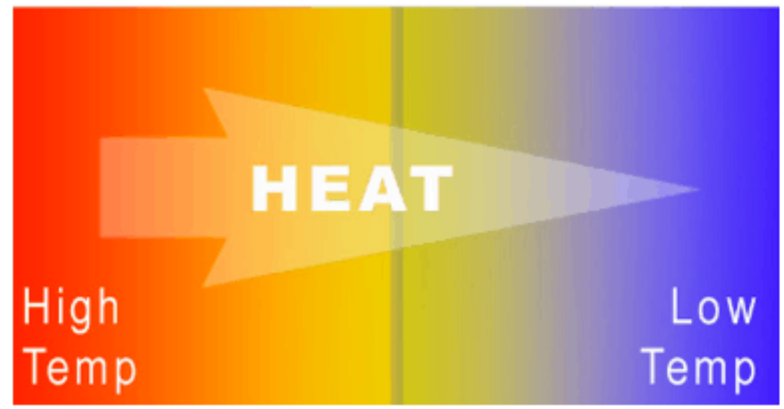
Surprises in Large Nc Thermodynamics



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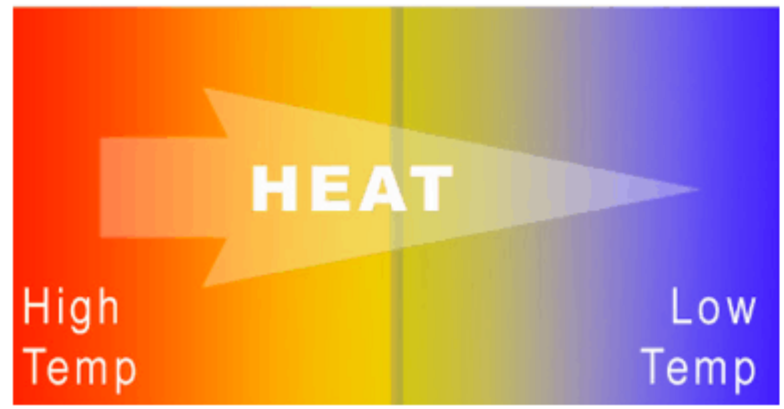

TDC, Scott Lawrence & Yukari Yamauchi (In Preparation)

An Overview

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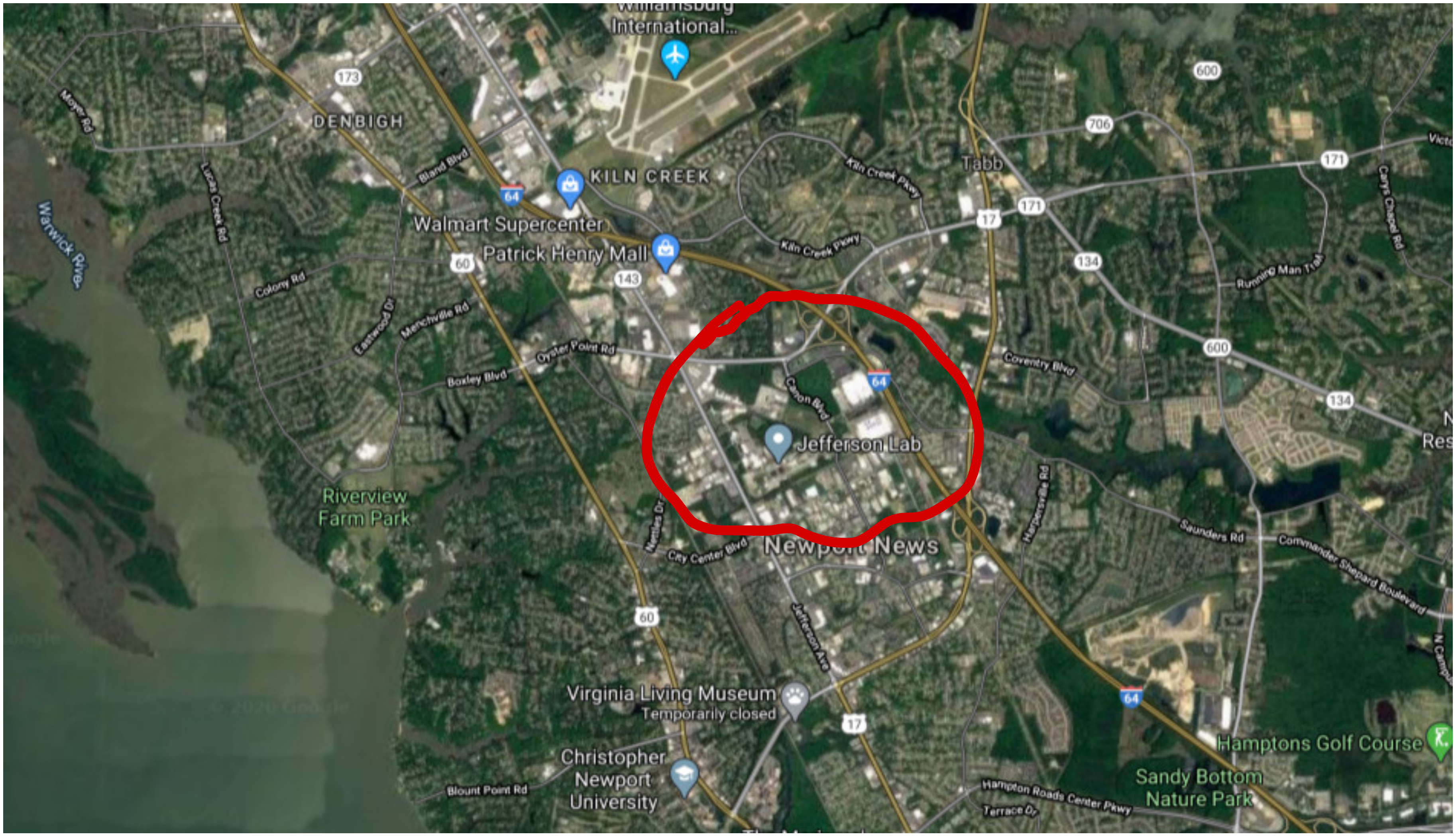


International...
DENBIGH
KILN CREEK
Tabb
Walmart Supercenter
Patrick Henry Mall
Warwick Rive
Jefferson Lab
Riverview
Farm Park
Newport News
Virginia Living Museum
Temporarily closed
Christopher
Newport
University
Hamptons Golf Course
Sandy Bottom
Nature Park

An Overview

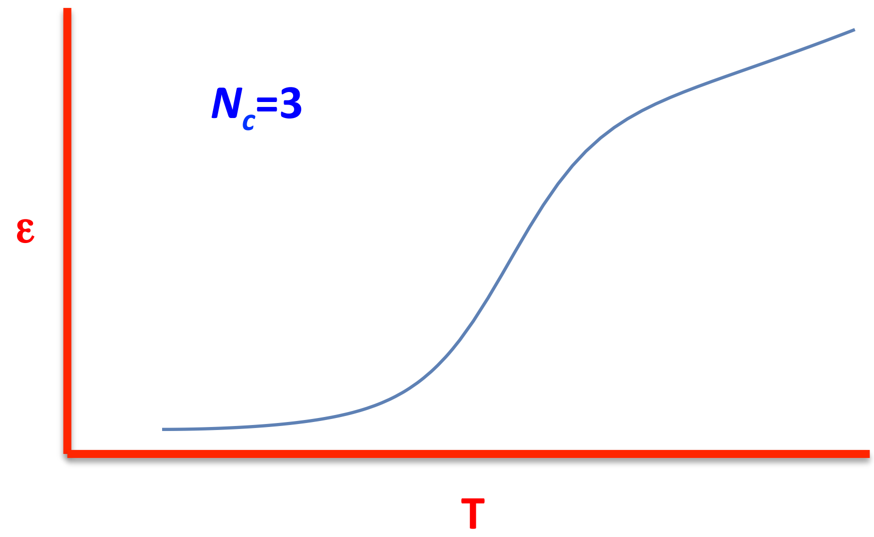
- Introduction
  - Some cautions
  - Standard results
  - Assumptions
- Some surprises
  - A metastable supercooled phase with **negative absolute pressure**.
  - A **clean** demonstration of a strongly coupled regime of plasma.
  - Peculiar behavior at the endpoint of the hadronic phase; breakdown of standard thermodynamic limit.

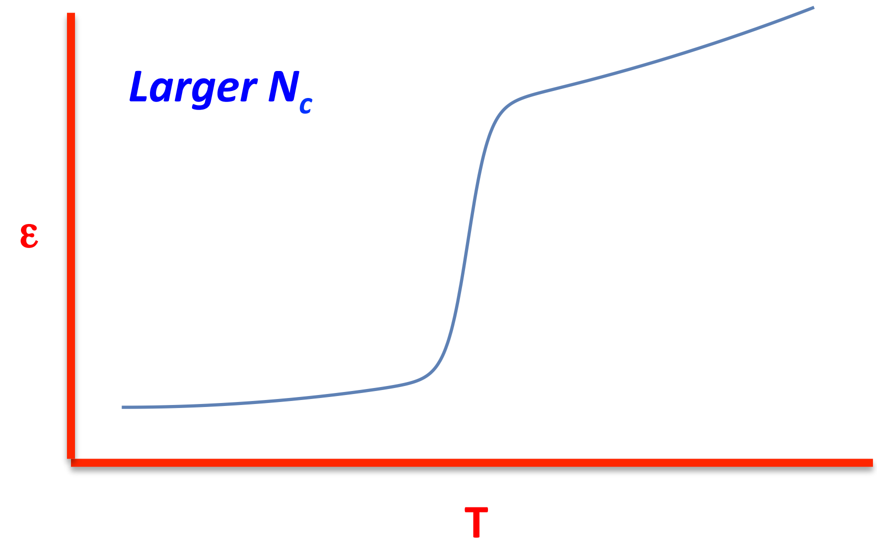
A Motto for $1/N_c$ practitioners

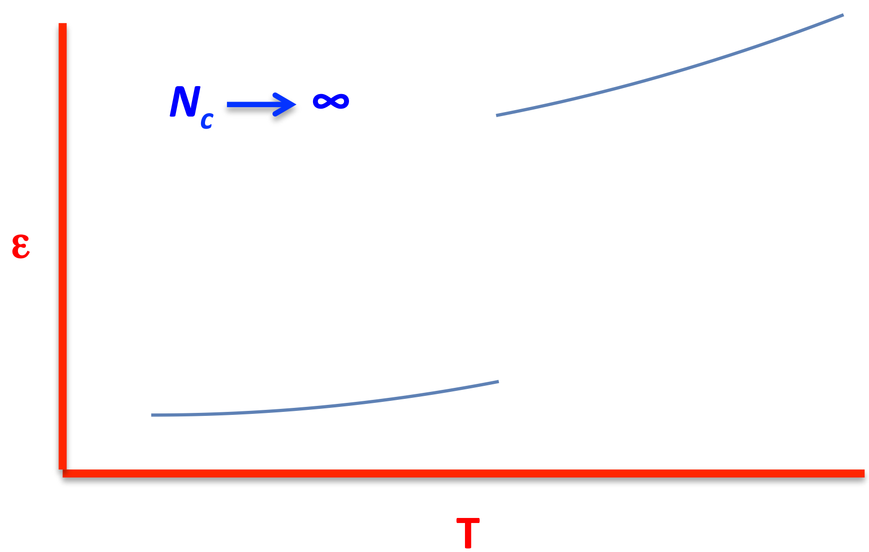
We may well be wrong but at least we are systematic

To the extent that $1/N_c$ corrections are modest, the large N_c world may be a useful cartoon version of the physical world.

However thermodynamic properties around phase transitions or rapid cross-overs are likely to be cases where the cartoon is insufficient.







A crossover for N_c=3 can become increasing sharp as N_c increases and as it goes to ∞, the qualitative behavior can change from being a crossover to a first order transition—a qualitatively different behavior.

This is precisely what we believe happens for QCD.

Despite the qualitative differences there may be useful insights by considering the large N_c limit.

Some standard large N_c results (Witten, 't Hooft 1970s)

- Mesons and glueballs exist as unmixed narrow states with masses of order unity in a $1/N_c$ expansion:

  $$\boxed{m_{\text{meson}} \sim N_c^{0} \quad , m_{\text{glueball}} \sim N_c^{0}}$$

- Meson-meson, meson-glueball and glueball-glueball interactions vanish as $N_c \to \infty$. A coupling with n_m mesons and n_g glueballs scales as $\boxed{N_c^{1-n_g-\frac{1}{2}n_m+\delta_{0,n_m}}}$.
  - Widths scales: $\boxed{\Gamma_{\text{meson}} \sim N_c^{-1} \quad , \quad \Gamma_{\text{glueball}} \sim N_c^{-2}}$
  - Meson-meson & meson-glueball cross-section scales as $\sim N_c^{-1}$
  - glueball-glueball cross-section scales as $\sim N_c^{-2}$

- There are an infinite number of glueballs and mesons with any given fixed quantum numbers as $N_c \to \infty$

- Baryons have masses that scale as $\boxed{m_{\text{baryon}} \sim N_c^{1}}$

Some standard large N_c thermodynamic results:

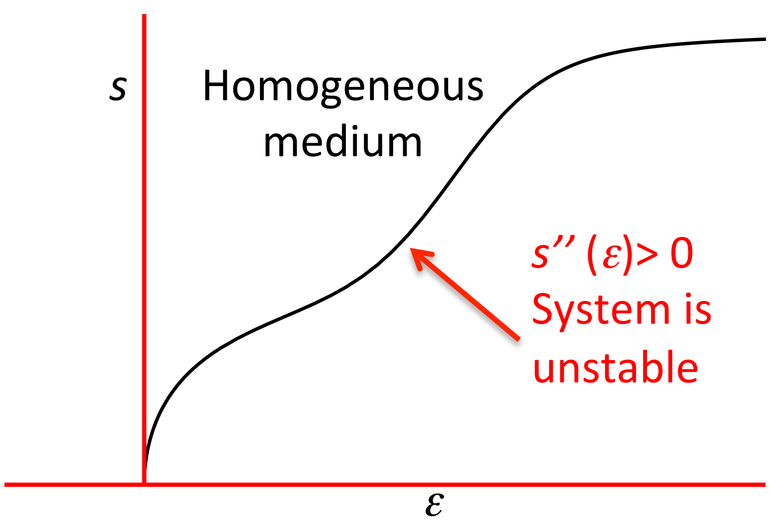
- Previous results imply that in a hadronic phase the system becomes a weaky coupled hadronic gas composed of mesons and glueballs with with the energy density scaling as N_c^0
- RG analysis indicates that the QCD becomes weakly coupled at a momentum transfer that scale as $\sim N_c^0$.
  - The system enters a quark-gluon plasma regime at temperature that scales as $\sim N_c^0$.
  - The energy density in the quark-gluon plasma regime scales as $\sim N_c^2$.
- The discrepancy between the N_c^0 behavior in the hadronic regime and the N_c^2 behavior in the plasma regime implies that there must be a phase transition (first or second order)—at least as $N_c \rightarrow \infty$.

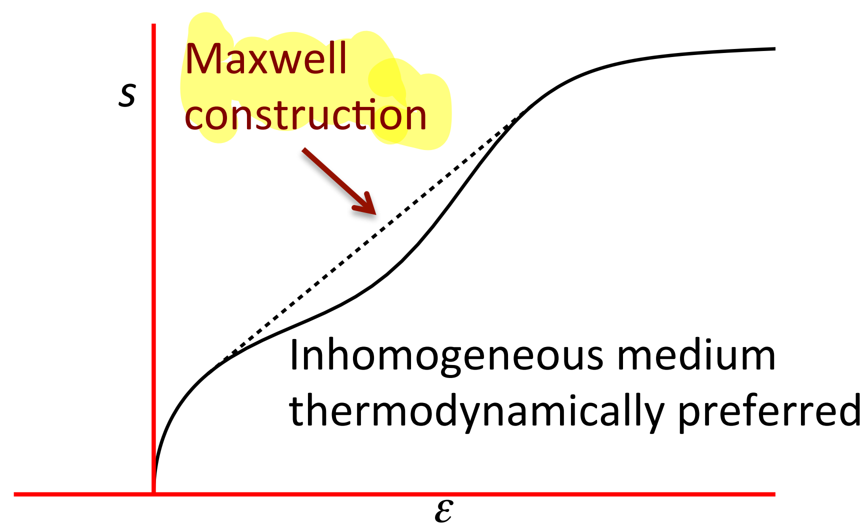
Some standard large N_c thermodynamic results:

– There is a strong reason to believe that this phase transition should be first order.
  - In the large N_c limit quark loops are suppressed. Thus one expects the thermodynamics of QCD to become equivalent to Yang-Mills as N_c gets large.
  - Yang Mills is known to have a first order transition at $N_c=3$.
  - Lattice simulations by the Oxford Group (*Teper and collaborators*) in the early 2000s indicate that the first order transition persists at larger N_c with latent hear growing as N_c^2 as one would expect if the first-order transition persisted up to infinity.

