Some Important Questions

- What's the rate of B violation in the hot, $\phi = 0$ phase?

- What is the order and strength of the electroweak phase transition?

The hot B violation rate

dimensional analysis:

$$\Gamma \equiv \frac{\text{rate}}{\text{volume}} = \text{something} \cdot T^4$$

Result used for years in literature:

$$\Gamma = \# \alpha_w^4 T^4$$

($\#$ ← non-perturbative)

Correct analysis: (Arnold, Son + Yaffe

$$\Gamma = \# \alpha_w^5 T^4$$

($\#$ ← non-perturbative)

How to measure #?

Simulate classical thermal field theory on a spatial lattice.

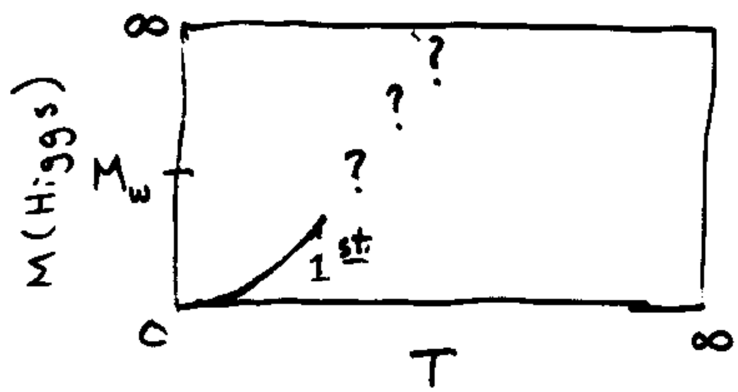
Difference between classical and quantum theories is perturbatively calculable. (Arnold '97)

The measurement (1 week old!):

$$\Gamma = (29 \pm 6) \alpha_w^5 T^4$$ (Moore, Hu, Müll

The Electroweak Phase Diagram

Perturbation theory gives:

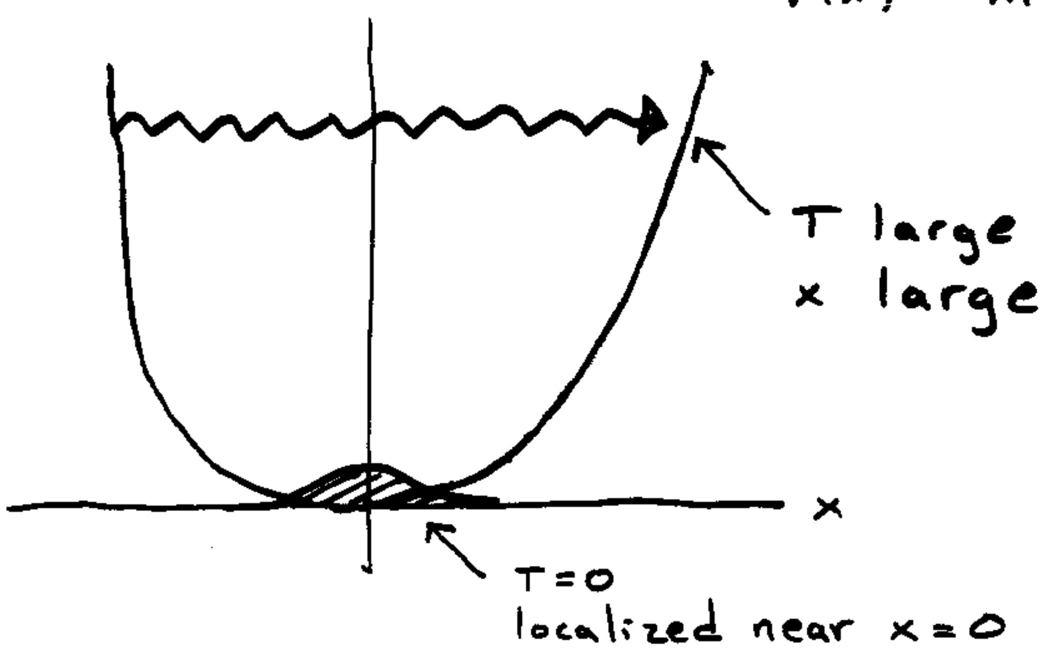


How can perturbation theory fail?

