Axino dark matter and baryon number asymmetry from *Q*-ball decay in gauge mediation

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based on
S.Kasuya, EK, M.Kawasaki arXiv:1202.4067

Introduction

The origins of baryon number asymmetry and the dark matter of the universe are still mysteries in cosmology.

baryon

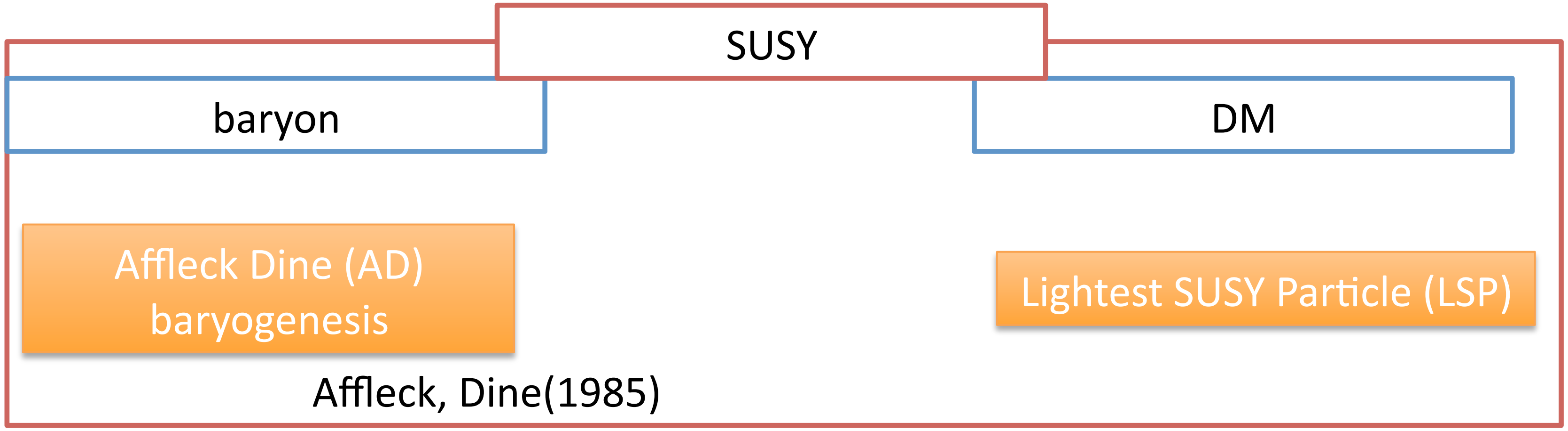
dark matter

but from observations, we know the energy densities of baryon and DM are at the same order

$$\frac{\rho_{\mathrm{DM}}}{\rho_b} = 5$$

?

Baryogenesis and LSP



SUSY

baryon

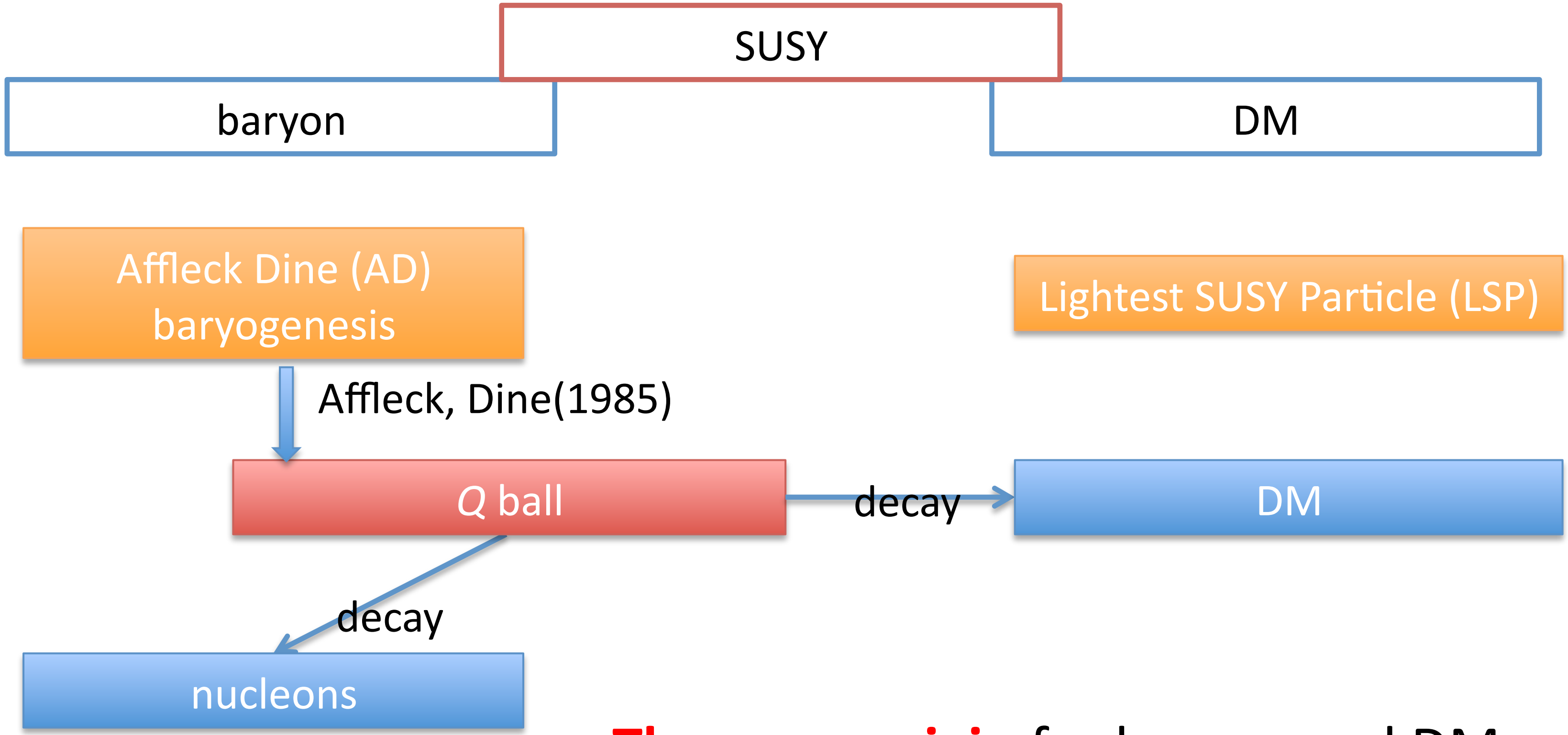
DM

Affleck Dine (AD) baryogenesis

Lightest SUSY Particle (LSP)

Affleck, Dine(1985)

The same origin of baryon and DM



SUSY

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Q ball

decay

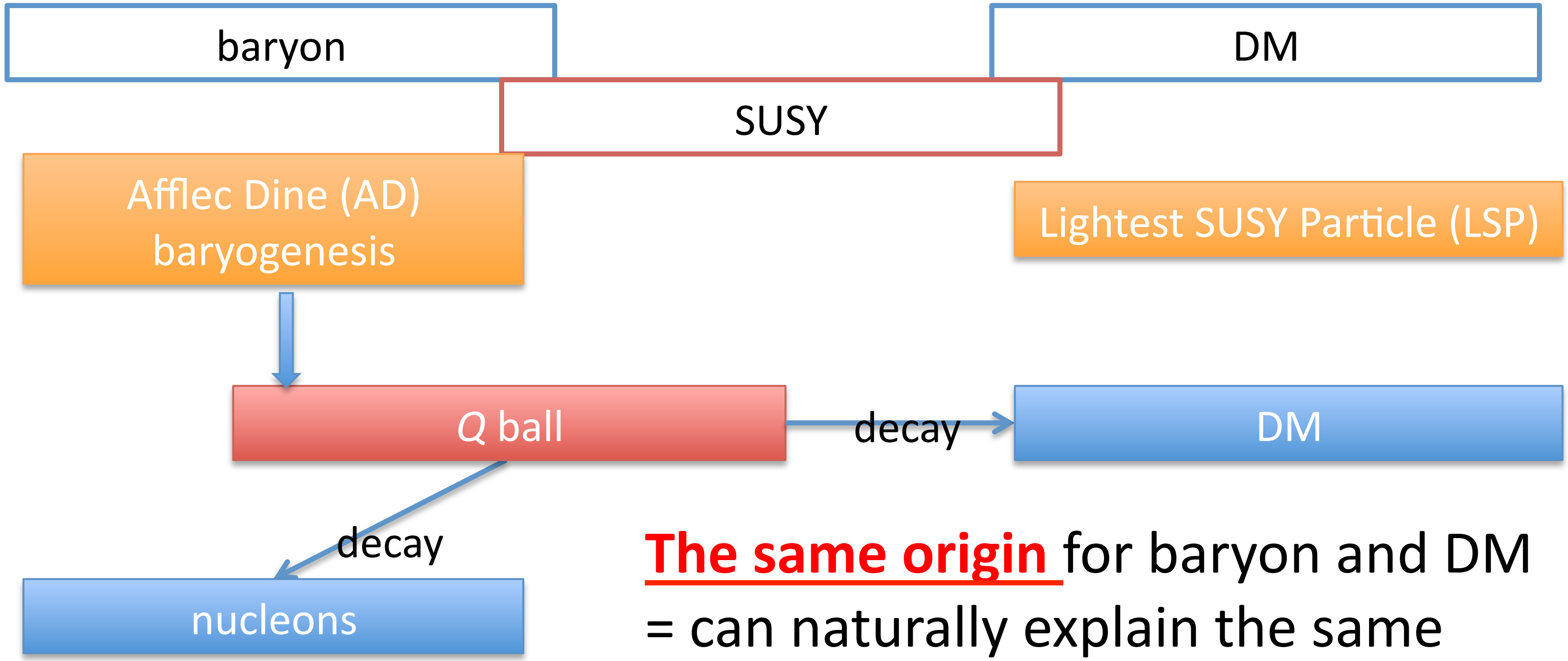
DM

decay

nucleons

The same origin for baryon and DM
= can naturally explain the same order of the energy densities.

