Opening the window to the co-genesis with Affleck-Dine mechanism in gravity mediation

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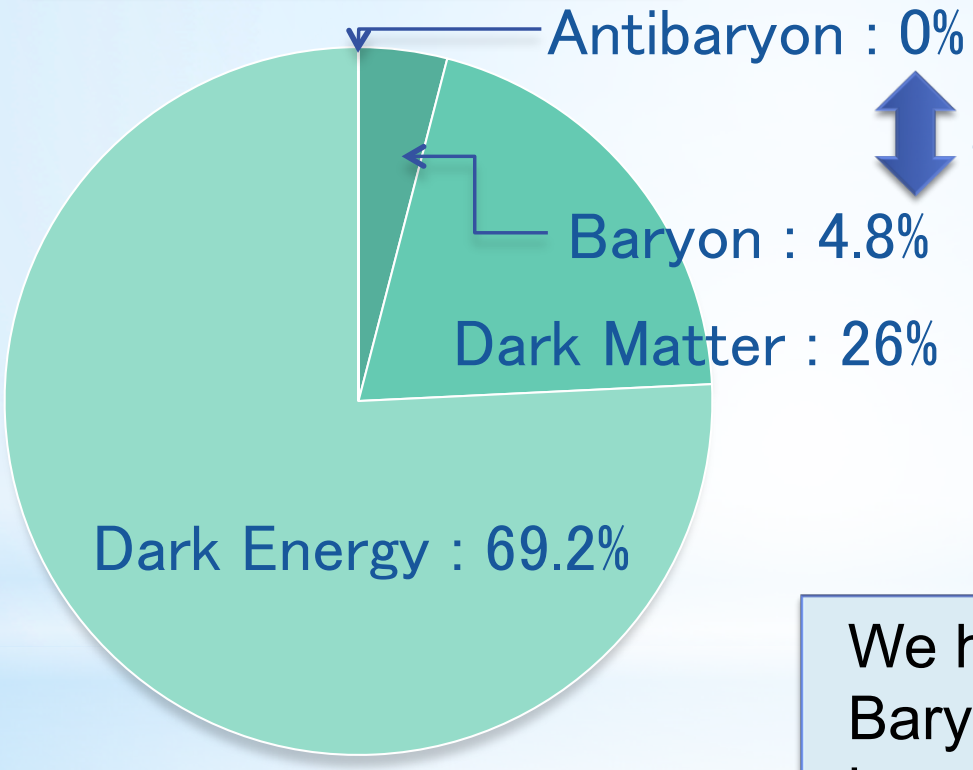
A. Kamada, M. Kawasaki and M.Y., Phys. Lett. B **719** (2013) 9

COSMO 2013 @Cambridge, UK

Introduction: motivation

Content of the Universe



Planck (2013)

asymmetry

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

coincidence problem

→ B# and DM have the same origin?

We have proposed a scenario of Baryon and DM co-genesis in gravity or anomaly mediation

Introduction: SUSY

"SM particles"

quark
lepton
higgs
gauge boson
- B boson
- W boson
- gluon

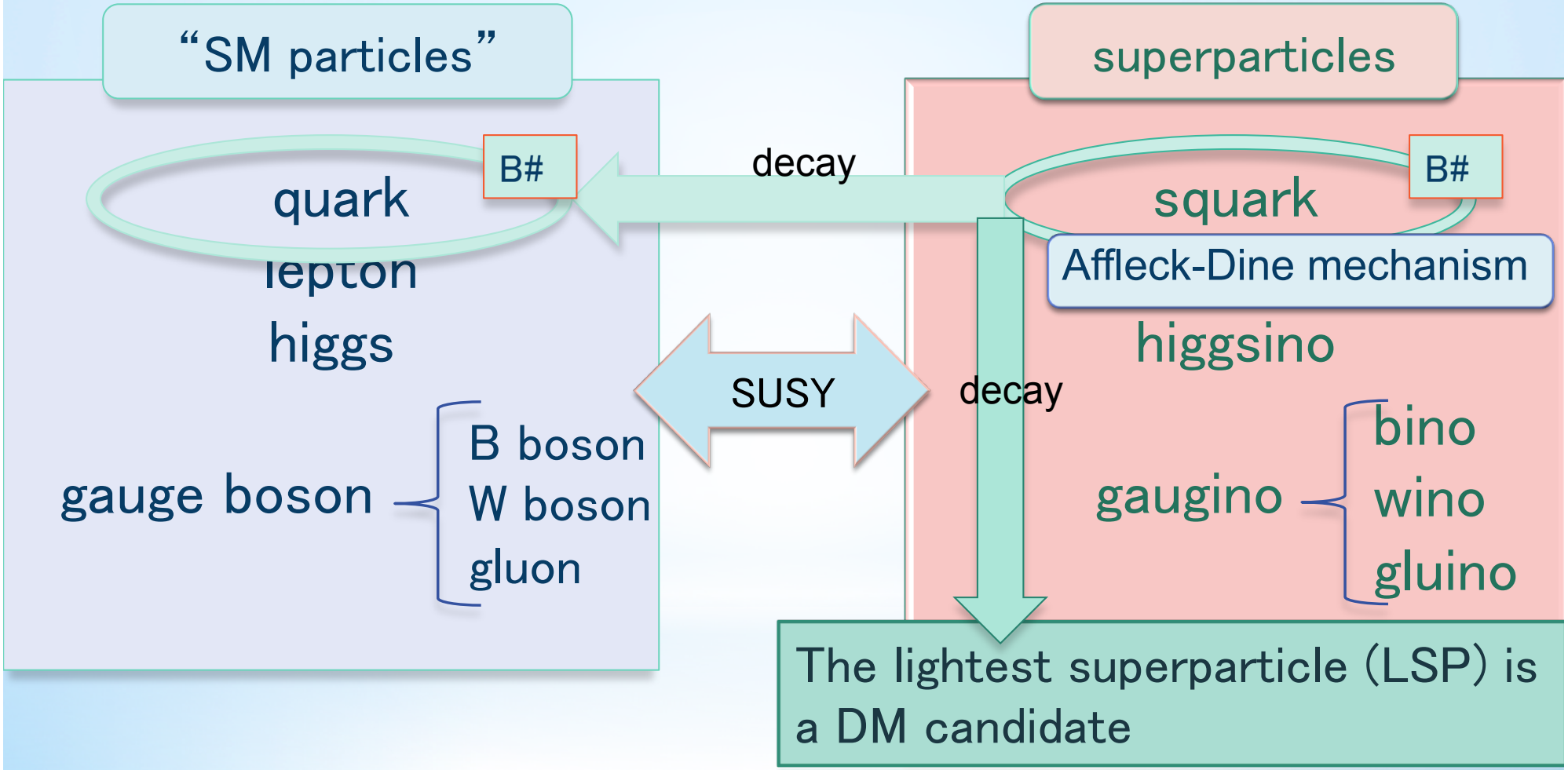
SUSY

superparticles

squark
slepton
higgsino
gaugino
- bino
- wino
- gluino

The lightest superparticle (LSP) is a DM candidate

Introduction: SUSY



Introduction: Affleck–Dine baryogenesis

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

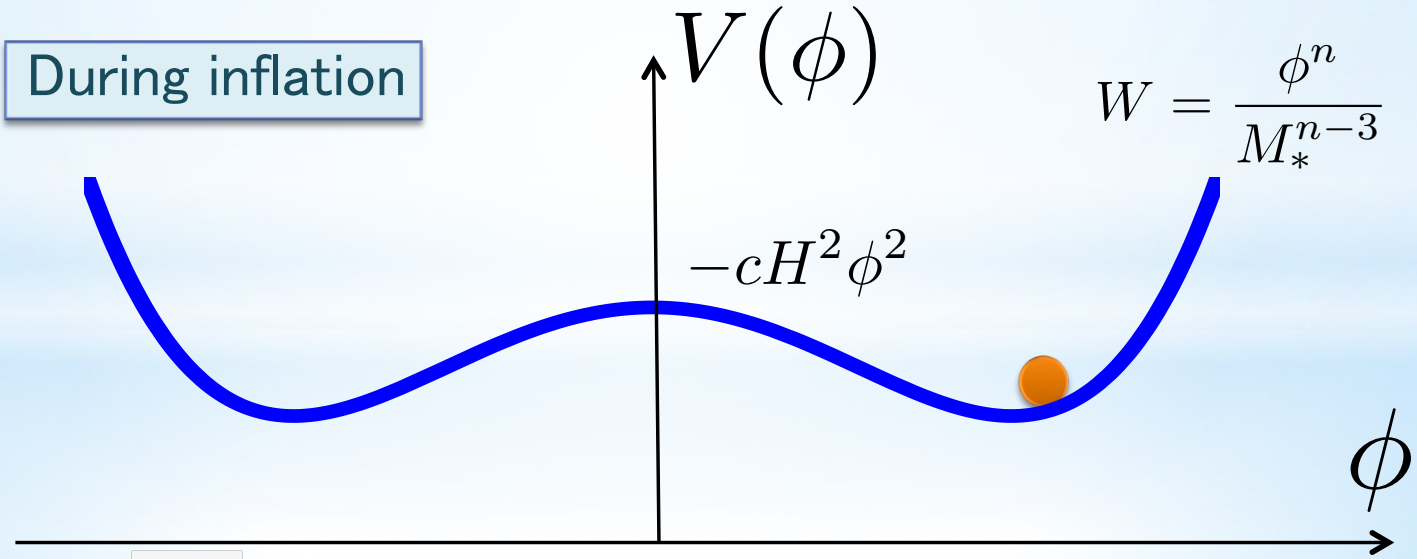
SUSY → many flat directions (denoted by ϕ)

