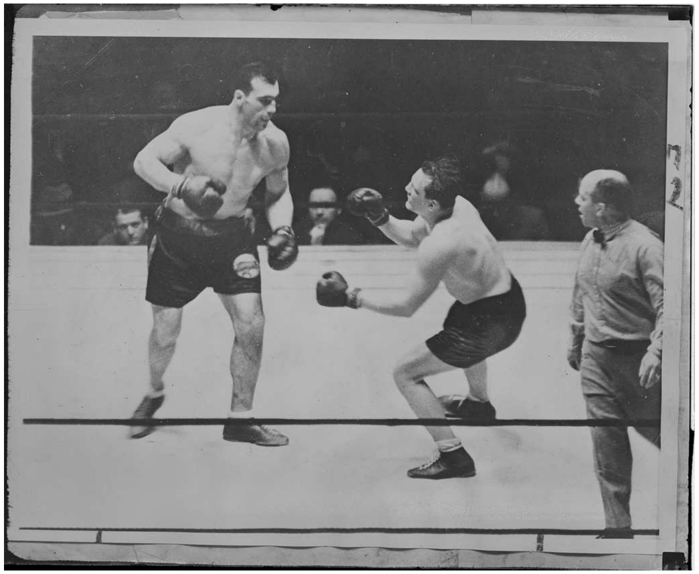
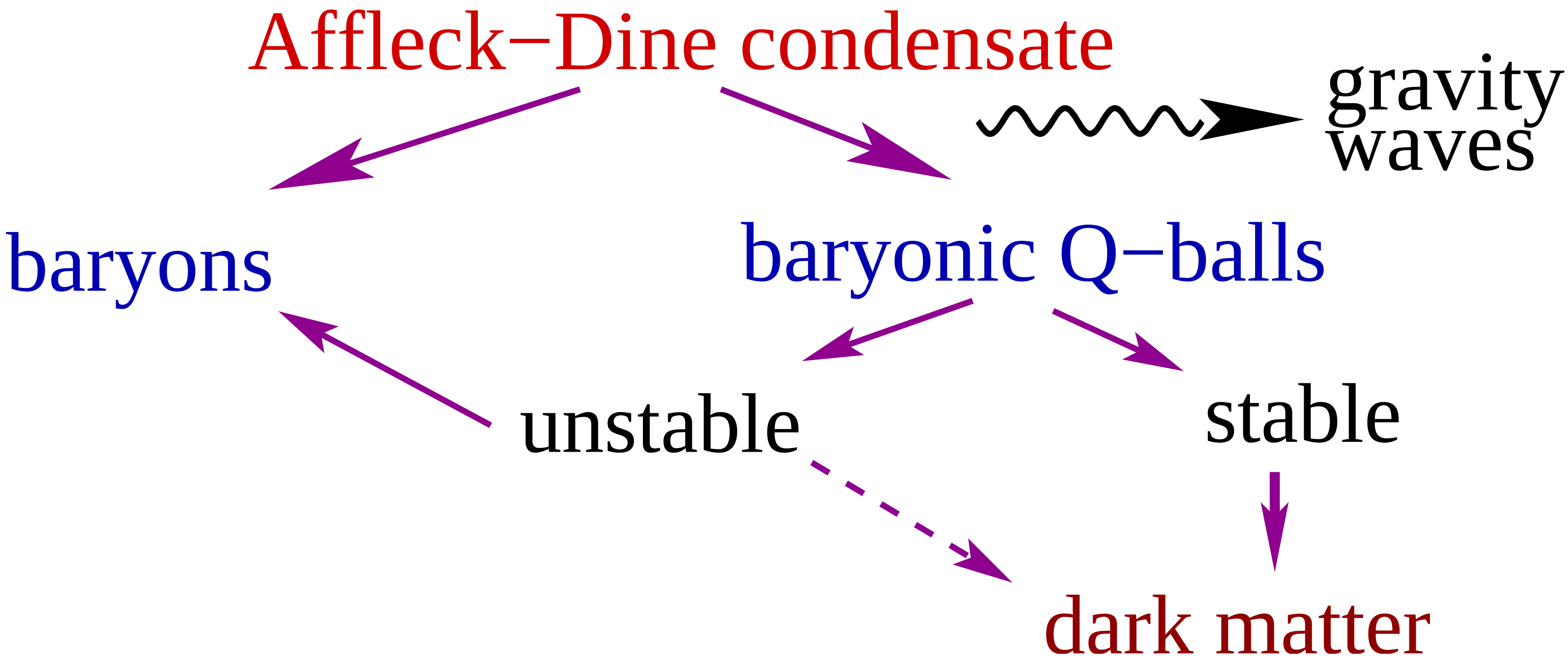
Dark matter heavyweights

- SUSY and Q-balls
  - Inflation+SUSY$\Rightarrow$ Q-balls
  - stable Q-balls as dark matter
  - interactions with matter, detection, constraints
- The IceCube discovery and very heavy dark matter



Echoes of supersymmetry in the early universe



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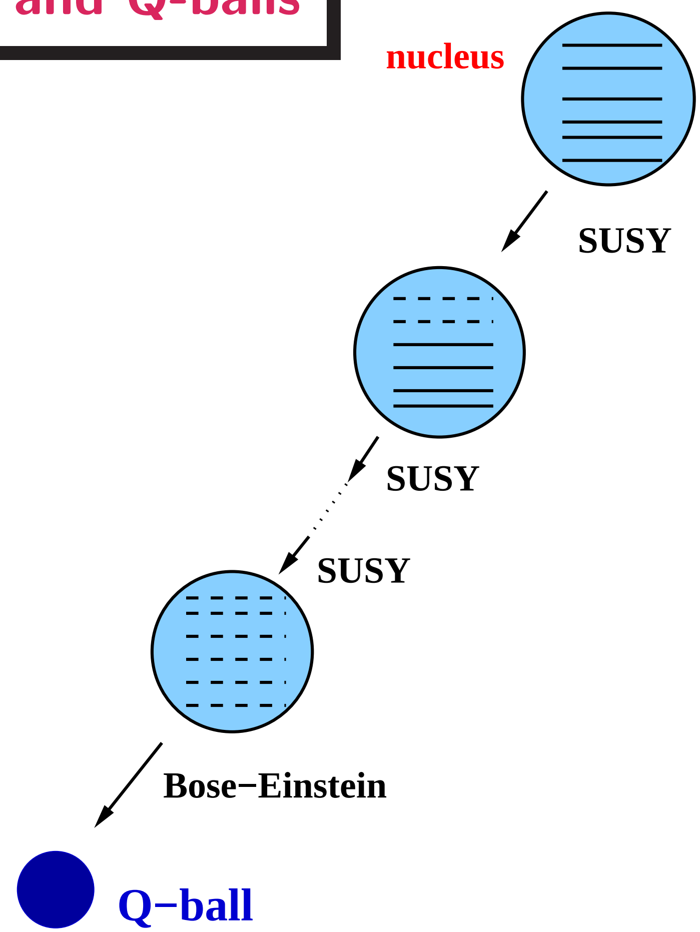

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$\Rightarrow$ Q-ball [Rosen; Friedberg, Lee, Sirlin; Coleman]

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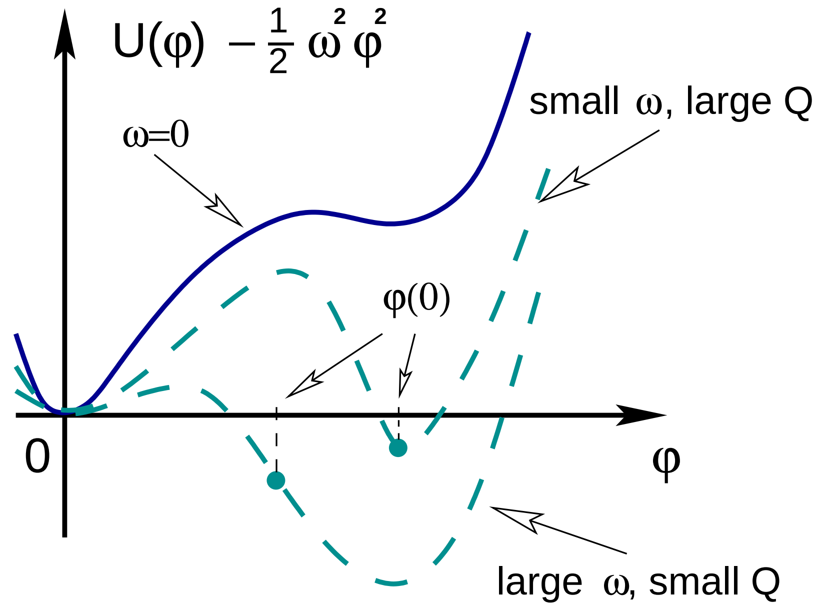
- Finally, minimize $\mathcal{E}$ with respect to ω.

Q-balls exist whenever $\hat{U}_\omega(\phi) = U(\phi) - \frac{1}{2}\omega^2\phi^2$ is not positive definite for some value of ω.



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- attractive scalar interactions (tri-linear terms, flat directions) force $(U(\phi)/\phi^2) = \min$ for non-vacuum values.

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

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Such B-balls are entirely stable.

