0
	3	3	3	$(1+p)$	$(1+p)$			$(15+p)$						
$\text{U}(1)_A$	2	2	2	p	p	0	0	$(14+p)$	0	0	-1	q_S	0	0
	0	0	0	p	p			$(13+p)$						

The Model

- Superpotential:

$$\mathscr{W} = Y_e L H_d \overline{E} + Y_d Q H_d \overline{D} + Y_u Q H_u \overline{U} + Y_\nu L H_u \overline{\nu}$$
$$+ \kappa_1 \overline{UDD}\Phi + \kappa_2 L L \overline{E}\Phi + \kappa_3 L Q \overline{D}\Phi \ ,$$

baryogenesis, DM

- After SUSY breaking:

$$\mathscr{W}^{np}_{eff} \supset M_\Phi \Phi \overline{\Phi} + \kappa_4 QQQL + \kappa_5 \overline{UUDE}$$
$$+ \kappa_6 \overline{UDD}\overline{\nu} + \kappa_7 L L \overline{E}\overline{\nu} + \kappa_8 L Q \overline{D}\overline{\nu} + \ldots$$

$$K \supset \kappa\, X^\dagger X \Phi^6 + k_{H_u H_d} \frac{X^\dagger}{M_{pl}} H_u H_d + h.c.$$

moduli asymmetry

μ-term

Anomaly Cancellation - Anomalous U(1)$_A$

- Anomaly coefficients:

$$\left.\begin{array}{r}[\mathrm{SU}(3)_C]^2\times \mathrm{U}(1)_A\\ [\mathrm{SU}(2)_W]^2\times \mathrm{U}(1)_A\\ [\mathrm{U}(1)_Y]^2\times \mathrm{U}(1)_A\\ [\mathrm{U}(1)_A]^3\\ [\mathrm{gravity}]^2\times \mathrm{U}(1)_A\end{array}\right.\quad \left\{\begin{array}{lcl}\mathcal{A}_{CCA} &=& \frac{1}{2}\Big[\sum_{i=1}^{3}(3q^i_{\mathbf{10}}+q^i_{\bar{\mathbf{5}}})\Big]\\ \mathcal{A}_{WWA} &=& \frac{1}{2}\Big[(q_{H_u}+q_{H_d})+\sum_{i=1}^{3}(3q^i_{\mathbf{10}}+q^i_{\bar{\mathbf{5}}})\Big]\\ \mathcal{A}_{YYA} &=& \frac{1}{2}\Big[(q_{H_u}+q_{H_d})+\frac{5}{3}\sum_{i=1}^{3}(3q^i_{\mathbf{10}}+q^i_{\bar{\mathbf{5}}})\Big]\cdot\frac{3}{5}\\ \mathcal{A}_{AAA} &=& 2(q^3_{H_u}+q^3_{H_d})+5\sum_{i=1}^{3}(2(q^i_{\mathbf{10}})^3+(q^i_{\bar{\mathbf{5}}})^3)+q^3_\sigma+\sum_{i=1}^{3}(q^i_{\overline{N}})^3+\mathcal{A}^{\mathrm{hidden}}_{YAA}\\ \mathcal{A}_{GGA} &=& 2(q_{H_u}+q_{H_d})+5\sum_{i=1}^{3}(2q^i_{\mathbf{10}}+q^i_{\bar{\mathbf{5}}})+\sum_{\mathrm{SM\ singlet}}q_s+\mathcal{A}^{\mathrm{hidden}}_{GGA}\end{array}\right.$$

- Cancellation of anomaly a lá Green-Schwarz

$$\frac{\mathcal{A}_{CCA}}{k_C}=\frac{\mathcal{A}_{WWA}}{k_W}=\frac{\mathcal{A}_{YYA}}{k_Y}=\frac{\mathcal{A}_{AAA}}{3k_A}=\frac{\mathcal{A}_{GGA}}{24}=2\pi^2\delta_{\mathrm{GS}}$$

- SU(5) compatibility:

$$\frac{\mathcal{A}_{CCA}}{k_C}=\frac{\mathcal{A}_{WWA}}{k_W}=\frac{\mathcal{A}_{YYA}}{k_Y}=\frac{\mathcal{A}_{GGA}}{24}=\frac{(16+3p)}{4}$$

