Long-lived Signature

Koichi Hamaguchi (Tokyo U.)

@「LHCが切り拓く新しい物理」, Tokyo U., April '09

based on.....S.Asai, KH, S.Shirai, arXiv:0902.3754

SCHOOL OF SCIENCE
THE UNIVERSITY OF TOKYO

IPMU INSTITUTE FOR THE PHYSICS AND MATHEMATICS OF THE UNIVERSE

introduction

Long-lived particle の例（in SUSY)

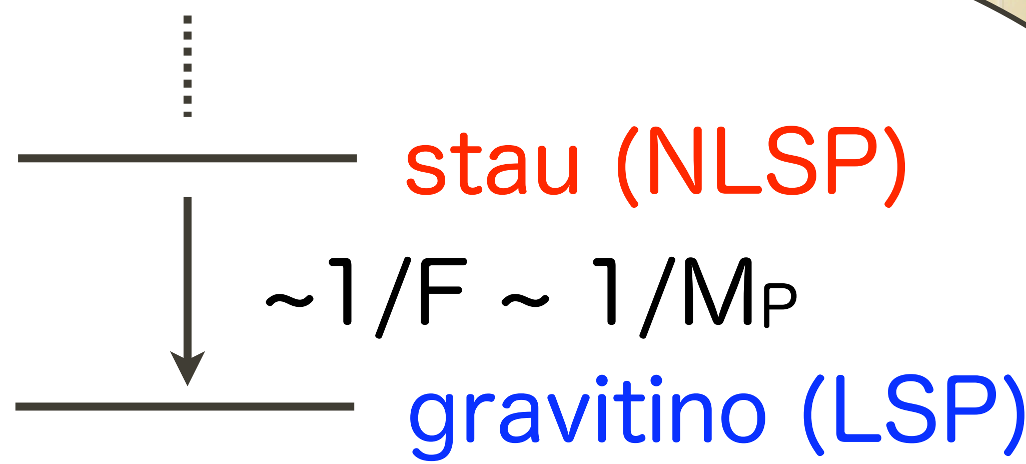
赤・・・charged
青・・・missing

stau → gravitino + tau (gravitino LSP)

stau → neutralino + ta

stau → neutrino + ta

neutralino → gravitino



wino(±) → wino(0) + pi(±) (a … on)

gluino → neutralino + q, qbar (split SUSY)

Long-lived particle の例（in SUSY)

赤・・・charged
青・・・missing

stau ➔ gravitino + tau (gravitino LSP)

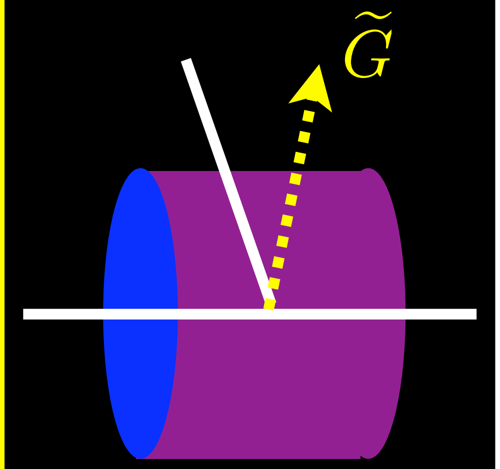
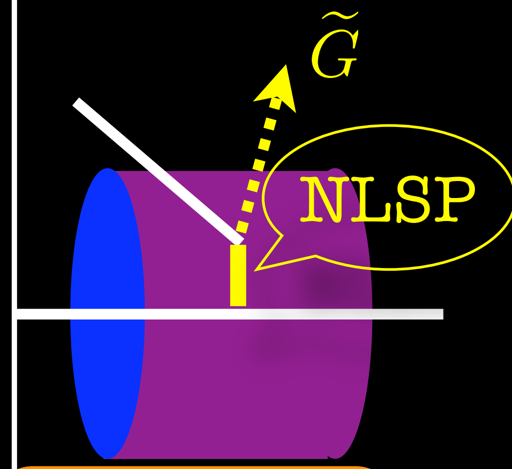
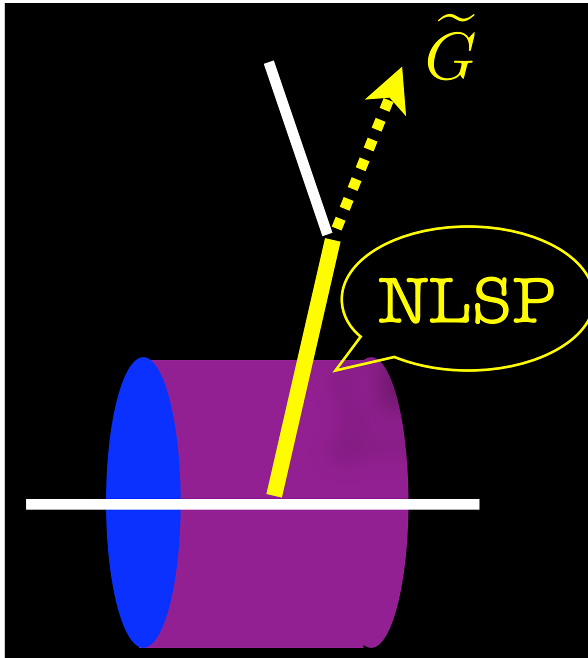
stau ➔ neutralino + tau (質量縮退)

stau ➔ neutrino + tau (small R-parity violation)

neutralino ➔ gravitino + photon (gravitino LSP)

wino(±) ➔ wino(0) + pi(±) (anomaly mediation)

gluino ➔ neutralino + q, qbar (split SUSY)

Gravitino and NLSP at the LHC		 次の東さんのトーク	 今日はこれの話
$\tilde{\tau}$ NLSP	(cf. 昨年の白井くんのトーク) 寿命測れる？？	“kink” in charged track 寿命測れる	charged track 寿命測れる？
$\tilde{\chi}^0$ NLSP	$2\gamma + E_{\mathrm{T,miss}}$	non-pointing photon 寿命測れる	the same as $\tilde{\chi}^0$ LSP signal....

何故 Long-lived charged particle (e.g. long-lived stau) を考えるのか？

- 理由１：long-lived stau は event としては exotic だがモデルはそんなに exotic じゃない。

  （聞く人にも依ると思いますが・・・。）

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- 理由２：もしあったら、寿命を測る事がとても大事だから。(SUSY breaking scale の測定、もしかしたら Planck scale の測定も？！)
  (cf. 去年の私のトーク)

Side Remark

Planck scale measurement

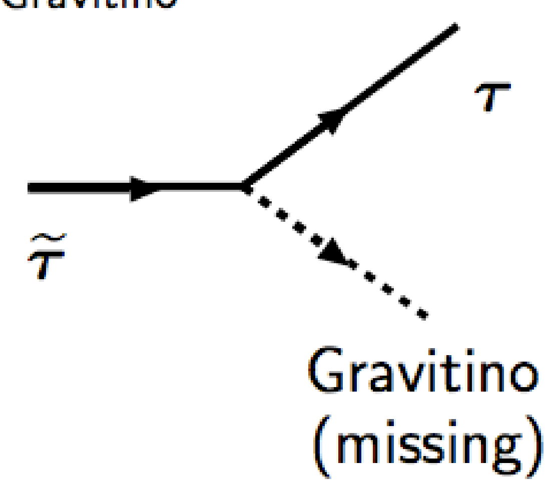
W.Buchmüller, K.Hamaguchi, M.Ratz, T.Yanagida '04

slepton

lepton

$$\mathcal{L}_{\text{Supergravity}} \supset \frac{-1}{\sqrt{2}M_{\text{P}}} \partial_\nu \widetilde{\tau}^* \overline{\psi}^\mu \gamma^\nu \gamma_\mu P_R \tau + \text{h.c.} + \cdots$$

Gravitino



Side Remark

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

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

Prediction of the Supergravity

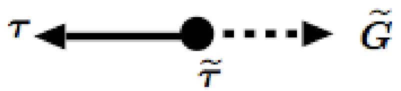
$$\Longleftrightarrow \quad M_P^2(\text{supergravity}) = \frac{1}{48\pi}\frac{1}{\Gamma_{\tilde{\tau}}}\frac{m_{\tilde{\tau}}^5}{m_{\tilde{G}}^2}\left(1 - \frac{m_{\tilde{G}}^2}{m_{\tilde{\tau}}^2}\right)^4$$

measurable

(using energy momentum)

"measurable"

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



consistency check!!

$$M_P^2(\text{gravity}) = (8\pi G_N)^{-1} = (2.44 \times 10^{18}\ \text{GeV})^2$$

Newton const.

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  (cf. 去年の私のトーク)

- 理由３：cosmology (Li-7問題)

thermal history

time	temperature	
??	~ 0	inflation
??	T_R	reheating
$\approx$		baryogenesis $\rightarrow n_B/s \simeq 10^{-10}$
~ 1 sec	~ 1 MeV	Big Bang Nucleosynthesis $\rightarrow$ D, ^{4}He, $\cdots$
$\approx$		$\downarrow$
14 Gyr	2.7 K	observed

