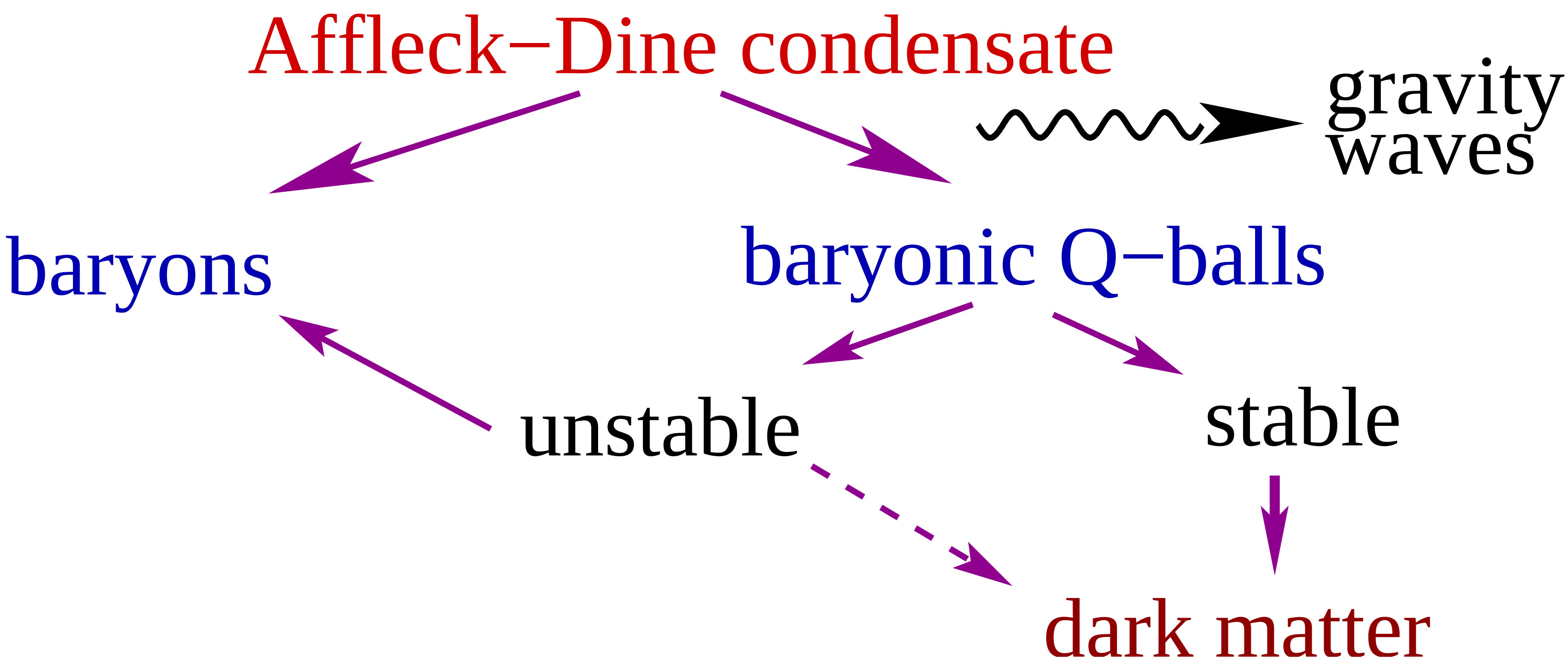
Echoes of supersymmetry: the relic Q-balls

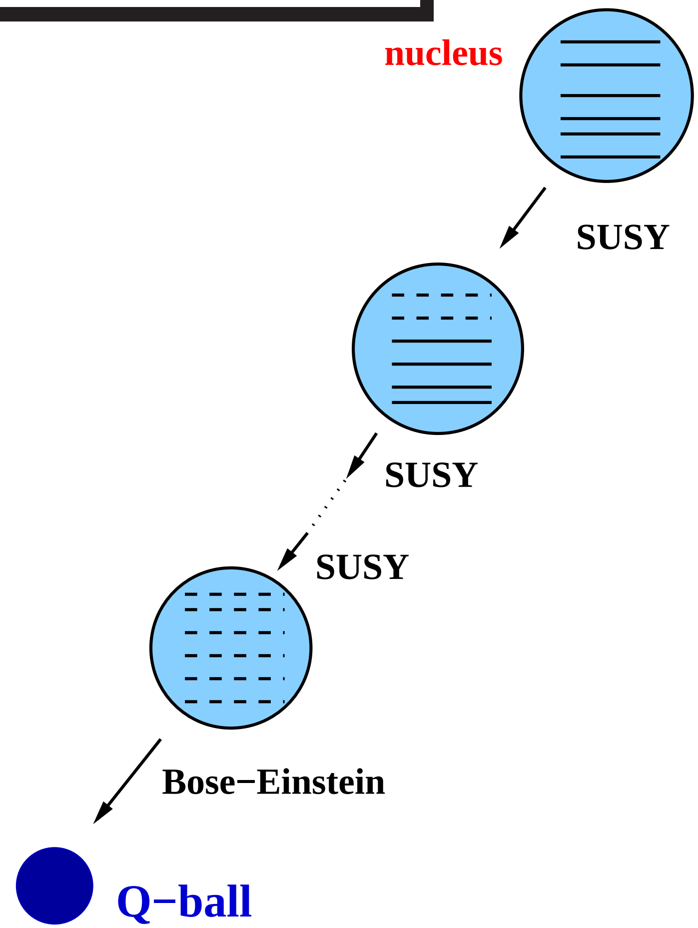
- SUSY and Q-balls
- Inflation+SUSY$\Rightarrow$ Q-balls
- stable Q-balls as dark matter
- interactions with matter, detection, constraints