Anomaly Cancellation

- Discrete R Symmetry

$$
\begin{cases}
\mathcal{A}_{CCR} &= \dfrac{1}{2}\Big[\sum_{i=1}^{3}(3q^i_{\mathbf{10}} + q^i_{\bar{\mathbf{5}}})\Big] - 3R \\
\mathcal{A}_{WWR} &= \dfrac{1}{2}\Big[(q_{H_u} + q_{H_d}) + \sum_{i=1}^{3}(3q^i_{\mathbf{10}} + q^i_{\bar{\mathbf{5}}})\Big] - 5R \\
\mathcal{A}_{YYR} &= \dfrac{1}{2}\Big[(q_{H_u} + q_{H_d} - 11R) + \dfrac{5}{3}\sum_{i=1}^{3}(3q^i_{\mathbf{10}} + q^i_{\bar{\mathbf{5}}})\Big] \cdot \dfrac{3}{5} \\
\mathcal{A}_{GGR} &= 2(q_{H_u} + q_{H_d} - 2R) + 5\sum_{i=1}^{3}(2q^i_{\mathbf{10}} + q^i_{\bar{\mathbf{5}}} - 3R) + \sum_{\text{SM singlet}} q_s \\
& \quad + \mathcal{A}^{\text{hidden}}_{GGR} + 33R
\end{cases}
$$

Early Epoch: Moduli Asymmetry

- Asymmetry generating term from Kähler potential:

$$K \supset \kappa X^\dagger X \Phi^6$$

<X> ~ $m_{3/2}$: SUSY breaking effect

- moduli potential

$$V = m_\phi^2|\phi|^2 + m_{3/2}^2 M^2 F\Big(\frac{|\phi|^2}{M^2}\Big) + \Big[\kappa\frac{m_{3/2}^2}{M^4}\phi^6 + h.c.\Big] + \ldots$$

- ϕ-evolution

$$\dot{q}_\phi + 3Hq_\phi = -i\Big(\phi\frac{\partial V}{\partial\phi} - \phi^*\frac{\partial V}{\partial\phi^*}\Big) = \frac{6\, m_{3/2}^2}{M^4}\,\mathrm{Im}[\kappa\phi^6]$$

- ϕ-number asymmetry

$$\varepsilon \equiv \frac{q_\phi(t_0)}{n_\phi + n_{\phi^*}} \sim |\kappa|\Big(\frac{m_{3/2}}{m_\phi}\Big)^2$$

Intermediate Epoch: Moduli Oscillations

- Coherent oscillations of moduli:

$$\varepsilon \equiv \frac{q_\phi(t_0)}{n_\phi + n_{\phi^*}} \sim |\kappa| \left(\frac{m_{3/2}}{m_\phi}\right)^2$$

- ϕ-number asymmetry preserved during coherent oscillation

- O(1) asymmetry at the on-set of moduli decay

Late Epoch: Moduli Decay

- Superpotential: $W \supset \frac{1}{M} \overline{UDD}\Phi$
- moduli decay

$$\phi \to qq\tilde{q} \qquad \Gamma_\phi = \xi \frac{m_\phi^3}{M^2}$$

  - ϕ dominates energy density before decay
  - baryon number density $n_b = q_\phi$
  - resulting asymmetry

$$\frac{n_b}{s} \sim 10^{-10}|\kappa|\left(\frac{m_{3/2}}{10^3\ \mathrm{TeV}}\right)^2\left(\frac{5\times 10^4\ \mathrm{TeV}}{m_\phi}\right)^{3/2}\left(\frac{M_{pl}}{M}\right)$$

Dark Matter via Moduli Decay

- LSP: Wino dark matter — Moroi, Randall (1999)
  - strong pair co-annihilation: thermal relic abundance too small
  - non-thermal contribution from moduli decay

$$\mathcal{L}_{\rm G} = \int d^2\theta \frac{\lambda_{\rm G}}{M_*} \phi W^\alpha W_\alpha + {\rm h.c.}$$

  - DM relic abundance $\Omega_{DM} h_0^2 \simeq 0.1 \Big(\frac{m_\chi}{700\ {\rm GeV}}\Big)^3 \Big(\frac{5\times 10^4\ {\rm TeV}}{m_\phi}\Big)^{3/2} \Big(\frac{M}{M_P}\Big)$
  - DM and Baryon numbers: no moduli mass dependence

$$\frac{\Omega_{DM}}{\Omega_b} \sim 5\ |\kappa|^{-1} \Big(\frac{1\ {\rm GeV}}{m_{nuc}}\Big)\Big(\frac{m_\chi}{700\ {\rm GeV}}\Big)^3 \Big(\frac{10^3\ {\rm TeV}}{m_{3/2}}\Big)^2 \Big(\frac{M}{M_P}\Big)^2$$

