Signs of a Hidden Sector from Supersymmetry(s)

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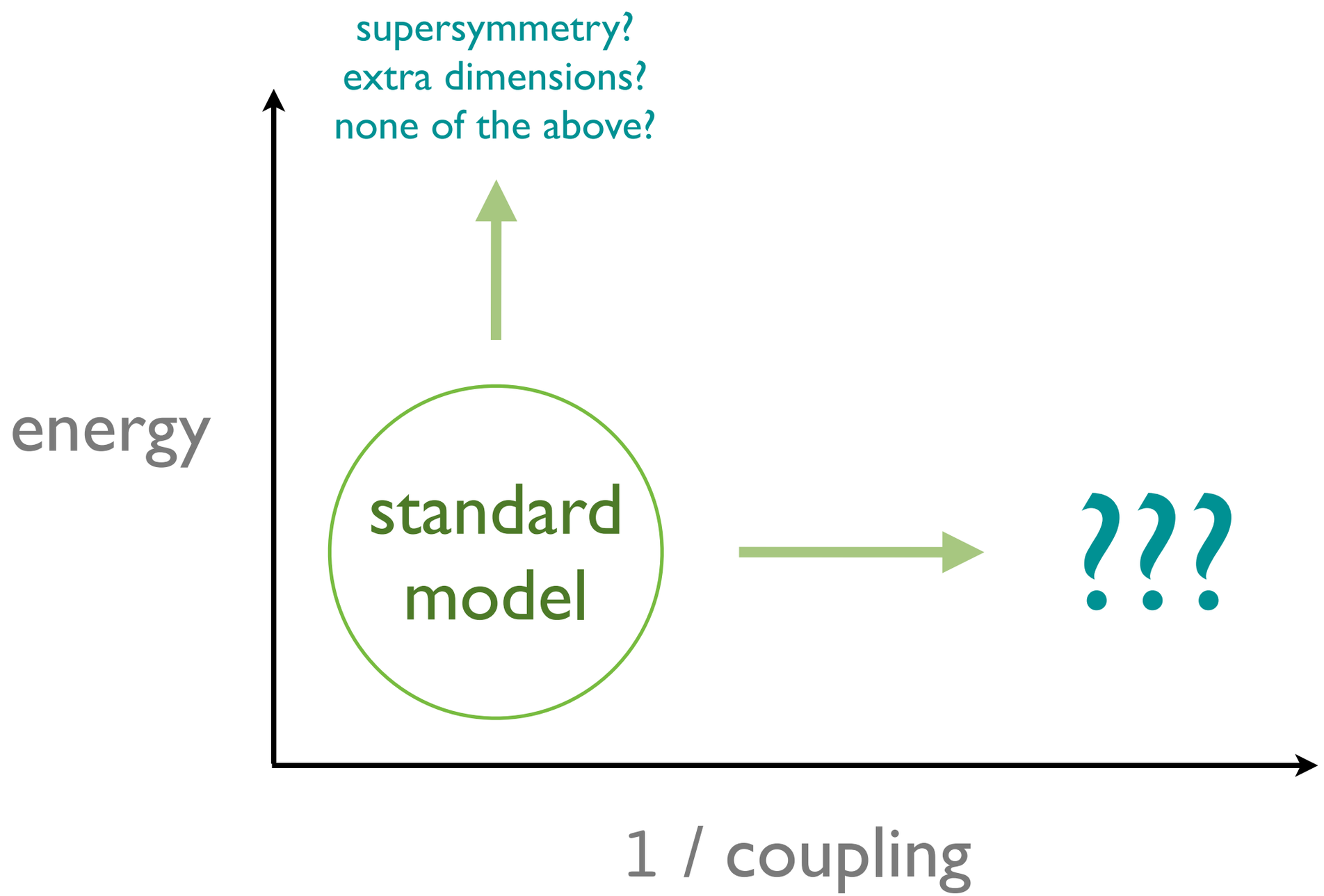
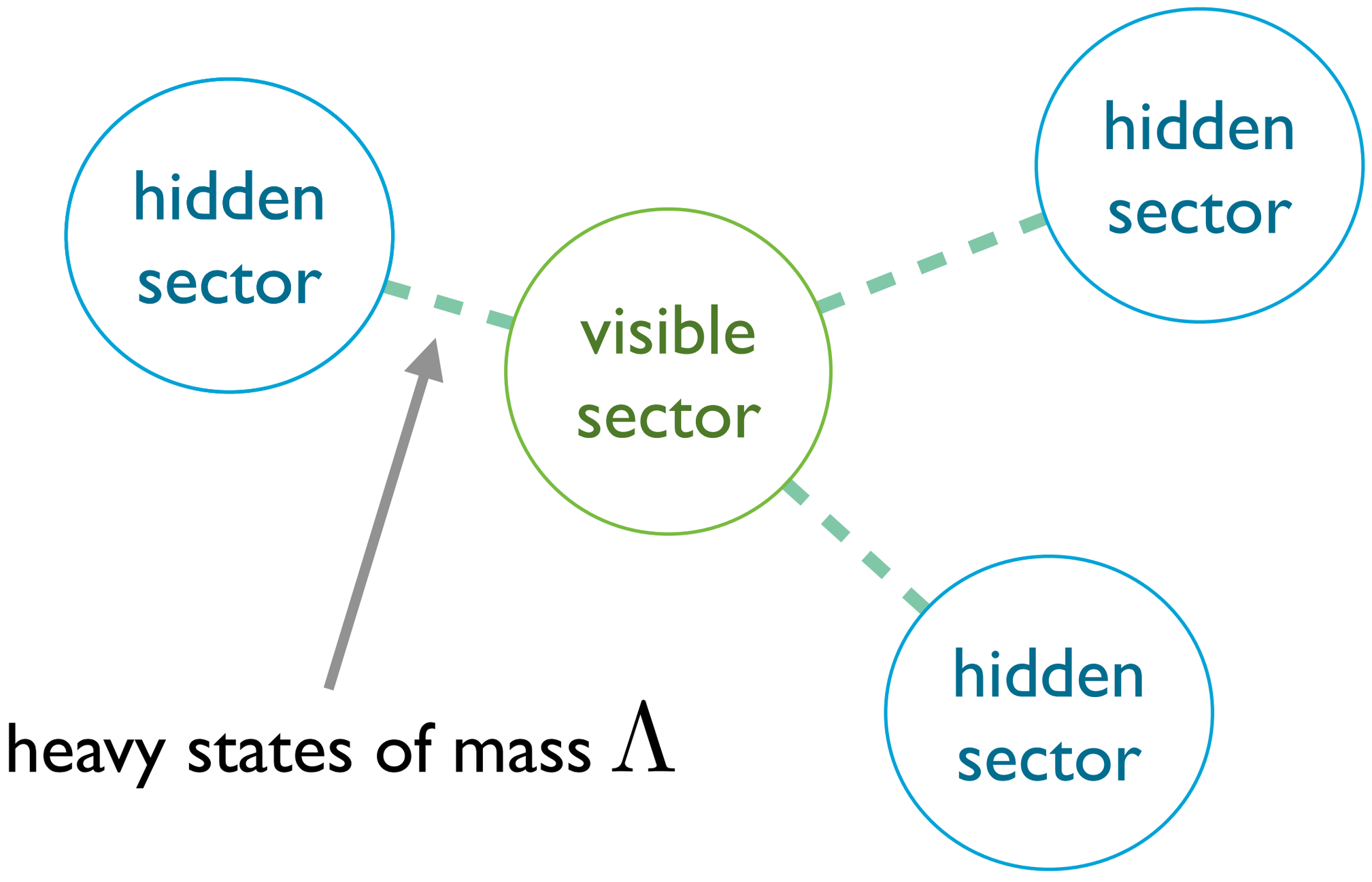
C.C., Nomura (1008.5153)
C.C., Mardon, Nomura, Thaler (1004.4637)
C.C., Nomura, Thaler (1002.1967)
C.C., Ruderman, Wang, Yavin (0902.3246)

motivations

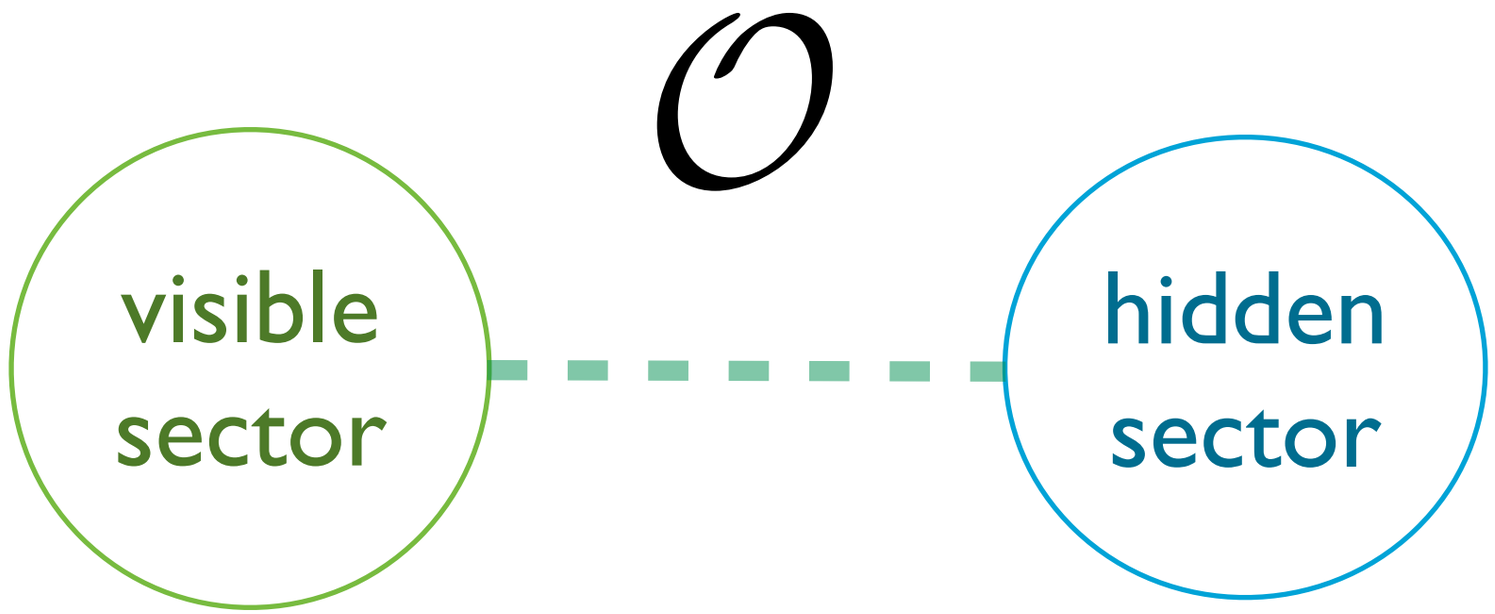
sideways physics



hidden worlds?



a tale of two sectors



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

Signs of a hidden sector due to...

Symmetry Reason:

Sectors share symmetry.

Internal

B, L, PQ

Spacetime

E, p, SUSY

Effective Theory:

Portal is marginal.

d>4

decoupling

d=4

non-decoupling

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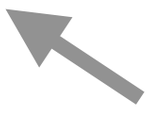

goldstino portal

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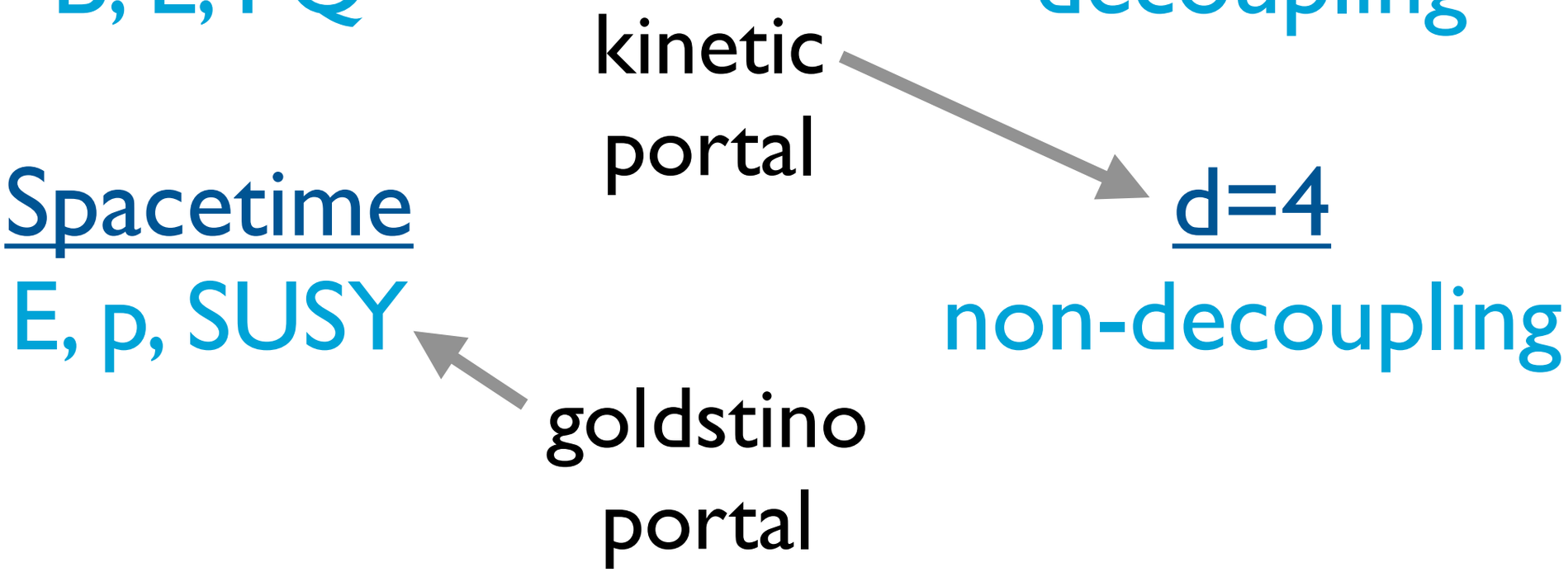
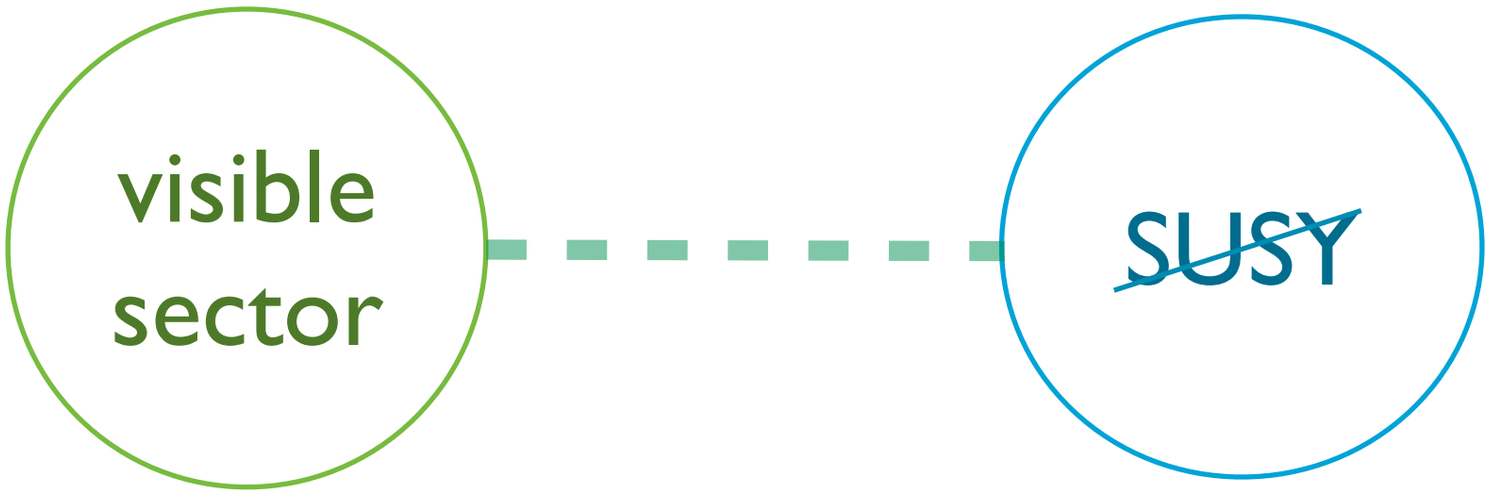


goldstino portal

the SUSY template



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

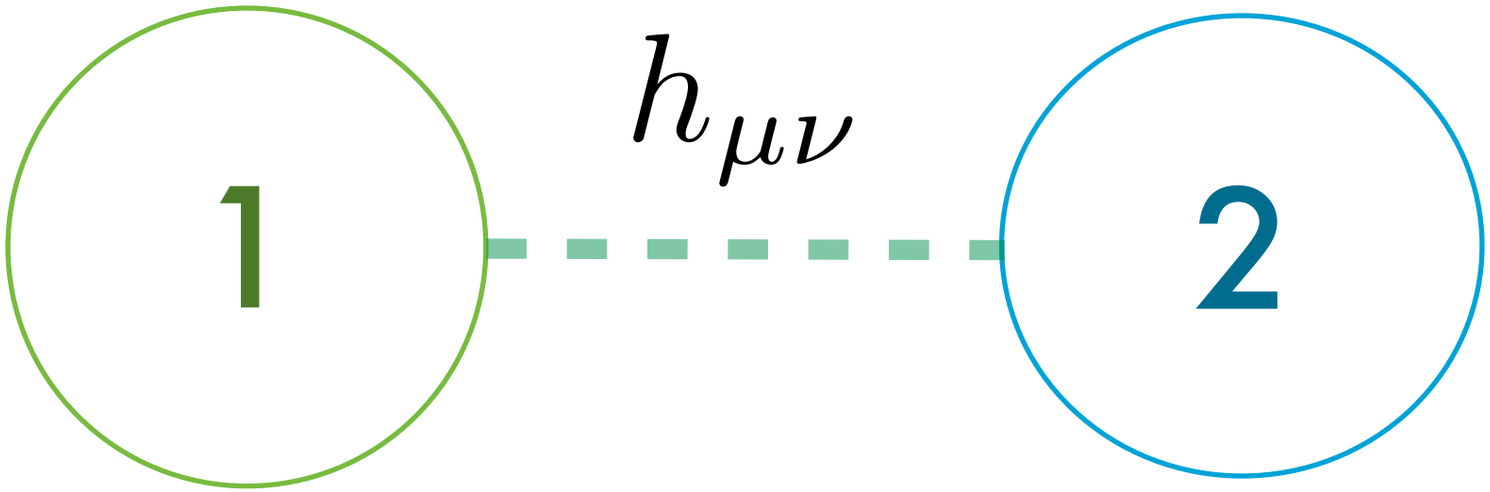
SUSY breaking arises from a single source.

