Breaking Supersymmetry Made Easy, Viable, and Generic

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XLIInd Rencontres de Moriond, March 11, 2007

with Yasunori Nomura

hep-ph/0612186, 0701231

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- Growing concern in the community
  - If there is new physics below TeV, we should have seen its hints by now. Most likely we don't find anything at the LHC.
- Now I think
  - It is quite likely to find new physics, especially supersymmetry, at the LHC!

Likelihood of viable SUSY

Landscape of theories

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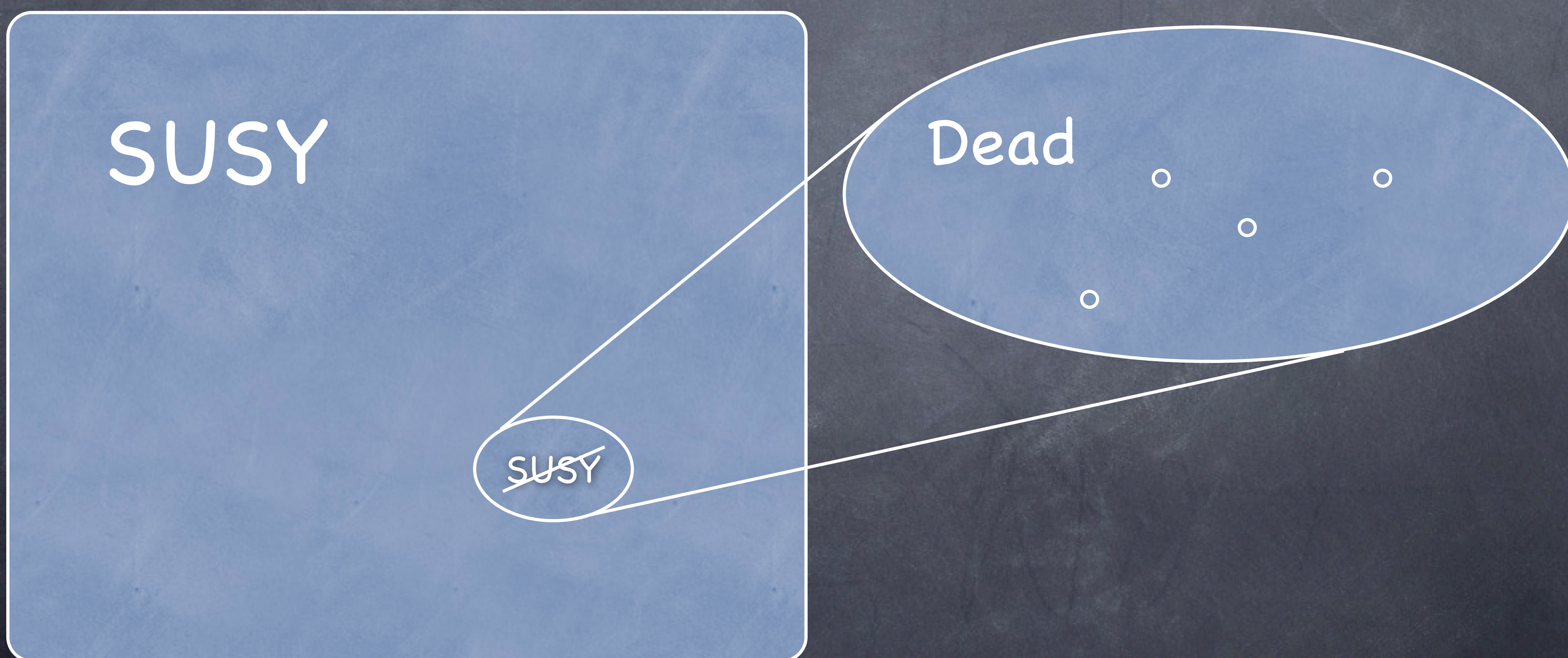

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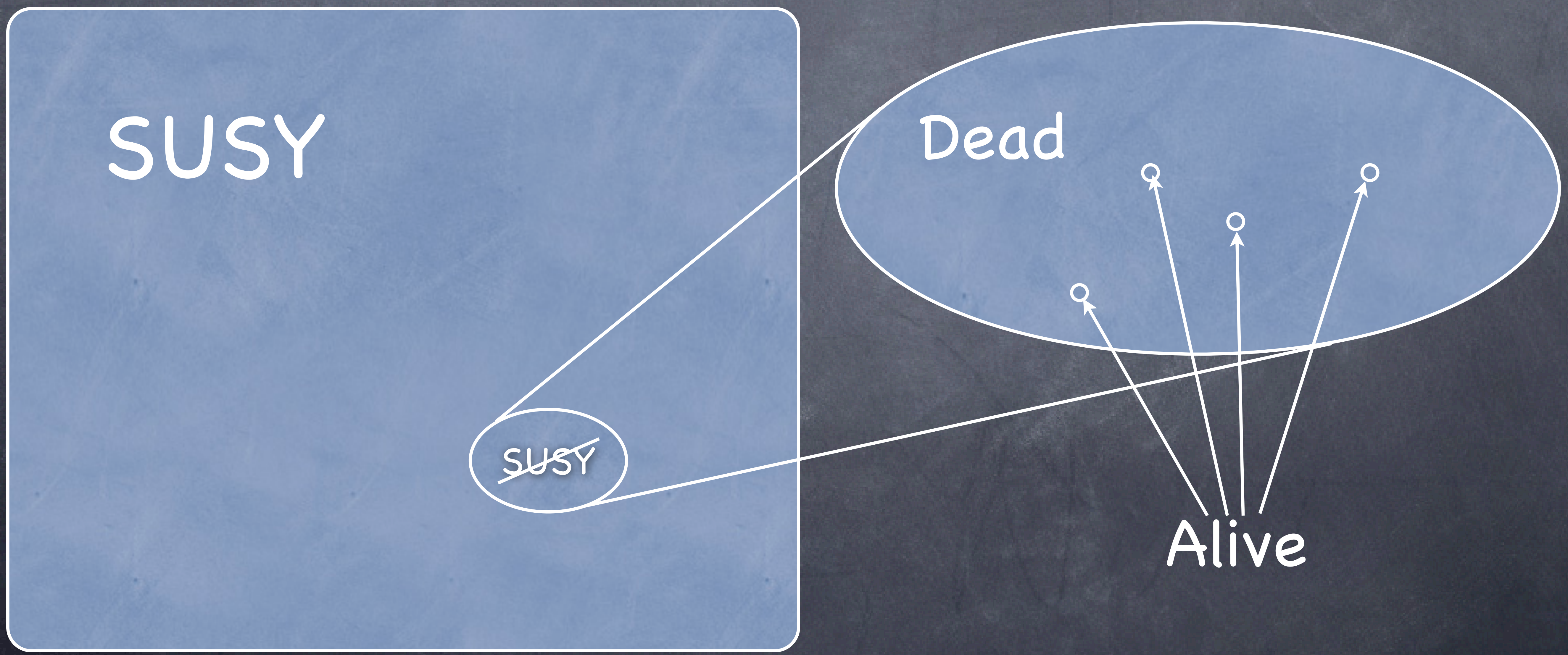

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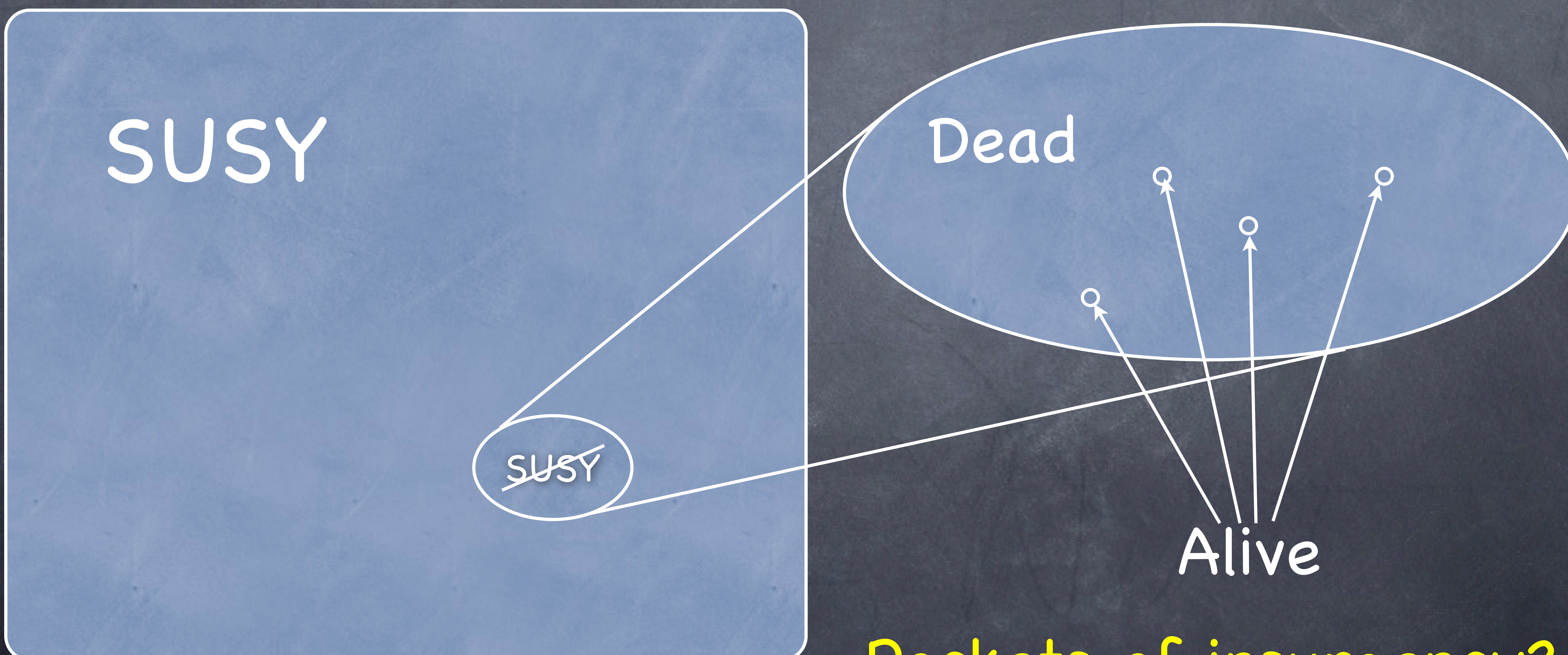

Pockets of insurgency?

