Cosmology and the LHC

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Outline

- Cosmology in a nutshell
- Dark matter:
  - evidence
  - WIMPs
  - Warm dark matter: gravitinos?
- Baryon asymmetry
  - Electroweak baryon number violation
  - Electroweak transition
  - What can make electroweak mechanism work?
- What do we learn from CMB anisotropies
  - Primordial perturbations
  - Adiabatic and isocurvature modes
- Miscellanea
- Conclusion

Cosmology in a nutshell

- The Universe at large is homogeneous, isotropic and expanding. 3d space is Euclidean. All this is encoded in space-time metric

$$ds^2 = dt^2 - a^2(t)\mathbf{dx}^2$$

$\mathbf{x}$: comoving coordinates, label distant galaxies.

$a(t)dx$: physical distances.

$a(t)$: scale factor, grows in time; a_0: present value (matter of convention)

$$z(t) = \frac{a_0}{a(t)} - 1 : \quad \text{redshift}$$

$$H(t) = \frac{\dot{a}}{a} : \quad \text{Hubble parameter, expansion rate}$$

- Present value

$$H_0 = [70.4 \pm 1.4]\ \frac{\mathrm{km/s}}{\mathrm{Mpc}} = (14 \cdot 10^9\ \mathrm{yrs})^{-1}$$

$1\ \mathrm{Mpc} = 3 \cdot 10^6\ \mathrm{light\ yrs} = 3 \cdot 10^{24}\ \mathrm{cm}$

- Hubble law (valid at $z \ll 1$)

$$z = H_0 r$$

Fig.

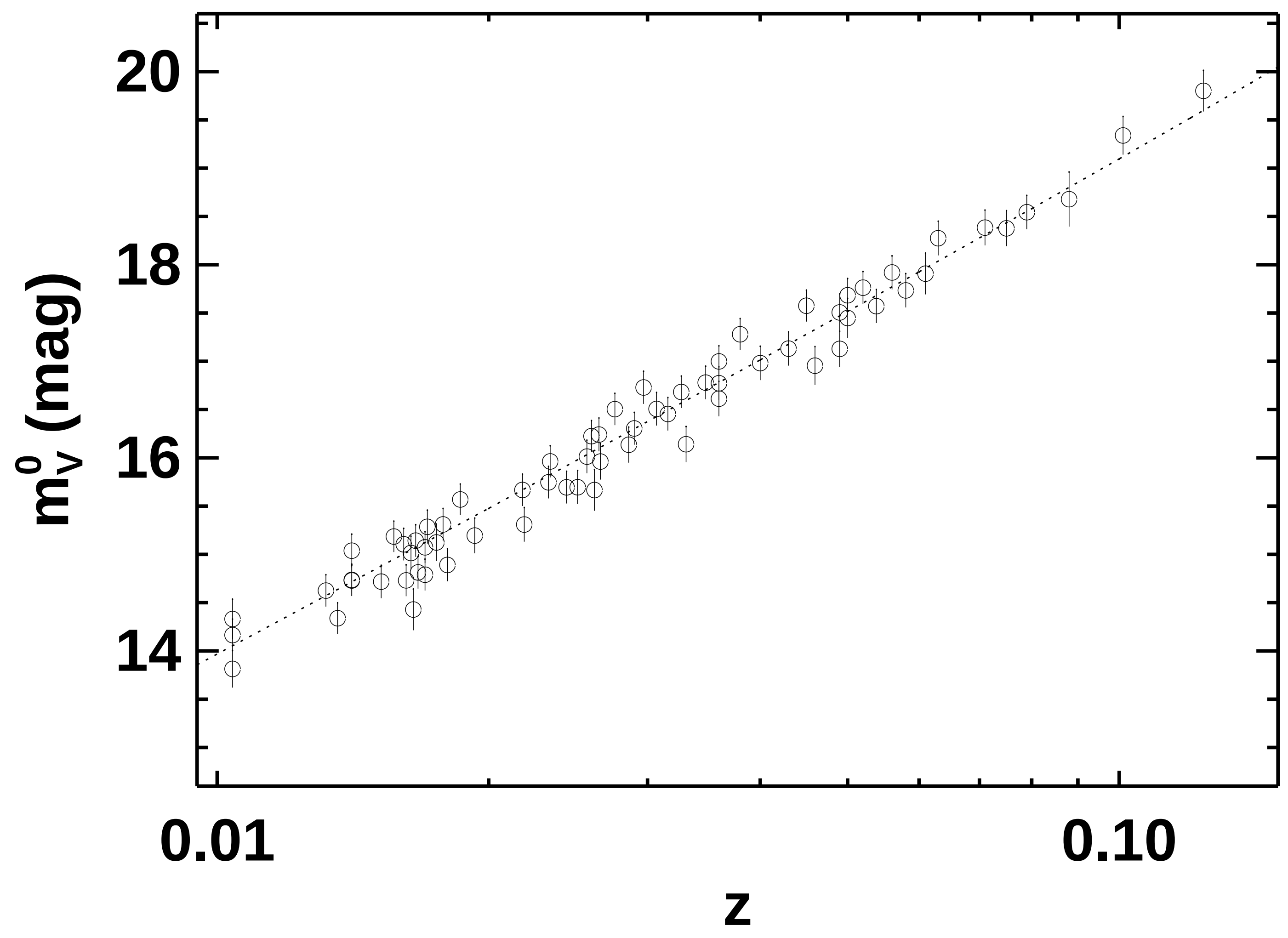
- The Universe is warm: CMB temperature today

$$T_0 = 2.726\ \mathrm{K}$$

Fig.

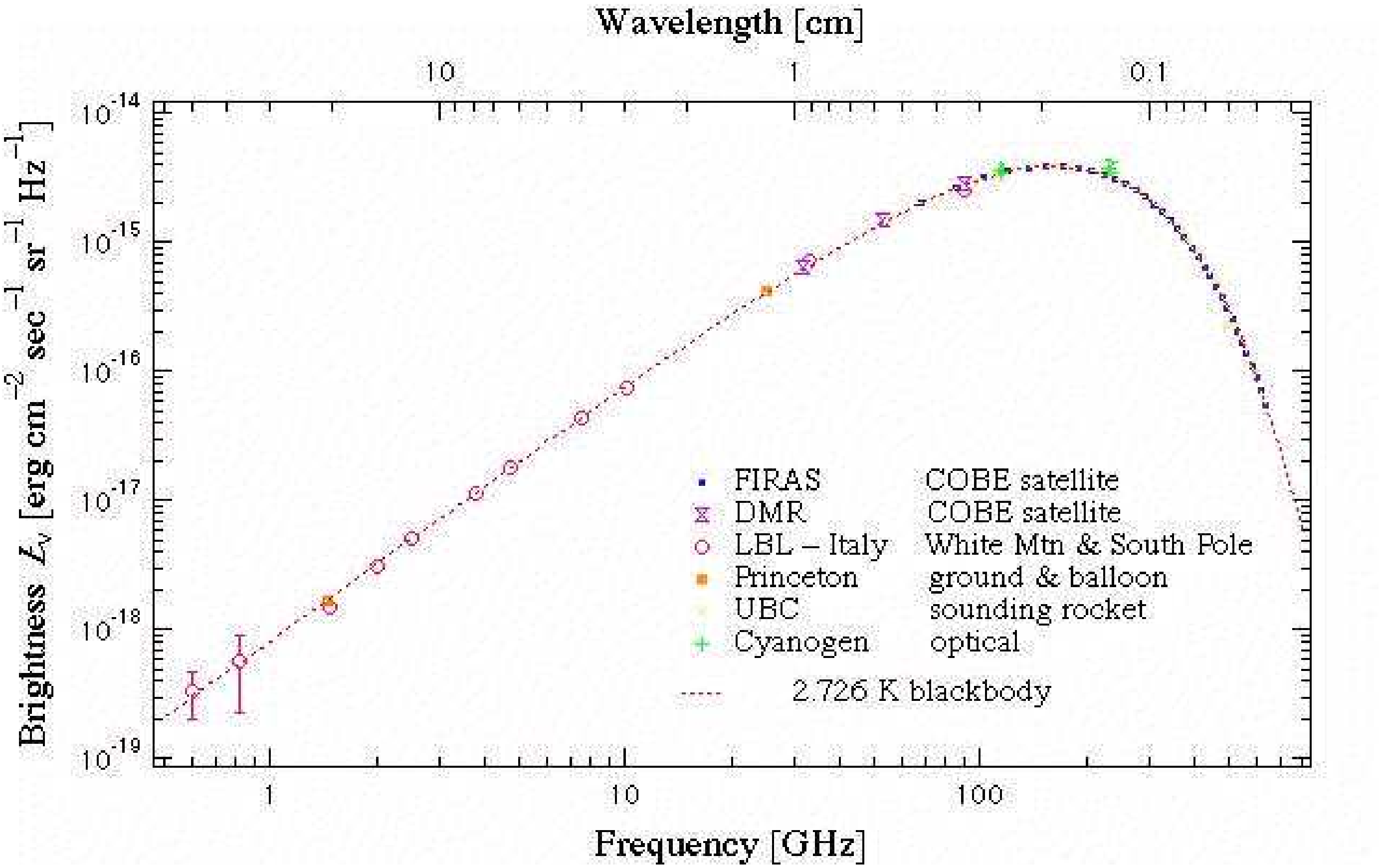
It was denser and warmer at early times.

Hubble diagram for SNe1a



$$\text{mag} = 5\log_{10} r + \text{const}$$

CMB spectrum



$$T = 2.726\ \mathrm{K}$$

- Present number density of photons

$$n_\gamma = \#T^3 = 410 \frac{1}{\mathrm{cm}^3}$$

- Present entropy density

$$s = 2 \cdot \frac{2\pi^2}{45} T_0^3 + \text{neutrino contribution} = 3000 \frac{1}{\mathrm{cm}^3}$$

In early Universe

$$s = \frac{2\pi^2}{45} g_* T^3$$

g_*: number of degrees of freedom with $m \lesssim T$.

Entropy density scales exactly as a^{-3}

Temperature scales approximately as a^{-1}.

- Friedmann equation: expansion rate of the Universe vs energy density ρ:

$$\left(\frac{\dot{a}}{a}\right)^2 \equiv H^2 = \frac{8\pi}{3M_{Pl}^2}\rho$$

$(M_{Pl} = G^{-1/2} = 10^{19}$ GeV), no spatial curvature.

