# Signs of a Hidden Sector from Supersymmetry(s)

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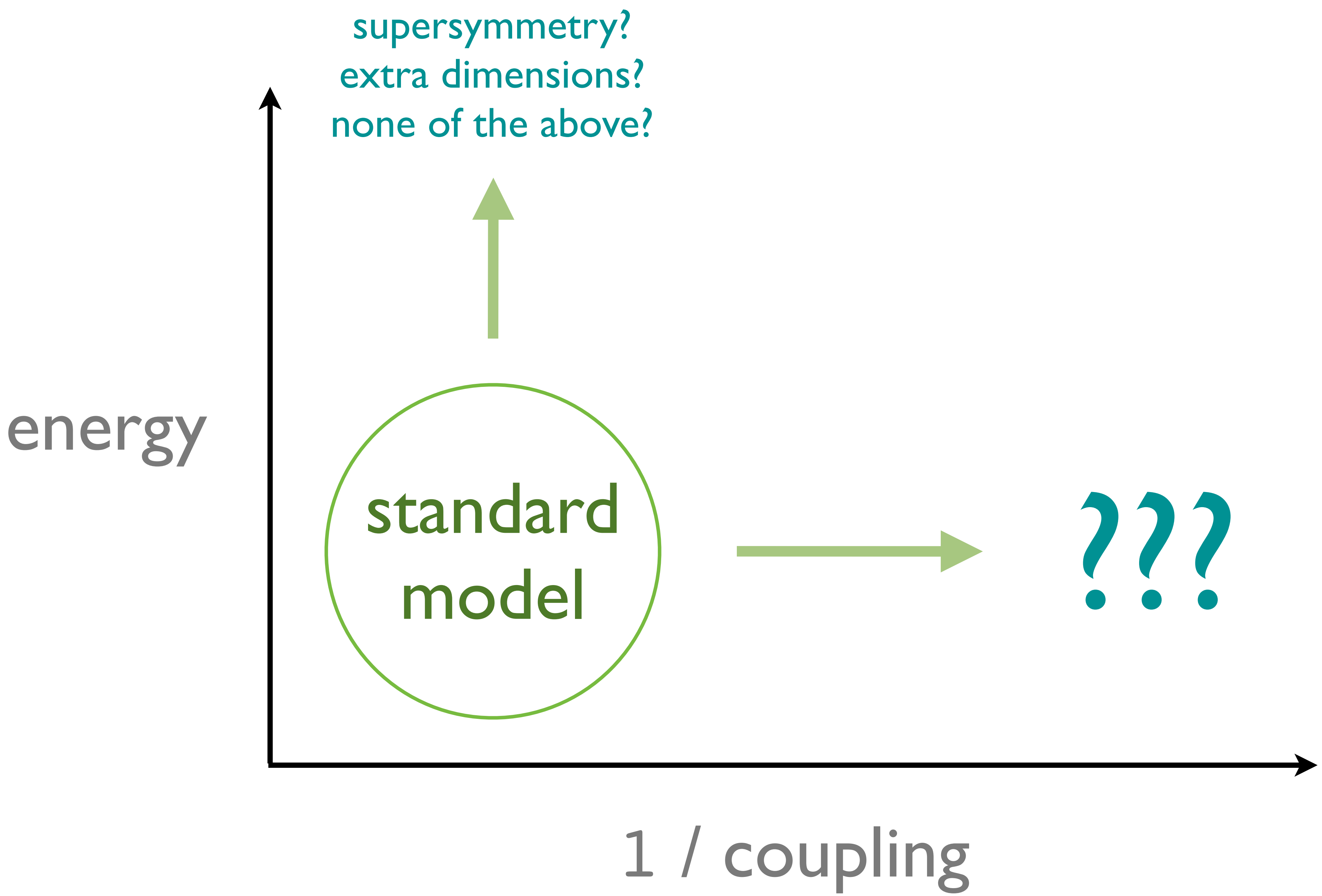
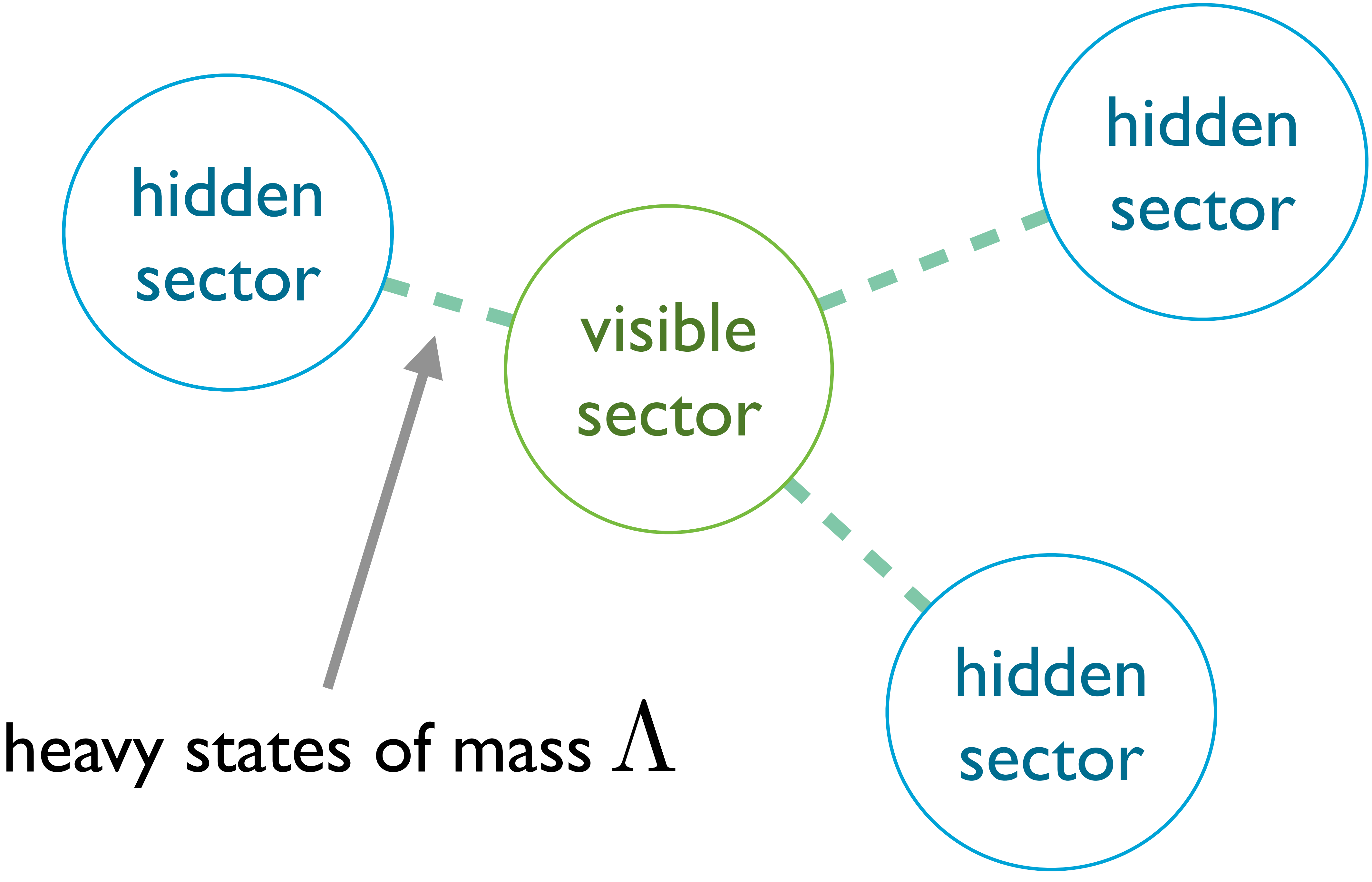
C.C., Nomura (1008.5153)
C.C., Mardon, Nomura, Thaler (1004.4637)
C.C., Nomura, Thaler (1002.1967)
C.C., Ruderman, Wang, Yavin (0902.3246)

# motivations

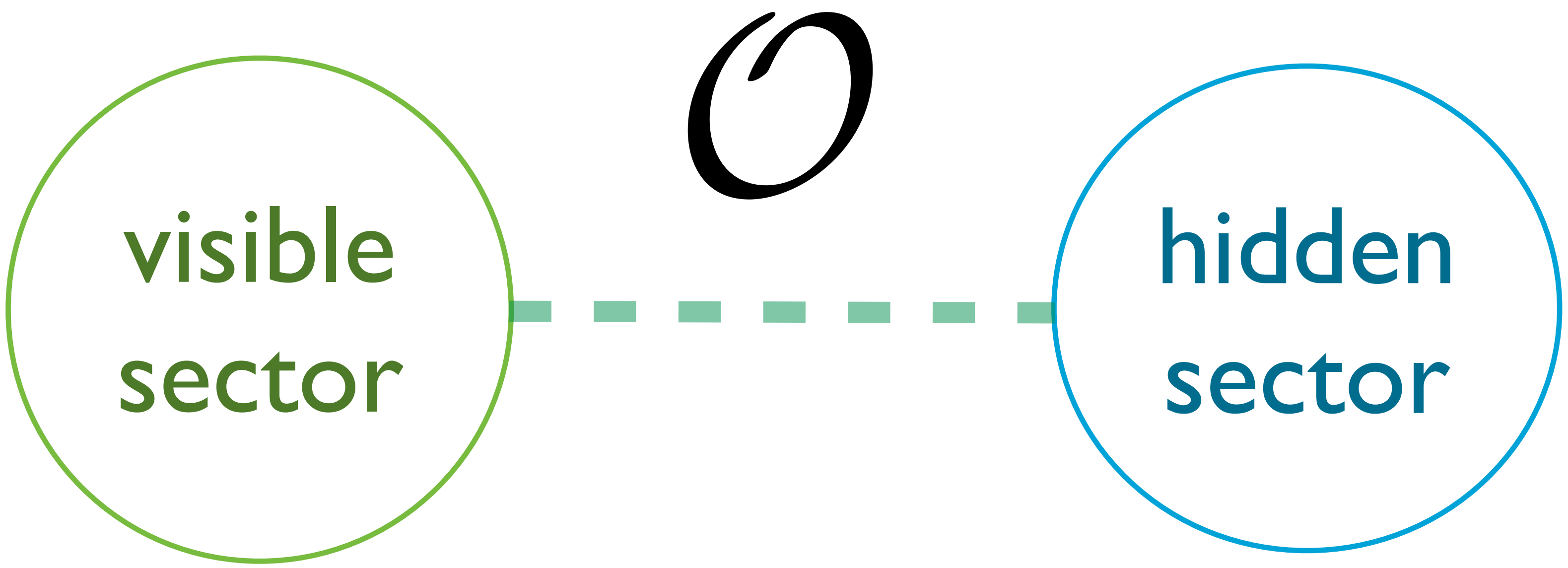
# sideways physics



# hidden worlds?



# a tale of two sectors




$\phi, \psi, F_{\mu\nu}$ $\qquad$ $\phi', \psi', F'_{\mu\nu}$

Why should we expect physics as $\Lambda \to \infty$ ?

# not quite hidden sector?

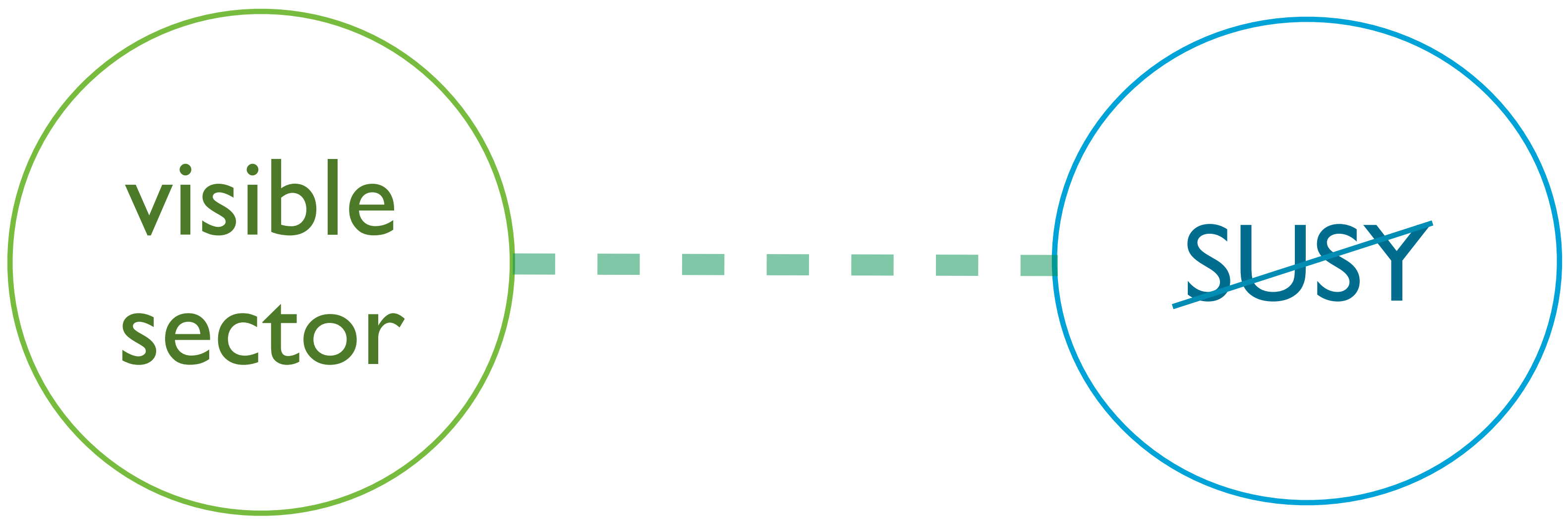
Signs of a hidden sector may be expected at low energies if there exist

a) Shared symmetries (UV). B or L number. Spacetime symmetries? Goldstini Portal.

b) Marginal Portal Operators (IR). Do not decouple at low energies. Kinetic Portals.