ex)

$$\tilde{\bar{u}}_1^R = \frac{1}{\sqrt{3}}\phi \qquad \tilde{\bar{d}}_1^G = \frac{1}{\sqrt{3}}\phi \qquad \tilde{\bar{d}}_2^B = \frac{1}{\sqrt{3}}\phi$$

squark → B#

During inflation



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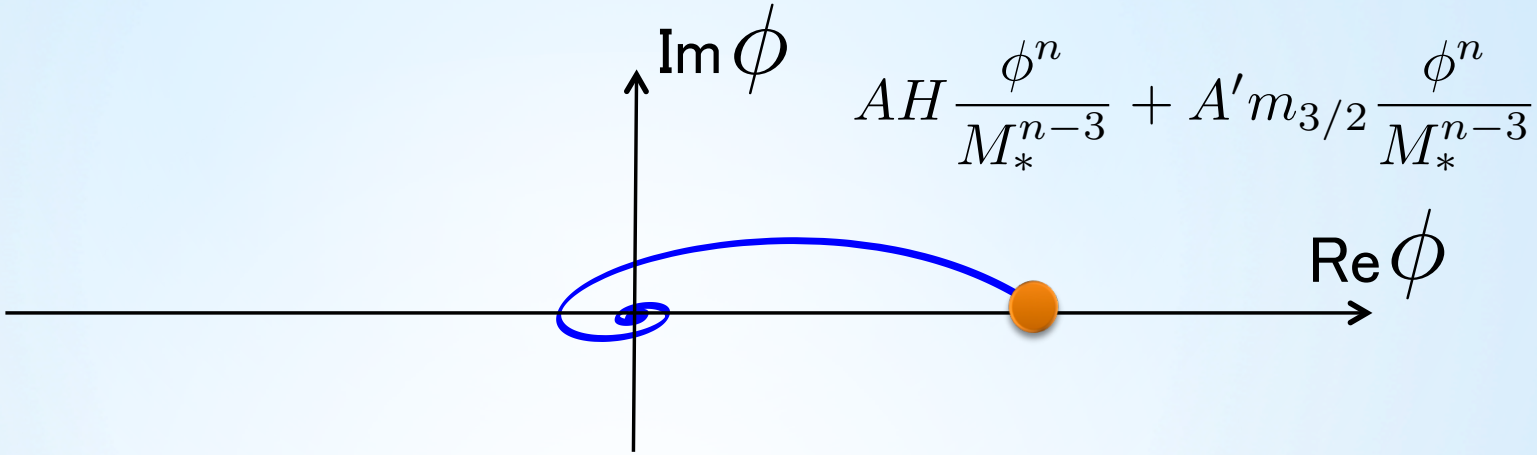
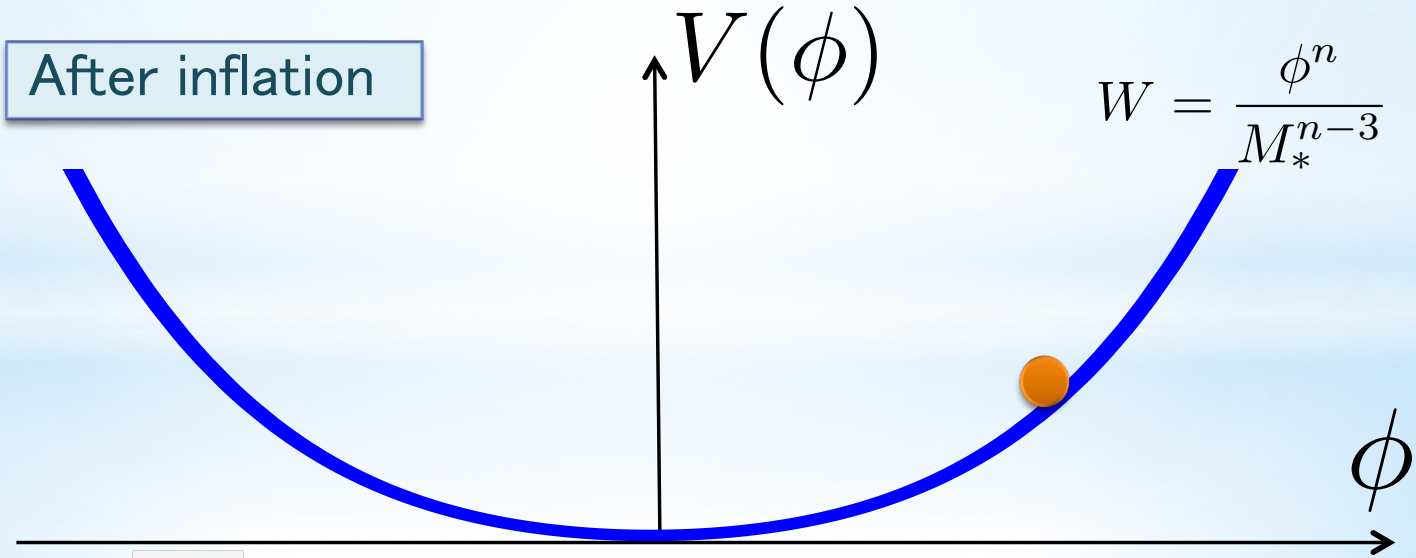


$$AH\frac{\phi^n}{M_*^{n-3}} + A' m_{3/2}\frac{\phi^n}{M_*^{n-3}}$$

After inflation

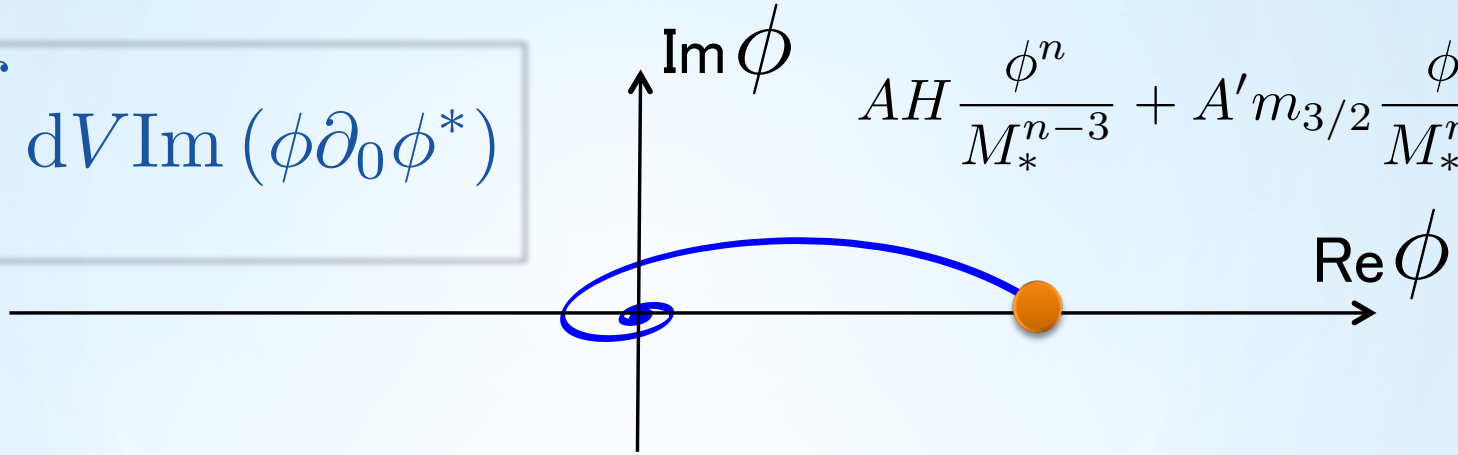


$$W = \frac{\phi^n}{M_*^{n-3}}$$

Introduction: Affleck–Dine baryogenesis

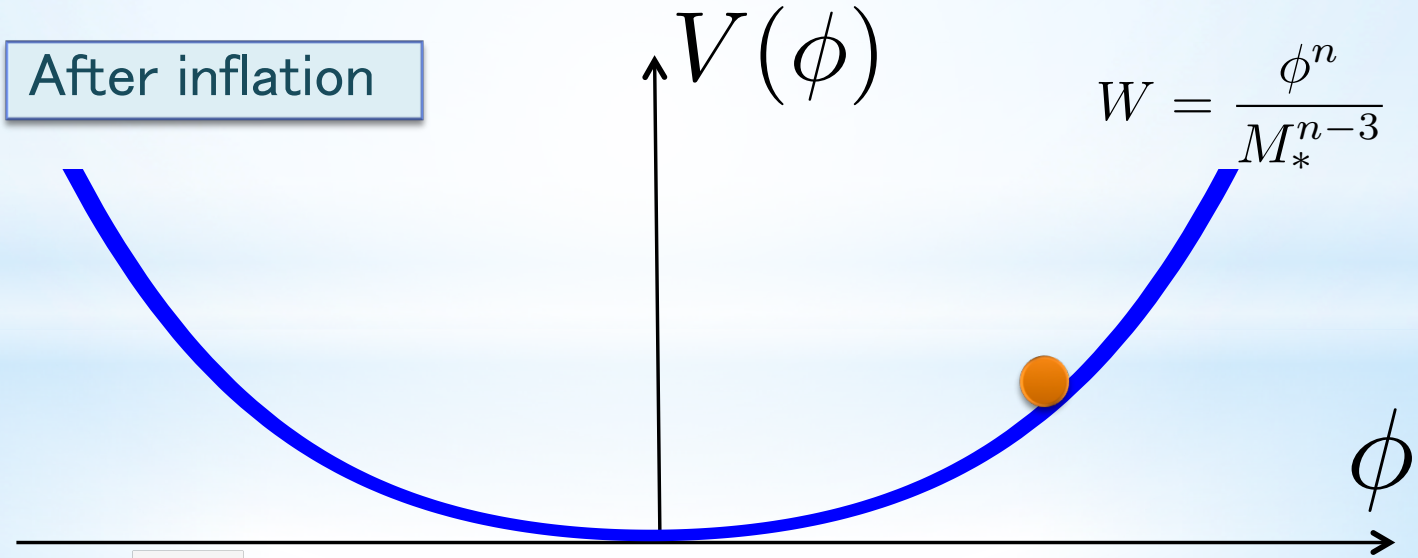
Affleck, Dine, 85
Dine, Randall, Thomas, 96