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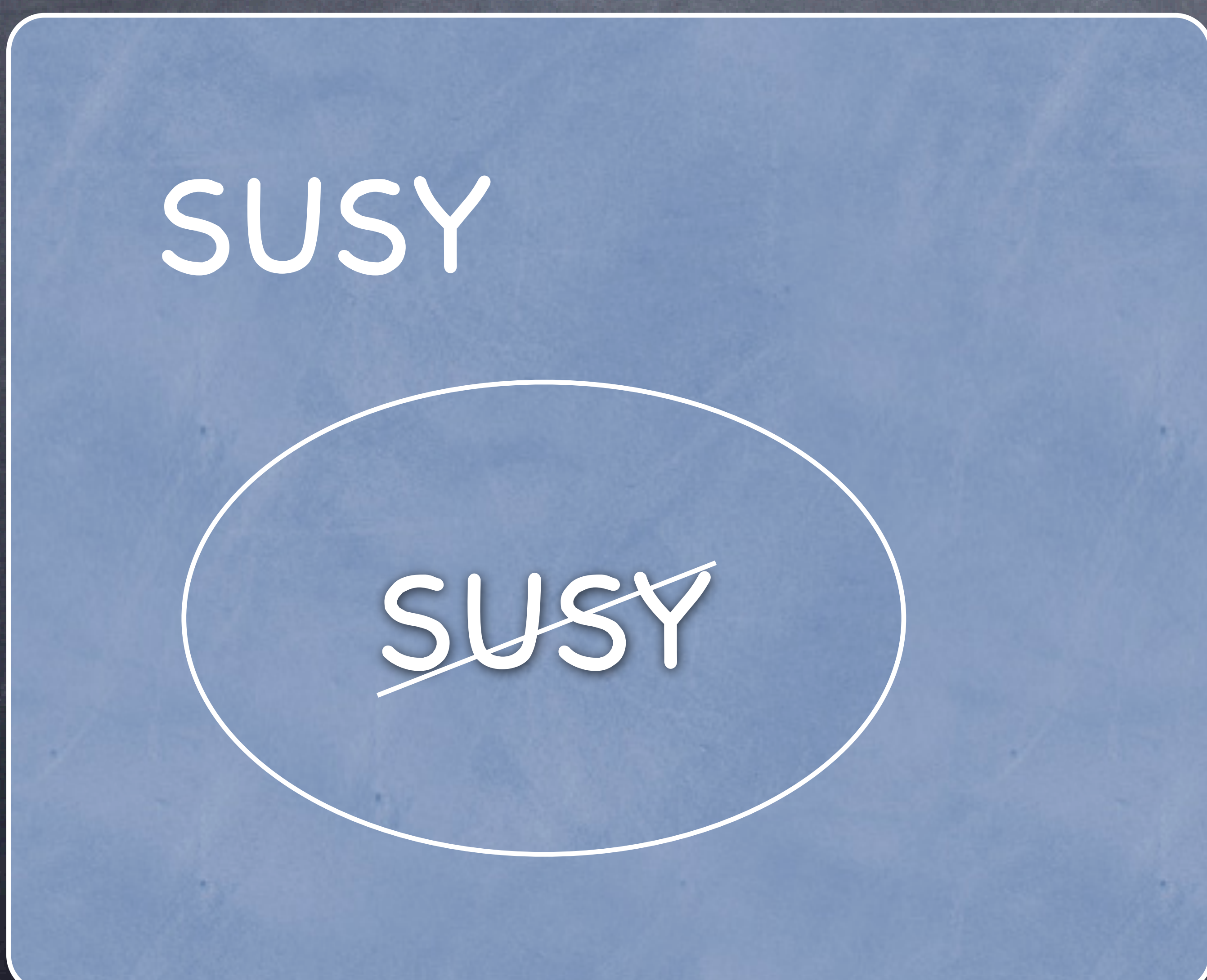

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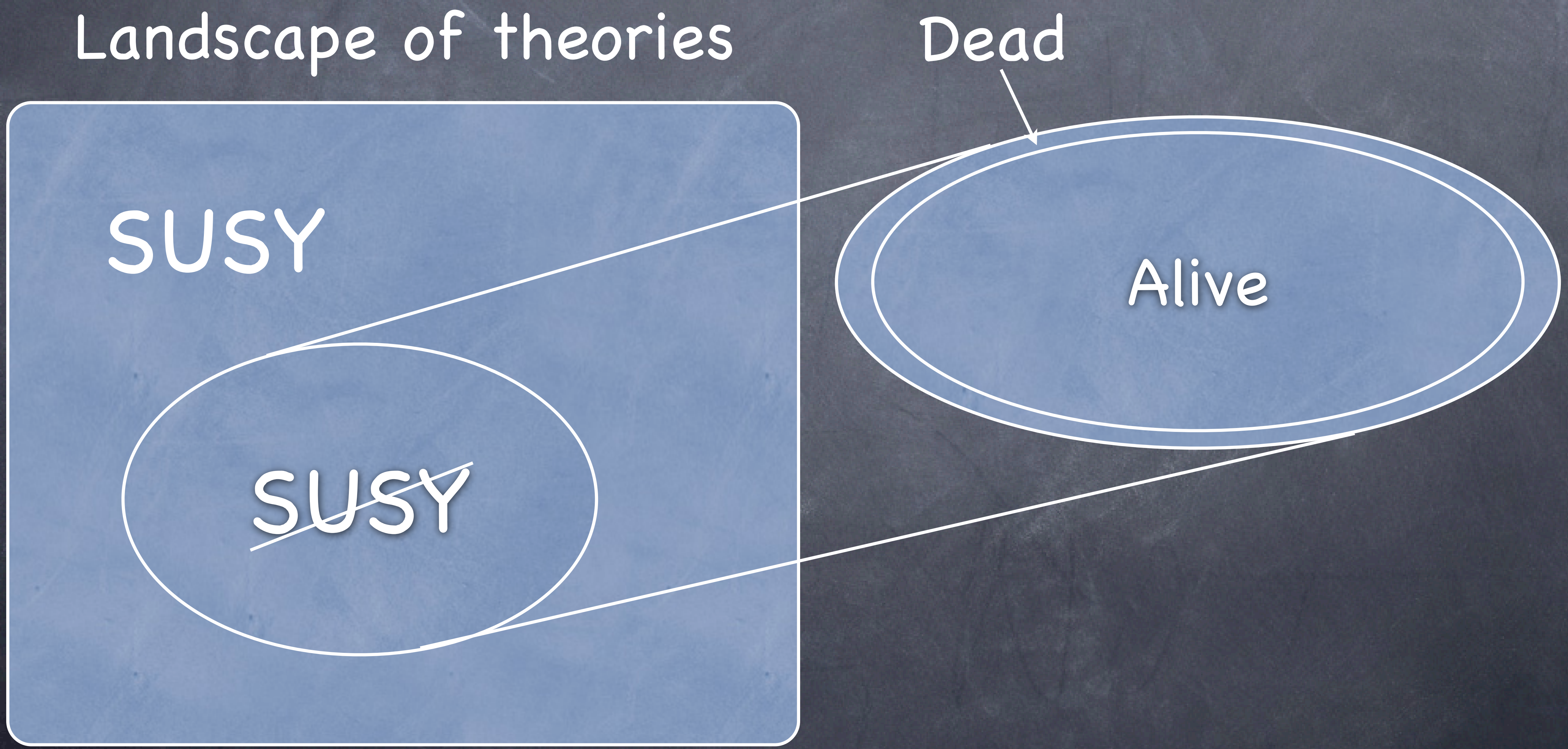

