LSPがGravitinoになるモデル と LHCでの物理

Koichi Hamaguchi (Tokyo U.)

@ LHCが切り拓く新しい素粒子物理学, Mar. 2008

Plan

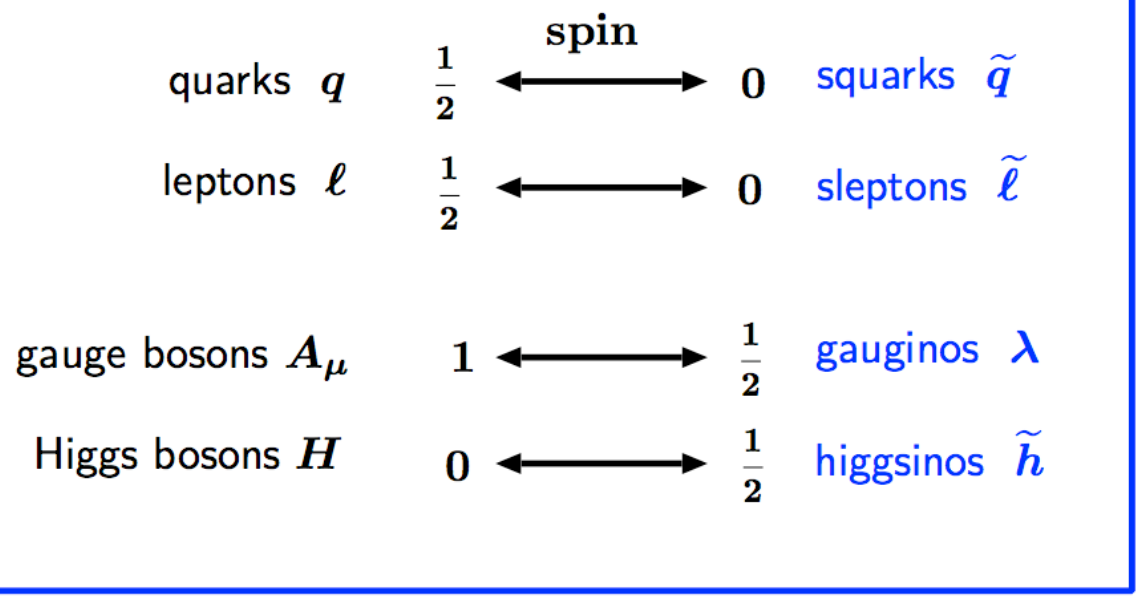
- Gravitino と SUSY models
- Gravitino と Cosmology
- Gravitino LSP と LHC での物理

Gravitino と SUSY models

	spin
quarks q	$\frac{1}{2}$
leptons ℓ	$\frac{1}{2}$
gauge bosons A_μ	1
Higgs bosons H	0

Standard Model

Supersymmetry (SUSY)



(1) solves the naturalness problem

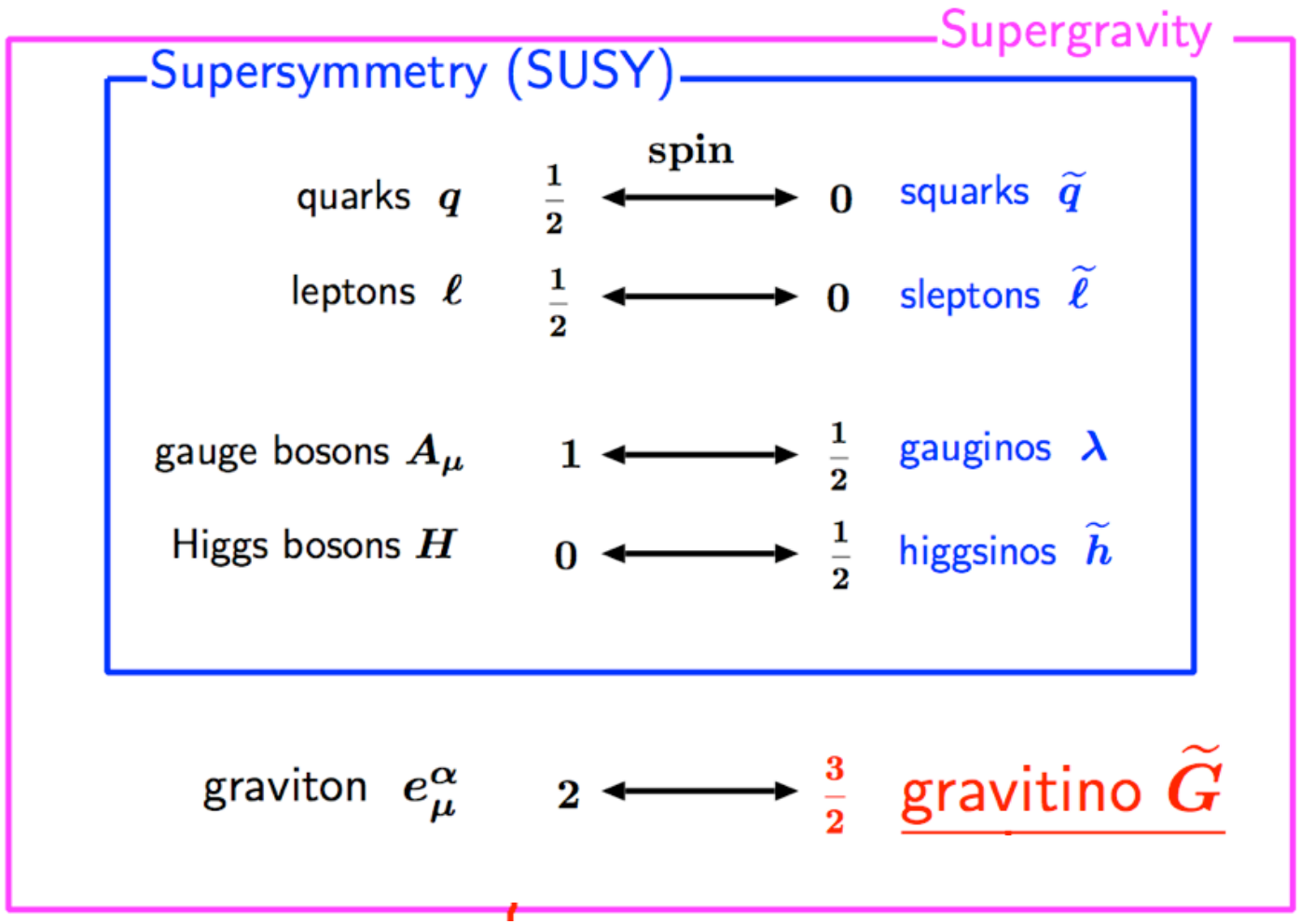
(2) leads to coupling unification

(3) has dark matter candidate

Supersymmetry (SUSY)

	spin		spin	
quarks q	$\frac{1}{2}$	$\longleftrightarrow$	0	squarks $\tilde{q}$
leptons ℓ	$\frac{1}{2}$	$\longleftrightarrow$	0	sleptons $\tilde{\ell}$
gauge bosons A_μ	1	$\longleftrightarrow$	$\frac{1}{2}$	gauginos λ
Higgs bosons H	0	$\longleftrightarrow$	$\frac{1}{2}$	higgsinos $\tilde{h}$

graviton e_μ^α


Supergravity
Supersymmetry (SUSY)
spin
quarks q
$\frac{1}{2}$
0
squarks $\tilde{q}$
leptons ℓ
$\frac{1}{2}$
0
sleptons $\tilde{\ell}$
gauge bosons A_μ
1
$\frac{1}{2}$
gauginos λ
Higgs bosons H
0
$\frac{1}{2}$
higgsinos $\tilde{h}$
graviton e_μ^α
2
$\frac{3}{2}$
gravitino $\tilde{G}$

Superstring

Supergravity

Supersymmetry (SUSY)

	spin		spin	
quarks q	$\frac{1}{2}$	⟷	0	squarks $\tilde{q}$
leptons ℓ	$\frac{1}{2}$	⟷	0	sleptons $\tilde{\ell}$
gauge bosons A_μ	1	⟷	$\frac{1}{2}$	gauginos λ
Higgs bosons H	0	⟷	$\frac{1}{2}$	higgsinos $\tilde{h}$
graviton e_μ^α	2	⟷	$\frac{3}{2}$	gravitino $\tilde{G}$

Superstring

Supergravity

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quarks q	$\frac{1}{2}$	⟷	0	squarks $\tilde{q}$
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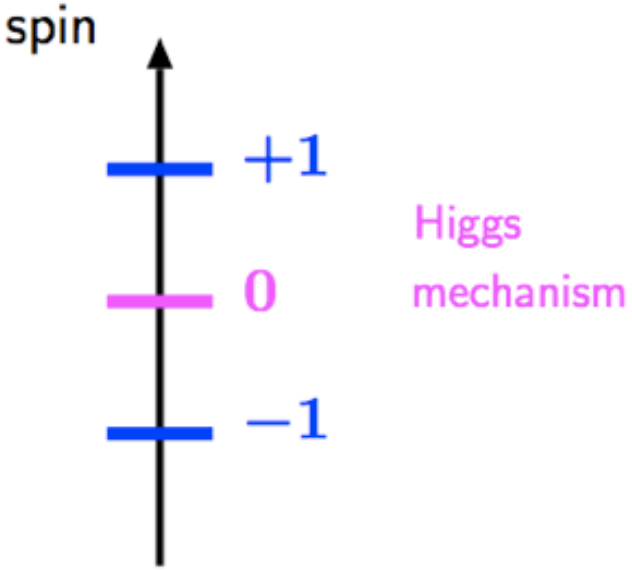
gauge bosons A_μ	1	⟷	$\frac{1}{2}$	gauginos λ
Higgs bosons H	0	⟷	$\frac{1}{2}$	higgsinos $\tilde{h}$
graviton e_μ^α	2	⟷	$\frac{3}{2}$	gravitino $\tilde{G}$

Electroweak Symmetry と比べてみる

Electroweak symmetry

→ spontaneously broken



Z, W bosons

→ discovered in 1983

→ establish Standard Model

Electroweak Symmetry と比べてみる

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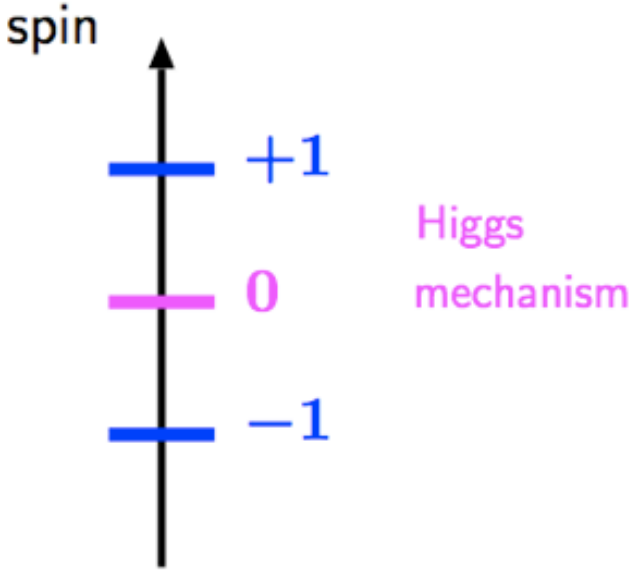
→ spontaneously broken



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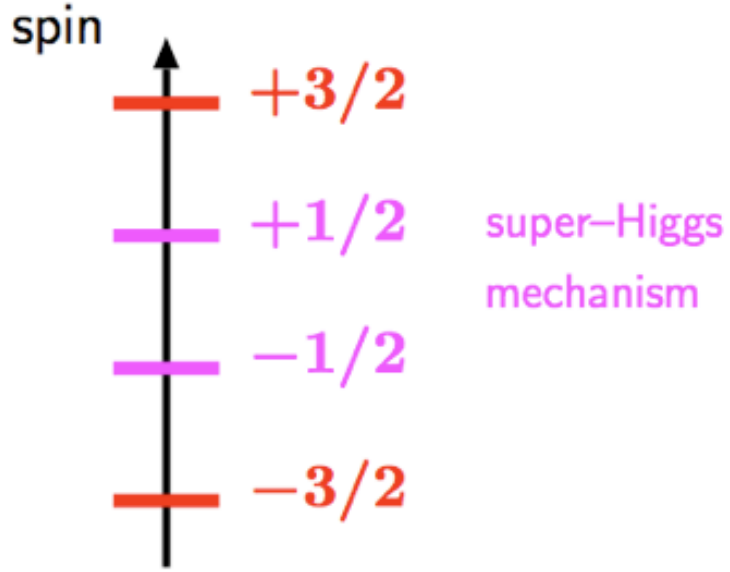


Gravitino

→ discovered in 20XX (?!)
→ establish **Supergravity** !!

Electroweak Symmetry と比べてみる

Electroweak symmetry
→ spontaneously broken

Supergravity
→ spontaneously broken

gauge boson mass

$$m_V = g \langle \varphi \rangle$$

gauge coupling

Higgs VEV

gravitino mass

$$m_{\tilde{G}} = \frac{1}{\sqrt{3} M_{\rm P}} \langle F \rangle$$

SUGRA coupling

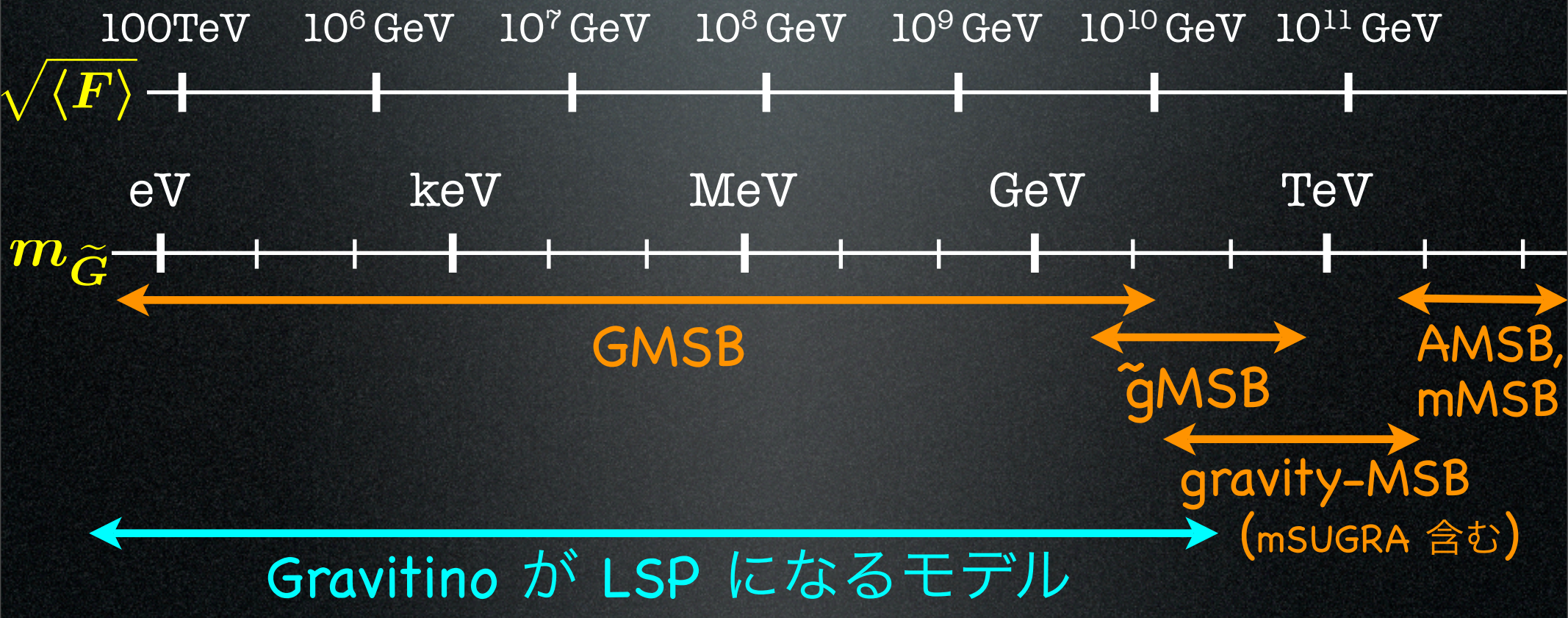
SUSY breaking VEV

Gravitino

- Gravitino Interaction: extremely weak

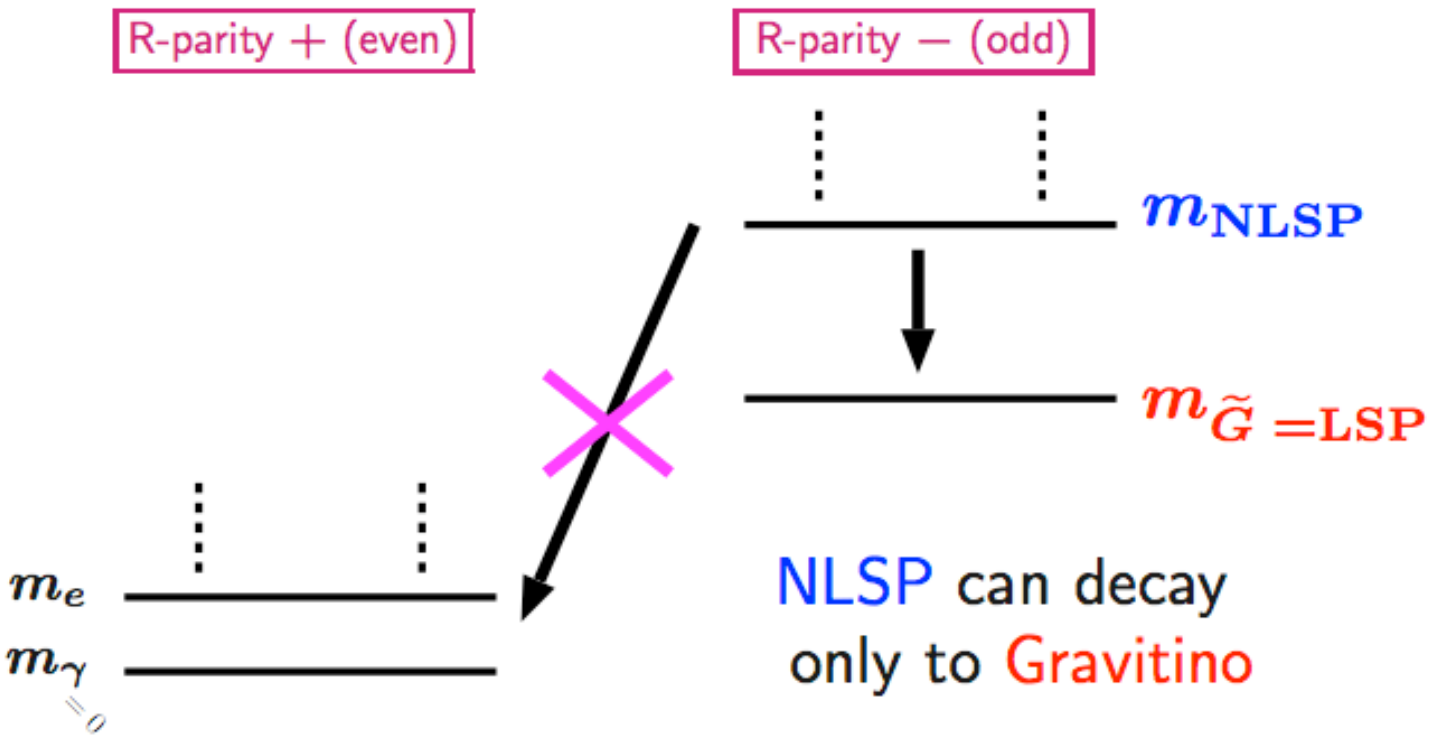
  suppressed by $\sim \dfrac{1}{M_{\rm P}}$ (or $\sim \dfrac{1}{F} \sim \dfrac{1}{M_{\rm P} m_{\tilde{G}}}$)

- Gravitino Mass $m_{\tilde{G}} = \dfrac{1}{\sqrt{3} M_{\rm P}} \langle F \rangle$: model dependent



NLSP (Next-to-Lightest SUSY Particle)

In Gravitino LSP scenario, the NLSP decay always include the gravitino.



Interaction

$$\sim \frac{1}{F} \sim \frac{1}{M_{\rm P} m_{\tilde{G}}}$$

NLSP (Next-to-Lightest SUSY Particle)

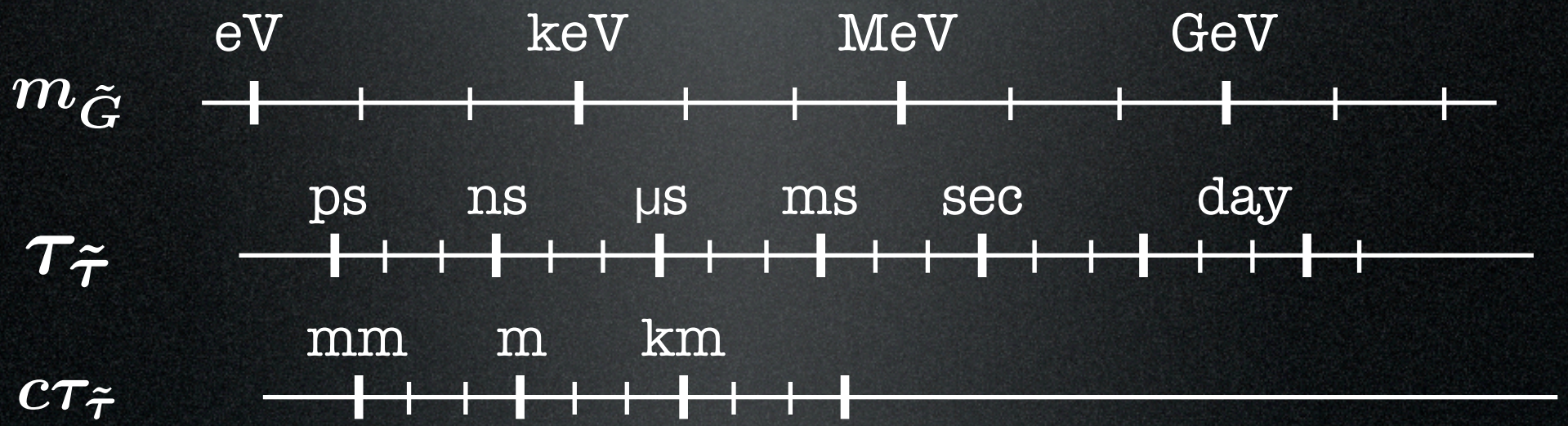
In Gravitino LSP scenario, the NLSP decay always include the gravitino.

For a slepton NLSP,.....

$$\Gamma(\tilde{\tau} \to \tilde{G}\tau) \simeq \frac{m_{\tilde{\tau}}^5}{48\pi m_{\tilde{G}}^2 M_{\rm pl}^2}\left(1-\frac{m_{\tilde{G}}^2}{m_{\tilde{\tau}}^2}\right)^4$$

