Probing T_R at the LHC with long-lived staus.

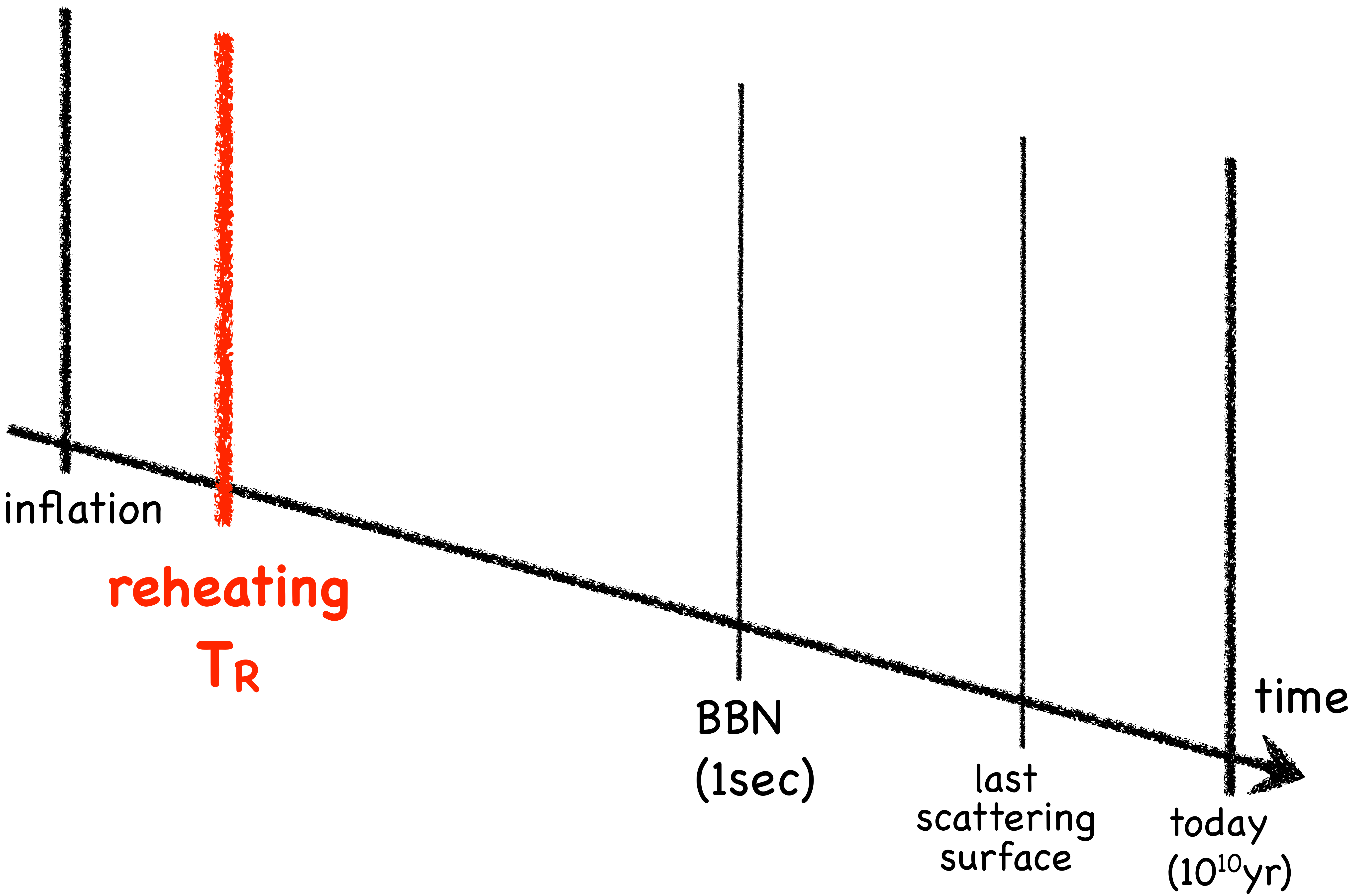
Koichi Hamaguchi (Tokyo U. + IPMU)

based on, M.Endo, KH, K.Nakaji, [arXiv:1008.2307]
+ M.Endo, KH, K.Nakaji, in preparation

+ S.Asai, KH, S.Shirai, [arXiv:0902.3754] PRL,103,141803

Non-Thermal Cosmological Histories of Universe
at Michigan Center for Theoretical Physics, October, 2010

(Non-) Thermal History of the Universe



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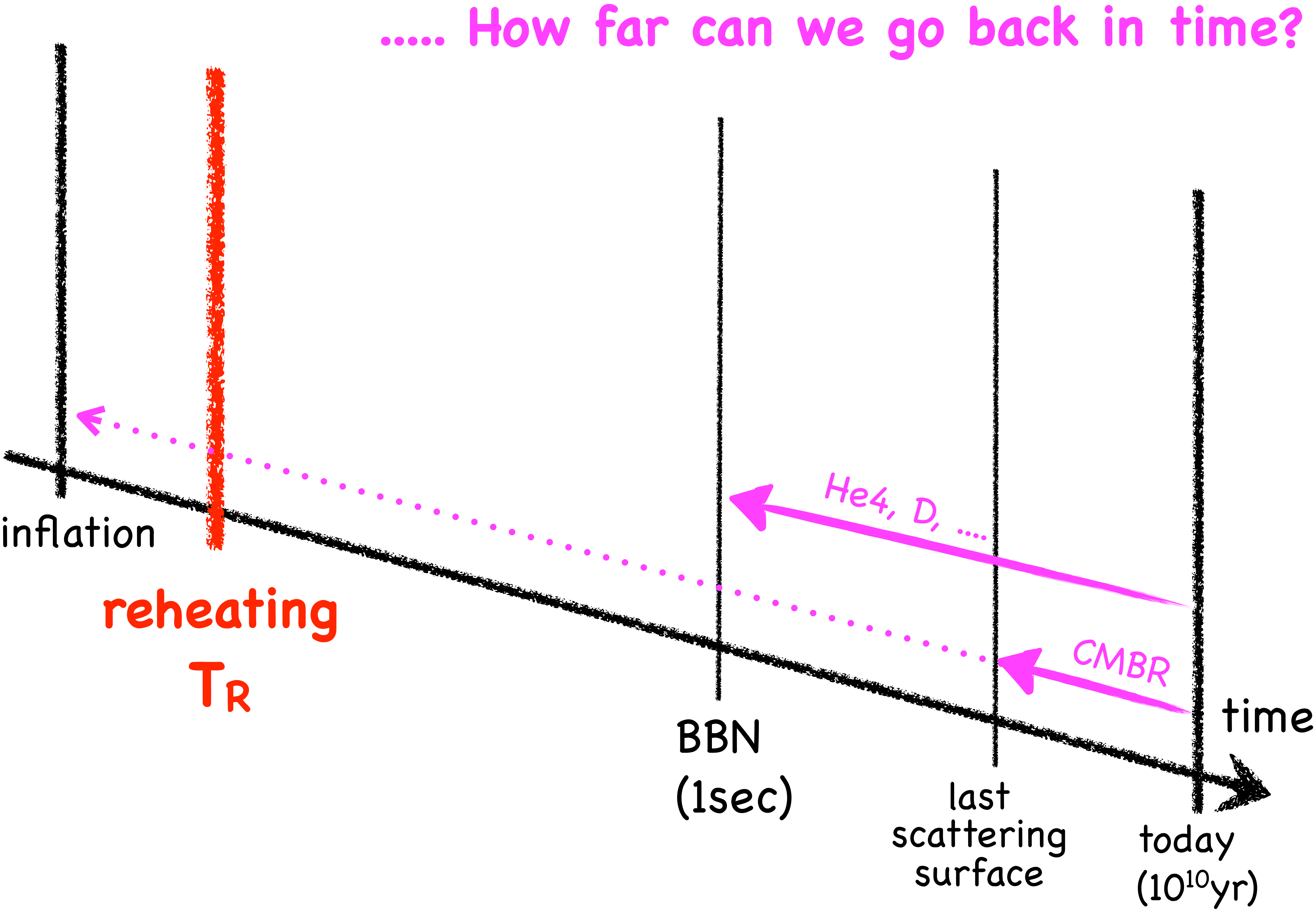

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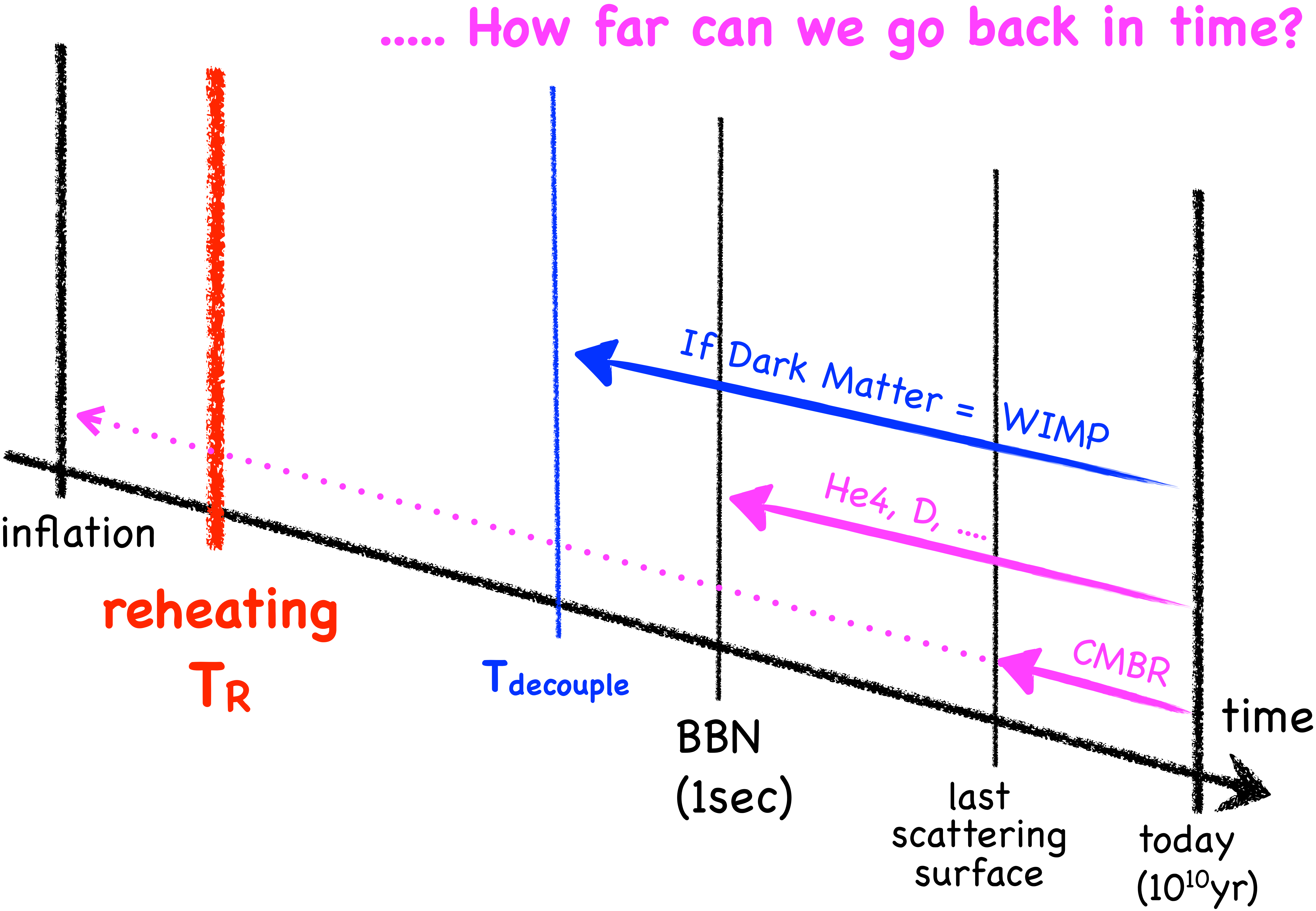

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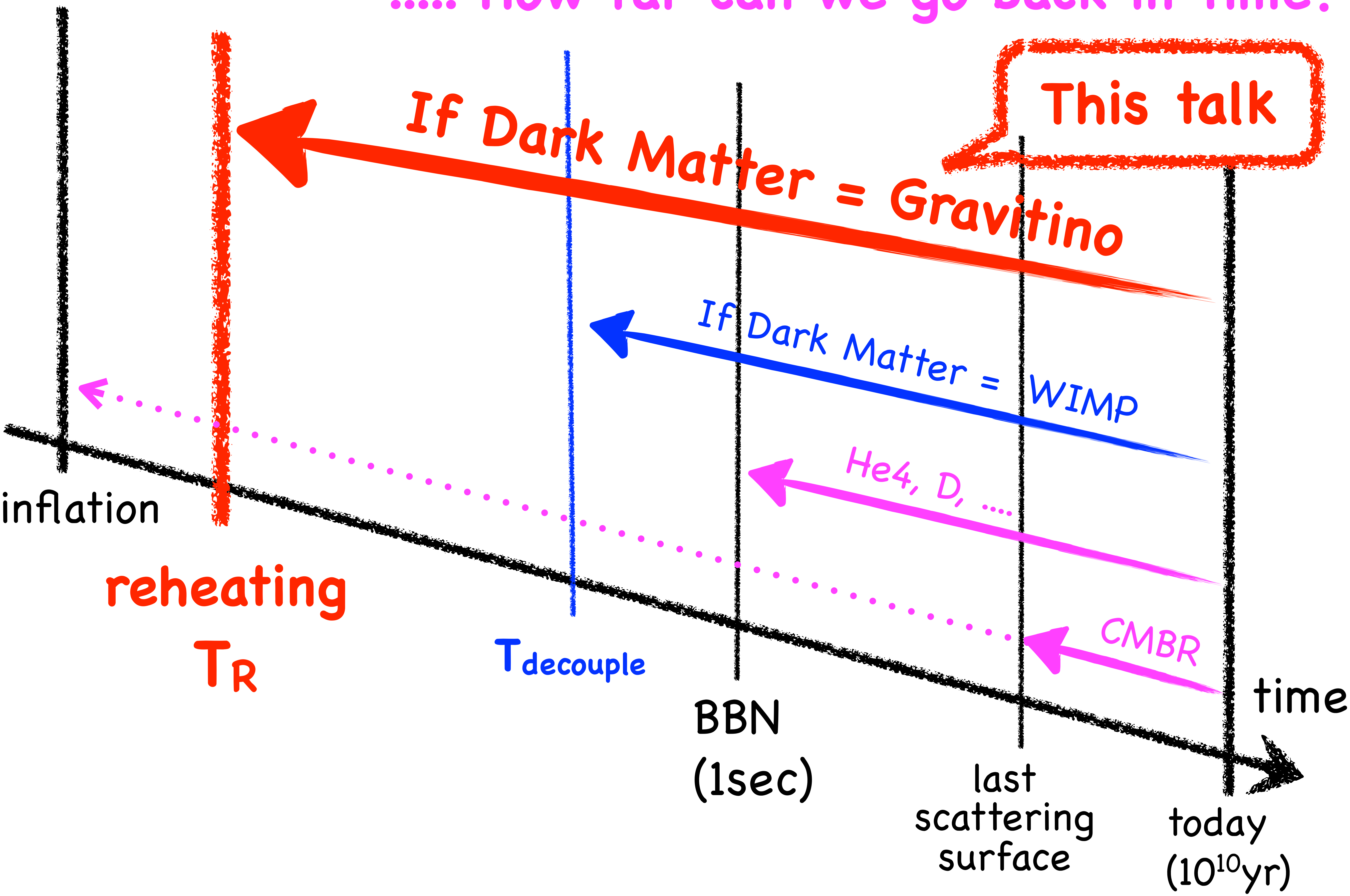
..... How far can we go back in time?



