Supercooling in Theories with Strong Dynamics at the TeV scale

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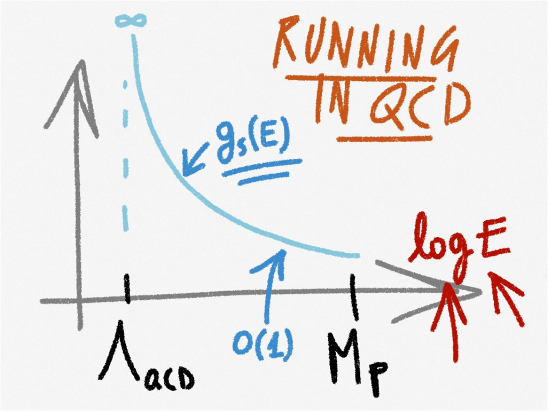
$$M_P \equiv \text{scale of gravity} \sim G_N^{-1/2}$$

$$v_{EW} \equiv \text{scale of electroweak breaking} \approx 10^{-16} M_P$$

Hierarchy problem: lack of understanding of the smallness of v_{EW} with respect to M_P

$\Lambda_{QCD} \equiv$ where strong interactions *become* strong $\approx 10^{-19} M_P$



$$\Lambda_{QCD} = \exp\left(-8\pi^2/7g_s^2(M_P)\right) M_P$$

Easy to generate large hierarchies with $g_s(M_P) \lesssim 1$

We <u>do</u> understand the smallness of Λ_{QCD}/M_P!

Speculation: also v_{EW} is generated by some coupling becoming strong

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Λ_{QCD} sets the mass of the QCD resonances *and* the binding energy of its constituents the quarks

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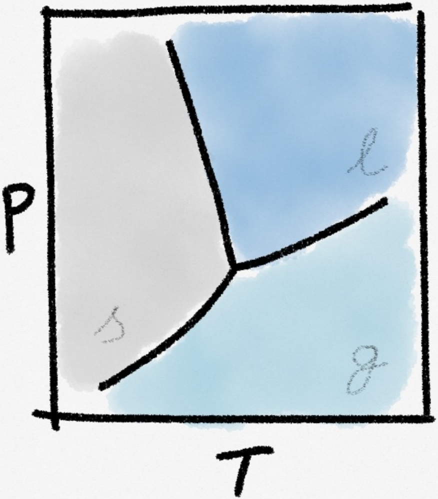
Phase transition for $T > \Lambda_{QCD}$: bounds break and quarks deconfine

$$\Rightarrow \quad \Rightarrow \quad \text{Plasma Phase}$$

We expect an analogous confinement p.t. in the Electro-Weak sector, with $T_c \sim v_{EW}$

Phase transitions are relevant in early Universe evolution

This can be well described by equilibrium thermodynamics (with occasional deviations) *supercooling*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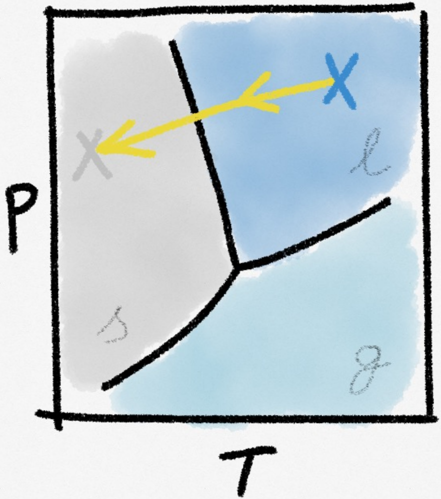
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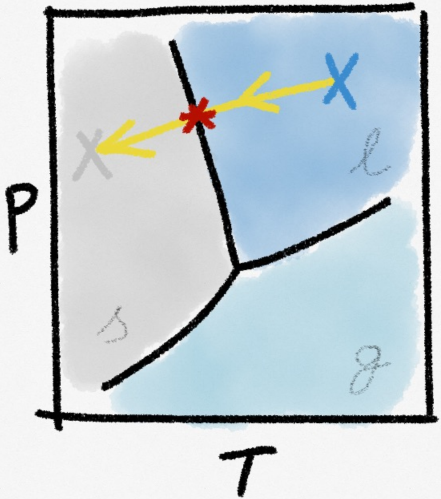

