Cosmology and Particle Physics

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Lecture 3

Outline of Lecture 3

- Warm dark matter
  - Sterile neutrino
  - Gravitino
- Dark matter summary
- Baryon asymmetry of the Universe
  - Generalities.
  - Electroweak baryon number non-conservation

Warm dark matter

- Clouds over CDM

  Numerical simulations of structure formation with CDM show

  - Too many dwarf galaxies

    A few hundred satellites of a galaxy like ours —

    But much less observed so far

  - Too high density in galactic centers ("cusps")

- No serious worry yet

  But what if one really needs to suppress small structures?

High initial momenta of DM particles $\Longrightarrow$ Warm dark matter

Digression. Cosmological (particle) horizon

Light travels along $ds^2 = dt^2 - a^2(t)d\mathbf{x}^2 = 0 \Longrightarrow dx = dt/a(t)$.
If emitted at $t = 0$, travels finite coordinate distance

$$\eta = \int_0^t \frac{dt'}{a(t')} \propto \sqrt{t} \quad \text{at radiation domination}$$

$\eta \propto \sqrt{t} \Longrightarrow$ visible Universe increases in time

Fig.

Physical size of horizon at time t

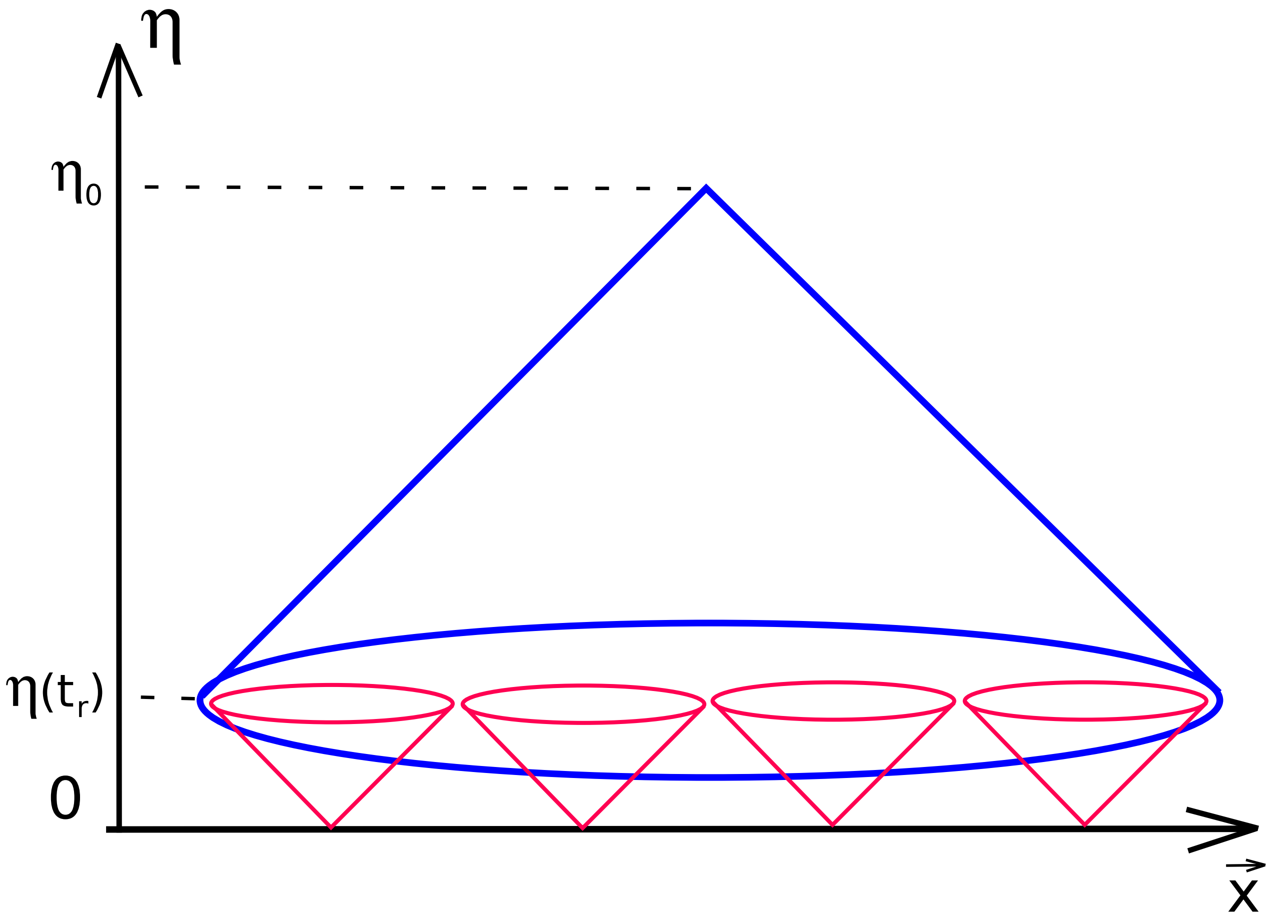
$$l_{H,t} = a(t) \int_0^t \frac{dt'}{a(t')} = 2t \quad \text{at radiation domination}$$

In hot Big Bang theory at both radiation and matter domination

$$l_{H,t} \sim t \sim H^{-1}(t)$$

Today $l_{H,t_0} \approx 15$ Gpc $= 4.5 \cdot 10^{28}$ cm

Causal structure of space-time in hot Big Bang theory



Warm dark matter

- Decouples when relativistic, $T_f \gg m$.

