Title: Reheating Constraints on Inflationary Theories Coupled to SUSY embedding of SM

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Abstract: TBA

Reheating Constraints on Inflationary Theories Coupled to SUSY embedding of SM

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Requirements for Inflation

- Quasi dS: $\frac{\ddot{a}}{a} > 0$ for about 60 e-folds.
  - Flat potential.
  - Seems difficult in computable string embedding.
- Inflation must end (at least temporarily): structure does not grow in dS domination.
- Spatial inhomogeneities of gauge invariant scalar perturbations must be sufficiently small and Gaussian
  - Measurable primordial non-Gaussianities? Need better data.
- After inflation ends, the universe must reheat: RD
  - BBN $T > 5\ \mathrm{MeV}$
  - At odds with CC solution of shift symmetries. [see e.g. Itzhaki 06]
- After inflation ends, unwanted relics must not be created
  - Monopoles $T < M_{\mathrm{GUT}}$

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How hard is it to reheat to a phenomenologically viable temperature?

- Not particularly hard unless solving the CC problem, engineering features (defects or inflation scale), have moduli problem, and/or have a top-down model.
- Min: Hawking temperature per light dof e.g. $T = \frac{(10^{15}\ \mathrm{GeV})^2}{2\pi\sqrt{3}M_p} \sim 10^{10}\ \mathrm{GeV}$
  - Of course, can easily be diluted by w=0 matter/inflaton.
  - For low scale inflation, $T = \frac{(10^3\ \mathrm{GeV})^2}{2\pi\sqrt{3}M_p} \sim 10^{-4}\ \mathrm{eV}$: we have to work with couplings and make sure that the slow-roll is not destablized.
- Max: GUT scale (monopoles)? Planck (Hagedorn) scale?
- Important for observables? Typically. e.g.

$$\frac{d\ln[k/k_i(T_{RH}, g_*(T_{RH}), \phi_e)]}{d(\phi/M_p)} = -\left(\frac{1}{M_p}\frac{V(\phi)}{V'(\phi)} - \frac{M_p}{2}\frac{V'(\phi)}{V(\phi)}\right)$$

- Hence, why discuss it?
  - Connects inflation to SM.
  - Understanding the possible thermal histories is a goal of inflation.
  - Excuse to talk about couple of topics difficult to connect otherwise.

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- Should we build inflationary models that contain Affleck-Dine only or can inflationary scenarios with reheating temperatures of 1 TeV consistent with BAU?

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Gravitino Bound

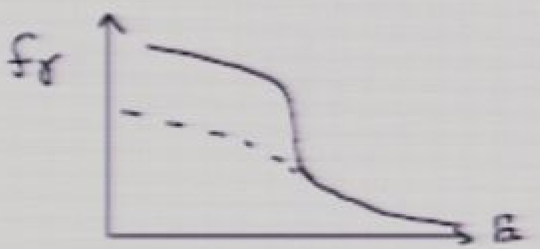
- Decay products distorts the plasma spectrum
- e.g. high energy photons can dissociate elements:

model dependent: late time decays of massive particles

High energy γ injection distorts spectrum:

For $E_\gamma \gtrsim \frac{m_e^2}{22T}$, $\gamma + \gamma_{background} \rightarrow e^+ e^-$ effective.

$\Rightarrow$ γ spectrum is suppressed



$\Rightarrow$ If $B_A \gtrsim \frac{m_e^2}{22T}$, γ-dissociation is not effective.

Condition to destroy D by γ:

$T_{decay} \lesssim 10\,\text{keV} \Rightarrow \boxed{\tau \gtrsim 10^4\,s}$

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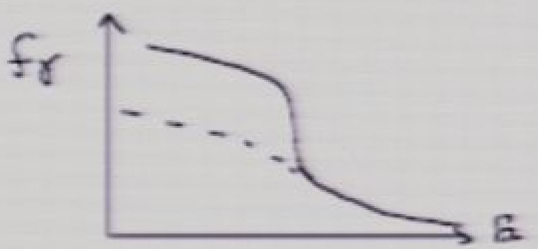

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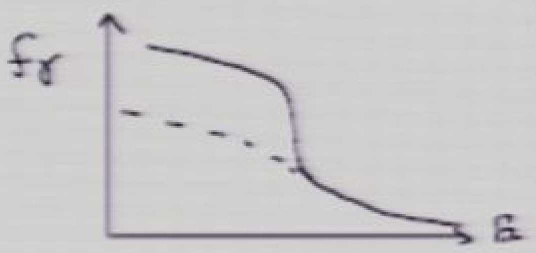

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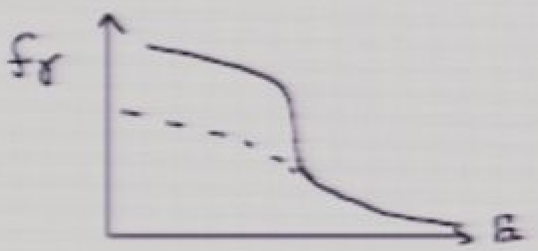

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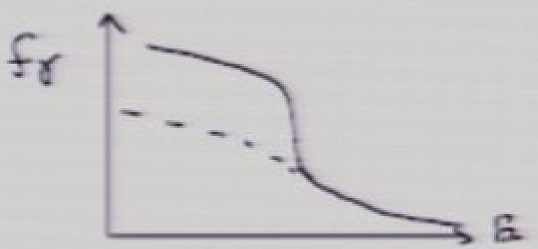

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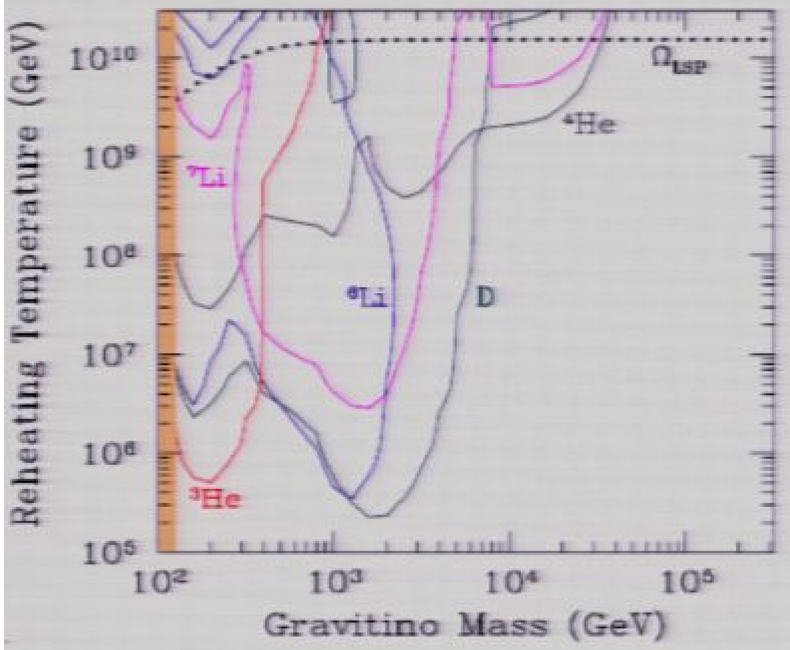

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$m_{1/2}$	300 GeV
m_0	141 GeV
A_0	0
$\tan\beta$	30
μ_H	389 GeV
$m_{\chi_1^0}$	117 GeV
$\Omega_{LSP}^{(thermal)}h^2$	0.111

[Kawasaki et al 08]

$m_{3/2}$	Case 1	Case 2	Case 3	Case 4
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10 TeV	2×10^9 (^{4}He)	2×10^9 (^{4}He)	2×10^9 (^{4}He)	2×10^9 (^{4}He)
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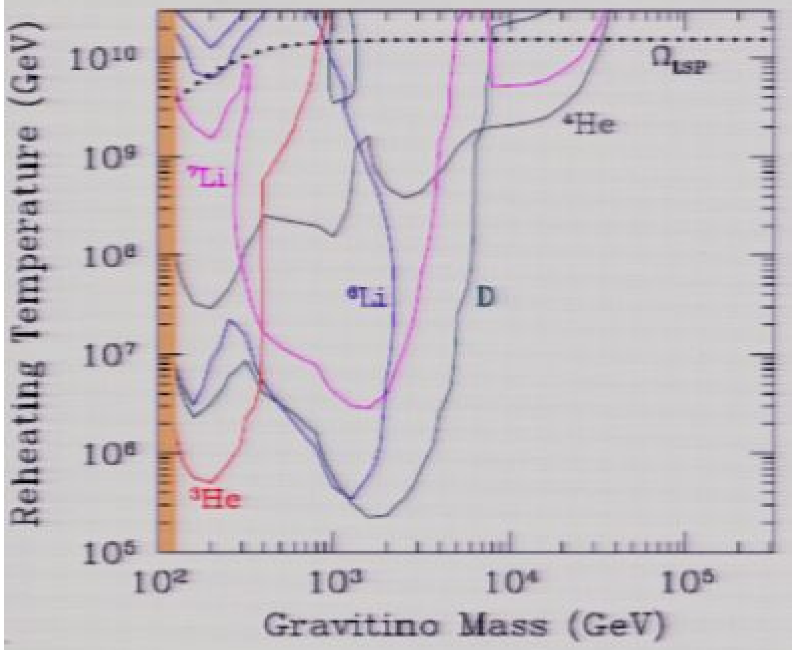

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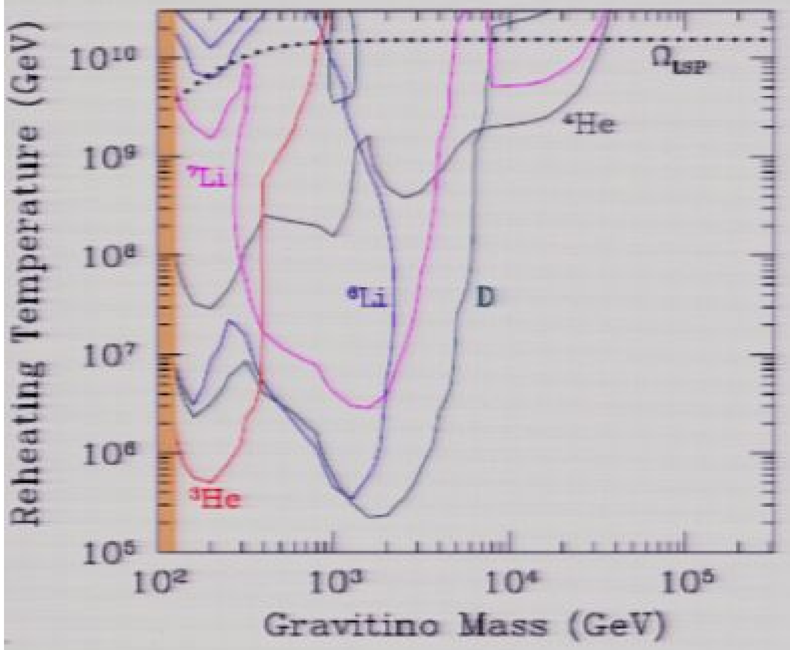

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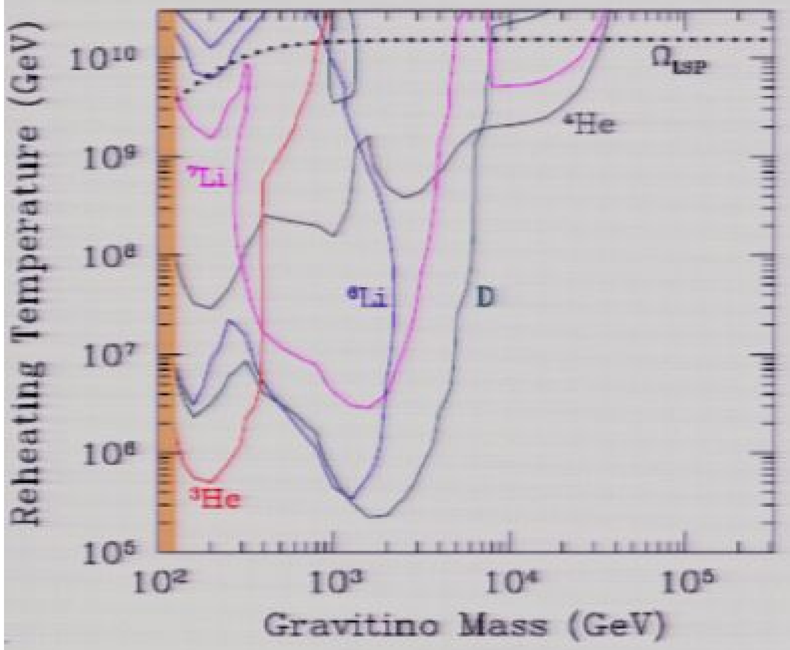