The same origin of baryon and DM



The same origin for baryon and DM
= can naturally explain the same order of the energy densities.

scenarios

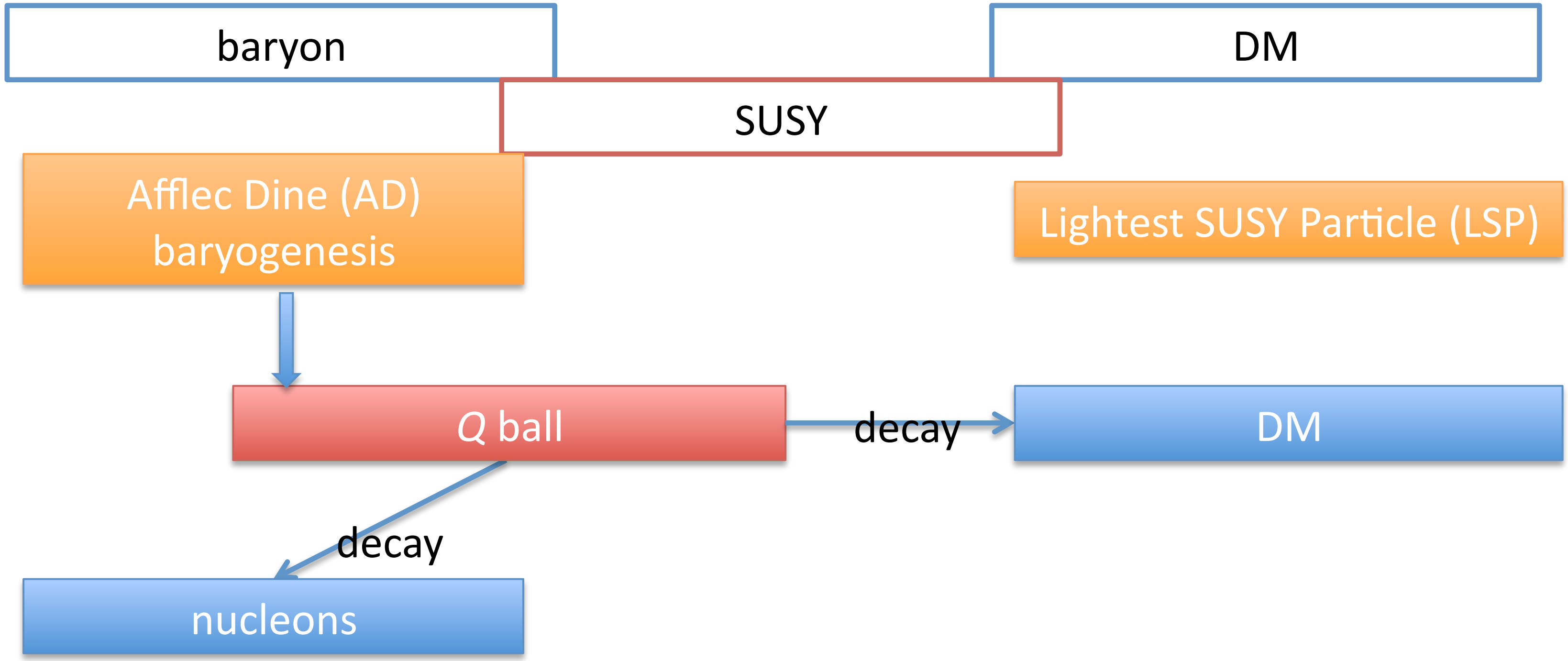
gravity mediation

Neutralino DM	Enqvist, McDonald(1998)
Higgsino&Wino	Fujii, Hamaguchi(2002)
Gravitino	Seto(2006)
Axino	Roszkowski, Seto(2007)

gauge mediation

Gravitino	Shoemaker, Kusenko (2009) Kasuya, Kawasaki (2011) Doddato, McDonald (2011)
Axino	Kasuya, EK, Kawasaki(2012)

The same origin of baryon and DM



baryon

DM

SUSY

Afflec Dine (AD) baryogenesis

Lightest SUSY Particle (LSP)

Q ball

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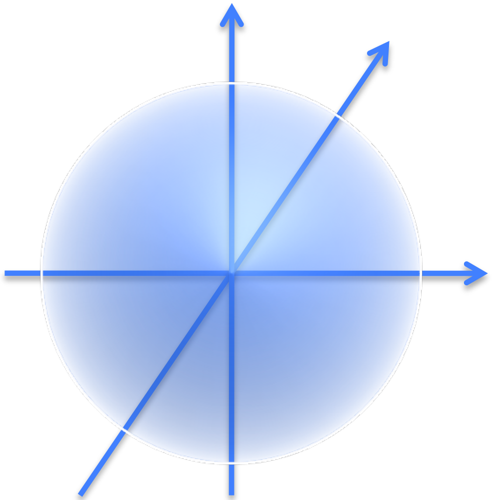
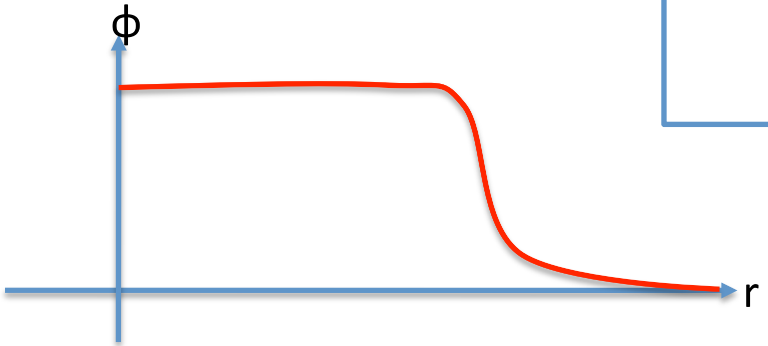
Gauge mediated SUSY breaking & Axino dark mater

This scenario can provide the energy density ratio between DM and baryon.
We investigate the allowed regions of axion parameters and Q ball parameters.

What is *Q* ball?





The lowest energy configuration of scalar fields with global U(1) charge Q
Non-topological soliton
Coleman (1985)

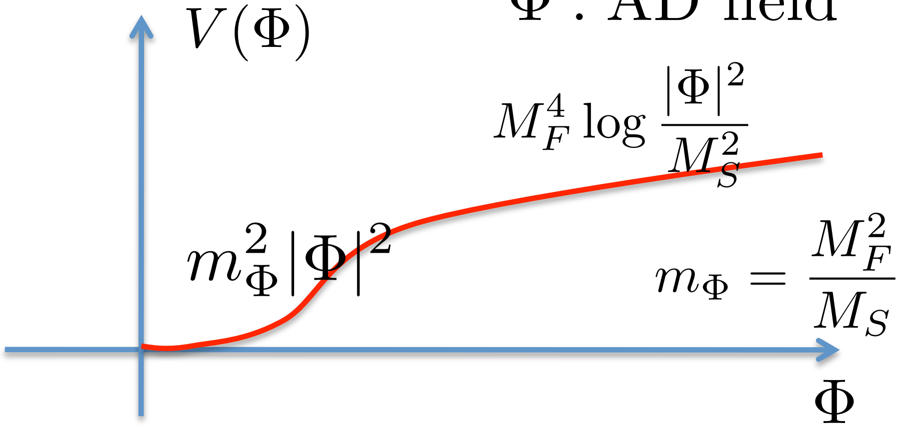
The Q ball solution exists in MSSM
Kusenko (1997)

