Co-genesis of baryon and dark matter from Q-ball decay in anomaly mediation

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

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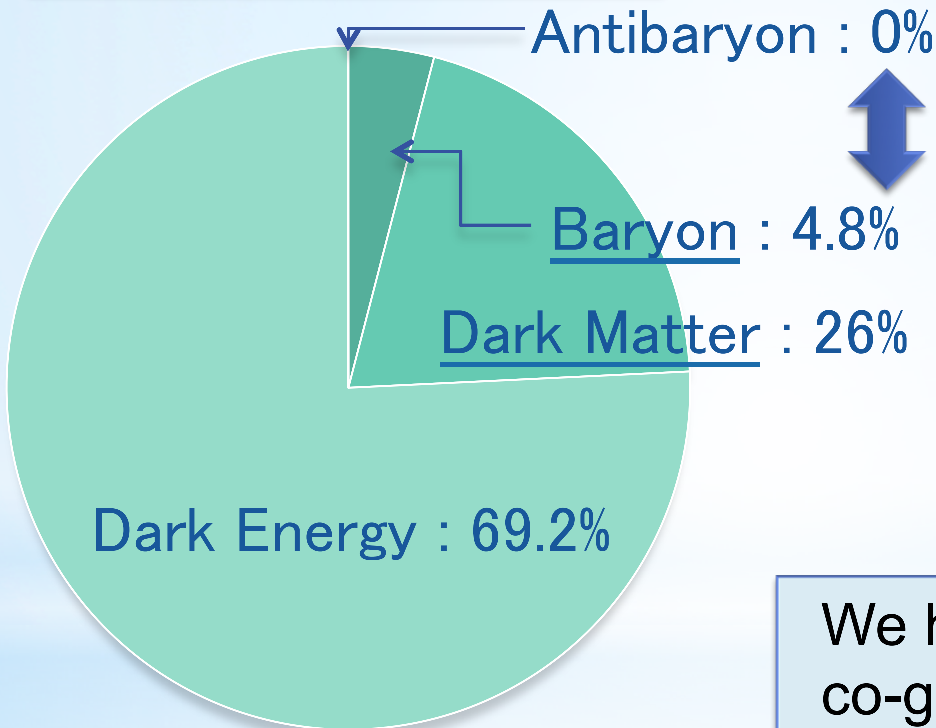
Introduction: motivation

Content of the Universe



Planck (2013)

Antibaryon ↕ Baryon: asymmetry

Baryon and Dark Matter:

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

coincidence problem

→ Baryon and DM have a common origin?

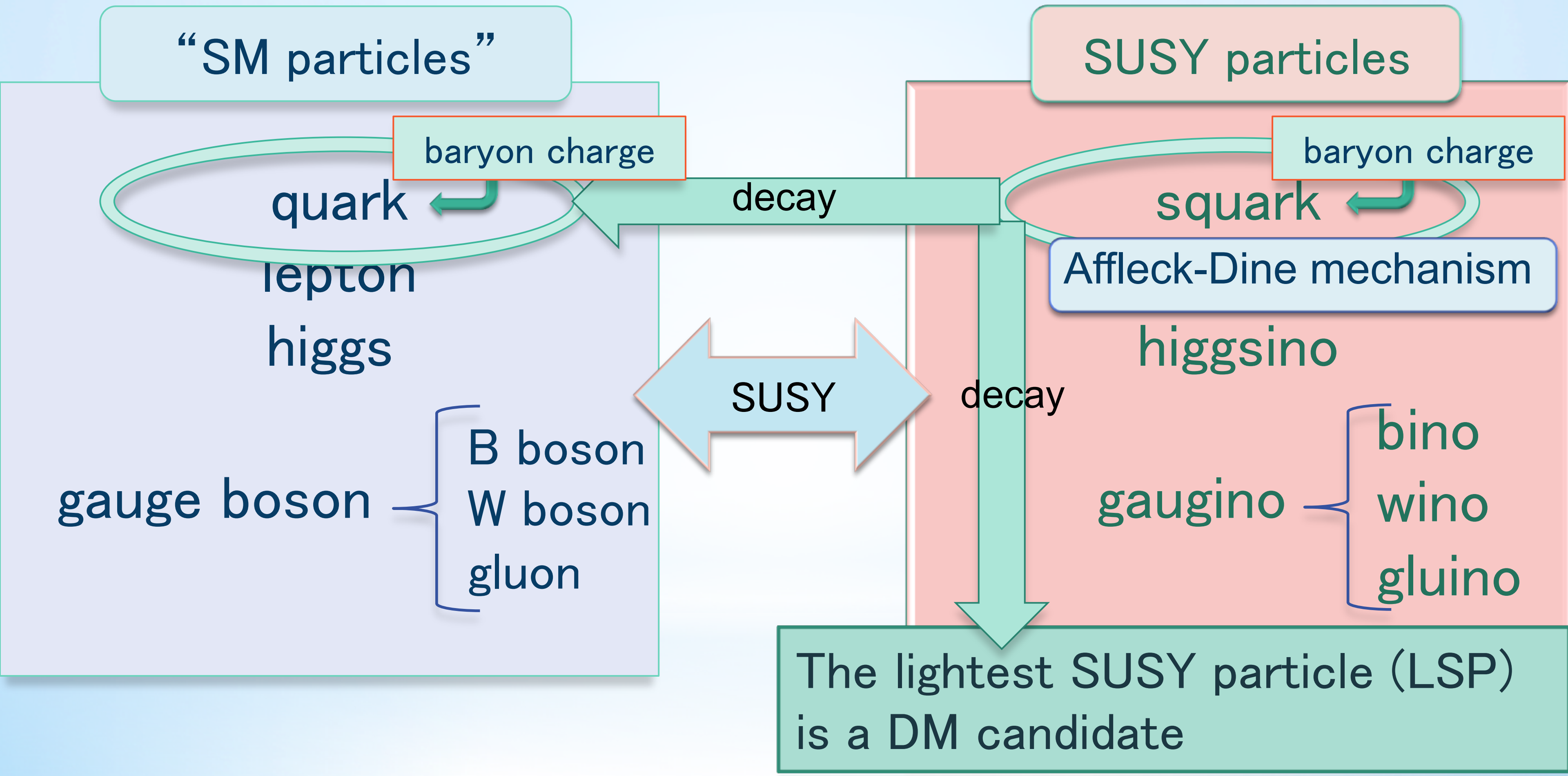
We have proposed a scenario for co-genesis of baryon and DM assuming low energy SUSY

Introduction: SUSY

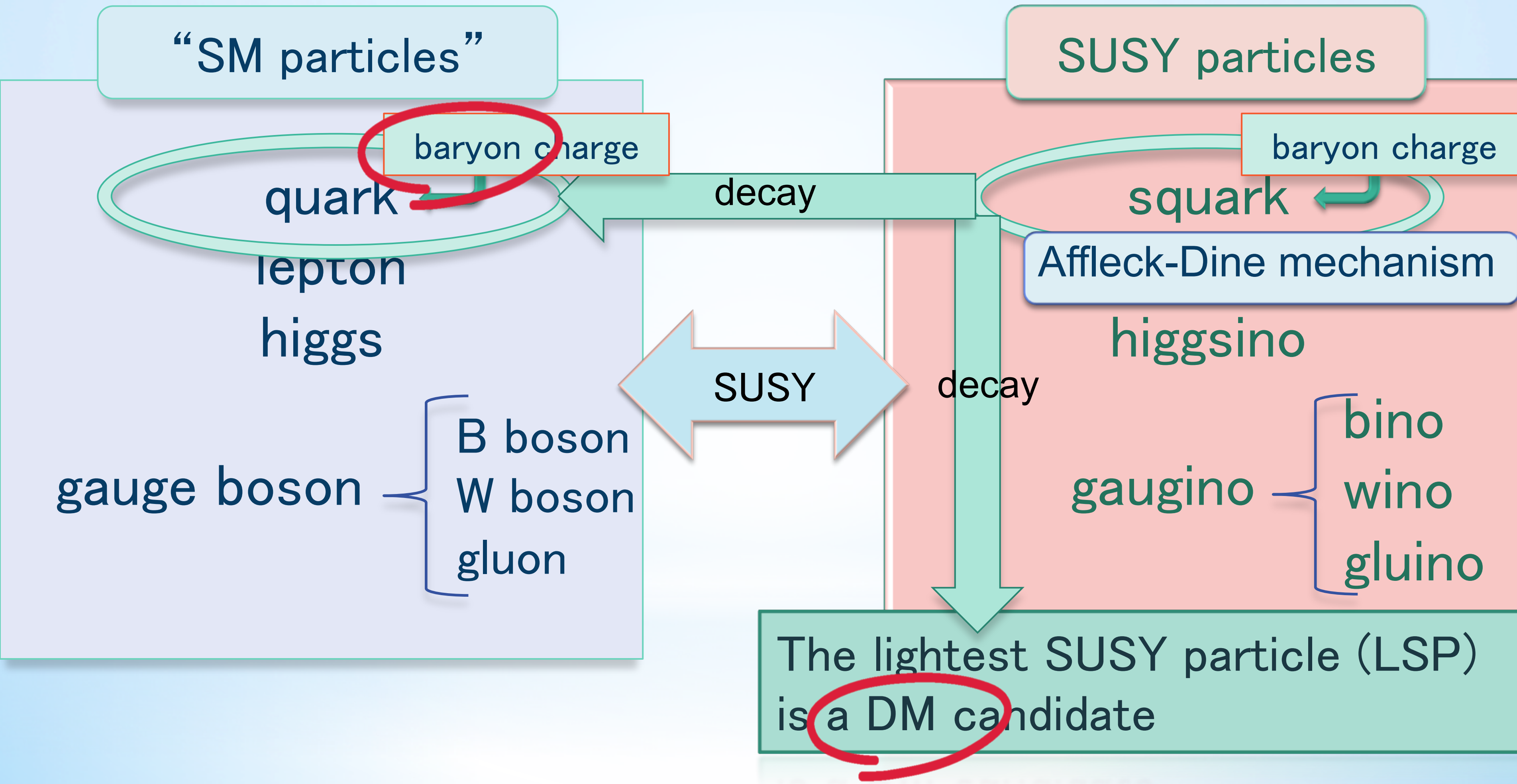
“SM particles”		SUSY particles
quark ← baryon charge	⟷ SUSY ⟷	squark ← baryon charge
lepton		slepton
higgs		higgsino
gauge boson: B boson, W boson, gluon		gaugino: bino, wino, gluino

