Dark Matter and Collider Physics

Koichi Hamaguchi (Tokyo U., Dept.of Phys. and IPMU)

at KEK, October '08

SCHOOL OF SCIENCE
THE UNIVERSITY OF TOKYO

IPMU INSTITUTE FOR THE PHYSICS AND MATHEMATICS OF THE UNIVERSE

before starting.....

Nobelprize.org

Congratulations!!

The Nobel Prize in Physics 2008

"for the discovery of the mechanism of spontaneous broken symmetry in subatomic physics"

"for the discovery of the origin of the broken symmetry which predicts the existence of at least three families of quarks in nature"

Photo: SCANPIX

Yoichiro Nambu

1/2 of the prize

Photo: Universtity of Chicago

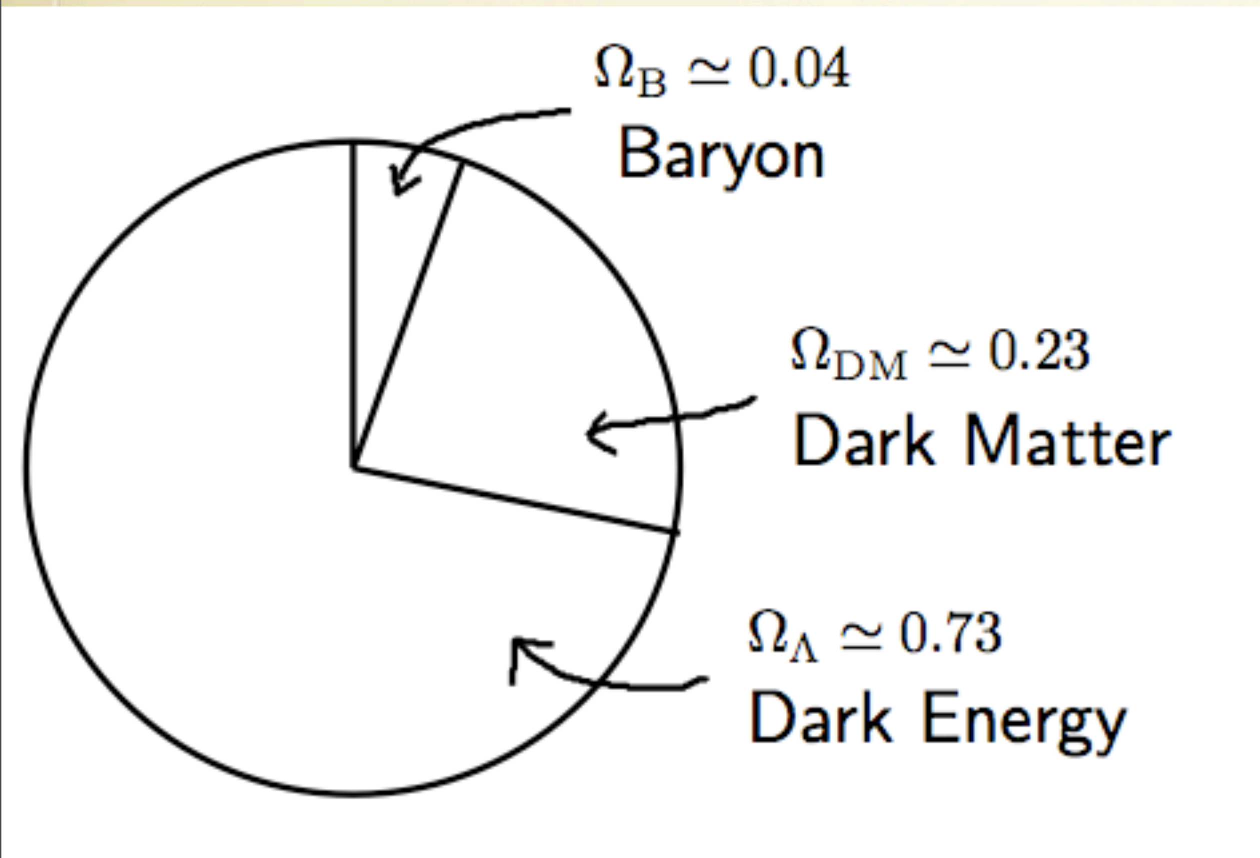
Makoto Kobayashi

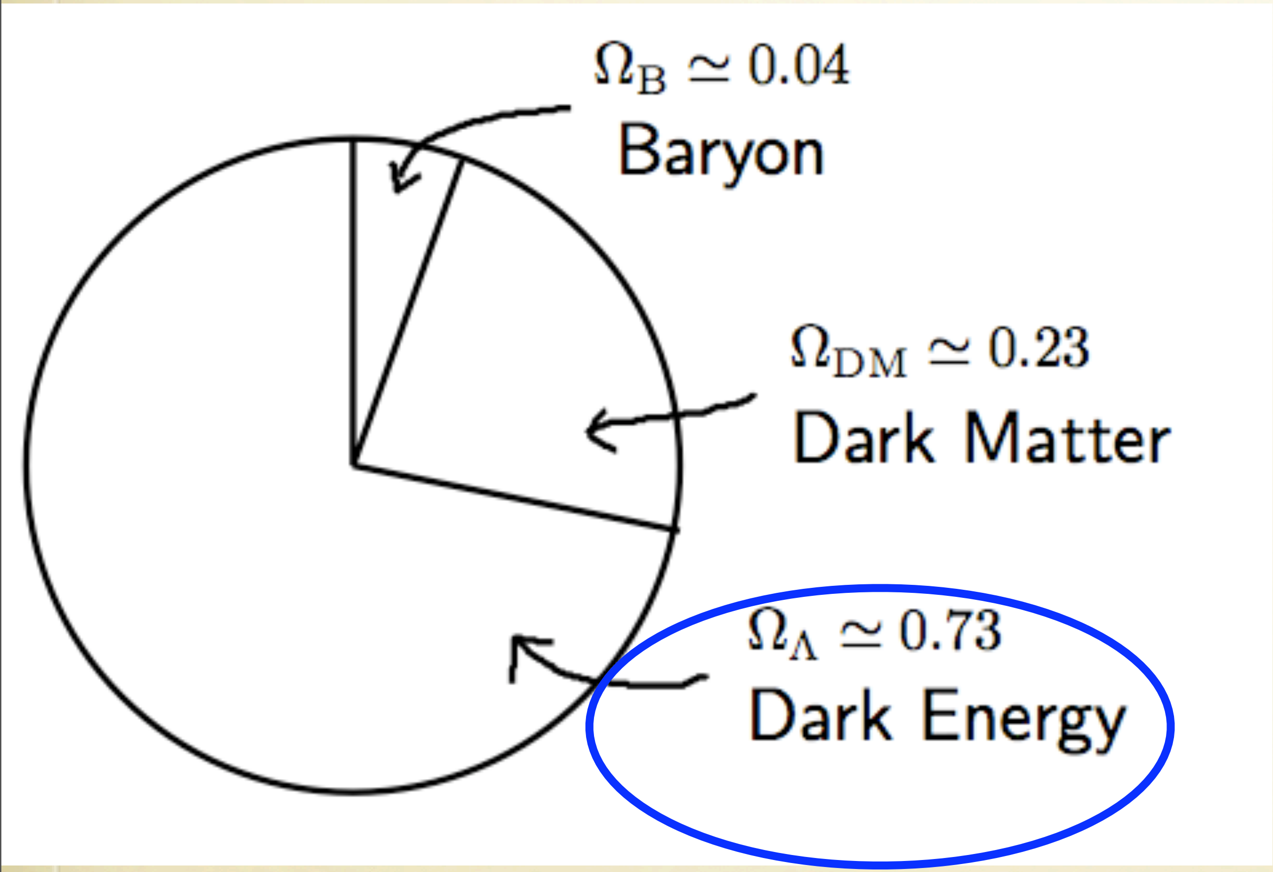
1/4 of the prize

Photo: Kyoto University

Toshihide Maskawa

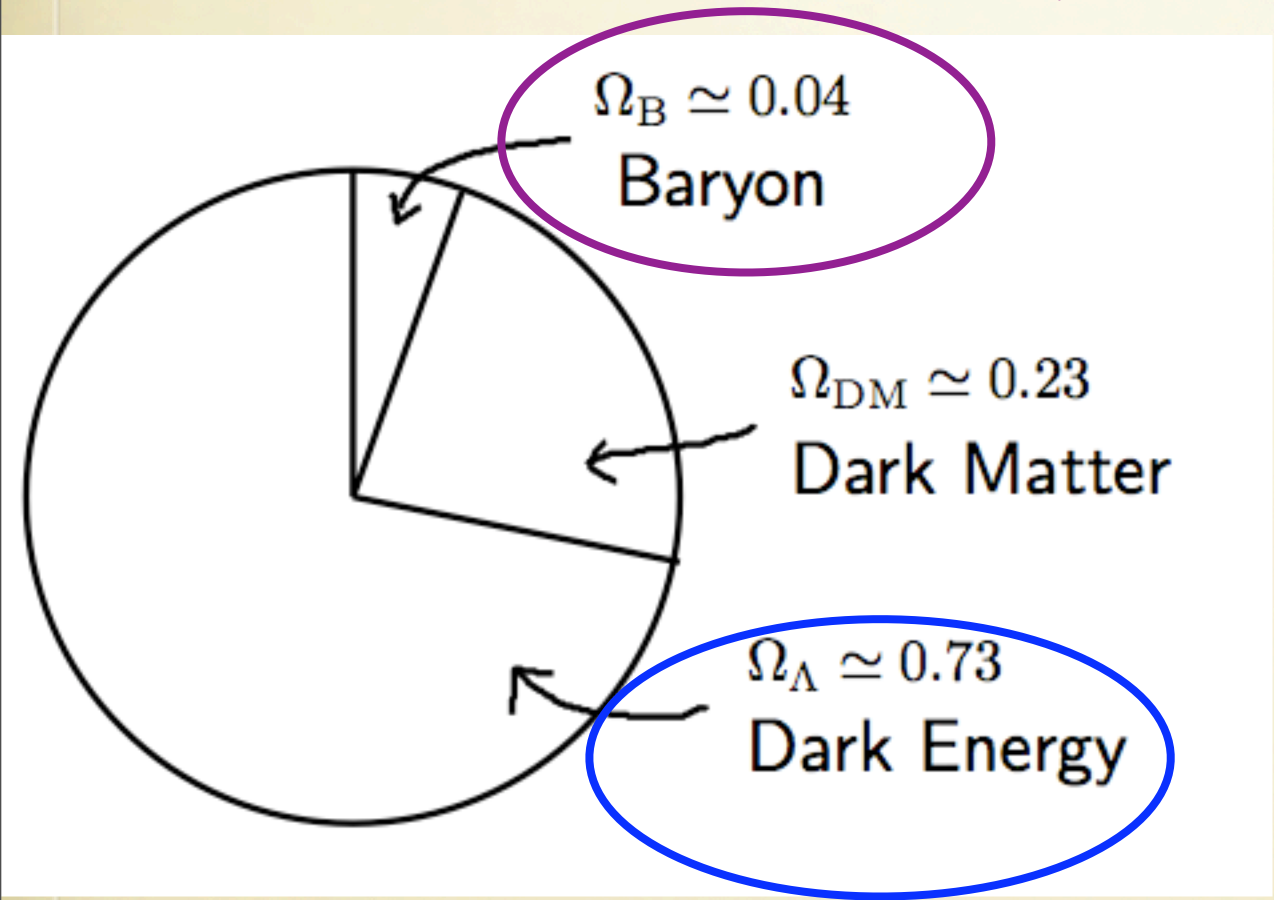
1/4 of the prize


$\Omega_B \simeq 0.04$
Baryon
$\Omega_{DM} \simeq 0.23$
Dark Matter
$\Omega_\Lambda \simeq 0.73$
Dark Energy



this is too difficult.....

This is also a problem...!



this is too difficult.....

Baryon $\frac{n_B}{s} = 0.87 \times 10^{-10}$

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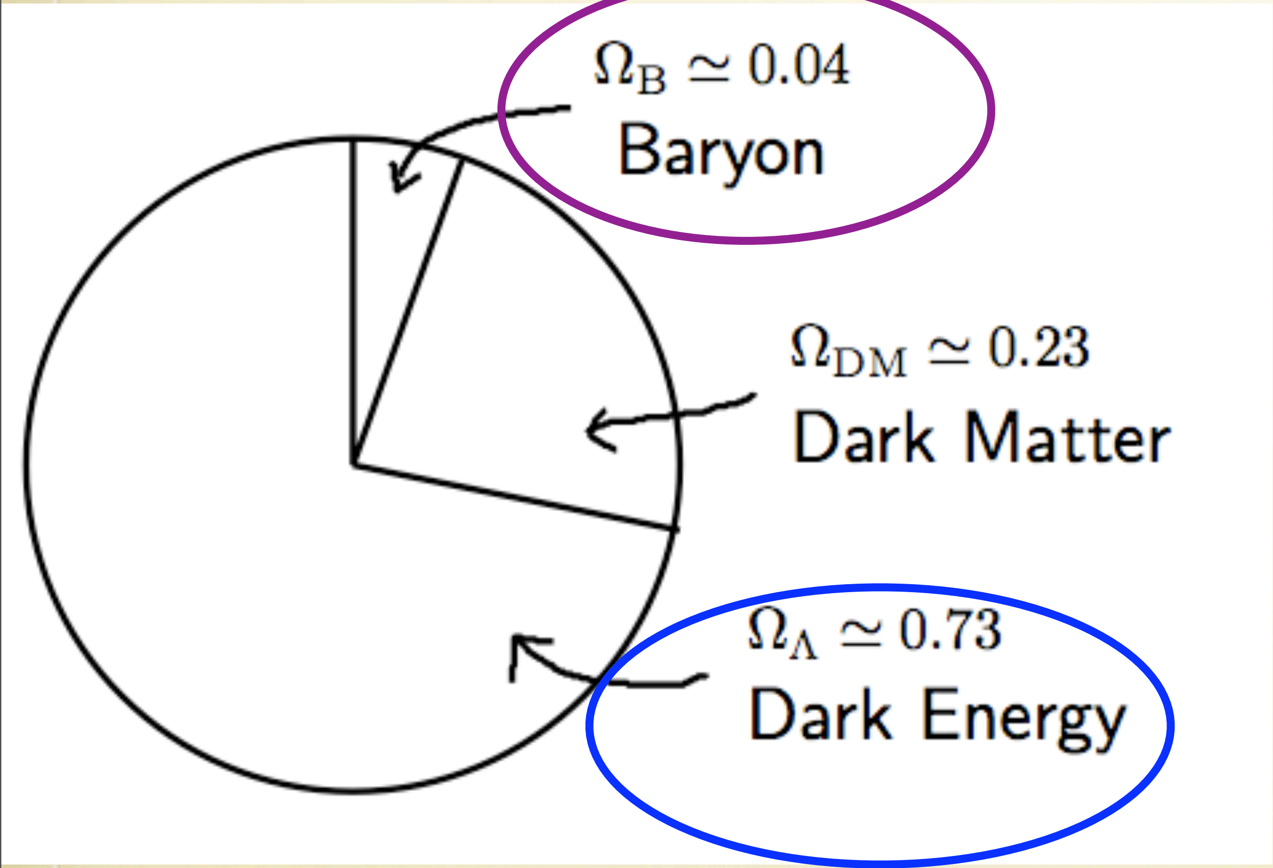


this is too difficult.....

Baryon asymmetry is small ?!

At high temperature......

300,000,000 + 1

300,000,000

$$\frac{n_{\mathrm{baryon}}}{s} \sim 0.03$$

Baryon

$$\frac{n_{\mathrm{anti-baryon}}}{s} \sim 0.03$$

Anti-Baryon

Baryon asymmetry is small ?!

Today.....

● 1

Baryon $\dfrac{n_B}{s} = 0.87 \times 10^{-10}$

Baryon asymmetry is large ?!

- If there were no baryon asymmetry......

At high temperature......

300,000,000

$$\frac{n_{\text{baryon}}}{s} \sim 0.03$$

Baryon

300,000,000

$$\frac{n_{\text{anti-baryon}}}{s} \sim 0.03$$

Anti-Baryon

Baryon asymmetry is large ?!

- If there were no baryon asymmetry......

  Today.....

$$\frac{n_{\rm baryon}}{s} \sim 10^{-18}$$

$$\frac{n_{\rm anti-baryon}}{s} \sim 10^{-18}$$

Baryon

Anti-Baryon

Baryon asymmetry is large ?!

- If there were no baryon asymmetry......

Today.....

$$\frac{n_{\mathrm{baryon}}}{s} \sim 10^{-18}$$

$$\frac{n_{\mathrm{anti-baryon}}}{s} \sim 10^{-18}$$

$\ll 10^{-10}$!!

Baryon

-Baryon

Baryon asymmetry is large ?!

- If there were no baryon asymmetry......

Today.....

$$\frac{n_{\mathrm{baryon}}}{s} \sim 10^{-18}$$

0^{-18}

$\ll$ 10 !!

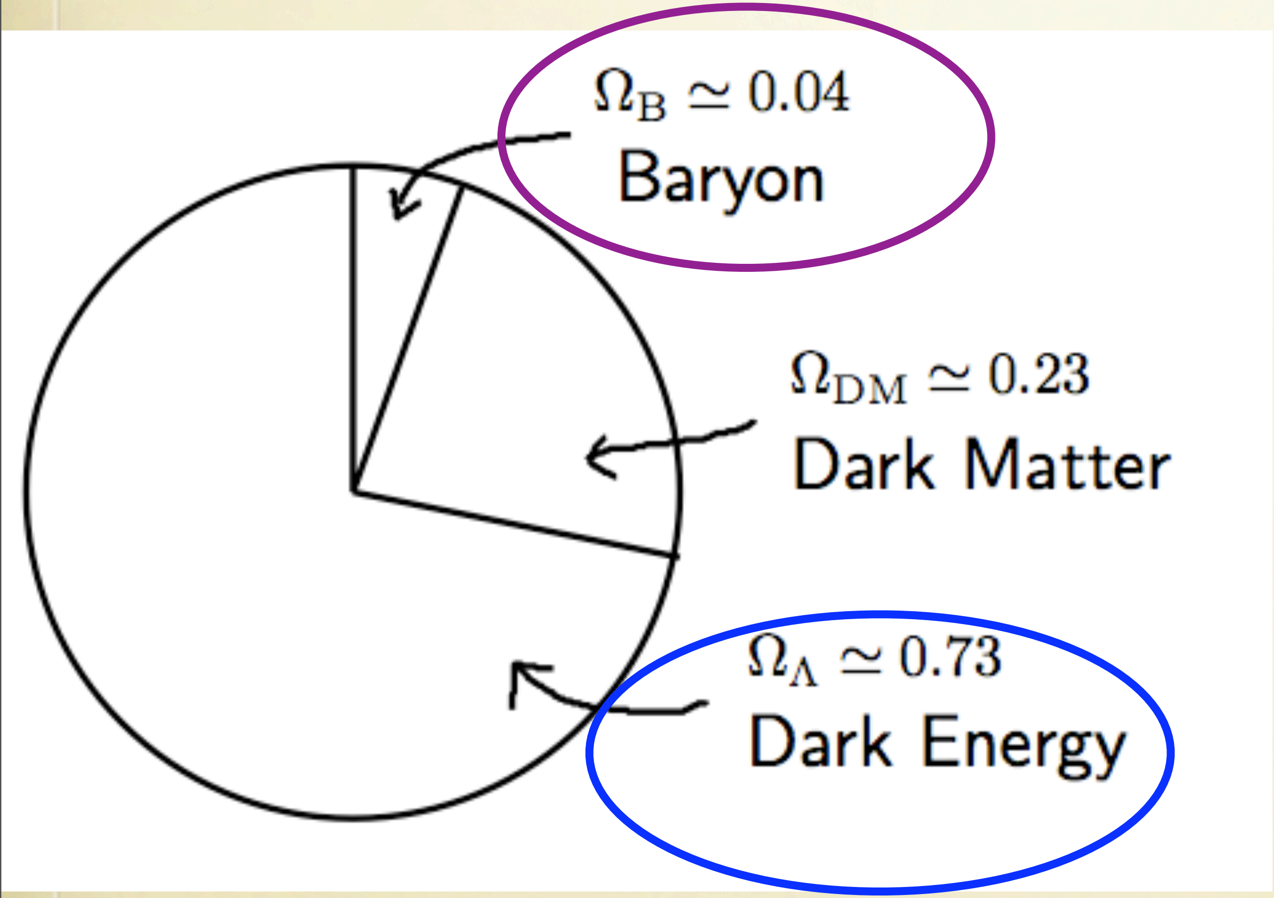
ryon

-Baryon

needs some Baryogenesis mechanism ☛ CP violation

(e.g., Leptogenesis,
Affleck-Dine baryogenesis,...)

This is also a problem...!



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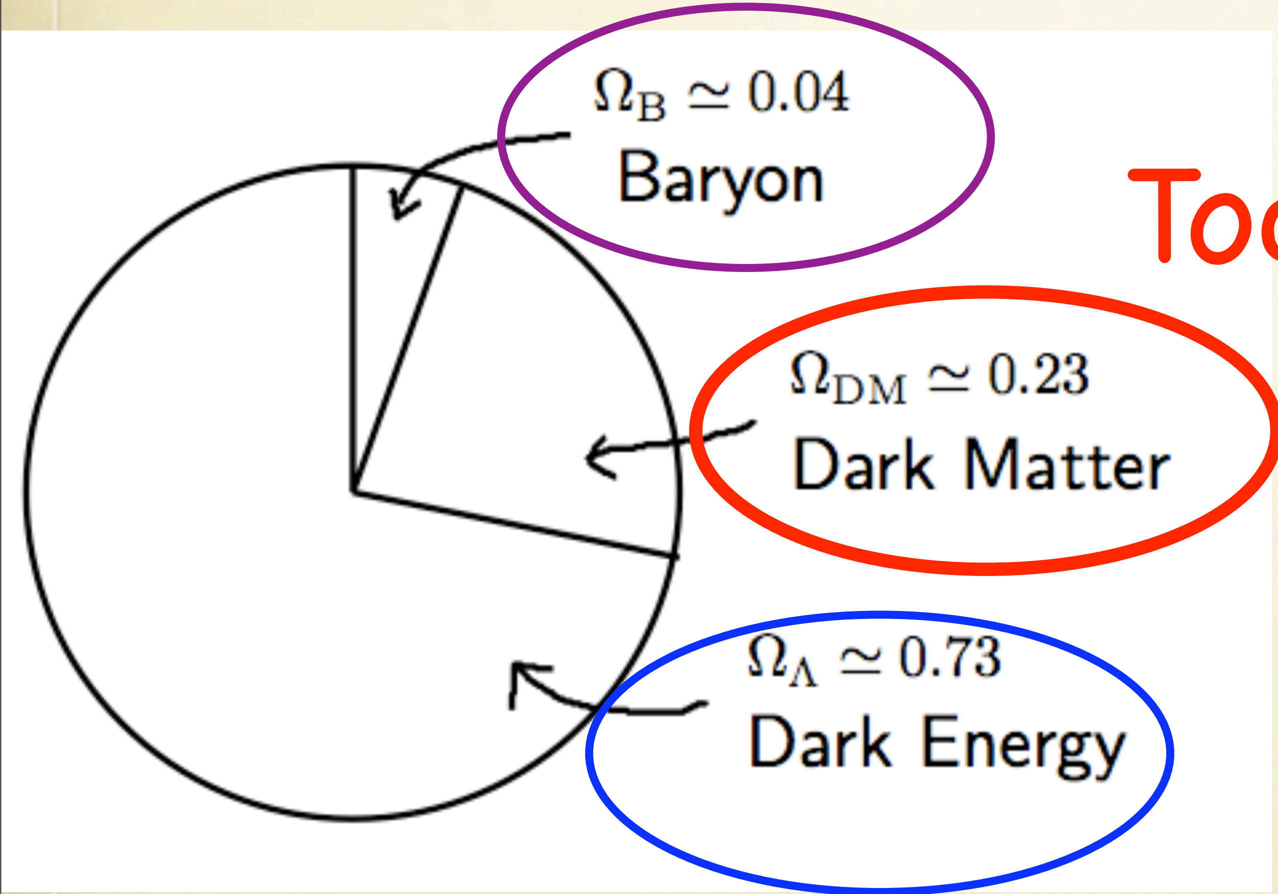
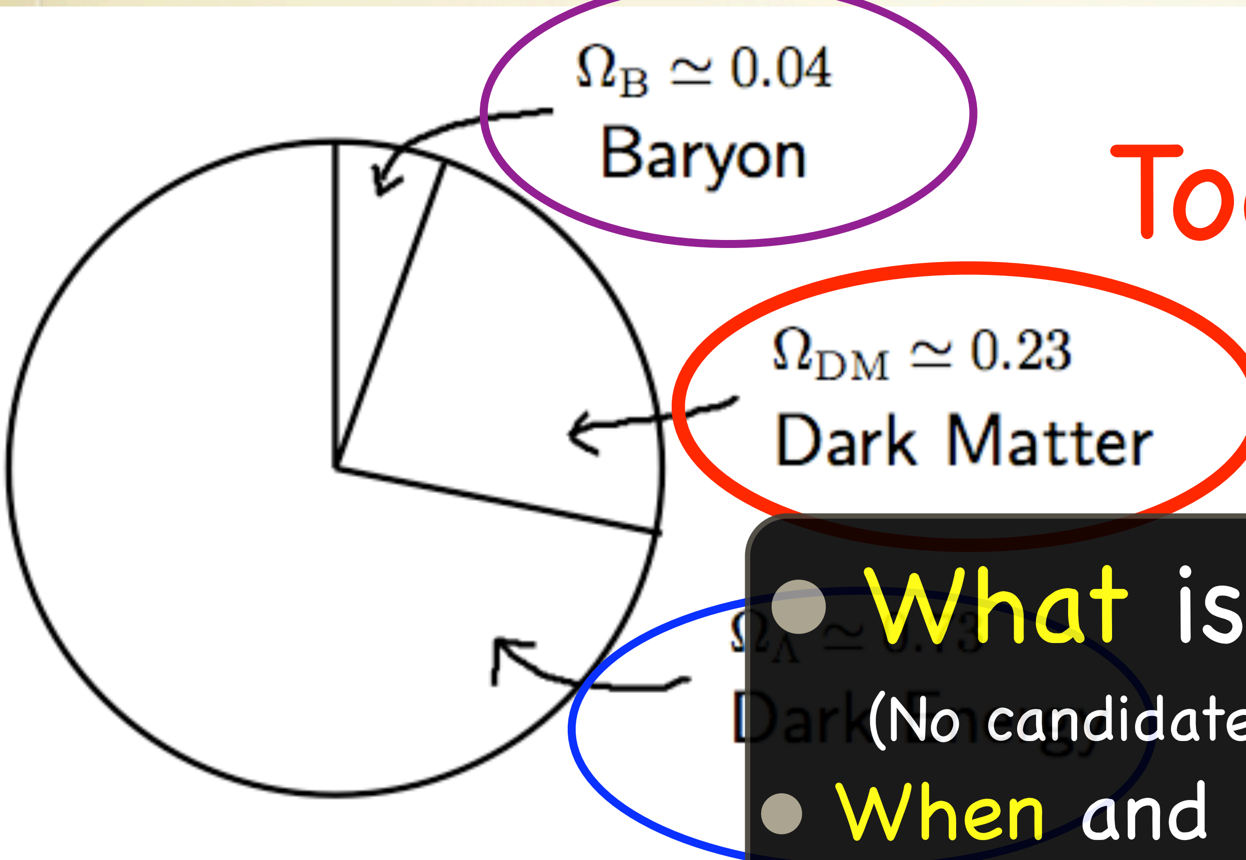


Today's talk

this is too difficult.....

This is also a problem...!



Today's talk

this is

- What is it?
  (No candidate in the Standard Model!)
- When and how was it produced in the early universe??
- direct/indirect detection??
- Testable at Colliders?!

Today: discuss four different DM candidates
(as long as time allows.....)

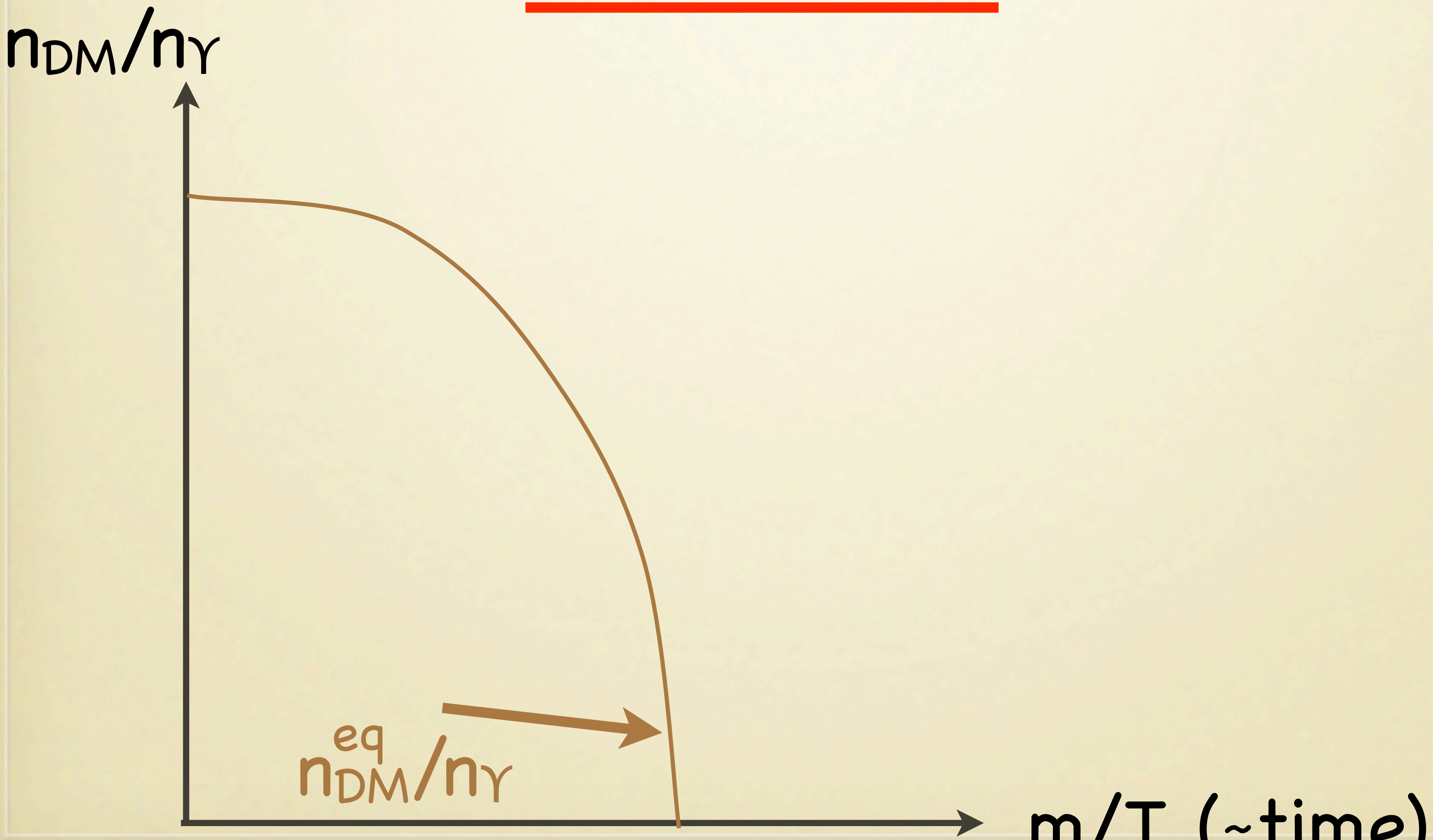
- standard thermal relic WIMP
- non-thermal WIMP (☛ cosmic ray signatures?)
- gravitino DM
  (+ long-lived charged particle) (☛ BBN signature?)
- decaying (gravitino) DM (☛ cosmic ray signatures?)

..... and their collider signatures/tests.

- standard thermal relic WIMP

WIMP (weakly interacting massive particle)
Dark Matter

thermal relic



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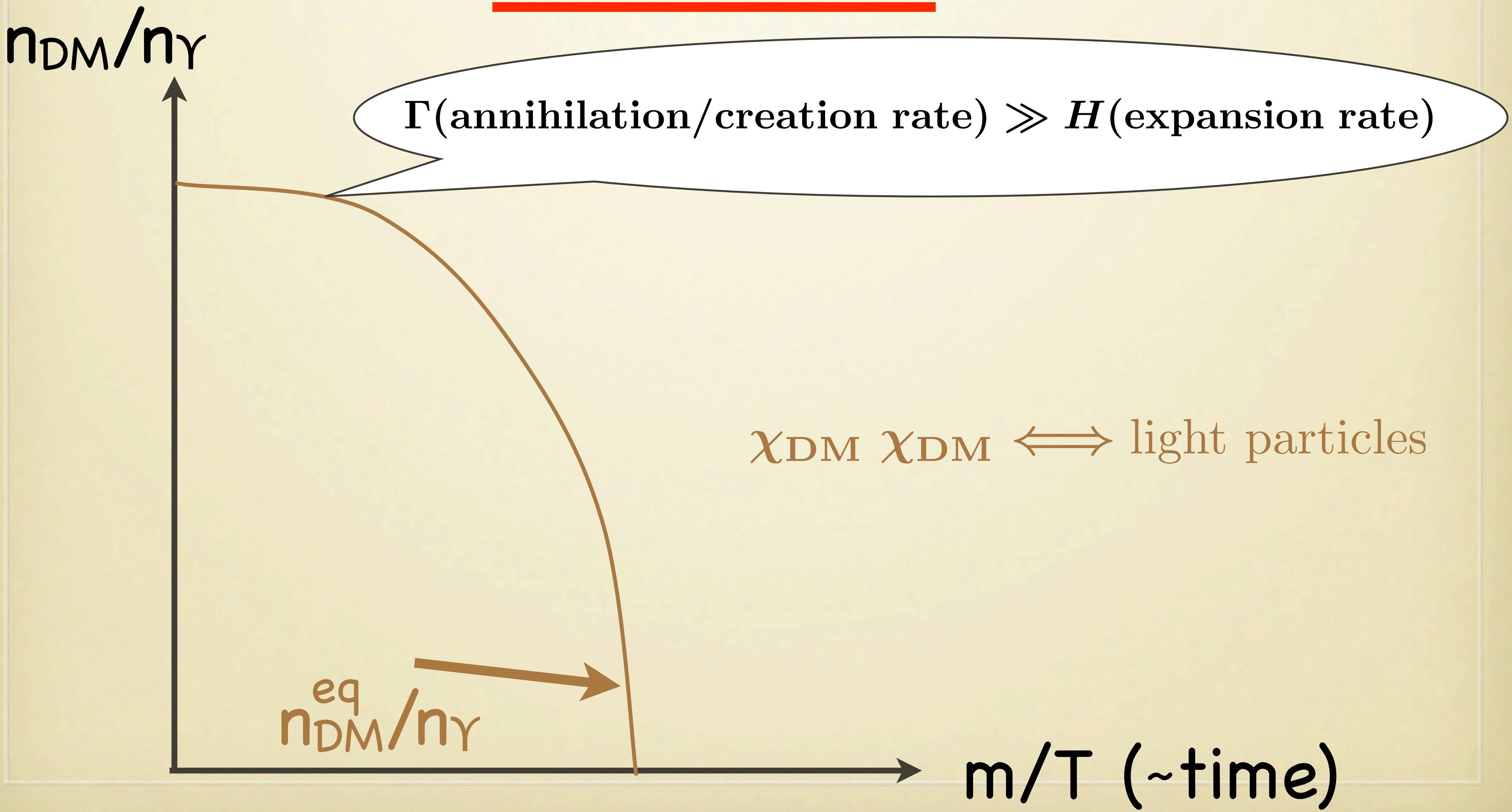

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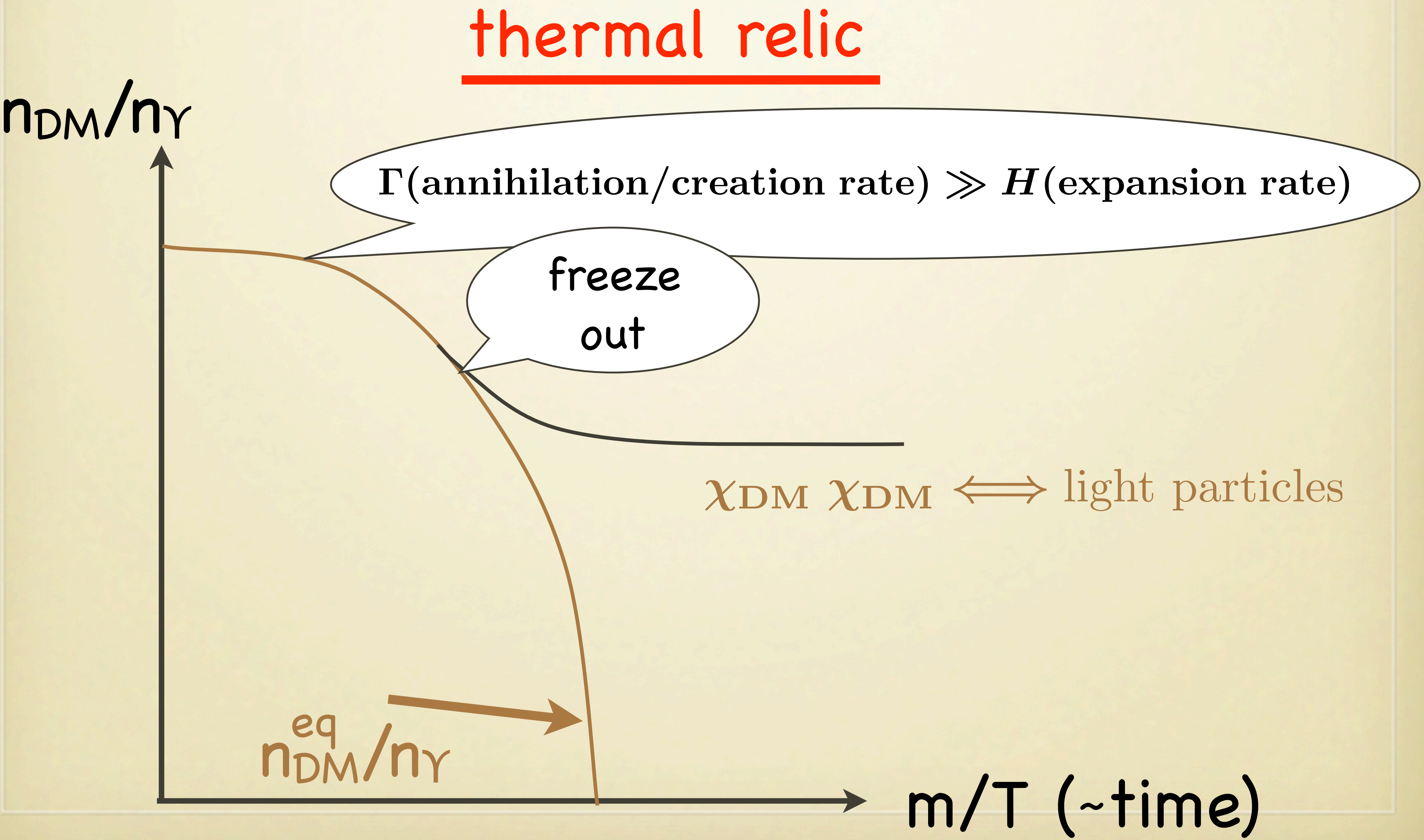

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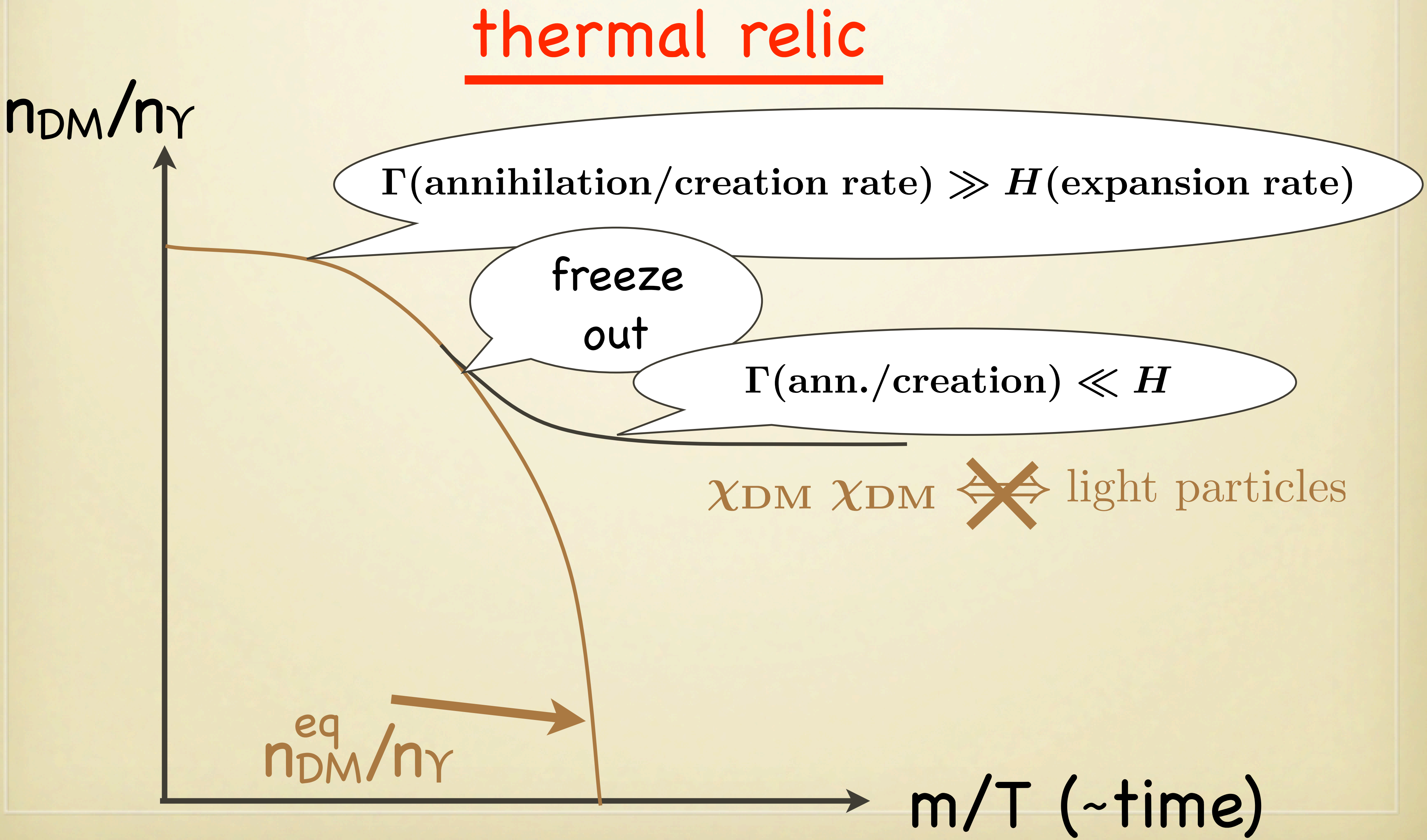

