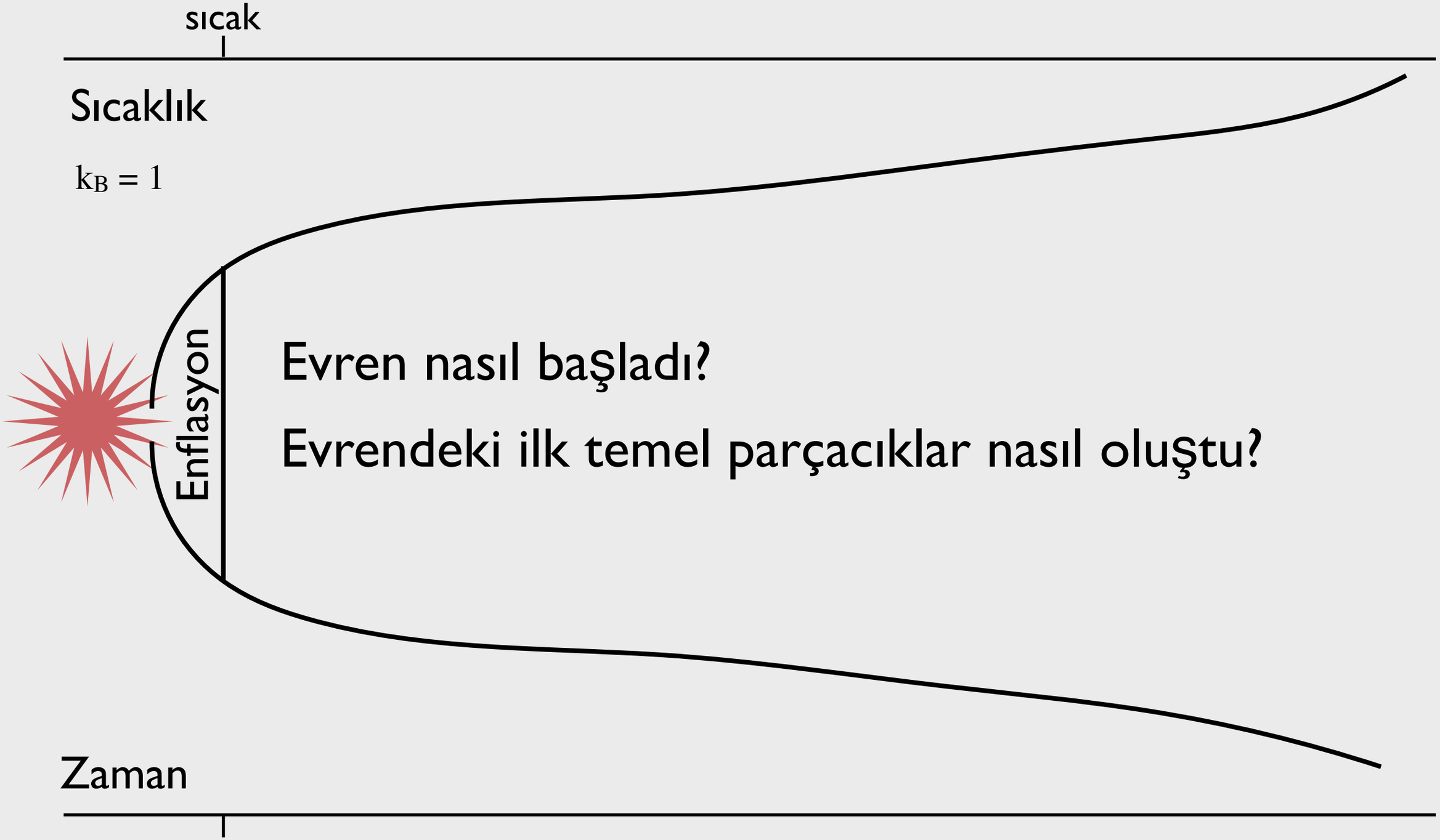
Bir varmış bir yokmuş: Evrendeki antimadde nereye gitti?

Seyda Ipek

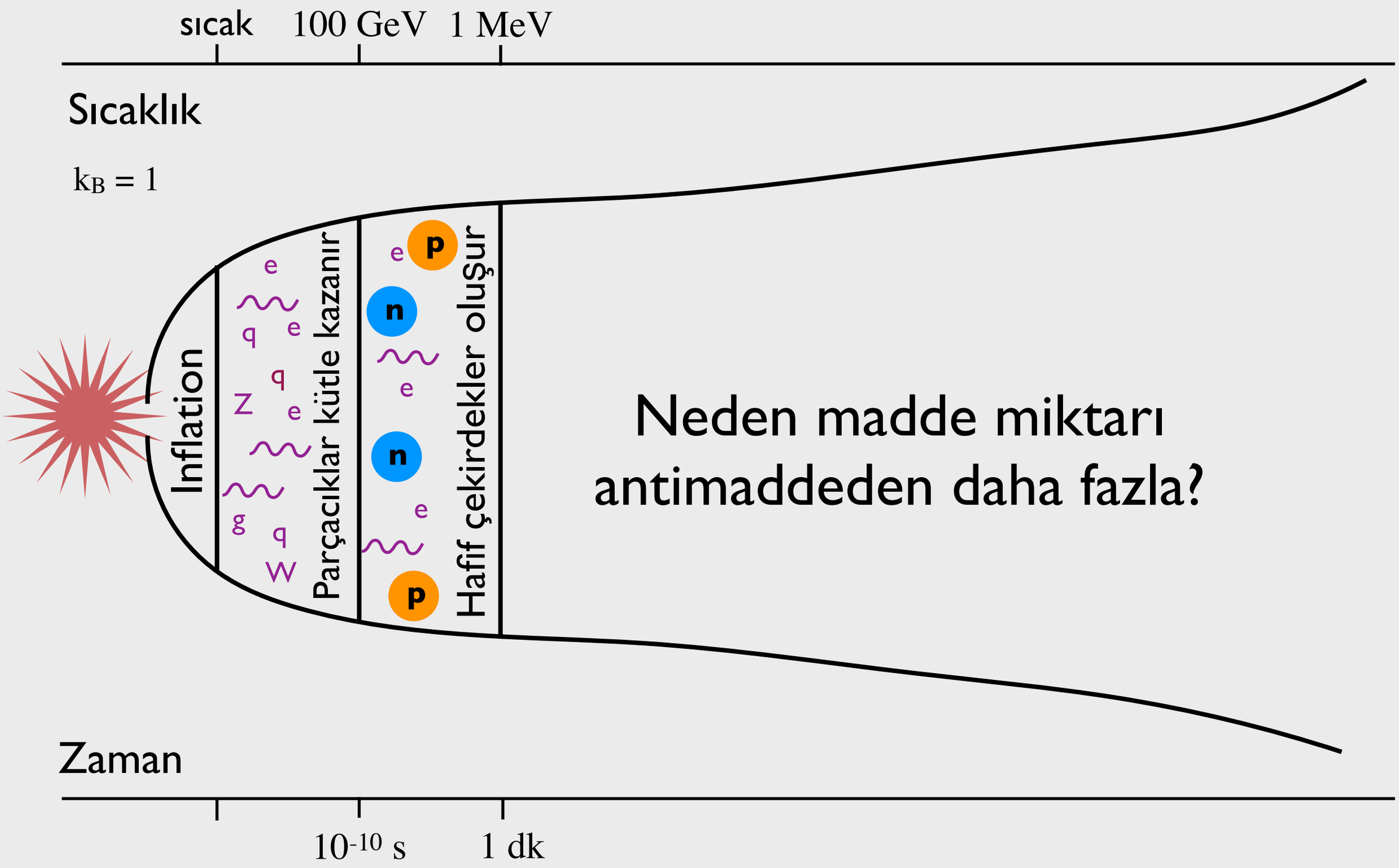
Carleton UNIVERSITY
Canada's Capital University

Evrenimizin kısa tarihi



Evrenimizin kısa tarihi

Evrenimizin kısa tarihi



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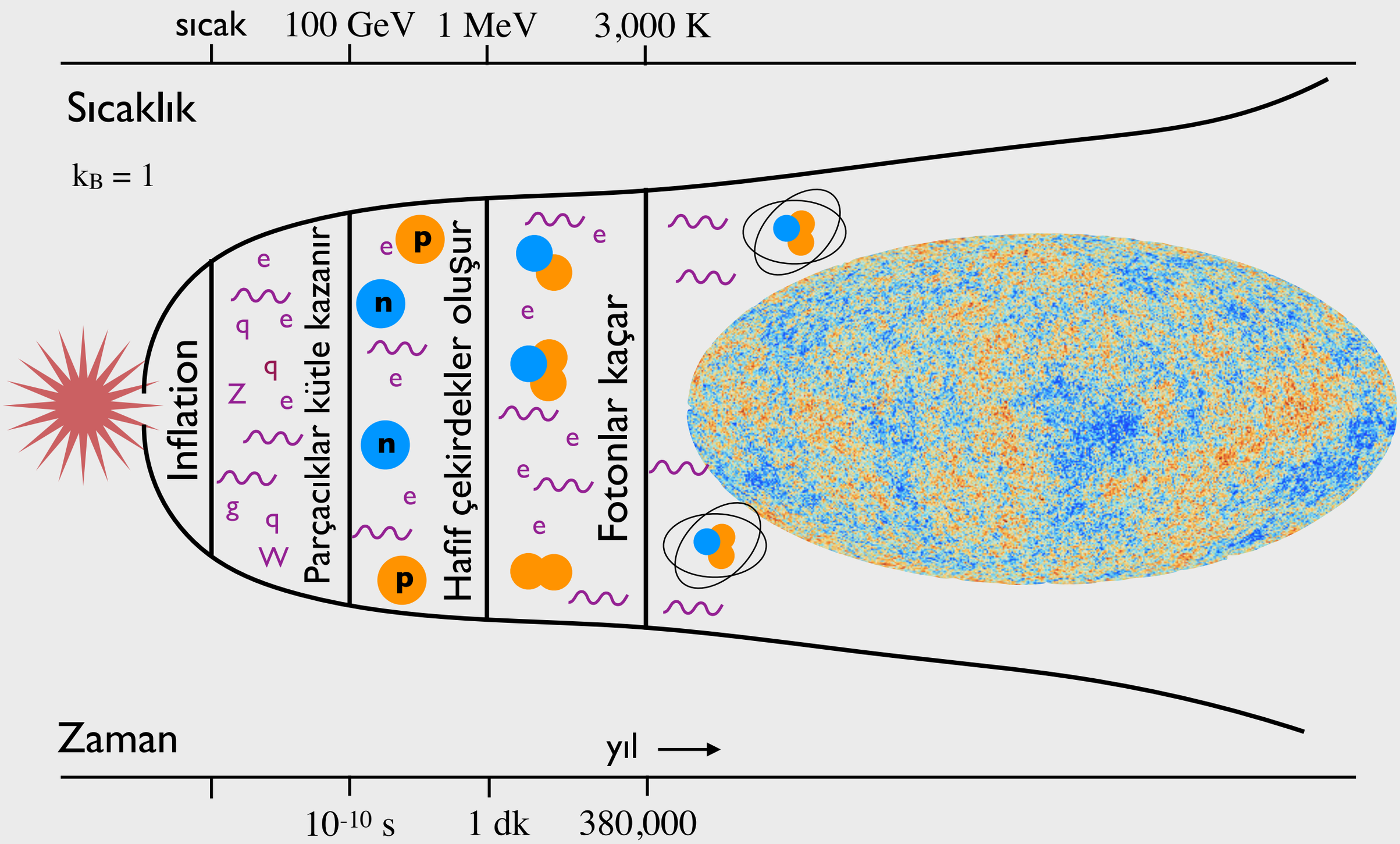
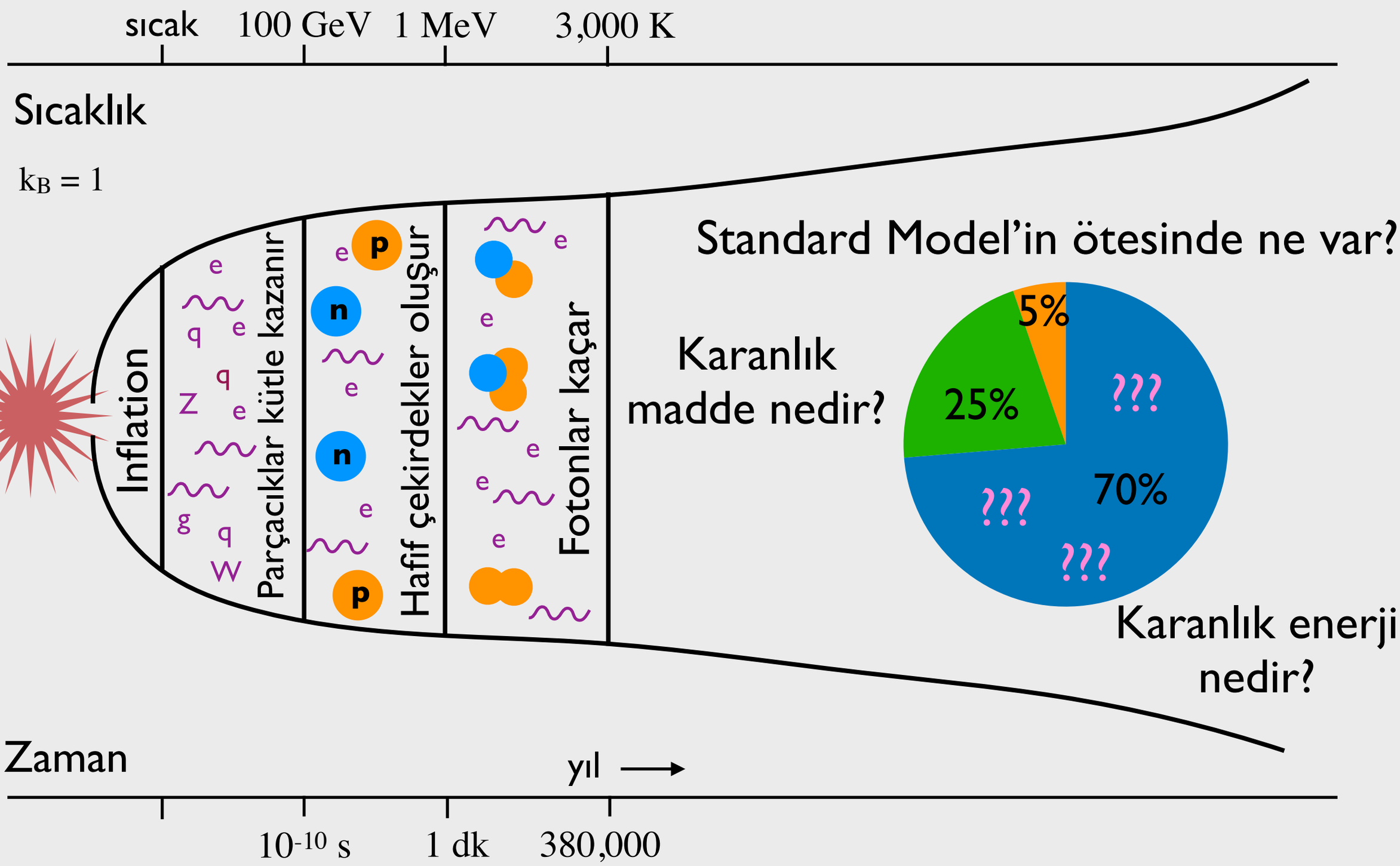
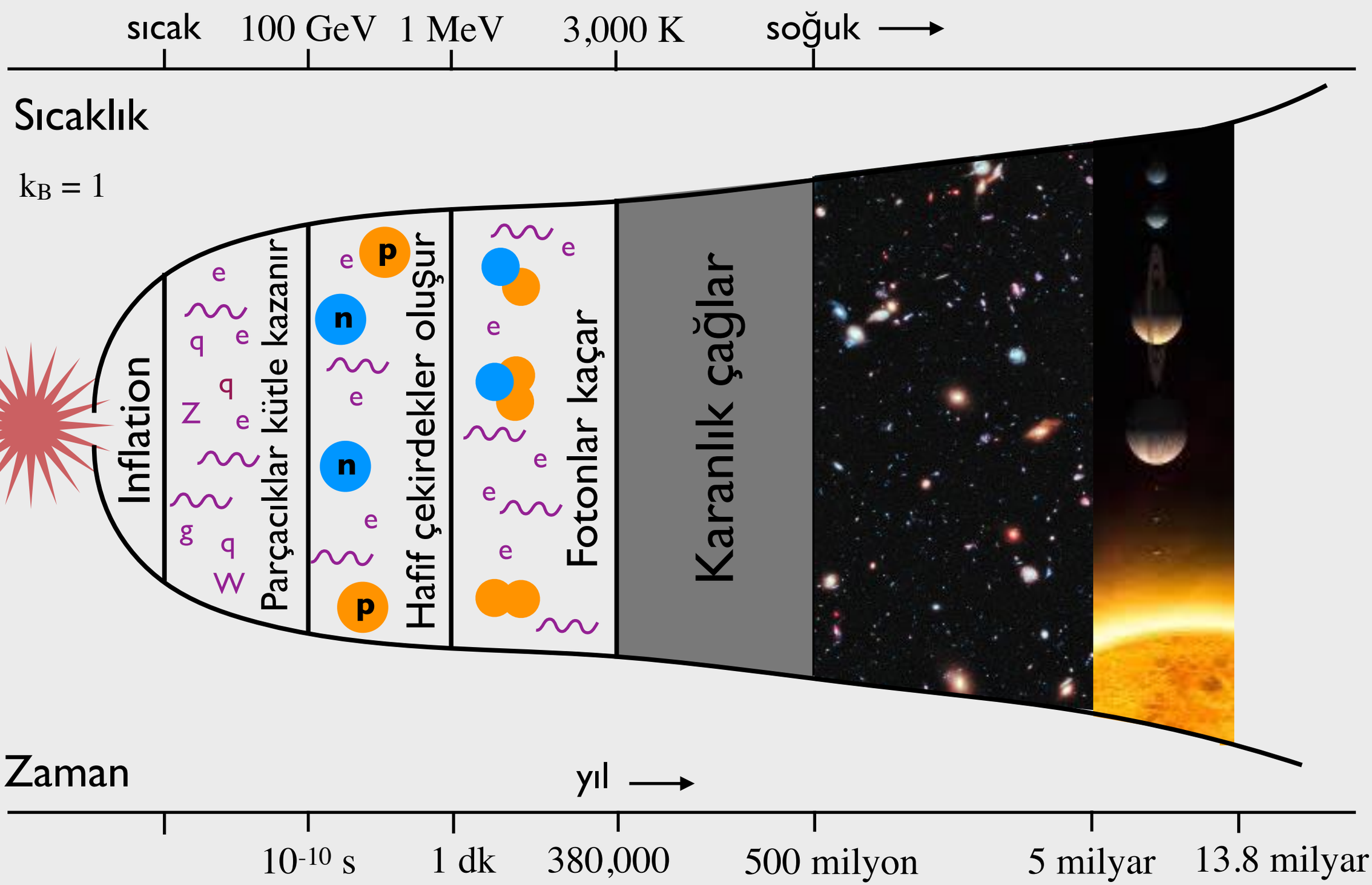


