

# Gauge Mediation at Early Stage LHC

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# Plan

1. SUSY Standard Model とMediation機構
2. Gauge Mediationのシグナル
3. Low Scale Gauge MediationとLHC

# 1. SUSY Standard Model とMediation機構

# Supersymmetry



- Hierarchy Problem
- Coupling Unification
- Dark Matter

# Minimal SUSY Standard Model (MSSM)

Standard Model (SM)

Lepton

Quark

Gauge boson

Scalar Higgs

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Standard Model (SM)

Lepton

Quark

Gauge boson

Scalar Higgs

SUSY breaking

SUSY Partner

Scalar Lepton

Scalar Quark

Gaugino

Higgsino

Gets **heavy**.



# Weak Scale SUSY

- Hierarchy Problem
- GUT Unification
- Predictable Dark Matter

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- Hierarchy Problem
- GUT Unification
- Predictable Dark Matter

→  $M_{\tilde{B}} = \mathcal{O}(10 - 100) \text{ GeV}$



# Weak Scale SUSY

- Hierarchy Problem

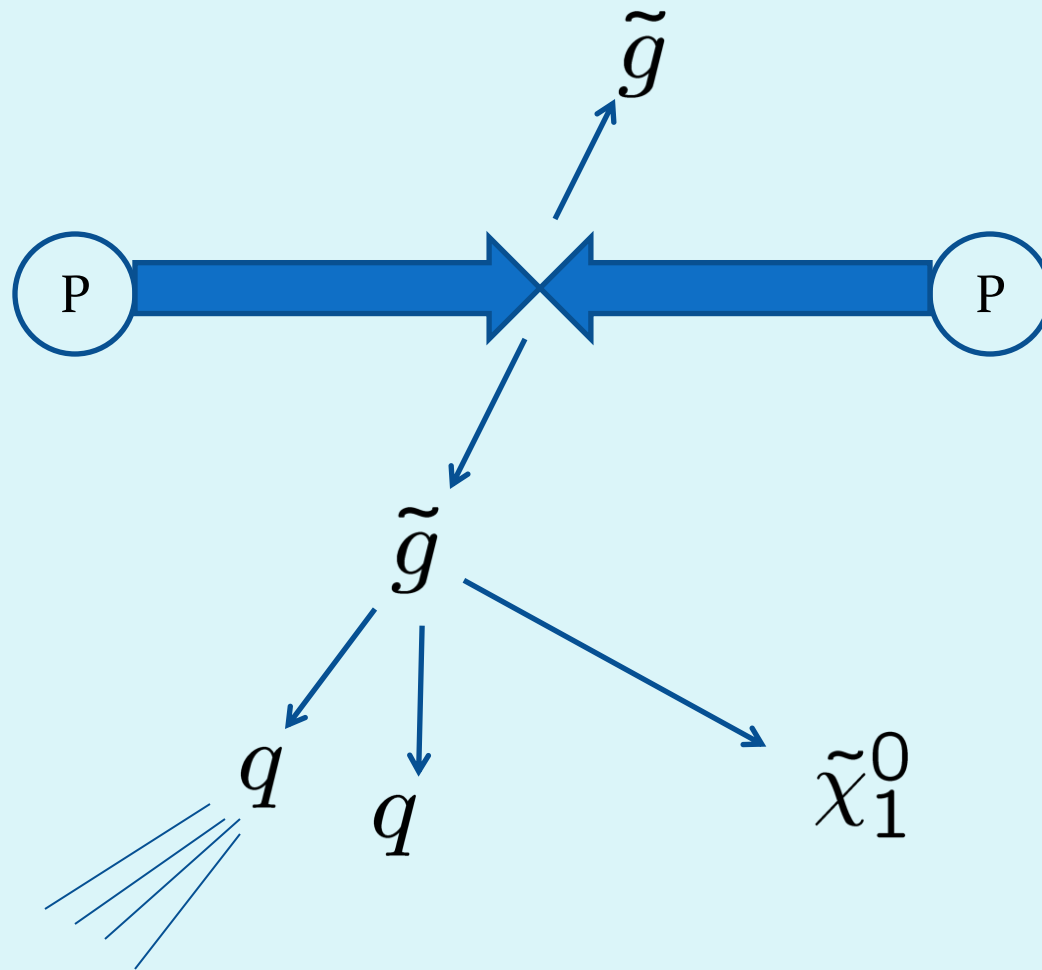
- GUT Unification

$$M_{\tilde{g}} = \mathcal{O}(100 - 1000) \text{ GeV}$$

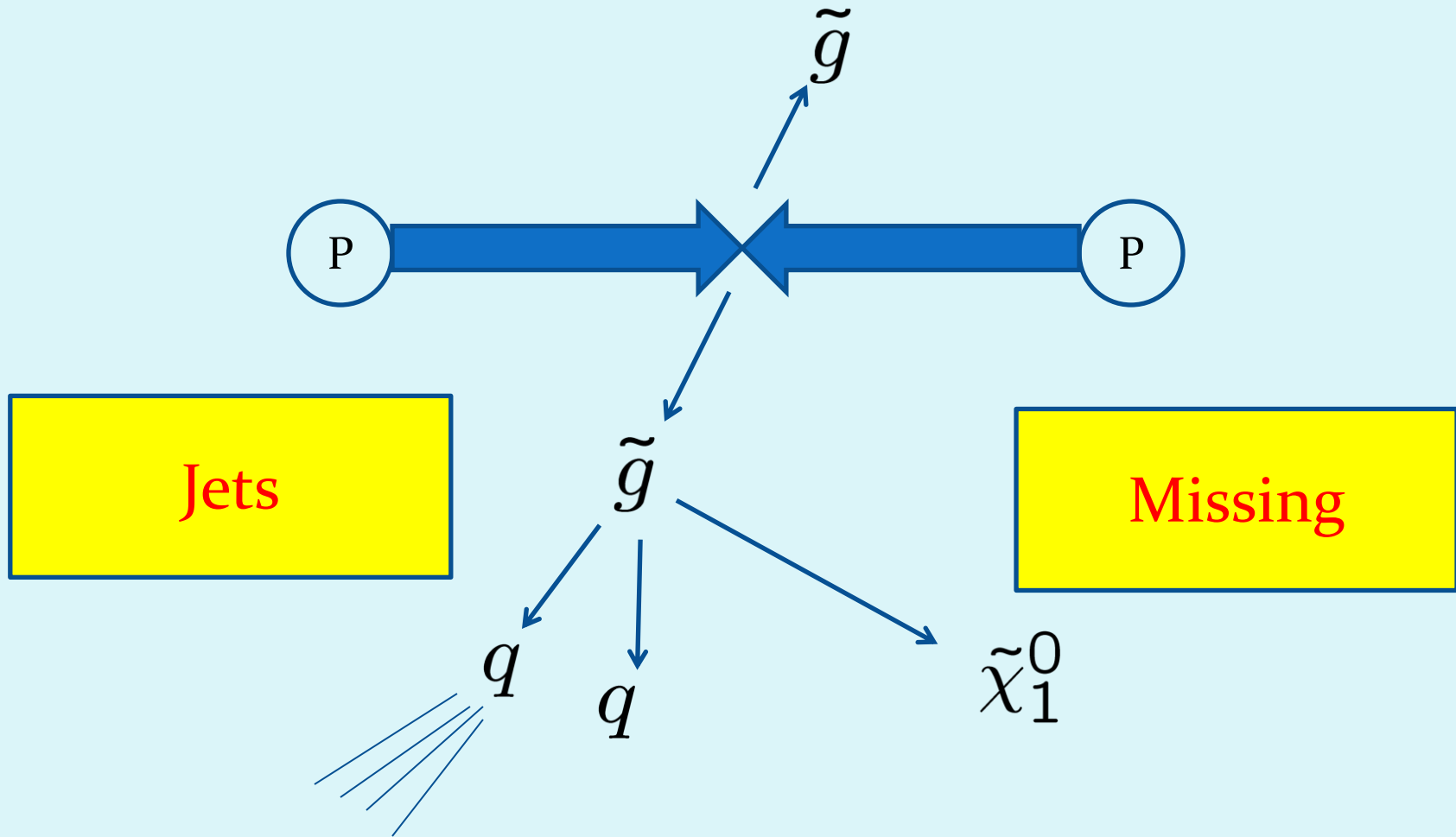
- Predictable Dark Matter

$$\rightarrow M_{\tilde{B}} = \mathcal{O}(10 - 100) \text{ GeV}$$

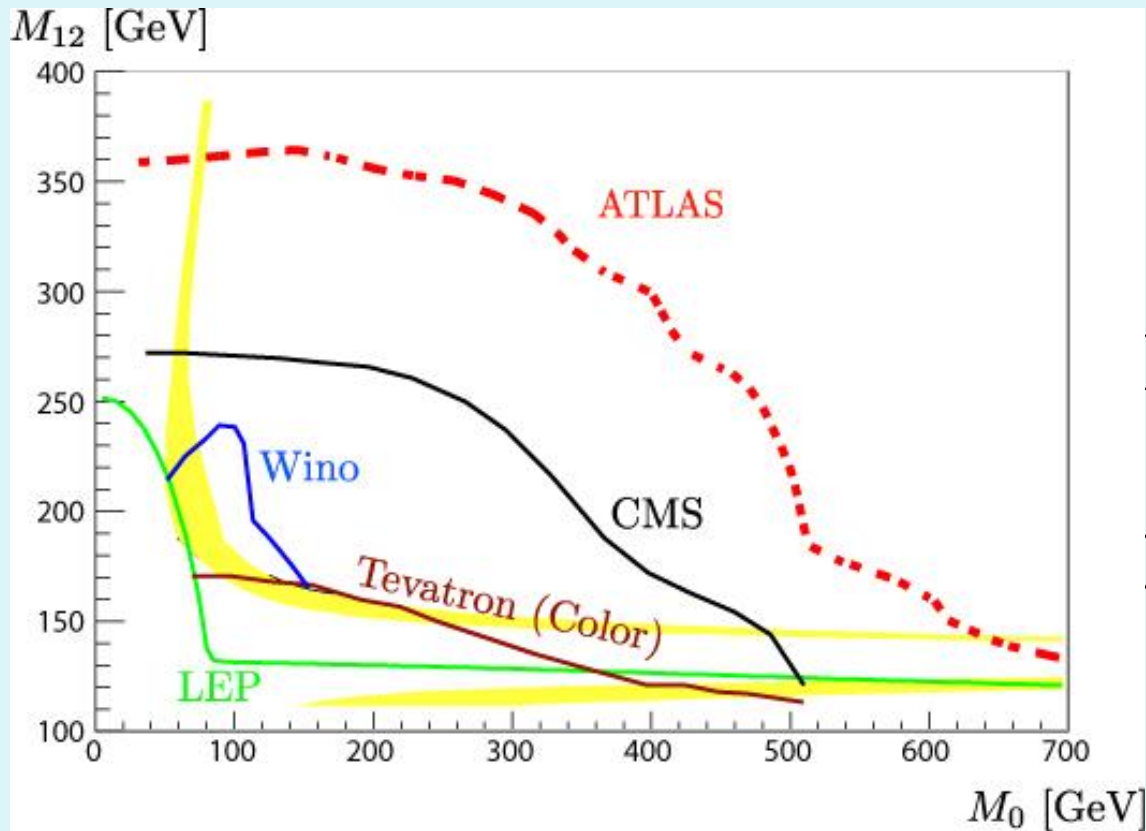
# Event Topology at LHC



# Event Topology at LHC



# Weak Scale SUSY



000) GeV  
↑  
00) GeV

SUSYは良いところだけではない

# SSMの利点と問題点

## 利点

- Hierarchy Problem
- GUT Unification
- Predictable Dark Matter

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- Hierarchy Problem
- GUT Unification
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## 問題点

- Flavor/CP Problem
- Cosmological Gravitino Problem
- UV completion

# SSMの利点と問題点

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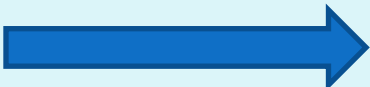
Gravitinoが大きな役割を果たす



# Gravitino

$$m_{3/2} \approx \frac{\Lambda^2}{M_P} \approx 1 \text{ eV} \left( \frac{\Lambda}{100 \text{ TeV}} \right)^2$$

(Local) SUSY  Gravitino

SUSY breaking   $m_{3/2} \approx \frac{\Lambda^2}{M_P}$

$$M_P = 2.4 \times 10^{18} \text{ GeV}$$

$\Lambda$  : SUSY breaking scale.

$$m_{3/2} = 1 \text{ eV} - 100 \text{ TeV}$$

# GravitinoとFlavor/CP Problem

SUGRAを考えると以下のようなhigher dimensional operatorが存在する

$$\int d^4\theta k^{ij} \frac{ZZ^\dagger}{M_P^2} q_i q_j^\dagger \quad \longrightarrow \quad m_{3/2}^2 k^{ij} \tilde{q}_i \tilde{q}_j^\dagger$$

$$\begin{aligned} \langle Z \rangle &= F\theta^2 && : \text{SUSY breaking field} \\ q_i &&& : \text{MSSM field} \end{aligned}$$

# GravitinoとFlavor/CP Problem

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$$\langle Z \rangle = F\theta^2 \quad : \text{SUSY breaking field}$$

$$q_i \quad : \text{MSSM field}$$

$m_0^2 \tilde{d} \tilde{d}^\dagger$  のようなgravity mediationに現れるsoft massが生成される

# GravitinoとFlavor/CP Problem 2

SUGRAを考えると以下のようなhigher dimensional operatorが存在する

$$\int d^4\theta k^{ij} \frac{ZZ^\dagger}{M_P^2} q_i q_j^\dagger \quad \longrightarrow \quad m_{3/2}^2 k^{ij} \tilde{q}_i \tilde{q}_j^\dagger$$

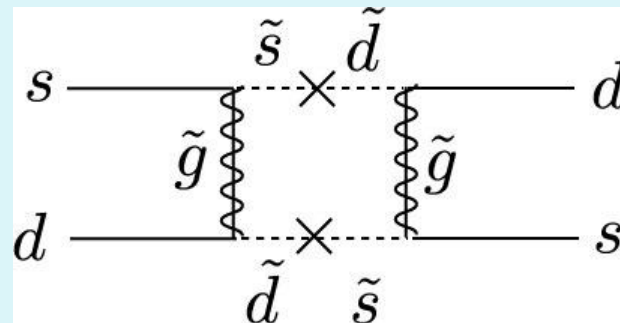
$$\langle Z \rangle = F\theta^2 \quad : \text{SUSY breaking field}$$

$$q_i \quad : \text{MSSM field}$$

一般には

$$\tilde{s} \tilde{d}^\dagger$$

のようなFlavorを破るような寄与が存在する



# GravitinoとFlavor/CP Problem 2

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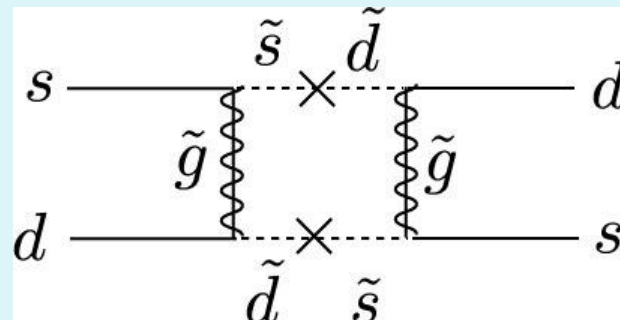
$$q_i \quad : \text{MSSM field}$$

一般には

$$\tilde{s}\tilde{d}^\dagger$$

のようなFlavorを破るような寄与が存在する

$$\frac{m_{\tilde{s}\tilde{d}}^2}{m_{\tilde{s}}^2} \lesssim 10^{-2} \quad \text{for } M_{\text{SUSY}} = 500 \text{ GeV}$$



# GravitinoとFlavor/CP Problem 2

SUGRAを考えると以下のようなhigher dimensional operatorが存在する

$$\int d^4\theta k^{ij} \frac{ZZ^\dagger}{M_P^2} q_i q_j^\dagger \longrightarrow m_{3/2}^2 k^{ij} \tilde{q}_i \tilde{q}_j^\dagger$$

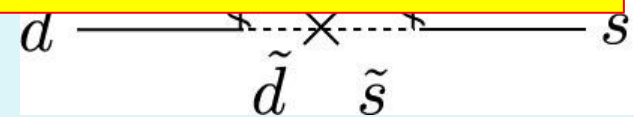
Gravitinoを軽くする

or

SUSY scaleを上げる

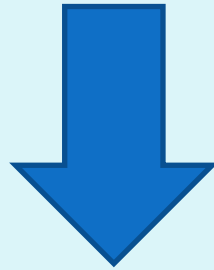
or

このような項を禁止する機構やfine-tuningが必要

$$\frac{m_{\tilde{s}\tilde{d}}^2}{m_{\tilde{s}}^2} \lesssim 10^{-2} \quad \text{for } M_{\text{SUSY}} = 500 \text{ GeV}$$


# Gravitinoと宇宙

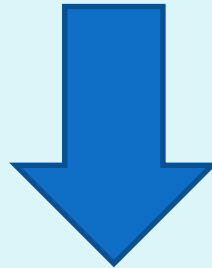
Gravitinoは宇宙の発展史に(余計な)影響を与える



Gravitinoの性質や存在量を考える必要あり

# Gravitinoと宇宙

Gravitinoは宇宙の発展史に(余計な)影響を与える



Gravitinoの性質や存在量を考える必要あり

主に質量

宇宙の詳細な歴史  
インフレーションモデルなど



# Gravitinoの質量と性質

**Case I:** Heavy Gravitino  $> O(100)$  GeV

不安定. Strength of interaction  $\frac{1}{M_P}$

**Case II:** Light Gravitino

安定. 暗黒物質の候補?

