Signals from phase transitions in the early universe

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Outline

Modern cosmology is inflationary cosmology

- Simplest model of the very early Universe: Inflation[(1)]
- Energy density of Universe dominated by homogeneous scalar field $\bar{\phi}(t)$
- Explosive decay of the scalar field into particles is the "Hot Big Bang".
- General relativity + quantum fluctuations[(2)] in scalar field.
- $\rightarrow$ large, flat universe, uniform density, with small fluctuations
- Thermal equilibrium - for most particle species, most of the time.
- Observable relics require departure from equilibrium

[(1)] Starobinsky (1980); Sato (1981); Guth (1981); Mukhanov & Chibisov (1981); Linde (1982); Hawking & Moss (1982); Albrecht & Steinhardt (1982); Guth & Pi (1982); Hawking(1982); Hawking & Moss (1983); Bardeen, Steinhardt, Turner, (1983)

[(2)] Mukhanov & Chibisov (1981); Guth & Pi (1982); Hawking(1982); Hawking & Moss (1983); Bardeen, Steinhardt, Turner, (1983)

Departures from equilbrium

- “Freeze-out" (loss of chemical equilibrium) - dark matter, neutrinos
- “Decoupling" (loss of kinetic equilibrium) - photons/CMB
- Phase transitions:
  - 1st order: metastable states
  - 2nd order: critical slowing down
  - Cross-over: negligible departure from equilibrium

Phase transitions & cosmology

Phase transitions happened in real time in early Universe:

Thermal Changing $T(t)$ — Vacuum Changing field $\sigma(t)$

- **QCD phase transition**
  - Thermal, cross-over. (First order: strangelets, axion balls, magnetic fields)
- **Electroweak phase transition**
  - Thermal, 1st order?: electroweak baryogenesis[3]
  - Vacuum, continuous: cold electroweak baryogenesis[4]
- **Grand Unified Theory & other high-scale phase transitions**
  - Thermal: topological defects[5]
  - Vacuum: hybrid inflation, topological defects, ... [6]

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(3) Kuzmin, Rubakov, Shaposhnikov 1988
(4) Smit and Tranberg 2002-6; Smit, Tranberg & Hindmarsh 2007
(5) Kibble 1976; Zurek 1985, 1996; Hindmarsh & Rajantie 2000
(6) Copeland et al 1994; Kofman, Linde, Starobinsky 1996

Thermodynamic relations for cosmology

Particle reaction rates large compared with expansion rate $H \propto 1/t$

$$n\langle \sigma v \rangle \ll H \qquad \begin{cases} \sigma & \text{Scattering cross-section} \\ n & \text{Number density of scatterers} \\ v & \text{Relative speed} \\ \langle \dots \rangle & \text{Thermal average} \end{cases}$$

Early Universe very close to thermal equilibrium: expansion isentropic.

$$S = sa^3 = \text{const.} \qquad \text{Entropy density } s.$$

Thermodynamic relations:

$$s = \frac{dp}{dT}, \quad sT = \rho + p \qquad \left(\to \rho = T^2 \frac{d}{dT} \left(\frac{p}{T} \right) \right)$$

NB Need to calculate only pressure (easiest in QFT)
NB Eqm fails for neutrinos at $T \simeq 1$ MeV, WIMPs at $T \simeq 1 - 10$ GeV.

Relativistic and non-relativistic ideal gases

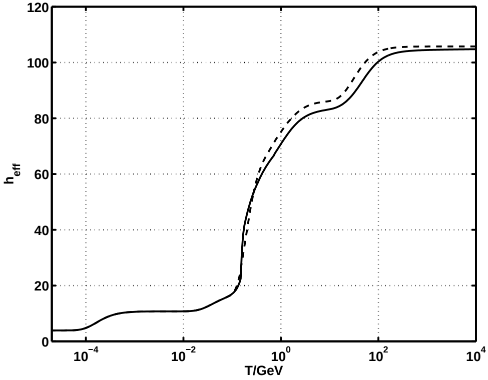
Quantity	*Relativistic B*	$\times$ *(F)*	*Non-relativistic* $(T \ll m)$
Number density	$n_r = g\frac{\zeta(3)}{\pi^2}T^3$	$\left(\frac{3}{4}\right)$	$n_m = g\left(\frac{mT}{2\pi}\right)^{\frac{3}{2}}\exp(-m/T)$
Energy density	$\rho_r = g\frac{\pi^2}{30}T^4$	$\left(\frac{7}{8}\right)$	$\rho_m = mn_m(T)$
Pressure	$p_r = g\frac{\pi^2}{90}T^4$	$\left(\frac{7}{8}\right)$	$p_m = n_m(T)T \ll \rho_m$
Entropy density	$s_r = g\frac{2\pi^2}{45}T^3$	$\left(\frac{7}{8}\right)$	$s_m = mn_m(T)/T \ll s_r(T)$