Echoes of supersymmetry: relic Q-balls



SUSY and Q-balls

Why would one suspect that
SUSY $\Rightarrow$ Q-balls?



Q-balls

Let us consider a complex scalar field $\phi(x,t)$ in a potential that respects a U(1) symmetry: $\phi \to e^{i\theta}\phi$. vacuum: $\phi = 0$

conserved charge: $Q = \frac{1}{2i}\int \left(\phi^\dagger \overleftrightarrow{\partial_0} \phi\right) d^3x$

$Q \neq 0 \Rightarrow \phi \neq 0$ in some finite domain $\Longrightarrow$ Q-ball

Q-balls exist if $U(\phi)\,/\phi^2 = \min, \;\; \text{for } \phi = \phi_0 > 0$

Finite ϕ_0: $M(Q) \propto Q$

Flat potential ($U(\phi) \sim \phi^p, p < 2$); $\phi_0 = \infty$:

$$M(Q) \propto Q^\alpha, \alpha < 1$$

Q-balls exist in (softly broken) SUSY because

- the theory has scalar fields
- the scalar fields carry conserved global charge (baryon and lepton numbers)
- attractive scalar interactions (tri-linear terms, flat directions) force $(U(\phi)/\phi^2) = \min$ for non-vacuum values.

MSSM, gauge mediated SUSY breaking

Baryonic Q-balls (B-balls) are entirely stable if their mass per unit baryon charge is less than the proton mass.

$M(Q) = M_S Q^{3/4} \Rightarrow$

$\frac{M(Q_B)}{Q_B} \sim M_S Q^{-1/4} < 1\text{GeV}$

$$\text{for } Q_B \gg \left(\frac{M_S}{1\ \text{TeV}}\right)^4 \gtrsim 10^{12}$$

Such B-balls are entirely stable.

Baryon asymmetry

$$\eta \equiv \frac{n_B}{n_\gamma} = \left(6.1\,^{+0.3}_{-0.2}\right) \times 10^{-10}$$

What happened right after the Big Bang?

- Inflation probably took place
- Baryogenesis – definitely *after* inflation

Standard Model is not consistent
with the observed baryon asymmetry (assuming inflation)

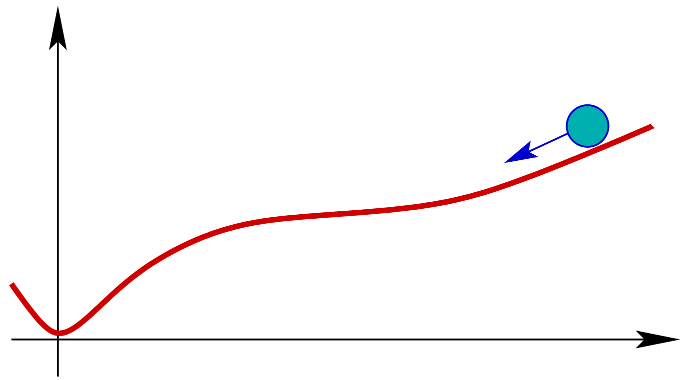
Affleck–Dine baryogenesis

- Natural if SUSY+Inflation
- Can explain matter
- Can explain **dark** matter
- Predictions can be tested soon

Inflation

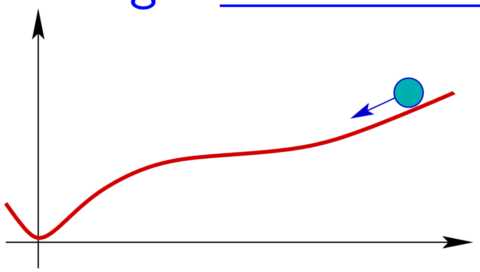
All matter is produced during reheating after inflation.

SUSY $\Rightarrow$ flat directions.
During inflation, scalar fields are displaced from their minima.