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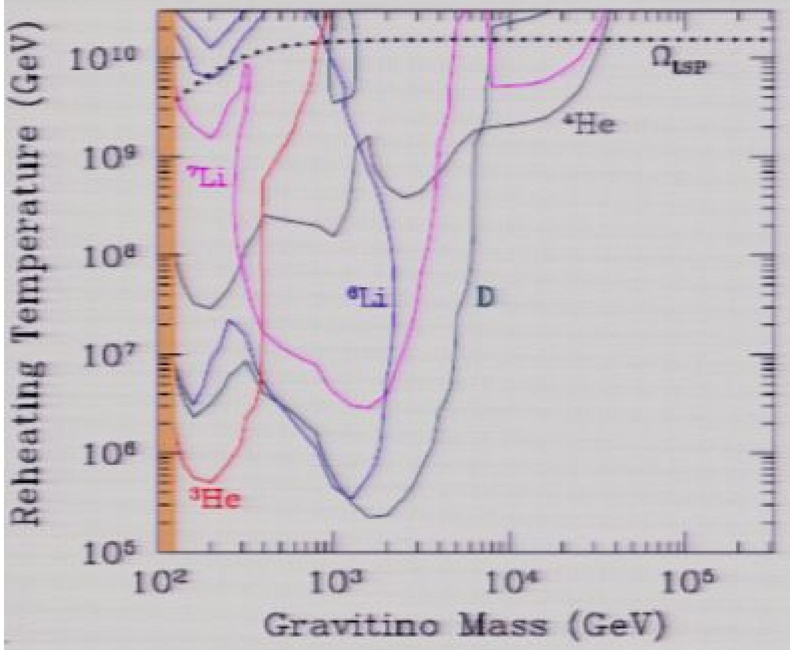

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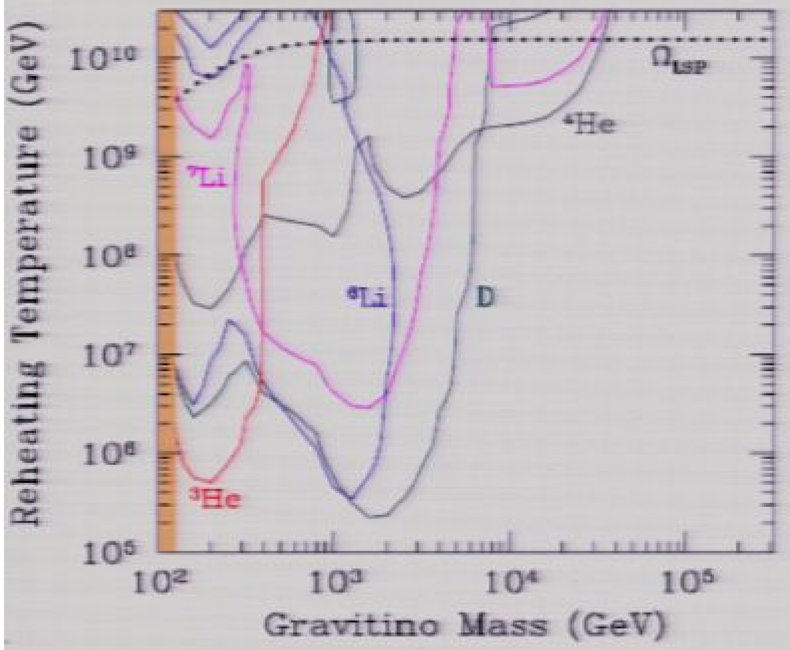
10 TeV	2×10^9 (^{4}He)	2×10^9 (^{4}He)	2×10^9 (^{4}He)	2×10^9 (^{4}He)
30 TeV	9×10^9 (^{4}He)	8×10^9 (^{4}He)	7×10^9 (^{4}He)	8×10^9 (^{4}He)

Hence, low

Gravitino Bound



	Case 1
$m_{1/2}$	300 GeV
m_0	141 GeV
A_0	0
$\tan\beta$	30
μ_H	389 GeV
$m_{\chi_1^0}$	117 GeV
$\Omega_{\rm LSP}^{\rm (thermal)}h^2$	0.111

[Kawasaki et al 08]

$m_{3/2}$	Case 1	Case 2	Case 3	Case 4
300 GeV	1×10^6 (^{3}He)	4×10^5 (^{3}He)	1×10^6 (^{3}He)	—
1 TeV	5×10^5 (^{6}Li)	9×10^5 (^{6}Li)	3×10^5 (^{6}Li)	3×10^6 (^{6}Li)
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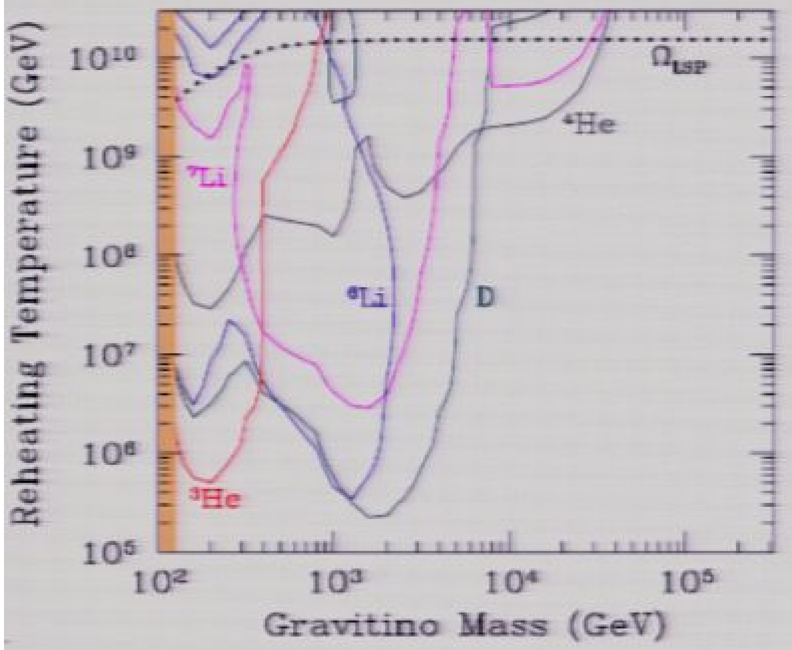

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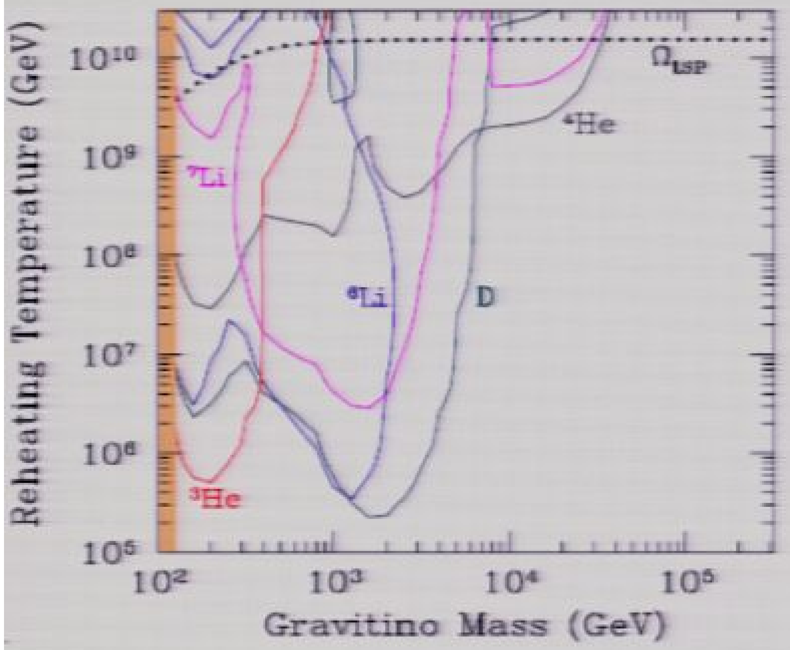

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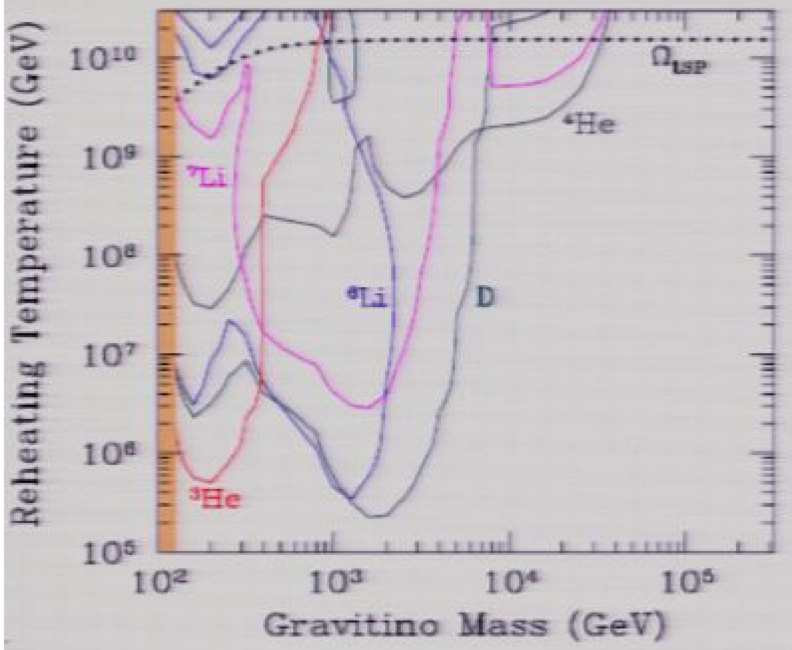

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$\nu_R \to HL$

$\nu_R \to \bar{H}\bar{L}$

Non-pert. SU(2) → Baryon number

CP violation

$$\mathcal{M} = \mathcal{M}_t + (R + iI)(\mathcal{R} + i\mathcal{I})$$

tree

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Key: 1) interference 2) absorptive part (loops cut)

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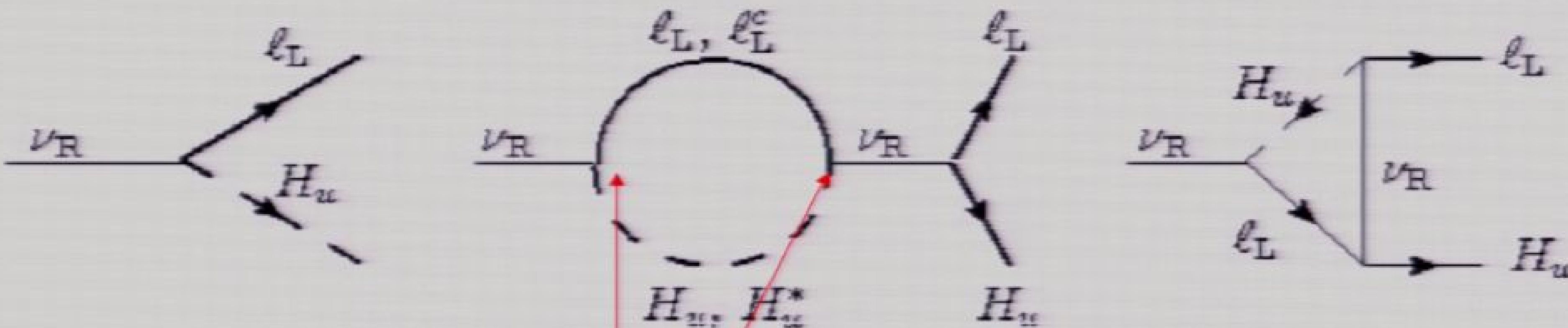

[Fukugita, Yanagida 86; Luty 92; Covi, Roulet, Vissani 96; Plumacher 97]

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See-saw: $m_\nu \sim \frac{y^2 v^2}{M_R} < m_{\rm max} \quad \longrightarrow \quad M_R \gtrsim 10^8 \text{ GeV}$