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



$$AH\frac{\phi^n}{M_*^{n-3}} + A' m_{3/2}\frac{\phi^n}{M_*^{n-3}}$$

After inflation



$$W = \frac{\phi^n}{M_*^{n-3}}$$

Introduction: Q-ball

Coleman, 85

AD baryogenesis → coherent oscillation with B#

↑ spatially unstable

→ fragment into non-topological solitons

: Q-balls (with B#)

Then, before the BBN,

Q-balls decay into
- quarks (→ baryon)
- superparticles (→ DM)

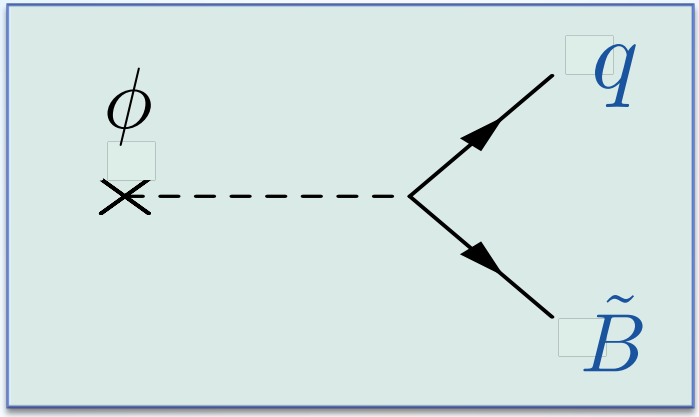
Baryon and DM have the same origin

→ naturally explains the observed baryon-to-DM ratio (1/5)

Q-ball decay rates (into binos)

Cohen, *et. al*, 86

Q-ball decay rates can be roughly estimated from the collection of the elementary processes like



$\times Q$

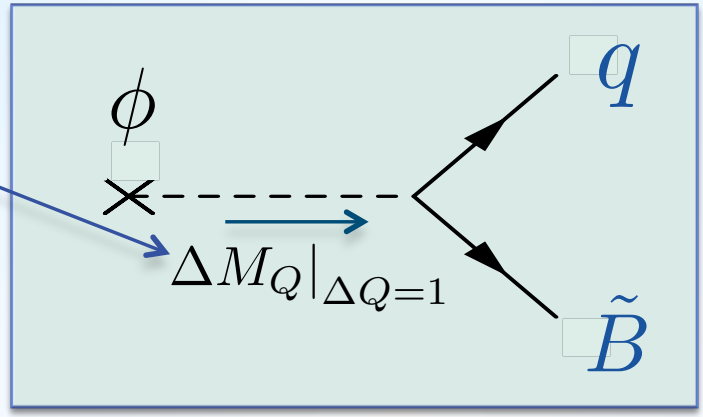
B# carried by the Q-ball

Q-ball decay rates (into binos)

Cohen, *et. al*, 86

Q-ball decay rates can be roughly estimated from the collection of the elementary processes like

difference of Q-ball energy



$\times Q$

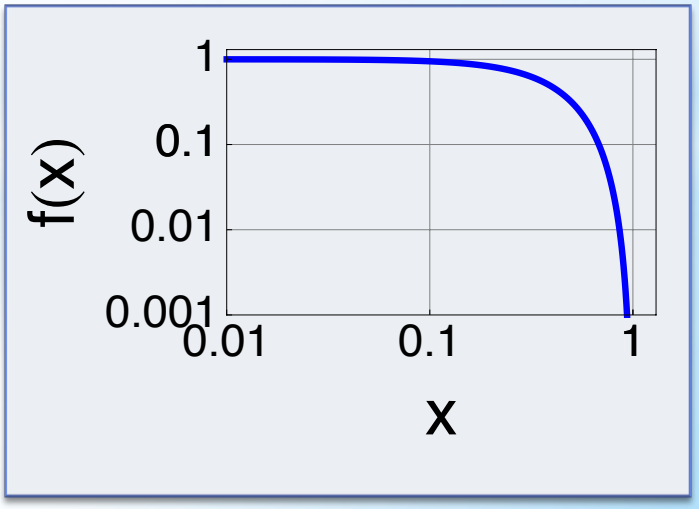
B# carried by the Q-ball

However,
fermion production rates are saturated by the Pauli exclusion principle

$$\frac{dN_{\tilde{B}}}{dt} \simeq \text{(phase space volume per unit time)}$$

$$= 4\pi R^2 \times \frac{E^3}{96\pi^2} \times f\left(\frac{m_{\tilde{B}}}{E}\right)$$

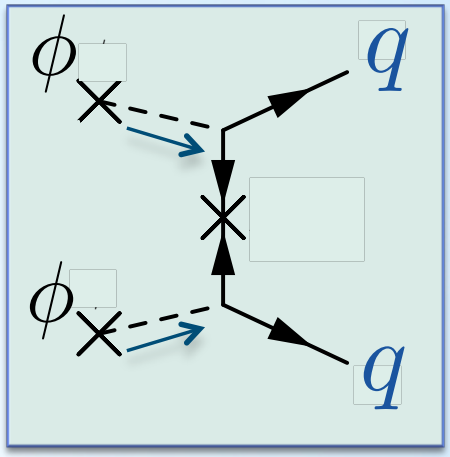
$$\left(E = \Delta M_Q|_{\Delta Q=1}\right)$$



Q-ball decay rates (into quarks)

Kawasaki, M.Y., 13

Q-ball can decay into quarks via gluino exchange



- $\Delta M_Q|_{\Delta Q=2} = 2 \times \Delta M_Q|_{\Delta Q=1}$

  ➡ $\times 2^3$ for quark production rate

- many # of DOFs: color, flavor, left-right handed

  ➡ $\times n_q$ for *total* quark production rate

  (# of DOFs of quarks interacting with Q-ball)

typically, $n_q \approx 15$

Therefore, the ratio of the Q-ball decay rates into quarks and binos is given by

$$\frac{B_q}{B_{\tilde{B}}} = \frac{8 \times n_q}{f\left(\frac{m_{\tilde{B}}}{E}\right)}$$

B# and DM co-genesis : setup

Kamada, Kawasaki, M.Y., 13

- We assume Q-balls are made up of only right handed squarks

- mass spectrum

heavy

gluino, higgsino

squark $\simeq \Delta M_Q|_{\Delta Q=1}$

bino

wino = LSP = DM

$$m_{\tilde{W}} = \mathcal{O}\left(E_{\mathrm{EW}}\right)$$

light

B# and DM co-genesis : setup

Kamada, Kawasaki, M.Y., 13

- We assume Q-balls are made up of only right handed squarks

  Since right handed squarks have no SU(2) charge,
  these Q-balls do not decay into winos

- mass spectrum

heavy

gluino, higgsino

squark $\simeq \Delta M_Q|_{\Delta Q=1}$

bino

wino = LSP = DM

$$m_{\tilde{W}} = \mathcal{O}\left(E_{\rm EW}\right)$$

light

→ Q-balls decay only into quarks and binos

branching ratio:

$$\frac{B_q}{B_{\tilde{B}}} = \frac{8 \times n_q}{f\left(\frac{m_{\tilde{B}}}{E}\right)}$$

→ Then, the binos decay into winos.

If these winos do **NOT** annihilate,

$$\frac{\Omega_b}{\Omega_{\rm DM}} = \frac{m_p}{3m_{\tilde{W}}}\frac{B_q}{B_{\tilde{B}}} \simeq \frac{1}{5}\,!$$

B# and DM co-genesis : a remark

Kamada, Kawasaki, M.Y., 13

- We assume that these winos do NOT annihilate (**)

Q-balls need to decay after the time of wino freeze-out

AD mechanism
↓
Q-ball
↓ ↓
quarks, binos
↓
winos (DM)

B# and DM co-genesis : a remark

Kamada, Kawasaki, M.Y., 13

AD mechanism
↓
Q-ball
↓ ↓
quarks, binos
↓
winos (DM)

- We assume that these winos do NOT annihilate (**)

↓

Q-balls need to decay after the time of wino freeze-out

↓

- Larger Q-balls decay later
- If a large value of B# is generated by the AD mechanism, large Q-balls are formed

$$\frac{\rho_{\rm B}}{s} \gg \left.\frac{\rho_{\rm B}}{s}\right|_{\rm obs}$$

In order to satisfy the condition (**), a large value of B# is generated

→ B# has to be diluted ⇒ { thermal inflation / domain wall decay

B# and DM co-genesis : setup

Kamada, Kawasaki, M.Y., 13

- We assume Q-balls are made up of only right handed squarks

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- mass spectrum

heavy

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squark $\simeq \Delta M_Q|_{\Delta Q=1}$

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→ Q-balls decay only into quarks and binos