- Cosmological horizon: distance that signals can travel from Big Bang to time t,

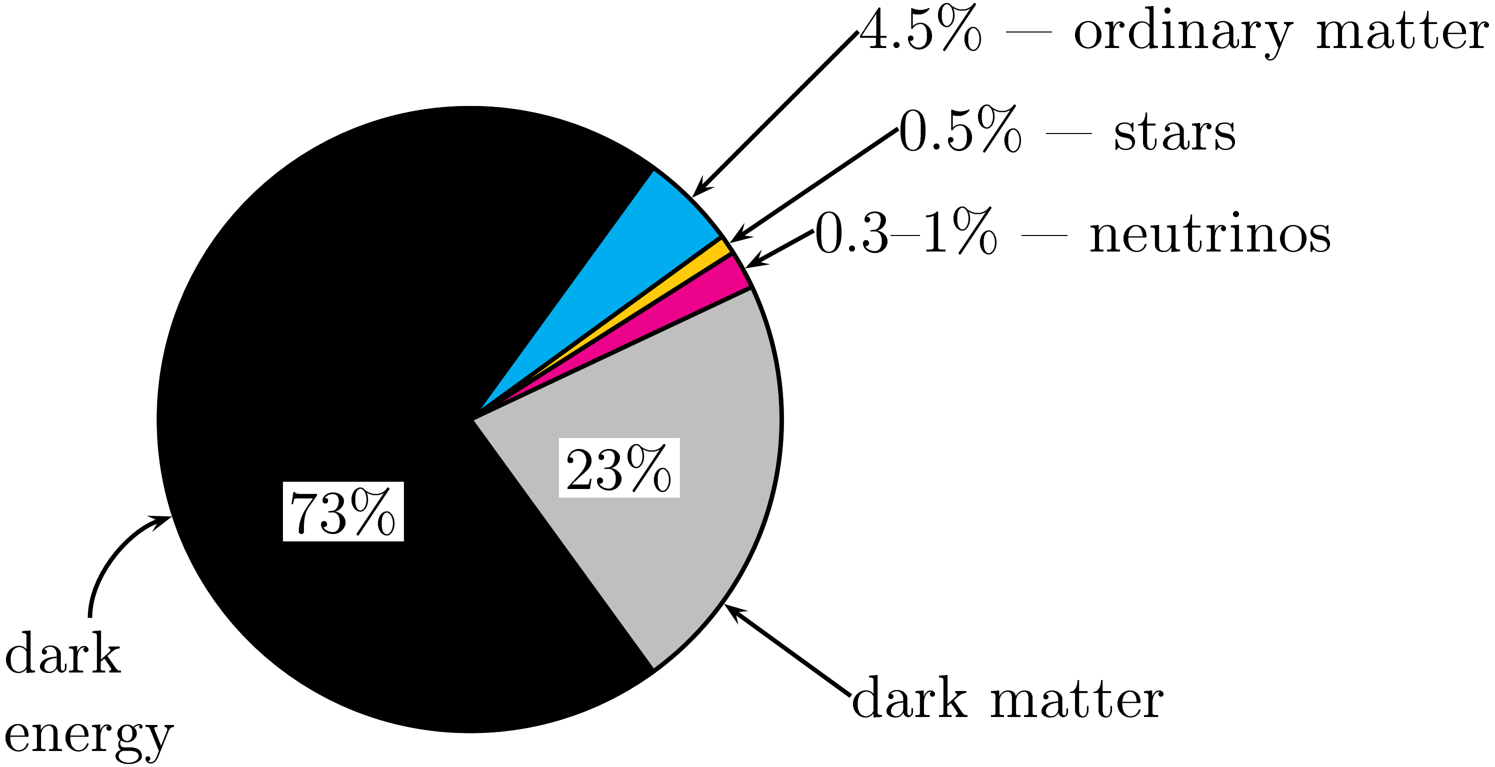
$$l(t) \sim H(t)^{-1}$$

Today $l_0 \approx 15$ Gpc $= 4.5 \cdot 10^{28}$ cm

- Present energy density

$$\rho_0 = \rho_c = \frac{3M_{Pl}^2}{8\pi} H_0^2 = 5 \cdot 10^{-6} \ \frac{\text{GeV}}{\text{cm}^3}$$

Energy balance in the present Universe



- Different components behave differently in time
  - Matter (dark matter + baryons)

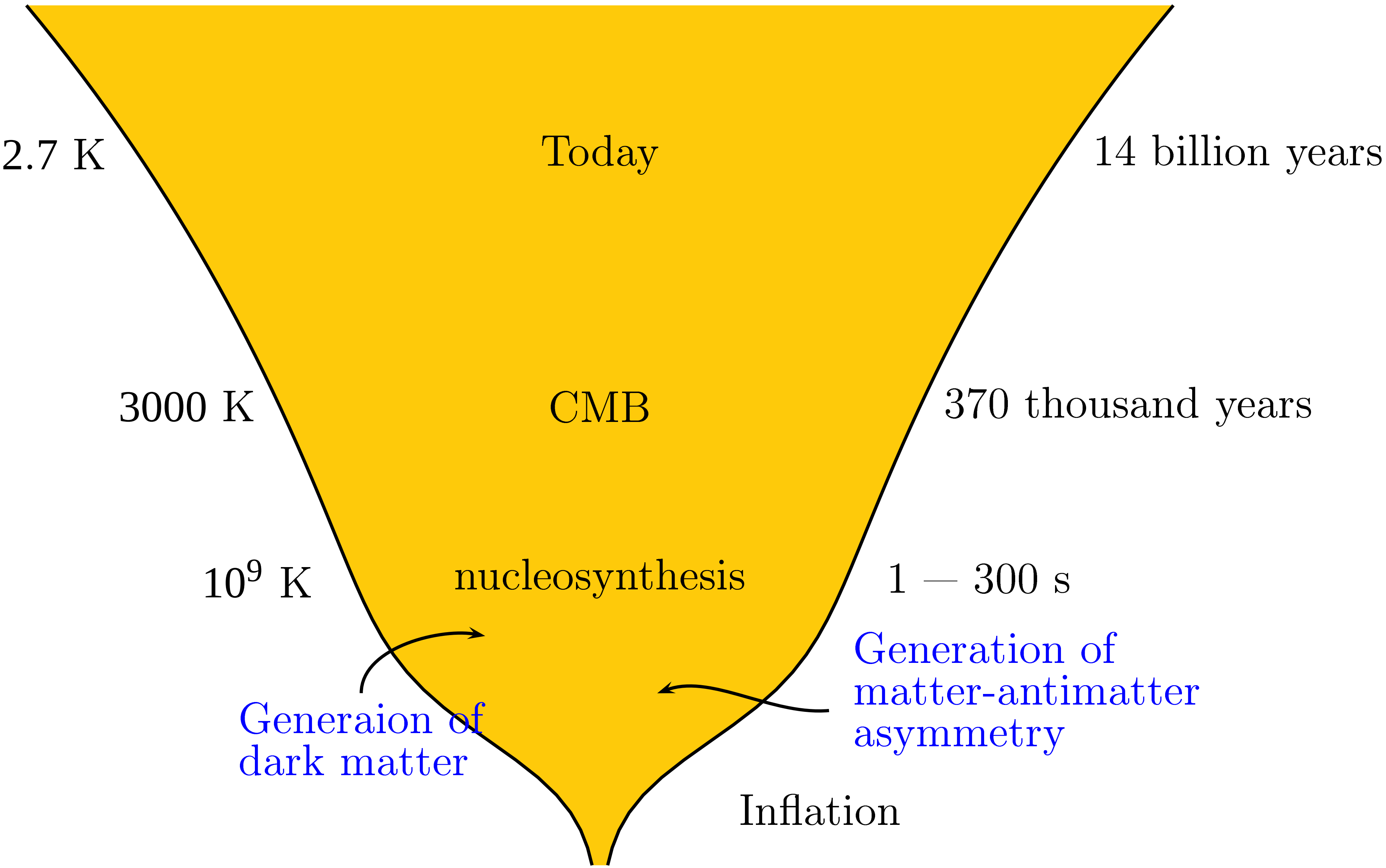
$$\rho_M(t) \propto n_M(t) \propto \frac{1}{a^3(t)}$$

  - Radiation (photons + neutrinos at early times): $T(t) \propto 1/a(t)$,

$$\rho_{rad}(t) \propto n_\gamma(t) T(t) \propto \frac{1}{a^4(t)}$$

  - Dark energy Λ:

$$\rho_\Lambda \approx \text{const}$$


2.7 K
Today
14 billion years
3000 K
CMB
370 thousand years
10^9 K
nucleosynthesis
1 — 300 s
Generation of matter-antimatter asymmetry
Generaion of dark matter
Inflation

Dark matter

- Astrophysical evidence: measurements of gravitational potentials in galaxies and clusters of galaxies
  - Velocity curves of galaxies

