CP violation and cosmology

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- CP and the origin of baryon asymmetry

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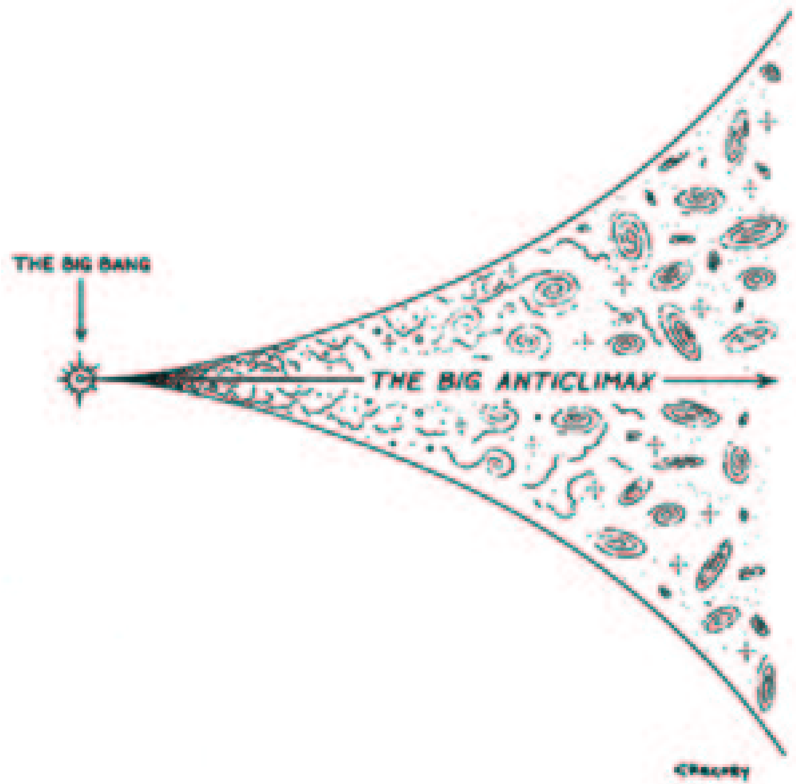

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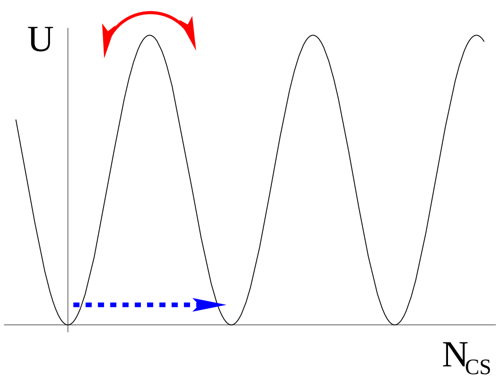
All three conditions are satisfied in the Standard Model (to some extent)

- B violation



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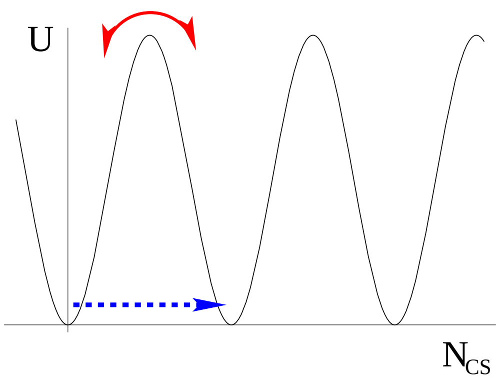

Instantons violate B with
$\sigma \propto e^{-4\pi/\alpha} \sim 10^{-170}$
(tunneling)
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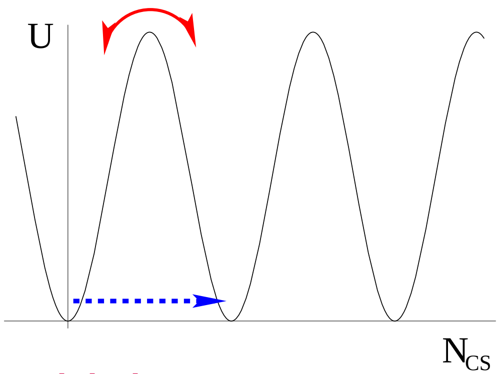

Instantons violate B with $\sigma \propto e^{-4\pi/\alpha} \sim 10^{-170}$ (tunneling) too small!

At high temperature transitions occur via sphalerons, over the barrier. No suppression!

In the Standard Model

- $\mathbf{B}$ violation
- $\mathbf{B}, \mathbf{C}, \mathbf{CP}$ not conserved
- universe out of equilibrium at EW phase transition

ELECTROWEAK BARYOGENESIS!

[Kuzmin, Rubakov, Shaposhnikov ’85]

Unfortunately, EW baryogenesis in the SM does not work.

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Can SUSY help? (More scalar fields, more parameters...)

