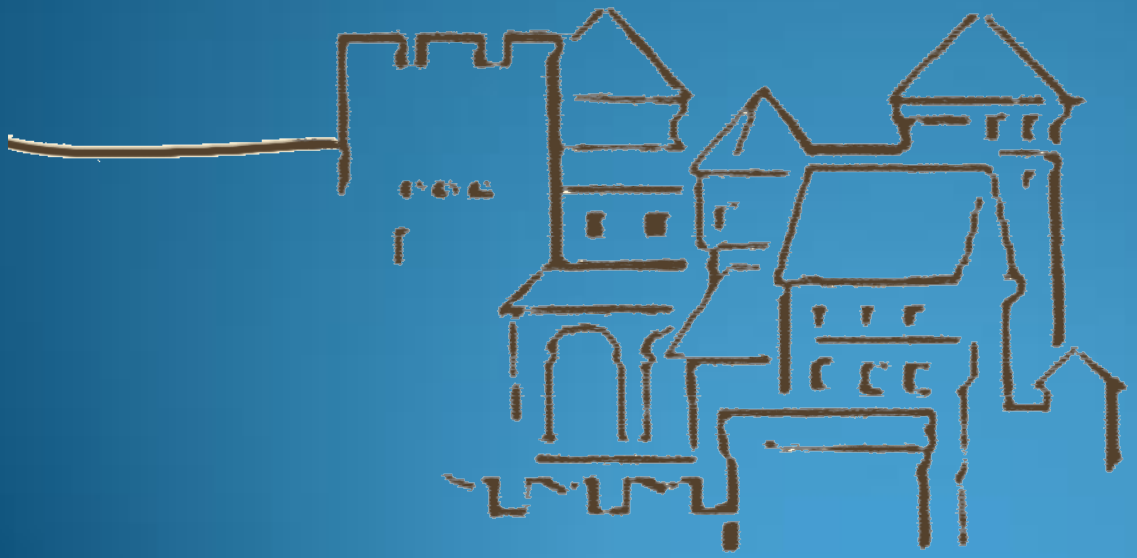
Matter versus antimatter

the grand battle



Alexander Kartavtsev

23 July 2013

Angels and demons

Outline

1. Experimental observations
2. Theoretical advancements
3. Electroweak baryogenesis
4. Baryogenesis via leptogenesis
5. Current status
6. Summary

Antimatter predicted (1928)

Paul Dirac

$$(i\gamma^{\mu}\partial_{\mu}-m)\psi=0$$

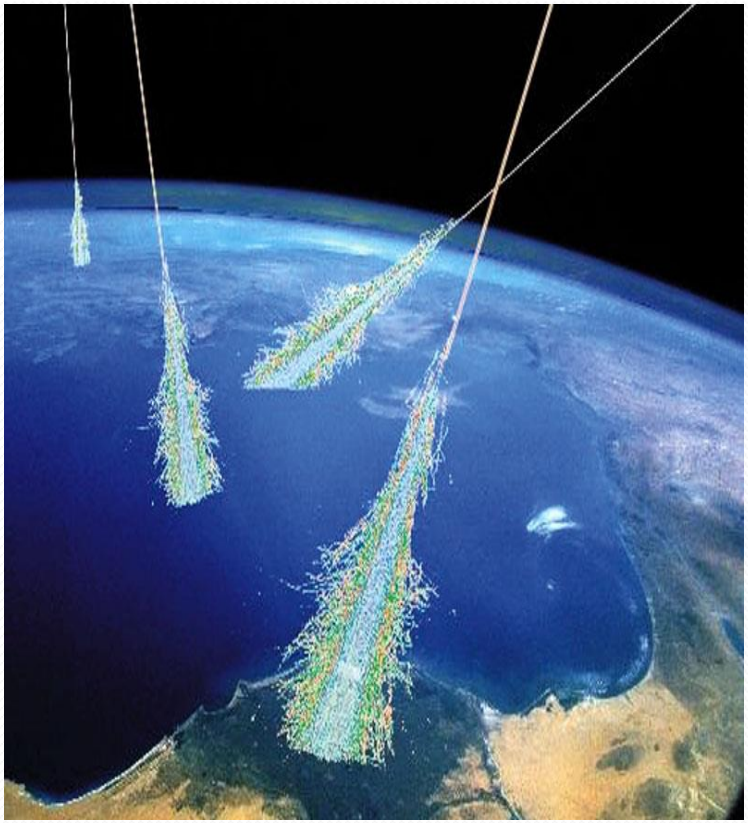
… during his postgraduate years he concentrated solely on his research, and stopped only on Sunday, when he took long strolls alone …

Antimatter discovered (1932)

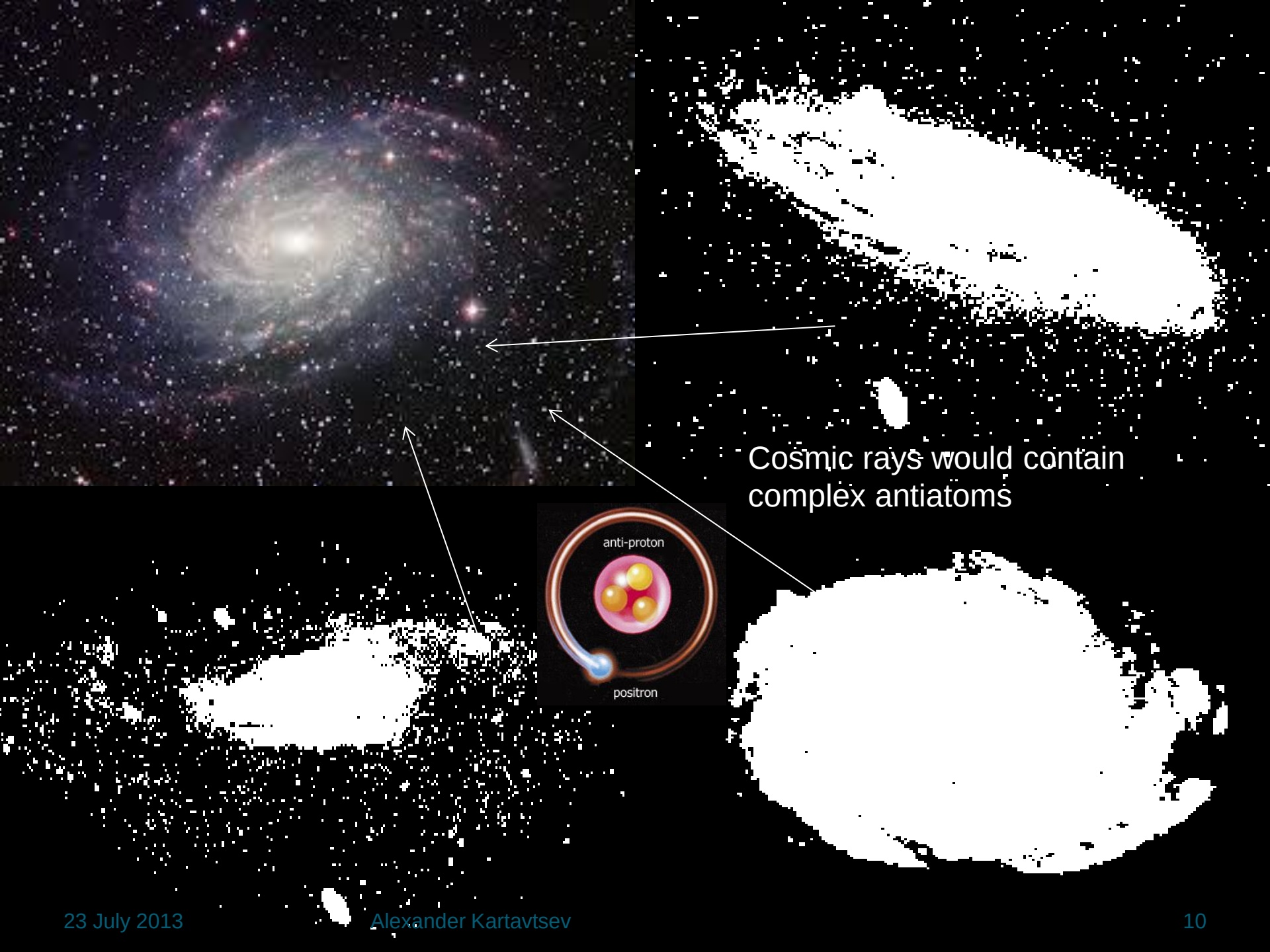
Carl Anderson

Cosmic rays (1936)

Homi Bhabha



Cosmic rays contain positrons and antiprotons


Cosmic rays would contain
complex antiatoms
anti-proton
positron

we are having a
COUNTER-CULTURE
moment.

we are celebrating the 50TH
ANNIVERSARY of the peace sign.

