BEYOND THE STANDARD MODEL

Lecture II

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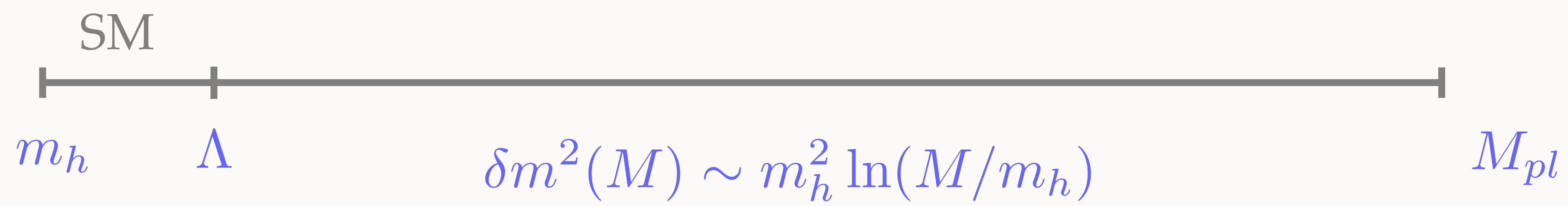
THE HIERARCHY PROBLEM

- Natural expectation for scalar fields: $m_s \sim \Lambda$
- natural EWSB needs new physics near TeV

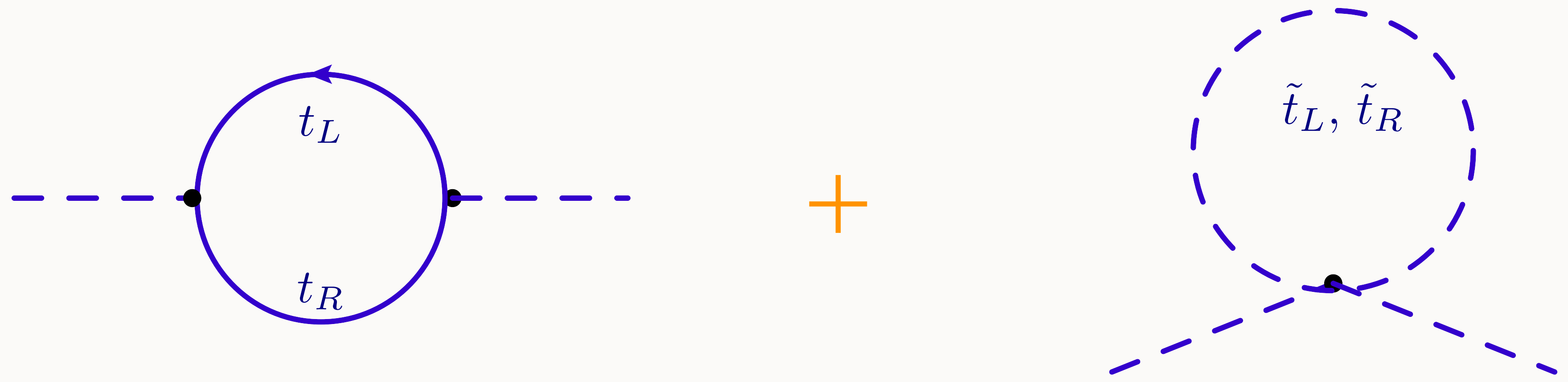
- but this new physics must be special: theory above Λ must be free of quadratic divergences

THE HIERARCHY PROBLEM

- Idea 1: cancellation of quadratic divergences



- new physics closely related to SM:



$-\frac{3}{8\pi^2}\lambda_t^2\Lambda^2$

$+\frac{3}{8\pi^2}\lambda_t^2\Lambda^2$

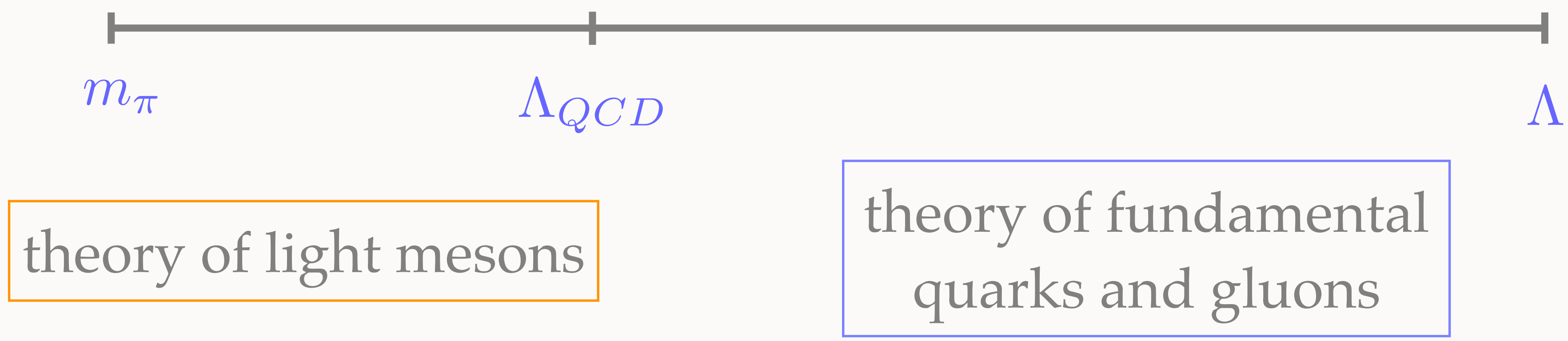
THE HIERARCHY PROBLEM

- Complete solution: cancellation must be exact
    - This requires a lot of new states!
    - symmetry to relate couplings of NP to those of the SM
        - e.g.: SUSY
    - If there is no symmetry, then cancellation is accidental and will break down at higher scales: defers hierarchy problem

THE HIERARCHY PROBLEM

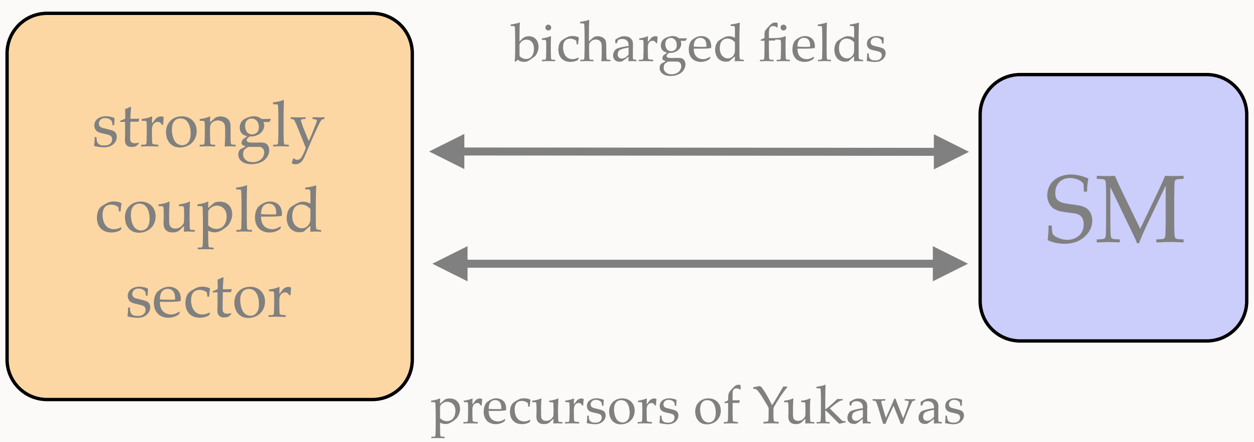
- Idea 2: get rid of the problematic operator

- Analogy: *QCD*

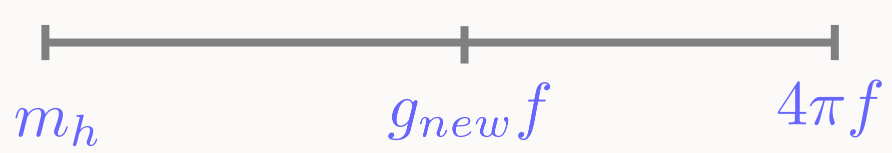


THE HIERARCHY PROBLEM

- In these models the Higgs is a composite state

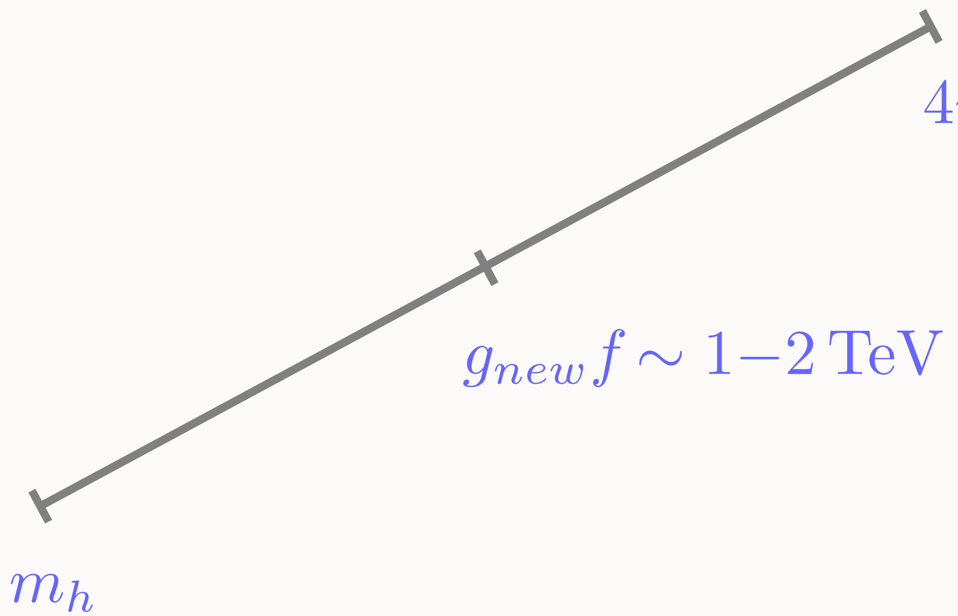


- Confinement triggers chiral symmetry breaking
  - SM-like Higgs is a pseudo-Nambu-Goldstone boson



THE HIERARCHY PROBLEM

- Minimal set of collider signatures:



  - New strongly coupled partons

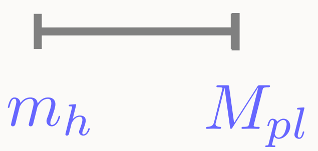
  - New composite resonances, coupling most strongly to *W, Z, H, t*

  - Deviations in Higgs properties: $\mathcal{O}(v^2/f^2) \sim 10\%$

    - additional goldstones?

THE HIERARCHY PROBLEM

- Idea 3: no running

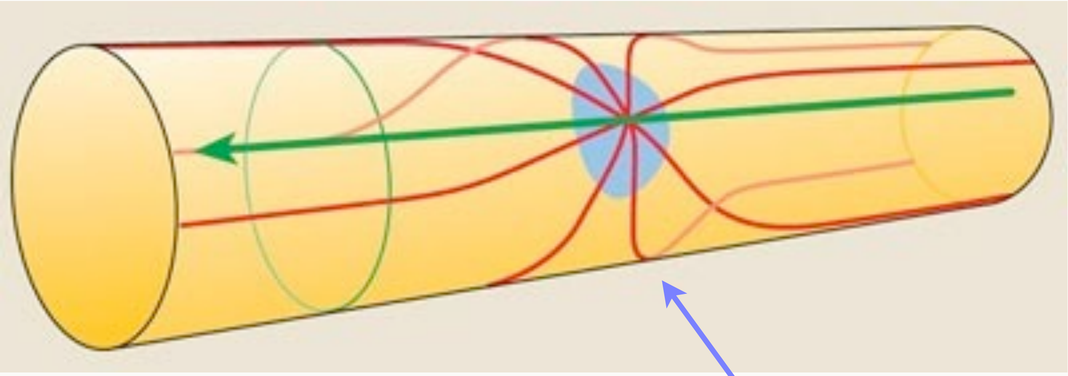


- apparent weakness of gravity compared to SM forces is an illusion due to geometry of spacetime
    - SM particles are inherently 4D (string theory makes this plausible)
    - various models: flat, warped, ...