Strength of interaction  $\frac{1}{m_{3/2} M_P}$

# Gravitinoの質量と性質

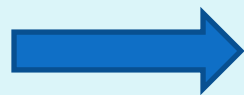
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不安定. Strength of interaction  $\frac{1}{M_P}$

**Case II:** Light Gravitino

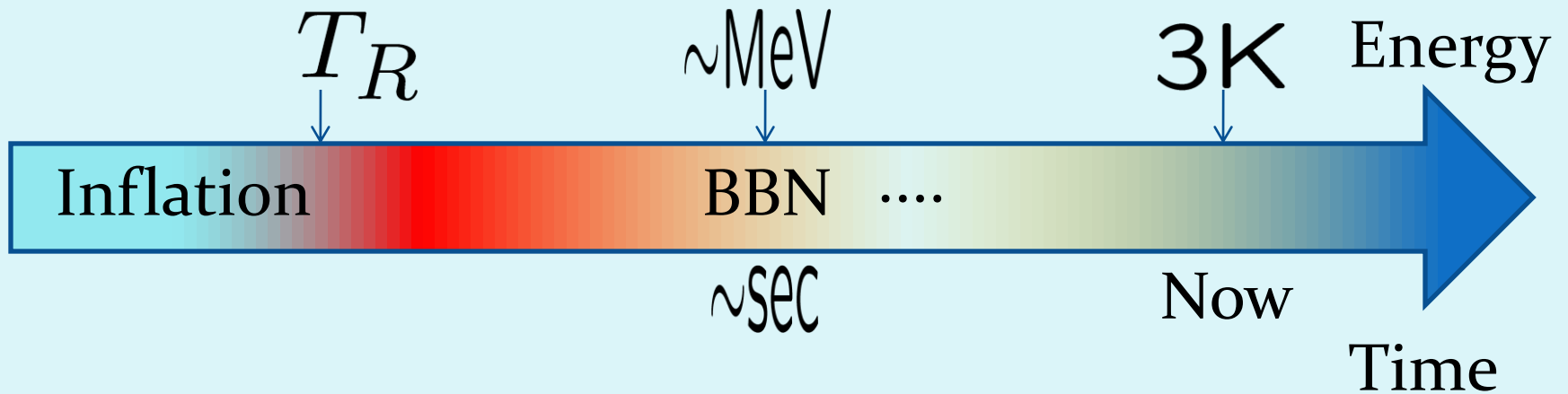
安定. 暗黒物質の候補?

Strength of interaction  $\frac{1}{m_{3/2}M_P}$

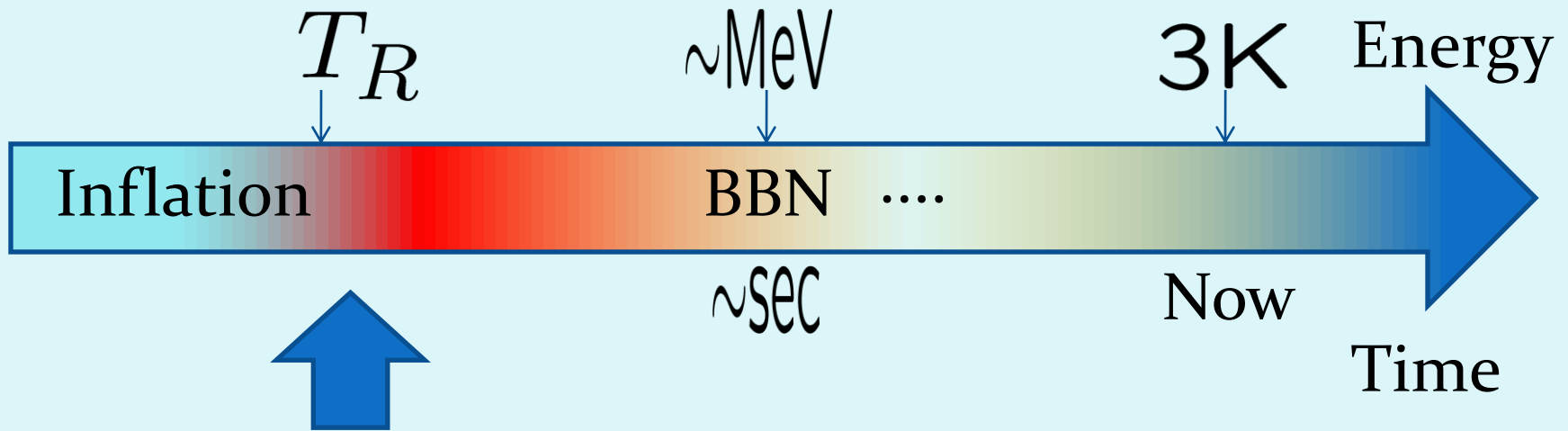


質量が軽いと相互作用が強い

# Gravitino production



# Gravitino production



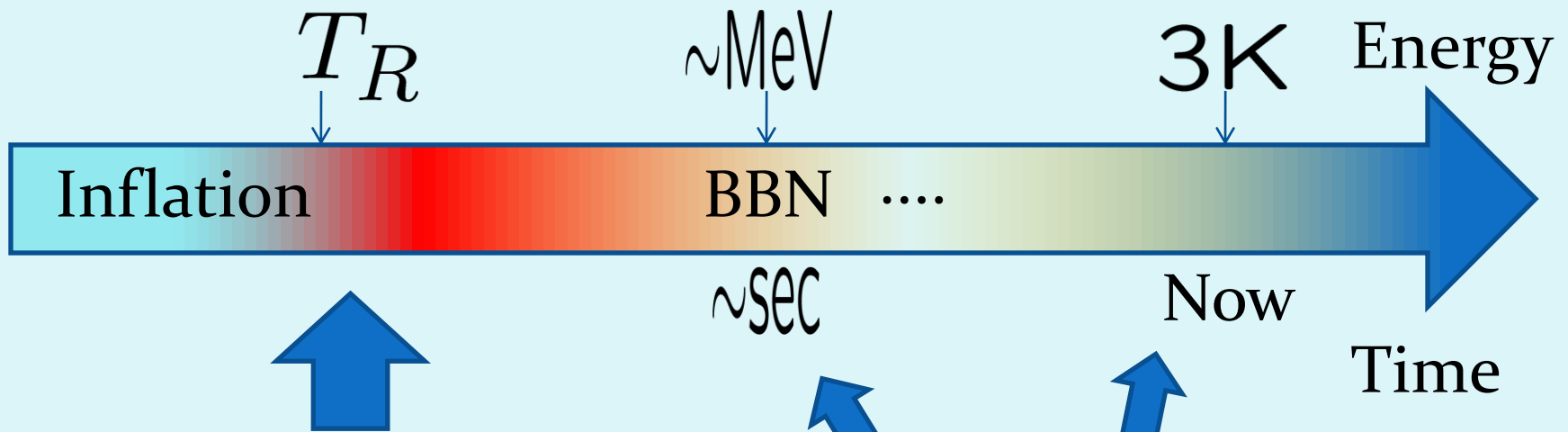
Gravitino production

熱散乱

SUSY粒子の崩壊

Inflatonなどのhidden fieldからの生成

# Gravitino production



Gravitino production

熱散乱

SUSY粒子の崩壊

Inflatonなどのhidden fieldからの生成

Gravitino Problem

# Gravitino Problem

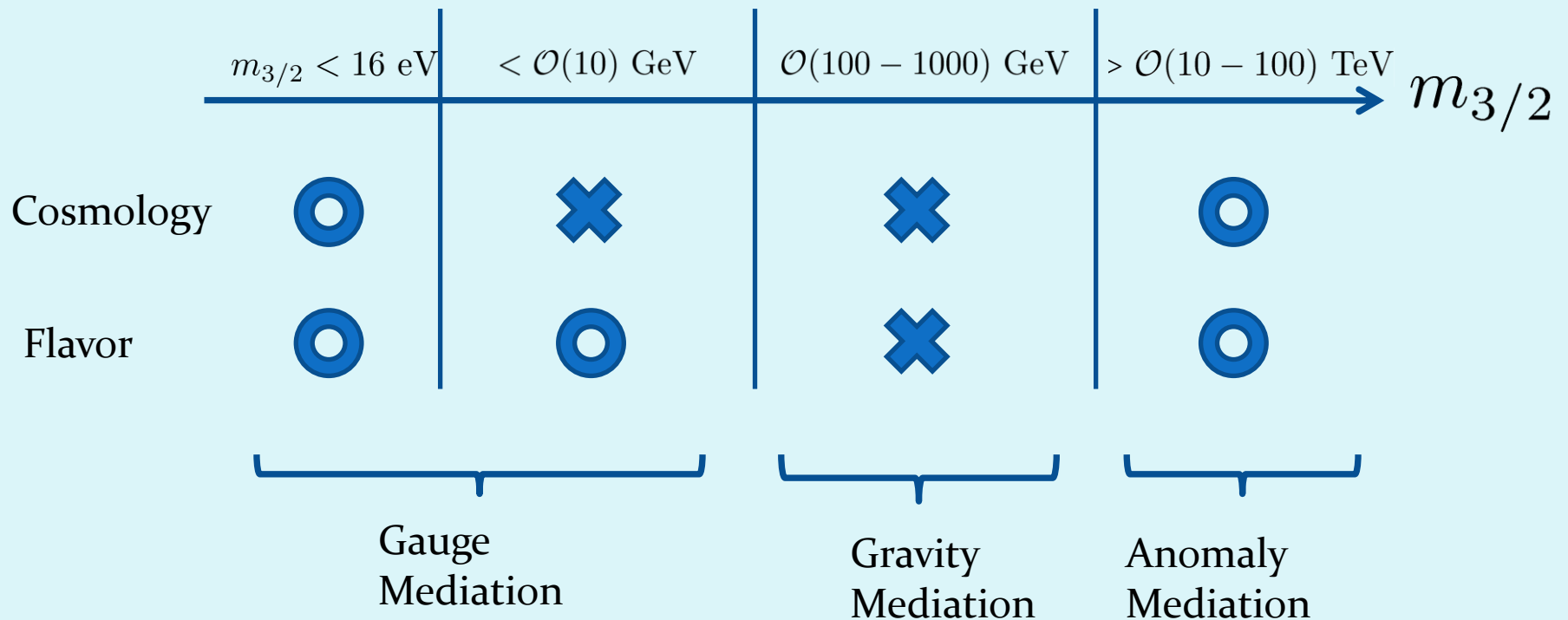
1. **Heavy case**  $m_{3/2} > \mathcal{O}(100)$  GeV

Unstable. Spoilage of BBN.

2. **Light case**  $\mathcal{O}(10)$  GeV  $> m_{3/2} > \mathcal{O}(1)$  MeV

Stable. Overclosure of Universe.

# Gravitino Massと諸問題



# Gravitino Massと諸問

Gravitinoの寿命が短いので生成されても問題を起こさない

$$\tau \sim 0.1 \text{ sec} \left( \frac{m_{3/2}}{10 \text{ TeV}} \right)^{-3}$$

	$m_{3/2} < 16 \text{ eV}$	$< \mathcal{O}(10) \text{ GeV}$	$\mathcal{O}(100 - 1000) \text{ GeV}$	
Cosmology	○	×	×	○
Flavor	○	○	×	○
	Gauge Mediation		Gravity Mediation	Anomaly Mediation



# Massと諸問

Gravitinoのエネルギー密度が小さいので問題ない

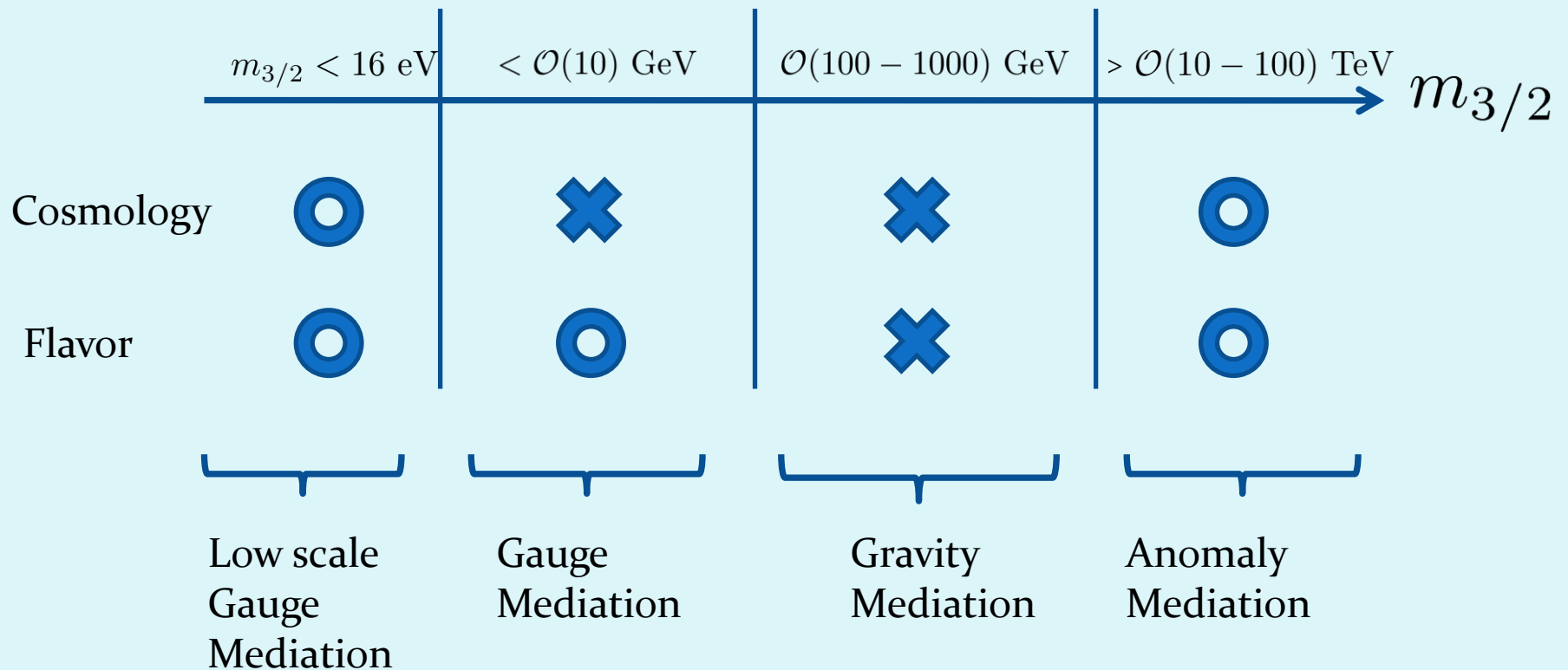
$$\Omega h^2 = 0.05 \left( \frac{m_{3/2}}{100 \text{ eV}} \right)$$

Gravitinoの寿命が短いので生成されても問題を起こさない

$$\tau \sim 0.1 \text{ sec} \left( \frac{m_{3/2}}{10 \text{ TeV}} \right)^{-3}$$

	$\mathcal{O}(10) \text{ GeV}$	$\mathcal{O}(100 - 1000) \text{ GeV}$	
Cosmology	○	×	○
Flavor	○	○	○
	Gauge Mediation		Anomaly Mediation
		Gravity Mediation	

# Gravitino Massと諸問題



# Gravity Mediation

$$M_{\text{gaugino}} \sim M_{\text{scalar}} \sim m_{3/2} = \mathcal{O}(100) \text{ GeV}$$

## 利点

- Hierarchy Problem ○
- GUT Unification ○
- Predictable Dark Matter ○

## 問題点

- Flavor/CP Problem ✕
- Cosmological Gravitino Problem ✕
- UV completion ✕

# Anomaly Mediation

$$M_{\text{gaugino}} = \mathcal{O}(100) \text{ GeV}, M_{\text{scalar}} \sim m_{3/2} = \mathcal{O}(100) \text{ TeV}$$

## 利点

- Hierarchy Problem ✖
- GUT Unification ○
- Predictable Dark Matter △




## 問題点

- Flavor/CP Problem ○
- Cosmological Gravitino Problem ○
- UV completion ✖




# Gauge Mediation

$$M_{\text{scalar}} \sim (?)M_{\text{gaugino}} = \mathcal{O}(100) \text{ GeV}, m_{3/2} < \mathcal{O}(10) \text{ GeV}$$

## 利点

- Hierarchy Problem 
- GUT Unification 
- Predictable Dark Matter 

## 問題点

- Flavor/CP Problem 
- Cosmological Gravitino Problem 
- UV completion 

# Gravitino Massと諸問題

	Low scale Gauge Mediation	Gauge Mediation	Gravity Mediation	Anomaly Mediation
Hierarchy	○	○	○	×
GUT	○	○	○	○
Dark Matter	×	△	○	△
Cosmology	○	×	×	○
Flavor	○	○	×	○
UV	○	○	×	×

# Gravitino Massと諸問題

LHC signalはだいたい同じ

	Low scale Gauge Mediation	Gauge Mediation	Gravity Mediation	Anomaly Mediation
Hierarchy	○	○	○	×
GUT	○	○	○	○
Dark Matter	×	△	○	△
Cosmology	○	×	×	○
Flavor	○	○	×	○
UV	○	○	×	×

[Asai, Moroi, Yanagida: 08]

[Asai, Azuma, Jinnouchi, Moroi, SS, Yanagida: 08]

# Gravitino Massと諸問題

LHC signalはだ

統計がたま  
ればWino  
Co-NLSPのt  
ラックが見え  
るかも

	Low scale Gauge Mediation	Gauge Mediation	Gravity Mediation	Anom. Mediation
Hierarchy	○	○	○	×
GUT	○	○	○	○
Dark Matter	×	△	○	△
Cosmology	○	×	×	○
Flavor	○	○	×	○
UV	○	○	×	×



# Gravitino Massと諸問題

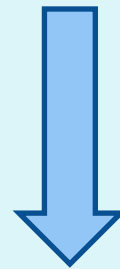
変なLHC signalを出す可能性

	Low scale Gauge Mediation	Gauge Mediation	Gravity Mediation	Anomaly Mediation
Hierarchy	○	○	○	×
GUT	○	○	○	○
Dark Matter	×	△	○	△
Cosmology	○	×	×	○
Flavor	○	○	×	○
UV	○	○	×	×