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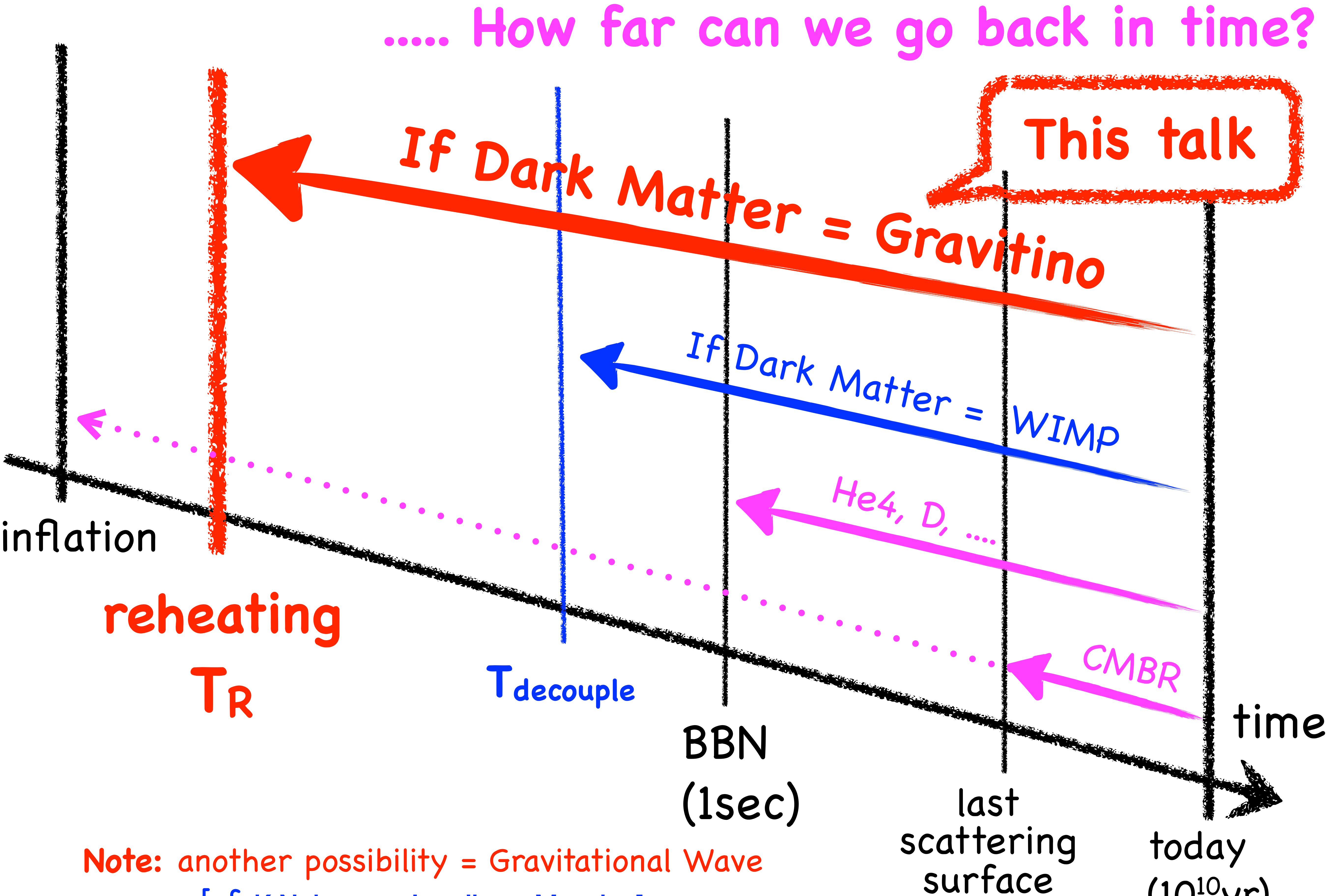

Note: another possibility = Gravitational Wave

[cf. K.Nakayama's talk on Monday]

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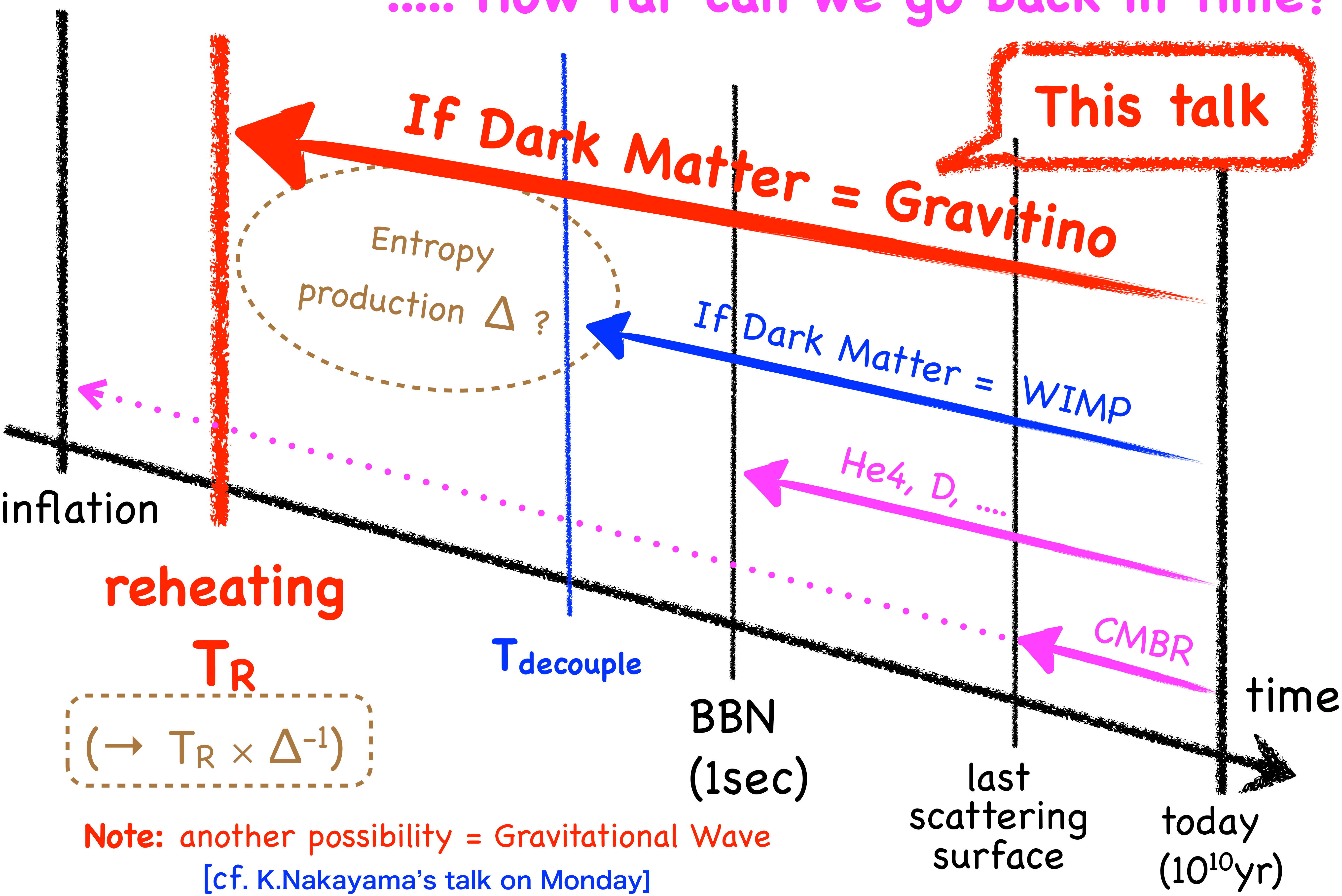

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before the main part,... a comment on moduli problem

$$\Gamma_X = \frac{c}{4\pi}\frac{m_X^3}{M_P^2} \qquad T_X = (\pi^2 g_*/90)^{-1/4}\sqrt{M_P \Gamma_X}$$
$$\simeq 5.5 \times 10^{-3}\ \mathrm{MeV} \cdot c^{\frac{1}{2}} \left(\frac{m_X}{1\ \mathrm{TeV}}\right)^{3/2}$$

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Moduli-Induced Gravitino Problem

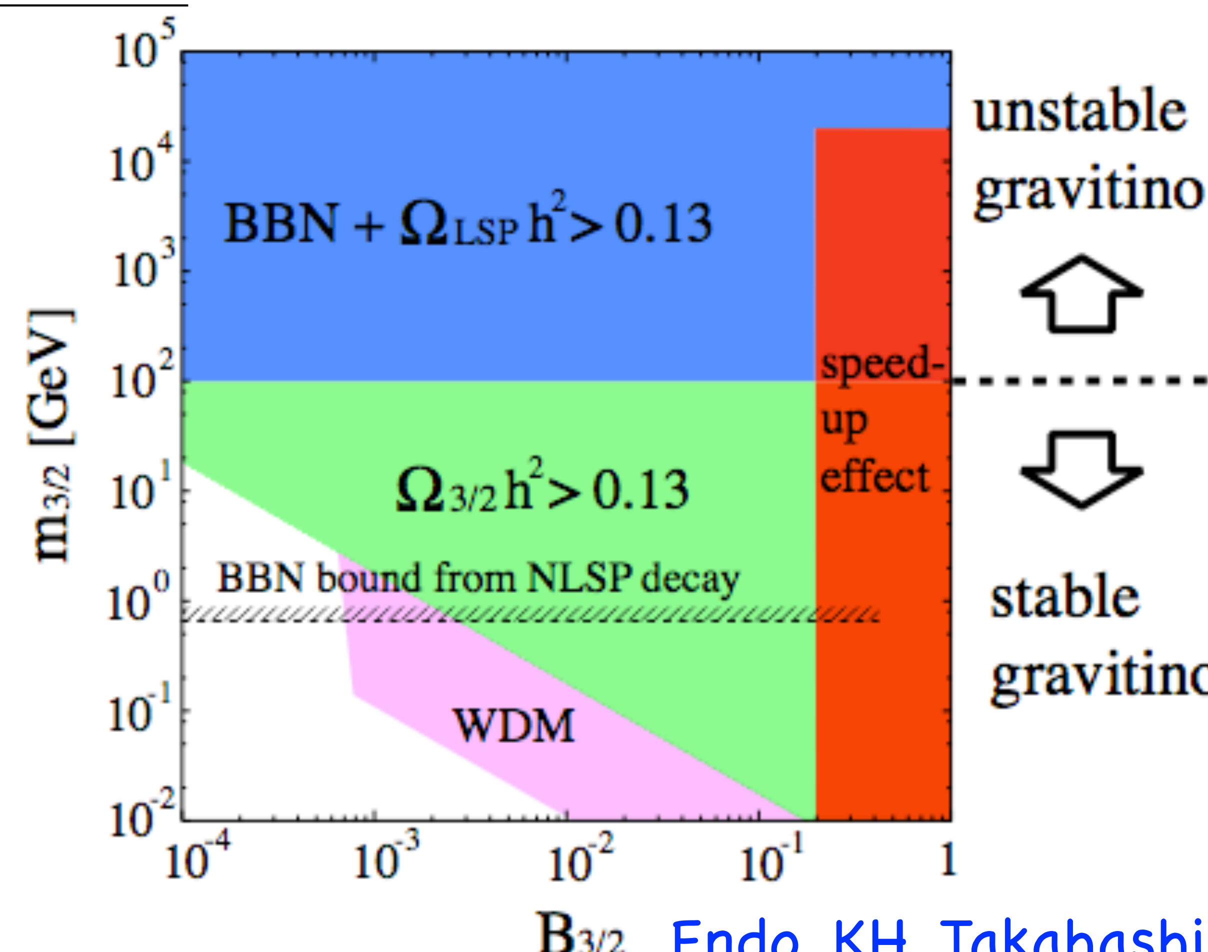
Endo, **KH**, Takahashi, 0602061
Nakamura, Yamaguchi, 0602081
Asaka, Nakamura, Yamaguchi, 0604132
Dine, **Kitano**, Morisse, Shirman, 0604140
Endo, **KH**, Takahashi, 0605091

$$\Gamma(X_{R,I}\rightarrow 2\psi_{3/2}) \simeq \frac{1}{288\pi}\frac{|G_X|^2}{g_{X\bar{X}}}\frac{m_X^5}{m_{3/2}^2},$$

Generically, $|G_X| > m_{3/2}/m_X$
---> Br(X → 2 gravitinos) ≃ O(1) !!!

===> Serious problems,

even if T_X > 1 MeV.



Endo, KH, Takahashi,'06

$m_{\rm NLSP}$ = 100 GeV. We have chosen m_X = 10^3 TeV and $c = 1$ as representative values. The bounds become severer for larger m_X.

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solutions:

★ 2 $m_{3/2} > m_X$
★ enhanced moduli total decay rate
(e.g., low cut-off) ---> Br << 1
★ $|G_X| << m_{3/2} / m_X$
(by tuning Kahler potential)
★ no moduli domination
(e.g., by $H_{inf} < m_X$)
★ etc...

Main messages of this talk:

In SUSY models with **gravitino LSP** + **stau NLSP,**

- T_R > a few 10^8 GeV

  → tested at 7 TeV 1fb^{-1} (≃ within 1.5 years !)

- Stau lifetime can be measured at the LHC.

  (→ T_R may be determined,

  assuming $\Omega_{\tilde{G}}^{\rm thermal} h^2 \simeq \Omega_{\rm DM} h^2$. If not, → upper bound on T_R.)

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outline of this talk:

1 Introduction

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- naturalness, coupling unification, DM, ...
- many non-SUSY scenarios for BSM → low E cut-off

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

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

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

gravitino : $\tilde{G}$

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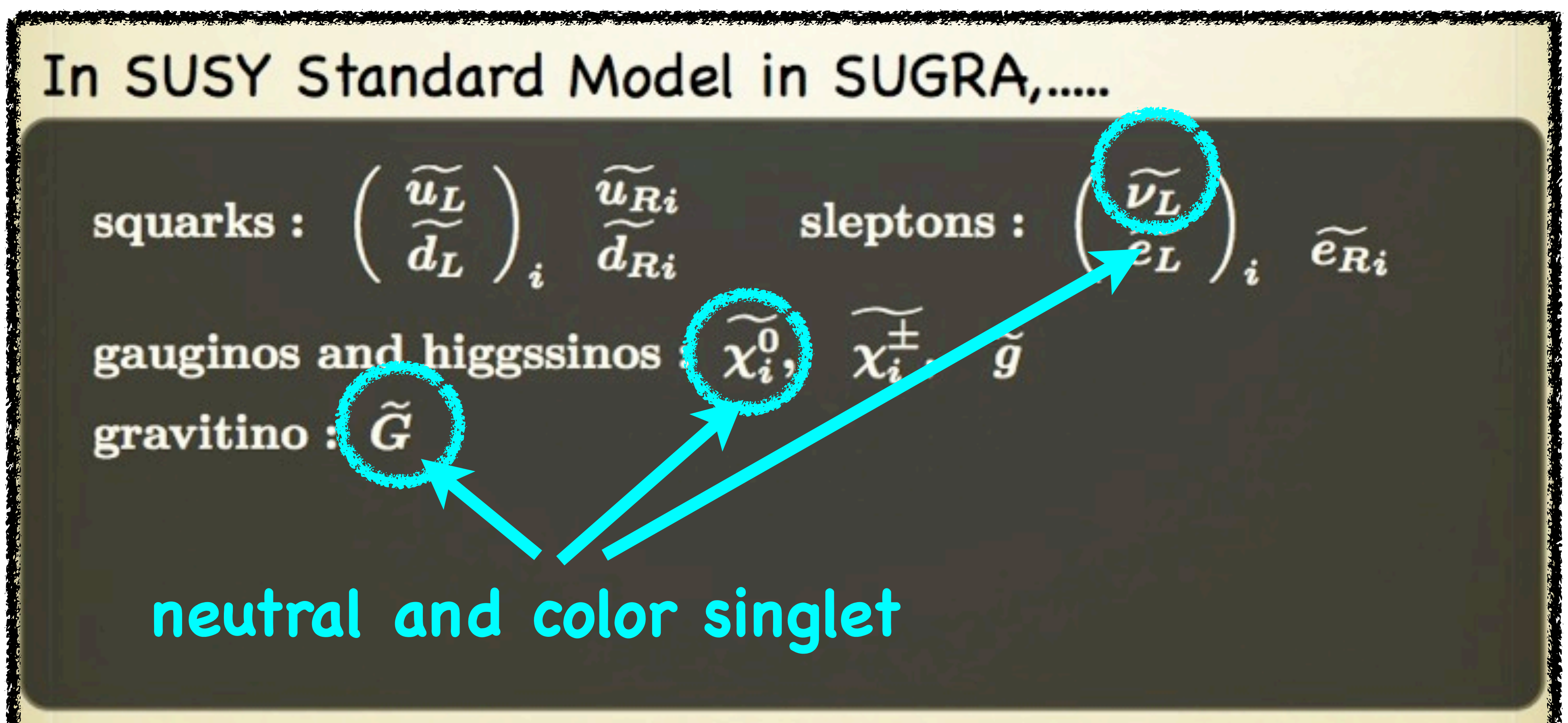

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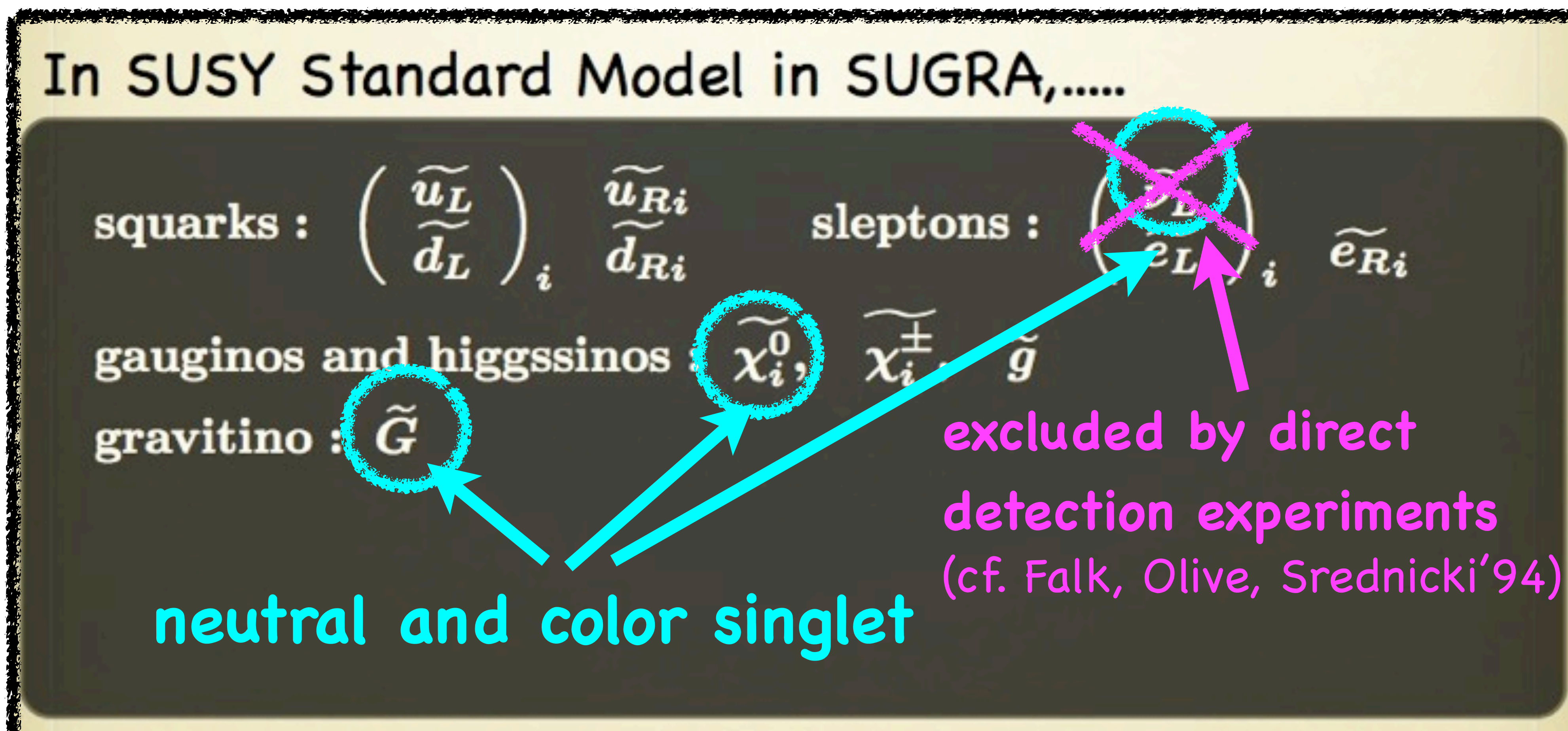

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→ only gravitino or neutralino are allowed.

