Title: Long-lived Staus in the early Universe and at the LHC

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Abstract:

Long-lived Staus in the Early Universe and at the LHC

Koichi Hamaguchi (Tokyo U. and IPMU)

at BBN workshop, Perimeter Institute, May'08

based on the works

KH, T.Hatsuda, M.Kamimura, Y.Kino, T.T.Yanagida '07; (= M.Kamimura et.

KH, M.M.Nojiri, A.de Roeck '06;

KH, Y.Kuno, T.Nakaya, M.M.Nojiri '04;

W.Buchmüller, KH, M.Ratz, T.Yanagida '04

+ Buchmuller, Covi, KH, Ibarra, Yanagida,'07

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Summary

(Wine is waiting for us...)

- In SUSY, Gravitino LSP and Stau NLSP with a long lifetime $\tau > O(1)$ sec (especially > 1000 sec) is a natural choice.
  → may affect the BBN!

- It can be tested at the LHC!
  - can precisely measure the mass,
  - and hence the thermal relic abundance,
  - and if staus can be trapped, the lifetime can also be precisely measured !

Introduction

- As we've heard so far in this workshop,.....
- Charged particle X^- with $\tau_X > O(1)$ sec (especially > 1000 sec) [Catalyzed BBN, Pospelov,'06] may affect/jeopardize/help the BBN!
- I discuss such a possibility in SUSY.

- before discussing SUSY, some general comments on X^- :
- in general,.....

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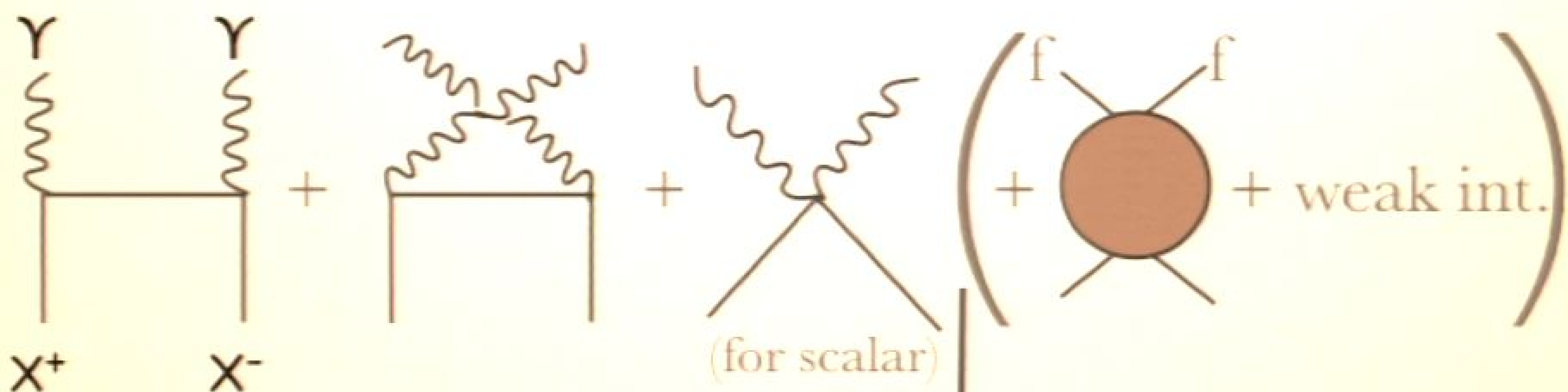
$$\left.\frac{n_{X^-}}{s}\right|_{\text{thermal relic}} = \mathcal{O}(0.1-1)\times 10^{-13}\left(\frac{m_X}{100\ \text{GeV}}\right)$$

$$\Longleftrightarrow \left.\frac{n_{X^-}}{n_B}\right|_{\text{thermal relic}} = \mathcal{O}(0.1-1)\times 10^{-3}\left(\frac{m_X}{100\ \text{GeV}}\right)$$



model independent, just QED!

$$\langle \sigma v(X^+X^- \to \gamma\gamma)\rangle = \frac{\pi\alpha_{\text{em}}^2}{m_X^2}\left(\begin{array}{l}\times 1 \text{ for fermion,}\\ \times 2 \text{ for scalar}\end{array}\right)$$

model dependent, but only O(1) effects

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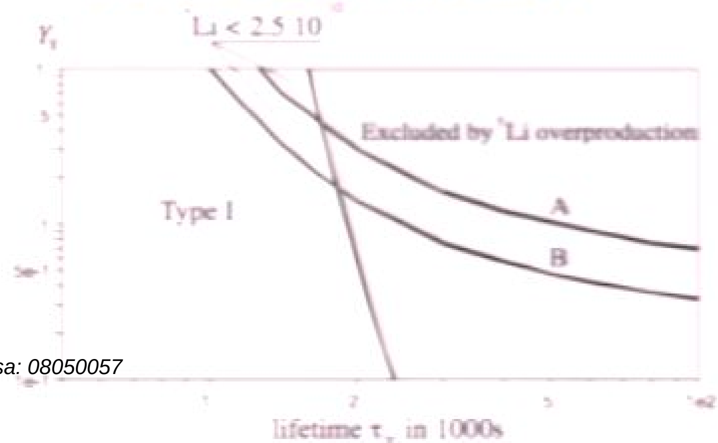
- Thus, e.g., $n_{X^-}/n_B \gtrsim 0.04$ requires $m_X > \mathcal{O}(\text{TeV})$.

(exception: non-therm production

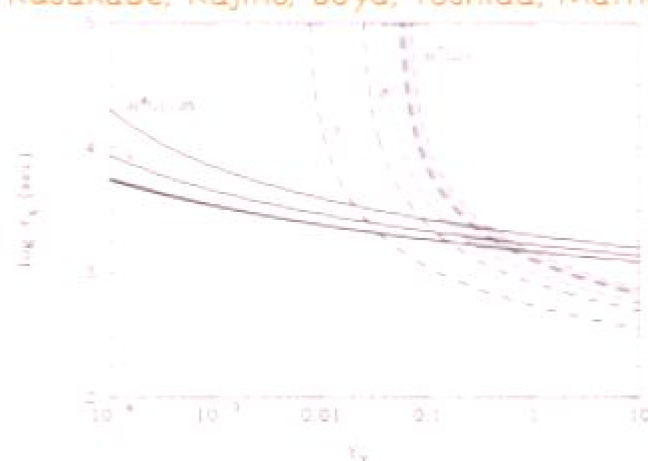
cf. possible solution to ^{7}Li problem

hard to se at the LHC

Bird, Koopmans, Pospelov,'07;



Kusakabe, Kajino, Boyd, Yoshida, Mathews'07



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- On the other hand, $m_X \gtrsim 100\ \text{GeV (LEP bound)}$

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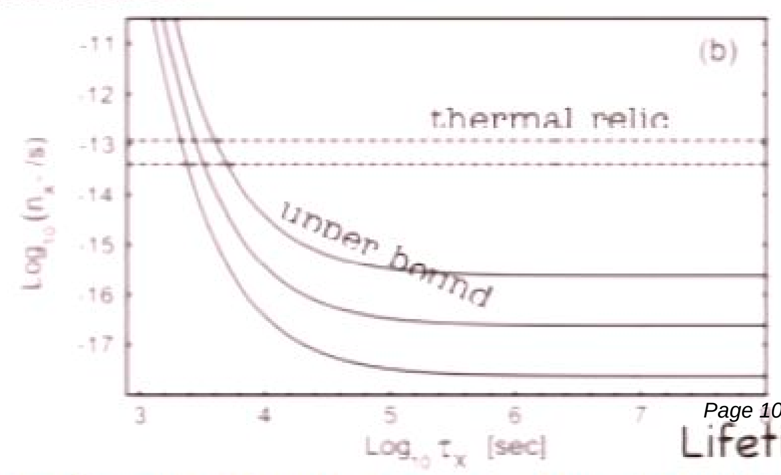
- On the other hand, $m_X \gtrsim 100\ \text{GeV (LEP bound)}$

$$\Longrightarrow n_{X^-}/s \gtrsim \mathcal{O}(0.1-1)\times 10^{-13}$$

$$\Longrightarrow \tau_X < 10^4\ \text{sec} \quad (^6\text{Li})$$

M.Pospelov'06 + others

abundance



Lifetime

exception:
entropy production / low reheating
cf. Buchmuller, KH, Ibe, Yanagida,06; Takayama,07

now let's discuss in the framework of SUSY...

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In SUSY, a long-lived charged particle
is realized in models with

Gravitino LSP

+

Stau NLSP

LSP = the Lightest SUSY Particle
NLSP = the Next-to-Lightest SUSY Particle

another possibility:
neutralino LSP + stau NLSP
with degenerate masses
(cf. ..., Kohri, Koike, Sato,
Shimomura, Yamanaka,'07, '08)

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But,...

- Why Gravitino LSP?
- (What is Gravitino?)
- Why Stau NLSP?
- Why τ_{stau} > 1 sec (or O(1000) sec) ?
- How natural are those choices from particle physics viewpoint?

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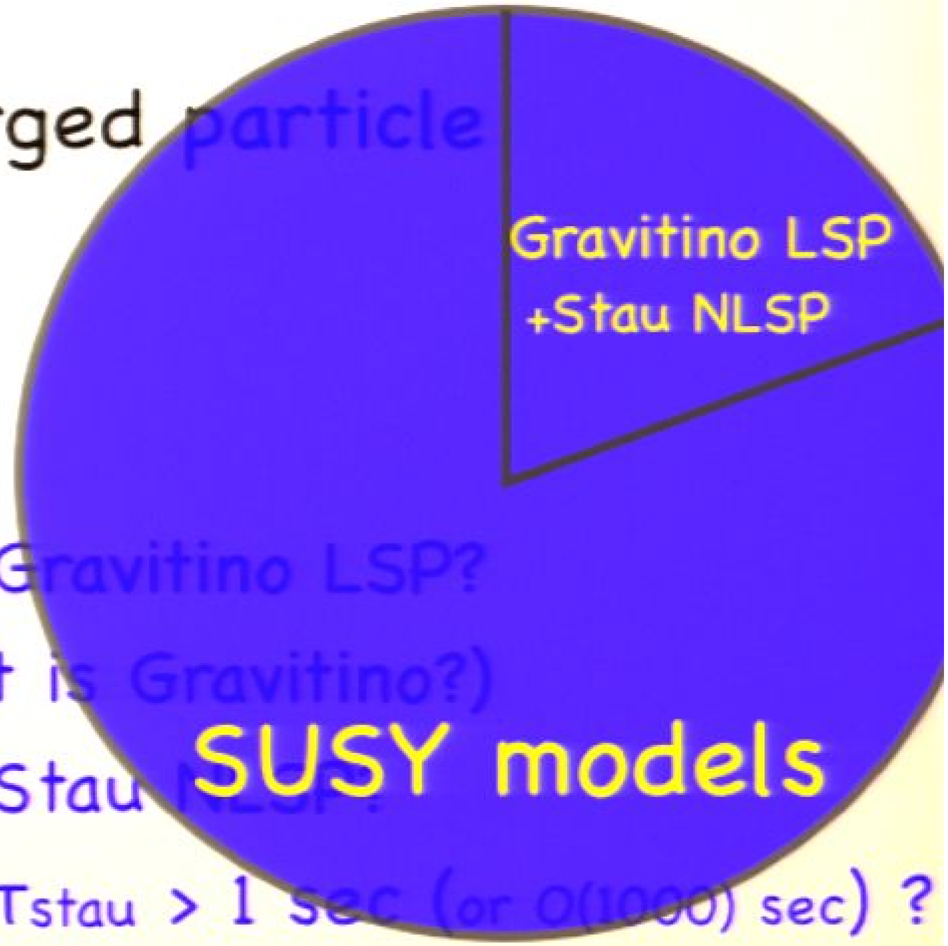

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- What is Gravitino?

What is Gravitino?

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

Standard Model

What is Gravitino?

Supersymmetry (SUSY)

		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 $\tilde{h}$

(1) solves the naturalness problem

(2) leads to coupling unification

(3) has dark matter candidate

What is Gravitino?

Supersymmetry (SUSY)

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graviton e_μ^α

- What is Gravitino?

Superstring $\supset$ Supergravity

Supergravity

Supersymmetry (SUSY)

	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	$2 \longleftrightarrow \frac{3}{2}$	gravitino $\tilde{G}$

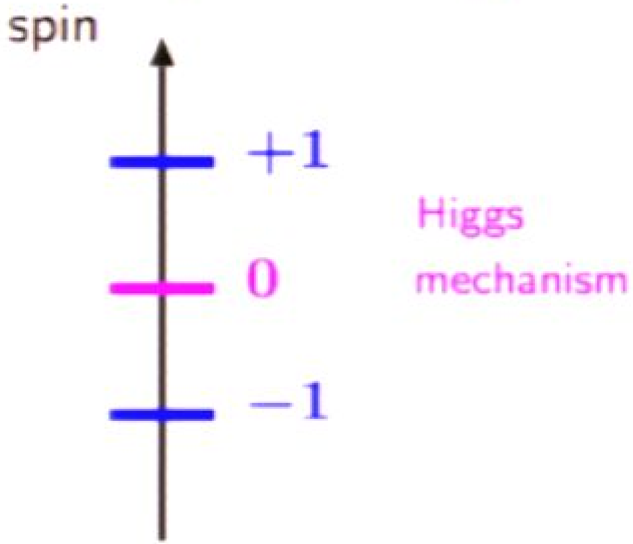
extremely weakly interacting

What is Gravitino?

Compare it with Electroweak Symmetry

Electroweak symmetry

→ spontaneously broken



Z, W bosons

→ discovered in 1983

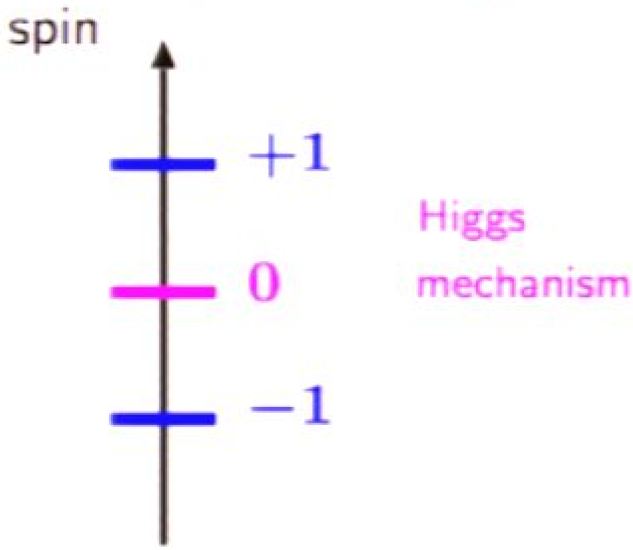
→ establish Standard Model

- What is Gravitino?

Compare it with Electroweak Symmetry

Electroweak symmetry

→ spontaneously broken



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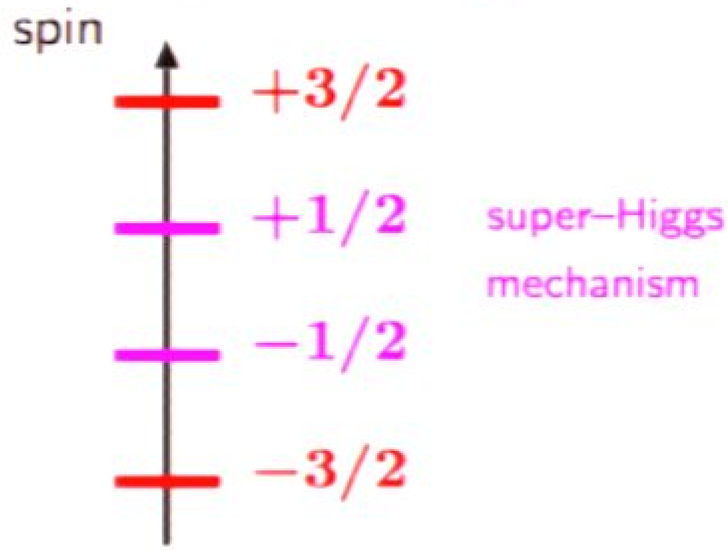

Gravitino

→ discovered in 20XX (?!)

→ establish **Supergravity** !!

- What is Gravitino?

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 ?

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- ..... among 29 SUSY particles?

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

- Why Gravitino LSP ?

Dark Matter in SUSY

R-parity ... to avoid too rapid baryon/lepton number violation

Standard Model particle:	$A \rightarrow A$
SUSY partner particle:	$B \rightarrow -B$

Interactions

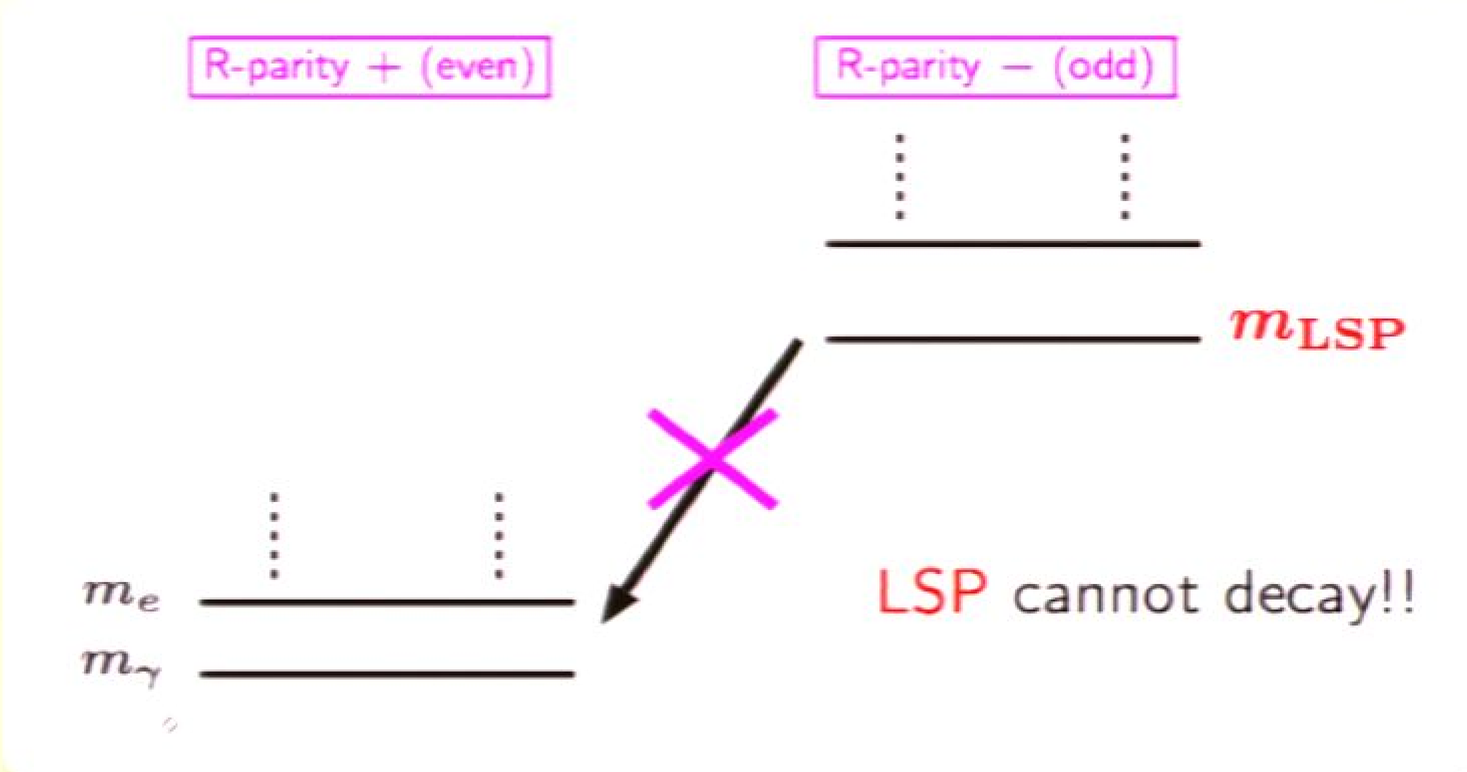
- $B\ A_1\ A_2$ .... forbidden ✕ $B \rightarrow A_1 + A_2$
  $-\ +\ +$
- $B_1\ B_2\ A$ .... allowed ◎ $B_1 \rightarrow B_2 + A$
  $-\ -\ +$

• 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 : $\begin{pmatrix} \widetilde{u_L} \\ \widetilde{d_L} \end{pmatrix}_i \quad \begin{matrix} \widetilde{u_{Ri}} \\ \widetilde{d_{Ri}} \end{matrix}$ 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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excluded by direct detection experiment (cf. Falk, Olive, Srednicki,'94

neutral and color-singlet

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neutral and color-singlet

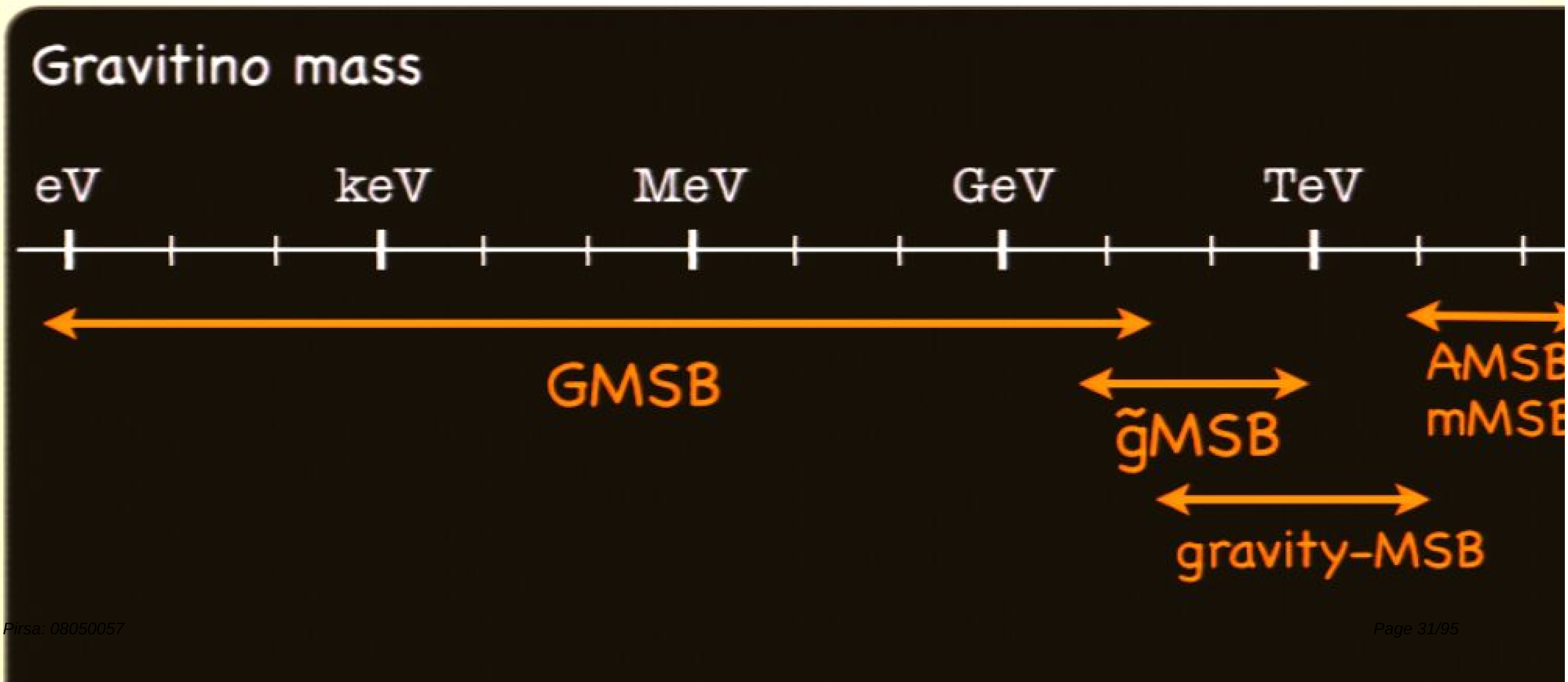
Only Neutralino and Gravitino are viable candidates!

- Why Gravitino LSP ?

experimental bound — naturalness

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

- Gravitino mass..... model dependent.



