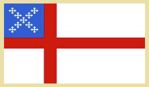
The Collider-Cosmology Interface I

M.J. Ramsey-Musolf

U Mass Amherst



AMHERST CENTER FOR FUNDAMENTAL INTERACTIONS

Physics at the interface: Energy, Intensity, and Cosmic frontiers

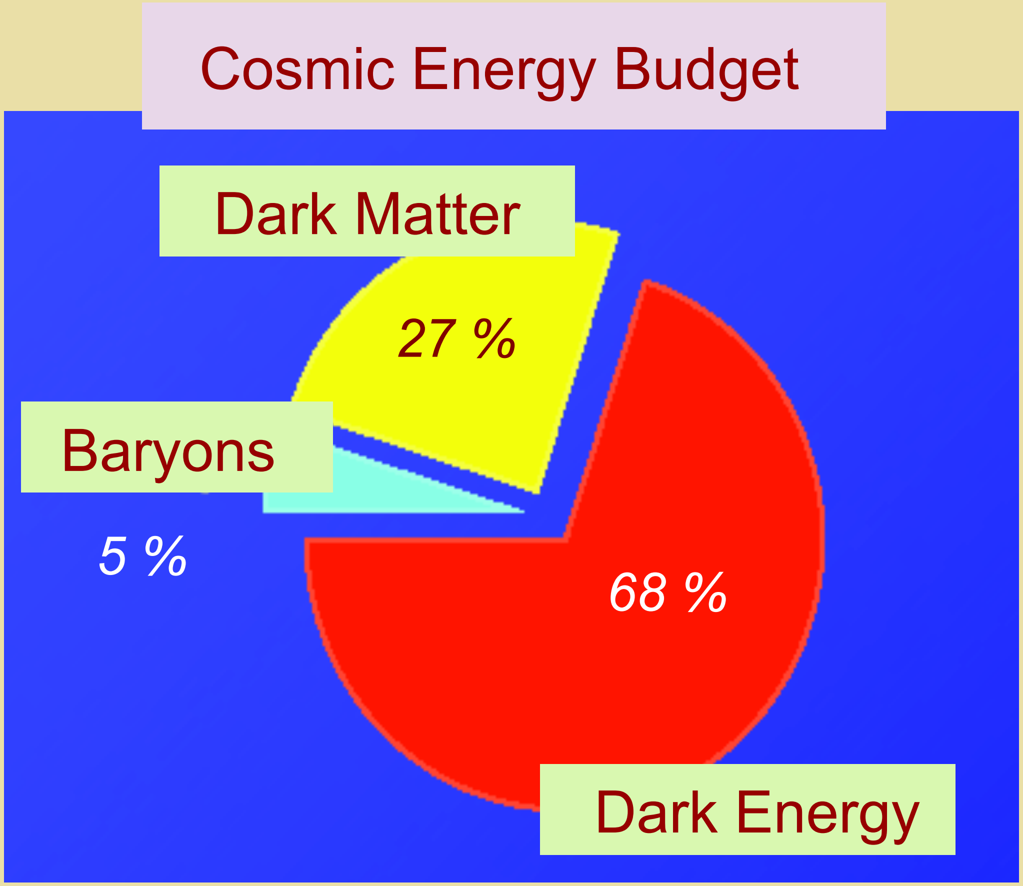
University of Massachusetts Amherst

http://www.physics.umass.edu/acfi/

HEP School, Lanzhou
8/1-8/18

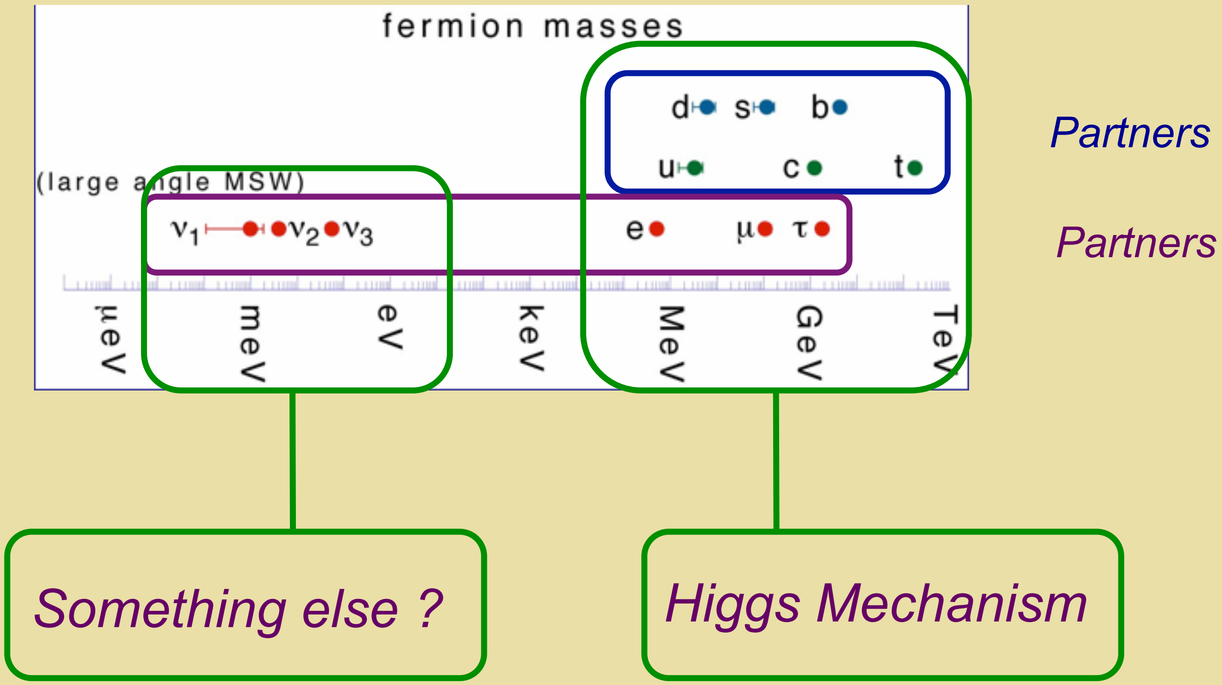
"Big Questions"

The Origin of Matter

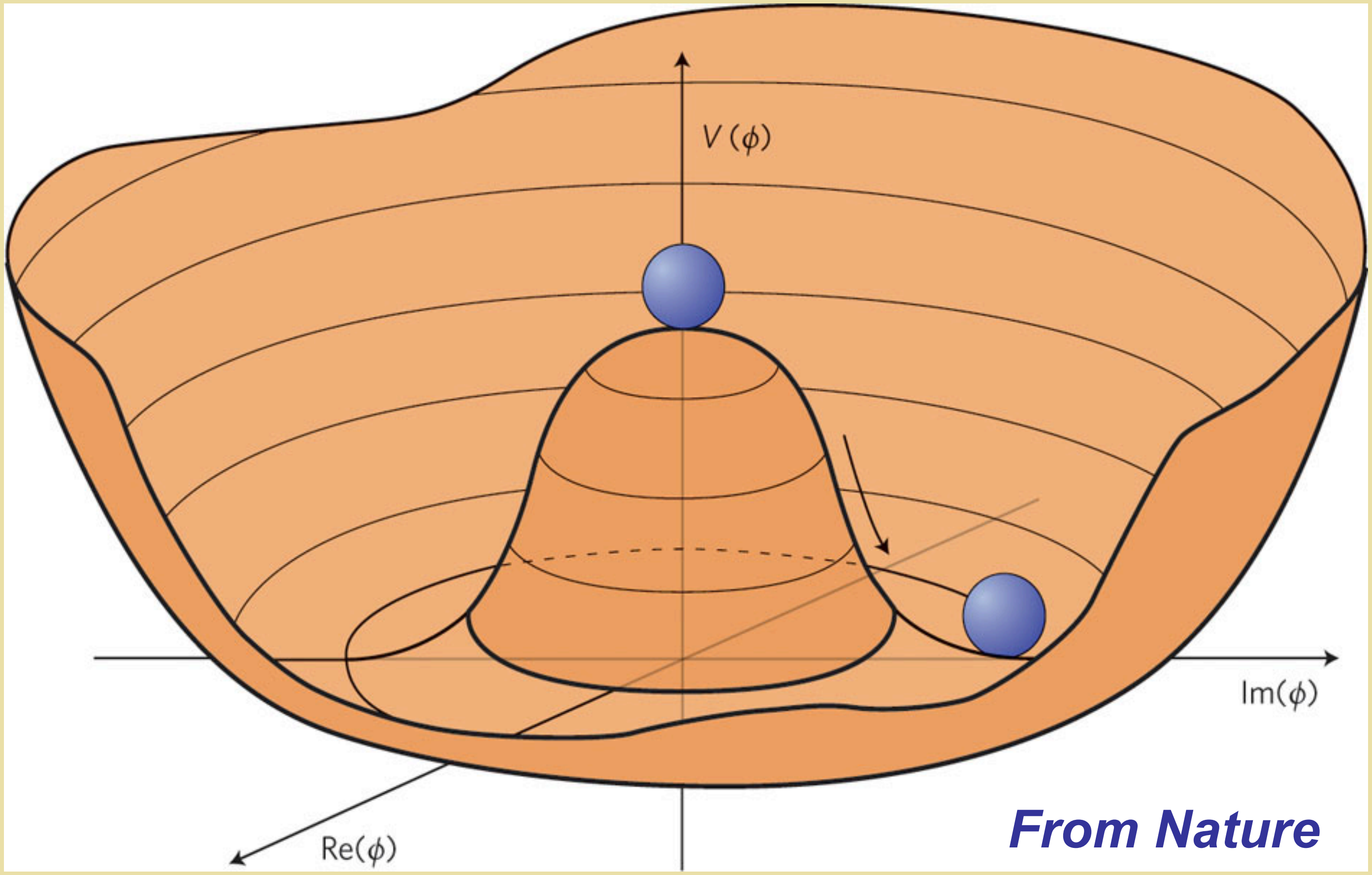


Explaining the origin, identity, and relative fractions of the cosmic energy budget is one of the most compelling motivations for physics beyond the Standard Model

Elementary Fermion Masses



EWSB: The Scalar Potential



How did this potential evolve with temperature ?

Collider Physics & the Early Universe

- *Why does the universe contain more matter than antimatter ?*
- *What is the dark matter and what are its interactions ?*
- *What is the thermal history of electroweak symmetry-breaking ?*
- *What additional particles & interactions were active in the early universe and at what epoch in cosmic history ?*

Collider Physics & the Early Universe

Lecture I

- *Give an overview of particle physics in cosmic history*
- *Explain the time-temperature-mass connection*
- *Introduce the context of baryogenesis & finite-T symmetry breaking*

Lecture II

- *Explain how leptogenesis works*
- *Explain how collider searches and other experiments can probe leptogenesis scenarios*

Collider Physics & the Early Universe

Lecture III

- *Explain how electroweak baryogenesis works*
- *Discuss dynamics of the electroweak phase transition*
- *Discuss EWPT-dark matter connection*
- *Discuss LHC & future collider probes of EWPT & related dark matter scenarios*

Lecture I Goals

- *Introduce key concepts & framework for describing particle interactions in the early universe*
- *Set the context for the discussion of baryogenesis scenarios & their connection to BSM physics*
- *Introduce the key ideas for analyzing spontaneous symmetry-breaking at non-zero temperature: finite-T effective potential*
- *Invite questions !*

Lecture I Outline

I. Cosmic Thermal History and Particle Physics

II. General Relativity & Thermodynamics: Relating time, temperature, & mass

III. Matter-Antimatter Asymmetry

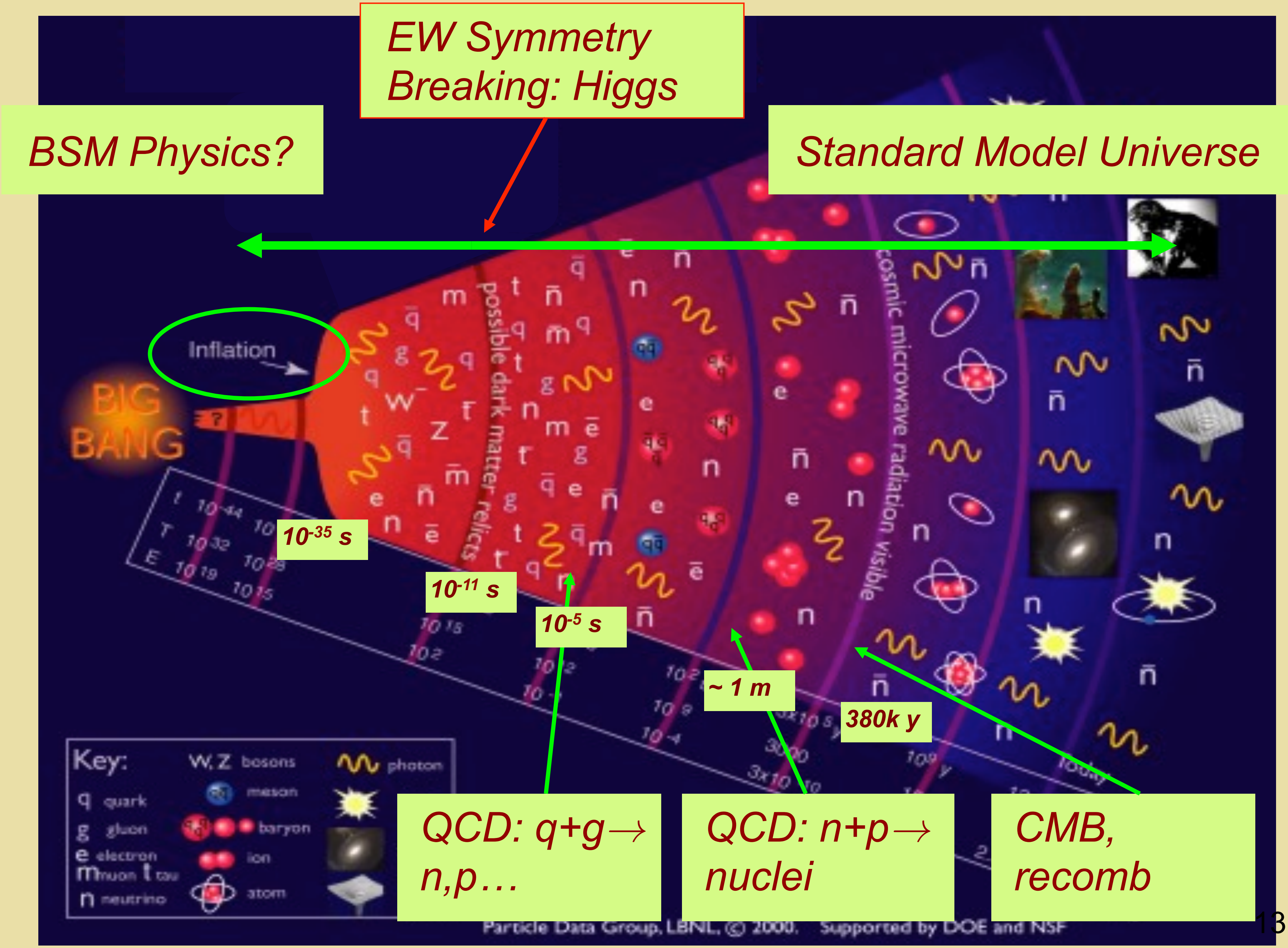
IV. Symmetry-Breaking at Non-zero T

References

- *“Modern Cosmology”, S. Dodelson*
- *“The Early Universe”, E. Kolb & M. Turner*
- *“Finite Temperature Field Theory”, A. Das*

I. Cosmic Thermal History & Particle Physics: Overview

Symmetries & Cosmic History



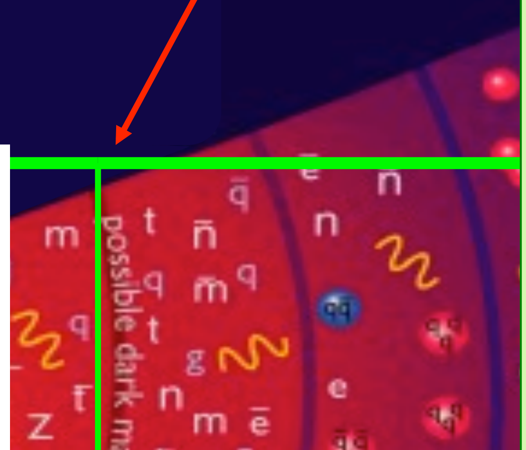
Symmetries & Cos

EW Symmetry Breaking: Higgs ?

BSM Physics ?

Large Hadron Collider

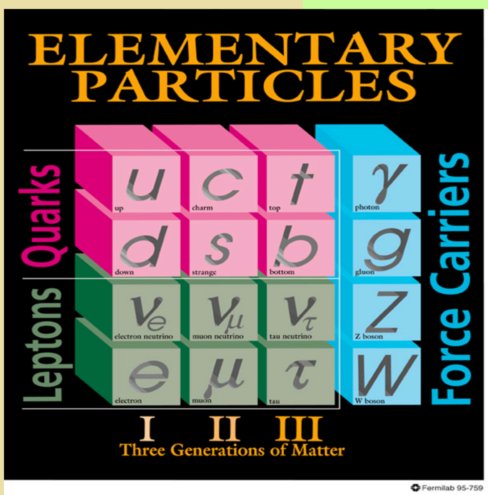
CERN



- Non-zero vacuum expectation value of neutral Higgs breaks electroweak sym and gives mass:

$$m_e = \lambda_e \langle H^0 \rangle$$

- Is it the Standard Model Higgs?
- Is there more than one?



Puzzles the St'd Model may or may not solve:

$SU(3)_c \times SU(2)_L \times U(1)_Y \rightarrow U(1)_{EM}$

How is electroweak symmetry broken?
How do elementary particles get mass ?

