A solution to the baryon-DM coincidence problem in the mSUGRA/CMSSM model with a 126 GeV Higgs boson

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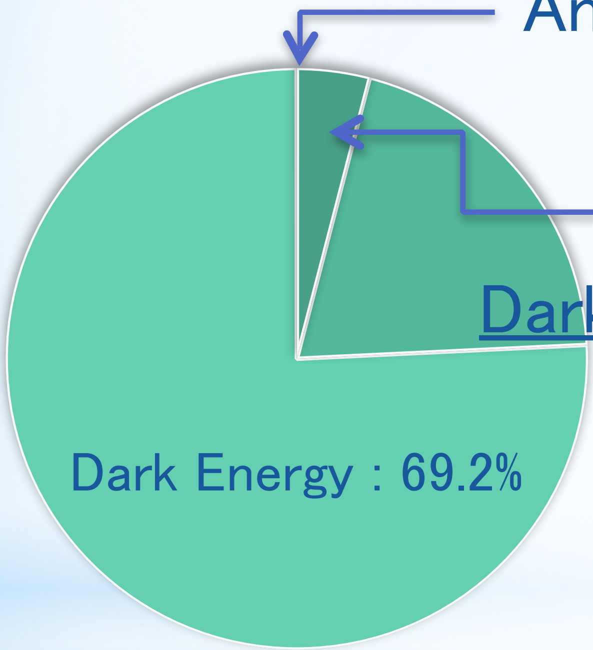
A. Kamada, M. Kawasaki and M.Y.,
Phys. Lett. B 719 (2013) 9 [arXiv:1211.6813[hep-ph]],
[arXiv:1405.6577]

SUSY 2014 @Manchester, England

Introduction: motivation

Content of the Universe



Antibaryon : 0%

⇕ asymmetry

Baryon : 4.8%

Dark Matter : 26%

$$\frac{1}{5} = \mathcal{O}(1)$$

coincidence problem

→ Baryon and DM have a common origin?

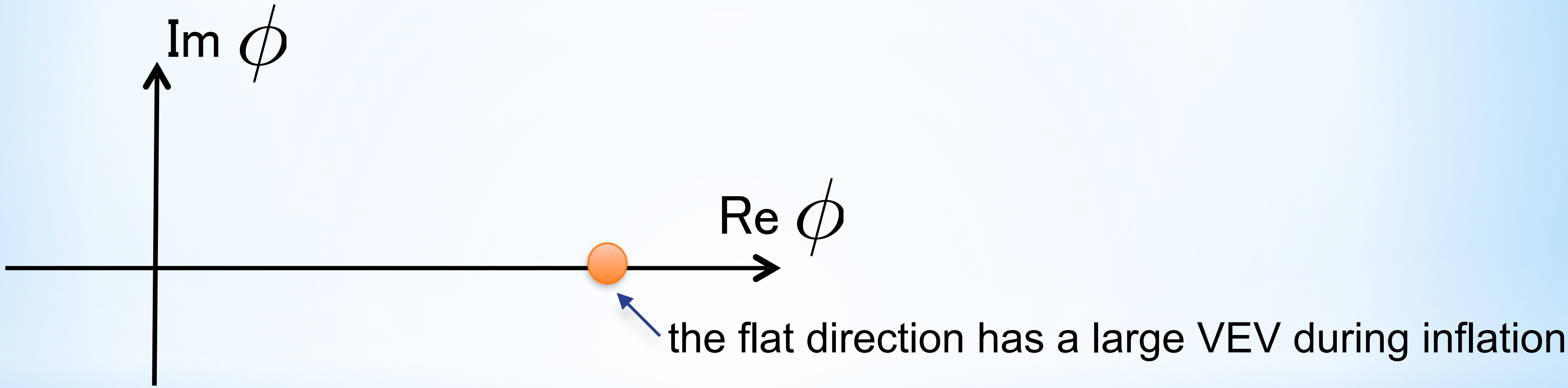
Planck (2013)

We have proposed a scenario for co-genesis of baryon and DM in the CMSSM

Introduction: Affleck–Dine mechanism

Affleck, Dine, 85
Dine, Randall, Thomas, 96

The Affleck–Dine baryogenesis generates the baryon asymmetry using a flat direction (denoted by ϕ)



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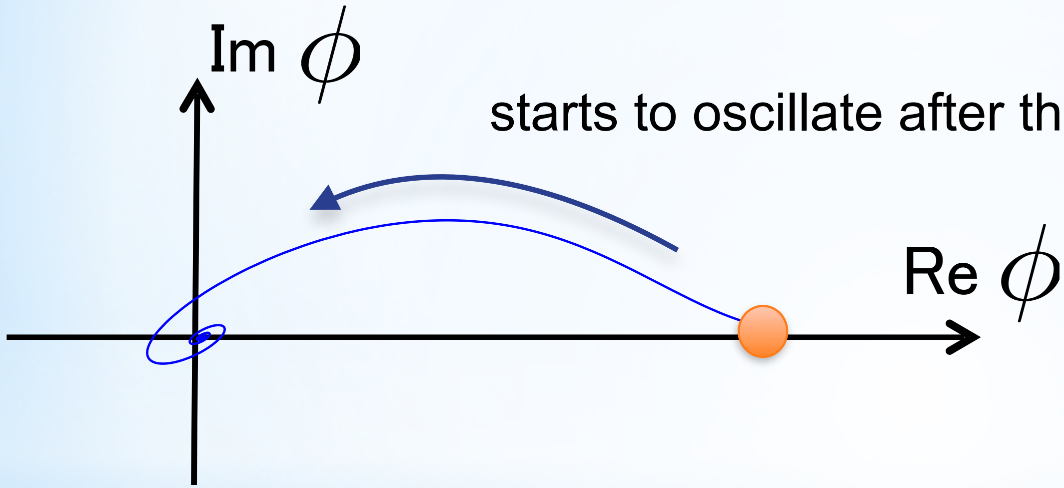

starts to oscillate after the end of inflation

$$B = \int \mathrm{d}V \mathrm{Im}\left(\phi \partial_0 \phi^*\right)$$

$$Y_B \equiv \frac{n_B}{s} \sim \frac{T_{\mathrm{RH}}}{m_\phi}\left(\frac{\langle\phi\rangle}{M_{\mathrm{Pl}}}\right)^2$$

observation: 10^{-10}

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coherently oscillates (spatially homogeneous)

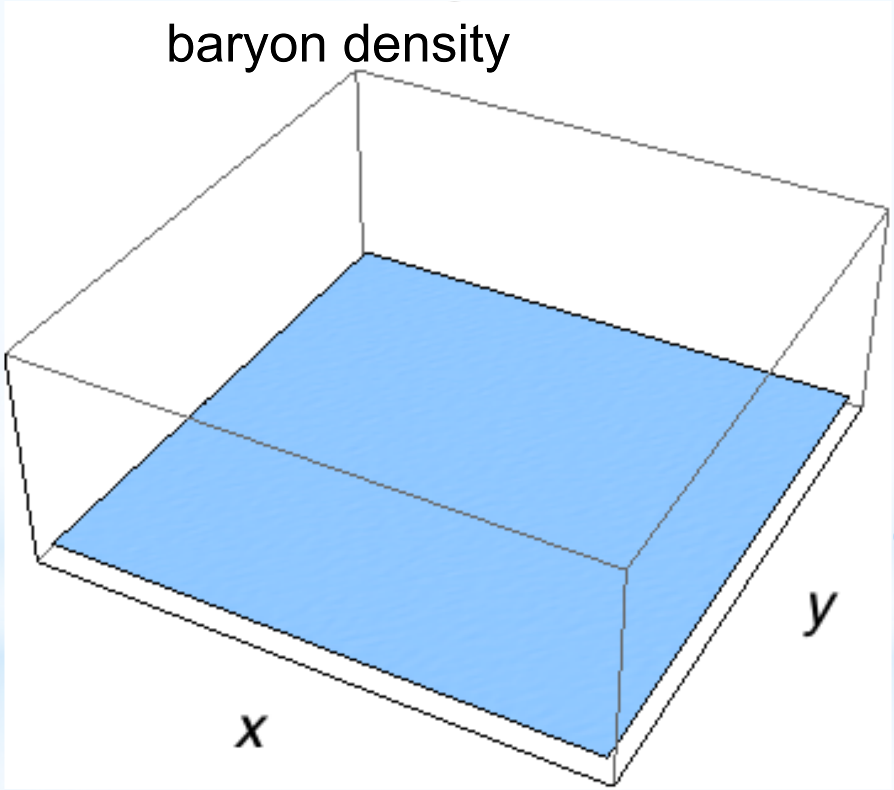
Coleman, 85
Kusenko, 97
Kusenko, Shaposhnikov, 98

In many cases, however, this coherent oscillation is unstable and fragments into non-topological solitons called <u>Q–balls</u>