Evrenimizin kısa tarihi

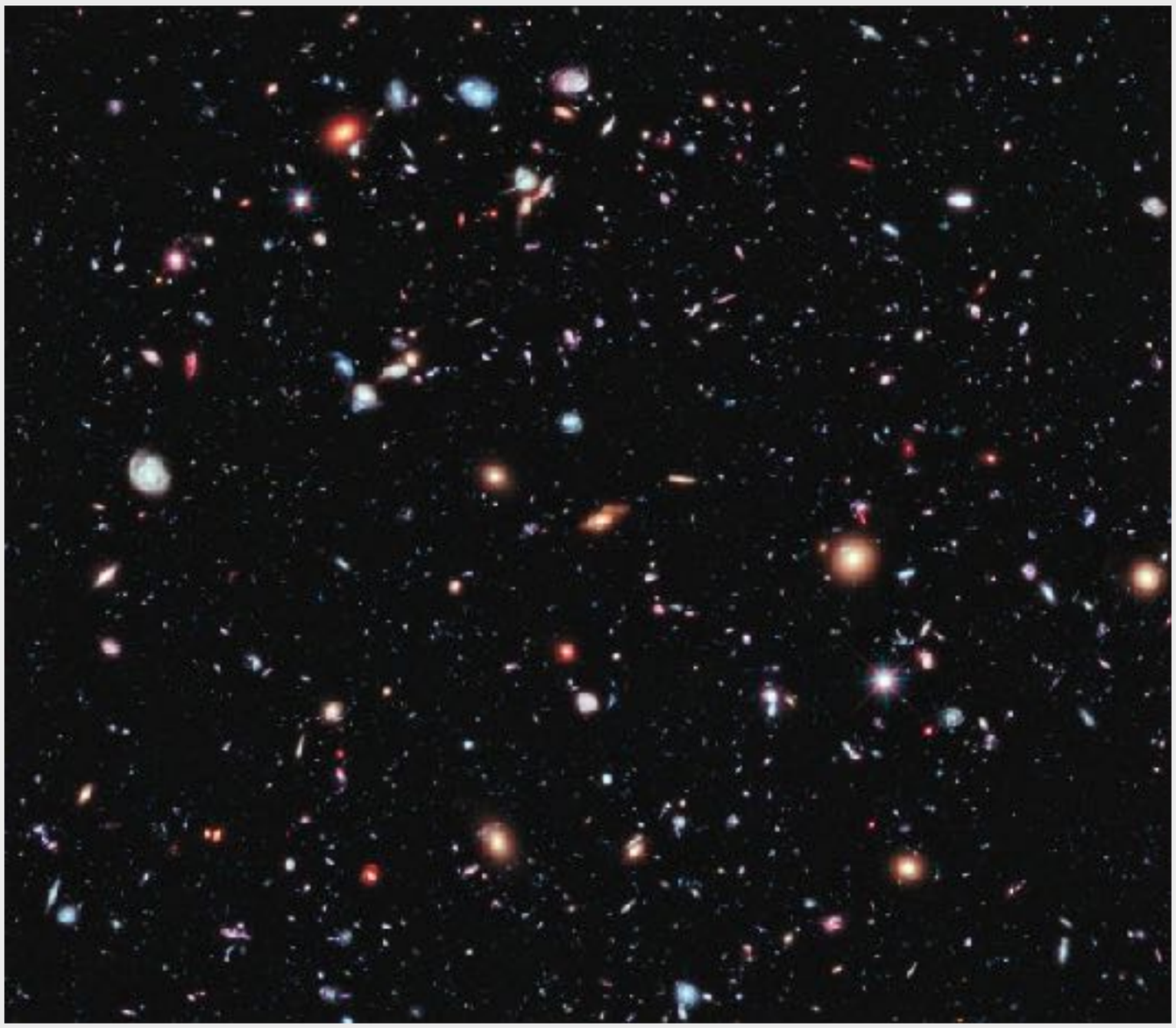


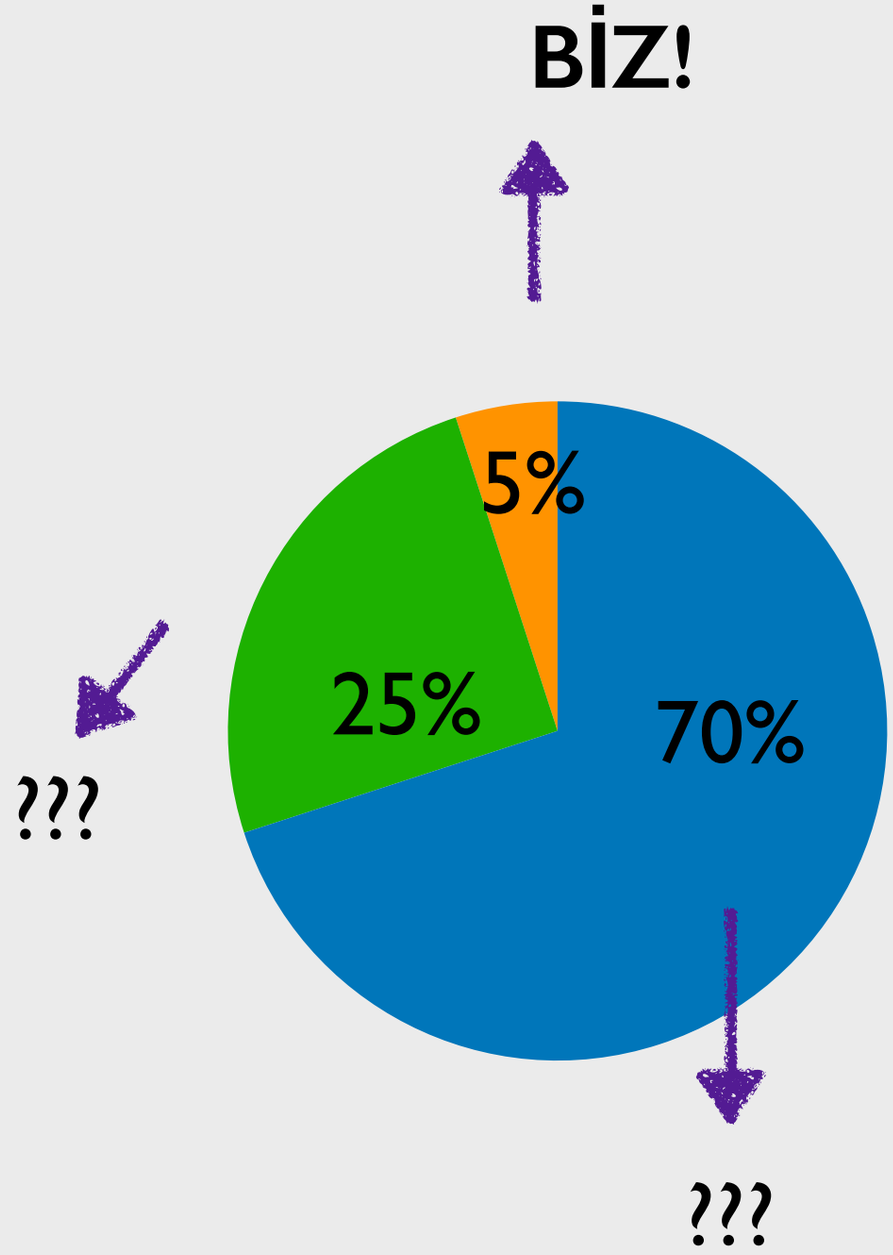
Evrenimizin kısa tarihi



Evrenin içinde ne var?

Evrenimiz (birkaç yüz milyon yaşında)
image from Hubble Space Telescope

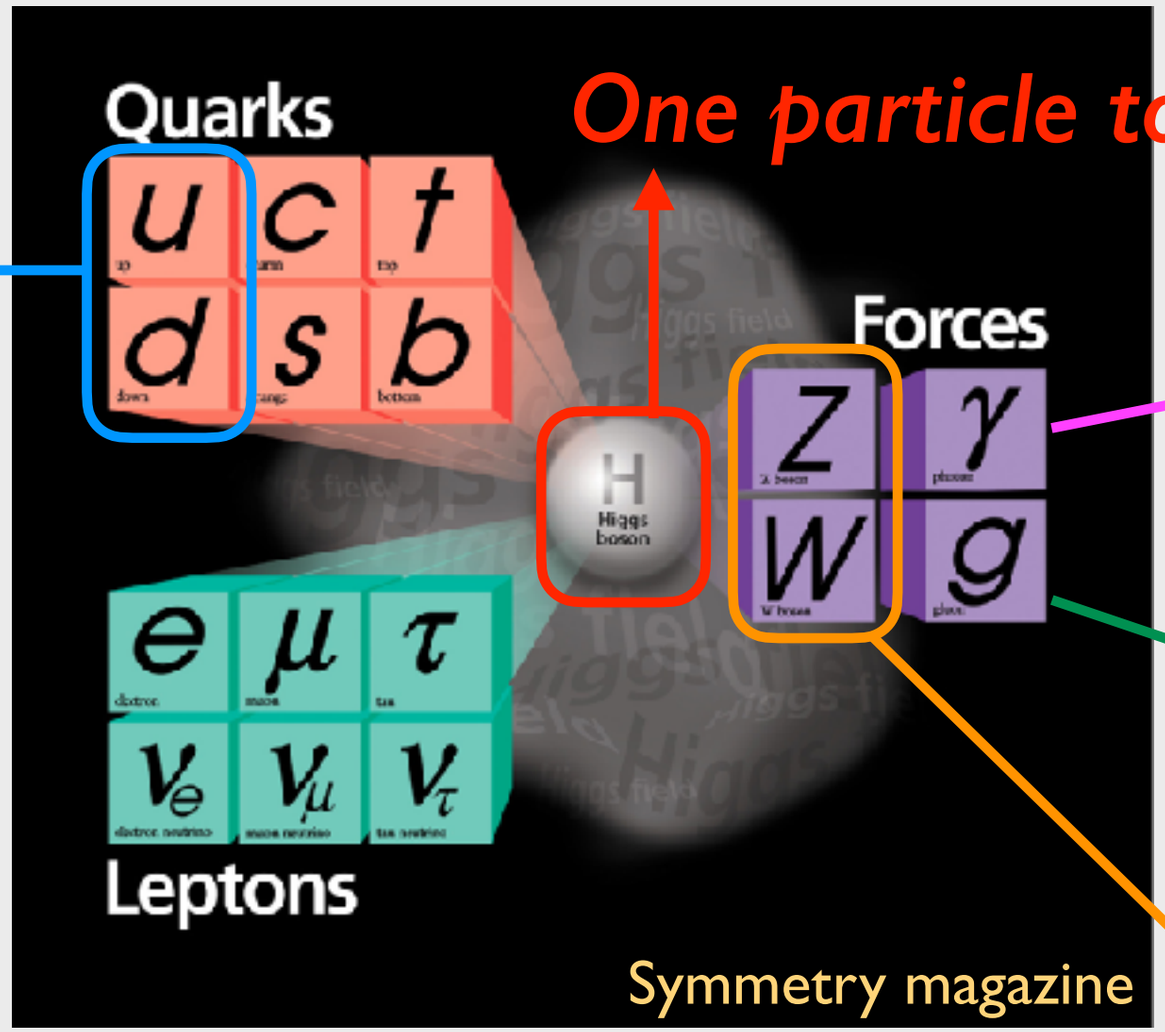




Normal madde nedir?

Parçacık fiziğinin Standart Modeli (SM) tarafından anlatılan temel parçacıklar

proton ve nötronları oluşturur



Elektromanyetik kuvvet

Güçlü nükleer kuvvet

Zayıf nükleer kuvvet

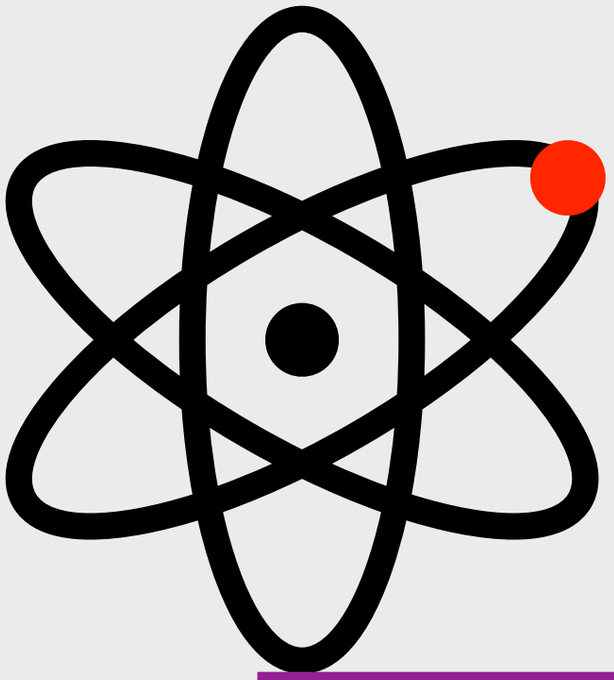
Yerçekimi???