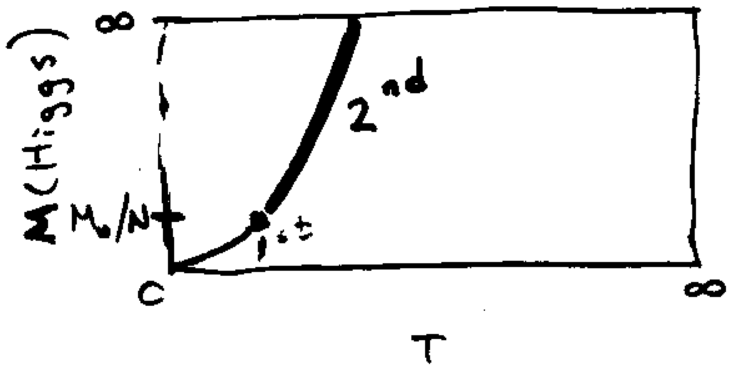
Example: very slightly anharmonic oscillator

$$V(x) \sim m^2 x^2 + \lambda x^4$$

λ small!!



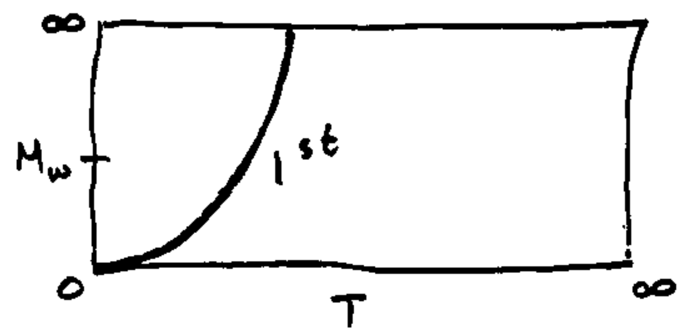
Large N: $N = \#$ Higgs doublets



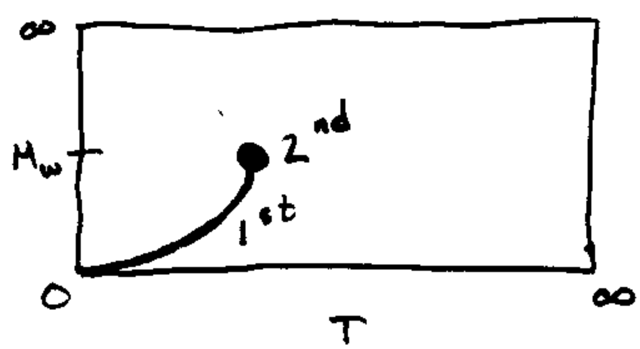
ε expansion:

$d = 3$ spatial dims.

$\rightarrow d = 4 - \varepsilon$ spatial dims. $(\varepsilon \ll 1)$



Lattice data:



One Reason Why CP Violation is Way Radically Cool

Observation: There are more baryons in the universe than anti-baryons.*

Or... the net baryon number is non-zero

$$B > 0.$$

Or, more meaningfully,

$$n_B > 0.$$

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* at least on the scale of the galactic cluster.