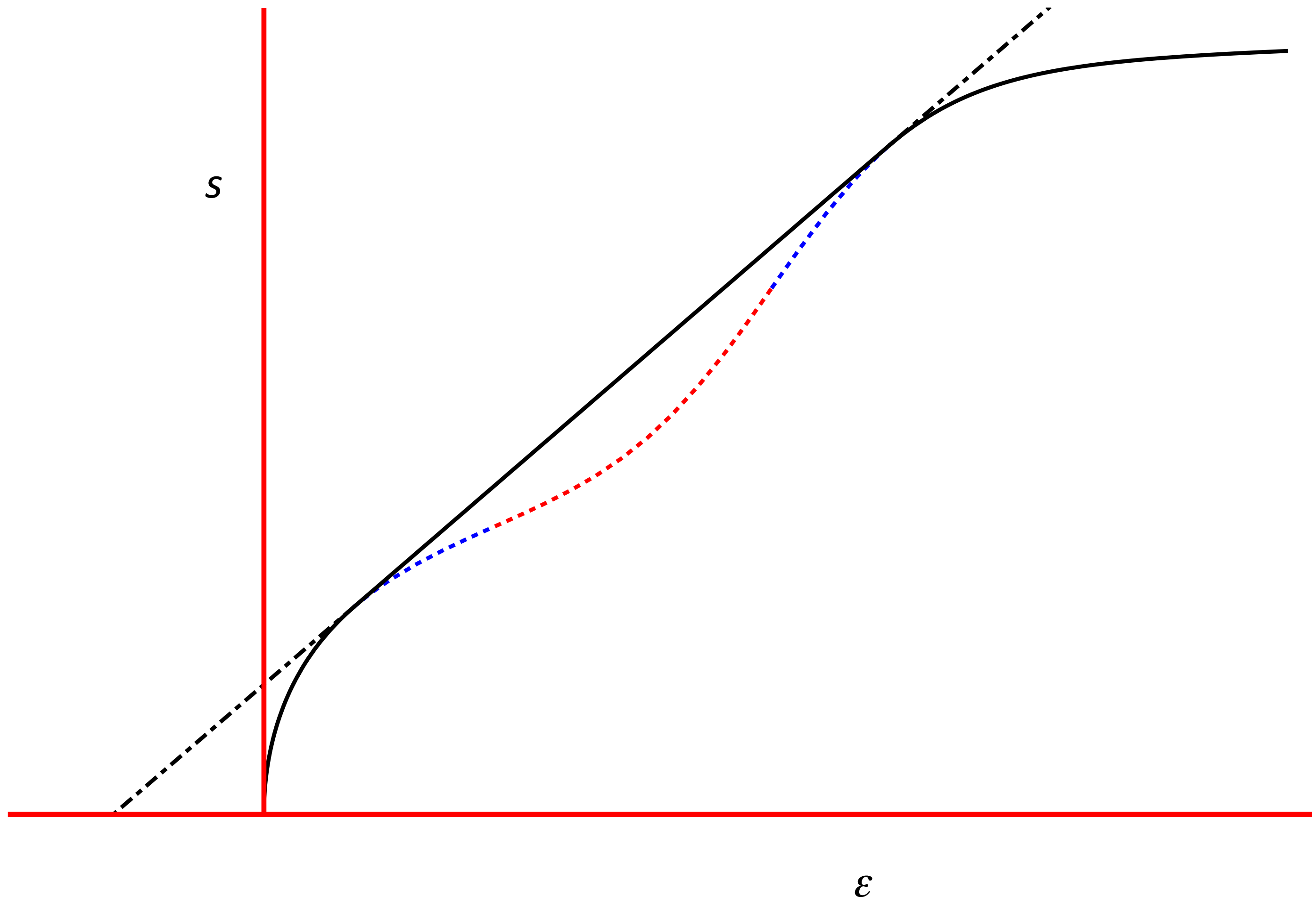
Throughout this talk, it will be assumed that a first order transition exists between a hadron and plasma phase

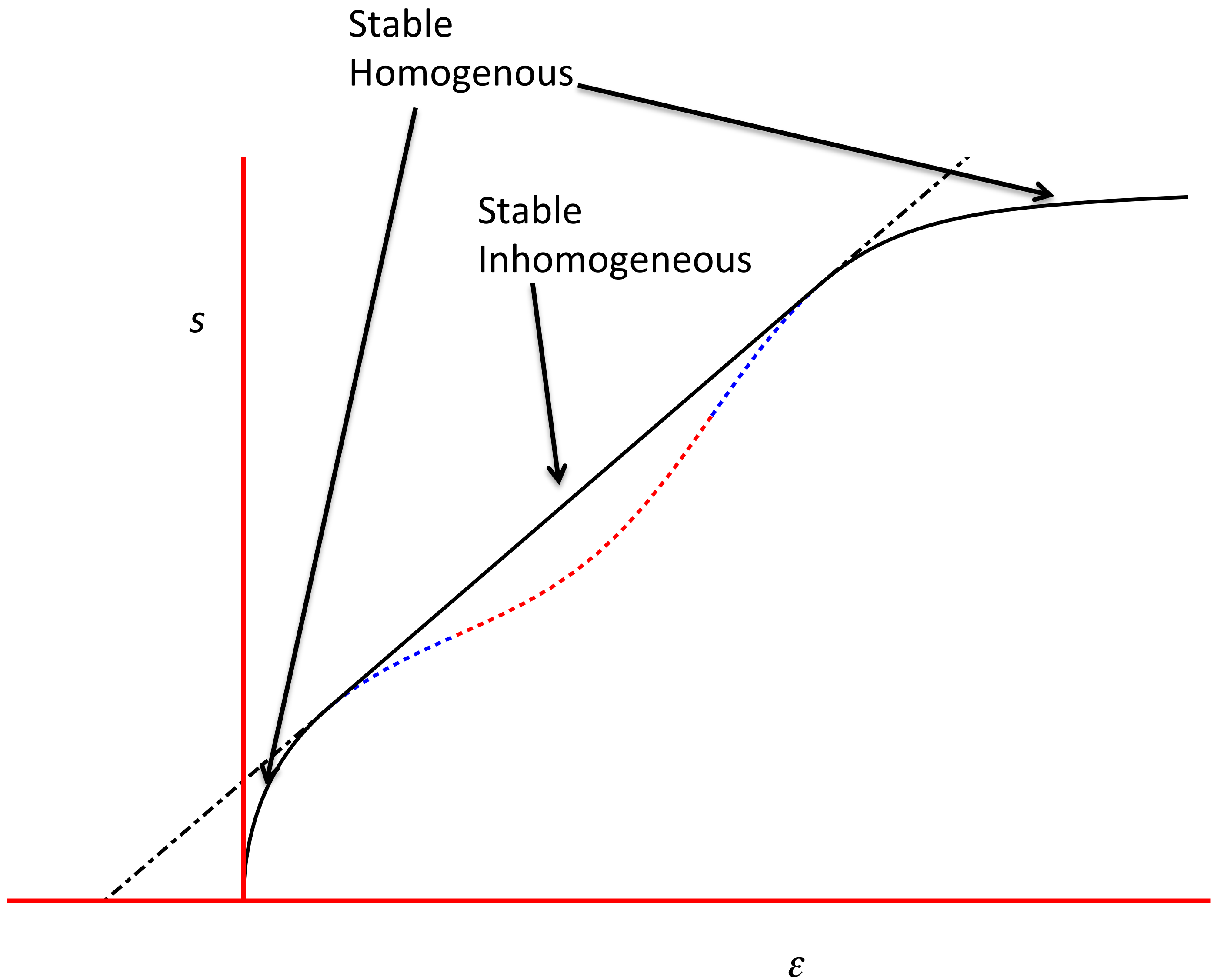
- This talk will mostly use the microcanonical ensemble as this provides the most insight for these problems.
  - Key quantity $S(E)$ where $S(E)$ is the log of the number of accessible states at E.
  - $S'(E)=1/T$
  - In thermodynamic limit of large volumes relevant quantities are entropy density, s, and energy density ε: $\boxed{s(\varepsilon) = \lim_{V\to\infty} S(\varepsilon V)/V}$
  - Thermodynamic stability implies $\boxed{s''(\varepsilon)\leq 0.}$