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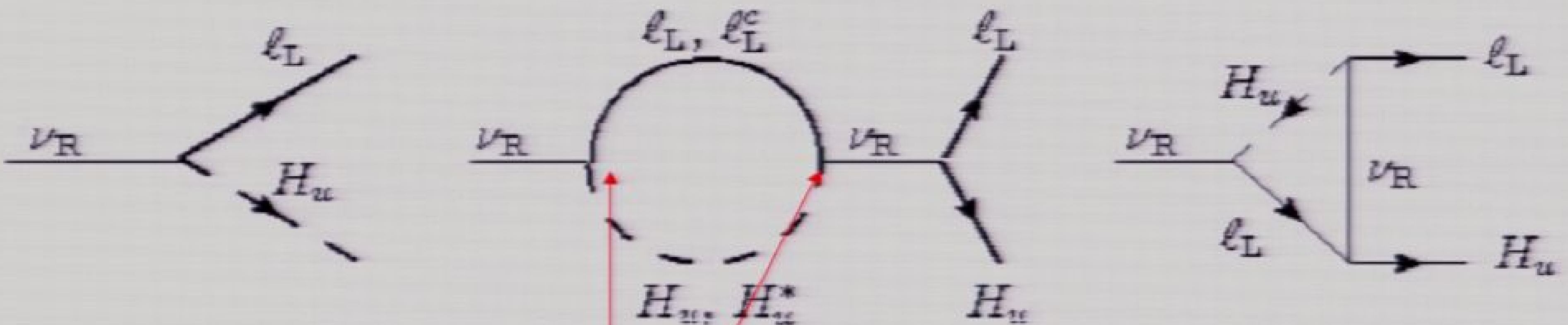

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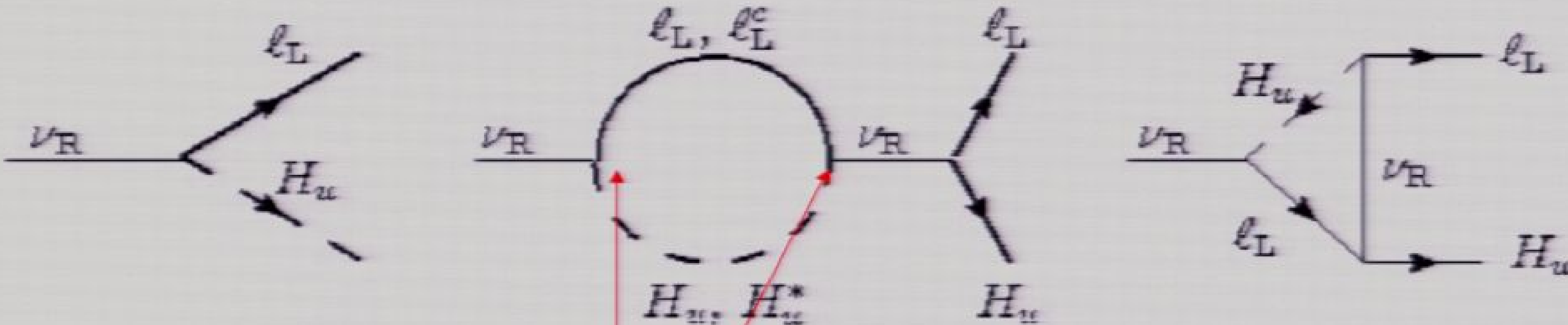

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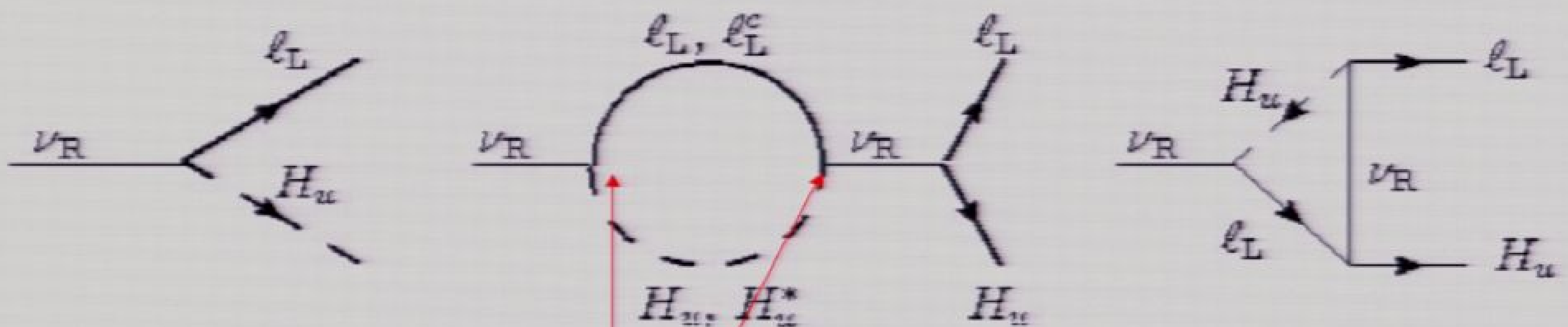

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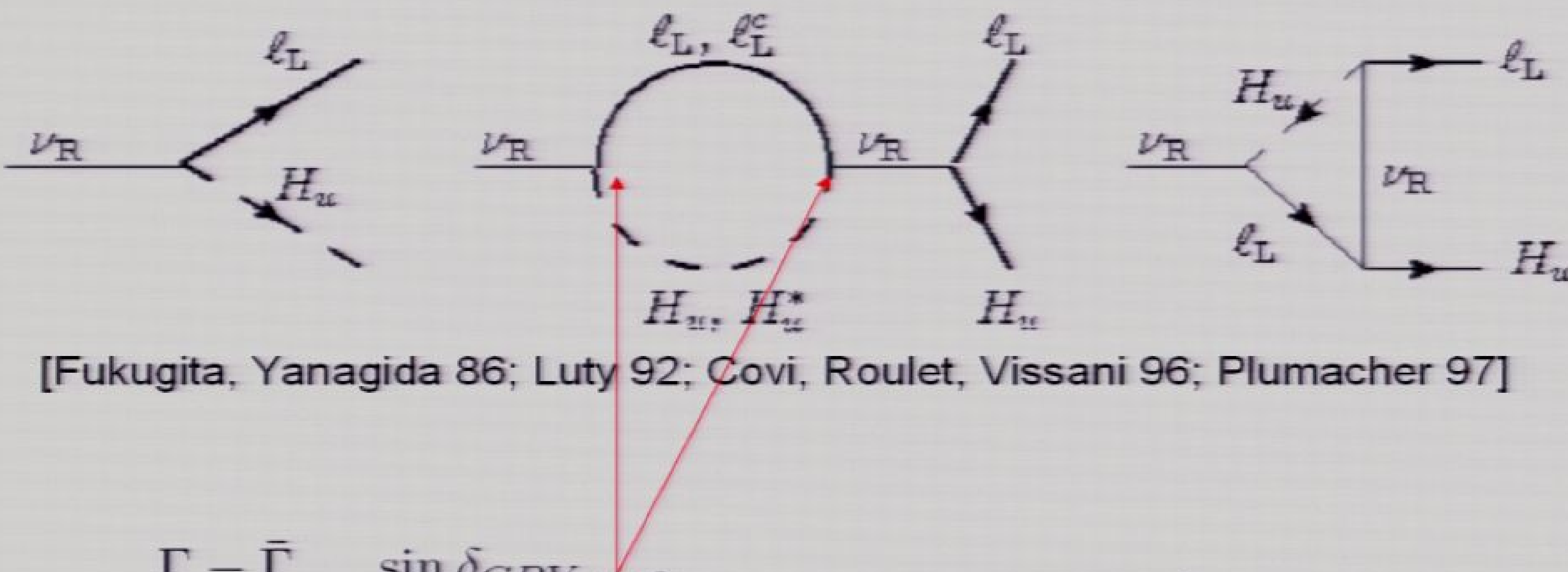

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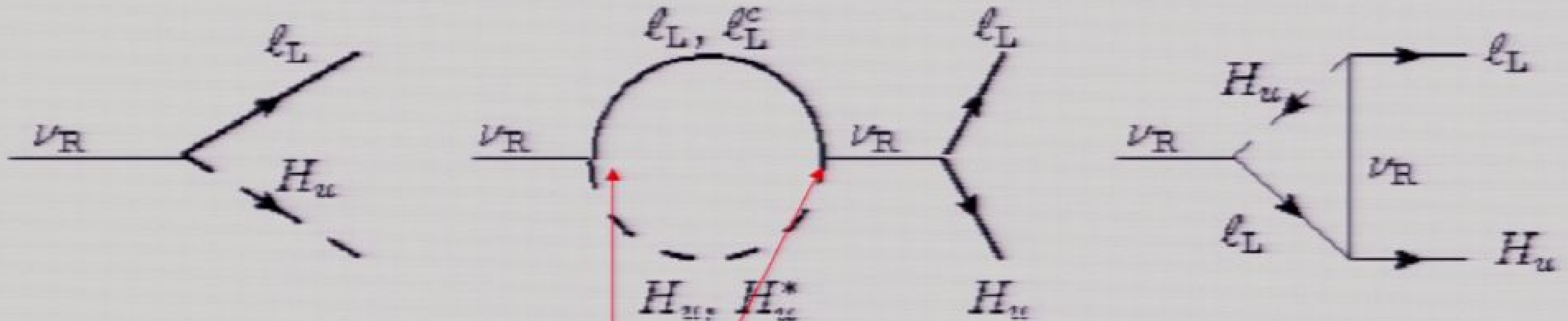

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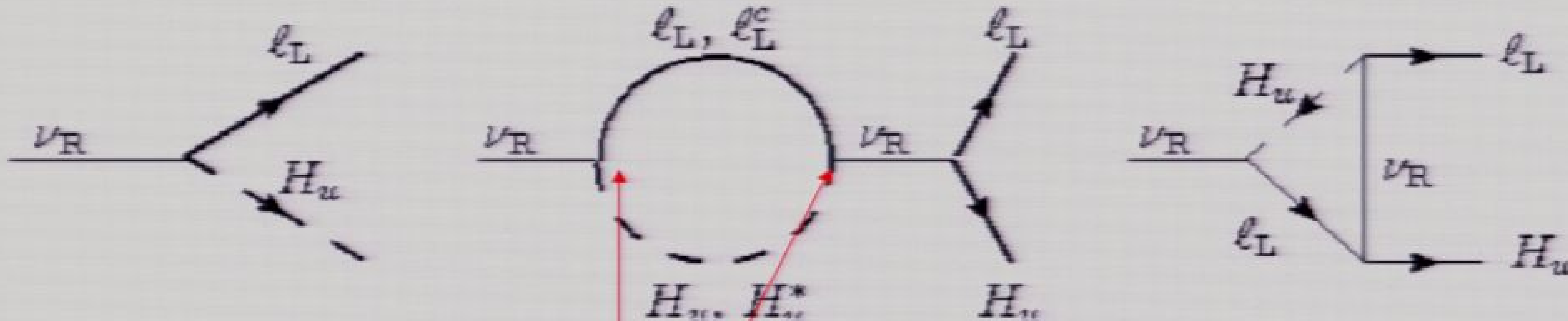

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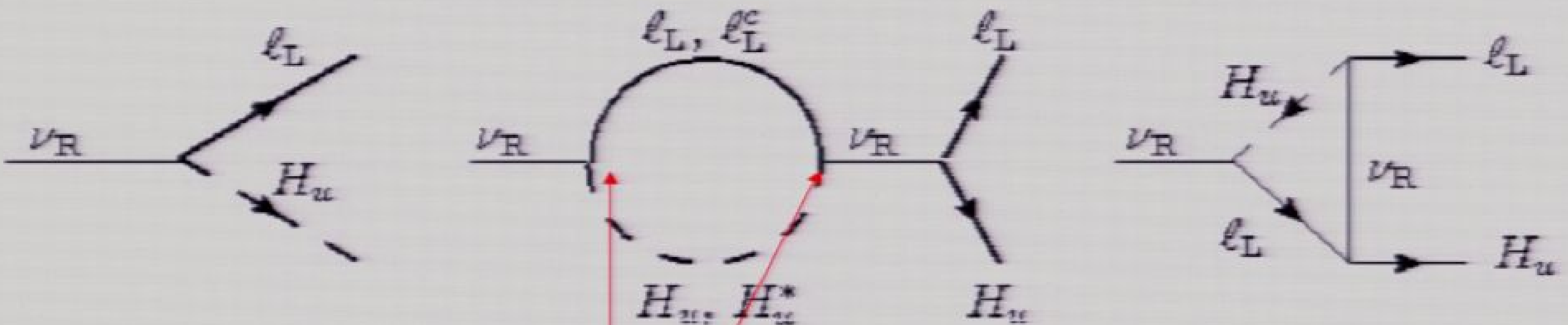