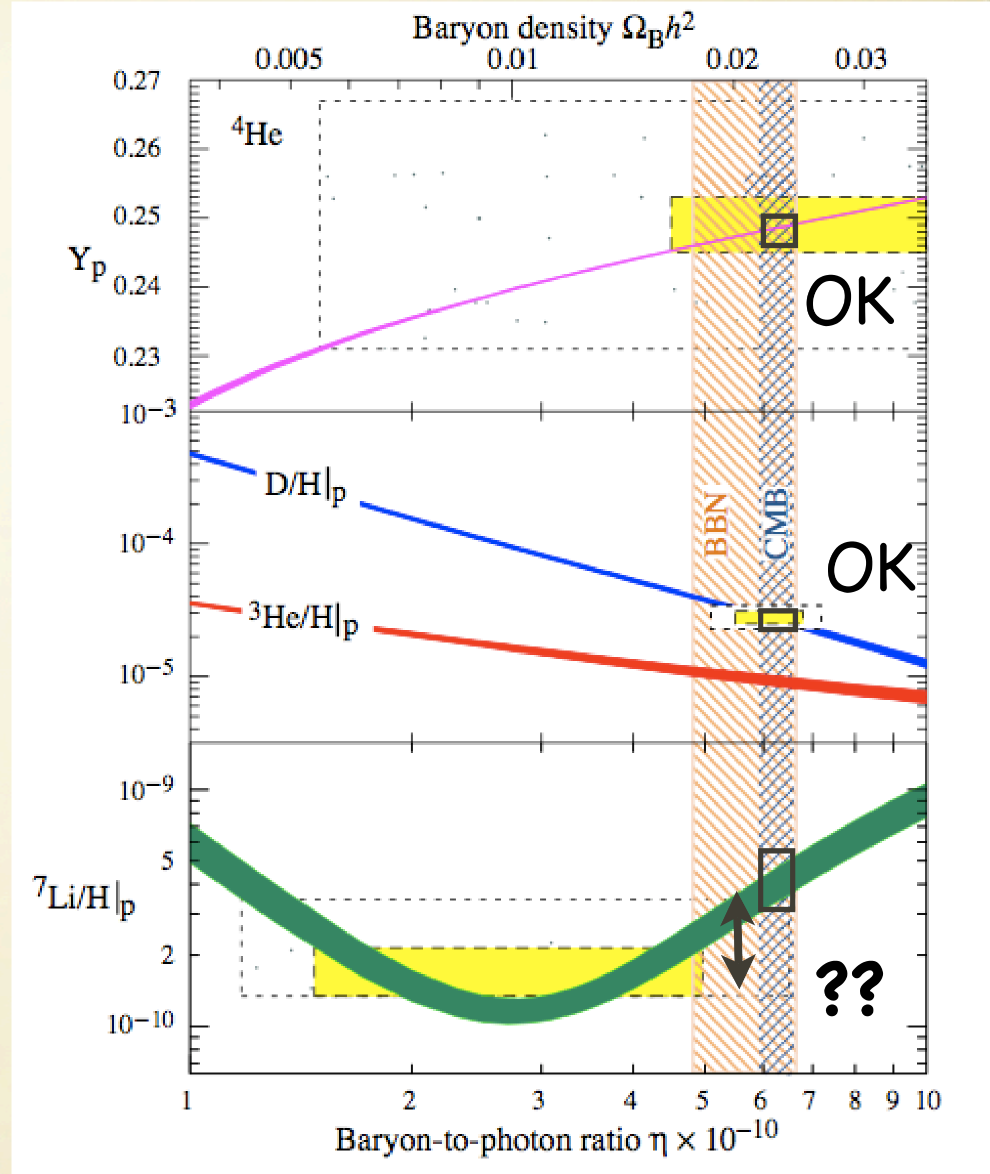
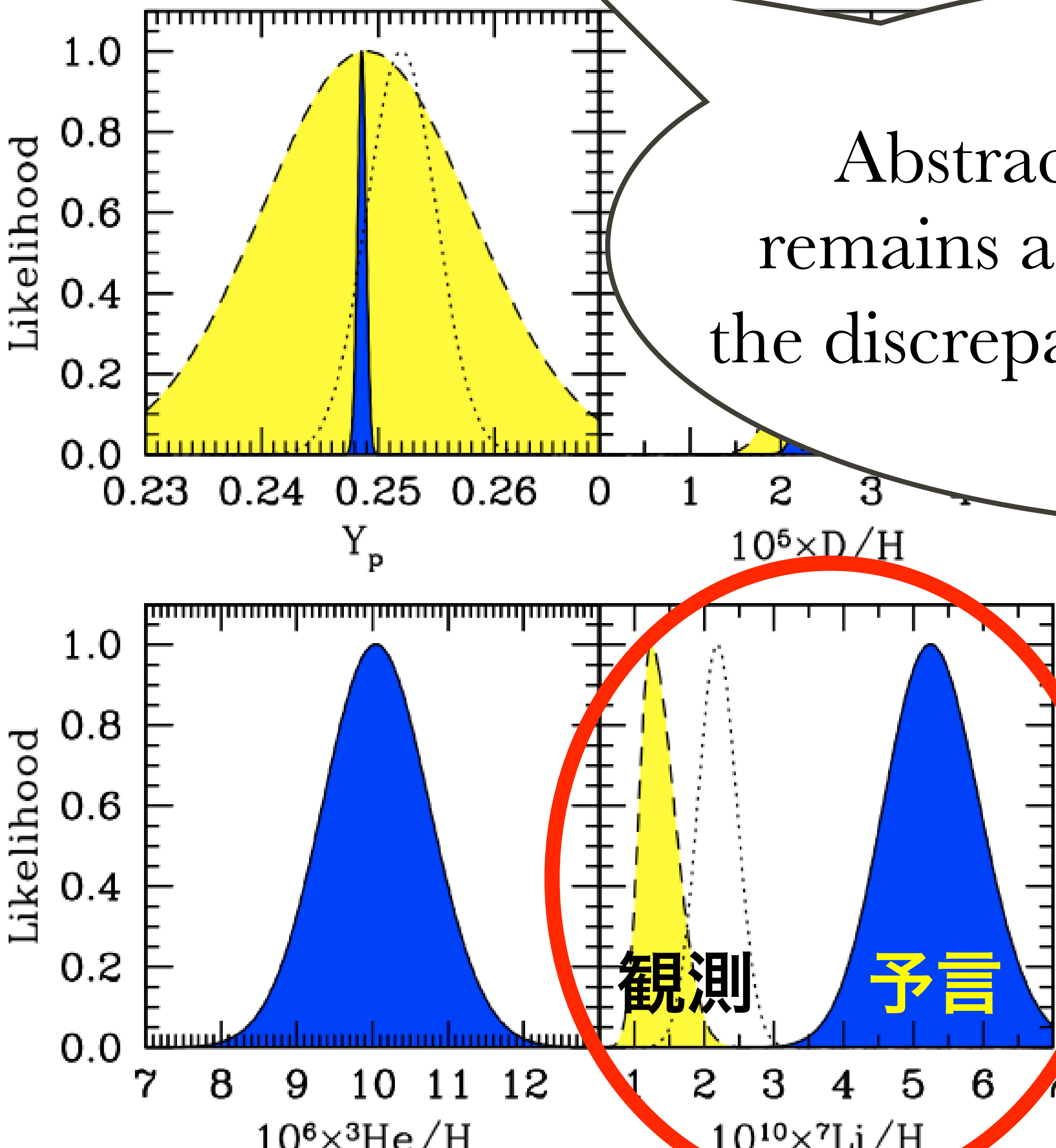
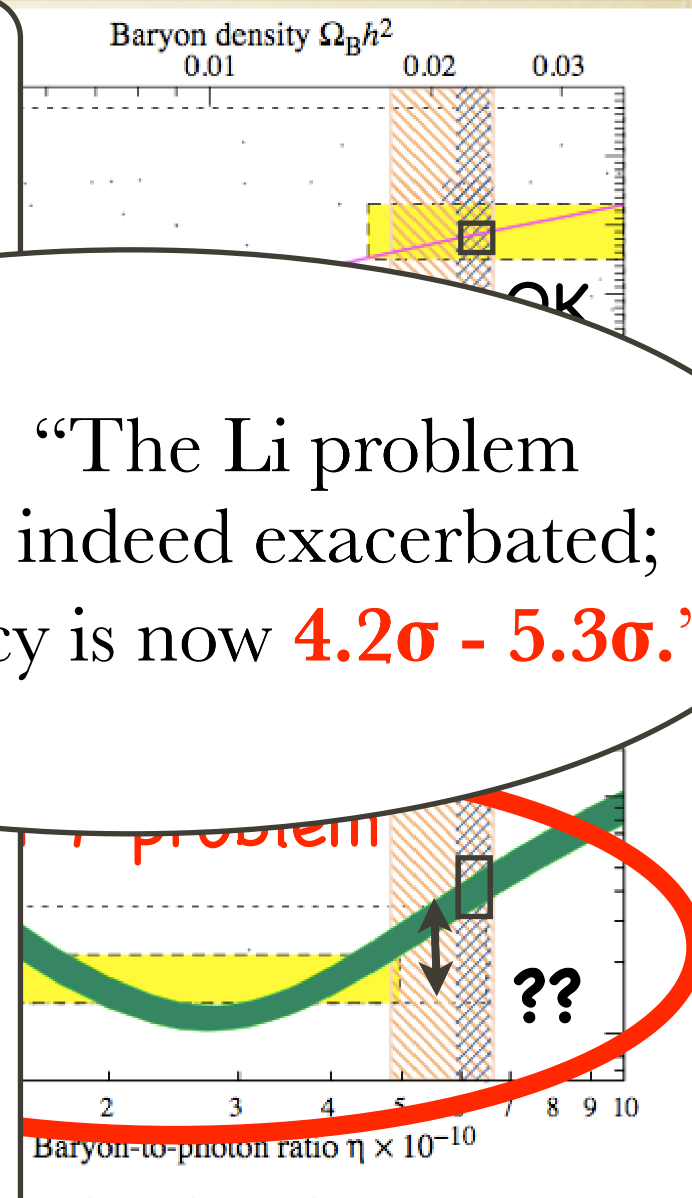


Fig. from Review of Particle Physics

recently, reanalyzed by
Cyburt, Fields, Olive, 0808.2818



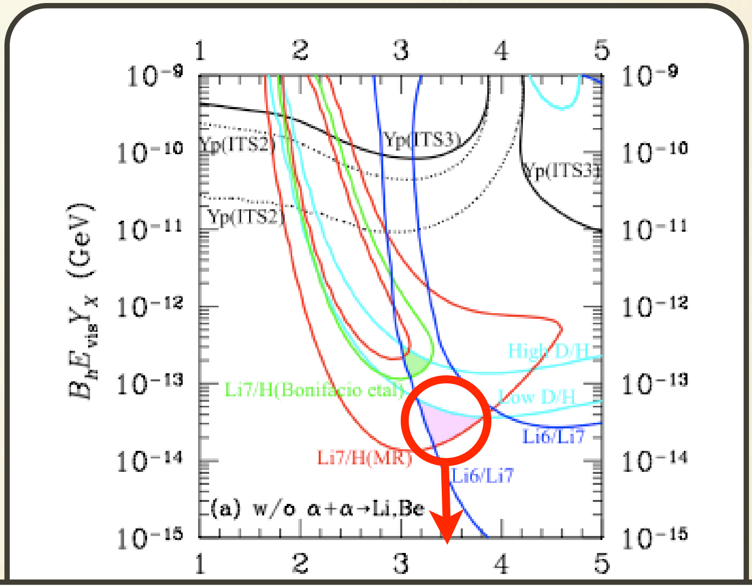
Abstract: "The Li problem remains and indeed exacerbated; the discrepancy is now **4.2σ - 5.3σ.**"



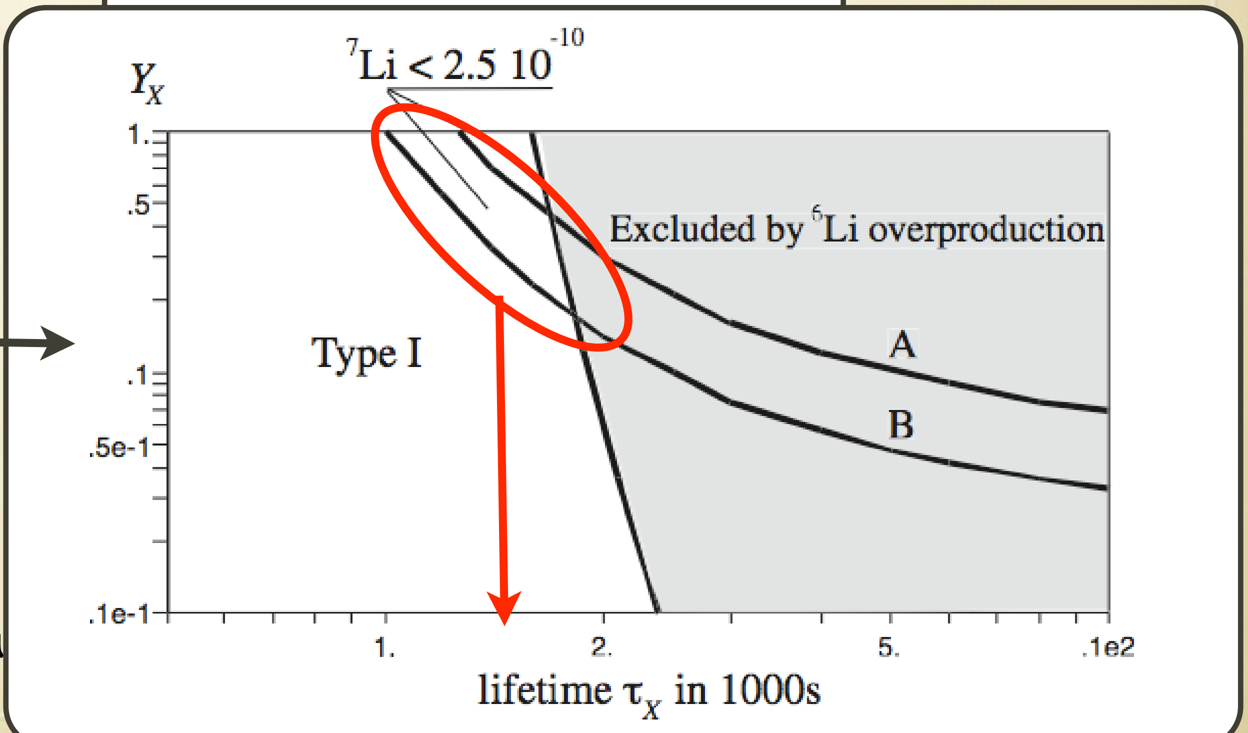
eview of Particle Physics

This Li-7 problem may be solved if there is a long-lived [O(1000 sec)] charged particle !

decay effect:
(destroy Li-7)
(not necessarily charged)
Jedmzik,'04;
+ (many others)
+ Cumberbatch, Ichikawa, Kawasaki, Kohri, Silk, Starkman,'07



catalysis effect:
$(^7Be\ X^-)+p \rightarrow (^8B\ X^-)+\gamma$
Pospelov,'06;
+ Bird, Koopmans, Pospelov,'07
+ Kusakabe, Kajino, Boyd, Yoshida, Mathews,'07,
+ Kamimura, Kino, Hiyama,'08
(cf. Takayama,'08, Jedamzik,'08, Jittoh, Kohri, Koike, Sato, Shimomura Yamanaka'07'08)



Mission:

long-livec … ne LHC,

e.a., stau

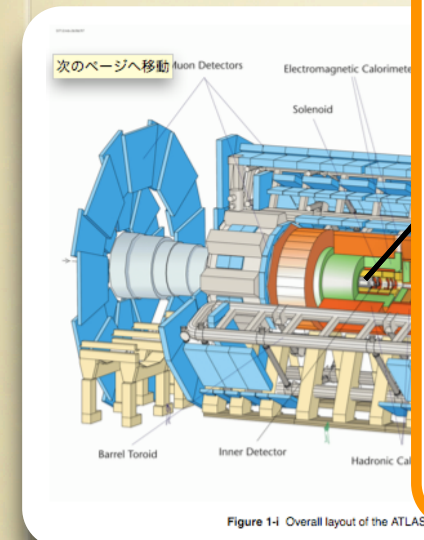
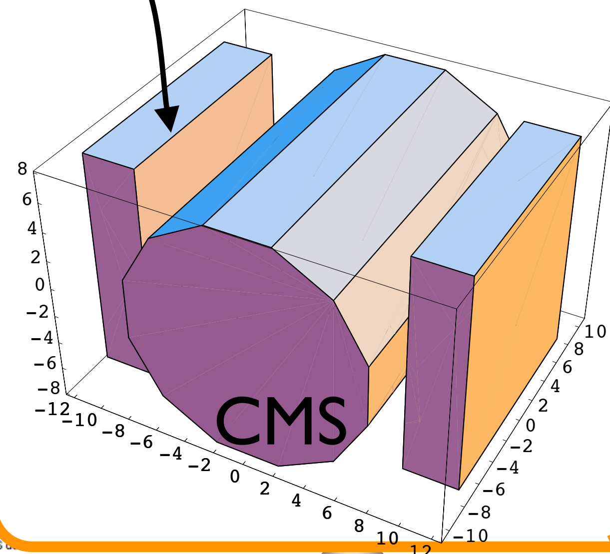
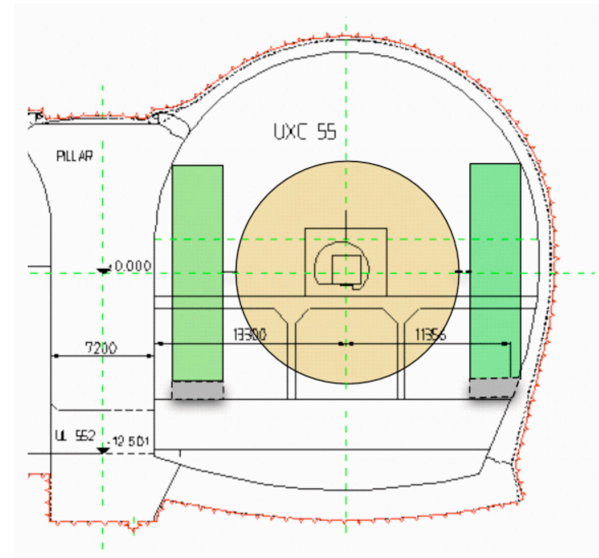


Figure 1-i Overall layout of the ATLAS

stopper-detector

KH, Kuno, Nakaya, Nojiri '04
KH, Nojiri, DeRoeck '06





If its lifetime is long (> 1 sec), can we see its decay??

Yes! with additional stoppers.