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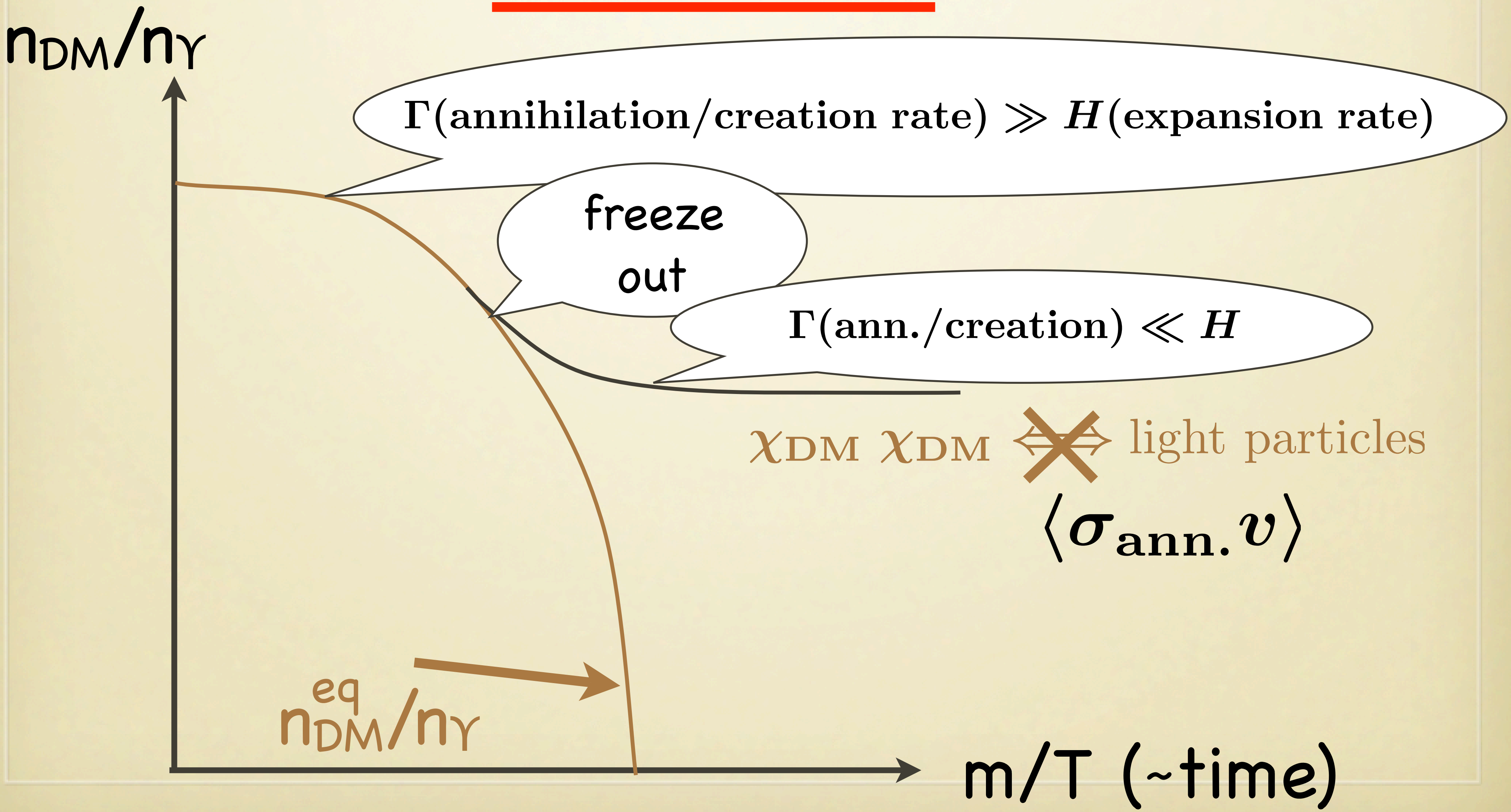

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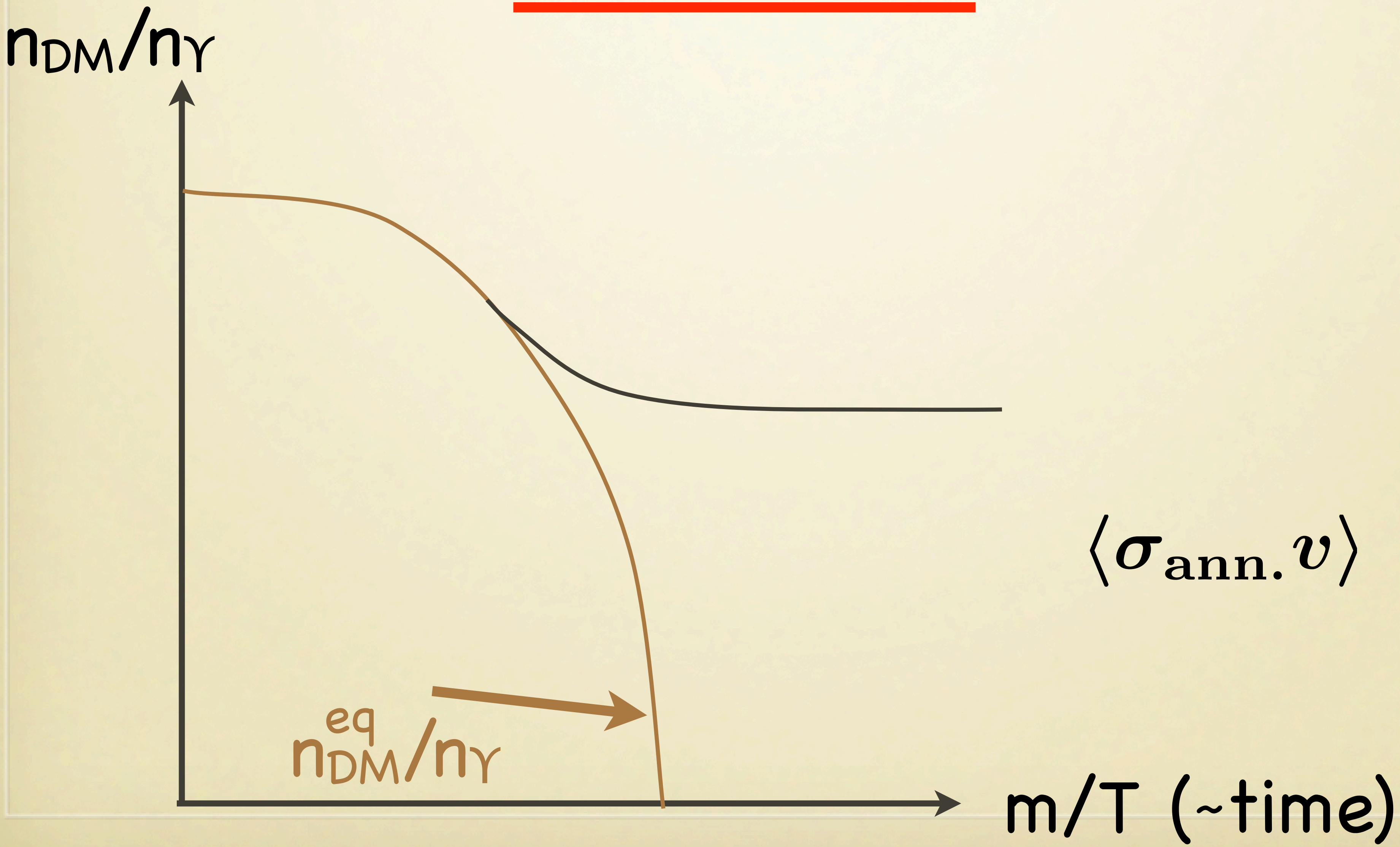

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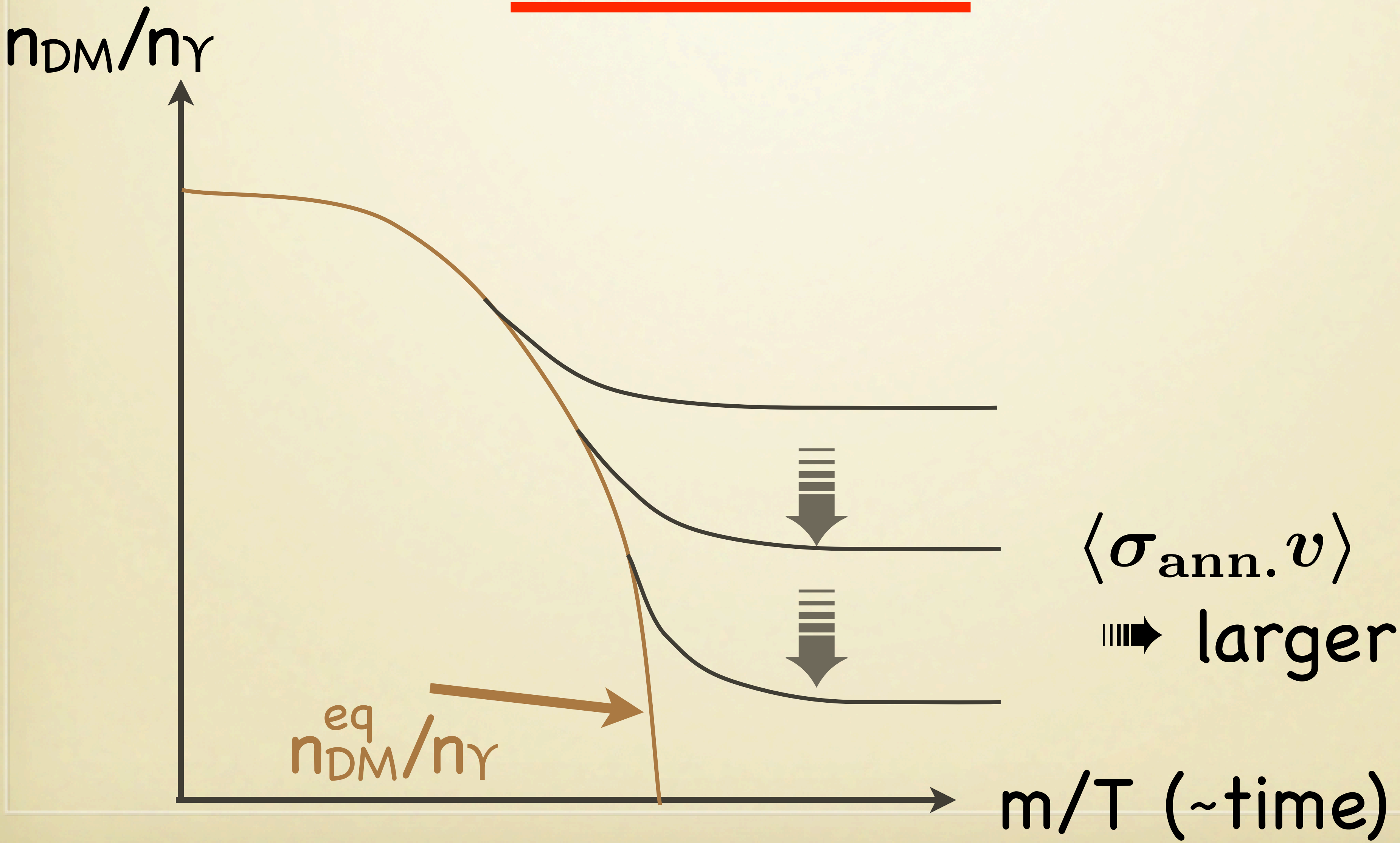
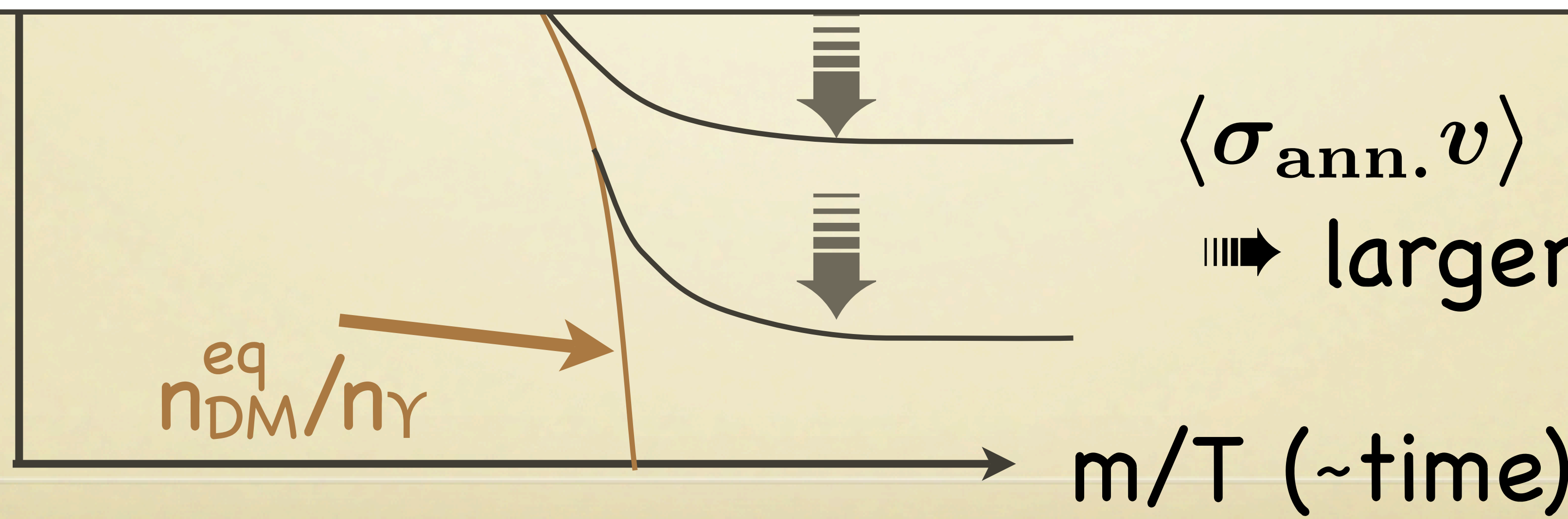


WIMP (weakly interacting massive particle) Dark Matter

thermal relic

$$\Omega_{\rm DM}^{\rm thermal} = \frac{s_0}{3M_P^2 H_0^2}\frac{0.76 x_f}{g_*^{1/2} M_P \langle \sigma_{\rm ann.} v\rangle}$$



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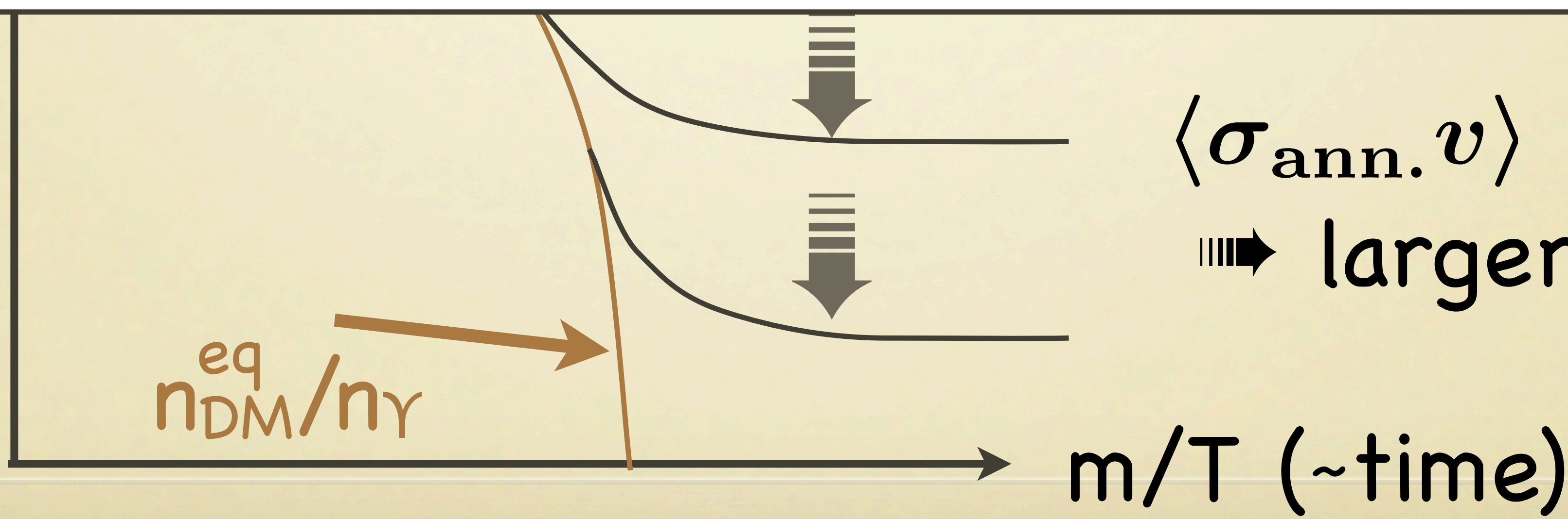
all known



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$$\Omega_{\rm DM}^{\rm thermal} = \frac{s_0}{3M_P^2 H_0^2}\frac{0.76 x_f}{g_*^{1/2} M_P \langle \sigma_{\rm ann.} v\rangle} \sim 0.2 \cdot \left(\frac{1\ {\rm pb}}{\langle \sigma_{\rm ann.} v\rangle}\right)$$

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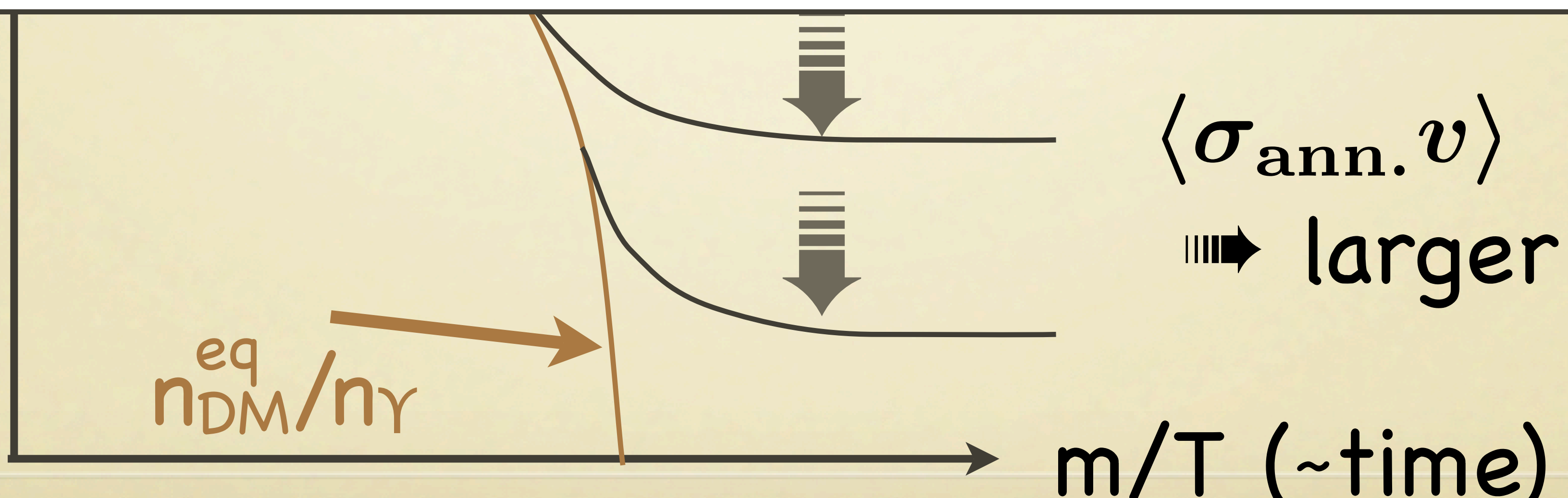

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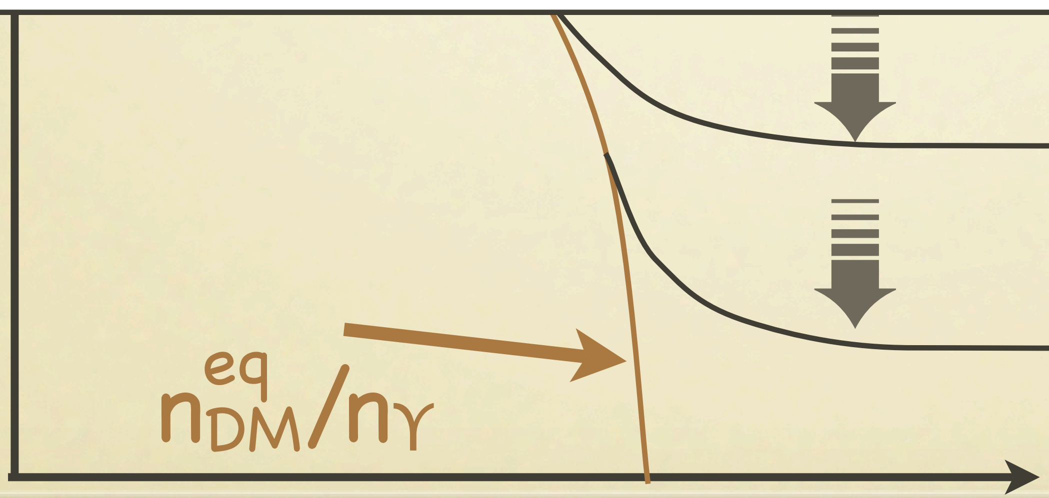
all known



$\langle \sigma_{\rm ann.} v\rangle$ ➠ larger

m/T (~time)

WIMP (weakly interacting massive particle) Dark Matter

thermal relic

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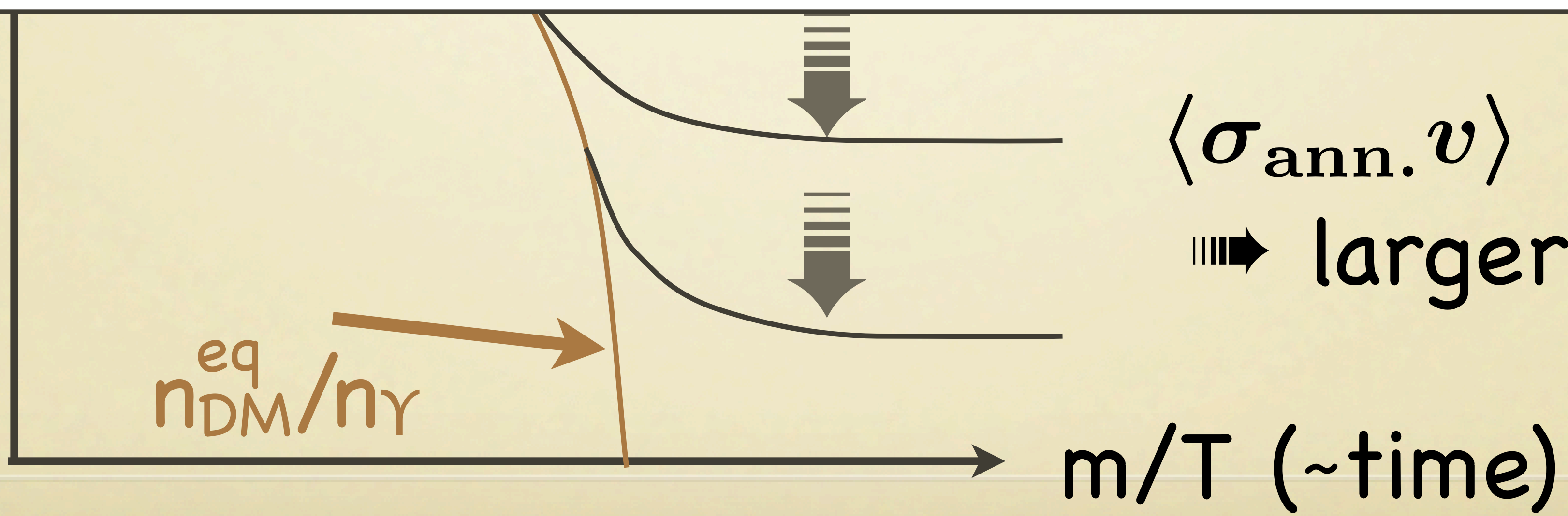
weak



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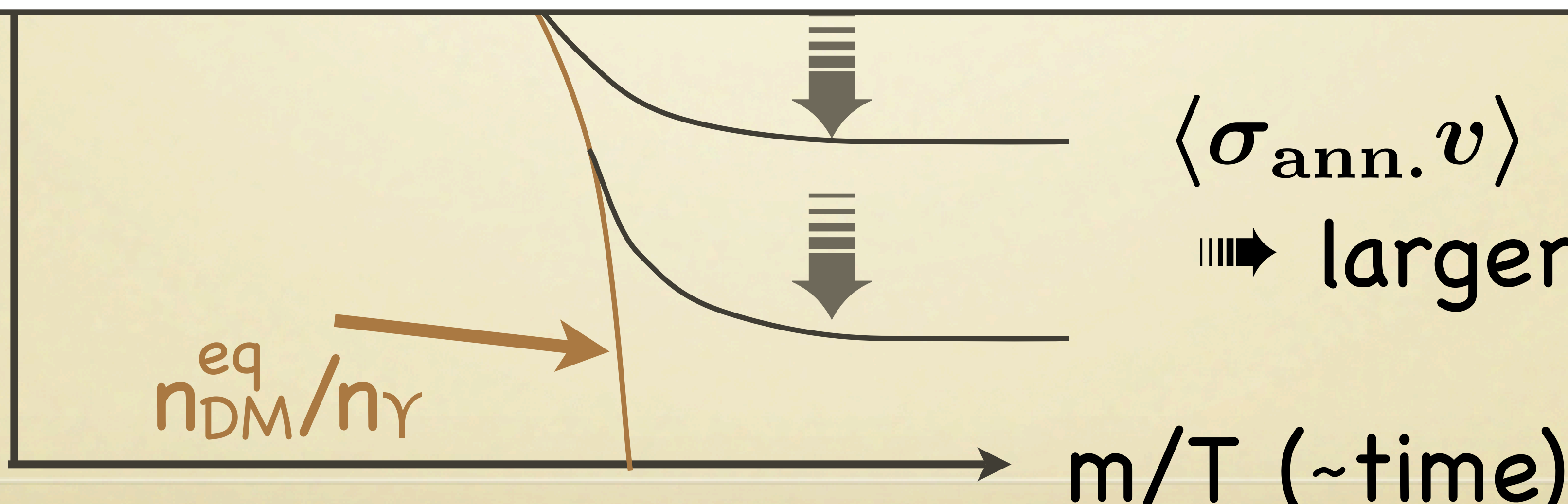
weak　　weak scale !!



WIMP Dark Matter: **Collider Signature/Test**

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qualitatively..... missing P_T at the LHC!

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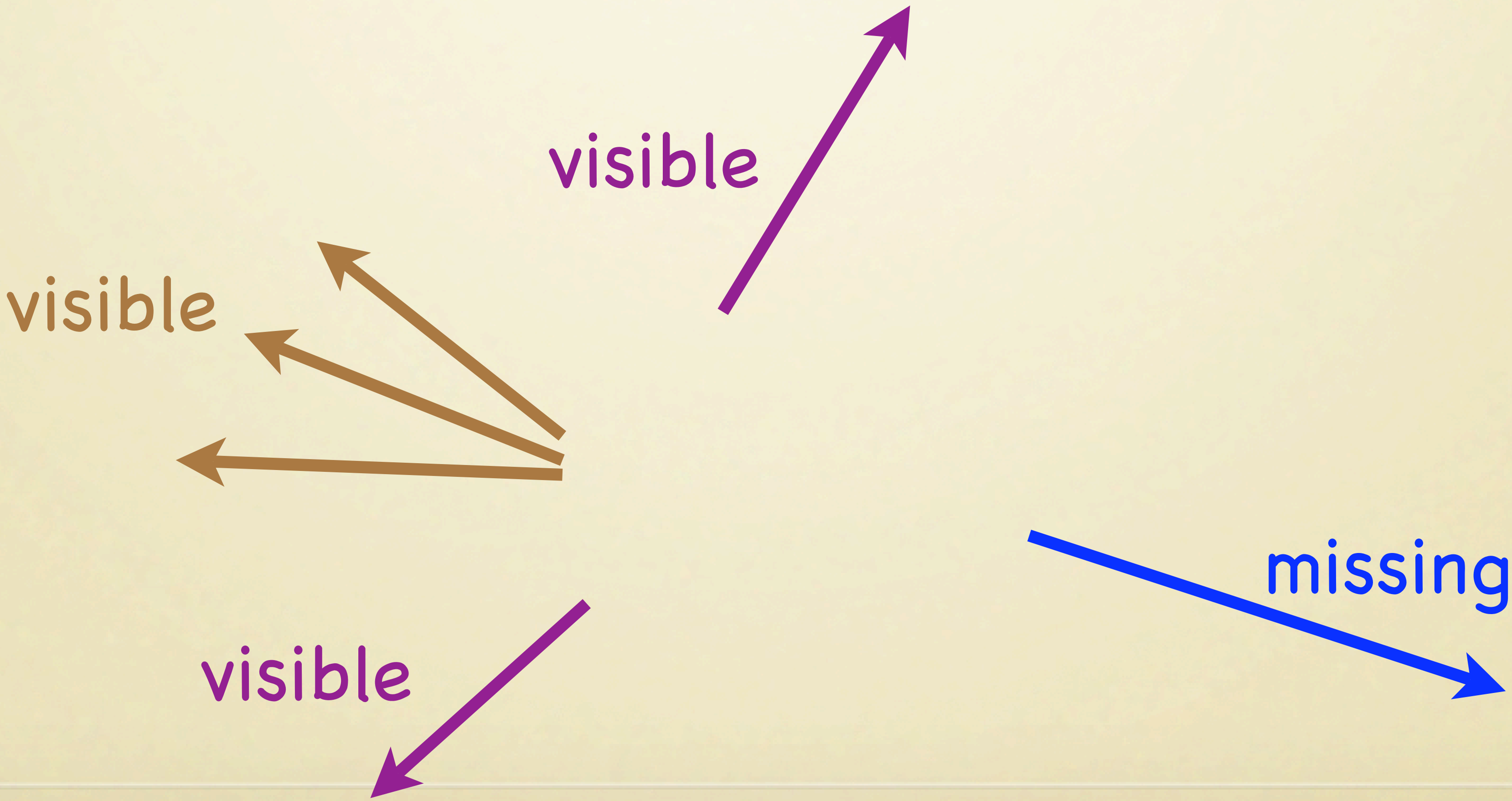
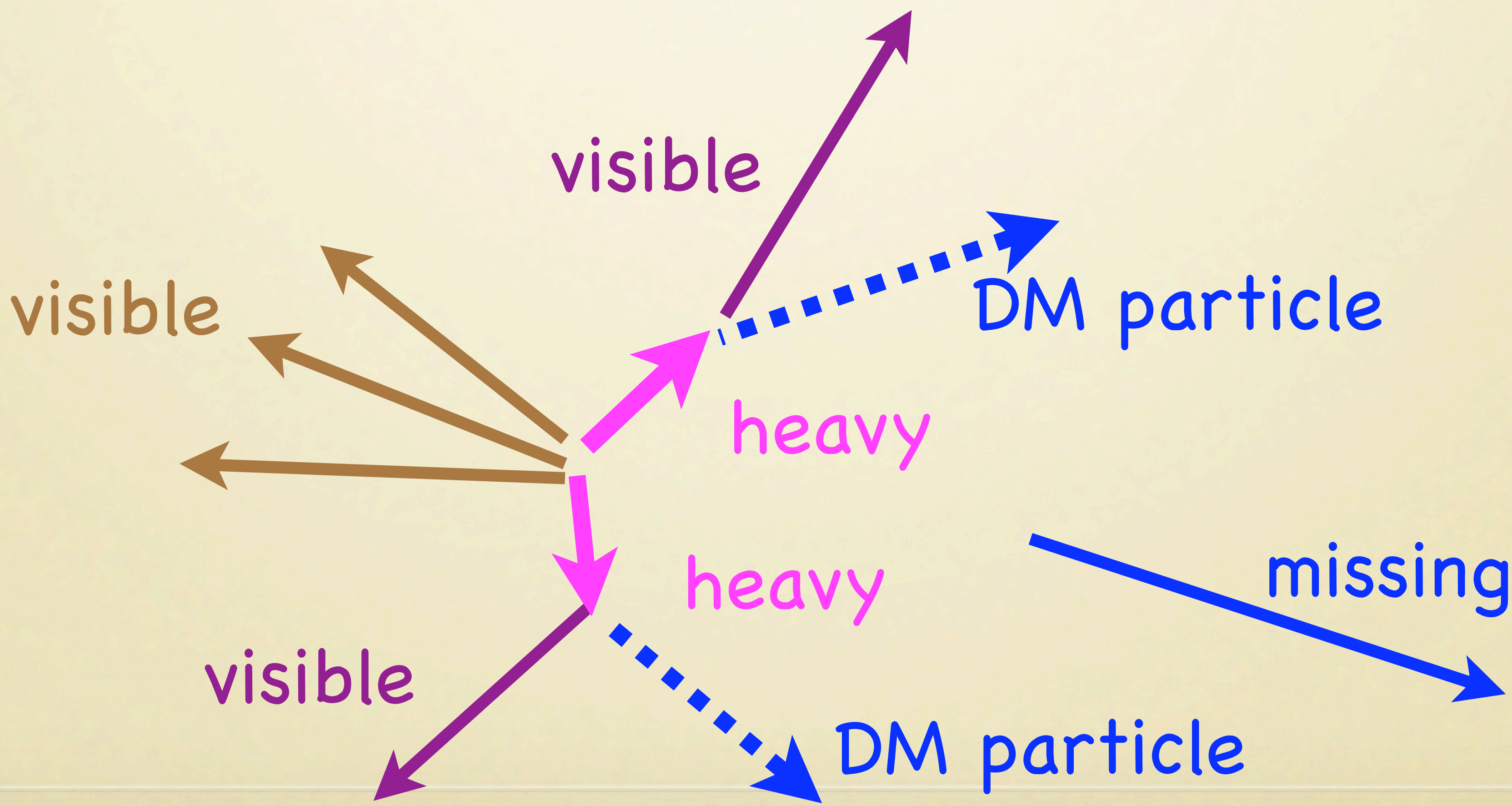


WIMP Dark Matter: Collider Signature/Test

qualitatively..... missing P_T at the LHC!



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quantitatively.....???

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quantitatively.....???

$$\Omega_{\rm DM}^{\rm thermal} \sim 0.2 \cdot \left(\frac{1\ \rm pb}{\langle \sigma_{\rm ann.} v \rangle} \right)$$

Check it !!

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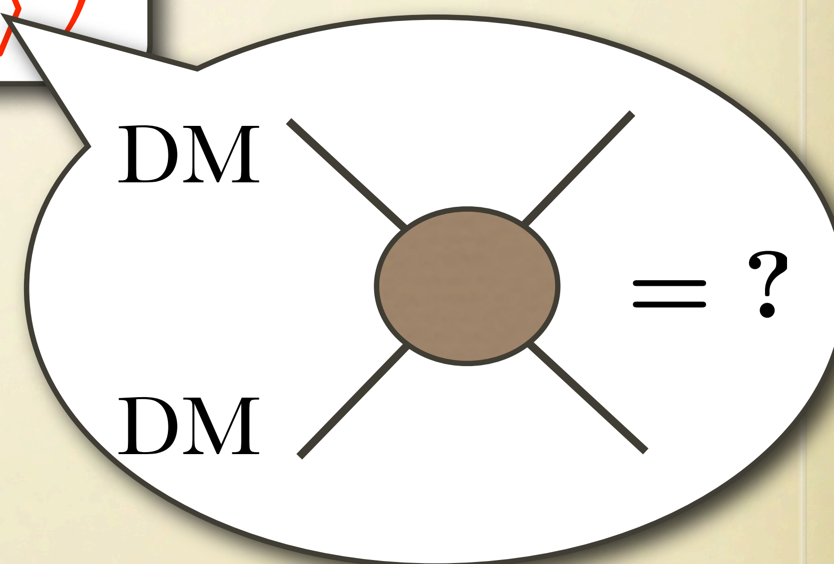

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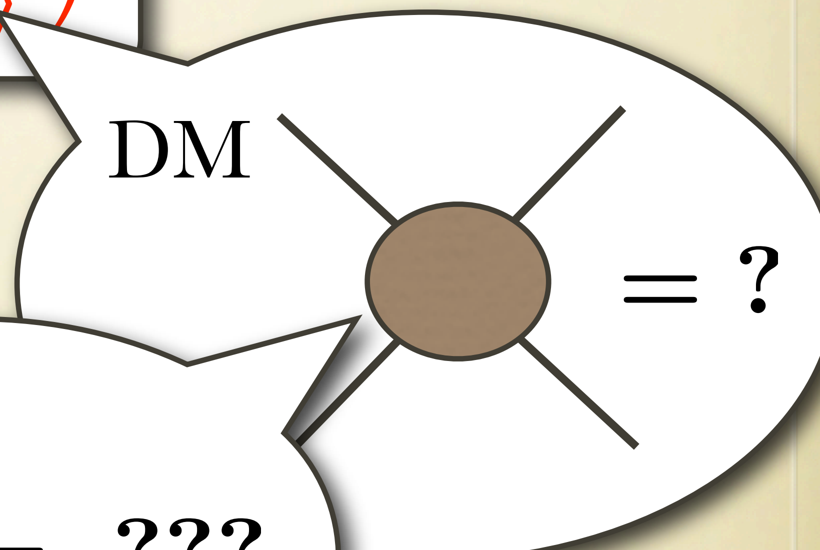


$$\mathcal{L}_{\rm DM} = \ ???$$

mass, couplings...

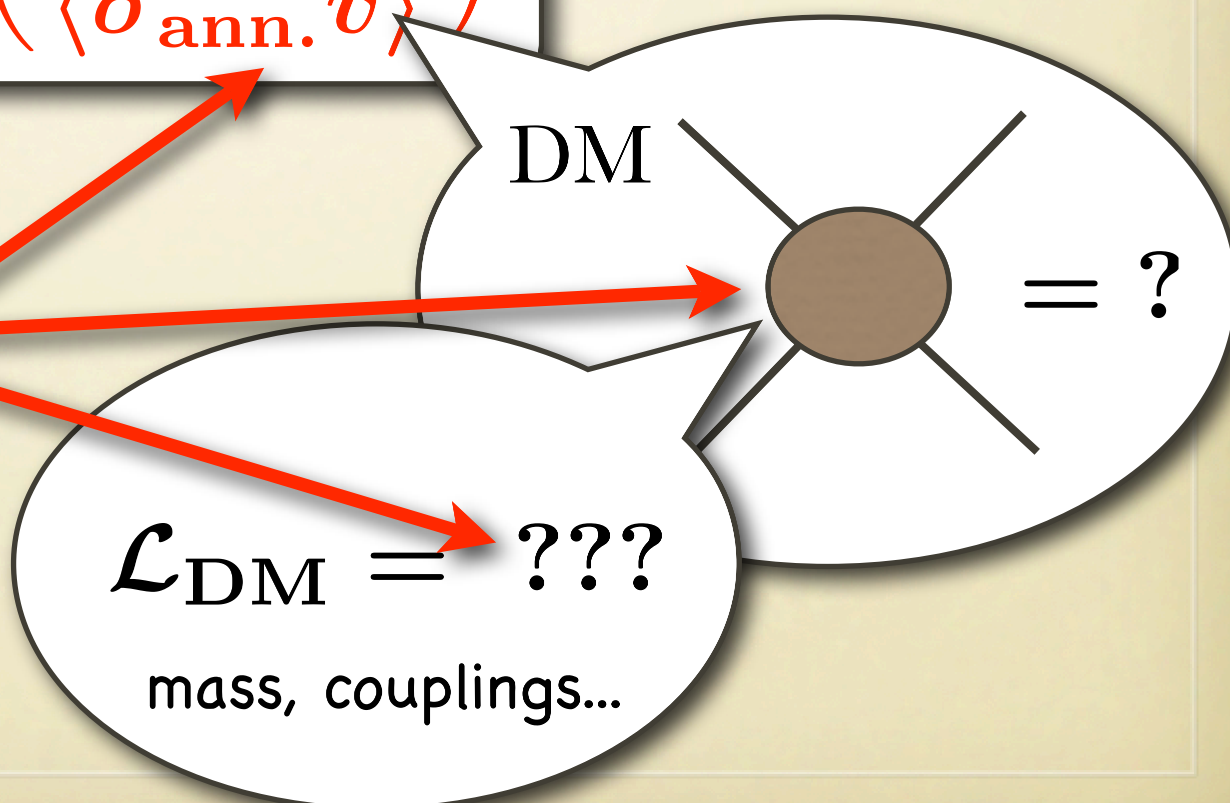
WIMP Dark Matter: Collider Signature/Test

quantitatively.....???

$$\Omega_{\rm DM}^{\rm thermal} \sim 0.2 \cdot \left(\frac{1\ \rm pb}{\langle \sigma_{\rm ann.} v \rangle} \right)$$

Check it !!

calculable using collider measurements!!



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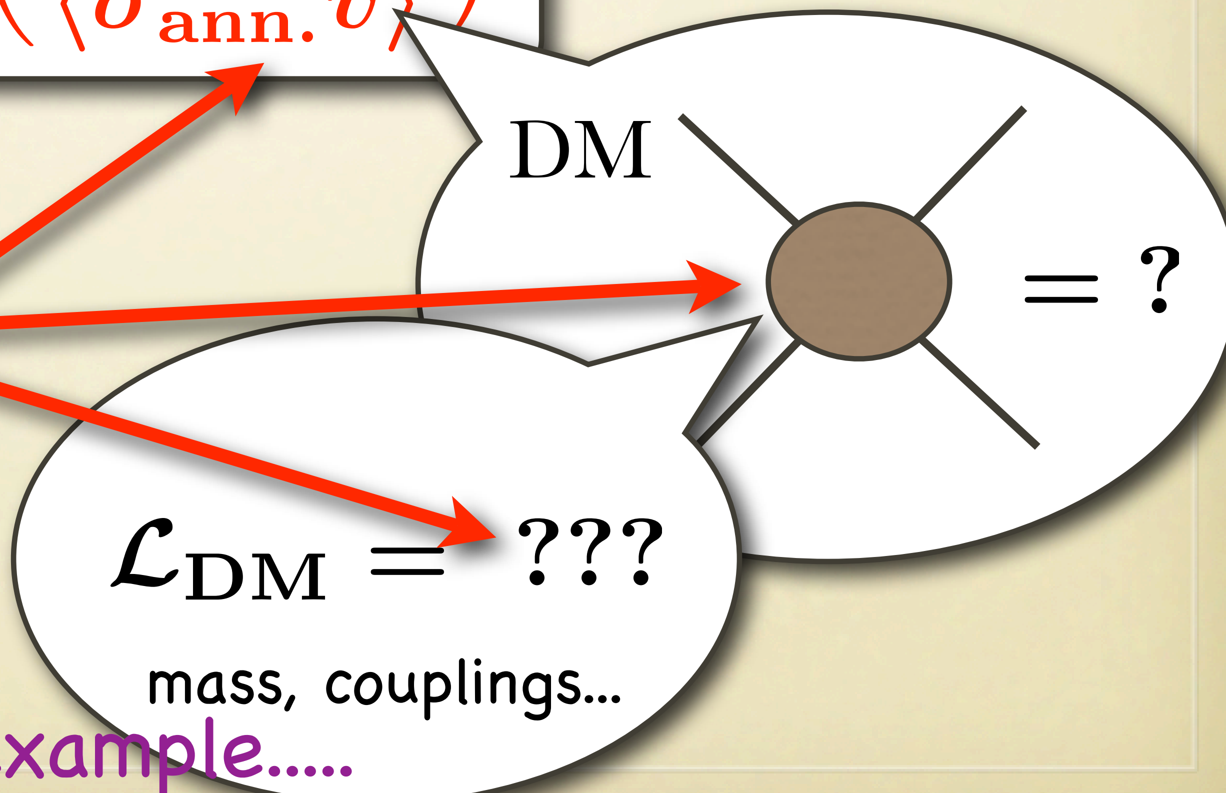


Let's consider SUSY example.....

