Baryogenesis and leptogenesis

重子数生成与轻子数生成

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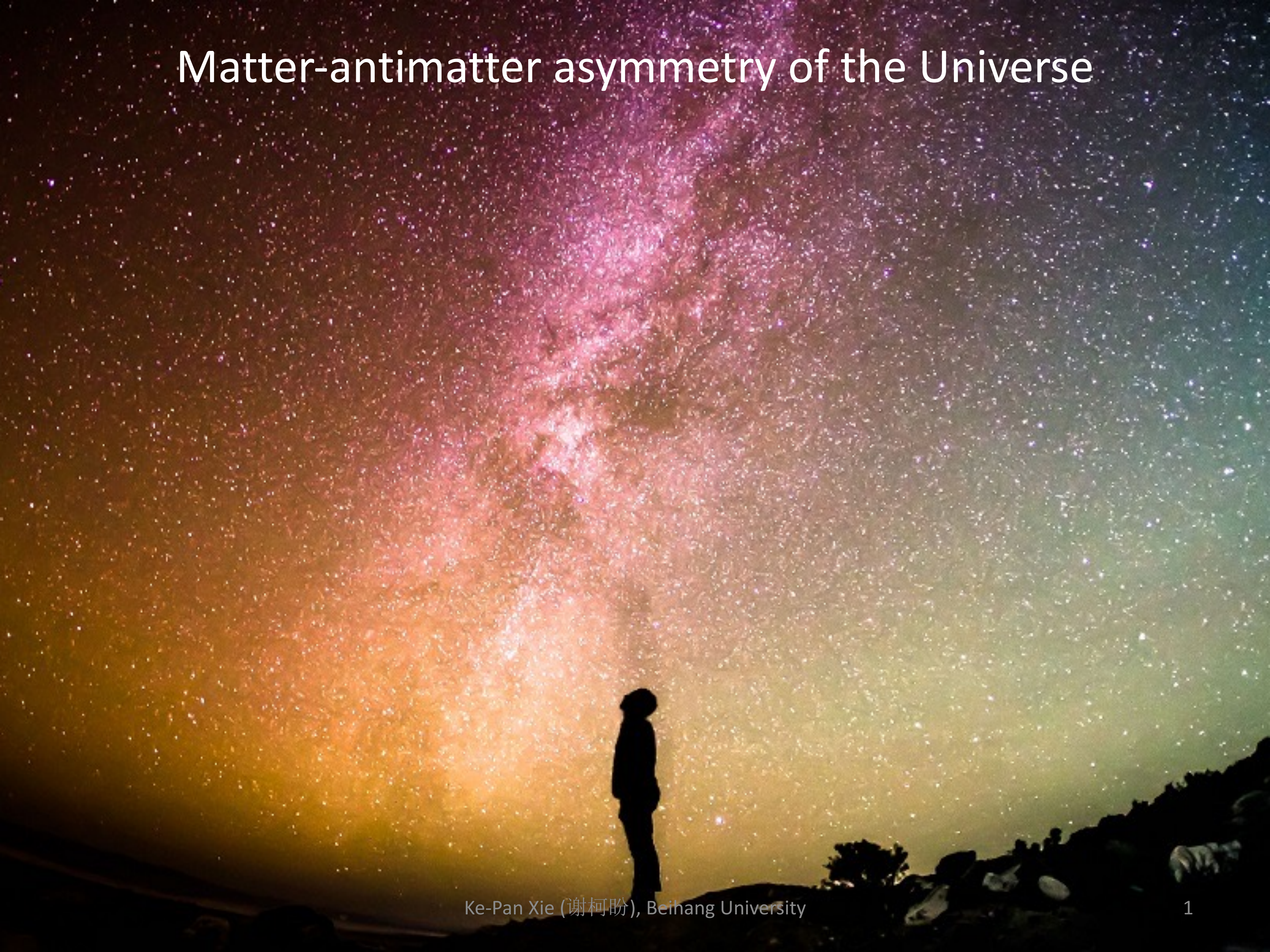
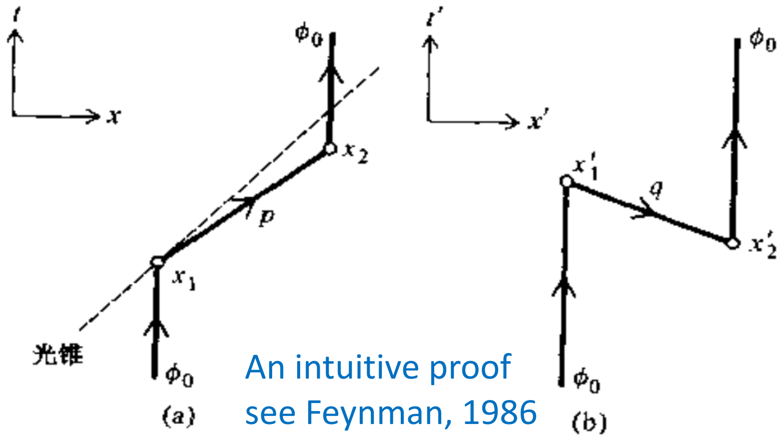
Matter-antimatter asymmetry of the Universe



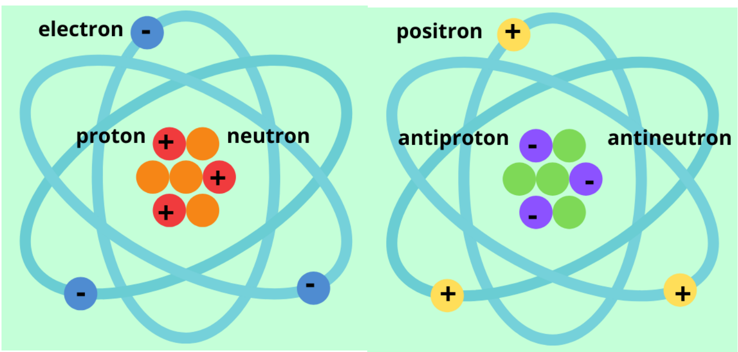
The antimatter

Consequence of the **relativistic quantum field theory**



An intuitive proof
see Feynman, 1986

Atom
Antiatom

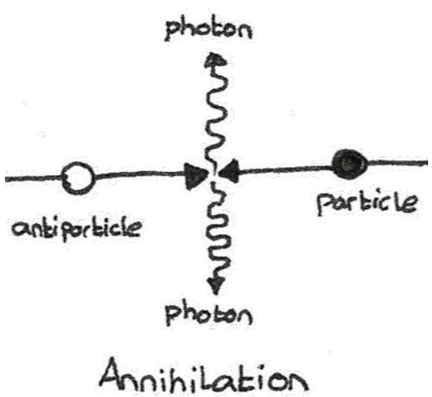


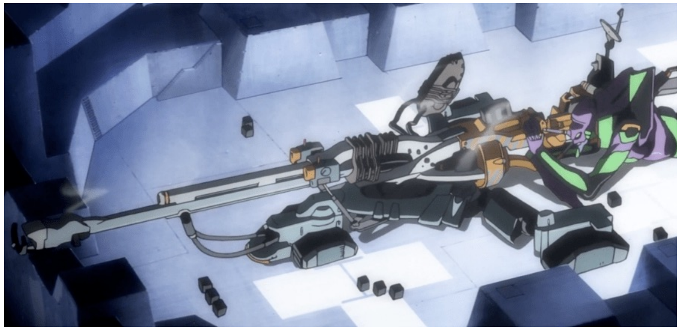
Discovery: positron (1932), antiproton (1955), antineutron (1956), antihydrogen (1990s)

Feature 1

Particle		Antiparticle
Mass	=	Mass
Spin	=	Spin
Lifetime	=	Lifetime
Charge	=	−Charge

Feature 2



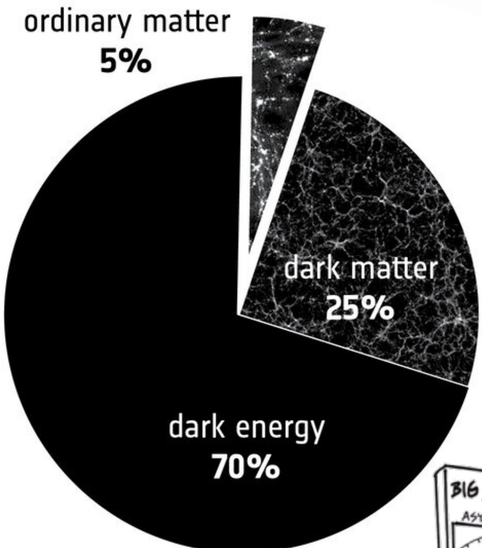


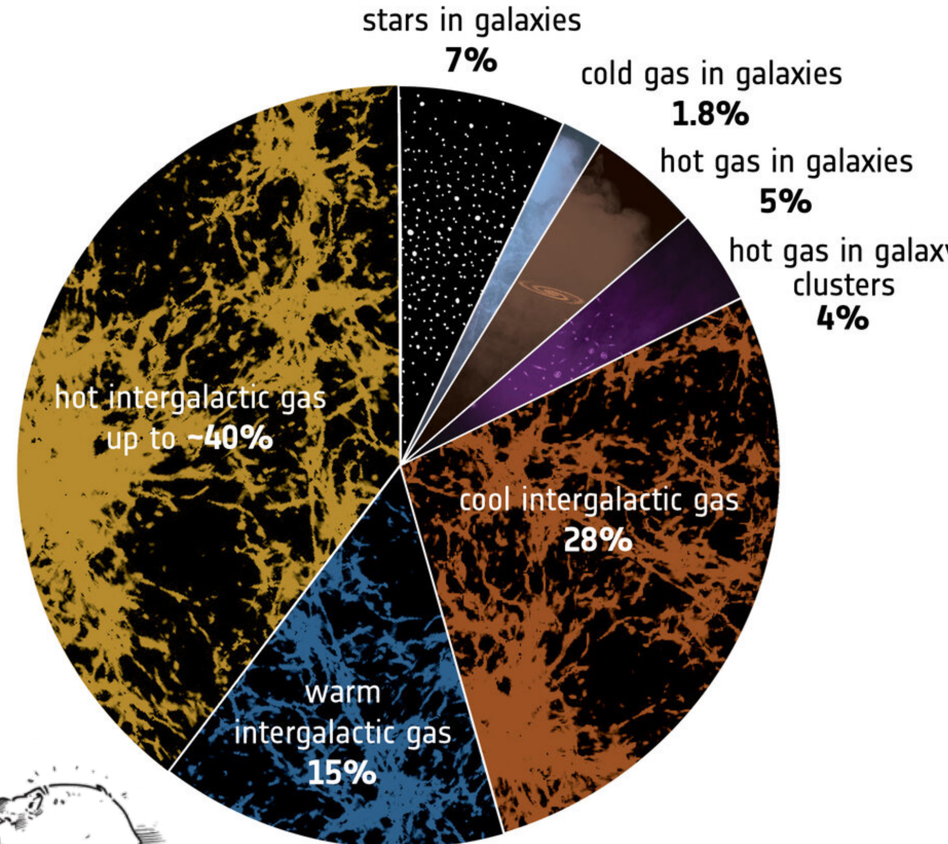
"Positron cannon"

The mystery

Mass fractions in the **visible matter**

- Hydrogen (proton): $\sim 74\%$
- Helium: $\sim 24\%$
- Other: $\sim 2\%$





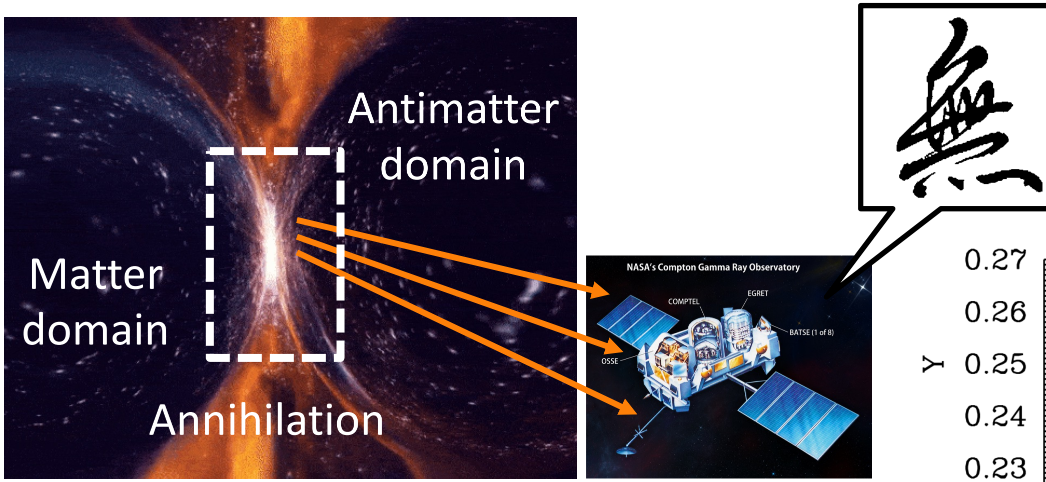
No antimatter
at cosmological scale!