# goldstini portal

# the SUSY template




Our intuitions about SUSY phenomenology are dictated by a simplifying assumption:

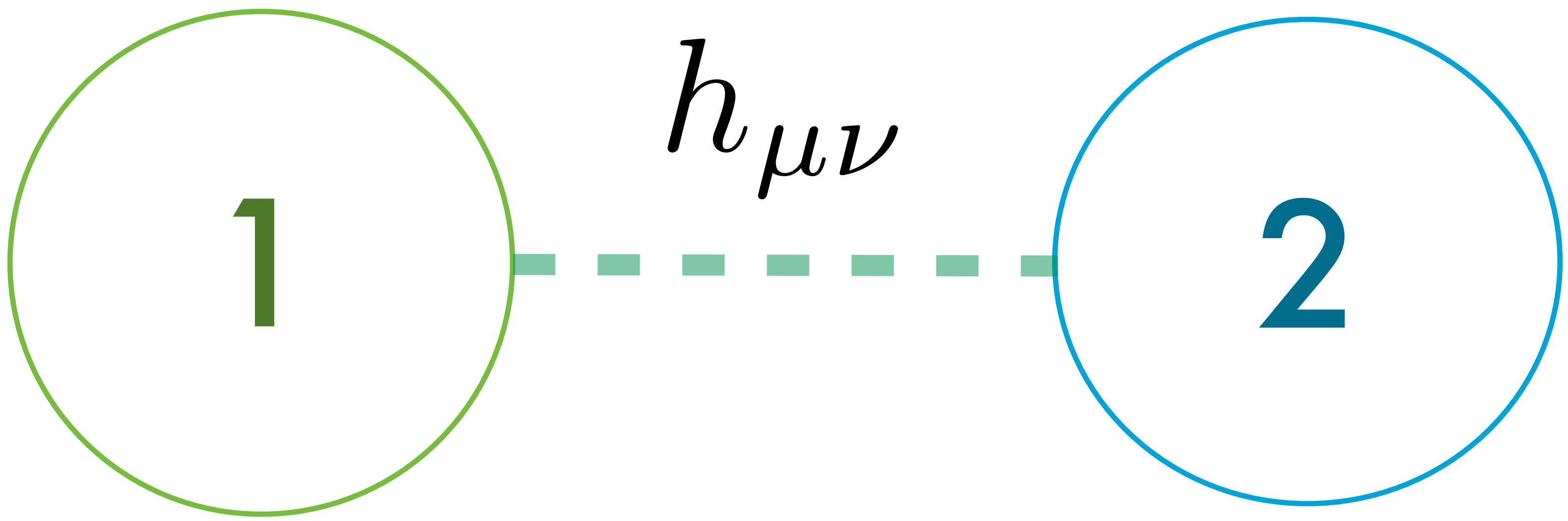
SUSY breaking arises from a single source.

# enhanced spacetime symmetries


Consider two decoupled sectors. Momentum is separately conserved due to sequestering, so

$$\text{Poincare} \overset{\text{decouple}}{\longrightarrow} \text{Poincare}_1 \otimes \text{Poincare}_2$$

# adding gravity




Gravity explicitly breaks the enhanced symmetry down to the diagonal,

$$\text{Poincare}_1 \otimes \text{Poincare}_2 \stackrel{\text{gravity}}{\longrightarrow} \text{Poincare}$$

# enhanced SUSY

If our world is supersymmetric, then likewise

$$\mathrm{SUSY} \stackrel{\mathrm{decouple}}{\rightarrow} \mathrm{SUSY}_1 \otimes \mathrm{SUSY}_2$$

where SUGRA preserves the diagonal combo.
Analogous reasoning applies to N sectors.

What about SUSY breaking???

# SUSY(s) breaking


$X_1 \ni \eta_1$ $\quad$ $X_2 \ni \eta_2$

If your favorite mechanism for SUSY breaking is natural, then it may be realized more than once! Here $F_1 \geq F_2$ w/o loss of generality.

# goldstone analogy

~~$U(1)_1$~~

$$f_1$$

~~$U(1)_2$~~

$$f_2$$

$$\phi_1 \ni \pi_1 \qquad \phi_2 \ni \pi_2$$

Here $U(1)_{diag}$ is gauged in analogy with SUGRA.

One goldstone eaten. One goldstone physical.

# super-higgs mechanism

Same is true for goldstini.

longitudinal gravitino

$$\begin{pmatrix} \eta_1 \\ \eta_2 \end{pmatrix} = \begin{pmatrix} \cos\theta & -\sin\theta \\ \sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} \tilde{G} \\ \zeta \end{pmatrix}$$

uneaten goldstino

where we have defined

$$\sin\theta = F_2/F_{\rm eff} \qquad F_{\rm eff} = \sqrt{F_1^2 + F_2^2}$$

# a special setup

~~SUSY~~$_1$ $F_1$

~~SUSY~~$_2$ $F_2$

~~SUSY~~$_3$ $F_3$

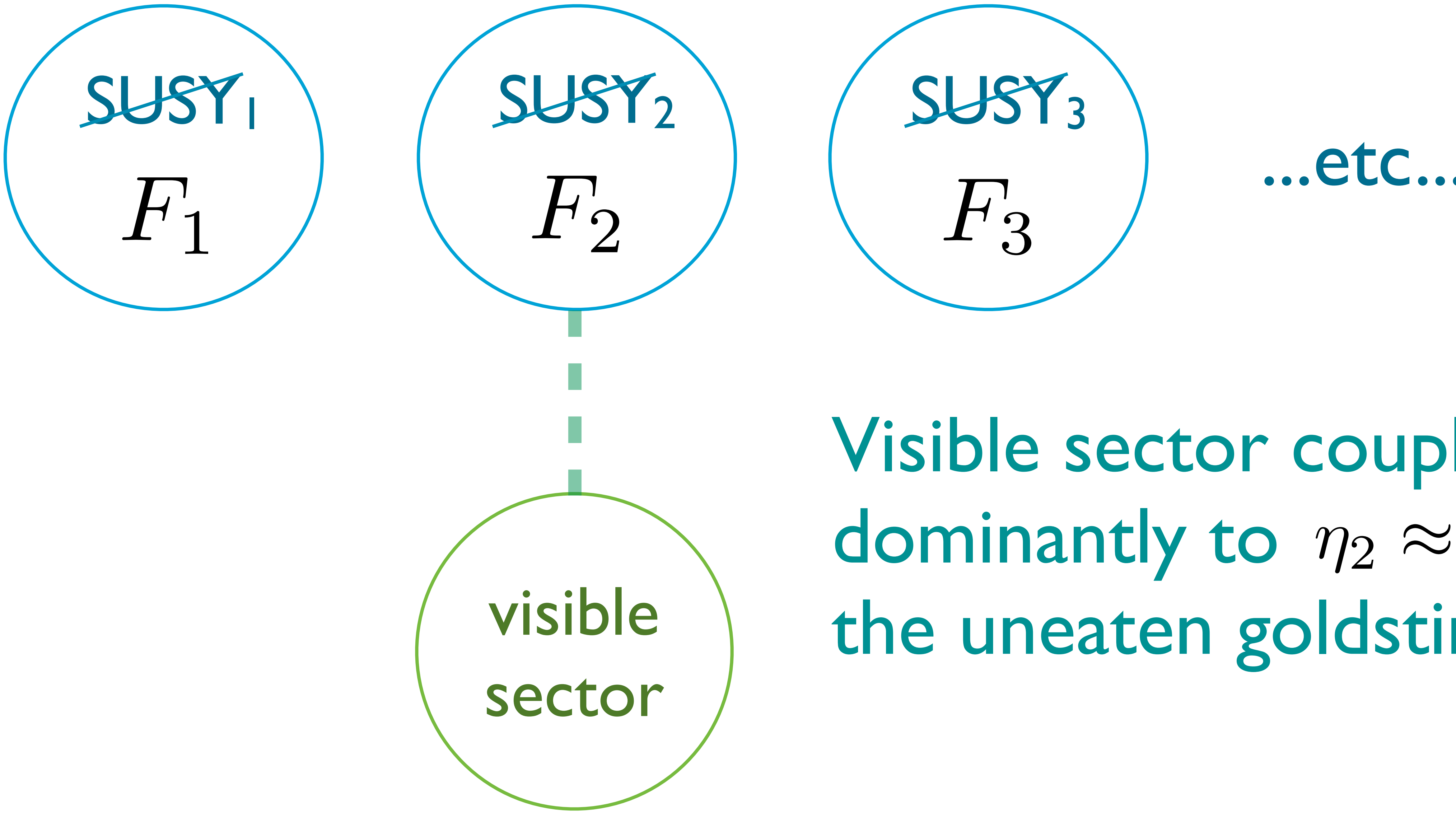
...etc...

visible sector

Conventional SUSY is a rather preferred scenario in which

$$\eta_1 \approx \tilde{G}$$

# a generic setup




Visible sector couples dominantly to $\eta_2 \approx \zeta$, the uneaten goldstino.

# rising tide lifts all goldstini

Goldstini are not massless!

$$m_\zeta = 2m_{3/2}$$

at tree level due to SUGRA effects. I claim that this mass relation

1) is fixed by SUGRA symmetries.

2) can substantially alter SUSY pheno.

# why $2m_{3/2}$?

The relation $m_\zeta = 2m_{3/2}$ can be derived via

a) Explicit Computation (Wess + Bagger).

b) Explicit Computation (Compensators).

c) Symmetry Arguments.

# lessons from goldstones

Goldstones are massless. Why?

$$\mathcal{L}_{\text{unit}} = \frac{1}{2} m^2 A_\mu^2$$

$$A_\mu \stackrel{\text{Stück.}}{\longrightarrow} A_\mu + \partial_\mu \pi / m$$

Because they are edible! Hence, for U(1)$^N$,

$$\mathcal{L} = \frac{1}{2} \sum_i \partial_\mu \pi_i \partial^\mu \pi_i + \ldots$$

# edible goldstini

Applying the same reasoning to goldstini,

$$\mathcal{L}_{\mathrm{unit}} = m_{3/2}\psi_\mu \sigma^{\mu\nu}\psi_\nu + \mathrm{h.c.}$$

$$\psi_\mu \overset{\mathrm{Stück.}}{\rightarrow} \psi_\mu + m_{3/2}^{-1}\partial_\mu \eta + \sigma_\mu \bar{\eta}$$

Hence, for SUSY$^{\mathrm{N}}$,

$$\mathcal{L} = \frac{1}{2}\sum_i (2m_{3/2})(\eta_i^2 + \bar{\eta}_i^2) + \ldots$$

# deviations from $2m_{3/2}$

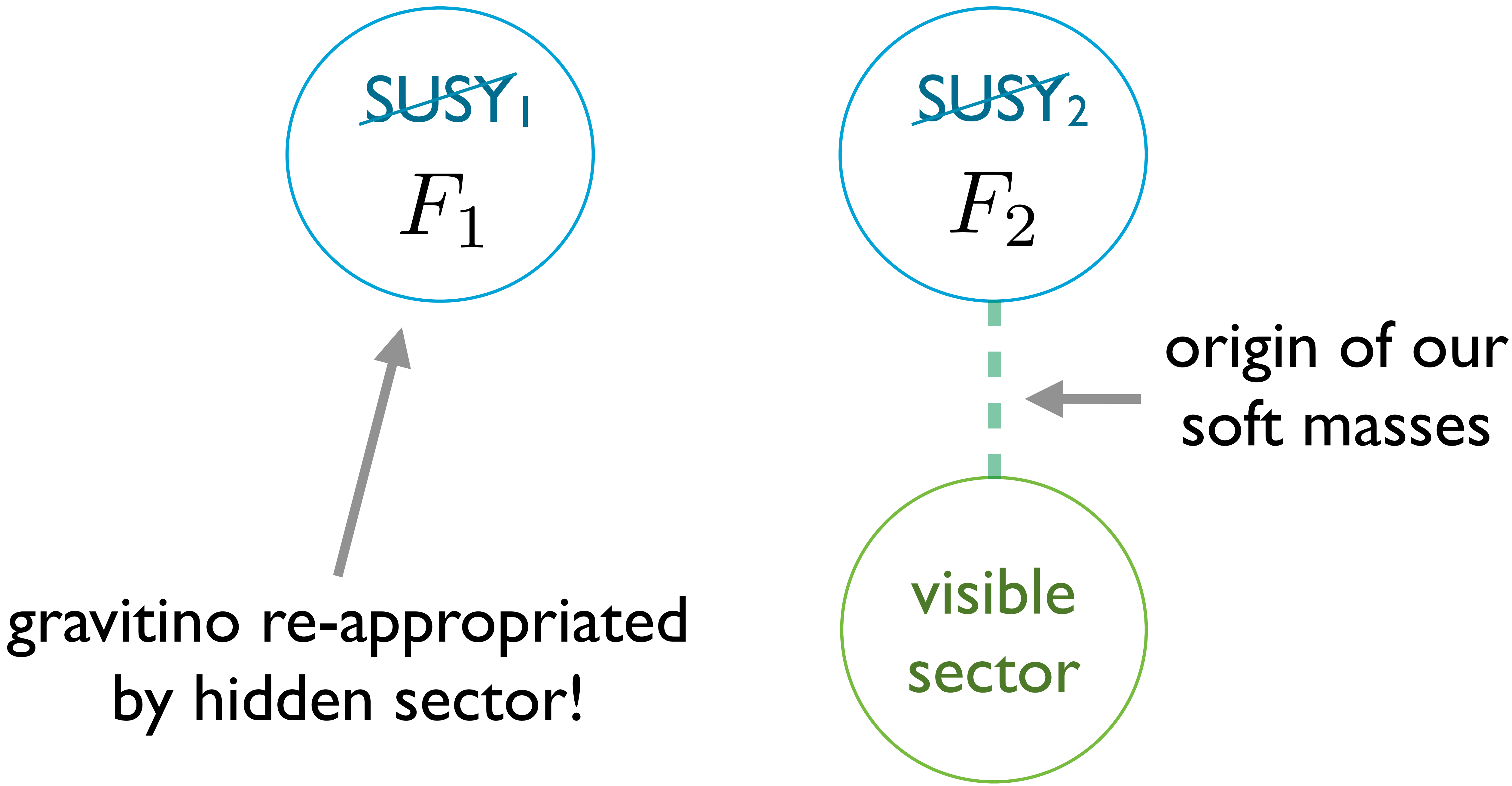
Corrections to $m_\zeta = 2m_{3/2}$ occur given

I) Non-sequestered Operators. Enhanced $SUSY^N$ explicitly broken.