“Antimadde” nedir?

proton + elektron

=

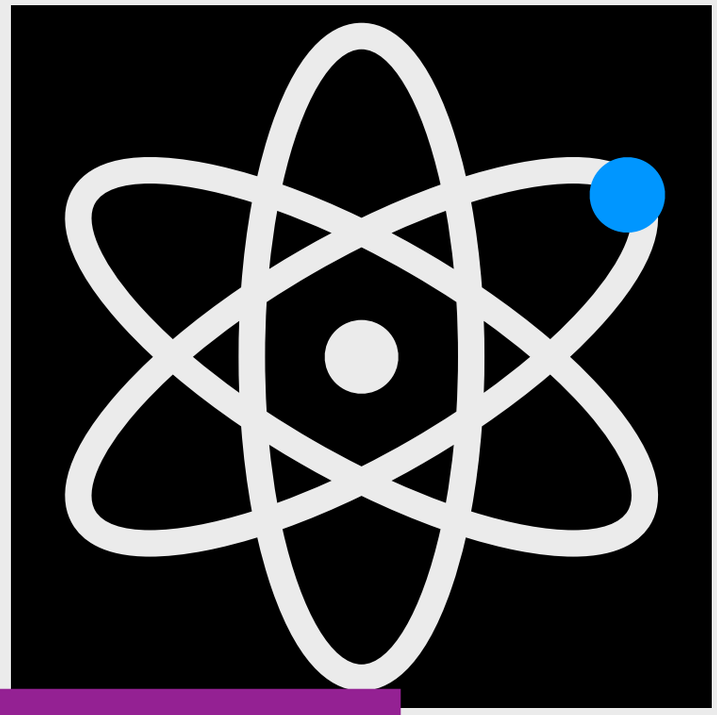
hidrojen



anti-proton + positron

=

anti-hidrojen

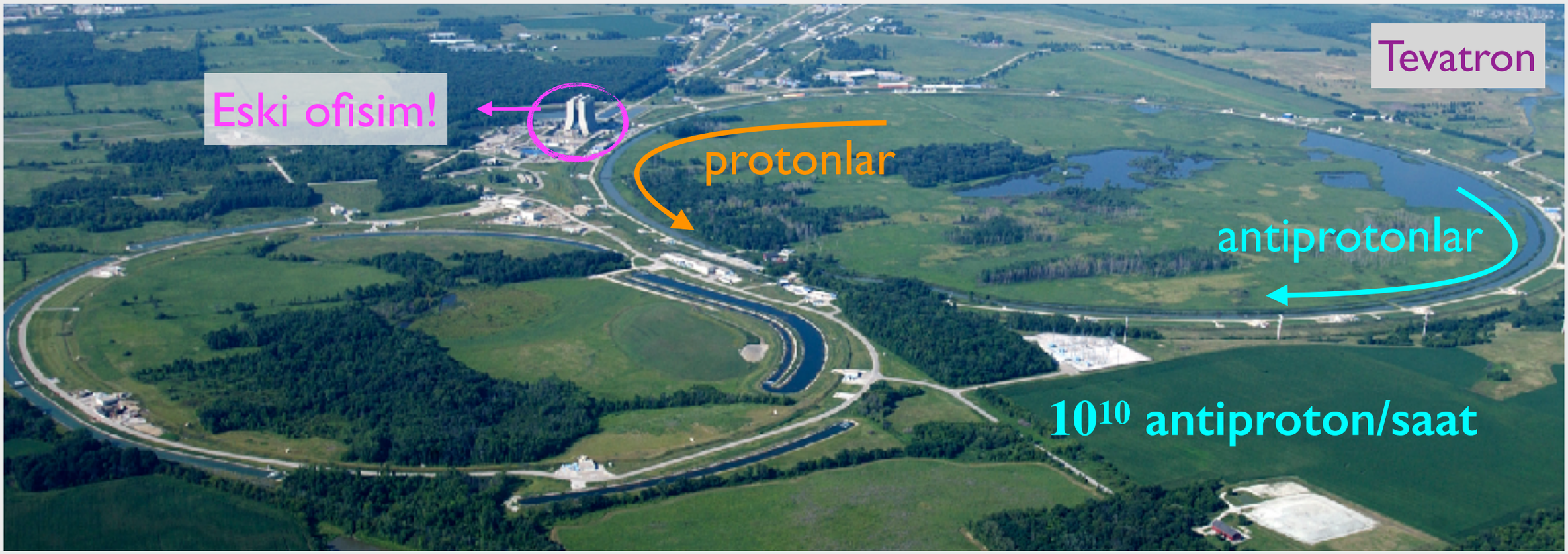


aynı
kütle

zıt
kuantum yükler

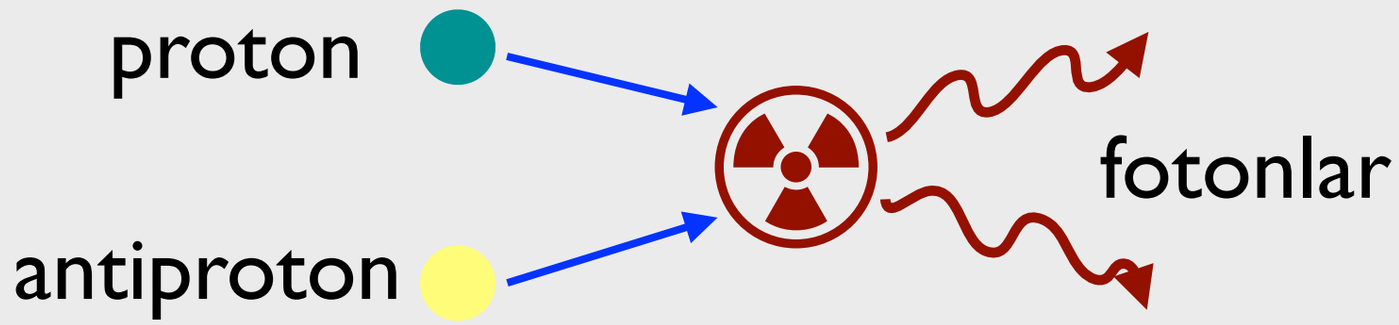
Antimadde normal bir şey

Fermilab'da yüksek miktarda antiproton üretilmekteydi

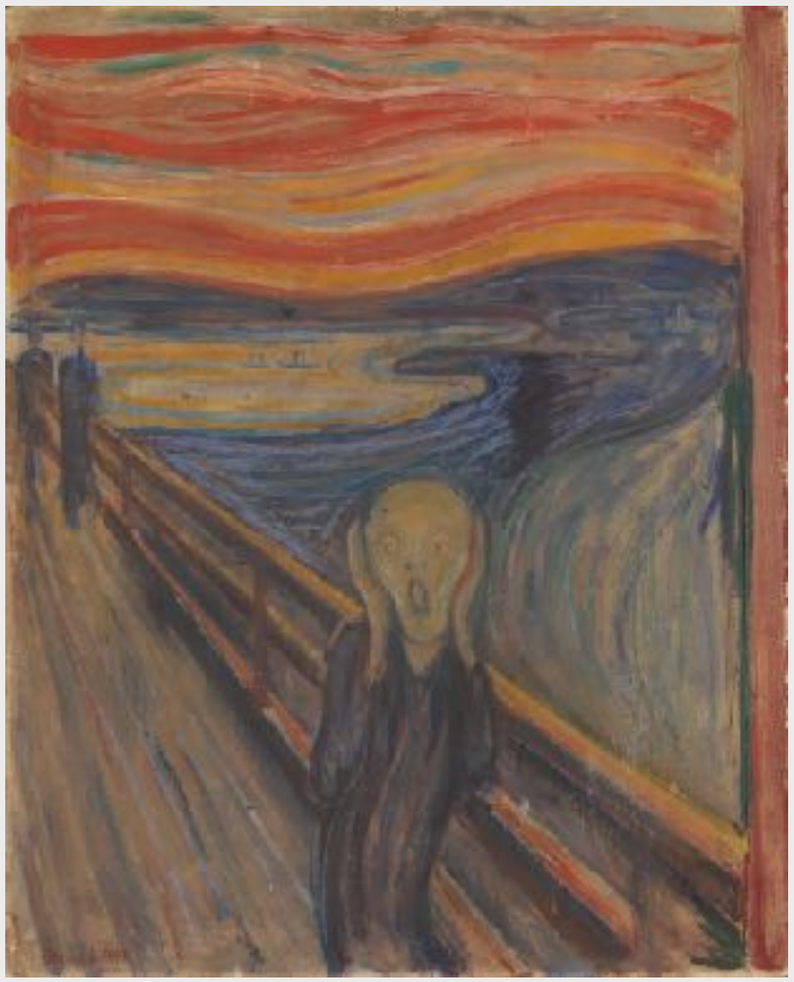


Büyük Hadron Çarpıştırıcısı (LHC @CERN)
hala çok miktarda antimadde üretiyor!

Evrenimizde hiç antimadde yok



madde ve antimadde biraraya geldiğinde birbirlerini yok ederler



The Scream - Edvard Munch

ÇEVREMİZDE ANTİMADDE OLSAYDI BURADA OLMAZDIK!!!

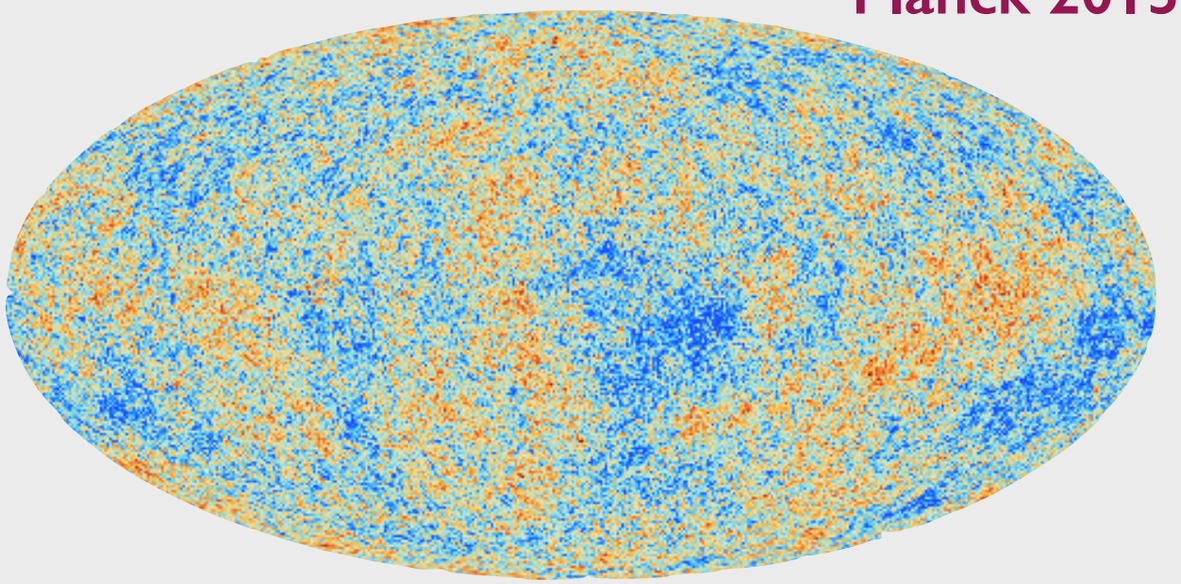
Ama buradayız…

Madde—Antimadde Asimetrisi sayesinde!

Evrenin Madde Asimetrisi

Kozmik Mikrodalga Arkaplanı

Planck 2015



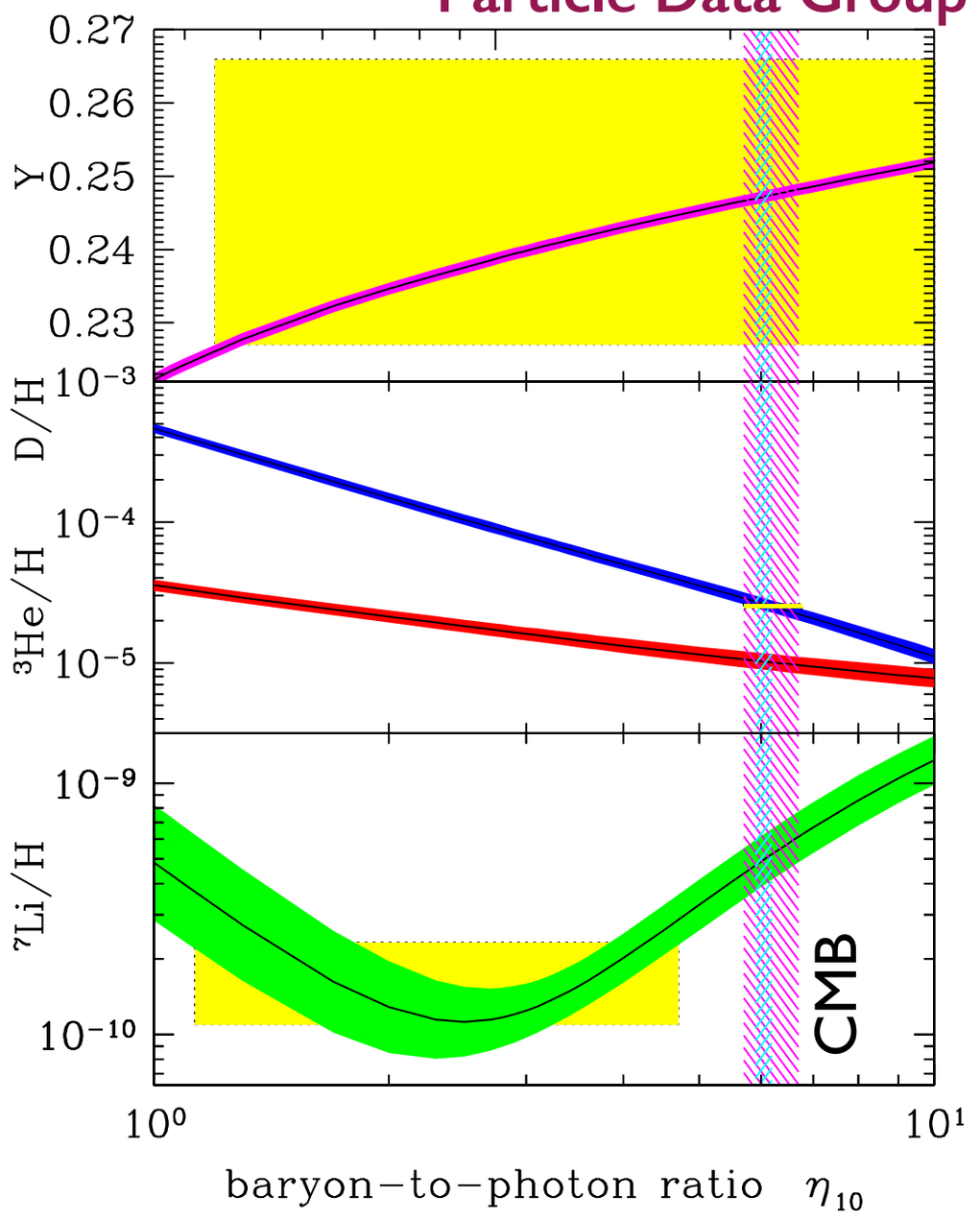
Baryon-foton oranı

$$\eta = \frac{n_B - n_{\bar{B}}}{n_\gamma} \simeq 6 \times 10^{-10}$$

İlk oluşan hafif elementler

(Big Bang Nucleosynthesis)

Particle Data Group



Antimadde nasıl kaybolur?