Where is the

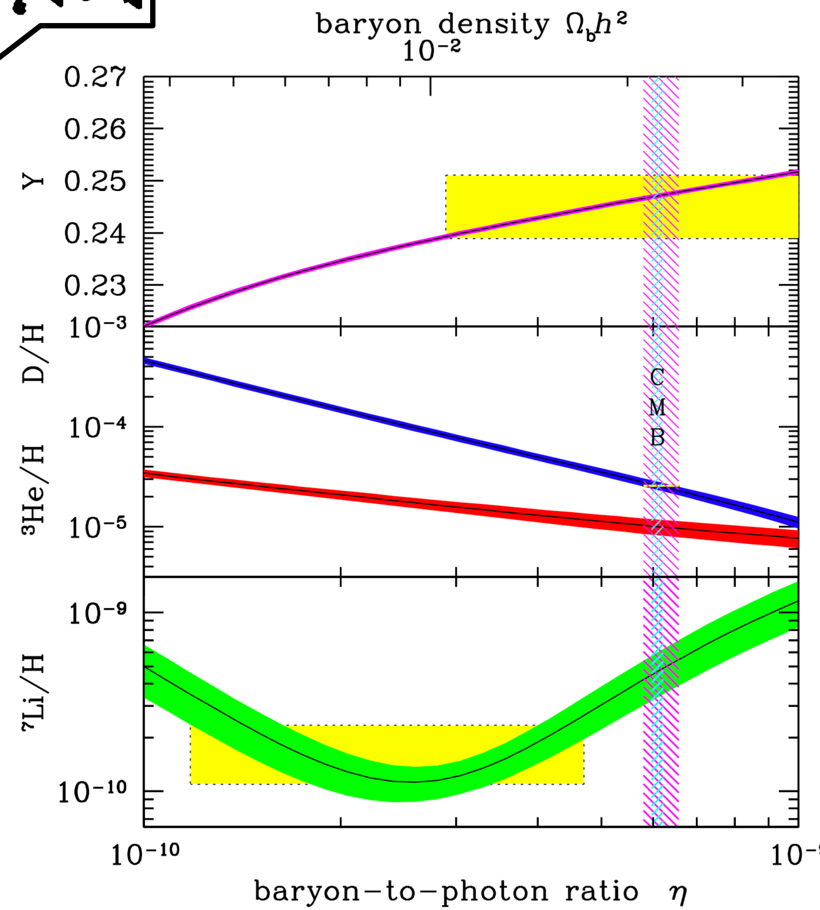
antimatter?

How do we know it?

Evidence 1: gamma-ray (non-)detection A. G. Cohen *et al*, Astrophys. J. 495, 539 (1998)



Null results



Evidence 2: big bang nucleosynthesis

Yeh *et al*, J. Cosmol. Astropart. Phys. 2022, 10, 046 (2022)

Evidence 3: Cosmic Microwave Background (CMB)

Planck Collaboration, Astron. Astrophys. 641, A6 (2020)

Baryon number density

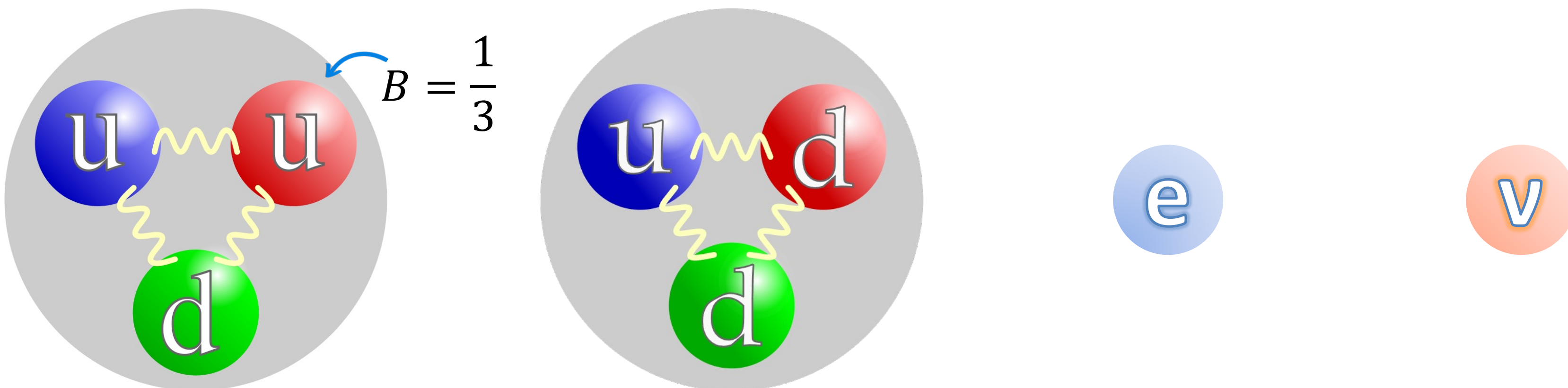
$$Y_B = \frac{n_B - n_{\bar{B}}}{s} \approx \frac{n_B}{s} \approx 0.9\times 10^{-10}$$

Entropy density

Matter asymmetry? Baryon asymmetry!

Matter-antimatter asymmetry refers to **baryon-antibaryon asymmetry**

- Baryon: composite, contains an odd number of quarks
- Lepton: elementary fermion, doesn't undergo strong interaction



Proton
Baryon number $B = 1$

Neutron
$B = 1$

Electron
Lepton number $L = 1$

Neutrino
$L = 1$

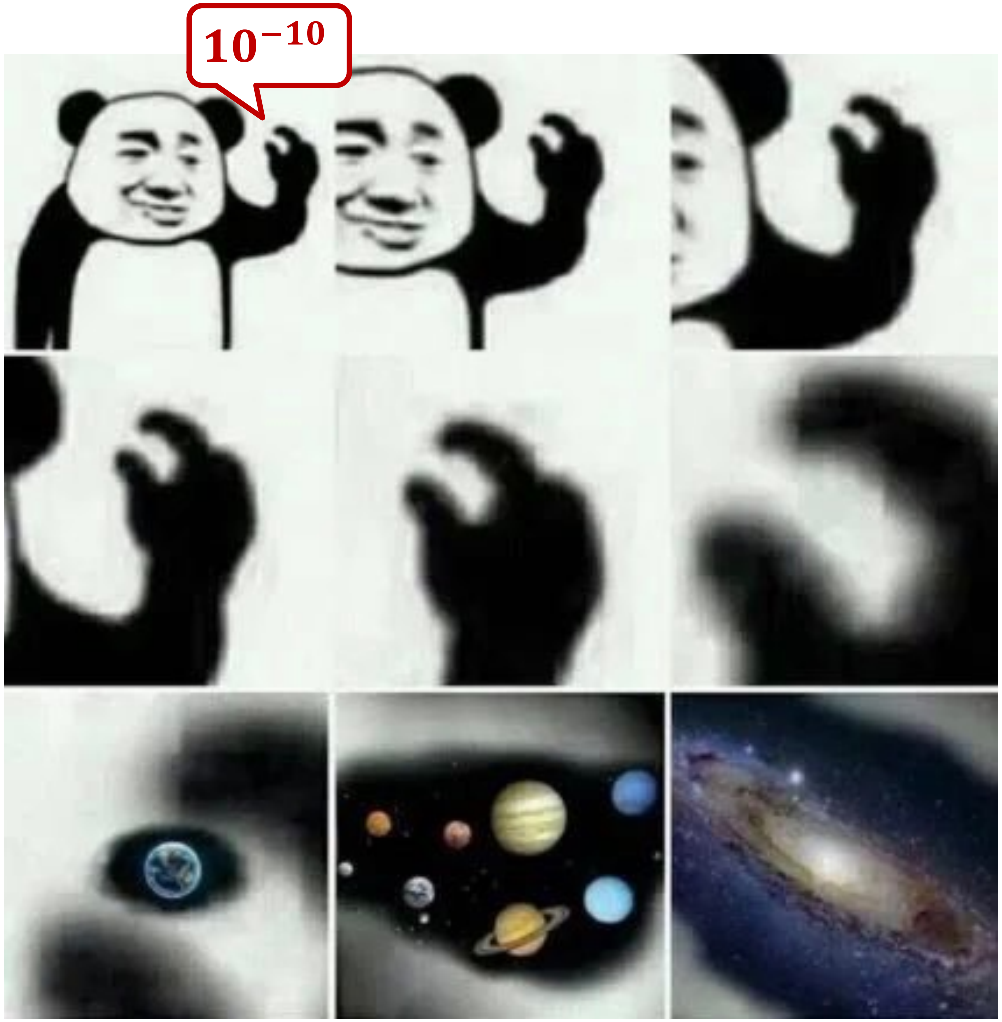
$$m_p \approx m_n \approx 1836 \cdot m_e\text{; and } m_\nu \approx 0$$

- Matter is dominated by the **baryonic matter** ⇒ measured by CMB acoustic peaks
- Participated in BBN ⇒ measured by abundance of the elements
- $Y_B \approx 10^{-10}$; however, the value of Y_L is still an open question

Asymmetric, but not too asymmetric

Given $Y_B = n_B/s \approx 0.9\times10^{-10}$ or $\eta_B = n_B/n_\gamma \approx 6\times10^{-10}$ --

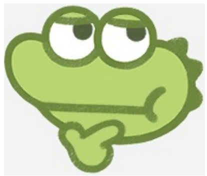
The early Universe

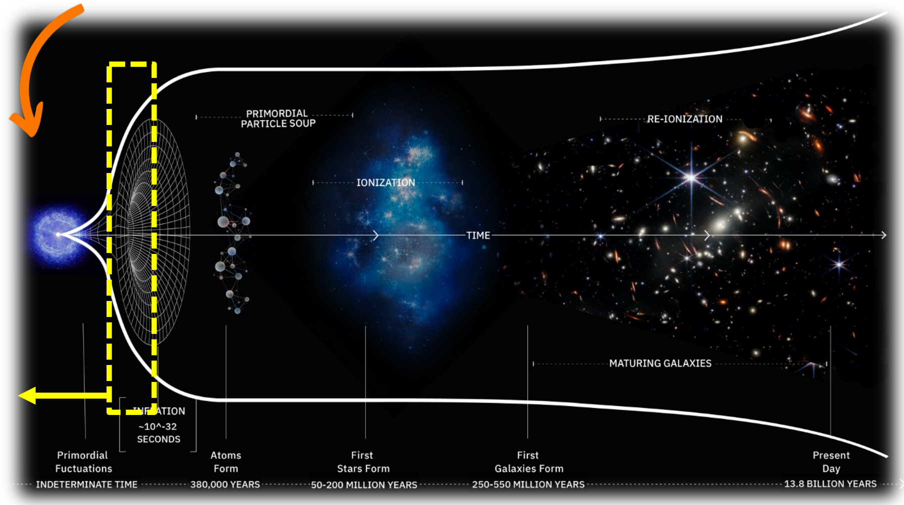


Now

Mystery or not?

An issue of **Initial condition**? An asymmetric Universe at the beginning?





Reheating after inflation:
Entropy produced exponentially

The initial $Y_{B0} \to e^{-3N} Y_{B0}$, with $N \gtrsim 58 \Rightarrow$ a suppression of 10^{-76}

After inflationary reheating, Y_B must be ≈ 0

The observed baryon asymmetry must be generated **after reheating** and **before BBN**

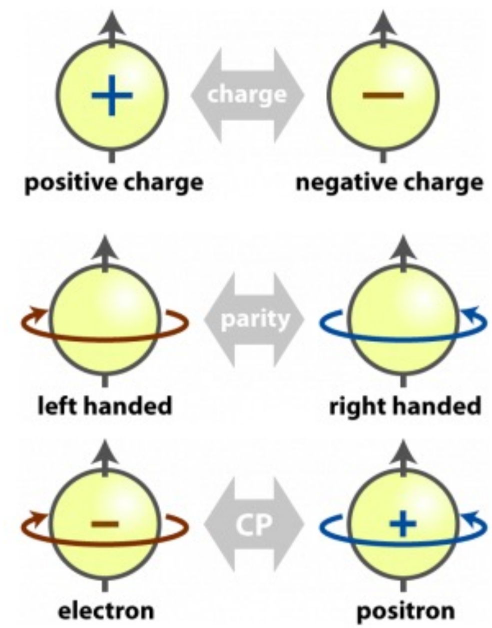
- Called ***baryogenesis*** (重子数生成)
- The Standard Model of particle physics fails to realize it

A mystery about the origin of our matter world, a clear evidence for new physics beyond the Standard Model

How to realize baryogenesis?