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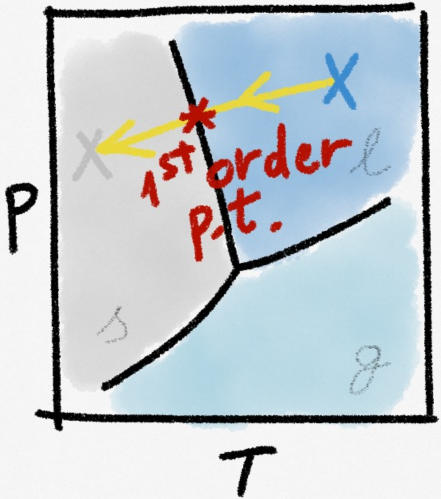
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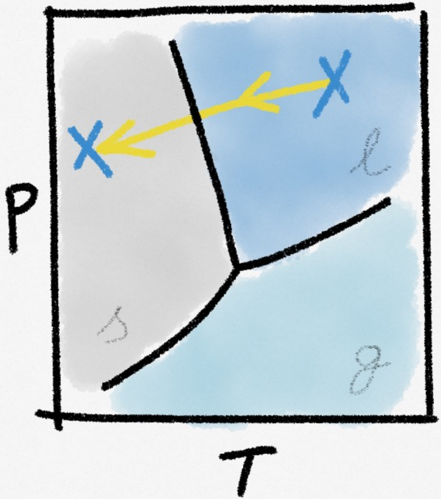
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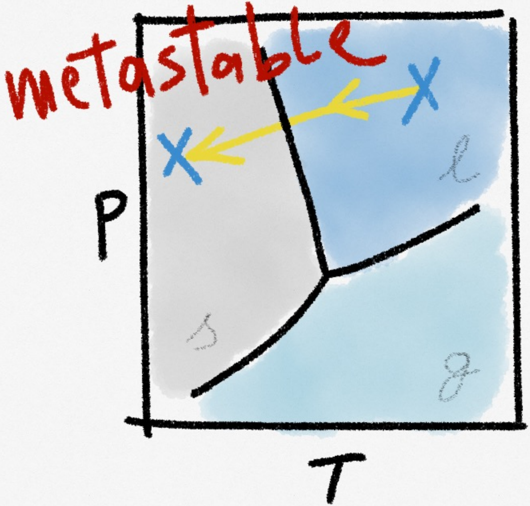
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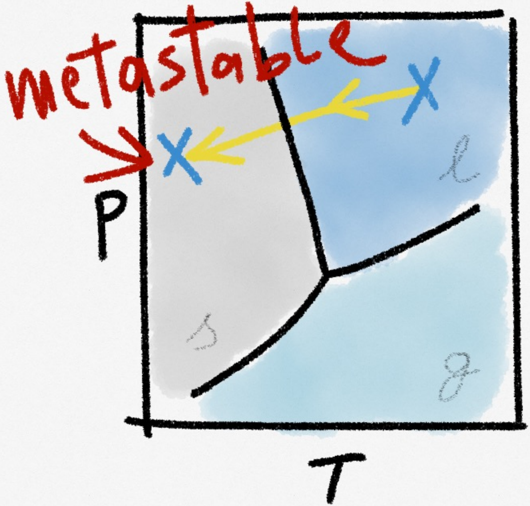
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The supercooled phase ends when *bubbles* of the stable phase form, expand and meet

