5. EARLY UNIVERSE PHASE TRANSITIONS, BIG BANG NUCLEOSYNTHESIS, DARK ENERGY

QUESTION : WHAT IS A PHASE TRANSITION?

ANSWER: MATTER CHANGES FROM ONE PHASE TO ANOTHER. Example: H_20 molecules can be liquid (water) or gas (steam) or solid (ice).

QUESTION : WHAT IS A FIRST ORDER PHASE TRANSITION?

ANSWER: CRITICAL T (T_c), BUBBLES FORM, LATENT HEAT NEEDED

QUESTION: WHAT IS A COSMOLOGICAL PHASE TRANSITION?

ANSWER: THE UNIVERSE'S VACUUM STATE CHANGES TO A DIFFERENT VACUUM STATE. WE NEED TO DISCUSS SOME QUANTUM THEORY

QUESTION: WHEN WERE LIGHT ATOMIC NUCLEI FORMED (NUCLEOSYNTHESIS). WHAT DOES IT TEACH US ABOUT ELEMENTARY PARTICLES

ANSWER: ABOUT 1-100 sec AFTER THE BIG BANG. NUCLEOSYNTHESIS DETERMINES NUMBER OF GENERATIONS (NUMBER OF NEUTRINO FLAVORS)

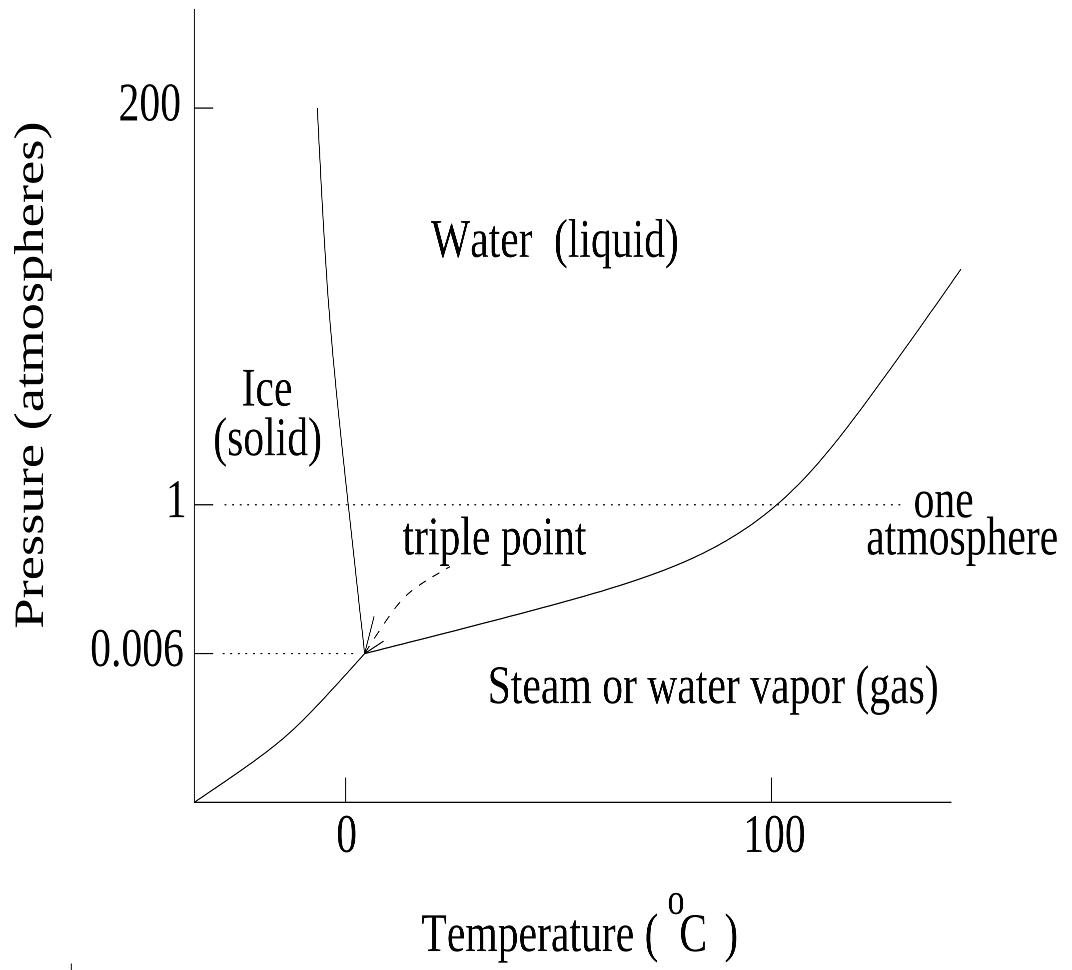
QUESTION: WHAT IS DARK ENERGY? TESTS AT PRESENT TIME?