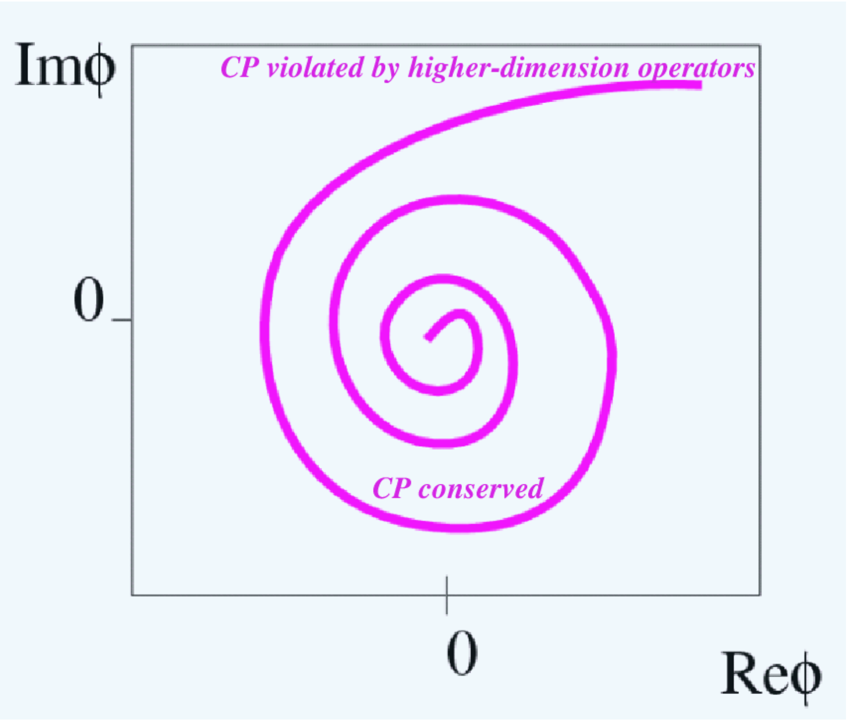
Affleck – Dine baryogenesis

at the end of inflation
a scalar condensate
develops a large VEV
along a **flat direction**



CP violation is due to time-dependent background.

Baryon asymmetry: $\phi = |\phi| e^{i\omega t}$



Affleck – Dine baryogenesis: an example

Suppose the flat direction is lifted by a higher dimension operator $W_n = \frac{1}{M^n}\Phi^{n+3}$. The expansion of the universe breaks SUSY and introduces mass terms $m^2 \sim \pm H^2$.

The scalar potential:

$$V = -H^2|\Phi|^2 + \frac{1}{M^{2n}}|\Phi|^{2n+4}$$

Assume the **inflation scale** $E \sim 10^{15}$ **GeV** The Hubble constant $H_I \approx E^2/M_p \approx 10^{12}$ **GeV**. $T_R \sim 10^9$ **GeV**

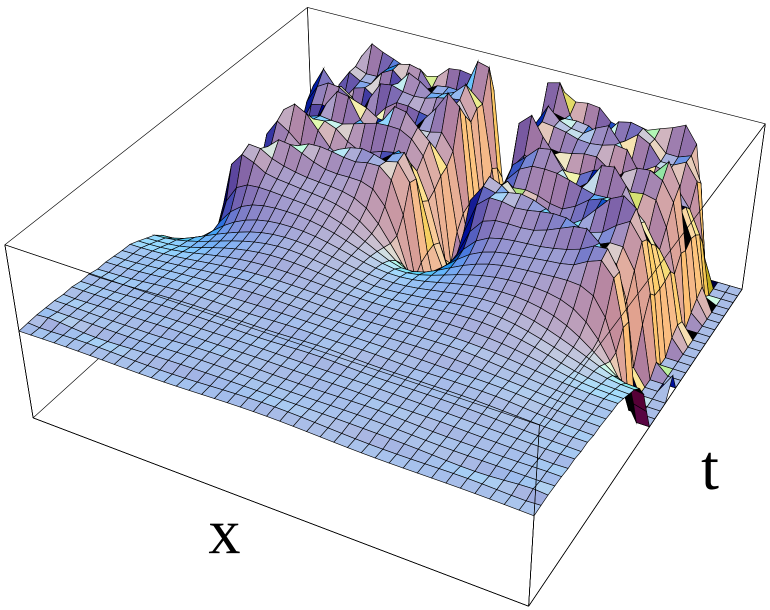
In this example, the final baryon asymmetry is

$$\frac{n_B}{n_\gamma} \sim \frac{n_B}{(\rho_I/T_R)} \sim \frac{n_B}{n_\Phi}\frac{T_R}{m_\Phi}\frac{\rho_\Phi}{\rho_I}$$

$$\sim 10^{-10}\left(\frac{T_R}{10^9\mathrm{GeV}}\right)\left(\frac{M_p}{m_{3/2}}\right)^{\frac{(n-1)}{(n+1)}}$$

Correct baryon asymmetry for $n = 1$. (For $n > 1$, too big.)
[see, e.g., review by Dine, AK]