NB Isentropic expansion $s_r \propto a^{-3}$ means $T_r \propto 1/a$.
NB $m = 0$ particles out of kinetic equilibrium maintain distribution: $E \propto 1/a$.
Effective numbers of degrees of freedom for energy & entropy densities:

$$\rho = \frac{\pi^2}{30}g_{\rm eff}(T)T^4, \quad s = \frac{2\pi^2}{45}h_{\rm eff}(T)T^3,$$

Effective number of relativistic species of the Standard Model

Olive 1981 (dashed), Hindmarsh and Philipsen 2005 (solid)[7]



Temp.	Event
100 GeV	*t* non-relativistic
1 GeV	*b* non-relativistic
500 GeV	*c*, τ non-relativistic
200 MeV	QCD phase transition
30 MeV	μ non-relativistic
2 MeV	ν freeze-out
0.2 MeV	*e* non-relativistic
1 eV	matter = radiation
0.1 eV	photon decoupling

[7] Quark mass thresholds: Laine & Schröder 2006

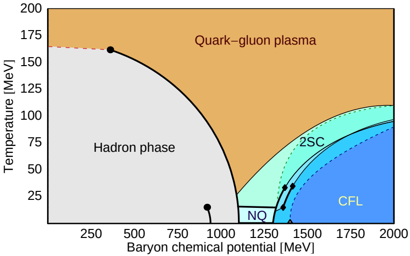
Degrees of freedom 0.4 – 40 GeV: mostly coloured

		Mass	g		Mass	g	
	γ	0	2	g	0	16	
	ν_e	$\lesssim$ 1 eV	2	u	3 MeV	12	
	ν_μ	$\lesssim$ 1 eV	2	d	7MeV	12	
	ν_τ	$\lesssim$ 1 eV	2	s	76 MeV	12	
	e	0.5 MeV	4	c	1.2 GeV	12	
	μ	106 MeV	4	b	4.2 GeV	12	
	τ	1.7 GeV	4	t	174 GeV	12	
	W	80 GeV	6				
	Z	91 GeV	3				
	h	125 GeV	3				
40 GeV:			$\frac{7}{8}18 + 2$			$\frac{7}{8}60 + 16$	68.5/84.25
0.4 GeV:			$\frac{7}{8}14 + 2$			$\frac{7}{8}36 + 16$	47.5/61.75

Cannot ignore QCD interactions.

QCD phase diagram

- $\eta_B = n_B/n_\gamma = (6.15 \pm 0.15) \times 10^{-10}$ (WMAP7 + H0 + BAO)[8]
- Cross-over at low chemical potential

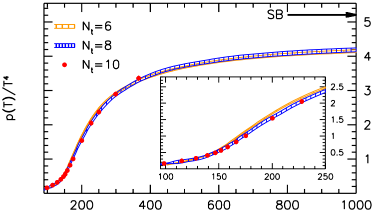


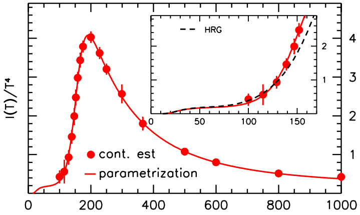
Ruester et al hep-ph/0503184

[8] Komatsu et al 2010

QCD equation of state

- Budapest-Marseille-Wuppertal lattice (physical quark masses)[9]
- Shown: pressure and trace anomaly $I(T) = \rho(T) - 3p(T)$ (with fit)





- Can model with hadronic resonance gas (low T) and dimensional reduction (high T)

[9] Borsányi et al. (2010)

Dark matter

Evidence for dark matter:

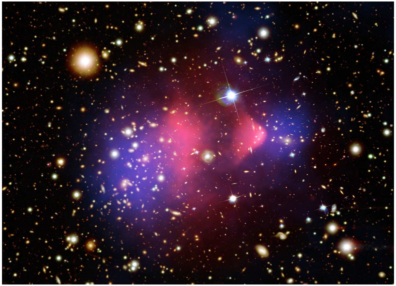
- Rotation of spiral galaxies
- Velocities of galaxies in clusters
- X-ray flux from hot gas
- Gravitational lensing
- Cosmic Microwave Background

Conclusions:

- DM is slow, collisionless particles (“Cold")
- $\Omega_{\rm DM} \equiv \rho_{\rm DM}/\rho_{\rm tot} \simeq 0.3$

Bullet cluster:[a]

- Dark matter from lensing
- X-rays show gas



[a] Markevitch et al 2005, Clowe et al 2006

WIMP relic density and QCD

Weakly Interacting Massive Particle:
Mass m, energy density ρ_X, annihilations $XX \to \ldots$ with total cross-section σ.