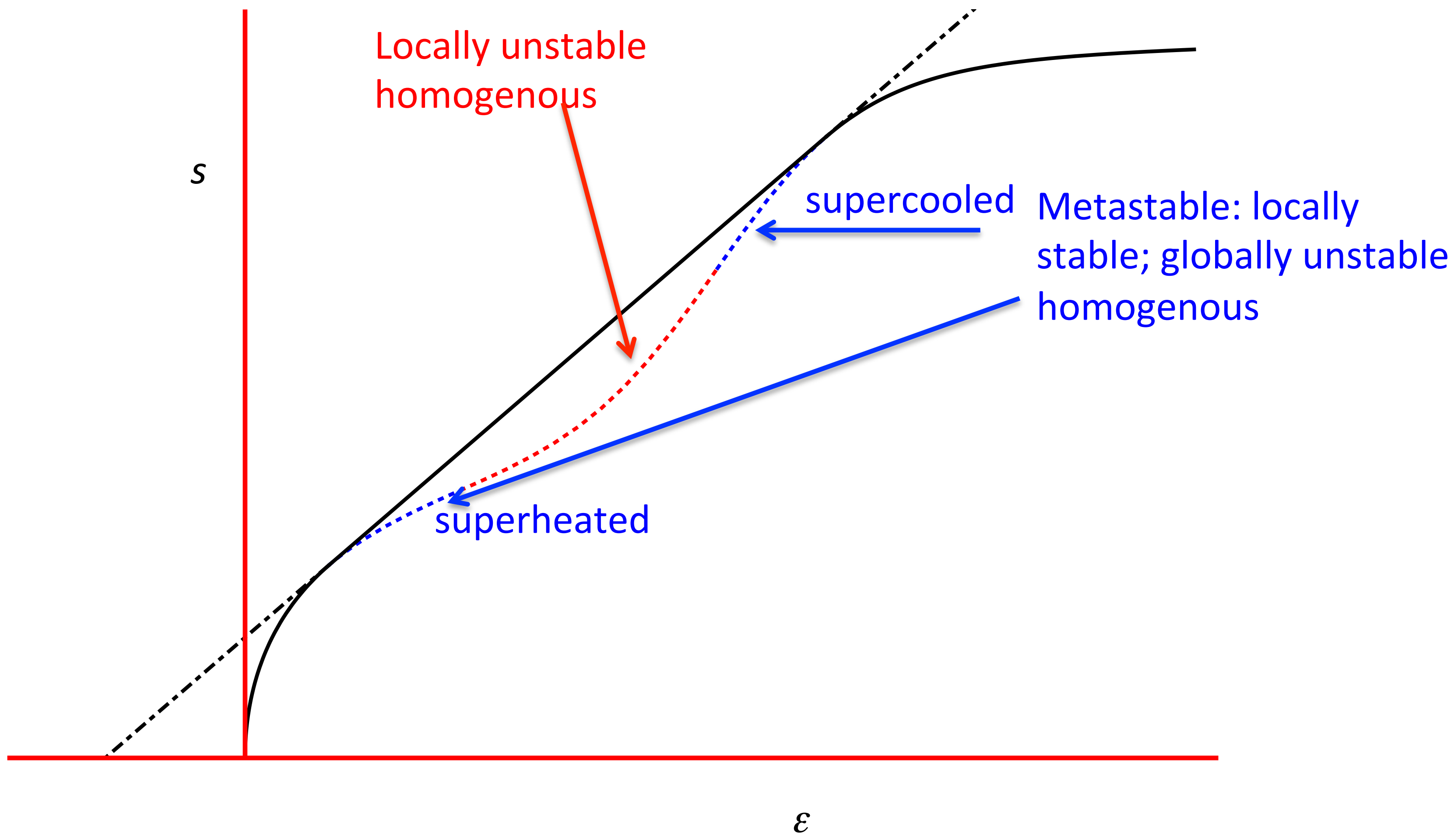


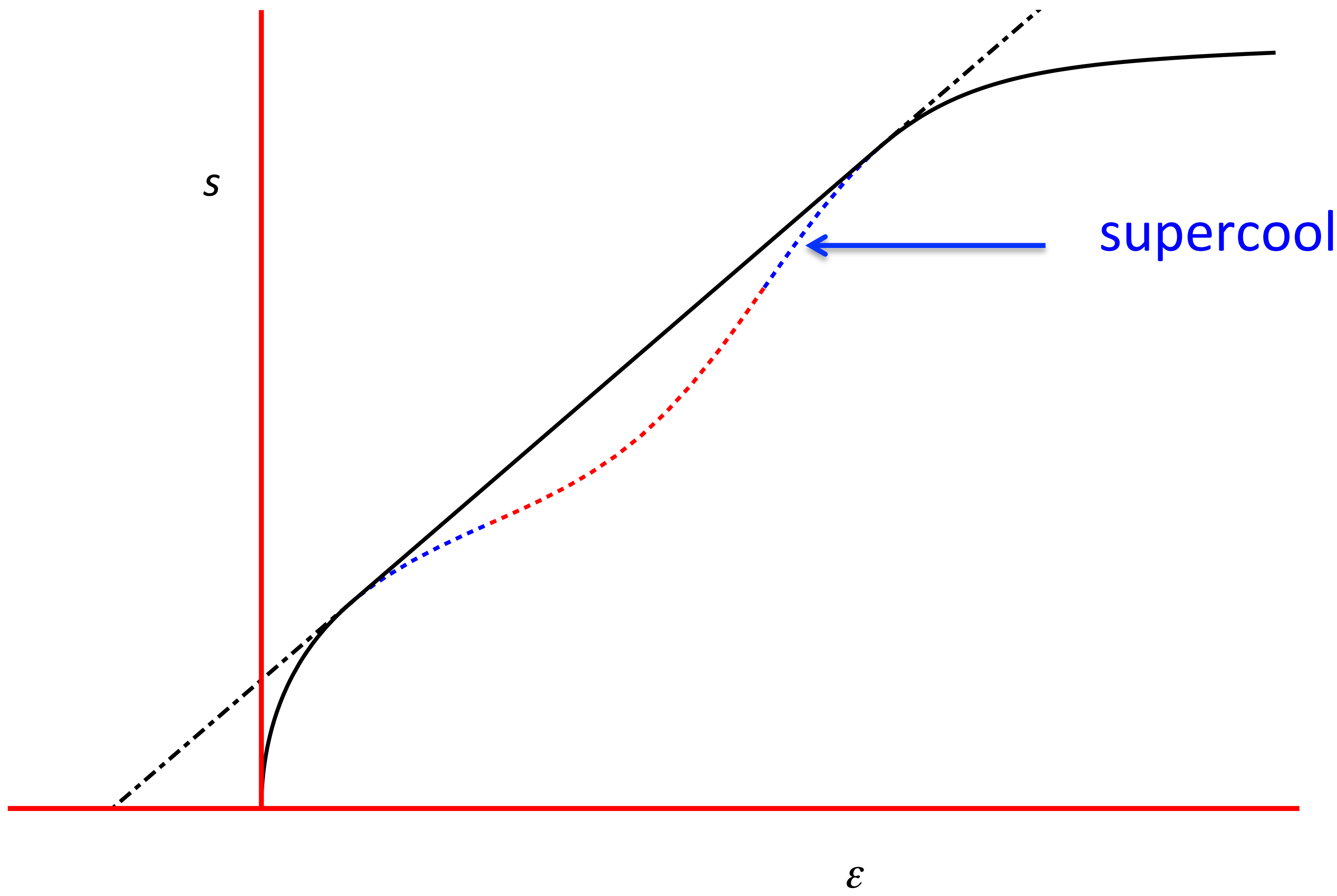
Generic first order transition



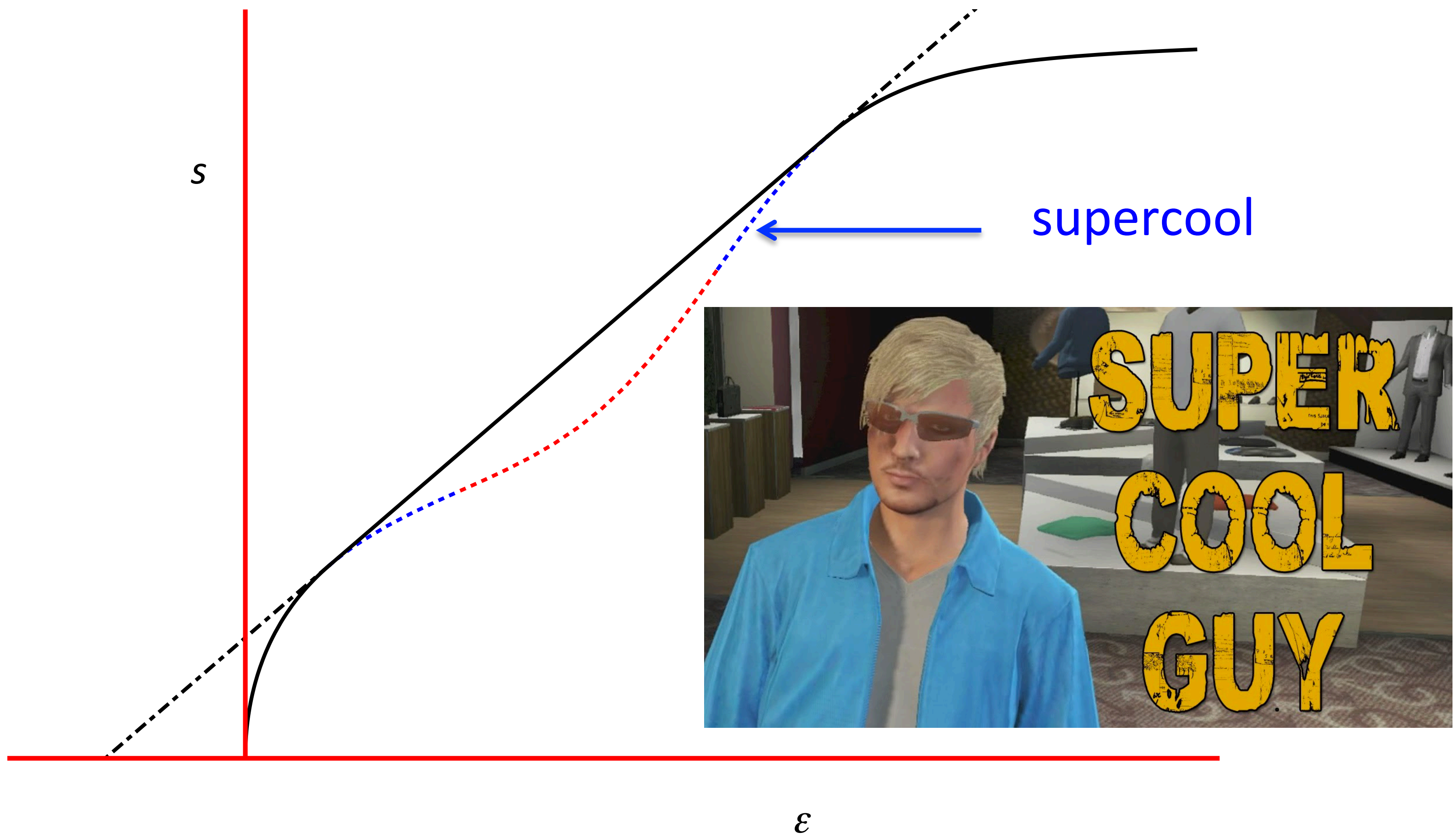


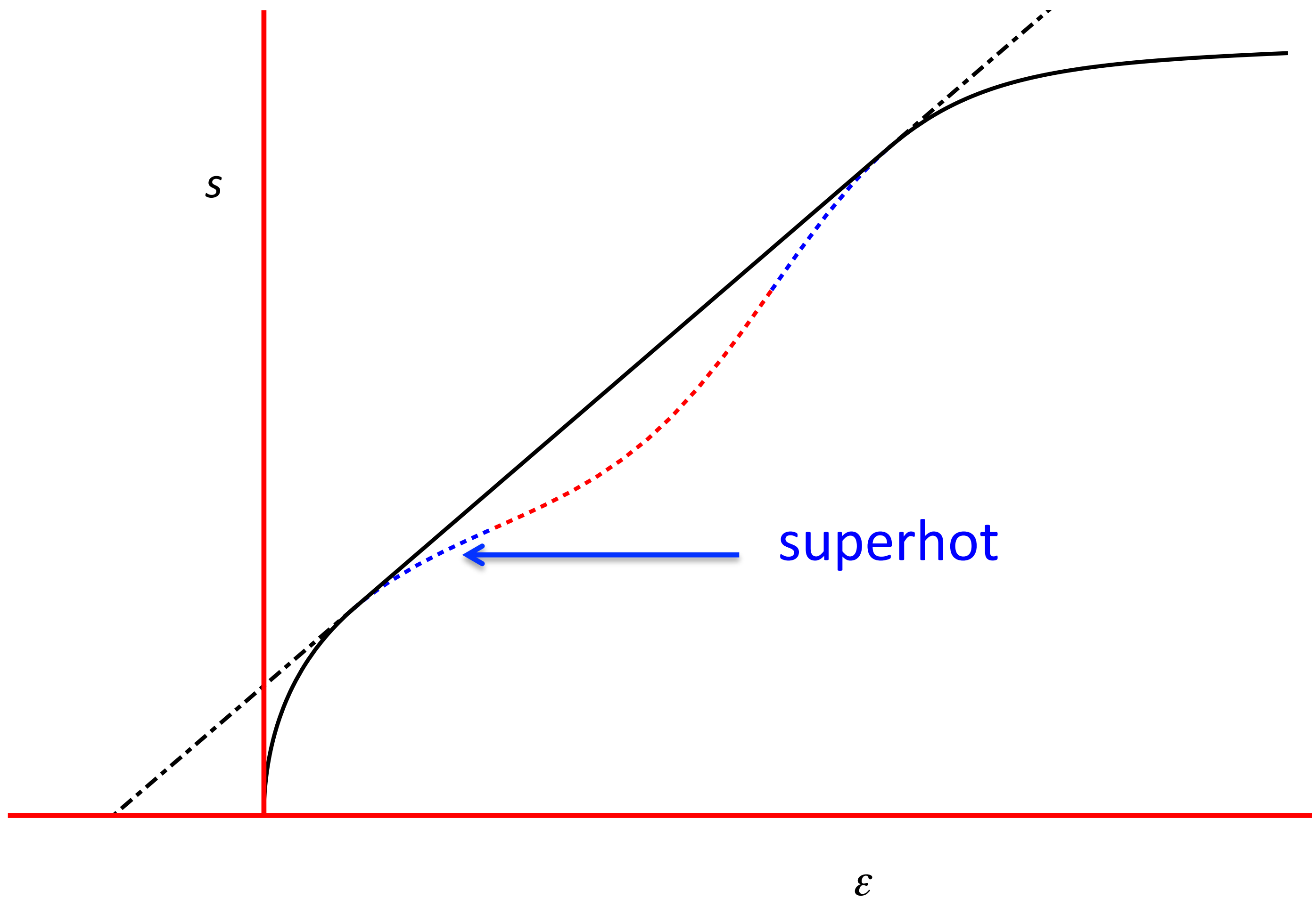
Stable
Homogenous
Stable
Inhomogeneous
s
ε

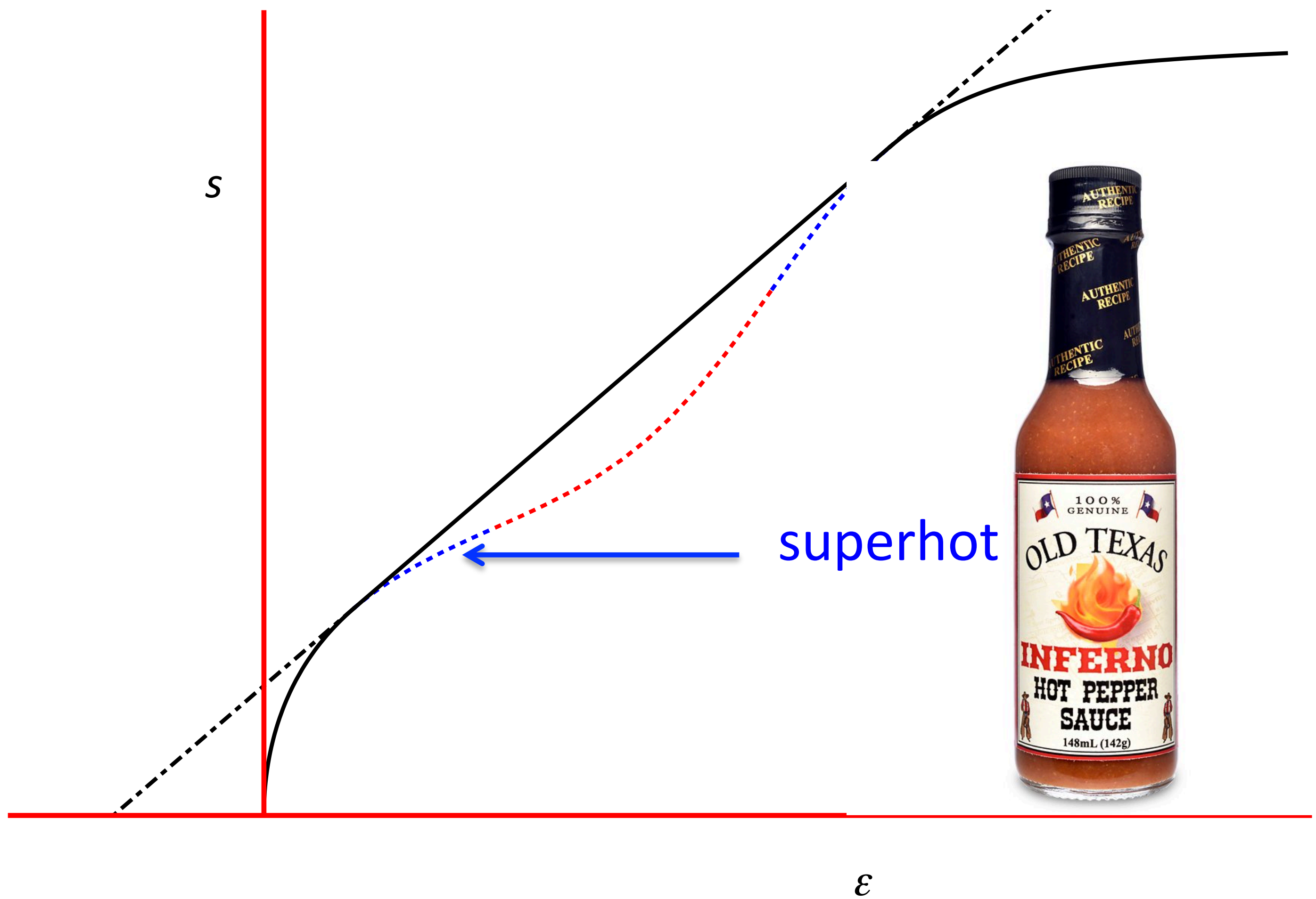

Locally unstable
homogenous
s
supercooled
Metastable: locally
stable; globally unstable
homogenous
superheated
ε