ANSWER: ANTI-GRAVITY (INFLATION)-VACUUM ENERGY. SUPERNOVAE VELOCITIES

THE EVOLUTION OF THE UNIVERSE
COSMOLOGICAL PHASE TRANSITIONS
BIG BANG NUCLEOSYNTHESIS

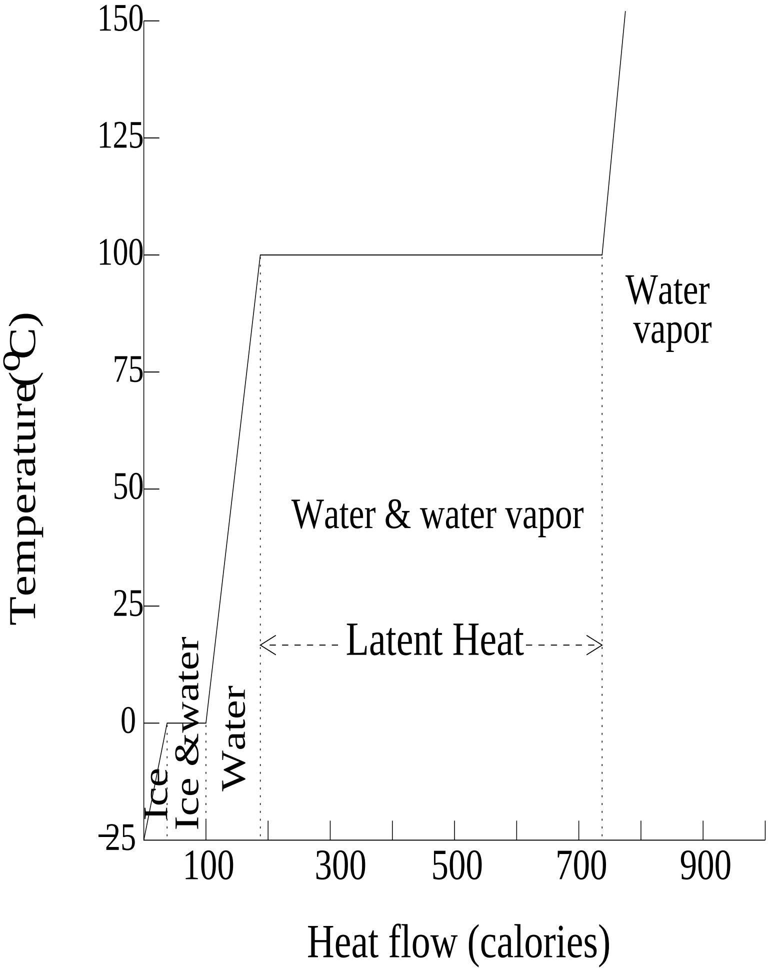
t = Time	T = Temperature Events
10^{-35}s	10^{14} GeV Big Bang, Strings, Inflation Very early. Current particle theory no good
EWPT --> 10^{-11}s	100 GeV ELECTROWEAK PHASE TRANSITION Particles (Higgs) get masses. Particle Theory o.k.. Baryogenesis (more particles than antiparticles) needs one supersymmetric particle.
QCDPT --> 10^{-5}s	100 MeV QCD PHASE TRANSITION Quantum Chromodynamics theory Quark (Plasma) condenses to hadrons (protons...) OUR PRESENT UNIVERSE BEGINS
H^2, He --> 1−100 s	Nucleosynthesis: Helium, light nuclei formed 1.0×10^9 ^oK Superconducting Universe
380,000 years	0.25 ev, 3,000 ^{o}K Atoms (electrically) neutral Last scattering of light (electromagnetic radiation) from big bang: Cosmic Microwave Background
1 billion years	early galaxies form
9 billion years	Our solar system has formed
14 billion years	2.7 ^{o}K Now

PHASES OF WATER (LIQUID), ICE (SOLID), STEAM (GAS)



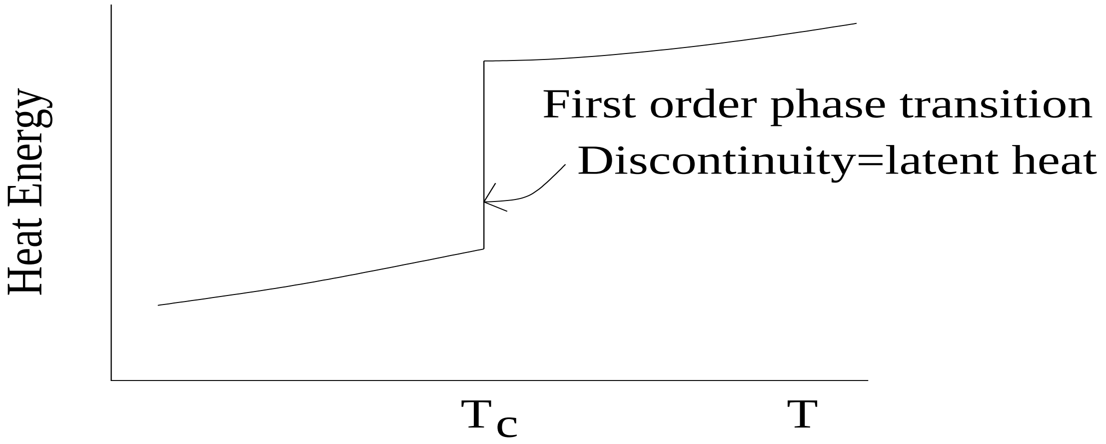
Phase Diagram of Water for Pressure vs Temperature

LATENT HEAT PRODUCES PHASE CHANGES AT CONSTANT T

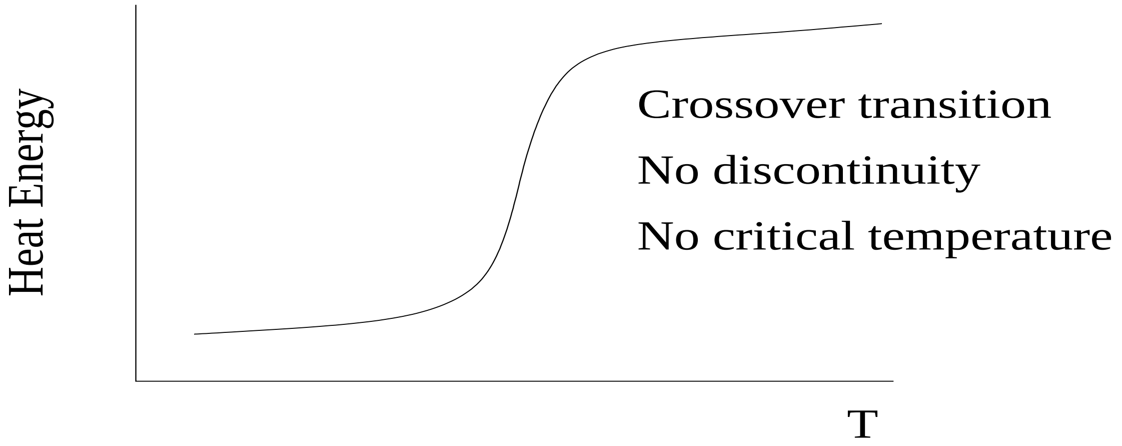


PHASES OF WATER WITH HEAT FLOWING INTO ONE GALLON OF WATER

First order vs higher order phase transitions



T_c = critical temperature



EARLY UNIVERSE PHASE TRANSITIONS

WE NEED THE BASIC INGREDIENTS OF QUANTUM MECHANICS:
STATES, OPERATORS, EXPECTATION VALUES

$$
\begin{aligned}
|\,\mathrm{state1}> &\equiv \mathrm{state1} \\
A &= \mathrm{operatorA}
\end{aligned}
$$

Operator A operates on a quantum state producing another quantum state:

$$
A|\,\mathrm{state1}> \;=\; |\,\mathrm{state2}> \,,
$$

where state2 is another quantum state; state2 might also be the same as state1.