Introduction: Q-ball

Coleman, 85

two-dimensional simulation
of Q-ball formation



The coherent oscillation is homogeneous just after starting oscillation

⇩

Small quantum fluctuations grow to form Q-balls

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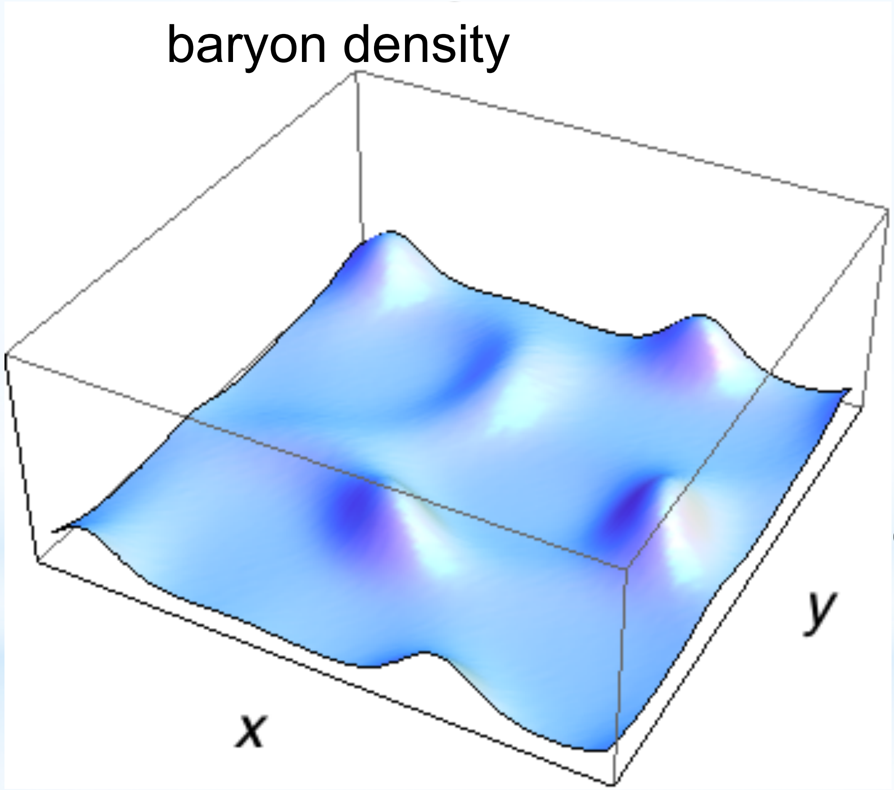

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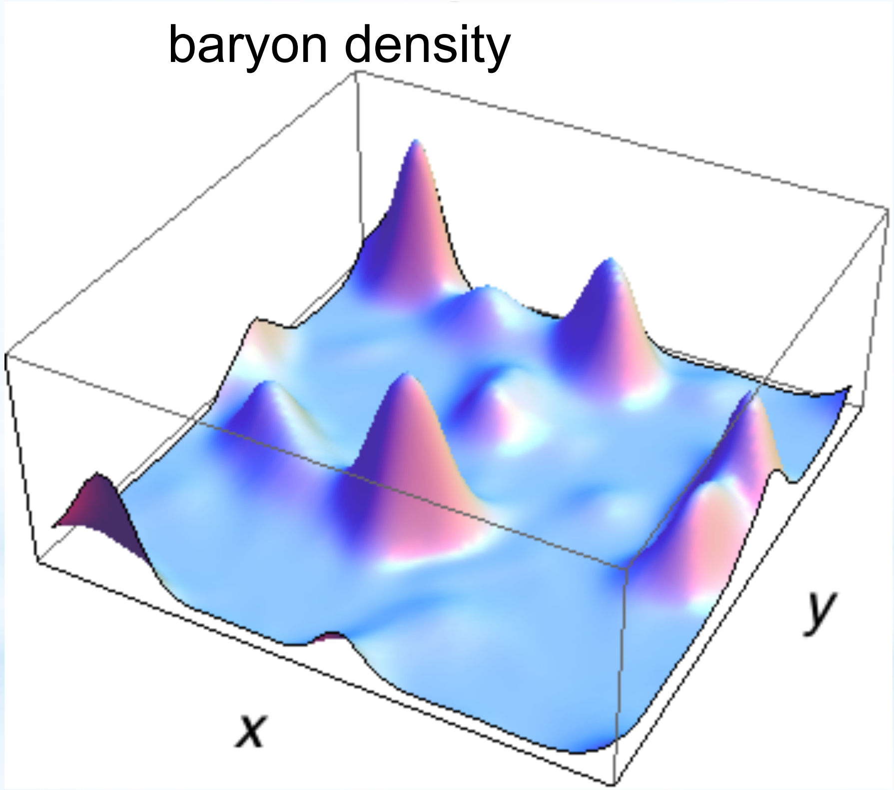

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Although Q-balls are very long-lived solitons,

Cohen, et. al., 86

they gradually evaporate into
- quarks (→ baryon)
- light SUSY particles (→ DM)

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Baryon and DM are generated from the common origin

→ naturally explains the observed baryon-to-DM ratio: $\Omega_b/\Omega_{\rm DM} = \mathcal{O}(1)$

Enqvist, McDonald, 99
Fujii, Hamaguchi, 02
Roszkowski, Seto, 07
Shoemaker, Kusenko, 09
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Doddato, McDonald, 13
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I… …ent oscillation is unstable
a… solitons called Q–balls

We need to compute
these branching ratios

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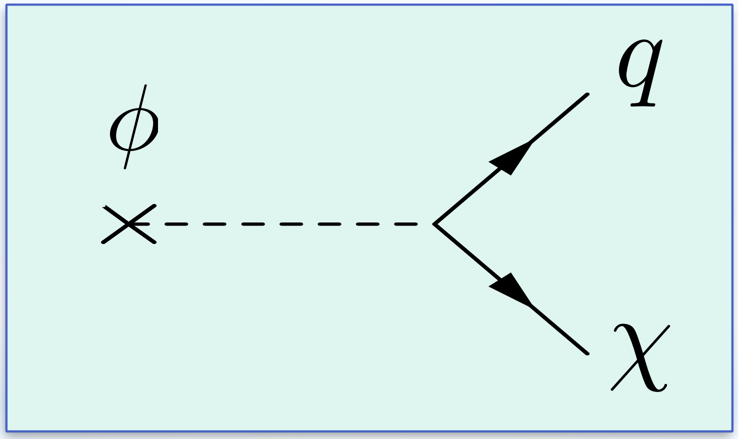
Q-ball decay rates (into binos)

Cohen, et. al, 86

The evaporation of Q-ball might be regarded as the collection of elementary decay processes:



$\times Q$

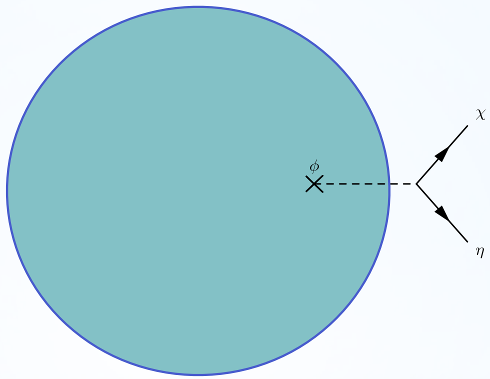
B# carried by the Q-ball

However…

Q-ball decay rates (into binos)

Cohen, et. al, 86

However, Q-balls are localised squark condensations which carry very large baryon number and evaporate into fermions (e.g. quarks and gauginos)



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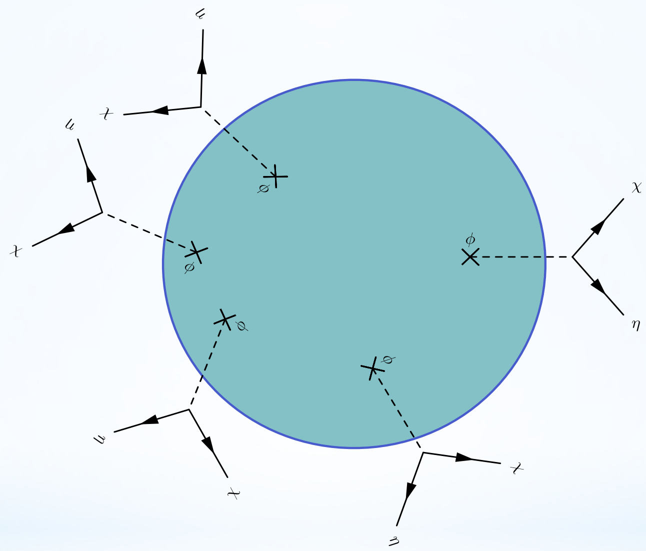

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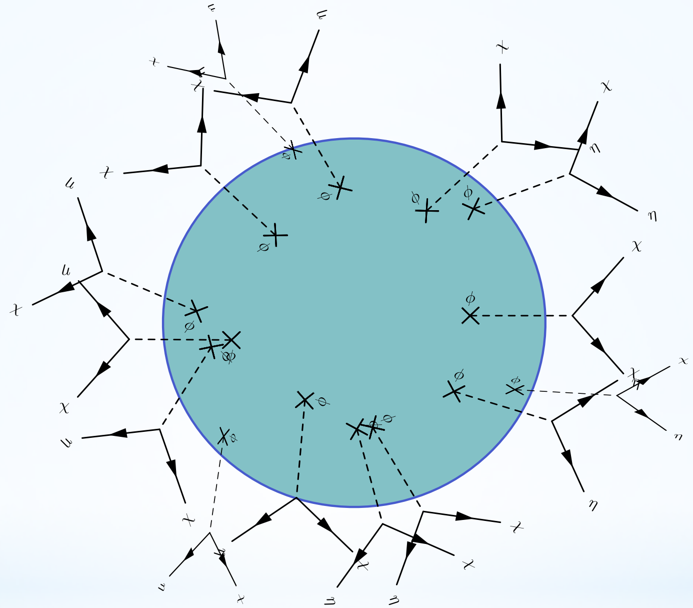

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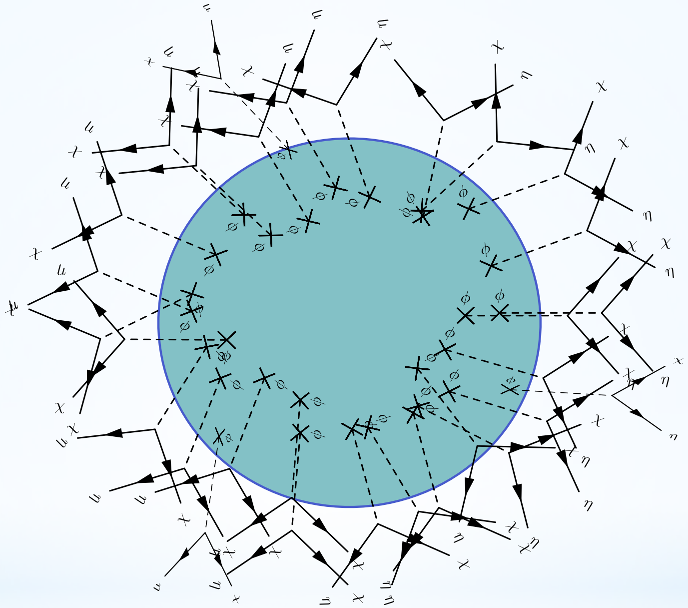

Since fermions obey the Pauli exclusion principle,
there is a certain upper bound for their flux on Q-ball surface!