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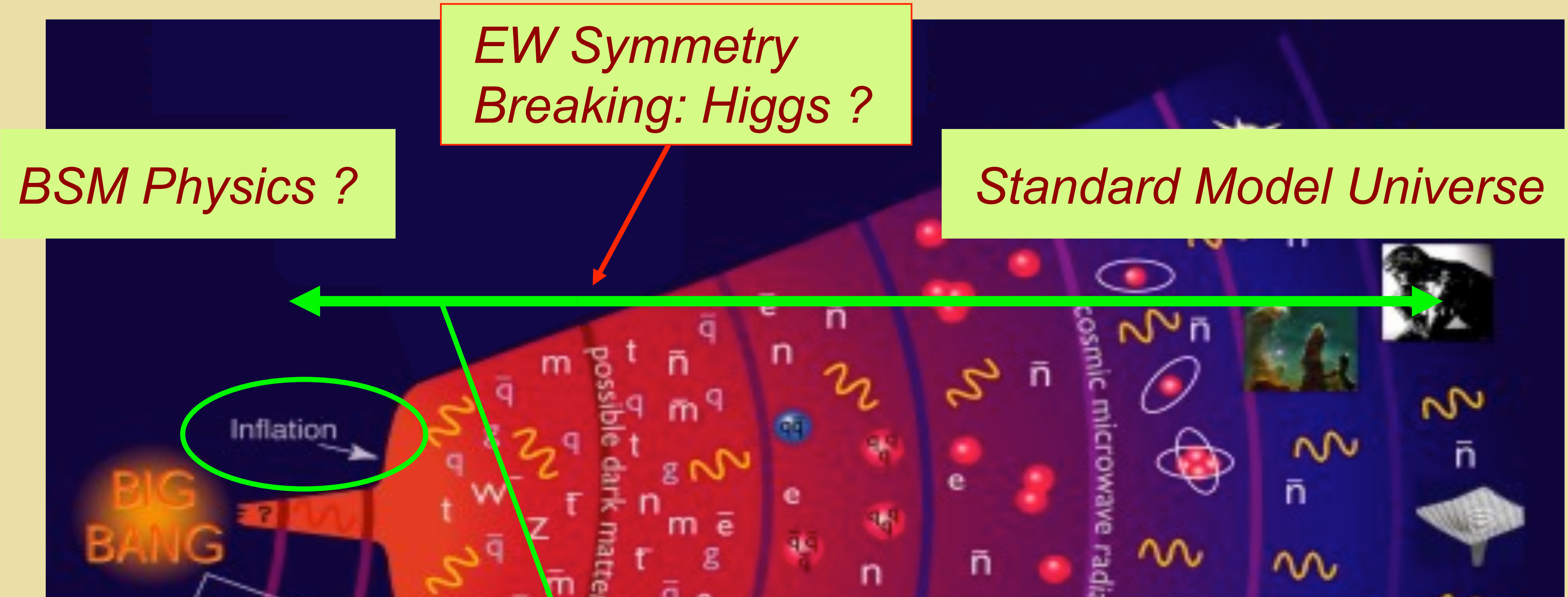
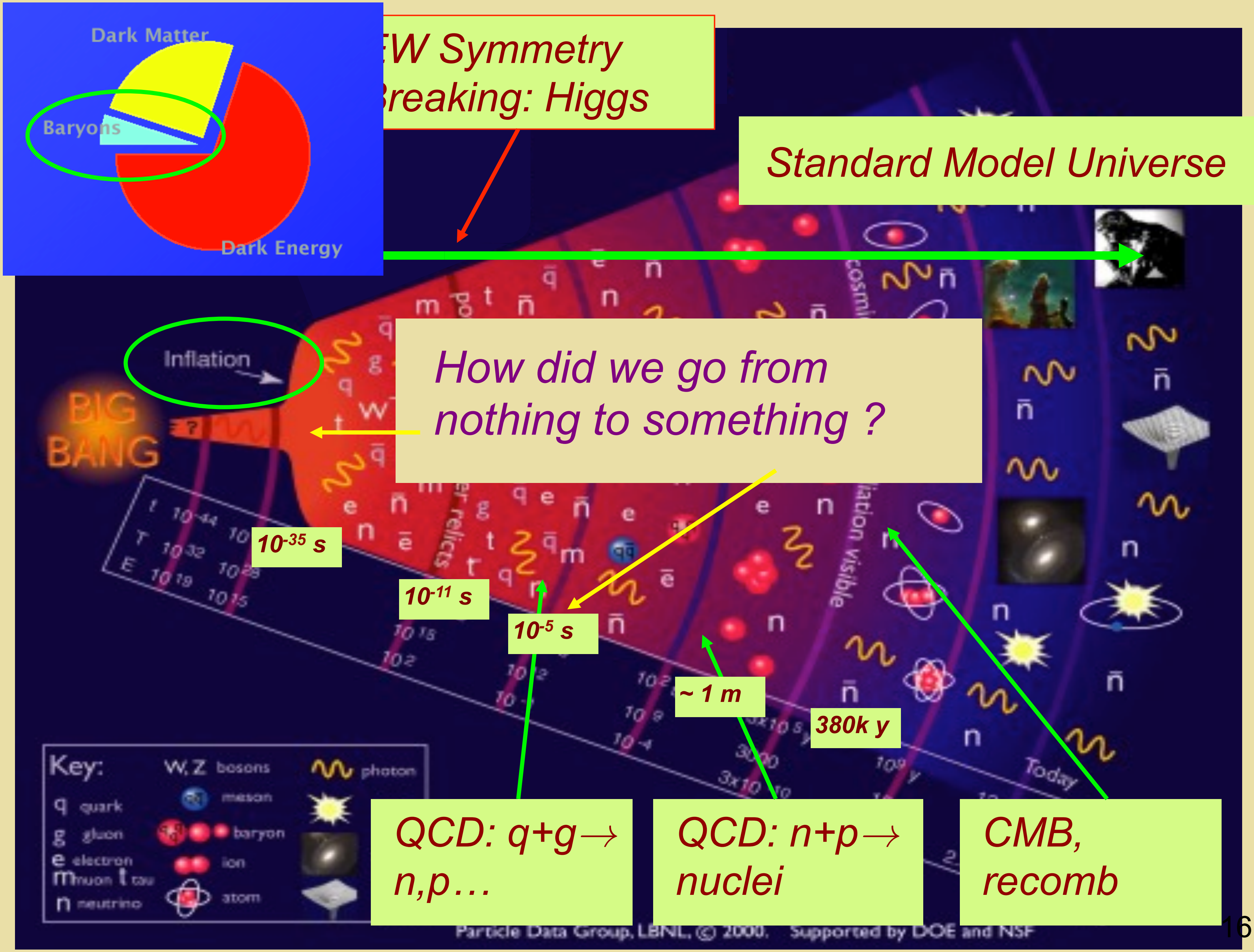
Symmetries & Cosmic History



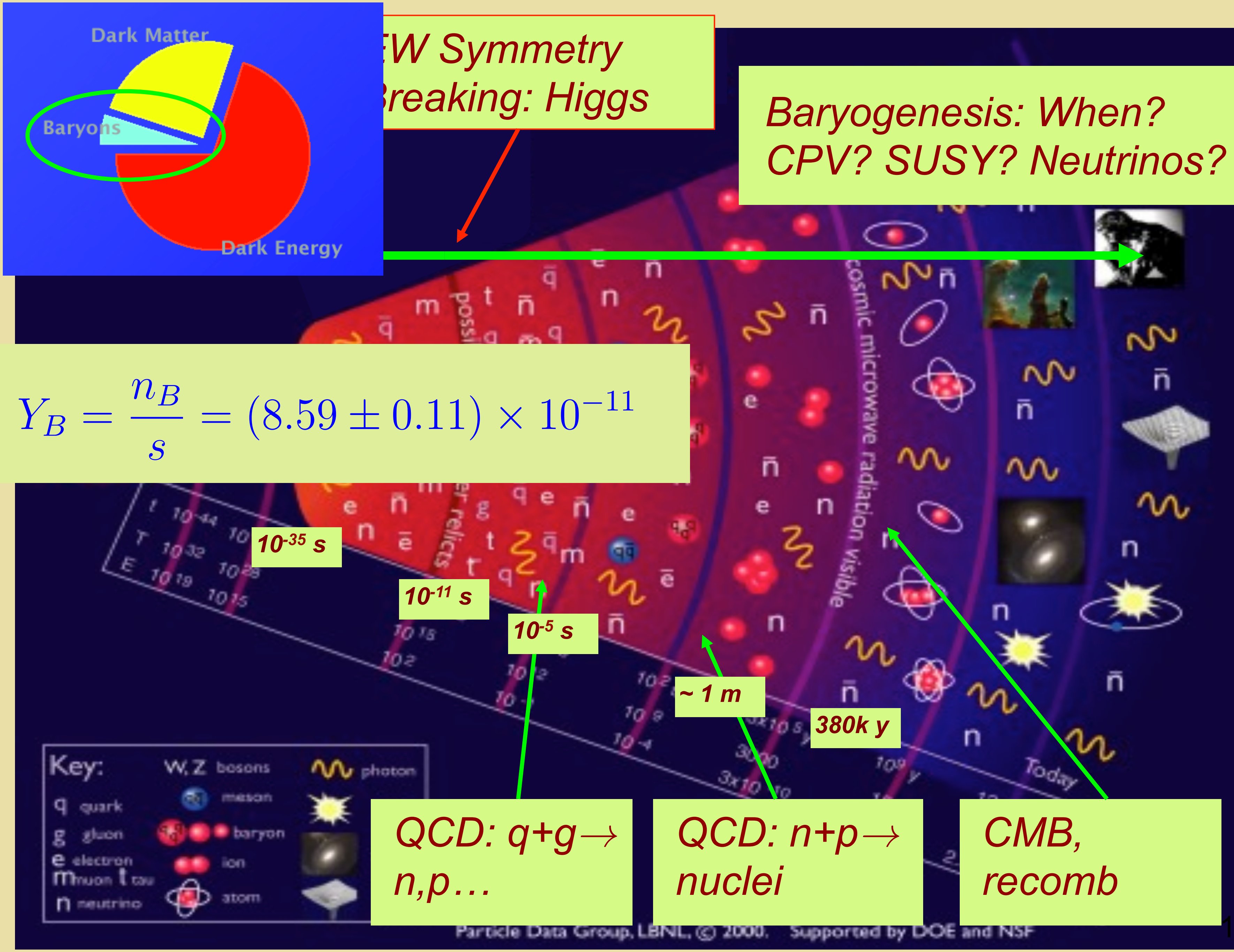
Puzzles the Standard Model can't solve

1. *Origin of matter*
2. *Unification & gravity*
3. *Weak scale stability*
4. *Neutrinos*

Symmetries & Cosmic History



Symmetries & Cosmic History



EW Symmetry Breaking: Higgs

Baryogenesis: When? CPV? SUSY? Neutrinos?

$$Y_B = \frac{n_B}{s} = (8.59 \pm 0.11) \times 10^{-11}$$

10^{-35} s

10^{-11} s

10^{-5} s

~ 1 m

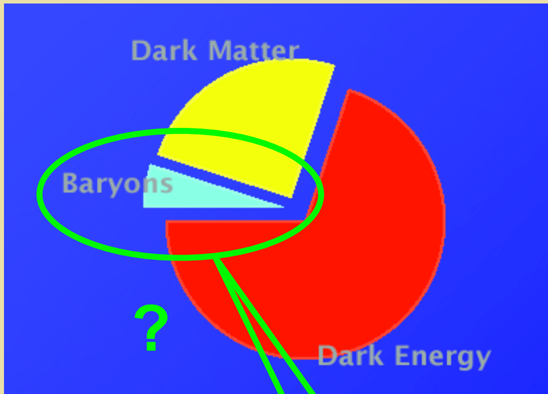
380k y

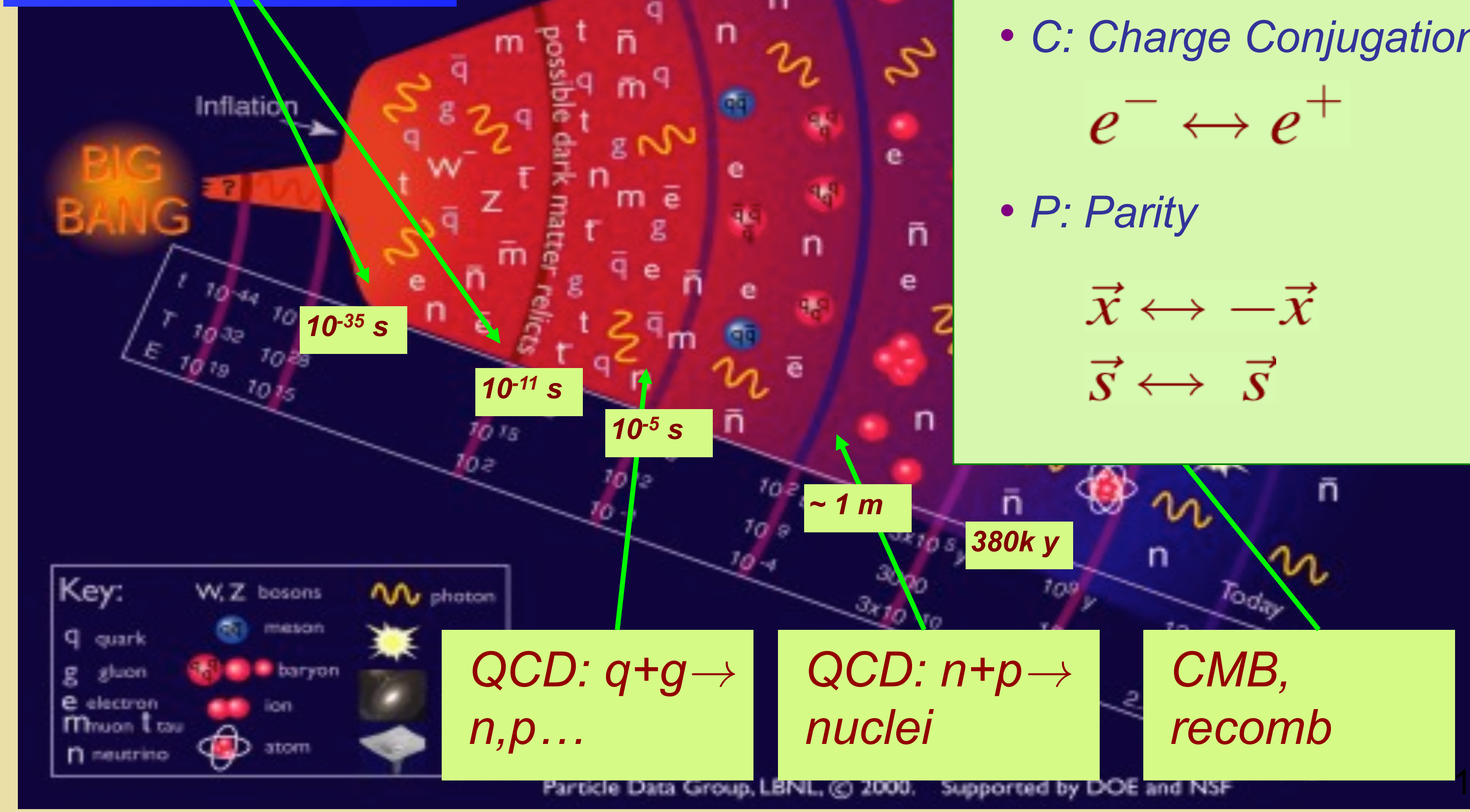
QCD: q+g→ n,p…

QCD: n+p→ nuclei

CMB, recomb

Symmetries & Cosmic History





EW Symmetry Breaking: Higgs

Baryogenesis: When? CPV? SUSY? Neutrinos?