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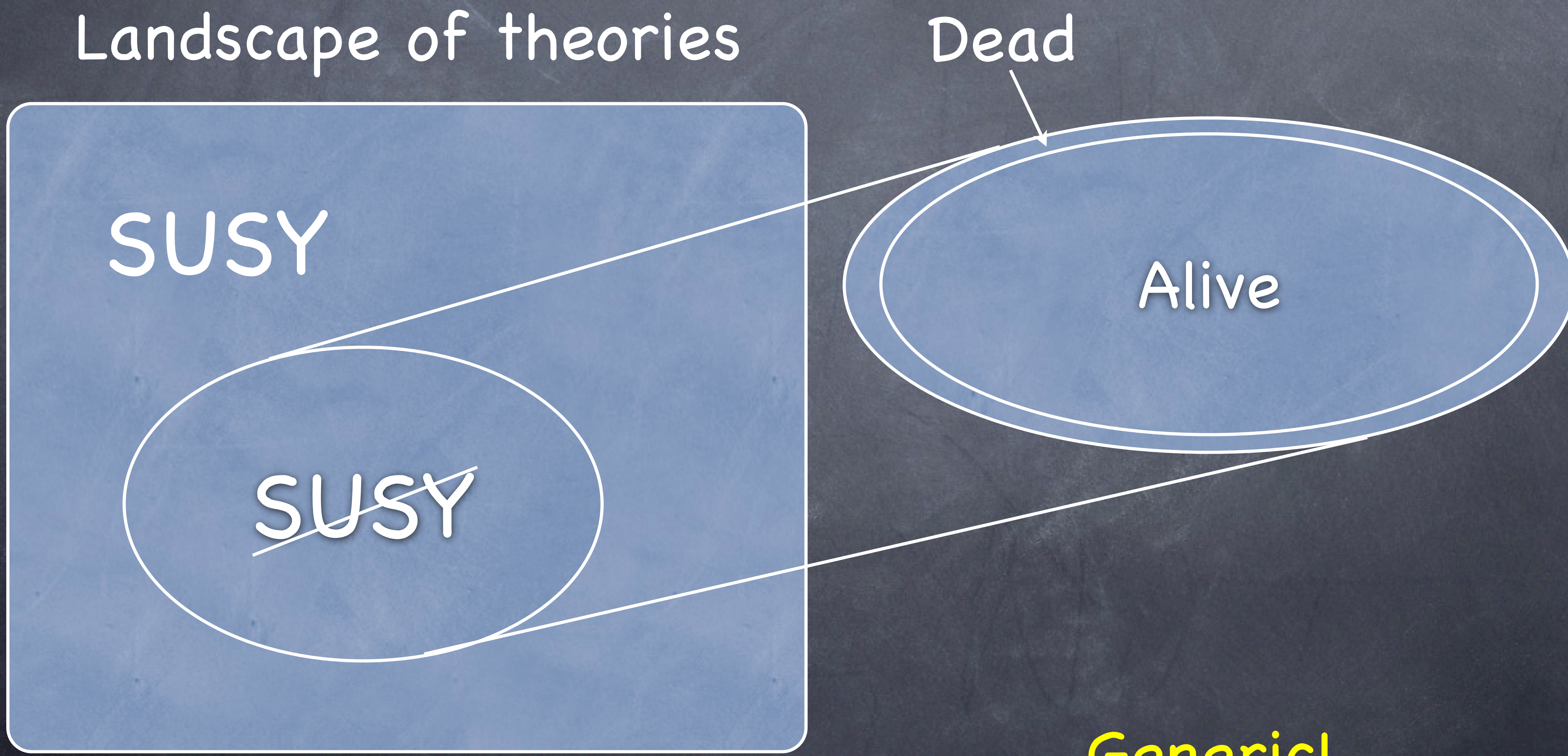


Generic!

Why supersymmetry? "hierarchy problem"

- At the end of 19th century: a "crisis" about electron
  - Like charges repel: hard to keep electric charge in a small pack
  - Electron is point-like $<10^{-17}$cm
- Need a lot of energy to keep it small!

$$\Delta m_e c^2 \sim \frac{e^2}{r_e} \sim \mathrm{GeV}\frac{10^{-17}\mathrm{cm}}{r_e}$$

$$\begin{aligned} m_e^0 &= -3.141082 \text{ GeV} \\ \Delta m_e &= +3.141593 \text{ GeV} \\ m_e &= +0.000511 \text{ GeV} \end{aligned}$$

- Correction $\Delta m_e c^2 > m_e c^2$ for $r_e < 10^{-13}$cm
- Breakdown of theory of electromagnetism

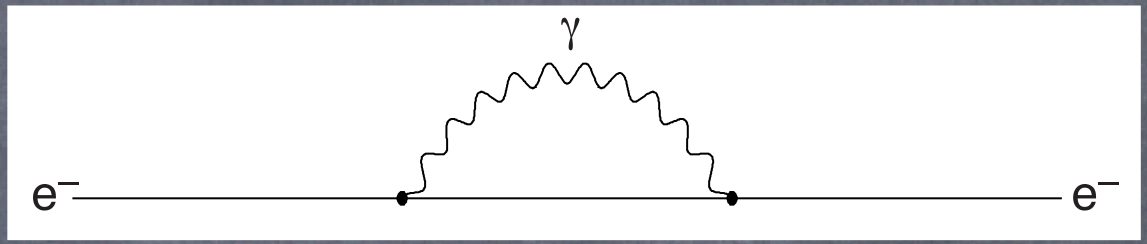
  $\Rightarrow$ Can't discuss physics below 10^{-13}cm

Anti-Matter Comes to Rescue by Doubling of #Particles

- Electron creates a force to repel itself
- Vacuum bubble of matter anti-matter creation/annihilation
- Electron annihilates the positron in the bubble

⇒ only 10% of mass

even for Planck-size $r_e \sim 10^{-33}$cm



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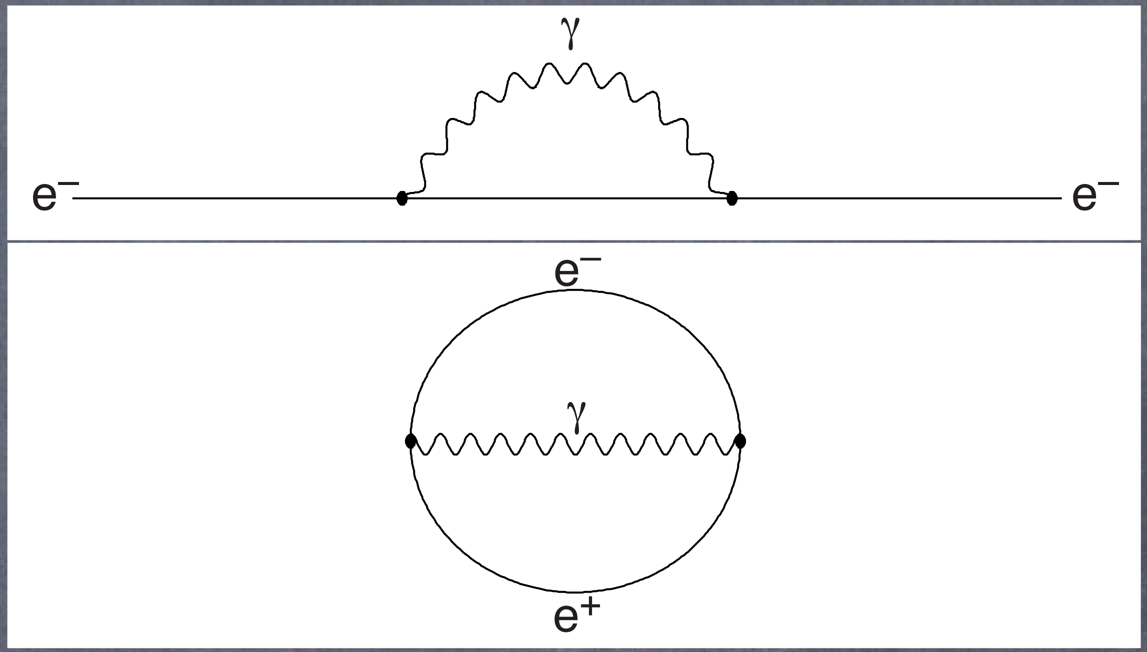