- Density parameter of WIMP: $\Omega_X = \rho_X/\rho_c$
- Define $h = H_0/(100\ \mathrm{km\,s^{-1}\,Mpc^{-1}}) = 0.704 \pm 0.025$ (WMAP7)
- $\Omega_X h^2 \simeq \frac{10^{-10}\ \mathrm{GeV}^{-2}}{\sigma}\frac{x_f}{g_*^{\frac{1}{2}}(T)} = 0.1120 \pm 0.0056$ (WMAP7)
- Where:
  - $x_f = m/T_f$, T_f - temperature at freeze-out. $x_f \sim 25$
  - $g_*^{1/2}(T) = \frac{h_{\mathrm{eff}}}{g_{\mathrm{eff}}^{1/2}}\left(1 + \frac{T}{3}\frac{d\ln h_{\mathrm{eff}}}{dT}\right)$.
- WIMP density depends on eqn. of state at $T \simeq 4(m/100\mathrm{GeV})$ GeV [10]
- Planck: $\Delta(\Omega_X h^2) \simeq 0.001$ [11] - QCD effects few %, significant

[10] Hindmarsh, Philipsen 2005
[11] Balbi et al 2003

Other cosmology where QCD is important

- Production of sterile neutrinos[12].
  - Sterile neutrinos density depends on $g_{\text{eff}}(T)$ at $T \sim T_{\text{QCD}}$
- Production of gravitinos[13]
  - Gravitinos produced by bremmstrahlung during scattering
  - Most scattering is by strongly coupled states

(12) Dodelson, Widrow 1994; Asaka, Laine, Shaposhnikov 2006; Laine & Shröder 2012
(13) Weinberg 1982, Nanopoulos, Olive Srednicki 1983; Ellis, Kim, Nanopoulos 1984; Bolz, Brandenburg, Buchmuller 2002; Rychkov, Strumia 2007

Free energy of an ideal gas

- Free energy density $f = \rho - Ts$ (also $f = -p$)
- To find equilibrium state we minimise free energy
- Dimensions: $f = T^4\phi(m/T)$ with $\phi(0) = -g\pi^2/90$.

Pressure due to particles of mass m in equilibrium (zero chemical potential) $\eta = \pm 1$ (FD/BE)):

$$p = \int \bar{d}^3k \frac{1}{e^{E/T} + \eta} \frac{k^2}{3E}, \qquad E = (k^2 + m^2)^{\frac{1}{2}}$$

Free energy density ($f = -kT \ln Z/V$):

$$f = -\eta T \int \bar{d}^3k \ln(1 + \eta e^{-E/T})$$

Note $f = -p$ by partial integration.

Free energy: exact formulae in high T expansion

Bosons:

$$f_B = -\frac{\pi^2}{90}T^4 + \frac{m^2T^2}{24} - \frac{(m^2)^{\frac{3}{2}}T}{12\pi} - \frac{m^4}{64\pi^2}\ln\left(\frac{m^2}{a_bT^2}\right) - \frac{m^4}{16\pi^{\frac{5}{2}}}\sum_\ell(-1)^\ell\frac{\zeta(2\ell+1)}{(\ell+1)!}\left(\frac{m^2}{4\pi^2T^2}\right)^\ell$$

Fermions:

$$f_F = -\frac{\pi^2}{90}\frac{7}{8}T^4 + \frac{m^2T^2}{48} + \frac{m^4}{64\pi^2}\ln\left(\frac{m^2}{a_fT^2}\right) + \frac{m^4}{16\pi^{\frac{5}{2}}}\sum_\ell(-1)^\ell\frac{\zeta(2\ell+1)}{(\ell+1)!}(1-2^{-2\ell-1})\Gamma(\ell+\tfrac{1}{2})\left(\frac{m^2}{4\pi^2T^2}\right)^\ell$$

$a_b = 16\pi^2\ln(\frac{3}{2} - 2\gamma_E)$, $a_f = a_b/16$, $\gamma_E = 0.5772\ldots$ (Euler's constant)

Effective potential for scalar field with gauge fields and fermions

Let scalar field give masses to

- scalars ($M_S(\bar\phi)$),
- vectors ($M_V(\bar\phi)$)
- (Dirac) fermions ($M_F(\bar\phi)$)

$$
\begin{aligned}
V_T(\bar\phi) &= V_T(0) + \tfrac{1}{2}\mu^2\bar\phi^2 + \tfrac{1}{4!}\lambda\bar\phi^4 \\
&+ \frac{T^2}{24}\left(\sum_S M_S^2(\bar\phi) + 3\sum_V M_V^2(\bar\phi) + 2\sum_F M_F^2(\bar\phi)\right) \\
&- \frac{T}{12\pi}\left(\sum_S (M_S^2(\bar\phi))^{\frac{3}{2}} + 3\sum_V (M_V^2(\bar\phi))^{\frac{3}{2}}\right) + \cdots
\end{aligned}
$$

Again, can neglect higher order terms where $M^2(\phi)/T^2 \ll 1$.