10,000,000,001

kuarklar

10,000,000,000

antikuarklar

Kurallar: Sakharov Koşulları

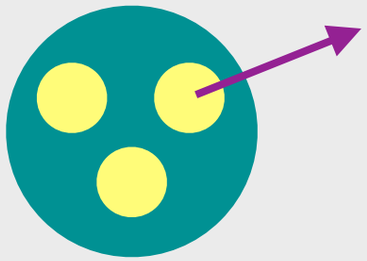
1. Baryon (madde) sayısı korunan bir nicelik olamaz
2. Yük ve Yük-Parite (CP) simetrileri kırılmak zorundadır
3. Termodinamik dengeden uzaklaşmak gerekir

Baryon sayısı ihlali

Bundan sonra daha çok proton ve nötronlardan bahsedeceğiz

Baryon sayısı, spin gibi, kuantum bir özellik

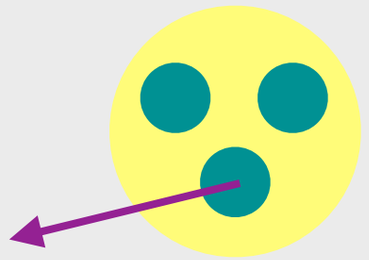
proton



kuarklar: $B = 1/3$

$B = 1$

antiproton



antikuarklar: $B = -1/3$

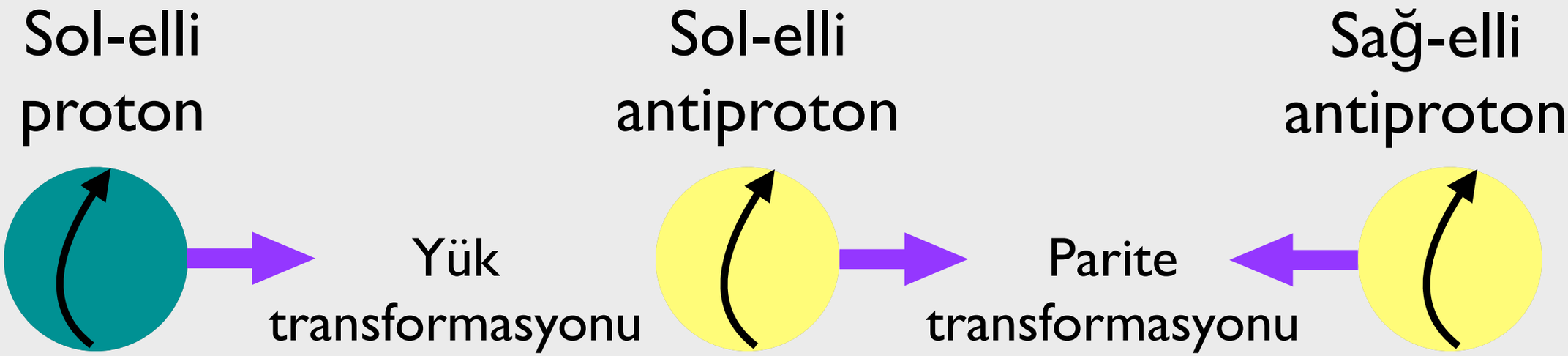
$B = -1$

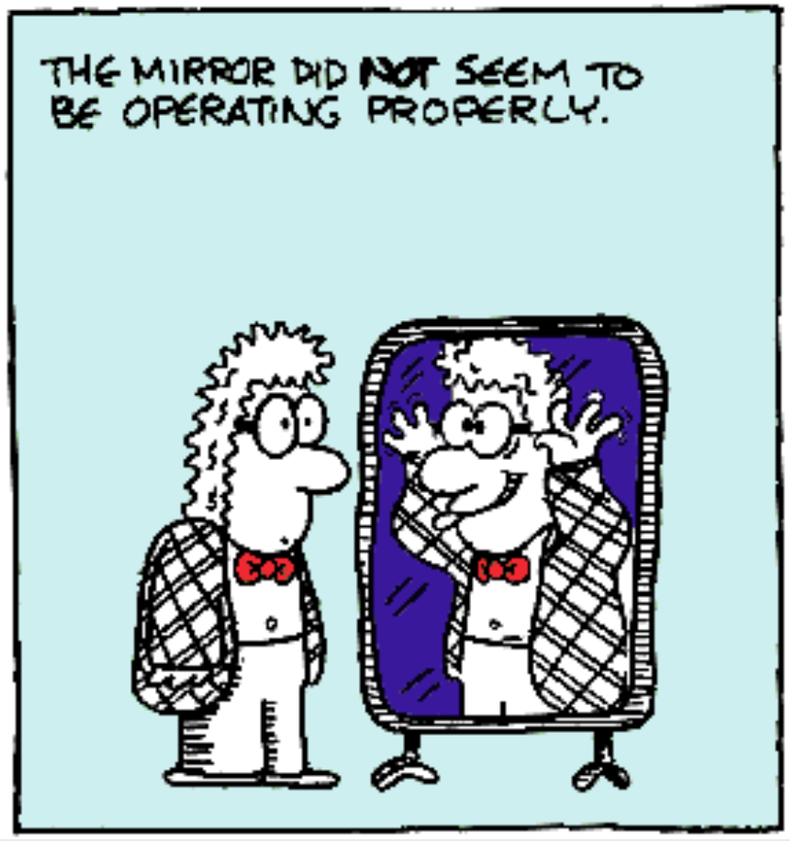
Evrenin başlangıcı: # kuarklar = # antikuarklar

$$\Delta_B \equiv n_B - n_{\bar{B}} = 0$$

Korunan bir sayı olamaz, yoksa hep sıfır kalırdı!

CP simetrisi ihlali

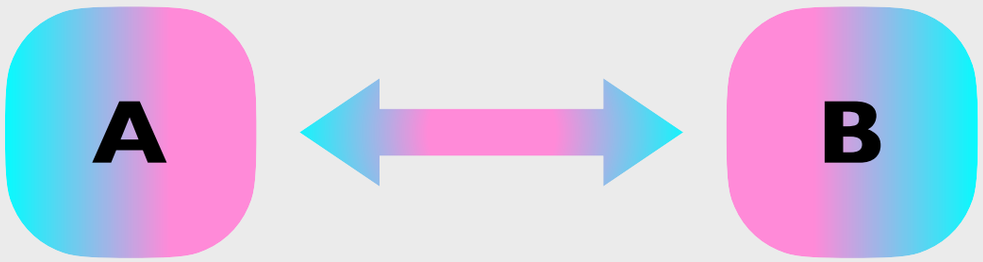




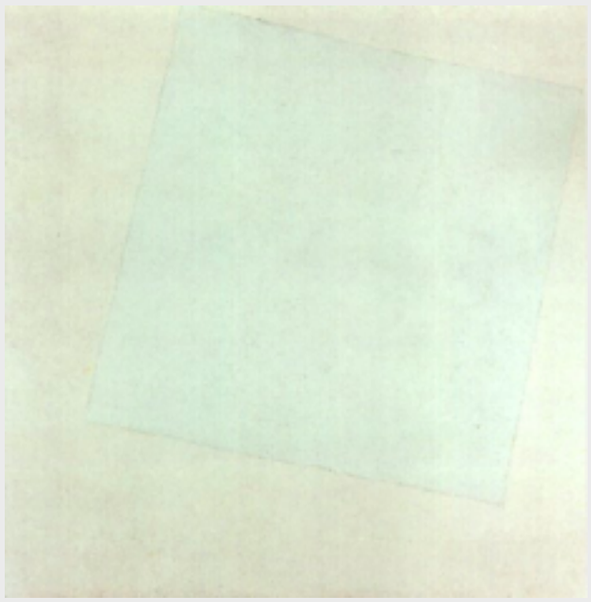
Parçacıklar ve antiparçacıklar arasında bir farklılık olmalı

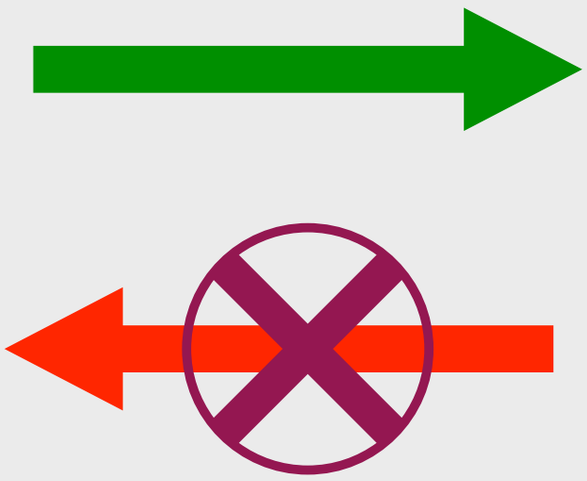
Termal dengeden düşüş

Termal dengede ilginç hiçbir şey olmaz



Sıfır baryon asimetrisi



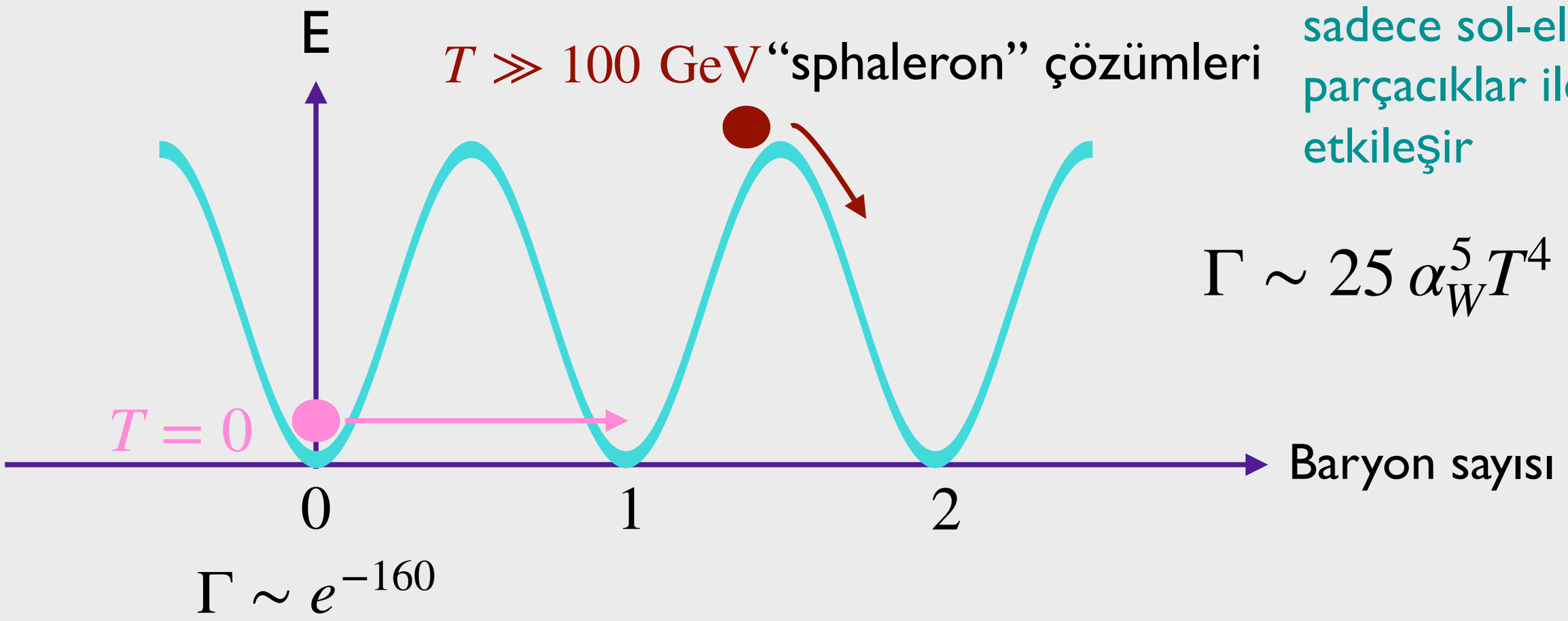


Azıcık baryon asimetrisi

Pillars of Creation,
Eagle Nebule,
Hubble Space Telescope

SM ve baryon sayısı ihlali

1. Baryon sayısı ihlali zayıf kuvvetli etkileşimlerde mevcut



Şu anda baryon sayısı değişmiyor

SM ve CP asimetrisi

2. CP simetrisi zayıf kuvvet etkileşimlerinde ihlal ediliyor

P-ihlali Chien-Shiung Wu tarafından ^{60}Co beta ışımasında keşfedildi (1956)

$$^{60}\mathrm{Co} \rightarrow {}^{60}\mathrm{Ni} + e^- + \bar{\nu} + 2\gamma$$

elektronun tercihi bir yönü var!

Harika! AMA bu ihlal gözlemlediğimiz baryon asimetrisini üretmek için teknik sebeplerden dolayı <u>yeterli değil</u>.

