The matter – antimatter asymmetry of the universe and baryogenesis

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Lecture for KICP Cosmology Class
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Baryogenesis Reviews in General

- Kolb & Wolfram’s *Baryon Number Generation in the Early Universe* (1979)
- Riotto's *Theories of Baryogenesis* [hep-ph/9807454]} (emphasis on GUT-BG and EW-BG)
- Riotto & Trodden's *Recent Progress in Baryogenesis* [hep-ph/9901362] (touches on EWBG, GUTBG, and ADBG)
- Dine & Kusenko *The Origin of the Matter-Antimatter Asymmetry* [hep-ph/0303065] (emphasis on Affleck-Dine BG)
- Cline's *Baryogenesis* [hep-ph/0609145] (emphasis on EW-BG; cartoons!)

Leptogenesis Reviews

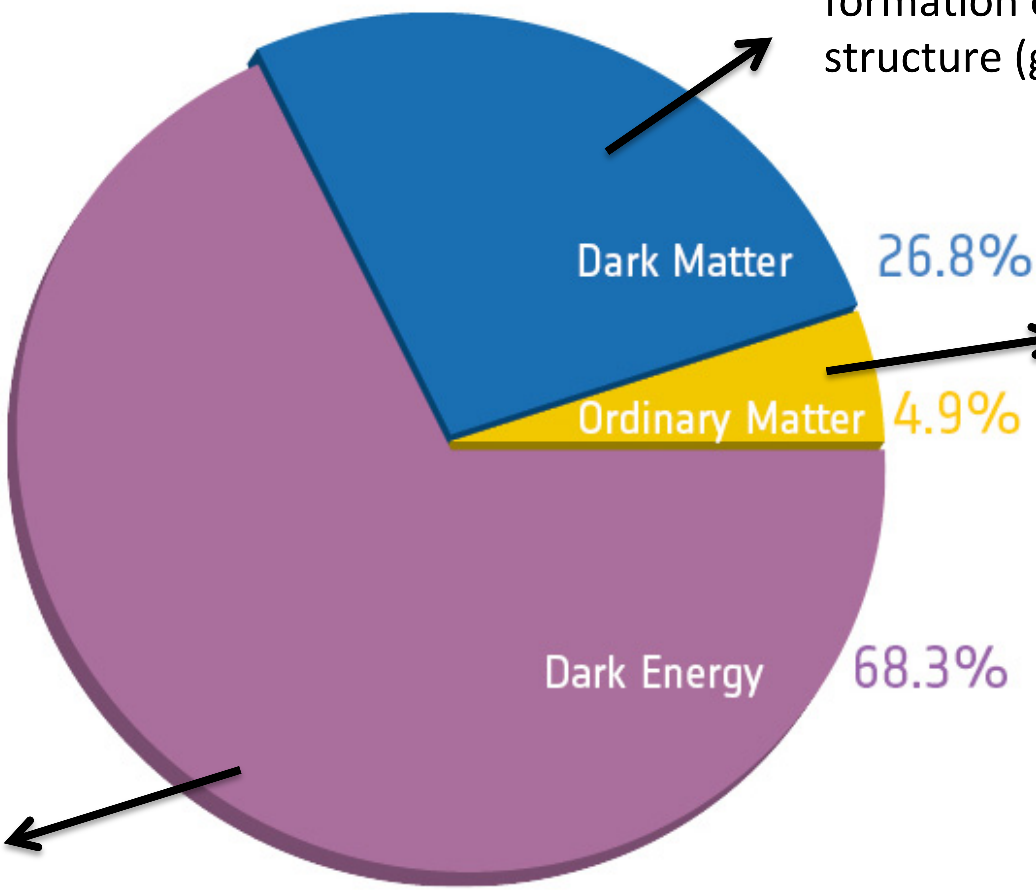
- Buchmuller, Di Bari, & Plumacher’s *Leptogenesis for Pedestrians*, [hep-ph/0401240]
- Buchmulcer, Peccei, & Yanagida's *Leptogenesis as the Origin of Matter*, [hep-ph/0502169]

Electroweak Baryogenesis Reviews

- Cohen, Kaplan, & Nelson's *Progress in Electroweak Baryogenesis*, [hep-ph/9302210]
- Trodden's *Electroweak Baryogenesis*, [hep-ph/9803479]
- Petropoulos's *Baryogenesis at the Electroweak Phase Transition*, [hep-ph/0304275]
- Morrissey & Ramsey-Musolf *Electroweak Baryogenesis*, [hep-ph/1206.2942]
- Konstandin's *Quantum Transport and Electroweak Baryogenesis*, [hep-ph/1302.6713]

Constituents of the Universe

formation of large scale structure (galaxy clusters)



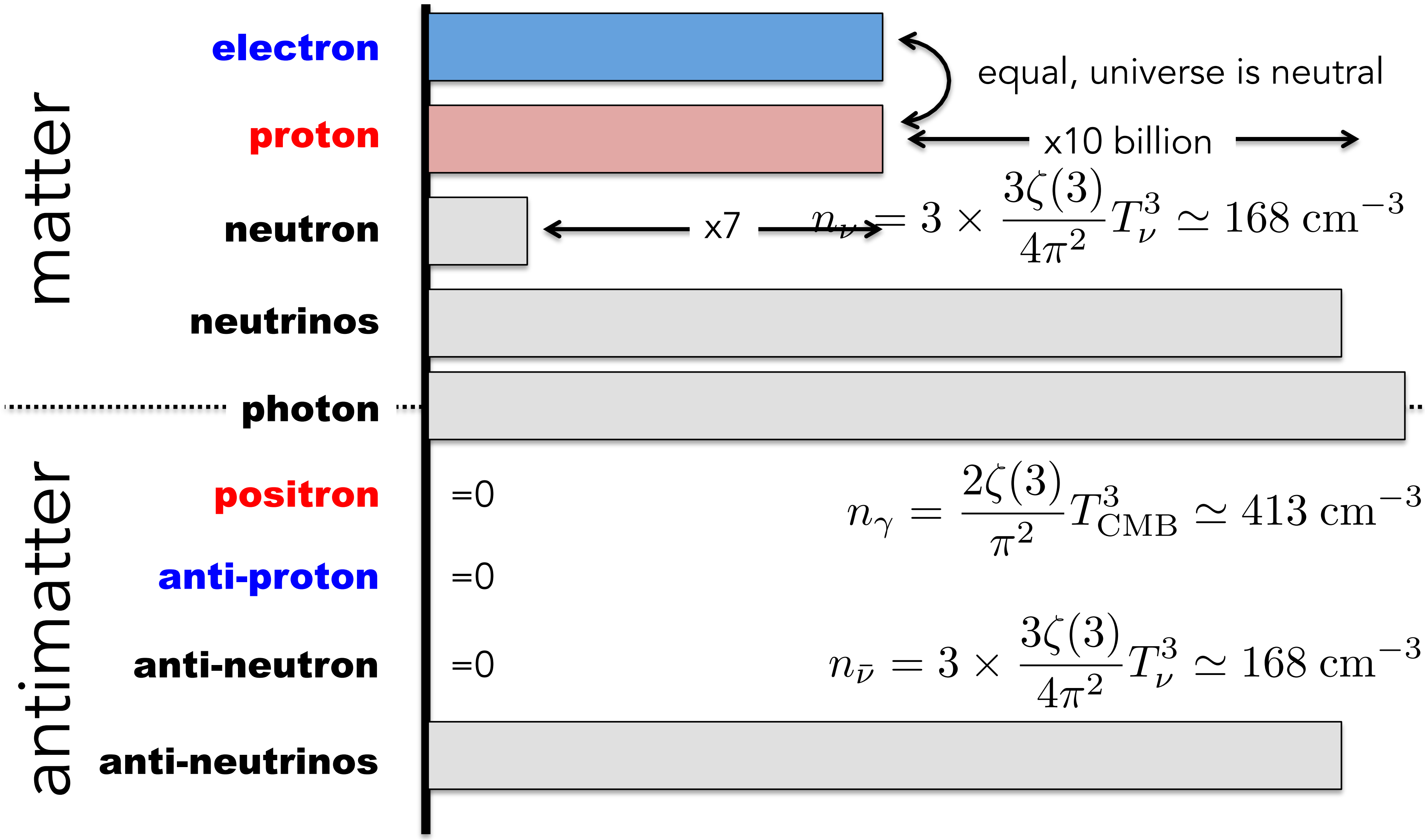
stars, planets, dust, people

late time accelerated expansion

Image stolen from the Planck website

What does "ordinary matter" refer to?