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Q-ball decay rates (into binos)

Cohen, et. al, 86

Fermion production rates are in fact saturated by the Pauli blocking effect! (Cohen, Coleman, Georgi, Manohar, 86)

⇒ evaporation rates of Q-ball into gauginos (higgsinos) are given by

$$\frac{\mathrm{d}N_\chi}{\mathrm{d}t} \simeq \text{(phase space volume filled with daughter particles per unit time)}$$

$$=$$

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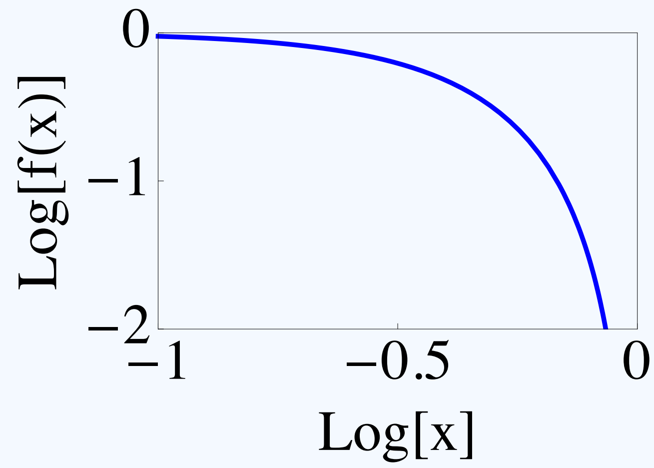
$$\frac{\mathrm{d}N_\chi}{\mathrm{d}t} \simeq \text{(phase space volume filled with daughter particles per unit time)}$$

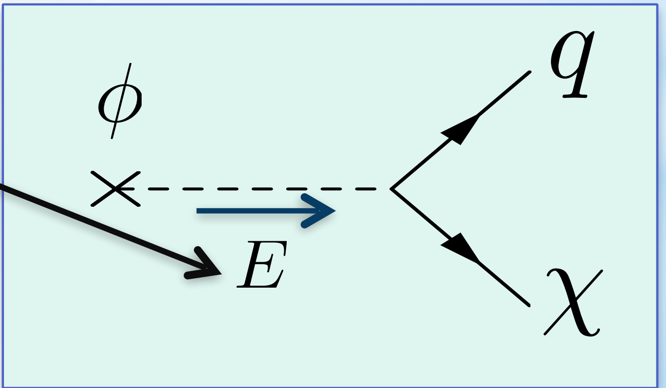
$$= n_\chi \times \text{(surface area)} \times \frac{E^3}{96\pi^2} \times f\left(\frac{m_\chi}{E}\right)$$



n_χ: # of quantum states

$$\begin{cases} n_{\text{bino}} = 1 \\ n_{\text{wino}} = 3 \\ n_{\text{higgsino}} = 4 \end{cases}$$

E: reaction energy $\approx m_{\tilde{q}}$

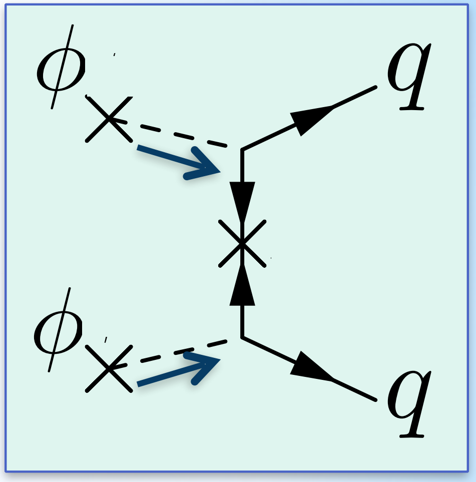


Q-ball decay rates (into quarks)

Kawasaki, M.Y., 13

Q-balls can evaporate into quarks via gluino (higgsino) exchange

⇨ (reaction energy) $\approx 2m_{\tilde{q}}$



$$\frac{\mathrm{d}N_q}{\mathrm{d}t} \simeq n_q \times \text{(surface area)} \times \frac{(2m_{\tilde{q}})^3}{96\pi^2}$$

(# of quantum states of quarks interacting with Q-ball)

$n_q \leq 3 \times 6 \times 2$ = color, flavor, left-right handed

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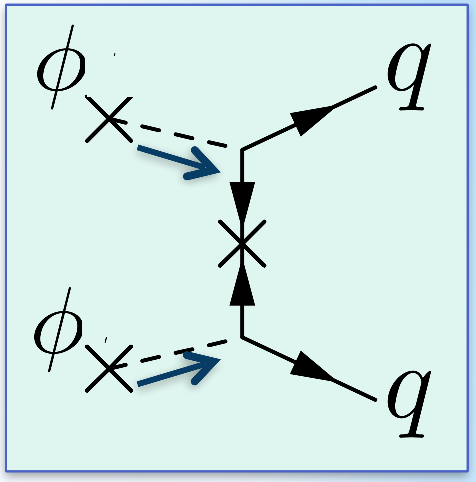

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The ratio of branchings is given by

$$\frac{B_q}{B_{\rm SUSY}} \simeq \frac{8 n_q}{\sum_\chi n_\chi f\left(\frac{m_\chi}{m_{\tilde{q}}}\right)}$$

Baryon and DM co-genesis :

Kamada, Kawasaki, M.Y., 13

The ratio of branchings is given by

$$\frac{B_q}{B_{\rm SUSY}} \simeq \frac{8n_q}{\sum_\chi n_\chi f\left(\frac{m_\chi}{m_{\tilde{q}}}\right)}$$

$$\frac{\Omega_b}{\Omega_{\rm DM}} = \frac{m_p}{3m_{\rm LSP}}\frac{B_q}{B_{\rm SUSY}} = \mathcal{O}(1)\,!$$

The baryon-DM coincidence is originated from Q-ball decay!

Application to the CMSSM

Kamada, Kawasaki, M.Y., 14

Baryon and DM co-genesis : assumption of low T_{RH}

Kamada, Kawasaki, M.Y., 14

In the CMSSM,
low reheating temperature ($T_{\rm RH} \lesssim m_{\rm LSP}/10$) is favoured in the following reasons:

- In most parameter regions,
  bino (LSP) thermal relic density is over-abundant for $T_{\rm RH} \gtrsim m_{\rm LSP}/10$
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-
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- Since we account for the amount of baryon asymmetry by the ADBG, low T_{RH} requires a larger VEV for the flat direction. ← $Y_B \propto T_{\rm RH} \langle \phi \rangle^2$
  This implies that the ADBG predicts larger (= long-lived) Q-balls.
  (note: Q-balls have to evaporate after DM freeze-out
  to realise the co-genesis scenario)

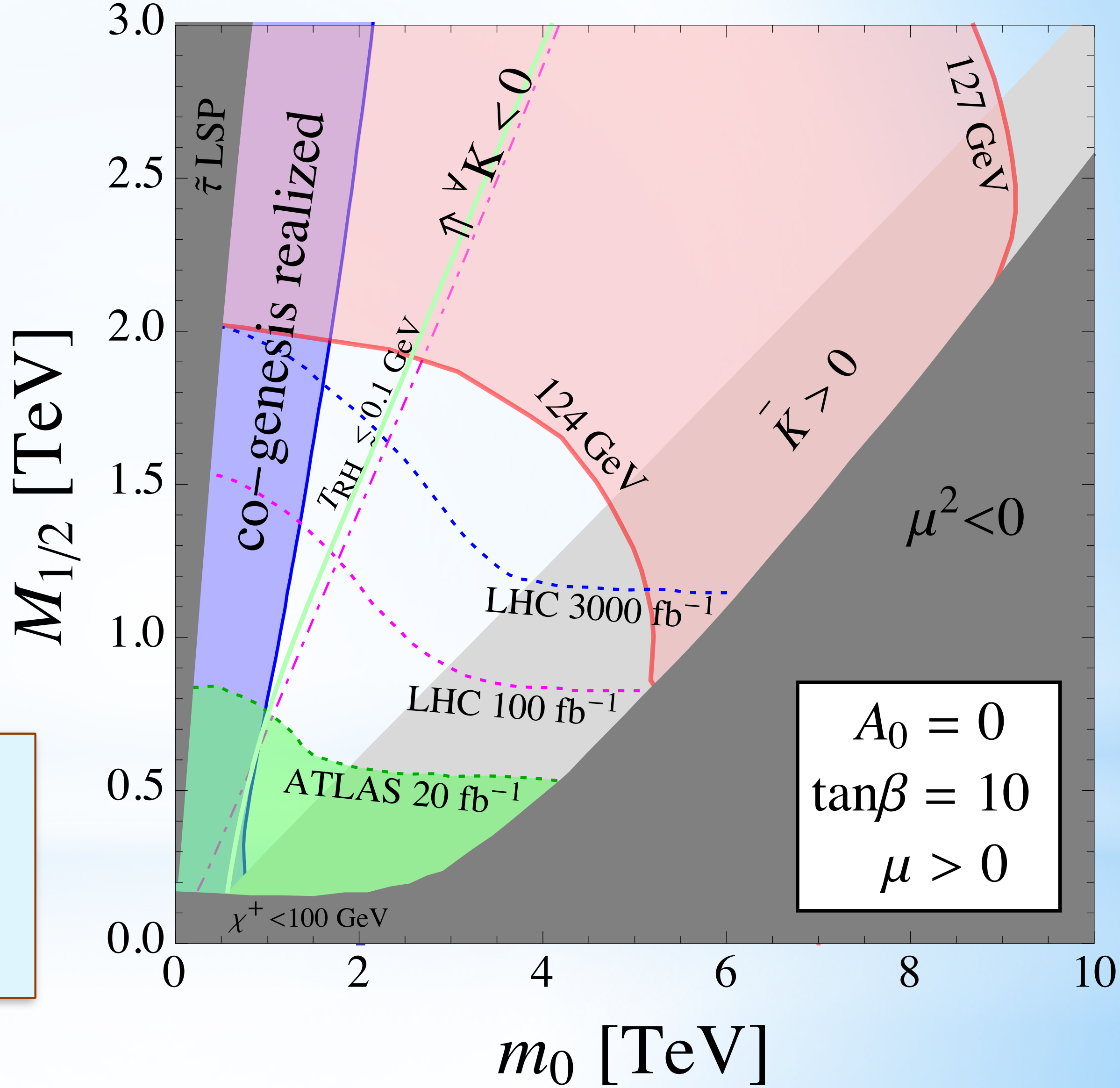
- To avoid the baryonic isocurvature constraint, low T_{RH} is favoured.