    Fig.
  - Velocities of galaxies in clusters

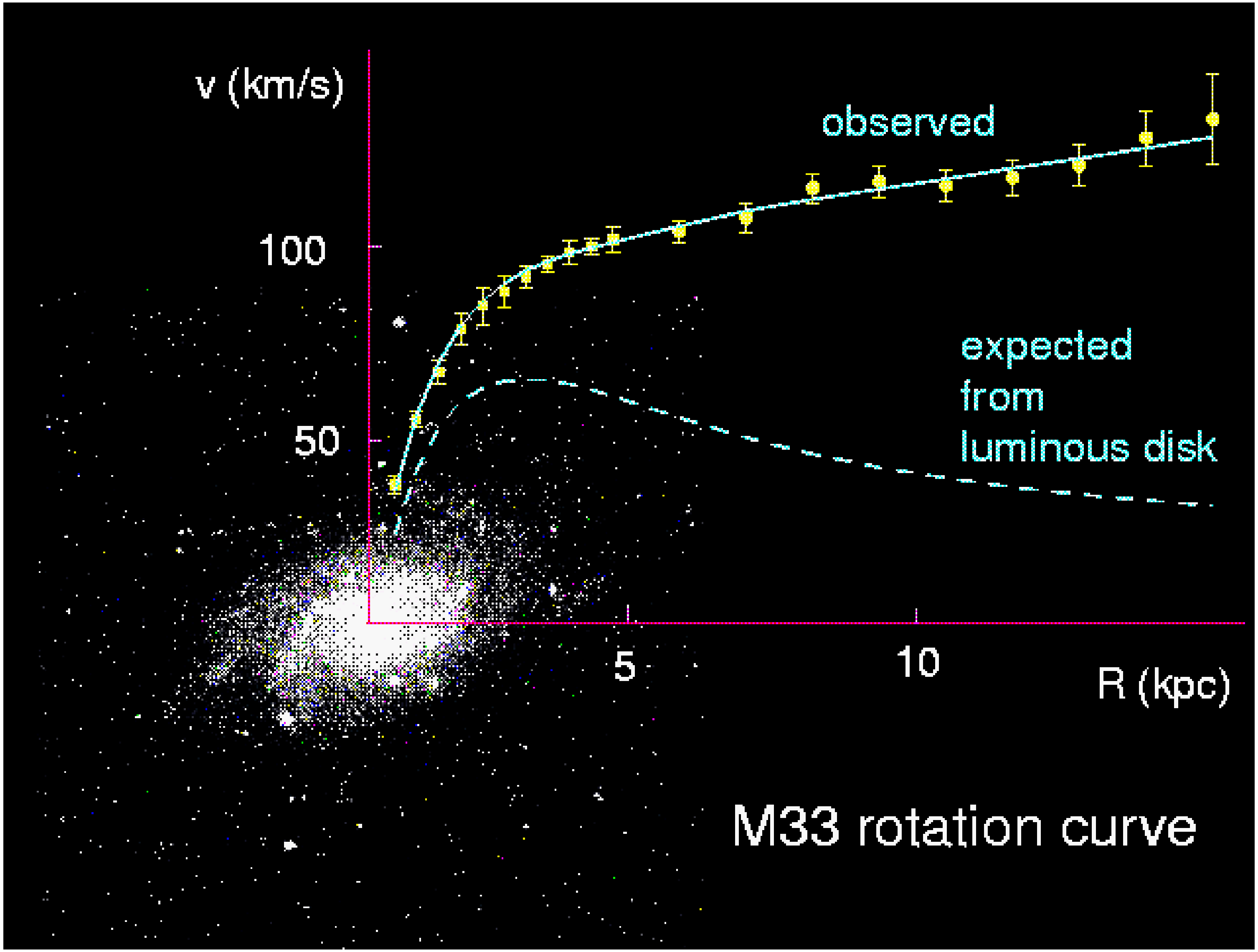
    Original Zwicky's argument, 1930's

$$v^2 = G\frac{M(r)}{r}$$

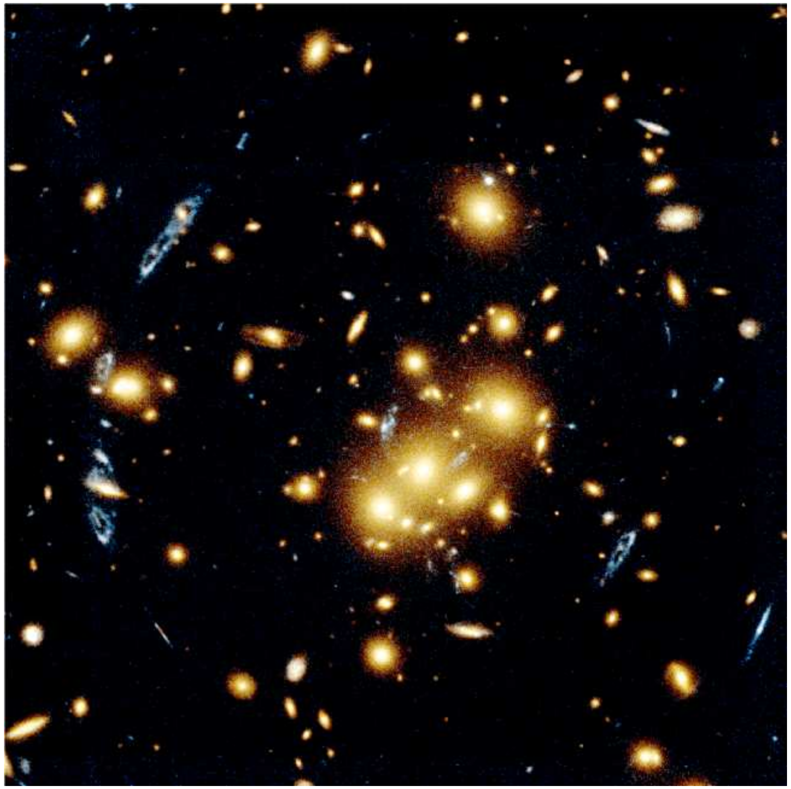
  - Temperature of gas in X-ray clusters of galaxies
  - Gravitational lensing of clusters

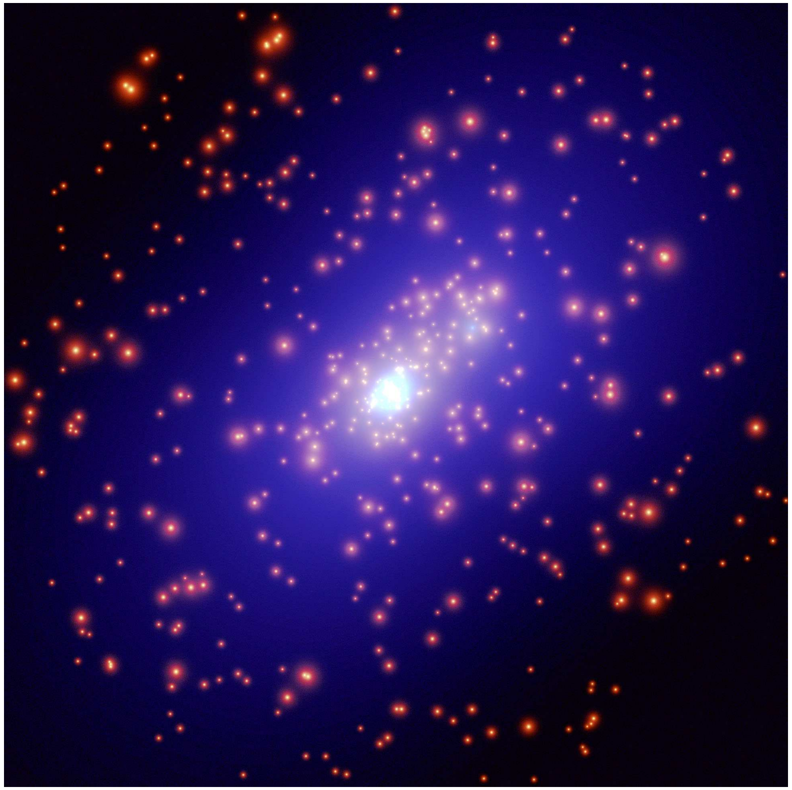
    Fig.
  - Etc.

Rotation curves



Gravitational lensing





Outcome

$$\Omega_M \equiv \frac{\rho_M}{\rho_c} = 0.27$$

Assuming mass-to-light ratio everywhere the same as in clusters
NB: in clusters sit 10 % of galaxies

Nucleosynthesis, CMB:

$$\Omega_B = 0.046$$

The rest is non-baryonic, $\Omega_{DM} \approx 0.23$.

Physical parameter: mass-to-entropy ratio. Stays constant in time. Its value

$$\left(\frac{\rho_{DM}}{s}\right)_0 = \frac{\Omega_{DM}\rho_c}{s_0} = \frac{0.2 \cdot 0.5 \cdot 10^{-6}\ \text{GeV cm}^{-3}}{3000\ \text{cm}^{-3}} = 3 \cdot 10^{-10}\ \text{GeV}$$

Cosmological evidence: growth of structure

CMB anisotropies: baryon density perturbations at recombination ≈ photon last scattering, $T = 3000$ K, $z = 1100$:

$$\delta_B \equiv \left(\frac{\delta\rho_B}{\rho_B}\right)_{z=1100} \simeq \left(\frac{\delta T}{T}\right)_{CMB} = (\text{a few}) \cdot 10^{-5}$$

In matter dominated Universe, matter perturbations grow as

$$\frac{\delta\rho}{\rho}(t) \propto a(t)$$

Perturbations in baryonic matter grow after recombination only

If not for dark matter,

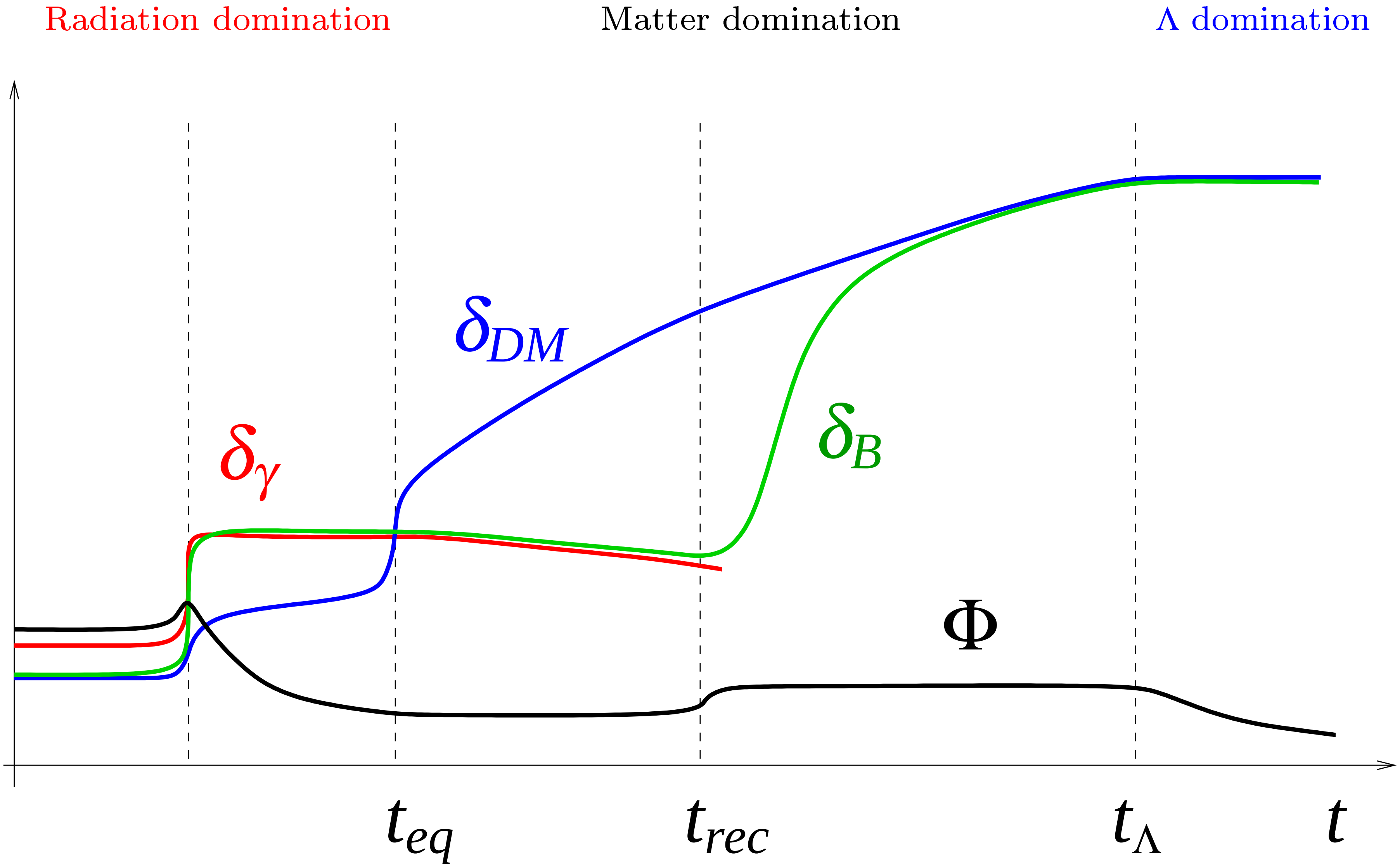
$$\left(\frac{\delta\rho}{\rho}\right)_{today} = 1100 \times (\text{a few}) \cdot 10^{-5} = (\text{a few}) \cdot 10^{-2}$$

No galaxies, no stars...

Perturbations in dark matter start to grow much earlier

(already at radiation-dominated stage)

Growth of perturbations (linear regime)



NB: Need dark matter particles non-relativistic early on.

Neutrinos are not considerable part of dark matter

UNKNOWN DARK MATTER PARTICLES ARE
CRUCIAL FOR OUR EXISTENCE

Cold dark matter, CDM

$$m_{DM} > \text{a few} \cdot 10 \text{ keV}$$

Warm dark matter

$$m_{DM} \simeq 1 - 10 \quad \text{keV}$$

WIMPs

Simple but very suggestive scenario

- Assume there is a new heavy stable particle X
  - Interacts with SM particles via pair annihilation (and crossing processes)

$$X + X \leftrightarrow q\bar{q}\,,\text{etc}$$

  - Mass: M_X, annihilation cross section at non-relativistic velocity v: $\sigma(v)$
- Assume that maximum temperature in the Universe was high, $T \gtrsim M_X$
- Calculate present mass density

- Friedmann equation:

$$\left(\frac{\dot{a}}{a}\right)^2 \equiv H^2 = \frac{8\pi}{3M_{Pl}}\rho$$

  - Early epoch (radiation dominated): Stefan–Boltzmann

$$\rho = \frac{\pi^2}{30} g_* T^4$$

g_*: number of relativistic degrees of freedom (about 100 in SM at $T \sim 100$ GeV). Hence

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

with $M_{Pl}^* = M_{Pl}/(1.66\sqrt{g_*}) \sim 10^{18}$ GeV at $T \sim 100$ GeV

- Number density of X-particles in equilibrium at $T < M_X$: Maxwell–Boltzmann

$$n_X = g_X \left(\frac{M_X T}{2\pi} \right)^{3/2} \mathrm{e}^{-\frac{M_X}{T}}$$

- Mean free time wrt annihilation:

$$\tau_{ann} \equiv \Gamma_{ann}^{-1} = \frac{1}{n_X \langle \sigma v \rangle}$$

- Freeze-out: $\Gamma_{ann}(T_f) \sim H(T_f) \Longrightarrow \; n_X(T_f)\langle \sigma v \rangle \sim T_f^2 / M_{Pl}^* \Longrightarrow$

$$T_f \simeq \frac{M_X}{\log(M_X M_{Pl}^* \langle \sigma v \rangle)}$$

NB: large log $\Longleftrightarrow$ $T_f \sim M_X/30$

Define $\langle \sigma v \rangle \equiv \sigma_0$ (constant for s-wave annihilation)

- Number density at freeze-out

$$n_X(T_f) = \frac{T_f^2}{\sigma_0 M_{Pl}^*}$$

- Number-to-entropy ratio at freeze-out and later on

$$\frac{n_X(T_f)}{s(T_f)} = \#\frac{n_X(T_f)}{g_* T_f^3} = \#\frac{\log(M_X M_{Pl}^* \sigma_0)}{M_X \sigma_0 g_* M_{Pl}^*}$$

where $\# = 45/(2\pi^2)$.