Break:
Dark Matter in SUSY

Dark Matter in SUSY

Supersymmetry (SUSY)

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

(1) solves the naturalness problem

(2) leads to coupling unification

(3) has dark matter candidate

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 ✕ $B \rightarrow A_1 + A_2$

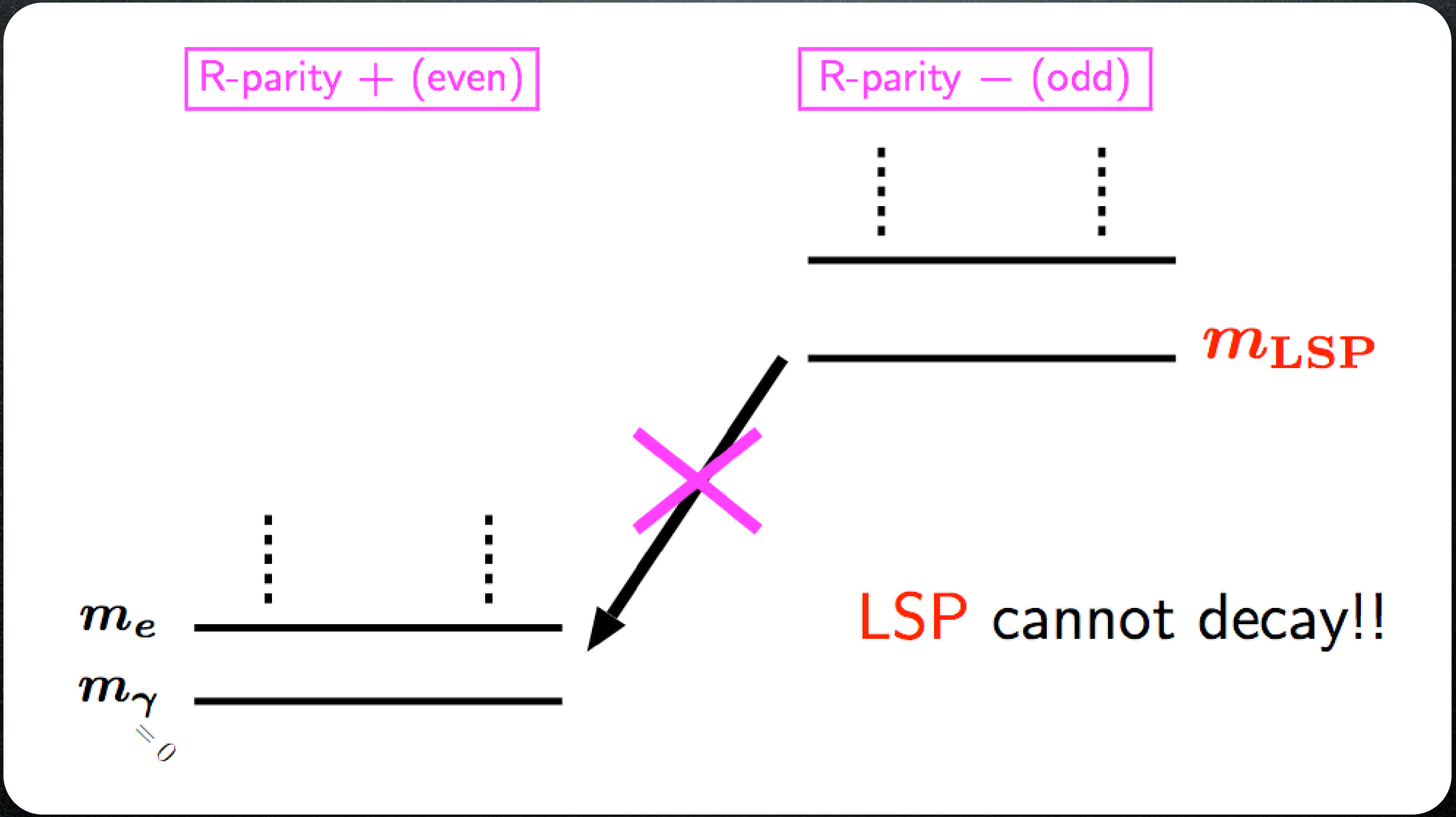
  $-\ +\ +$

- $B_1\ B_2\ A$ .... allowed ◎ $B_1 \rightarrow B_2 + A$

  $-\ -\ +$

Dark Matter in SUSY

In SUSY models + R-parity, the Lightest SUSY Particle (= LSP) is stable.



→ If neutral, Dark Matter candidate!

Dark Matter in SUSY

Supersymmetry (SUSY)

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} $\ni$ neutralino = WIMP !!

(1) solves the naturalness problem

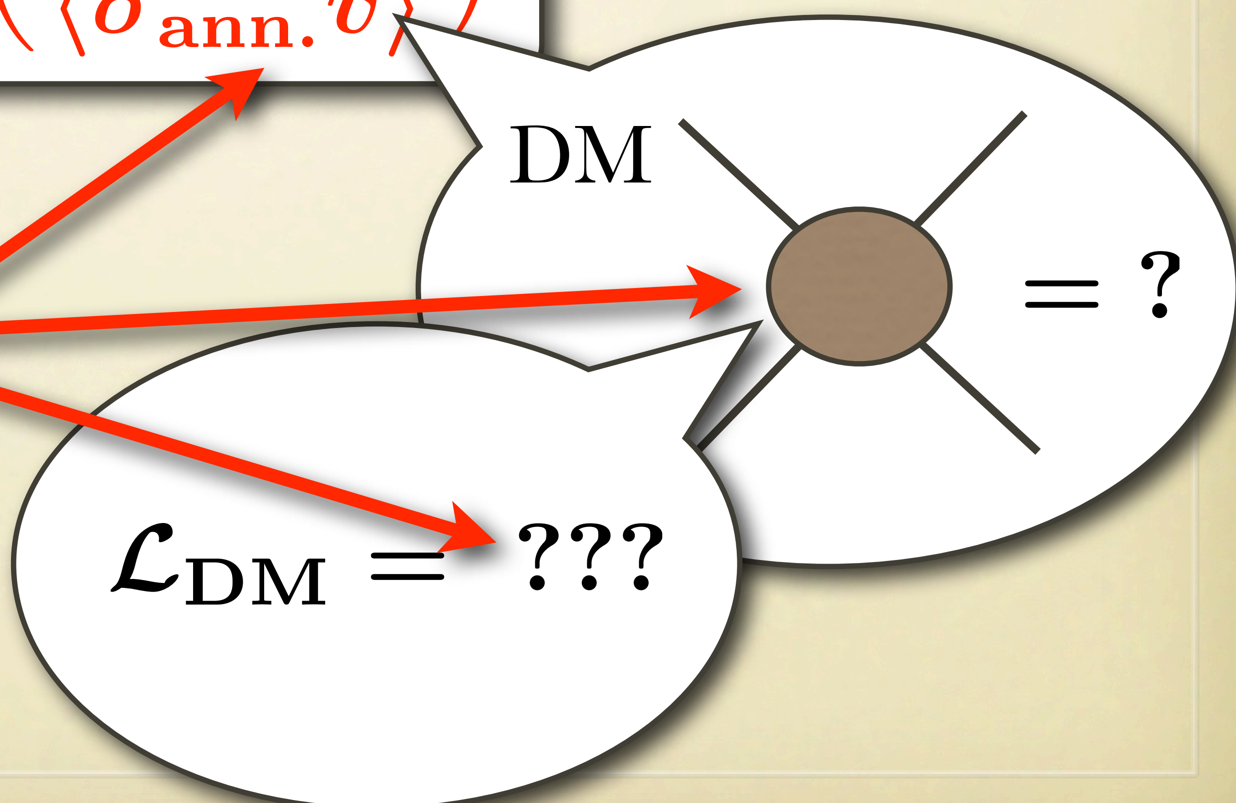
(2) leads to coupling unification

(3) has dark matter candidate

WIMP Dark Matter: Collider Signature/Test

$$\Omega_{\rm DM}^{\rm thermal} \sim 0.2 \cdot \left(\frac{1\ \rm pb}{\langle \sigma_{\rm ann.} v \rangle} \right)$$

calculable using collider measurements!!



WIMP

Study in SUSY models

various studies:

cf.

Allanach, Belanger, Boudjema, Pukhov,'04

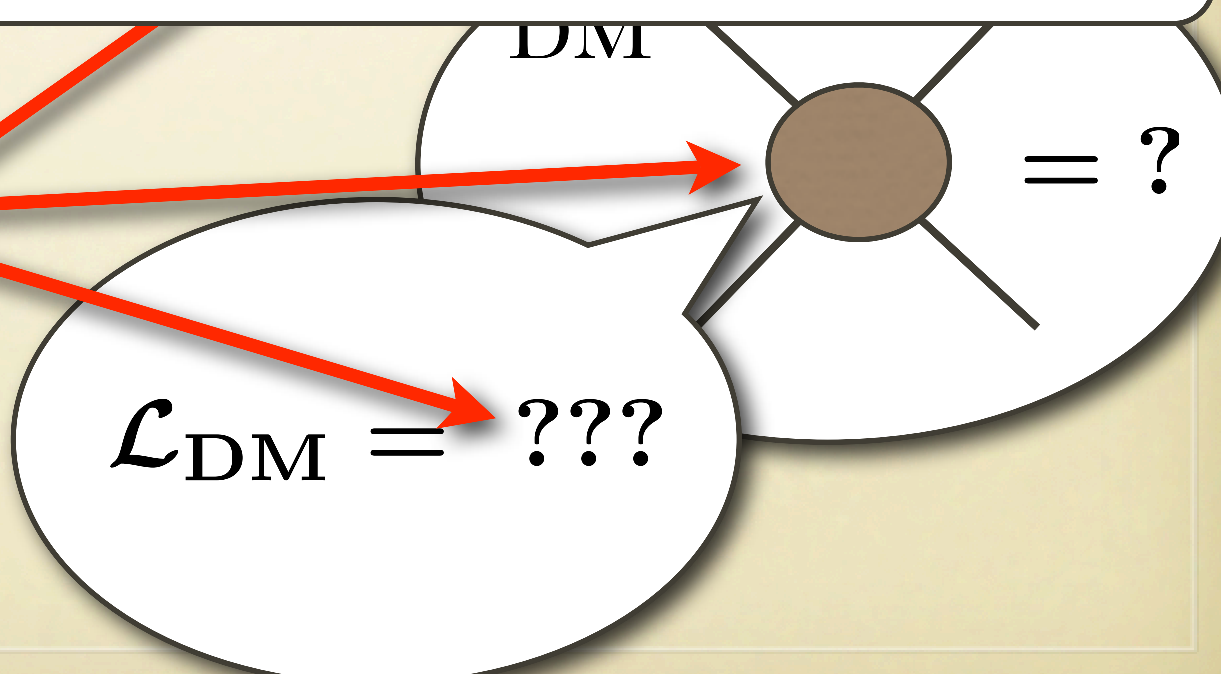
Moroi, Shimizu, Yotsuyanagi,'05

Nojiri, Polesello, Tovey,'05

Baltz, Battaglia, Peskin, Wizansky,'06

$\Omega_{\rm DM}^{\rm therm}$

calculable using collider measurements!!



example: (Baltz, Battaglia, Peskin, Wizansky,'06)

$$\mathcal{L}_{\mathrm{SUSY}} = \mathcal{L}_{\mathrm{SUSY}}\Big(\{\text{many parameters}\}\Big)$$

Generic SUSY model: # of parameters = ∞

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∪

MSSM (Minimal SUSY Standard Model): 108 parameters

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$\cup$

MSSM (Minimal SUSY Standard Model): 108 parameters

$\cup$

flavor/CP conserving MSSM: 24 parameters

- gaugino and Higgsino masses: m_1, m_2, m_3, μ
- slepton masses: $m^2(L_i)$, $m^2(\bar{e}_i)$, $i = 1, 2, 3$
- squark masses: $m^2(Q_i)$, $m^2(\bar{u}_i)$, $m^2(\bar{d}_i)$, $i = 1, 2, 3$
- Higgs potential terms: m_A, $\tan\beta$
- A terms: A_τ, A_b, A_t

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Note:
still much more generic than mSUGRA, mGMSB, mAMSB,.....

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collider measurement

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$\mathcal{L}_{\text{SUSY}}$

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collider measurement

$\langle \sigma_{\text{ann.}} v \rangle$

$\mathcal{L}_{\text{SUSY}}$

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example: (Baltz, Battaglia, Peskin, Wizansky,'06)

$\Omega_{\chi}^{\text{thermal}}$

$\langle \sigma_{\text{ann.}} v \rangle$

$\mathcal{L}_{\text{SUSY}}$

collider measurement

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example: (Baltz, Battaglia, Peskin, Wizansky,'06)

$\Omega_{\mathrm{DM}} \sim 0.22$ ⟷ $\Omega_{\chi}^{\mathrm{thermal}}$

check it !!!

$\langle \sigma_{\mathrm{ann.}} v \rangle$

$\mathcal{L}_{\mathrm{SUSY}}$

collider measurement

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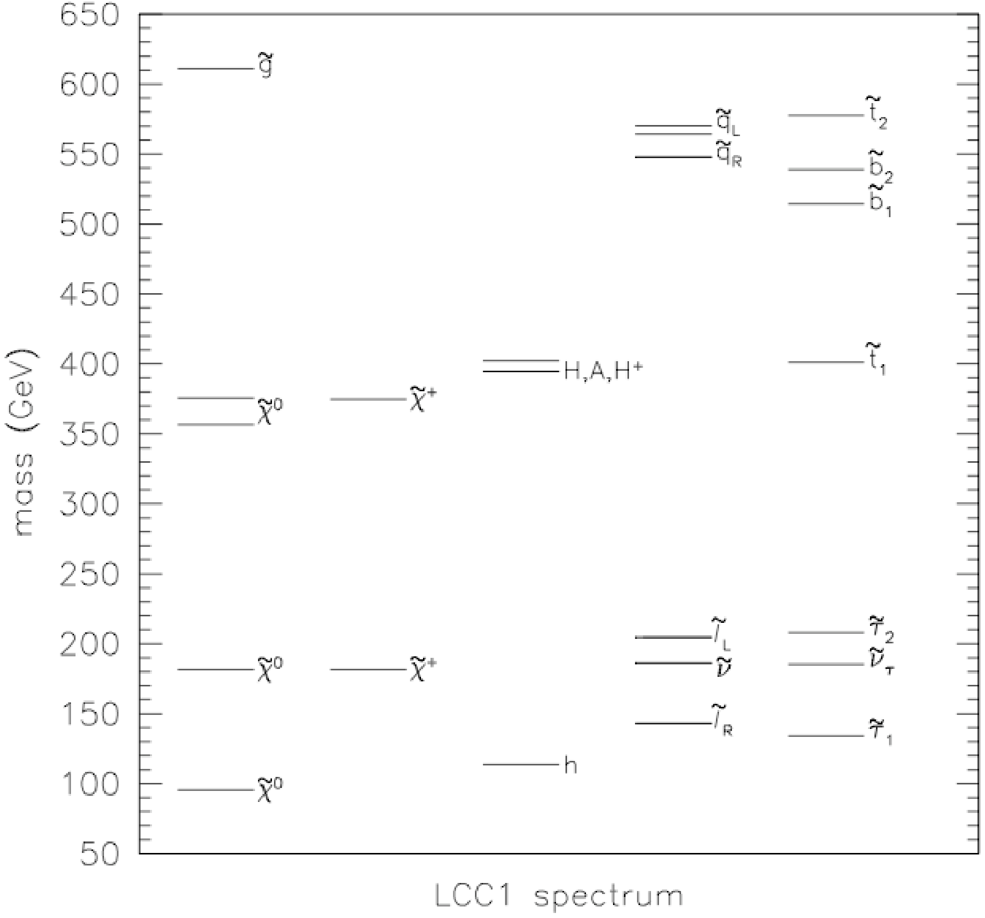
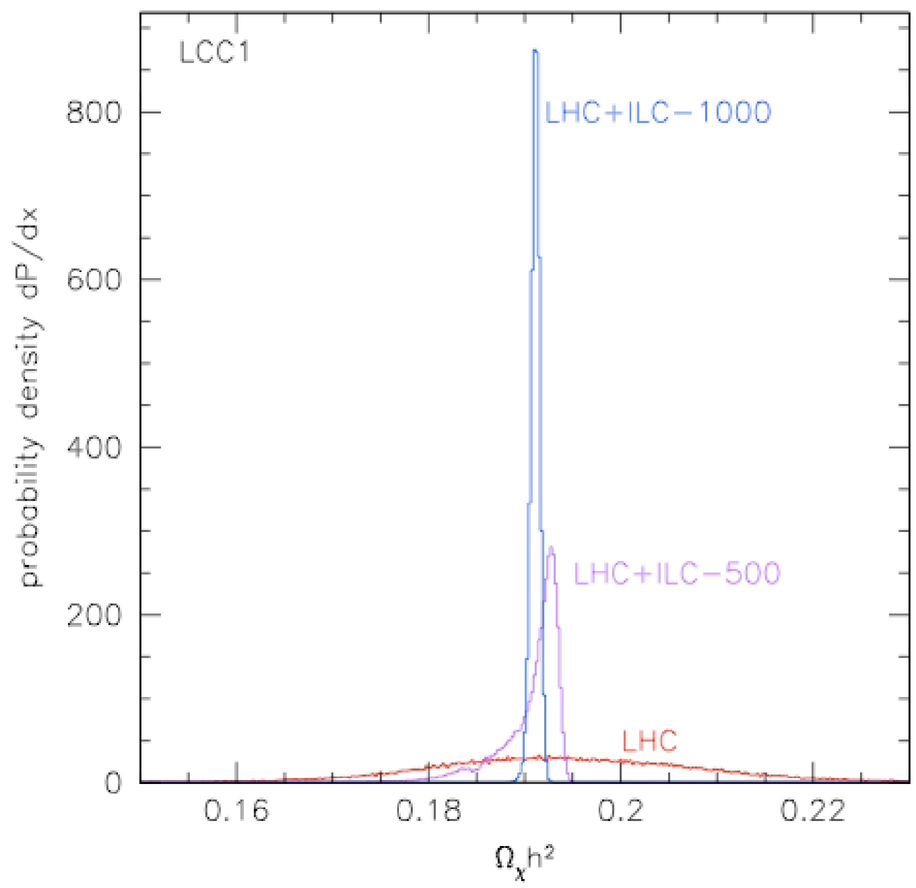
- Higgs potential terms: m_A, $\tan\beta$
- A terms: A_τ, A_b, A_t

example: (Baltz, Battaglia, Peskin, Wizansky,'06)





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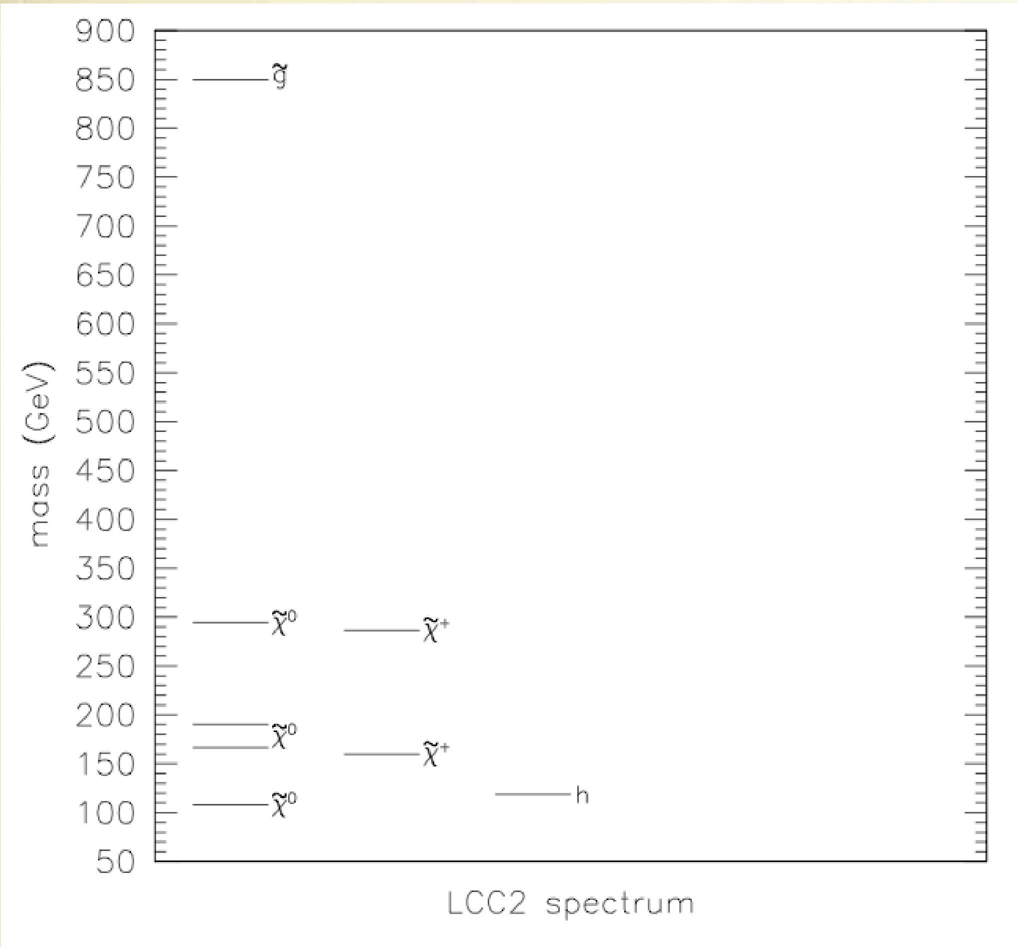

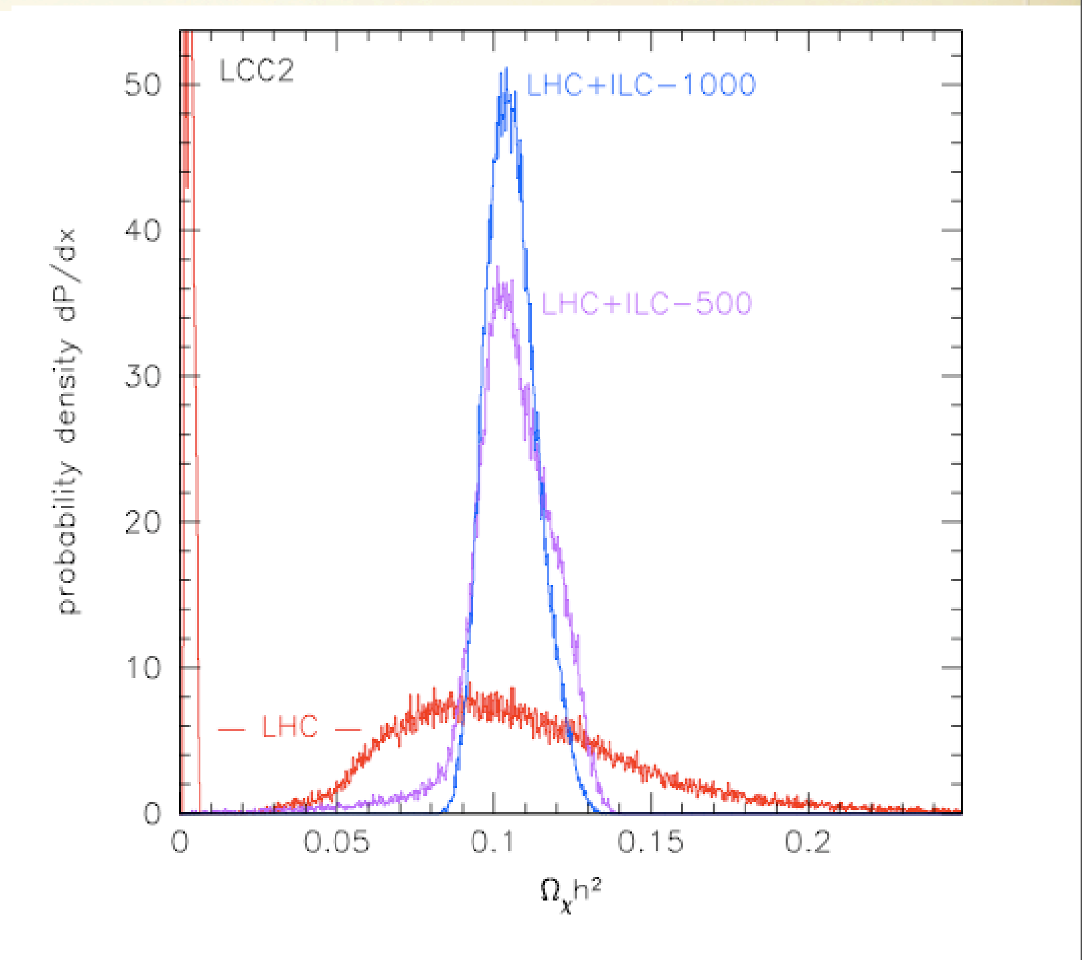

WIMP Dark Matter: Collider Signature/Test

$$\Omega_{\mathrm{DM}}^{\mathrm{thermal}} \sim 0.2 \cdot \left(\frac{1\ \mathrm{pb}}{\langle \sigma_{\mathrm{ann.}} v \rangle} \right)$$

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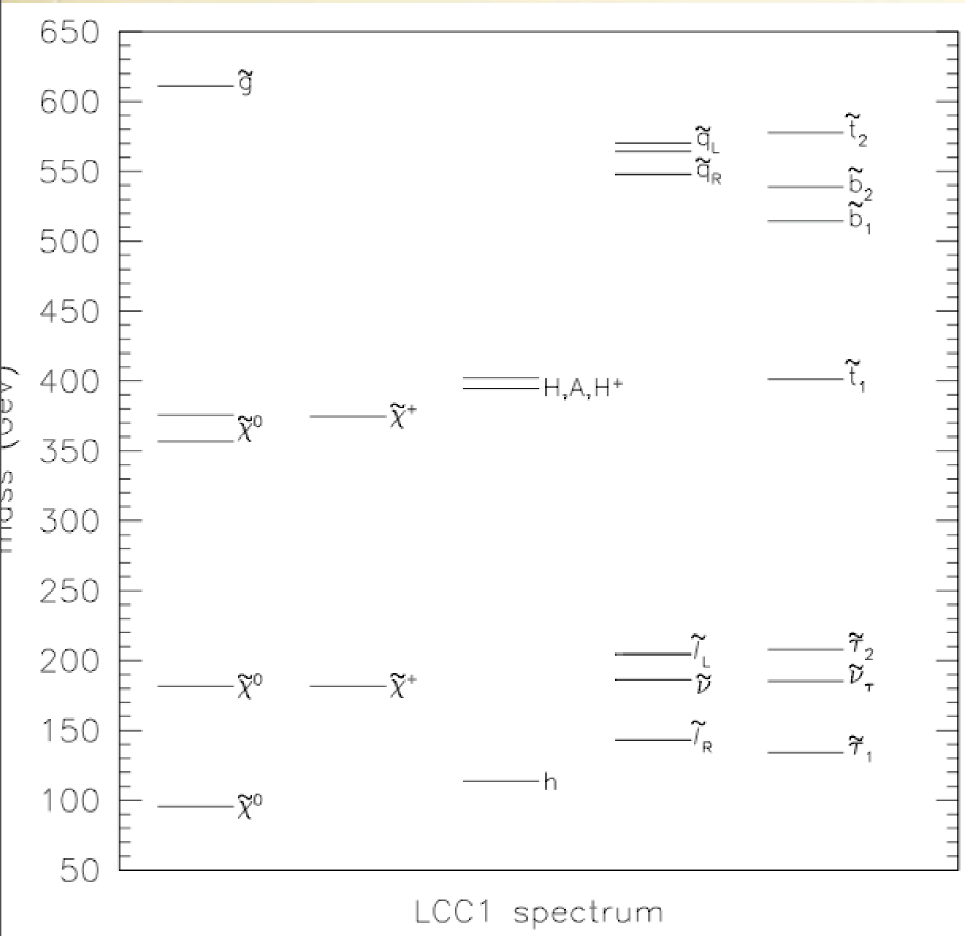

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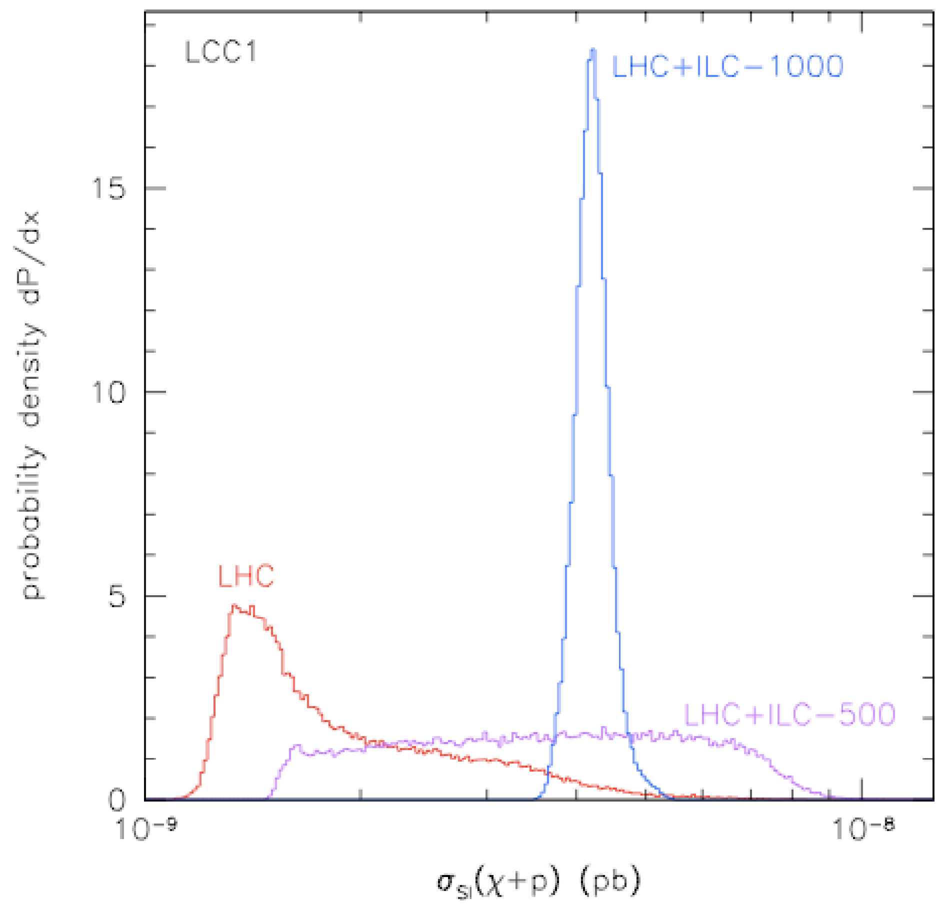

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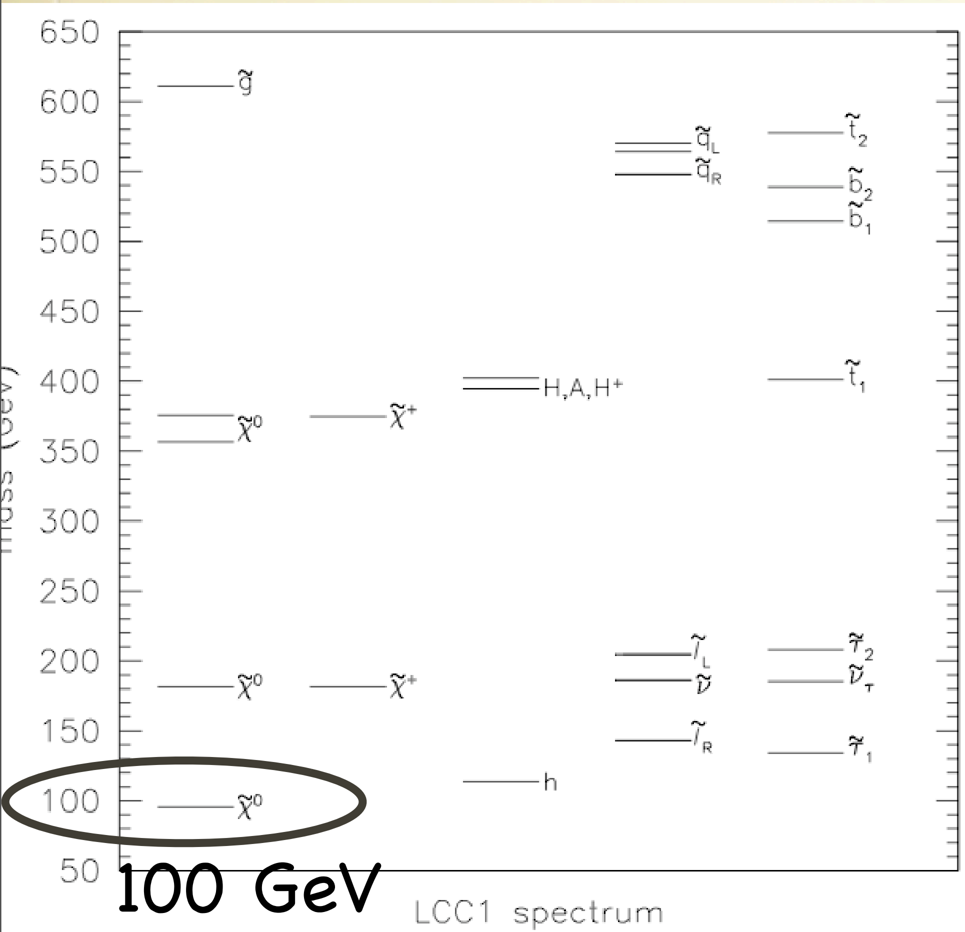

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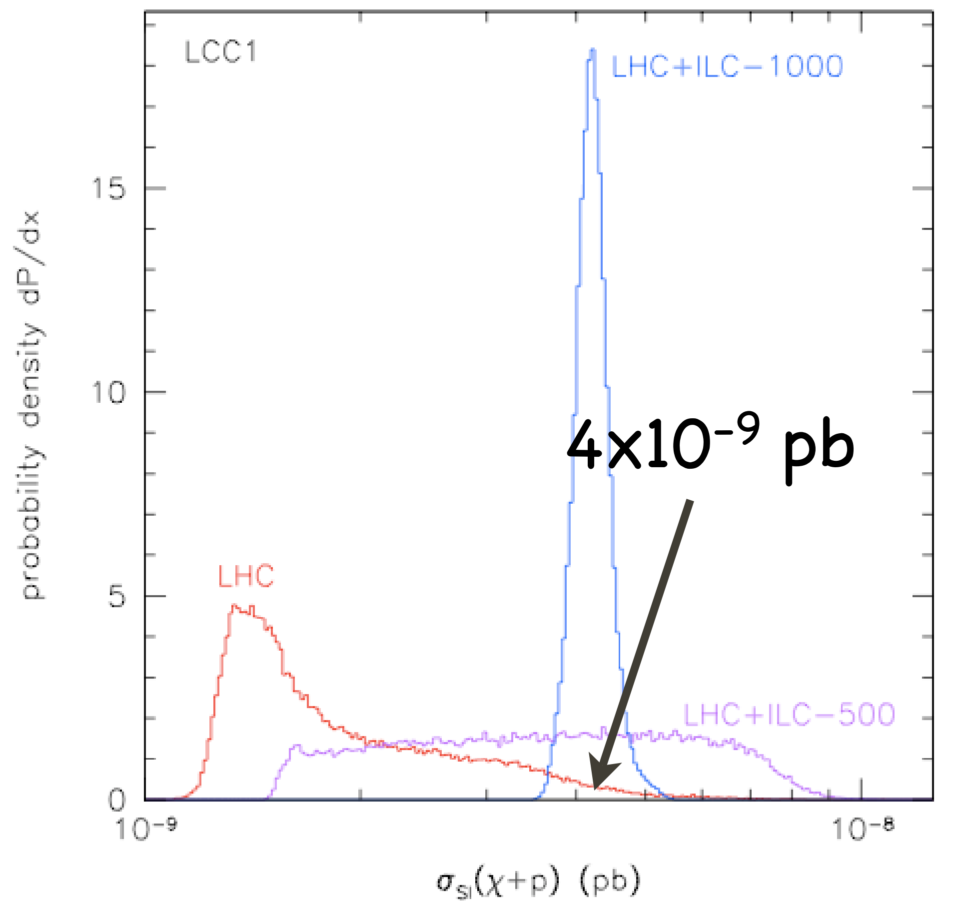

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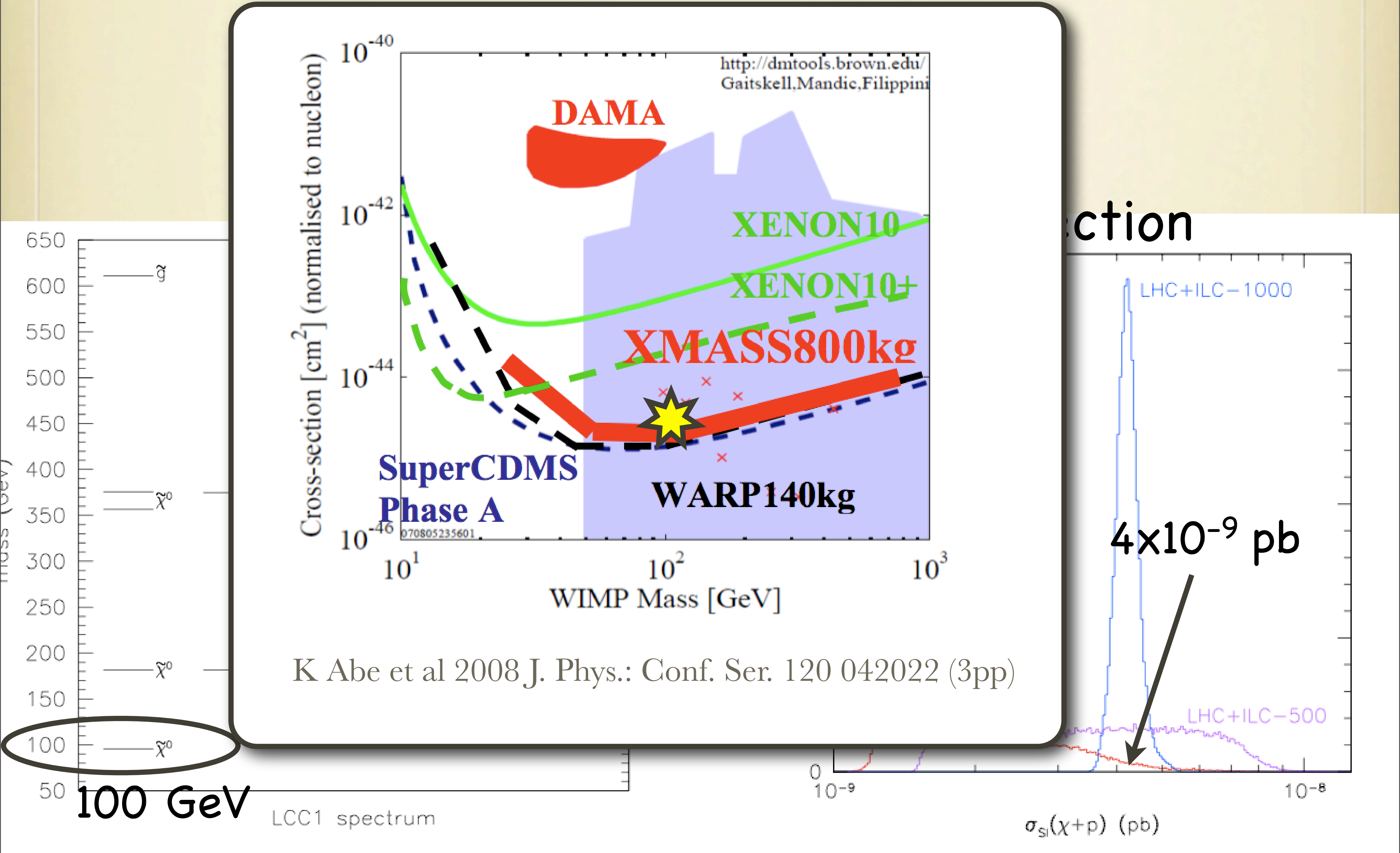

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If (in)direct signatures ➠ can multiple-check!!

- non-thermal WIMP (☚ cosmic ray signatures?)

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This may be suggested by recent Cosmic Ray observations.....

