

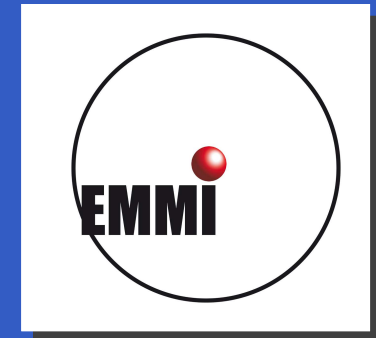
Quark Matter in the Early Universe

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HEIDELBERG



FIAS-EMMI Day, Frankfurt Institute for Advanced Studies
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Work done with Tillmann Boeckel

Boeckel and JSB, PRL 105 (2010) 041301
Boeckel, Hempel, Sagert, Pagliara, Sa'd, JSB,
JPG 37 (2010) 094005

and Simon Schettler

Schettler, Boeckel, JSB, arXiv:1010.4857 and 1012.3342
[astro-ph.CO]

Prelude: the bubbling universe

Breaking news: violence in the universe!



New Scientist, issue of May 22, 2010

REPAIRING REALITY
Computer games to
save the world

TASTE OF TINY
The nanofood
revolution

INFLATION II
Contains scenes of
significant violence

NewScientist

WEEKLY 22 May 2010

FREE!
10 BEST
JOBS IN
SCIENCE

SECRETS OF THE ICE AGES

Earth's roller-coaster climate explained



THIS WEEK

Big bang, part II: the big boil

Did a second furious expansion and a seething mass of bubbles follow the universe's birth?

Rachel Coustard

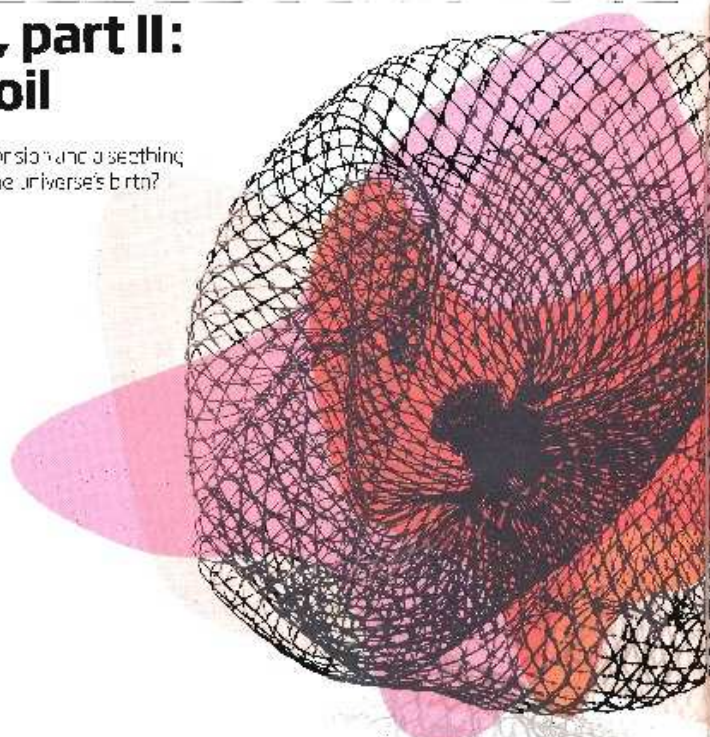
Did the big bang boil? The birth of our universe could have seethed with hot bubbles, and perhaps, a second period of rapid expansion. Such an episode may even still an imprint on the universe that persists to this day and today, even within the wrong track bubble that is dark matter.

Just as theorists try to offer insights into the inflationary epoch thought to have ended the universe as we know it.

This process is thought to have amplified tiny quantum fluctuations in the vacuum, giving rise to the megastuctures we see all around us in the universe today.

A second, prolific and transformative is thought to have followed but on the heels of inflation. Just 10⁻³² seconds and told said at 10²⁸ degrees, the universe expanded from a superhot soup of sub-nuclear particles called a quark-gluon plasma (QGP) into particles such as protons and neutrons. But exactly how this happened is far from clear.

Decades ago, physicists suspected that quarks could have been abundant and violent in that era, but the universe expanded through inflation, freezing the QGP into a dense soup of hadrons. But how did the quarks get to form? These hadrons release the energy of the quarks and gluons into the vacuum, and particles composed of quarks and gluons are formed. The hadrons are produced, but they are not yet stable. They are produced, but they are not yet stable. They are produced, but they are not yet stable.



have seen the seeds of intergalactic magnetic structures that persist today. It is, however, still a mystery.

Yet, computer simulations of conditions in the early universe soon began to indicate the transition from the superhot QGP of the matter we see today wasn't nearly so dramatic. This was indicated in 2006, when researchers at the University of

"Just microseconds old, the universe condensed from a superhot soup of sub-nuclear particles"

Wright reported the results of rigorous calculations that showed that the transition must have been smooth. "This was supposed to be the final word on the subject," says Thomas Schaefer, a nuclear physicist at the University of Bielefeld.

Now some physicists are arguing that we ought to reconsider whether the cosmos could be "boiling" with a sea of all-over-the-place quarks and gluons as violently as it would and might even have been present by an additional phase

of rapid expansion of the universe. And this is because of a simulation of QGP in which matter and antimatter are found in equal amounts. This, in turn, implies that the early universe, which is thought to have contained both and new particles of matter for every billion pairs of antimatter, must allow these particles to annihilate each other, leaving behind only a small amount of matter. But what makes up the stars and galaxies we see today? Yet last year, Tommi Schwab and Mark Suasa, Ettore

- In this section
- Re-lighting the fire in the mind, page 10
- Oil from spill sliding in deep-water drama, page 11
- Shadocks provide a window into artificial life, page 16



based on estimates from previous models, they'd claim the universe's total mass included 10¹⁰ quarks about 10⁻¹² of a second after the big bang. If we're right, they must have a several billion-fold of annihilating with other dark matter particles.

"A big uncertainty is how long the universe would expand and cool before bubbles began to form"

conference. They have calculated that about 10⁻¹² of a second after the big bang, the interactions of quarks and gluons drop the quarks to a rapid expansion of the universe. This secondary "inflation" would have ended our signs of a high-mass matter system, they calculated. Schwab says, "The universe may still have bubbles, but for now the looks suspicious, says Schaefer, who is not associated with the study. To proceed, for any, physicists must first understand what conditions lead to such violent, bubbly first-order phase transitions in QGP. New laboratory experiments

different properties than those that are currently favored. If dark-matter particles were more abundant, the early universe, if we're right, they must have a several billion-fold of annihilating with other dark matter particles.

Problematically, these less-interactive dark-matter candidates, if they exist, may be beyond the range of detection of experiments such as the Large Hadron Collider at CERN, says Bielefeld. Generally, if the LHC does find a dark-matter candidate, then it's over.

It's probably a case of an error that is too small. Right now the two new studies raise more questions than they answer. The physics of QGP, which contains more matter than any matter is difficult to create, and little is known about how they behave. A big uncertainty is how long the universe would expand and cool before bubbles began to form. "Probably, it's calculated that the universe may still have bubbles, but for now the looks suspicious, says Schaefer, who is not associated with the study. To proceed, for any, physicists must first understand what conditions lead to such violent, bubbly first-order phase transitions in QGP. New laboratory experiments

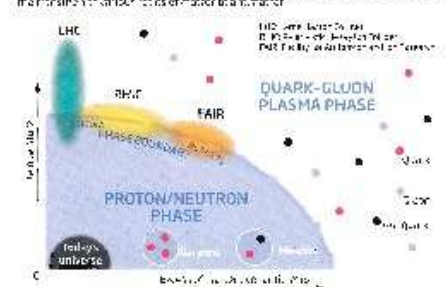
to probe the behavior of quarks and gluons in the early universe, like that of a bubble. Although quarks and gluons are created by colliding heavy atoms like gold, the high energies involved tend to produce equal or a abundant amounts of matter and antimatter.

By lowering the energy of collisions—reducing the size of the bubbles in the laboratory—Brookhaven National Laboratory in Upton, New York, hopes to probe the behavior of the plasma in situations in which quarks and gluons form a quark-gluon plasma. The facility for antimatter and ion research at Brookhaven, Cornell University, will begin its first major study in 2010, looking for the QGP's phase transition.

Spelling it out, the finding demonstrates that a bubble of matter formation occurred in the early universe is an ongoing, ongoing process. One caveat will be to find out if quarks and gluons are still forming or if they are still forming. The researchers could form a quark-gluon plasma in the laboratory, but it was created when the bubble collapsed.

If had occurred, the discovery in the field of hadron physics, says Schwab. "It just shows that the story might not be as simple as we think."