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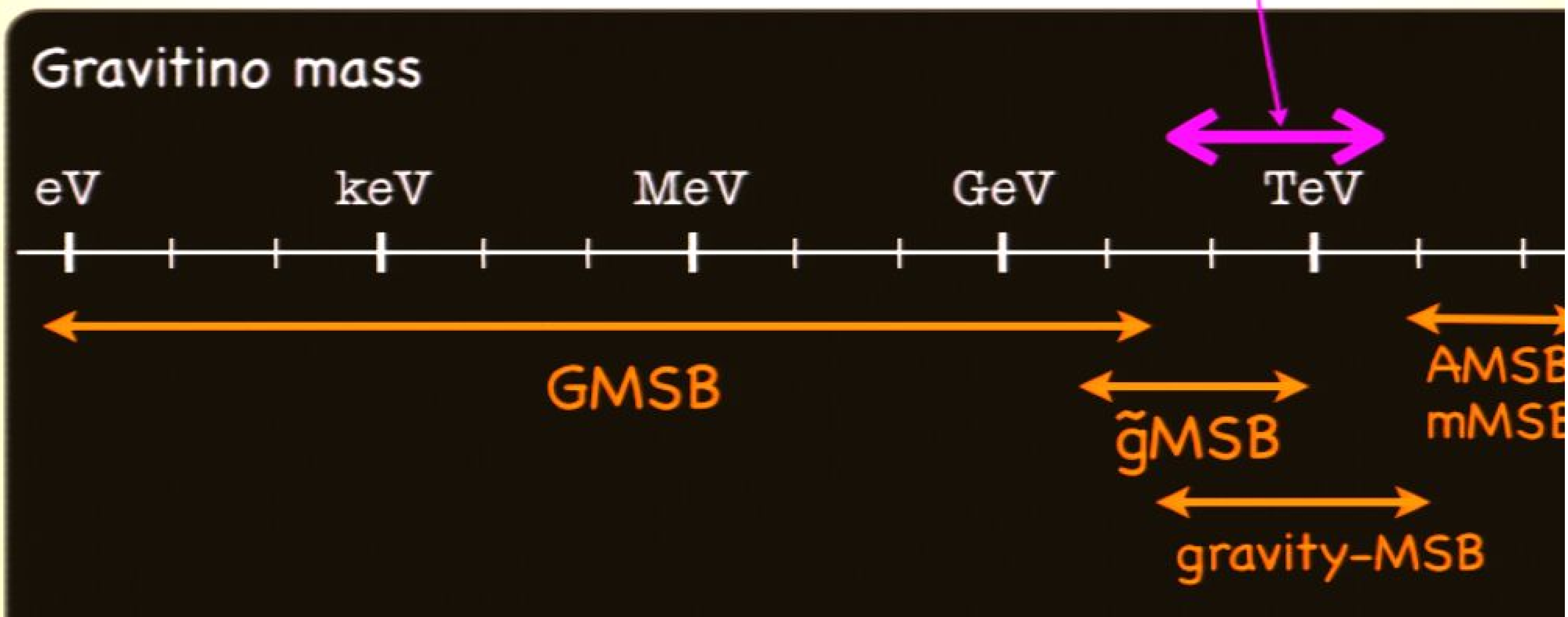

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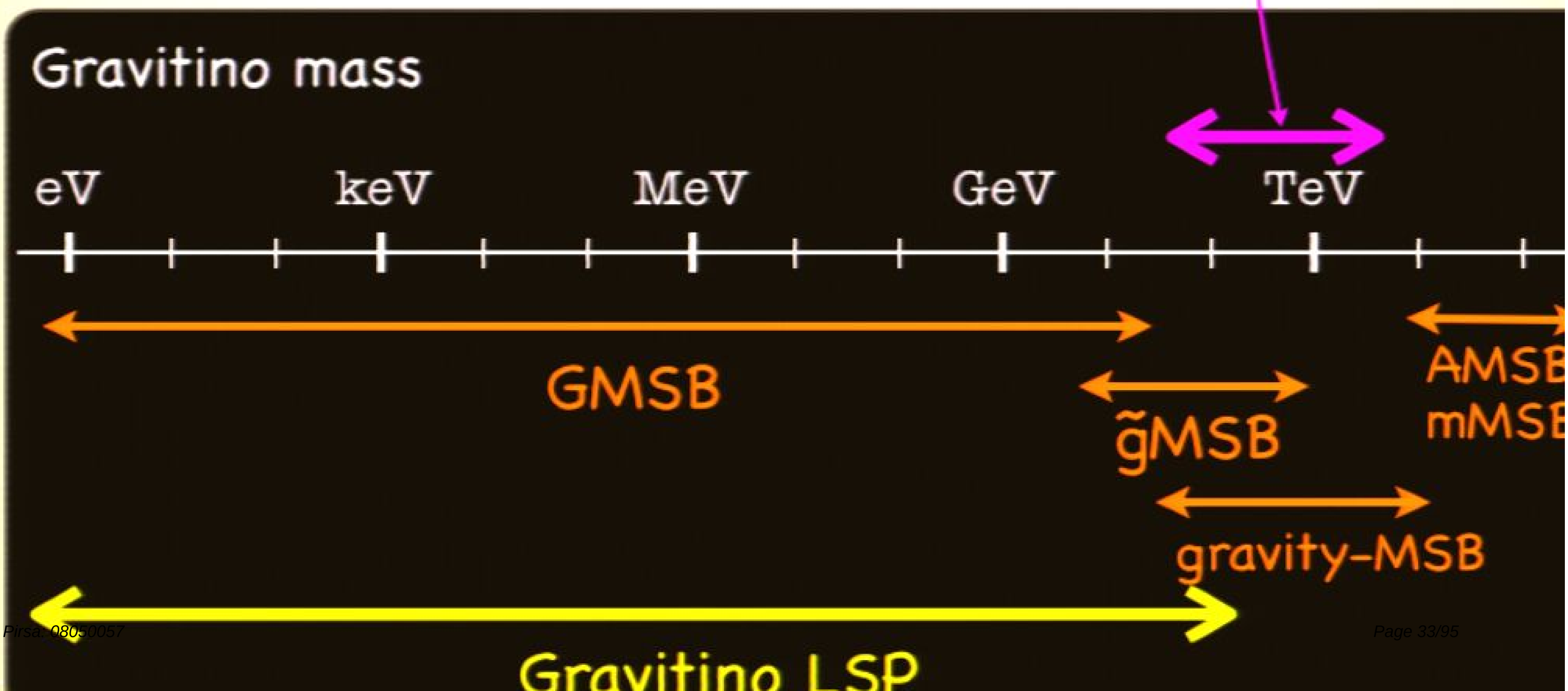

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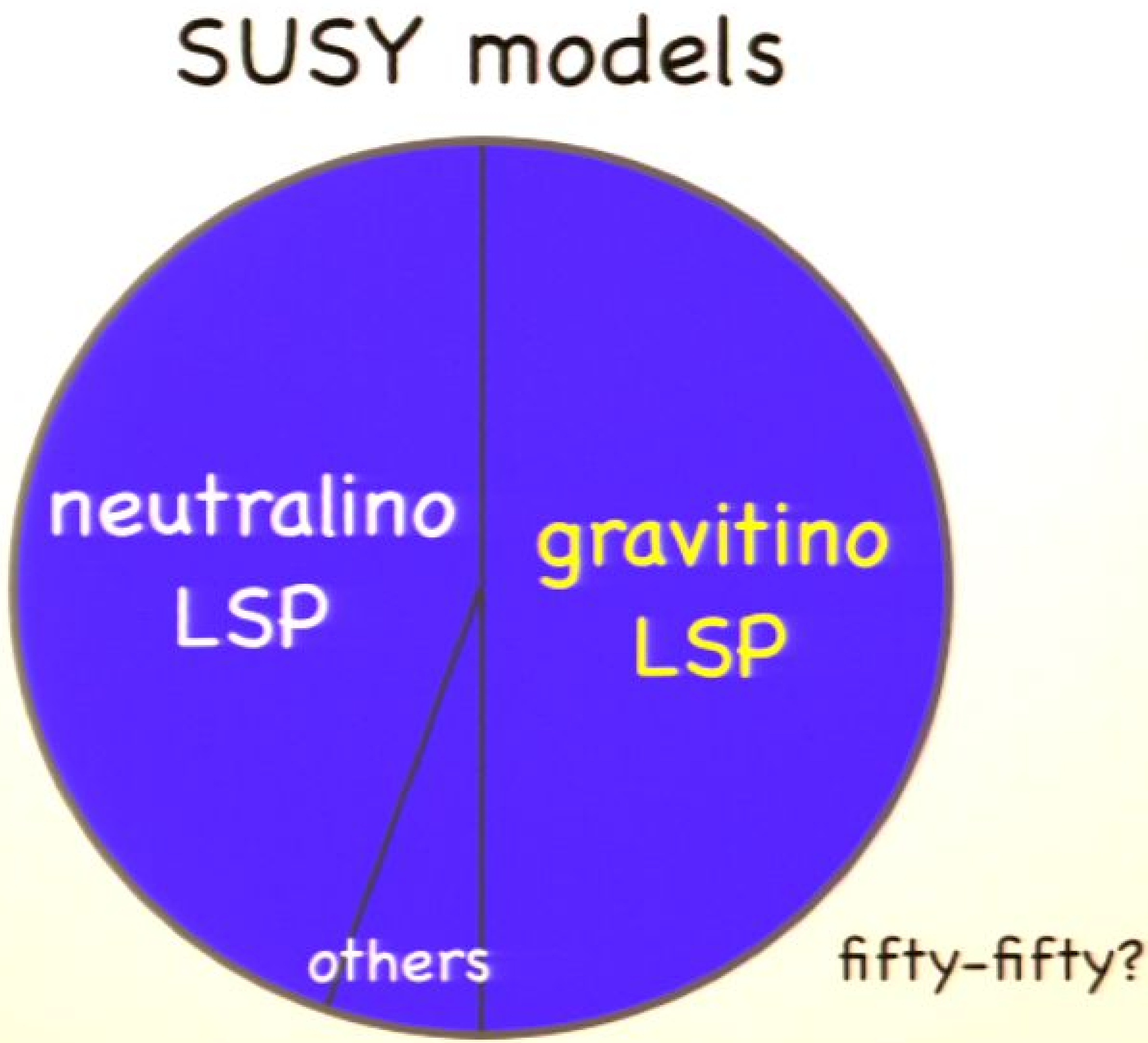
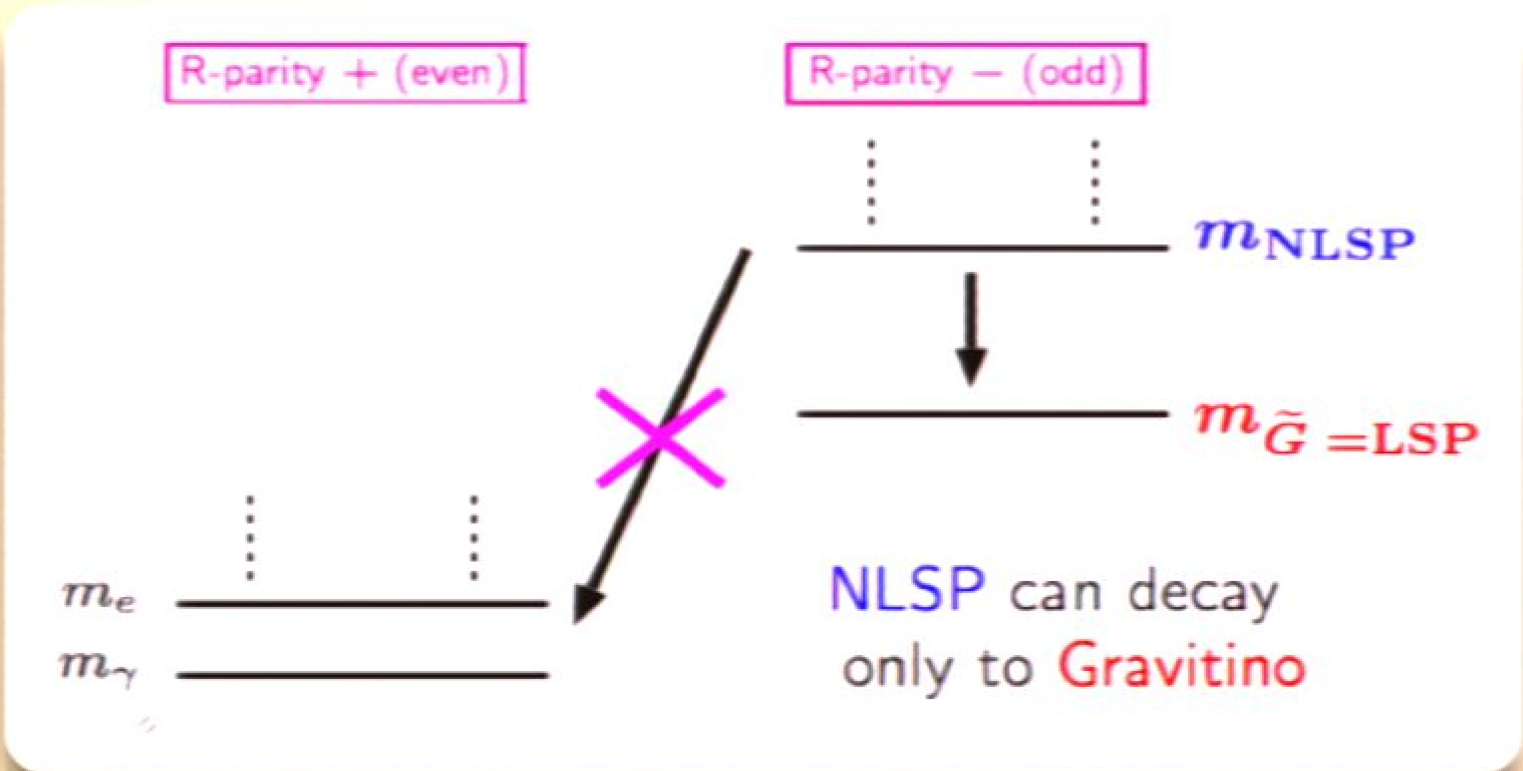


NLSP (Next-to-Lightest SUSY Particle)

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



extremely weak interaction

- Why Stau NLSP ?

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- ..... among 28 NLSP candidates?

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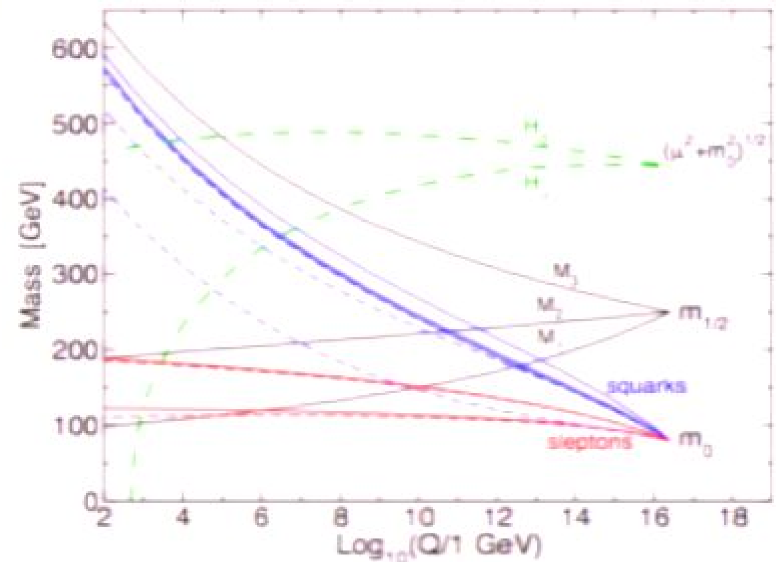
stau (i=3)

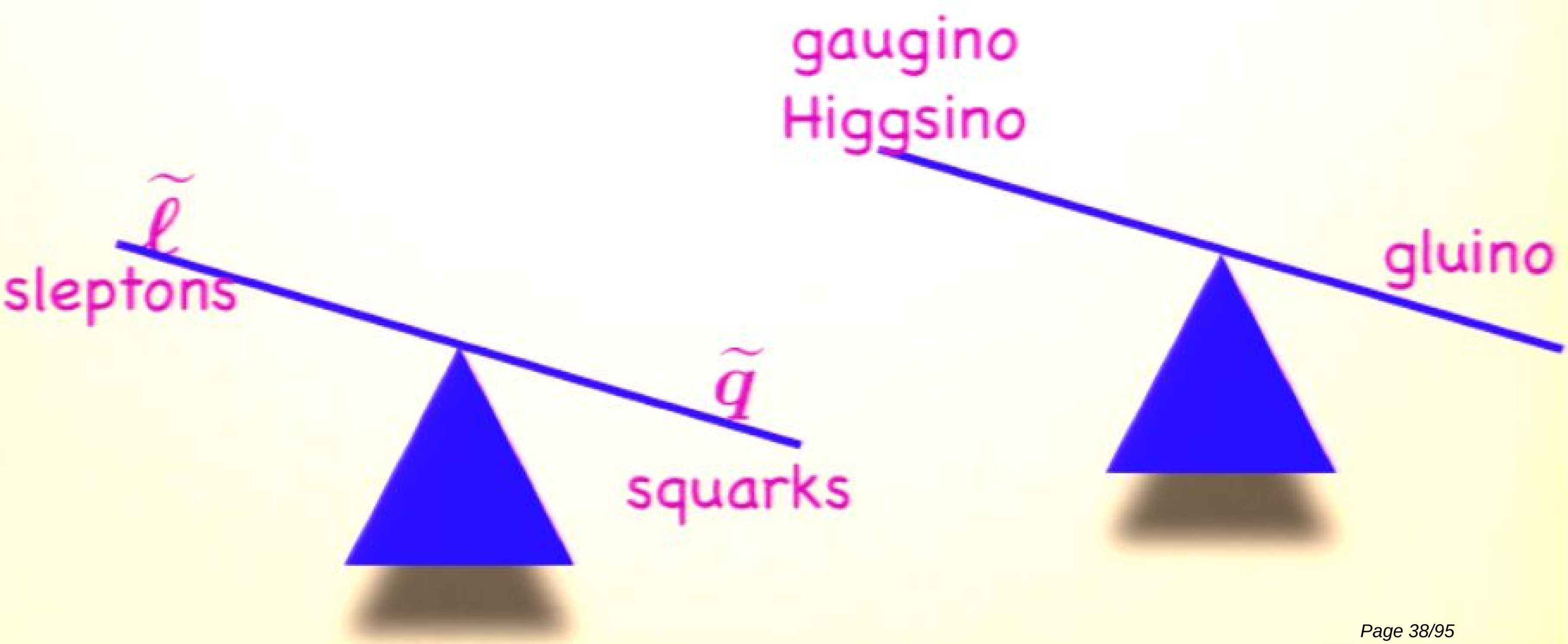
gauginos and higgssinos : $\widetilde{\chi_i^0}, \quad \widetilde{\chi_i^\pm}, \quad \tilde{g}$

gravitino : $\widetilde{G}$

- Why Stau NLSP ?
  - In general, from RGE, tendency is
    - M(color singlet) < M(colored)



typical RG evolution (from S.P.Martin, hep-ph/97093



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  - In general, from RGE, tendency is
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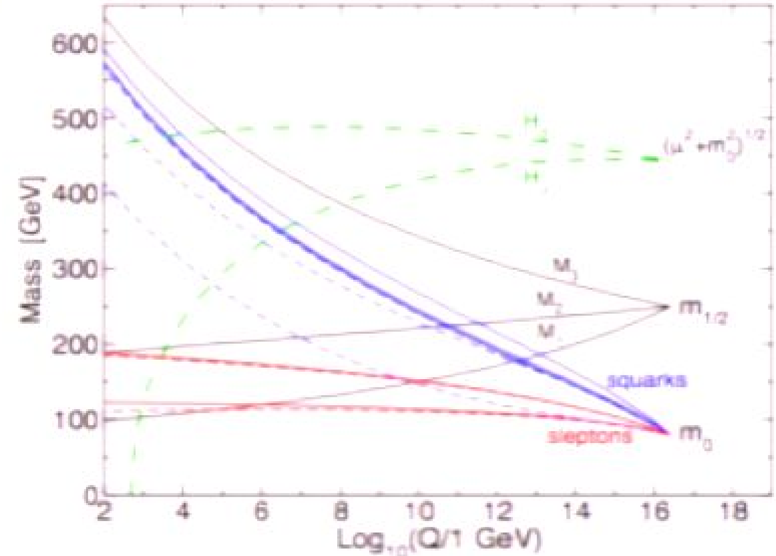
    - M(weak singlet) < M(weak charged)



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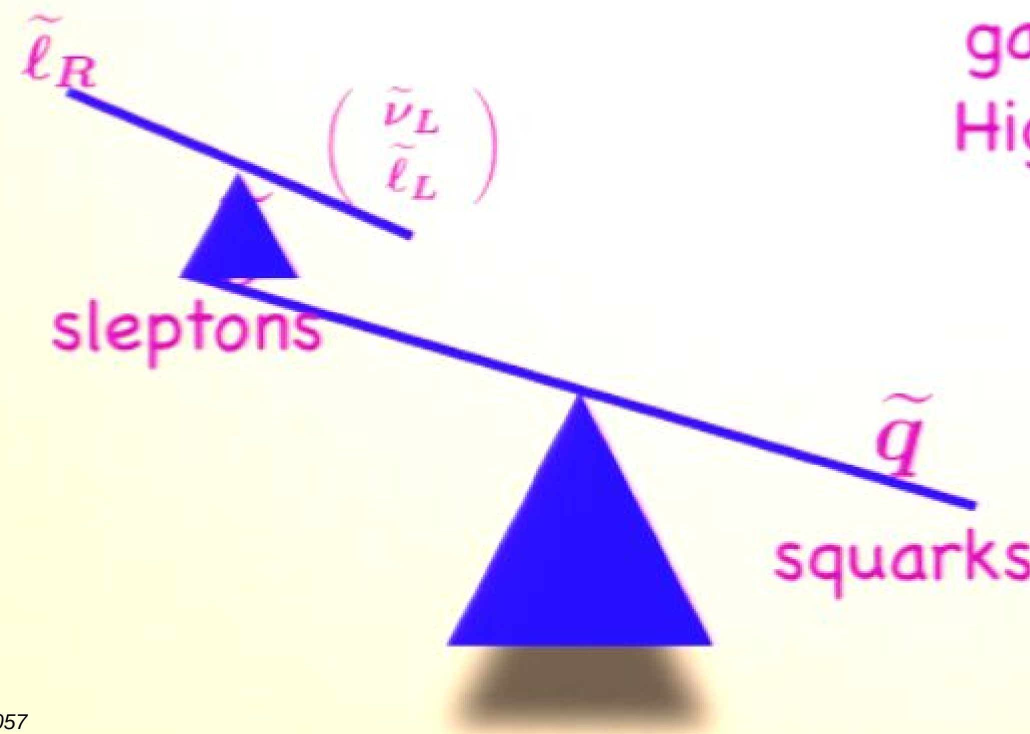

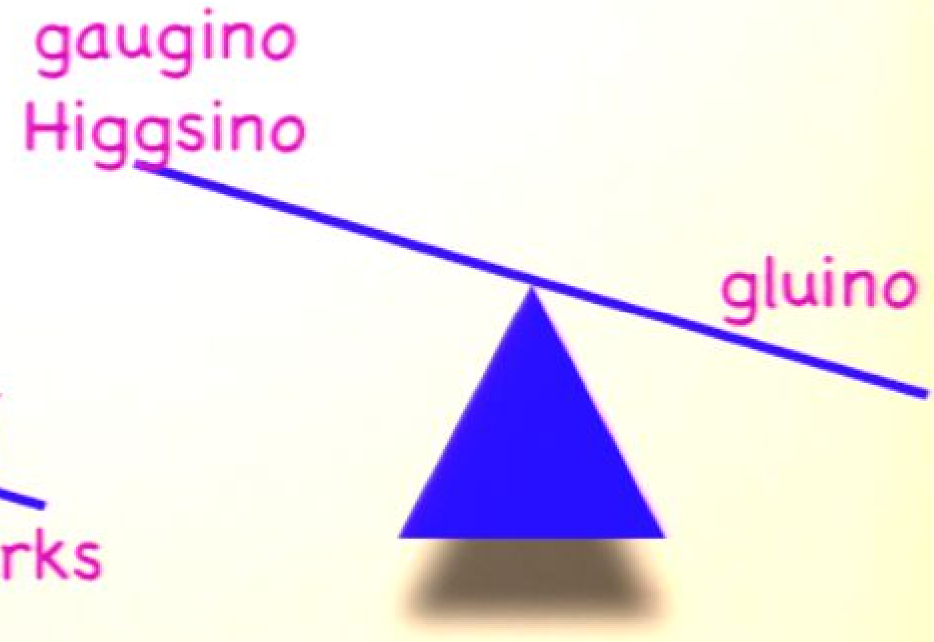

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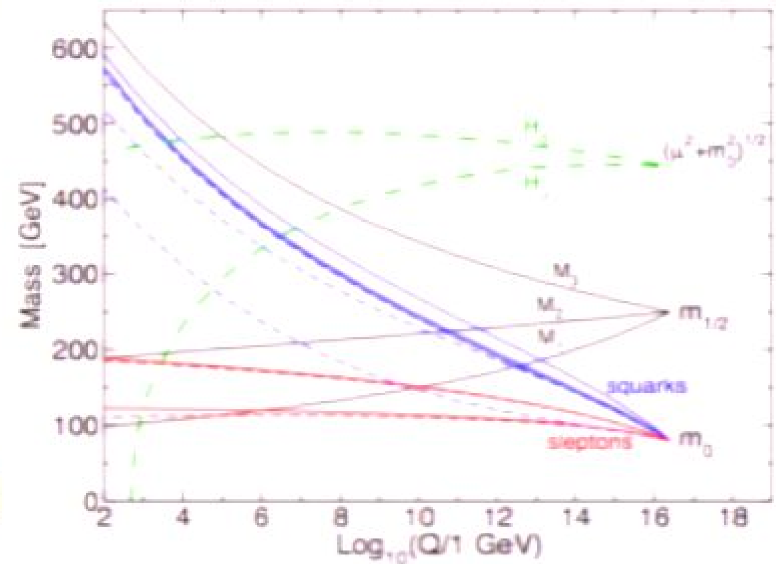
    - M(3rd family) < M(1st and 2nd family)



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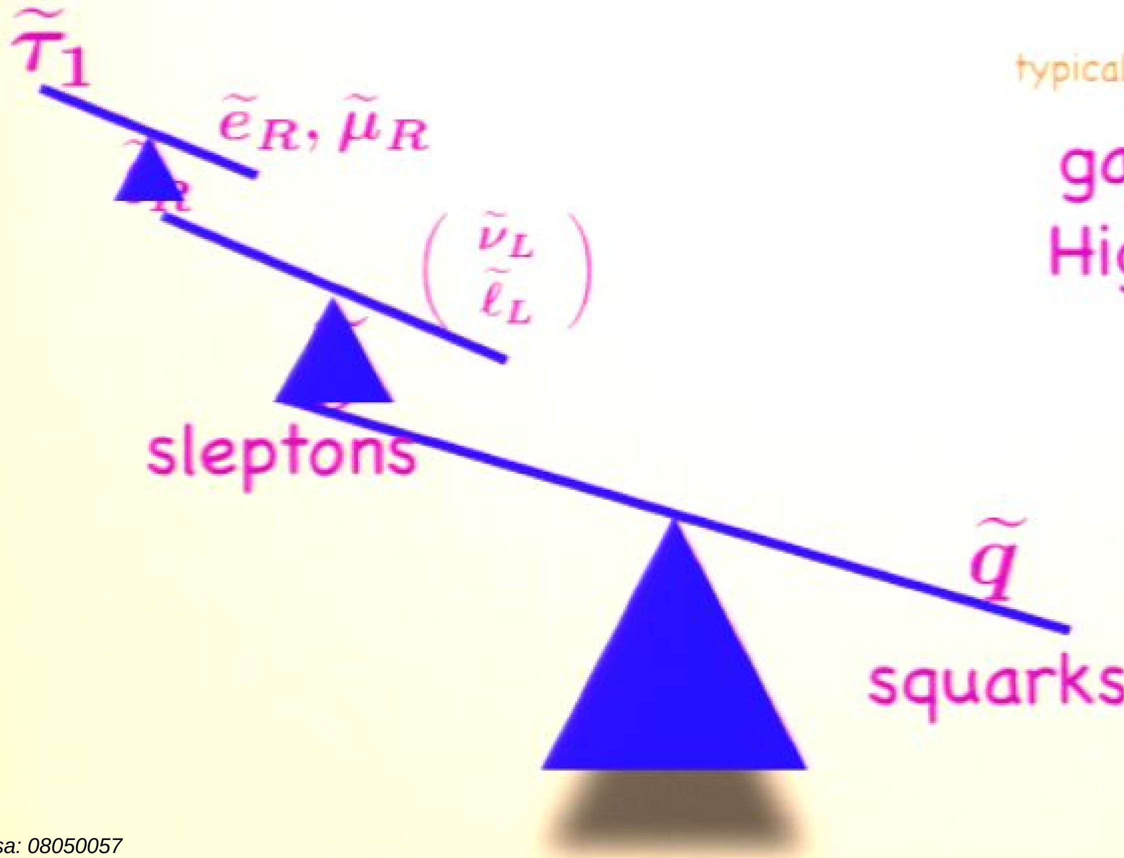

