# Dark matter and missing energy – what is there apart from SUSY?

Koichi Hamaguchi (Tokyo U.)

at LHC New Physics Forum, Heidelberg, February '09

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# long-lived charged particle

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based on...

S.Asai, KH, S.Shirai, arXiv:0902.3754 ☛ today!!

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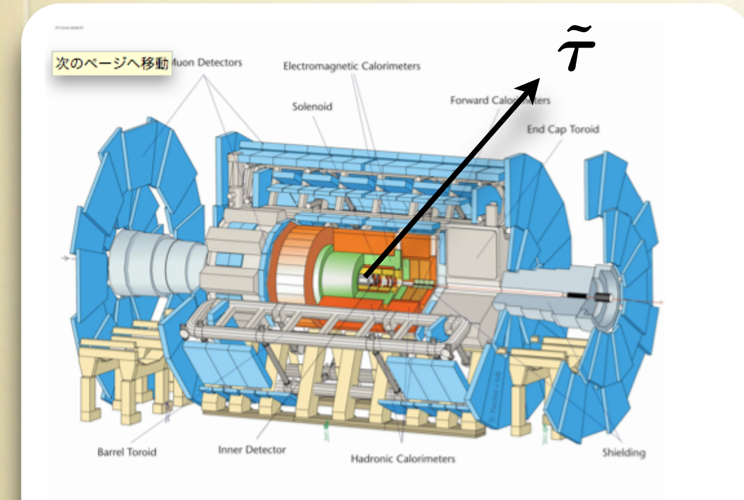
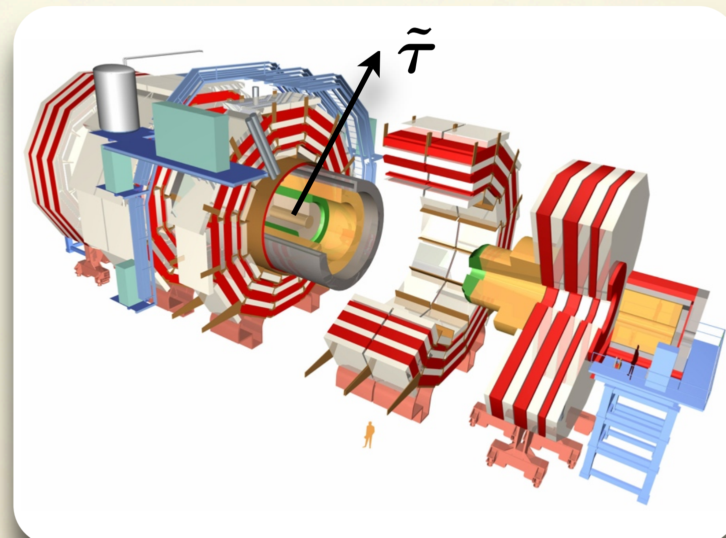


Figure 1-i Overall layout of the ATLAS detector.

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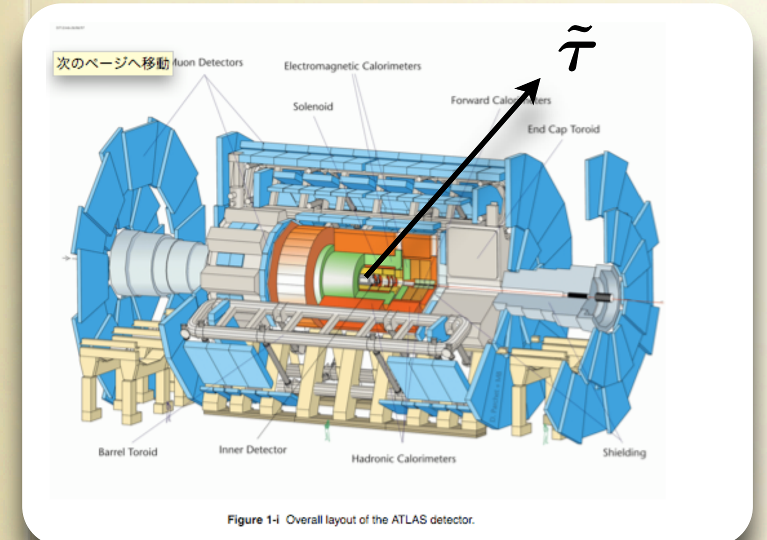

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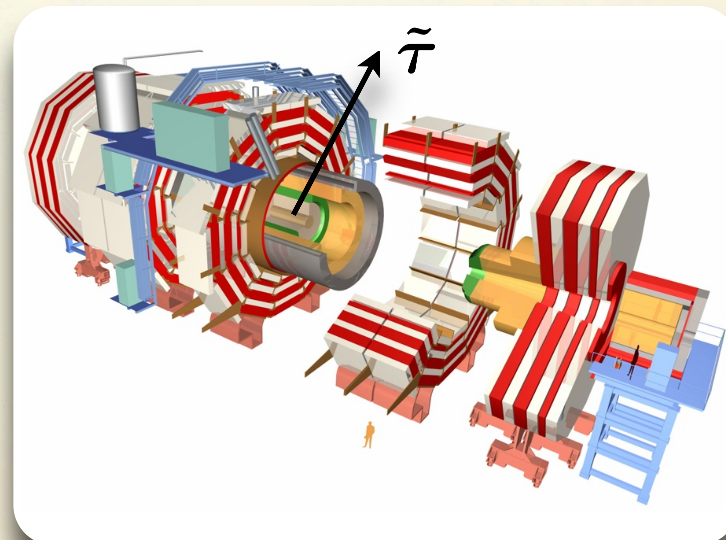


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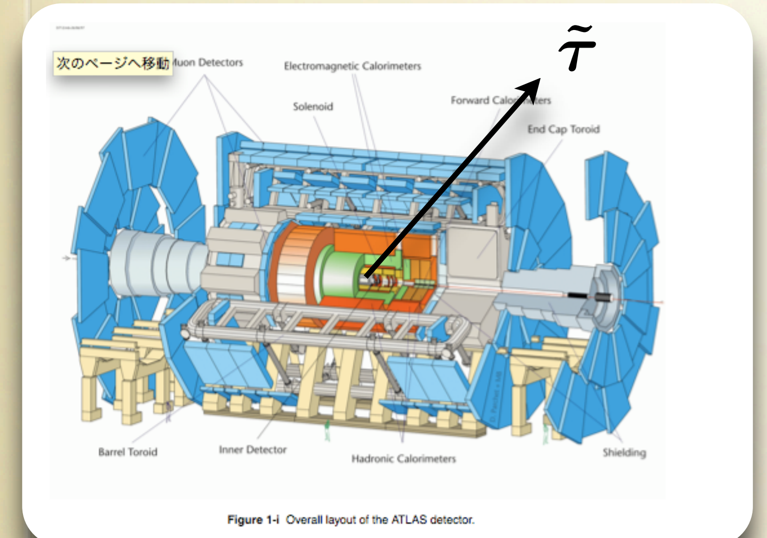

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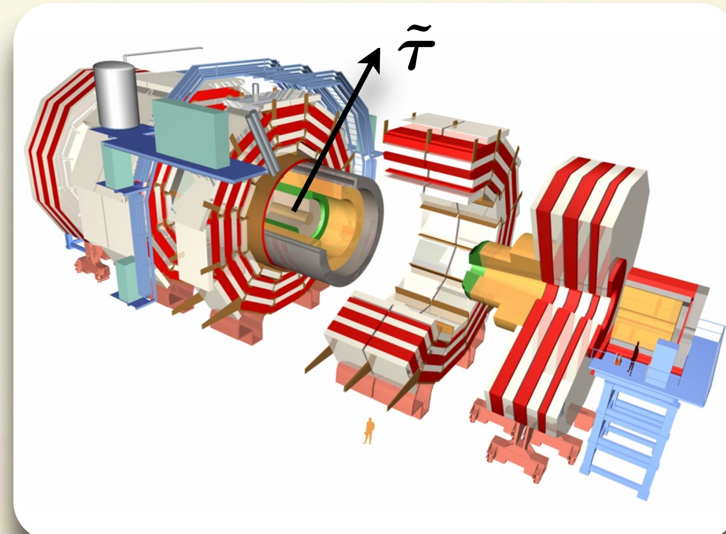


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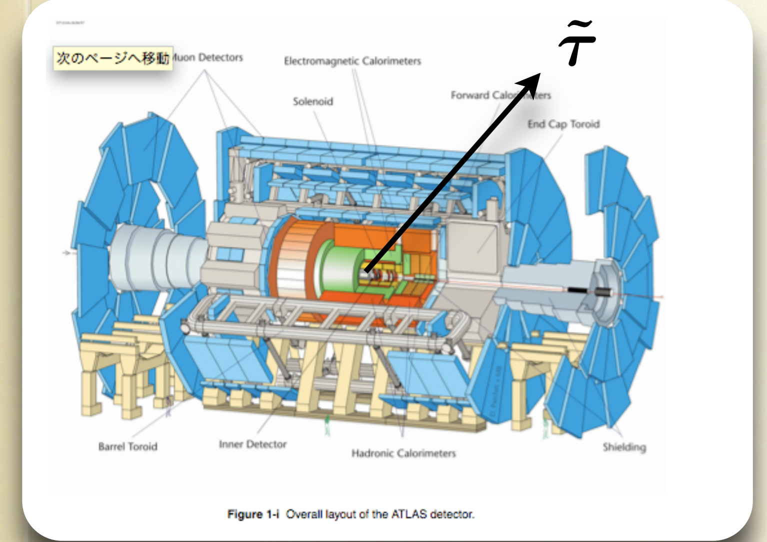

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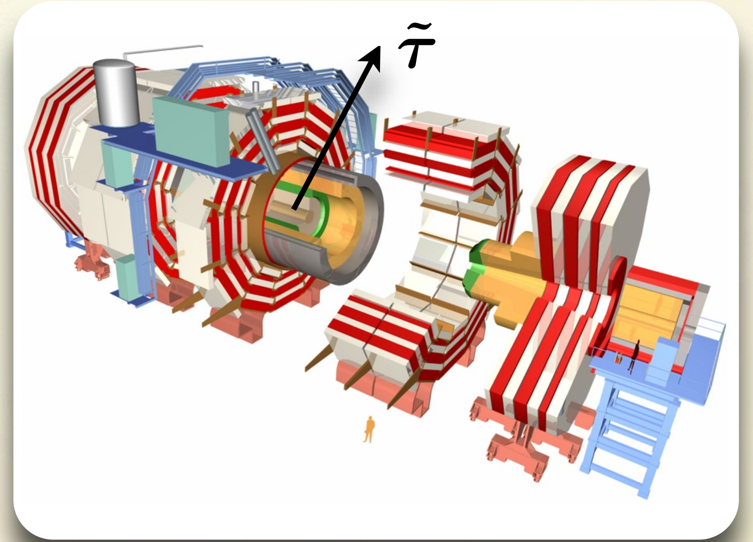


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this talk

before presenting our proposal,...

# Motivation

--- why long-lived charged particle??

--- why its lifetime is so important??

before presenting our proposal,...

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(1) Li7 problem in Big-Bang Nucleosynthesis (☚ model independent)

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(2) SUSY models with gravitino LSP

# Motivation

(1) Li7 problem in Big-Bang Nucleosynthesis (☛ model independent)

## thermal history

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

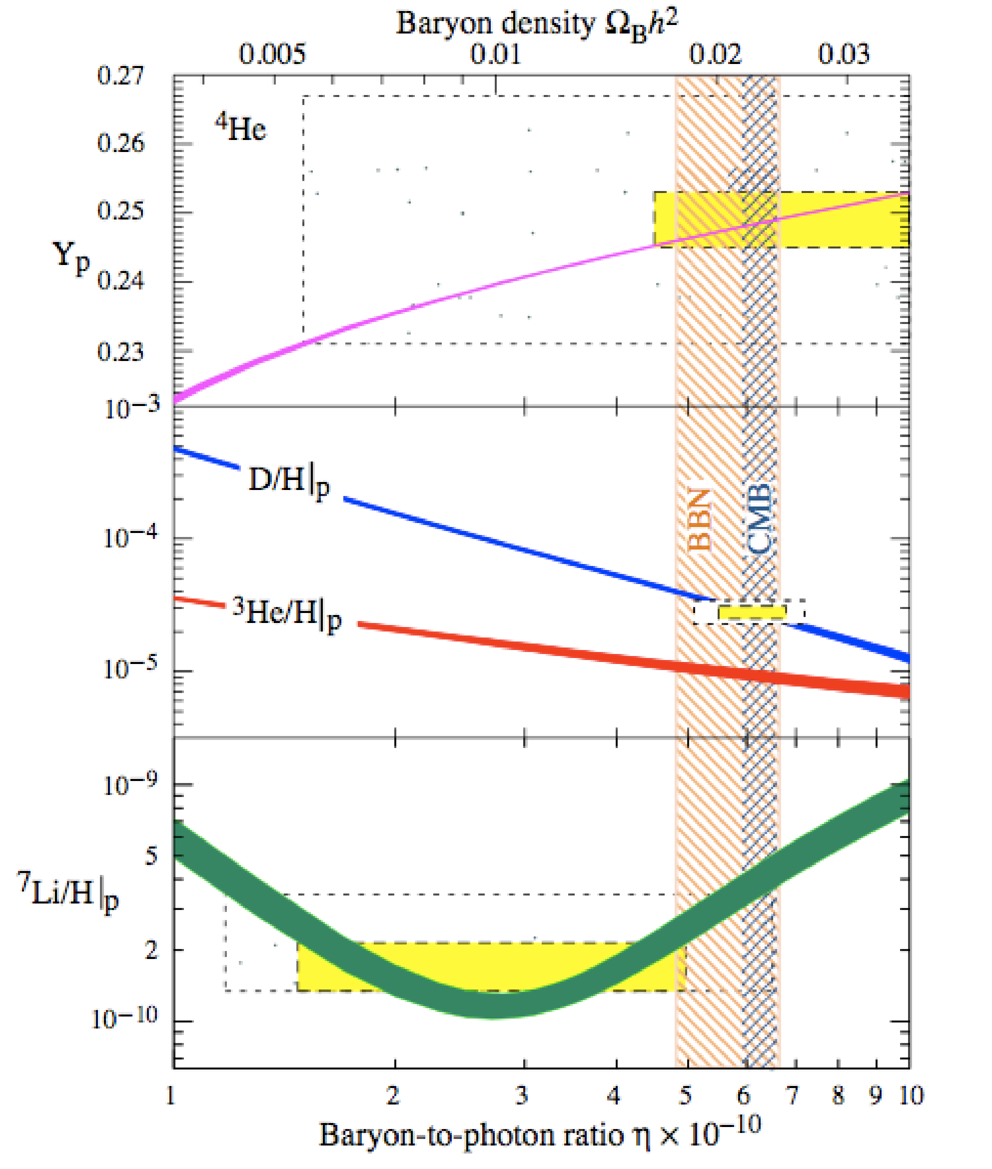


Fig. from Review of Particle Physics

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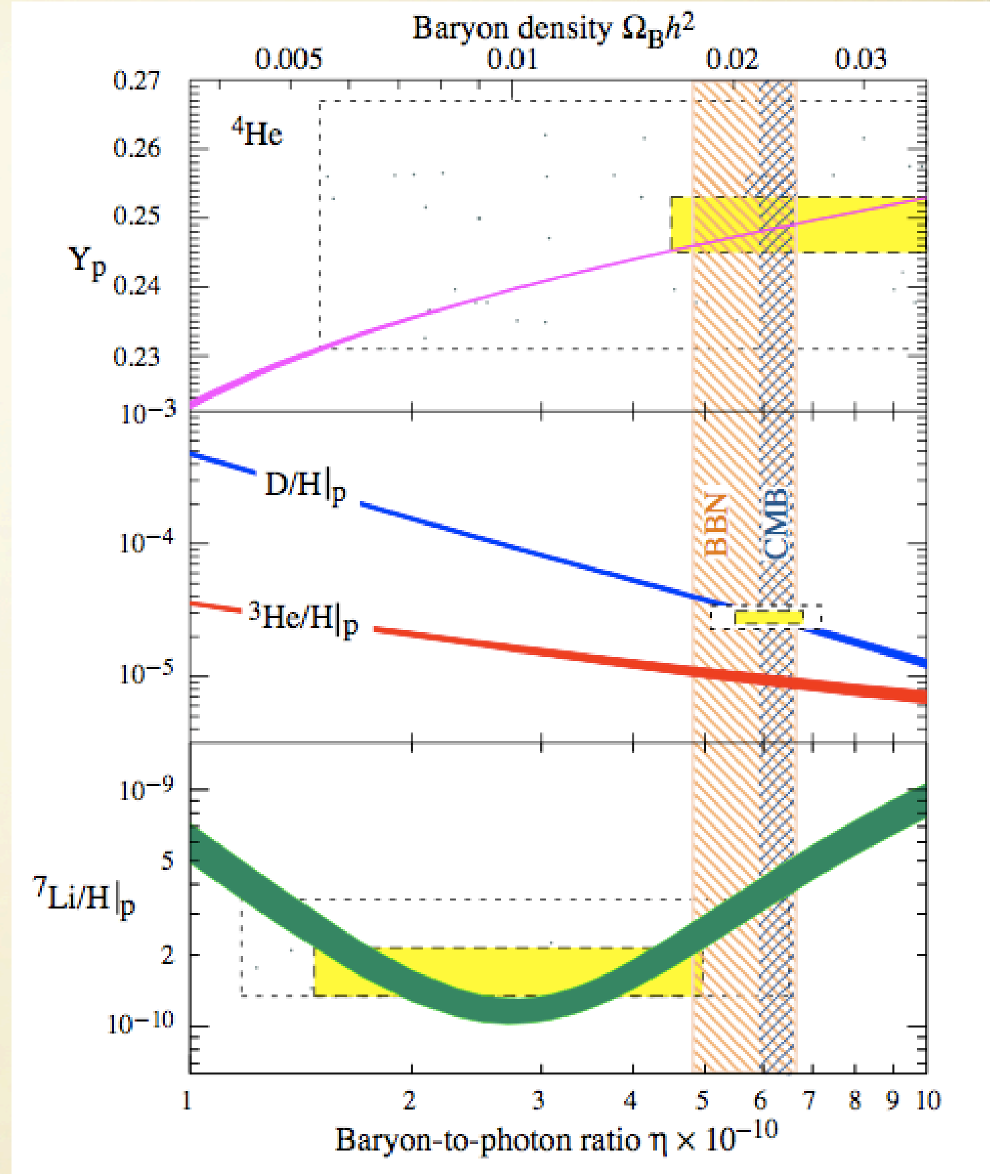


If there is a long-lived charged particle.... → affects the BBN!!

1. decay's effect
2. catalysis effect

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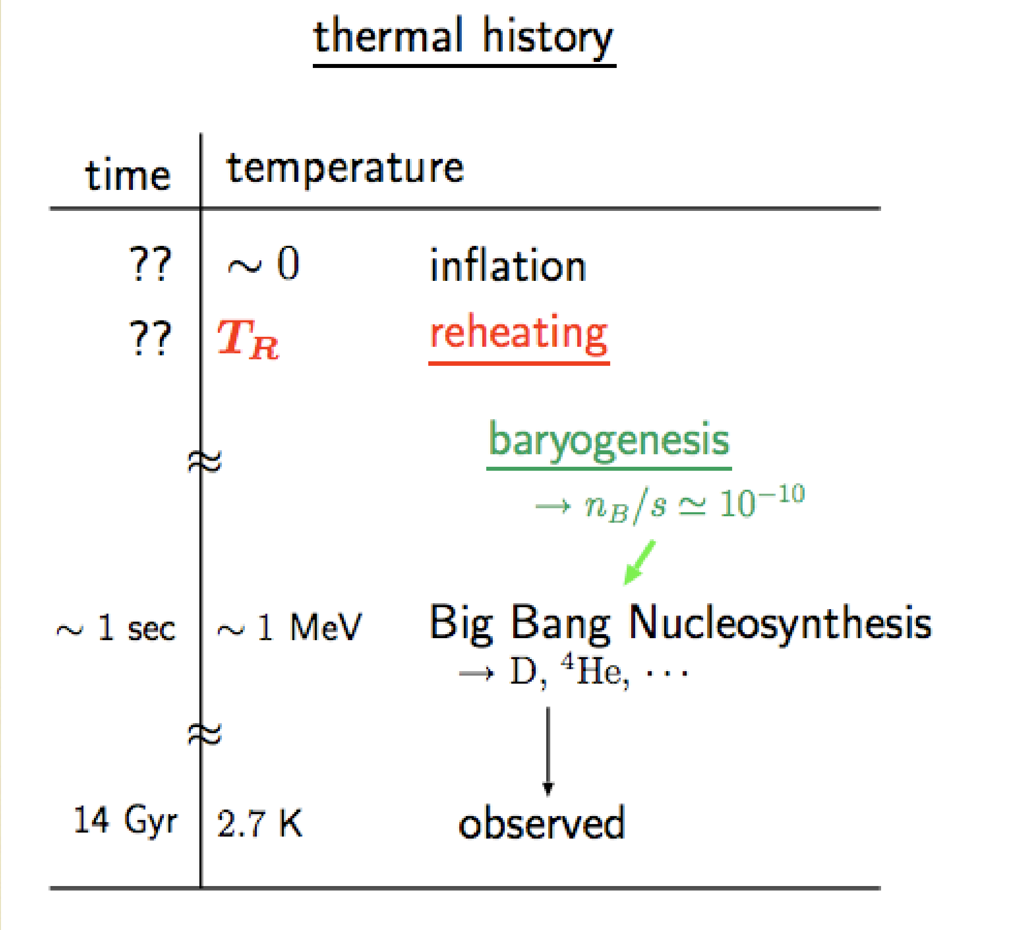