Lifetime (decay length) of NLSP stau

e.g., for $m_{\tilde{\tau}} = 100\ \mathrm{GeV}$,



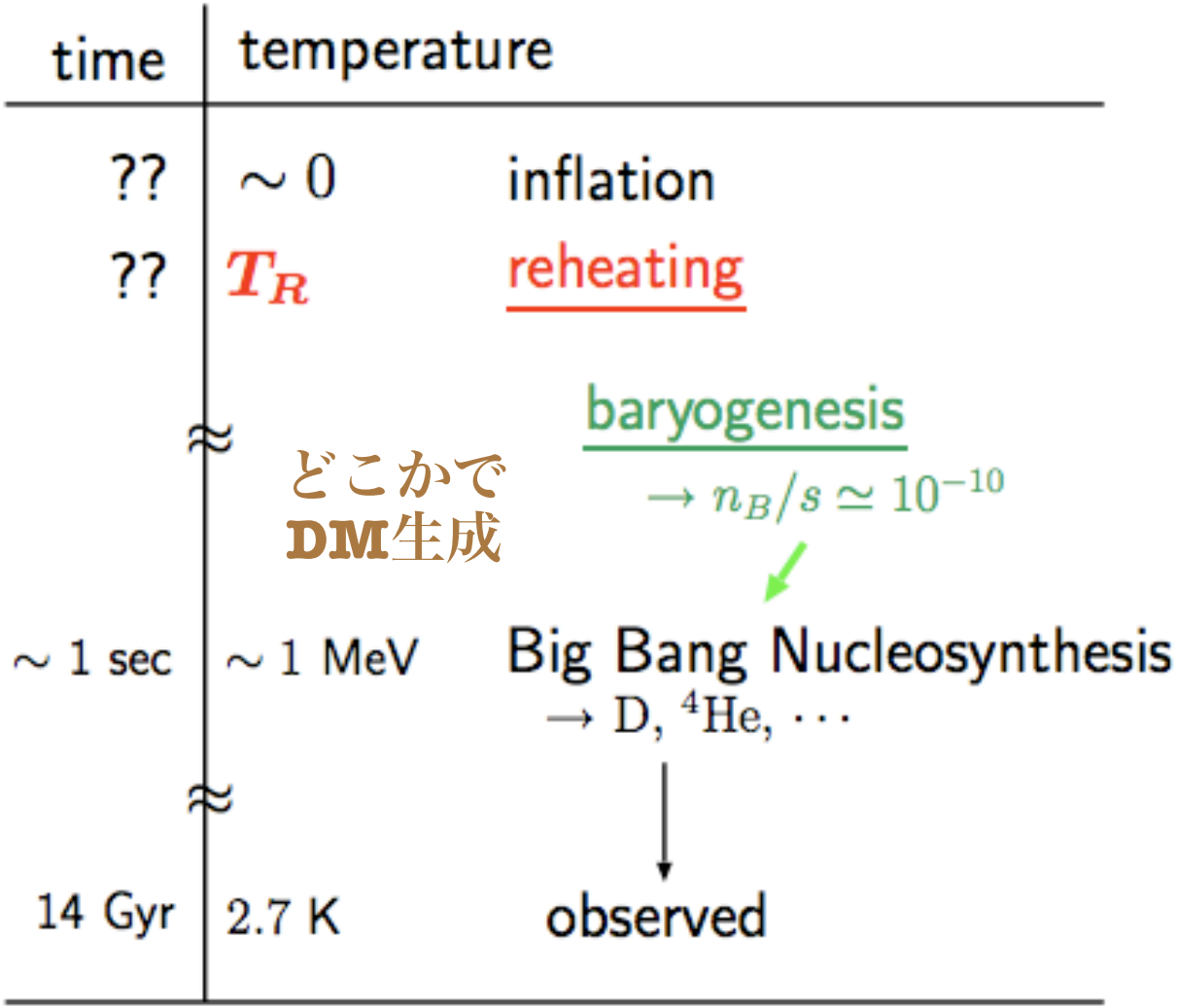
Gravitino と Cosmology

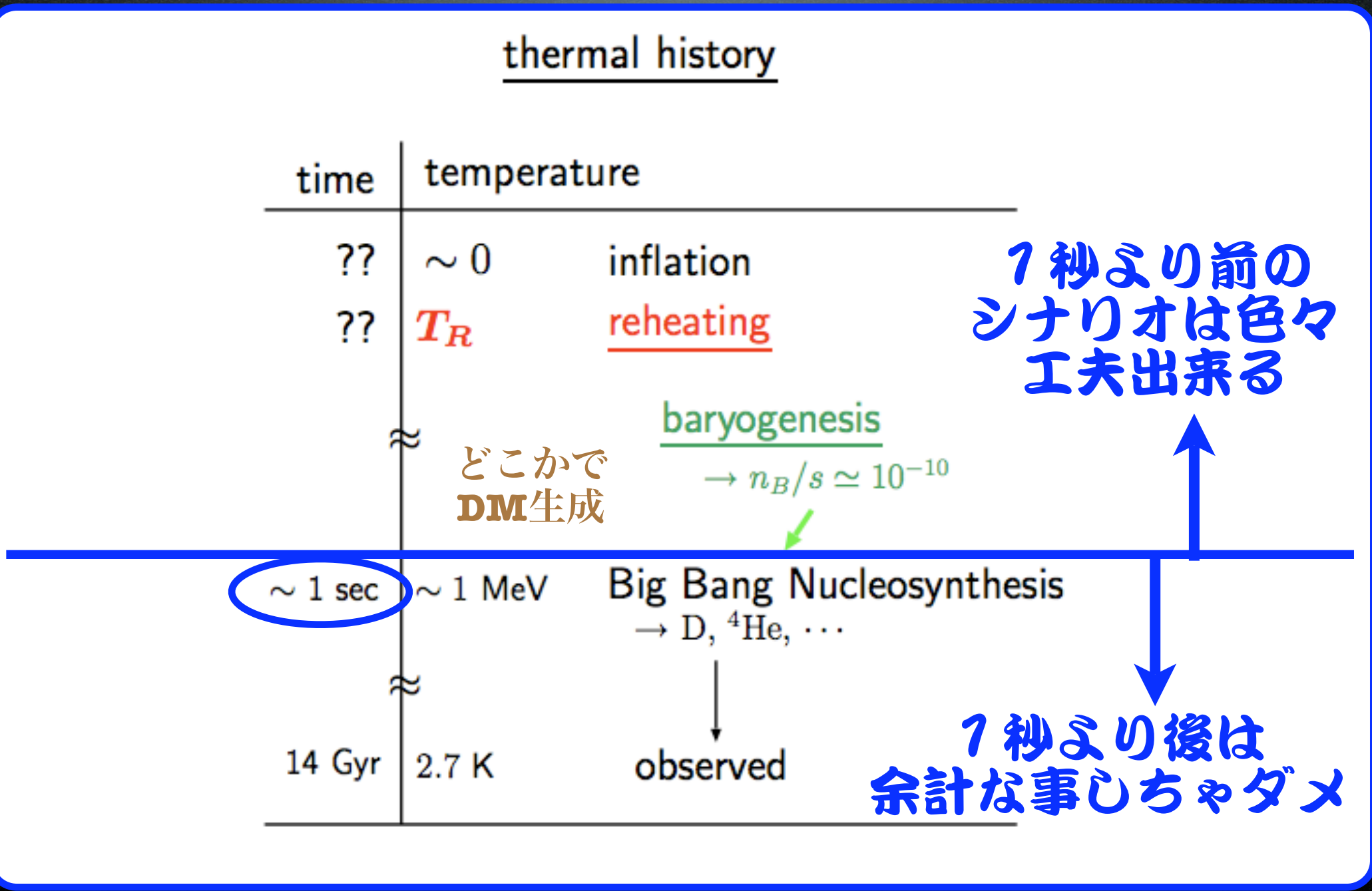
Gravitino と Cosmology

初期宇宙論的には寿命が

1 秒を超えたら “Long-lived”

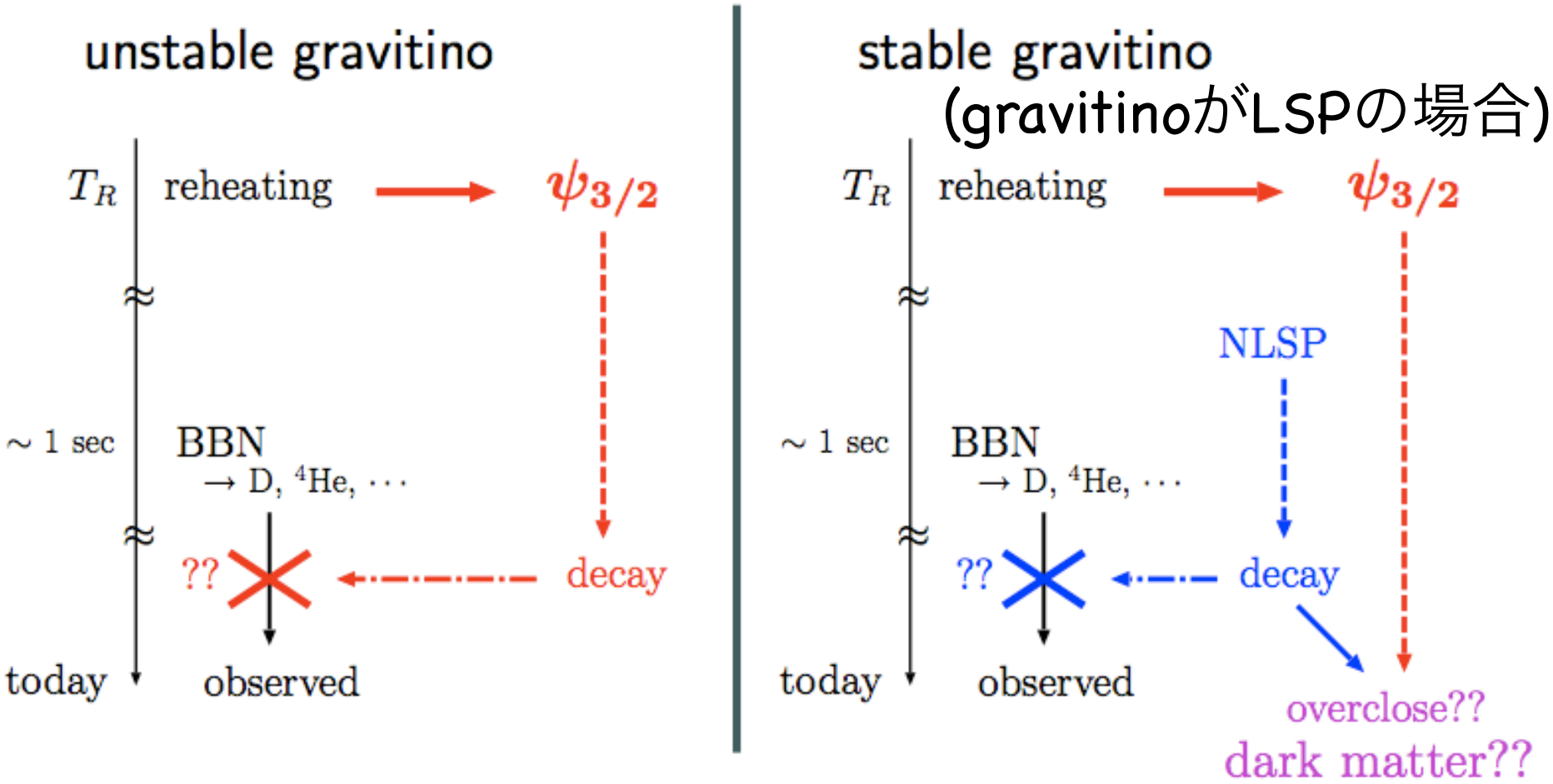
thermal history




thermal history
time
temperature
??
~ 0
inflation
??
T_R
reheating
baryogenesis
$\rightarrow n_B/s \simeq 10^{-10}$
どこかで
DM生成
~ 1 sec
~ 1 MeV
Big Bang Nucleosynthesis
$\rightarrow$ D, ^{4}He, $\cdots$
14 Gyr
2.7 K
observed
1秒より前の
シナリオは色々
工夫出来る
1秒より後は
余計な事しちゃダメ

Gravitino Problems

thermal history with gravitino $\psi_{3/2}$



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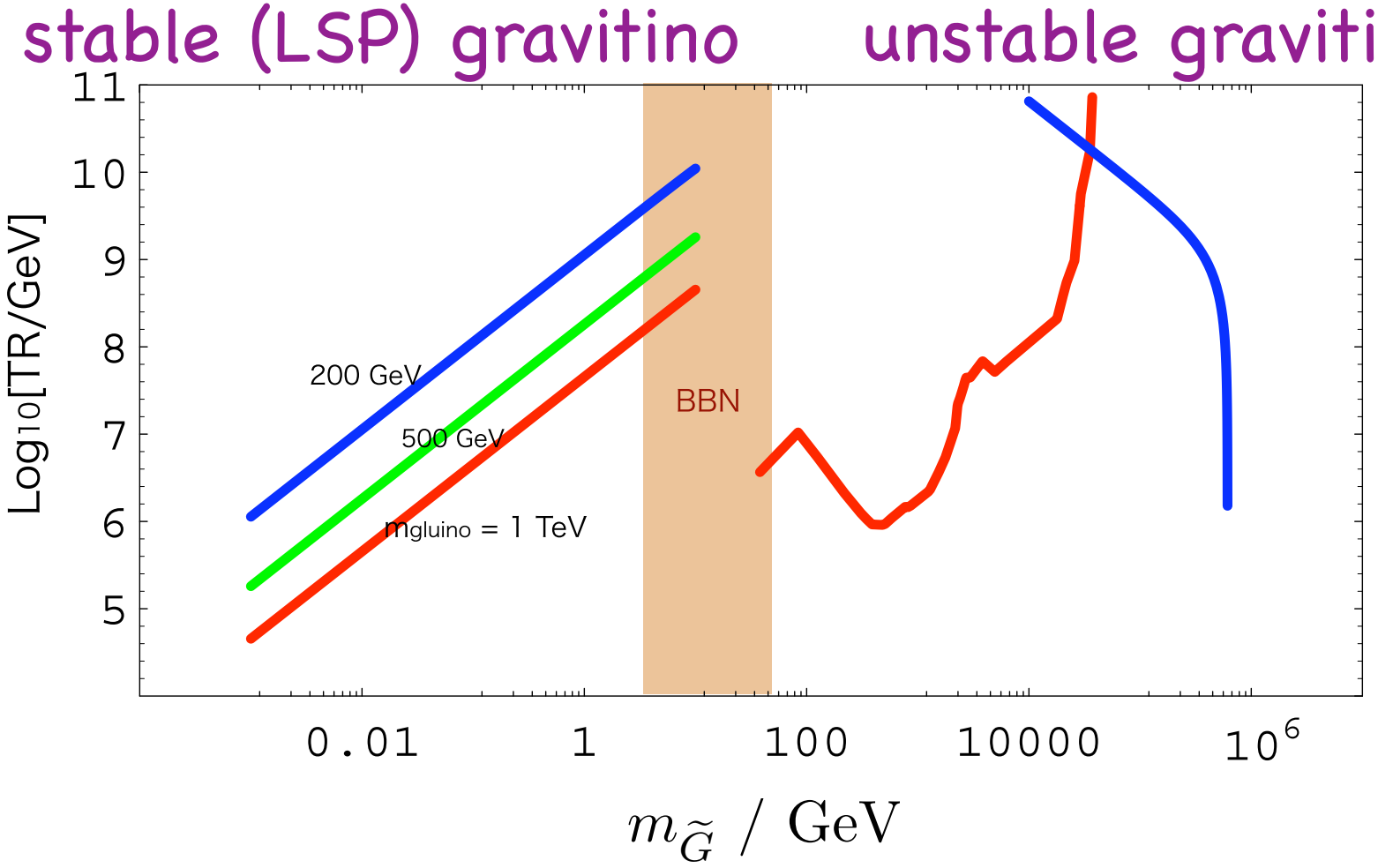
Gravitino Problems



(NOTE: precise line positions in this figure may be out-dated.)

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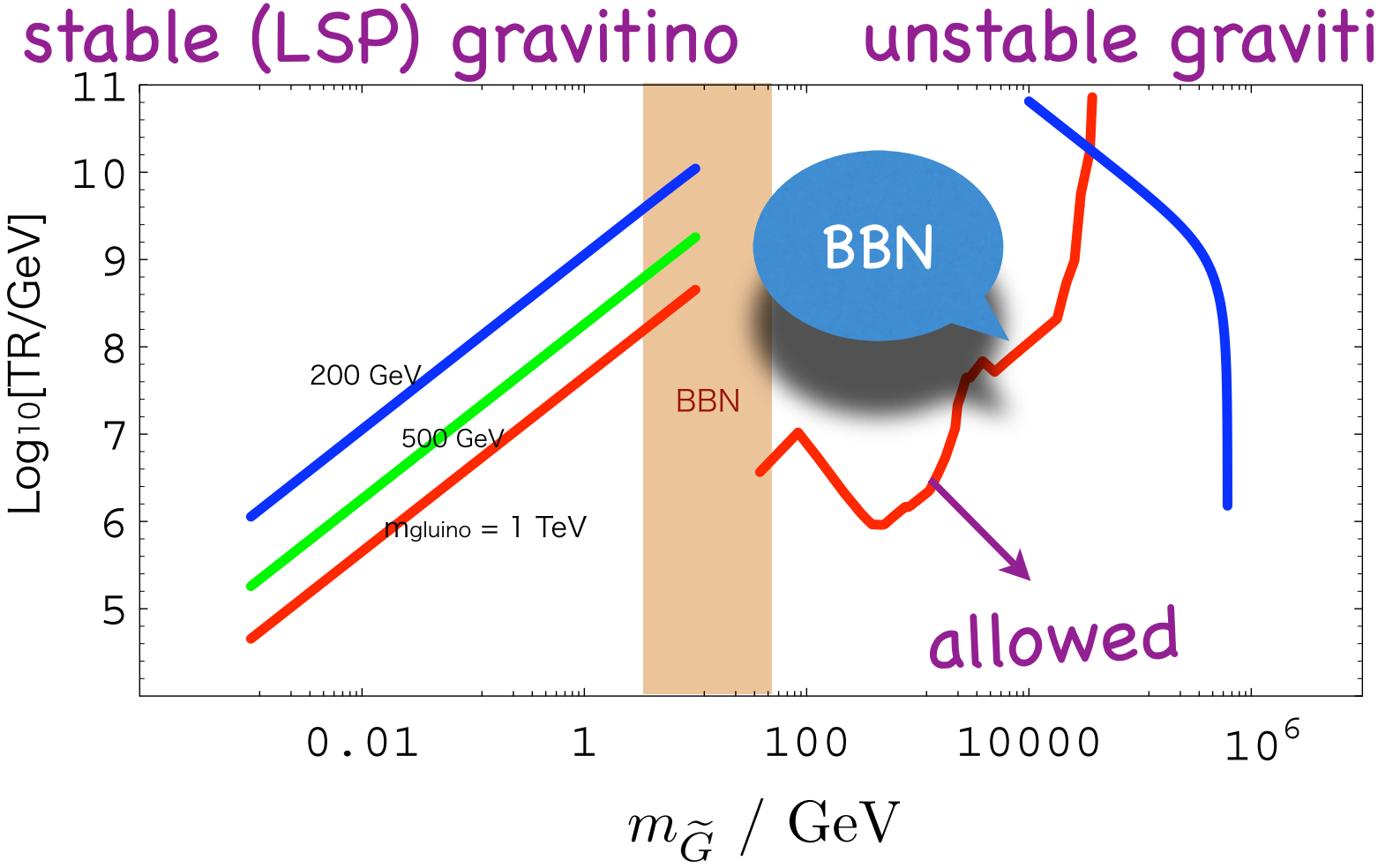

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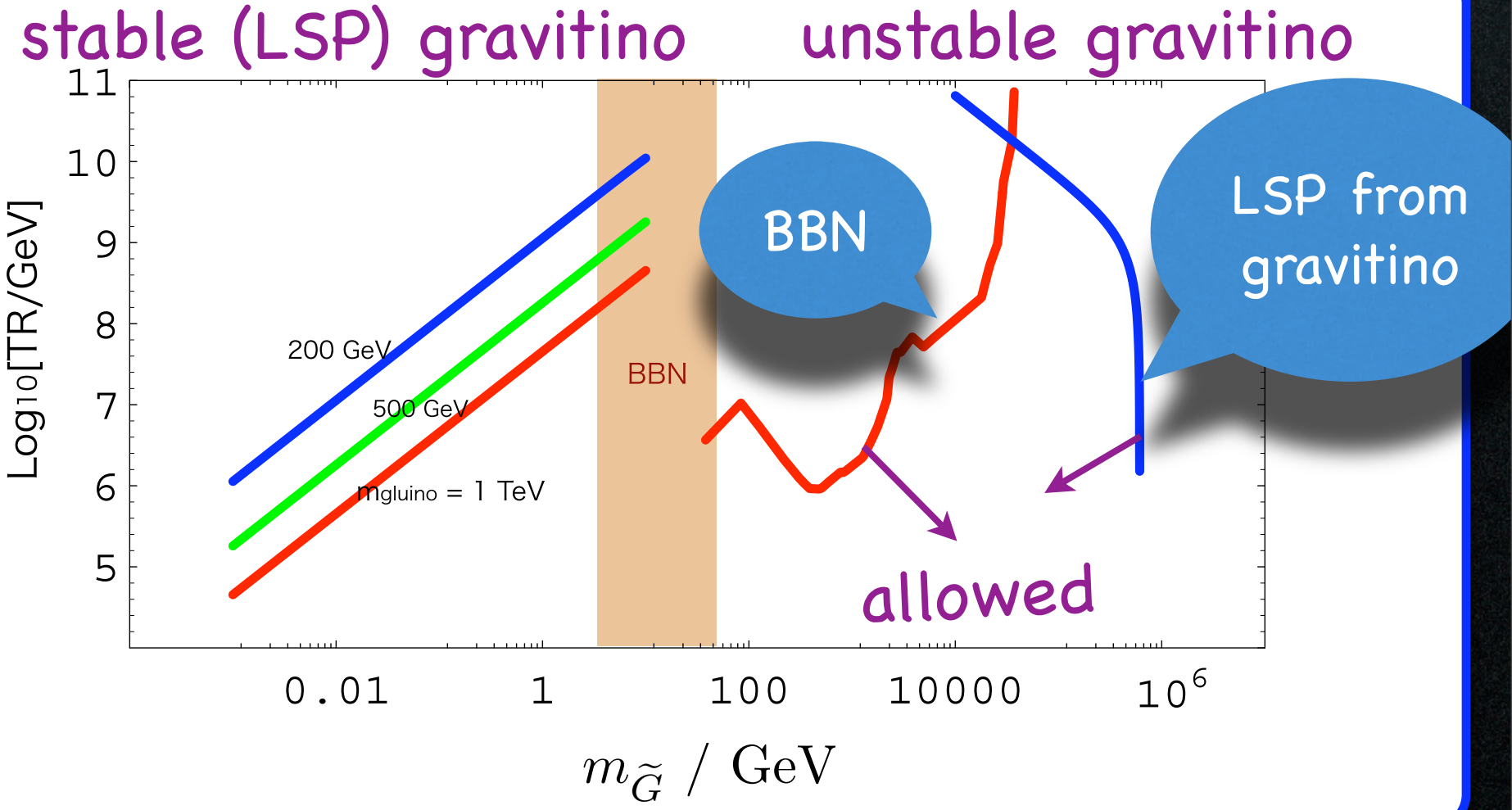

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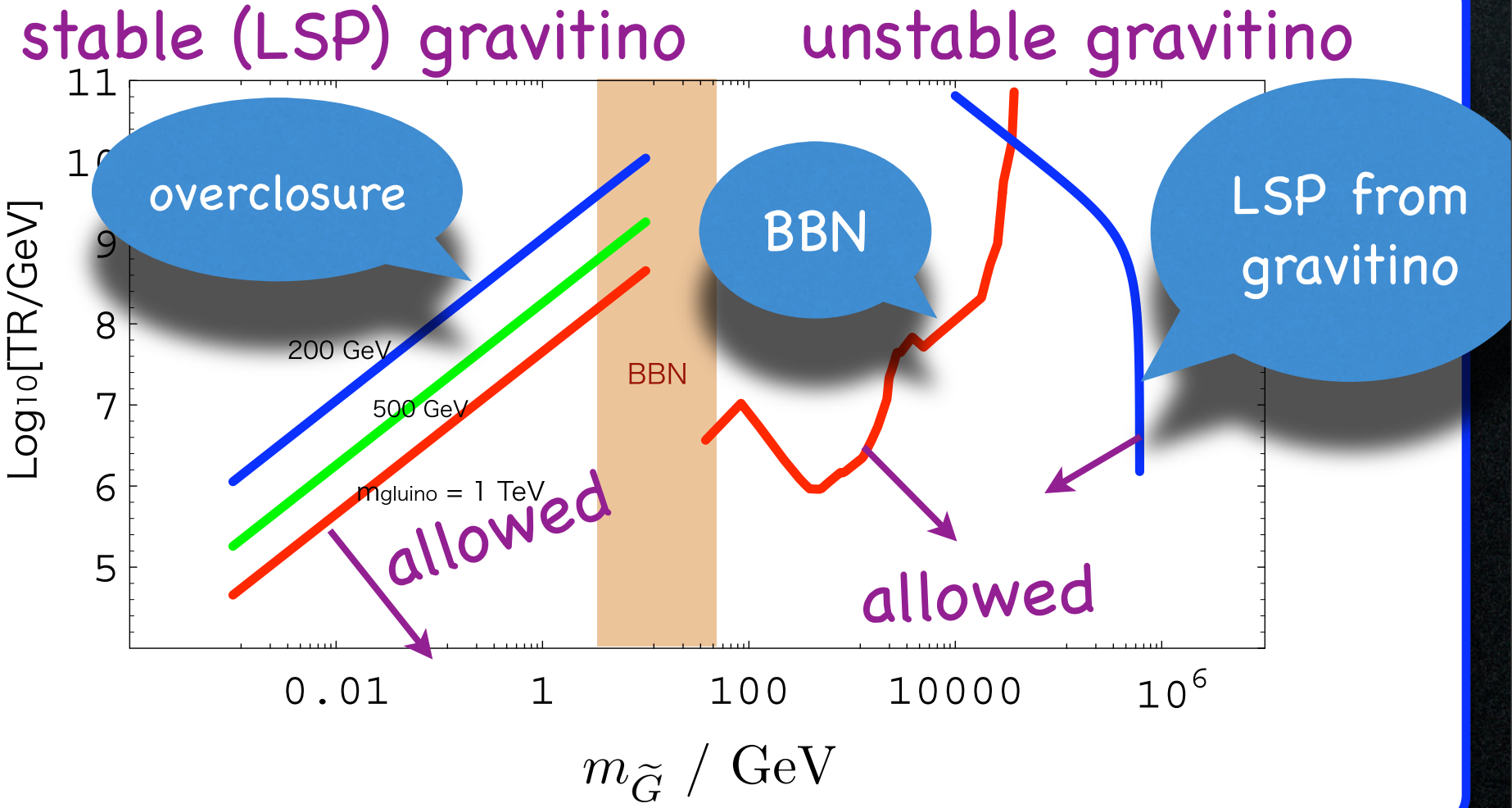

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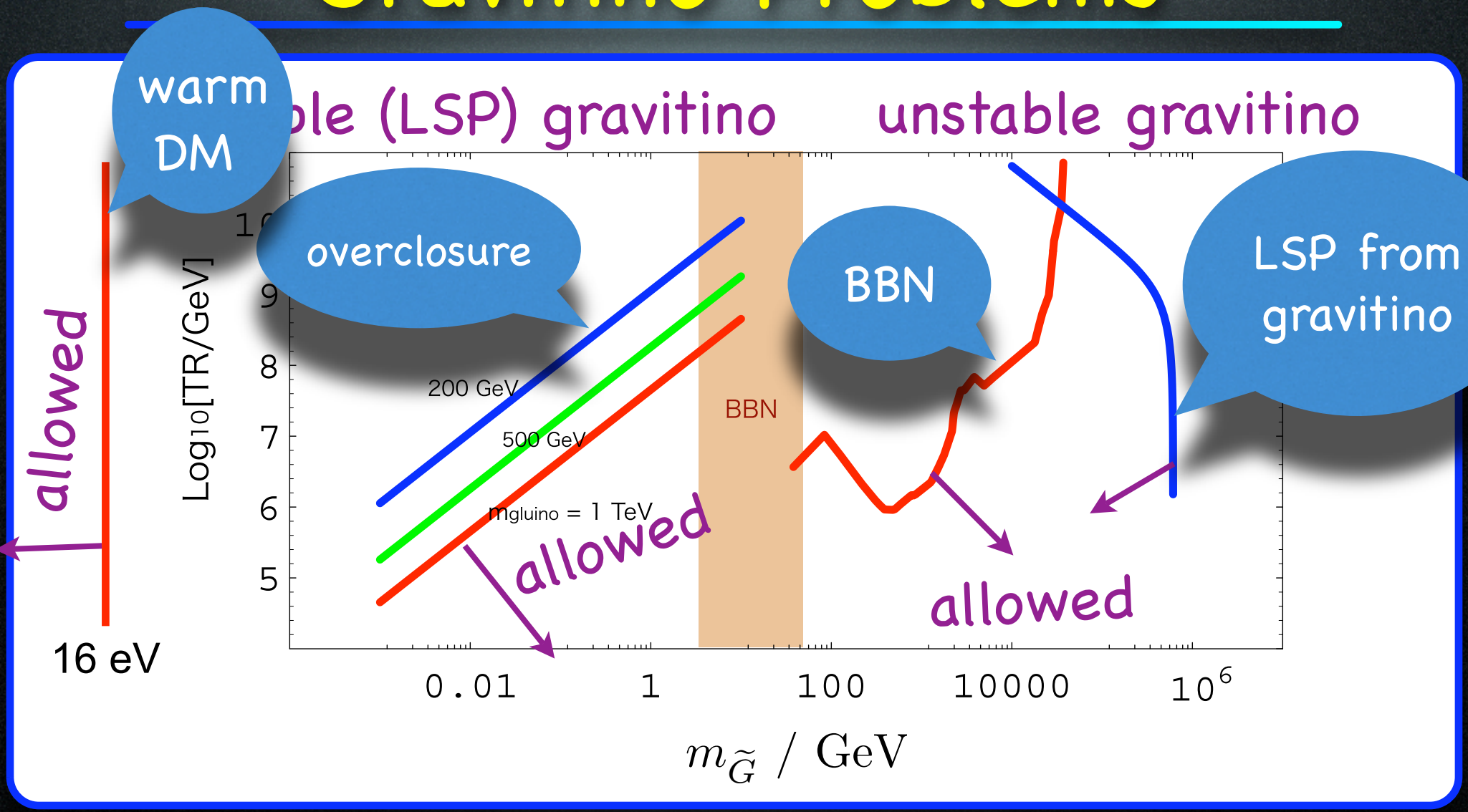