The so-called Sakharov conditions Sakharov, Pisma Zh.Eksp.Teor.Fiz. 5 (1967) 32-35
First clearly stated in Ignatiev *et al*, Phys. Lett. B 76 (1978) 436–438 (see Cline, 1807.08749)

Baryon number violation
- Otherwise $B \equiv 0$



C & CP violation, otherwise:
- C means $n_B \equiv n_{\bar{B}}$
- CP means $n_{B_L} \equiv n_{\bar{B}_R}$ and $n_{B_R} \equiv n_{\bar{B}_L}$

Departure from equilibrium
- Otherwise, active B-violating processes erase any B-asymmetry

SM v.s. Sakharov conditions (1)

Baryon number violation: ✓

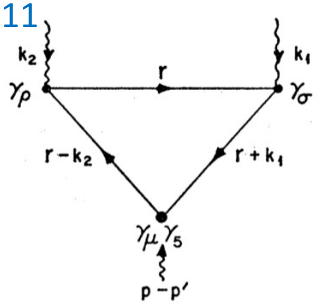
B is conserved at the classical level: $\partial_\mu J^\mu_B = 0$ with

$$J^\mu_B = \frac{1}{3}\left(\bar{u}\gamma^\mu u + \bar{d}\gamma^\mu d + \bar{c}\gamma^\mu c + \bar{s}\gamma^\mu s + \bar{t}\gamma^\mu t + \bar{b}\gamma^\mu b\right)$$

Quantum anomaly via the instanton 't Hooft, Phys.Rev.Lett. 37 (1976) 8-11

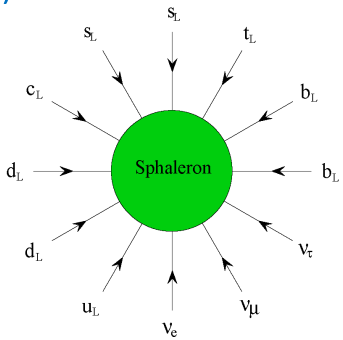
$$\partial_\mu J^\mu_B = -\frac{3}{32\pi^2}\left(g_W^2 W^a_{\mu\nu}\widetilde{W}^{a\mu\nu} - g_Y^2 B_{\mu\nu}\tilde{B}^{\mu\nu}\right)$$

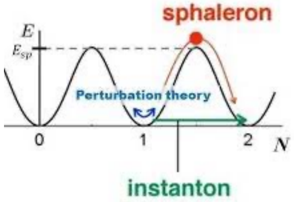
However, reaction rate $\propto e^{-16\pi^2/g_W^2} \sim 10^{-160}$, negligible



EW sphaleron at finite temperature Kuzmin *et al*, Phys.Lett.B 155 (1985) 36

- $\mathcal{O}_{\rm eff} = \prod_i [\bar{q}_L^{c,i} q_L^i][\bar{\ell}_L^{c,i}\ell_L^i]$, reaction rate $\propto e^{-m_W/(\alpha_W T)}$
- When $T \gtrsim 140$ GeV, the EW symmetry is restored, $\langle h\rangle = 0$ thus $m_W = 0$: active sphaleron!





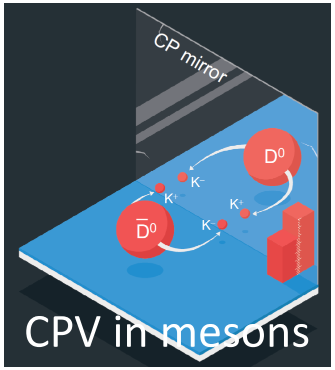
Both effects:

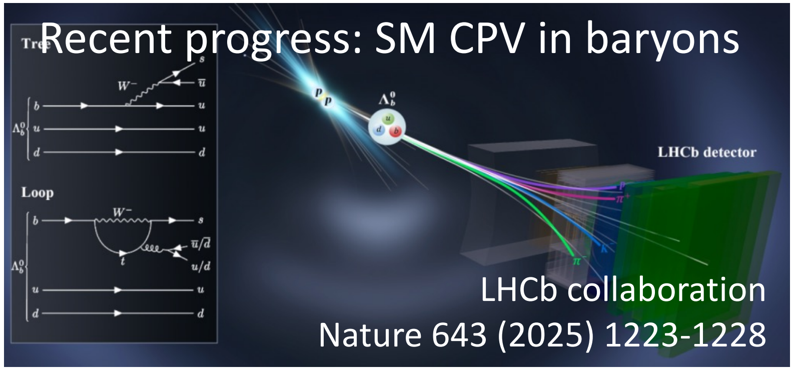
Nonperturbative, **violating $B + L$, but conserving $B - L$**

SM v.s. Sakharov conditions (2)

C & CP violation: ✗

- C & P maximally violated via EW chiral gauge group $SU(2)_L \times U(1)_Y$
- CP slightly violated via $-y_u^{ij}\bar{q}_L^i \widetilde{H} u_R^j - y_d^{ij}\bar{q}_L^i H d_R^j$, only 1 CP phase in the CKM matrix. **NOT sufficient**





Departure from equilibrium: ✗

<u>Decay of heavy particle(s)</u>

The SM couplings are not weak, typically $\Gamma \gg H$ at $T = m$

The decay processes are *too fast*

<u>First-order phase transition(s)</u>

Vacuum jumps, bubble nucleation

However, the SM EW symmetry breaking is a *smooth* crossover

In summary ✓✗✗, the SM cannot satisfy the Sakharov conditions!

Baryogenesis in new physics

Four well-known and extensively-studied **paradigms** of baryogenesis:

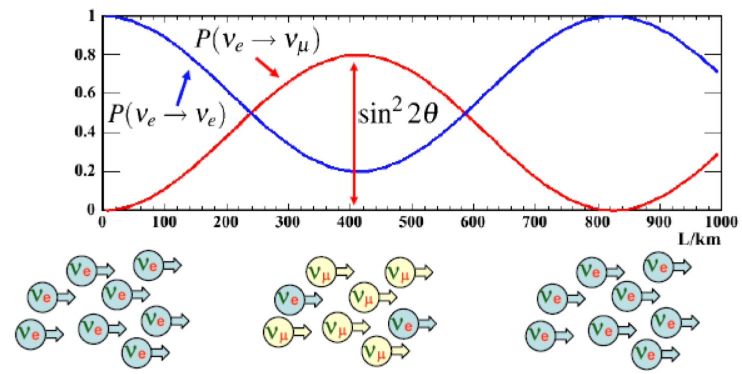
1. Out-of-equilibrium decay scenarios
2. The Affleck-Dine mechanism
3. Electroweak baryogenesis
4. Spontaneous baryogenesis

- They contribute the most original, classic, and inspiring ideas and frameworks for baryogenesis
- Most of them can be related to neutrino physics

Out-of-equilibrium decay scenarios

Neutrino mass and leptogenesis

SM neutrino ν_L: left-handed, massless
However, oscillation experiments:
- At least two generations of massive neutrinos, $m_\nu \sim 0.1\ \text{eV}$

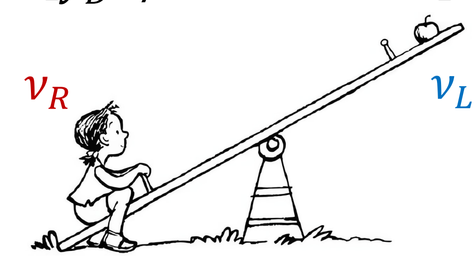


One popular explanation:
The (type-I) seesaw mechanism Minkowski, Phys.Lett.B 67 (1977) 421-428

Right-handed neutrino — SM Higgs doublet — SM lepton doublet

$$\mathcal{L} \supset \frac{1}{2} M \bar{\nu}_R^c \nu_R - \left(y_D \bar{\ell}_L \widetilde{H} \nu_R + \text{h.c.}\right) \qquad M_\nu = \begin{bmatrix} 0 & y_D v/\sqrt{2} \\ y_D v/\sqrt{2} & M \end{bmatrix}$$

$$m_\nu \sim \frac{y_D^2 v^2}{2M} \sim 0.1\ \text{eV} \times \left(\frac{y_D}{0.5}\right)^2 \left(\frac{10^{14}\ \text{GeV}}{M}\right)$$



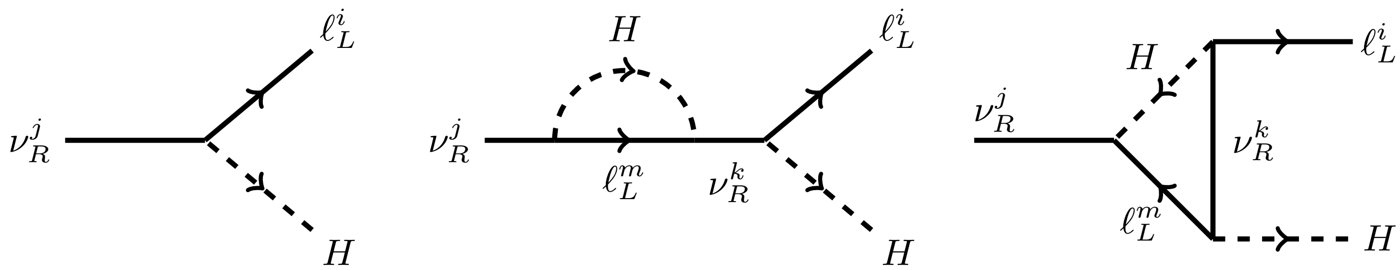
- Majorana mass M violates L
- y_D contains extra CP phases
- $\nu_R \to \ell H, \bar{\ell} H^*$ out of eq.

} Net lepton number generated → **baryon number** via EW sphaleron

Called ***leptogenesis*** (轻子数生成) Fukugita & Yanagida, Phys.Lett.B 174 (1986) 45-47

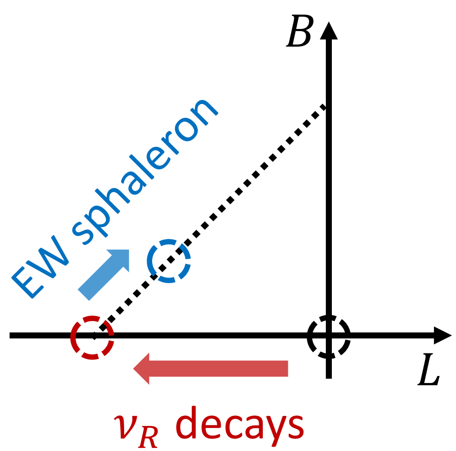
Decay of the right-handed neutrino

CP-violating decay of ν_R Covi *et al*, Phys.Lett.B 384 (1996) 169-174



$$\epsilon_j = \frac{\sum_i \Gamma\left(\nu_R^j \to \ell_L^i H\right) - \Gamma\left(\nu_R^j \to \bar{\ell}_L^i H^*\right)}{\sum_i \Gamma\left(\nu_R^j \to \ell_L^i H\right) + \Gamma\left(\nu_R^j \to \bar{\ell}_L^i H^*\right)} \propto \mathrm{Im}\left[\left(y_D y_D^\dagger\right)^2\right]$$

6 CP phases for 3 generations of leptons, leading to $\epsilon_j \neq 0$



EW sphaleron works:

$$Y_B = \frac{28}{79} Y_{B-L}$$

Not erasing Y_B because $M\bar{\nu}_R^c \nu_R$ **violates $B - L$**

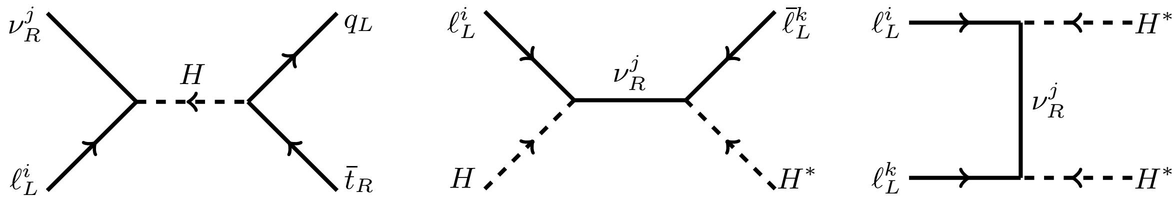
Naively, $Y_B \approx Y_{\rm ideal} = \left(n_{\nu_R}/s\right) \cdot \epsilon_j \approx \epsilon_j / g_{*s}$