KH, Kuno, Nakaya, Nojiri,'04
Feng, Smith,'04
KH, Nojiri, De Roeck,'06

Yes! without additional material. Asai, KH, Shirai,'09

this talk

実は、去年の同じ研究会（08年3月）で

「LSPがGravitinoになるモデルと
LHCでの物理」

というタイトルでお話して・・・

その時、Long-lived stau の話を
して、最後のスライドで次のような
質問をしました。

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？）

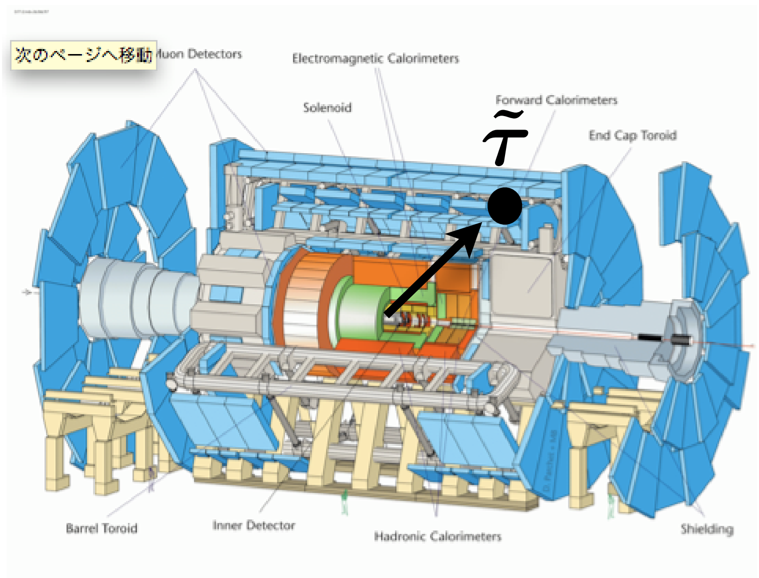


Figure 1-i Overall layout of the ATLAS detector.

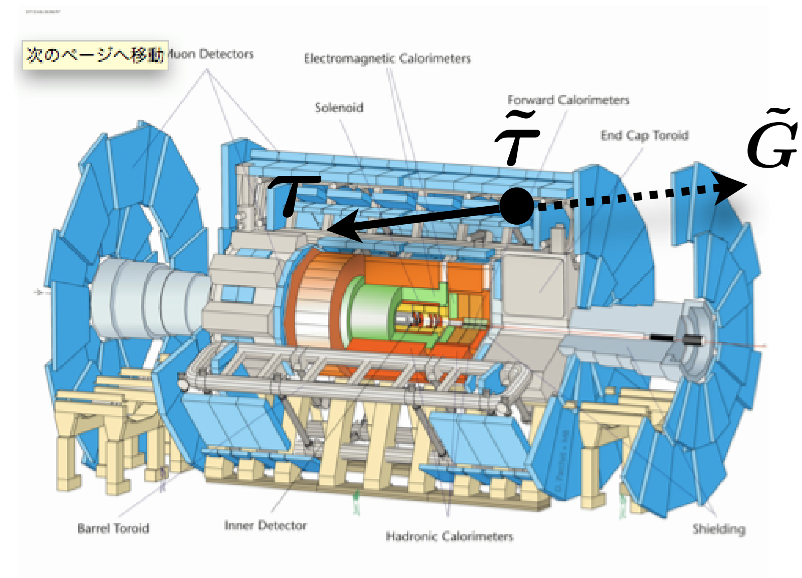


Figure 1-i Overall layout of the ATLAS detector.

何とかしてこいつら identify 出来ないでしょうか？

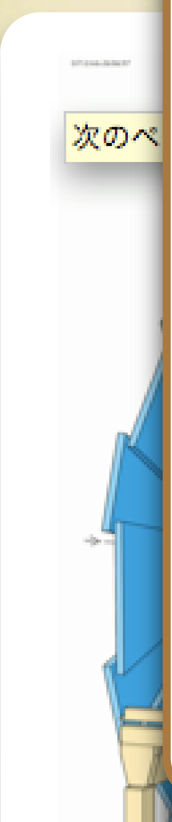
(cf. Dimopoulos達の “stopping gluino” (at ATLAS) hep-ph/0506242)

今日はこの続きのお話をします。

Stop and Decay
of
Long-lived Charged Massive Particles
at the LHC detectors

S.Asai, KH, S.Shirai, arXiv:0902.3754

- typically most of staus have large velocity and escape from detector.



- momentum measurement p
- + TOF (time of flight) measurement T

  ⇨ velocity β = L/T
- mass m = p/(βγ)

  cf. 昨日の河野さんのtalk

  cf. De Roeck, Ellis, Gianotti, Moortgat, Olive, Pape, 05

$$\frac{\Delta m_{\tilde{\tau}}}{m_{\tilde{\tau}}} = \frac{\Delta p}{p} \oplus \beta\gamma^2 \frac{\Delta t}{L} \qquad \simeq 10-20\% \qquad \text{in each event}$$

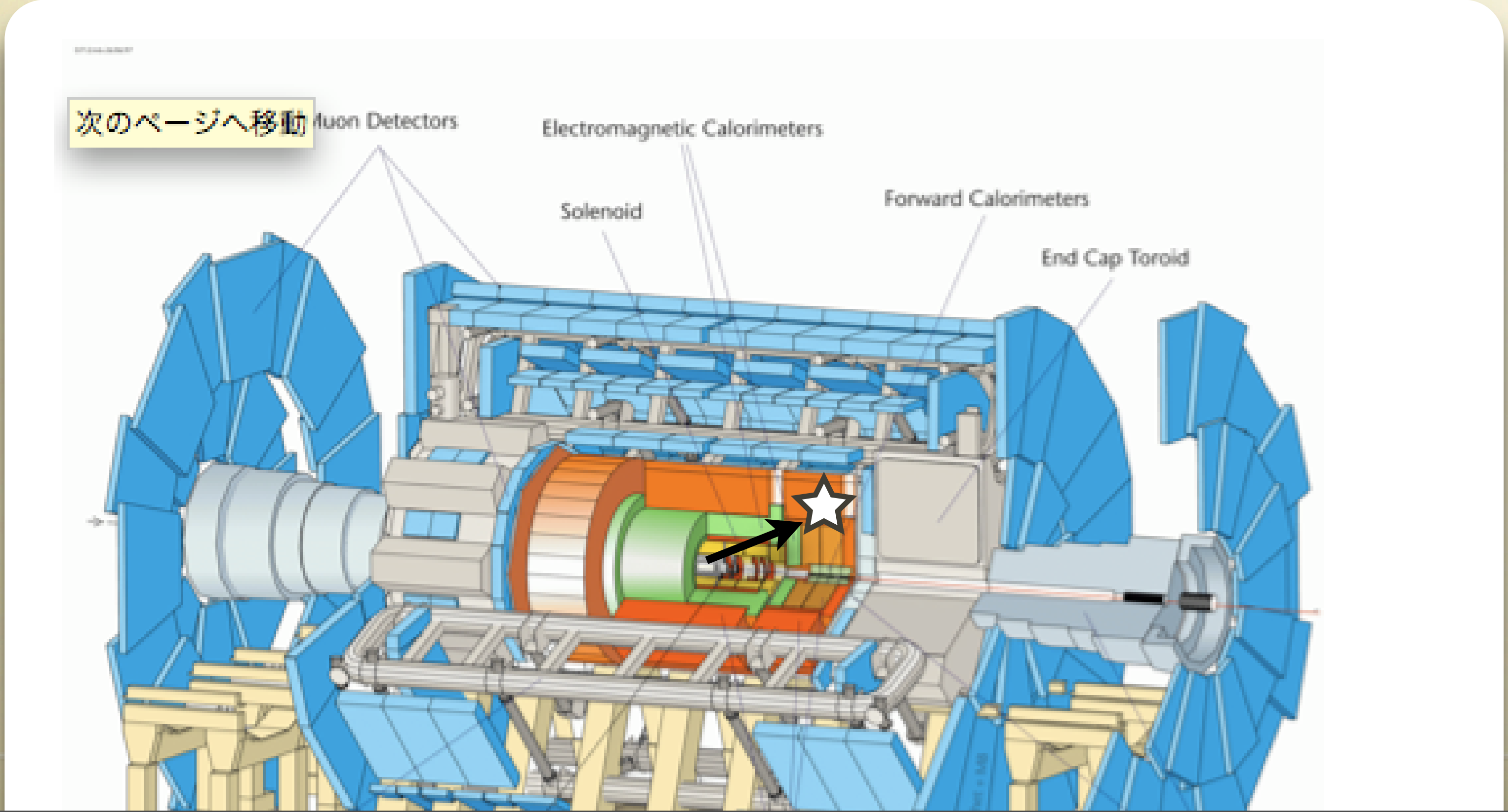
$$\mathcal{O}(1000)\ \tilde{\tau} \ \rightarrow \boxed{\frac{\Delta m_{\tilde{\tau}}}{m_{\tilde{\tau}}} < 1\%}$$

- さらに他の粒子の質量（やスピンも?!）測れる

  (Hinchliffe,Paige,'98, Ambrosanio et.al.,'00, ...

  ..... Rajaraman,Smith 0708, Kitano 0801, 0806,.....)

- typically most of staus have large velocity and escape from detector.
- some of them have sufficiently small velocity and stop at calorimeters.



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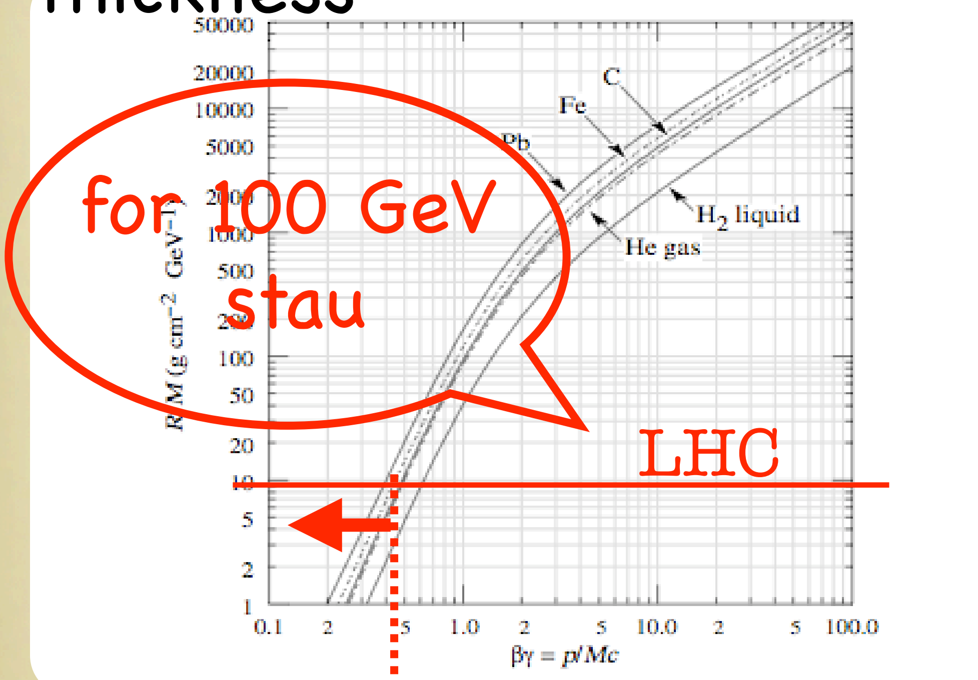
thickness



βγ (= momentum／mass)

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

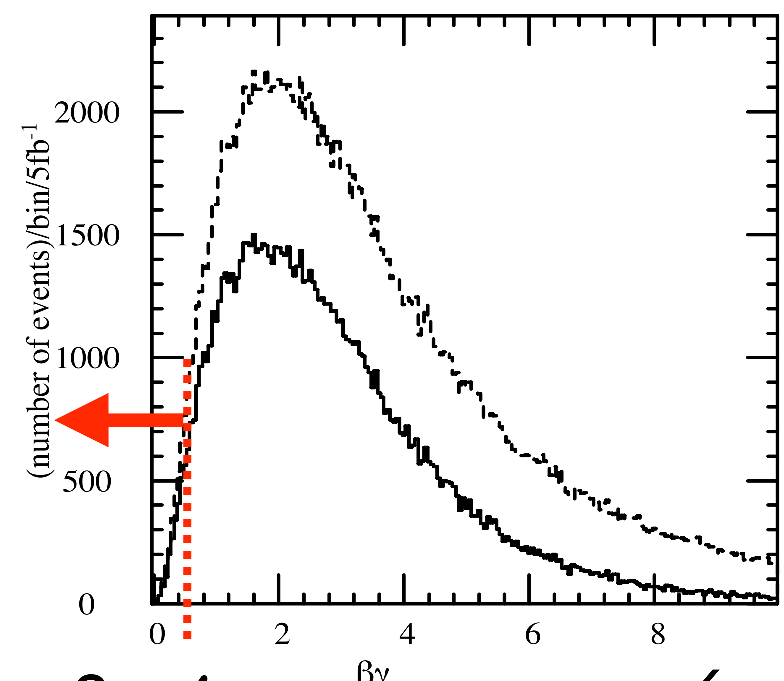


Fig. from KH, Kuno, Nakaya, Nojiri '04

βγ (= momentum／mass)

• typically most of staus have large velocity and escape from detector.