If the system is in state1, what is the value of operator A:

$$
\begin{aligned}
<\ \mathrm{state1}| &\equiv \text{“adjoint}'' \text{ of state1} \\
<\ \mathrm{state1}|A|\,\mathrm{state1}> &\equiv \text{EXPECTATION VALUE OF A} \,,
\end{aligned}
$$

where the expectation value is the average value of A that we would find if we carried out a measurement. Note that A does not have an exact value, Heisenberg's Uncertainty Principle, unless state1=state2 (eigenvalue).

Quantum Mechanics is complicated, but we need these basic ideas to understand Early Universe (Cosmological) phase transitions.

ELECTROWEAK PHASE TRANSITION (EWPT)

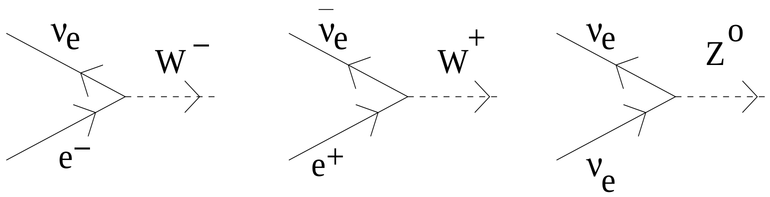
1)PARTICLES GET MASS, 2) MAGNETIC FIELDS CREATED, 3) BARYOGENESIS– MORE QUARKS THAN ANTIQUARKS ?

Review of STANDARD EW THEORY:

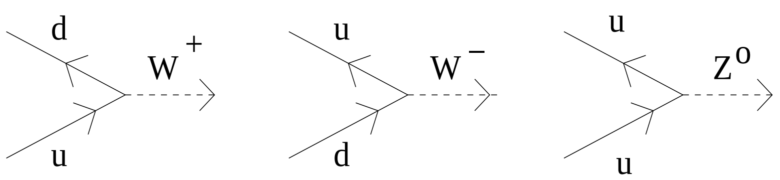
FERMIONS (spin 1/2 particles) are (e^-, ν_e) and the μ and τ leptons with their neutrino partners; and the quarks (q_u, q_d) and the other two quark generations. THREE GENERATIONS OF LEPTONS and QUARKS

GAUGE BOSONS (spin 1 particles) are W^+, W^-, Z^o and photon (γ)

HIGGS a scalar boson (spin 0), ϕ, completes the Standard Model



Lepton weak interaction conserves CP−No Baryogenesis



Quark weak interaction violates CP−Baryogenesis Possible

BARYOGENSIS FROM THE EWPT REQUIRES A FIRST ORDER PHASE TRANSITION

BARYOGENESIS–MORE BARYONS[QUARKS] THAN ANTIBARYONS[ANTIQUARKS] and GUTS

No baryogenesis during thermal equilibrium: energy density of particles at equilibrium depends only on mass and spin. Therefore $n_q = n_{\bar{q}}$

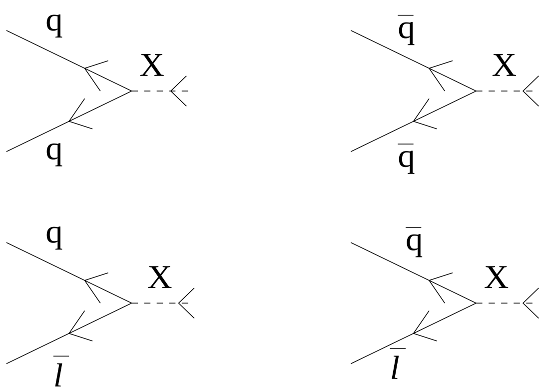
It has been shown that in the Standard Electroweak model a first-order phase transition is needed to explain baryogenesis

Grand Unified Theories–GUTS can give baryogenesis at the time of inflation $10^{-34} - 10^{-32}$ **s.**

GUTS BARYOGENESIS PROCESSES

ADDITIONAL GAUGE BOSONS IN GUTS = X

DIAGRAMS OF X GUTS PROCESSES



GUTS CONJECTURE: BARYOGENESIS AT 10^{-34} S

THE EWPT, THE HIGGS PHENOMENON, AND POSSIBLE MSSM FOR BARYOGENESIS

The EWPT is characterized by the vacuum value of the Higgs field= expectation value of ϕ in vacuum state

$$|0, T> \equiv \text{vacuum state fortemperature} = \text{T} .$$

The vacuum state of the universe is the state with all matter removed. It has (as the CMBR proved) about 3/4 of the energy of the universe (dark energy).

A cosmological phase transformation involves changing from one vacuum to a different vcuum

The expectation value of the Higgs field $= < 0, T|\phi|0, T >$ **for temperature=T**

If there is a first order EWPT at temperature $= T_c$

$$< 0, T|\phi|0, T > = 0 \ \text{for T} > \text{T}_\text{c}$$
$$< 0, T|\phi|0, T > \neq 0 \ \text{for T} < \text{T}_\text{c}$$

For $T < T_c$**,** $< 0, T|\phi|0, T > \propto$ **Higgs mass = energy: DARK ENERGY**

Mass of the Higgs and the EWPT:

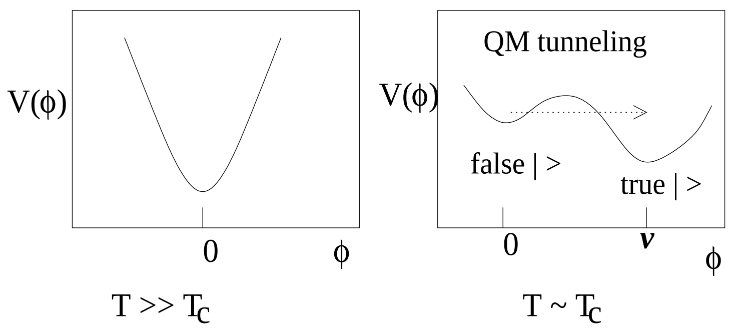
The mass of the Higgs is given by $< |\phi| >$. Therefore, if there is a first order EWPT the Higgs mass goes from 0 to the nonzero M_H as the temperature drops through T_c, at about 10^{-11} s after the B.B

If there is a crossover EWPT the Higgs mass grows from zero through a range of temperatures and times, also at about 10^{-11} s.