However, usually $Y_B / Y_{\rm ideal} \lesssim 0.01$

Due to the washout effects in the thermal bath

Story in the thermal bath

Annihilation processes



$\Delta L_{\rm SM} = 1$ $\Delta L_{\rm SM} = 2$

Evolution: typically described a set of **Boltzmann equations**

- $z = M/T$; when time evolves, $T \searrow$ and $z \nearrow$
- Consider the **yield** $Y = n/s$

Scattering

$$\frac{\mathrm{d}Y_{\nu_R}}{\mathrm{d}z} = -(D+S)\left(Y_{\nu_R} - Y_{\nu_R}^{\rm eq}\right)$$

$$\frac{\mathrm{d}Y_{B-L}}{\mathrm{d}z} = \epsilon \cdot D\left(Y_{\nu_R} - Y_{\nu_R}^{\rm eq}\right) - W Y_{B-L}$$

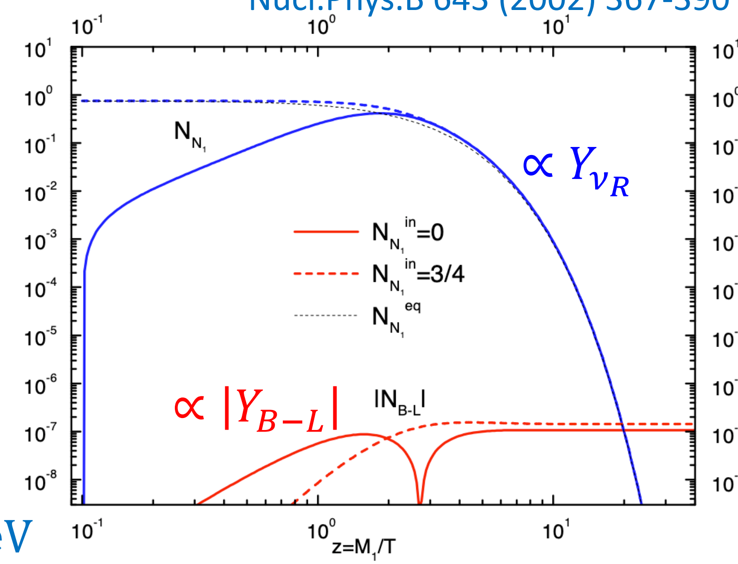
Decay Washout

Initial condition: $Y_{B-L}(z_i) = 0$

Goal: $Y_{B-L}\left(M/T_{\rm sph}\right) \sim 10^{-10}$

Sphaleron decouple, ≈ 132 GeV

Buchmuller *et al*,
Nucl.Phys.B 643 (2002) 367-390



Variations of leptogenesis

Vanilla leptogenesis:

- Hierarchy $M_3 \gg M_2 \gg M_1$, lightest ν_R^1 dominates Y_{B-L}
- Davidson-Ibarra bound Davidson & Ibarra, Phys.Lett.B 535 (2002) 25-32

$$|\epsilon_1| \lesssim 10^{-7}\left(\frac{m_\nu}{0.1\ \mathrm{eV}}\right)\left(\frac{M_1}{10^9\ \mathrm{GeV}}\right)$$

- Typically needs $M_1 > 10^9$ GeV for the observed Y_B

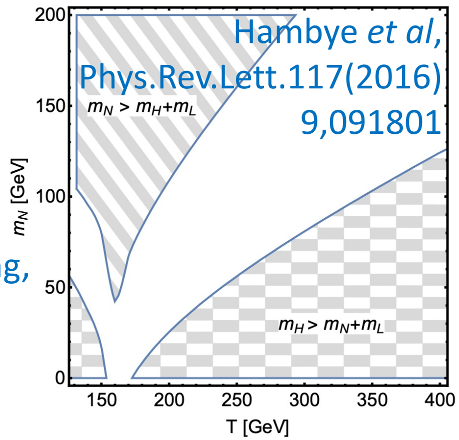
Resonant leptogenesis: near-degeneracy, $|M_1 - M_2| \approx \Gamma_1$

- ϵ_1 can reach $\mathcal{O}(1)$ for $M_1 \sim \mathrm{TeV}$

Pilaftsis *et al*, Nucl.Phys.B 692 (2004) 303-345 [original]; Chauhan *et al*, Nucl.Phys.B 986 (2023) 116058 [review]

Higgs decay leptogenesis: thermal mass, $H \to \bar{\ell}\nu_R$

- M_1 can be as low as 2 GeV

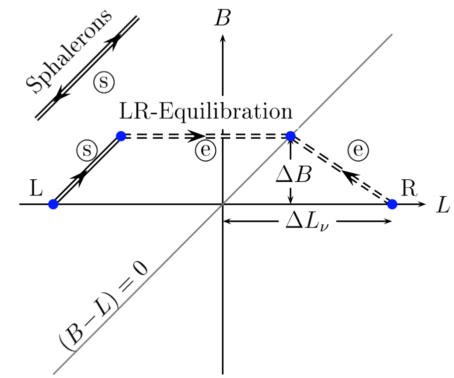


Other neutrino-mass mechanisms

- Type-II seesaw Ma *et al*, Phys. Rev. Lett. 80, 5716 (1998); Gu, Zhang, and Zhou, Phys. Rev. D 74, 076002 (2006); etc
- Inverse seesaw Aoki *et al*, PTEP 2015 (2015) 11, 113B03;
- Loop-induced ν-mass Hugle *et al*, Phys.Rev.D 98 (2018) 2, 023020

Reviews Pilaftsis, J.Phys.Conf.Ser. 171 (2009) 012017; Xing & Zhao, Rept.Prog.Phys. 84 (2021) 6, 066201

Some remarks on leptogenesis



Q: Are Majorana neutrinos necessary?

A: No. If left- and right-handed fermions do not equilibrate, Dirac neutrinos can also do leptogenesis

Because EW sphaleron only affects $(B-L)_L$

Dick *et al*, Phys.Rev.Lett. 84 (2000) 4039-4042; Murayama *et al*, Phys.Rev.Lett. 89 (2002) 271601

Q: Howe does leptogenesis link to the neutrino experimental data?

A: 3 CP phases available at low-energy

1 Dirac $\delta_{\rm CP}$ (via oscillation), 2 Majorana α_{21}, α_{31} (via e.g. $0\nu\beta\beta$). Current data imply a large $\delta_{\rm CP}\sim 3\pi/2$

However, a realistic model typically contains more phases (e.g., the vanilla leptogenesis has 6)

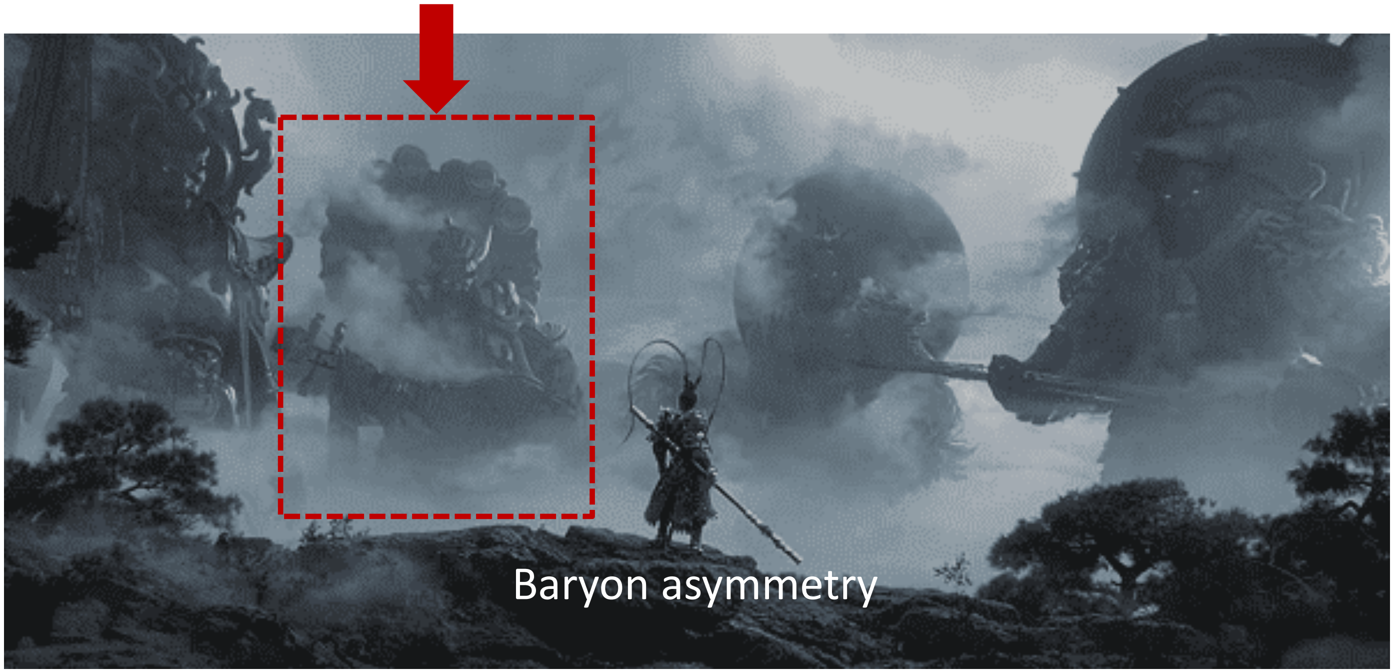
Very challenging to realize leptogenesis via only $\delta_{\rm CP}$

Branco *et al*, Rev.Mod.Phys. 84 (2012) 515-565 [review]; For some trials, see Dolan *et al*, 1802.08373; Li *et al*, 2105.01317; Shao *et al*, 2504.19697; etc

Q: Is there a lepton asymmetry in our Universe?

A: Hint of $Y_L\sim 10^{-3}$, but still an open question Kawasaki *et al*, JCAP 08 (2022) 08, 041; Burns *et al*, Phys.Rev.Lett. 130 (2023) 13, 131001; Domcke *et al*, Phys.Rev.Lett. 130 (2023) 26, 261803; etc

The Affleck-Dine mechanism



Scalar field evolution

Supersymmetry partners: same quantum number, different spins

quark $q \leftrightarrow$ squark $\tilde{q}$ (scalar); $\ell \leftrightarrow$ slepton $\tilde{\ell}$ (scalar)

Affleck & Dine proposed: Nucl. Phys. B 249 (1985) 361–380

- An appropriate *mixture* of $\tilde{q}$ and/or $\tilde{\ell}$ has a flat direction, $V(\phi) = 0$
- A nonzero potential is given by Dine *et al*, Nucl.Phys.B 458 (1996) 291-326

Mediated by gravity, requires $c < 0$

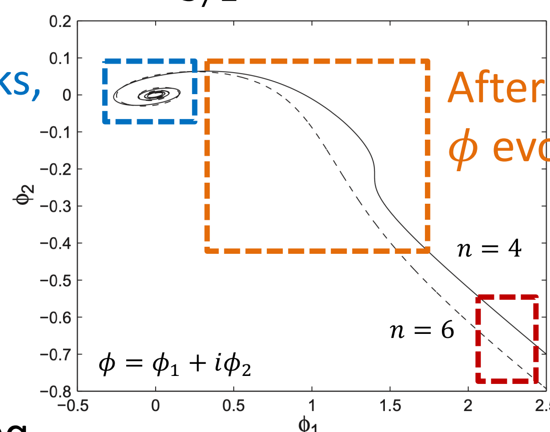
$$V(\phi) = \left(m_\phi^2 + cH^2\right)|\phi|^2 + \left[\frac{\left(Am_{3/2} + aH\right)\lambda\phi^n}{nM_*^{n-3}} + \mathrm{h.c.}\right] + \frac{|\lambda|^2|\phi|^{2n-2}}{M_*^{2n-6}}$$

SUSY soft-breaking $m_\phi \sim \mathrm{TeV}$

SUSY soft-breaking $m_{3/2} \sim \mathrm{TeV}$

High-dim operator $M_* \sim 10^{16}\ \mathrm{GeV}$

Eventually, only m_ϕ works, oscillating, B conserved



After inflation, $H \sim 1/t$, ϕ evolves, B generated

$$\ddot{\phi} + 3H\dot{\phi} + V' = 0$$

Large $\langle\phi\rangle$ during inflation, $H \sim 10^{13}\ \mathrm{GeV}$

Allahverdi *et al*, New J.Phys. 14 (2012) 125013

Reminder

1. The A-term breaks B
2. Nonzero $\langle\phi\rangle$ violates CP
3. Condensate of ϕ out of eq.

Variations of the AD mechanism

The AD mechanism represents a paradigm of realizing baryogenesis via *coherent field evolution*, not limited to SUSY sfermions