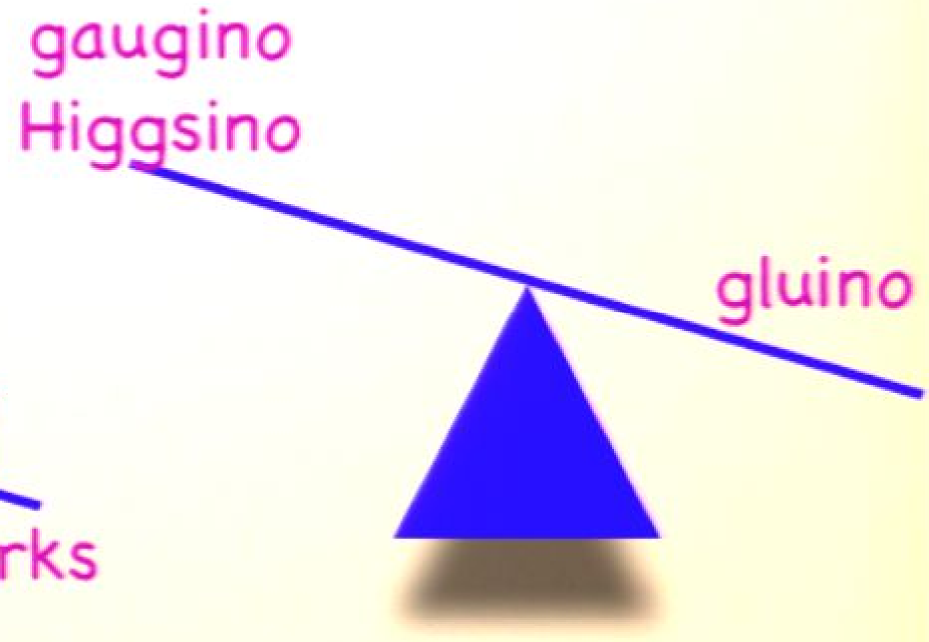

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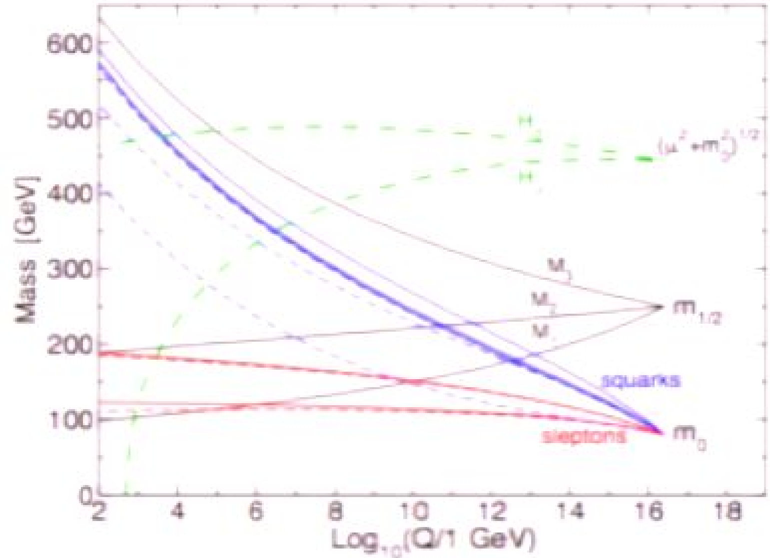

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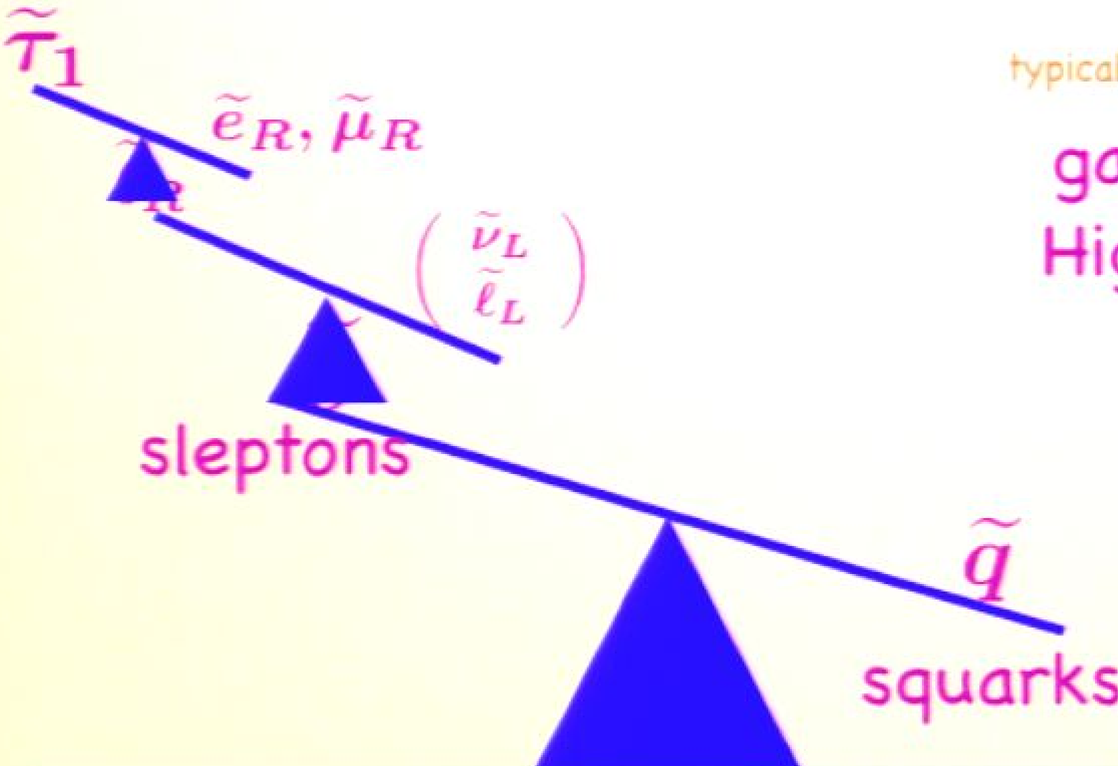
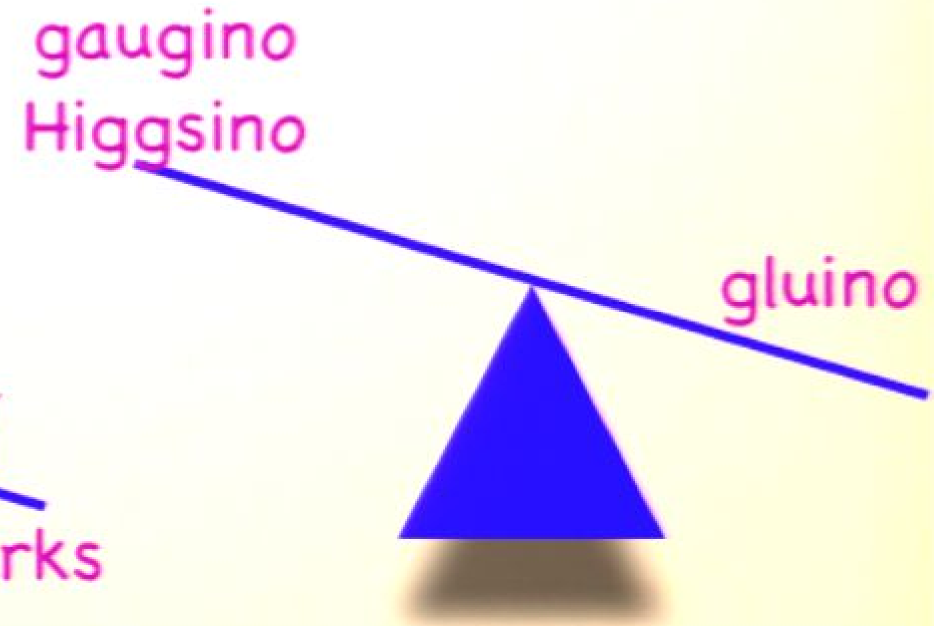
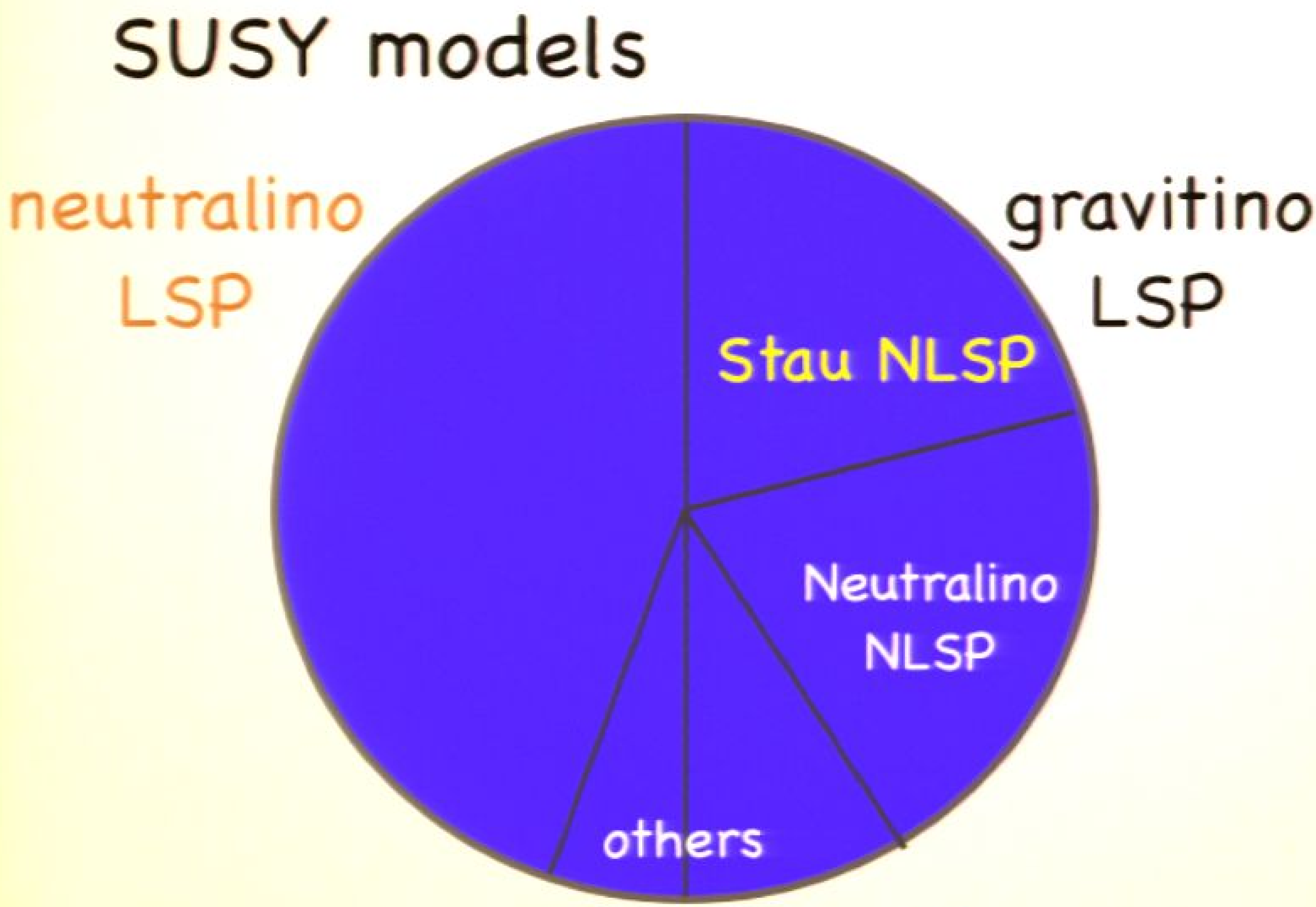




- In most cases, either Stau or Neutralino is the NLSP

- Why Stau NLSP ?



- Gravitino LSP and Stau NLS[P]

is a natural choice

- Why $\tau_{stau} > 1$ sec (or O(1000) sec) ?

- Why τ_{stau} > 1 sec (or O(1000) sec) ?

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

Lifetime of Stau

e.g., for m(stau) = 200 GeV

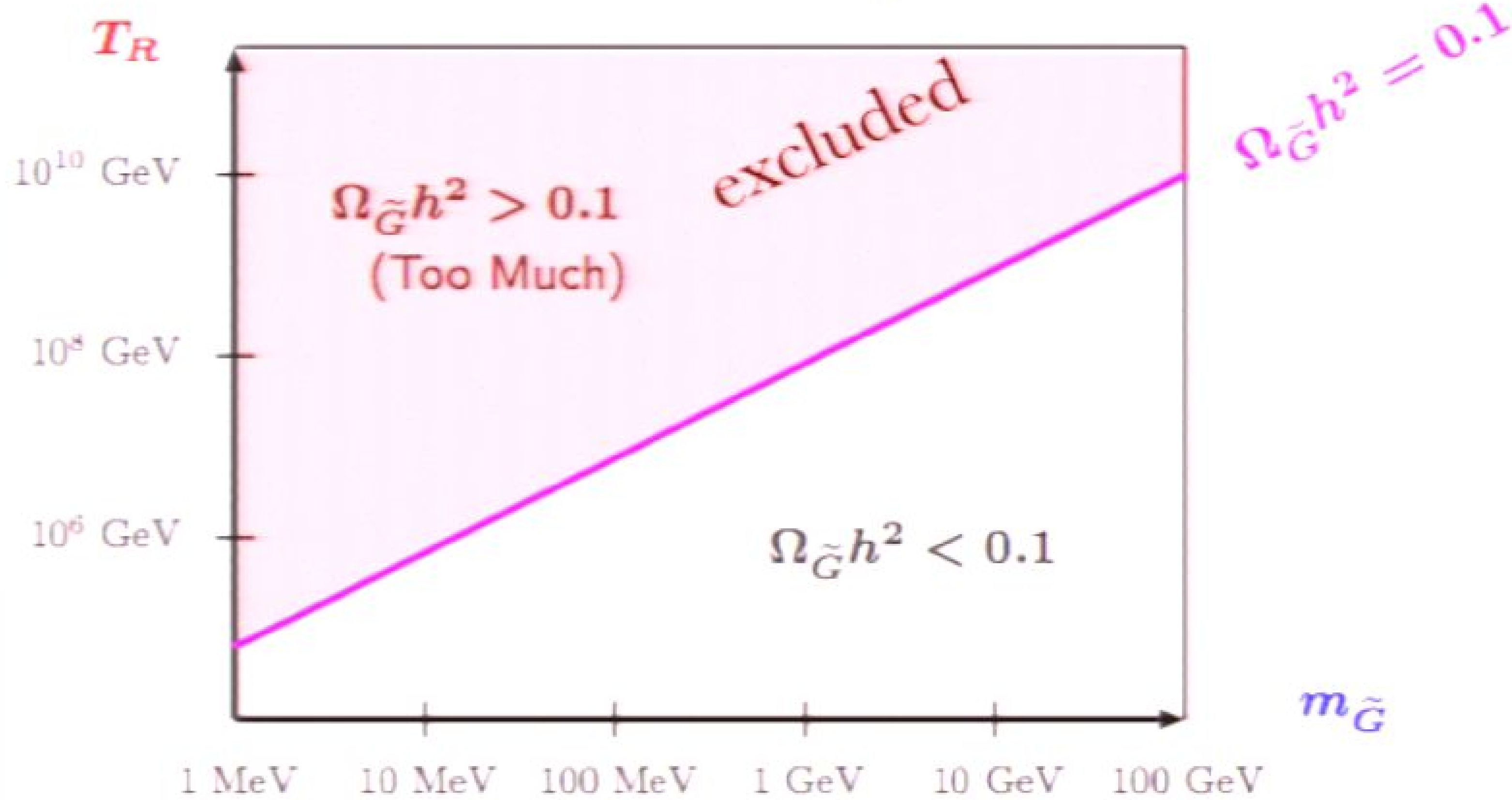
- Why Ts

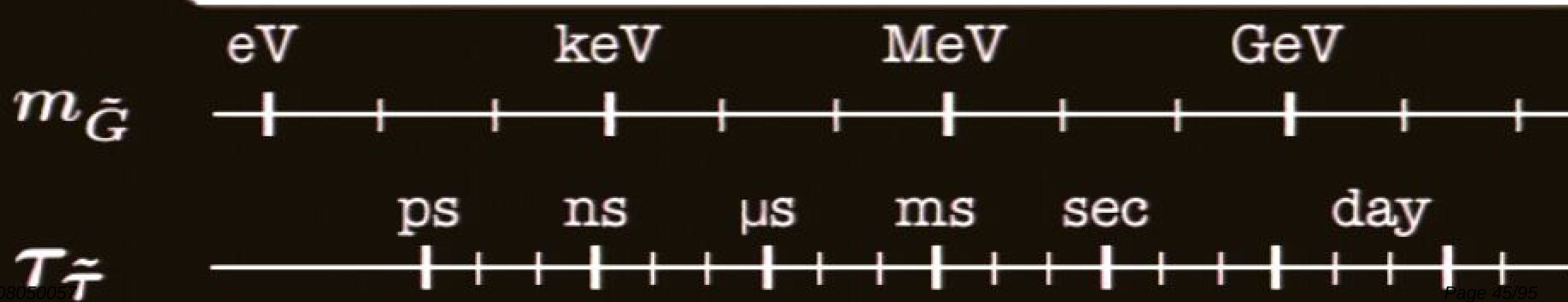
Γ(

Lifetime

- Gravitino Problem (for stable gravitino)

cf. talks by F.D.Steffen and J.Pradler.





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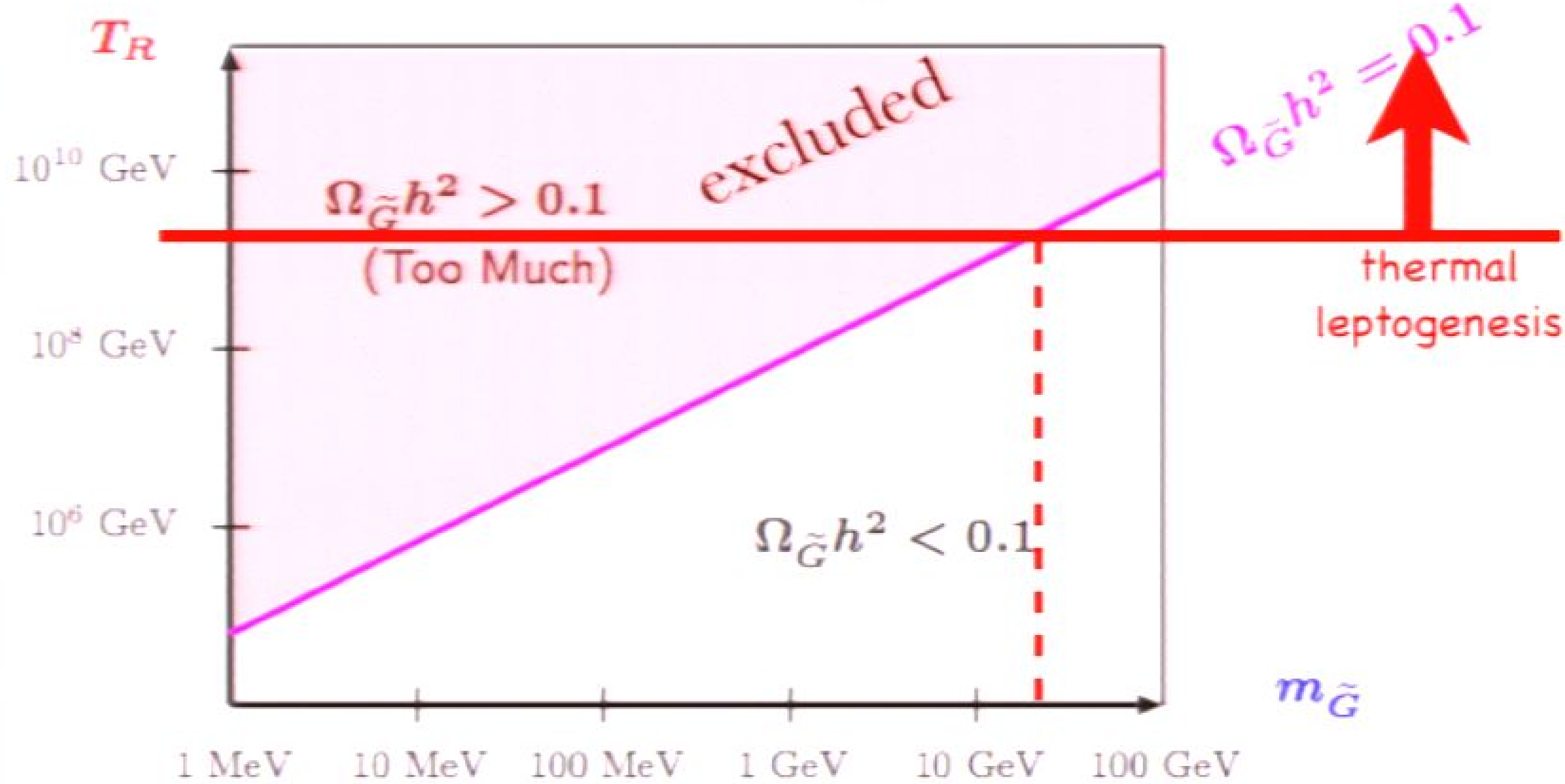

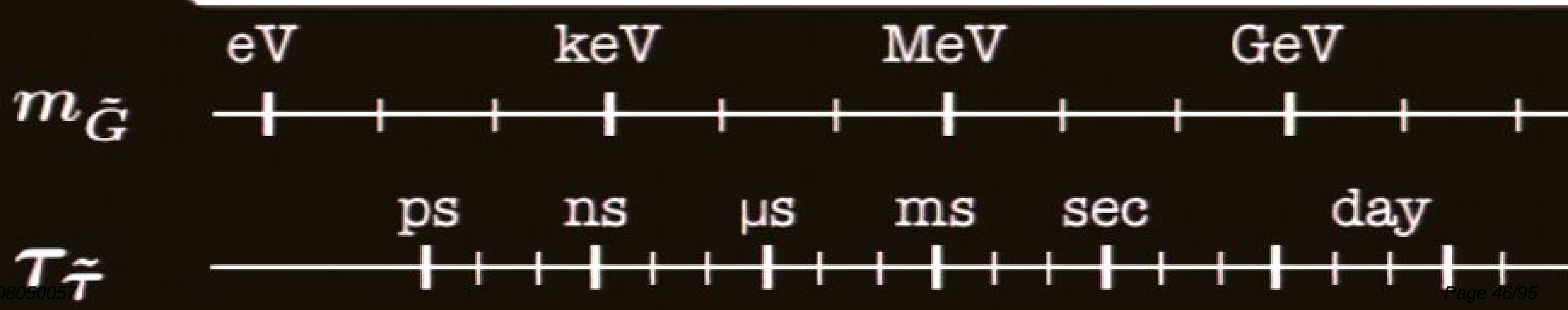

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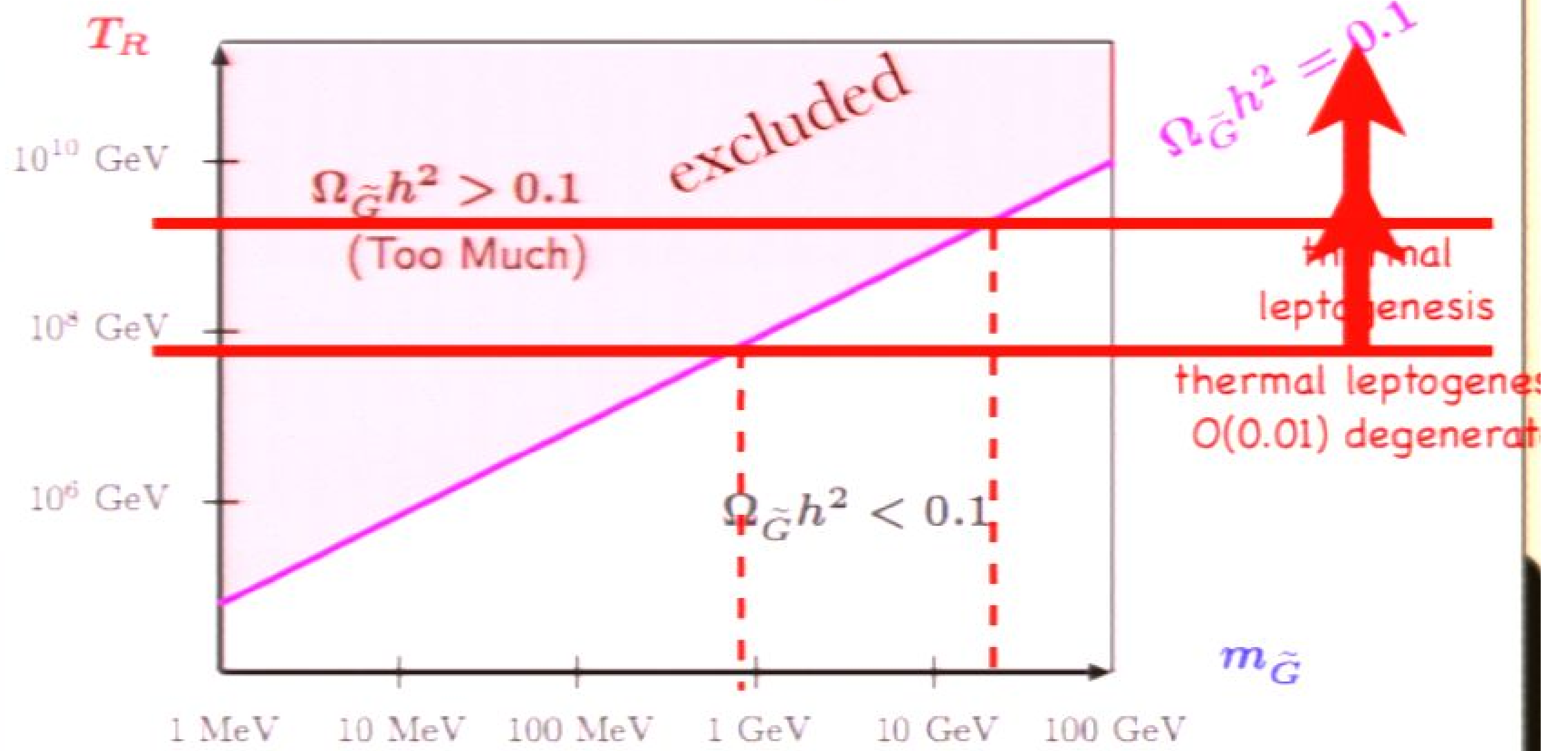

