Outline of Lecture 2

- Baryon asymmetry of the Universe.
  - What’s the problem?
  - Electroweak baryogenesis.
    - Electroweak baryon number violation
    - Electroweak transition
    - What can make electroweak mechanism work?
- Dark energy

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 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.

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

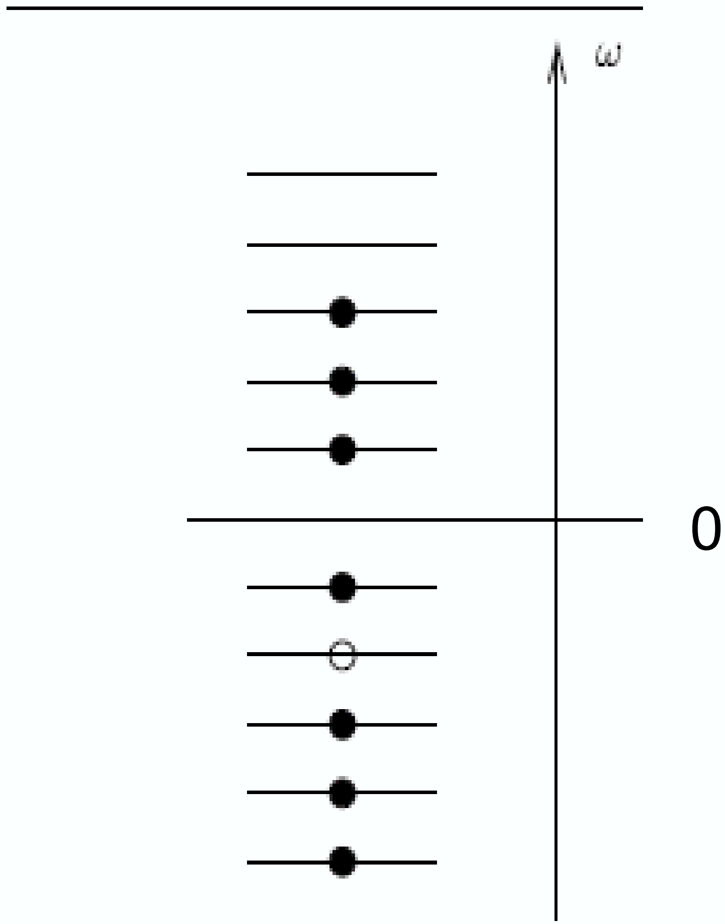
$$i\frac{\partial}{\partial t}\psi = i\gamma^0\vec{\gamma}(\vec{\partial} - ig\vec{A})\psi = H_{Dirac}(t)\psi$$

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?

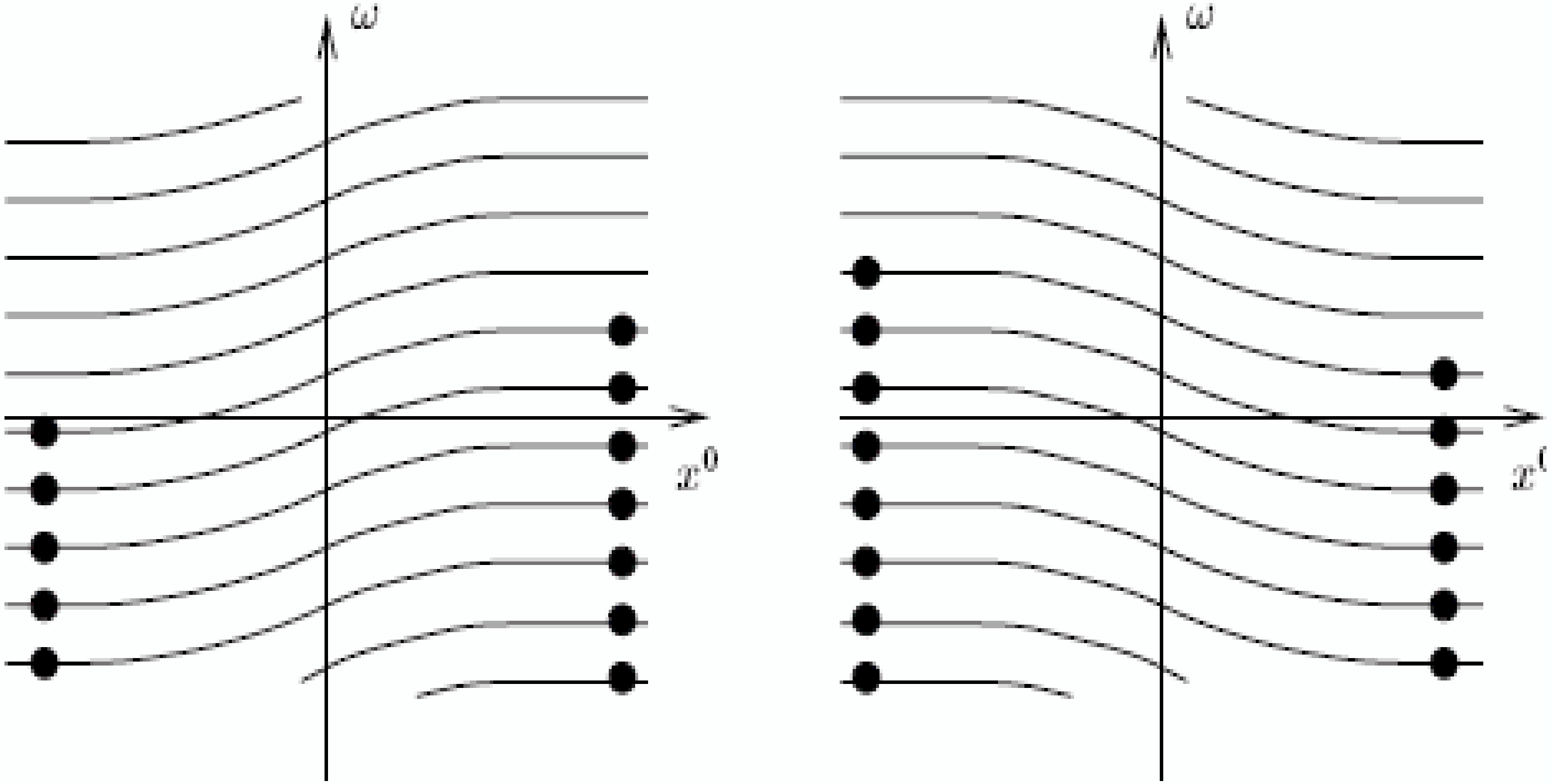
Dirac picture at $\vec{A} = 0$, $t \to \pm\infty$