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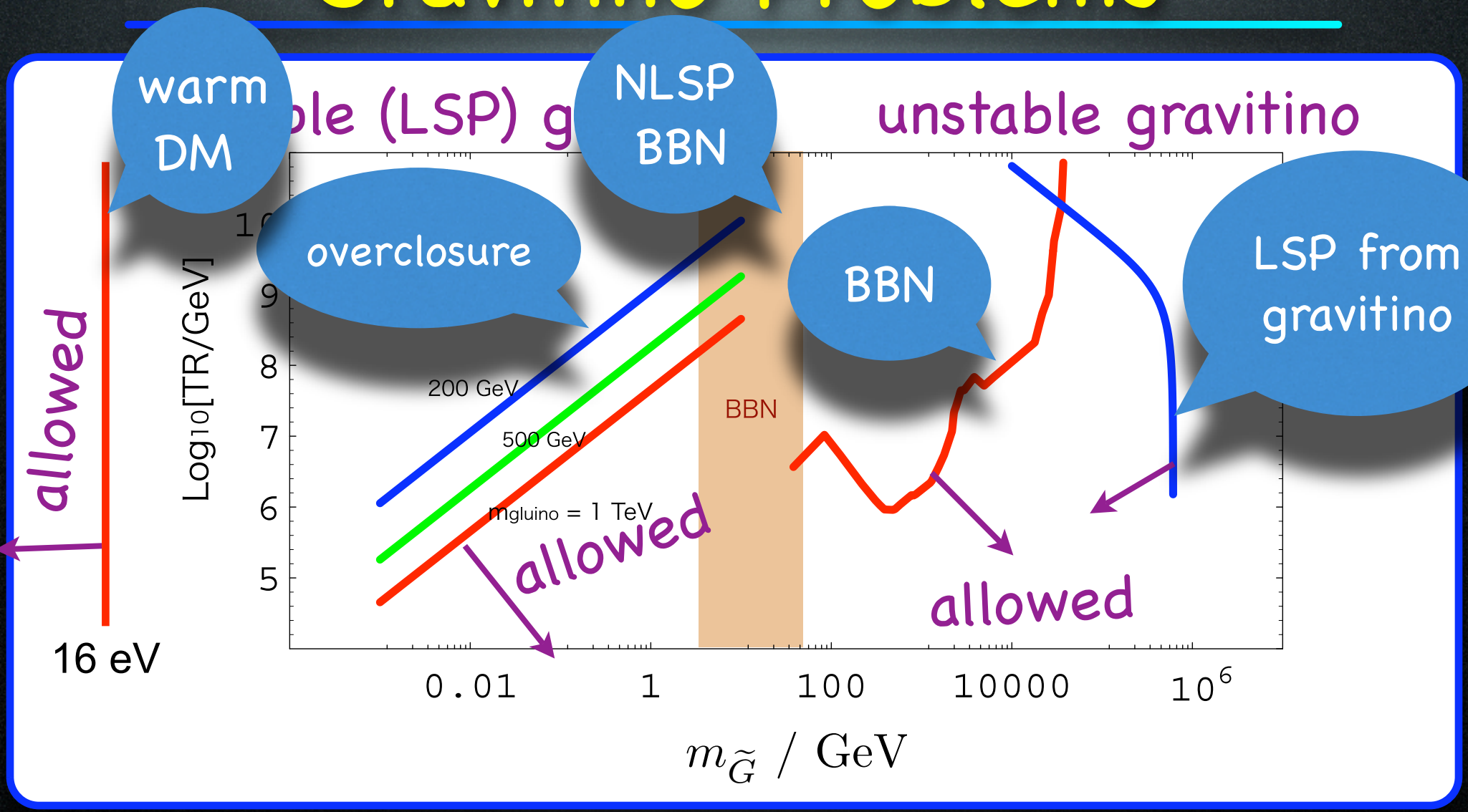

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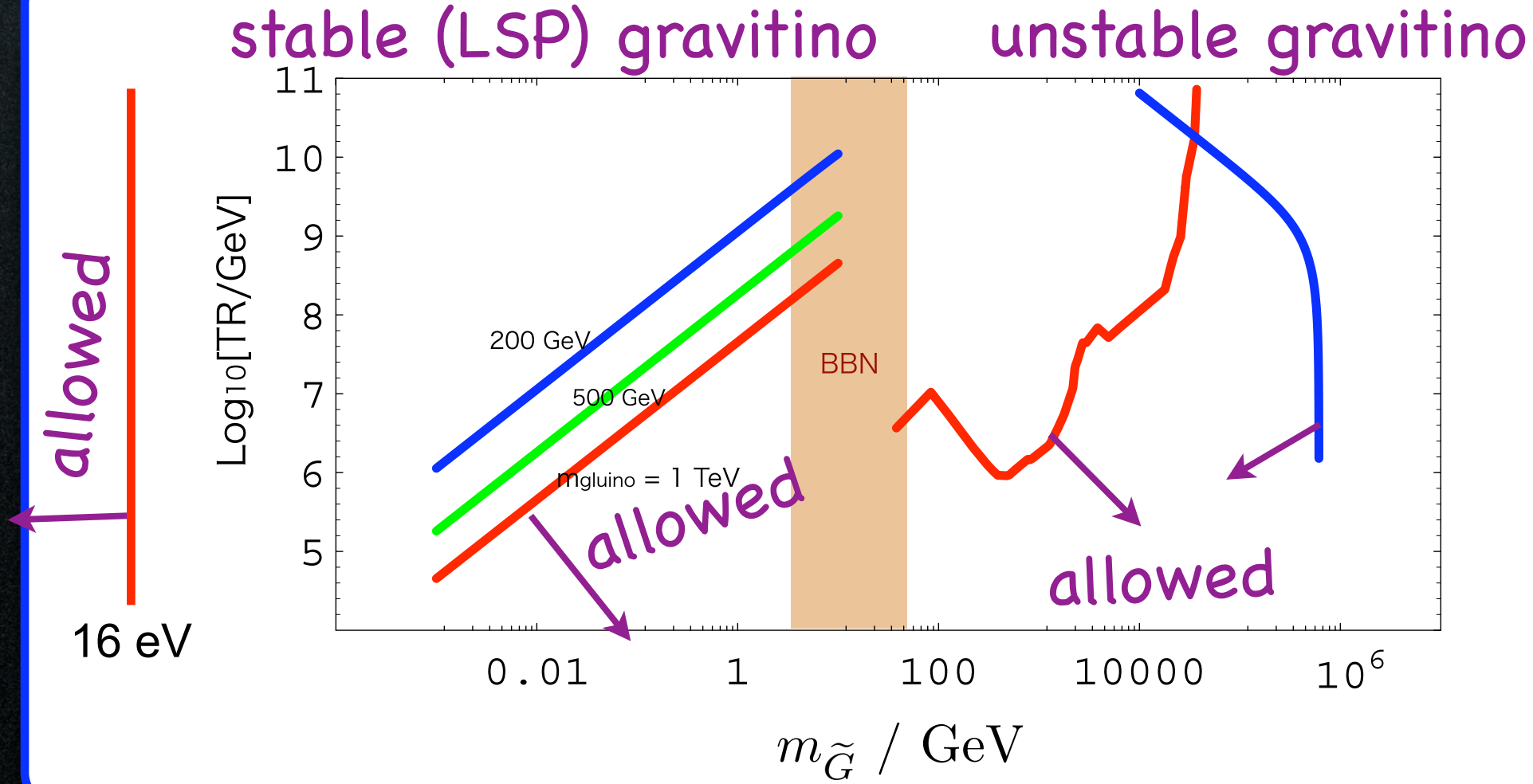

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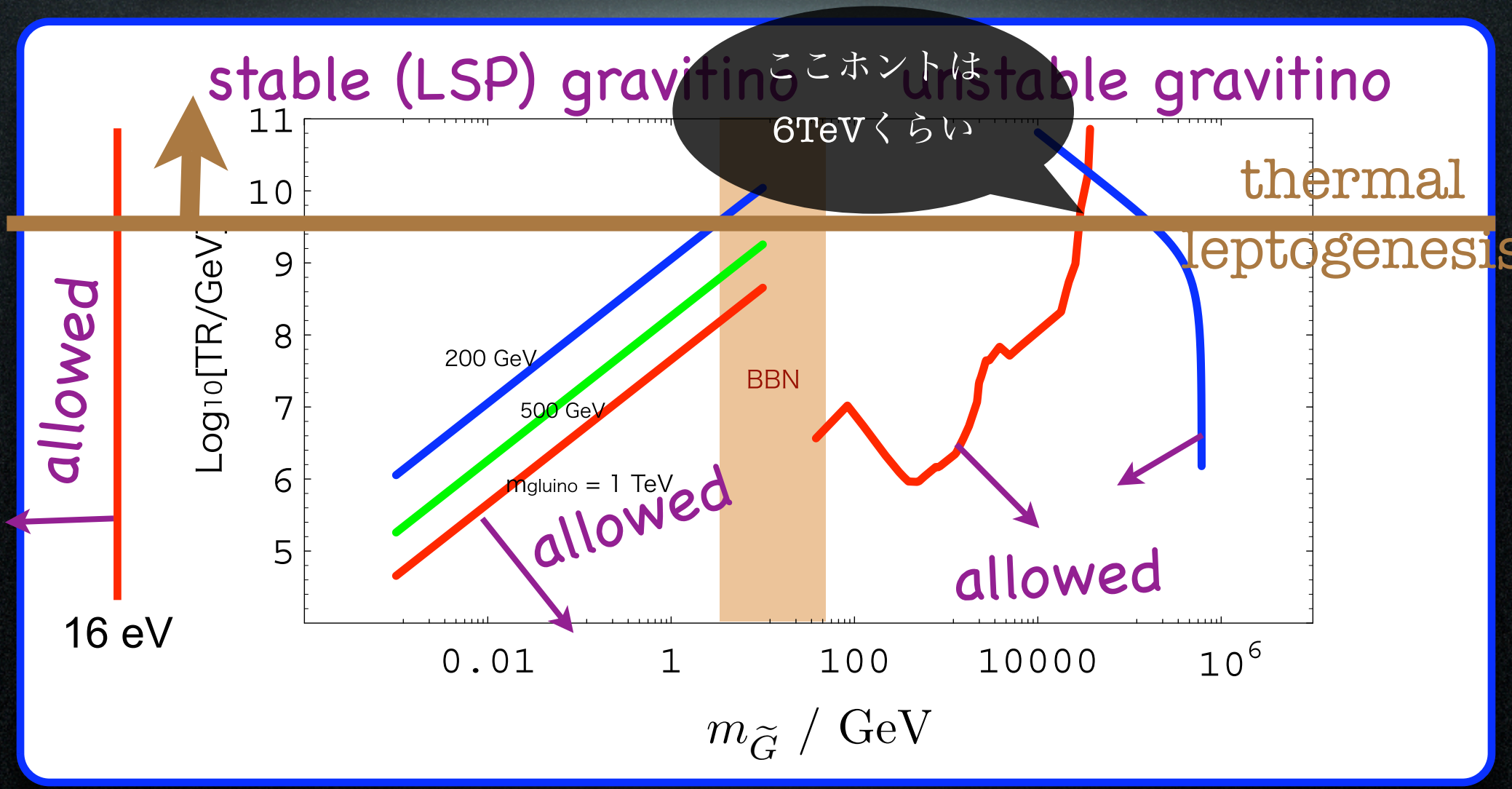

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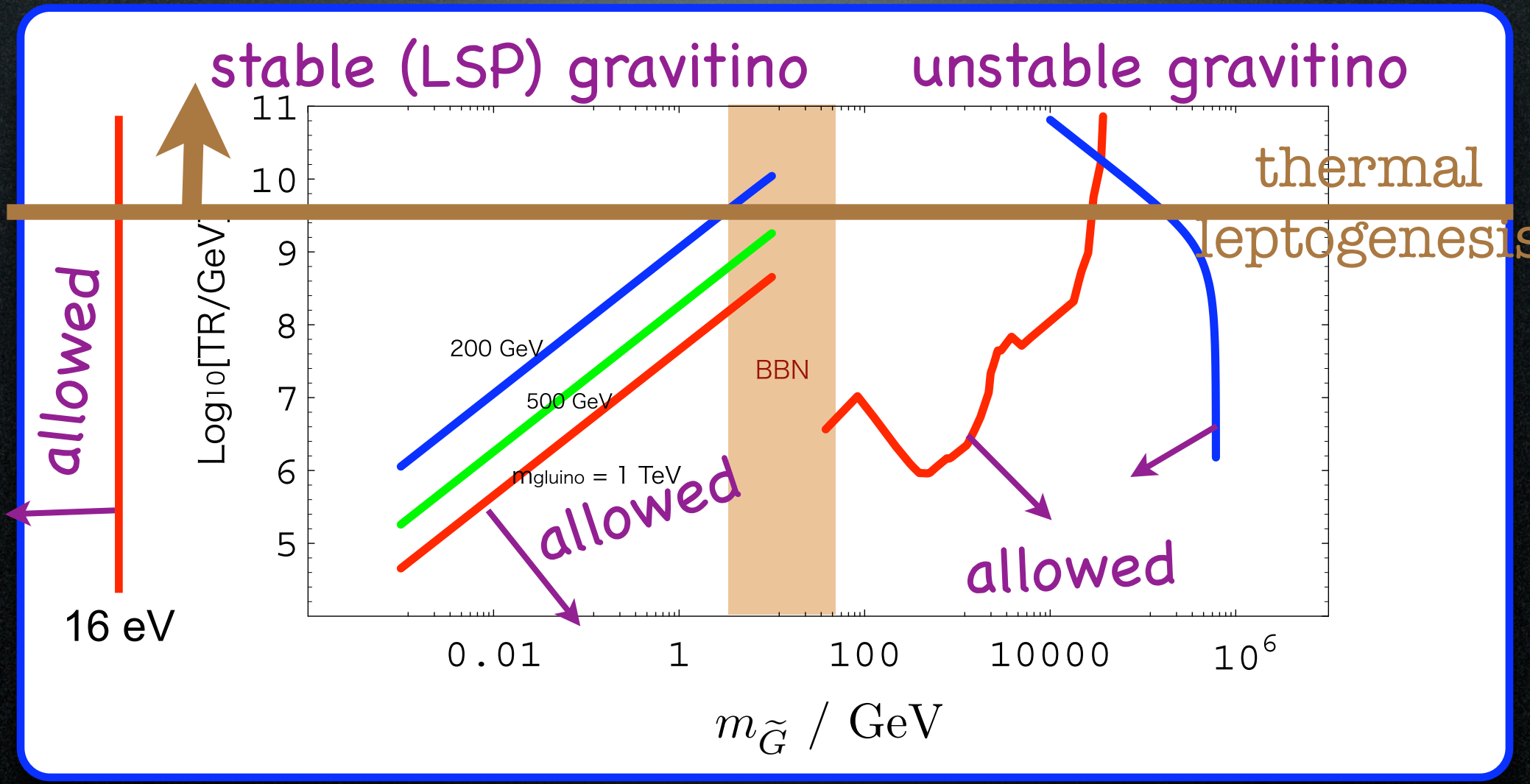

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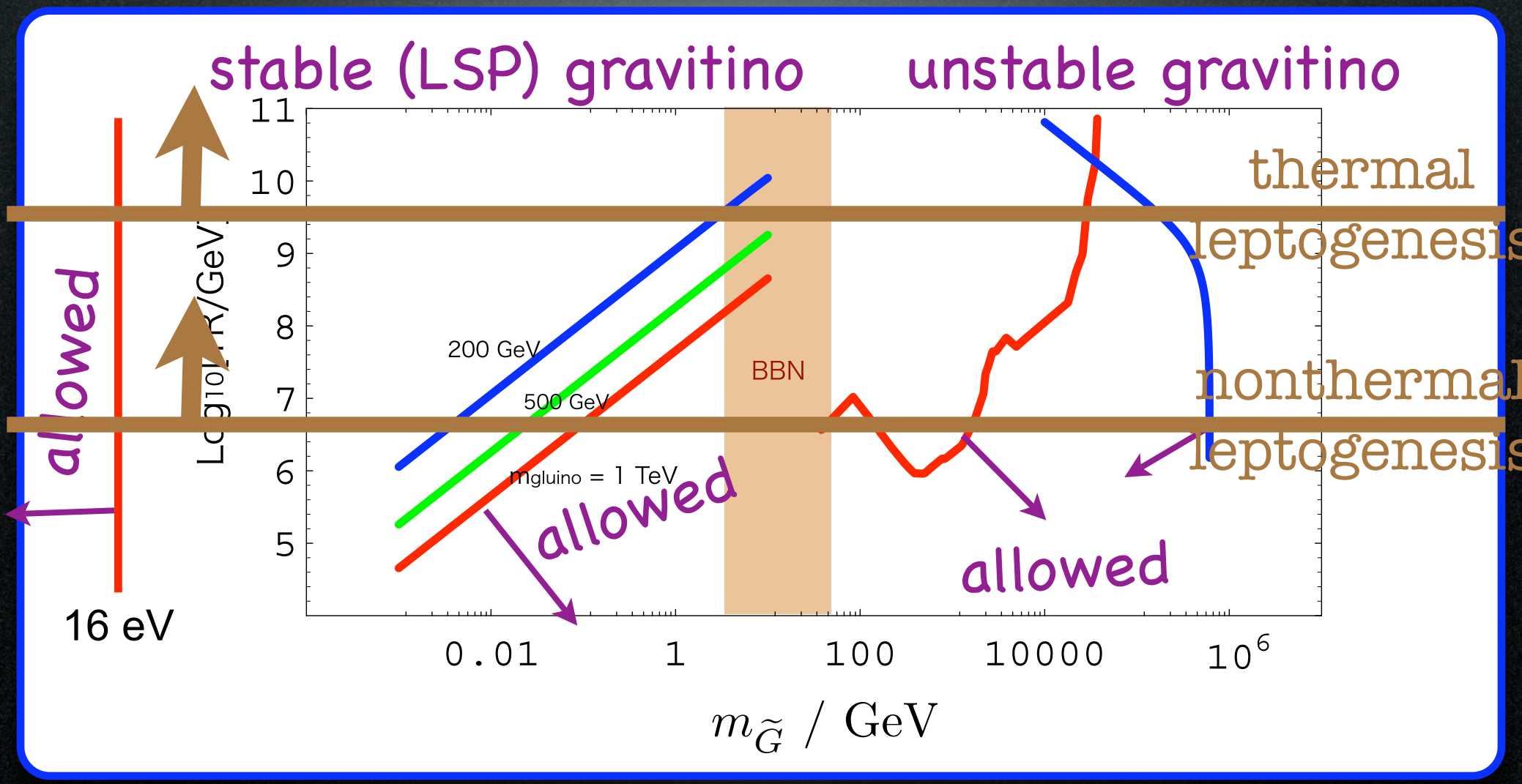

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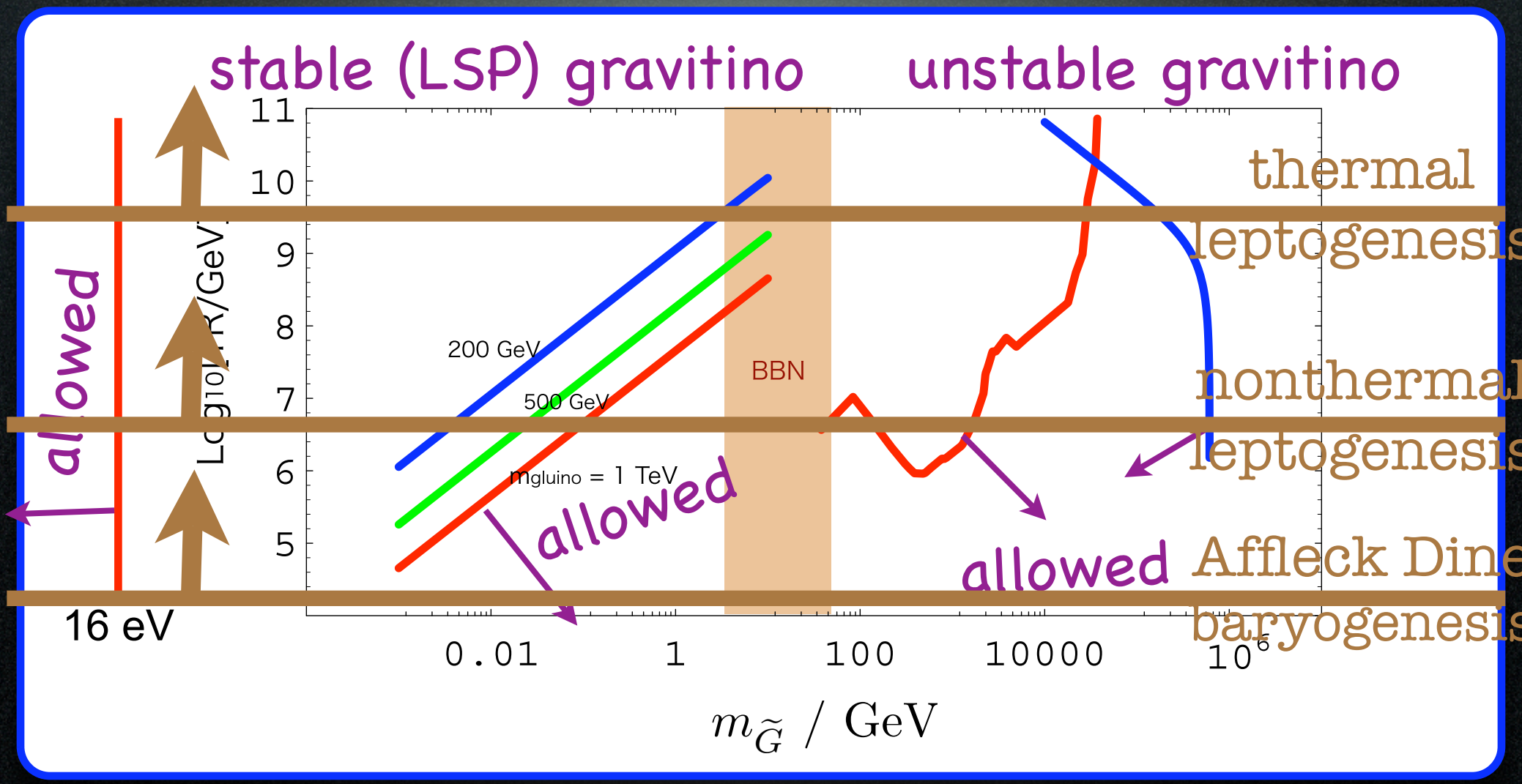

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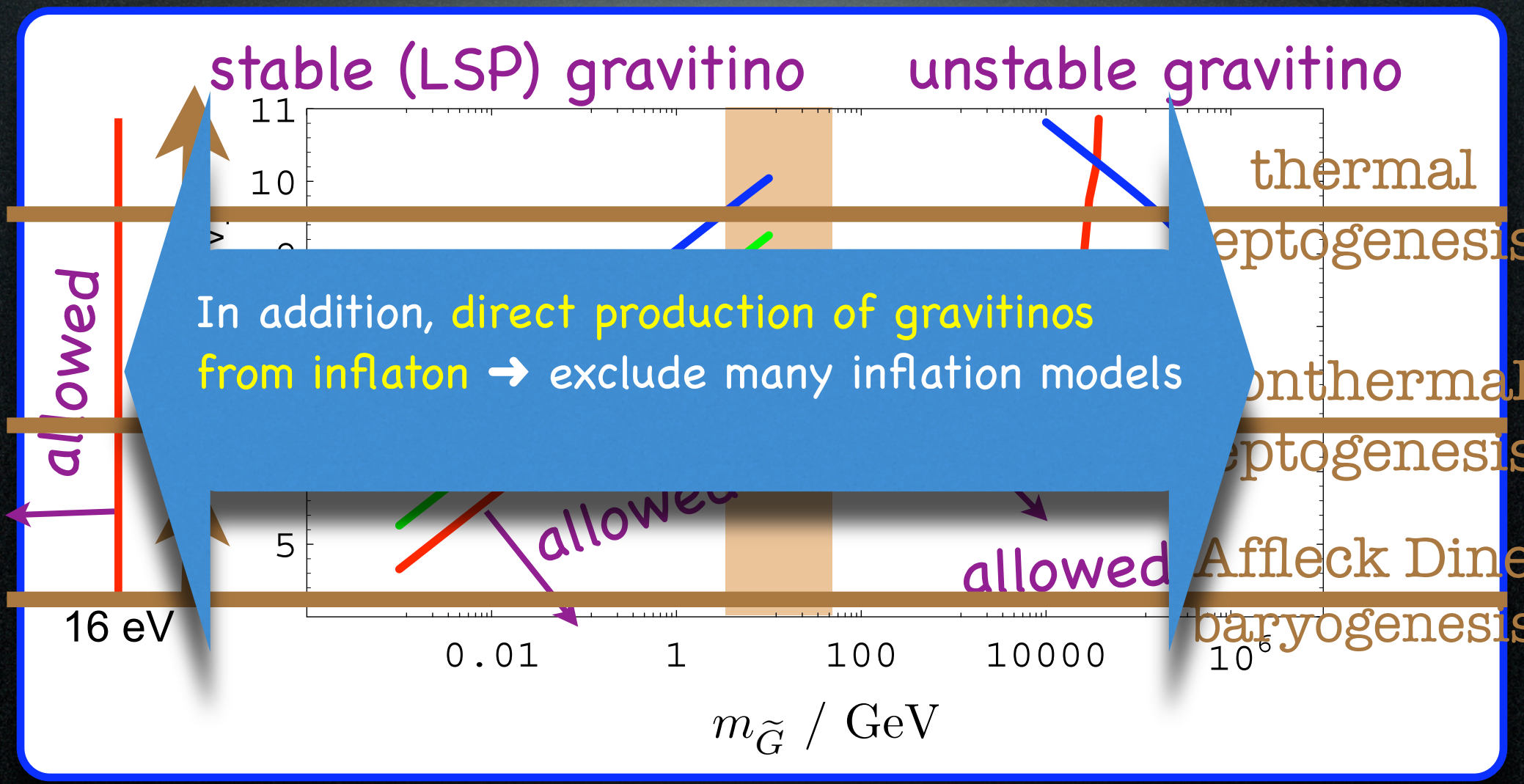