- Mass-to-enropy ratio

$$\frac{M_X n_X}{s} = \#\frac{\log(M_X M_{Pl}^* \sigma_0)}{\sigma_0 \sqrt{g_*(T_f)} M_{Pl}}$$

- Most relevant parameter: annihilation cross section $\sigma_0 \equiv \langle \sigma v \rangle$ at freeze-out

$$\frac{M_X n_X}{s} = \# \frac{\log(M_X M_{Pl}^* \sigma_0)}{\sigma_0 \sqrt{g_*(T_f)} M_{Pl}}$$

- Correct value, mass-to-entropy $= 3 \cdot 10^{-10}$ GeV, at

$$\sigma_0 \equiv \langle \sigma v \rangle = (1 \div 2) \cdot 10^{-36} \text{ cm}^2$$

  - Weak scale cross section.

    Gravitational physics and EW scale physics combine into

$$\text{mass-to-entropy} \simeq \frac{1}{M_{Pl}} \left(\frac{\text{TeV}}{\alpha_W} \right)^2 \simeq 10^{-10} \text{ GeV}$$

  - Mass M_X should not be much higher than 100 GeV

Weakly interacting massive particles, WIMPs.

Cold dark matter candidates. To be discovered at LHC.

SUSY: neutralinos, $X = \chi$

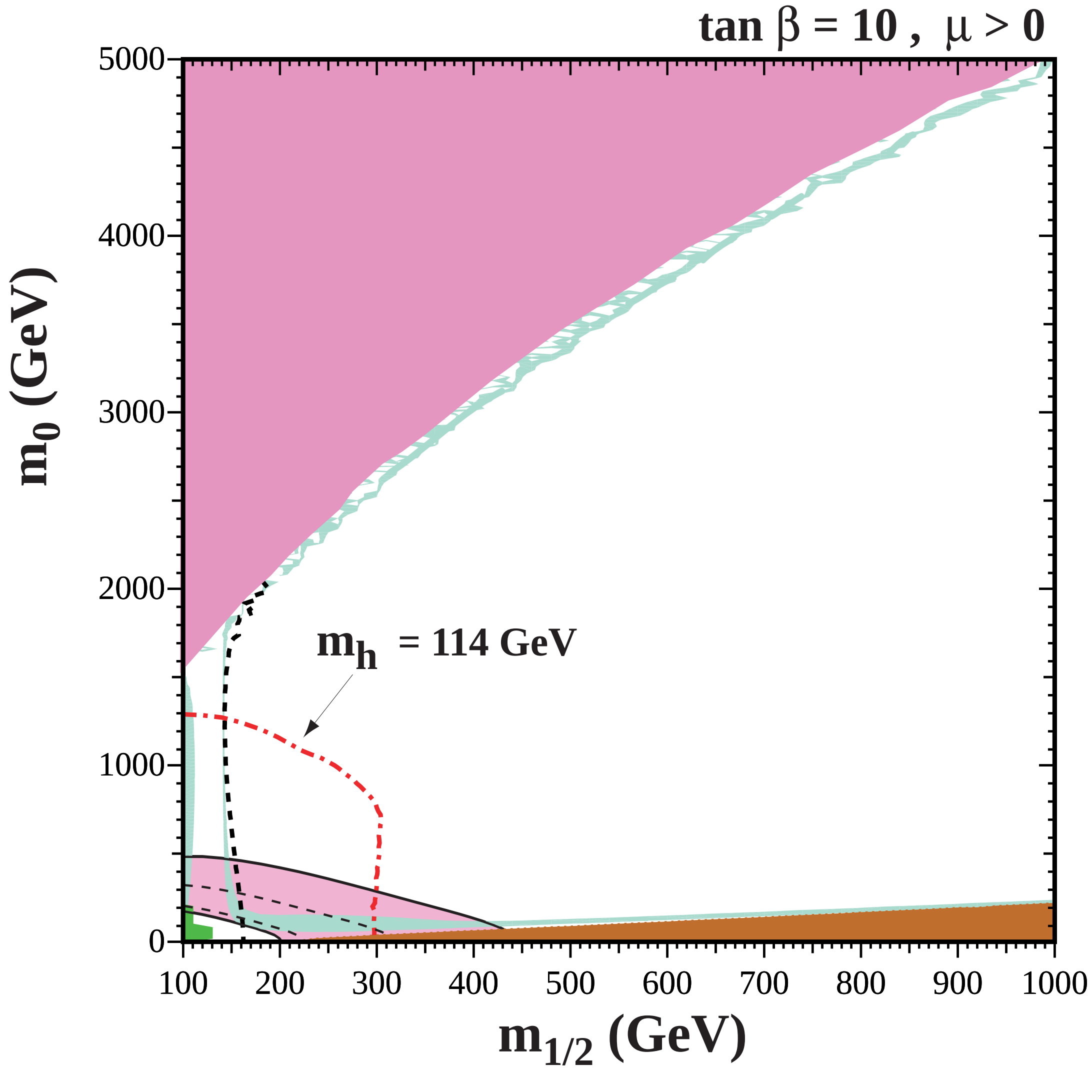
But situation is rather tense already: annihilation cross section is often too low

Important supperssion factor: $\langle \sigma v \rangle \propto v \propto \sqrt{T/M_\chi}$ because of p-wave annihilation in case $\chi\chi \to Z^* \to f\bar{f}$:

Relativistic $f\bar{f} \Longrightarrow$ total angular momentum $J = 1$

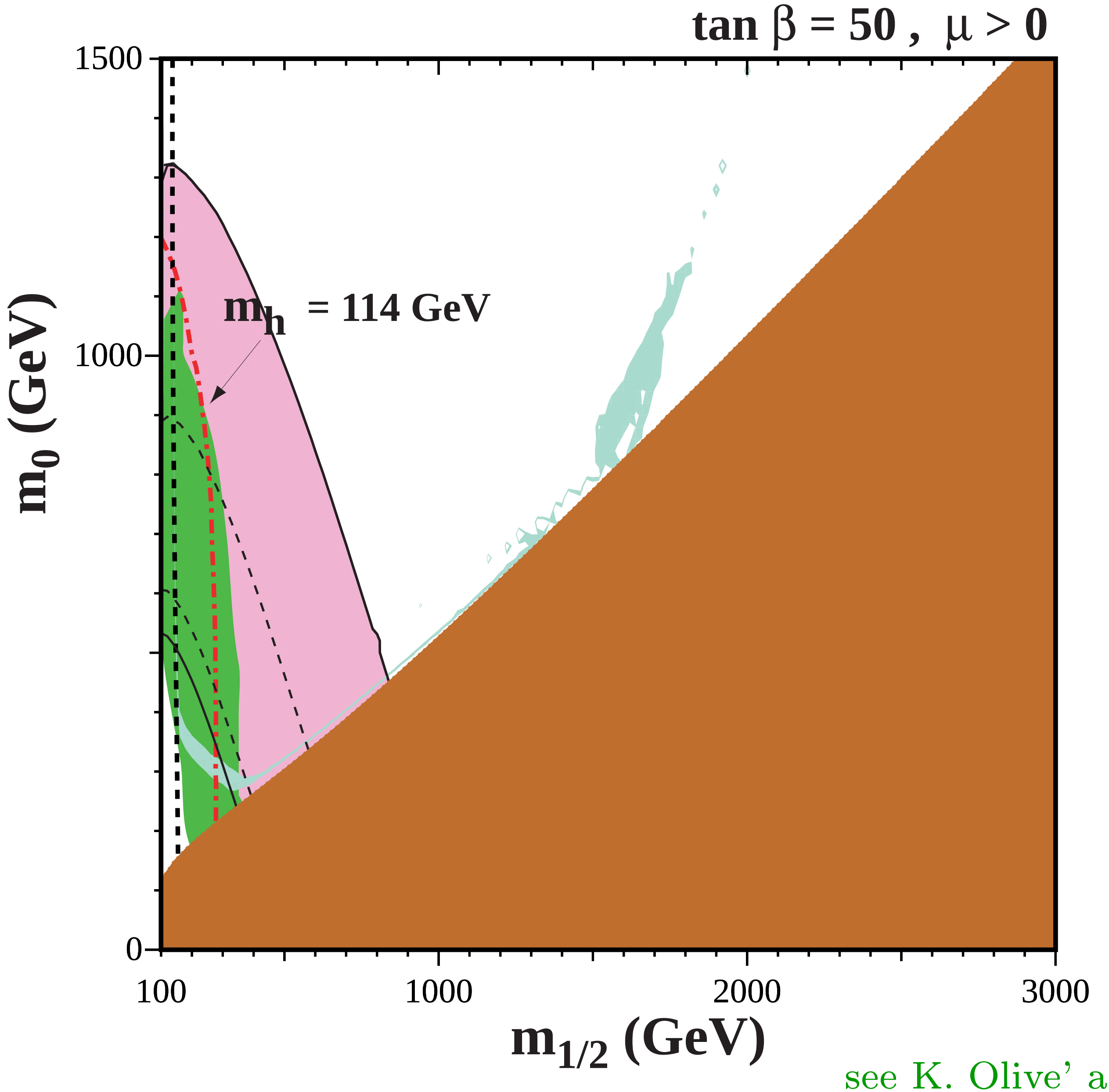
$\chi\chi$: identical fermions $\Longrightarrow$ $L = 0$, parallel spins impossible $\Longrightarrow$ p-wave

mSUGRA at fairly low $\tan\beta$



see K. Olive' astro-ph/0503065

Larger $\tan\beta$ is better



see K. Olive' astro-ph/0503065

Warm dark matter: gravitinos?

- 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 less than 20 observed so far

  - Too high density in galactic centers (“cusps”)

- Not crisis yet

  But what if one really needs to suppress small structures?