Thermal electroweak baryogenesis in the MSSM

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- light stop ⇒ stronger phase transition
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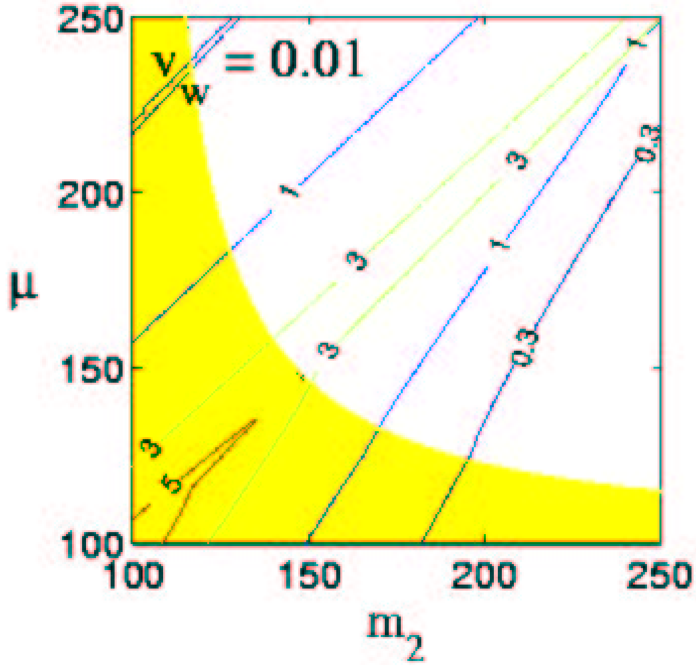
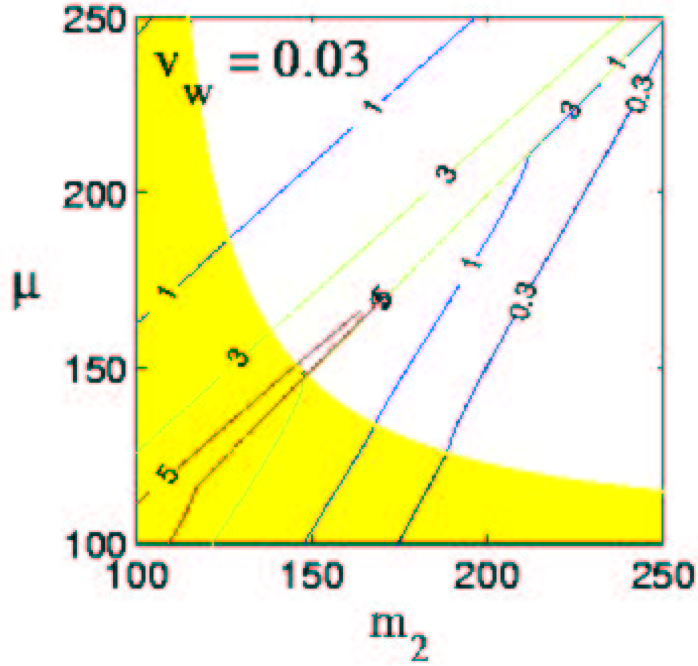
$$\overline{\psi}_R M_\chi \psi_L = (\overline{\widetilde{w}^+}, \overline{\widetilde{h}_2^+})_R \begin{pmatrix} m_2 & gH_2(x) \\ gH_1(x) & \mu \end{pmatrix} \begin{pmatrix} \widetilde{w}^+ \\ \widetilde{h}_1^+ \end{pmatrix}_L + \mathrm{h.c.}$$

m_2 and μ are complex ⇒ spatially varying complex phases in the wall

Contours of baryon asymmetry in units 10^{-10} [Cline,Joyce,Kainulainen]. Shaded limits are excluded by LEP2 limits on chargino mass, $m_{\chi^{\pm}} > 104$ GeV.





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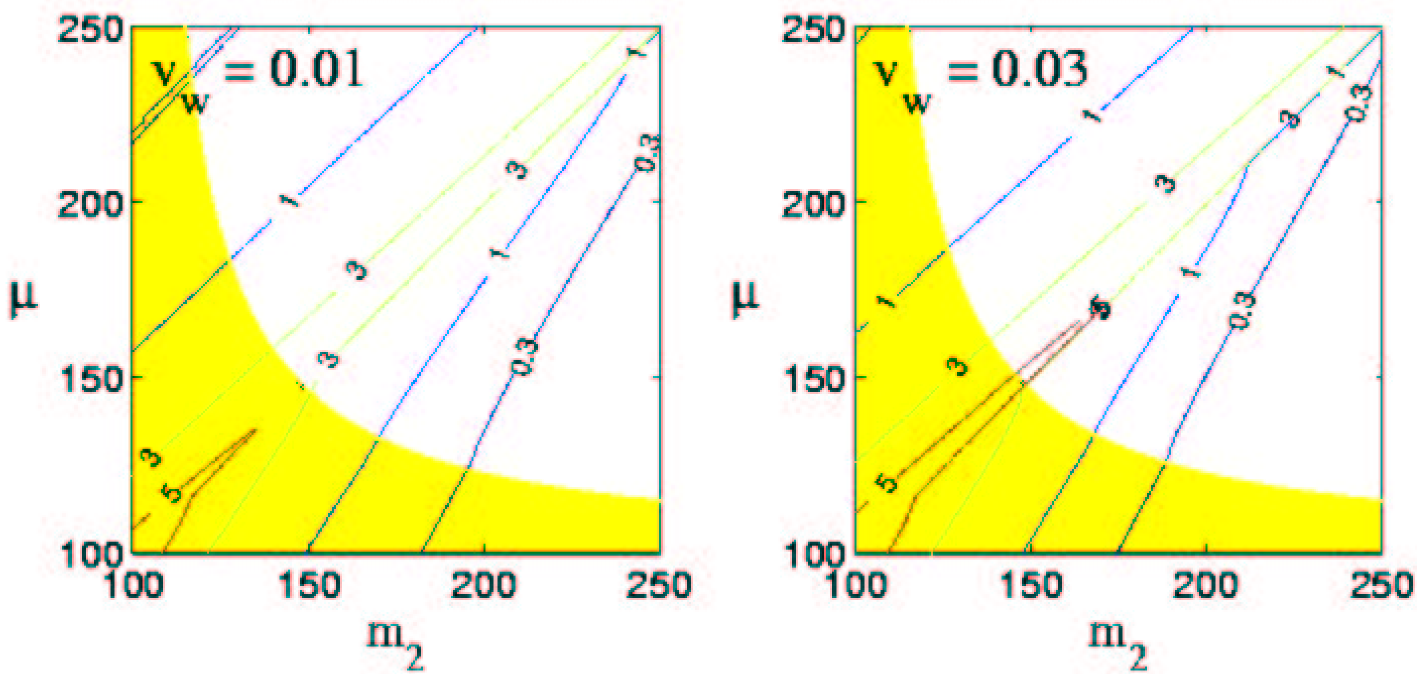

Assumptions: $\mathbf{\tan\beta \lesssim 3}$; “optimal” wall velocity $\boldsymbol{v_w \approx 0.02}$; *very thin* wall, $\boldsymbol{l_w \approx 6/T}$.