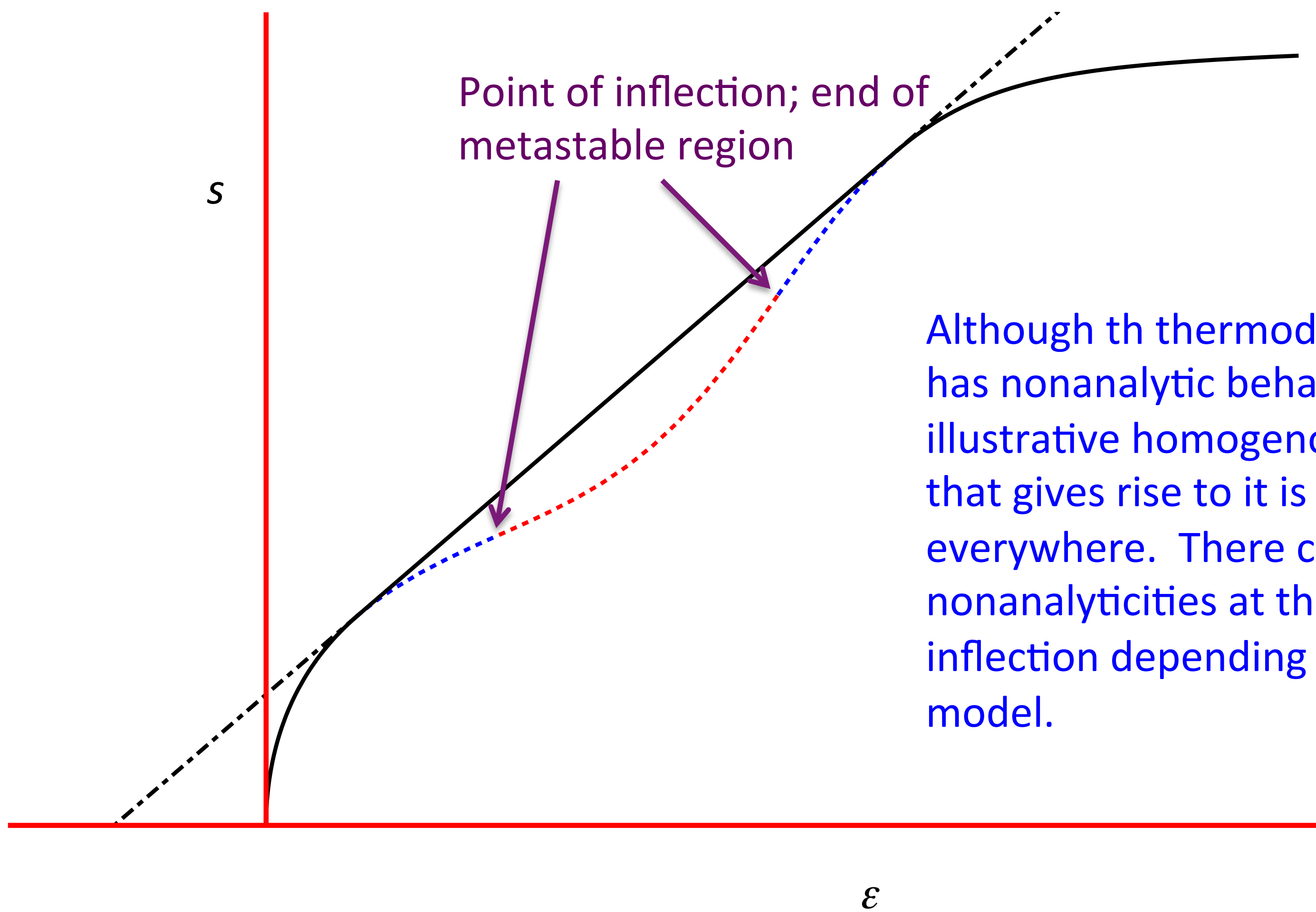
s
supercool
ε


s
supercool
SUPER
COOL
GUY
ε

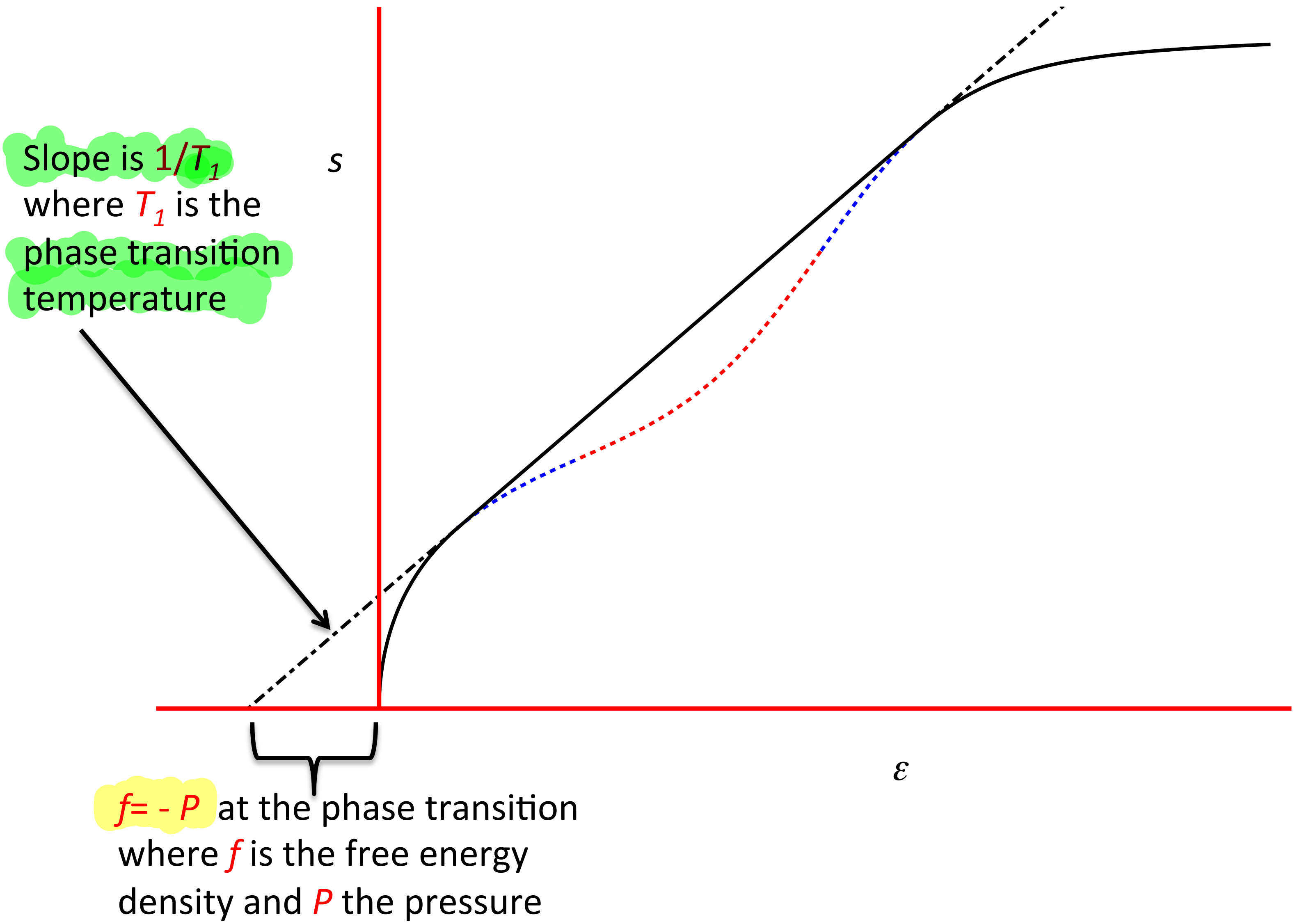

s
superhot
ε



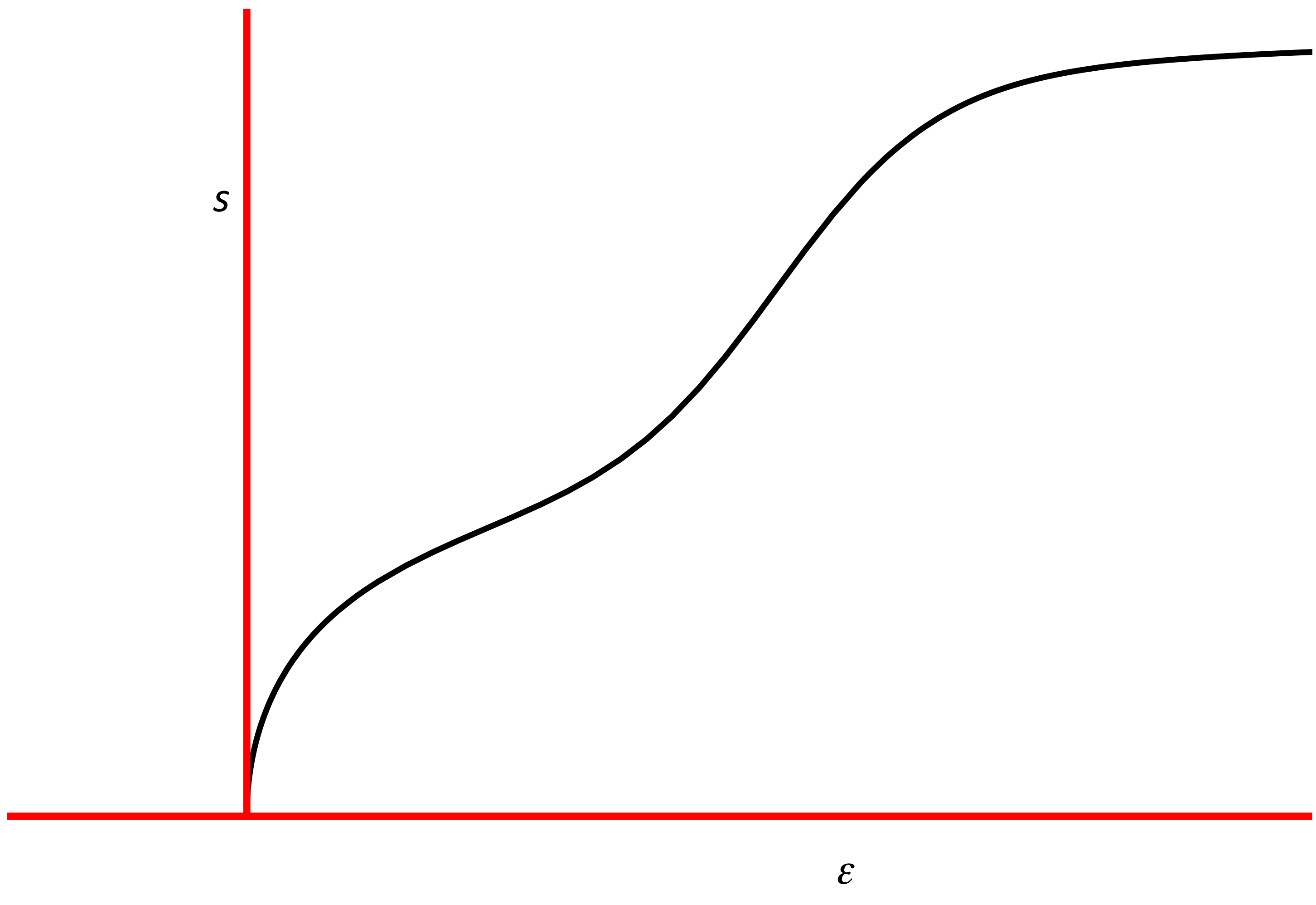
s
ε
superhot
AUTHENTIC RECIPE
100% GENUINE
OLD TEXAS
INFERNO
HOT PEPPER SAUCE
148mL (142g)



Although th thermodynamics has nonanalytic behavior, his illustrative homogenous curve that gives rise to it is analytic everywhere. There can be nonanalyticities at the points inflection depending on the model.


Slope is 1/T_1
where T_1 is the
phase transition
temperature
s
ε
f= - P at the phase transition
where f is the free energy
density and P the pressure

What happens at large N_c ?



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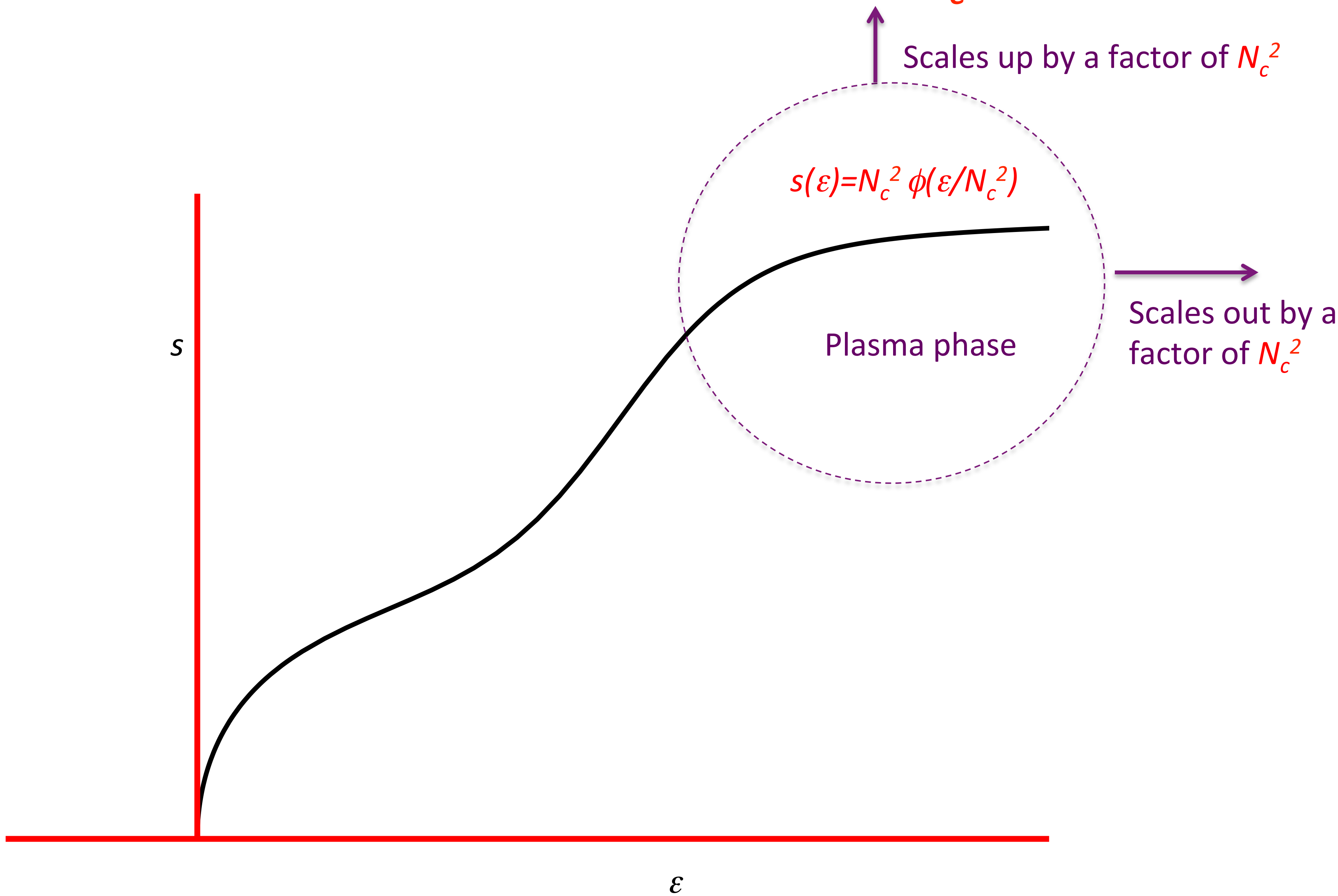

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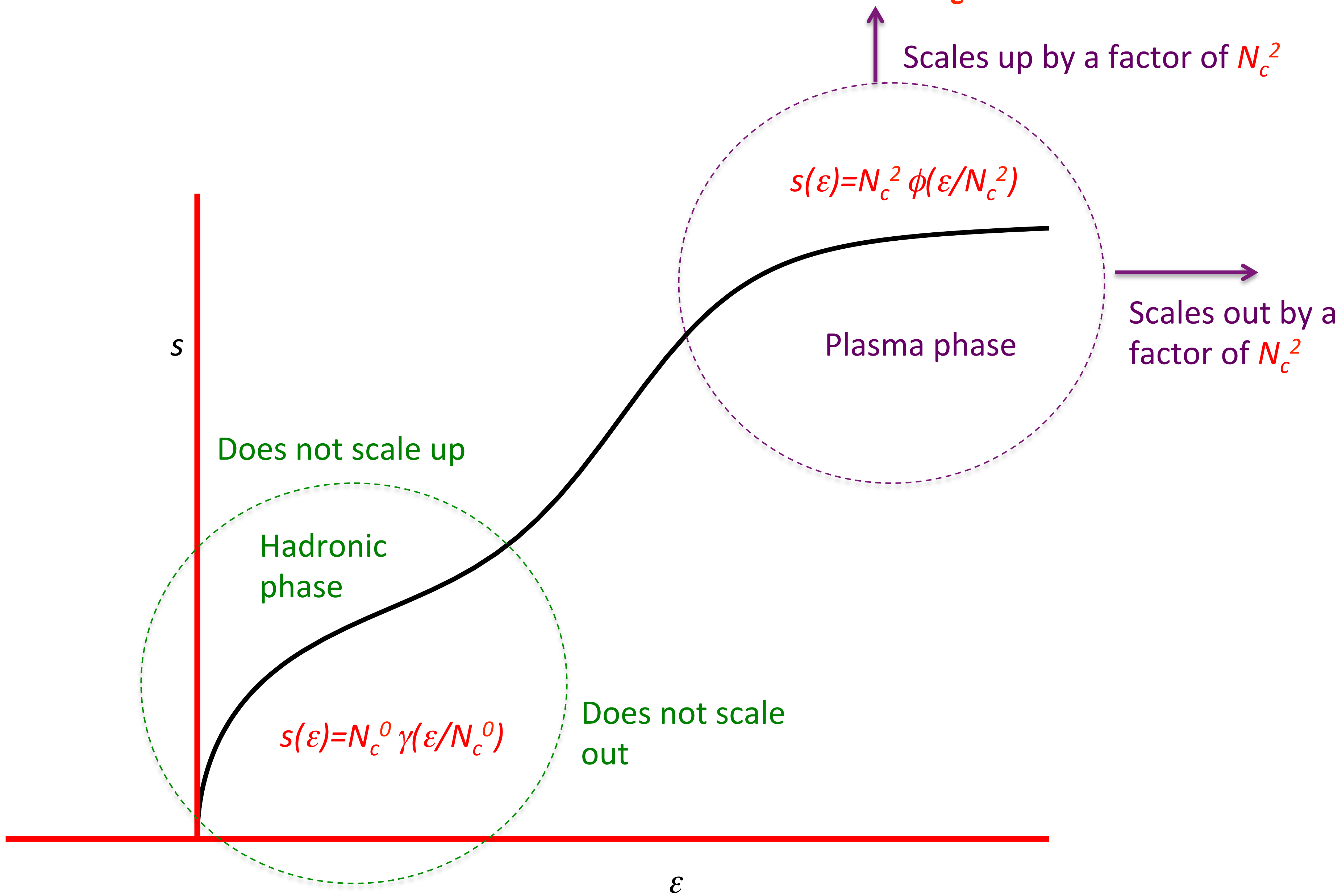

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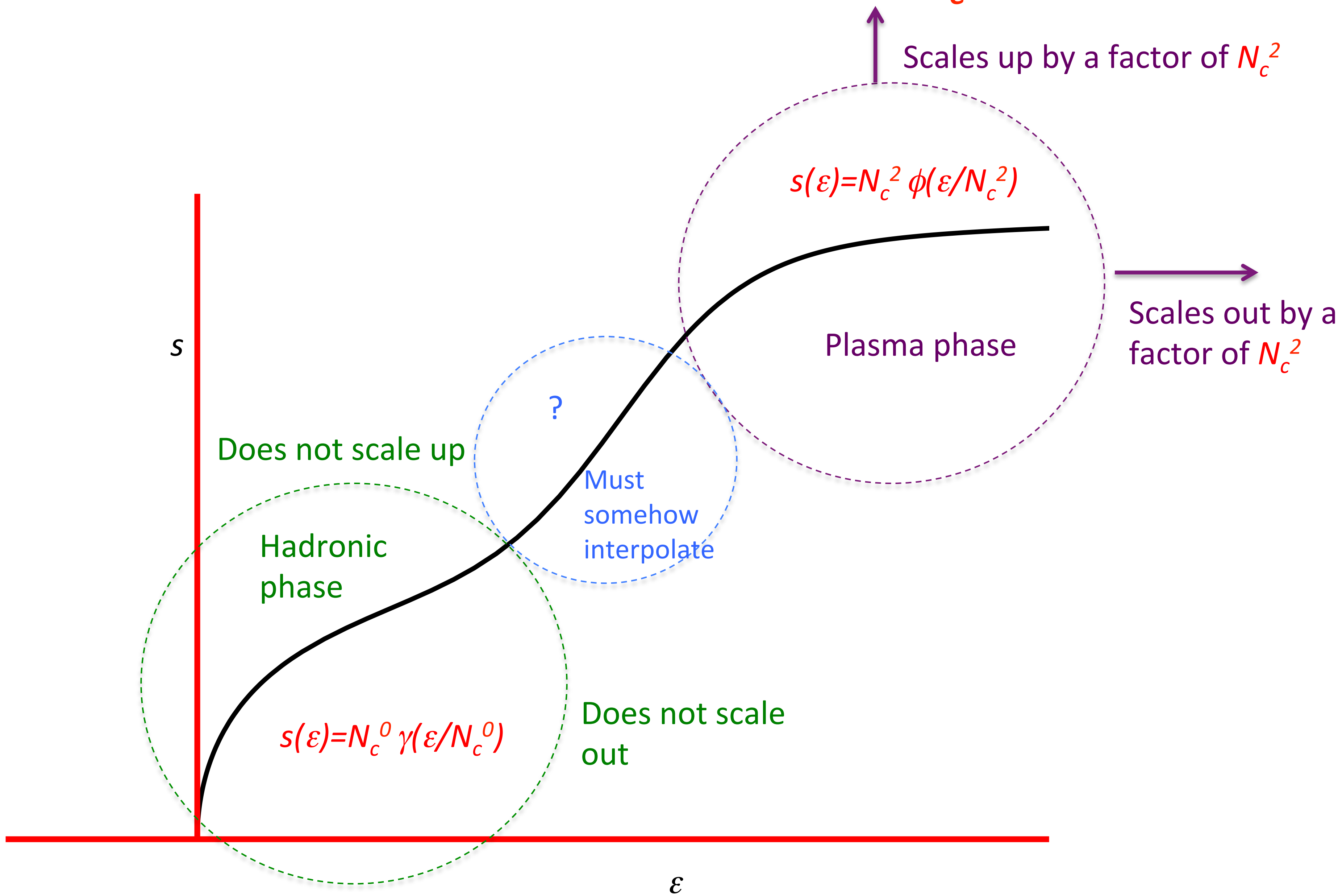