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

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Inflation

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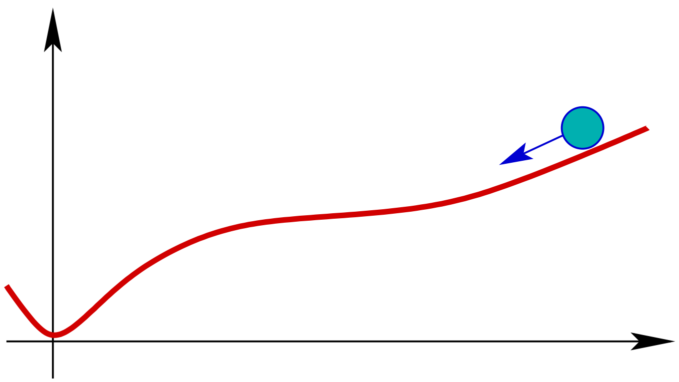
SUSY $\Rightarrow$ flat directions.
During inflation, scalar fields
are displaced from their minima.



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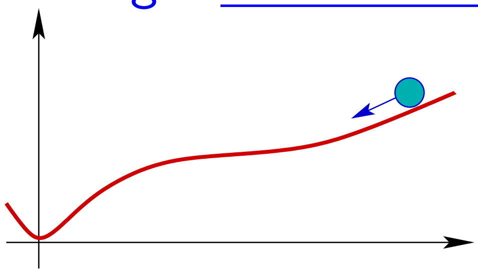

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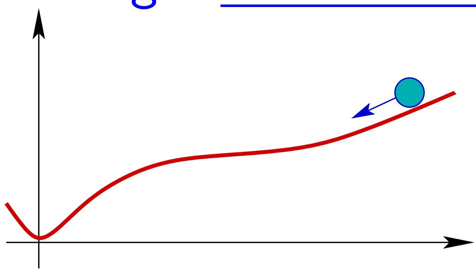

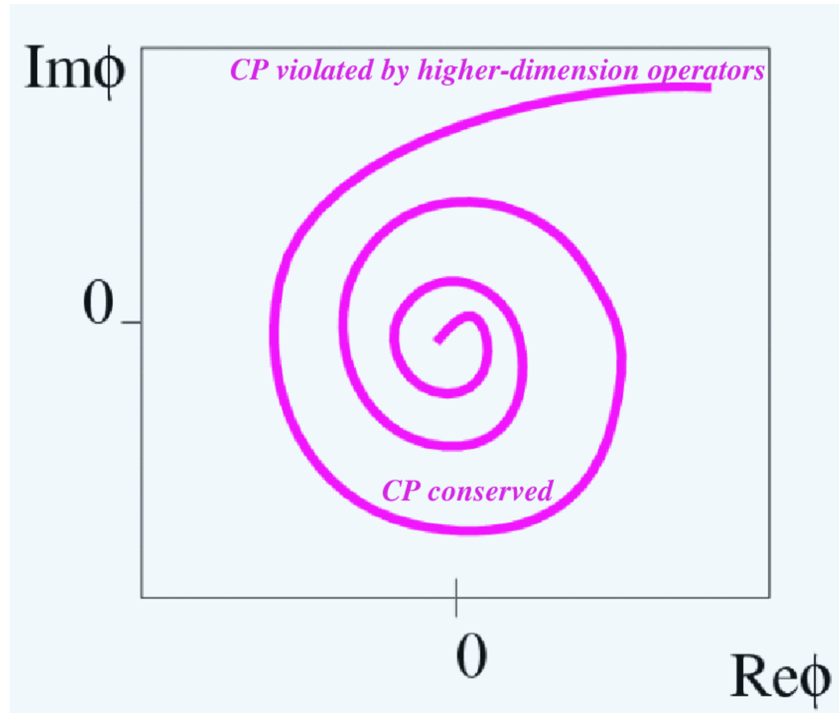

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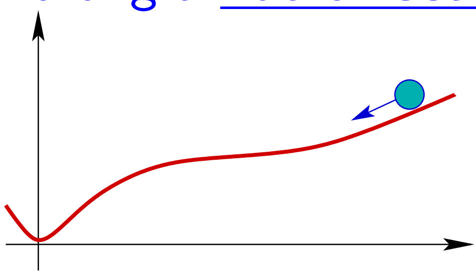
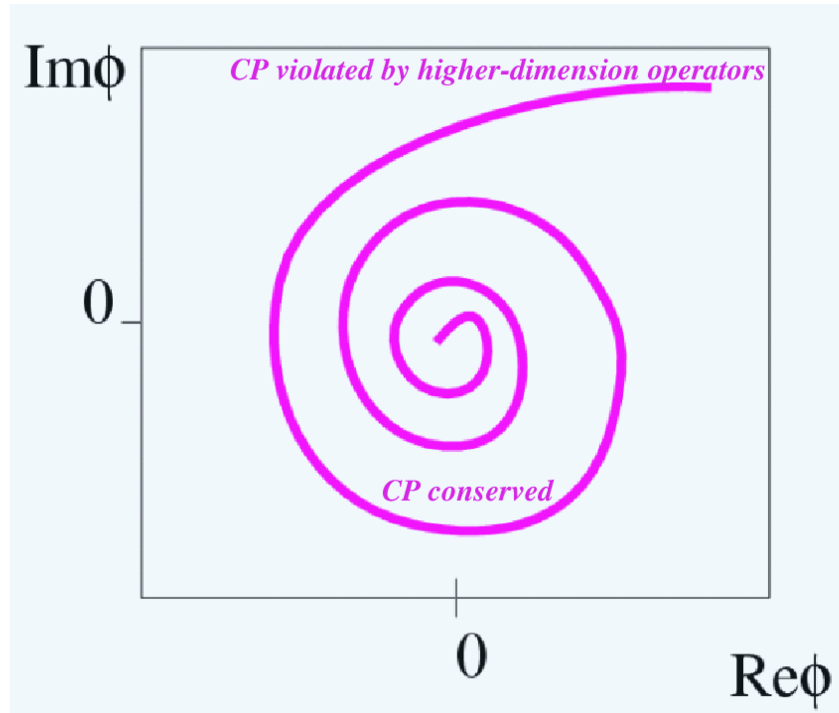


CP violation is due to time-dependent background.



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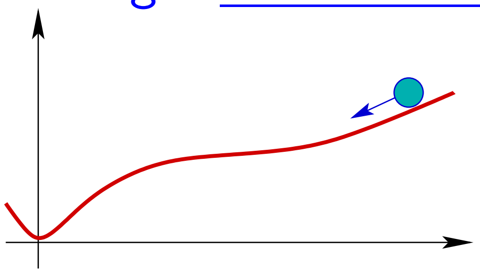

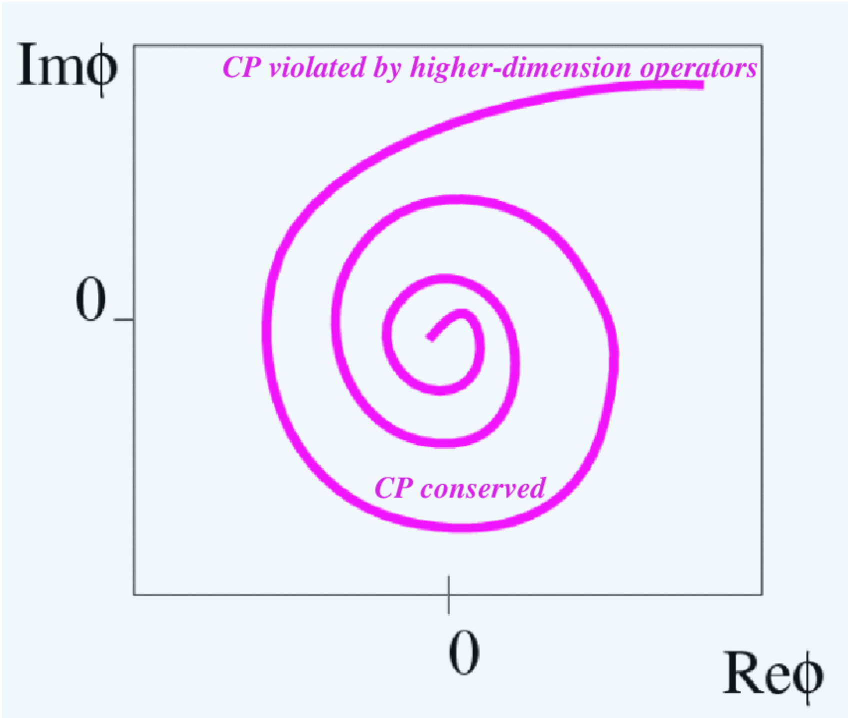

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Baryon asymmetry: $\phi = |\phi| e^{i\omega t}$

Affleck – Dine baryogenesis: an example [Dine+AK, Rev.Mod.Phys.]

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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

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

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

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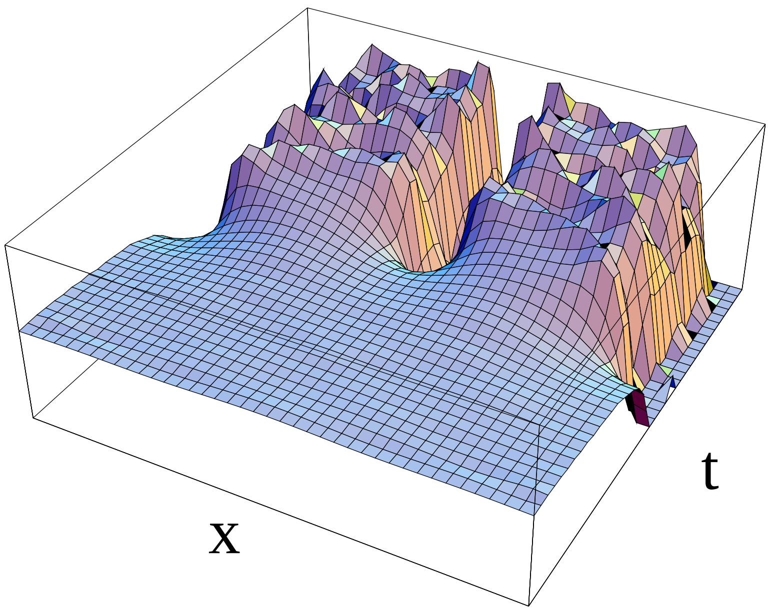
Correct baryon asymmetry for $n = 1$.