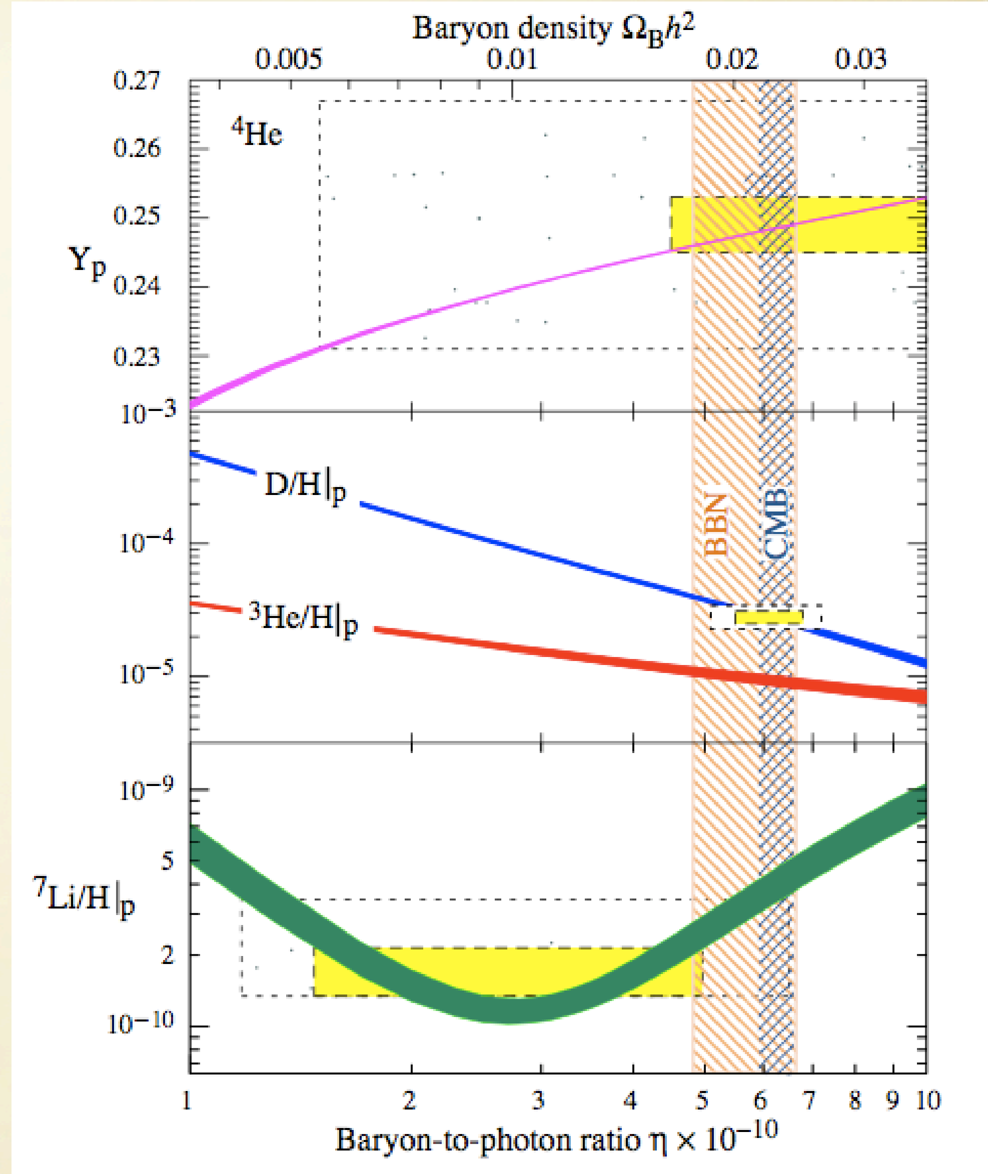


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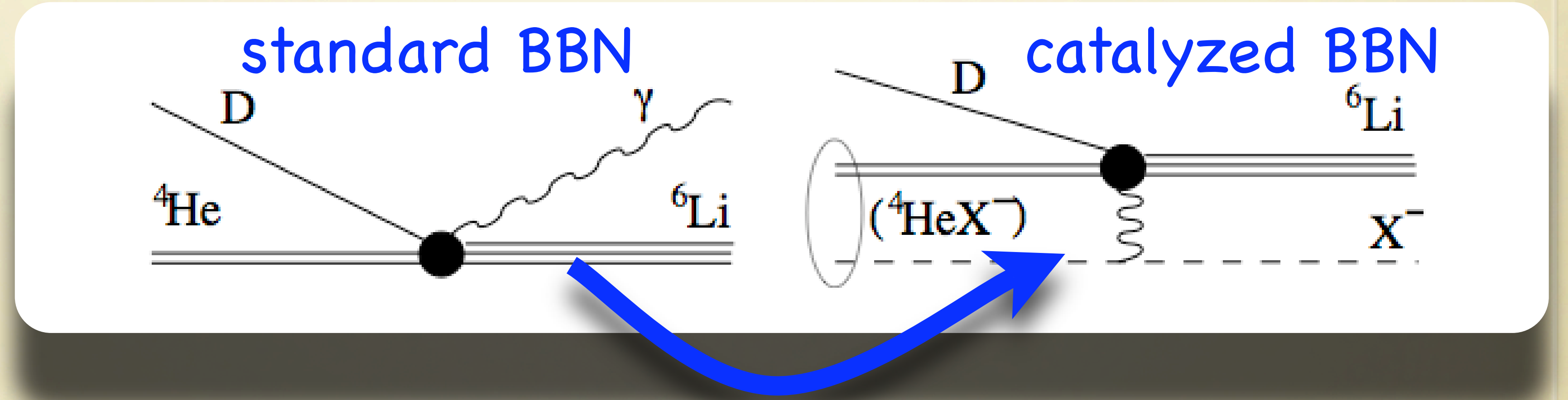


$O(10^9)$ enhancement !!!
→ too much Li6 !!!

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

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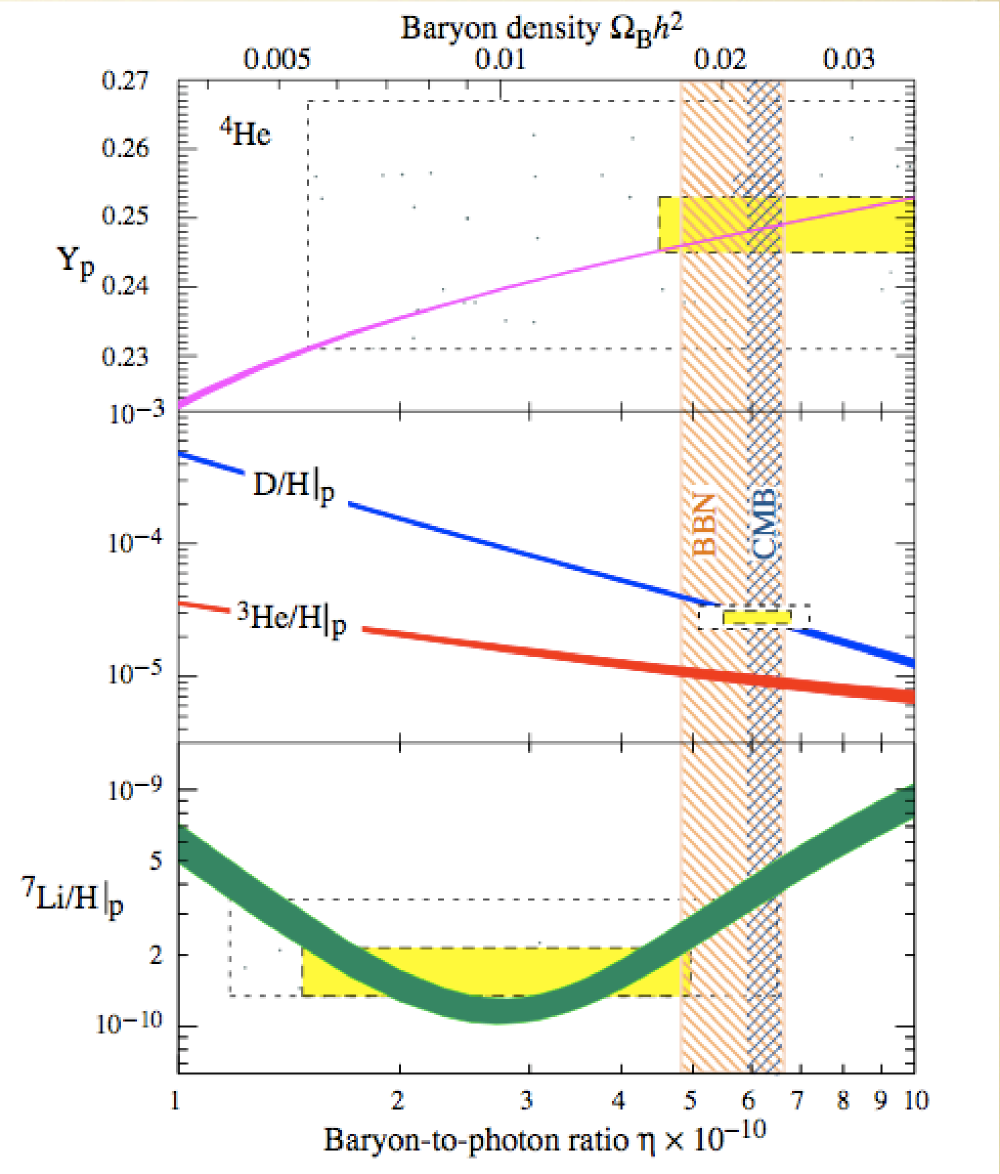


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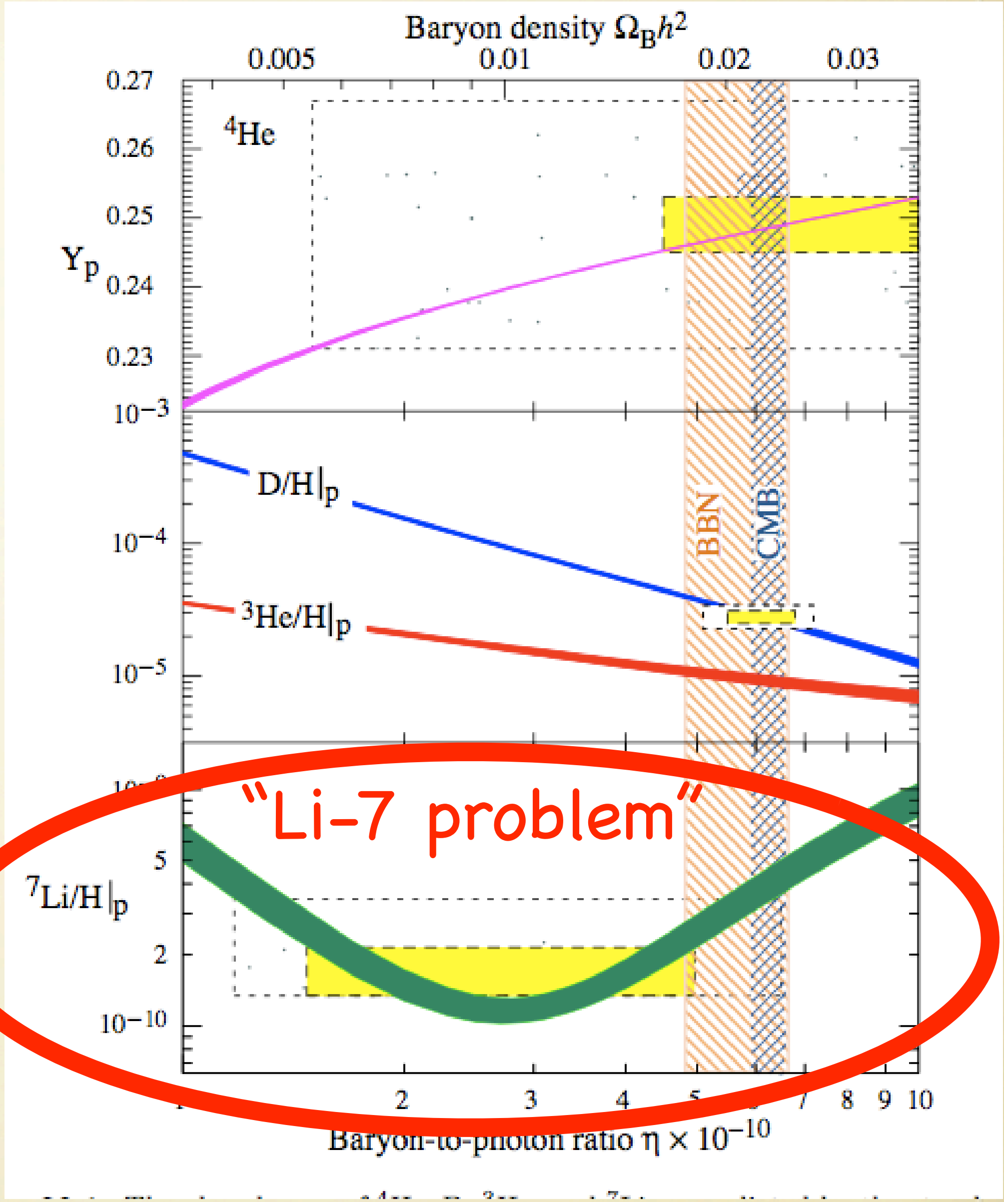


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recently, reanalyzed by
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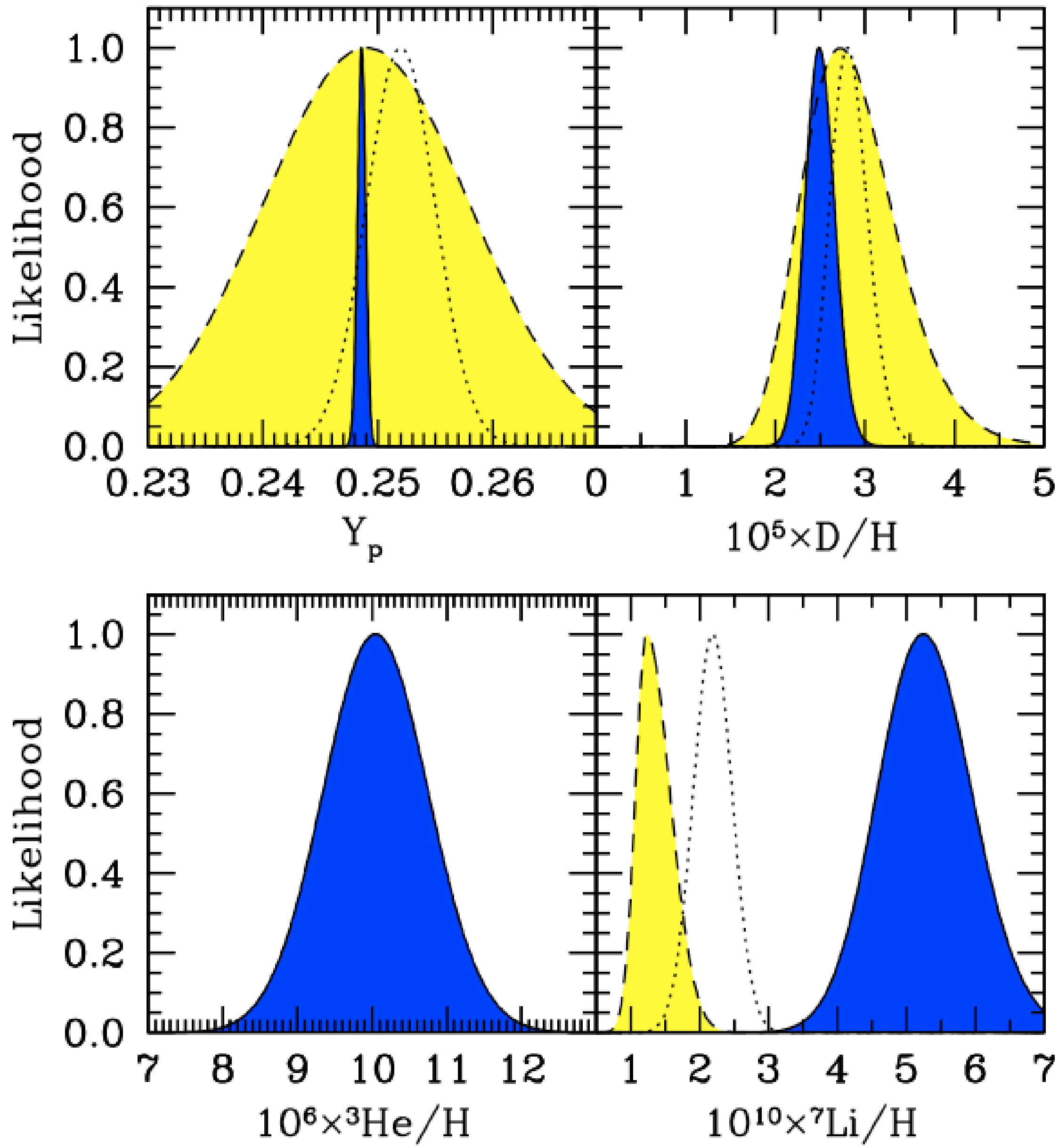