The lightest SUSY particle (LSP) is a DM candidate

Introduction: SUSY



Introduction: SUSY



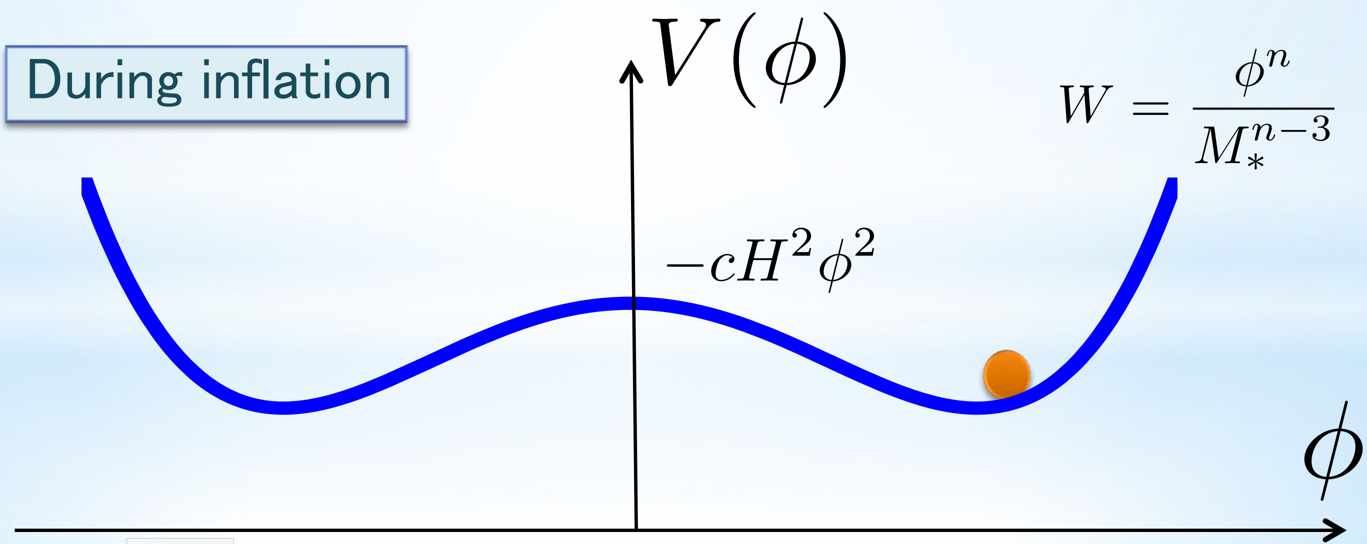
Introduction: Affleck–Dine mechanism

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

Consider a flat direction (denoted by ϕ)
which carries a non-zero baryon charge

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

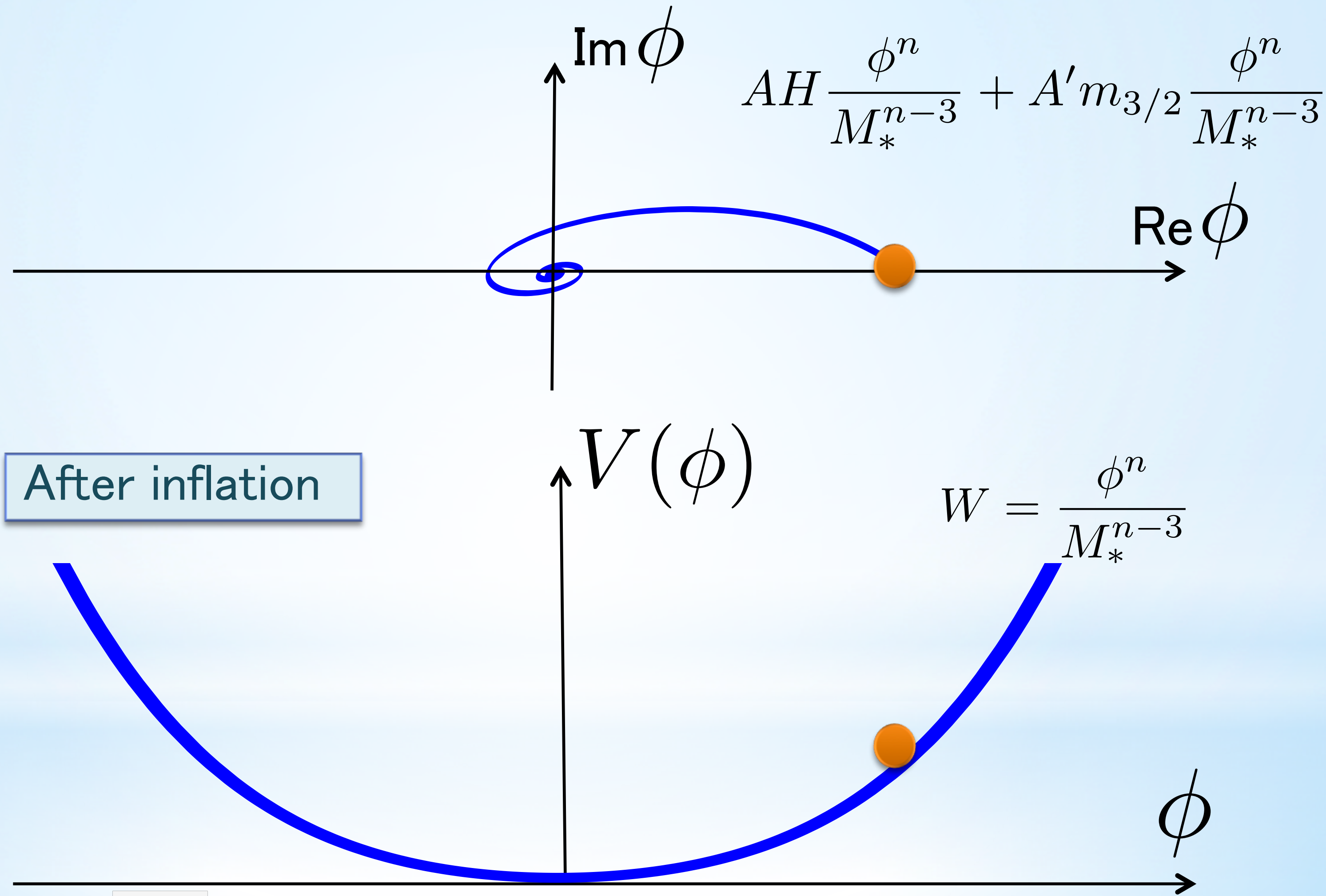
During inflation



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

Introduction: Affleck–Dine mechanism

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



Introduction: Affleck–Dine mechanism

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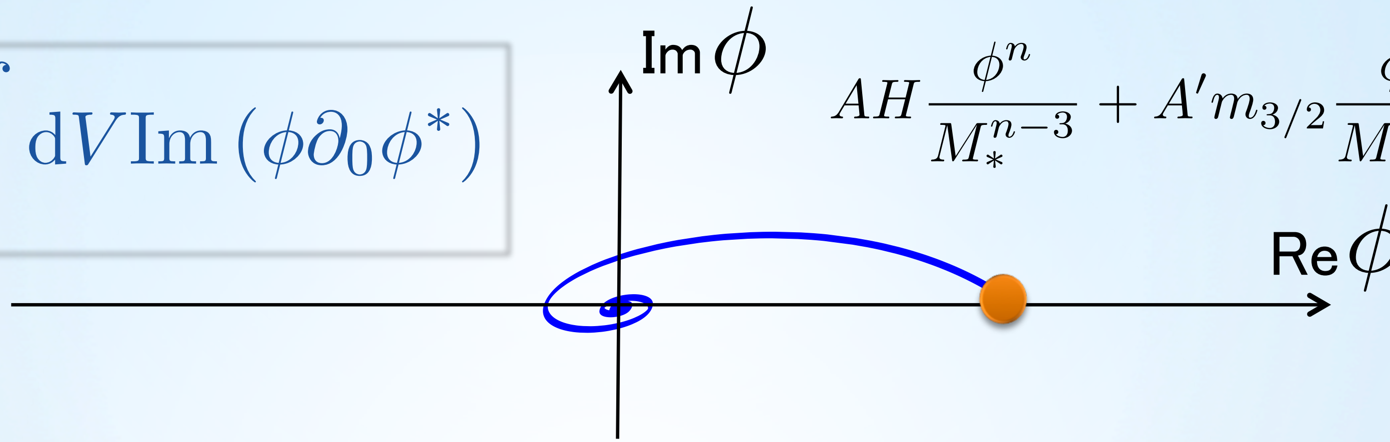
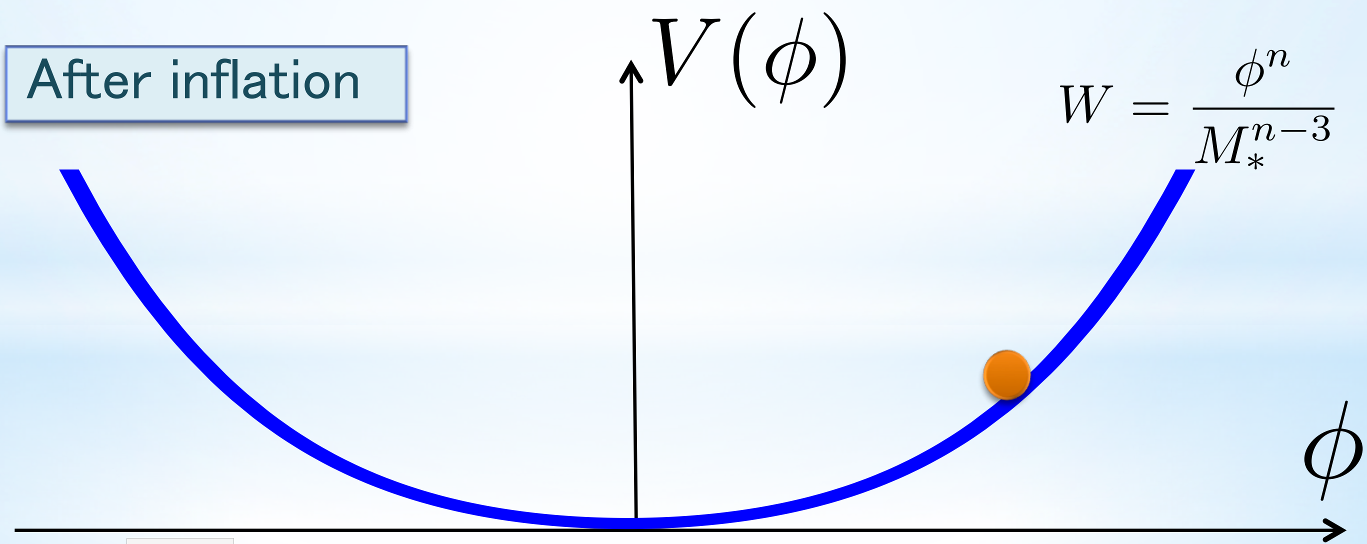
$$B = \int \mathrm{d}V \mathrm{Im}\left(\phi \partial_0 \phi^*\right)$$

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



After inflation

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



Introduction: Q-ball

Coleman, 85

Affleck-Dine mechanism → coherent oscillation with B#

↑

spatially unstable

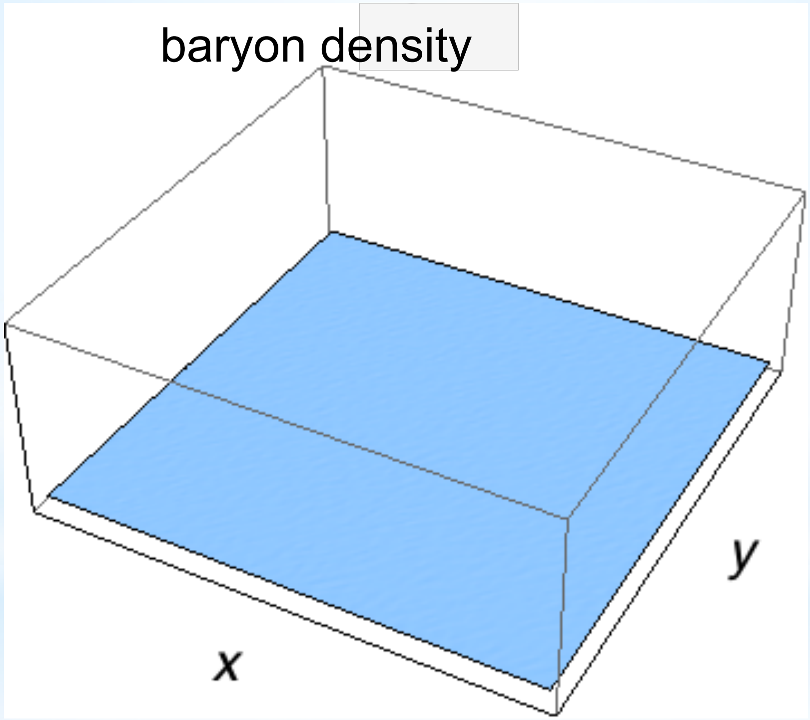
➡ fragment into non-topological solitons

: Q-balls (with B#)

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

Introduction: Q-ball

Coleman, 85

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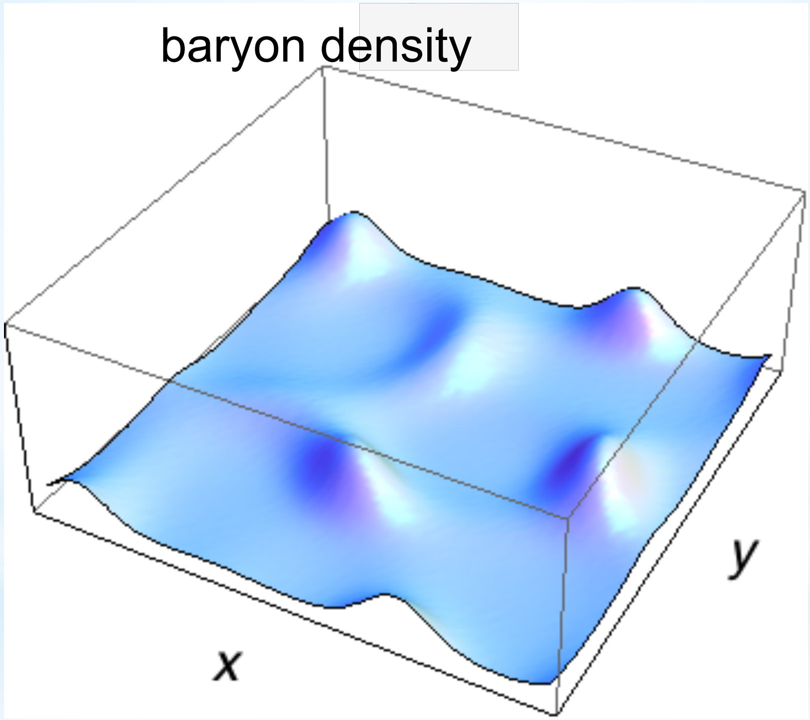