Fragmentation of the Affleck-Dine condensate



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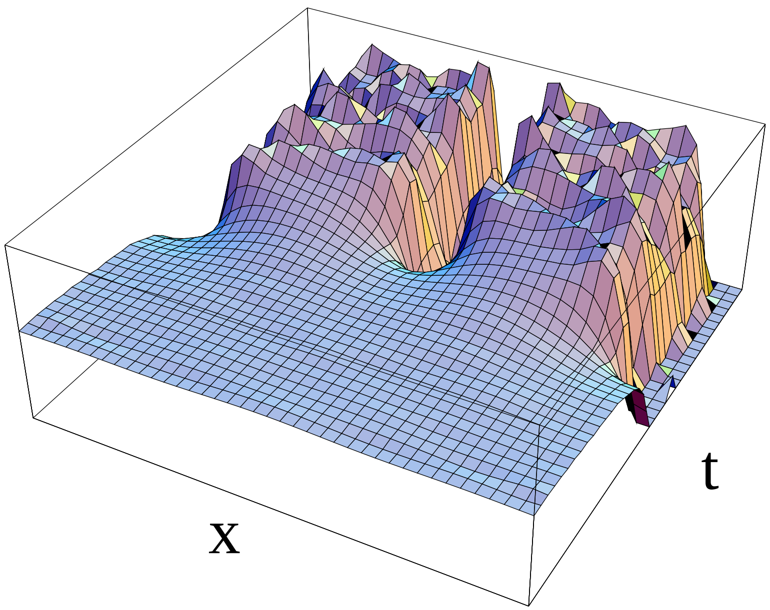

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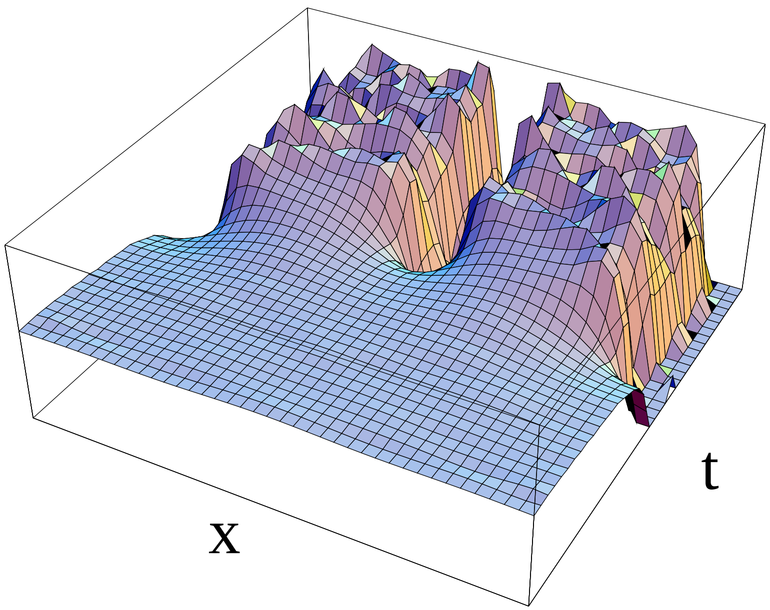

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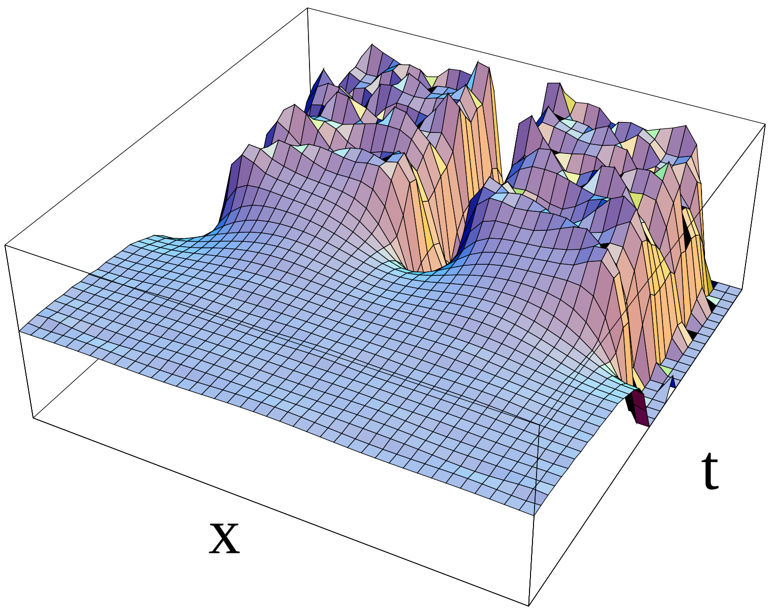

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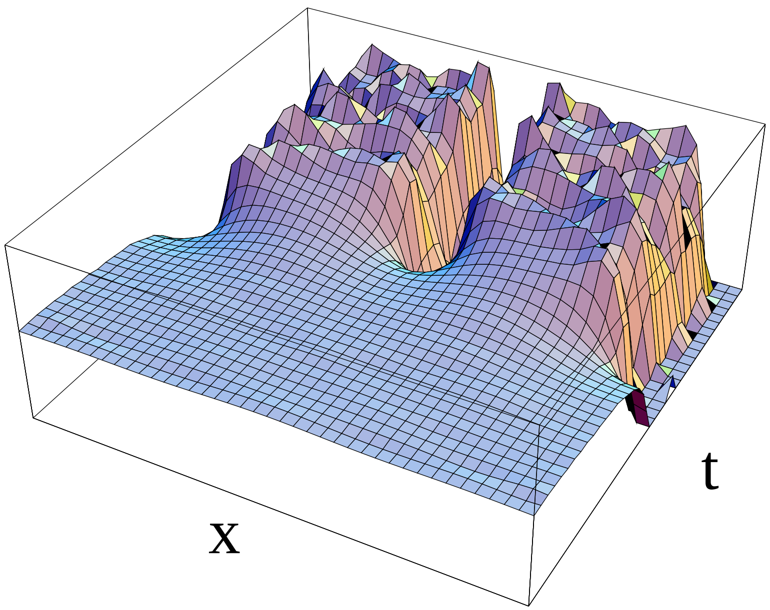

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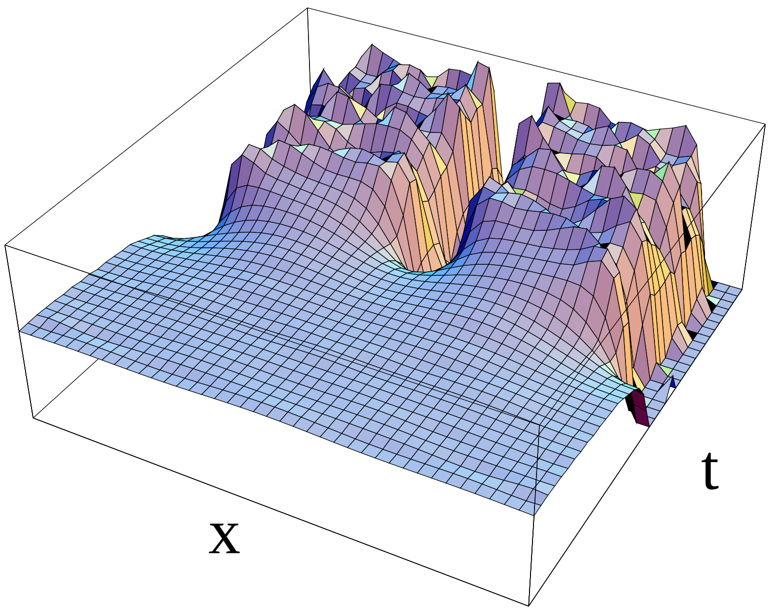

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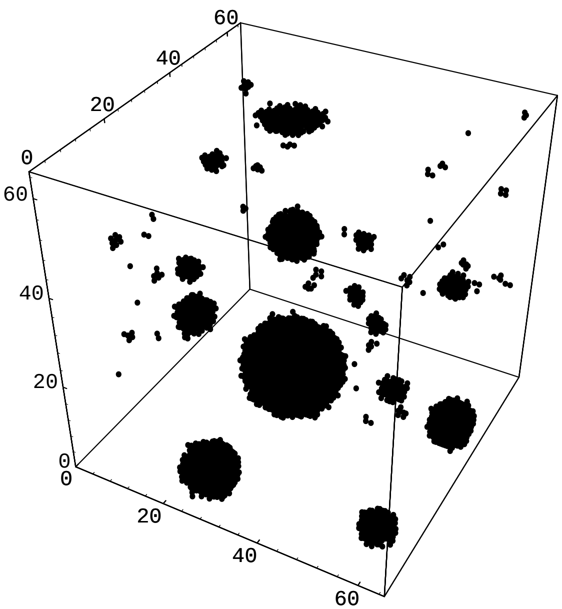
Fragmentation ≈ pattern formation