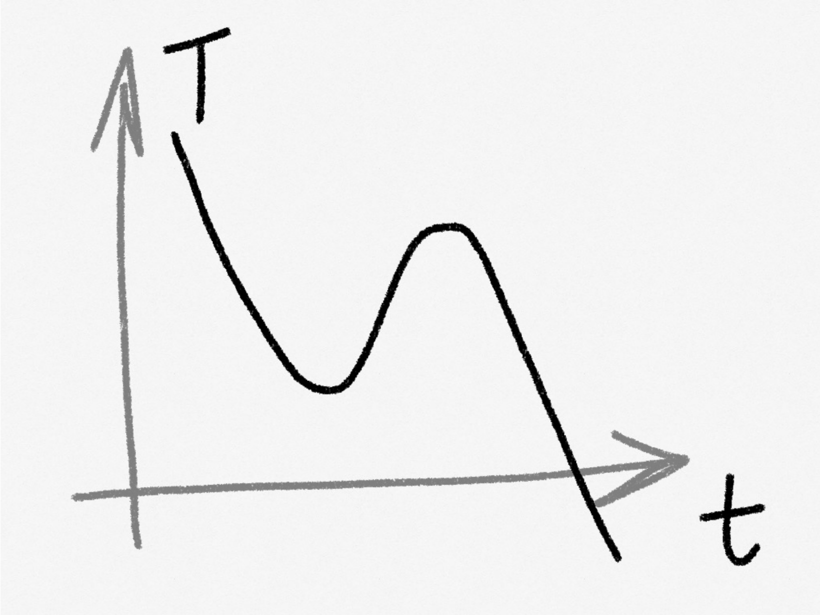
Confinement EW phase transition: predicted to be generically 1st order and slow

Not enough bubbles of the stable phase form $\rightarrow$ the Universe keeps expanding and cooling in the wrong phase (plasma)