and we are
remembering

1968

forty years on

PEACE

LOVE

we are digging

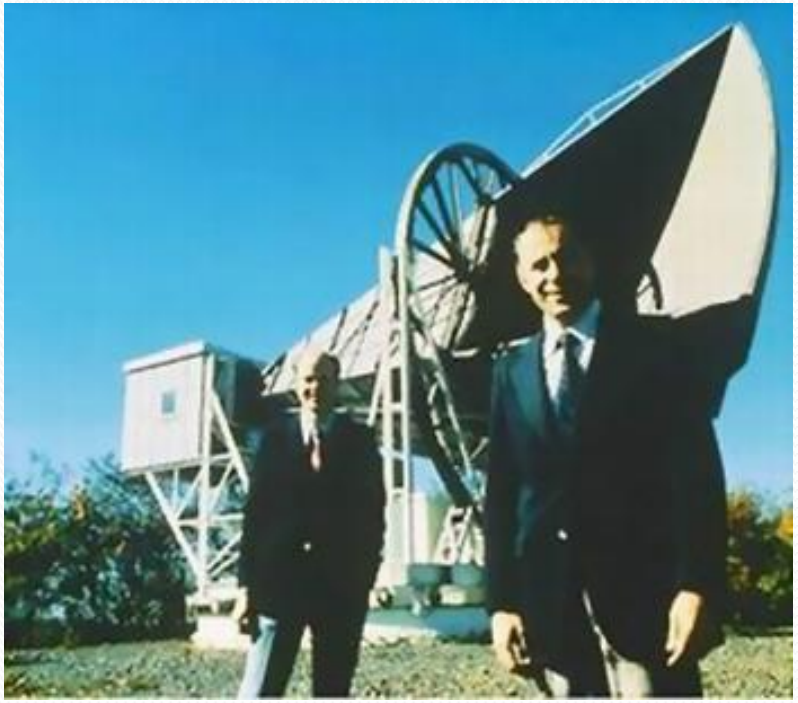
BOHEMIAN LUXURY,
GORGEOUS GREEN GIFTS
& ALTERNATIVE STYLE

have a cool yule and a

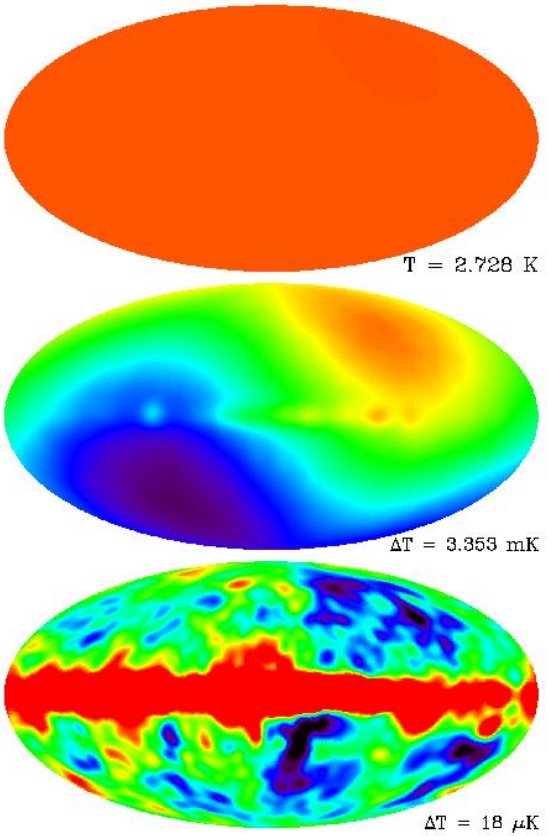
HIPPIE
HOLIDAY

PICKY HIPPIES LOVE
THE BARNEYS NEW YORK
GIFT CARD

CMB (1965)

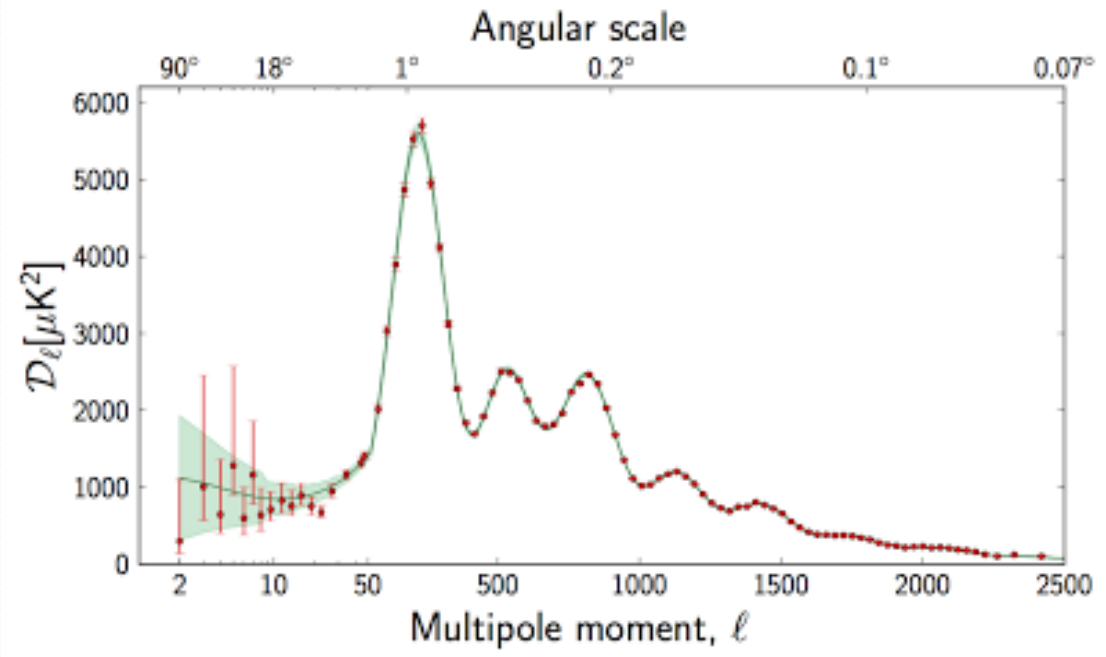


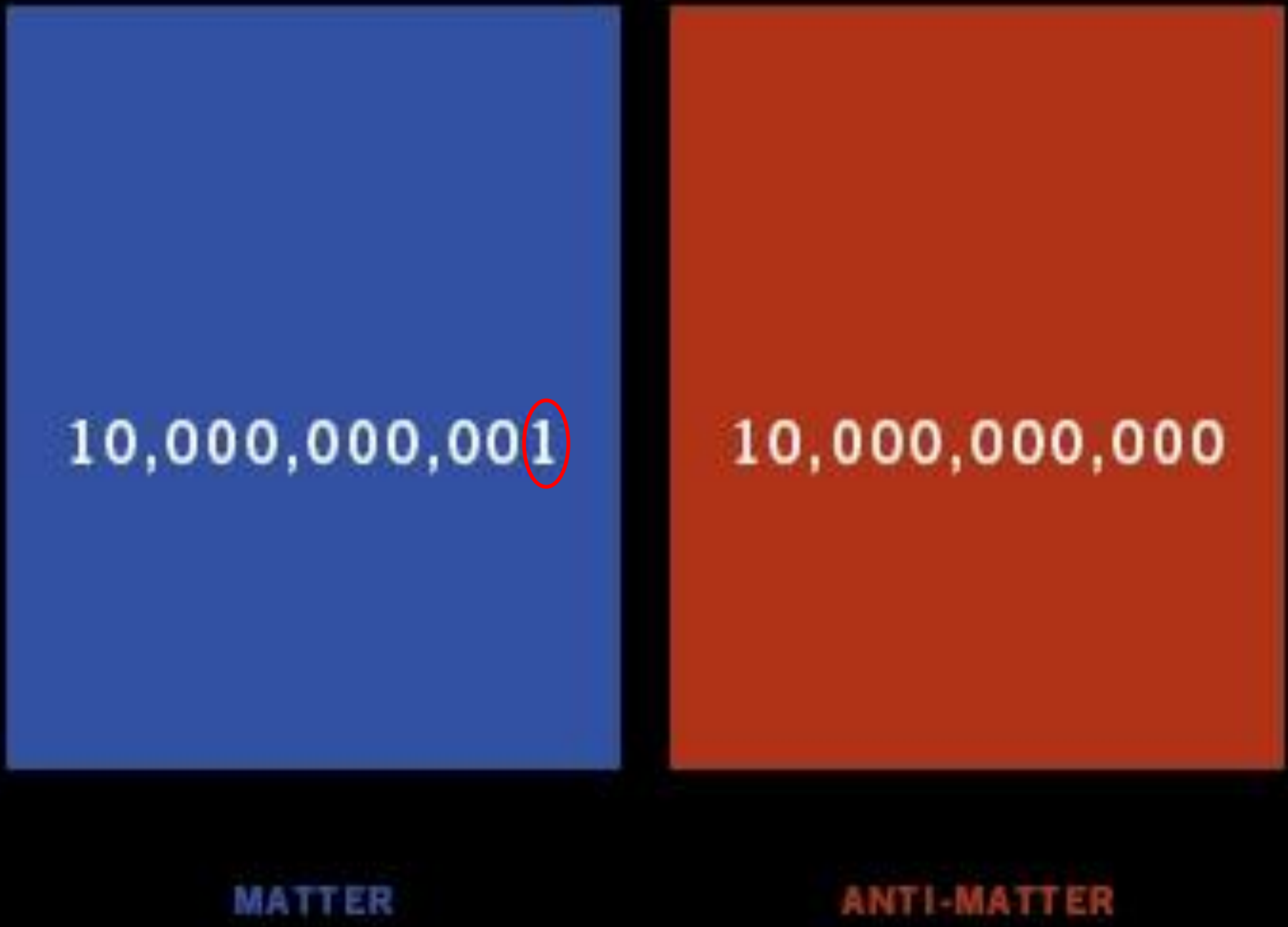
Robert Woodrow Wilson
Arno Allan Penzias