EW baryogenesis in the MSSM will be ruled out with (any!) improvement of bounds on the lightest Higgs mass, and also if the light stop is ruled out. Alternatively, MSSM may soon be discovered.

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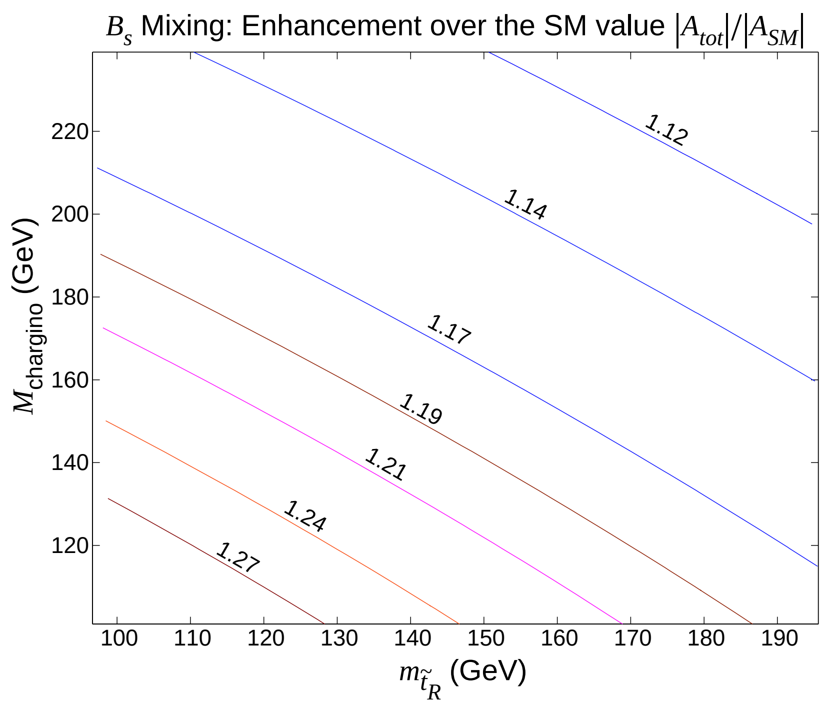

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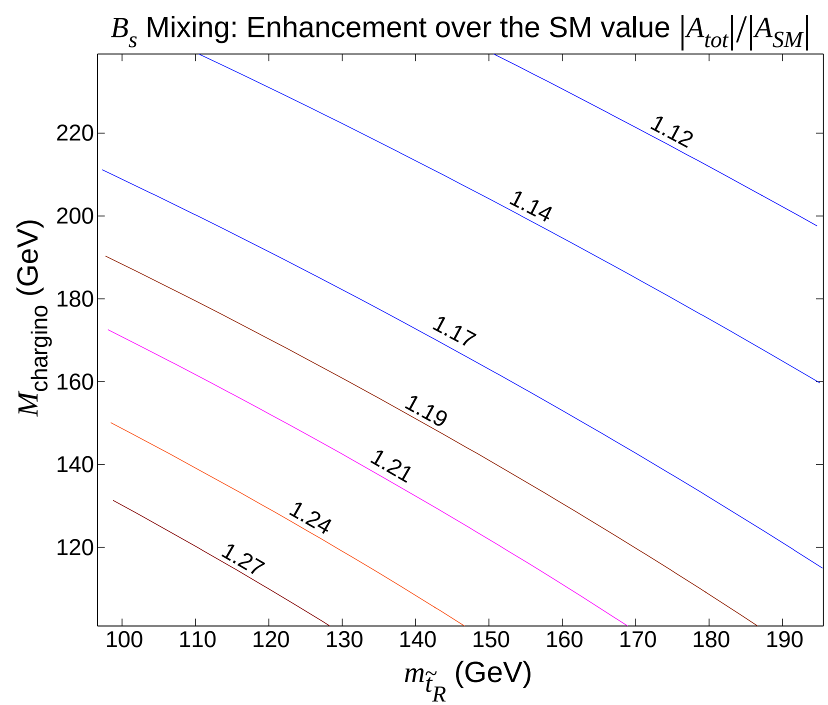

But need to know V_{ub} to **5-10%**

and $\sin 2\beta$ to **a few %**

Leptogenesis

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CP violation in the neutrino mass matrix? [Kayser]

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- Affleck-Dine baryogenesis
- electroweak baryogenesis at preheating

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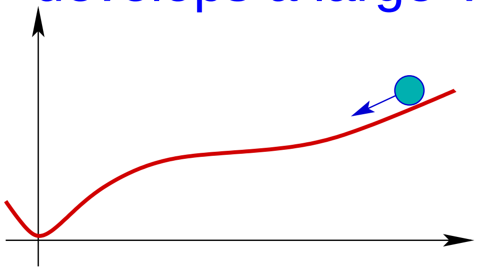

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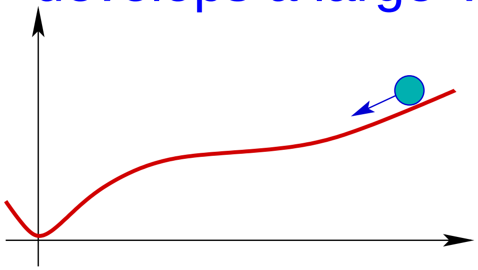