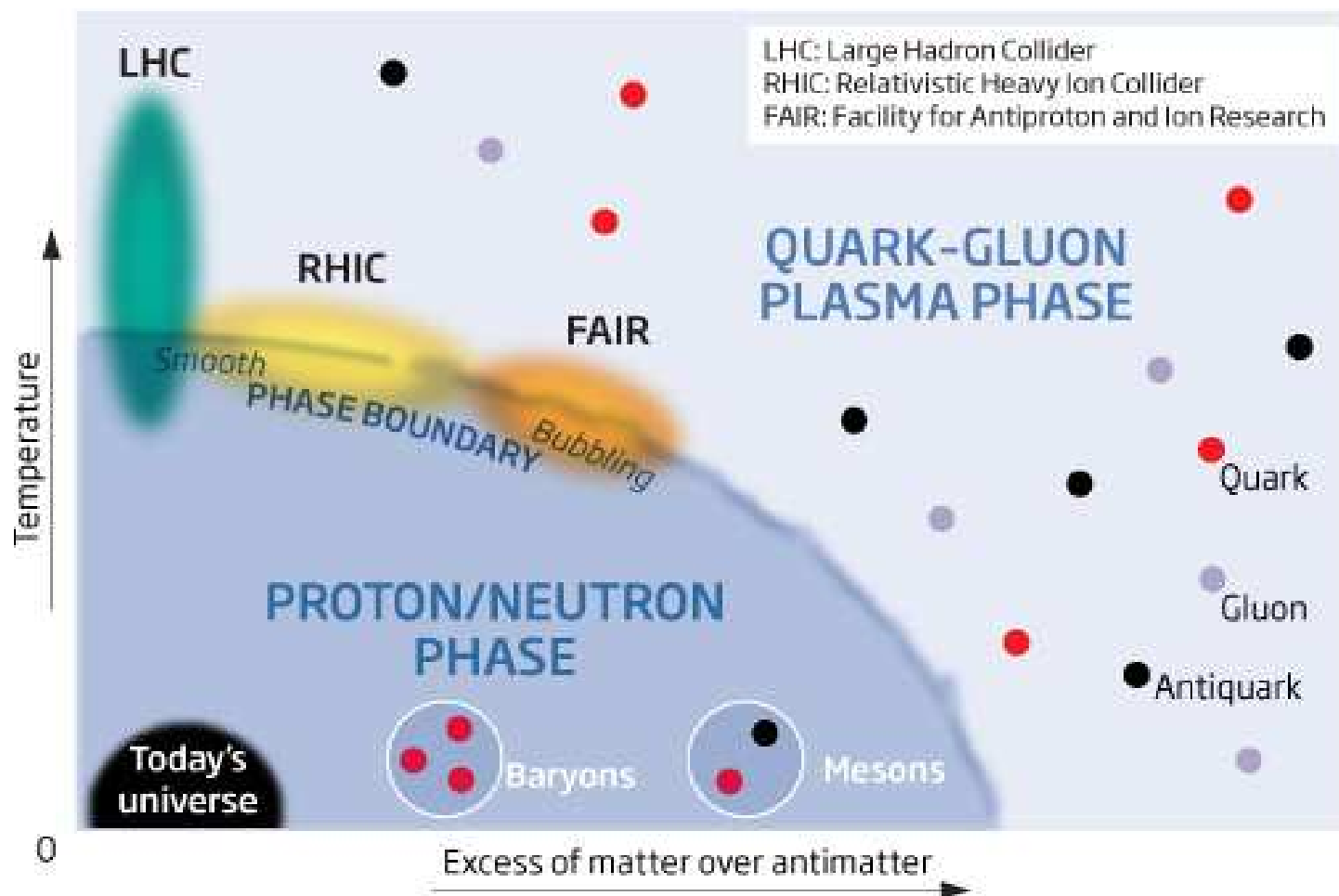
Just a phase the universe went through: After the universe cooled, the quark-gluon plasma condensed into a bubbling phase change to form the particles we know today. Bubbles of matter and antimatter formed in the early universe.



Big bang II: the 'new scientist picture'

Just a phase the universe went through ©NewScientist

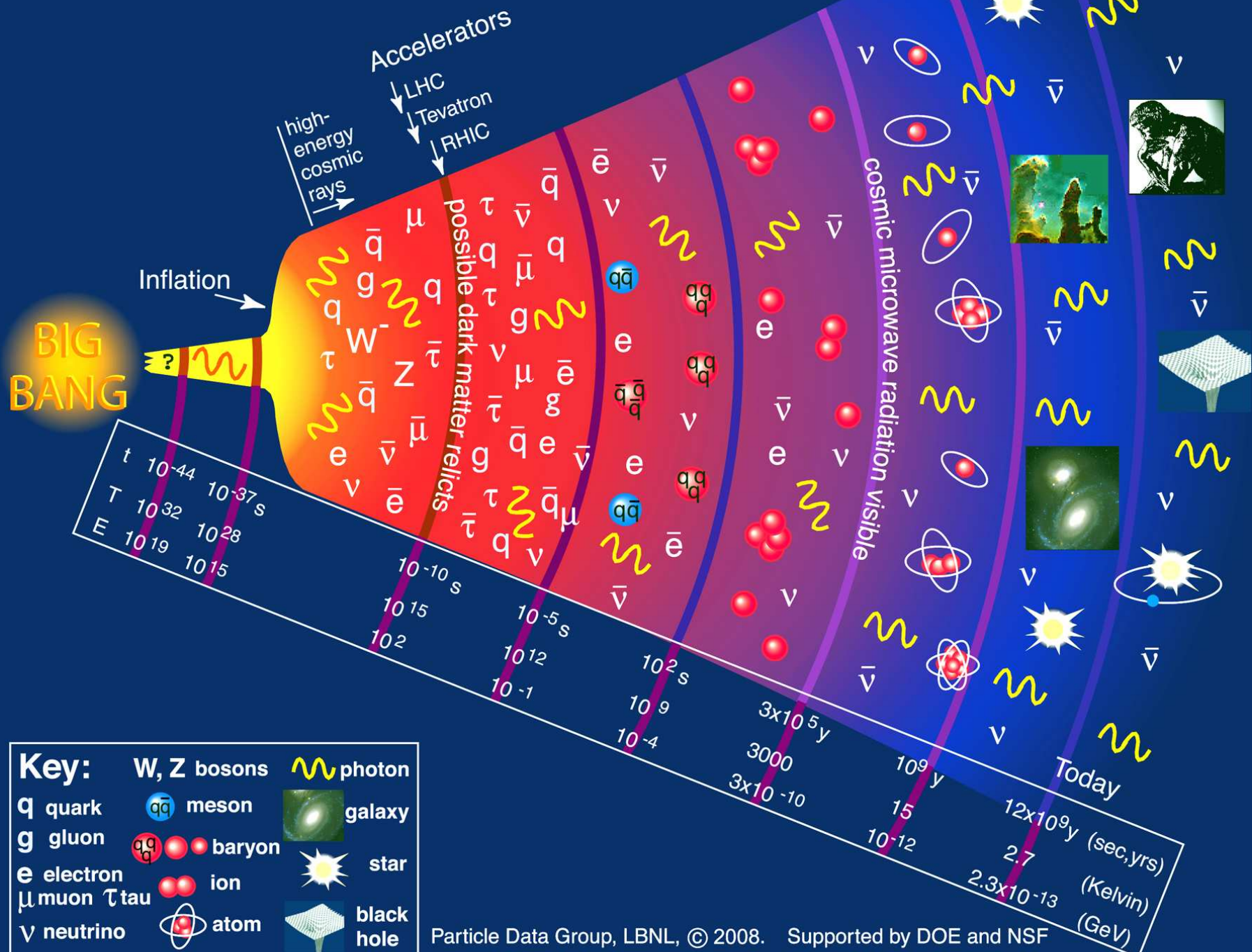
As the early universe cooled, the quark-gluon plasma underwent either a smooth or a "bubbling" phase change to form the matter we see today. Experiments are set to probe the transition at various ratios of matter to antimatter