- C: Charge Conjugation

$$e^- \leftrightarrow e^+$$

- P: Parity

$$\vec{x} \leftrightarrow -\vec{x}$$
$$\vec{s} \leftrightarrow \vec{s}$$

10^{-35} s

10^{-11} s

10^{-5} s

~ 1 m

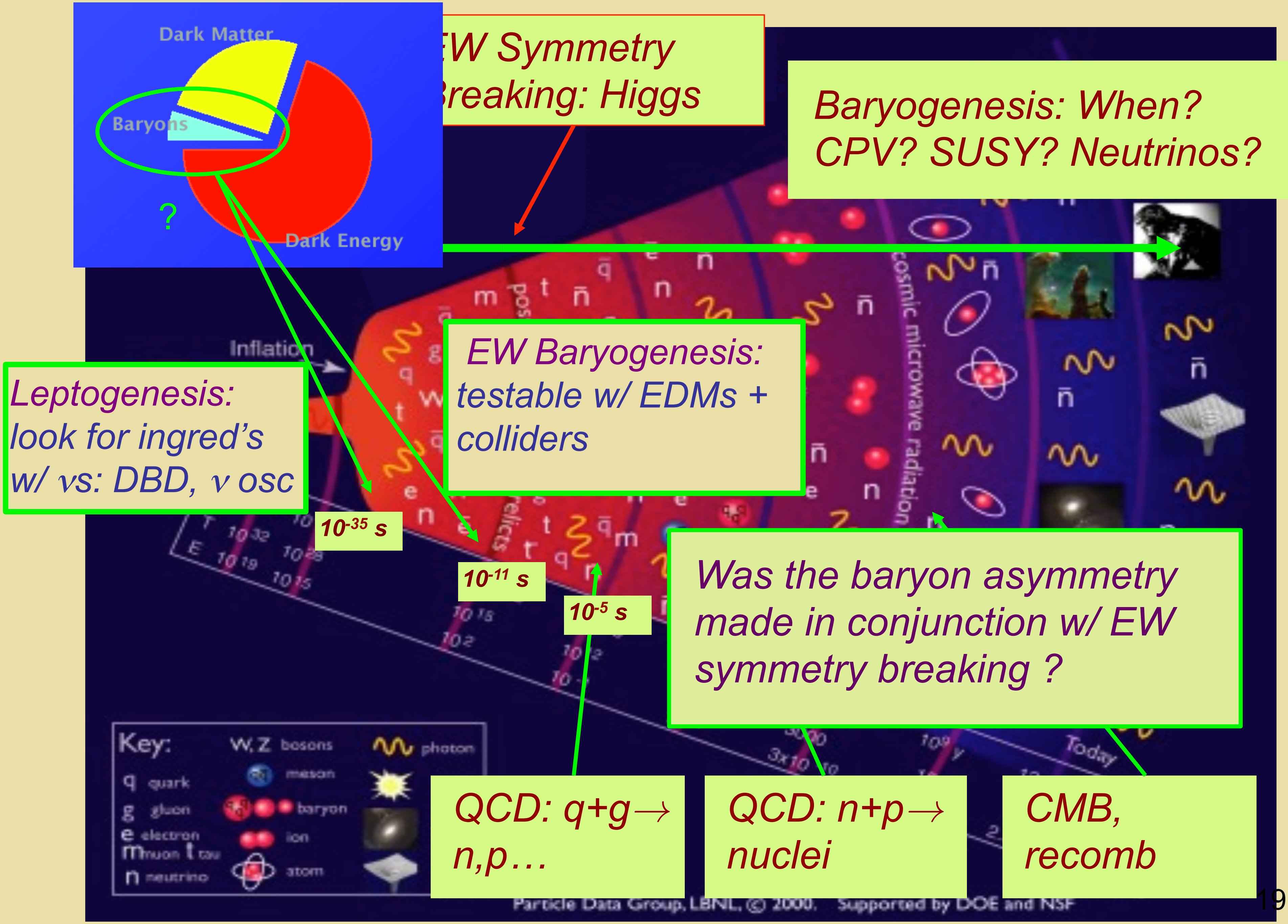
380k y

QCD: q+g→ n,p…

QCD: n+p→ nuclei

CMB, recomb

Symmetries & Cosmic History



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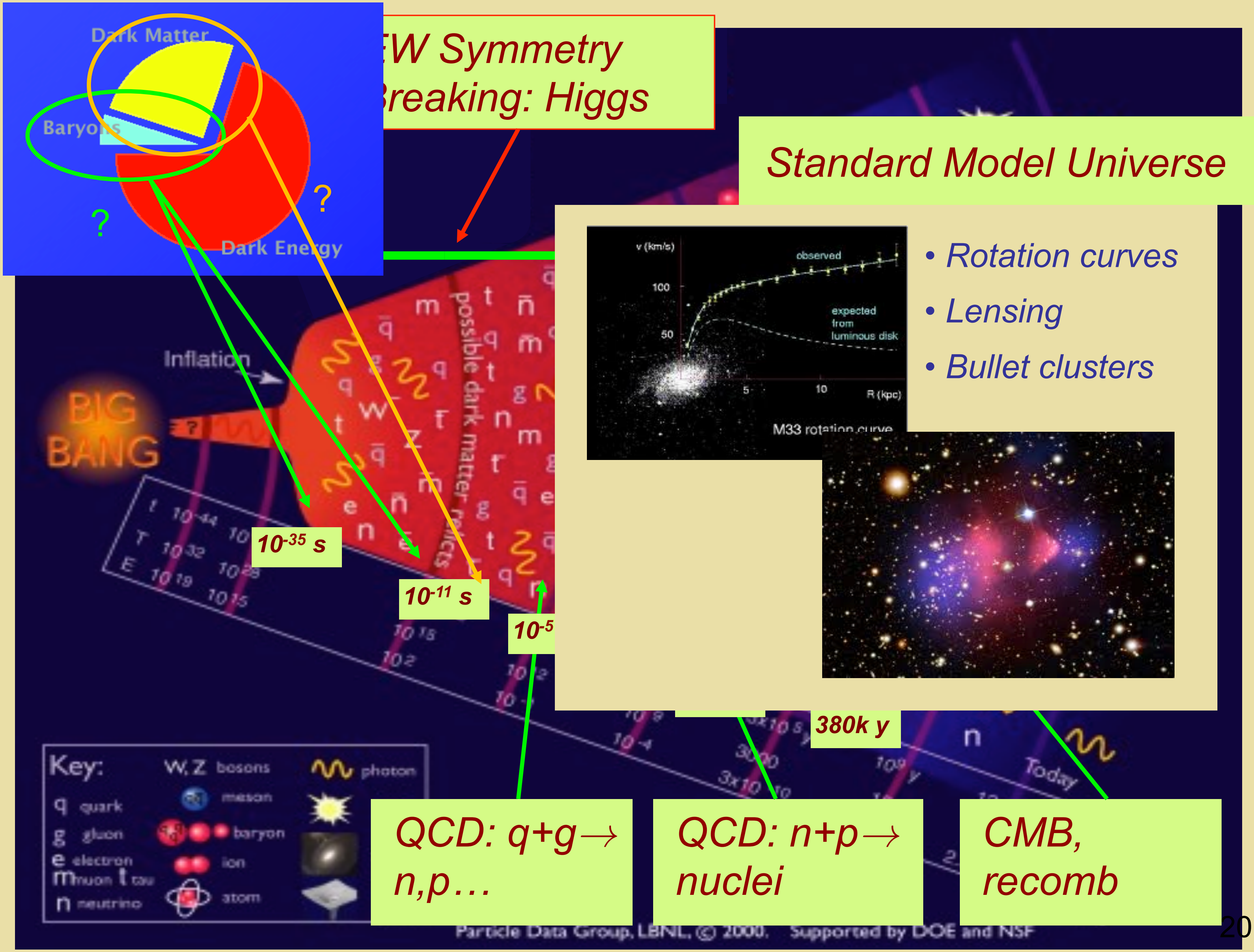

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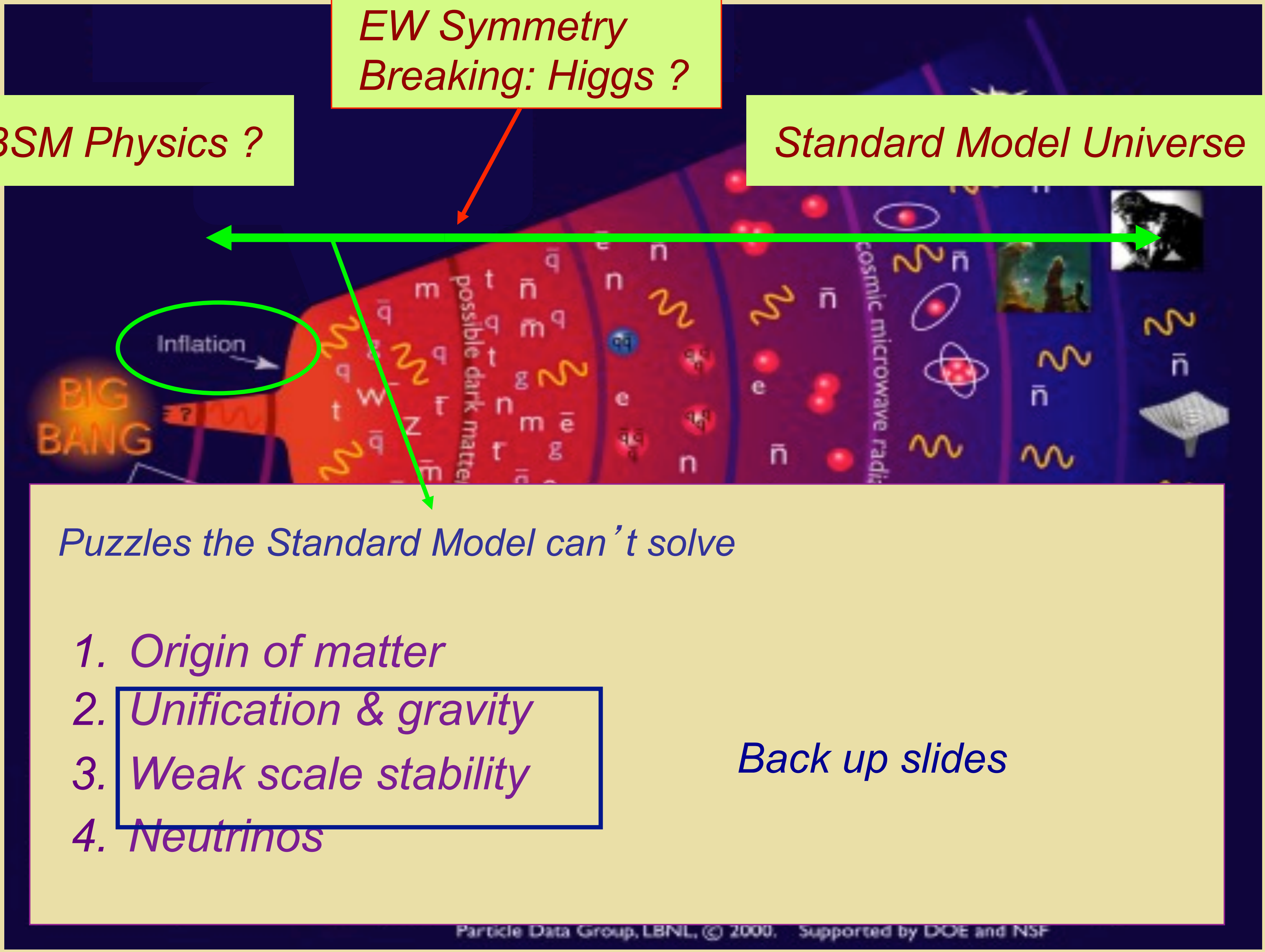


EW Symmetry Breaking: Higgs ?

BSM Physics ?

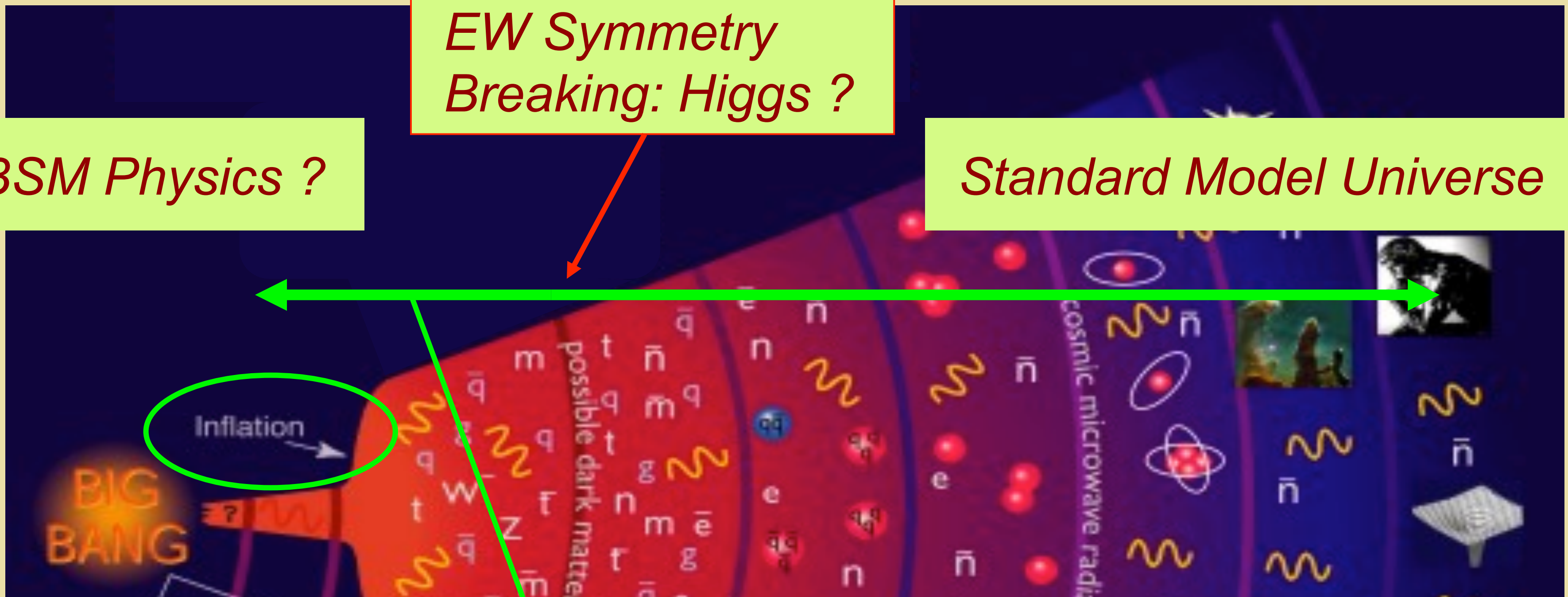
Standard Model Universe

Puzzles the Standard Model can't solve

1. *Origin of matter*
2. *Unification & gravity*
3. *Weak scale stability*
4. *Neutrinos*

Back up slides

Symmetries & Cosmic History



EW Symmetry Breaking: Higgs ?

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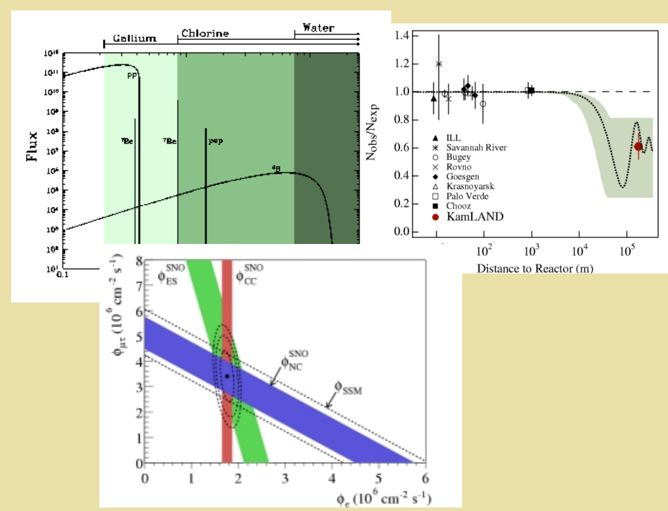
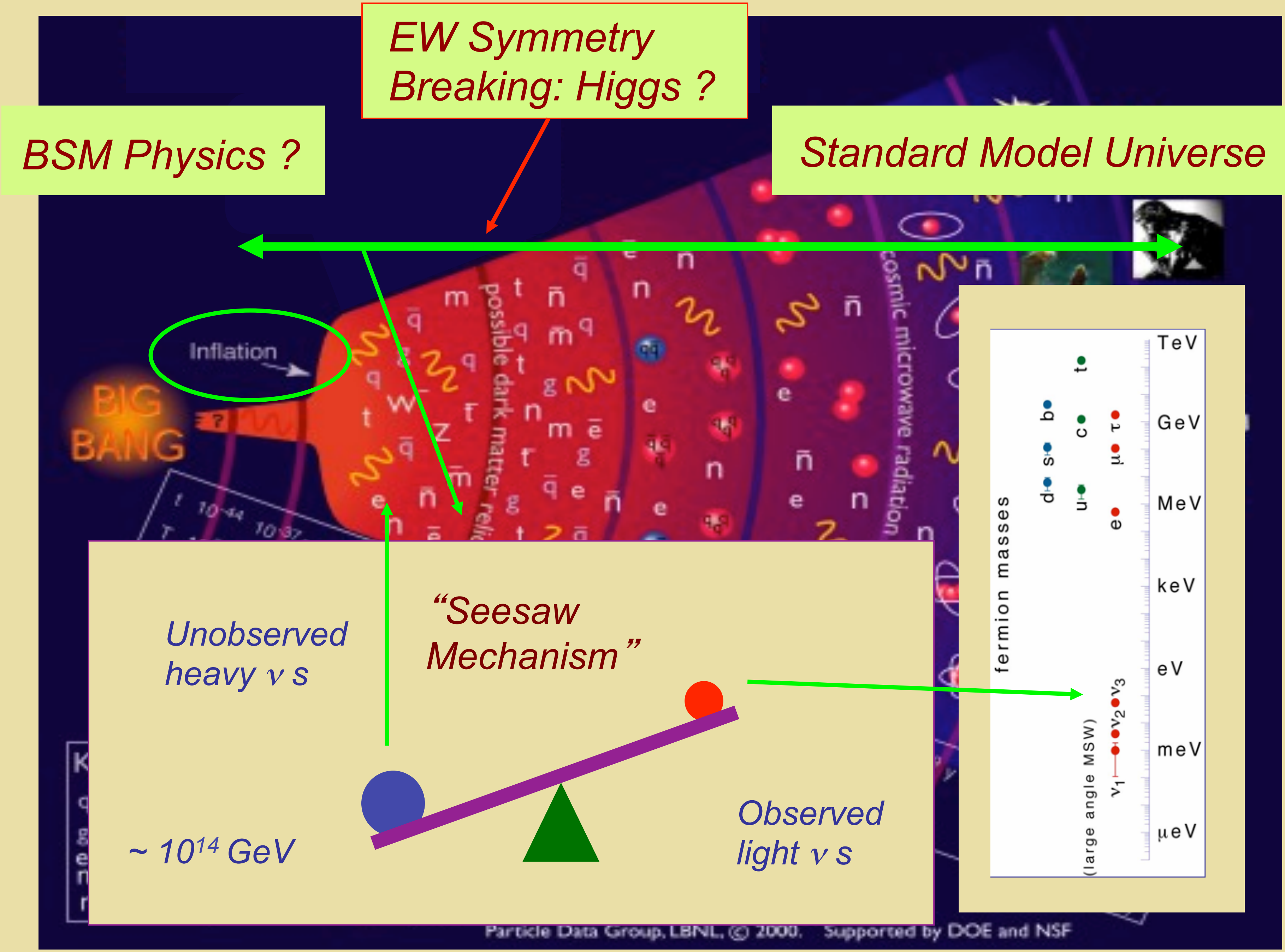
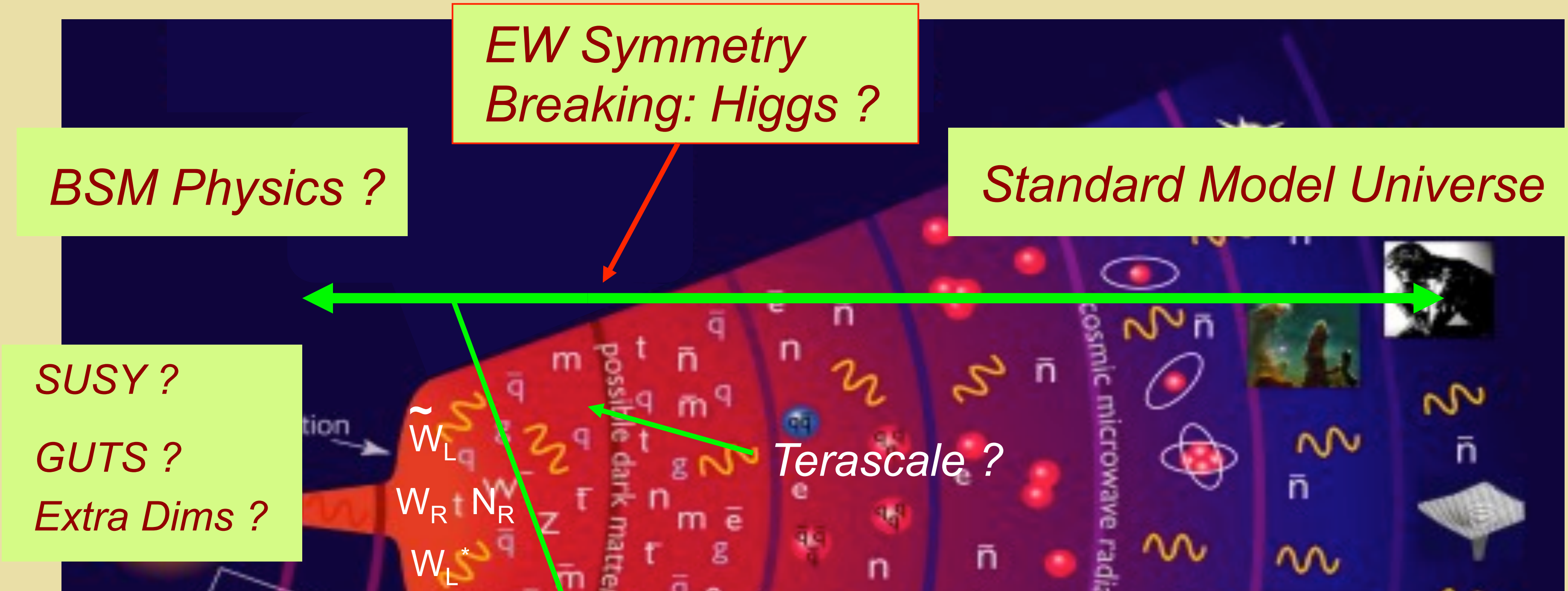