Axiogenesis Co *et al*, Phys.Rev.Lett. 124 (2020) 11, 111602

- Large $U(1)_{\rm PQ}$ charge from *saxion* field oscillation → SM quark chiral asymmetry (QCD sphaleron) → Baryon asymmetry (EW sphaleron)

Nambu-Goldstone (NG) baryogenesis Harigaya, JHEP 08 (2019) 085

- Flat direction realized by NG boson, without SUSY

Type-II seesaw AD mechanism Barrie, Han, Murayama Phys.Rev.Lett.128(2022)14,141801

- A triplet BSM Higgs Δ,

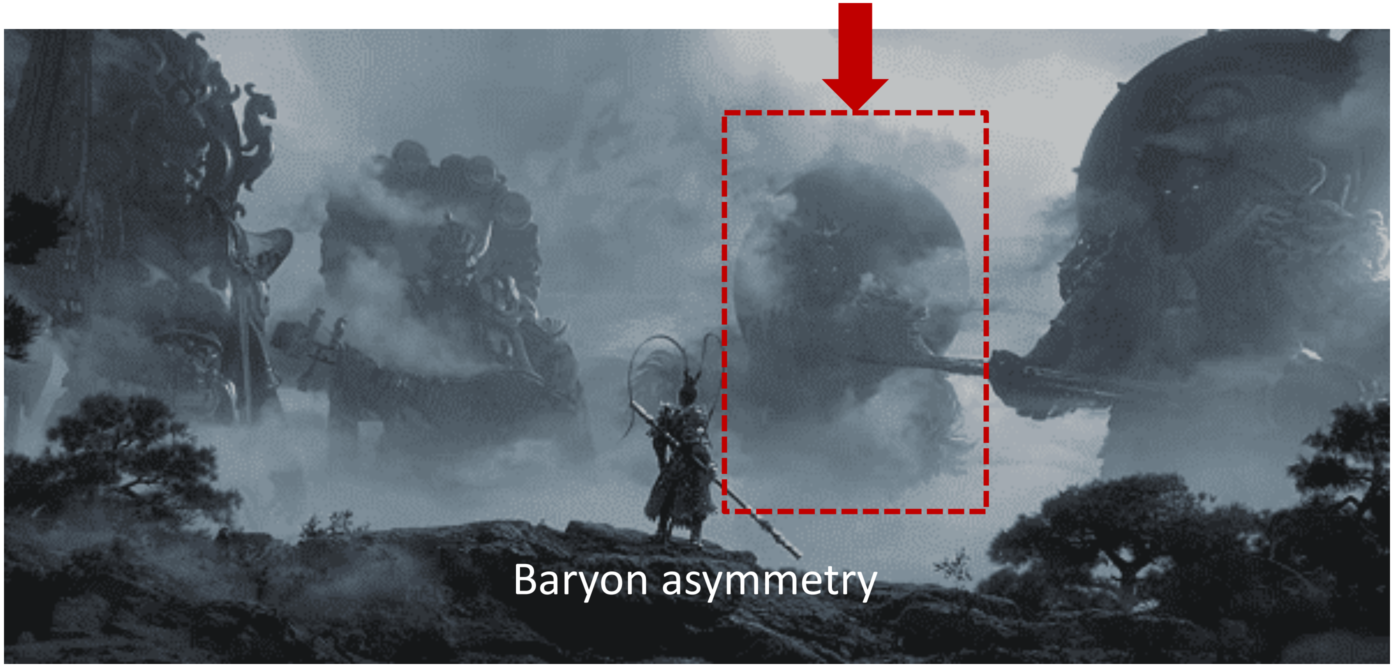
$$\mathcal{L} \supset -\mu H^\dagger \Delta \widetilde{H} - \frac{1}{2} y_{ij} \bar{L}_i^c \Delta L_j + \text{h.c.}$$

$$m_\nu \approx y \frac{\mu v^2}{2 m_\Delta}$$

- AD mechanism from Δ evolution, generating L, then converted to B via EW sphaleron
- Higgs inflation

Solving three problems in a model

Electroweak baryogenesis



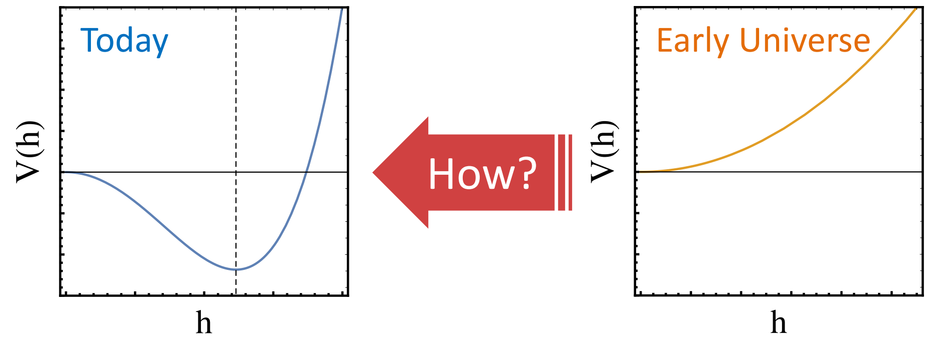
Electroweak phase transition

Today: $\langle h \rangle = 246$ GeV

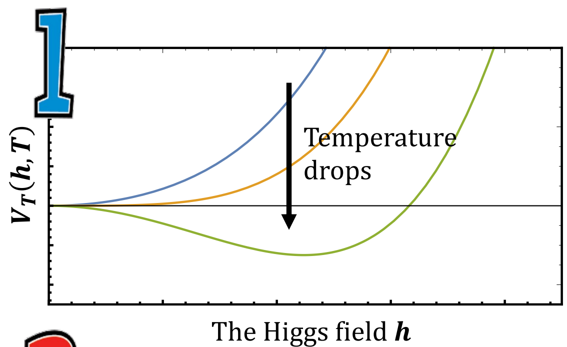
- $SU(2)_L \times U(1)_Y \rightarrow U(1)_{\rm EM}$
- SM particles massive