II) Anomalous Dimensions / Warping. Large corrections to tree level approximation.

III) Gravitational SUSY Breaking. Add'l kinetic mixing of goldstini w/ gravitino.

# annexing the visible sector



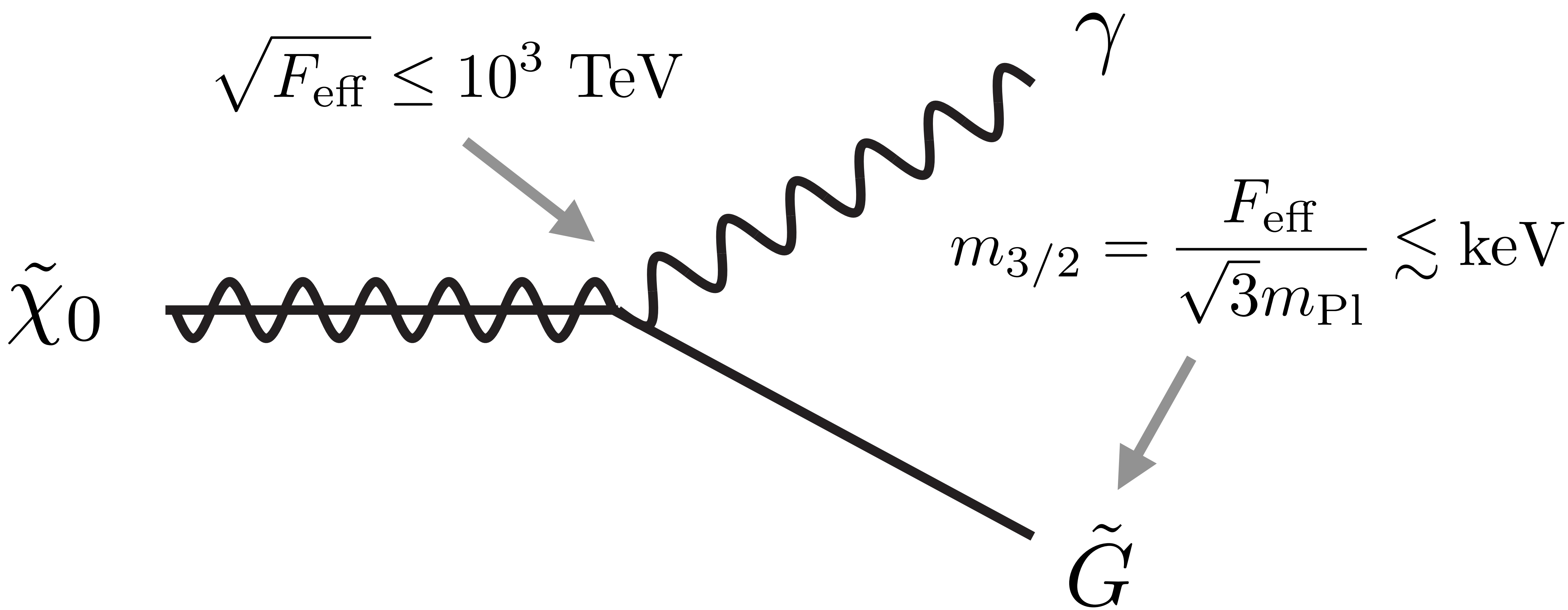
# bottom line

| field | coupling | mass |
| --- | --- | --- |
| $\tilde{G}$ | $\dfrac{\tilde{m}^2}{F_{\rm eff}}$ | $m_{3/2}$ $\left(=\frac{F_{\rm eff}}{\sqrt{3}M_{\rm Pl}}\right)$ |
| equivalent to heavy gravitino { $\zeta$ | $\dfrac{\tilde{m}^2}{F_2}$ | $2m_{3/2}$ $\left(=\frac{2F_{\rm eff}}{\sqrt{3}M_{\rm Pl}}\right)$ |

# goldstini pheno

# standard GMSB

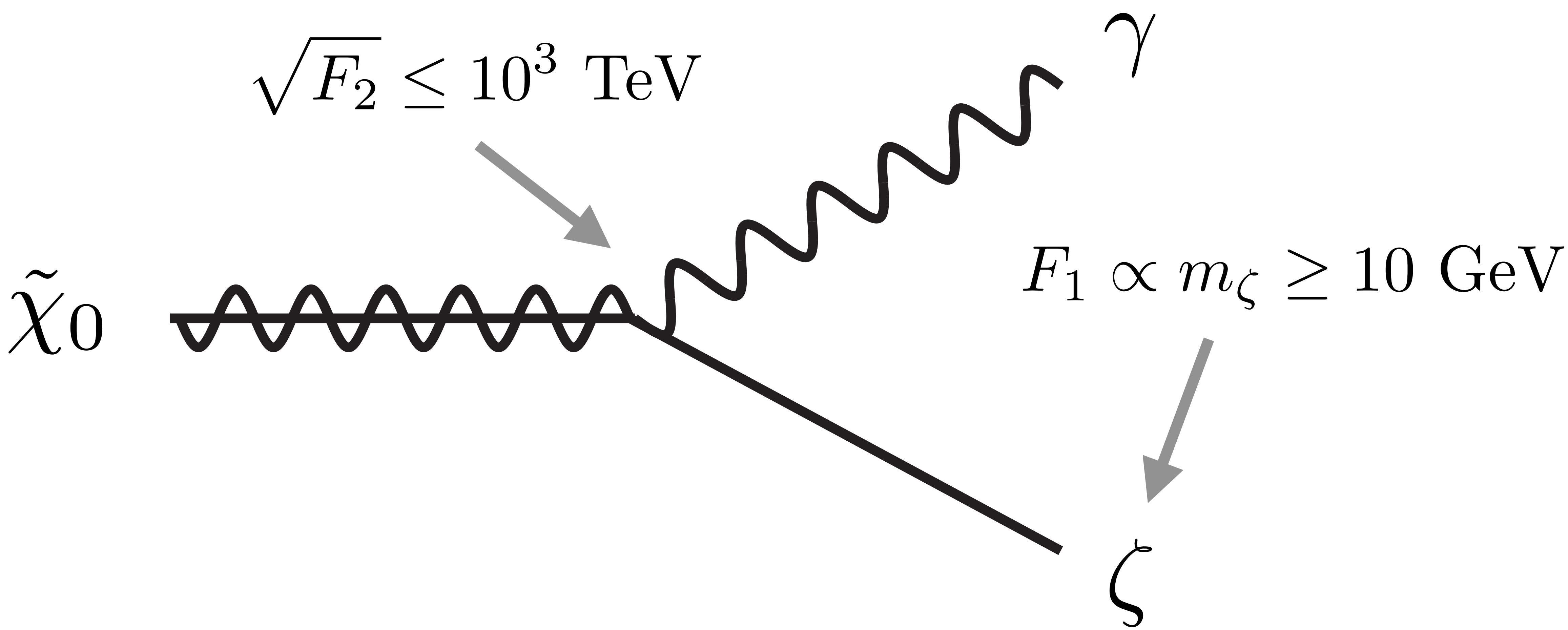
Lightest observable sparticle (LOSP) is a bino.




If decay is prompt, gravitino basically massless.

# anomalously heavy "gravitino"

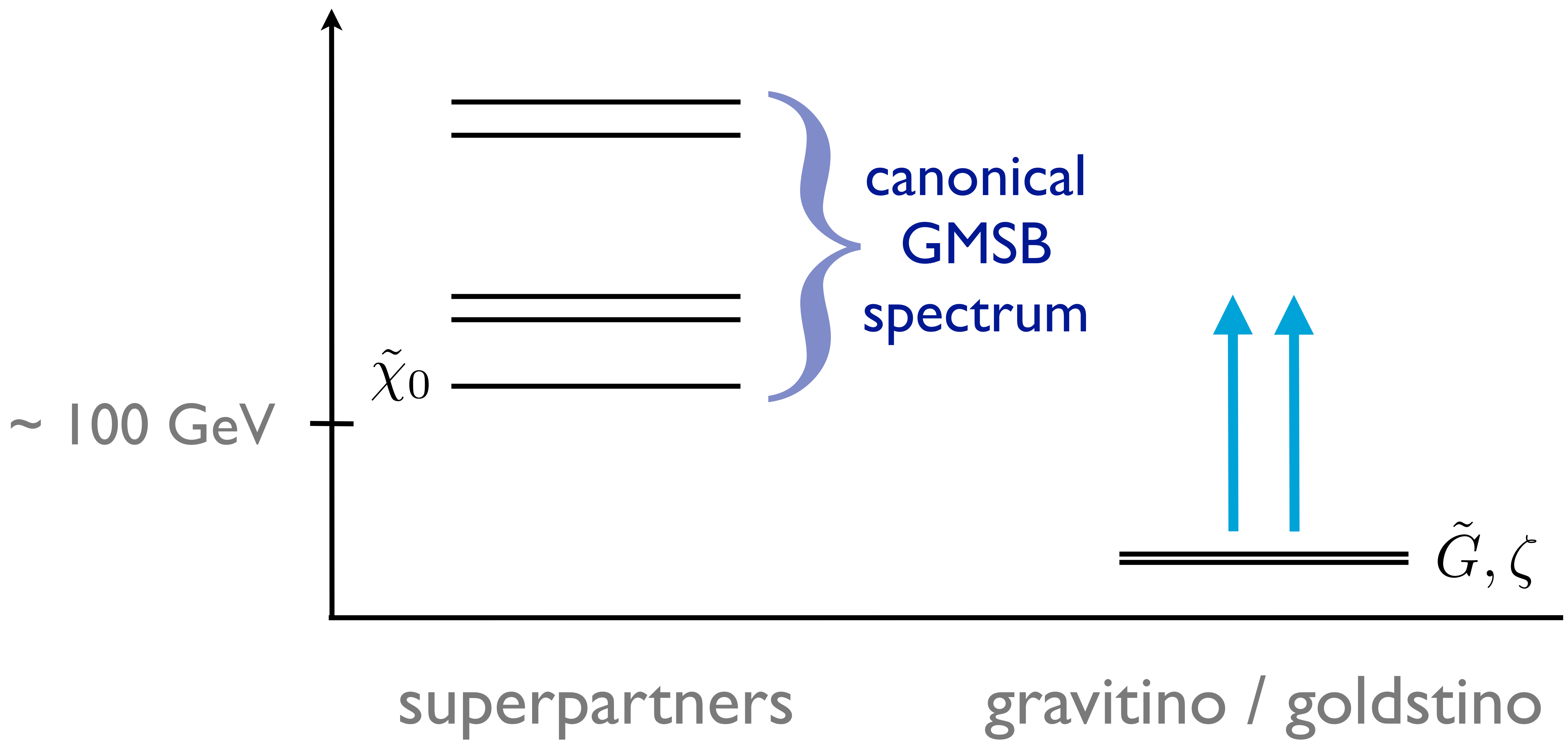
With goldstino there exists a dominant decay




yielding promptly decaying "heavy" gravitino.