With a crossover phase transformation, baryogenesis does not work. One needs GUTS or some other mechanism

Standard EW theory for ϕ near $T \approx T_c$

$$\ddot{\phi} \ = \ \text{effects of the gauge fields } + V(\phi) \ ,$$



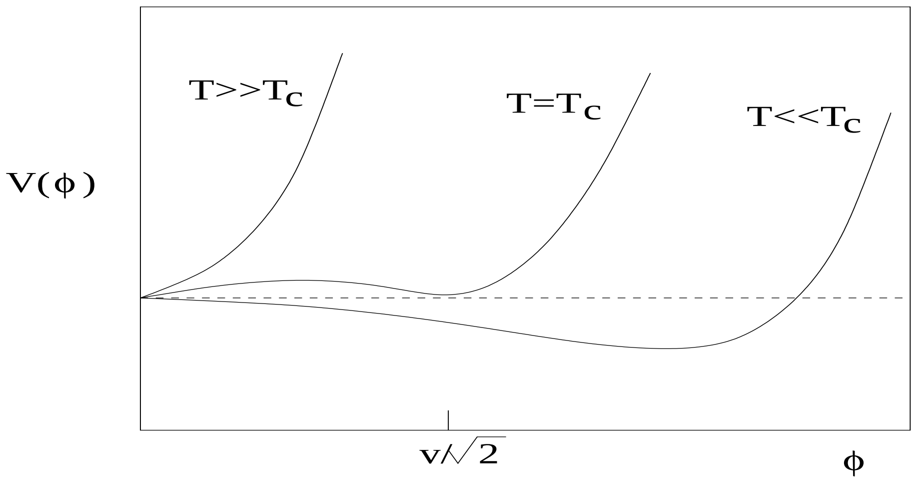
$< \phi > \ = \ v$ at T_c for true vacuum

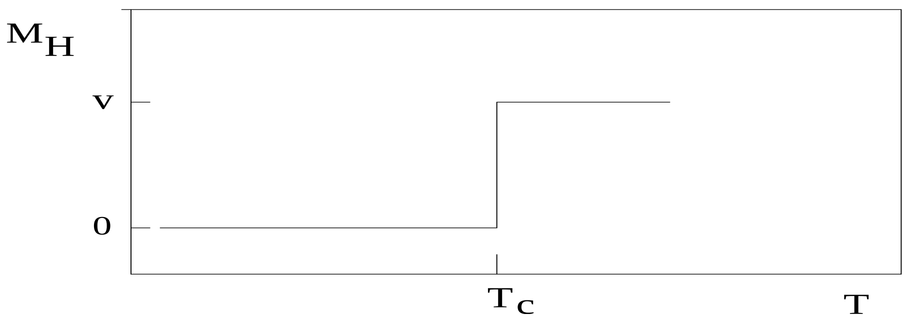
$< \phi > \ = 0$ is a false vacuum

QM tunneling takes universe from false to true vacuum

EWPT and Higgs mass with first order EWPT

$$V(\phi) = -\mu^2 \phi^2 + \lambda^2 \phi^4$$





All particles except photon get mass

$$
\begin{aligned}
M_H &= v \\
M_W &= gv/\sqrt{2} \;\; \text{g} = \text{strong coupling constant} \\
M_Z &= M_W/cos(\theta_W) \;\; \theta_{\text{W}} = \text{Weinberg angle} \\
m_e &\propto m_u \propto m_d \propto v
\end{aligned}
$$

Standard Model: M_W**= 37 GeV /sin(**θ_W**)** $\simeq$ **80 GeV**

$M_Z = \simeq$ **90 GeV**

BARYOGENESIS WORKS IF $M_H \leq$ **60 GeV)**

EWPT IN THE STANDARD EW MODEL VS MSSM (MINIMAL SUPERSYMMETRIC MODEL):

IF M_H IS GREATER THAN ABOUT 60 GeV, EWPT IN THE STANDARD EW MODEL IS NOT FIRST ORDER–AS PROVED BY DETAILED CALCULATIONS

IT IS NOW KNOWN THAT $M_H > 60$ GeV

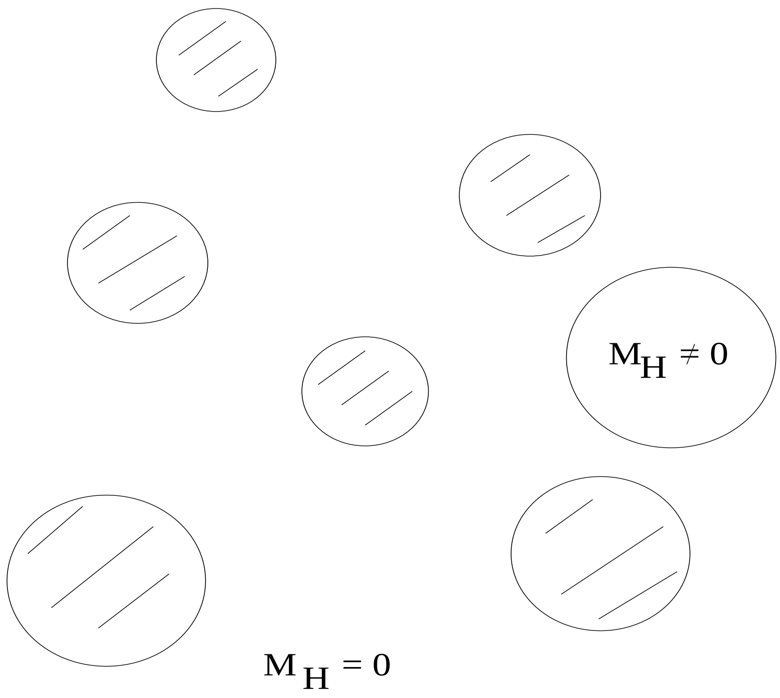
THUS BARYOGENESIS AT THE TIME OF THE EWPT IS NOT EXPECTED IN THE STANDARD EW MODEL

