Anomaly Mediated Supersymmetry Breaking for Chiral Gauge Theories

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Outline

- Background & Why AMSB?
- How AMSB works
- Chiral gauge theory dynamics

Calculating Chiral Dynamics

Lattice Calculations

- Simulates nonperturbative gauge interactions on a lattice
- Unrealistic due to fermion doubling problem

Tumbling

- Postulates condensates that successively break symmetry down to QCD-like theories
- Is still a conjecture

SUSY

- Dynamics are often fully solvable due to holomorphy
- We haven't found SUSY, so we need results for the non-SUSY theories

SUSY Breaking

Most methods

- Lack of theoretical control
- Phase transitions at the dynamical scale
- Different universality classes

Anomaly mediated SUSY breaking (AMSB)

- Squarks & gauginos become massive
- UV insensitivity
- Same universality class?

AMSB Summary

- Additional tree level term in the potential

$$\mathcal{L}_{\text{tree}} = m\left(\phi_i \frac{\partial W}{\partial \phi_i} - 3W\right) + c.c.$$

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- Loop level piece in trilinear couplings, and scalar & gaugino masses

$$m_\lambda(\mu) = -\frac{\beta(g^2)}{2g^2}(\mu)m \qquad m_i^2(\mu) = -\frac{1}{4}\dot{\gamma}_i(\mu)m^2$$

$$A_{ijk}(\mu) = -\frac{1}{2}(\gamma_i + \gamma_j + \gamma_k)(\mu)m$$

- All terms determined from energetically local physics → UV insensitivity
- In the asymptotically free limit, $m_i^2 > 0$, the theory is stabilized

SU(N) with an Antisymmetric Tensor

- Large class of chiral gauge theories
- UV: An antisymmetric tensor A, F fundamentals, and N+F-4 antifundamentals
- IR: several composite fields H, M, & B^k
- Some of the theories are potential GUTs
- Important "electric" and "magnetic" dualities

	$SU(N)$	$SU(F)$	$SU(N+F-4)$	$U(1)_1$	$U(1)_2$	$U(1)_R$
A	$\binom{N}{2}$	1	1	0	$-2F$	$\frac{-12}{N}$
F	N	F	1	1	$N-F$	$2-\frac{6}{N}$
$\overline{F}$	N^*	1	$N+F-4$	$\frac{-F}{N+F-4}$	F	$\frac{6}{N}$
$H=A\overline{F}\,\overline{F}$	1	1	$\binom{N+F-4}{2}$	$\frac{-2F}{N+F-4}$	0	0
$M=\overline{F}F$	1	F	$N+F-4$	$\frac{N-4}{N+F-4}$	N	2
$B_k=F^k A^{(N-k)/2}$	1	$\binom{F}{k}$	1	k	$(k-F)N$	$2k-6$
$\overline{B}=\overline{F}^N\ (F\geq 4)$	1	1	$\binom{N+F-4}{N}$	$\frac{-4F}{N+F-4}$	$4F$	$\frac{24}{N}$

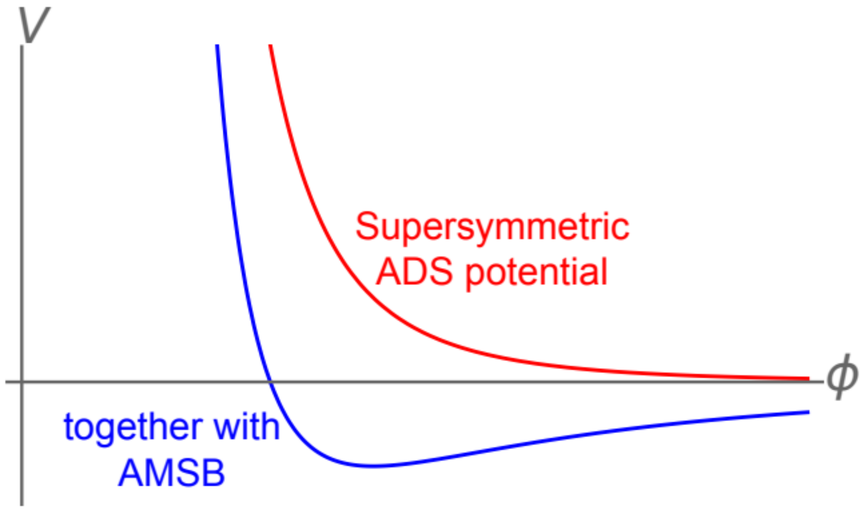
SU(N) & F=1 Superpotentials

- The superpotential is generated by gluino condensation in an Sp(1) subgroup of SU(N)

$$W = \left(\frac{\Lambda^{2N+2}}{(B_1 Pf\ H)}\right)^{1/2} \quad \text{(for odd N)}$$

$$W = \left(\frac{\Lambda^{2N+2}}{(B_0 M H^{(N-4)/2})}\right)^{1/2} \quad \text{(for even N)}$$