THE HIERARCHY PROBLEM

- consider n flat extra dimensions:

R



$$V(r) = \frac{m}{M_{Pl(4+n)}^{n-2}} \frac{1}{R^n} \frac{1}{r}$$

but for $r > R$, field propagation is 4-dimensional

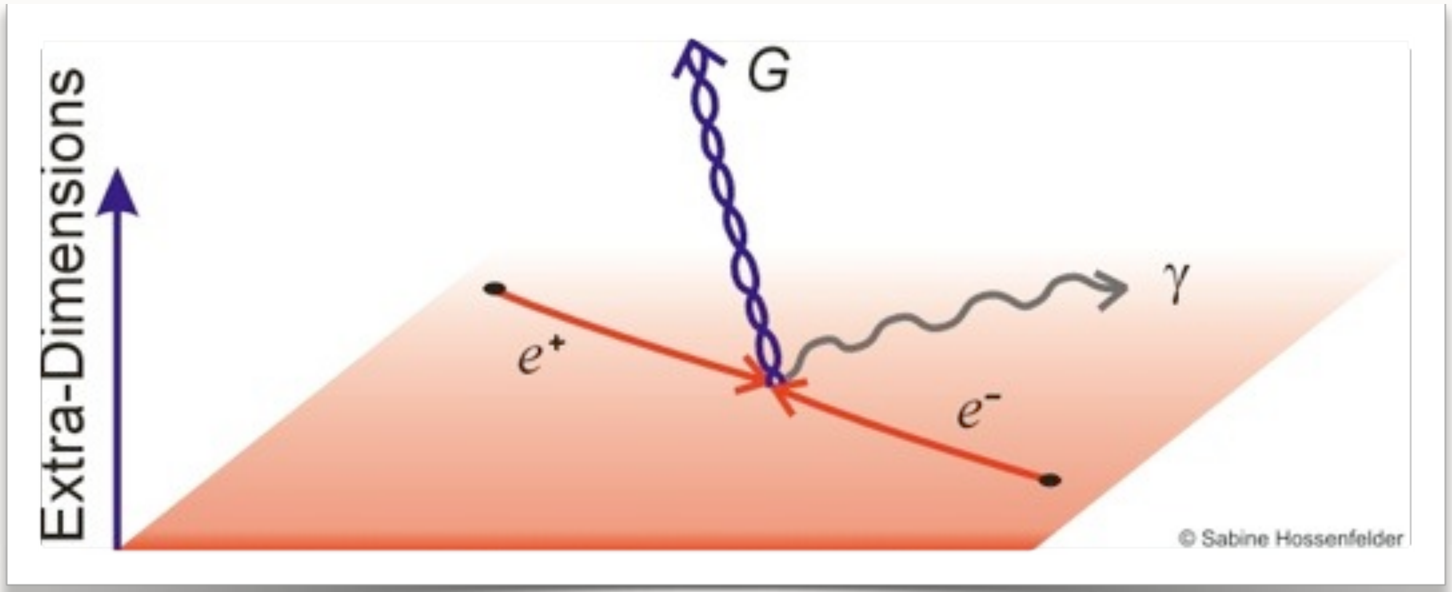
short distance behavior is 4+n-dimensional

$$V(r) = \frac{m}{M_{Pl(4+n)}^{n-2}} \frac{1}{r^{n+1}}$$

- if volume of extra dimensions is large in units of Planck length, 4D gravity appears weak: $M_{Pl(4+n)} R^n = M_{Pl(4)}$

THE HIERARCHY PROBLEM

- Some collider signatures:
  - production of Kaluza-Klein gravitons:



mono-(jet, *W*, *Z*, photon) recoiling against large *MET*

  - ...maybe quantum black holes?!

THE HIERARCHY PROBLEM

- I am going to focus on SUSY
  - In my view: most compelling as a theory of the universe
  - Many consequences of SUSY as applied to the hierarchy problem are qualitatively similar to those of other models
    - partner particles for SM
    - parity symmetry leading to dark matter candidates (MET)
    - collider searches for heavy states with SM charges

SUPERSYMMETRY

- Theory of 1 complex scalar + 1 Weyl fermion:

$$\mathcal{L} = \partial_\mu \phi \, \partial^\mu \phi^* + i\bar{\psi}\gamma^\mu \partial_\mu \psi$$

  - invariant under supersymmetry transformation:

$$\delta\phi = \bar{\epsilon}\psi \qquad\qquad \delta\psi = -i\epsilon\gamma^\mu \partial_\mu \phi$$

- two SUSY variations yield a translation:

$$[\delta_1, \delta_2]\, \phi = -i\bar{\epsilon}_2 \gamma^\mu \epsilon_1 \partial_\mu \phi$$

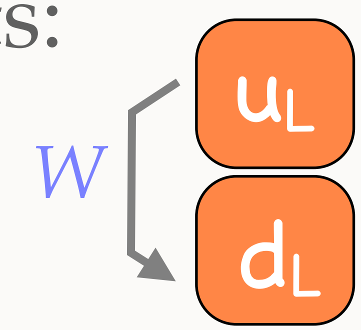
  - recall $\delta\phi = a^\mu \partial_\mu \phi$: generated by momentum

SUPERSYMMETRY

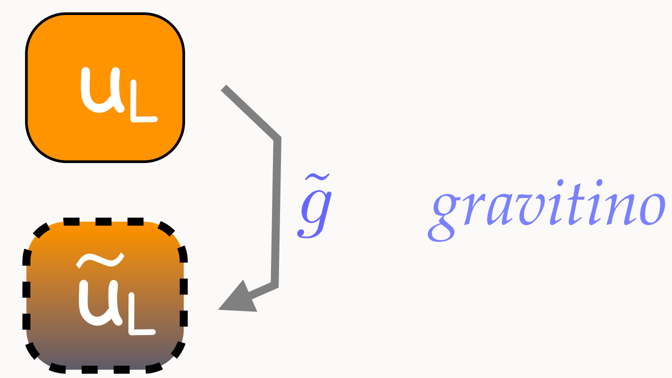
- SUSY is thus inherently intertwined with spacetime (Poincare) symmetry
  - SUSY: a statement about background spacetime
  - we can’t pick and choose a subsector of the universe to supersymmetrize
  - the kinds of representations of SUSY that we can have depend on particle’s Lorentz quantum numbers, in particular, on their spin.

SUPERSYMMETRY

- Multiplets:



- $SU(2)_L$ $SU(3)_c$



- supermultiplets: particle and superpartner
  - fermion - sfermion $(\tilde{u}_L, u_L)$
  - gauge boson - gaugino $(\tilde{B}, B_\mu)$
  - Higgs boson - higgsino $(H_u, \tilde{H}_u)$

chiral multiplets

vector multiplets

SUPERSYMMETRIC THEORIES

- Supersymmetry restricts possible interactions
  - Analogy: EWSB
  - Below scale of EWSB, u_R, u_L seem to have quantum numbers allowing Dirac mass term: $m_u \, u_R u_L$
  - But forbidden under underlying $SU(2)_L$ x $U(1)_Y$ - need $\frac{y_u v}{\sqrt{2}} u_R u_L$
  - from the parent interaction $y_u \, H \, u_R Q_L$
  - which also yields the interaction $\frac{y_u}{\sqrt{2}} h \, u_R u_L$

SUPERSYMMETRIC THEORIES

- SUSY relates Yukawa interactions $HQ_L u_R$ to quartic scalar couplings $|H|^2|\tilde{Q}_L|^2, \ldots$
- useful compact formalism: superpotential

$$W = y_u Q_L H u_R + \ldots$$

superfields

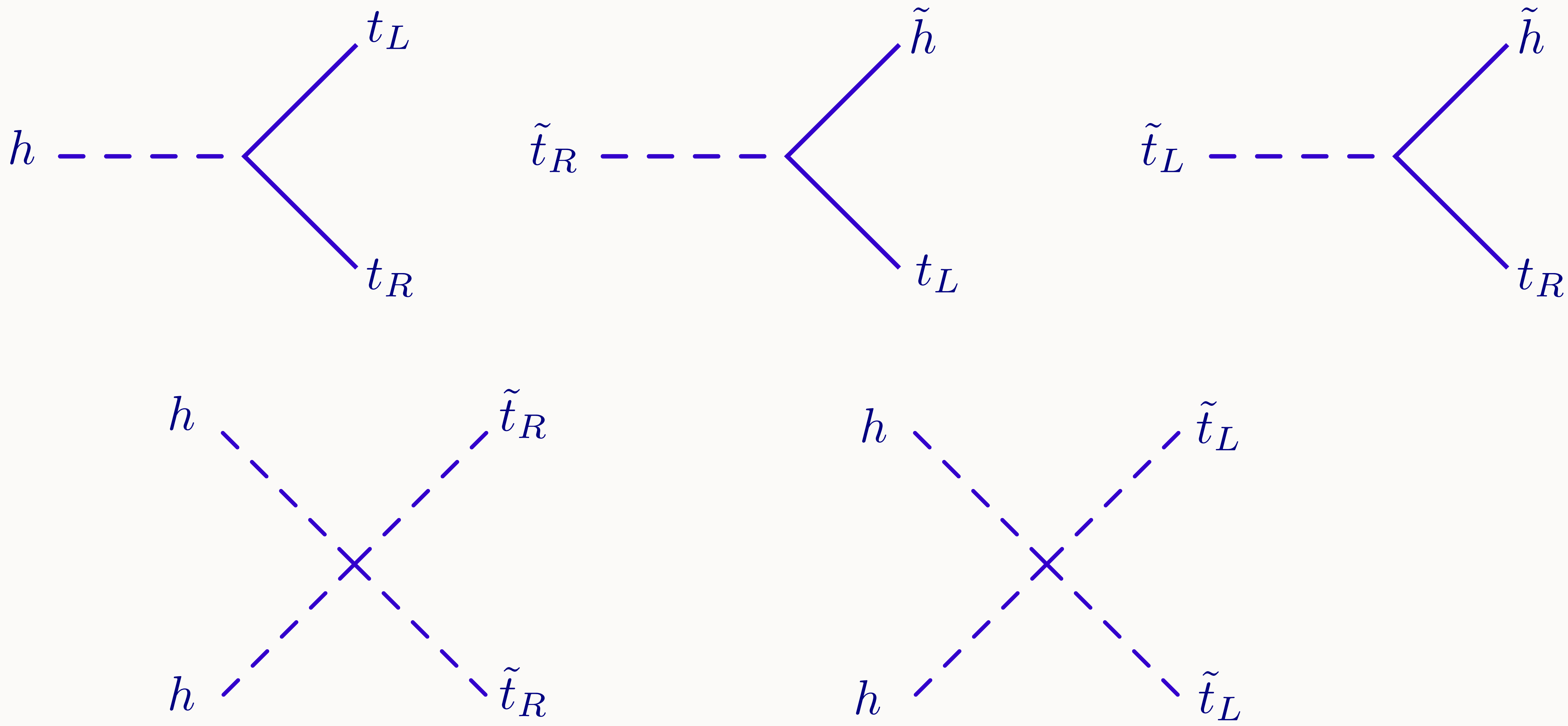
renormalizable interactions are cubic

- determines all supersymmetric interactions between chiral multiplets:

$$\mathcal{L}_{Yuk} = -W_{ij}\psi_i\psi_j \qquad V(\phi) = |W_i|^2$$

SUPERSYMMETRIC THEORIES

- Thus one cubic superpotential term yQ_LHu_R encodes



SUPERSYMMETRIC THEORIES

- SM Yukawas:

$$\mathcal{L}_{SM} = y_d Q_L H d_R + y_\ell L_L H e_R + y_u Q_L H^c u_R$$

  - But only superfields, not their complex conjugates, can appear in W: cannot be supersymmetrized