Neutrinos & the Flavor Problem



Symmetries & Cosmic History



Puzzles the Standard Model can't solve

1. *Origin of matter*
2. *Unification & gravity*
3. *Weak scale stability*
4. *Neutrinos*

What are the symmetries & particles of the early universe beyond those of the SM?

What is the associated mass scale?

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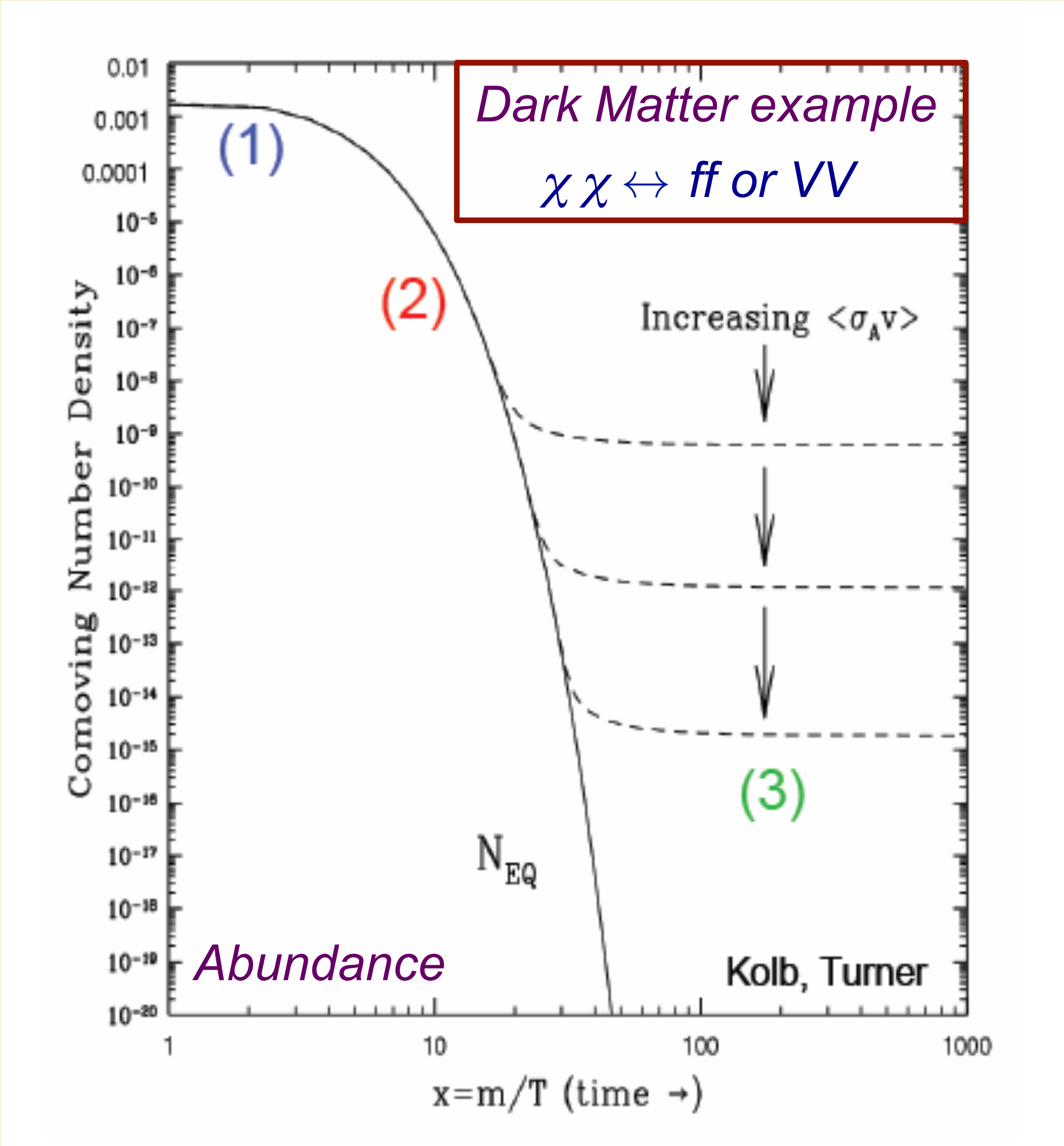
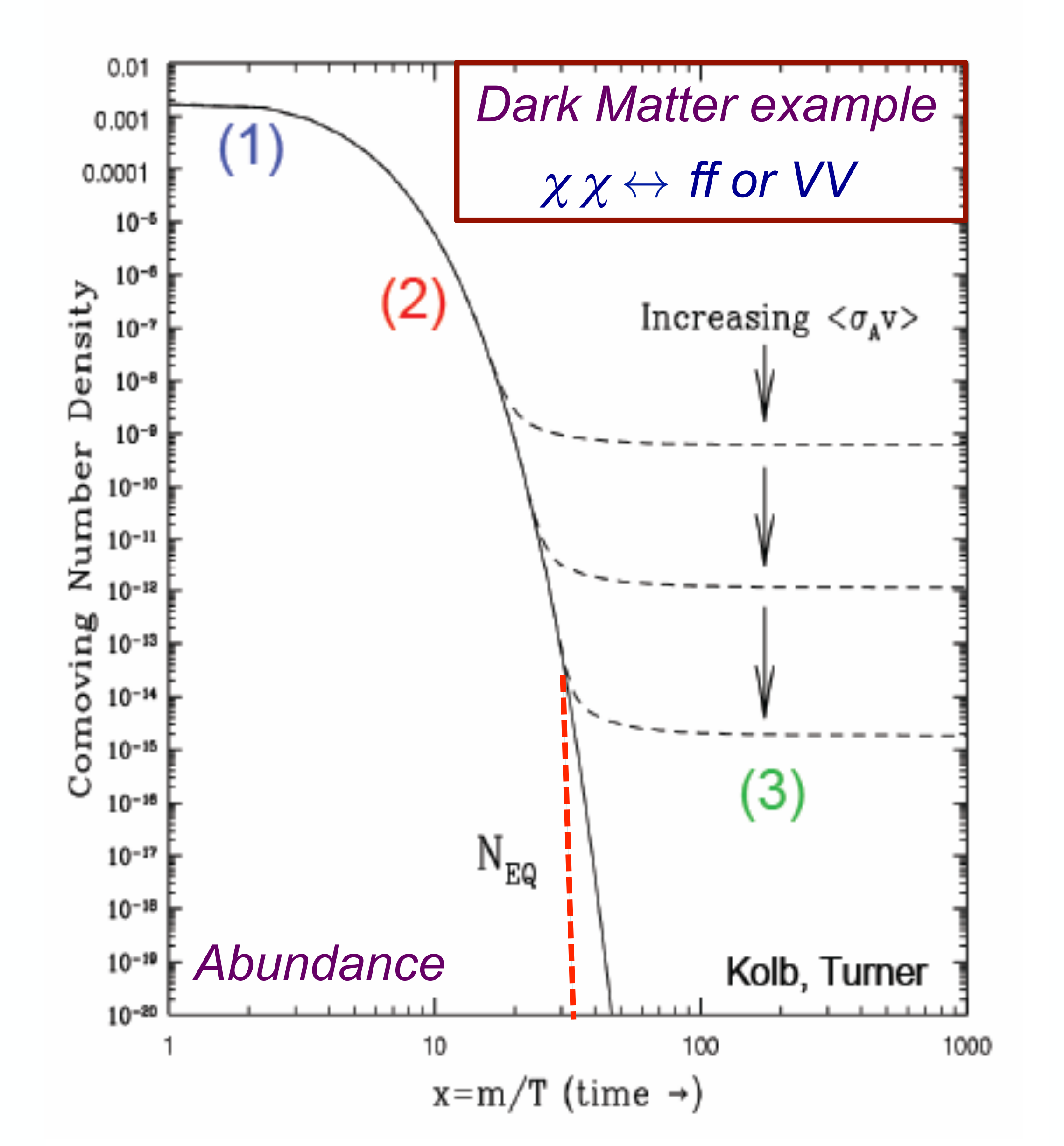
Relating Time, Temperature, & Mass



Boltzmann Eqs:

1) $N \sim N_{EQ}$
2) N starts to depart from N_{EQ}
3) N "freezes out" at x_f

Freeze Out



Boltzmann Eqs:

1) $N \sim N_{EQ}$
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3) N "freezes out" at x_f

$x_f \sim \mathcal{O}(10) \rightarrow$

$T \sim m / 10$

II. General Relativity & Thermodynamics

How do we relate time & temperature in the early universe ?

Expanding, Isotropic, Flat Universe

Einstein

$$G_{\mu\nu} = 8\pi G T_{\mu\nu}$$

Einstein Tensor: Built out of metric tensor $g_{\mu\nu}$

Energy-Momentum Tensor: Built out of energy density & pressure

Dependence on time

Dependence on temperature

Expanding, Isotropic, Flat Universe

Friedman-Robertson-Walker

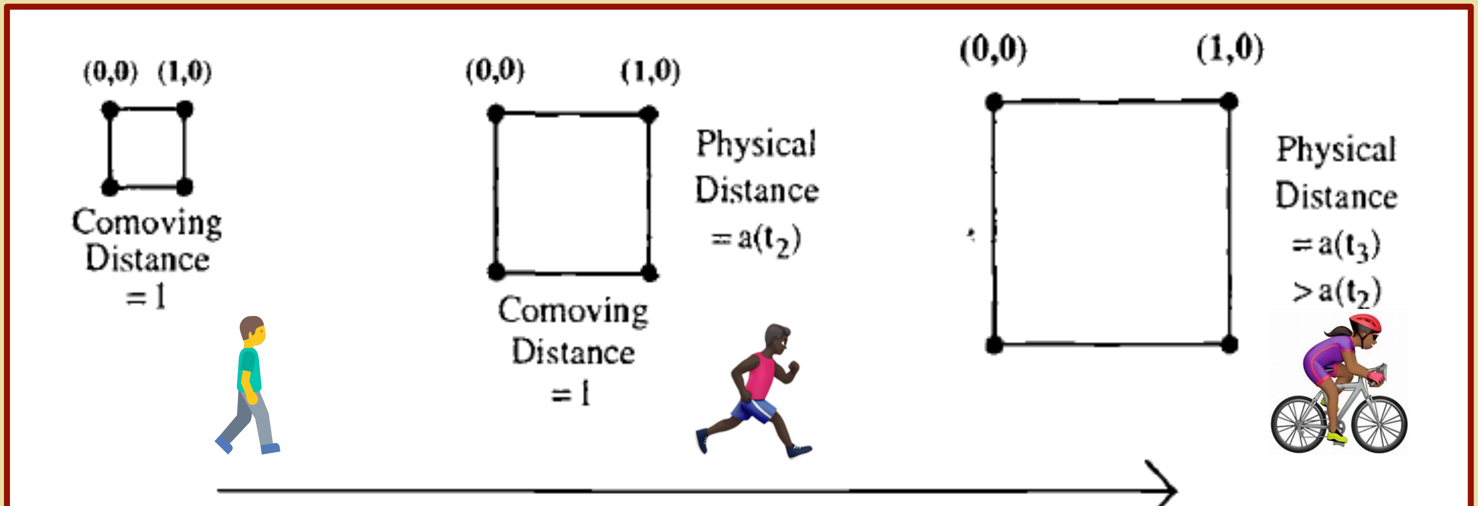
$$g_{\mu\nu} = \mathrm{diag}\left(1, -a^2, -a^2, -a^2\right)$$

- *Isotropic*
- *Expanding: a = a(t)*
- *Flat*

Expanding, Isotropic, Flat Universe

Friedman-Robertson-Walker

$$g_{\mu\nu} = \mathrm{diag}\left(1, -a^2, -a^2, -a^2\right)$$



S. Dodelson

Expanding, Isotropic, Flat Universe

Einstein & Friedman-Robertson-Walker

$$G_{00} = 8\pi G T_{00} = 8\pi G \rho \qquad G_{00} = 3\left(\frac{\dot{a}}{a}\right)^2$$

Expansion rate (time evolution) →

$$\left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi}{3} G\rho$$

← Energy density (temperature)

"Friedman Equation" (flat universe)

Expanding, Isotropic, Flat Universe

Hubble Rate

$$H(t) \equiv \frac{\dot{a}}{a}$$

Hubble Rate Today

$$H_0 = h\left[0.98 \times 10^{10}\,\mathrm{yr}\right]^{-1}$$

Relativistic particles

$$\rho = \begin{cases} \left(\frac{\pi^2}{30}\right) g T^4 & \text{bosons} \\ \\ \left(\frac{7}{8}\right)\left(\frac{\pi^2}{30}\right) g T^4 & \text{fermions} \end{cases}$$

Relating Time & Temperature

Friedman equation

$$H(t)^2 = \frac{8\pi}{3} G \left(\frac{\pi^2}{30}\right) g_* T^4$$

Time evolution of a

$$a \propto \begin{cases} t^{1/2} \,, & \text{radiation} \\ t^{2/3} \,, & \text{matter} \\ \exp(H_0 t) \,, & \text{vacuum} \end{cases}$$

Reduced Planck Mass

$$G = \frac{1}{8\pi M_P^2}$$

$$M_P = 2.435 \times 10^{18}\,\text{GeV}$$

Relating Time & Temperature

Radiation era

$$a \propto t^{1/2} \longrightarrow \frac{\dot{a}}{a} = \frac{1}{2t}$$

$$t = \frac{1}{2H}$$

$$H(t) = \left[\left(\frac{\pi^2}{90}\right) g_*\right]^{1/2} \frac{T^2}{M_P}$$

Relating Time & Temperature

Radiation era

$$\frac{t_2}{t_1} = \left(\frac{T_1}{T_2}\right)^2$$

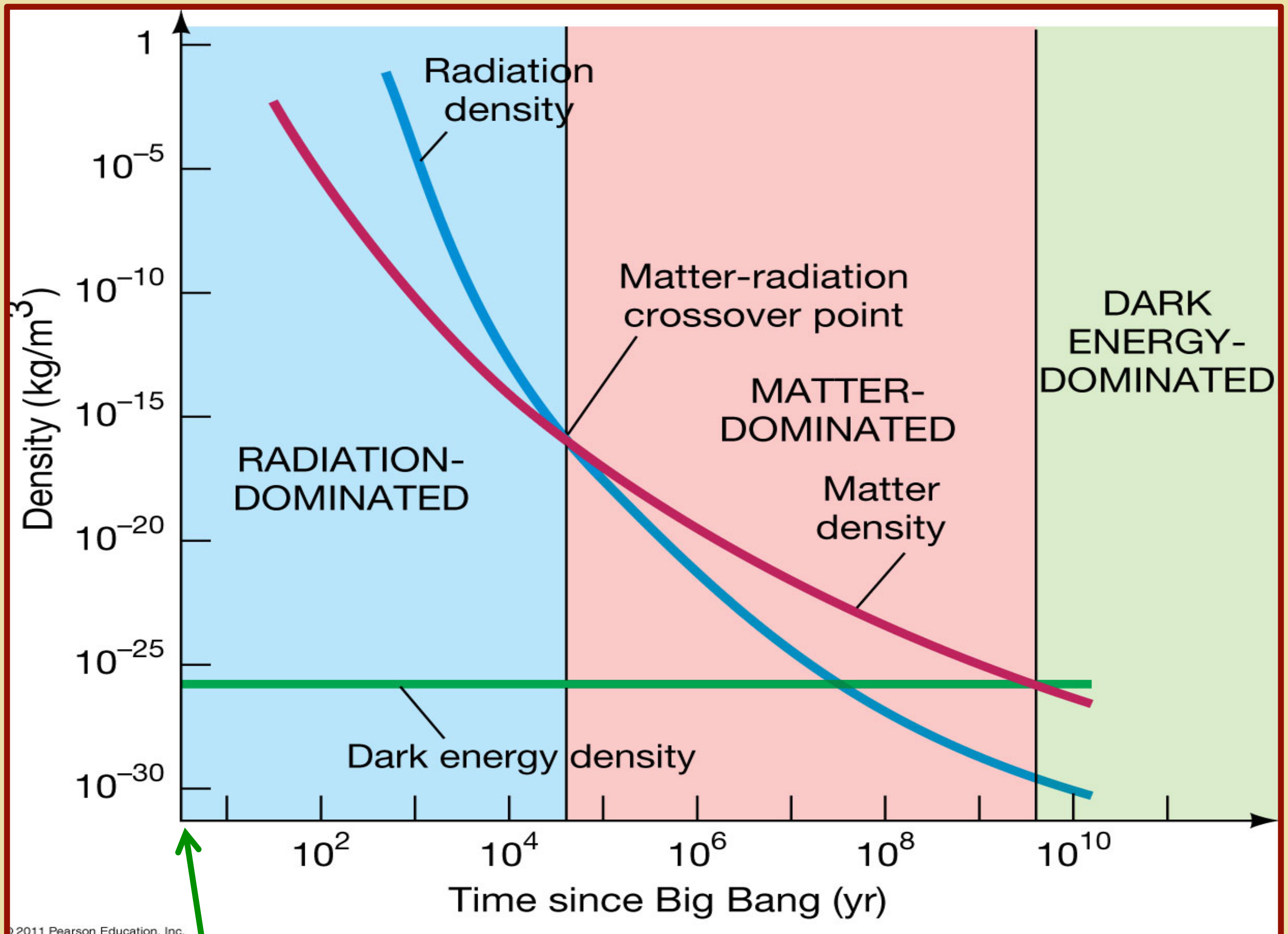
Radiation, Matter, & Vacuum Epochs

Dependence of ρ on a

$$\rho \propto \begin{cases} a^{-4}\ , & \text{radition dominated} \\ \\ a^{-3}\ , & \text{matter dominated} \end{cases}$$