TIME EVOLUTION OF LEVELS

IN SPECIAL (TOPOLOGICAL) GAUGE FIELDS

Left-handed fermions Right-handed

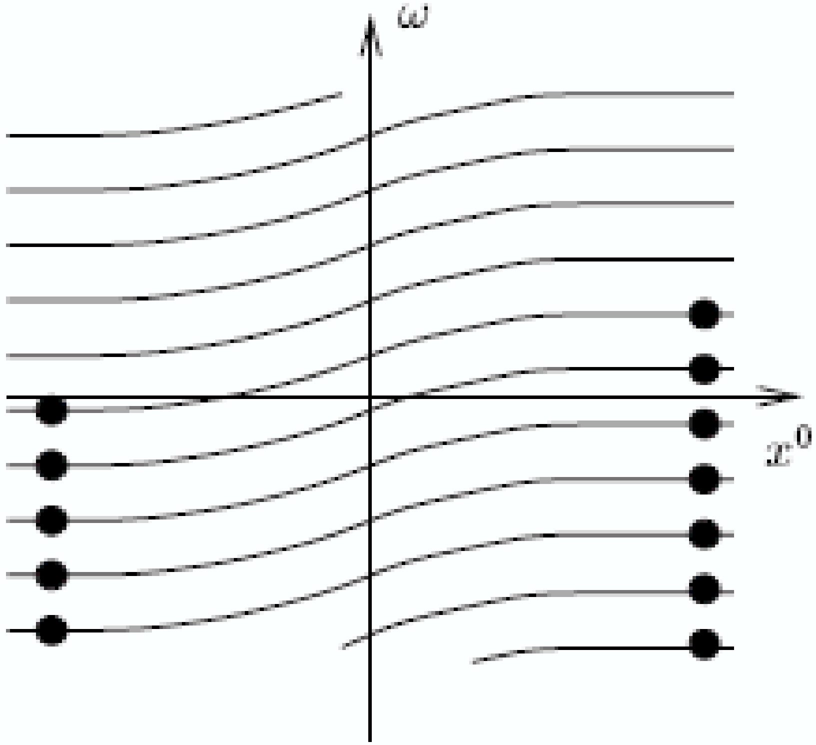


The case for QCD

$B = N_L + N_R$ 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 in the same way

NB: Non-Abelian gauge fields only (in 4 dimensions)

QCD: Violation of Q^5 is a fact.

In chiral limit $m_u, m_d, m_s \to 0$,
global symmetry is $SU(3)_L \times SU(3)_R \times U(1)_B$,
not symmetry of Lagrangian $SU(3)_L \times SU(3)_R \times U(1)_B \times U(1)_A$

Need large field fluctuations. At zero temprature their rate is suppressed by

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

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

$$H^{-1} = \frac{M_{Pl}^*}{T_{EW}^2} \sim 10^{14}\ \text{GeV}^{-1} \sim 10^{-10}\ \text{s}$$

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.