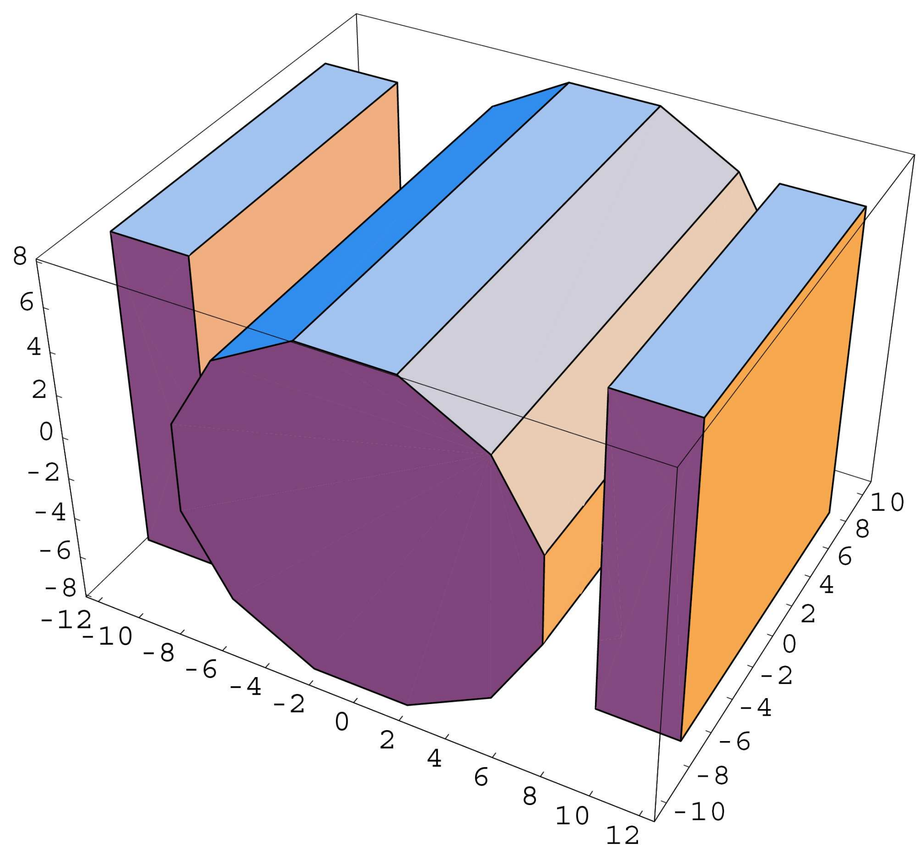
# GMSB w/ neutralino DM

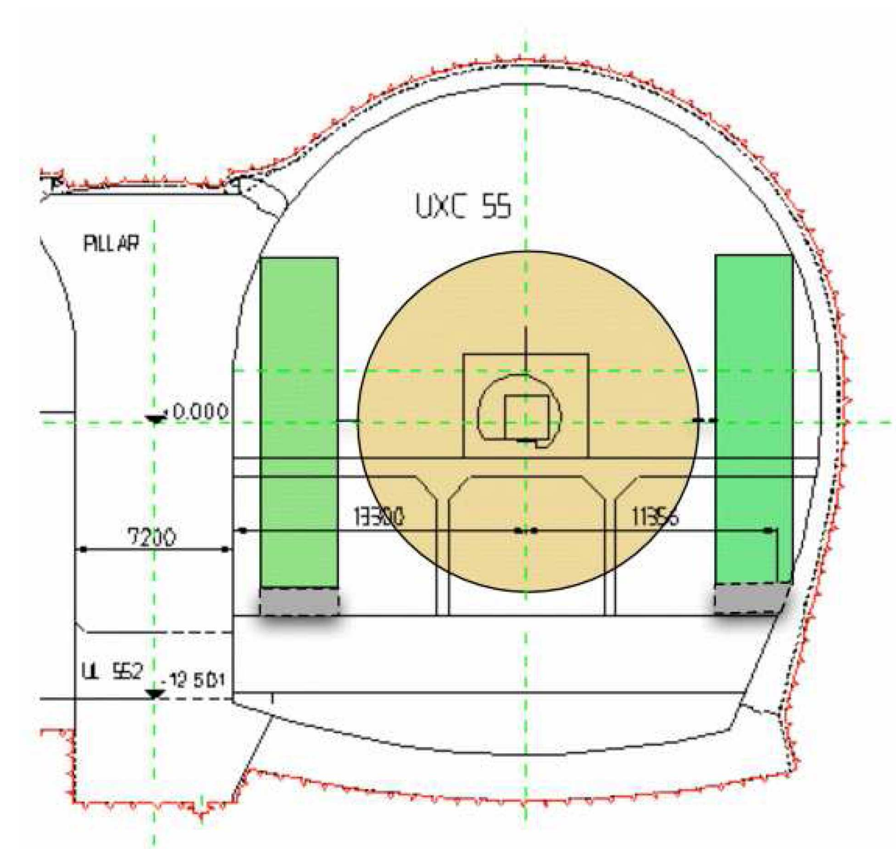
In fact, we can increase $F_1$ at fixed $F_2$ so,



# long-lived charged LOSP

If LOSP is charged and $\sqrt{F_2} \geq 10^3\ \mathrm{TeV}$, then these long-lived CHAMPs can be stopped!

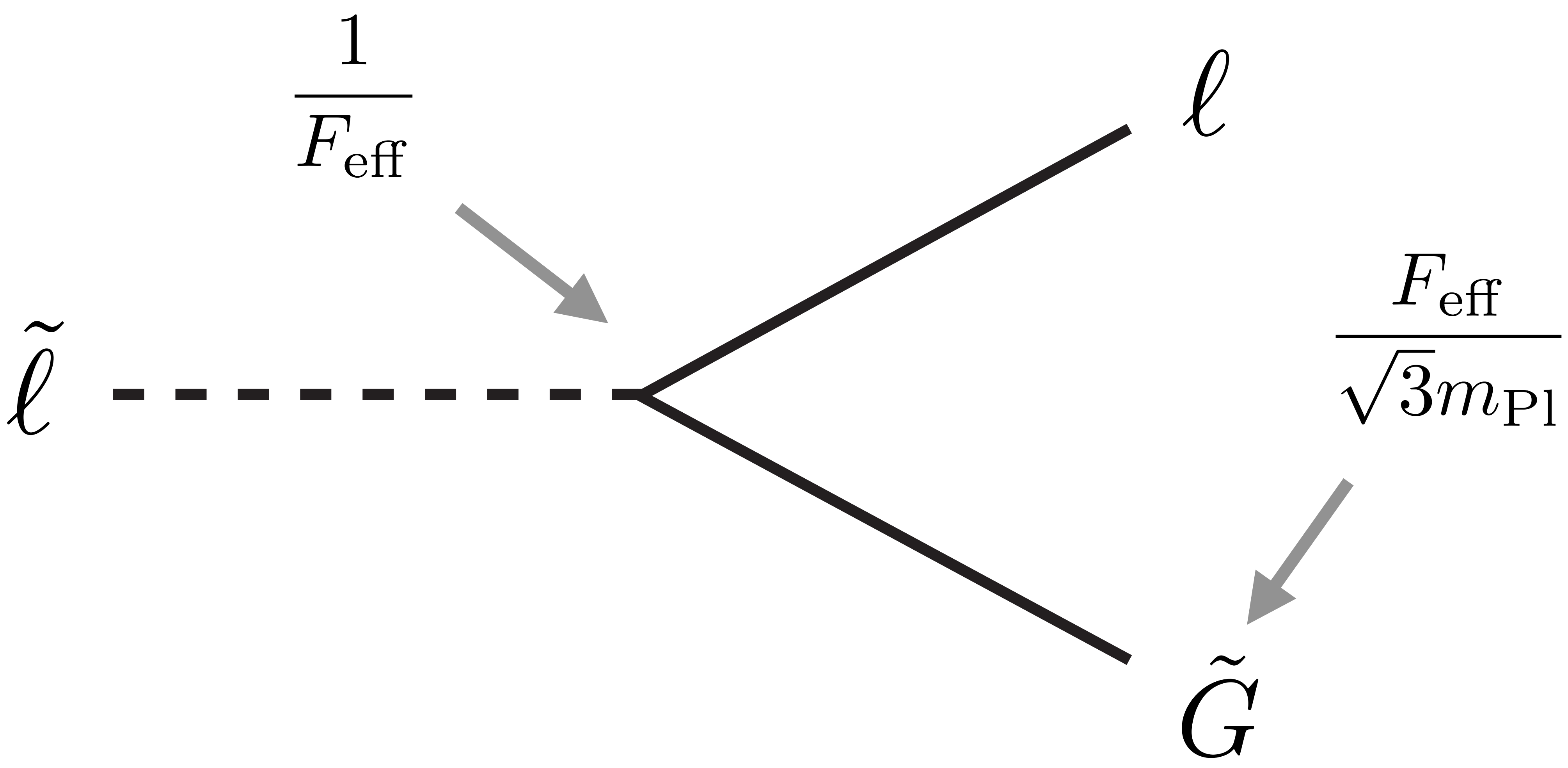





hep-ph/0612060 (Hamuguchi, Nojiri, de Roeck)
hep-ph/0506246 (Arvanitaki, Dimopoulos, Pierce, Rajendran, Wacker)
hep-ph/0409248 (Hamaguchi, Kuno, Nakaya, Nojiri)

# measure the Planck mass

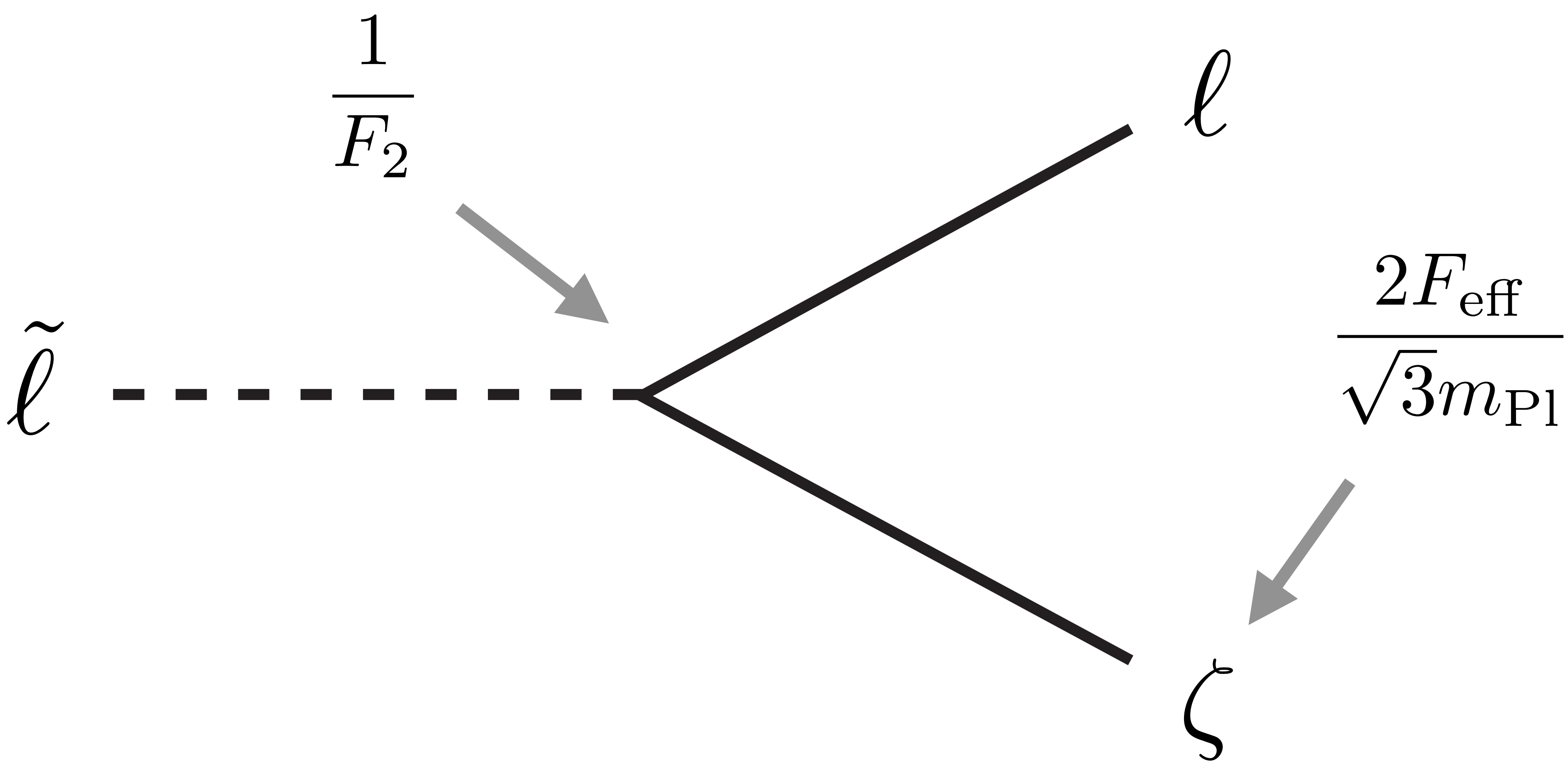
Given a conventional gravitino,




we can measure Planck mass.

# (mis)measure the Planck mass

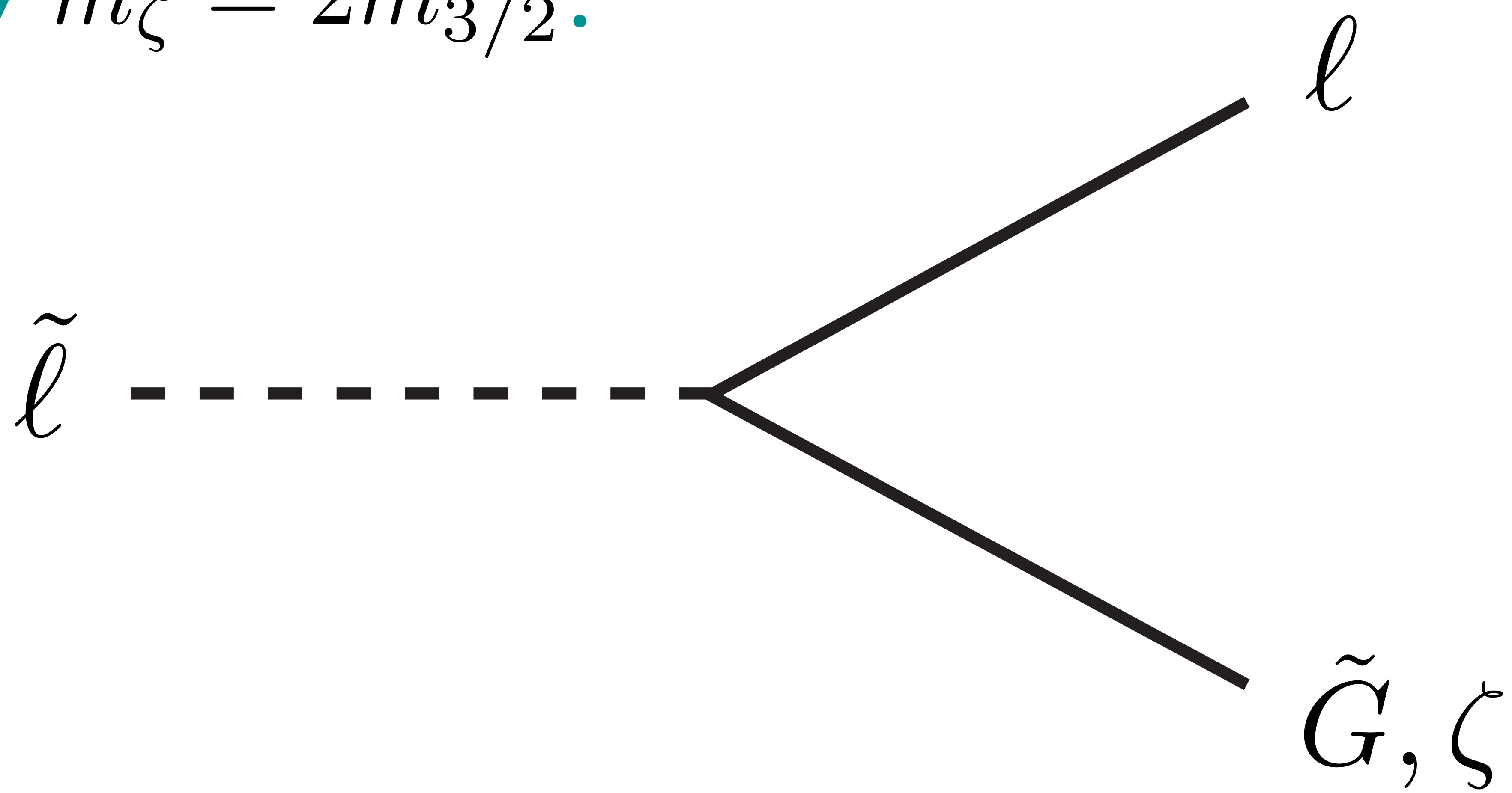
In contrast, if there exist goldstini, then




we mismeasure the Planck mass by $F_2/2F_{\text{eff}}$ .