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

Warm dark matter

- Decouples when relativistic, $T_f \gg m$.
- Remains relativistic until $T \sim m$ (assuming thermal distribution). Does not feel gravitational potential before that.
- Perturbations of wavelengths shorter than horizon size at that time get smeared out $\Longrightarrow$ small size objects do not form ("free streaming")
- Horizon size at $T \sim m$

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

Present size of this region

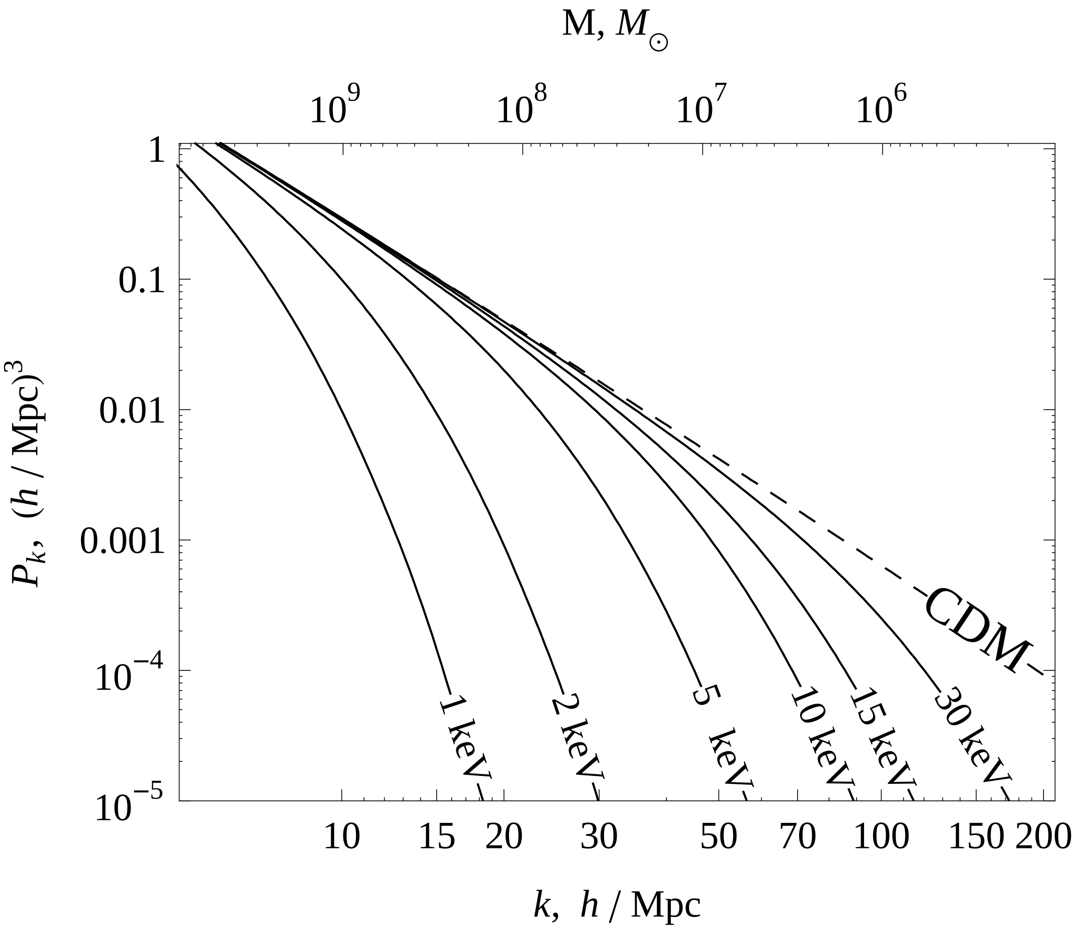
$$l(t_0) = \frac{T}{T_0} l(T) = \frac{M_{Pl}}{mT_0}$$

(modulo g_* factors).
Objects of initial size smaller than l_0 are less abundant

- Initial size of dwarf galaxy $l_{dwarf} \sim 100$ kpc $\sim 3 \cdot 10^{23}$ cm
  Require
  $$l_0 \simeq \frac{M_{Pl}}{mT_0} \sim l_{dwarf}$$
  $\Longrightarrow$ 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 keV range
  are good warm dark matter candidates

Suppression of density perturbations



P_k: power spectrum of density perturbations.

see Gorbunov, Khmelnitsky, V.R., 0805.2836 [hep-ph]

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

- Decay width of superpartners into gravitino + SM particles

$$\Gamma_{\tilde{S}} \simeq \frac{M_{\tilde{S}}^5}{F^2} \simeq \frac{M_{\tilde{S}}^5}{m_{3/2}^2 M_{Pl}^2}$$

$M_{\tilde{S}}$ = mass of superpartner $\tilde{S}$

Gravitino production in decays of superpartners

$$\frac{d(n_{3/2}/s)}{dt} = \frac{n_{\tilde{S}}}{s}\Gamma_{\tilde{S}}$$

$n_{\tilde{S}}/s = \mathrm{const} \sim g_*^{-1}$ for $T \gtrsim M_{\tilde{S}}$, while $n_{\tilde{S}} \propto \mathrm{e}^{-M_{\tilde{S}}/T}$ for $T \ll M_{\tilde{S}}$ $\Longrightarrow$ production most efficient at $T \sim M_{\tilde{S}}$ (slow cosmological expansion with unsuppressed $n_{\tilde{S}}$)

$$\frac{n_{3/2}}{s} \simeq \frac{\Gamma_{\tilde{S}}}{g_* H(T \sim M_{\tilde{S}})} \simeq \frac{M_{Pl}^*}{g_* M_{\tilde{S}}^2} \cdot \frac{M_{\tilde{S}}^5}{m_{3/2}^2 M_{Pl}^2}$$

Mass-to-entropy ratio

$$\frac{m_{3/2} n_{3/2}}{s} \simeq \frac{M_{\tilde{S}}^3}{m_{3/2}} \frac{1}{g_*^{3/2} M_{Pl}}$$

$$\frac{m_{3/2} n_{3/2}}{s} \simeq \sum_{\tilde{S}} \frac{M_{\tilde{S}}^3}{m_{3/2}} \frac{1}{g_*^{3/2} M_{Pl}}$$

For $m_{3/2} =$ a few keV, mass-to-entropy$= 3 \cdot 10^{-10}$ GeV

$M_{\tilde{S}} \simeq 100 \div 300$ GeV   Definitely in LHC range

Need light superpartners

and low maximum temperature in the Universe, $T_{max} \lesssim 1$ TeV to avoid overproduction in collisions of superpartners (and in decays of squarks and gluinos if they are heavy)

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

Longer lifetime for heavier gravitino (CDM candidate)

WEAK SCALE PHYSICS MAY WELL BE RESPONSIBLE FOR GENERATION OF DARK MATTER

Is this guaranteed?

By no means. Another good DM candidate: axion.

Plus a lot of exotica...

Crucial impact of LHC to cosmology,
direct and indirect dark matter searches

- WIMP, signal at LHC:
  - Strongest possible motivation for direct and indirect detection
    - Inferred interactions with baryons $\Longrightarrow$ strategy for direct detection
  - A handle on 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
  - A lot of work to make sure that it is indeed DM particle
  - Hard time for direct and indirect searches

- No signal at LHC
  - Need luck to figure out who is dark matter particle
  - 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: $n_B/s = 0.9 \cdot 10^{-10}$

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

Sakharov'67, Kuzmin'70

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

Can baryon asymmetry be due to electroweak physics?

Baryon number is violated in electroweak interactions.

Non-perturbative effect 't Hooft' 76

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

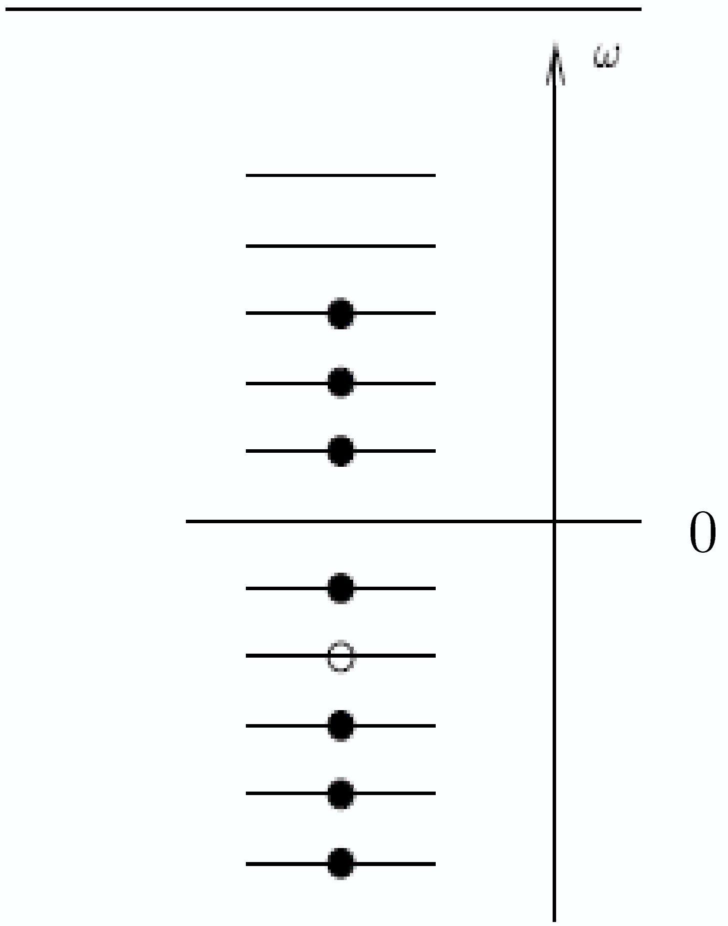
$$i\frac{\partial}{\partial t}\psi = i\gamma^0\vec{\gamma}(\vec{\partial} - ig\vec{A})\psi = H_{Dirac}(t)\psi$$

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

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

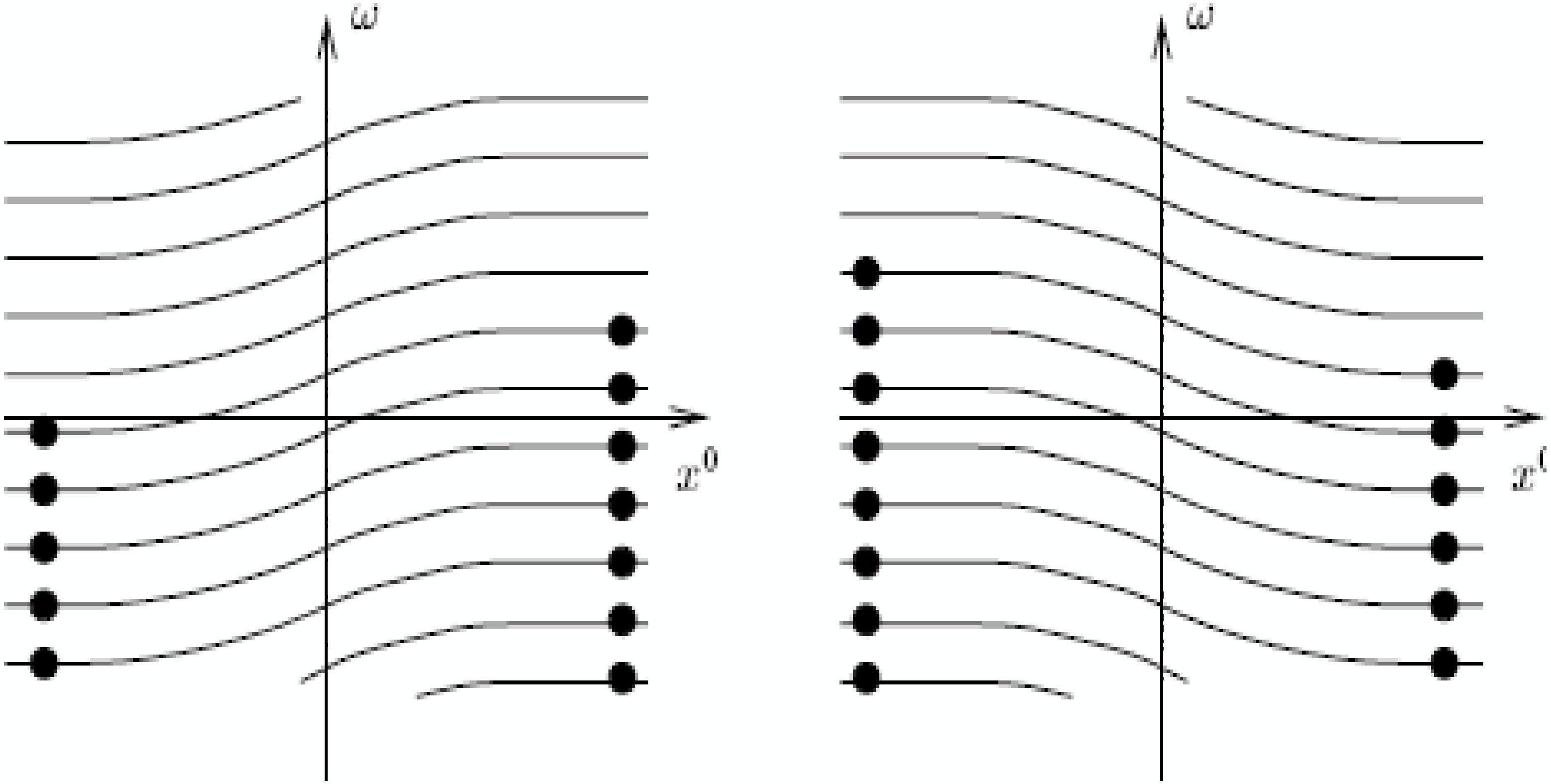
How do eigenvalues behave in time?