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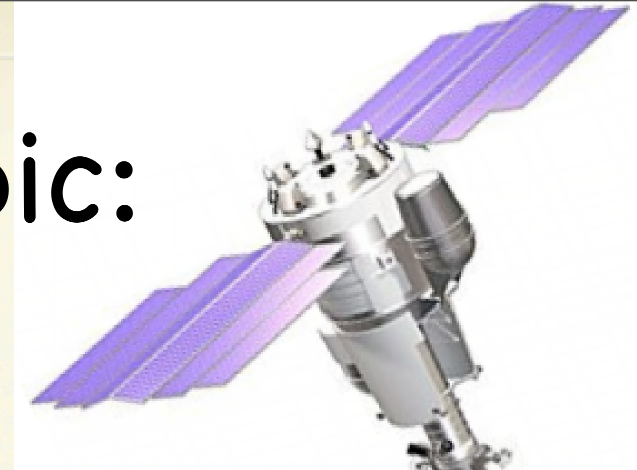
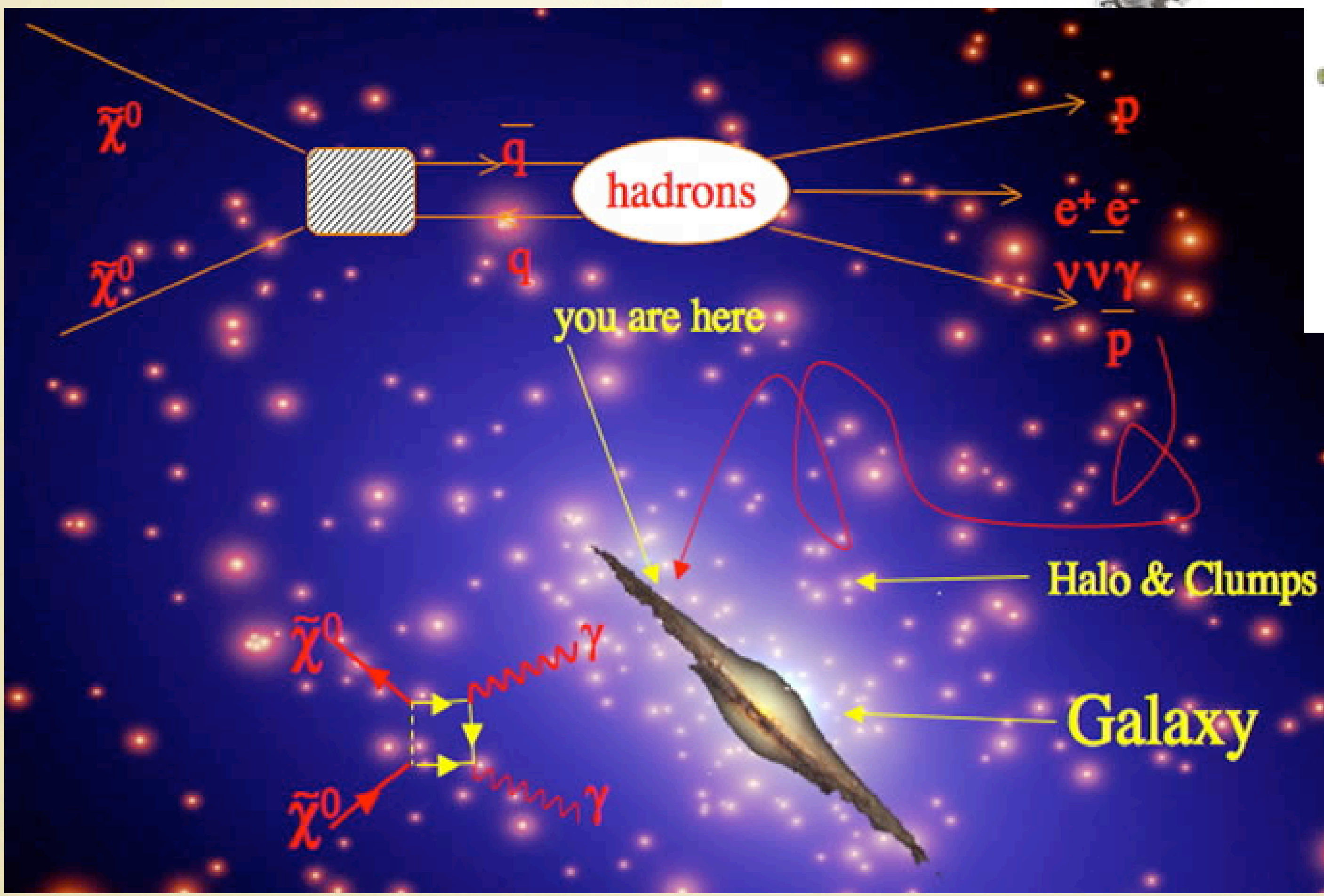
recent hot topic: PAMELA





figures from PAMELA homepage http://pamela.roma2.infn.it

recent hot topic:

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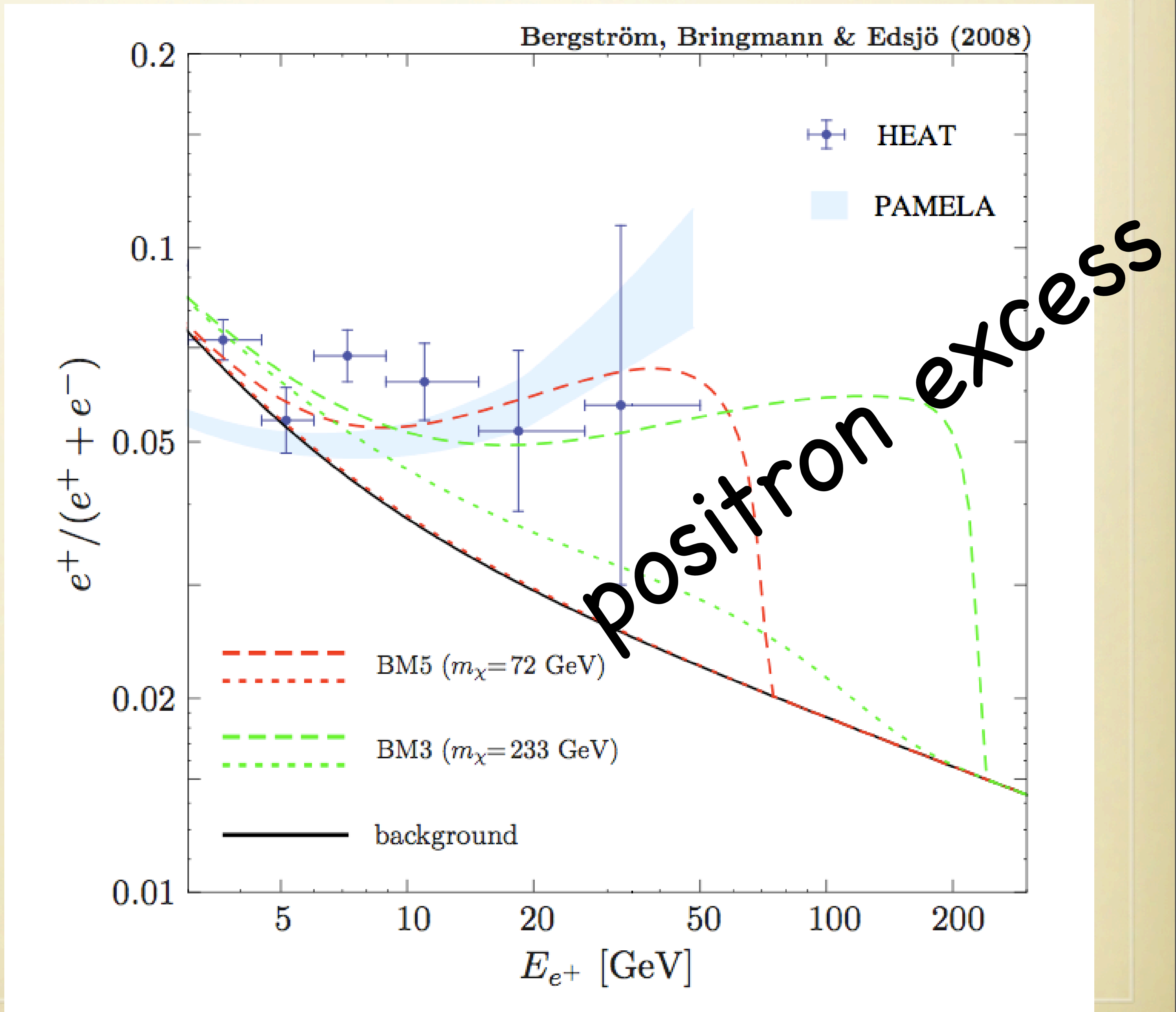

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(note: not published yet!)

naturenews

Published online 2 September 2008 | Nature | doi:10.1038/455007a

News

Physicists aflutter about data photographed at conference

Digital cameras snap slides ahead of publication.

Geoff Brumfiel (/news/author/Geoff+Brumfiel/index.html)

An Italian-led research group's closely held data have been outed by paparazzi physicists, who photographed conference slides and then used the data in their own publications.

Is this the right place for digital cameras?

F. Chmura/Alamy

For weeks, the physics community has been buzzing with the latest results on 'dark matter' from a European satellite mission known as PAMELA (Payload for Antimatter Matter Exploration and Light-nuclei Astrophysics). Team members have talked about their latest results at several recent conferences (see ***Nature* 454, 808; 2008** (http://www.nature.com/uidfinder/10.1038/454808b)), but beyond a quick flash of a slide, the collaboration has not shared the data. Many high-profile journals, including *Nature*, have strict rules about authors publicizing data before publication.

It now seems that some physicists have taken matters into their own hands. At least two papers recently appeared on the preprint server arXiv.org showing representations of PAMELA's latest findings (**M. Cirelli *et al.* http://arxiv.org/abs/0808.3867; 2008** (http://arxiv.org/abs/0808.3867) , and **L. Bergstrom *et al.* http://arxiv.org/abs/0808.3725; 2008** (http://arxiv.org/abs/0808.3725)). Both have recreated data from photos taken of a PAMELA presentation on 20 August at the Identification of Dark Matter conference in Stockholm, Sweden.

"We had our digital cameras ready," says Marco Cirelli, a theorist at the Institute of Theoretical Physics in Gif-sur-Yvette, France, and one of those who took pictures. The preprints fully acknowledge the source of the data and reference the presentation photographed.

PAMELA has been attracting such interest because it has reportedly seen an excess of high-energy positrons in space. Those positrons could stem from the collision and annihilation of dark-matter particles, which could make up most of the mass of the Universe. If the data hold up, they would be the most direct clue yet to the nature of dark matter.

The satellite's finding comes at a time when theoretical physicists are desperate for dark-matter data to test their ideas against. "There hasn't been much progress," says Adam Falkowski, a theorist at CERN, Europe's particle-physics laboratory near Geneva, Switzerland. "The hunger for new results in the community is big."

Piergiorgio Picozza, PAMELA's principal investigator and a physicist at the University of Rome Tor Vergata, says he is "very, very upset" by the data being incorporated into a publication. But Cirelli maintains that he and others have done nothing wrong. "We asked the PAMELA people [there], and they said it was not a problem," he says.

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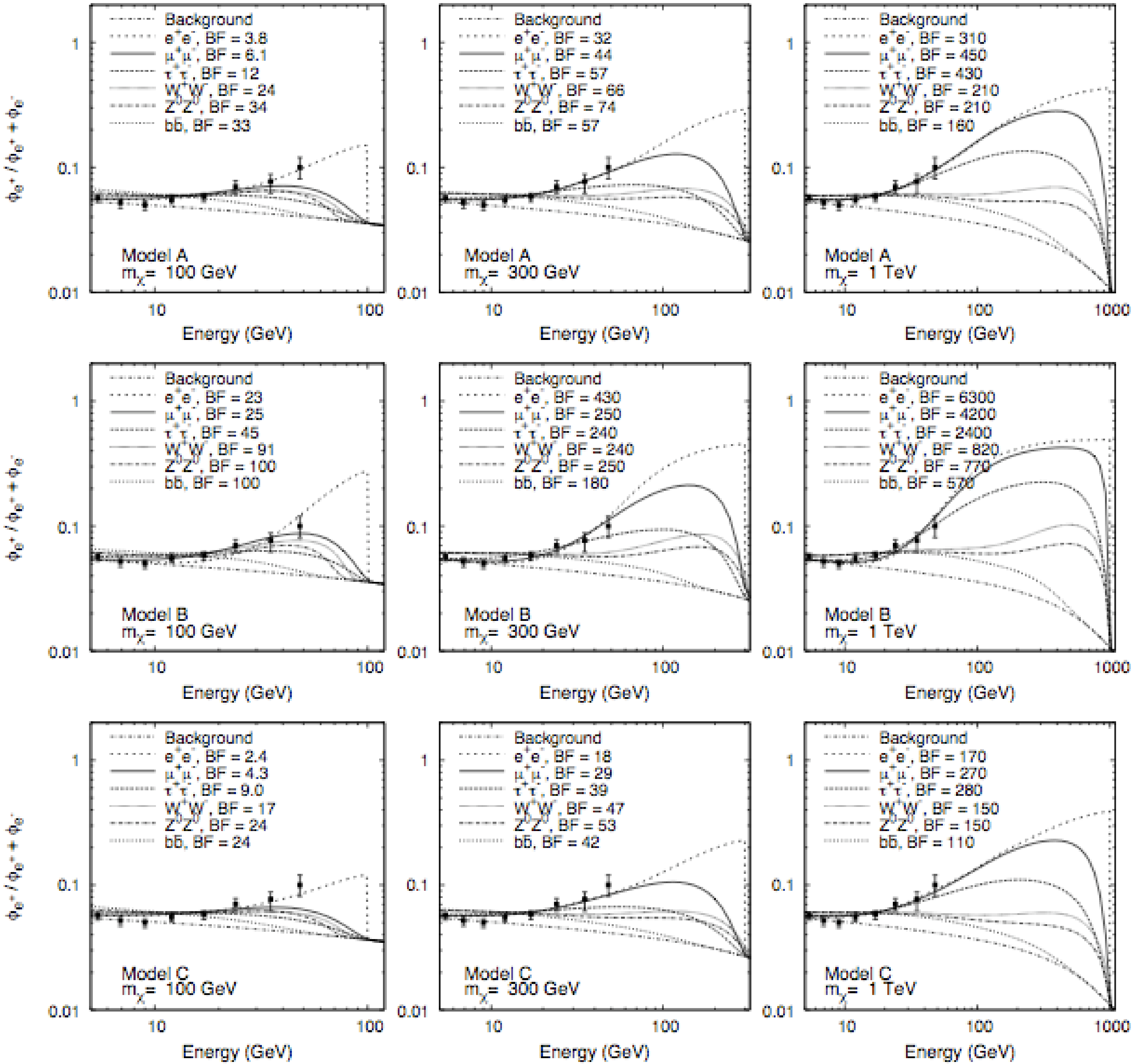
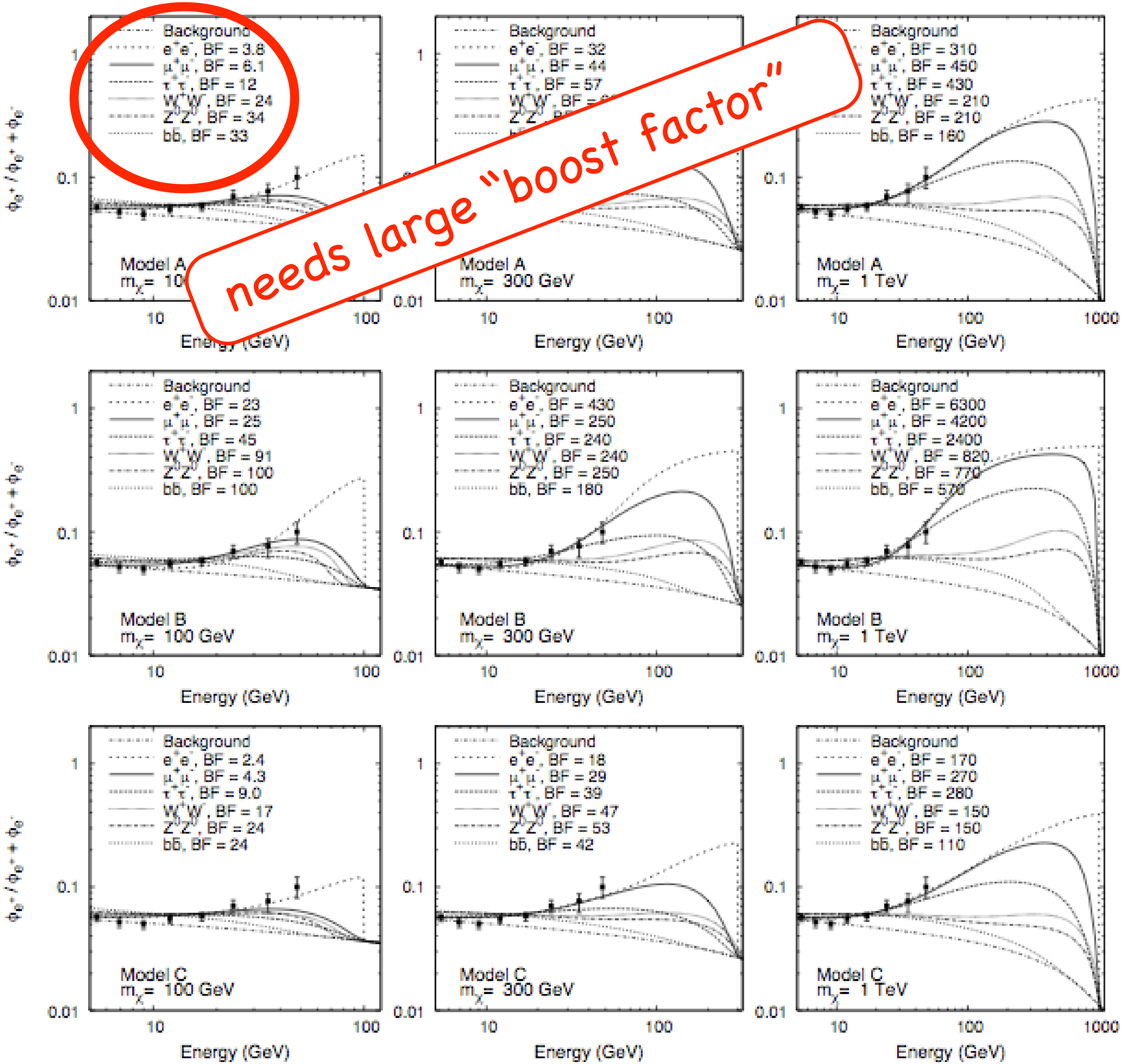


fig. from Cholis et.al. 0809.1683



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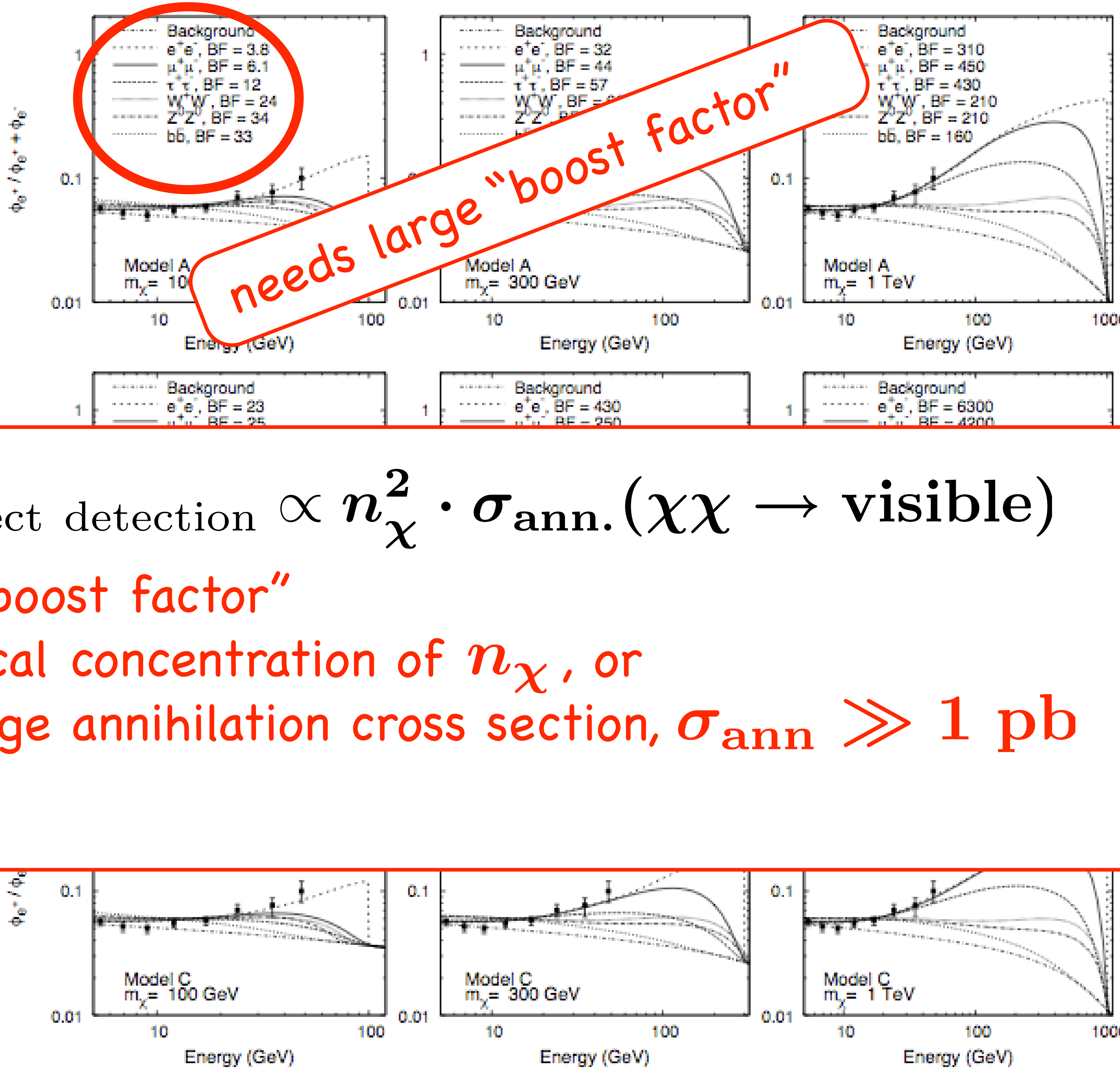

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large "boost factor"

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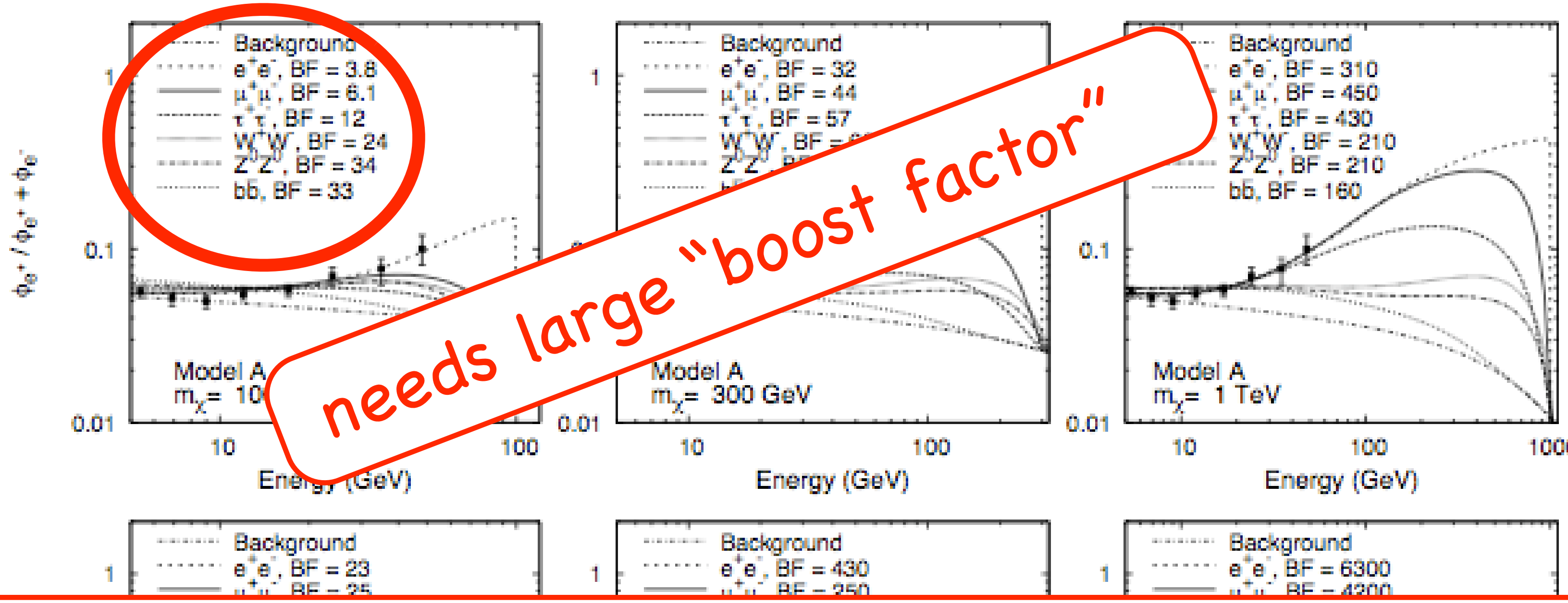

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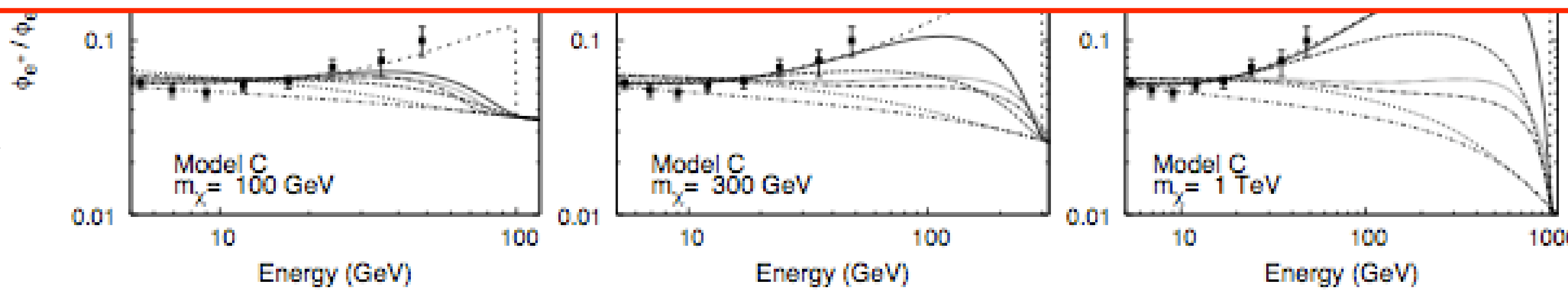
...... but then, $\Omega_{\rm DM} \ll 0.2$???



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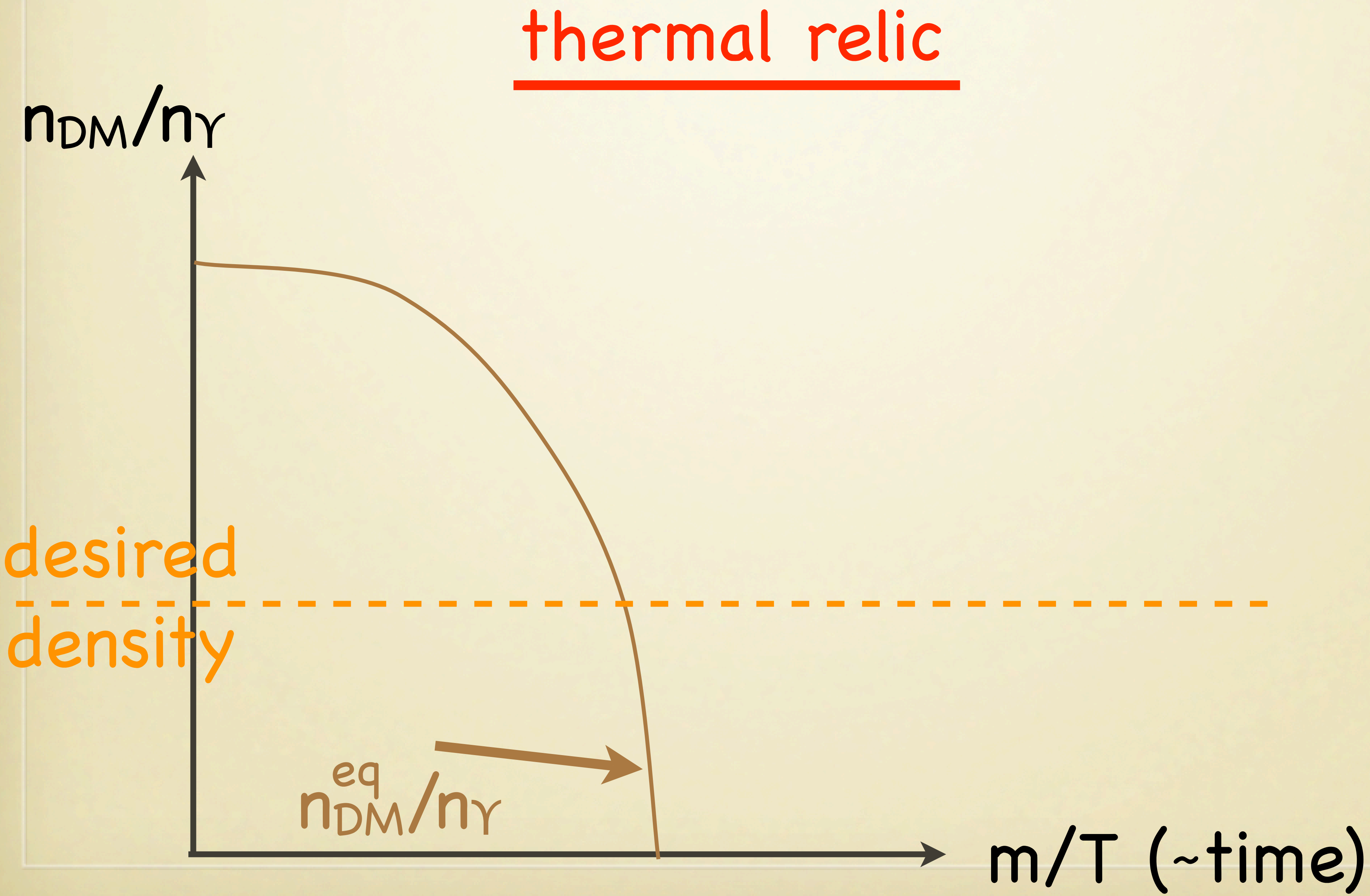

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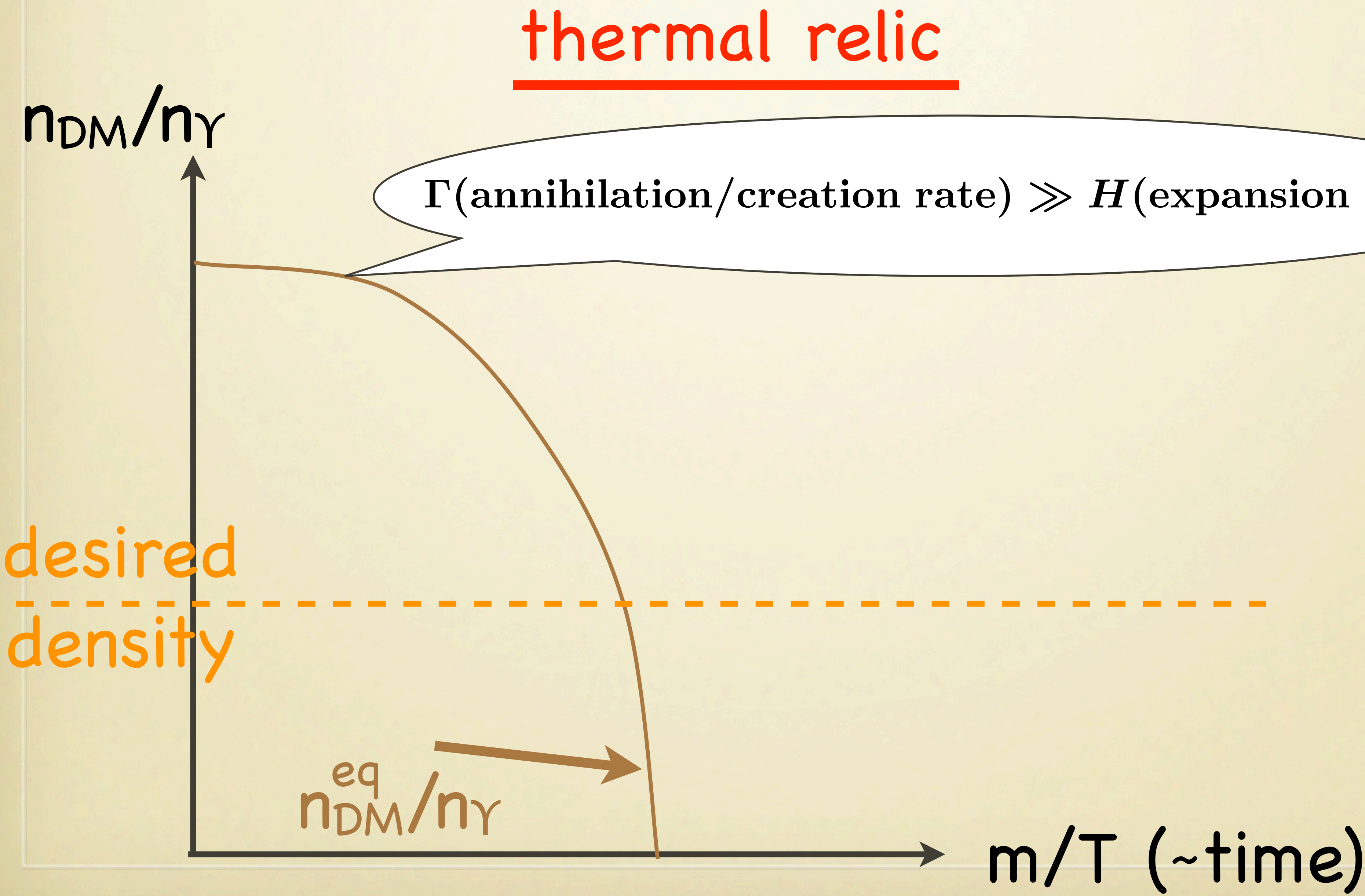
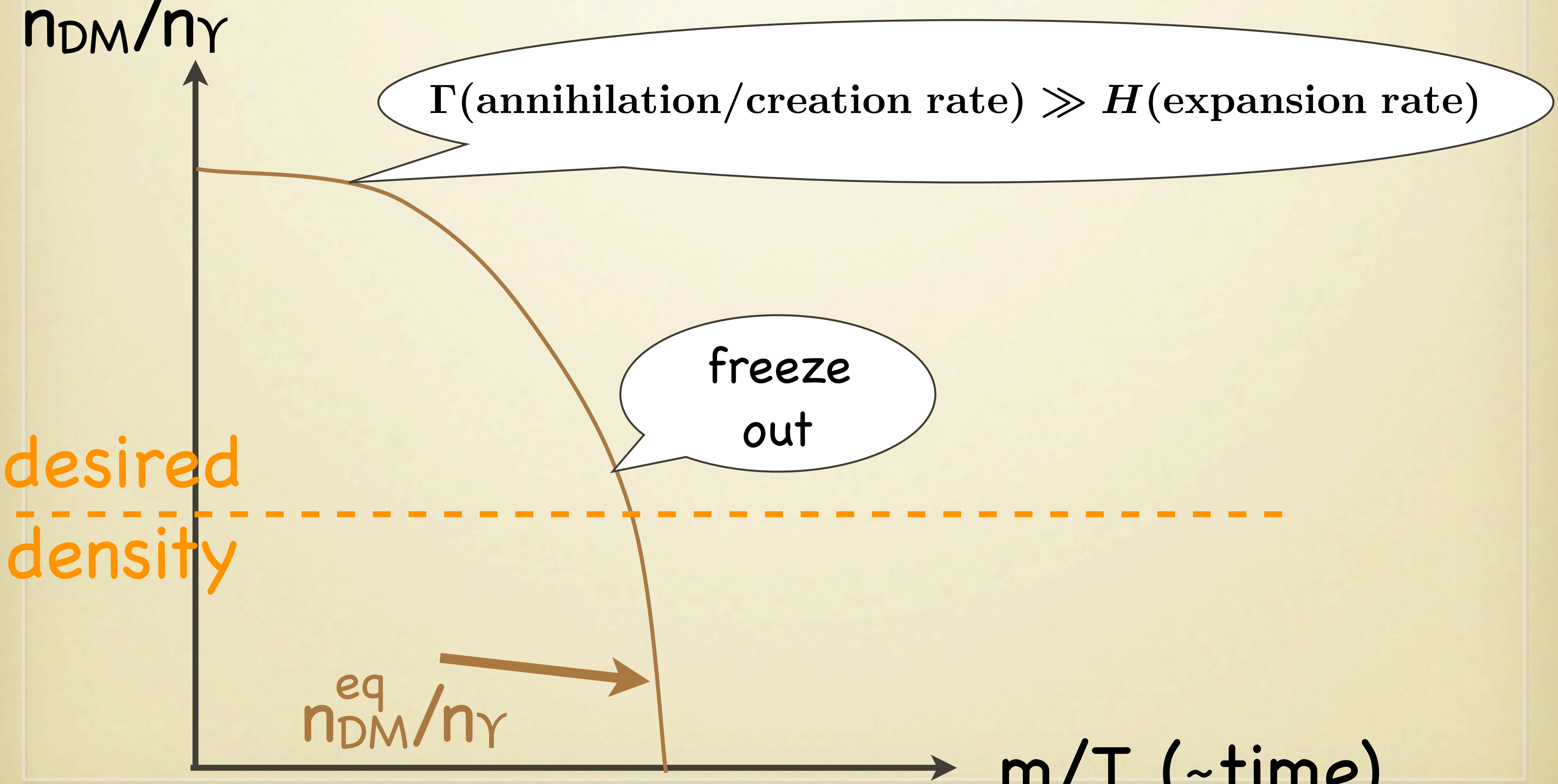


Non-thermal WIMP Dark Matter

thermal relic



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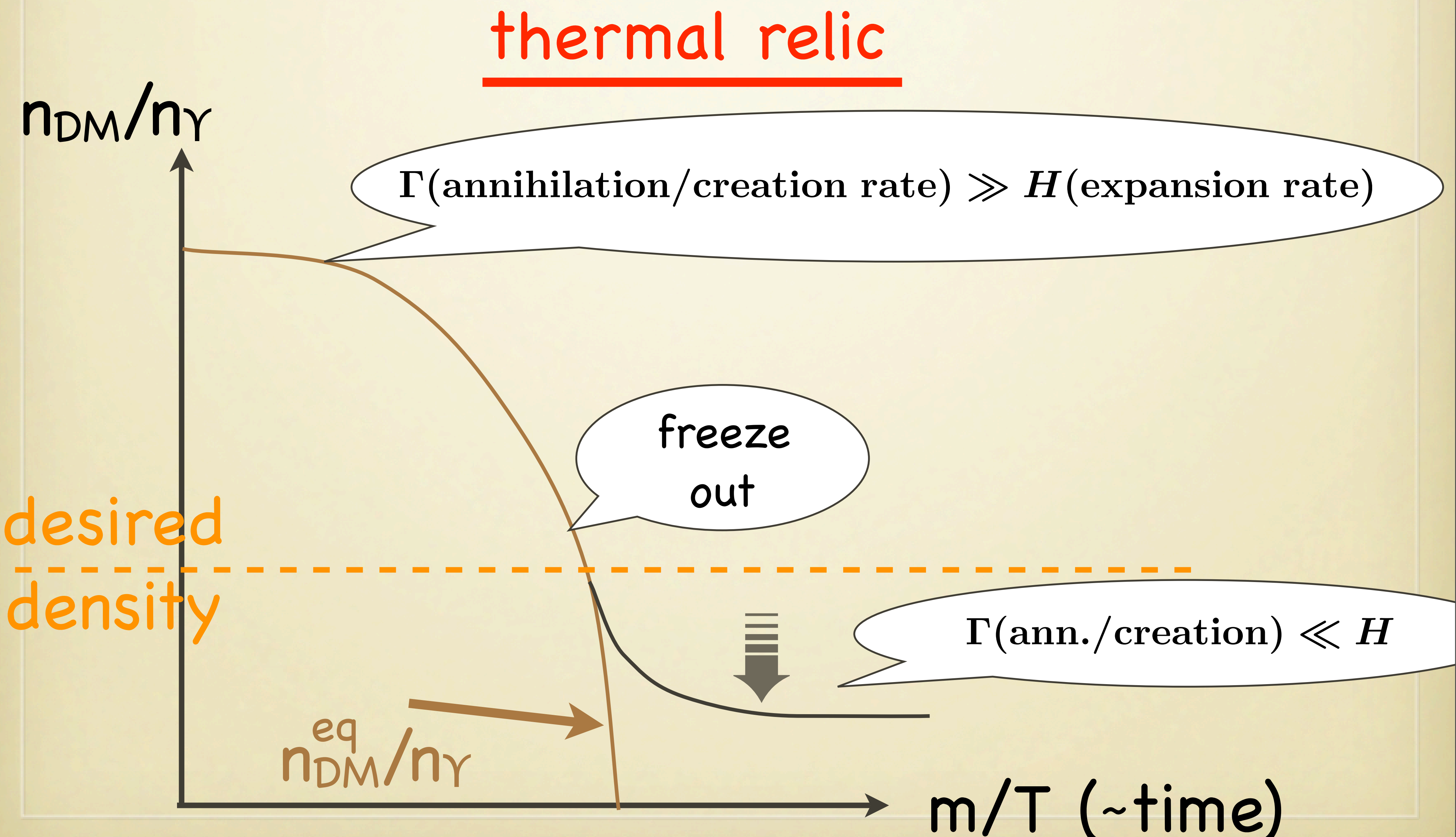

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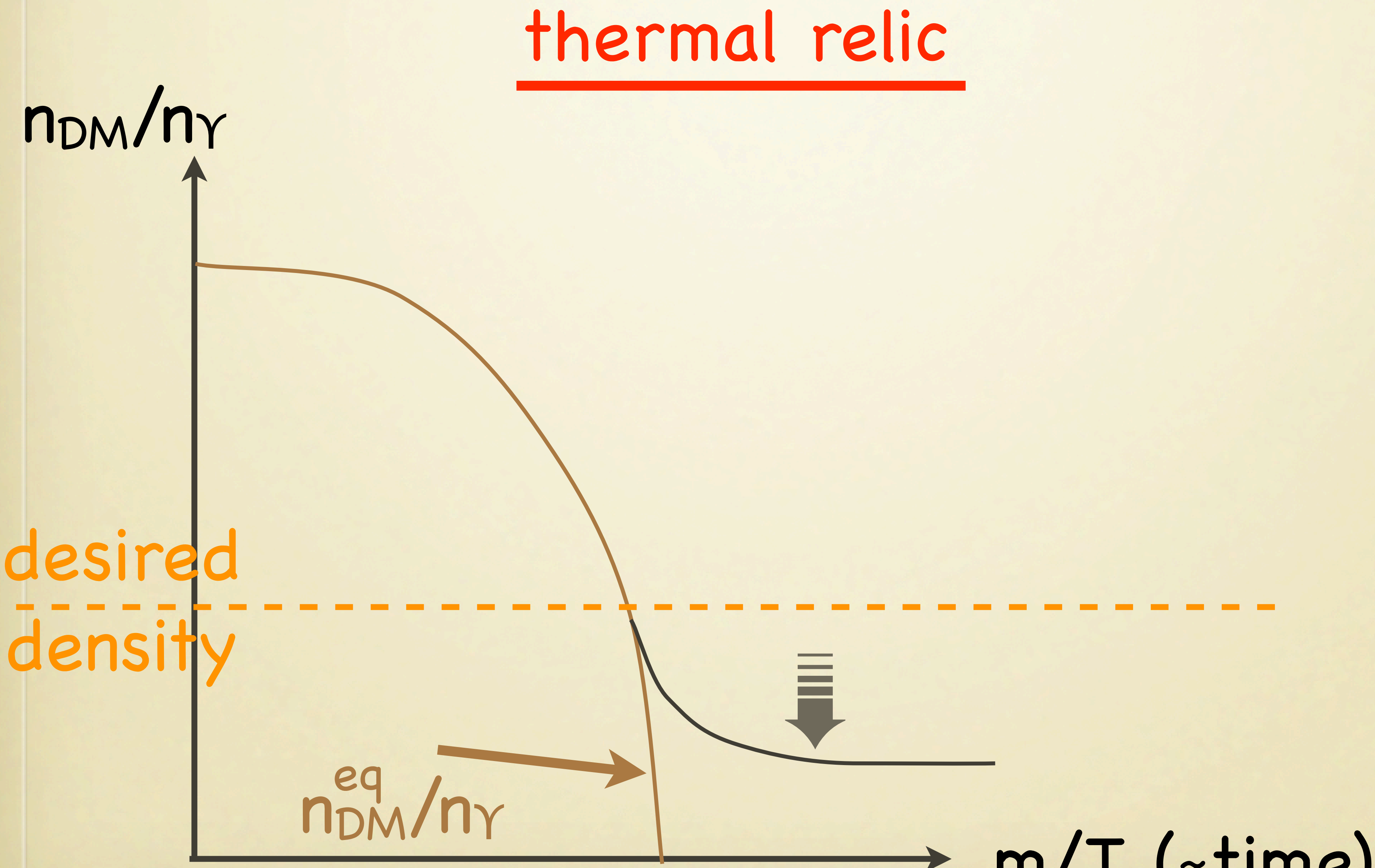

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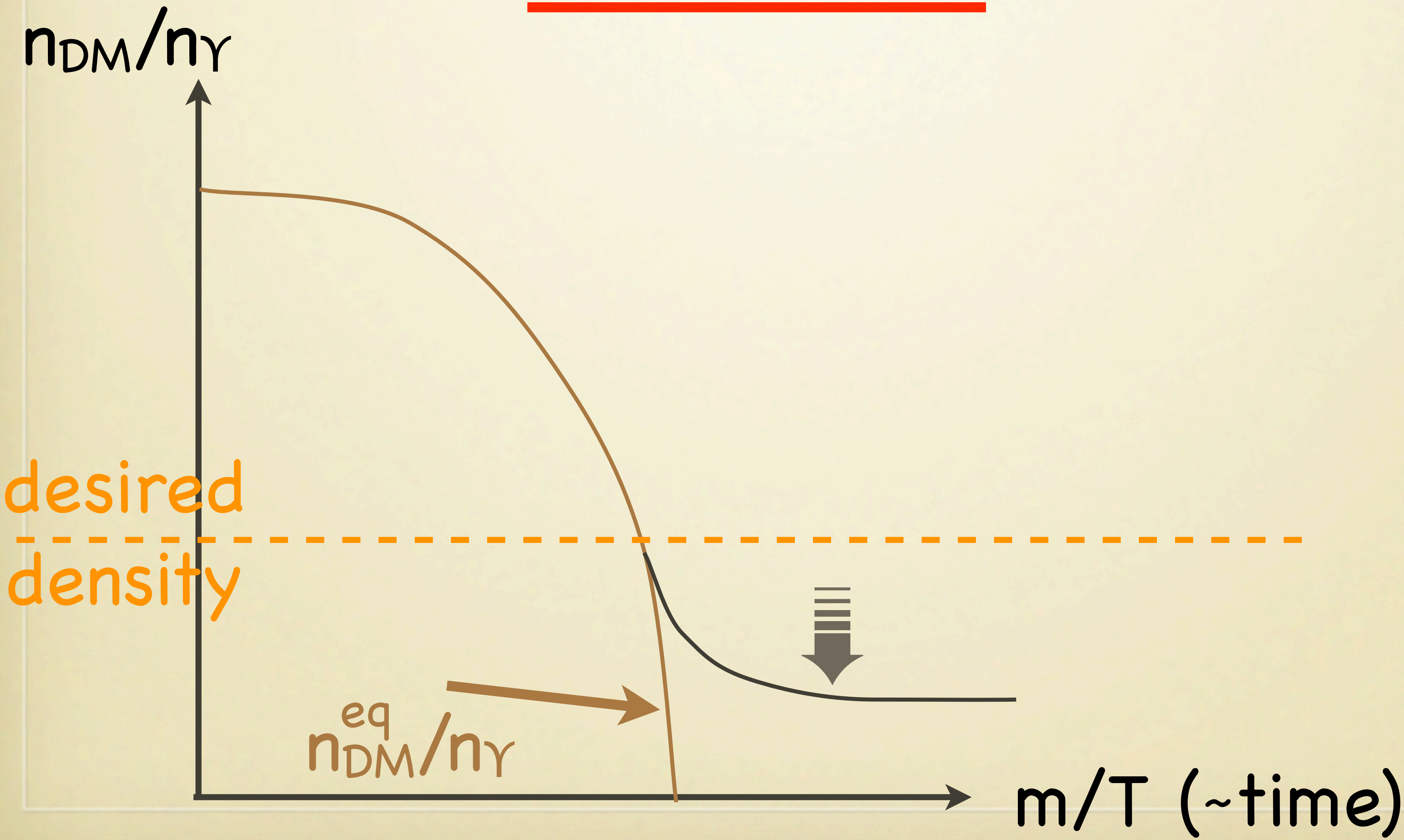