Vacuum epoch: ρ independent of a

Radiation, Matter, & Vacuum Epochs



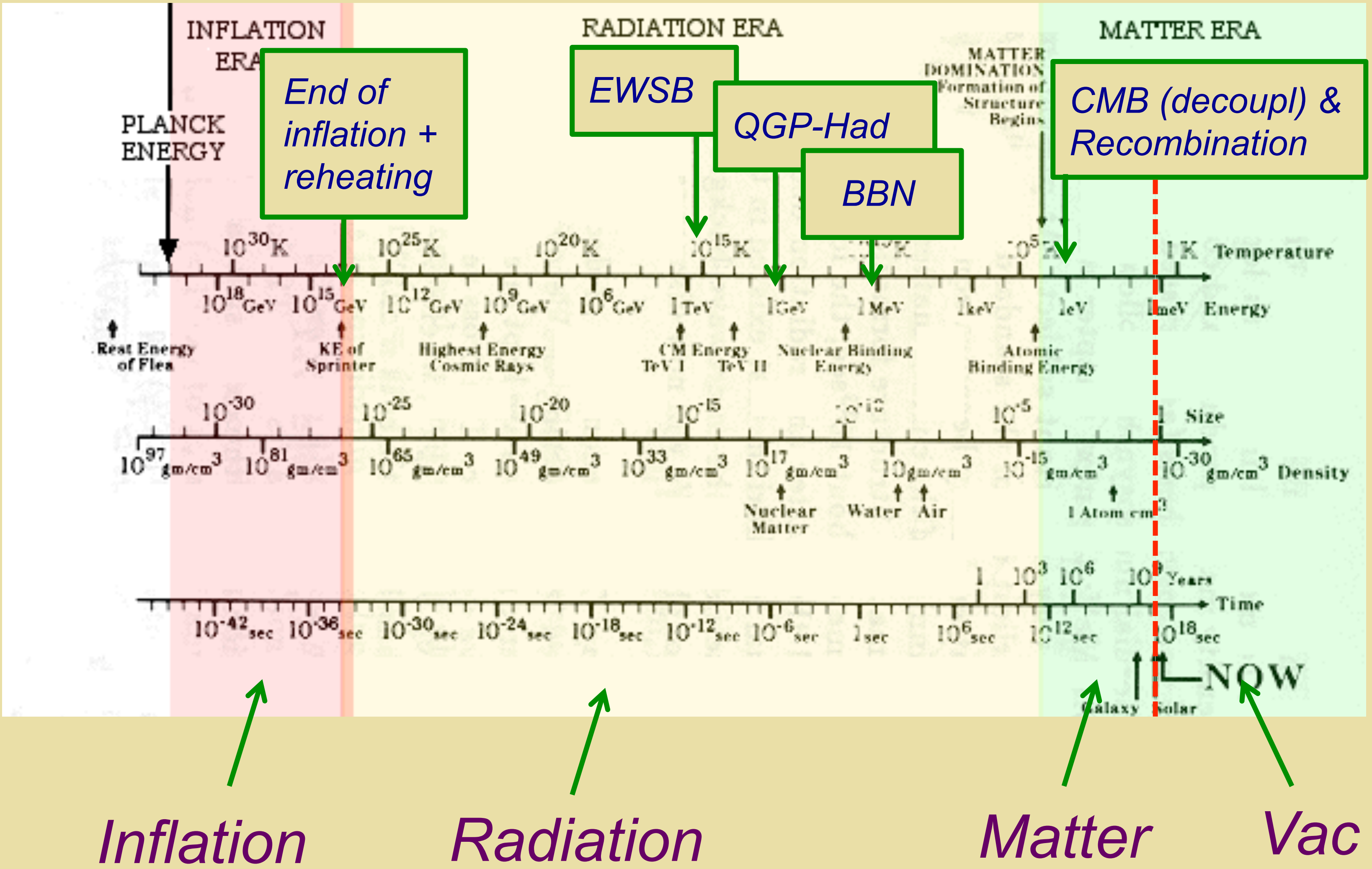
Particle physics

J. Brau, U. Oregon

Relating Time & Temperature

	Time	Temperature	Dynamics
Radiation era	10^{-35} s	10^{27} K	Inflation ends
	10^{-11} s	10^{15} K	EWSB
	10^{-5} s	10^{12} K	Confinement
	10 s	10^{9} K	BBN
Matter era	380k Yr	2.7 K	Recomb

Thermal History



Particle Decoupling & Freeze Out

Number Density & Entropy

Comoving (a-independent) :

$$Y = \frac{n}{s}$$

Relativistic species in equilibrium

$$Y_{\rm rel}^{\rm EQ} = \frac{45\zeta(3)g}{2\pi^4 g_{*s}}$$

Non-relativistic species in equilibrium

$$Y_{\rm non-rel}^{\rm EQ} = \frac{45g}{4\sqrt{2}\pi^5 g_{*s}} \left(\frac{M}{T}\right)^{3/2} \exp\left[\frac{-M+\mu}{T}\right]$$

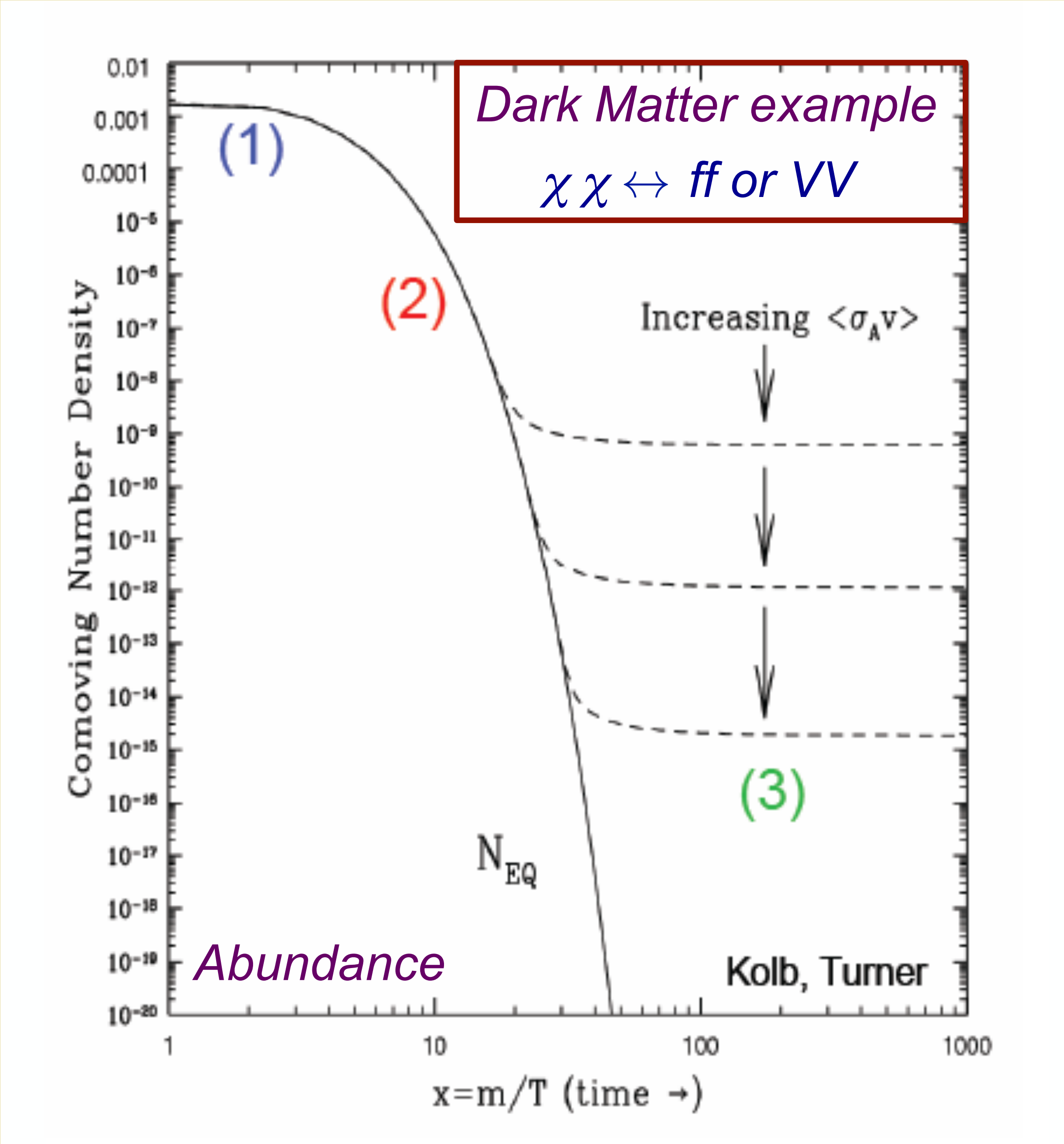
Boltzmann Equations (Classical)

$$\frac{dY_N}{dz} = -\left(D + S\right)\left(Y_N - Y_N^{\mathrm{EQ}}\right) - A\left[Y_N^2 - \left(Y_N^{\mathrm{EQ}}\right)^2\right]$$

Decay *Scattering* *Annihilation*

$$z \equiv \frac{M}{T}$$

Particle Abundances: t, T, & m



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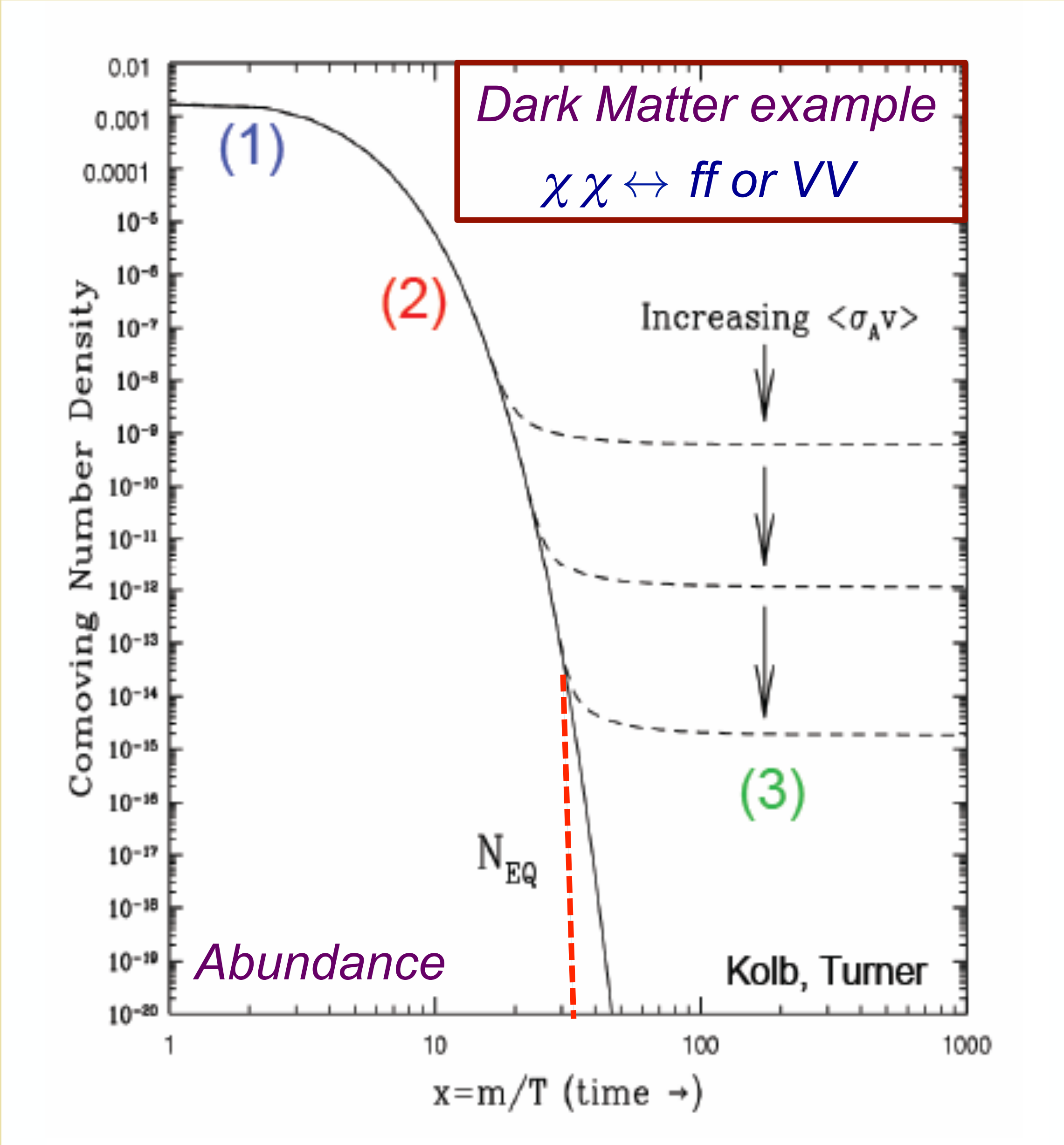

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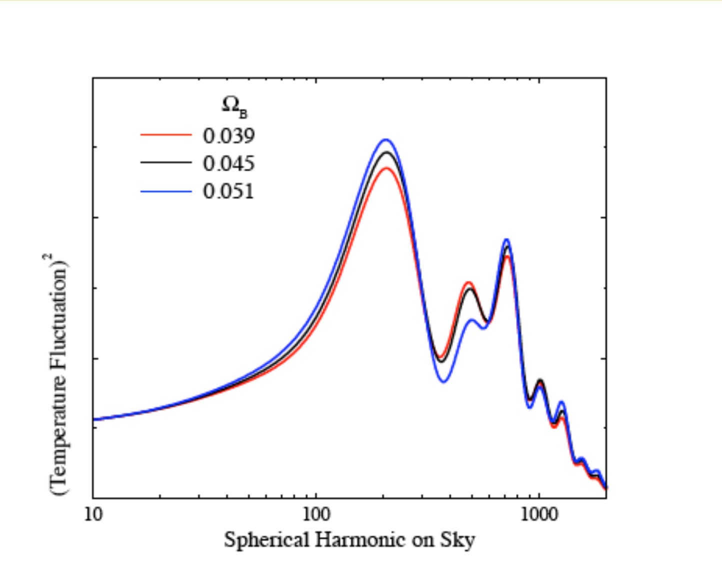
III. Matter-Antimatter Asymmetry

Cosmic Baryon Asymmetry

$$Y_B = \frac{n_B}{s} = (8.59 \pm 0.11) \times 10^{-11}$$

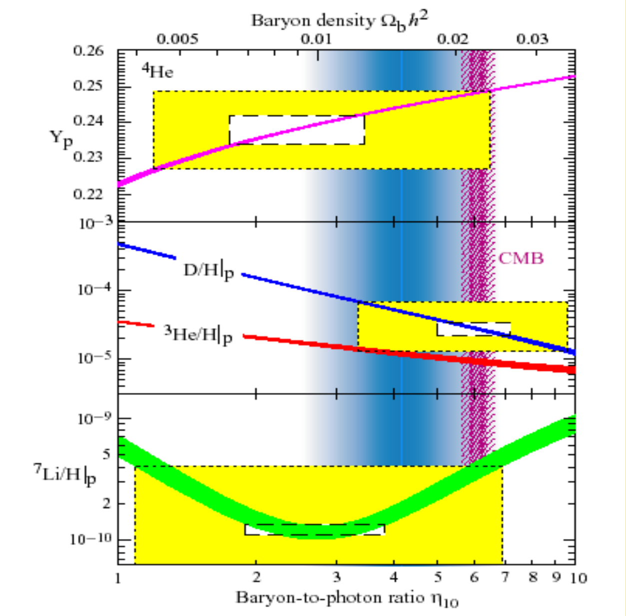
Cosmic Microwave Bcknd:

Shape of anisotropies depends on Y_B

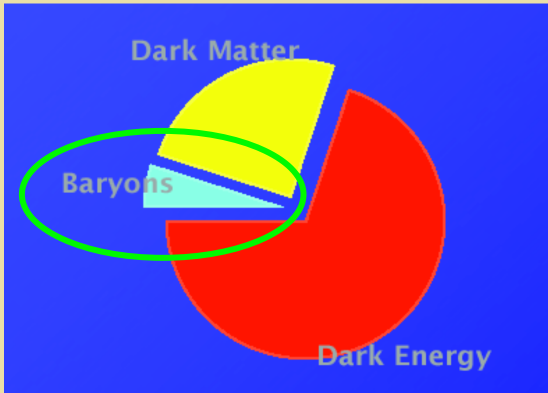


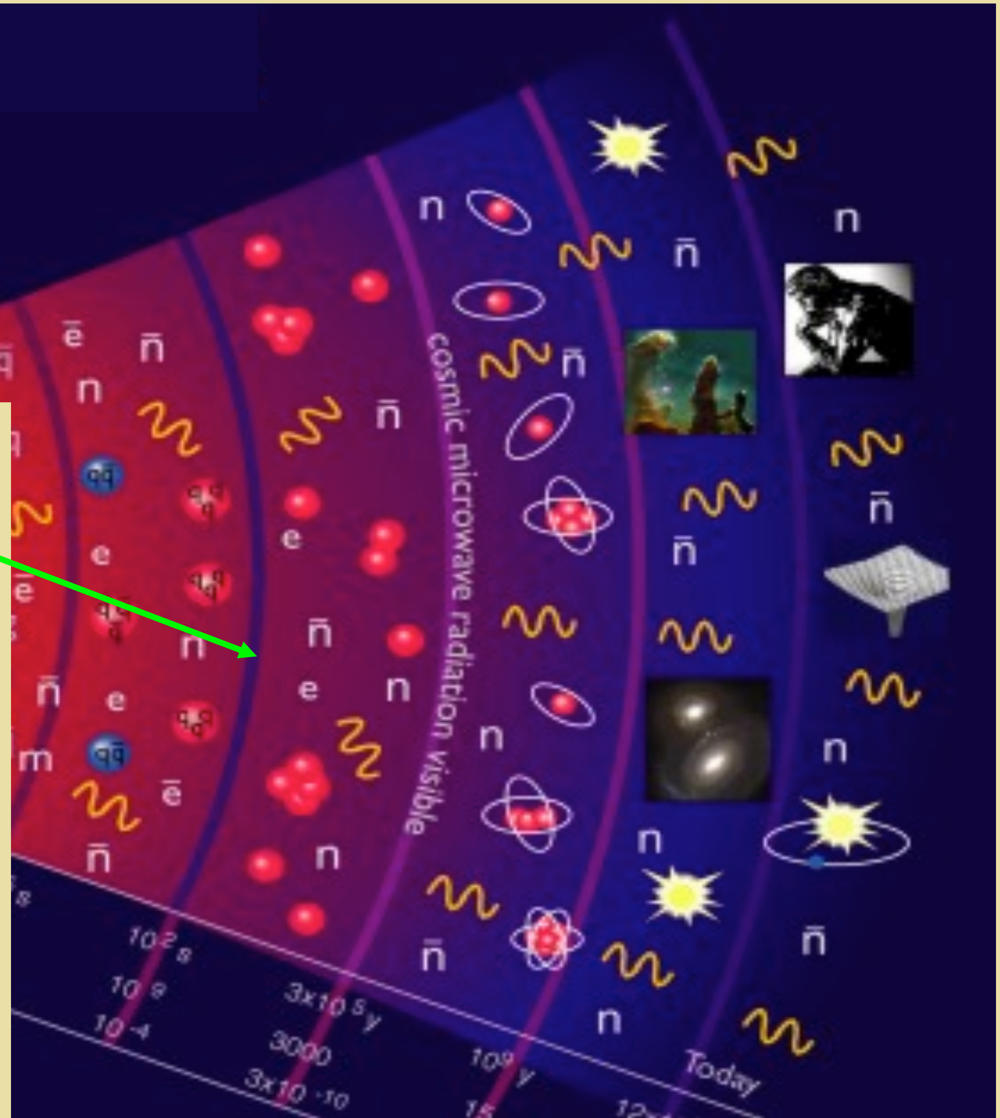
Big Bang Nucleosynthesis:

Light element abundances depend on Y_B



Cosmic Baryon Asymmetry





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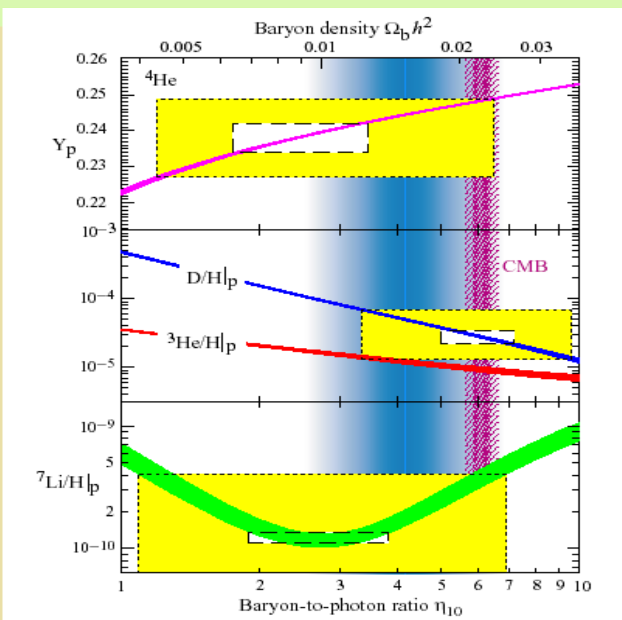
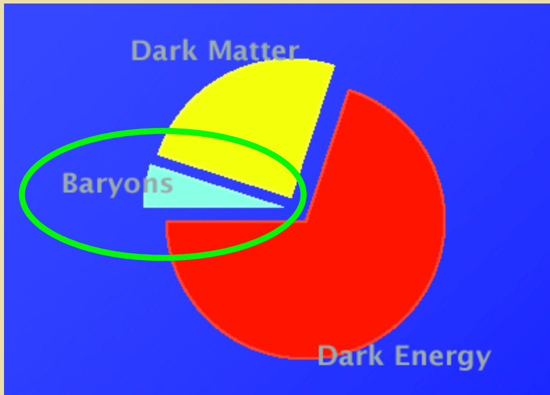
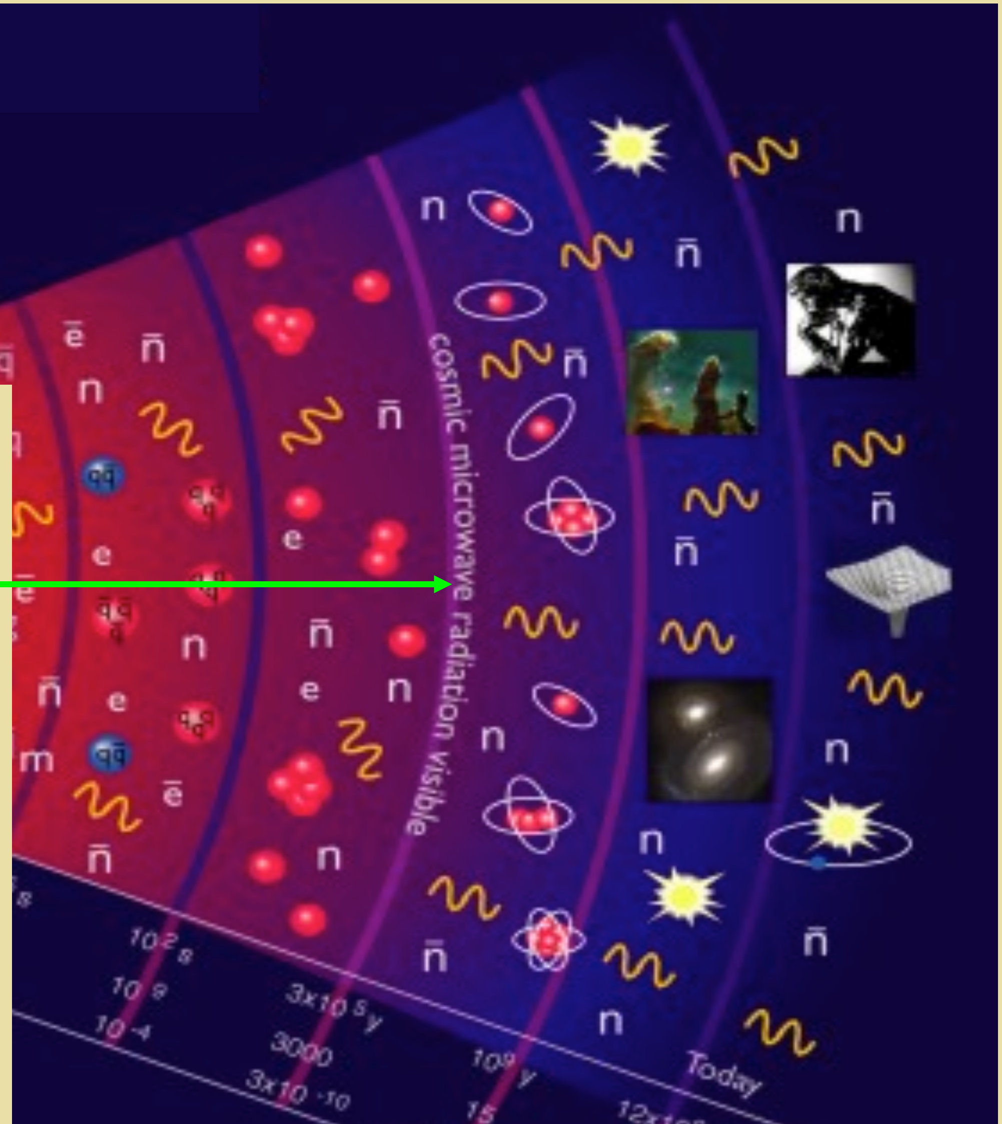


$$Y_B = \frac{n_B}{s} = (8.59 \pm 0.11) \times 10^{-11}$$

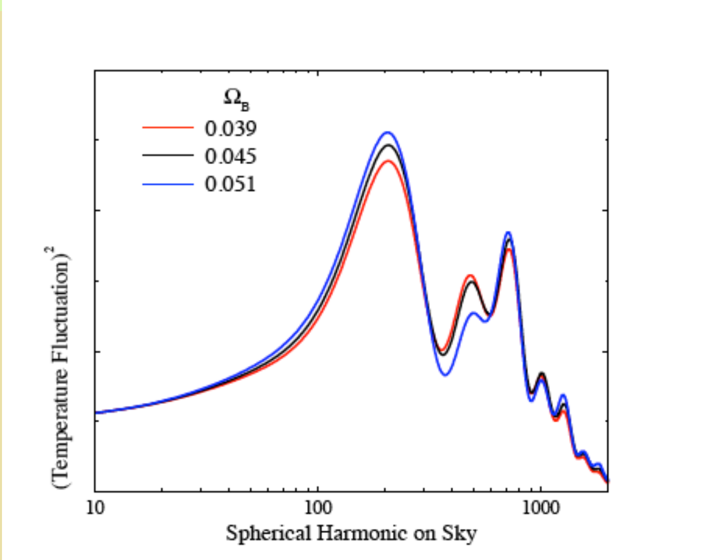
Cosmic Baryon Asymmetry





Cosmic Microwave Bcknd:

Shape of anisotropies depends on Y_B



$$Y_B = \frac{n_B}{s} = (8.59 \pm 0.11) \times 10^{-11}$$

Segregated Matter & Antimatter ?

- *Absence of γ-rays $\rightarrow$ Must separate on scales of > 10^{15} $M_\odot$ (See, e.g., Steigman '08)*
- *$N\overline{N}$ annihilation in equilibrium down to ~ 22 MeV $\rightarrow$ $n_B / s \sim n_{\overline{B}} / s \sim 7 \times 10^{-20}$*
- *At T ~ 38 MeV $n_B / s \sim n_{\overline{B}} / s \sim 8 \times 10^{-11}$ $\rightarrow$ New mechanism to separate N & $\overline{N}$ needed*
- *At T ~ 38 MeV, horizon contains ~ 10^{-7} $M_\odot$ $\rightarrow$ Far too little to satisfy absence of X-rays*

Observed Y_B must result from early univ particle physics

Ingredients for Baryogenesis

- *B violation*
- *C & CP violation*
- *Out-of-equilibrium or CPT violation*

Ingredients for Baryogenesis

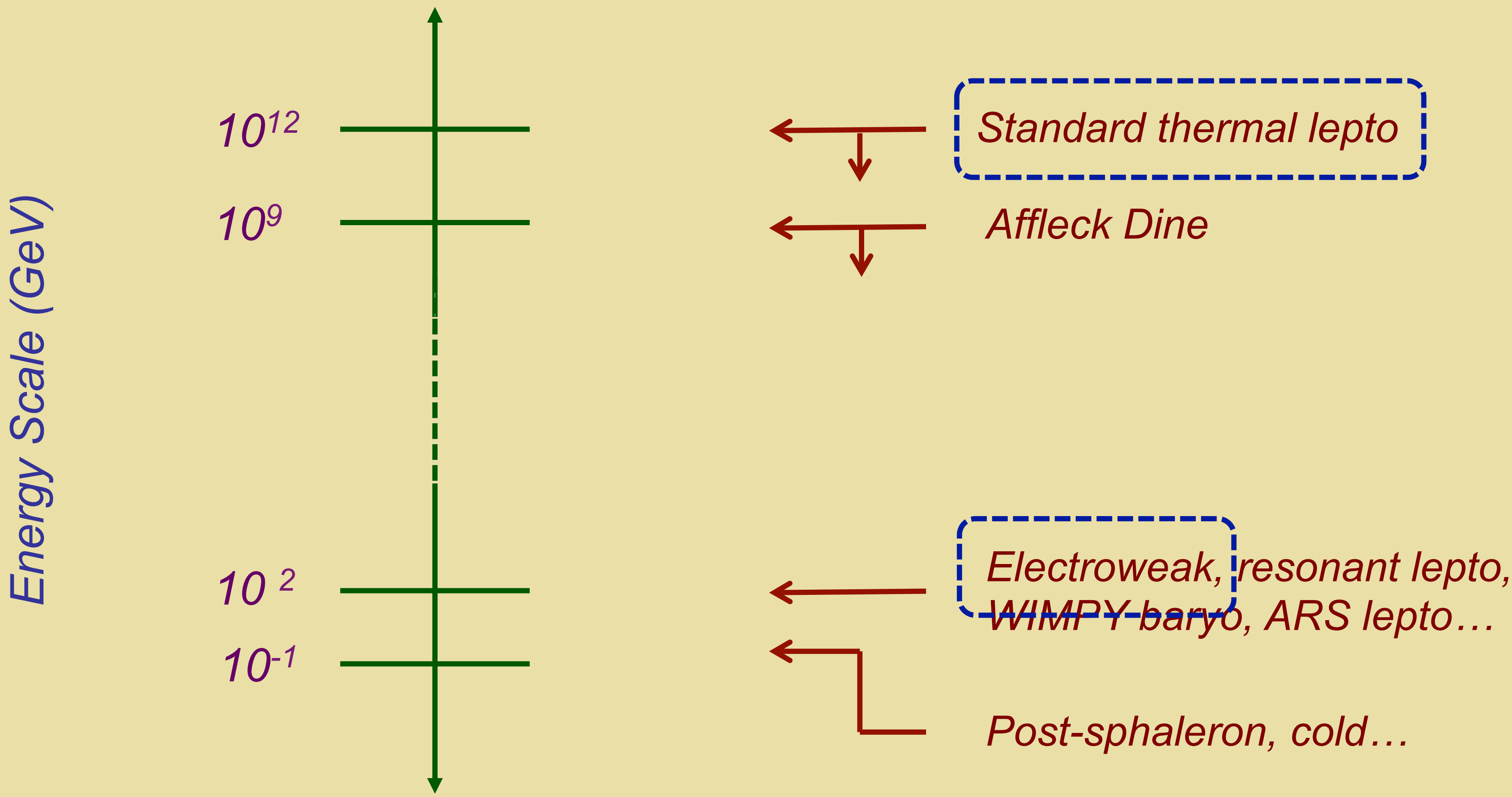
	Standard Model	*BSM*
• *B violation (sphalerons)*	✔	✔
• *C & CP violation*	✖	✔
• *Out-of-equilibrium or CPT violation*	✖	✔

Ingredients for Baryogenesis

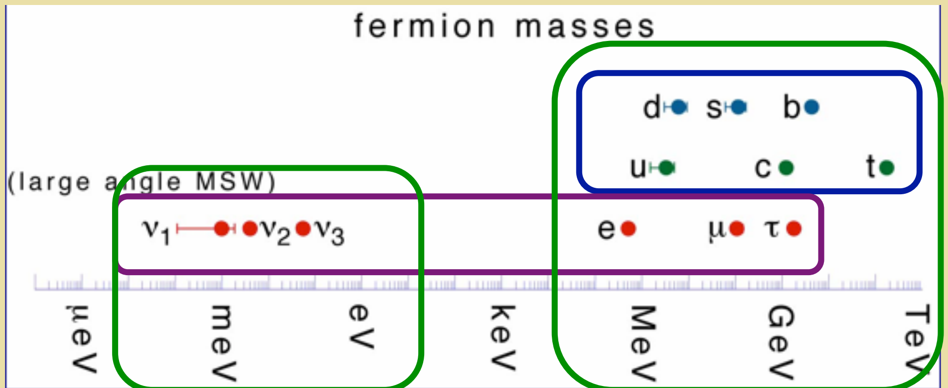
Scenarios: leptogenesis, EW baryogenesis, Afflek-Dine, asymmetric DM, cold baryogenesis, post-sphaleron baryogenesis…

	Standard Model	BSM
• B violation (sphalerons)	✔	✔
• C & CP violation	✖	✔
• Out-of-equilibrium or CPT violation	✖	✔

Baryogenesis Scenarios



Fermion Masses & Baryon Asymmetry



Partners

Partners

Something else ?