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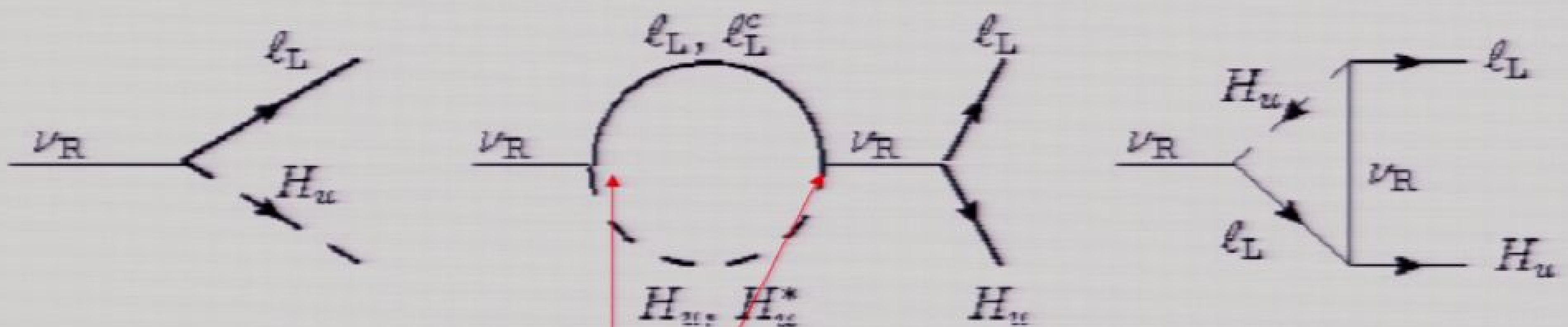

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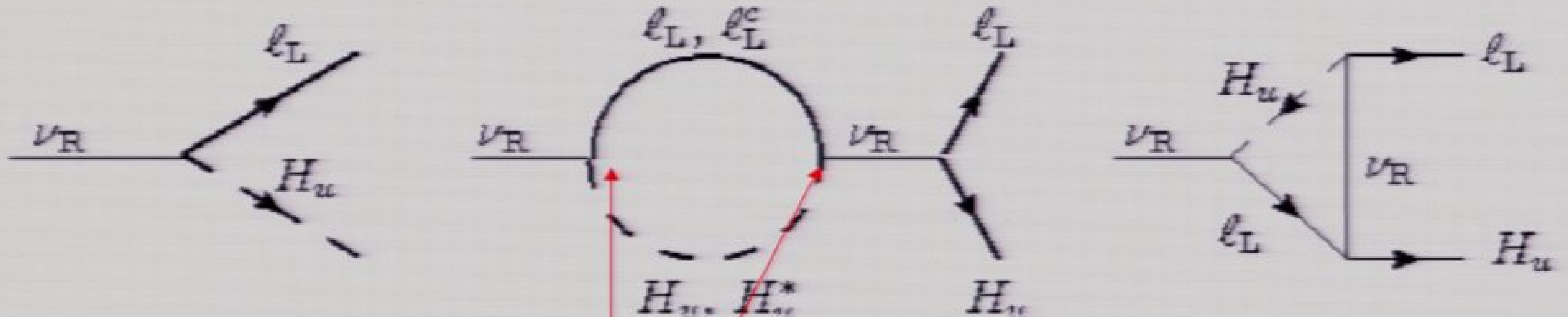

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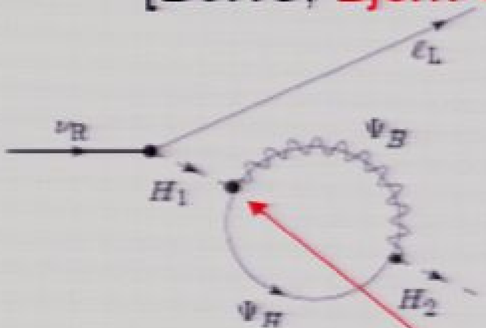
[DJHC, Bjorn Garbrecht, Michael Ramsey-Musolf 0904.1591]



$$m_{H_2} > M_1 + \mu$$

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[kinematic constraint: e.g. consider CM]

[MSSM]

$$\mathcal{L} \supset -(m^2_{H_u} + \mu^2) H^\dagger_u H_u - (m^2_{H_d} + \mu^2) H^\dagger_d H_d - b\left(H^T_u H_d + H^\dagger_u H^*_d\right) - \mu \bar{\Psi}_{\tilde{H}^+} \Psi_{\tilde{H}^+} - \mu \bar{\Psi}_{\tilde{H}^0} \Psi_{\tilde{H}^0}$$
$$-\frac{g_1}{\sqrt{2}}\left[\bar{\Psi}_{\tilde{H}^+}\left(-H^{-*}_d P_L + e^{i\phi^M_\mu} H^+_u P_R\right)\Psi_{\tilde{B}} + \bar{\Psi}_{\tilde{H}^0}\left(-H^{0*}_d P_L - e^{i\phi^M_\mu} H^0_u P_R\right)\Psi_{\tilde{B}} + \text{h.c.}\right]$$
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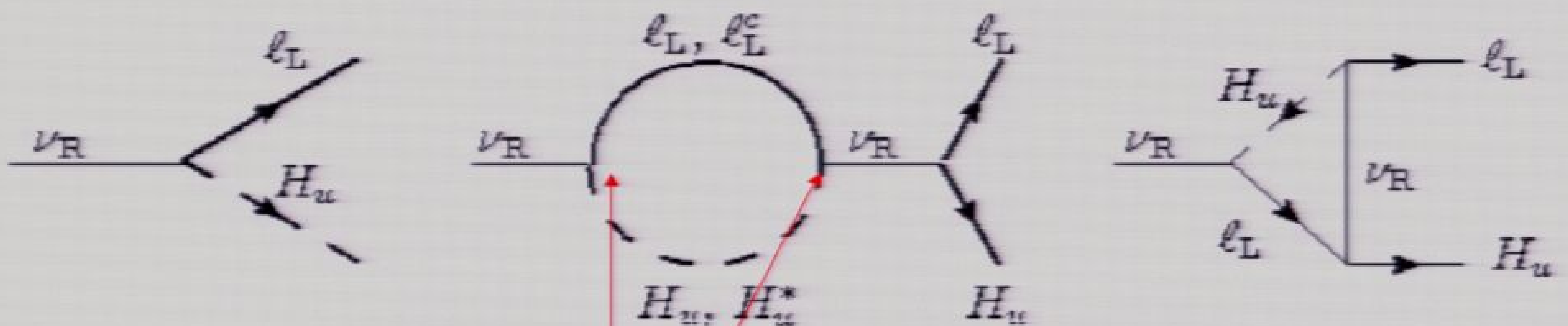
Previous Lore Continued



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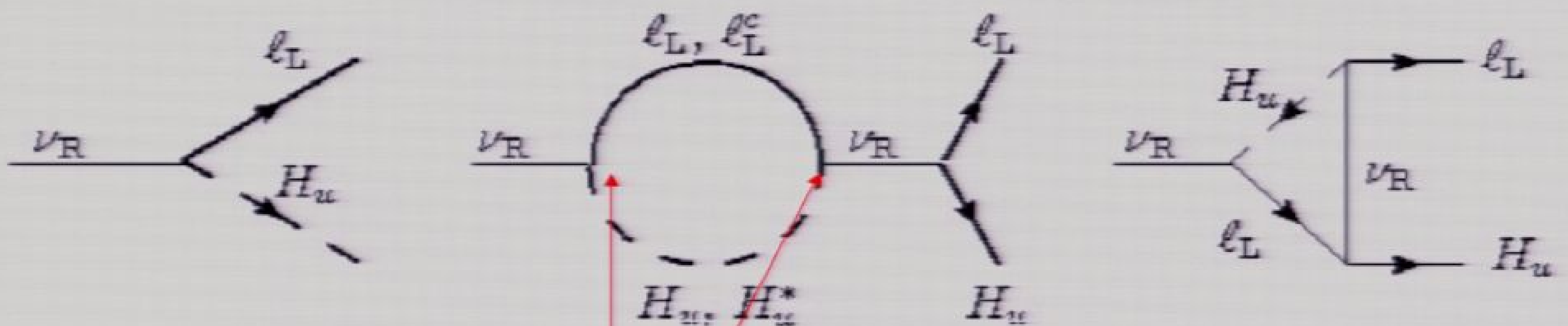

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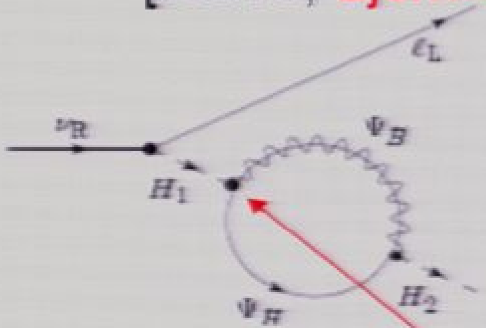

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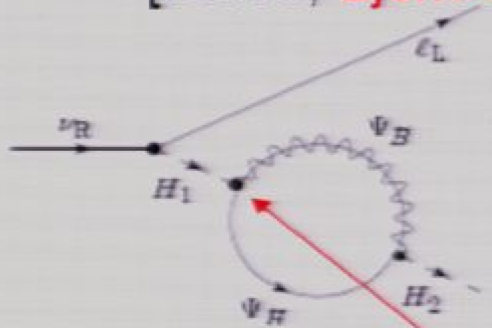

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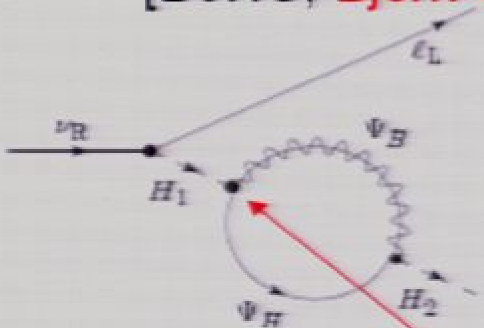
[DJHC, Bjorn Garbrecht, Michael Ramsey-Musolf 0904.1591]



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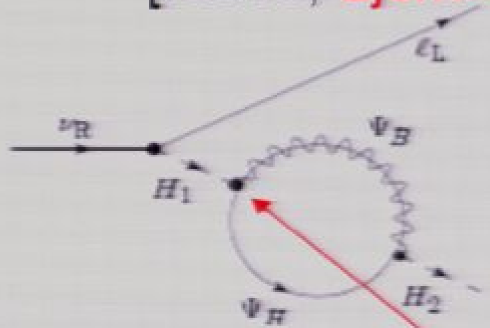

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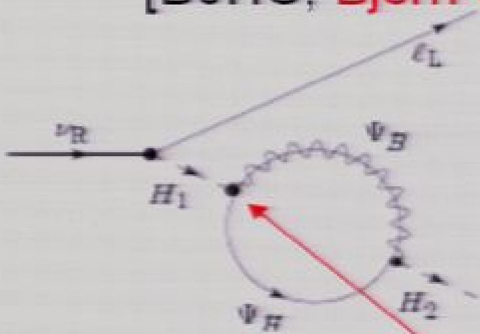

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Feed into Boltzmann equations. [Standard treatment e.g. hep-ph/0401240]

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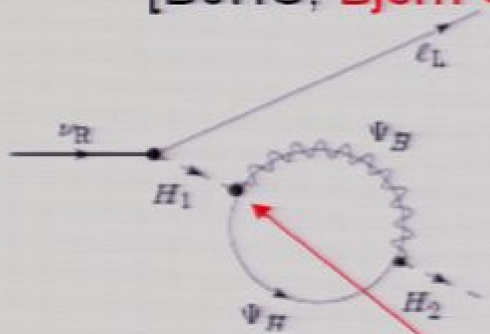

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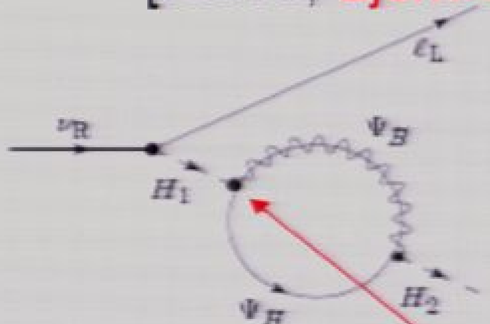

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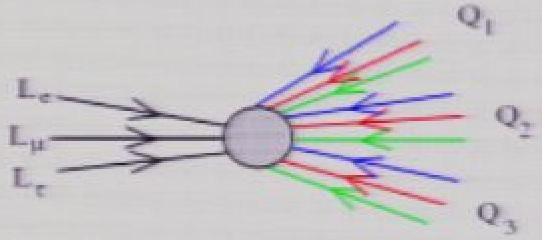
B+L violated in the SM by $F\tilde{F}_{\mathrm{SU(2)}}$:

[e.g. Kuzmin, Rubakov, Shaposhnikov 87]



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[DJHC, Bjorn Garbrecht, Sean Tulin 08]

[Differs from Harvey, Turner 90 and]

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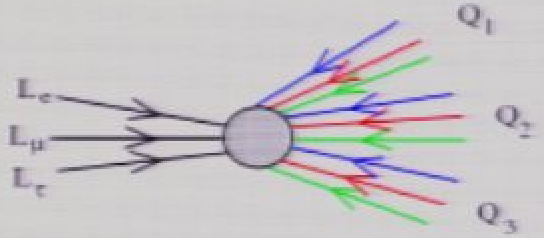

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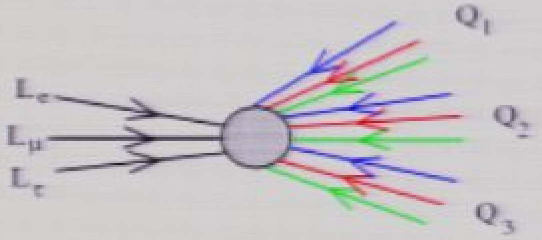

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Previous slide

$$\eta_{\rm B} = 4 \times 10^{-3} \frac{B}{B-L} \frac{10^{-3}\text{eV}}{\tilde{m}} \varepsilon^{\text{tot}}_{M,A,t}$$

$$\tilde{m} = y^2 v^2 / m_{\nu_{\rm R}}$$

WMAP 3yr:

$$\eta_B \approx 6.3 \times 10^{-10}$$

Typical required phase is small if all the mass scales in are similar.

$$\sin\phi^{M,A}_{\mu} \approx 4 \times 10^{-6} \frac{\tilde{m}}{10^{-3}\text{eV}} \frac{1}{\cos\alpha \sin\alpha} \frac{m^2_{H_2} - m^2_{H_1}}{\Lambda_{M,A}\Delta x_{M,A}}$$

To be done

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Next example of reheating constraints:

Beware of giant Q-balls (in MSSM)

[Micha Berkooz, DJHC, Tomer Volansky 05]

MSSM has many flat directions (moduli)

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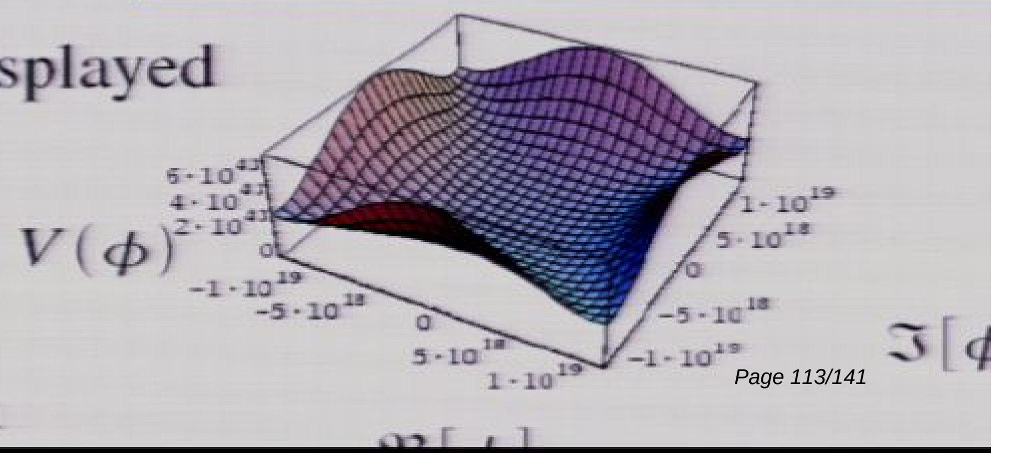

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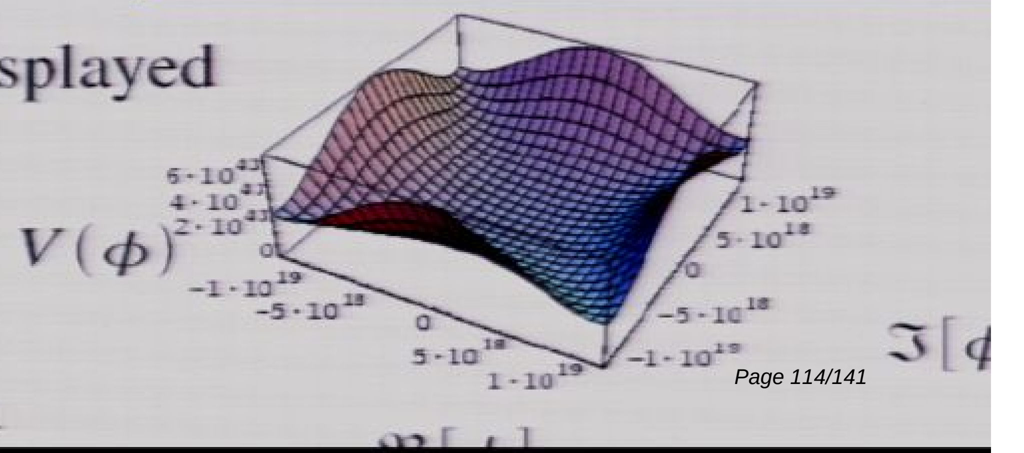

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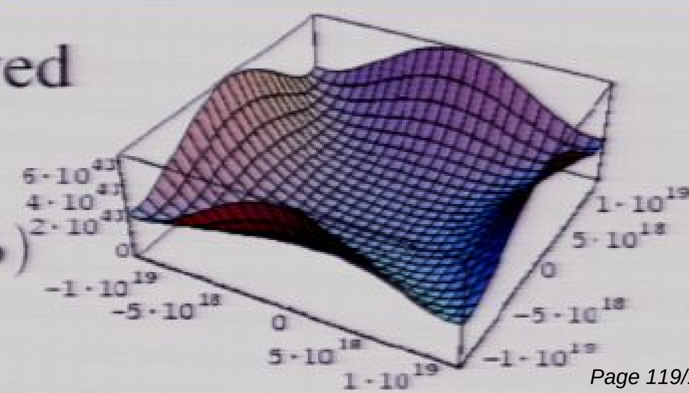
computed in MSSM

Generically U(1) violating

e.g. $(\frac{m_{3/2}}{M_{pl}})^{2}(\phi^{4}+\overline{\phi}^{4}$

ote: bothreal and imaginary parts displayed



at direction field init cond. at the end
inflation is typically of order M_p

Here, they feel a kick for angular motion.

What is a (giant) Q-ball?

- Nontopological, time-dependent soliton solution [Coleman 85; T.D. Lee; Rosen]
- Source of quasi-stability
  - Almost conserved angular momentum in the U(1): Charge Q
  - Interaction is such that E/Q < m

$$\mathrm{Min}\left[\frac{U''(\phi_0)}{\phi_0^2}\right] \rightarrow \phi_0 \neq 0$$

Example: [K. Enqvist, J. McDonald 98]

$$V(|\phi|) = m_\phi^2|\phi|^2\left(1 + K\ln\left[\frac{|\phi|^2}{M^2}\right]\right)$$

$$K < 0$$

$$\phi = \phi_0 e^{-r^2/R^2} e^{i\omega t}$$

$$R = \frac{\sqrt{2}}{m_\phi\sqrt{-K}}$$

Large vev → giant

$$Q = \frac{\phi_0^2 \pi^{-3/2}}{|K|^{3/2} m_\phi^2}\left[1 - K(1 - \frac{1}{2}\ln\left(\frac{\phi_0^2}{M^2}\right)\right]$$

$$\frac{P}{\rho} = \frac{K}{2+K}$$

Negative pressure! → binding

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Upshot

$$Q = \frac{\phi_0^2 \pi^{3/2}}{|K|^{3/2} m_\phi^2} \left[1 - K(1 - \frac{1}{2} \ln \left(\frac{\phi_0^2}{M^2} \right) \right]$$

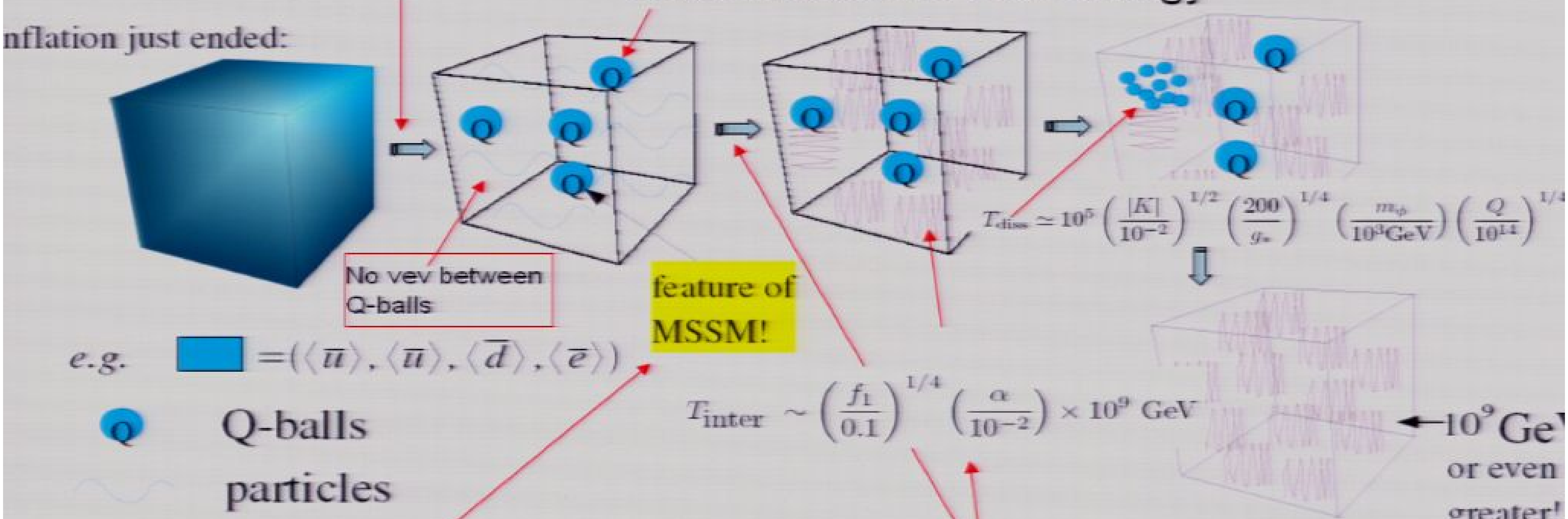
$$Q \sim \frac{\phi_0^2}{m_\phi^2 |K|^{3/2}} \gtrsim 10^{28}$$

As explained in the next slide, it will play a role in dissociation:

$$T_{\rm diss} \simeq 10^5 \left(\frac{|K|}{10^{-2}} \right)^{1/2} \left(\frac{200}{g_*} \right)^{1/4} \left(\frac{m_\phi}{10^3 {\rm GeV}} \right) \left(\frac{Q}{10^{14}} \right)^{1/4} {\rm GeV}$$

(Naïve) Fate of Flat Directions

Picture supported by numerical simulations [Kasuya, Kawasaki 00] and analytic arguments.



This argument is incorrect!