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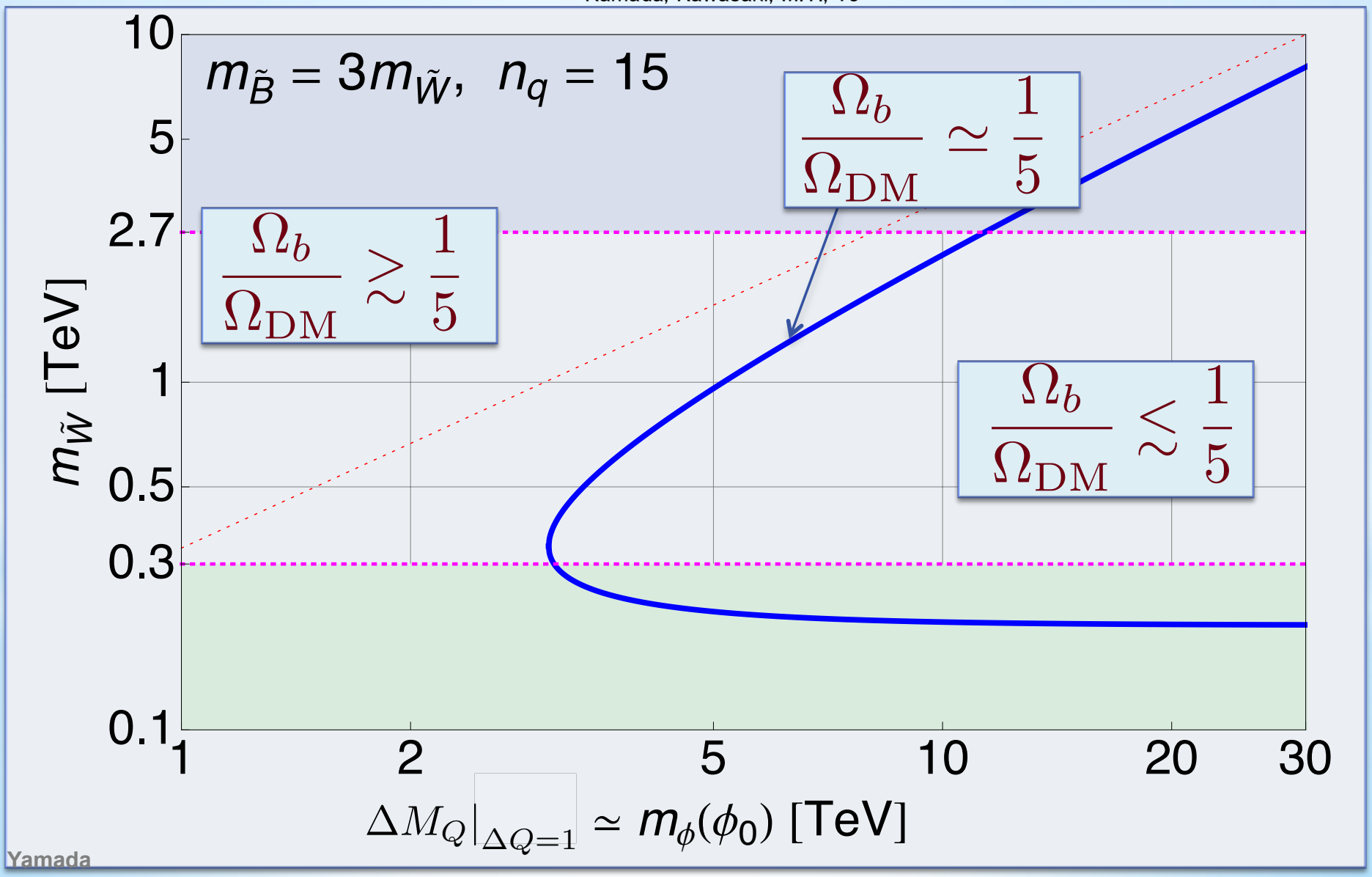
→ Then, the binos decay into winos.

If these winos do **NOT** annihilate,

$$\frac{\Omega_b}{\Omega_{\rm DM}} = \frac{m_p}{3m_{\tilde{W}}} \frac{B_q}{B_{\tilde{B}}} \simeq \frac{1}{5} \; !$$

B# and DM co-genesis : results

Kamada, Kawasaki, M.Y., 13



B# and DM co-genesis : results

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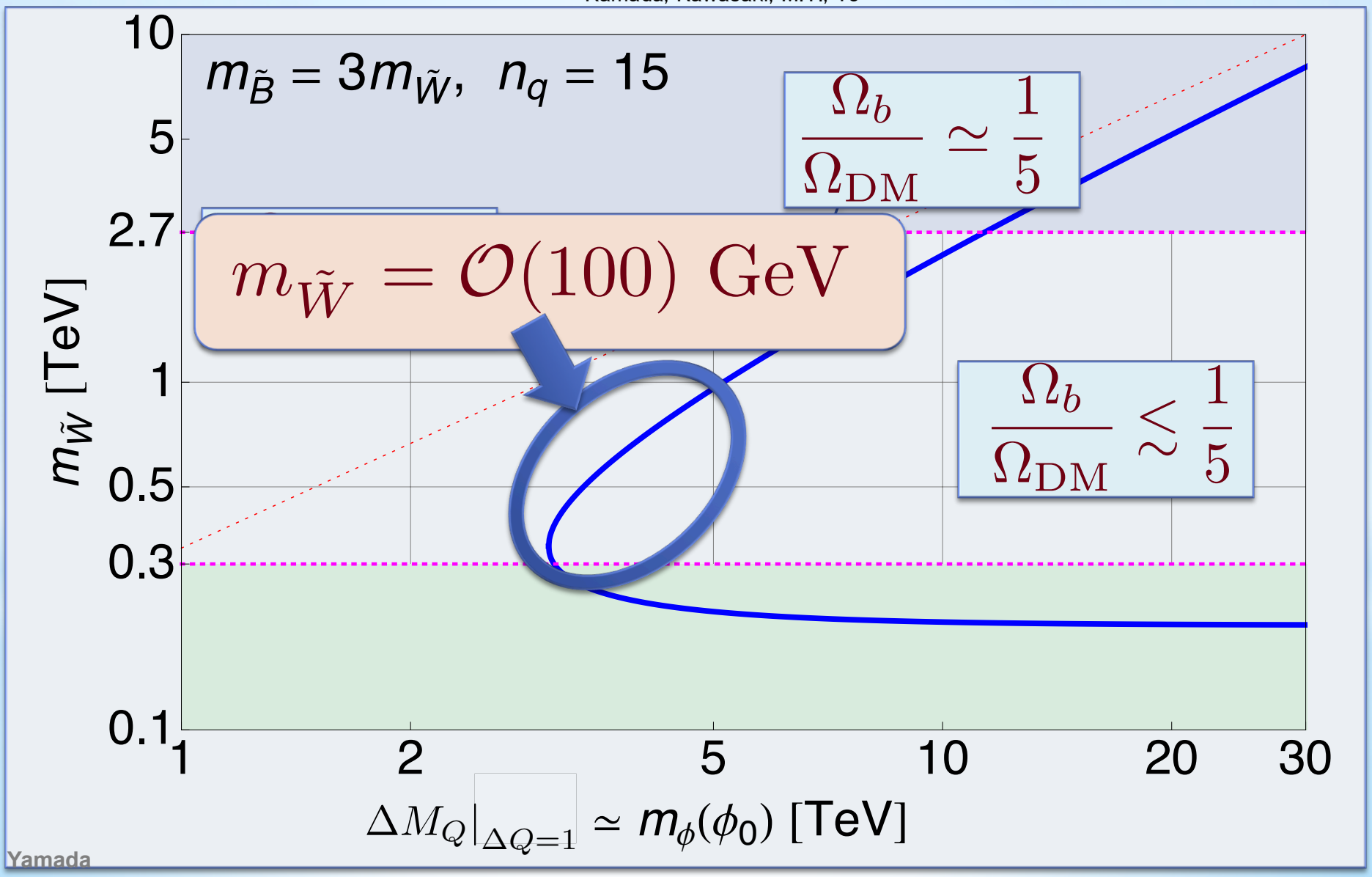

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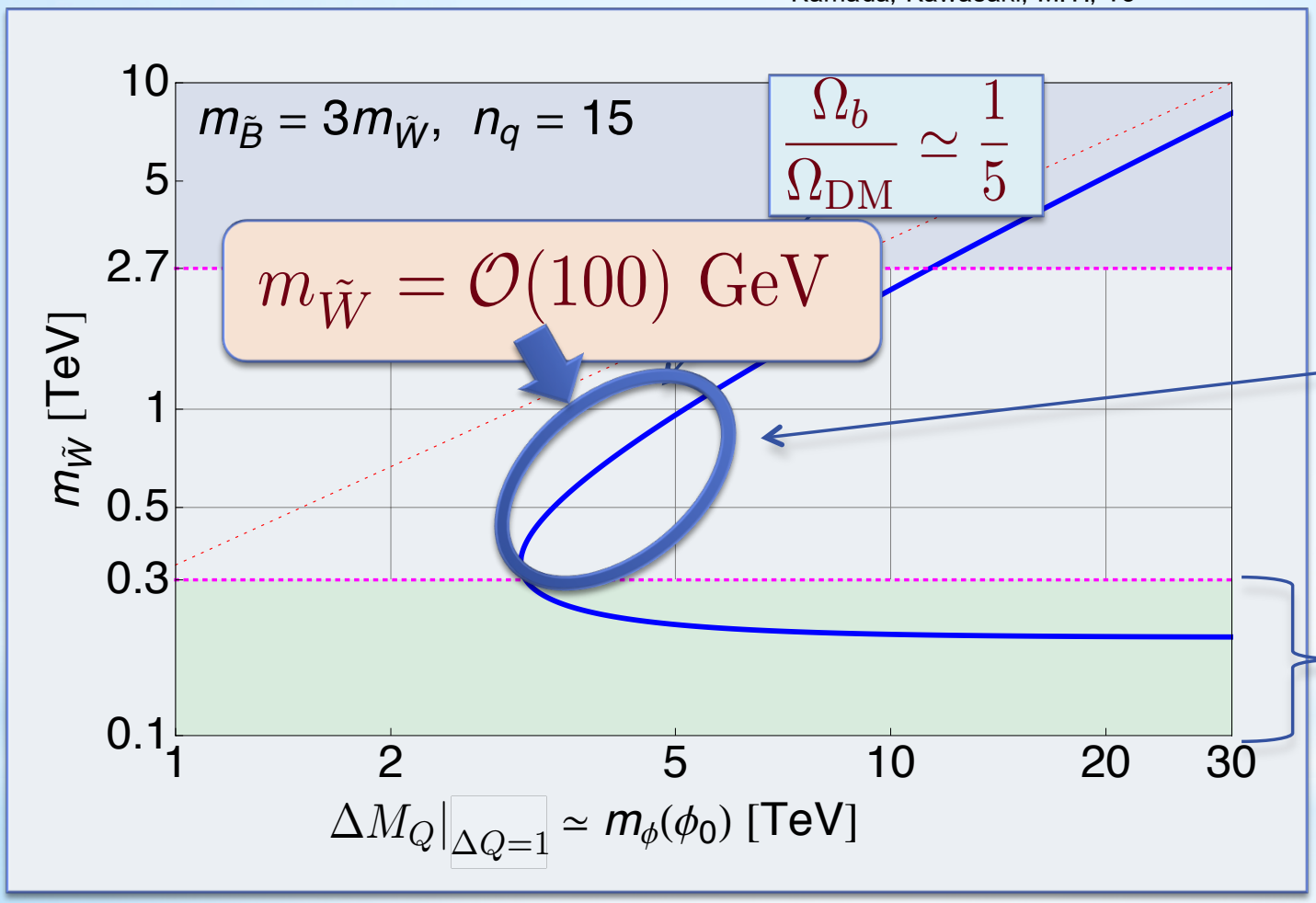