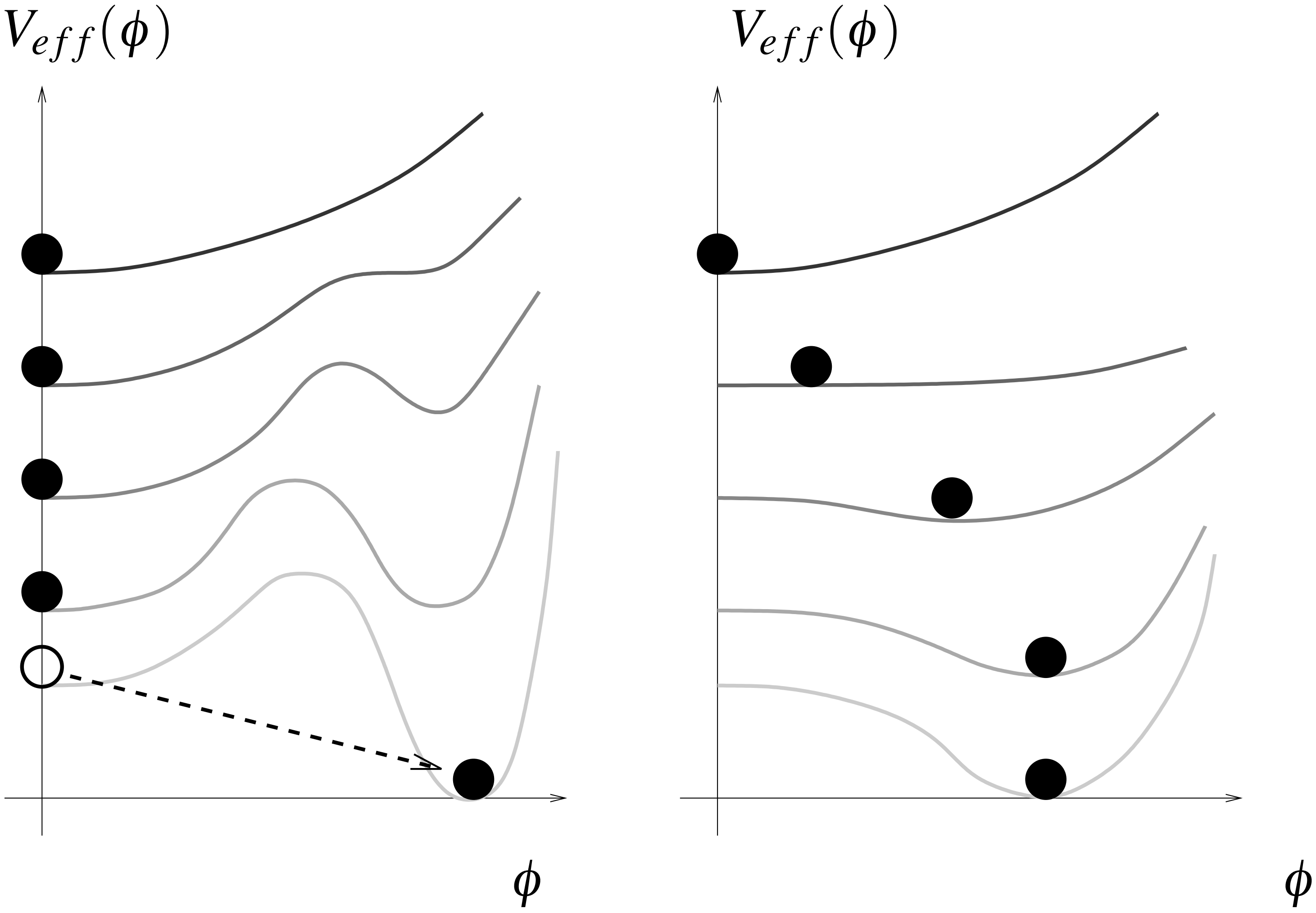
Bubbles then expand at $v \sim 0.1c$

Fig

Beginning of transition: about one bubble per horizon

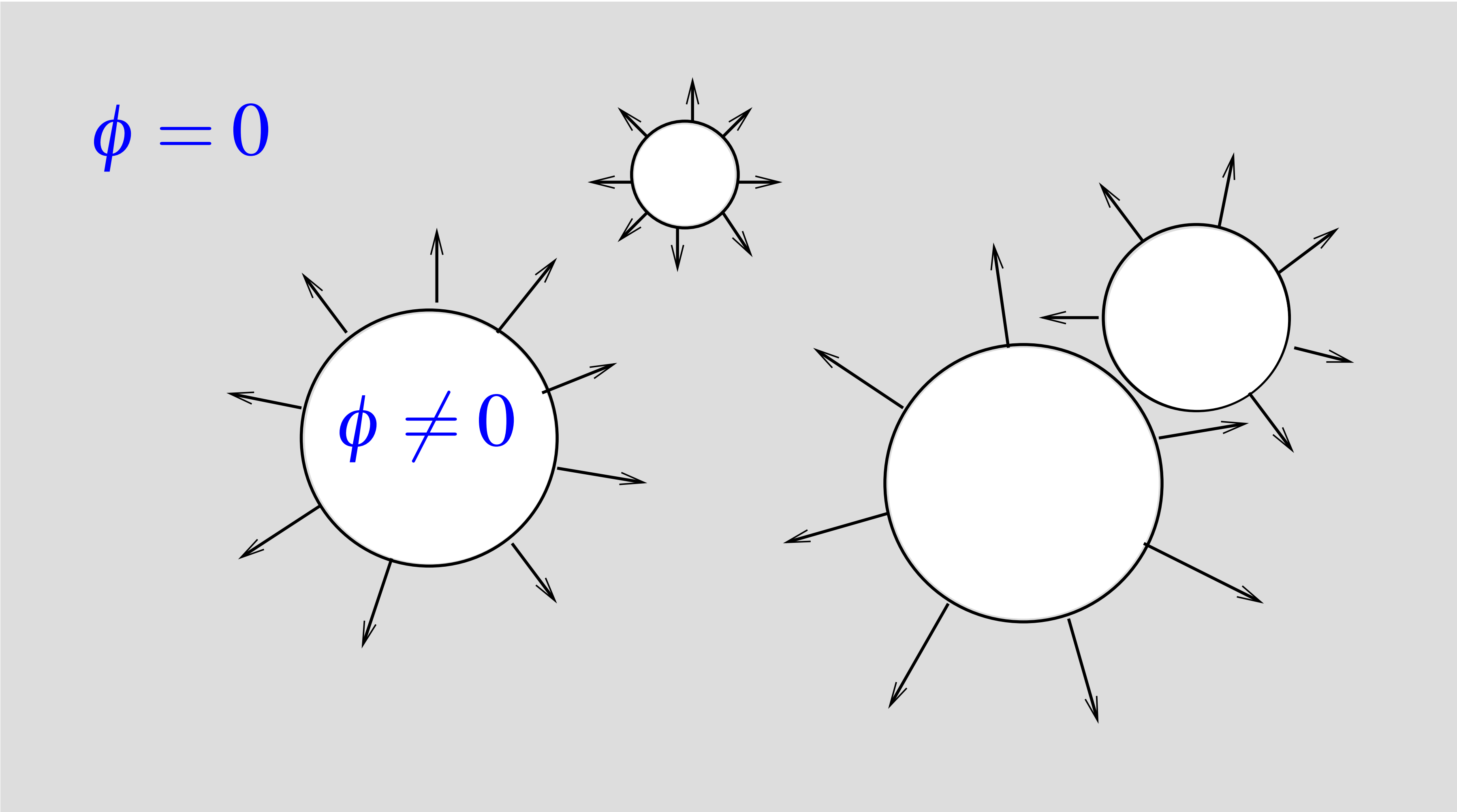
Bubbles born microscopic, $r \sim 10^{-16}$ cm, grow to macroscopic size, $r \sim 0.1 H^{-1} \sim 1$ mm, before their walls collide

Boiling Universe, strongly out of equilibrium



1st order

2nd order



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

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

Necessary condition:

Baryon asymmetry generated during transition should not be washed out aferwards
$\Longrightarrow$ B-violating processes must be switched off in broken phase
$\Longrightarrow$ Just after transition

$$\langle \phi \rangle_T > T$$

Does this really happen?

Not in SM

Temperature-dependent effective potential, one loop

$$V_{eff} = (-m^2 + \alpha T^2)|\phi|^2 - \frac{\beta}{3} T|\phi|^3 + \frac{\lambda}{4}|\phi|^4$$

$\alpha = O(g^2)$, $\beta = O(g^3)$. Cubic term weird,

$$-\frac{\beta}{3} T \left(\phi^\dagger \phi\right)^{3/2}$$

But crucial for 1st order phase transition. Obtains contributions from bosons only