  Option: never in thermal equilibrium, but created at $T = T_f \gg m$ with momenta of order T_f

- Momenta decrease as $p \propto a^{-1} \propto T \implies p \sim T$ at all times after T_f. Remain relativistic until $T \sim m$. DM does not feel gravitational potentials before that.

- Perturbations of wavelengths shorter than horizon size at that time get smeared out $\implies$ small size objects do not form ("free streaming")

- Horizon size at $T \sim m$

$$l(T) = H^{-1}(T \sim m)$$

Recall

$$H(T) = \frac{T^2}{M^*_{Pl}}$$

with $M^*_{Pl} = M_{Pl}/(1.66\sqrt{g_*}) \sim 5 \cdot 10^{18}$ GeV at $T \lesssim 1$ MeV

- Horizon size at $T \sim m$

$$l_H(T) = H^{-1}(T \sim m) \sim \frac{M_{Pl}^*}{T^2} = \frac{M_{Pl}^*}{m^2}$$

Present size of this region

$$l_c = \frac{T}{T_0} l(T) = \frac{M_{Pl}}{m T_0}$$

(modulo g_* factors).

Objects of initial comoving size smaller than l_c are less abundant

- Size of region that collapsed into dwarf galaxy
  $l_{dwarf} \sim 100$ kpc $\sim 3 \cdot 10^{23}$ cm
  Require

$$l_c \simeq \frac{M_{Pl}}{mT_0} \sim l_{dwarf}$$

$\Longrightarrow$ obtain mass of DM particle

$$m \sim \frac{M_{Pl}}{T_0 l_{dwarf}} \sim 3 \text{ keV}$$

($M_{Pl} = 10^{19}$ GeV, $T_0^{-1} = 0.1$ cm).

- Particles of masses in 3 – 10 keV range
  are good warm dark matter candidates (assuming they had thermal velocities)

Phase space density constraint

Phase space density

$$f(\mathbf{x},\mathbf{p}) = \frac{dN}{d^3x\, d^3p} = \# \frac{\rho(\mathbf{x})}{M_X} \cdot \frac{1}{M_X^3 v_X^3}$$

$v_X^2 =$ dark matter velocity dispersion. Both ρ and v_X^2 are measured in dwarf galaxies: $\rho_X \sim 15$ GeVcm^{-3}, $v_X^2 \sim (4 \text{ km/s})^2$

Fermions: Pauli principle

$$f(\mathbf{x},\mathbf{p}) < \frac{g_X}{(2\pi)^3}$$

This gives bound

$$M_X > \# \left(\frac{\rho_X}{v_X^3}\right)^{1/4} \gtrsim 1 \text{ keV}$$

Stronger bounds if initial thermal distribution assumed.

Even stronger bounds from Ly-α forest.

Digression: fuzzy dark matter

Bosons: no Pauli principle. But

de Broglie wavelength must be smaller than size of object (dwarf galaxy)

$$\frac{2\pi}{M_X v_X} < r_{dwarf} \sim 1 \text{ kpc}$$

$$M_X \gtrsim \text{a few} \cdot 10^{-22} \text{ eV}$$

In principle detectable through pulsar timing!

Sterile neutrinos

- May give masses to ordinary neutrinos
- One sterile neutrino species can be light.
  Seemingly, nothing wrong with $m_{\nu_s} = 3 - 10$ keV
- Mix with ordinary neutrinos (say, ν_e), mixing angle θ_s.
  In vacuum, and in Universe below $T \sim 200$ MeV

$$P_{\nu_e \to \nu_s} = \sin^2 2\theta_s \cdot \sin^2 \left(\frac{\Delta m^2 \, t}{E} \right)$$

  Rapid oscillations, $P_{\nu_e \to \nu_s} = \frac{1}{2} \sin^2 2\theta_s$. Process starts anew after collision of ν_e with another particle in cosmic plasma.
- Production rate

$$d(n_s a^3)/dt = \Gamma_{\nu_e} \cdot (n_{\nu_e} a^3) \cdot \frac{1}{2} \sin^2 2\theta_s$$

$\Gamma = \# G_F^2 T^5 =$ collision rate of ν_e.

- Strong matter effects at $T \gtrsim 200$ MeV, production negligible.
- Most efficient creation at $T_s \sim 200$ MeV.

$$\frac{n_s}{n_{\nu_e}} \simeq H^{-1}(T_s) \cdot \Gamma_{\nu_e}(T_s) \cdot \sin^2 2\theta_s$$