Quantifying B density of universe (n_B)

When $T \gg m(\text{proton})$,

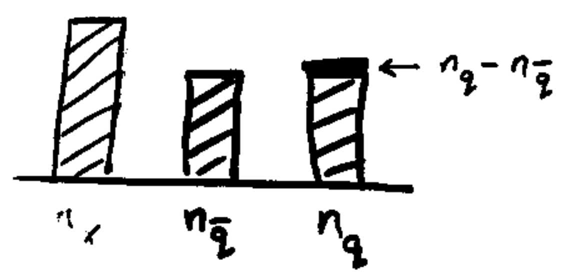
$$\gamma\gamma \rightleftharpoons q\bar{q}$$

causes

$$n_q \sim n_{\bar{q}} \sim n_\gamma \sim n \text{ (anything else)}.$$

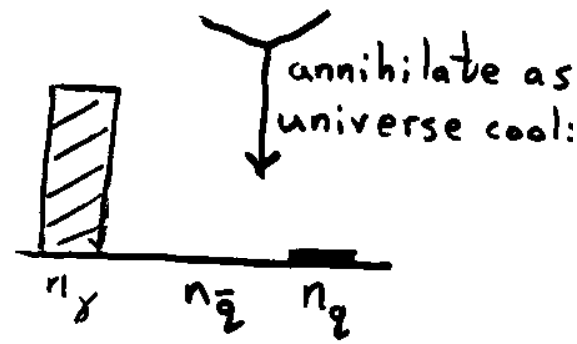
Suppose

$T \gg m(\text{proton})$:



Then

$T \ll m(\text{proton})$:



$$\frac{n_B - n_{\bar{B}}}{n_B}\text{(Early universe)} \sim \frac{n_B - n_{\bar{B}}}{n_\gamma}\text{ (Early universe)}$$

$$\sim \frac{n_B}{n_\gamma}\text{ (Today)}$$

$$\sim 10^{-9}$$

Why did the early universe have

1,000,000,001 quarks

for every 1,000,000,000 anti-quarks?

If B is exactly conserved, then

> There is **no** explanation.
> It's just an initial condition.

Sakharov's three conditions for baryogenesis

(1) B violation

(2) C and CP violation

(3) disequilibrium

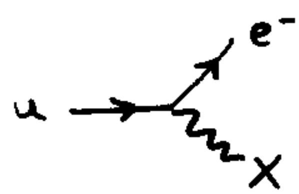
In equilibrium, there's no arrow of time, so CPT gives

distribution (baryons) = distribution (anti-baryons)

$$N_B = N_{\bar{B}}$$

GUT Baryogenesis

B violation:



- explicit B violation
- unsuppressed for $k_B T \gtrsim M_X \sim 10^{16}$ GeV

CP violation:

Usual CKM stuff plus extra GUT stuff

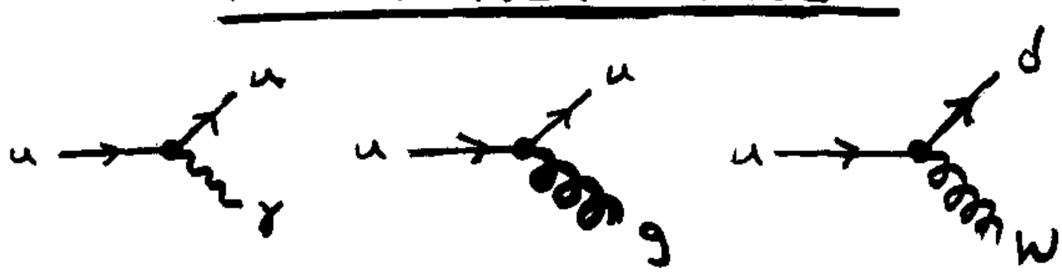
Disequilibrium:

Rapid expansion of universe at $k_B T \sim 10^{16}$ GeV.

☹ Not yet any direct evidence for GUTs (proton decay, magnetic monopoles)

☹ Need accelerator $10^{13} \times$ (Tevatron) to probe all parameters.

The Standard Model



B violation? Absurd!

BUT...

(1) B is an <u>anomalous</u> symmetry of the Standard Model.

Other examples:
- scaling violation at high energy
- $\pi^0 \to \gamma\gamma$

(2) B is violated only by <u>non-perturbative</u> electroweak processes.