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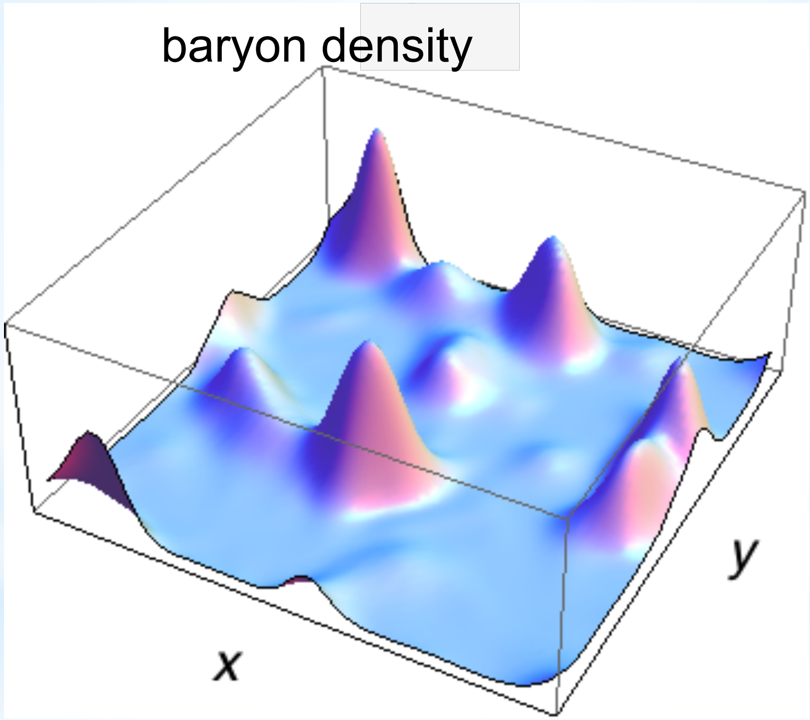

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Small quantum fluctuations grow to form Q-balls

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⇒ fragment into non-topological solitons

: Q-balls (with B#)

Since Q-balls are made up of squarks,

Q-balls then decay into
- quarks (→ baryon)
- light SUSY particles (→ DM)

before the BBN epoch.

Baryon and DM are generated from the common origin

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

Introduction: Q-ball

Coleman, 85

Affleck-Dine mechanism → coherent oscillation with B#

spatially unstable

We need to compute
the branching ratio
for these decay modes

ical solitons

-balls (with B#)

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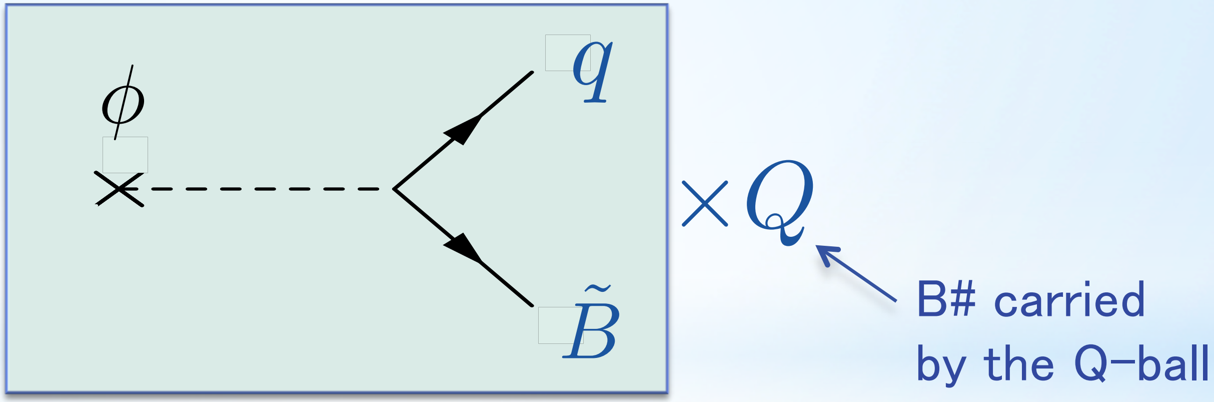
Q–ball decay rates (into binos)

Cohen, *et. al,* 86

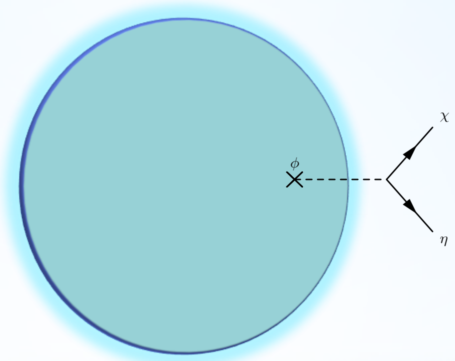
Naively, the decay of Q–ball can be regarded as the collection of elementary decay processes:



Q-ball decay rates (into binos)

Cohen, *et. al*, 86

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



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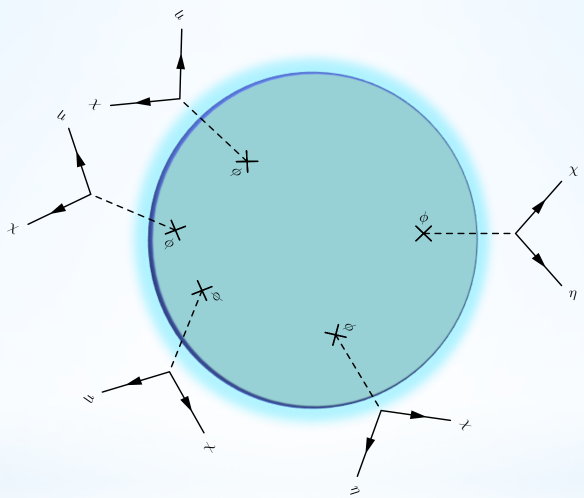

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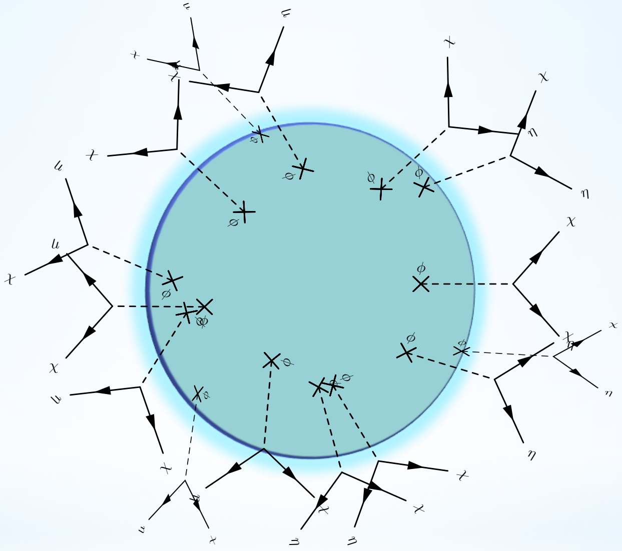

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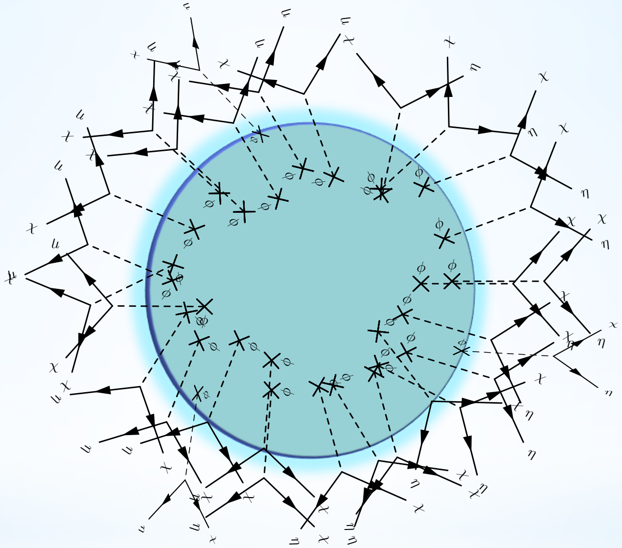


Since fermions obey the Pauli exclusion principle,
there is a certain upper bound for the production rate of fermions
from Q-ball decay!

Q-ball decay rates (into binos)

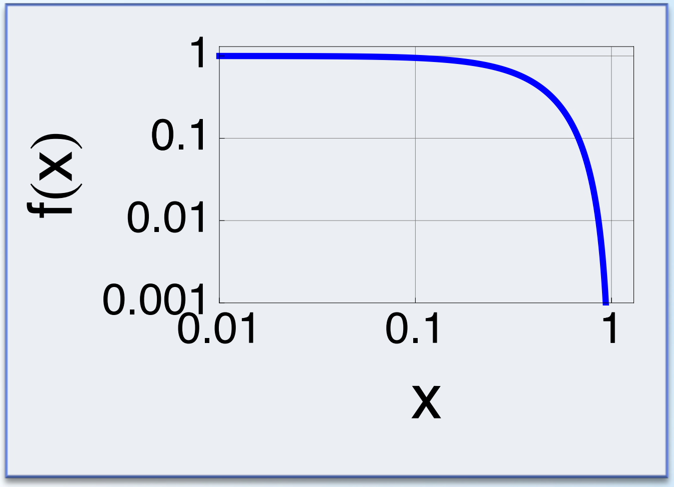
Cohen, *et. al*, 86

Fermion production rates are in fact saturated by the Pauli blocking effect!

➡ The Q-ball decay rate into binos is given by

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

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

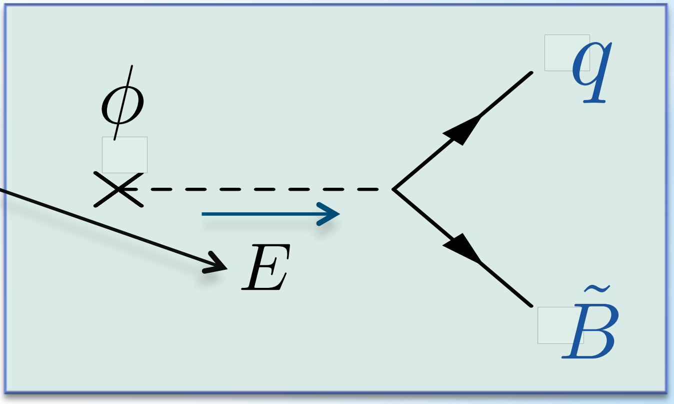


E : reaction energy

$\approx m_{\tilde{q}}$

↑

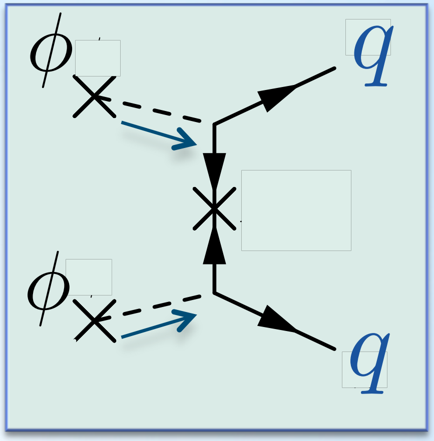
(in anomaly or gravity mediation)



Q−ball decay rates (into quarks)

Kawasaki, M.Y., 13

Q−balls can decay into quarks via gluino exchange



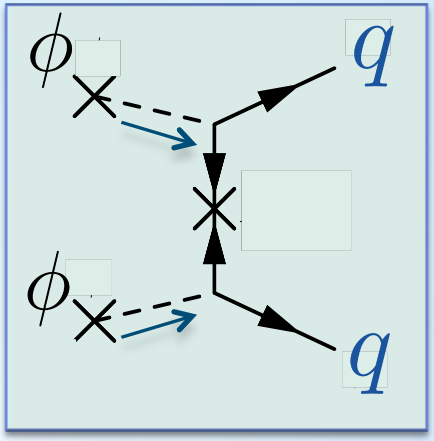
- (reaction energy) $\approx 2m_{\tilde{q}}$

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

Q−ball decay rates (into quarks)

Kawasaki, M.Y., 13

Q−balls can decay into quarks via gluino exchange



- (reaction energy) $\approx 2m_{\tilde{q}}$
  - ⇒ $\times 2^3$ for quark production rate
- many # of quantum states: color, flavor, left−right handed
  - ⇒ $\times n_q$ for *total* quark production rate

    ↖ (# of quantum states of quarks interacting with Q−ball)

In our scenario, $n_q \approx 15$

The ratio of the Q-ball decay rates into quarks and binos is therefore given by

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

Baryon 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 (Q-ball)

  bino

  wino = LSP = DM

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

  light

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  light

→ Q−balls decay only into quarks and binos

branching ratio:

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

→ Then, the binos decay into winos.