Let's break it down to elementary particles & compare number densities …



What is antimatter?

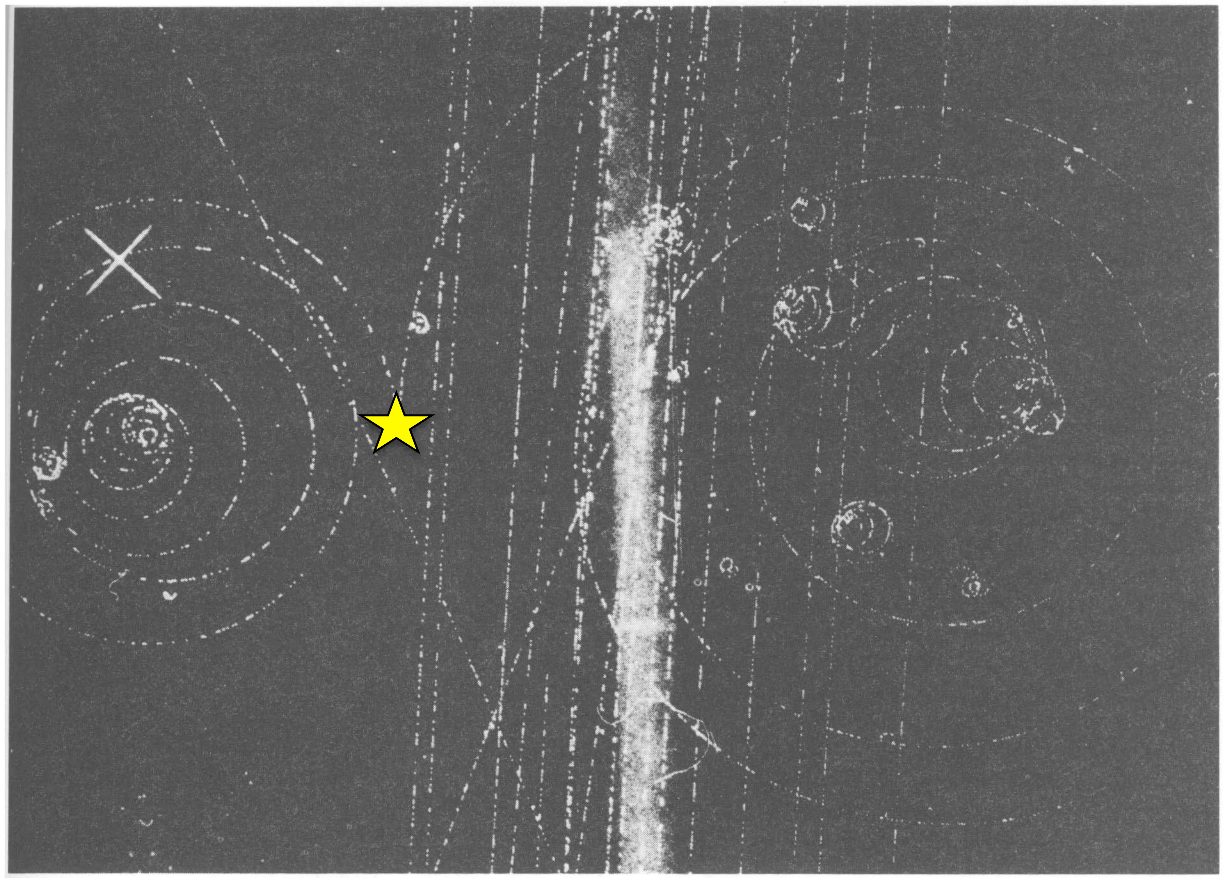
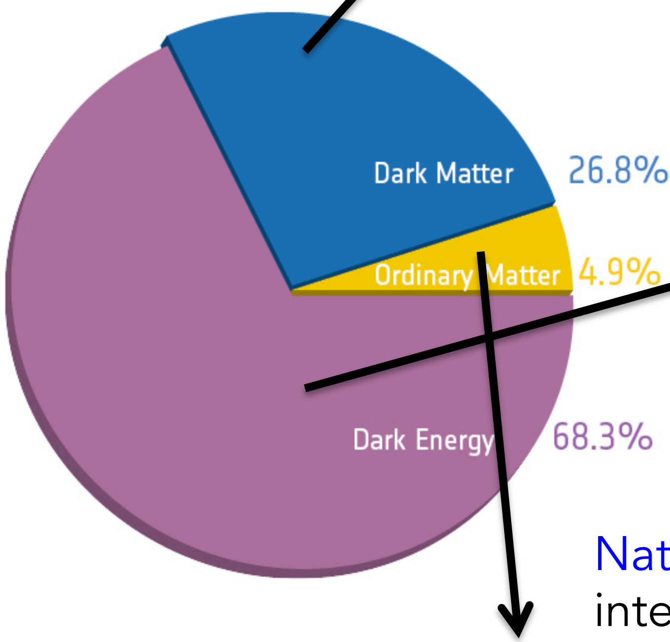


Figure 73 CREATION OF ANTIMATTER, here a positron, becomes visible in a bubble chamber where the trajectory of any electrically charged particle with an electric charge is marked by a trail of bubbles in liquid helium. The positron, whose clockwise spiraling path in the chamber magnetic field fills the right two-thirds of the photo, is the antiparticle of the electron, whose path is the smaller counterclockwise spiral. The electron-positron pair was created by a photon that is invisible because it has no charge. (Photo by Nicholas P. Samios.)

First predicted by Dirac (1928). Positron discovered by Carl Anderson (1932), which earned him the 1936 Nobel Prize in Physics.

Three Problems of Modern Cosmology

Nature: How do we incorporate dark matter into particle physics? (WIMP? Axion? WIMPzilla? ….)
Origin: What process established the abundance of dark matter? (thermal freeze out? misalignment mech? …)



Nature: How do we incorporate dark energy into models of particle physics & gravity? (cosmological constant? quintessence? f(R) ….)
Origin: What process established the abundance of dark energy? (coincidence problem, CC problem)

Nature: How do we describe these particles and their interactions? ➔ Use the Standard Model!
Origin: What process established the excess of matter over antimatter?

Baryogenesis studies the origin of the matter / antimatter asymmetry (or “baryon asymmetry”) of the universe.

Outline

(1) A few common questions about the matter-antimatter asymmetry

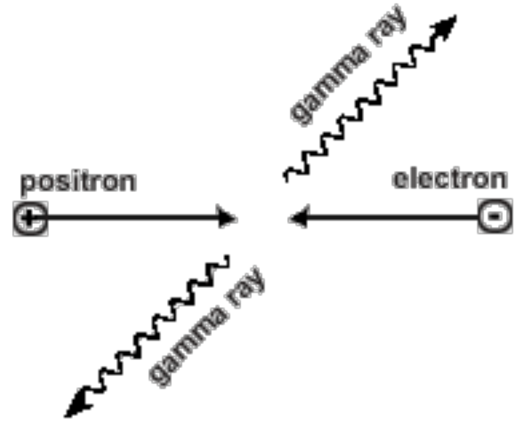
(2) What is required in order to create the matter-antimatter asymmetry? (Sakharov criteria)

(3) A few popular models of baryogenesis

(1) A Few Common Questions

Matter / antimatter sequestration?

- How do we know that the moon is not made of antimatter?



- The non-observation of gamma ray emission pushes the sequestration scale beyond the cosmological horizon. [Steigman (1976); Cohen, De Rujula, & Glashow (1998)]

- Even if the universe has equal abundances of matter and antimatter globally, we live in a pocket of matter that is larger than about 100 Gly .

- It is difficult to explain how such large matter / antimatter domains would have formed. Requires acausal dynamics.

Initial condition or baryogenesis?

- Late time cosmology is insensitive to the physics of baryogenesis. In other words, for the purposes of studying BBN or the CMB, you can treat the matter-antimatter asymmetry as an initial condition. This does not mean that the "problem is solved."