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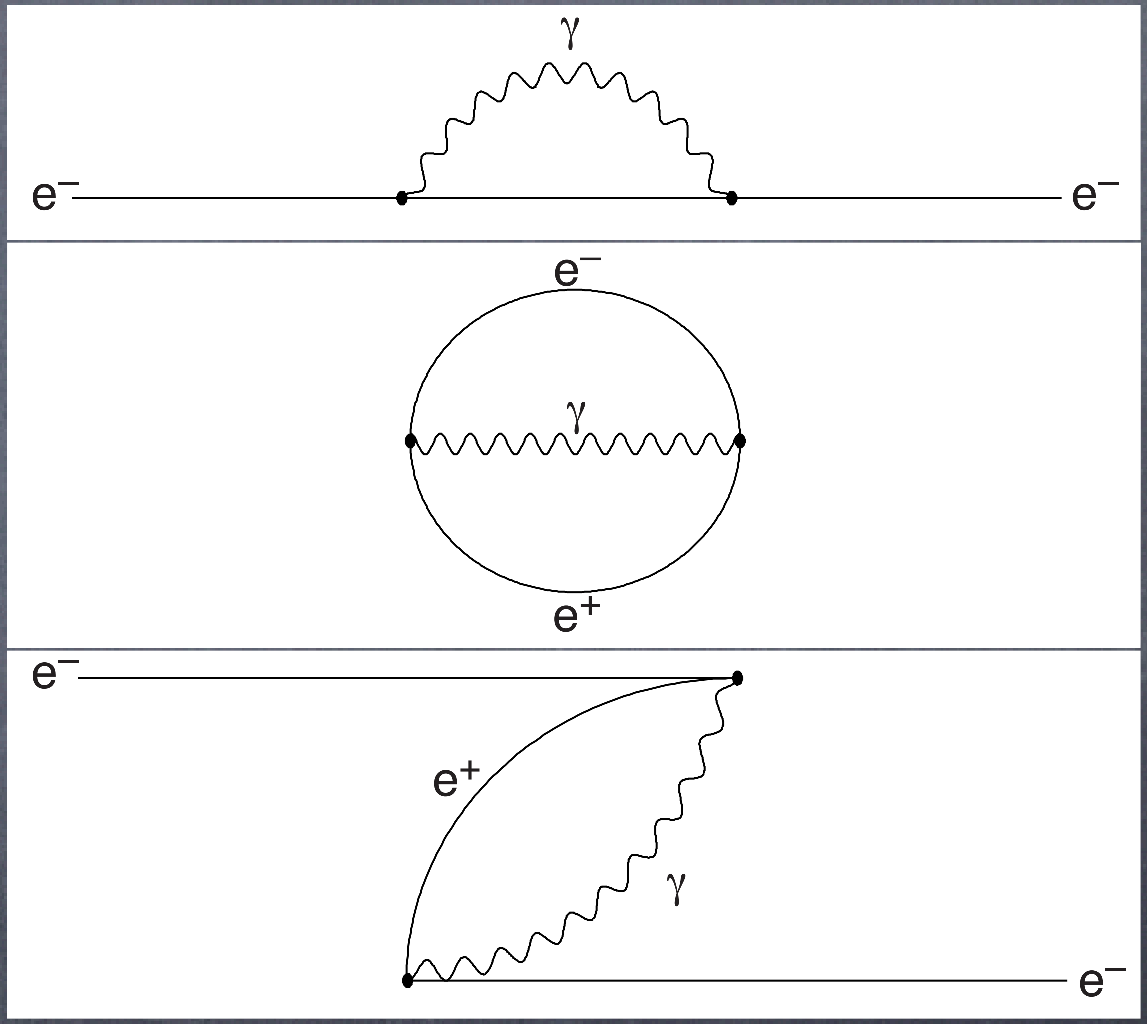

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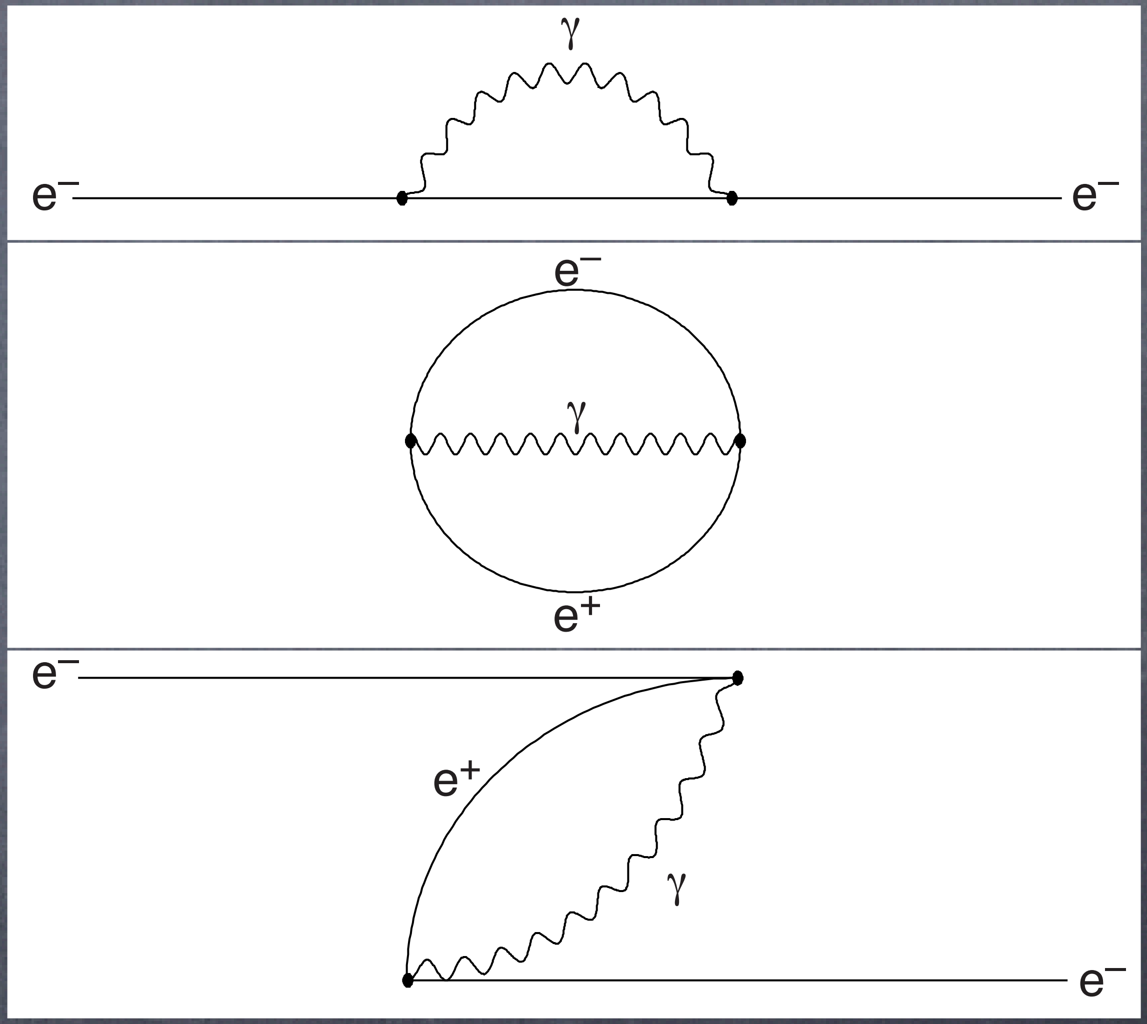
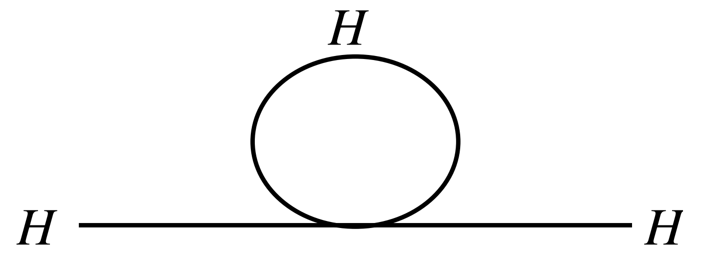


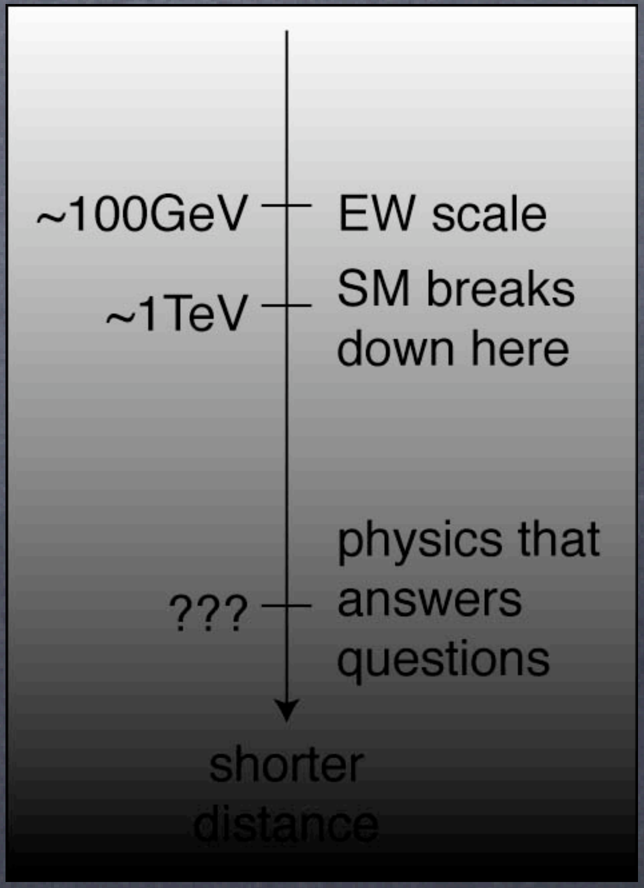
$$\Delta m_e \sim m_e \frac{\alpha}{4\pi} \log(m_e r_e)$$