SUPERSYMMETRY:EVERY PARTICLE GET A MATE. QUARKS (FERMIONS) GET SQUARKS (BOSONS), GAUGE BOSONS GET FERMION MATES. THESE SUPERSYMMETRY PARTICLES MIGHT BE VERY HEAVY, AND NOT DETECTABLE WITH CURRENT ACCELERATORS

MSSM: IT HAS BEEN SHOWN THAT IF THE TOP QUARK HAS A SS MATE, THE STOP, AND IF THE MASS OF THE STOP IS LESS THAN 200 GeV, THEN THERE IS A FIRST ORDER EWPT

ONE ONLY NEEDS ONE RELATIVELY LIGHT SUPERSYMMETRIC PARTICLE TO HAVE A FIRST ORDER EWPT–THIS WILL BE TESTED AT CERN IN THE NEXT FEW YEARS

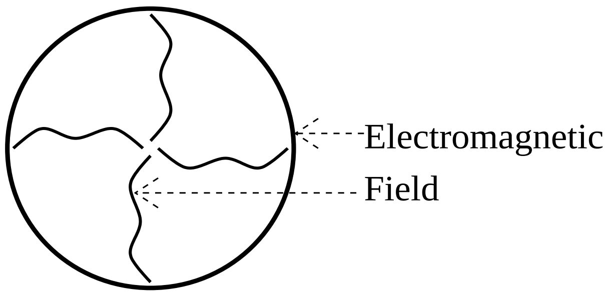
First order EWPT: Bubbles form



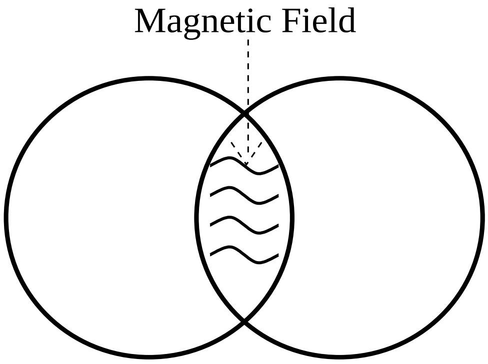
Bubbles of universe with $M_H \neq 0$ form in universe with $M_H = 0$. $\langle\phi\rangle \neq 0$ inside bubbles, $\langle\phi\rangle = 0$ outside bubbles. i.e., a new vacuum is created within the bubbles by the EWPT

Bubble formation ⇒ magnetic fields

During bubble nucleation electromagnetic fields form



After bubbles collide and merge magnetic fields form

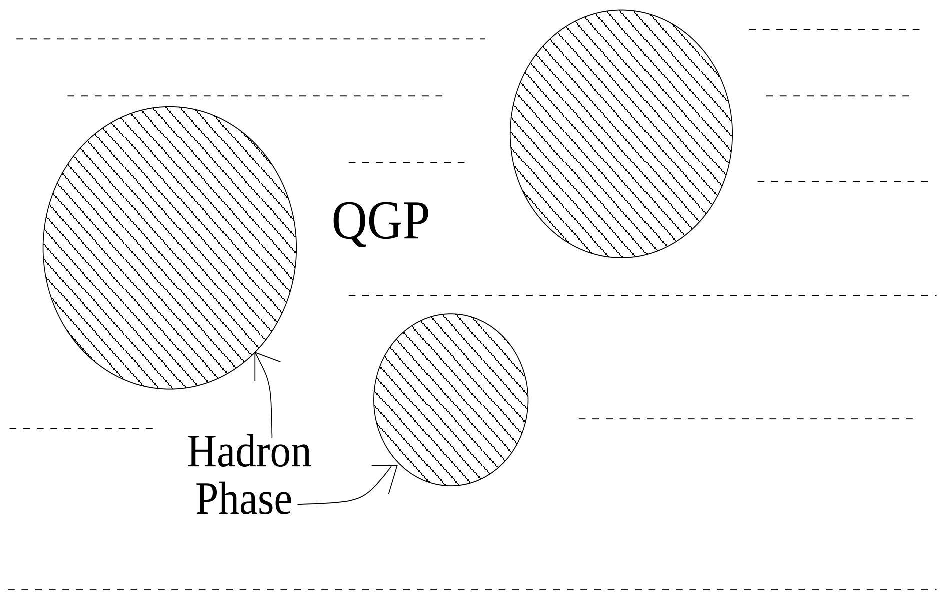


Seeds for galactic magnetic fields ?

Electromagnetic field creation during EWPT bubbble nucleation: E.M. Henley, M.B. Johnson, L.S. Kisslinger, Phys.Rev. D81, 085035, (2010)

Magnetic seed fields created during EWPT bubble collisions: T. Stevens, M.B. Johnson, L.S. Kisslinger, E.M. Henley, W-Y. P. Hwang, M. Burkart, Phys. Rev. D77, 023501 (2009)

QCD PHASE TRANSITION (QCDPT)



When T ~ 150 Mev the QCD phase transition starts .

Bubbles of hadronic matter matter form within the Quark Gluon Plasma (QGP). By 10^{-4} s all quarks ave condensed. The universe consists of protons, neutrons, etc, as well as leptons and photons. It is too hot for nuclei or atoms to form.