- Inflation evacuates the universe of matter. Any pre-existing matter-antimatter asymmetry is diluted by a factor of at least Exp[60] = 10^(26). Relying on pre-inflationary initial conditions make the problem much worse! See Krnjaic (2016).

- The modern perspective is that reheating produced a symmetric universe (equal abundances of matter & antimatter). Then the excess of matter developed dynamically through a processes called "baryogenesis." However, the asymmetry may also have developed during reheating, e.g. directly through inflaton decay.

When did baryogenesis occur?

- For the success of BBN (prediction of abundances of light elements), it is necessary that the universe was once in thermal equilibrium with a matter-antimatter asymmetry at temperature

$$T > 4.7\ \mathrm{MeV}$$
$$t < 0.03\,\mathrm{sec}$$

de Salas et al (1511.0067)

- Baryogenesis could have occurred anytime between reheating and BBN. However, most models favor baryogenesis during or prior to the electroweak epoch (T = 100 GeV, t = 10 ps)

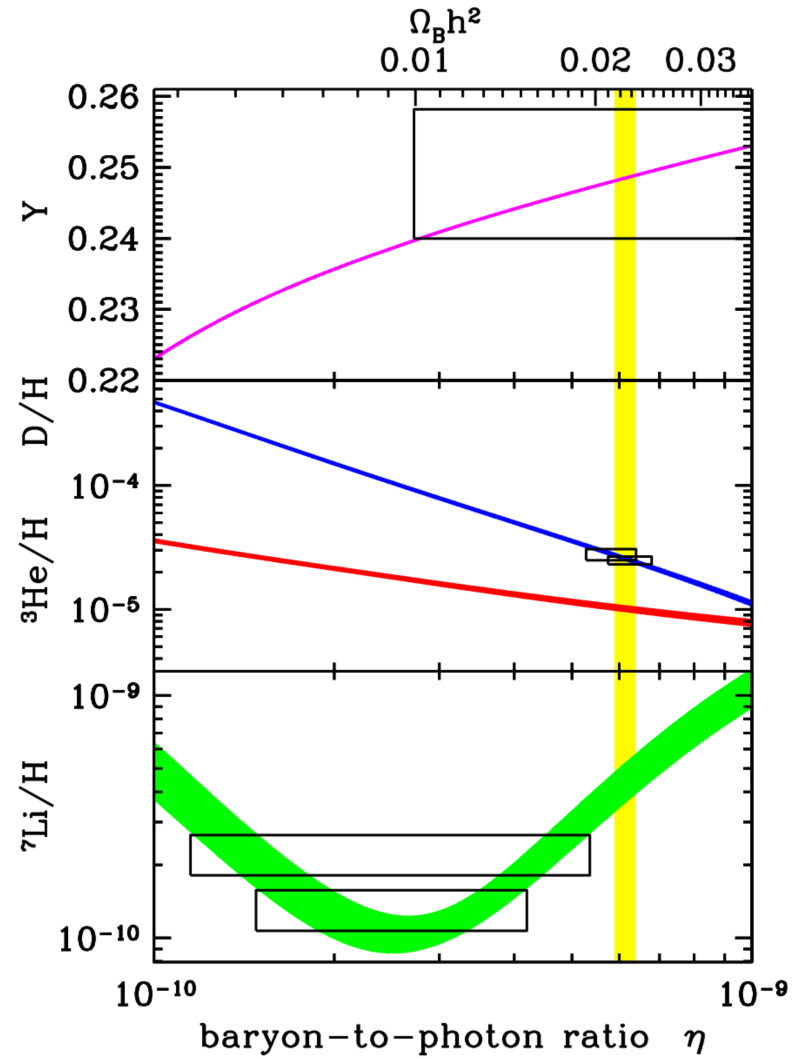


Fig. 1. Primordial abundances versus η, courtesy of R. Cyburt

How do we quantify the M/A asymmetry?

- Number density of baryon number (B-number)

$$n_B = (n_e - n_{\bar{e}}) + (\Sigma_i n_{\nu_i} - n_{\bar{\nu}_i}) + (n_p - n_{\bar{p}}) + (n_n - n_{\bar{n}})$$

- Baryon-to-Photon Ratio
  ➔ Intuitive to understand.

$$\eta_B = \frac{n_B}{n_\gamma} \qquad \text{where} \qquad n_\gamma = \frac{2\zeta(3)}{\pi^2} T^3$$

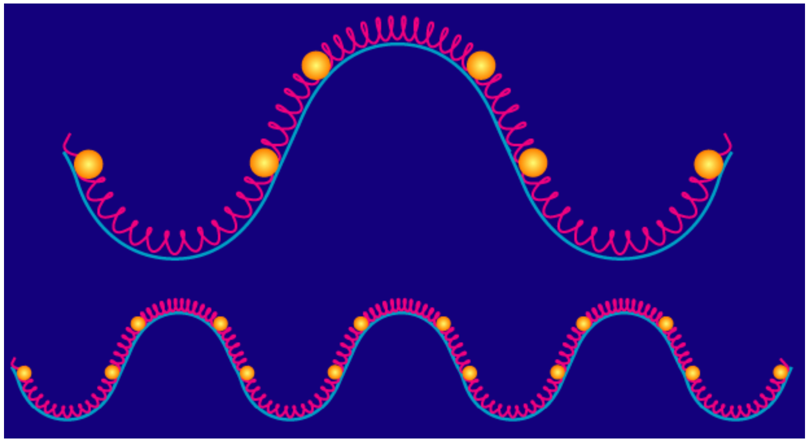
- Baryon-to-Entropy Ratio
  ➔ Conserved under adiabatic expansion of the universe.
  ➔ Most commonly used measure of the baryon asymmetry of the universe

$$Y_B = \frac{n_B}{s} \qquad \text{where} \qquad s = \frac{2\pi^2}{45} g_{*,S} T^3$$

How do we measure the M/A asymmetry?