## 2. Gauge Mediationのシグナル

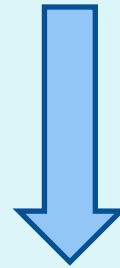
# Minimal GMSB

Hidden  $F \neq 0$

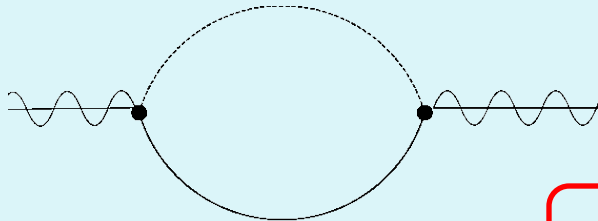


$$kS\bar{\psi}\psi \quad \langle S \rangle = F\theta^2$$

Messenger  $\psi \sim (d, \ell)$

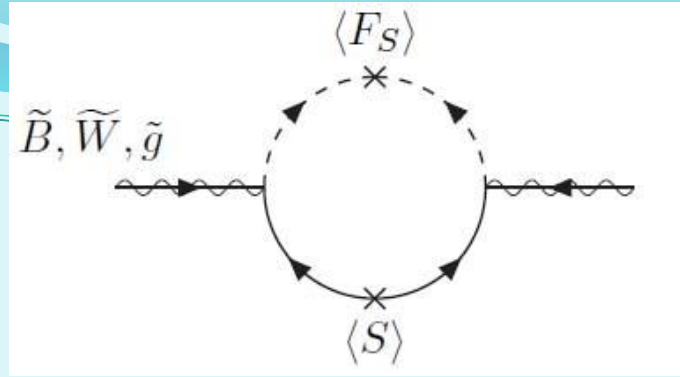


SM gauge interaction



MSSM

# Minimal GMSB



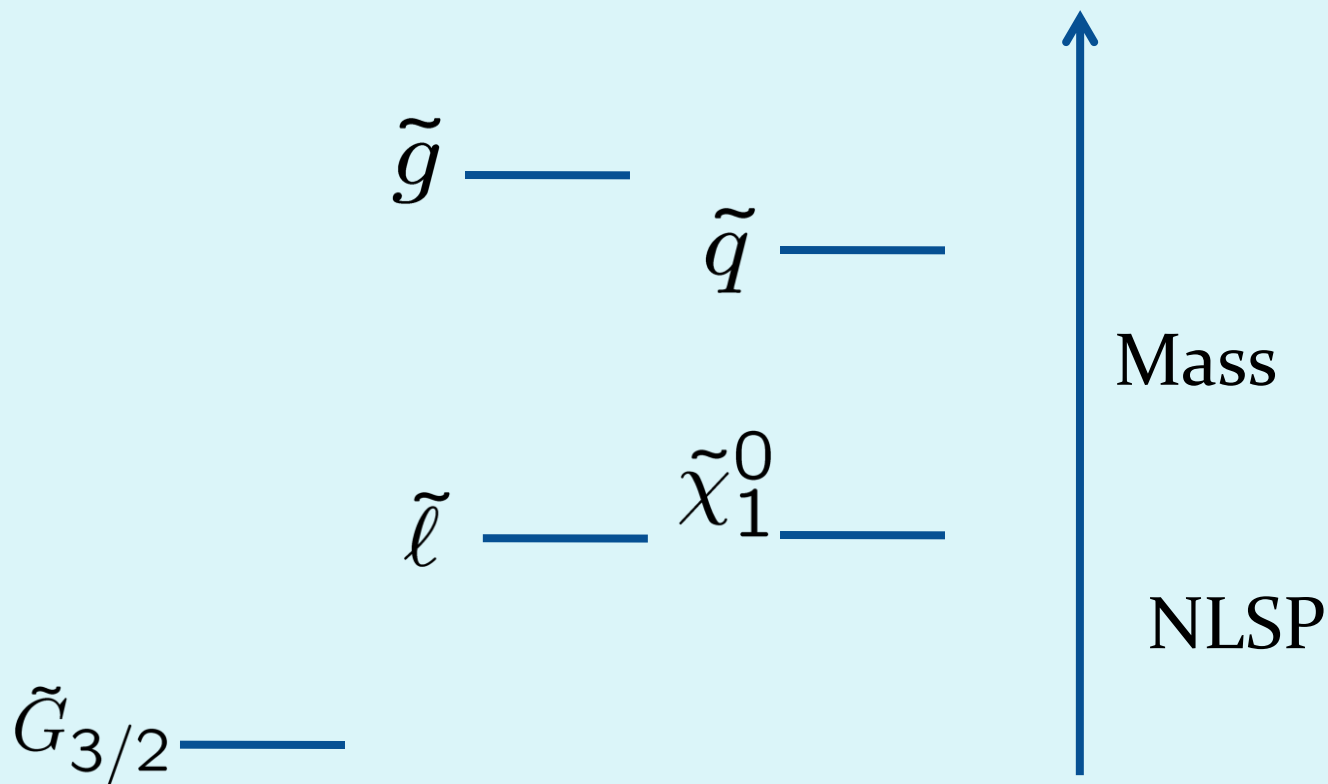
$$m_{\text{scalar}}^2 = 2N_{\text{mess}} \left( \frac{\alpha}{4\pi} \right)^2 \left( \frac{kF}{M_{\text{mess}}} \right)^2 \left( 1 + \mathcal{O} \left( \frac{kF}{M_{\text{mess}}^2} \right) \right)$$

$$m_{\text{gaugino}} = N_{\text{mess}} \left( \frac{\alpha}{4\pi} \right) \frac{kF}{M_{\text{mess}}} \left( 1 + \mathcal{O} \left( \frac{kF}{M_{\text{mess}}^2} \right) \right)$$

$$M^2 > kF, N_{\text{mess}} = \mathcal{O}(1)$$

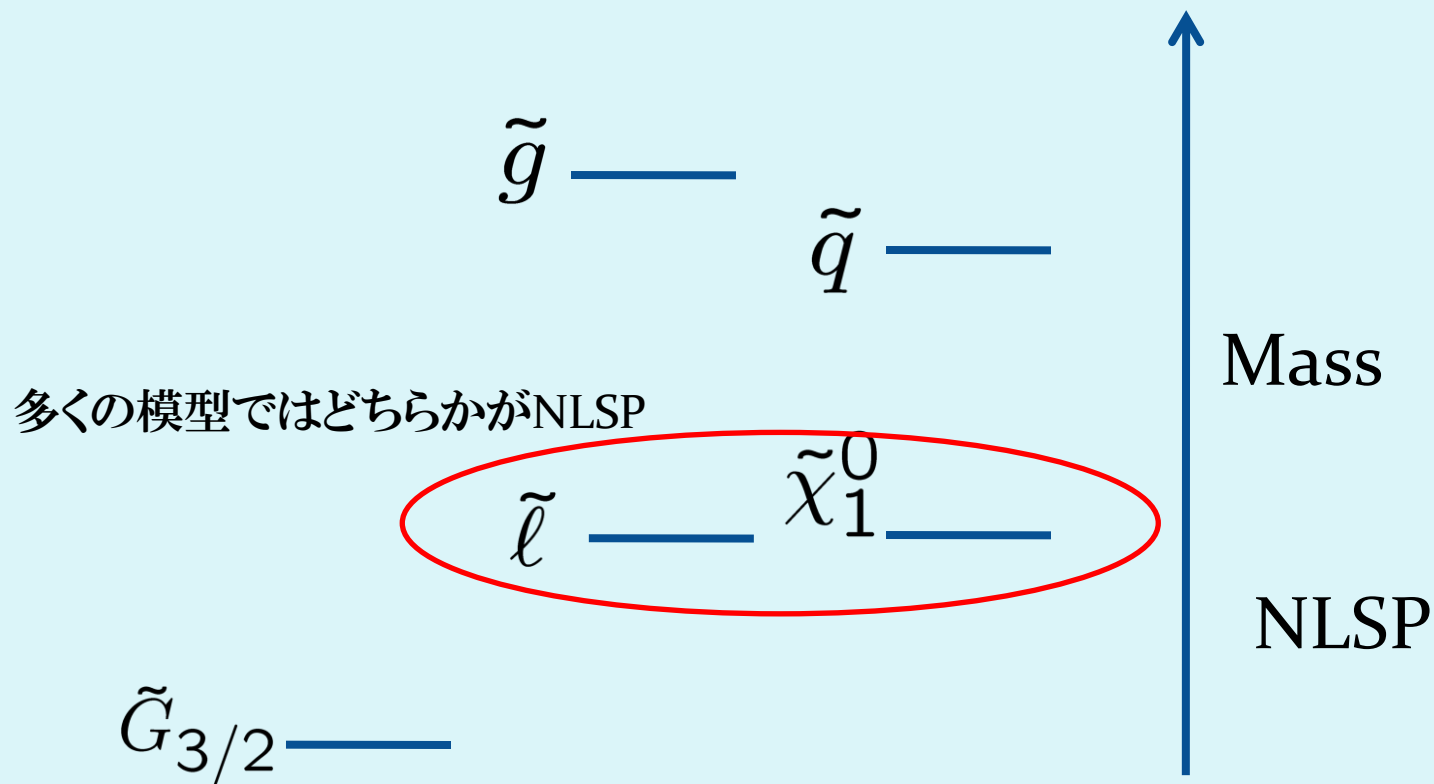
# Mass Spectrum

BinoはvLSP (visible LSP)である必要はない

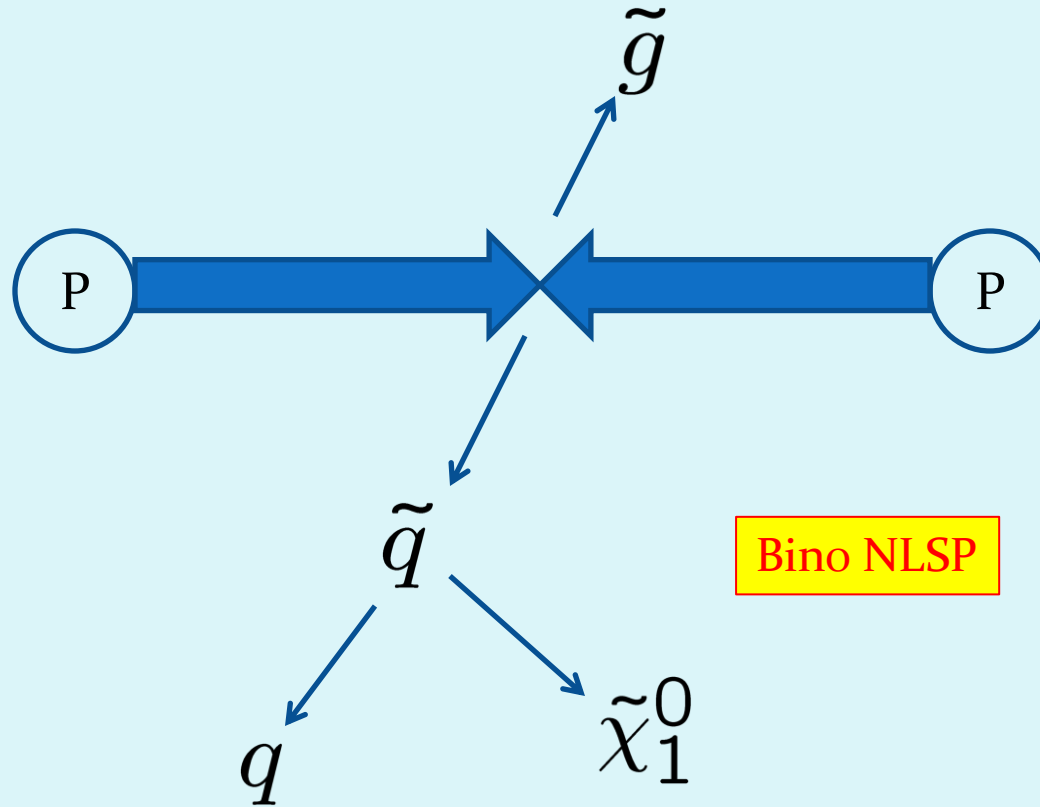


# Mass Spectrum

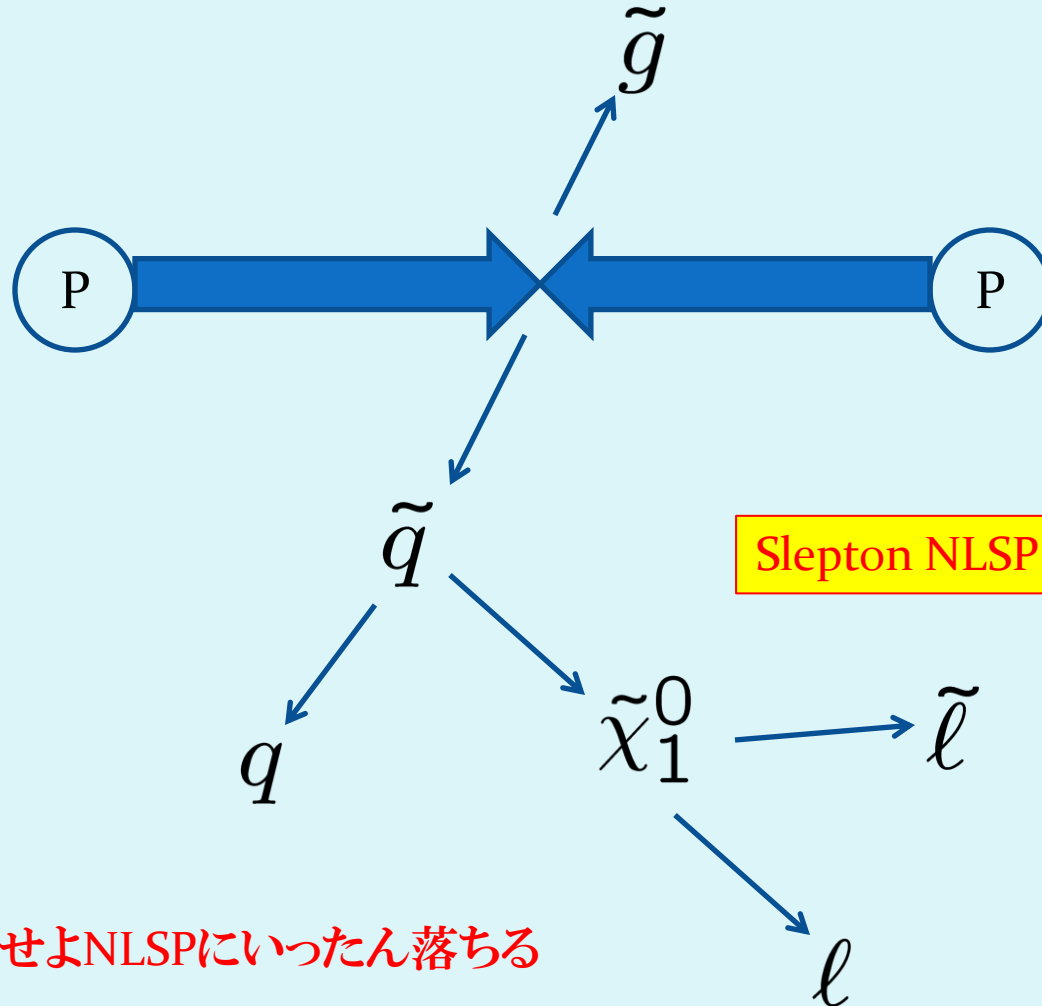
BinoはvLSP (visible LSP)である必要はない



# GMSBでのEvent Topology



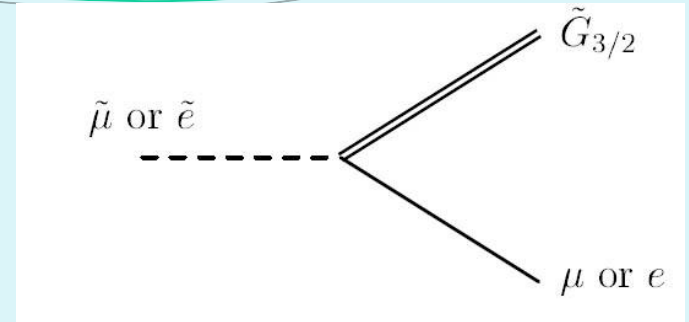
# GMSBでのEvent Topology



いずれにせよNLSPにいったん落ちる



# NLSP Decay



$$\text{NLSP} \rightarrow \text{SM} + \tilde{G}_{3/2}$$

$$c\tau \simeq 20 \mu\text{m} \left( \frac{m_{3/2}}{1 \text{ eV}} \right)^2 \left( \frac{m_{\text{NLSP}}}{100 \text{ GeV}} \right)^{-5}$$