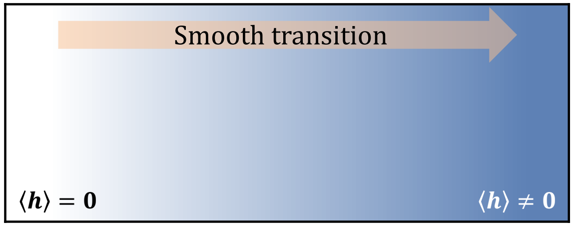
Early Universe: $\langle h \rangle = 0$

- $SU(2)_L \times U(1)_Y$ preserved
- SM particles massless



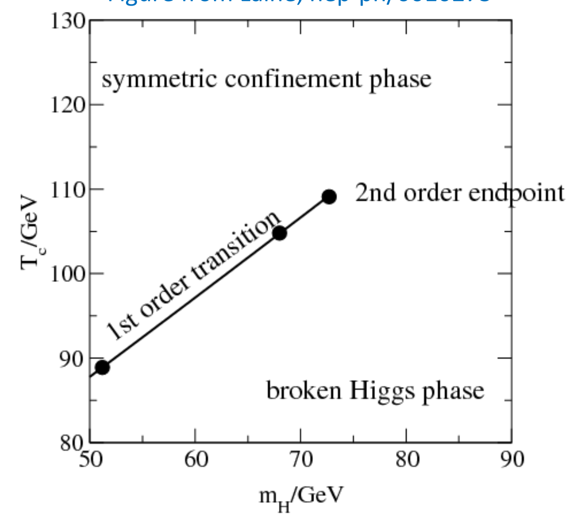
SM! Unfortunately

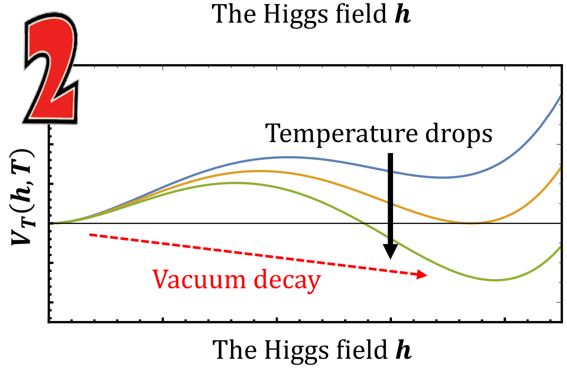


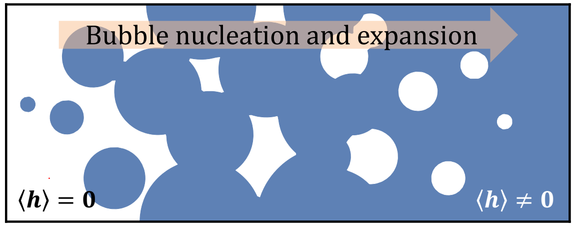


≈ equilibrium

Figure from Laine, hep-ph/0010275





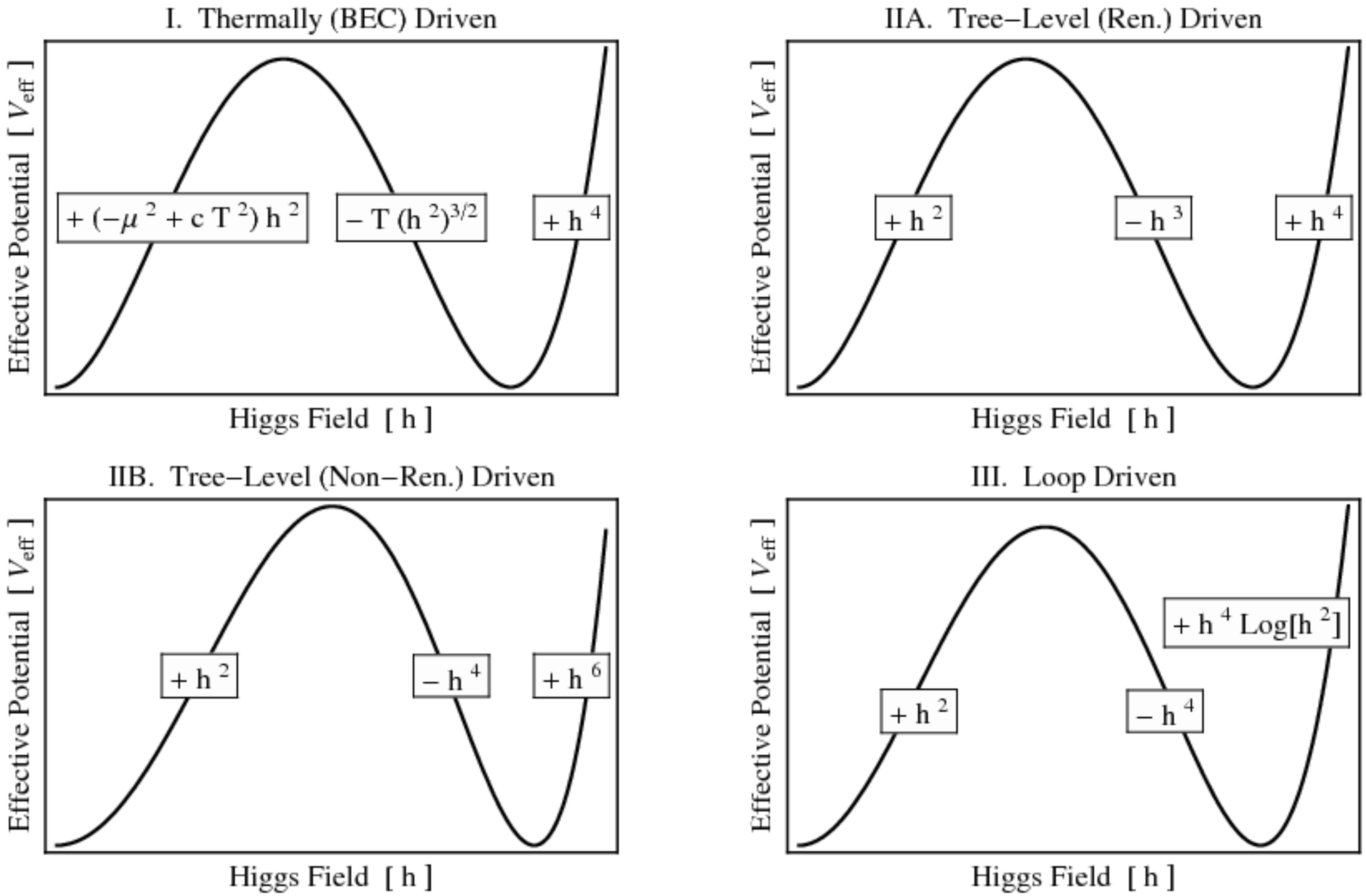


out of equilibrium

Needs new physics

Realizing a first-order EWPT

Four main scenarios Chung, Long, Wang, Phys.Rev.D 87 (2013) 2, 023509



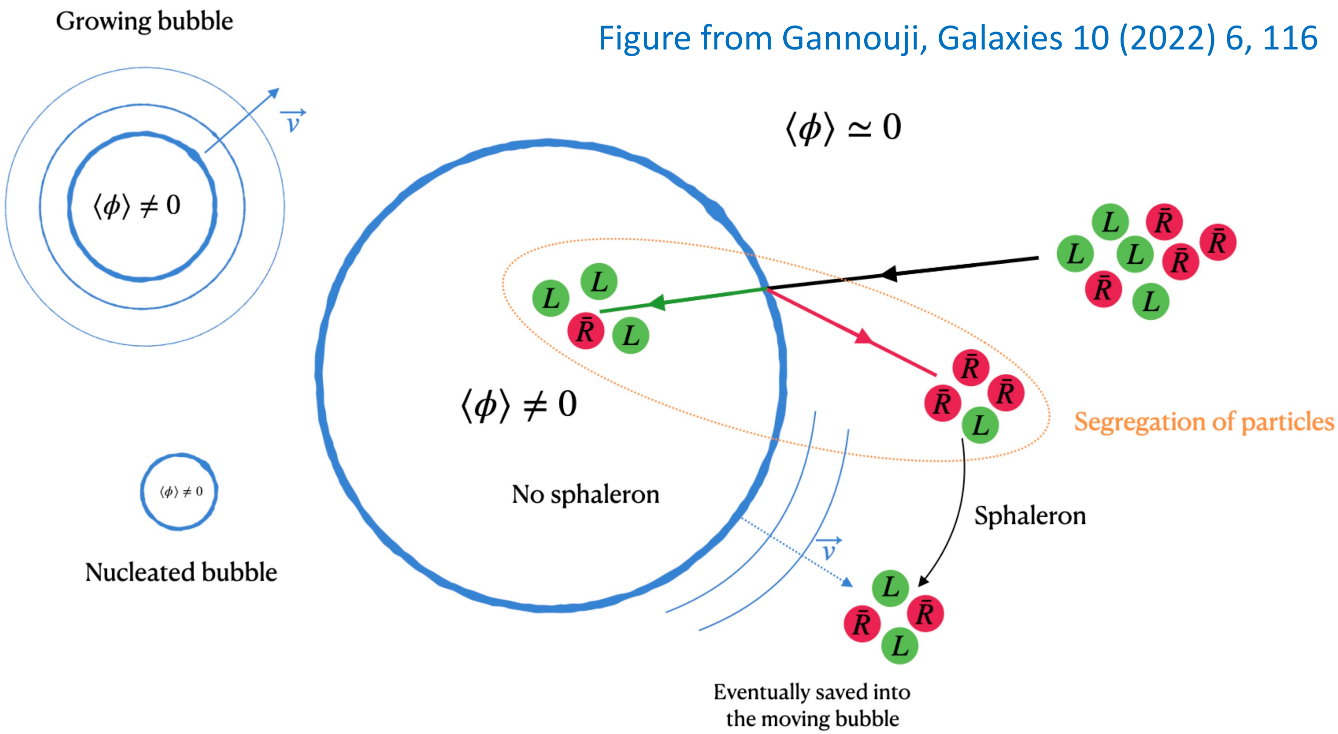
Also see the reviews Mazumdar *et al*, Rept.Prog.Phys. 82 (2019) 7, 076901; LISA collaboration, JCAP 03 (2020) 024; Athron, Wu, *et al*, Prog.Part.Nucl.Phys. 135 (2024) 104094; etc

Electroweak baryogenesis

Started from the late 1980s, still active today Reviews: Trodden, Rev.Mod.Phys. 71 (1999) 1463-1500; Morrissey & Ramsey-Musolf, New J.Phys. 14 (2012) 125003; van de Vis *et al*, 2508.09989

Taking the *popular* **nonlocal** EW baryogenesis as an example

Figure from Gannouji, Galaxies 10 (2022) 6, 116



- On the wall: CP-violating scattering causing a **chiral asymmetry** Y_{LR}
- Outside the bubble: $Y_{LR} \to Y_B$ via EW sphaleron
- Inside the bubble: $\langle\phi\rangle/T > 1$, EW sphaleron **decouples**, Y_B frozen

Choosing a fermion to transport

Quantitatively, described by a set of **Boltzmann equations**

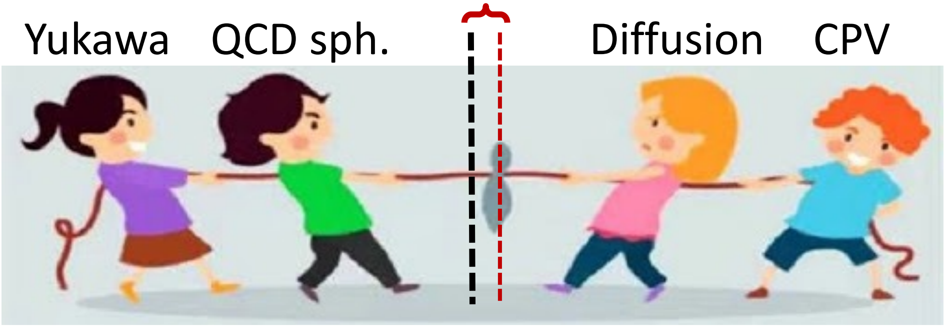
$$\text{fermion scattering} \xrightarrow{\text{CPV}} \text{chiral asymmetry} \xrightarrow{\text{Sph.}} \text{baryon asymmetry}$$

- Which fermion do we need?

Naïvely, the top quark: sizeable interaction with h, large CP phase Joyce *et al*, Phys.Rev.Lett. 75 (1995) 1695-1698; Fromme *et al*, JHEP 03 (2007) 049; etc

However, also suffers from large washout

Chiral asymmetry (ChA)



Washing out ChA   Enhancing ChA

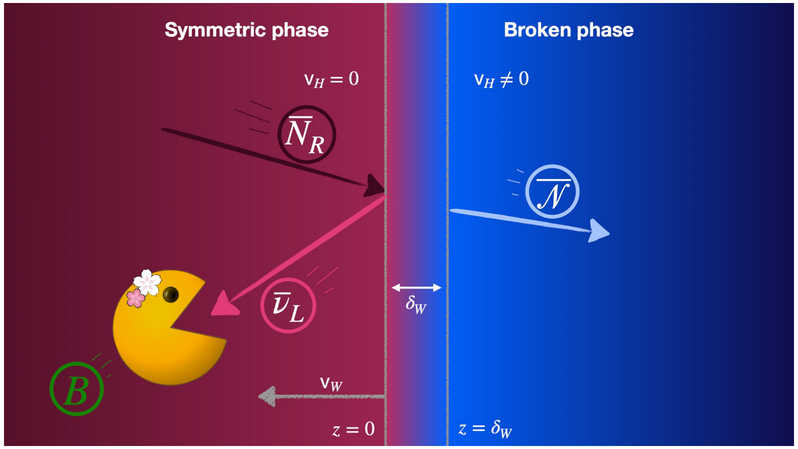
The past decade: lepton transport

- Small CP phase, but easy to diffuse, and experience small washout

[τ-mediated] Guo *et al*, Phys.Rev.D96(2017)115034; Vries *et al*, JHEP04(2019)024; **KPX**, JHEP02(2021)090; etc
[μ-mediated] Fuchs *et al*, Phys. Rev. Lett. 124 (2020) 181801

Relation to neutrinos

EW baryogenesis can also be related to **neutrino physics**

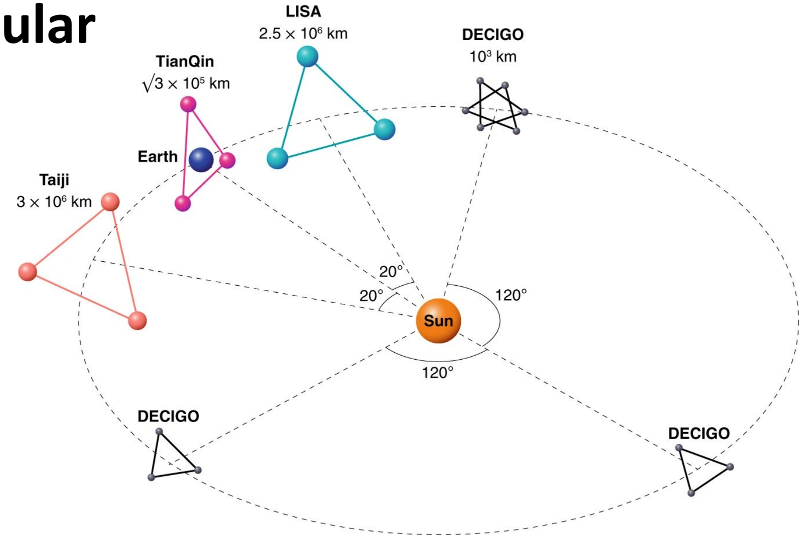


- Based on low-scale neutrino mass generation models, i.e. inverse or linear seesaw
- Transport of the neutrinos

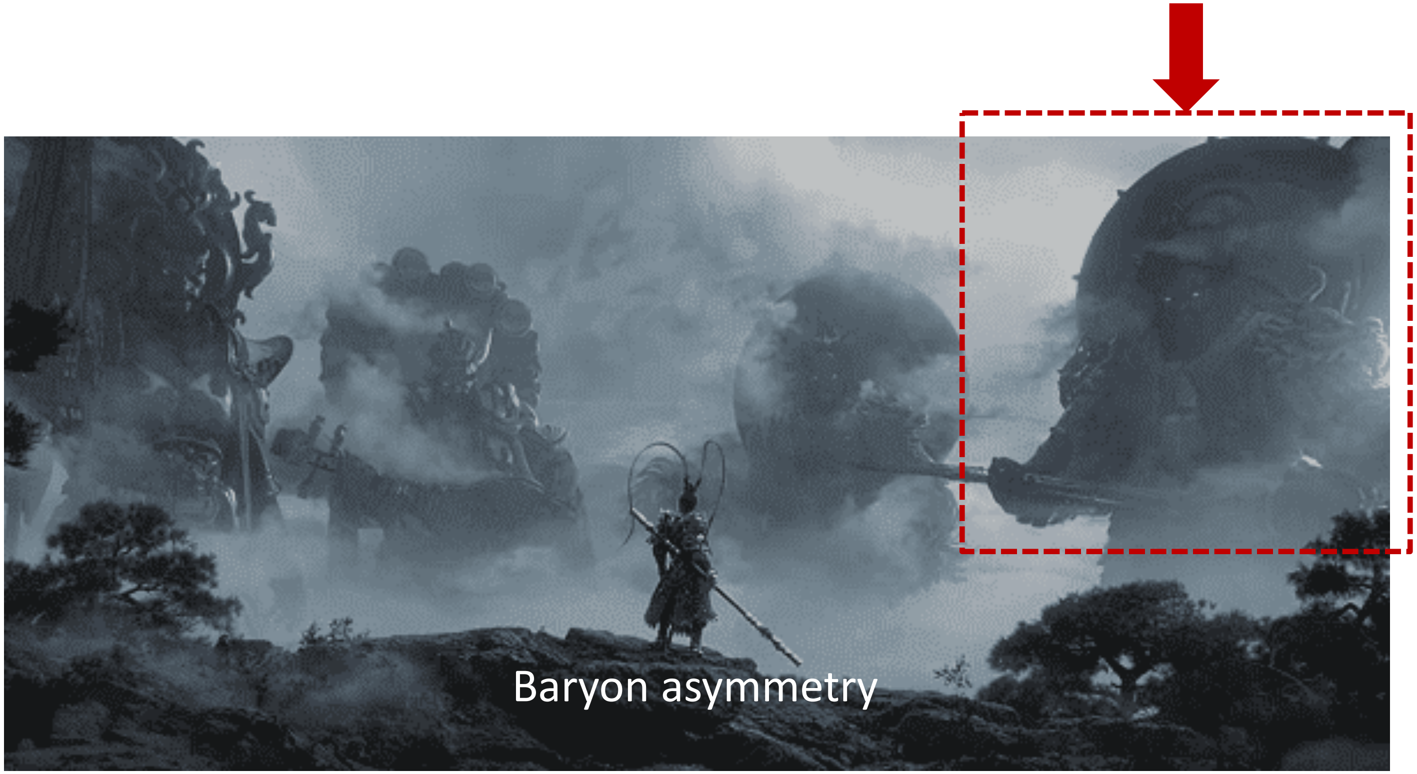
Fernández-Martínez *et al*, JHEP 10 (2020) 063

EW baryogenesis is currently **very popular**

- Naturally at TeV scale, closely related to Higgs physics
- EW phase transition gravitational waves detectable at near-future interferometers