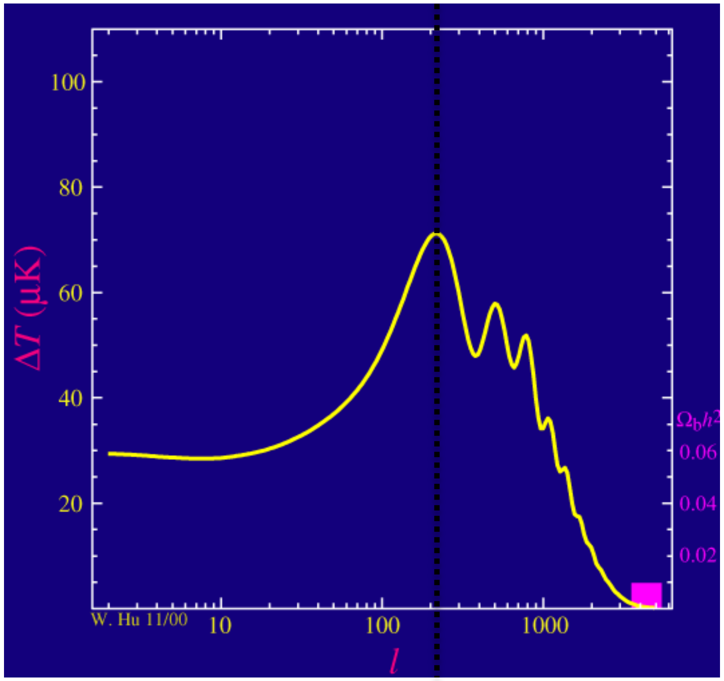
Big Bang Nucleosynthesis

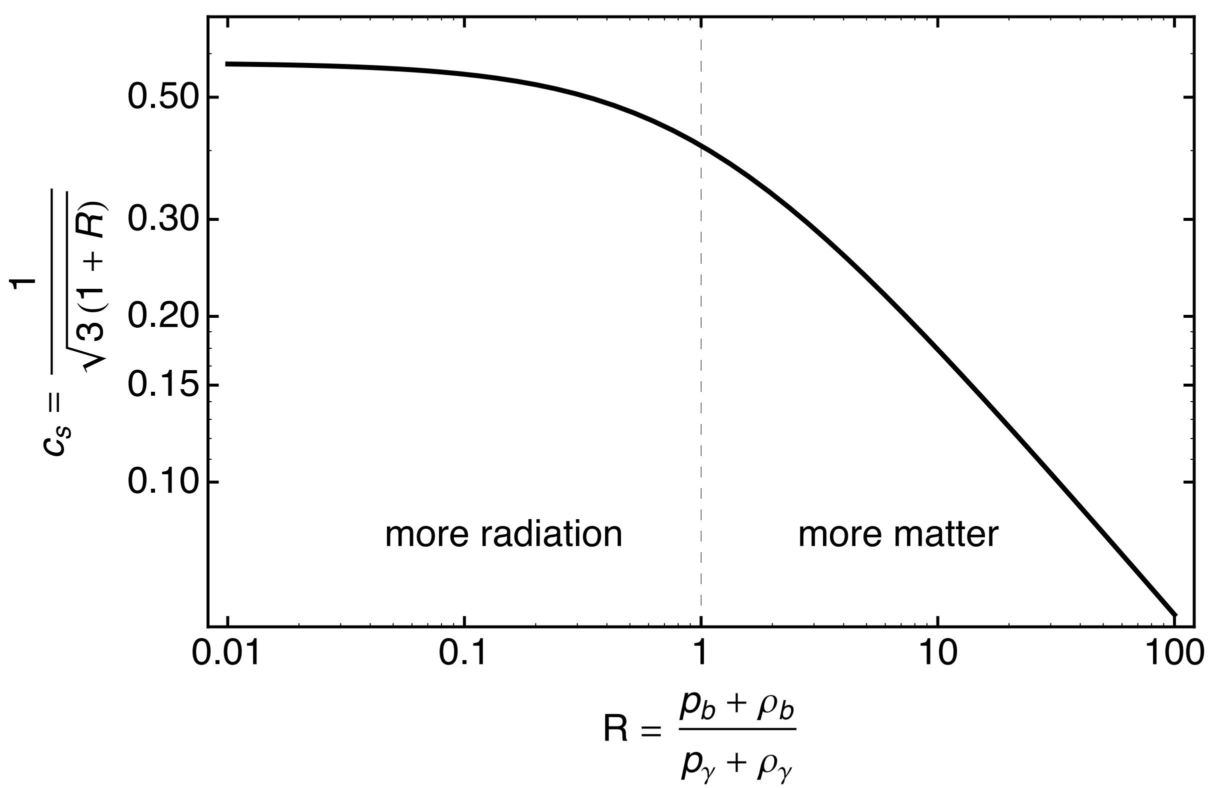
You need to know the baryon density to predict the abundances of light elements. See previous slide.



Cosmic Microwave Background

→ More baryons
→ Reduces sound speed of the baryon-photon fluid.
→ Reduces sound horizon. Peaks moves to smaller angular scales (larger ell).
→ BPF behaves more like pressureless dust and less like radiation. Enhances compression peaks, suppresses rarefaction peaks. (aka, baryon loading)





Sound horizon: $$r_s(\eta) = \int_0^\eta d\eta'\, c_s(\eta')$$

Peaks in power spec.: $k_{\mathrm{peak}} = n\pi / r_s$

What is the value of the matter / antimatter asymmetry?

Planck 2015 Cosmological Parameters

Parameter	TT+lowP 68 % limits	TT+lowP+lensing 68 % limits	TT+lowP+lensing+ext 68 % limits	TT,TE,EE+lowP 68 % limits	TT,TE,EE+lowP+lensing 68 % limits	TT,TE,EE+lowP+lensing+ext 68 % limits
$\Omega_b h^2$	0.02222 ± 0.00023	0.02226 ± 0.00023	0.02227 ± 0.00020	0.02225 ± 0.00016	0.02226 ± 0.00016	0.02230 ± 0.00014
$\Omega_c h^2$	0.1197 ± 0.0022	0.1186 ± 0.0020	0.1184 ± 0.0012	0.1198 ± 0.0015	0.1193 ± 0.0014	0.1188 ± 0.0010
$100\theta_{MC}$	1.04085 ± 0.00047	1.04103 ± 0.00046	1.04106 ± 0.00041	1.04077 ± 0.00032	1.04087 ± 0.00032	1.04093 ± 0.00030
τ	0.078 ± 0.019	0.066 ± 0.016	0.067 ± 0.013	0.079 ± 0.017	0.063 ± 0.014	0.066 ± 0.012
$\ln(10^{10} A_s)$	3.089 ± 0.036	3.062 ± 0.029	3.064 ± 0.024	3.094 ± 0.034	3.059 ± 0.025	3.064 ± 0.023
n_s	0.9655 ± 0.0062	0.9677 ± 0.0060	0.9681 ± 0.0044	0.9645 ± 0.0049	0.9653 ± 0.0048	0.9667 ± 0.0040

$$\Omega_b h^2 \simeq 0.02230 \pm 0.00014$$

… Next let's relate this to $Y_B = n_B / s$

$$\Omega_b h^2 = \frac{\rho_b}{\rho_c}\left(\frac{H_0}{H_{100}}\right)^2$$

where $\quad H_{100} \equiv 100\,\mathrm{km/sec/Mpc}$

$$= \frac{m_p n_b + m_e n_e}{3H_0^2 M_{\mathrm{pl}}^2}\left(\frac{H_0}{H_{100}}\right)^2$$

$$= \frac{n_b}{s}\left(\frac{2\pi^2}{45} g_{*,S} T_0^3\right)\frac{m_p}{3H_{100}^2 M_{\mathrm{pl}}^2}$$

$$g_{*,S} \simeq 3.91\ ,\ T_0 \simeq 2.72\,\mathrm{kel}\ ,\ m_p \simeq 0.938\ \mathrm{GeV}$$

$$\Omega_b h^2 \simeq (2.59 \times 10^8)\frac{n_b}{s}$$

$$\Omega_b h^2 \simeq 0.02230 \pm 0.00014$$

$$\boxed{n_b/s \simeq (0.861 \pm 0.005) \times 10^{-10}}$$

(10^{-10} is the magic number)

What if baryogenesis had not occurred?

At T >~ GeV there would be equal abundances of protons & antiprotons.
As the temperature drops to T ~ 20 MeV, annihilations freeze out:

Annihilation: $$p\bar{p} \to \pi^+\pi^-$$

Cross Section: $$\langle \sigma v \rangle \approx m_p^{-2}$$

Equilibrium density: $$n_p = n_{\bar{p}} \approx (m_p T)^{3/2} e^{-m_p/T}$$

Hubble Param: $$3H^2 M_{\rm pl}^2 = (\pi^2/30) g_* T^4$$

Freeze Out Condition: $$\langle \sigma v \rangle n_p \approx H \quad \text{at} \quad T_{\rm ann} \approx 20 \text{ MeV}$$

Relic Abundance: $$\frac{n_p}{n_\gamma} = \frac{n_{\bar{p}}}{n_\gamma} \simeq 10^{-18}$$

(much smaller than observed BAU)

Kolb & Turner, Sec 5.2 & 6.2

(2) Ingredients for Baryogenesis

What is required to generate an M/A asymmetry?

That is to say, we want

(1) You prepare the system in thermal equilibrium at temperature T_i with $Y_B = 0$.
(2) Baryogenesis happens.
(3) You find the system in thermal equilibrium at temperature T_f with Y_B != 0.

For instance, T_i could be 10^{10} GeV, just after reheating, and T_f could be 1 eV, just before recombination.

Can we say anything general about what happens in Step 2?

Yes!

Sakharov (1967); Kolb & Wolfram (1979)

The Sakharov Criteria

There are three requirements that any model of baryogenesis must satisfy.

(1) There must exist an interaction that violates B-number.

➔ `You must be able to convert anti-matter into matter or vice versa.'

➔ Let's use the language of quantum mechanics.