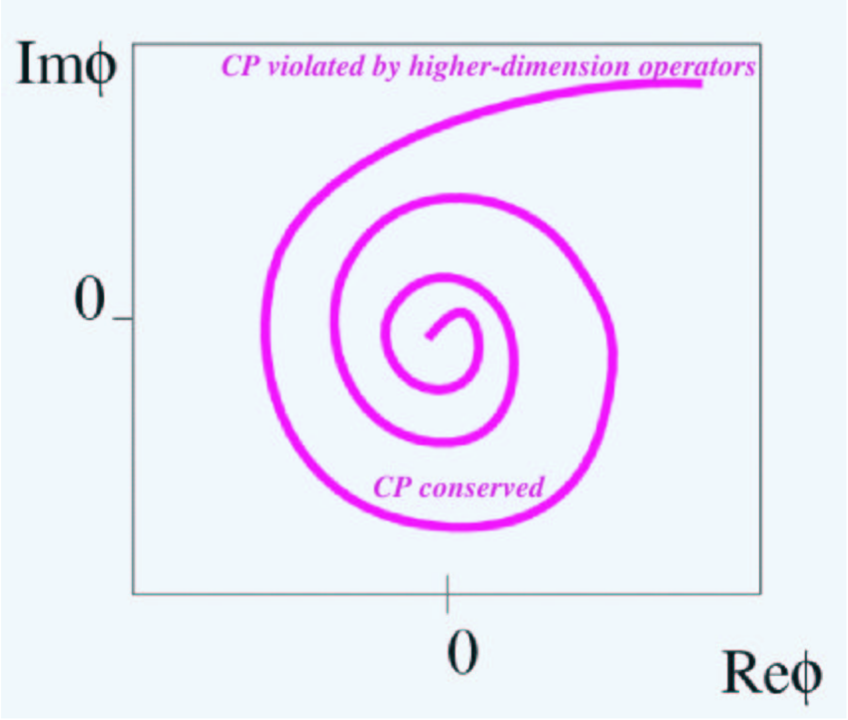

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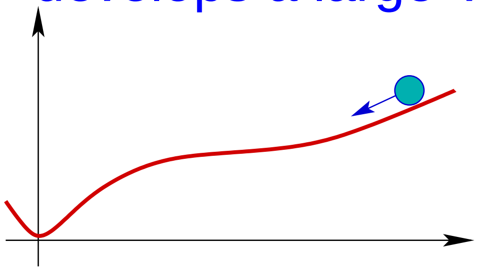
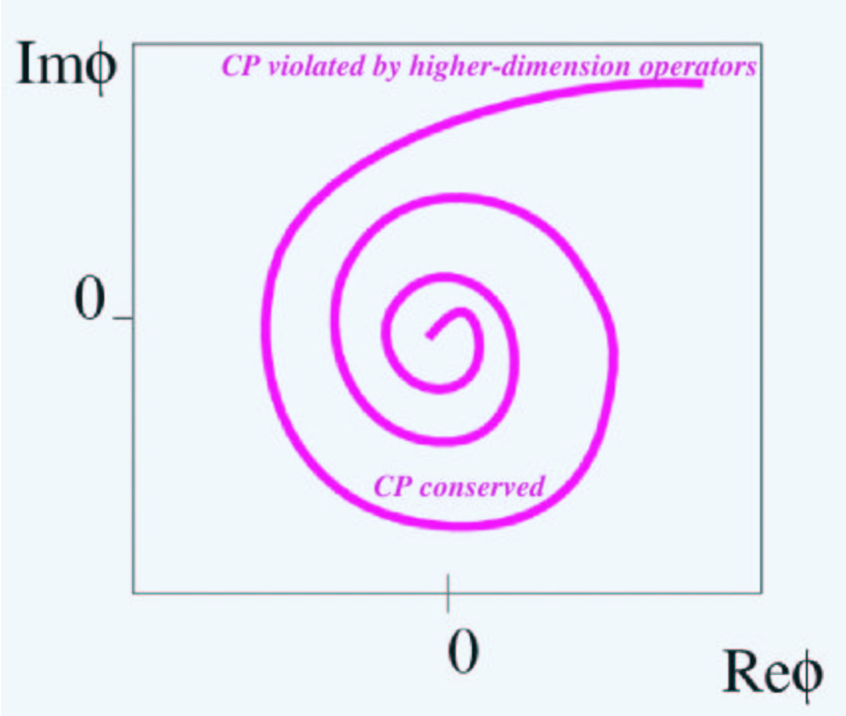


CP violation is due to time-dependent background.



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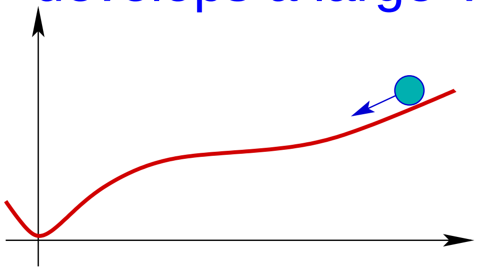