Spontaneous baryogenesis



The third Sakharov condition

The complete statement --

- Departure from equilibrium **or $\boldsymbol{CPT}$ violation**, because

$$\langle B\rangle_{\text{eq}} = \text{tr}\left[Be^{-H/T}\right] = \text{tr}\left[(CPT)Be^{-H/T}(CPT)^{-1}\right]$$
$$= \text{tr}\left[(CPT)B(CPT)^{-1}e^{-H/T}\right] = -\text{tr}\left[Be^{-H/T}\right] = -\langle B\rangle_{\text{eq}} = 0$$

This *lecture* assumes CPT invariance except this and the next page

C: charge conjugation
P: spatial parity
T: time reversal

$\boldsymbol{CPT}$ theorem: Lüders, Kong.Dan.Vid.Sel.Mat.Fys.Med. 28N5 (1954) 5, 1-17

A local quantum field theory with Lorentz invariance and a Hermitian Hamiltonian must have CPT symmetry

If CPT is preserved:

- Particle and antiparticle have the same mass, and hence the same <u>equilibrium distribution</u> → no baryon asymmetry

If CPT is broken:

- Lorentz invariance is also violated Greenberg, Phys.Rev.Lett. 89 (2002) 231602
- Baryon asymmetry may be generated in equilibrium

Spontaneous baryogenesis

CPT violation in the early Universe Cohen and kaplan, Phys.Lett.B 199 (1987) 251-258

$$\mathcal{L}_{\rm int} = \frac{1}{\Lambda}\partial_\mu\phi \cdot J_B^\mu$$ ⟵ Baryon current

After inflation, ϕ almost spatially homogeneous, $\mathcal{L}_I \to \dot{\phi} J_B^0/\Lambda$

Let $\dot{\phi}/\Lambda = \mu$, considering $J_B^0 = n_B - n_{\bar{B}}$,

$$\mathcal{L}_{\rm int} \to \mu \cdot (n_B - n_{\bar{B}})$$

Chemical potential, yielding baryon number $B \approx \mu T^2$ **in thermal bath**

More details:

- ϕ slow rolls, and B freeze-in
- $\mathcal{L}_{\rm int}$ drops out of equilibrium before the ending of slow-roll
- Then B is frozen
- ϕ decays via $\mathcal{L}_{\rm int}$
- ϕ can't be the inflaton, as it should continue rolling after reheating

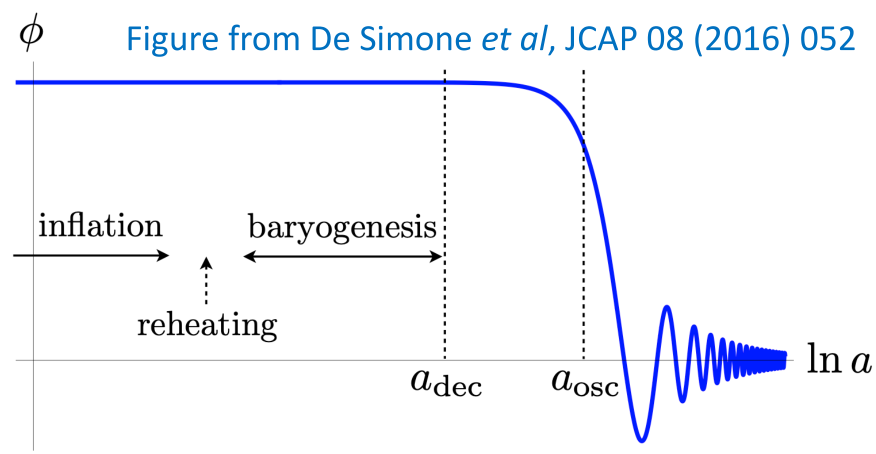


Figure from De Simone *et al*, JCAP 08 (2016) 052

More discussions see Arbuzova *et al*, Phys.Rev.D 94 (2016) 12, 123501

More mechanisms

Due to limitation of time & knowledge, I'm not able to cover all topics
I will focus on some **leptogenesis** mechanisms

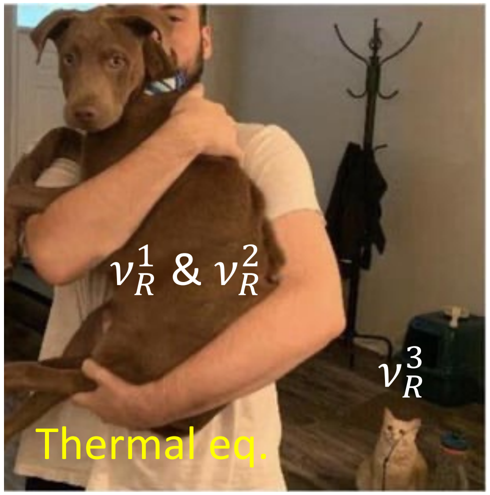
Generally speaking: all mechanisms transferring L to B can be called leptogenesis (not necessarily related to particle decay).

Leptogenesis via oscillation

The **ARS** mechanism Akhmedov *et al*, Phys.Rev.Lett.81(1998)1359-1362

- $M \lesssim 246\ \mathrm{GeV}$, ν_R below the electroweak scale
- Three ν_R's oscillate
- Majorana mass small, $L_{\mathrm{SM}} + L_1 + L_2 + L_3 \approx 0$, no lepton number is generated overall
- Yukawa hierarchy: ν_R^1 & ν_R^2 in equilibrium, but ν_R^3 NOT in equilibrium

- $L_1 + L_2$ is communicated to L_{SM} then B via EW sphaleron
- A net Y_B is generated
- ν_R^3 equilibrates at a low temperature, after sphaleron decouples, no impact onY_B



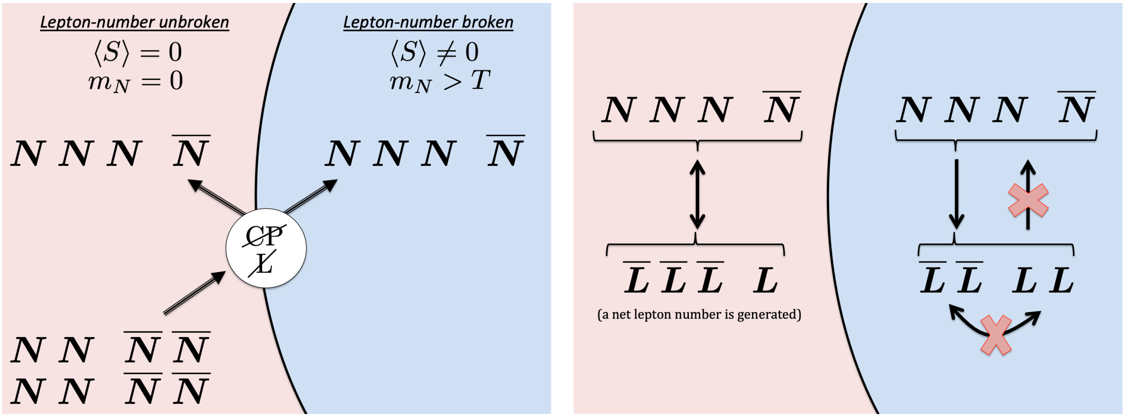
A recent review Drewes *et al*, Int.J.Mod.Phys.A 33 (2018) 05n06, 1842002

Leptogenesis via FOPTs (1)

Similar to EW baryogenesis, but first-order phase transitions (FOPTs) occur in **other scalar fields** instead of the Higgs

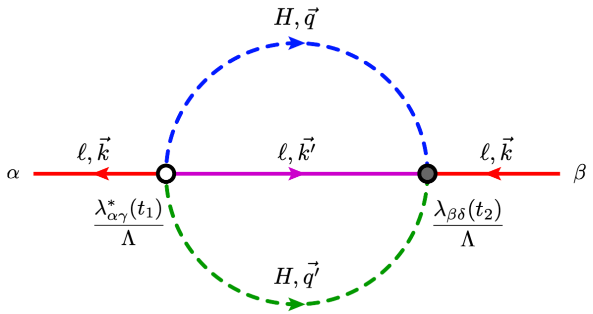
Scenario 1: Lepton-number-violating FOPT, neutrino transport

Long, Tesi, and Wang, JHEP 10 (2017) 095



Scenario 2: CP-violating FOPT, Weinberg operator

Pascoli, Turner, and Zhou, Phys.Lett.B 780 (2018) 313-318



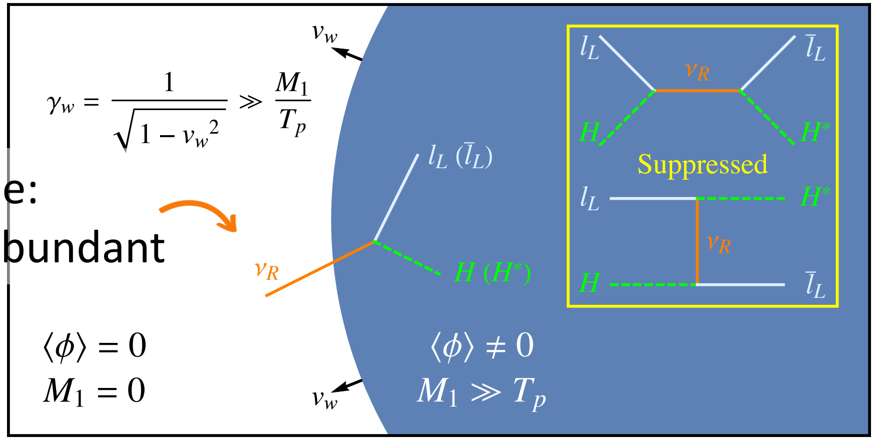
$$\mathcal{L}_W = \frac{\lambda_{\alpha\beta}}{\Lambda}\ell_{\alpha L}HC\ell_{\beta L}H + \text{h.c.}\,,$$

Leptogenesis via FOPTs (2)

More “violent” scenarios based on supercooled FOPTs

Scenario 1 Huang and **KPX**, JHEP 09 (2022) 052; also Baldes *et al*, Phys. Rev. D 104 (2021) 115029; Chun *et al*, JHEP 09 (2023) 164

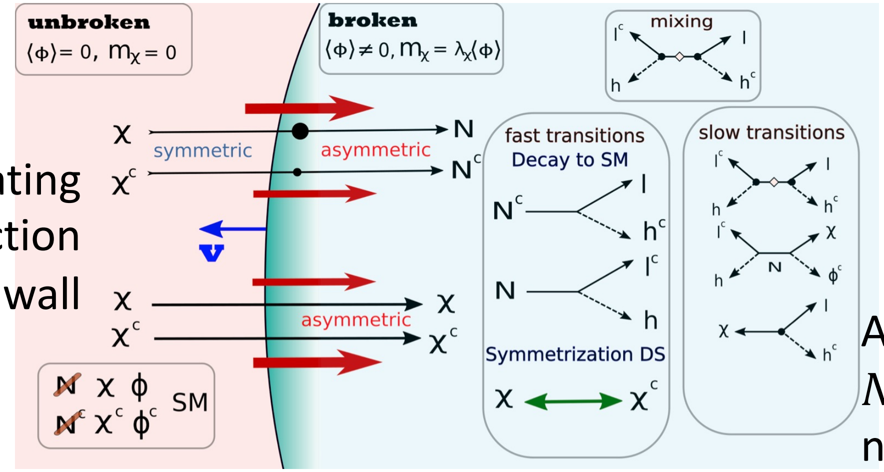
Outside the bubble:
ν_R massless and abundant



After penetration:
ν_R superheavy
and immediately decays, no thermal washout

Scenario 2 Azatov *et al*, JHEP 10 (2021) 043

CP-violating
particle production
on the wall



After production:
N decays immediately,
no thermal washout

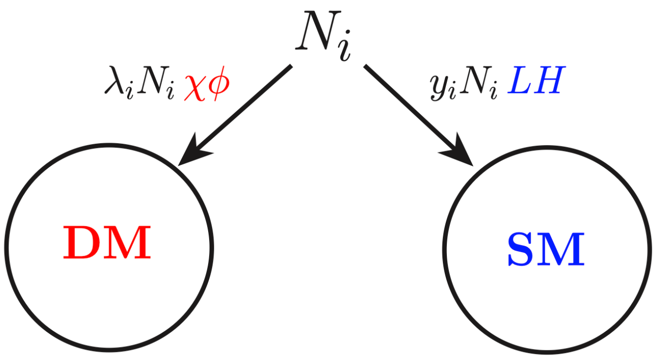
Leptogenesis & dark matter

The asymmetric dark matter paradigm Zurek, Phys.Rept. 537 (2014) 91-121 [review]