- Must introduce two Higgs doublets $H_u,\ H_d$

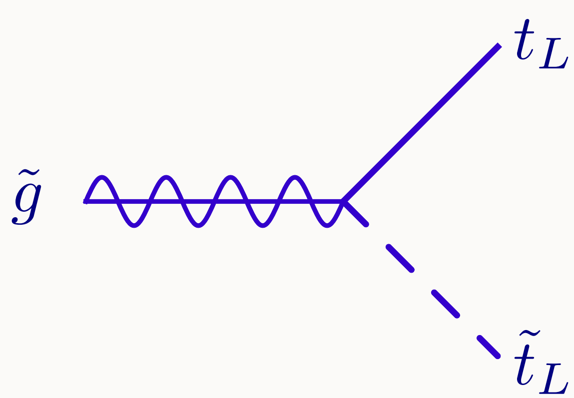
  - also fixes up quantum consistency of MSSM: anomaly cancellation

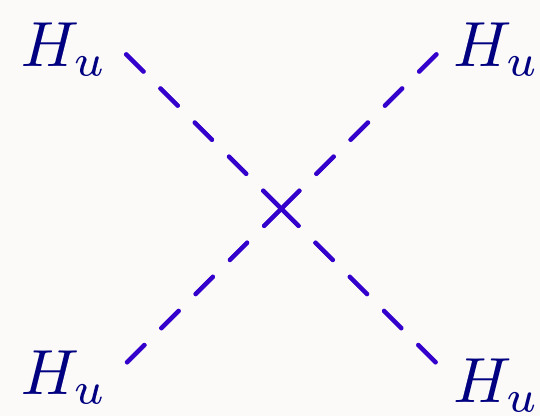
- SUSY quadratic Higgs potential terms from $W = \mu H_u H_d$

SUPERSYMMETRIC THEORIES

- What about gauge interactions?
  - Gauge invariance uniquely dictates interactions of gauge bosons with charged particles
  - SUSY relates these to gaugino interactions and new scalar quartics,

$$\mathcal{L}_{new} = -\sqrt{2}g(\phi^* t^a \psi)\lambda^a + H.c. - \frac{g^2}{2}(\phi^* t^a \phi)^2$$





SUPERSYMMETRIC MSSM

- This gives us the SUSY-preserving part of the MSSM:

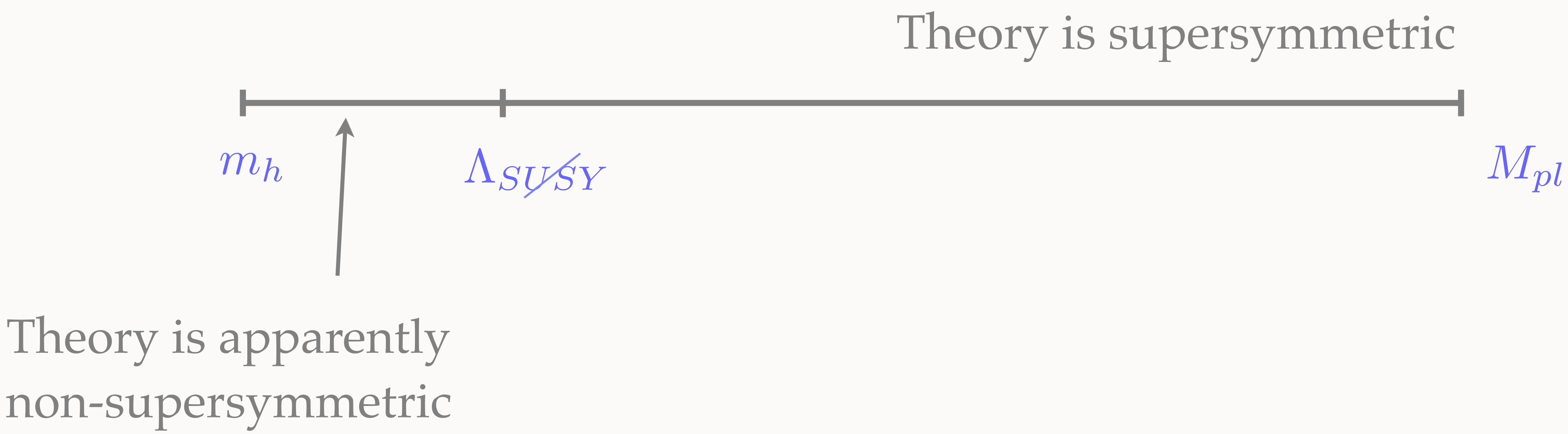
particles	sparticles
$\begin{pmatrix} u_L \\ d_L \end{pmatrix}$ u_R d_R $\begin{pmatrix} \nu_L \\ e_L \end{pmatrix}$ e_R ν_R	$\begin{pmatrix} \tilde{u}_L \\ \tilde{d}_L \end{pmatrix}$ $\tilde{u}_R$ $\tilde{d}_R$ $\begin{pmatrix} \tilde{\nu}_L \\ \tilde{e}_L \end{pmatrix}$ $\tilde{e}_R$ $\tilde{\nu}_R$
H_u H_d	$\tilde{H}_u$ $\tilde{H}_d$
g^a_μ W^a_μ B_μ	$\tilde{g}^a$ $\tilde{W}^a$ $\tilde{B}$

- Extremely predictive!
  - More than double the particles of the SM
  - Fewer parameters

- Of course, SUSY is broken in nature...

SUSY BREAKING

- How can we break SUSY without spoiling the solution to the hierarchy problem?
    - Must break SUSY spontaneously



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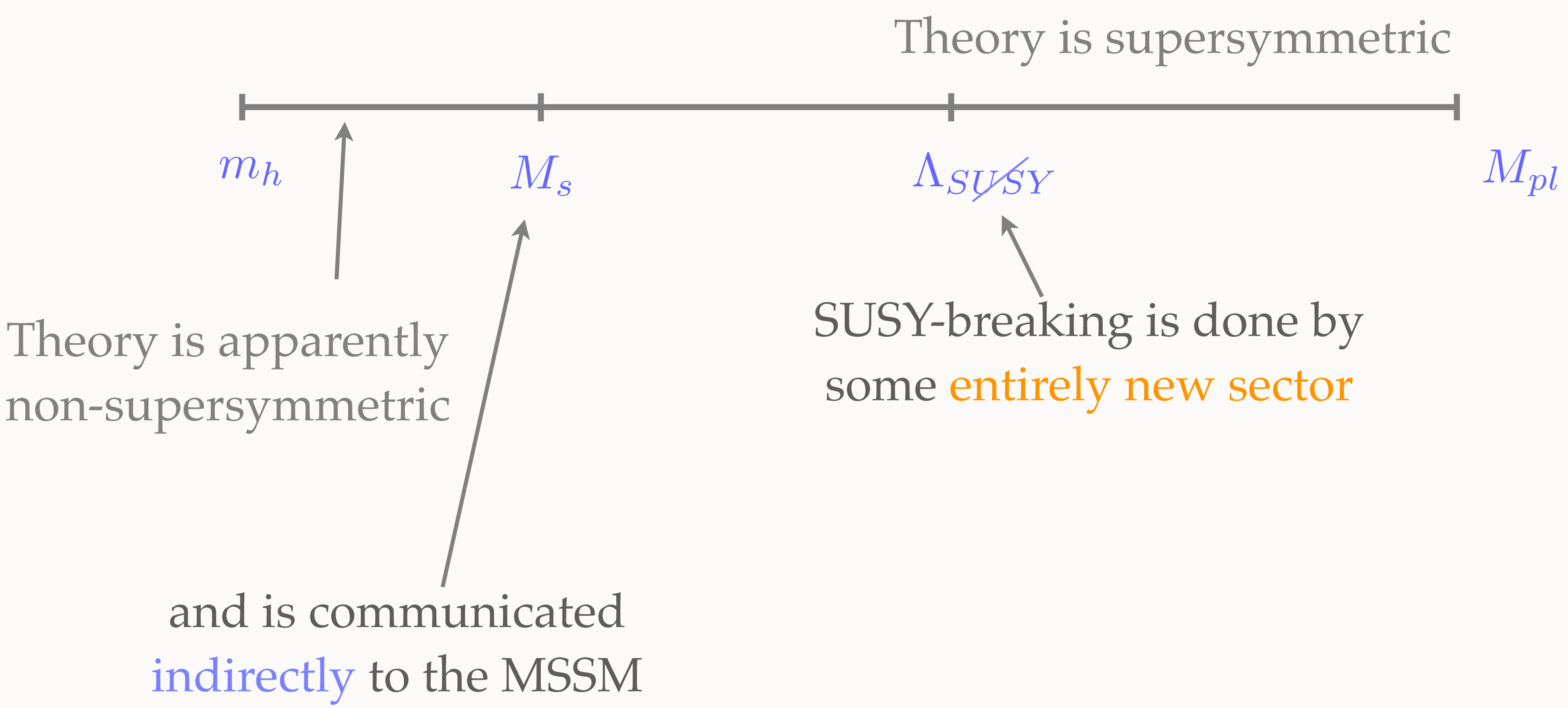

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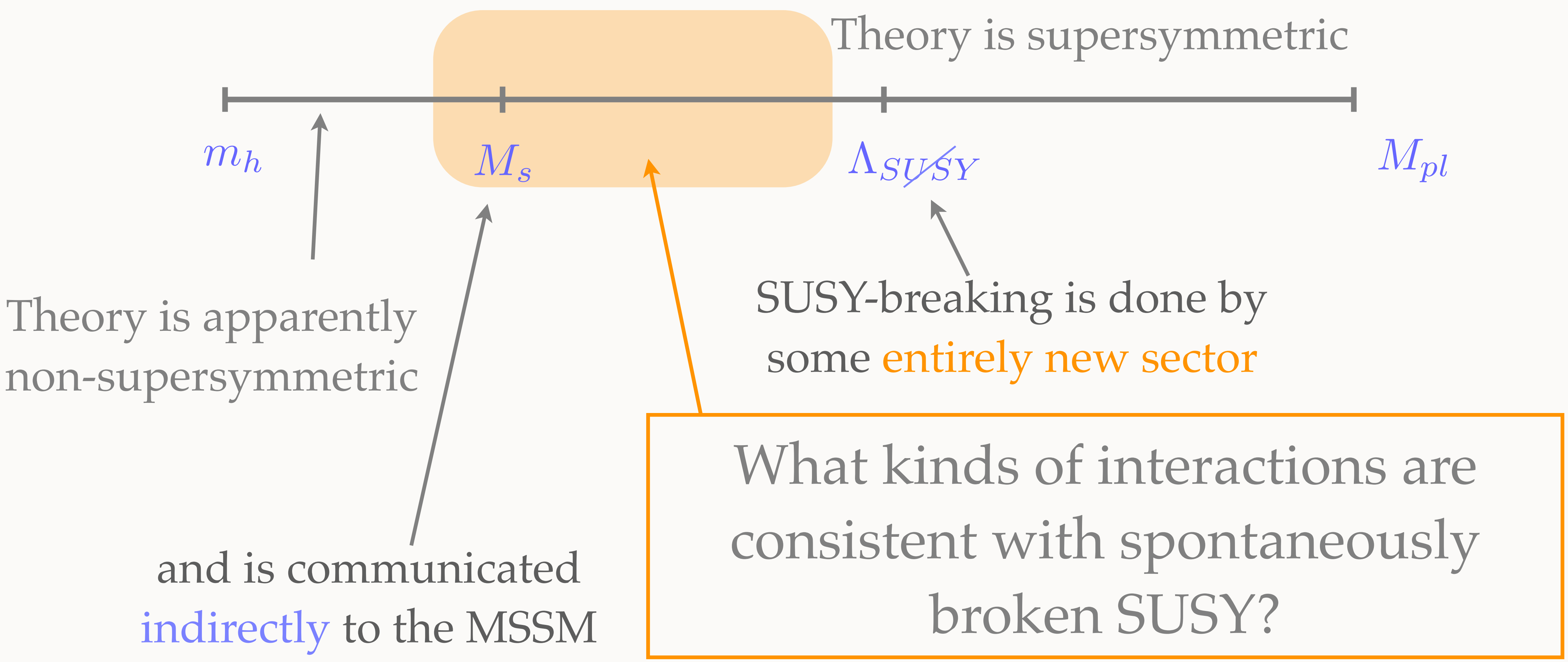
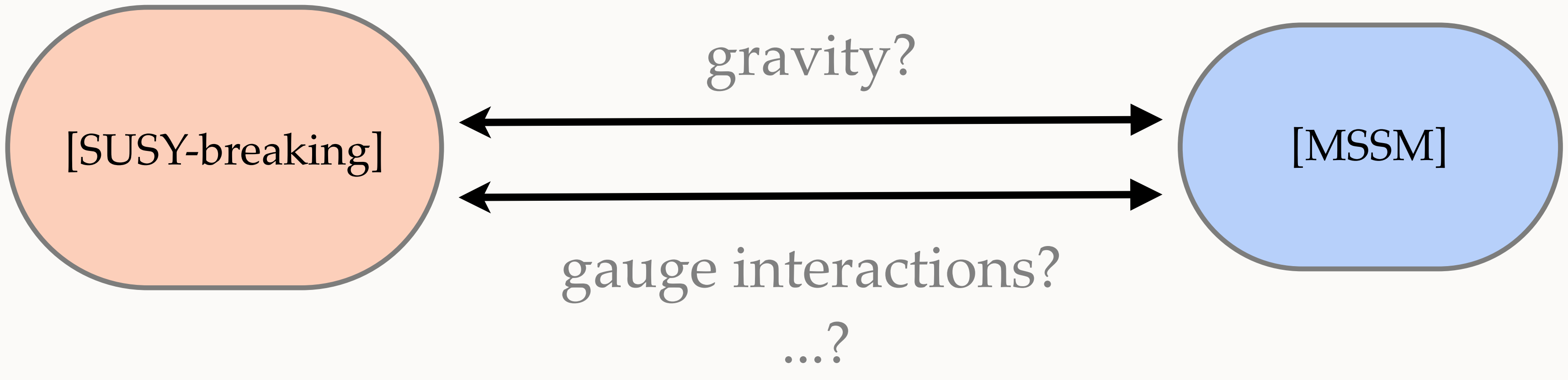


