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Title: The Mystery of the Matter in the Universe

Author(s): Fuyuto, Kaori

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The Mystery of the Matter in the Universe

Kaori Fuyuto

Los Alamos National Laboratory

Los Alamos NATIONAL LABORATORY EST. 1943

THEORETICAL DIVISION Since 1943

December 3, 2021
University of Arizona


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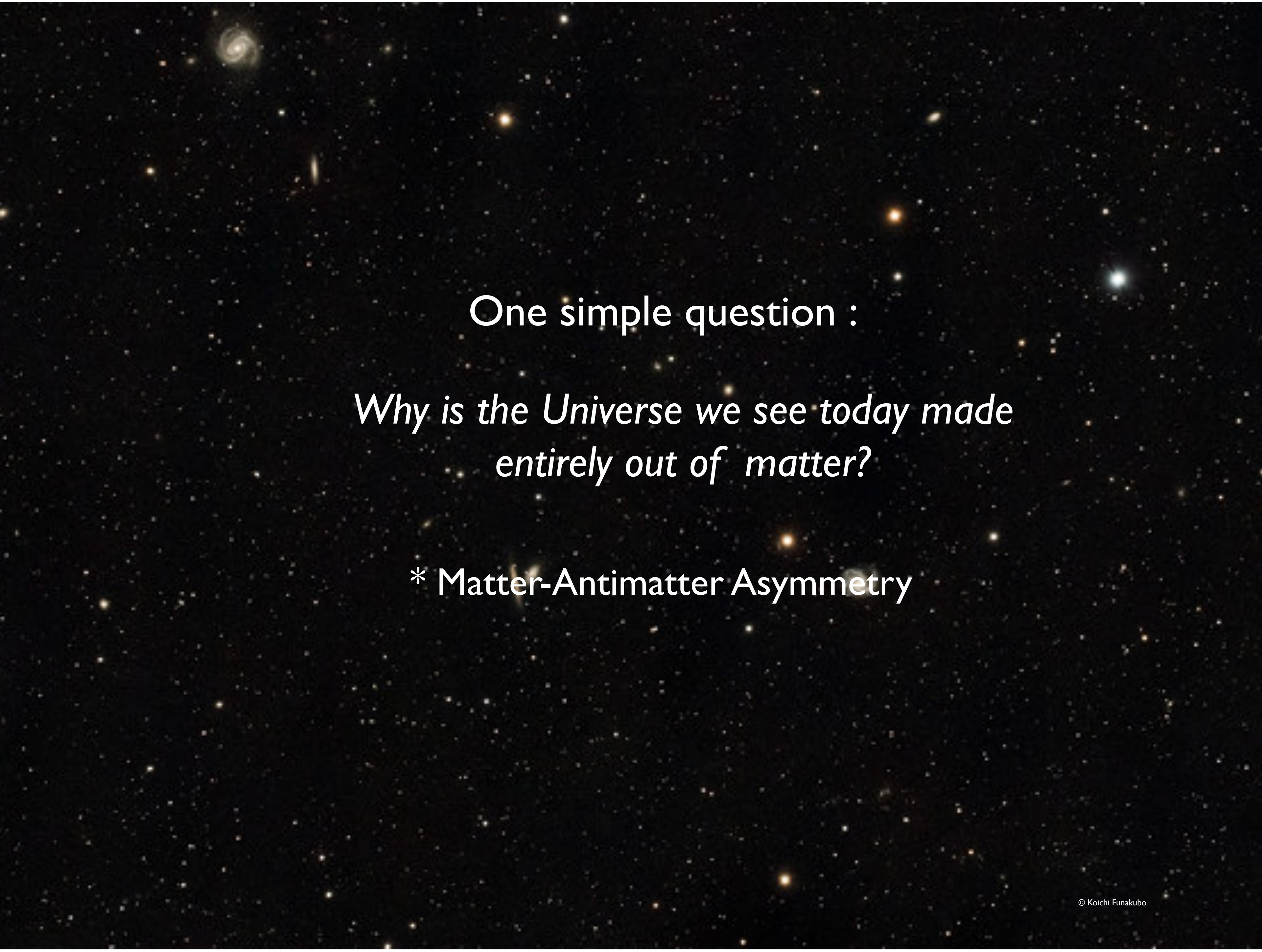
One simple question :

Why do we exist?