Scenario 1 Falkowski *et al*, JHEP 05 (2011) 106

Elementary particle dark matter

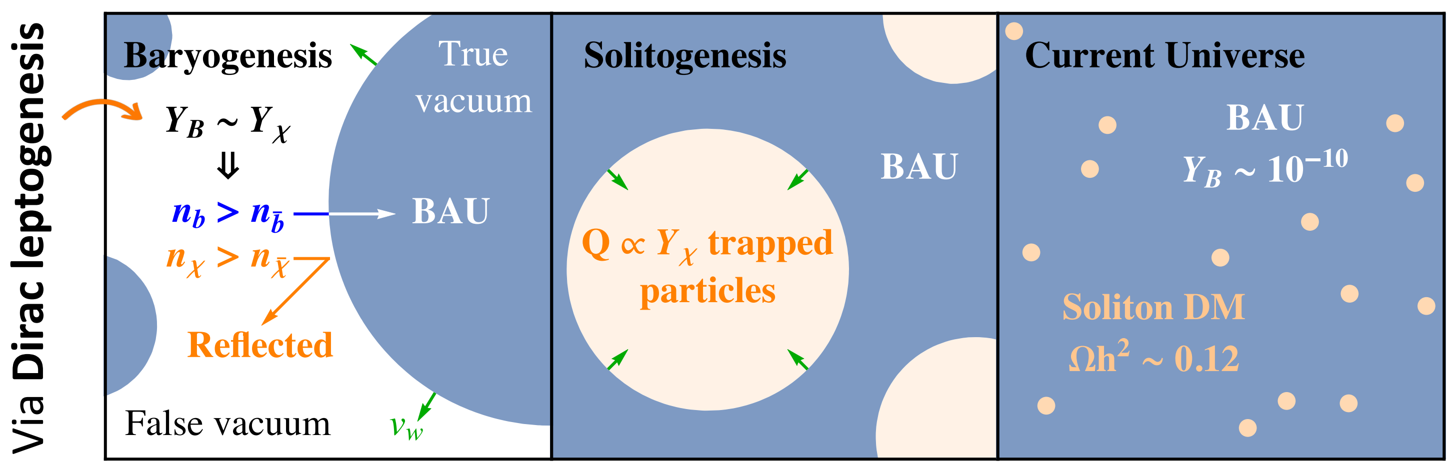
- Right-handed neutrino decay generates $B-L$ asymmetry and dark matter



Scenario 2 Kanemura, Li, and **KPX**, 2504.08304

Macroscopic dark matter: nontopological solitons

- Needs the assistance of the *cosmic bubbles*



Conclusion & outlook

What we do know:

- There is a baryonic matter asymmetry in the Universe
- It was generated between reheating and big bang nucleosynthesis
- Needs physics beyond the Standard Model

What we don't know:

- **Generation scale**. Grand unification (10^{16} GeV), vanilla leptogenesis (10^{11} GeV), electroweak (10^{2} GeV), or even sub-GeV scale?
- **Baryogenesis mechanism**. Particle decay, coherent scalar evolution, fermion transport, or even CPT violation?
- **Testability**. Neutrino oscillation, electric dipole moment, collider experiments, or gravitational waves?

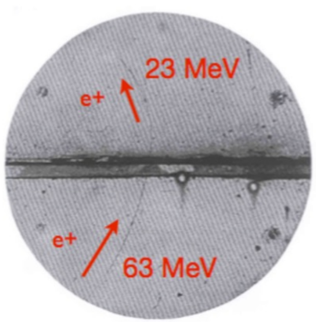
Still a long way to understand the mystery of matter and antimatter!

Thank you!

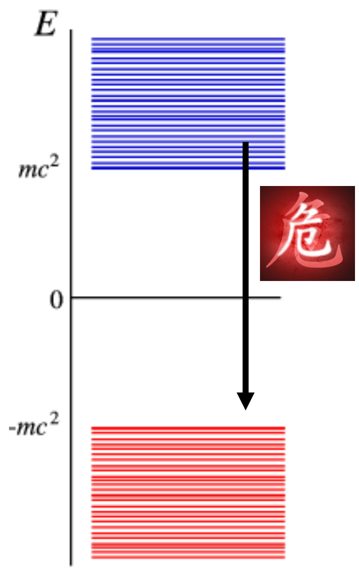
Backup: the positron

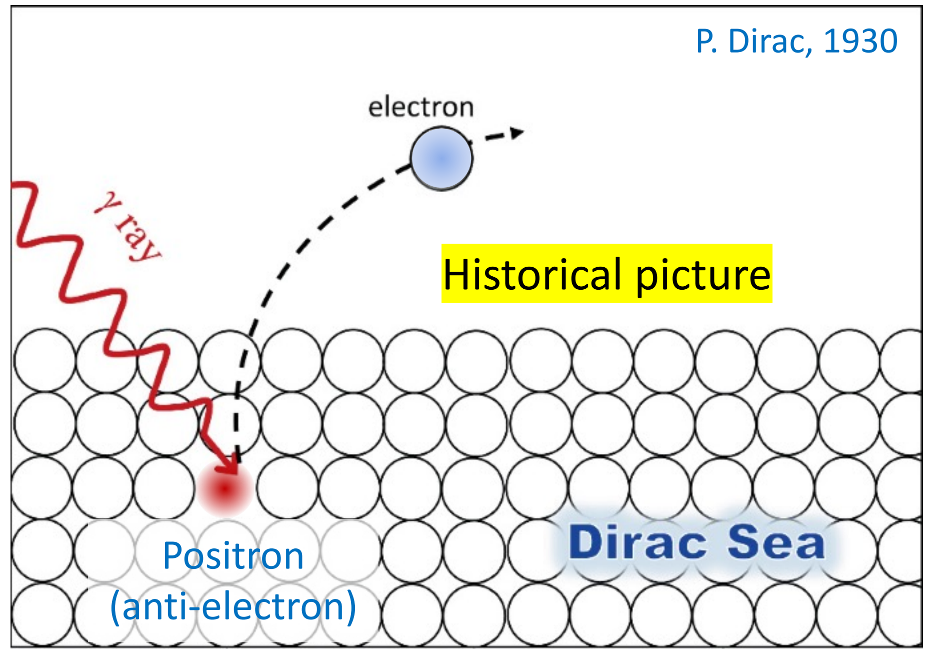
Origin: **negative energy** solution of the Dirac **wave equation**

- $(i\gamma^\mu \partial_\mu - m)\psi = 0$
- $H\psi = E\psi$



C. Anderson, 1932

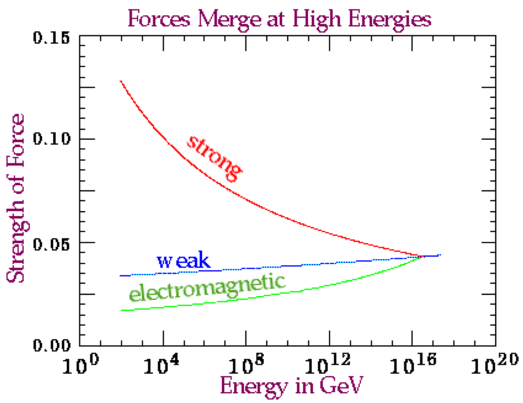




Modern explanation: the Dirac **field equation**

- $\psi(x) \sim \sum_{\vec{p},r} c_r(\vec{p}) u_r(\vec{p}) e^{-ipx} + d_r^\dagger(\vec{p}) v_r(\vec{p}) e^{-ipx}$
- Single-particle state: electron $c^\dagger|0\rangle$ or positron $d^\dagger|0\rangle$, both with **positive energy**
- *No infinite electron sea anymore!*

Backup: GUT baryogenesis



The grand unified theories (GUTs): unify strong, weak, and electromagnetic interactions

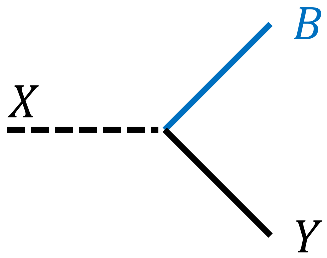
Starting from Georgi & Glashow, Phys.Rev.Lett. 32 (1974) 438-441, still very active today

Candidates: $SU(5)$, $SU(8)$, $SO(10)$, E_6, ...

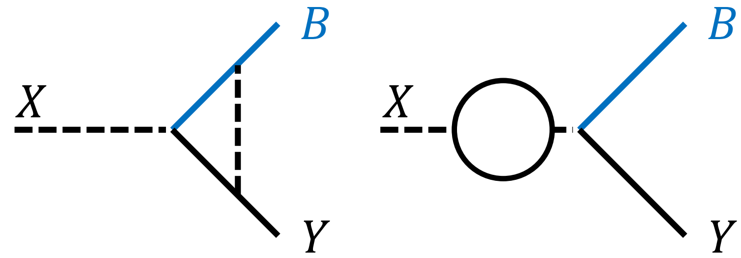
- ✓ Well-motivated theories
- Quarks & leptons in the same representation, allowing for B-violating interactions
- More interactions, containing extra CP-violating phases
- Heavy Higgs or gauge bosons: out-of-equilibrium decay via $X \to qq, q\bar{\ell}$
- ✓ Baryon asymmetry generated

Backup: asymmetric decay

Let X be a heavy particle with decay channel $X \to BY$



+ loop corrections, e.g.,



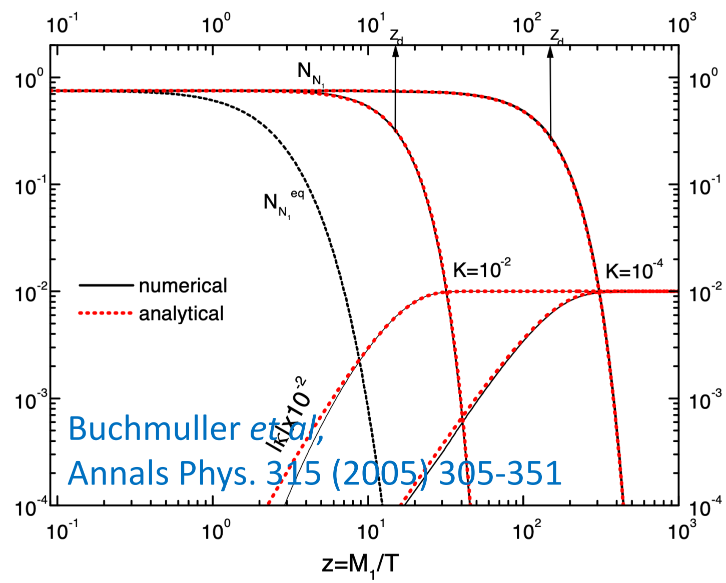
CP-violating couplings in the loops, causing *partial width* difference

$$\epsilon = \frac{\Gamma(X \to BY) - \Gamma(\bar{X} \to \bar{B}\bar{Y})}{\Gamma_X + \Gamma_{\bar{X}}} > 0$$

**Total width* $\Gamma_X \equiv \Gamma_{\bar{X}}$ (CPT invariance)

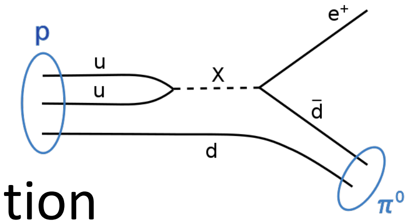
A typical thermal history:

1. When $T \gg m_X$, X in equilibrium, with $n_X \sim T^3$
2. At $T \sim m_X$, $\Gamma_X \ll H$, not decaying, $n_X \gg n_X^{\text{eq}} \sim e^{-m_X/T}$
3. When $T \lesssim m_X$, out-of-equilibrium decay: baryogenesis



Buchmuller *et al.*, Annals Phys. 315 (2005) 305-351

Backup: difficulties in GUT baryogenesis



Difficulty: $\Lambda_{\text{GUT}} \sim 10^{16}$ GeV, too high to directly test

Possible solutions:

- Proton decay (e.g. $p \to e^{+}\pi^{0}$): baryon number violation
- Electric dipole moment of elementary particles: CP violation

Difficulty: inflation theory requires $T_{\text{rh}} \lesssim 10^{14}$ GeV, X particles might never be in equilibrium!

Possible solution:

- X's are exponentially produced from **preheating** during the inflaton coherent oscillation Riotto *et al*, Ann.Rev.Nucl.Part.Sci. 49 (1999) 35-75; hep-ph/9807454

Difficulty: $B-L$ is conserved in many GUTs, and the EW sphaleron will erase any $B+L$ asymmetry before EW phase transition

Possible solutions:

- Adding $B-L$-violating operator Fukugita & Yanagida, Phys.Rev.Lett. 89 (2002) 131602
- Using chiral asymmetry Kamada, Phys.Rev.D 97 (2018) 10, 103506