If the annihilation of wino can be neglected,

$$\frac{\Omega_b}{\Omega_{\mathrm{DM}}} = \frac{m_p}{3m_{\tilde{W}}}\frac{B_q}{B_{\tilde{B}}} = \mathcal{O}(1)\,!$$

Baryon and DM co-genesis : a remark

Kamada, Kawasaki, M.Y., 13

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

↓

Q–balls need to decay sufficiently later than the time of wino freeze–out

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

Baryon and DM co-genesis : a remark

Kamada, Kawasaki, M.Y., 13

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

↓

Q-balls need to decay sufficiently later than 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

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

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

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

→ B# (Q-balls) has to be diluted

Baryon and DM co−genesis : setup

Kamada, Kawasaki, M.Y., 13

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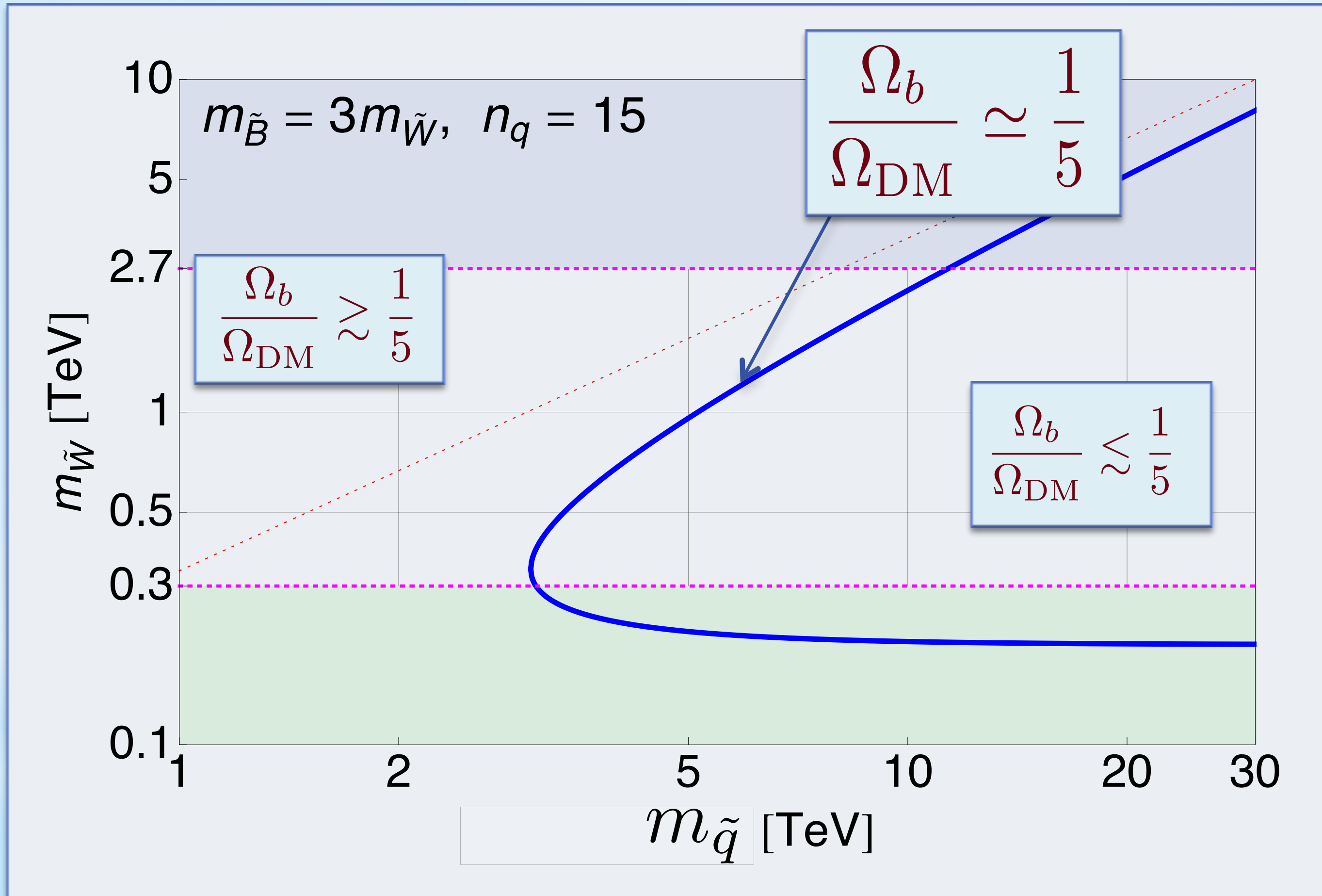
$$\frac{\Omega_b}{\Omega_{\mathrm{DM}}} = \frac{m_p}{3 m_{\tilde{W}}} \frac{B_q}{B_{\tilde{B}}} = \mathcal{O}(1)\,!$$

Baryon and DM co-genesis : results

Kamada, Kawasaki, M.Y., 13

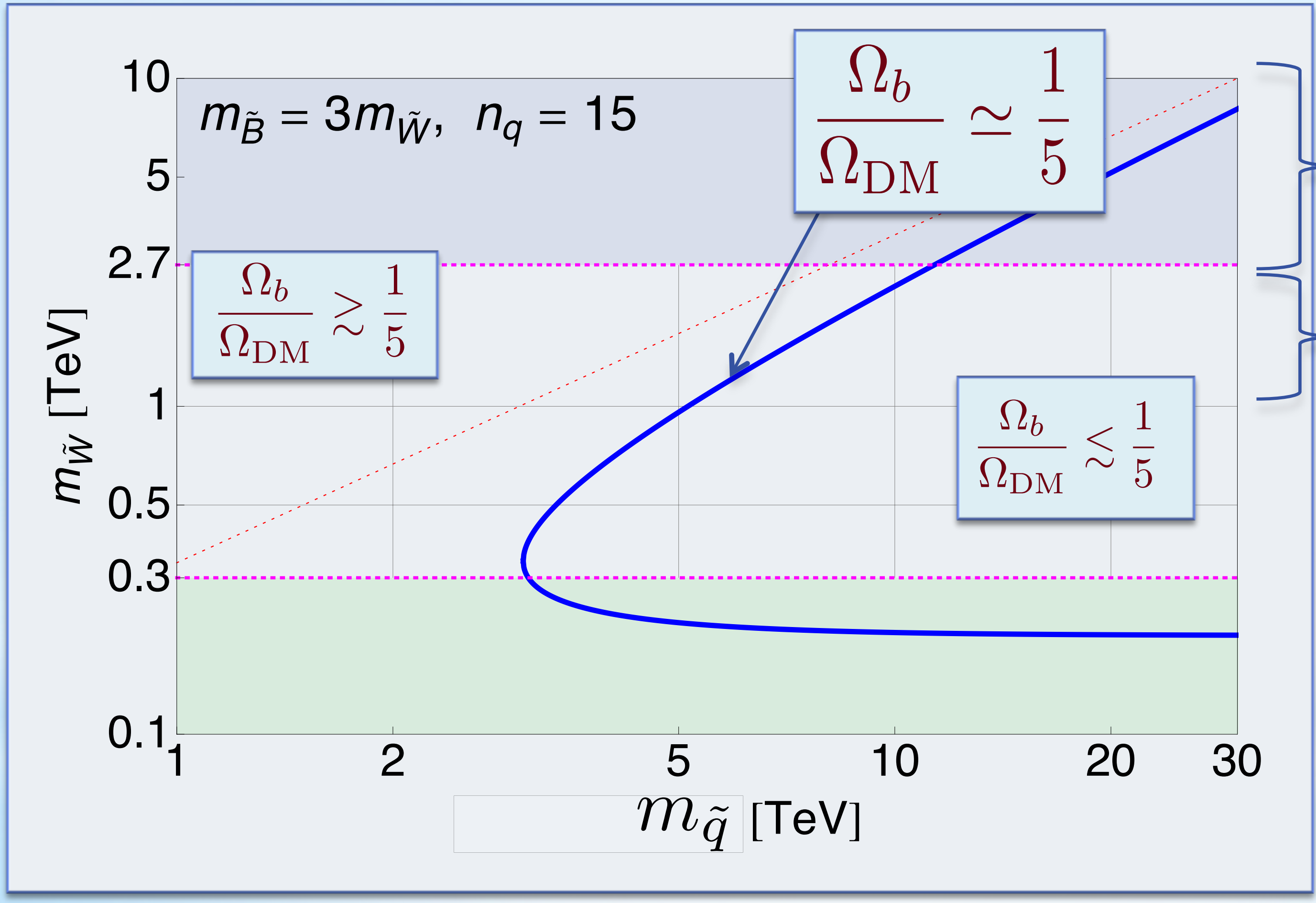


$$\frac{\Omega_b}{\Omega_{\rm DM}} = \frac{m_p}{3m_{\tilde{W}}} \frac{B_q}{B_{\tilde{B}}}$$