SM ve termal denge

3. SM'de gereki zamanda termal dengeden düşen etkileşim yok

SM ve termal denge

3. SM'de gereki zamanda termal dengeden düşen etkileşim yok

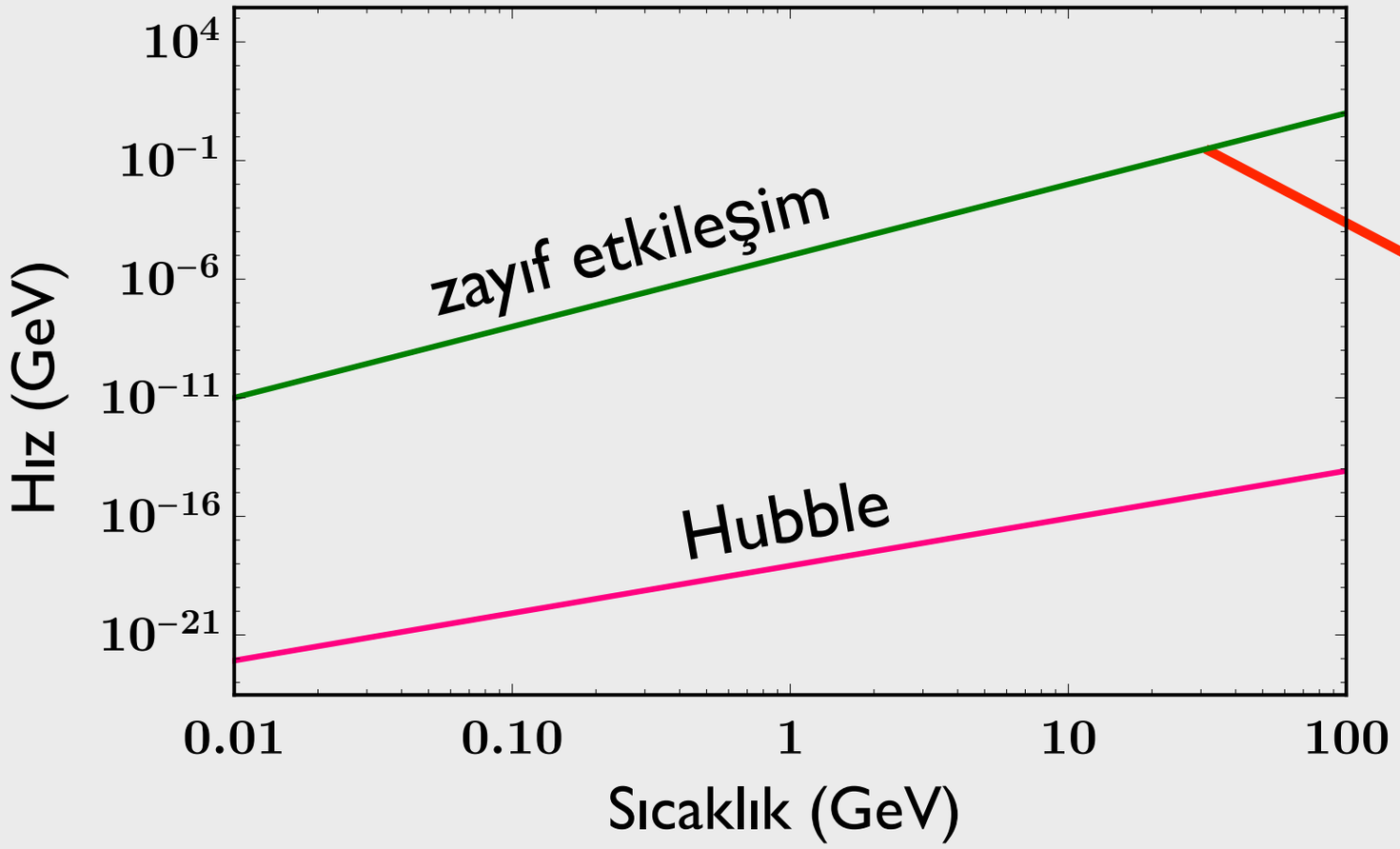
Zayıf nükleer etkileşimlerin hızı

$$\Gamma_{\text{weak}} \sim G_F^2 \times T^3$$

vs

Evrenin genişleme hızı

$$H \sim \frac{T^2}{M_{\text{Planck}}}$$



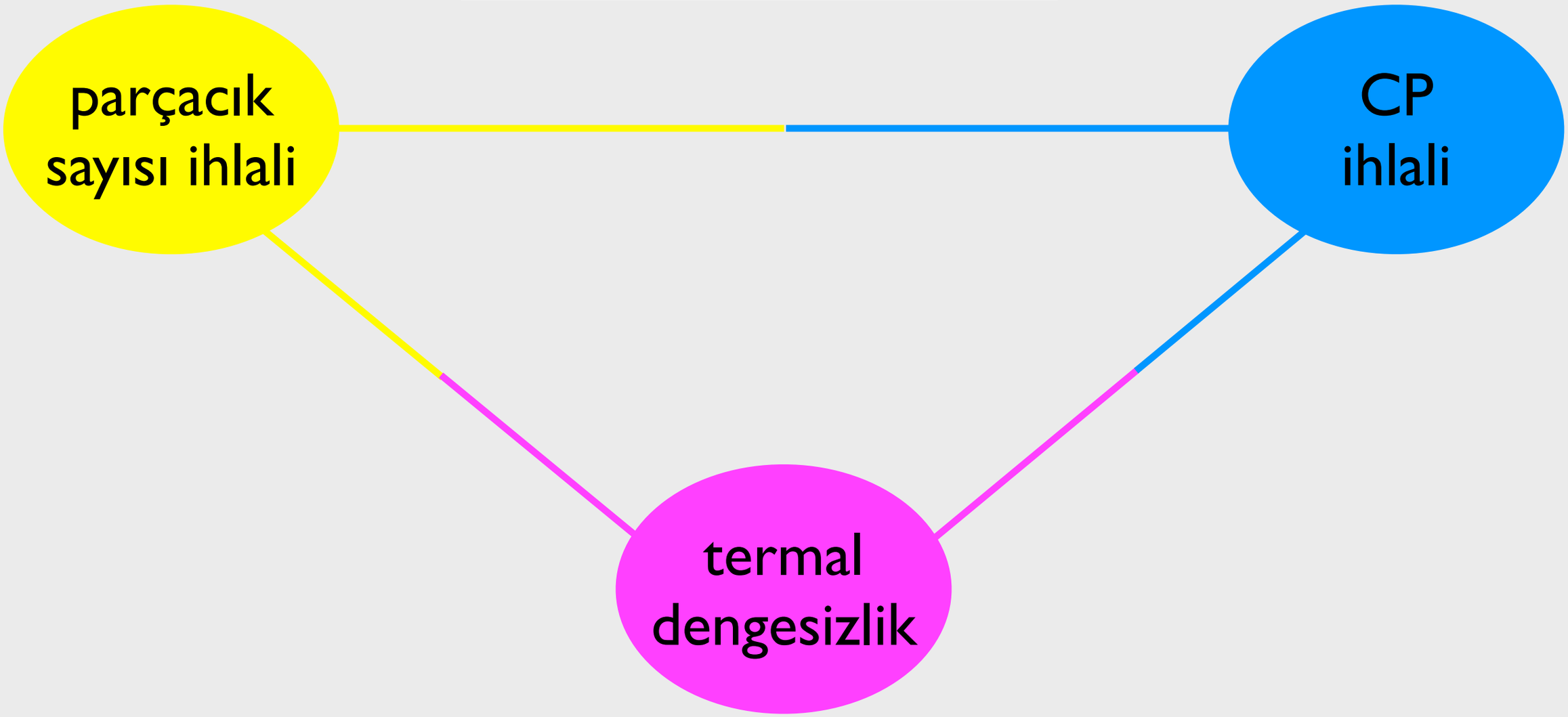
Çok hızlı!

Evren her zaman termal dengede!

Standart Model evrendeki madde—antimadde asimetrisini açıklayamıyor!

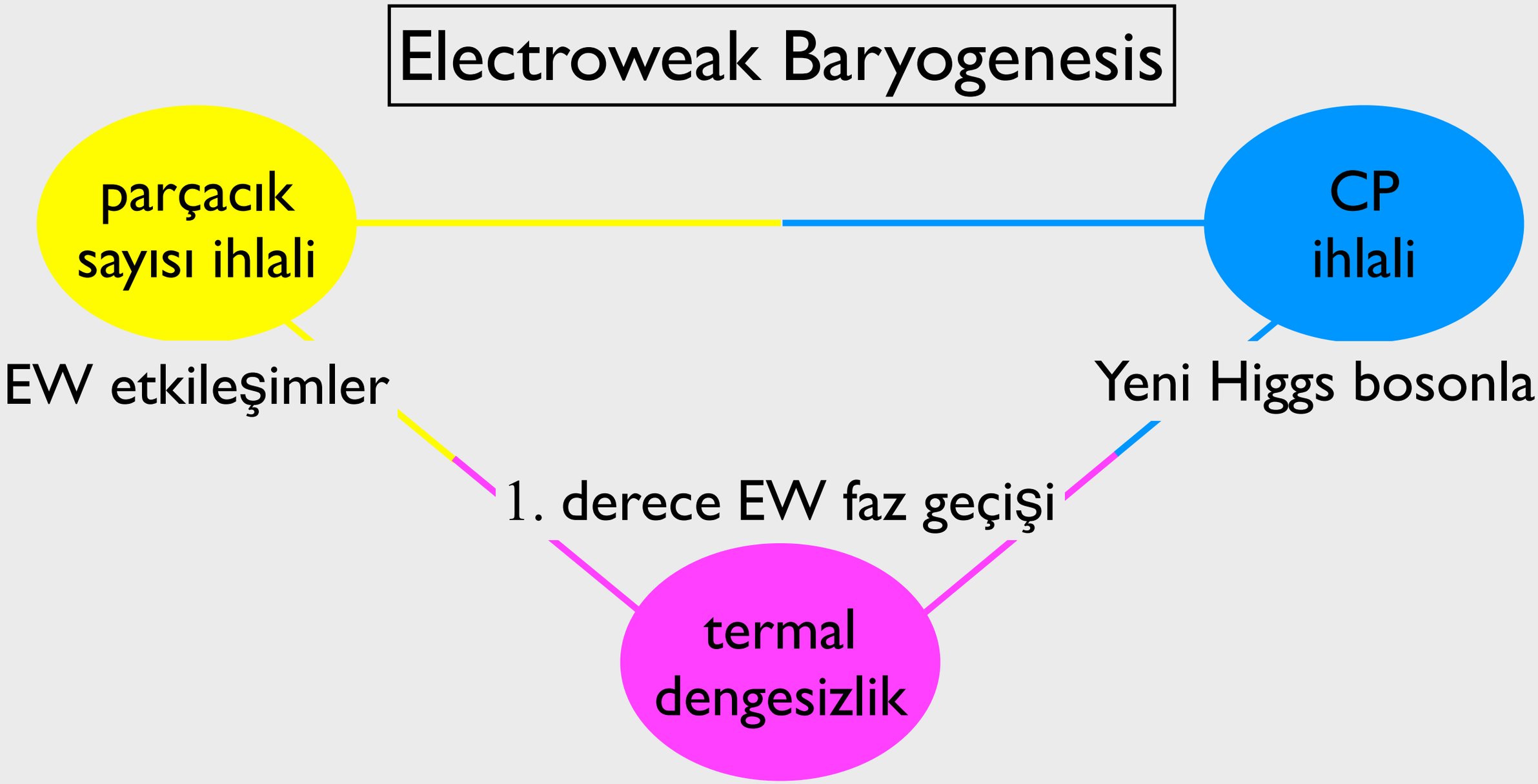
Standart Model ötesi yeni fizik!

Sakharov koşulları



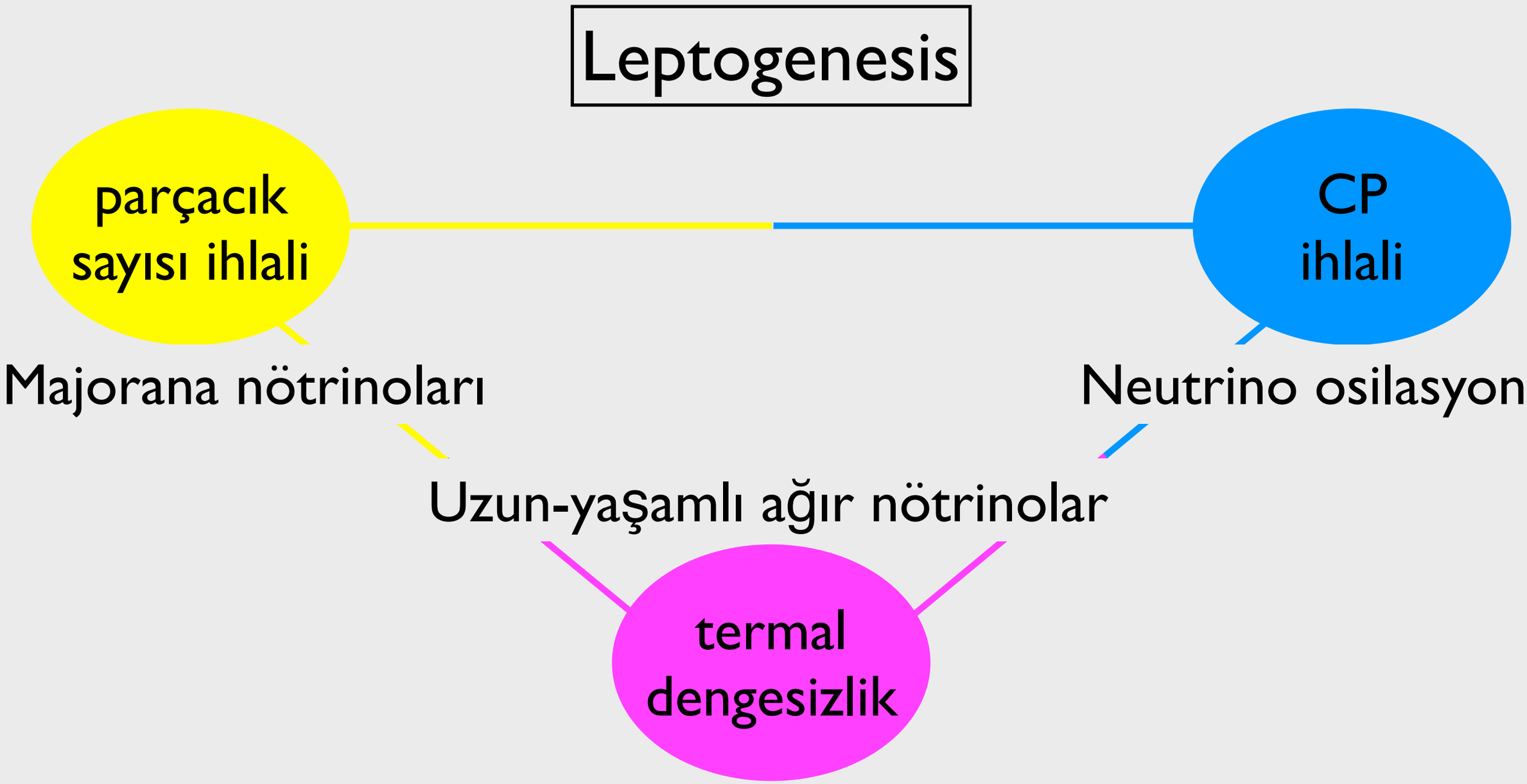
+ Standart Model ile etkileşmesi gerek!

Standart Model ötesi yeni fizik!



Review article: D. Morrissey, M. Ramsey-Musolf, New J.Phys. 14 (2012) 125003

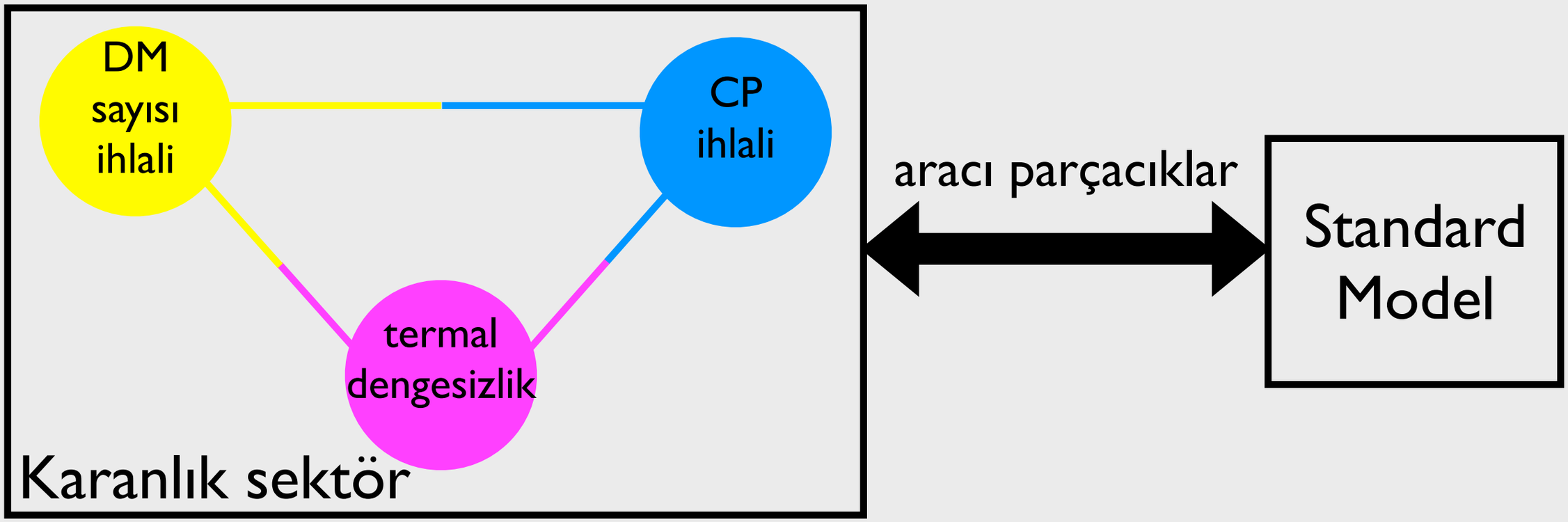
Standart Model ötesi yeni fizik!