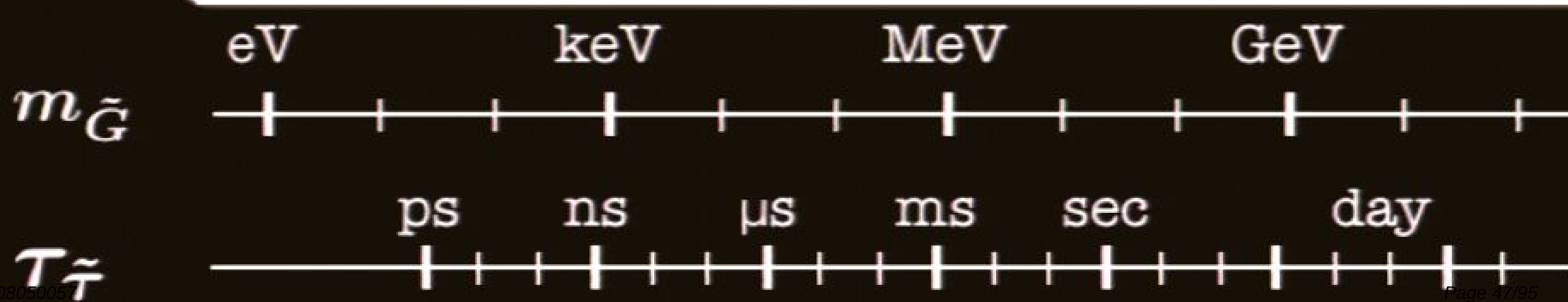

- Why Ts

Γ(

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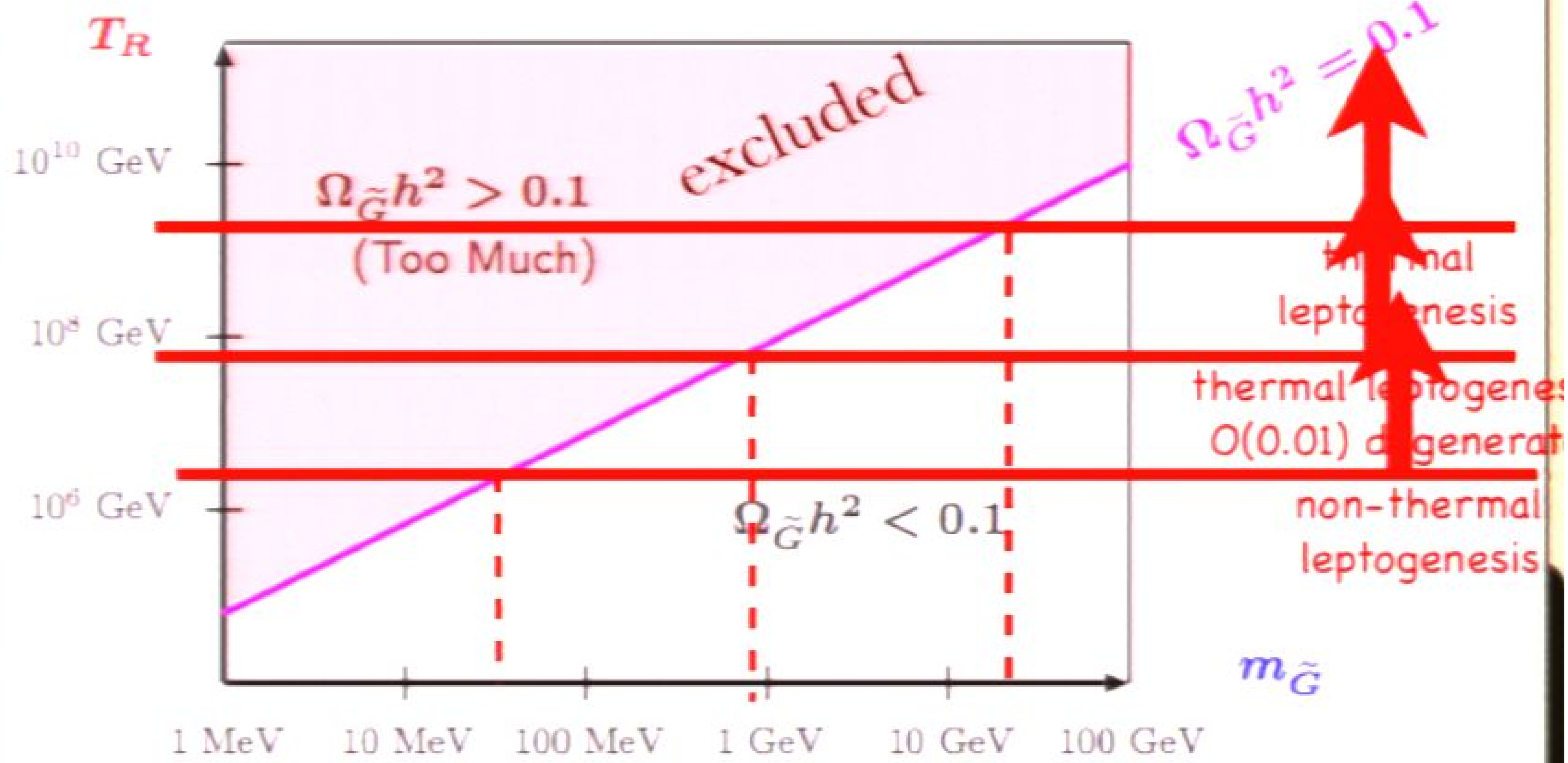
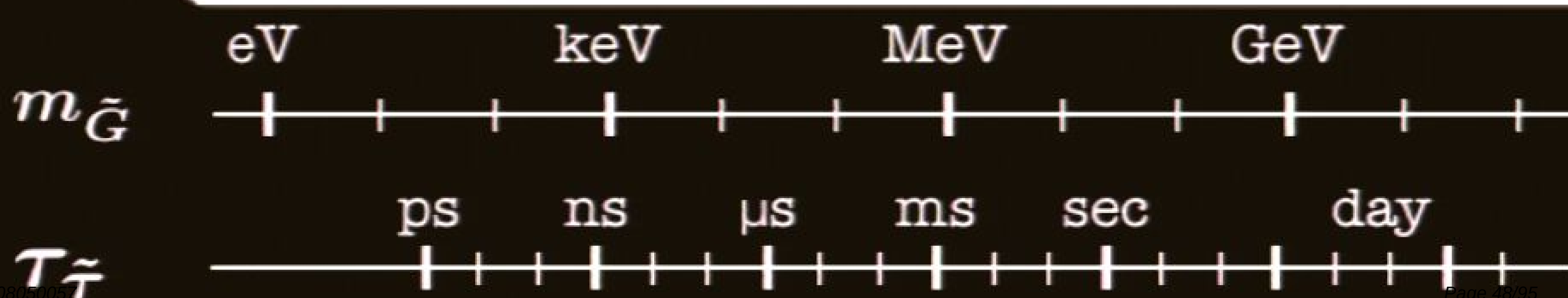
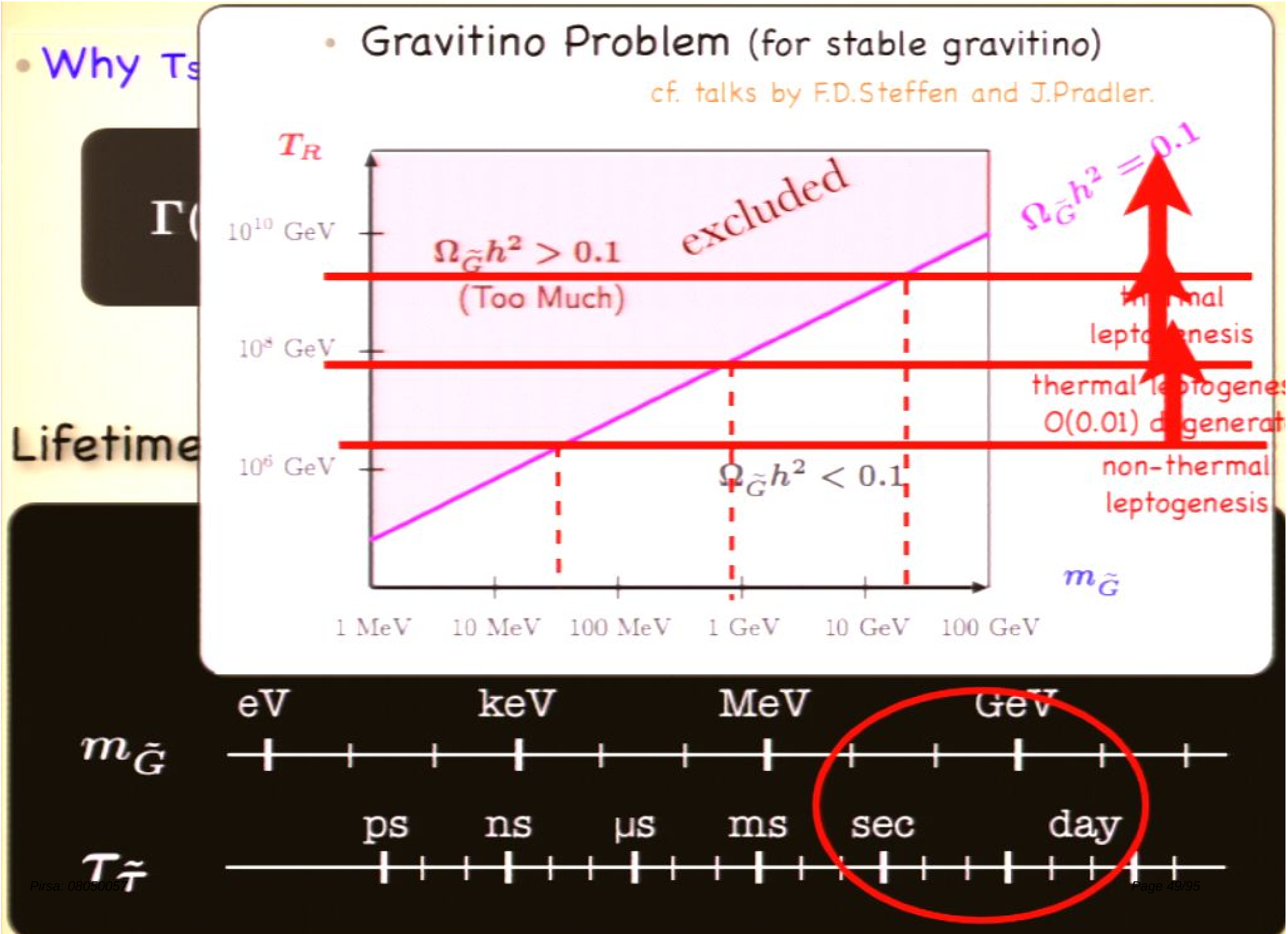


Lifetime





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T_R
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10^8 GeV
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excluded
$\Omega_{\tilde{G}}h^2 > 0.1$
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leptogenesis
non-thermal
leptogenesis
$m_{\tilde{G}}$
1 MeV
10 MeV
100 MeV
1 GeV
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100 GeV
eV
keV
MeV
GeV
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ps
ns
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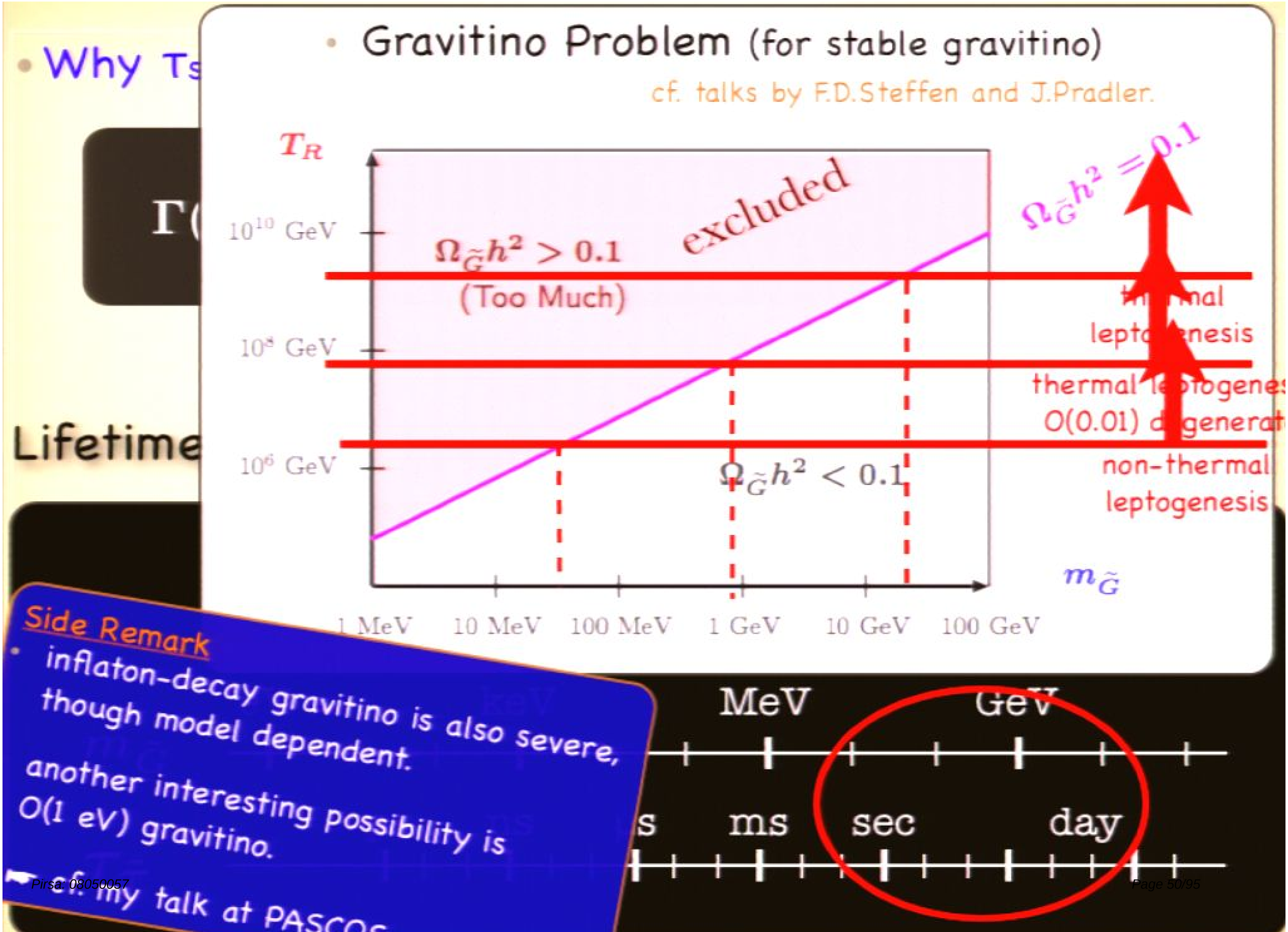
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non-thermal leptogenesis
$m_{\tilde{G}}$
1 MeV
10 MeV
100 MeV
1 GeV
10 GeV
100 GeV
Side Remark
inflaton-decay gravitino is also severe, though model dependent.
another interesting possibility is O(1 eV) gravitino.
cf. my talk at PASCOS
MeV
GeV
s
ms
sec
day

Another Side Remark

- thermal leptogenesis TR > 10^9GeV → mG > O(10) GeV
- → Tstau >> 1000 sec. → excluded?? (unless diluted)

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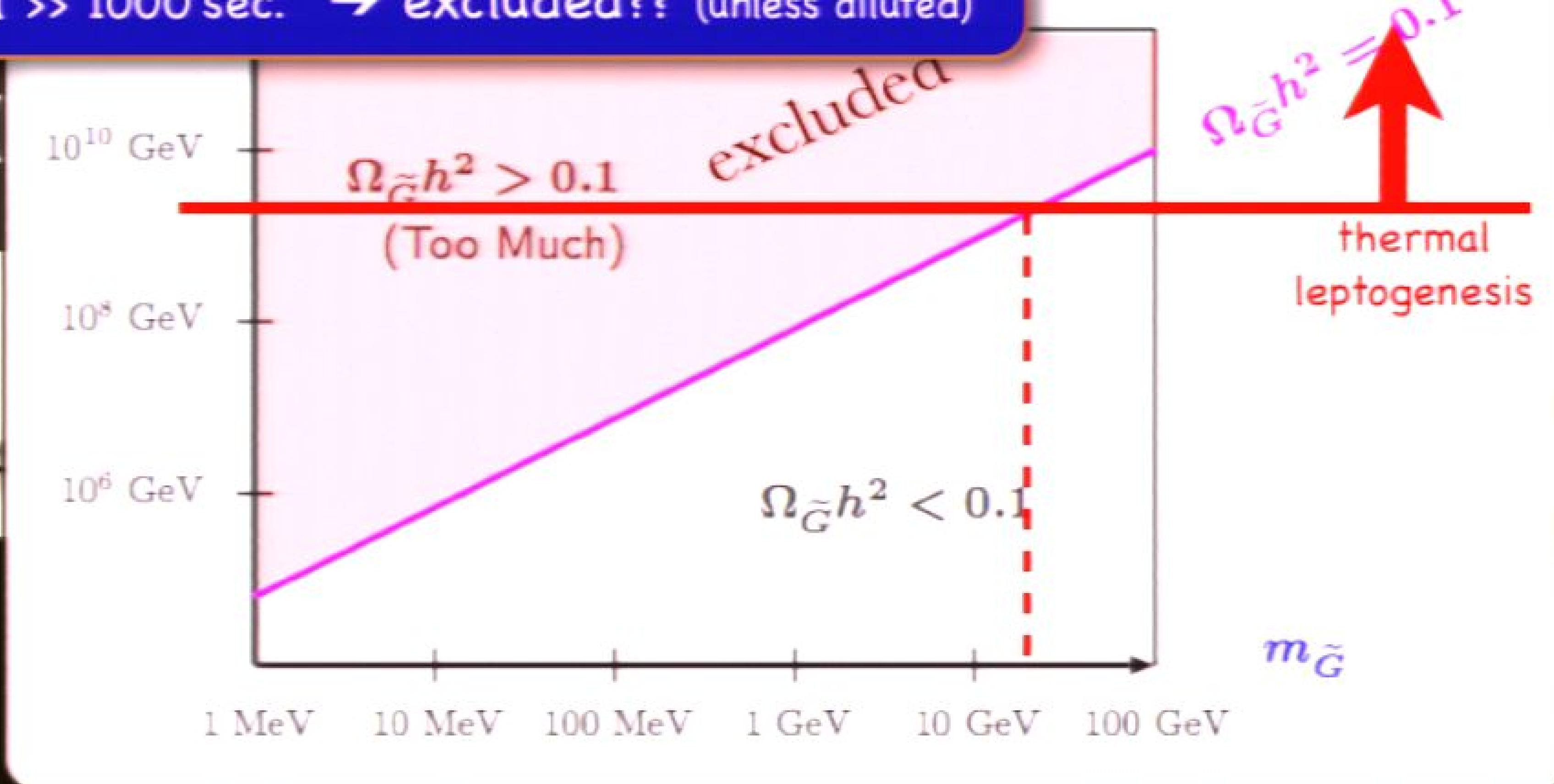
Γ(



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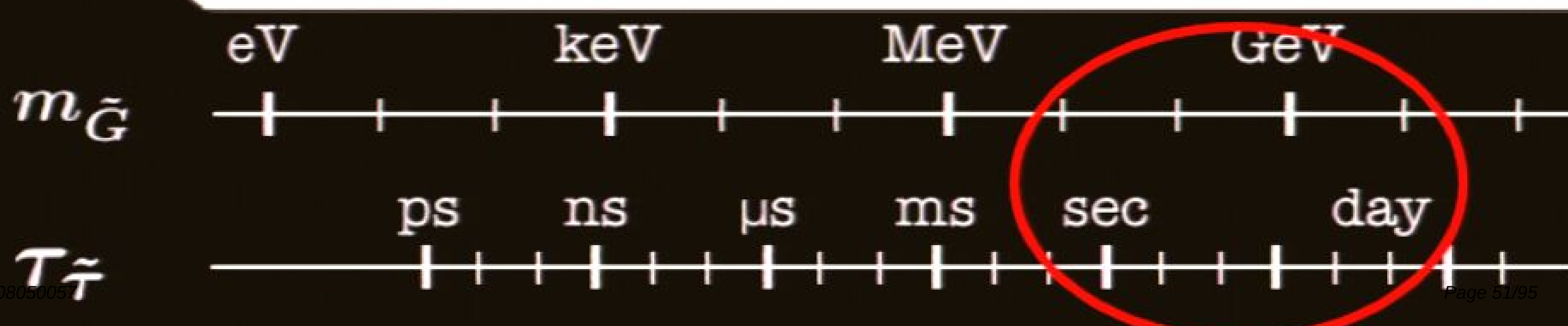

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A solution: a small R-parity violation can help it.

- $\lambda > 10^{-14}$ is large enough to make Tstau < 1000 sec,
- $\lambda < 10^{-7}$ is small enough to satisfy the constraints including baryon washout,
- and to make the gravitino stable, i.e. $T_{gravitino} > T_{universe}$.
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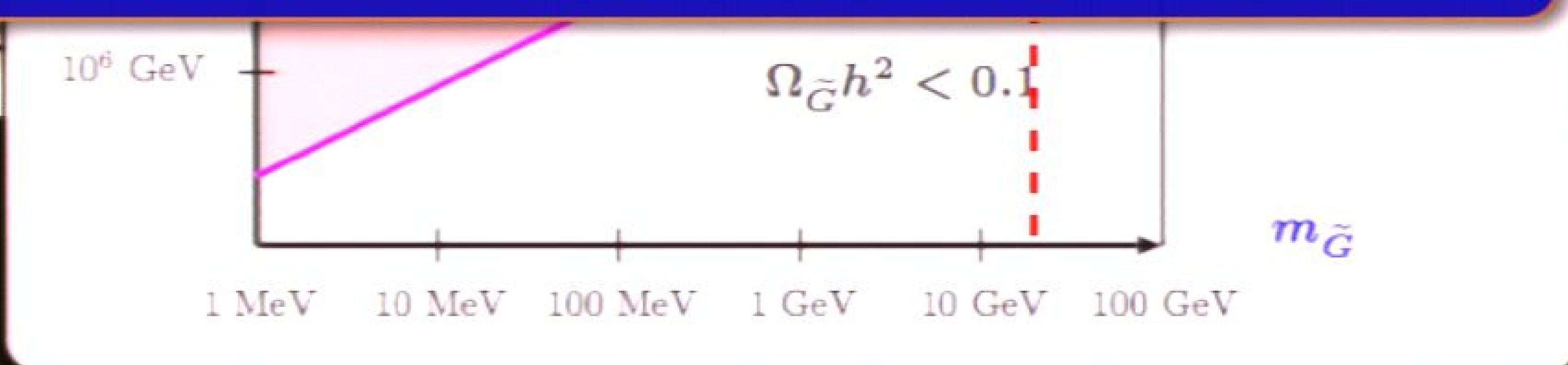