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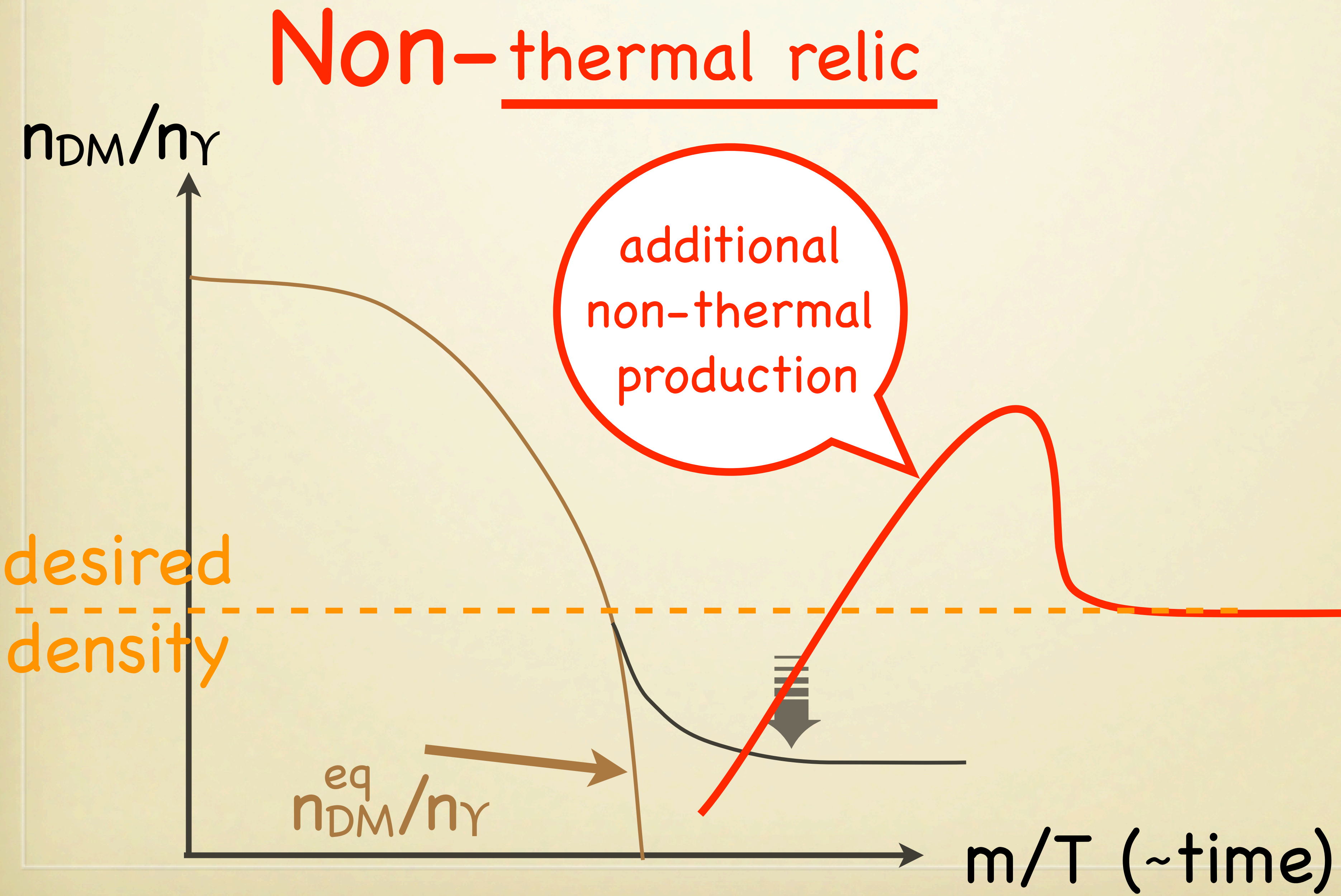

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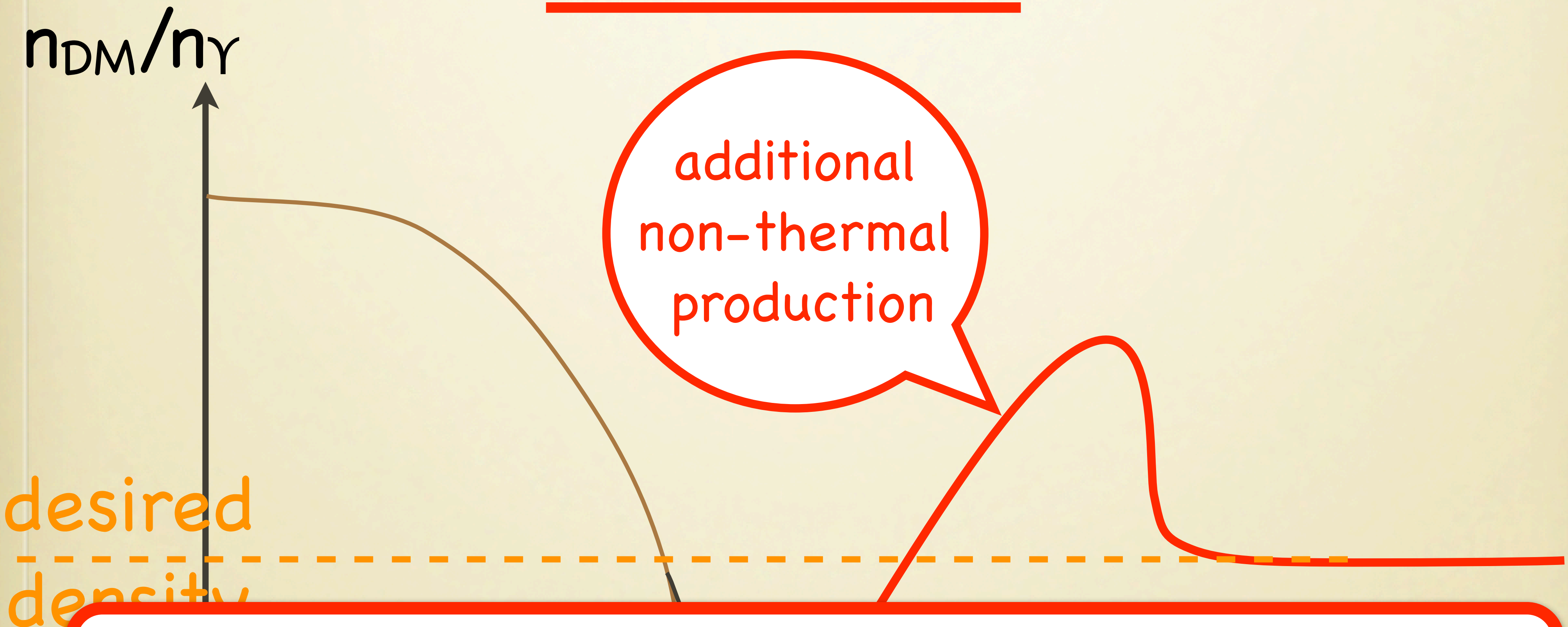


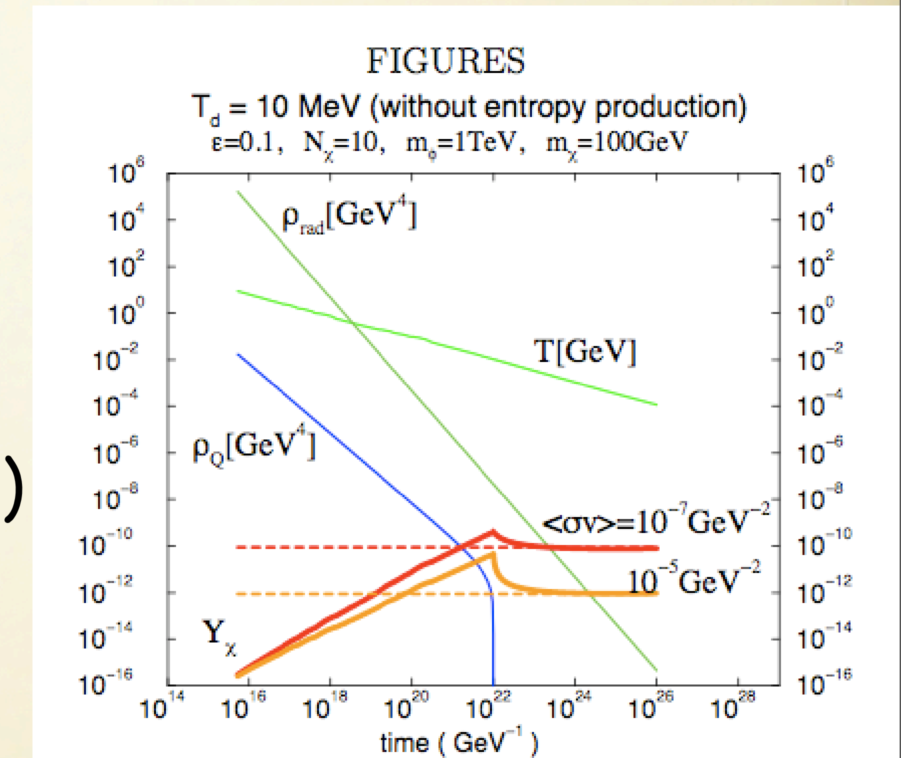
$$\Omega_{\rm DM}^{\rm non-thermal} \sim 0.2 \left(\frac{100 \text{ pb}}{\langle \sigma_{\rm ann.} v\rangle}\right) \left(\frac{m_\chi}{100 \text{ GeV}}\right) \left(\frac{0.1 \text{ GeV}}{T_{\rm non\ thermal}}\right)$$

Non-thermal WIMP Dark Matter

an example (... my favorite)

Affleck-Dine baryogenesis
(= a natural baryogenesis in SUSY)

☛ Q-ball production
(generic consequence)



Fujii, Hamaguchi, '01 and '02

☛ Q-ball decay at late time
(= non-thermal production of neutralinos!)

(cf. moduli decay; Moroi Randall,'99)

Non-thermal WIMP Dark Matter

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Test it via collider measurement !!

Especially $\sigma_{\rm ann} \gg 1\ \rm pb$ would confirm the non-thermal Dark Matter !

$$\Gamma_{\rm direct\ detection} \propto n_\chi \cdot \sigma^{\rm elastic}_{\chi N}$$

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- gravitino DM
  (+ long-lived charged particle) (☛ BBN signature?)

thermal history

time	temperature	
??	~ 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

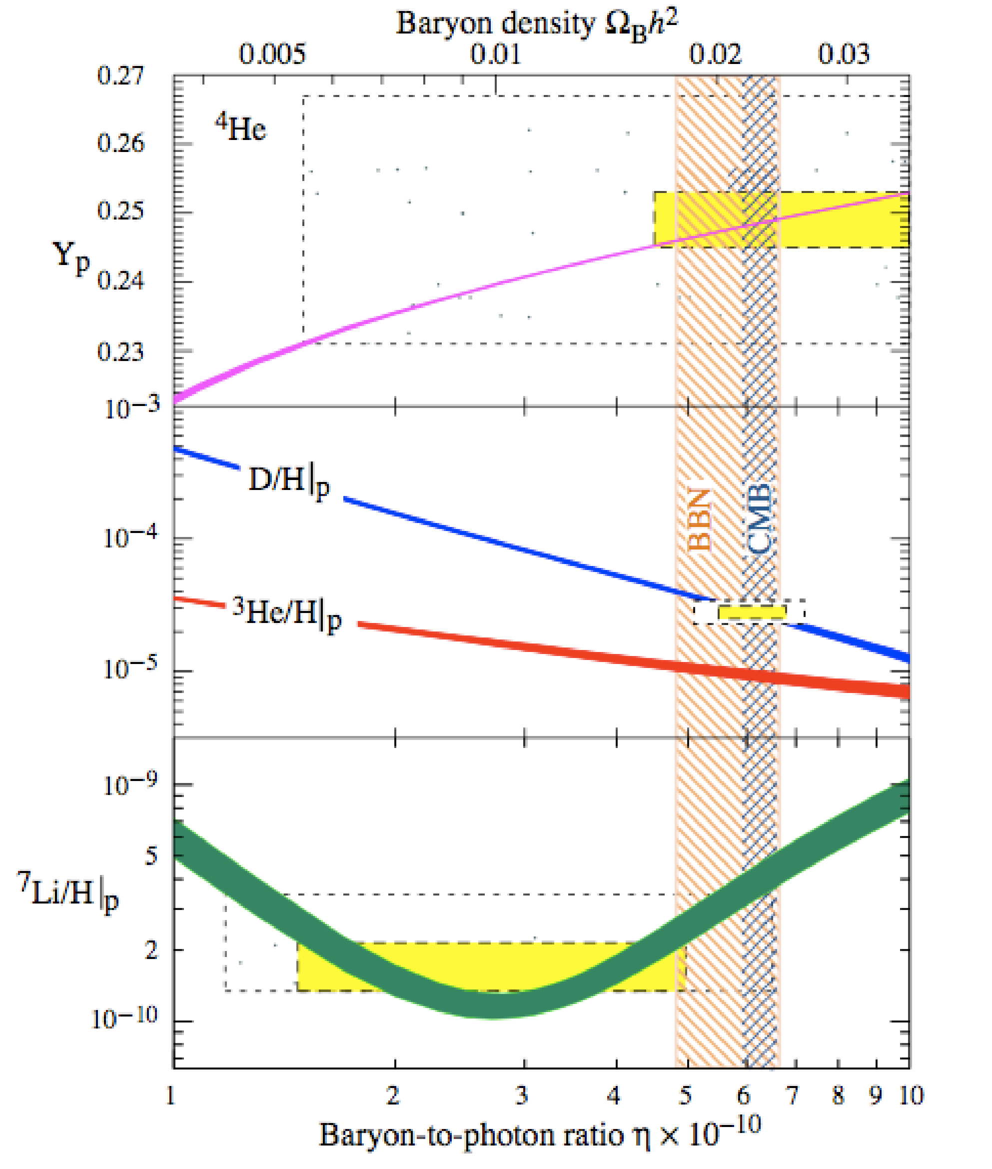

Fig. from Review of Particle Physics

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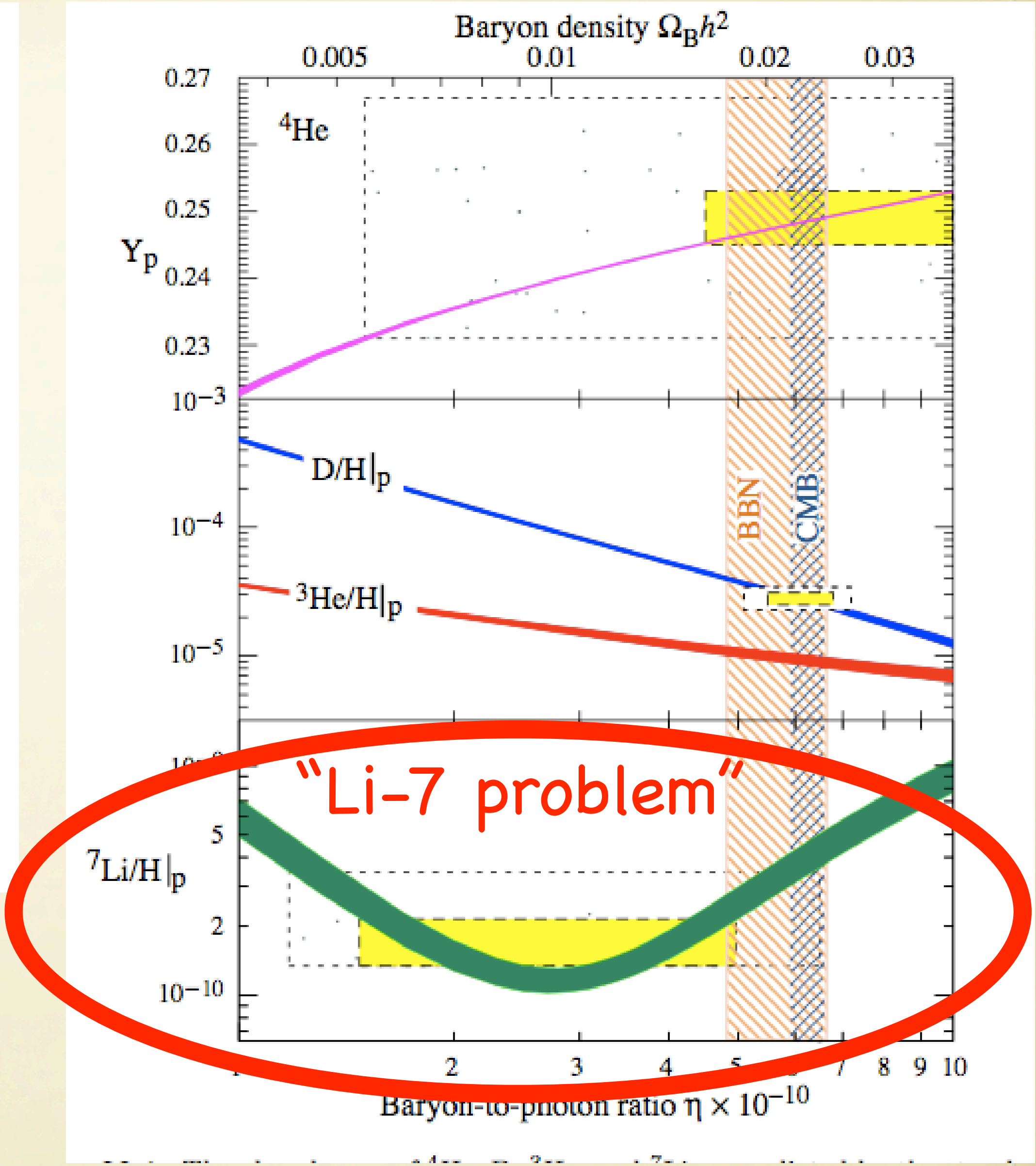
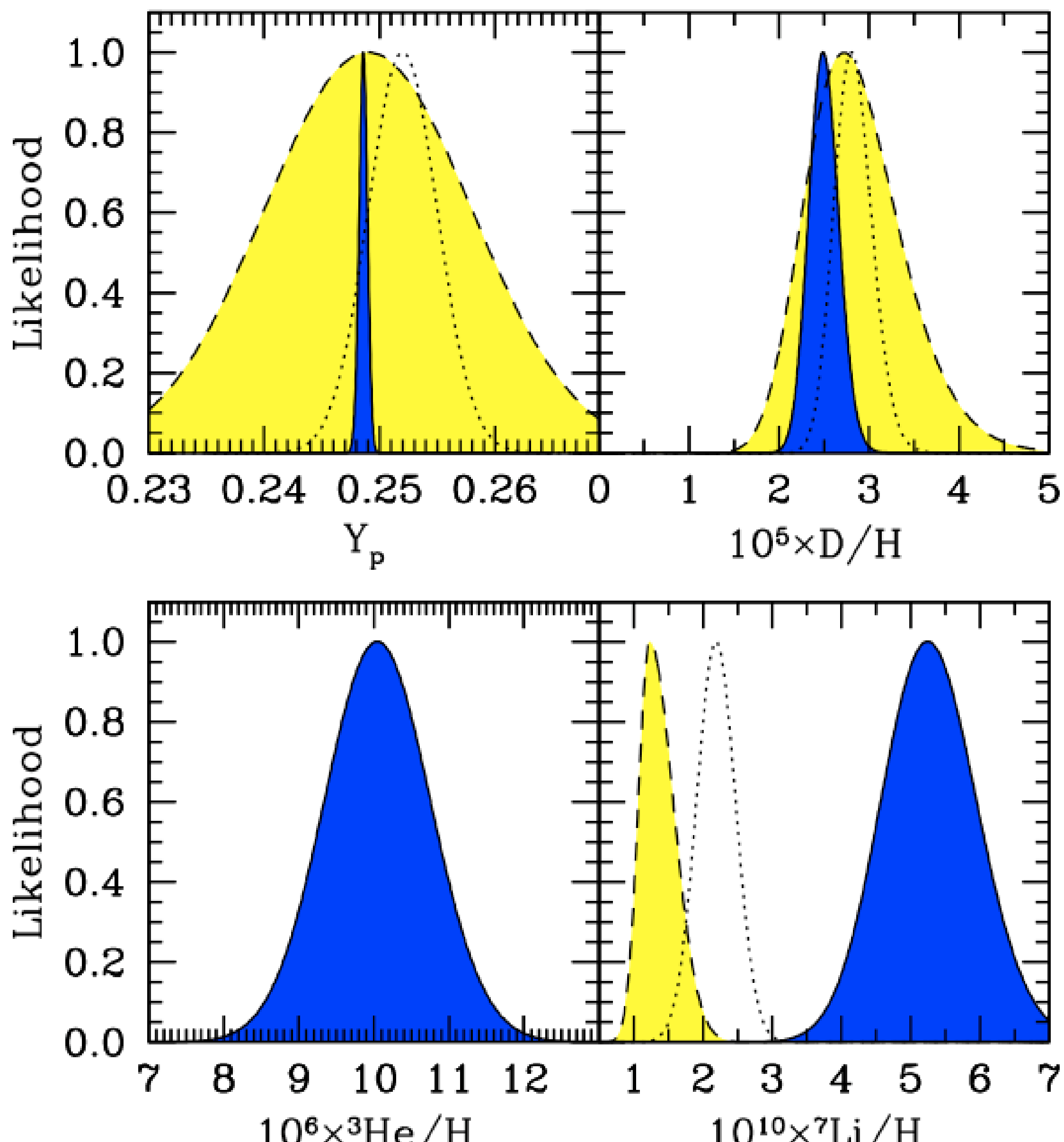
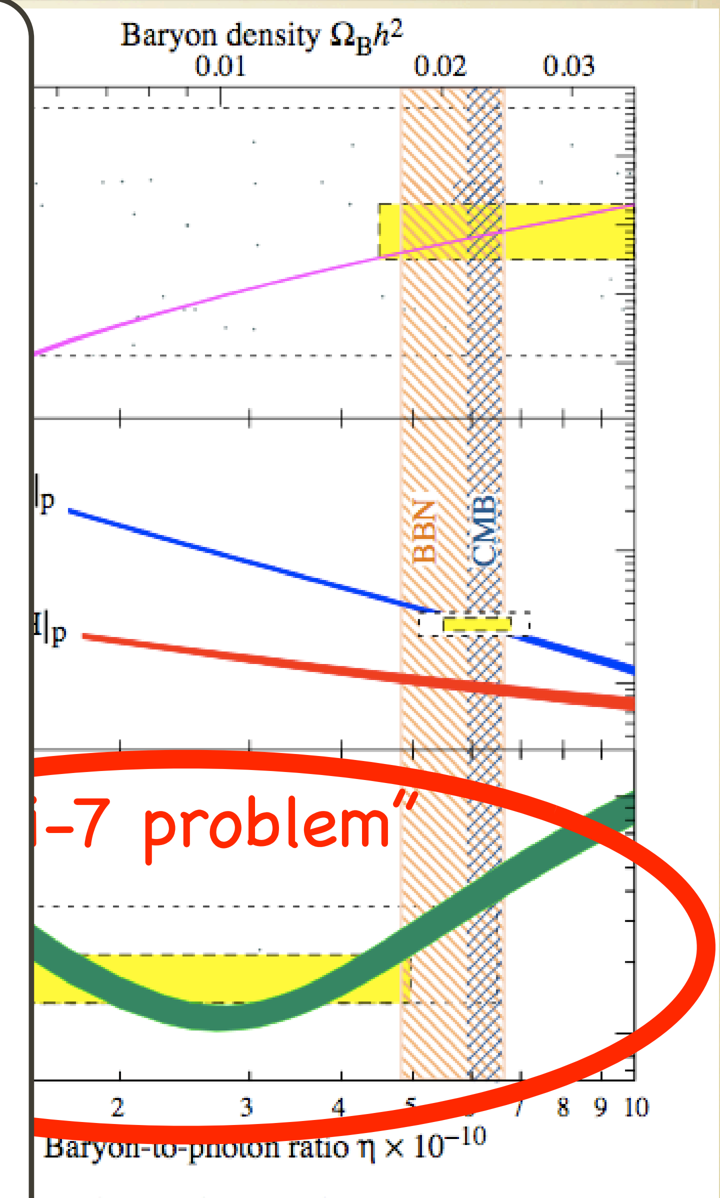


Fig. from Review of Particle Physics

recently, reanalyzed by Cyburt, Fields, Olive, 0808.2818





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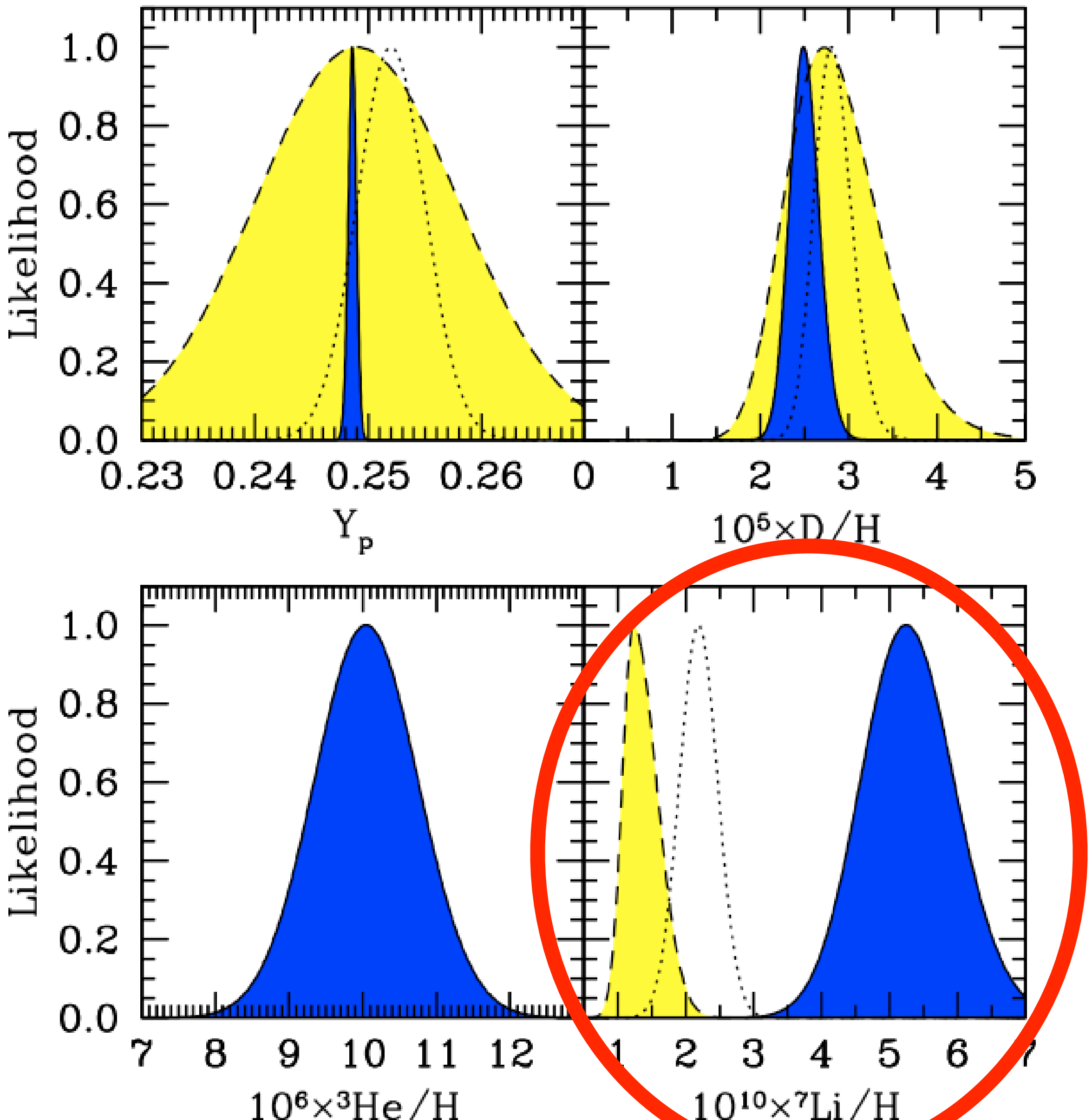

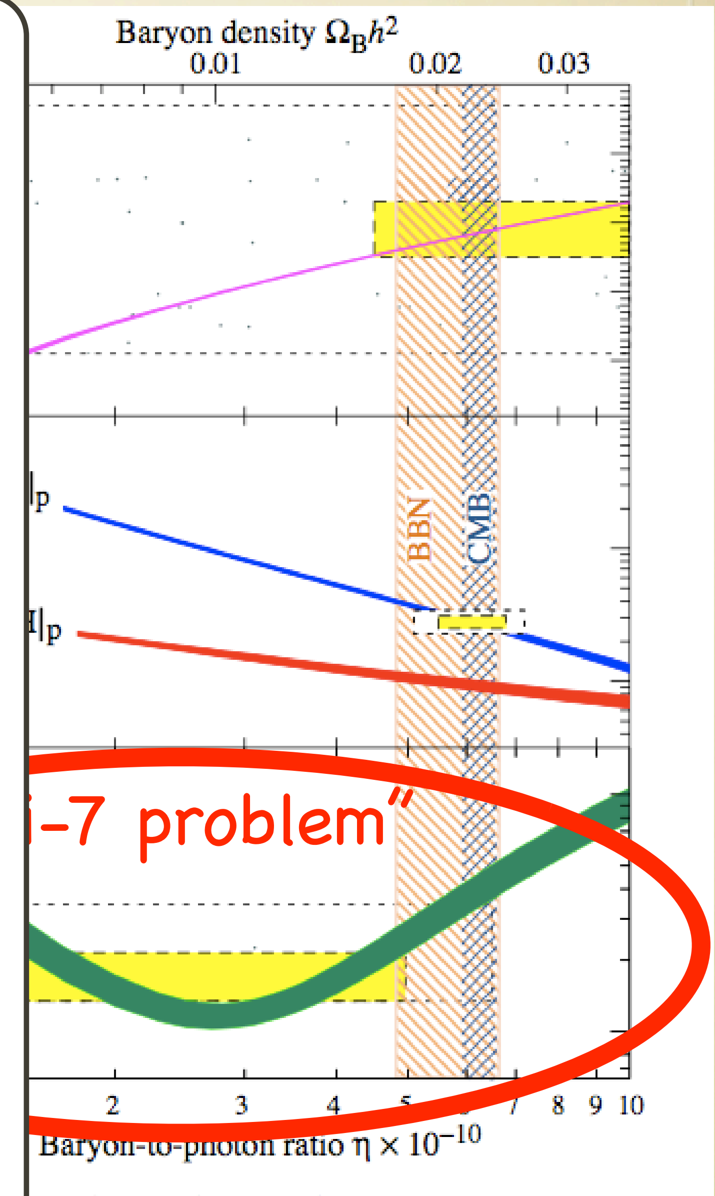

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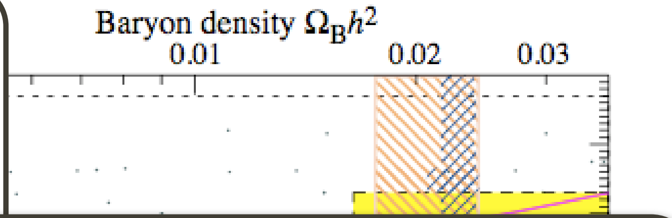

Abstract

The lithium problem arises from the significant discrepancy between the primordial ^{7}Li abundance as predicted by BBN theory and the WMAP baryon density, and the pre-Galactic lithium abundance inferred from observations of metal-poor (Population II) stars. This problem has loomed for the past decade, with a persistent discrepancy of a factor of $2-3$ in ^{7}Li/H. Recent developments have sharpened all aspects of the Li problem. Namely: (1) BBN theory predictions have sharpened due to new nuclear data, particularly the uncertainty on ^{3}He$(\alpha,\gamma)^7$Be, has reduced to 7.4%, and with a central value shift of $\sim +0.04$ keV barn. (2) The WMAP 5-year data now yields a cosmic baryon density with an uncertainty reduced to 2.7%. (3) Observations of metal-poor stars have tested for systematic effects, and have reaped new lithium isotopic data. With these, we now find that the BBN+WMAP predicts $^7\text{Li/H} = (5.24^{+0.71}_{-0.67}) \times 10^{-10}$. The Li problem remains and indeed is exacerbated; the discrepancy is now a factor $2.4-4.3$ or 4.2σ (from globular cluster stars) to 5.3σ (from halo field stars). Possible resolutions to the lithium problem are briefly reviewed, and key nuclear, particle, and astronomical measurements highlighted.

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

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decay effect:
(destroy Li-7)
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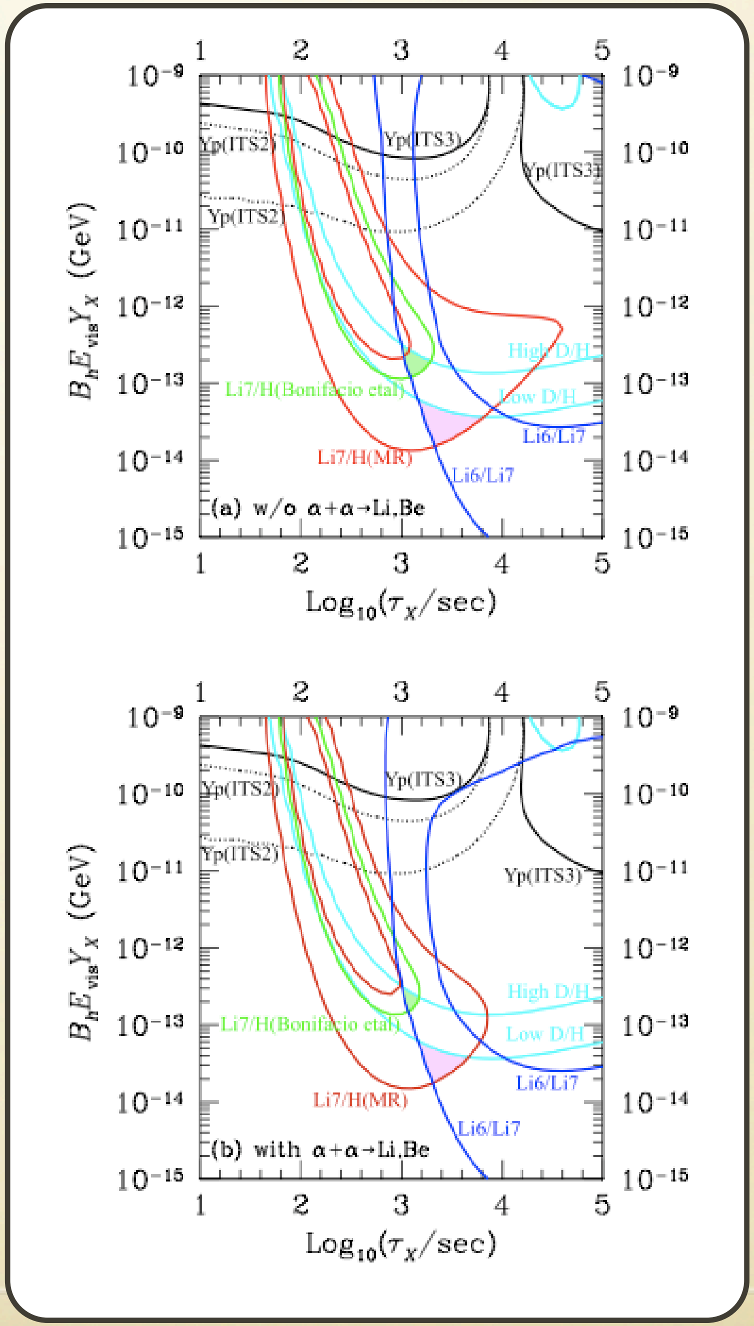
Jedmzik,'04;
+ (many others)
+ Cumberbatch, Ichikawa, Kawasaki, Kohri, Silk, Starkman,'07 →



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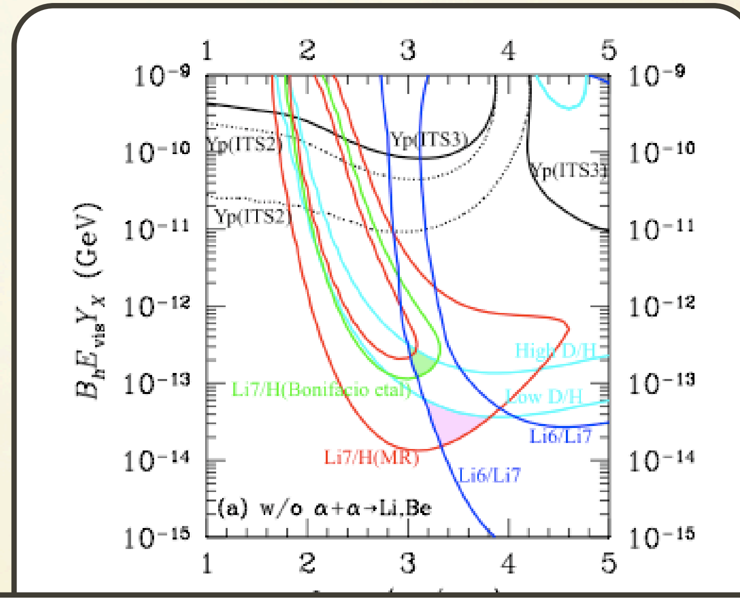

catalysis effect:
$(^7Be\ X^-)+p \rightarrow (^8B\ X^-)+\gamma$
Pospelov,'06;
+ Bird, Koopmans, Pospelov,'07
+ Kusakabe, Kajino, Boyd, Yoshida, Mathews,'07,
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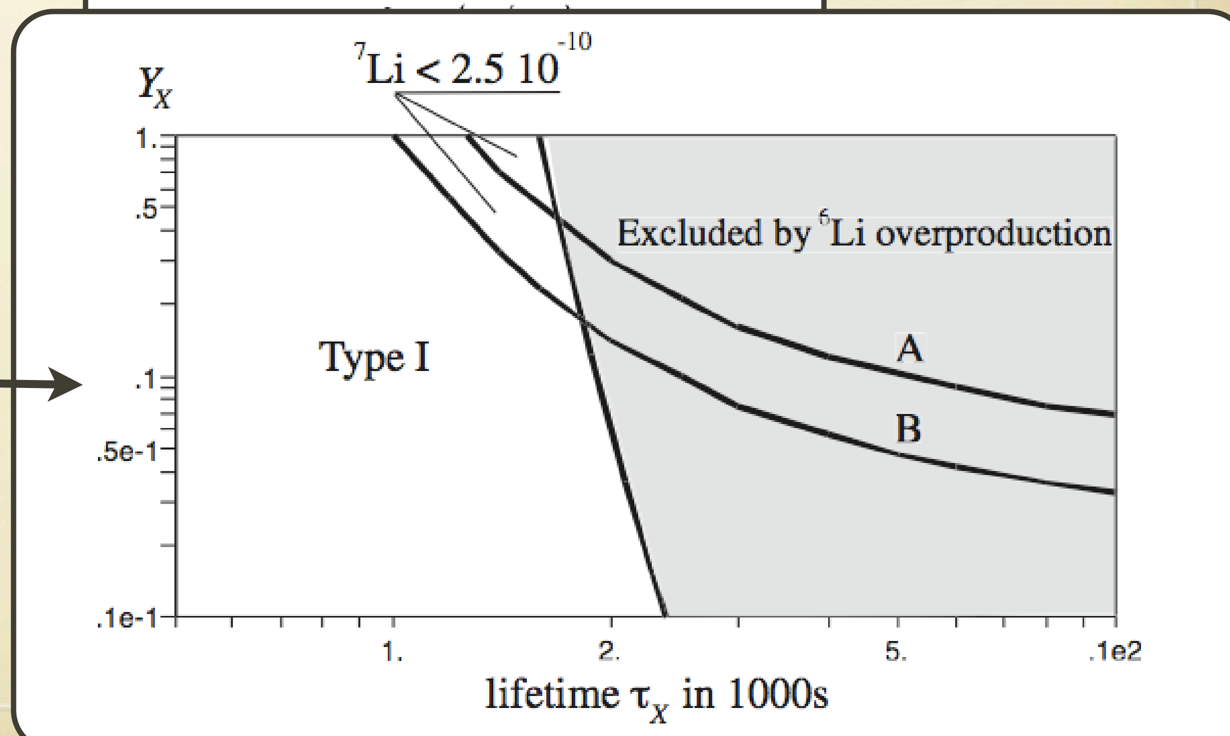

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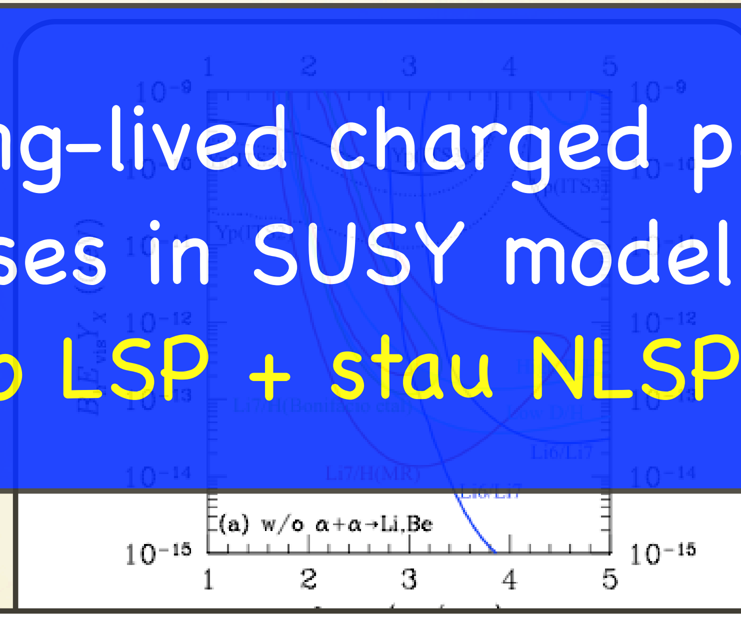

☛ Such a long-lived charged particle naturally arises in SUSY models with gravitino LSP + stau NLSP!!