$m_{3/2} \gtrsim \text{keV}$   Detectorの外まで長生き

$m_{3/2} \lesssim \text{keV}$   Detector内で崩壊

# NLSPの崩壊の観測、測定についてみる

- In-flight decayなどが見つければBSMの最も直接的証拠
- 寿命が測ることができればグラビティーノの質量が分かる

# Lifetimeとシグナル

**Case I:** short lifetime  $c\tau < \mathcal{O}(10) \text{ m}$

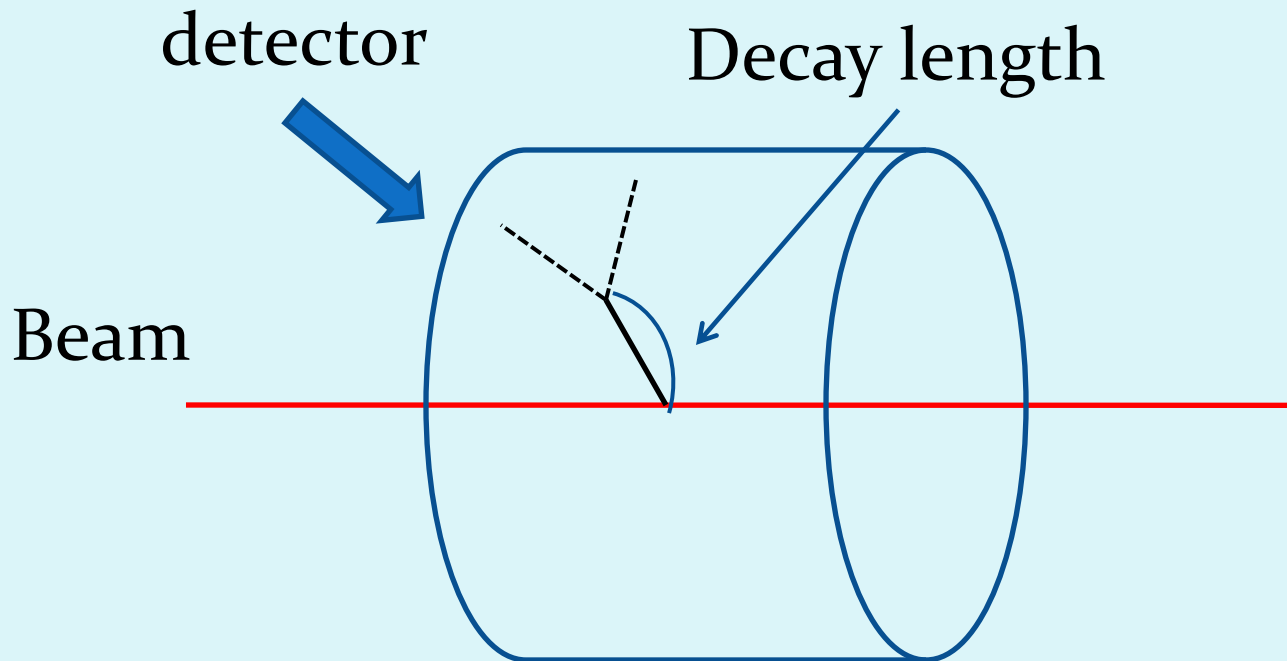
detector size

**Case II:** semi-long lifetime  $\mathcal{O}(10) \text{ m} < c\tau < \mathcal{O}(10^3) \text{ km}$

**Case III:** long lifetime  $\tau > \mathcal{O}(0.01) \text{ sec}$

# 崩壊長が短いとき

Case I: short lifetime  $c\tau < \mathcal{O}(10)$  m  $m_{3/2} < \text{keV}$



# 崩壊長が短いときの方法

Case I: short lifetime

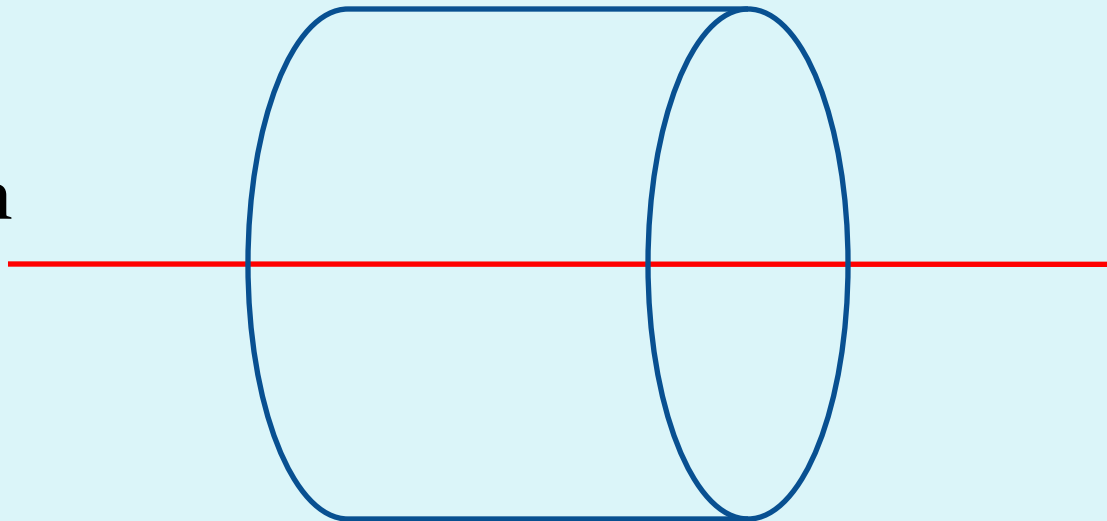
- B-taggingのようにdisplaced vertexを見る  
 $\mathcal{O}(100) \mu\text{m}$  Decay productに荷電粒子が必要
- 内部飛跡検出器を利用  
 $\mathcal{O}(10) \text{ cm}$  NLSPが荷電粒子である必要あり  
Decay productはなんでもOK
- EM Cal  
 $\mathcal{O}(10) \text{ cm}$  Non-pointing photonとかもOK

# 崩壊長がdetectorより大きめの時

$$\text{keV} < m_{3/2} < \text{MeV}$$

Case II: semi-long lifetime  $\mathcal{O}(10) \text{ m} < c\tau < \mathcal{O}(10^3) \text{ km}$

Beam

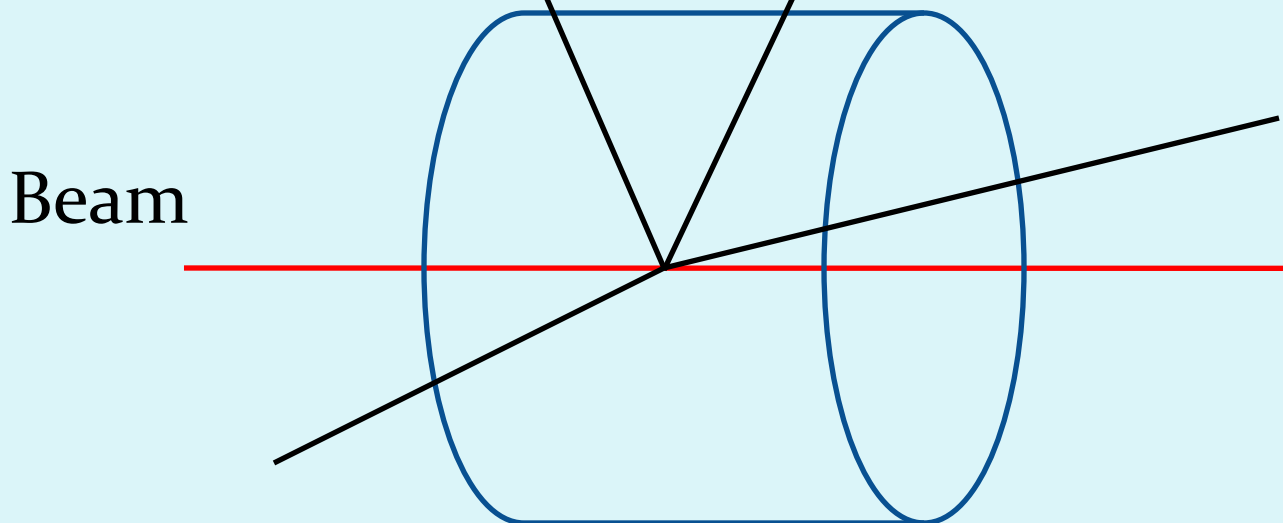


# 崩壊長がdetectorより大きめの時

$$\text{keV} < m_{3/2} < \text{MeV}$$

Case II: semi-long lifetime  $\mathcal{O}(10) \text{ m} < c\tau < \mathcal{O}(10^3) \text{ km}$

Almost all NLSPs escape

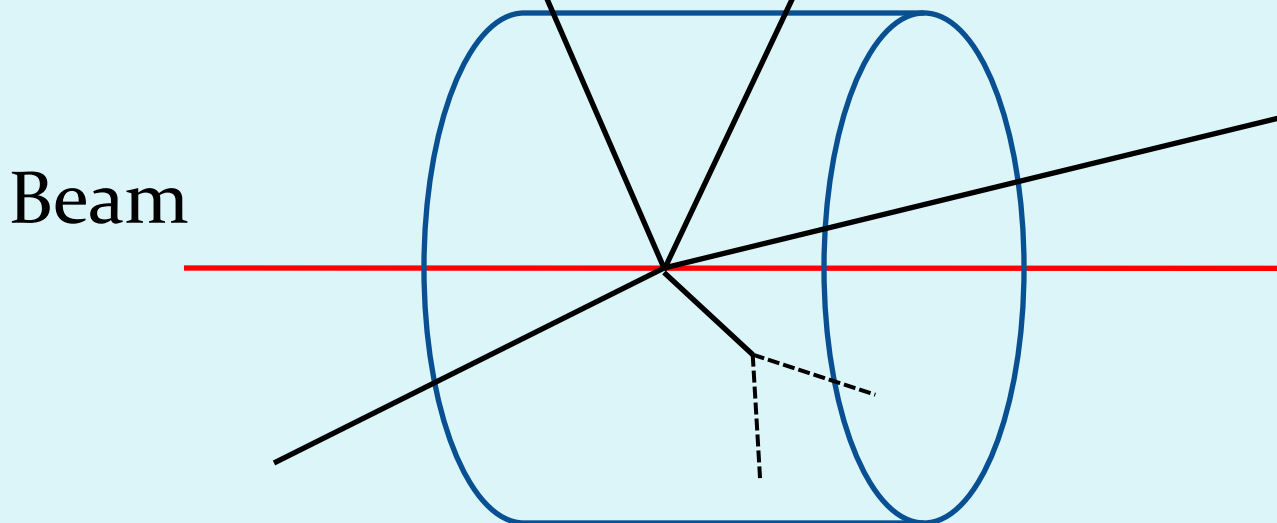


# 崩壊長がdetectorより大きめの時

$$\text{keV} < m_{3/2} < \text{MeV}$$

Case II: semi-long lifetime  $\mathcal{O}(10) \text{ m} < c\tau < \mathcal{O}(10^3) \text{ km}$

Almost all NLSPs escape



一部の崩壊はdetector内でも起きうる



# 崩壊長がdetectorより大きめの時

$$\text{keV} < m_{3/2} < \text{MeV}$$

Case II: semi-long lifetime  $\mathcal{O}(10) \text{ m} < c\tau < \mathcal{O}(10^3) \text{ km}$

Almost all NLSPs escape

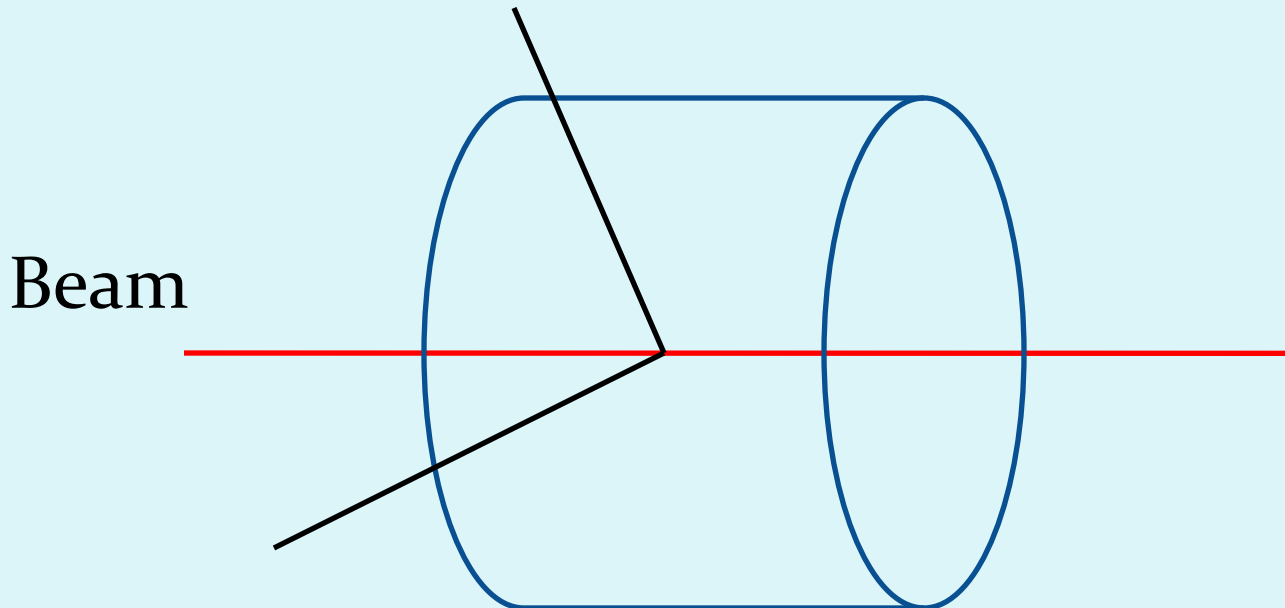
$$c\tau \sim \frac{\# \text{ of NLSPs}}{\# \text{ of decays inside of detector}} \times \text{detector size}$$

一部の崩壊はdetector内でも起きうる

# 崩壊長がdetectorよりずっと大きい時

$$m_{3/2} > \text{MeV}$$

Case III: long lifetime  $\tau > \mathcal{O}(0.1) \text{ sec}$



Bino NLSPの場合は、missing energyにしか見えない

Slepton NLSPの場合はmassive charged trackが見える

# Stopped Slepton

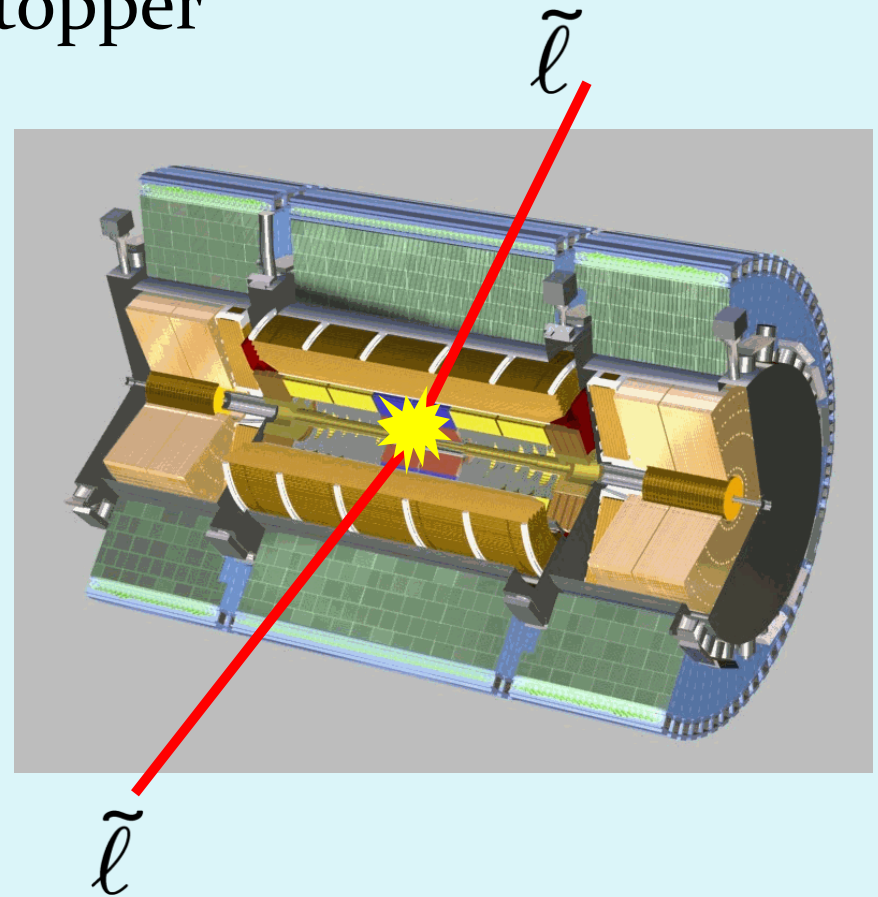
[Asai, Hamaguchi, SS:09]

Detector as stopper

For ATLAS HCAL

Barrel 1440 mm Fe

Endcap 1400 mm Cu



# Stopped Slepton

[Asai, Hamaguchi, SS:09]

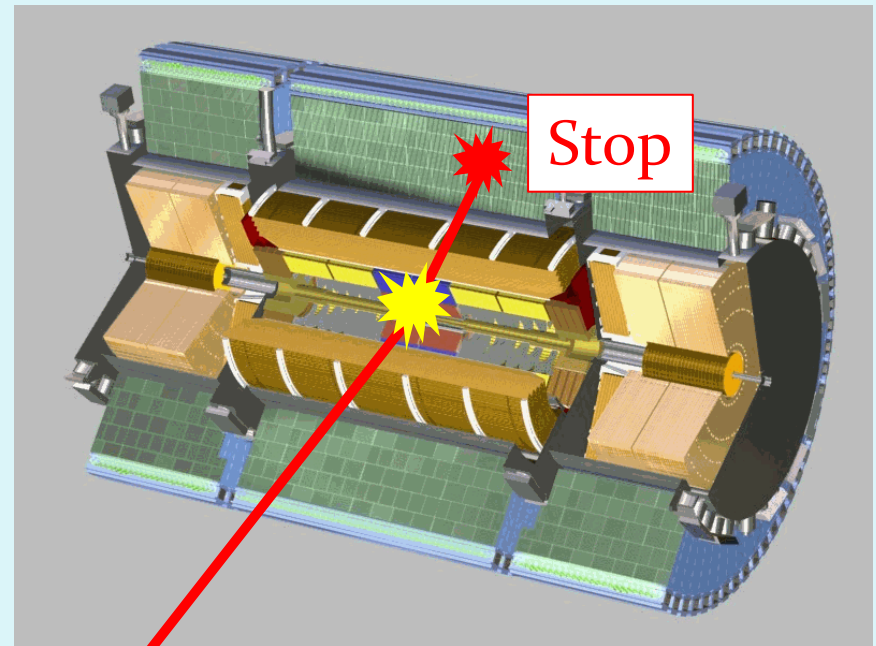
Detector as stopper

$\tilde{\ell}$

For ATLAS HCAL

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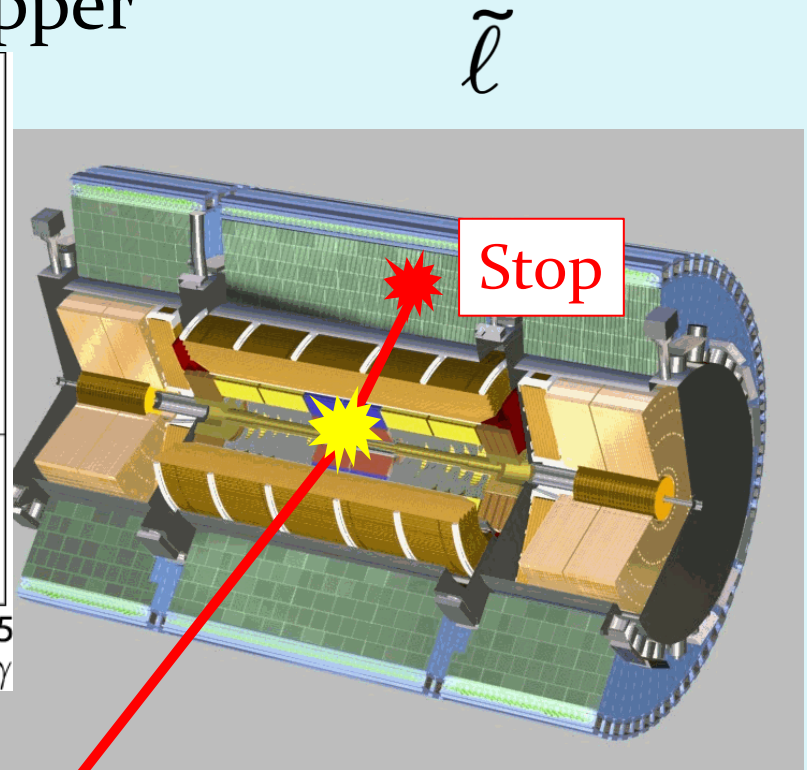
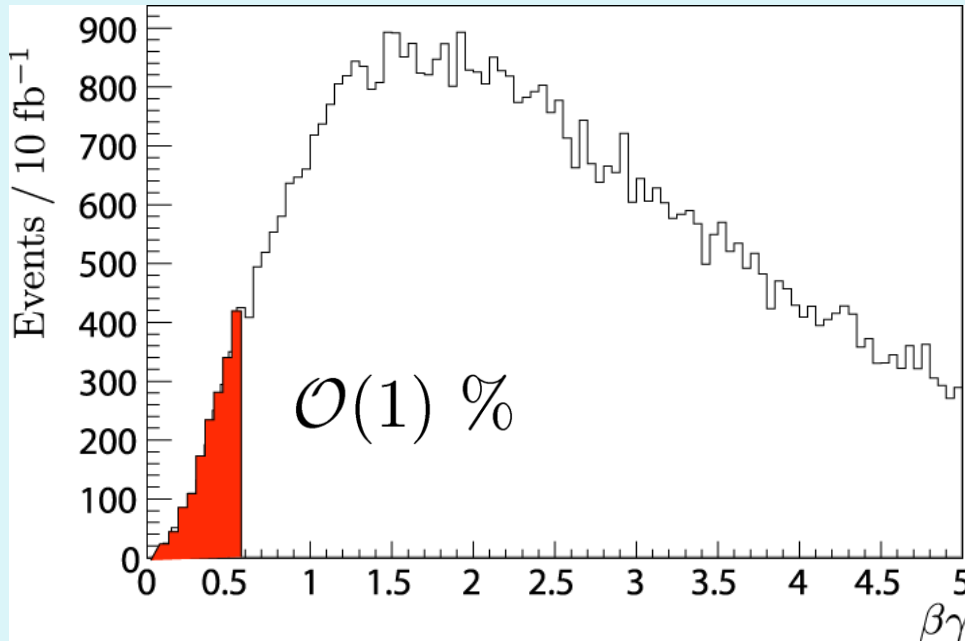