Outline

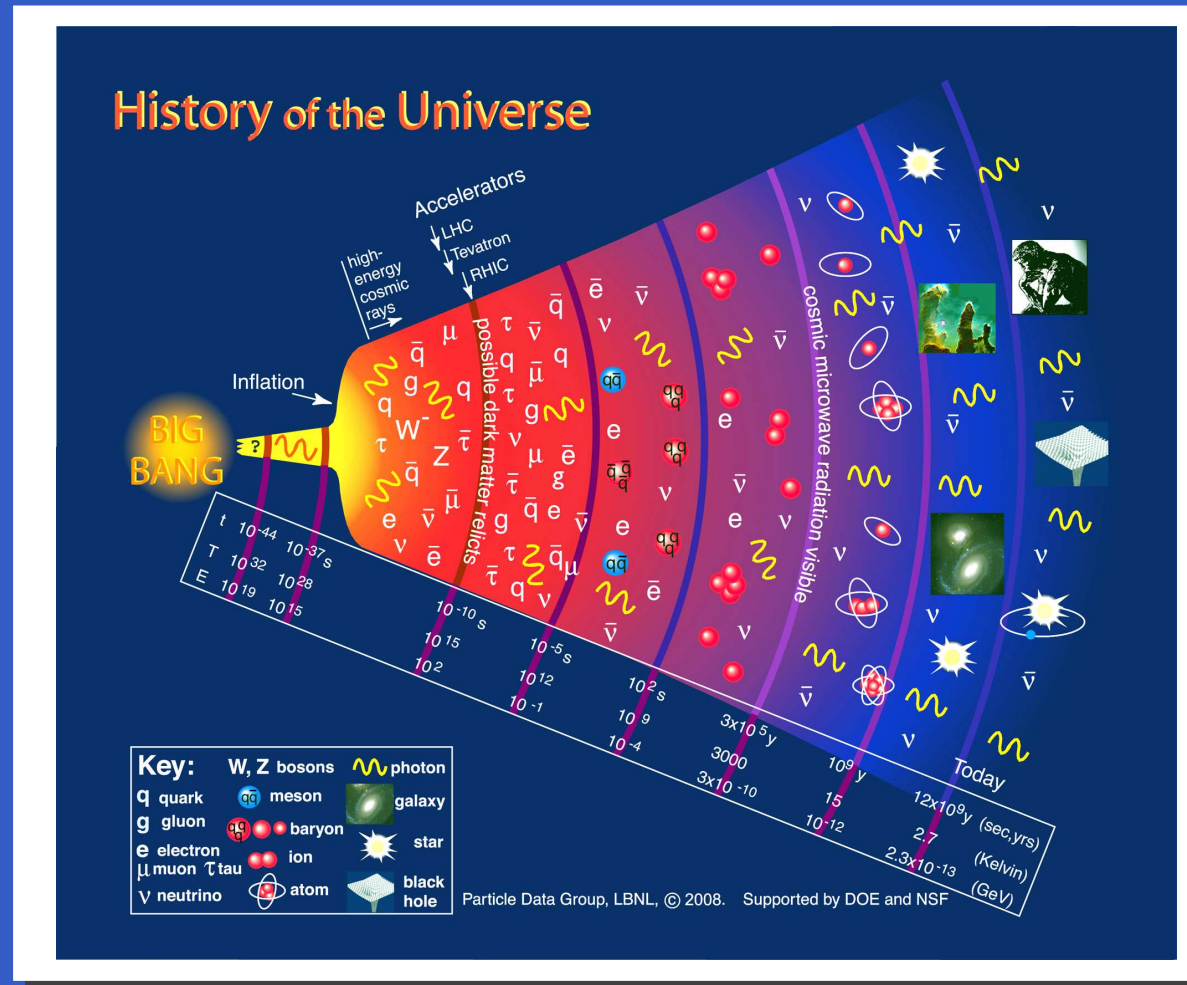
- Standard cosmology
- QCD phase transition with a little inflation
- Ingredients: Affleck-Dine baryogenesis, metastable vacuum, bubble nucleation
- Implications and possible signals:
 - large-scale structure
 - WIMPs and mini black holes
 - cosmological magnetic fields
 - gravitational wave background
- Summary

History of the Universe



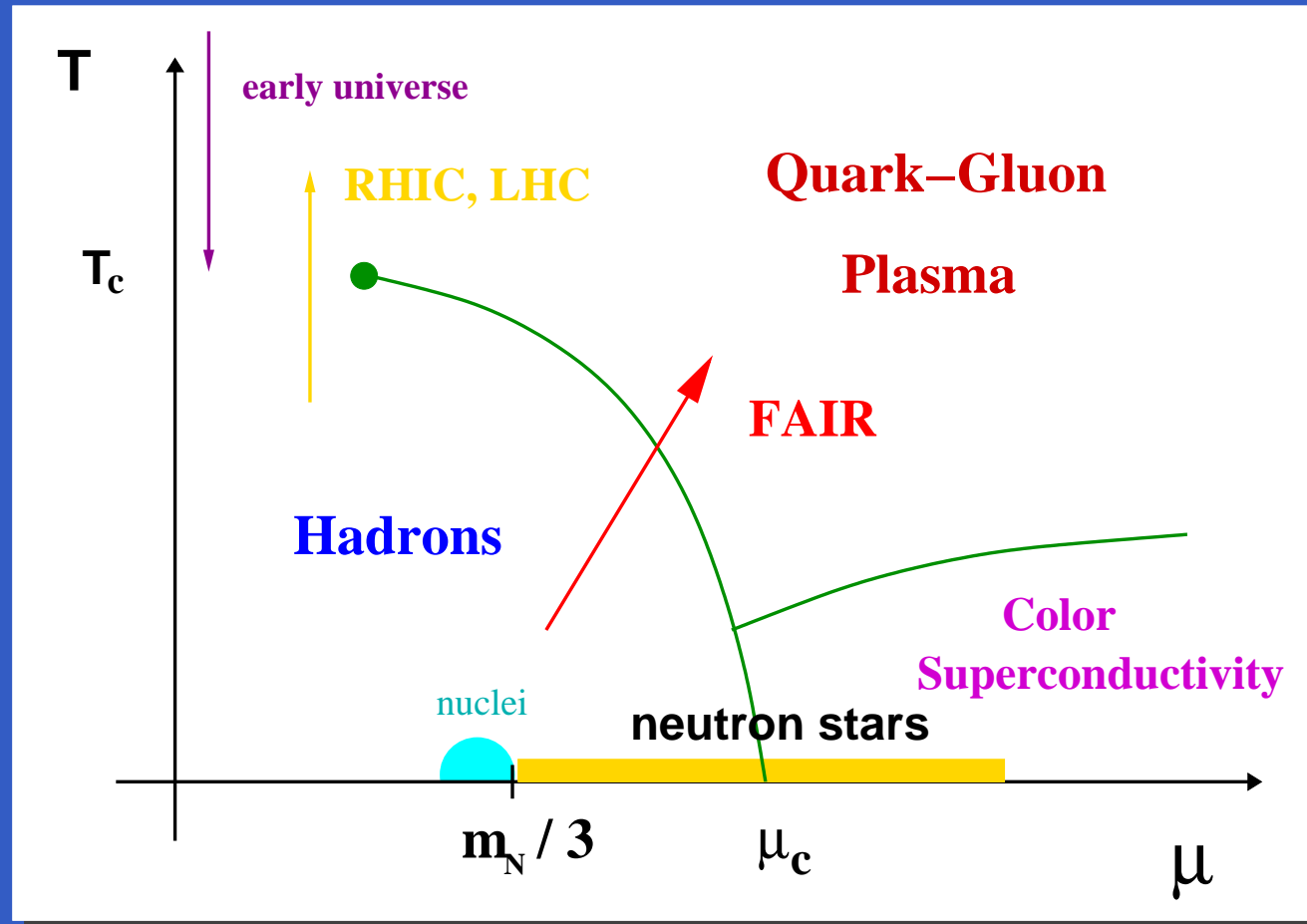
Particle Data Group, LBNL, © 2008. Supported by DOE and NSF

History of the early universe



- Early universe: temperature increases with scale parameter as a^{-1}
- at $t = 1\text{s}$ to 3 minutes: BBN ($T = 0.1$ to 1 MeV)
- at $t \approx 10^{-5}\text{s}$: QCD phase transition ($T \approx 170$ MeV)
- at $t \approx 10^{-10}\text{s}$: electroweak phase transition ($T \approx 100$ GeV)

Phase Transitions in QCD



- early universe at small baryon density and high temperature
- neutron star matter at small temperature and high density
- first order phase transition at high density
- probed by heavy-ion collisions with CBM@FAIR!

Standard cosmology

from microwave background radiation and big bang nucleosynthesis:

$$n_B/s \sim n_B/n_\gamma \sim \mu T^2 / T^3 \sim \mu/T \sim 10^{-9}$$

note: baryon number per entropy is conserved

⇒ early universe evolves along $\mu/T \sim 10^{-9} \sim 0$

⇒ crossover transition, nothing spectacular, no cosmological signals

Friedmann equation for radiation dominated universe:

$$H^2 = \frac{8\pi G}{3} \rho \sim g(T) \frac{T^4}{M_p^2}$$

$g(T)$: effective number of relativistic degrees of freedom at T

Hubble time (true time $t = 3t_H$ for radiation dominated universe):

$$t_H = \frac{1}{H} \sim g^{-1/2} \frac{M_P}{T^2} \implies \frac{t}{1 \text{ sec}} \sim \left(\frac{1 \text{ MeV}}{T} \right)^2$$

A little inflation at the QCD phase transition

what happens if the early universe passes through a first order phase transition?