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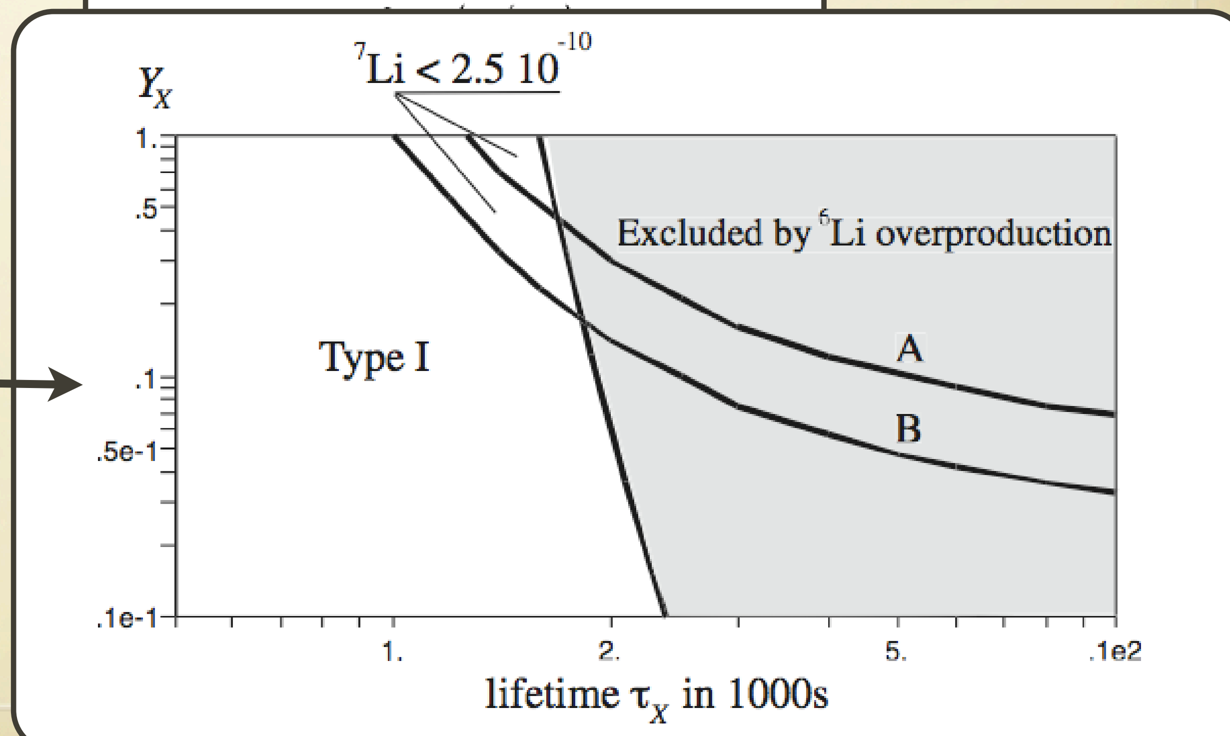

- What is Gravitino?

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 $\tilde{h}$

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graviton e_μ^α

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Supergravity

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- Why Gravitino LSP ?

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- ..... among 29 SUSY particles?

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

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Dark Matter candidates in SUSY Standard Model

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neutral and color-singlet

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neutral and color-singlet

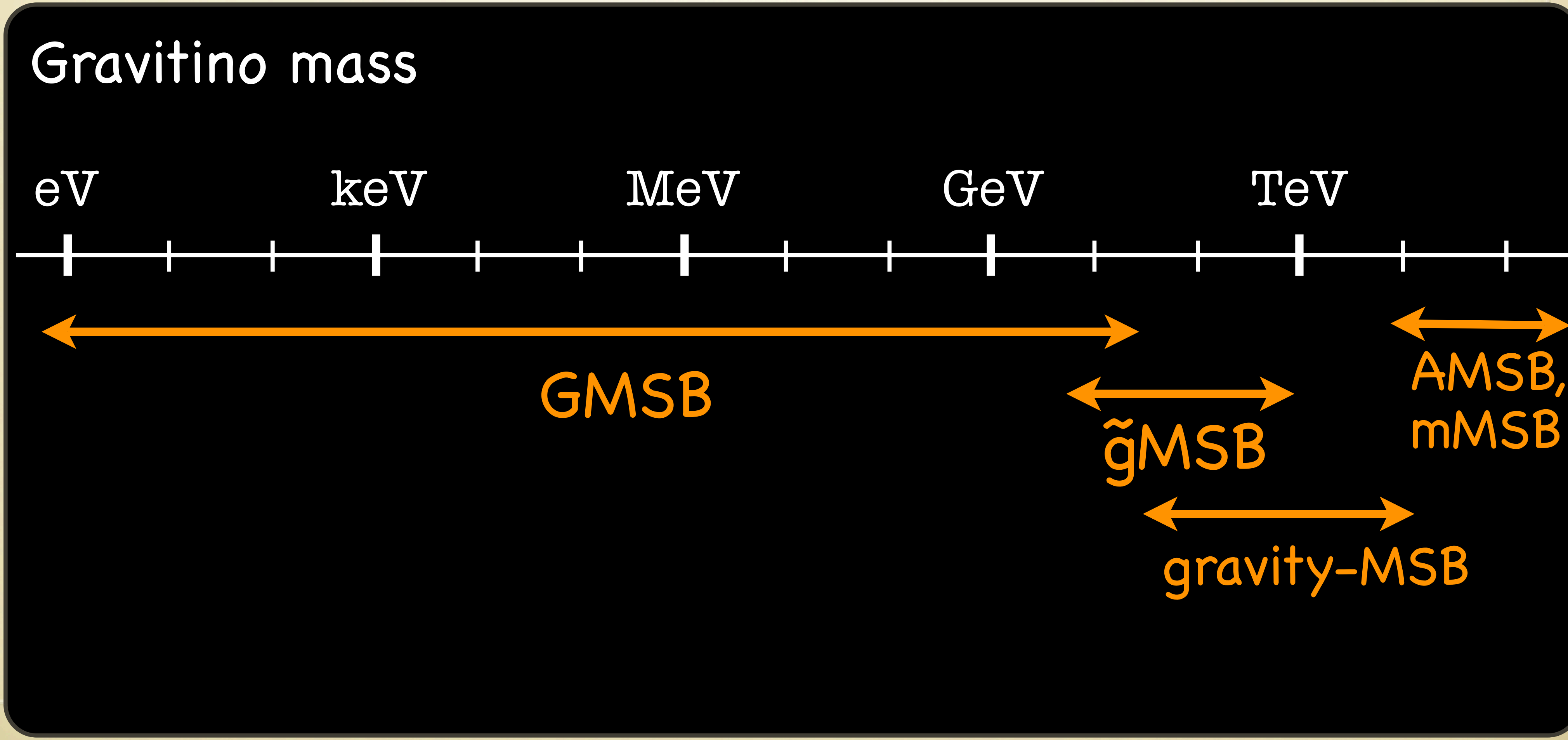
Only Neutralino and Gravitino are viable candidates!

- Why Gravitino LSP ?

experimental bound naturalness

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

- Gravitino mass..... model dependent.



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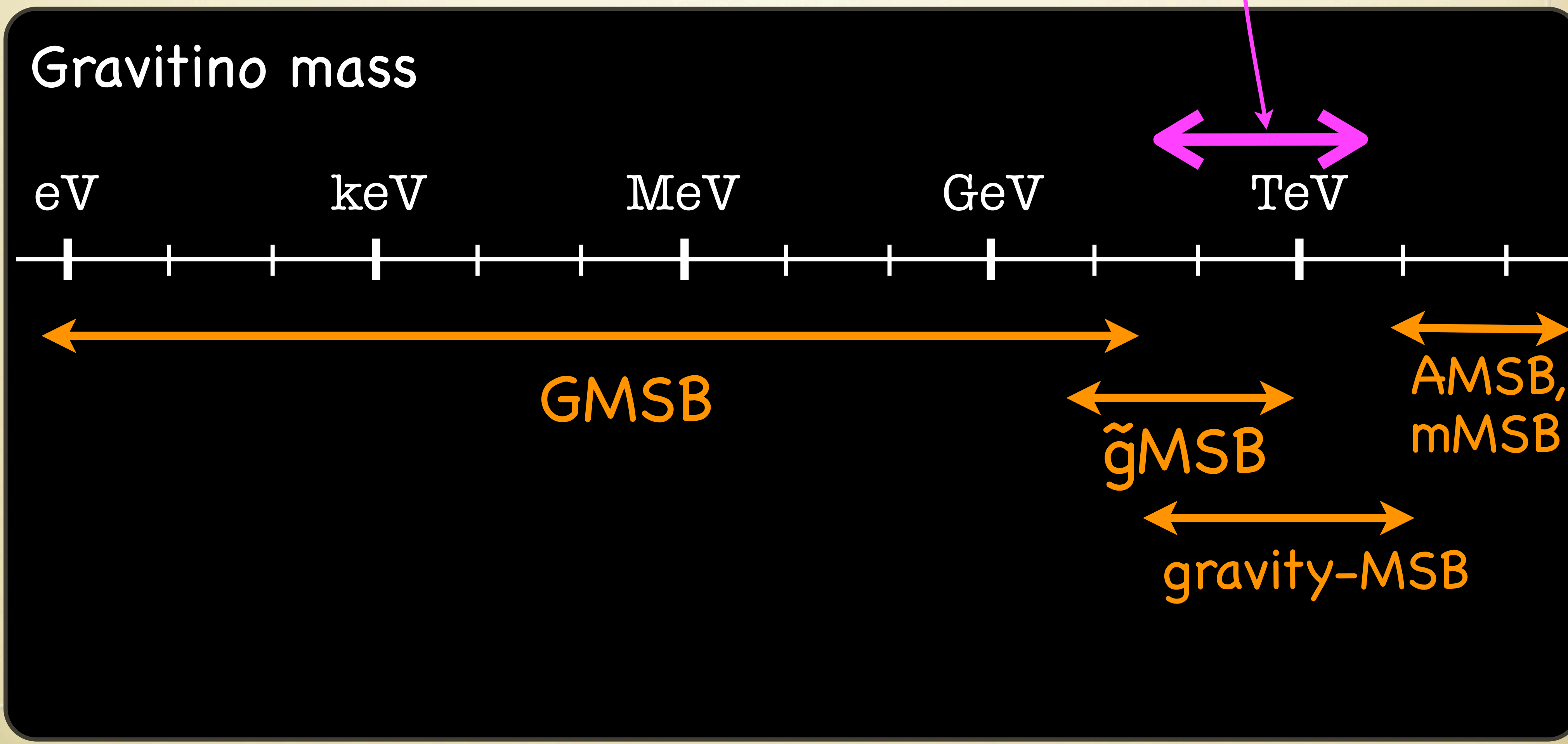

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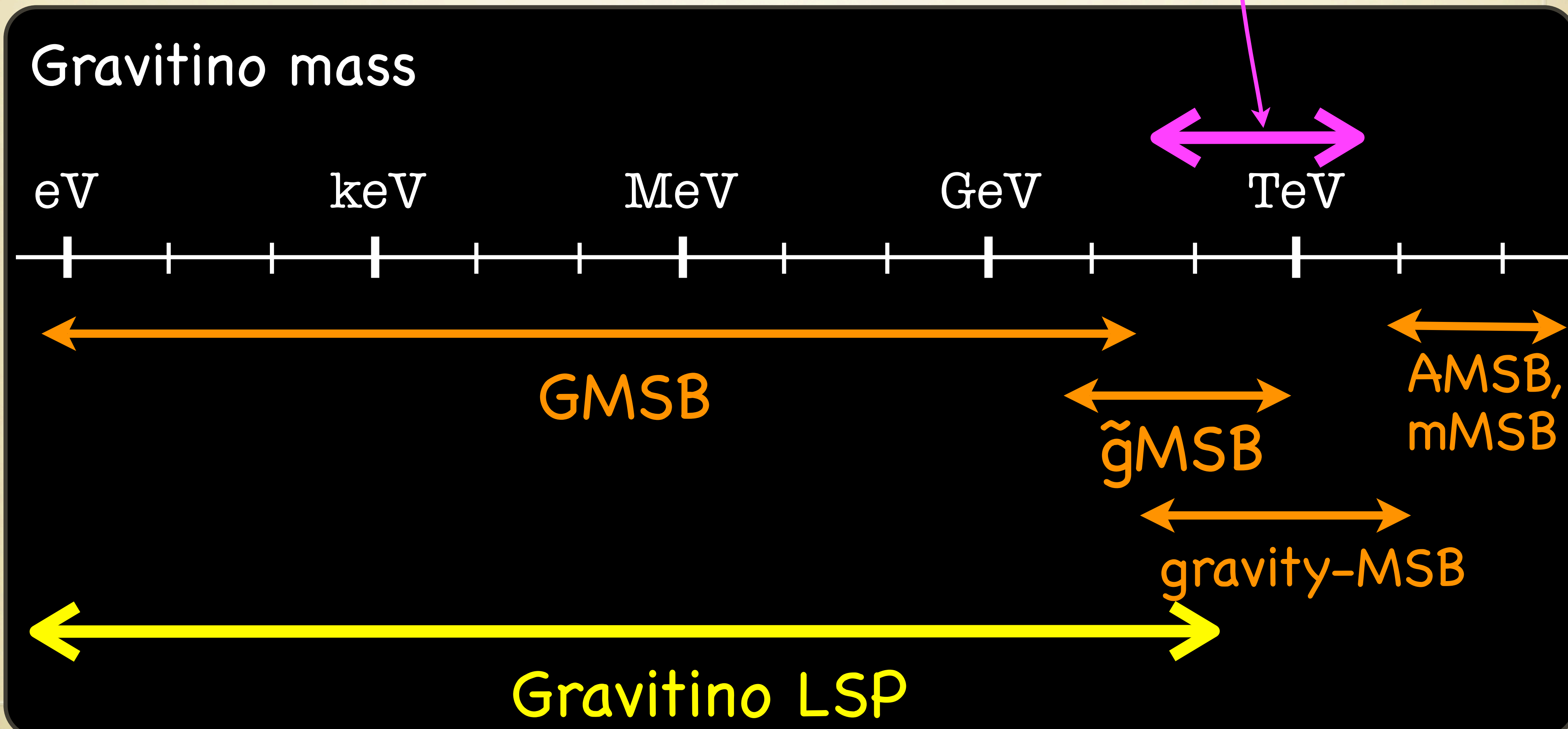

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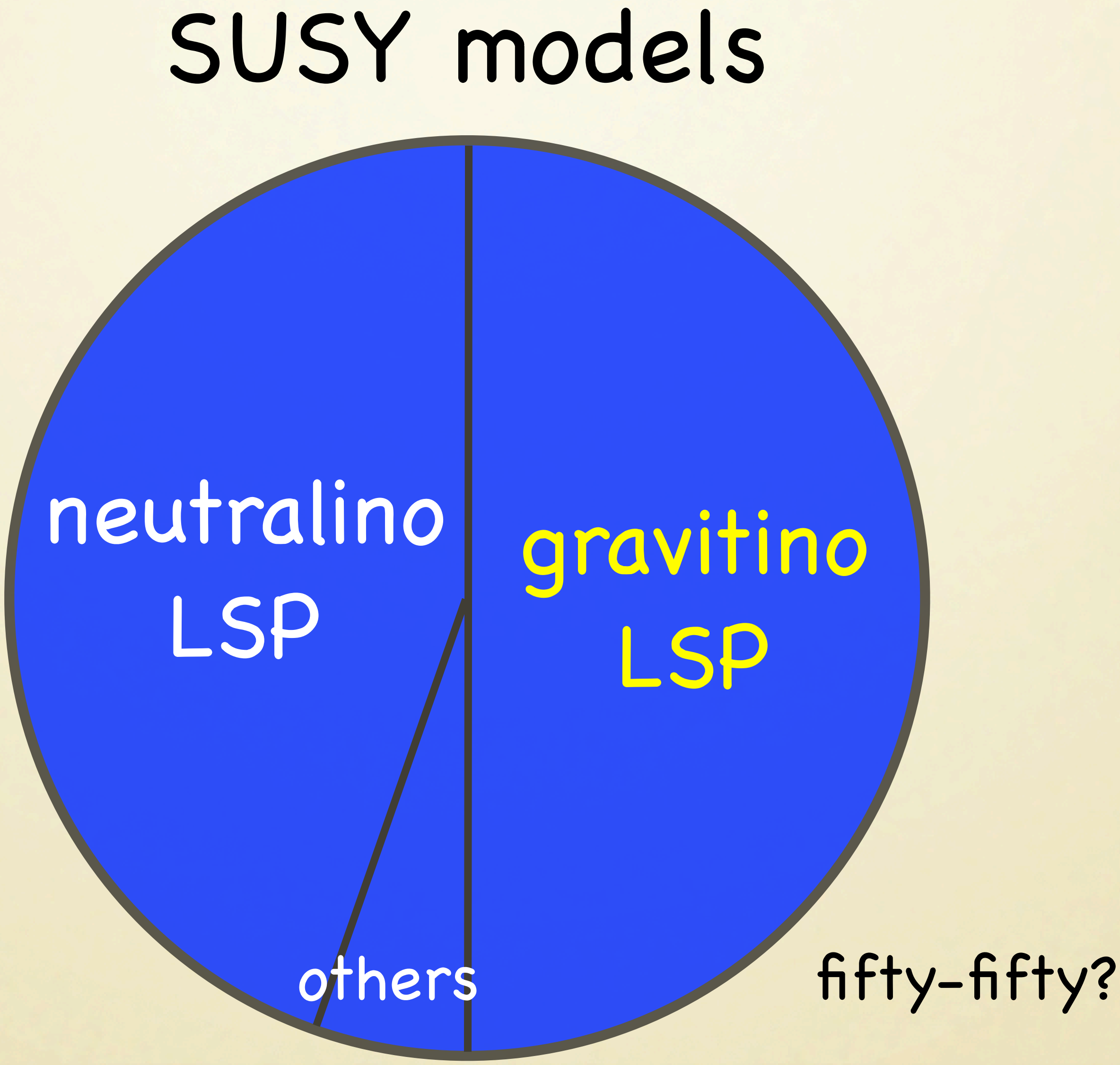
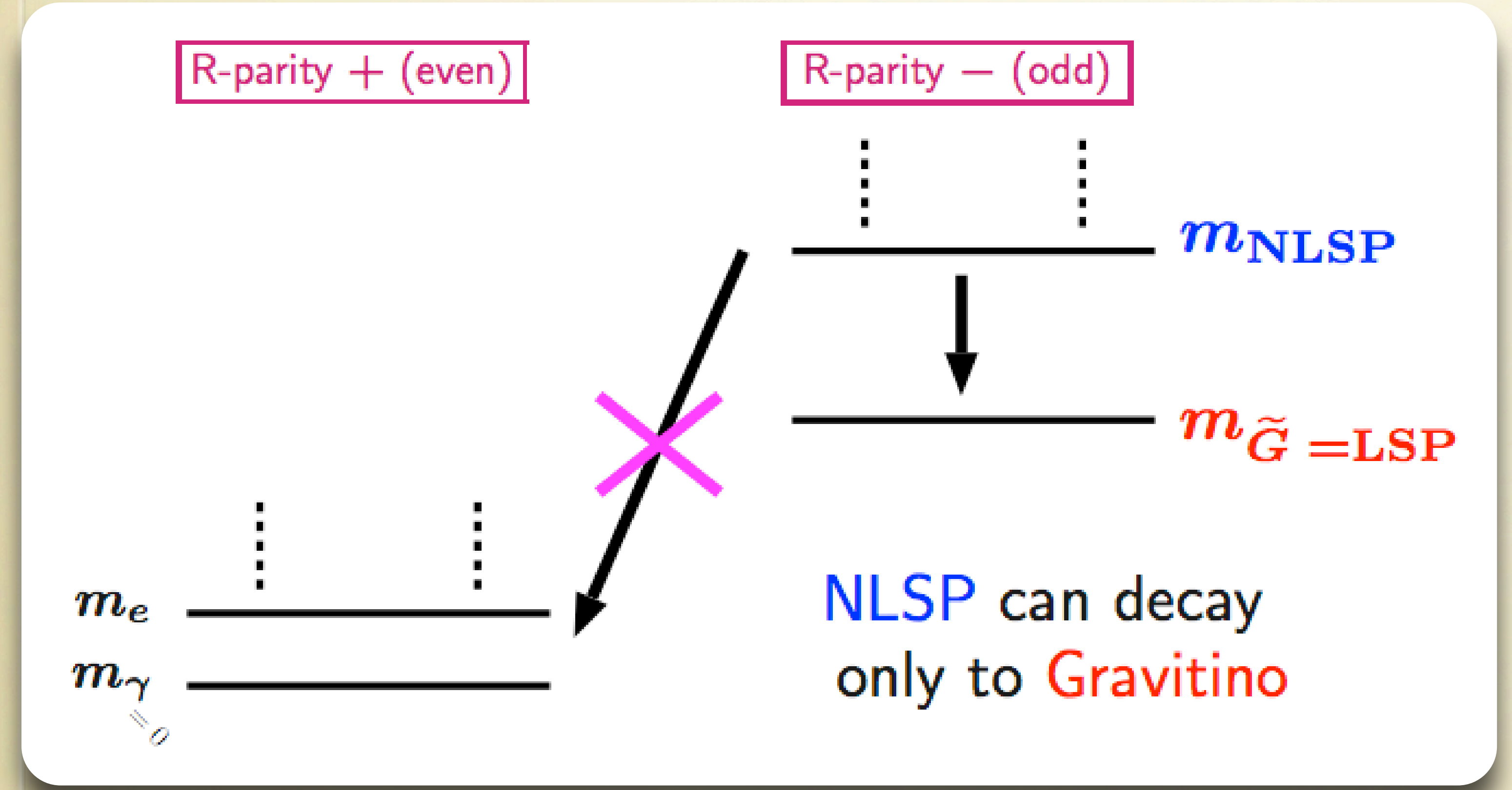


NLSP (Next-to-Lightest SUSY Particle)

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



extremely weak interaction

- Why Stau NLSP ?

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- ..... among 28 NLSP candidates?

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

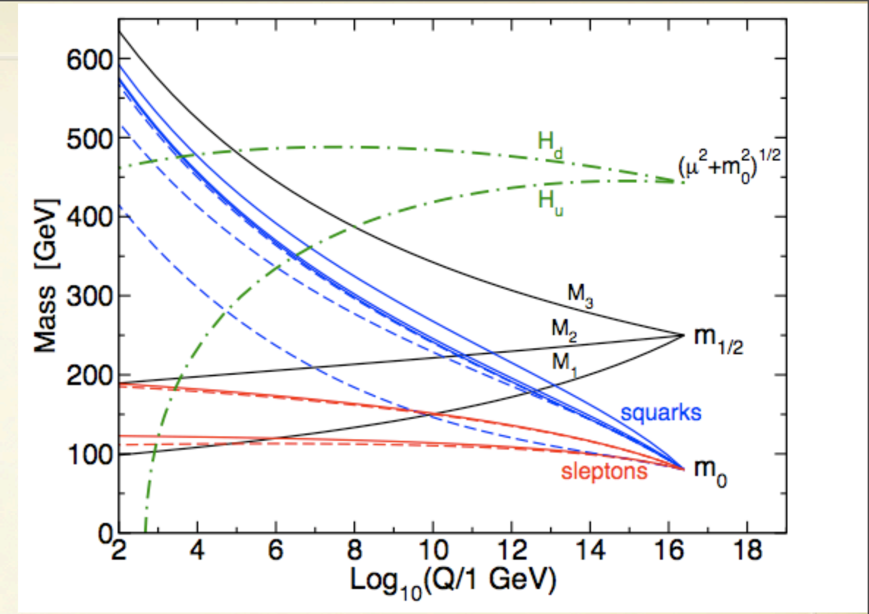
stau (i=3)

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

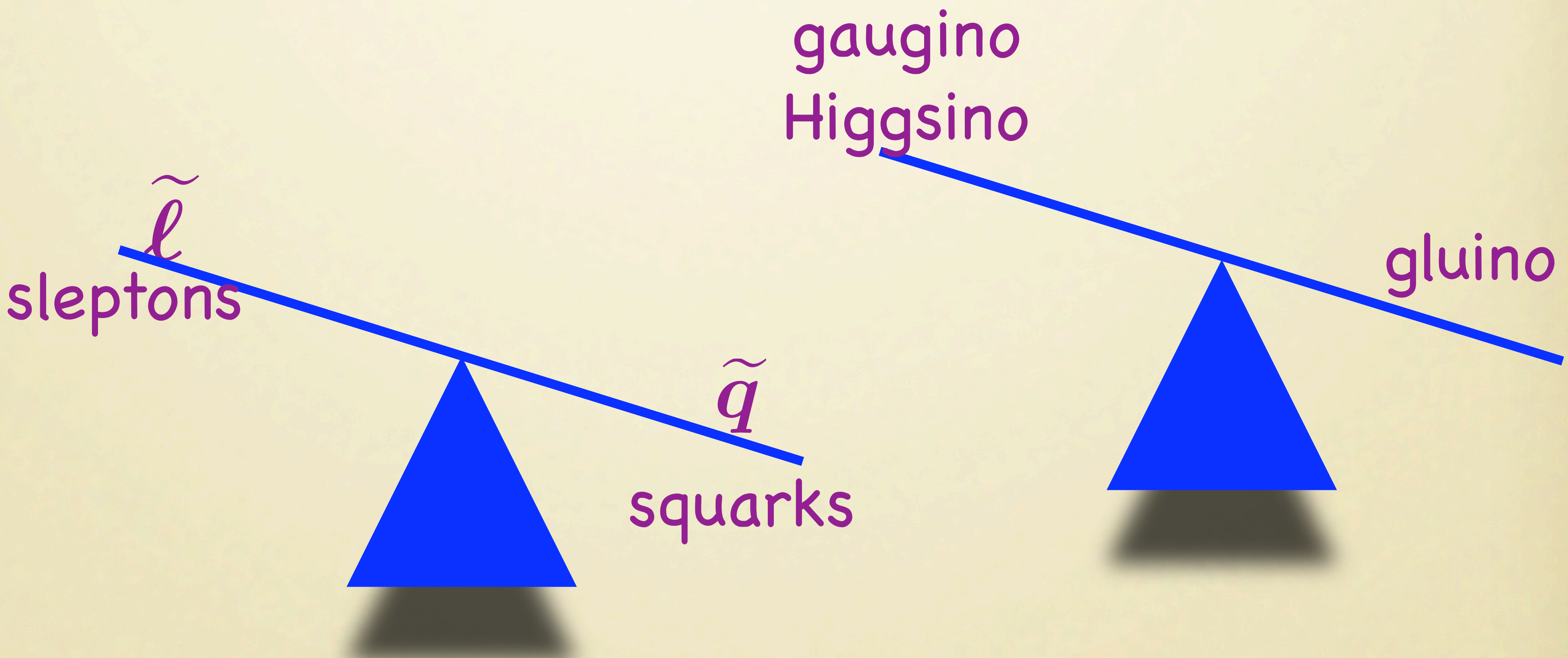
$$\text{gravitino}: \widetilde{G}$$

Why Stau NLSP ?

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



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



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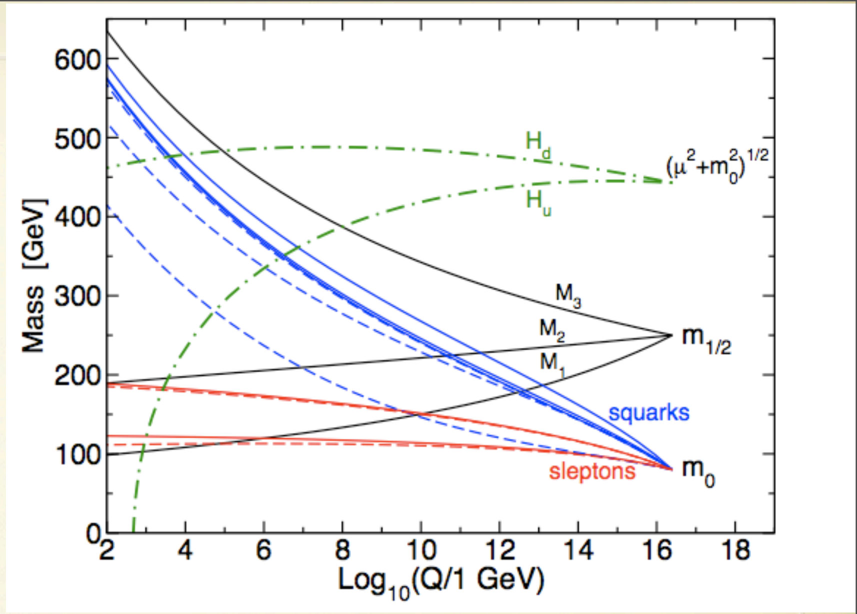

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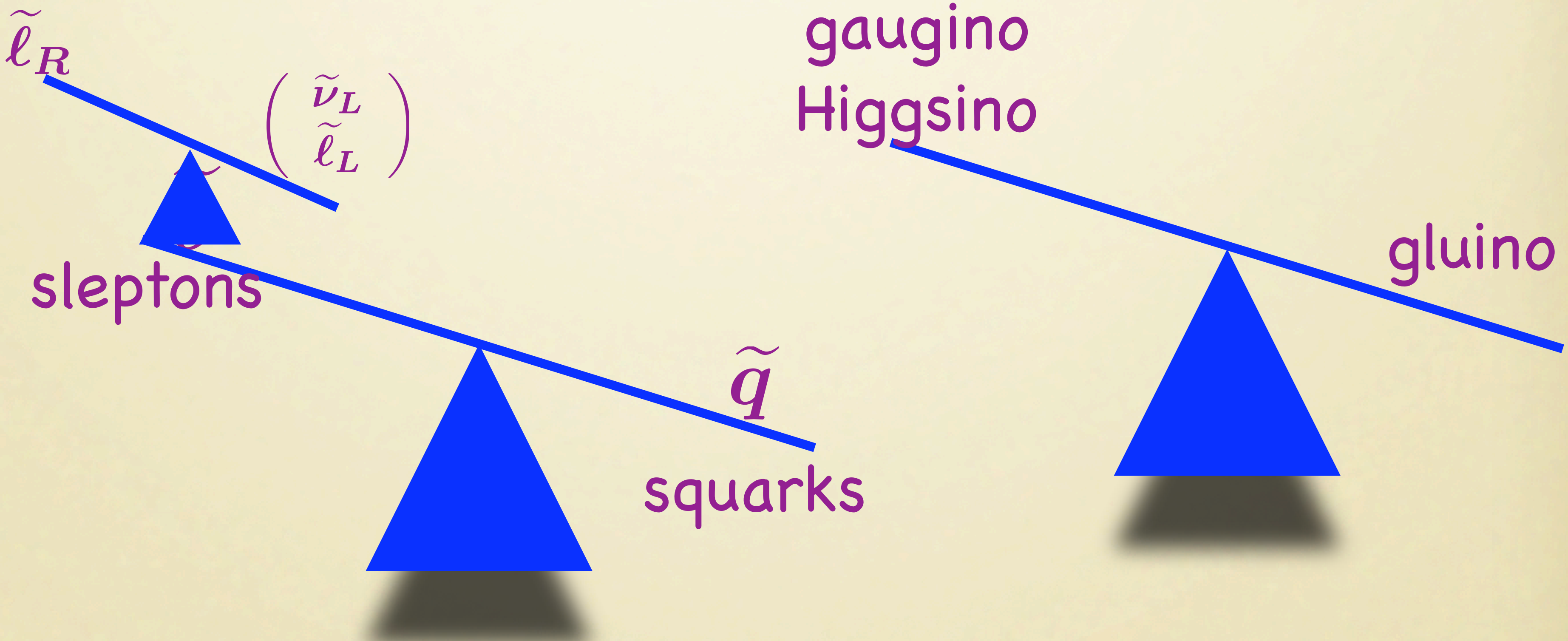
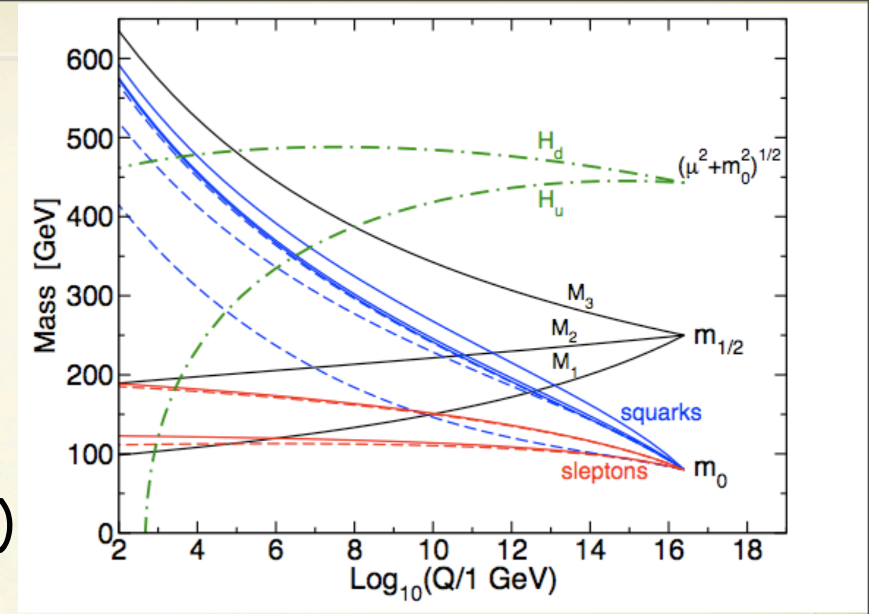


Why Stau NLSP ?

- 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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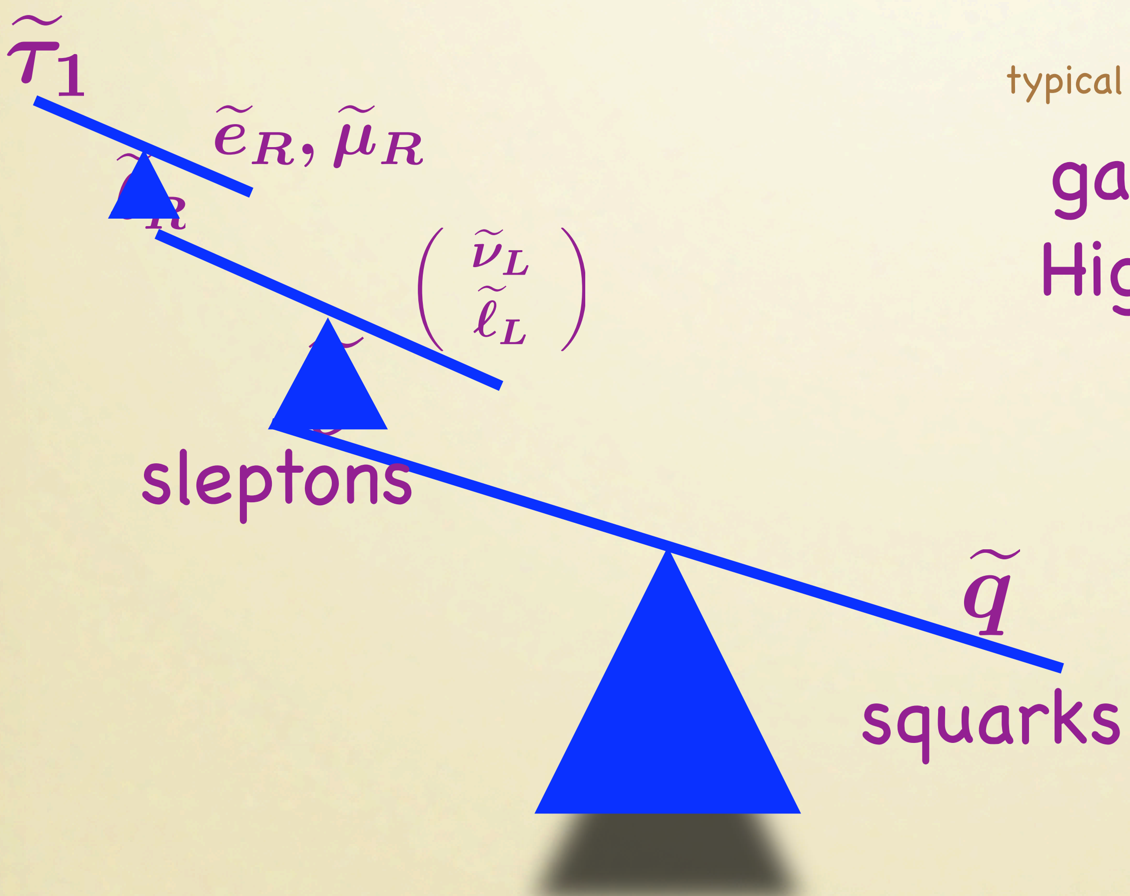

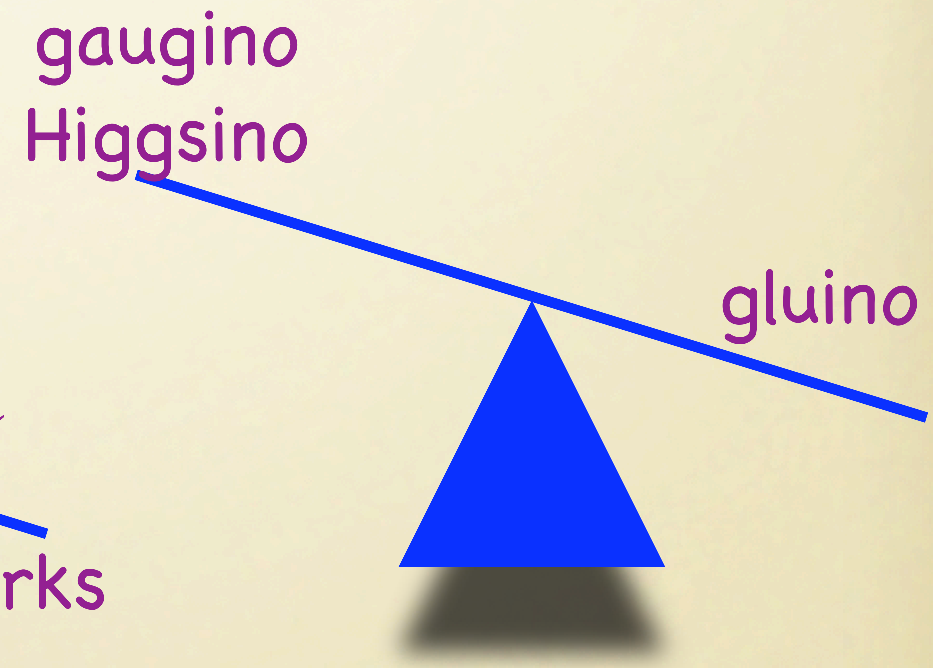

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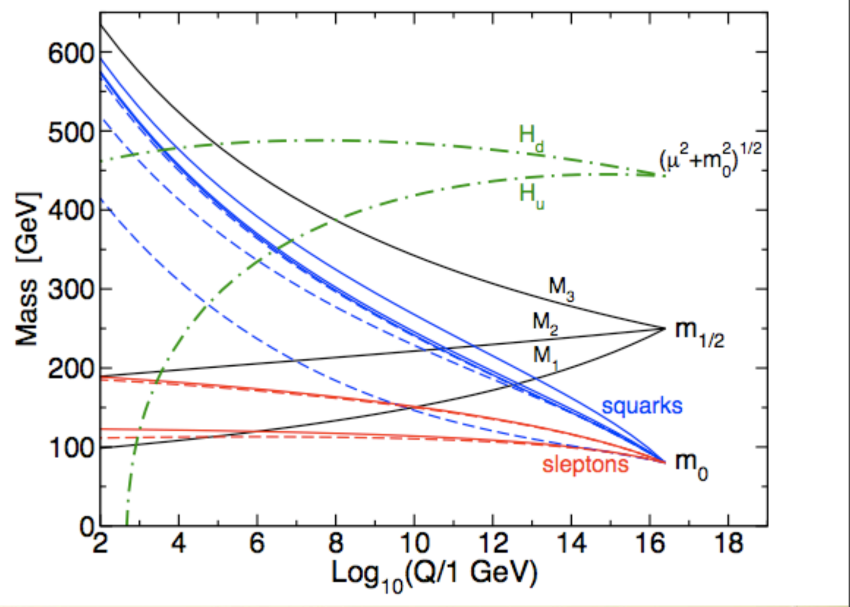

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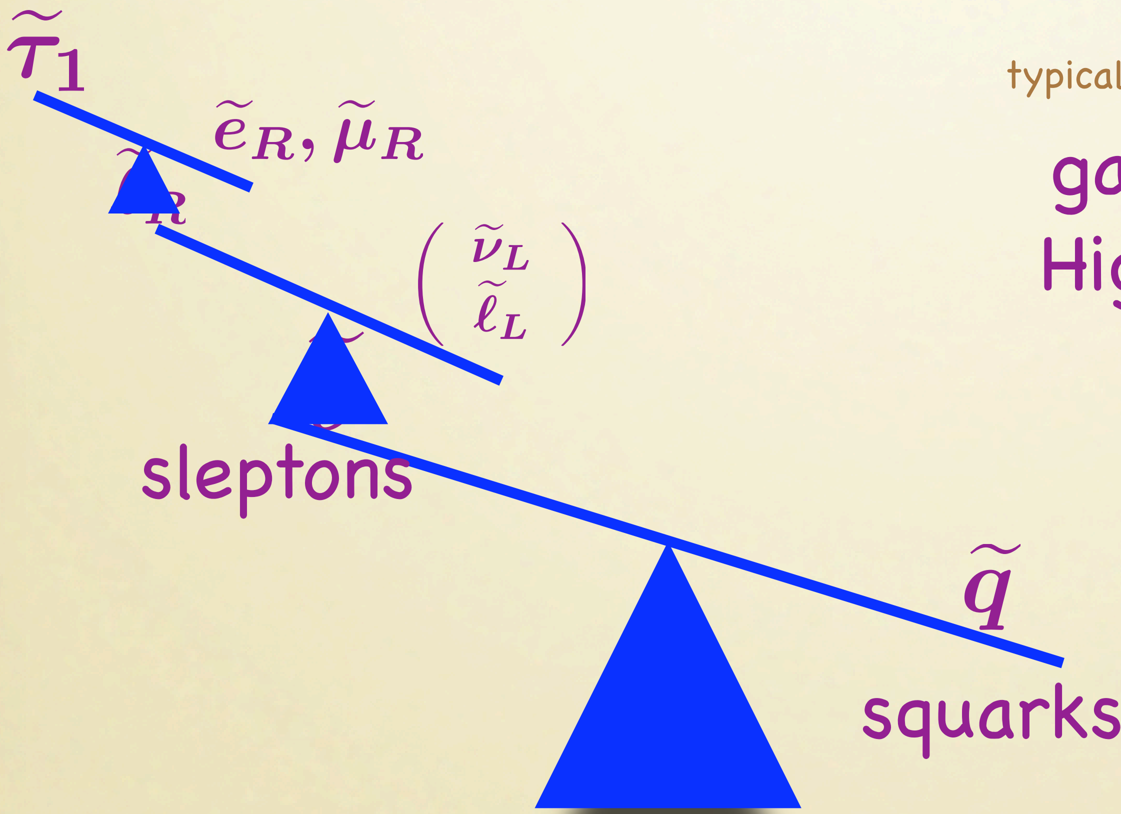
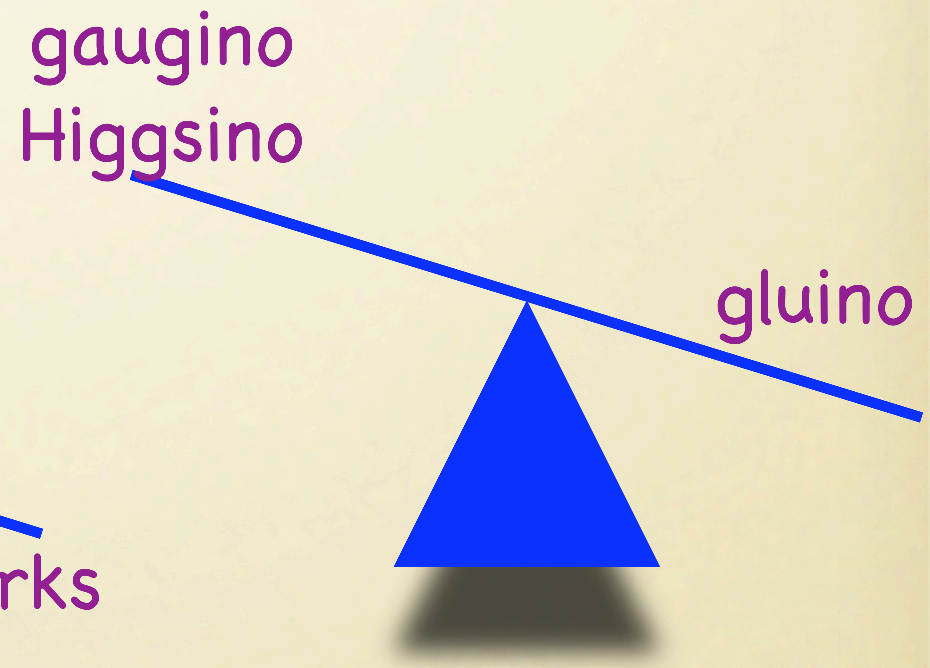
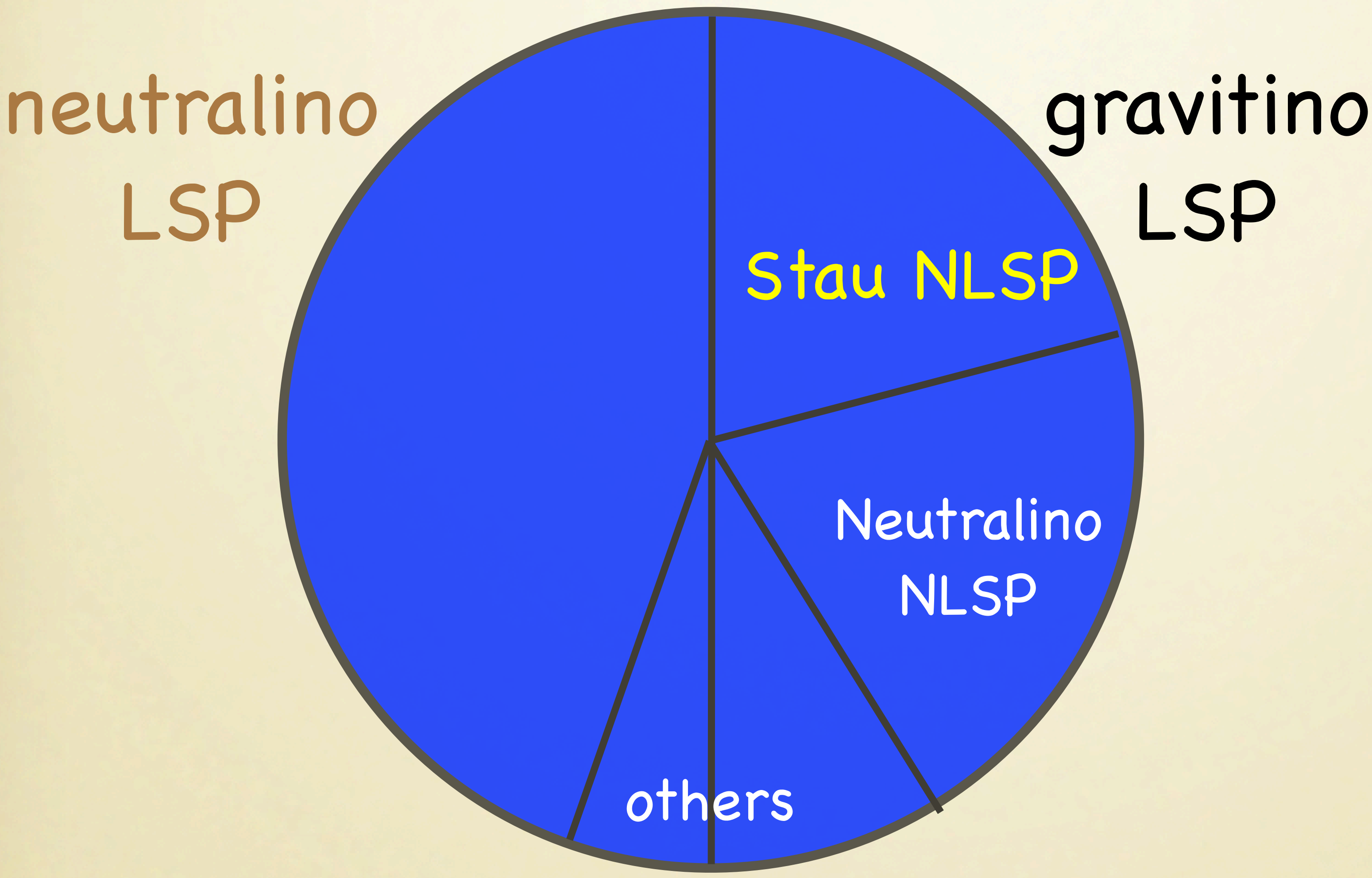




- In most cases, either Stau or Neutralino is the NLSP

- Why Stau NLSP ?