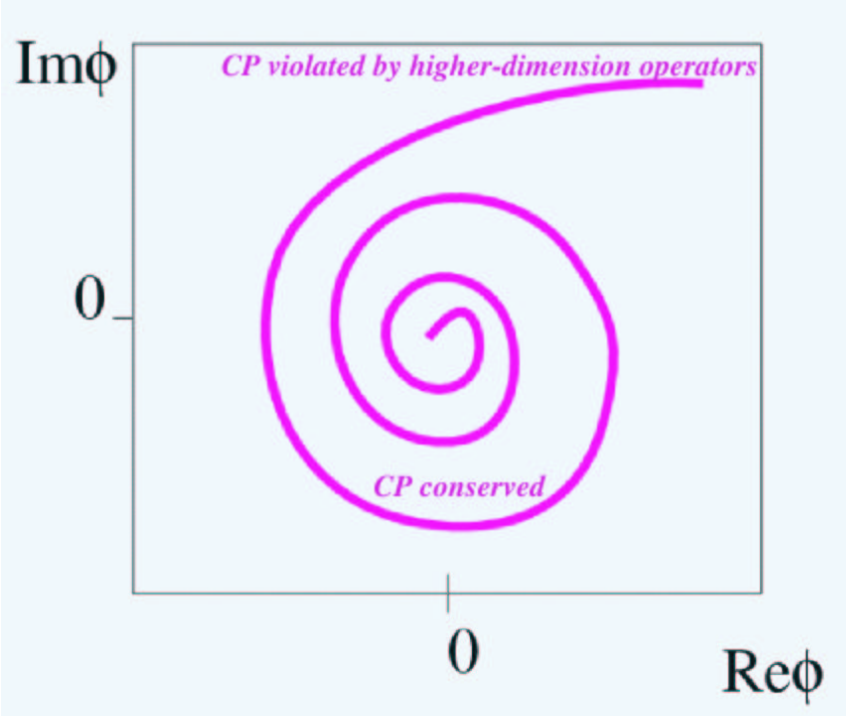

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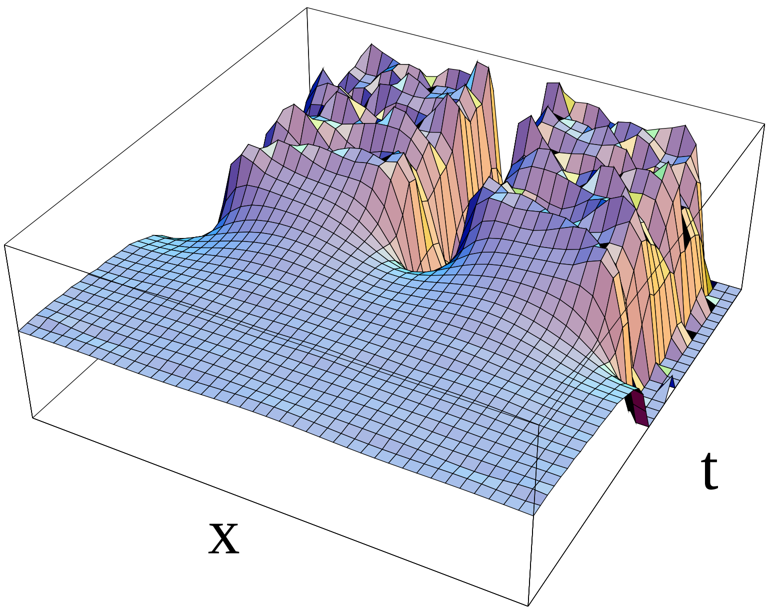
CP violation seed – from high-scale physics

Fragmentation of Affleck-Dine condensate can produce Q-balls



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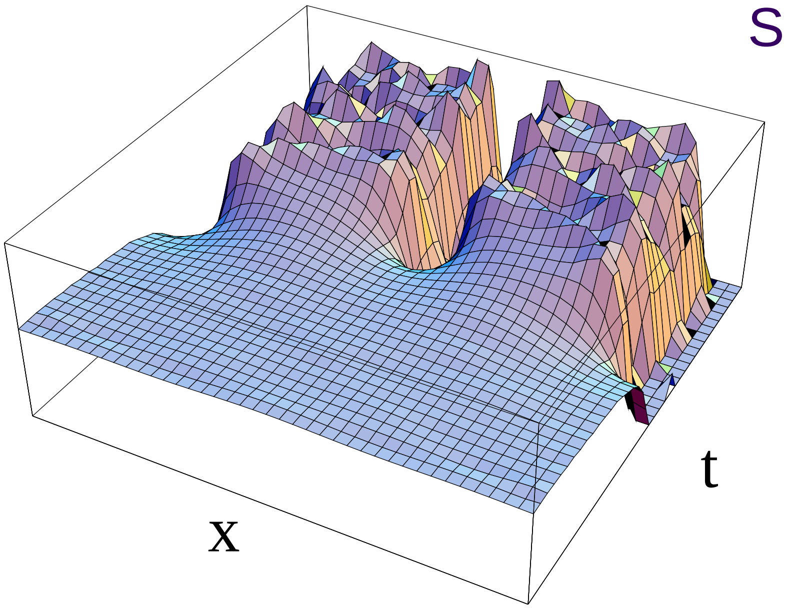

SUSY Q-balls may be stable or unstable

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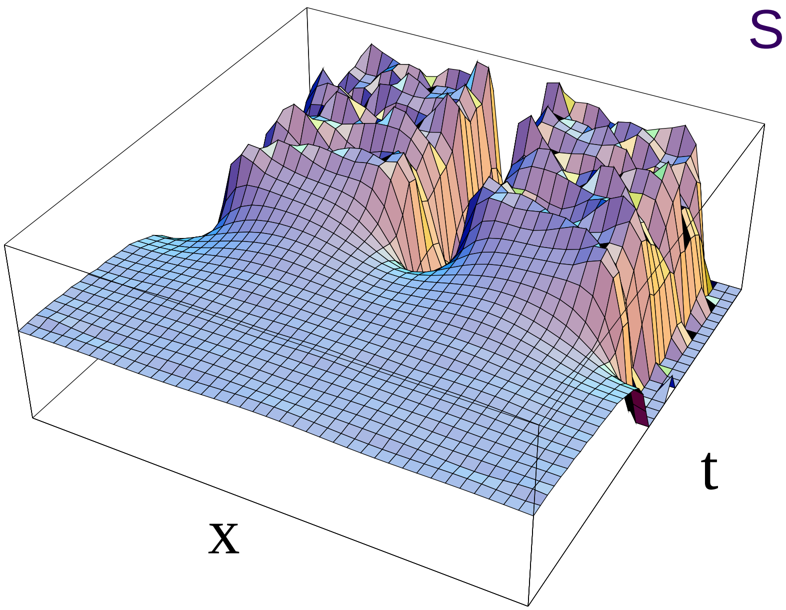