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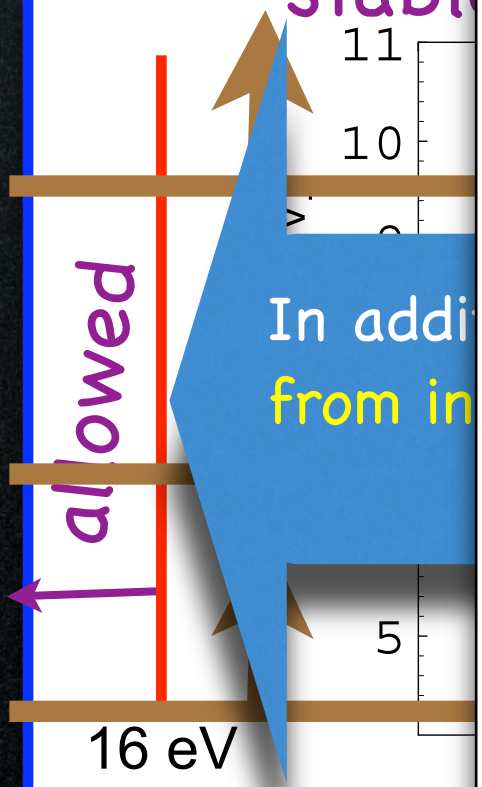

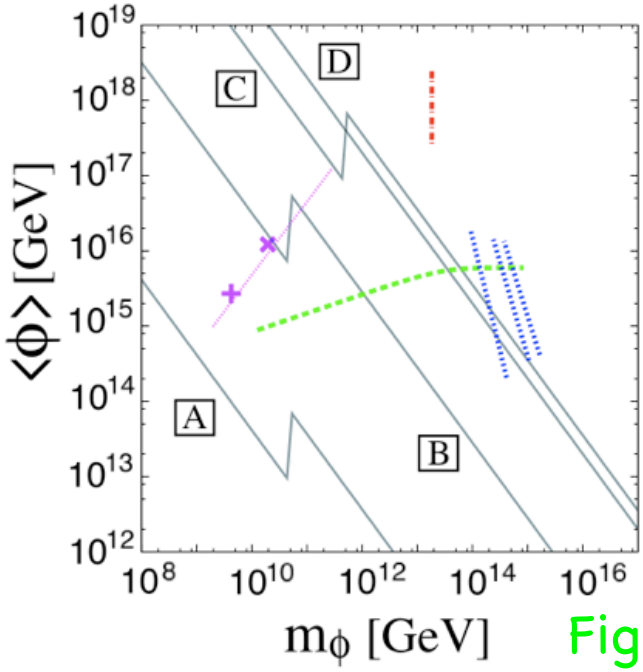

Fig. from Endo, Takahashi, Yanagida, '07

FIG. 3: Constraints from the gravitino production by the inflaton decay, for $m_{3/2} = 1\,\mathrm{TeV}$ with $B_h = 1$ (case A), $m_{3/2} = 1\,\mathrm{TeV}$ with $B_h = 10^{-3}$ (case B), $m_{3/2} = 100\,\mathrm{TeV}$ (case C), and $m_{3/2} = 1\,\mathrm{GeV}$ (case D). The region above the solid (gray) line is excluded for each case. For

$m_{\tilde{G}}$ / GeV

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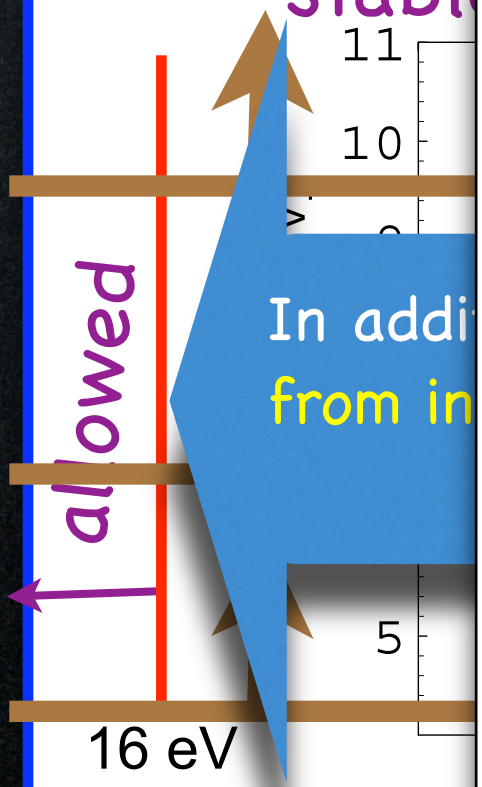
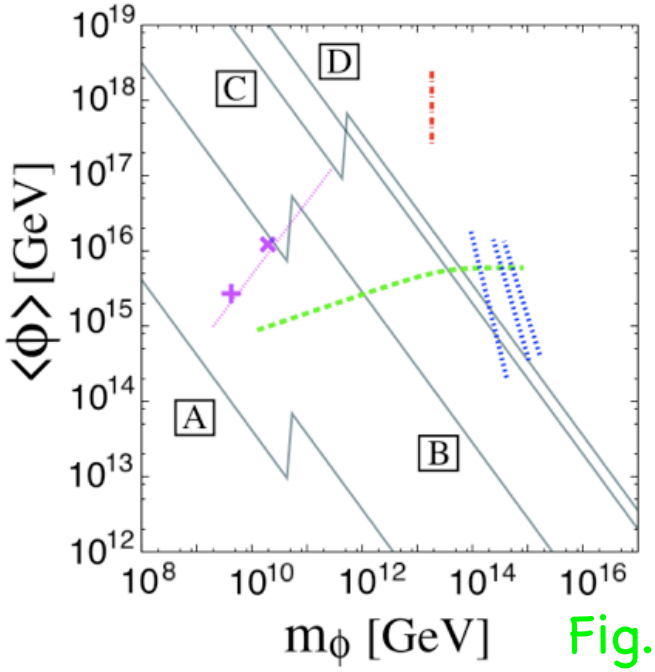
Gravitino Problems





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実は、gravity-MSB（mSUGRA含む）は

宇宙論的には非常に苦しい！

Sorry, I drop references.

gravitino と cosmology

- 実は、gravity-MSB（mSUGRA 含む）は宇宙論的には非常に苦しい。
- naive な宇宙シナリオを考えると、
  mG > 10 TeV（AMSB or mMSB）と,
  mG < 10 eV /mG ~ 1GeV（GMSB）が楽。
- ただし他の領域も exclude されているワケではなく inflation model を工夫して、再加熱温度も下げて baryogenesisも低温のを選んで・・・と1秒より前の初期宇宙シナリオを工夫（無茶）すれば何とかなります。
- 逆にLHC で LSP（gravitino or not）や NLSP の性質が分かれば、宇宙論に強い制限！

Gravitino LSP と LHC での物理と NLSP

コライダー的には寿命が

$c\tau$= O(1mm - 10m) なら(?) "Long-lived"

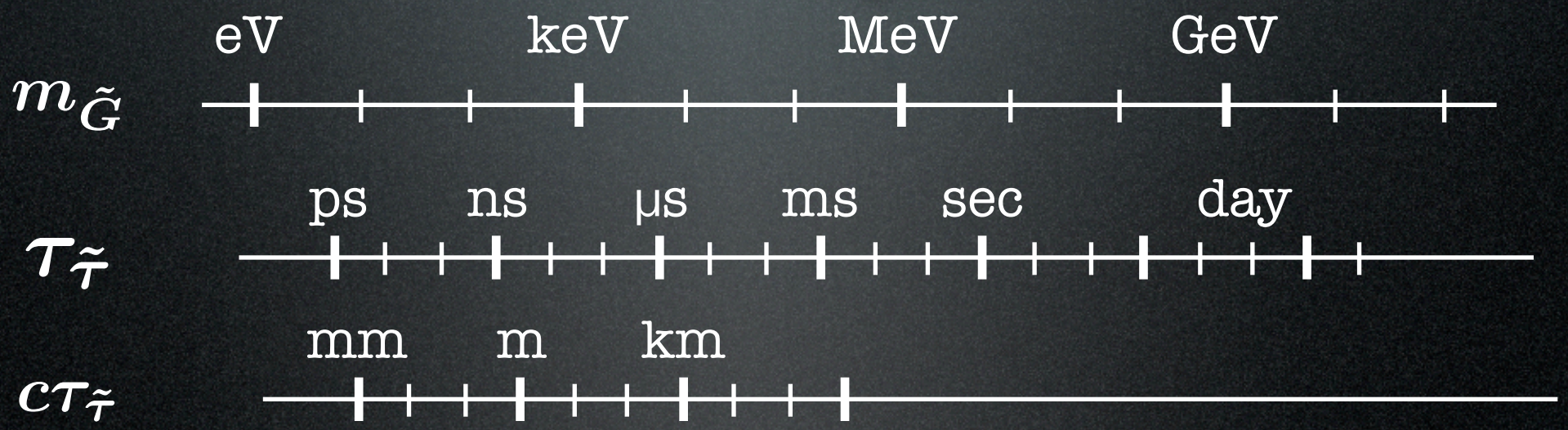
$c\tau$ > O(100m) なら "stable"

NLSP lifetime

$$\Gamma(\tilde{\tau} \to \tilde{G}\tau) \simeq \frac{m_{\tilde{\tau}}^5}{48\pi m_{\tilde{G}}^2 M_{\rm pl}^2}\left(1 - \frac{m_{\tilde{G}}^2}{m_{\tilde{\tau}}^2}\right)^4$$

Lifetime (decay length) of NLSP stau

e.g., for $m_{\tilde{\tau}} = 100\ \mathrm{GeV}$,



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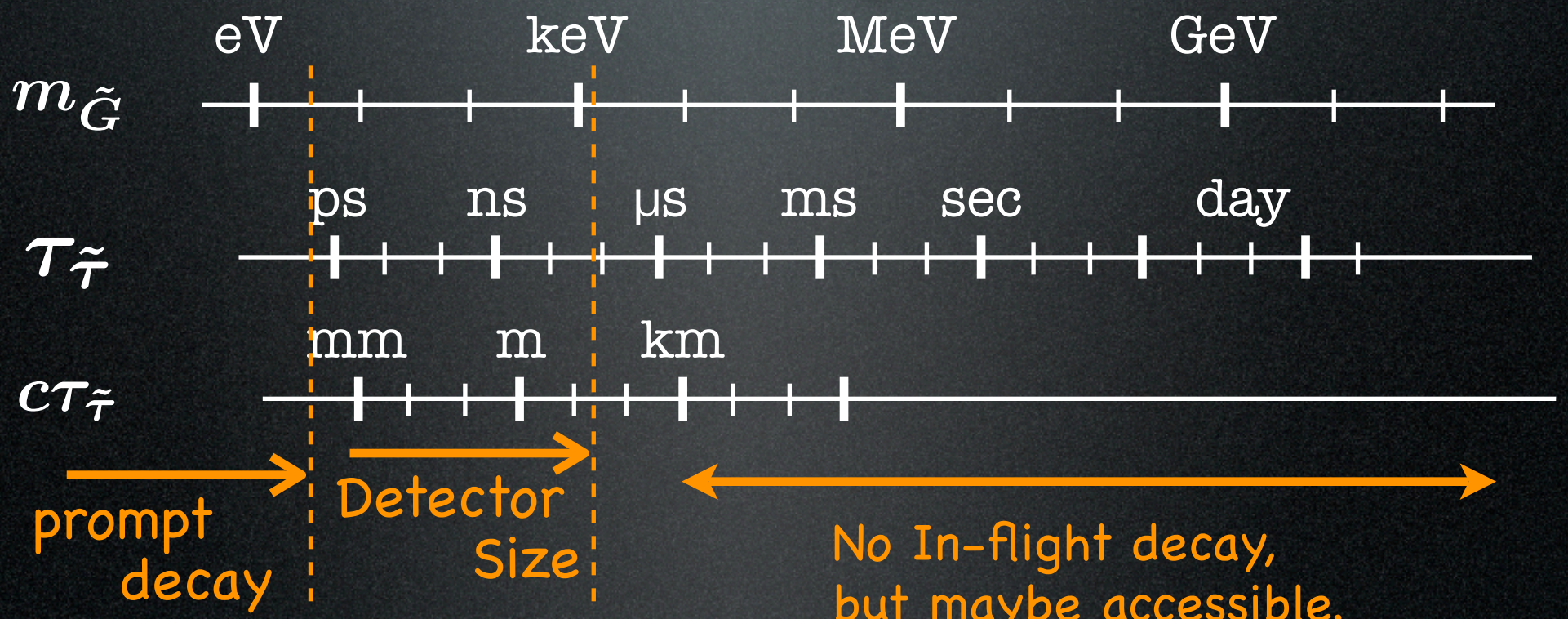


NLSP lifetime

$$\Gamma(\tilde{\tau} \to \tilde{G}\tau) \simeq \frac{m_{\tilde{\tau}}^5}{48\pi m_{\tilde{G}}^2 M_{\rm pl}^2}\left(1 - \frac{m_{\tilde{G}}^2}{m_{\tilde{\tau}}^2}\right)^4$$

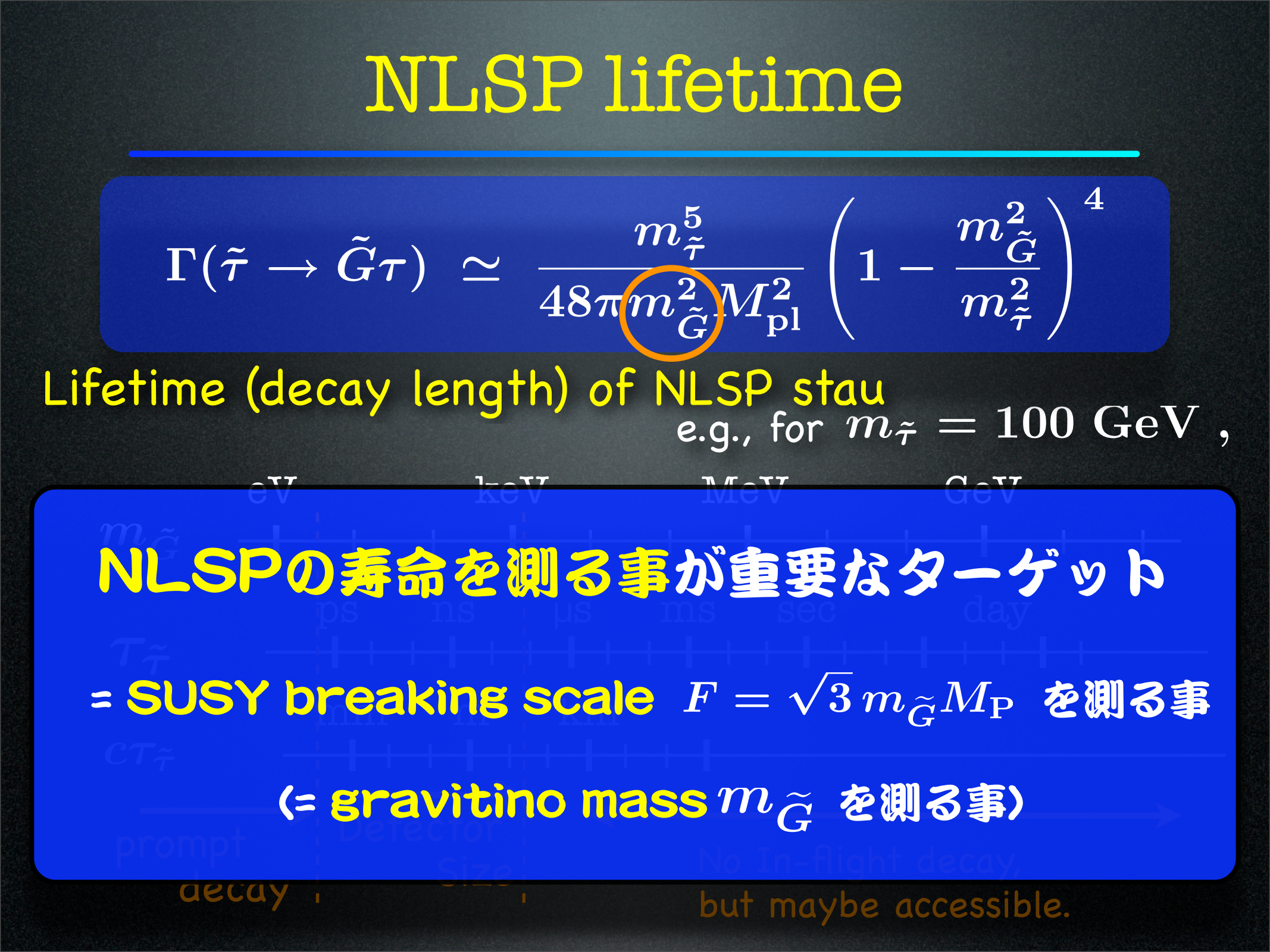
Lifetime (decay length) of NLSP stau

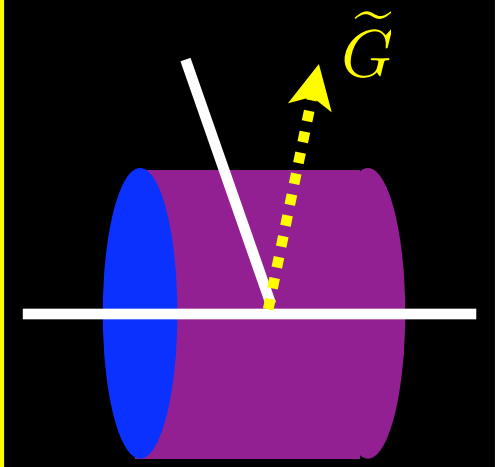
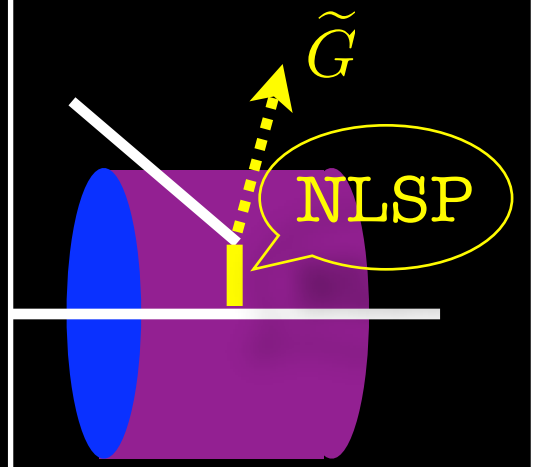
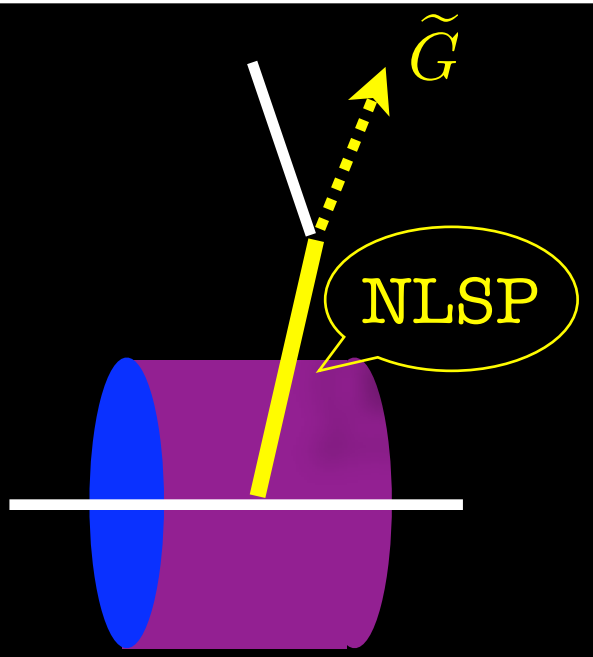
e.g., for $m_{\tilde{\tau}} = 100\ \mathrm{GeV}$,

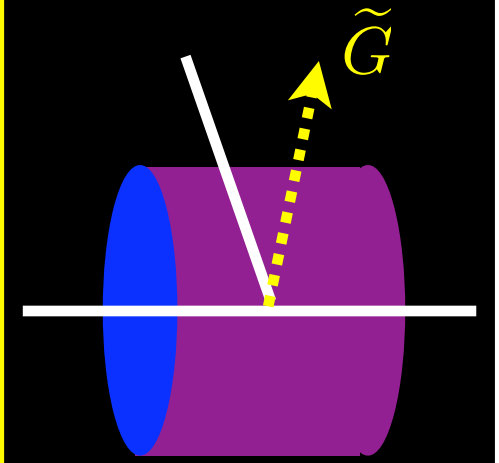
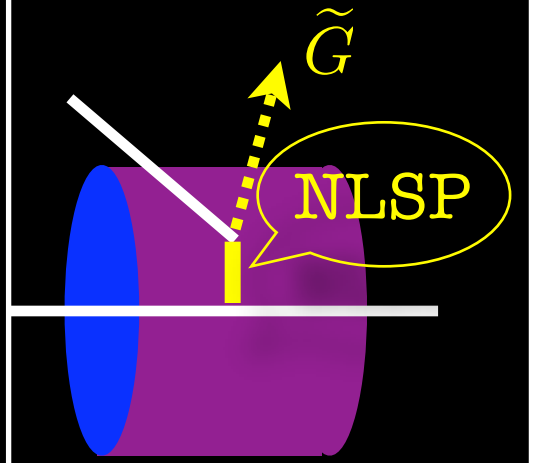
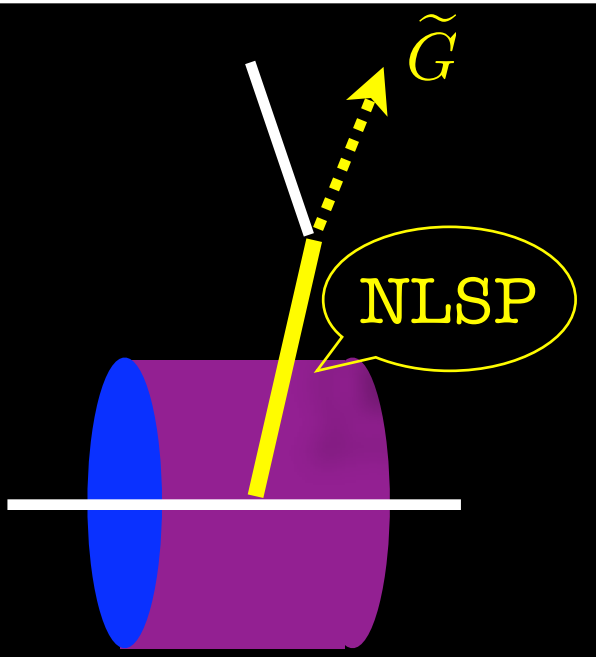
NLSPの寿命を測る事が重要なターゲット

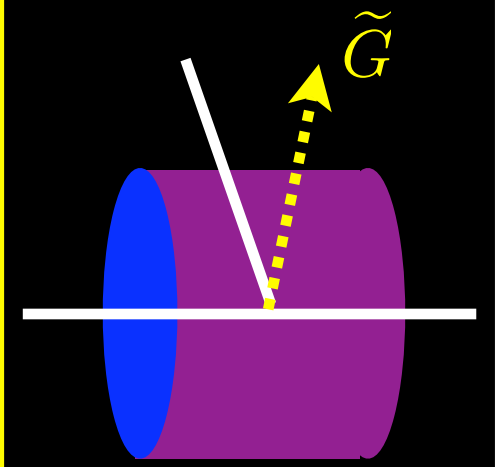
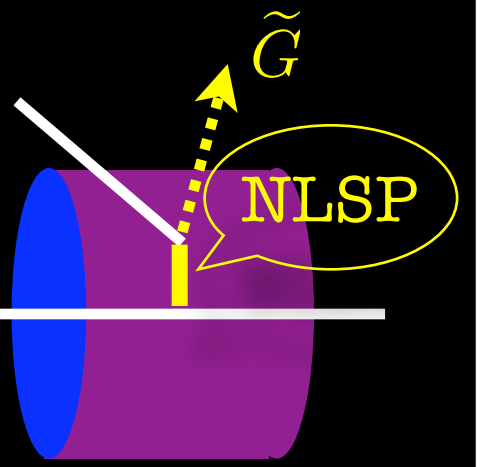
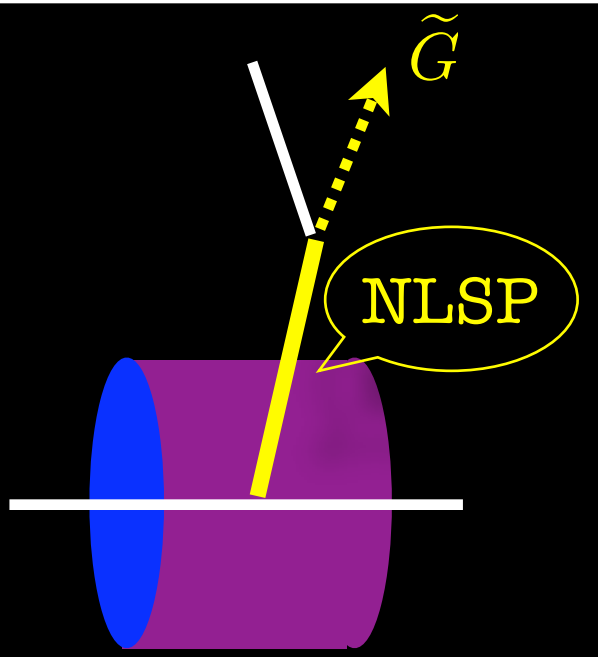
= SUSY breaking scale $F = \sqrt{3}\, m_{\tilde{G}} M_{\rm P}$ を測る事

(= gravitino mass $m_{\tilde{G}}$ を測る事)



Gravitino and NLSP at the LHC			
$\widetilde{\tau}$ NLSP		"kink" in charged track	charged track
$\widetilde{\chi}^0$ NLSP	$2\gamma + E_{\mathrm{T,miss}}$	non-pointing photon	$\widetilde{\chi}^0$ the same as LSP signal....

Gravitino and NLSP at the LHC			
$\widetilde{\tau}$ NLSP		“kink” in charged track 寿命測れる	charged track
$\widetilde{\chi}^0$ NLSP	$2\gamma + E_{\mathrm{T,miss}}$	non-pointing photon	the same as $\widetilde{\chi}^0$ LSP signal....