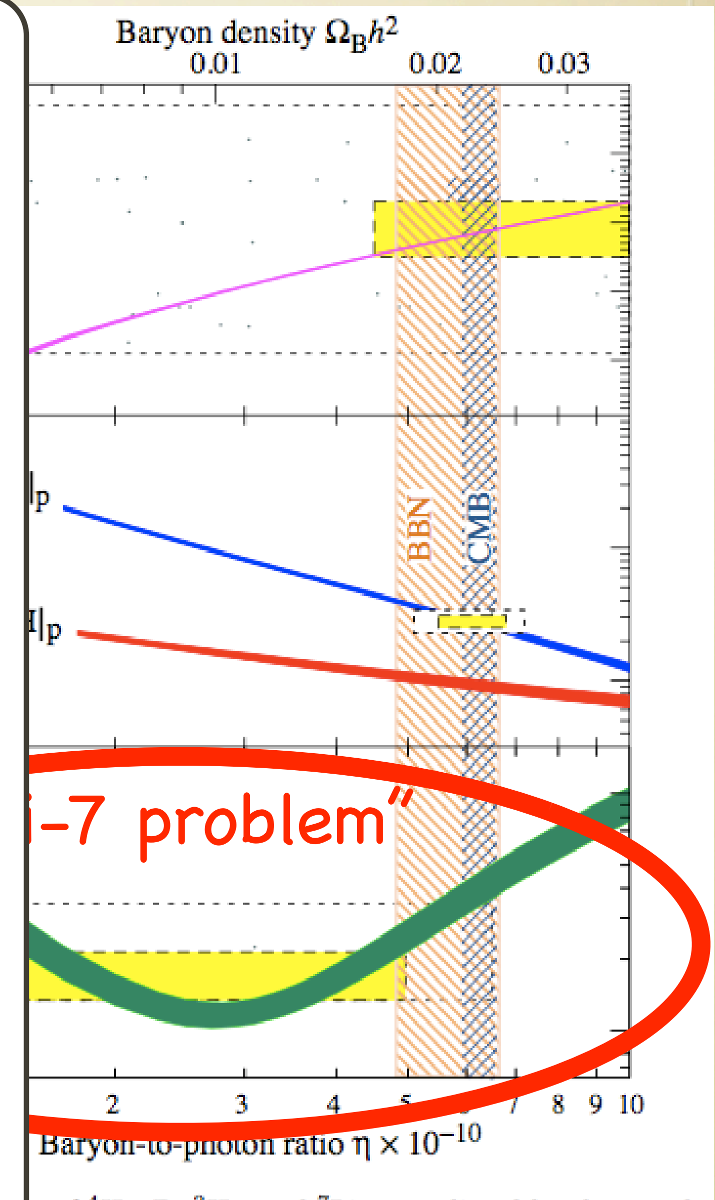


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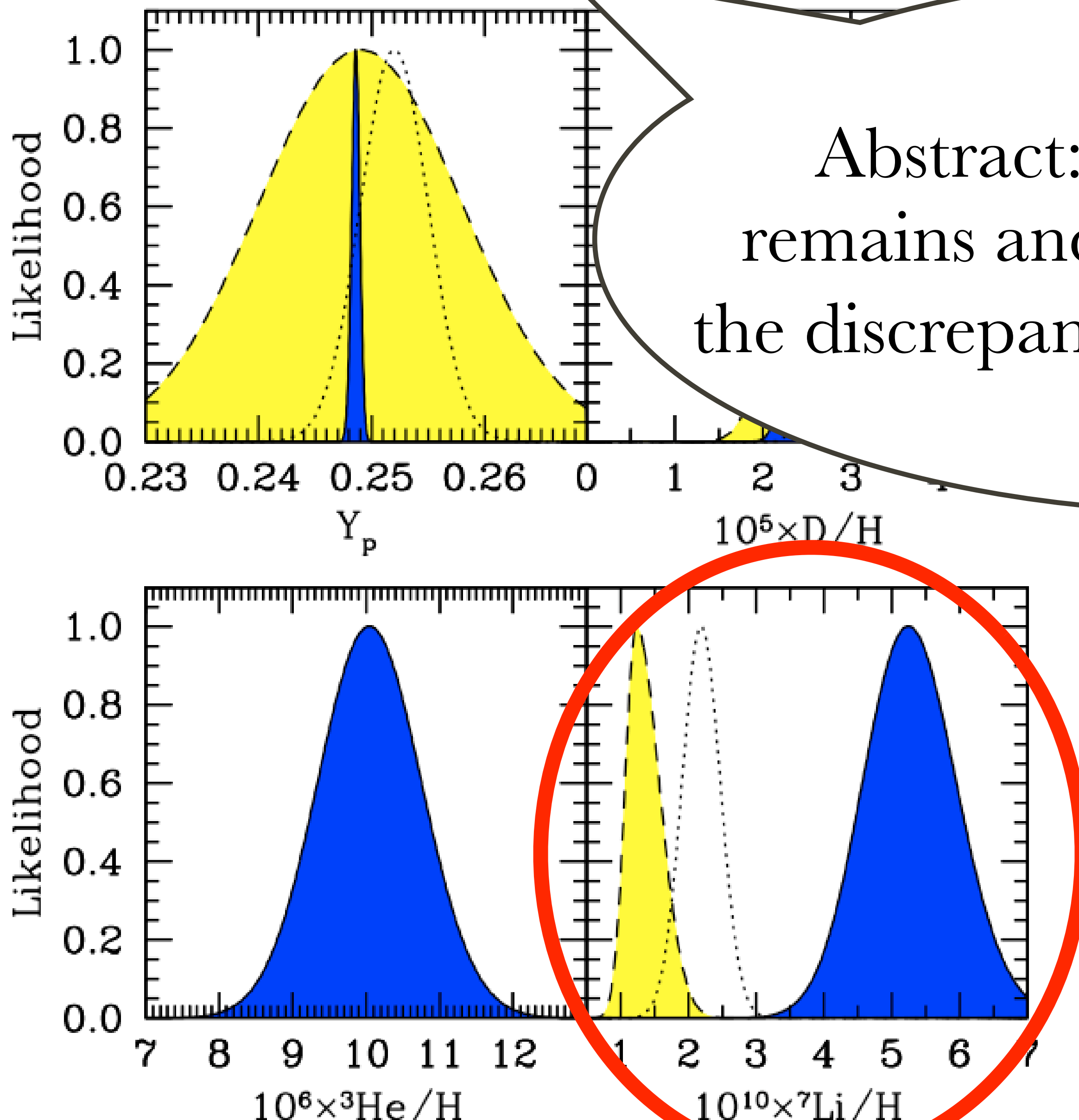
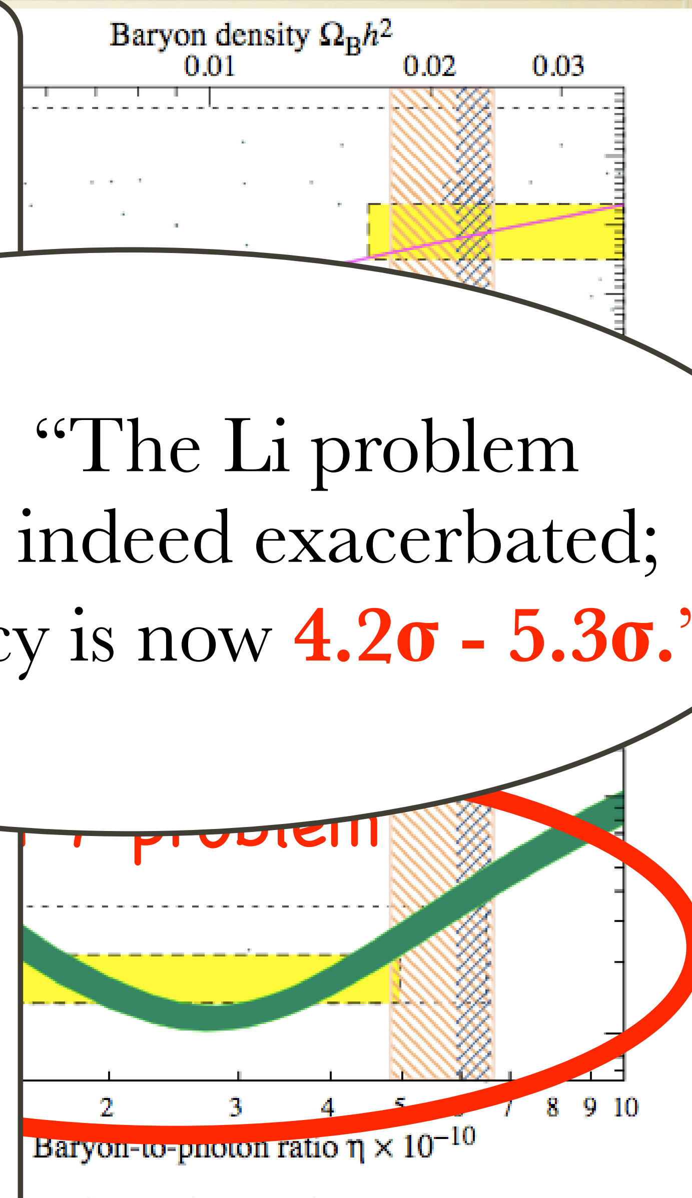



Abstract: "The Li problem remains and indeed exacerbated; the discrepancy is now **4.2σ - 5.3σ.**"



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

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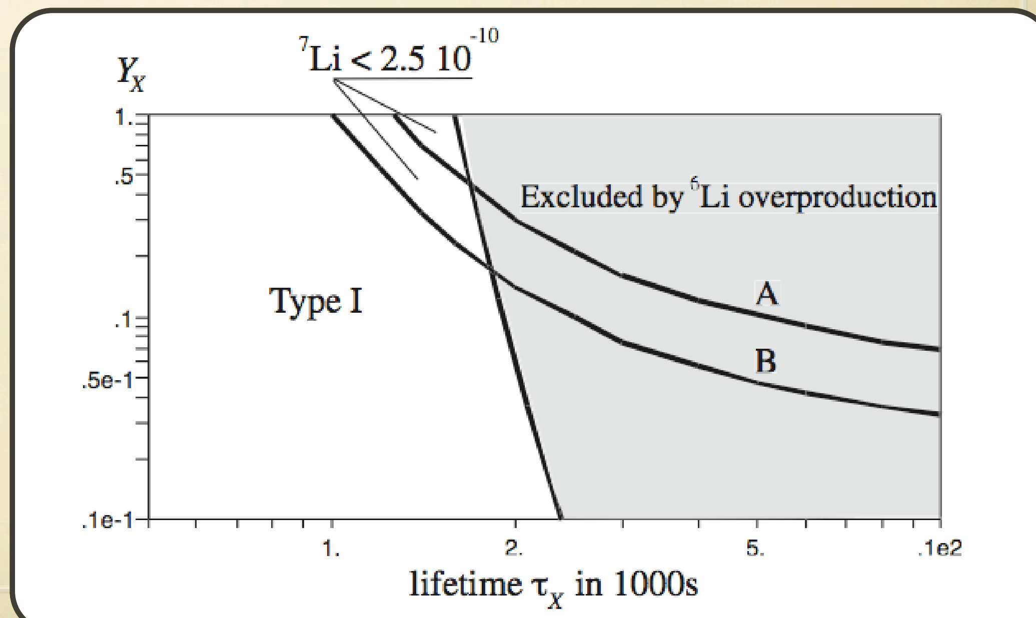

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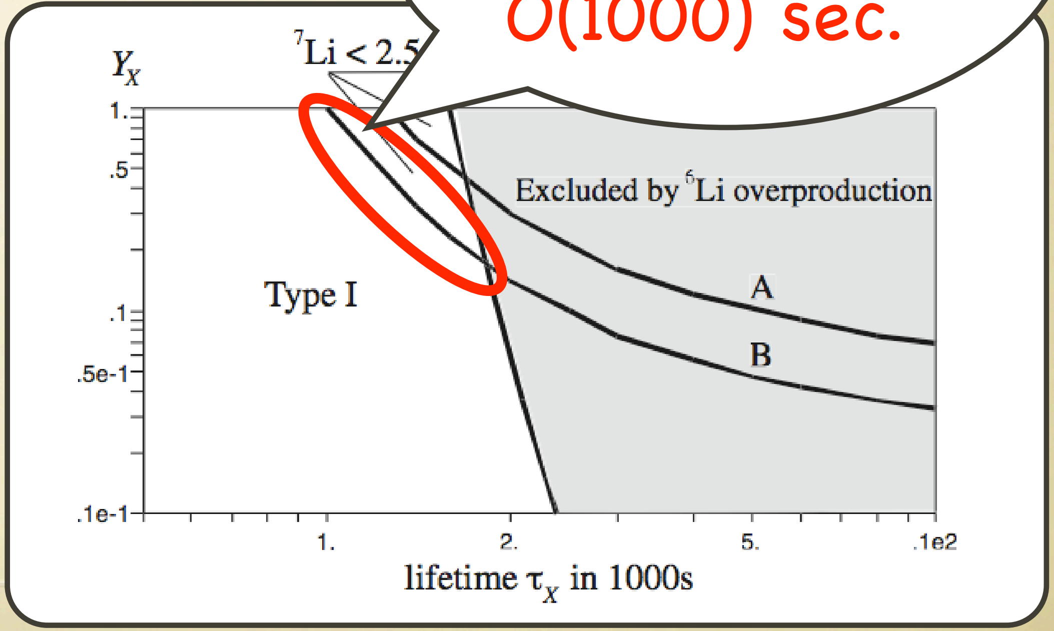

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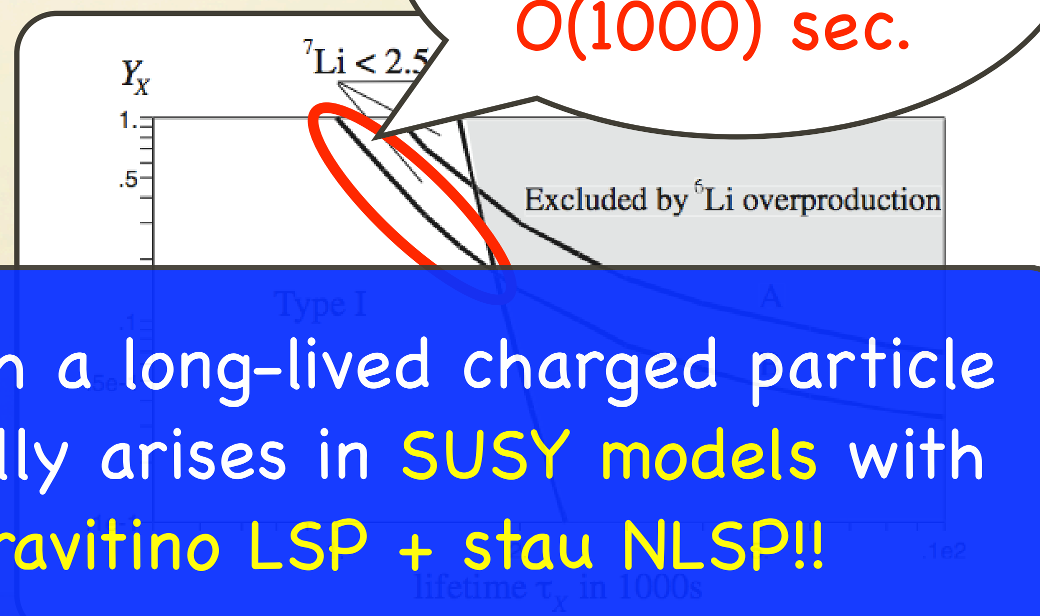


..... if
X lifetime is
O(1000) sec.

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

# Motivation

(2) SUSY models with gravitino LSP

- What is Gravitino?

**Supersymmetry (SUSY)**

| | | **spin** | | |
|---|---|---|---|---|
| quarks $q$ | $\frac{1}{2}$ | $\longleftrightarrow$ | $0$ | squarks $\tilde{q}$ |
| leptons $\ell$ | $\frac{1}{2}$ | $\longleftrightarrow$ | $0$ | sleptons $\tilde{\ell}$ |
| gauge bosons $A_\mu$ | $1$ | $\longleftrightarrow$ | $\frac{1}{2}$ | gauginos $\lambda$ |
| Higgs bosons $H$ | $0$ | $\longleftrightarrow$ | $\frac{1}{2}$ | higgsinos $\tilde{h}$ |

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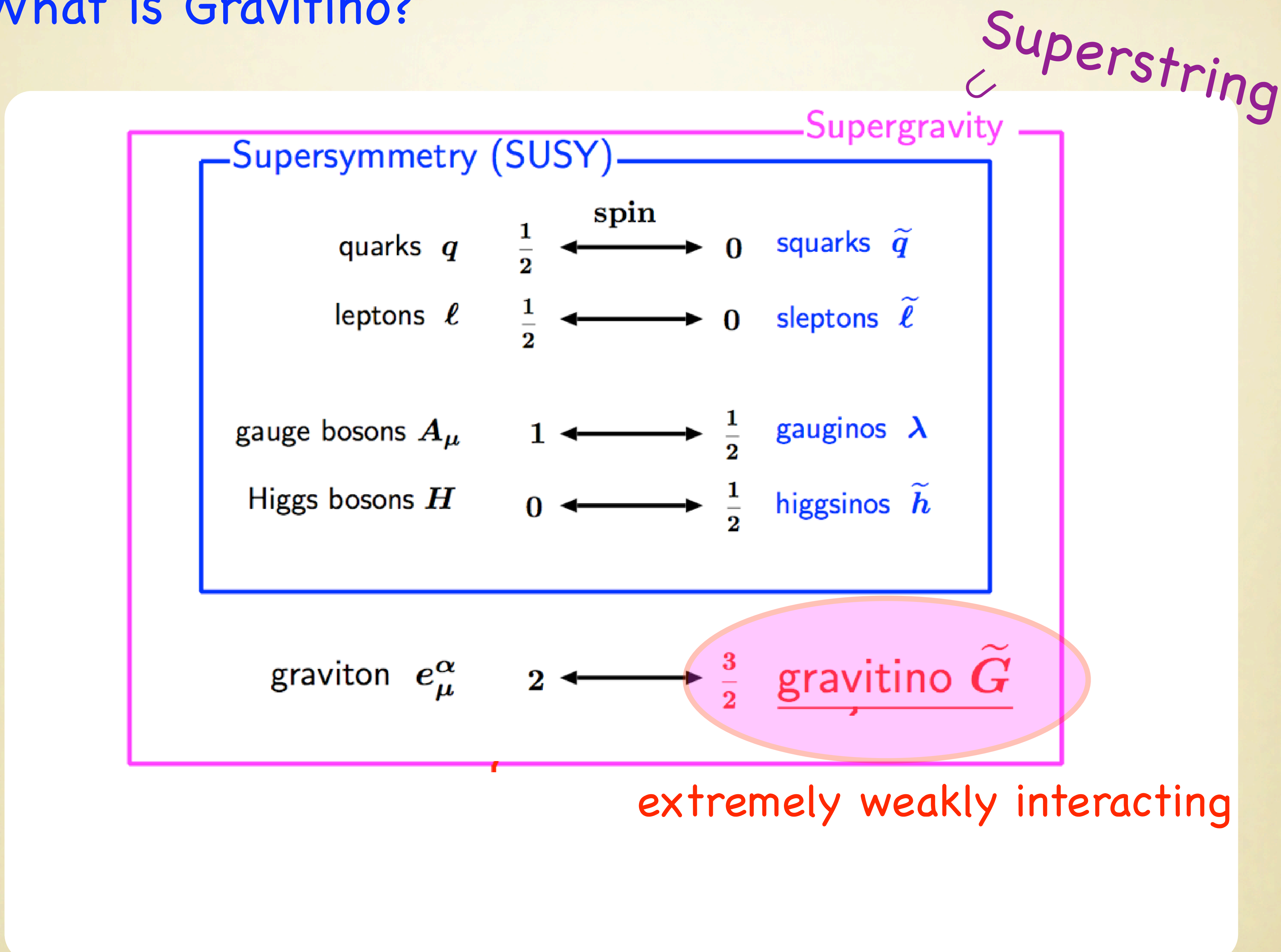
graviton $e_\mu^\alpha$

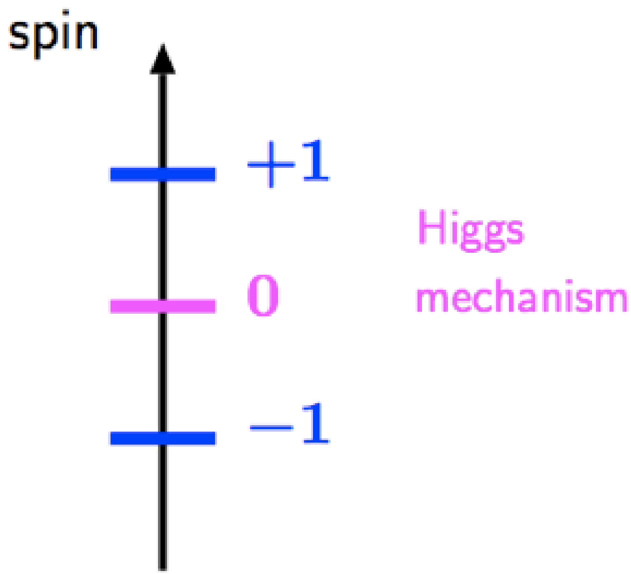
- What is Gravitino?



# Compare it with Electroweak Symmetry

Electroweak symmetry

→ spontaneously broken




## $Z, W$ bosons

→ discovered in 1983

→ establish Standard Model

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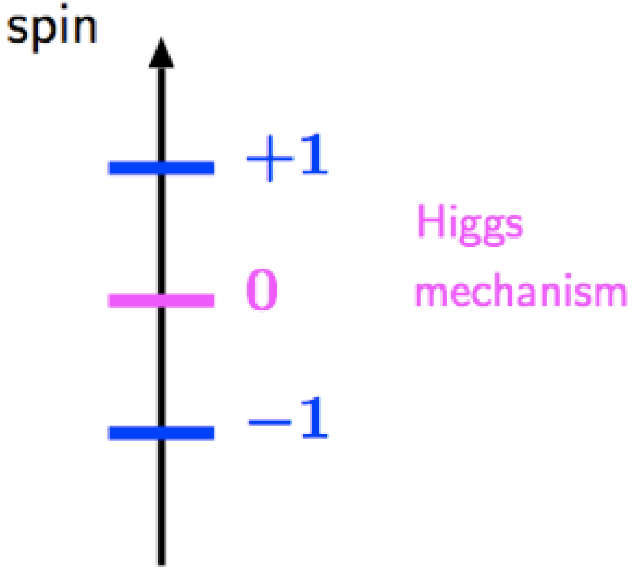


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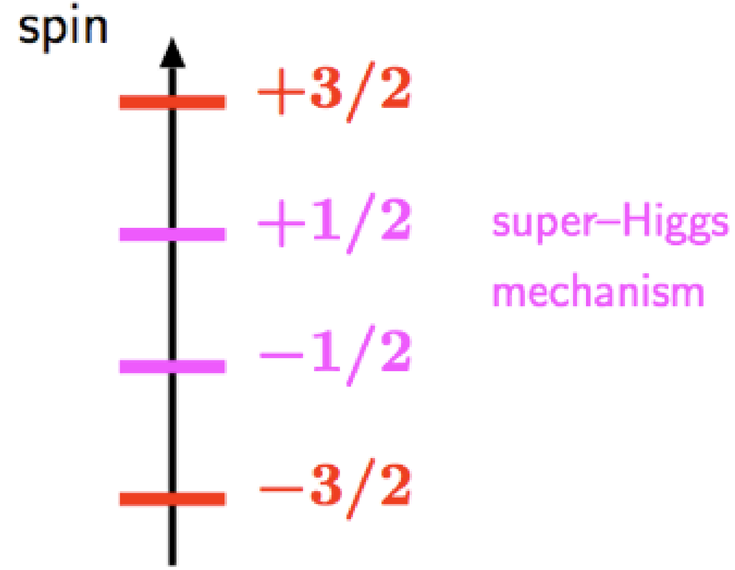



**Gravitino**

$\longrightarrow$ discovered in 20XX (?!)
$\longrightarrow$ establish **Supergravity** !!

# Compare it with Electroweak Symmetry

Electroweak symmetry
$\rightarrow$ spontaneously broken

Supergravity
$\rightarrow$ spontaneously broken

**gauge boson mass**

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

gauge coupling

Higgs VEV

**gravitino mass**

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

SUGRA coupling

SUSY breaking VEV

- Why Gravitino LSP ?

- Why Gravitino LSP ?

- ..... among 29 SUSY particles?