FIRST ORDER QCDPT
QUARK CONDENSATE IS LATENT HEAT

QCD fields and particles and quark condensate:

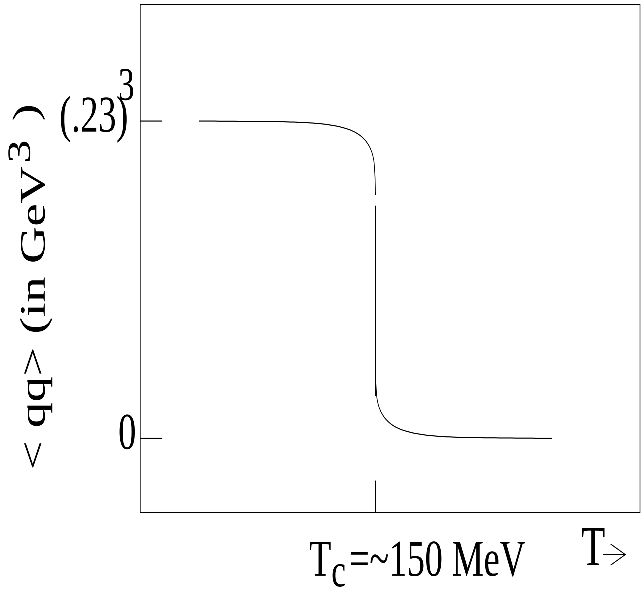
$$\begin{aligned} q(x) &= \text{quark field} \\ \bar{q}(x) &= \text{antiquark field} \\ |> &= \text{vacuum state} \\ <|\bar{q}(x)q(x)|> &= \text{quark condensate} \\ &= \text{vacuum expectation value of } \bar{\text{q}}(\text{x})\text{q}(\text{x}) \end{aligned}$$

$$\begin{aligned} <|\bar{q}(x)q(x)|> &= 0 \text{ in quark gluon plasma phase} \\ &\simeq -(.23\, GeV)^3 \text{ in hadron phase} \end{aligned}$$

That is, with a first order QCD phase transition the quark condensate goes from zero to a finite value at the critical temperature (about 150 MeV).

$<|\bar{q}(x)q(x)|>$ **is vacuum energy, dark energy.**

If the QCDPT is first order:

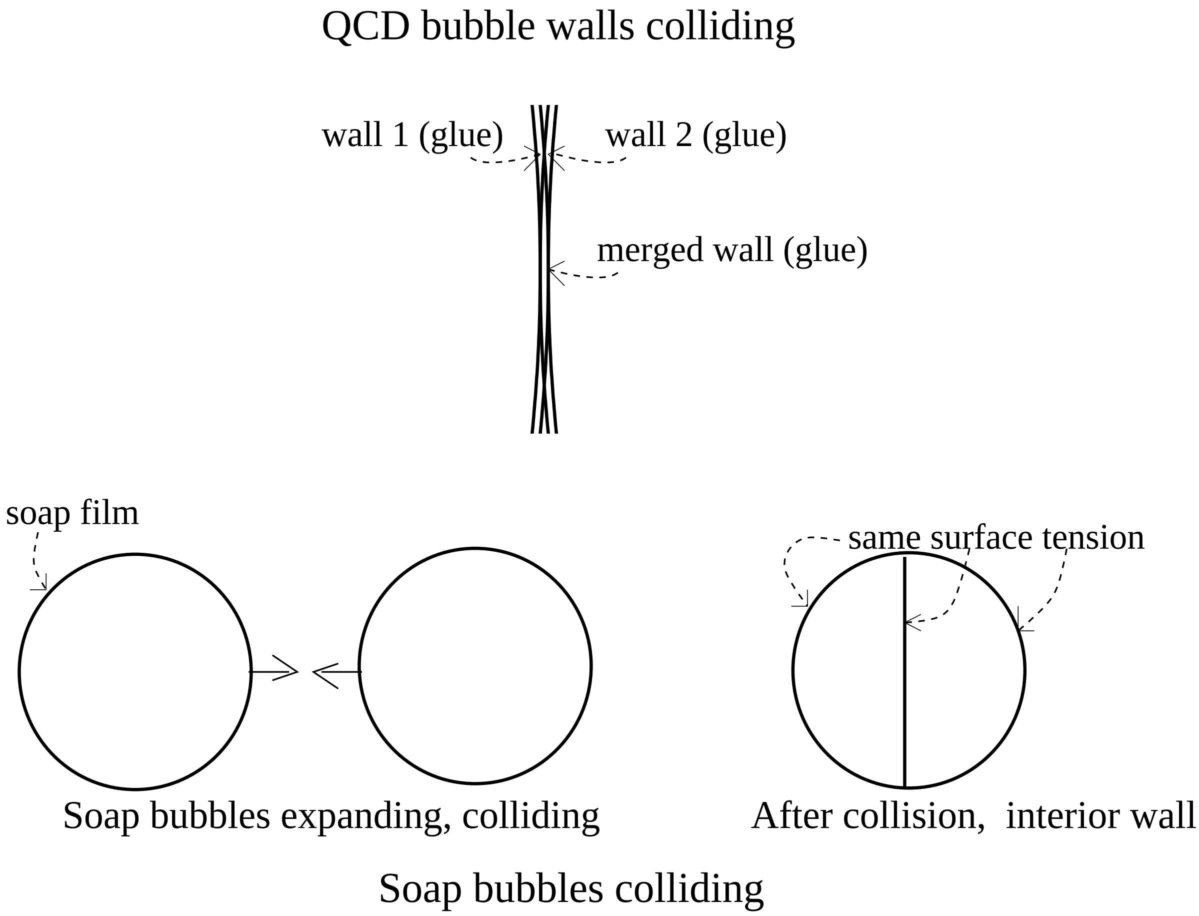


< qq> = latent heat for QCDPT

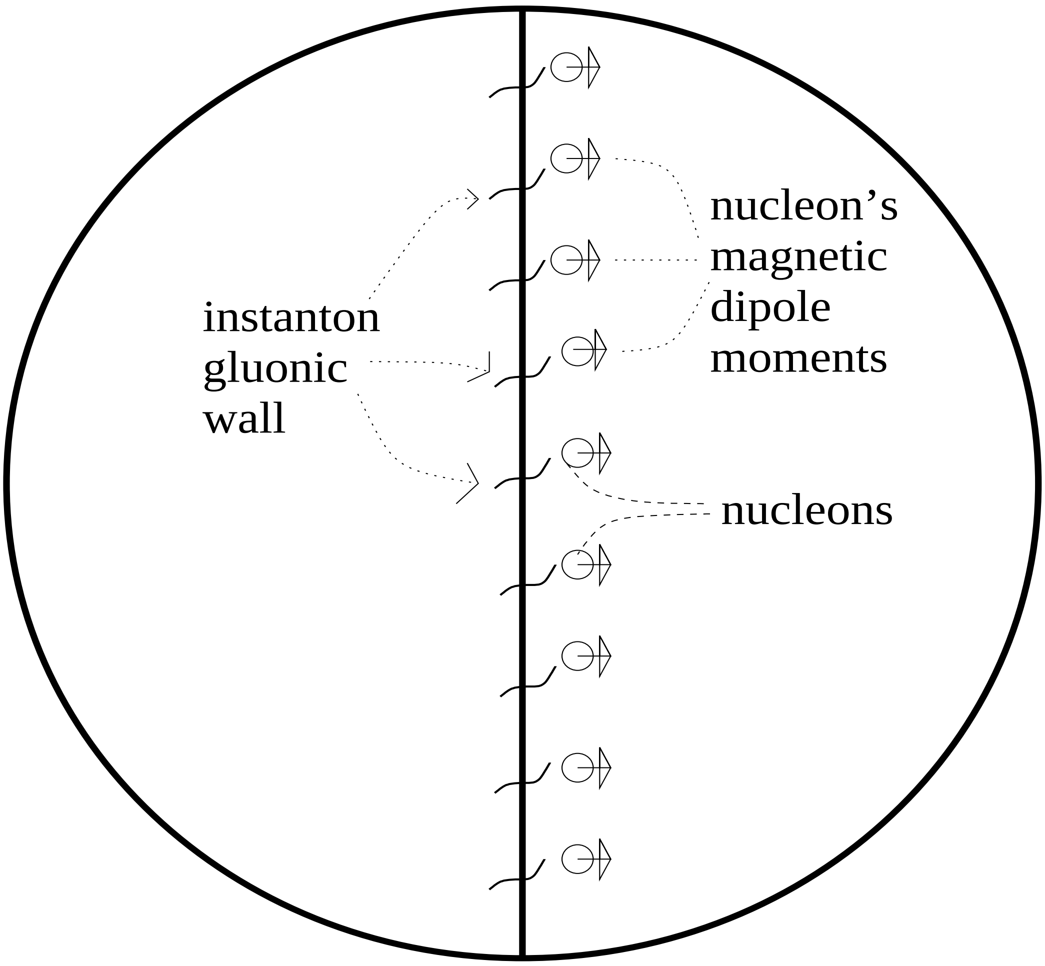
T decreases from 300 MeV ($t=10^{-5}$ s) to 100 MeV ($t=10^{-4}$ s)

Recent lattice gauge (basic QCD theory computed on large computers) calculations have shown that the QCDPT IS FIRST ORDER

Interior gluonic wall created by bubble collision



Magnetic field creation during QCDPT



Oriented magnetic dipole moments form a magnetic wall

Gluonic wall decays in ~10^{-8}s. Magnetic wall lives on

OBSERVABLE MAGNETIC EFFECTS FROM QCDPT OR EWPT

Magnetic walls from QCDPT lead to Temperature-Polarization correlations different from inflation and other models–LSK (Phys. Rev. D66 (2002) 053011). Might be observed with future CMBR experiments

Magnetic walls in QCDPT might provide the seeds for galactic and extra-galactic magnetic fields that have been observed. Our new work discussed below.

To test if magnetic seeds from the EWPT can account for the magnetic structures observed now, one must evolve them from very early times to our present time. Work in progress

Gravity Waves: Produced by magnetic fields created during EWPT or QCDPT. (See Kahniashvili, Kisslinger, Stevens, Phys.Rev.D81:023004,2010)

Gallactic and Cluster Magnertic Fields-a very old astrophysical mystery being investigated: Magnetic Fields from QCD Phase Transitions, A. G. Tevzadze, L. Kisslinger, A. Brandenburg, and T. Kahniashvili, Work in progress.

Prediction of Cosmological Constant Λ In Veneziano Ghost Theory of QCD, Zhou Li-juan, Ma Wei-xing, Leonard S. Kisslinger, arXiv:1204:384/astro-ph

The cosmological constant Λ, a form of dark energy, is given from Einstain's equations of general relativity by

$$\Lambda = 8\pi G \rho_\Lambda$$

where ρ_Λ is the vacuum energy density, called dark energy density.

From the QCD Veneziano ghost theory model of Urban and Zhitnitsky

$$\rho_\Lambda = c\frac{2HN_f}{m_{\eta'}} m_q \langle 0 \mid : \bar{q}(0)q(0) : \mid 0 \rangle, \tag{1}$$

where m_q is the current quark mass, c is a known constant, and $\langle 0 \mid : \bar{q}(0)q(0) : \mid 0 \rangle \mid$ is the local quark condensate. Using the standard current quark mass and local quark condensate

$$\begin{aligned} \rho_\Lambda^{theory} &\simeq (3.6 \times 10^{-3} eV)^4 \\ &\simeq 6.25 \rho_\Lambda^{observed} . \end{aligned}$$

Using a nonlocal quark condensate, $\langle 0 \mid : \bar{q}(x)q(0) : \mid 0 \rangle = g(x^2)\langle 0 \mid : \bar{q}(0)q(0) : \mid 0 \rangle$, with $g(x^2)$ estimated in prevous work by Jung and L. S. Kisslinger, and Johnson and Kisslinger, we found $\rho_\Lambda^{nonlocal\ theory} \simeq \rho_\Lambda^{observed}$

Therefore, we find that the cosmological constant (dark energy) can be explained by the nonlocal quark condensate. For future work we are determining the temperature dependence of Λ, as the quark condensate was zero before the QCDPT.

BIG BANG NUCLEOSYNTHESIS.
LIGHT ATOMIC NUCLEI CREATED

t$\simeq 10^{-4}$ **sec, T=100 MeV–just after the QCDPT:**
Only atomic nuclei are p=proton and n=neutron.

There is an n-p equilibrium:

$$\begin{aligned} n &\leftrightarrow p + e^- + \bar{\nu} \\ \nu + n &\leftrightarrow p + e^- \\ e^+ + n &\leftrightarrow p + \bar{\nu} \end{aligned}$$

During the period 1 sec to 10min, Big Bang Nucleosysnthesis:

Notation:

Light Nuclei:
H^1**=p,** H^2**=D=deuterium=n+p,** He^3 **= 2p+n,**
He^4 **= 2p+2n**

A(Z)=nucleus has Z protons and N neutrons.