Gravitino and NLSP at the LHC			
$\widetilde{\tau}$ NLSP		"kink" in charged track 寿命測れる	charged track
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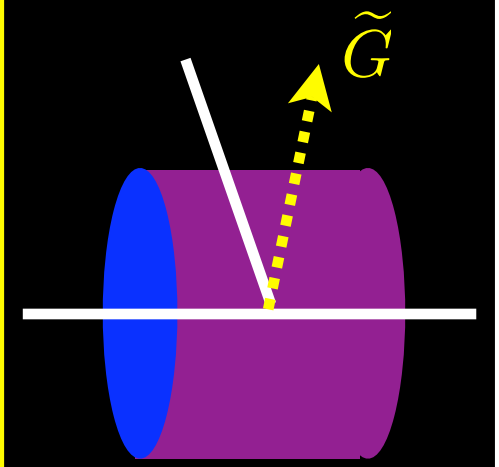
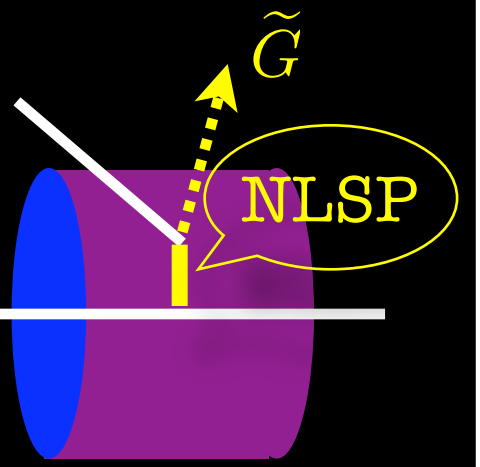
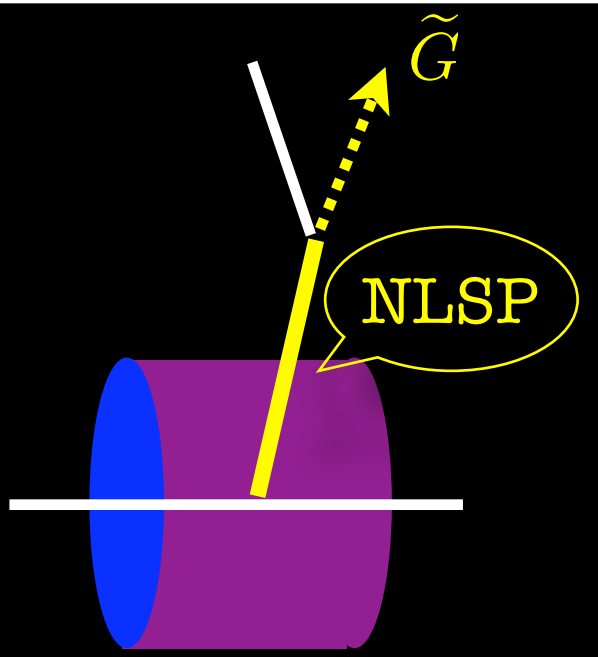
次のトークで？

Gravitino and NLSP at the LHC			
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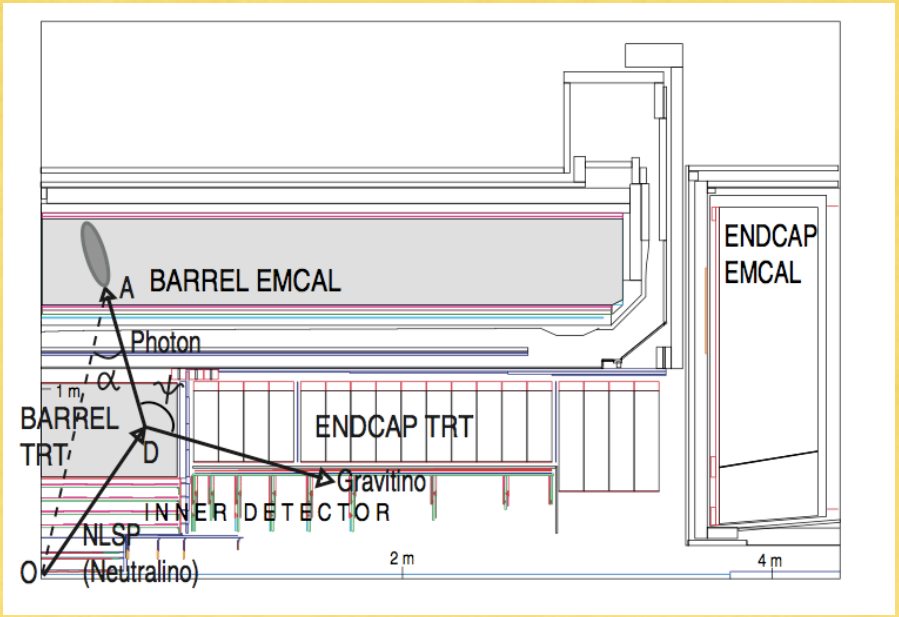
次のトークで？

Gravitino



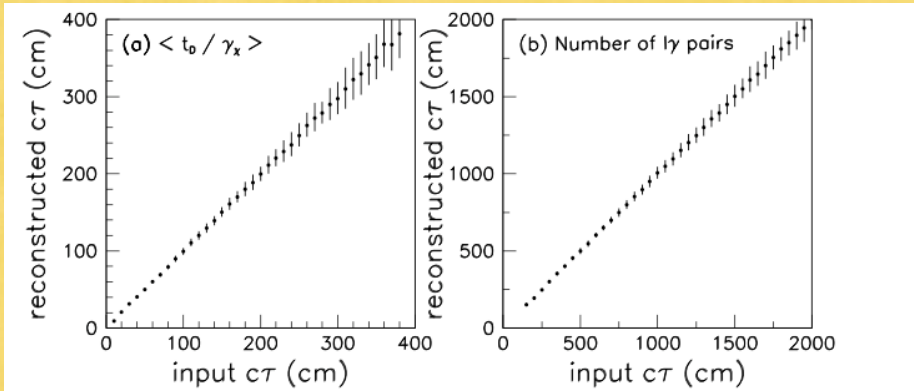
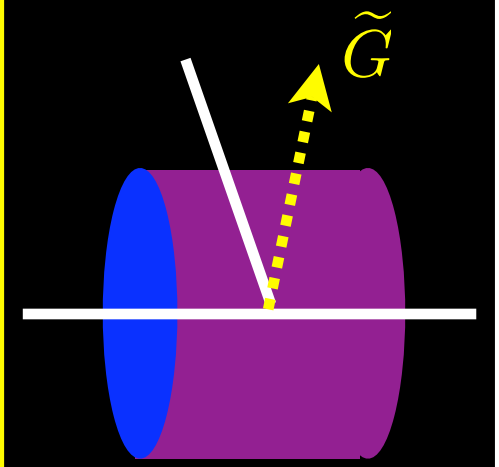
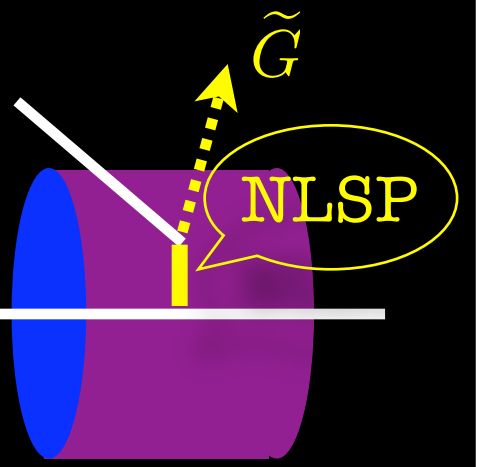
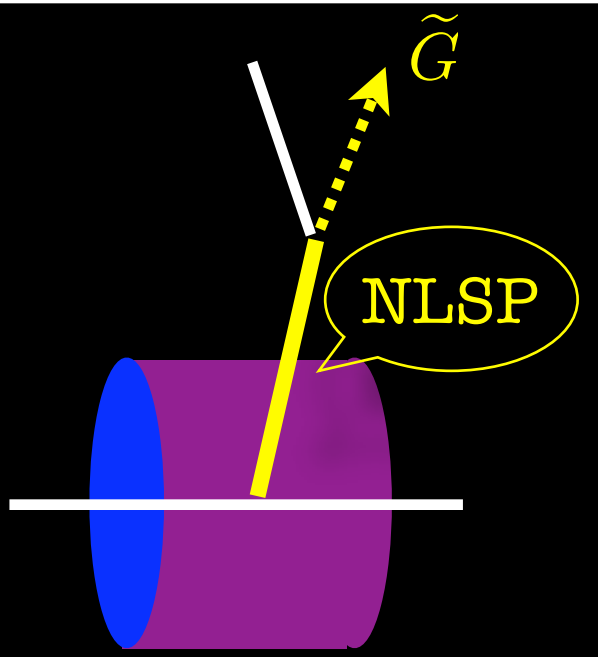


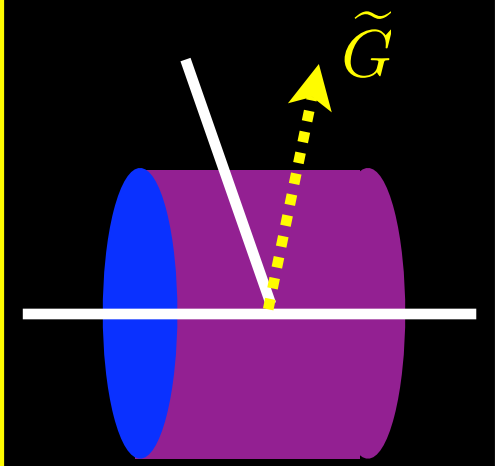
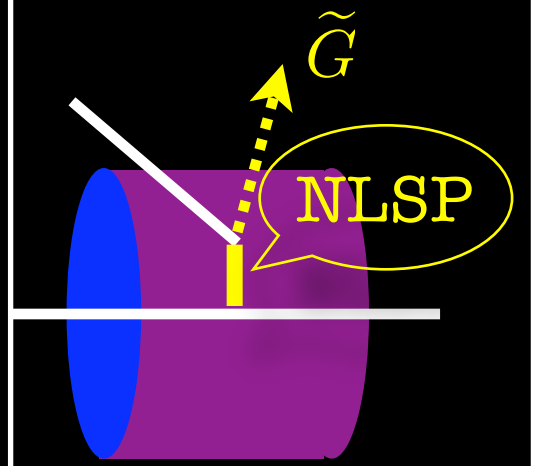
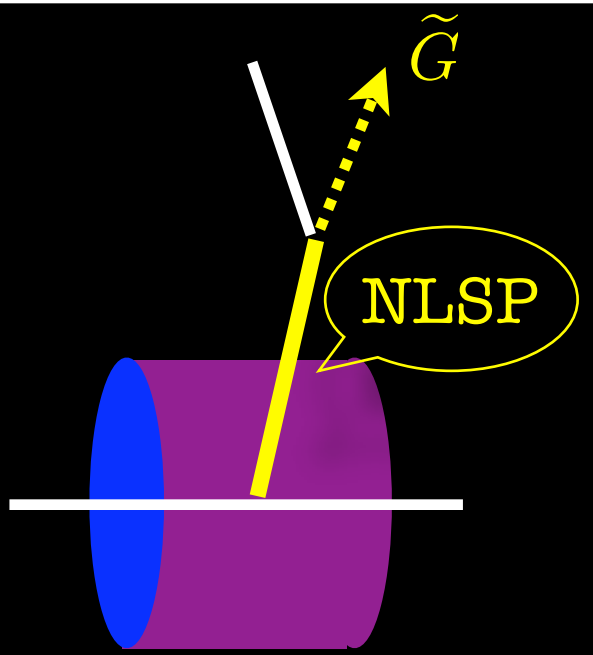
FIG. 7: Estimated resolution of the lifetime $c\tau$ for an integrated luminosity of 13.9 fb^{-1} from (a) the average t_D/γ_χ and (b) the number of $\ell\gamma$ pairs $N_{\ell\gamma}$. The input $m_{\tilde{\ell}}$ and $m_{\tilde{\chi}}$ are used for the reconstruction and their errors are ignored.

Kawagoe, Kobayashi, Nojiri, Ochi, '03

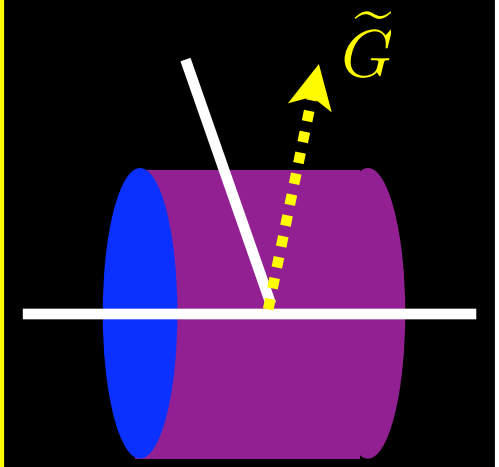
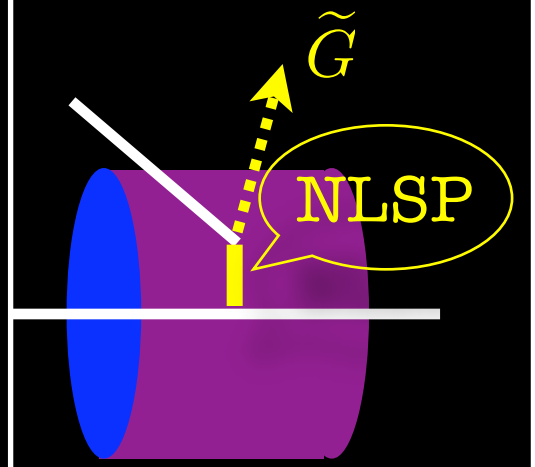
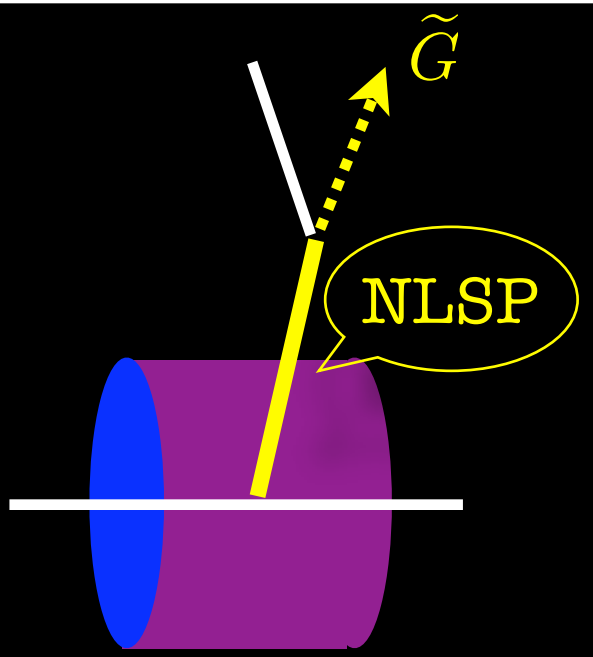
$\tilde{\chi}^0$ NLSP	$2\gamma + E_{\mathrm{T,miss}}$	non-pointing photon 寿命測れる	$\tilde{\chi}^0$ the same as LSP signal....

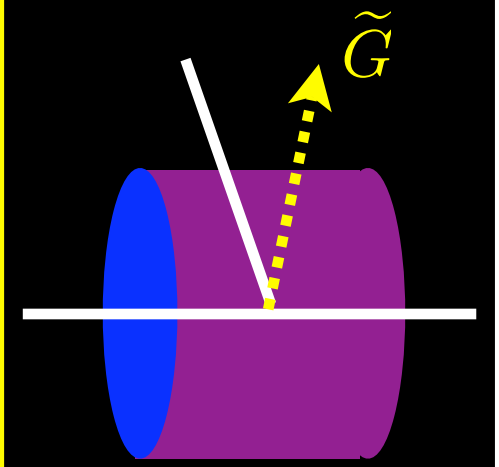
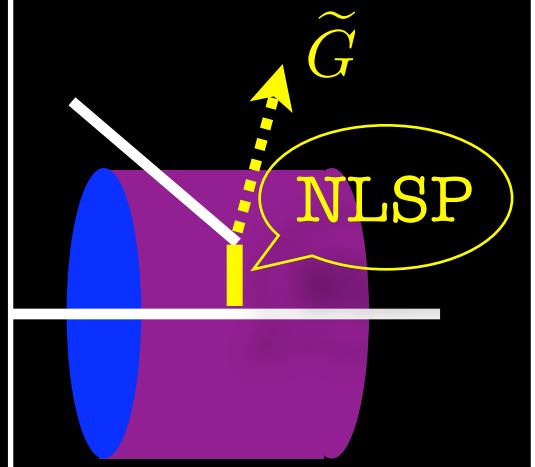
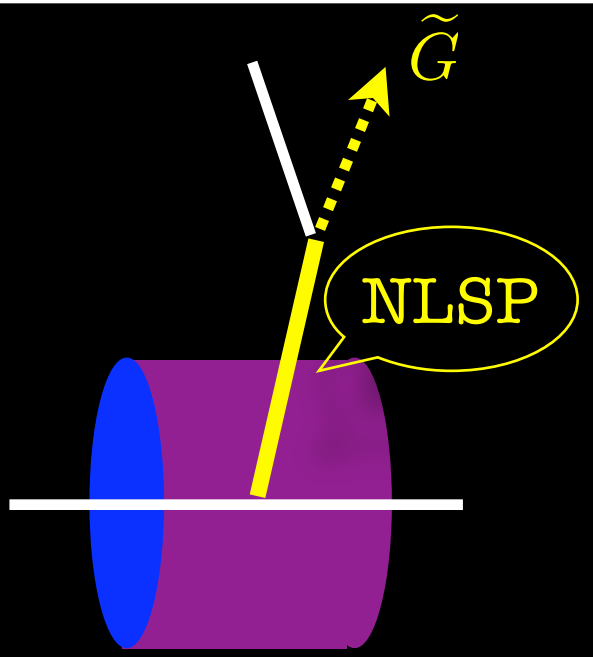
Gravitino and NLSP at the LHC			
$\widetilde{\tau}$ NLSP		"kink" in charged track 寿命測れる	charged track
$\widetilde{\chi}^0$ NLSP	$2\gamma + E_{\mathrm{T,miss}}$	non-pointing photon 寿命測れる	the same as $\widetilde{\chi}^0$ LSP signal....

次のトークで？

Gravitino and NLSP at the LHC			
$\widetilde{\tau}$ NLSP	寿命測れる？！	kink in charged track 寿命測れる	charged track
$\widetilde{\chi}^0$ NLSP	$2\gamma + E_{\mathrm{T,miss}}$	non-pointing photon 寿命測れる	the same as $\widetilde{\chi}^0$ LSP signal....

次のトークで？

Gravitino and NLSP at the LHC			
$\widetilde{\tau}$ NLSP	白井さんのトークで 寿命測れる？！	次のトークで？ "kink" in charged track 寿命測れる	charged track
$\widetilde{\chi}^0$ NLSP	$2\gamma + E_{\mathrm{T,miss}}$	non-pointing photon 寿命測れる	the same as $\widetilde{\chi}^0$ LSP signal....

Gravitino and NLSP at the LHC			
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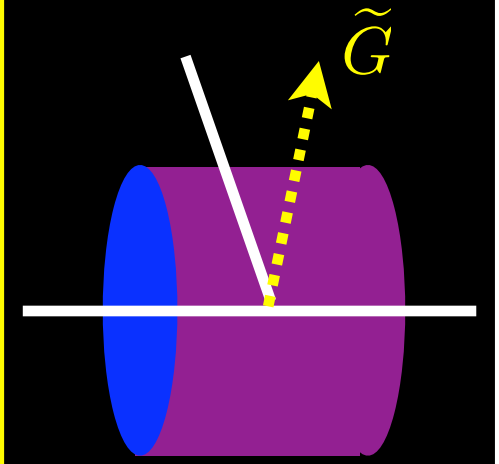
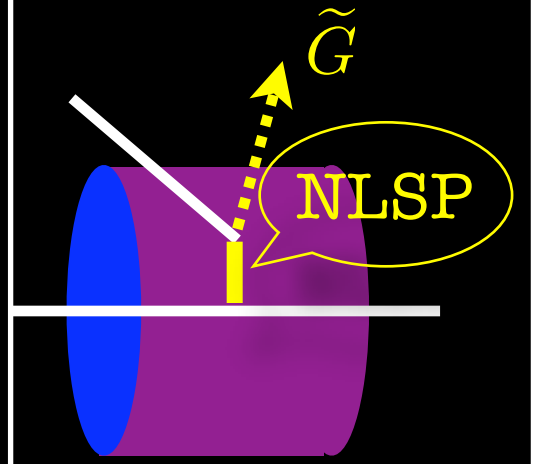
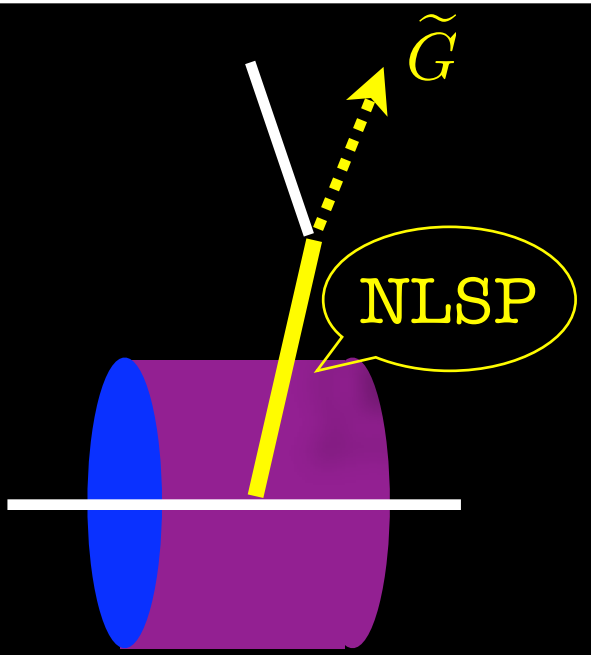
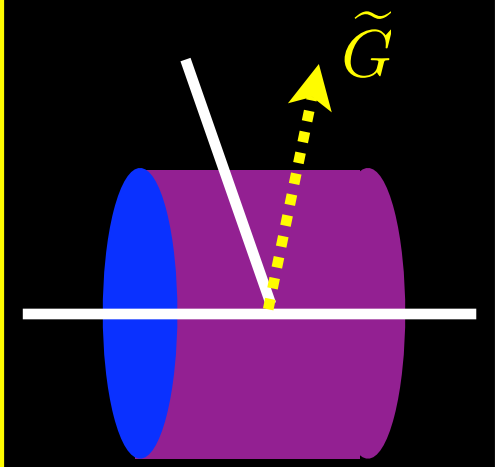
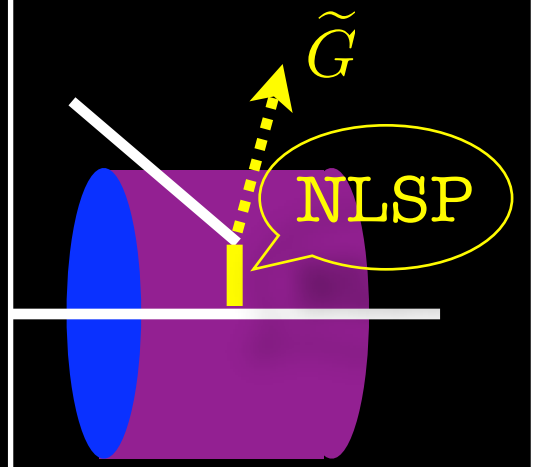
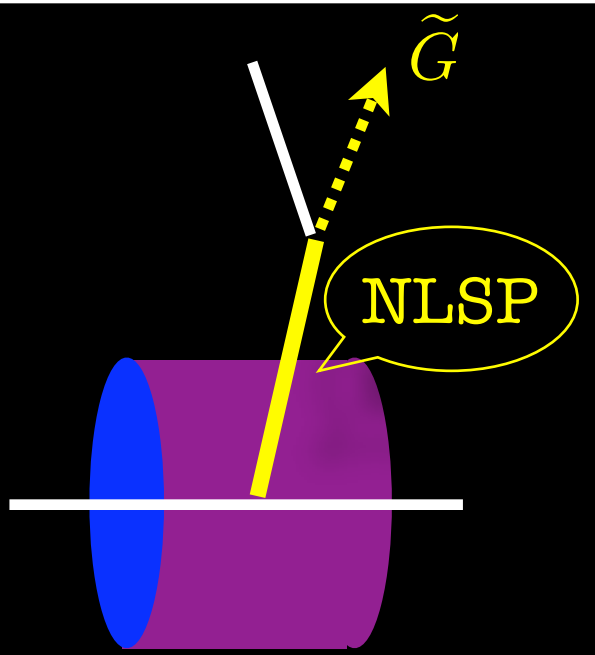
Gravitino and NLSP at the LHC			
$\tilde{\tau}$ NLSP	白井さんのトークで 寿命測れる？！	次のトークで？ "kink" in charged track 寿命測れる	charged track 寿命測れる？ + SUGRA test?!
$\tilde{\chi}^0$ NLSP	$2\gamma + E_{\mathrm{T,miss}}$	non-pointing photon 寿命測れる	the same as $\tilde{\chi}^0$ LSP signal....

Gravitino and NLSP at the LHC			
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$\tilde{\chi}^0$ NLSP	$2\gamma + E_{\mathrm{T,miss}}$	non-pointing photon 寿命測れる	the same as $\tilde{\chi}^0$ LSP signal....

Long-lived staus @ LHC

We will see long-lived charged particle (like muon).

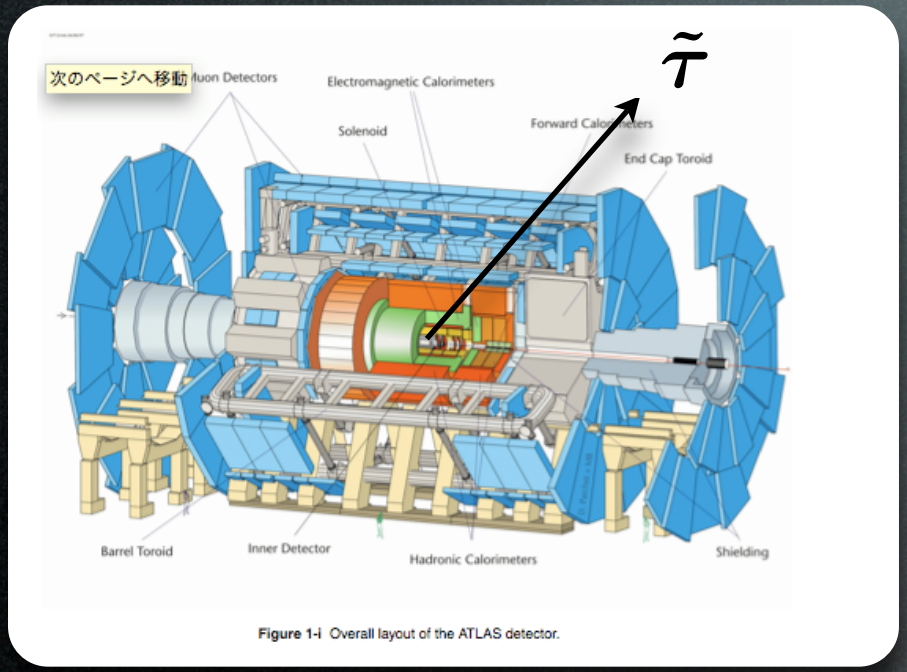


Figure 1-i Overall layout of the ATLAS detector.