Fragmentation of the Affleck-Dine condensate



[AK, Shaposhnikov]

small inhomogeneities can grow

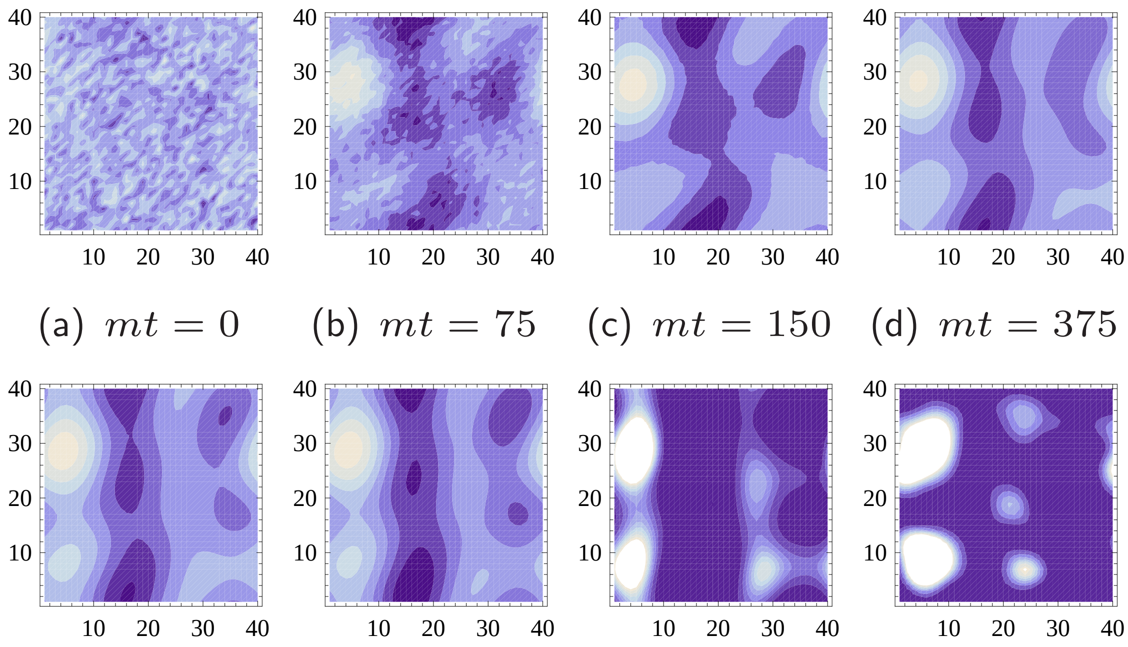
unstable modes:

$$0 < k < k_{\max} = \sqrt{\omega^2 - U''(\phi)}$$

$\Rightarrow$ **Lumps of baryon condensate**

$\Rightarrow$ **Q-balls**

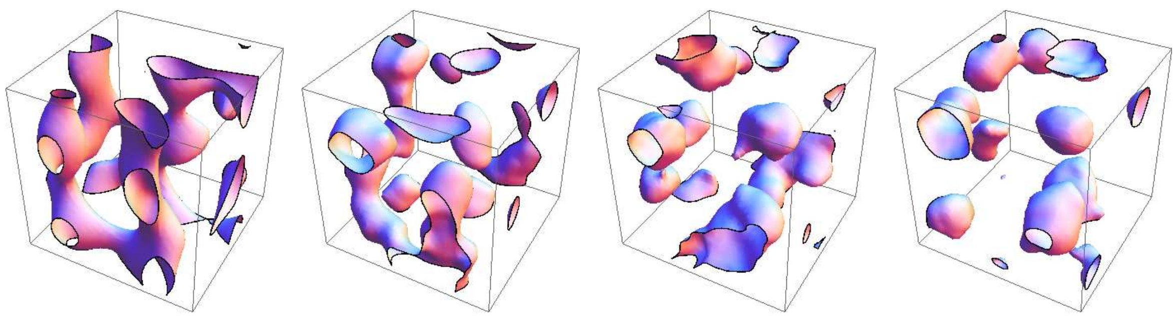
Numerical simulations of the fragmentation