Higgs repels itself, too



$$\Delta m_H^2 c^4 \sim \left(\frac{\hbar c}{r_H}\right)^2$$

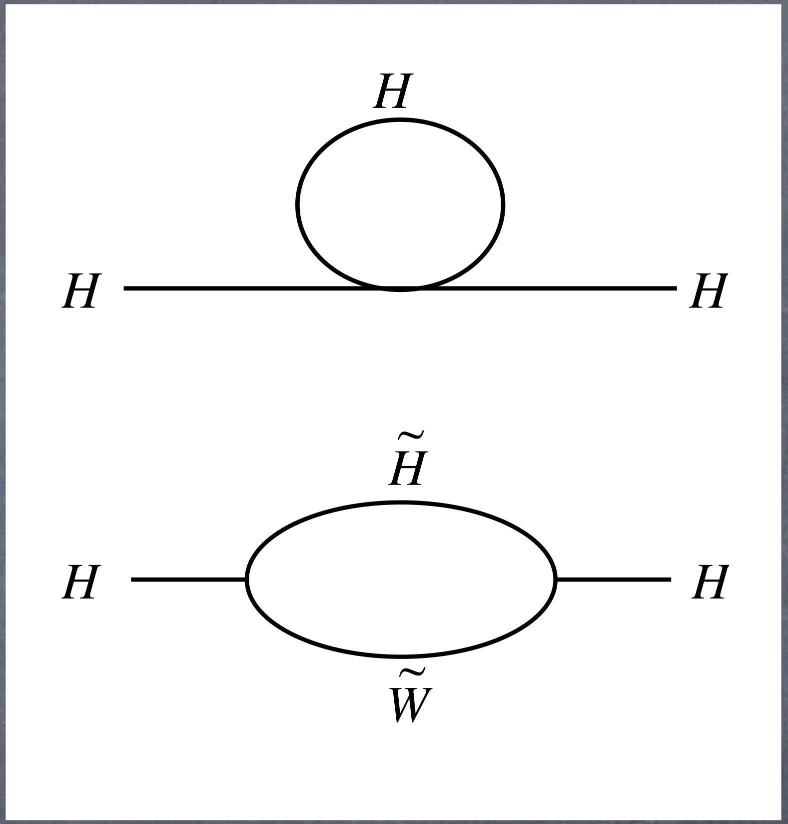
- Just like electron repelling itself becaus of its charge, Higgs boson also repels itself
- Requires a lot of energy to contain itself in its point-like size!
- Breakdown of theory of weak force
- Can't discuss physics < $\text{TeV}^{-1} = 10^{-17}$cm



History repeats itself?

- Double #particles again ⇒

  superpartners
- "Vacuum bubbles" of superpartners cancel the energy required to contain Higgs boson in itself
- Standard Model made consistent with whatever physics at shorter distances



$$\Delta m_H^2 \sim \frac{\alpha}{4\pi} m_{SUSY}^2 \log(m_H r_H)$$

Want m_{SUSY}<TeV for >1% tuning

But SUSY is broken

- For each term in the superpotential

$$W_{MSSM} = Y_u^{ij} Q_i u_j^c H_u + Y_d^{ij} Q_i d_j^c H_d + Y_l^{ij} L_i e_j^c H_d + \mu H_u H_d$$

- we can have the "A-terms" and "B-term"

$$A_u^{ij} Y_u^{ij} Q_i u_j^c H_u + A_d^{ij} Y_d^{ij} Q_i d_j^c H_d + A_l^{ij} Y_l^{ij} L_i e_j^c H_d + B\mu H_u H_d$$

- scalar masses for all scalars

$$m_{Qij}^2 \tilde{Q}_i^* \tilde{Q}_j + m_{uij}^2 \tilde{u}_i^* \tilde{u}_j + m_{dij}^2 \tilde{d}_i^* \tilde{d}_j + m_{Lij}^2 \tilde{L}_i^* \tilde{L}_j + m_{eij}^2 \tilde{e}_i^* \tilde{e}_j + m_{H_d}^2 |H_d|^2 + m_{H_u}^2 |H_u|^2$$

- gaugino mass for all three gauge factors

$$M_1 \tilde{B} \tilde{B} + M_2 \tilde{W}^a \tilde{W}^a + M_3 \tilde{g}^a \tilde{g}^a$$

- A(18x3)+B(2)+m(9x5+2)+M(2x3)+μ(2)=111
  $U(1)_R \times U(1)_{PQ}$ removes only two phases
  cf. SM has two params in the Higgs sector
  107 more parameters than the SM!

“Typical” parameters excluded

- “typical” parameters of SUSY breaking
  $\Rightarrow$ too large FCNC and CP violation
- Made worse after beautiful B data

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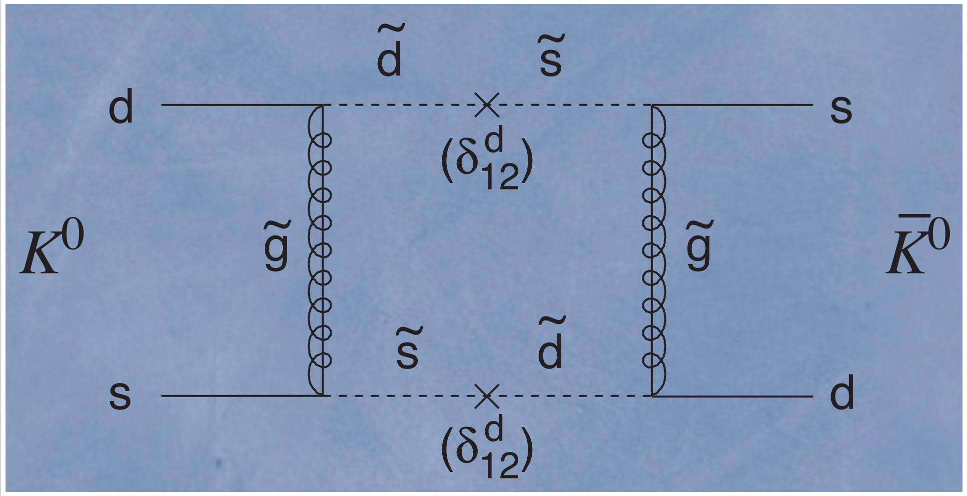
$$(\tilde{d}, \tilde{s}, \tilde{b})^* m_0^2 \begin{pmatrix} 1 & (\delta_{12}^d) & (\delta_{13}^d) \\ (\delta_{21}^d) & 1 & (\delta_{23}^d) \\ (\delta_{31}^d) & (\delta_{32}^d) & 1 \end{pmatrix} \begin{pmatrix} \tilde{d} \\ \tilde{s} \\ \tilde{b} \end{pmatrix}$$

$$(\delta_{12}^d) < 0.001 \frac{m_{SUSY}}{500 \text{ GeV}}$$



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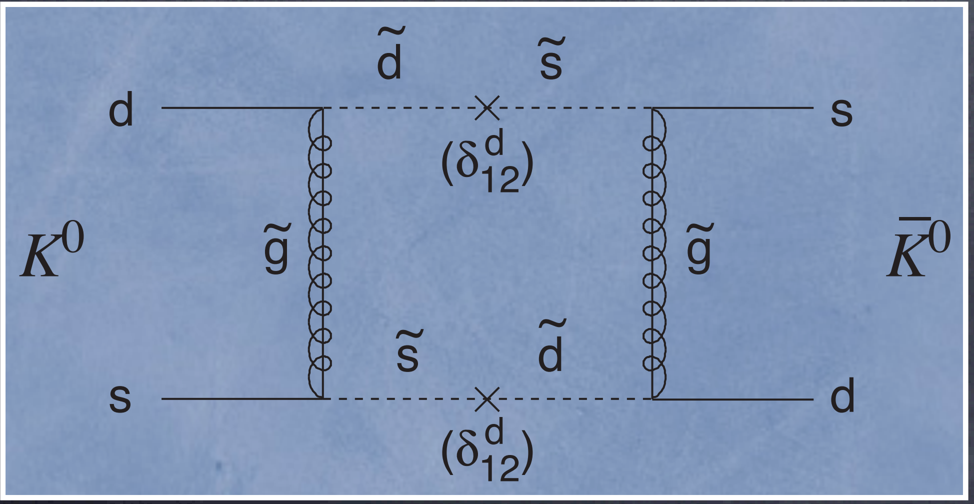
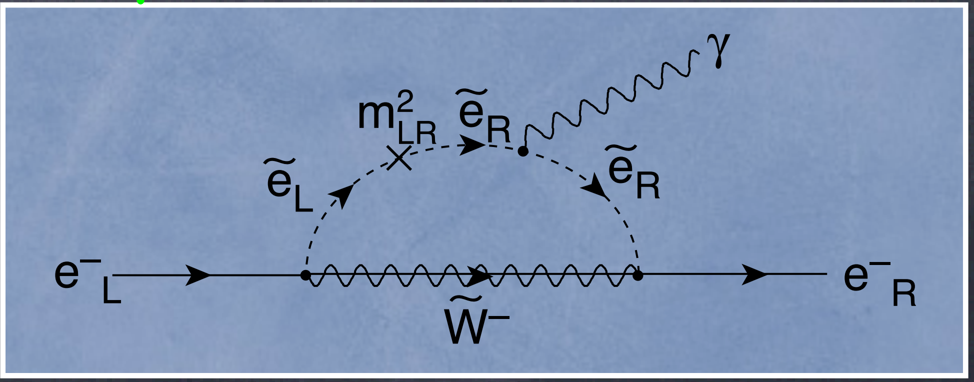