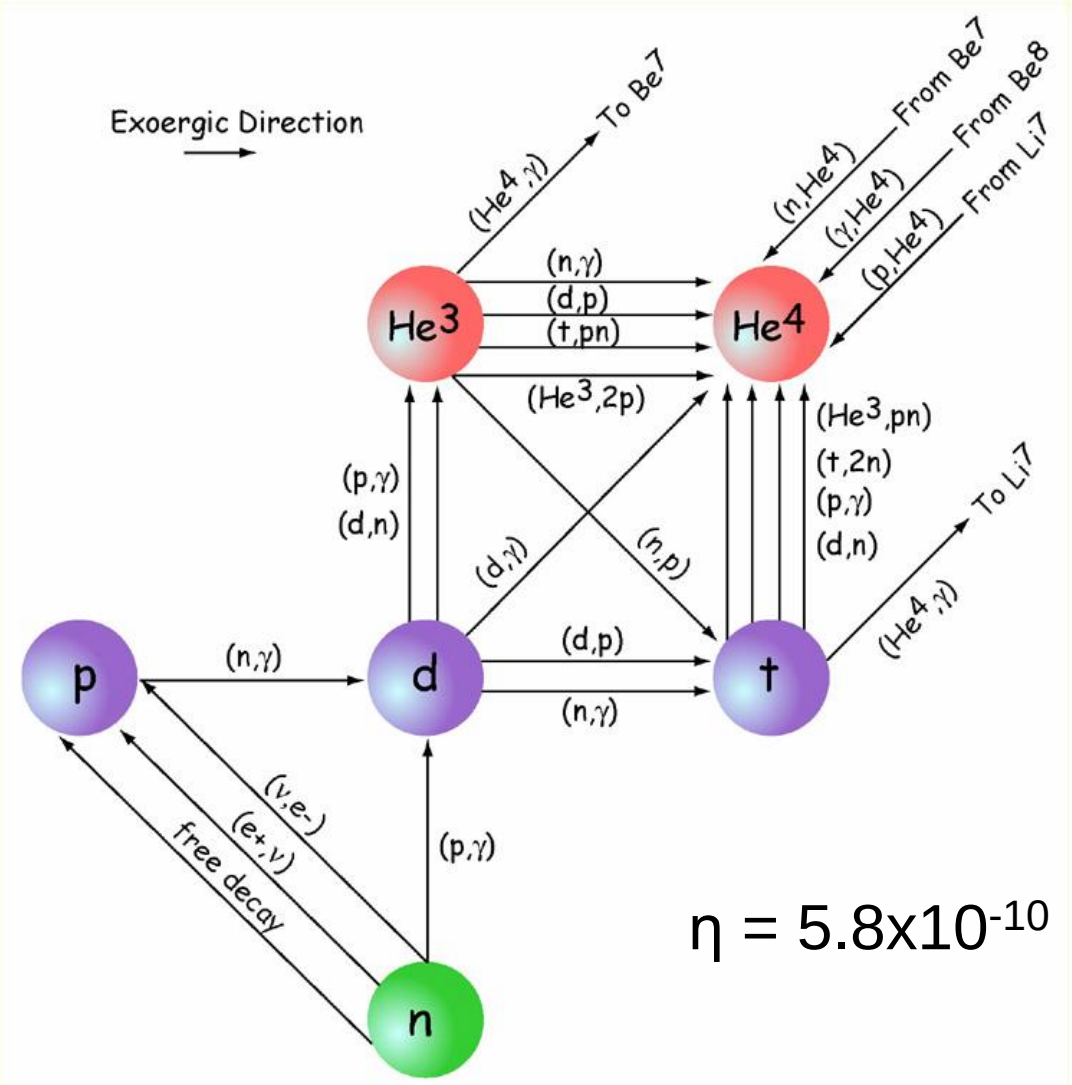
Baryon to photon ratio

$$\eta = \left.\frac{N_B}{N_\gamma}\right|_{T=3\,\mathrm{K}} = \left.\frac{N_B - N_{\bar{B}}}{N_\gamma}\right|_{T=3\,\mathrm{K}} \sim \left.\frac{N_B - N_{\bar{B}}}{N_B + N_{\bar{B}}}\right|_{T \gtrsim 1\,\mathrm{GeV}} = 6.1\text{x}10^{-10}$$



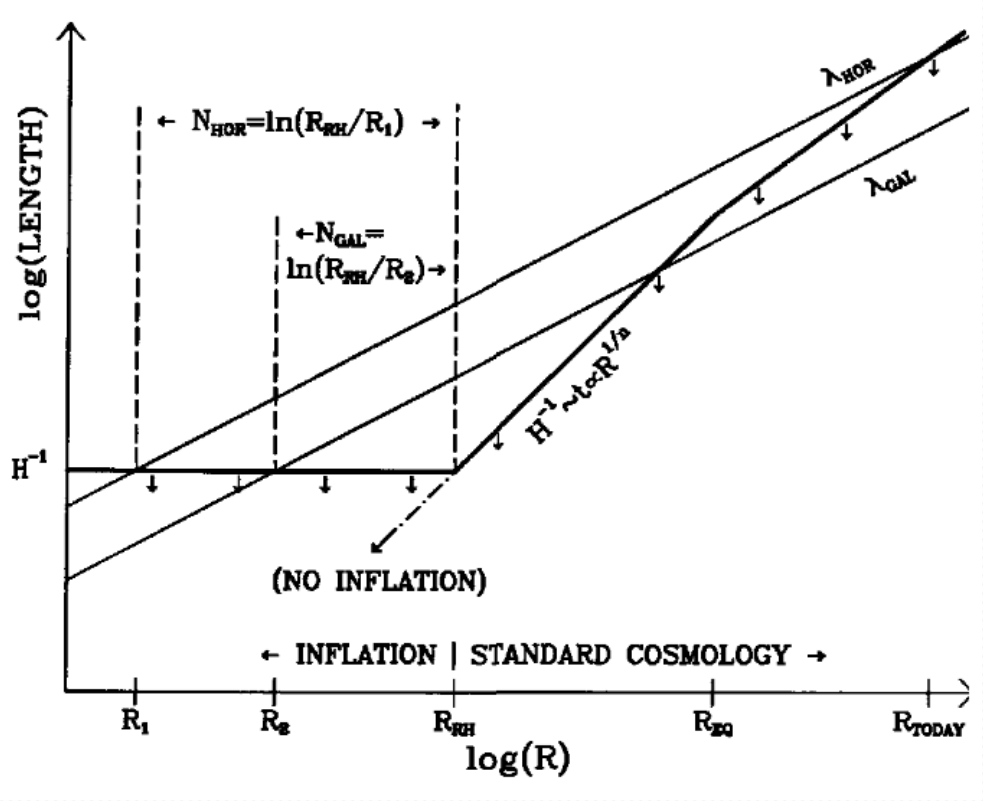

10,000,000,001
10,000,000,000
MATTER
ANTI-MATTER

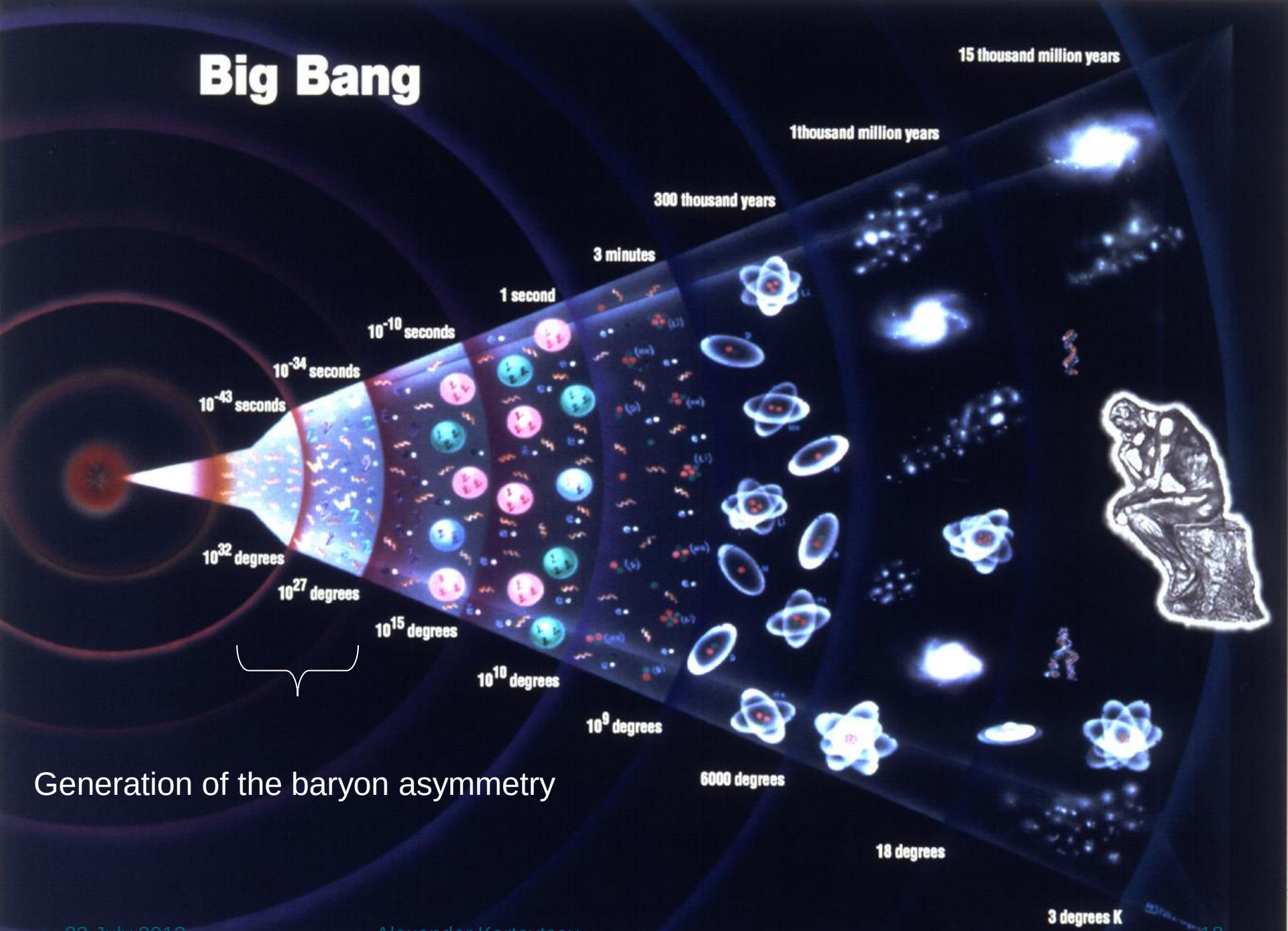
BBN


Exoergic Direction
(He4,γ)
To Be7
(n,He4)
From Be7
(γ,He4)
From Be8
(p,He4)
From Li7
(n,γ)
(d,p)
(t,pn)
He3
He4
(He3,2p)
(He3,pn)
(t,2n)
(p,γ)
(d,n)
(p,γ)
(d,n)
(d,γ)
(n,p)
To Li7
(He4,γ)
p
(n,γ)
d
(d,p)
(n,γ)
t
(ν,e-)
(e+,ν)
free decay
(p,γ)
n
η = 5.8x10-10