- is this possible? \implies Yes! no contradiction with present data
- could this be observable? \implies Yes! by gravitational waves

1st order phase transition \implies false metastable vacuum

\implies de Sitter solution \implies (additional small) inflationary period

$$H = \dot{a}/a \sim M_p^{-1} \rho_v^{1/2} = H_v = \text{const.} \rightarrow a \sim \exp(H_v \cdot t)$$

just a few e-folds are enough (standard inflation needs $N \sim 50$):

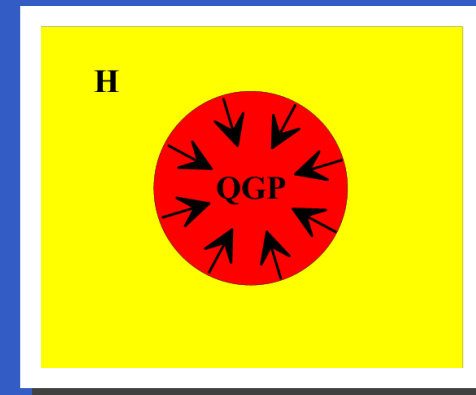
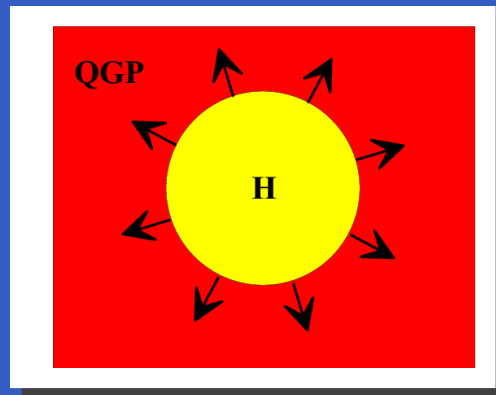
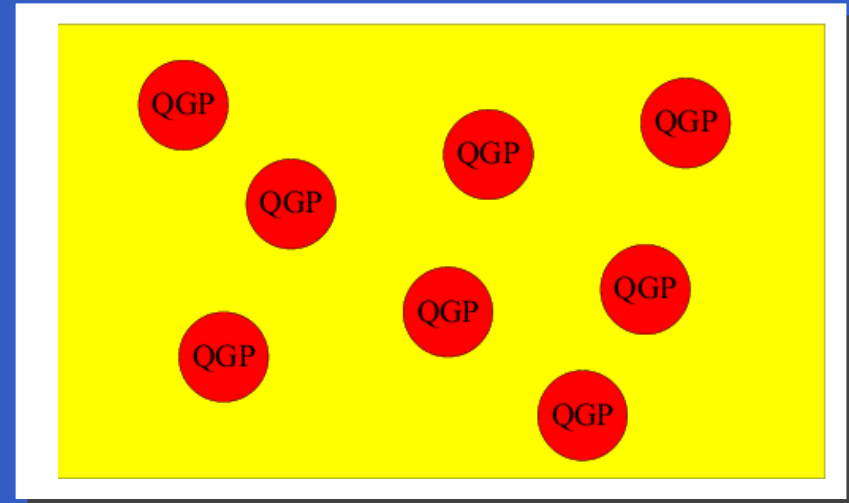
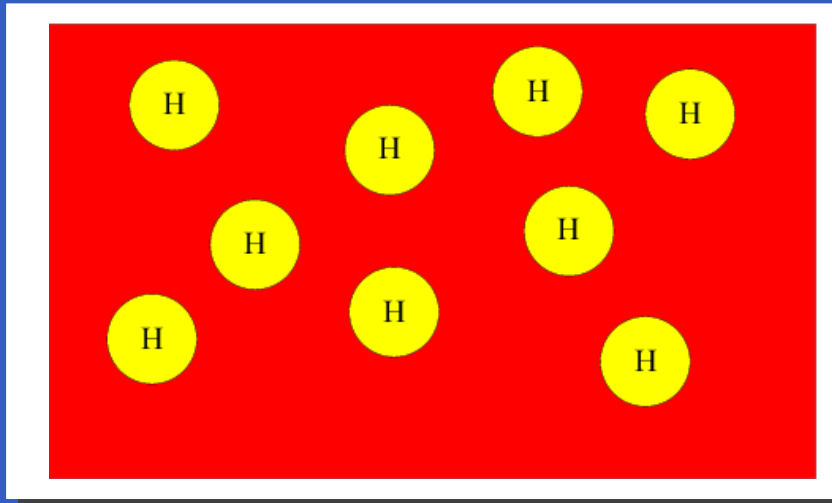
$$\left(\frac{\mu}{T}\right)_f \approx \left(\frac{a_i}{a_f}\right)^3 \left(\frac{\mu}{T}\right)_i$$

Hence $(\mu/T)_i \sim \mathcal{O}(1)$ for just $N = \ln(a_f/a_i) \sim \ln(10^3) \sim 7$ e-folds

(first order phase transition by a large lepton asymmetry: Schwarz, Stuke 2009)

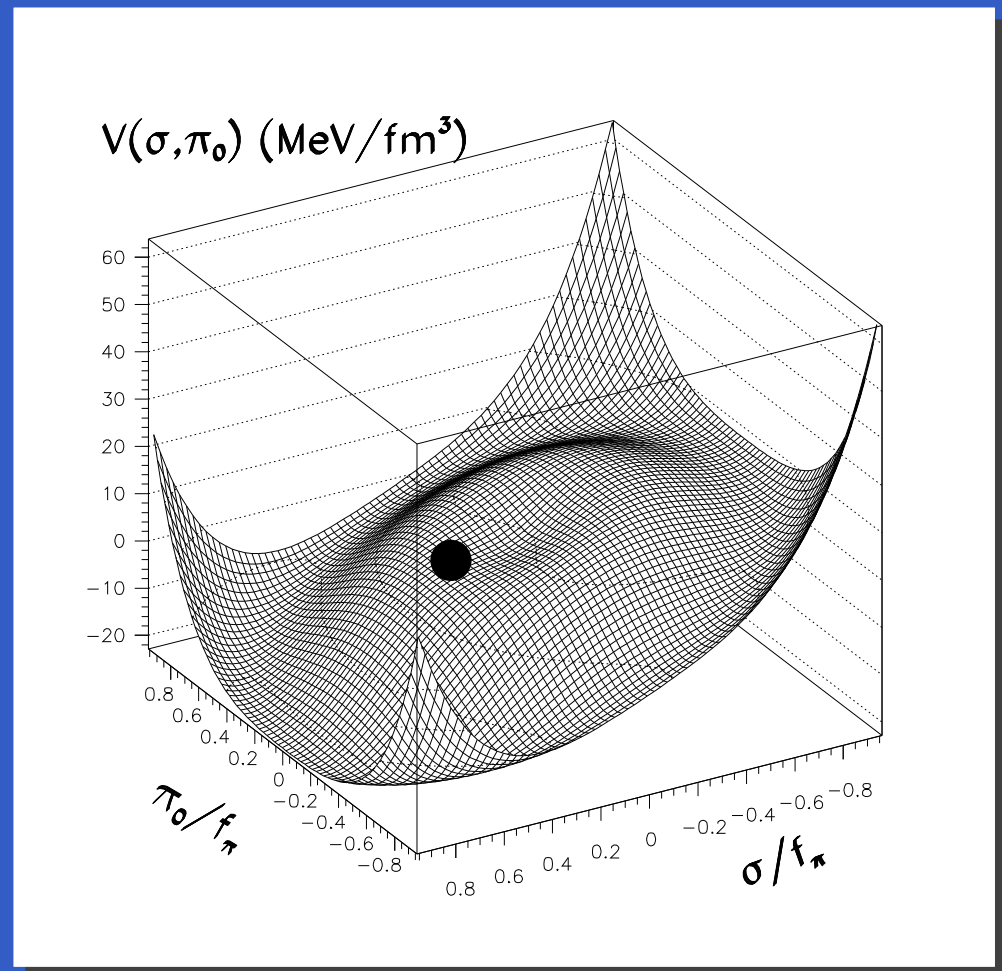
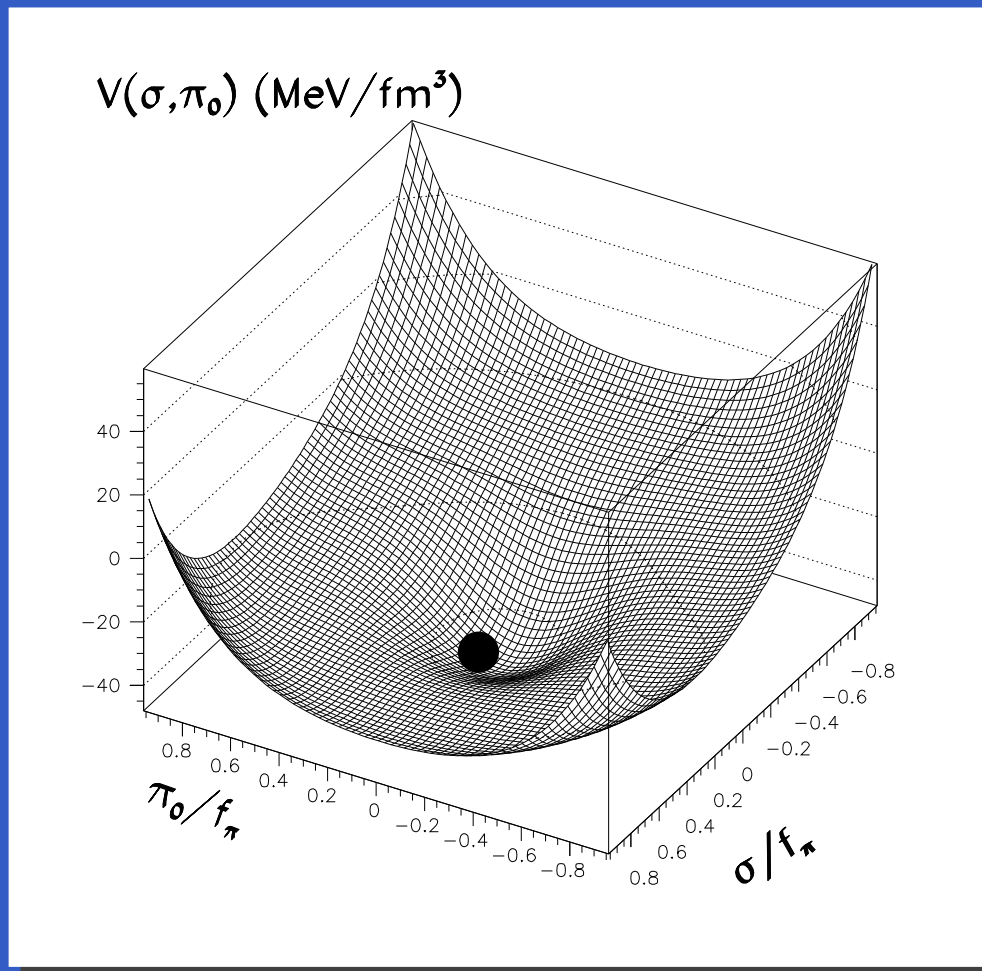
Cosmic Phase Transition by Bubble Nucleation