will be proved by AMS-02

already excluded

Ibe, Matsumoto, Yanagida, (2012)

Summary

Kamada, Kawasaki, M.Y., 13

We have proposed a new scenario of B# and DM co-genesis

- Gravity or anomaly mediation with wino LSP is considered
- We assume Q-balls are made up of only right handed squarks

$$\frac{\Omega_b}{\Omega_{\rm DM}} \simeq \frac{1}{5}$$

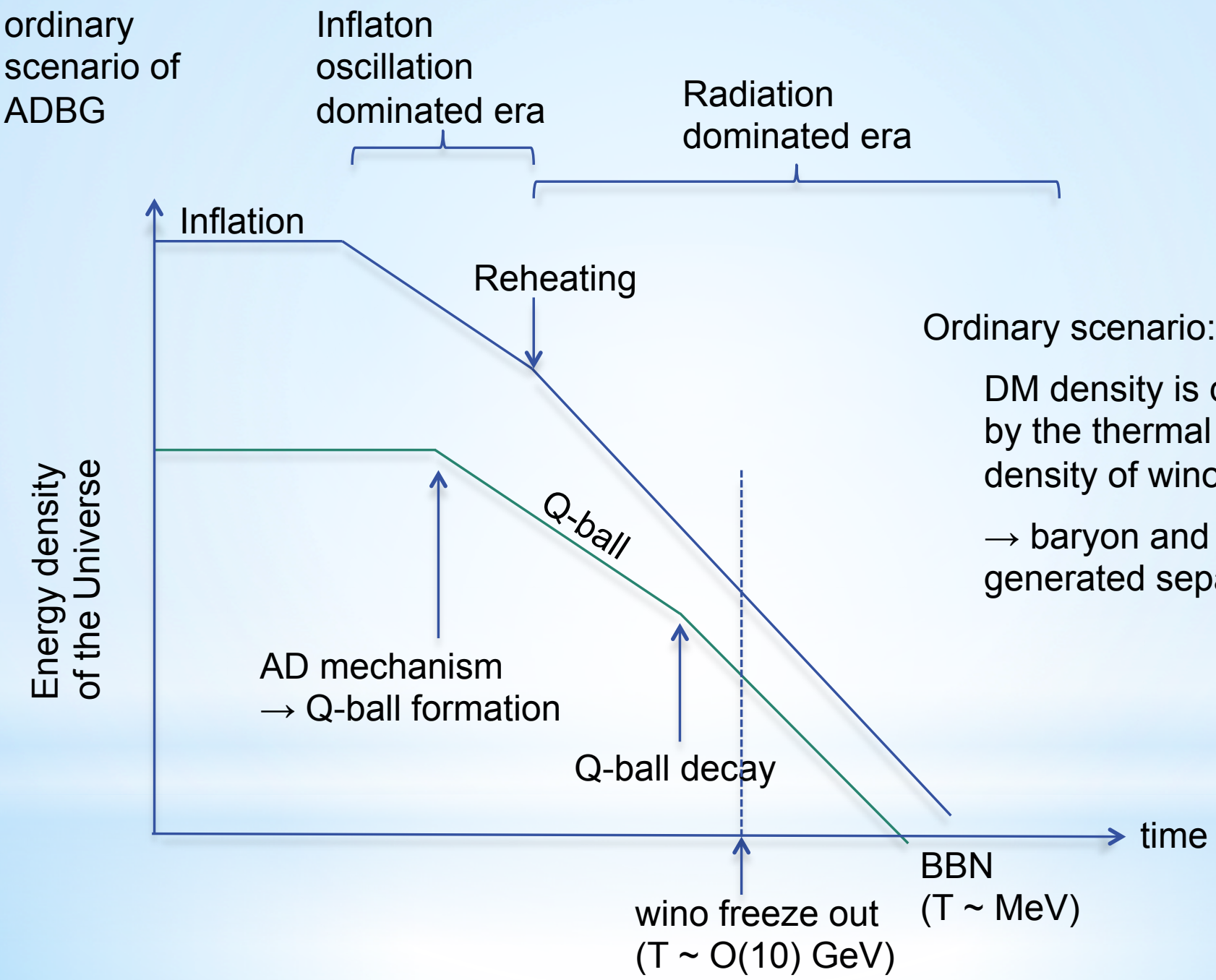
O(100) GeV wino DM can explain

This will be proved by AMS-02

- However, some entropy production mechanism is needed

thermal inflation
domain wall decay

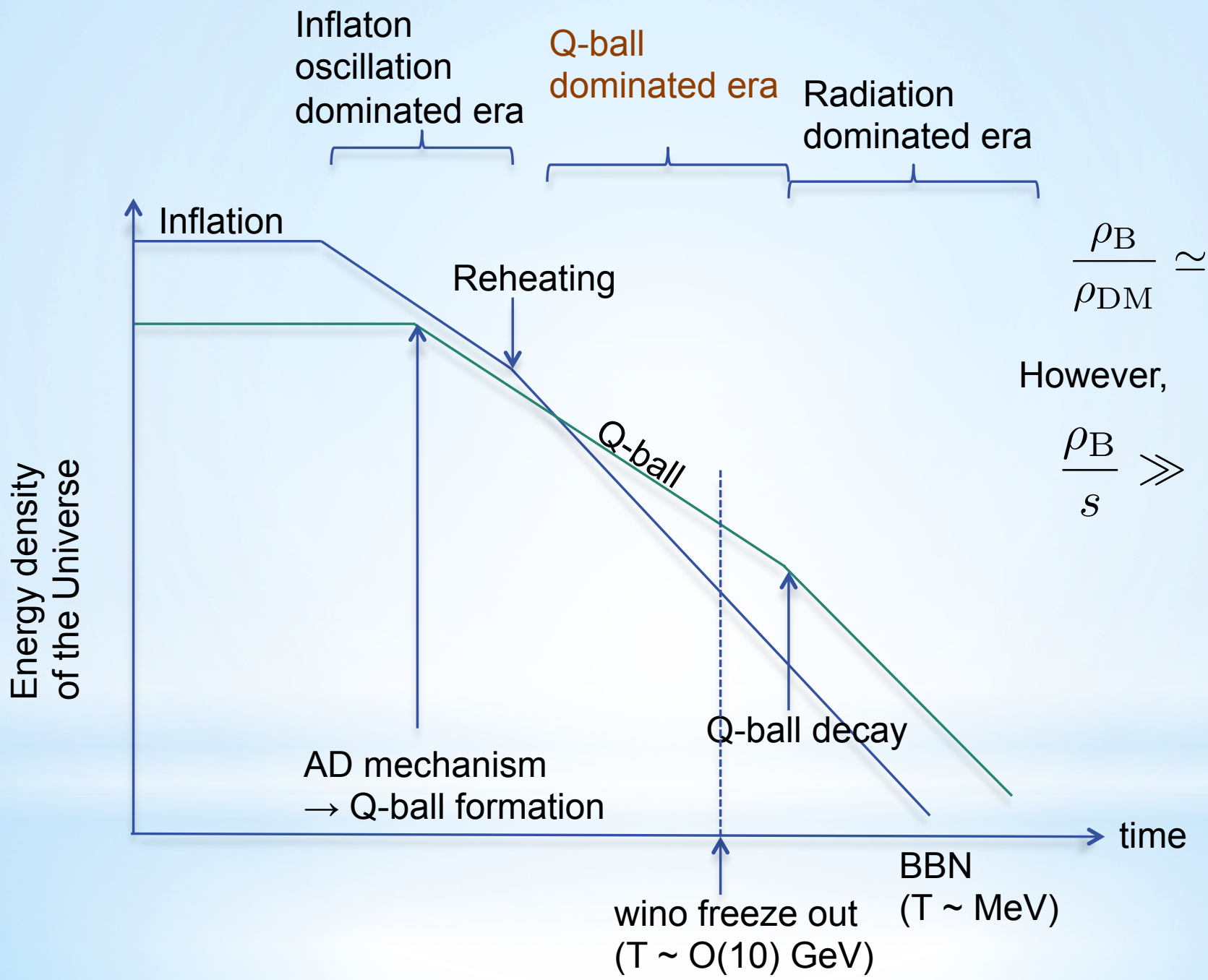
back up slides



Ordinary scenario:

DM density is determined by the thermal relic density of wino

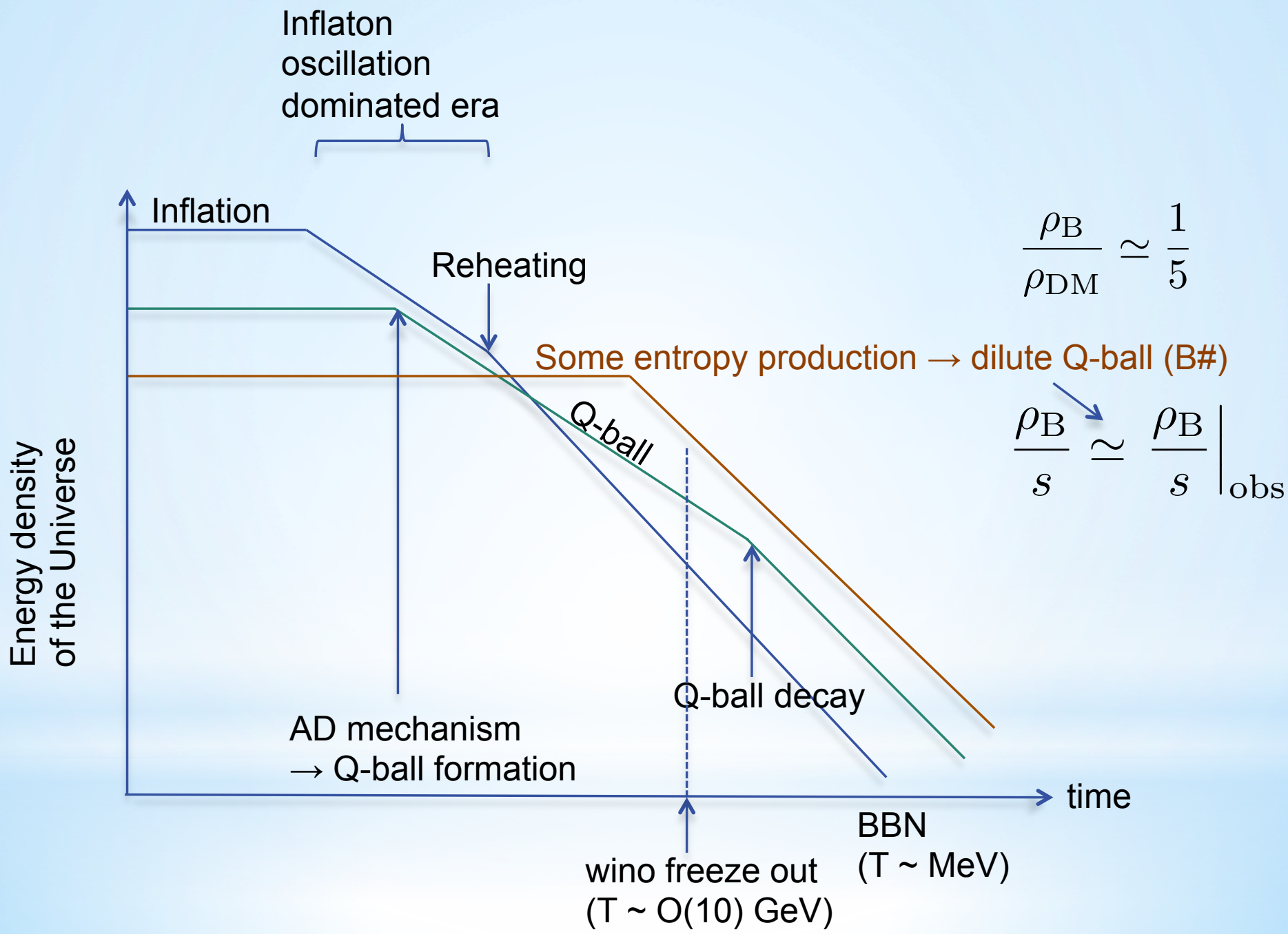
→ baryon and DM are generated separately



$$\frac{\rho_{\rm B}}{\rho_{\rm DM}} \simeq \frac{1}{5}$$

However,

$$\frac{\rho_{\rm B}}{s} \gg \left.\frac{\rho_{\rm B}}{s}\right|_{\rm obs}$$



$$\frac{\rho_{\rm B}}{\rho_{\rm DM}} \simeq \frac{1}{5}$$

$$\frac{\rho_{\rm B}}{s} \simeq \left.\frac{\rho_{\rm B}}{s}\right|_{\rm obs}$$

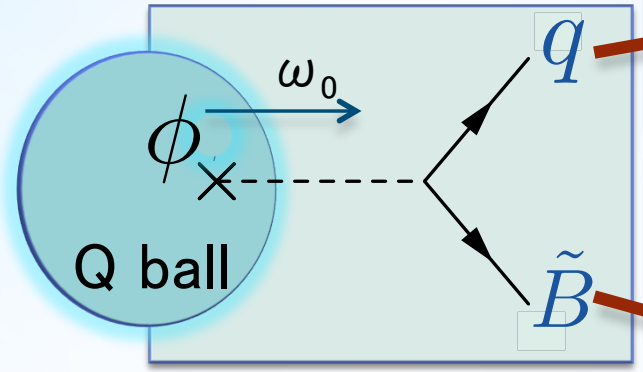
Q-ball decay rate

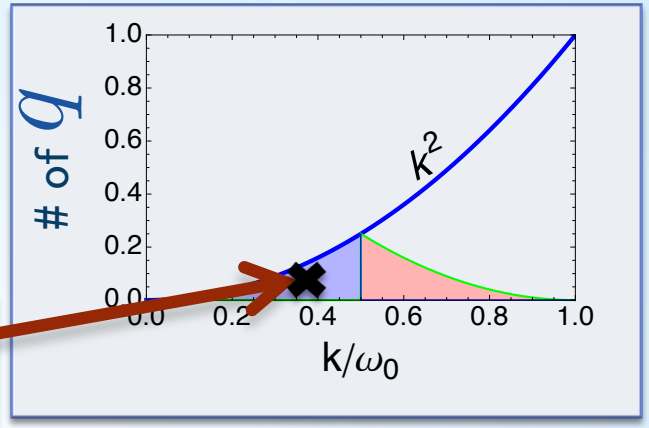
Cohen, *et. al*, 86

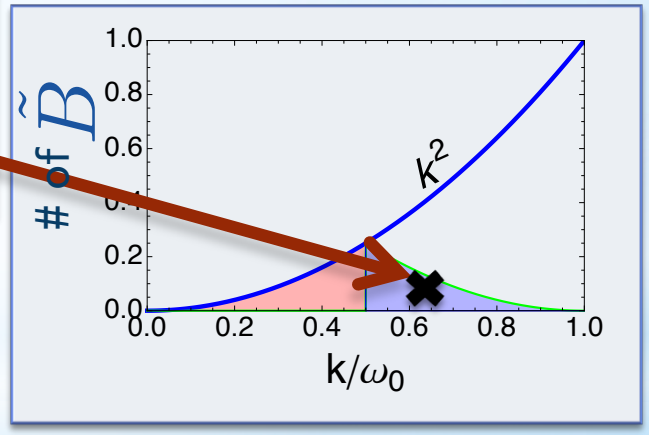
upper bound of flux (massless):

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

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







bino production rate

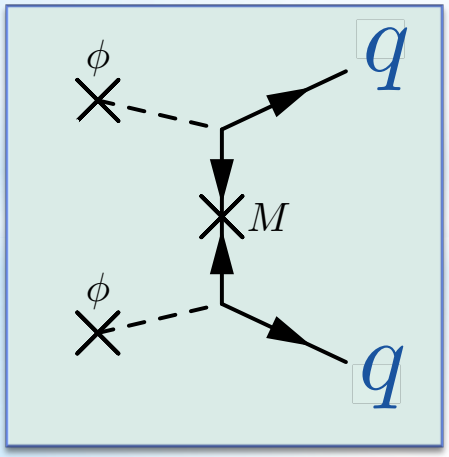
$$\left(R \sim \omega_0^{-1}\right)$$

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

	gluino exchange	bino exchange	higgsino exchange
$\tilde{\bar{u}}_1^R = \frac{1}{\sqrt{3}}\phi$	u_1^G, u_1^B	u_1^R	
$\tilde{\bar{d}}_1^G = \frac{1}{\sqrt{3}}\phi$	d_1^R, d_1^B	d_2^G	
$\tilde{\bar{d}}_2^B = \frac{1}{\sqrt{3}}\phi$	d_2^G, d_2^R	d_2^B	