• some of them have sufficiently small velocity and stop at calorimeters.

example of SUSY model point SPS7 (σ_{SUSY} = 3.5 pb)

35000 SUSY events

TABLE II: The number of stopping staus for 10 fb^{-1}.

with cuts	without cuts
400	805

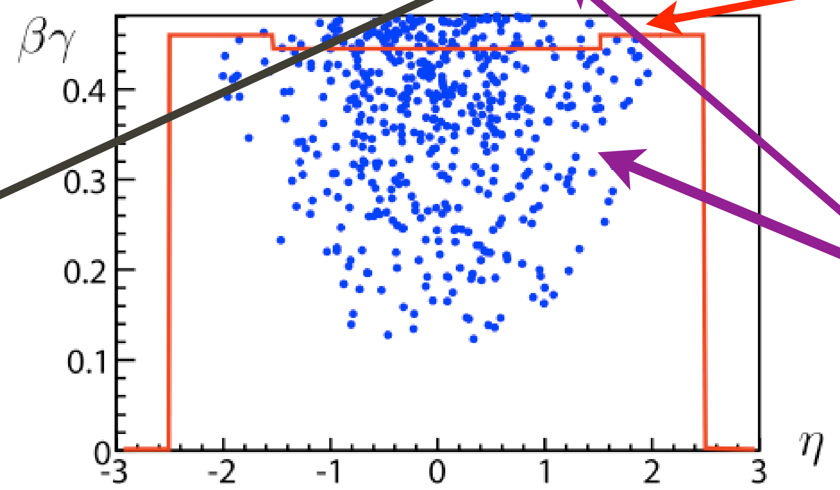


FIG. 1: $\eta - \beta\gamma$ distribution of the staus. The red line shows the limit for the stau to stop in the detector.

Thickness: assume Fe 1440mm (barrel) Cu 1400mm (end-cap)

stopped events

- about 1% of total SUSY events
- a few per day (for 10^{33}/cm^2 s)

from Asai, KH, Shirai '09

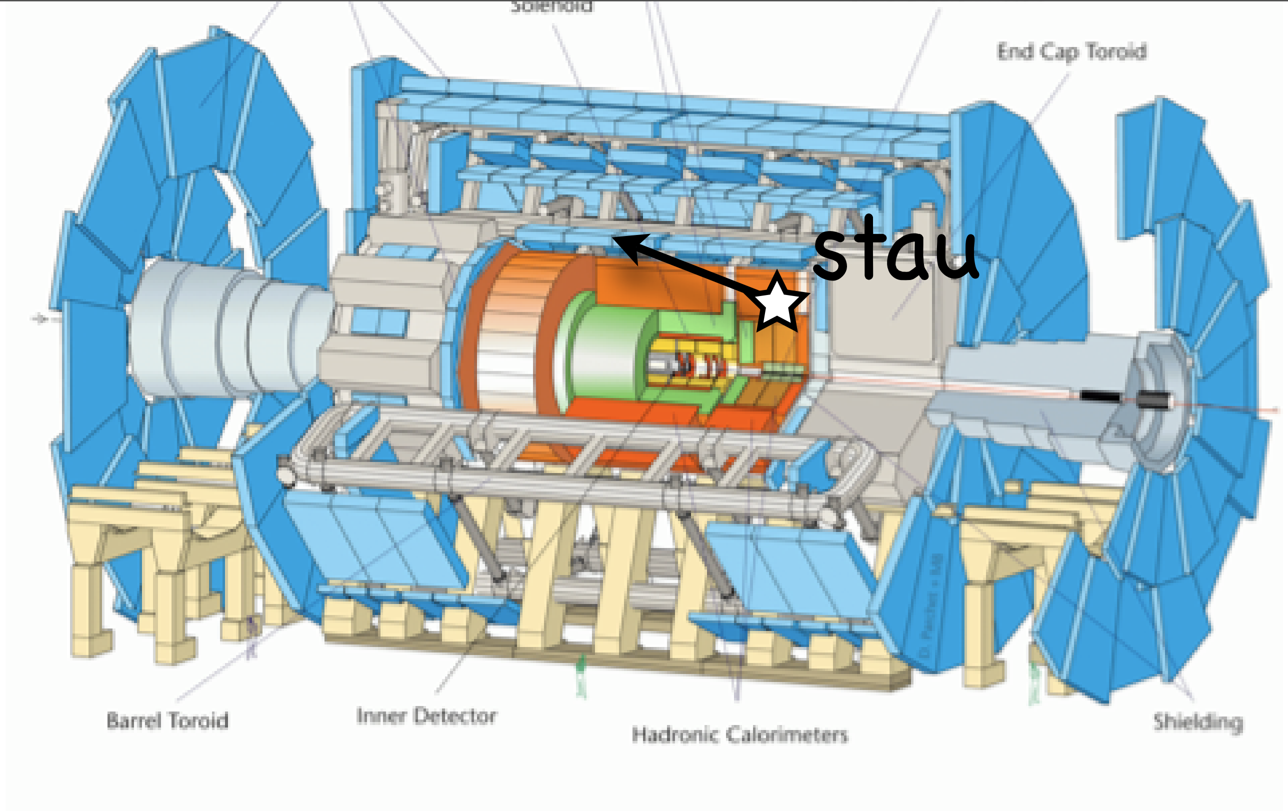


Figure 1-i Overall layout of the ATLAS detector.

- but their late-time decay has wrong timing and wrong direction;
- difficult to reject backgrounds
- difficult to trigger.

..... during pp collision.

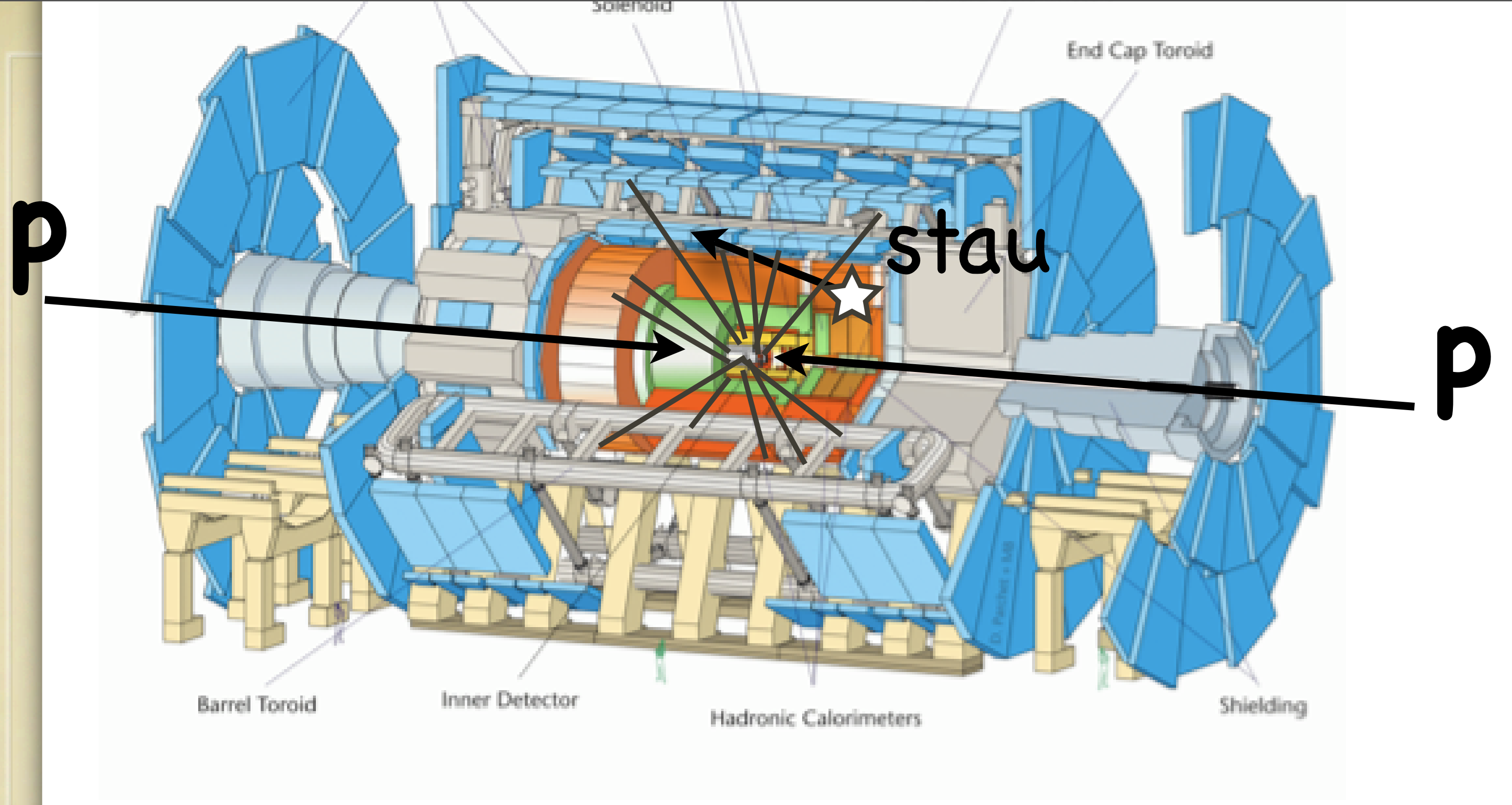


Figure 1-i Overall layout of the ATLAS detector.

- but their late-time decay has wrong timing and wrong direction;
- difficult to reject backgrounds
- difficult to trigger.

..... during pp collision.

Idea:

stop the pp collision !!

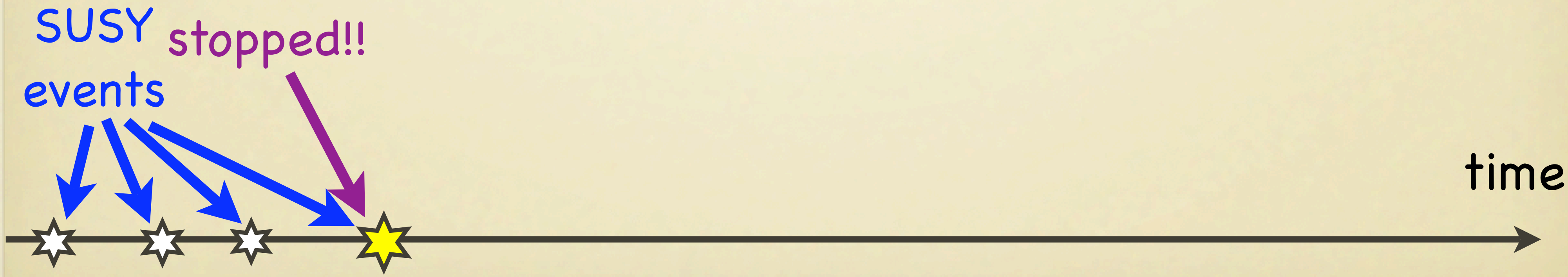
....and optimize the trigger
to detect the stau decay
(= isolated energetic cluster in HCAL)

two possible strategies:

- for short lifetime: use beam-damp signal.
- for long lifetime: use shutdown time.

- for short lifetime: use beam-damp signal.

(I) select the stopping event by online Event Filter.



- for short lifetime: use beam-damp signal.

(I) select the stopping event by online Event Filter.

(1) missing ET > 100 GeV
(2) 1 jet PT > 100 GeV + 2 jets PT > 50 GeV

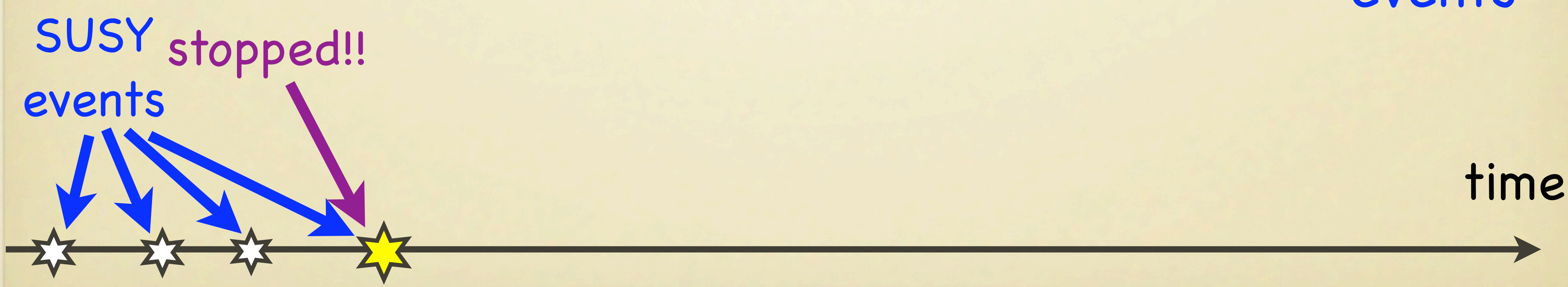
(3) isolated track with PT > 0.1 m(stau).