$$f_B = \frac{1}{\mathrm{e}^{E/T} - 1} \simeq \frac{T}{E} \equiv \frac{T}{\sqrt{\mathbf{p}^2 + g^2|\phi|^2}} \simeq \frac{T}{g|\phi|} \quad \text{at} \quad |\mathbf{p}| \ll T\,, \;\; g|\phi| \ll T$$

Bose enhancement $\Longleftrightarrow$ no analyticity in $g^2|\phi|^2$

At phase transition $(-m^2 + \alpha T^2) = 0$,

$$V_{eff} = -\frac{\beta}{3} T \phi^3 + \frac{\lambda}{4} \phi^4$$

Hence

$$\langle \phi \rangle_T = \frac{\beta}{\lambda} T = \# \frac{g_W^3}{\lambda} T$$

Given the Higgs mass bound

$$m_H = \sqrt{2\lambda} v > 114 \text{ GeV}$$

one finds $\langle \phi \rangle_T < T$, asymmetry would be washed out even if generated

Furtermore, in SM

- No phase transition at all; smooth crossover
- Way too small CP-violation

What can make EW mechanism work?

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

    $\Longrightarrow$ not much heavier than 300 GeV

  E.g. light stop

- Plus extra source of CP-violation.

  Better in Higgs sector $\Longrightarrow$ Several Higgs fields

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

Dark energy

- Homogeneously distributed over the Universe, does not clump into galaxies, galaxy clusters.
- Determines the expansion rate at late times $\Longrightarrow$ Relation between distance and redshift. Expansion of the Universe accelerates.

Fig.