- **Global U(1) charge Q is considered to be the baryon number** which is also global U(1) charge in MSSM

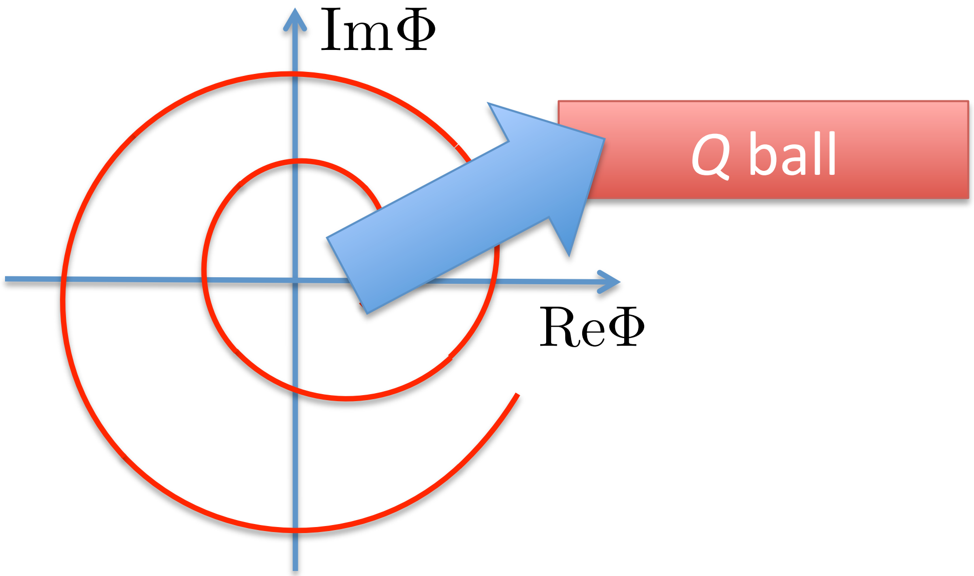
- **The AD condensate (= squarks, sleptons and higgs) may fragment into *Q* balls** during its rotation in the potential to create the baryon number.

Q ball in gauge mediated SUSY breaking

Φ : AD field



de Gouvêa, Moroi, Murayama (1997)



Q-ball charge

$$Q = 6 \times 10^{-5} \left(\frac{\phi_{\rm osc}}{M_F} \right)^4$$

Kasuya, Kawasaki (2001)

baryon number

$$B = \frac{1}{3} Q$$

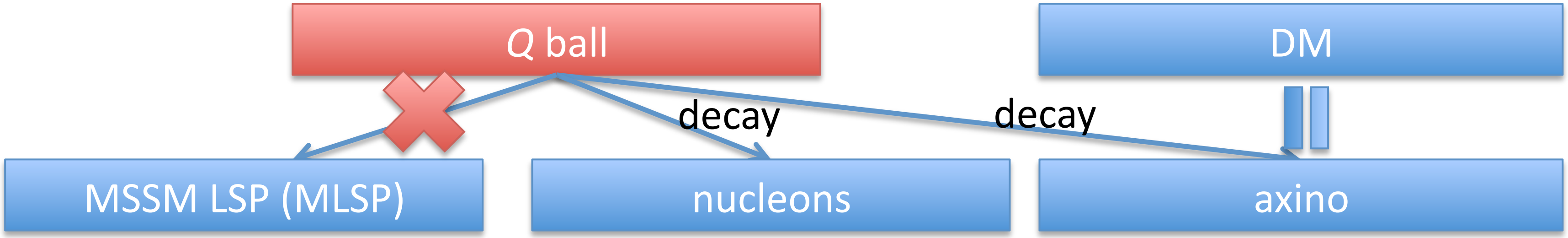
$$M_Q \simeq \frac{4\sqrt{2}\pi}{3} M_F Q^{3/4},$$

$$R_Q \simeq \frac{1}{\sqrt{2}} M_F^{-1} Q^{1/4},$$

$$\omega_Q \simeq \sqrt{2}\pi M_F Q^{-1/4},$$

$$\phi_Q \simeq M_F Q^{1/4},$$

Q-ball decay



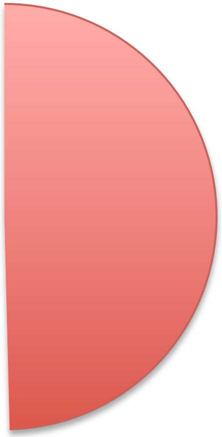
might be harmful to the BBN

The *Q* ball can decay into a particle only if the mass of the particle is less then the *Q*-ball mass per charge.

$$\boxed{\max(m_{\tilde{a}}, \frac{1}{3}m_N) < \frac{M_Q}{Q} < m_{\mathrm{MLSP}}}$$

The decay into MLSP only happens after the *Q*-ball charge becomes small

Kasuya, Takahashi (2007)



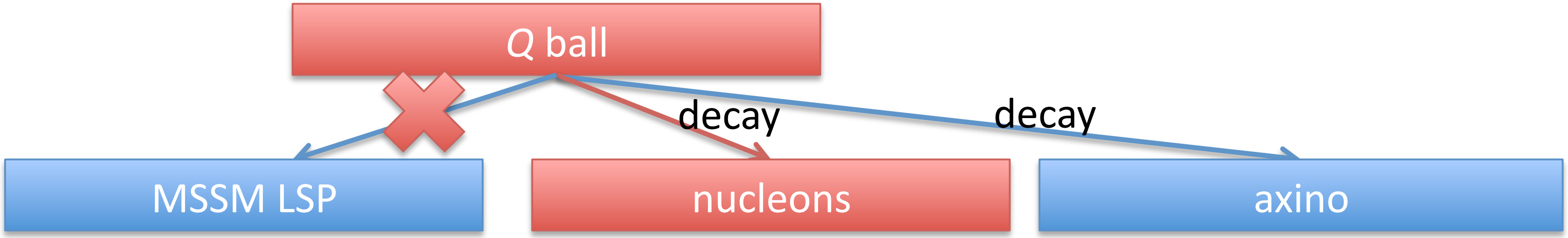
Q-ball decays only from its surface and the decay rate is given by

$$\Gamma_Q^{(\mathrm{sat})} \simeq \frac{\pi}{24\sqrt{2}} M_F Q^{-5/4} \qquad \frac{f_{\mathrm{eff}}\phi_Q}{\omega_Q} \gtrsim 1$$

$$\Gamma_Q^{(\mathrm{unsat})} \simeq 3\pi \frac{f_{\mathrm{eff}}\phi_Q}{\omega_Q} \Gamma_Q^{(\mathrm{sat})} \qquad \frac{f_{\mathrm{eff}}\phi_Q}{\omega_Q} \ll 1$$

Cohen, Coleman, Georgi, Manohar (1986)

Q-ball decay into nucleons



Q ball

decay

decay

MSSM LSP

nucleons

axino

Decay into nucleons = saturated

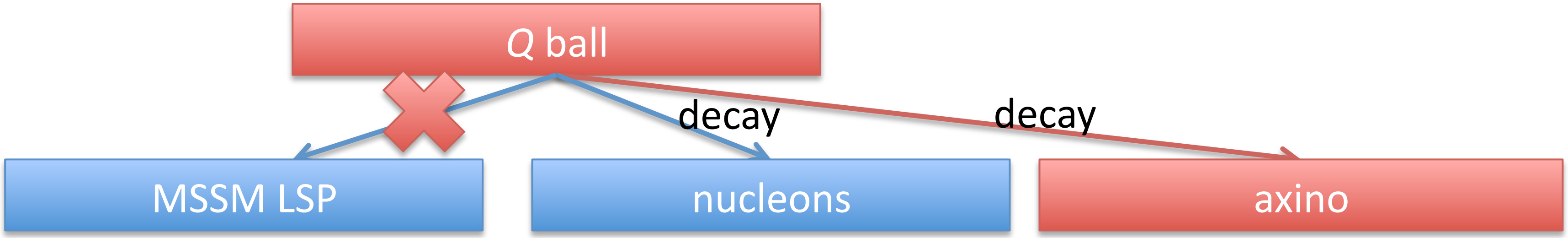
$$f_{\rm eff} \simeq \frac{\zeta^{1/2} g_s^2}{\sqrt{2}\pi}\frac{\phi_Q}{(m_{\tilde{g}}\omega_Q)^{1/2}}$$