(4) extrapolate the track to calorimeter and energy deposit < 0.2 p(stau).
(5) extrapolate the track to muon system and no muon track.

standard SUSY cuts

stau candidate

select stopping events



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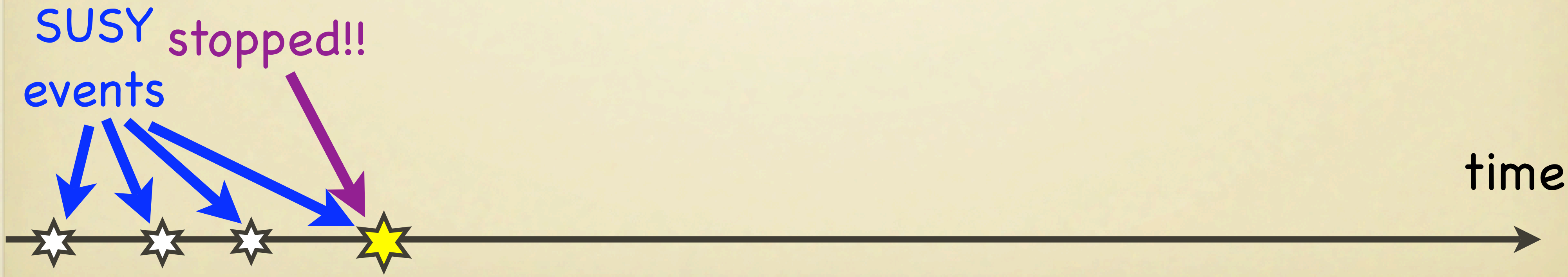
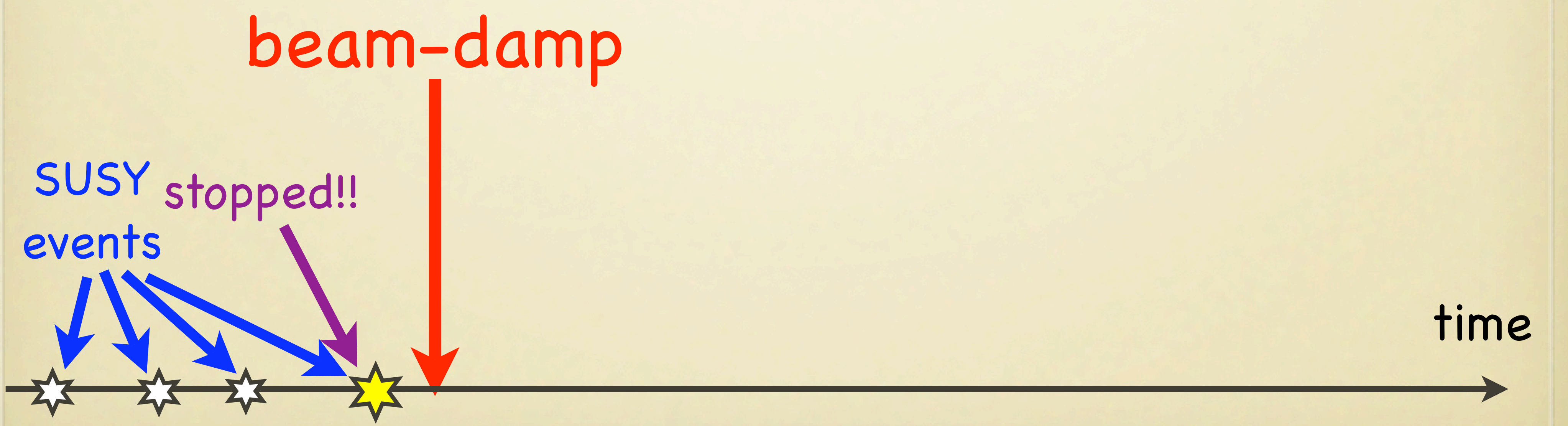


• for short lifetime: use beam-damp signal.

(I) select the stopping event by online Event Filter.

(II) send a beam-damp signal, which immediately stops the pp collision.



• for short lifetime: use beam-damp signal.

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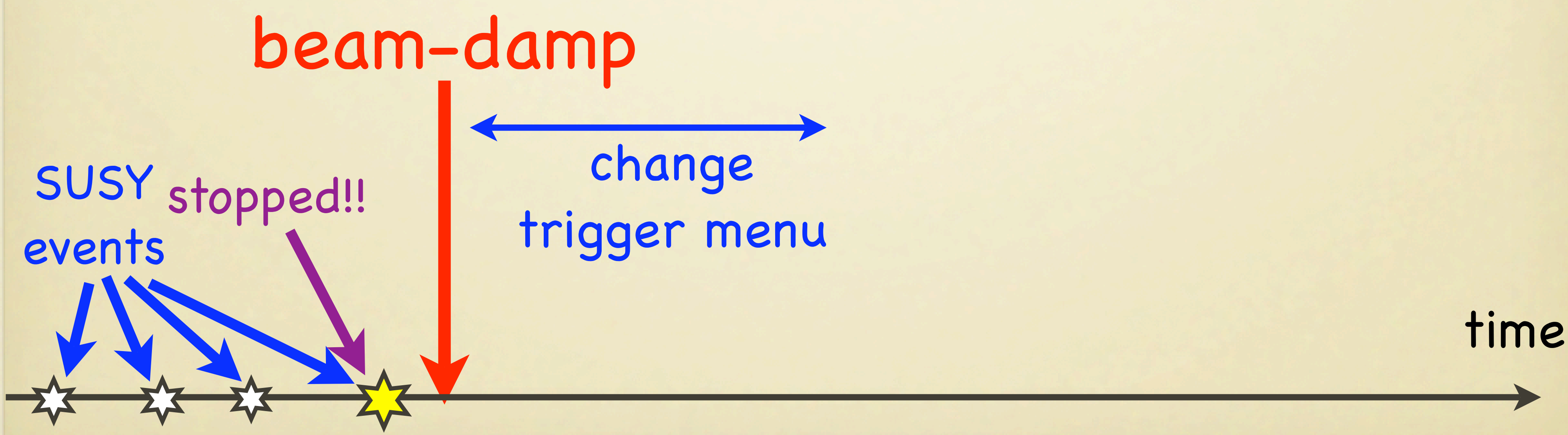
trigger

(III) change the trigger menu to the one optimized for stau decay.



- for short lifetime: use beam-damp signal.

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(III) change the trigger menu to the one optimized for stau decay.

(IV) wait for stau decay.

- for short lifetime: use beam-damp signal.

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trigger

(III) change the trigger menu to the one optimized for stau decay.

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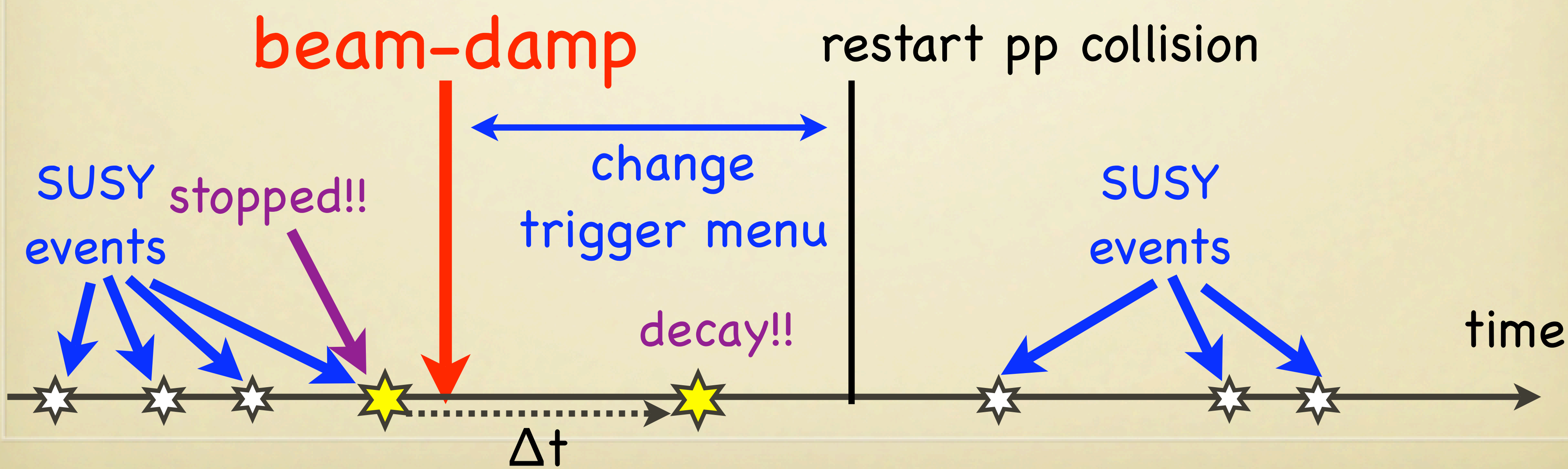
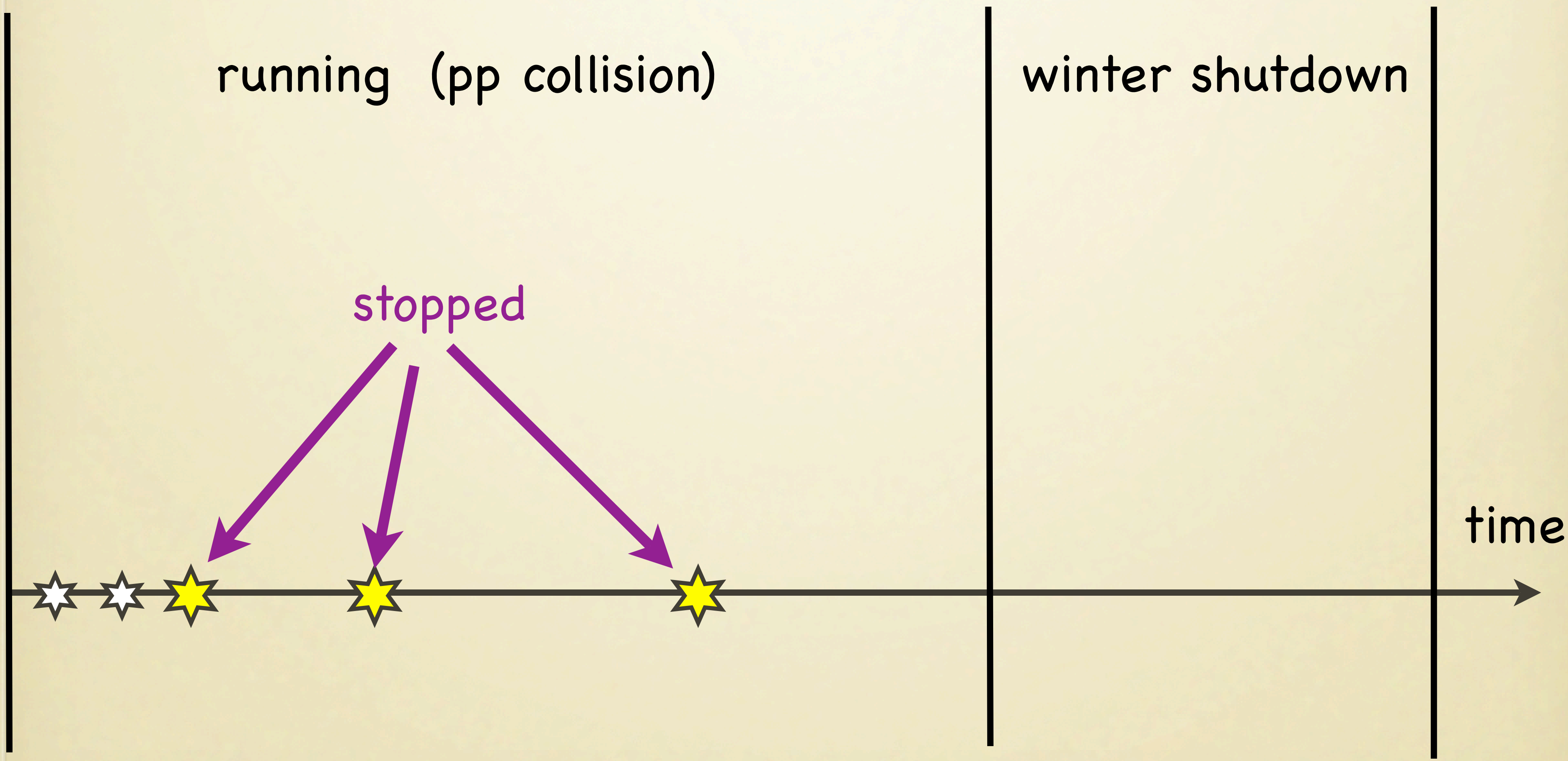


- for long lifetime: use shutdown time



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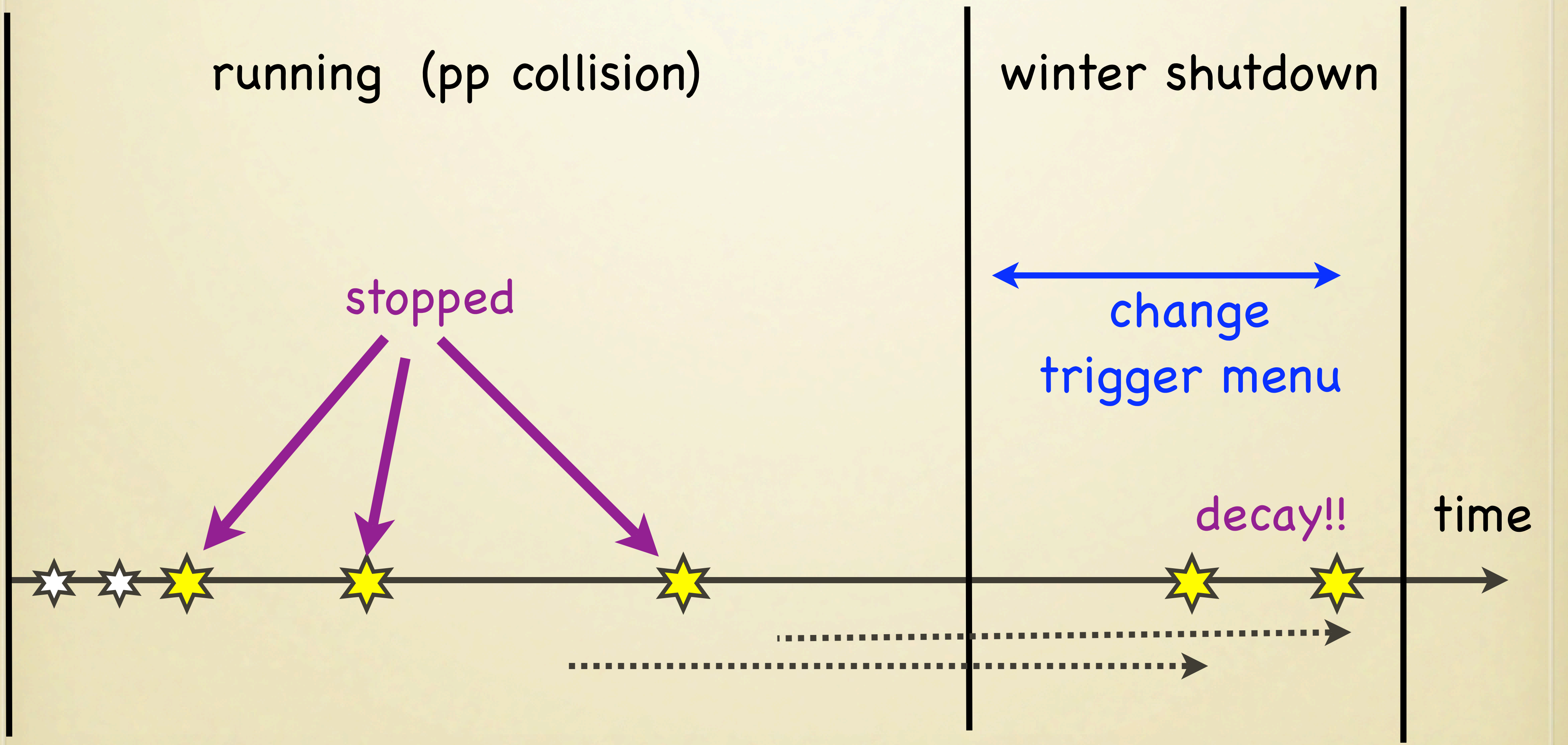


•lifetime measurement: SUMMARY

TABLE III: Expected statistical errors for each lifetime. $\langle N_D \rangle$ is the expected number of staus' decays in the corresponding period.