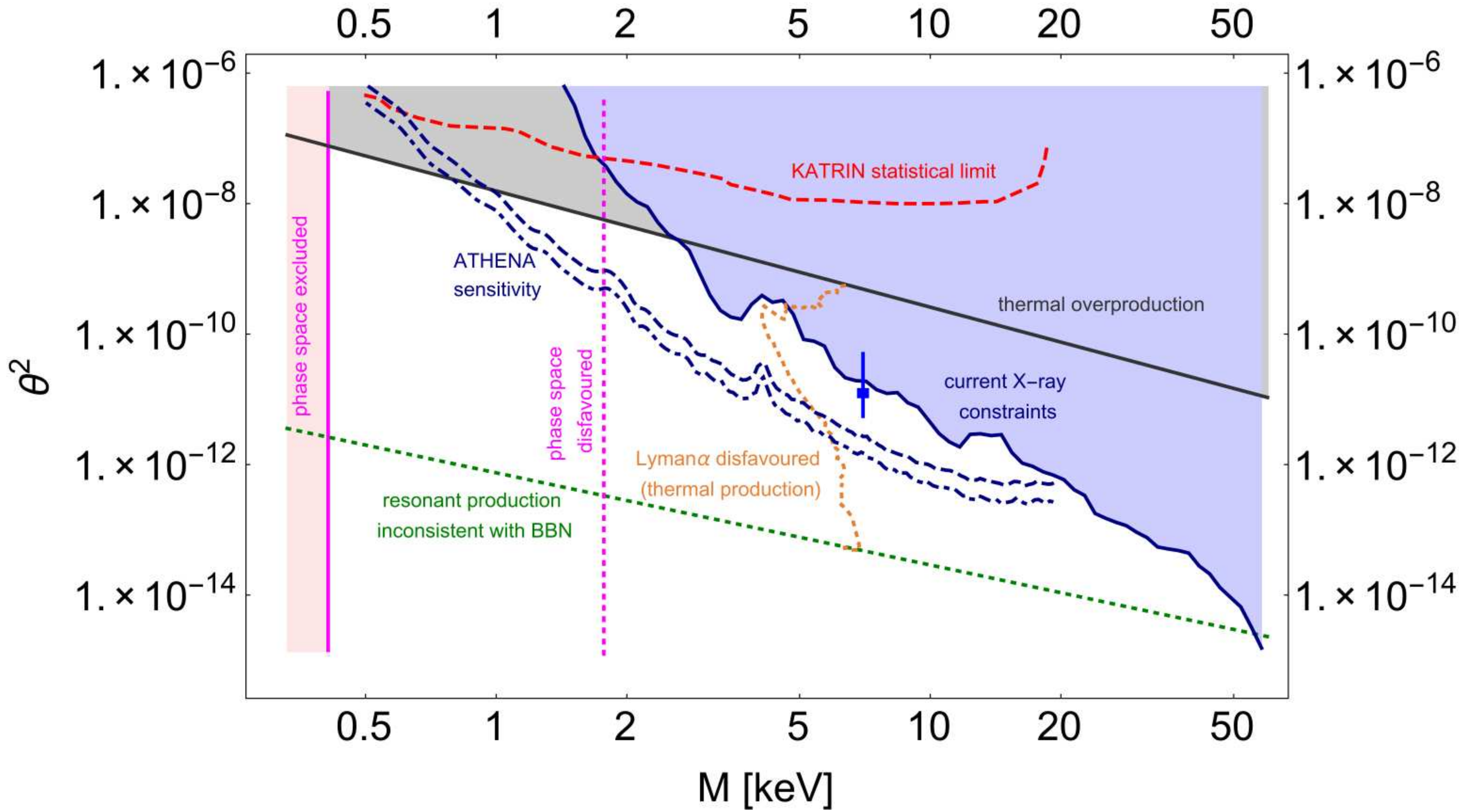
Presently, $n_{\nu_e} \approx 100$ cm^{-1}. Recall $H(T) = T^2/M^*_{Pl}$ and get

$$\Omega_s \simeq 0.2 \cdot \left(\frac{\sin 2\theta_s}{10^{-4}}\right)^2 \cdot \left(\frac{m_{\nu_s}}{1 \text{ keV}}\right)$$

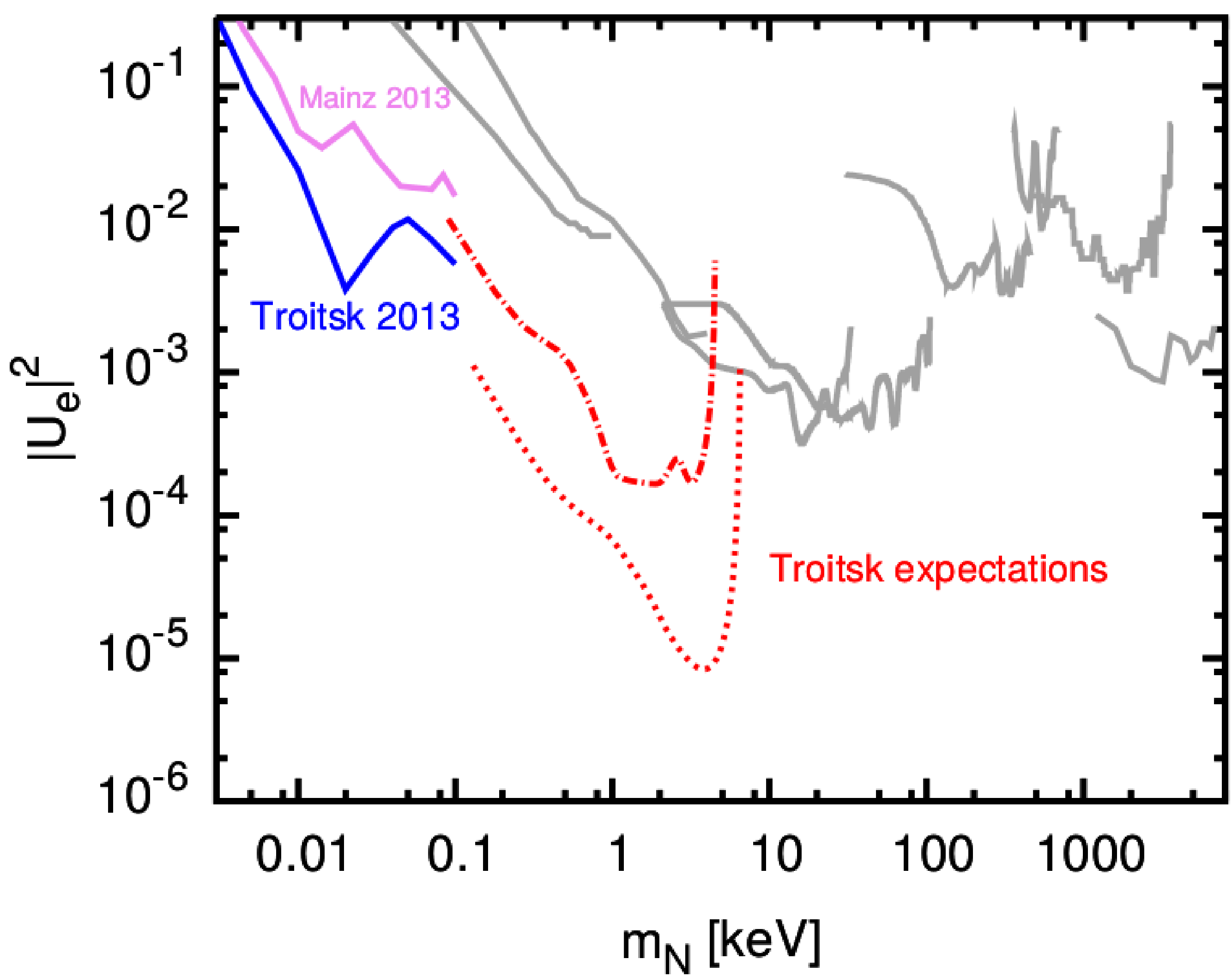
- Long lifetime: $\tau_{\nu_s} \gg 10^{10}$ yrs for $m_{\nu_s} = 3 - 10$ keV, $\sin 2\theta_s = 10^{-4} - 10^{-5}$
- $\nu_s \to \nu\gamma \Longrightarrow$ Search for photons with $E = m_{\nu_s}/2$ from sky.