(Kämpfer 2000)



- QCD phase transition by bubble nucleation → Witten (1984) on strange matter
- inflation controlled by surface tension possible
→ tepid inflation of Kämpfer (1986, 1988a, 1988b, 1989, 2000)
- realization in chiral effective model by Borghini, Cottingham, Vinh Mau (2000)

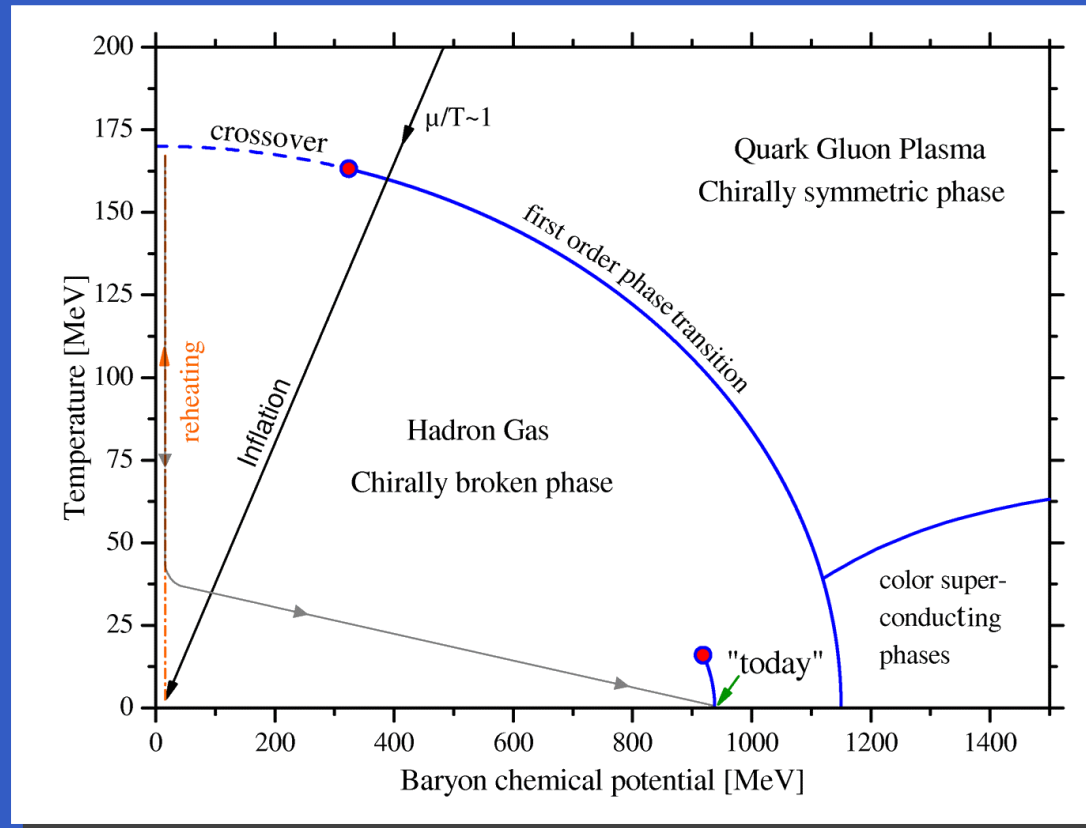
First-order phase transition: linear σ model



(Scavenius, Dumitru 1999)

- potential within the linear σ model at finite temperature
- left plot: high T , right plot: low T , system being trapped in false vacuum state
- possibility of a 'quench' at finite μ , two scalar fields in QCD – hybrid inflation?

A little inflation in the QCD phase diagram



(Boeckel and JSB, 2010)

- start with $\mu/T \sim 1$ (possible for e.g. Affleck-Dine baryogenesis)
- universe trapped in false vacuum at the transition line
- supercooling and dilution with $\mu/T = \text{const.}$
- decay to the true vacuum state \rightarrow reheating to $T \sim T_c$ so that $\mu/T \sim 10^{-9}$

WIMPs and Black Holes

- freeze-out of weakly interacting massive particles (WIMPs):

$$\Omega_{CDM} \sim \sigma_{\text{weak}} / \sigma_{\text{ann.}}$$

- ρ_{CDM} will be larger by $(a_f/a_i)^3$ during freeze-out *before* inflation
- need substantially reduced annihilation cross section, correspondingly reduced production cross section
- can be checked @LHC! (if SUSY particles are not found)
- primordial black hole production due to collapsing bubbles:

$$M_{bh} \sim M_{\text{hubble}} \sim 1M_{\odot}$$

as the total energy density after inflation is involved

(Jedamzik 1997; Kapusta, Springer 2007)

Tensor perturbations and QCD trace anomaly

- crucial input for tensor perturbations in GR: trace anomaly of QCD!
- EoM for tensor perturbation amplitude $v_k = a \cdot h_k$ in Fourier space (gauge invariant):

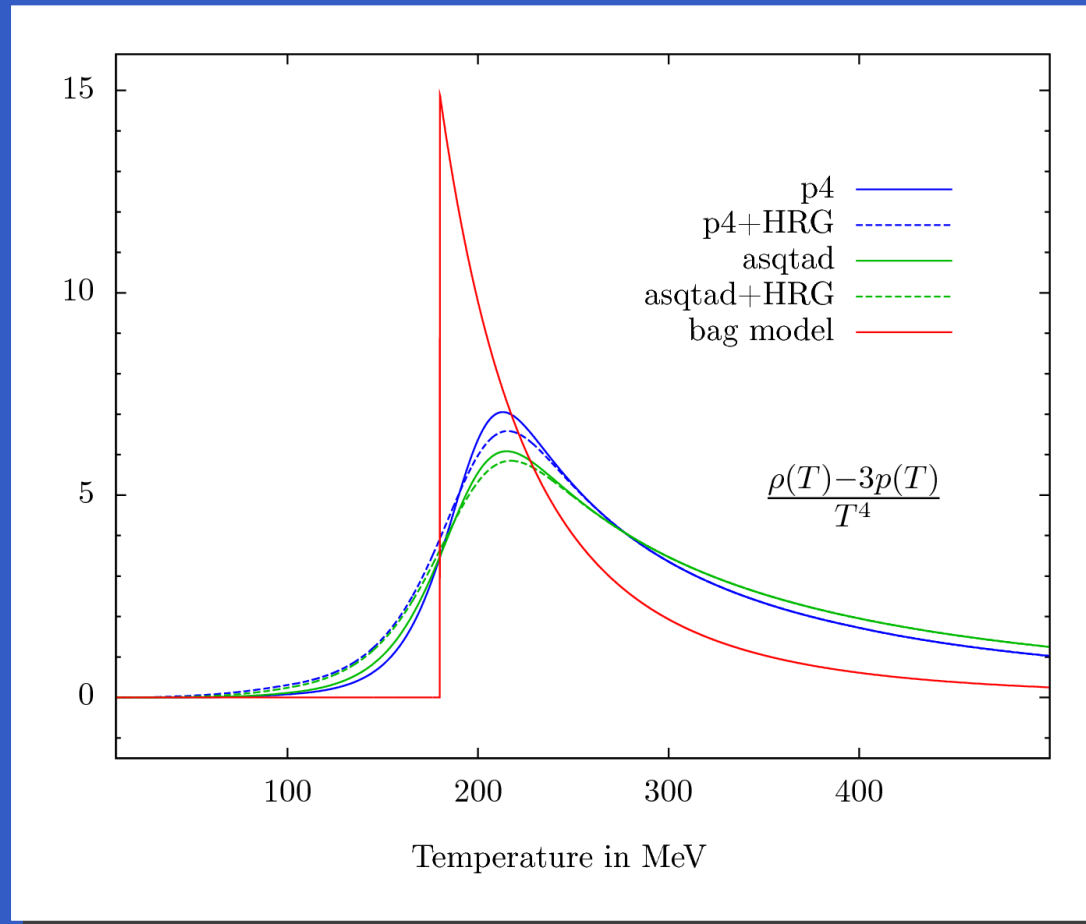
$$v_k''(\eta) + \left(k^2 - \frac{a''}{a} \right) v_k(\eta) = 0$$

where

$$\frac{a''}{a} = \frac{4\pi G a^2}{3} (\rho - 3p)$$

- only input needed: QCD trace anomaly
- use several lattice parameterizations, compare with simple bag model