Harigaya, Mukaida, Kamada, Kawasaki, M.Y., 14

Baryon and DM co-genesis : results

SOFTSUSY 3.3.6
FeynHiggs 2.10.0
Buchmueller et. al., 12, 13
Feng, Kant, Profumo, Sanford, 13
Baer, Barger, Lessa, Tata, 09, 12

Kamada, Kawasaki, M.Y., 14



uncertain, ≦ 36

$$\frac{\Omega_b}{\Omega_{DM}} = \frac{m_p}{3m_{LSP}} \frac{8n_q}{\sum_\chi n_\chi f\left(\frac{m_\chi}{m_{\tilde{q}}}\right)}$$

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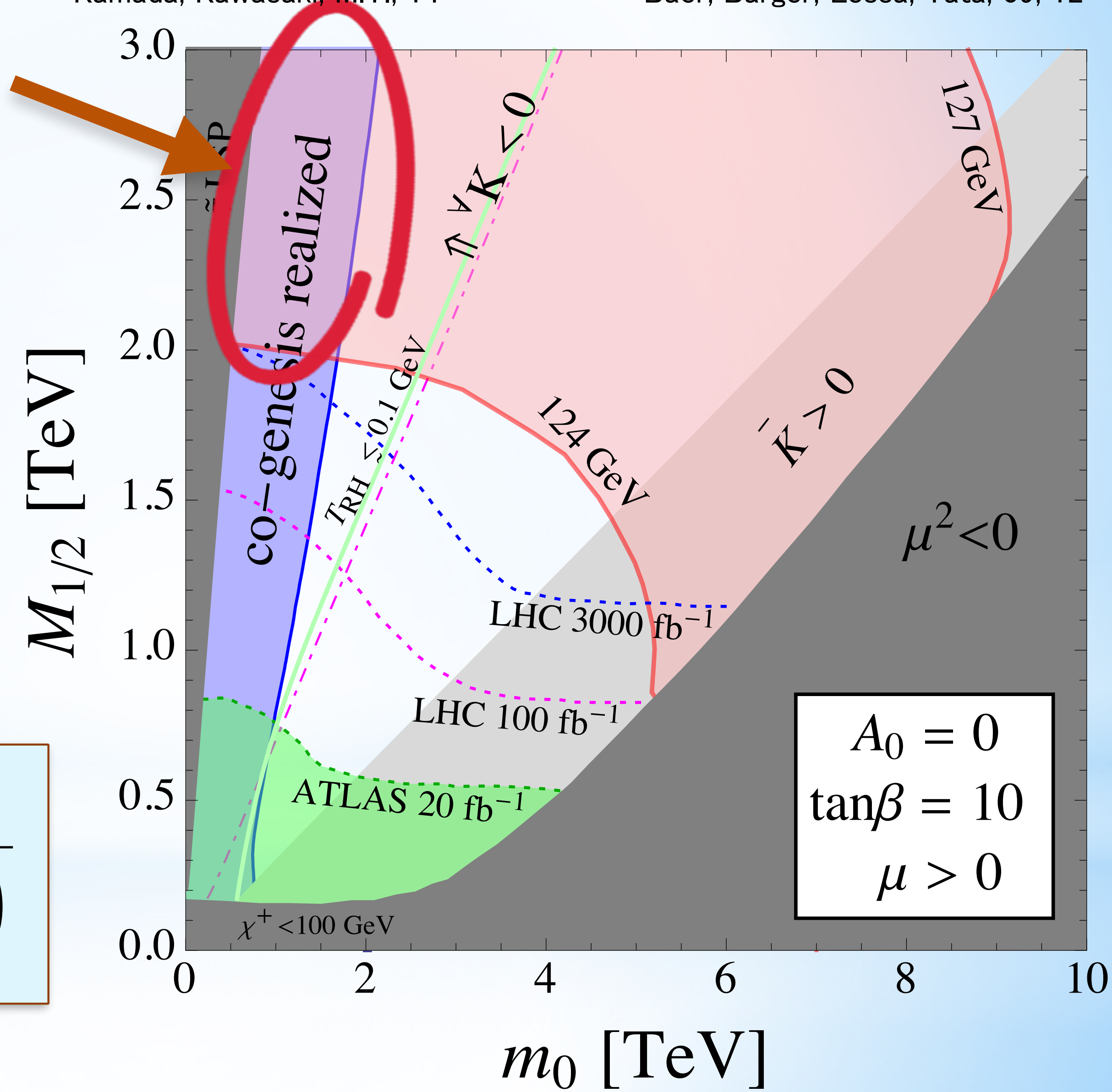

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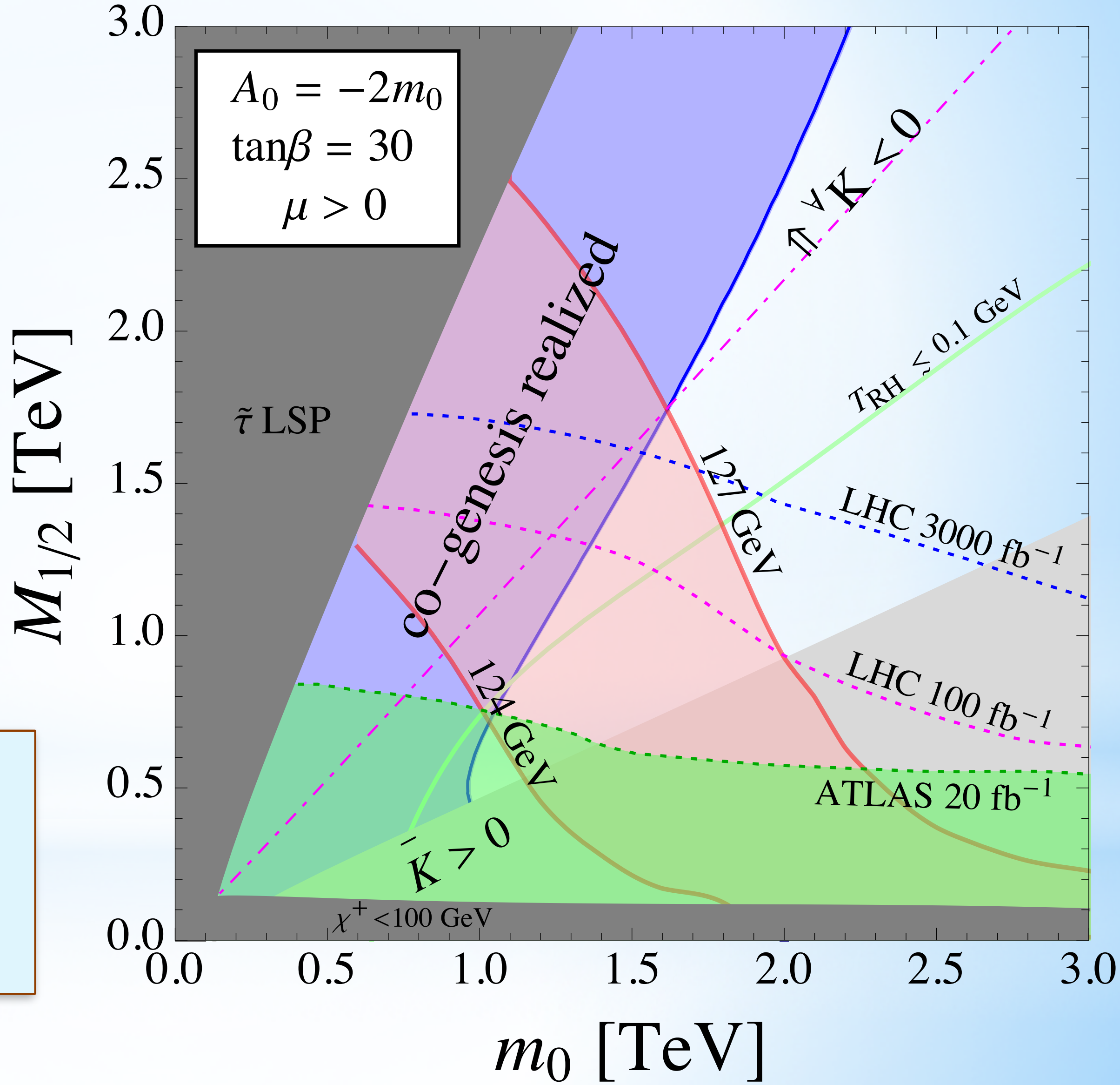