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

Baryon and DM co-genesis : results

Kamada, Kawasaki, M.Y., 13

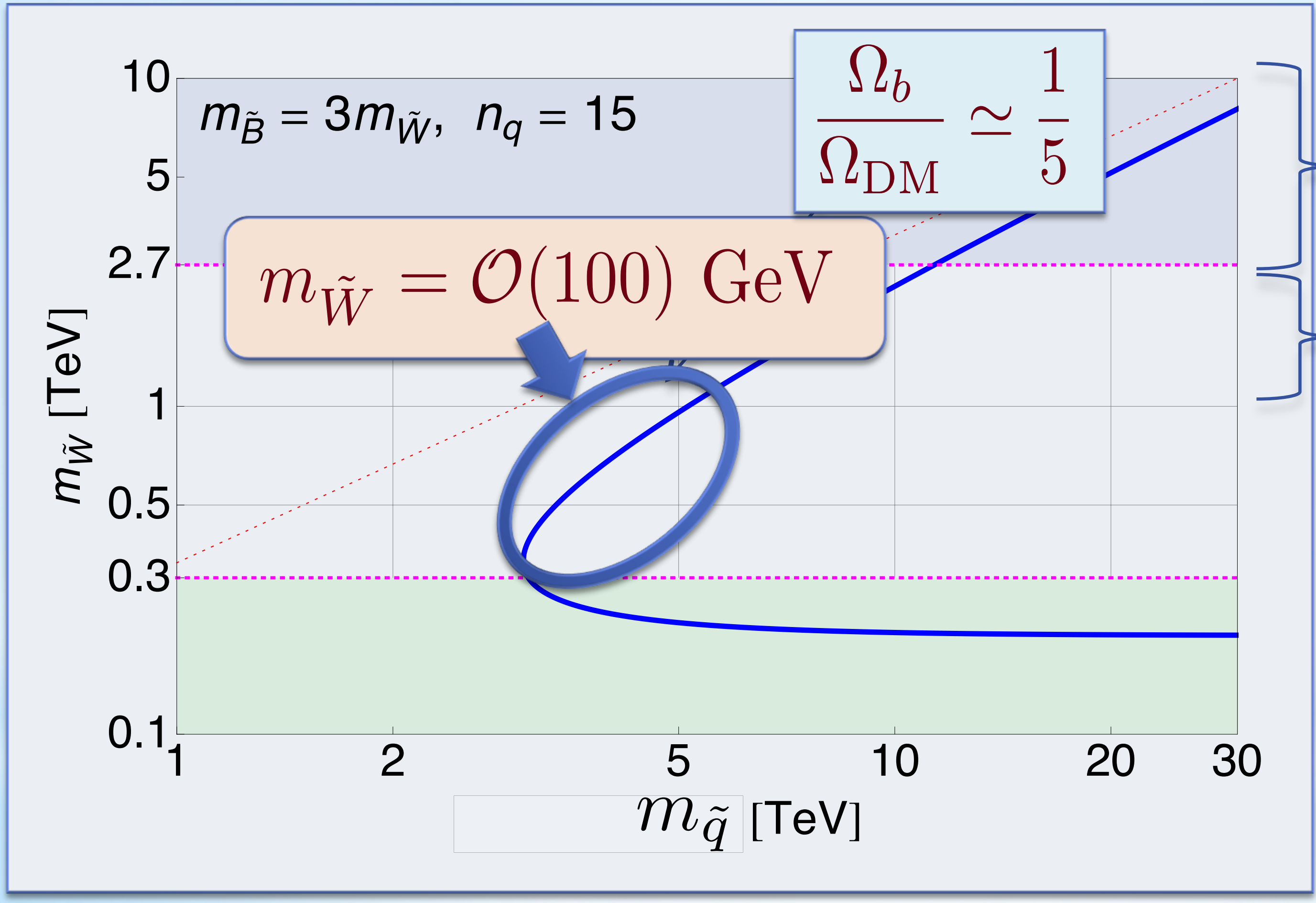


The thermal relic density of the wino overcloses the Universe

The thermal relic density of the wino can not be neglected

Baryon and DM co-genesis : results

Kamada, Kawasaki, M.Y., 13



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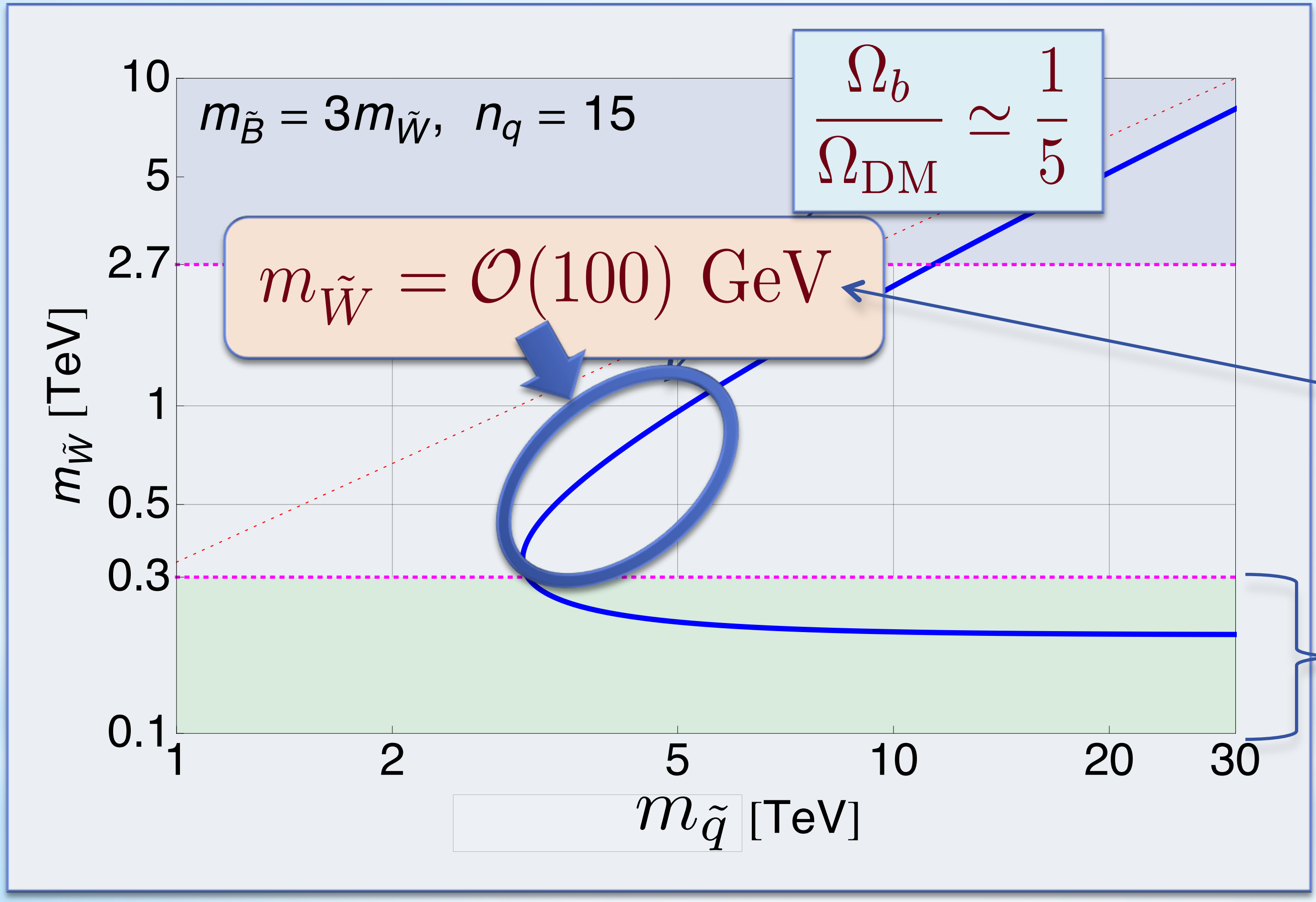


will be indirectly detected by AMS-02

already excluded

Ibe, Matsumoto, Yanagida, (2012)

Summary

Kamada, Kawasaki, M.Y., 13

We have proposed a scenario for co-genesis of baryon and DM in anomaly (or gravity) mediation with wino LSP and have overcome the baryon-DM coincidence problem

$\mathcal{O}(100)$ GeV wino DM can explain

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

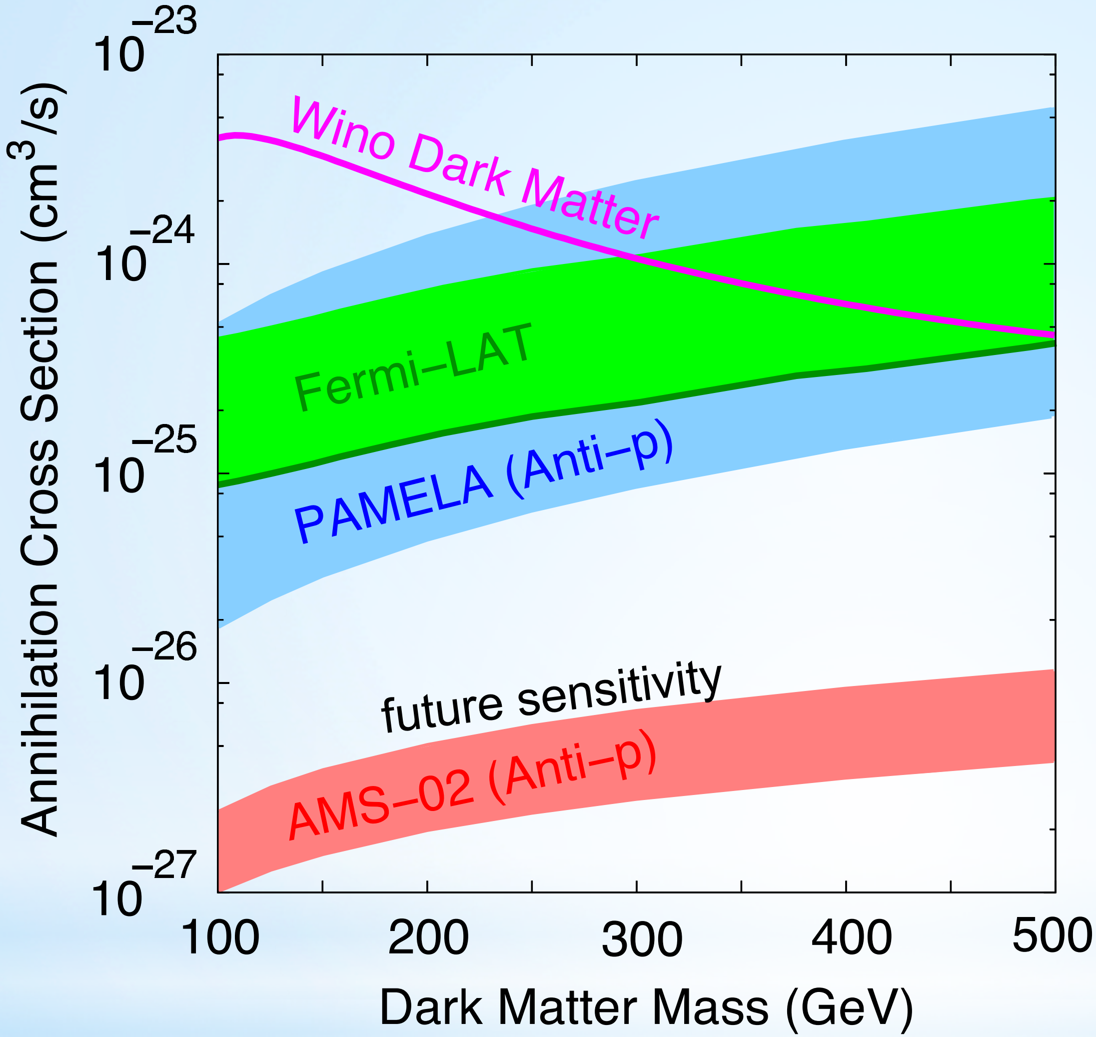
This will be indirectly detected by AMS-02

- However, some entropy production mechanism is needed

e.g. second inflation

- In the case of higgsino LSP,...

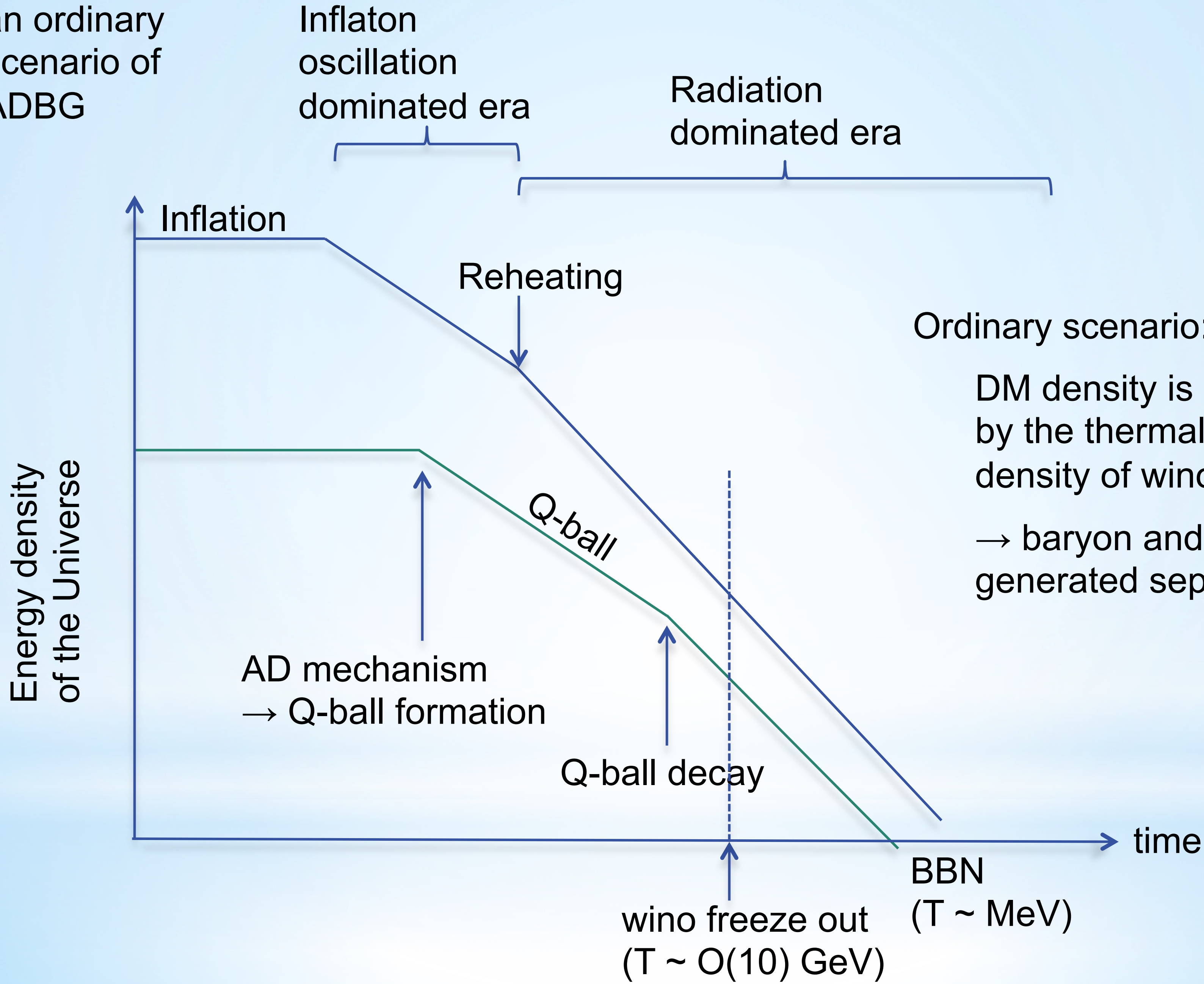
back up slides



The large uncertainties come from the uncertainties in dark matter profiles.