At low enough temperature ($T \ll v_{EW}$) an *inflationary expansion* starts

Eventually the Universe must have transitioned to the confined phase

Followed by entropy release (reheating)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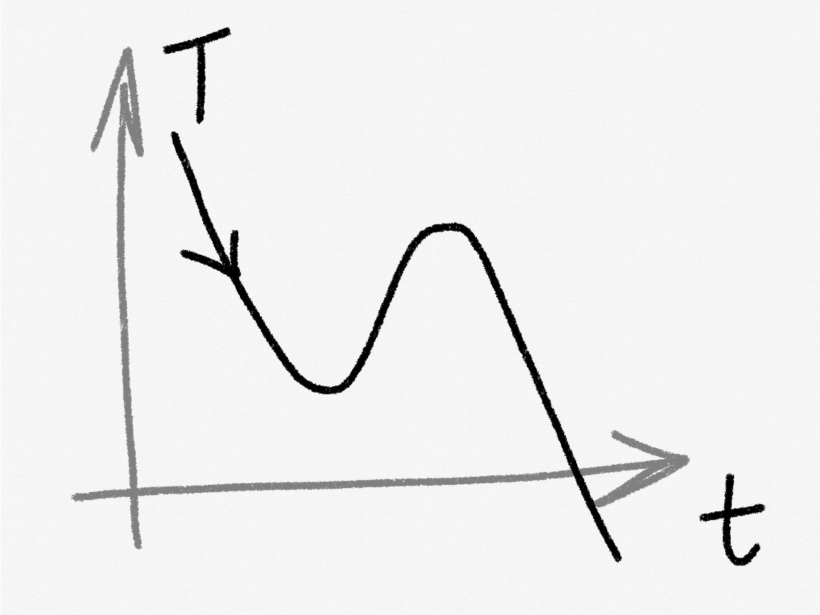
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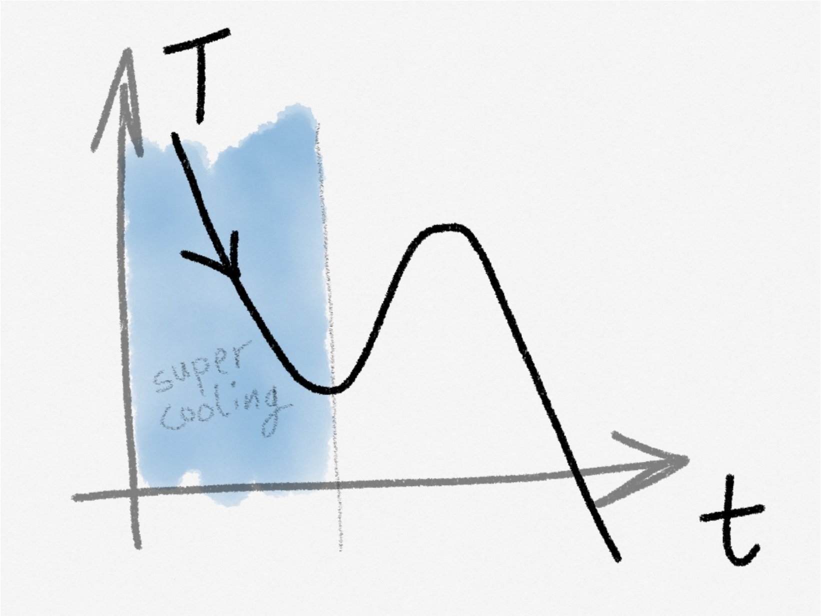
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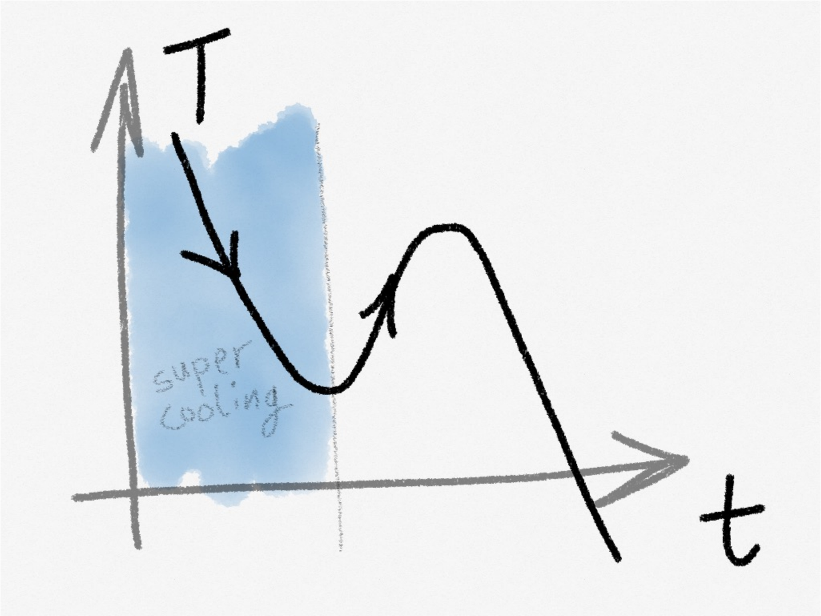