- EDM $H \propto \vec{s} \cdot \vec{E}$
- stringent limits on electron, neutron, and Hg atom
- either m_{SUSY}>TeV or phase<10^{-2}



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Self-righteous

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Intelligent Design

Special Model I
SUSY Breaking

- Breaking SUSY has been difficult
- Nelson-Seiberg: you need either
  - non-generic superpotential
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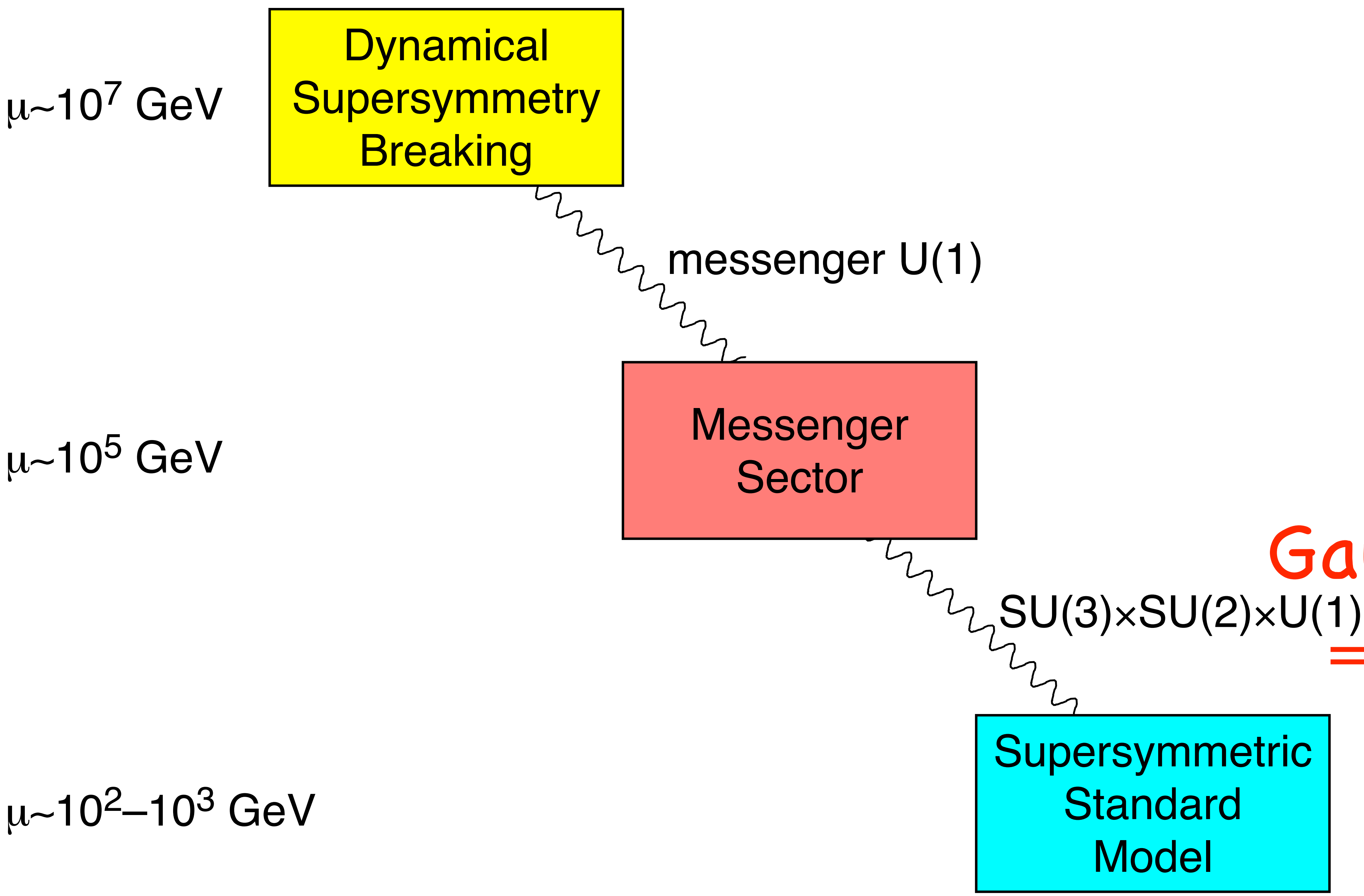
$$W = A\bar{F}^{+}\bar{F}^{-} + \bar{F}^{0}(F^{+}S^{-} + F^{-}S^{+}) + FF^{0}S^{0}$$

Special Model II
Mediation Mechanism



Gauge Mediation
⇒flavor blind

Dine–Nelson–Nir–Shirman

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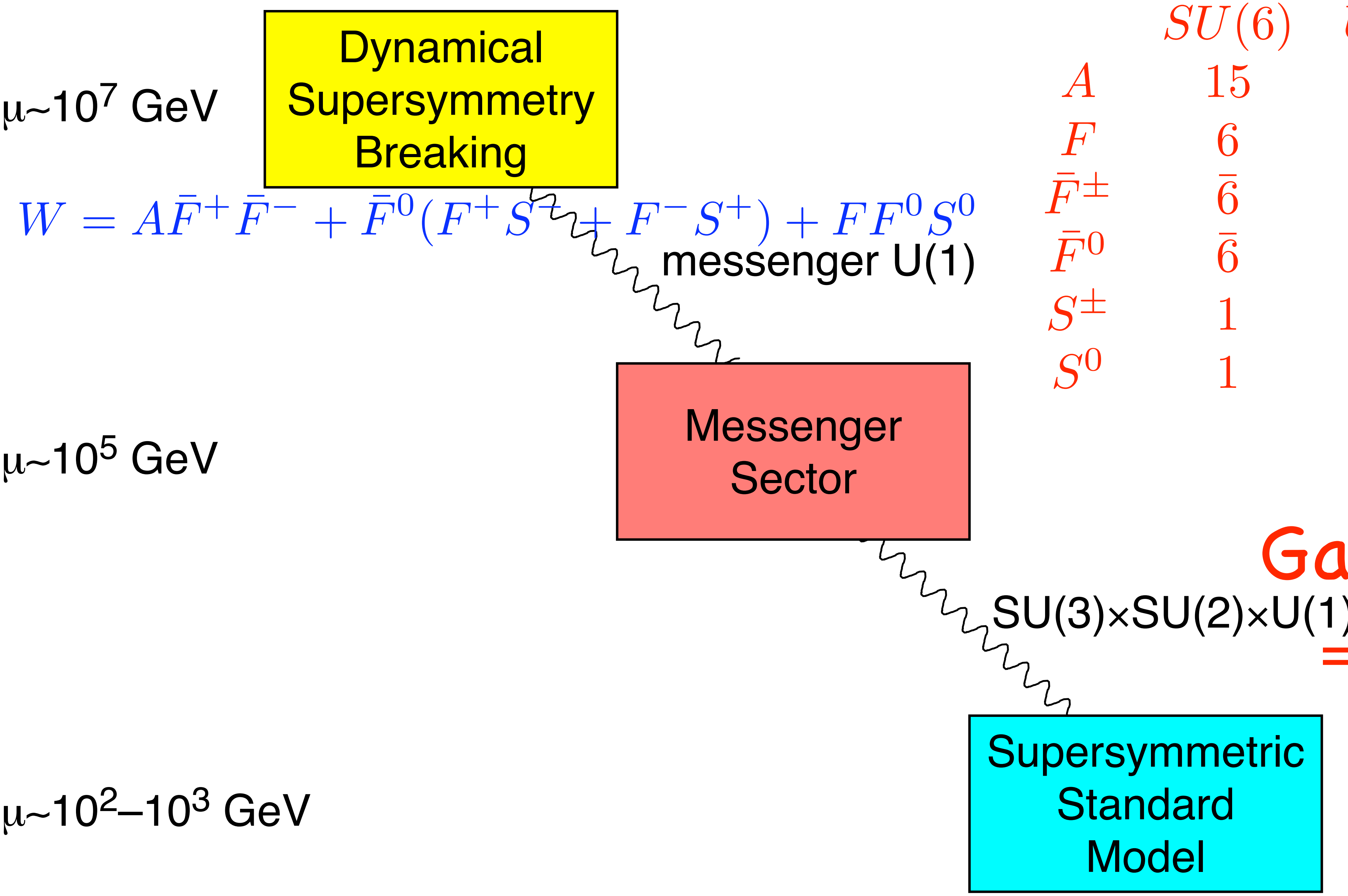