Ellis et al. (1984)

$$\frac{f_{\rm eff}\phi_Q}{\omega_Q} \simeq 3.2\times 10^{17}\zeta^{1/2} g_s^2 \left(\frac{m_{\tilde{g}}}{\rm TeV}\right)^{-1/2}\left(\frac{M_F}{10^4{\rm GeV}}\right)^{1/2}\left(\frac{Q}{10^{21}}\right)^{7/8} \gg 1$$

$$\zeta \sim |V_{\rm CKM}|^4 \gtrsim 10^{-12}$$

Q-ball decay into axinos



Q ball

decay

decay

MSSM LSP

nucleons

axino

Decay into axinos = saturated or unsaturated

$$f_{\mathrm{eff}}^{(\tilde{a})} = \frac{\alpha_s^2}{\sqrt{2}\pi^2} \frac{m_{\tilde{g}}}{f_a} \log\left(\frac{f_a}{m_{\tilde{g}}}\right)$$

Covi et al. (2002)

$$\frac{f_{\mathrm{eff}}^{(\tilde{a})}\phi_Q}{\omega_Q} \simeq 5.1 \times 10^{-5} \left(\frac{f_a}{10^{14}\mathrm{GeV}}\right)^{-1} \log\left(\frac{f_a}{10^{14}\mathrm{GeV}}\right) \left(\frac{Q}{10^{21}}\right)^{1/2}$$

The branching ratio is given by

$$B_{\tilde{a}} = \frac{\Gamma_Q^{(\tilde{a})}}{\Gamma_Q^{(\mathrm{sat})}} \simeq 4.8 \times 10^{-4} \left(\frac{f_a}{10^{14}\mathrm{GeV}}\right)^{-1} \log\left(\frac{f_a}{10^{3}\mathrm{GeV}}\right) \left(\frac{Q}{10^{21}}\right)^{1/2}$$

Baryon, axino and MLSP abundances from *Q*-ball decay

$$n_b \simeq \frac{\epsilon}{3} n_\phi$$

$$n_{\tilde{a}} \simeq B_{\tilde{a}} n_\phi$$

$$n_{\rm MLSP} \simeq \frac{Q_{\rm cr}}{Q} n_\phi$$

$$Q_{\rm cr} = \frac{M_Q}{m_{\rm MLSP}} = \frac{1024\pi^2}{81}\left(\frac{M_F}{m_{\rm MLSP}}\right)^4$$

$$\frac{\rho_{\tilde{a}}}{\rho_b} \simeq \frac{3 m_{\tilde{a}} B_{\tilde{a}}}{m_N \epsilon} \simeq 5$$

$$Y_b \equiv \frac{\rho_b}{s} \simeq \frac{3}{4} T_{\rm RH} \left.\frac{n_b}{\rho_{\rm rad}}\right|_{\rm RH}$$

$$\simeq 10^{-10}$$

$$\left.\frac{Y_b}{10^{-10}}\right|_{\rm sat} \simeq 2.3 \times 10^2 \left(\frac{m_{\tilde{a}}}{\rm GeV}\right)\left(\frac{\beta}{6\times 10^{-5}}\right)^{-3/4}\left(\frac{T_{\rm RH}}{10^7\,{\rm GeV}}\right)\left(\frac{M_F}{10^4\,{\rm GeV}}\right)\left(\frac{Q}{10^{21}}\right)^{3/4}$$

$$\left.\frac{Y_b}{10^{-10}}\right|_{\rm unsat} \simeq 0.11 \left(\frac{m_{\tilde{a}}}{\rm GeV}\right)\left(\frac{f_a}{10^{14}\,{\rm GeV}}\right)^{-1}\log\left(\frac{f_a}{10^3\,{\rm GeV}}\right)\left(\frac{\beta}{6\times 10^{-5}}\right)^{-3/4} \times \left(\frac{T_{\rm RH}}{10^7\,{\rm GeV}}\right)\left(\frac{M_F}{10^4\,{\rm GeV}}\right)\left(\frac{Q}{10^{21}}\right)^{5/4}.$$

Baryon, axino and MLSP abundances from *Q*-ball decay

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$$\frac{\rho_{\tilde a}}{\rho_b} \simeq \frac{3 m_{\tilde a} B_{\tilde a}}{m_N \epsilon} \simeq 5$$

$$Y_b \equiv \frac{\rho_b}{s} \simeq \frac{3}{4} T_{\rm RH} \left.\frac{n_b}{\rho_{\rm rad}}\right|_{\rm RH}$$

$$\simeq 10^{-10}$$

MLSP is produced when Q ball charge becomes small enough.

$$\boxed{\max\left(m_{\tilde a}, \frac{1}{3} m_N\right) < \frac{M_Q}{Q} < m_{\rm MLSP}}$$

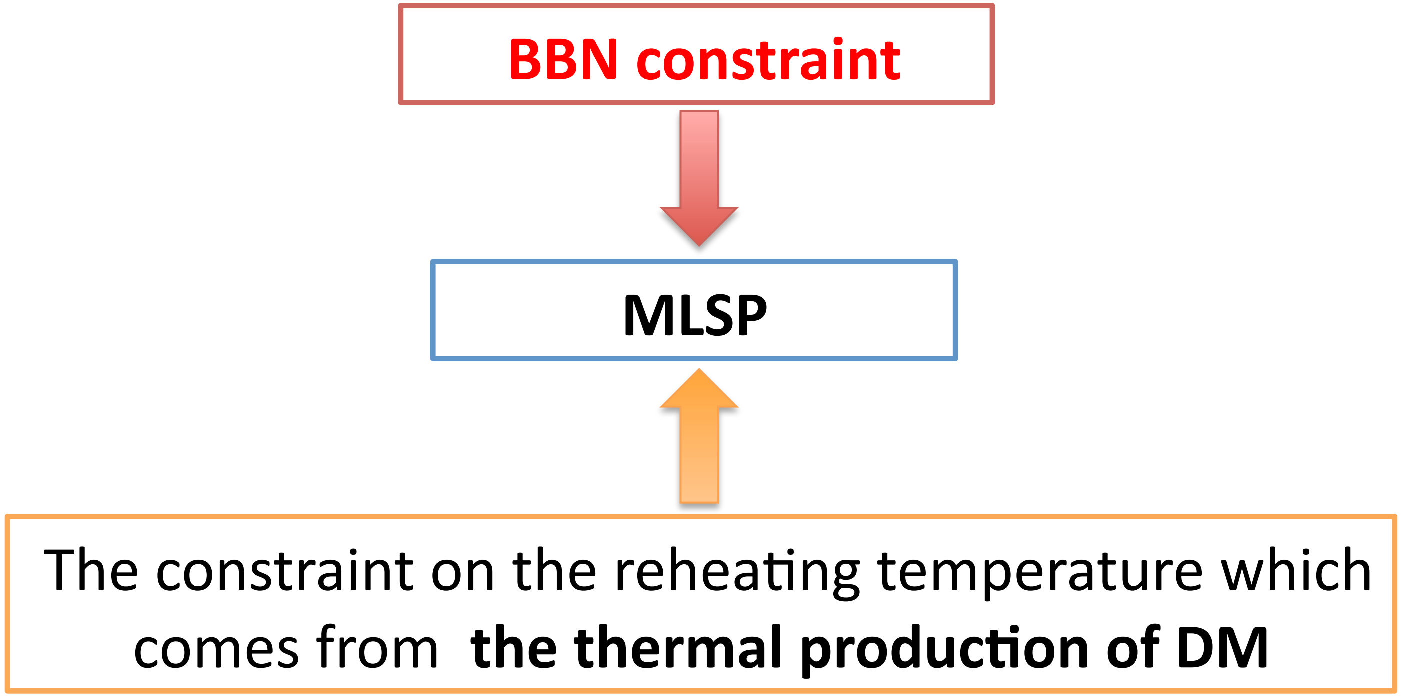
$$\frac{\rho_{\rm MLSP}}{s} \simeq \begin{cases} 6.2 \times 10^{-18}{\rm GeV} \left(\frac{m_{\tilde a}}{\rm GeV}\right)^{-1} \left(\frac{m_{\rm MLSP}}{100{\rm GeV}}\right)^{-3} \left(\frac{M_F}{10^4{\rm GeV}}\right)^4 \left(\frac{Q}{10^{21}}\right)^{-1} \\ 1.3 \times 10^{-14}{\rm GeV} \left(\frac{m_{\tilde a}}{\rm GeV}\right)^{-1} \left(\frac{f_a}{10^{14}{\rm GeV}}\right) \left(\log \frac{f_a}{10^3{\rm GeV}}\right)^{-1} \left(\frac{m_{\rm MLSP}}{100{\rm GeV}}\right)^{-3} \left(\frac{M_F}{10^4{\rm GeV}}\right)^4 \left(\frac{Q}{10^{21}}\right)^{-3/2} \end{cases}$$