Review article: S. Davidson, et al, Phys.Rept. 466 (2008) 105-177

Standart Model ötesi yeni fizik!

Asimetrik kararanlık madde



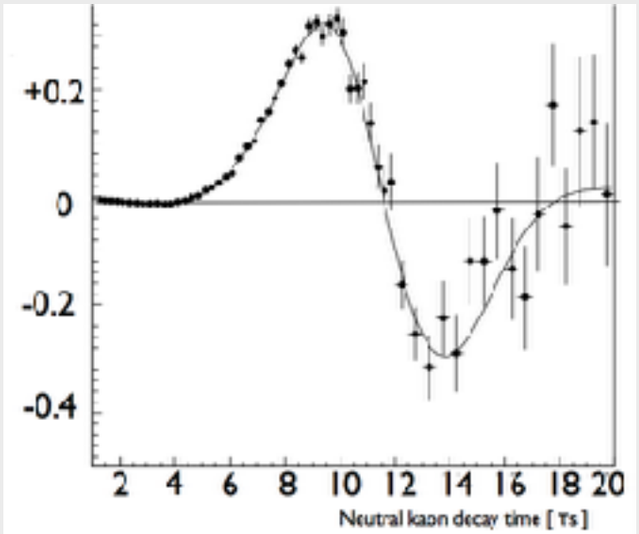
Review article: K. Zurek, Phys.Rept. 537 (2014) 91-121

CP simetrisi ihlali:
Parçacık-antiparçacık osilasyonları

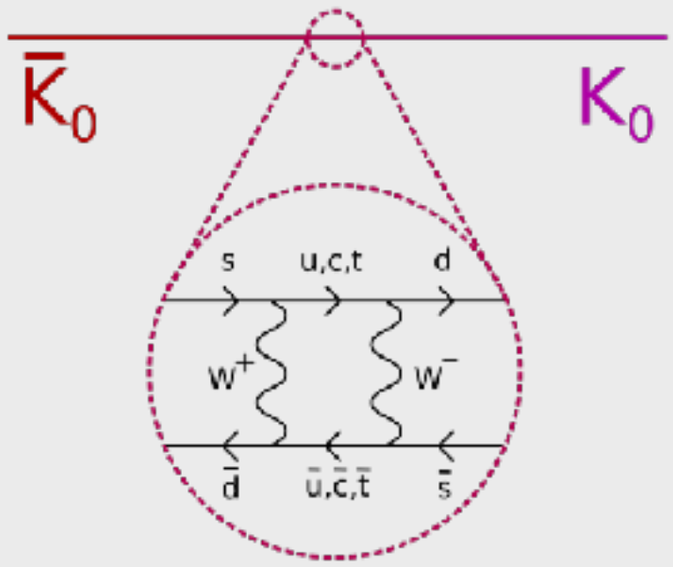
SI, J. March-Russell, PRD 93 (2016), no.12
C.M. Ayber, T. Chowdhury, **SI**, PRD 113 (2026) 11

CP simetrisi ihlali: Parçacık-antiparçacık osilasyonları

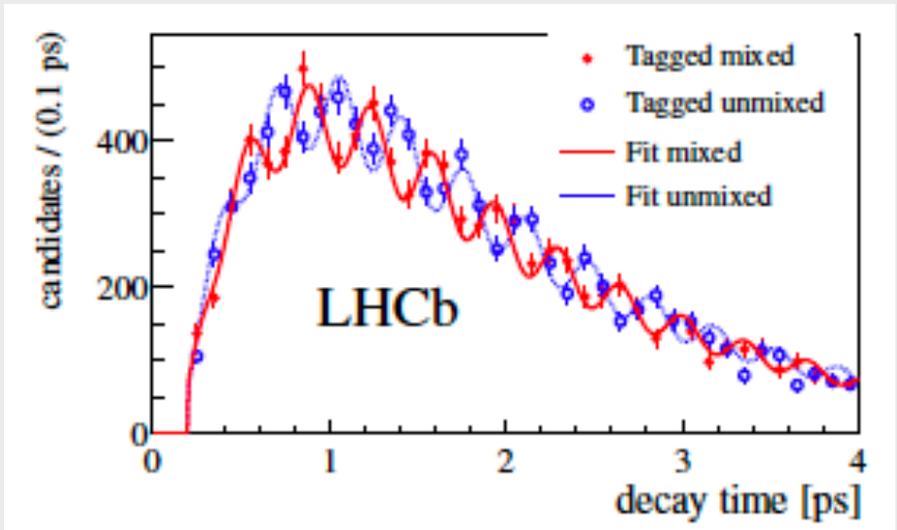
CPLear, 1990-96



Kaon

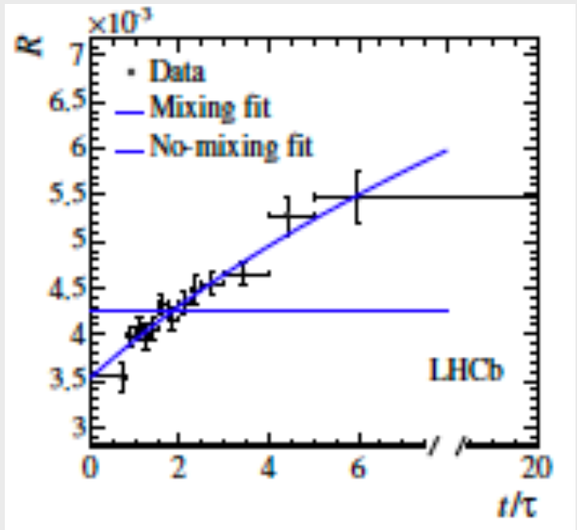


LHCb, 1304.4741



B mezonları

LHCb, 1211.1230

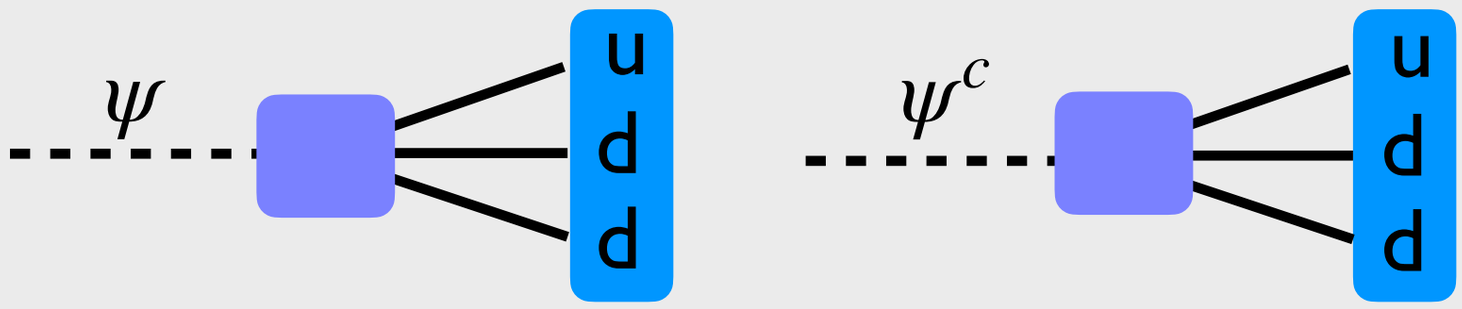


D mezonu

Parçacık-antiparçacık osilasyonlarının CP ihlilalinde özel bir yeri mi var?

Parçacık-antiparçacık osilasyonları

ψ, ψ^c fermion ve kütleleri şu matris ile verilsin: $\mathbf{M} = \begin{pmatrix} M & m \\ m & M \end{pmatrix}$



Bazı süpersimetrik modellerde doğal olarak bulunuyorlar

Sistemin Hamiltonian'ı:

$$\mathbf{H} = \mathbf{M} - \frac{i}{2}\mathbf{\Gamma} \xrightarrow{\text{eigenstates}} |\psi_{H,L}\rangle = p|\psi\rangle \pm q|\psi^c\rangle$$

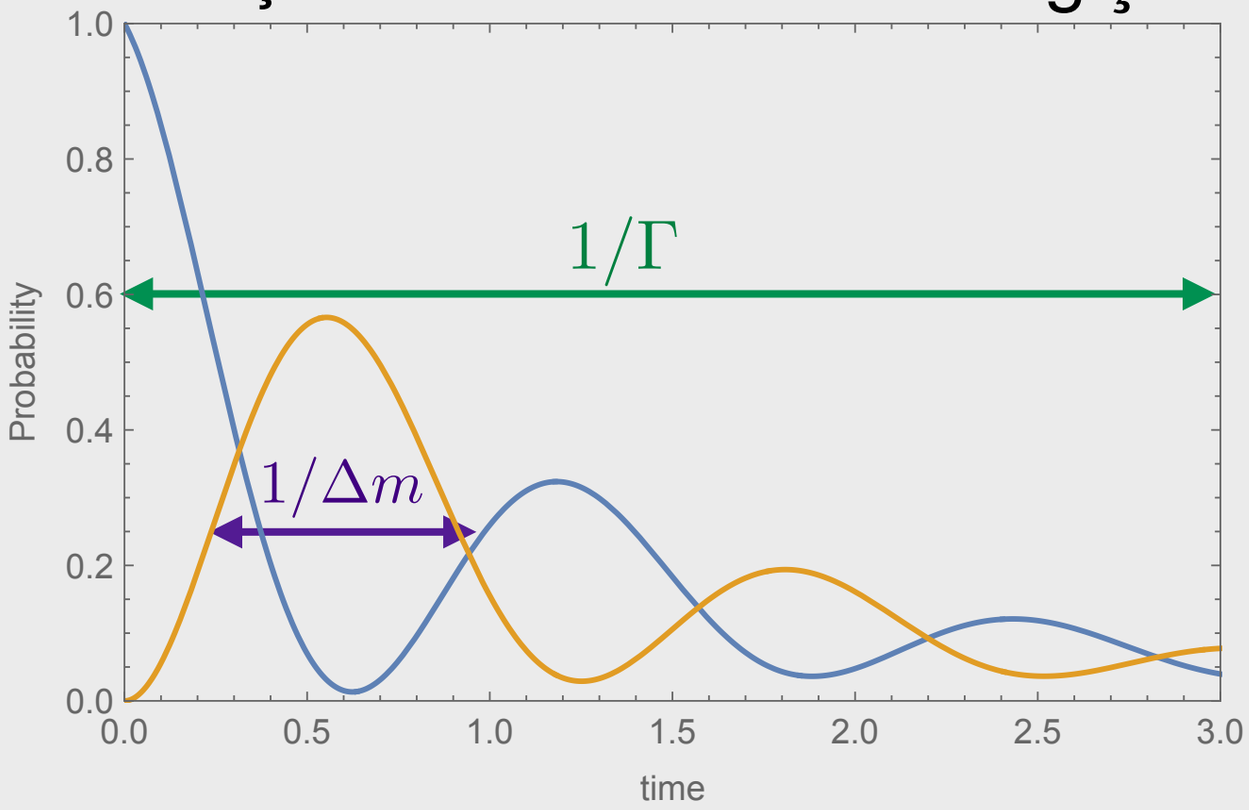
$$\mathbf{\Gamma} \simeq \Gamma \begin{pmatrix} 1 & 2\,r\,e^{i\phi_\Gamma} \\ 2\,r\,e^{-i\phi_\Gamma} & 1 \end{pmatrix}$$

Kütle özhalleri ≠ etkileşim özhalleri

Osilasyonlar!

Parçacık-antiparçacık osilasyonları

Parçacık özhalinin zamanla değişimi



Osilasyon frekansı:

$$\Delta m = M_H - M_L \simeq 2m$$

önemli parametre: $$x \equiv \frac{\Delta m}{\Gamma}$$

ϵ: CP ihlali ölçüsü

→ en yüksek değeri $x \sim 1$

Osilasyonların üç hali

$x \gg 1$	$x \sim 1$	$x \ll 1$
Çok hızlı	Tam kıvamında	Çok yavaş

Erken evrende osilasyonlar

Osilasyon — Saçılma

$$zH\frac{d\mathbf{Y}}{dz} = -i\big(\mathbf{HY}-\mathbf{YH}^{\dagger}\big) - \frac{\Gamma_{\pm}}{2}[O_{\pm},[O_{\pm},\mathbf{Y}]] - s\langle\sigma v\rangle_{\pm}\left(\frac{1}{2}\{\mathbf{Y},O_{\pm}\bar{\mathbf{Y}}O_{\pm}\}-Y_{\rm eq}^2\right)$$