Under normal conditions:

$$\text{rate} \sim e^{-4\pi/\alpha_w} \sim 10^{-170} = \text{zero.}$$

At very high temperature $(T \gg M_w/\alpha_w)$ rate is unsuppressed!

Electroweak Phase Transition

Example: a ferromagnet

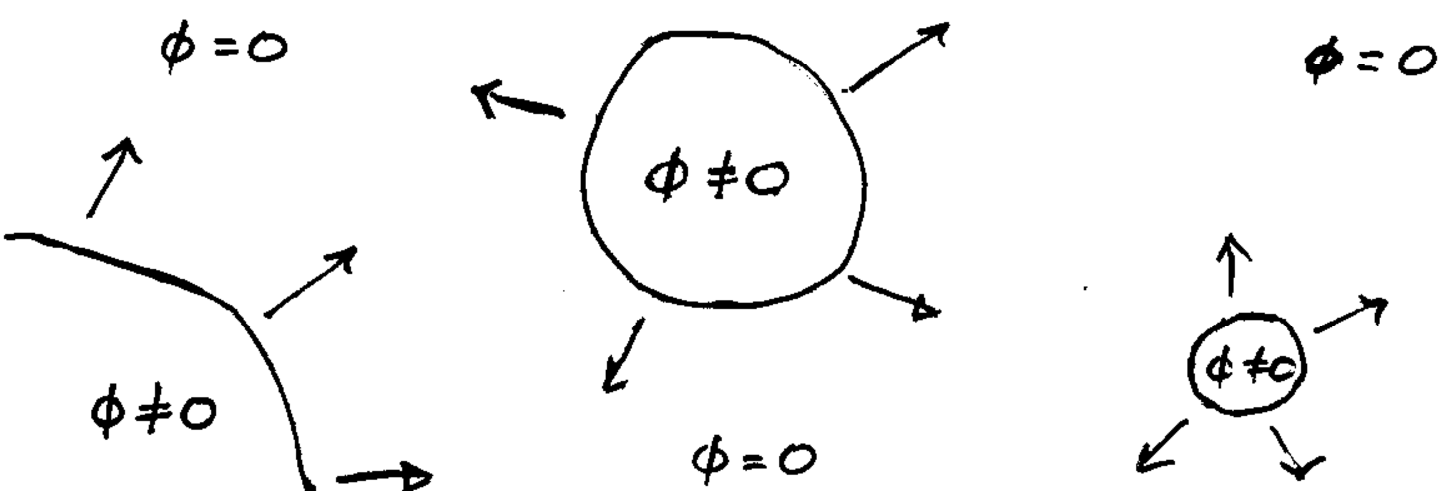
low T: $\langle M \rangle \neq 0$ rotational invariance brok
high T: $\langle M \rangle = 0$ rotational invariance resto