saturated case

unsaturated case

Constraints on the MLSP abundance

There are constraints on the MLSP abundance



BBN constraint

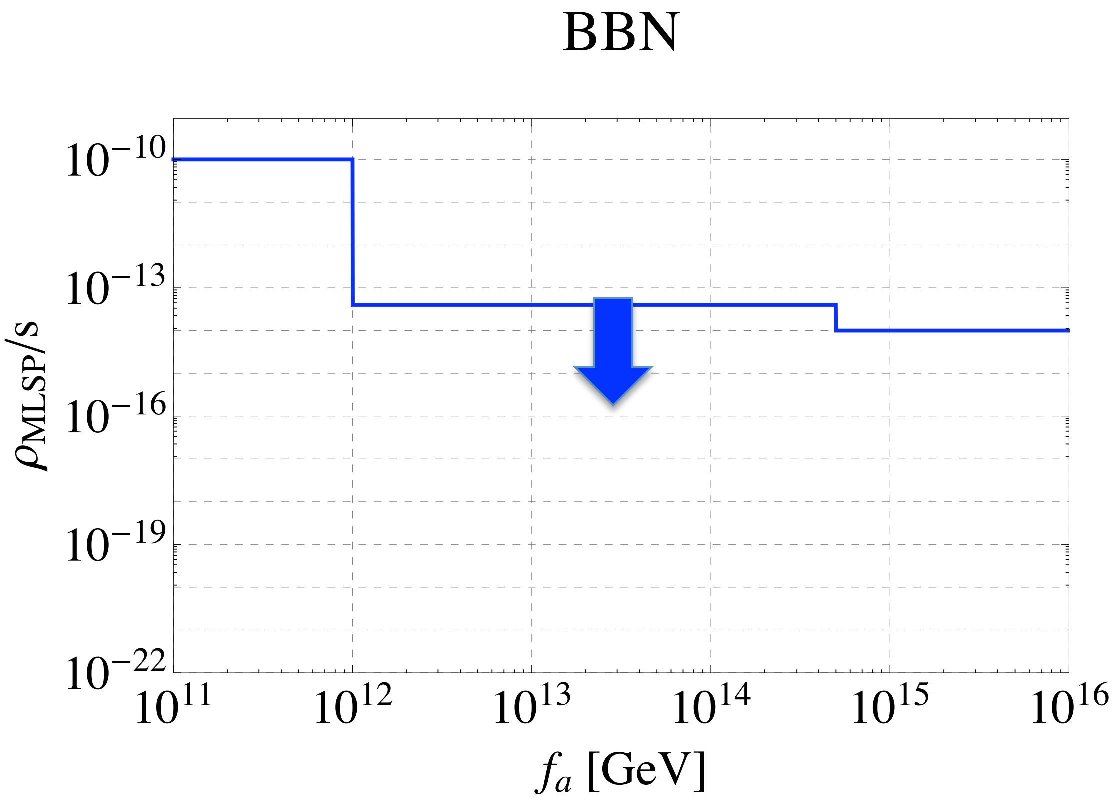
MLSP

The constraint on the reheating temperature which comes from **the thermal production of DM**

BBN constraint

The decay of the MLSP may affect abundances of light elements synthesized during the BBN, so the MLSP abundance should be small enough for the successful BBN.

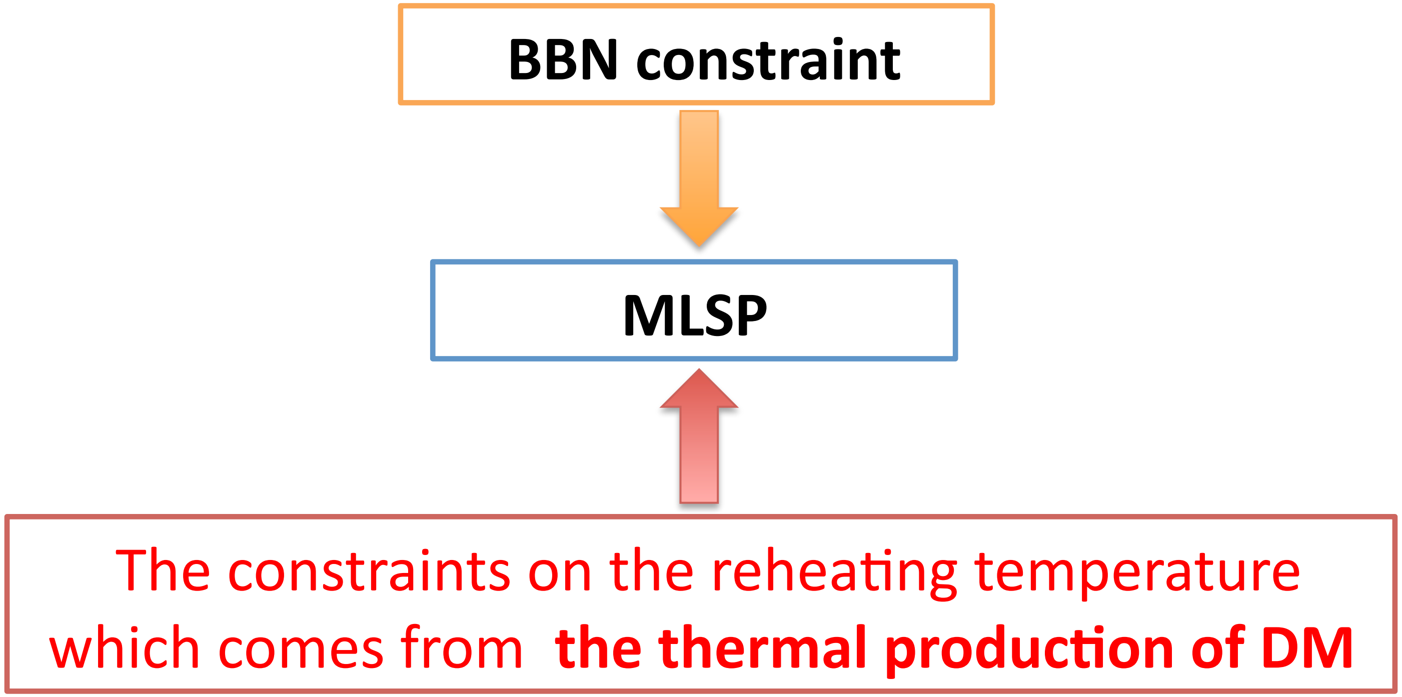
Here we suppose **MLSP = neutralino** and **m_{MLSP}=100 GeV**



Kawasaki, Kohri, Moroi (2005)
Kohri, Moroi, Yotsuyanagi (2006)
Kawasaki, Kohri, Moroi, Yotsuyanagi (2008)

Constraints on the MLSP abundance

There are constraints on the MLSP abundance



BBN constraint

MLSP

The constraints on the reheating temperature which comes from **the thermal production of DM**

- thermal axino production
  depends on axion models (KSVZ, DFSZ)
- thermal gravitino production

Thermally produced DM constraint

Thermally produced axino and gravitino should be less than the dark matter produced by Q ball decay

$$\boxed{\max\left(\Omega_{\tilde{a}}^{\mathrm{TH}}, \Omega_{3/2}^{\mathrm{TH}}\right) h^2 < \Omega_{\mathrm{DM}} h^2 \simeq 0.11}$$

$$\Rightarrow \quad T_{\mathrm{RH}} < T_{\mathrm{RH,\,max}}$$

Thermally produced DM constraint

depends on axion model
KSVZ or DFSZ

$$\max\left(\Omega_{\tilde{a}}^{\mathrm{TH}}, \Omega_{3/2}^{\mathrm{TH}}\right) h^2 < \Omega_{\mathrm{DM}} h^2 \simeq 0.11$$

$\Omega_{\tilde{a}}^{\mathrm{TH}}$ depends on $m_{\tilde{a}}$, f_a and T_{RH} for KSVZ

depends on $m_{\tilde{a}}$, f_a for DFSZ
at low reheating temperature

for DFSZ at low T_{RH} → **direct constraint on $m_{\tilde{a}}$ and f_a**

we have to use gravitino thermal production
constraint on T_{RH}

→ $T_{\mathrm{RH}} < T_{\mathrm{RH,\,max}}$

Thermally produced DM constraint

$$\boxed{\max\left(\Omega_{\tilde{a}}^{\rm TH},\Omega_{3/2}^{\rm TH}\right)h^2 < \Omega_{\rm DM}h^2 \simeq 0.11}$$

$$\Rightarrow \quad T_{\rm RH} < T_{\rm RH,\,max}$$

$$\boxed{\frac{\rho_{\rm MLSP}}{s} \propto \begin{array}{ll} \left(T_{\rm RH}\right)^{-2} & \textbf{for saturated case} \\ \left(T_{\rm RH}\right)^{-7/5} & \textbf{for unsaturated case} \end{array}}$$

$$\Rightarrow \quad \frac{\rho_{\rm MLSP}}{s} > \left.\frac{\rho_{\rm MLSP}}{s}\right|_{\rm min}$$