Fig. from ATLAS webpage

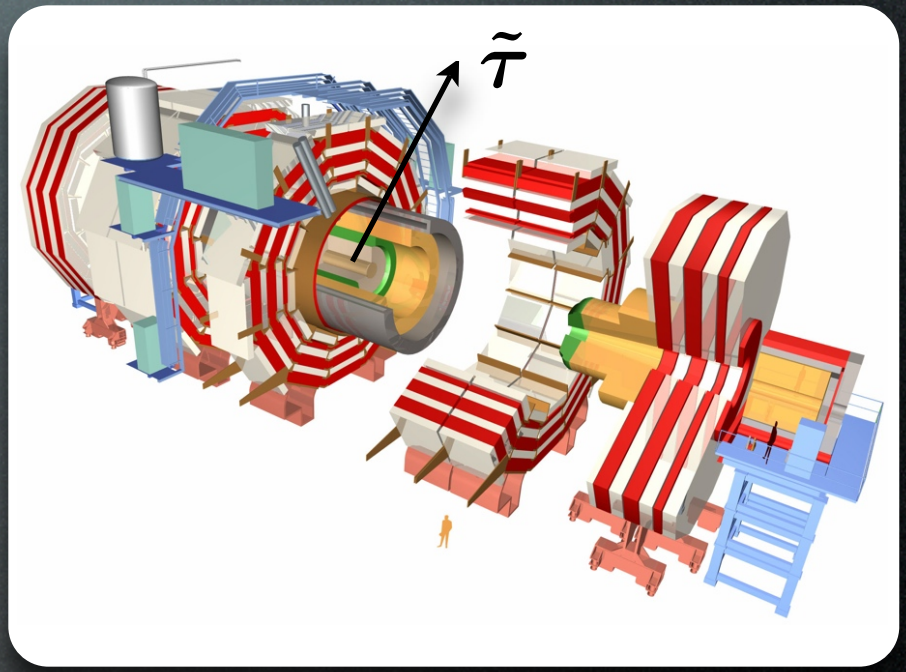


Fig. from CMS webpage

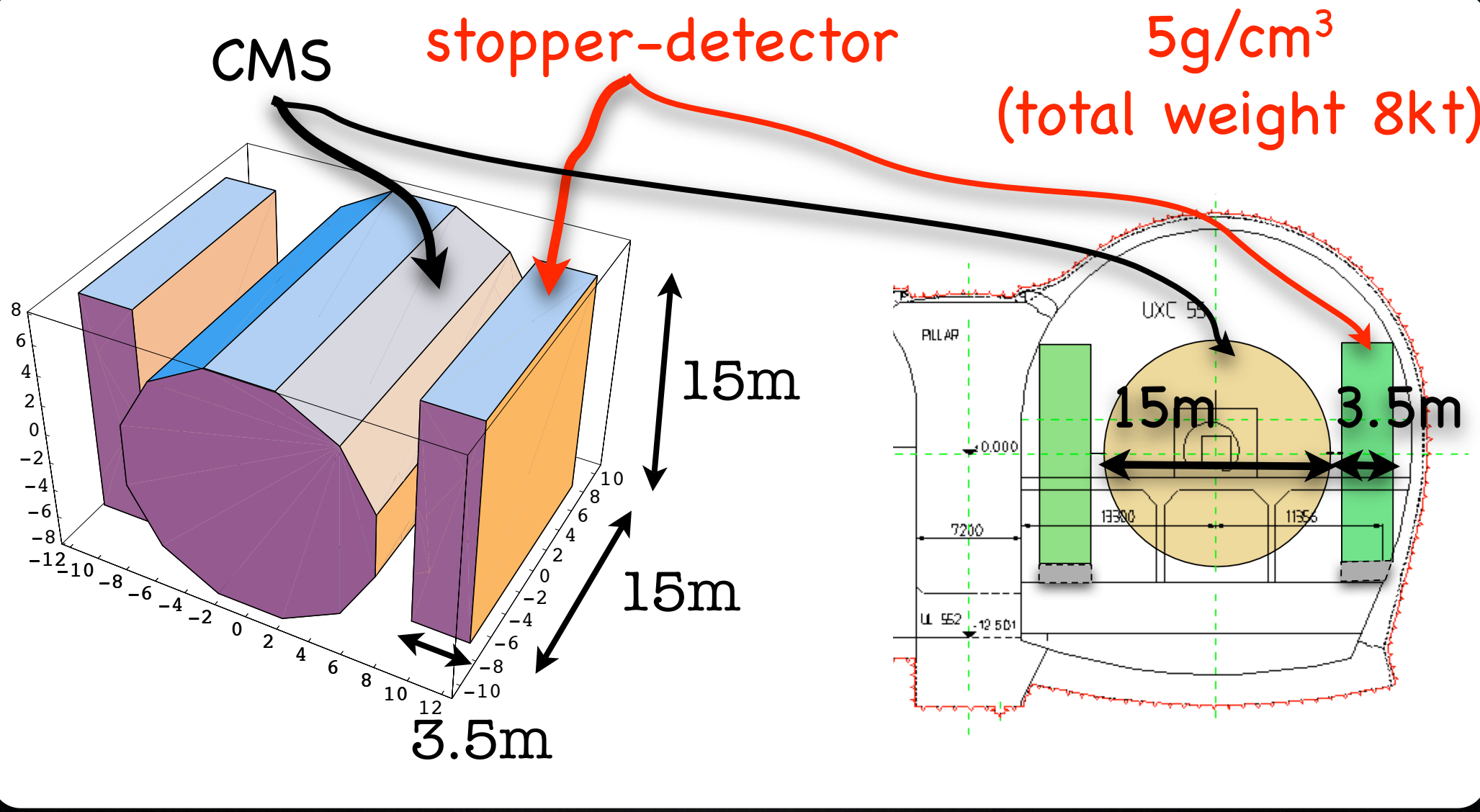
Spectacular events!
Many SUSY informations can be obtained!

But,..... we cannot see the stau decay (and gravitino)

stopper-detector

Maybe... stoppers next to main detectors.

Hamaguchi, Nojiri, De Roeck'06



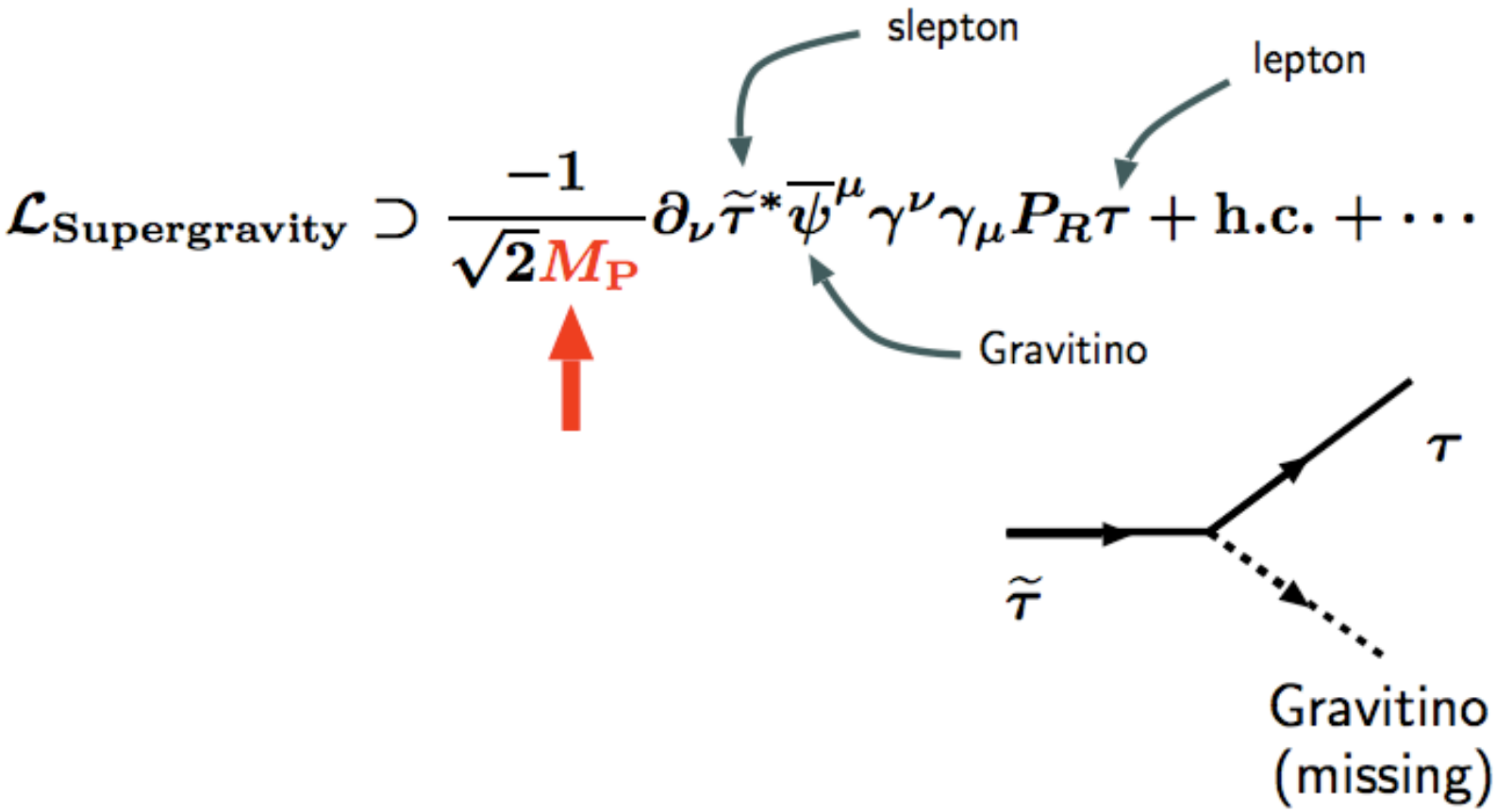
➔ maybe possible to install stopper-detectors.

test of SUGRA

プランクスケールが LHC で測れる ?!

Planck scale measurement

W.Buchmüller, K.Hamaguchi, M.Ratz, T.Yanagida '04



Planck scale measurement

W.Buchmüller, K.Hamaguchi, M.Ratz, T.Yanagida '04

$$\Gamma_{\tilde{\tau}}(\tilde{\tau} \to \tau + \tilde{G}) = \frac{m_{\tilde{\tau}}^5}{48\pi m_{\tilde{G}}^2 M_{\rm P}^2}\left(1 - \frac{m_{\tilde{G}}^2}{m_{\tilde{\tau}}^2}\right)^4$$

Prediction of the Supergravity

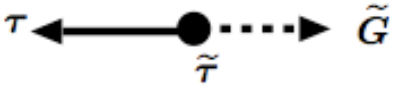
$$\Longleftrightarrow \quad M_{\rm P}^2(\text{supergravity}) = \frac{1}{48\pi}\frac{1}{\Gamma_{\tilde{\tau}}}\frac{m_{\tilde{\tau}}^5}{m_{\tilde{G}}^2}\left(1 - \frac{m_{\tilde{G}}^2}{m_{\tilde{\tau}}^2}\right)^4$$

measurable

(using energy momentum)

"measurable"

$m_{\tilde{G}}^2 = m_{\tilde{\tau}}^2 - 2m_{\tilde{\tau}}E_\tau - m_\tau^2$



consistency check!!

$$M_{\rm P}^2(\text{gravity}) = (8\pi G_{\rm N})^{-1} = (2.44 \times 10^{18}\ \text{GeV})^2$$

Newton const.

stopper-detector

We assume two stoppers next to CMS.

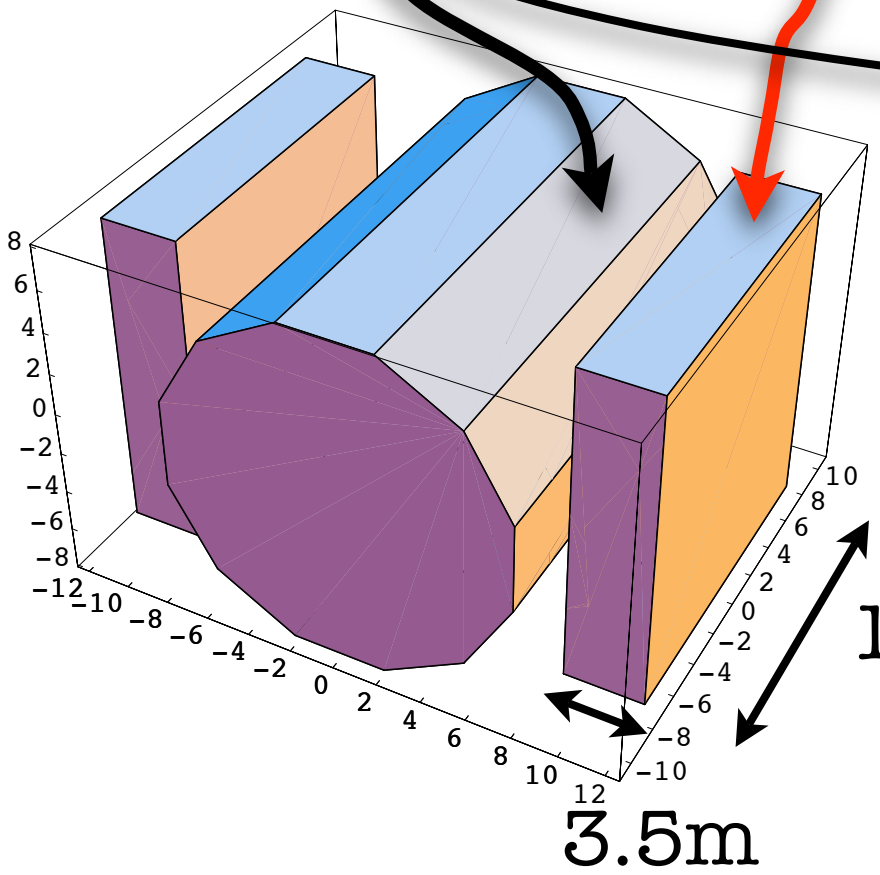
Hamaguchi, Nojiri, De Roeck'06

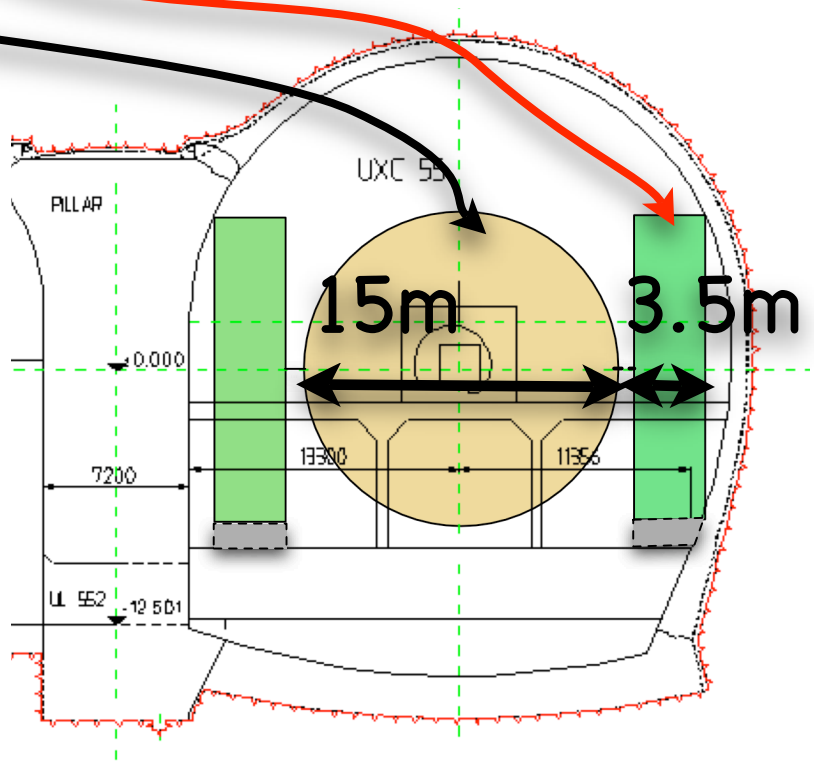
CMS

stopper-detector

5g/cm^3

(total weight 8kt)





→ maybe possible to install stopper-detectors.

stopper-detector

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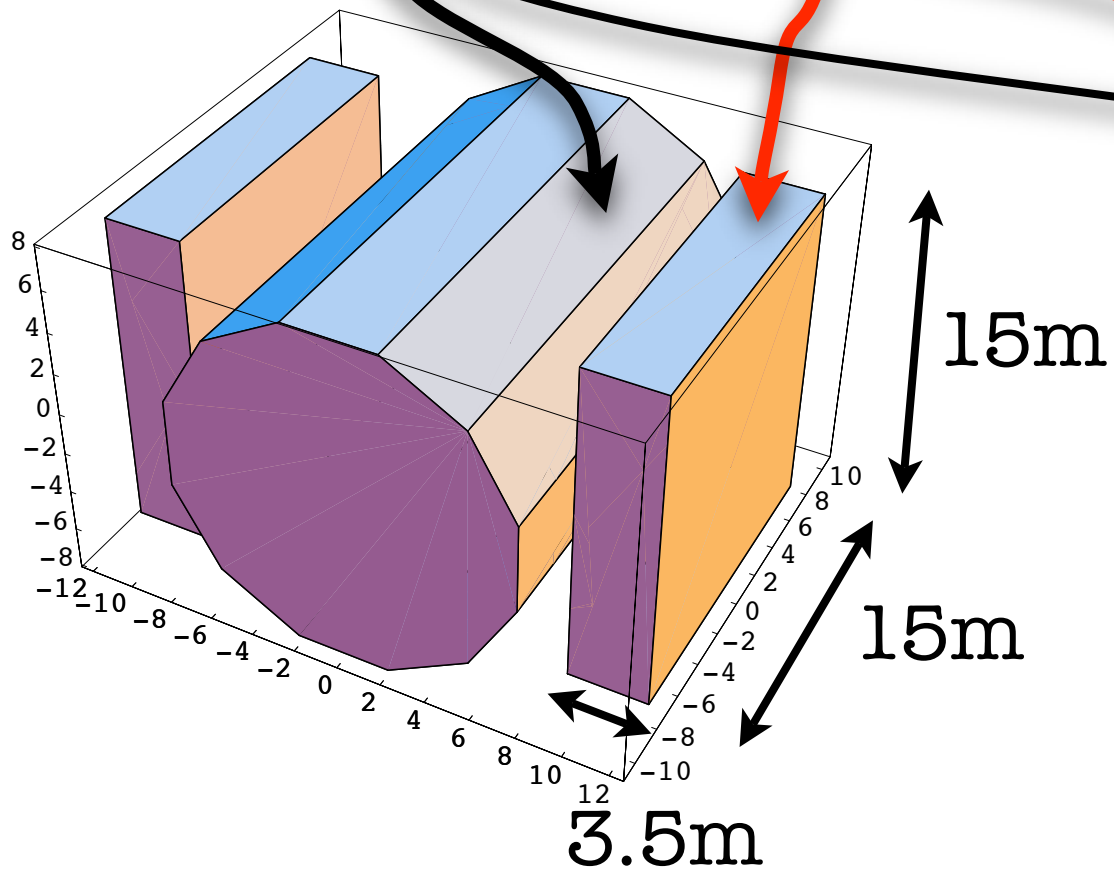
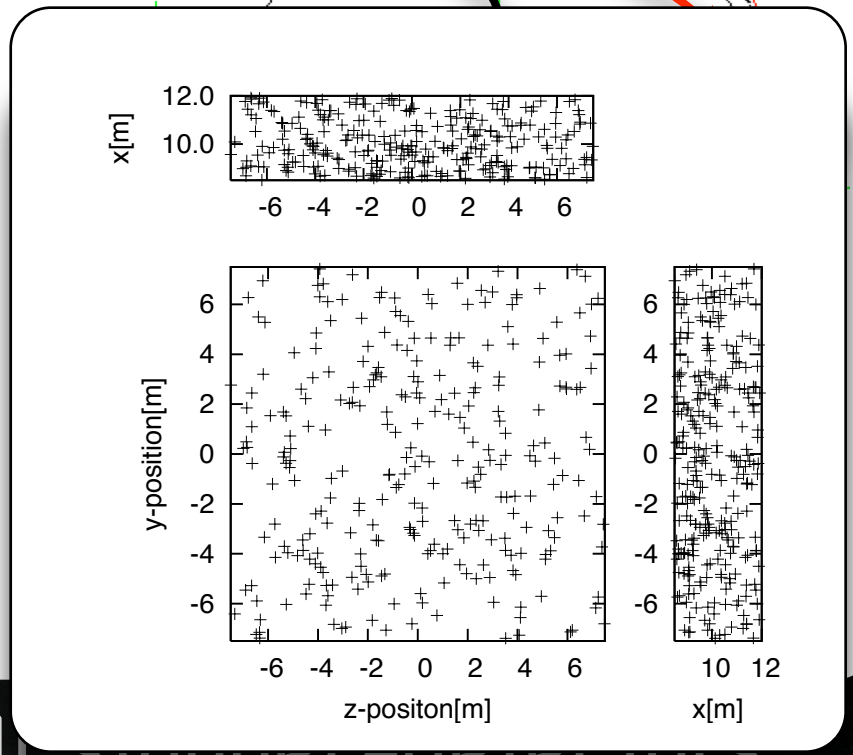
Hamaguchi, Nojiri, De Roeck'06





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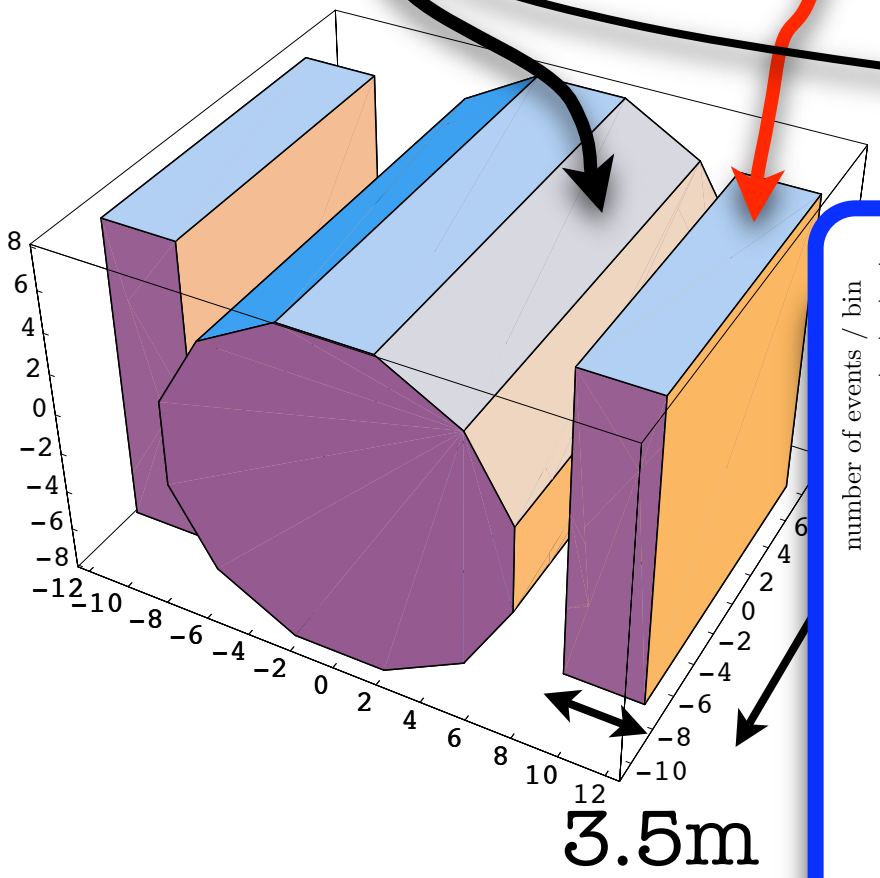
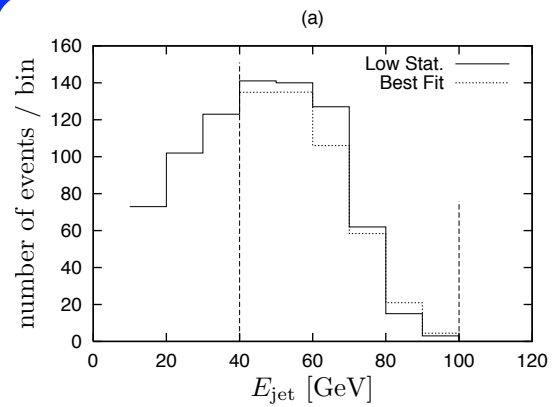
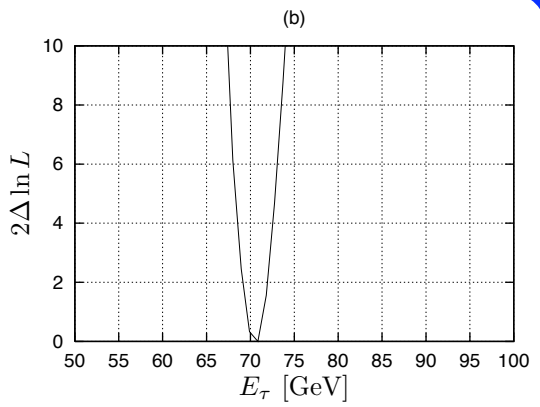
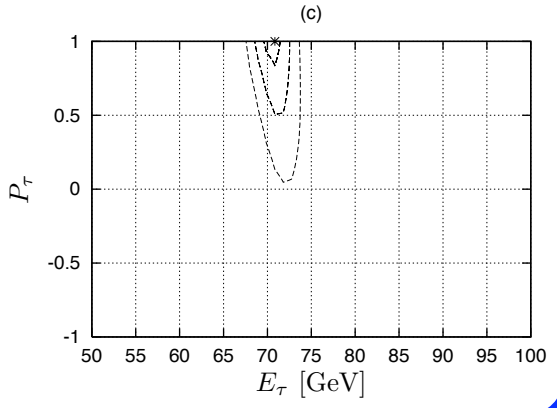
Hamaguchi, Nojiri, De Roeck'06









→ maybe possibl

stopper-detector

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Hamaguchi, Nojiri, De Roeck'06