One simple question :

Why is the Universe we see today made entirely out of matter?

* Matter-Antimatter Asymmetry

Particle and Antiparticle

Antiparticle : an opposite electric charge to particle

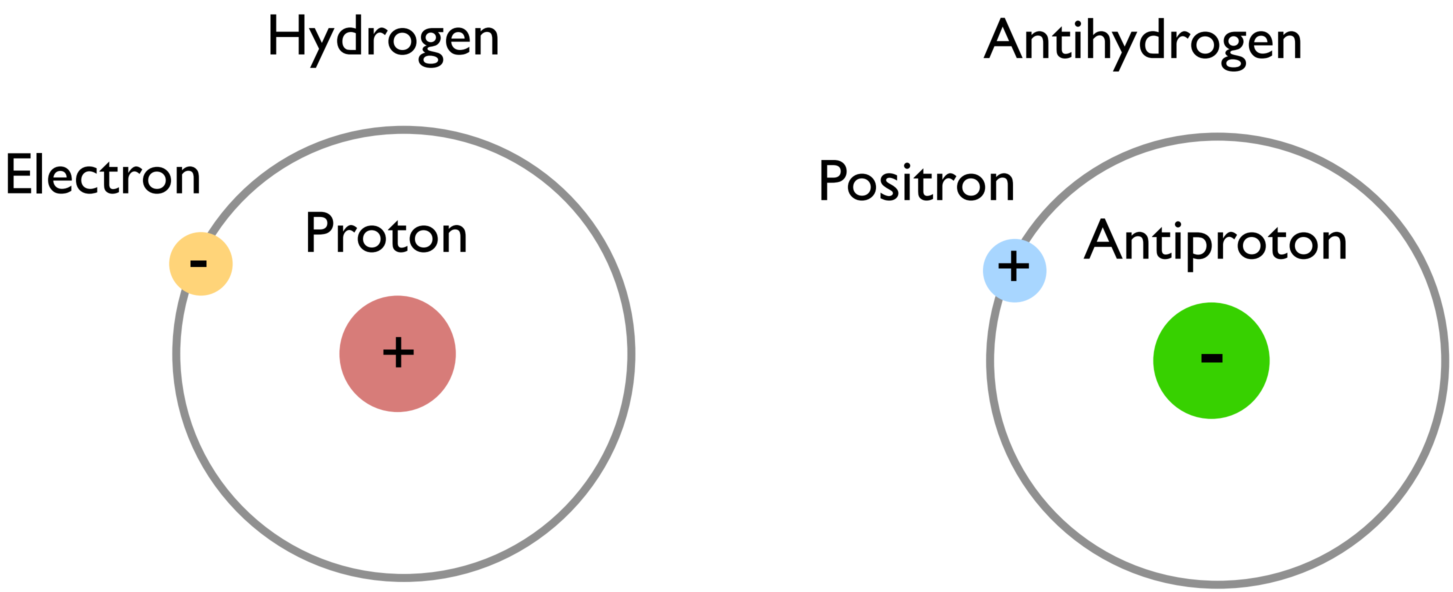
(or internal quantum numbers)

Ex) Electron Positron

Charge Transformation

Particle and Antiparticle

Antiparticle : an opposite electric charge to particle



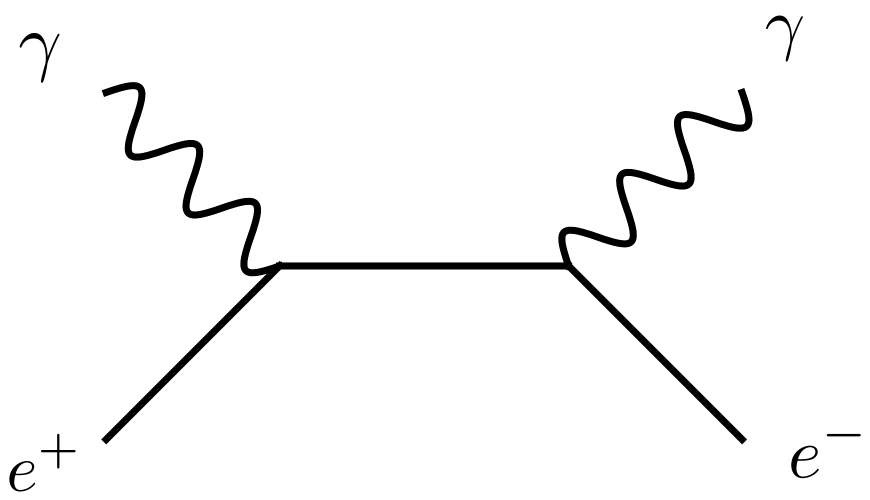
Antimatter is composed of antiparticles.