enhanced spacetime symmetries

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

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

adding gravity



Gravity explicitly breaks the enhanced symmetry down to the diagonal,

$$\mathrm{Poincare}_1 \otimes \mathrm{Poincare}_2 \overset{\mathrm{gravity}}{\rightarrow} \mathrm{Poincare}$$

enhanced SUSY

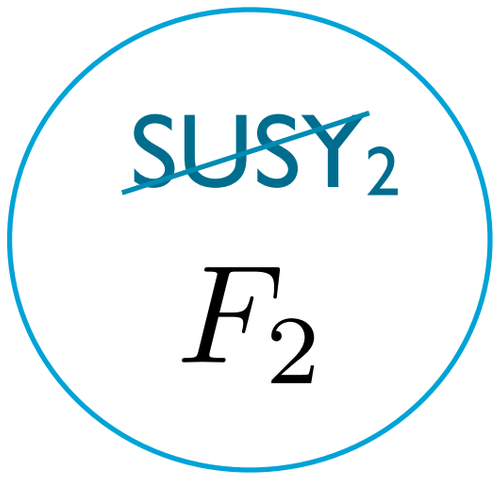
If our world is supersymmetric, then likewise

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

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

What about SUSY breaking???

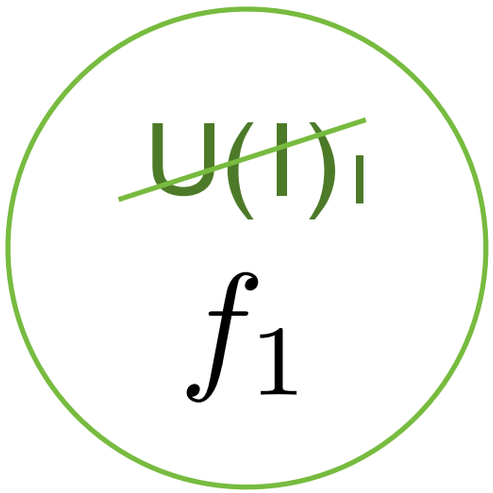
SUSY(s) breaking

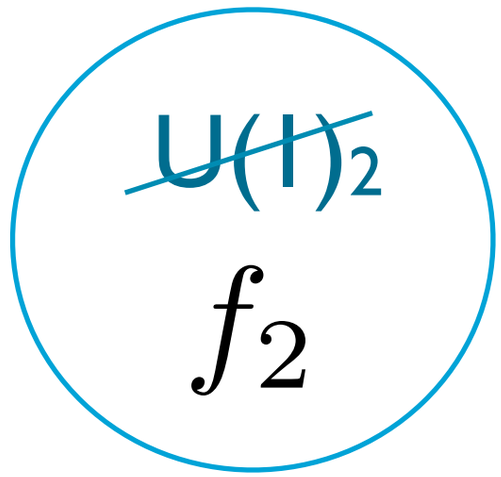


$X_1 \ni \eta_1$ $X_2 \ni \eta_2$

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





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

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

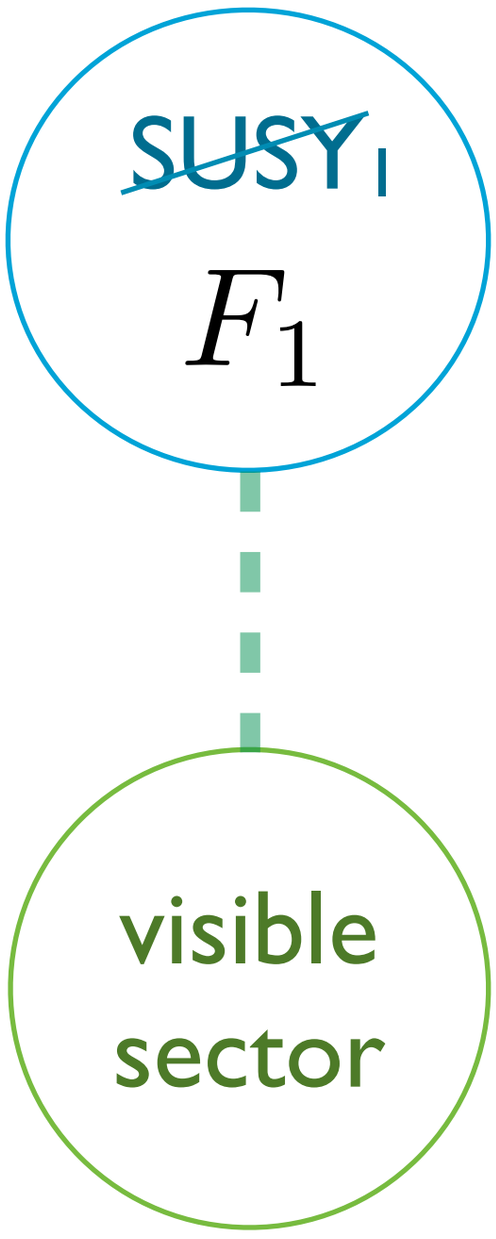
$$\begin{pmatrix} \eta_1 \\ \eta_2 \end{pmatrix} = \begin{pmatrix} \cos\theta & -\sin\theta \\ \sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} \tilde{G} \\ \zeta \end{pmatrix}$$

uneaten goldstino

where we have defined

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

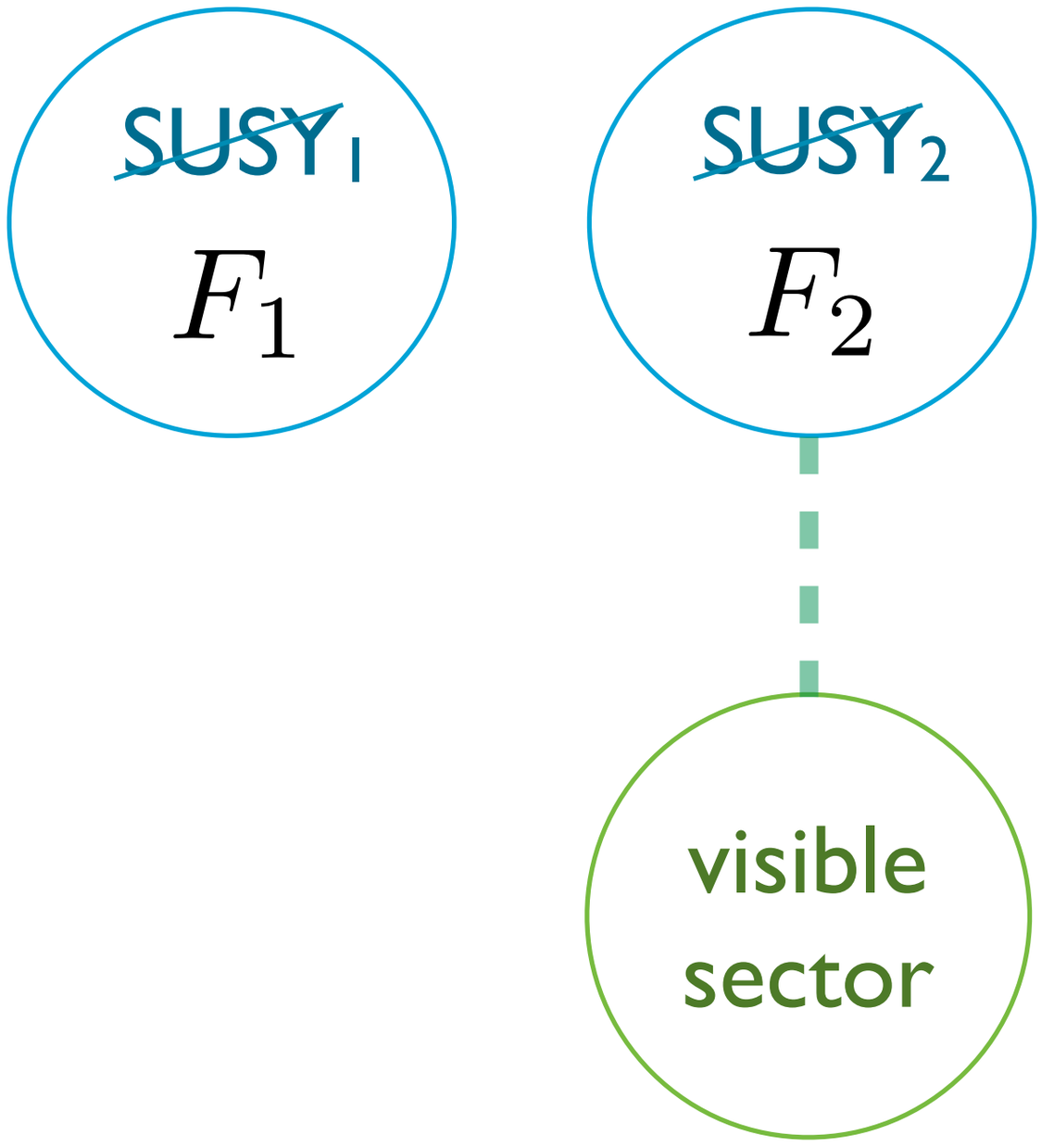
a special setup



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?

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

$$A_\mu \overset{\text{Stück.}}{\to} A_\mu + \partial_\mu \pi / m$$

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

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

edible goldstini

Applying the same reasoning to goldstini,

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

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

Hence, for SUSY^N,

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

deviations from $2m_{3/2}$

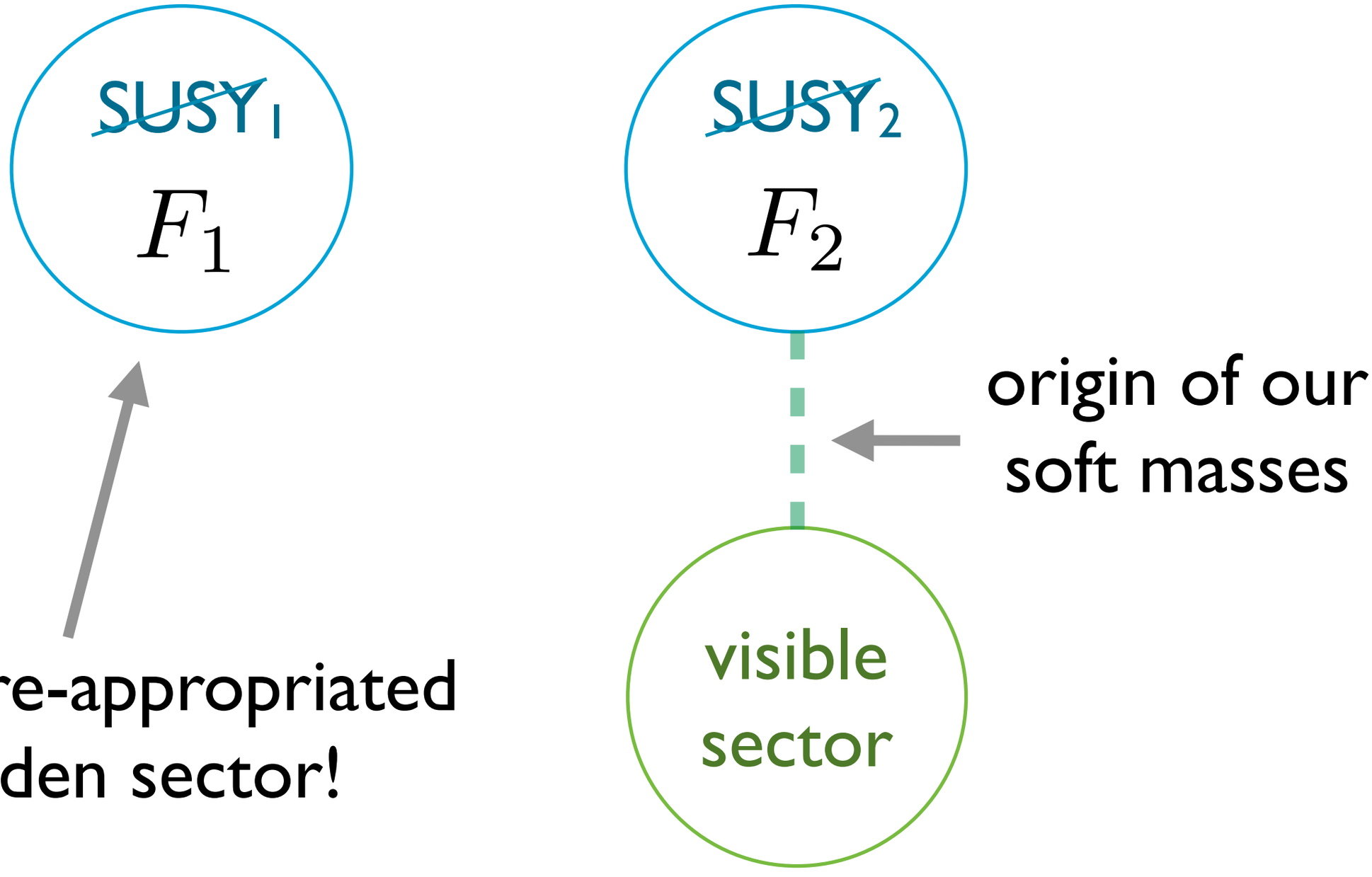
Corrections to $m_\zeta = 2m_{3/2}$ occur given:

- Non-sequestered Operators. Enhanced SUSY^N explicitly broken.

- Anomalous Dimensions / Warping. Large corrections to tree level approximation.