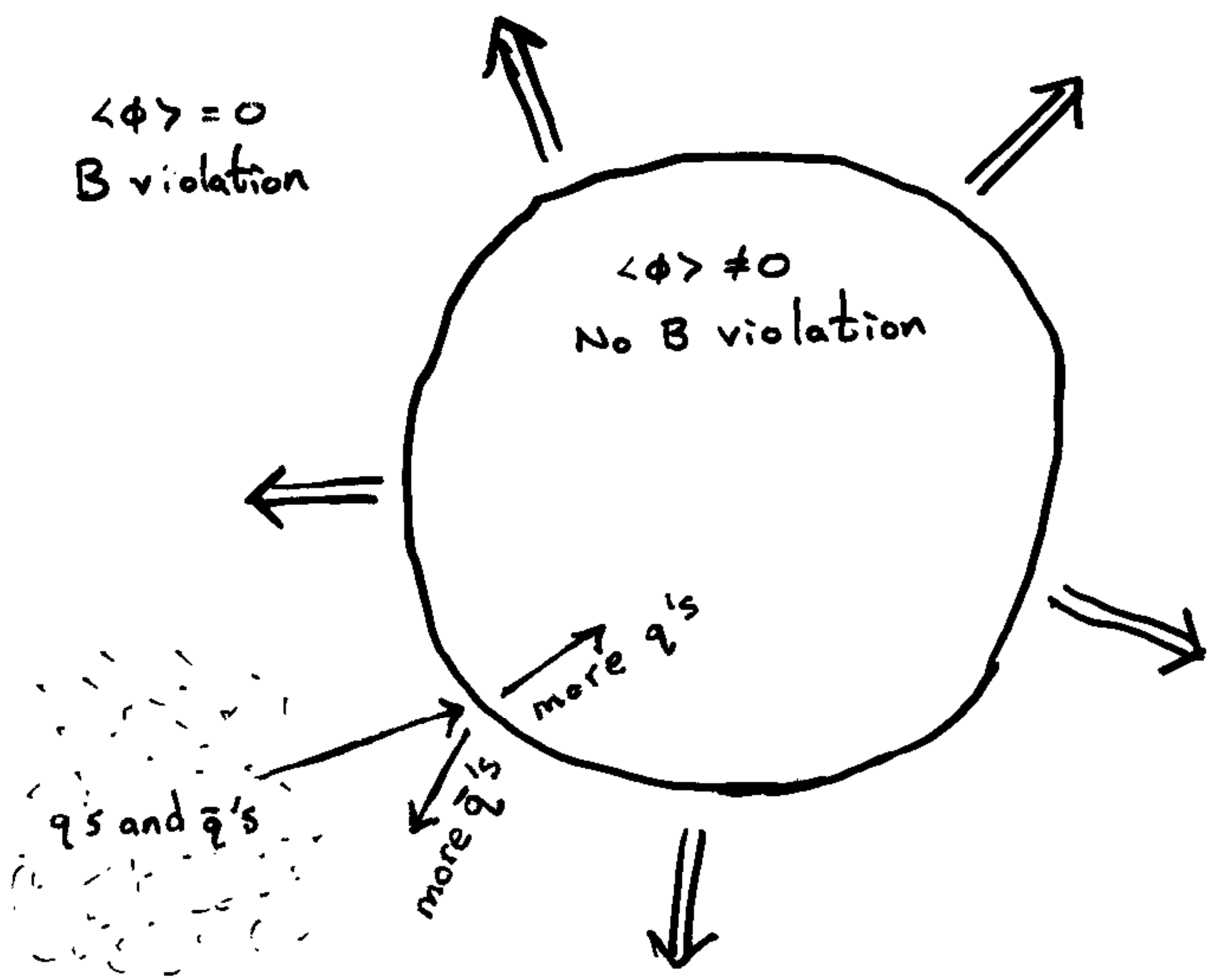
Electroweak Theory

low T: $\langle \phi \rangle \neq 0$ SU_2 broken
high T: $\langle \phi \rangle = 0$ SU_2 restored