Inflation

Alan Guth





Generation of the baryon asymmetry

Sakharov conditions (1967)

Andrei Sakharov

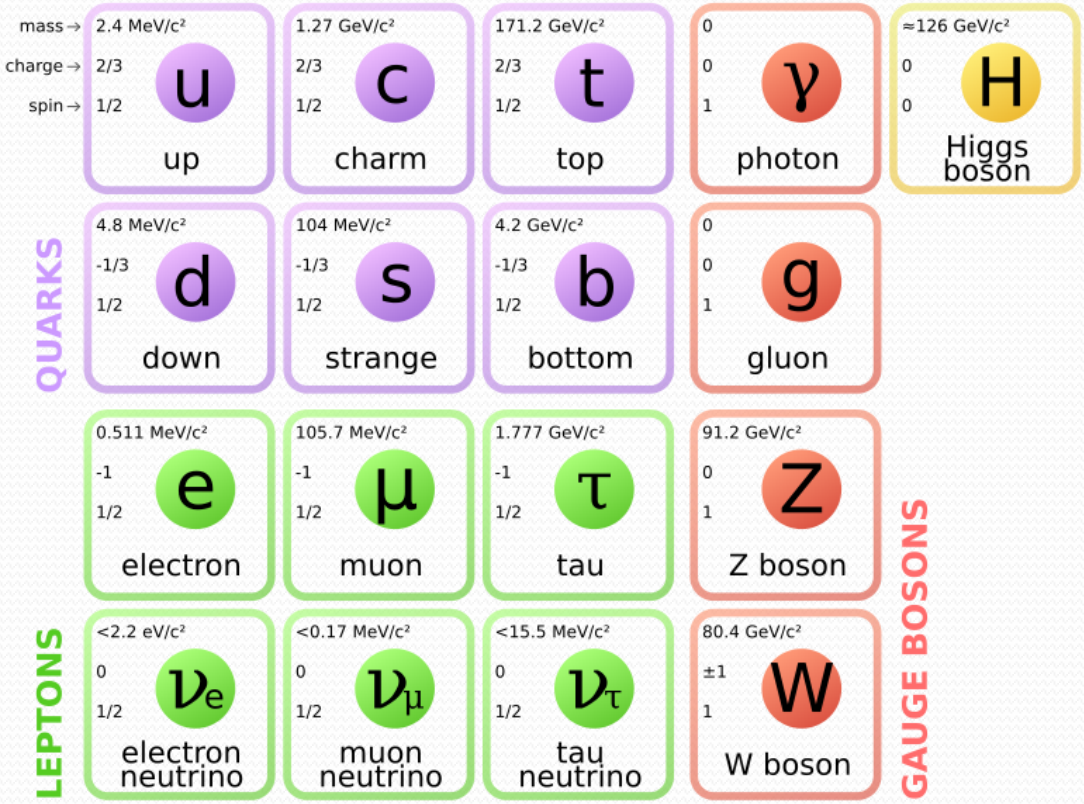
- Violation of baryon number
- C- and CP-violation
- Deviation from equilibrium

Standard model (1967)

Sheldon Glashow

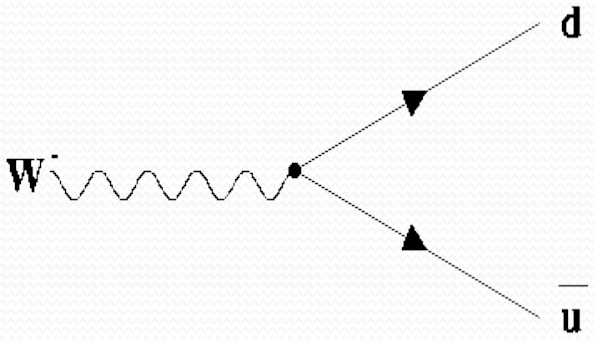
Steven Weinberg

Abdus Salam



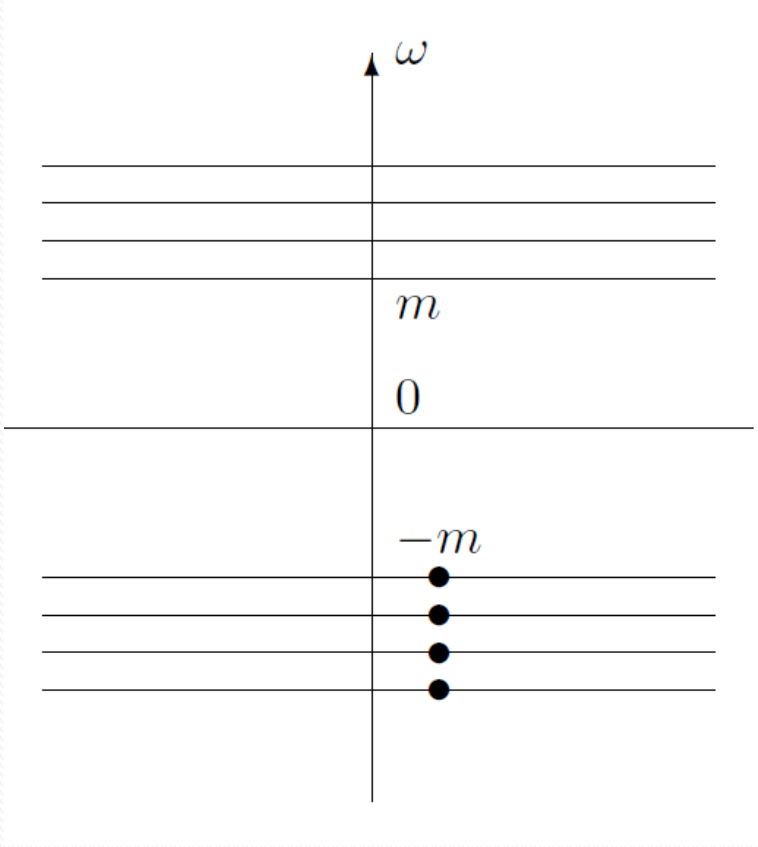
Baryon number violation ?

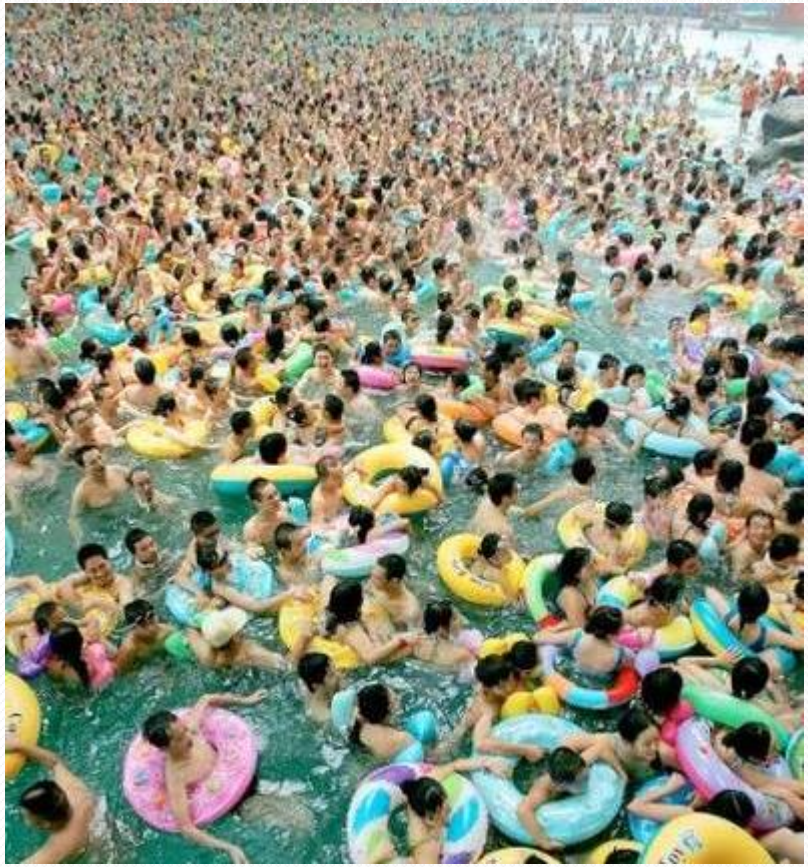
$$
\begin{aligned}
\mathcal{L} \;=\; & -\frac{1}{4}B_{\mu\nu}B^{\mu\nu} - \frac{1}{8}tr(\mathbf{W}_{\mu\nu}\mathbf{W}^{\mu\nu}) - \frac{1}{2}tr(\mathbf{G}_{\mu\nu}\mathbf{G}^{\mu\nu}) \\
& + (\bar{\nu}_L, \bar{e}_L)\,\tilde{\sigma}^{\mu} i D_{\mu} \begin{pmatrix} \nu_L \\ e_L \end{pmatrix} + \bar{e}_R \sigma^{\mu} i D_{\mu} e_R + \bar{\nu}_R \sigma^{\mu} i D_{\mu} \nu_R + (\text{h.c.}) \\
& - \frac{\sqrt{2}}{v}\left[(\bar{\nu}_L, \bar{e}_L)\,\phi M^{e} e_R + \bar{e}_R \bar{M}^{e} \bar{\phi} \begin{pmatrix} \nu_L \\ e_L \end{pmatrix} \right] \\
& - \frac{\sqrt{2}}{v}\left[(-\bar{e}_L, \bar{\nu}_L)\,\phi^{*} M^{\nu} \nu_R + \bar{\nu}_R \bar{M}^{\nu} \phi^{T} \begin{pmatrix} -e_L \\ \nu_L \end{pmatrix} \right] \\
& + (\bar{u}_L, \bar{d}_L)\,\tilde{\sigma}^{\mu} i D_{\mu} \begin{pmatrix} u_L \\ d_L \end{pmatrix} + \bar{u}_R \sigma^{\mu} i D_{\mu} u_R + \bar{d}_R \sigma^{\mu} i D_{\mu} d_R + (\text{h.c.}) \\
& - \frac{\sqrt{2}}{v}\left[(\bar{u}_L, \bar{d}_L)\,\phi M^{d} d_R + \bar{d}_R \bar{M}^{d} \bar{\phi} \begin{pmatrix} u_L \\ d_L \end{pmatrix} \right] \\
& - \frac{\sqrt{2}}{v}\left[(-\bar{d}_L, \bar{u}_L)\,\phi^{*} M^{u} u_R + \bar{u}_R \bar{M}^{u} \phi^{T} \begin{pmatrix} -d_L \\ u_L \end{pmatrix} \right] \\
& + \overline{(D_{\mu}\phi)} D^{\mu}\phi - m_h^2 [\bar{\phi}\phi - v^2/2]^2 / 2v^2 .
\end{aligned}
$$