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

annexing the visible sector



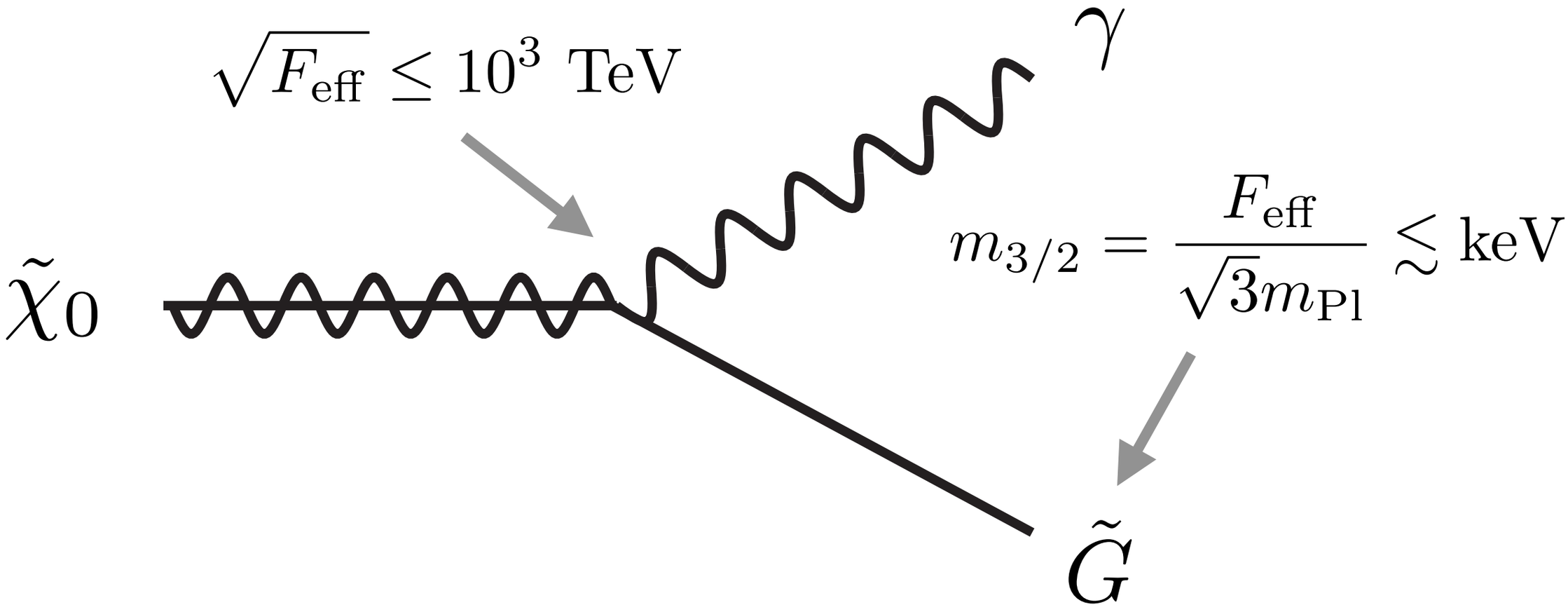
bottom line

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 $\{\ \zeta$	$\dfrac{\tilde{m}^2}{F_2}$	$2m_{3/2}\ \left(=\frac{2F_{\rm eff}}{\sqrt{3}M_{\rm Pl}}\right)$

goldstino pheno

standard GMSB

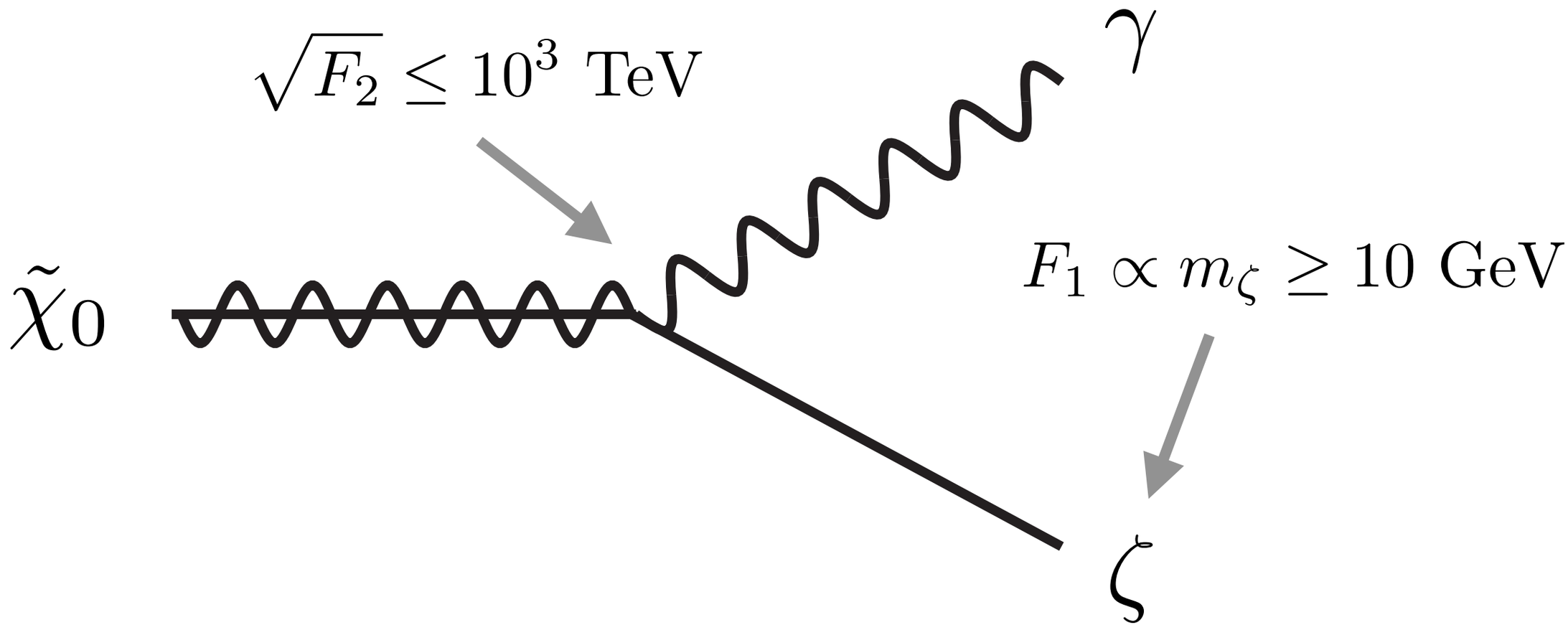
Lightest observable sparticle (LOSP) is a bino.



If decay is prompt, gravitino basically massless.

anomalously heavy "gravitino"

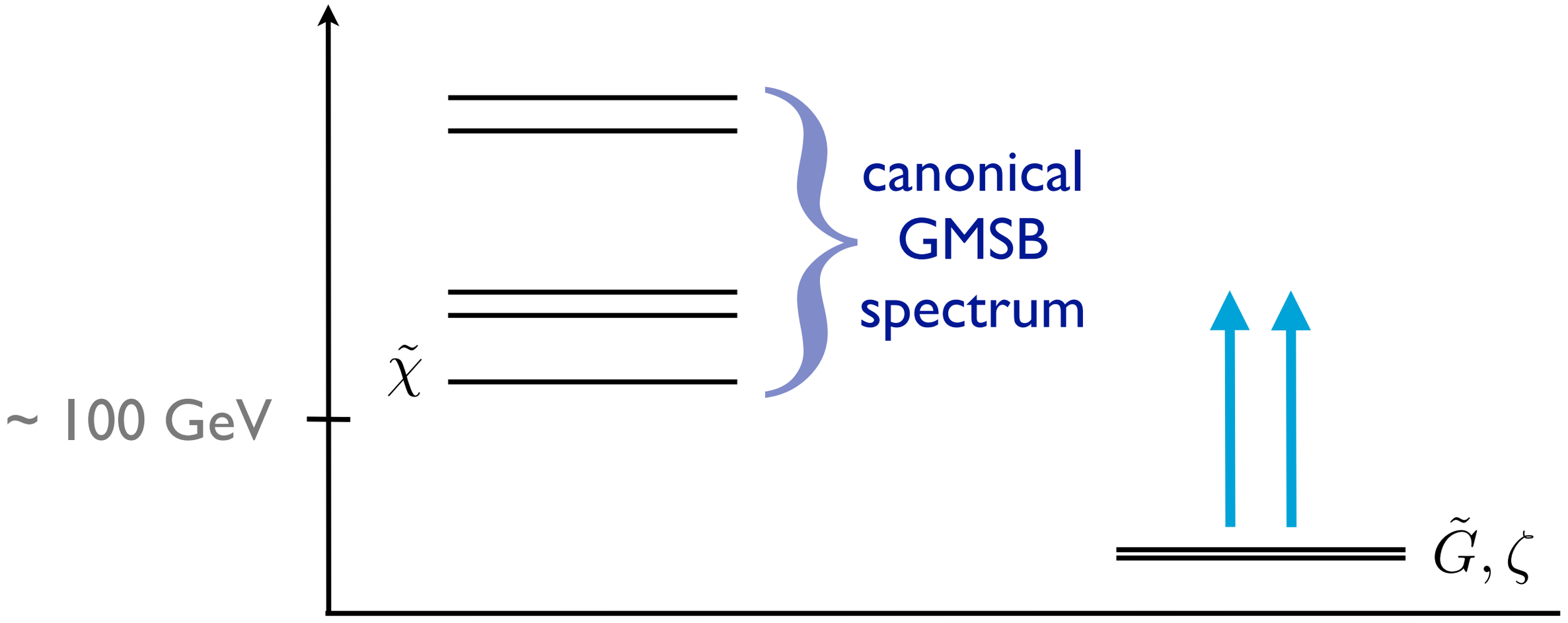
With goldstino there is a dominant decay



yielding promptly decaying "heavy" gravitino.

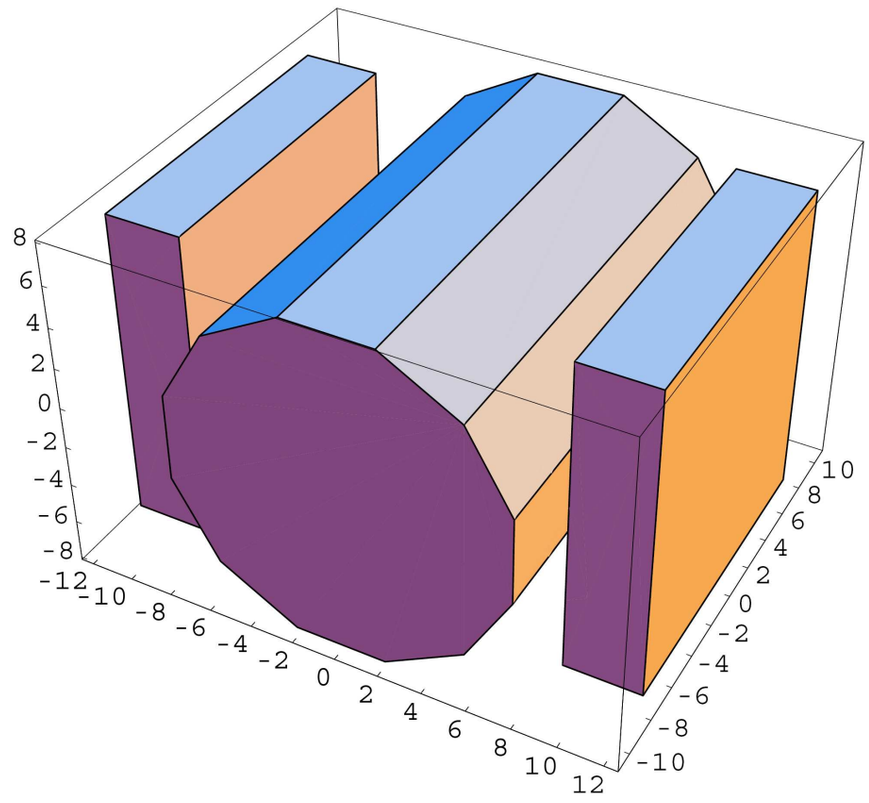
GMSB w/ neutralino DM

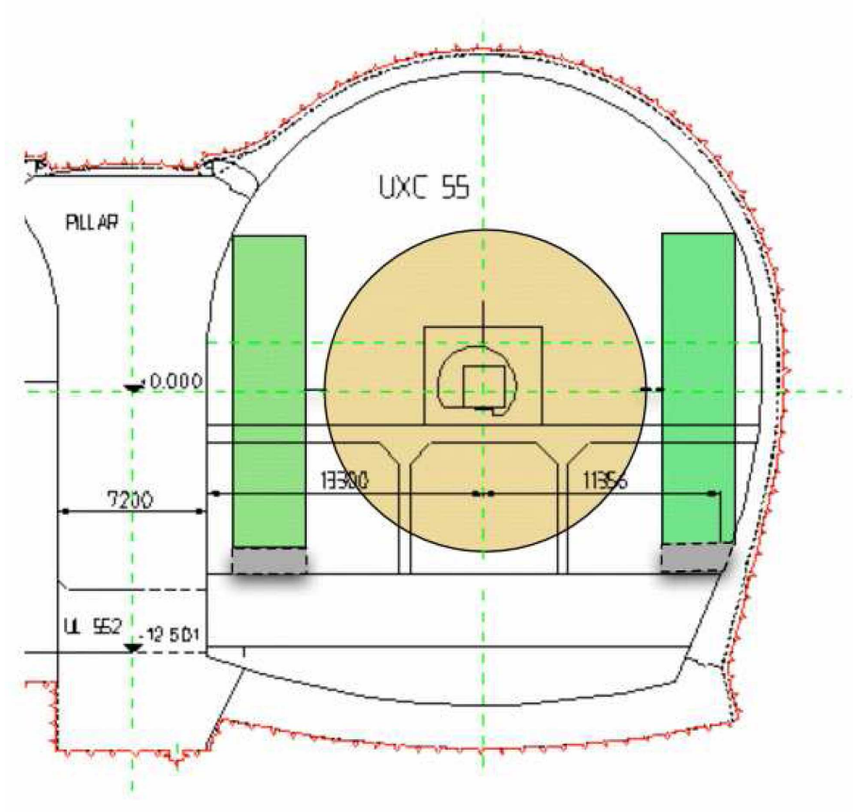
In fact, we can increase F_1 at fixed F_2 so,



long-lived charged LOSP

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

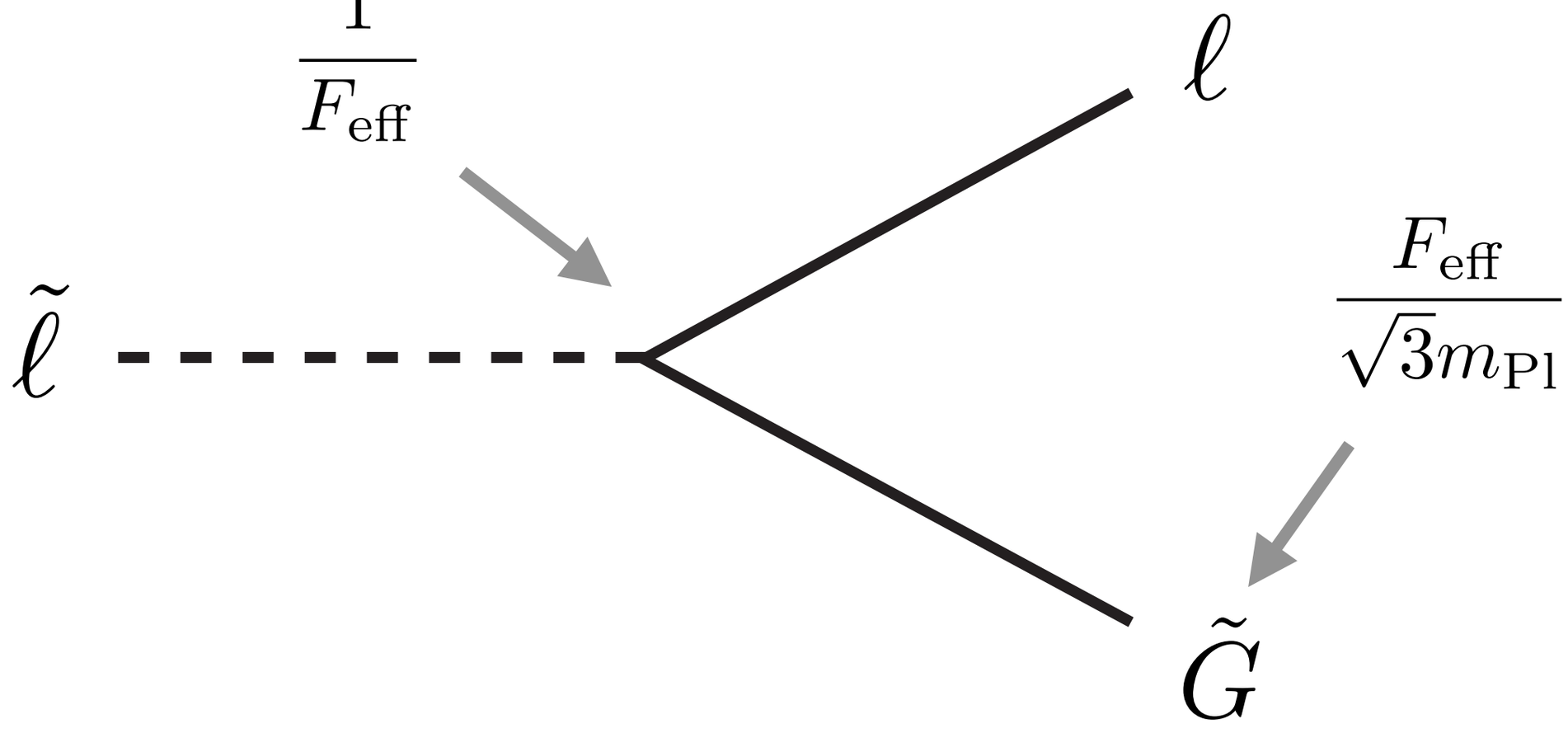




hep-ph/0612060 (Hamuguchi, Nojiri, de Roeck)
hep-ph/0506246 (Arvanitaki, Dimopoulos, Pierce, Rajendran, Wacker)
hep-ph/0409248 (Hamaguchi, Kuno, Nakaya, Nojiri)