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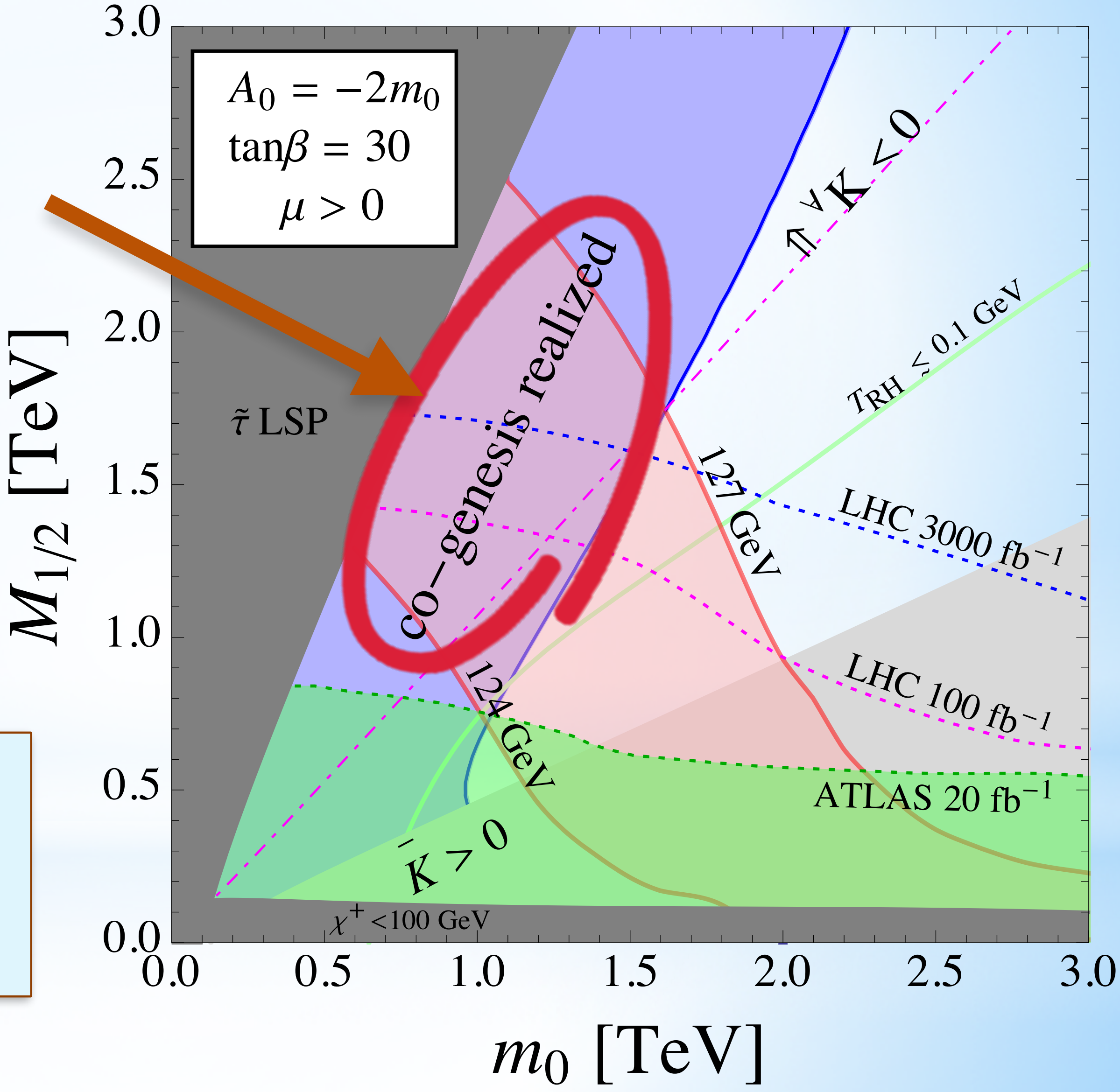

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$$\frac{\Omega_b}{\Omega_{\rm DM}} = \frac{m_p}{3m_{\rm LSP}} \frac{8n_q}{\sum_\chi n_\chi f\left(\frac{m_\chi}{m_{\tilde{q}}}\right)}$$

Summary

Kamada, Kawasaki, M.Y., 14

We have shown that
the baryon-DM coincidence problem can be solved in the CMSSM.

$$\frac{\Omega_b}{\Omega_{\rm DM}} = \mathcal{O}(1)$$

The result is consistent with the 126 GeV Higgs boson
and would be tested by future LHC experiments.

Note that
the scenario is applicable to a wide range of SUSY models in gravity mediation.

back up slides

Baryon and DM co-genesis : assumption of low T_{RH}

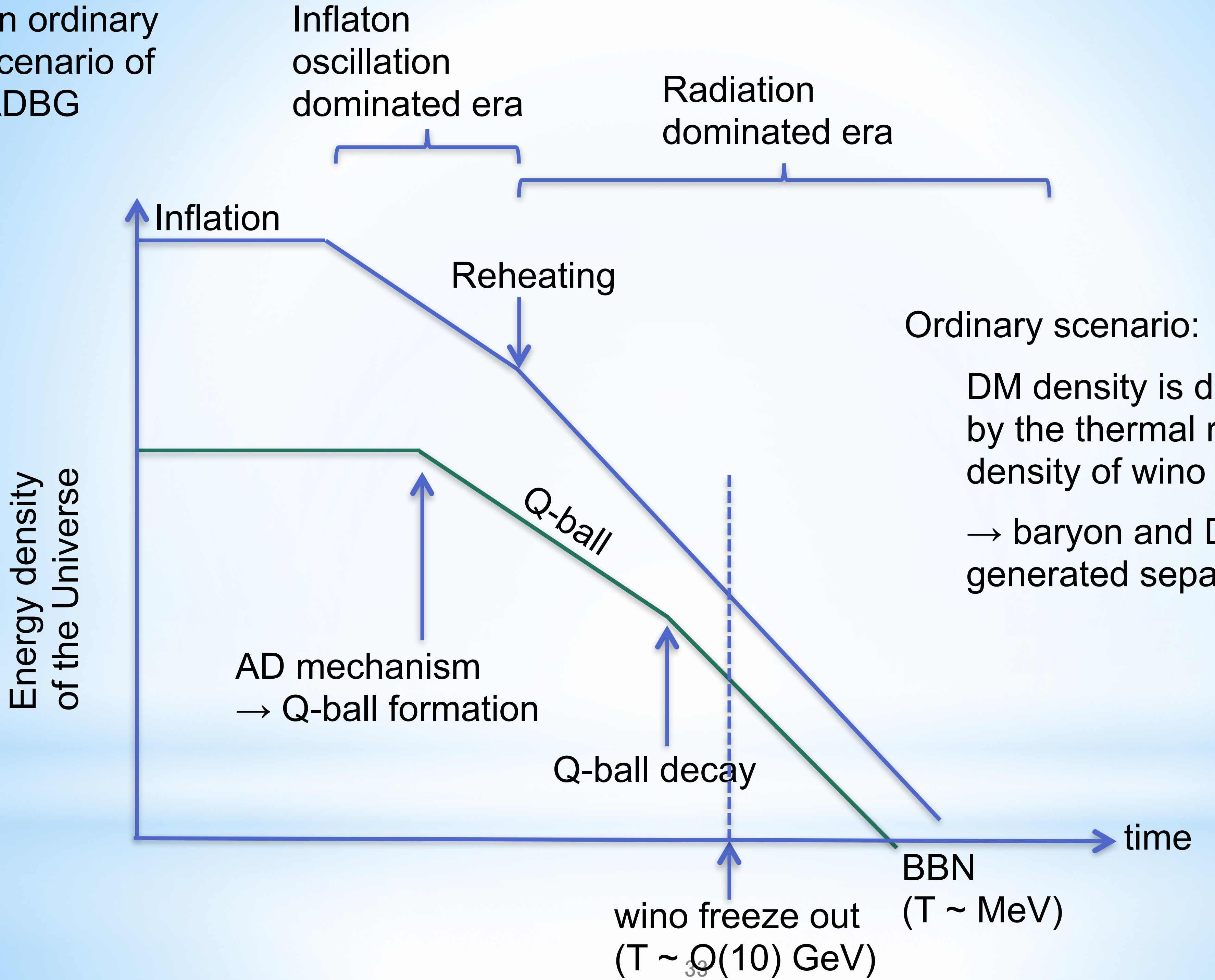
Kamada, Kawasaki, M.Y., 13

The annihilation of the LSP (mostly bino) should be irrelevant to realise the co-genesis scenario.