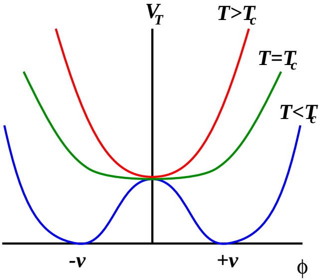
Symmetry restoration at high T

Suppose $\mu^2 < 0$ and $M(\bar\phi)/T \ll 1$.

$$\Delta V_T = \frac{1}{2}(-|\mu|^2 + \frac{1}{24}\lambda T^2)\bar\phi^2 + \frac{1}{4!}\lambda\bar\phi^4$$

Equilibrium at

$$\begin{aligned}\bar\phi^2 &= 6(|\mu^2| - \frac{1}{24}\lambda T^2)/\lambda \\ &= v^2(1 - T^2/T_c^2)\end{aligned}$$



- Critical temperature $T_c^2 = 24|\mu^2|/\lambda$
- Above T_c, equilibrium state is $\bar\phi = 0$
- $\phi \to -\phi$ symmetry is restored
- Second-order phase transition[14]
  discontinuity in specific heat, correlation length diverges $\xi = 1/m(T)$

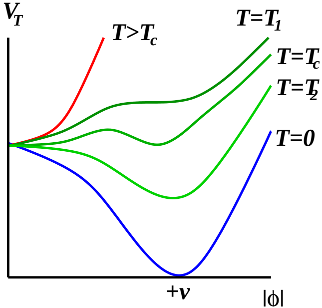
[14] Kirzhnitz & Linde (1974), Dolan & Jackiw (1974)

First order phase transition

Effective potential with multiple fields: cubic term important

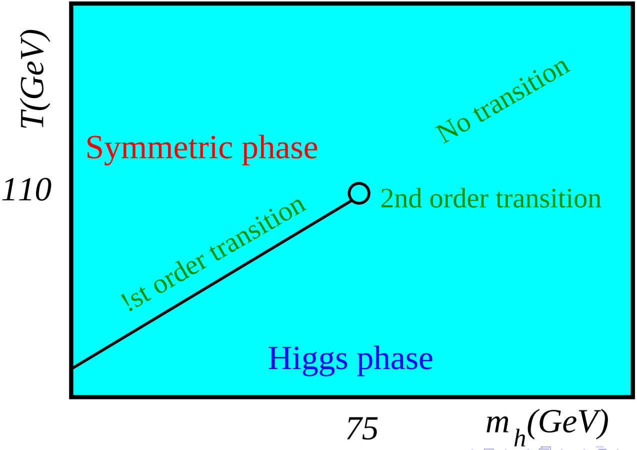
$$\Delta V_T \simeq \frac{\gamma}{2}(T^2 - T_2^2)|\bar{\phi}|^2 - \delta T|\bar{\phi}|^3 + \frac{1}{4!}\lambda|\bar{\phi}|^4$$

- Second order minimum develops at T_1
- Critical temperature T_c: free energies are equal.
- System can supercool below T_c.
- First order transition discontinuity in free energy



Phase transition in the Standard Model

Standard Model phase diagram (Kajantie et al 1996):



1st order phase transitions in SM extensions

- MSSM with light stops[15]
  - Effective theory near transition is SM + light coloured scalar
  - Increases strength of cubic term: $\Delta V_{\tilde{t}}^{(3)} = -48\frac{T}{12\pi}(m_{\tilde{t}}^2(\bar{\phi}))^{\frac{3}{2}}$
  - Non-perturbative contributions to $V_T(\phi)$ important[16]
  - Tightly constrained by $h \to \gamma\gamma$: need light neutralino[17]
- nMSSM ("nearly MSSM"):
  - Integrate out singlet[18]
  - $V_T(\phi) \simeq c_0 + c_1(T)\phi^2 + c_2\phi^4 + c_3\phi^6 + \cdots$
  - $c_2 < 0$ gives 1st order transition at tree level.