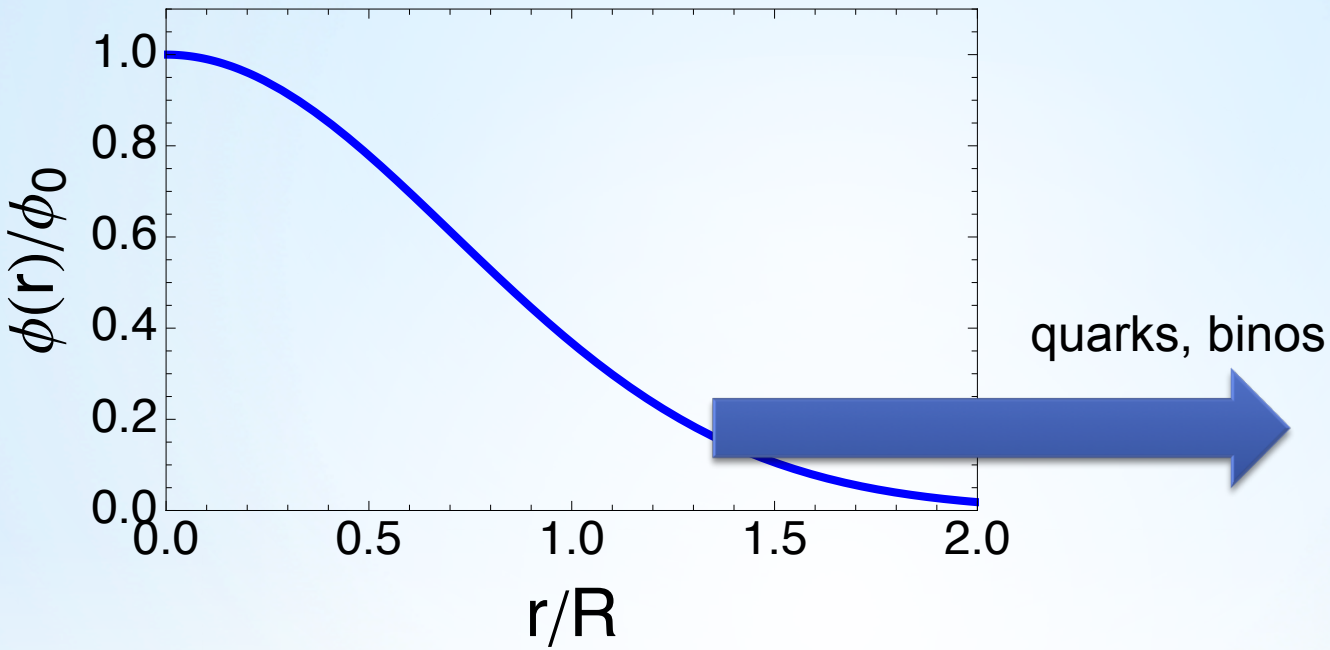
do not change color

(left handed)
top, bottom (Q_3)
$\rightarrow$ + 6



$n_q = 15$

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



squarks have large VEV → higgs do not have VEV
→ bino and wino do not mix with each other

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

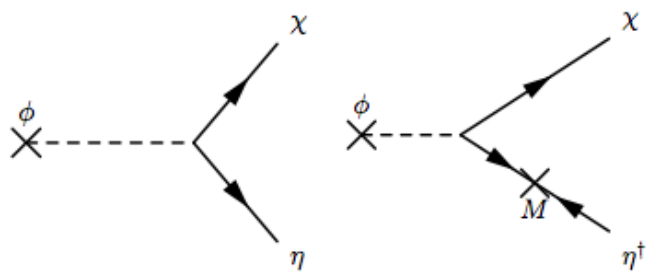


FIG. 14: Diagrams for $\phi \to \chi\eta$.

we can neglect herisity flip

×8 for M > omega_0
∝ M^2 for M < omega_0

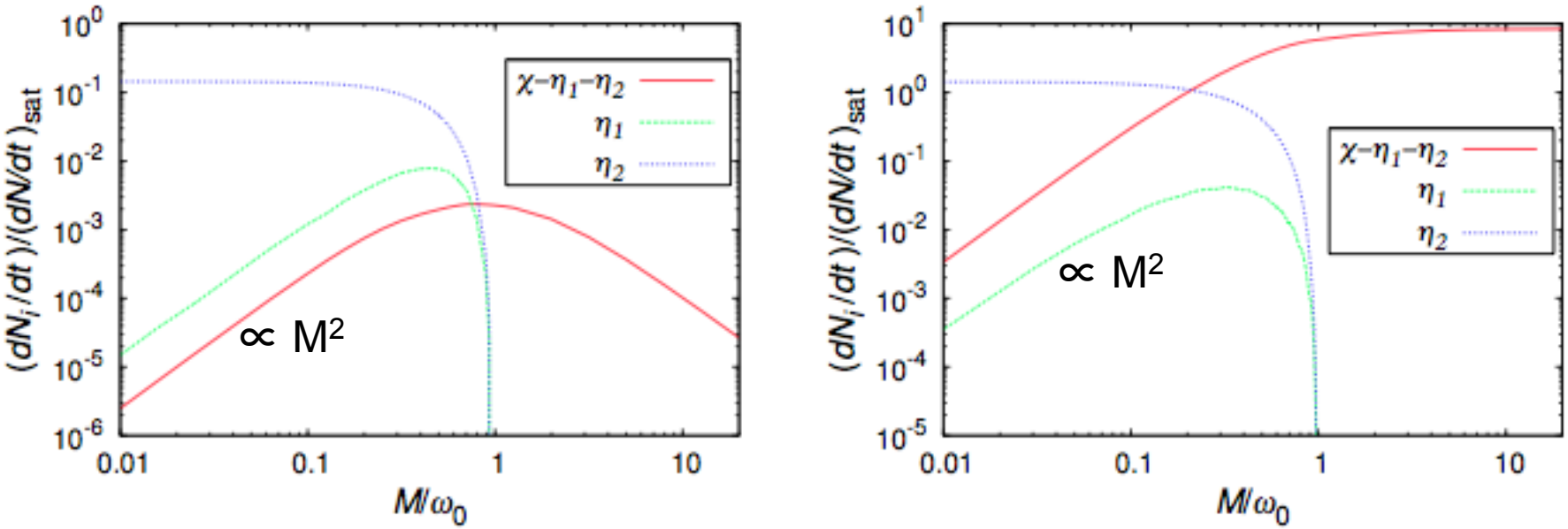


FIG. 12: Production rates of χ, η_1 and η_2 from Q balls as a function of M/ω_0 for $g\phi_0/\omega_0 = 0.1$ (left panel) and for $g\phi_0/\omega_0 = 10$ (right panel) with $R\omega_0 = \pi$ in the Yukawa theory with a massive fermion. The vertical axis is normalized by the saturated rate of Eq. (36).

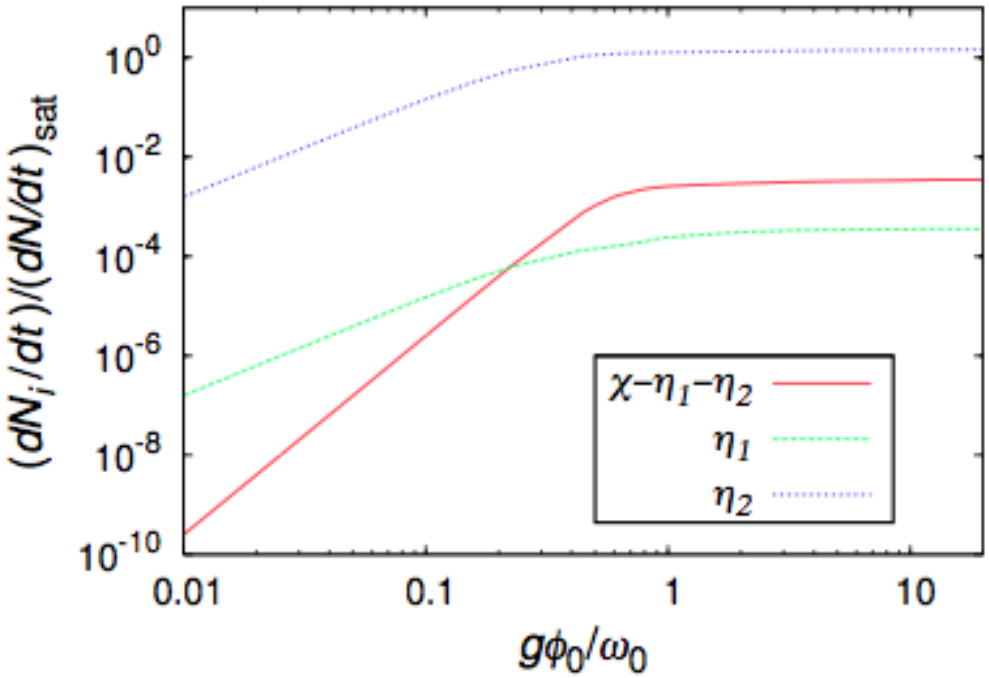


FIG. 13: Production rates of χ, η_1 and η_2 from Q balls as a function of $g\phi_0/\omega_0$ with $R\omega_0 = \pi$ and $M/\omega_0 = 0.01$ in the Yukawa theory with a massive fermion. The vertical axis is normalized by the saturated rate of Eq. (36).