(a) $mt = 0$ (b) $mt = 75$ (c) $mt = 150$ (d) $mt = 375$

(e) $mt = 525$ (f) $mt = 675$ (g) $mt = 825$ (h) $mt = 900$

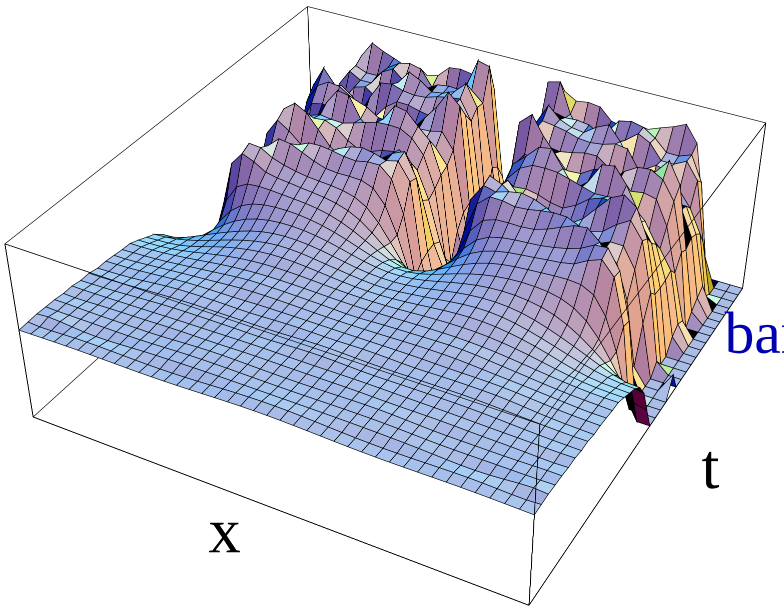
Three-dimensional charge density plots [Multamaki].

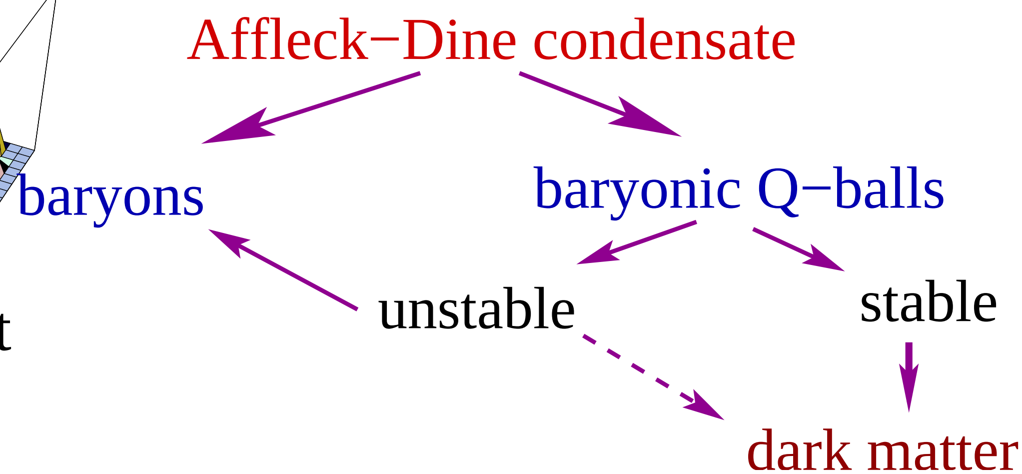


(i) $mt = 900$ (j) $mt = 1050$ (k) $mt = 1200$ (l) $mt = 1350$

Fragmentation of AD condensate can produce Q-balls

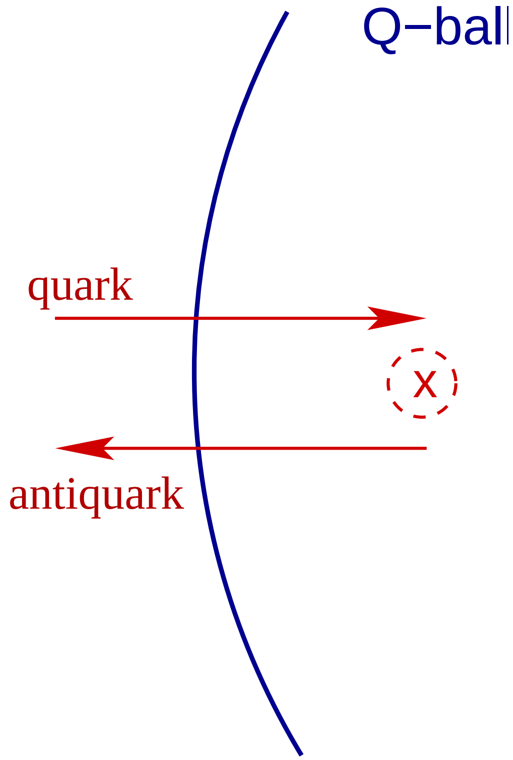
SUSY Q-balls may be stable or unstable
if stable ⇒ **dark matter**





[AK, Shaposhnikov; Enqvist, McDonald]

Interactions of SUSY Q-balls with matter



There is a Majorana mass term for quarks inside coming from the quark-squark-gluino vertex. **Probability ~ 1 for a quark to reflect as an antiquark.** Very fast!
[AK, Loveridge, Shaposhnikov].