  Straightforward version of scenario ruled out
  But more contrived (assuming lepton asymmetry or phase transition) does not: correct Ω_s for smaller $\sin 2\theta_s$.

Search for photons with $E = m_{\nu_s}/2$



Laboratory search: long way to go



Gravitinos

- Mass $m_{3/2} \simeq F/M_{Pl}$
  $\sqrt{F} =$ SUSY breaking scale.
  $\Longrightarrow$ Gravitinos light for low SUSY breaking scale.
  E.g. gauge mediation
- Light gravitino = LSP $\Longrightarrow$ Stable
- Correct present mass density for $m_{3/2} \sim 10$ keV, provided that
  - some superpartners are light, $M_{\tilde{S}} \simeq 100 \div 300$ GeV
  - maximum temperature in the Uiverse is low, $T_{max} \lesssim$ (a few) TeV to avoid overproduction in collisions of superpartners (and in decays of heavy squarks and gluinos)

Rather contrived scenario, but generating warm dark matter is always contrived

NB: $\Gamma_{NLSP} \simeq \frac{M_{\tilde{S}}^5}{m_{3/2}^2 M_{Pl}^2} \Longrightarrow c\tau_{NLSP} =$ a few $\cdot$ mm $\div$ a few $\cdot\, 100$ m

for $m_{3/2} = 1 \div 10$ keV, $M_{\tilde{S}} = 100 \div 300$ GeV

Dark matter summary

- WIMP:
  - Signal at the LHC $\Longrightarrow$ strongest possible motivation for direct and indirect detection
    - Inferred interactions with baryons $\Longrightarrow$ strategy for direct detection
  - Direct/indirect detection $\Longrightarrow$ strategies for search at the LHC
  - In either case: a window to the Universe at

$$T = (\text{a few}) \cdot 10 \text{ GeV} \div (\text{a few}) \cdot 100 \text{ GeV}$$

$$t = 10^{-11} \div 10^{-8} \text{ s}$$

cf. $T = 1$ MeV, $t = 1$ s at nucleosynthesis

- Gravitino-like
  - Find supersymmetry at the LHC first
  - A lot of work to make sure that LSP is gravitino and it is indeed DM particle
  - Direct and indirect searches hopeless
- No signal at the LHC
  - Good guesses: axion, ALP, sterile neutrino
  - Reasonable chance for searches for light weakly interacting particles: SHiP.
  - If not, need more hints from cosmology and astrophysics

Baryon asymmetry of the Universe

- There is matter and no antimatter in the present Universe.
- Baryon-to-photon ratio, almost constant in time:

$$\eta_B \equiv \frac{n_B}{n_\gamma} = 6 \cdot 10^{-10}$$

Baryon-to-entropy, constant in time: $n_B/s = 0.9 \cdot 10^{-10}$

What's the problem?

Early Universe ($T > 10^{12}$ K $= 100$ MeV):
creation and annihilation of quark-antiquark pairs $\Rightarrow n_q, n_{\bar{q}} \approx n_\gamma$
Hence

$$\frac{n_q - n_{\bar{q}}}{n_q + n_{\bar{q}}} \sim 10^{-9}$$

How was this excess generated in the course of the cosmological evolution?

Sakharov'67, Kuzmin'70

Sakharov conditions

To generate baryon asymmetry, three necessary conditions should be met at the same cosmological epoch:

- B-violation
- C- and CP-violation
- Thermal inequilibrium

NB. Reservation: L-violation with B-conservation at $T \gg 100$ GeV would do as well $\Longrightarrow$ Leptogenesis.

Can baryon asymmetry be due to electroweak physics?

Baryon number is violated in electroweak interactions.
"Sphalerons".