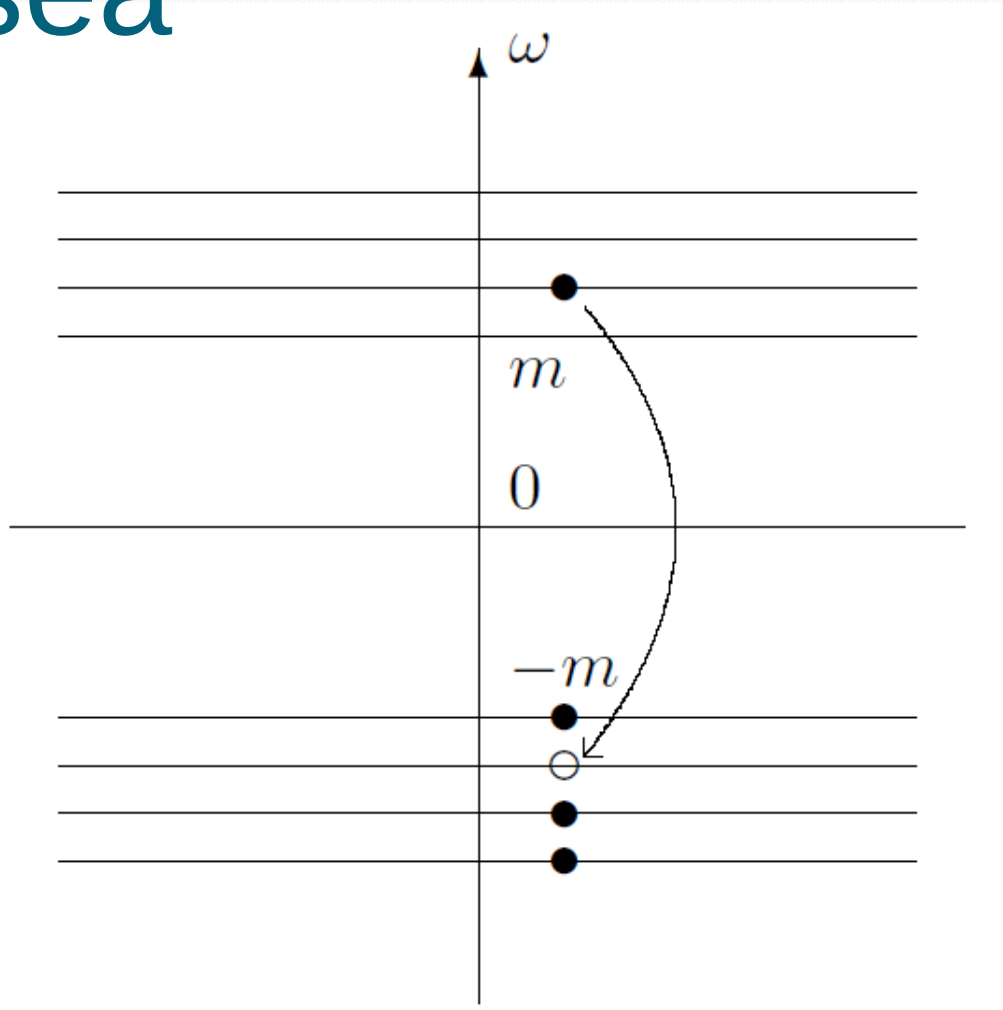

I ♥
80s
1980

Dirac sea





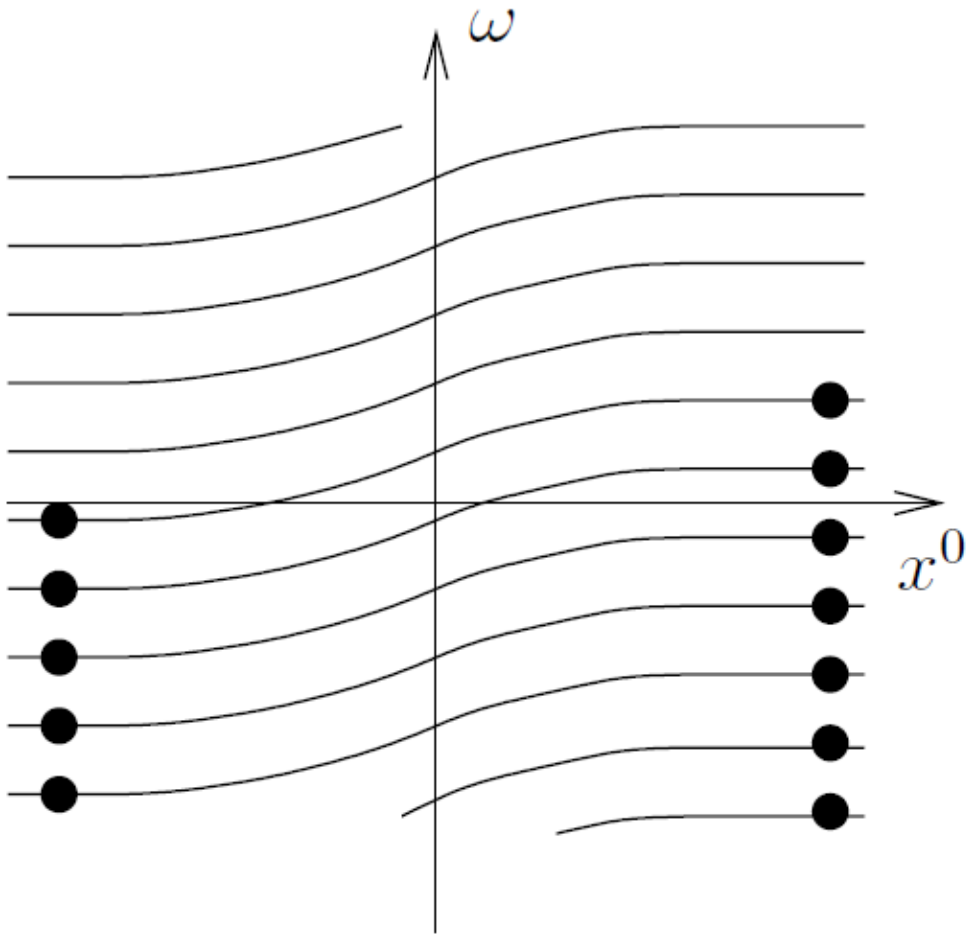
Dirac sea



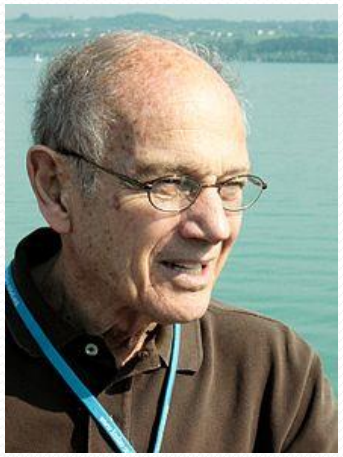
Sphalerons (1984)