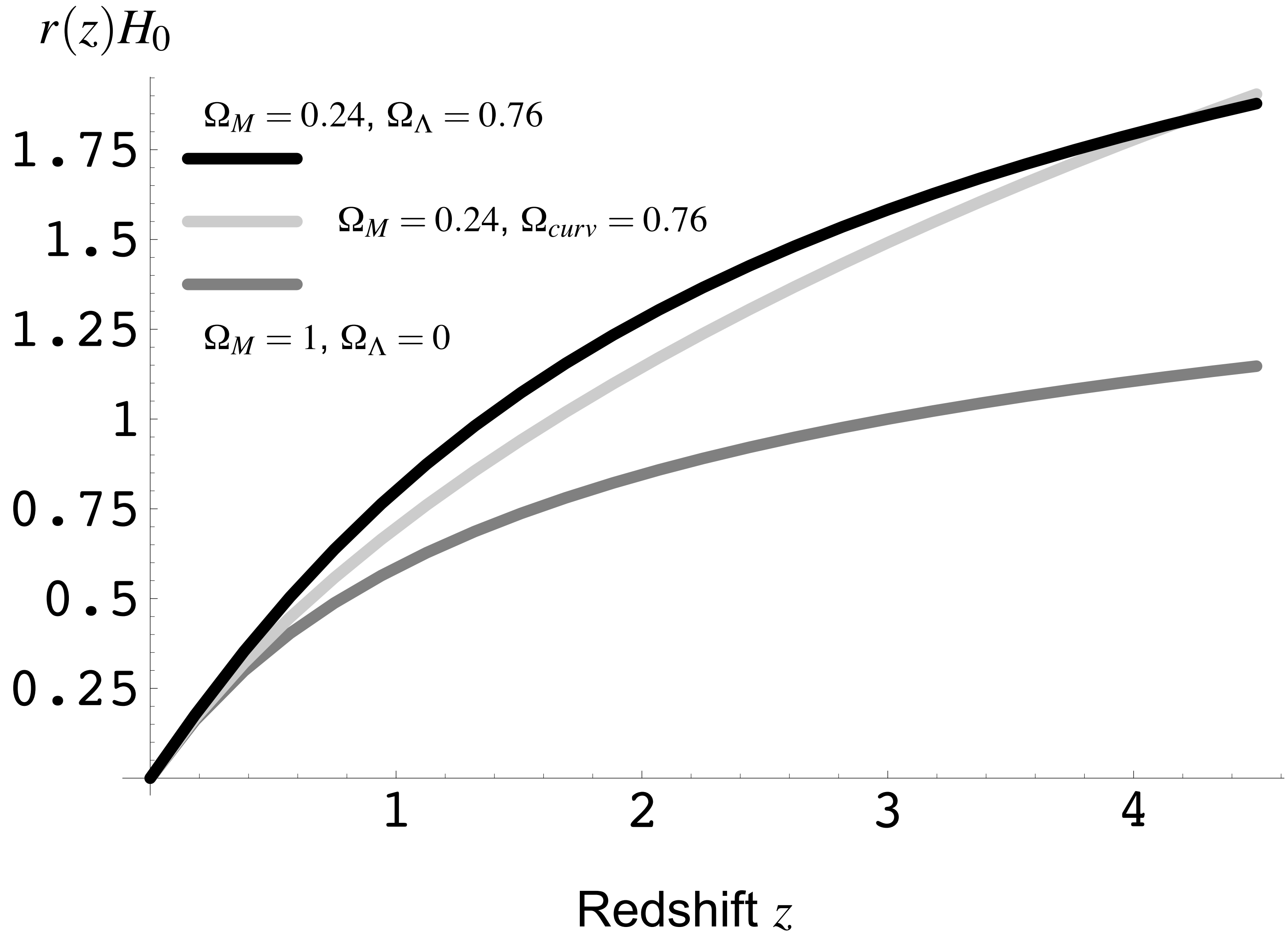
- Measure redshifts ("easy") and distances by using standard candles, objects whose absolute luminocity is known.