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

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

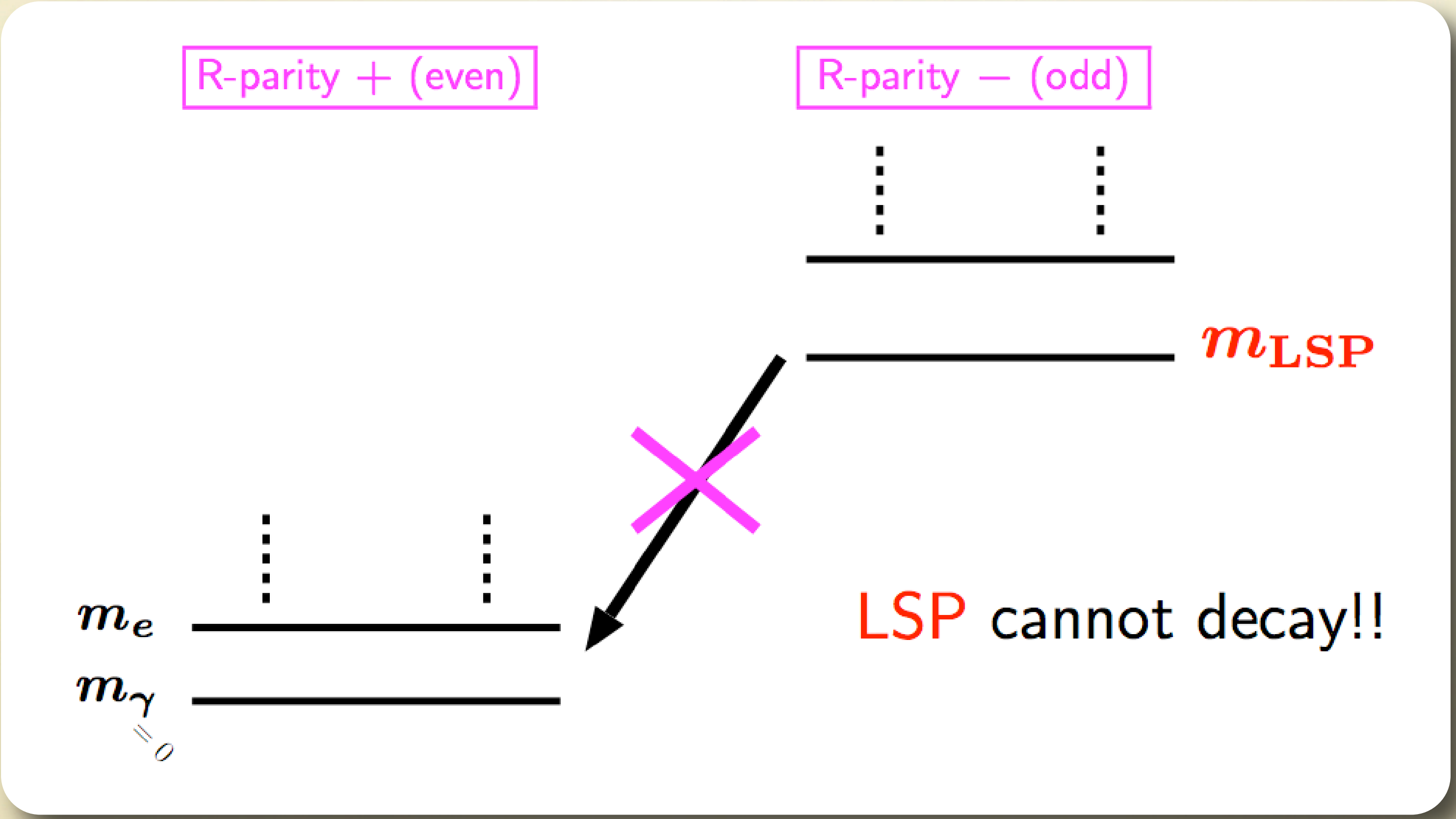
$$\text{gravitino}: \widetilde{G}$$

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

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neutral and color-singlet

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neutral and color-singlet

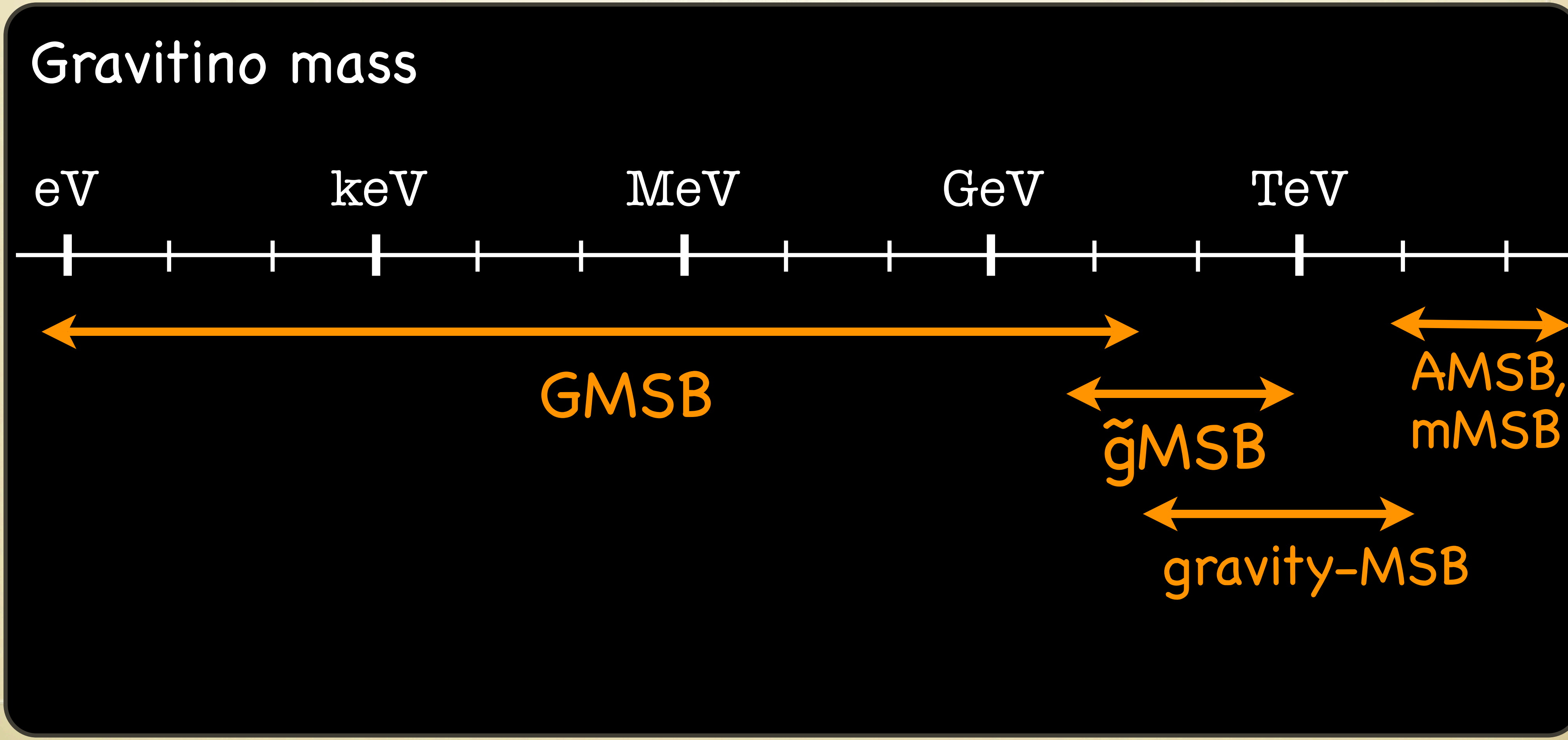
Only Neutralino and Gravitino are viable candidates!

- Why Gravitino LSP ?

- Other SUSY particle masses = O(100 GeV)-O(1 TeV)

  experimental bound (O(100 GeV)) — naturalness (O(1 TeV))

- Gravitino mass..... model dependent.



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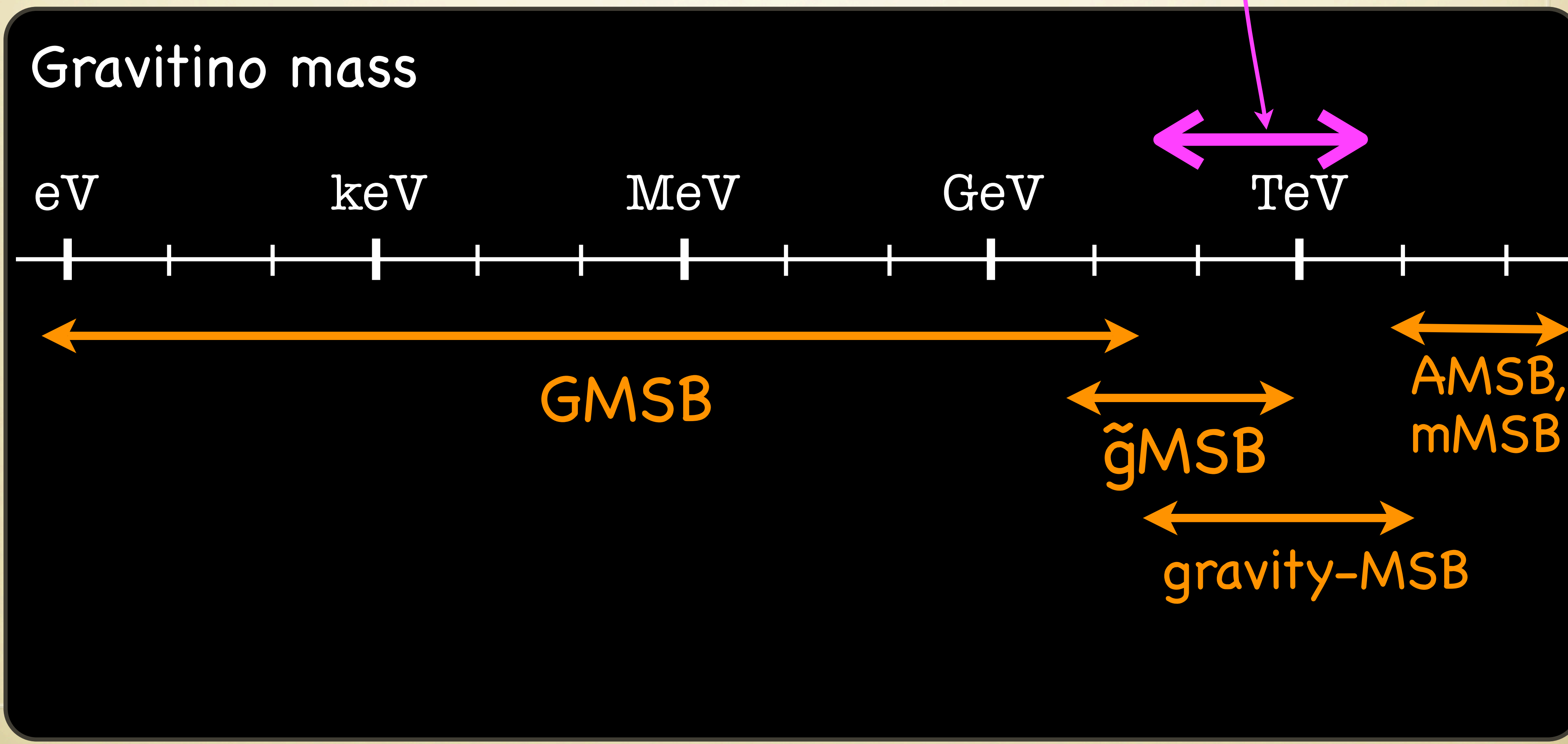

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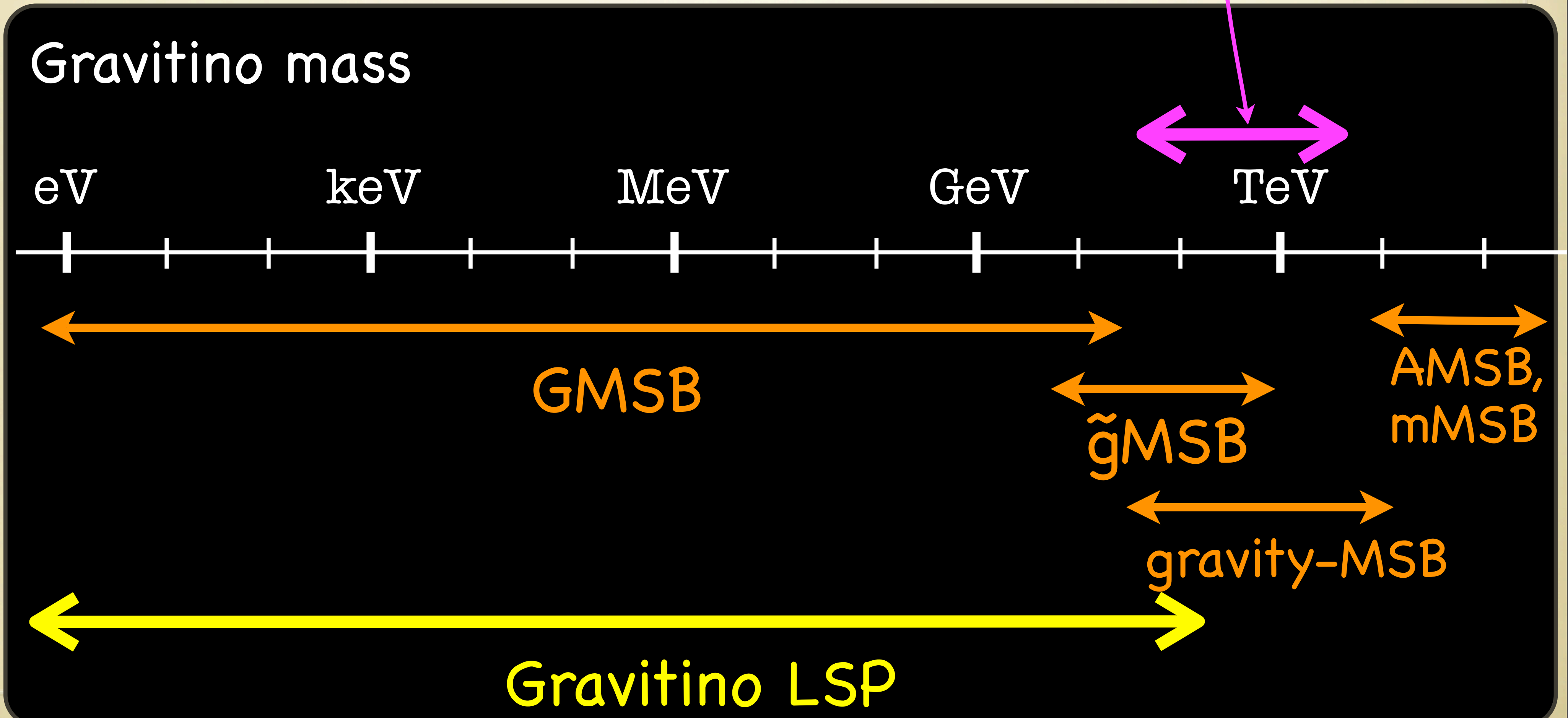

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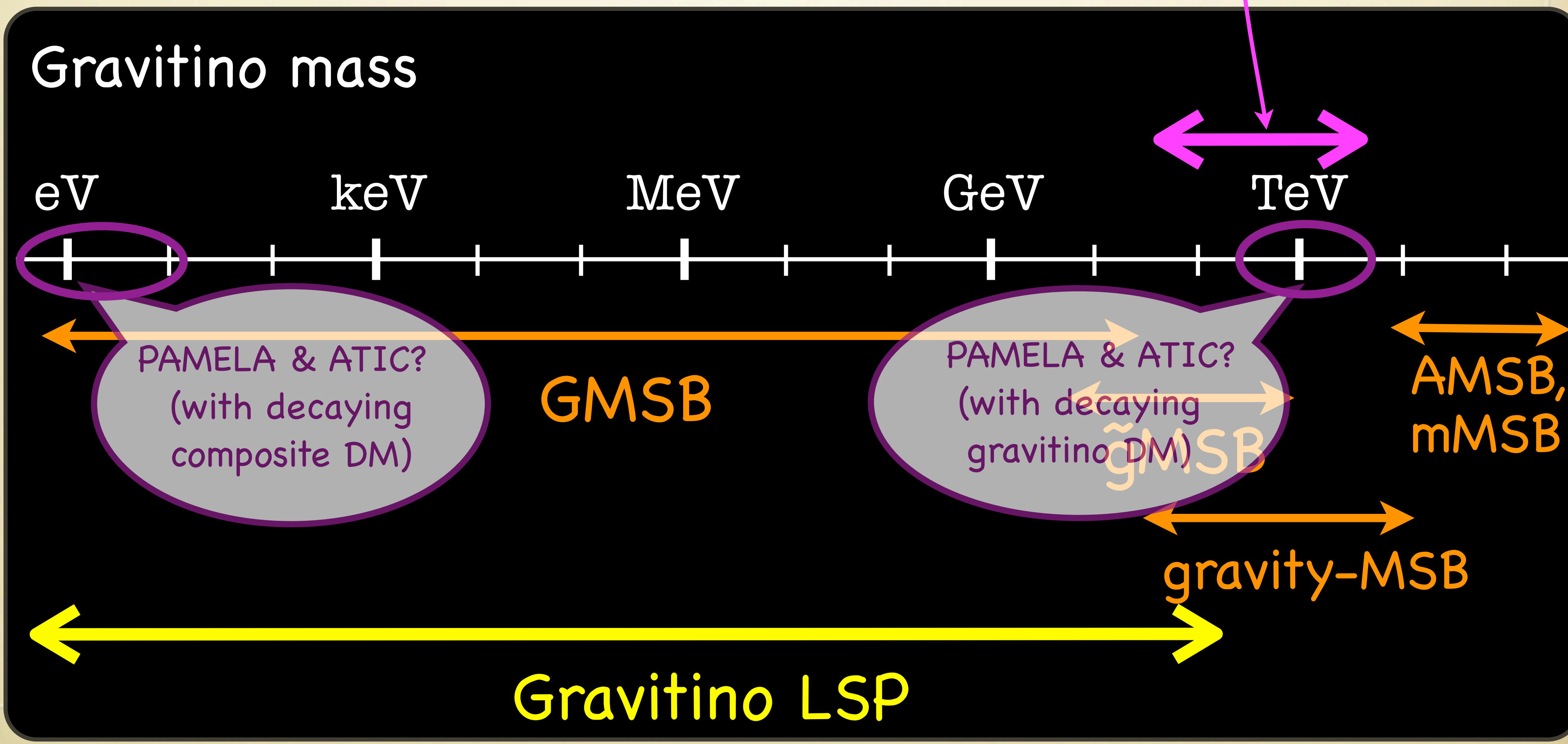

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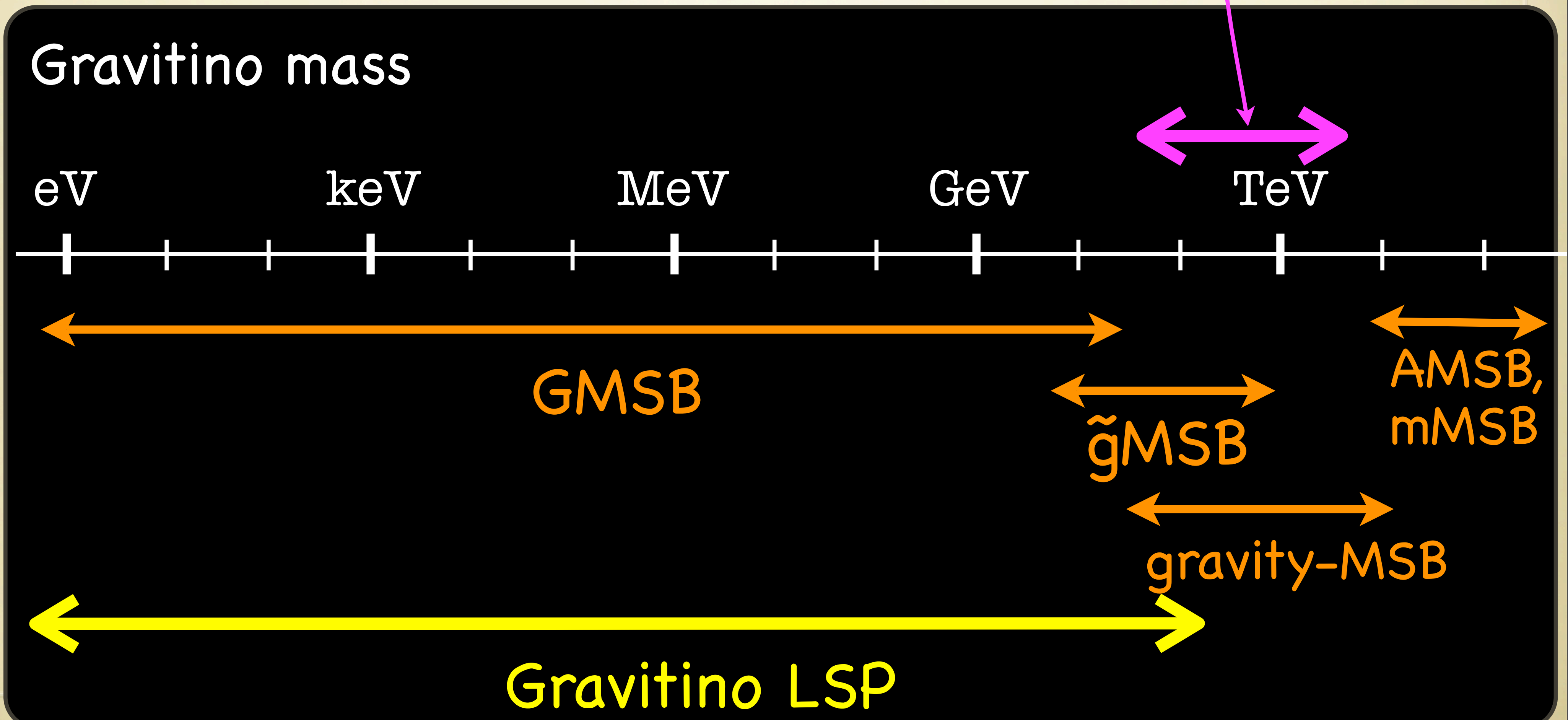