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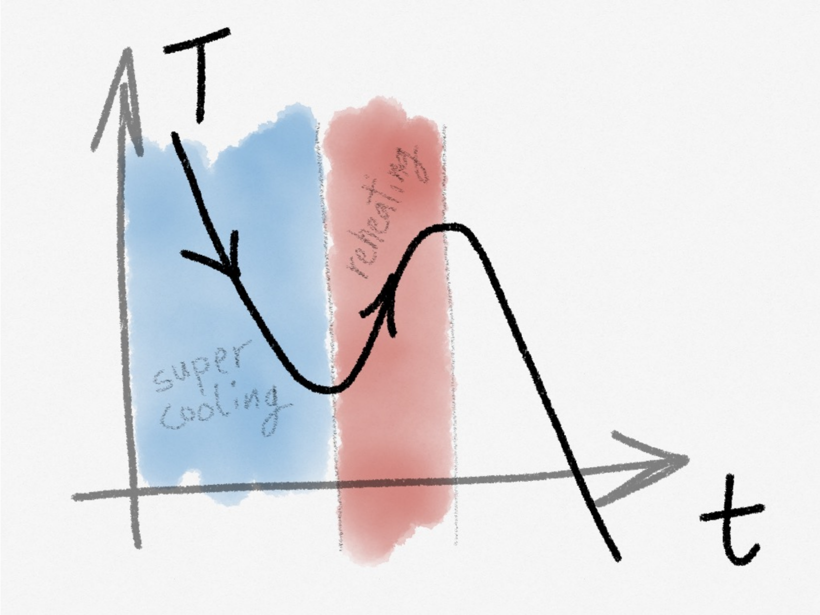
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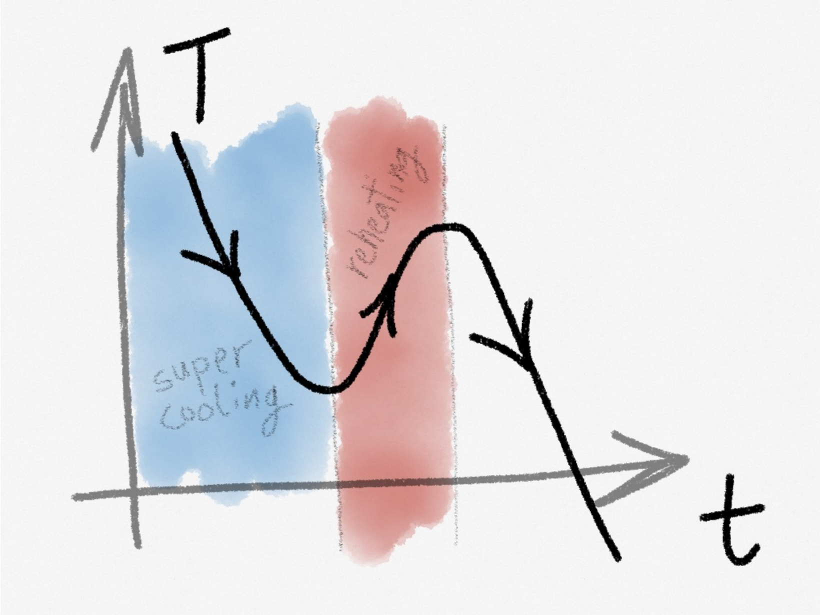
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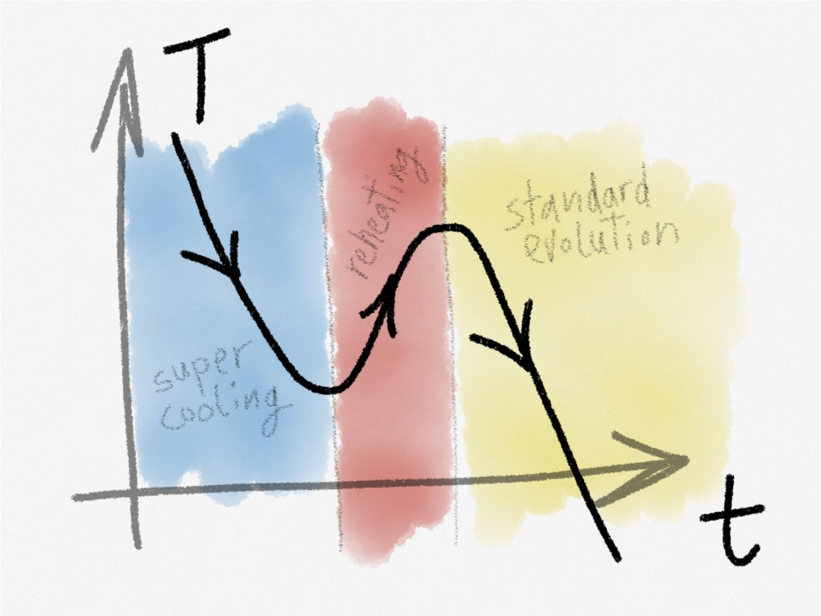
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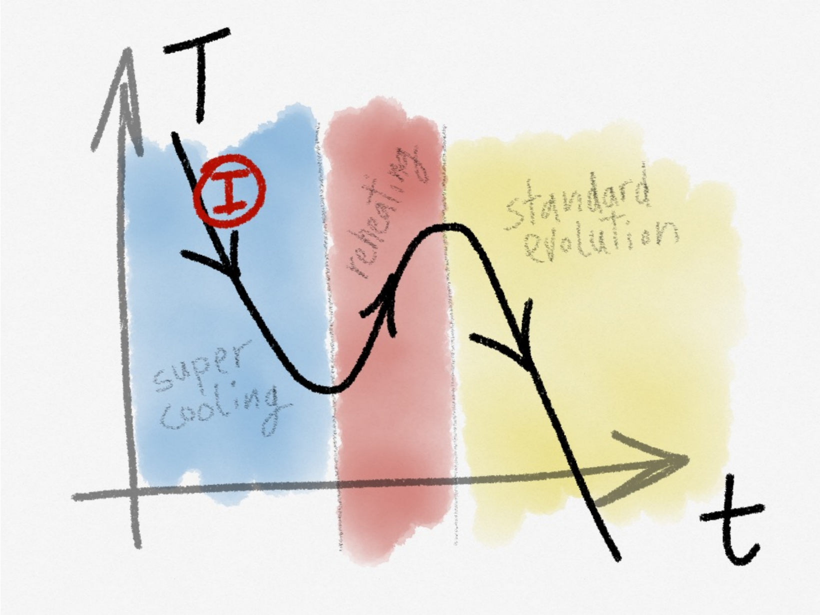