	10 fb^{-1}		100 fb^{-1}	
lifetime	$\langle N_D \rangle$	σ	$\langle N_D \rangle$	σ
0.1 sec	0.01	$\pm$0.1 sec	0.1	$\pm$0.1 sec
0.2 sec	1.8	$\pm$0.15 sec	18	$\pm$0.05 sec
0.5 sec	35	$\pm$0.1 sec	352	$\pm$0.03 sec
1 sec	96	$\pm$0.1 sec	956	$\pm$0.04 sec
10 sec	235	$\pm$0.7 sec	2353	$\pm$0.2 sec
100 sec	257	$\pm$7 sec	2574	$\pm$2.0 sec
1000 sec	217	$^{+180}_{-140}$ sec	2168	$\pm$51 sec
10 day	26	$\pm$2.2 day	262	$\pm$0.7 day
100 day	143	$^{+49}_{-25}$ day	1430	$^{+20}_{-13}$ day
10 year	14	$^{+7}_{-3}$ year	138	$^{+1.6}_{-1.2}$ year
50 year	2.8	$^{+110}_{-21}$ year	28	$^{+21}_{-12}$ year
300 year	0.5	–	5	$^{+224}_{-88}$ year

short

long

assumption

dead time: 1 sec
waiting time: 30 min.

running: 200 days
shutdown: 100 days

O(0.1 sec .... 100 years) can be probed!!

Summary

If we will see
long-lived charged massive particle at the LHC,
the lifetime measurement is important both for
cosmology and particle physics.

The discovery of late decay, and the lifetime
measurement is possible for a very wide range,
from O(0.1 sec) to O(100 years) !!!

Future works:

study of decay products (energy? particle IDs?)
what about long-lived colored particle (R-hadrons) ?

Backup Slides

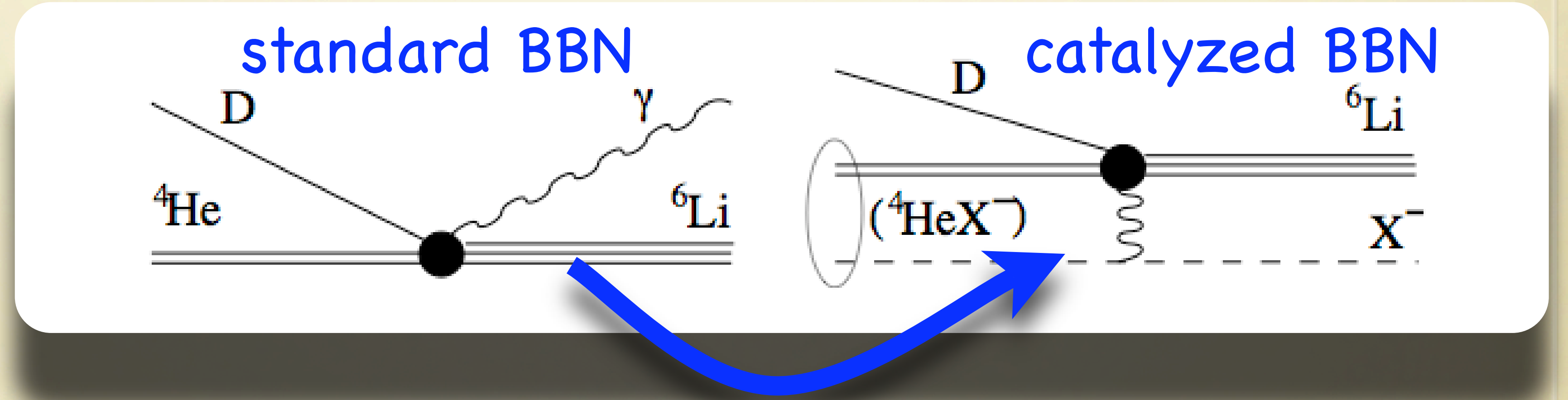
Catalyzed BBN (CBBN) Pospelov '06

If there were negatively charged particle, X^- at BBN,...

→ bound states with positively charged nuclei.

→ new catalyzed reactions occur!

(1) strong constraints (Li6) on X lifetime and abundance.



O(10^9) enhancement !!!
→ too much Li6 !!!

Pospelov '06;.......; KH, Hatsuda, Kamimura, Kino, Yanagida '07

Catalyzed BBN (CBBN) Pospelov '06

If there were negatively charged particle, X^- at BBN,...

→ bound states with positively charged nuclei.

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(1) strong constraints (Li6) on X lifetime and abundance.

(2) there may already exist a hint of this CBBN.

→ Li7 problem.

Catalyzed BBN (CBBN) Pospelov '06

If there were negatively charged particle, X^- at BBN,...

→ bound states with positively charged nuclei.

→ new catalyzed reactions occur!

(1) strong constraints (Li6) on X lifetime and abundance.

(2) there may already exist a hint of

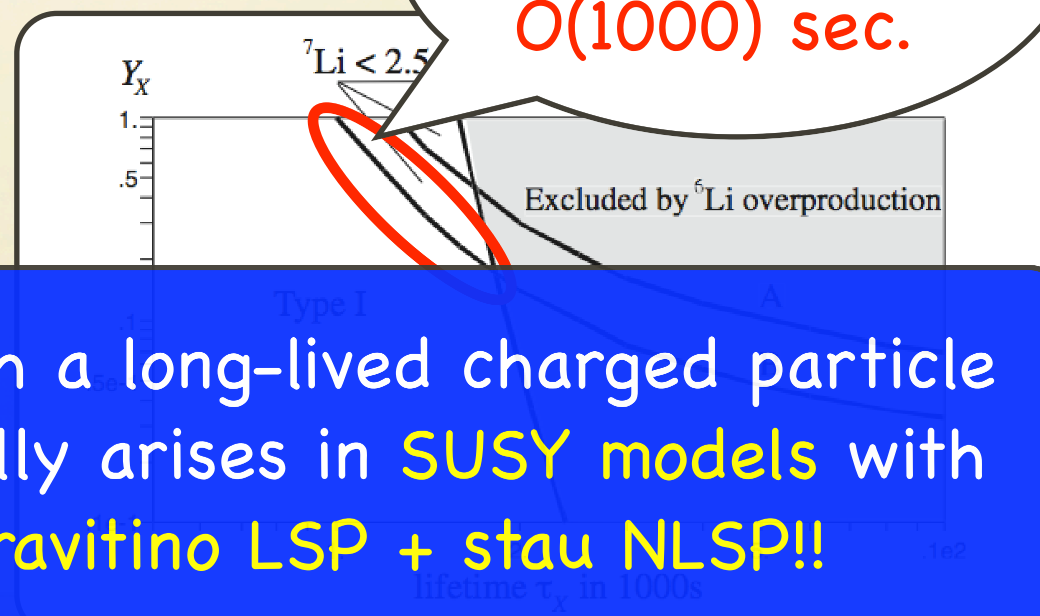
→ Li7 problem.

..... if X lifetime is O(1000) sec.

CBBN can solve it!

$(^7\mathrm{Be}\,X^-)+p \to (^8\mathrm{B}\,X^-)+\gamma$

Pospelov,'06;
+ Bird, Koopmans, Pospelov,'07
(+ many others)
+ Kamimura, Kino, Hiyama,'08



☛ Such a long-lived charged particle naturally arises in SUSY models with gravitino LSP + stau NLSP!!

What is Gravitino?

Superstring

⊃

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 $\tilde{G}$

extremely weakly interacting

- Why Gravitino LSP ?

- ..... among 29 SUSY particles?

$$\text{squarks}: \begin{pmatrix} \widetilde{u_L} \\ \widetilde{d_L} \end{pmatrix}_i \quad \widetilde{u_{Ri}} \quad \widetilde{d_{Ri}} \qquad \text{sleptons}: \begin{pmatrix} \widetilde{\nu_L} \\ \widetilde{e_L} \end{pmatrix}_i \quad \widetilde{e_{Ri}}$$

$$\text{gauginos and higgssinos}: \widetilde{\chi_i^0}, \quad \widetilde{\chi_i^\pm}, \quad \tilde{g}$$

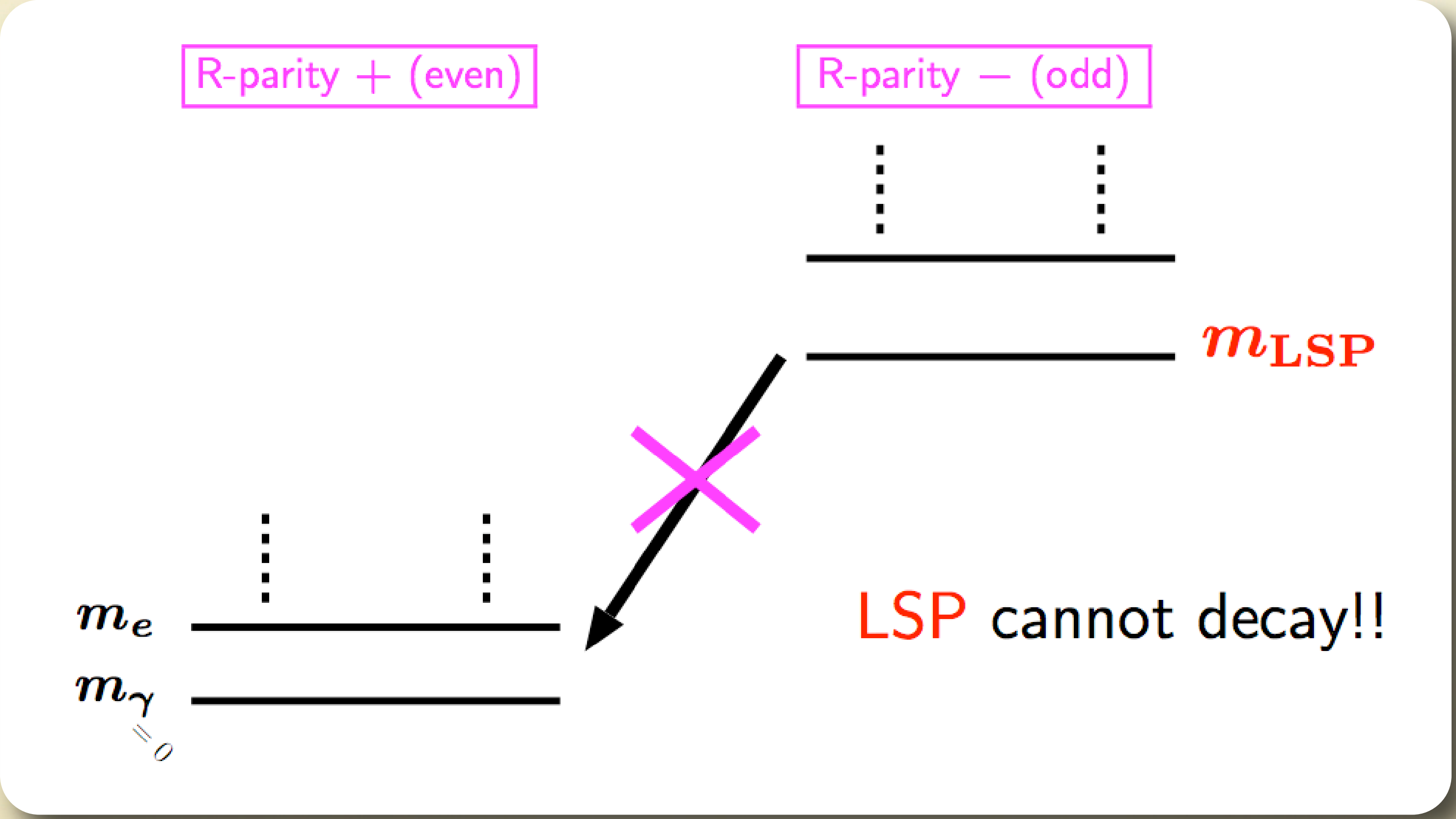
$$\text{gravitino}: \widetilde{G}$$

- Why Gravitino LSP ?

Dark Matter in SUSY

In SUSY models + R-parity,

LSP (=Lightest SUSY Particle) is stable.



→ If neutral, Dark Matter candidate!

- Why Gravitino LSP ?