SUSY models



- Gravitino LSP and Stau NLSP is a natural choice.

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

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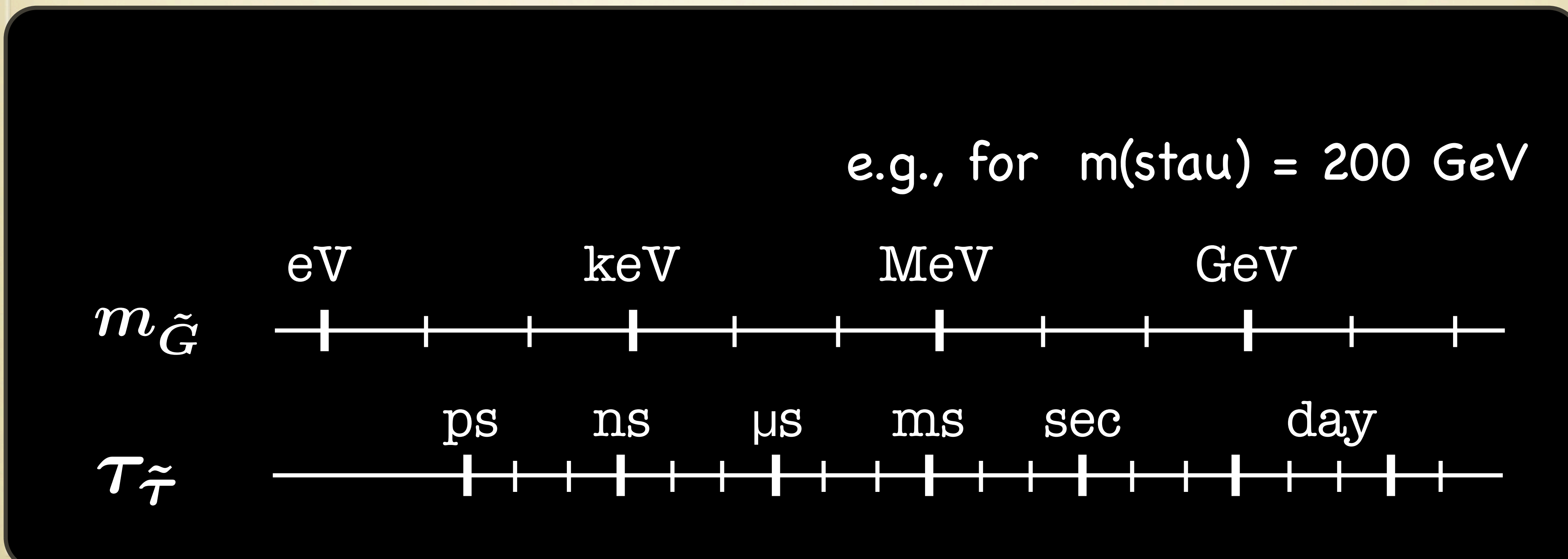
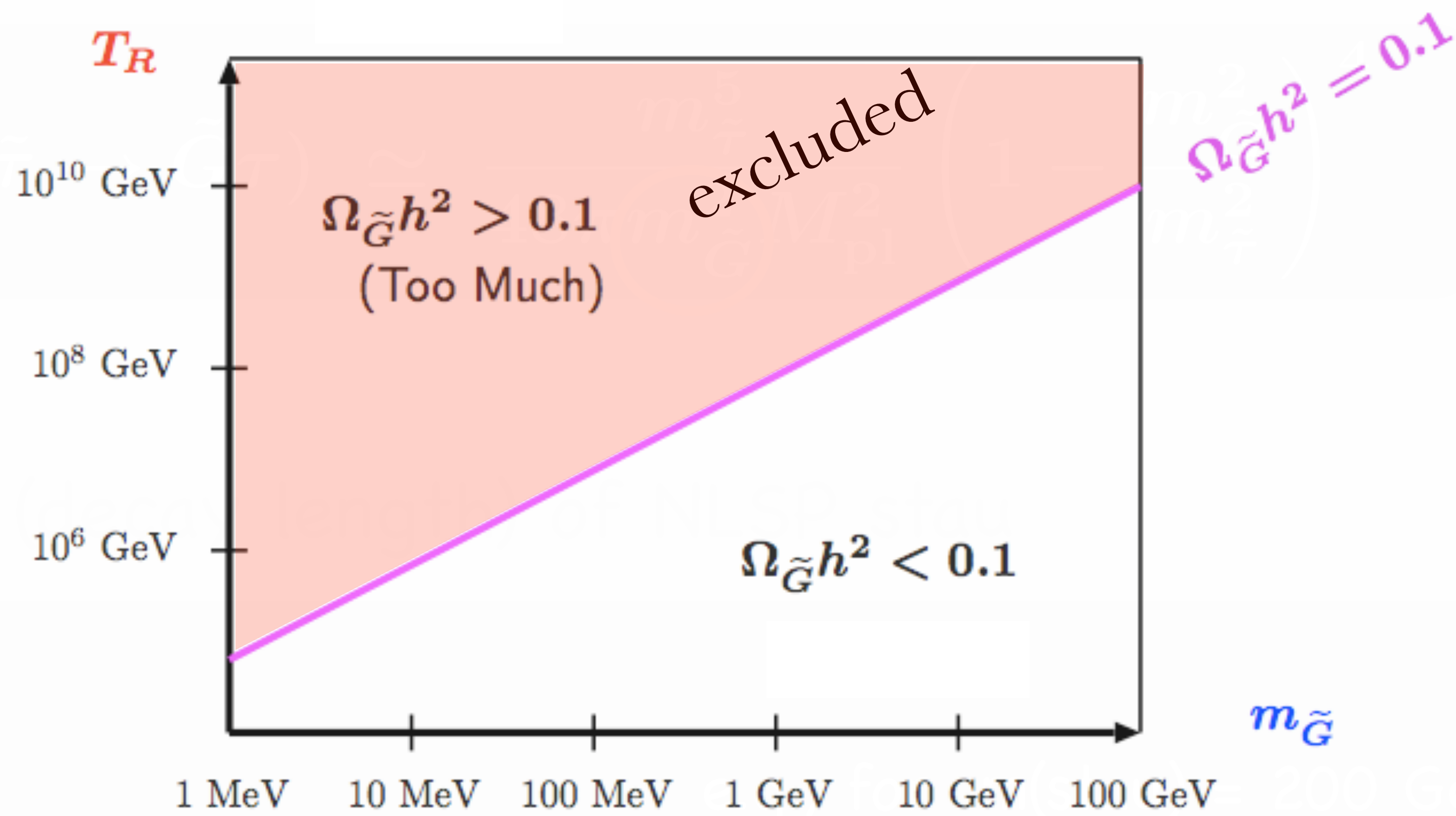
$$\Gamma(\tilde{\tau} \to \tilde{G}\tau) \simeq \frac{m_{\tilde{\tau}}^5}{48\pi m_{\tilde{G}}^2 M_{\rm pl}^2}\left(1 - \frac{m_{\tilde{G}}^2}{m_{\tilde{\tau}}^2}\right)^4$$

Lifetime of Stau



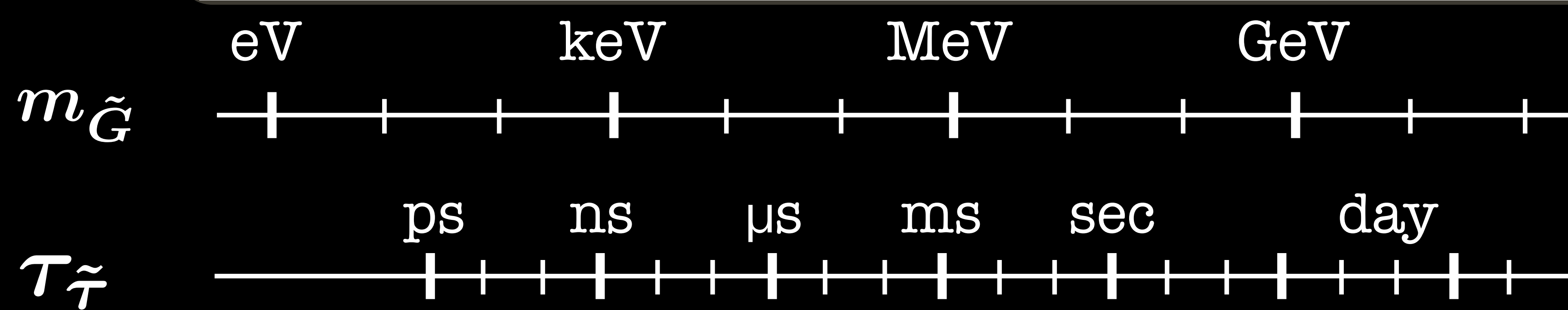
- Why τs

- Gravitino Problem (for stable gravitino)



$\Gamma($

Lifetime



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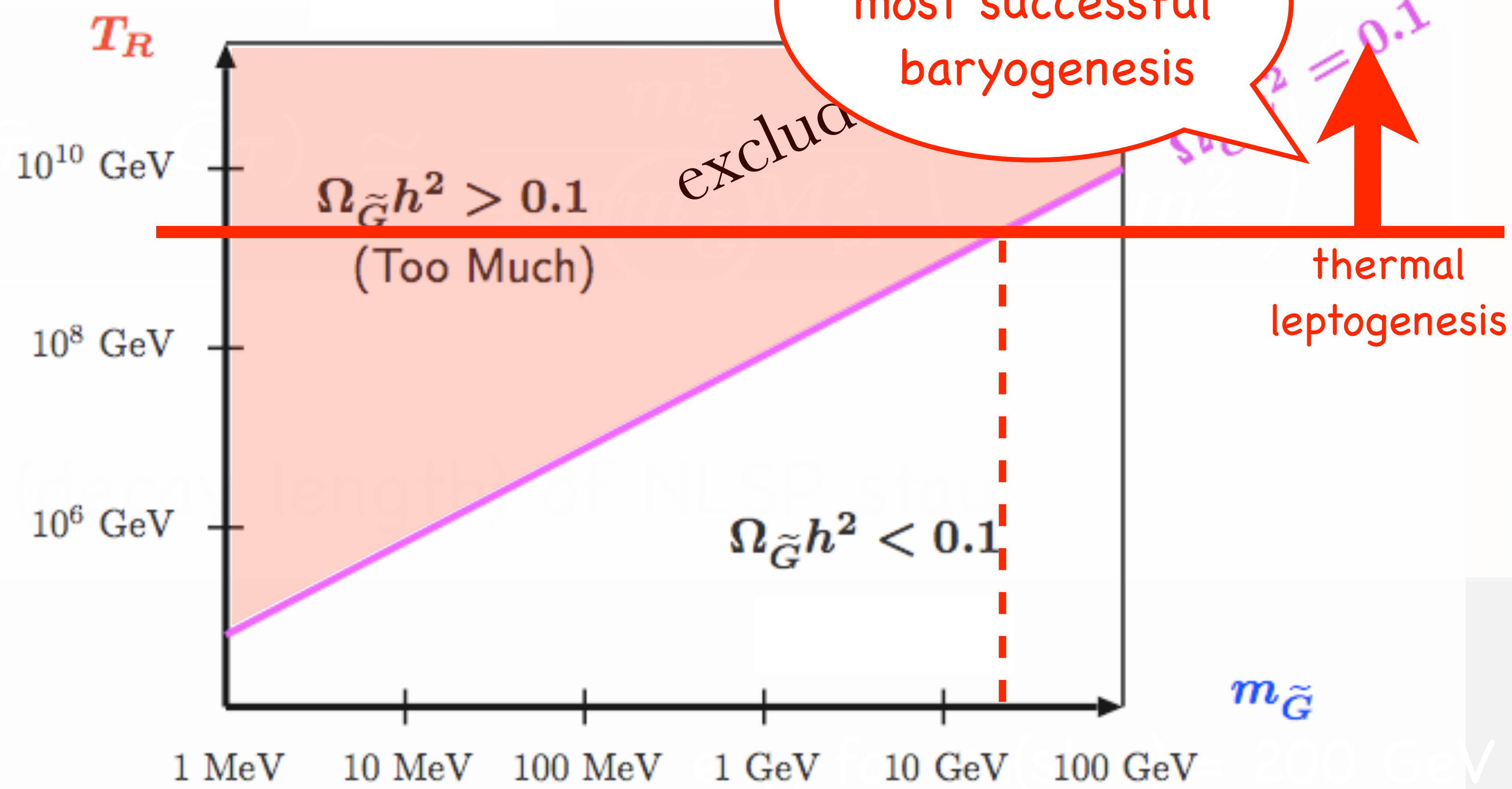
- Gravitino Problem (fo… ino)



$\Gamma($

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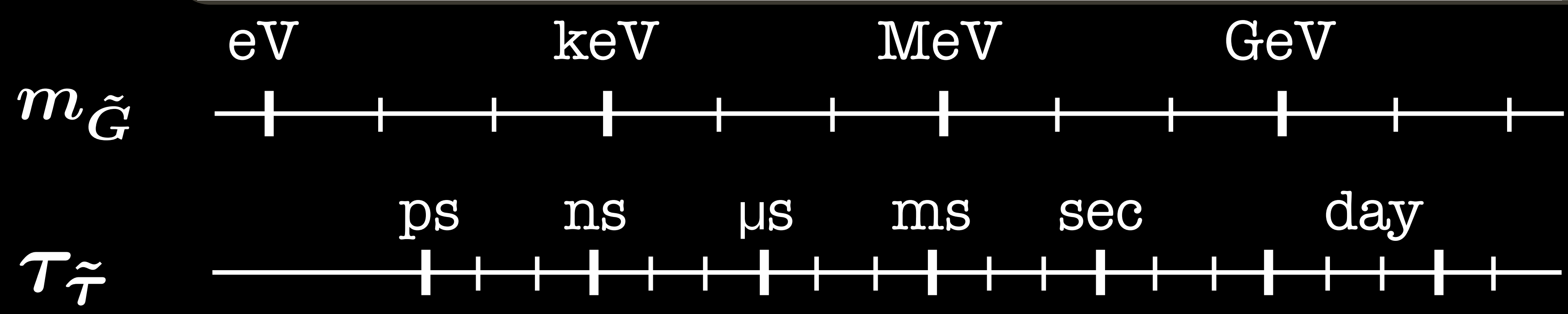

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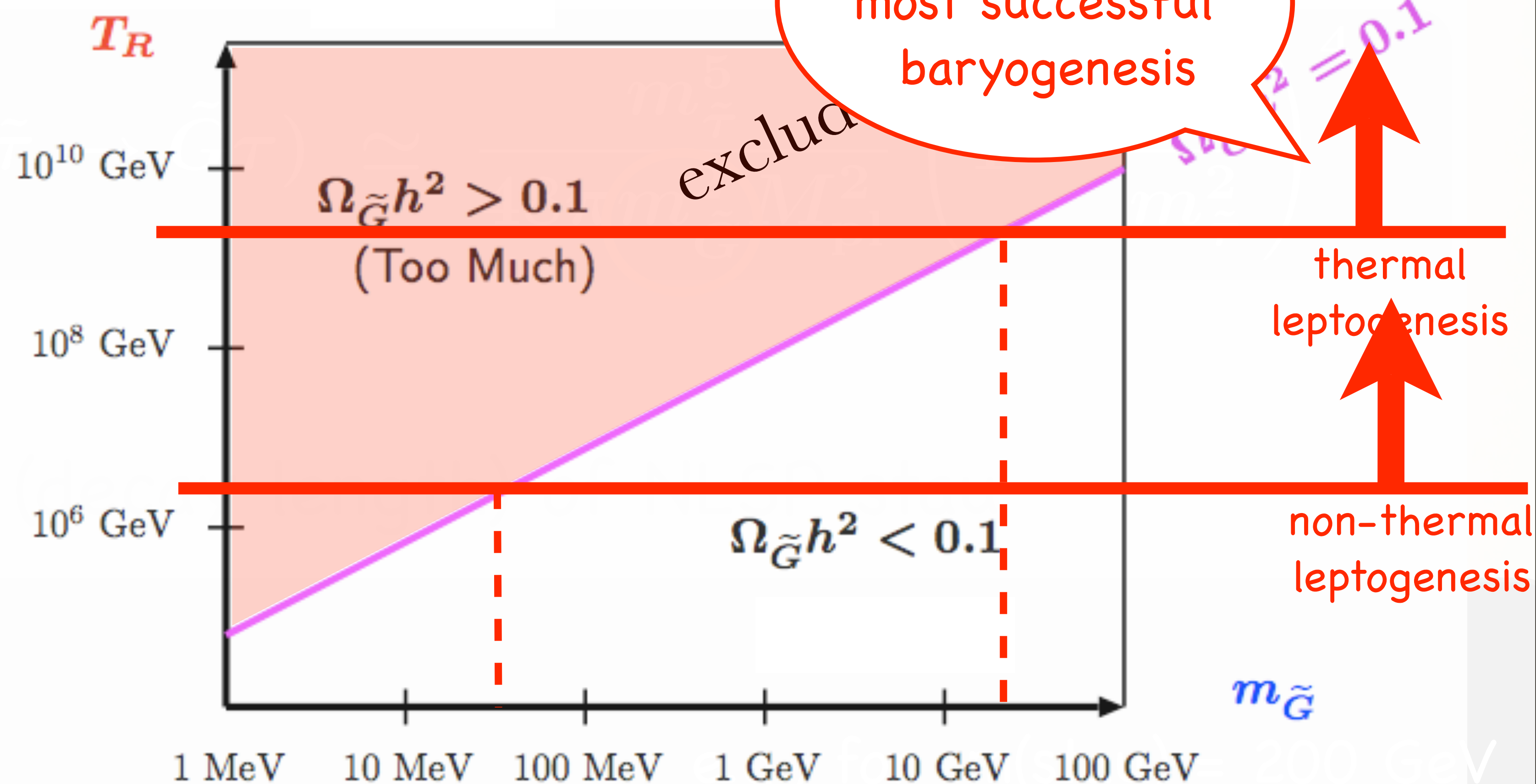

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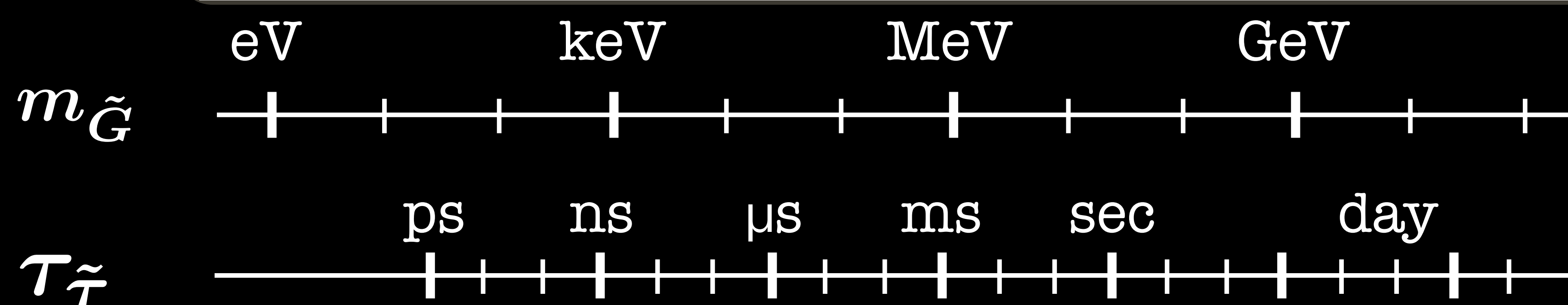

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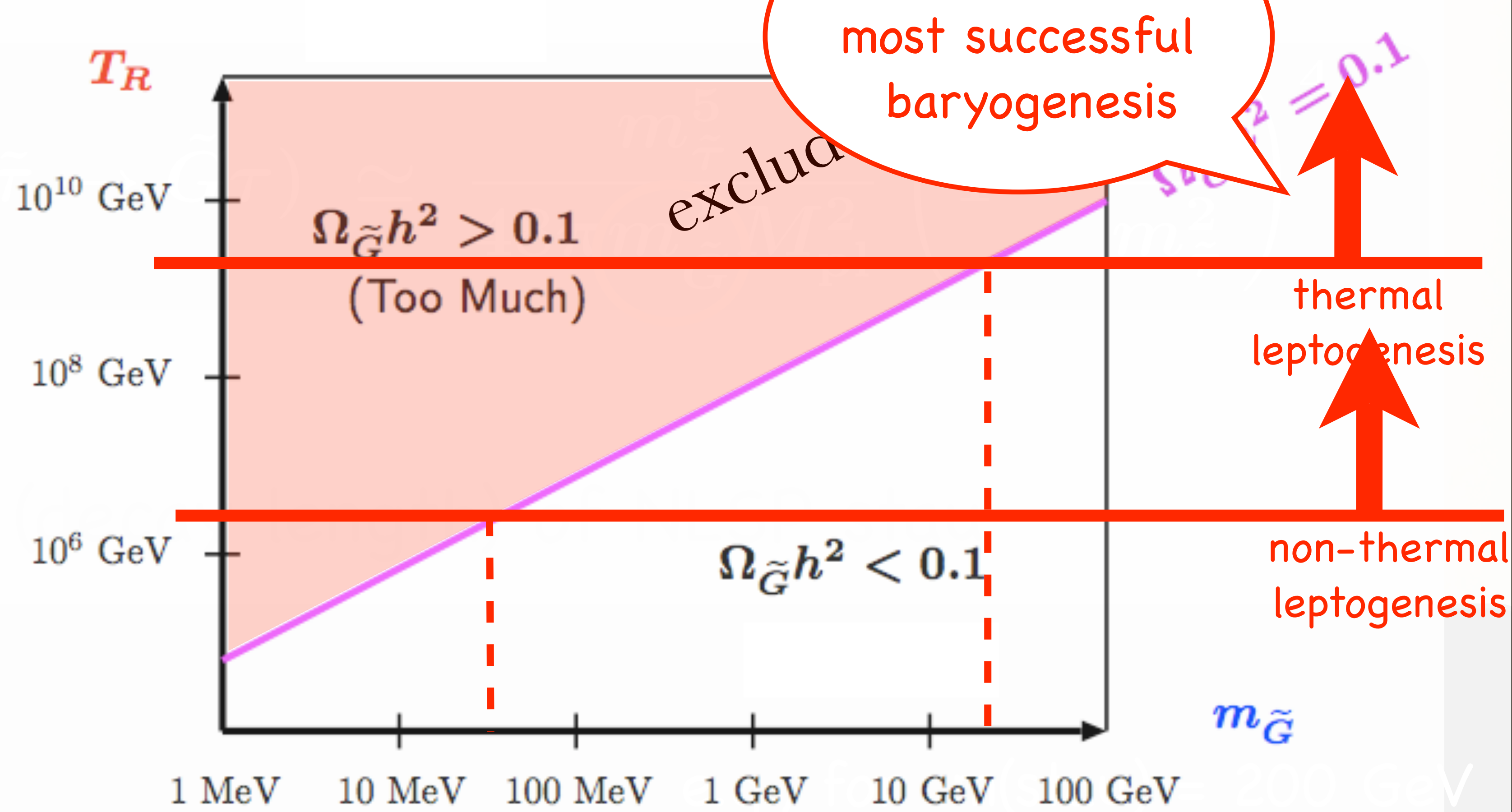

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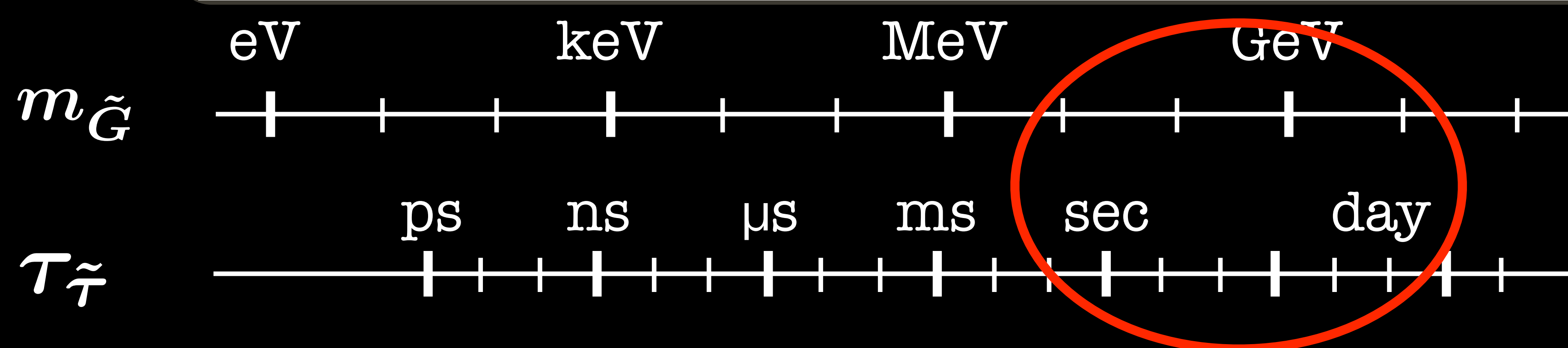

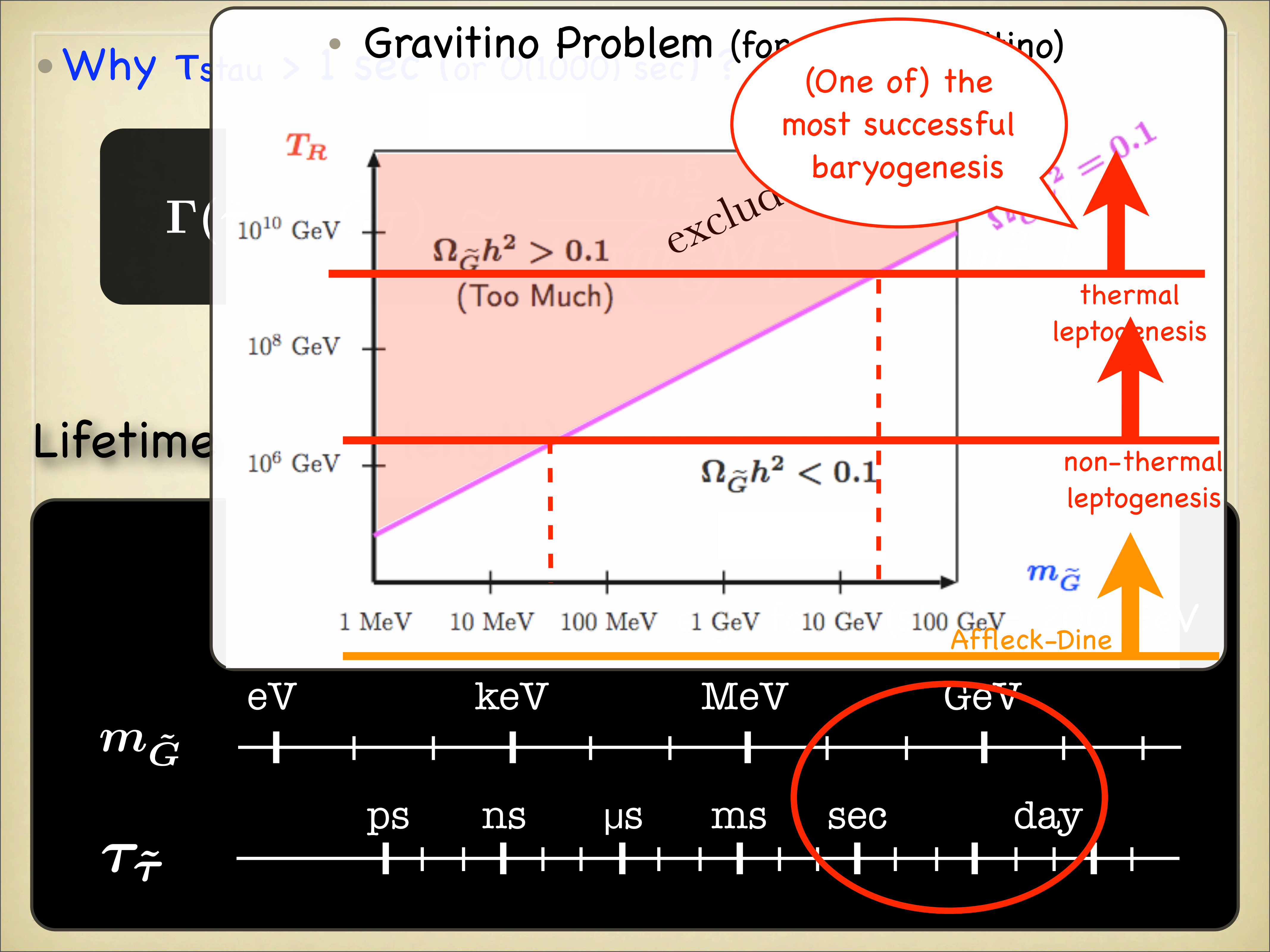

Why τstau > 1 sec (or O(1000) sec) ?
Lifetime
Gravitino Problem (for ... ino)
(One of) the most successful baryogenesis
T_R
10^{10} GeV
10^8 GeV
10^6 GeV
excluded
$\Omega_{\tilde{G}}h^2 > 0.1$
(Too Much)
$\Omega_{\tilde{G}}h^2 < 0.1$
thermal leptogenesis
non-thermal leptogenesis
Affleck-Dine
$m_{\tilde{G}}$
1 MeV
10 MeV
100 MeV
1 GeV
10 GeV
100 GeV
$m_{\tilde{G}}$
eV
keV
MeV
GeV
$\tau_{\tilde{\tau}}$
ps
ns
μs
ms
sec
day

- Why Tstau > 1 sec (or O(1000) sec) ?

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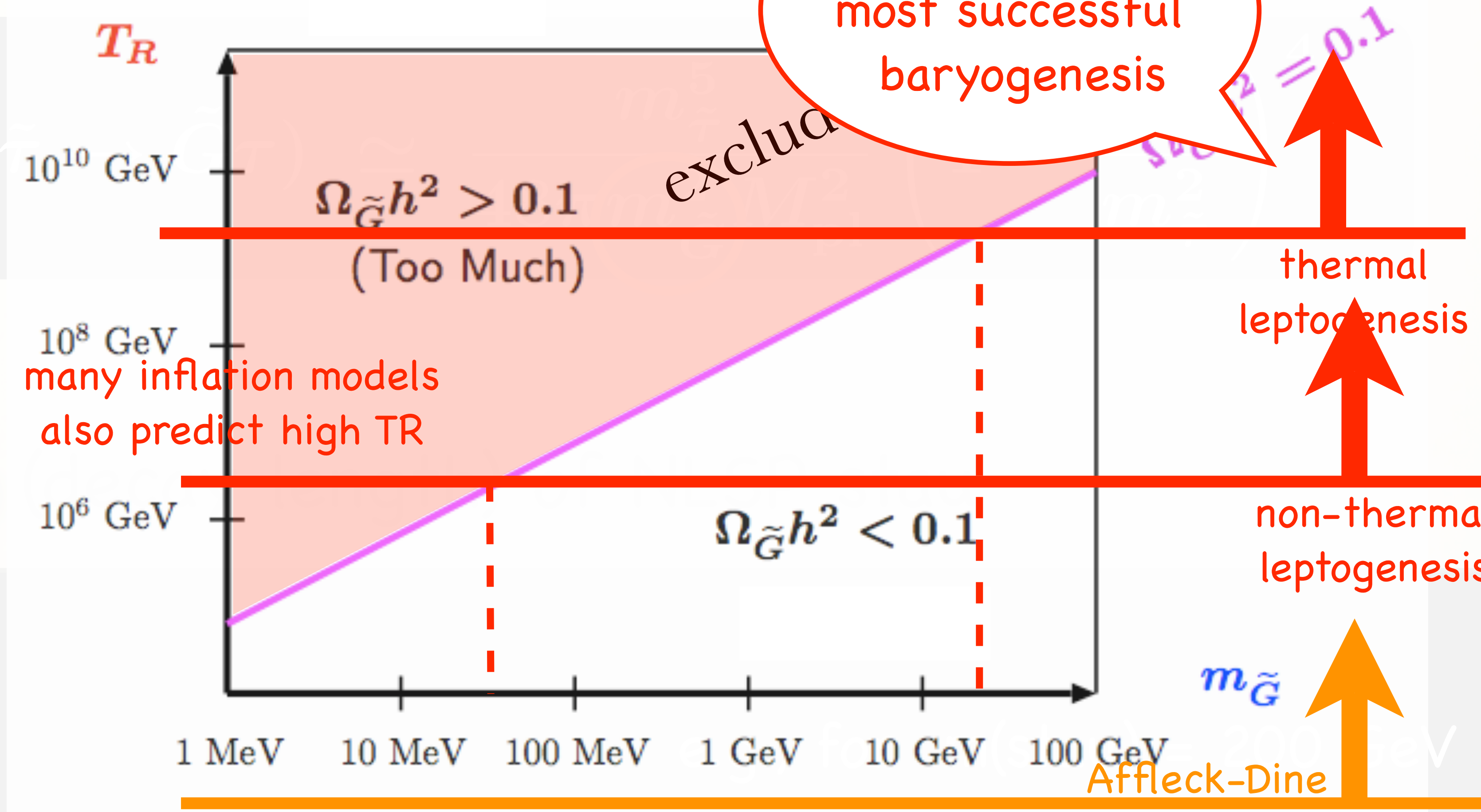
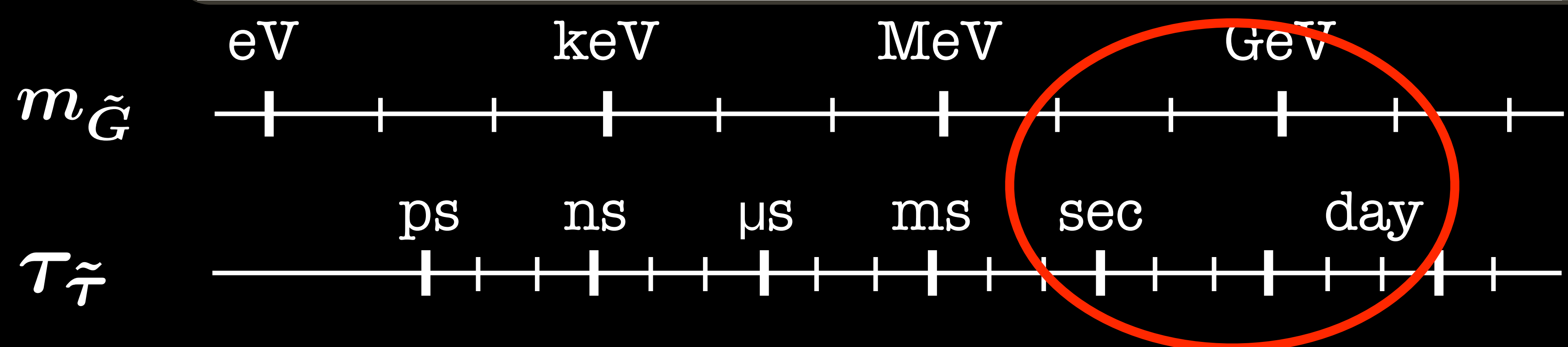
Lifetime

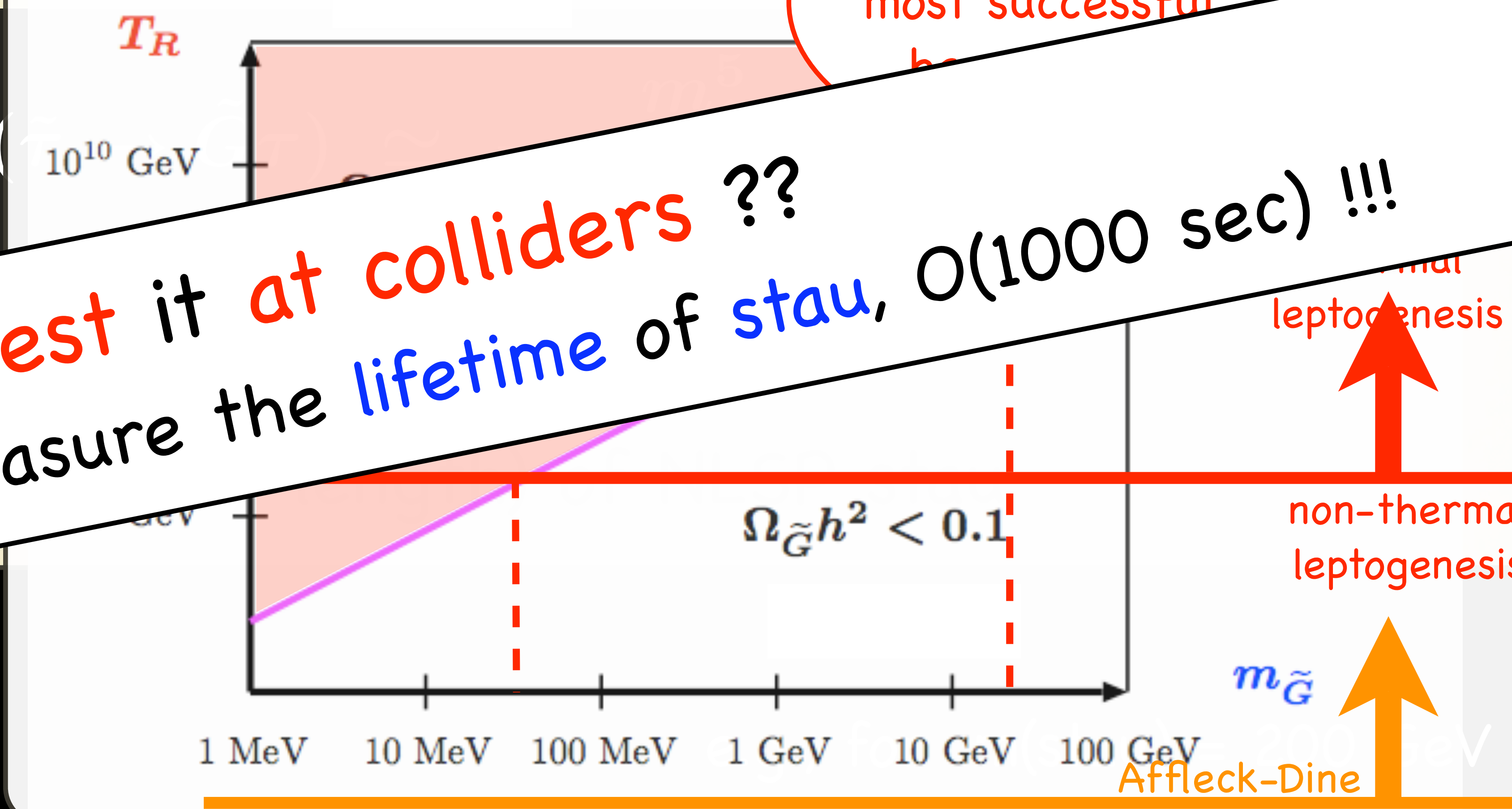




• Why τ_{stau} > 1 sec (or O(1000) sec) ?