Non-perturbative effect

Hint: triangle anomaly in baryonic current B^μ:

$$\partial_\mu B^\mu = \left(\frac{1}{3}\right)_{B_q} \cdot 3_{colors} \cdot 3_{generations} \cdot \frac{g_W^2}{32\pi^2} \varepsilon^{\mu\nu\lambda\rho} F^a_{\mu\nu} F^a_{\lambda\rho}$$

$F^a_{\mu\nu}$: $SU(2)_W$ field strength; g_W: $SU(2)_W$ coupling

Likewise, each leptonic current ($n = e, \mu, \tau$)

$$\partial_\mu L^\mu_n = \frac{g_W^2}{32\pi^2} \cdot \varepsilon^{\mu\nu\lambda\rho} F^a_{\mu\nu} F^a_{\lambda\rho}$$

Large field fluctuations, $F^a_{\mu\nu} \propto g_W^{-1}$ may have

$$Q \equiv \int d^3x dt \; \frac{g_W^2}{32\pi^2} \cdot \varepsilon^{\mu\nu\lambda\rho} F^a_{\mu\nu} F^a_{\lambda\rho} \neq 0$$

Then

$$B_{fin} - B_{in} = \int d^3x dt \; \partial_\mu B^\mu = 3Q$$

Likewise

$$L_{n,\ fin} - L_{n,\ in} = Q$$

B is violated, $B - L$ is not.

How can baryon number be not conserved without explicit B-violating terms in Lagrangian?

Consider massless fermions in background gauge field $\vec{A}(\mathbf{x},t)$ (gauge $A_0 = 0$). Let $\vec{A}(\mathbf{x},t)$ start from vacuum value and end up in vacuum.

NB: This can be a fluctuation

Dirac equation

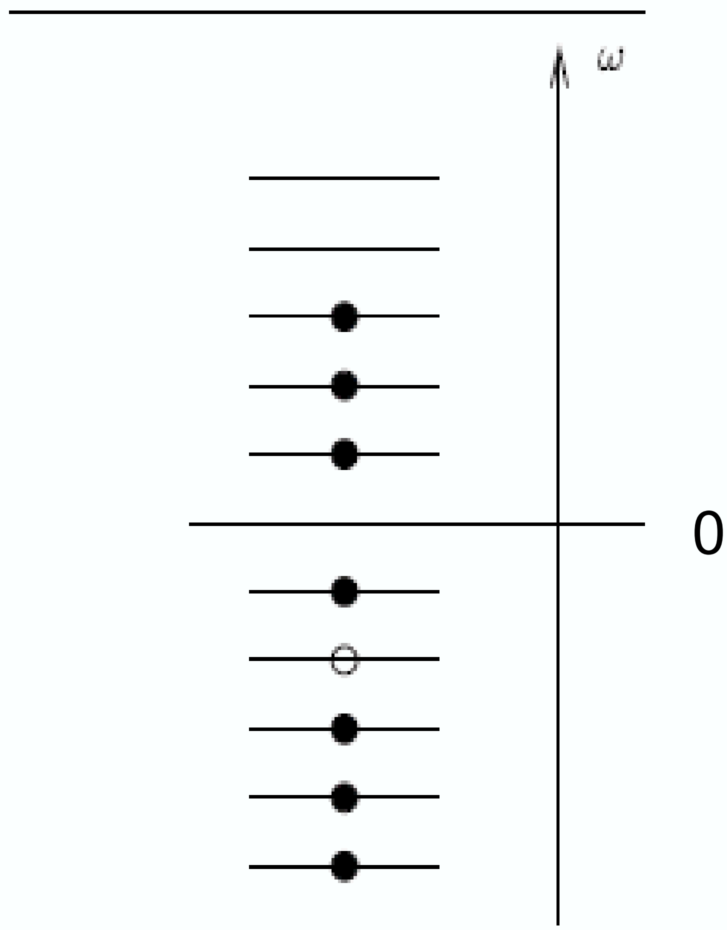
$$i\frac{\partial}{\partial t}\psi = i\gamma^0\vec{\gamma}(\vec{\partial} - ig\vec{A})\psi = H_{Dirac}(t)\psi$$

Suppose for the moment that $\vec{A}$ slowly varies in time. Then fermions sit on levels of instantaneous Hamiltonian,

$$H_{Dirac}(t)\psi_n = \omega_n(t)\psi_n$$

How do eigenvalues behave in time?