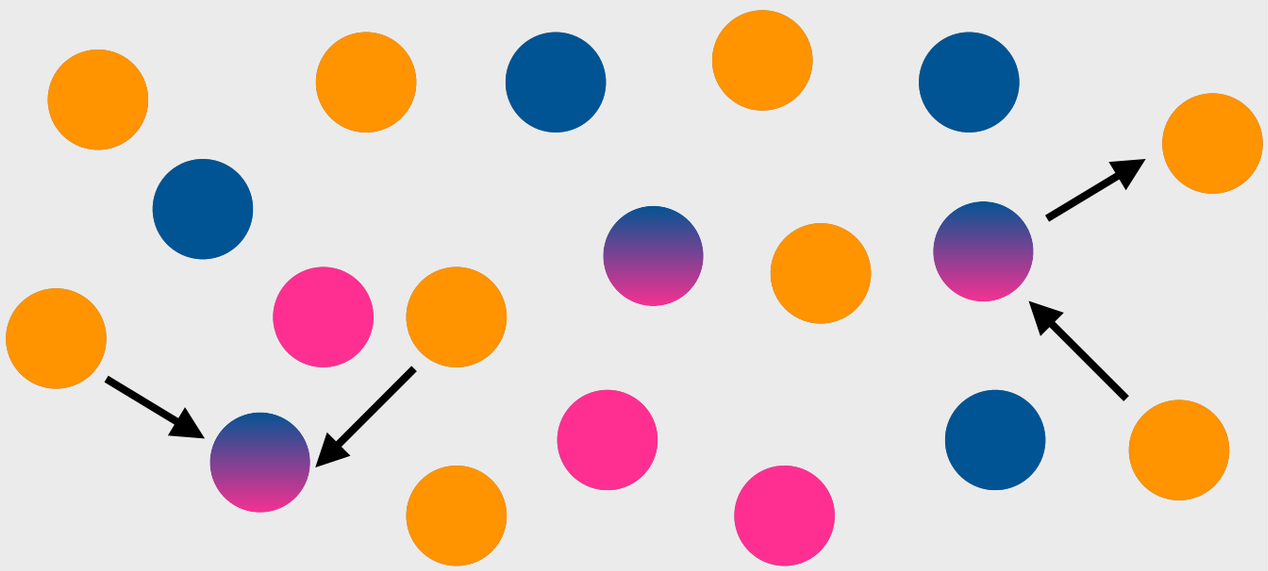
$z = M/T$

$\mathbf{H}$: Hamiltonian

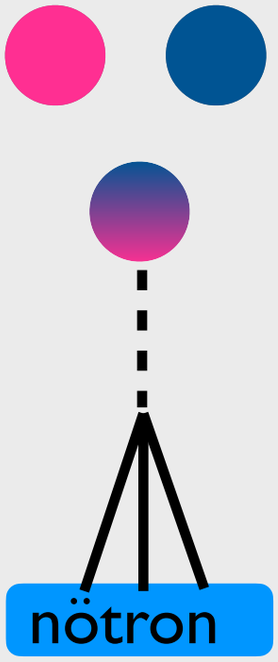
$\mathbf{Y}$: Yoğunluk matrisi

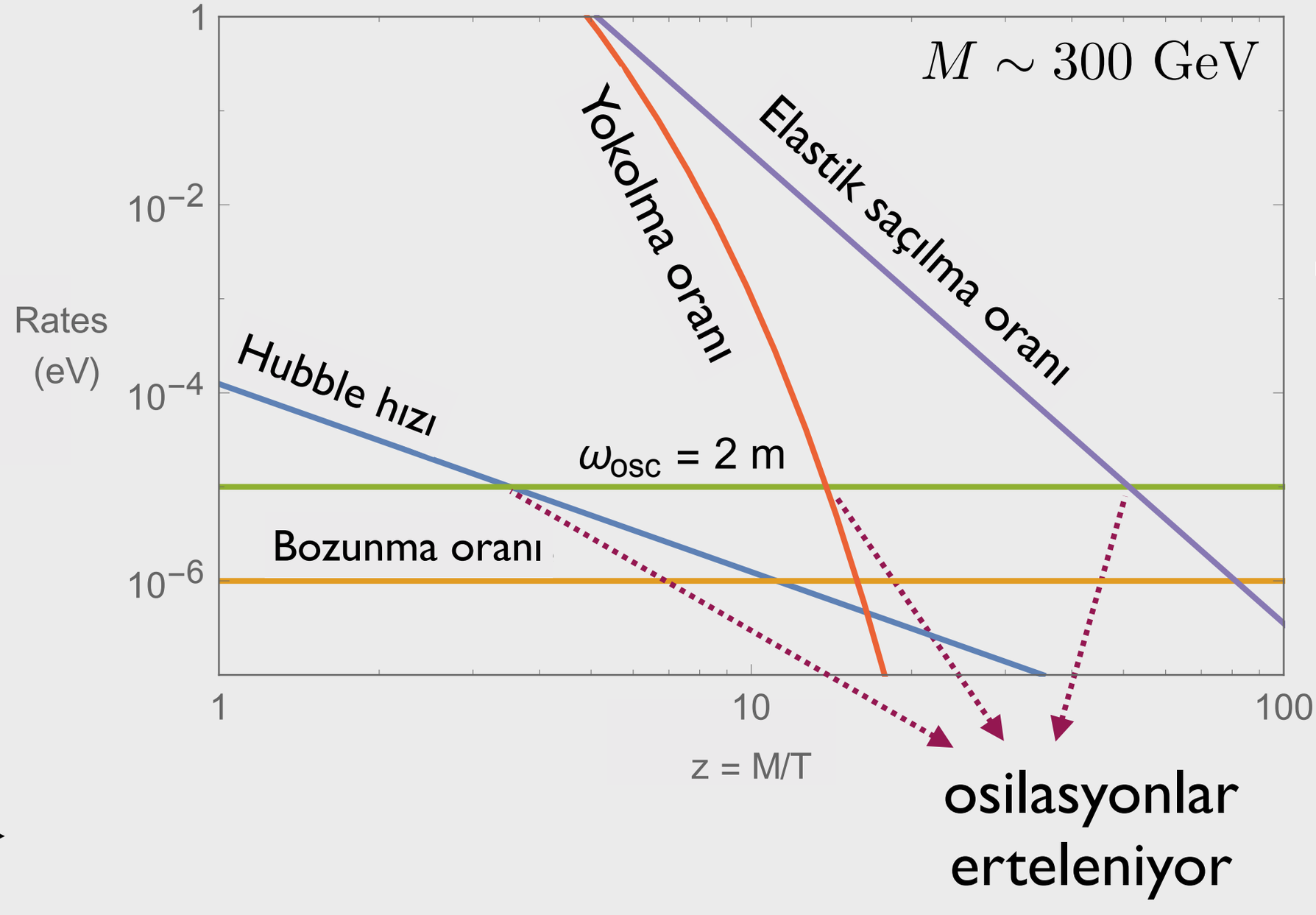
$O_{\pm} = \mathrm{diag}(1,\pm 1)$

yokolma

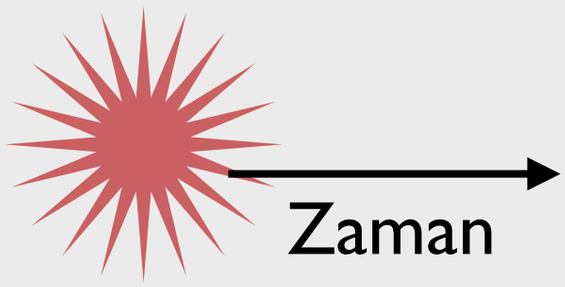


Erken evrende osilasyonlar





Big Bang?



osilasyonlar erteleniyor

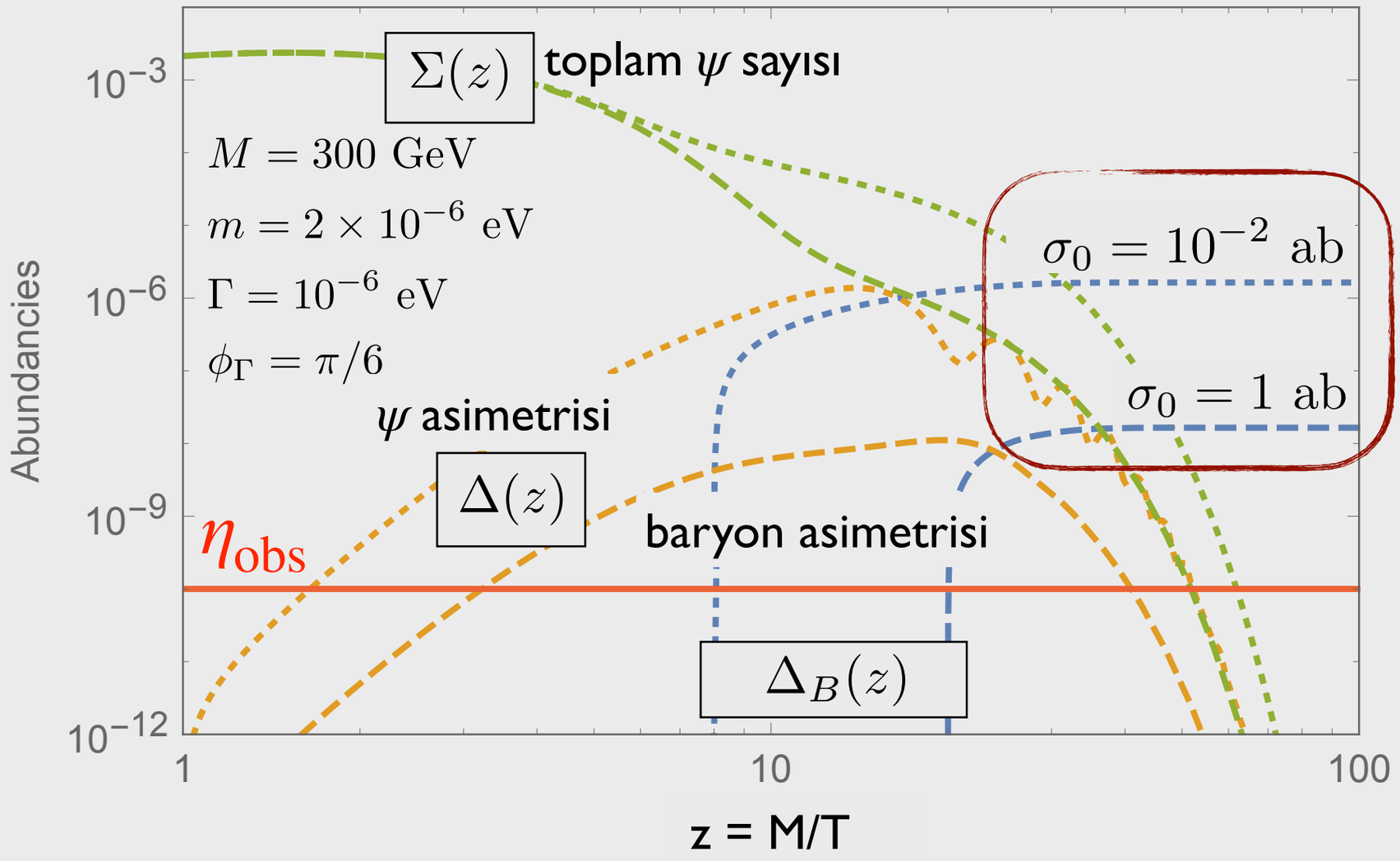
Baryon asimetrisi

baryon asimetrisi: $$\frac{d\Delta_B(z)}{dz} \simeq \frac{\epsilon\,\Gamma}{zH}\,\Sigma(z)$$

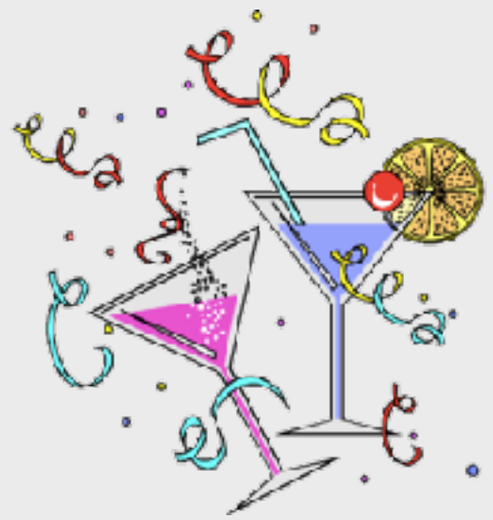
$$\Sigma \equiv \frac{n_\psi + n_{\psi^c}}{s}$$

$$\Delta \equiv \frac{n_\psi - n_{\psi^c}}{s}$$

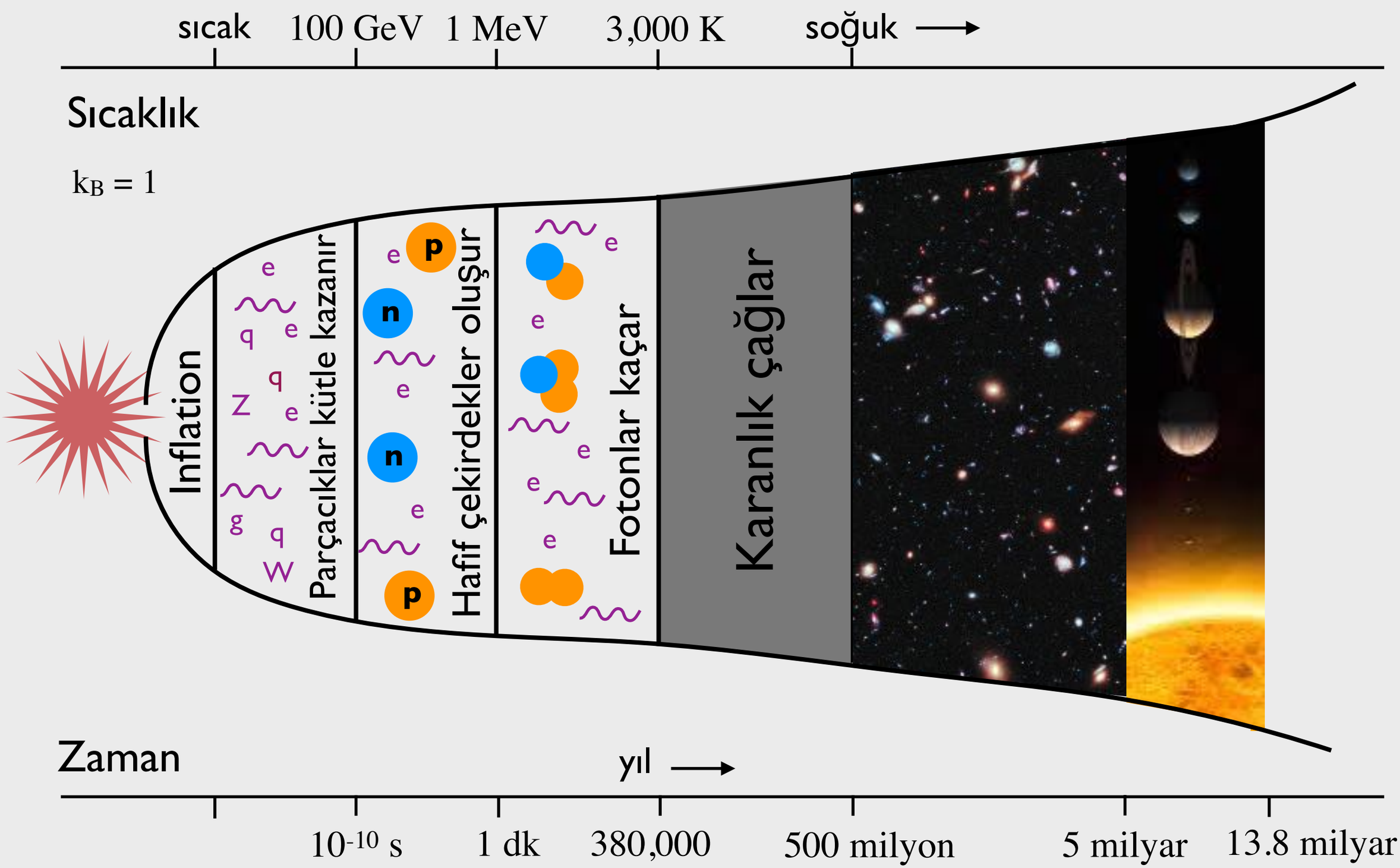
$$\Delta_B \equiv \frac{n_B - n_{\bar{B}}}{s}$$



BARYONLAR!