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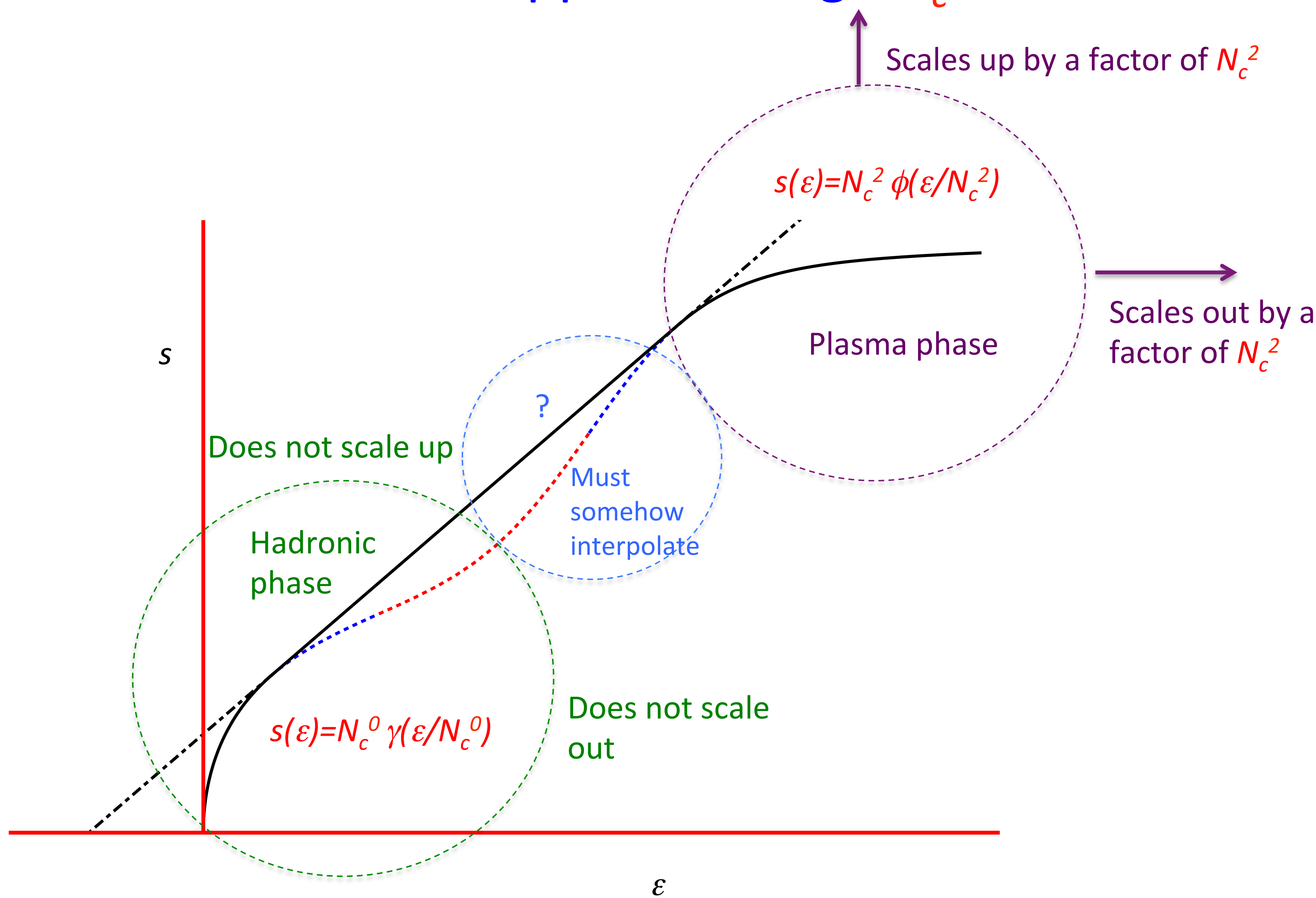

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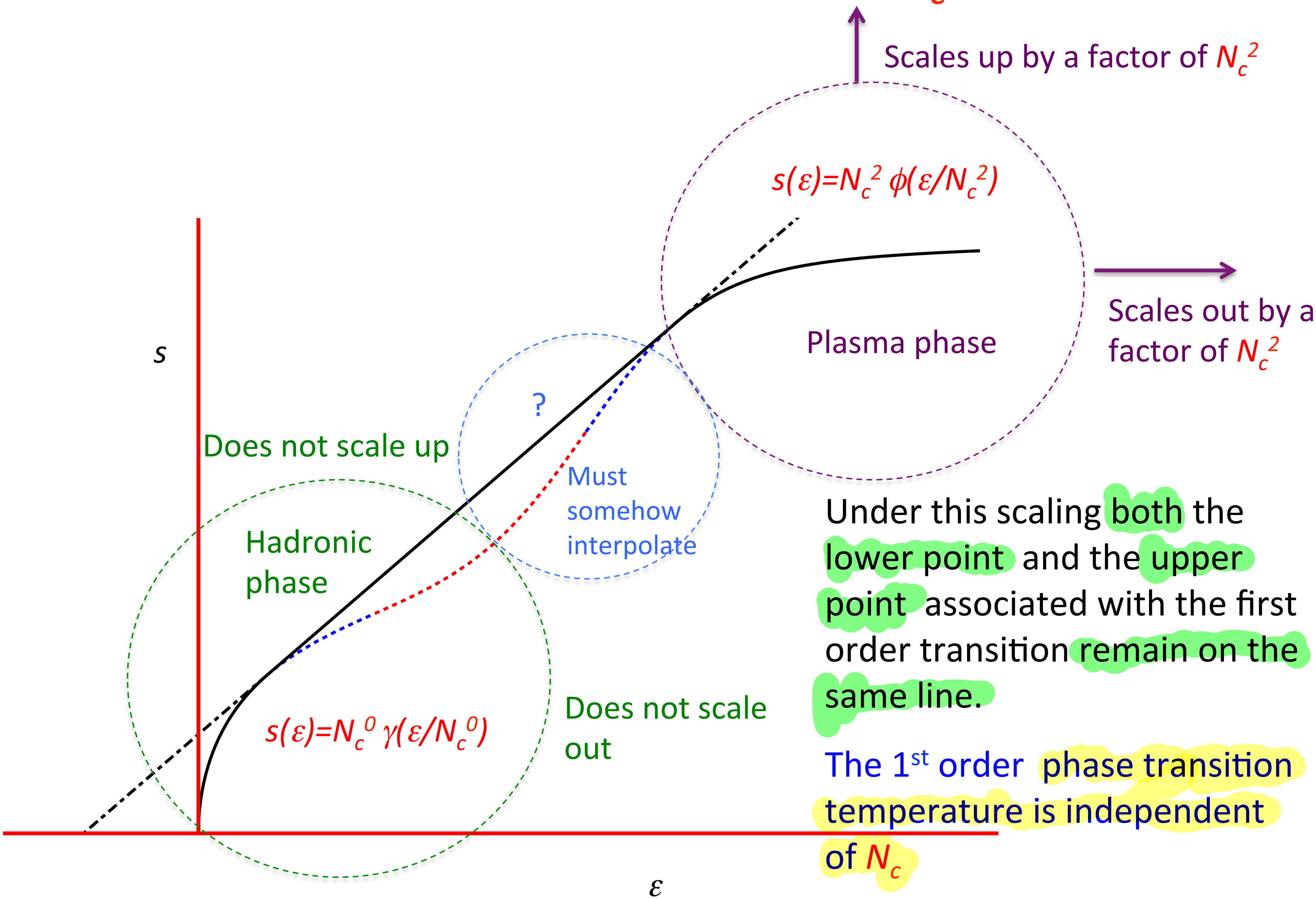
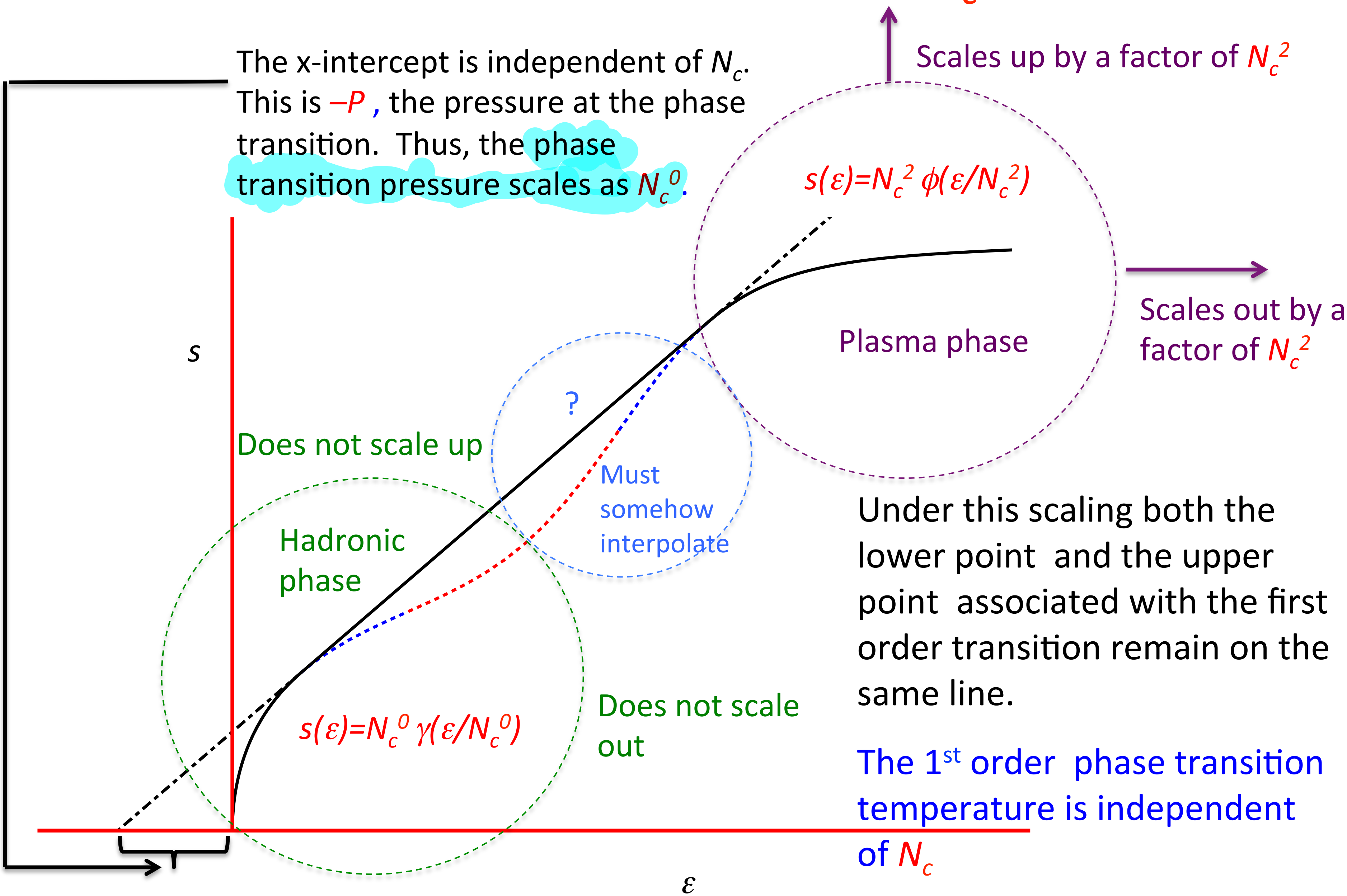


Under this scaling both the lower point and the upper point associated with the first order transition remain on the same line.

The 1st order phase transition temperature is independent of N_c

What happens at large N_c ?

The x-intercept is independent of N_c. This is $-P$, the pressure at the phase transition. Thus, the phase transition pressure scales as N_c^0.



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Implications for the plasma phase

- The phase transition temperature and pressure are each order N_c^0 (i.e. independent of N_c).
- But $P=-f=Ts-\varepsilon$ and in plasma phase s and ε are each $\mathcal{O}(N_c^2)$ and T is $\mathcal{O}(N_c^0)$. Thus generically P is expected to be $\mathcal{O}(N_c^2)$.
- However, near the phase transition but still in the plasma phase, Ts and ε cancel almost exactly, up to relative order N_c^{-2}.
- This cancelation is rather remarkable and leads to some quite surprising results.

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  – Evidence: Analysis based on hydrodynamics suggests that η/s is small (of order $(4\ \pi)^{-1}$). This implies that whatever the medium is its components must be strongly coupled.
    - Based on this people have described the medium formed in these collisions as a (nearly) perfect fluid.

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Others use different criteria for what constitutes a perfect fluid!

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    - Based on this people have described the medium formed in these collisions as a (nearly) perfect fluid.
  - While there is strong evidence that this medium is strongly coupled, the evidence that it is a "plasma" is more problematic.
    - There is no phase transition in QCD between the plasma and hadronic phases. The medium is called a plasma largely because it is far too dense to be a weakly couple hadronic gas.
    - But it is equally not a weakly couple quark-gluon plasma. So why "strongly coupled plasma" & not "strongly coupled hadronic gas"

– A possible cynical answer: RHIC was sold as a machine to discover the QGP and whatever it discovered would be labeled as a QGP!

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A question approaching philosophy: Is it even possible to find a medium in any system which is both clearly in the plasma regime and also clearly strongly coupled?

– Yes! The high temperature phase of Large N_c QCD just above the phase transition
  - Unlike QCD at $N_c=3$, there is a phase transition which cleanly delineates the hadronic from plasma phases. The high temperature phase is clearly a plasma.
  - While there is no practical way to test η/s for this system to demonstrates that the constituents were strongly coupled, if the plasma is composed of massless constituents (eg. gluons) there is another useful measure

$$\boxed{\Omega = \frac{\varepsilon}{3P}}$$

– Note that for an noninteracting system of massless constituents $P=\varepsilon/3$ so $\Omega=\varepsilon/(3P)=1$.

- Very weakly acting systems of massless constituents will thus have close to Ω unity.
- If however, $\boxed{\Omega = \frac{\varepsilon}{3P} >> 1}$ the system is clearly strongly coupled.
- Just above the first order phase transition in the plasma phase.

$$\boxed{\Omega = \frac{\varepsilon}{3P} \sim N_c^2}$$

At large N_c QCD unambiguously is both strongly coupled and in a plasma phase!

This is modulo the very reasonable assumption that a first order transition persists.

- It may be somewhat surprising that large N_c analysis gives a clean answer to this question.
- However, it makes a much more striking prediction about the supercooled phase: Negative absolute pressure.

Absolute pressure is the pressure relative to the vacuum

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- **Phrase is most often used to distinguish it from "gauge pressure".**
- **Gauge pressure is not the pressure of a gauge theory the pressure but rather the pressure read by a pressure gauge—which measure pressure relative to the ambient atmospheric pressure**

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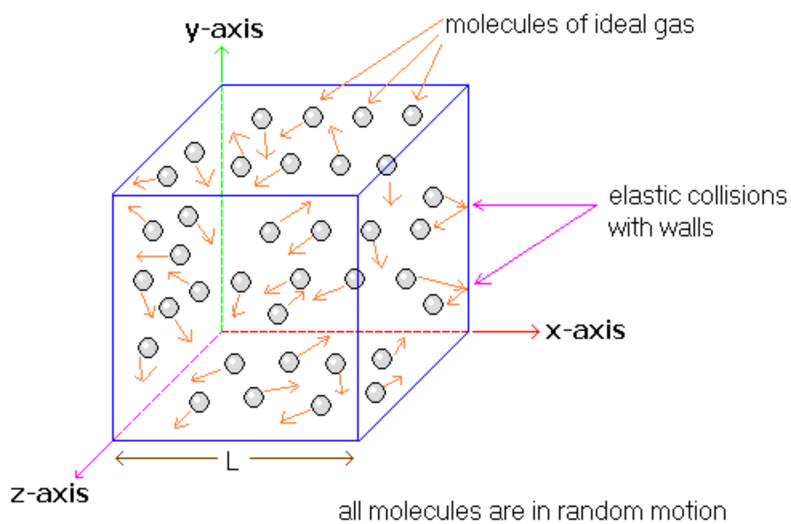

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- However, it makes a much more striking prediction about the supercooled phase: Negative absolute pressure.
  - Negative pressure absolute pressure violates our naïve kinetic theory intuition based on particles bouncing around in a gas.
  - Intuition based on experience with stable phases in which we never come across negative absolute pressure makes negative pressure seems weird.
  - **No go theorem:** systems with no chemical potentials or fixed densities of conserved quantities and with positive temperatures everywhere that are in a stable phase cannot have negative absolute pressure.

This follows from the condition *s* (*ε*) is everewhere concave down, and the facts that $s(0)=0$, $s'(\varepsilon)=T^{-1}>0$, and $P=Ts-\varepsilon$.