→ NLSP becomes long-lived. We assume stau NLSP.

(e.g., for m_{NLSP} = 200 GeV, lifetime = O(10sec - day) for $m_{gravitino}$ = O(0.1 - 10 GeV)

..... realized in many attractive models .....

- GMSB (in particular, with messenger # > 1)
- Sweet Spot SUSY [Ibe, Kitano '07] (cf. R.Kitano's talk)
- F-theory GUT [Marsano, Saulina, Schafer-Nameki '08 / Heckman, Shao, Vafa '10]

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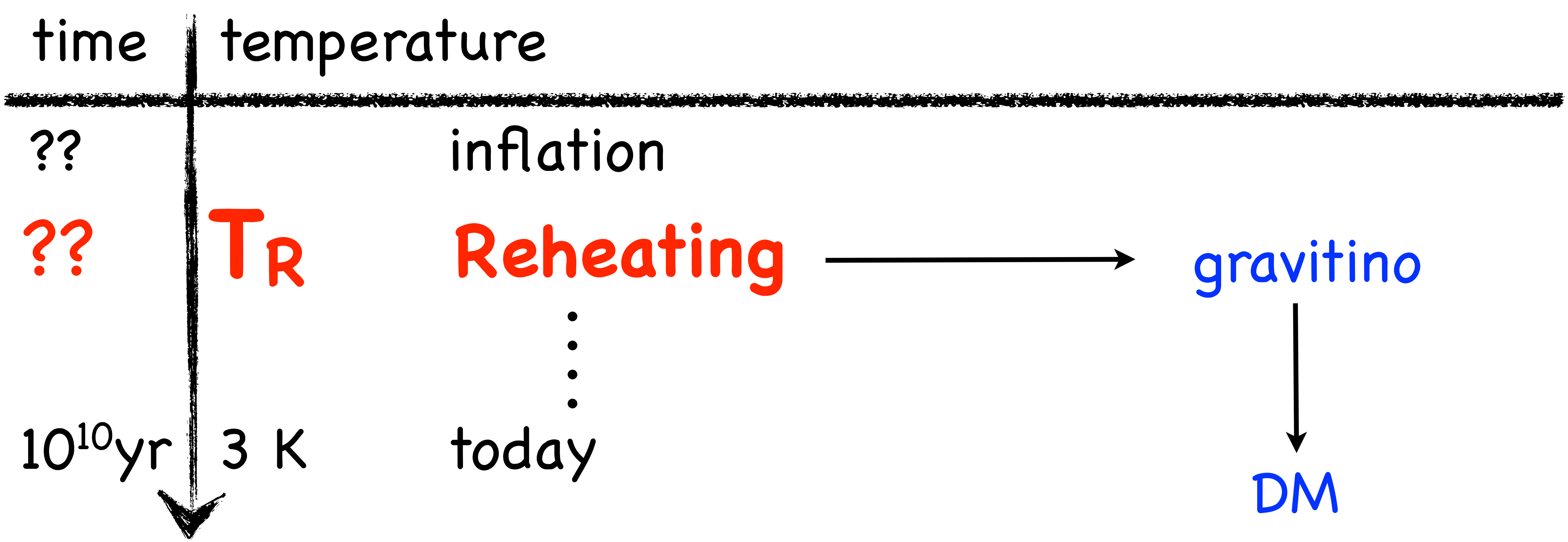
POINT: (thermally produced) gravitino abundance is determined by T_R.



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$$\Omega_{\tilde{G}}^{\rm thermal} h^2 \simeq 0.1 \left(\frac{3\,{\rm GeV}}{m_{\tilde{G}}}\right)\left(\frac{m_{\rm gluino}}{1\,{\rm TeV}}\right)^2\left(\frac{\mathbf{T_R}}{10^8\,{\rm GeV}}\right)$$

$$\leq \Omega_{\rm DM} h^2 = 0.11$$

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info at the LHC

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comments

(1) bino and wino contributions are usually small,

→ becomes comparable if $m_{\rm wino/bino} \simeq m_{\rm gluino}$.

$$\Omega_{3/2} h^2 \simeq \left(\frac{1\,{\rm GeV}}{m_{3/2}}\right)\left(\frac{T_R}{10^8\,{\rm GeV}}\right) \times \left[0.14\left(\frac{m_{\widetilde{B}}}{1\,{\rm TeV}}\right)^2 + 0.38\left(\frac{m_{\widetilde{W}}}{1\,{\rm TeV}}\right)^2 + 0.34\left(\frac{m_{\widetilde{g}}}{1\,{\rm TeV}}\right)^2\right],$$

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→ **replace T_R → $T_R \times \Delta^{-1}$ in the following discussion.**

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- stau NLSP decay: small for $m_{\rm stau}$ < 1 TeV.
- inflaton decay: small for large T_R [cf. Endo, Kawasaki, Takahashi, Yanagida '06-'07]
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→ **in the simplest case,** $\Omega_{\widetilde{G}}^{\rm thermal} h^2 = \Omega_{\rm DM} h^2 \simeq 0.1$

..... **if not,** $\Omega_{\widetilde{G}}^{\rm thermal} h^2 \leq \Omega_{\rm DM} h^2$ (→ upper bound on T_R)

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LHC

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2 use upper bound from BBN

3 stau lifetime → gravitino mass

2

Probing **high T_R scenario** at the LHC with long lived stau.

M.Endo, KH, K.Nakaji, arXiv:1008.2307

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thermal leptogenesis: $T_R > O(10^9)$ GeV

non-thermal leptogenesis: $T_R > O(10^6)$ GeV

some typical inflation models: $T_R = O(10^4 - 10^{13})$ GeV

.....

---> any signal at the LHC ???

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M.Endo, KH, K.Nakaji,
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Logic [Fujii, Ibe, Yanagida,'04]

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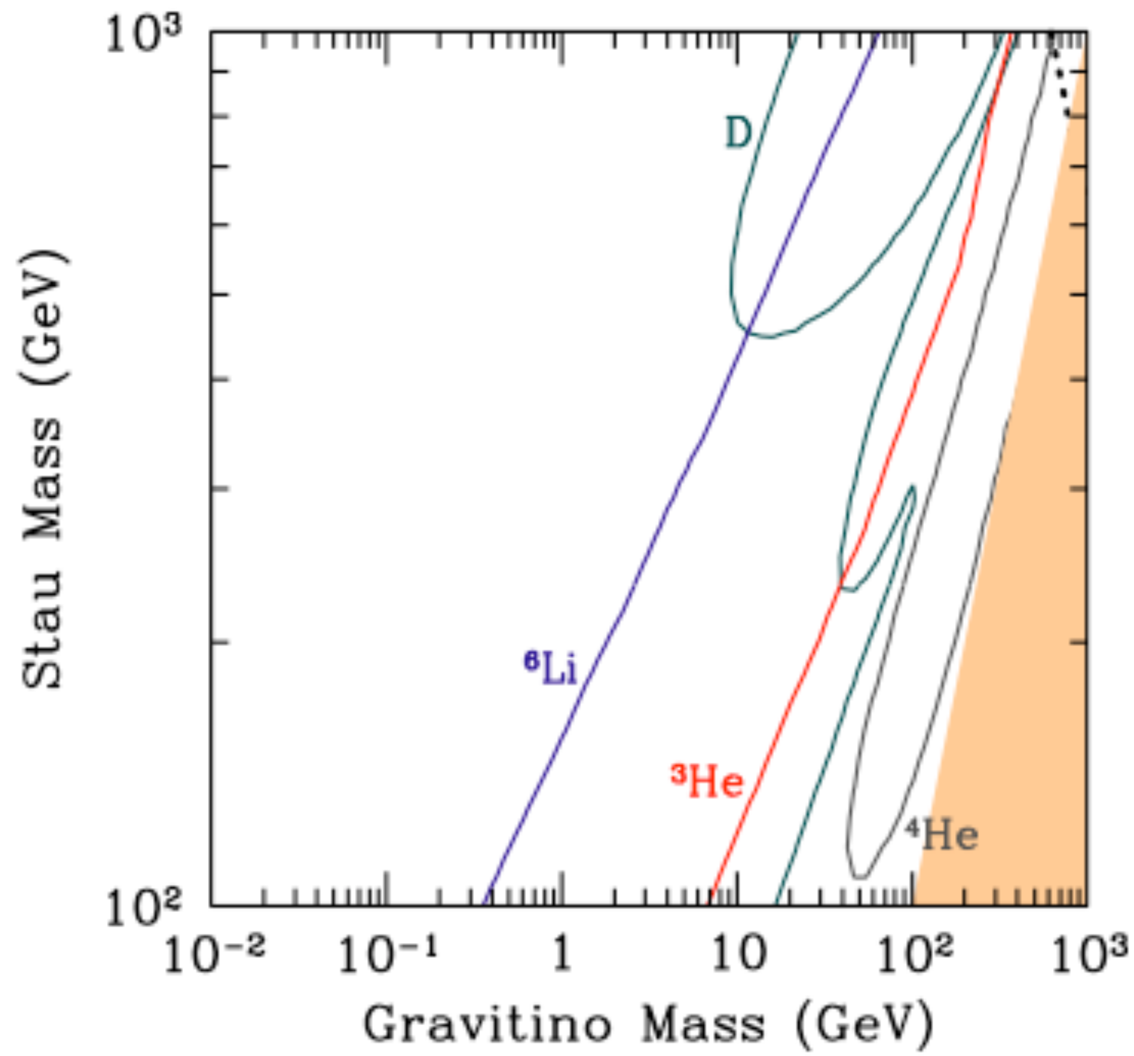

Kawasaki, Kohri, Moroi, Yotsuyanagi,'08

Assuming:
thermal relic abundance of stau

If not: the bound is relaxed.

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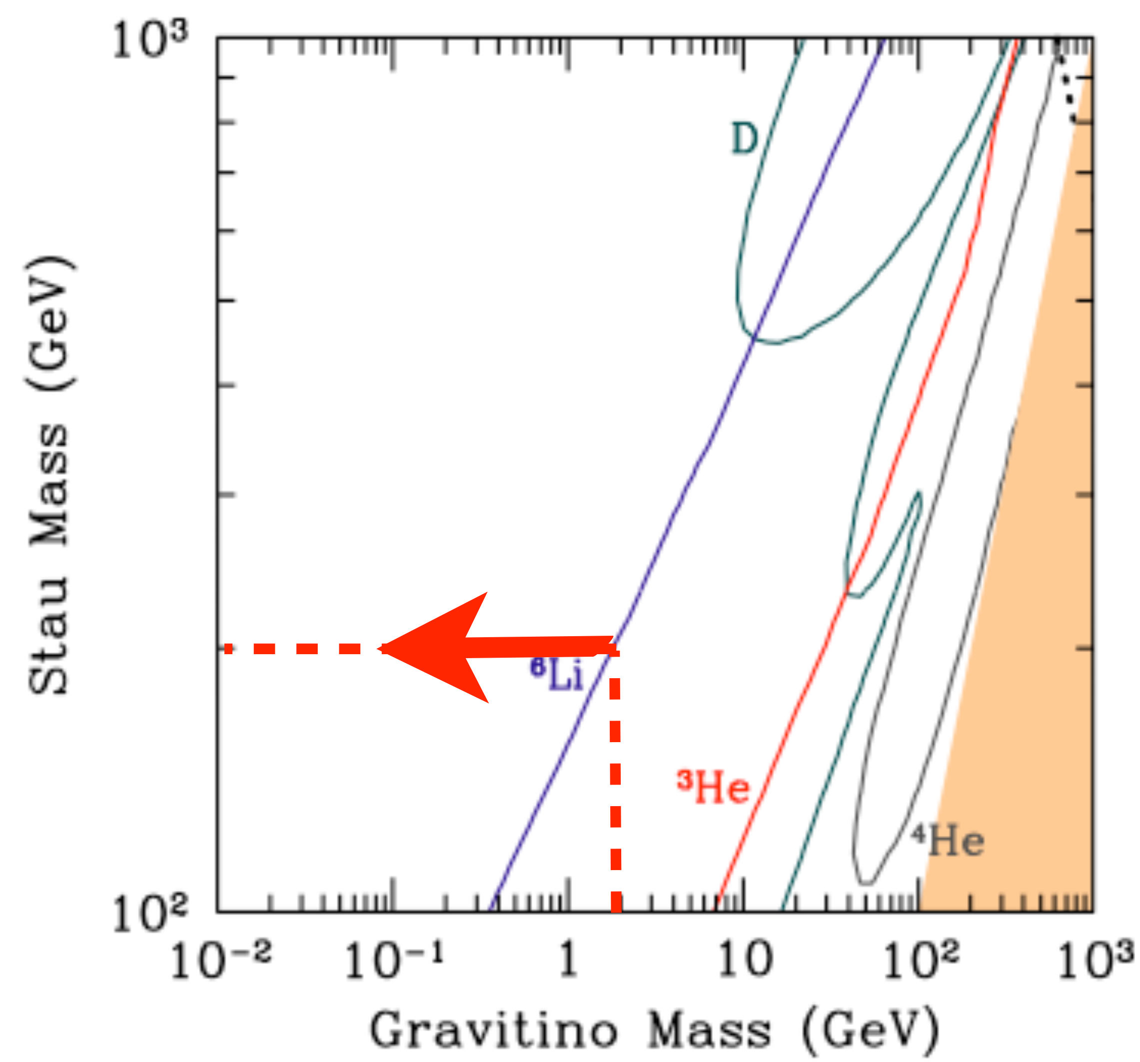

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(2) + for a given T_R

→ upper bound on gluino mass

Probing high T_R scenario at the LHC with long lived stau.

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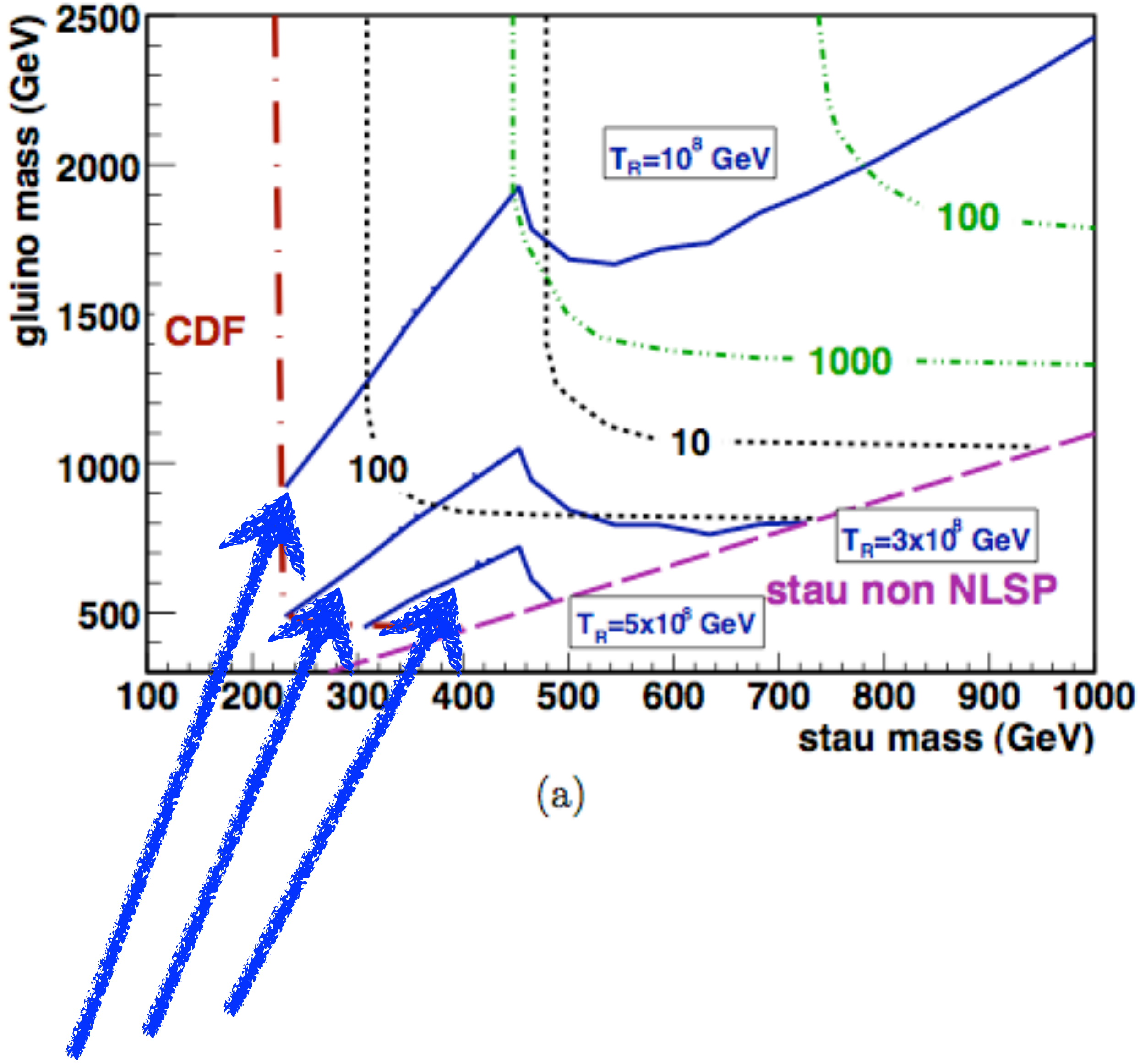
Result



(a)

upper bound on the gluino mass for given TR

Note: taken m(bino)=m(wino)=1.1m(stau) to have conservative bound on TR.