* We are made of matter.

Particle and Antiparticle

Antiparticle : an opposite electric charge to particle

* Feynman diagram

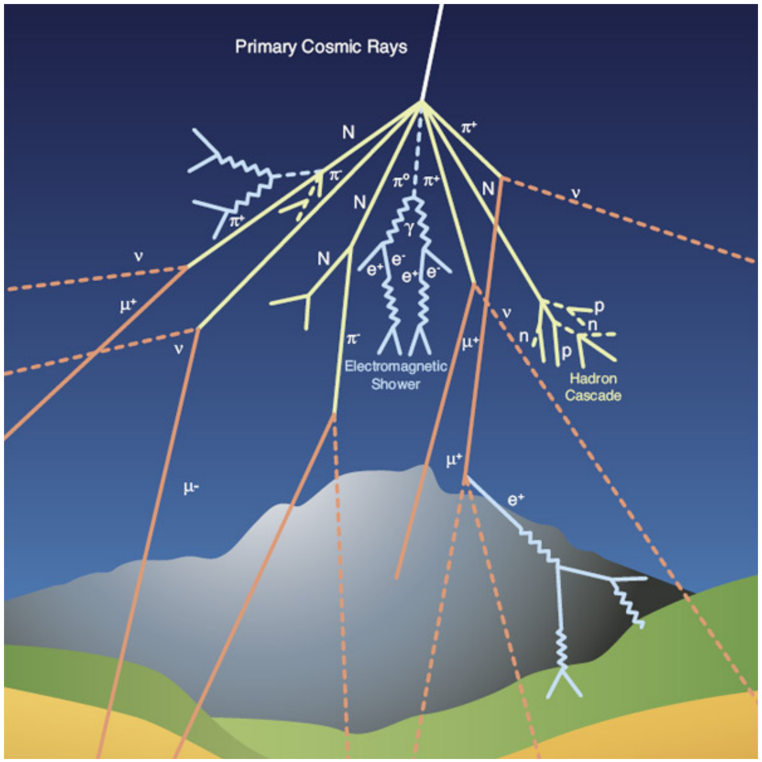


γ : Photon

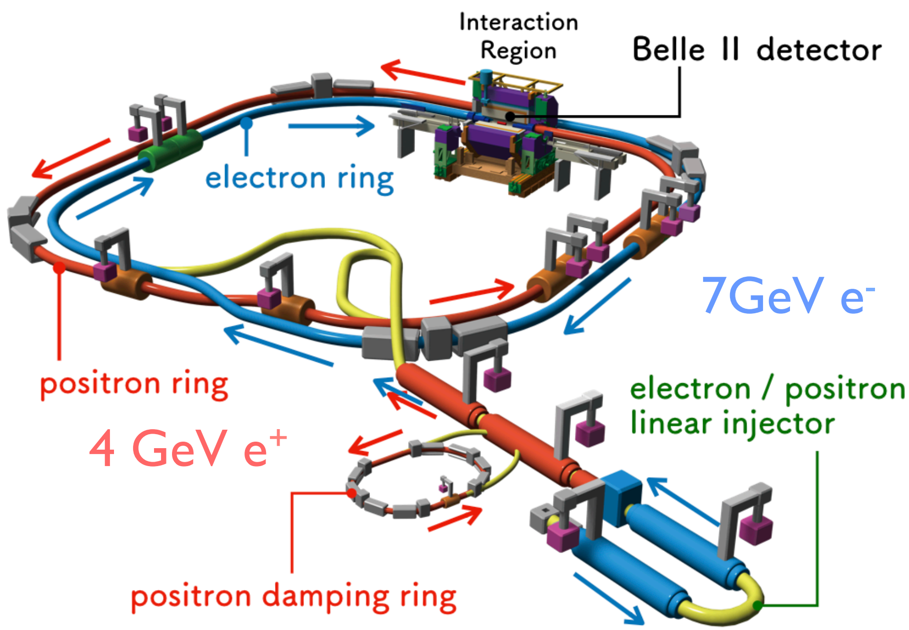
One key process : Annihilation of particle and antiparticle