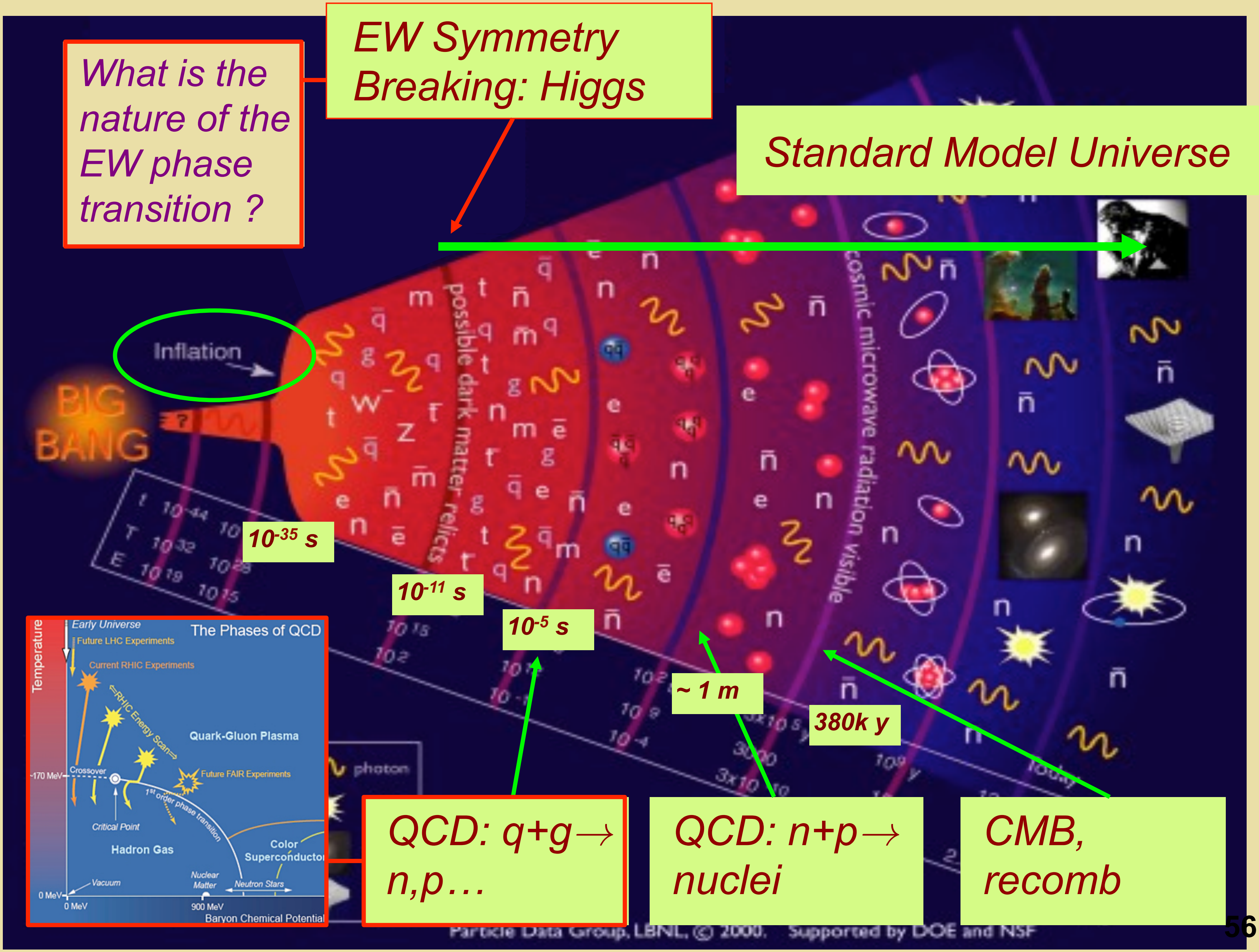
Higgs Mechanism

Leptogenesis: Baryon asymmetry & m_ν from lepton number violation

Electroweak baryogenesis: Baryon asymmetry & m_f from EW symmetry breaking

IV. Symmetry Breaking at Finite T

Symmetries & Cosmic History



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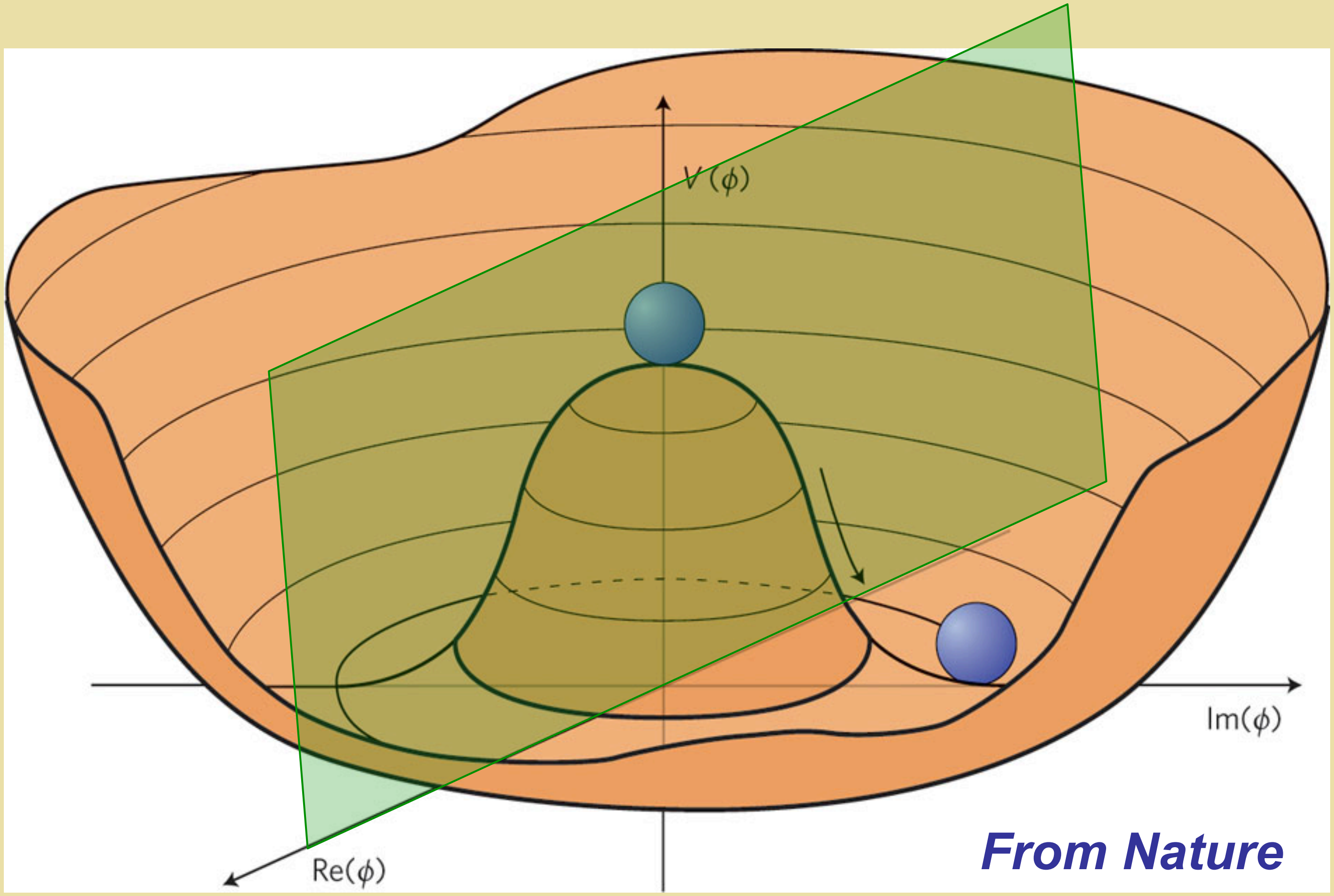
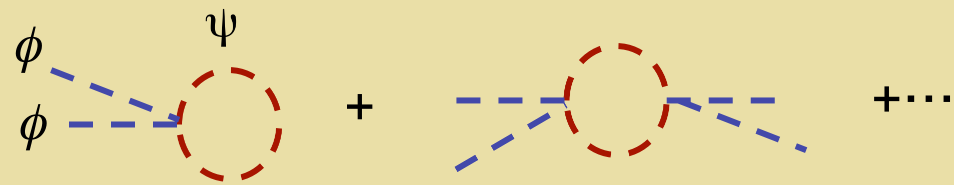


What was the thermal history of EWSB ?

Temperature Dependence of V(ϕ)

Effective Potential:



$$V_1(\phi_c, T) \;=\; \int \frac{d^3k}{(2\pi)^3}\; \tilde{I}[m(\phi_c)]$$

$$\beta \equiv \frac{1}{T}$$

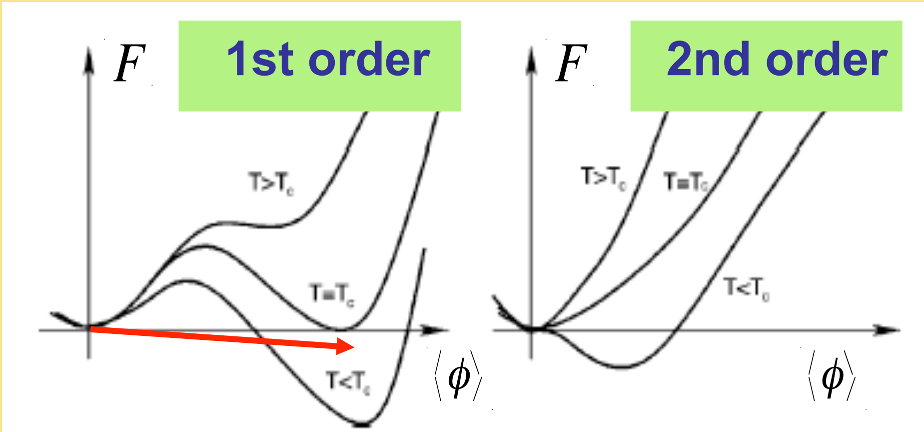
$$\tilde{I}[m(\phi_c)] \;=\; \frac{\omega}{2} + \frac{1}{\beta}\ln\left(1 - e^{-\beta\omega}\right)$$

$$\omega^2 = \vec{k}^2 + m^2(\phi_c)$$

T=0 part: Coleman-Weinberg

T-dependent part

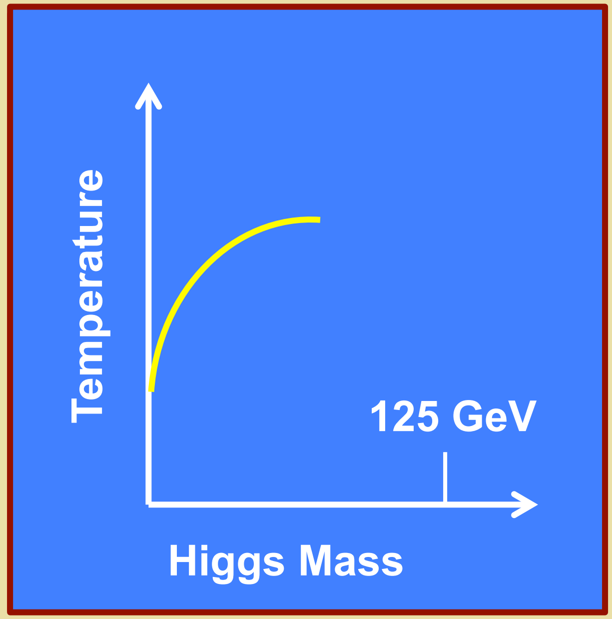
EW Phase Transition: St'd Model



Increasing m_h →

Lattice	Authors	M_h^C (GeV)
4D Isotropic	[76]	80 ± 7
4D Anisotropic	[74]	72.4 ± 1.7
3D Isotropic	[72]	72.3 ± 0.7
3D Isotropic	[70]	72.4 ± 0.9

SM EW: Cross over transition



EW Phase Diagram

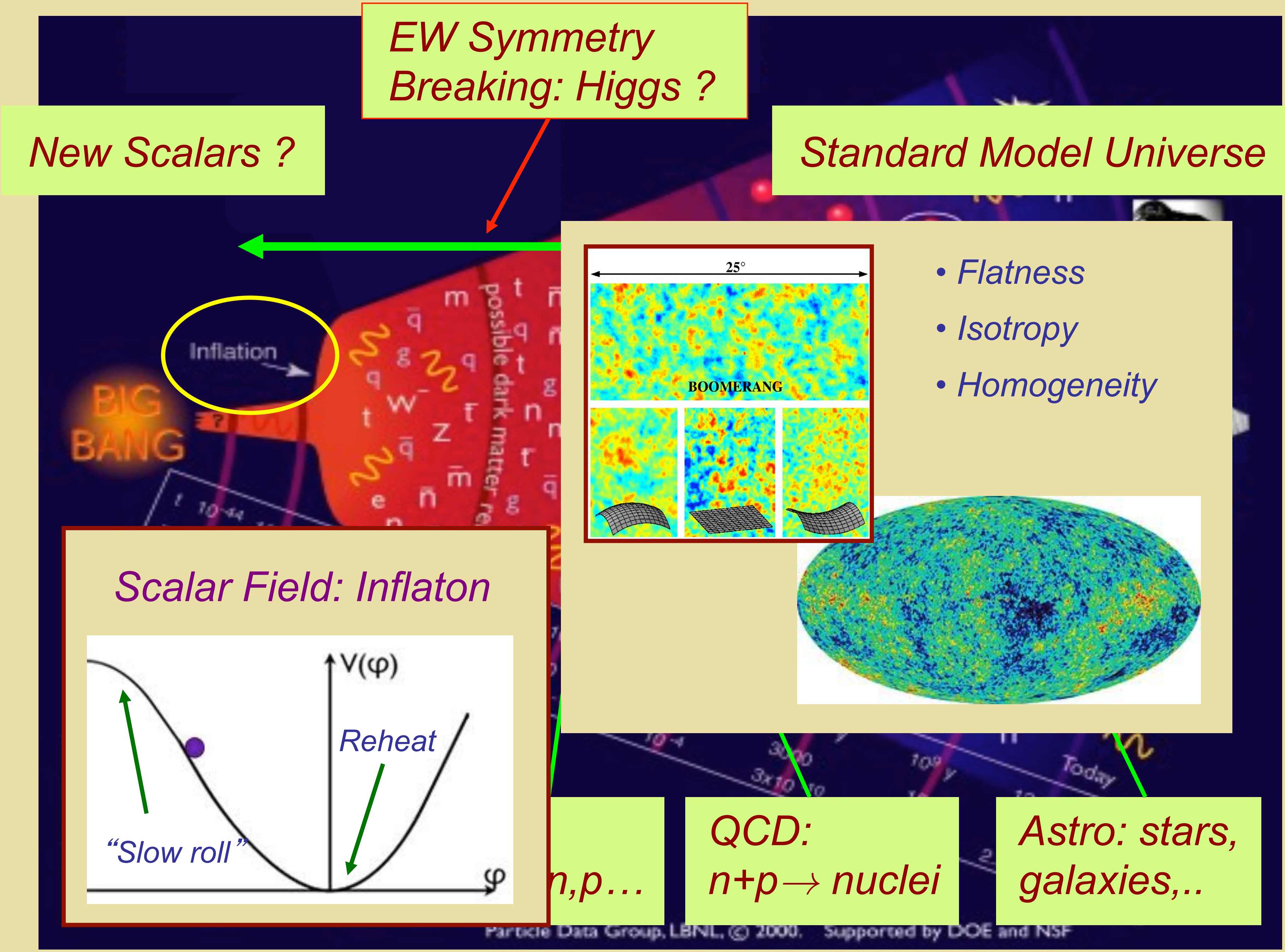
How does this picture change in presence of new TeV scale physics ? What is the phase diagram ?