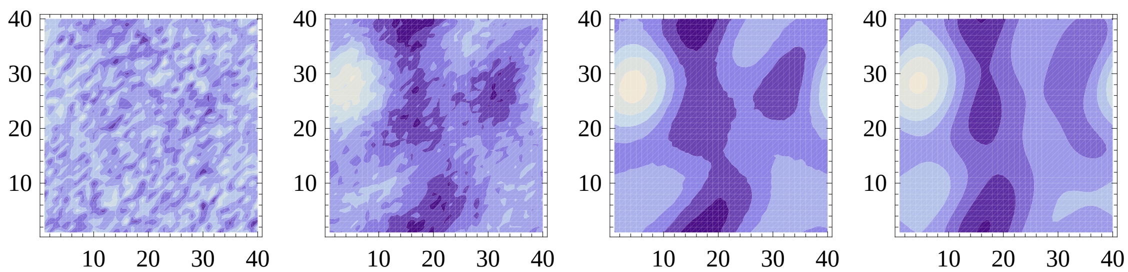
Familiar example:

Numerical simulations of the fragmentation

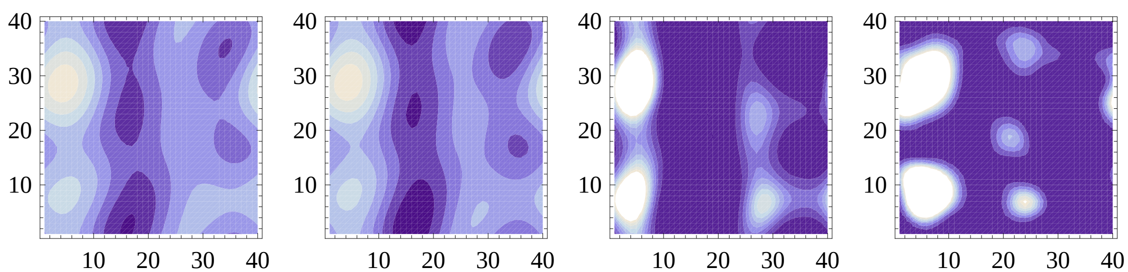


[Kasuya, Kawasaki]

Two-dimensional charge density plots [Multamaki].

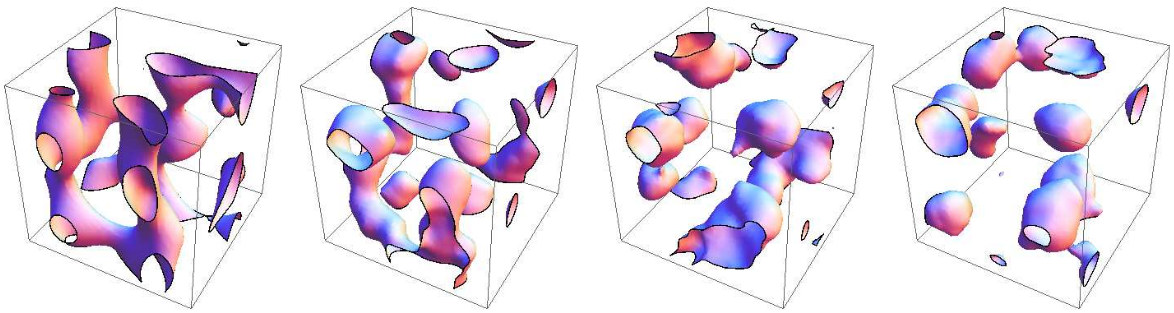


(a) $mt = 0$ (b) $mt = 75$ (c) $mt = 150$ (d) $mt = 375$



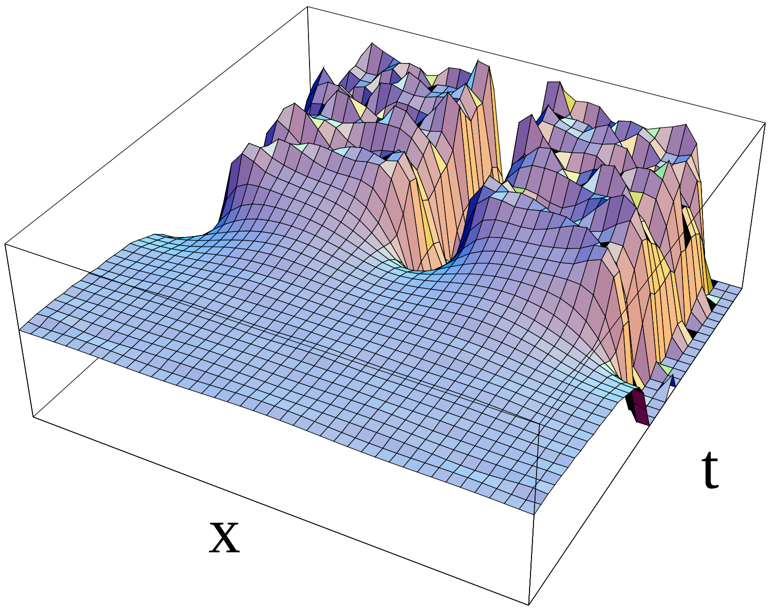
(e) $mt = 525$ (f) $mt = 675$ (g) $mt = 825$ (h) $mt = 900$

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



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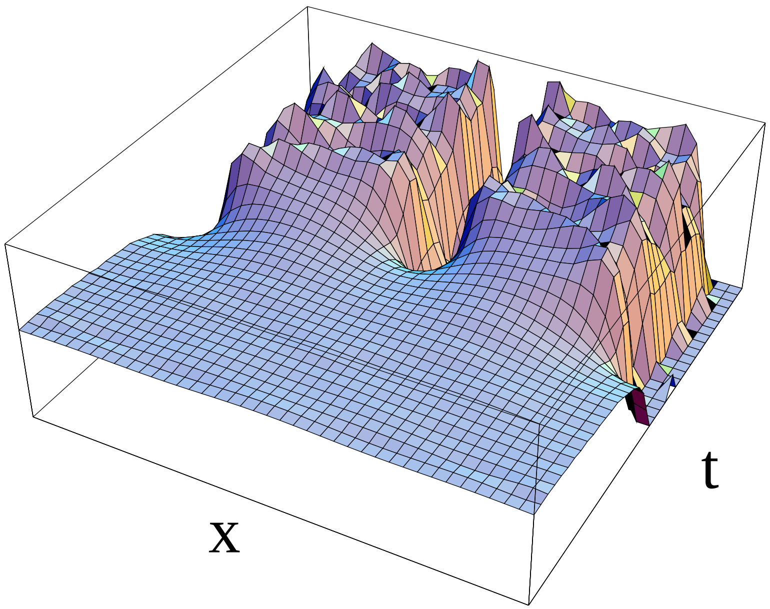

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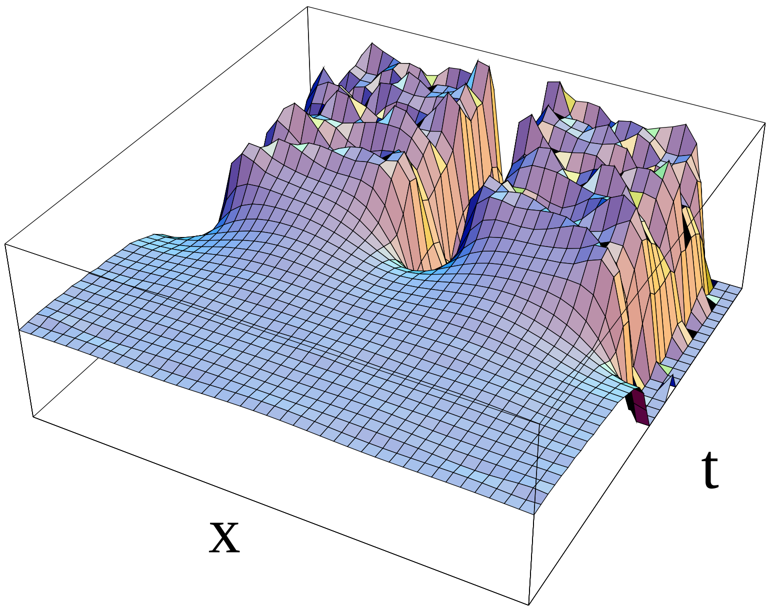

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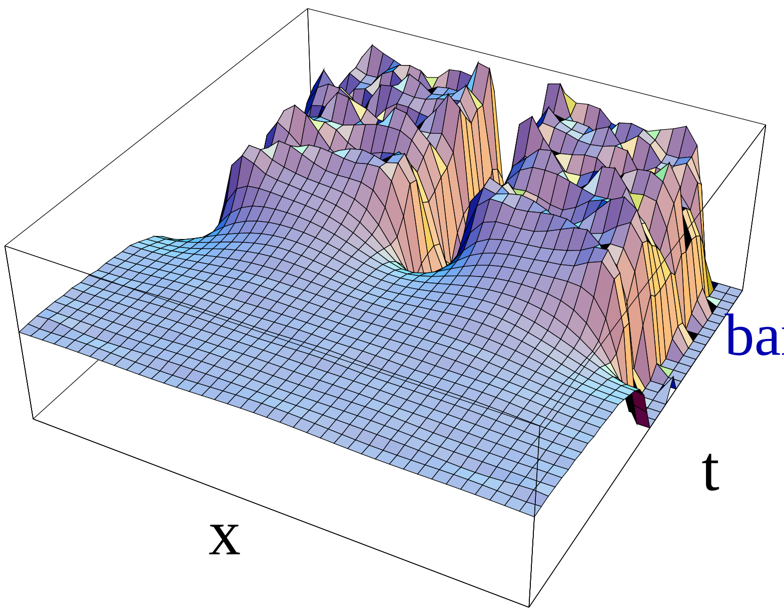

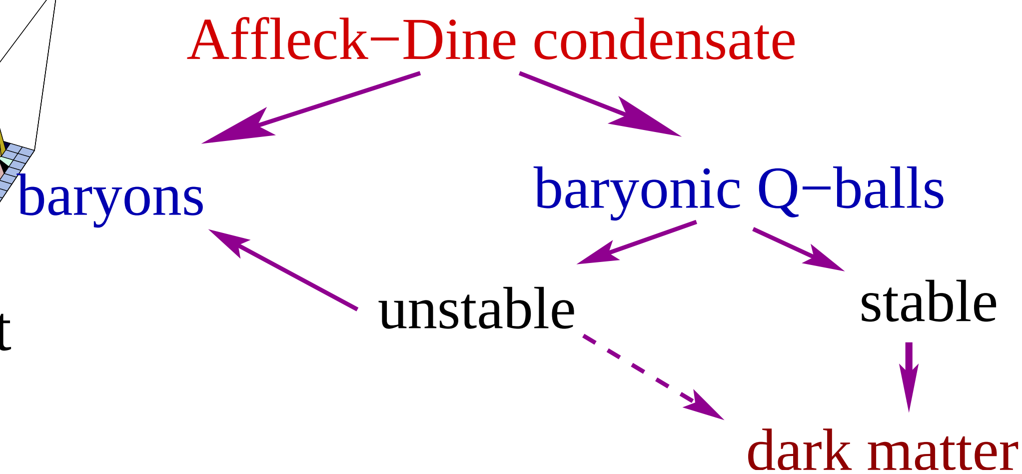

Dark matter in the form of stable SUSY Q-balls?