A "candidate event"

C.M.G. Lattes et al., Hadronic interactions of high energy cosmic-ray observed by emulsion chambers

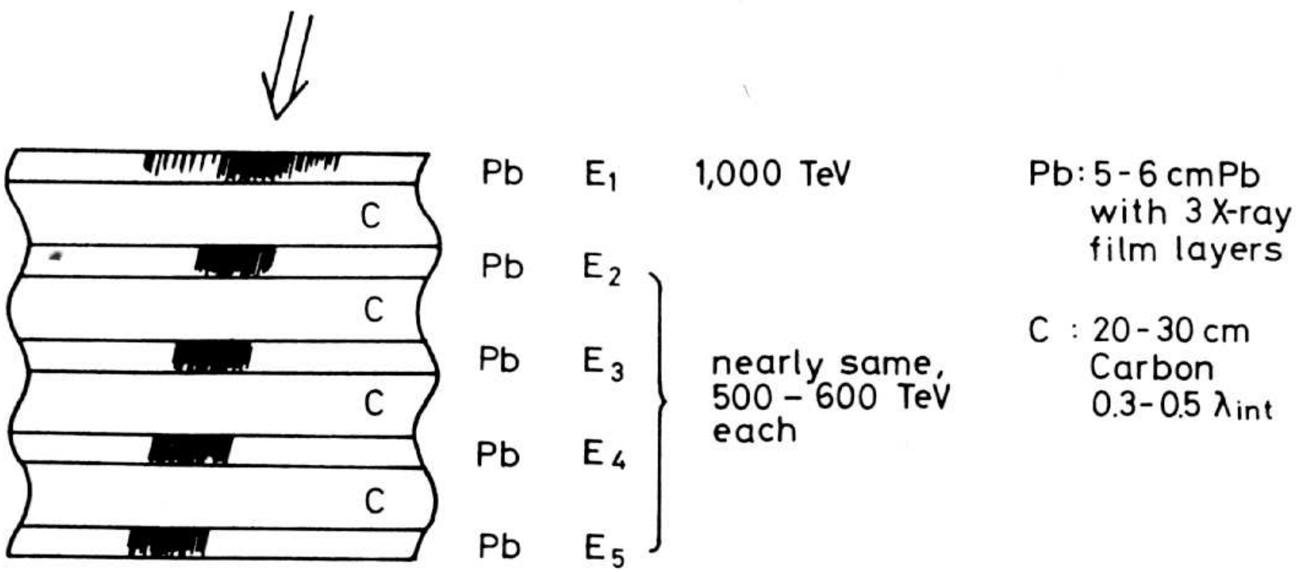


Fig. 47. Illustration of penetrating cores of Pamir experiment.

[Lattes, Fujimoto and Hasegawa, Phys.Rept. **65**, 151 (1980)]

Stable Q-balls as dark matter

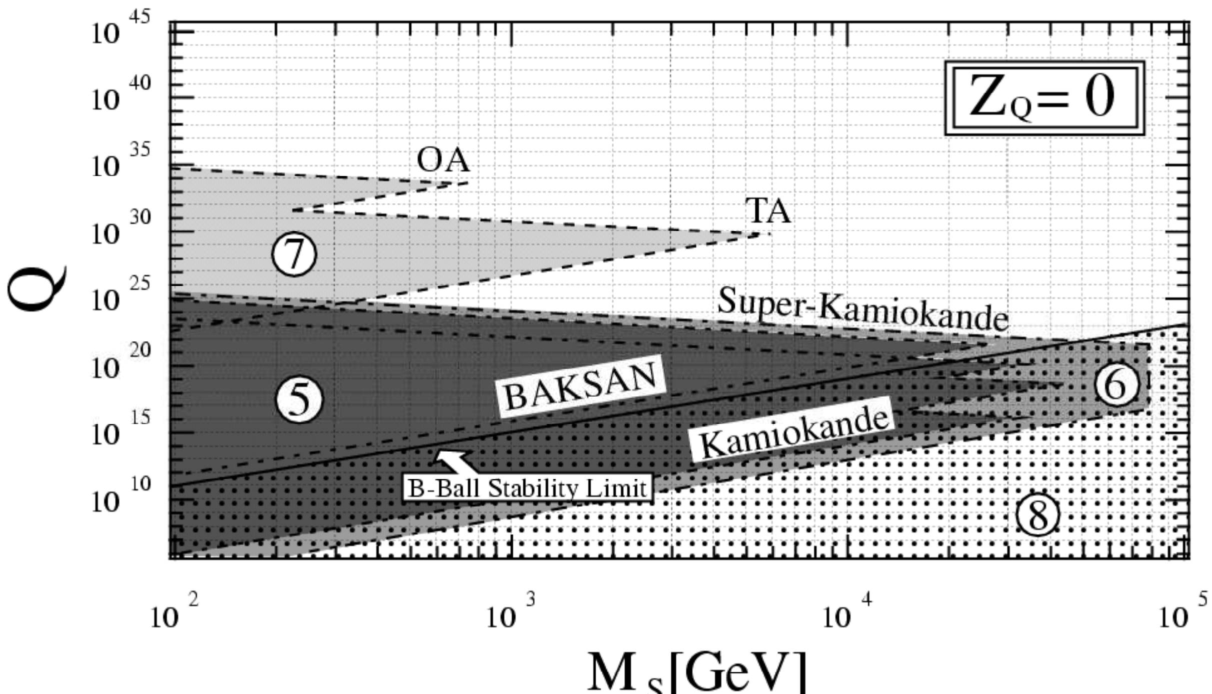
Q-balls can accommodate baryon number at lower energy than a nucleon $\Rightarrow$ **B-Balls catalyze proton decay** Signal:

$$\frac{dE}{dl} \sim 100 \left(\frac{\rho}{1\,\mathrm{g/cm^3}}\right) \frac{\mathrm{GeV}}{\mathrm{cm}}$$