Key Concepts

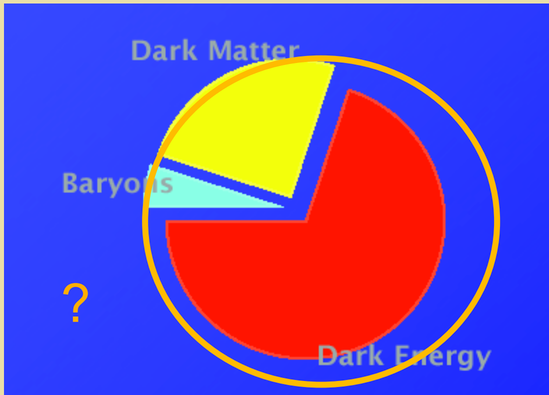
- *Einstein + FRW: linking time & temperature*
- *Thermal history: inflation, radiation era, matter era, & vacuum era*
- *Particle abundances & Boltzmann equations: linking interaction rates, masses, & T*
- *Baryon asymmetry & Sakharov conditions*
- *Thermal history of spontaneous symmetry breaking*

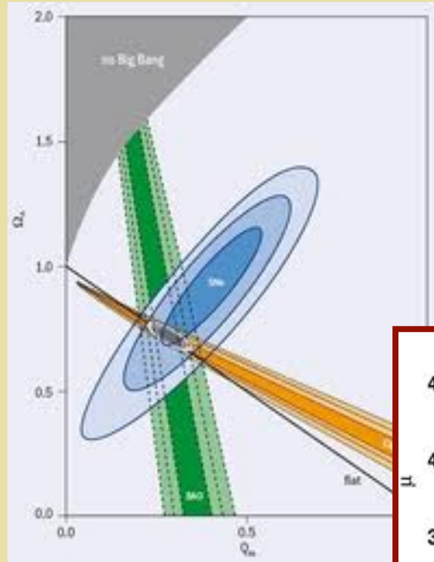
Back Up Slides

Symmetries & Cosmic History

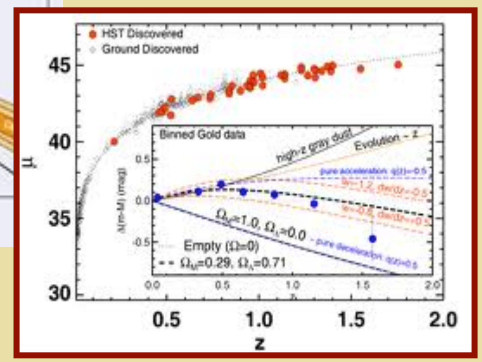


Symmetries & Cosmic History





- ΛCDM
- Supernovae
- BAO

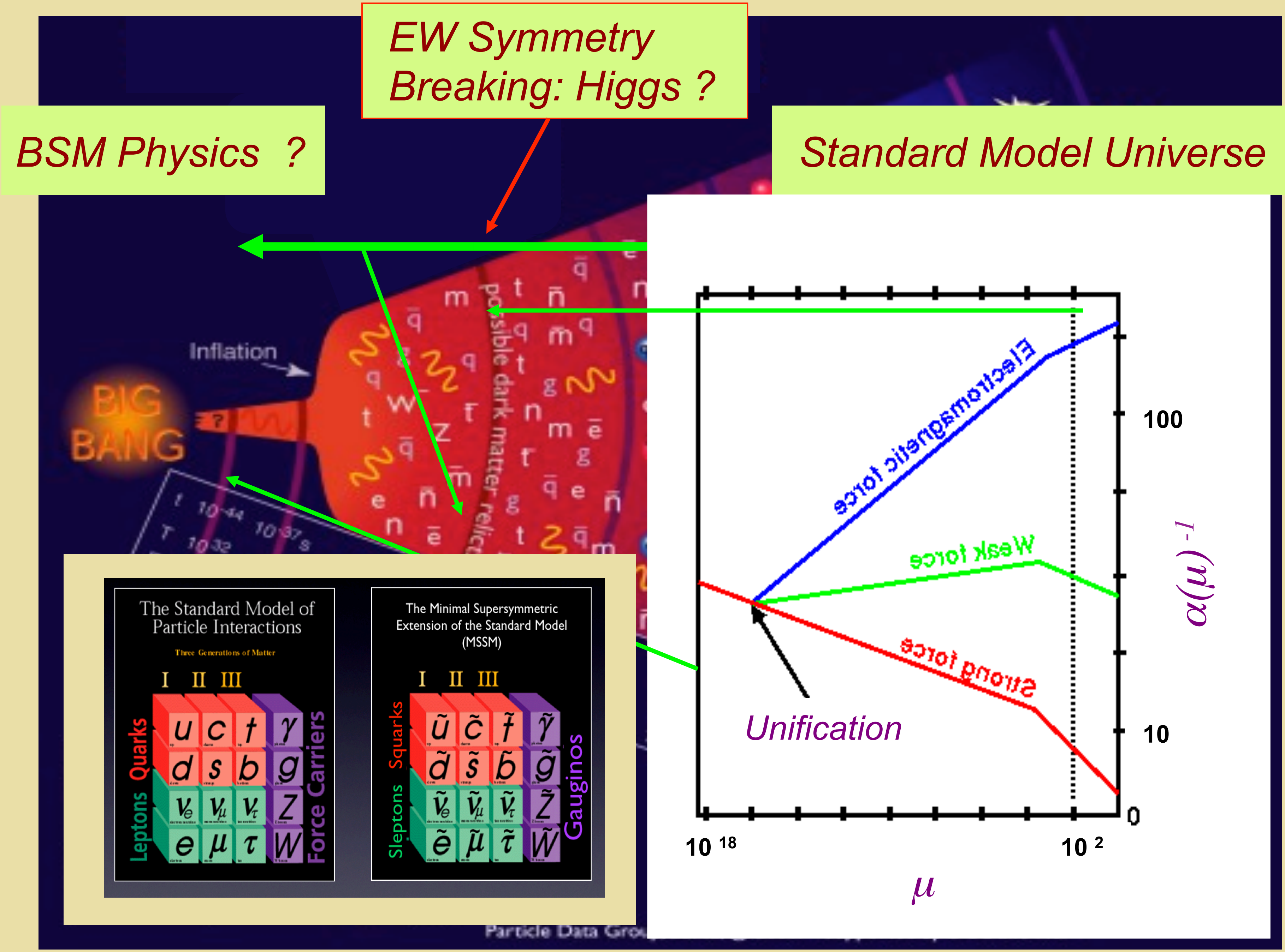


Cosmological constant ?

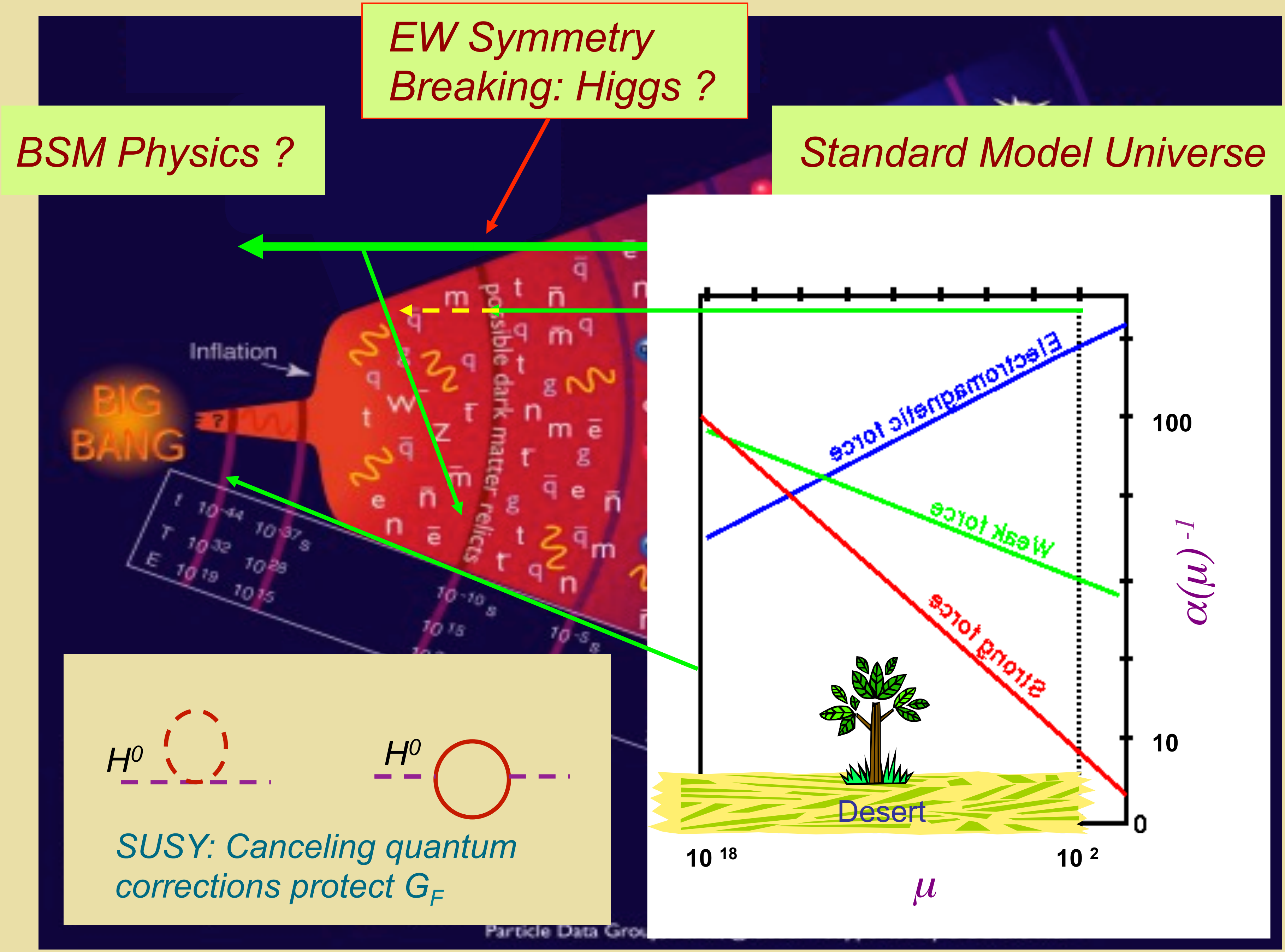
$$\dot{H} + H^2 = \frac{\ddot{a}}{a} = -\frac{4\pi G}{3}\left(\rho + \frac{3p}{c^2}\right) + \frac{\Lambda c^2}{3} > 0$$

Scalar Field: Quintessence ?

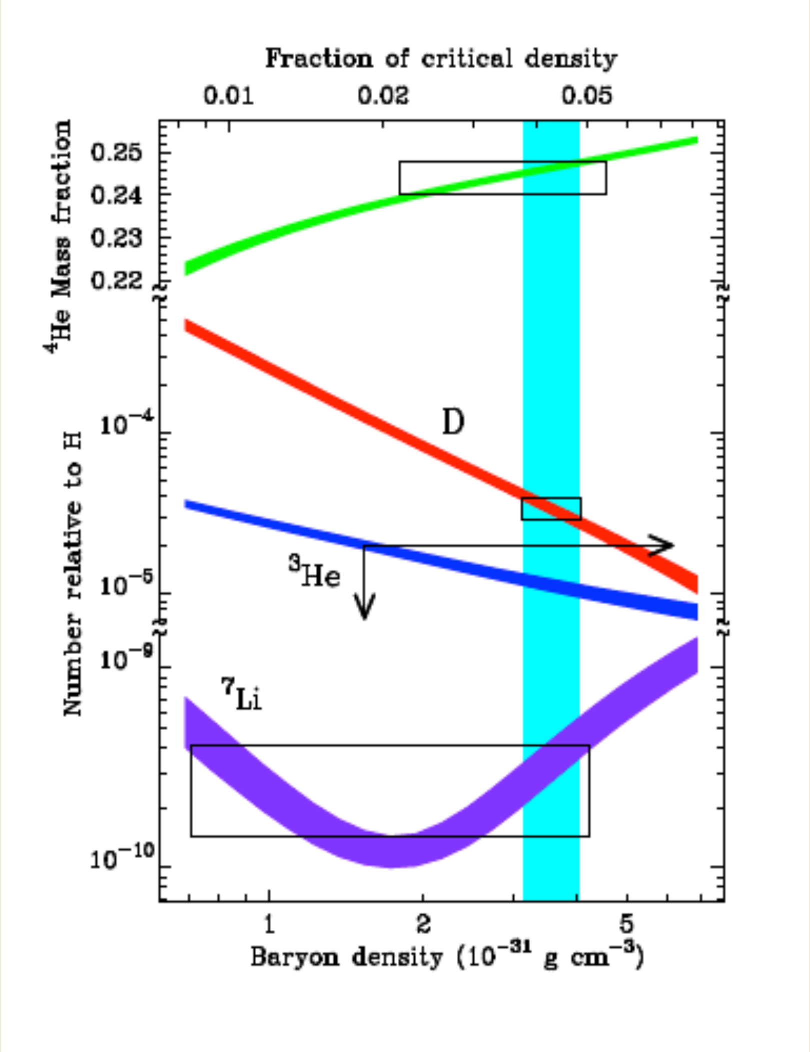
Symmetries & Cosmic History



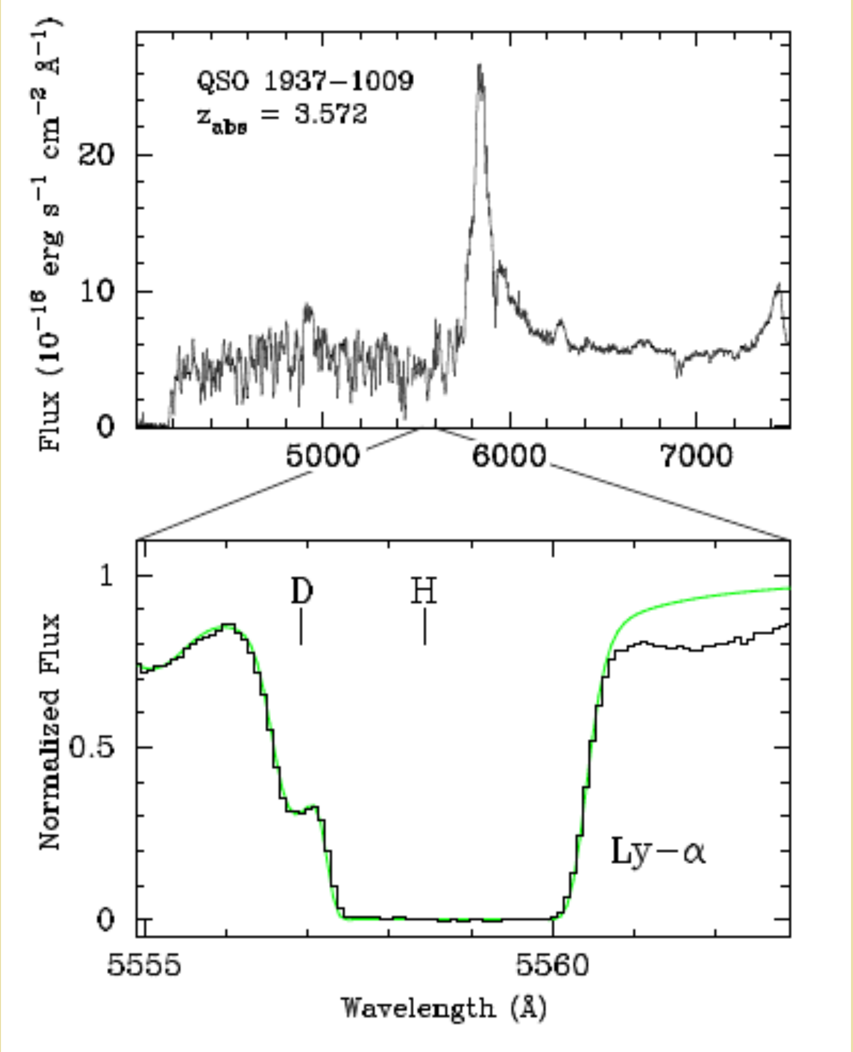
Symmetries & Cosmic History



BBN and Y_B



Fraction of critical density
0.01
0.02
0.05
0.25
0.24
0.23
0.22
^{4}He Mass fraction
10^{-4}
D
10^{-5}
^{3}He
10^{-9}
^{7}Li
10^{-10}
Number relative to H
1
2
5
Baryon density (10^{-31} g cm^{-3})



QSO 1937−1009
z_{abs} = 3.572
Flux (10^{-16} erg s^{-1} cm^{-2} Å^{-1})
20
10
0
5000
6000
7000
Normalized Flux
1
0.5
0
D
H
Ly−α
5555
5560
Wavelength (Å)

Expanding, Isotropic, Flat Universe

Einstein

$$G_{\mu\nu} = 8\pi G T_{\mu\nu}$$

$$G_{\mu\nu} \equiv R_{\mu\nu} - \frac{1}{2} g_{\mu\nu} \mathcal{R}$$

$$\mathcal{R} \equiv g^{\mu\nu} R_{\mu\nu}$$

$$R_{\mu\nu} = \Gamma^{\alpha}_{\mu\nu,\,\alpha} - \Gamma^{\alpha}_{\mu\alpha,\,\nu} + \Gamma^{\alpha}_{\beta\alpha}\Gamma^{\beta}_{\mu\nu} - \Gamma^{\alpha}_{\beta\nu}\Gamma^{\beta}_{\mu\alpha}$$

Relating Time & Temperature

Densities

$$\rho \;=\; \frac{g}{(2\pi)^3} \int d^3p\, E(\vec{p}) f(\vec{p})$$

$$n \;=\; \frac{g}{(2\pi)^3} \int d^3p\, f(\vec{p})$$

Distribution functions

$$f(\vec{p}) = \left\{\exp\left[\beta(E-\mu)\right] \pm 1\right\}^{-1}$$

Relating Time & Temperature

Energy Momentum Conservation

$$T^{\mu\nu}{}_{;\nu} = 0$$

$$d\left(\rho a^3\right) = -P da^3$$

Equation of State

$$P = \omega \rho$$

$$\rho \ \propto \ a^{-3(1+\omega)}$$

$$a \ \propto \ t^{2/[3(1+\omega)]}$$

Relating Time & Temperature

$$\rho \propto a^{-3(1+\omega)}$$

$$a \propto t^{2/[3(1+\omega)]}$$

$$\omega = \begin{cases} \frac{1}{3}\ , & \text{radiation (relativistic)} \\ 0\ , & \text{matter} \\ -1\ , & \text{vacuum (cos. constant)} \end{cases}$$

Time evolution of a

$$a \propto \begin{cases} t^{1/2}\ , & \text{radiation} \\ t^{2/3}\ , & \text{matter} \\ \exp(H_0 t)\ , & \text{vacuum} \end{cases}$$

Dimensional analysis

Number Density & Entropy

Quantities that depend on a:

$$n = \frac{g}{(2\pi)^3} \int d^3p\, f(\vec{p})$$ = N/V

$$s \equiv \frac{S}{V} = \frac{\rho + P}{T}$$

Relativistic D.O.F:

$$s = \left(\frac{2\pi^2}{45}\right) g_{*s} T^3$$

$$g_{*s} = \sum_{i=\text{bosons}} g_i \left(\frac{T_i}{T}\right)^3 + \left(\frac{7}{8}\right) \sum_{i=\text{fermions}} g_i \left(\frac{T_i}{T}\right)^3$$

Boltzmann Equations (Classical)

$$z \equiv \frac{M}{T} \qquad Y \equiv \frac{n}{s} \qquad \frac{d}{dt}(sa^3) = 0$$

$$\boxed{\dot{n} + 3Hn = s\dot{Y}}$$

Boltzmann Equations (Classical)

$$H(M) = 1.67\,\sqrt{g_*}\,\frac{M^2}{M_{\rm Pl}} \qquad\qquad dt = zH(M)^{-1}dz$$

$$\dot{n} + 3Hn = s\dot{Y} = \frac{sH(M)}{z}\,\frac{dY}{dz}$$