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$\Rightarrow$ **B-Balls catalyze proton decay** [AK,Kuzmin,Shaposhnikov,Tinyakov]
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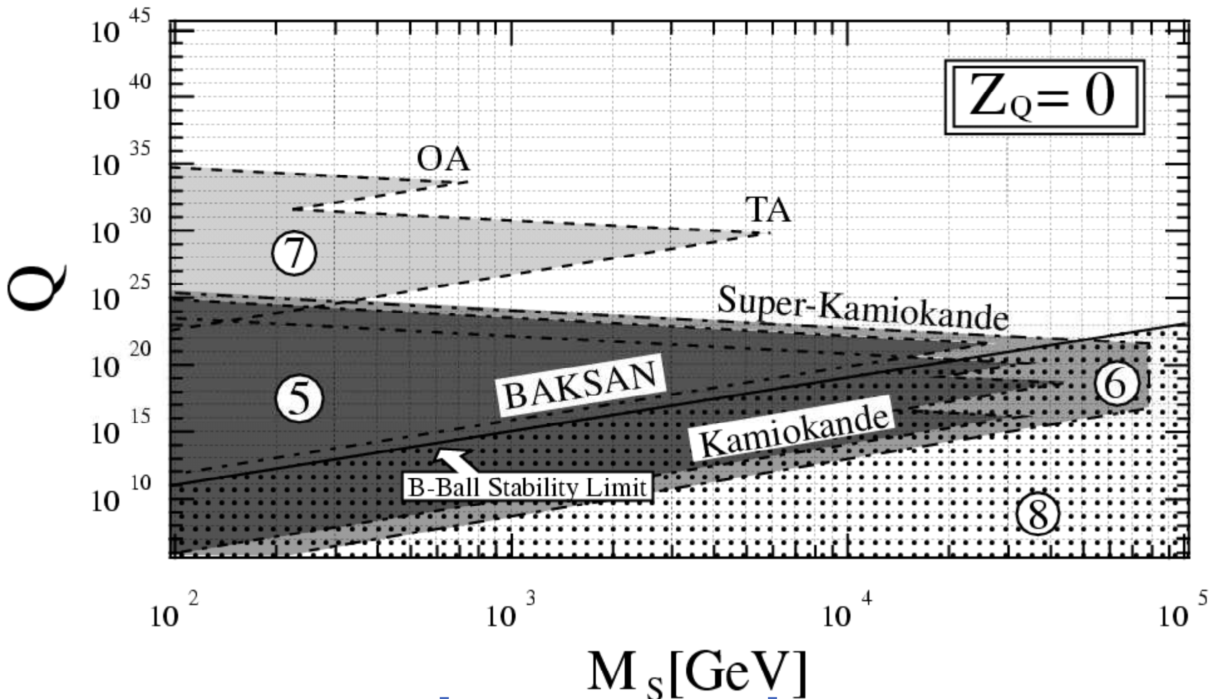
$\Rightarrow$ **experimental limits from Super-Kamiokande and other** ***large*** **detectors**

Present experimental limits



[Arafune *et al.*];

A "candidate event"

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

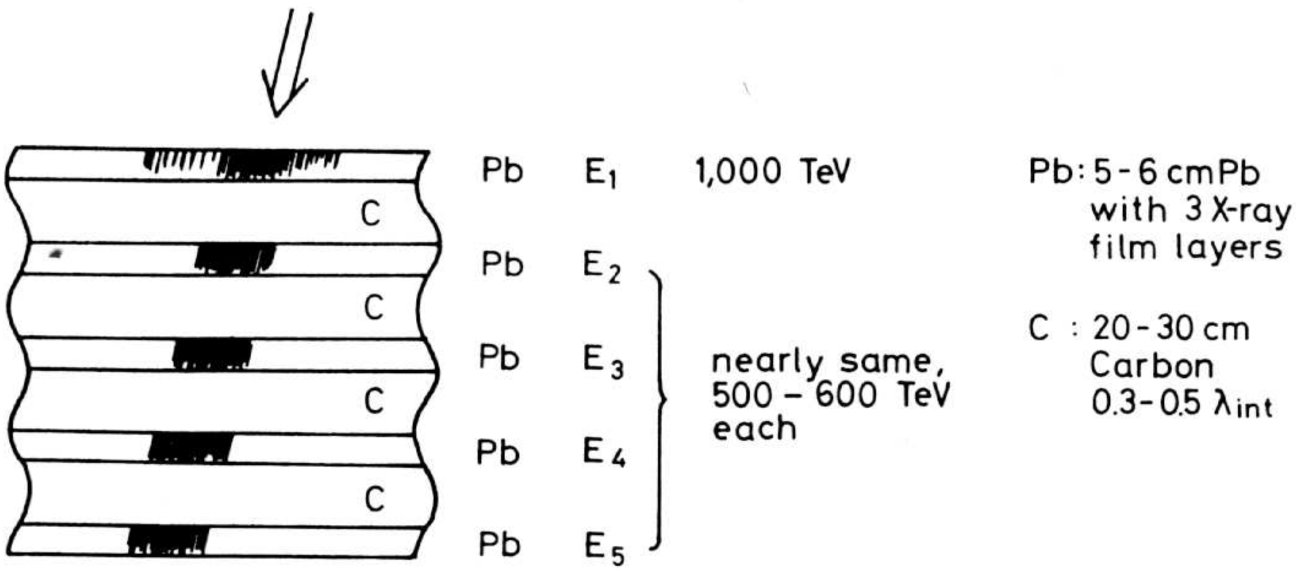


Fig. 47. Illustration of penetrating cores of Pamir experiment.

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

Unstable B-balls

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Hence, *Q-balls are unstable*.

Decay of Q-balls results in *late non-thermal production of LSP.*

Ordinary and dark matter arise from the same process. Hence, one may be able to **explain why Ω_{matter} and Ω_{dark} are not very different**. [AK;Fijii,Yanagida; Enqvist, McDonald; Laine, Shaposhnikov]

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- Dark matter is **gravitino** produced non-thermally from decay of unstable Q-balls [Fujii, Yanagida; Kawasaki et al.; AK, Shoemaker]

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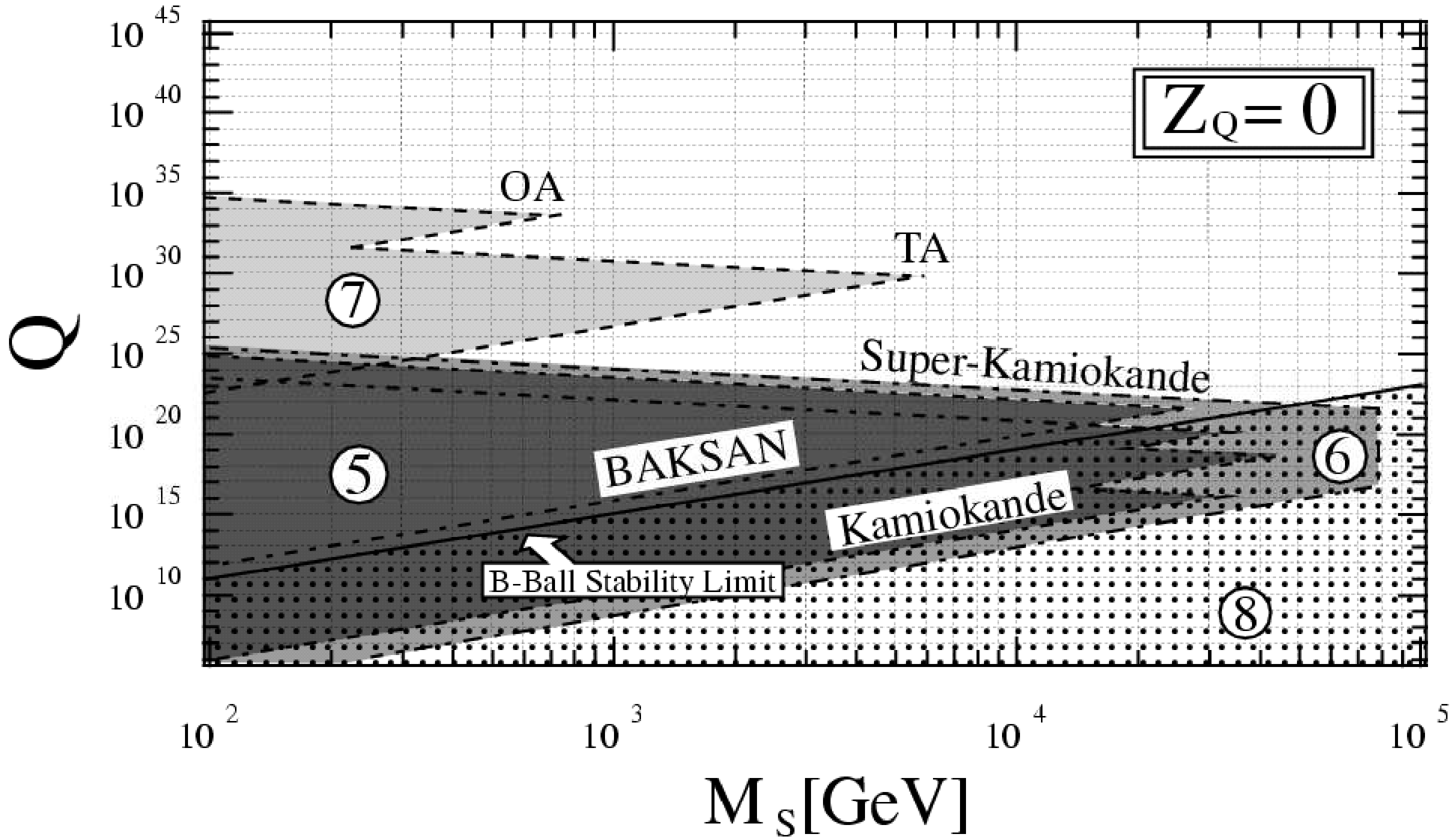
More specifically, $\Omega_{\rm B-ball}/\Omega_{\rm matter} \sim 6$ implies