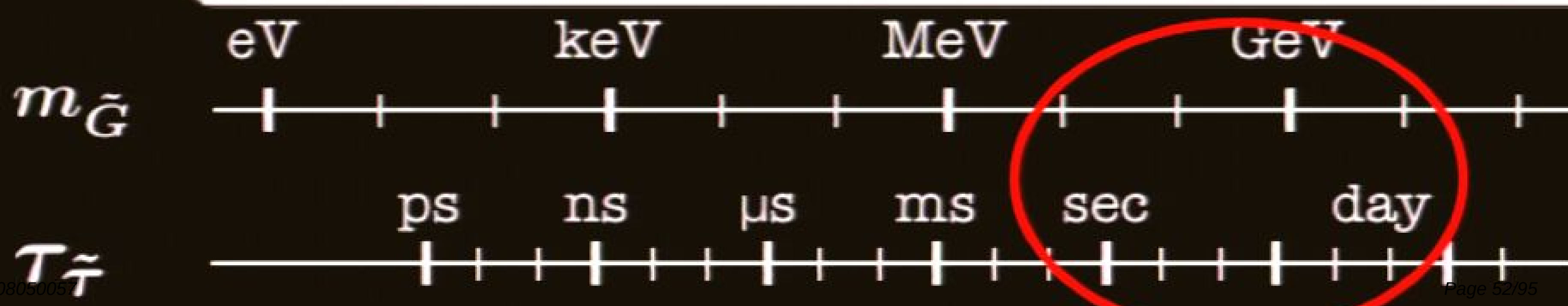

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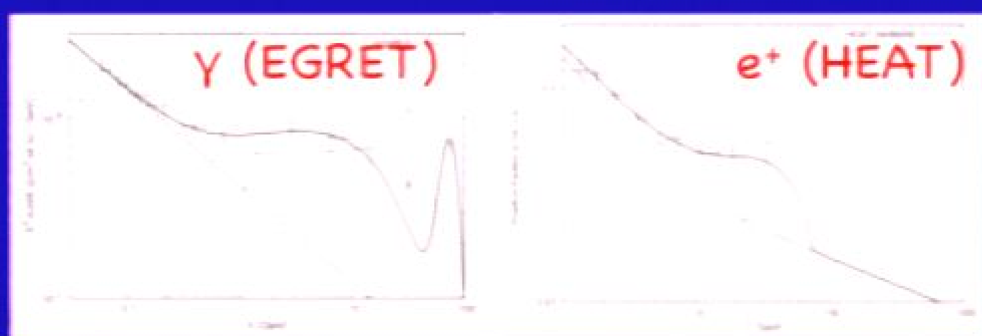
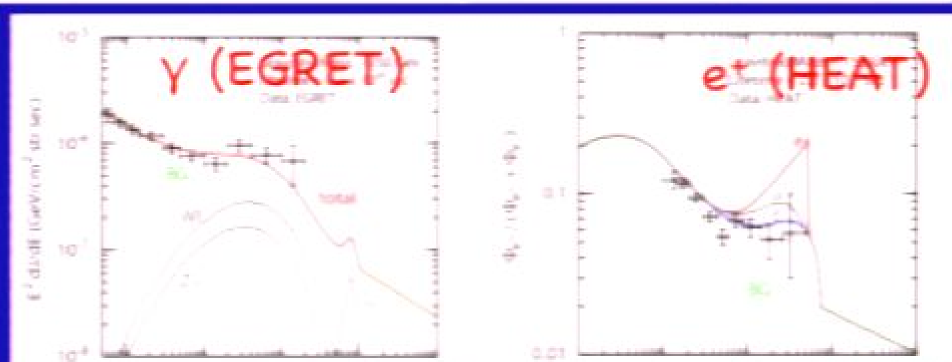
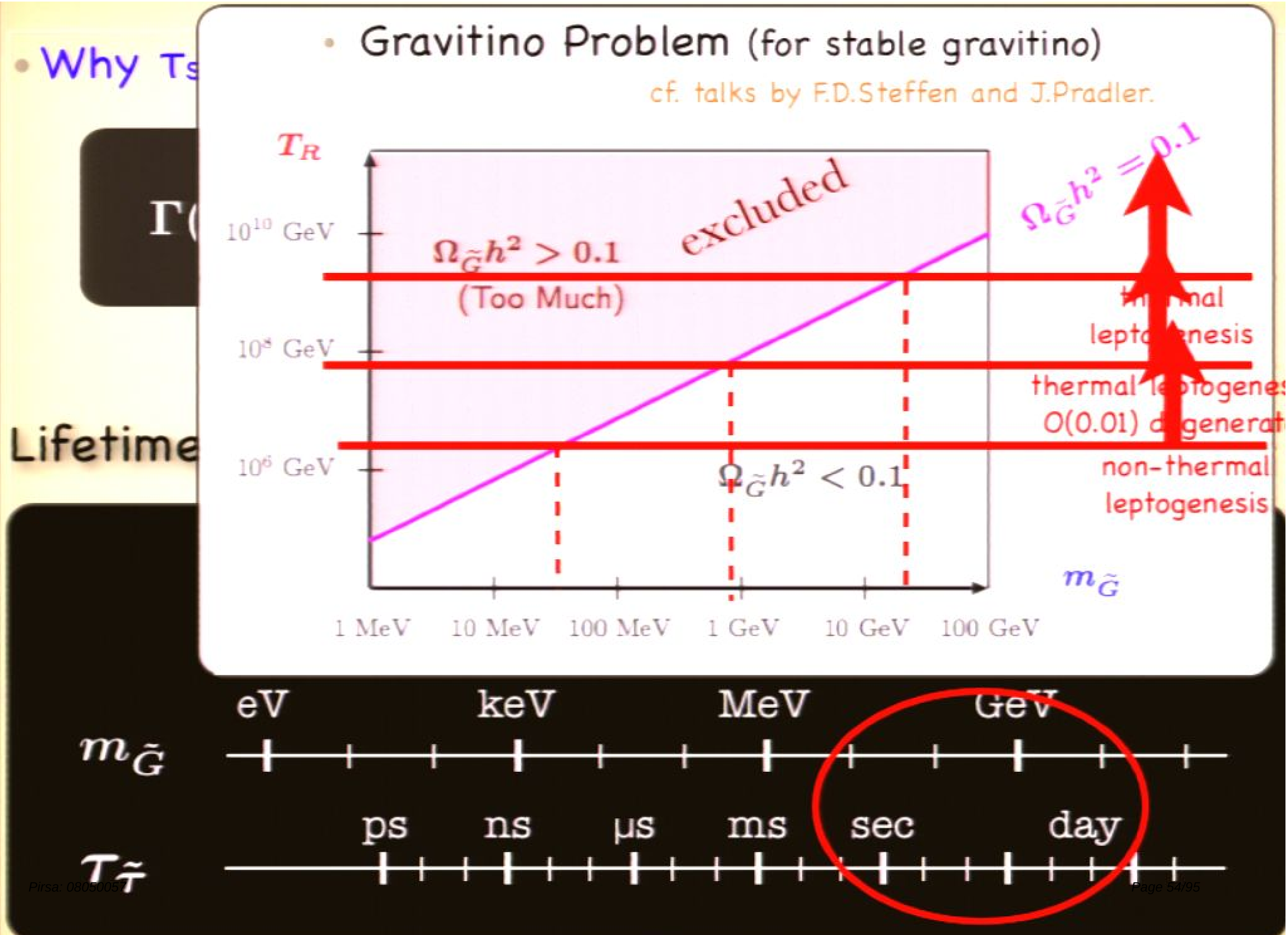
And the gravitino DM decay can be (or has already been?!) seen by CRs !!!

Ibarra, Tran,'08 →



Ishikawa, Matsumoto, Moroi,'08 →





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Long-lived Staus in the Early Universe

Long-lived Staus in the Early Universe

- ..... as we've heard so far in this workshop.
- Stau with $\tau > O(1)$ sec (especially > 1000 sec) [Catalyzed BBN, Pospelov,'06] may affect/jeopardize/help the BBN!

Long-lived Staus at the LHC

- can test it at the LHC ??
- can determine the abundance and lifetime of stau?

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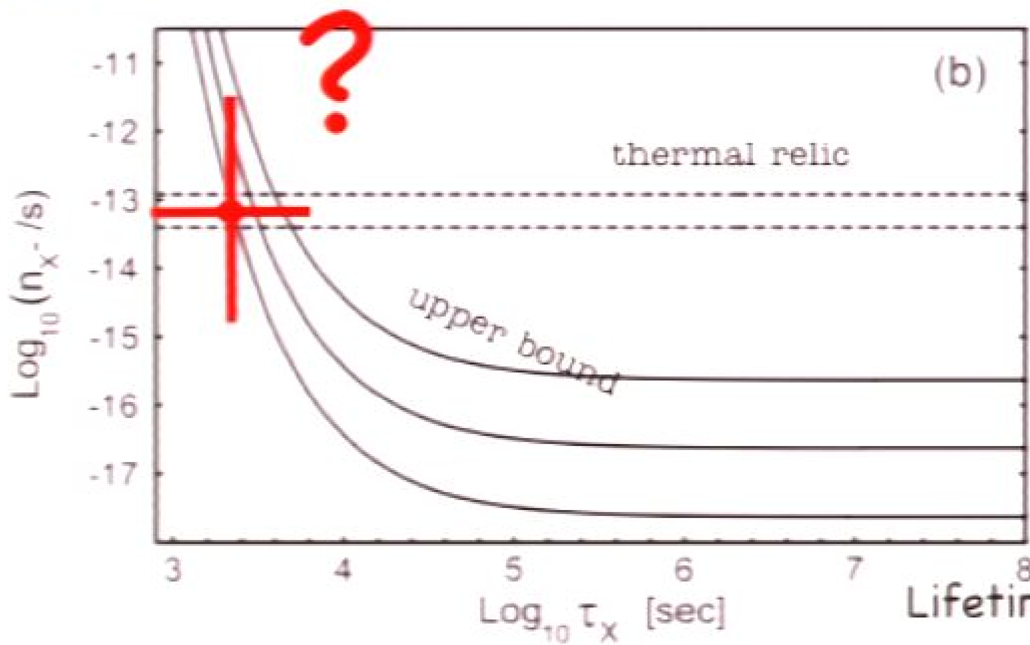

Lifetime

Fig. from KH, Hatsuda, Kamimura, Kino, Yanagida'07

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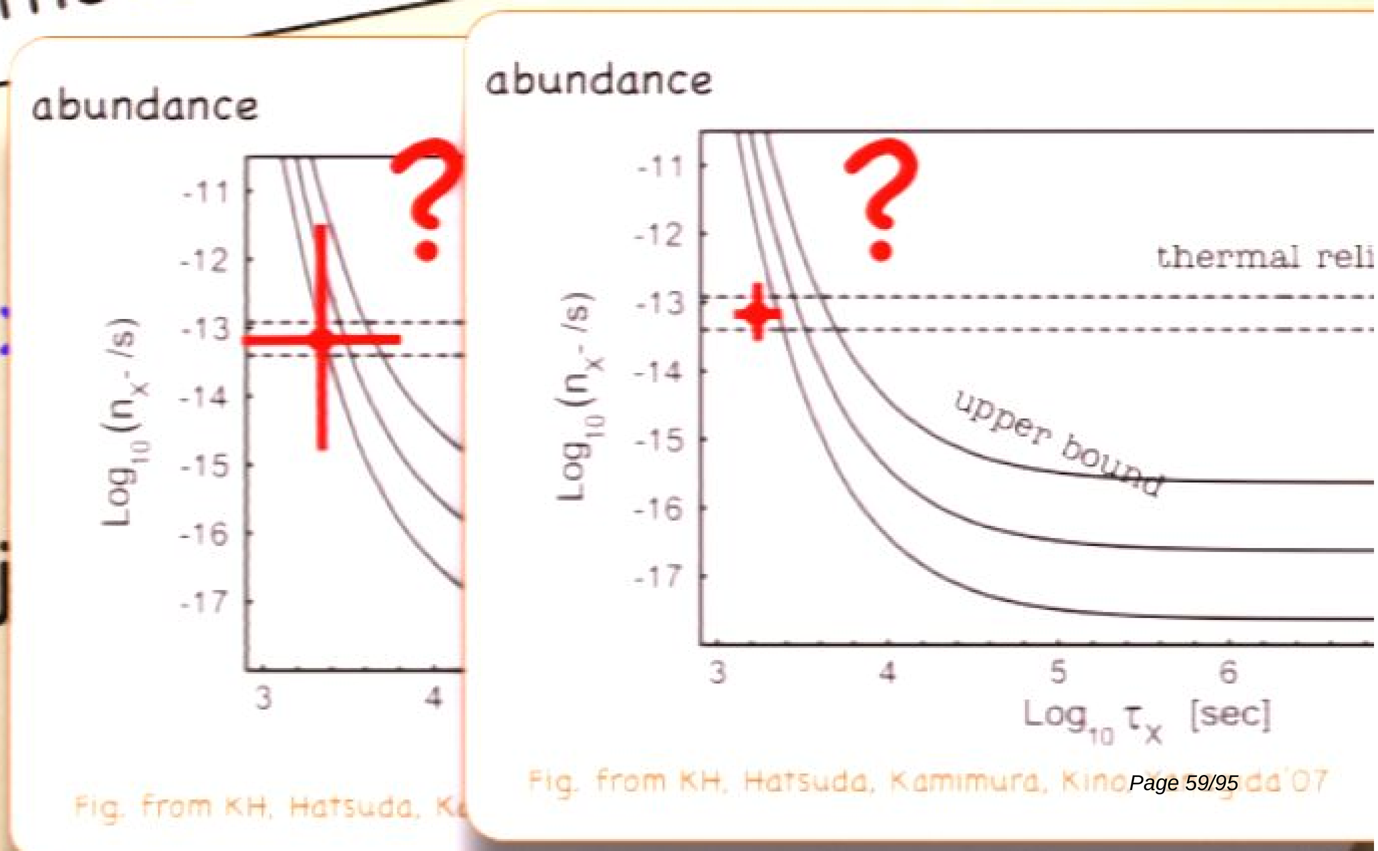
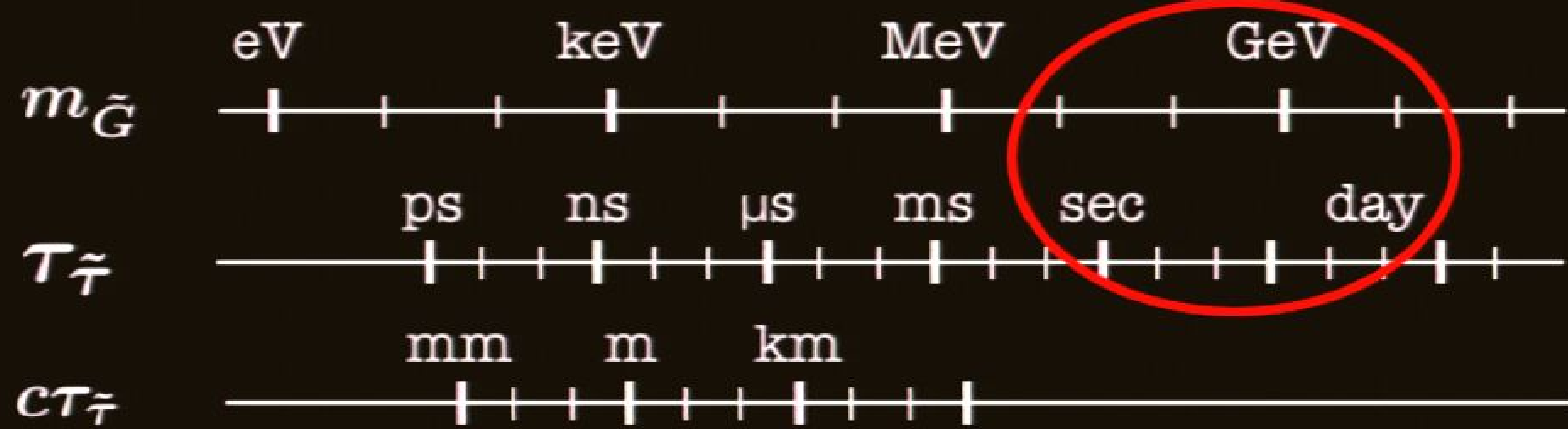


Long-lived Staus at the LHC

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

Lifetime (decay length) of Stau

e.g., for m(stau) = 200 GeV



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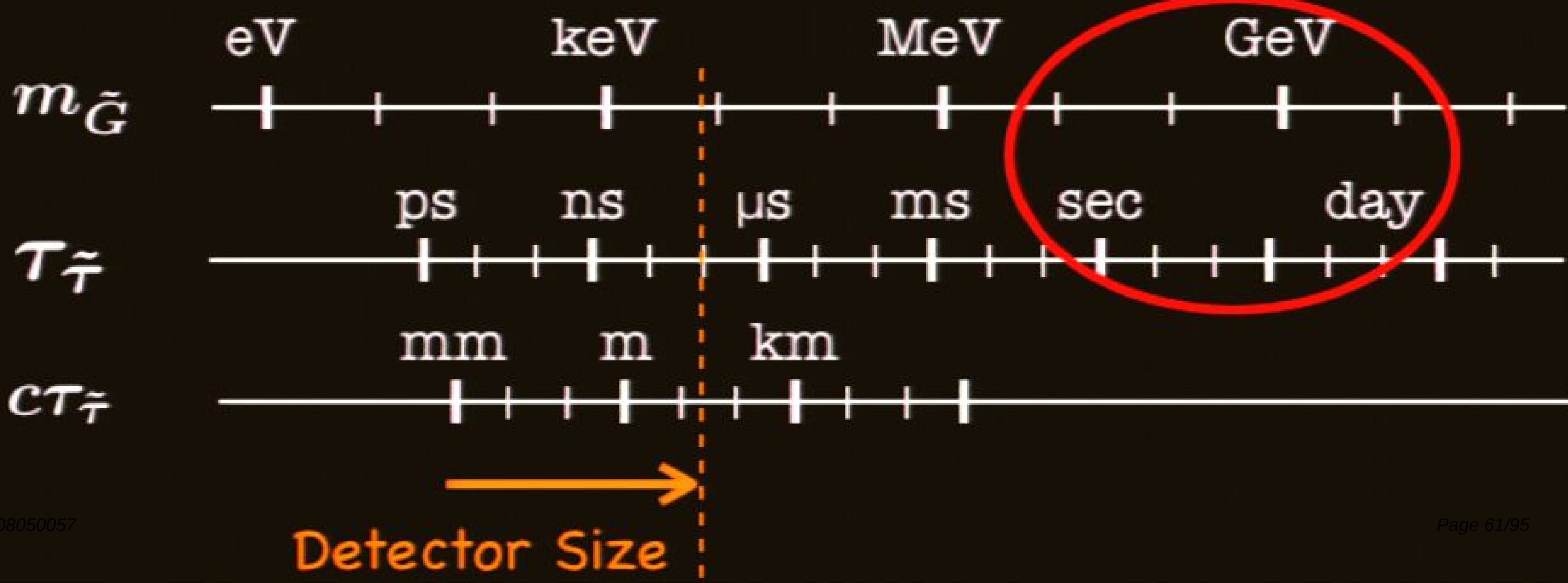

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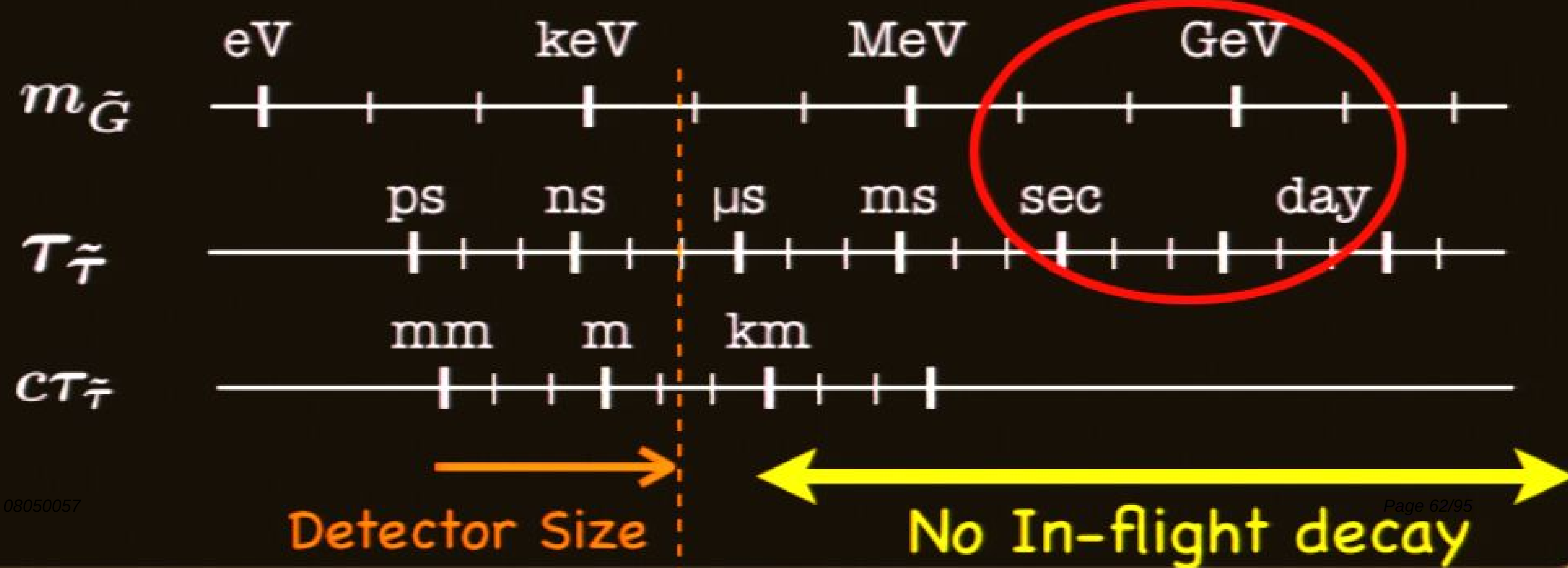

Long-lived staus @ LHC

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

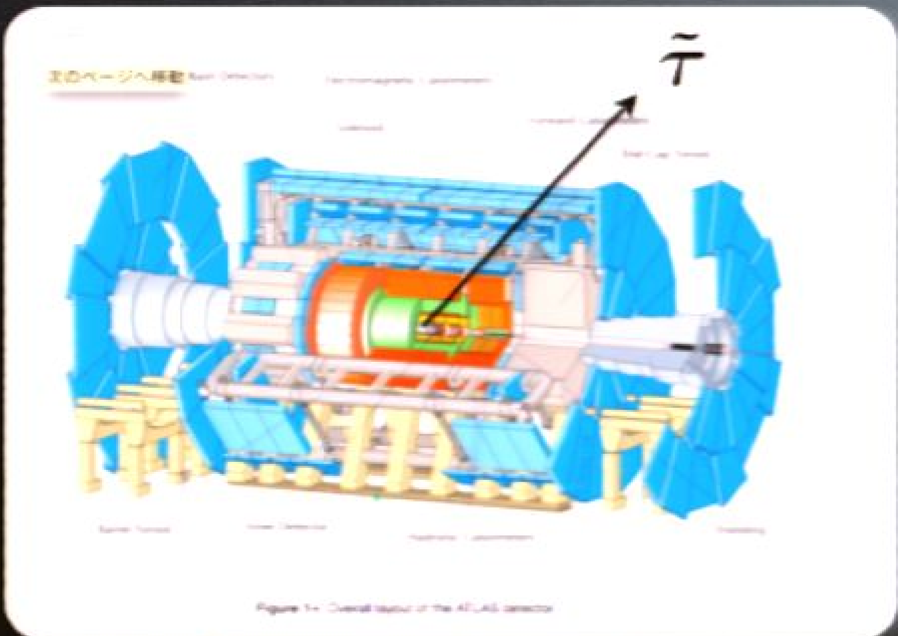

Fig. from ATLAS webpage

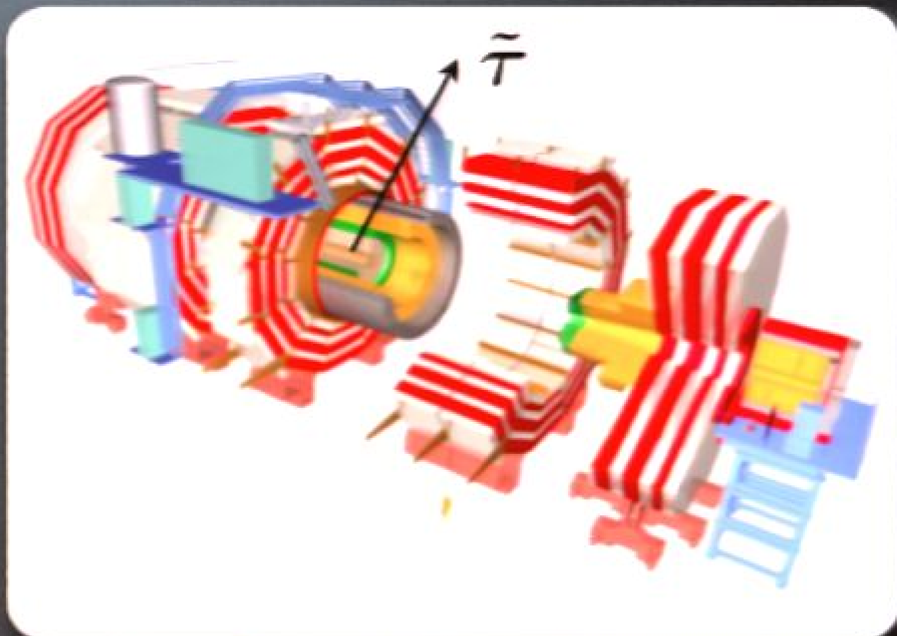

Fig. from CMS webpage

We will

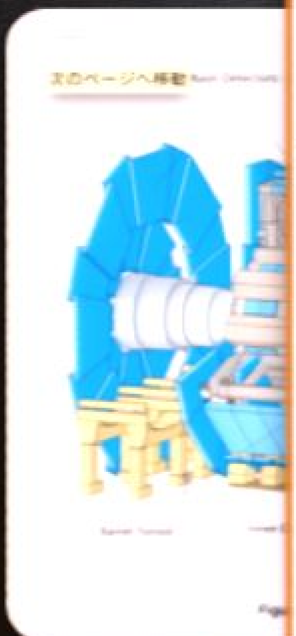

Fig. fro

- 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

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

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

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can determine the relic abundance !!!

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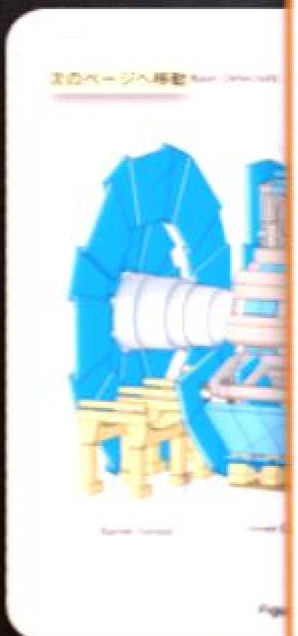

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..........but we cannot measure the stau lifetime.....