SUSY BREAKING

- Spontaneous SUSY-breaking yields a supertrace sum rule at tree level

$$\mathrm{Tr}\, m_S^2 - 2\mathrm{Tr}\, m_F^2 + 3\mathrm{Tr}\, m_V^2 = 0$$

- To get acceptable spectra, must break SUSY in a hidden sector:



SUSY BREAKING

- This induces the "soft SUSY-breaking" Lagrangian:

$$\mathcal{L}_{soft} = -\frac{1}{2}\left(M_3\tilde{g}\tilde{g} + M_2\tilde{W}\tilde{W} + M_1\tilde{B}\tilde{B} + H.c.\right)$$

masses for superpartners only

$$-\tilde{Q}_L^* M_Q^2 \tilde{Q}_L - \tilde{u}_R^* M_u^2 \tilde{u}_R - \tilde{d}_R^* M_d^2 \tilde{d}_R - \tilde{L}_L^* M_L^2 \tilde{L}_L - \tilde{e}_R^* M_e^2 \tilde{e}_R$$

trilinear couplings: one for each super-potential term

$$-\left(A_u \tilde{u}_R \tilde{Q}_L H_u + A_d \tilde{d}_R \tilde{Q}_L H_d + A_e \tilde{e}_R \tilde{L}_L H_d + H.c.\right)$$

and same in the Higgs sector

$$-m_{H_u}^2 H_u^* H_u - m_{H_d}^2 H_d^* H_d - (bH_u H_d + H.c.)$$

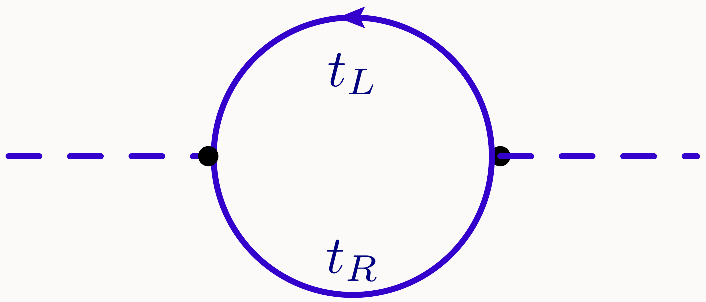
- over 100 free parameters!

SUSY BREAKING

- All soft SUSY-breaking terms are dimensionful
    - sensible: less important in the UV than in the IR
    - must vanish as $\Lambda_{\not{SUSY}} \to 0$
    - no changes in the renormalizable couplings $\Longrightarrow$ leading divergence cancellations unaffected
    - no new quadratic divergences are generated

SUSY BREAKING

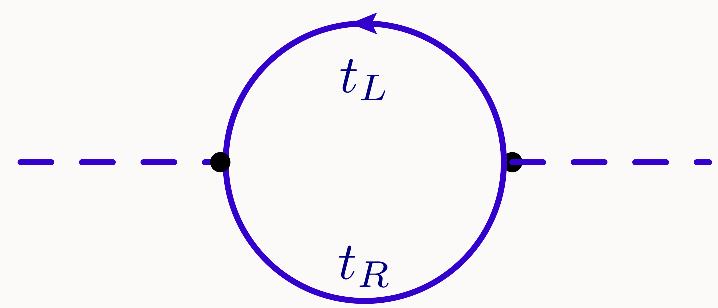
- Let's do an explicit example: top and stop loops



$$-i\,\delta m_h^2\big|_{top} = -2N_c y_t^2 \int \frac{d^4k}{(2\pi)^4}\,\frac{k^2+m_t^2}{(k^2-m_t^2)^2}$$

SUSY BREAKING

- Let’s do an explicit example: top and stop loops



$$-i\,\delta m_h^2\big|_{top} = -2N_c y_t^2 \int \frac{d^4k}{(2\pi)^4}\,\frac{k^2+m_t^2}{(k^2-m_t^2)^2}$$

overall minus sign from fermion loop

color degrees of freedom

vertices

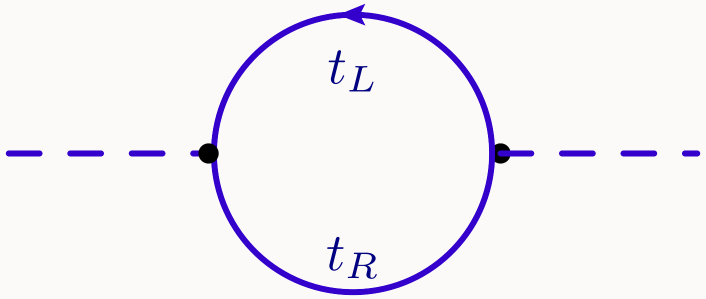
two propagators

logarithmic divergence

quadratic divergence

SUSY BREAKING

- Let’s do an explicit example: top and stop loops



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$$\delta m_h^2\big|_{top} = -\frac{3y_t^2}{8\pi^2}\left(\Lambda^2 - 3m_t^2 \ln\left(\frac{\Lambda^2+m_t^2}{m_t^2}\right) + \ldots\right)$$

SUSY BREAKING

- Let's do an explicit example: top and stop loops

$$\mathcal{L}_{stop} = -\frac{1}{2}(v+h)^2\left(|\tilde{t}_L|^2 + |\tilde{t}_R|^2\right)$$

SUSY-preserving

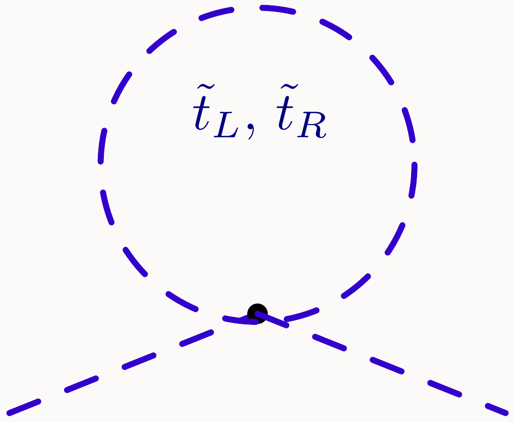
$$+m_R^2|\tilde{t}_R|^2 + m_L^2|\tilde{t}_L|^2$$

SUSY-breaking

- In general also SUSY-breaking contribution to trilinears

SUSY BREAKING

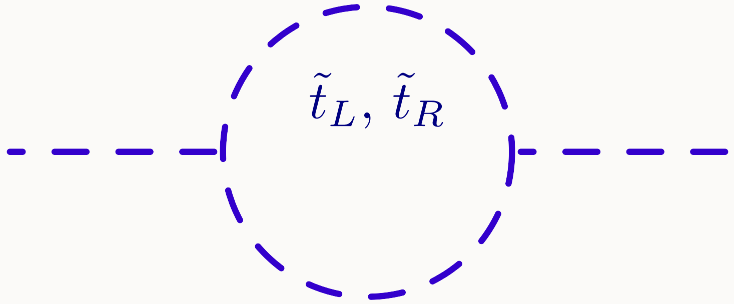
- Let's do an explicit example: top and stop loops



$$\delta m_h^2\big|_{stop\,1} = \frac{3y_t^2}{16\pi^2}\left(2\Lambda^2 - m_L^2 \ln\left(\frac{\Lambda^2 + m_L^2}{m_L^2}\right) - m_R^2 \ln\left(\frac{\Lambda^2 + m_R^2}{m_R^2}\right) + \ldots\right)$$

SUSY BREAKING

- Let's do an explicit example: top and stop loops



$$\delta m_h^2\big|_{stop\,2} = -\frac{3y_t^2}{8\pi^2}\left(m_t^2 \ln\left(\frac{\Lambda^2 + m_L^2}{m_L^2}\right) - m_t^2 \ln\left(\frac{\Lambda^2 + m_R^2}{m_R^2}\right) + \ldots\right)$$

No quadratic divergences:
dimensionally impossible

SUSY-breaking trilinears:
mt -> more general function

SUSY BREAKING

- Let's do an explicit example: top and stop loops
  - Add everything up:

$$\delta m_h^2\big|_{top} = -\frac{3y_t^2}{8\pi^2}\left(\Lambda^2 - 3m_t^2 \ln\left(\frac{\Lambda^2 + m_t^2}{m_t^2}\right) + \ldots\right)$$

$$\delta m_h^2\big|_{stop\,1} = \frac{3y_t^2}{16\pi^2}\left(2\Lambda^2 - m_L^2 \ln\left(\frac{\Lambda^2 + m_L^2}{m_L^2}\right) - m_R^2 \ln\left(\frac{\Lambda^2 + m_R^2}{m_R^2}\right) + \ldots\right)$$

$$\delta m_h^2\big|_{stop\,2} = -\frac{3y_t^2}{8\pi^2}\left(m_t^2 \ln\left(\frac{\Lambda^2 + m_L^2}{m_L^2}\right) - m_t^2 \ln\left(\frac{\Lambda^2 + m_R^2}{m_R^2}\right) + \ldots\right)$$

Quadratic divergence cancels independently of soft breaking terms

Exact SUSY: log divergence cancels too

SUSY BREAKING

- So about those >100 free parameters...
  - Tremendous constraints from flavor, CP
    - flavor structure can't be arbitrary: SUSY flavor problem
  - Top-down: specific mediation mechanisms impose characteristic relationships between soft parameters
    - gauge mediation, gravity mediation, anomaly mediation, ...
  - Bottom-up: CP-preserving, nearly flavor-symmetric sector
    - "pMSSM": a mere 20 parameters