- Since F = 1 < 3, the potential has runaway behavior and the coupling is small, so we describe the fields in terms of the UV fields



General Vacuum: Even N

- We studied general D-flat directions & found the new minimum along this direction
- **The general form of the vacuum occurs when F, $\bar{F}$, & A take this form where**

$$\rho = \left(\frac{(N-1)\Lambda^{N+1}}{\left[2^{2N+3}k!l!\right]^{1/2}(N+1)m}\right)^{1/N}$$ **for even N**

$$\mathcal{R}_n = \begin{pmatrix} 0 & \rho^n \\ -\rho^n & 0 \end{pmatrix}$$

$$k = \frac{N}{2}, l = \frac{N-4}{2}$$

$$F = \sqrt{2}\begin{bmatrix} 0 \\ \vdots \\ 0 \\ \rho \\ 0 \\ 0 \\ 0 \end{bmatrix} \quad \bar{F} = \sqrt{2}\begin{bmatrix} \rho & & 0 & 0 & 0 & 0 \\ & \ddots & & 0 & 0 & 0 \\ 0 & & \rho & 0 & 0 & 0 \end{bmatrix}$$

$$A = \frac{1}{\sqrt{2}}\begin{bmatrix} 2\mathcal{R}_1 & 0 & \dots & \dots & 0 \\ 0 & \ddots & \ddots & \ddots & \vdots \\ \vdots & \ddots & 2\mathcal{R}_1 & \ddots & \vdots \\ \vdots & \ddots & \ddots & \sqrt{2}\mathcal{R}_1 & 0 \\ 0 & \dots & \dots & 0 & \sqrt{2}\mathcal{R}_1 \end{bmatrix}$$

Broken Symmetries: Even N

- SU(N-3) breaks to Sp(N-4)
- $U(1)_R$ is broken by the Weyl compensator field
- One U(1) charge remains

$$Q_3 = Q_{SU(N-3)} + (N-3)Q_1$$

	$SU(N)$	$SU(N-3)$	$U(1)_1$	$U(1)_2$	$U(1)_3$
A	$\binom{N}{2}$	1	0	-2	0
F	N	1	1	$N-1$	N - 3
$\bar{F}$	N^*	$N-3$	$\frac{-1}{N-3}$	1	$0 \quad (i \neq N-3)$ $3-N \quad (i = N-3)$
$H = A\bar{F}\bar{F}$	1	$\binom{N-3}{2}$	$\frac{-2}{N-3}$	0	$0 \quad (i,j \neq N-3)$ $6-2N \quad (i\Vert j = N-3)$
$M = \bar{F}F$	1	$N-3$	$\frac{N-4}{N-3}$	N	$N-3 \quad (i \neq N-3)$ $0 \quad (i = N-3)$
$B_0 = F^0 A^{N/2}$	1	1	0	$-N$	0

Particle Masses: Even N

- Fermions all gain masses
  - t 'Hooft anomalies all vanish

$$\mathrm{Tr}(\mathrm{U}(1)_3):\;\; 0 + N(N-3) + N(3-N) = 0$$

$$\mathrm{Tr}(\mathrm{U}(1)_3^3):\;\; 0 + N(N-3)^3 + N(3-N)^3 = 0$$

- # of massless scalars and pseudoscalars varies with N
  - Matches number of broken gauge and global symmetries
- Passes the sum rule for canonical Kahler potentials
  - $\mathrm{Str}(M^2) = -2M_f^2 + M_b^2 = 0$

General Vacuum: Odd N

- We studied general D-flat directions & found the new minimum along this direction
- **The general form of the vacuum occurs when F, $\bar{F}$, & A take this form where**

$$\rho = \left(\frac{(N-1)\Lambda^{N+1}}{\left[2^{(2N+3)/2}k!\right]^{1/2}(N+1)m}\right)^{1/N}$$ **for odd N**

$$\mathcal{R}_n = \begin{pmatrix} 0 & \rho^n \\ -\rho^n & 0 \end{pmatrix}$$

$$F = \sqrt{2}\begin{bmatrix} 0 \\ \vdots \\ 0 \\ \rho \end{bmatrix} \quad \bar{F} = \sqrt{2}\begin{bmatrix} \rho & & 0 & 0 & 0 & 0 \\ & \ddots & & 0 & 0 & 0 \\ 0 & & \rho & 0 & 0 & 0 \end{bmatrix} \quad A = \frac{1}{\sqrt{2}}\begin{bmatrix} 2\mathcal{R}_1 & 0 & \dots & \dots & 0 \\ 0 & \ddots & \ddots & & \vdots \\ \vdots & \ddots & 2\mathcal{R}_1 & \ddots & \vdots \\ \vdots & & \ddots & \sqrt{2}\mathcal{R}_1 & 0 \\ 0 & \dots & \dots & 0 & 0 \end{bmatrix}$$

$$k = \frac{N}{2}$$

Broken Symmetries: Odd N

- SU(N-3) breaks to Sp(N-3)
- $U(1)_R$ is broken by the Weyl compensator field
- $U(1)_1$ is broken by B_1
- $U(1)_2$ charge remains