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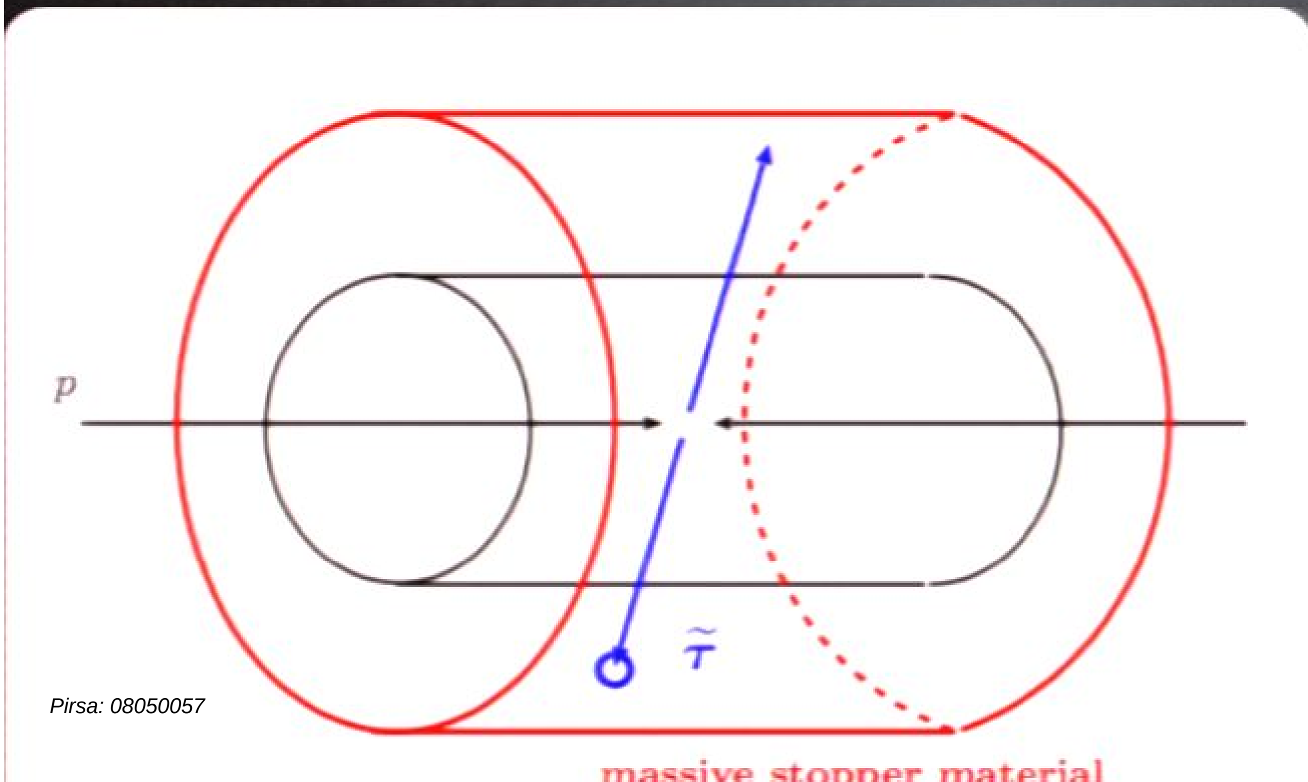
We would like to see the decay of stau (into gravitino).

→ We need to stop the staus.



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Feng, Smith '04

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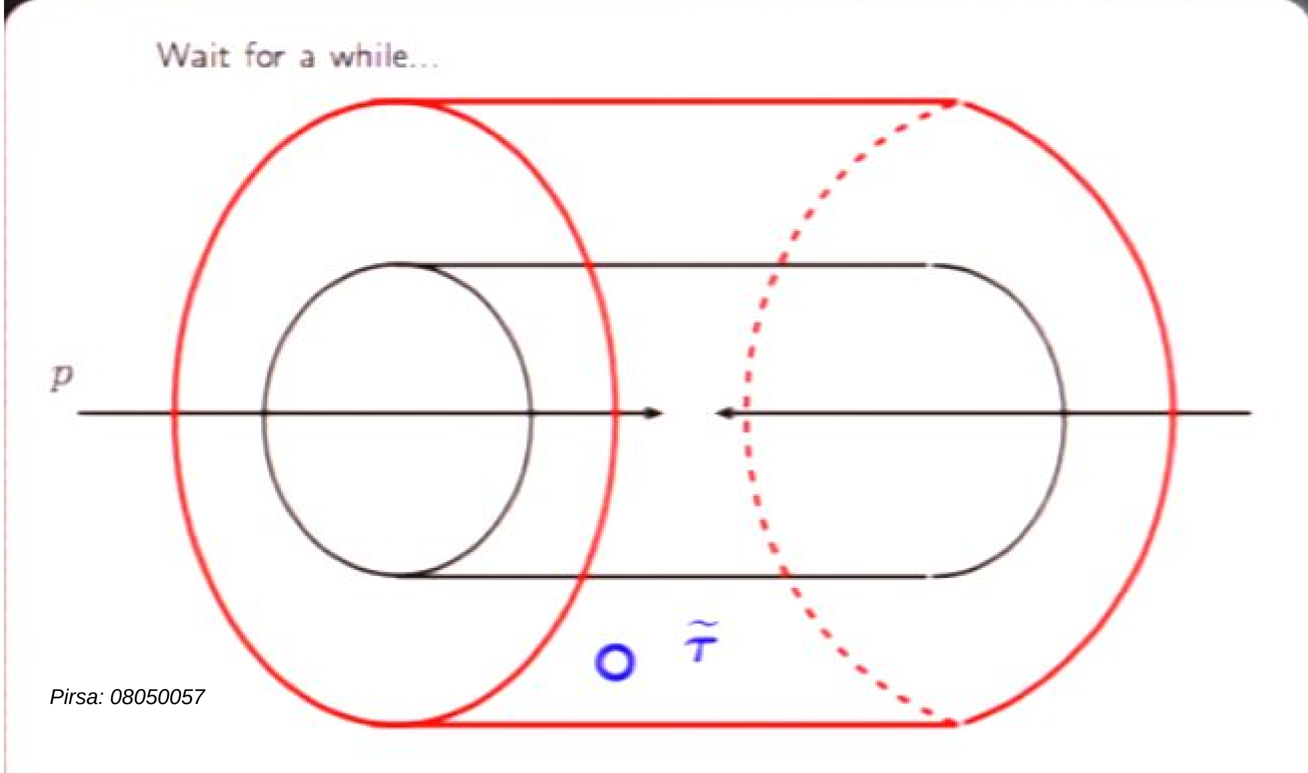

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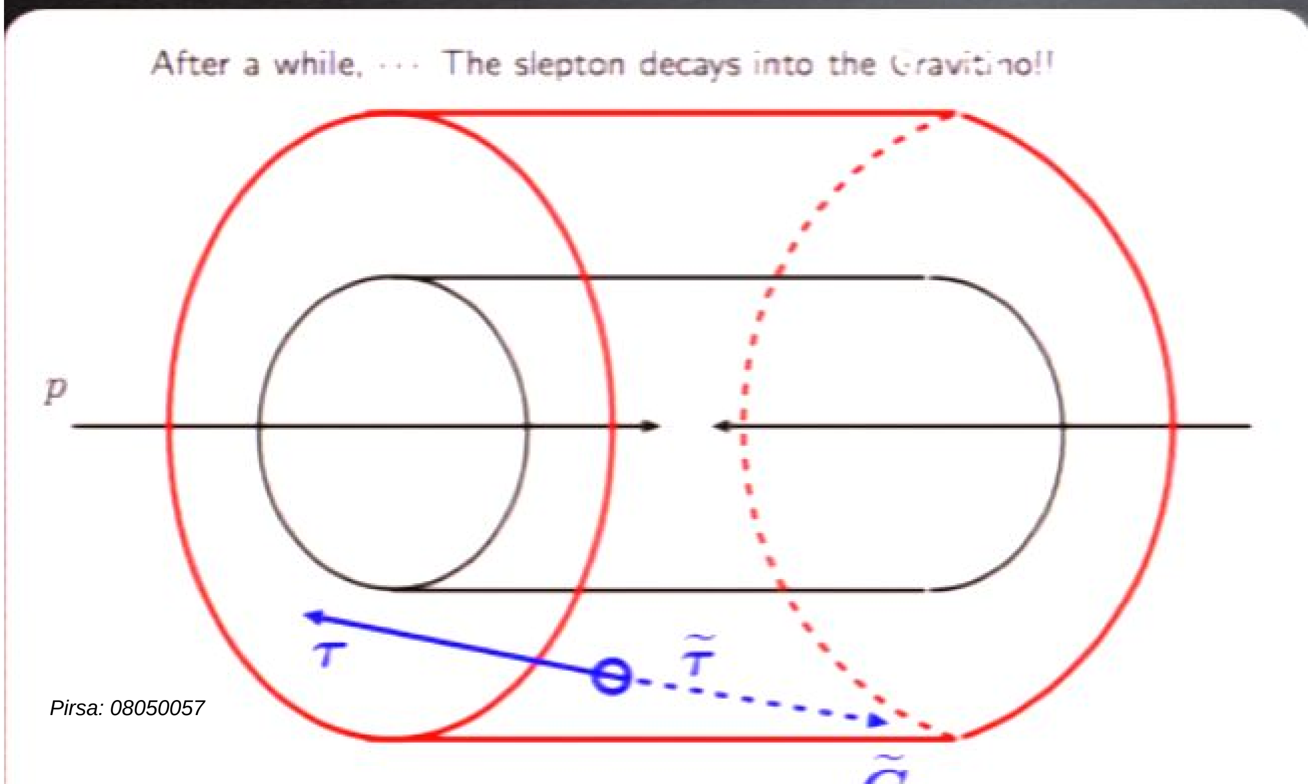

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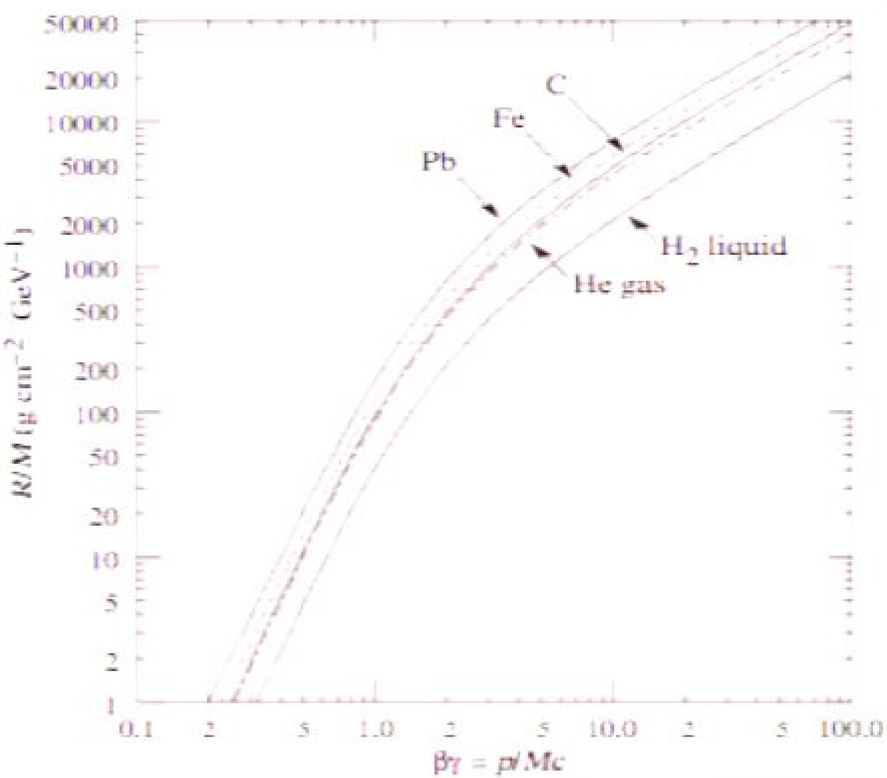
How thick the stopping material should be?



Review of Particle Physics

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

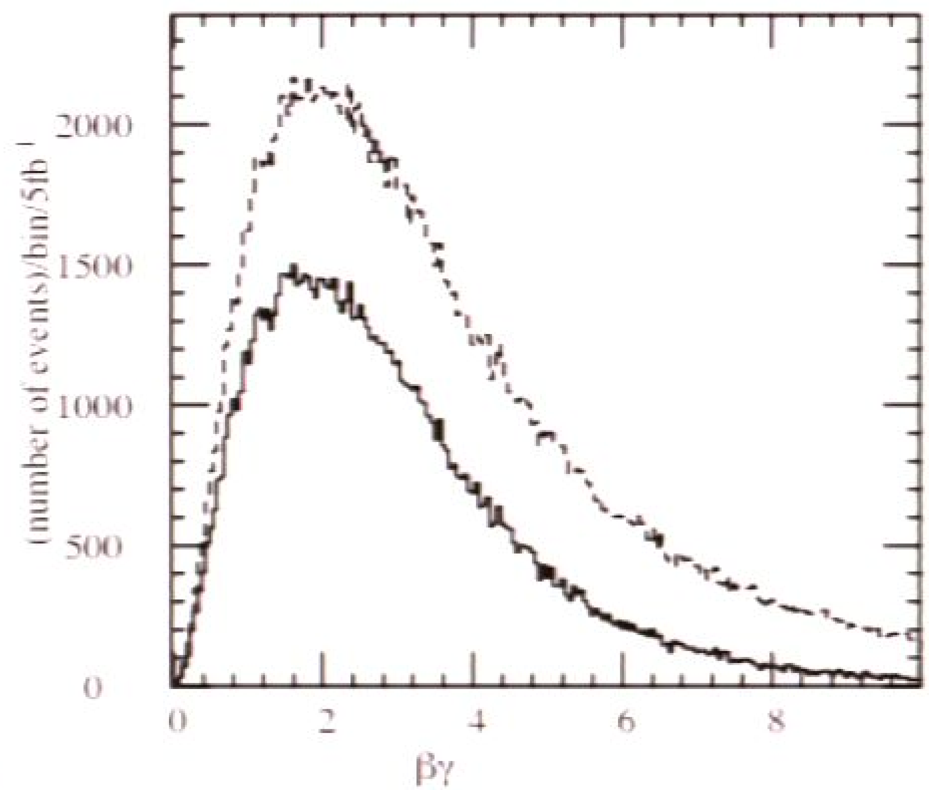


Fig. from Hamaguchi, Kuno, Nakaya, Nojiri '0

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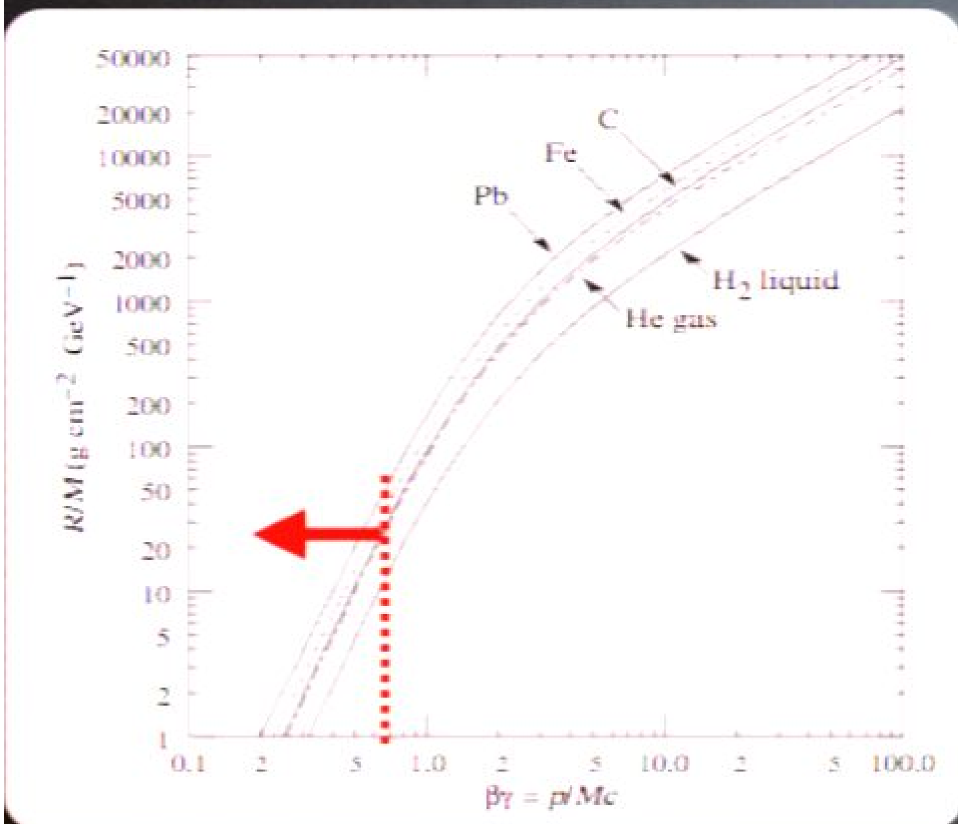

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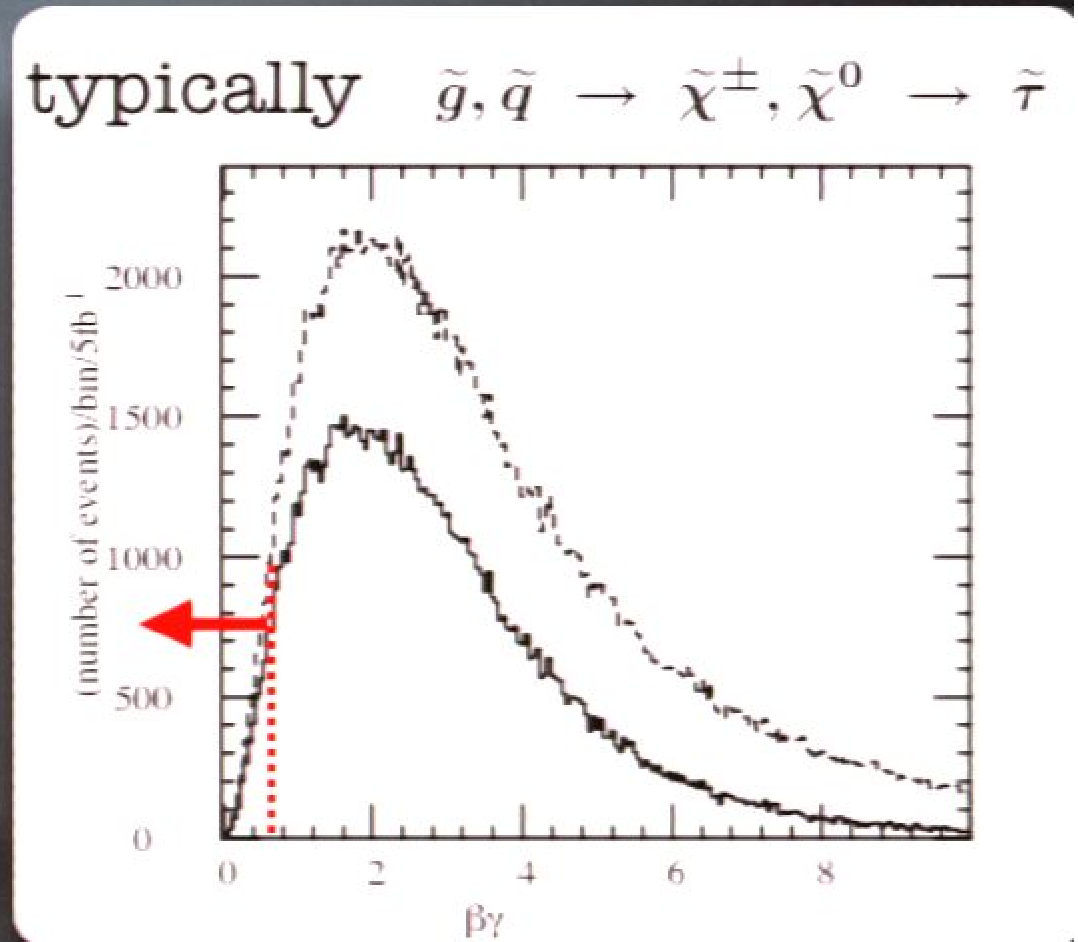

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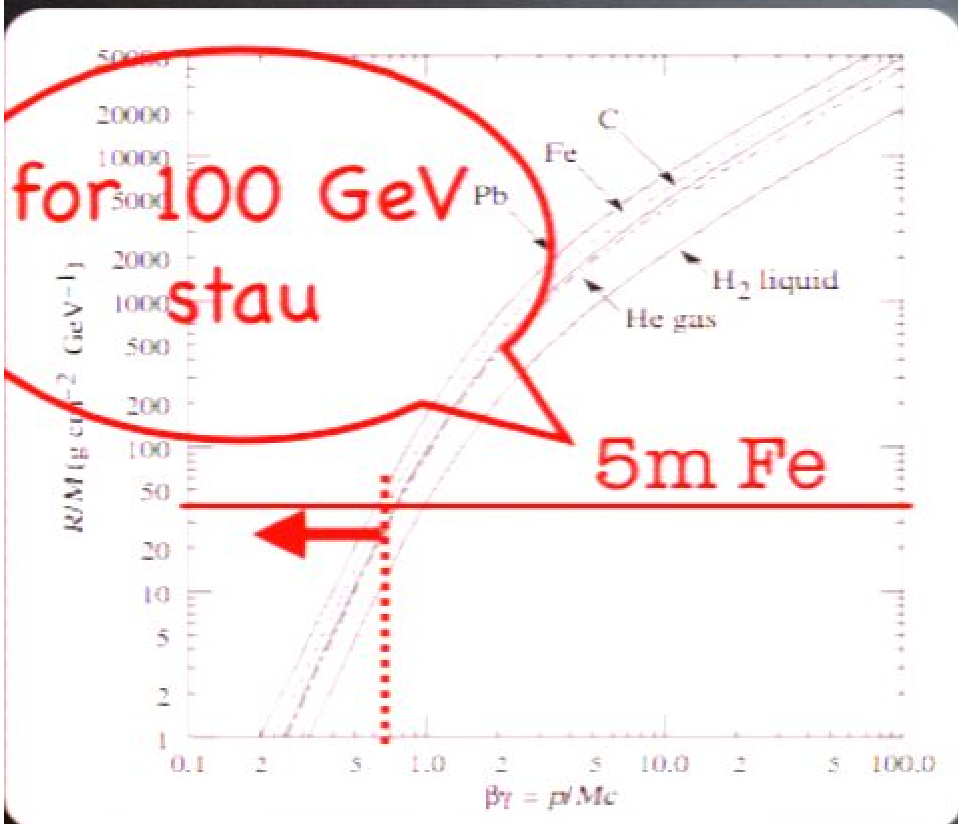

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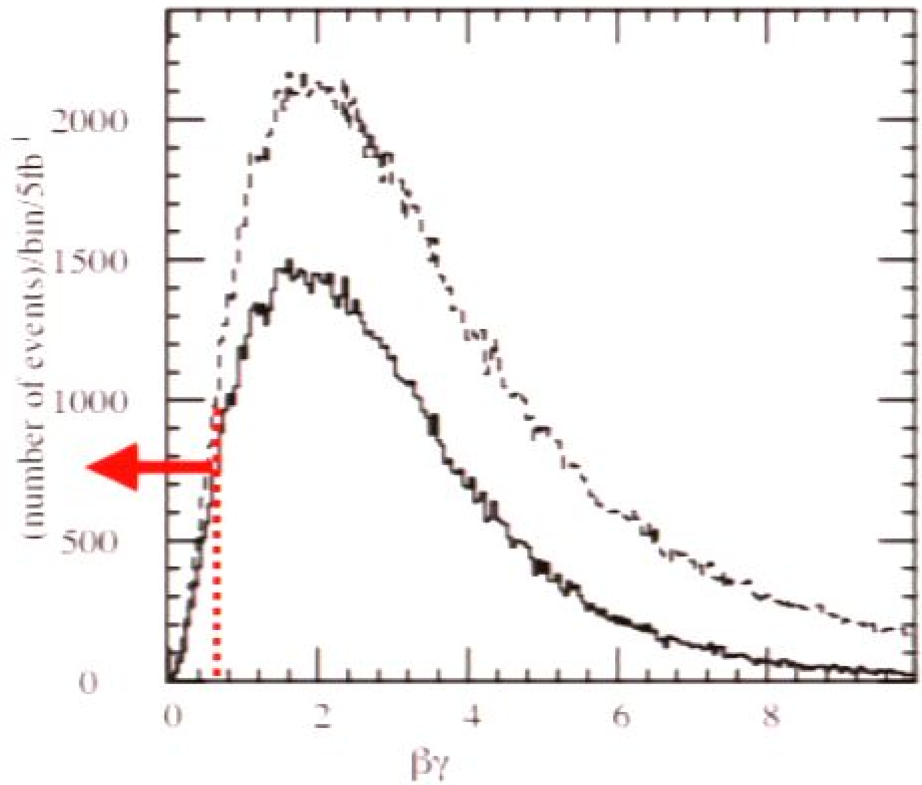

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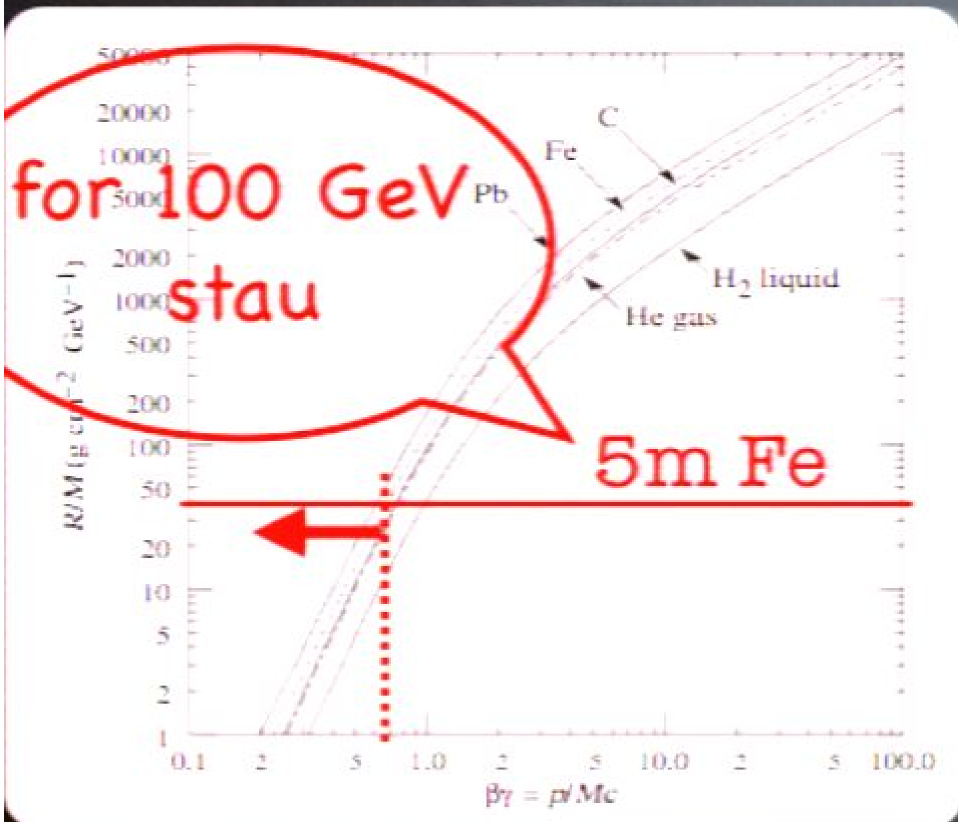