Frans Klinkhamer

Nick Manton

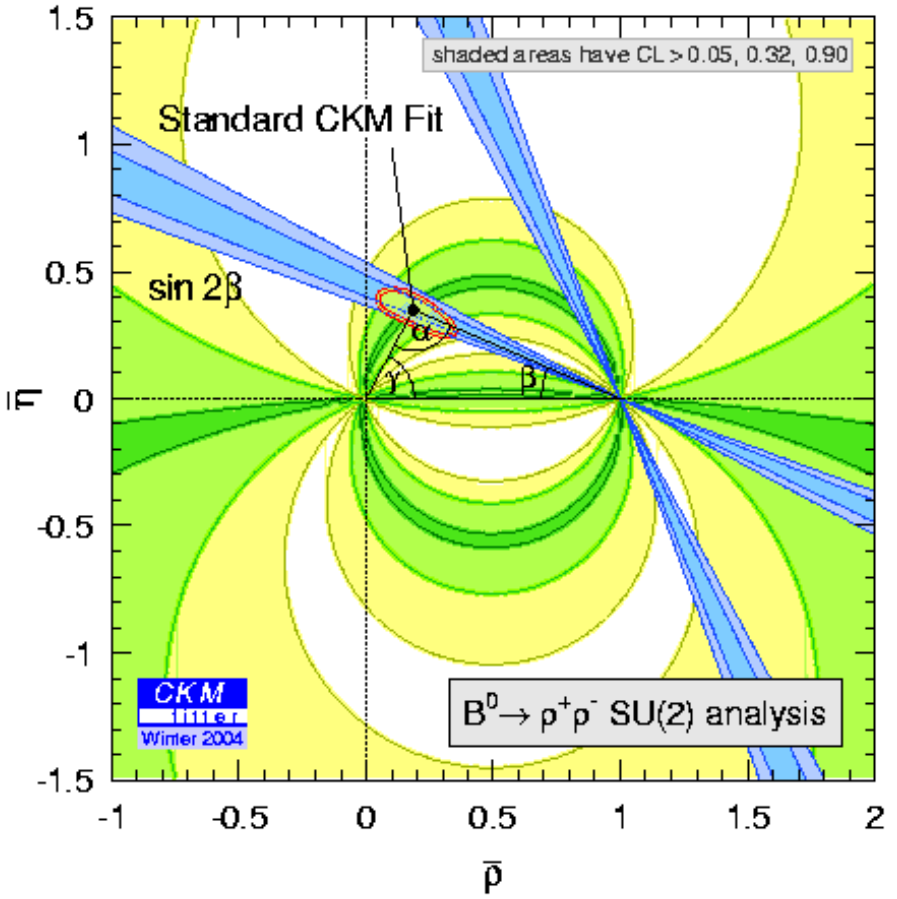


CP-violation

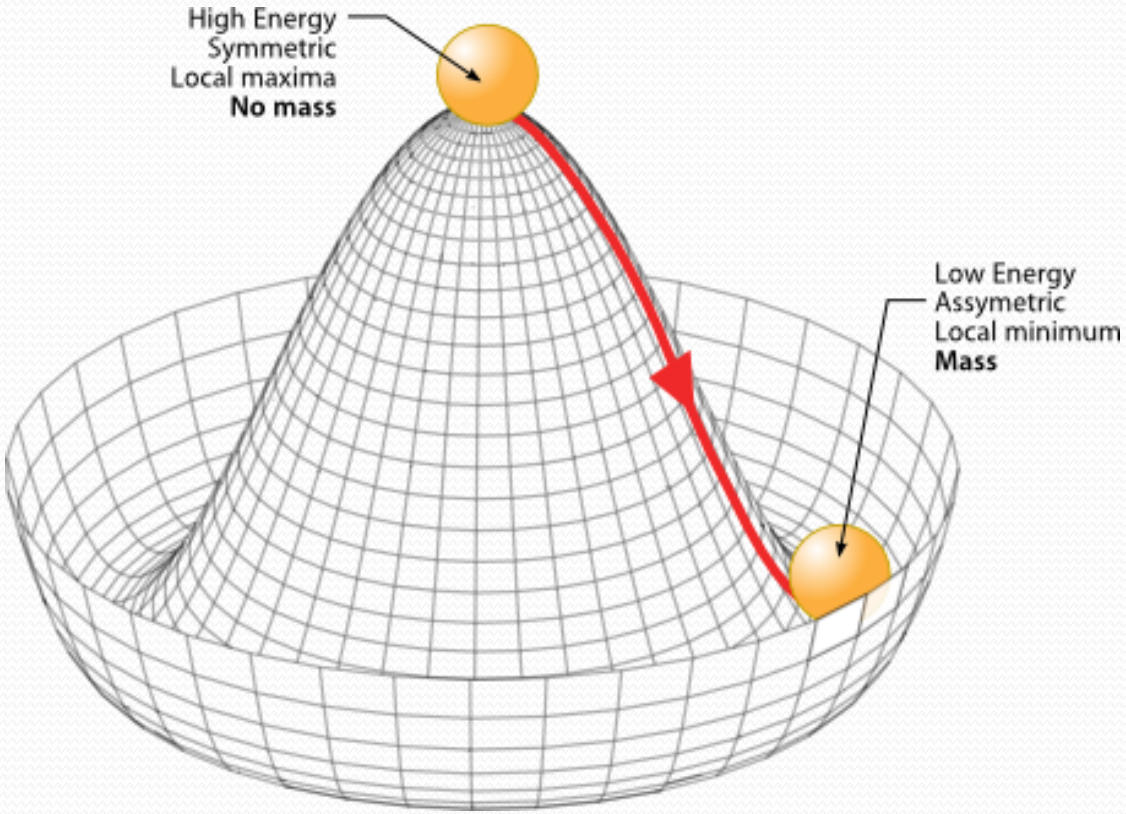


James Cronin

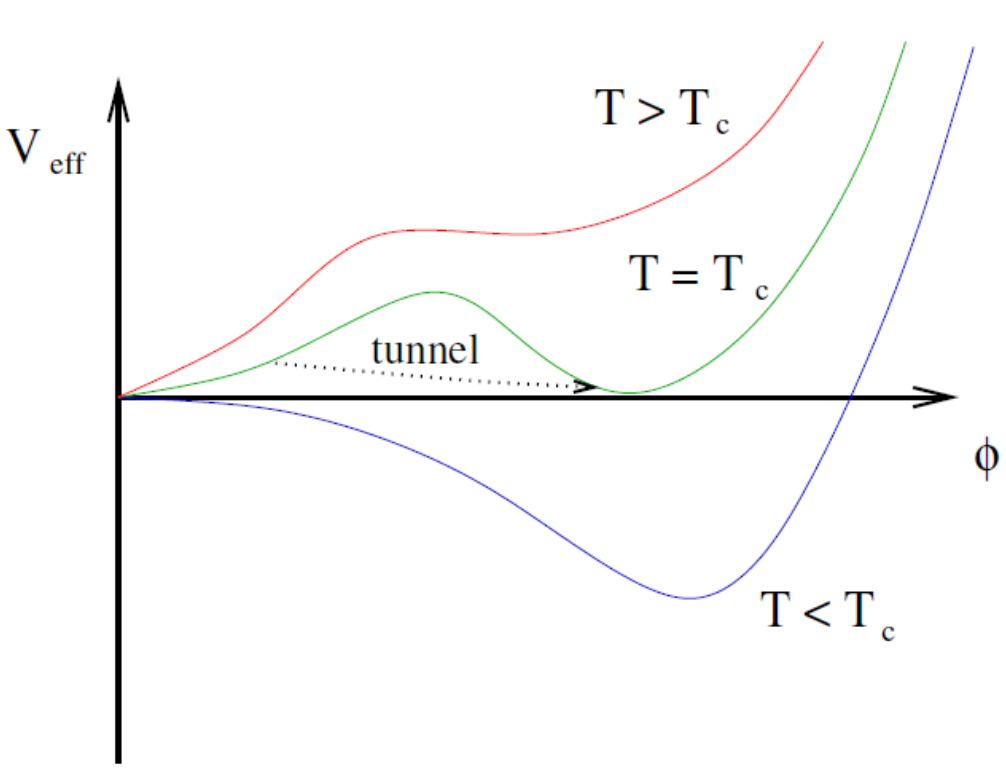
Val Fitch

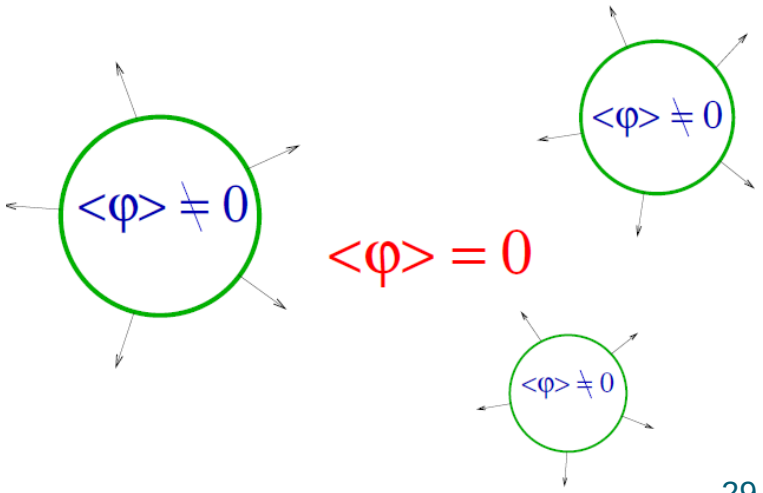


Deviation from equilibrium



First order transition ?