	$SU(N)$	$SU(N-3)$	$U(1)_1$	$U(1)_2$	$U(1)_R$
A	$\binom{N}{2}$	1	0	-2	$\frac{-12}{N}$
F	N	1	1	$N-1$	$2-\frac{6}{N}$
$\overline{F}$	N^*	$N-3$	$\frac{-1}{N-3}$	1	$\frac{6}{N}$
$H=A\overline{F}\,\overline{F}$	1	$\binom{N-3}{2}$	$\frac{-2}{N-3}$	0	0
$M=\overline{F}\,F$	1	$N-3$	$\frac{N-4}{N-3}$	N	2
$B_1=F^1 A^{(N-1)/2}$	1	1	1	0	-4

Particle Masses: Odd N

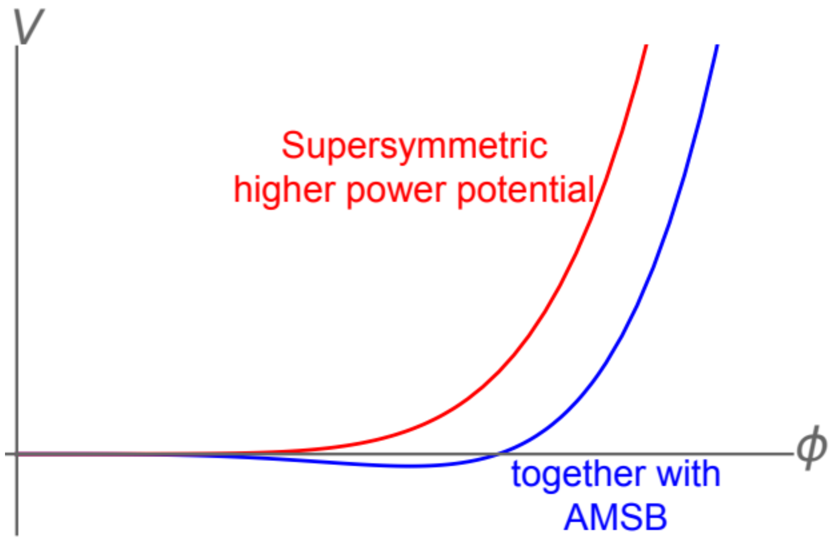
- Several massless fermions
  - t 'Hooft anomalies match

$$\mathrm{Tr}(\mathrm{U}(1)_3)\colon\ \frac{N(N-1)}{2}(-2) + N(N-1) + N(N-3)(1)$$
$$= (N-3)N$$
$$\mathrm{Tr}(\mathrm{U}(1)_3^3)\colon\ 0 + N(N-1)^3 + N(N-3)1^3$$
$$= (N-3)N^3$$

- # of massless scalars and pseudoscalars varies with N
  - Matches number of broken gauge and global symmetries
- Passes the sum rule for canonical Kahler potentials
  - $\mathrm{Str}(M^2) = -2M_f^2 + M_b^2 = 0$

Continuing Work

- Finish similar calculations for F=2
- F=3 and above are in the confining phase
  - Can calculate using the composite fields M, H, B_i
- Examine the electric-magnetic duality



Main Takeaways

- AMSB is a great method for approaching many otherwise insolvable theories with strong dynamics
- AMSB only depends on physics at the energy scales of interest: UV insensitivity
- AMSB passes many nontrivial tests, such as t 'Hooft anomaly matching, sum rules and counting of massless particles

Questions?

Backup Slides

Why Anomaly Mediation?