R-PARITY

- Unlike in the SM, we cannot write down all interactions allowed by gauge symmetries:

$$W = \mu H_u H_d + Y_u Q_L H_u u_R + Y_d Q_L H_d d_R + Y_e L_L H_d e_R$$

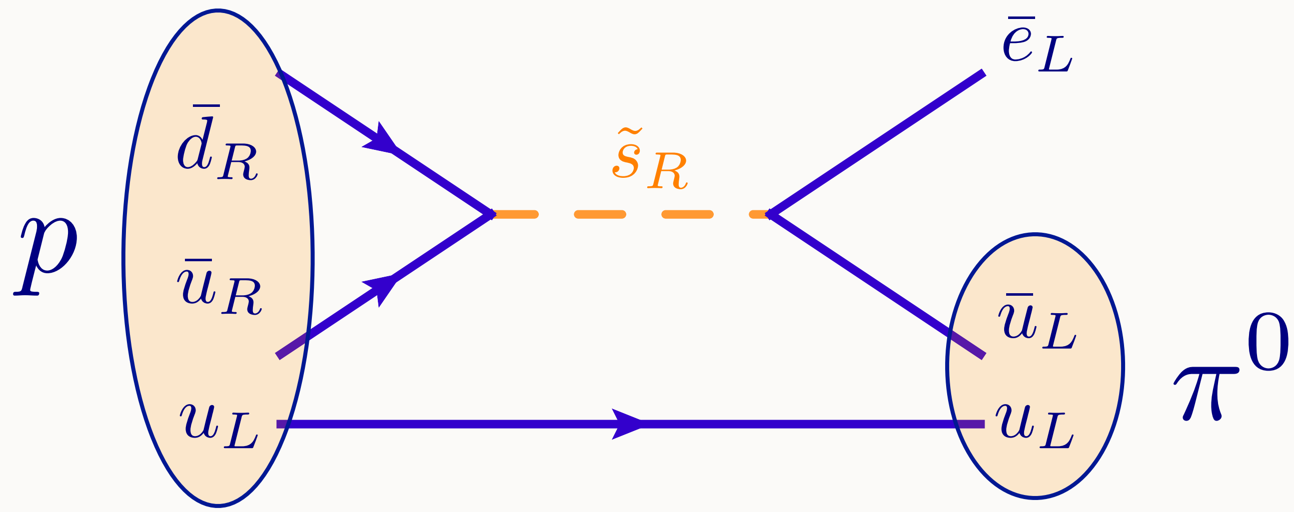
$$+\underline{\hat{\mu} H_u L_L} + \underline{\lambda'' u_R d_R d_R} + \underline{\lambda' Q_L L_L d_R} + \underline{\lambda L_L L_L e_R}$$

violates B violates L

- Leads to whole tensors of new B and L-violating couplings:
  - e.g. Yukawas, $\lambda''_{112}(u_R d_R)\tilde{s}_R\ ,\ \ \lambda'_{112}\tilde{s}_R(e_L u_L)$

R-PARITY

- Catastrophic proton decay:



- *B, L* violating Yukawa couplings must be extremely small:

$$\Gamma \sim \frac{|\lambda''_{112}\lambda'_{112}|^2 m_p^5}{m_{\tilde{s}}^4} < 10^{34} \text{ years}$$

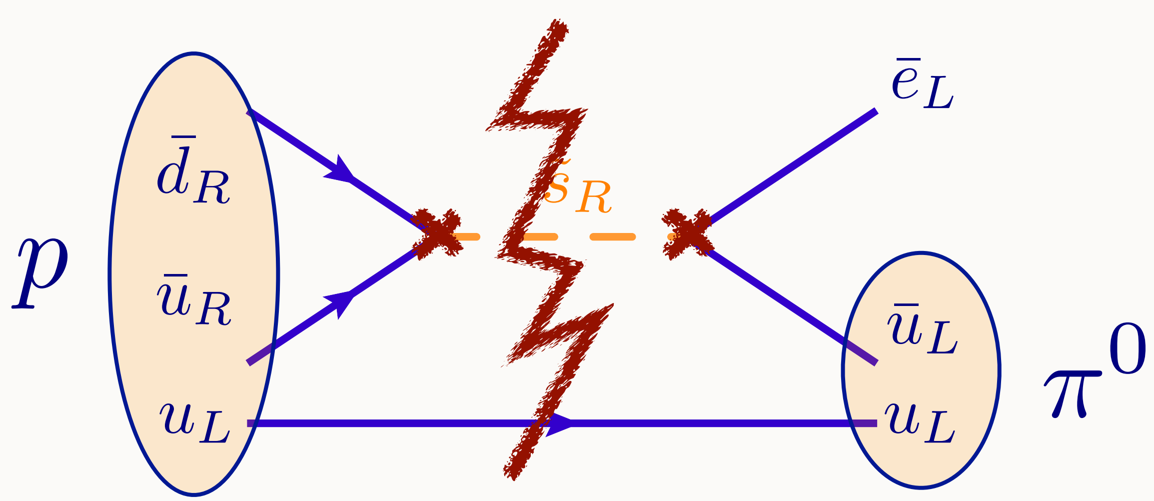
R-PARITY

- Easy solution: impose a new global symmetry:

$$W = \mu H_u H_d + Y_u Q_L H_u u_R + Y_d Q_L H_d d_R + Y_e L_L H_d e_R$$

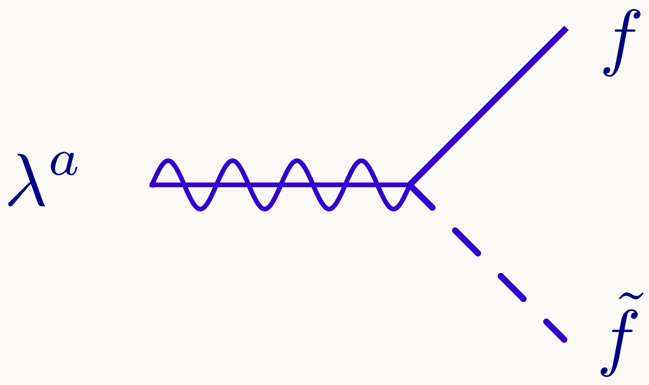
$$+\hat{\mu} H_u L_L + \lambda'' u_R d_R d_R + \lambda' Q_L L_L d_R + \lambda L_L L_L e_R$$

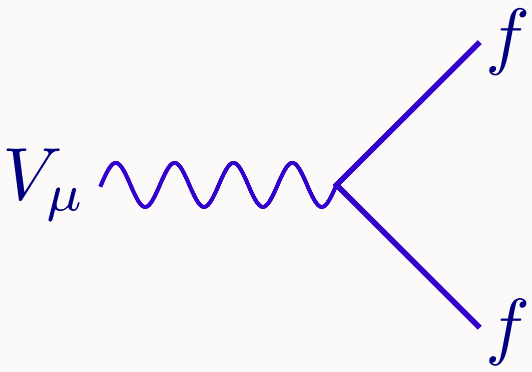
- impose matter parity: $P_M = (-1)^{3(B-L)}$



R-PARITY

- Gauge interactions:





- define *R*-parity:

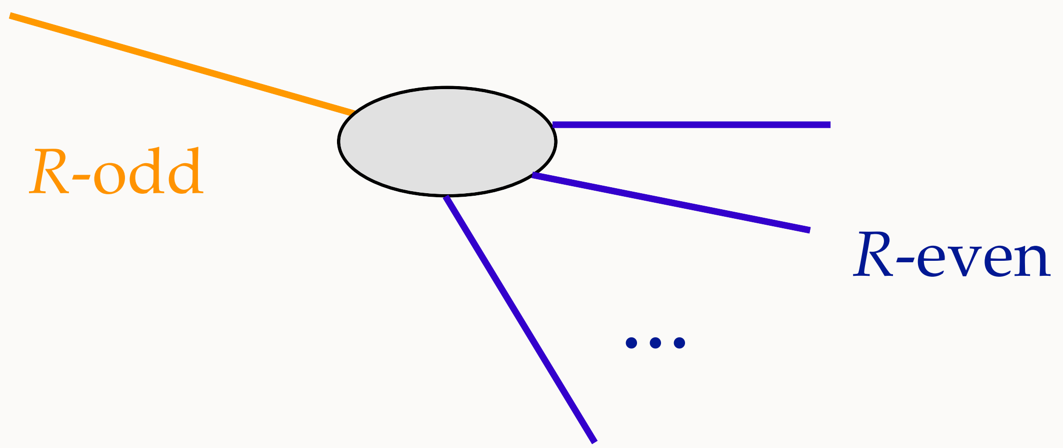
$$P_R = (-1)^{3(B-L)+2s}$$

  - exactly the same! but
    - easier to see consequences
    - natural in SUSY

even	odd
f (spin 1/2)	$\tilde{f}$ (spin 0)
V (spin 1)	$\tilde{V}$ (spin 1/2)
H (spin 0)	$\tilde{H}$ (spin 1/2)

R-PARITY

- Immediate consequence: lightest superpartner is stable



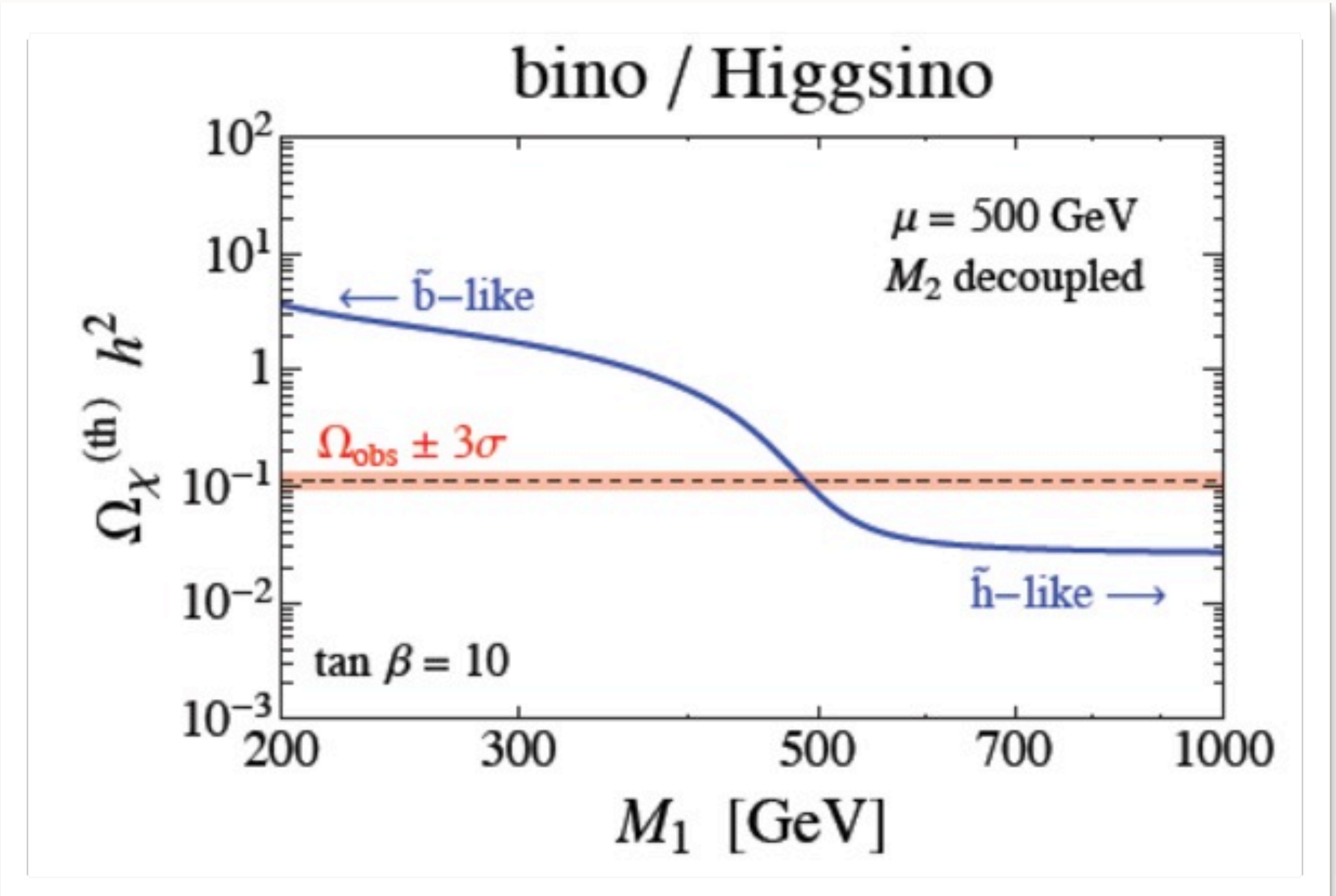
- This significantly restricts the spectrum:
  - lightest superpartner must be neutral
  - and must not over-close the universe