(15) Carena, Quiros, Wagner (1999), Laine Rummukainen (2001)
(16) Laine Rummukainen Nardini (2012)
(17) Carena et al (2012)
(18) Huber et al (2006)

Electroweak phase transition & baryogenesis

Sakharov conditions for baryogenesis:

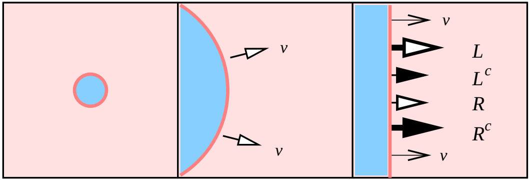
- **B violation:** Electroweak theory has *unstable* topological defects – sphalerons (S). Formation and decay of S results in change in $B + L$ of LH fermions.
- **C and CP violation:** C violation automatic in SM. CP violation needs more than CKM at high T[19]
- **non-equilibrium** Supercooling at 1st order phase transition?

[19] OK for cold electroweak baryogenesis (Salcedo, Smit, Tranberg)

(Hot) electroweak baryogenesis

Mechanism:[20]

- CP-violation in bubble wall field profile
- CP-asymmetry in reflection of fermions
- Chiral asymmetry → (Sphalerons) → baryon asymmetry



Signal: gravitational waves[21]

[20] Cohen, Kaplan, Nelson 1991

[21] Witten 1984, Kosowsky, Turner, Watkins 1986

Simulating a first order transition

- Relevant approximation for GWs: classical scalar field, classical relativistic fluid
- $T_\phi^{\mu\nu} = \partial^\mu\phi\partial^\nu\phi - g^{\mu\nu}\left[\frac{1}{2}\partial_\alpha\phi\partial^\alpha\phi\right]$
- $T_{\rm fluid}^{\mu\nu} = [\epsilon + p]\, U^\mu U^\nu + g^{\mu\nu} p$
- Equations:[22]
  - $-\ddot\phi + \nabla^2\phi - \frac{\partial V}{\partial\phi} = \eta W(\dot\phi + V^i\partial_i\phi)$
  - $\dot E + \partial_i(EV^i) + P[\dot W + \partial_i(WV^i)] - \frac{\partial V}{\partial\phi}W(\dot\phi + V^i\partial_i\phi) = \eta W^2(\dot\phi + V^i\partial_i\phi)^2.$
  - $\dot Z_i + \partial_j(Z_i V^j) + \partial_i P + \frac{\partial V}{\partial\phi}\partial_i\phi = -\eta W(\dot\phi + V^j\partial_j\phi)\partial_i\phi.$
  - W – relativistic γ-factor; V^i – fluid 3-velocity, E – fluid energy density; Z^i – fluid momentum density.
  - $\eta(\phi)$ – coupling

[22] Enqvist et al 1992; Kurki-Suonio, Laine 1996, Hindmarsh, Rummukainen, Weir (2013)

Bubbles

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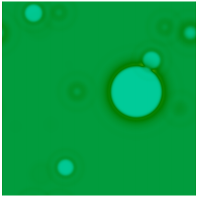
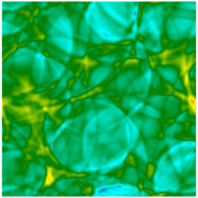
Fluid energy density



$t = 400 T_c^{-1}$



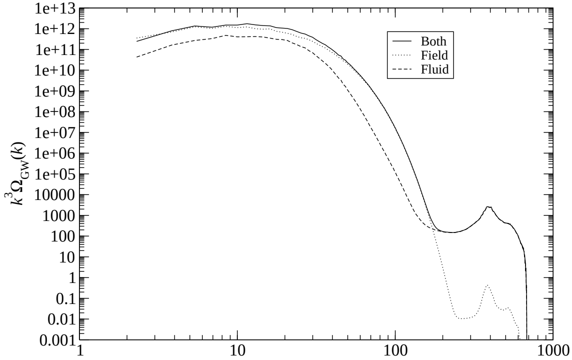
$t = 1200 T_c^{-1}$

Gravitational waves

Find metric perturbations h_{ij} from tranverse-traceless part of EM tensor Π_{ij}:

$$\ddot{h}_{ij} - \nabla^2 h_{ij} = 16\pi G \Pi_{ij}$$

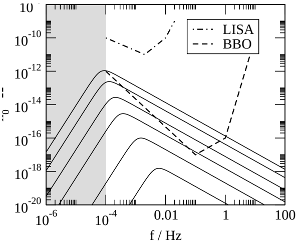
Gravitational wave power spectrum: $\frac{d\rho_{\mathrm{GW}}(k)}{d\ln k} = \frac{k^3}{32\pi G}\int d\Omega\, \dot{h}_{ij}(t,\mathbf{k})\dot{h}^*_{ij}(t,\mathbf{k})$



Current status: predictions and detection

Predictions

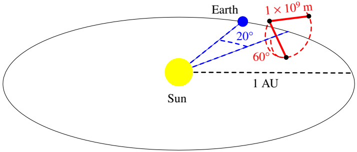
- Envelope approximation:[a]
  - All energy on bubble wall
  - Walls annihilate on collision
- Many bubble collisions in EA:[b]