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if stable ⇒ **dark matter**

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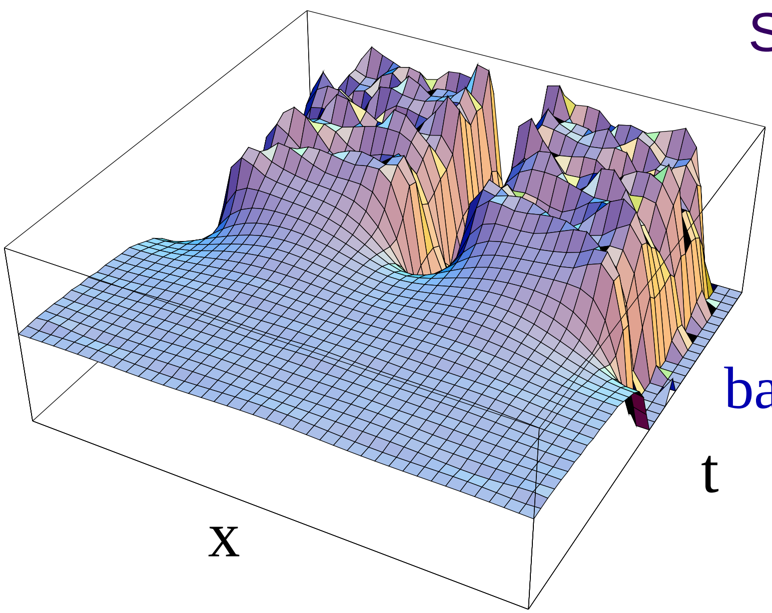

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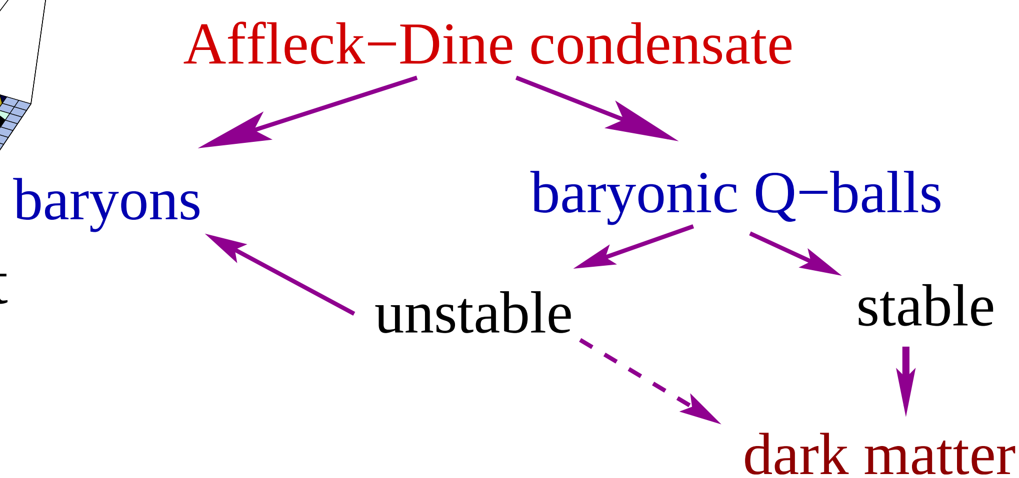

[AK, Shaposhnikov]

EW baryogenesis at preheating

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Inflation probably took place in the early universe

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At the end of inflation, the problems disappear:

- Preheating following inflation is a period when the universe is very far from thermal equilibrium
- Time-dependent scalar condensate, coherent on large scales, creates a CP non-invariant background sufficient for generating $\eta \sim 10^{-10}$.
- Wash-out of baryon asymmetry can be prevented if the reheat temperature is below electroweak transition temperature

⇒ EW baryogenesis at preheating

Krauss, Trodden
García-Bellido,Grigoriev,
AK,Shaposhnikov

$\Rightarrow$ EW baryogenesis at preheating

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Inflation $\rightarrow$ Reheating $\rightarrow$ equilibrium T_R

If $T_R < T_c \approx 100\mathrm{GeV}$, sphaleron transitions are suppressed when the system reaches equilibrium

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Can B-violating transitions similar to sphalerons take place during reheating?

-Yes. Preheating pumps energy into long-wavelength modes that make sphaleron-like transitions possible.

Parametric resonance:

Equation of motion for the Higgs has growing solutions:

$$\ddot{\phi}_k + [k^2 - M^2 + 3\lambda\langle\phi^2\rangle + g^2\sigma^2(t)]\phi_k = 0$$

Energy flow: Inflaton → Higgs → W,Z,...sphalerons?

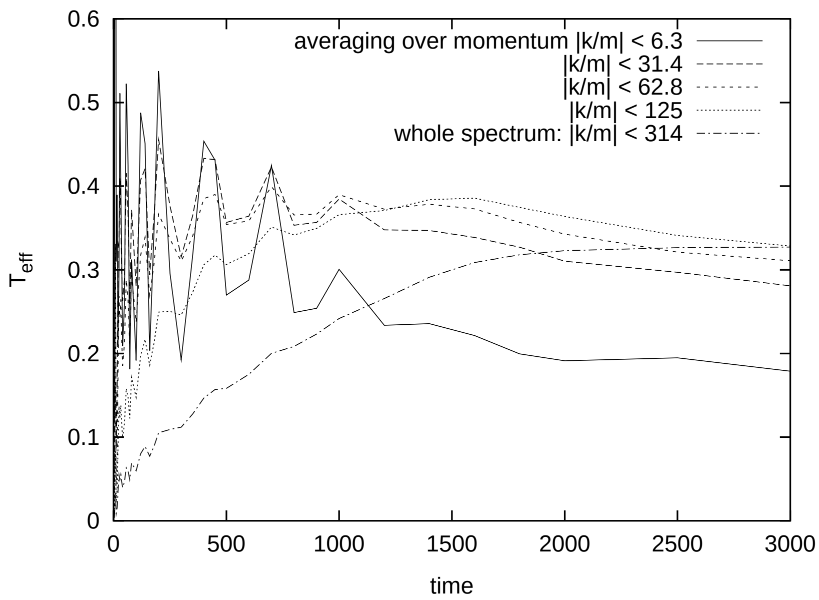
Estimate: $\Gamma_{\rm sph} \approx \alpha_W^4 T_{\rm eff}^4$ ($T_{\rm eff}$ from the low-energy modes)