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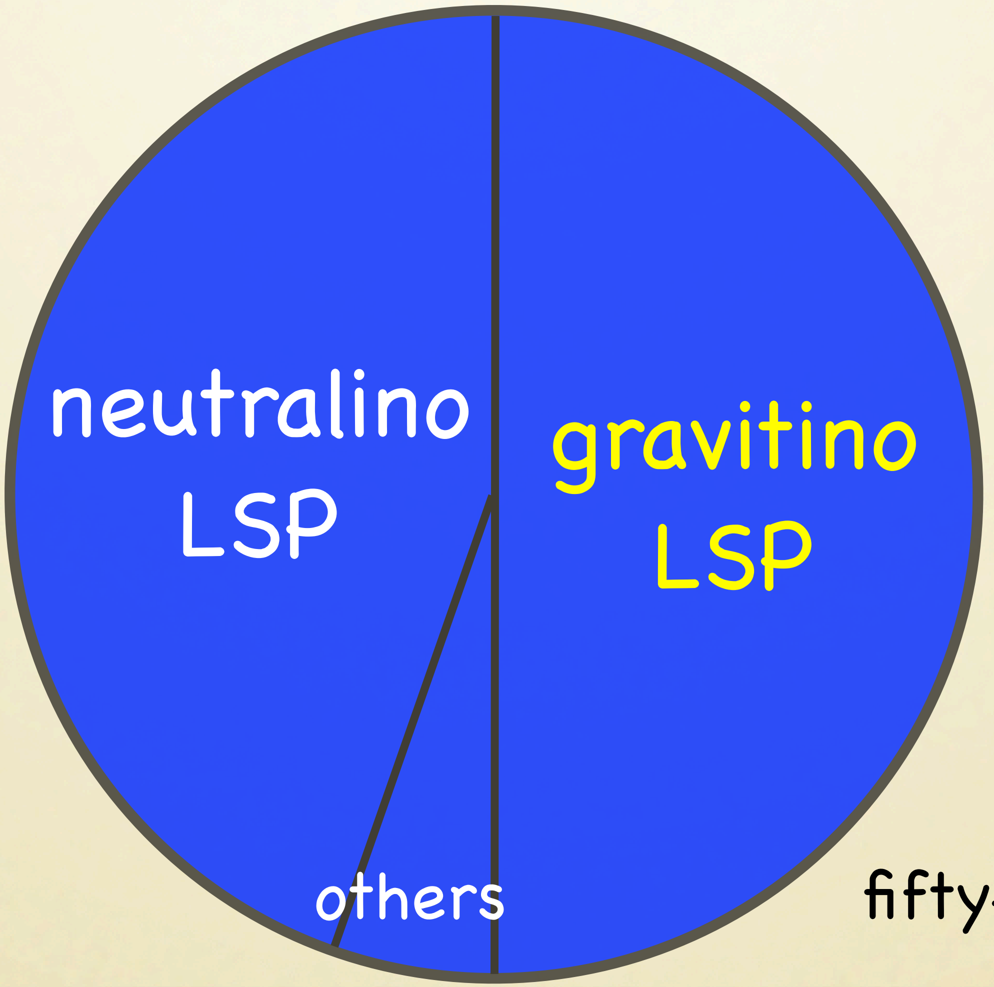
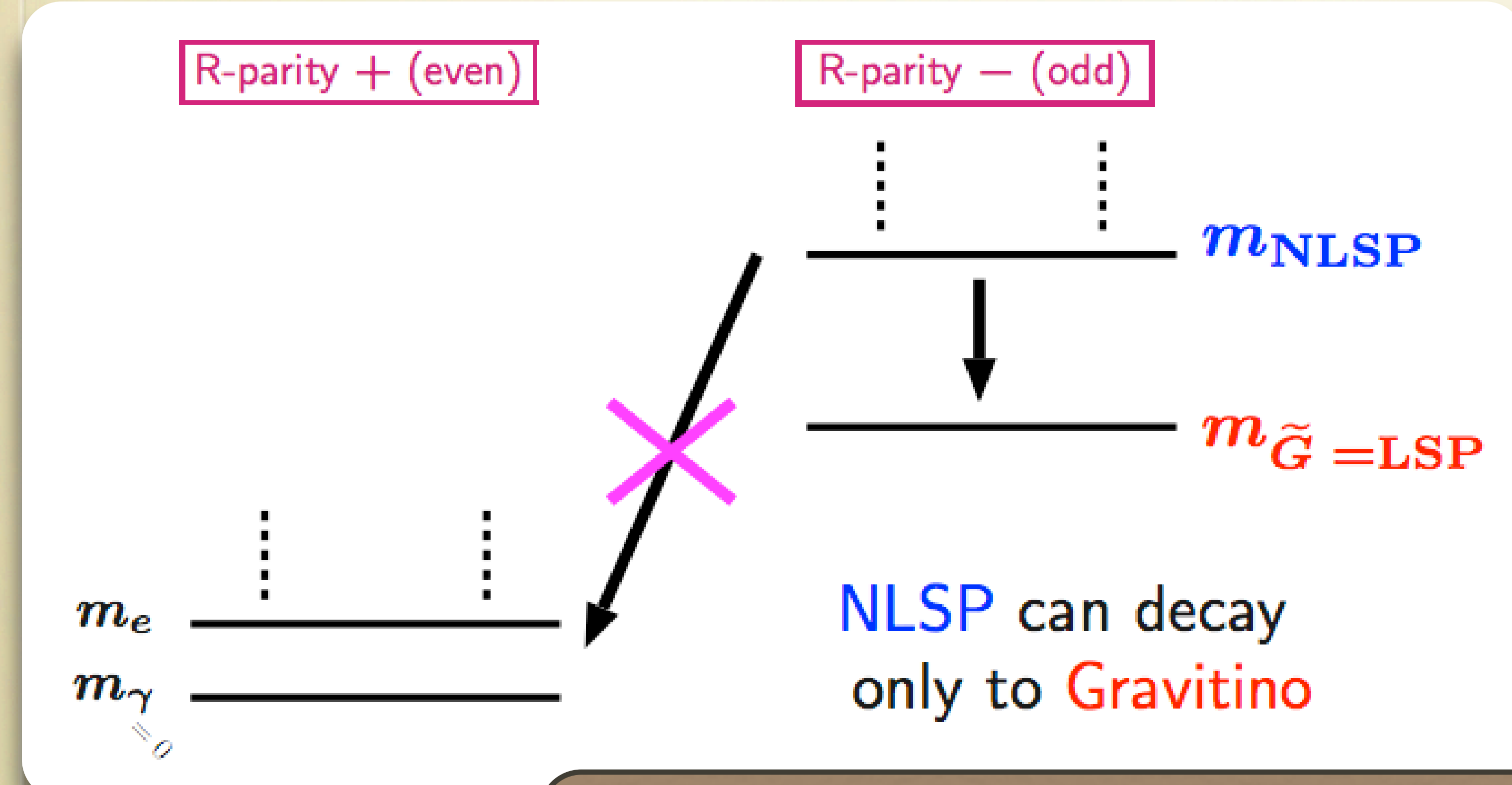
SUSY models




fifty-fifty?

# NLSP (Next-to-Lightest SUSY Particle)

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




extremely weak interaction

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

$$\tau_{\mathrm{NLSP}} \sim \mathcal{O}(\mathrm{day}) \quad \text{for} \quad m_{\tilde{G}} \sim 10 \text{ GeV}$$

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

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

- Why Stau NLSP ?

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

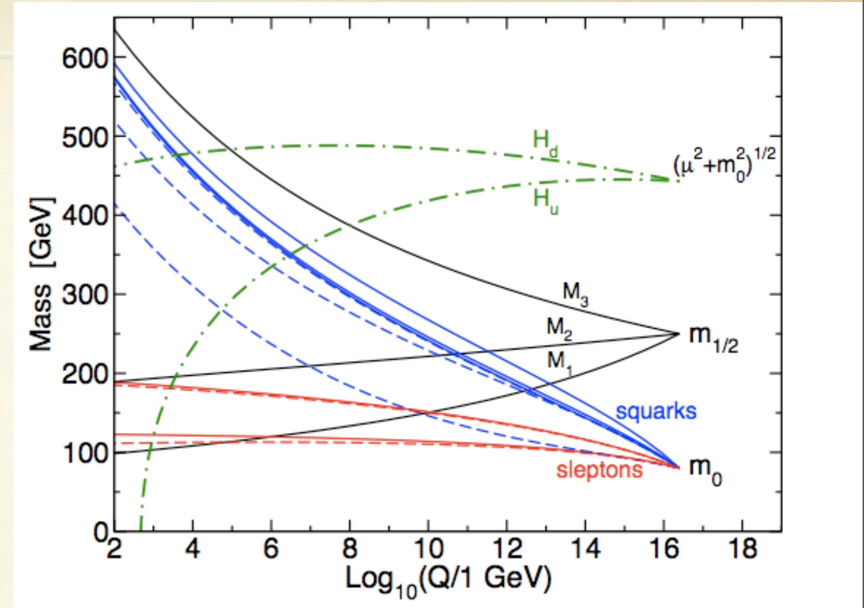
gauginos and higgssinos : $\widetilde{\chi_i^0}, \quad \widetilde{\chi_i^\pm}, \quad \widetilde{g}$

gravitino : $\widetilde{G}$

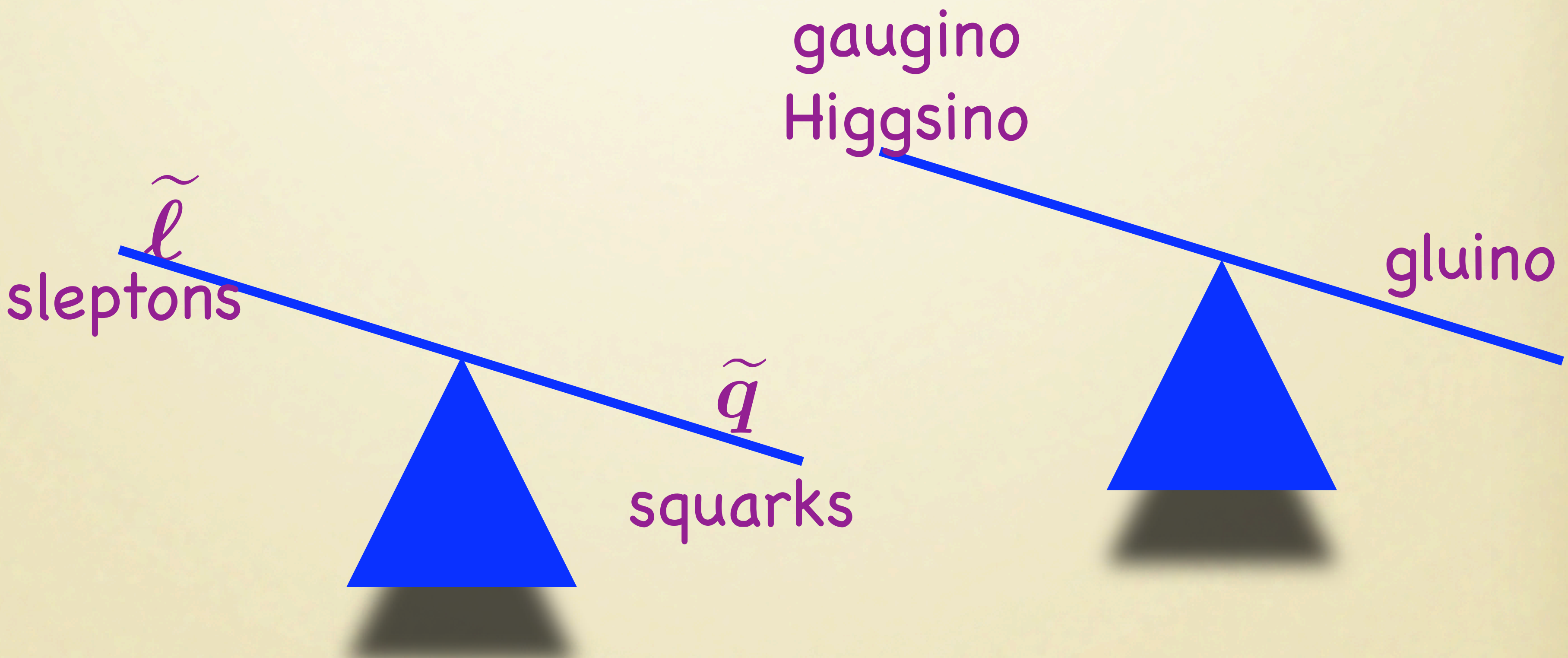
stau (i=3)

## Why Stau NLSP ?

- In general, from RGE, tendency is
  - M(color singlet) < M(colored)




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



# Why Stau NLSP ?

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  - M(color singlet) < M(colored)
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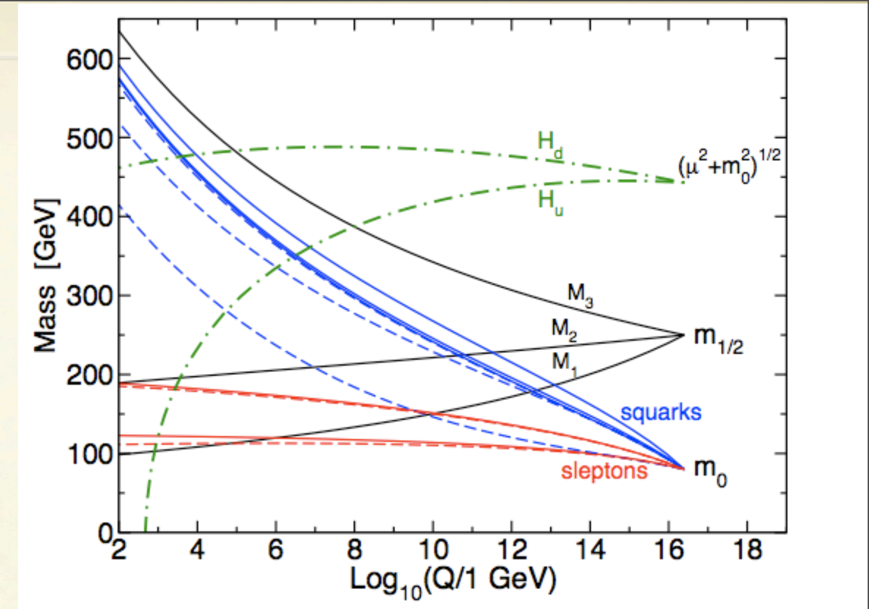


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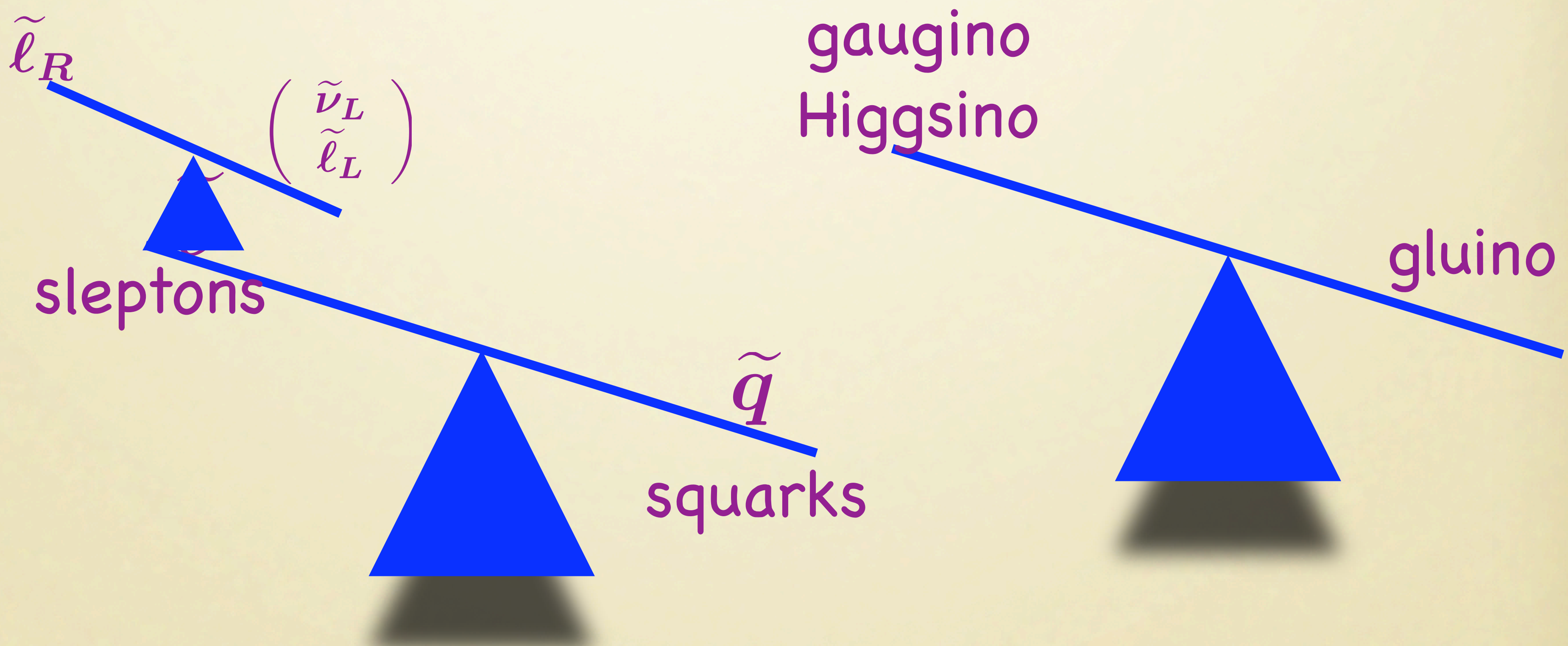
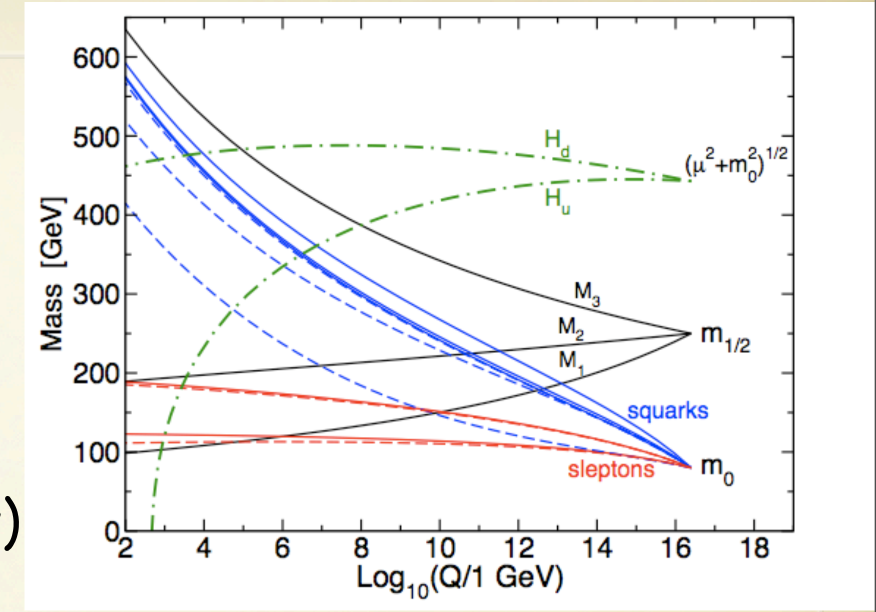


# Why Stau NLSP ?

- 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)

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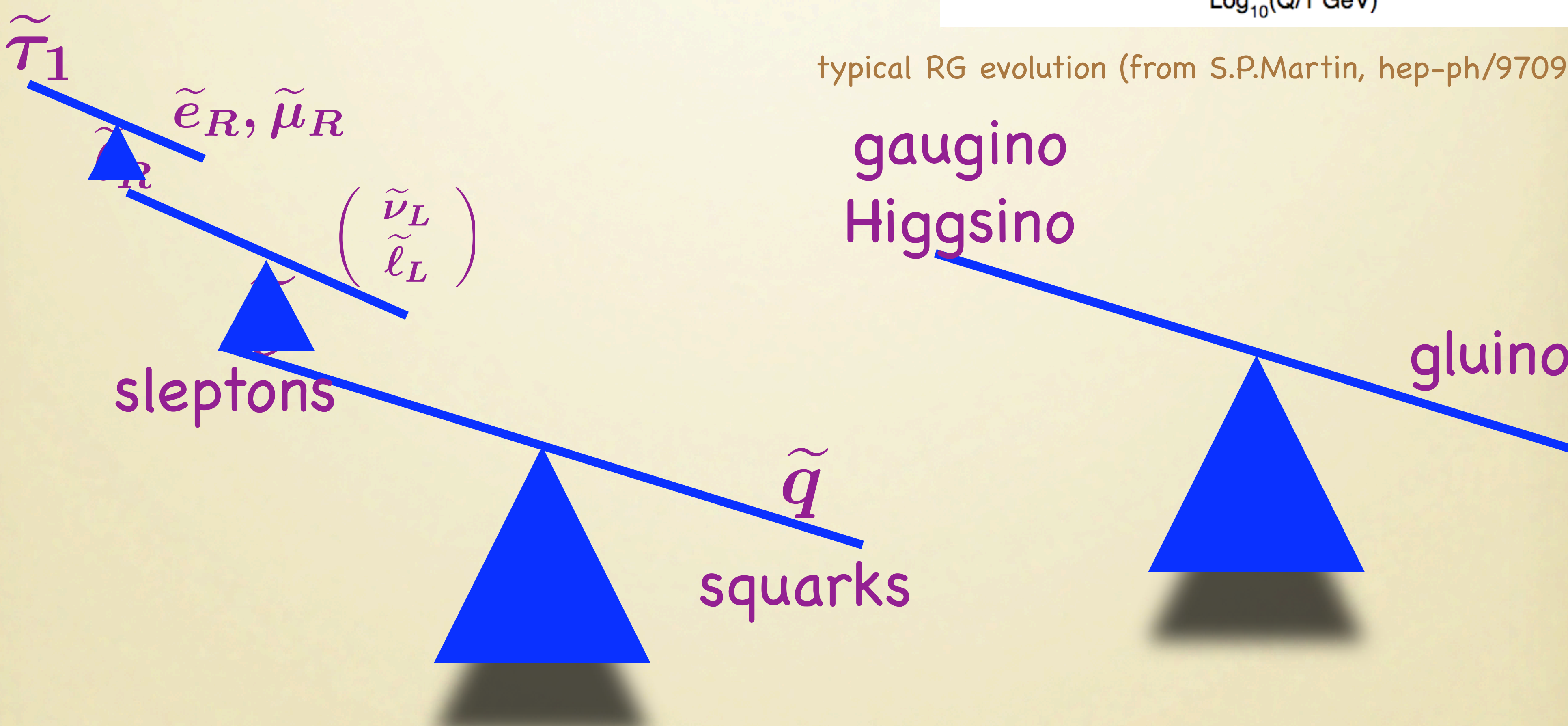

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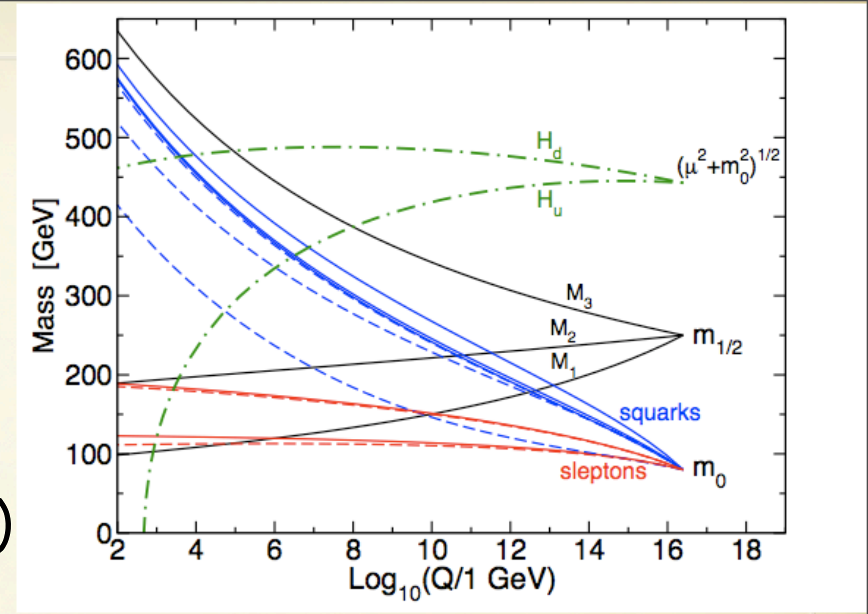