Evrenimizi anlamak



Backup slides

Particle—Antiparticle Oscillations

SI, J. March-Russell, PRD 93 (2016), no.12

Consider the Lagrangian for a pseudo-Dirac fermion:

$$\mathscr{L} \supset M\bar{\psi}\psi + \frac{m}{2}\overline{\psi^c}\psi + \boxed{g_1\,\bar{\psi}udd + g_2\,\overline{\psi^c}udd} + \mathrm{h.c.}$$

B number violation

This arises in certain supersymmetric models

$$\mathbf{H} = \mathbf{M} - \frac{i}{2}\mathbf{\Gamma} \quad \xrightarrow{\text{eigenstates}} \quad |\psi_{H,L}\rangle = p|\psi\rangle \pm q|\psi^c\rangle$$

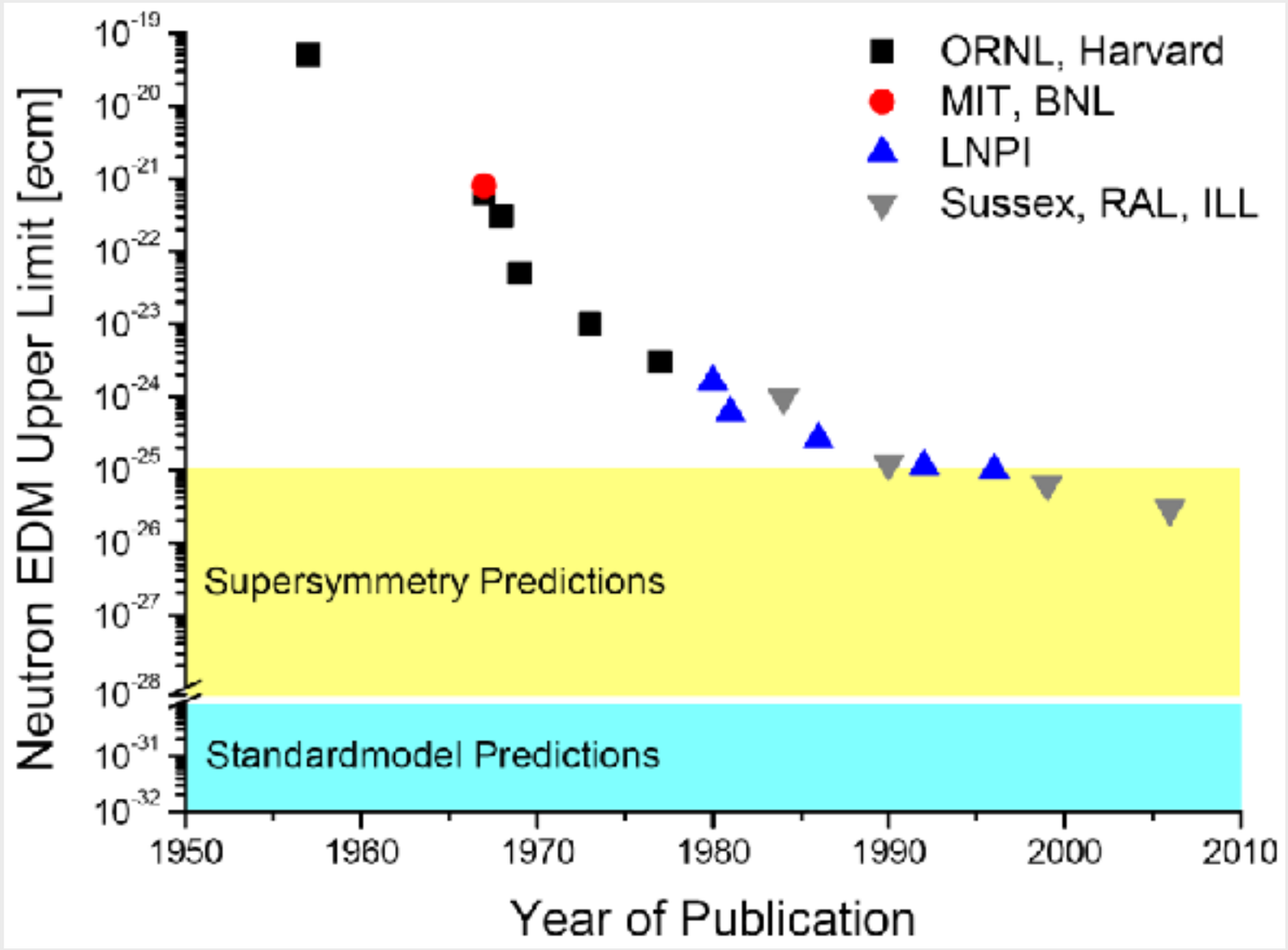
$$\mathbf{M} = \begin{pmatrix} M & m \\ m & M \end{pmatrix}$$

$$\mathbf{\Gamma} \simeq \Gamma \begin{pmatrix} 1 & 2\,r\,e^{i\phi_\Gamma} \\ 2\,r\,e^{-i\phi_\Gamma} & 1 \end{pmatrix}$$

mass states ≠ interaction states

Oscillations!

Strong CP Problem



$$d_n < 10^{-30}\ \mathrm{e}\cdot\mathrm{cm}$$

PRD 92, 092003 (2015)

$$\bar{\theta} < 10^{-10}$$

Why so small???

Andreas Krecht

strong CP problem

Baryon/Lepton number violation: Is it really necessary?

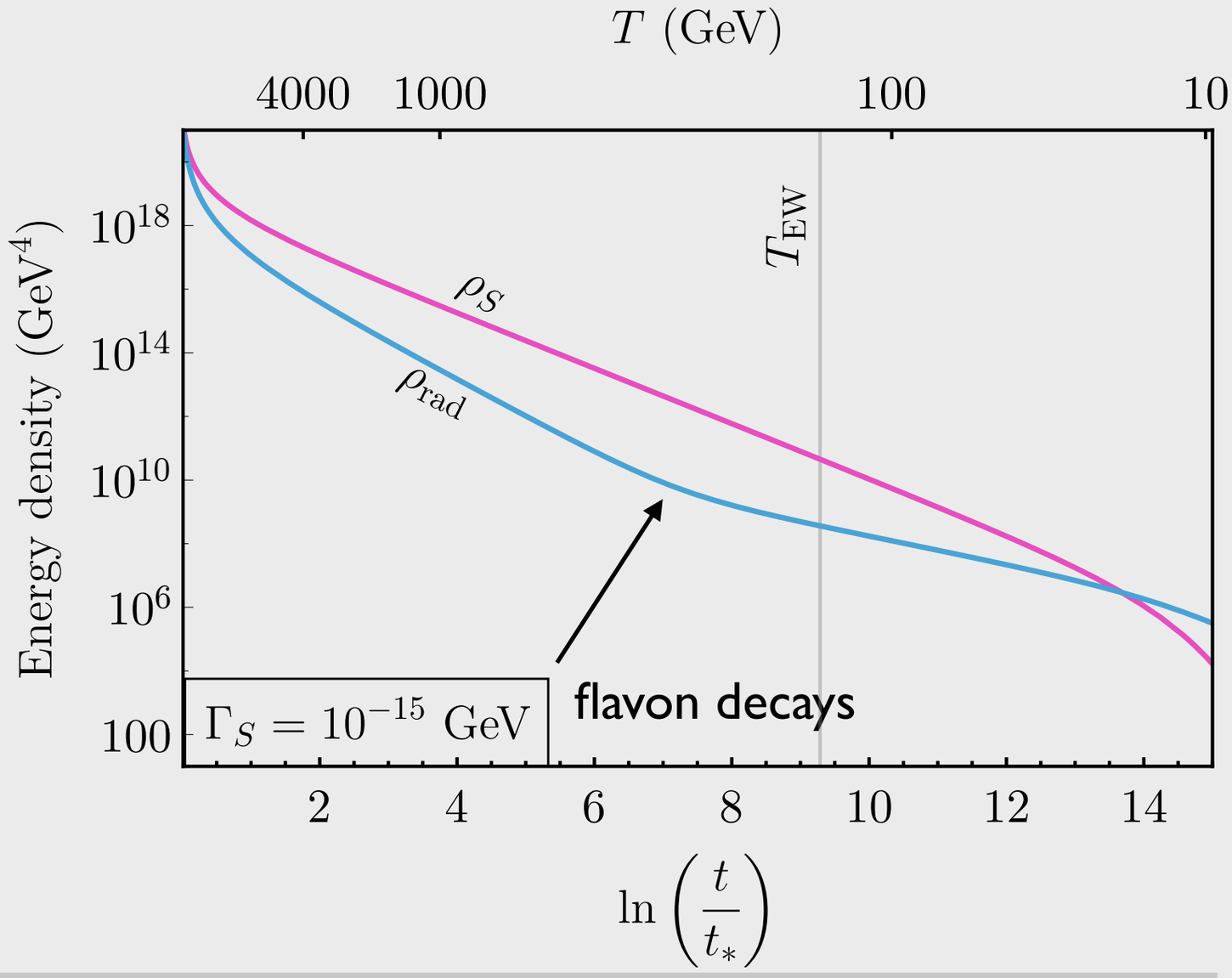
Why is there a hierarchy of masses in the SM? ➡ flavon!

$$y^{fg}\left(\frac{S}{\Lambda}\right)^{n_{fg}} \bar{e}^{f}_{R}\,\phi^{*}\,\ell^{g}_{L}$$

$\Lambda \sim 10^{9}$ GeV

energy density in flavon oscillations: $\rho_S \propto a^{-3}$

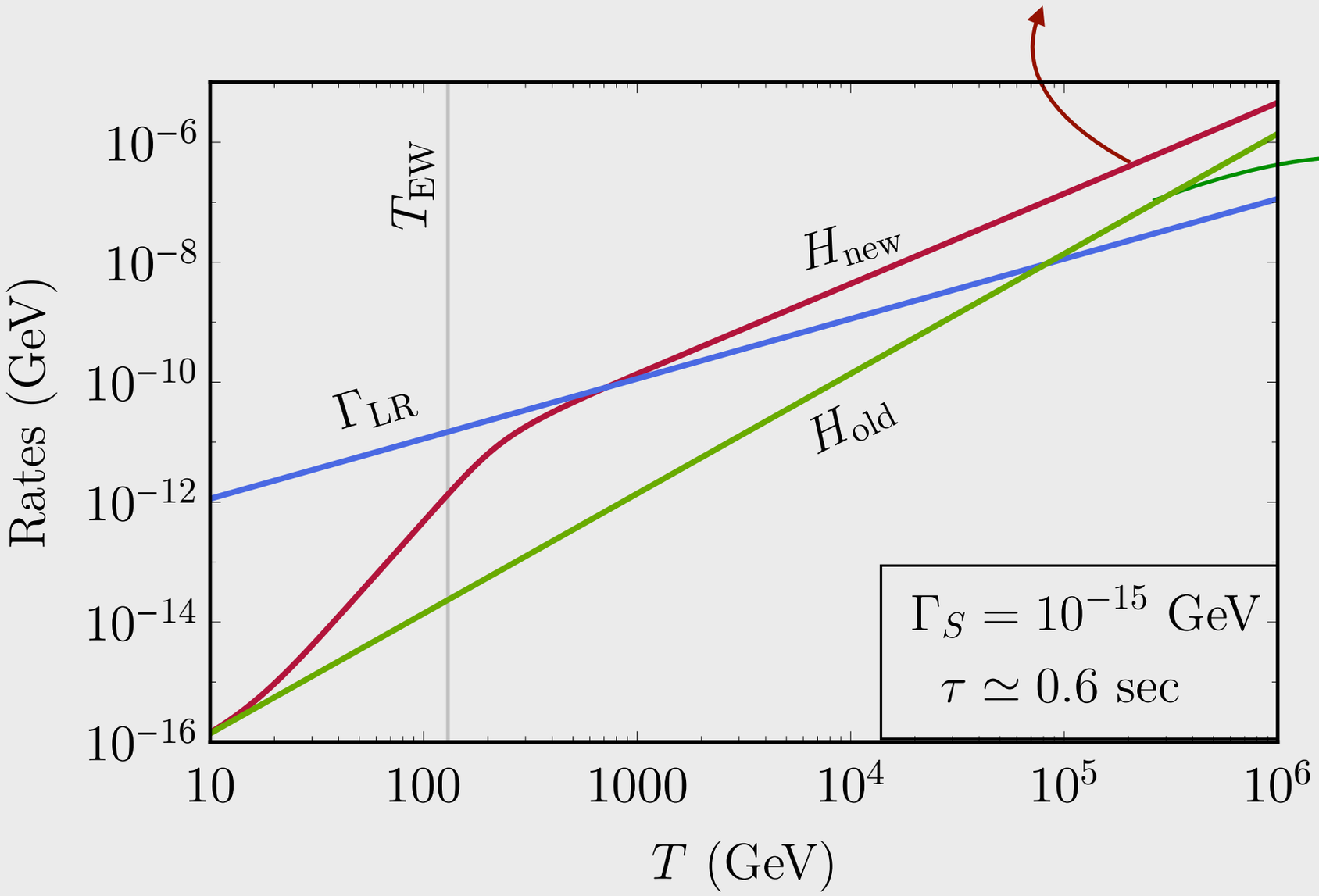
energy density in radiation: $\rho_{\rm rad} \propto a^{-4}$



Baryon/Lepton number violation: Is it really necessary?

Flavon cosmology:

Hubble rate is larger than expected from radiation domination

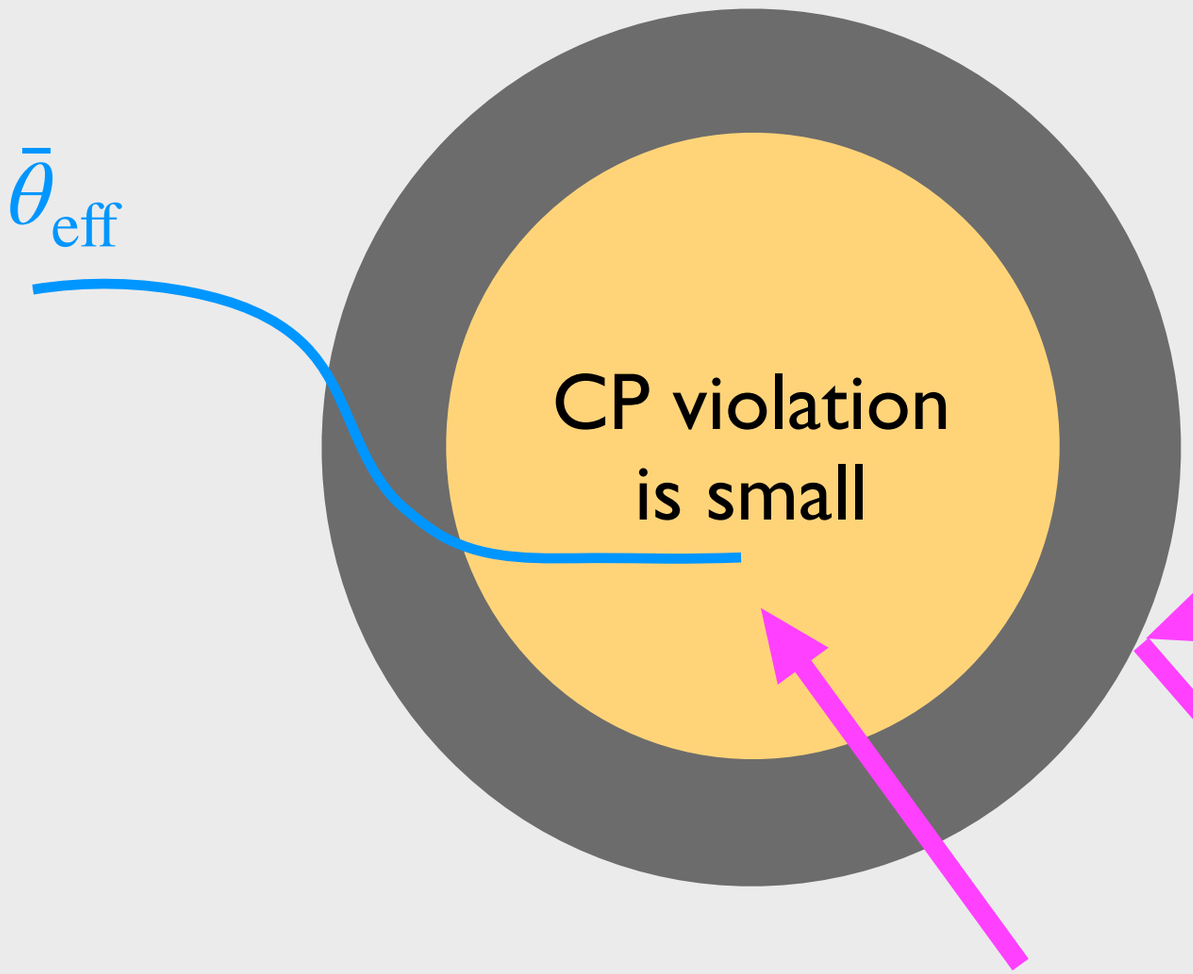


SM cosmology

CP violation via the axion

$T = \mathrm{TeV}$

There can be large CP violation outside the QCD bubbles



Quarks and antiquarks are colliding with the bubble

Some get in some don't

Interactions are CP violating!

New QCD wins the game!

$T = \mathrm{TeV}$

$\langle q\bar{q} \rangle = 0$

$\langle h \rangle = 0$

B

CP

$\langle q\bar{q} \rangle \sim \Lambda_{\mathrm{QCD}}$

$\langle h \rangle \sim \Lambda_{\mathrm{QCD}}$

B number conserved

CP conserved

Left-handed and right-handed particles have different interactions at the bubble wall

Baryon asymmetry is produced right outside the bubble

Bubble grows and sweeps this asymmetry in

Asymmetry is conserved inside the bubble

Recovering the SM

$\Lambda_{QCD} \sim$ TeV → proton mass ~ TeV!

Big Bang Nucleosynthesis worked → Need to recover SM before T ~ MeV

Can be achieved by extending the scalar sector