Antimatter on the Earth

1. Cosmic rays



2. In laboratories

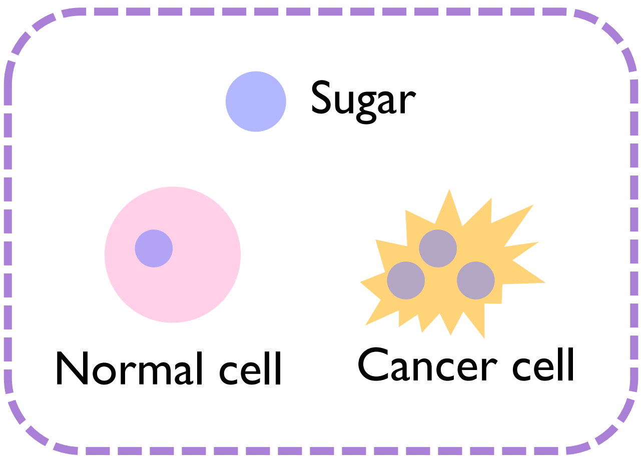


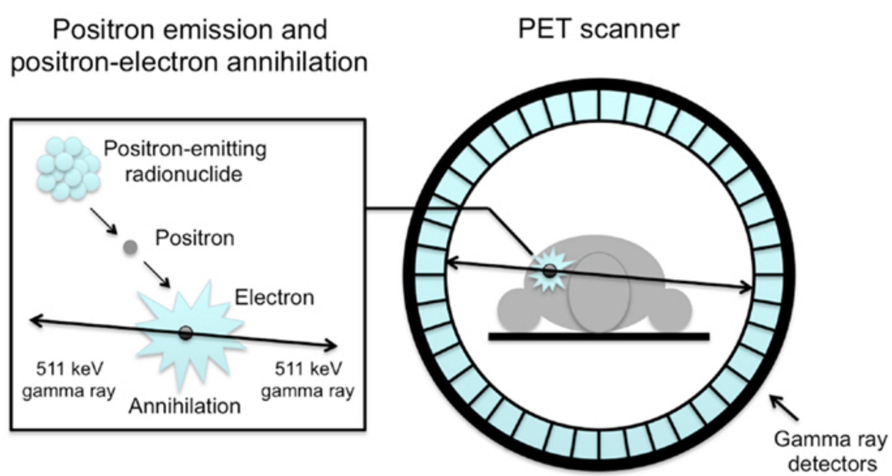
Ex) e^+e^- collider : SuperKEKB

Antimatter on the Earth

3. Application to medical treatment (to find cancer cells)

Positron Emission Tomography

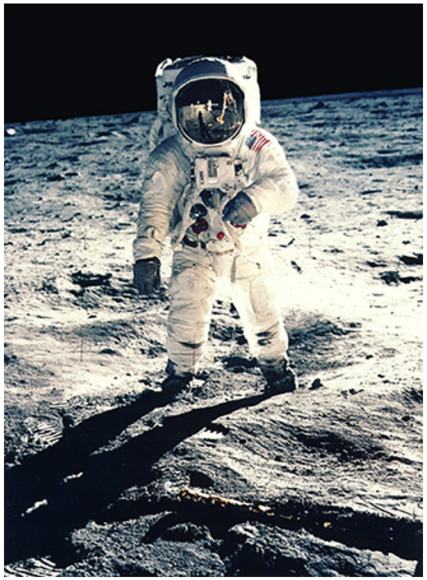




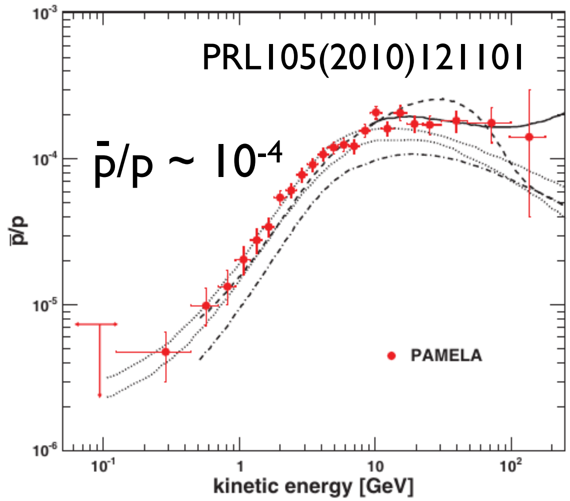