Constraints on the MLSP abundance

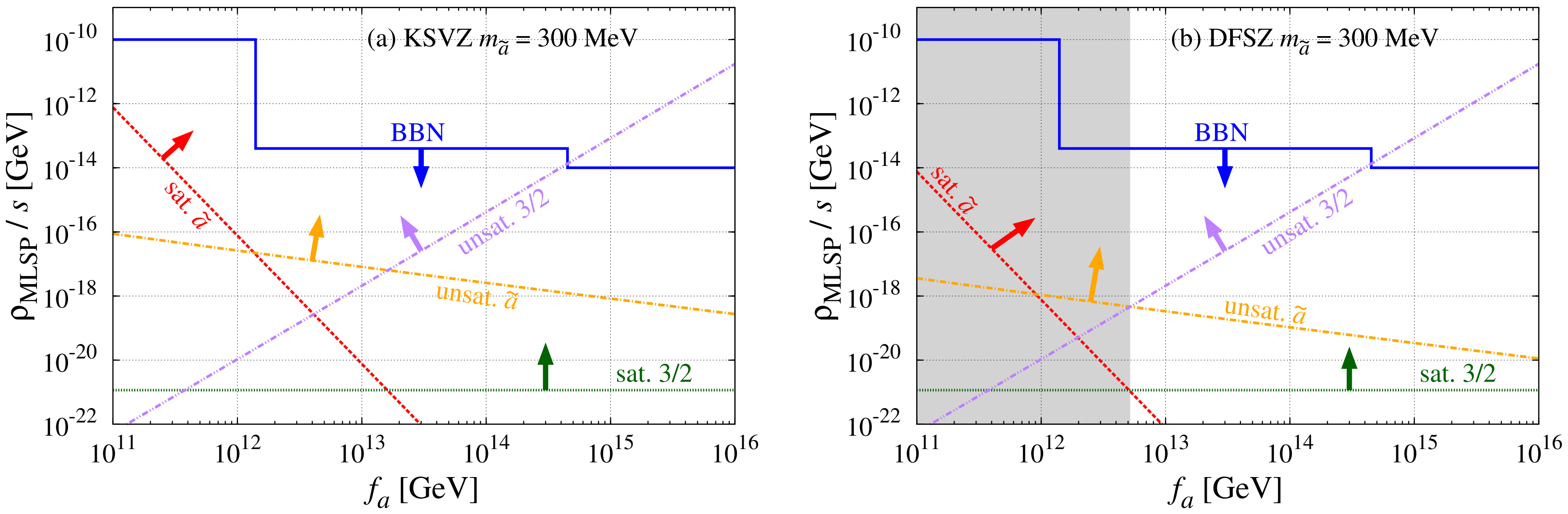
BBN constraint

↓

MLSP

↑

the thermal production of DM



KSVZ

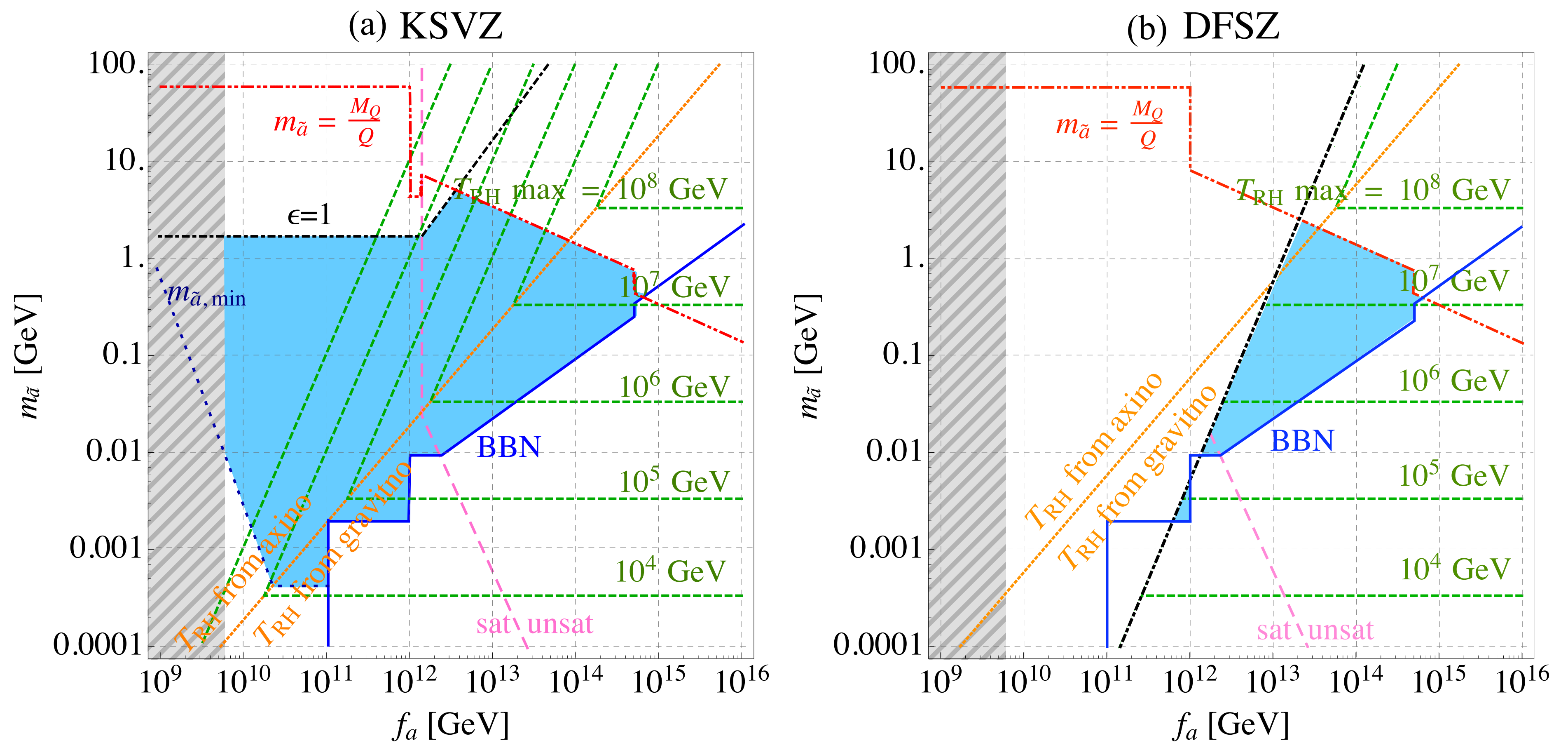
DFSZ

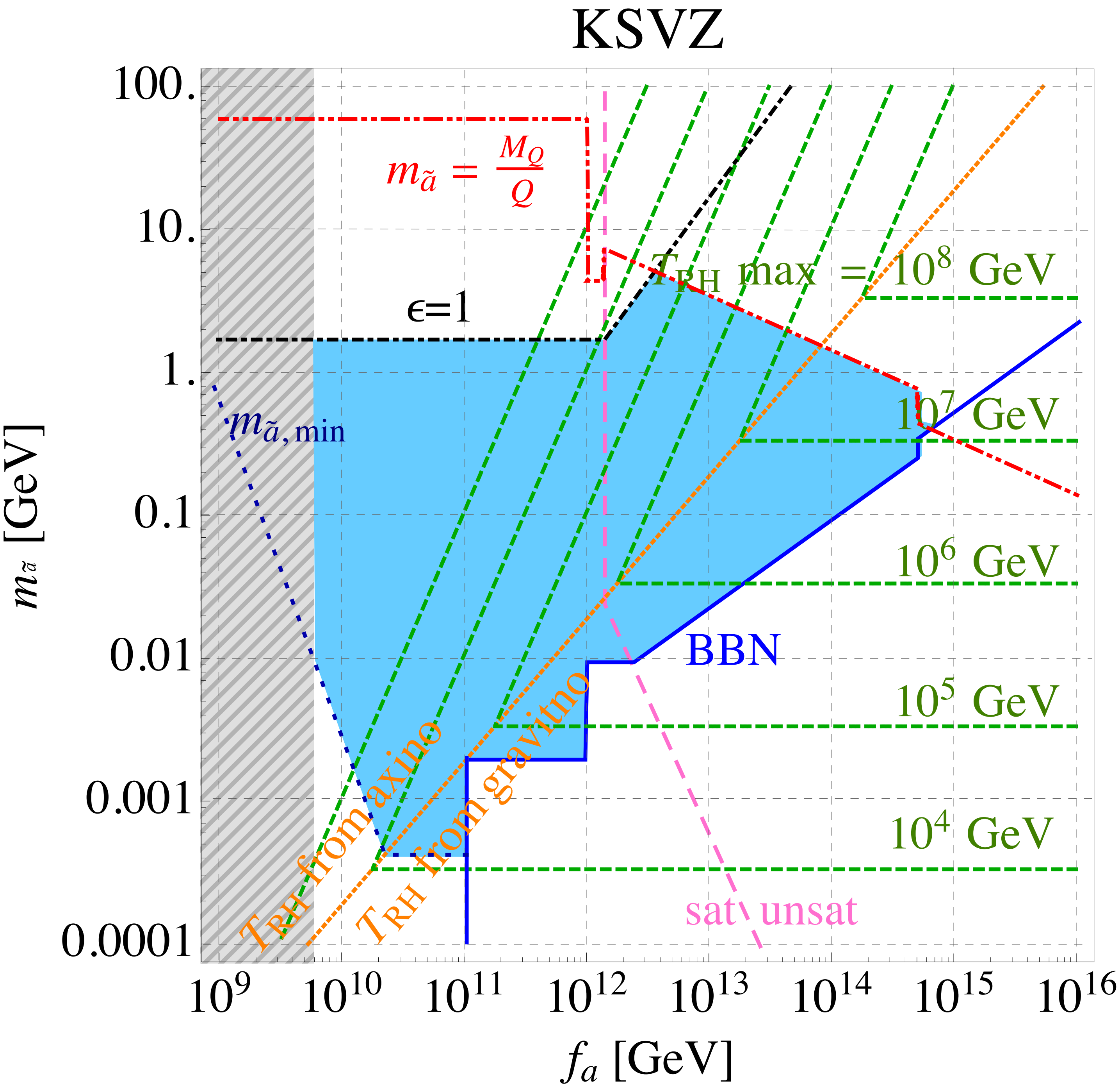
Allowed regions of axino model parameters