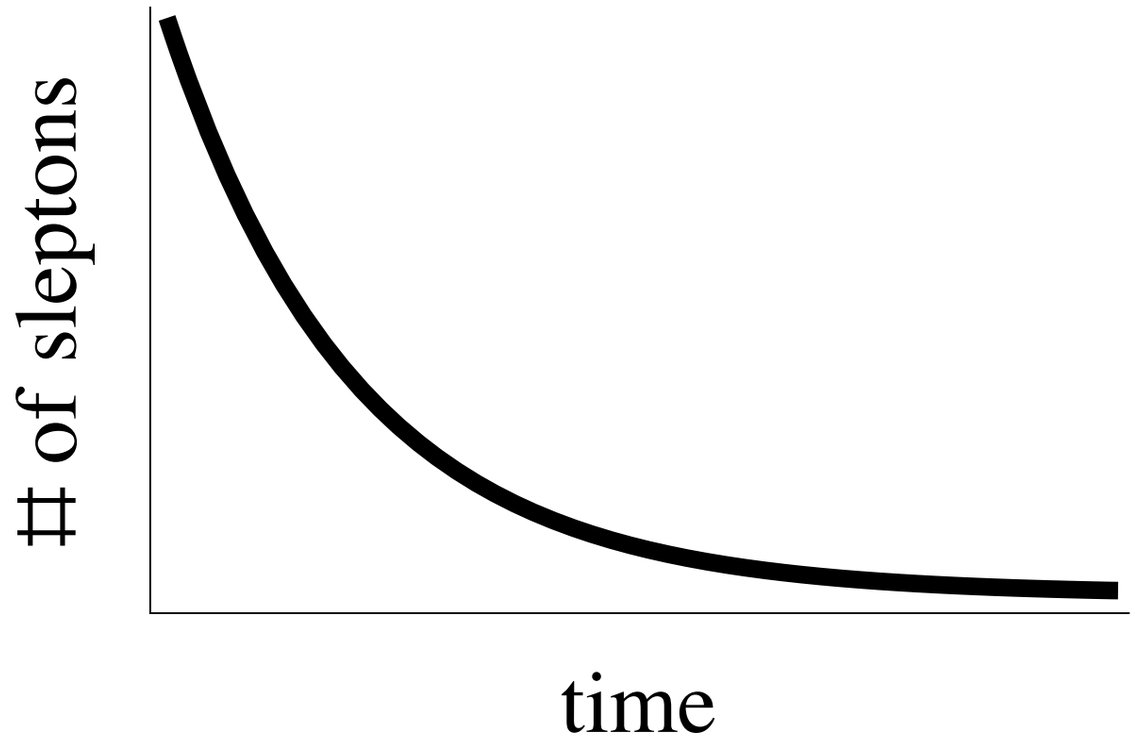
measure the Planck mass

Given a conventional gravitino,

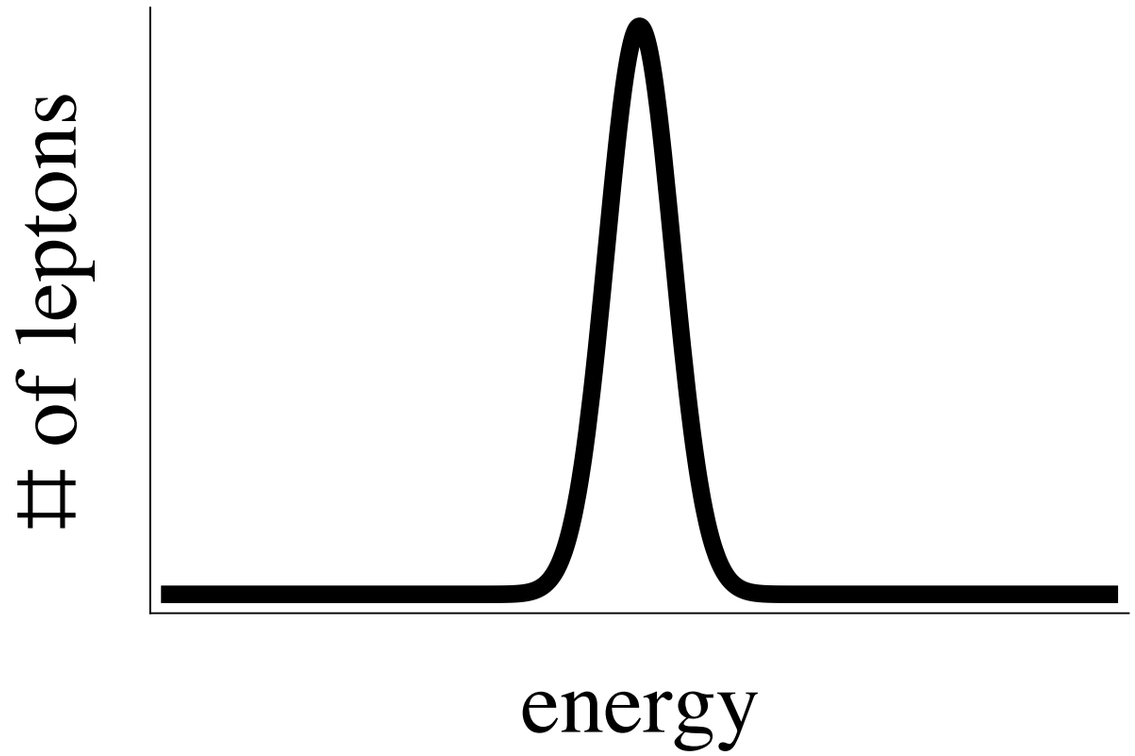


we can measure Planck mass.

lifetime measurement

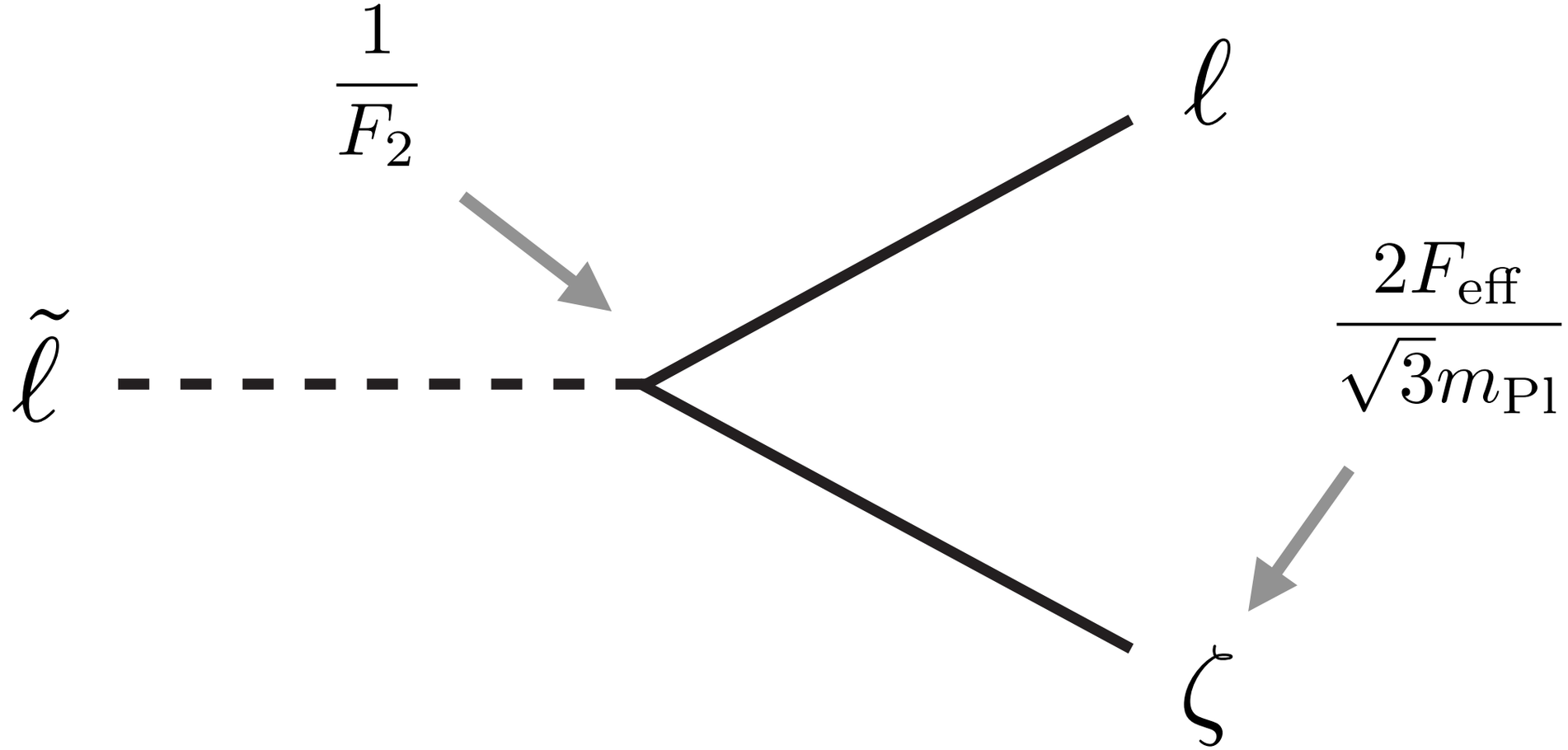


mass measurement



(mis)measure the Planck mass

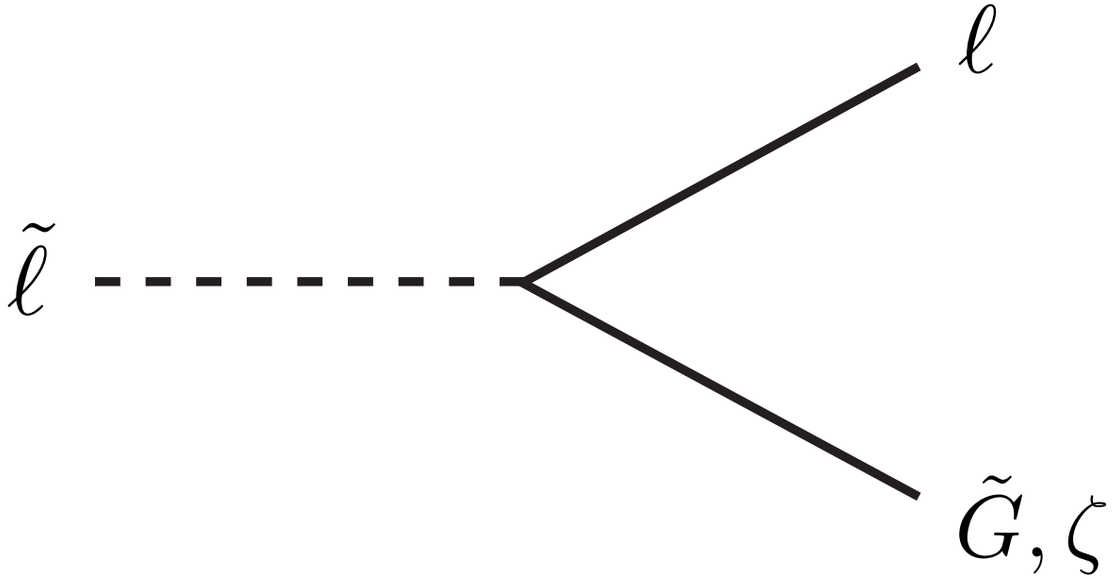
In contrast, if there exist goldstini, then

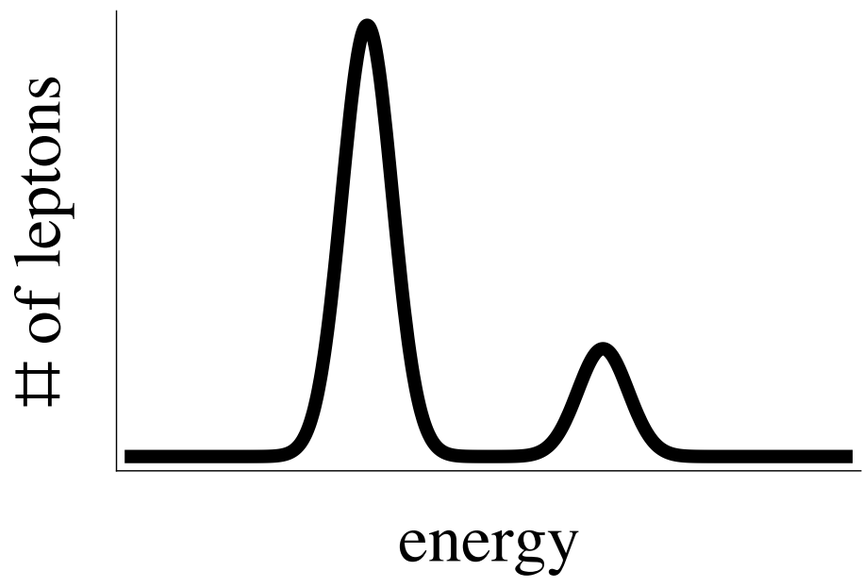


we mismeasure the Planck mass by $F_2/2F_{\rm eff}$.

smoking gun of a hidden sector

If lucky, measure gravitino, goldstino, and "2"!

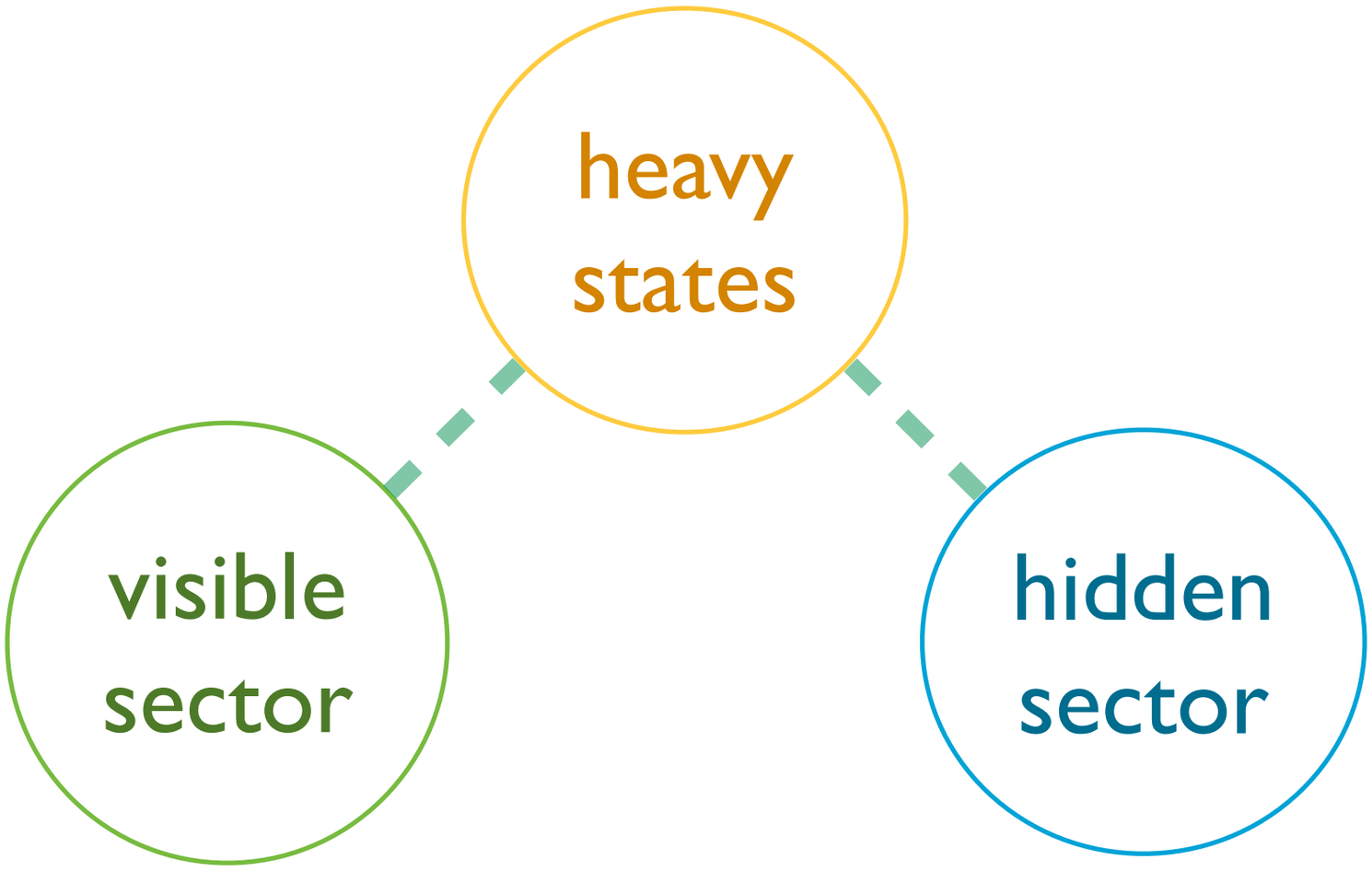




Discover sequestering + multi-SUSY breaking!