Ibe, Matsumoto, Yanagida, (2012)
hep-ph/1202.2253

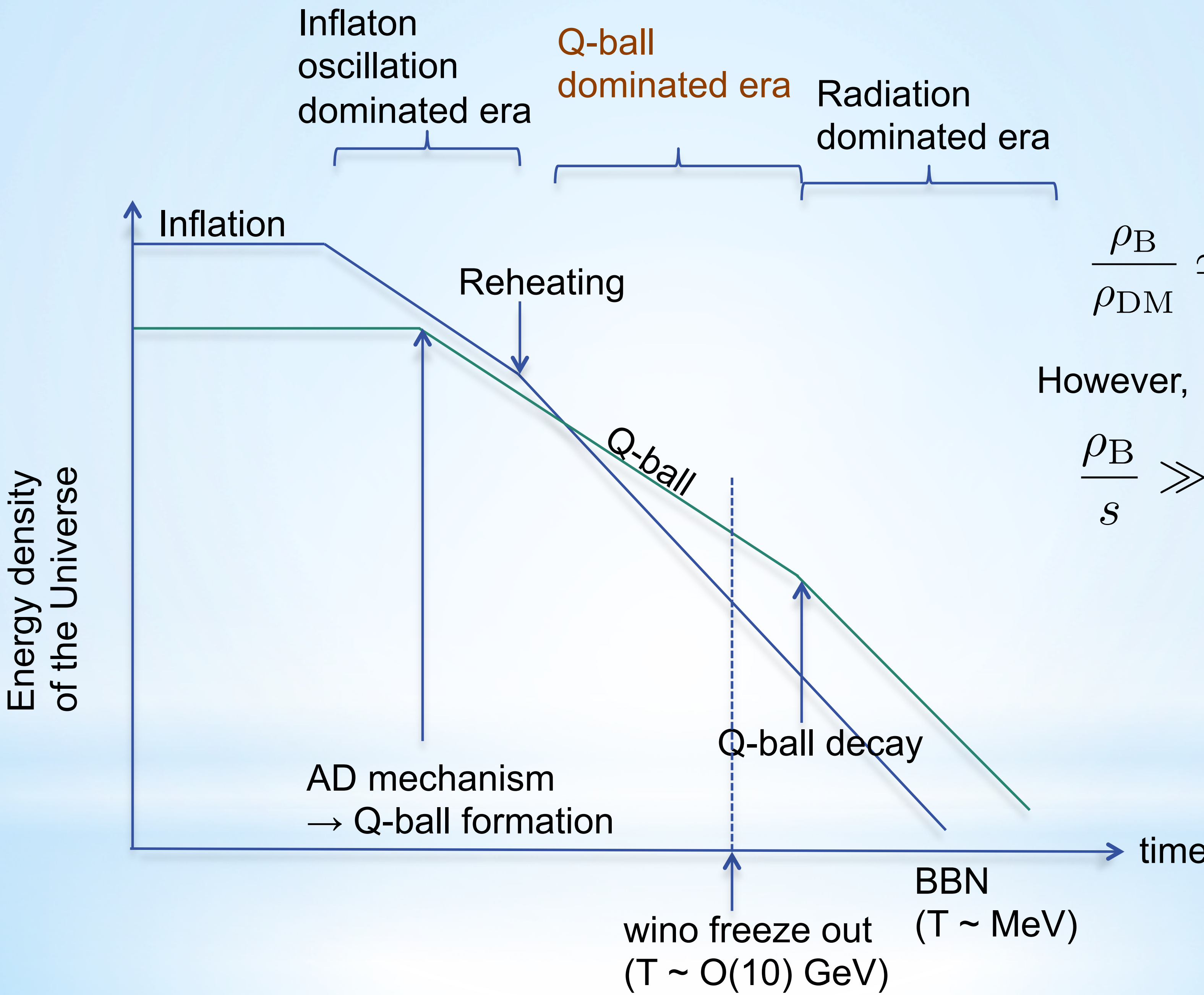
an ordinary scenario of ADBG



Ordinary scenario:

DM density is determined by the thermal relic density of wino

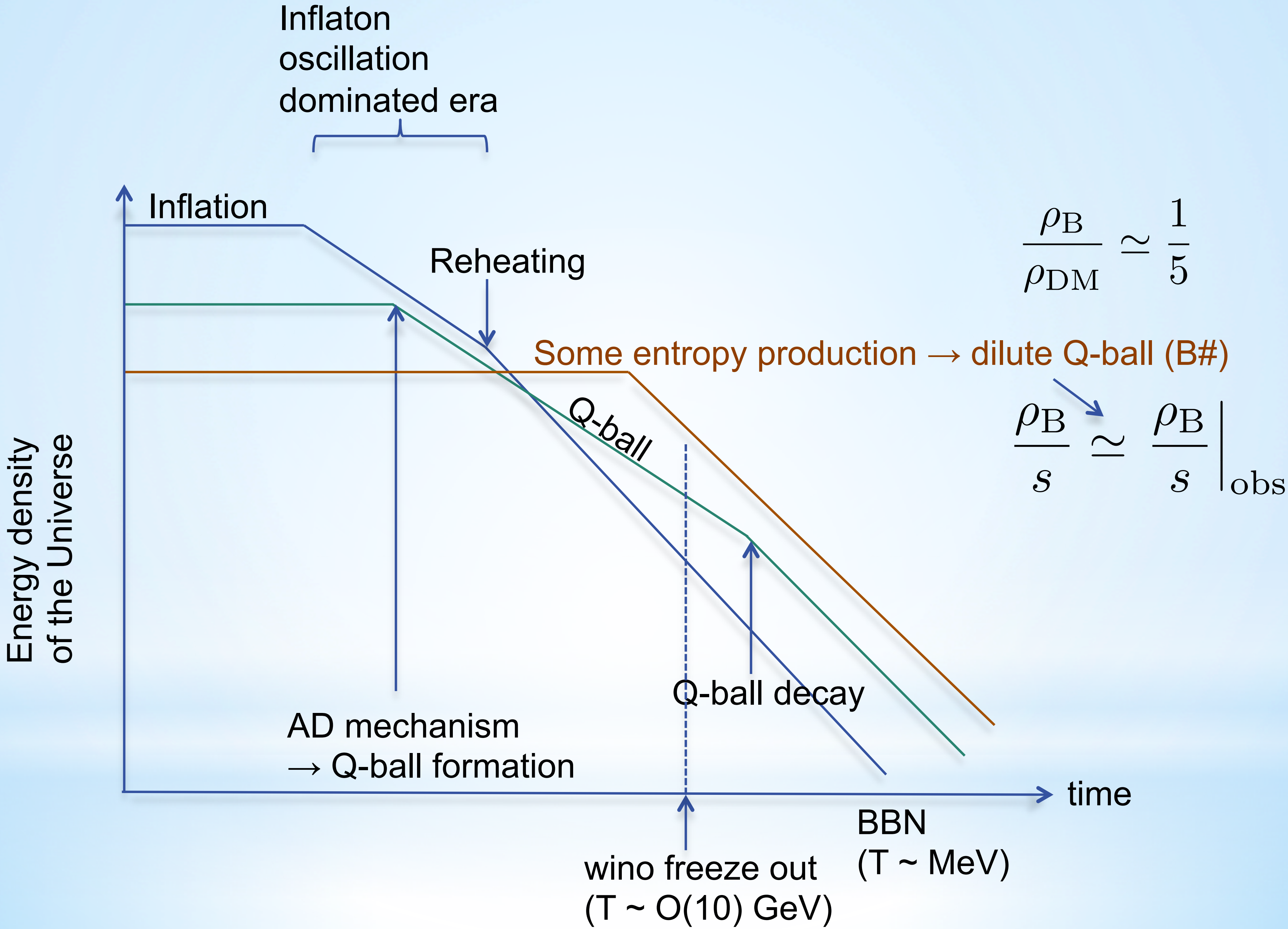
→ baryon and DM are generated separately



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

However,

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

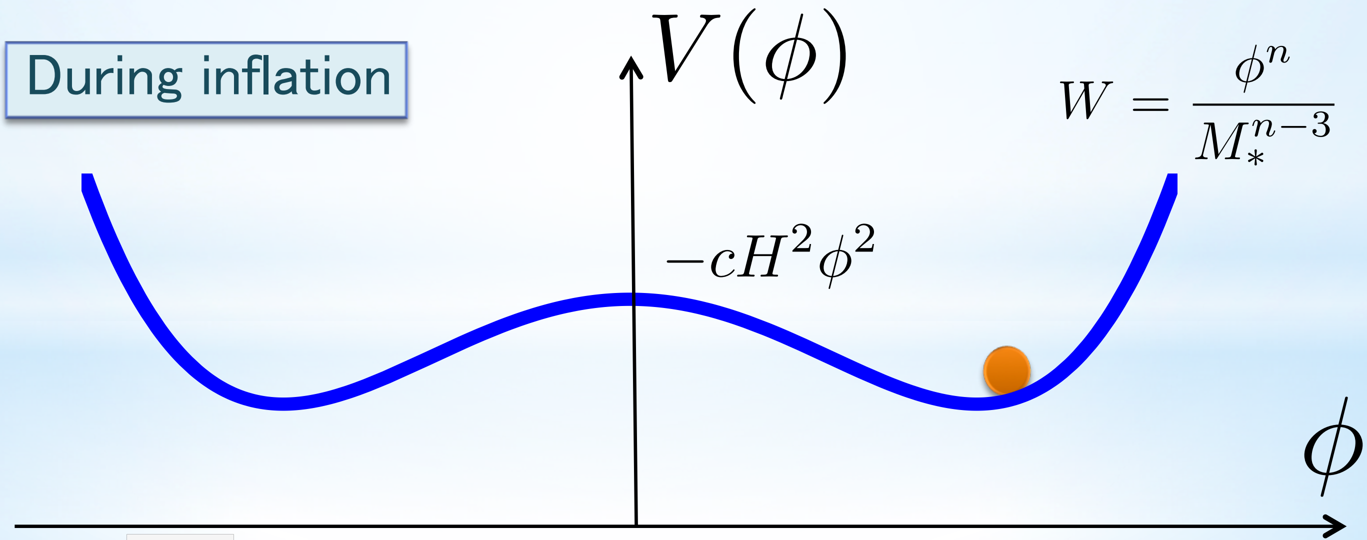

Inflaton
oscillation
dominated era
Inflation
Reheating
$\frac{\rho_B}{\rho_{DM}} \simeq \frac{1}{5}$
Some entropy production → dilute Q-ball (B#)
$\frac{\rho_B}{s} \simeq \left.\frac{\rho_B}{s}\right|_{obs}$
Q-ball
Energy density
of the Universe
Q-ball decay
AD mechanism
→ Q-ball formation
time
BBN
(T ~ MeV)
wino freeze out
(T ~ O(10) GeV)

Since $m_{3/2} \gg m_{\tilde{q}}$ in anomaly mediation,
the EW vacuum is a local minimum
and a flat direction may be trapped by a global vacuum
displaced from the EW vacuum.

We assume a gauged $U(1)_{B-L}$ model.
$U(1)_{B-L}$ is broken at the scale of v.

The flat direction can be trapped at that scale (v)
by the mechanism proposed by Fujii, Hamaguchi,
and Yanagida (hep-ph/0104186).

During inflation



Since the mass splitting between neutral and charged winos is very small (~0.1 GeV), neutral winos are easily excited into charged winos.