$m_{\tilde{a}} \sim O(\mathrm{MeV}) - O(\mathrm{GeV})$

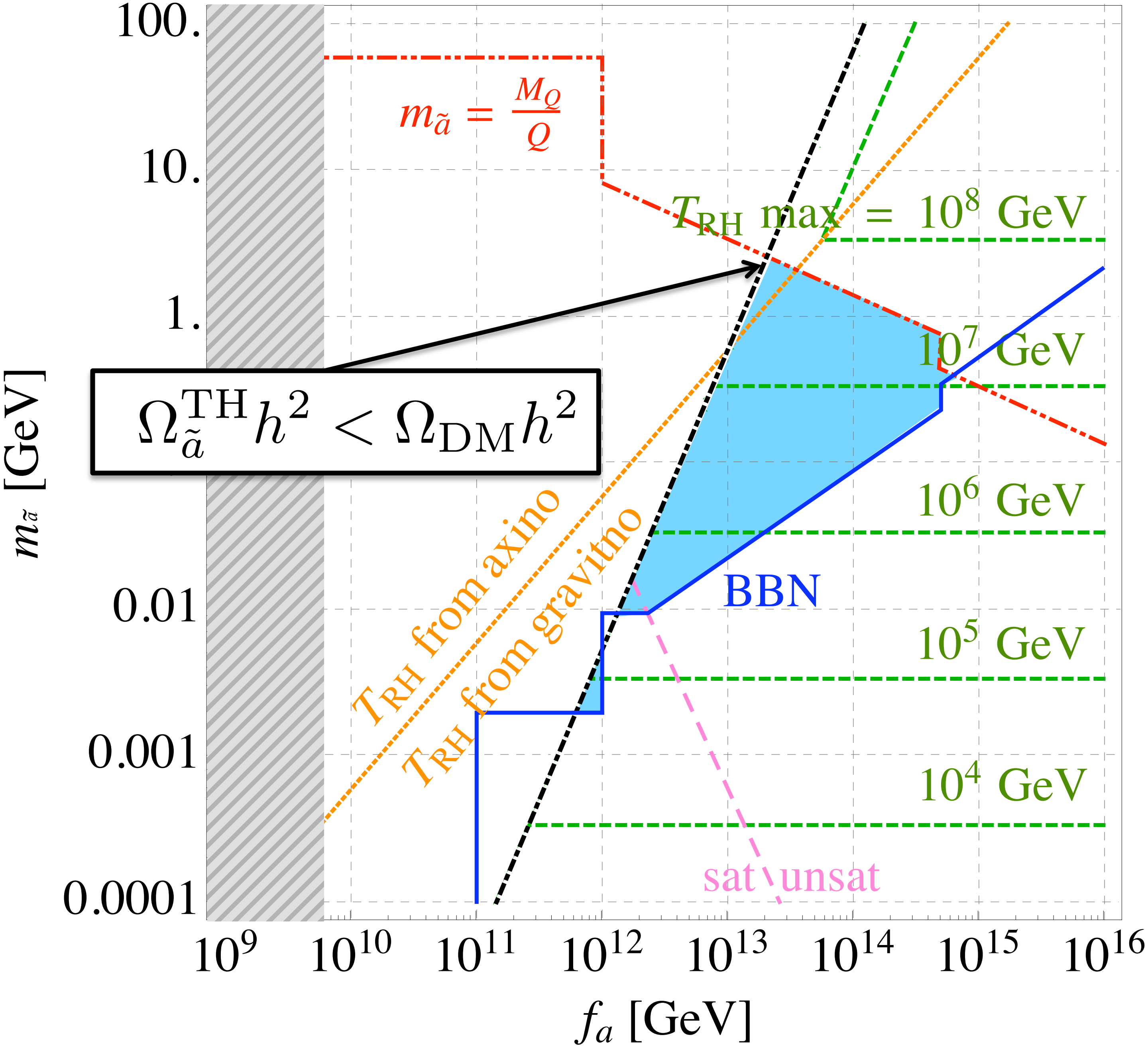
$6 \times 10^9\,\mathrm{GeV} \lesssim f_a \lesssim 5 \times 10^{14}\,\mathrm{GeV}$ (KSVZ model)

$10^{12}\,\mathrm{GeV} \lesssim f_a \lesssim 5 \times 10^{14}\,\mathrm{GeV}$ (DFSZ model)