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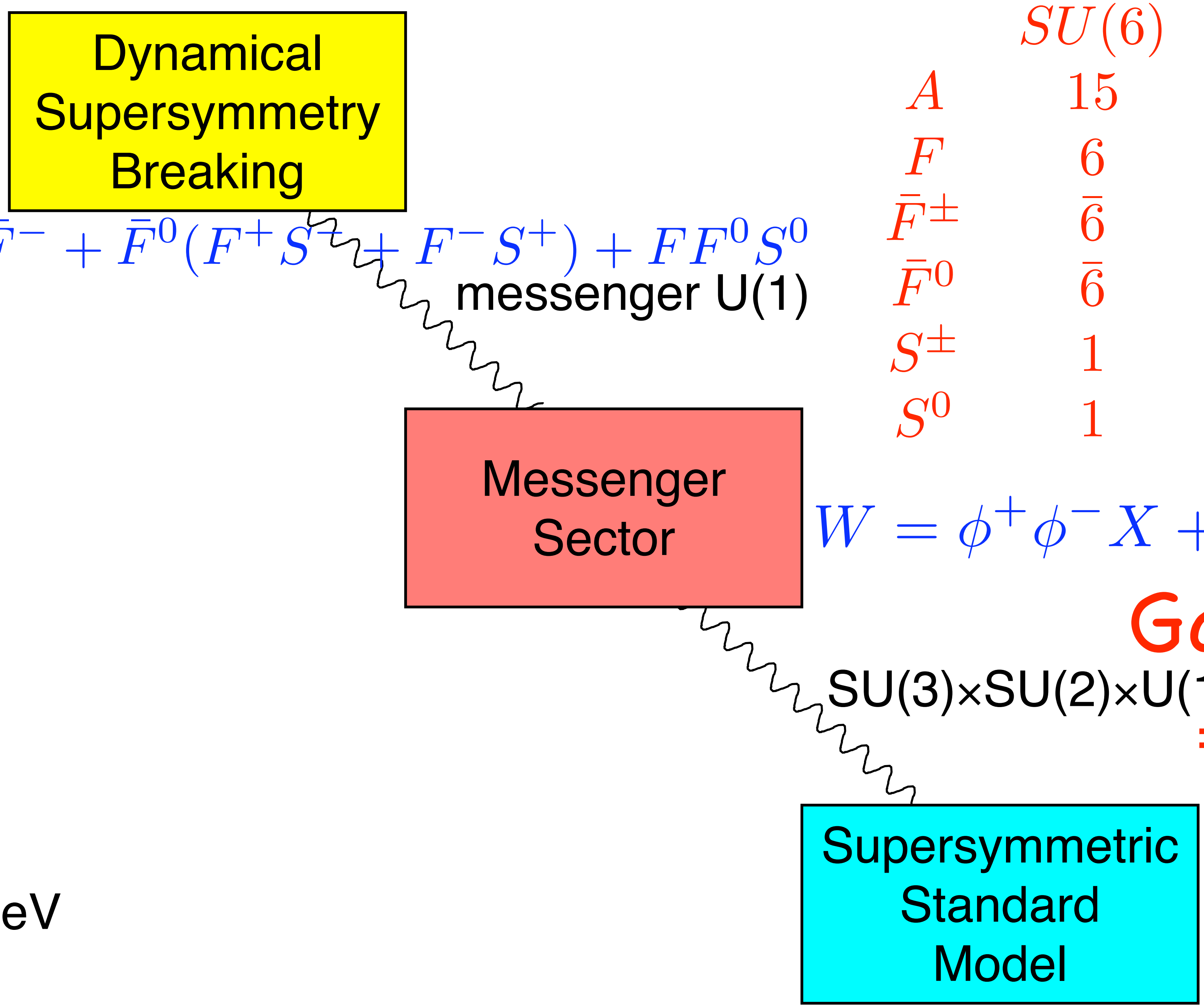
Mediation Mechanism

$\mu \sim 10^7$ GeV

$\mu \sim 10^5$ GeV

$\mu \sim 10^2$–10^3 GeV



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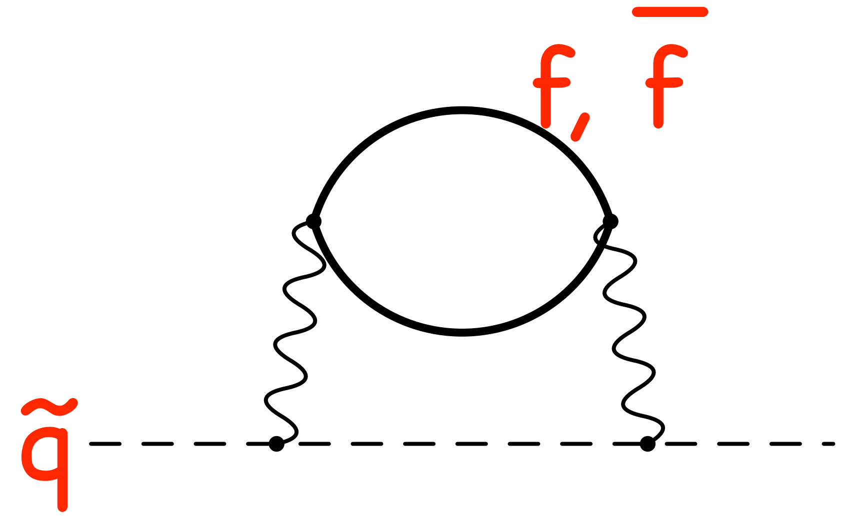
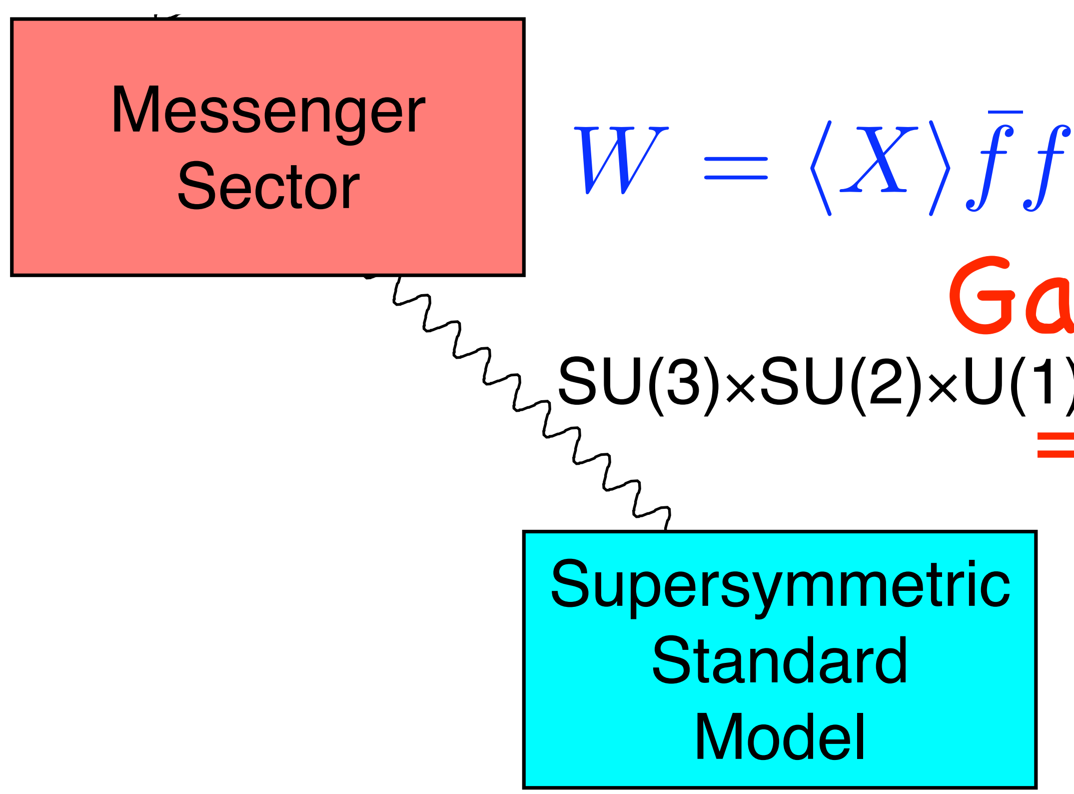
$$W = \phi^+\phi^- X + X^3 + X\bar{f}f$$

Gauge Mediation
$\Rightarrow$flavor blind

Dine–Nelson–Nir–Shirman

Special Model II
Mediation Mechanism





$$W = \langle X \rangle \bar{f} f$$

Gauge Mediation
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Dine–Nelson–Nir–Shirman

Special Model II
Mediation Mechanism

μ~10^7 GeV

Dynamical Supersymmetry Breaking

$$W = A\bar{F}^+\bar{F}^- + \bar{F}^0(F^+S^- + F^-S^+) + FF^0S^0$$

messenger U(1)

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μ~10^5 GeV

Messenger Sector

$$W = \phi^+\phi^- X + X^3 + X\bar{f}f$$

SU(3)×SU(2)×U(1)

Gauge Mediation
⇒flavor blind

μ~10^2–10^3 GeV

Supersymmetric Standard Model

Dine–Nelson–Nir–Shirman

Our Generic Scheme

Our Generic Scheme

SUSY SM

Our Generic Scheme

$M\bar{f}f$

SUSY SM

Our Generic Scheme

SUSY QCD

SU(Nc), SO(Nc), Sp(Nc)