QCD trace anomaly



(Schettler, Boeckel, JSB 2010)

- parameterization of lattice data with improved staggered fermion actions (asqtad and p4) and physical strange quark masses, with and without a hadron resonance gas (HRG)

(Bazavov et al., Bielefeld-BNL/RIKEN-Columbia collaboration 2009)

Gravitational wave background from QCD phase transition

- energy density in gravitational wave background: $\Omega_g(k) = \frac{1}{\rho_c} \frac{d\rho_g}{d \ln k}$
- mode h_k is damped by $1/a$ after horizon entry
- entropy conservation: $ga^3T^3 = \text{const.} \rightarrow H \sim T^2g^{1/2} \sim g^{-1/6}a^{-2}$
- as $\Omega_g \sim H_{in}^2 a_{in}^4 \sim g_k^{-1/3}$, so

$$\frac{\Omega_g(\nu \gg \nu^*)}{\Omega_g(\nu \ll \nu^*)} = \left(\frac{g_f}{g_i} \right)^{1/3} \sim 0.7$$

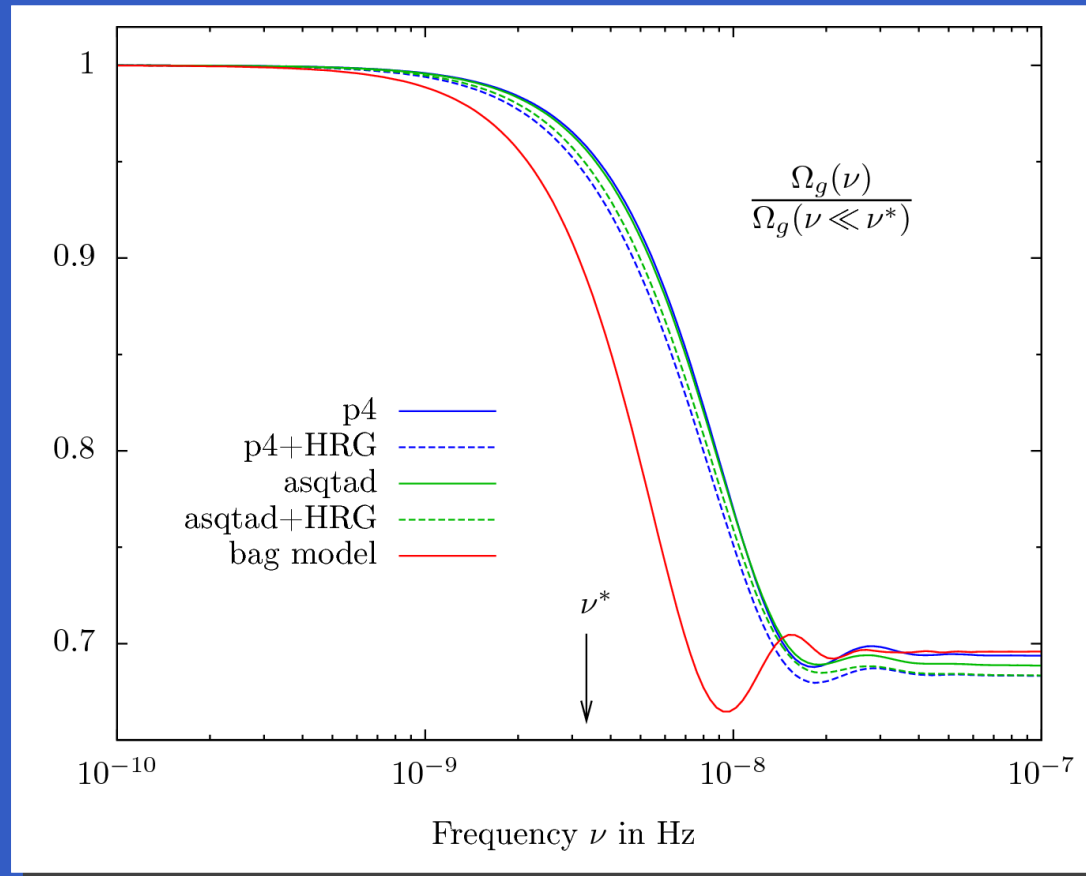
(Schwarz 1998)

- step in amplitude at frequency scale given by (redshifted) horizon scale at the transition point

$$\nu_{\text{peak}} \sim H_c \cdot T_{\gamma,0}/T_c \sim T_c/M_p \cdot T_{\gamma,0} \sim 10^{-7} \text{ Hz}$$

- maximum amplitude $h \sim a/a_0 \sim 10^{-12}$

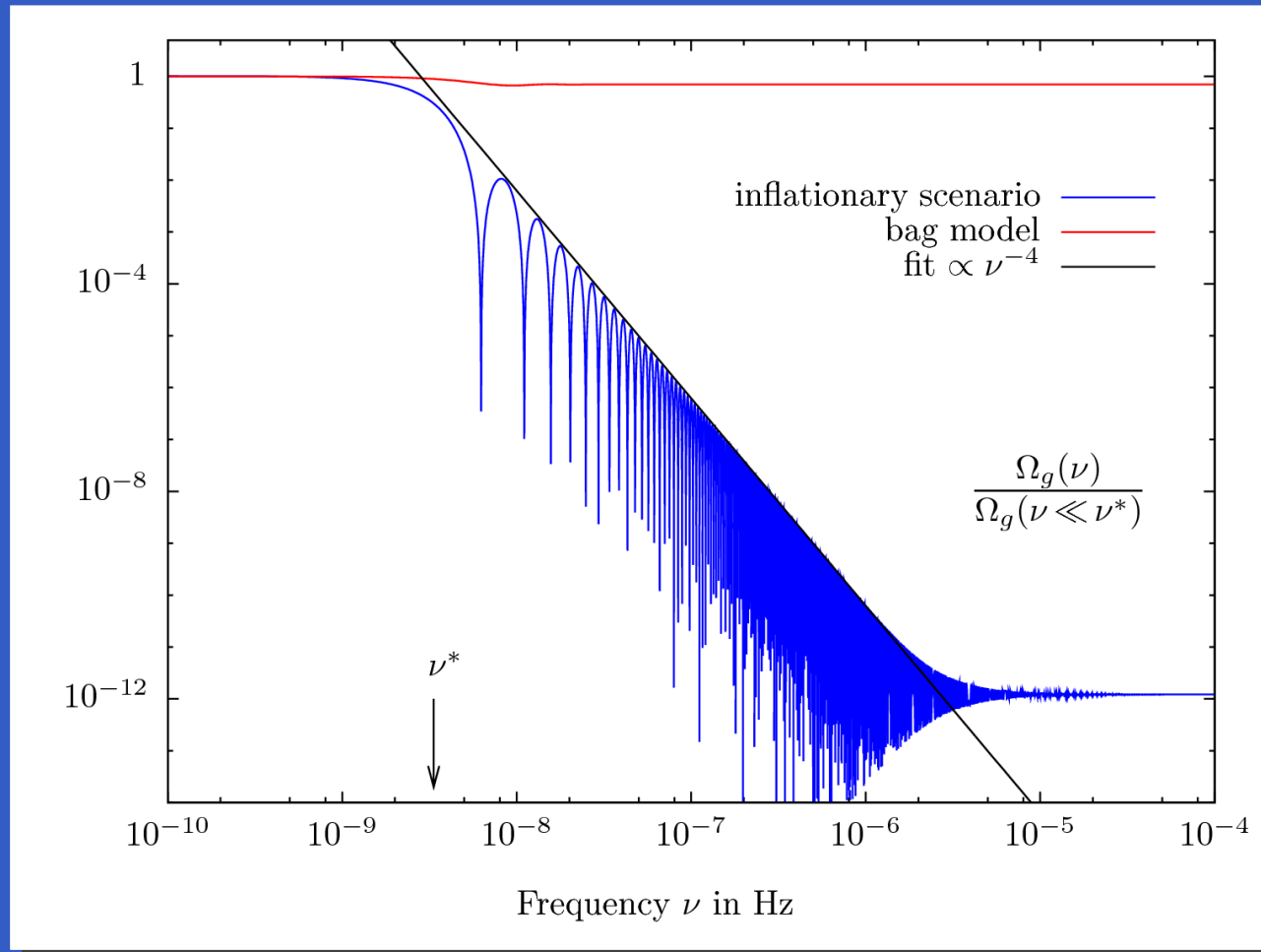
A step in the gravitational wave background



(Schettler, Boeckel, JSB 2010)

- step in gravitational wave background around $\nu \sim 10^{-7}$ Hz
- step in spectrum of about $(g_f/g_i)^{1/3} \sim 0.7$
- rather insensitive to details of the phase transition (Schwarz 1998)