Flavor Structure

- Yukawa interactions

$$\mathscr{W} \supset y^e_{ij}\left(\frac{\sigma}{M_{pl}}\right)^{n^e_{ij}} L_i\, H_d\, \overline{E}_j + y^d_{ij}\left(\frac{\sigma}{M_{pl}}\right)^{n^d_{ij}} Q_i\, H_d\, \overline{D}_j + y^u_{ij}\left(\frac{\sigma}{M_{pl}}\right)^{n^u_{ij}} Q_i\, H_u\, \overline{U}_j + y^\nu_{ij}\left(\frac{\sigma}{M_{pl}}\right)^{n^\nu_{ij}} L_i\, H_u\, \overline{\nu}_j$$

- Yukawa hierarchy a lá Froggatt-Nielsen

$$Y^f_{ij} = y^f_{ij}\left(\frac{\sigma}{M_{pl}}\right)^{n^f_{ij}} \longrightarrow y^f_{ij}\left(\frac{\langle\sigma\rangle}{M_{pl}}\right)^{n^f_{ij}} = y^f_{ij}\epsilon^{n^f_{ij}}$$

- expansion parameter $\epsilon = \frac{\langle\sigma\rangle}{M_{pl}} = \sqrt{\frac{g_s^2 A_{\mathrm{GGA}}}{192\pi^2}} \simeq \sin\theta_c = \mathcal{O}(0.2)$

Flavor Structure

- Charged Fermion Mass Matrices:

$$M_u \sim \langle H_u \rangle \begin{pmatrix} \epsilon^6 & \epsilon^5 & \epsilon^3 \\ \epsilon^5 & \epsilon^4 & \epsilon^2 \\ \epsilon^3 & \epsilon^2 & 1 \end{pmatrix} \quad ; \quad M_d \sim \langle H_d \rangle \epsilon^p \begin{pmatrix} \epsilon^4 & \epsilon^3 & \epsilon^3 \\ \epsilon^3 & \epsilon^2 & \epsilon^2 \\ \epsilon & 1 & 1 \end{pmatrix} \quad ; \quad M_e \sim \langle H_d \rangle \epsilon^p \begin{pmatrix} \epsilon^4 & \epsilon^3 & \epsilon \\ \epsilon^3 & \epsilon^2 & 1 \\ \epsilon^3 & \epsilon^2 & 1 \end{pmatrix}$$

- parameter p:

$$p \in \{2, 1, 0\} \qquad \tan\beta \equiv \langle H_u \rangle / \langle H_d \rangle \in \{5, 10, 20\}$$

- Naturally light Dirac neutrinos:

$$M_\nu \sim \langle H_u \rangle \epsilon^{13+2p} \begin{pmatrix} \epsilon^3 & \epsilon^2 & \epsilon \\ \epsilon^2 & \epsilon & 1 \\ \epsilon^2 & \epsilon & 1 \end{pmatrix}$$

- $$p \in \{0, 1, 2\} \longrightarrow \frac{m_\nu}{\langle H_u \rangle} \sim \{\epsilon^{13}, \epsilon^{14}, \epsilon^{15}\} \simeq \{10^{-9}, 10^{-11}, 10^{-12}\}$$

Nucleon Stability

- Δ(B-L) = 0: proton decay $p \to \overline{\nu} K^+$

$$QQQL \qquad \overline{UUDE}$$

constraints

Super-Kamiokande Collaboration (2014)

$$\text{family 1:} \quad \kappa_4, \kappa_5 \sim \frac{m_{3/2}}{M_{pl}^2} \epsilon^{10+p} \simeq \frac{4 \times 10^{-20}}{M_{pl}} \left(\frac{m_{3/2}}{10^3 \ \text{TeV}} \right) \epsilon^p \lesssim \frac{10^{-8}}{M_{pl}}$$

$$\text{family 3:} \quad \kappa_4, \kappa_5 \sim \frac{m_{3/2}}{M_{pl}^2} \epsilon^{6+p} \simeq \frac{3 \times 10^{-17}}{M_{pl}} \left(\frac{m_{3/2}}{10^3 \ \text{TeV}} \right) \epsilon^p \lesssim \frac{10^{-8}}{M_{pl}}$$