Dark Matter candidates in SUSY Standard Model

In SUSY Standard Model in SUGRA,.....

squarks : $\begin{pmatrix} \widetilde{u_L} \\ \widetilde{d_L} \end{pmatrix}_i \quad \widetilde{u_{Ri}} \quad \widetilde{d_{Ri}}$

sleptons : $\begin{pmatrix} \widetilde{\nu_L} \\ \widetilde{e_L} \end{pmatrix}_i \quad \widetilde{e_{Ri}}$

gauginos and higgssinos : $\widetilde{\chi_i^0}, \quad \widetilde{\chi_i^\pm}, \quad \widetilde{g}$

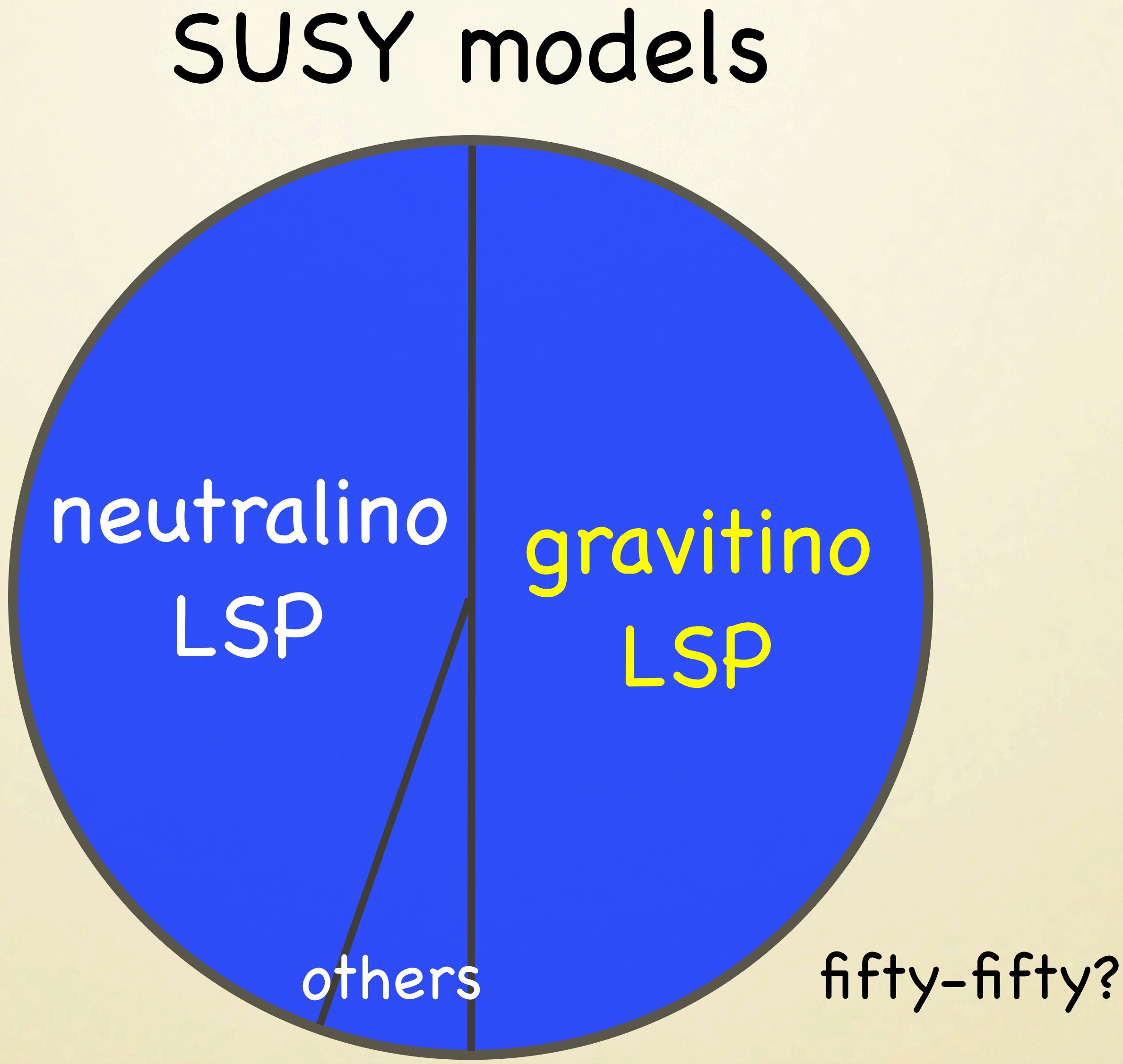
gravitino : $\widetilde{G}$

excluded by direct detection experiments (cf. Falk, Olive, Srednicki,'94)

neutral and color-singlet

Only Neutralino and Gravitino are viable candidates!

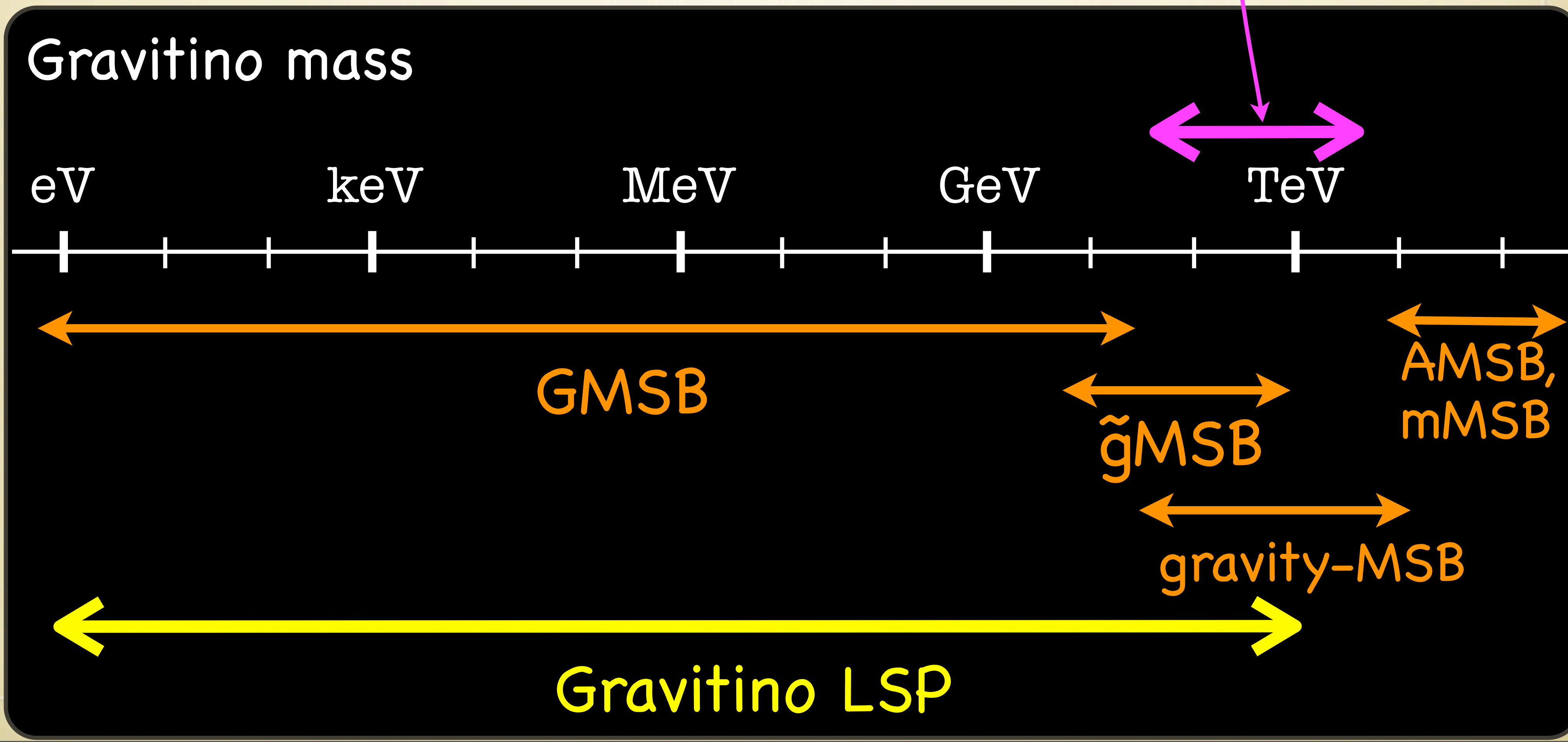
- まず、MSSM粒子＋gravitinoのうちDMになれるのは



- Why Gravitino LSP ?

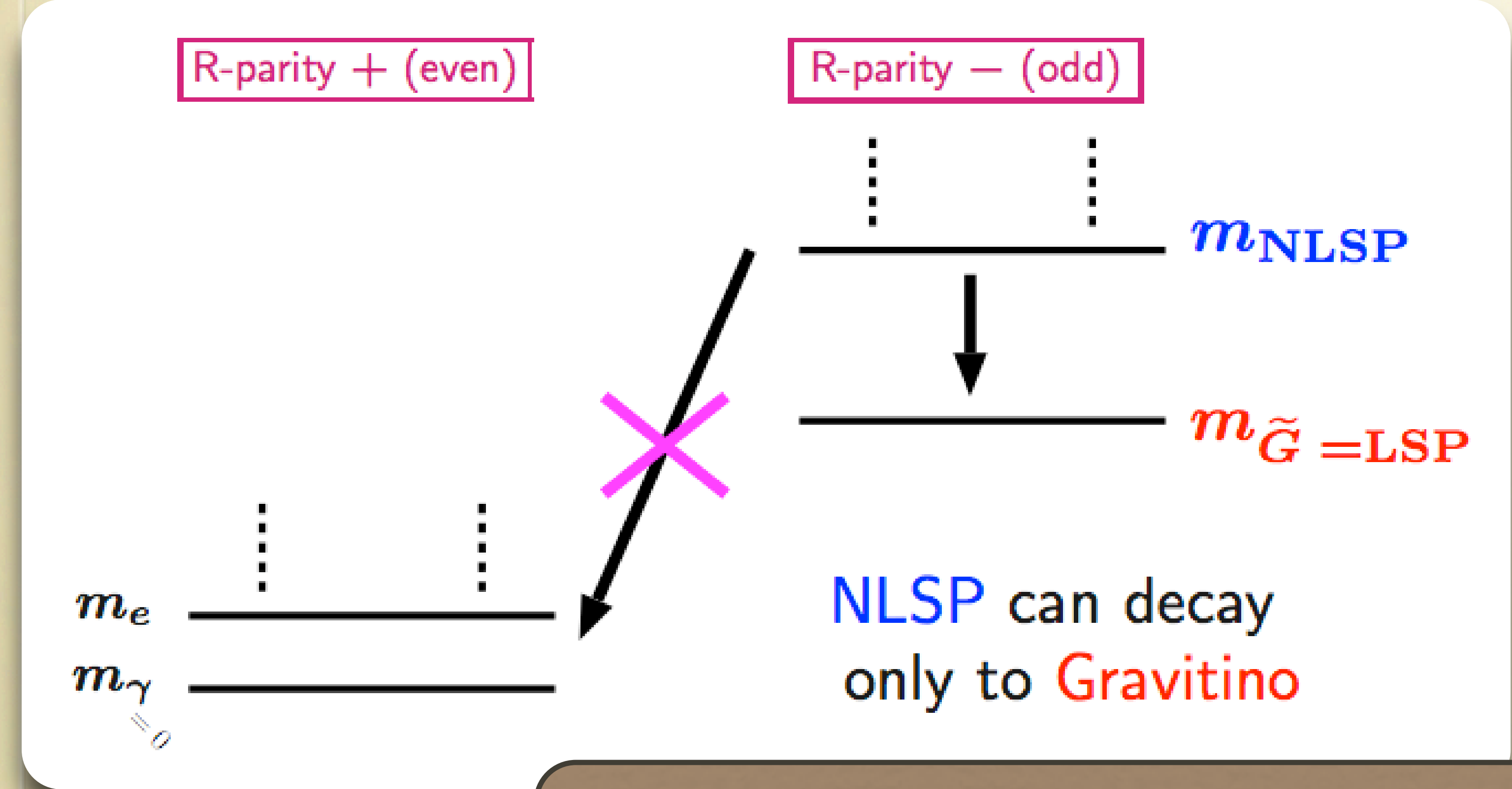
experimental bound naturalness

- Other SUSY particle masses = O(100 GeV)-O(1 TeV)
- Gravitino mass..... model dependent.



NLSP (Next-to-Lightest SUSY Particle)

In Gravitino LSP scenario, the NLSP is long-lived.



extremely weak interaction

Lifetime e.g. for $m_{\rm NLSP} \simeq 200$ GeV

$$\tau_{\rm NLSP} \sim \mathcal{O}(\text{day}) \quad \text{for} \quad m_{\tilde G} \sim 10\ \text{GeV}$$
$$\tau_{\rm NLSP} \sim \mathcal{O}(10\ \text{min}) \quad \text{for} \quad m_{\tilde G} \sim 1\ \text{GeV}$$
$$\tau_{\rm NLSP} \sim \mathcal{O}(10\ \text{sec}) \quad \text{for} \quad m_{\tilde G} \sim 0.1\ \text{GeV}$$

- Why Stau NLSP ?