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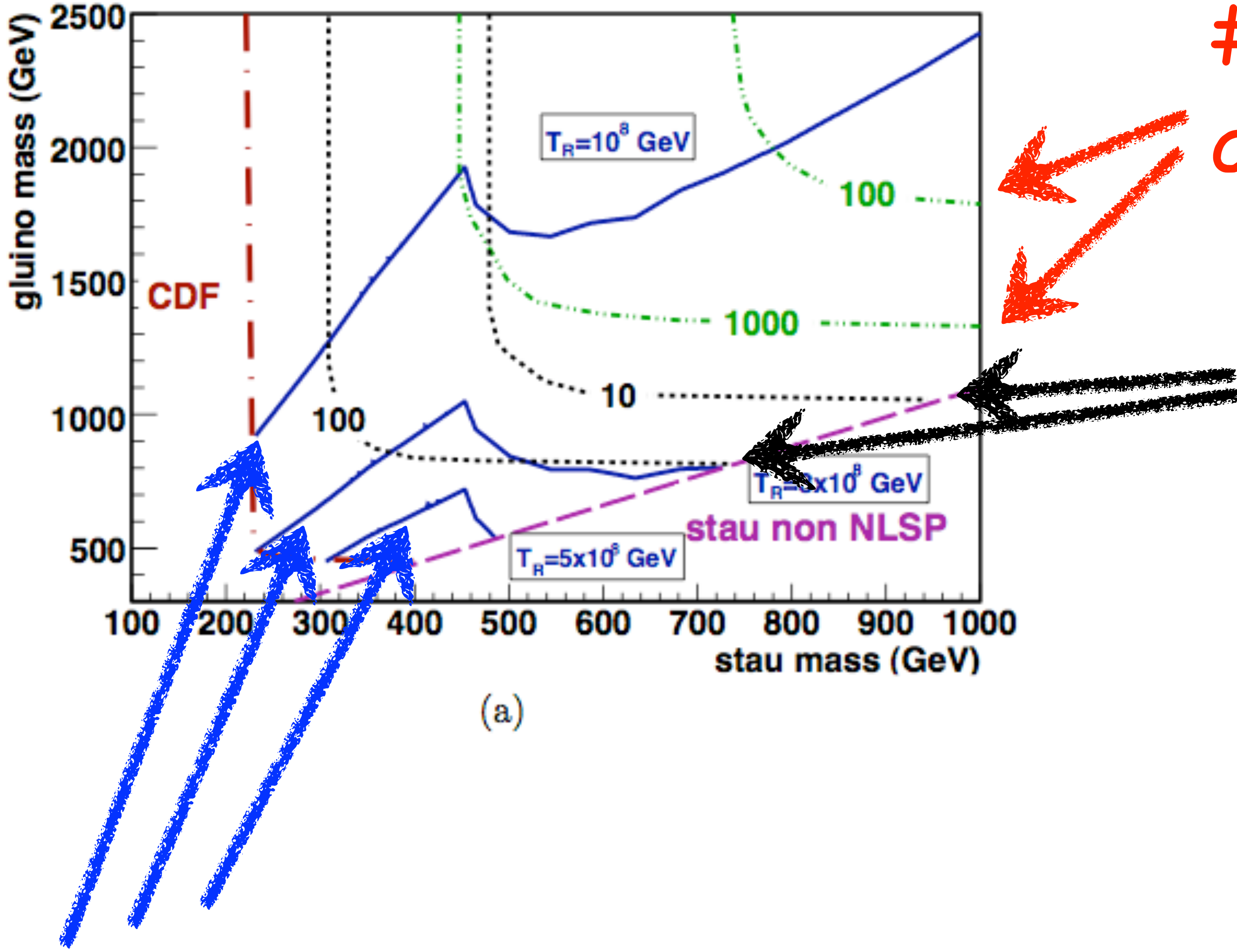

# of produced staus at 14 TeV 10fb^{-1}

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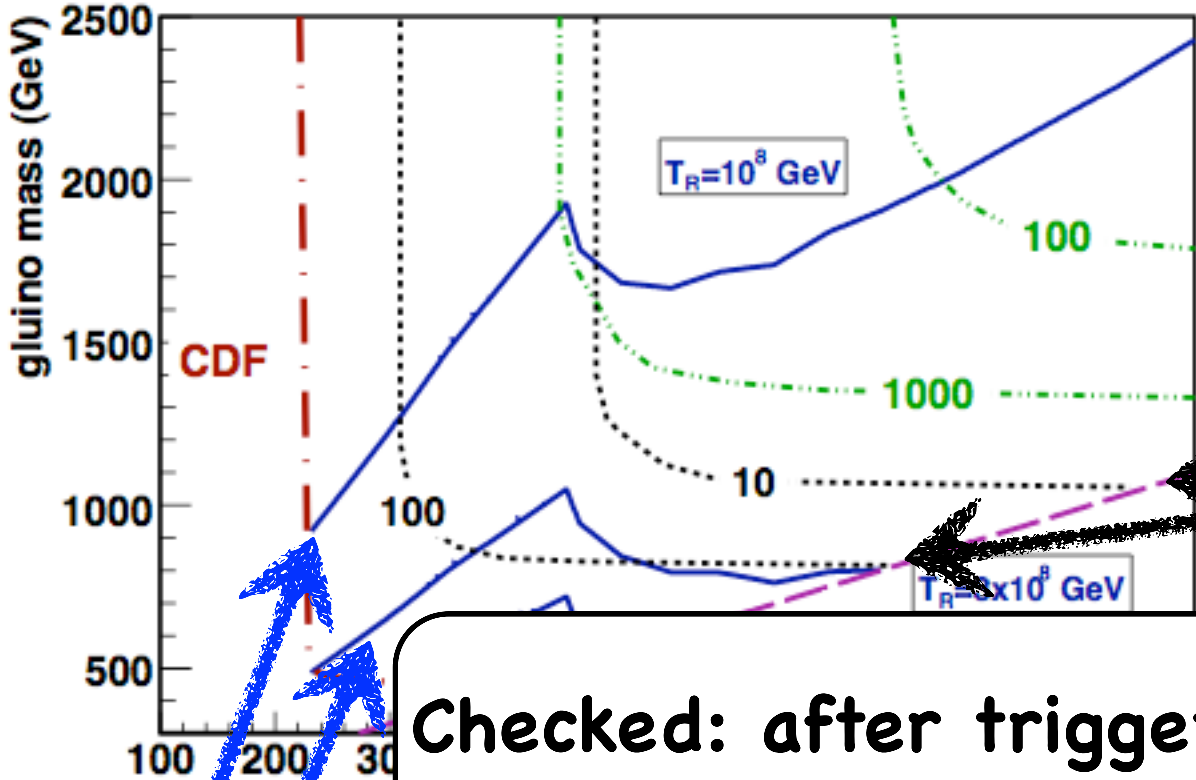


# of produced staus at 14 TeV $10fb^{-1}$

# of produced staus at 7 TeV $1fb^{-1}$

upper b

Checked: after triggers and cuts, 20-50% events remain.

trigger assumption:

>=1 isolated e (pT>20GeV), or

>=1 isolated mu (pT>40GeV), or

>=1 isolated tau (pT>100GeV), or

>=1 isolated stau (pT>40 GeV and β>0.7, eta<1.0 or β>0.8, eta<2.8), or

>=2 staus (pT>40 GeV and β>0.7, eta<1.0 or β>0.8, eta<2.8)

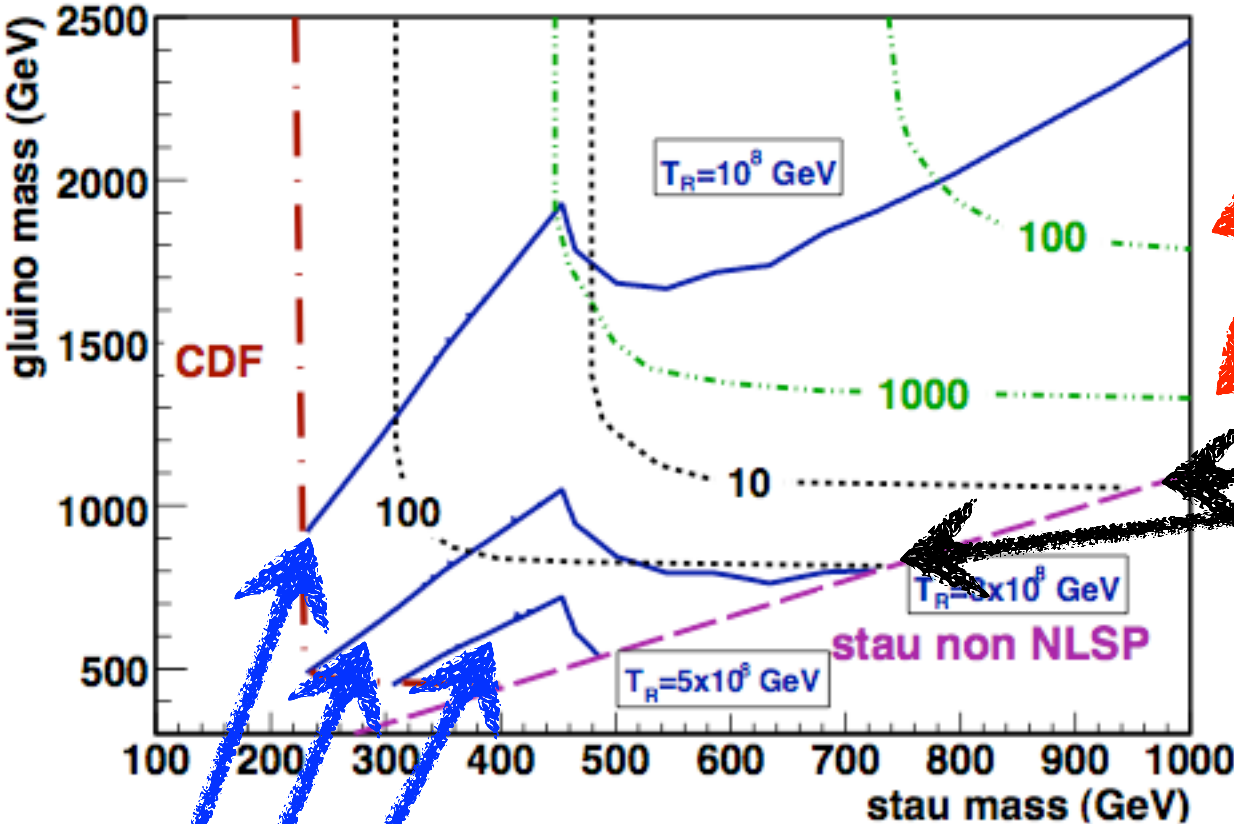
stau cuts assumptions:

pT > 20 GeV & eta < 2.5 & 0.5 < β < 0.9 **-> almost background free!**

Probing high T_R scenario at the LHC with long lived stau.

M.Endo, KH, K.Nakaji,
arXiv:1008.2307

Result



(a)

# of produced staus at 14 TeV 10fb^{-1}

# of produced staus at 7 TeV 1fb^{-1}

TR > a few 10^8 GeV can be probed at 7 TeV 1fb^{-1} !!!

upper bound on the gluino mass for given TR

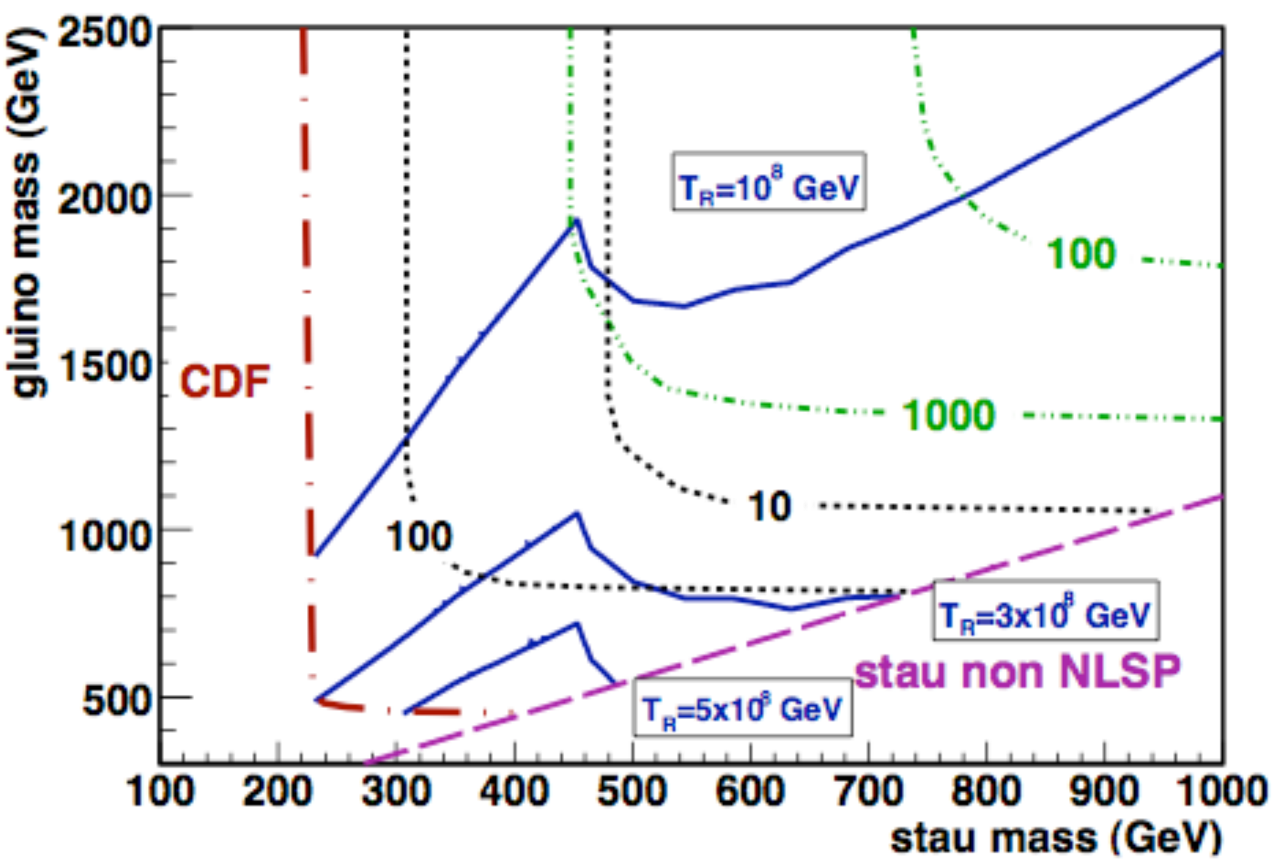
Probing high T_R scenario at the LHC with long lived stau.

M.Endo, KH, K.Nakaji,
arXiv:1008.2307

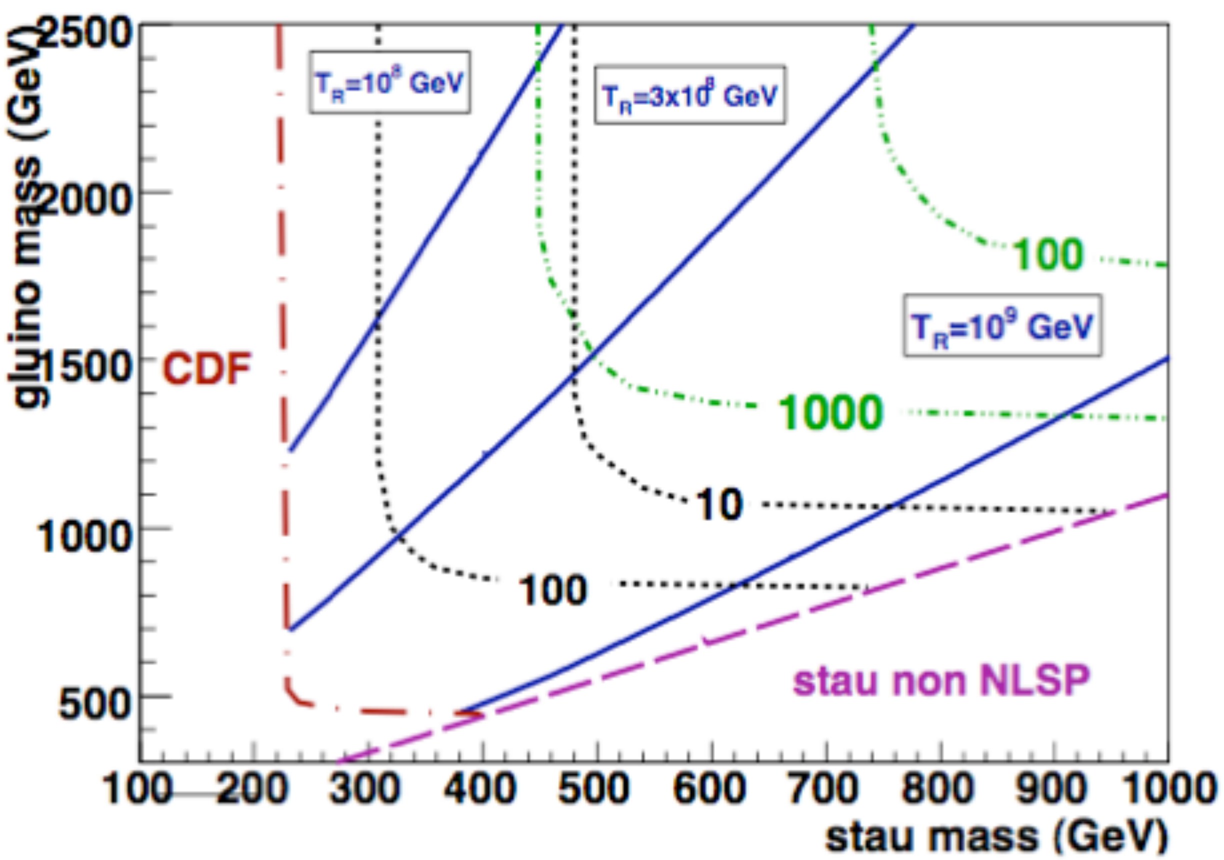
COMMENT

- So far we've assumed that the stau annihilation is dominated by EW process (which is usually the case)
- but if the stau-higgs coupling is extremely enhanced, stau abundance can be reduced (BBN bound is relaxed).