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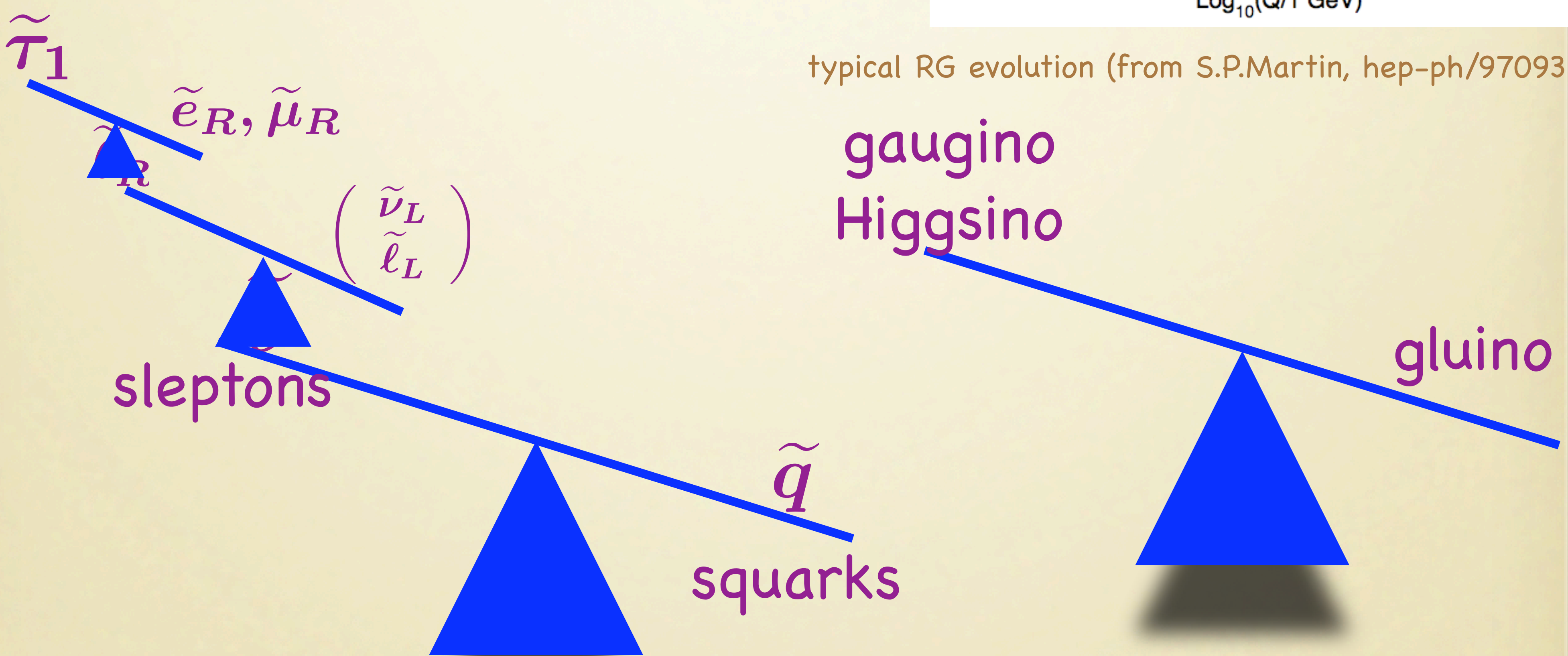
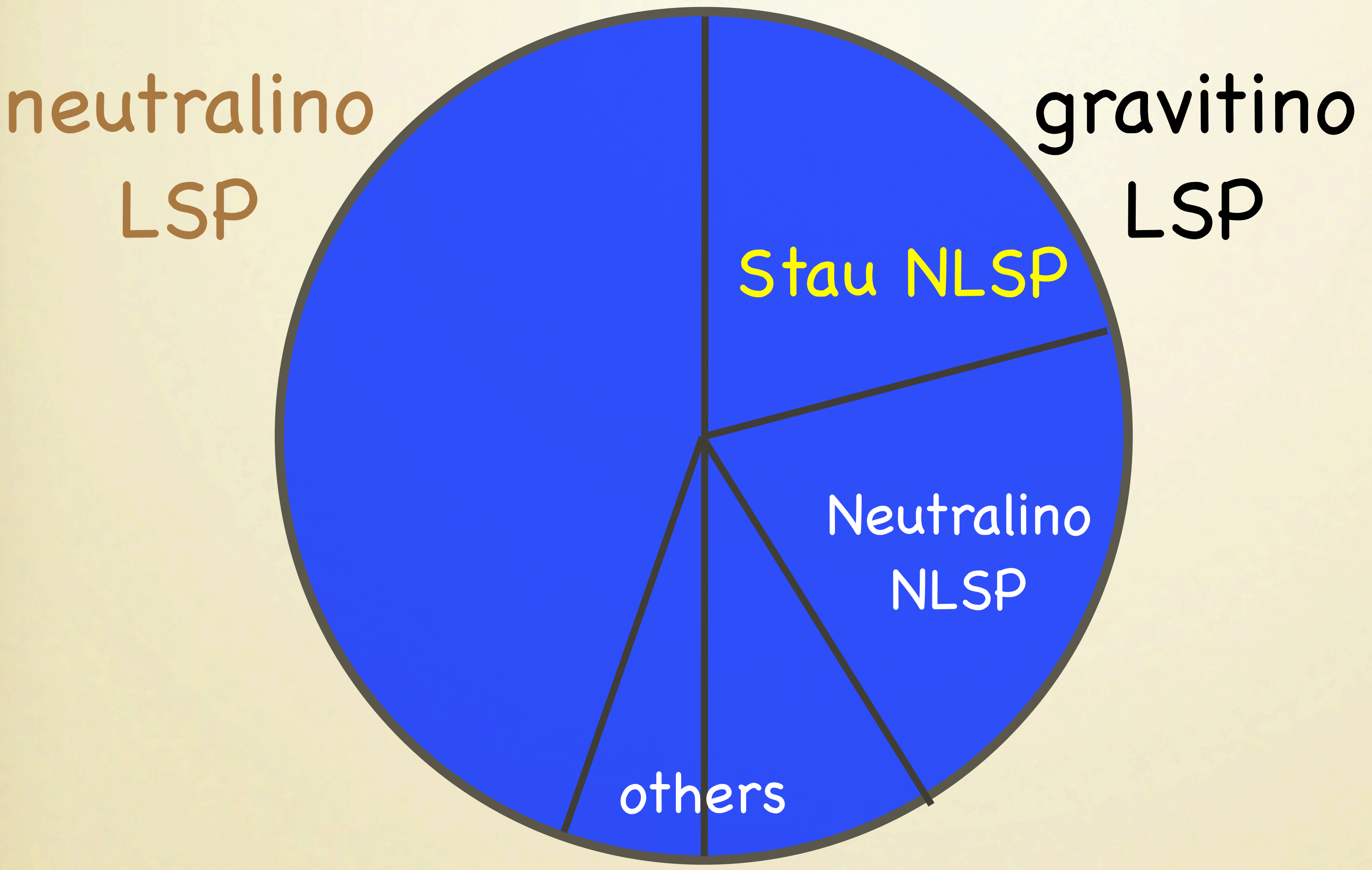



- In most cases, either Stau or Neutralino is the NLSP

- Why Stau NLSP ?

SUSY models

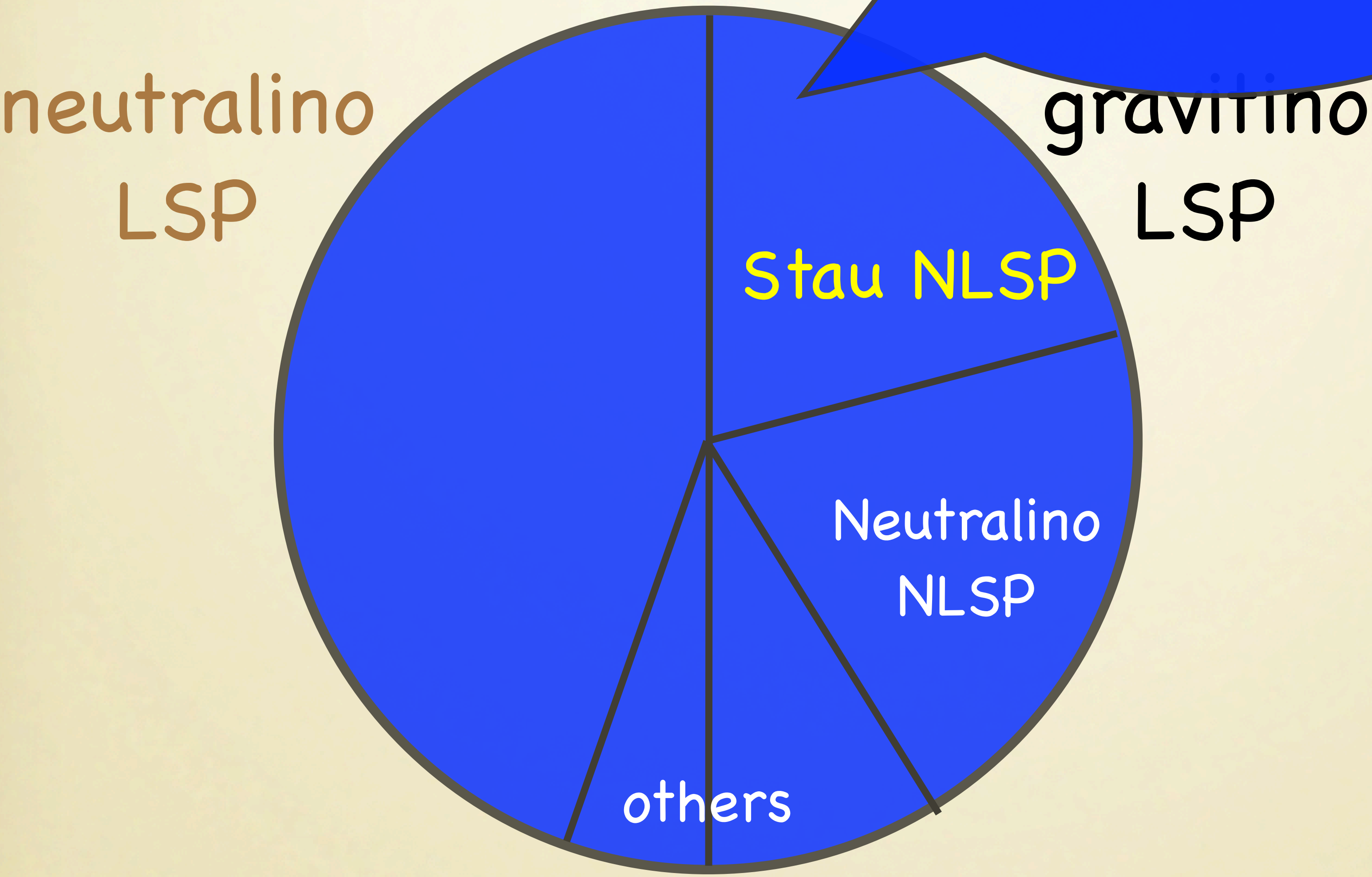



- Gravitino LSP and Stau NLSP is a natural choice.

- Why Stau NLSP ?

= Long-lived charged particle.

SUSY models



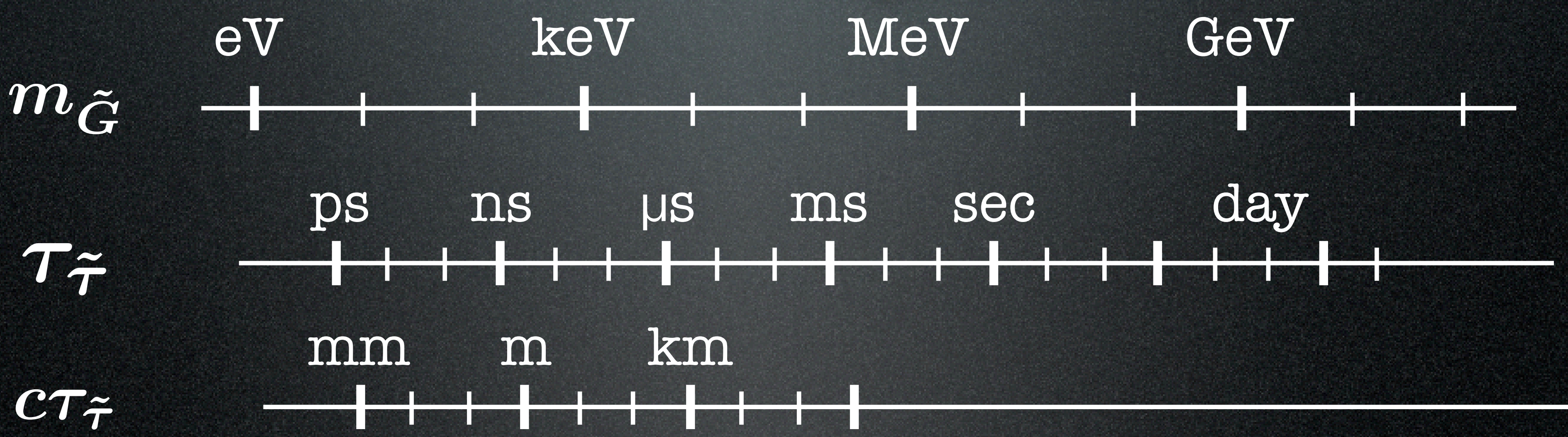

- Gravitino LSP and Stau NLSP is a natural choice.

# 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 (decay length) of NLSP stau

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



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Lifetime (decay length) of NLSP stau

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

eV keV MeV GeV

## Lifetime measurement

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

$\leftrightarrow$ gravitino mass $m_{\tilde{G}}$

# NLSP Lifetime

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

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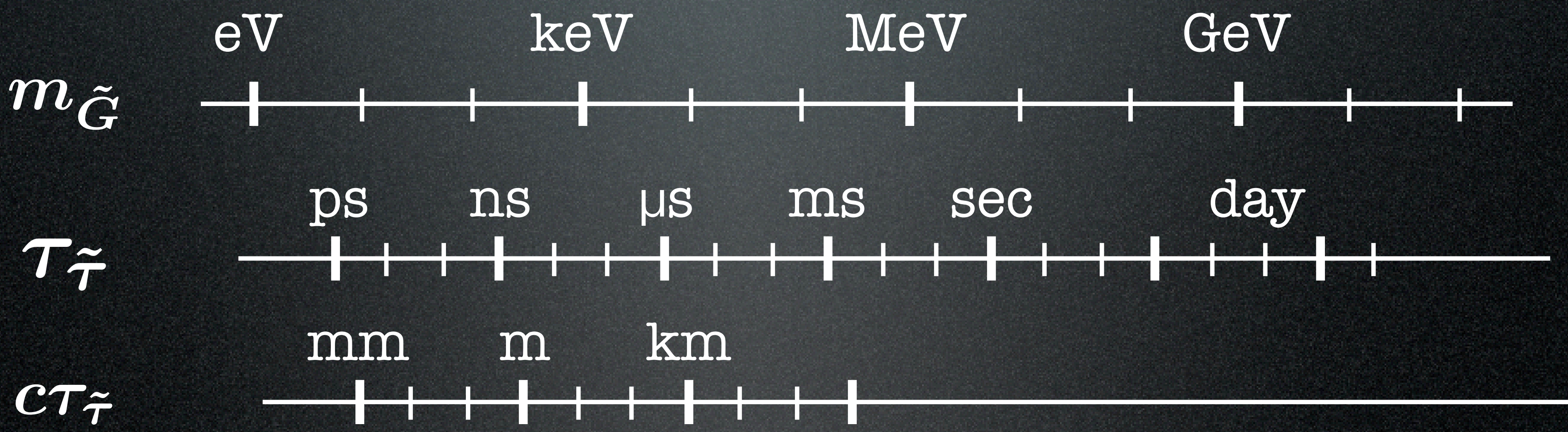

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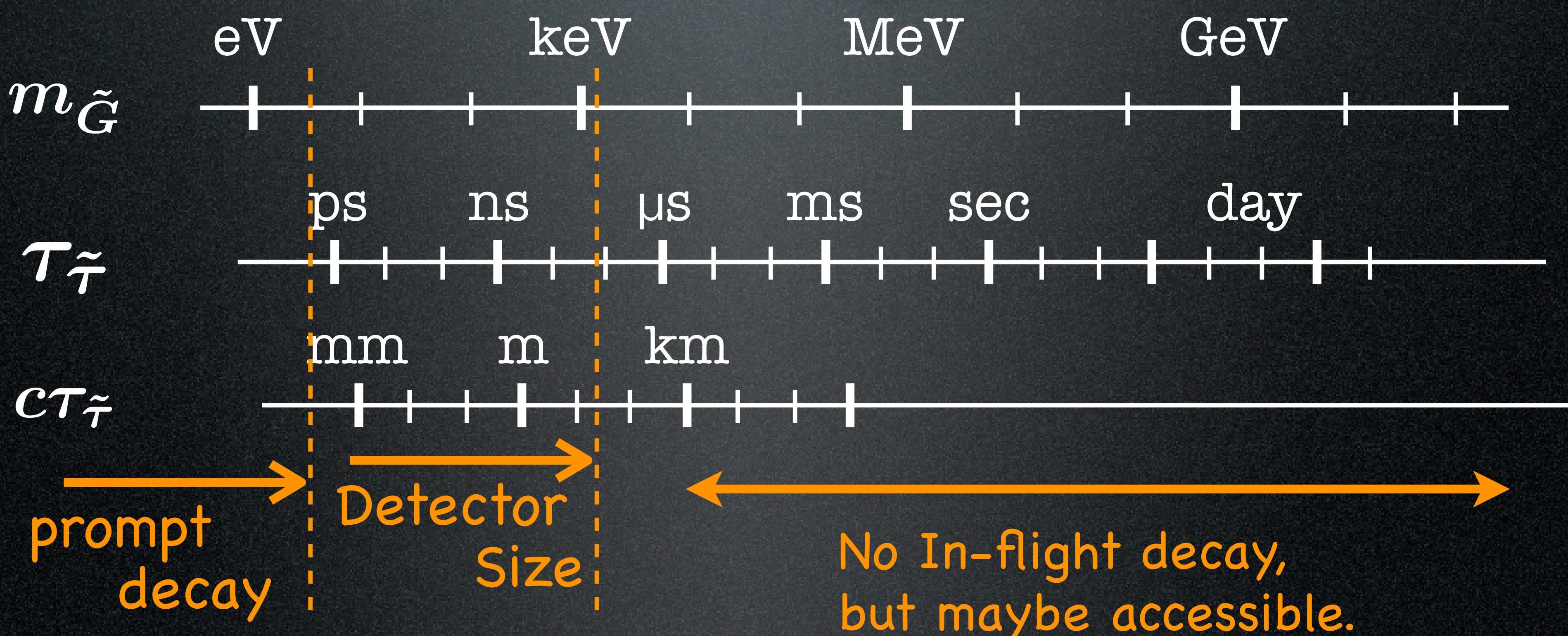

Side Remark

# Planck scale measurement

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

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# Planck scale measurement

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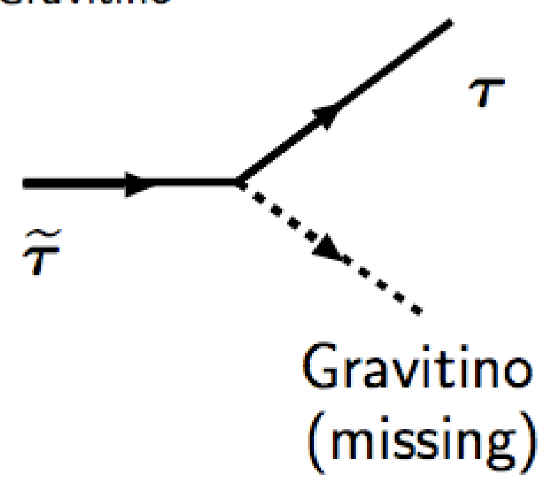
slepton

lepton

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

Gravitino



Side Remark

# Planck scale measurement

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

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

Prediction of the Supergravity

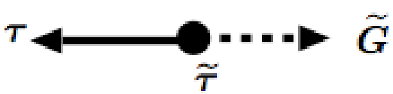
$$\Longleftrightarrow \quad M_P^2(\text{supergravity}) = \frac{1}{48\pi}\frac{1}{\Gamma_{\tilde{\tau}}}\frac{m_{\tilde{\tau}}^5}{m_{\tilde{G}}^2}\left(1 - \frac{m_{\tilde{G}}^2}{m_{\tilde{\tau}}^2}\right)^4$$

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.

# Stop and Decay
# of
# Long-lived charged massive particles
# (CHAMPs)
# at
# the LHC detectors

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

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

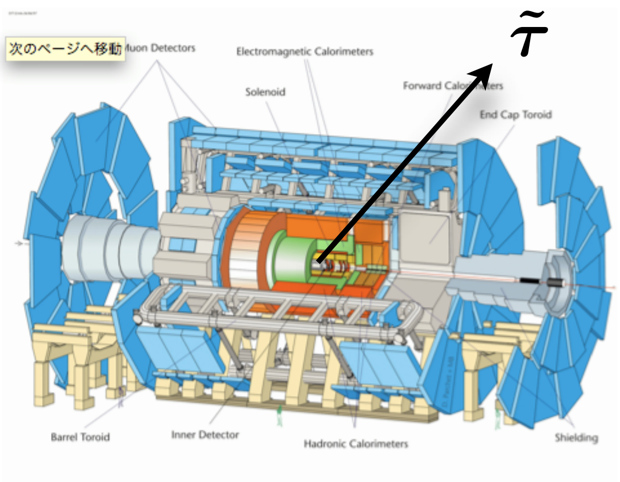
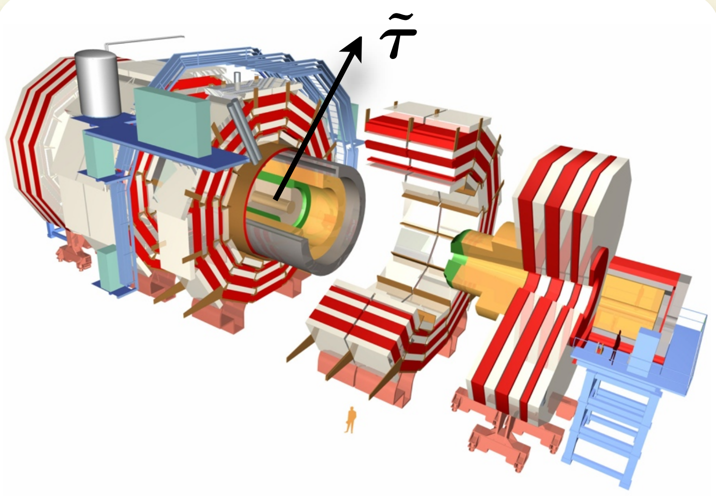



Figure 1-i Overall layout of the ATLAS detector.