CMS

stopper-detector

5g/cm^3
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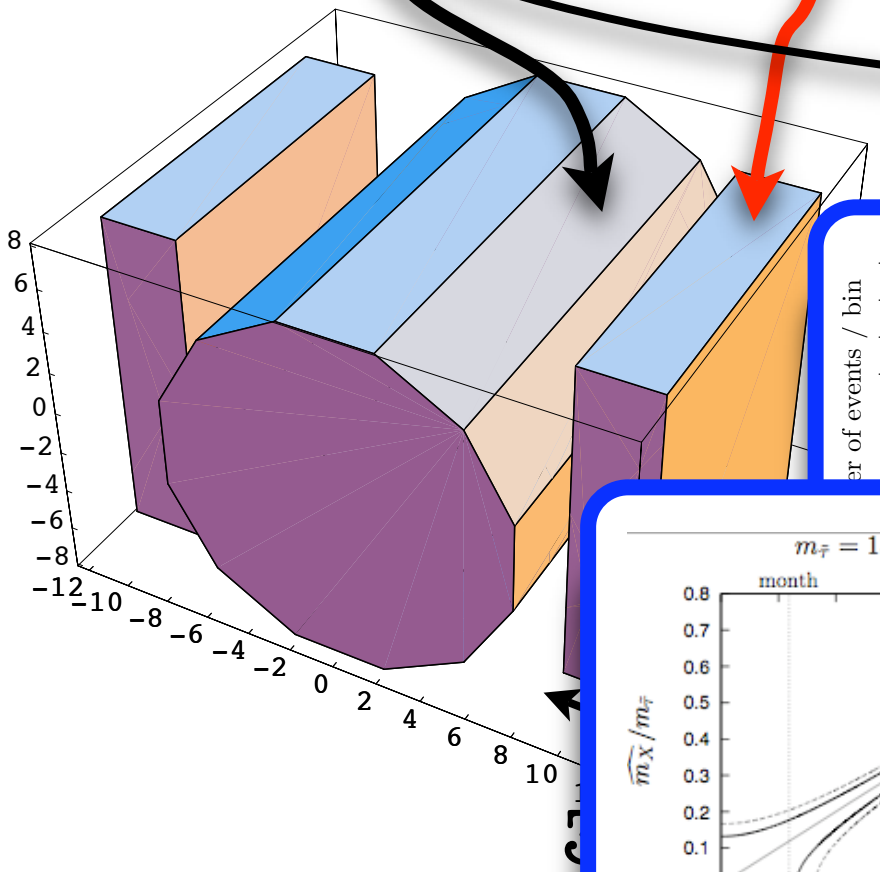
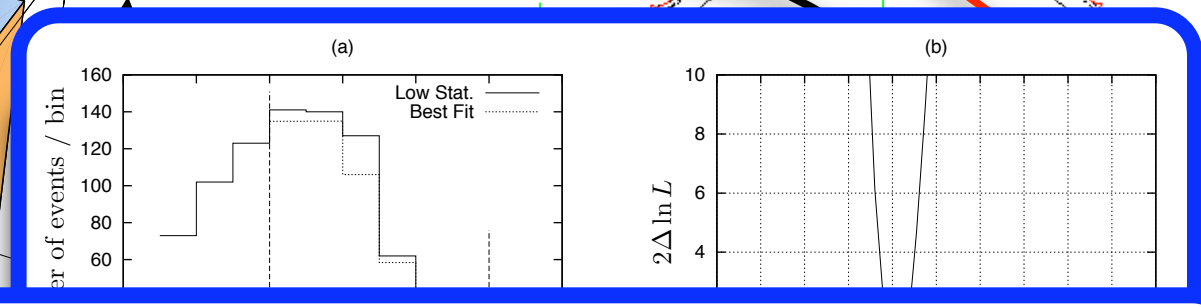
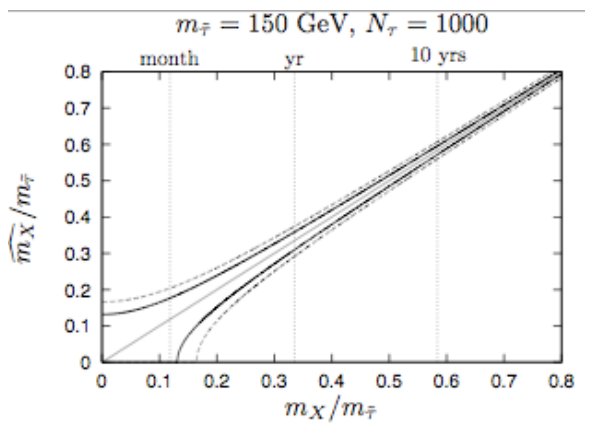
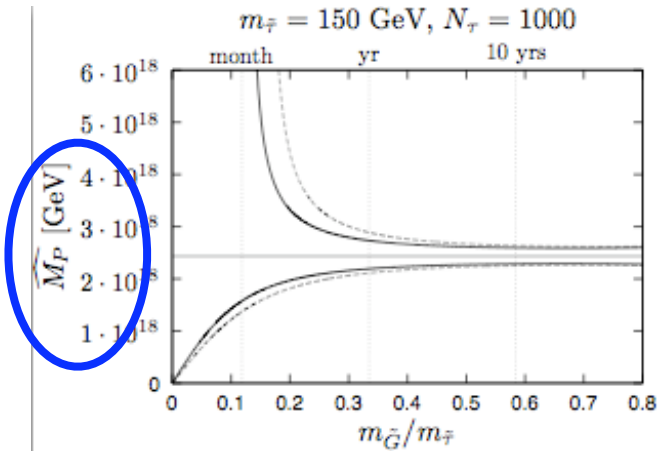
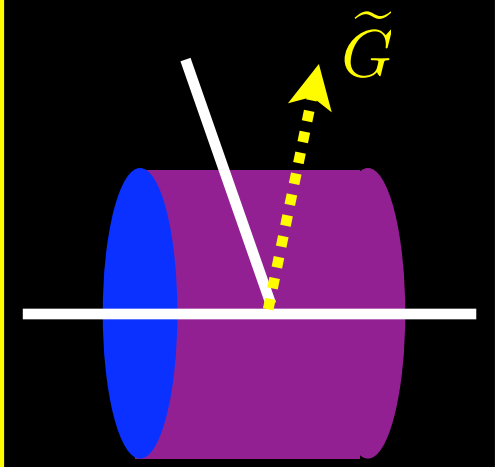
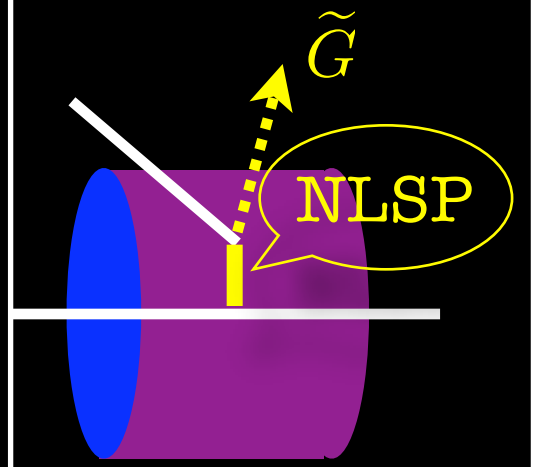
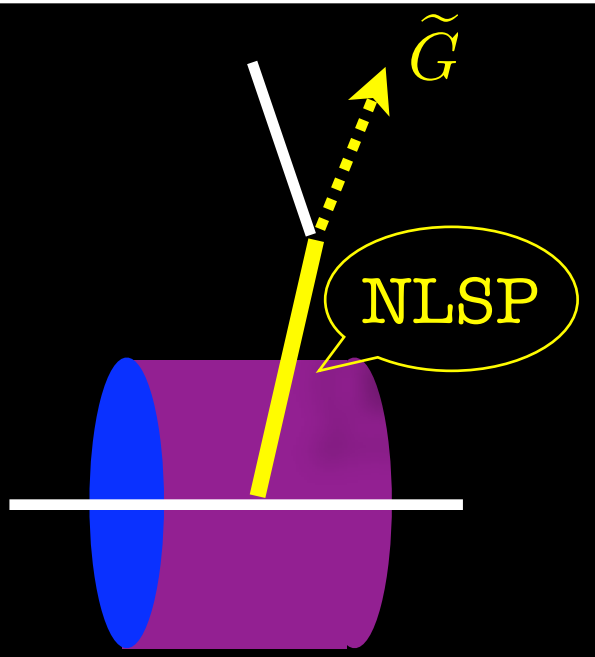


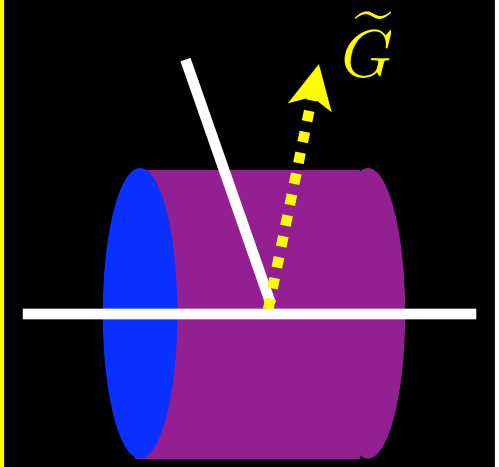
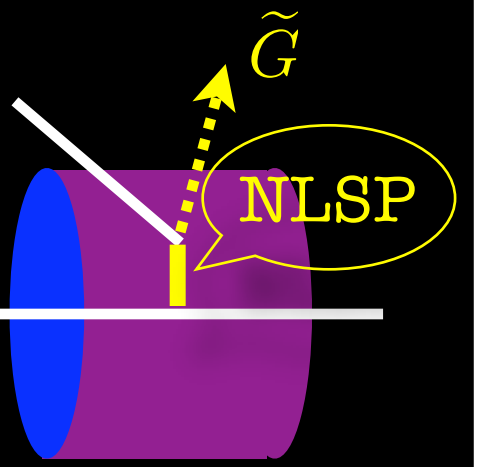
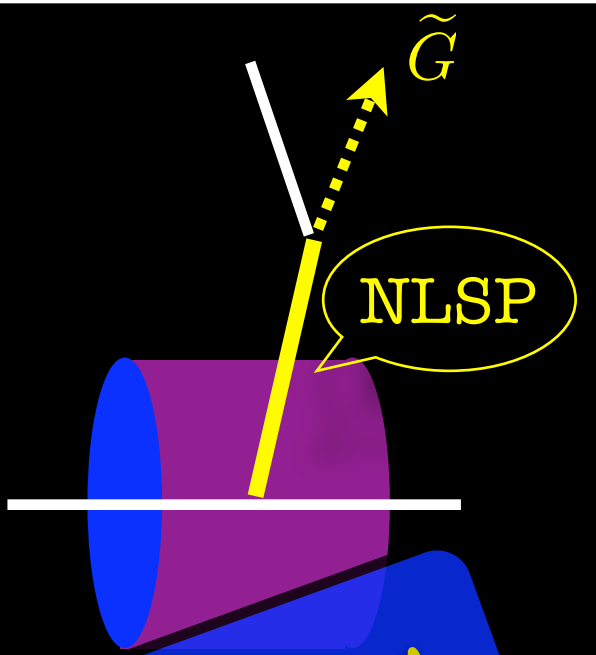






→ maybe p

Gravitino and NLSP at the LHC			
$\widetilde{\tau}$ NLSP	白井くんのトークで F determination	次のトークで？ "kink" in charged track F determination	charged track F determination + SUGRA test?!
$\widetilde{\chi}^0$ NLSP	$2\gamma + E_{\mathrm{T,miss}}$	non-pointing photon F determination	the same as $\widetilde{\chi}^0$ LSP signal....

Gravitino and NLSP at the LHC			
$\widetilde{\tau}$ NLSP	白井くんの トークで	次のトークで？ charged track	charged track F determination + SUGRA test?!
$\widetilde{\chi}^0$ NLSP	$2\gamma + E_{\mathrm{T,miss}}$	non-pointing photon F determination	the same as $\widetilde{\chi}^0$ LSP signal....

Let's see what the LHC will find.....!

質問！

中には detector 内で止まって、遅れて崩壊するやつも居るはずです。（beta < 0.4 くらい。遅すぎる？）

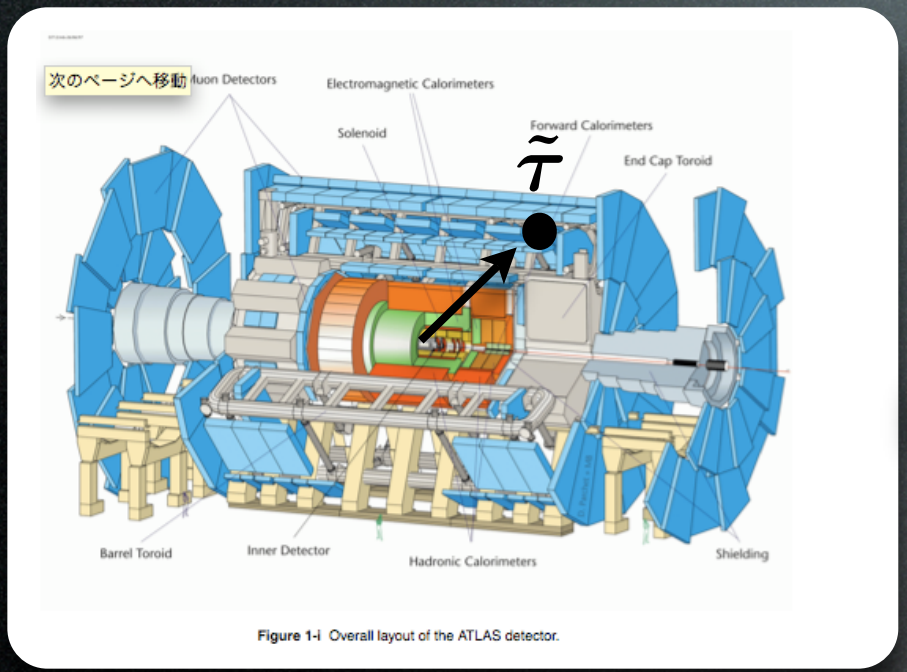


Figure 1-i Overall layout of the ATLAS detector.

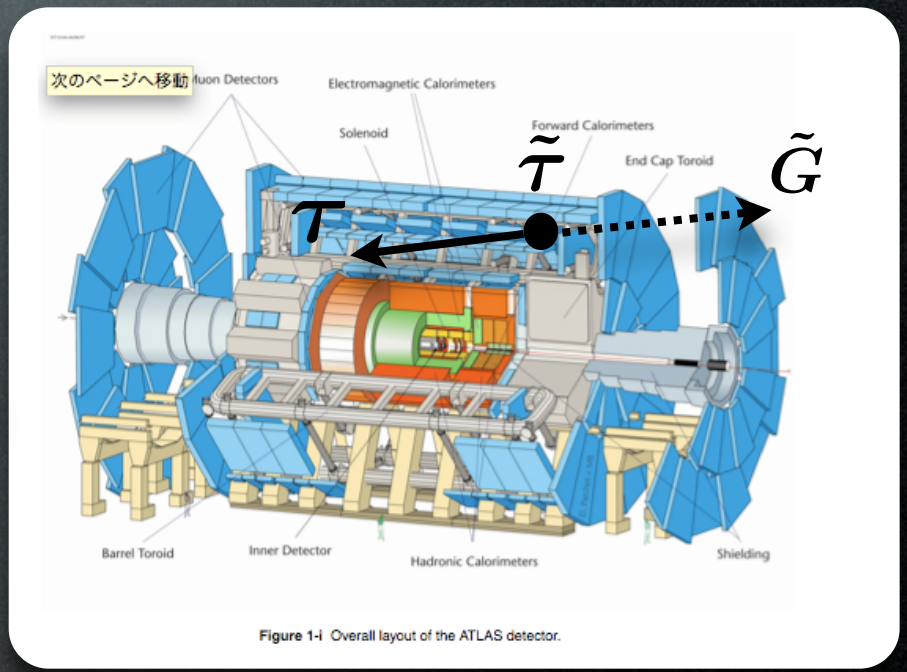


Figure 1-i Overall layout of the ATLAS detector.

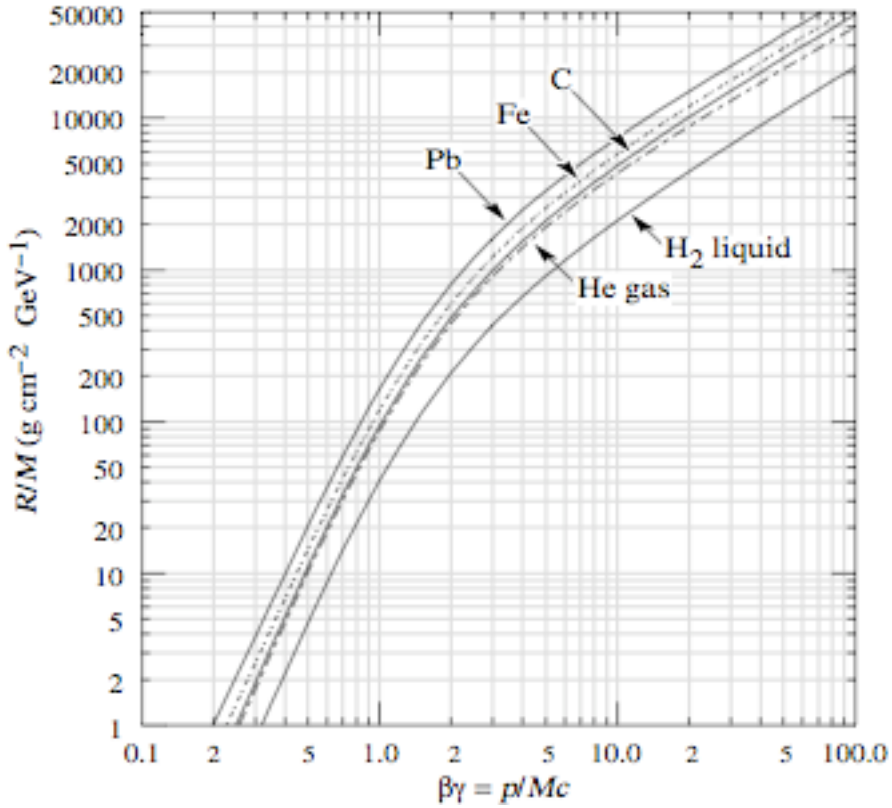
何とかしてこいつら identify 出来ないでしょうか？

(cf. Dimopoulos達の "stopping gluino" (at ATLAS) hep-ph/0506242)

Backup Slides

Long-lived staus @ LHC

How thick the stopping material should be?



Review of Particle Physics

typically $\tilde{g}, \tilde{q} \rightarrow \tilde{\chi}^{\pm}, \tilde{\chi}^{0} \rightarrow \tilde{\tau}$

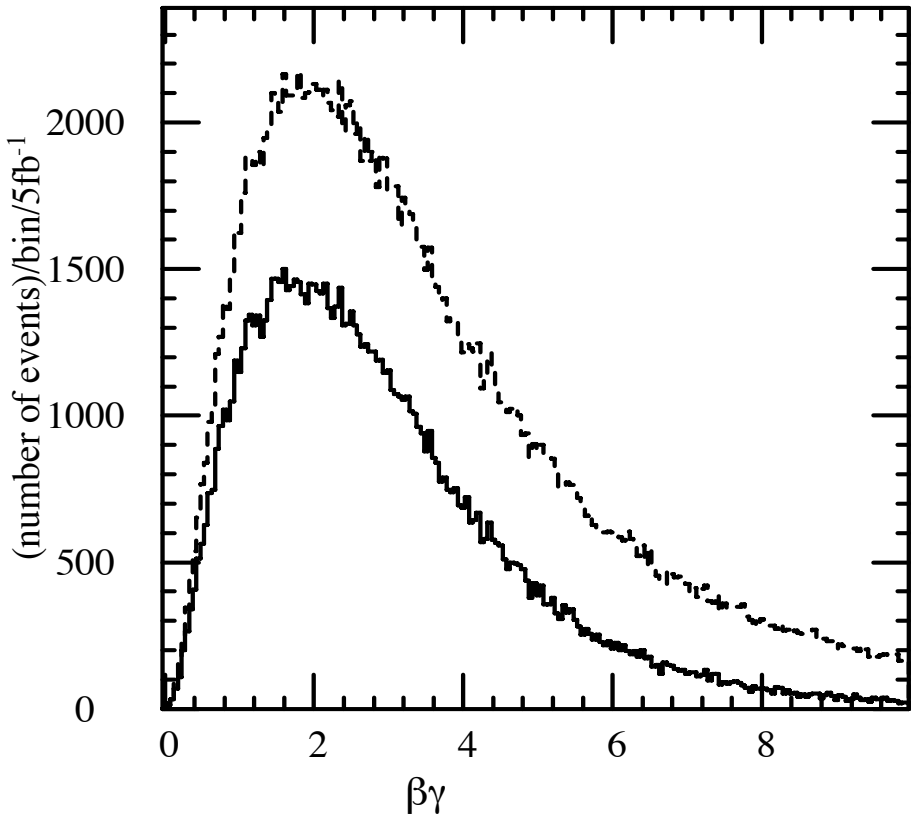


Fig. from Hamaguchi, Kuno, Nakaya, Nojiri '04

Long-lived staus @ LHC

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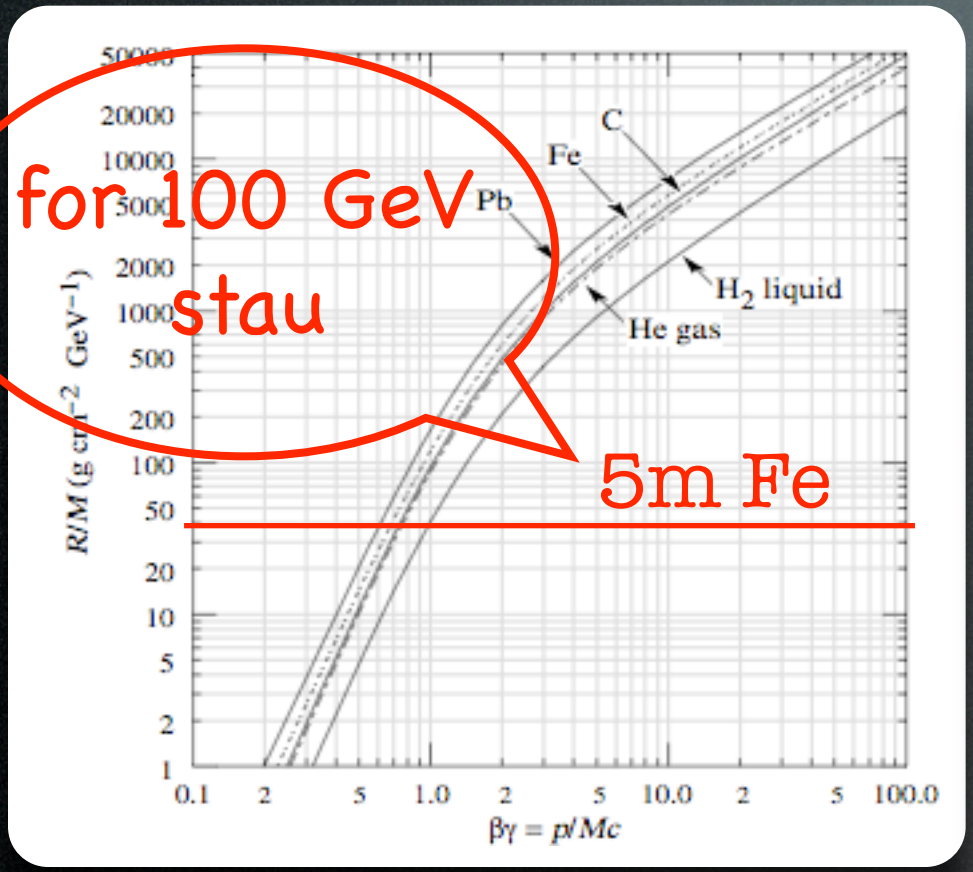

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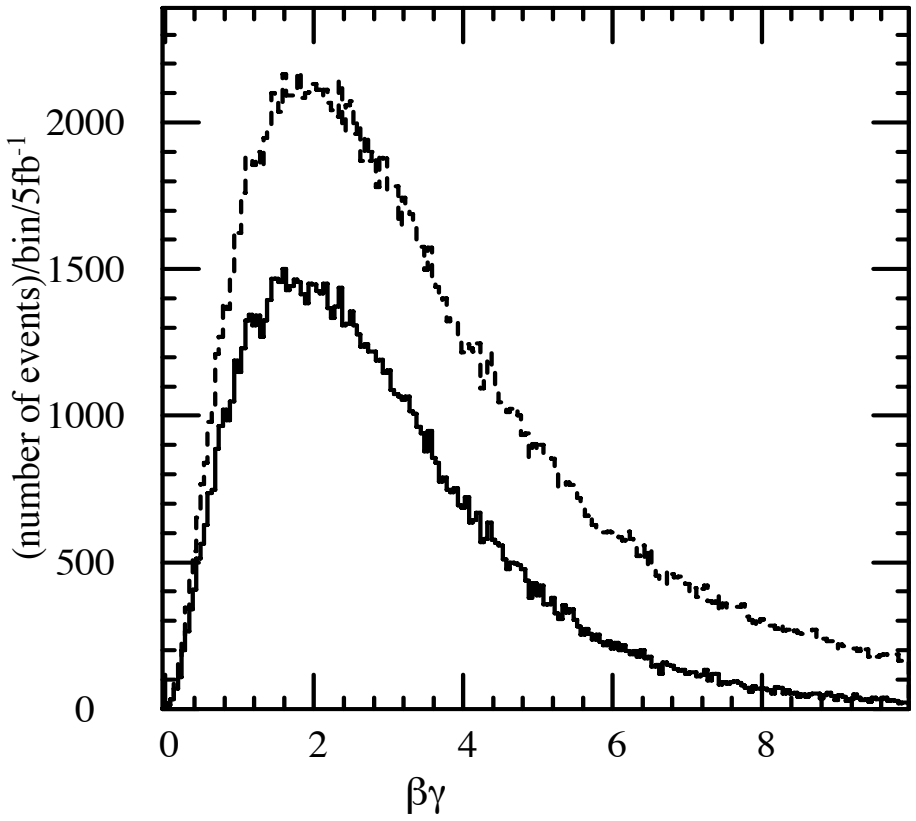