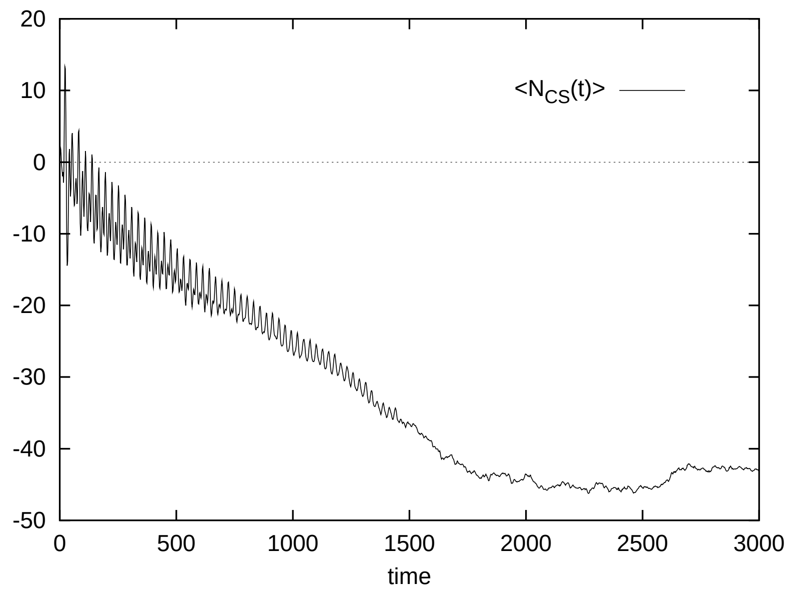
This estimate agrees with numerical simulations in 1+1 dimensions

García-Bellido,Grigoriev,
AK,Shaposhnikov
Phys.Rev.D60:123504,1999

Also, approximate analytical description [AK, Cornwall]

Numerical model





U(1) gauge field A_μ plus Higgs filed ϕ. C,CP violation introduced by term $\kappa\,\phi^*\phi\,\epsilon_{\mu\nu}F^{\mu\nu}$. In 1+1, the analogue of anomaly is $\partial_\mu j^\mu_F = -\frac{e}{4\pi}\,\epsilon_{\mu\nu}F^{\mu\nu}$, where $j^\mu_F = \bar\psi\gamma^\mu\psi$

possible seeds of CP violation

- **strong CP violation in the standard Model**, which vanishes in the present vacuum, may be inducted at the time of preheating and may provide a sufficient CP-violating background for baryogenesis via the coupling

$$\eta' \frac{1}{32\pi^2} \mathrm{Tr}\, G_{\mu\nu}\tilde{G}^{\mu\nu}$$

- **CP violation in the Higgs sector**
- **higher derivative terms**

Spontaneous baryogenesis at preheating

Cohen, Kaplan and Nelson: in a two Higgs doublet model, the Higgs field $H(x)$ in the bubble wall breaks CP. Similar (but more effective!) scenario at preheating: $H(x) \to H(t)$ [Cornwall,Grigoriev,AK] .

Higgs potential:

$$
\begin{aligned}
V(H_1, H_2) &= \lambda_1 (H_1^\dagger H_1 - v_1^2)^2 \\
&+ \lambda_2 (H_2^\dagger H_2 - v_2^2)^2 \\
&+ \lambda_3 [(H_1^\dagger H_1 - v_1^2) + (H_2^\dagger H_2 - v_2^2)]^2 \\
&+ \lambda_4 [(H_1^\dagger H_1)(H_2^\dagger H_2) - (H_1^\dagger H_2)(H_2^\dagger H_1)] \\
&+ \lambda_5 [\mathrm{Re}(H_1^\dagger H_2) - v_1 v_2 \cos\xi]^2 \\
&+ \lambda_6 [\mathrm{Im}(H_1^\dagger H_2) - v_1 v_2 \sin\xi]^2
\end{aligned}
$$

At finite temperature, all λ_k and v_i receive thermal corrections and depend on the temperature. During preheating the Higgs fields move along classical trajectory

$$H_i = \rho_i(t) e^{i\theta_i(t)}$$

that satisfies the equations of motion

$$\begin{aligned} \ddot{\theta}_i + 3h\dot{\theta}_i + \frac{\dot{\rho}_i}{\rho_i} + \rho_i^{-1}\frac{\partial V}{\partial \theta_i} &= 0, \\ \ddot{\rho}_i + 3h\dot{\rho}_i - \dot{\theta}_i^{\,2}\rho_i + \frac{\partial V}{\partial \rho_i} &= 0, \end{aligned}$$

During preheating, the Higgs fields change from their zero-temperature values at the end of inflation to some temperature-dependent VEV:

$$\begin{aligned} \text{at } T &= 0, \ \ \rho_i = v_i; \\ \text{at } T &= T_{_R}, \ \ \rho_i = v_i(T_{_R}). \end{aligned}$$

At the same time, the phase θ also changes:

$$\begin{aligned} \theta(0) &\equiv \theta_1(0) - \theta_2(0) = \xi, \\ \theta(T_{_R}) &\equiv \theta_1(T_{_R}) - \theta_2(T_{_R}) = \xi(T_{_R}). \end{aligned}$$