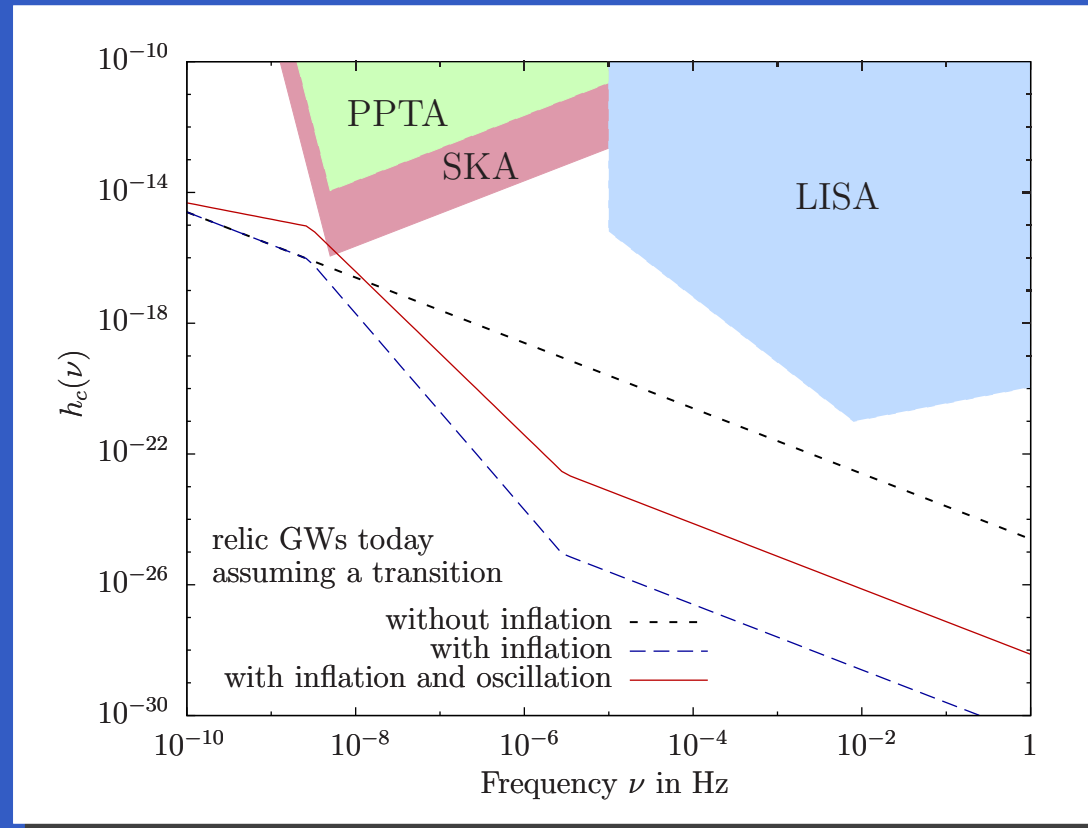
Spektrum of gravitational waves for a little inflation



(Schettler, Boeckel, JSB 2010)

- amplitudes are exponentially suppressed during inflation as $h \sim 1/a \sim \exp(H \cdot t)$
- gravitational wave background drops as ν^{-4}

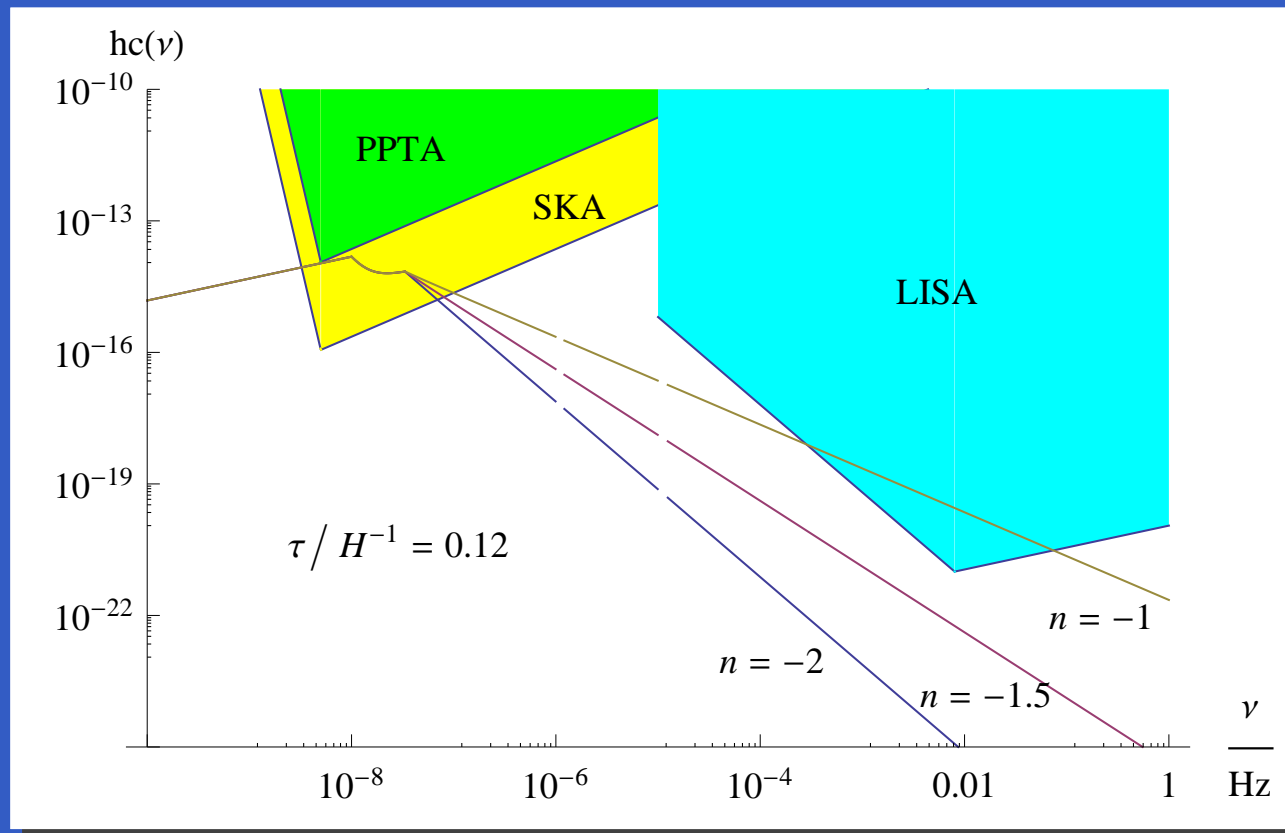
Observations of gravitational wave background



(Schettler, Boeckel, JSB 2010)

- gravitational wave amplitude versus frequency
- gravitational waves measurable with pulsar timing (PPTA and SKA) or space-based interferometers (LISA)
- step frequency in the amplitude close to highest sensitivity for pulsar timing

Gravitational waves from bubble collisions



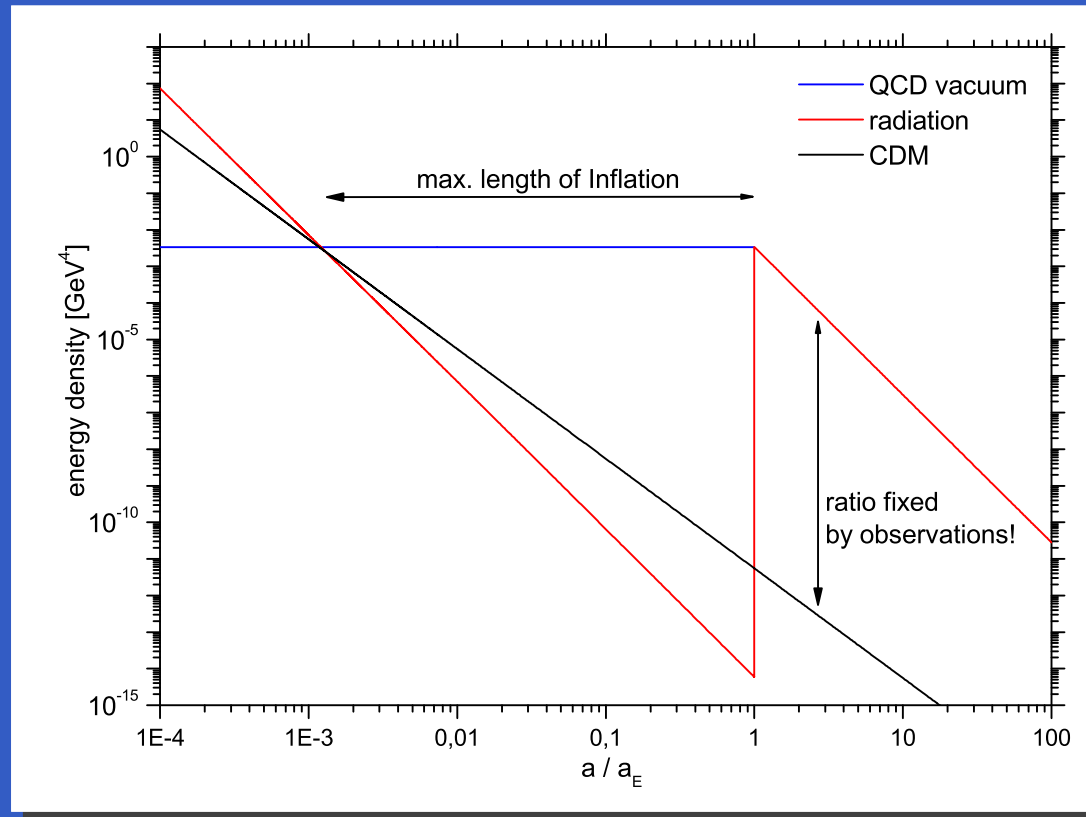
(Boeckel et al. 2010)