- First, we check whether the LSPs kinematically thermalised due to elastic scatterings (sfermion exchange) with the thermal plasma or not

thermalised → use the thermally averaged annihilation cross section

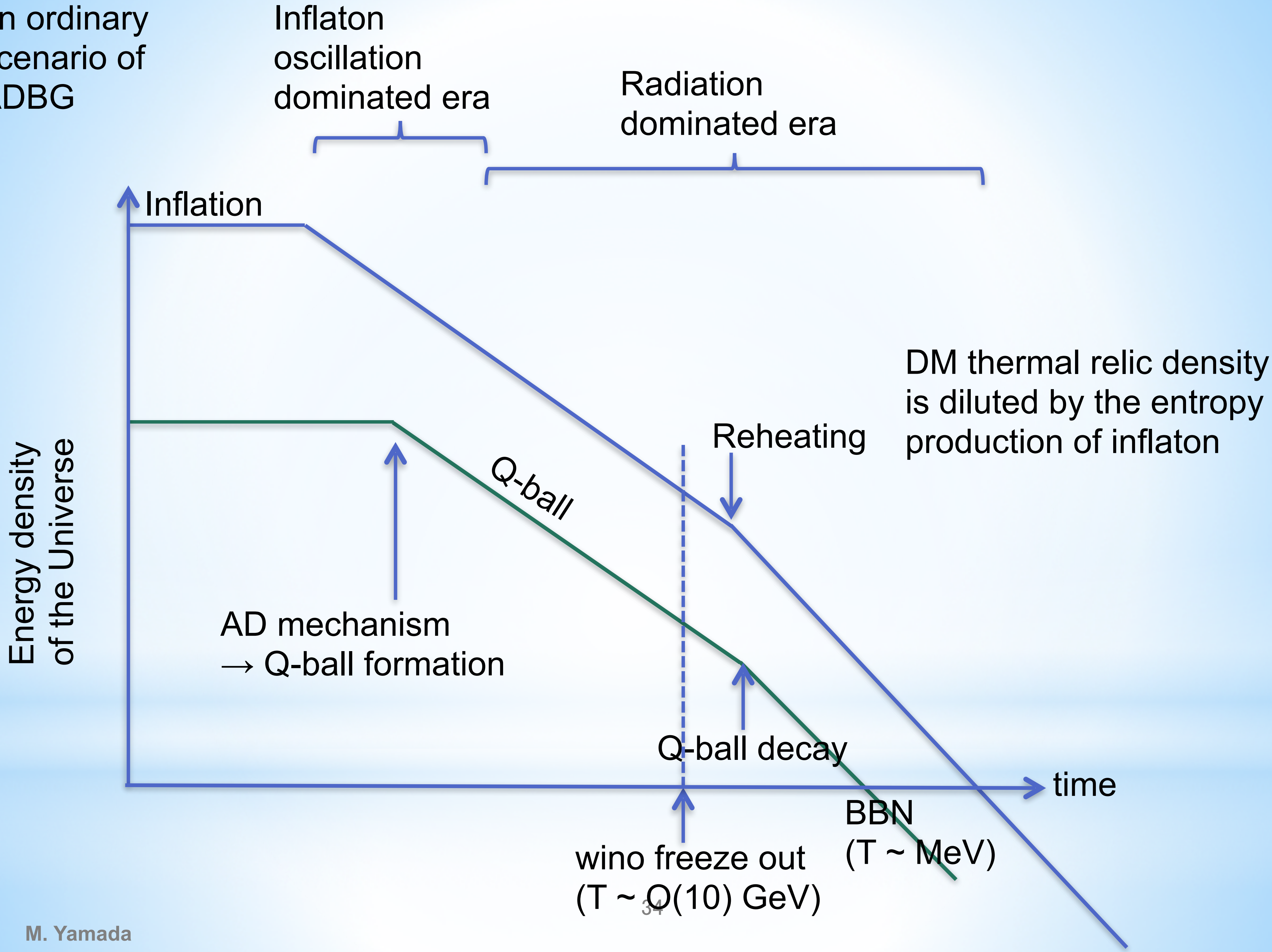
not thermalised → use the non-thermal annihilation cross section including enhancement of annihilation cross section due to resonance effects an ordinary scenario of ADBG



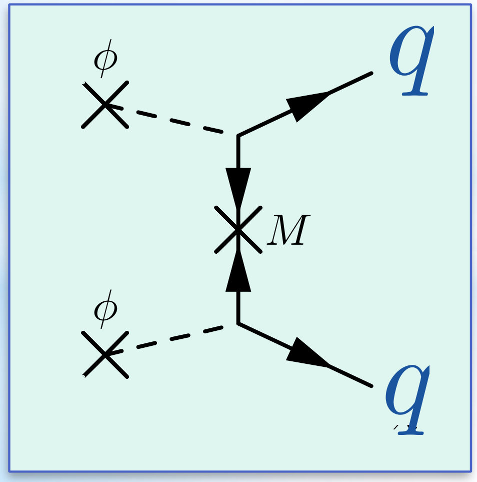
Ordinary scenario:

DM density is determined by the thermal relic density of wino

→ baryon and DM are generated separately an ordinary scenario of ADBG



	gluino exchange	bino exchange	higgsino exchange
$\tilde{\tilde{u}}_1^R = \frac{1}{\sqrt{3}}\phi$	u_1^G, u_1^B	u_1^R	
$\tilde{\tilde{d}}_1^G = \frac{1}{\sqrt{3}}\phi$	d_1^R, d_1^B	d_2^G	do not change color (left handed) top, bottom (Q_3) $\rightarrow$ + 6
$\tilde{\tilde{d}}_2^B = \frac{1}{\sqrt{3}}\phi$	d_2^G, d_2^R	d_2^B	



n_q = 15

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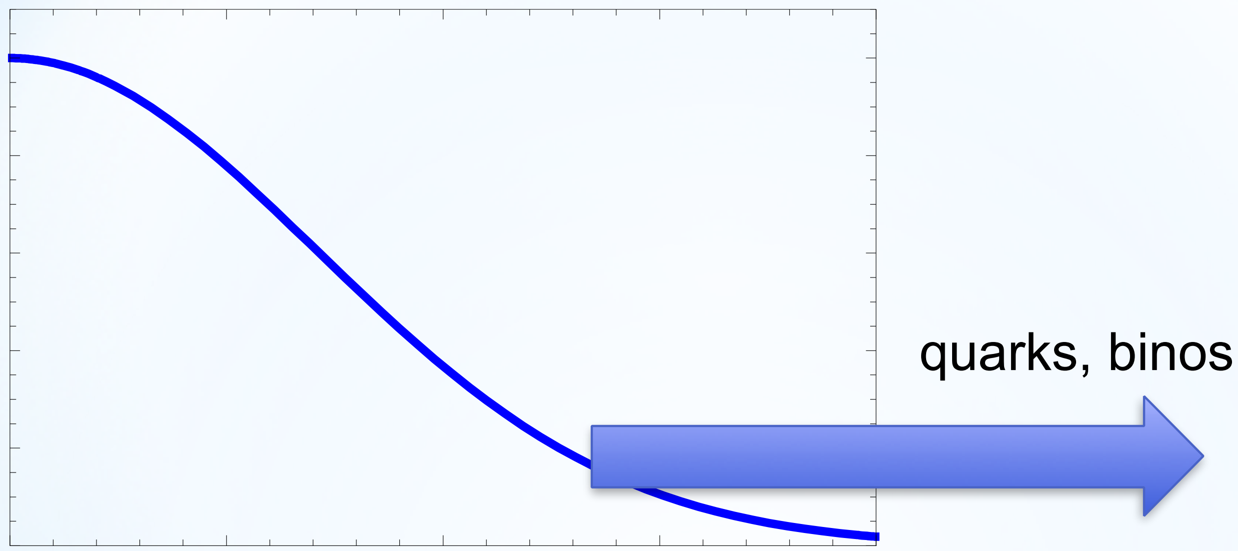
Q-ball configuration: $\Phi(r) = \Phi_0 \exp(-r^2 / R^2)$



squarks have VEVs inside Q-balls
→ higgs does not have VEV
→ bino and wino do not mix with each other

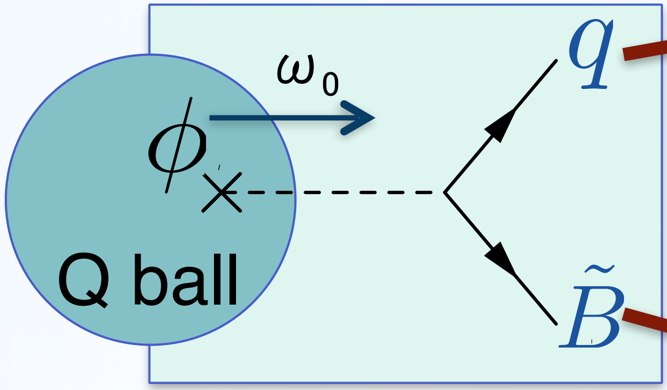
Q-ball decay rate

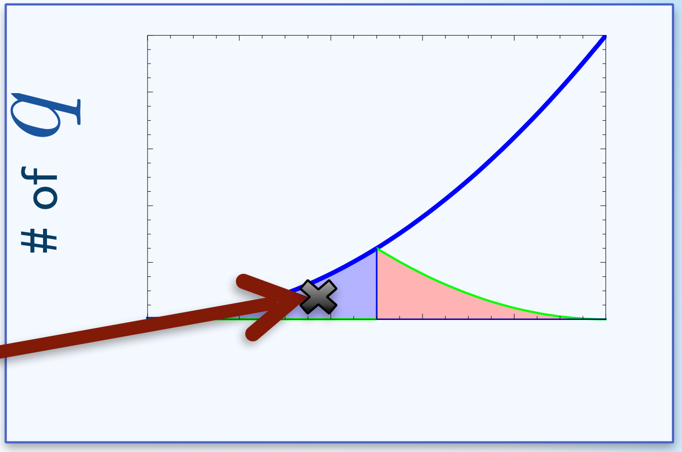
Cohen, et. al, 86

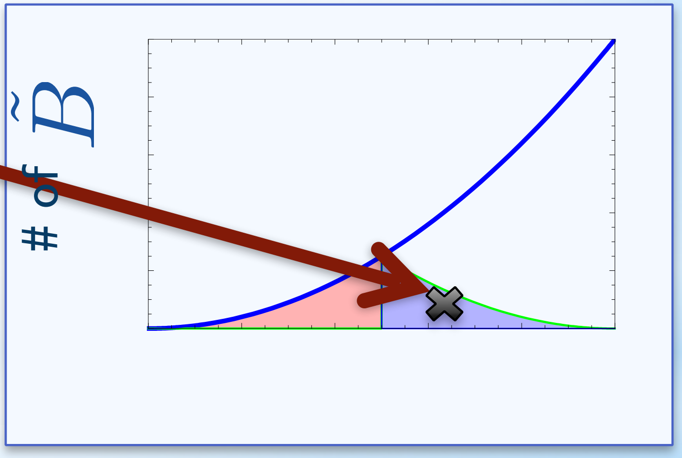
upper bound of flux (massless):

$$n \cdot j \lesssim 2 \int \frac{\mathrm{d}^3 k}{(2\pi)^3} \theta\left(\frac{\omega_0}{2} - |k|\right) \theta(k \cdot n) \hat{k} \cdot n$$

$$= \frac{2}{8\pi^2} \int_0^{\omega_0/2} k^2 \mathrm{d}k$$







bino production rate

$(R \sim \omega_0^{-1})$

$$\frac{\mathrm{d}}{\mathrm{d}t} N_{\tilde{B}} \lesssim 4\pi R^2 \times (\text{flux}) = \frac{R^2 \omega_0^3}{24\pi} \quad <<<< \quad \Gamma \times Q \sim g^2 \omega_0 \times \phi_0^2 / \omega_0^2$$

$$\mathcal{L}_{\rm int} = g\phi\chi\lambda + M_{\tilde{g}}\lambda\lambda + h.c.$$