R-PARITY: DARK MATTER

- Lightest Supersymmetric Particle is an attractive DM candidate:
  - electroweak interactions, electroweak scale mass
  - Possible candidates:
    - neutralinos $\tilde{B}, \tilde{W}^3, \tilde{h}_u, \tilde{h}_d$
    - sneutrinos $\tilde{\nu}_L, \tilde{\nu}_R$
  - the devil is in the details

R-PARITY: DARK MATTER

- Relic abundance delicate function of spectrum:



[Hall, Pinner, Ruderman]

R-PARITY: DARK MATTER

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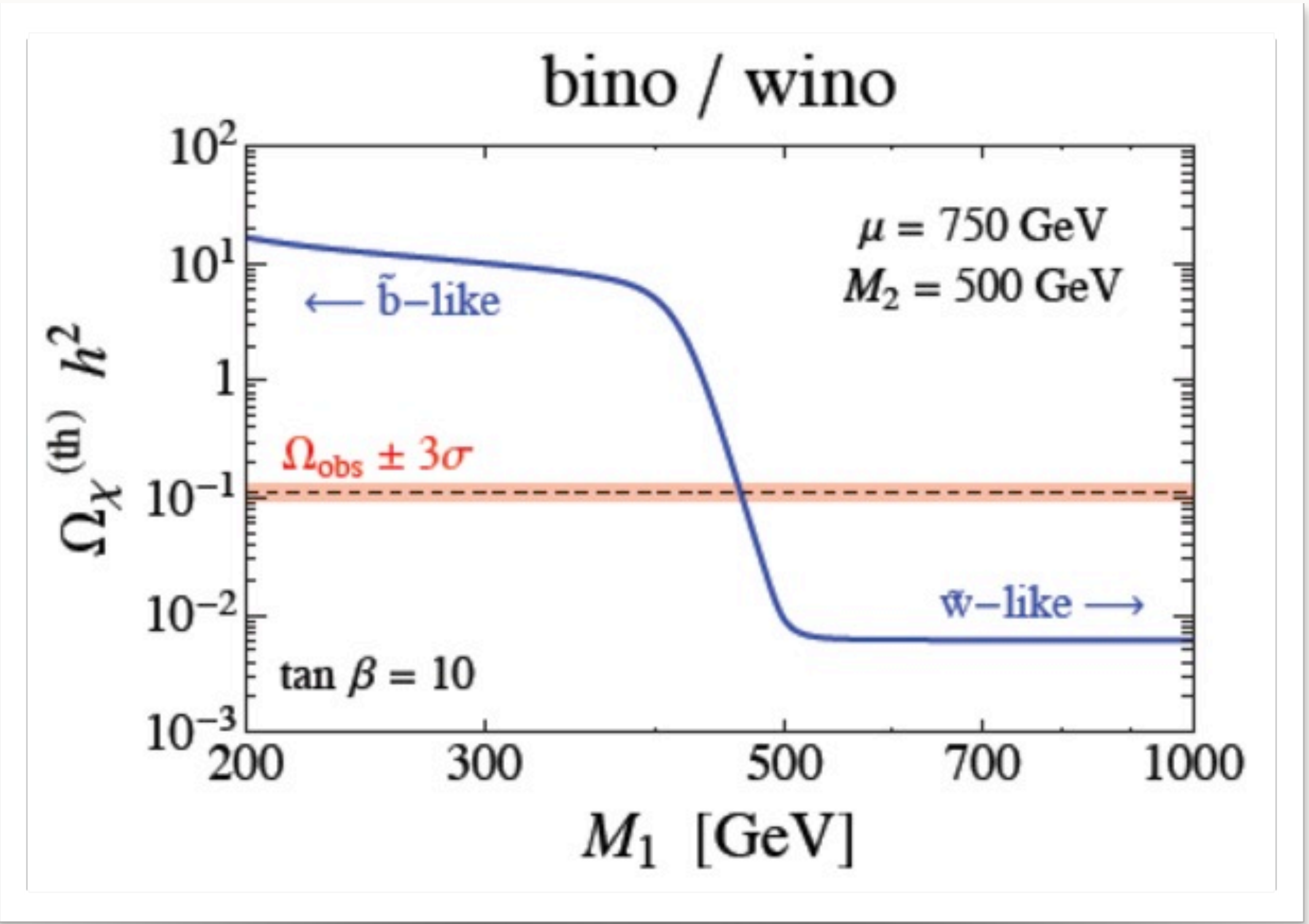
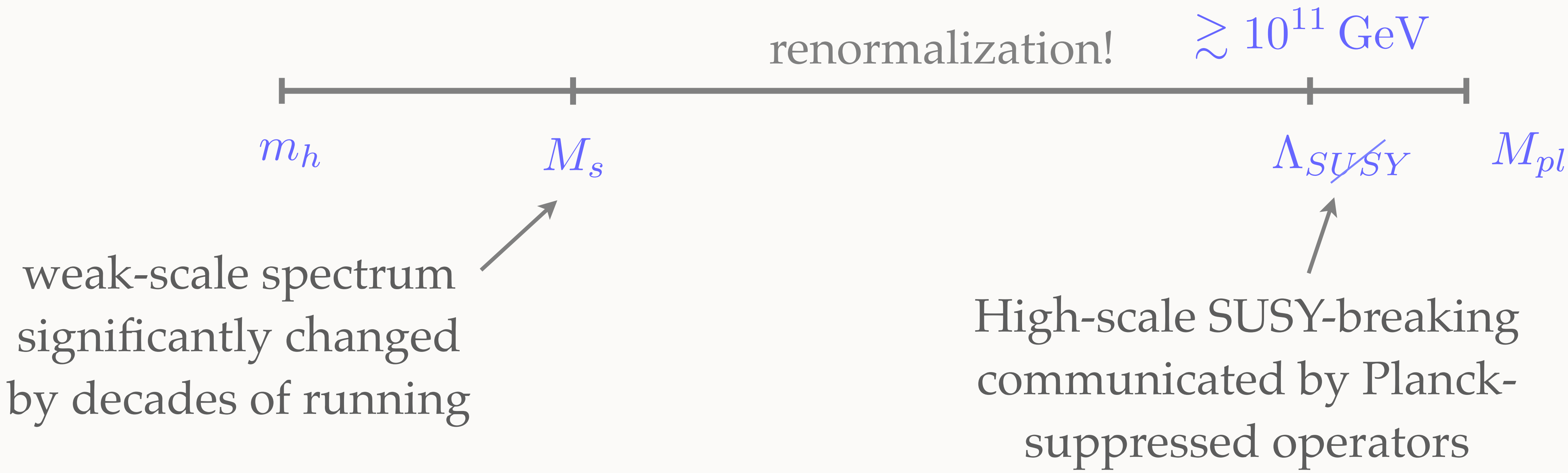


[Hall, Pinner, Ruderman]

MSSM SPECTRA

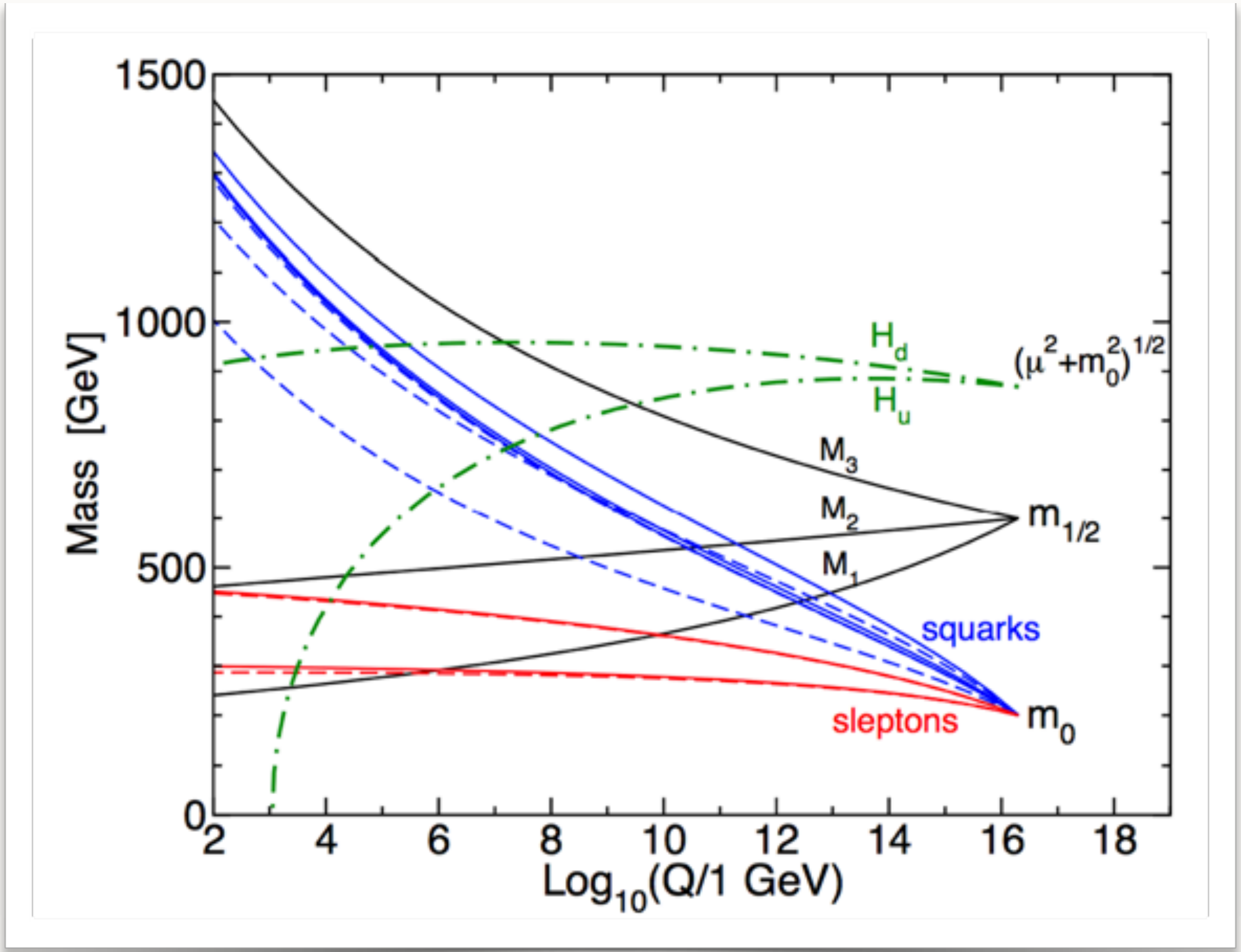
- High-scale SUSY breaking
  - e.g.: gravity-mediated



  - gravitino mass: $m_{3/2} = \dfrac{\Lambda^2_{SUSY}}{M_{Pl}}$ sets scale for soft masses

MSSM SPECTRA

- Effects of RG evolution:



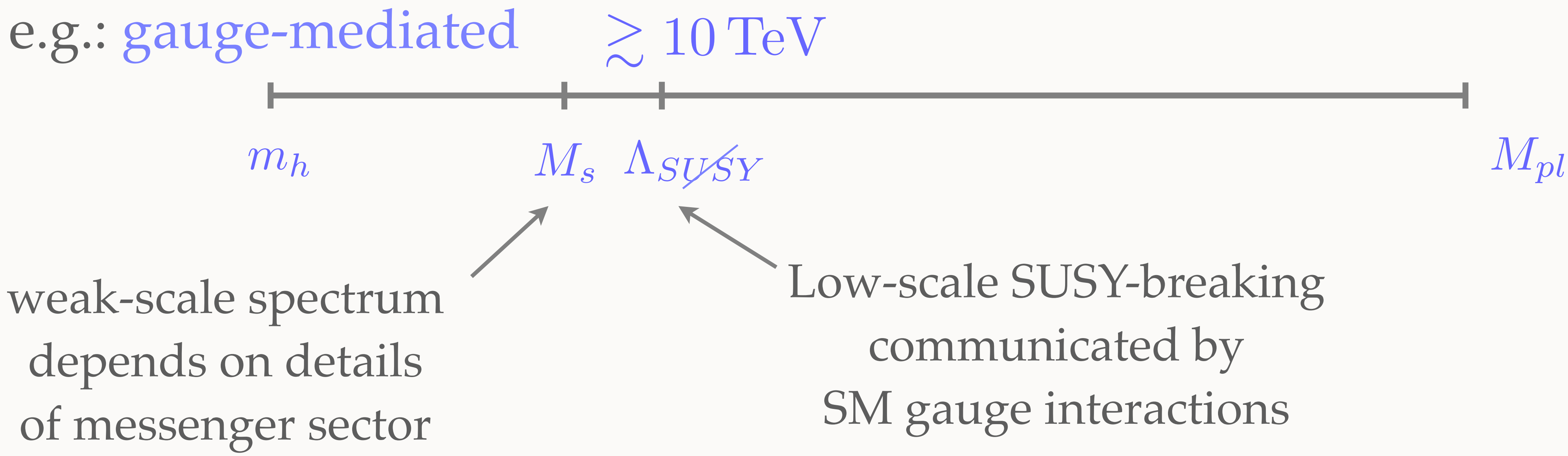
[Martin]

MSSM SPECTRA

- Simplest gravity-mediated model: mSUGRA
  - 100 parameters $\to$ 5
  - useful toy model! But highly simplified
- Biggest issue: flavor
  - Gravitational interactions don't care about flavor $\Longrightarrow$ anarchic flavor structure
  - Straightforward mediation requires sfermions $m \gtrsim 100$ TeV
  - (Maybe this is our universe? Not quite natural....)

MSSM SPECTRA

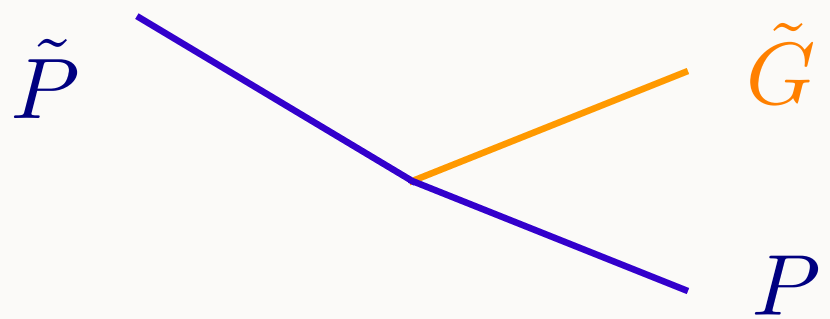
- Low-scale SUSY breaking
  - e.g.: gauge-mediated



  - gravitino mass: $m_{3/2} = \dfrac{\Lambda^2_{SUSY}}{M_{Pl}}$
  - soft masses: $m_{soft} \sim \dfrac{\alpha}{4\pi}\Lambda_{SUSY}$

MSSM SPECTRA

- Gravitino is the LSP
  - Cosmology very different - no more neutralino dark matter
  - Now charged superpartners can be the *NLSP*:



  - Decay of NLSP to gravitino can be prompt or displaced
- Big plus: neatly solves flavor problem

MSSM SPECTRA

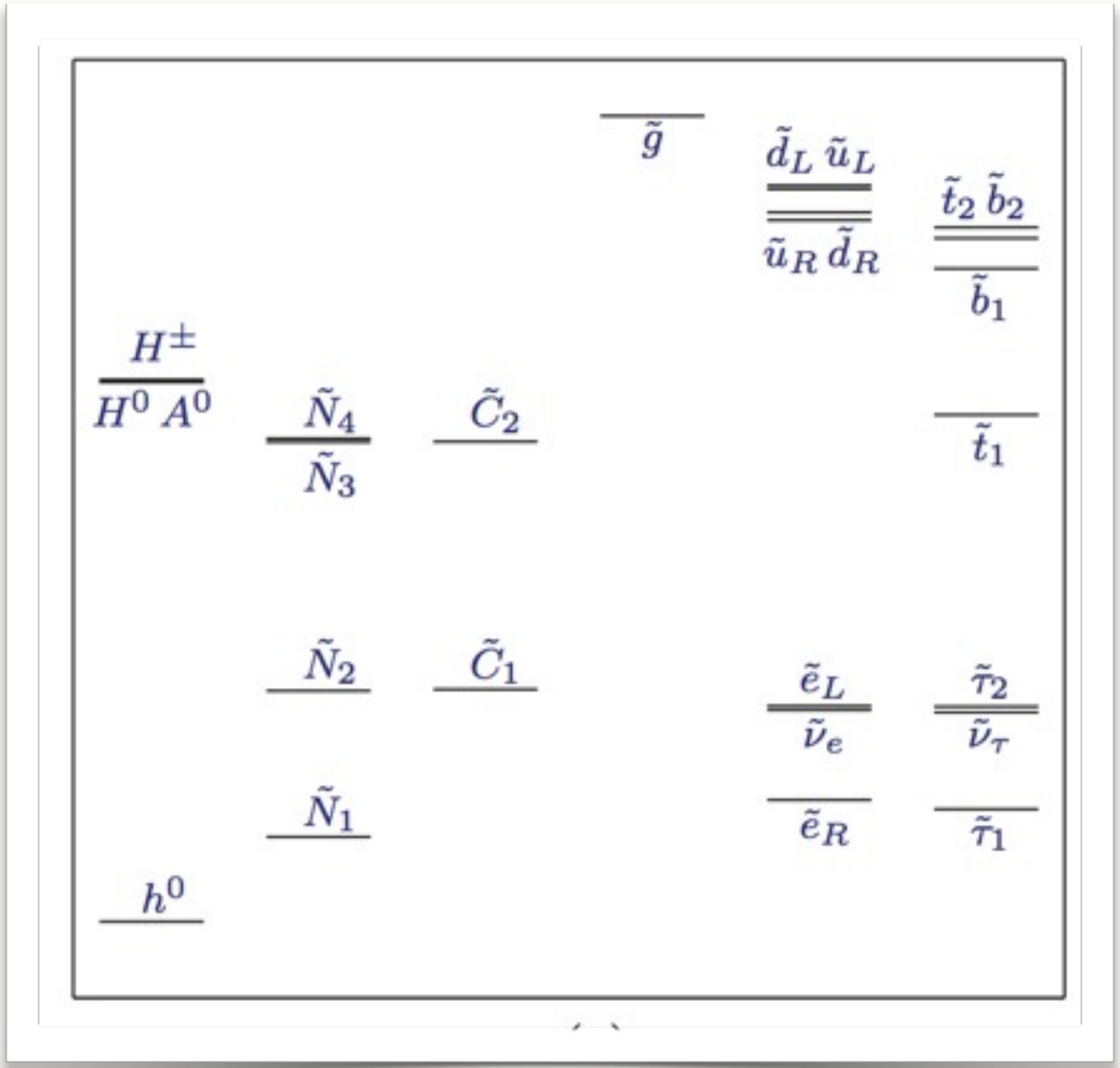
- But...
  - adding charged mediators can make it tricky to maintain gauge unification
  - new cosmological problems with non-thermally produced stable gravitinos
  - Biggest disadvantage: hard to accommodate $m_h = 125$ GeV

MSSM SPECTRA

- Have never yet found a completely convincing top-down model of SUSY-breaking
- Since experimental signatures extremely sensitive to detailed spectrum, also important to consider bottom-up approaches to make sure bases are covered

MSSM SPECTRA

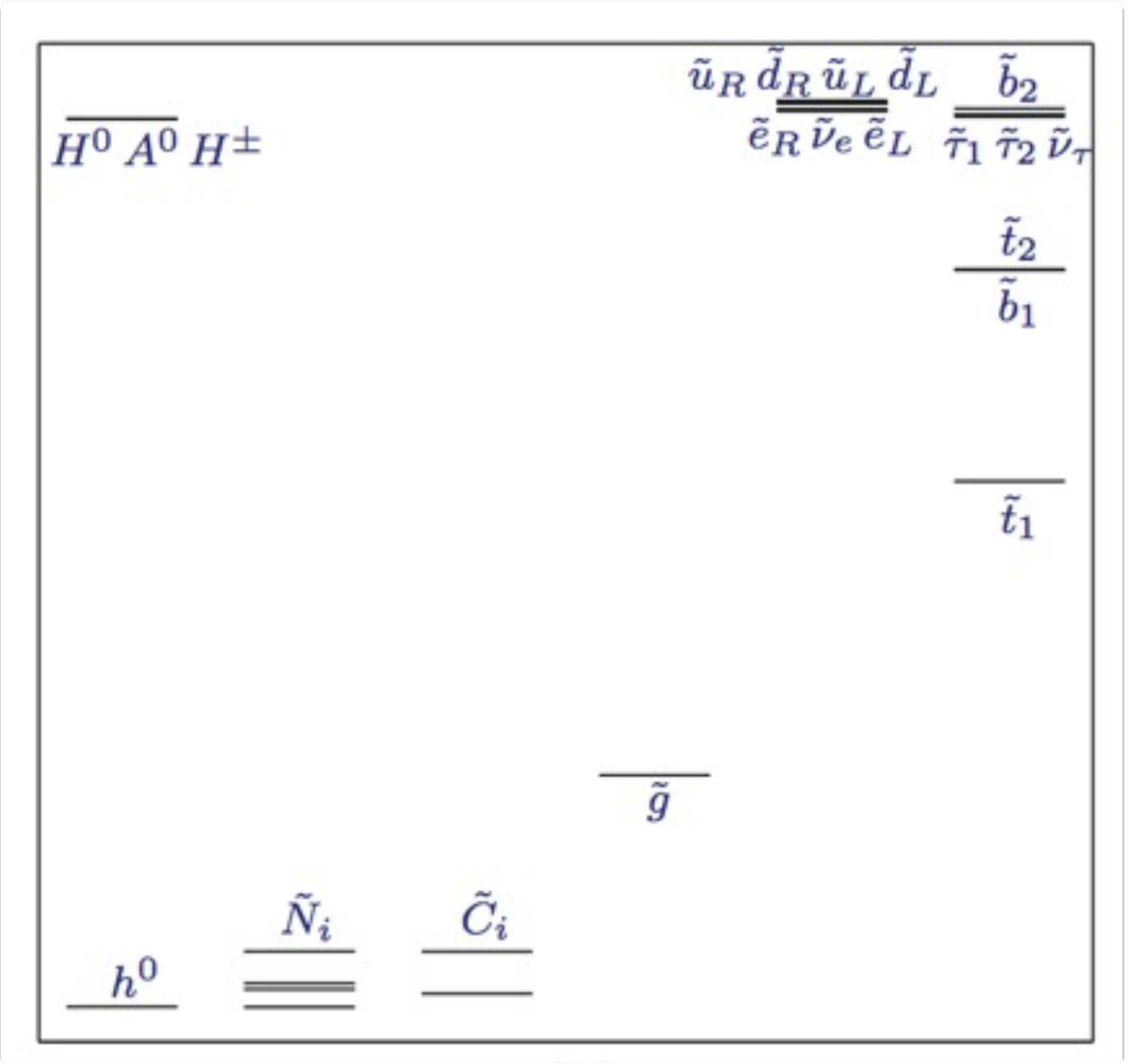
- Example gravity-mediated spectrum



[Martin]