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

$\Omega_{\rm B-ball}/\ \Omega_{\rm matter} \sim 6$



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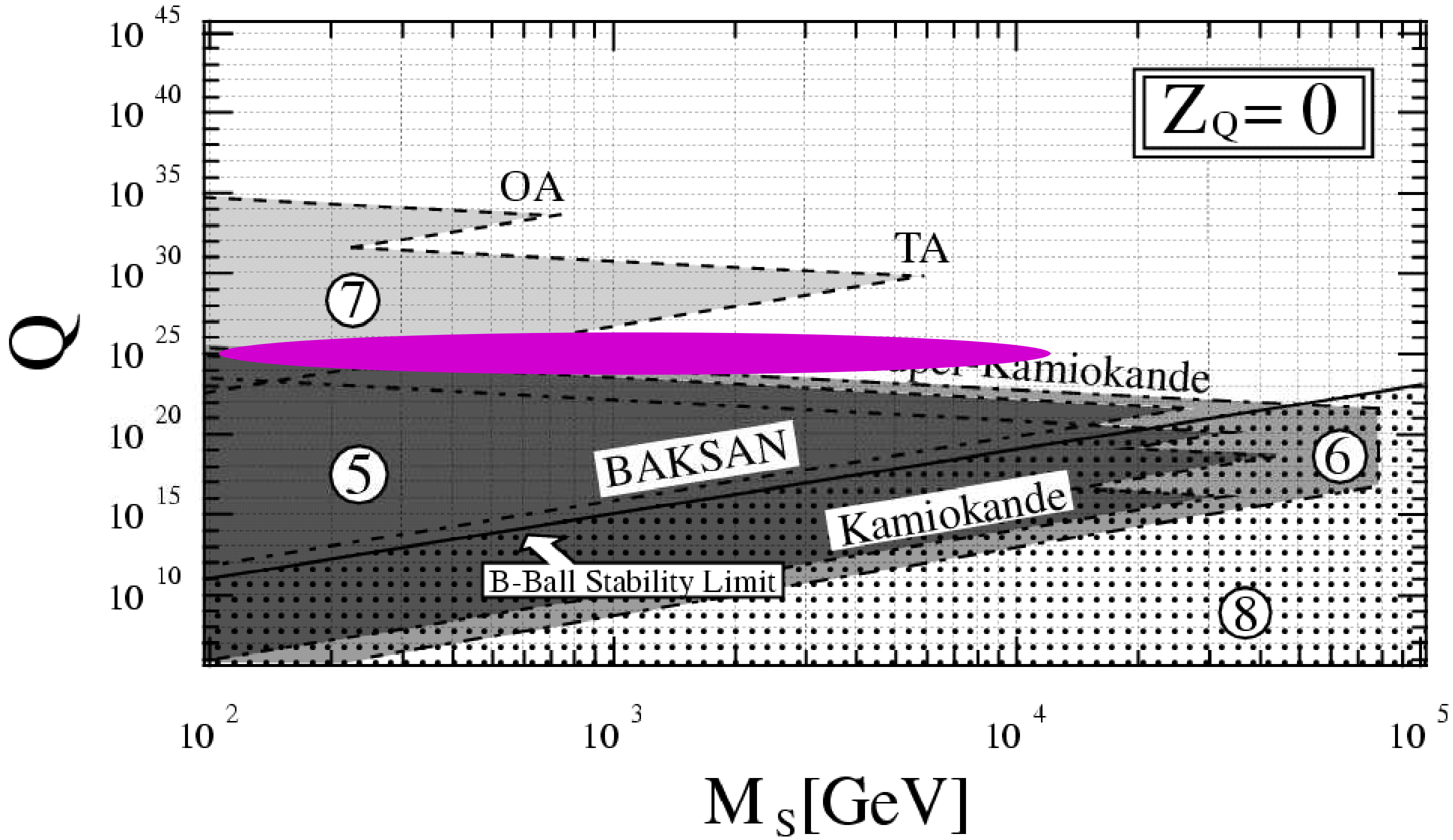

Astrophysical constraints

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- Q-balls pass through ordinary stars and planets

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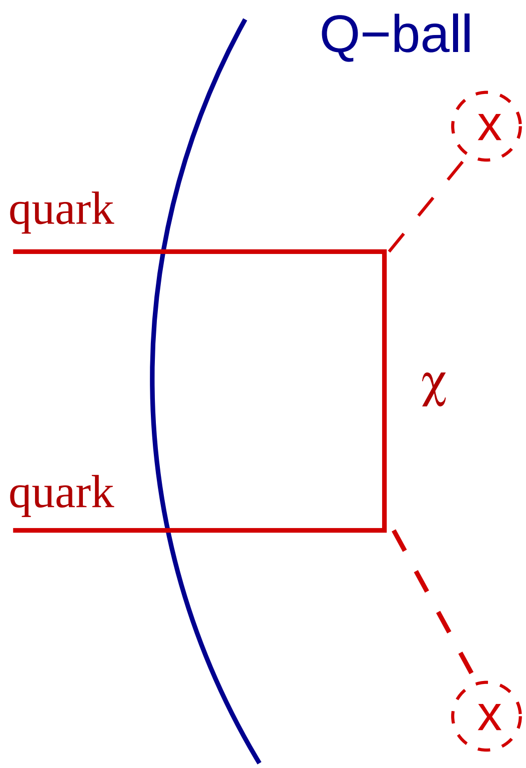
- SUSY Q-balls accumulate inside white dwarfs and neutron stars
- SUSY Q-balls can convert nuclear matter into squark condensate
  - first published estimates underestimated the rates
  - new rates too high, unless the **flat direction is lifted by baryon number violating operators**.

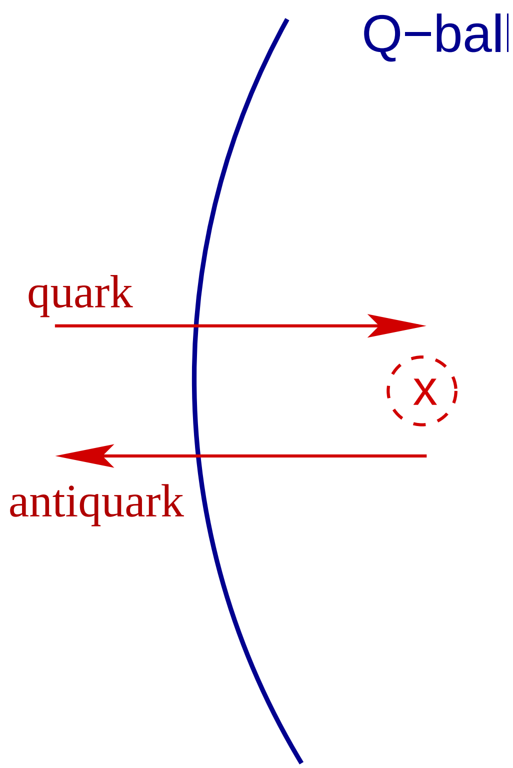
Interactions of SUSY Q-balls with matter (old picture)



$\propto \frac{1}{m_{\chi}^{2}}$, slow

This process was thought to limit the rate at which the Q-balls could process baryonic matter. Lifetimes of neutron stars were though to be greater than the age of the universe

Interactions of SUSY Q-balls with matter (correct picture)



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].

Interactions of SUSY Q-balls with matter

The MSSM Lagrangian contains terms describing interactions of quarks ψ with squarks ϕ and gluinos λ:

$$\mathcal{L} = -g\sqrt{2}T^a_{ij}(\lambda^a\sigma^2\psi_j\phi^*_i) + C.C. + ...$$

and also the Majorana mass terms for gluinos:

$$\mathcal{L}_{\mathcal{M}} = M\lambda_a\lambda_a.$$

Of course, the quarks also have Dirac mass terms.