– Concavity means that $s'(\epsilon_1) > s'(\epsilon_2)$ if $\epsilon_1 < \epsilon_2$

Thus

$$\boxed{\begin{aligned} s(\epsilon_a) &= \int_0^{\epsilon_a} \mathrm{d}\epsilon\, s'(\epsilon) > s'(\epsilon_a)\epsilon_a \\ P_a &= \frac{s(\epsilon_a)}{s'(\epsilon_a)} - \epsilon_a > \frac{s'(\epsilon_a)\epsilon_a}{s'(\epsilon_a)} - \epsilon_a > 0 \end{aligned}}$$

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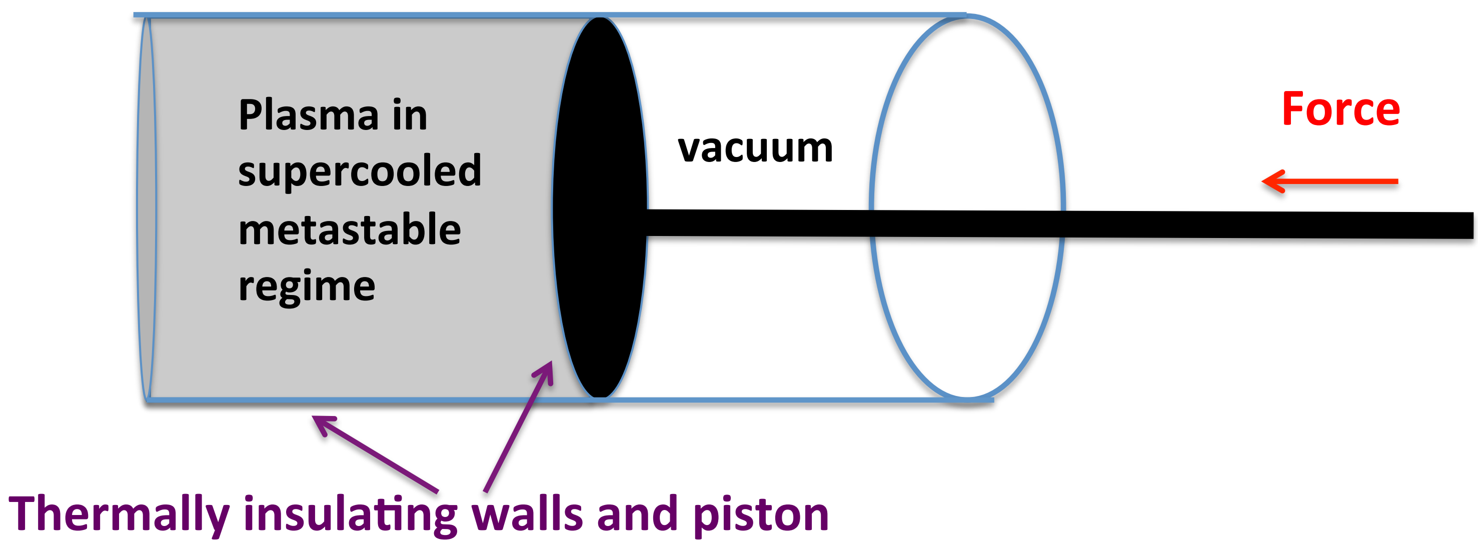
Thus
$$s(\epsilon_a) = \int_0^{\epsilon_a} \mathrm{d}\epsilon\, s'(\epsilon) > s'(\epsilon_a)\epsilon_a$$

$$P_a = \frac{s(\epsilon_a)}{s'(\epsilon_a)} - \epsilon_a > \frac{s'(\epsilon_a)\epsilon_a}{s'(\epsilon_a)} - \epsilon_a > 0$$

However this argument does not apply to metastable phases. Thus, it is possible that they have negative absolute pressure and at large N_c, they do provided a generic 1st order transitions suvrives at large N_c

Negative absolute pressure is remarkable



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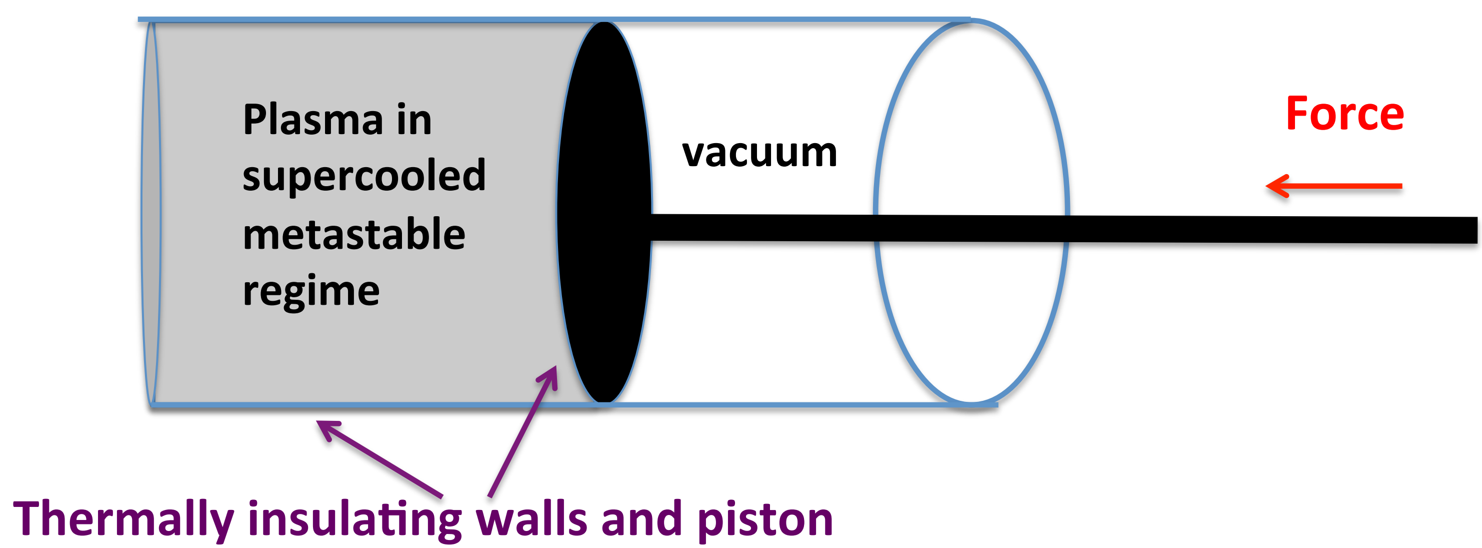
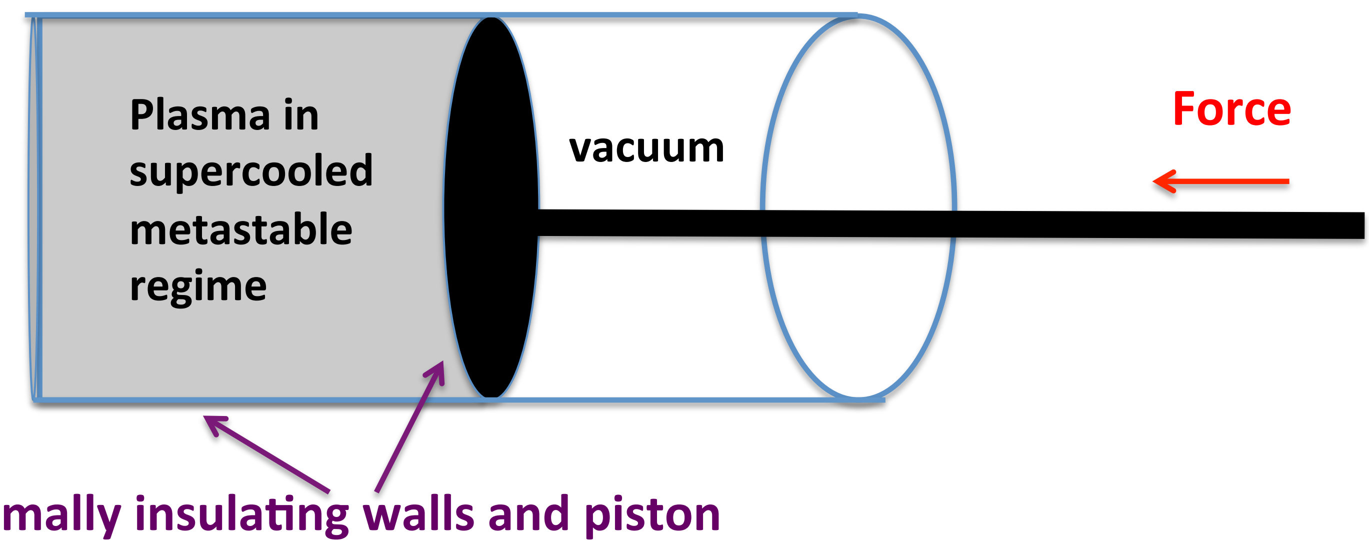


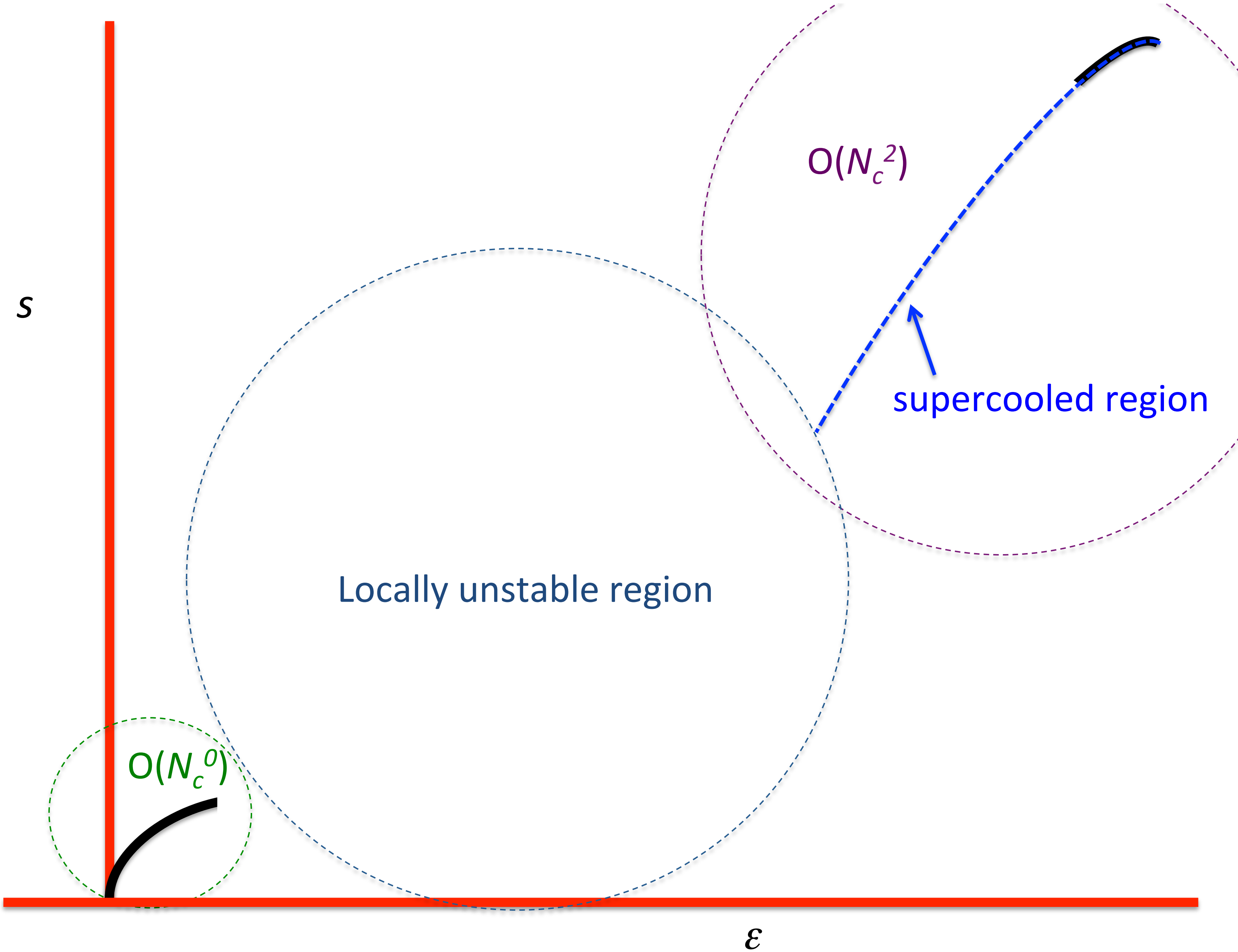
The medium is not just weird—it sucks!

Negative absolute pressure is remarkable

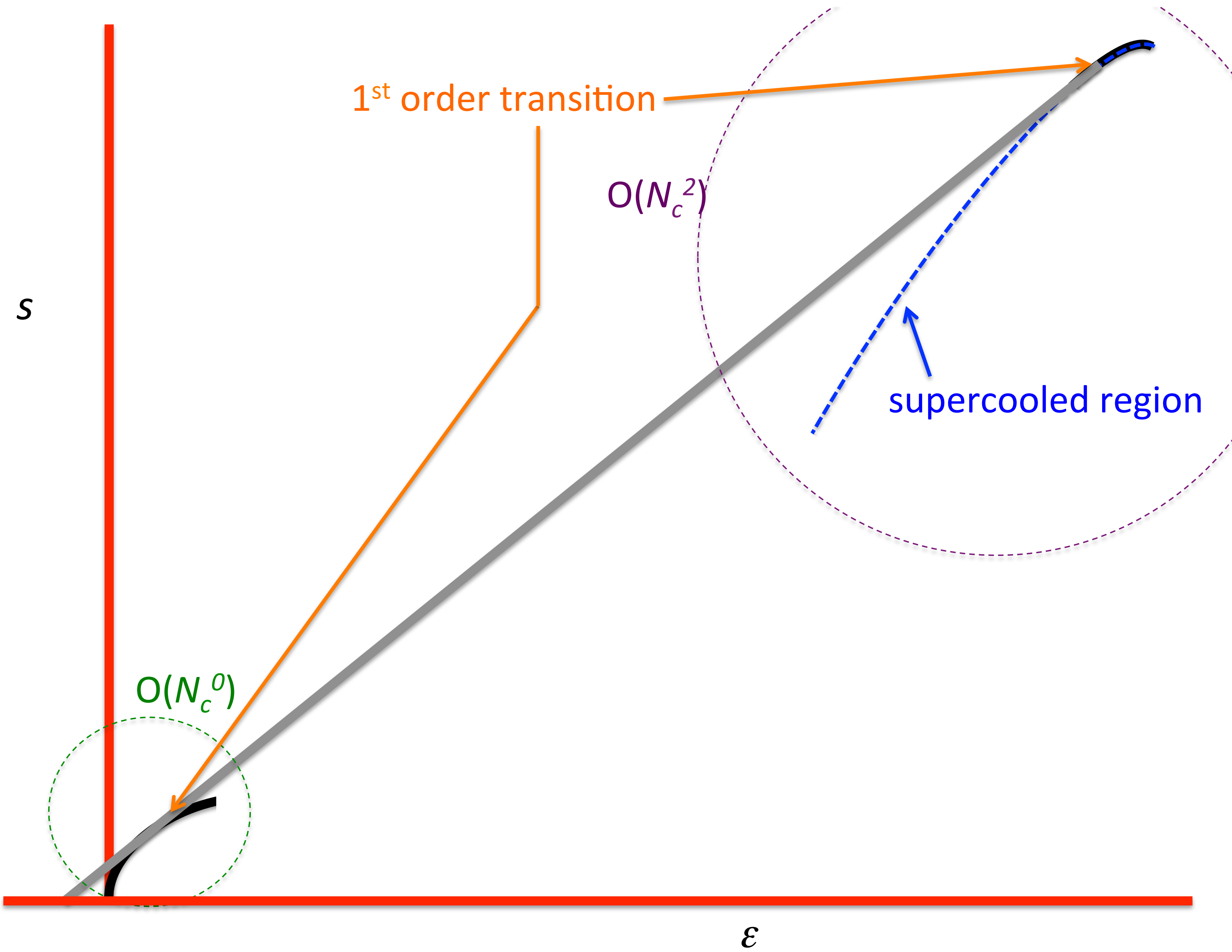


The medium is not just weird—it sucks!