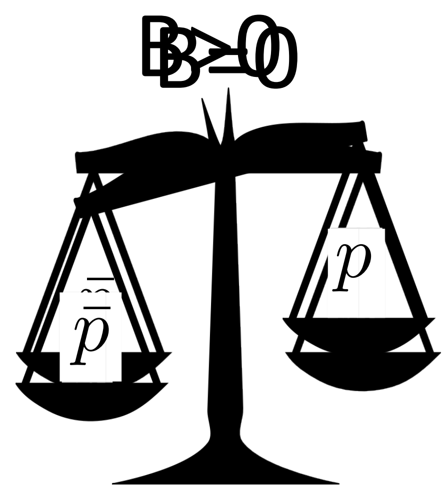
➔ Define an operator B that counts the number of matter particles as +1 and the number of antimatter particles as -1. For example,

$$\hat{B}\,|p\rangle = +|p\rangle\,, \quad \hat{B}\,|\bar{p}\rangle = -|\bar{p}\rangle\,, \text{ and } \quad \hat{B}\,|p\bar{p}\rangle = 0|p\bar{p}\rangle$$

➔ We need to pass from a state with <B> = 0 to a state with <B> > 0. Thus, B cannot be conserved:

$$\left[\hat{B}\,,\,\hat{H}\right] \neq 0 \qquad \text{(needed)}$$

Otherwise, eigenstates of B are also eigenstates of H, i.e. stationary states.



The Sakharov Criteria #2

There are three requirements that any model of baryogenesis must satisfy.

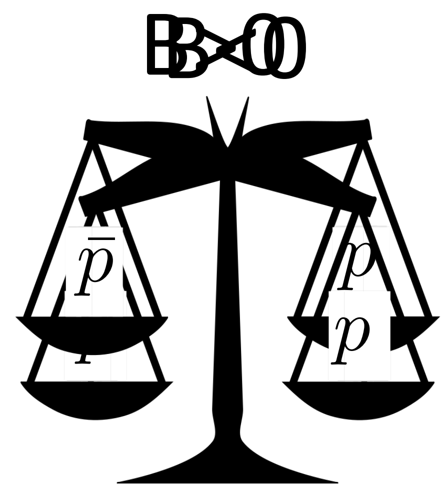
(2) The B-violating interaction must go out of thermal equilibrium.

➔ Suppose the interactions violate B. Now the system can move back-and-forth between states of of different B.

➔ While the system is in thermal equilibrium, the probability to be found in a given state only depends on the energy of that state. If the theory is invariant under CPT, then particles and anti-particles have the same mass. Then, a state with B=+1 is just as probable as a state with B=-1.

$$\langle \hat{B} \rangle_T = \mathrm{Tr}\big[e^{-\beta \hat{H}} \hat{B}\big] = \mathrm{Tr}\big[(\widehat{CPT})(\widehat{CPT})^{-1} e^{-\beta \hat{H}} B\big]$$
$$= \mathrm{Tr}\big[e^{-\beta \hat{H}} (\widehat{CPT})^{-1} \hat{B} (\widehat{CPT})\big] = -\langle \hat{B} \rangle_T$$

➔ The system will oscillate back and forth:



➔ To prevent this eternal flip-flop, there must be a time at which the B-violating interaction goes out of thermal equilibrium (i.e., it shuts down)

The Sakharov Criteria - #3

There are three requirements that any model of baryogenesis must satisfy.

(3) There must be an interaction that violates C & CP.
➔ 'You must bias the production of matter over antimatter.'

➔ C & CP are symmetries that relate particles to their anti-particle partners.
➔ If C & CP are unbroken, a antimatter-creating process will compete with the matter-creating process, and there will be no net effect.
➔ Easier to understand with a concrete example. (See next section)

(3) Models of Baryogenesis

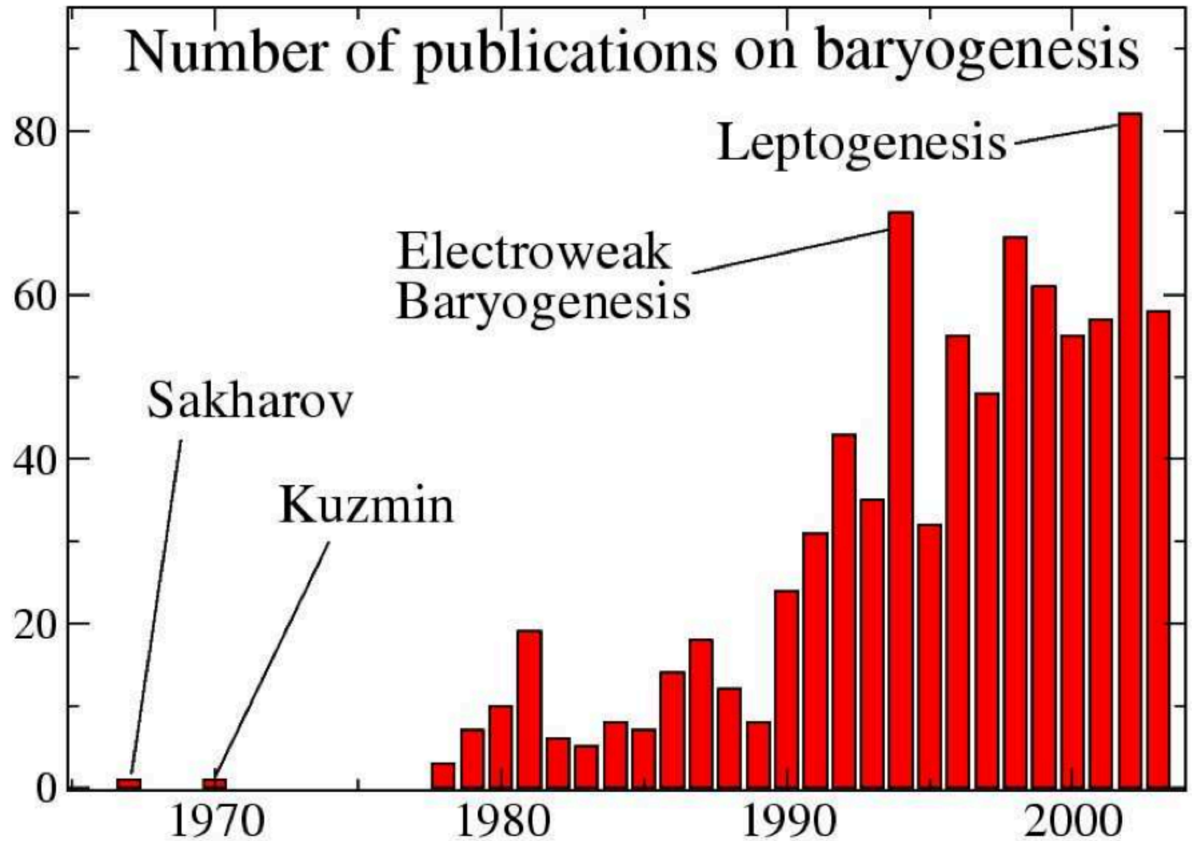


Fig. 3. Number of publications on baryogenesis as a function of time.

A plethora of models

Most Well-Studied

GUT Baryogenesis (1979)
Affleck-Dine Baryogenesis (1985)
Leptogenesis (1986)
Spontaneous Baryogenesis (1987)
Electroweak Baryogenesis (1990)

Interesting Alternatives

Baryogenesis from
- ➔ Cosmic Strings
- ➔ Magnetic Fields
- ➔ Black Holes

Dissipative Baryogenesis
Warm Baryogenesis
Cloistered Baryogenesis
Cold Baryogenesis
Planck Baryogenesis
Post-Sphaleron Baryogenesis
WIMPy Baryogenesis
Dirac Leptogenesis
Non-Local Electroweak Baryogenesis
Magnetic-Assisted EW Baryogenesis
Singlet-Assisted EW Baryogenesis

…

Leptogenesis – Heavy Majorana Neutrino & Seesaw

Let the SM be extended to include 3 heavy Majorana neutrinos N_i :

SM leptons

SM Higgs … gets a vev v = 246 GeV

$$\mathcal{L} = -\lambda\, LHN - \frac{1}{2} M_N NN + \text{h.c.}$$

$$\supset -\frac{1}{2}\begin{pmatrix}\nu & N\end{pmatrix}\begin{pmatrix}0 & M_D \\ M_D^T & M_N\end{pmatrix}\begin{pmatrix}\nu \\ N\end{pmatrix} + \text{h.c.} \qquad \left(M_D = \lambda v/\sqrt{2} \right)$$

$$\supset -\frac{1}{2} M_\nu \nu_\ell \nu_\ell - \frac{1}{2} M_h \nu_h \nu_h + \text{h.c.}$$

where the mass matrices for the light and heavy neutrinos are

$$M_\nu \approx -M_D M_N^{-1} M_D^T \qquad \text{and} \qquad M_h \approx M_N$$

This is the (Type-I) seesaw mechanism. The mass of the light Majorana neutrinos is predicted correctly if the mass scale of the heavy Majorana neutrino is 10^{12} GeV.

$$m_\nu \simeq (0.3\ \text{eV}) \left(\frac{\lambda}{0.1}\right)^2 \left(\frac{m_N}{10^{12}\ \text{GeV}}\right)^{-1}$$

Mohapatra, Rabindra, & Senjanovic; Schechter & Valle; Yanagida (1980)

Leptogenesis - Mechanism

In the model of leptogenesis, you first create a lepton number from the out of equilibrium &, CP-violating decay of the heavy Majorana neutrino. Then you partially convert the lepton-number into a B-number by electroweak sphaleron.