MSSM SPECTRA

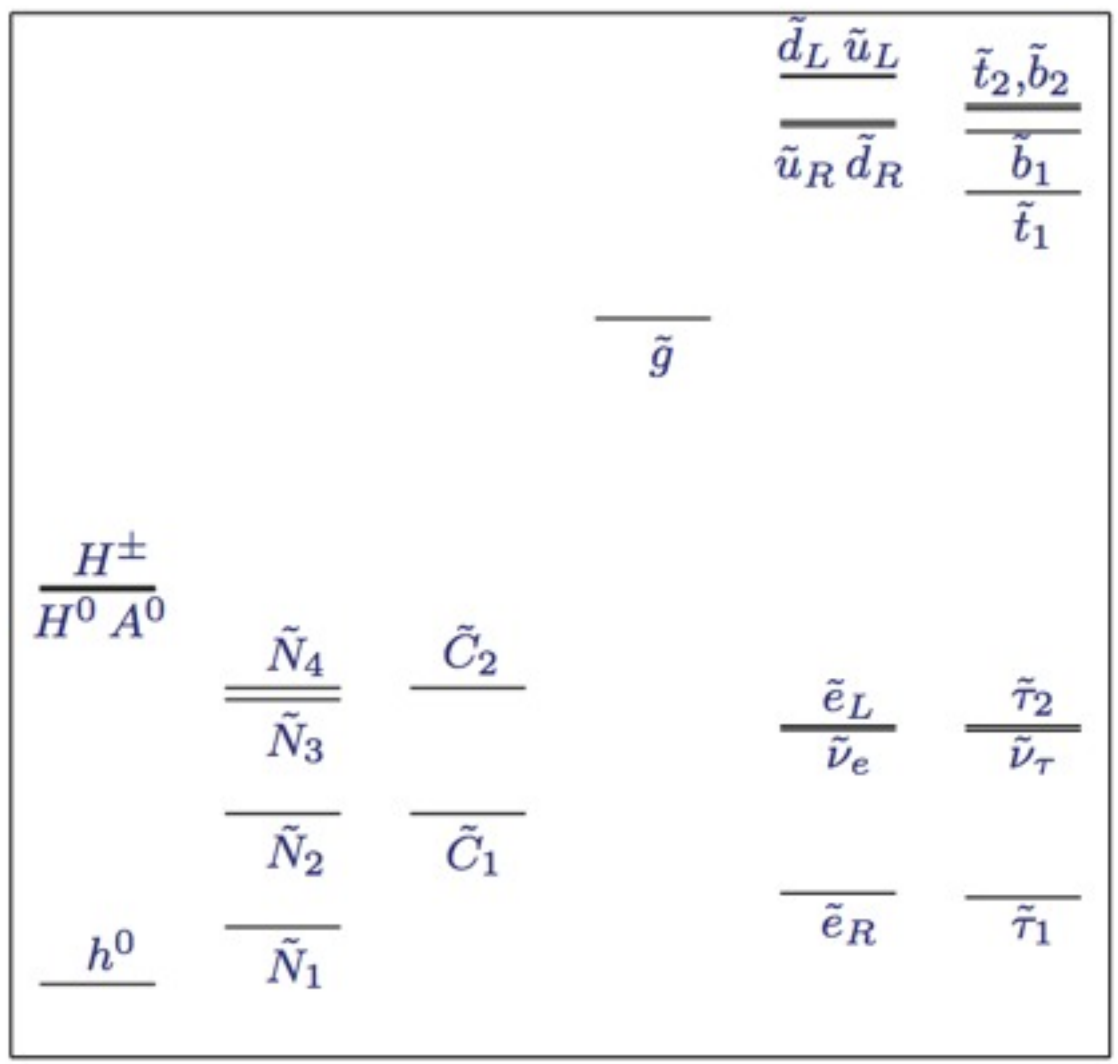
- Example gravity-mediated spectrum



[Martin]

MSSM SPECTRA

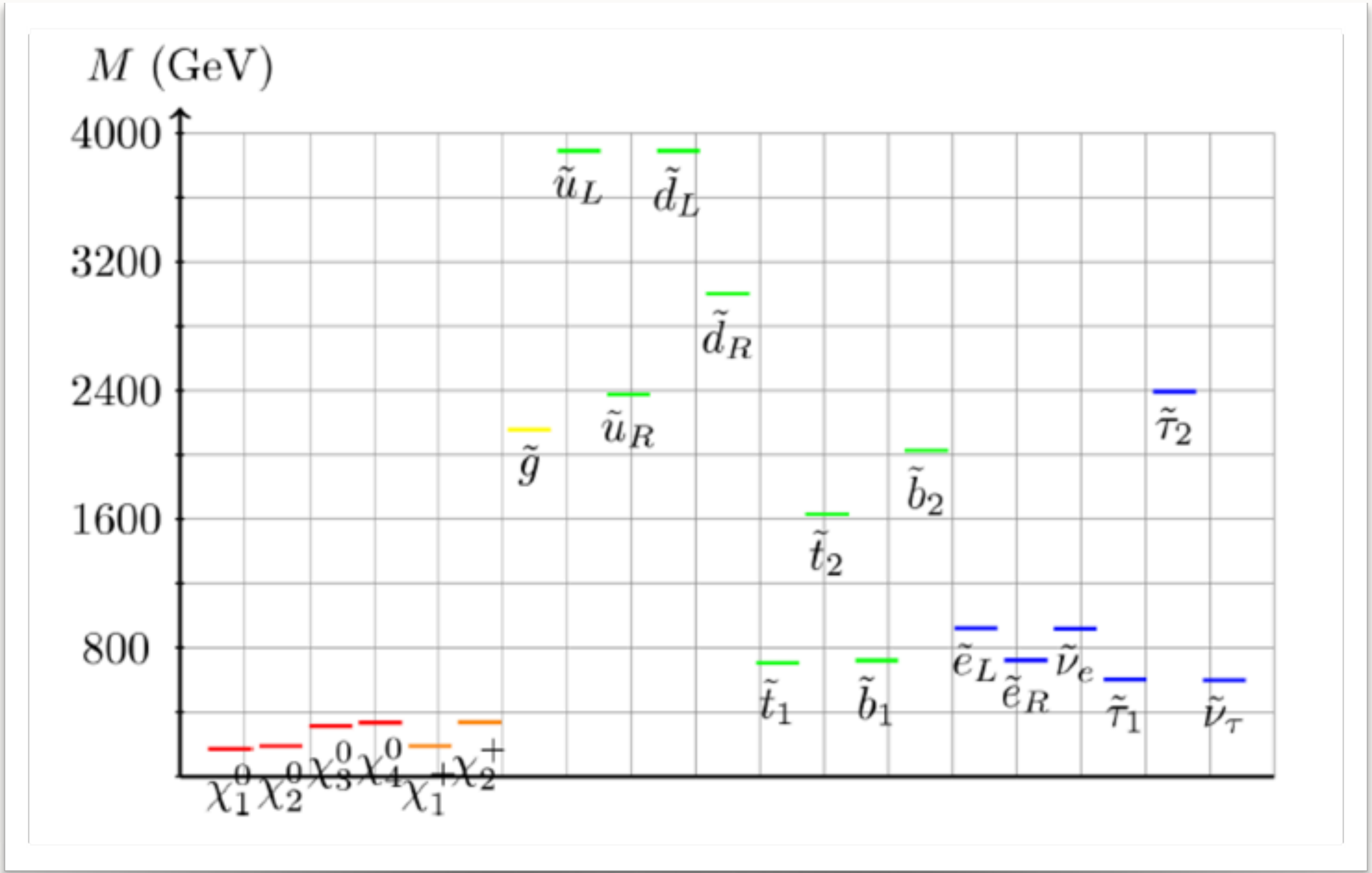
- Example gauge-mediated spectrum



[Martin]

MSSM SPECTRA

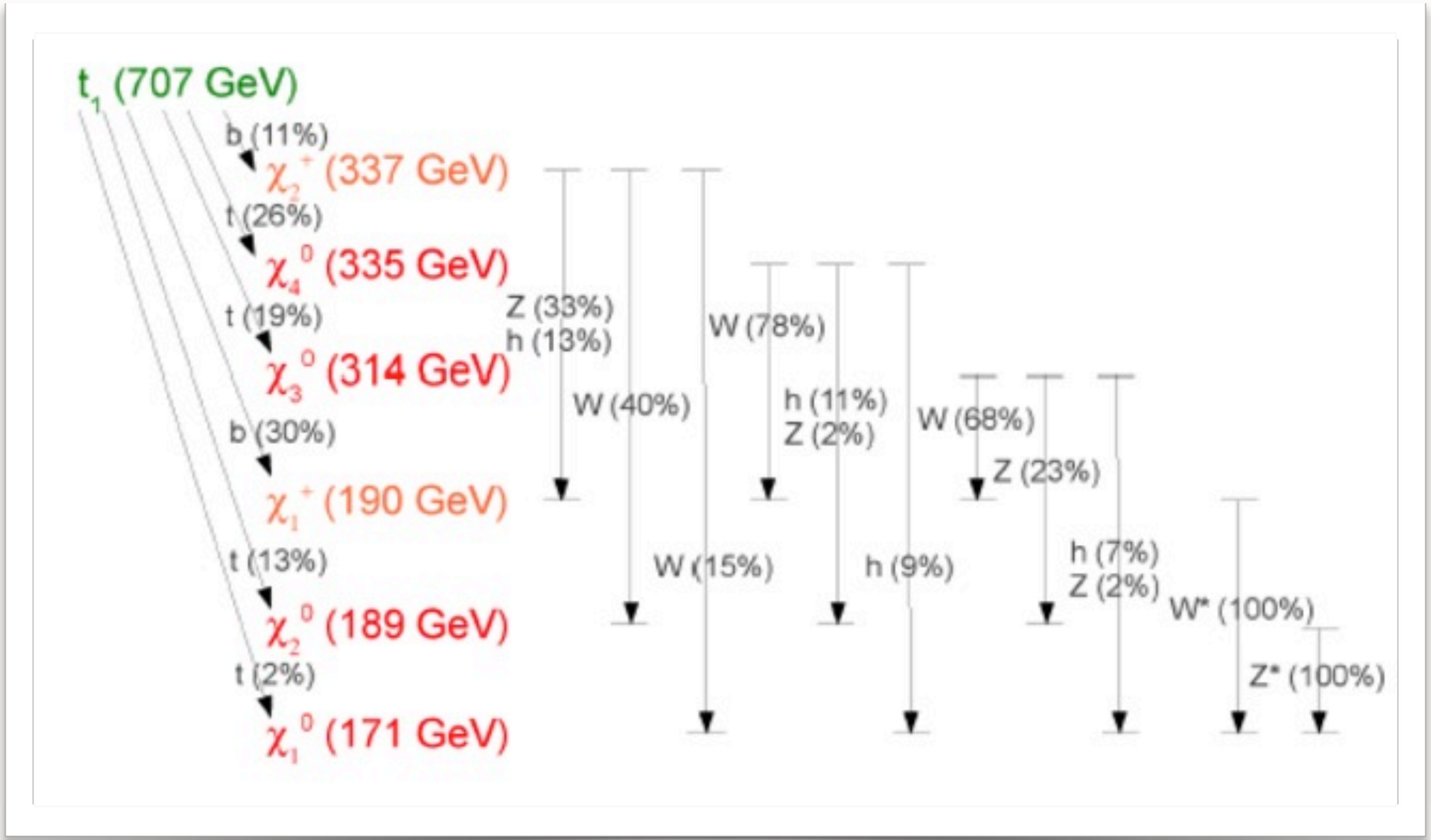
- Example bottom-up spectrum



[Cahill-Rowley, Hewett, Ismail, Rizzo]

MSSM SPECTRA

- Rich spectrum means complicated decays:



[Cahill-Rowley, Hewett, Ismail, Rizzo: 1407.4130]

MSSM SIGNALS

- Two questions to end on:
  - Given enormous complexity and variability of signals, how can we best design SUSY searches at colliders?
  - What should we make of lack of BSM signals so far?