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Long-lived staus @ LHC

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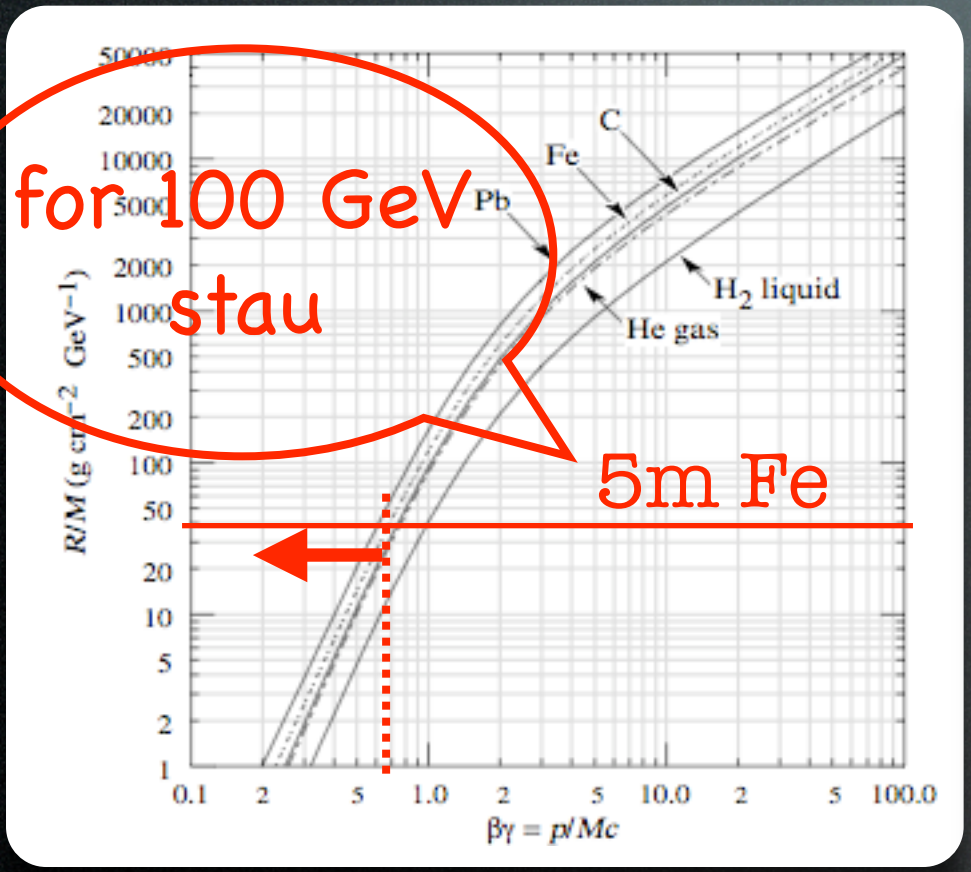

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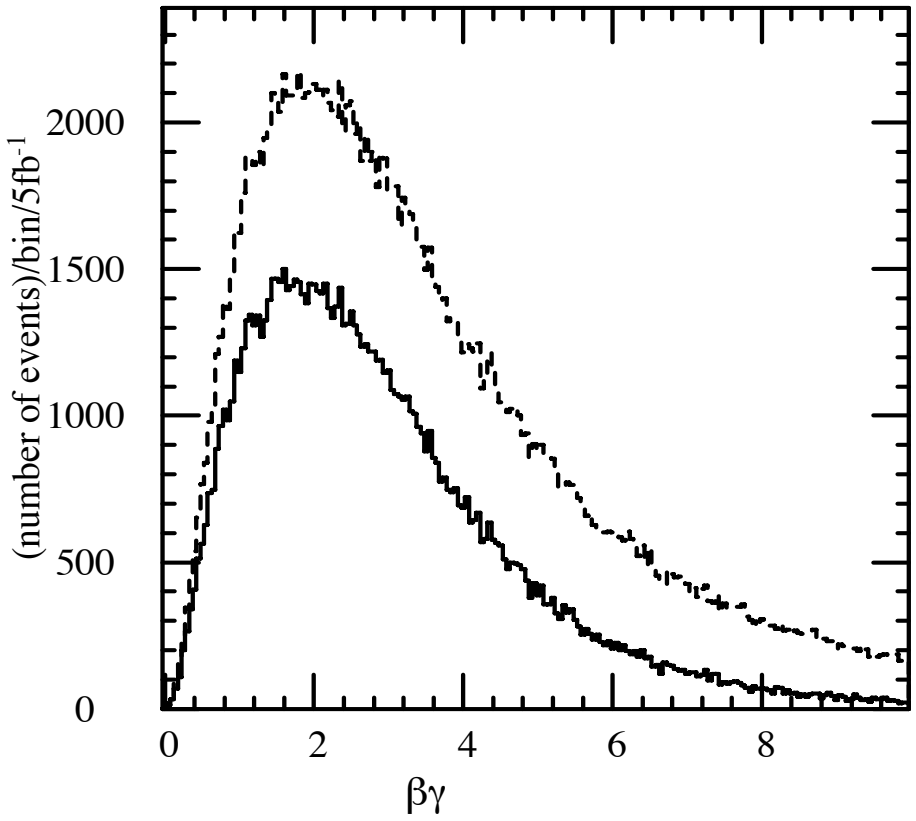

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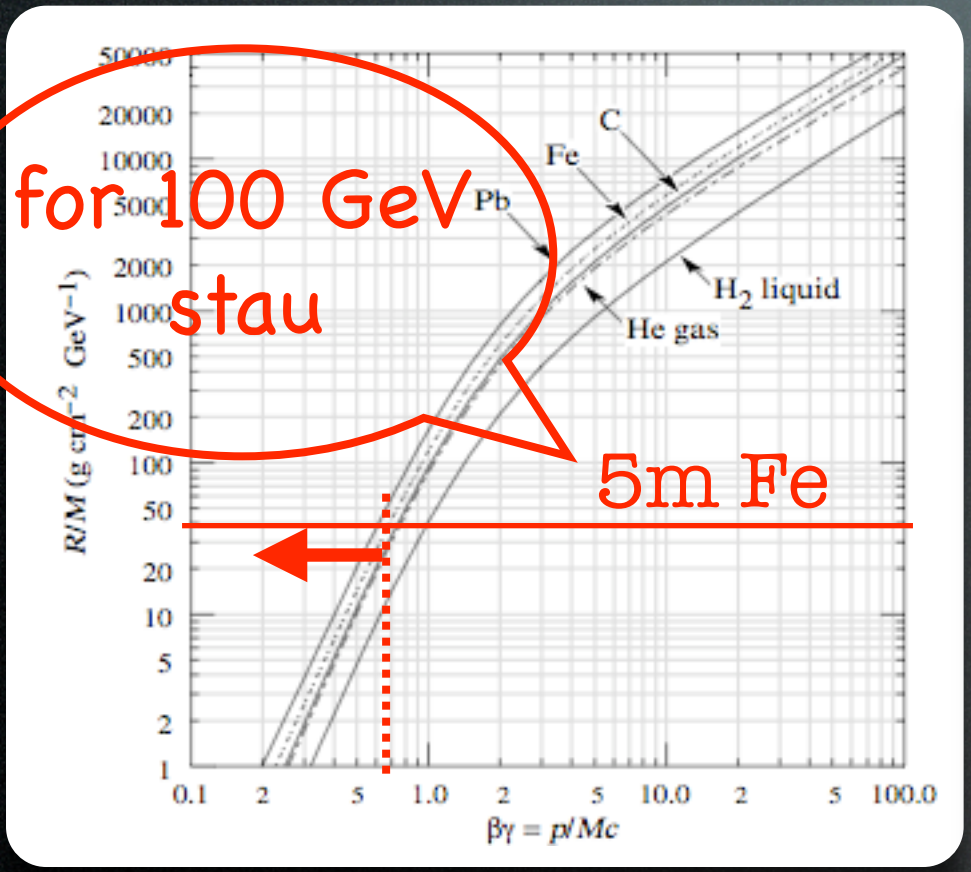

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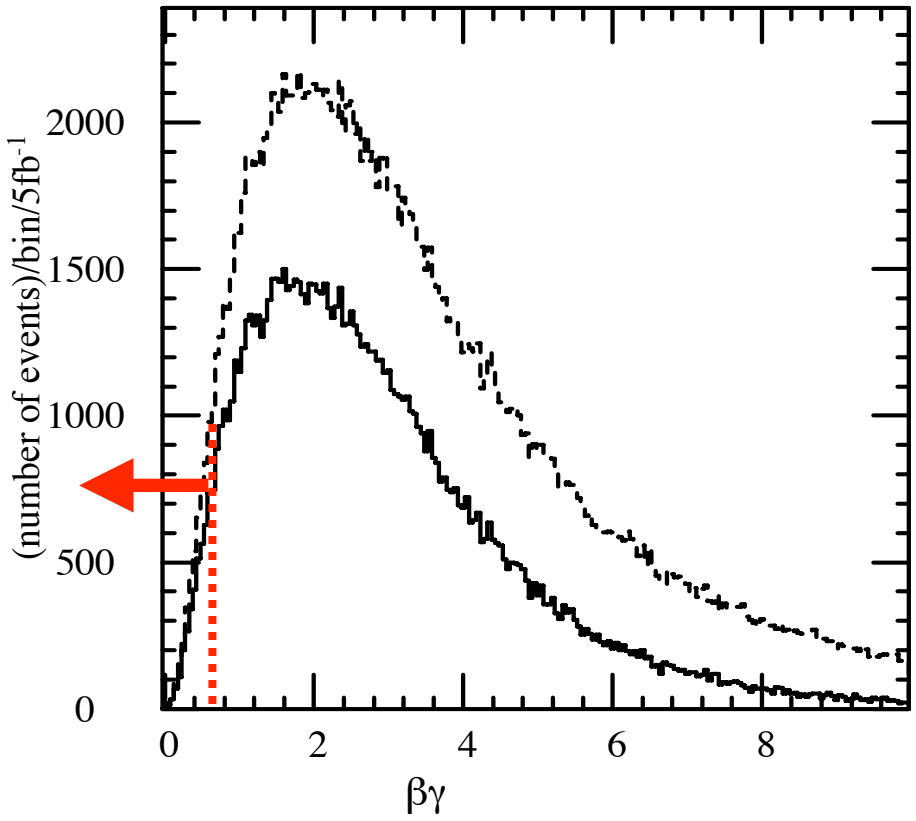

Fig. from Hamaguchi, Kuno, Nakaya, Nojiri '04

If thick enough, part of produced staus may be stopped.

Long-lived staus @ LHC

Ideas:

- Place an additional stopper-detector next to the main detector. [Hamaguchi, Kuno, Nakaya, Nojiri, '04]
- Place a water tank as stopper, and then drain the water to a reservoir. [Feng, Smith, '04]
- Use the stau stopped in the surrounding rock. [De Roeck, Ellis, Gianotti, Moortgat, Olive, Pape'05]

Long-lived staus @ LHC

Only this type
can identify the timing and position of
the stopping stau precisely.

Ideas:

- Place an additional stopper-detector next to the main detector. [Hamaguchi, Kuno, Nakaya, Nojiri, '04]
- Place a water tank as stopper, and then drain the water to a reservoir. [Feng, Smith, '04]
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[De Roeck, Ellis, Gianotti, Moortgat, Olive, Pape'05]

stopper = detector??

Hamaguchi, Kuno, Nakaya, Nojiri, '04

It's better if the stopper simultaneously serves as a real-time detector

- to identify the stopping position $\vec{x}_{\rm stop}$
- to record the stopping time $t_{\rm stop}$
- to record the decay time $t_{\rm decay}$
- and to study the decay products

for each NLSP event.

Actually, some existing detectors can serve as a realistic stopper-detector!!

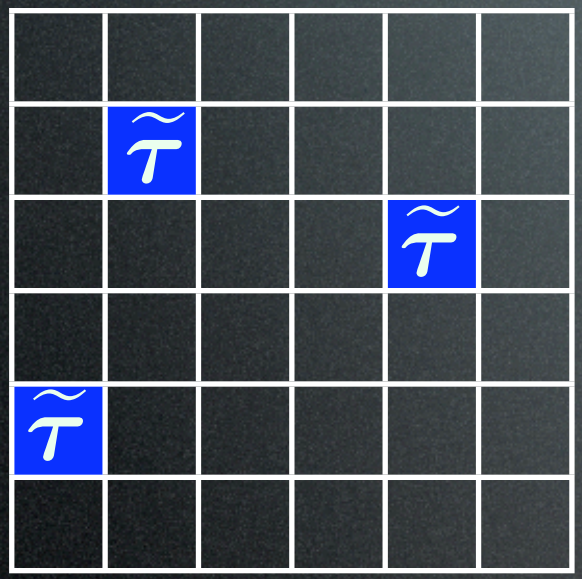
e.g. Soudan II 1989∼2001(?), Minnesota, USA

fine-grained tracking calorimeter for proton decay/neutrino exp., with drift tubes sandwiched between steel sheets.

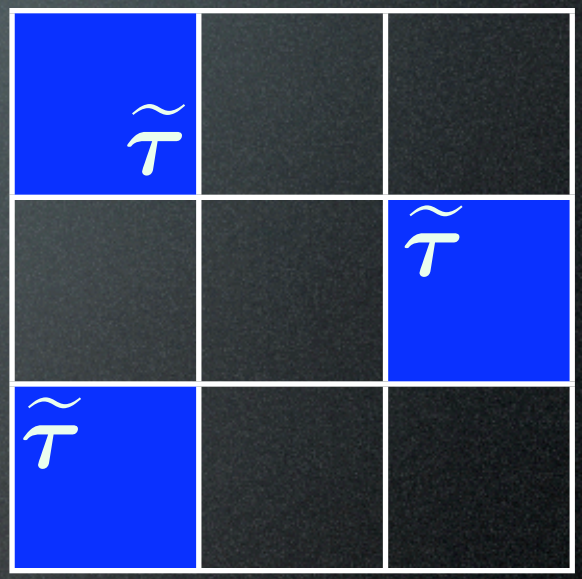
- total mass 0.96 kton
- track resolution 0.18 cm × 0.18 cm × 1cm.
- dead time of each tube $<$ (back ground μ rate)$^{-1}$

stopper = detector??

High segmentation is crucial to reduce the background...



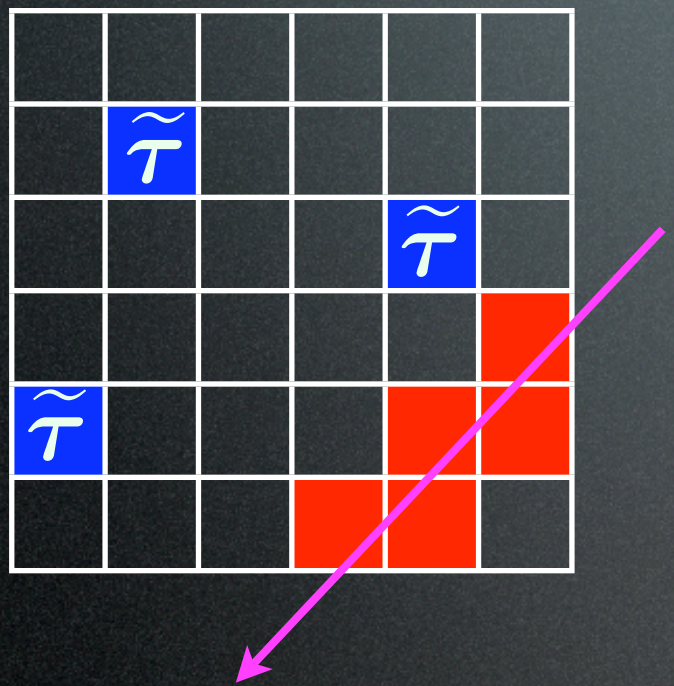
High segmentation

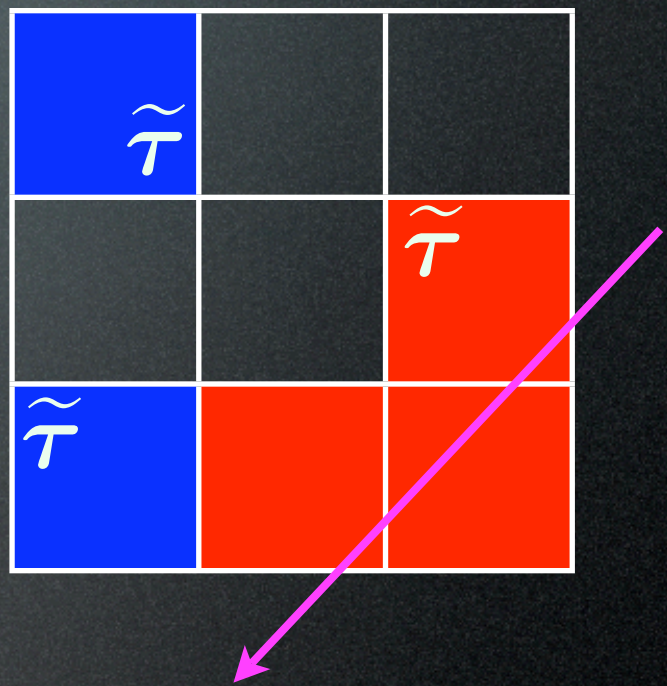


Low segmentation

stopper = detector??

High segmentation is crucial to reduce the background...



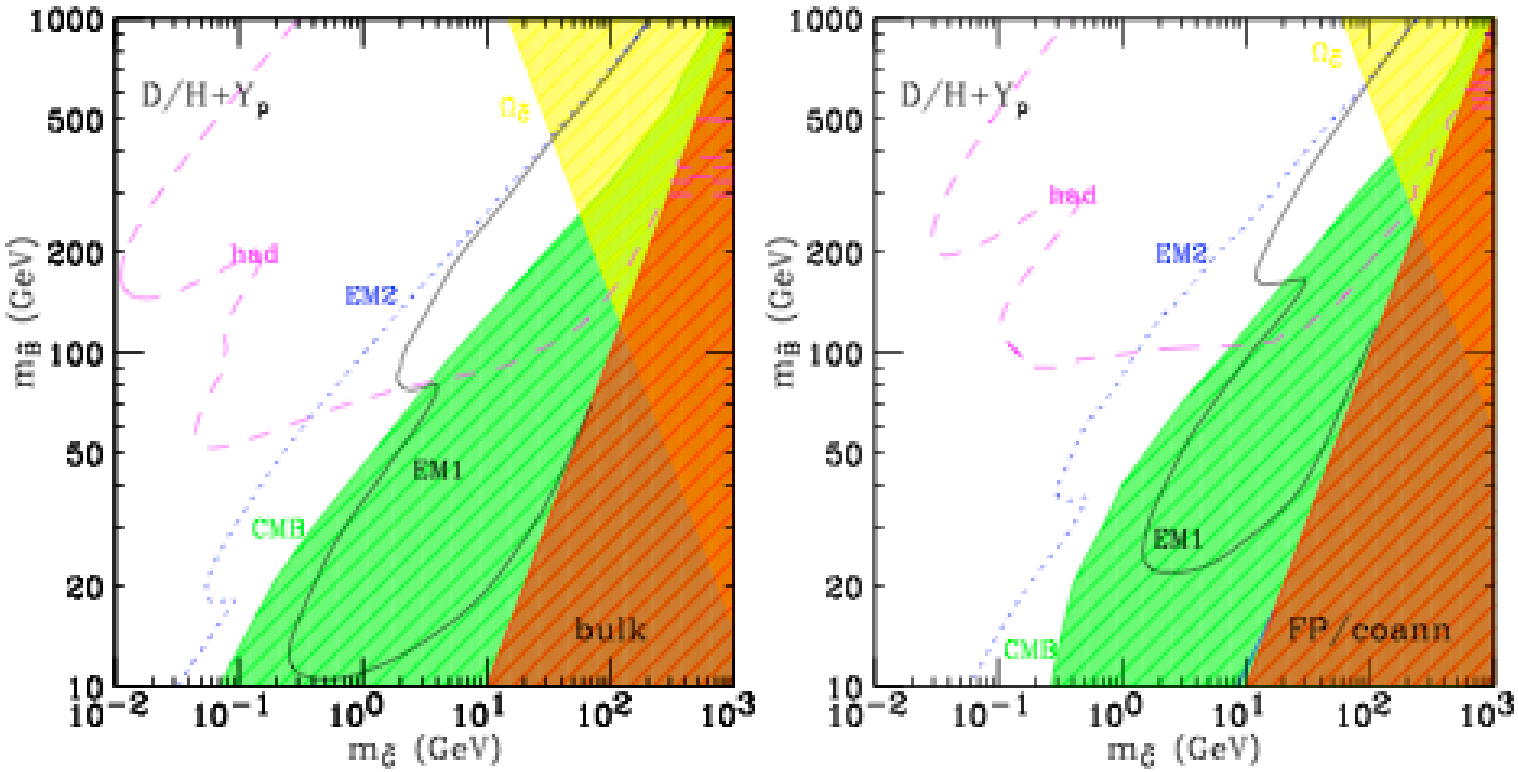


cf.

- atm. neutrino CC event < 1 event/kton/year ➔ OK.
- charged particle at the surface of detector < 1/cm^2/sec (?)
  ==> For SOUDAN II type detector, this corresponds to
  < 10% dead time of drift tube ➔ OK.

BBN bound:
(1) gravitino LSP + neutralino NLSP

Fig. from Feng, Su, Takatama, '04

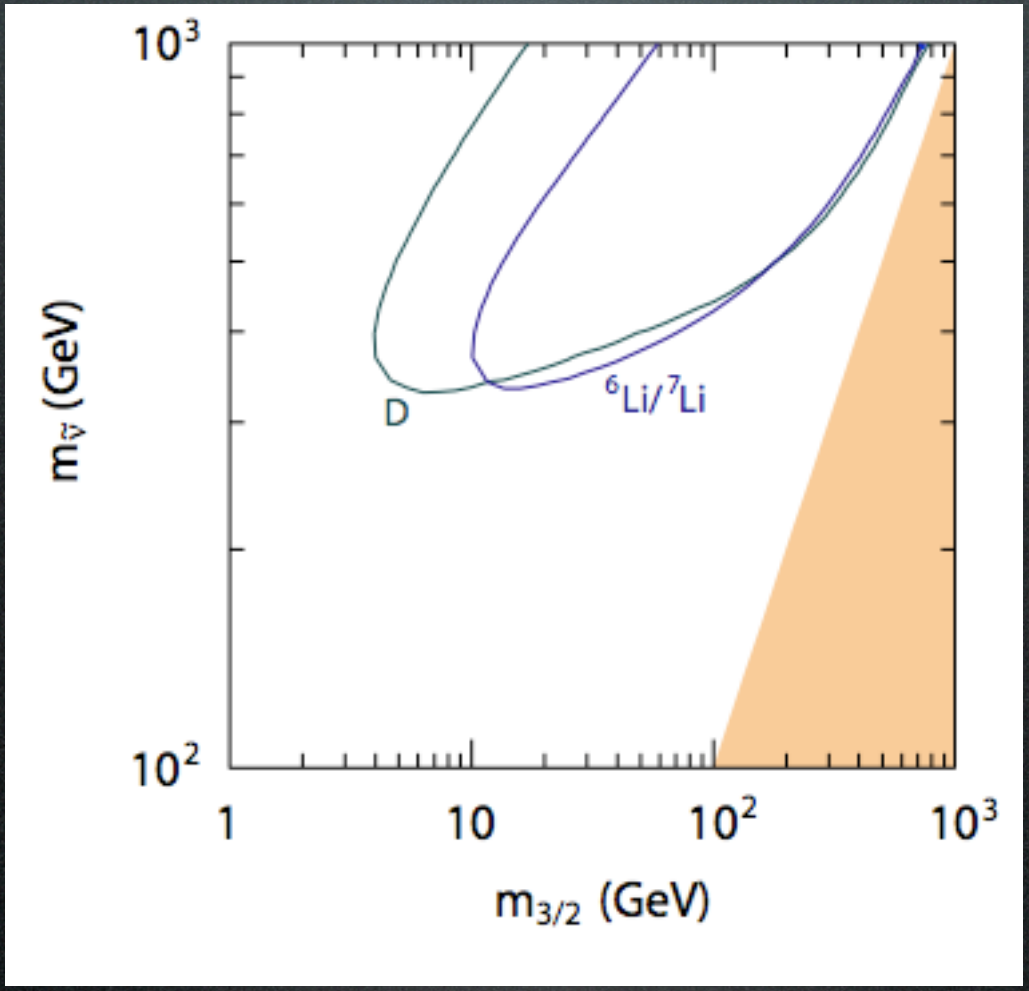


Very severe! $m_{\tilde{G}} < \mathcal{O}(0.01 - 1)\mathrm{GeV}$

back

BBN bound:
(3) gravitino LSP + sneutrino NLSP

Fig. from Kanzaki, Kawasaki, Kohri, Moroi,'06



back

BBN bound: (2) gravitino LSP + stau NLSP

Fig. from Kawasaki, Kohri, Moroi, hep-ph/0703122

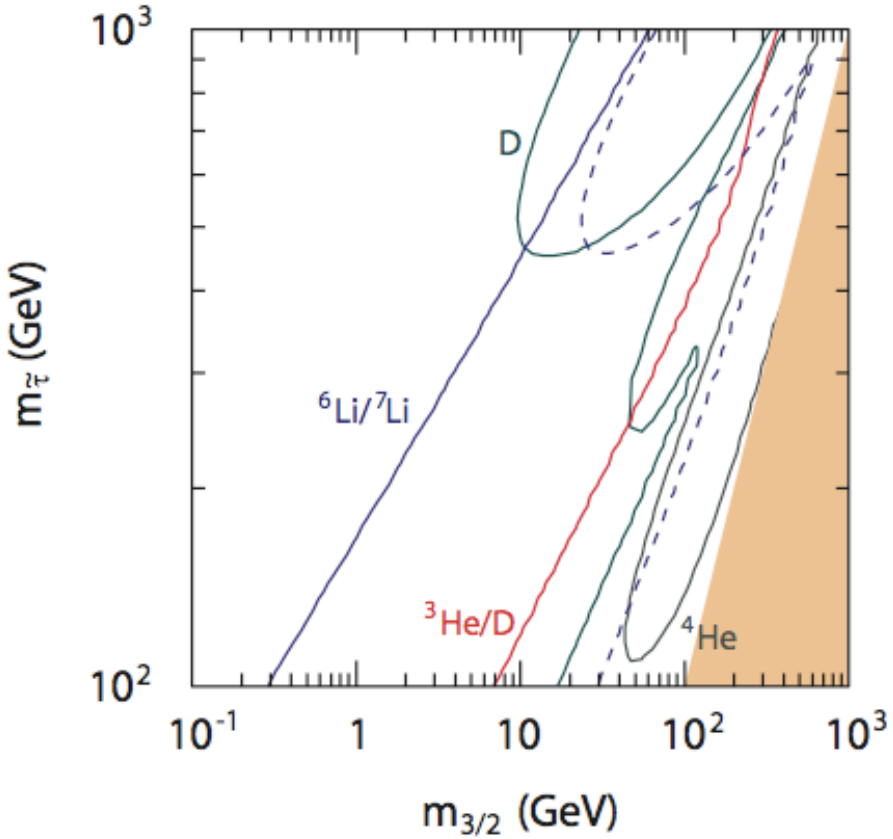


Figure 1: Constraints on $m_{3/2}$ vs. $m_{\tilde{\tau}_R}$ plane. The dashed line indicates the constraint from $(n_{^6\mathrm{Li}}/n_{^7\mathrm{Li}})_\mathrm{p}$ without taking account of the $\tilde{l}^-$-catalyzed process. We have shaded the region where $\tilde{\tau}_R$ becomes lighter than gravitino.