Understanding Non-Abelian Gauge Theories

- High temperature superconductors
- Strong interactions in particle physics

Anomaly Mediation: A Derivation

Anomaly Mediation

- We introduce a Weyl compensator or a "superspacetime background"

$$\boldsymbol{\mathcal{E}} = 1 + \theta^2 m$$

- All SUSY breaking encoded in m and thus in $\boldsymbol{\mathcal{E}}$
- It is inserted into the SUSY Lagrangian as:

$$\mathcal{L}_{tree} = \int d^4\theta\, \boldsymbol{\mathcal{E}}^* \boldsymbol{\mathcal{E}} K - \int \mathrm{d}^2\theta\, \boldsymbol{\mathcal{E}}^3 W$$

- If no mass term, can be removed by conformal transformation $\phi_i \to \boldsymbol{\mathcal{E}}^{-1}\phi_i$

$$\mathcal{L}_{tree} = \int d^4\theta\, \boldsymbol{\mathcal{E}}^* \boldsymbol{\mathcal{E}} \phi_i^* \phi_i - \int \mathrm{d}^2\theta\, \boldsymbol{\mathcal{E}}^3 \lambda \phi^3 + c.c.$$

$$\to \int d^4\theta\, \phi_i^* \phi_i - \int \mathrm{d}^2\theta\, \lambda \phi^3 + c.c.$$

Anomaly Mediation

- If mass term, dimensionful parameters get SUSY breaking
- For example

$$\mathcal{L}_{tree} = \int d^4\theta\, \boldsymbol{\mathcal{E}}^* \boldsymbol{\mathcal{E}}\, \phi_i^* \phi_i - \int \mathrm{d}^2\theta\, \boldsymbol{\mathcal{E}}^3 \left(\frac{1}{2} M \phi_i^2 + \lambda \phi^3 \right) + \ c.c.$$

$$\rightarrow \mathcal{L}_{tree} = \int d^4\theta\, \phi_i^* \phi_i - \int \mathrm{d}^2\theta \left(\frac{1}{2} M \boldsymbol{\mathcal{E}} \phi_i^2 + \lambda \phi^3 \right) + \ c.c.$$

- After integrating over the SUSY Grassmann coordinates, we get

$$\mathcal{L}_{\mathrm{tree}} = m \left(\phi_i \frac{\partial W}{\partial \phi_i} - 3W \right) + c.c.$$

Anomaly Mediation

- We get additional SUSY breaking at loop level from cutoff scale

$$Z\left(\frac{\mu}{M}\right) \to Z\left(\frac{\mu}{M\mathcal{E}}\right) = Z\left(1 + \gamma \frac{1}{2} ln \frac{\mu^2}{M^*\mathcal{E}^* M\mathcal{E}} + \frac{1}{2}\dot{\gamma}\frac{1}{4} ln^2 \frac{\mu^2}{M^*\mathcal{E}^* M\mathcal{E}} + \ \dots\right)$$

- The contribution to the potential is

$$\int d^4\theta\, Z\phi_i^*\phi_i = Z\left(F^*F + \gamma\frac{1}{2}(m^*\phi_i^*F + m\phi_i F^*) + \frac{1}{2}\dot{\gamma}m^*m\phi_i^*\phi_i\right)$$

- Integrating the auxiliary field F, we find

$$V = -\frac{1}{4}\dot{\gamma}m^*m\phi_i^*\phi_i \ -\frac{1}{2}(\gamma_i + \gamma_j + \gamma_k)\, m\lambda_{ijk}\phi_i\phi_j\phi_k + c.c.$$

Anomaly Mediation

- The coupling constant also shifts

$$\frac{1}{g^2}\left(\frac{\mu}{M}\right) \rightarrow \frac{1}{g^2}\left(\frac{\mu}{M\mathcal{E}}\right) = \frac{1}{g^2} - \theta^2 \frac{\beta(g^2)}{g^4} m$$

- Integrating θ, we find

$$\int d^2\theta \frac{1}{g^2}\left(\frac{\mu}{M\Phi}\right) w_\alpha w^\alpha \supset -\frac{\beta(g^2)}{4g^4} m\lambda\lambda$$

- And thus, we find

$$m_\lambda = -\frac{\beta(g^2)}{2g^2} m$$

Chiral Gauge Theory Dynamics

D-flat Condition

- Out of $\binom{N}{2} + \mathrm{N(N-3)} + \mathrm{N}$ fields, $(N^2-1)-(2^2-1)$ are eaten, leaving $\frac{N^2}{2} - \frac{5N}{2} + 4$ D-flat directions which correspond to the gauge invariants M, H, B_0
- The UV fields must be chosen to satisfy the D-flat condition
$$A^\dagger A + AA^\dagger + FF^\dagger - \bar{F}\bar{F}^\dagger = \mathrm{a\,I} \;\; (\text{where a is a constant})$$
- Due to gauge freedom and the D-flat condition, we are left with only N-2 independent parameters
- We studied general D-flat directions to find a well-defined minimum

Results

- Large class of chiral gauge theories
- With AMSB, we can find:
  - Vacuum structure
  - Broken/remaining symmetries
  - Fermion & scalar masses
  - t'Hooft anomaly matching conditions

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