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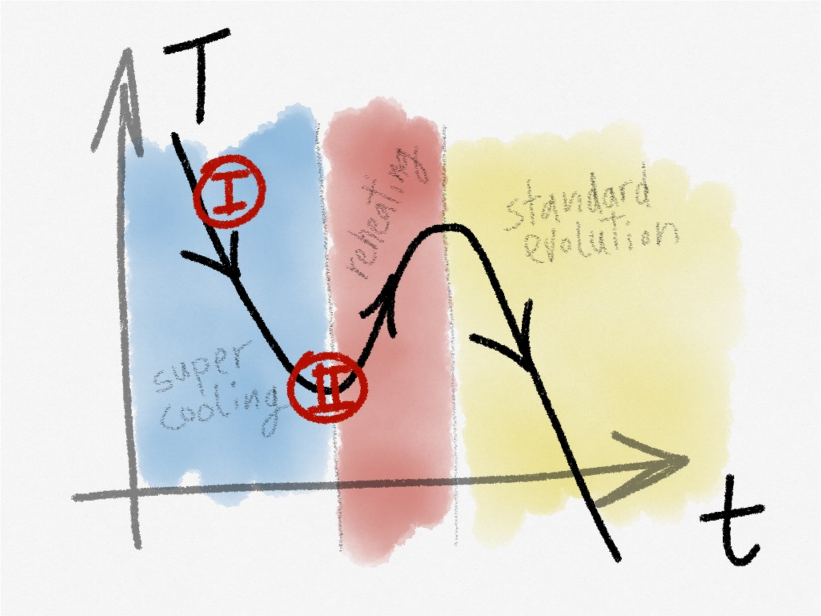
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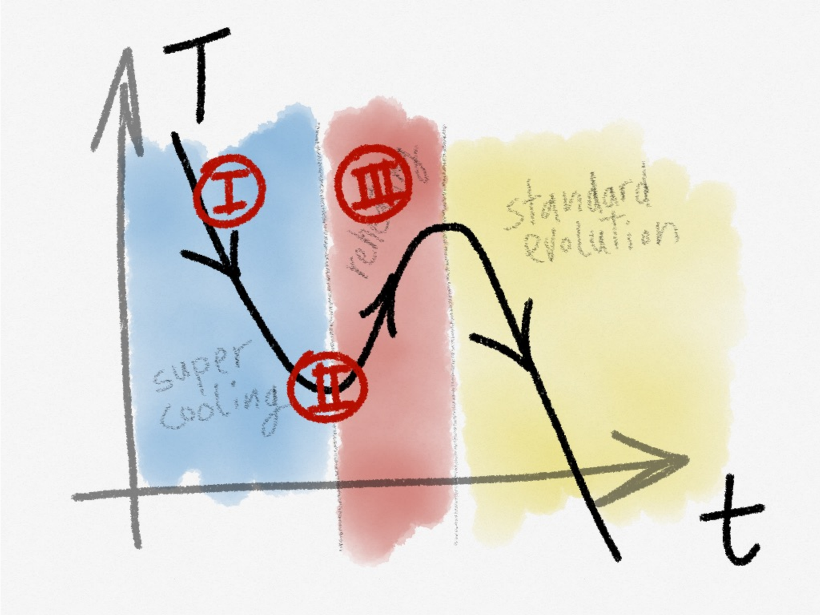
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I. Look for possible cosmic imprints of the supercooling epoch