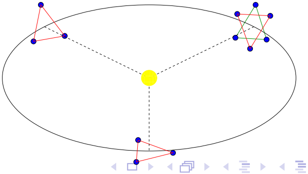
[a] Kamionkowski, Kosowski, Turner 1994
[b] Huber, Konstandin 2008

Space-based laser interferometers

eLISA (proposed, launch 2022):



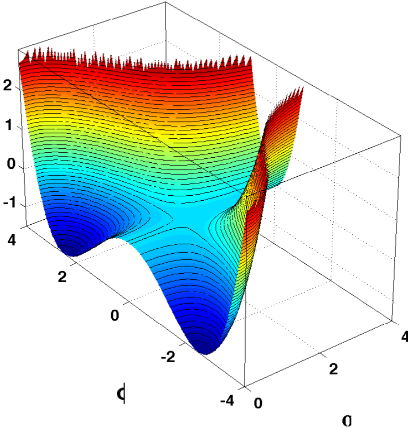
Big Bang Observer (proposed):



Hybrid inflation: vacuum phase transition

$$V(\phi,\sigma) = \frac{1}{2}\mu^2\phi^2 + \frac{1}{4!}\lambda\phi^4 + \frac{1}{4}\kappa\phi^2\sigma^2 + V(\sigma)$$

- σ another field e.g. inflaton
- $V(\sigma) = V_0 + \Delta V(\sigma)$
- Flat direction: Large $\langle\sigma(t)\rangle$, $\langle\phi\rangle = 0$
- Inflation with $H^2 \simeq \frac{1}{3m_P^2} V_0$
- Phase transition at $\langle\sigma\rangle = \sqrt{\frac{-2\mu^2}{\kappa}}$
- Transition terminates inflation
- Fast evolution to true vacuum: $\langle\sigma\rangle = 0$, $\langle\phi\rangle = \sqrt{-6\mu^2/\lambda}$



(Non-perturbative) field theory after inflation

- Preheating[23]
  - transfer of energy from homogeneous modes $\sigma(t), \phi(t)$ to higher momentum
- Reheating: decays of inflaton sector into SM particles, thermalisation[24]
- Formation of topological defects[25]
- Phase ordering following O(N) global symmetry breaking[26]

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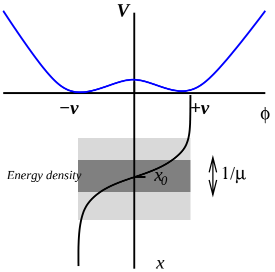
(23) Kofman, Linde, Starobinsky 1994, 1997
(24) Can be very slow: e.g. Buchmüller, Domcke, Schmitz, Vertongen 2010 - 2012
(25) Kibble 1976; Copeland et al 1994
(26) Turok, Spergel 1992; Boyanovsky, de Vega 1999

Topological defects: domain walls

$$\mathcal{L} = \tfrac{1}{2}\partial\phi\cdot\partial\phi - V(\phi), \qquad V(\phi) = V_0 - \tfrac{1}{2}\mu^2\phi^2 + \tfrac{1}{4!}\lambda\phi^4.$$

Field eqn. (Minkowski space)

$$\frac{\partial^2\phi}{\partial t^2} - \nabla^2\phi - \mu^2\phi + \frac{1}{3!}\lambda\phi^3 = 0$$



- Static solution $\phi = v\tanh(\mu z/\sqrt{2})$
- Energy density $T_{00} = v^4\mathrm{sech}^4(\mu z/\sqrt{2})$:
- Kink (1+1D), string (2+1D) or Domain Wall
- "Topologically" stable: field fixed at $|z| \to \infty$

A model field theory

Abelian Higgs model: complex scalar field $\phi(x)$, vector field $A_\mu(x)$.

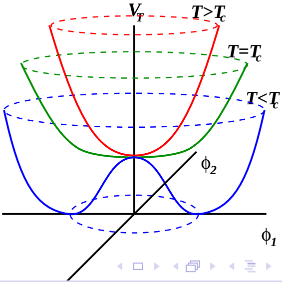
$$\mathcal{L}_{\text{eff}} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} + |D\phi|^2 - V_{\text{eff}}(\phi),$$

$$V_{\text{eff}}(\phi) \simeq V_0 + m_{\text{eff}}^2|\phi^2| + \frac{1}{4}\lambda|\phi|^4$$

where $m_{\text{eff}}^2(T) = \begin{cases} \frac{1}{12}(\lambda + 3e^2)T^2 - |\mu^2| & \text{Thermal} \\ \frac{1}{2}\kappa\sigma(t)^2 - |\mu^2| & \text{Vacuum} \end{cases}$.