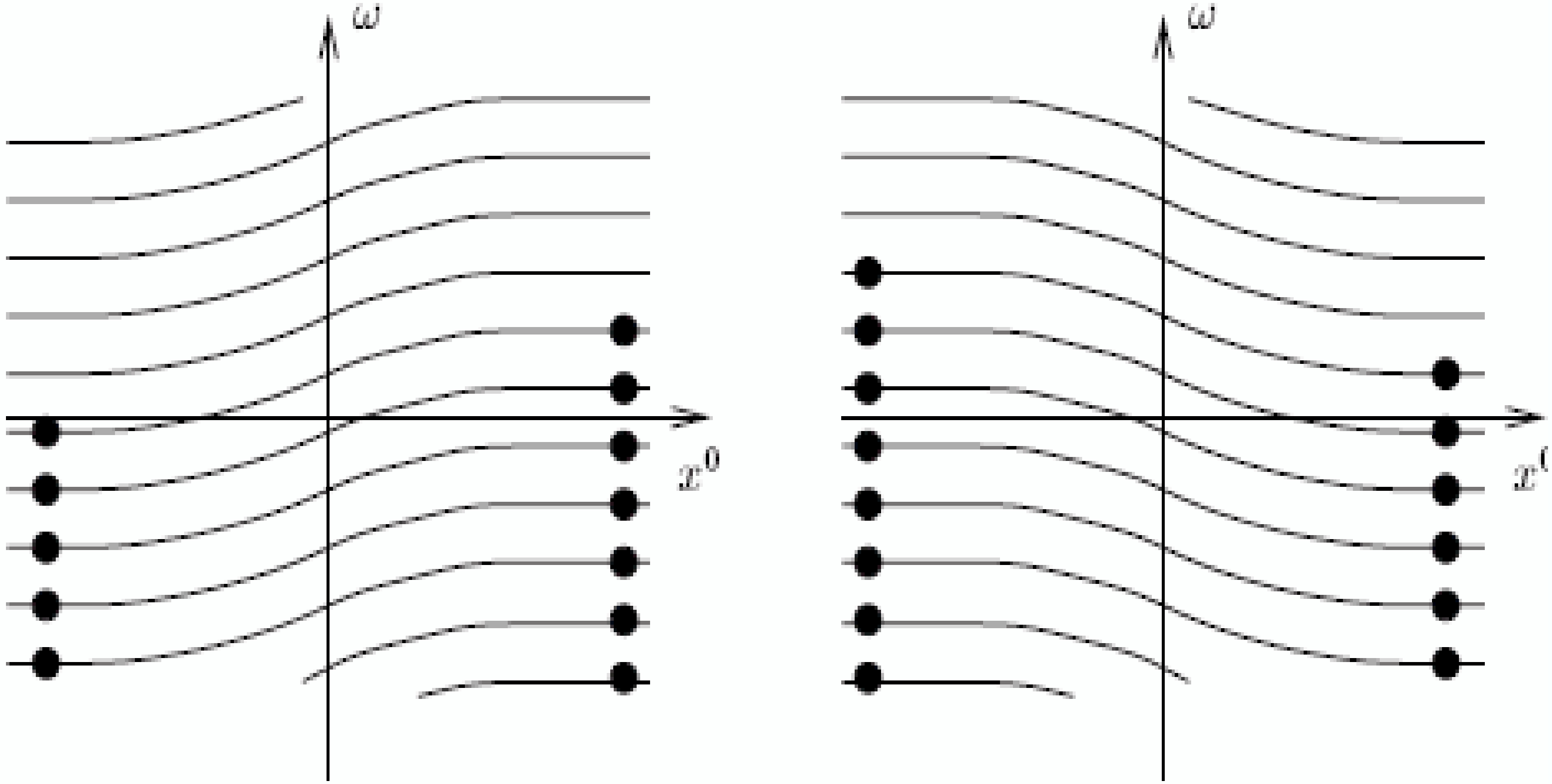
Dirac picture at $\vec{A} = 0$, $t \to \pm\infty$



TIME EVOLUTION OF LEVELS

IN SPECIAL (TOPOLOGICAL) GAUGE FIELDS

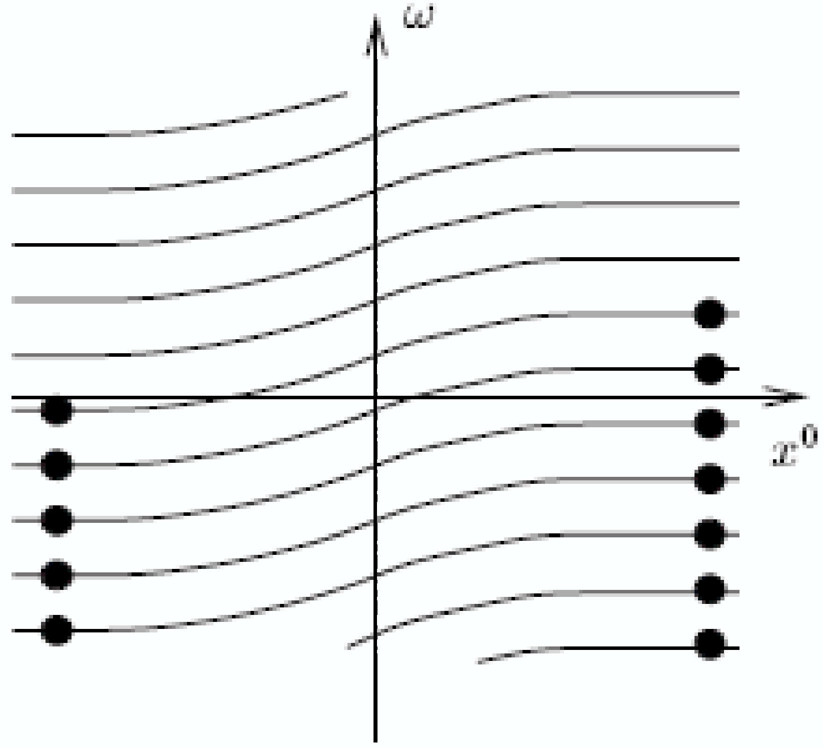
Left-handed fermions Right-handed



The case for QCD

$B = N_L + N_R$ is conserved, $Q^5 = N_L - N_R$ is not

If only left-handed fermions interact with gauge field, then number of fermions is not conserved



The case for $SU(2)_W$

Fermion number of every doublet changes by equal amount

Need large field fluctuations. At zero temprature these are instantons; their rate is suppressed by

$$e^{-\frac{16\pi^2}{g_W^2}} \sim 10^{-165}$$

High temperatures: large thermal fluctuations (“sphalerons”).

B-violation rapid as compared to cosmological expansion at

$$\langle \phi \rangle_T < T$$

$\langle \phi \rangle_T$: Higgs expectation value at temperature T.