The time derivative of θ serves as a chemical potential for the fermion number because of an effective coupling

$$(\partial_0 \theta) \, [\bar{\psi} \gamma^\mu \psi + ...]$$

B violation much faster than thermalization $\Rightarrow$ baryon number has time to equilibrate to min of free energy

The effective chemical potential μ_B is proportional to $\dot{\theta}$, and the equilibrium value of baryon asymmetry is

$$n_B \sim \langle\dot{\theta}\rangle T_R^2 \sim 10^{-10}\, T_R^3 \left(\frac{10^{-5} t_H}{t_R}\right)$$

where t_R is the time of reheating and t_H is the Hubble time at the electroweak scale

Cohen,Kaplan,Nelson: $H(x)$ and n_B far from equilibrium value. CGK: $H(t)$ and n_B close to instantaneous equilibrium

Too much CP violation...

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$$\bar{\theta} = \theta + \arg \det M$$

Experiment: $|\bar{\theta}| \ll 10^{-10}$!

Possible solution: Peccei-Quinn symmetry

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An elegant solution: $\bar{\theta}$ relaxes to zero dynamically, by a VEV of the **axion** .

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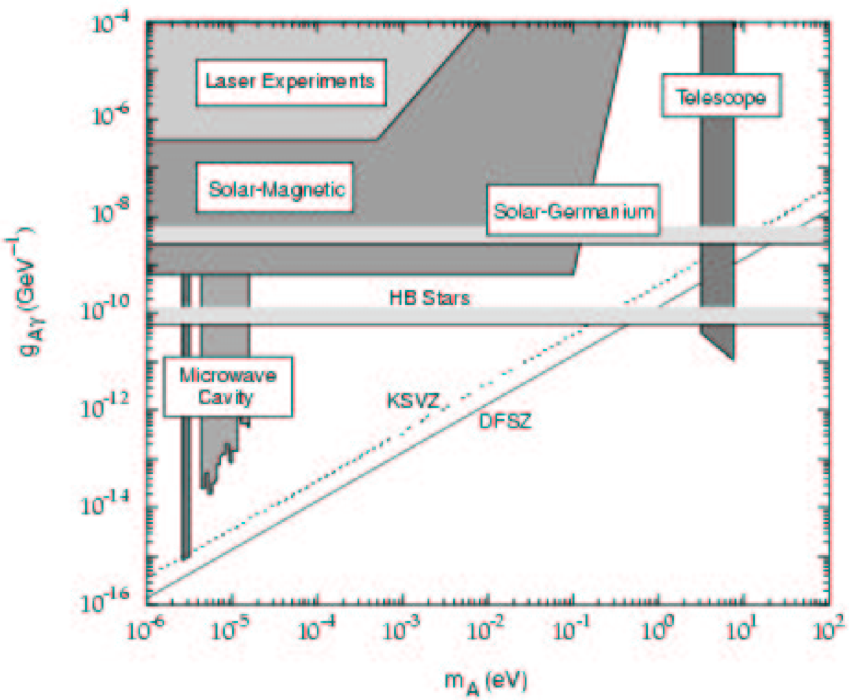
Axion is a weakly interacting particle $\Rightarrow$ **dark matter**

Axion dark matter



Conclusion

CP violation may be the reason we exist... if it is big enough

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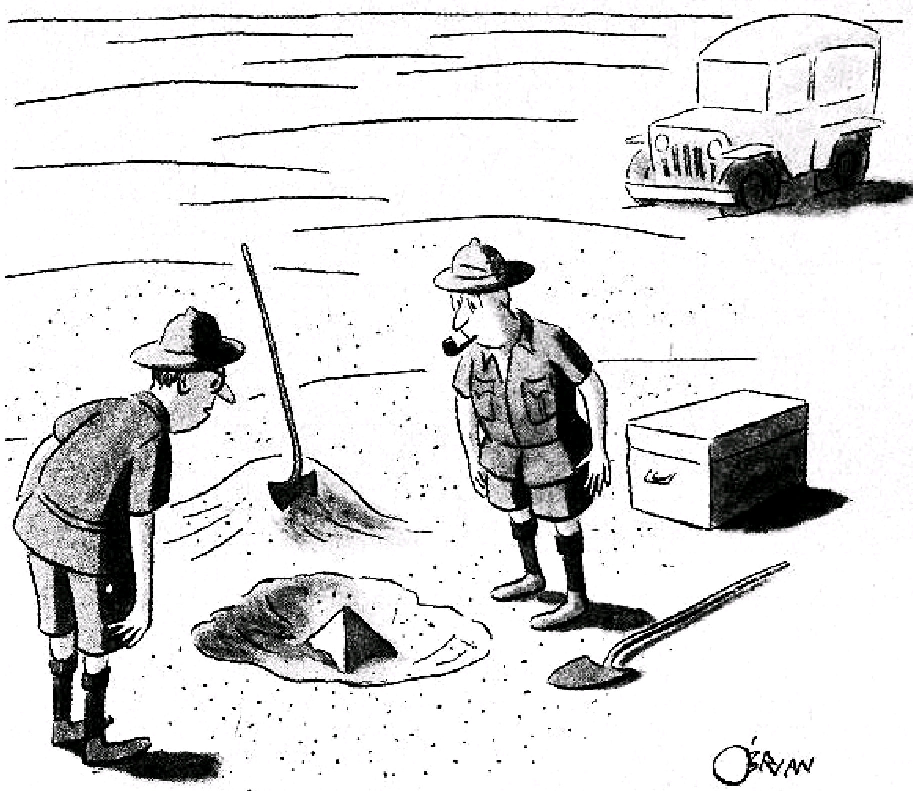

This could be the greatest discovery of the century. Depending, of course, on how far down it goes.