The heavy Majorana neutrino N is unstable; it can decay to SM leptons and Higgs

$$N \rightarrow LH \qquad \text{L-number increases by +1}$$

$$N \rightarrow \bar{L}\bar{H} \qquad \text{L-number decreases by -1}$$

Since the decay of N violates L-number we see that Sakharov #1 is satisfied.

The two decay channels are related by CP-conjugation. If CP is a good symmetry, then the two rates are equal & no net L-number is created. We need

$$\Gamma(N \rightarrow LH) > \Gamma(N \rightarrow \bar{L}\bar{H}) \qquad \text{(CP is violated)}$$

and then Sakharov #3 is satisfied.

Fukugita & Yanagida (1987)

Leptogenesis – Out of Equilibrium Decay

These decays of N are not occurring in vacuum. Instead, the system is the hot & dense plasma of the early universe. Thus, the inverse decay channel is open:

$$\Delta \mathrm{L} = +1: \qquad N \to LH \qquad \text{and} \qquad \bar{L}\bar{H} \to N$$

$$\Delta \mathrm{L} = -1: \qquad N \to \bar{L}\bar{H} \qquad \text{and} \qquad LH \to N$$

When does the decay occur?

$$\Gamma \approx \frac{\lambda^2}{8\pi} m_N \approx \frac{1}{4\pi} \frac{m_\nu}{v^2} m_N^2 \qquad \text{and} \qquad \tau = \Gamma^{-1}$$

How hot is the plasma at this time?

$$t_U = \tau \quad \to \quad T_d \approx \sqrt{\frac{\Gamma M_{\rm pl}}{2}} \left(\frac{\pi^2}{90} g_* \right)^{-1/4}$$

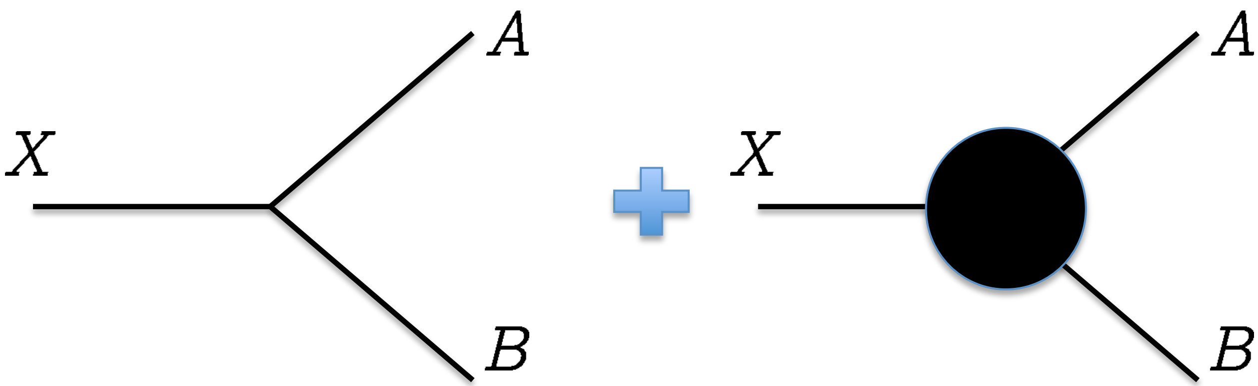
$$\approx \sqrt{\frac{1}{8\pi} \frac{m_\nu M_{\rm pl}}{v^2}} \left(\frac{\pi^2}{90} g_* \right)^{-1/4} m_N$$

$$\simeq 6.8 \sqrt{\frac{m_\nu}{0.1\ \mathrm{eV}}}\, m_N$$

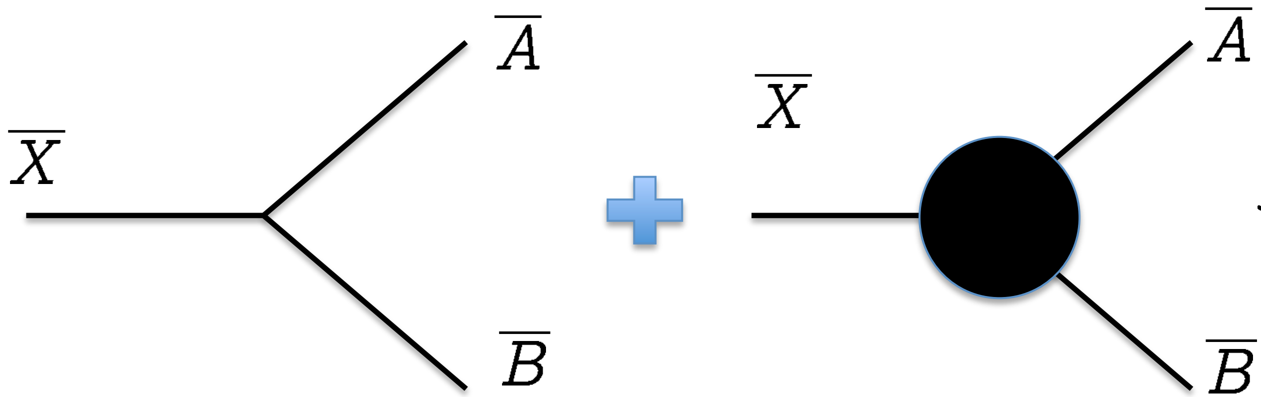
(Sakharov #2 is only partially satisfied. The inverse decay is not completely out of equilibrium, and will partially “washout” the L-number)

Leptogenesis – Calculating the CP-violating Decay

General picture --- to have CP-violation, you need complex phases & branch cuts



$$\mathcal{M}(X \to AB) = g_1\,\mathcal{A}_1 + g_2\mathcal{A}_2$$



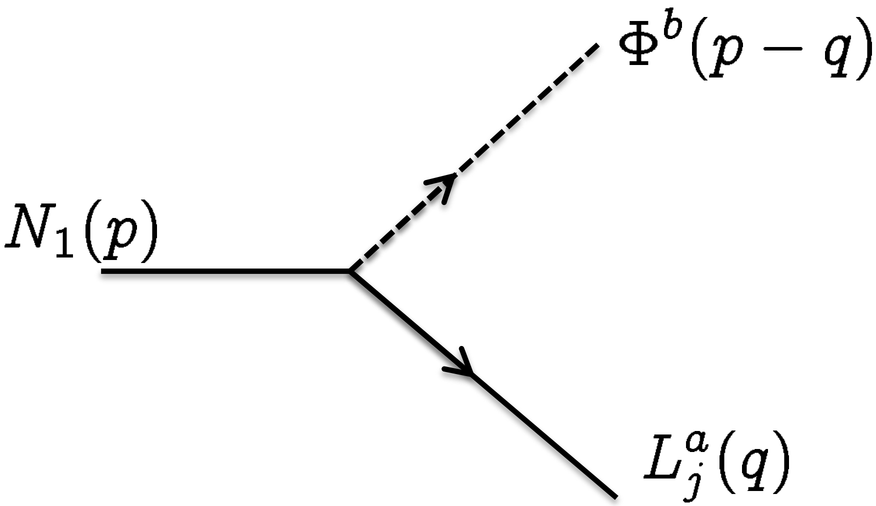
$$\mathcal{M}(\overline{X} \to \overline{AB}) = g_1^*\,\mathcal{A}_1 + g_2^*\mathcal{A}_2$$