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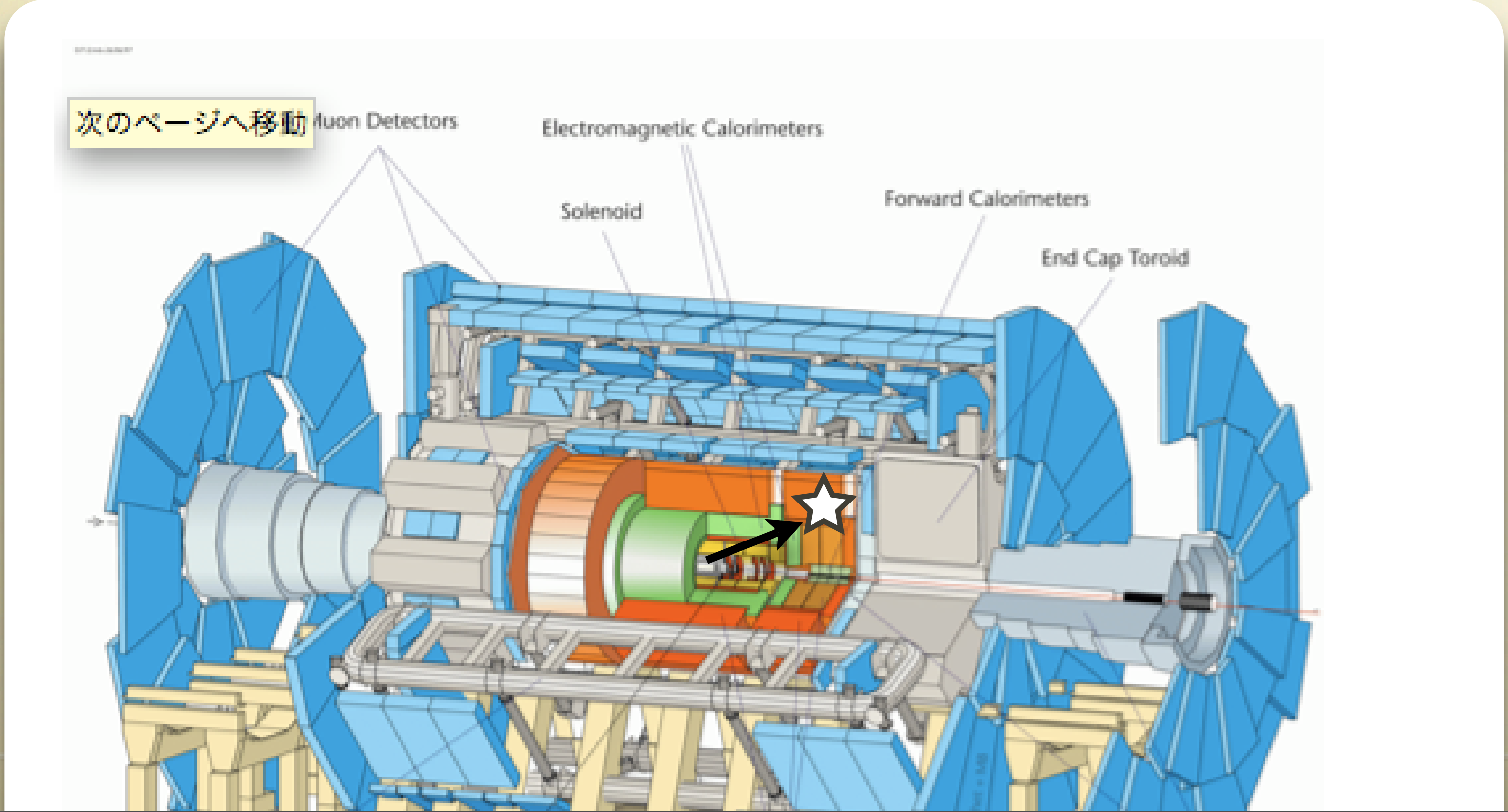
- some of them have sufficiently small velocity and stop at calorimeters.



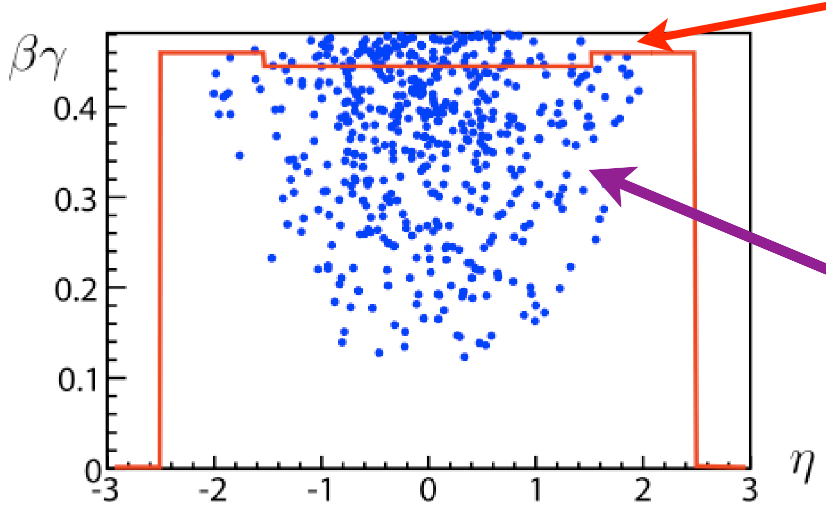
- typically most of CHAMPs have large velocity and escape from detector.
- some of them have sufficiently small velocity and stop at calorimeters.

example of SUSY model point SPS7 ( $\sigma_{SUSY}$ = 3.5 pb )

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

| with cuts | without cuts |
|---|---|
| 400 | 805 |

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




stopped events
- about 1% of total SUSY events
- a few per day

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

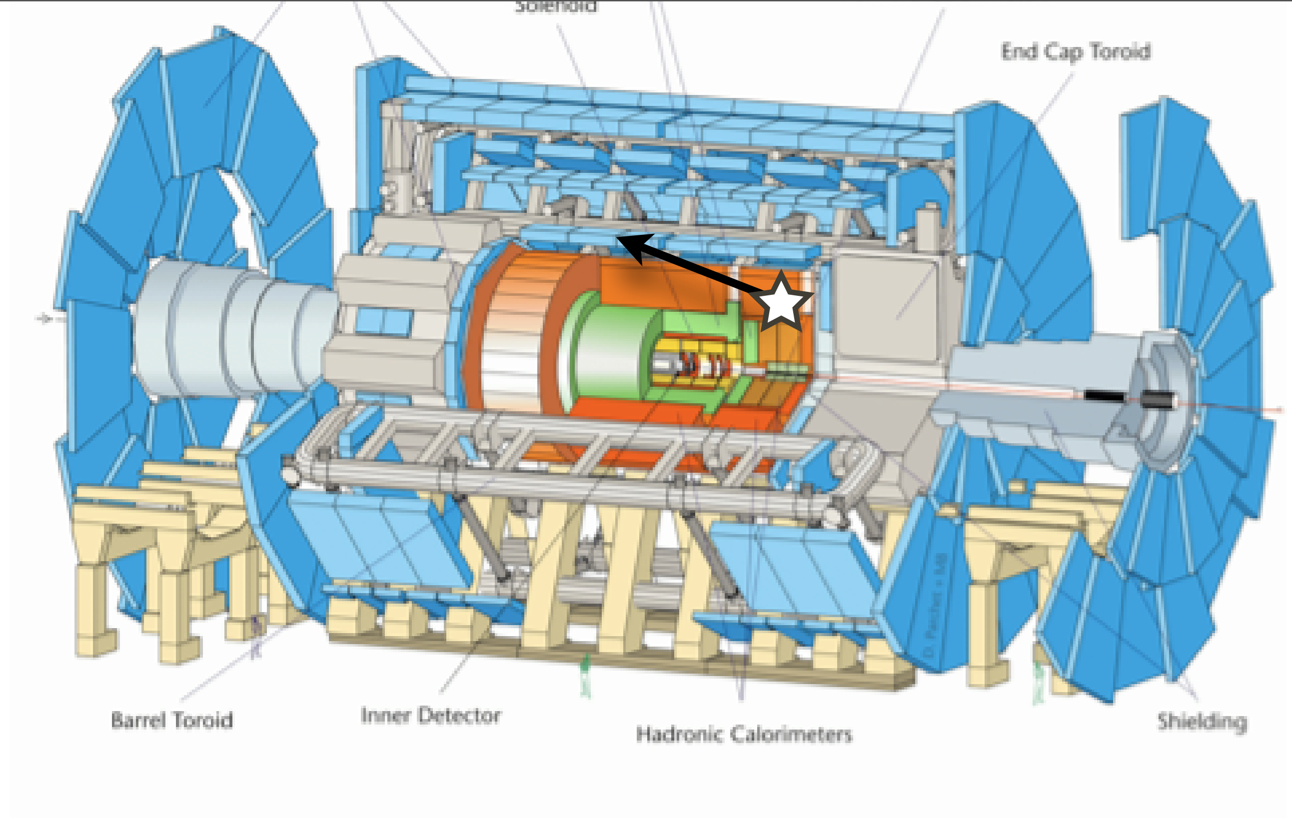



Figure 1-i Overall layout of the ATLAS detector.

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

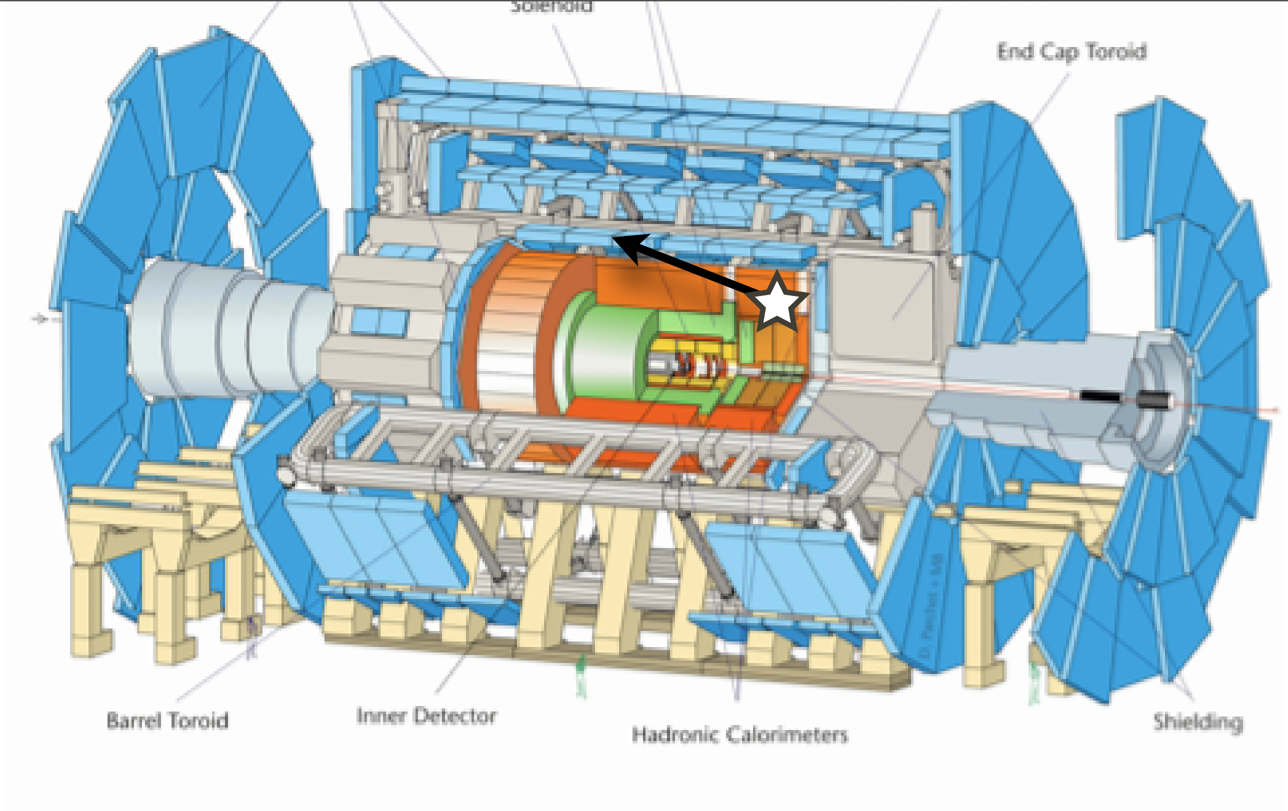



Figure 1-i Overall layout of the ATLAS detector.

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

..... during pp collision.

# Idea:

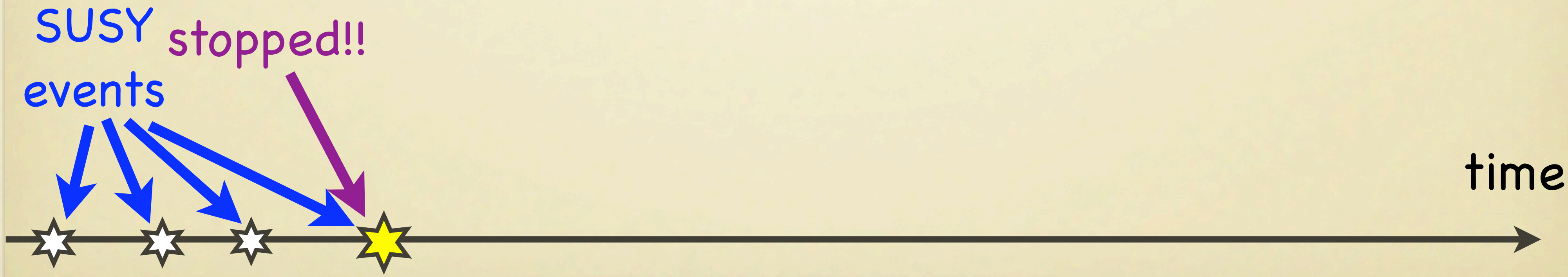
stop the pp collision !!

....and optimize the trigger to detect CHAMP decay.

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

- 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

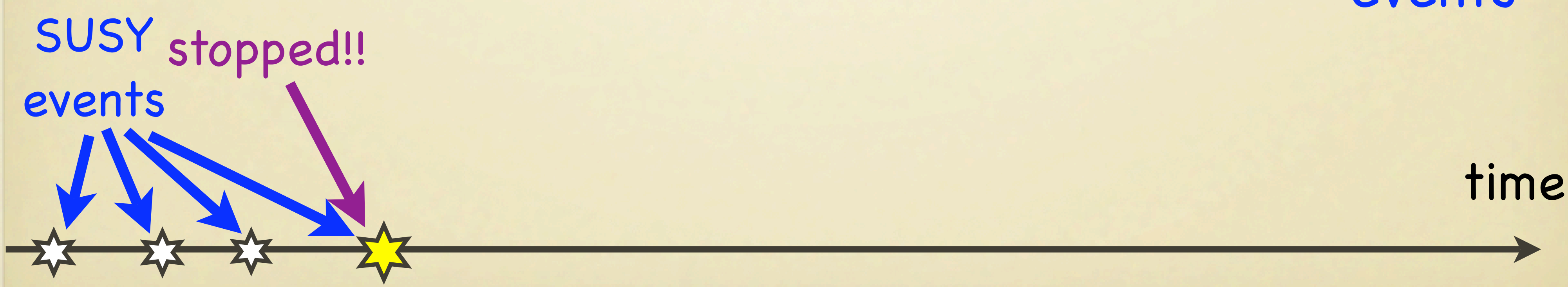
(3) isolated track with PT > 0.1 m(CHAMP).

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

standard SUSY cuts

CHAMP candidate

select stopping events



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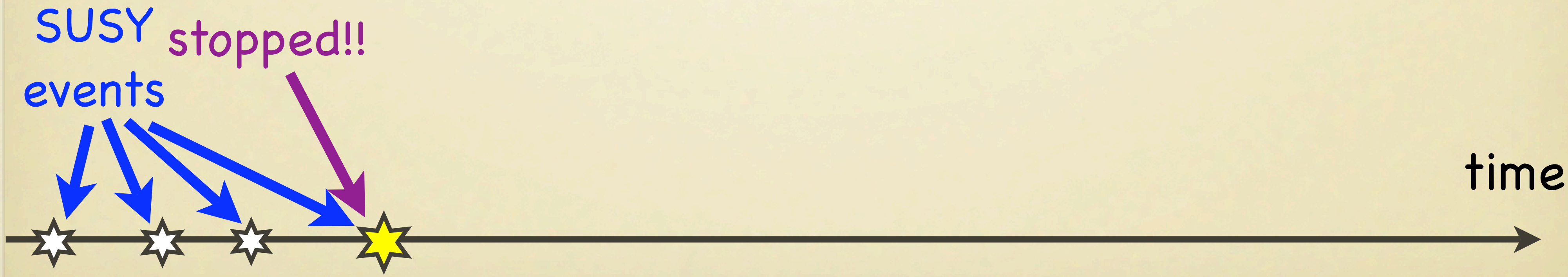
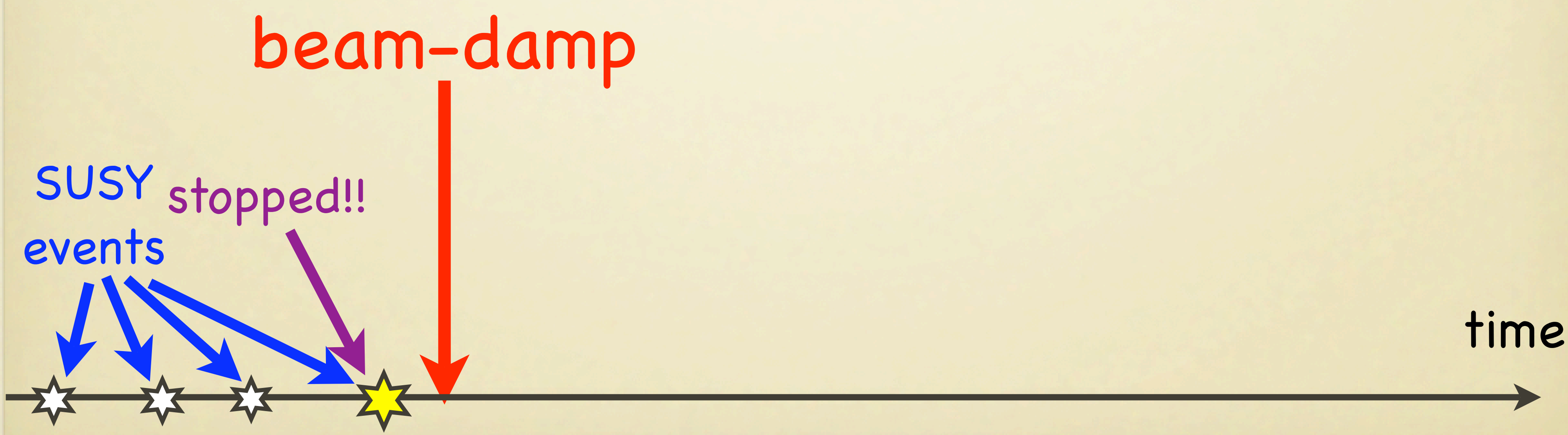


## • for short lifetime: use beam-damp signal.

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

trigger

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



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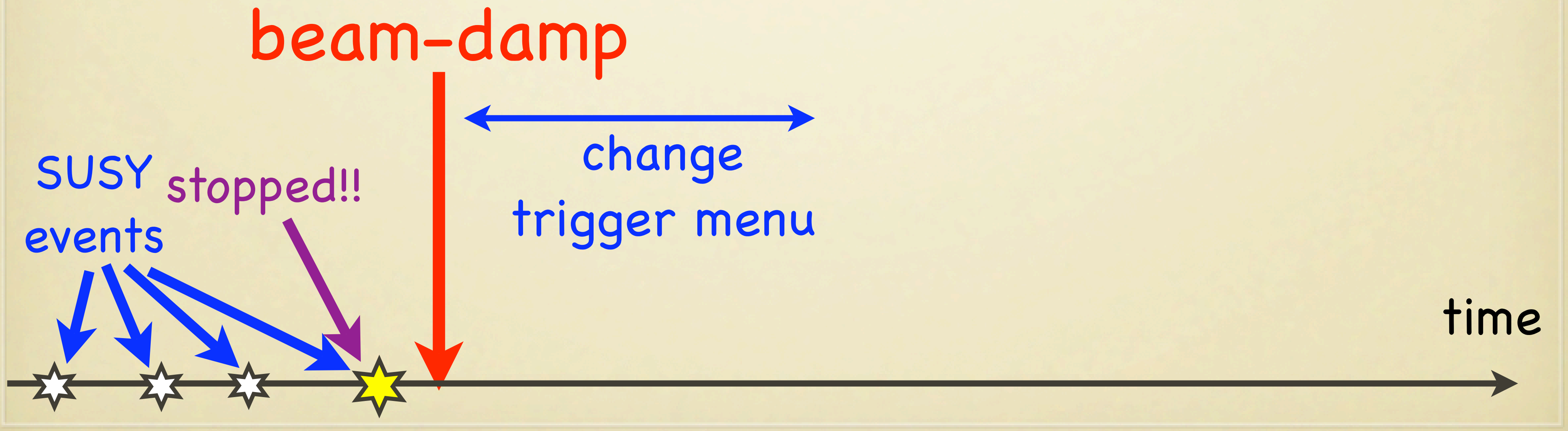
(III) change the trigger menu to the one optimized for CHAMP decay.