Supernovae 1a

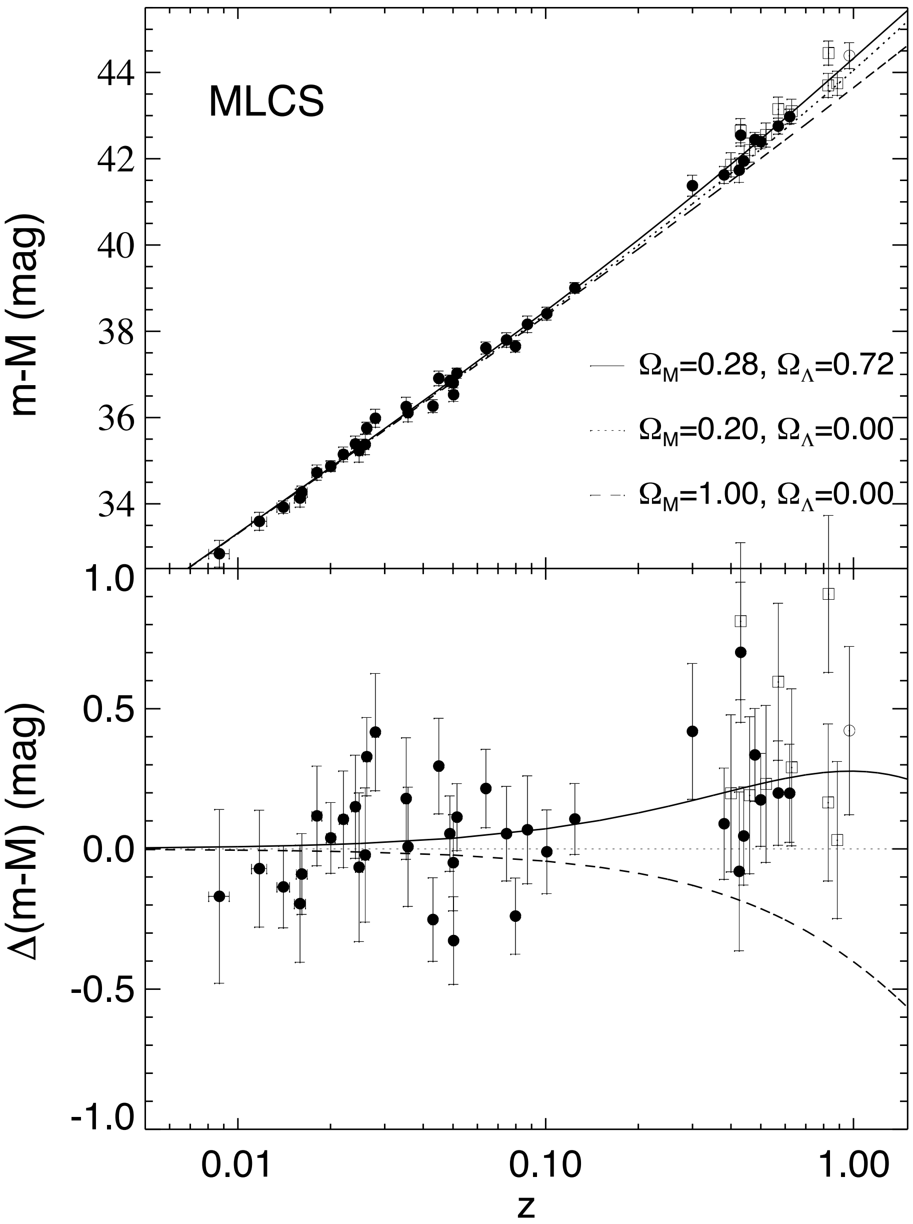
Figs.

- Other, independent measurements of ρ_Λ: cluster abundance at various z, CMB anisotropies combined with standard ruler at small redshift (baryon acoustic oscillations), etc.