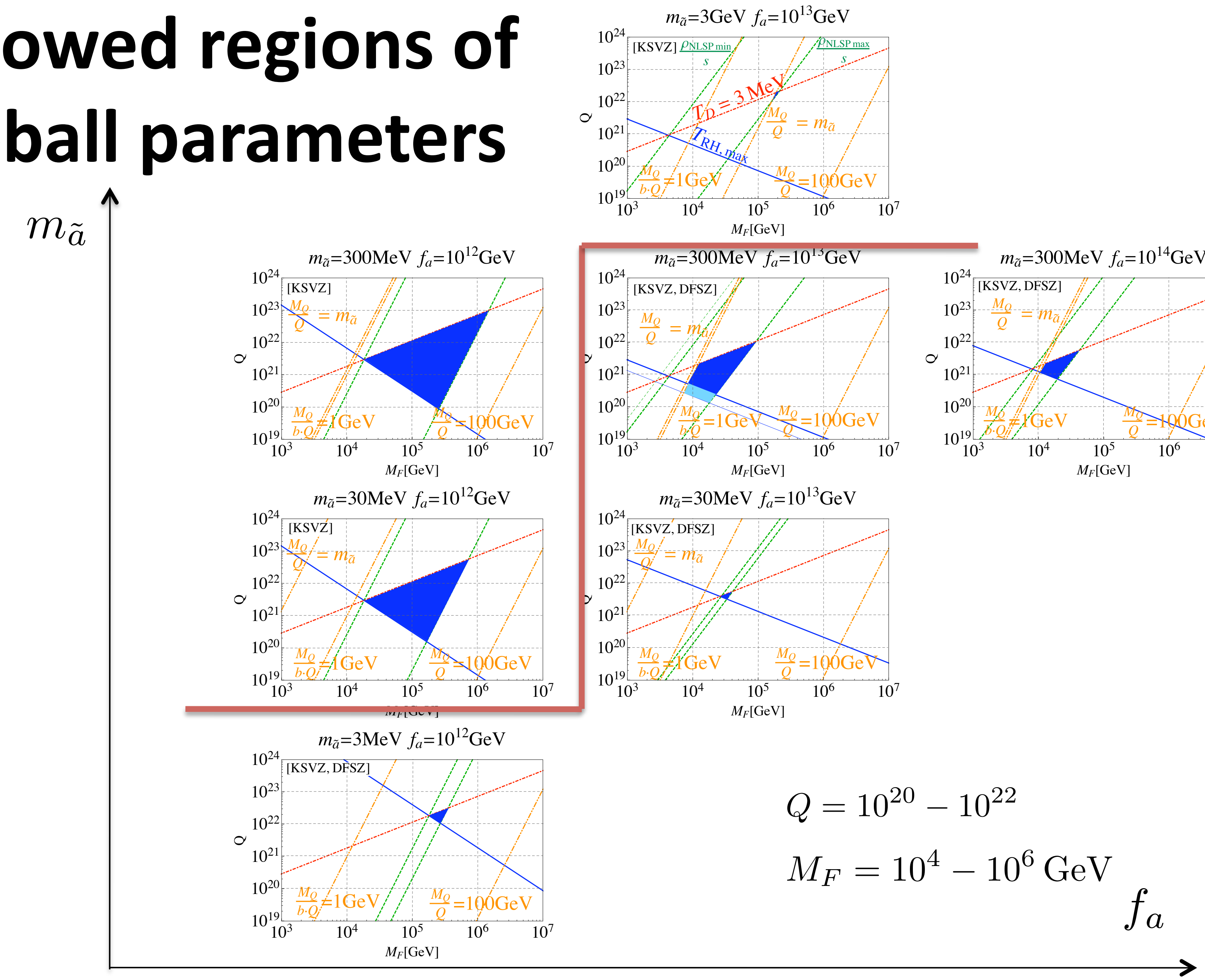



KSVZ
$m_{\tilde a} = \frac{M_Q}{Q}$
$T_{\rm RH}$ max = 10^8 GeV
10^7 GeV
10^6 GeV
10^5 GeV
10^4 GeV
ϵ=1
$m_{\tilde a,\,\rm min}$
BBN
sat
unsat
$T_{\rm RH}$ from axino
$T_{\rm RH}$ from gravitino
100.
10.
1.
0.1
0.01
0.001
0.0001
10^9
10^{10}
10^{11}
10^{12}
10^{13}
10^{14}
10^{15}
10^{16}
$m_{\tilde a}$ [GeV]
f_a [GeV]

DFSZ


$m_{\tilde{a}} = \frac{M_Q}{Q}$
$T_{\rm RH}$ max = 10^8 GeV
10^7 GeV
10^6 GeV
10^5 GeV
10^4 GeV
$\Omega_{\tilde{a}}^{\rm TH} h^2 < \Omega_{\rm DM} h^2$
$T_{\rm RH}$ from axino
$T_{\rm RH}$ from gravitno
BBN
sat
unsat
100.
10.
1.
0.01
0.001
0.0001
$m_{\tilde{a}}$ [GeV]
10^9
10^{10}
10^{11}
10^{12}
10^{13}
10^{14}
10^{15}
10^{16}
f_a [GeV]

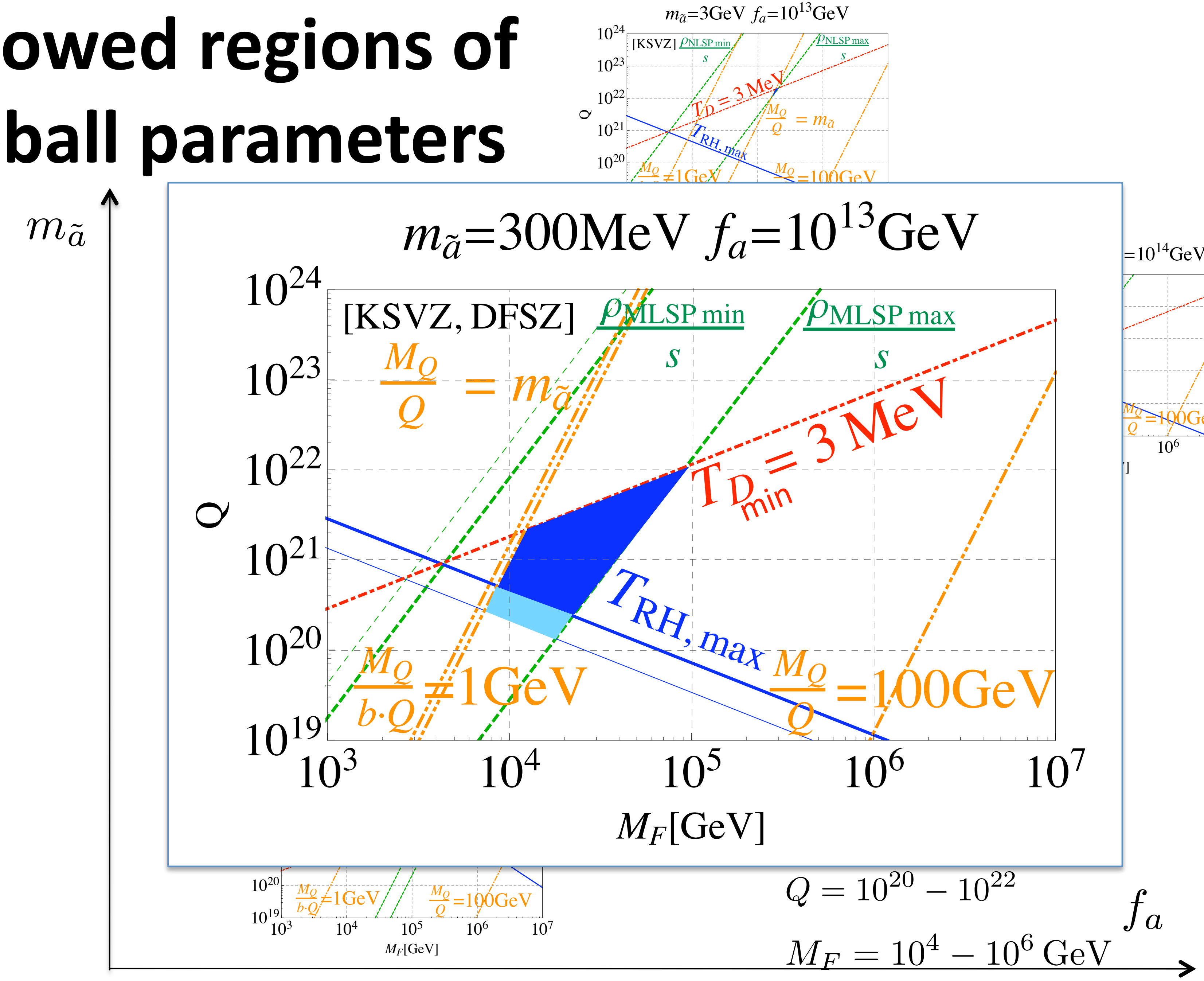
Allowed regions of *Q*-ball parameters



$$Q = 10^{20} - 10^{22}$$

$$M_F = 10^4 - 10^6\ \mathrm{GeV}$$

Allowed regions of *Q*-ball parameters



$Q = 10^{20} - 10^{22}$

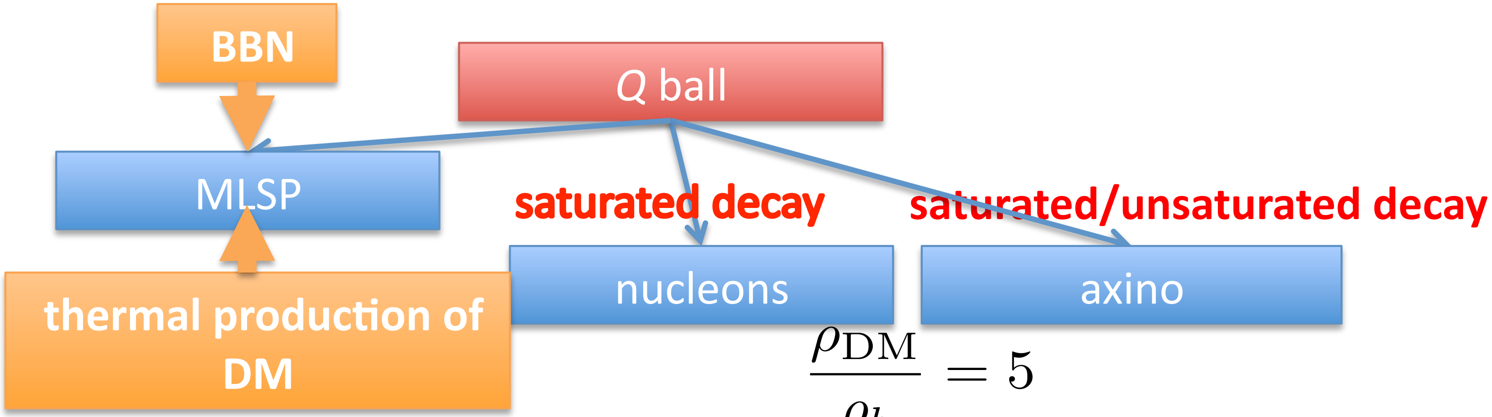
$M_F = 10^4 - 10^6$ GeV

Conclusion

- We investigated the model which gives the same origin for baryon and DM.

- This model can produce baryon number and axino DM, and the correct ratio between those energy densities without disturbing the BBN prediction.

- We found the there exist allowed regions of axino parameters and Q ball parameters.



BBN

Q ball

MLSP

saturated decay

saturated/unsaturated decay

nucleons

axino

thermal production of DM

$$\frac{\rho_{\rm DM}}{\rho_b} = 5$$