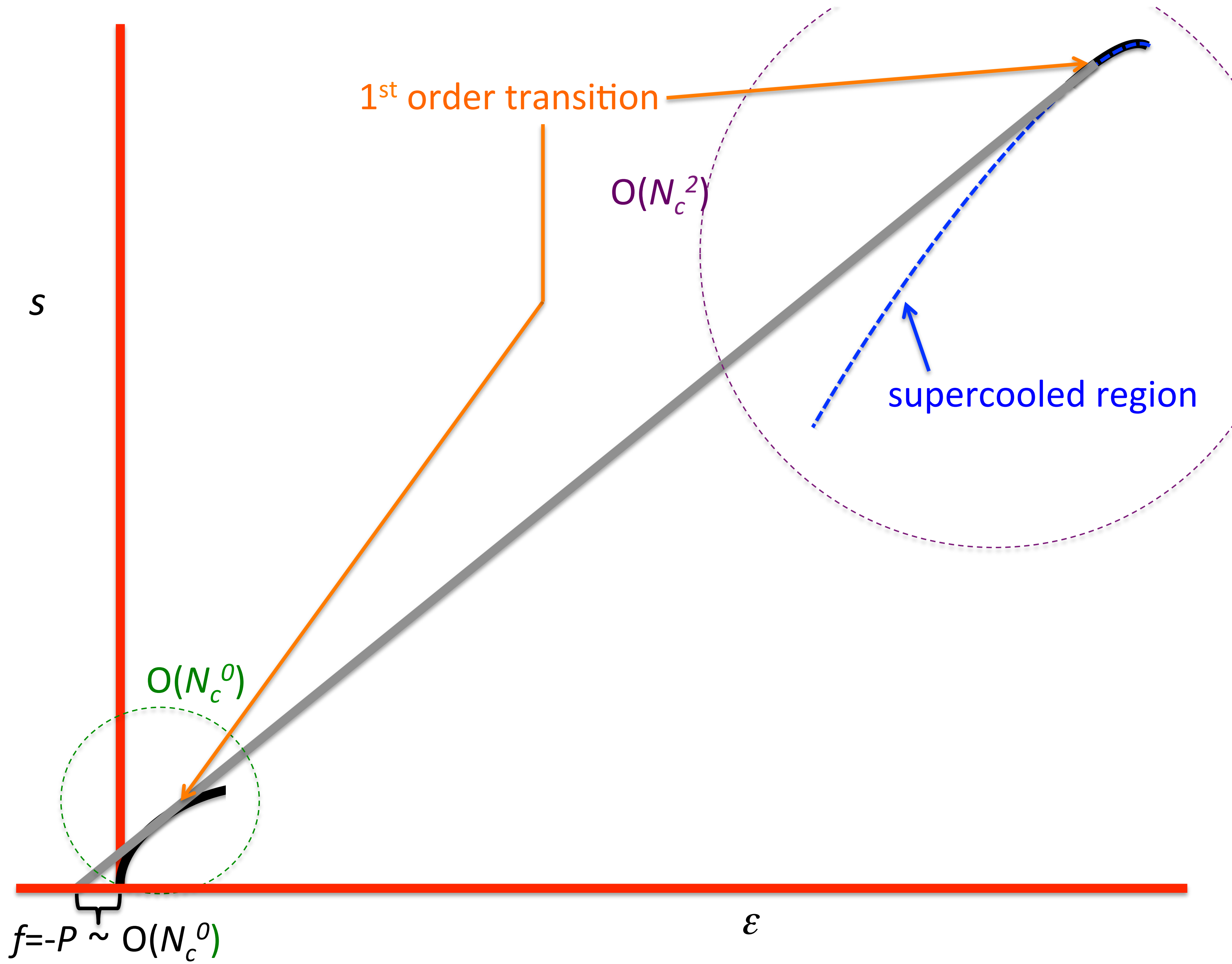
The break down of intuition based on kinetic theory, indicates that whatever this medium is, the pressure is not describable in terms of particles or quasiparticles that strike the wall transferring momentum and imparting an outward pressure. **This requires a strongly coupled theory where the quasiparticle motion is not dominant.**

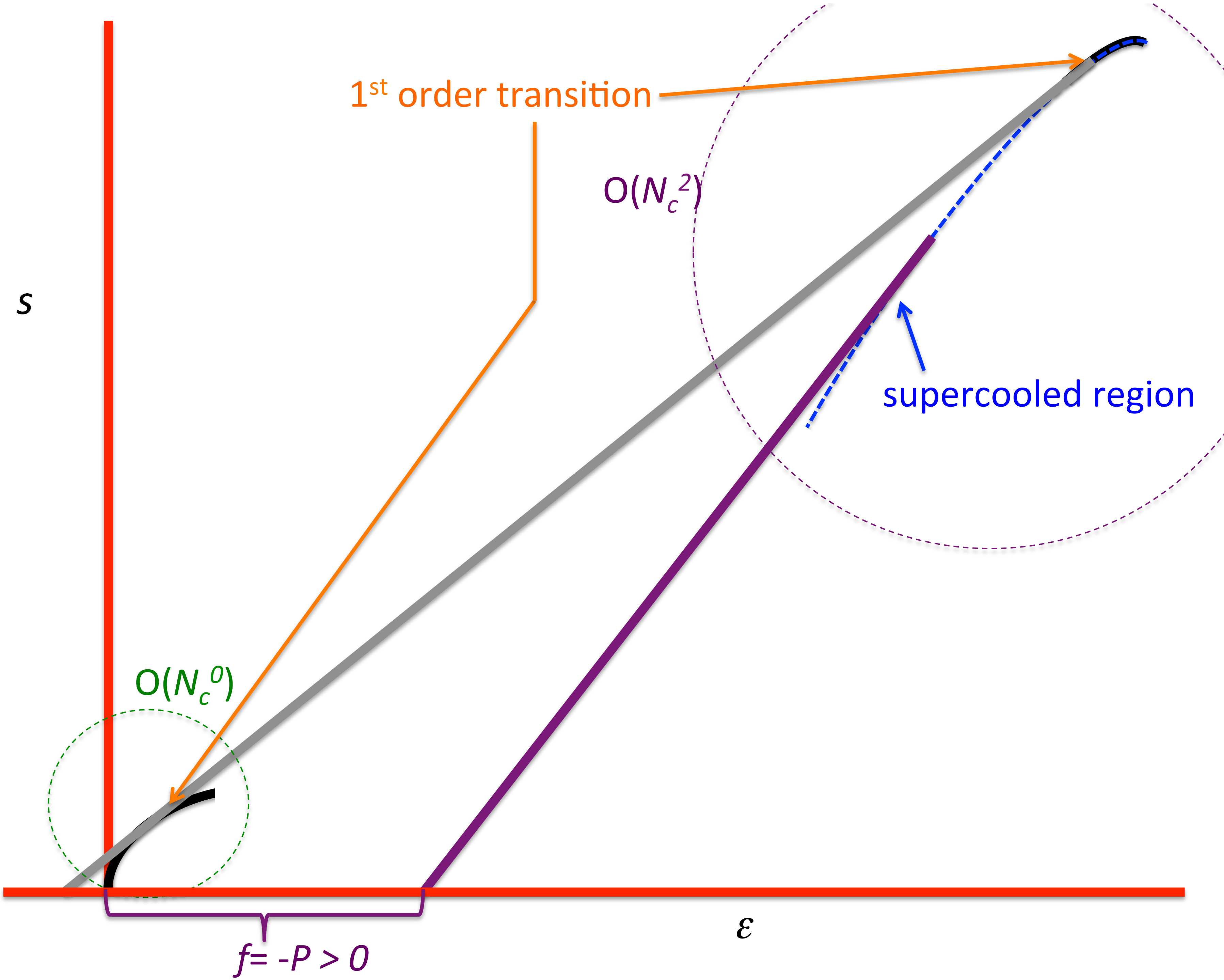


s
O(N_c^2)
supercooled region
Locally unstable region
O(N_c^0)
ε



1st order transition
$O(N_c^2)$
s
supercooled region
$O(N_c^0)$
ε


1st order transition
O(Nc2)
s
supercooled region
O(Nc0)
ε
f=-P ~ O(Nc0)



1st order transition
$O(N_c^2)$
s
supercooled region
$O(N_c^0)$
ε
$f = -P > 0$

An algebriac way to see this:

Assume that there is a supercooled phase that exists over a range of temperature of order N_c^{0} and let T_{sc} be in the supercool phase with $T_c - T_{sc} \sim N_c^{0}$

$$P(T_{sc}) = P(T_c) - \int_{T_{sc}}^{T_c} dT \, \tfrac{dP}{dT}$$

$$= P(T_c) - \int_{T_{sc}}^{T_c} dT \, s(T) \qquad \textbf{since } \tfrac{dP}{dT} = -\tfrac{df}{dT} = s$$

$$< \underbrace{P(T_c)}_{\sim N_c^0} - \underbrace{(T_c - T_{sc})}_{\sim N_c^0} \underbrace{s(T_{sc})}_{\sim N_c^2} \qquad \textbf{since } s(T) \textbf{ increases monotonically}$$

$T_c - T_{sc} > 0$ and $s(T_{sc}) > 0$, thus $P(Ts_c) < 0$ at large N_c

- There is a caveat.
  - There must be a supercooled regime with negtive absolute pressure at large N_c, **provided that a metastastable supercooled regime exists.**
  - Logically a first order transition could exist in which the phase transition point happens to coincide with a point of inflection at large N_c; if this happens there is no metastable regime.
  - There is no reason to expect this to happen based on large N_c analysis; and it would be even more interesting then negative absolute pressure.

So we can conclude something cool happens!

Either the metastable supercooled phase does not exist or it has negative absolute pressure.

- The focus so far has been on the plasma phase. Are there any surprises in the hadronic regime?

  Yes!

- The key to understanding them is the fact that large N_c QCD should have a Hagedorn spectrum.
  - This is a very old expectation (Thorn 1981) . It is based, in part on the belief that large N_c QCD becomes a string theory, and string theories have Hagedorn spectra
  - There is a generic argument without recourse to stringy models (a sort of "physicist's proof") that large N_c QCD based on the growth of the number of independent operators and natural assumptions about the onset of a viable perturbation for correlators (TDC 2009)

- a Hagedorn spectrum for the density of hadrons as a function of mass asymptotically $N(m) \sim m^{-d} \exp(m/T_H)$, where $N(m)$ is the number of mesons and glueballs with mass less than m, T_H, the Hagedorn temperature and is a mass parameter and $-d$ fixes power law prefactor.

- In the large N_c limit, T_H , corresponds to an upper bound on the temperature of hadronic matter

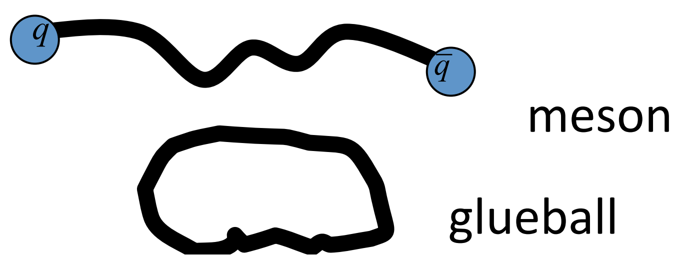
The Hagedorn Spectrum

The Hagedorn Spectrum

Strictly, it only makes sense for large N_c, since only at large N_c do hadrons become narrow and their masses well defined

- The value of the prefactor power $-d$ plays a nontrivial role in the large N_c thermodynamics (TDC 2006, Thorn 1981)
  - If $d>7/2$, the system can reach T_H with a finite energy density and entropy density; for $d \leq 7/2$ they diverge.

- The value of the prefactor power $-d$ plays a nontrivial role in the large N_c thermodynamics (TDC 2006, Thorn 1981)
  - If $d>7/2$, the system can reach T_H with a finite energy density and entropy density; for $d \leq 7/2$ they diverge.
  - There is a good reason to believe that $d = 4$.
    - $d = 4$ is the result for a bosonic string.
    - Highly excited mesons and glueballs are expected to look like excitations of flux tubes which become increasingly stringy as the flux tubes get long—as they do for highly excited states.



Historical Note

Modern string theory grew out of the failed attempt in pre-QCD days to treat strong interactions as a string theory.

It was ultimately abandoned

- **Phenomenological issues (a pesky massless spin-2 meson etc.)**
- **Theoretical consistency (negative norm states, tachyons)**
- **Emergence of QCD as a viable field theory for strong interactions**

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Historical Note

The d=4 suggested by stringy dynamics differs from Hagedorn's original proposal from 1965 which had d=5/2 . This had the T_H unreachable since it required an infinite energy. T_H *was* viewed as a maximum possible temperature roughly analogous to absolute zero.

d=5/2 was predicted based on Hagedorn's "statistical bootstrap model". To modern eyes (or at lest mine) it does not seem at all compelling but it led to a very important insight

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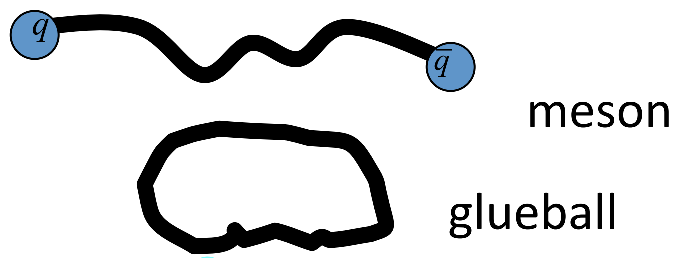
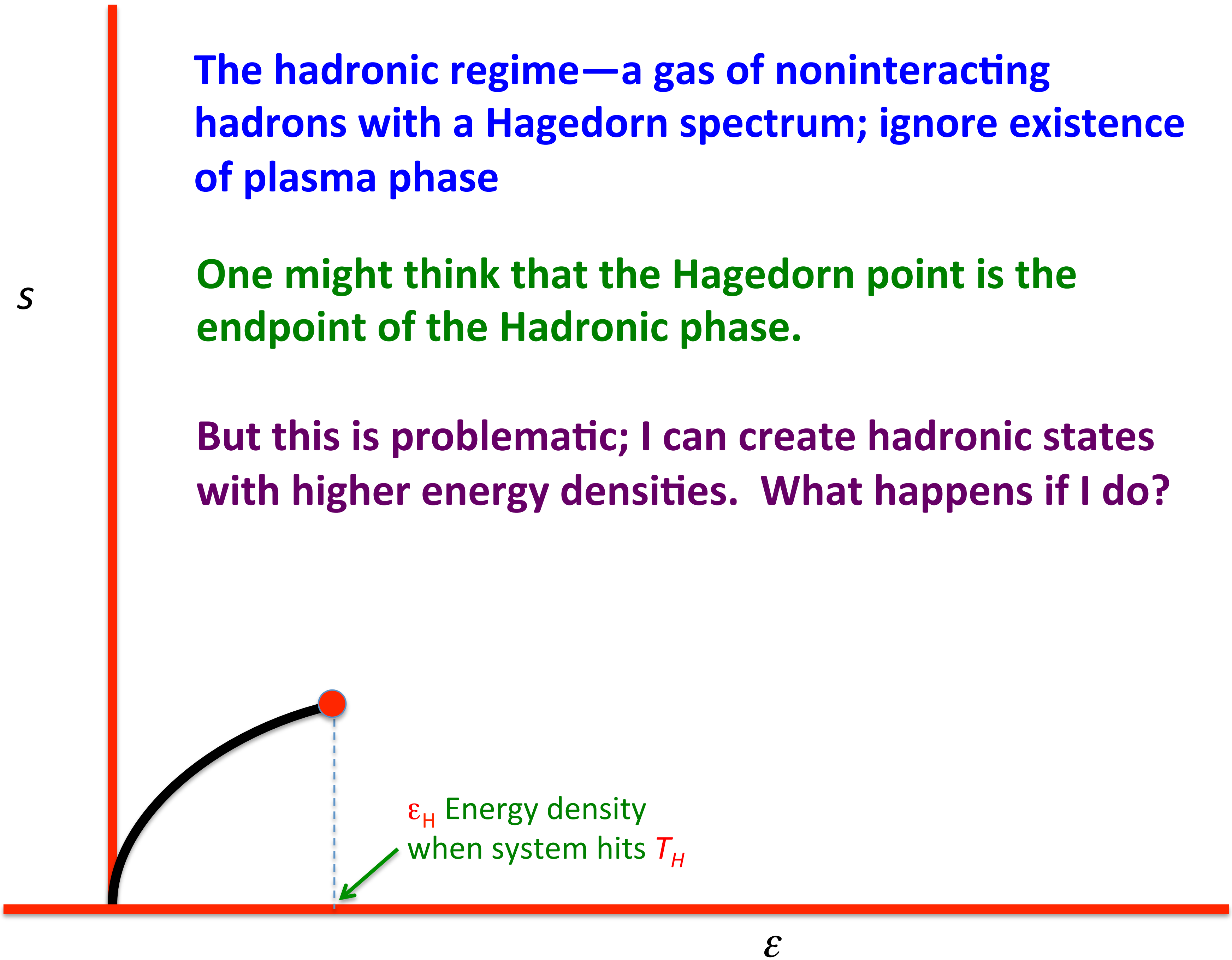


- $d>7/2$ is assumed in what follows.

The hadronic regime—a gas of noninteracting hadrons with a Hagedorn spectrum; ignore existence of plasma phase

One might think that the Hagedorn point is the endpoint of the Hadronic phase.

But this is problematic; I can create hadronic states with higher energy densities. What happens if I do?