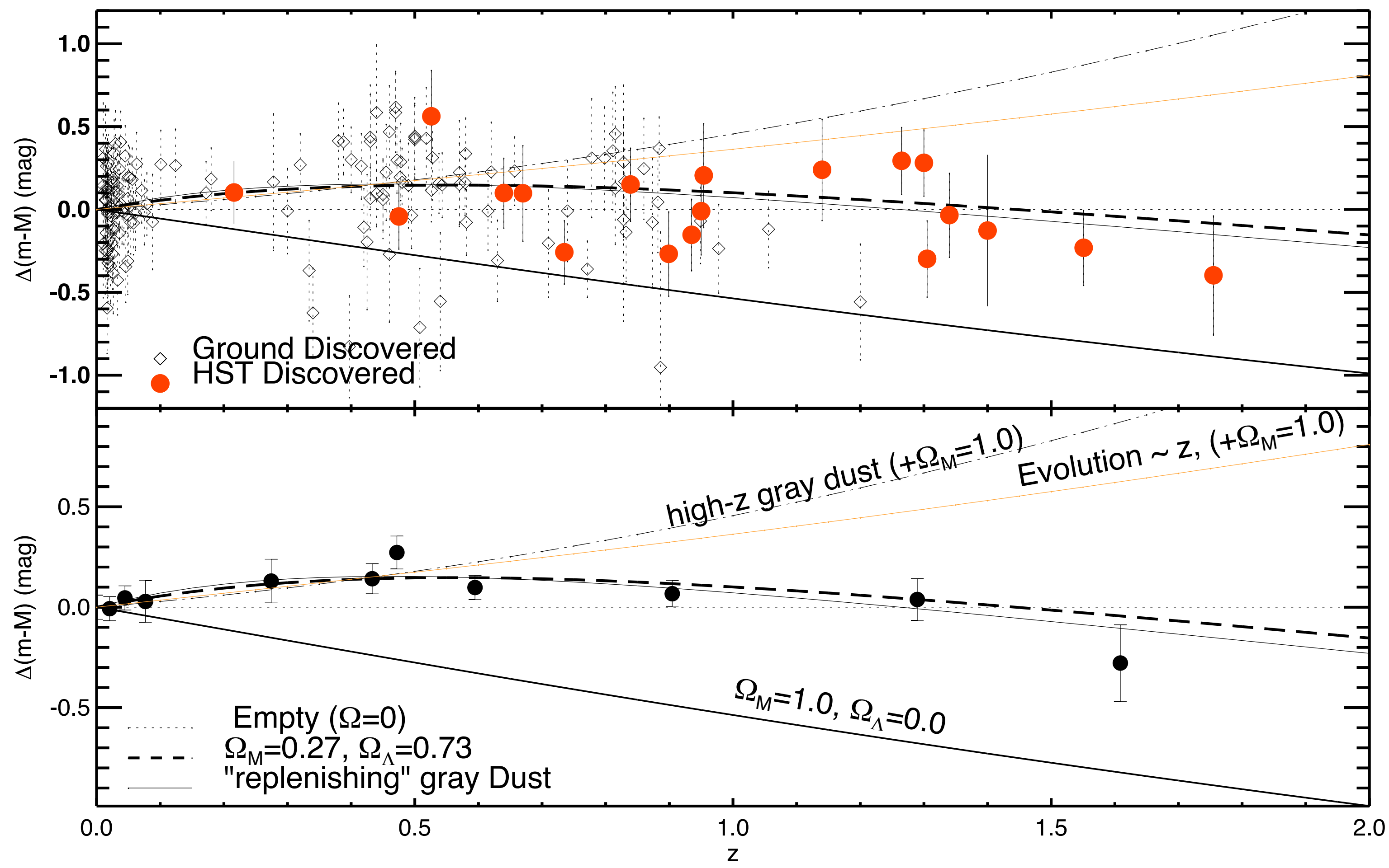
Distance-redshift for different models



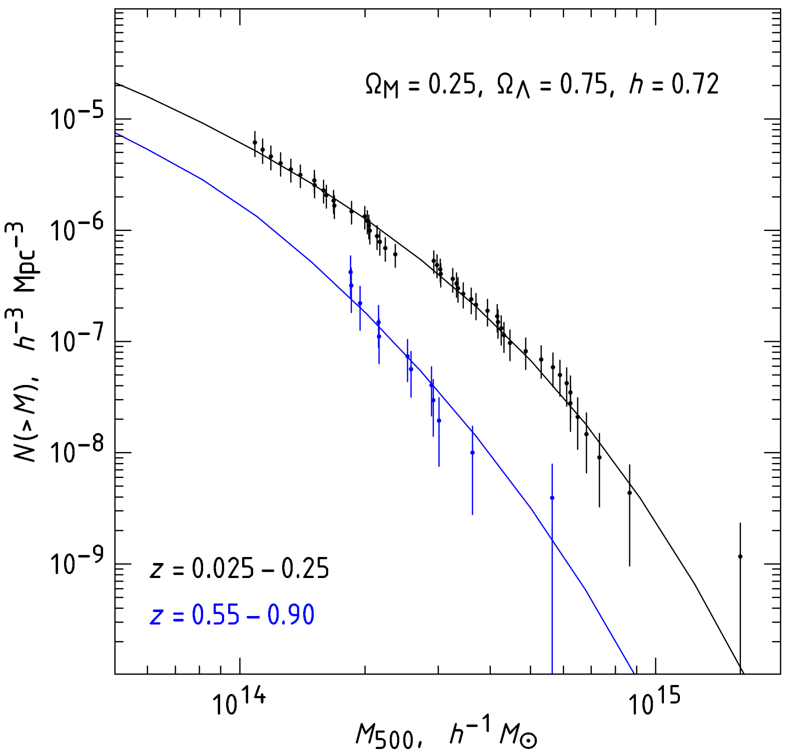
First SNe data, 1998

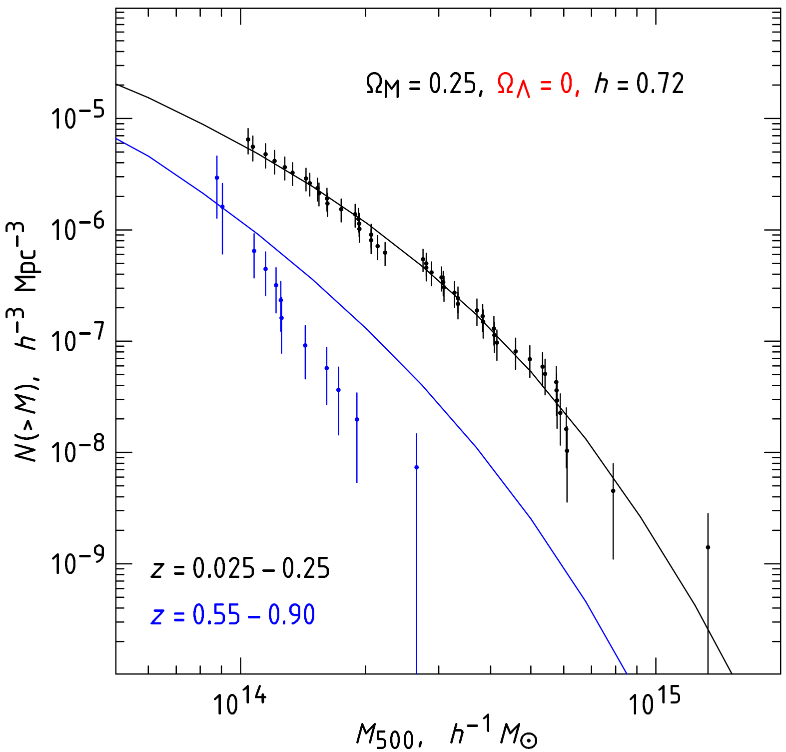


Newer SNe data



Cluster abundance





$\Omega_\Lambda = 0.75$

$\Omega_\Lambda = 0$, curvature domination

Who is dark energy?