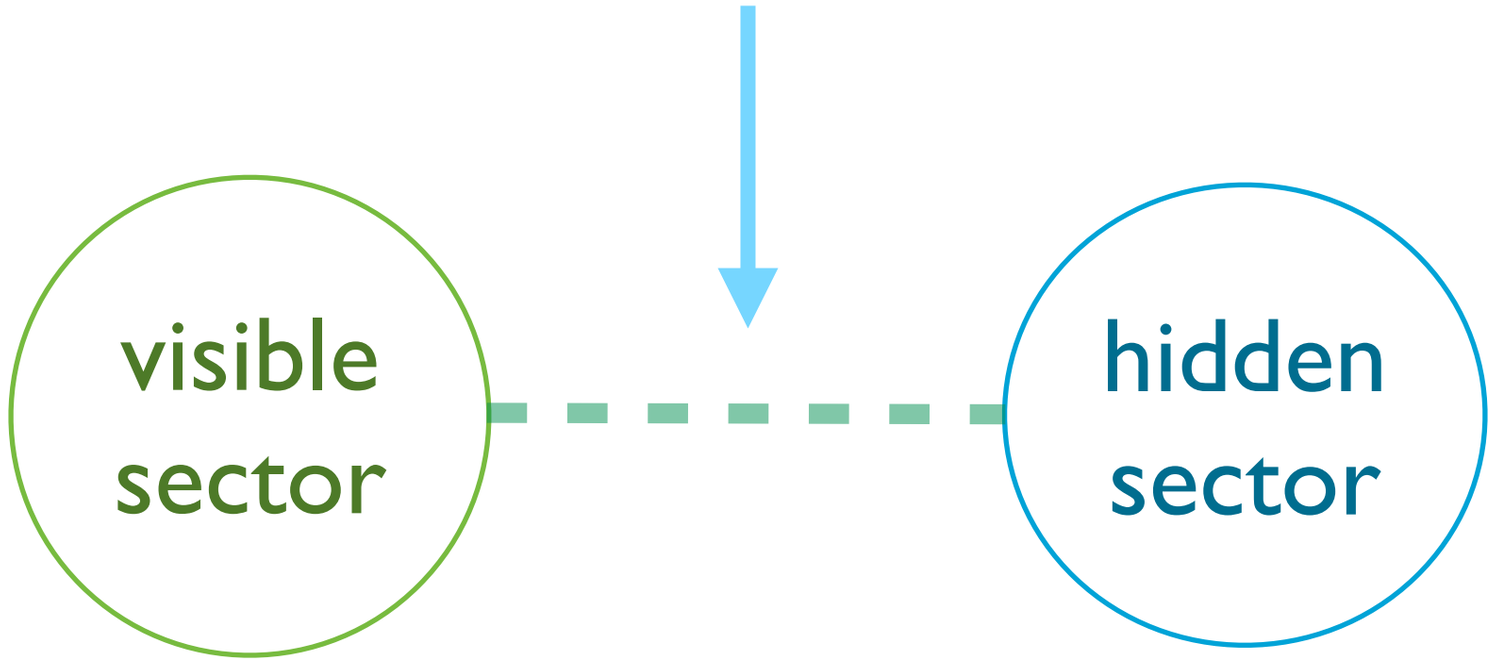
kinetic portals

Heavy states couple visible and hidden sectors.



Irrelevant operators decouple at low energies.

Marginal portal operators persist.



kinetic mixing portals

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

singlet portal

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

photon portal

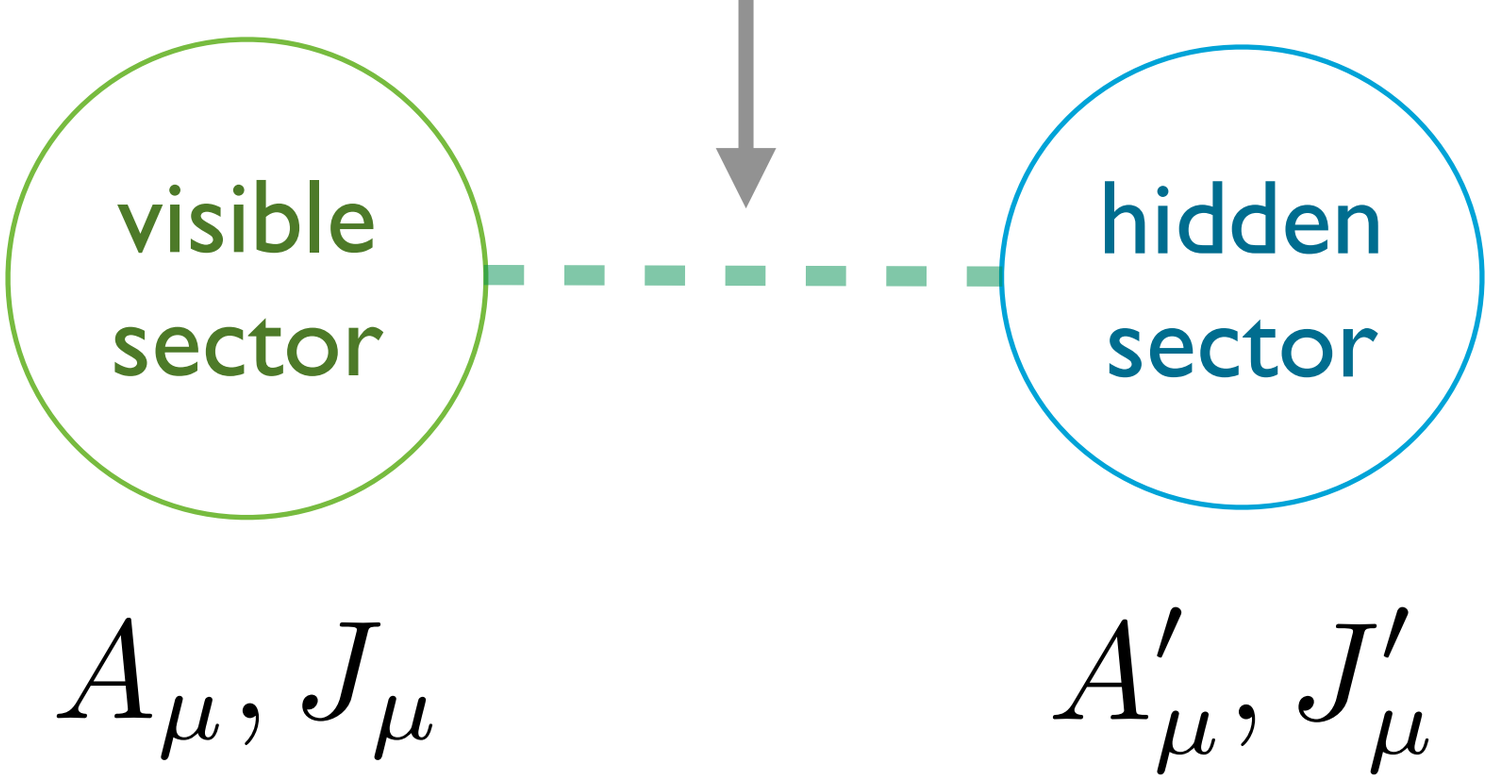
$$F_{\mu\nu} F^{\mu\nu\prime}$$

Marginal op's motivated by EFT!

photon portal

Assume existence of a hidden massive photon.

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



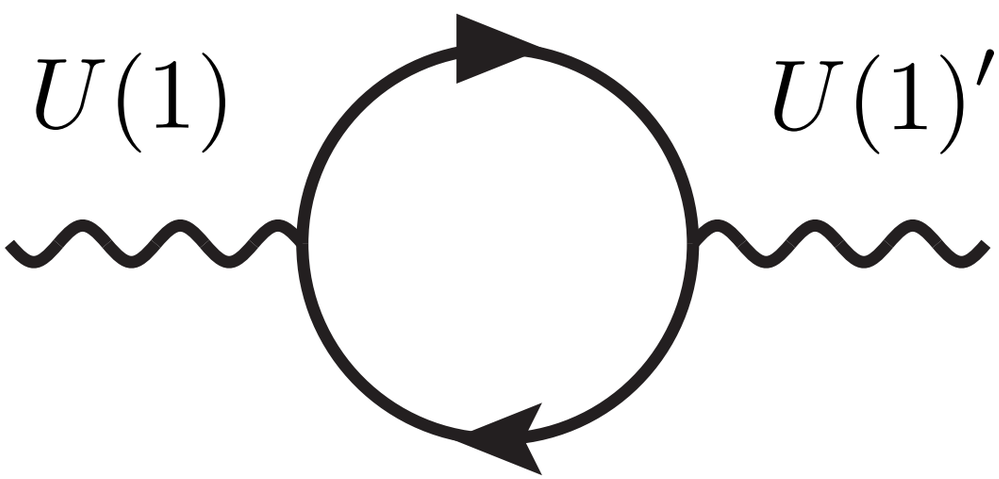
A_μ, J_μ

A'_μ, J'_μ

photon portal

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

is generated in UV by heavy particle loops.



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

the Holdom effect

By eliminating the kinetic mixing via a shift,

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

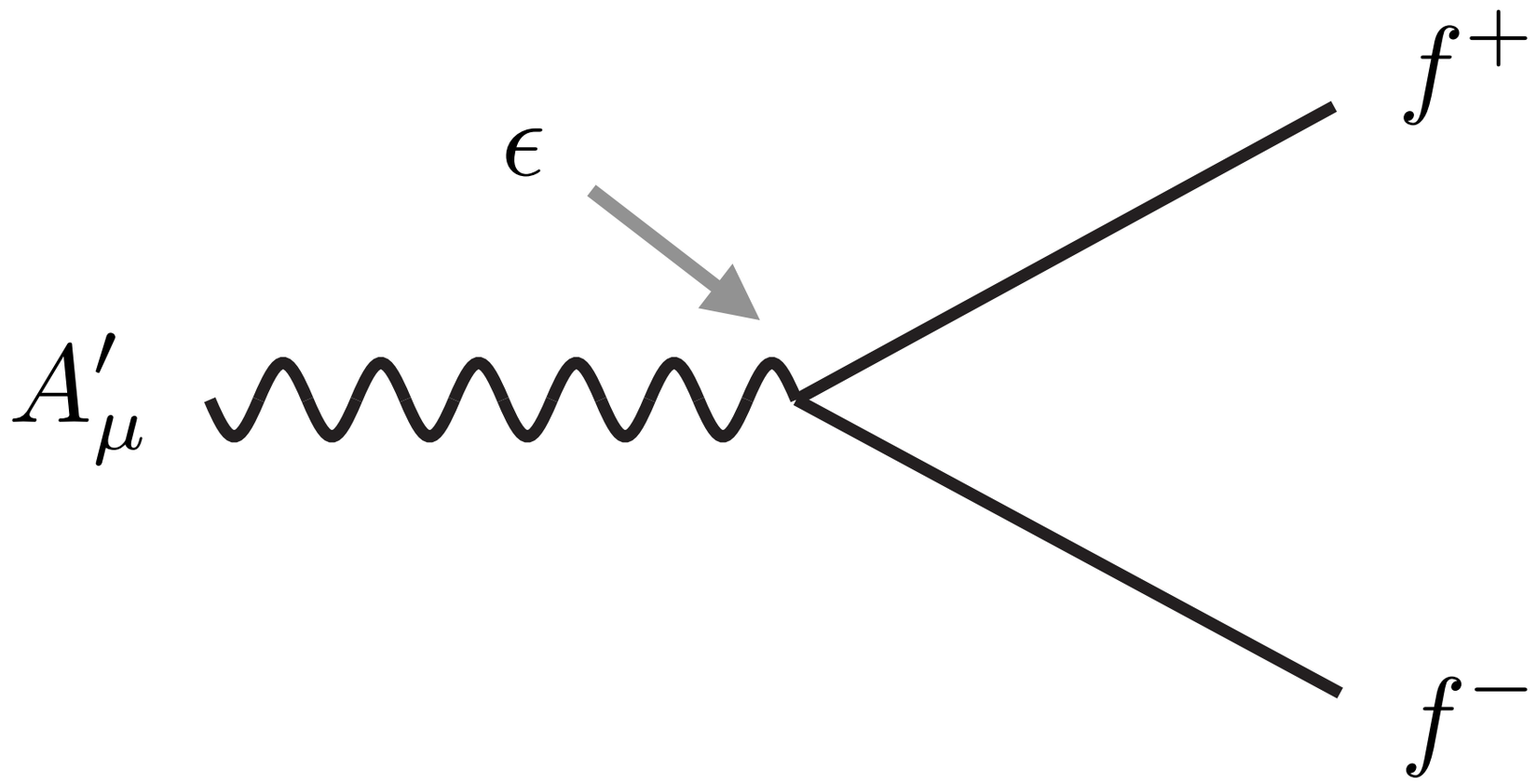
$$\mathcal{L} \to \mathcal{L} + \epsilon A'_\mu J^\mu$$

} 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

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

"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)':

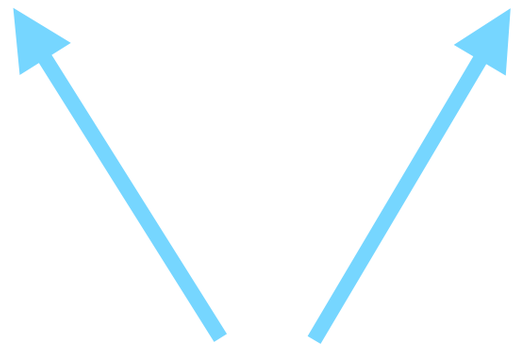
$$\mathcal{L}_{\text{eff}} = \underbrace{\epsilon \langle D \rangle} D'$$

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

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

scale generation

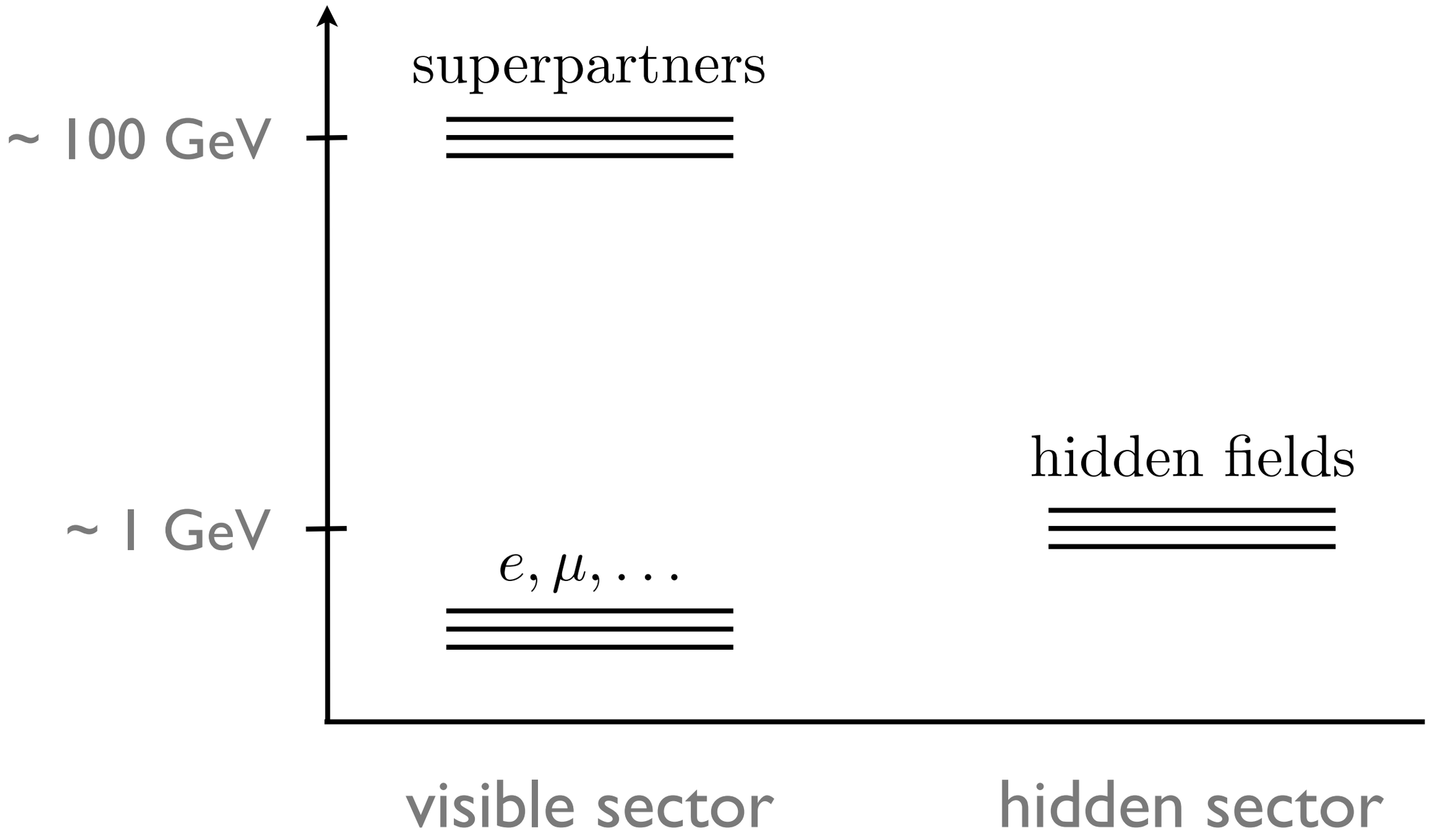
$$V_{\rm hid} = [g'(|h'|^2 - |h^{c\prime}|^2) + \epsilon\langle D\rangle]^2$$



Hidden higgs fields get vevs!