Inject sugar with radioactive isotope (positron emitter)

What about in the Universe?

1) Solar system



2) Our galaxy



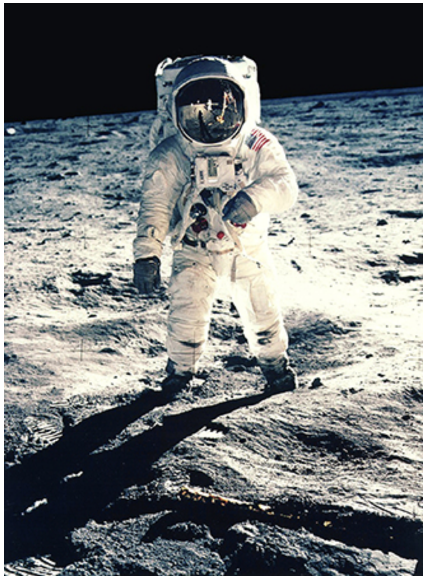
Secondary production by the interactions of cosmic rays

3) Antimatter galaxies at larger scale

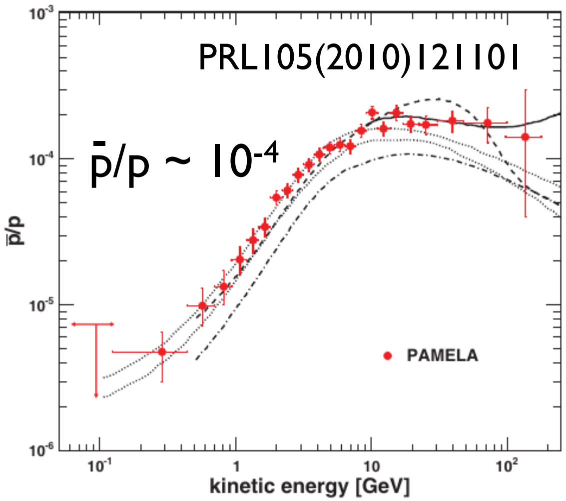
No observation of proton-antiproton annihilation

What about in the Universe?