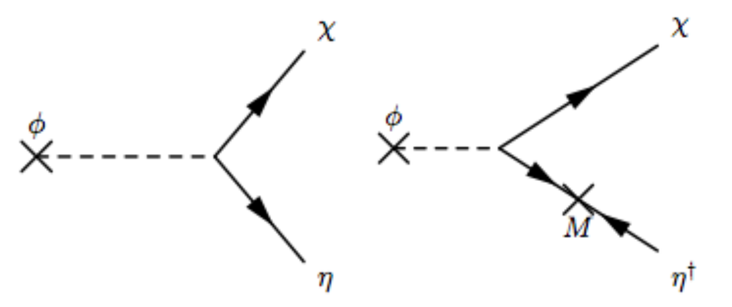


FIG. 14: Diagrams for $\phi \to \chi\eta$.

we can neglect helicity flips

×8 for M > omega_0

∝ M^2 for M < omega_0

Kawasaki, M.Y.
hep-ph/1209.5781

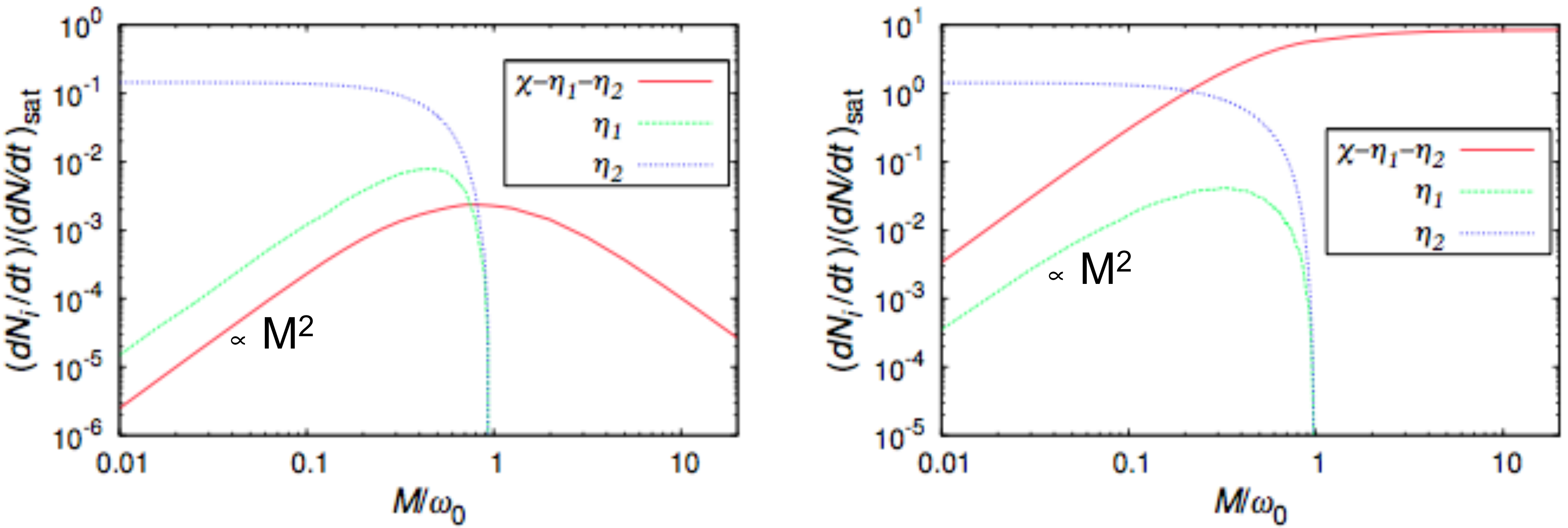
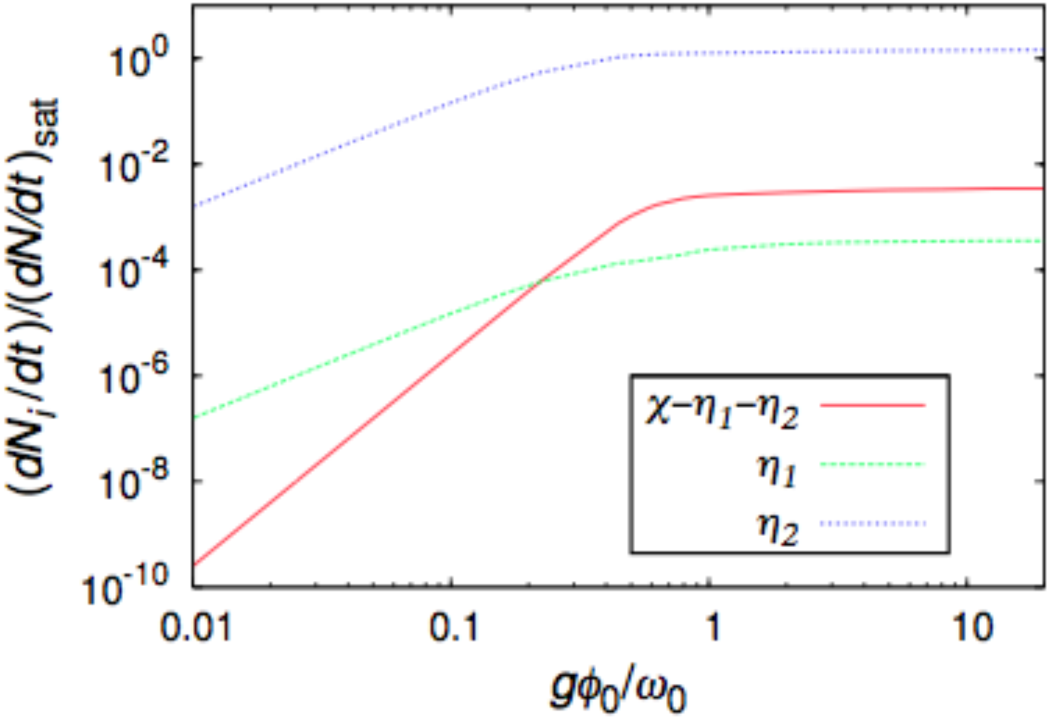


FIG. 12: Production rates of χ, η_1 and η_2 from Q balls as a function of M/ω_0 for $g\phi_0/\omega_0 = 0.1$ (left panel) and for $g\phi_0/\omega_0 = 10$ (right panel) with $R\omega_0 = \pi$ in the Yukawa theory with a massive fermion. The vertical axis is normalized by the saturated rate of Eq. (36).



Kawasaki, M.Y.
hep-ph/1209.5781

FIG. 13: Production rates of χ, η_1 and η_2 from Q balls as a function of $g\phi_0/\omega_0$ with $R\omega_0 = \pi$ and $M/\omega_0 = 0.01$ in the Yukawa theory with a massive fermion. The vertical axis is normalized by the saturated rate of Eq. (36).

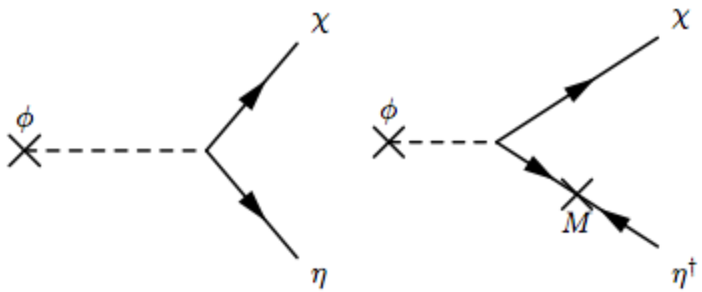


FIG. 14: Diagrams for $\phi \to \chi\eta$.

if gluinos are much lighter than squarks,
gluino exchange processes are irrelevant

$$\mathcal{L}_{\rm int} = g\phi\chi\lambda + M_{\tilde{g}}\lambda\lambda + h.c.$$

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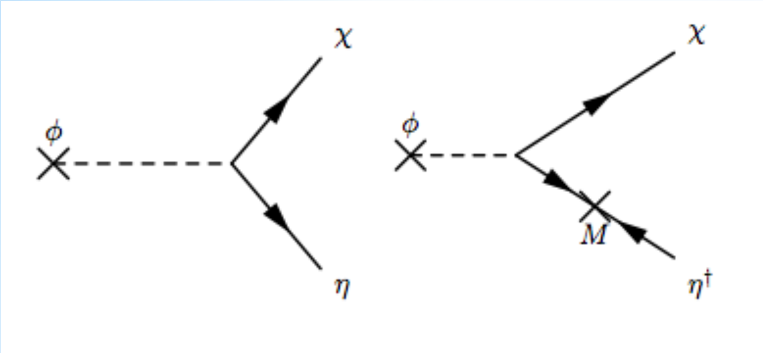
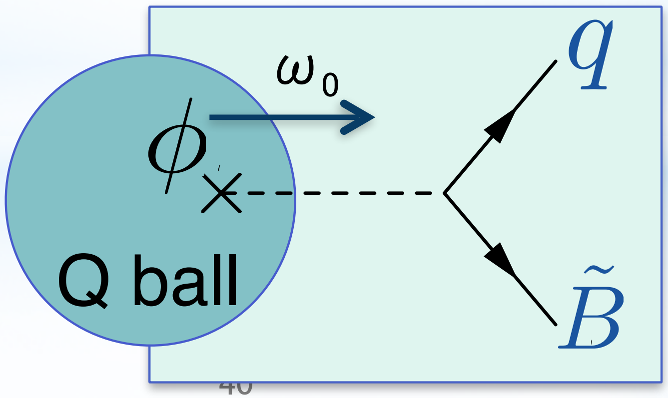


FIG. 14: Diagrams for $\phi \to \chi\eta$.