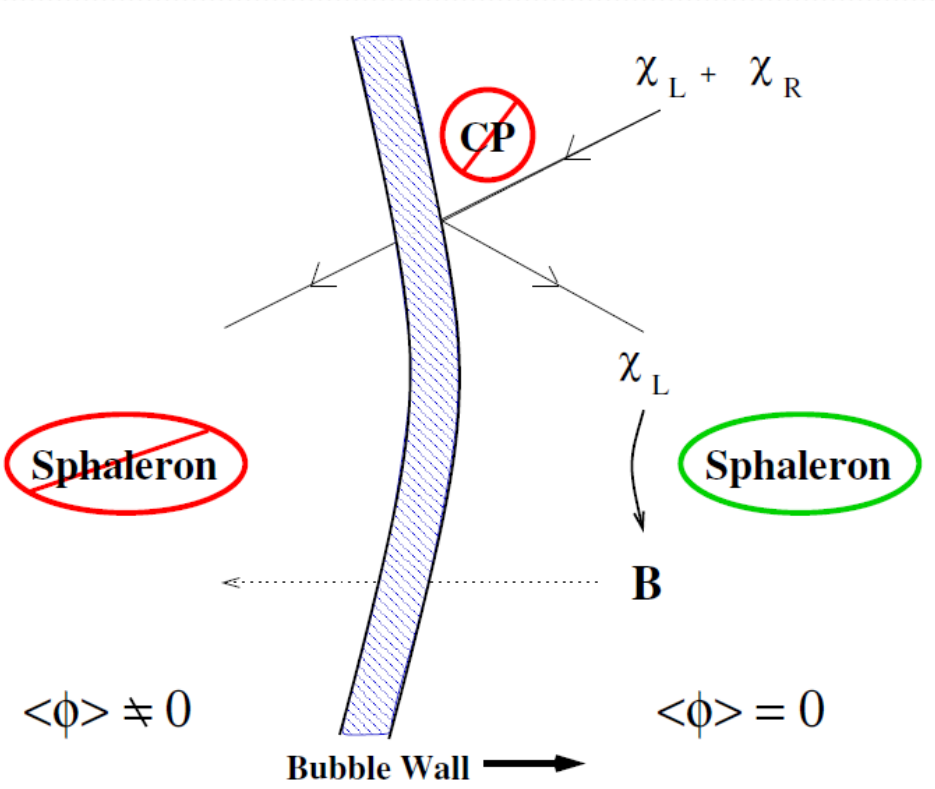


Electroweak baryogenesis (1985)

Valery Rubakov

Vadim Kuzmin

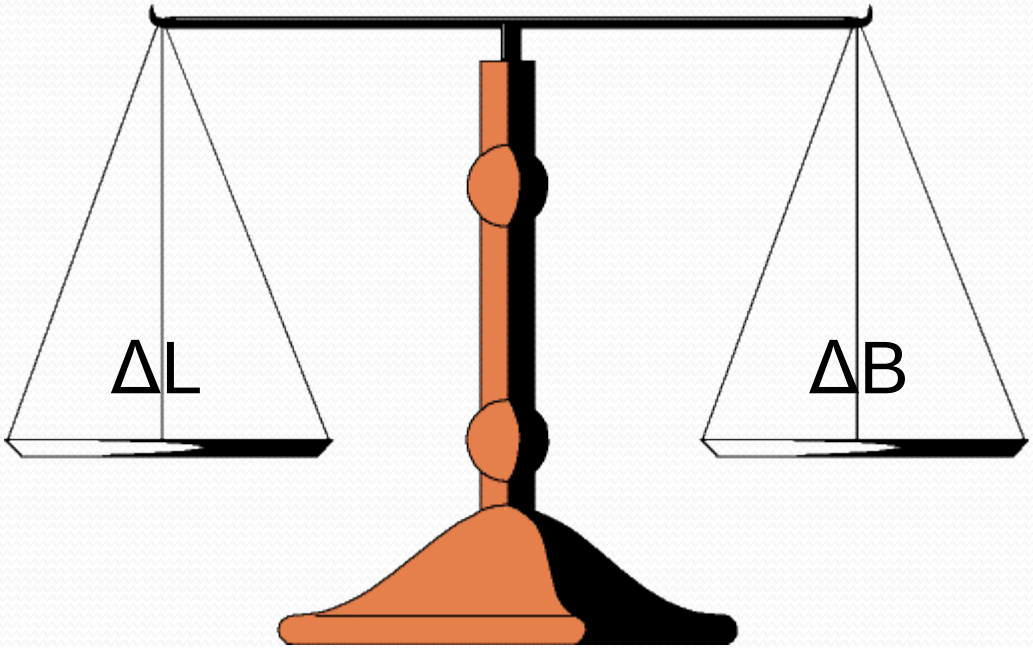
Mikhail Shaposhnikov



B-L = const.

Quarks	u up	c charm	t top
	d down	s strange	b bottom
Leptons	ν_e e neutrino	ν_μ μ neutrino	ν_τ τ neutrino
	e electron	μ muon	τ tau

sphaleron scales

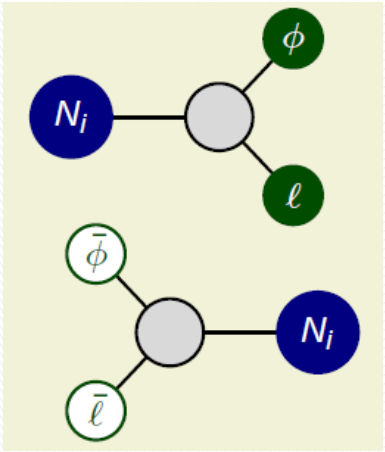


B-L=const.

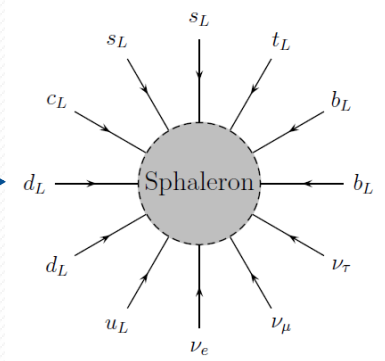
Leptogenesis (1986)