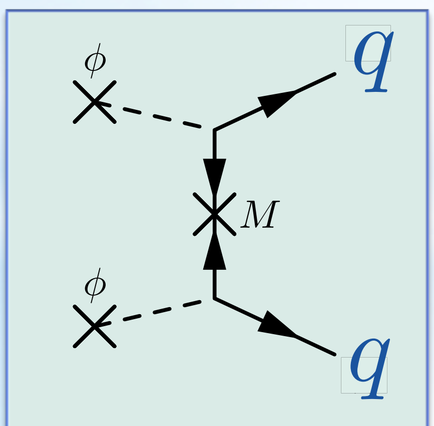
Since charged winos interact with radiation through the $U(1)_{EM}$ gauge interaction, the charged winos lose their energy very rapidly.

The charged winos then decay into neutral winos (DM).

The DM (neutral wino) is cold due to these effects unless they are produced non-thermally just before the BBN.

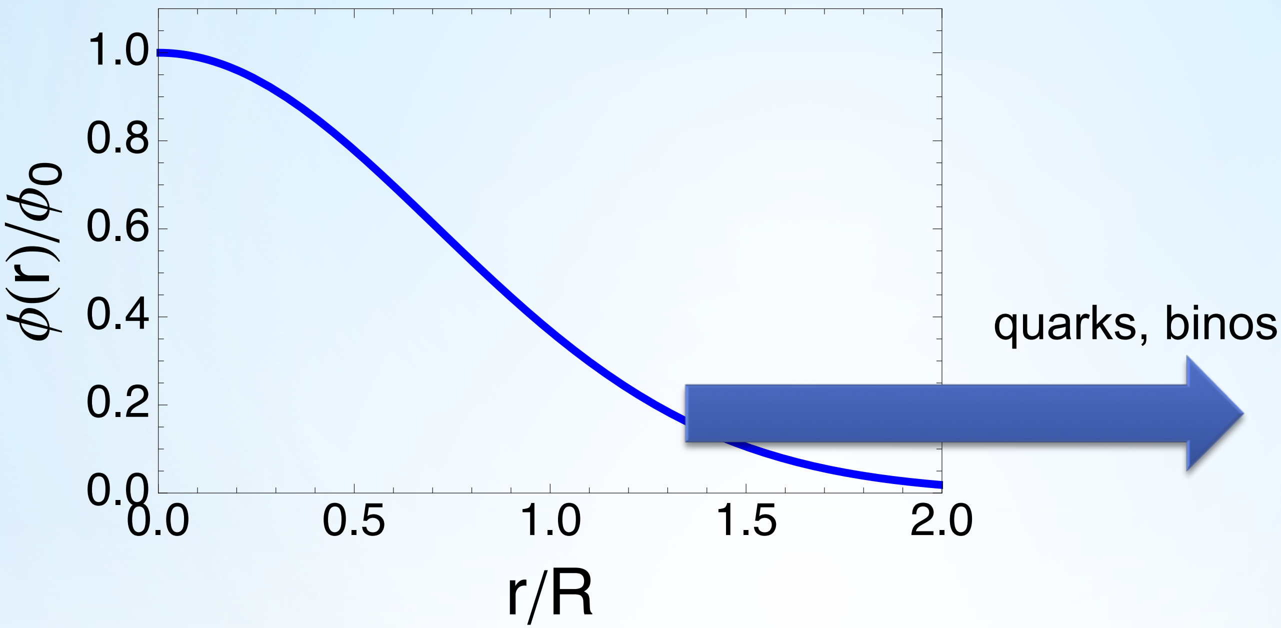
Ref:
Ibe, Kamada, and Matsumoto (hep-ph/1210.0191)

	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	do not change color (left handed) top, bottom (Q_3) $\rightarrow$ + 6
$\tilde{\bar{d}}_2^B = \frac{1}{\sqrt{3}}\phi$	d_2^G, d_2^R	d_2^B	



n_q = 15

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

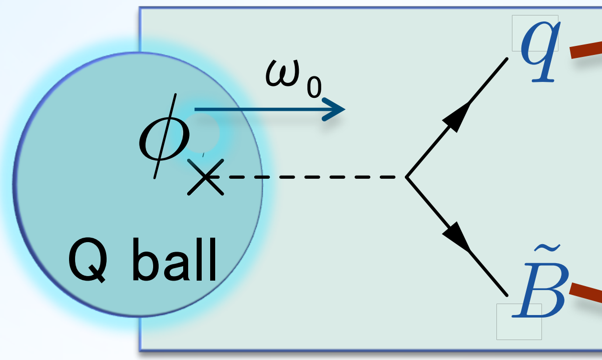
Q-ball decay rate

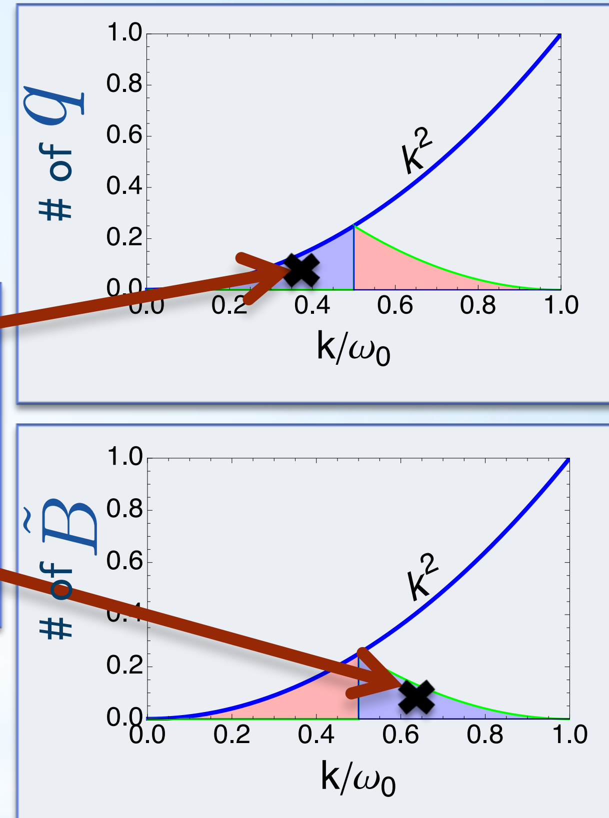
Cohen, *et. al*, 86

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

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

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

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

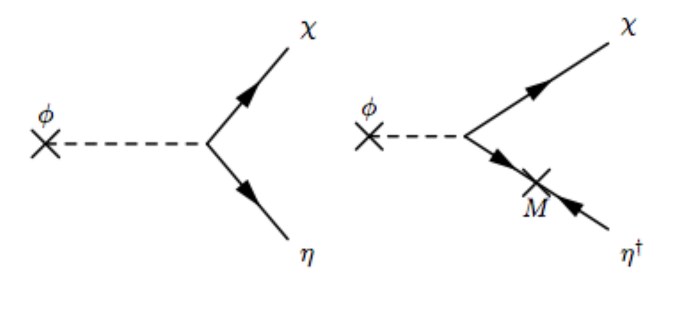


FIG. 14: Diagrams for $\phi \to \chi\eta$.

we can neglect helicity flips

×8 for M > omega_0
∝ M² for M < omega_0

Kawasaki, M.Y.

hep-ph/1209.5781

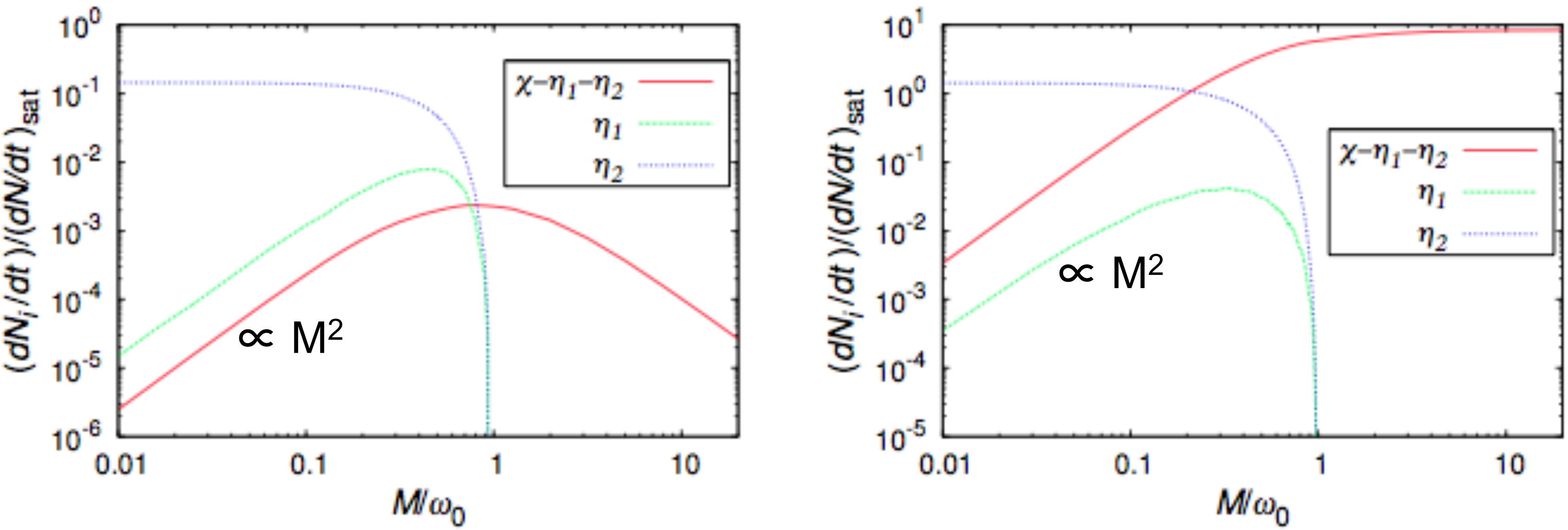
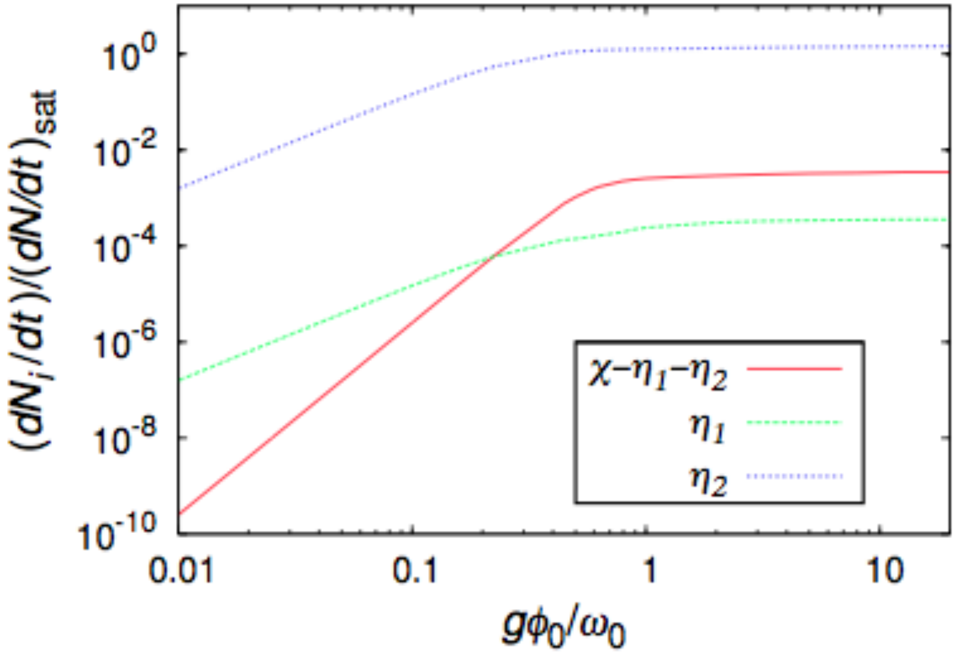


FIG. 12: Production rates of χ, η_1 and η_2 from Q balls as a function of M/ω_0 for $g\phi_0/\omega_0 = 0.1$ (left panel) and for $g\phi_0/\omega_0 = 10$ (right panel) with $R\omega_0 = \pi$ in the Yukawa theory with a massive fermion. The vertical axis is normalized by the saturated rate of Eq. (36).



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).

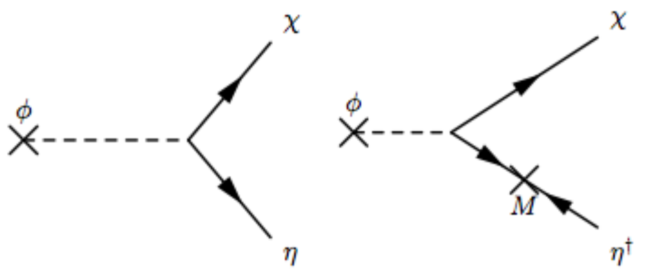


FIG. 14: Diagrams for $\phi \to \chi\eta$.