- ..... among 28 NLSP candidates?

squarks : $\begin{pmatrix} \widetilde{u_L} \\ \widetilde{d_L} \end{pmatrix}_i \quad \widetilde{u_{Ri}} \quad \widetilde{d_{Ri}}$ sleptons : $\begin{pmatrix} \widetilde{\nu_L} \\ \widetilde{e_L} \end{pmatrix}_i \quad \widetilde{e_{Ri}}$

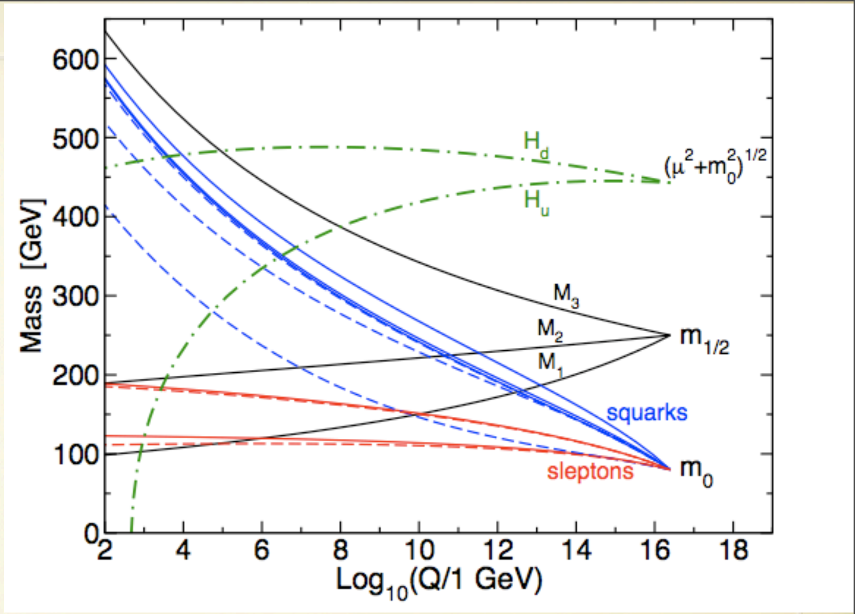
gauginos and higgssinos : $\widetilde{\chi_i^0}, \quad \widetilde{\chi_i^{\pm}}, \quad \tilde{g}$

gravitino : $\widetilde{G}$

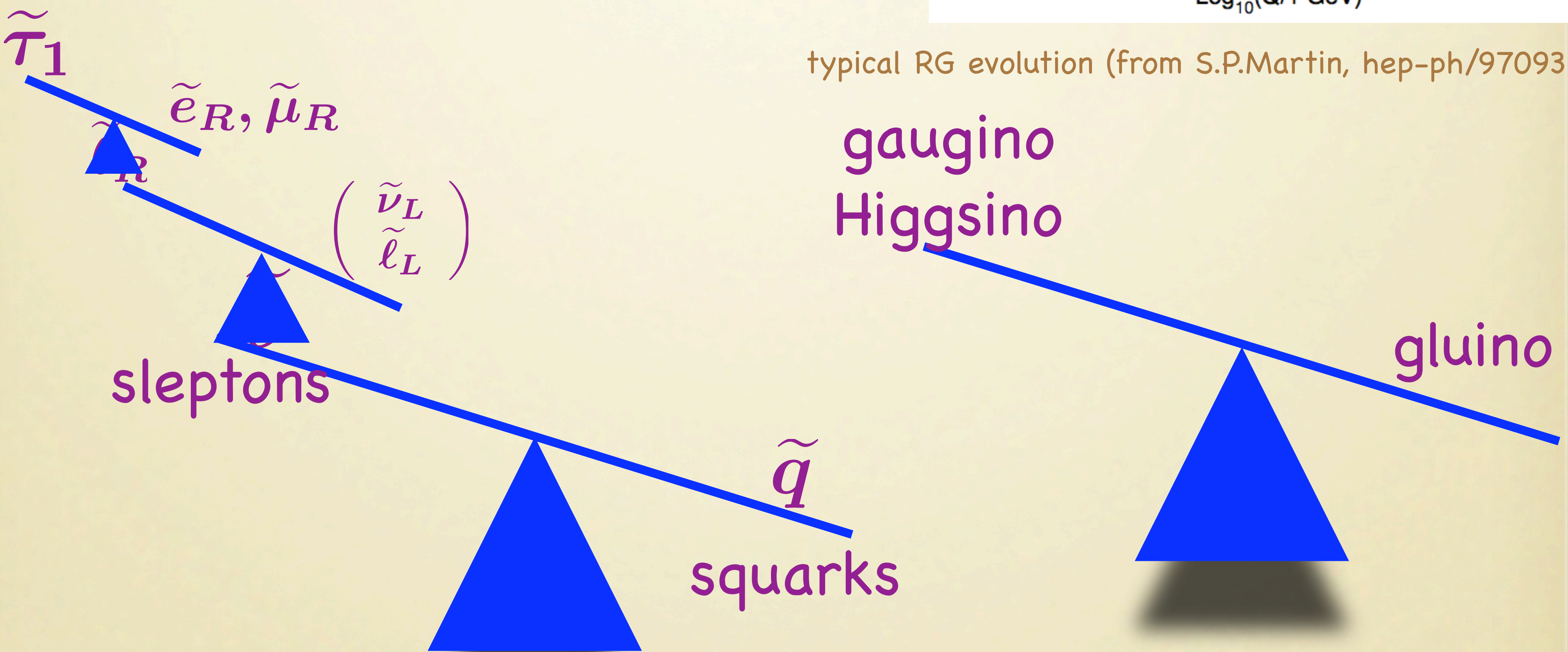
stau (i=3)

- # Why Stau NLSP ?

- In general, from RGE, tendency is
  - M(color singlet) < M(colored)
  - M(weak singlet) < M(weak charged)
  - M(3rd family) < M(1st and 2nd family)

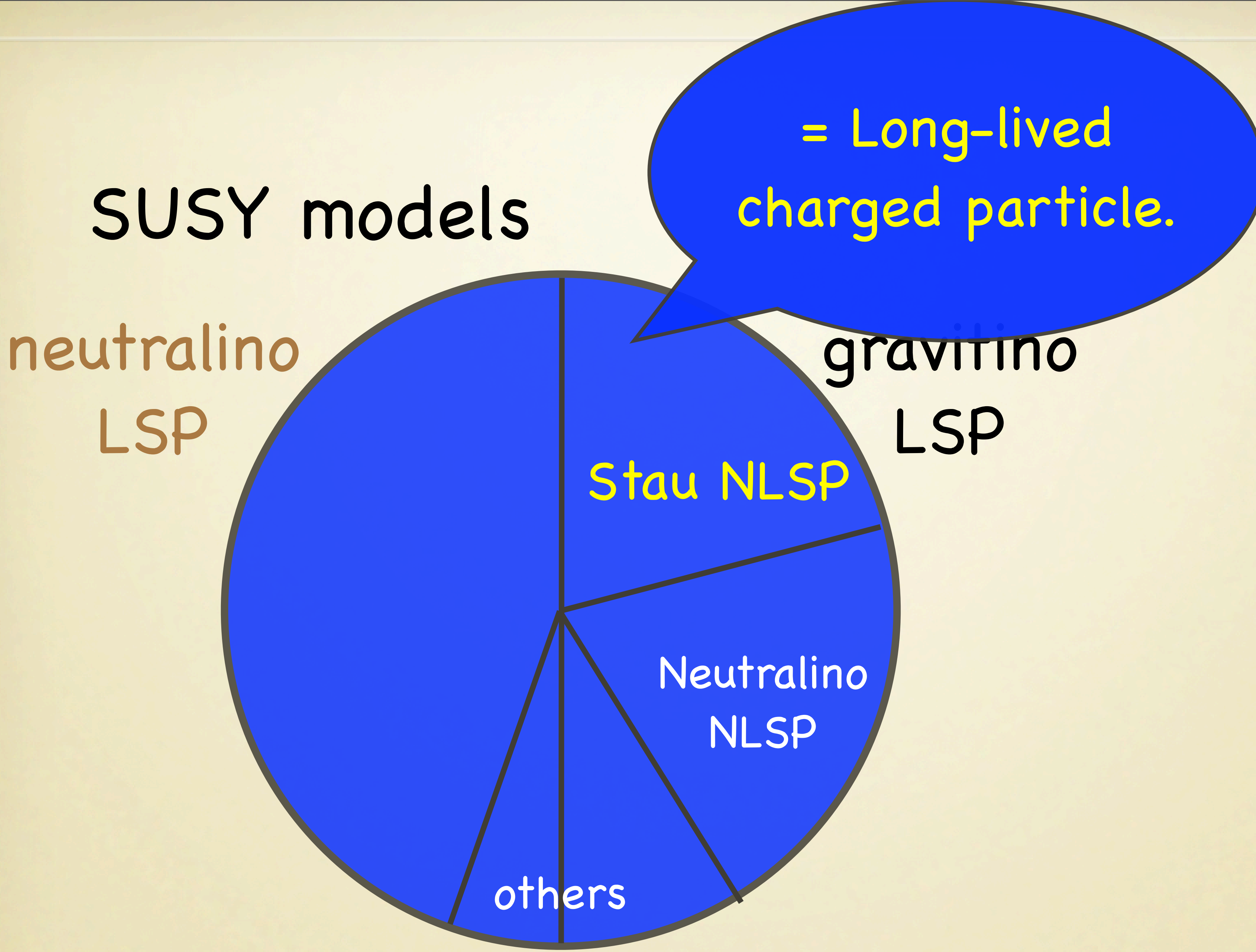


typical RG evolution (from S.P.Martin, hep-ph/9709356)



- In most cases, either Stau or Neutralino is the NLSP

SUSY models



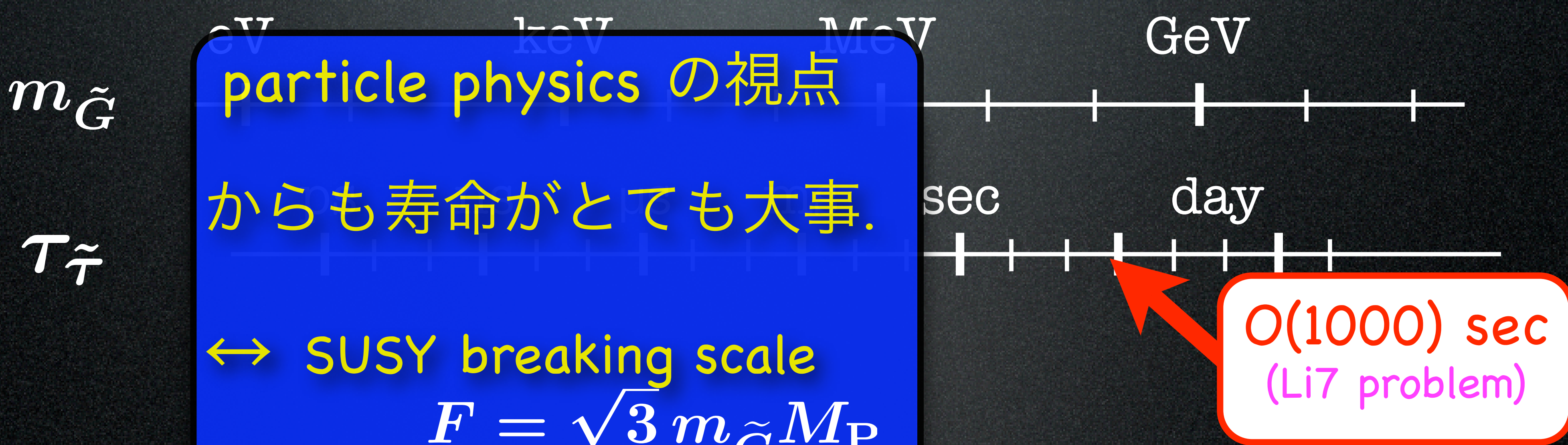
- Gravitino LSP and Stau NLSP is a natural choice.

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 of NLSP stau

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



particle physics の視点

からも寿命がとても大事.

↔ SUSY breaking scale

$$F = \sqrt{3}\, m_{\tilde{G}} M_{\rm P}$$

↔ gravitino mass

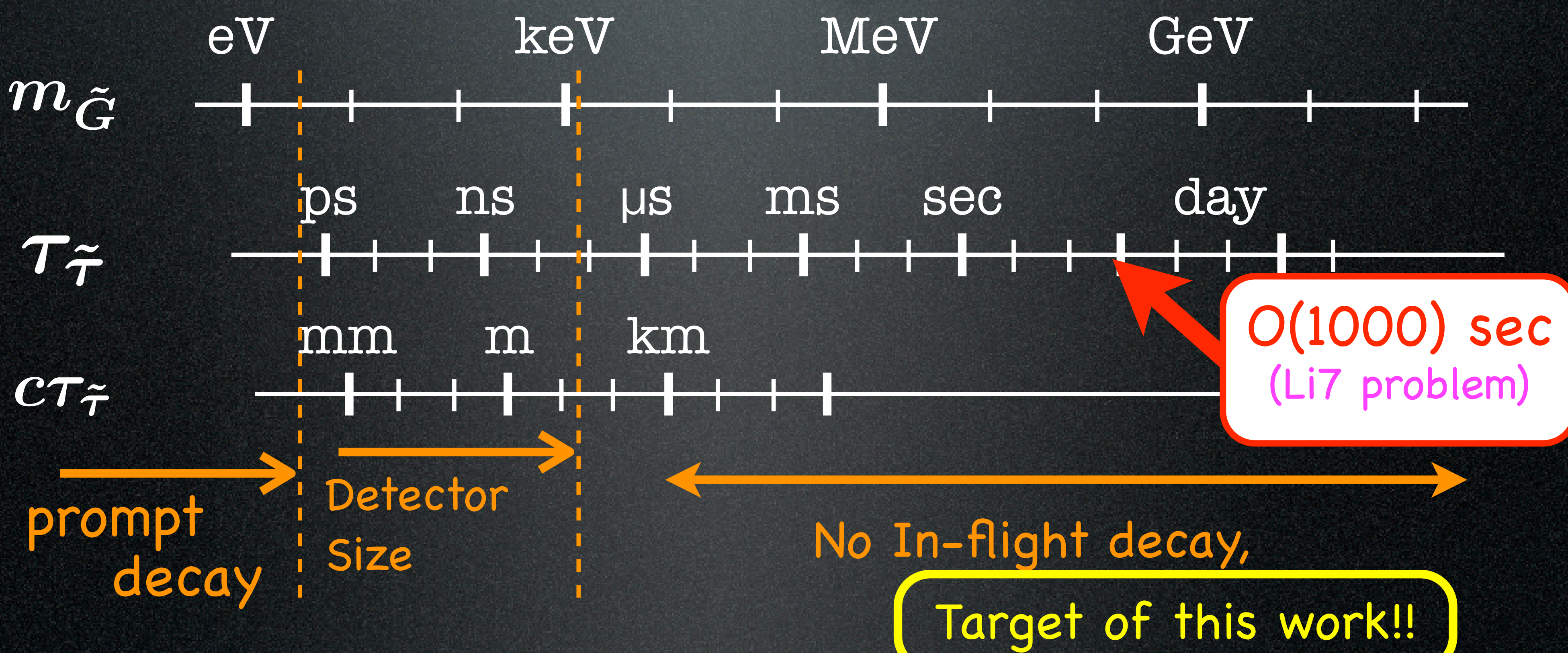
$$m_{\tilde{G}}$$

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 $m_{\tilde{\tau}} = 100\ \mathrm{GeV}$,



Side Remark

Planck scale measurement

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