Heavy $\Rightarrow$ low flux

$\Rightarrow$ **experimental limits from Super-Kamiokande and other *large* detectors**

Present experimental limits



[Arafune *et al.*];

$$\boldsymbol{\Omega_{\mathrm{B-ball}}/\ \Omega_{\mathrm{matter}} \sim 5}$$

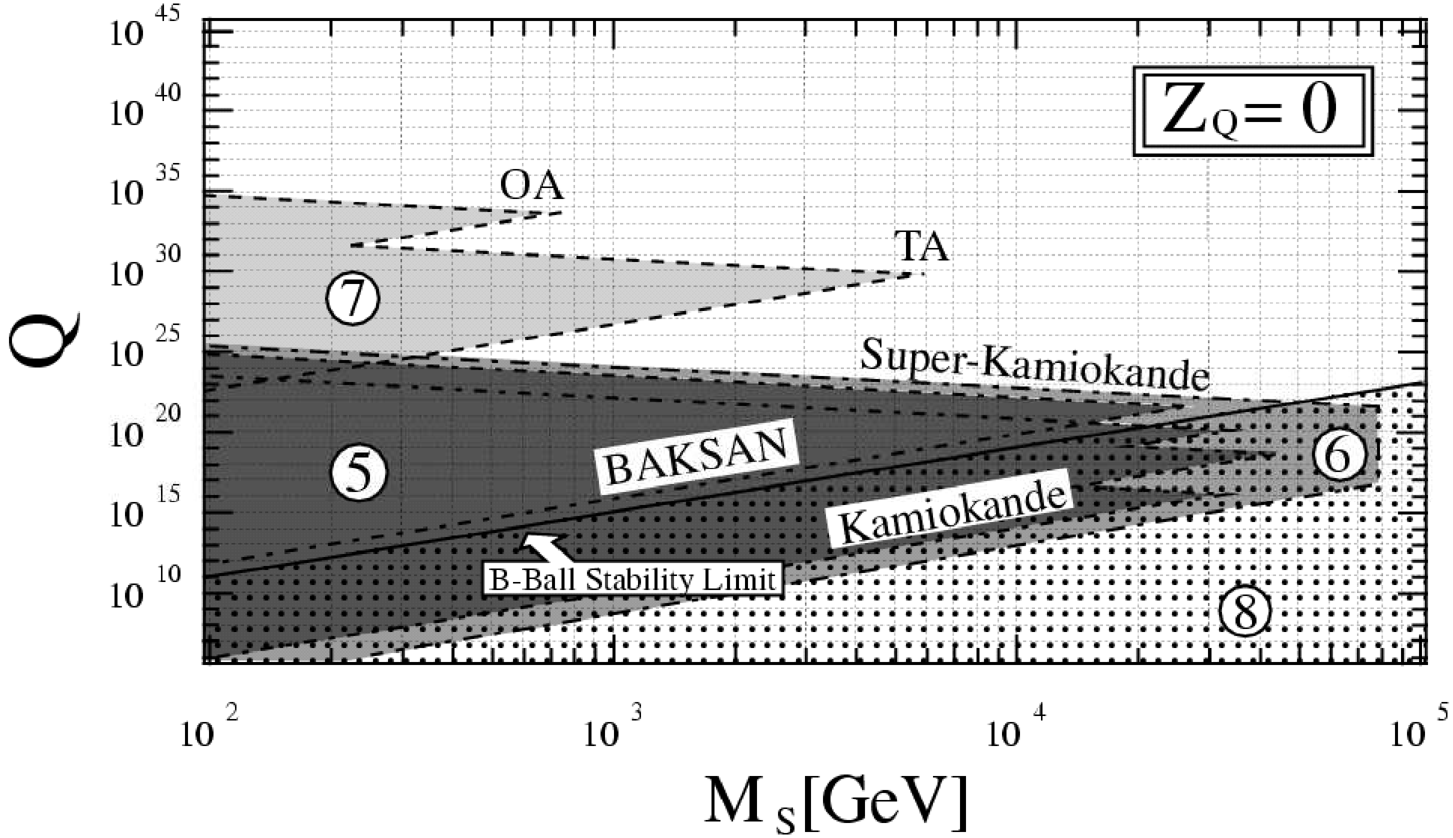
[Laine, Shaposhnikov]

- Gauge-mediated SUSY breaking
- $\boldsymbol{Q_{\mathrm{B}} \sim 10^{26\pm 2}}$ (in agreement with numerical simulations)