Masataka Fukugita

Tsutomu Yanagida



→ ΔL →

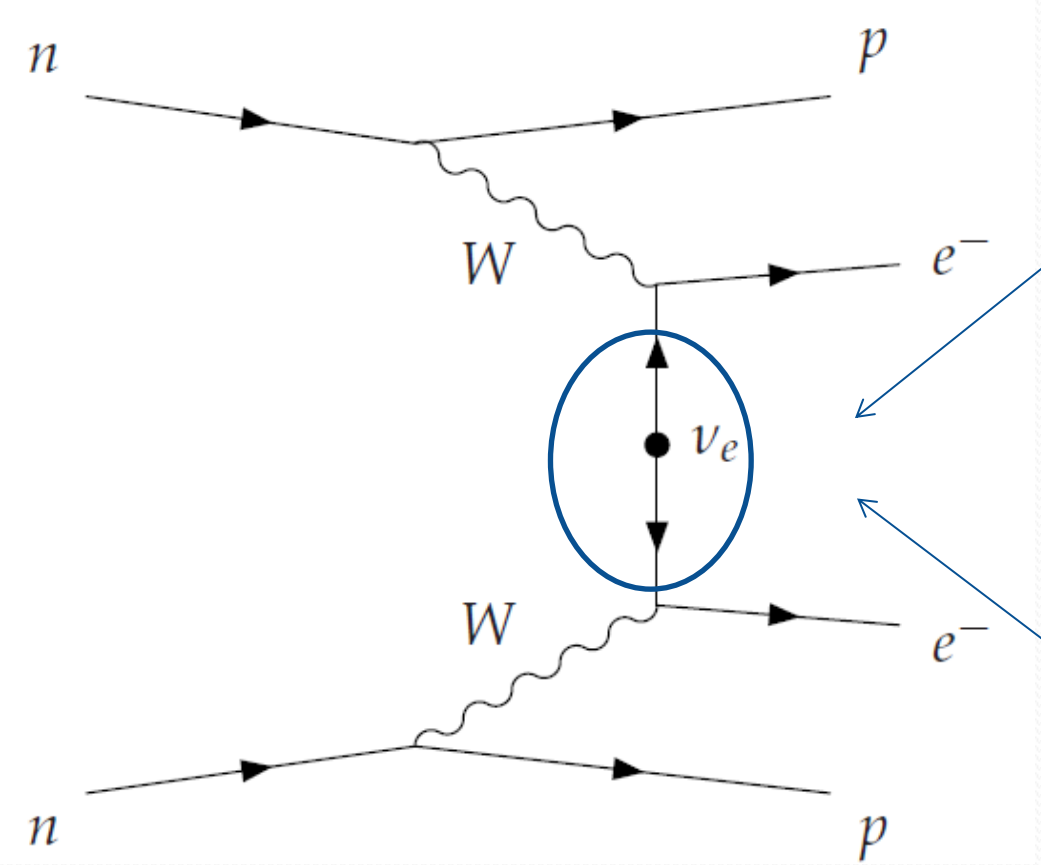


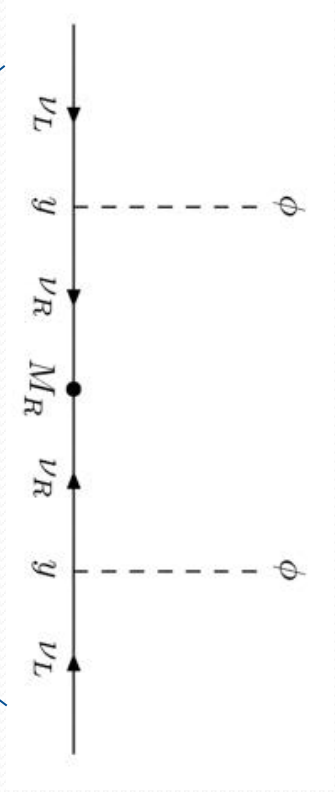
↓

ΔB

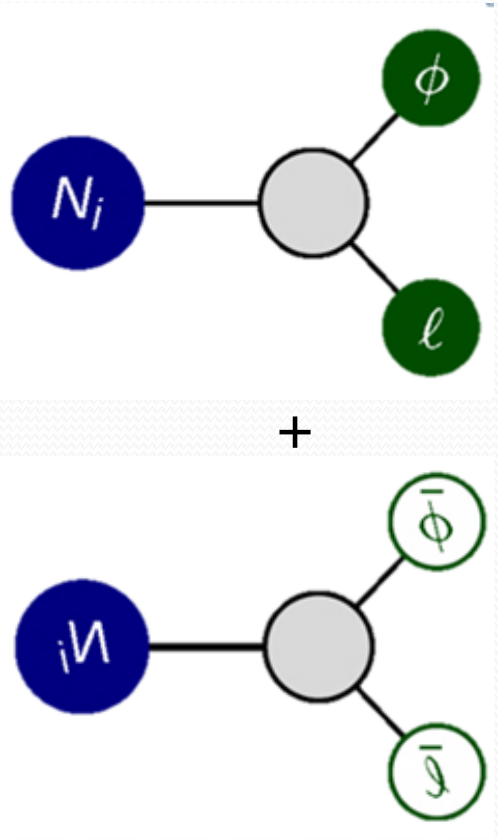
↓

Lepton number violation





CP-violation



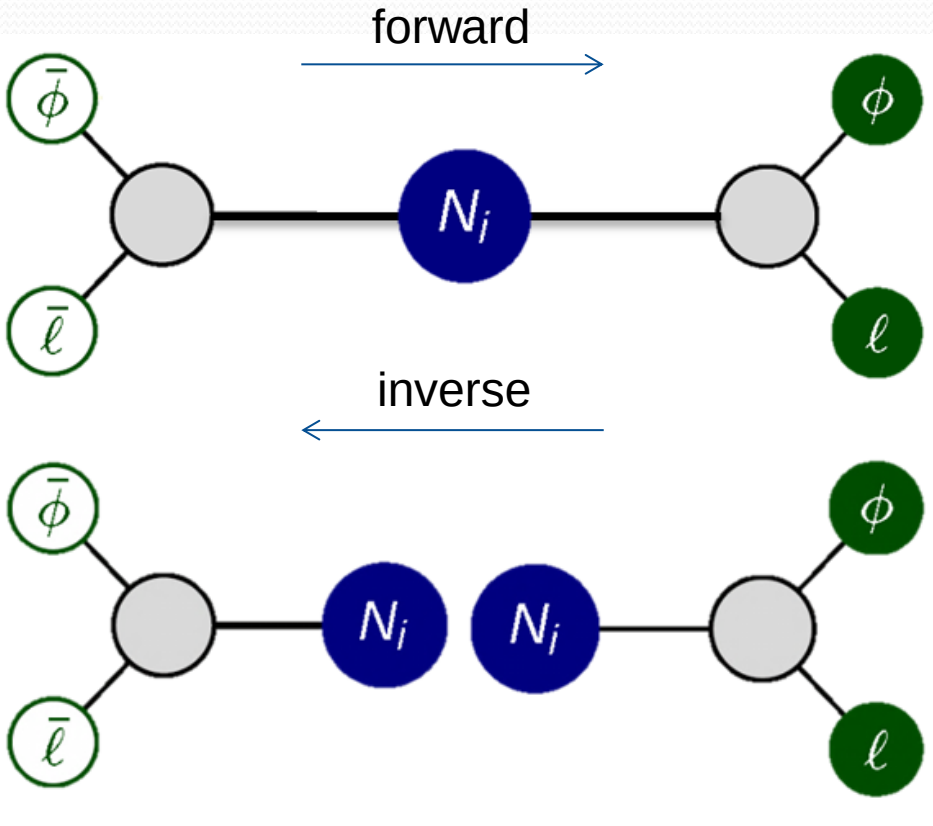
$$\Gamma(X \to Y_L + B_L) = \Gamma(\overline{X} \to \overline{Y}_R + \overline{B}_R)$$

$$\Gamma(X \to Y_R + B_R) = \Gamma(\overline{X} \to \overline{Y}_L + \overline{B}_L)$$

$$\Gamma(X \to Y_L + B_L) + \Gamma(X \to Y_R + B_R) =$$

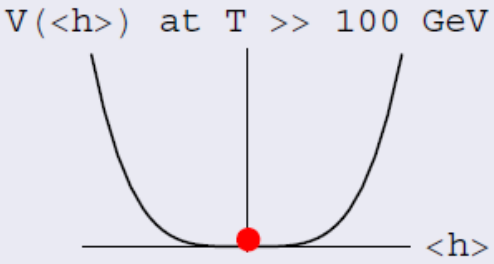
$$\Gamma(\overline{X} \to \overline{Y}_R + \overline{B}_R) + \Gamma(\overline{X} \to \overline{Y}_L + \overline{B}_L)$$

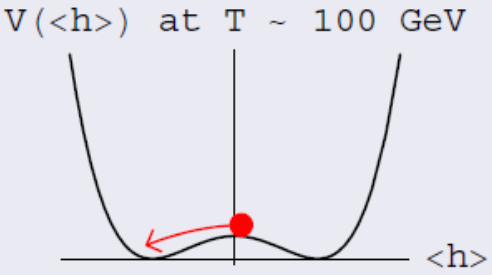
Deviation from equilibrium



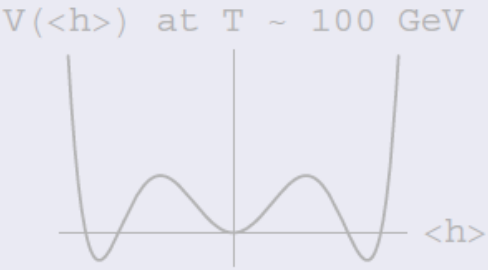
LHC (2012)

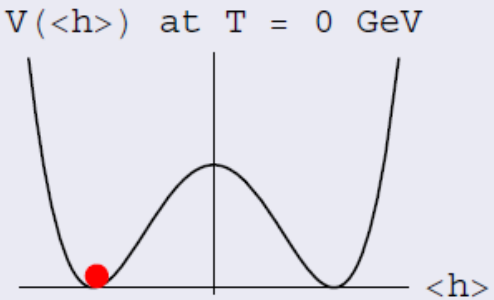
m_H=126 GeV



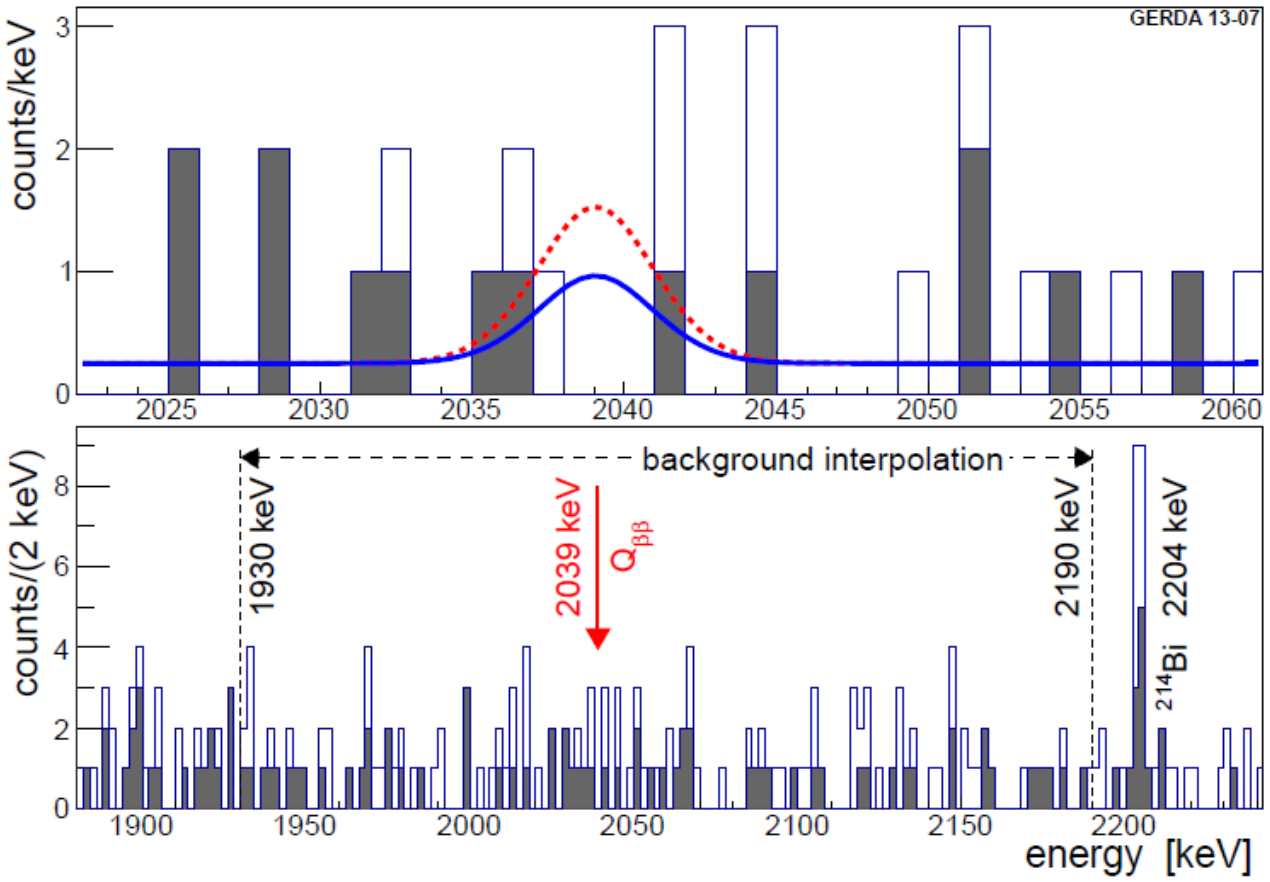


cross-over
e.g. SM





GERDA (2013)


GERDA 13-07
counts/keV
counts/(2 keV)
background interpolation
1930 keV
2039 keV
$Q_{\beta\beta}$
2190 keV
^{214}Bi 2204 keV
energy [keV]

Summary

- The Universe is baryonically asymmetric
- SM contains all ingredients but the generated asymmetry is way too small
- An option are SUSY-like extensions combined with electroweak baryogenesis
- Adding heavy Majorana neutrinos we can explain neutrino masses and the baryon asymmetry


(c) mein-tegernsee.de

See-saw mechanism