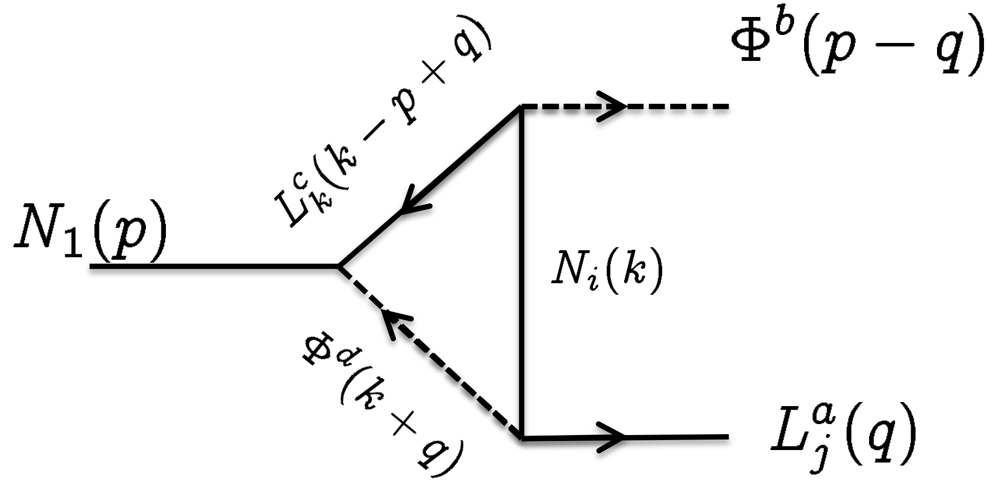
$$|\mathcal{M}(X \to AB)|^2 - |\mathcal{M}(\overline{X} \to \overline{AB})|^2 = -4\,\mathrm{Im}[g_1 g_2^*]\,\mathrm{Im}[\mathcal{A}_1\mathcal{A}_2^*]$$

1. complex phases
2. branch cut in loop momentum integral

Leptogenesis – Calculating the CP-violating Decay

Really, you do this one-loop calculation …





$$i\mathcal{M} = \bar{u}(q)(-i\epsilon^{ab}\lambda^{\nu}_{j1}P_R)u(p)$$

$$i\mathcal{M} = \bar{u}(q)(-i\epsilon^{ad}\lambda^{\nu}_{jk}P_R)\sum_{i,k=1,2,3}\sum_{c,d=1,2}\int\frac{d^4k}{(2\pi)^4}\frac{i(\not{k}+M_i)}{k^2-M_i^2+i\epsilon}(-i\epsilon^{cb}\lambda^{\nu}_{ki}P_R)$$

$$\frac{i(\not{k}-\not{p}+\not{q})}{(k-p+q)^2+i\epsilon}(-i\epsilon^{cd}\lambda^{\nu\,\dagger}_{1k}P_L)\frac{i}{(k+q)^2+i\epsilon}u(p)$$

λ_{ji}

Leptogenesis – Calculating the CP-violating Decay

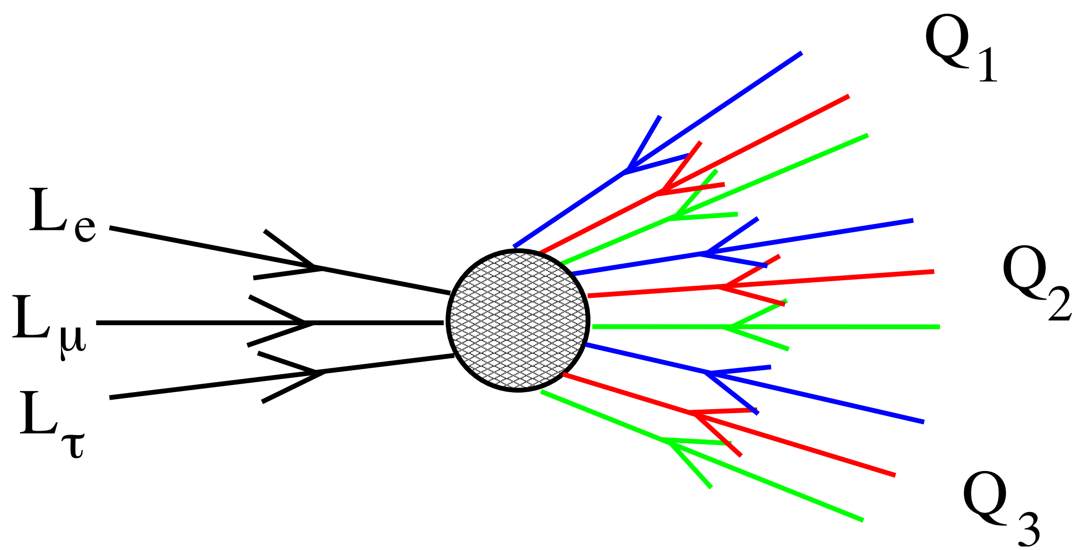
And the result is …

$$\begin{aligned}
\varepsilon_1 &= \frac{\Gamma(N_1 \to LH) - \Gamma(N_1 \to \bar{L}\bar{H})}{\Gamma(N_1 \to LH) + \Gamma(N_1 \to \bar{L}\bar{H})} \\
&= \frac{3}{16\pi} \frac{1}{(\lambda\lambda^\dagger)_{11}} \sum_{i=2,3} \mathrm{Im}[(\lambda\lambda^\dagger)^2_{i1}] \frac{M_1}{M_i} \qquad\qquad M_{2,3} \gg M_1
\end{aligned}$$

Leptogenesis – Electroweak Sphaleron

Now we have created a lepton asymmetry (excess of electrons over positrons).
How do we turn this into a baryon asymmetry (excess of quarks over anti-quarks)?

The Standard Model already contains a process that violates B-number. It is known as the electroweak sphaleron ("sphaleros" is Greek for "ready to fall").



Klinkhammer & Manton (1984); Kuzmin, Rubakov, & Shaposhnikov (1985); Harvey & Turner (1990)
but also identified earlier by Dashen, Hasslacher, & Neveu (1974) and Boguta (1983)

Leptogenesis – L-to-B Conversion

The electroweak sphaleron is in equilibrium at temperatures T >~ 130 GeV.

It partially converts the L-number into B-number. Roughly speaking,

$$Y_L(\text{after L-to-B}) = +\frac{1}{2}Y_L(\text{before L-to-B})$$
$$Y_B(\text{after L-to-B}) = -\frac{1}{2}Y_L(\text{before L-to-B})$$

But more accurately,

$$Y_L(\text{after}) = -\frac{51}{79}Y_{B-L}(\text{before})$$
$$Y_B(\text{after}) = +\frac{28}{79}Y_{B-L}(\text{before})$$

Harvey & Turner (1990)

Leptogenesis – Final Baryon Asymmetry

Now putting together all of the pieces,

$$Y_B \approx -\frac{28}{79}\frac{\kappa_{\mathrm{w.o.}}}{g_{*,S}}\varepsilon_1$$

Confirming that the light neutrinos are Majorana particles (e.g., if neutrinoless double beta decay were observed) would provide indirect evidence in support of leptogenesis as an explanation of the matter / antimatter asymmetry.
➔ Big advantage for this model

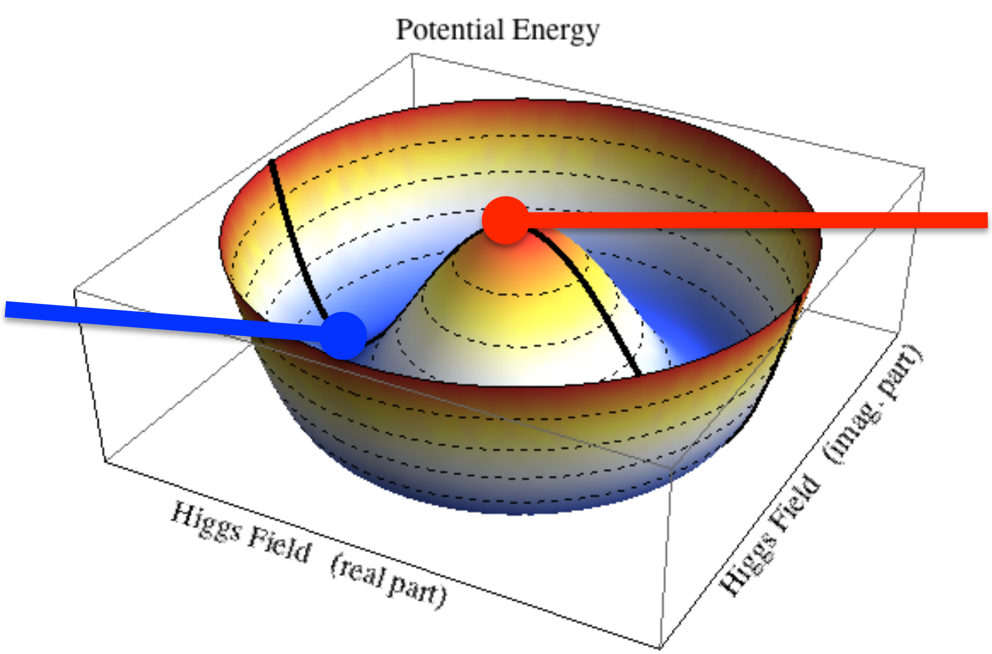
However, we cannot directly probe the physics at scales ~10^{12} GeV.
➔ A disadvantage for this model

Electroweak Baryogenesis – Higgs Field

In the model of electroweak baryogenesis, the matter / antimatter asymmetry is generated at the electroweak phase transition due to the CP-violating interactions of particles scattering at the Higgs field bubble wall.