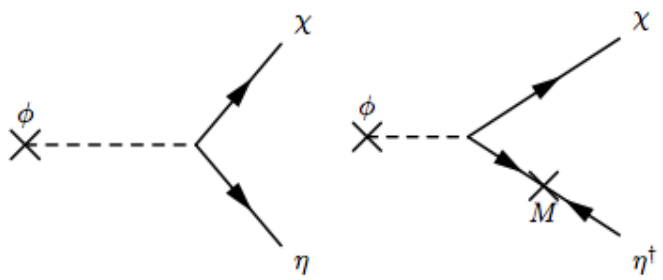


FIG. 14: Diagrams for $\phi \to \chi\eta$.

if the gluino mass is sufficiently small,
the gluino exchange process can be neglected

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

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

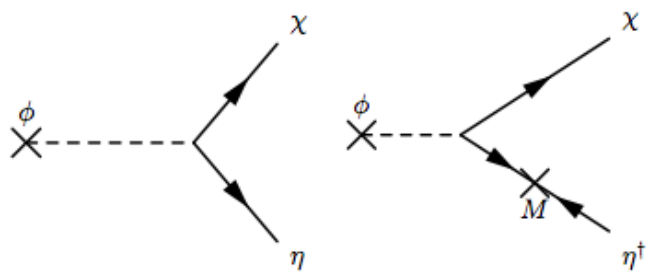
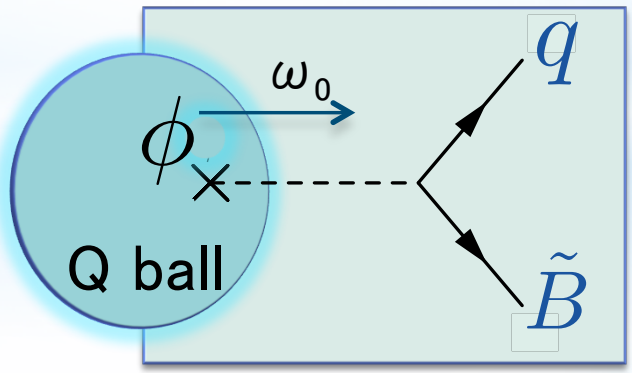


FIG. 14: Diagrams for $\phi \to \chi\eta$.

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

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



$$\omega_0 = 1$$

non-zero bino mass

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

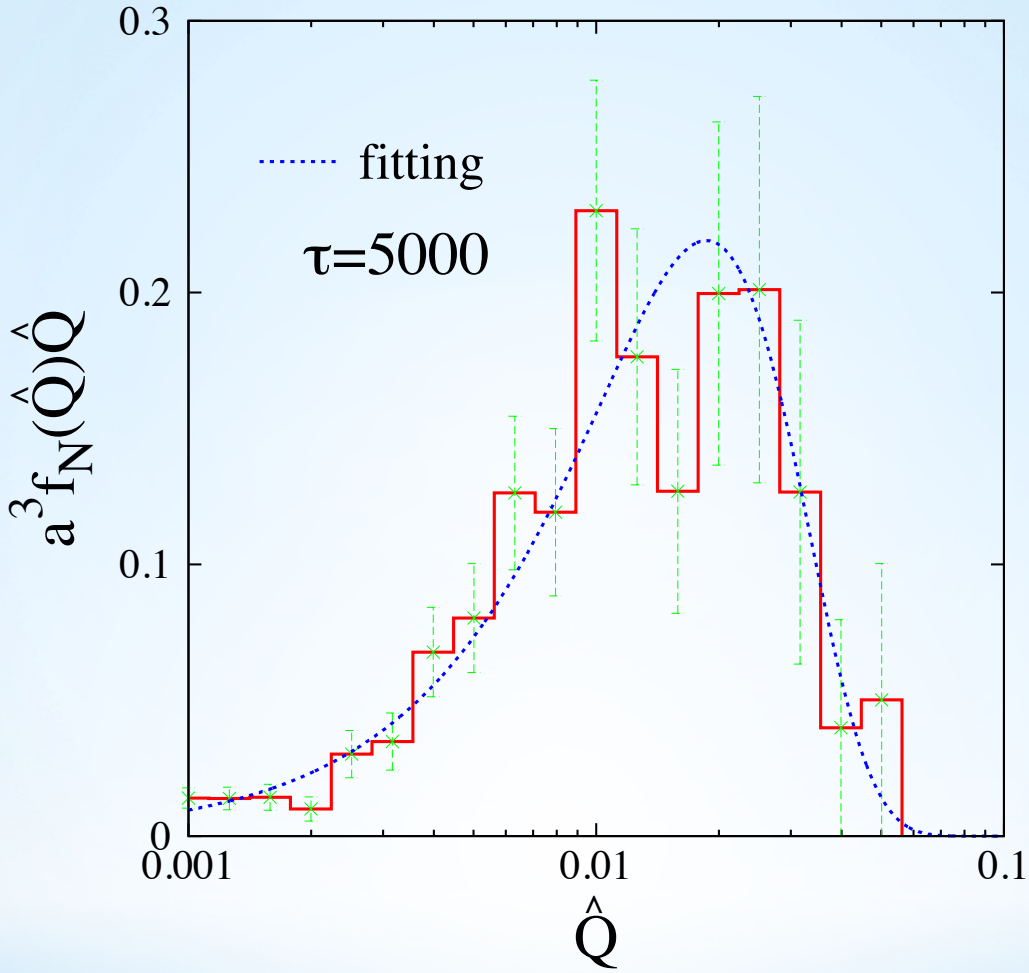
for $m > 1/2$

determined by the lower flux

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

for $m < 1/2$

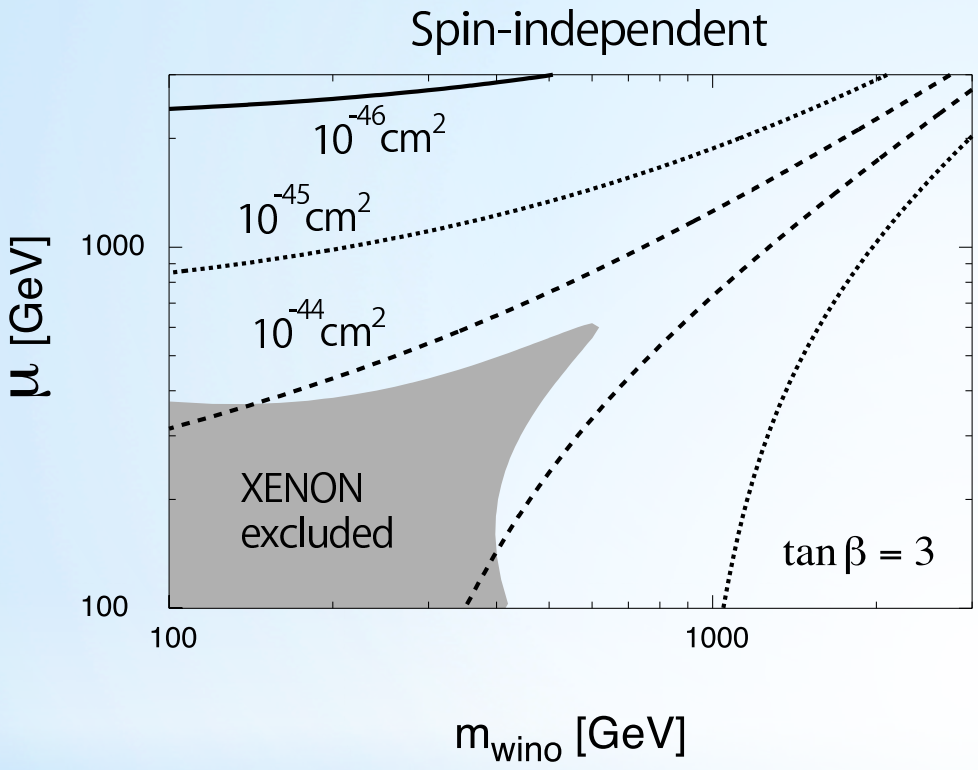
$$v = p/E = \sqrt{E^2 - m^2}/E$$

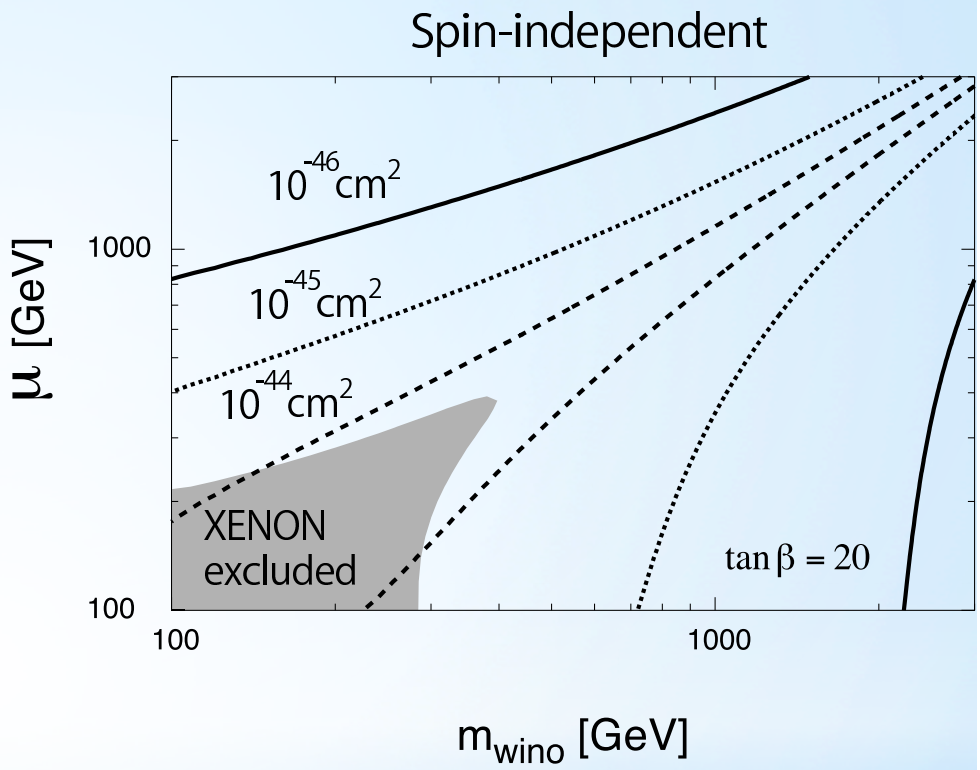


charge density distribution of Q-balls

Hiramatsu, Kawasaki, Takahashi
1003.1779

constraints from direct detection of wino DM





Moroi, Nakayama
1112.3123