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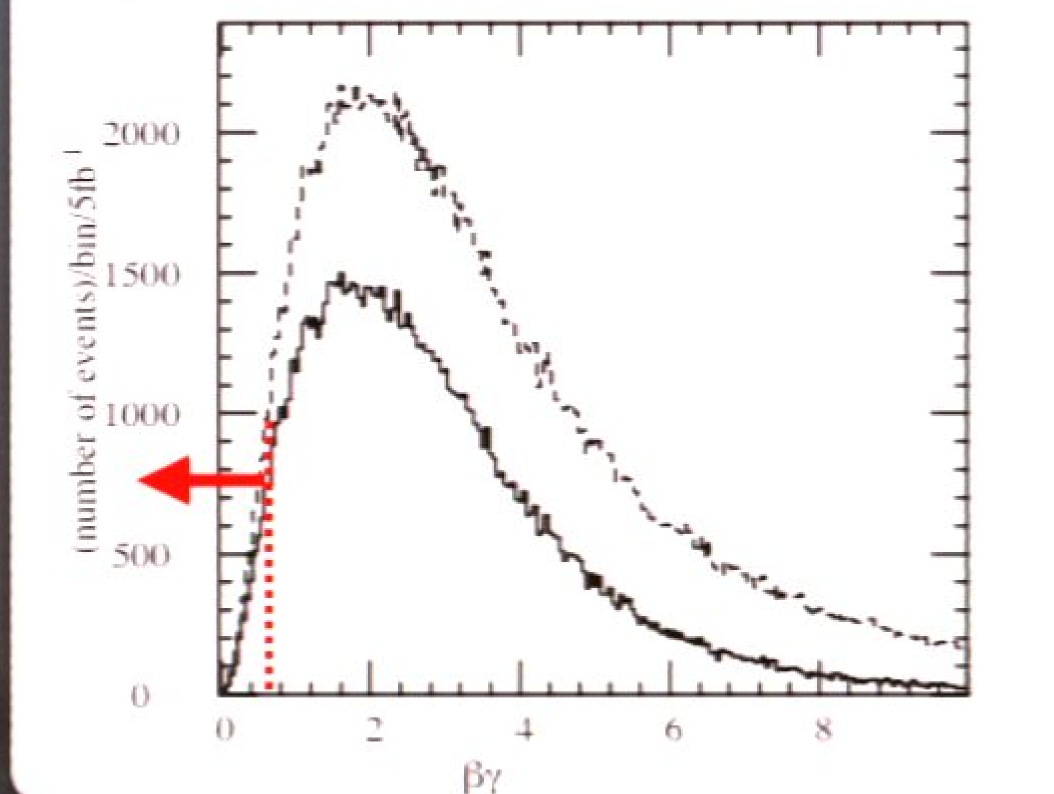

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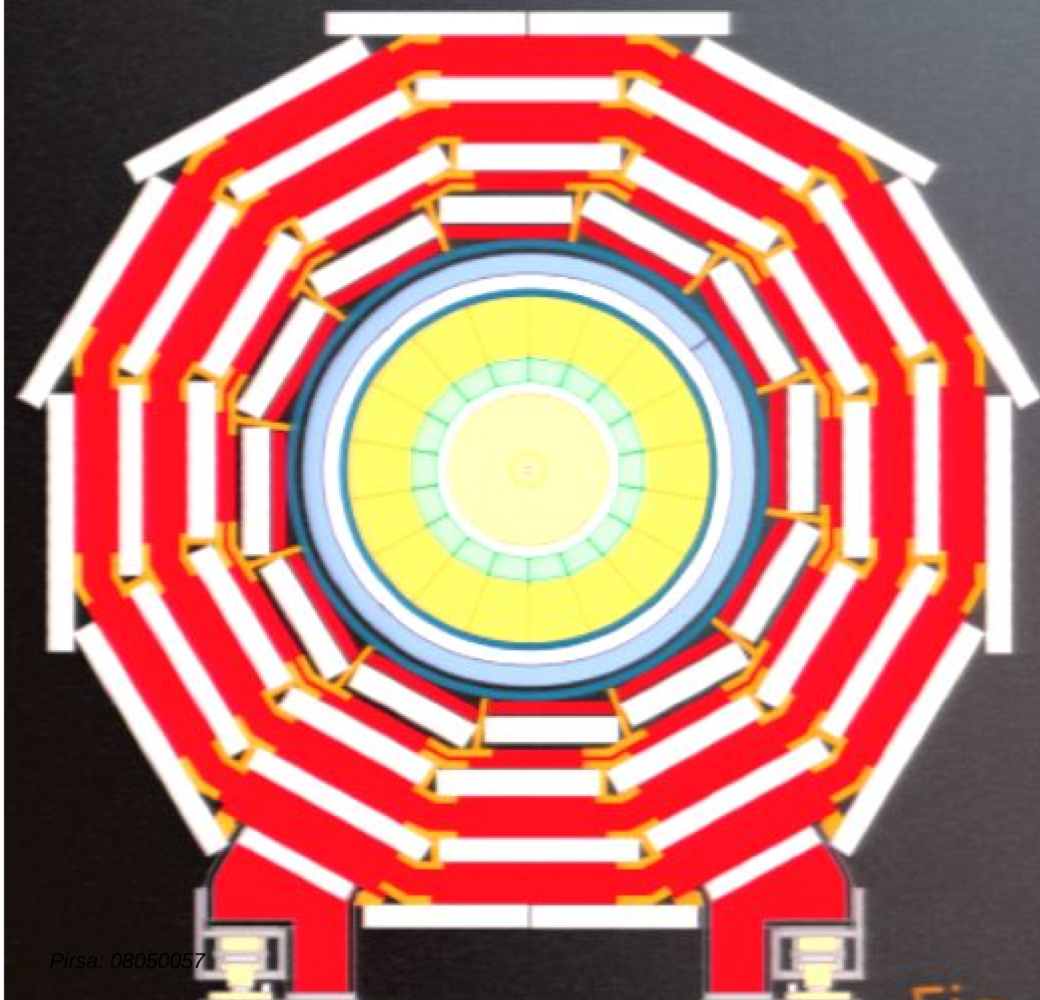
If thick enough, part of produced staus may be stopped

Long-lived staus @ LHC

Actually, the LHC detector themselves can stop part of staus...



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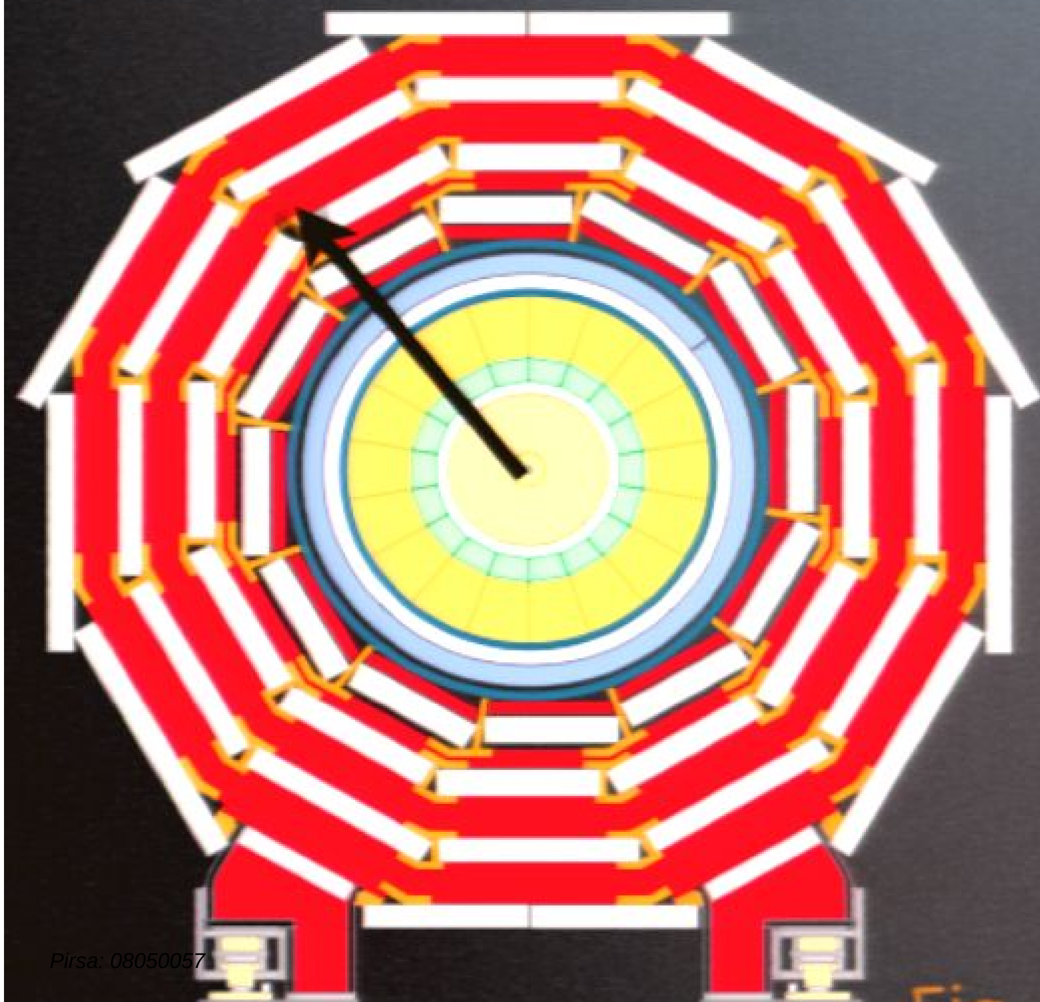

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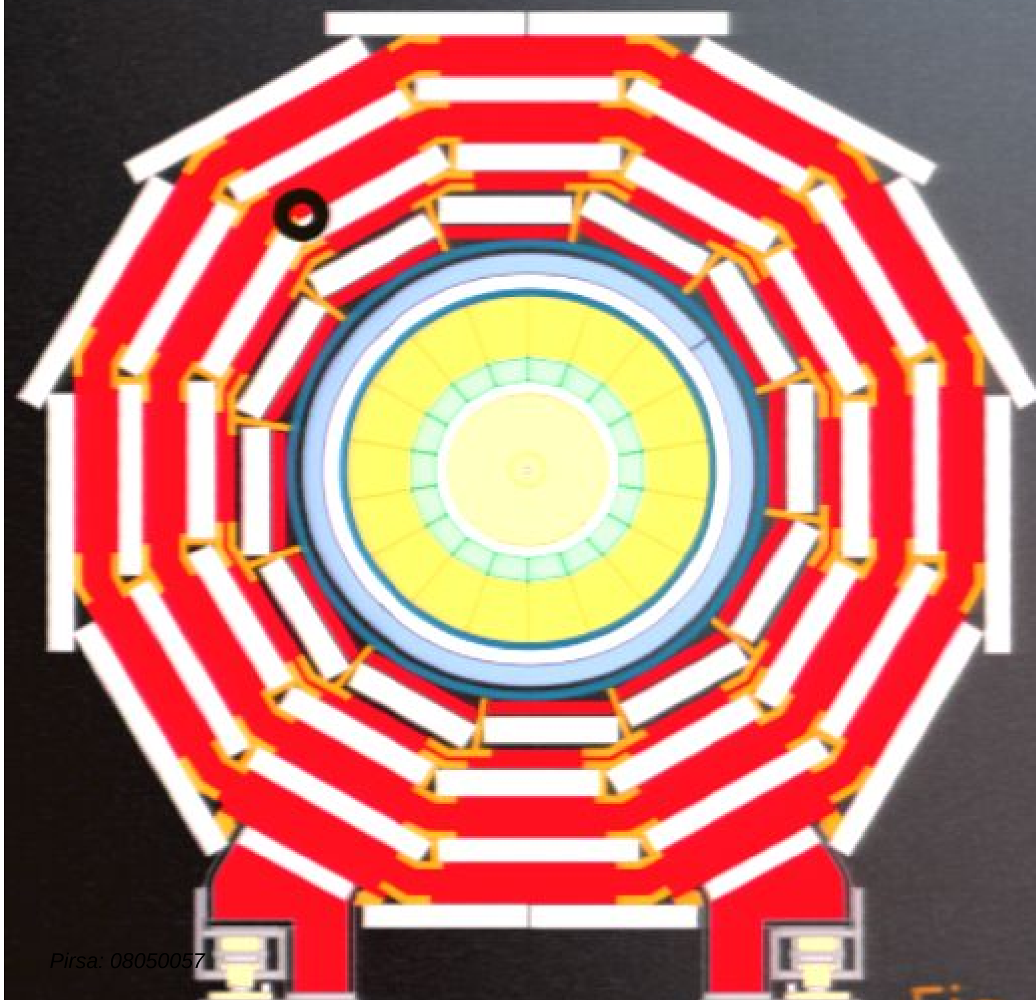

However, even if we can precisely identify the position where the stau is stopped and record it,.....

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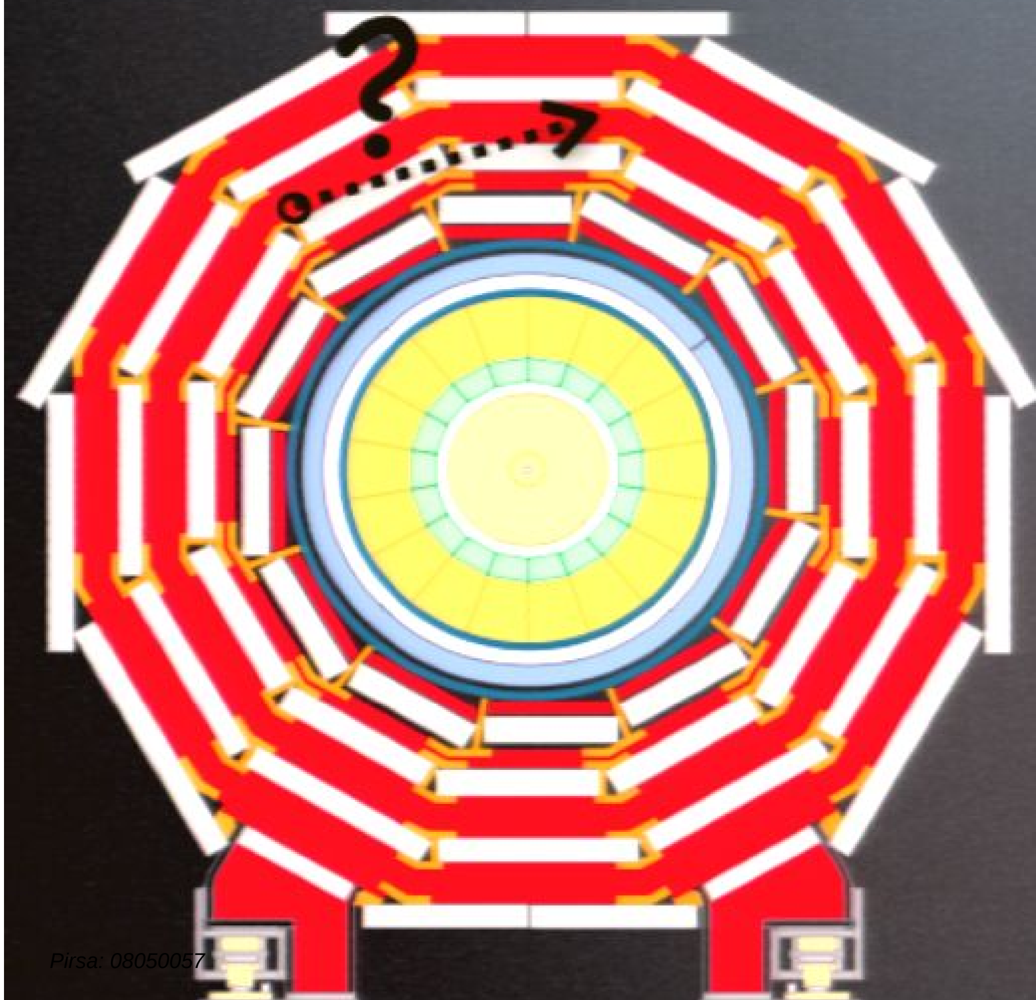


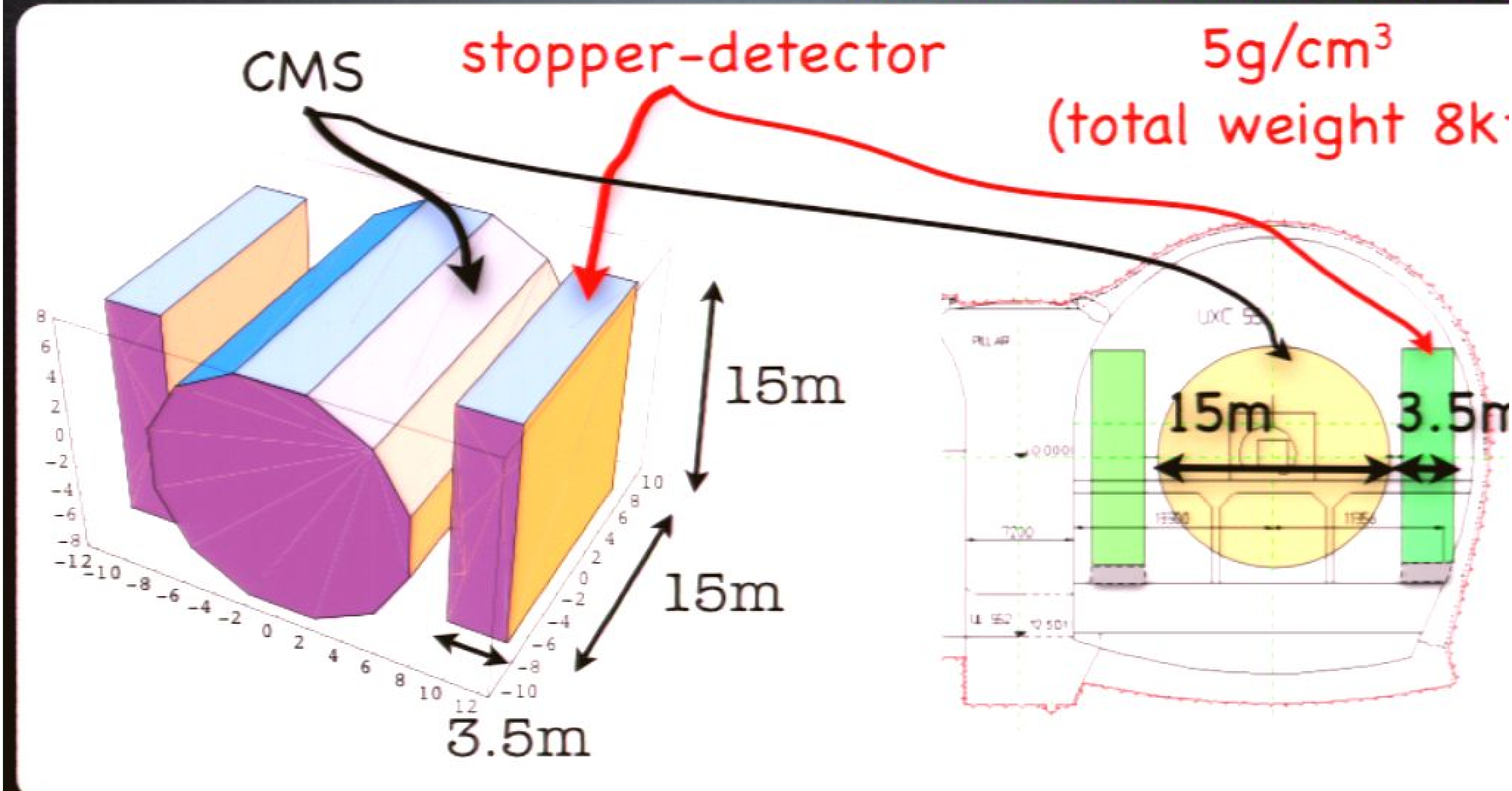
However, even if we can precisely identify the position where the stau is stopped and record it,.....

it is difficult to identify the stau decay, which is out-of-time and not originating from beam interaction point.

stopper-detector

Assume two stoppers next to CMS.

Hamaguchi, Nojiri, De Roeck'06



→ maybe possible to install stopper-detectors

stopper-detector

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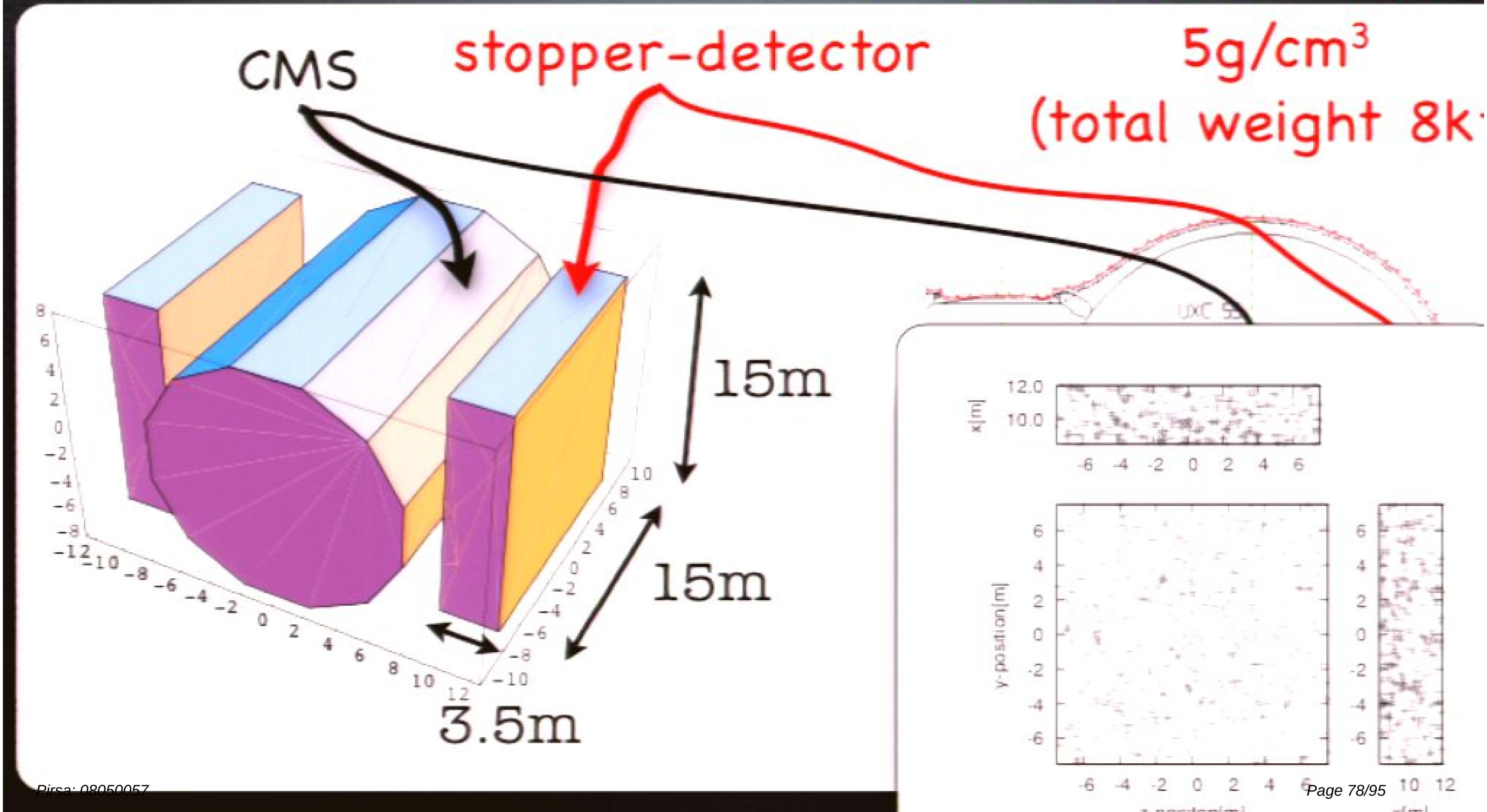

→ maybe possible to install

How many staus can be stopped?

Point	ϵ	ζ	η
$M_{1/2}$	440	1000	1000
m_0	20	100	20
$\tan\beta$	15	21.5	23.7
$m_{\tilde{g}}$ [GeV]	1025	2191	2190
$m_{\tilde{\chi}^0}$ [GeV]	175	417	416
$m_{\tilde{\tau}}$ [GeV]	154.2	343.5	324.3
σ(SUSY) [pb]	3.03	2.27×10^{-2}	2.34×10^{-2}
stopped in the stopper detector per 10^5 events	255	250	254
stopped for 300 fb^{-1}	4636	34	36

TABLE I: Some model points in mSUGRA model from [4]. The mass spectrum and production cross section relevant to our study are shown.

about 3 years
gh luminosity run

Λ [TeV]	40	50	60	70	80
$m_{\tilde{g}}$ [TeV]	0.93	1.13	1.34	1.54	1.74
$m_{\tilde{\chi}^0}$ [GeV]	161.7	205.3	248.7	292.1	335.4
$m_{\tilde{\tau}}$ [GeV]	120.5	150.1	179.9	209.8	239.9
σ(SUSY) [pb]	5.24	1.68	0.64	0.28	0.13
stopped in the stopper detector per 10^5 events	282	274	274	294	302
stopped for 300fb^{-1}	8830	2762	1052	494	236

TABLE II: Some model points in gauge mediation model. The production cross section and mass

up to O(1000) stau
may be trapped!