- Vacuum = cosmological constant
  By Lornetz-invariance

$$T_{\mu\nu}^{vac} = \text{const} \cdot \eta_{\mu\nu}$$

  $\text{const} = \rho_\Lambda$, fundamental constant of Nature.
  $\rho_\Lambda = (2 \cdot 10^{-3}\ \text{eV})^4$: ridiculously small.
  No such scales in fundamental physics.
  Problem for any interpretation of dark energy

- Definition of energy density and pressure:

$$T_{\mu\nu} = (\rho, p, p, p)$$

  Hence, for vacuum $p = -\rho$.

- Parametrize: $p_{DE} = w\rho_{DE} \Longrightarrow \quad w_{vac} = -1$

w determines evolution of dark energy density:

$$dE = -pdV \implies d(\rho a^3) = -pd(a^3) \implies \frac{d\rho}{dt} = -3\frac{\dot{a}}{a}(p+\rho)$$

$$\frac{\dot{\rho}_\Lambda}{\rho_\Lambda} = -3(w+1)\frac{\dot{a}}{a}$$

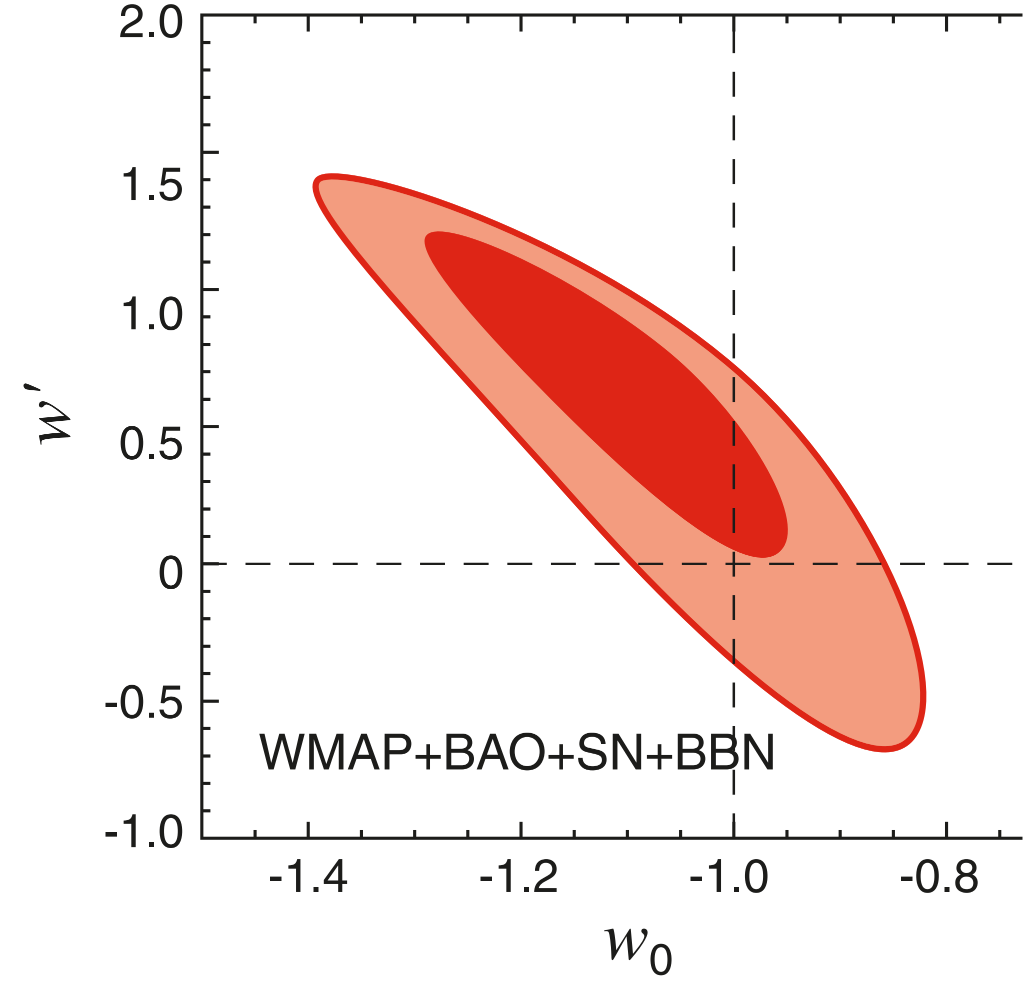
Options:

- Vacuum: $w = -1$, ρ_Λ constant in time.
- Quintessence, "usual" field (modulo energy scale): $w > -1$, ρ_Λ decays in time.
- Phantom: $w < -1$, ρ_Λ grows in time.; typically has instabilities
- General relativity modified at cosmological scales. Effective dark energy depends on time.

Present situation

$$w' = \frac{dw}{dz}$$

$$w_0 = w_{today}$$



More precise data coming soon
to reveal the nature of dark energy.