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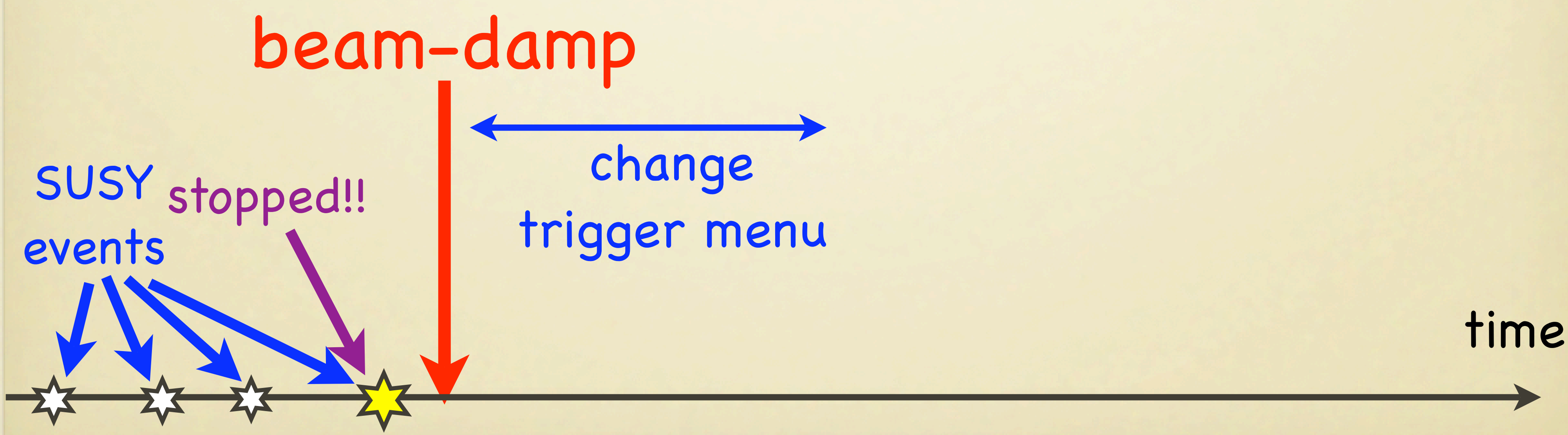
(IV) wait for CHAMP decay.



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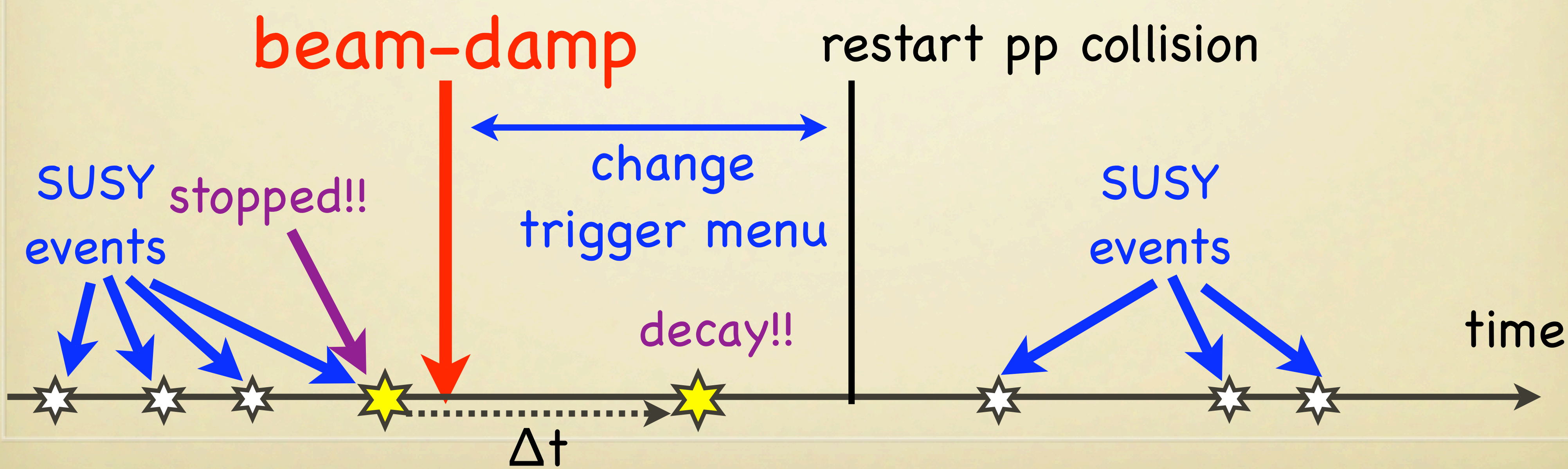

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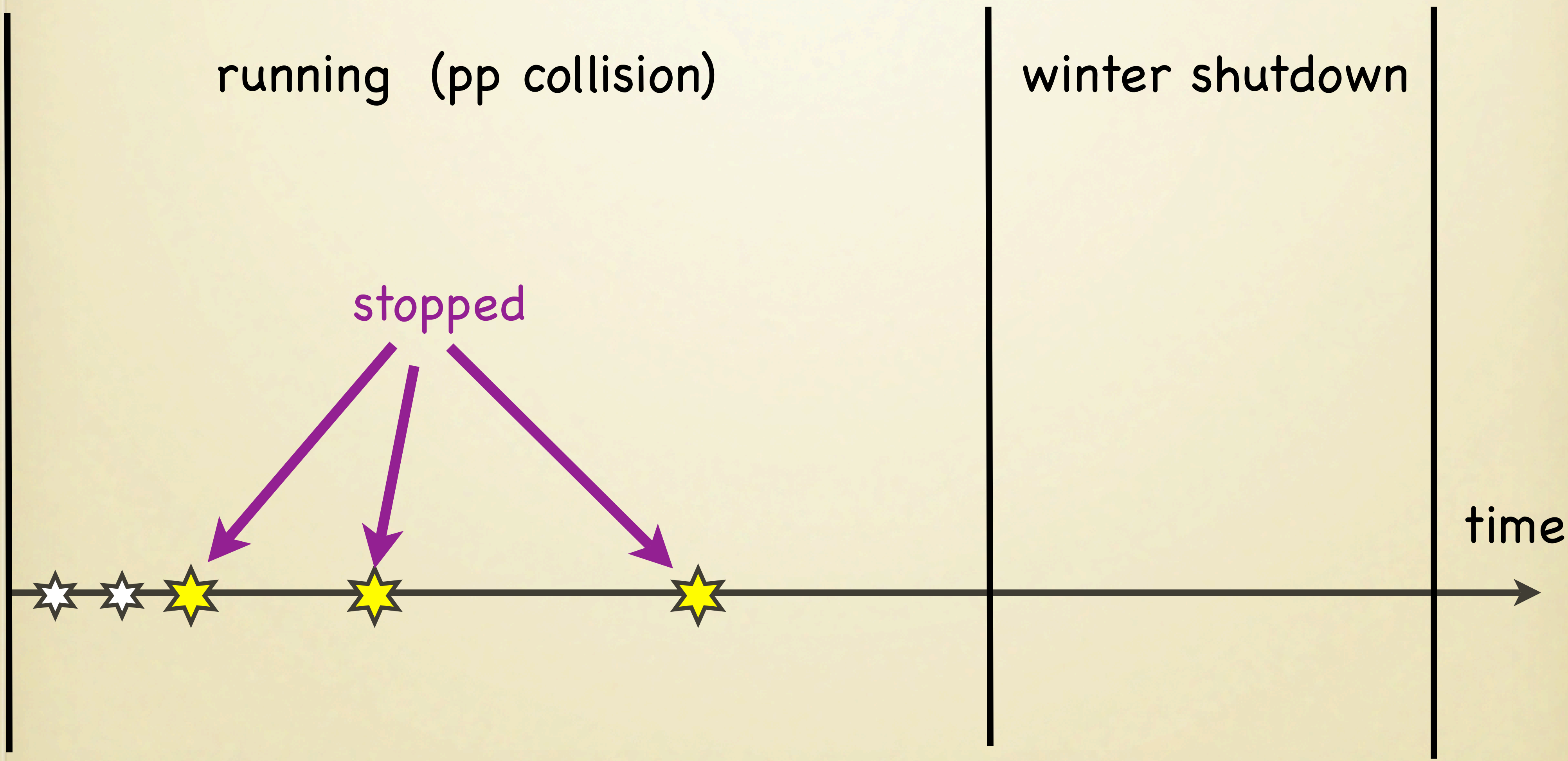

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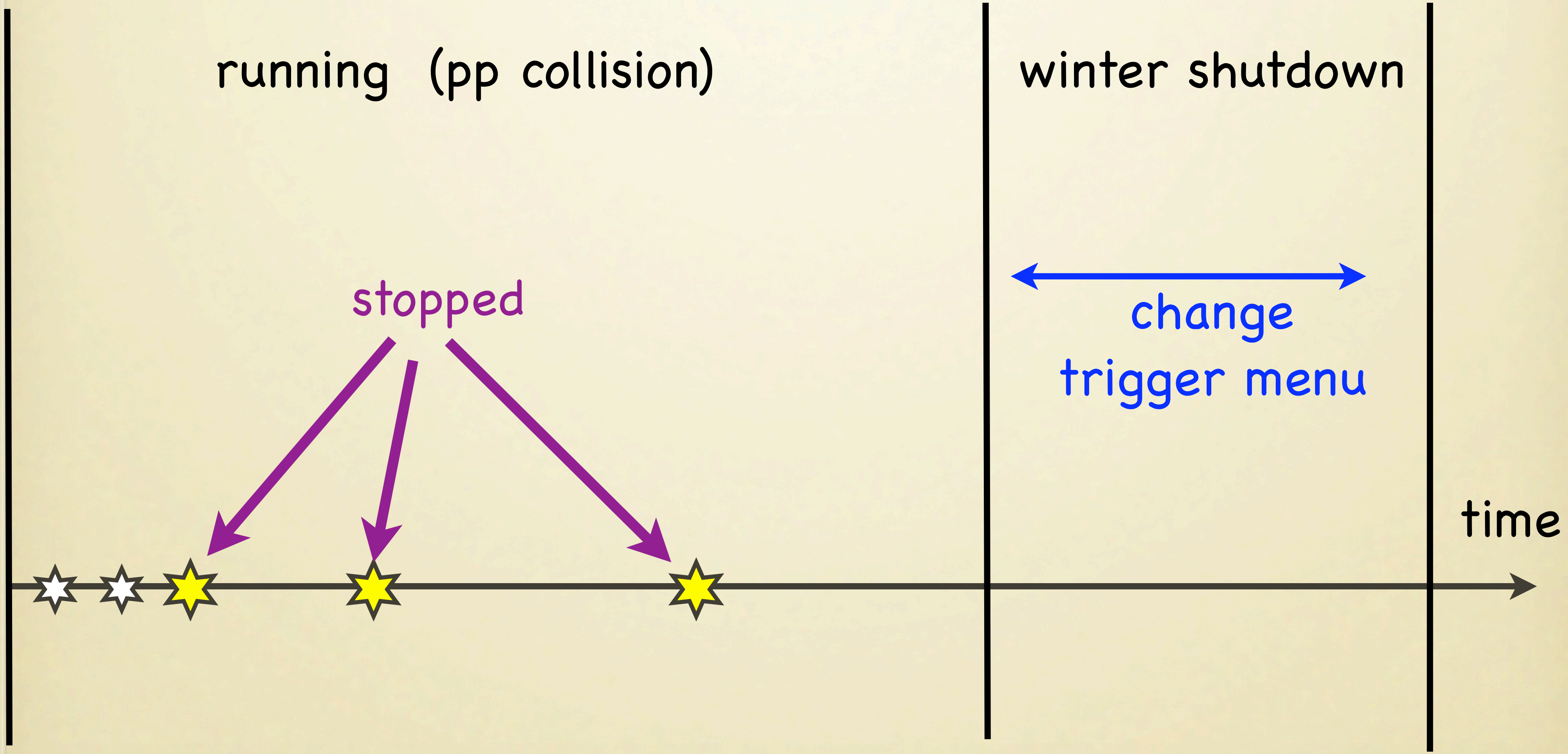

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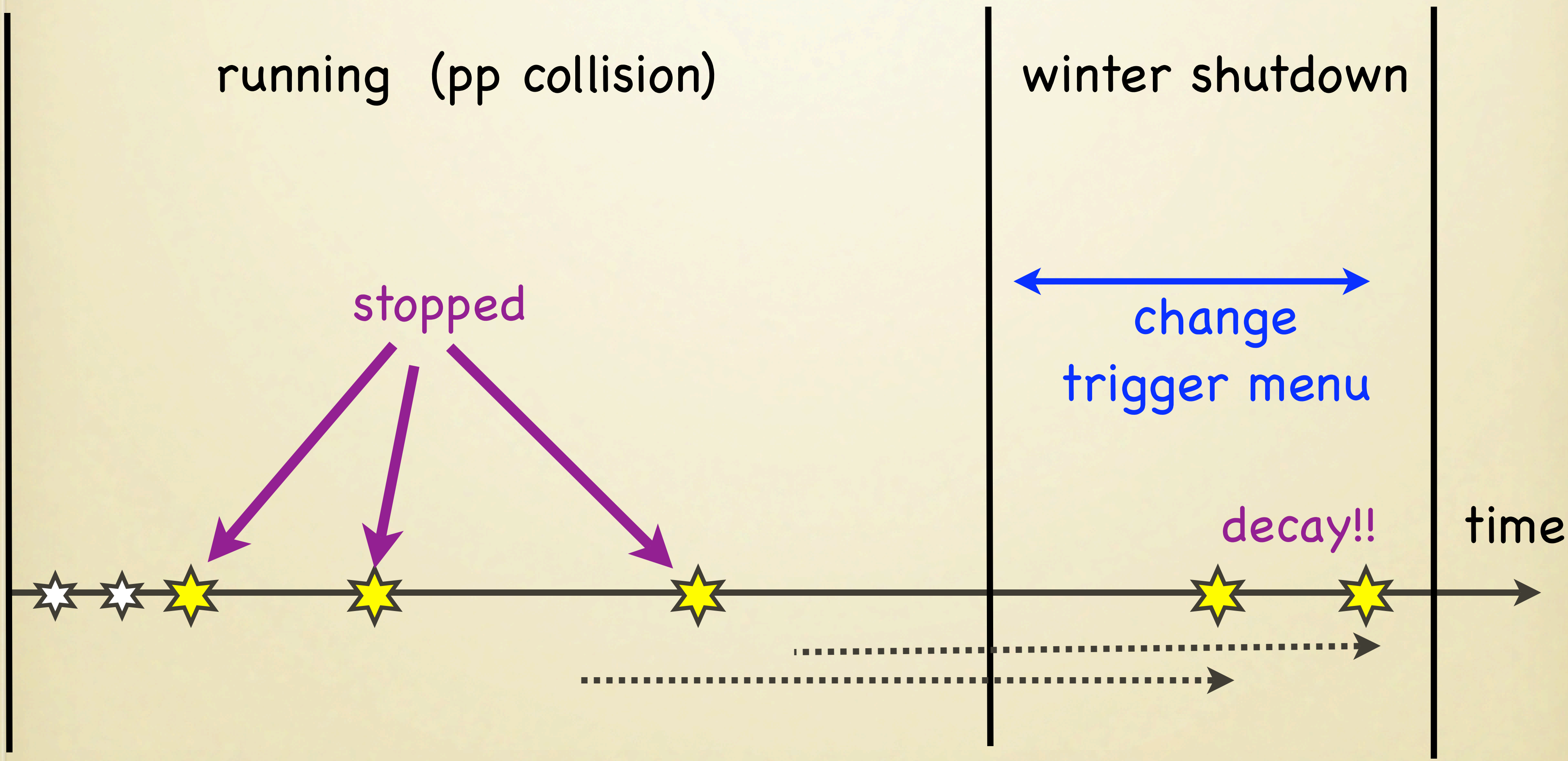


# •lifetime measurement: SUMMARY

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 | $\langle N_D \rangle$ | $\sigma$ | $\langle N_D \rangle$ | $\sigma$ |
| 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.

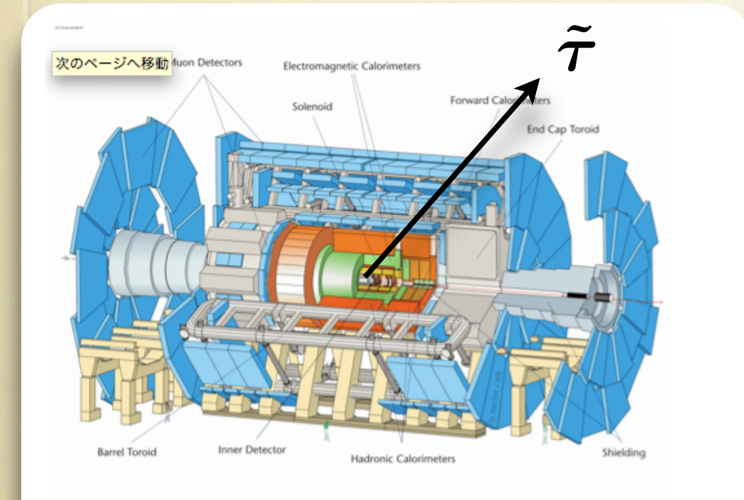
The discovery of late decay, and the lifetime measurement is possible for a very wide range,
from O(0.1 sec) to O(100 years) !!!

Future works:

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

# Backup Slides

Suppose that we will see
long-lived charged massive particle at the LHC,
e.g., stau NLSP in SUSY models.

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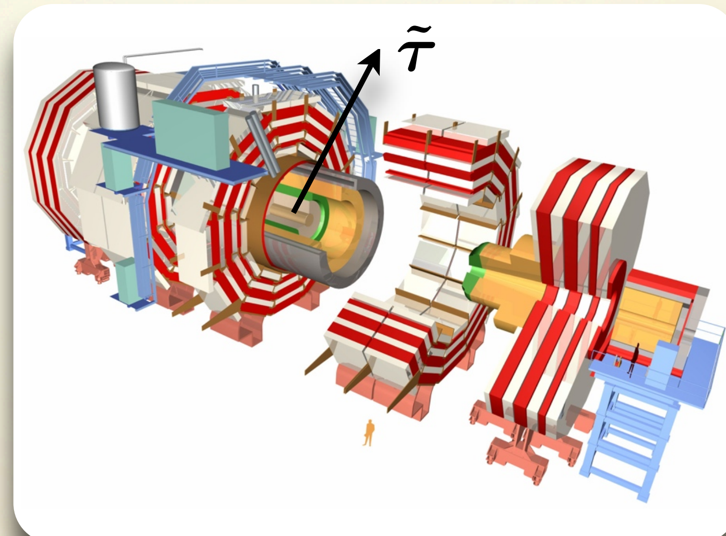
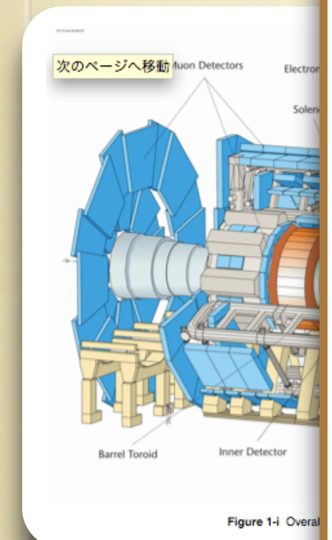


Suppos

long-li

e.g., st




- momentum measurement p

- + TOF (time of flight) measurement T

 ⇨ velocity β = L/T

- mass m = p/(βγ) cf. De Roeck, Ellis, Gianotti, Moortgat, Olive, Pape, 05

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

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

- Properties of other particles can also be studied from kinematical information.

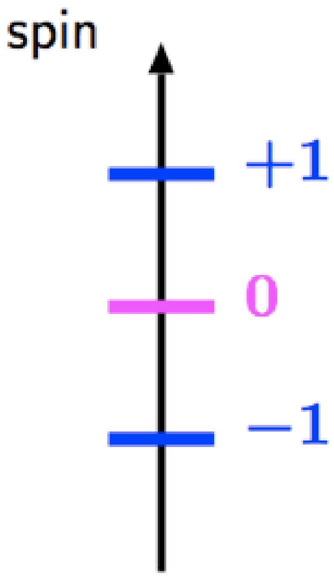
- then, the next target is the lifetime!!!

( Note: searches inside sea water exclude completely stable massive charged particle.)

- What is Gravitino?

## Compare it with Electroweak Symmetry

Electroweak symmetry
$\to$ spontaneously broken

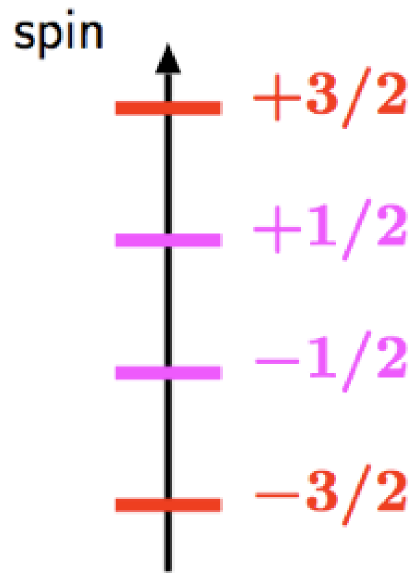



Higgs mechanism

**$Z, W$ bosons**

$\to$ discovered in 1983
$\to$ establish Standard Model

Supergravity
$\to$ spontaneously broken




super–Higgs mechanism

**Gravitino**

$\to$ discovered in 20XX (?!)
$\to$ establish **Supergravity** !!

- What is Gravitino?

## Compare it with Electroweak Symmetry

Electroweak symmetry
→ spontaneously broken

Supergravity
→ spontaneously broken

**gauge boson mass**

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

$g$: gauge coupling

$\langle \varphi \rangle$: Higgs VEV

**gravitino mass**

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

$\sqrt{3} M_{\rm P}$: SUGRA coupling

$\langle F \rangle$: SUSY breaking VEV