- Δ(B-L) = 2 ⇒ neutron-antineutron oscillation

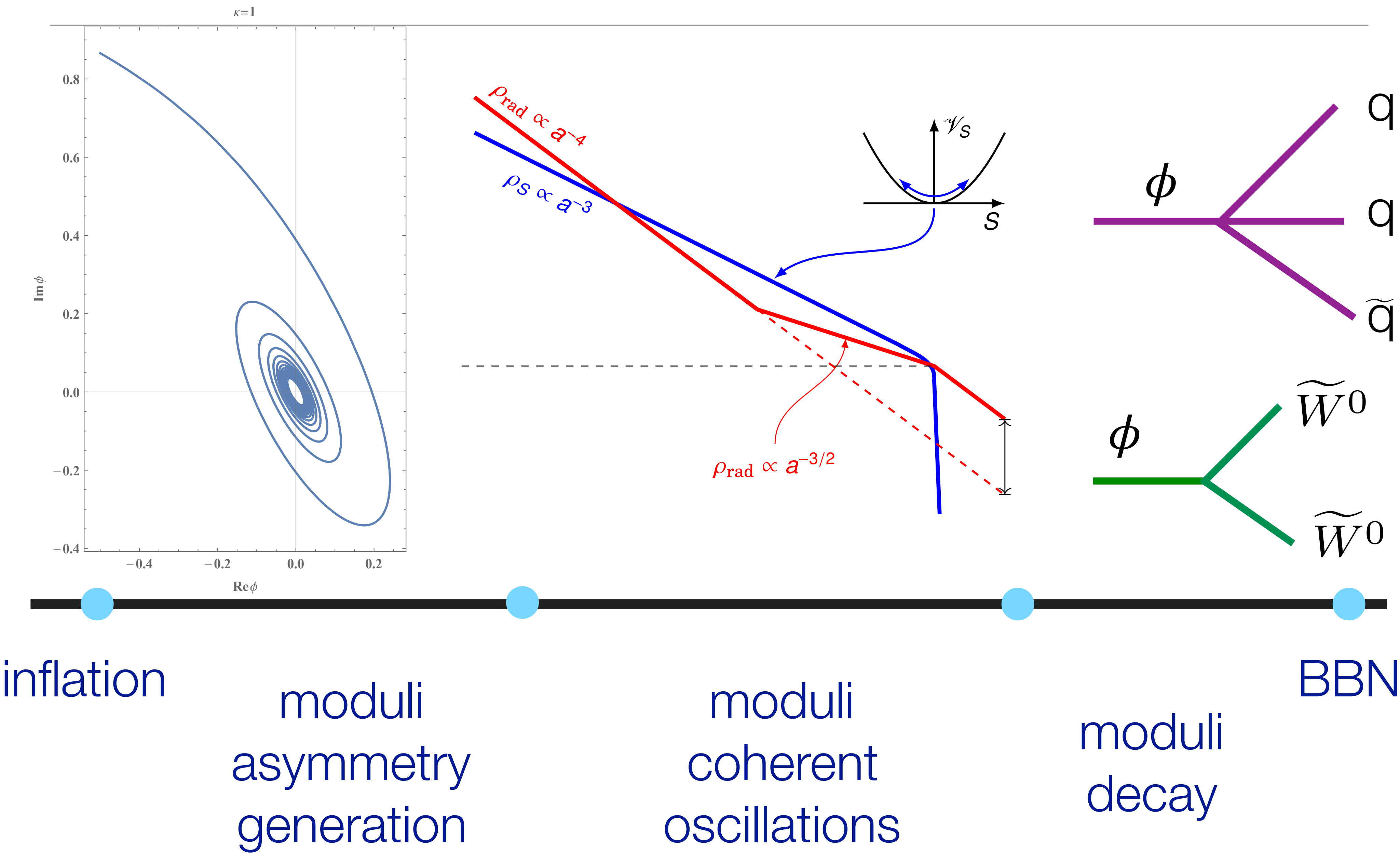
$$\mathscr{W}_{eff} \supset \frac{\epsilon^{5+2p}}{M} \overline{UDD} \Phi + M_\Phi \Phi \overline{\Phi} \qquad \mathbf{O}_{n-\overline{n}} = \frac{\epsilon^{10+4p}}{M^2 M_\Phi} \left(\overline{UDD} \right)^2$$

constraint $\tau_{n-\overline{n}}^{\text{bound}} \gtrsim 2 \times 10^{32}$ years

Super-Kamiokande Collaboration (2015)

$$\Rightarrow \quad M_\Phi \gtrsim 10^{-1} \epsilon^{-4p} \left(\frac{M_{pl}}{M} \right)^2 \ \text{GeV}$$

Summary



κ=1
Im ϕ
Re ϕ
ρ_rad ∝ a^-4
ρ_S ∝ a^-3
ρ_rad ∝ a^-3/2
𝒱_S
S
ϕ
q
q
q̃
ϕ
W̃^0
W̃^0
inflation
moduli asymmetry generation
moduli coherent oscillations
moduli decay
BBN

Summary

MSSM with

anomaly-free discrete R symmetry Z_{12}^R

- μ-term ✓
- nucleon stability ✓
- moduli potential $V(\phi, \phi^*)$ → baryogengesis ✓, dark matter ✓

anomalous $U(1)_A$

- flavor structure a lá Froggatt-Nielsen ✓
- Dirac neutrino masses ✓

$$\frac{\Omega_{DM}}{\Omega_b} \sim 5$$ ✓