Possibility to generate baryon asymmetry at electroweak epoch, $T_{EW} \sim 100$ GeV ?

Problem: Universe expands slowly. Expansion time

$$H^{-1} \sim 10^{-10} \text{ s}$$

Too large to have deviations from thermal equilibrium?

The only chance: 1st order phase transition, highly inequilibrium process

Electroweak symmetry is restored, $\langle\phi\rangle_T = 0$ at high temperatures

Just like superconducting state becomes normal at “high” T

Transition may in principle be 1st order

Fig

1st order phase transition occurs from supercooled state via spontaneous creation of bubbles of new (broken) phase in old (unbroken) phase.

Bubbles then expand at $v \sim 0.1c$

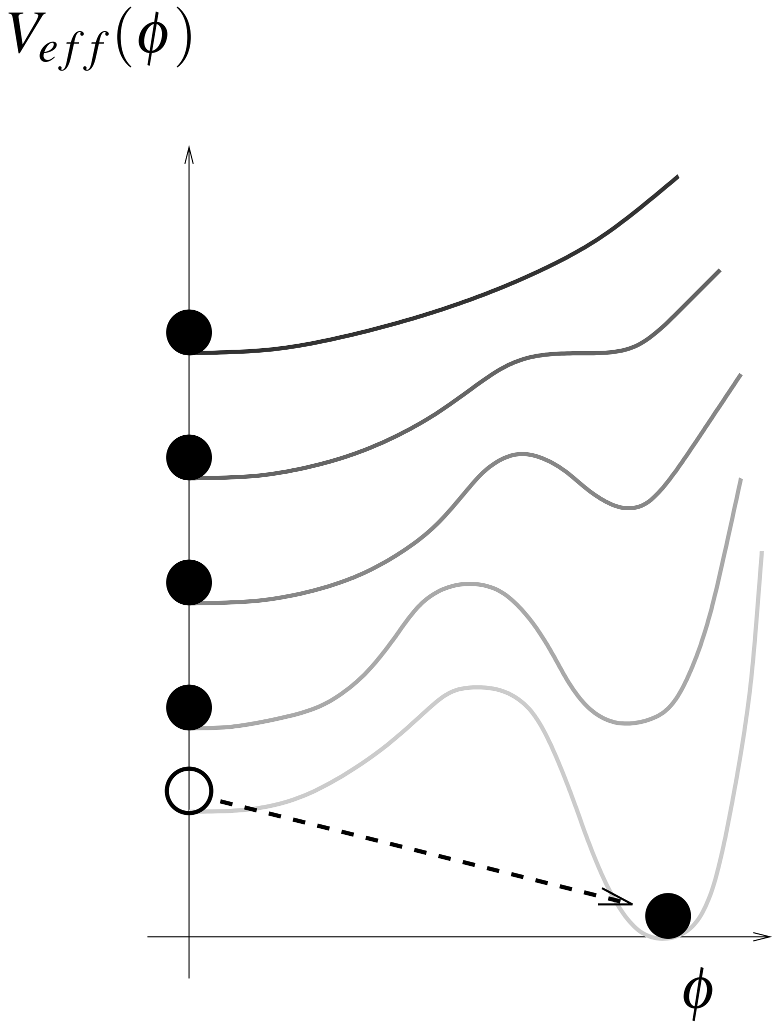
Fig

Beginning of transition: about one bubble per horizon

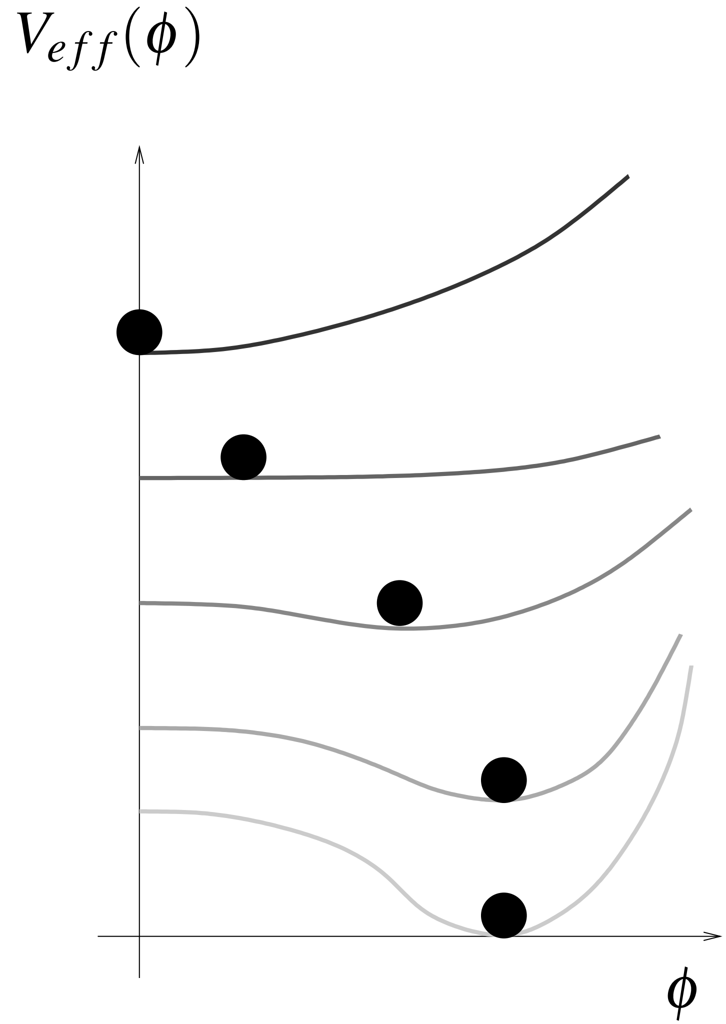
Bubbles born microscopic, $r \sim 10^{-16}$ cm, grow to macroscopic size, $r \sim 0.1 H^{-1} \sim 1$ mm, before their walls collide