II. Exit form supercooling:

- When? (number of e-folds N_e)
- How? (microscopic mechanism that induced efficient bubble formation)

III. Cosmic traces of reheating? e.g. gravitational waves (LISA range of sensitivity)

II

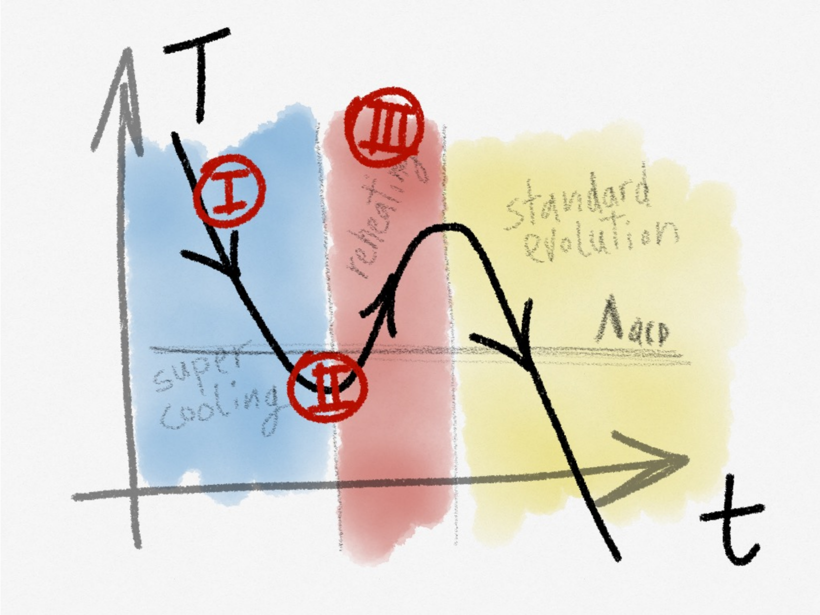
T is a clock during inflation (not just de Sitter space)

- different physical scales are explored

Eventually one reaches the QCD scale: confinement phase transition (the QCD one!)

Quark condensation can be a seed for the formation of bubble of the $\underline{EW}$ confined phase ($\sim$ Witten '80)