Formation of Q-balls ~ preheating

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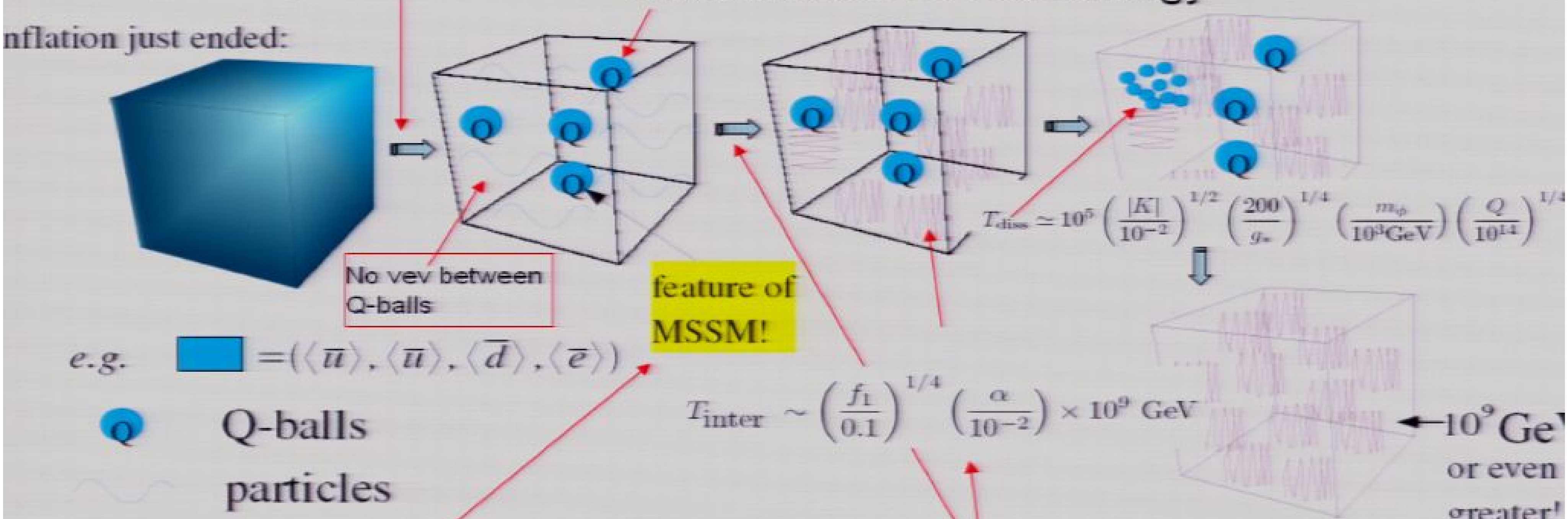

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$= (\langle \overline{u} \rangle, \langle \overline{u} \rangle, \langle \overline{d} \rangle, \langle \overline{e} \rangle)$

$T_{inter} \sim \left(\frac{f_1}{0.1}\right)^{1/4} \left(\frac{\alpha}{10^{-2}}\right) \times 10^9 \mathrm{~GeV}$

$\leftarrow 10^9$ Ge

Formation of Q-balls ~ preheating

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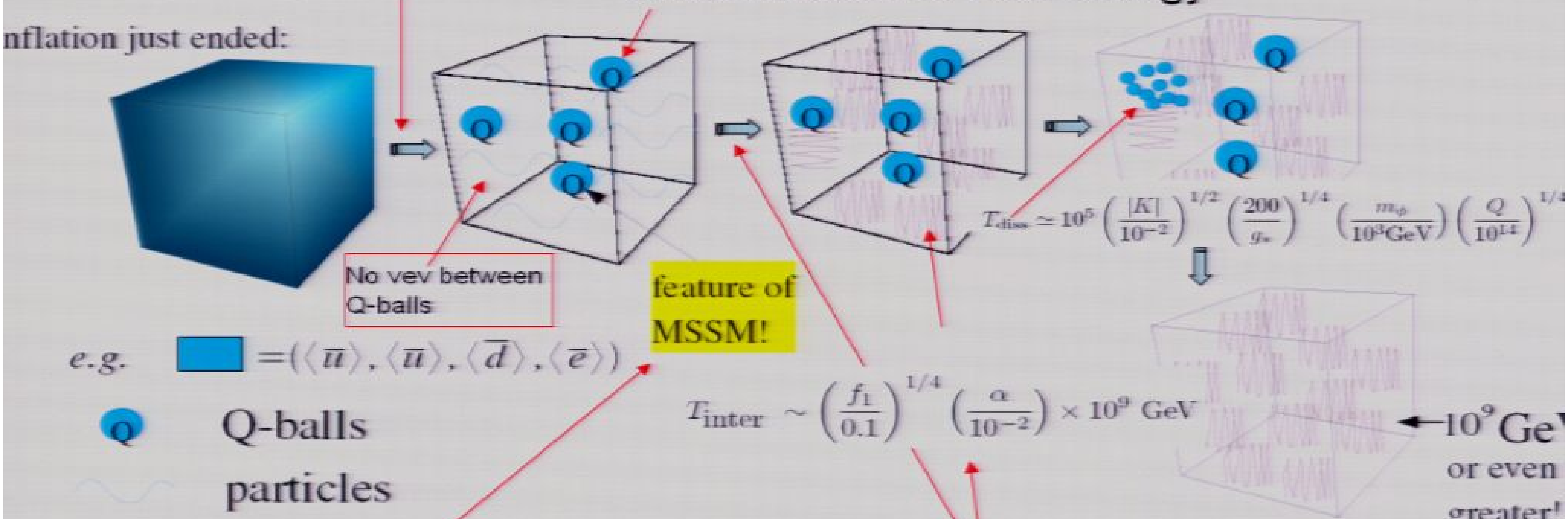
Small fraction of total energy



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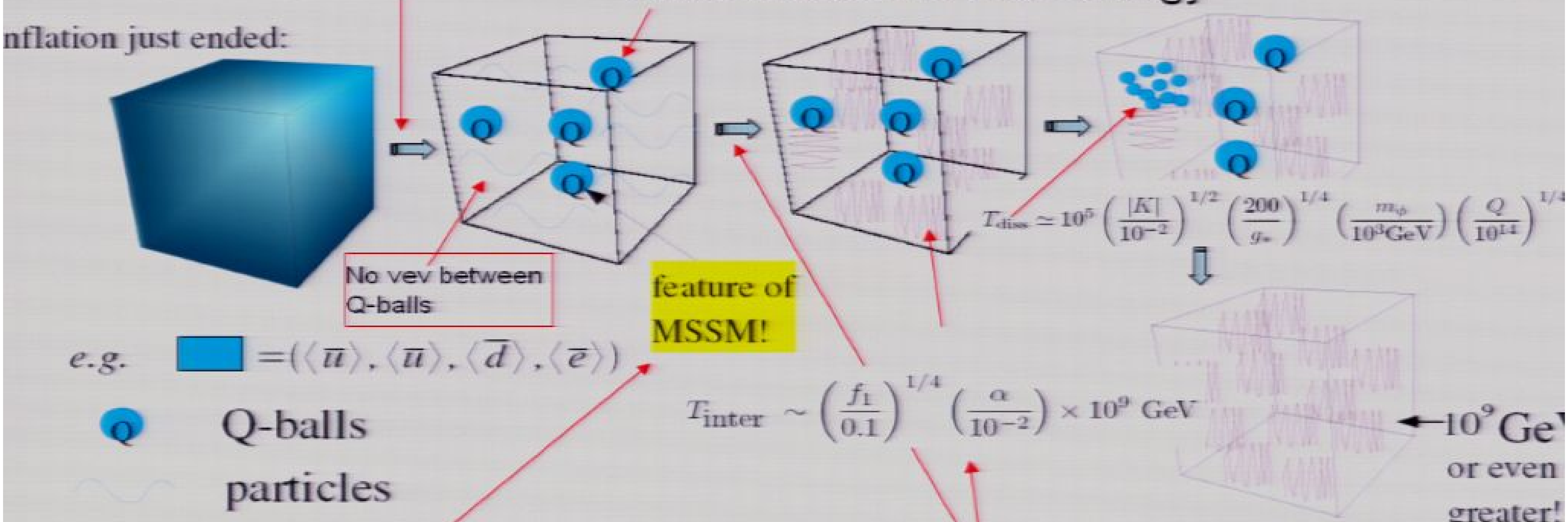

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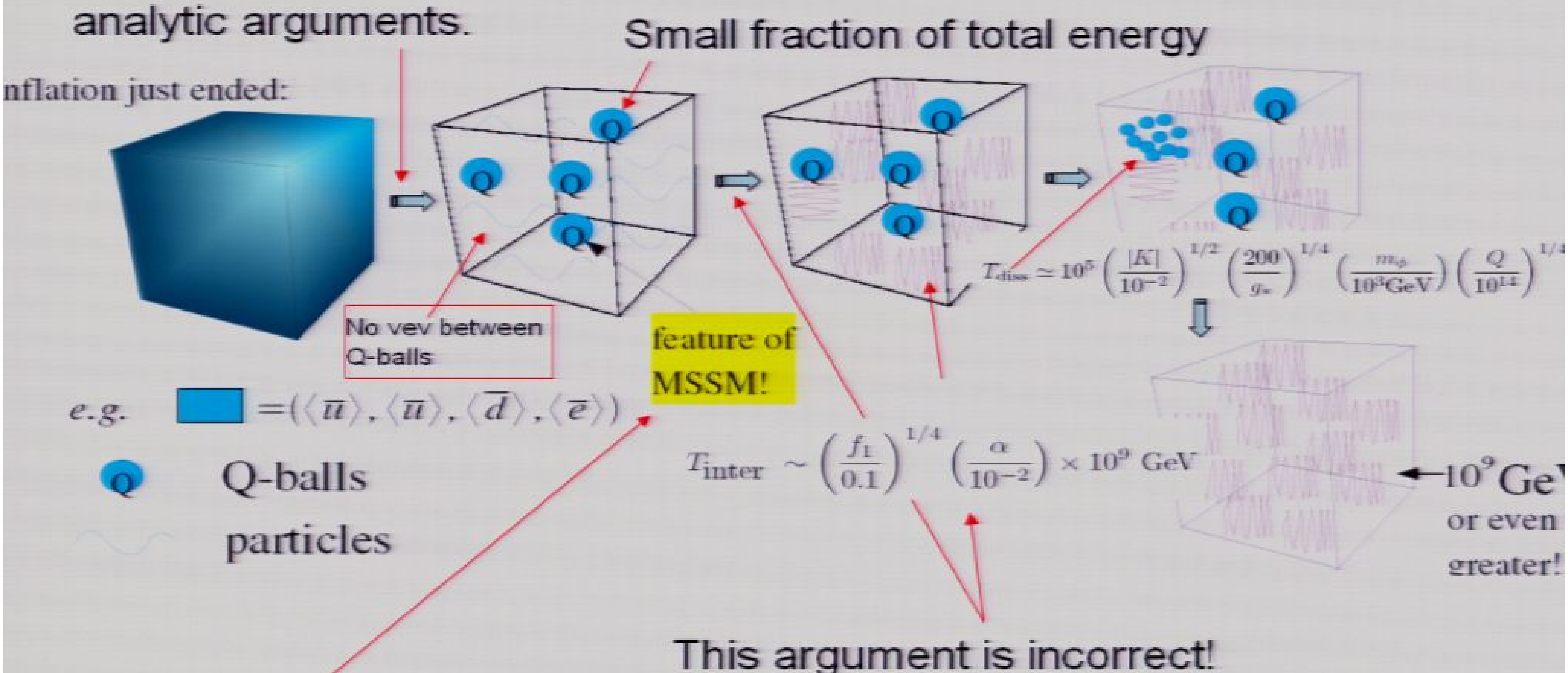
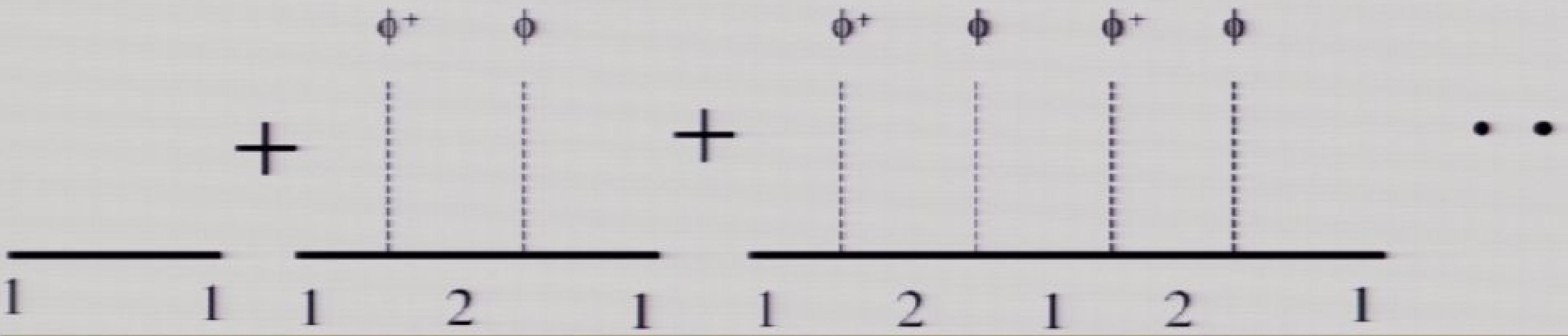


Formation of Q-balls ~ preheating

Finite density mass

- Q-ball charge is large → the density of particles **between** the Q-balls is also large!

e.g. $L_I = -g\phi\overline{\psi_1}\psi_2$ ← particles between the Q-balls



$$\delta m_{\psi_{12}} \approx \sqrt{g^2\langle\phi^+\phi\rangle} \sim g\phi_0\left(\frac{a_i}{a}\right)^{3/2} \sim gO(M_{pl})\left(\frac{a_i}{a}\right)^{3/2} \gg m_\phi \sim m_{3/2}$$

Hence, $\phi \rightarrow \psi_1\psi_2$ is suppressed (nearly forbidden, "kinematically")

Similar result applies to bosons.