Boiling Universe, strongly out of equilibrium

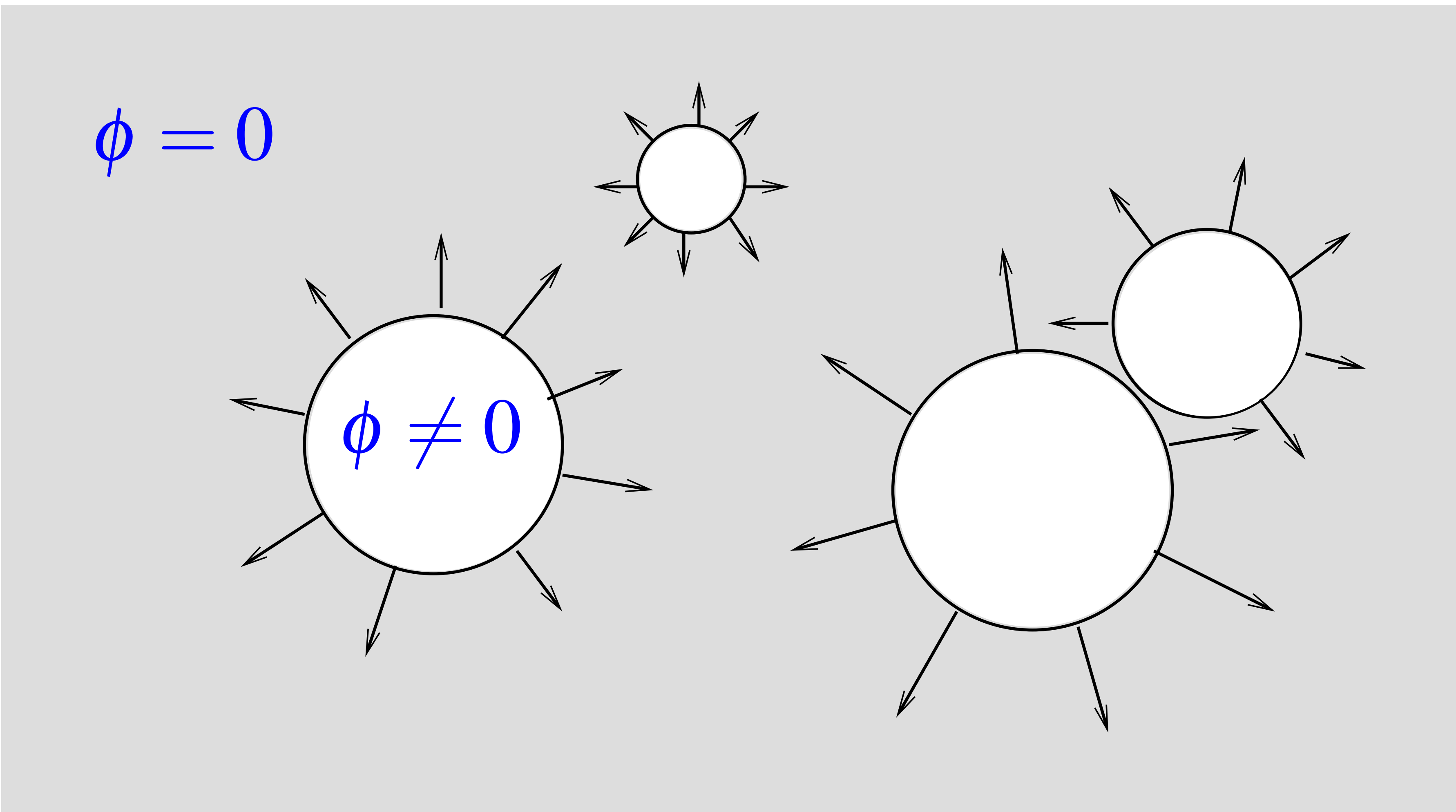
$V_{eff}(\phi)$ = free energy density



1st order



2nd order



$\phi = 0$
$\phi \neq 0$

Baryon asymmetry may be generated in the course of 1st order phase transition, provided there is enough C- and CP-violation.

Does this really happen?

Not in SM

- Given the Higgs boson mass

$$m_H = \sqrt{2\lambda} v = 125 \text{ GeV}$$

No phase transition at all; smooth crossover

- Way too small CP-violation

What can make EW mechanism work?

- Extra bosons
  - Should interact fairly strongly with Higgs(es)
  - Should be present in plasma at $T \sim 100$ GeV

    $\Longrightarrow$ not much heavier than 300 GeV

- Plus extra source of CP-violation.

  Better in Englert–Brout–Higgs sector $\Longrightarrow$ Several scalar fields
  - Electric dipole moments of neutron and electron.
  - Recent limit $d_e < 1.1 \cdot 10^{-29}$ e cm (ACME) kills many concrete models

More generally, EW baryogenesis requires complex dynamics in EW symmetry breaking sector at $E \sim (\text{a few}) \cdot 100$ GeV

LHC's FINAL WORD

Is EW the only appealing scenario?

By no means!

— Leptogenesis

— Something theorists never thought about

Why $\Omega_B \approx \Omega_{DM}$?