The electroweak phase transition was the dynamical process by which the Higgs field acquired its vacuum expectation value in the early universe:

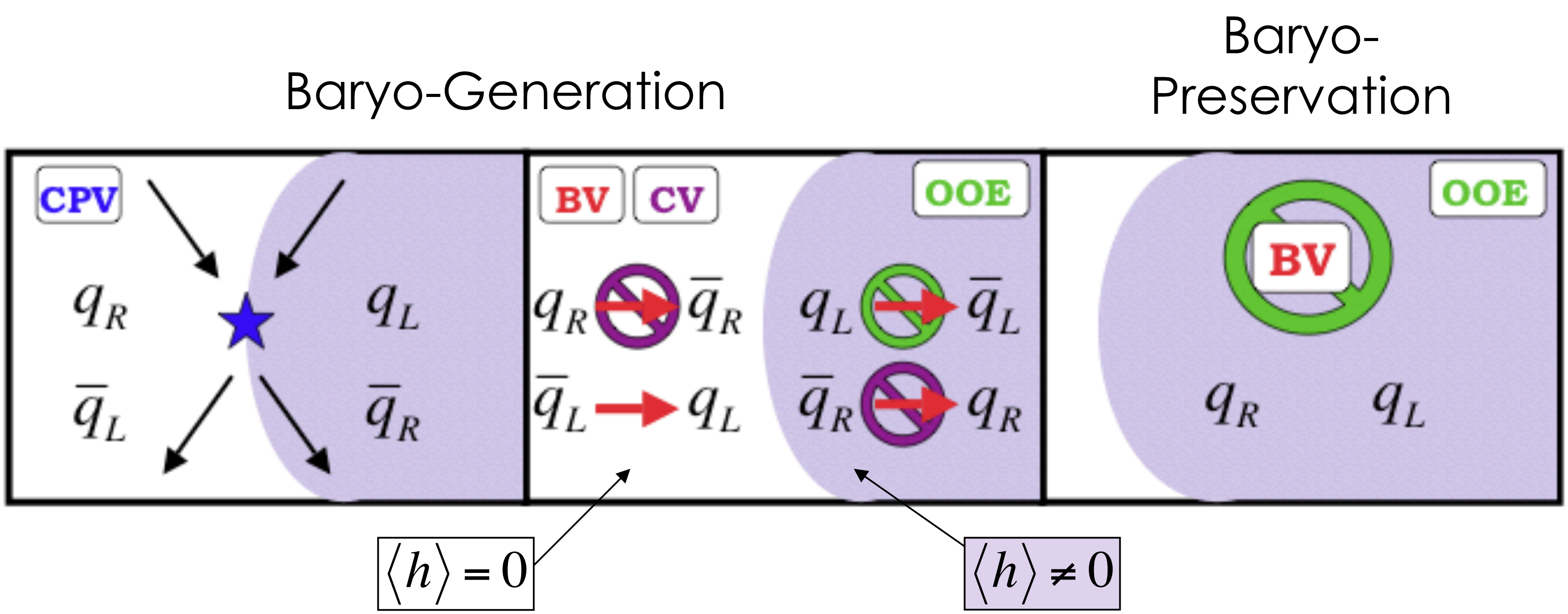
Today the Higgs field has a nonzero vacuum expectation value, which induces masses for the quarks, leptons, and weak gauge bosons



In the early universe, the Higgs field sat at the origin in field space, and the electroweak symmetry was restored.

Electroweak Baryogenesis – Mechanism

As the universe cooled through the electroweak epoch (T ~ 100 GeV, t_U ~ ns), the Higgs field experienced a first order phase transition. Bubbles with nonzero <h> nucleated in a background of <h>=0 phase.



CPV = CP-violation
CV = C-violation (weak interactions)
BV = B-number violation (EW-sphaleron)
OOE = Out Of Equilibrium ("shutoff")

Cohen, Kaplan, & Nelson (1990); Huet & Nelson (1995)

Electroweak Baryogenesis – Calculation

Three steps

(1) Creation of a particle asymmetry at the bubble wall results from the CP-violating interactions of particles in the plasma with the Higgs field. E.g., quarks and antiquarks have different reflection probabilities.

(2) Movement of charge in space & redistribution of charge from one species to another is described by a system of transport (Boltzmann) equations.

(3) Inside the bubble, electroweak sphalerons threaten to washout the baryon asymmetry. In order for these to be out of equilibrium, we say that the phase transition must be "strongly" first order.

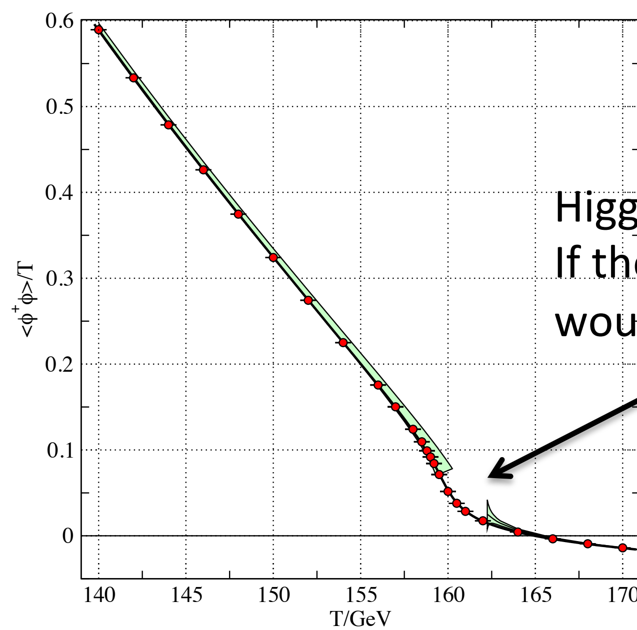
Electroweak Baryogenesis – It doesn't work in the SM

Problems:

(1) Not enough CP-violation in the quark sector. (CP-violating phase in the CKM matrix is too small).

$$\det\left([M_u^2, M_d^2]\right) = F_u F_d J \qquad \text{and} \qquad J = 3\times 10^{-5}$$

(2) The electroweak phase transition is not first order.



Higgs field changes smoothly. If the PT were 1st order, there would be a discontinuity here.

Outlook on Baryogenesis

It's a big problem of one little number, why is $Y_B \sim 10^{-10}$ rather than 0?

There are lots of (clever) idea for baryogenesis!

The challenge is falsifiability. Most models operate at energies, which are inaccessible to laboratory probes. E.g., leptogenesis & GUT baryogenesis.

EW baryogenesis is different, since it requires new physics at the weak scale, which is currently probed by high energy collider experiments. In fact, the absence of evidence for SUSY at the LHC has already disfavored the most compelling models of EW baryogenesis.

If we can't access baryogenesis in the lab, we may hope to find indirect evidence through other cosmological relics, which can be produced in association with the baryon asymmetry. E.g., topological defects, primordial magnetic fields, and gravitational waves. In particular, GW's are a general prediction of first order phase transition, and they may give us an additional handle on EW baryogenesis.

Lots of room for clever model building and further observational probes.