Note ϕ vev = 0

Note ϕ are too cold to dissociate the Q-balls.

Also, due to SUSY, one can show

$\delta m_\phi < O(m_{3/2})$

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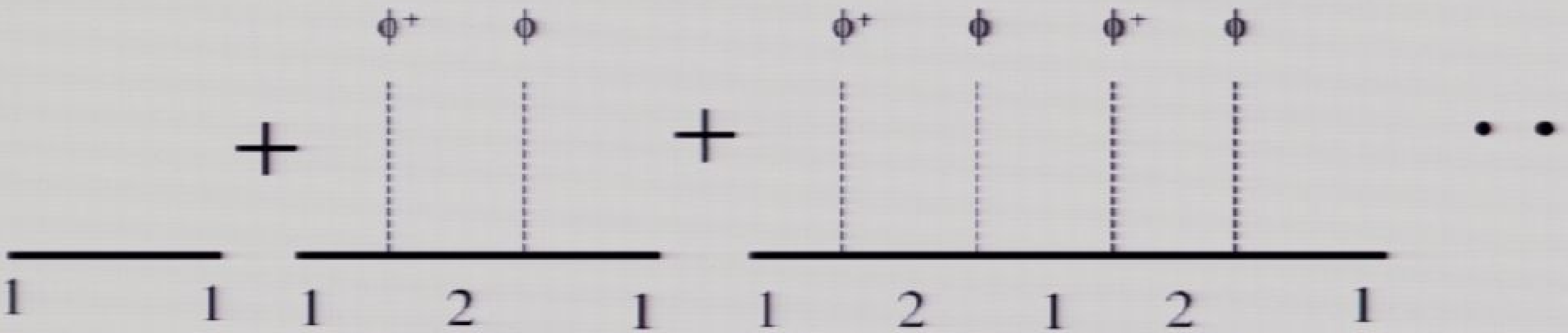

$$\delta m_{\psi_{1,2}} \approx \sqrt{g^2\langle\phi^+\phi\rangle} \sim g\phi_0\left(\frac{a_i}{a}\right)^{3/2} \sim gO(M_{pl})\left(\frac{a_i}{a}\right)^{3/2} \gg m_\phi \sim m_{3/2}$$

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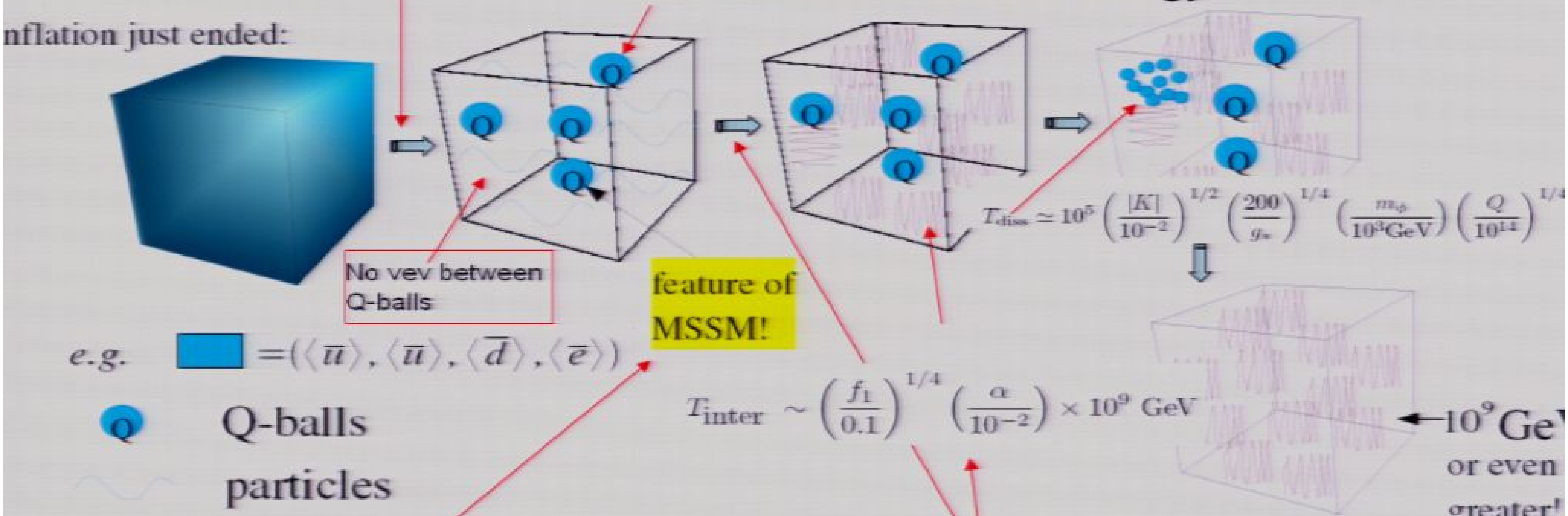

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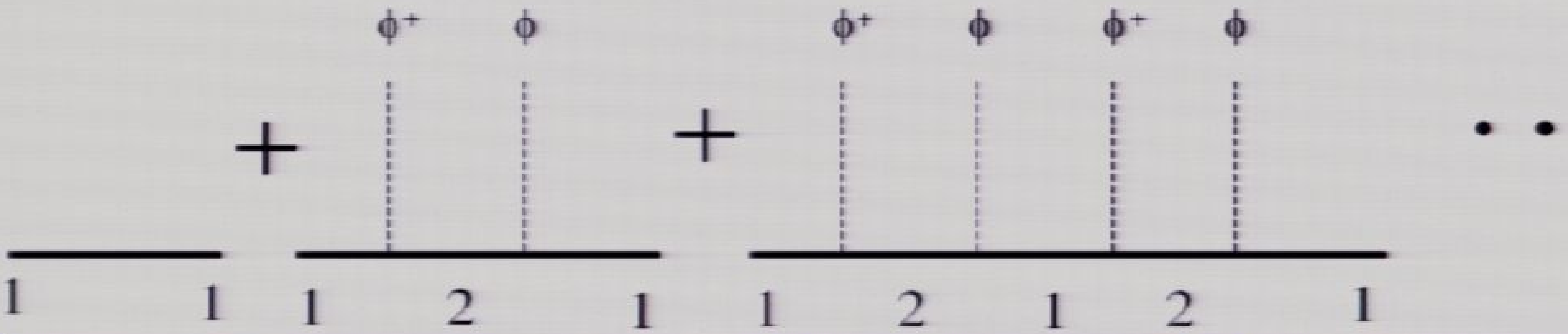

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Also, due to SUSY, one can show

$$\delta m_{\psi} < O(m_{3/2})$$

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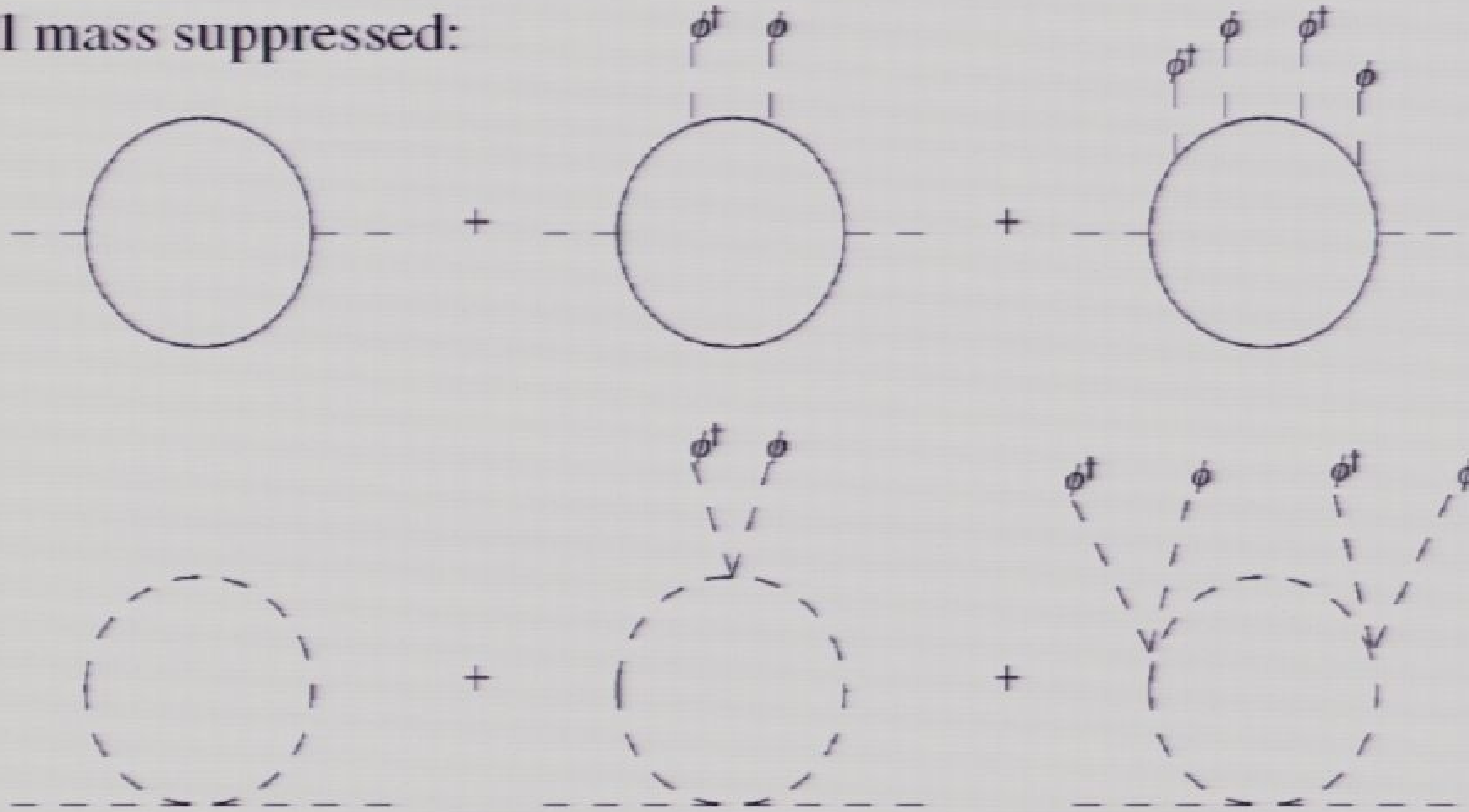
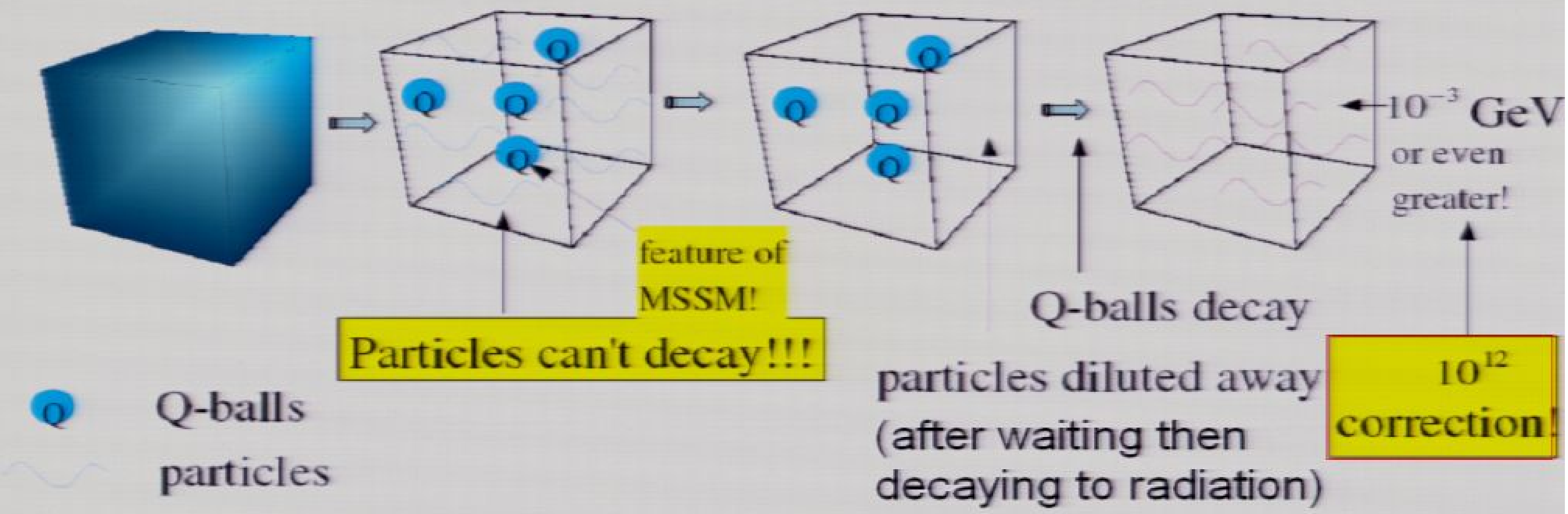