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

scale generation



"portal in"

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

Remove photino mixing via shift,

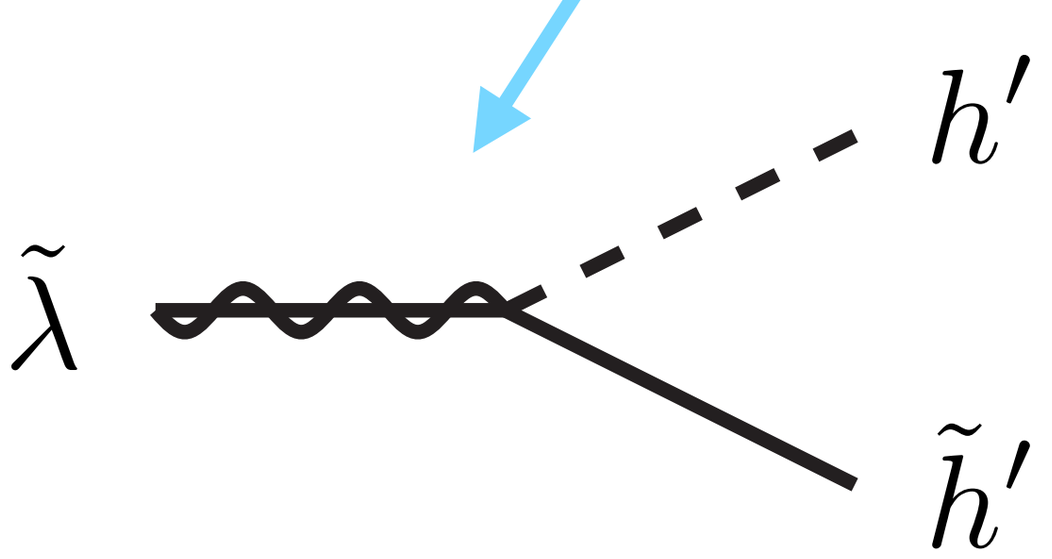
$$\tilde{\lambda}' \to \tilde{\lambda}' + \epsilon\tilde{\lambda}$$

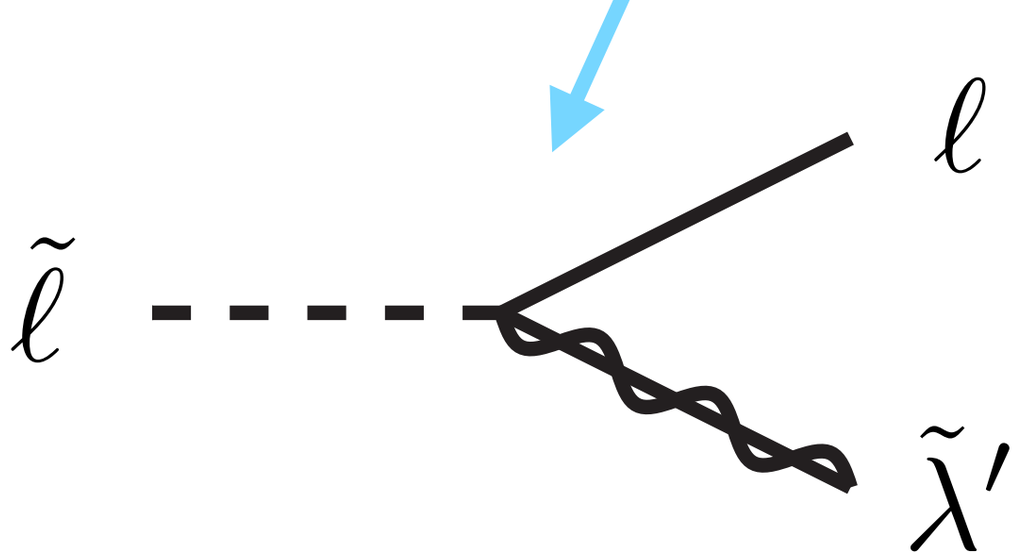
and induce a milli-charge interaction,

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

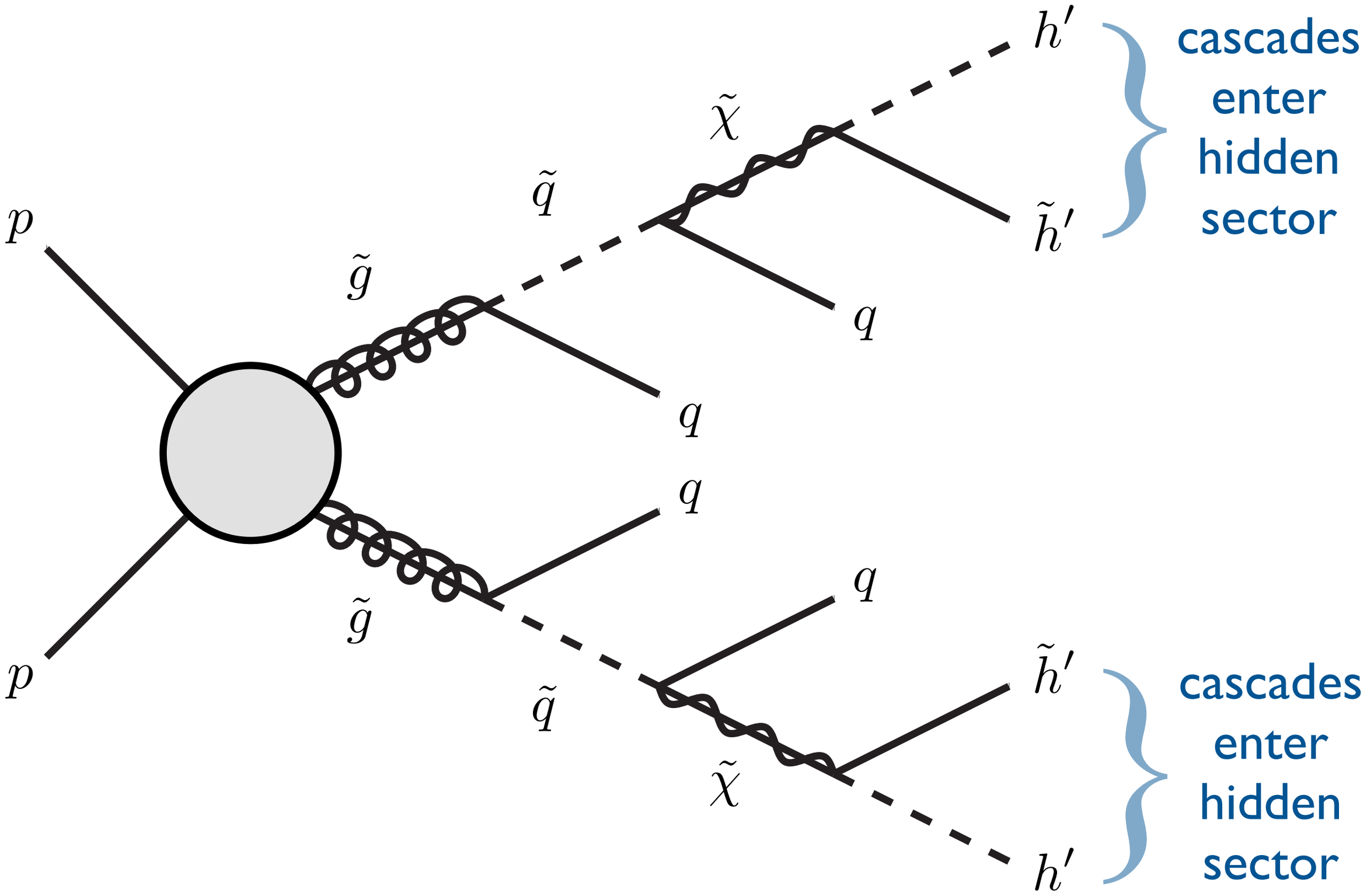
"portal in"

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





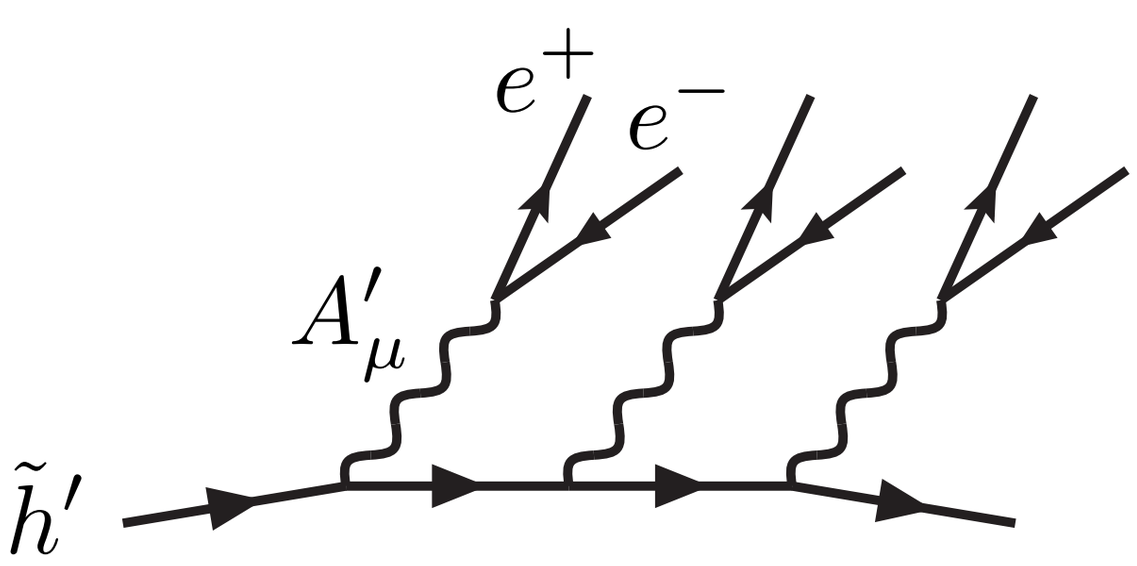
R-parity forces SUSY cascades into hidden sector.


p
$\tilde{g}$
$\tilde{q}$
$\tilde{\chi}$
h'
$\tilde{h}'$
q
q
cascades
enter
hidden
sector
p
$\tilde{g}$
$\tilde{q}$
$\tilde{\chi}$
q
$\tilde{h}'$
h'
cascades
enter
hidden
sector

"portal out"

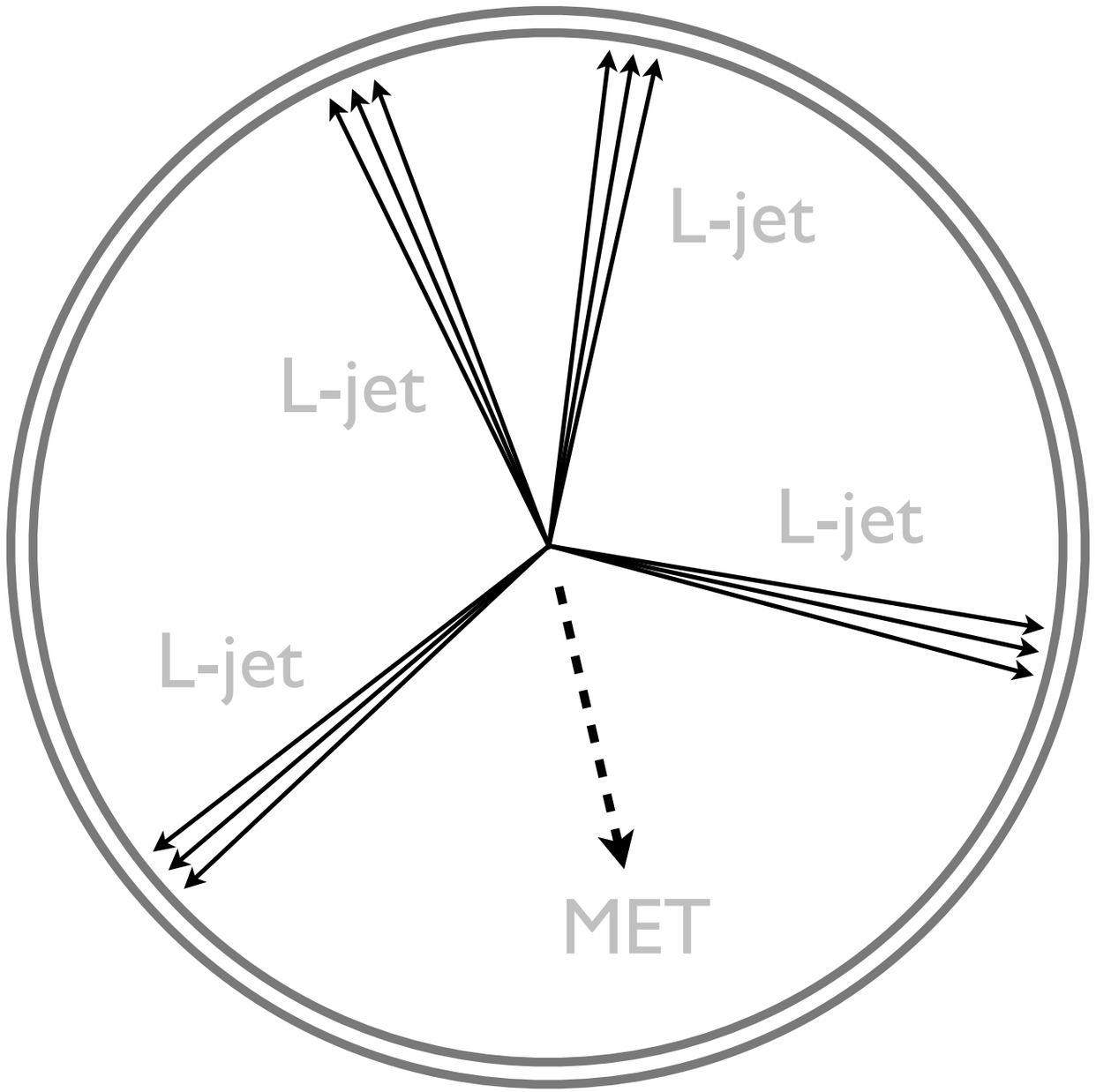
$$\epsilon \left(F_{\mu\nu} F^{\mu\nu\prime} + i\tilde{\lambda}^\dagger \bar{\sigma}_\mu \partial^\mu \tilde{\lambda}' + DD' \right)$$

Hidden cascades yield U(1)' vector bosons which decay visibly into SM fields.