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

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

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

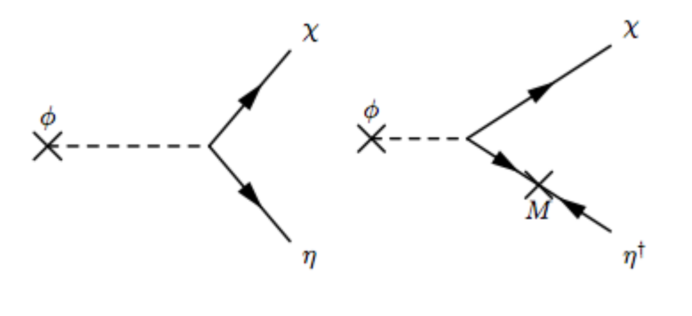
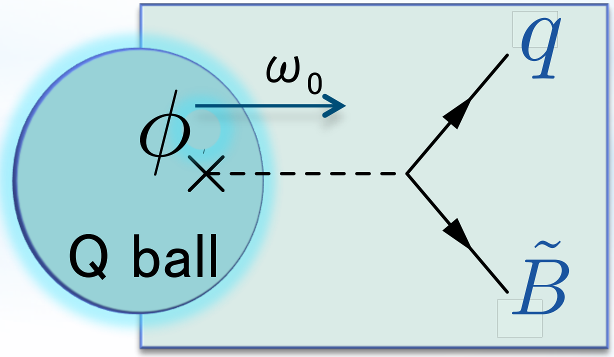


FIG. 14: Diagrams for $\phi \to \chi\eta$.

Loop diagrams can be neglected inside Q-balls
because fields interacting with Φ gain the large mass of $g\Phi_0$ ($>>>>\omega_0$)

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



$$\omega_0 = 1$$

Case of non-zero bino mass

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

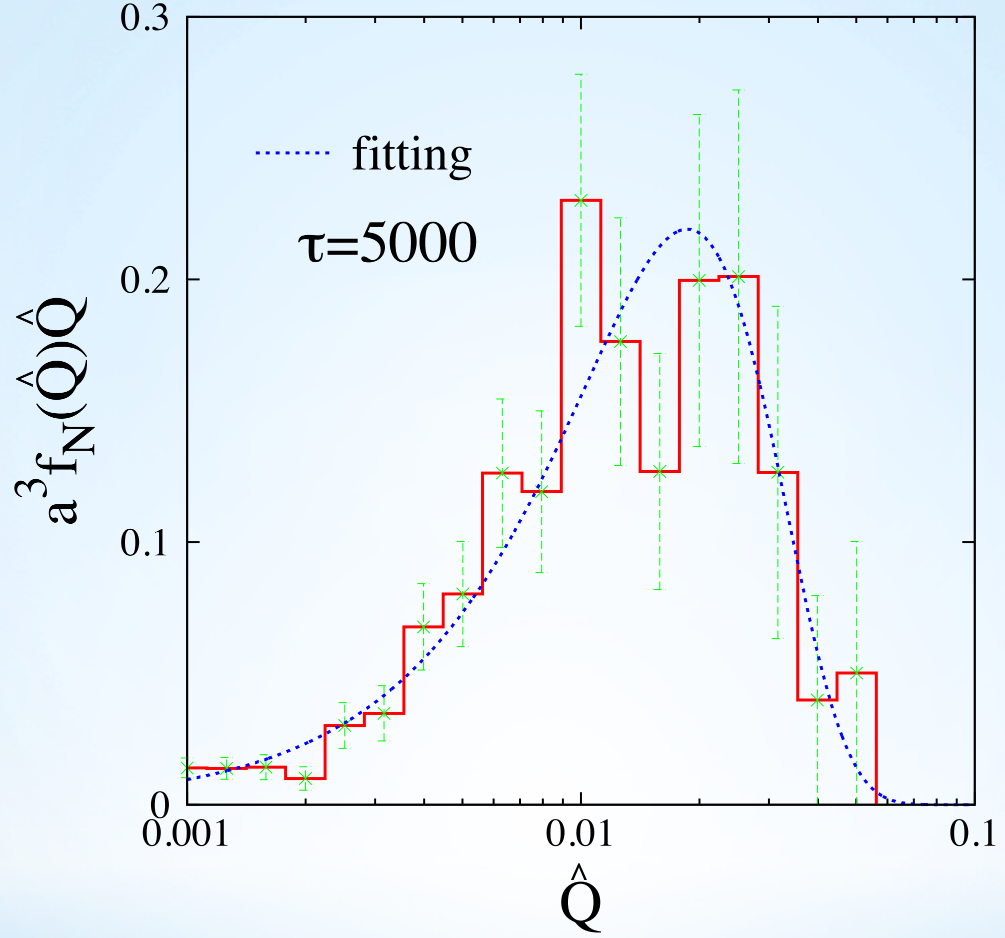
for $m > 1/2$

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

$$\frac{1}{8\pi^2}\int_m^{1/2} dE \ E\sqrt{E^2 - m^2}v$$

for $m < 1/2$

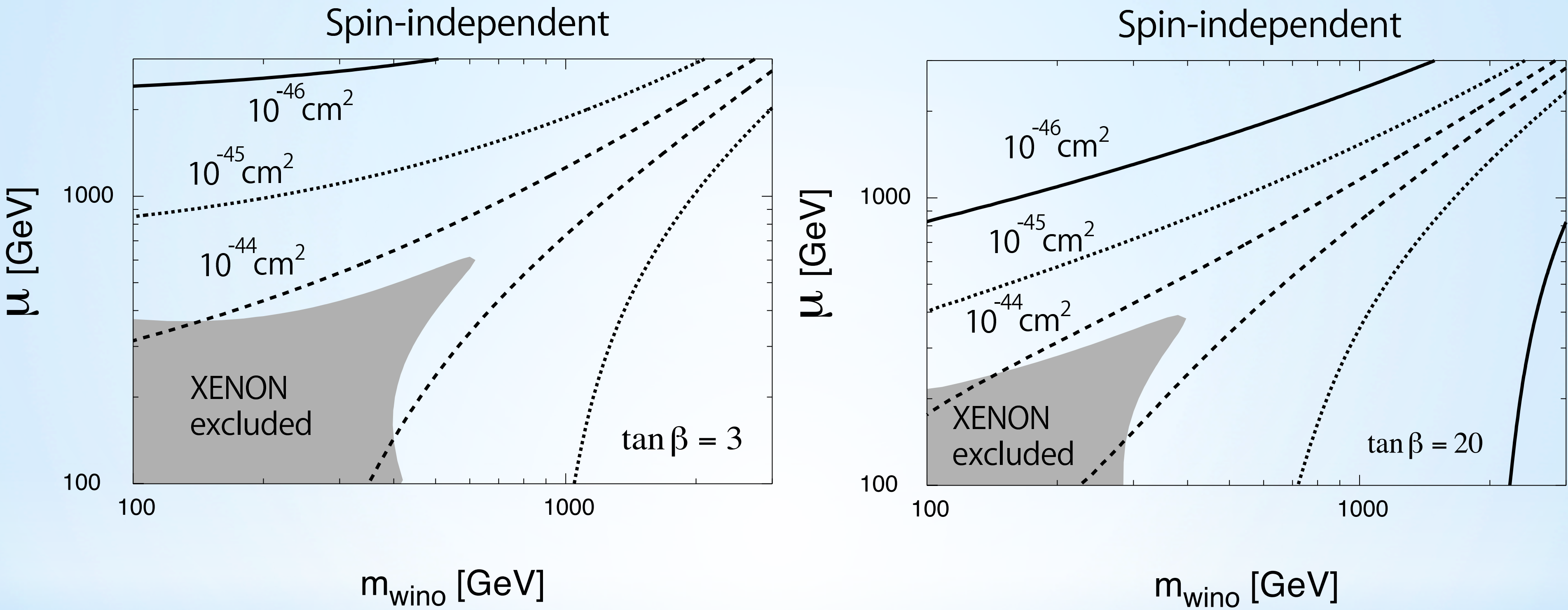
$$v = p/E = \sqrt{E^2 - m^2}/E$$



Charge density distribution of Q-balls

Hiramatsu, Kawasaki, and Takahashi
hep-ph/1003.1779

Constraints from the direct detection of wino DM



Moroi and Nakayama
hep-ph/1112.3123

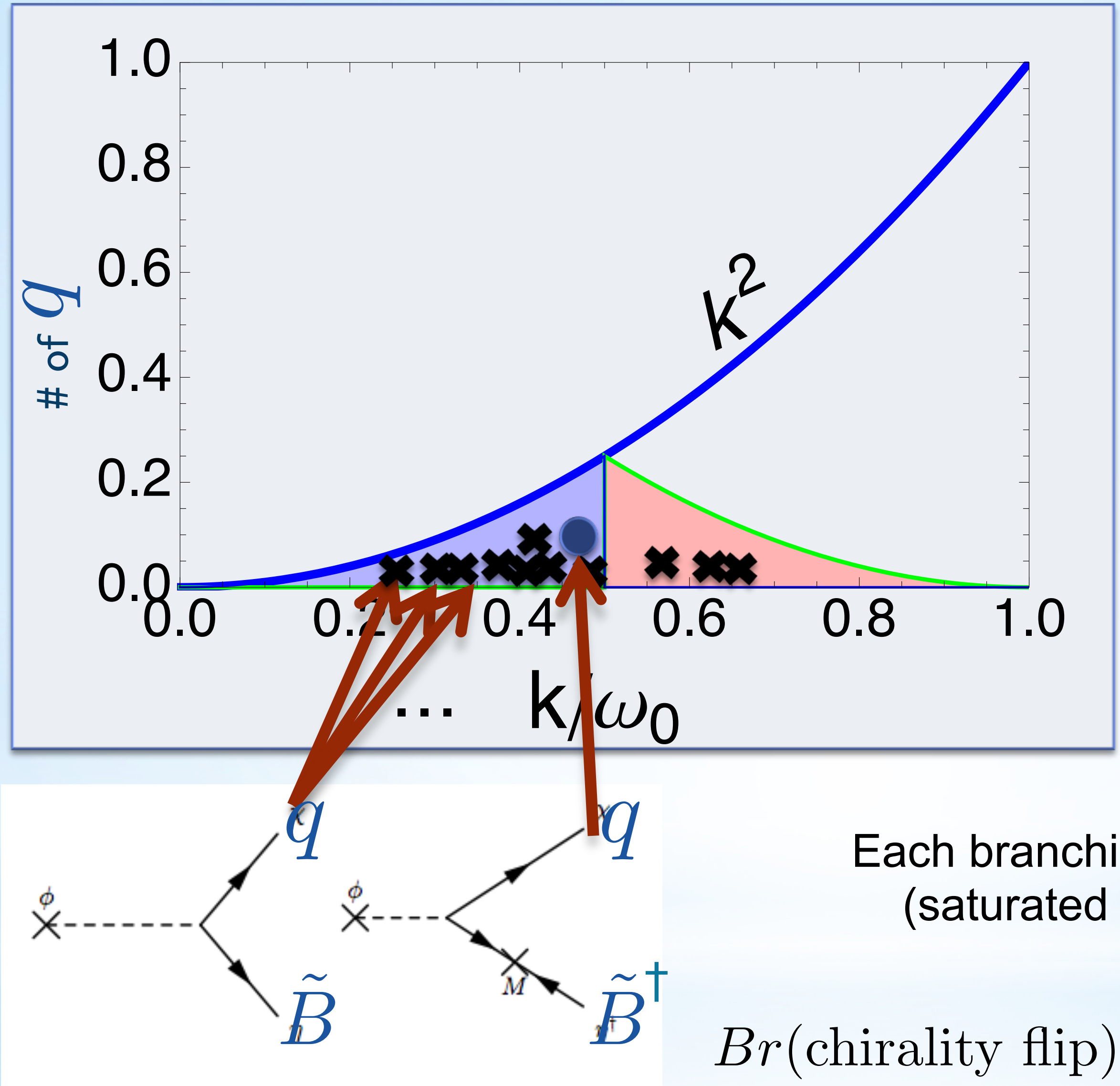


FIG. 14: Diagrams for $\phi \to \chi\eta$.

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

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

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