# smoking gun of a hidden sector

If lucky, measure gravitino and goldstino and verify $m_\zeta = 2m_{3/2}$.




Discover sequestering + multi-SUSY breaking!

# kinetic portals

# kinetic mixing portals

$$\partial_\mu \phi^\dagger \partial^\mu \phi'$$

$$i\psi^\dagger \bar{\sigma}_\mu \partial^\mu \psi'$$

$$F_{\mu\nu} F^{\mu\nu\prime}$$

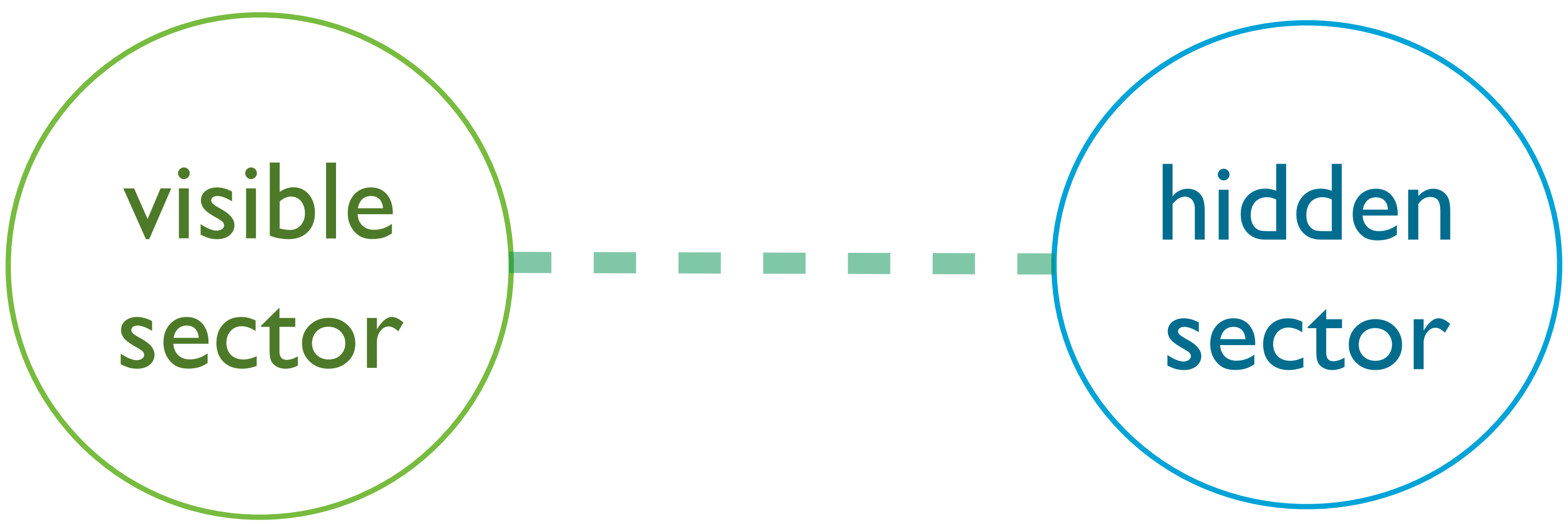
singlet portal (first two operators)

photon portal (last two operators)

Marginal op's motivated by EFT!

# photon portal

# hidden photon



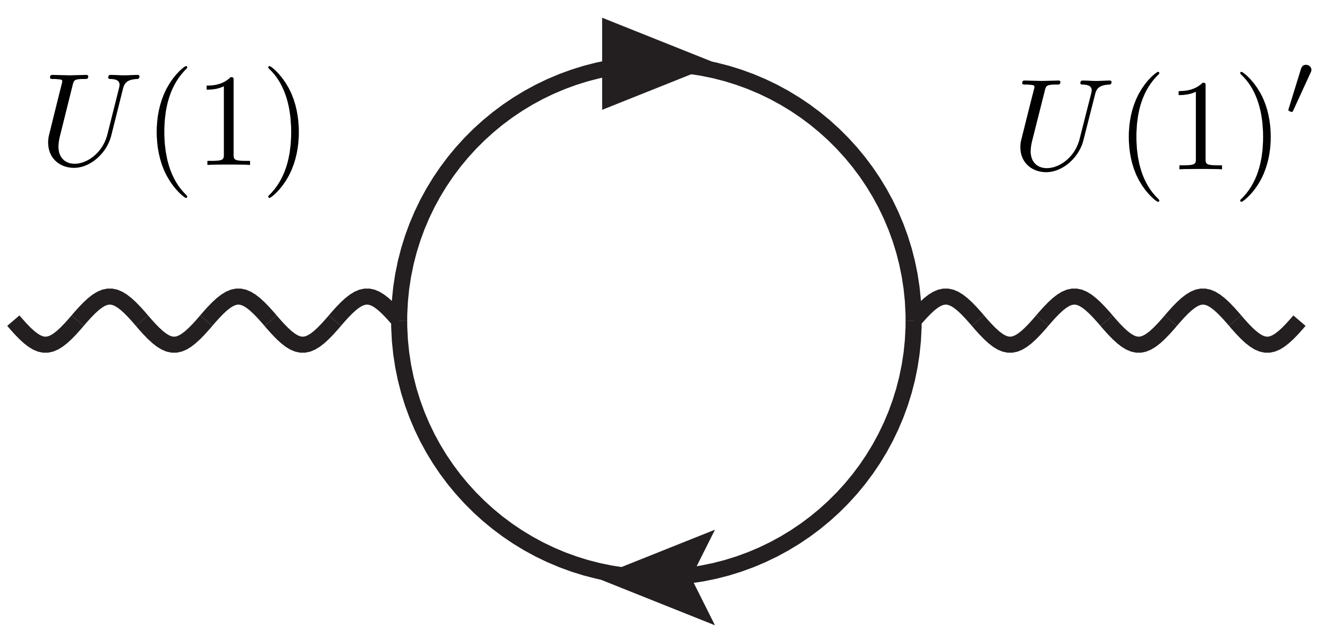

$A_\mu, J_\mu$ $\quad$ $A'_\mu, J'_\mu$

Assume existence of a hidden massive photon.

# photon portal

$$\epsilon\, F_{\mu\nu} F^{\mu\nu\prime}$$

is generated in UV by heavy particle loops.




$$\epsilon = \frac{gg'}{16\pi^2} \log \frac{M_1}{M_2}$$
$$\simeq 10^{-5} - 10^{-2}$$

# the Holdom effect

By eliminating the kinetic mixing via a shift,

$$A_\mu \to A_\mu + \epsilon A'_\mu$$

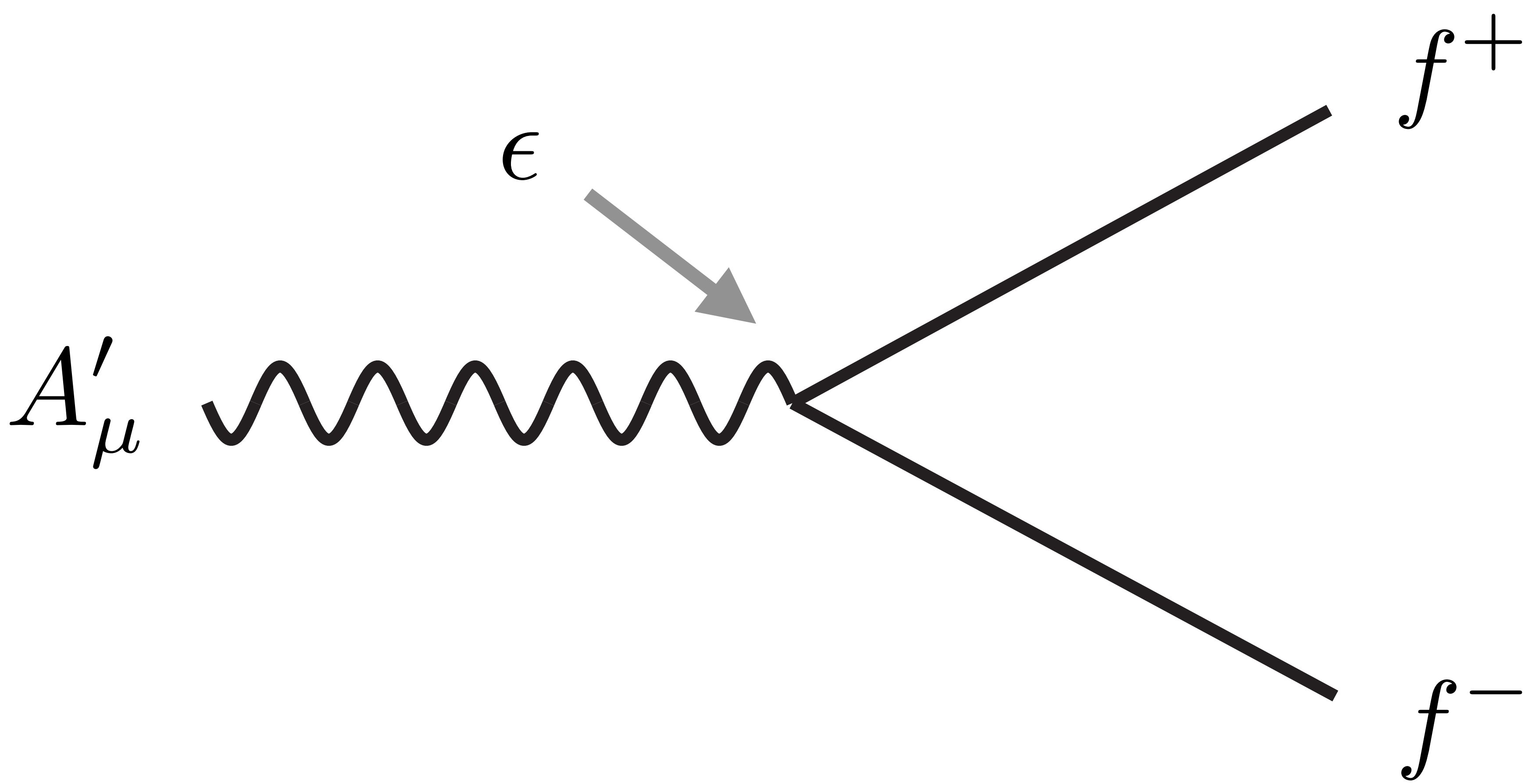
$$\mathcal{L} \to \mathcal{L} + \epsilon A'_\mu J^\mu$$

electric current couples to U(1)' vector boson

we induce a milli-charge interaction.

# the Holdom effect

Hence, the hidden photon decays visibly via




where $f^\pm$ is a quark or charged lepton.