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



TIME EVOLUTION OF LEVELS
IN SPECIAL (TOPOLOGICAL) GAUGE FIELDS

Left-handed fermions Right-handed

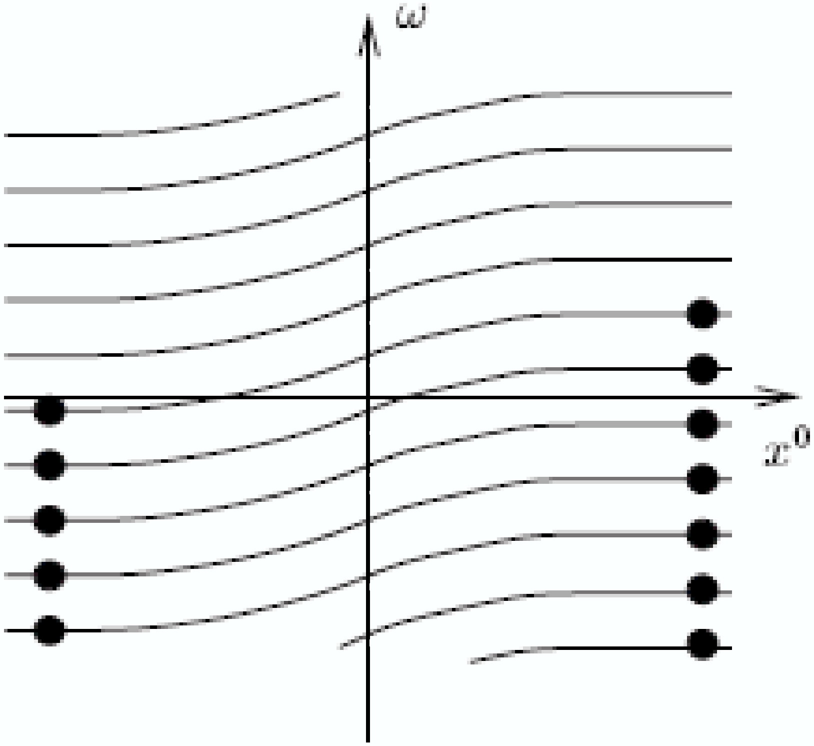


The case for QCD

$B = N_L + N_R$ 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 ?

However, Universe expands slowly. Expansion time

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

Too large to have deviations from thermal equilibrium?

Electroweak transition

Electroweak symmetry is restored 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.

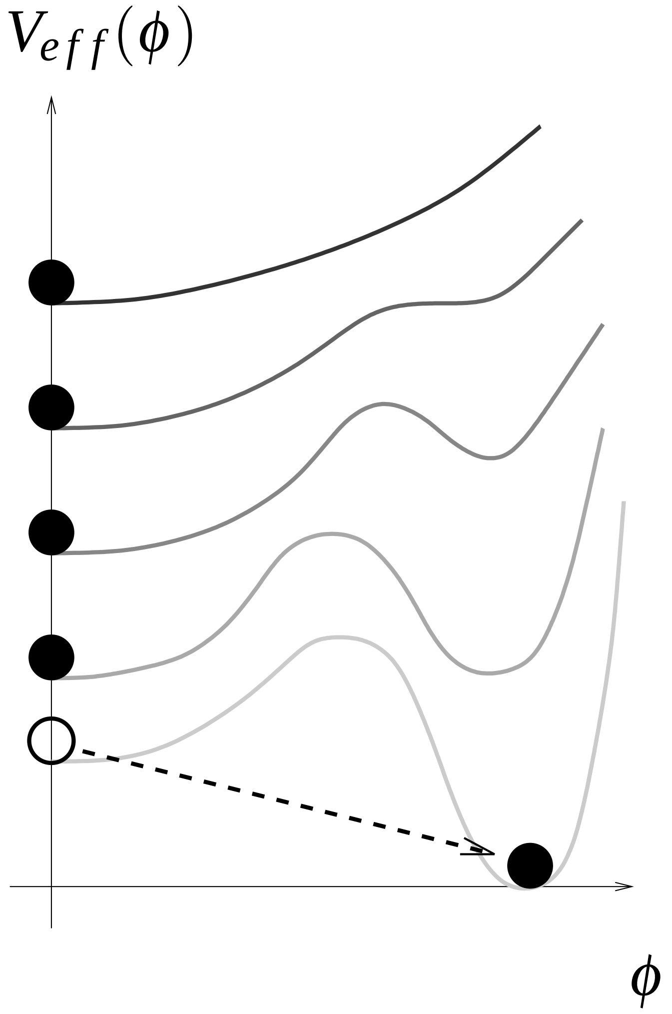
Bubbles then expand at $v \sim 0.1c$

Fig

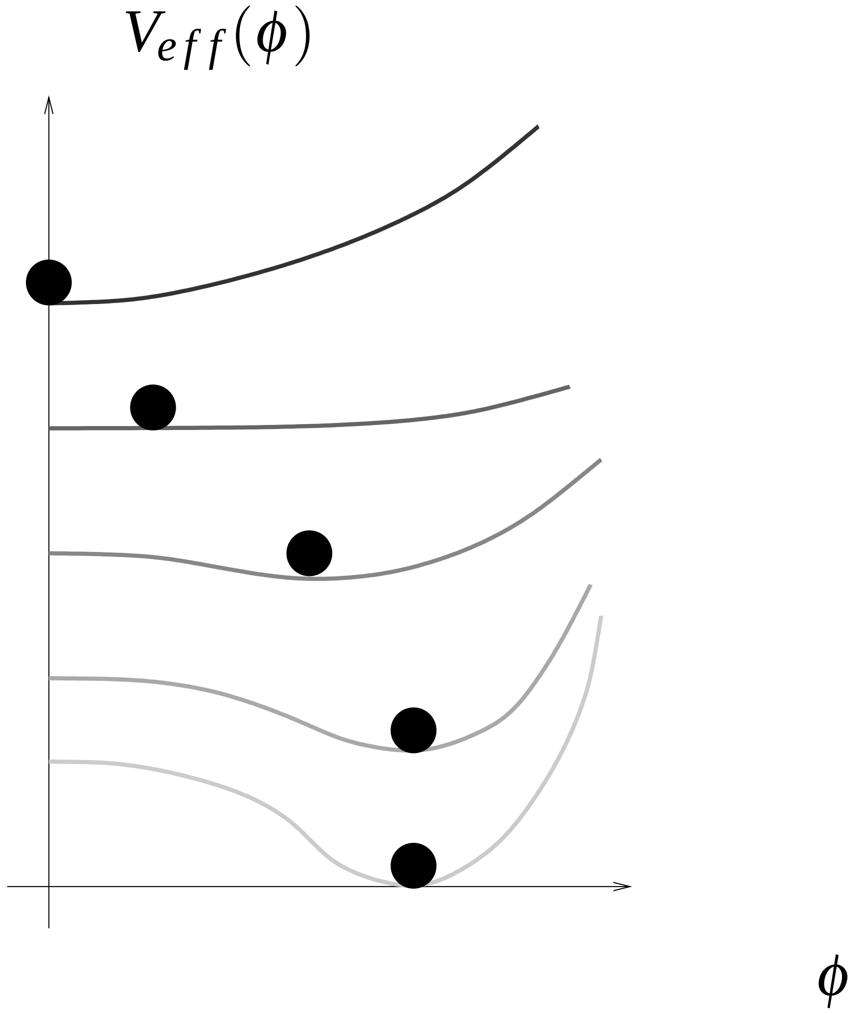
Beginning of transition: about one bubble per horizon

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

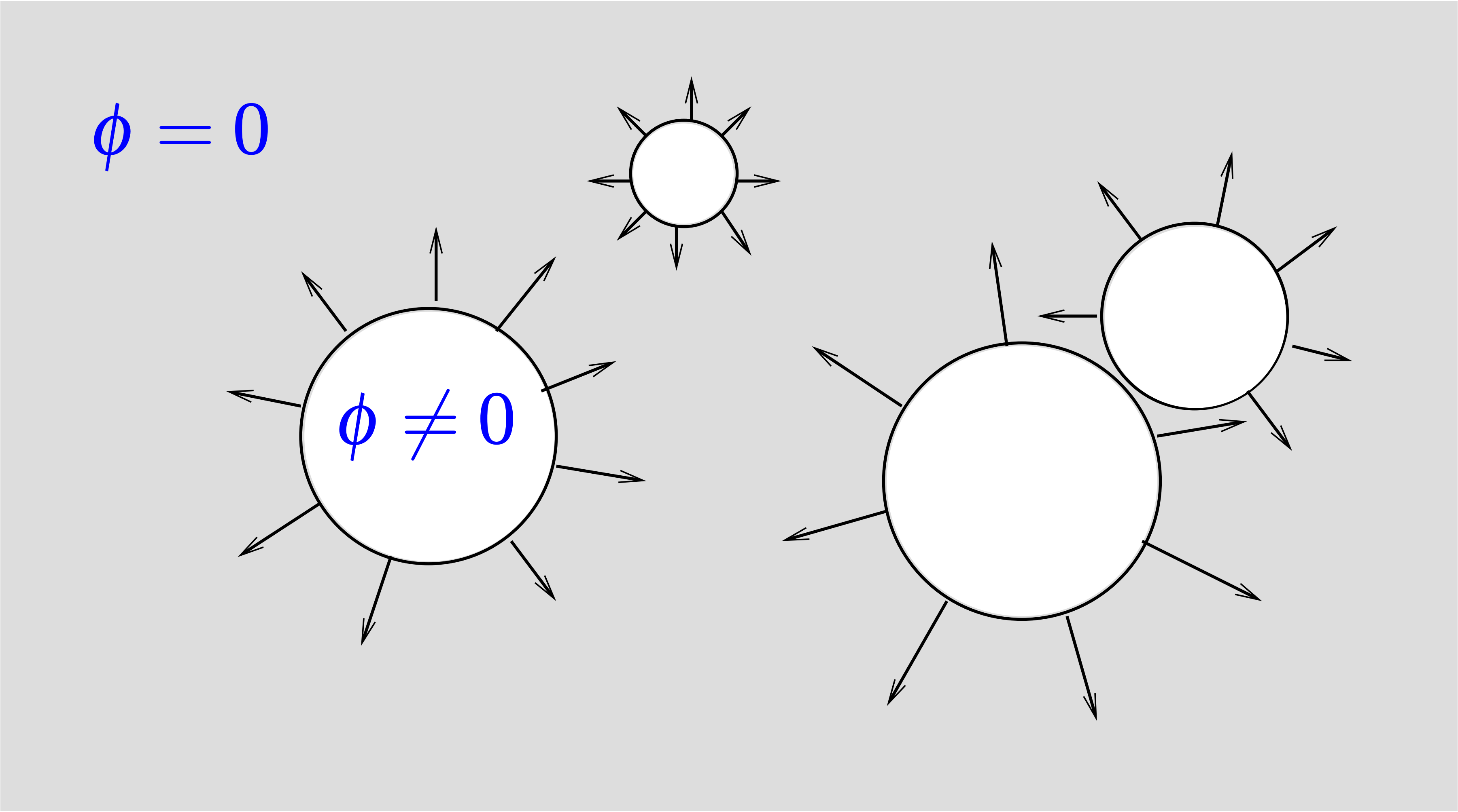
Boiling Universe, strongly out of equilibrium



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

Are we on right track assuming that dark matter and baryon asymmetry were generated at the hot stage of cosmological evolution, not at post-inflationary reheating stage?