[Ratz, Schmidt-Hoberg, Winkler,'08, Pradler, Steffen,'08]



(a) = normal case



(b) = reduced Ystau

3 stau lifetime measurement (and T_R)

S.Asai, KH, S.Shirai, [arXiv:0902.3754] PRL,103,141803
+ M.Endo, KH, K.Nakaji, in progress

see also earlier work on "stopping gluinos" [hep-ph/0506242]
Arvanitaki, Dimopoulos, Pierce, Rajendran, Wacker

Many independent motivations to measure
the **lifetime of long-lived charged massive particles.....**

- Planck scale measurement, if mG is determined by kinematics
  [Buchmuller, KH, Ratz, Yanagida,'08]
- Test of FIMP mechanism [cf. talks by T.Moroi and L.Hall]
- Li problem/solution [cf. talk by K.Olive]
- etc etc

3 stau lifetime measurement (and T_R)

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$$\Omega_{\tilde{G}}^{\rm thermal} h^2 \simeq 0.1 \left(\frac{3\,{\rm GeV}}{m_{\tilde{G}}} \right) \left(\frac{m_{\rm gluino}}{1\,{\rm TeV}} \right)^2 \left(\frac{T_R}{10^8\,{\rm GeV}} \right)$$

So far we've used only the upper bound: $m_{\tilde{G}} \leq m_{\tilde{G}}^{\rm max}(m_{\tilde{\tau}})$
.... Can we determine gravitino mass more directly??
---> stau lifetime measurement!!

$$\Omega_{\widetilde{G}}^{\text{thermal}} h^2 \simeq 0.1 \left(\frac{3\,\text{GeV}}{m_{\widetilde{G}}} \right) \left(\frac{m_{\text{gluino}}}{1\ \text{TeV}} \right)^2 \left(\frac{\mathbf{T_R}}{10^8\,\text{GeV}} \right)$$

$$\Omega_{\widetilde{G}}^{\text{thermal}} h^2 \simeq 0.1 \left(\frac{3\,\text{GeV}}{m_{\widetilde{G}}}\right) \left(\frac{m_{\text{gluino}}}{1\,\text{TeV}}\right)^2 \left(\frac{\mathbf{T_R}}{10^8\,\text{GeV}}\right)$$

$$= \Omega_{\text{DM}} h^2 = 0.11$$

↑ assumption

(if not, $T_R \to T_R^{max}$)

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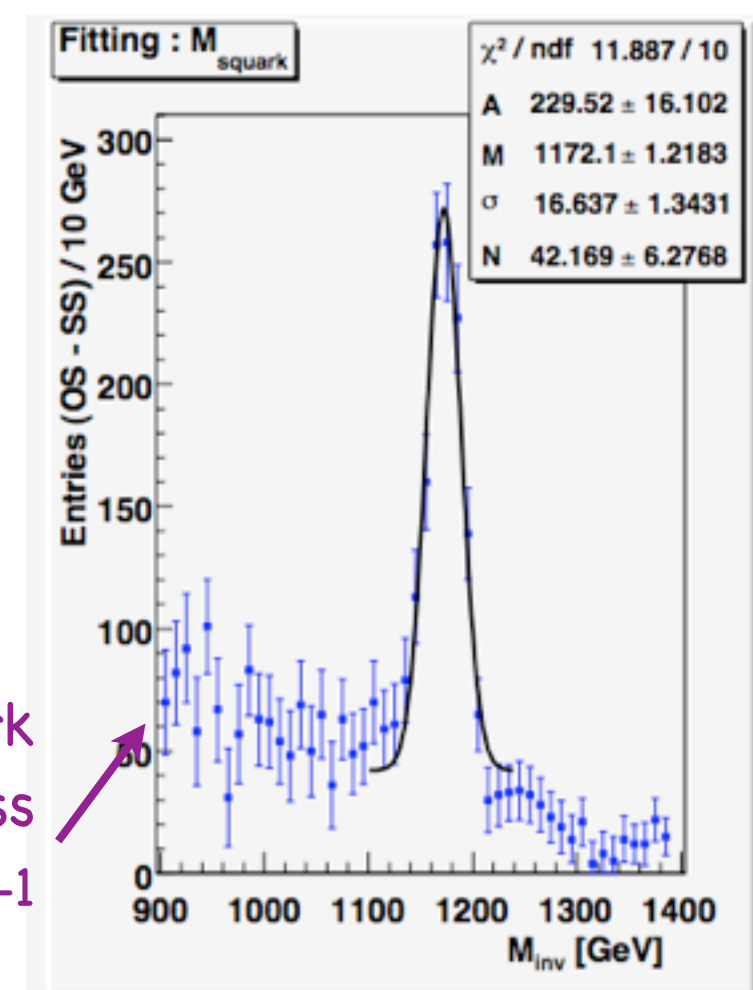
$$= \Omega_{\rm DM} h^2 = 0.11$$

assumption

(if not, $T_R \to T_R^{max}$)

by invariant mass method

[cf. Ito, Kitano, Moroi,'09]



Gluino mass is more difficult but should be possible at high luminosity

$$\Omega_{\widetilde{G}}^{\text{thermal}} h^2 \simeq 0.1 \left(\frac{3\,\text{GeV}}{m_{\widetilde{G}}}\right) \left(\frac{m_{\text{gluino}}}{1\,\text{TeV}}\right)^2 \left(\frac{\mathbf{T_R}}{10^8\,\text{GeV}}\right)$$

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↑ assumption

(if not, $T_R \to T_R^{max}$)

$$\tau_{\widetilde{\tau}} = \frac{48\pi M_{\rm pl}^2 m_{\widetilde{G}}^2}{m_{\widetilde{\tau}}^5}$$

$$\Omega_{\tilde{G}}^{\rm thermal} h^2 \simeq 0.1 \left(\frac{3\,\rm GeV}{m_{\tilde{G}}}\right)\left(\frac{m_{\rm gluino}}{1\,\rm TeV}\right)^2\left(\frac{T_R}{10^8\,\rm GeV}\right)$$

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by velocity measurement

(+ momentum masurement) mass = p/(βγ)

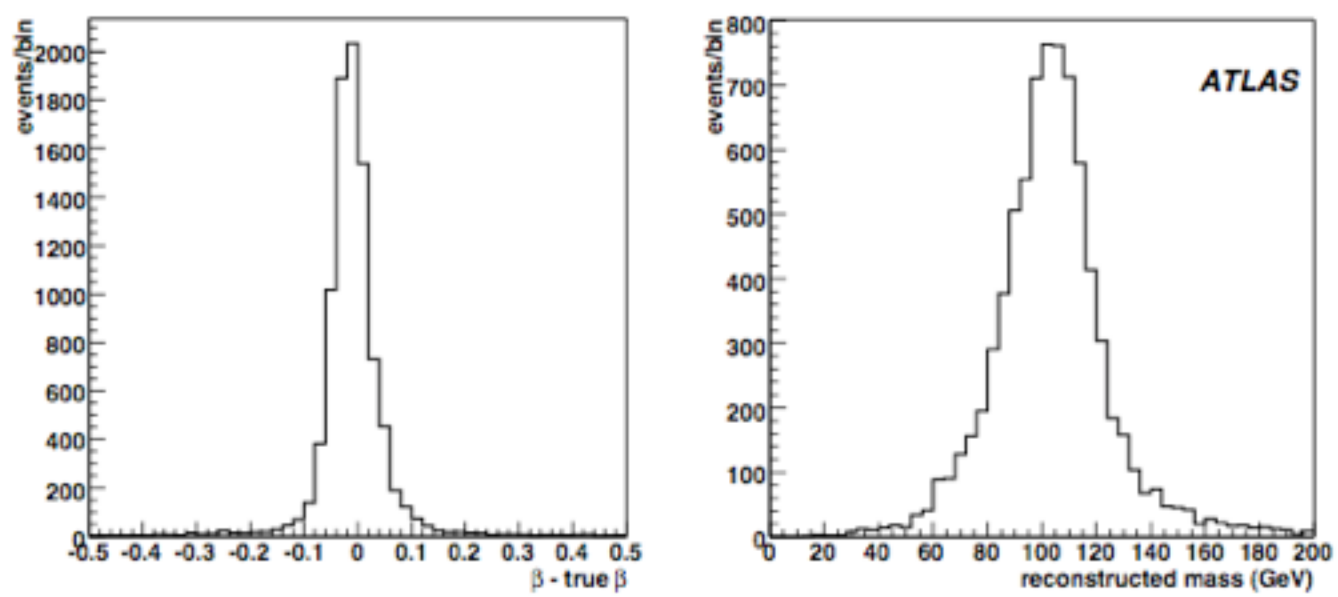

Figure 18: β resolution and reconstructed mass for sleptons from the GMSB5 sample.

ATLAS, 0901.0512

$$\Omega_{\widetilde{G}}^{\text{thermal}} h^2 \simeq 0.1 \left(\frac{3\,\text{GeV}}{m_{\widetilde{G}}}\right) \left(\frac{m_{\text{gluino}}}{1\,\text{TeV}}\right)^2 \left(\frac{T_R}{10^8\,\text{GeV}}\right)$$

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by velocity measurement

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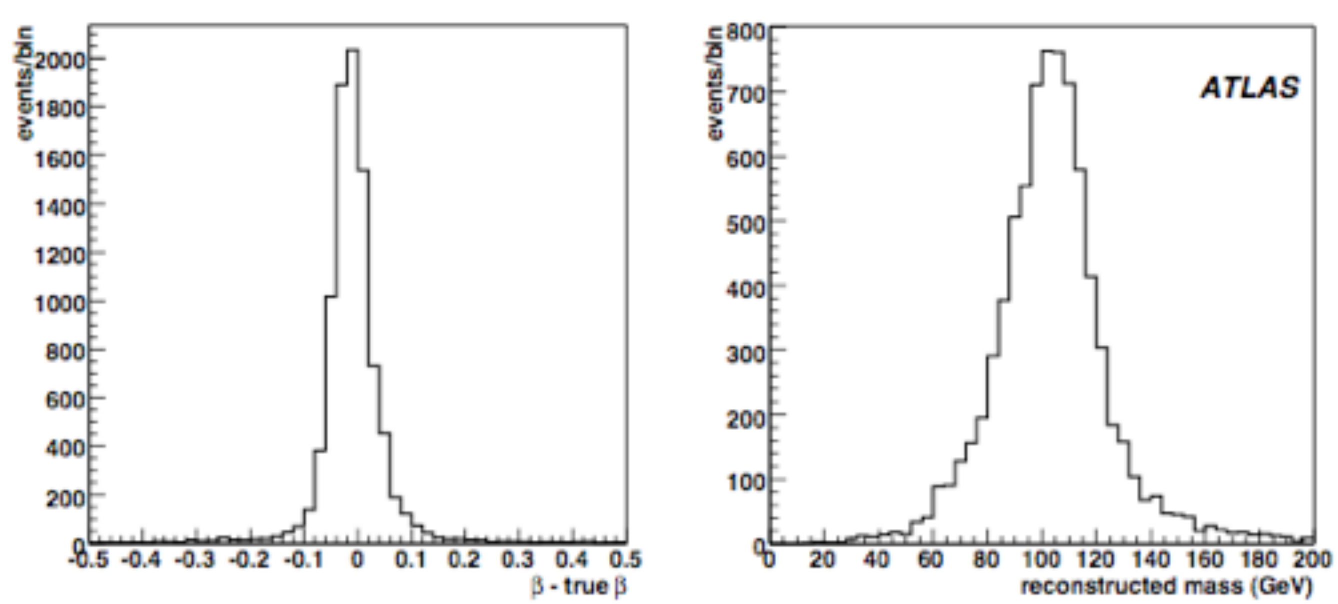
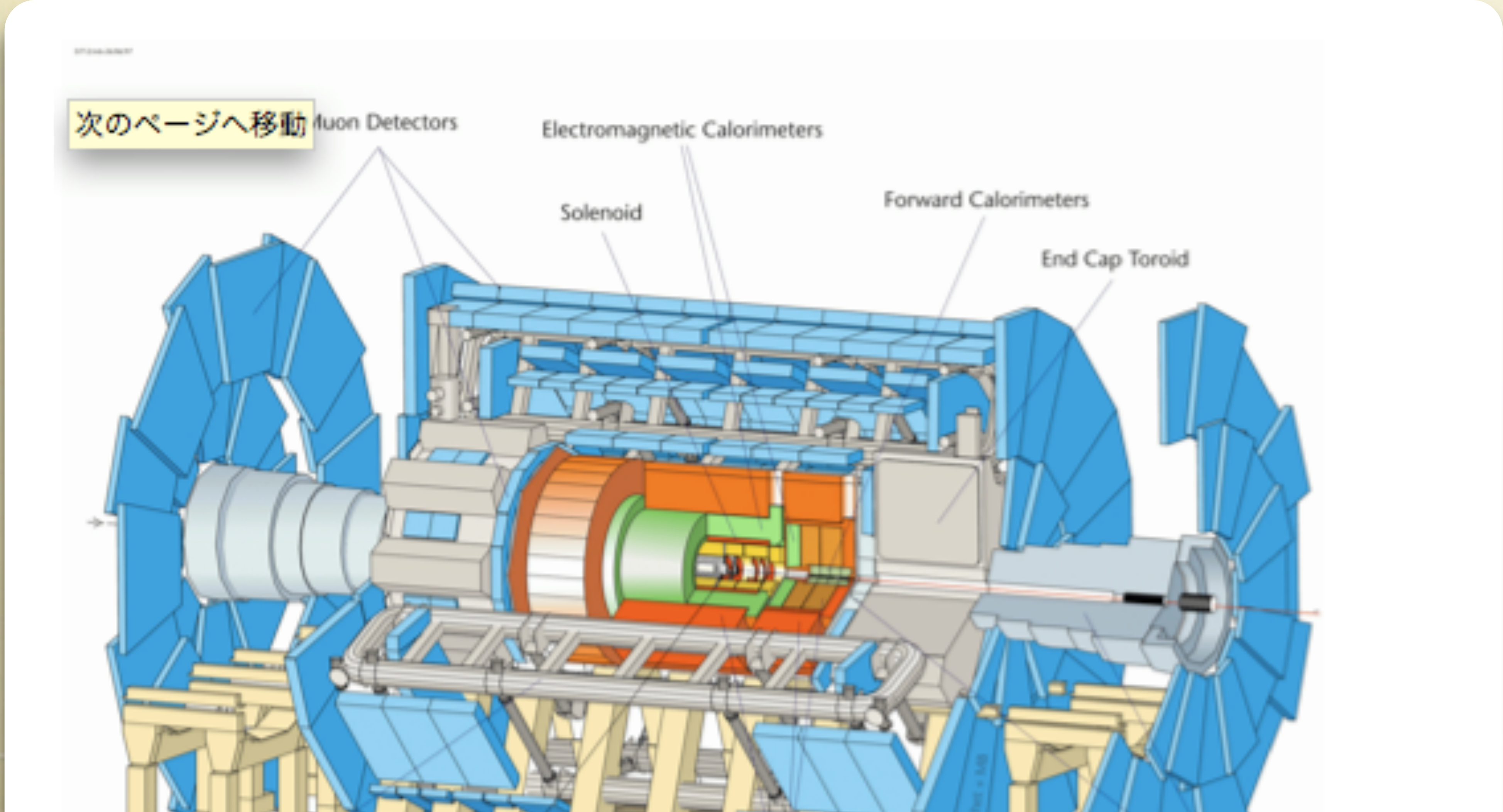


Figure 18: β resolution and reconstructed mass for sleptons from the GMSB5 sample.