A=N+Z=atomic number

At about 2-3 min one can show (see Kolb-Turner):

Defining P(A(Z)) = ratio of number density of A(Z) nucleus to number density of protons, with three generations of neutrinos, one finds at t= 3min, T=.08 MeV:

$$\begin{aligned} P(D) &\simeq 10^{-5} \\ P(He^3) &\simeq 10^{-5} \\ P(He^4) &\simeq 0.23 \end{aligned}$$

EXPERIMENTS CONFIRM THESE PROBQABILITIES. THIS CONFIRMS THE STANDARD MODEL, WITH THREE ACTIVE NEUTRINOS, ν_e, ν_μ, ν_τ. THERE CAN ALSO BE STERILE NEUTRINOS, WITH ESSENTIALLY NO INTERACTIONS

DARK MATTER: WHAT IS IT-SOME THEORIES

As we saw in our discussion of the EWPT, the standard model, with three generations of quarks and leptons, is not expected to be the final model of elementary particles. Supersymmetry might be correct, with every particle in the standard model having a partner.

The SUPERSYMMETRIC PARTNER of a standard particle might have a very weak interaction. It could be DARK MATTER. LHC EXPERIMENTS IN PROGRESS.

In our discussion of supernova explosions and the resulting pulsars we discussed the possibility that the large pulsar velocities might be caused by the emission of sterile neutrinos.

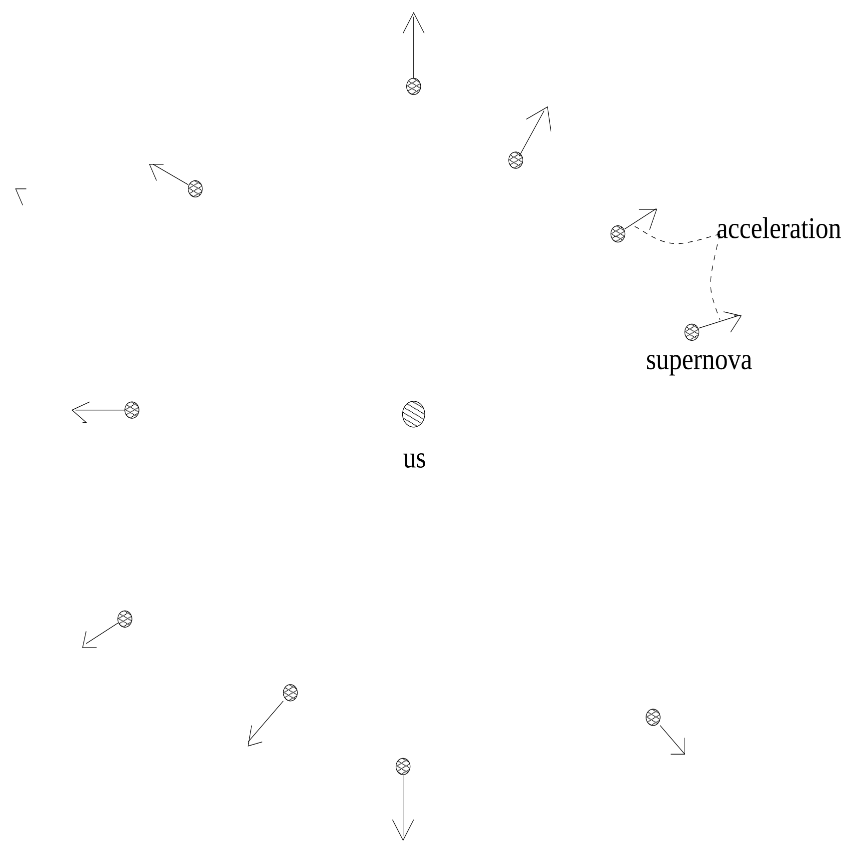
STERILE NEUTRINOS are beyond the standaed model. It is possible that heavy, very weakly interacting, sterile neutrinos are DARK MATTER.

WORK IN PROGRESS: LSK and collaborator Trevor Stevens are working on a model IN WHICH DARK MATTER GETS ITS MAS VIA INTERACTION WITH DARK ENERGY DURING THE EWPT, when all particles got their mass (with MSSM theory).

DARK ENERGY = ENERGY OF THE VACUUM

Both $< |\psi_{Higgs}| > \Rightarrow$ **Higgs mass and** $< |\bar{q}(x)q(x)| > =$ **quark condensate are vacuum energy. Dark energy?**

Observation of Dark Energy: Supernovae Acceleration first seen a few years ago [Saul Perlmutter, CMU Dickson Prize (2010), 2011 Nobel prize in Physics (shared with Brian P. Schmidt and Adam G. Riess)]



From Friedmann's equation, if the cosmologucal constant, Λ**, is large enough, Hubbles expansion increases. Outward pressure overcomes gravitational attraction.** Λ **represents dark energy, measured to be 73% of the energy of the universe by WMAP CMBR.**

THE EVOLUTION OF THE UNIVERSE
(REVIEW)

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10^{-35} s	10^{14} GeV Big Bang, Strings, Inflation Very early. Current particle theory no good
10^{-11} s	100 GeV Electroweak Phase Transition Particles (Higgs) get masses. Particly theory ok. Baryogenesis? (more particles than antiparticles)
10^{-5} s	100 MeV QCD (quark−hadron) phase transition Quarks(elementary) condense to Protons
1−100 s	Nucleosynthesis: Helium, light nuclei formed 1.0X 10^{9} ^{o}K Superconducting Universe
380,000 years	0.25 ev, 3,000 ^{o}K Atoms (electrically) neutral Last scattering of light (electromagnetic radiation) from big bang: Cosmic Microwave Background
1 billion years	early galaxies form
9 billion years	our solar sstem with planet earth has formed
14 billion years	2.7 ^{o}K Now

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COMPOSITION OF THE UNIVERSE NOW: 4% ORDINARY MATTER, 23% DARK MATTER, 73% DARK ENERGY.

STAY TUNED. MAYBE SOMEDAY WE'LL UNDERSTAND OUR UNIVERSE MUCH BETTER.