Initial conditions for perturbations:

- Adiabatic mode: $\delta\rho, \delta T \neq 0$, but chemical composition same everywhere,

$$\delta\left(\frac{\rho_B}{s}\right) = \delta\left(\frac{\rho_{DM}}{s}\right) = 0$$

This must be the only mode if dark matter and baryon asymmetry were generatd at hot stage

Otherwise

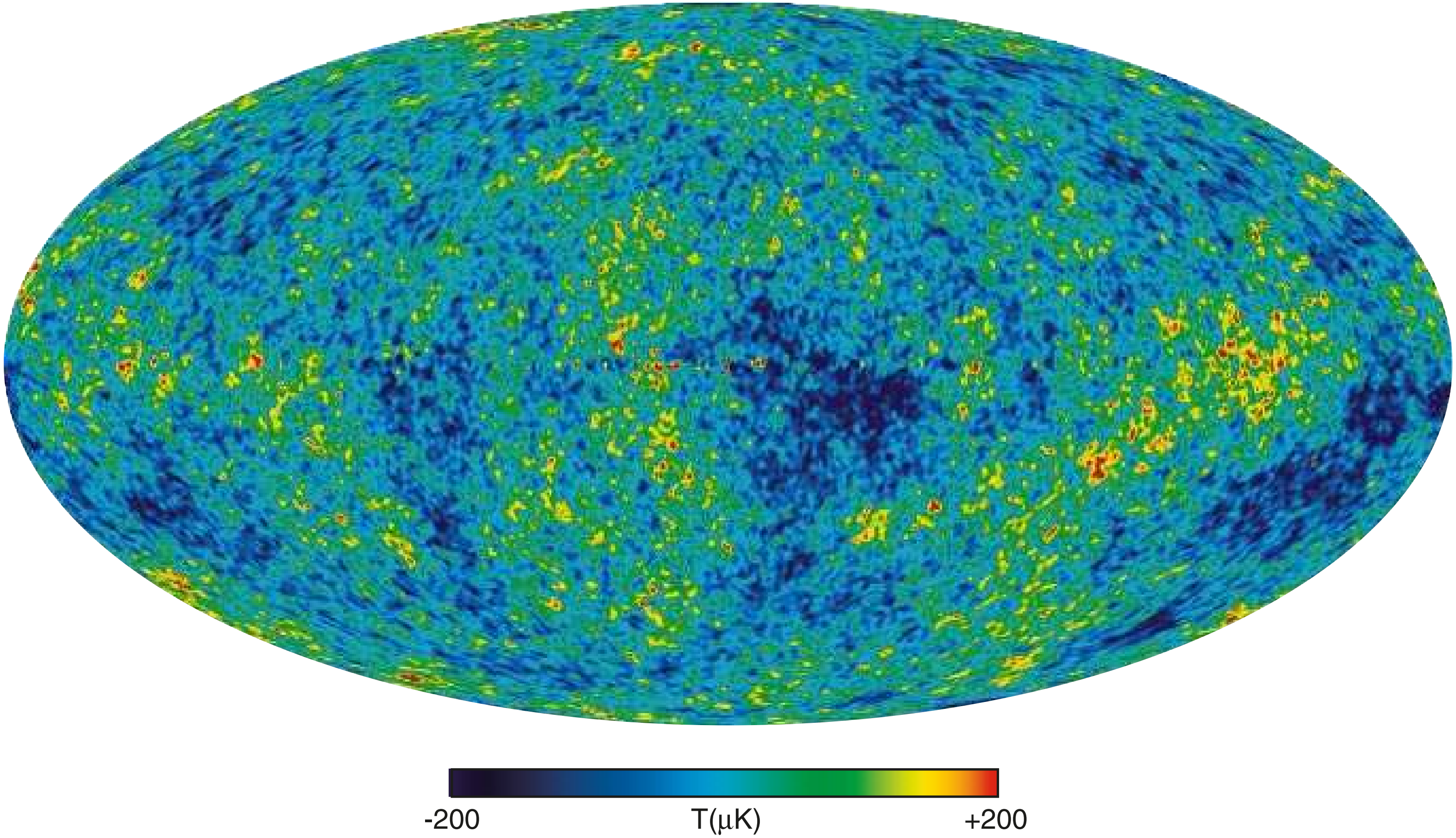
- Isocurvature modes: $\delta T = 0 \implies \delta\rho \approx 0$, but

$$\delta\left(\frac{\rho_B}{s}\right) \neq 0 \quad \text{(Baryon iso)} \qquad \text{or} \qquad \delta\left(\frac{\rho_{DM}}{s}\right) \neq 0 \quad \text{(DM iso)}$$

CAN ONE TELL?

CMB sky

$$T = 2.726^\circ K, \quad \frac{\delta T}{T} \sim 10^{-5}$$



WMAP

Understanding CMB anisotropy spectrum

- Decompose temperature fluctuation in spherical harmonics (starting from $l = 2$)

$$\delta T(\theta,\varphi) = \sum_{l,m} a_{lm} Y_{lm}(\theta,\varphi)$$

Large $l \Longleftrightarrow$ small angular scales

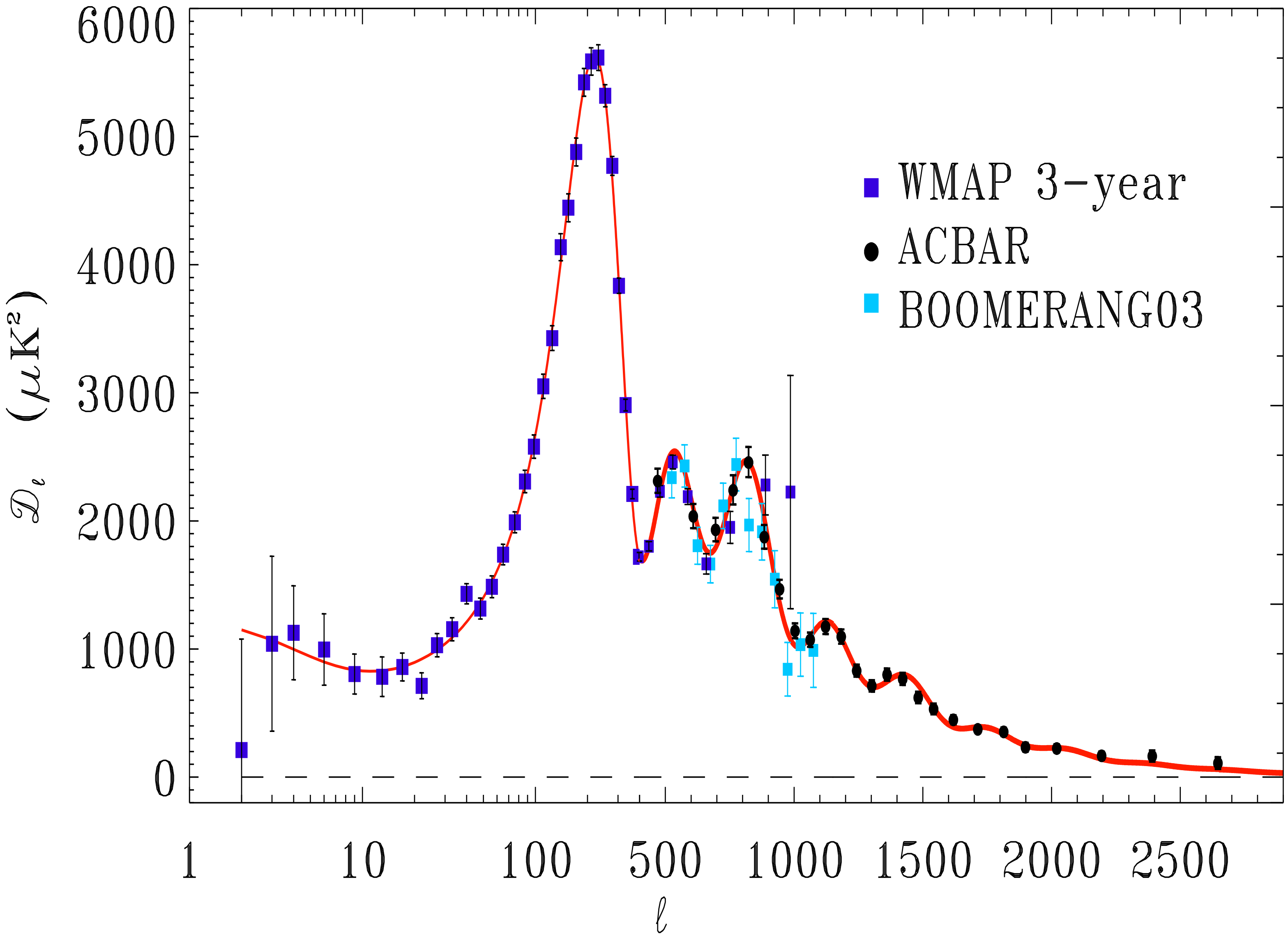
- a_{lm}: Gaussian random variables,

$$\langle a_{lm} a_{l'm'} \rangle = C_{lm} \delta_{ll'} \delta_{mm'}$$

averaged over ensemble of Universes like ours.
Isotropy: $C_{lm} = C_l$ independent of m

- Temperature fluctuation

$$\langle \delta T^2(\mathbf{n}) \rangle = \sum_l \frac{2l+1}{4\pi} C_l \approx \int \frac{dl}{l} \frac{l(l+1)}{2\pi} C_l$$

6000
5000
4000
3000
2000
1000
0
$\mathcal{D}_\ell \quad (\mu K^2)$
1
10
100
500
1000
1500
2000
2500
ℓ
WMAP 3-year
ACBAR
BOOMERANG03

What's behind?