ATLAS, 0901.0512

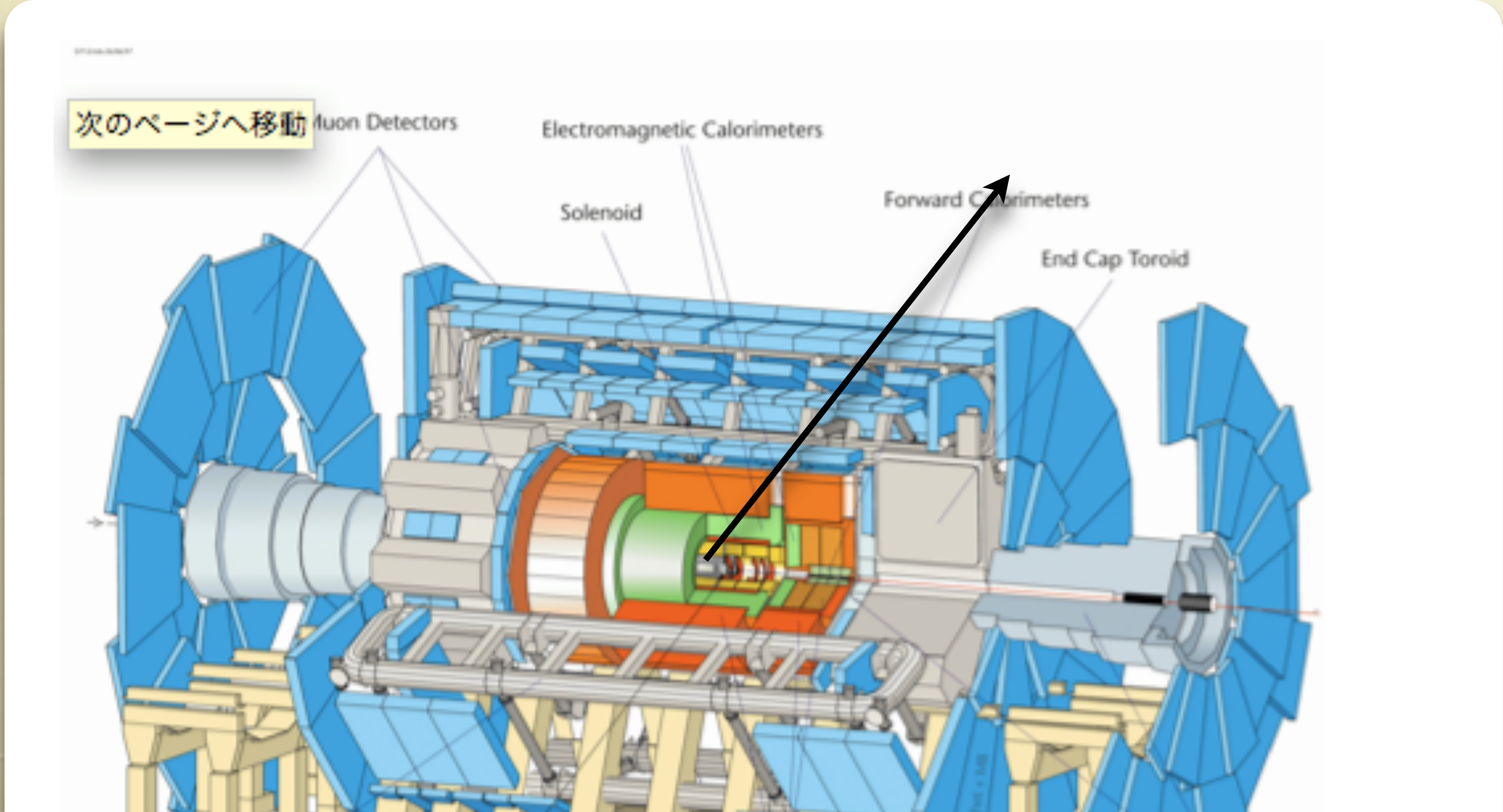
stau lifetime measurement [Asai, KH, Shirai,'09]

- at the LHC,.....



stau lifetime measurement [Asai, KH, Shirai,'09]

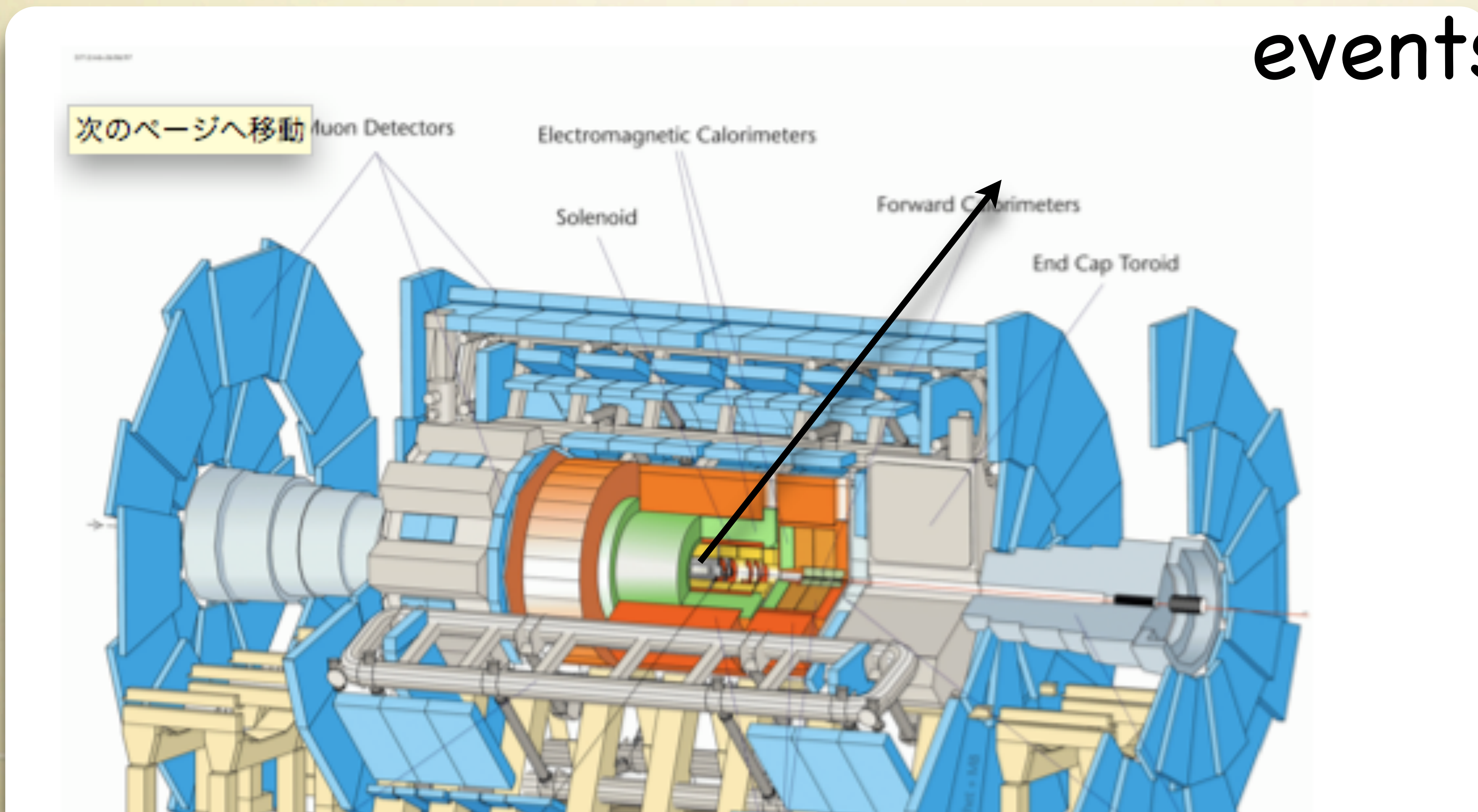
- typically most of staus have large velocity and escape from detector.



stau lifetime measurement [Asai, KH, Shirai,'09]

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

but we can't see its decay in these events.....



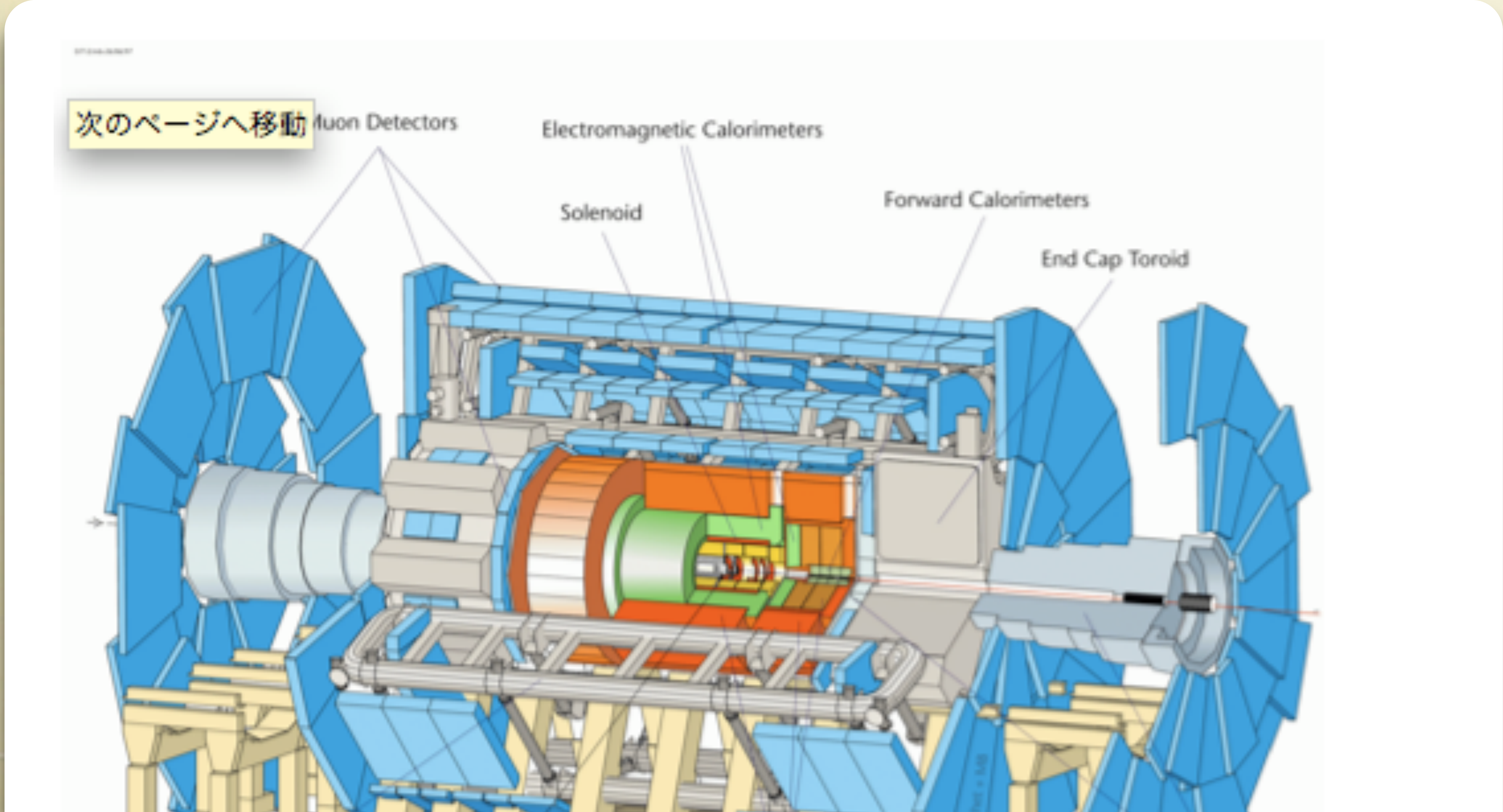
cf. proposals to stop them outside detector:

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

But not realistic now....

stau lifetime measurement [Asai, KH, Shirai,'09]

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



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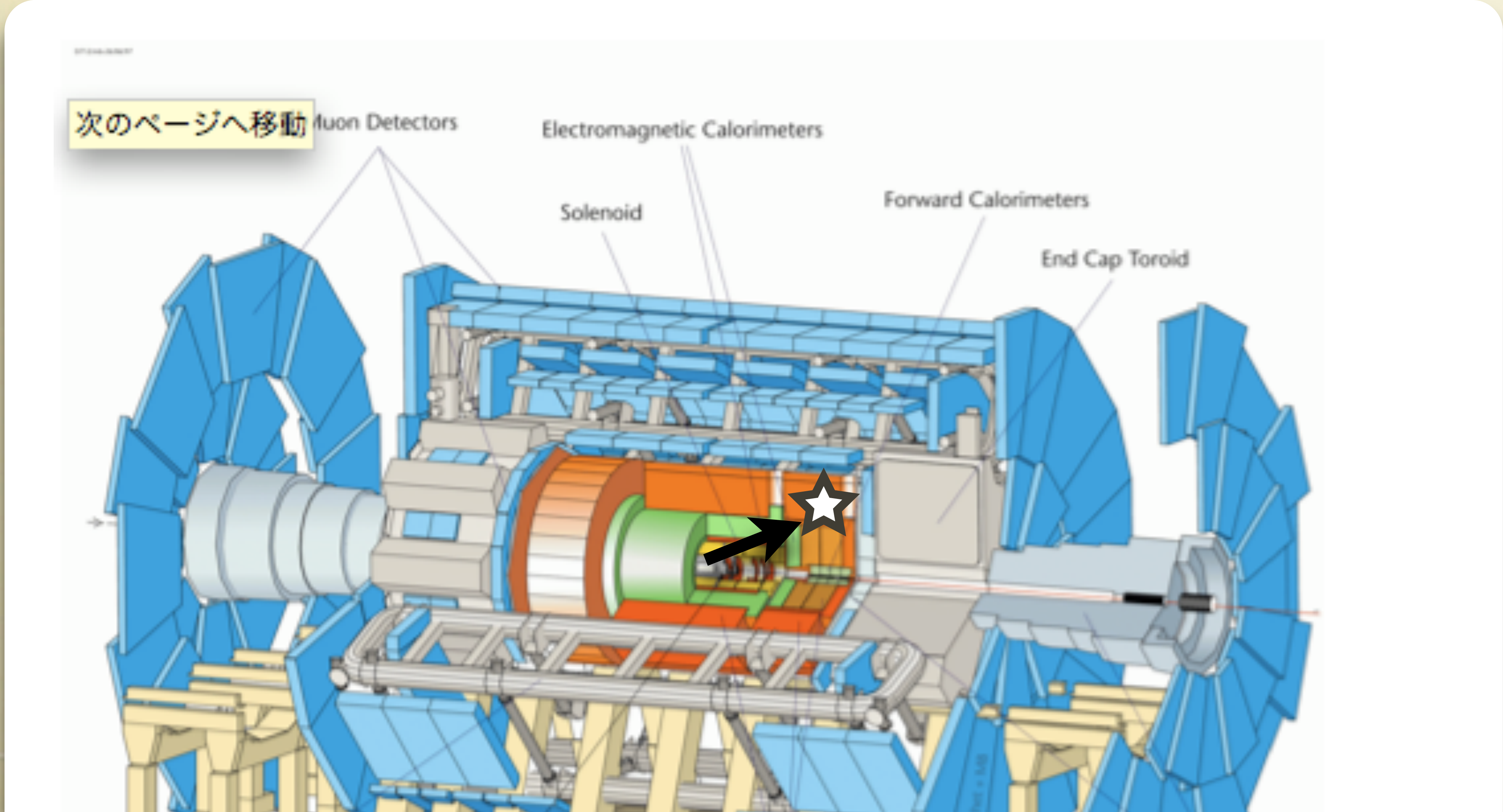


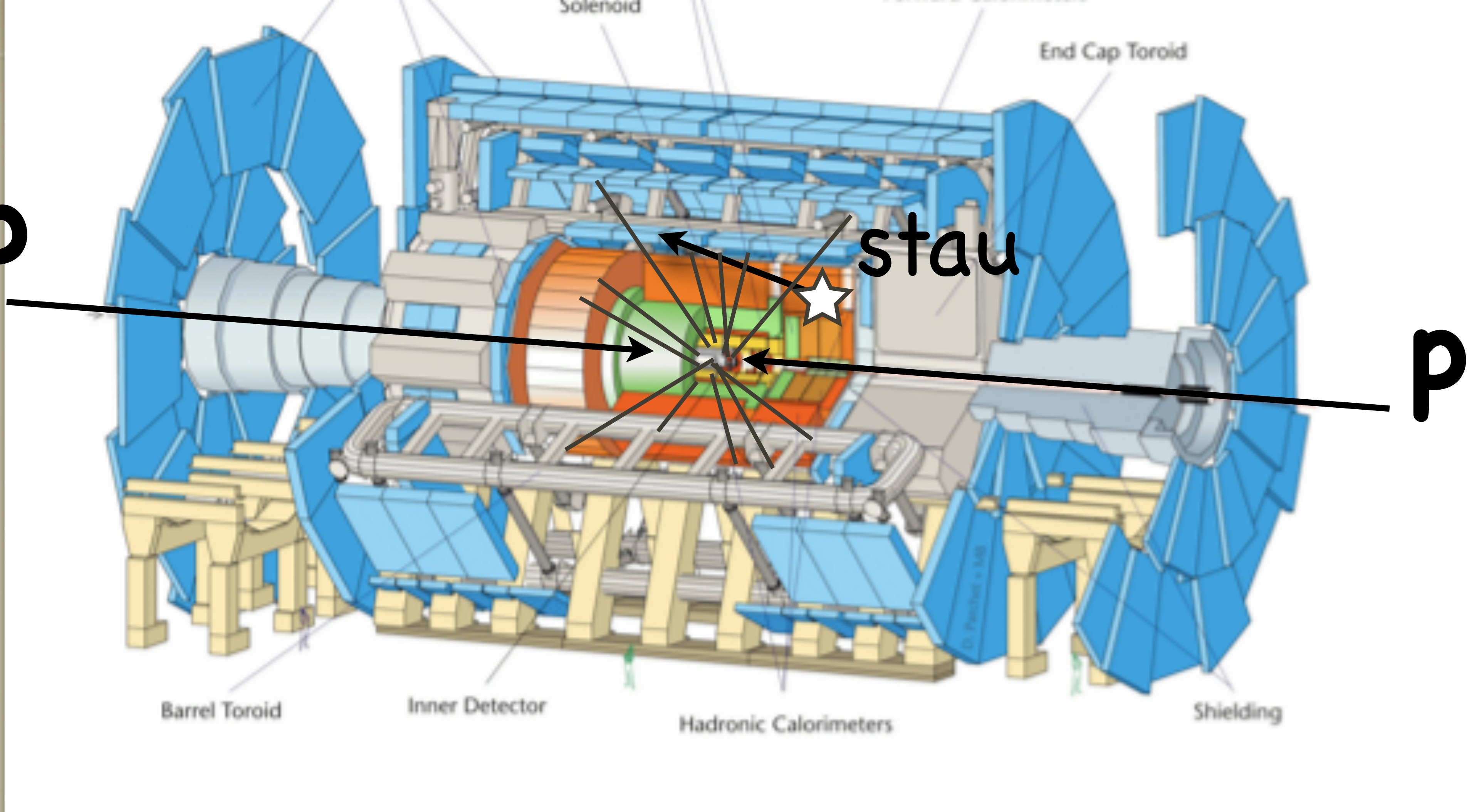


Figure 1-i Overall layout of the ATLAS detector.

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

..... during pp collision.