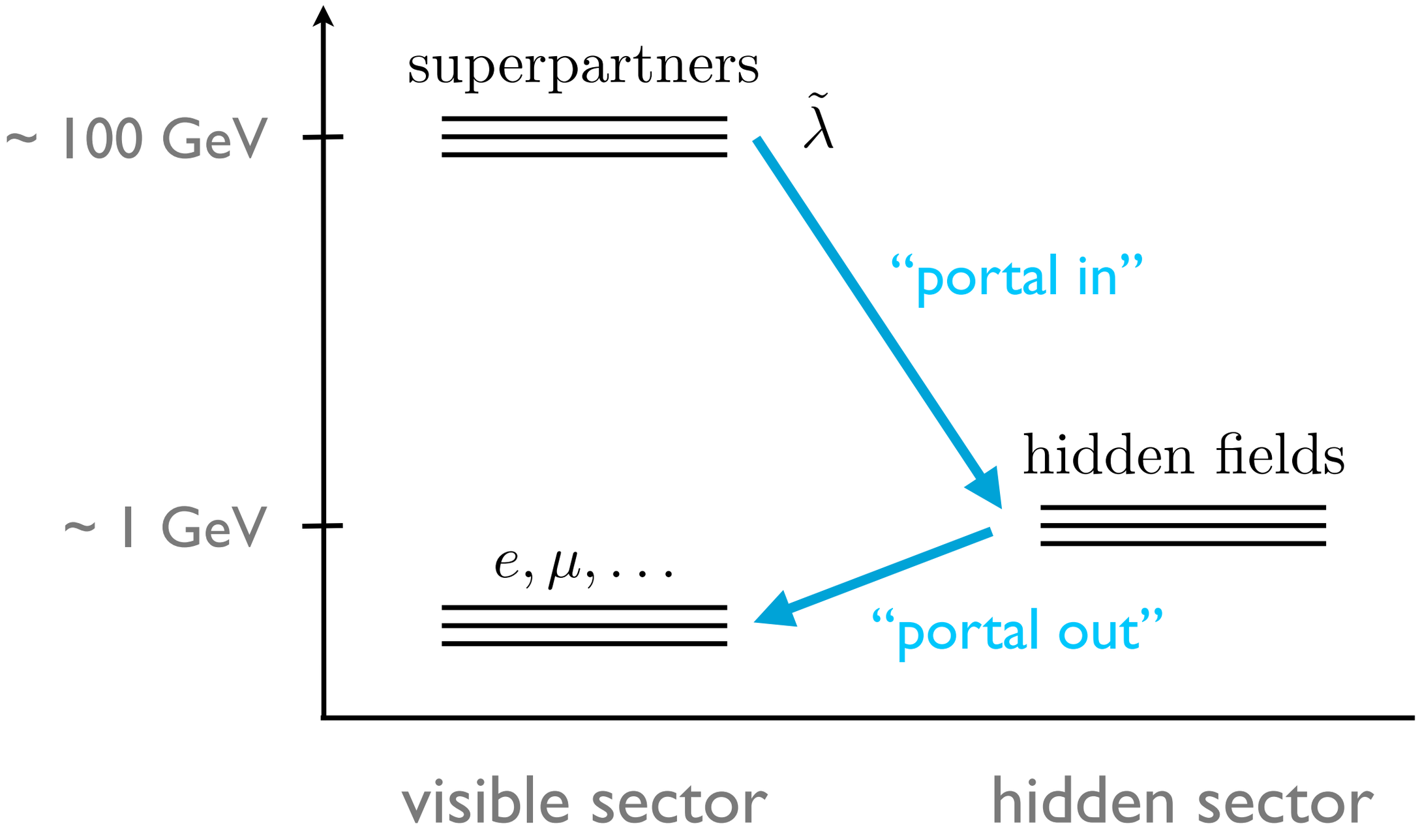


highly columnated "lepton jets" have invariant mass ~GeV

lepton jets



in the collider...



the 2nd option

Bottom line: gauge singlets can kinetically mix!

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

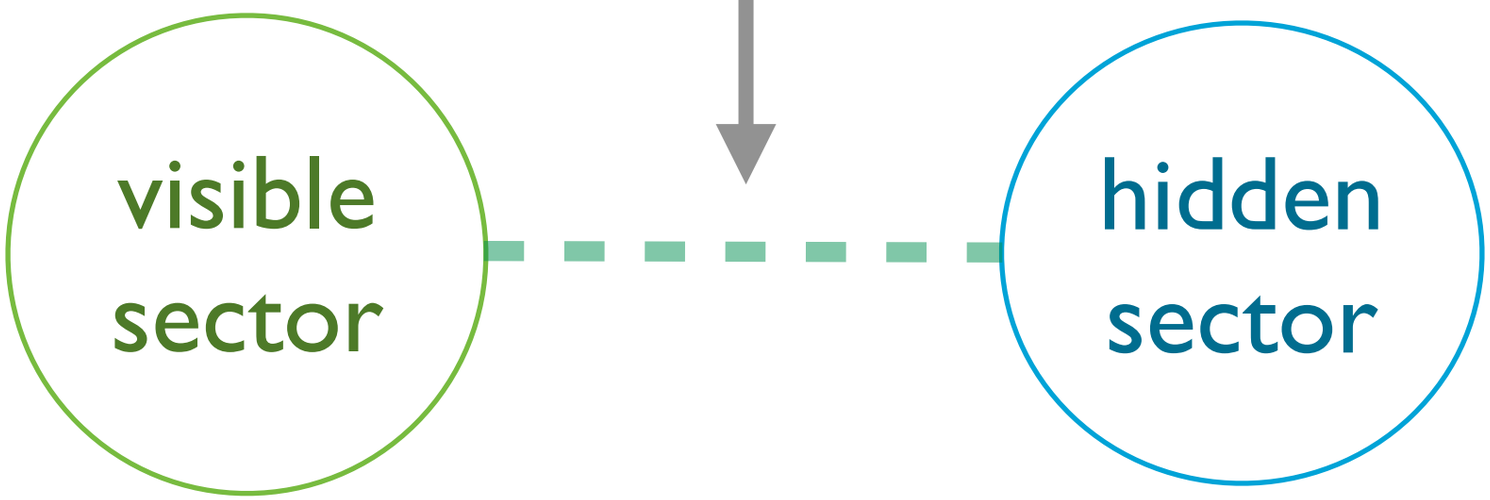
then why not $\epsilon \int d^4\theta \, S^\dagger S'$???

The unexplored half of kinetic mixing space.

singlet portal

Singlet extended MSSM with $W = \lambda S H_u H_d$.

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



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

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':

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

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

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

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,

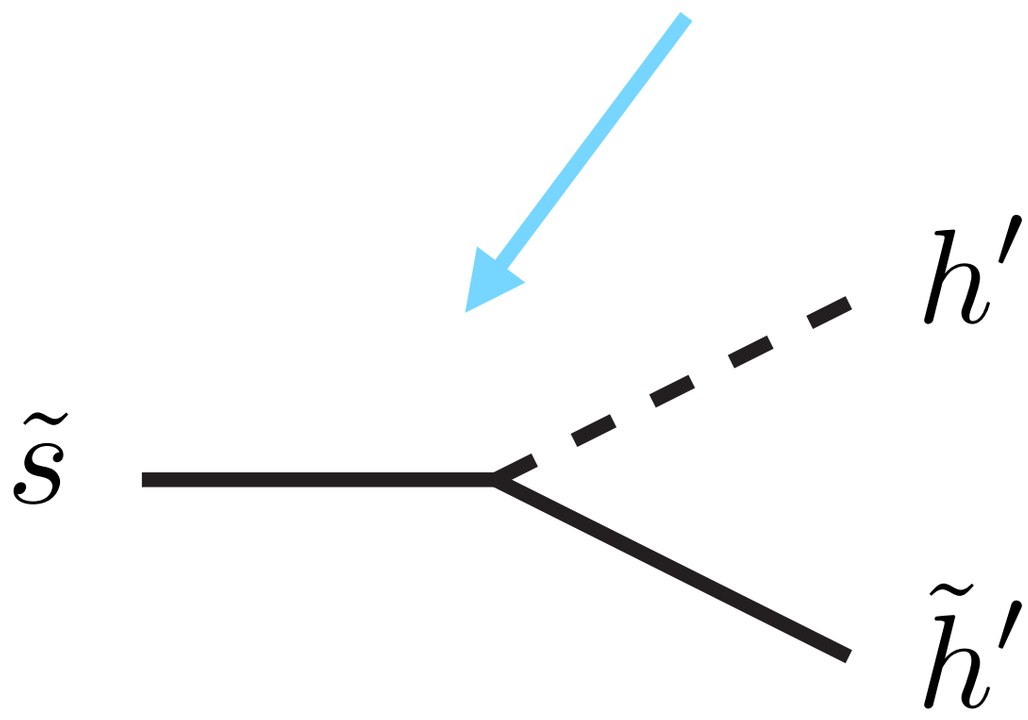
$$\Delta\mathcal{L} = \epsilon\tilde{s}\tilde{J}' + \epsilon\mathcal{O}(m_{\tilde{s}'}/m_{\tilde{s}})\tilde{s}'\tilde{J}$$

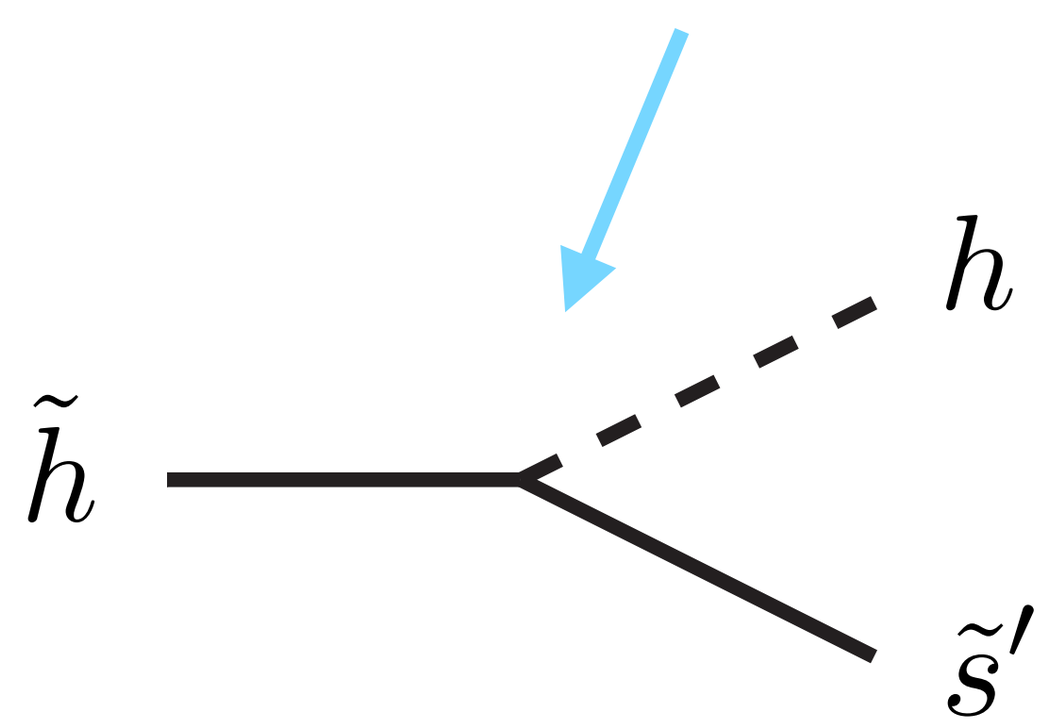
$$\tilde{J} \equiv \partial\mathcal{L}/\partial\tilde{s}$$

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

"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,

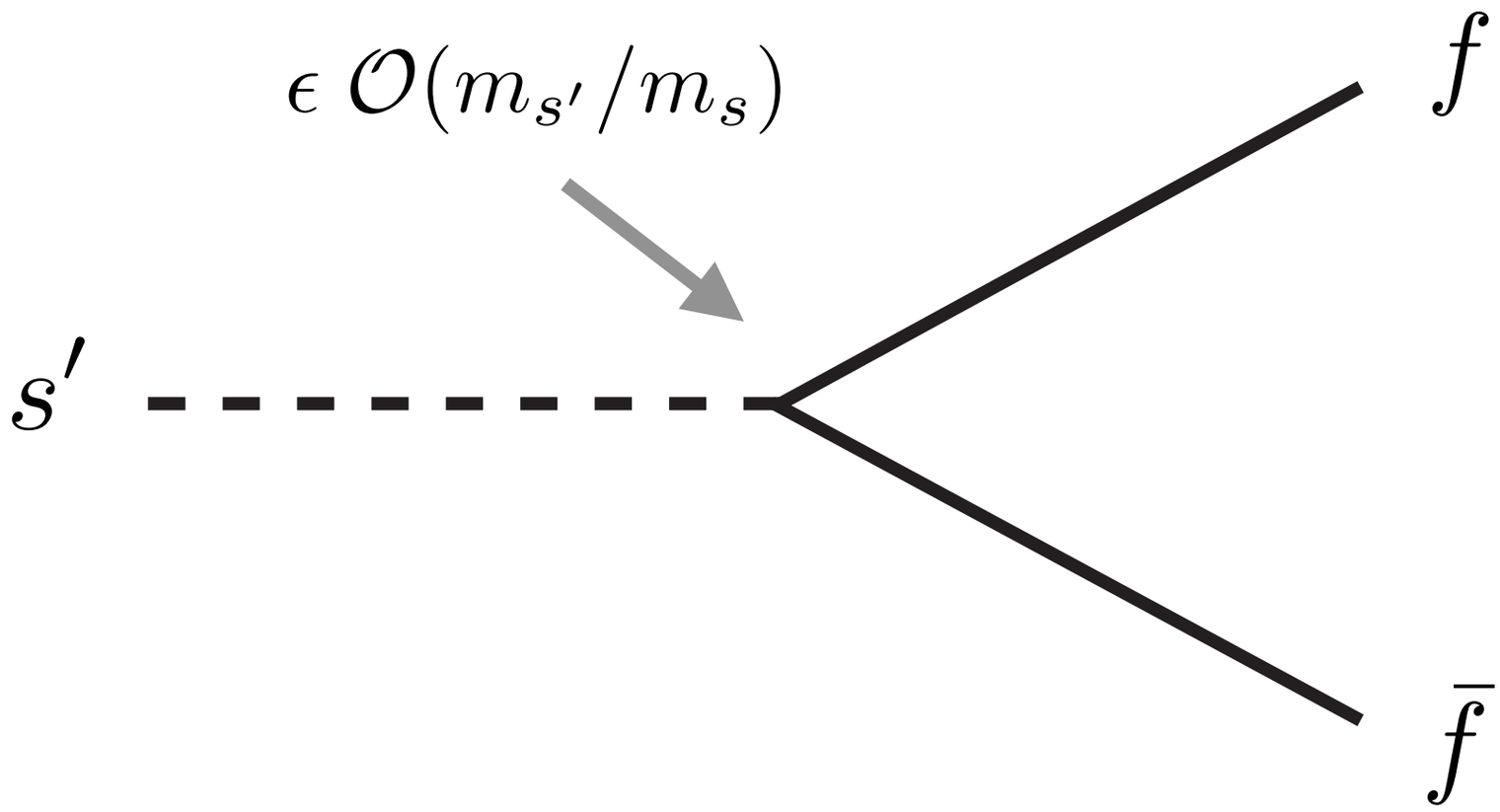
$$\Delta \mathcal{L} = \epsilon s J' + \epsilon \mathcal{O}(m_{s'}/m_s) s' J$$