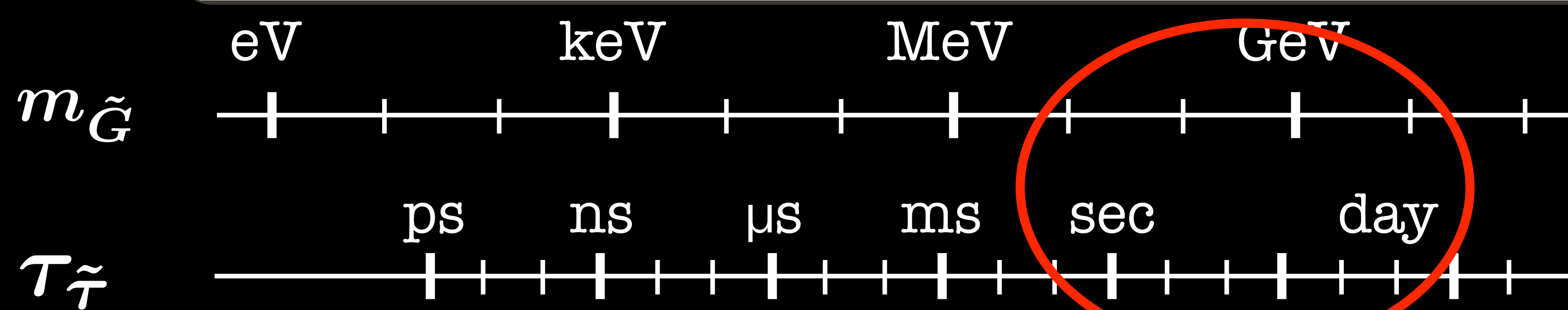
• Gravitino Problem (for ...ino)

(One of) the most successful



• can test it at colliders ??

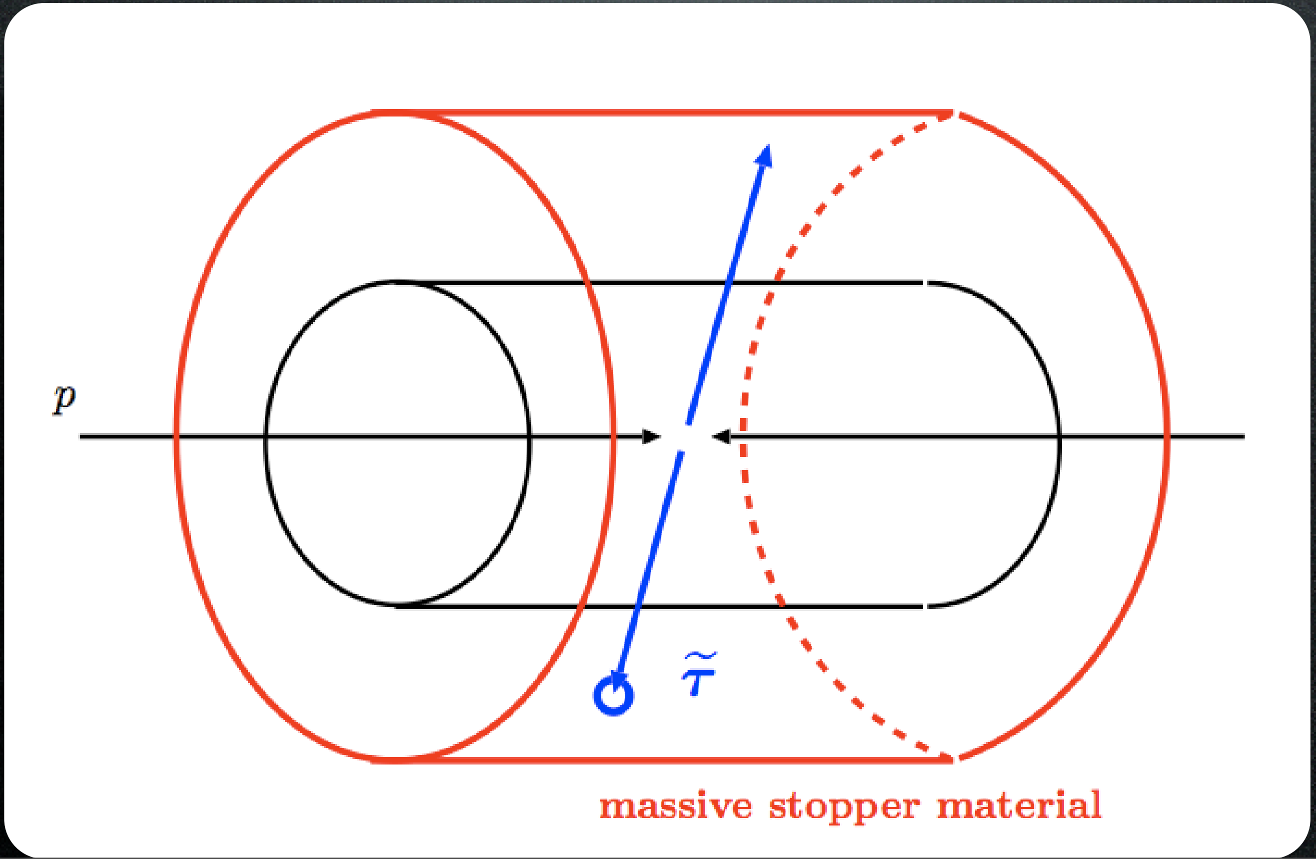
• ☛ measure the lifetime of stau, O(1000 sec) !!!



Long-lived staus @ colliders

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

→ We need to stop the staus.



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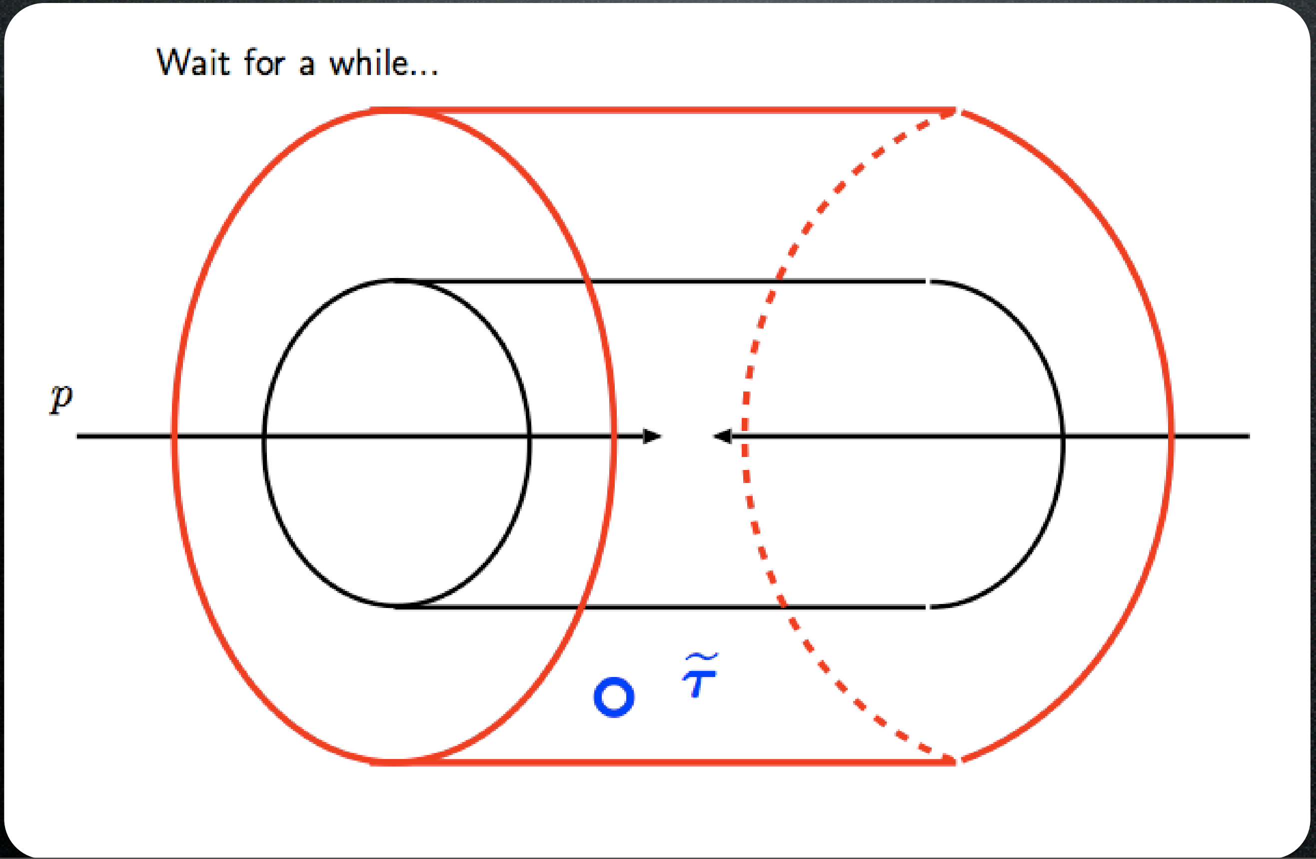

Long-lived staus @ colliders

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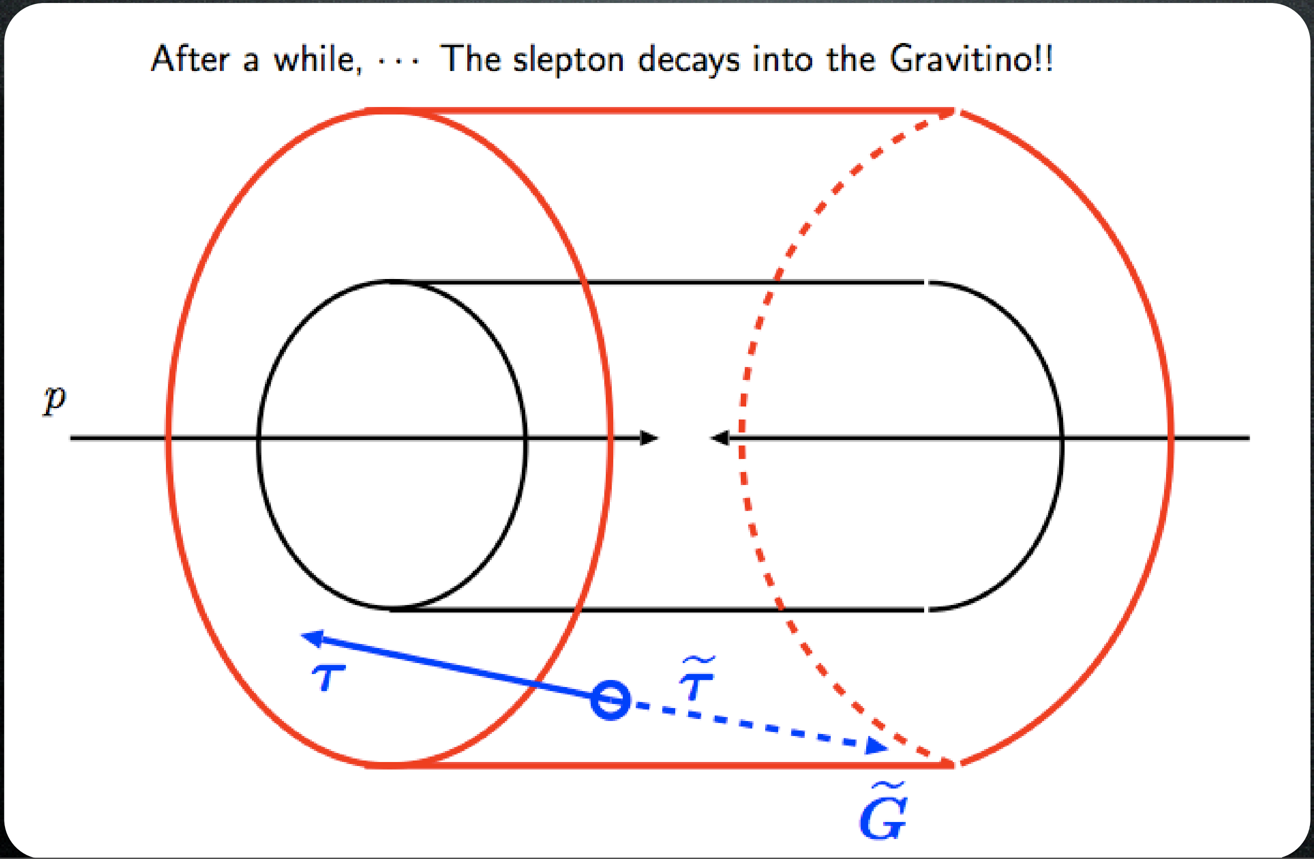
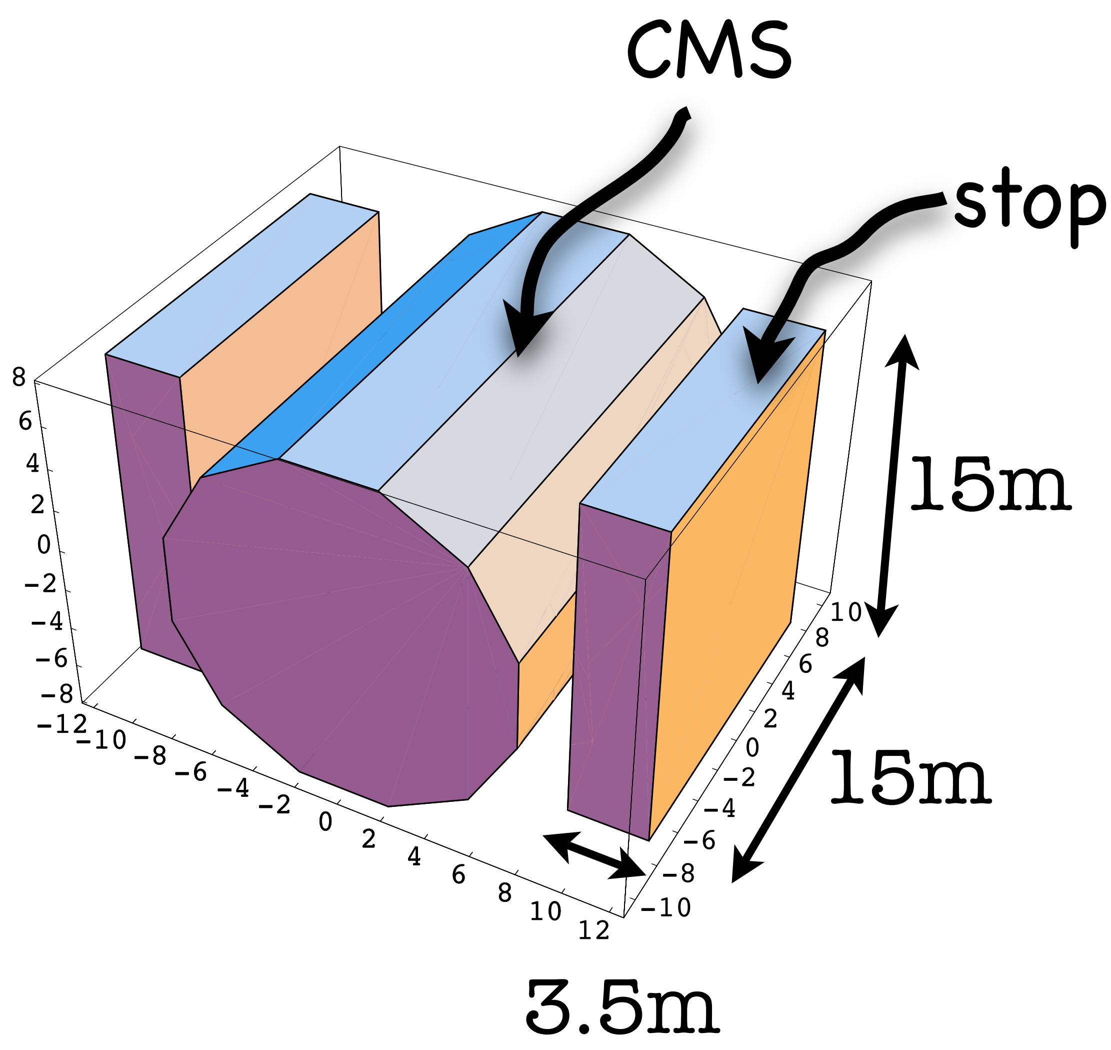


stopper-detector

At LHC, we may place stoppers.

Hamaguchi, Nojiri, De Roeck'06
cf. Hamaguchi, Kuno, Nakaya, Nojiri '04



$5\,\mathrm{g/cm^3}$
(total weight 8kt)

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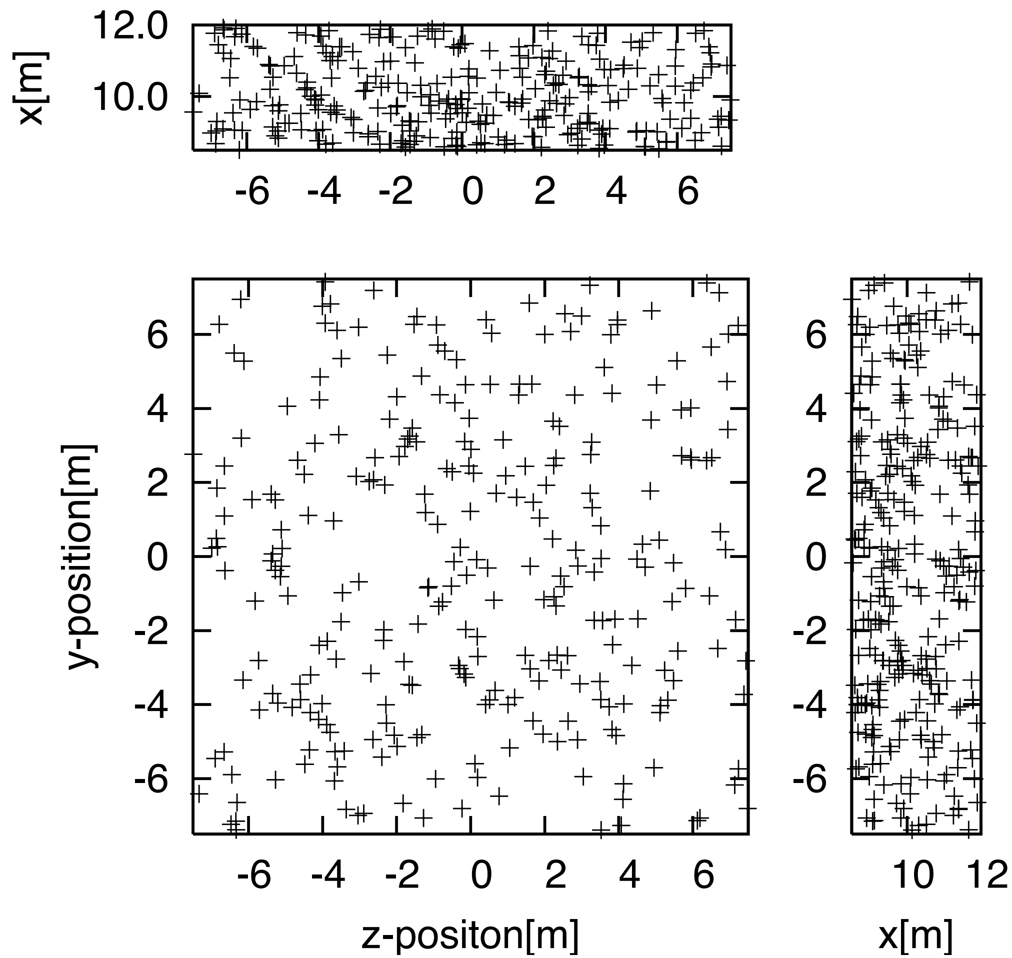

er-detector

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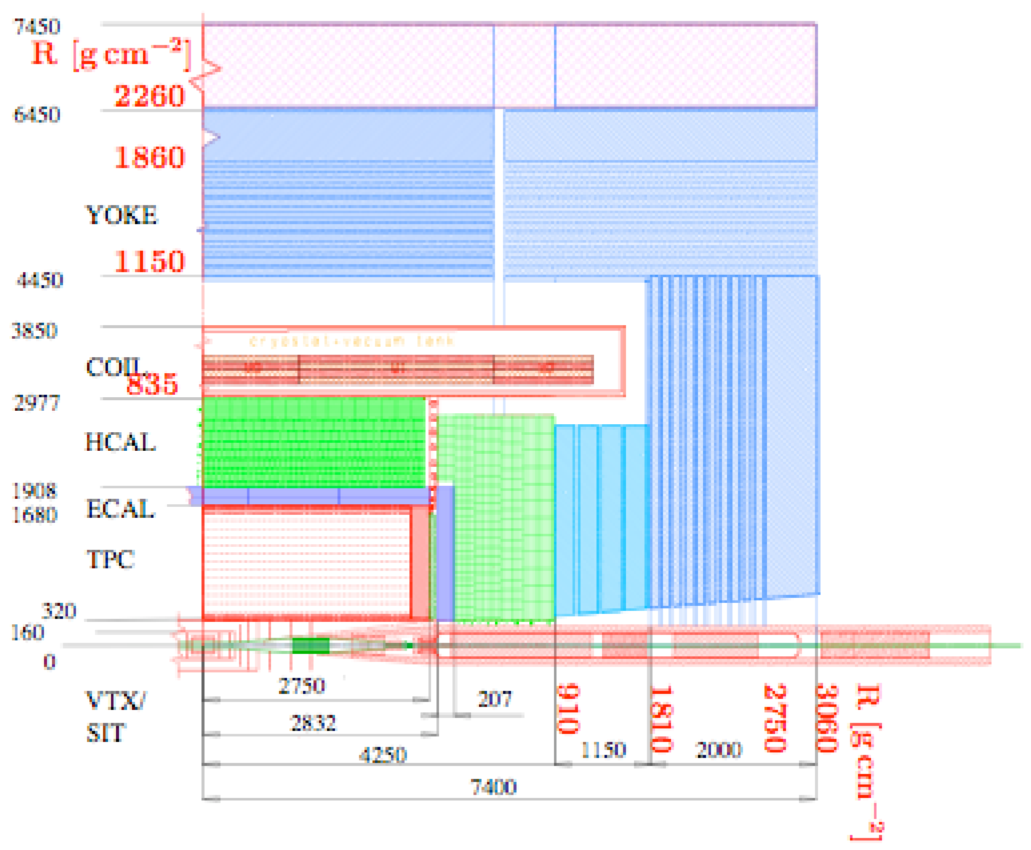
charged NLSP at ILC

Martyn, '06

At ILC, Highly segmented HCAL can serve as stopper-detector!



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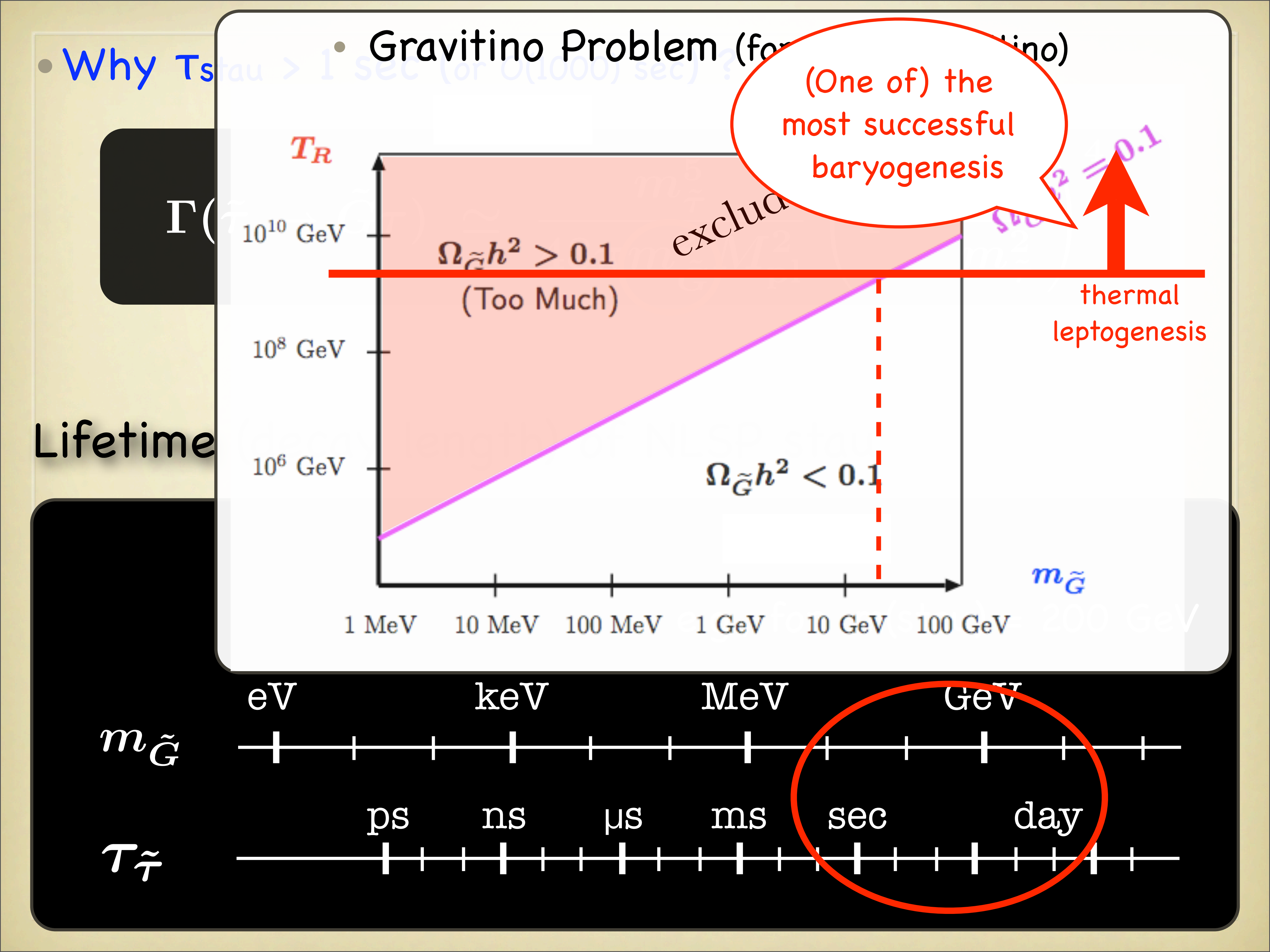

Why τs
Lifetime
Gravitino Problem (fo ino)
(One of) the most successful baryogenesis
T_R
10^{10} GeV
10^8 GeV
10^6 GeV
exclud
$\Omega_{\tilde{G}}h^2 > 0.1$
(Too Much)
$\Omega_{\tilde{G}}h^2 < 0.1$
$=0.1$
thermal leptogenesis
$m_{\tilde{G}}$
1 MeV
10 MeV
100 MeV
1 GeV
10 GeV
100 GeV
eV
keV
MeV
GeV
$m_{\tilde{G}}$
ps
ns
μs
ms
sec
day
$\tau_{\tilde{\tau}}$

- thermal leptogenesis TR > 10^9GeV → mG > O(10) GeV
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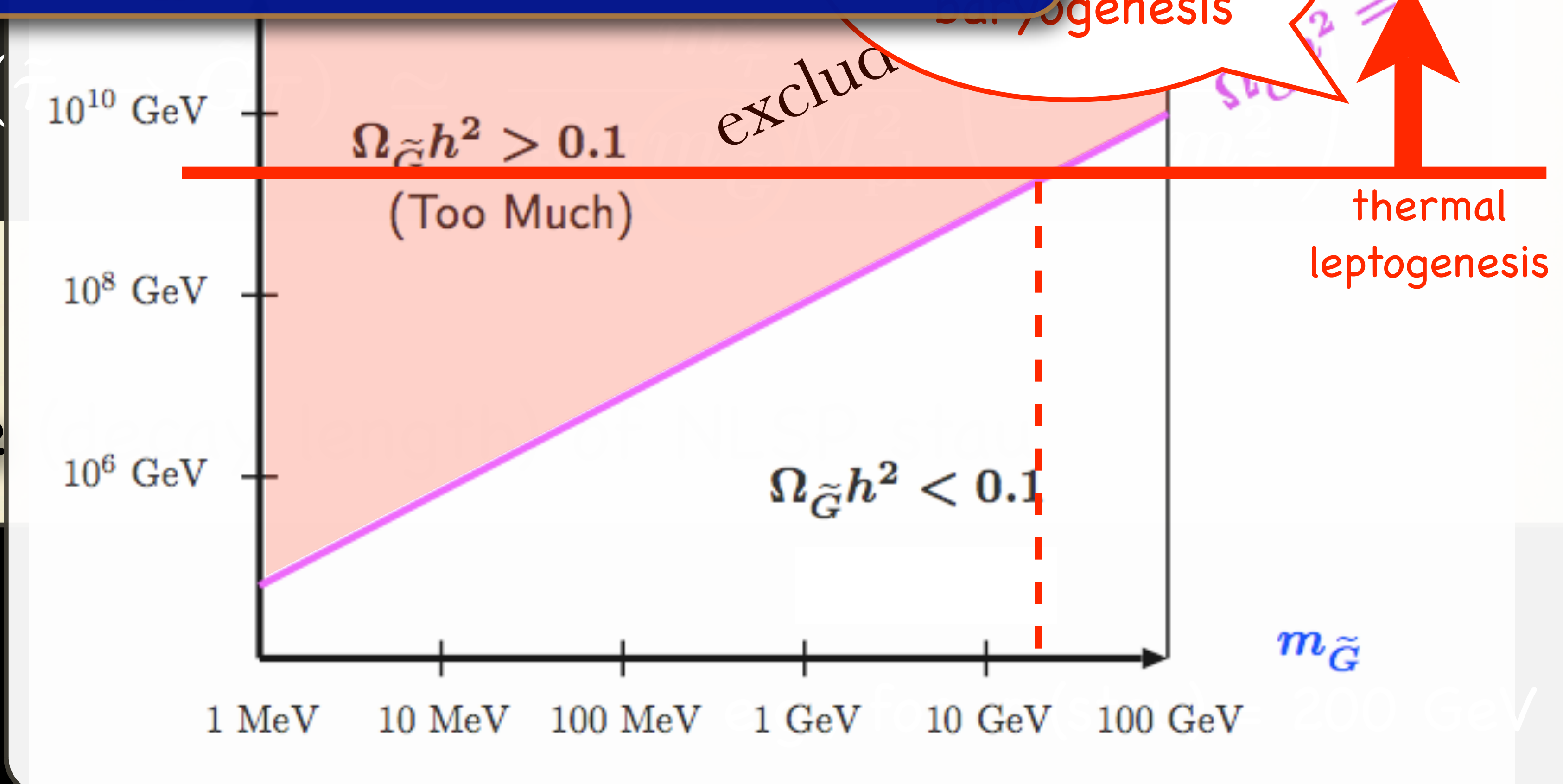
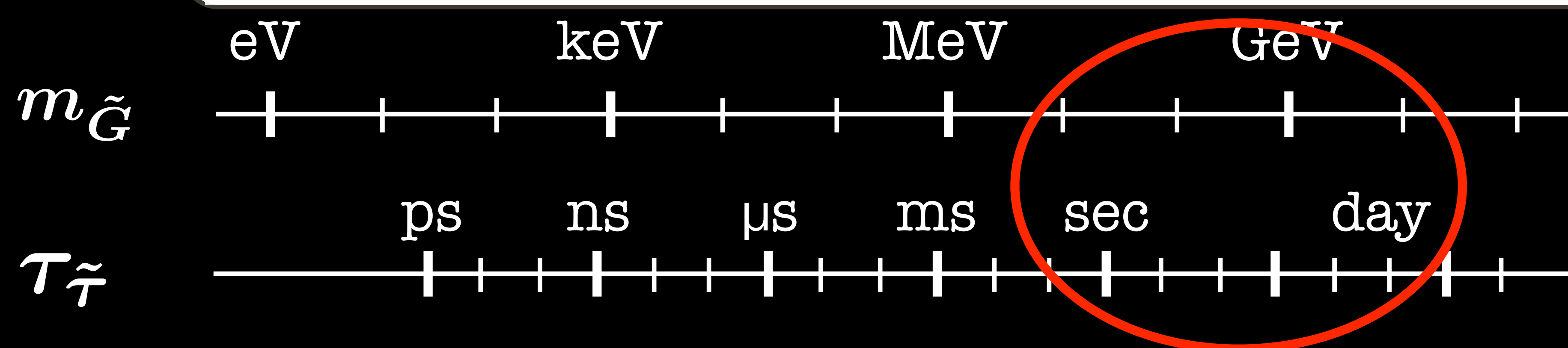
Lifetime





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

- λ > 10^{-14} is large enough to make Tstau < 1000 sec,
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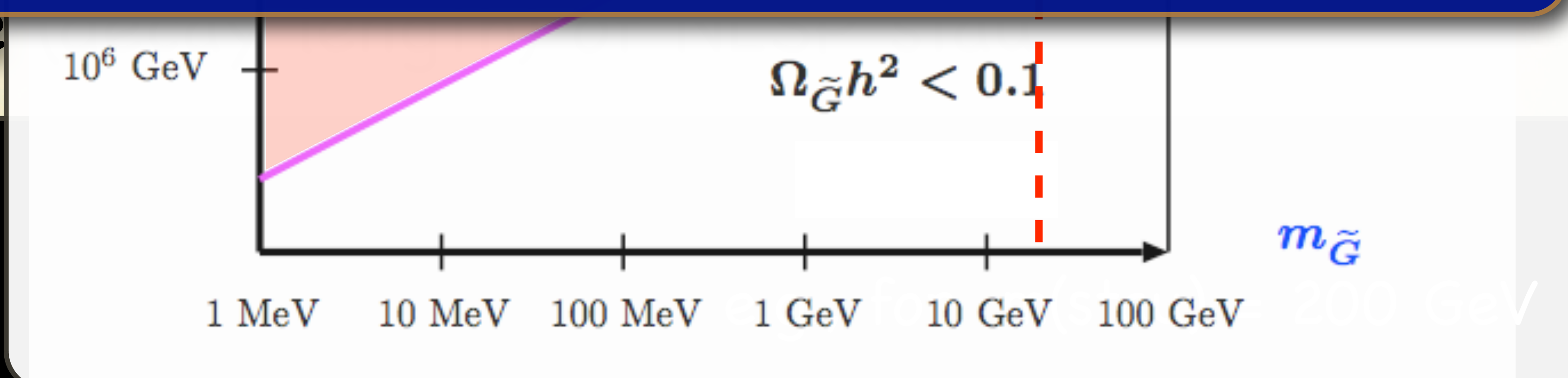

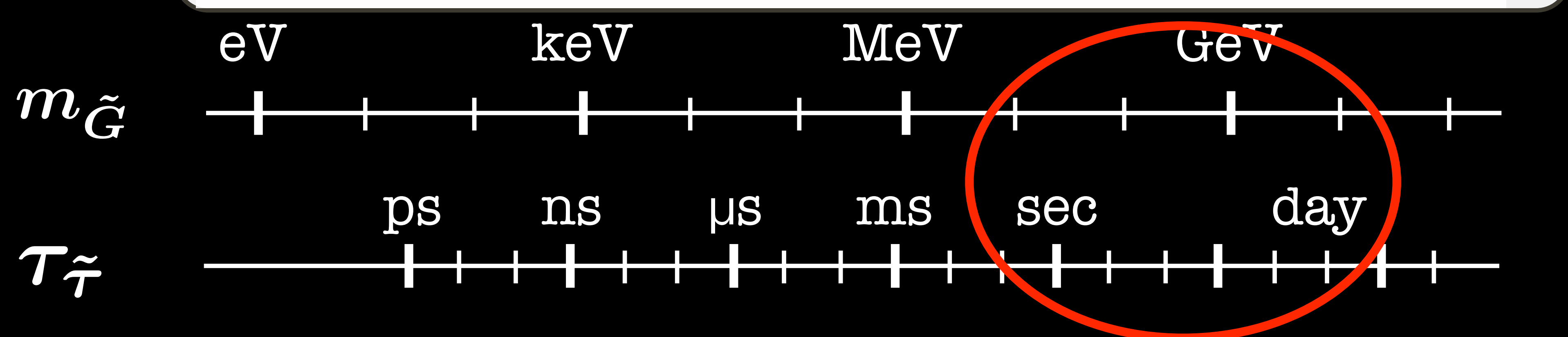

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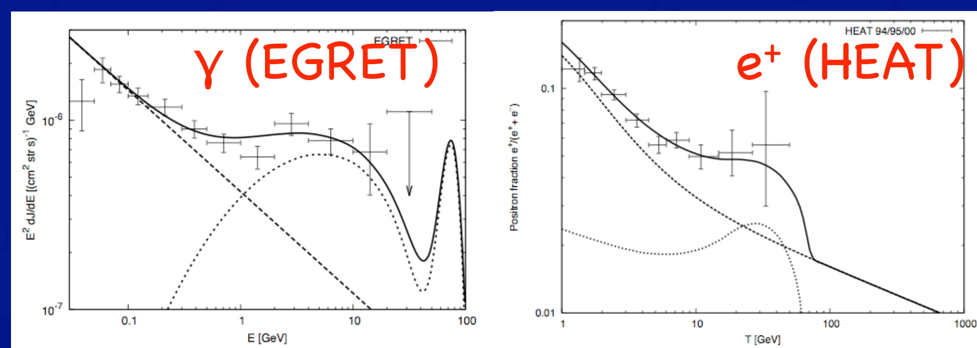
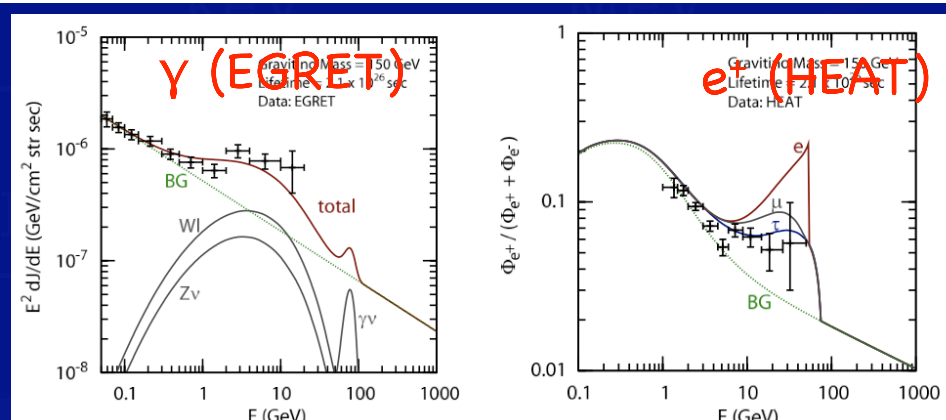


Ishikawa, Matsumoto, Moroi,'08 →



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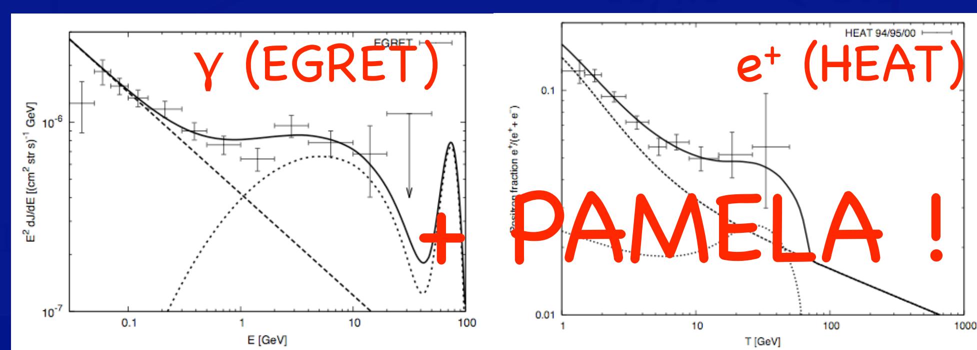

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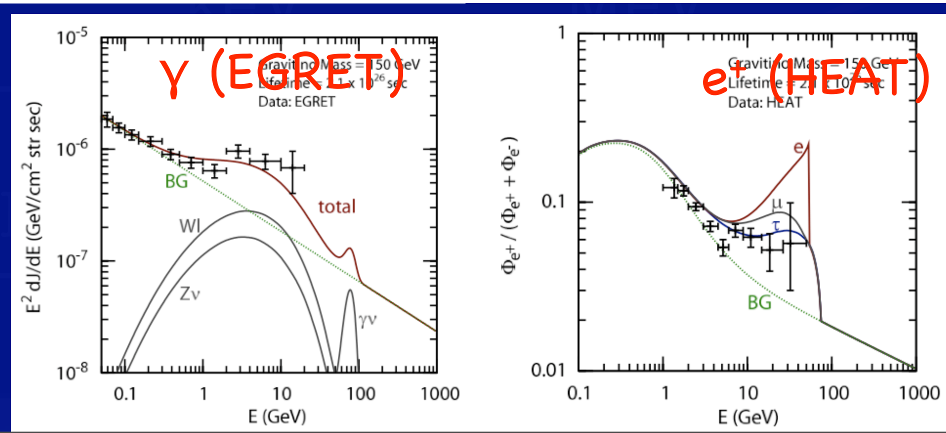

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…ino)
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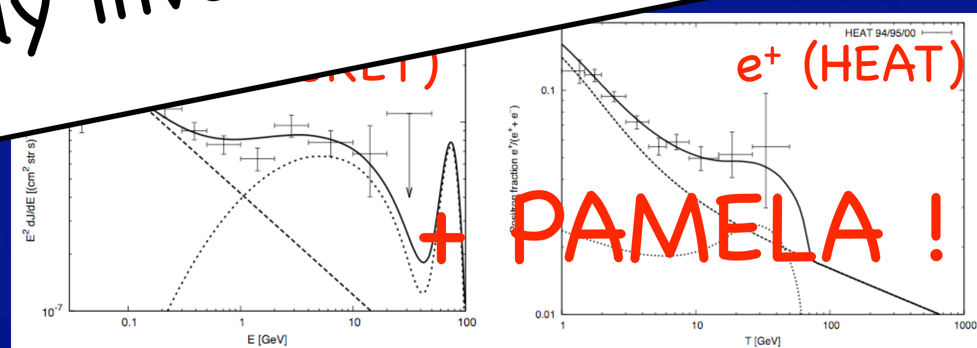
- can **test** it **at colliders** ??
- ☛ check the small R-parity violation !!!
- ☛ not fully investigated, needs more study!!

…een?!)

…barra, Tran,'08 →



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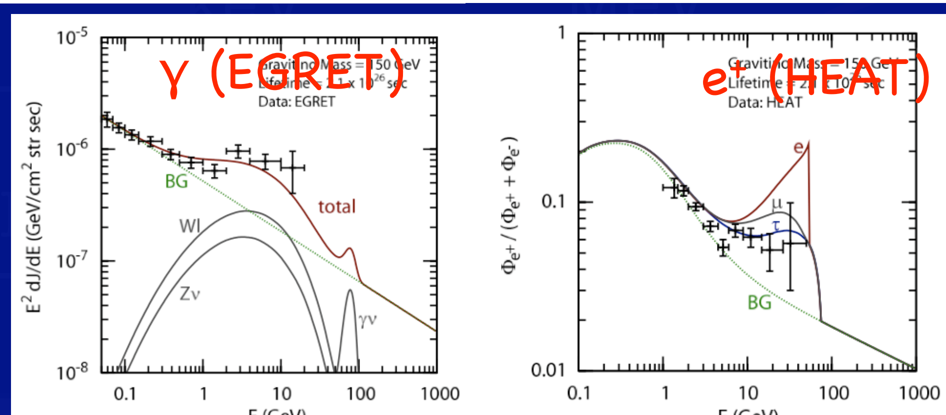
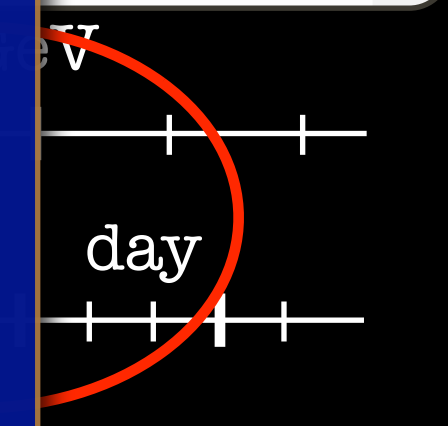


$m_{\tilde G}$

…eV – 200 GeV



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