Potential energy function $V_T(\phi)$ changes shape at

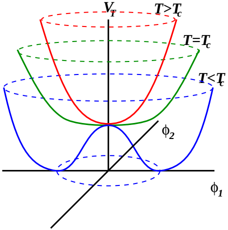
- critical temperature $T_c = \sqrt{\frac{12}{\lambda+3e^2}}|\mu|$ or
- critical field $\sigma_c = \sqrt{\frac{2}{\kappa}}|\mu|$



Formation and evolution: Abelian Higgs in expanding universe

$$S = -\int d^4x \sqrt{-g}\left(g^{\mu\nu}D_\mu\phi^* D_\nu\phi + V(\phi) + \frac{1}{4e^2}g^{\mu\rho}g^{\nu\sigma}F_{\mu\nu}F_{\rho\sigma}\right),$$

Complex scalar field $\phi(\mathbf{x},t)$, vector field $A_\mu(\mathbf{x},t)$
Covariant derivative $D_\mu = \partial_\mu - iA_\mu$.
Potential $V(\phi) = \frac{1}{2}\lambda(|\phi|^2 - v^2)^2$.
Metric $ds^2 = a^2(\tau)(-d\tau^2 + d\mathbf{x}^2)$
τ: conformal time, $\propto t, t^{\frac{1}{2}}$



Temporal gauge ($A_0 = 0$) field equations (index raised with Minkowski metric).

$$\ddot\phi + 2\frac{\dot a}{a}\dot\phi - D^2\phi + \lambda a^2(|\phi|^2 - v^2)\phi = 0,$$

$$\partial^\mu\left(\frac{1}{e^2}F_{\mu\nu}\right) - ia^2(\phi^* D_\nu\phi - D_\nu\phi^*\phi) = 0,$$

Abelian Higgs model simulations

- Numerical solution of partial differential equations by standard methods
- Initial conditions: $\phi(\mathbf{x})$ Gaussian random field, correlation length small
- Expansion produces damping

Abelian Higgs model simulations: energy density isosurfaces

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Abelian Higgs model simulations: Field isosurfaces, electric fields

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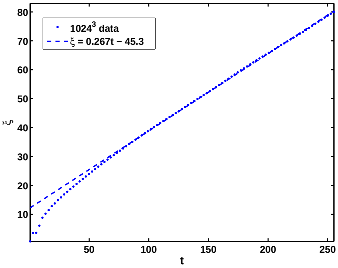
Abelian Higgs model simulations: string length scale

Friedmann background (matter era)



Total length of field zeros: L
Network scale: $\xi = \sqrt{(V/L)}$
Scaling: $L/V \propto t^{-2}$
Hence $\xi \propto t$

Mass per unit length μ
Energy density $\rho_s = \mu L/V = \mu/\xi^2 \sim t^{-2}$
Critical (total) energy density $\rho_c \sim 1/Gt^2$
Density parameter $\Omega_s = \rho_s/\rho_c \sim G\mu$ - **constant**.

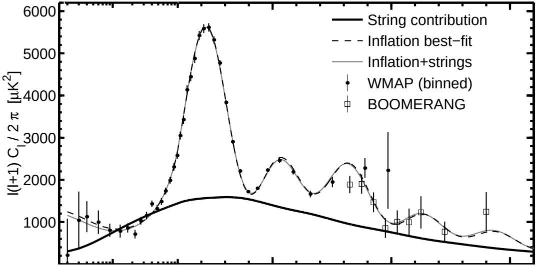
Cosmic string CMB using Abelian Higgs

Multipole moments:
$a_{lm} = \int d\Omega \Delta T(\mathbf{n}) Y^*_{lm}(\mathbf{n})$

Angular power spectrum:

$$C_l = \sum_{m=-l}^{l} |a_{lm}|^2$$

Anisotropy power:
$l(l+1)C_l/(2\pi)$



Strings normalised to WMAP3 ($\ell = 10$)[a]

[a] Bevis, Hindmarsh, Kunz, Urrestilla (2006)

Limits from WMAP7 [27]: $f_{10} < 9.5\%$, $G\mu < 0.57 \times 10^{-6}$

[27] Bevis et al 2011

Other signals from cosmic defects

- Gravitational waves.[28] Generic features:[29]
  - scale-invariant spectrum
  - amplitude $\Omega_{\rm gw}(\omega) \sim 10^{-3}\,(v/M_{\rm P})^4$,
- Cosmic rays[30]
  - GeV-scale γ-rays (EGRET, FERMI/LAT)
  - UHECRs (Auger)
  - Neutrinos (Ice Cube)
- Decaying defects are sources of
  - baryon number[31]
  - dark matter[32]