$\tilde{\ell}$

# Stopped Slepton

[Asai, Hamaguchi, SS:09]

Detector as stopper



$\tilde{\ell}$

# Observation of Late-time Decay

Slepton Production



Trapped in Detector



Time

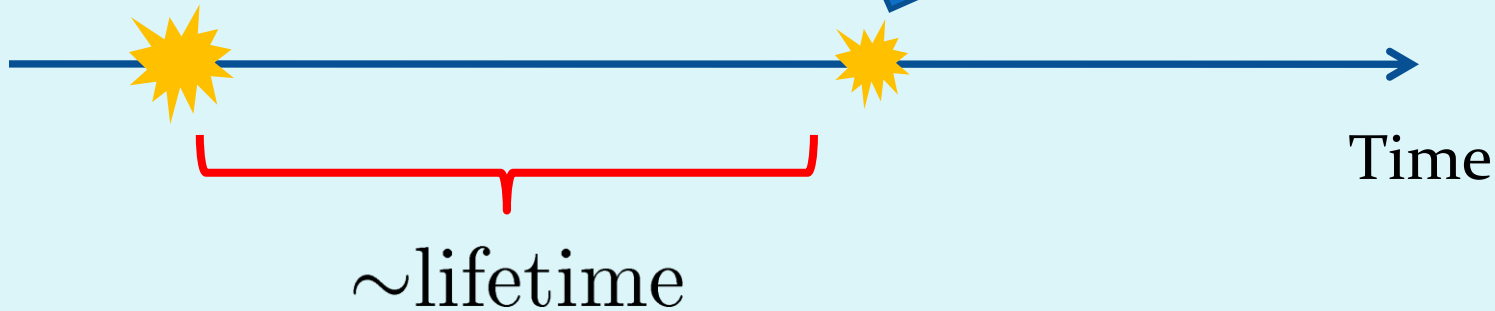
# Observation of Late-time Decay

Slepton Production



Trapped in Detector

Decay



Lifetime Measurement is Possible

# Long-lived Slepton で色々 (宣伝)

1. long-lived Sleptonを使うと他のSUSY粒子の性質も調べられる

詳細については藺藤さんのポスター発表で

2. Sleptonがlong-livedになるのはGravitino LSP  
の場合以外にも

- R-parity violation模型におけるSlepton LSP
- Slepton co-NLSP

などがある。

これらの区別については中路さんポスター発表にて

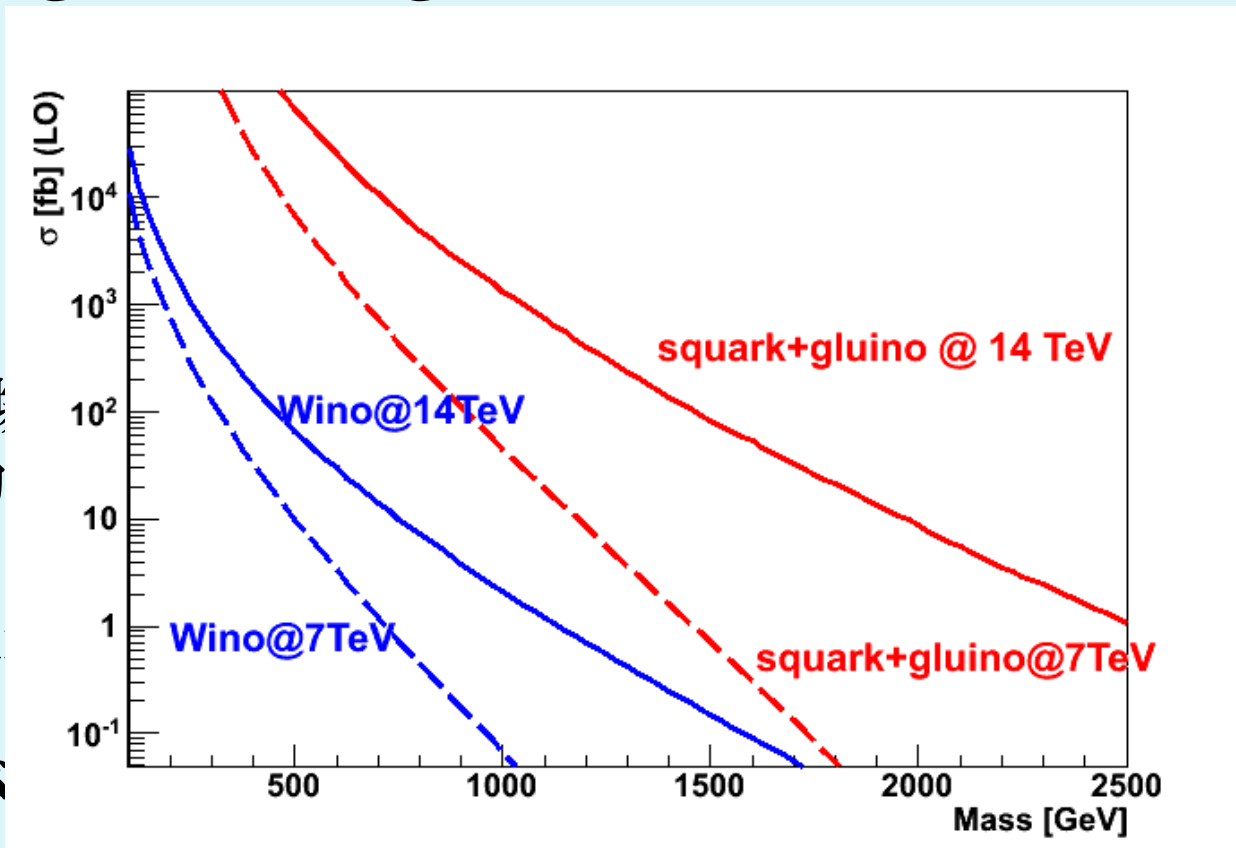


# ここまでのまとめ

- Gauge MediationではSleptonやBinoがLong-livedになることがある
- 多くの場合、SMやconventional SUSY model にはないような特徴的シグナルをだす
- Long-lived sleptonの場合はSUSY eventが数個あれば見えるはず
- 統計がたまれば、寿命などの情報も得ることができる

# ここまでのまとめ

- Gauge
- 多くの場  
特徴的
- Long-l
- 統計が



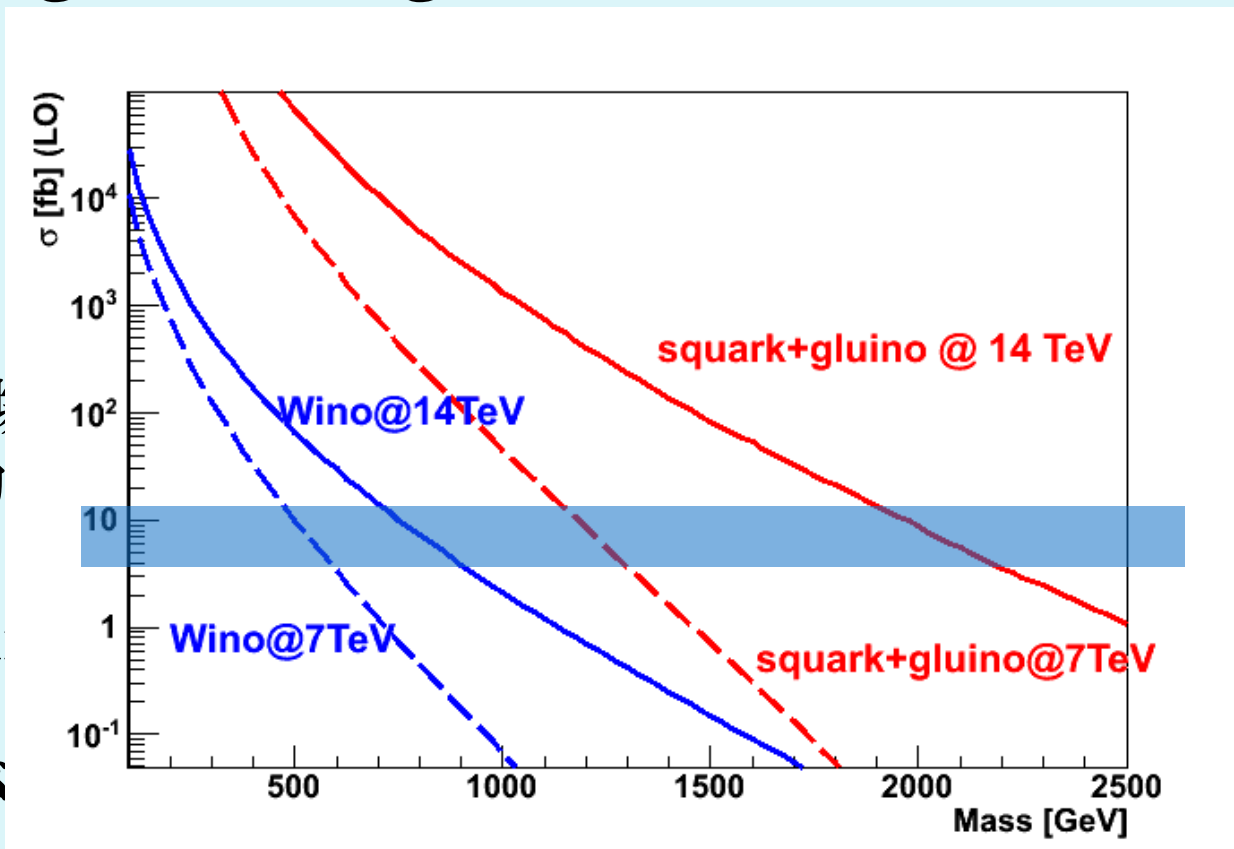
なることがある

いような

で見えるはず

# ここまでのまとめ

- Gauge
- 多くの場  
特徴的
- Long-l
- 統計が



なることがある

いような

で見えるはず

# GMSBでのSUSY粒子の質量

GMSBにはGravity MediationにあるようなSUSY scaleを決めるような“定量的な”基準がない。

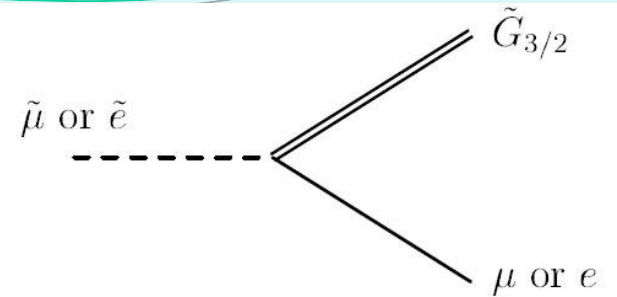
しかしGravitino massに対するSoft MassのUpper-boundは存在するかも

$$M_{\text{soft}} \lesssim \frac{\alpha_{\text{SM}}}{4\pi} \sqrt{F} = \alpha_{\text{SM}} \times 5 \text{ TeV} \left( \frac{m_{3/2}}{1 \text{ eV}} \right)^{1/2}$$

Low scale GMSBの場合、ちょうどLHCの手が届きそう  
( $m_{3/2} < 16 \text{ eV}$ )

# Low energy gauge mediationとLHC

# Gravitino LSP at LHC



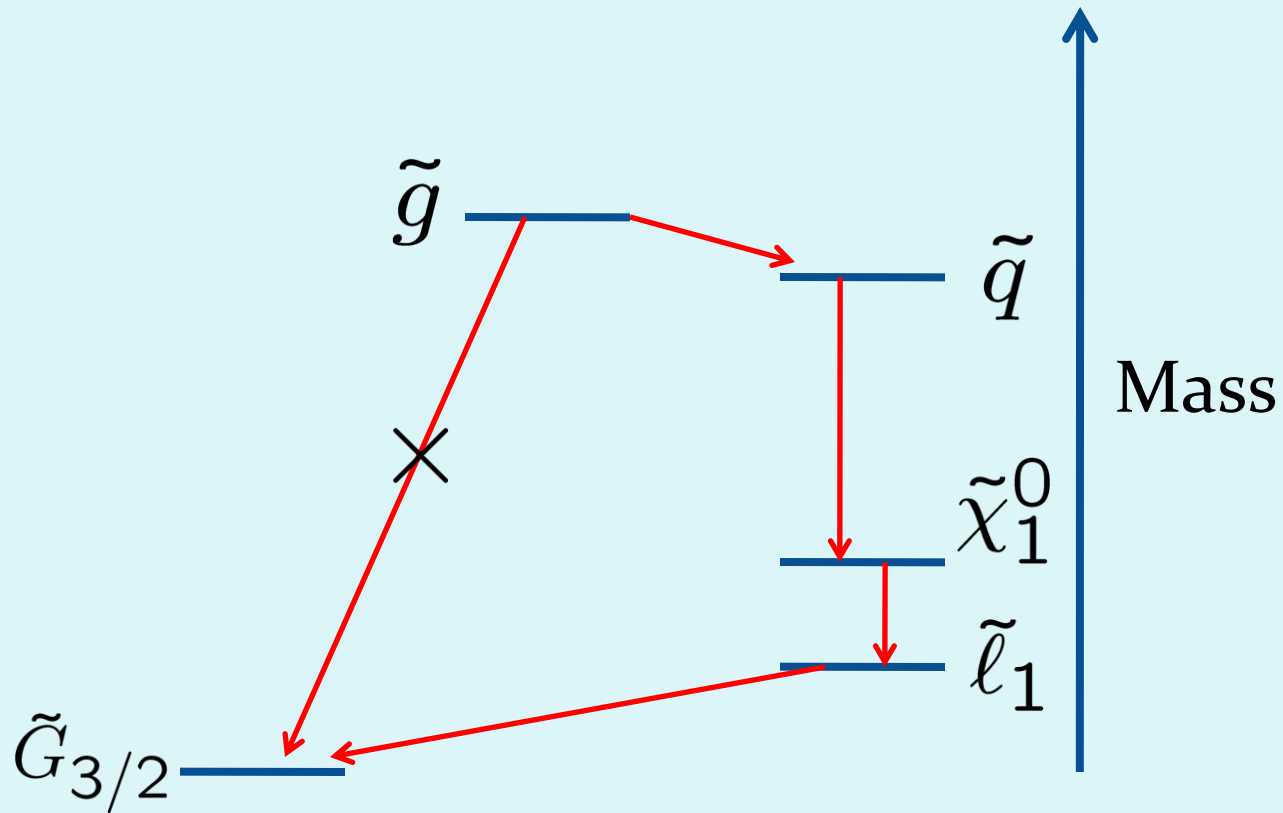
$$\tilde{\ell} \rightarrow \ell + \tilde{G}_{3/2}$$

$$\tilde{B} \rightarrow \gamma + \tilde{G}_{3/2}$$

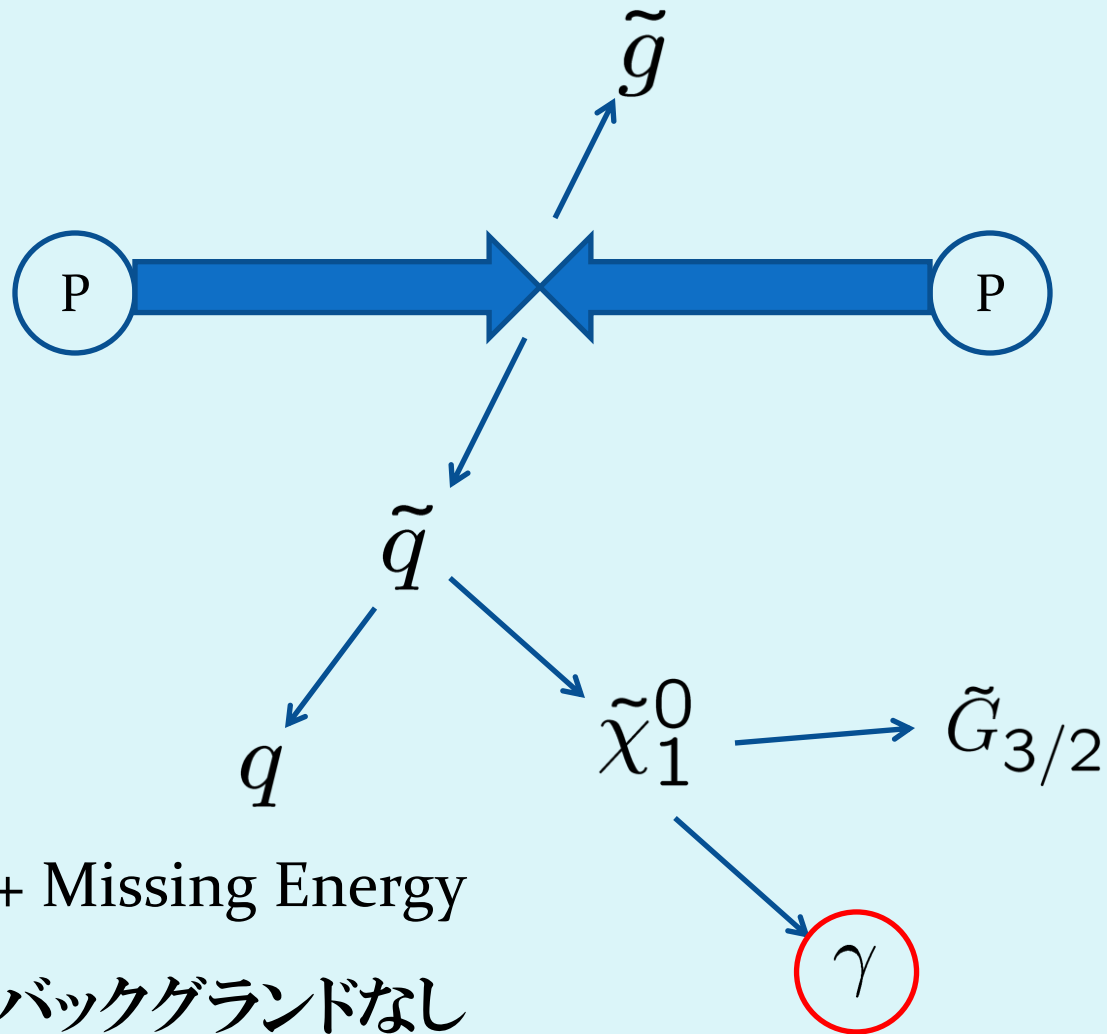
$$c\tau \simeq 20 \mu\text{m} \left( \frac{m_{3/2}}{1 \text{ eV}} \right)^2 \left( \frac{m_{\text{NLSP}}}{100 \text{ GeV}} \right)^{-5}$$

All MSSM particles decay inside of detector.