Idea:

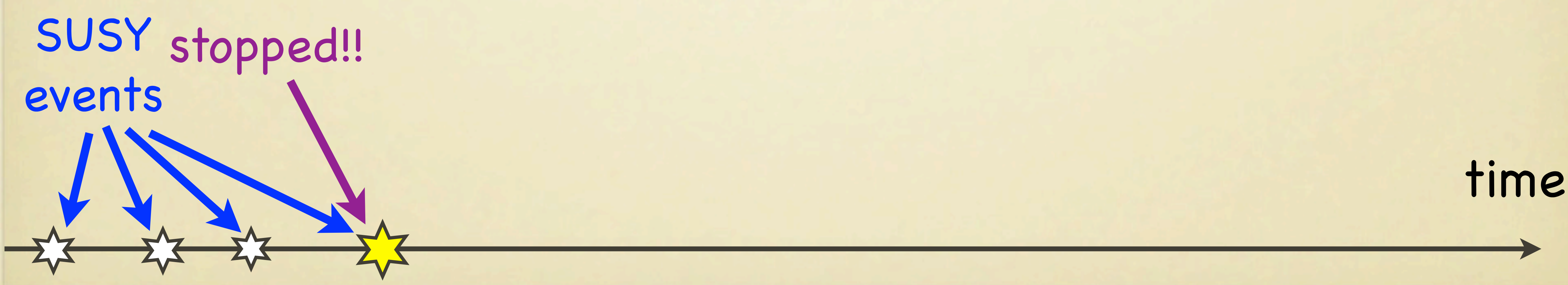
use periods of no pp collision !!

possible strategies:

- for short lifetime: use beam-dump signal.
  (or use empty bunch [CMS study, '09])
- for long lifetime: use shutdown time.

- for short lifetime: use beam-dump signal.

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



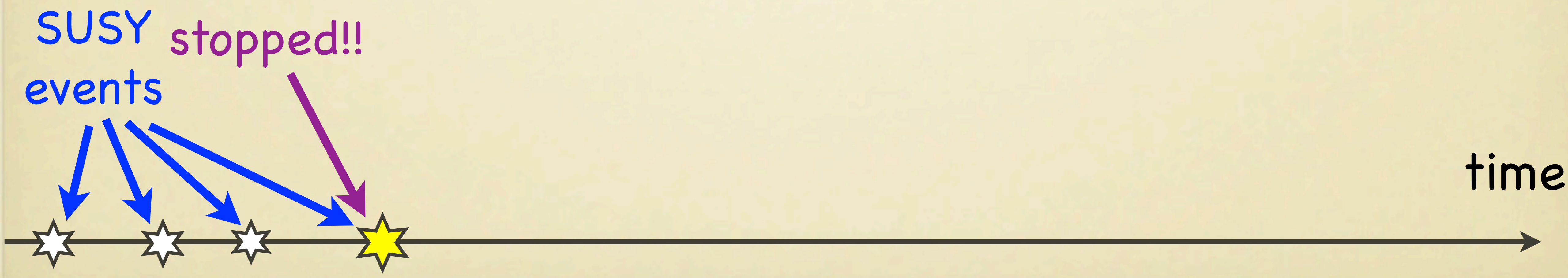
• for short lifetime: use beam-dump signal.

(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.



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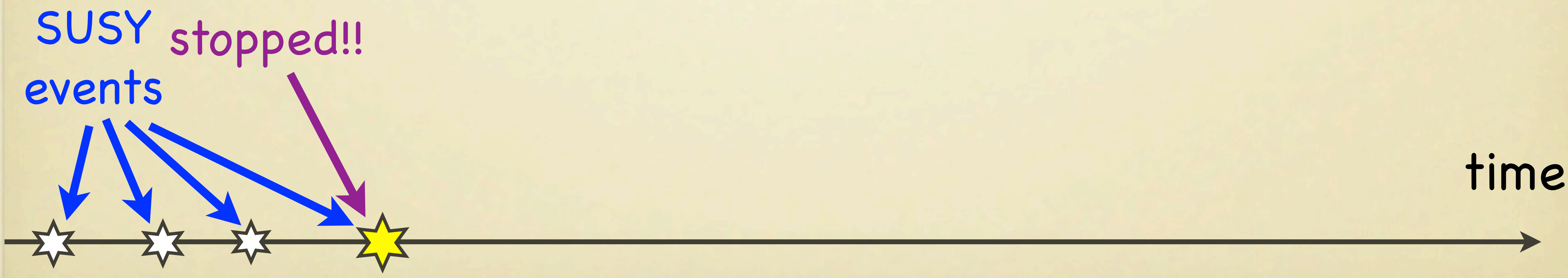
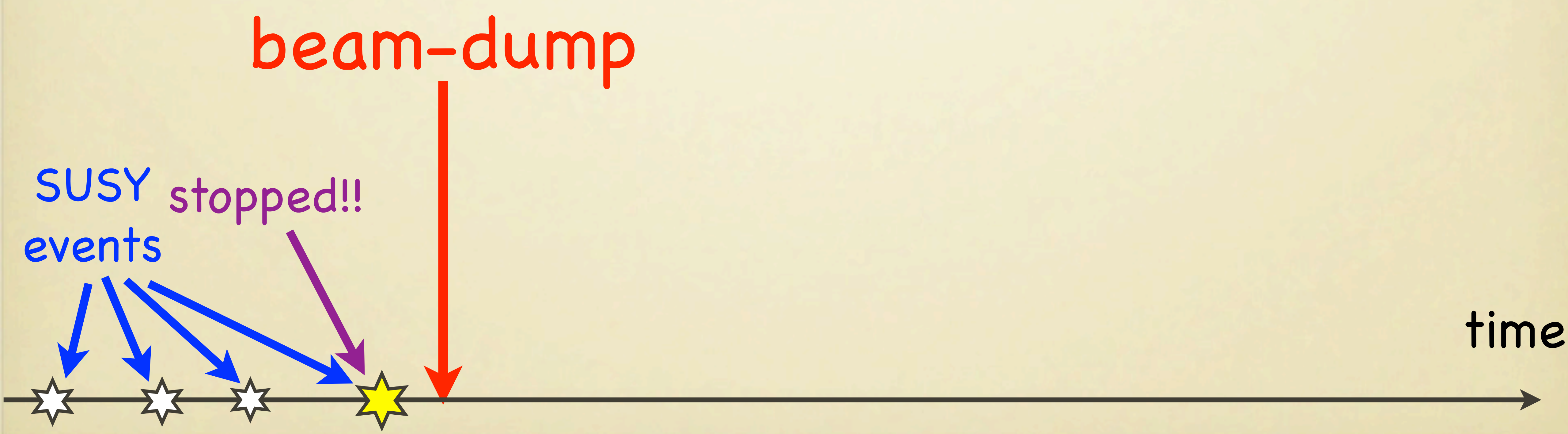


- for short lifetime: use beam-dump signal.

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

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

trigger



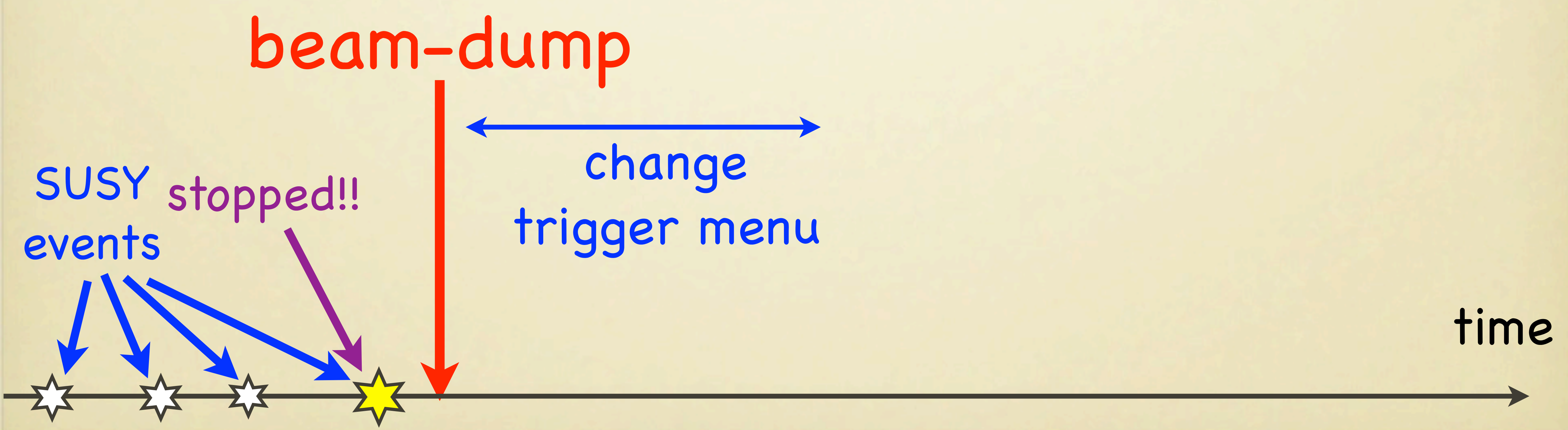
- for short lifetime: use beam-dump signal.

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

trigger

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

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



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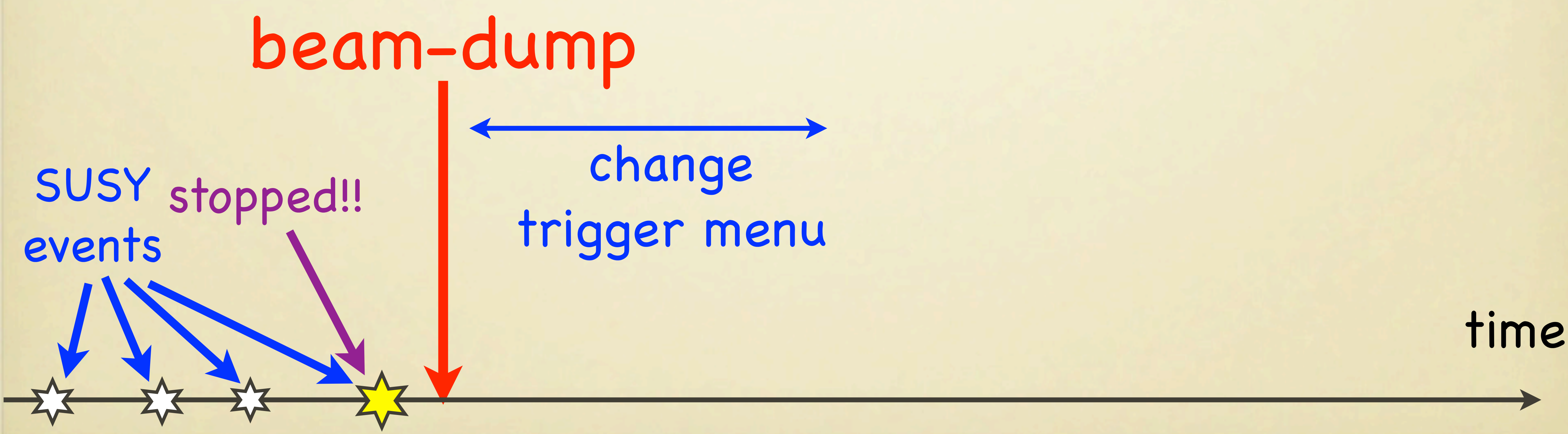
(IV) wait for stau decay.



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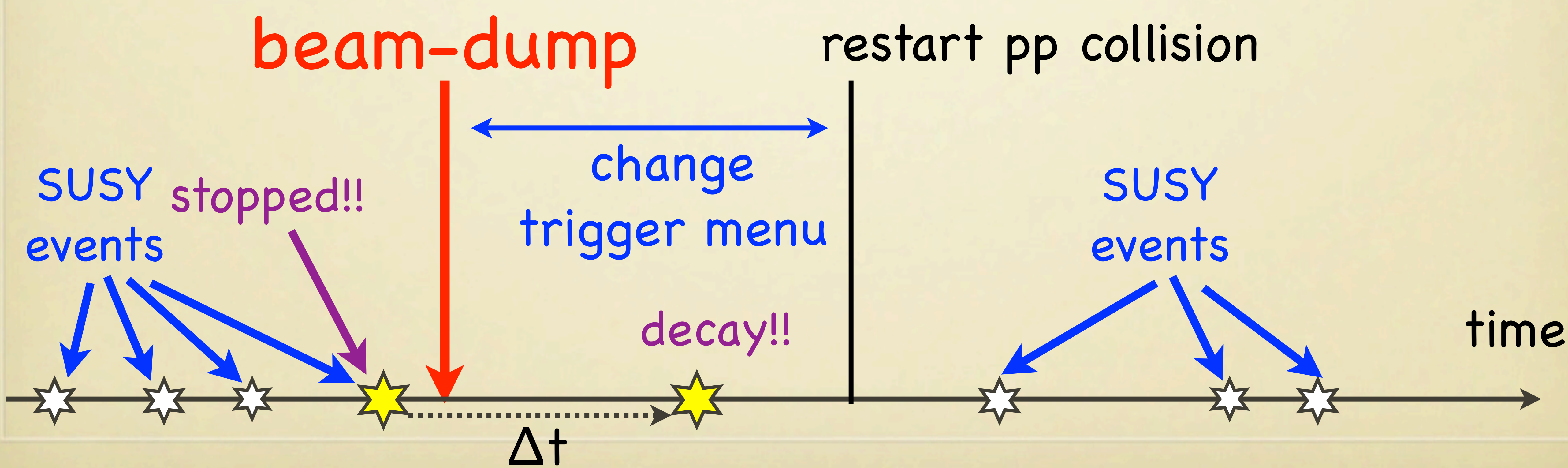
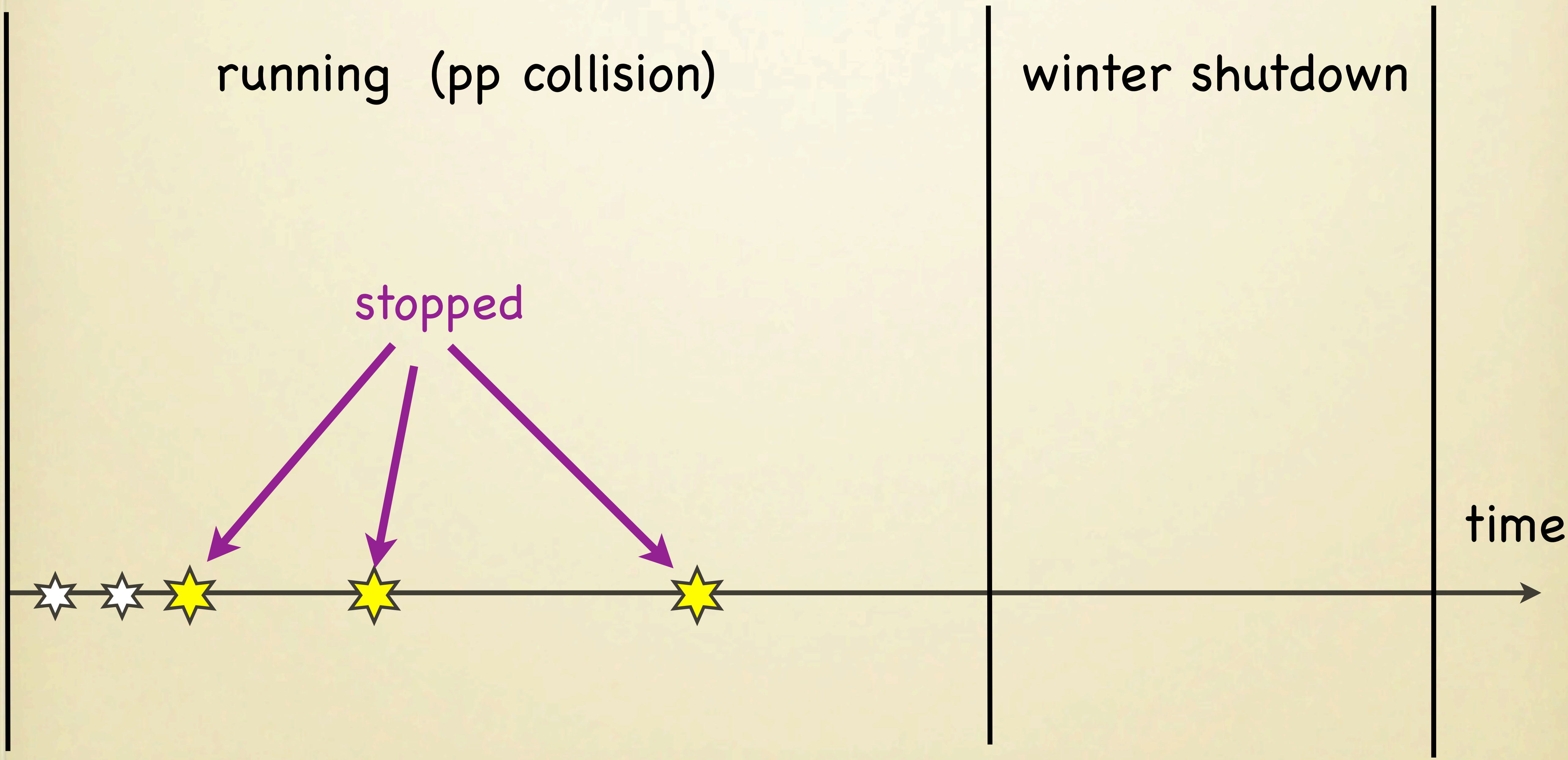
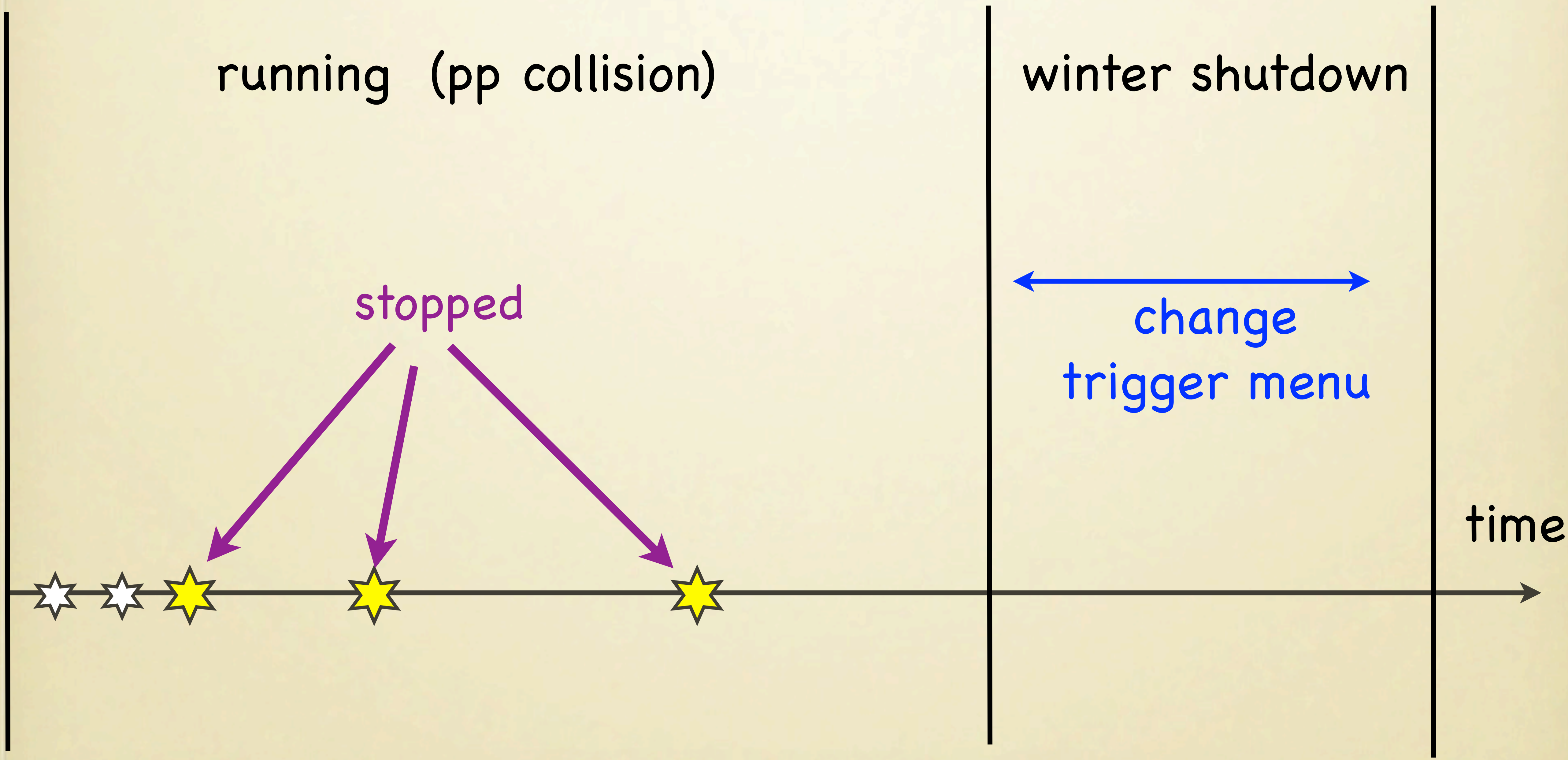