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SUSY SM

Our Generic Scheme

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$m_Q \bar{Q} Q$

$M \bar{f} f$

SUSY SM

Our Generic Scheme

$$\frac{1}{M_{Pl}}\bar{Q}Q\bar{f}f$$

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SUSY QCD

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SUSY SM

no $U(1)_R$ symmetry imposed

most general superpotential

wide choice of gauge groups, matter content

$$N_c < N_f < \frac{3}{2}N_c$$

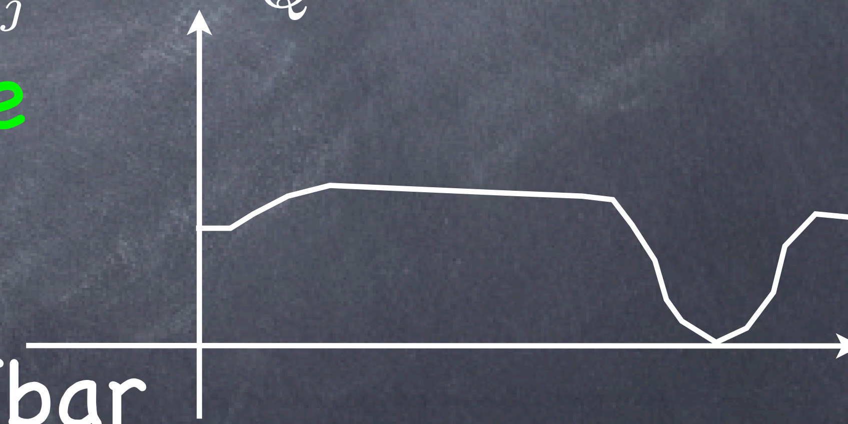
How it works (Most technical slide)

- SUSY SU(N_c) QCD $N_c<N_f<3N_c/2$ $W = m_Q^{ij}\bar{Q}_i Q_j$
- low-energy free magnetic theory ($m_Q<\Lambda$)

$$W = m_Q^{ij}\Lambda M_{ij} + M_{ij}\bar{q}^i q^j$$

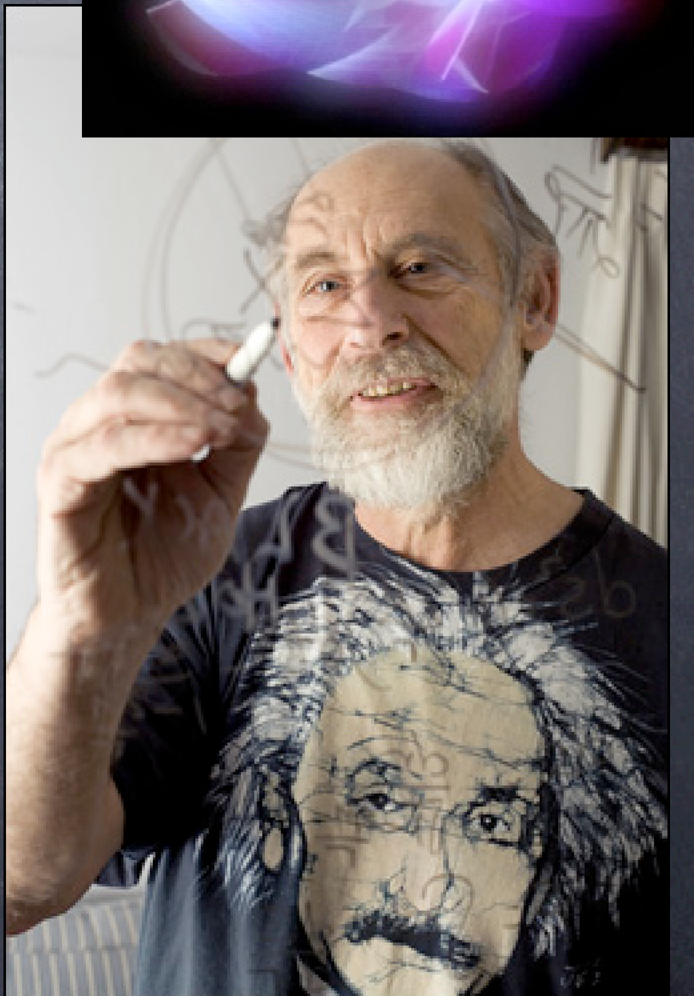
- SUSY breaking @ $M_{ij}=0$, $\frac{\partial W}{\partial M_{ij}} = m_Q^{ij} \neq 0$
- Local minimum with long lifetime

$$W = \frac{1}{M_{Pl}}\bar{Q}Q\bar{f}f$$



- Generates SUSY breaking in f, fbar
- their loops⇒gauge mediation

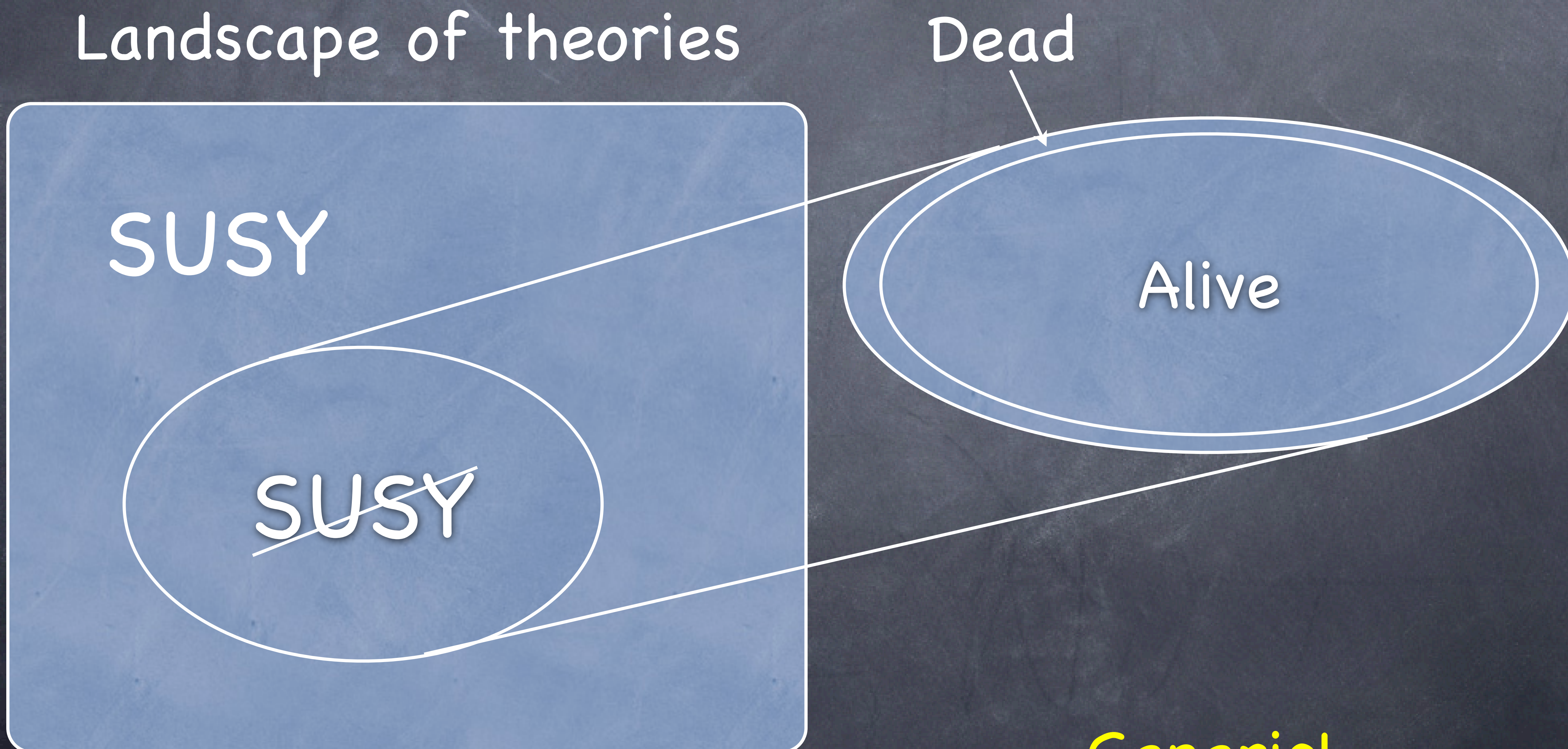
Good news for string theory



- String theory does not predict unique solution
- "Landscape" of possibilities for gauge groups, matter content, number of SUSY
- We at least need SM
- We tend to get extra "junks", i.e. extra gauge groups, extra vector-like matter
- the "junks" are precisely what we need to break SUSY via gauge mediation

Easy, Viable, Generic!

Likelihood of viable SUSY



Generic!

Experimental Consequences

- Very wide range of parameters and models
- SUSY dark matter = gravitino?
- long-lived charged particle (stau)?
- “LSP” decay into photon+gravitino?
- specific mass spectrum of SUSY particles
  - in principle depends on “hidden” sector
- other dark matter candidates

Conclusion

- SUSY breaking happens in a wide class of models expected in the "landscape" of supersymmetric theories (easy, generic)
- Most of them provide successful gauge mediation (viable)
- flavor-blind and CP-conserving SUSY
- It is completely OK to have SUSY<TeV
- Looking forward to Tevatron/LHC!