# SUSY Particles' decays



# Decay Chain (Bino NLSP)

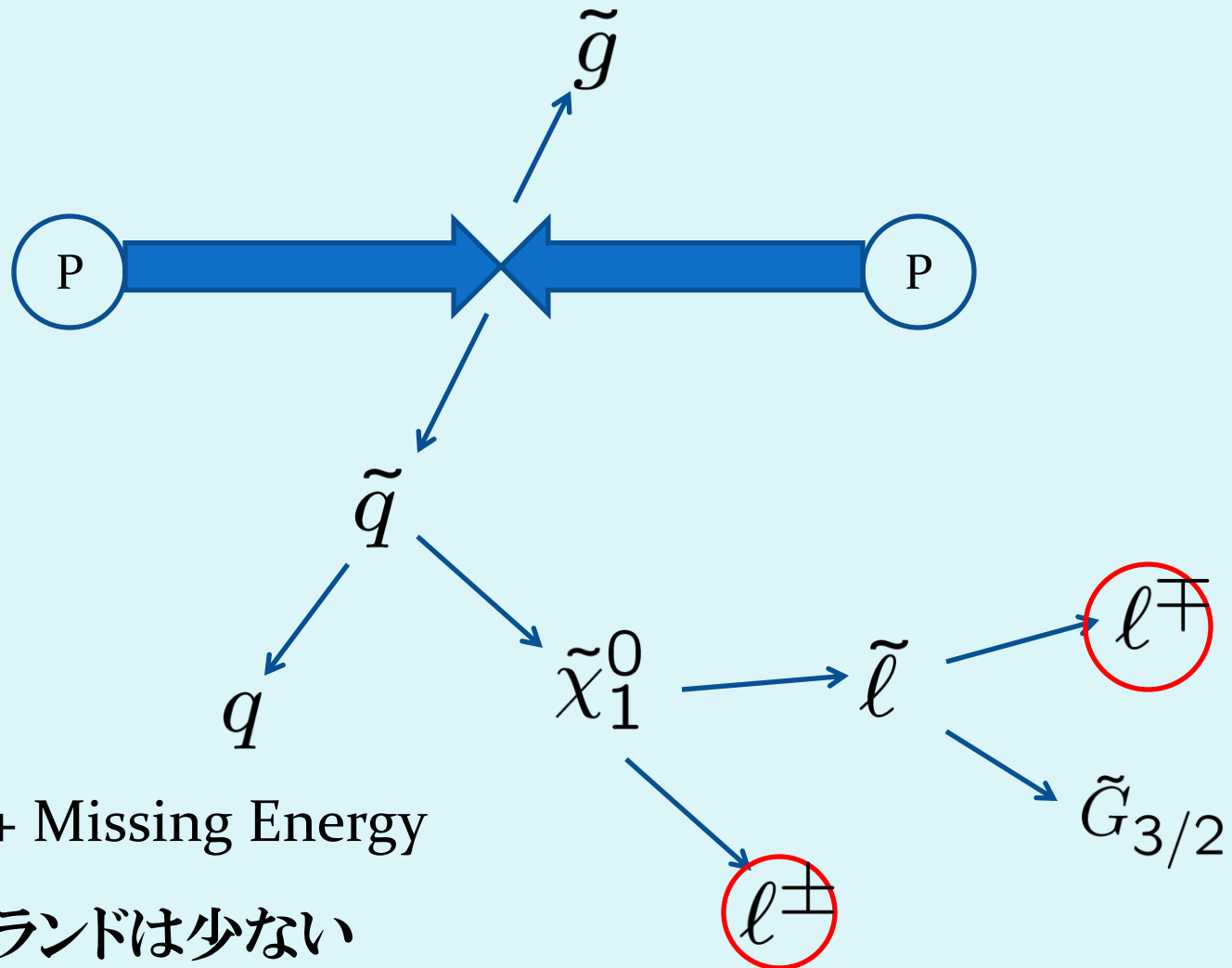


Photon + Missing Energy

ほとんどバックグラウンドなし



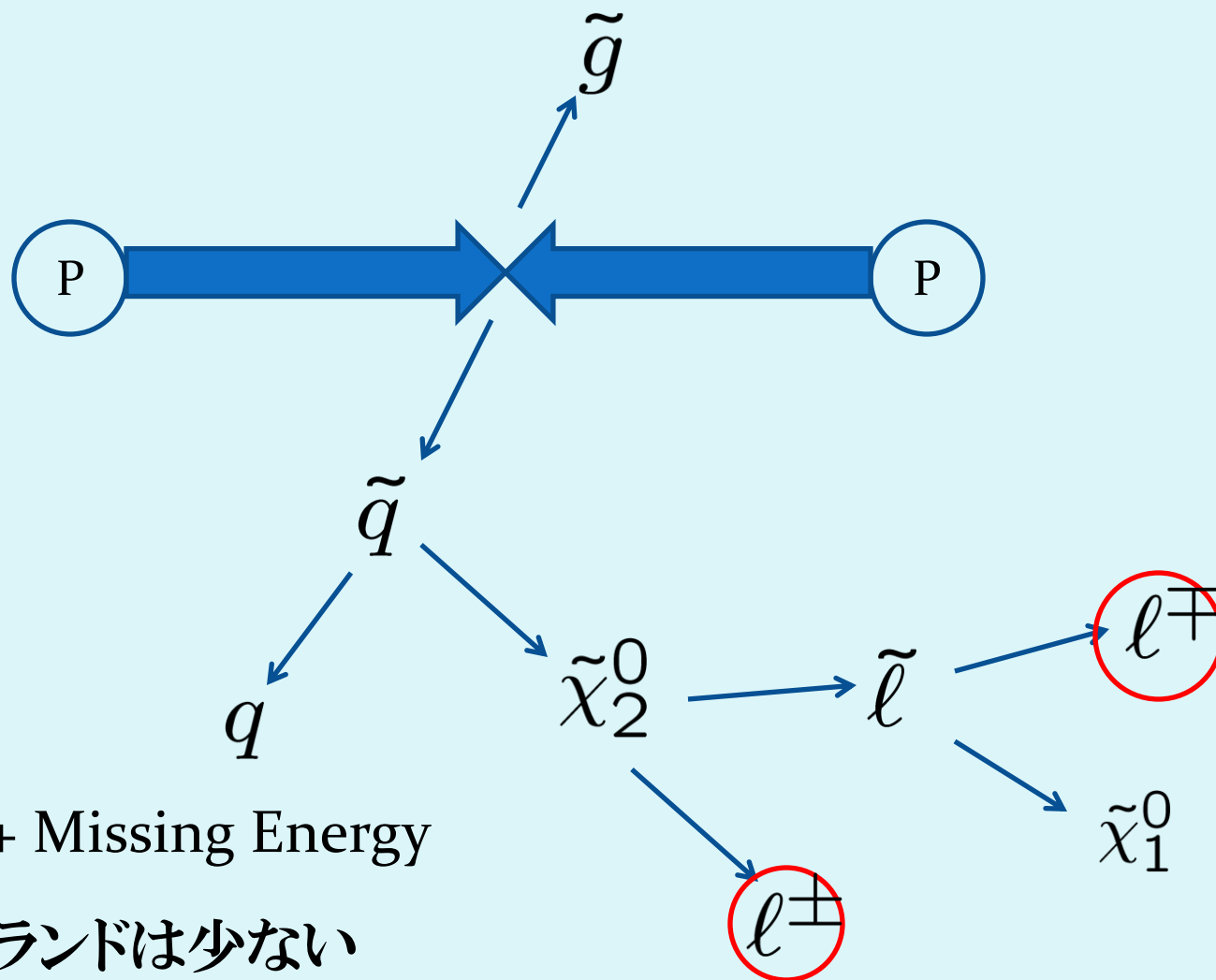
# Decay Chain (Slepton NLSP)



Lepton + Missing Energy

バックグラウンドは少ない

# 宣伝2

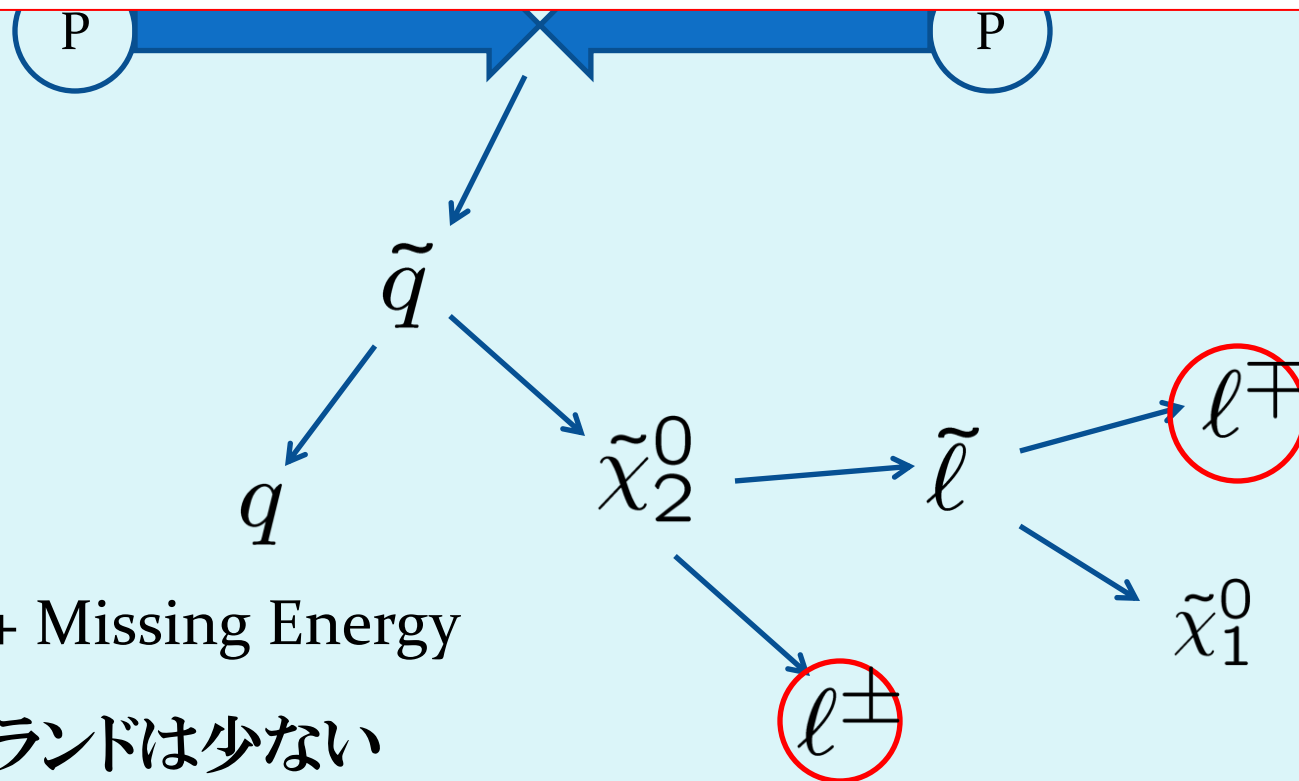


Lepton + Missing Energy

バックグラウンドは少ない

# 宣伝2

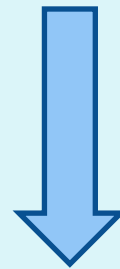
SUGRAでも似たようなシグナルがある。  
これらのモデルの区別をearly stageでどこまでできるかについては中村さんのtalkにて



次にGauge Mediationでのsoft massの上限を見る

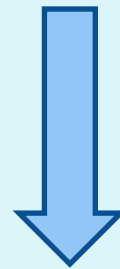
# Minimal GMSB

Hidden  $F \neq 0$

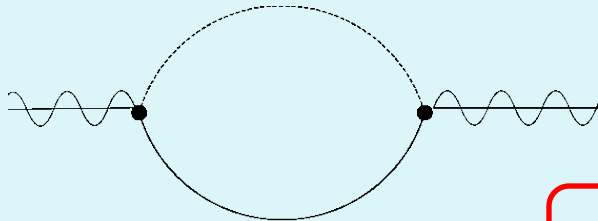


$$kS\bar{\psi}\psi \quad \langle S \rangle = F\theta^2$$

Messenger  $\psi \sim (d, \ell)$



SM gauge interaction



MSSM

# Minimal GMSB

$$W \ni kS\bar{\psi}\psi \quad \langle S \rangle = F\theta^2$$

$$m_{\text{scalar}}^2 = 2N_{\text{mess}} \left(\frac{\alpha}{4\pi}\right)^2 \left(\frac{kF}{M_{\text{mess}}}\right)^2 \left(1 + \mathcal{O}\left(\frac{kF}{M_{\text{mess}}^2}\right)\right)$$

$$m_{\text{gaugino}} = N_{\text{mess}} \left(\frac{\alpha}{4\pi}\right) \frac{kF}{M_{\text{mess}}} \left(1 + \mathcal{O}\left(\frac{kF}{M_{\text{mess}}^2}\right)\right)$$



$$m_{3/2} \approx F/M_{\text{P}}$$


$$m_{3/2} \approx \mathcal{O}(1) \text{ eV} \left(\frac{m_{\text{gluino}}}{1 \text{ TeV}}\right) \left(\frac{M_{\text{mess}}}{100 \text{ TeV}}\right)$$

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$kF < M_{\text{mess}}$   Messenger scalarがタキオンにならないため  
 $m_{\text{scalar}}^2 = M_{\text{mess}}^2 \pm kF$

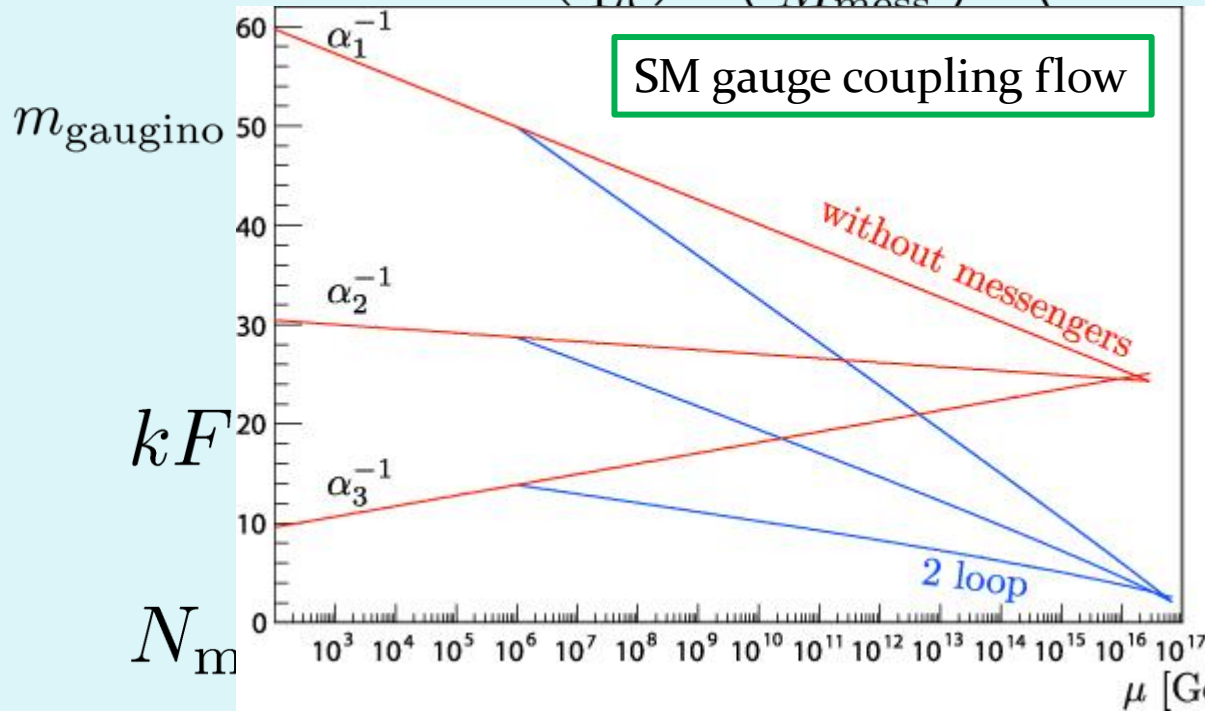
$N_{\text{mess}} \lesssim 5$   Landau poleを避けるため