# SUSY photon portal

$$\epsilon \int d^2\theta \, W_\alpha W^{\alpha\prime}$$

which in terms of components is

$$\epsilon \left( F_{\mu\nu} F^{\mu\nu\prime} + i\tilde{\lambda}^\dagger \bar{\sigma}_\mu \partial^\mu \tilde{\lambda}' + D D' \right)$$

"portal out" "portal in" "scale generation"

# scale generation

$$\epsilon \left(F_{\mu\nu}F^{\mu\nu\prime} + i\tilde{\lambda}^{\dagger}\bar{\sigma}_{\mu}\partial^{\mu}\tilde{\lambda}' + DD'\right)$$

Effective Fayet-Iliopolis term for U(1)':

$$\mathcal{L}_{\text{eff}} = \underbrace{\epsilon\langle D\rangle}_{} D'$$

$$= \epsilon g_Y v^2 \cos 2\beta$$

$$\simeq (0.1 - 5\ \text{GeV})^2$$

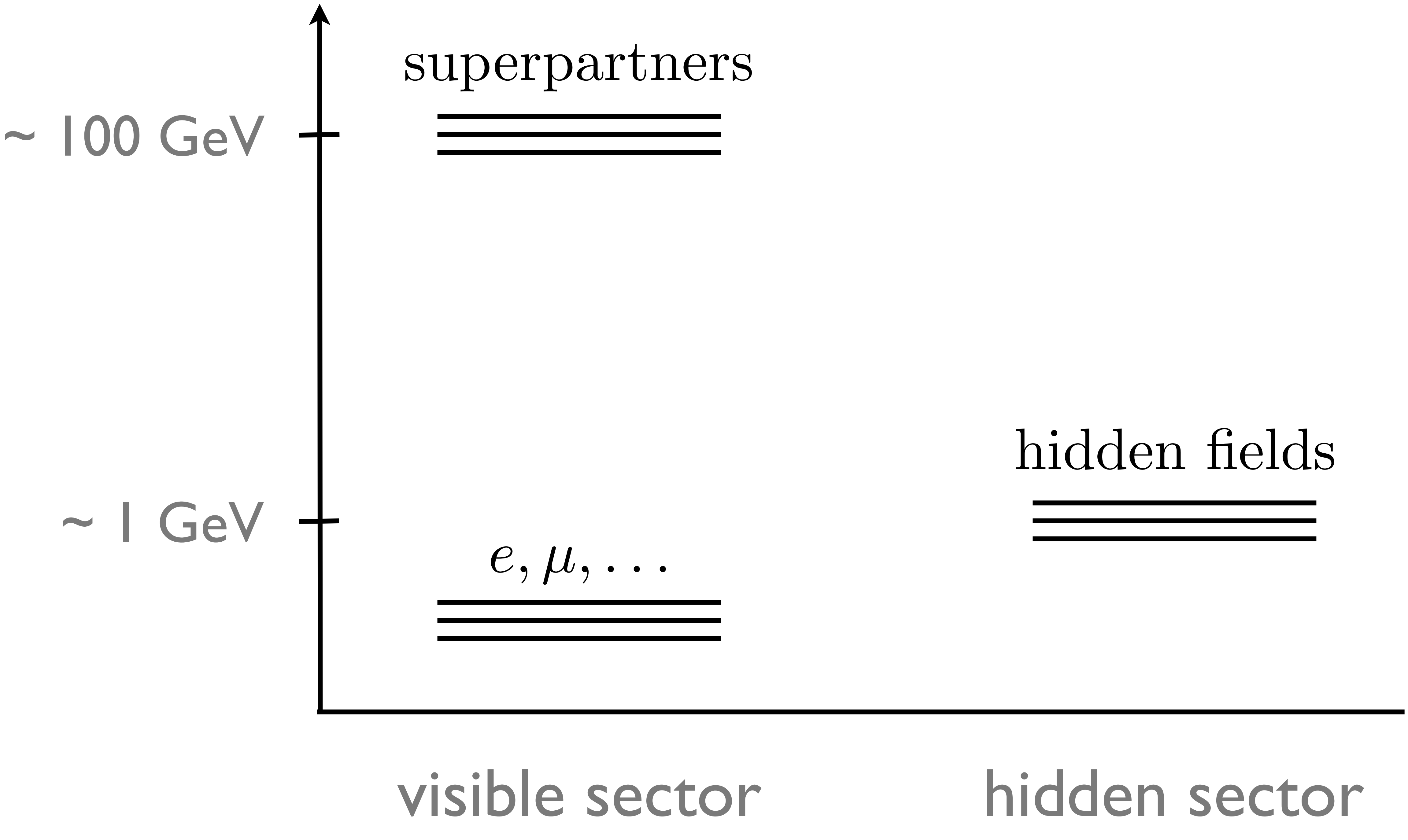
# scale generation

$$V_{\rm hid} = [g'(|h'|^2 - |h^{c\prime}|^2) + \epsilon\langle D\rangle]^2$$

Hidden higgs fields get vevs!

Modulo add'l scales (tree masses, ~~SUSY~~, etc), hidden sector acquires GeV scale spectrum.

# scale generation



# “portal in”

$$\epsilon \left( F_{\mu\nu} F^{\mu\nu\prime} + i\tilde{\lambda}^\dagger \bar{\sigma}_\mu \partial^\mu \tilde{\lambda}' + D D' \right)$$

Remove photino mixing via shift,

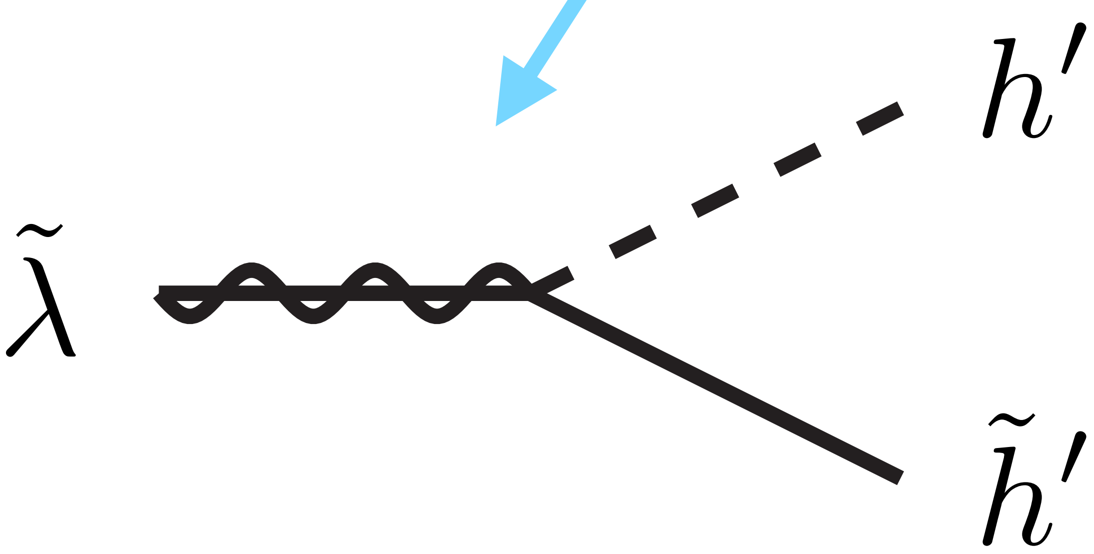
$$\tilde{\lambda}' \to \tilde{\lambda}' + \epsilon \tilde{\lambda}$$

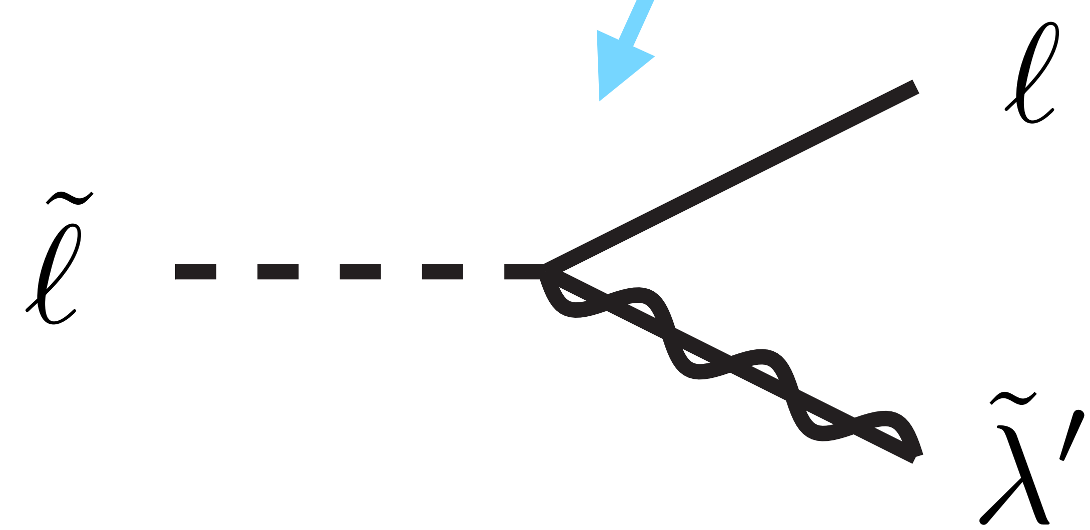
and induce a milli-charge interaction,

$$\Delta \mathcal{L} = \epsilon \tilde{\lambda} \tilde{J}' + \epsilon \mathcal{O}(m_{\tilde{\lambda}'}/m_{\tilde{\lambda}}) \tilde{\lambda}' \tilde{J}$$

# “portal in”

$$\Delta\mathcal{L} = \epsilon\tilde{\lambda}\tilde{J}' + \epsilon\mathcal{O}(m_{\tilde{\lambda}'}/m_{\tilde{\lambda}})\tilde{\lambda}'\tilde{J}$$



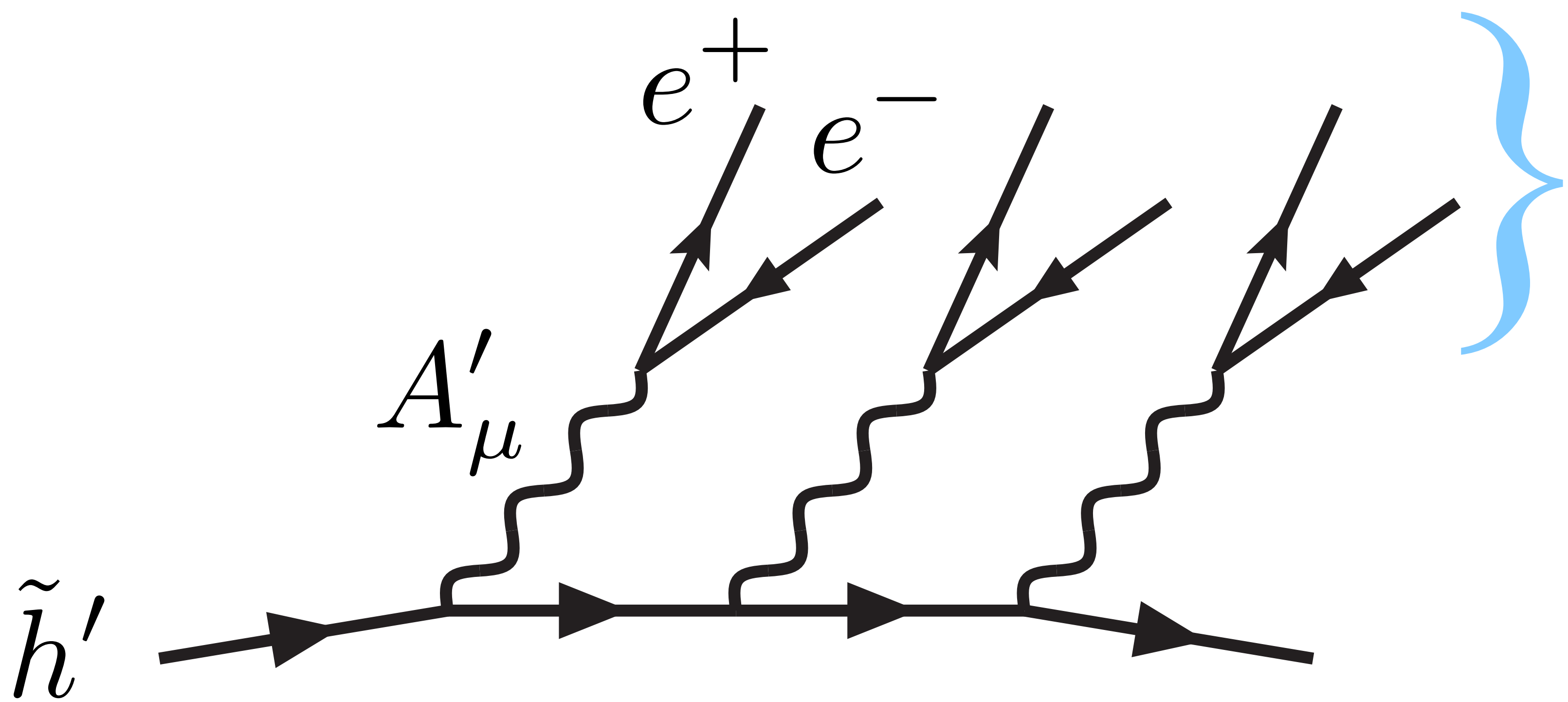




R-parity forces SUSY cascades into hidden sector.