- Primordial density perturbations (not explained within hot Big Bang theory; need long preceding epoch to generate them, e.g, inflation) and possibly primordial gravity waves:
  - a_{lm} random Gaussian $\Longleftrightarrow$ $\delta\rho(\mathbf{k})$ random Gaussian
    Hint towards origin: enhanced vacuum fluctuations of almost non-interacting quantum field, e.g., inflaton
  - Flat (Harrison–Zeldovich) or almost flat primordial power spectrum

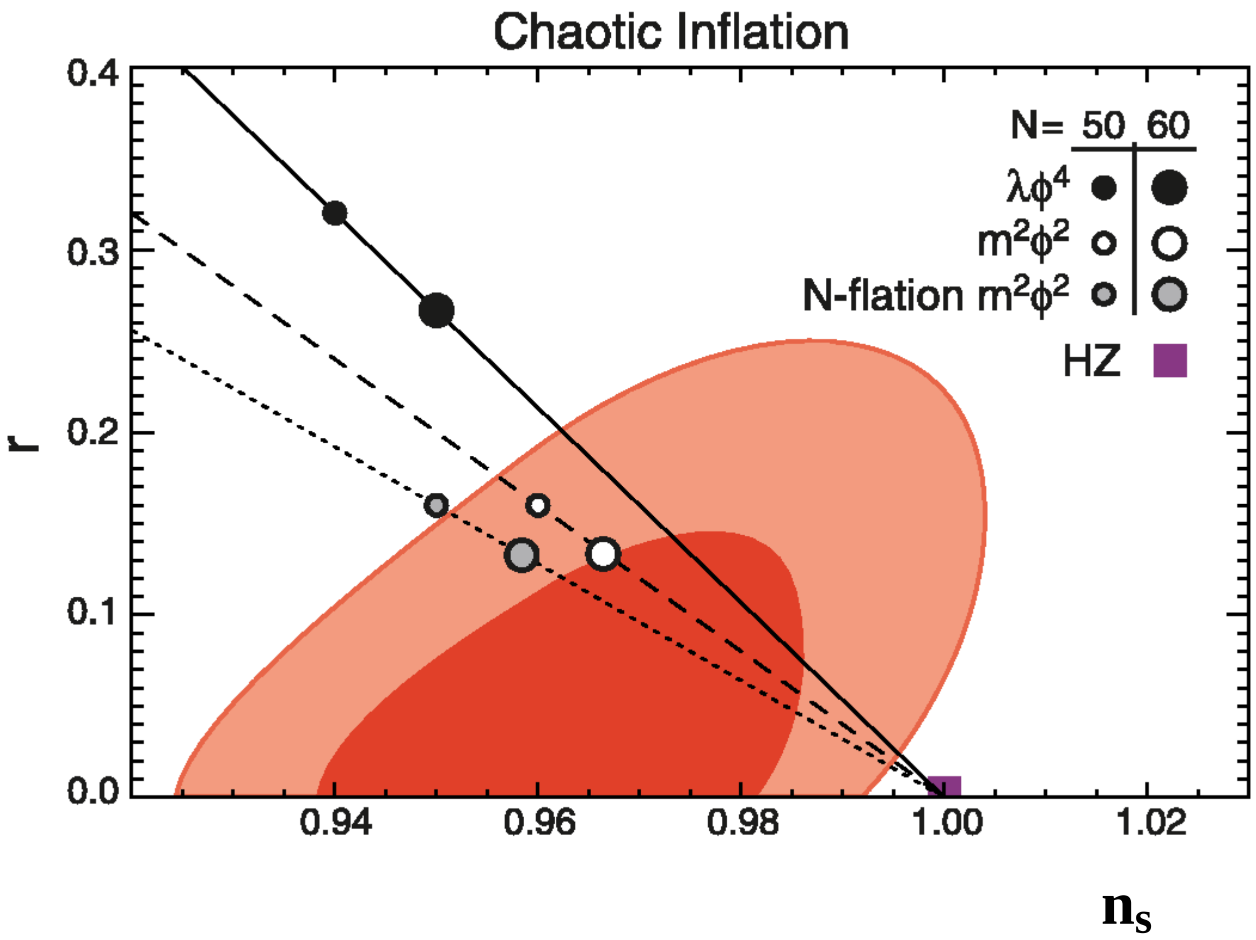
$$\left\langle \left(\frac{\delta\rho(\mathbf{x})}{\rho} \right)^2 \right\rangle = \int_0^\infty \frac{dk}{k} A_s \cdot \left(\frac{k}{k_*} \right)^{n_s - 1}$$

with $n_s - 1 = -0.040 \pm 0.014$ (assuming no gravity waves)

  - Small adimixture, if any, of gravity waves,

$$r \equiv \frac{\text{Gravity waves}}{\text{Density perturbations}} < 0.2$$

Scalar tilt vs tensor power



Further evolution

- Perturbations in baryon-photon plasma $\Longleftrightarrow$ sound waves. Comoving momentum k conserved, physical momentum $k/a(t)$ gets redshifted.
- Mode of comoving momentum k oscillates as

$$\text{Baryon-photon:} \qquad \frac{\delta\rho}{\rho}(k,t) \propto \cos\left(\int_0^t dt \; \frac{v_s k}{a(t)}\right)$$

$v_s =$ sound velocity.

NB: Phase of oscillations fixed!

Early times, $k/a \ll H$: one mode is constant, another rapidly decays away.

- Perturbations in DM do not oscillate.
  No pressure — no oscillations.

- acoustic oscillations $\Longrightarrow$ oscillations in momenta at recombination:

Baryon-photon: $$\frac{\delta\rho}{\rho}(k,t) \propto \cos\left(\int_0^{t_r} dt\ \frac{v_s k}{a(t)}\right)$$

- Interference between perturbations in baryon-photon component and dark matter component, if these are of common origin

Effects on CMB:

All at last scattering

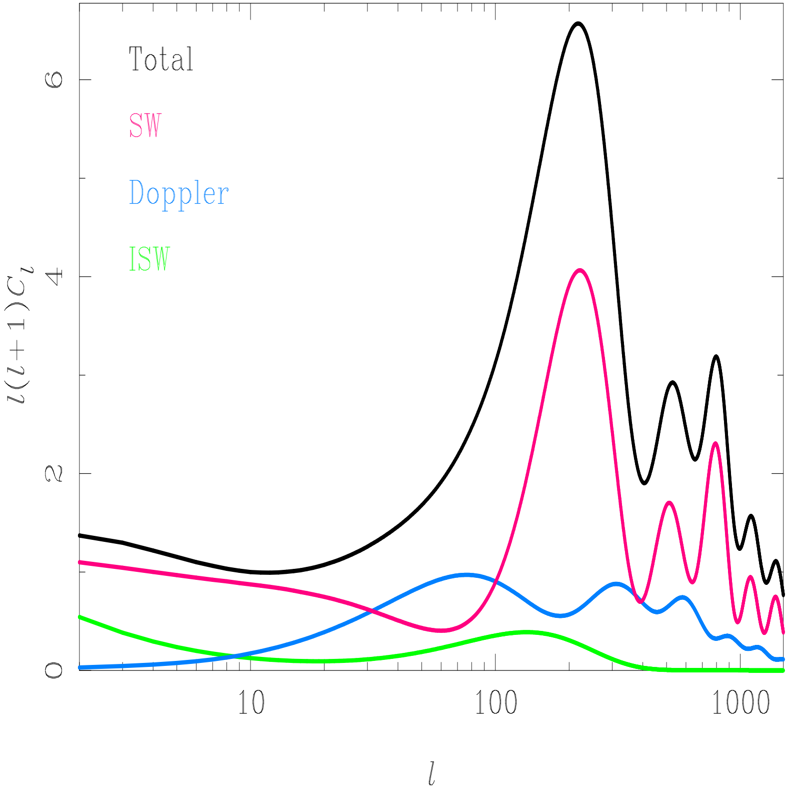
- Temperature perturbations, $\delta T \propto \delta\rho_{rad}$ $\Longleftrightarrow$ baryon-photon component
- Gravitational potential $\Longleftrightarrow$ dark matter mostly
- Doppler effect $\Longleftrightarrow$ baryon-photon component.

Adiabatic mode: baryons, photons and dark matter work together

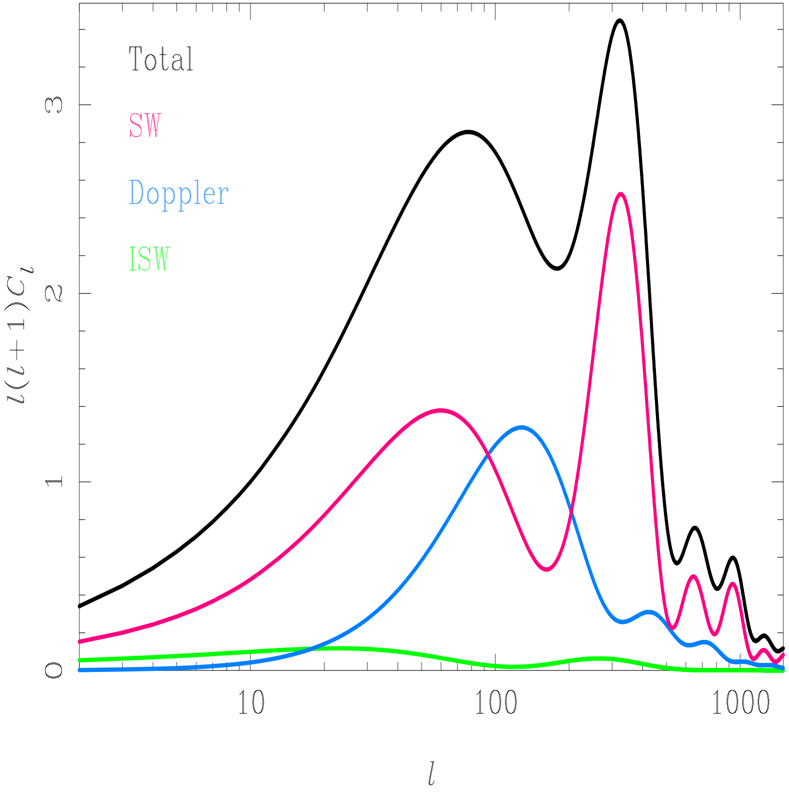
CDM iso: CMB anisotropy is completely different

Similarly for baryon iso

Calculated CMB anisotropy spectrum



Adiabatic



Isocurvature

see Challinor, astro-ph/0403344

Observations consistent with purely adiabatic

Isocurvature $\lesssim 10\%$

This does favor generation of baryon asymmetry
and dark matter at hot stage.

BUT

Even small admixture of isocurvature mode(s)
would make a big difference

Watch out Planck!

Extra dimensions/low scale gravity

- Would obviously have major impact on cosmology
- Fundamental gravity scale $\Lambda_G \sim$ TeV
  $\Longrightarrow$ Standard cosmological evolution at best from $T \sim$ TeV
  - Inflation, if any, occured at energy densities of at most TeV^4
  - Dark matter, baryon asymmetry generated below $T \sim$ TeV

OR

All that happened in quantum gravity regime

- Dream
  - Study quantum gravity at colliders
  - Study earliest cosmology at colliders
- A lot of fun — and jobs — for us and our grand-grandchildren, experimentalists and theorists

But cosmology may be telling us something different — and unpleasant

- Friendly fine-tunings
  - Cosmological constant $\sim (10^{-3}\ eV)^4$

    Just right for galaxies to get formed
  - Primordial density perturbations $\frac{\delta\rho}{\rho} \sim 10^{-5}$

    Just right to form stars
    but not supermassive galaxies w/o planets
  - Dark matter sufficient to produce structure

Also

  - Light quark masses and α_{EM}

    Just right for $m_n > m_p$
    but stable nuclei
  - Many more...

Is the electroweak scale a friendly fine-tuning?

Anthropic principle/environmentalism

"Our location in the Universe
is neccessarily priviledged to
the extent of being compatible
with our existence as observers"
Brandon Carter'1974

Fig

Recent support from "string landscape"

We exist where couplings/masses are right

Problem: never know which parameters are environmental and which derive from underlying physics

Disappointing, but may be true

May gain support from LHC, if not enough new physics

横山　操「グランド キャニオン」1961年

To conclude

LHC may well discover things crucial for our existence

Dark matter
Dynamics behind baryon asymmetry

Quite possibly not particular ones discussed here

May find something even more profound

Like extra dimensions/TeV-scale gravity

Quite possibly something else

May support anthropic viewpoint

And in any case will change the landscape of physics,
cosmology included