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(28) Krauss 1992, Fenu et al 2009
(29) Figueroa, Hindmarsh, Urrestilla 2012. Cosmic string loops $\sim (v/M_{\rm P})^2$ (Vilenkin 1981)
(30) Bhattacharjee, Sigl 1999
(31) Bhattacharjee, Kibble, Turok 1984
(32) Jeannerot, Zhang, Brandenberger 1999

Putting it all together: model-building for cosmology

- Particle physics: must include Standard Model (with 125 GeV Higgs!)
- Cosmology: inflation, reheating, baryogenesis, dark matter, dark energy

Ideology:

- Supersymmetry greatly reduces tuning both in inflaton and SM sectors
- Keep it simple: minimal F-term inflation, Minimal Supersymmetric SM
- Keep it predictive: renormalisable couplings only.

Model-building rules deriving from ideology:

1. The field content of minimal F-term inflation and the MSSM.
2. The symmetries of minimal F-term inflation and the MSSM.
3. Renormalisable couplings only.
4. An inflaton-sector $U(1)'$ gauge symmetry coupled to the MSSM.

A Minimal Renormalisable Inflationary Supersymmetric Standard Model

Model-building rules give a unique class of models[33]

- Superpotential: $W = W_A + W_X + W_I$
- Consisting of:
  - Pure MSSM part: $W_A = H_2 Q Y_U U + H_1 Q Y_D D + H_1 L Y_E E + H_2 L Y_N N$
  - Unique coupling part: $W_X = \frac{1}{2}\lambda_2 N N \Phi - \lambda_3 S H_1 H_2$.
  - Pure F-term inflation part: $W_I = \lambda_1 \Phi \overline{\Phi} S - M^2 S$
- μ-term from $\langle s \rangle$
- RH neutrino masses from $\langle \phi \rangle$
- All other renormalisable terms forbidden by symmetries
- All B-violating operators forbidden by Y' and R
- Assume canonical Kähler potential

[33] HIndmarsh, Jones 2012, 2013 (to appear)

Related models

Same field content:

- $Y' = B - L$ [34]. Neutrino masses from $\langle\phi\rangle$, but μ-term not specified.
- $U(1)' \to SU(2)_R$ [35].
- F_D inflation[36]. $\langle s\rangle$ gives both μ and (TeV-scale) N masses.

Even fewer fields:

- Higgs inflation[37] and νMSM[38]
- Higgs-Dilaton theories[39]

[34] Buchmüller, Domcke, Schmitz, Vertongen (2010-2012)
[35] Dvali, Lazarides, Shafi (1997)
[36] Garbrecht, Pallis, Pilftsis (2006)
[37] Bezrukov, Shaposhnkov 2008,9
[38] Asaka (Blanchet) Shaposhnikov (2005), Shaposhnikov, Tkachev 2006
[39] Shaposhnikov, Zenhausern (2009); Garcia-Bellido et al (2011)

MRISSM features

- MSSM (with neutrinos)
- F-term hybrid inflation (3 MSSM singlets + U(1)$'$ symmetry)
- Dynamical explanation of μ-term and RH neutrino masses
- Second period of Higgs-driven "thermal" inflation $T_{\rm rh} \sim 10^9$ GeV
- Reduced amount of F-term inflation: $n_s \simeq 0.976$
- Neutralino DM (from gravitino decays or freeze-out)
- Leptogenesis from RH neutrino decays (if $M_{N_1} \lesssim 10^9$ GeV)
- Baryogenesis (if electroweak phase transition is 1st order)
- Cosmic strings, $G\mu_{\rm cs} \simeq 10^{-7}$, consistent with CMB

Details elsewhere ... [40]

[40] Hindmarsh, Jones 2012, 2013 (to appear)

Summary

- There were phase transitions in the early Universe
- QCD phase transition affects production of weakly-interacting particles
- Electroweak transition makes baryon number and gravitational waves in SM extensions
- Hybrid inflation can generate topological defects: CMB, gravitational waves
- Cosmic strings, if formed, have $G\mu < 0.55 \times 10^{-6}$
- MRISSM: a Minimal renormalisable inflationary supersymmetric Standard Model

Future

- Gravitino production uncertain by factor up to 2
- Baryon number calculation still order-of-magnitude
- Gravitational wave production from 1st order phase transition (fluid!)
- Gravitational wave and particle production from strings still uncertain
- “Effective theories of everything"
- and ... **DATA!**
  - Higgs structure $\rightarrow$ EW phase transition
  - Beyond the SM ...
  - Dark matter $\rightarrow$ universe at $T \sim 5\,\text{GeV}$
  - Planck CMB $\rightarrow$ universe at $E \sim 10^{15}\,\text{GeV}$
  - Large Scale Structure, gravitational waves ...
- Towards a complete history of the universe from 10^{-36} seconds on