# “portal out”

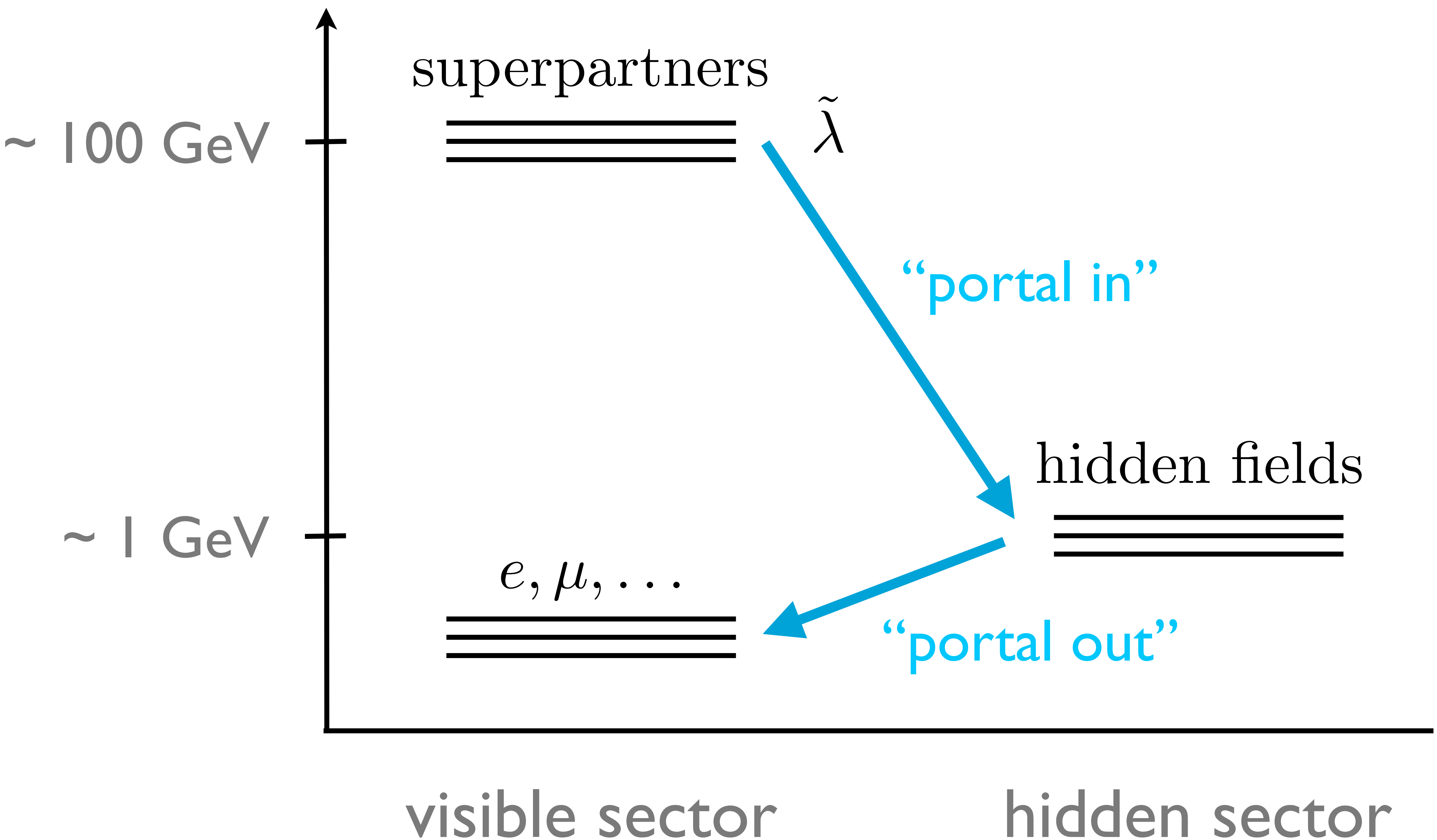
$$\epsilon\left(F_{\mu\nu}F^{\mu\nu\prime} + i\tilde{\lambda}^{\dagger}\bar{\sigma}_{\mu}\partial^{\mu}\tilde{\lambda}^{\prime} + DD^{\prime}\right)$$

Hidden cascades / bremstrahlung yield U(1)’ bosons that return as SM fields.




highly columnated “lepton jets” have invariant mass ~GeV

# in the collider...



# the 2nd possibility

Gauge singlets can kinetically mix.

So if $\epsilon \int d^2\theta \, W_\alpha W^{\alpha\prime}$ is allowed,

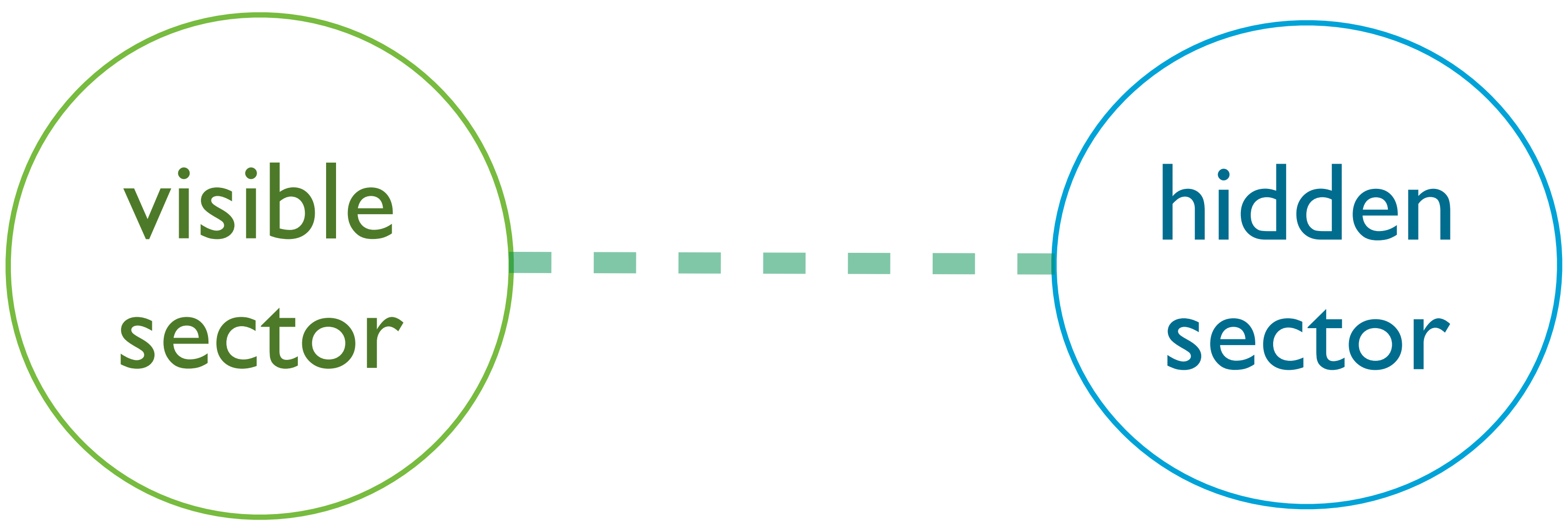
then why not $\epsilon \int d^4\theta \, S^\dagger S'$ ?

↑

The unexplored half of kinetic mixing space.

# singlet portal

# singlet-extended MSSM




$$S \ni s, \tilde{s} \qquad\qquad S' \ni s', \tilde{s}'$$

S couples to the visible sector via $W = \lambda S H_u H_d$.

# singlet portal

$$\epsilon \int d^4\theta \; S^\dagger S'$$

which in terms of components is

$$\epsilon \left( \partial_\mu s^\dagger \partial^\mu s' + i\tilde{s}^\dagger \bar{\sigma}_\mu \partial^\mu \tilde{s}' + F_S^\dagger F_{S'} \right)$$

"portal out" "portal in" "scale generation"

# scale generation

$$\epsilon \left(\partial_\mu s^\dagger \partial^\mu s' + i\tilde{s}^\dagger \bar{\sigma}_\mu \partial^\mu \tilde{s}' + F_S^\dagger F_{S'}\right)$$

Effective Polonyi term for S':

$$\mathcal{L}_{\rm eff} = \underbrace{\epsilon \langle F_S^\dagger \rangle}_{} F_{S'}$$

$$= \epsilon \lambda v^2 \sin 2\beta + \ldots$$

$$\simeq (0.1 - 100\ \mathrm{GeV})^2$$

# scale generation

For example, the superpotential

$$W_{\rm hid} = \kappa' S'^3/3$$

induces hidden sector symmetry breaking.

$$V_{\rm hid} = |\kappa' s'^2 + \epsilon\langle F_S\rangle|^2$$

# "portal in"

$$\epsilon\left(\partial_\mu s^\dagger \partial^\mu s' + i\tilde{s}^\dagger \bar{\sigma}_\mu \partial^\mu \tilde{s}' + F_S^\dagger F_{S'}\right)$$

Remove singlino mixing via shift,

$$\tilde{s}' \to \tilde{s}' + \epsilon \tilde{s}$$

and induce the interaction,

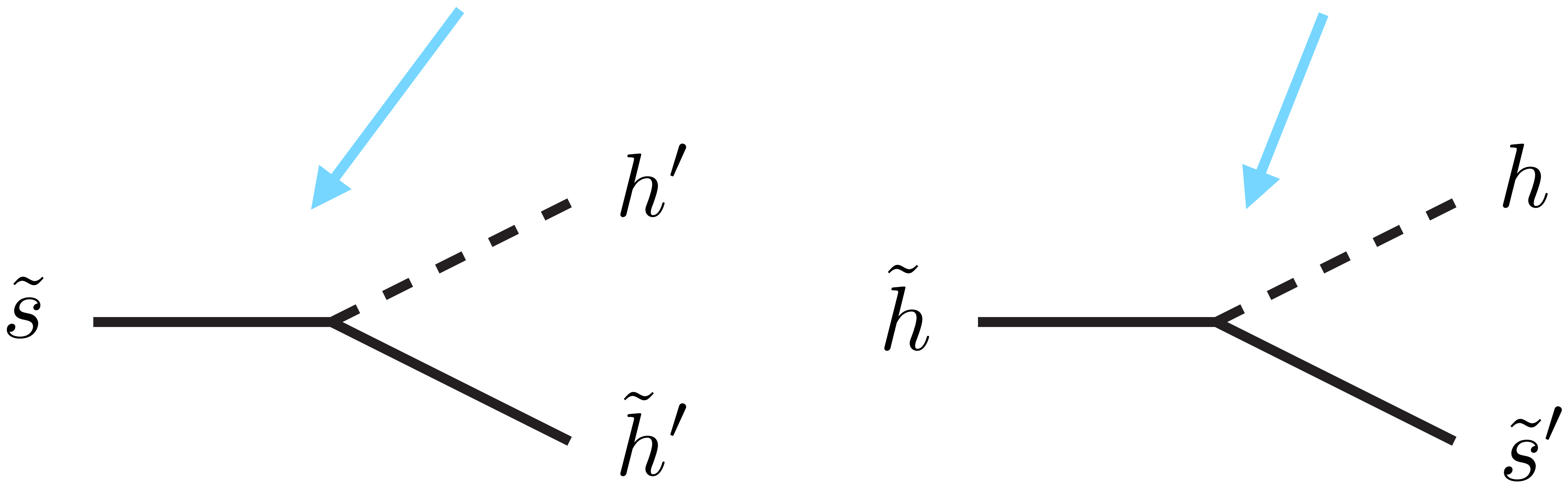
$$\Delta\mathcal{L} = \epsilon \tilde{s} \tilde{J}' + \epsilon \mathcal{O}(m_{\tilde{s}'}/m_{\tilde{s}}) \tilde{s}' \tilde{J}$$

$$\tilde{J} \equiv \partial\mathcal{L}/\partial\tilde{s}$$

$$\tilde{J}' \equiv \partial\mathcal{L}/\partial\tilde{s}'$$

# “portal in”

$$\Delta\mathcal{L} = \epsilon \tilde{s}\tilde{J}' + \epsilon\mathcal{O}(m_{\tilde{s}'}/m_{\tilde{s}})\tilde{s}'\tilde{J}$$




R-parity forces SUSY cascades into hidden sector.

# “portal in”

Since hidden sector couples via $W = \lambda S H_u H_d$,
“portal in” is associated with higgs prod!

$$\frac{\#\text{ of SUSY events with } h}{\#\text{ of SUSY events}} \approx O(10^{-2} - 1)$$

2-body decays prop to higgs vev associated with
3-body decays with physical higgs plus phase space.

# “portal out”

$$\epsilon \left(\partial_\mu s^\dagger \partial^\mu s' + i\tilde{s}^\dagger \bar{\sigma}_\mu \partial^\mu \tilde{s}' + F_S^\dagger F_{S'}\right)$$

Remove singlet mixing via shift,

$$s' \to s' + \epsilon s$$

and induce the interaction,

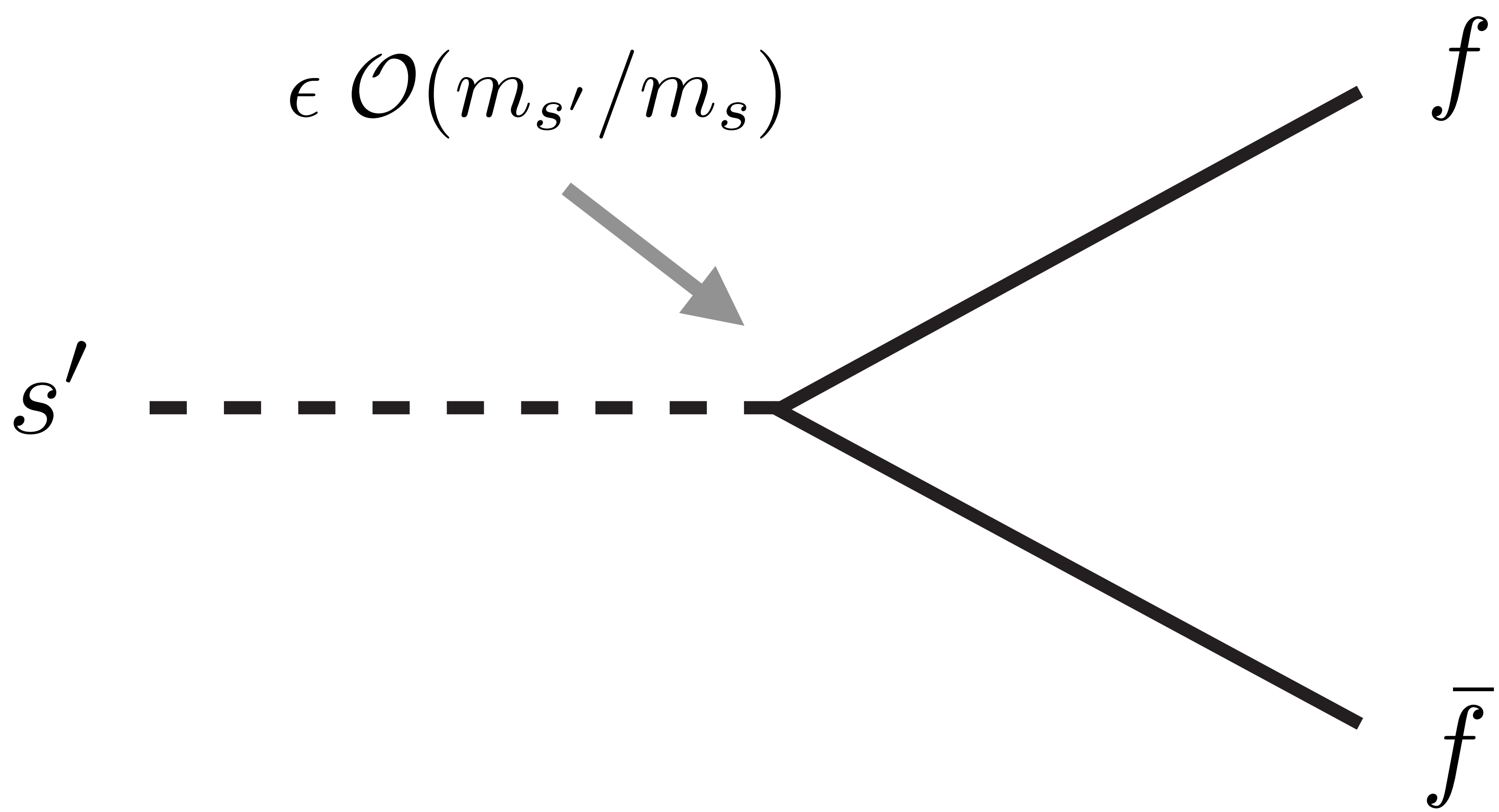
$$\Delta\mathcal{L} = \epsilon s J' + \epsilon \mathcal{O}(m_{s'}/m_s) s' J$$