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

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

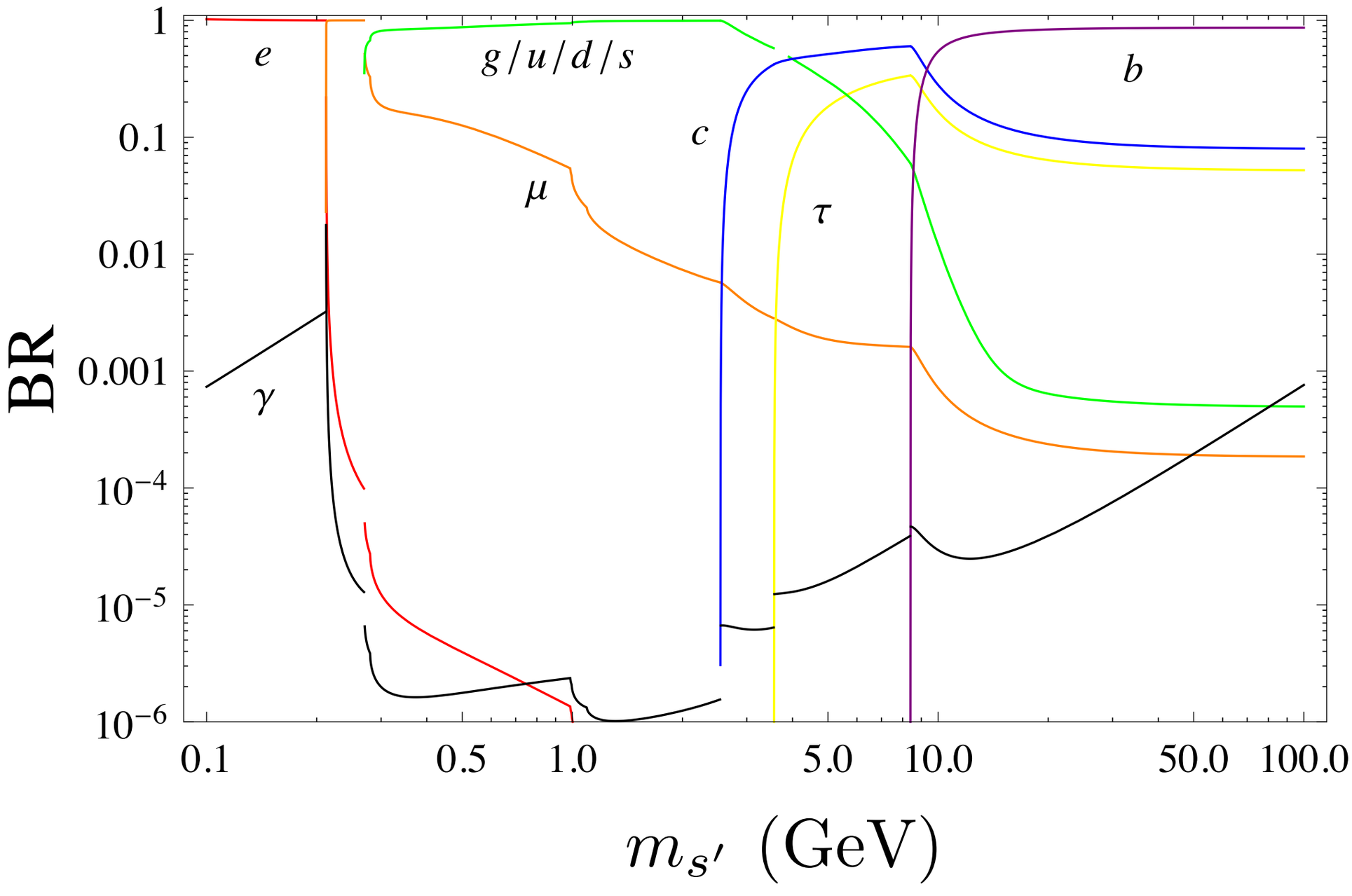
"portal out"

Hence, the hidden singlet decays visibly via



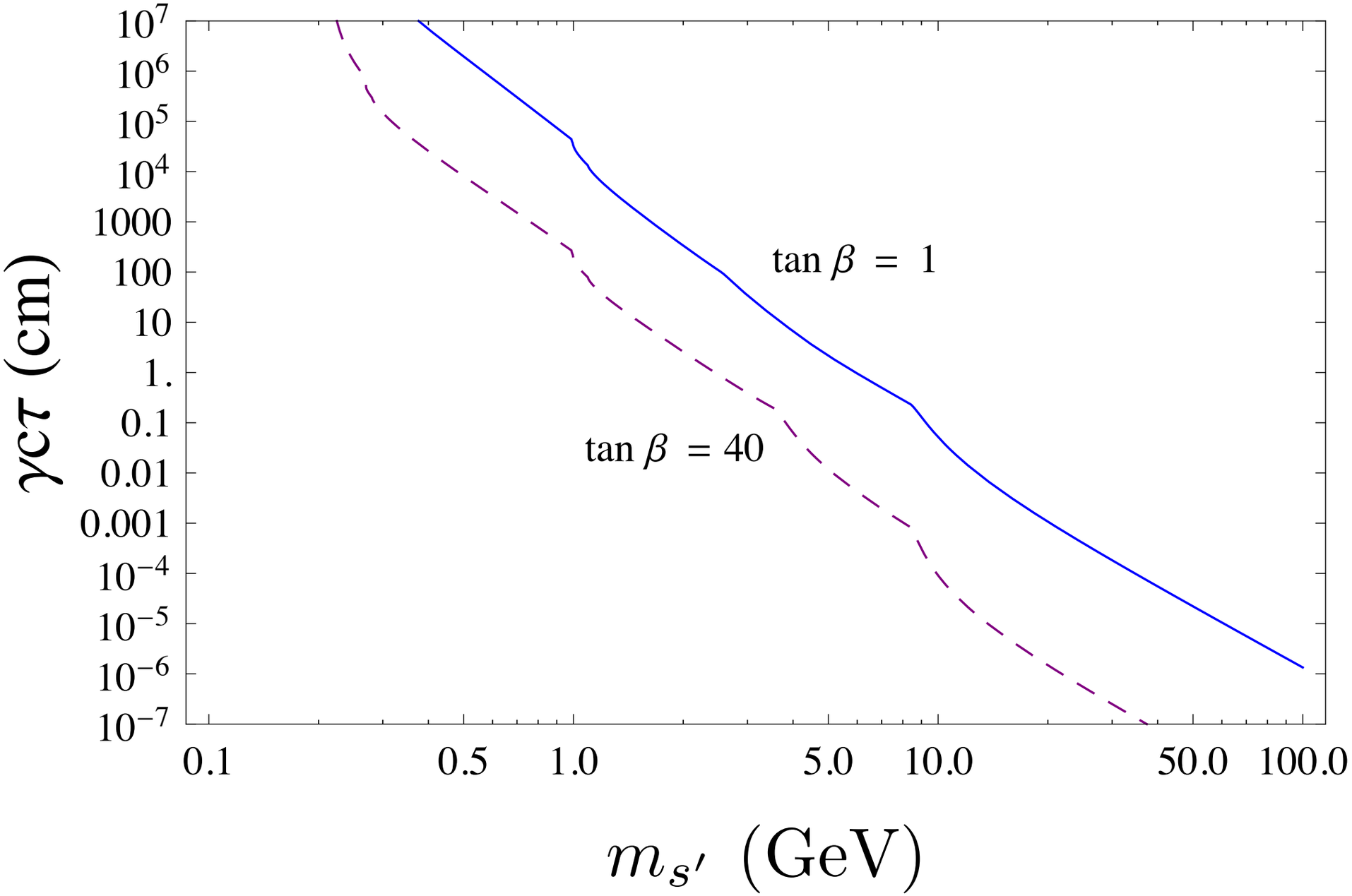
where f is the heaviest allowed SM fermion.

s' decays like light higgs



$\tan\beta = 1$

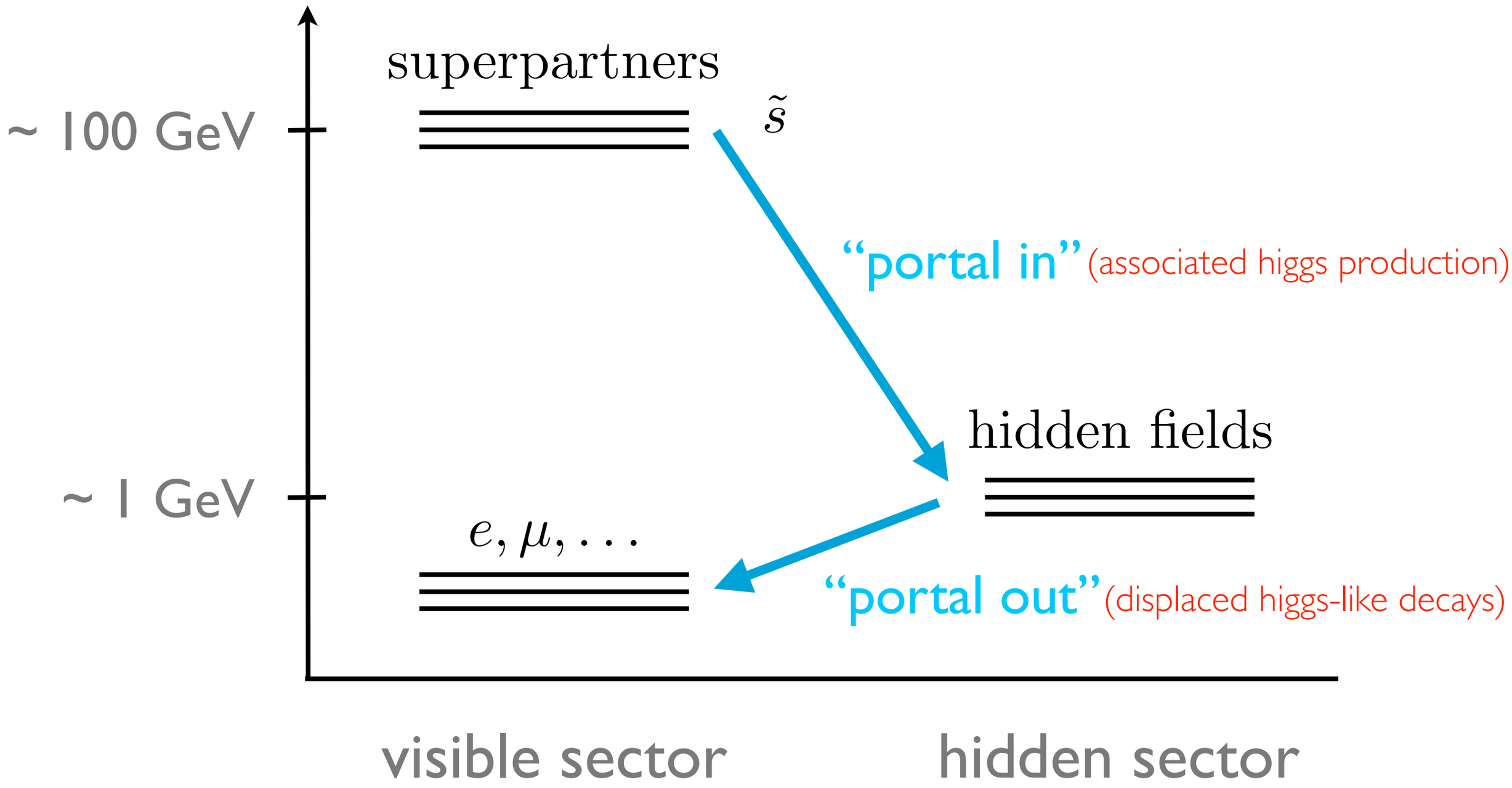
s' decays displaced



$\epsilon = 10^{-2}$

$m_s = 300$ GeV

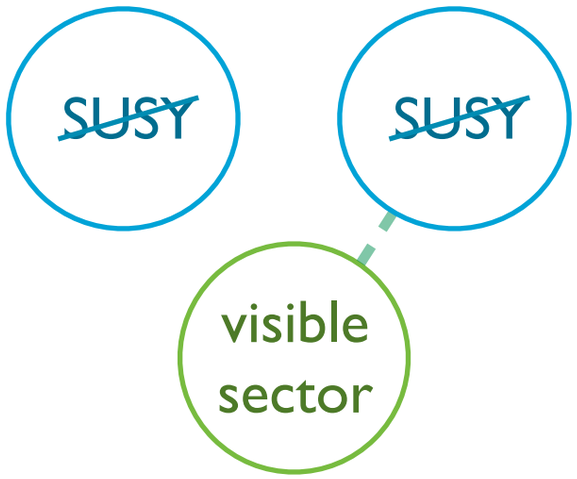
in the collider...

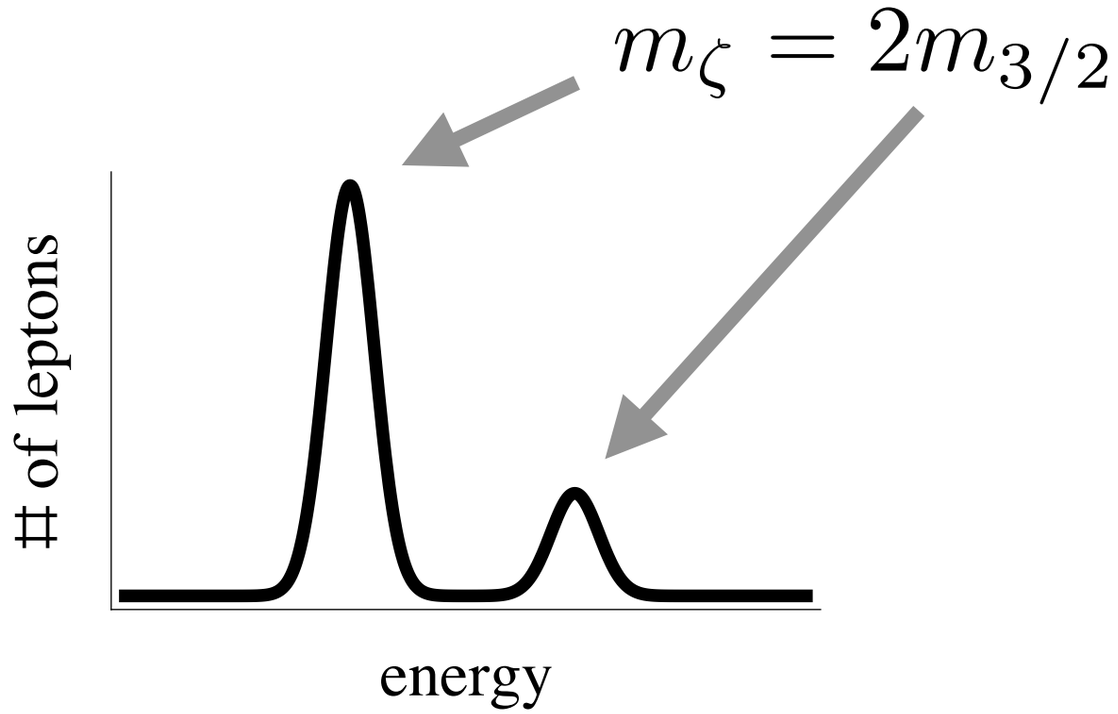


conclusions

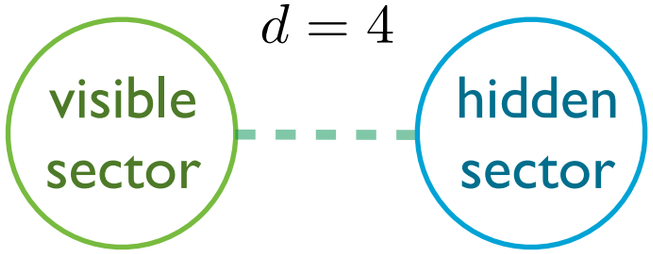
SUSY can probe hidden physics!

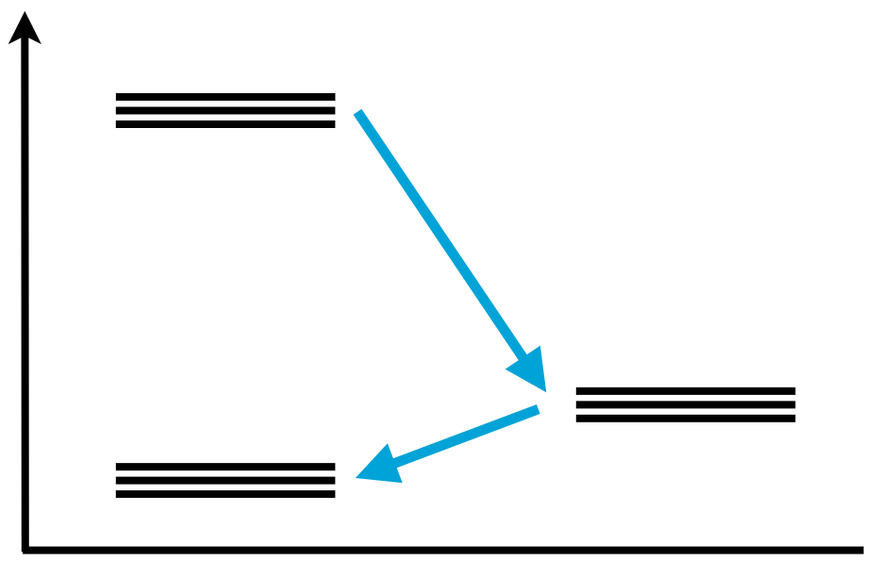
- Goldstini Portal:





- Kinetic Portals:





thanks!