• for long lifetime: use shutdown time



- for long lifetime: use shutdown time



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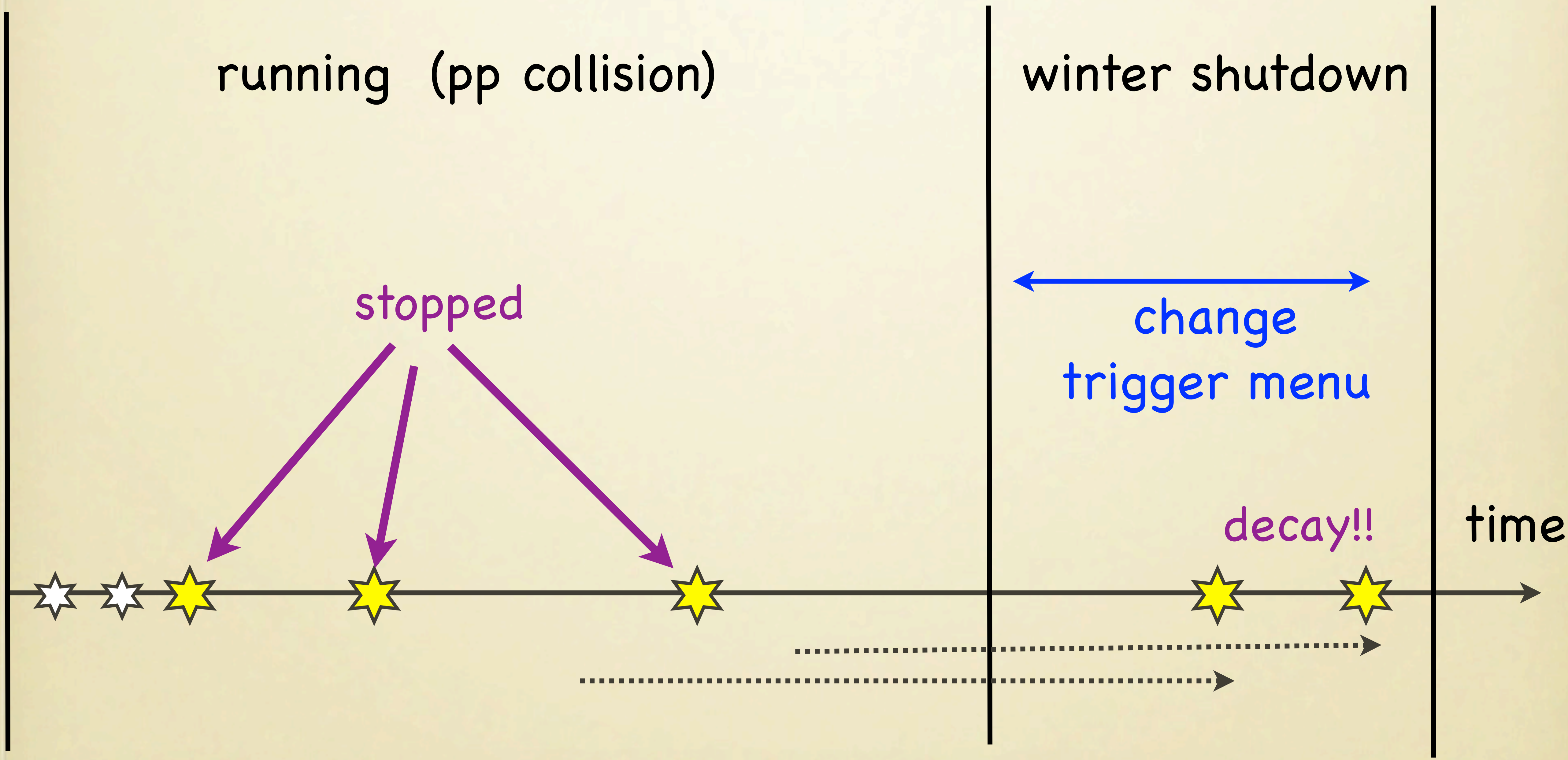

•lifetime measurement: Result

TABLE I: Expected statistical errors for each lifetime. $\langle N_D \rangle$ is the expected number of staus' decays in the corresponding period. For 100 fb^{-1} and $\tau_X \simeq \mathcal{O}(1)$ sec, the empty-bunch method will be useful. (See discussion below.) [SPS7 point, 1 year data]

	10 fb^{-1}		100 fb^{-1}	
lifetime	$\langle N_D \rangle$	σ	$\langle N_D \rangle$	σ
0.1 sec	0.008	± 0.1 sec	-	-
0.2 sec	1.2	± 0.15 sec	-	-
0.5 sec	23	± 0.1 sec	-	-
1 sec	64	± 0.1 sec	-	-
10 sec	156	± 0.9 sec	-	-
100 sec	171	± 9 sec	-	-
1000 sec	144	$^{+230}_{-170}$ sec	-	-
10 day	26	± 2.2 day	262	± 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!!

$$\Omega_{\widetilde{G}}^{\mathrm{thermal}} h^2 \simeq 0.1 \left(\frac{3\,\mathrm{GeV}}{m_{\widetilde{G}}}\right) \left(\frac{m_{\mathrm{gluino}}}{1\,\mathrm{TeV}}\right)^2 \left(\frac{\mathbf{T_R}}{10^8\,\mathrm{GeV}}\right)$$

$$= \Omega_{\mathrm{DM}} h^2 = 0.11$$

assumption

(if not, $T_R \rightarrow T_R^{max}$)

$$\tau_{\widetilde{\tau}} = \frac{48\pi M_{\mathrm{pl}}^2 m_{\widetilde{G}}^2}{m_{\widetilde{\tau}}^5}$$

can be determined at the LHC !!!

SUMMARY

Main message of this talk:

In SUSY models with **gravitino LSP + stau NLSP,**

- T_R > a few 10^8 GeV
  → tested at 7 TeV $1fb^{-1}$ (≃ within 1.5 years !)

- Stau lifetime can be measured at the LHC.
  (→ T_R may be determined,
  assuming $\Omega_{\widetilde{G}}^{\rm thermal} h^2 \simeq \Omega_{\rm DM} h^2$. If not, → upper bound on T_R.)

---

* with entropy production Δ, replace $T_R \to T_R \times \Delta^{-1}$

DISCUSSION

gravitational wave may probe TR (and dilution).

Nakayama, Saito, Suwa, Yokoyama, [arXiv:0804.1827] JCAP0806(2008)020
[cf. talk on Monday]

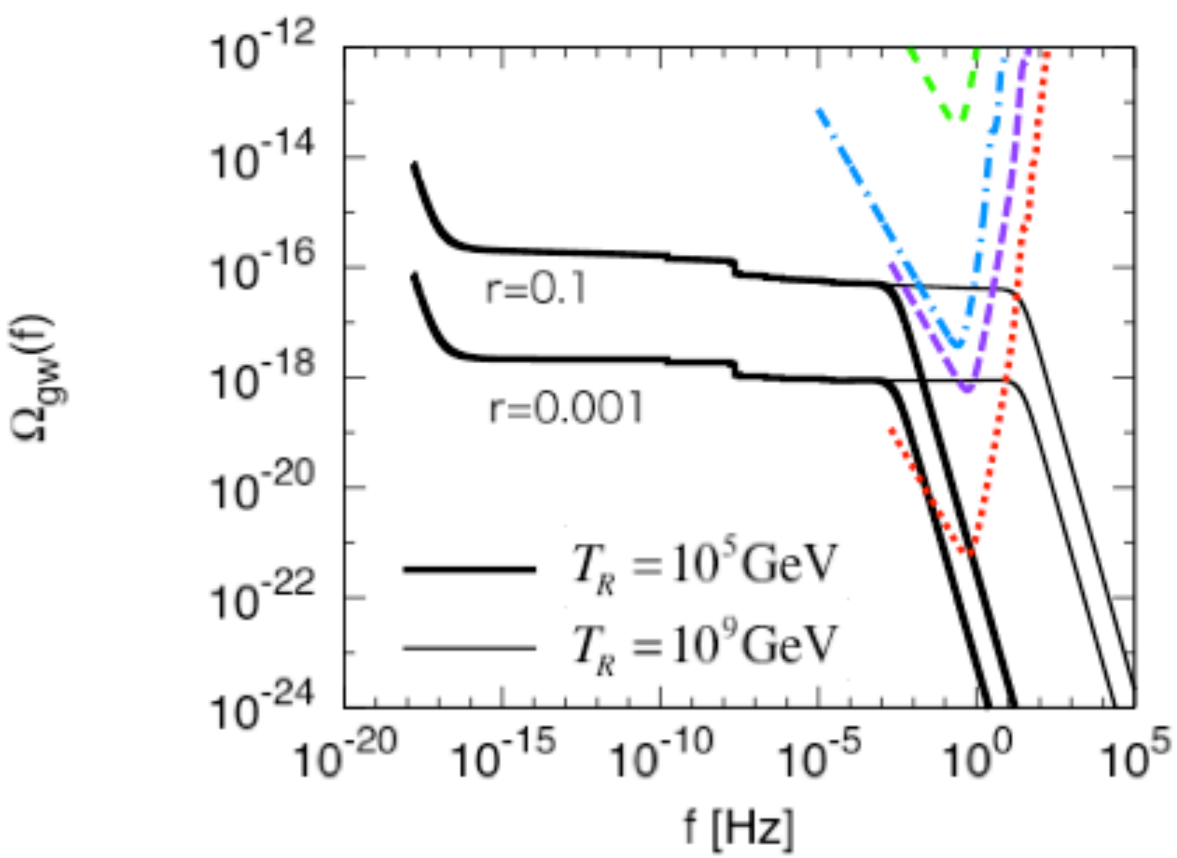

Figure 3. Primordial gravitational wave spectrum for $T_R = 10^9$ GeV and $T_R = 10^5$ GeV are shown by thin and thick lines for $r = 0.1$ and 0.001. Also shown are expected sensitivity of DECIGO (green dashed), correlated analysis of DECIGO (blue dot-dashed), ultimate-DECIGO (purple dashed) and correlated analysis of ultimate-DECIGO (red dotted), from upper to lower.

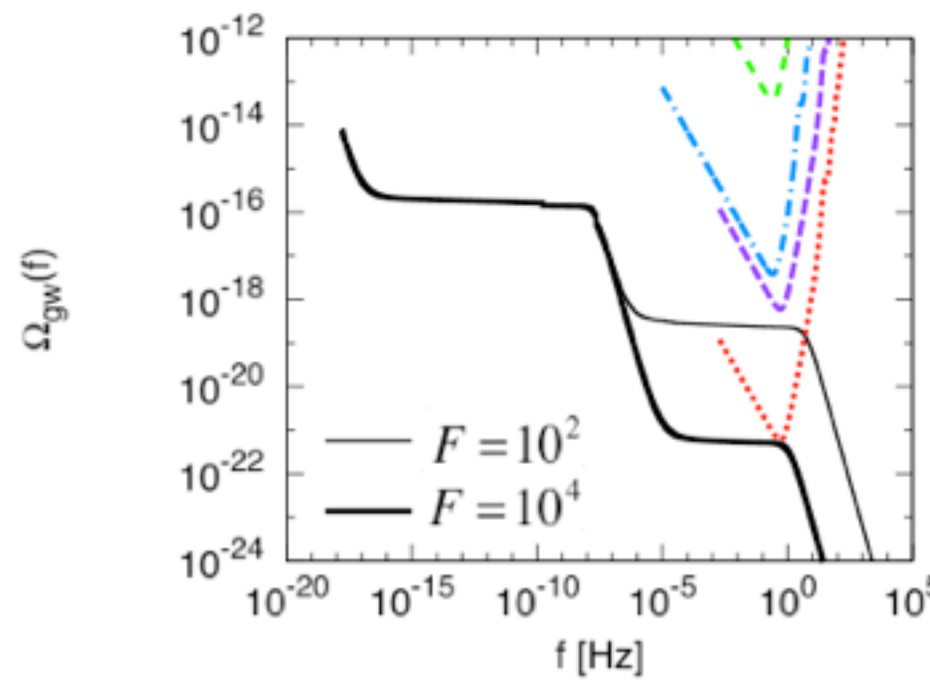

Figure 6. Gravitational wave spectrum for the dilution factor $F = 10^2$ and 10^4. Here we have fixed $r = 0.1$, $T_R = 10^9$ GeV and $T_\chi = 1$ GeV.

additional slides

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

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

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

from Asai, KH, Shirai '09

(See related work "stopping gluino", Arvanitaki et.al.)

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

with cuts	without cuts
400	805

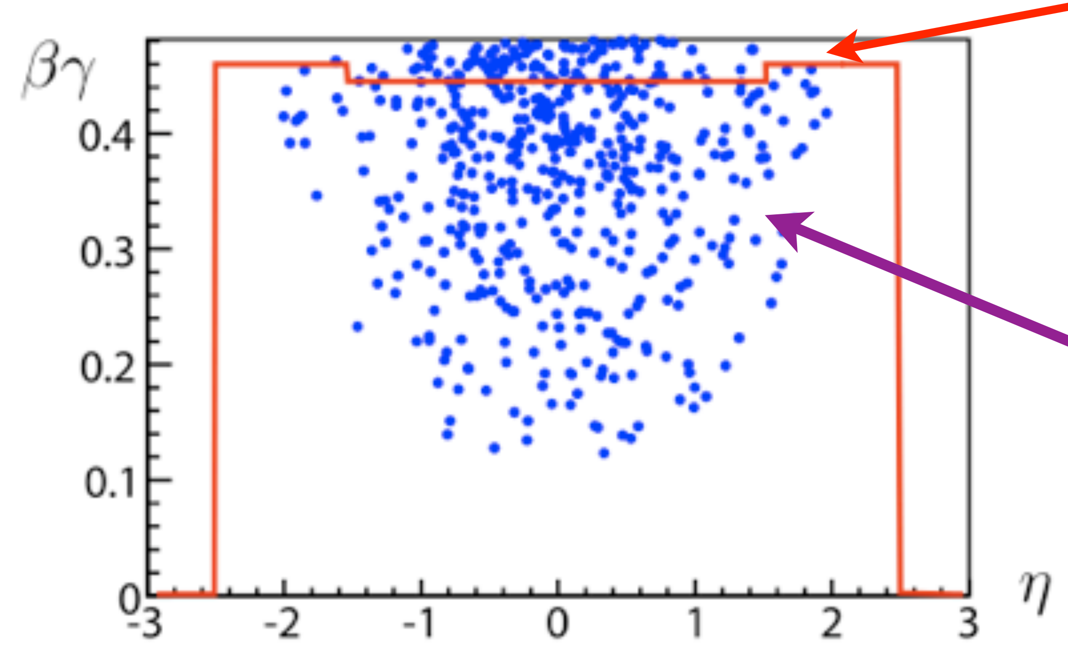

FIG. 1: $\eta - \beta\gamma$ distribution of the staus. The red line shows the limit for the stau to stop in the detector.

assume (ATLAS):
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)

lifetime measurement: “empty bunch” method
(cf. CMS study, CMS PAS EXO-09-001)

compared to “beam-dump” method,.....

advantages:

- pp collision can continue
- sensitive to (much) shorter lifetime

disadvantages:

- difficult to correspond the stop and decay, if lifetime is longer than the empty bunch period.
- # of decay observed is reduced.