Correct picture



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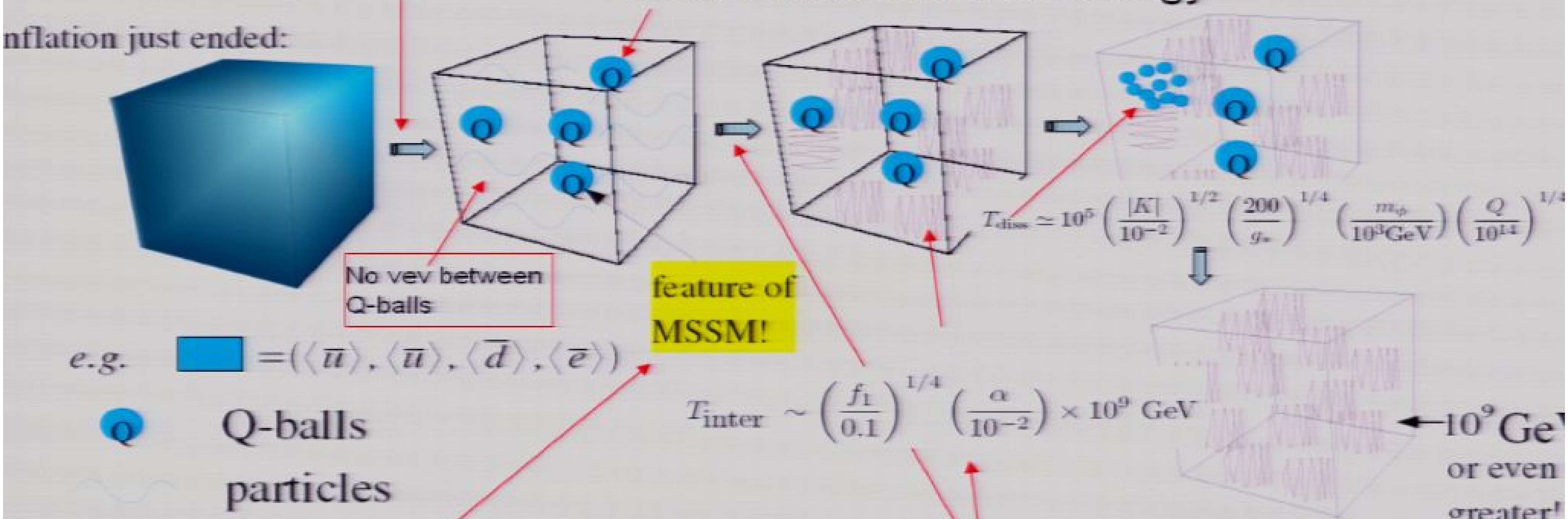

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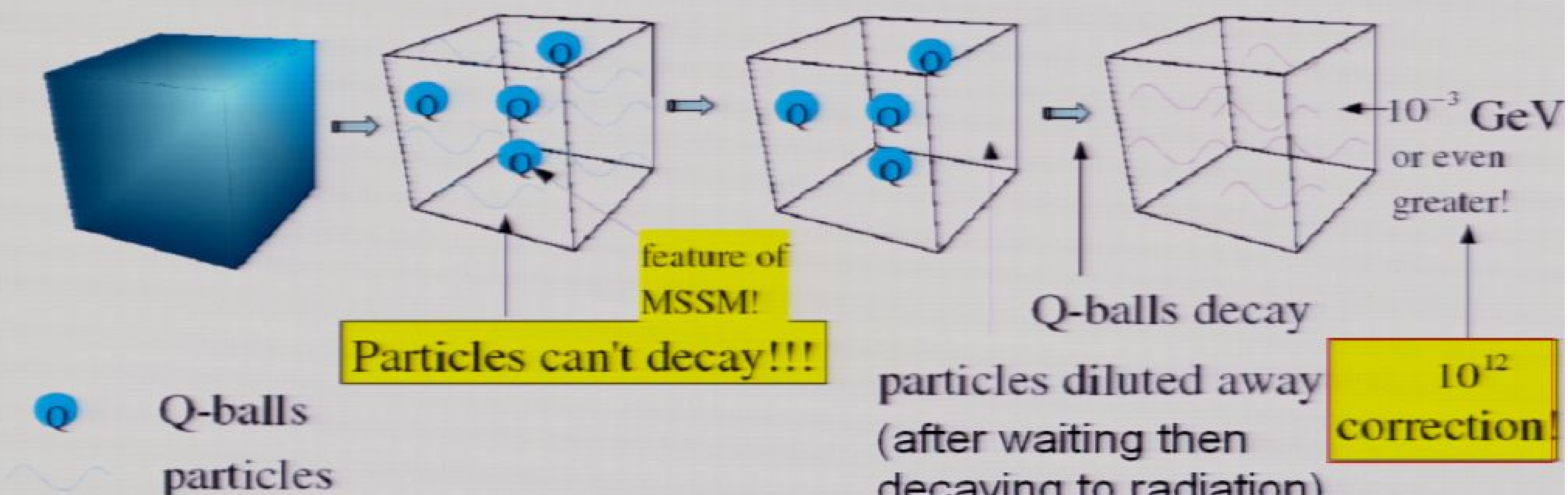
Formation of Q-balls ~ preheating

Correct picture



(after waiting then
decaying to radiation)

(Naïve) Fate of Flat Directions

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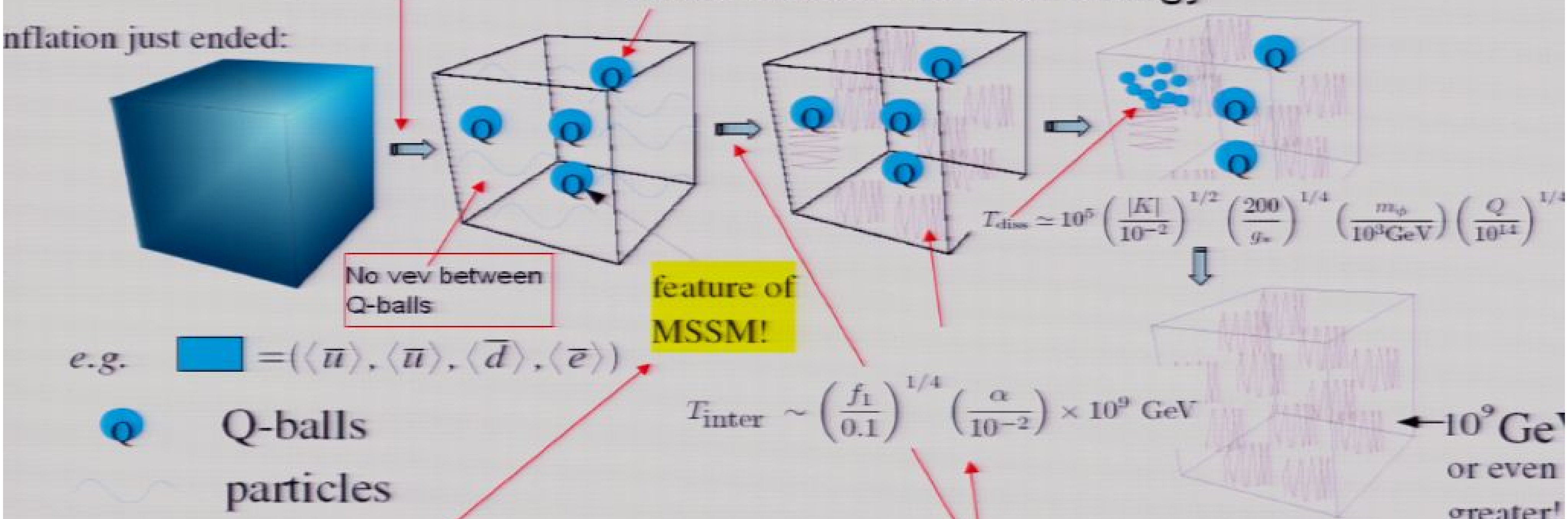

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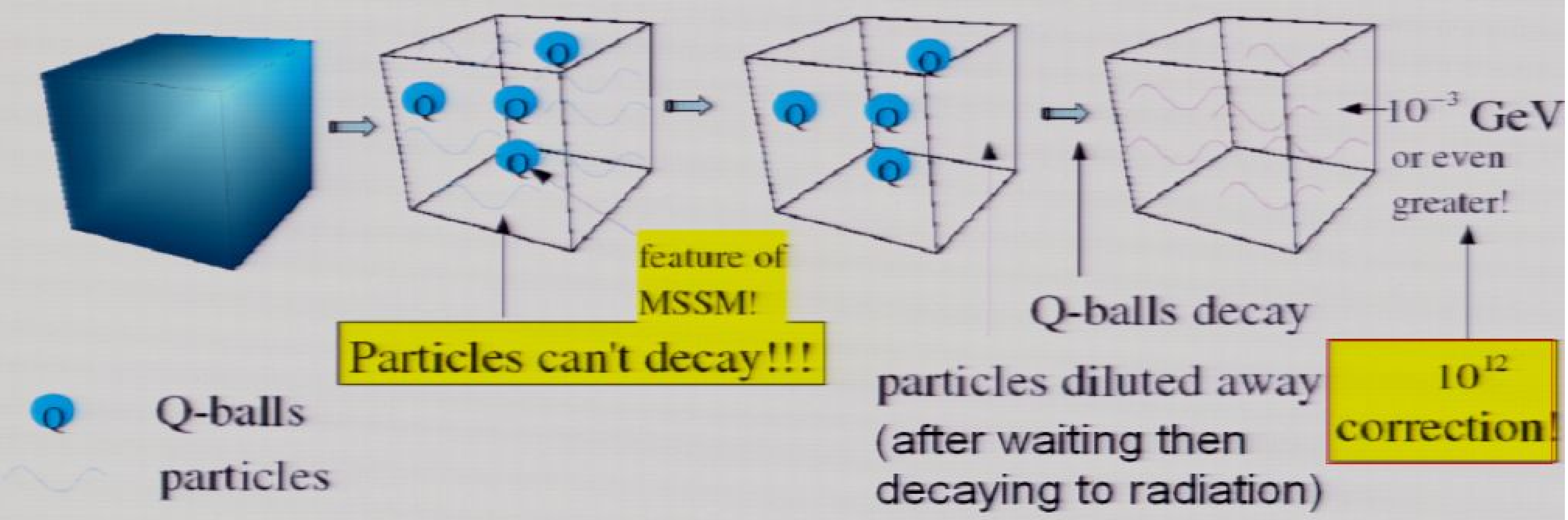

Summary of difficulties

Since must reheat to T> 3 MeV.

usual: inflation + MD -> RD (BBN) -> MD -> today
consequence of new Q-ball decay dynamics:

1) bad: inflation + MD -> RD (gas decay) -> MD (BBN?) ->
RD (Q-giant decay) -> MD -> today

2) bad: inflation+MD -> RD (gas decay) -> thermal inflation + MD -
RD (BBN?) -> MD -> RD (Q-ball decay) -> MD -> today

Thermal inflation here requires significant engineering!

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Thermal inflation here requires significant engineering!

Which flat directions are safe?

$H_u H_d$ and $H_u L$ (i.e. only flat directions involving Higgs)

since $K = \frac{dm_\phi^2}{d \ln \mu} > 0$ $\frac{P}{\rho} = \frac{K}{2+K}$

$H_u L$ → dangerous for B asymmetry

Tuned models of thermal inflation can cure most of these problems.

Conclusion

- Consider reheating constraints of inflation if LHC discovers SUSY
- Thermal leptogenesis is generically viable even when $T_{\rm RH}$ =1 TeV. [0904.1591]
- Q-ball formation can be generic in MSSM after inflation ends causing a subtle moduli problem that does not depend on the vev but on cold gas between the Q-balls. [hep-ph/0507218, hep-ph/0510186]