$k \lesssim 1$

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フェオンにならないため

$$m_{\text{scalar}} = M_{\text{mess}}^2 \pm kF$$

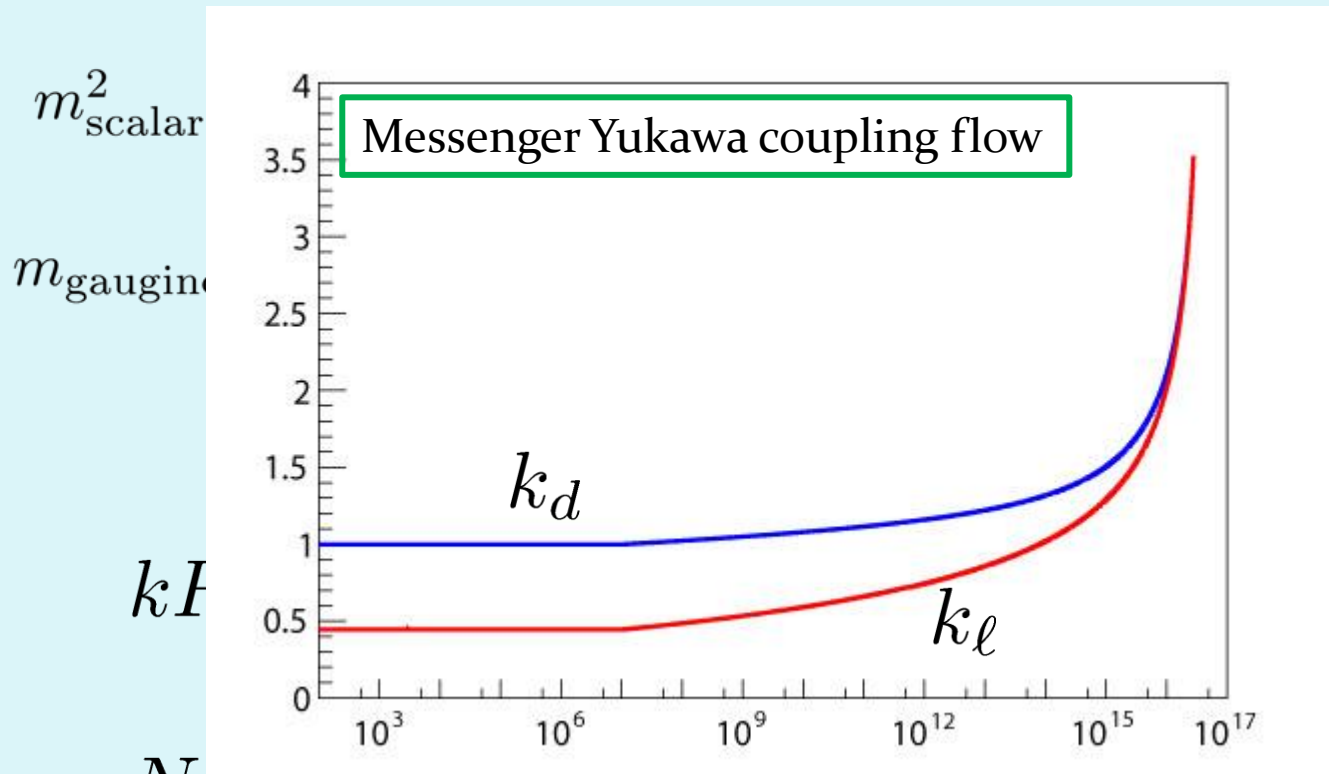
ため

$$k \lesssim 1$$



# Minimal GMSB

$$W \ni k S \bar{\psi} \psi \quad \langle S \rangle = F \theta^2$$



$$\left( \frac{F}{M_{\text{mess}}^2} \right)$$

にならないため  
 $= M_{\text{mess}}^2 \pm kF$

$$N_{\text{mess}} \sim 5$$

$$k \lesssim 1$$



Landau poleを避けるため

# Minimal GMSB

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$$kF < M_{\text{mess}}$$



Messenger scalarがタキオンにならないため

$$m_{\text{scalar}}^2 = M_{\text{mess}}^2 \pm kF$$

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真空の安定性という条件を加えるともっと厳しくなる

# Vacuum of Minimal GMSB

$$\langle S \rangle = F_S \theta^2$$



$$W_{\cancel{\text{SUSY}}}(S) = -F_S^\dagger S$$

(Low-energy effective)

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Including interaction with messengers

$$W = kS\bar{\psi}\psi + M\bar{\psi}\psi + W_{\cancel{\text{SUSY}}}(S) \quad \psi \sim (d, \ell)$$

$$F = \frac{\partial W}{\partial S} = \frac{\partial W_{\cancel{\text{SUSY}}}(S)}{\partial S} + k\bar{\psi}\psi$$

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$\langle \bar{\psi}\psi \rangle \neq 0 \quad \rightarrow \quad \text{F-term condition satisfied}$

$$\langle S \rangle = -M/k$$

SUSY breaking vacuum は安定でない

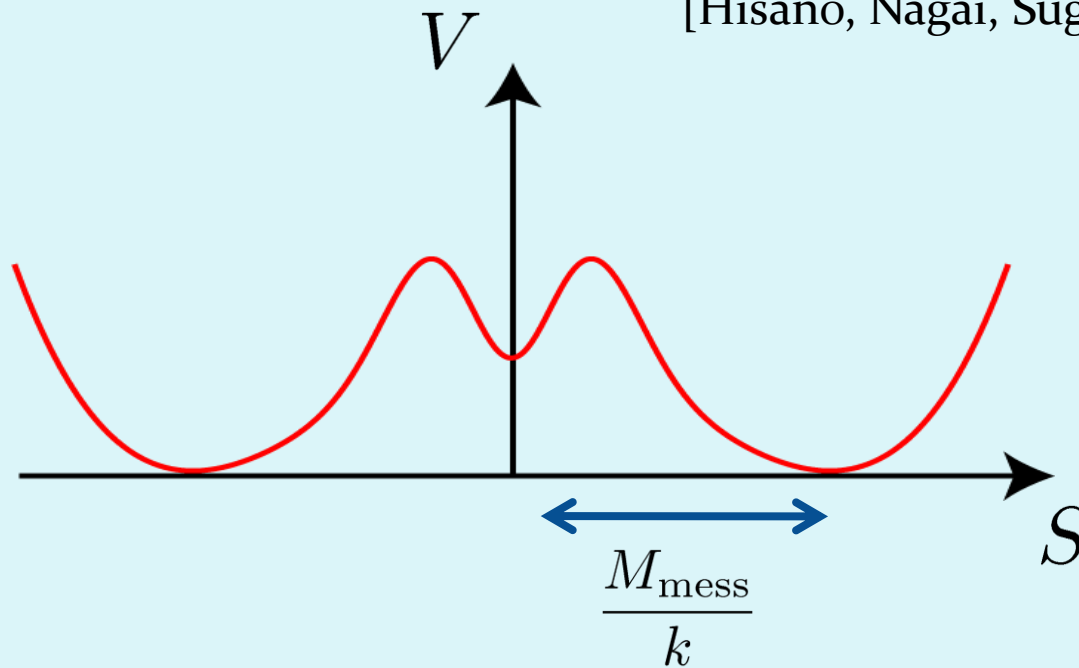
# 真空の不安定

- Metastable だけど宇宙年齢より長生きの真空を求める
- SUSY breaking の真空が完全に安定な模型を考える

# 準安定真空ver

[Hisano, Nagai, Senami, Sugiyama: 07]

[Hisano, Nagai, Sugiyama, Yanagida: 08]



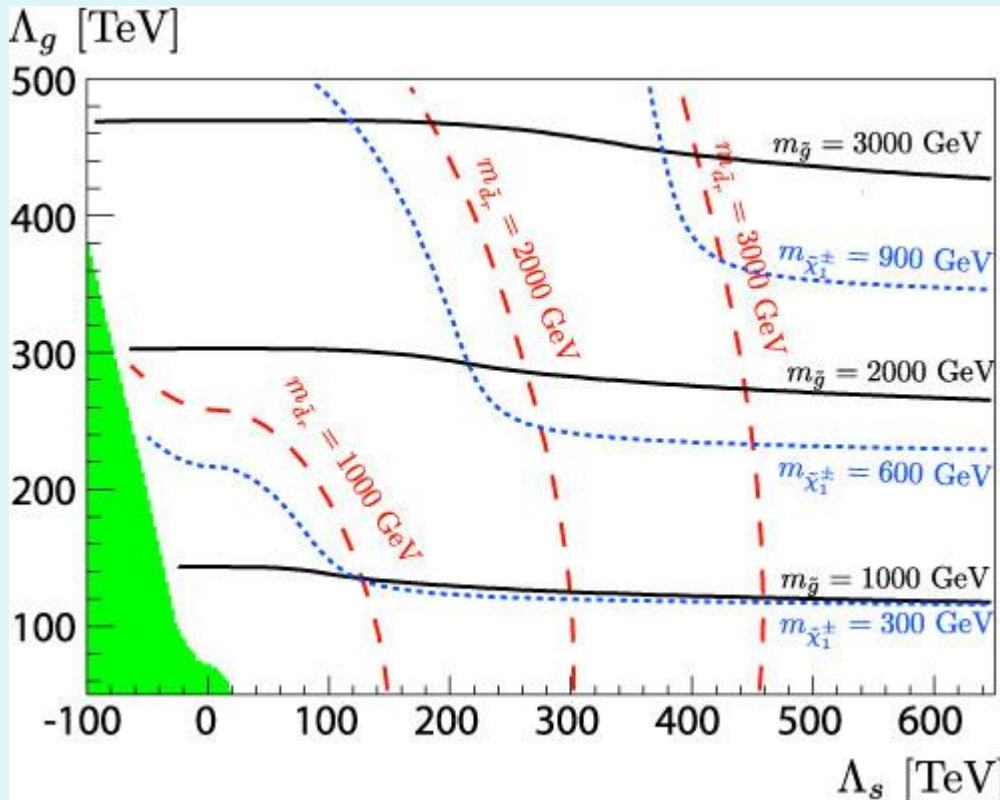
Messenger の質量を上げれば、真空の寿命が延びる



Soft Massが下がる



# LHC Reach (Metastable ver.)

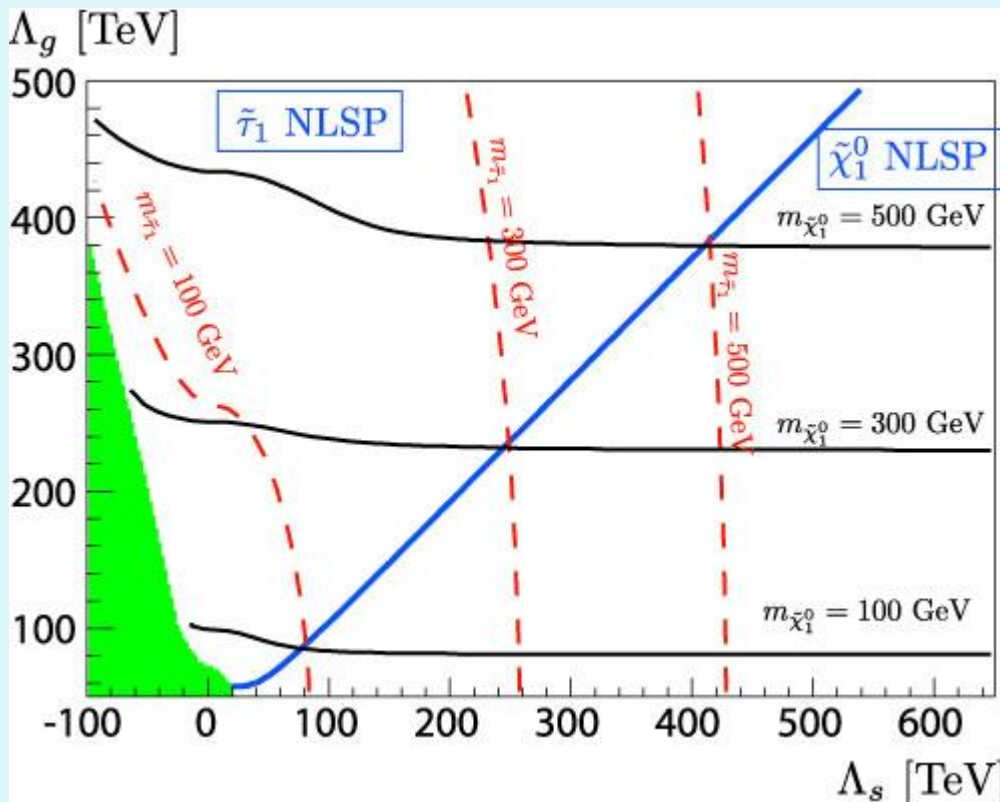


$$M_a = \frac{\alpha_a}{4\pi} \Lambda_g$$

$$m_{\phi_i}^2 = \Lambda_s^2 \sum_a \left( \frac{\alpha_a}{4\pi} \right)^2 C_a(i)$$

@ messenger scale

# LHC Reach (Metastable ver.)

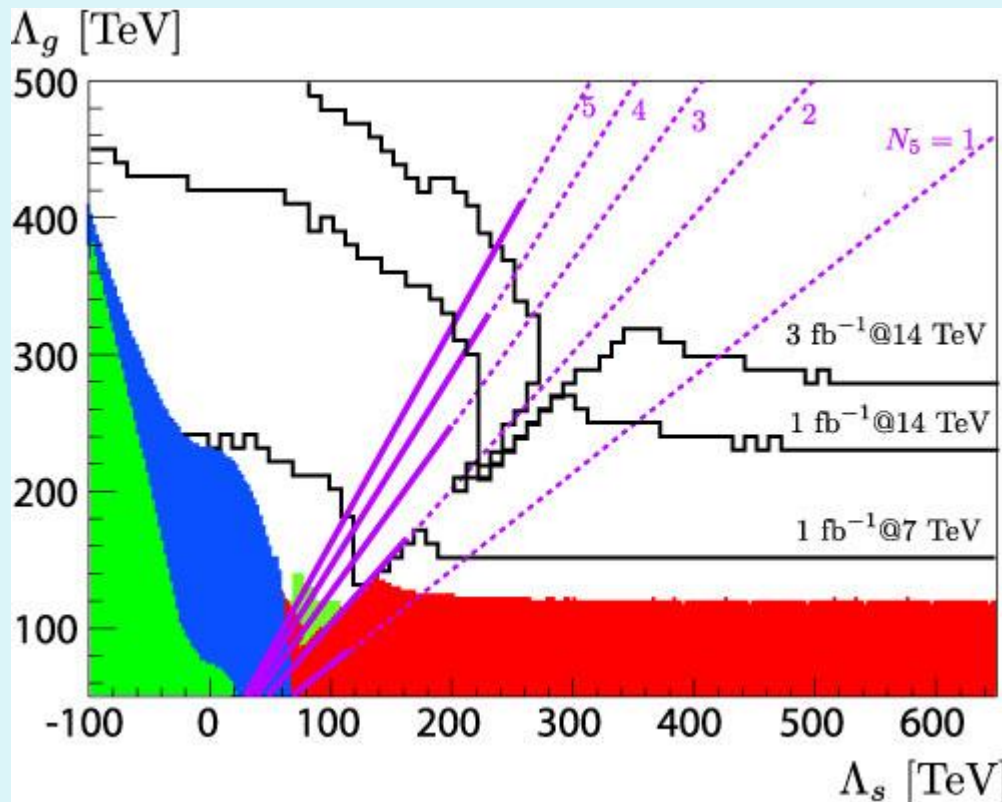


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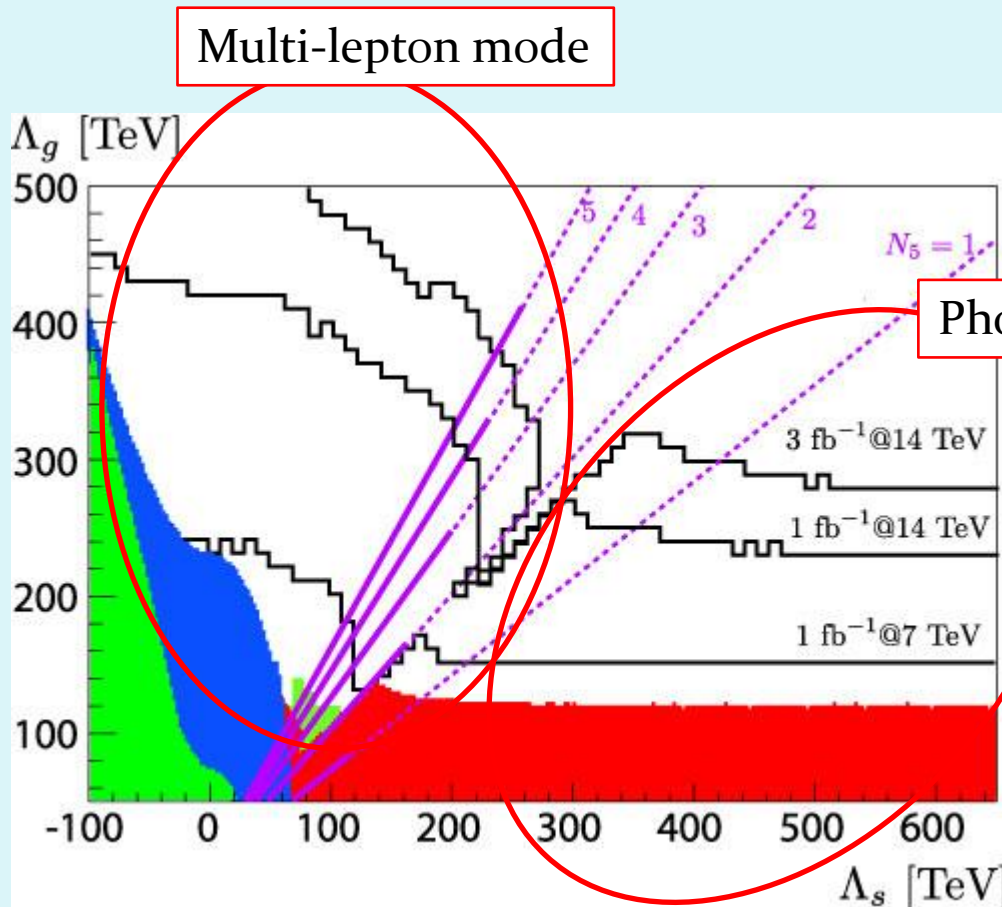
$$m_{\phi_i}^2 = \Lambda_s^2 \sum_a \left( \frac{\alpha_a}{4\pi} \right)^2 C_a(i)$$

@ messenger scale

-----  
Minimal GMSBのパラメータ

—————  
Minimal GMSB  
with  
sufficient stability  
 $m_{32} < 16 \text{ eV}$   
のパラメータ