Hamaguchi, Nojiri,

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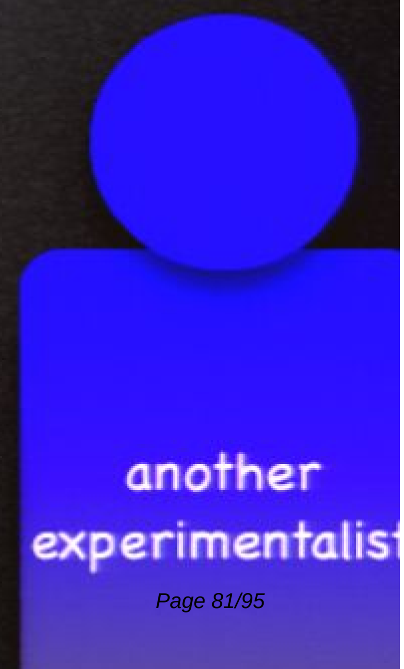
stopped in the stopper detector per 10^5 events	282	274	274	294	302
stopped for 300fb^{-1}	8830	2762	1052	494	236

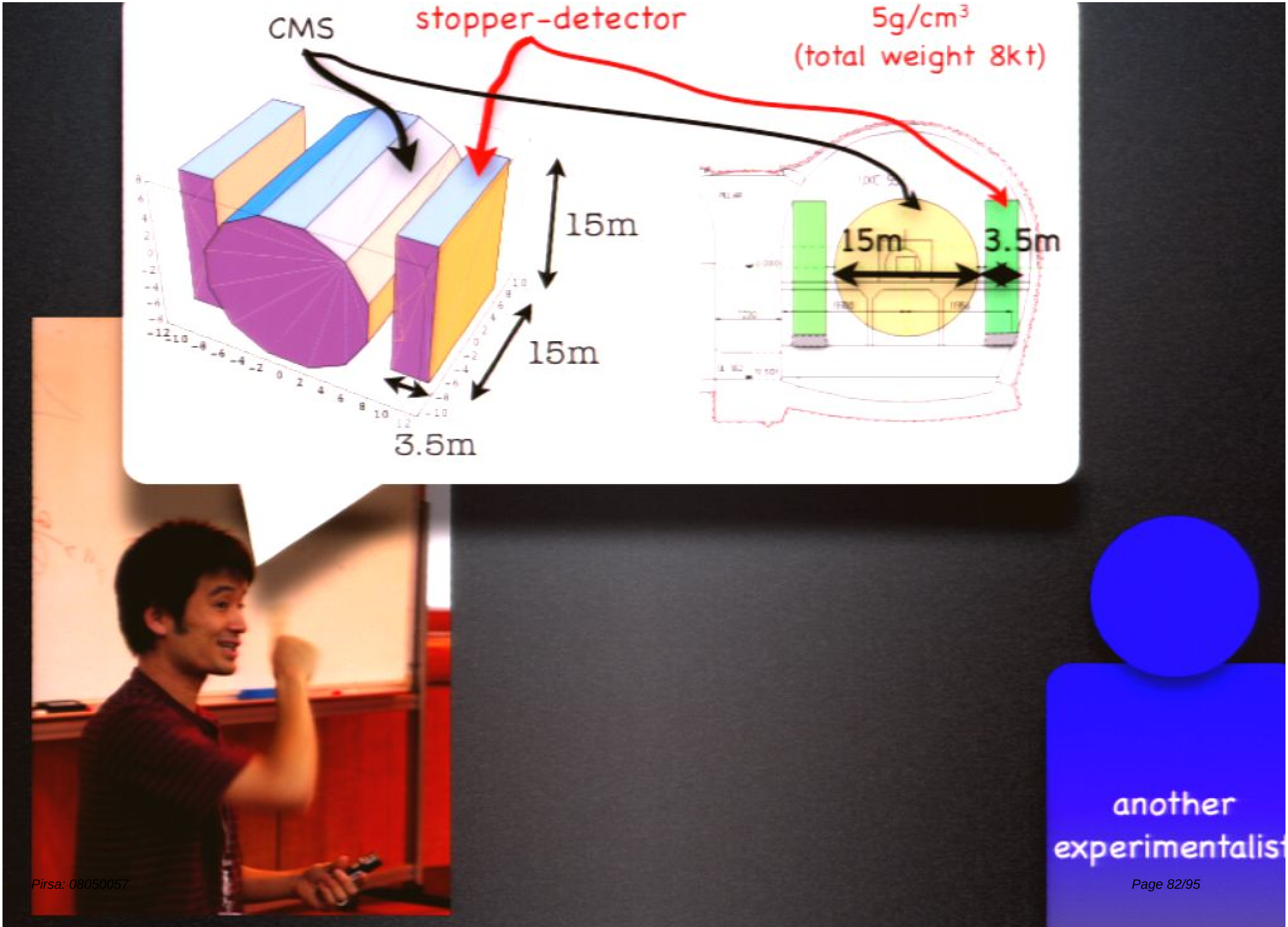
TABLE II: Some model points in gauge mediation model. The production cross section and mass

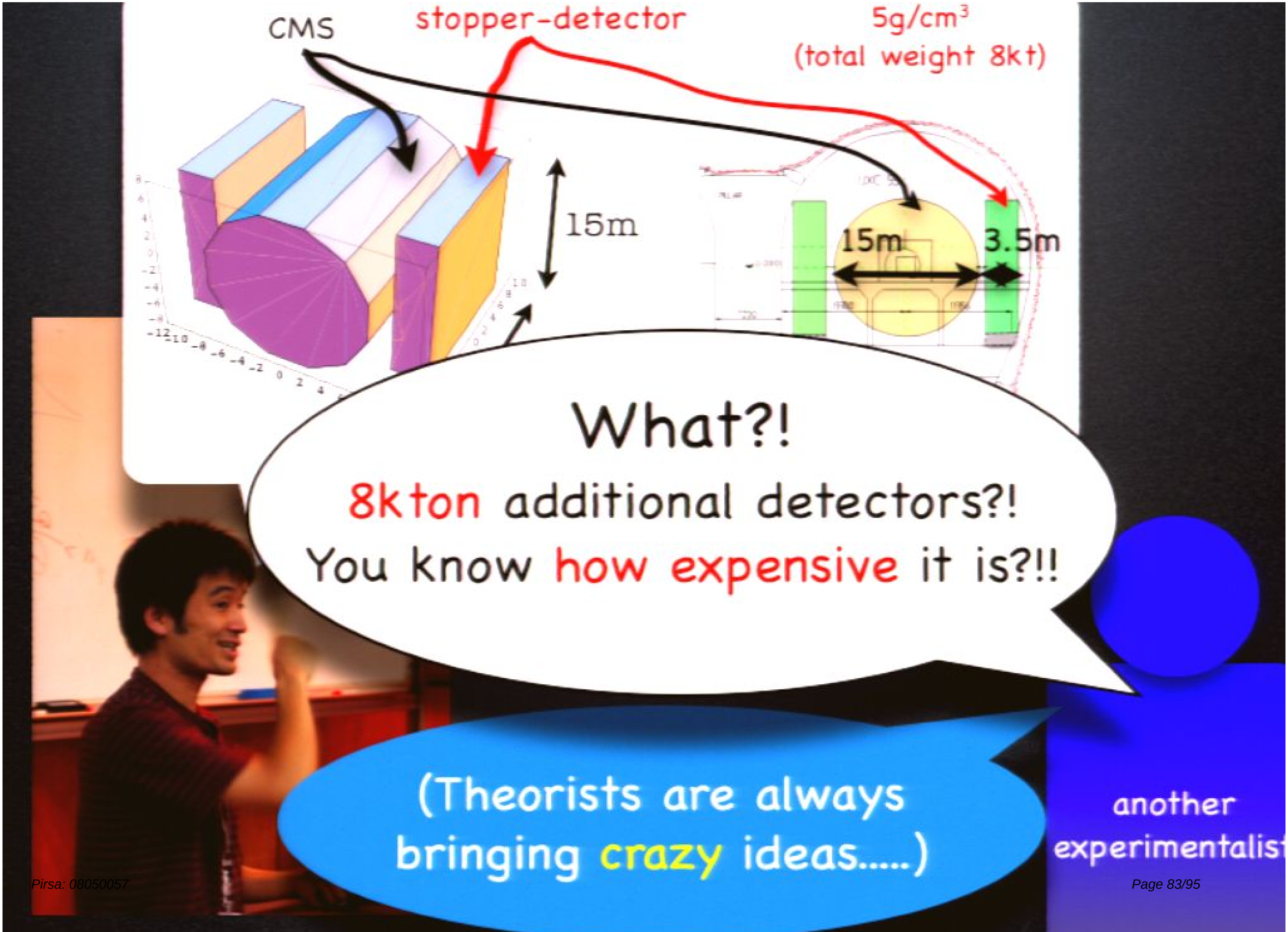
up to O(1000) stau
may be trapped!

$$\Longrightarrow \frac{\Delta\tau_{\tilde{\tau}}}{\tau_{\tilde{\tau}}} \sim \mathcal{O}(\%) \; !!$$

Hamaguchi, Nojiri,
De Roeck, '06


another
experimentalist


CMS
stopper-detector
5g/cm³
(total weight 8kt)
15m
15m
3.5m
15m
3.5m
another
experimentalist



CMS
stopper-detector
5g/cm³
(total weight 8kt)
15m
15m
3.5m
What?!
8kton additional detectors?!
You know how expensive it is?!!
(Theorists are always bringing crazy ideas.....)
another experimentalist

Side Remark
cf. Steffen's talk

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"

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

$\tau \longleftarrow \tilde{\tau} \cdots\rightarrow \tilde{G}$

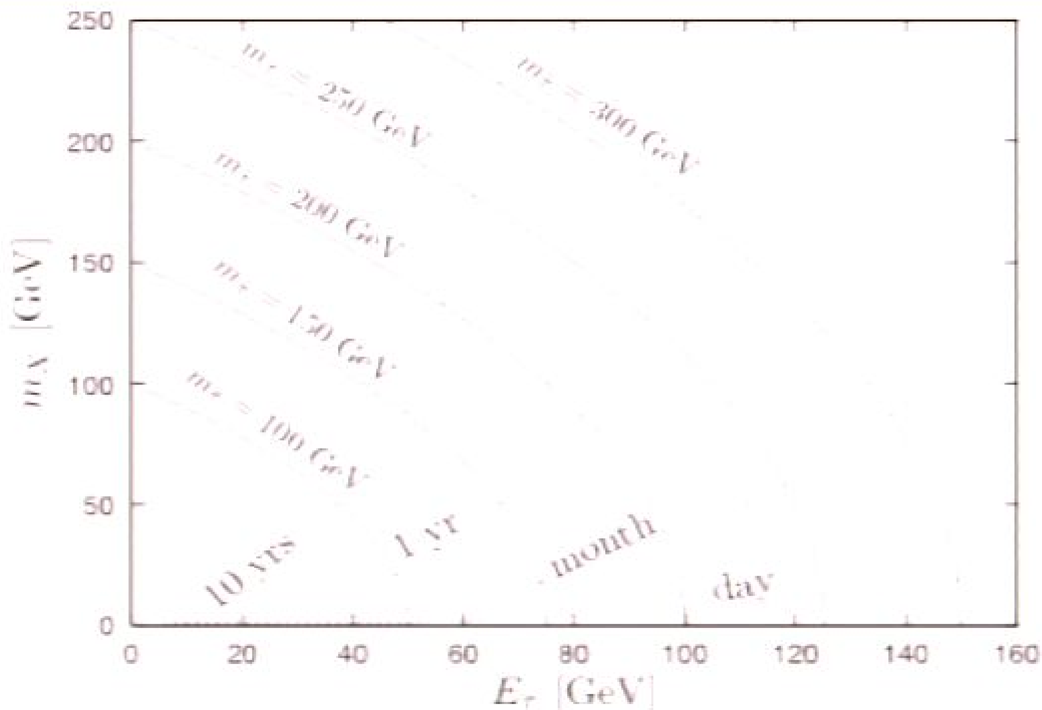
consistency check!!

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

Side Remark
cf. Steffen's talk

Planck scale measurement

Crucial to determine the tau energy precisely.



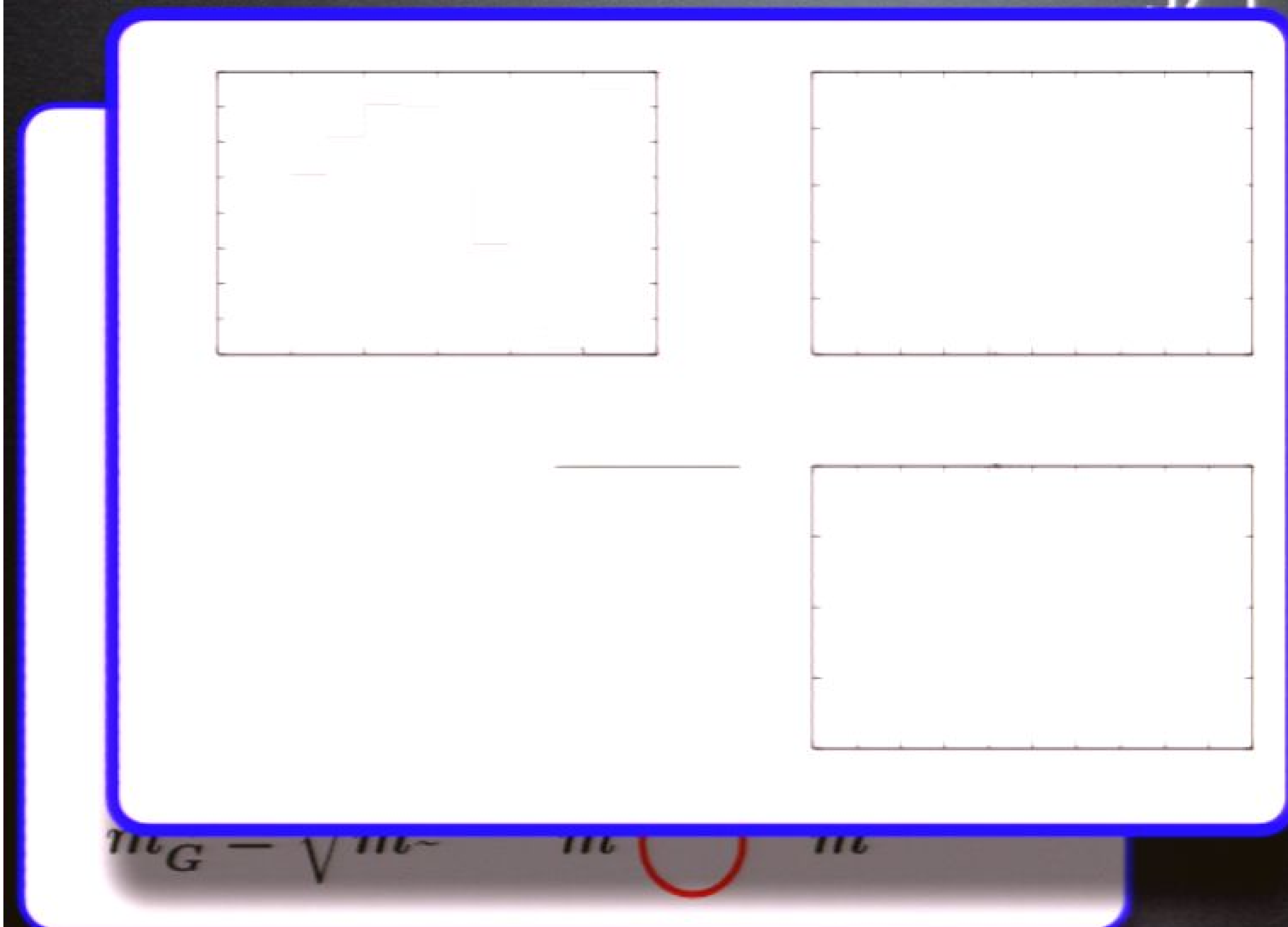
$$m_{\tilde{G}} = \sqrt{m^2 \quad m \quad m^2}$$

Figs. from Hamaguchi, Nojiri, De Roeck, '06

ide Remark
cf. Steffen's talk

Planck scale measurement

Crucial to determine the tau energy precisely.

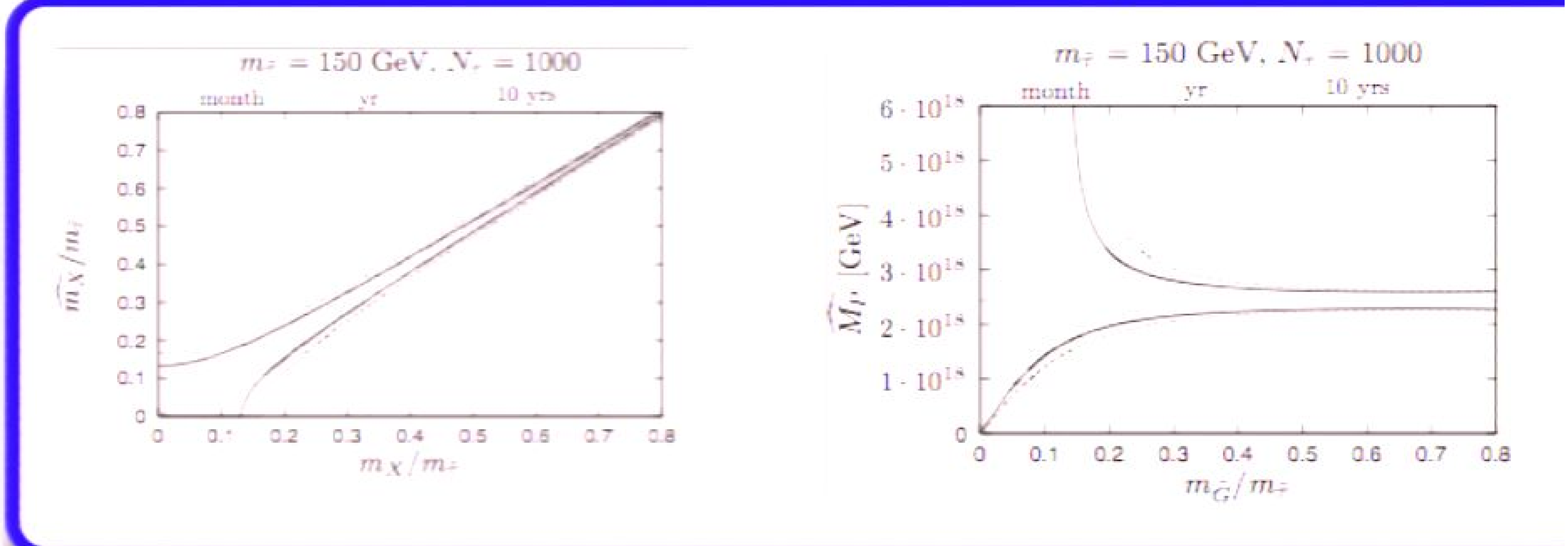


Figs. from Hamaguchi, Nojiri, De Roeck, '06

ide Remark
cf. Steffen's talk

Planck scale measurement

Crucial to determine the tau energy precisely.



Figs. from Hamaguchi, Nojiri, De Roeck, '06

ide Remark
cf. Steffen's talk

gravitino vs axino at the LHC

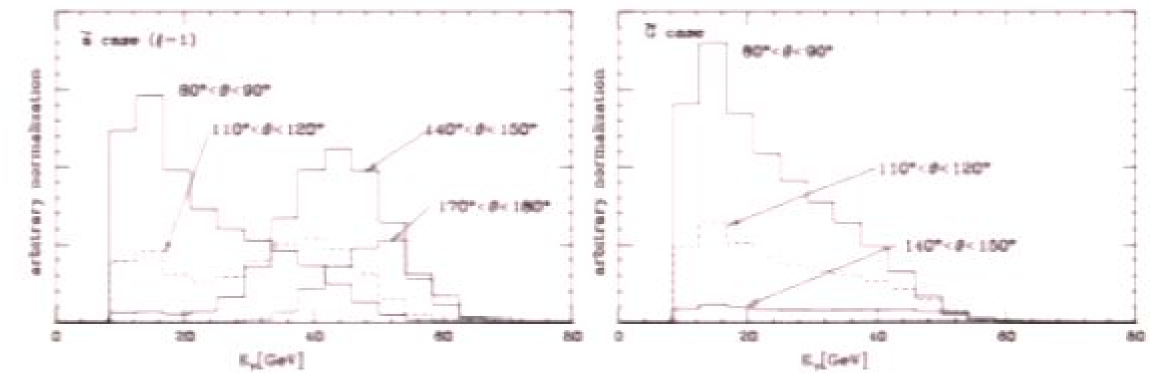


FIG. 18: The distribution of E_γ in some θ intervals for $\tilde\tau \to \tau\gamma X$ decay. left panel: $X = \tilde a$ ($\xi = 1$), right panel: $X = \tilde G$. $m_{\tilde\tau} = 100$ GeV, and $m_{\tilde B} = 130$ GeV.

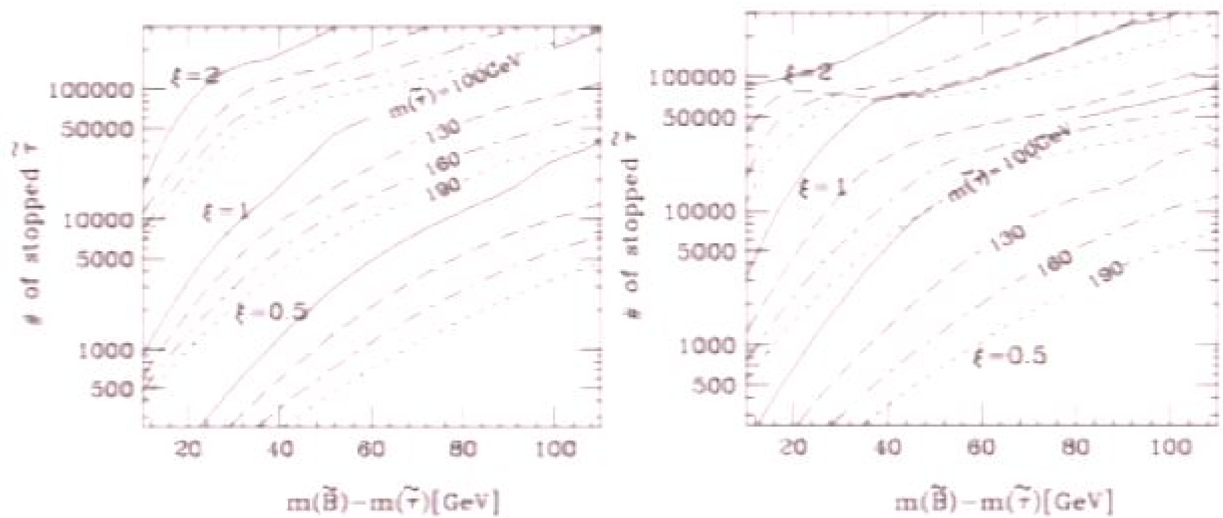
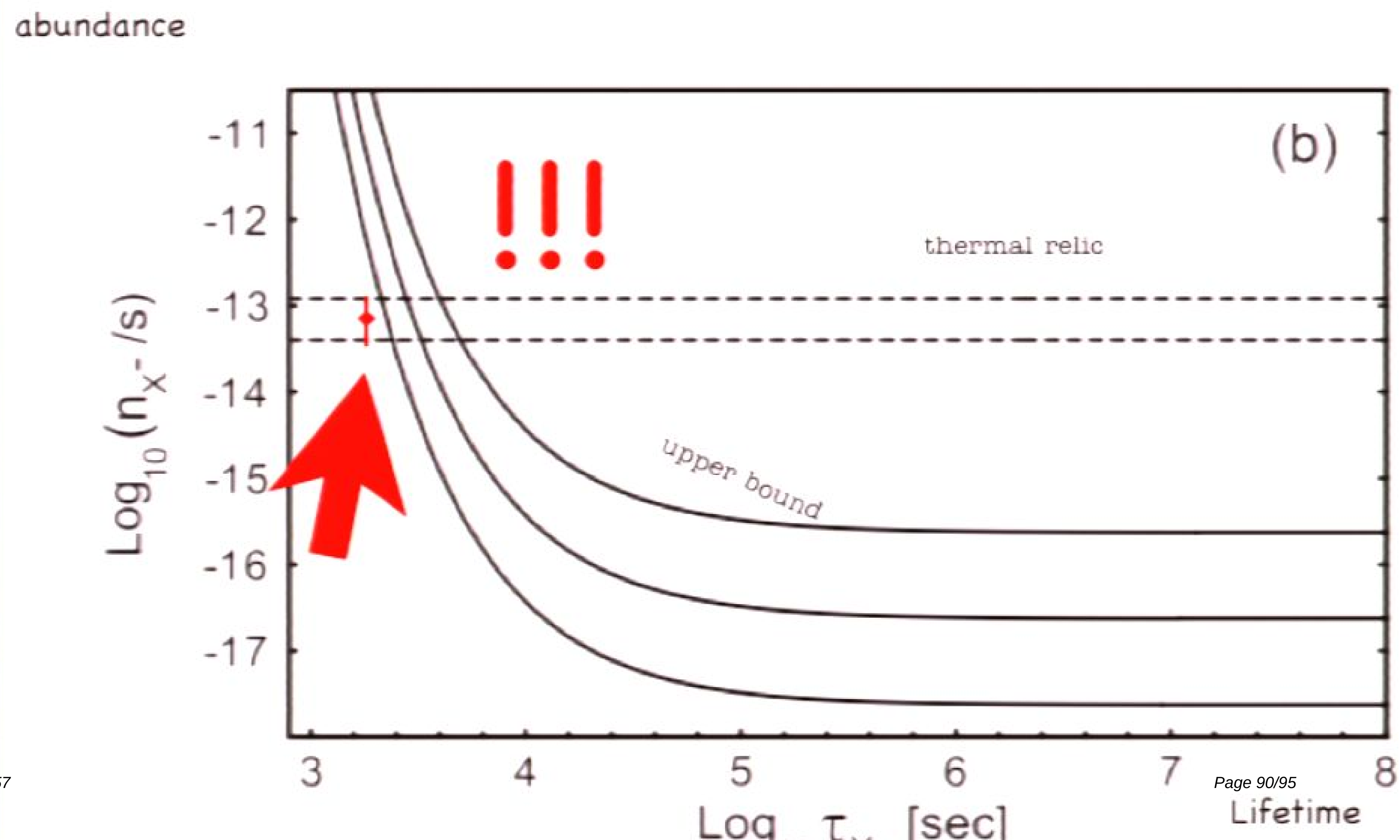


FIG. 19: Statistics required to distinguish axino scenario from gravitino scenario. left for $m_{\tilde G} = m_{\tilde a} = 1$ GeV and right for $m_{\tilde G} = m_{\tilde a} = 30$ GeV

$$\frac{\Delta Y_{\tilde{\tau}}}{Y_{\tilde{\tau}}} \sim^{+100\%}_{-50\%} \quad \text{and} \quad \frac{\Delta \tau_{\tilde{\tau}}}{\tau_{\tilde{\tau}}} \sim \mathcal{O}(\%)$$

$$\frac{\Delta Y_{\tilde{\tau}}}{Y_{\tilde{\tau}}} \sim^{+100\%}_{-50\%} \quad \text{and} \quad \frac{\Delta \tau_{\tilde{\tau}}}{\tau_{\tilde{\tau}}} \sim \mathcal{O}(\%)$$



Summary

- In SUSY, Gravitino LSP and Stau NLSP is a natural choice.

- Long-lived Stau with $\tau > O(1)$ sec (especially > 1000 sec) may affect the BBN!

- It can be tested at the LHC!
  - can precisely measure the mass,
  - and hence the thermal relic abundance,
  - and if staus can be trapped, the lifetime can also be precisely measured !


2006 5 13

No Signal

VGA-1

No Signal

VGA-1