- first order transition produces tensor perturbations → gravitational waves
- amplitude scales as $h(\nu) \propto \nu^{-1/2}$ for $\nu < H$ (white noise) and as $h(\nu) \propto \nu^{-2 \dots -1}$ for $\nu > H$ (multi bubble collisions) (Kamionkowski, Kosowsky, Turner 1994; Huber, Konstandin 2008)

Summary

- first order transition could have happened in the early universe
- need large initial μ/T and a metastable false vacuum state
- large-scale structure modified up to $M \sim 10^9 M_\odot$
(without QCD inflation only up the horizon mass $\sim 10^{-9} M_\odot$)
- cold dark matter density is diluted by 10^{-9}
→ need different WIMP annihilation cross section as
 $\Omega_{\text{CDM}} \sim \sigma_{\text{weak}}/\sigma_{\text{ann}}$ or larger WIMP mass (probed by LHC!)
- generation of the seeds of (extra)galactic magnetic fields:
→ possible within the standard model again
- modified gravitational wave background:
observable with pulsar timing and LISA

A little inflation – evolution of densities



(Boeckel and JSB, arXiv:0906.4520)

- energy density falls as a^{-4} until $\rho \sim \Lambda_{\text{QCD}}^4$
- then $\rho = \text{const.}$ → inflationary period starts
- reheating at the end of inflation
- maximum length of inflation for scale parameter a from CDM density $\sim 10^3$

End of phase transition by bubble nucleation

bubble of new phase grows if they exceed a critical bubble size
free energy:

$$\Delta F = -\frac{4\pi}{3}R^3 \Delta p + 4\pi R^2 \sigma$$

with a critical bubble size of $R_c = 2\sigma / \Delta p$, nucleation rate:

$$\Gamma = P_0 \exp(-\Delta F/T) \text{ with } P_0 \sim T^4$$

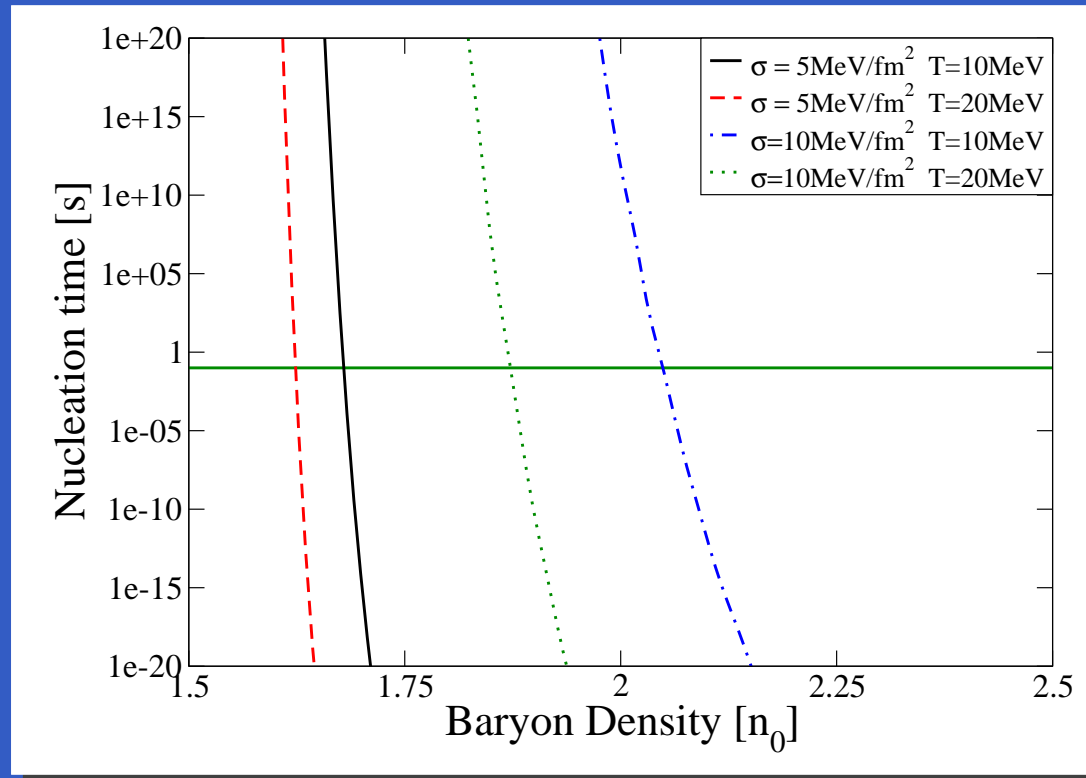
depends crucially on surface tension σ and pressure difference Δp :

$$\frac{\Delta F_c}{T} = \frac{16\pi\sigma^3}{3T(\Delta p)^2} = \frac{16\pi}{3} \left(\frac{\sigma}{200\text{MeVfm}^{-2}} \right)^3 \left(\frac{200\text{MeV}}{T} \right) \left(\frac{200\text{MeVfm}^{-3}}{\Delta p} \right)^2$$

exponential suppression!

in general $\sigma = \sigma(T)$ as the barrier vanishes for low T
(ensures a graceful exit!)

Bubble nucleation timescales and surface tension



(Mintz, Fraga, Pagliara, JSB 2009)

failure to nucleate $\tau_{\text{nucl}} > t_{\text{hubble}}$ for $\sigma > 120 \text{ MeV/fm}^2$
(MIT bag model with $B^{1/4} = 145 \text{ MeV}$)

(Jenkovszky, Sysoev, Kämpfer 1990; Csernai, Kapusta 1992; Mintz, Fraga, Pagliara, JSB 2010)

surface tension in QCD: $\sigma = 50 - 150 \text{ MeV/fm}^2$ or smaller or larger ...

(Voskresensky, Yasuhira, Tatsumi 2003; Palhares, Fraga 2010)

Power Spectrum of Dark Matter

- dark matter mass within horizon at $T_c \approx 170 \text{ MeV}$: $10^{-9} M_\odot$
- boosted by little inflation by $(a_f/a_i)^3 \approx 10^9$ so that mass scales of up to $1 M_\odot$ are affected
- additional effect for modes $k_{ph} < H$ at the beginning of inflation
- two scales involved: $H^2 \propto \rho_v \sim \text{const.}$ and $\dot{H} = -4\pi G(\rho + p) = -4\pi G(\rho_{dm} + 4\rho_r/3) \propto (a_i/a)^q$ where $q = 3 \dots 4$
- three spectral regimes:
 - $(k_{ph}/H)_i > a_f/a_i$: always subhubble
 - $a_f/a_i > (k_{ph}/H)_i > (a_i/a_f)^{q/2}$: intermediate
 - $(k_{ph}/H)_i < (a_i/a_f)^{q/2}$: unaffected
- highest mass scale affected is $M_{max} \sim 10^{-8} M_\odot (a_f/a_i)^{3q/2} \sim (10^6 - 10^8) M_\odot$
- relation to cuspy core, subhalo issues of structure formation?

Seeds for magnetic fields

- primordial magnetic fields produced by bubble collisions in first order phase transition (Cheng, Olinto 1994)
- charge dipole layer at surface, high baryon density contrast
- magnetic field can be $B_{QCD} \sim 10^8 - 10^{10}$ G
- amplified by MHD turbulence to equipartition value
 $B_{eq} = \sqrt{8\pi T^4 v_f^2} \sim 10^{12}$ G (Sigl, Olinto, Jedamzik 1997)
- little inflation scenario boosts magnetic fields by higher density and larger baryon diffusion length
- can explain presently observed (extra)galactic magnetic field strength $B_{obs} \sim 0.1 - 1 \mu\text{G}$
works for GUT and QCD phase transition
(Caprini, Durrer, Fenn 2009)

Producing gravitational waves with bubbles

energy emitted in gravitational waves (quadrupole formula):

$$E_{GW} \sim G \ddot{Q}^2 \tau$$

with duration of collision τ and separation of bubbles $d \sim \tau$

$$\ddot{Q} \sim \frac{\rho_v \cdot d^3 \cdot \tau^2}{\tau^3} \sim \rho_v \tau^2$$

energy relative to total energy:

$$\frac{E_{GW}}{E_v} \sim \frac{G \rho_v^2 \tau^2}{\rho_v \tau^3} \sim G \rho_v \tau^2 \sim \left(\frac{\tau}{H^{-1}} \right)^2$$

limit from Parkes Pulsar Timing Array PPTA: $\tau/H^{-1} < 0.12$

will be improved by full PPTA data set and by Square Kilometre Array SKA in the future