Depending on parameters of Higgs sector, transition between these phases

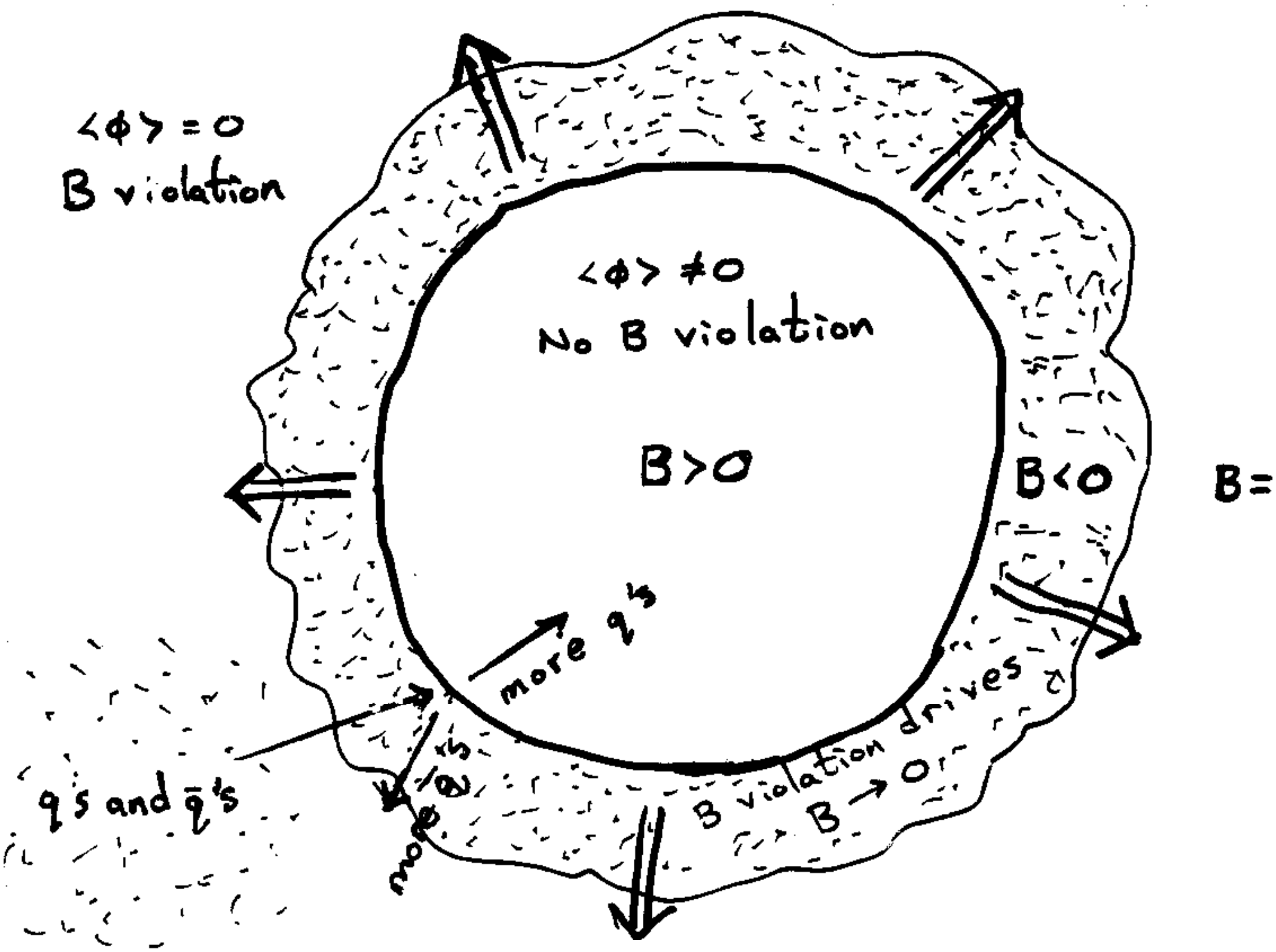
could be a 1^{st} order transition
could be a supercooled 1^{st} order transit





Recall: Need $T \gtrsim E_b \sim \frac{M_w}{g_w^2}$ to get unsuppressed B violation.

Recall: $M_w \sim g_w \phi$.



<u>Recall</u>: Need $T \gtrsim E_b \sim \frac{M_W}{g_W^2}$ to get unsuppressed B violation.

<u>Recall</u>: $M_W \sim g_W \phi$.

Does this mean CKM predicts $n_B/n_\gamma = 10^{-10}$?

No.

New CP violation is required in the Higgs sector. That requires more than just a single Higgs doublet.

- Such CP violation is natural enough in multiple Higgs models like the Minimal Supersymmetric Standard Model.
- Non-minimal Higgs sector is also required for a 1^{st} order phase transition consistent with experimental limits on the Higgs mass.