In the basis $\{\psi_L, \psi_R, \lambda\}$, the mass matrix has a (simplified) form:

$$\begin{pmatrix} 0 & m & \varphi_L \\ m & 0 & \varphi_R \\ \varphi_L & \varphi_R & M \end{pmatrix}$$

The squark fields ϕ grow large inside the Q-ball. This mass term causes a quark to scatter off a Q-ball as an antiquark, with probability of order 1.

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Signatures in detectors do not change significantly

Neutron stars: can they survive long enough?

Pulsars ages: oldest pulsars have $(\dot{P}/P) \sim (0.3 - 3) \times 10^{-10} \mathrm{yr}^{-1}$

Some pulsars are also known to be (at least) as old as **10 Gyr** based on the cooling ages of their white dwarf companions

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Inside a neutron star Q-ball VEV grows fast and reaches values at which the flat direction is lifted by higher-dimension operators

Generally, the lifting terms can be written in the form

$$V^n(\phi)_{\rm lifting} \approx \lambda_n M^4 \left(\frac{\phi}{M}\right)^{n-1+m} \left(\frac{\phi^*}{M}\right)^{n-1-m}$$

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- If $m = 0$, Q-balls change the way they grow after reaching a certain size Q_c.

Q-balls along "Flat" and "Curved" directions

	FD	CD
φ	$\frac{1}{\sqrt{2}}\Lambda Q^{1/4}$	$\varphi_{\max}$
ω	$\pi\sqrt{2}\Lambda Q^{-1/4}$	$\Lambda^2\varphi_{\max}^{-1} = \pi\sqrt{2}\Lambda {Q_c}^{-1/4} = \omega_c$
M	$4\pi\frac{\sqrt{2}}{3}\Lambda Q^{3/4}$	ωQ
R	$\frac{1}{\sqrt{2}\Lambda}Q^{1/4}$	$\left(\frac{3}{8\pi}\frac{1}{\Lambda^2\varphi_{\max}}Q\right)^{1/3} = (\frac{3}{2})^{1/3}(Q/Q_c)^{1/12}R_{FD}$

The change from FD to CD makes the Q-ball grow faster and neutron star is destroyed:

	FD Q-balls	CD Q-balls
t	**10^{10} years**	**1500 years**

Q-balls that go from FD to CD for $\boldsymbol{Q < 10^{57}}$ are ruled out, unless the lifting terms can break the baryon number.

White Dwarfs

White dwarfs can also accumulate SUSY Q-balls. The rate of consumption is lower because of the lower density. Nevertheless, one should consider a possible limit coming from the fact that some very old (10 Gyr) white dwarfs are known to have cooled down to very low temperatures; they emit

$$L_{\rm wd} = 3 \times 10^{-5} L_\odot = 7 \times 10^{28}\, {\rm erg/s}.$$

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Q-balls must not produce more heat than this.

No new limits arise. For $m = 0$, Q-balls are ruled out by stability of neutron stars. For $m \neq 0$, the rate of heat release is much less than $L_{\rm wd}$.

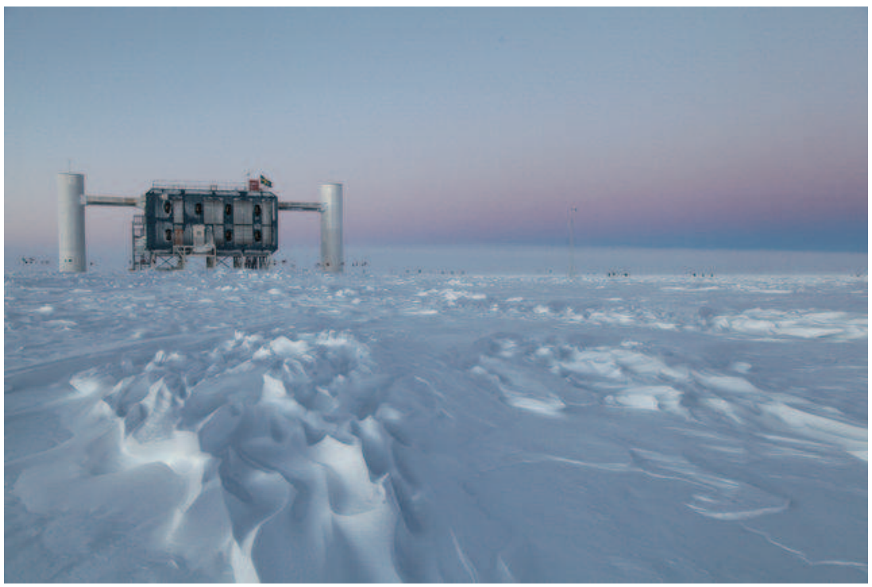
Another caveat: electric charge

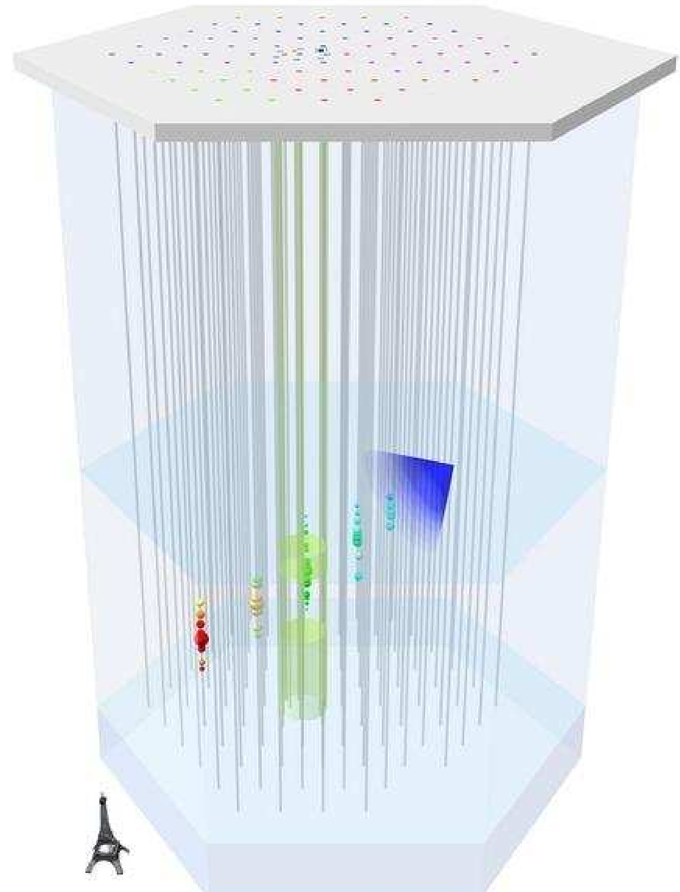
While the flat directions are gauge-invariant, a small number of scalar quanta can decay until kinematically forbidden. [AK,Shoemaker]

This makes DM Q-balls electrically charged. Different signature: small ionization instead of massive pion production.

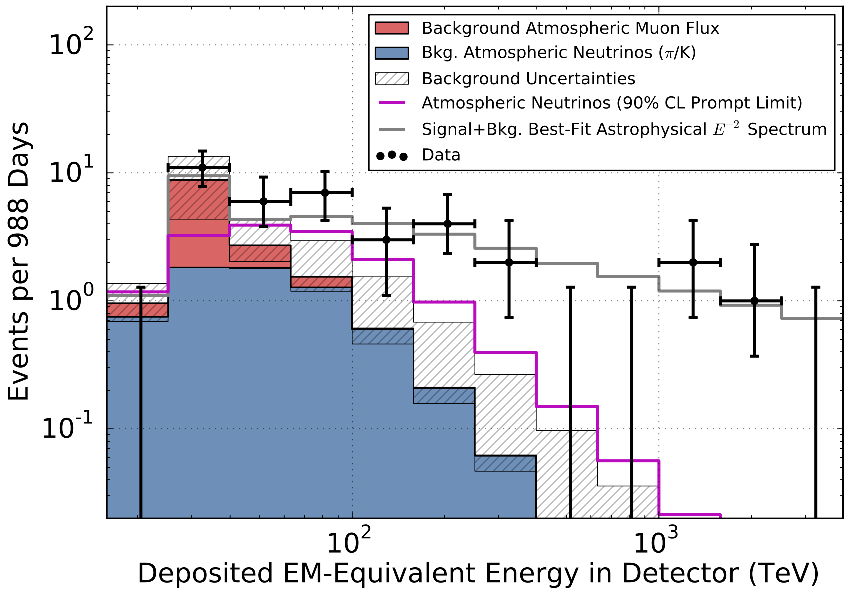
Difficult to detect in Super-K, HAWC, and other large detectors.