$$T_{exit} \sim \Lambda_{QCD}$$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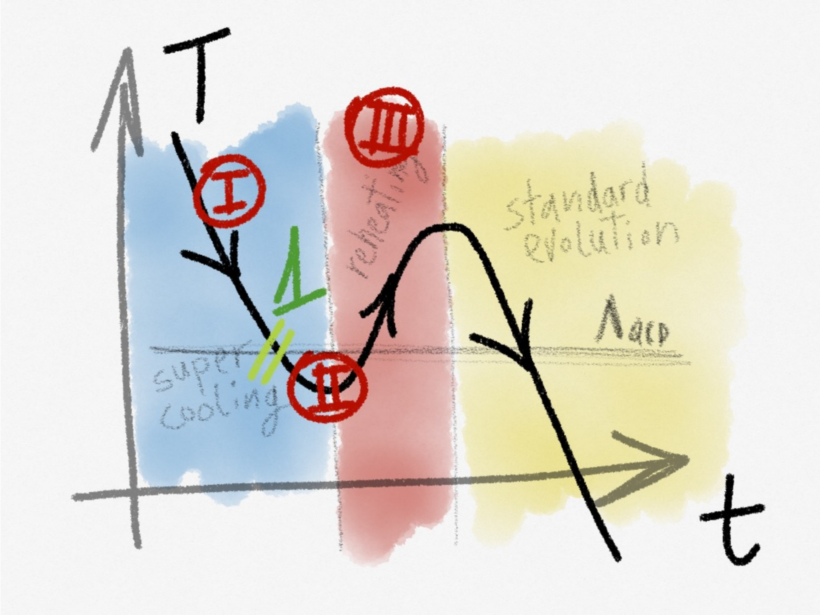

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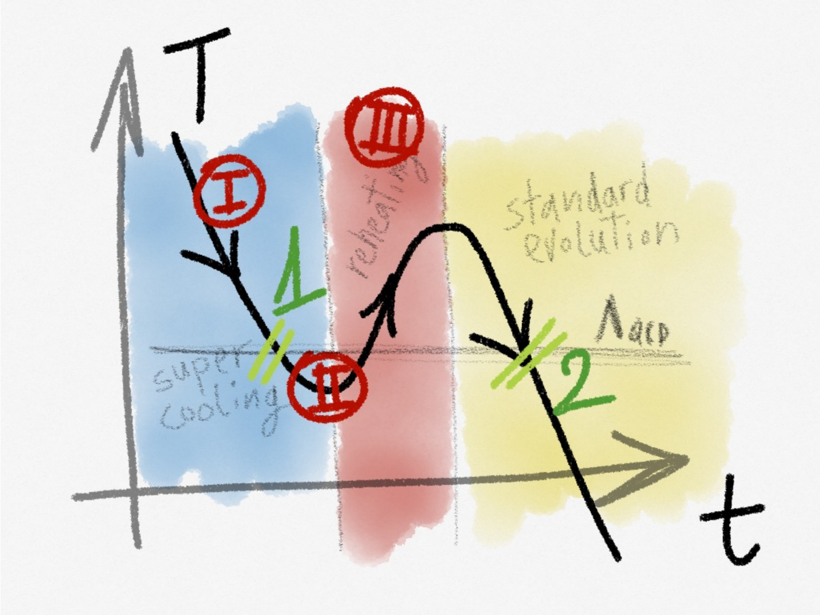
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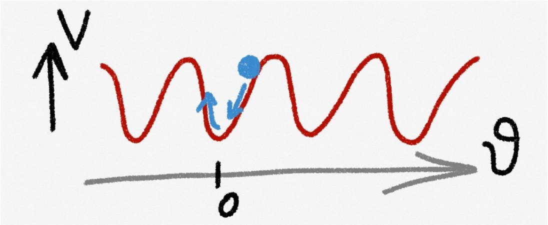
Axion: required by the Peccei-Quinn solution to the *strong CP problem*

Non-trivial potential $V(\theta)$ for $T < \Lambda_{QCD}$, with minimum at $\theta = 0$

Initial misalignment ($\theta_{in} \neq 0$) $\rightarrow$ axion contribution to energy density (dark matter-like)



Avoiding overproduction of axion DM puts a constraint on f, the scale of PQ breaking

$$f \lesssim 10^{11} GeV$$

Assumes $\theta_{in} = O(1)$ at the QCD p.t. (the "standard" one)

With supercooling down to $T < \Lambda_{QCD}$, there is an earlier QCD p.t.!

- θ can be relaxed to $\theta \ll 1$

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Relax bounds on f: as large as $10^{13} GeV$ in some regions of parameter space