# LHC Reach (Metastable ver.)



Multi-lepton mode

Photon mode

$$M_a = \frac{\alpha_a}{4\pi} \Lambda_g$$

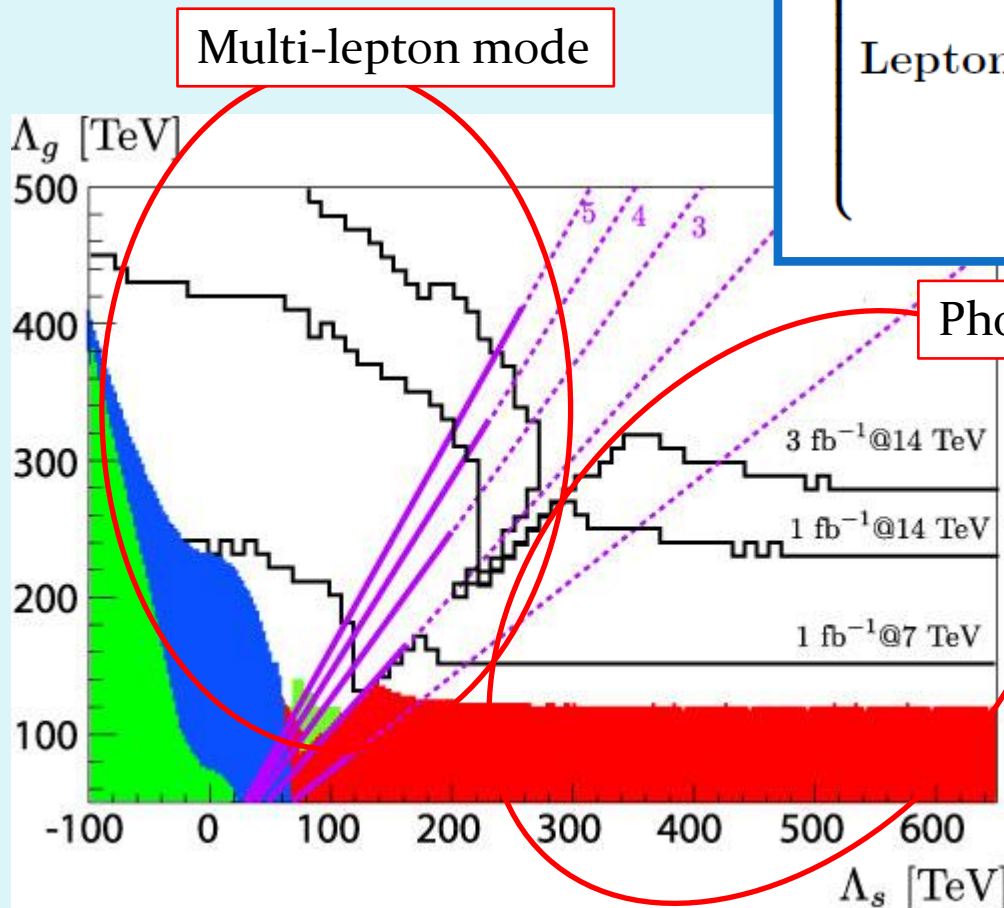
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@ messenger scale

-----  
Minimal GMSBのパラメータ

—————  
Minimal GMSB  
with  
sufficient stability  
 $m_{32} < 16 \text{ eV}$   
のパラメータ

# LHC Reach (M)



Multi-lepton mode

Photon mode

@ messenger scale

$$\left\{ \begin{array}{l} \text{Photon modes} \left\{ \begin{array}{l} 1 \text{ photon} + (1\ell, 2 \geq \ell) \\ 2 \geq \text{photon} \end{array} \right. \end{array} \right.$$

$$\left\{ \begin{array}{l} \text{Lepton modes} \left\{ \begin{array}{l} 0\ell + (2\tau, 3 \geq \tau) \\ 1\ell + (0\tau, 1\tau, 2 \geq \tau) \\ SS2\ell + (0\tau, 1\tau, 2 \geq \tau) \\ 3\ell + (0\tau, 1\tau, 2 \geq \tau) \\ 4 \geq \ell \end{array} \right. \end{array} \right.$$

Minimal GMSBのパラメータ

Minimal GMSB  
with  
sufficient stability  
 $m_{32} < 16 \text{ eV}$   
のパラメータ

# 真空の不安定

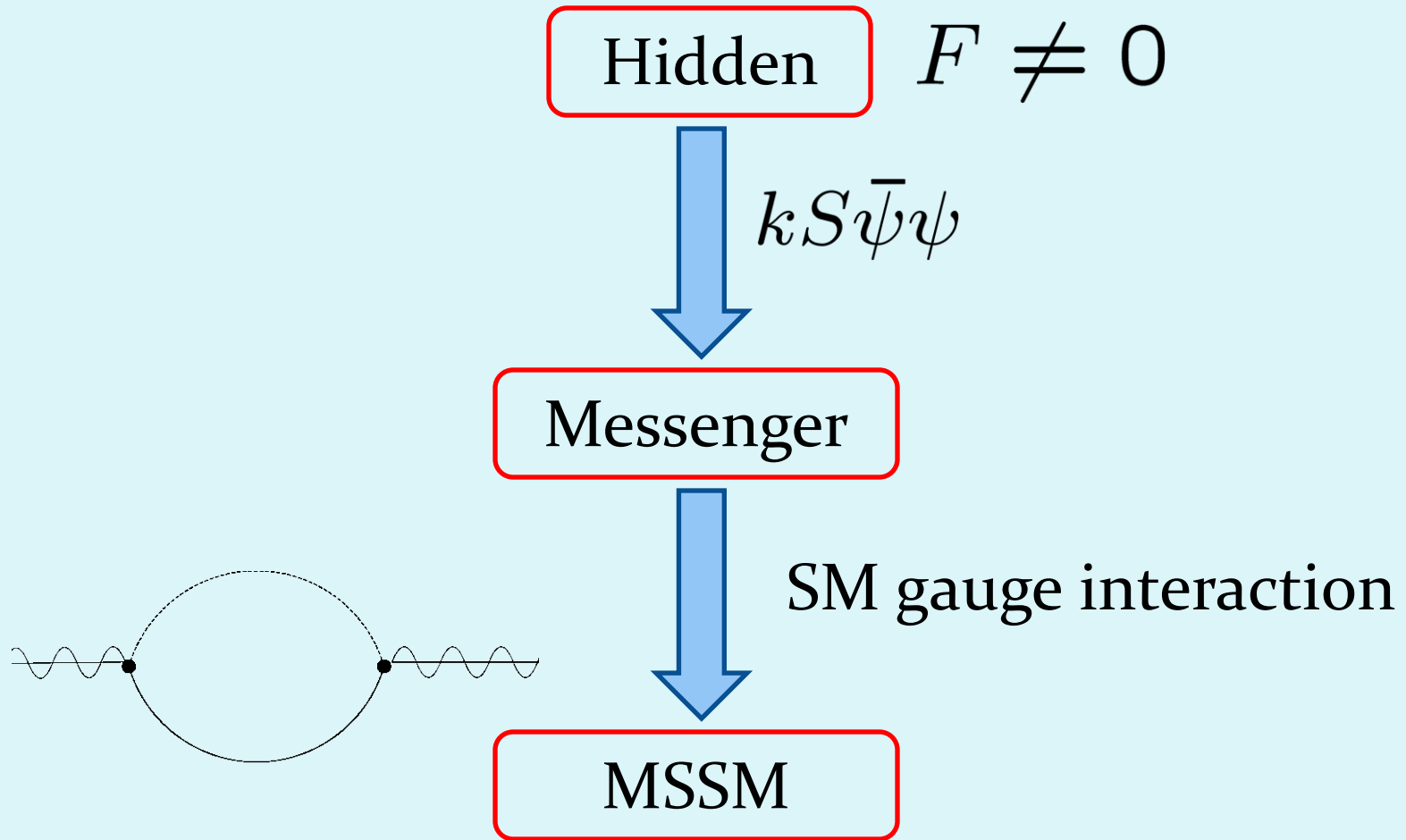
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# Stable GMSB





# Stable GMSB

Hidden  $F \neq 0$

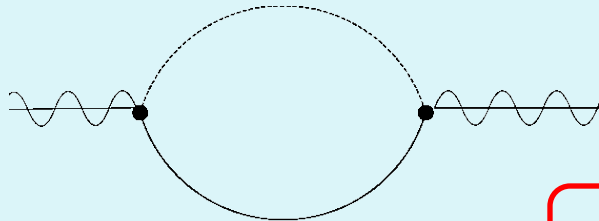
Hidden Gauge interaction

~~$k_S \bar{\psi} \psi$~~

e.g. semi-direct GMSB  
[N. Seiberg, et.al., 08]

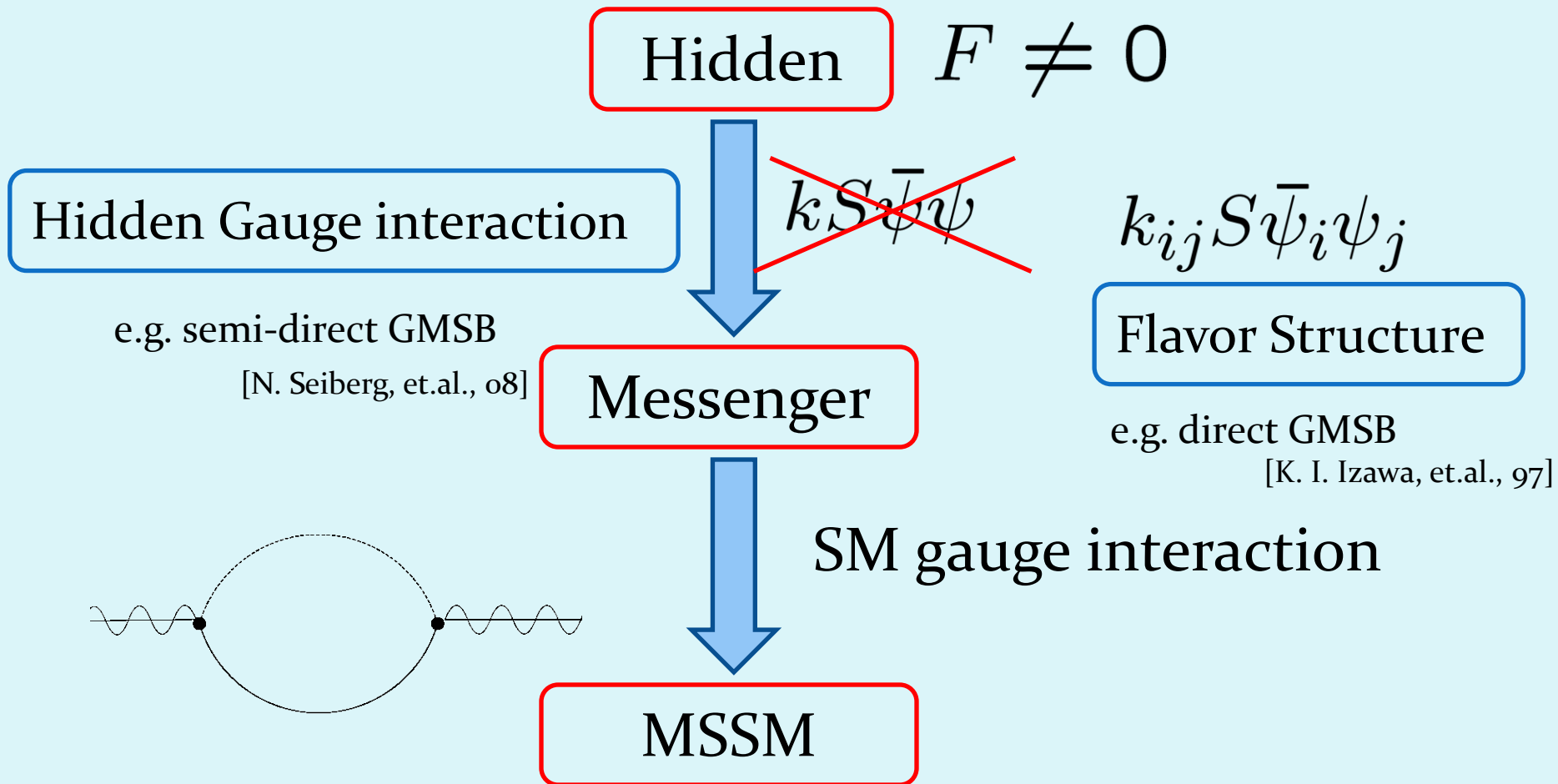
Messenger

SM gauge interaction



MSSM

# Stable GMSB



# Mass Spectrum (Stable ver.)

$$m_{\text{scalar}}^2 \approx \left(\frac{\alpha}{4\pi}\right)^2 \left(\frac{kF}{M_{\text{mess}}}\right)^2 \left(1 + \mathcal{O}\left(\frac{kF}{M_{\text{mess}}^2}\right)\right)$$

$$m_{\text{gaugino}} \approx \left(\frac{\alpha}{4\pi}\right) \frac{kF}{M_{\text{mess}}} \left(1 + \mathcal{O}\left(\frac{kF}{M_{\text{mess}}^2}\right)\right)$$

$$M^2 > kF$$

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$$M^2 > kF$$

- F-term gauge mediation with stable vacuum
  - e.g. direct GMSB
- Messengers have only mass term in superpotential
  - e.g. semi-direct GMSB
- 
- 
-



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非常に厳しい質量上限 [Sato, Yonekura: 09]

- F-term gauge mediation with stable vacuum

e.g. direct GMSB

- Messengers have only mass term in superpotential

e.g. semi-direct GMSB

Perturbativeなパラメータではlow scale GMSBを実現するのは非常に難しい

[SS, Yamazaki, Yonekura: 10]

# Mass Spectrum (Stable ver.)

$$m_{\text{scalar}}^2 \approx \left(\frac{\alpha}{4\pi}\right)^2 \left(\frac{kF}{M_{\text{mess}}}\right)^2 \left(1 + \mathcal{O}\left(\frac{kF}{M_{\text{mess}}^2}\right)\right)$$

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Suppression on gaugino mass



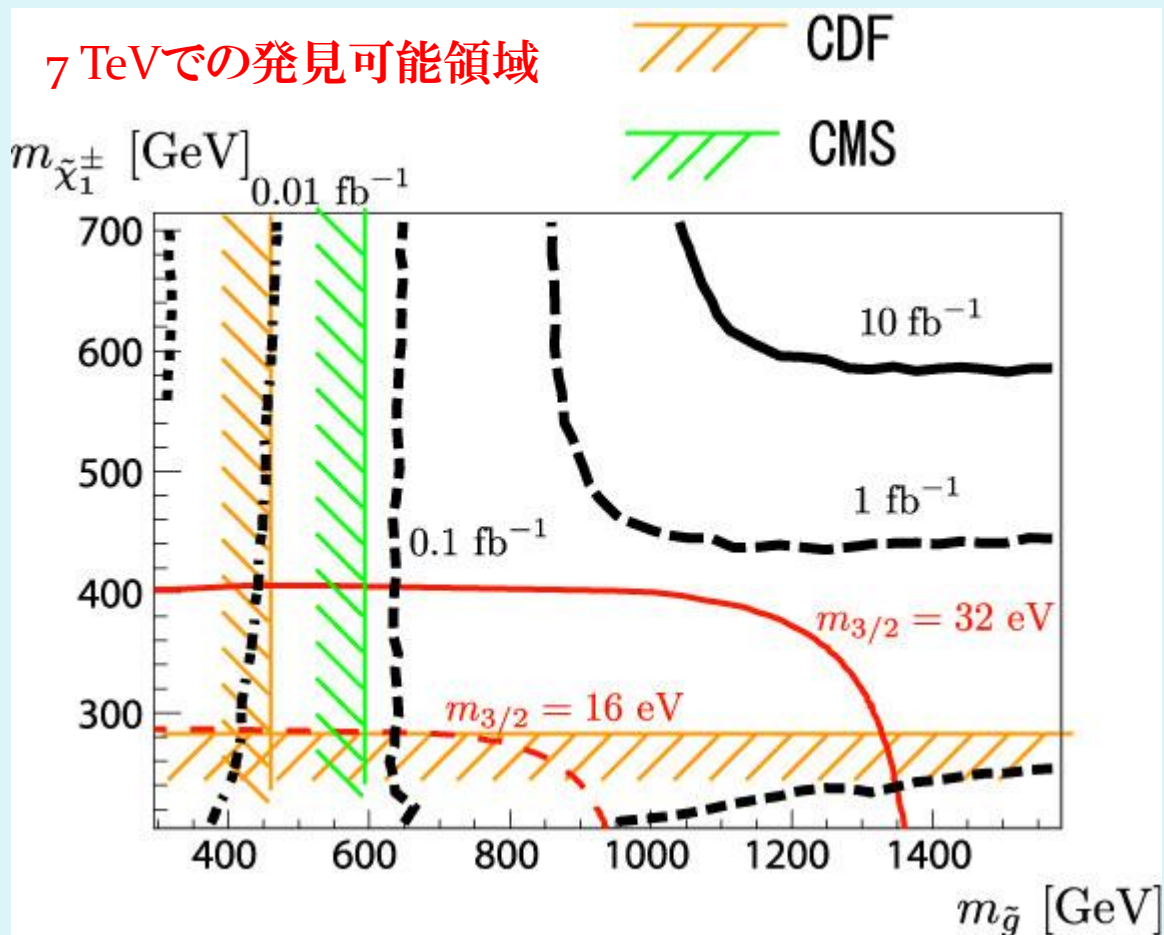
$$\frac{m_{\text{gaugino}}}{m_{\text{scalar}}} \approx \left(\frac{kF}{M_{\text{mess}}^2}\right)^p \ll 1$$



# LHC Reach (Stable ver.)

LHC physicsはgauginoで支配される

[Sato,SS: 10]



宇宙論的に興味深い  
16 eVより軽いグラビティーノは  
現時点でもほぼexclude.

より重たい場合でも今年中に  
十分発見できる.

# まとめ

- Gravity Mediationだけではなく、Gauge Mediationも十分にmotivationのある模型である.
- Gauge Mediationで出てくるlong-lived particleはSMにはない、もつともconvincingなBSMのシグナルである.
- Cosmologyから好まれるlow scale gauge mediationにはMSSM粒子の質量に強い上限がつく. さらに信号も特徴的なので早い段階で見つかるはず.