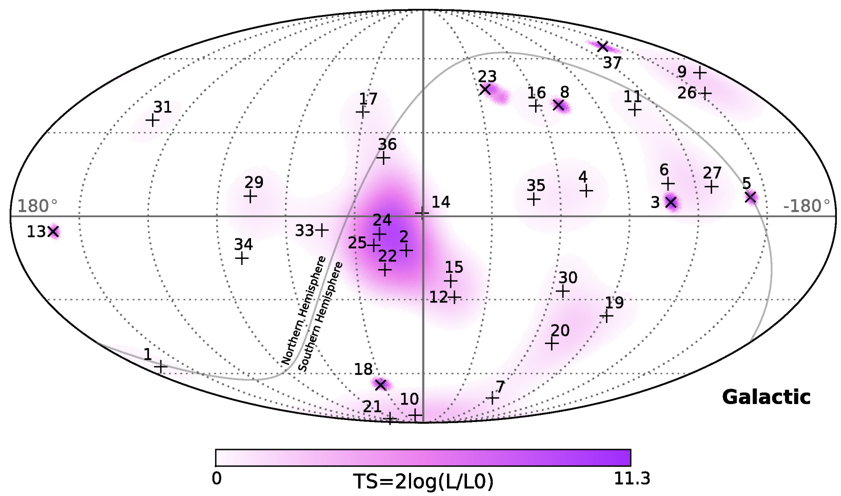
IceCube detector





PeV neutrinos discovered by IceCube



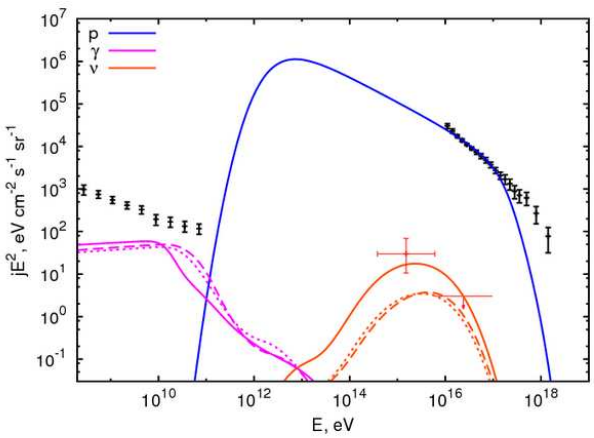


Features: no events at the Glashow resonance; apparently, a peak at $1-2$ PeV;

An astrophysical explanation

A peaked spectrum at 1 PeV can result from cosmic rays accelerated in AGN and interacting with photon backgrounds, assuming that secondary photons explain the observations of TeV blazars.

prediction: PRL **104**, 141102 (**2010**)
consistency with the IceCube 2012 discovery: PRL 111, 041103 (2013)



PRL **104**, 141102 (2010) PHYSICAL REVIEW LETTERS week ending 9 APRIL 2010

Secondary Photons and Neutrinos from Cosmic Rays Produced by Distant Blazars

Warren Essey,[1] Oleg E. Kalashev,[2] Alexander Kusenko,[1,3] and John F. Beacom[4,5,6]

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[2]*Institute for Nuclear Research, 60th October Anniversary Prospect 7a, Moscow 117312 Russia*
[3]*IPMU, University of Tokyo, Kashiwa, Chiba 277-8568, Japan*
[4]*Center for Cosmology and Astro-Particle Physics, Ohio State University, Columbus, Ohio 43210, USA*
[5]*Department of Physics, Ohio State University, Columbus, Ohio 43210, USA*
[6]*Department of Astronomy, Ohio State University, Columbus, Ohio 43210, USA*

(Received 27 December 2009; revised manuscript received 22 February 2010; published 8 April 2010)

Secondary photons and neutrinos produced in the interactions of cosmic ray protons emitted by distant active galactic nuclei (AGN) with the photon background along the line of sight can reveal a wealth of new information about the intergalactic magnetic fields, extragalactic background light, and the acceleration mechanisms of cosmic rays. The secondary photons may have already been observed by gamma-ray telescopes. We show that the secondary neutrinos improve the prospects of discovering distant blazars by IceCube, and we discuss the ramifications for the cosmic backgrounds, magnetic fields, and AGN models.

DOI: 10.1103/PhysRevLett.104.141102 PACS numbers: 95.85.Pw, 98.54.Cm, 98.70.Sa, 95.85.Ry

PRL **111,** 041103 (2013) PHYSICAL REVIEW LETTERS week ending 26 JULY 2013

PeV Neutrinos from Intergalactic Interactions of Cosmic Rays Emitted by Active Galactic Nuclei

Oleg E. Kalashev,[1] Alexander Kusenko,[2,3] and Warren Essey[2]

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(Received 28 February 2013; revised manuscript received 14 June 2013; published 24 July 2013)

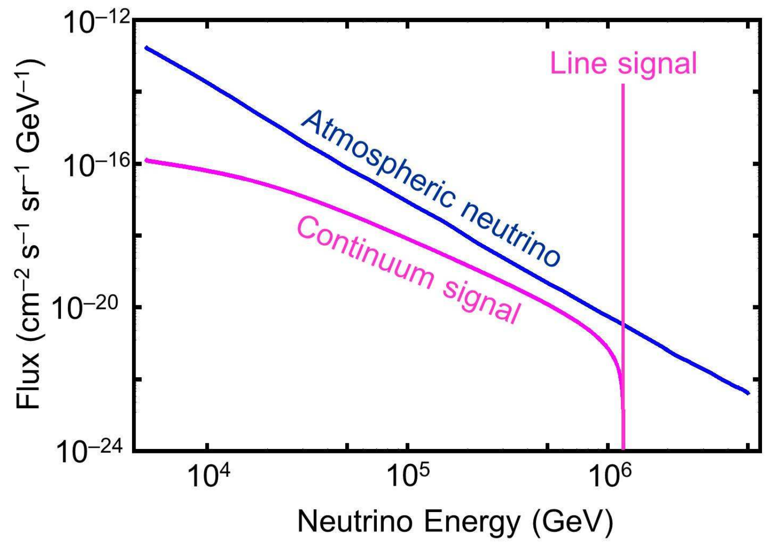
The observed very high energy spectra of *distant* blazars are well described by secondary gamma rays produced in line-of-sight interactions of cosmic rays with background photons. In the absence of the cosmic-ray contribution, one would not expect to observe very hard spectra from distant sources, but the cosmic ray interactions generate very high energy gamma rays relatively close to the observer, and they are not attenuated significantly. The same interactions of cosmic rays are expected to produce a flux of neutrinos with energies peaked around 1 PeV. We show that the diffuse isotropic neutrino background from many distant sources can be consistent with the neutrino events recently detected by the IceCube experiment. We also find that the flux from any individual nearby source is insufficient to account for these events. The narrow spectrum around 1 PeV implies that some active galactic nuclei can accelerate protons to EeV energies.

DOI: 10.1103/PhysRevLett.111.041103 PACS numbers: 95.85.Ry, 98.54.Cm, 98.70.Sa

A more exciting possibility: decaying dark matter

Dark matter with mass $\gtrsim 2$ PeV

$$X \to \nu + \text{SM particle}$$



[Feldstein, AK, Matsumoto, Yanagida]

Models of very heavy dark matter decaying into PeV neutrinos

- Gravitino with R-parity violation
- Hidden sector gauge boson
- A singlet in extra dimension
- A right-handed/sterile neutrino
- ...

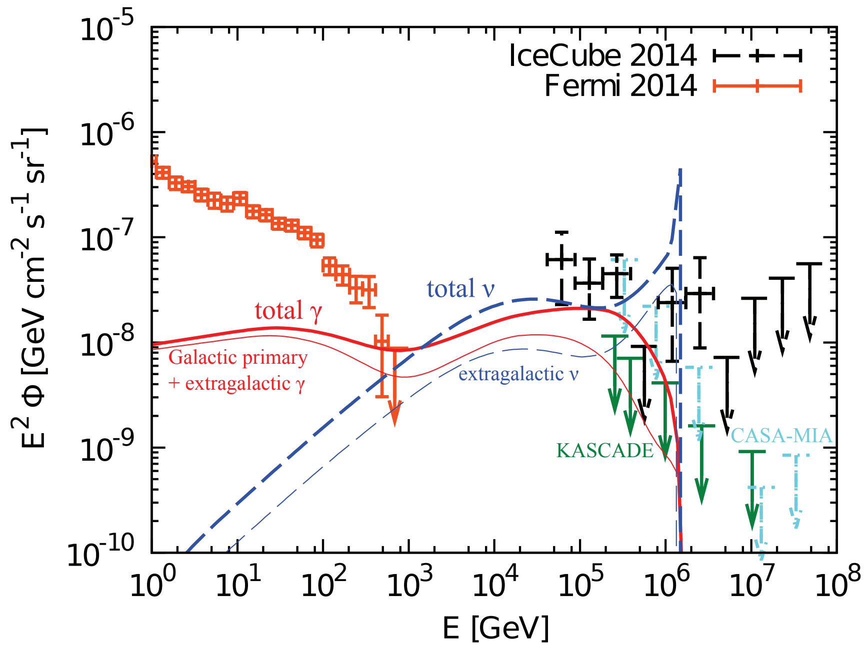
Case	Spin	$SU(2)_L$	$U(1)_Y$	Decay Operator
1.	0	3	1	$\bar{L}^c \phi L$
2.	1/2	0	0	$\bar{L} H^c \psi$
3.	1/2	3	0	$\bar{L} \psi^a \tau^a H^c$
4.	1/2	2	$-1/2$	$\bar{L} F \psi$
5.	1/2	3	-1	$\bar{L} \psi^a \tau^a H$
6.	1	0	0	$\bar{L} \gamma_\mu V^\mu L$
7.	3/2	0	0	$(\bar{L} i D_\mu H^c) \gamma^\nu \gamma^\mu \psi_\nu$

[Feldstein, AK, Matsumoto, Yanagida]

Models/discussion: Feldstein et al., Esmaili & Serpico, Bhattacharya et al., Ahlers

Model-dependent gamma-ray constraints

The dark matter explanation is consistent with multimessenger observations and limits.
These constraints are model-dependent, but common features exist in the spectra.



[Murase et al.]

Need more data, especially from *IceCube-Gen2* !

Conclusions

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Conclusions

- Very heavy dark matter is a well-motivated possibility.
- SUSY + Inflation $\Rightarrow$ Q-balls, some may be stable, may be dark matter
- Typical size large $\Rightarrow$ typical density small $\Rightarrow$ need large detectors to search for relic Q-balls
- IceCube discovery of PeV neutrinos could point to a very heavy relic particle decay. (However, astrophysical explanations are possible and plausible.)