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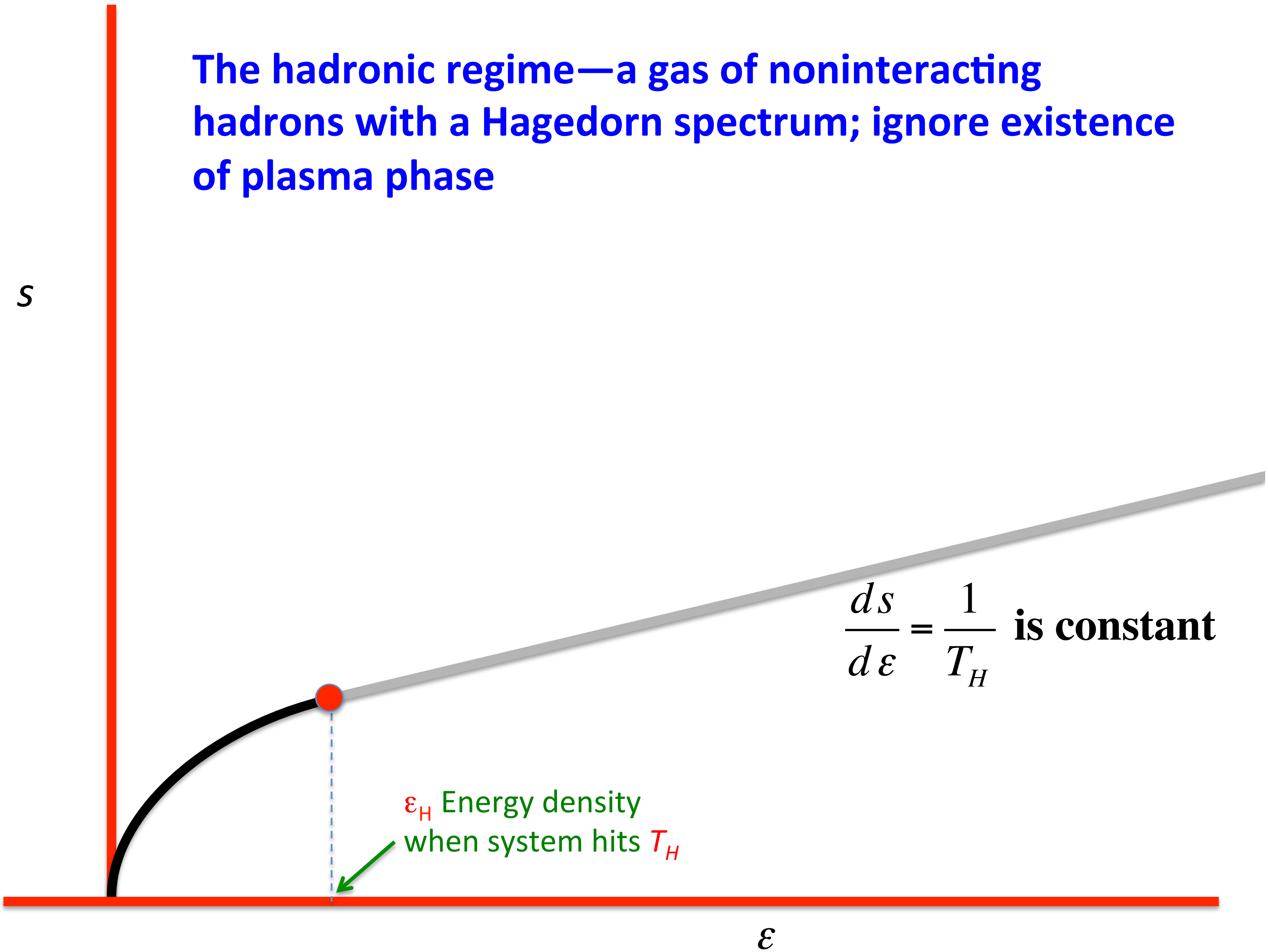

Beyond the Hagedorn point

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Why?

Look at thermodynamics subject to an artificial constraint that only masses greater than some large value m_{max} are included. The physical result is when the constraint is removed and m_{max} goes to ∞.

$$s(\varepsilon) = \lim_{m_{\max}\to\infty} \sum_{k=1}^{k_{\max}} s(\varepsilon, m_k)$$

$$\textbf{with } m_{k_{\max}} = m_{\max}$$

This is just an ideal gas with a finite number of components until limit is taken. Thus, the canonical and microcanonical descriptions are equivalent. Canonically, these systems have a well-defined T.

Beyond the Hagedorn point

As $m_{max} \rightarrow \infty$

- **T is bounded from above by T_H since otherwise ε diverges.**
- **For $\varepsilon > \varepsilon_H$, is also bounded from below by T_H. This follows from the fact that at any finite m_{max}, the system is a relativistic ideal gas with a finite (but very large) number of species. Such systems have $\boxed{dT/d\varepsilon = -T^2 s''(\varepsilon) \geq 0}$ everywhere.**

Ergo for $\varepsilon > \varepsilon_H$ $T = T_H$ and $\boxed{ds/d\varepsilon = 1/T_H}$ is constant. As seen in the figure.

We have verified this behavior via a sophisticated analytic calculation and via numerical experiments by fixing energy and directly summing over hadrons up to a cutoff which we increase until it is very large.

The hadronic regime—a gas of noninteracting hadrons with a Hagedorn spectrum; ignore existence of plasma phase

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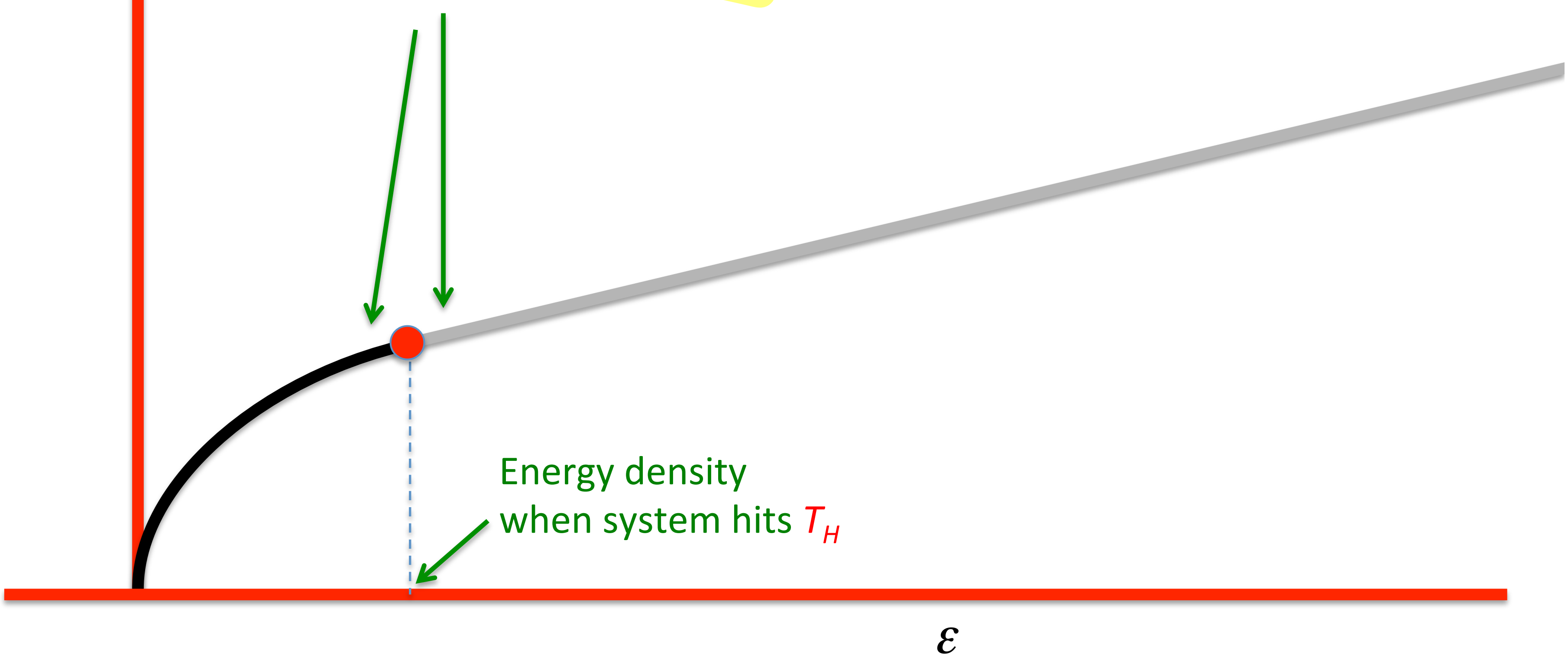
This is very peculiar.

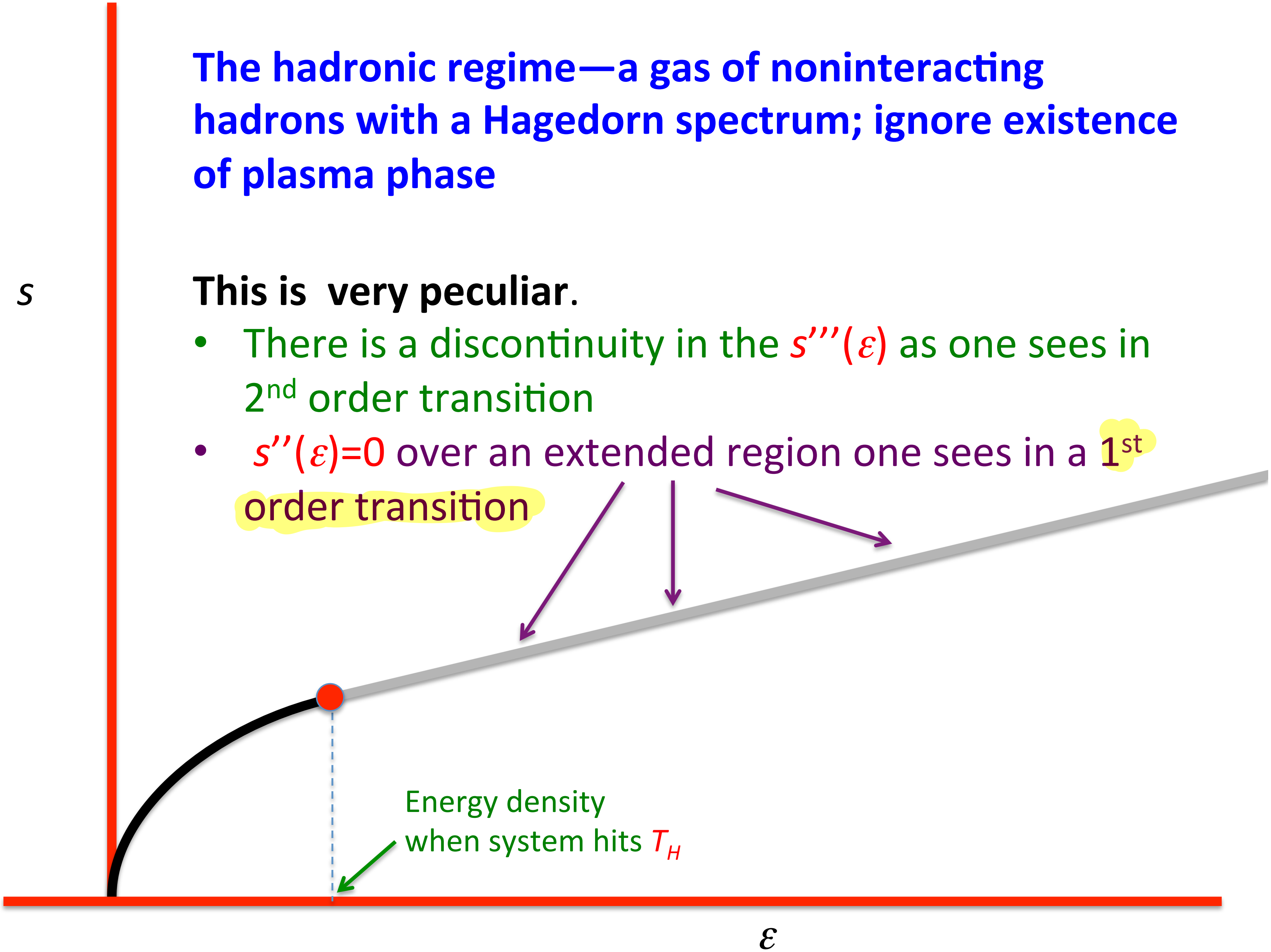
- There is a discontinuity in the $s'''(\varepsilon)$ as one sees in 2nd order transition



The hadronic regime—a gas of noninteracting hadrons with a Hagedorn spectrum; ignore existence of plasma phase

This is very peculiar.

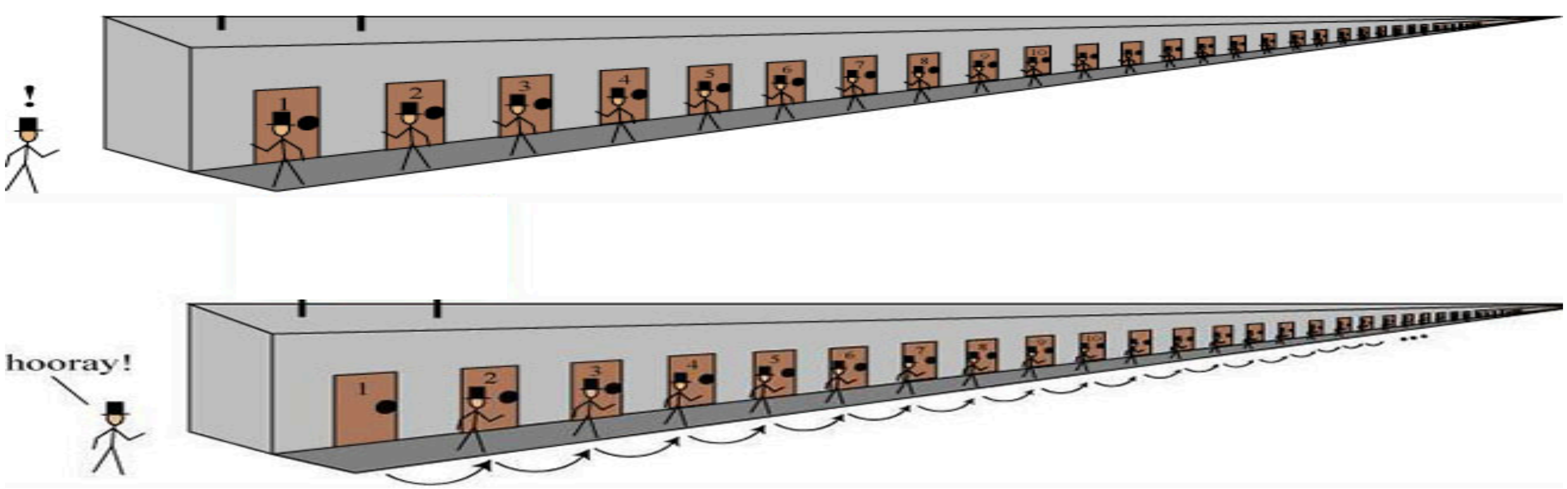
- There is a discontinuity in the $s'''(\varepsilon)$ as one sees in 2nd order transition
- $s''(\varepsilon)=0$ over an extended region one sees in a 1st order transition



- What is going on?
  - There appears to be a breakdown of the thermodynamic limit in which the microcanonical and canonical descriptions become identical at large volumes.
  - While work is still in progress, currently all indications suggest that in a large but finite volume, all of the excess energy beyond $V\varepsilon_H$ is typically contained in a single extremely massive particle.
    - When the volume doubles with the same energy density, instead of doubling the number of heavy particles one still has one but it is twice as massive.

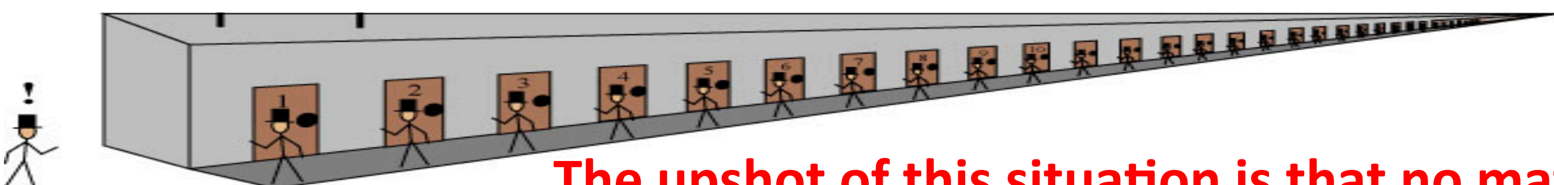
- Dynamically if the system were infinite in size and at an energy density of ε_H and energy in the form of low mass hadrons is added to the system.
  - The lower mass states would thermalize at T_H and the excess energy would be pushed upward to higher masses.
  - This would happen continually and the energy would be pushed to ever higher mass hadrons.
  - The process would not stop if the system is of infinite size.

Situation is a bit reminiscent of Hilbert's Grand Hotel

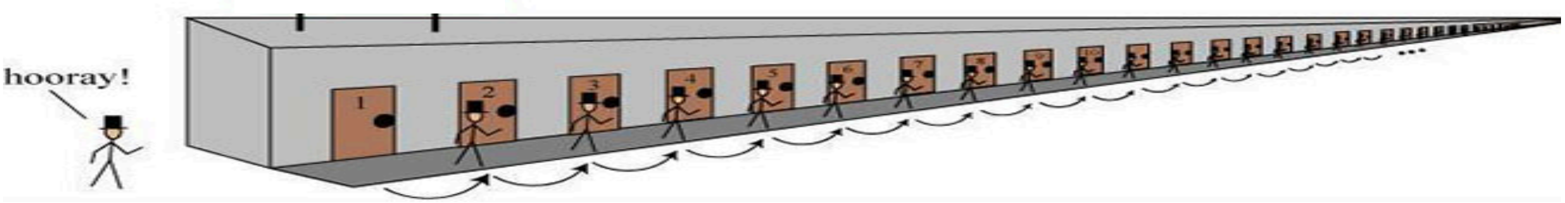


Situation is a bit reminiscent of Hilbert's Grand Hotel

Although the hadronic regime is thermodynamically full at T_H , there is always room for more hadronic ε.



The upshot of this situation is that no matter how big the system, the thermodynamic limit in never reached.



Conclusions/Surprises

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The endpoint of the metastable hadronic phase of large N_c QCD is odd and indicates a breakdown of the usual thermodynamic limit