Loop diagrams can be neglected inside Q-balls
because fields interacting with Φ gain the large mass of $g\Phi_0$ (>>>>ω_0)

Loop diagrams can be also neglected outside Q-balls
because the decay rate is determined by the Pauli blocking effect
at the surface of Q-ball



Case of non-zero bino mass

$$\omega_0 = 1$$

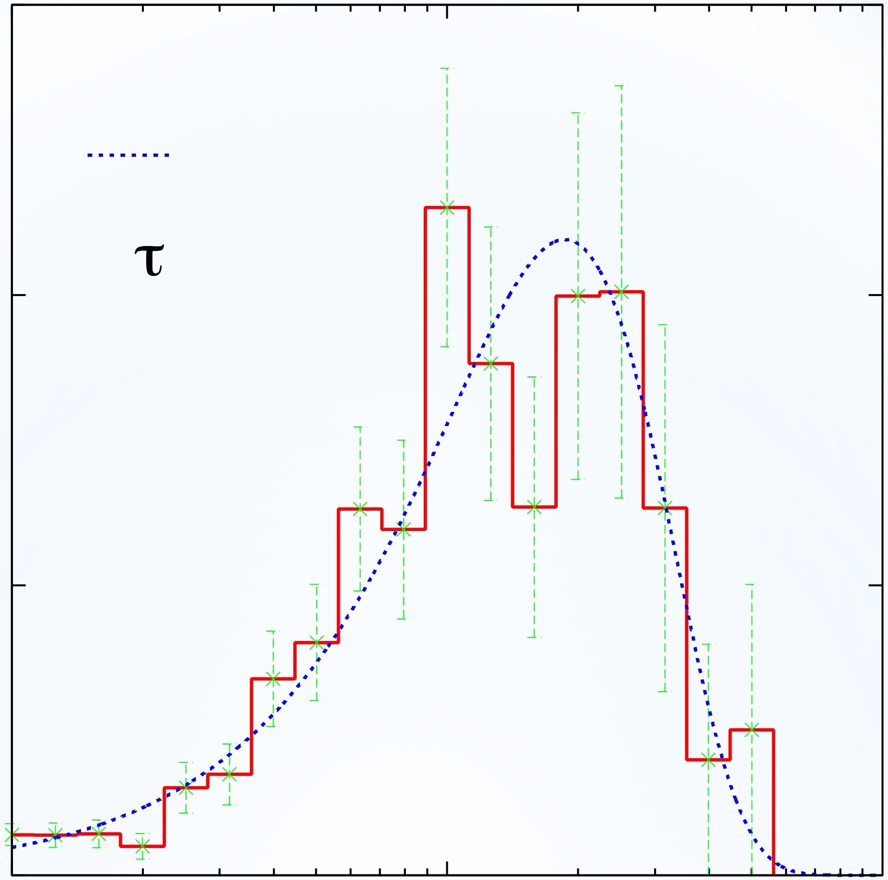
$$\frac{1}{8\pi^2}\int_0^{1-m} dE \ \mathrm{Min}[E^2, (1-E)\sqrt{(1-E)^2 - m^2} v]$$ for $$m > 1/2$$

$$\frac{1}{8\pi^2}\int_0^{1/2} dE \ \mathrm{Min}[E^2, (1-E)\sqrt{(1-E)^2 - m^2} v] + \frac{1}{8\pi^2}\int_m^{1/2} dE \ E\sqrt{E^2 - m^2} v$$

for $$m < 1/2$$

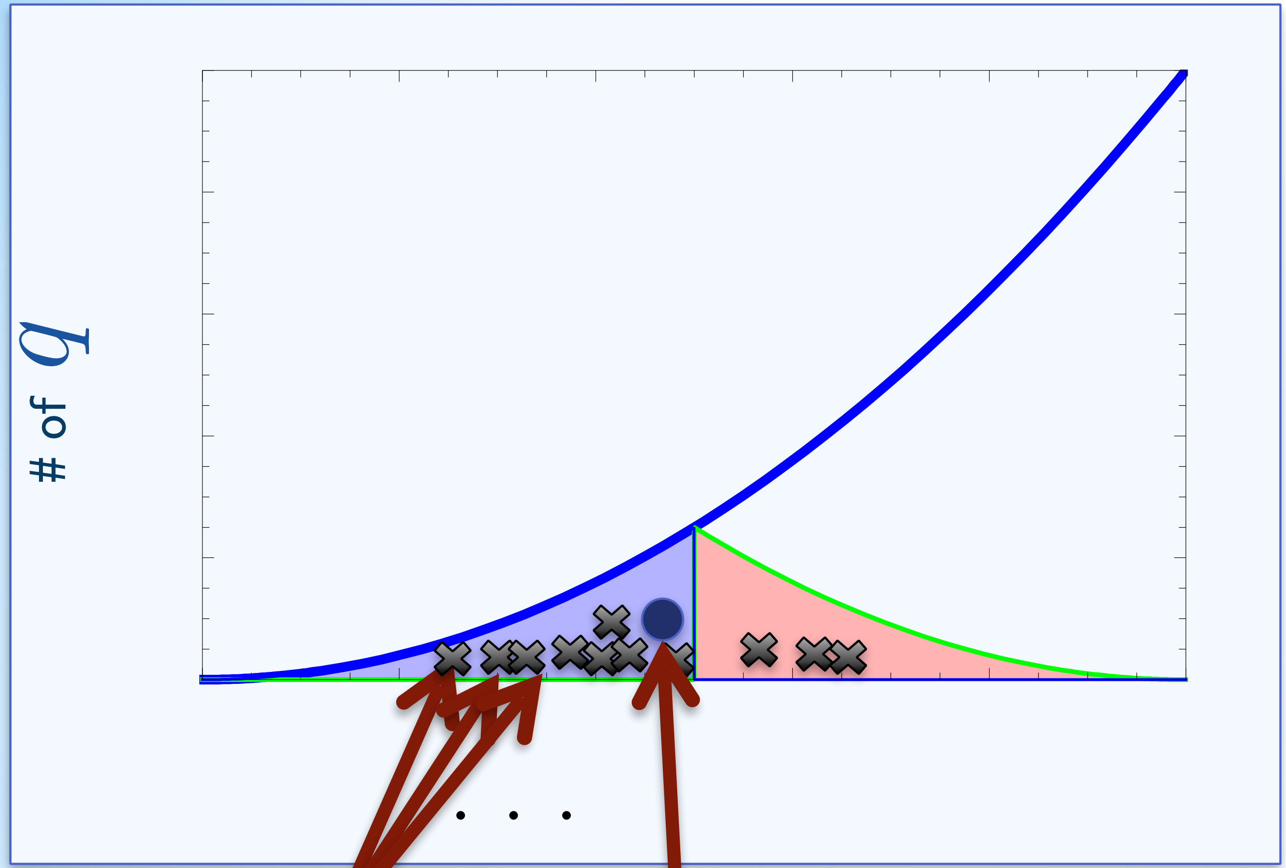
$$v = p/E = \sqrt{E^2 - m^2}/E$$

M. Yamada



Charge density distribution of Q-balls

Hiramatsu, Kawasaki, and Takahashi
hep-ph/1003.1779



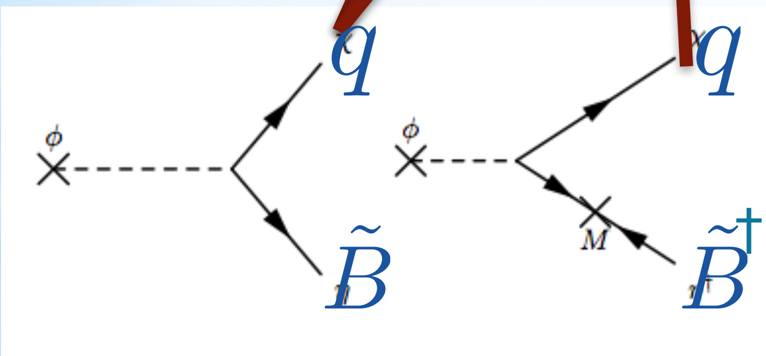


FIG. 14: Diagrams for $\phi \to \chi\eta$.

Each branching ratio is given by
(saturated rate) × Br(elementary process).

$$Br(\text{chirality flip}) = M^2/\omega_0^2$$

$$\mathcal{L}_{\text{int}} = g\phi\chi\lambda + M_{\tilde{g}}\lambda\lambda + h.c.$$