$$J \equiv \partial\mathcal{L}/\partial s$$

$$J' \equiv \partial\mathcal{L}/\partial s'$$

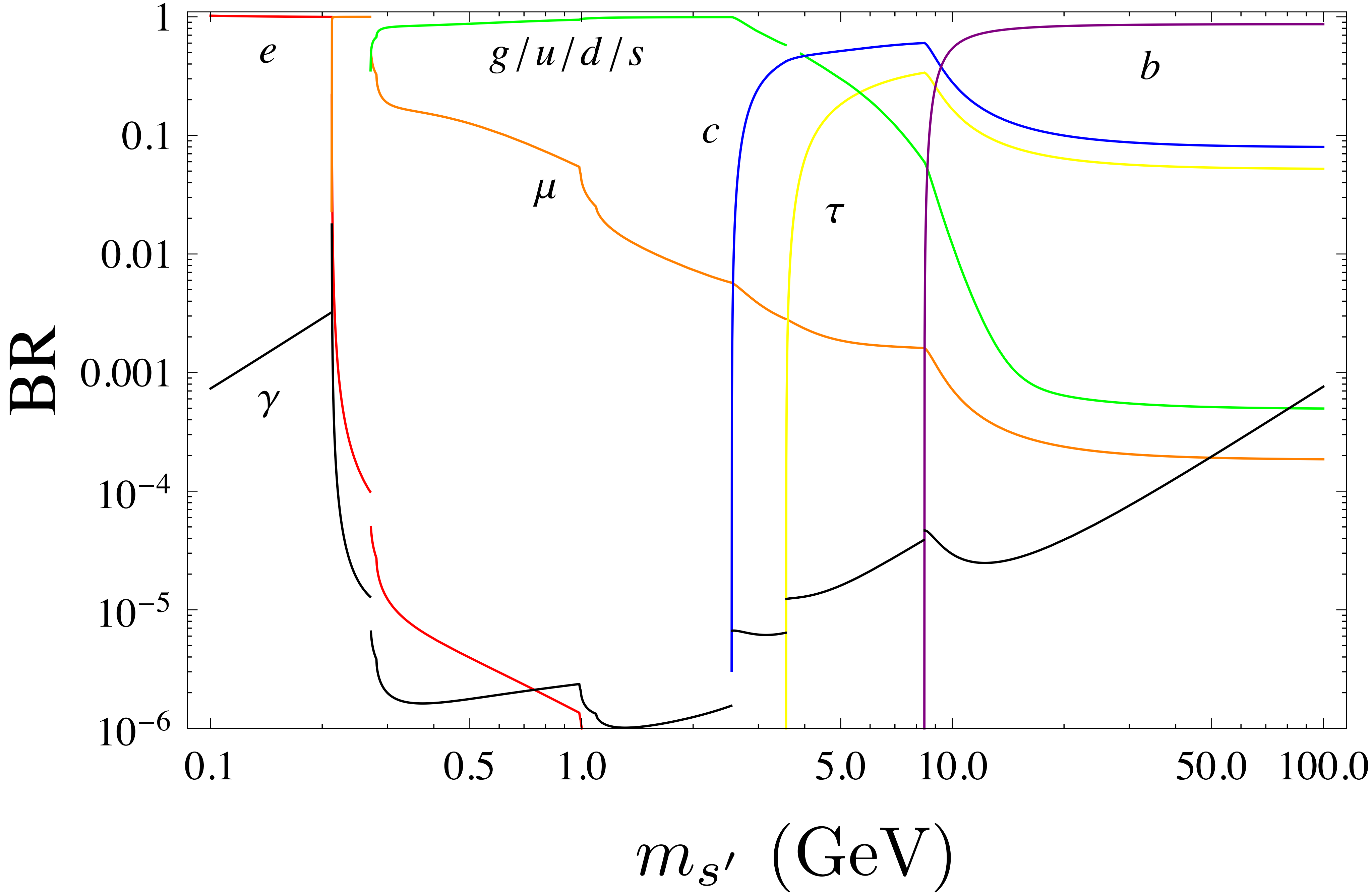
# “portal out”

Hence, the hidden singlet decays visibly via



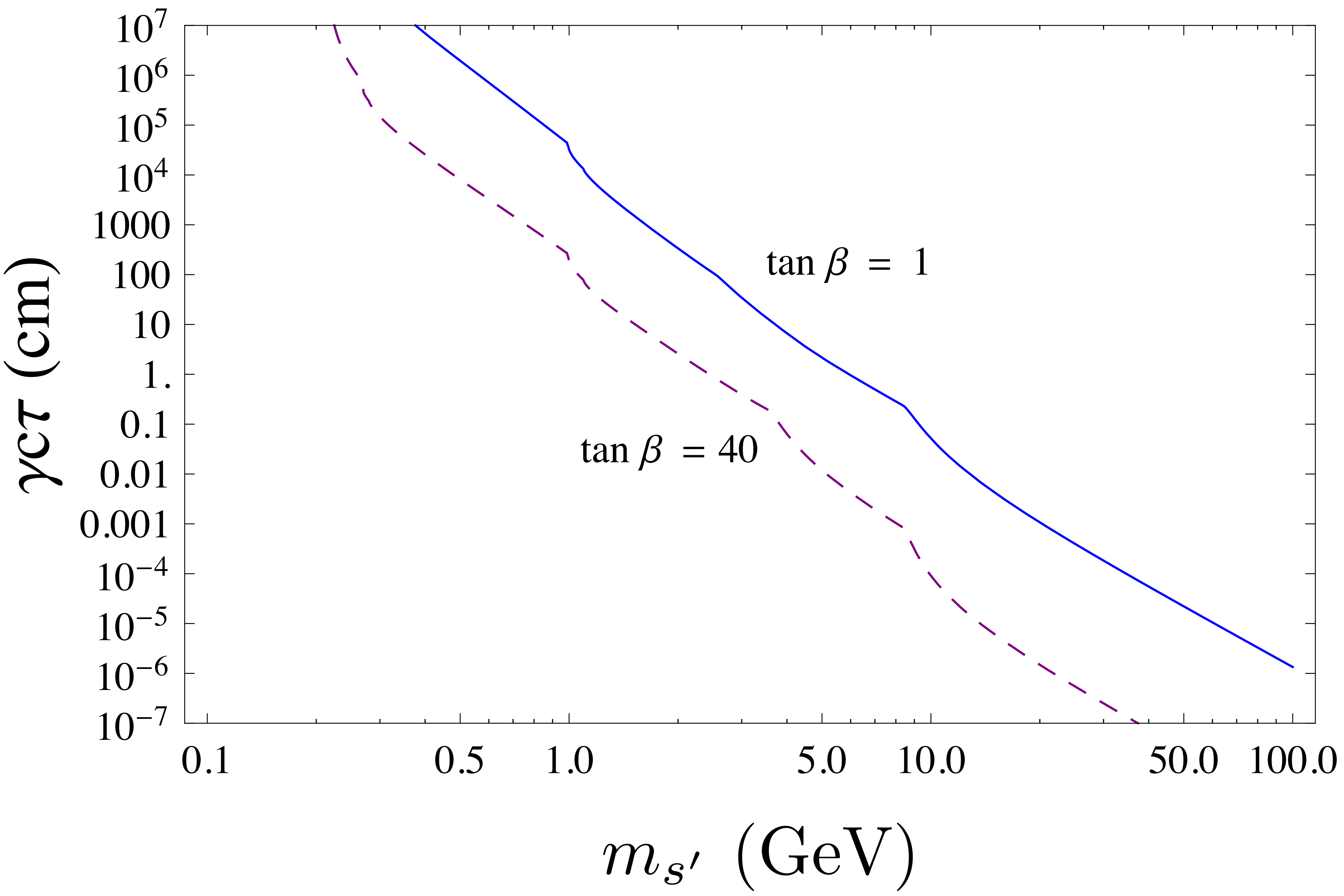

where $f$ is the heaviest allowed SM fermion.

# s’ decays like light higgs




$\tan\beta = 1$

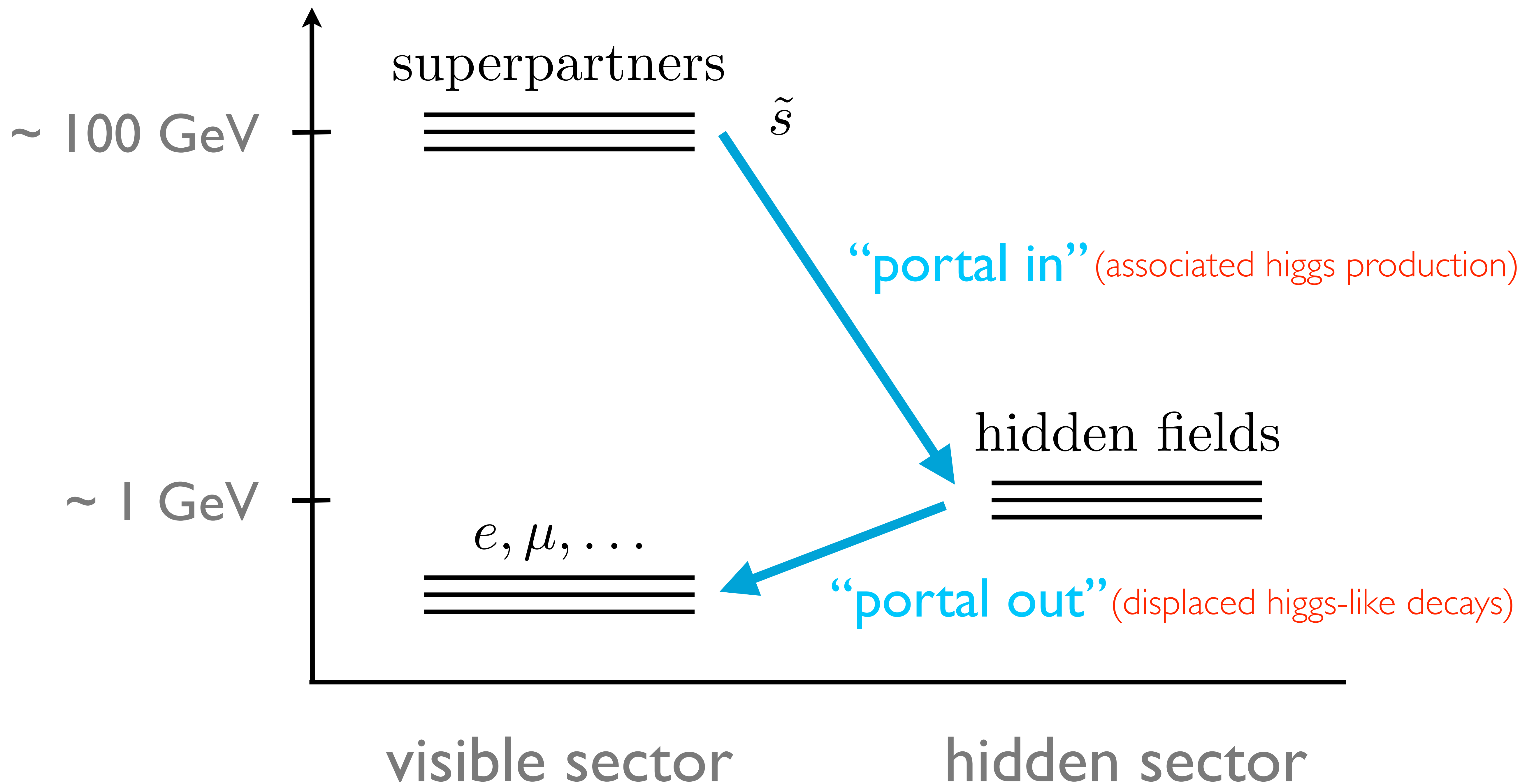
# s' decays displaced




$\epsilon = 10^{-2}$

$m_s = 300$ GeV

# in the collider...



# distinguishing kinetic portals

The singlet portal can be distinguished from the photon portal through

I) Associated higgs production in SUSY evts.

II) Return decays are highly displaced.

III) Return decays go to heaviest kinematically accessible SM state (no electrons).

# conclusions

1) SUSY, if broken multiply, yields goldstini which can drastically change LHC pheno and provide a smoking gun of sequestering.

2) SUSY, via kinetic mixing, motivates light hidden sectors which provide distinctive "portal in" + "portal out" signatures.