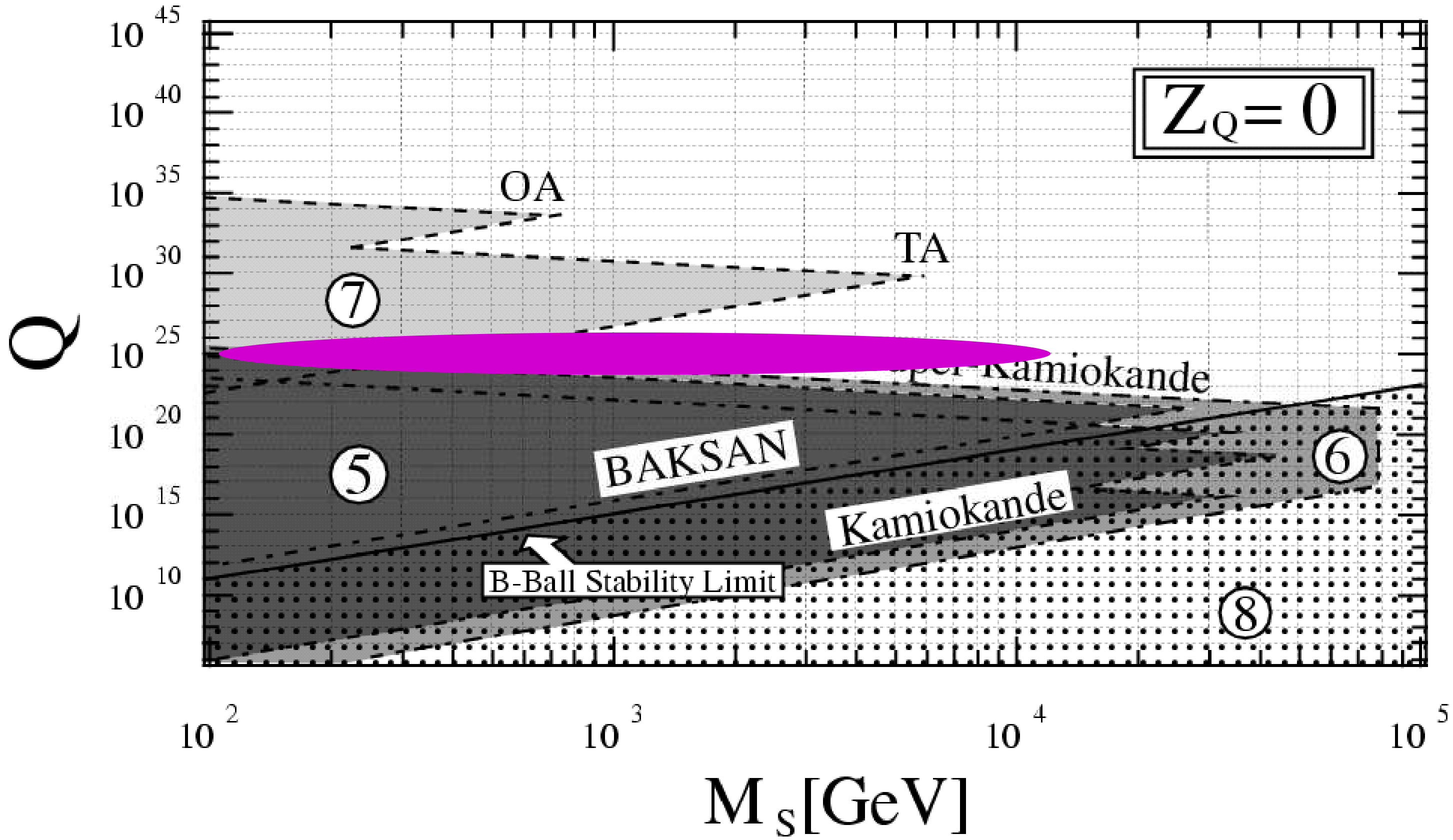
More specifically, $\boldsymbol{\Omega_{\mathrm{B-ball}}}/\Omega_{\mathbf{matter}} \sim 5$ implies

$$\boldsymbol{\eta_{\mathrm{B}} \sim 10^{-10} \left(\frac{M_{\mathrm{SUSY}}}{\mathrm{TeV}}\right) \left(\frac{Q_{\mathrm{B}}}{10^{26}}\right)^{-1/2}}$$

$$\Omega_{B-\mathrm{ball}} / \ \Omega_{\mathrm{matter}} \sim 5$$



$$\Omega_{\mathrm{B-ball}} / \ \Omega_{\mathrm{matter}} \sim 5$$



Conclusion

- SUSY + Inflation $\Rightarrow$ Q-balls, some may be stable, can be dark matter
- Typical size large $\Rightarrow$ typical density small $\Rightarrow$ need large detectors to search for relic Q-balls
- Current bounds from Super-K. Future search using IceCube, HAWC possible.