1) Solar system



2) Our galaxy

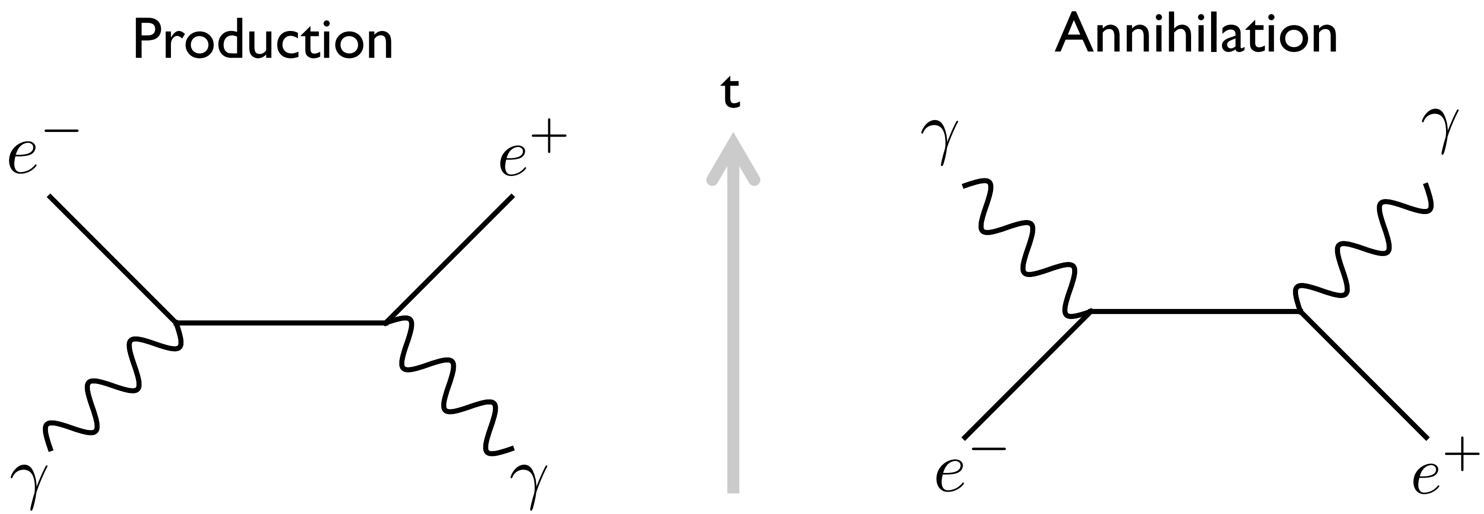


Secondary production by the interactions of cosmic rays

As far as we see our Universe, everything is made of matter.

Why is there more matter than antimatter?

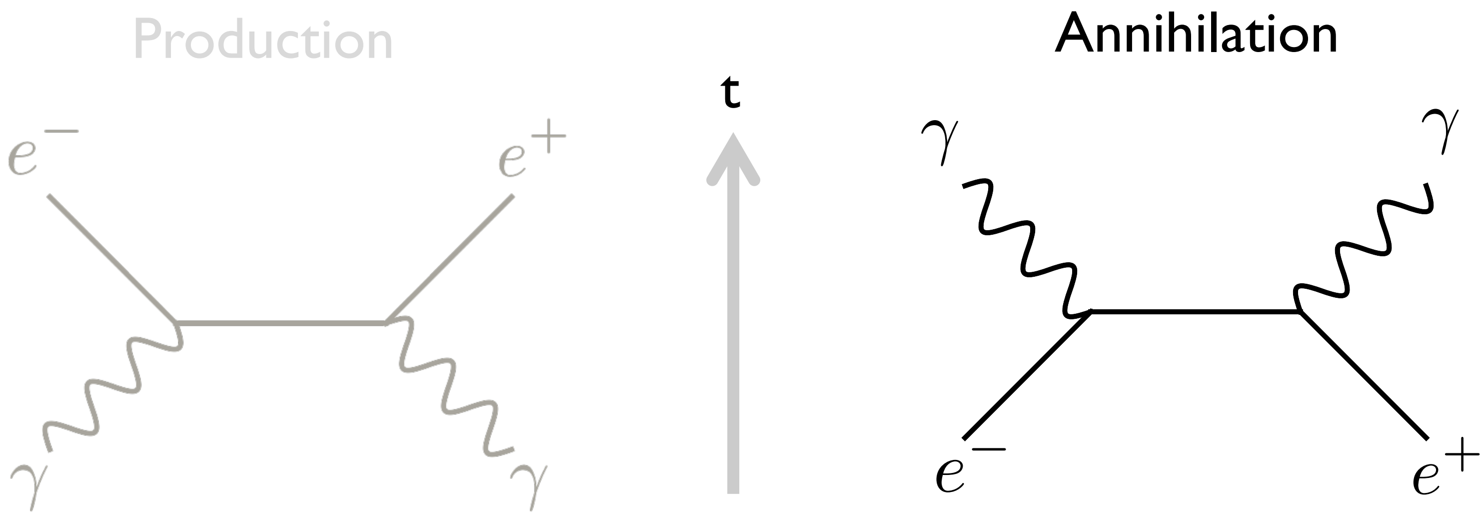
Early Universe



In the early Universe, both production and annihilation occur.

Photon energy E_γ ~ Temperature of the Universe T

Early Universe

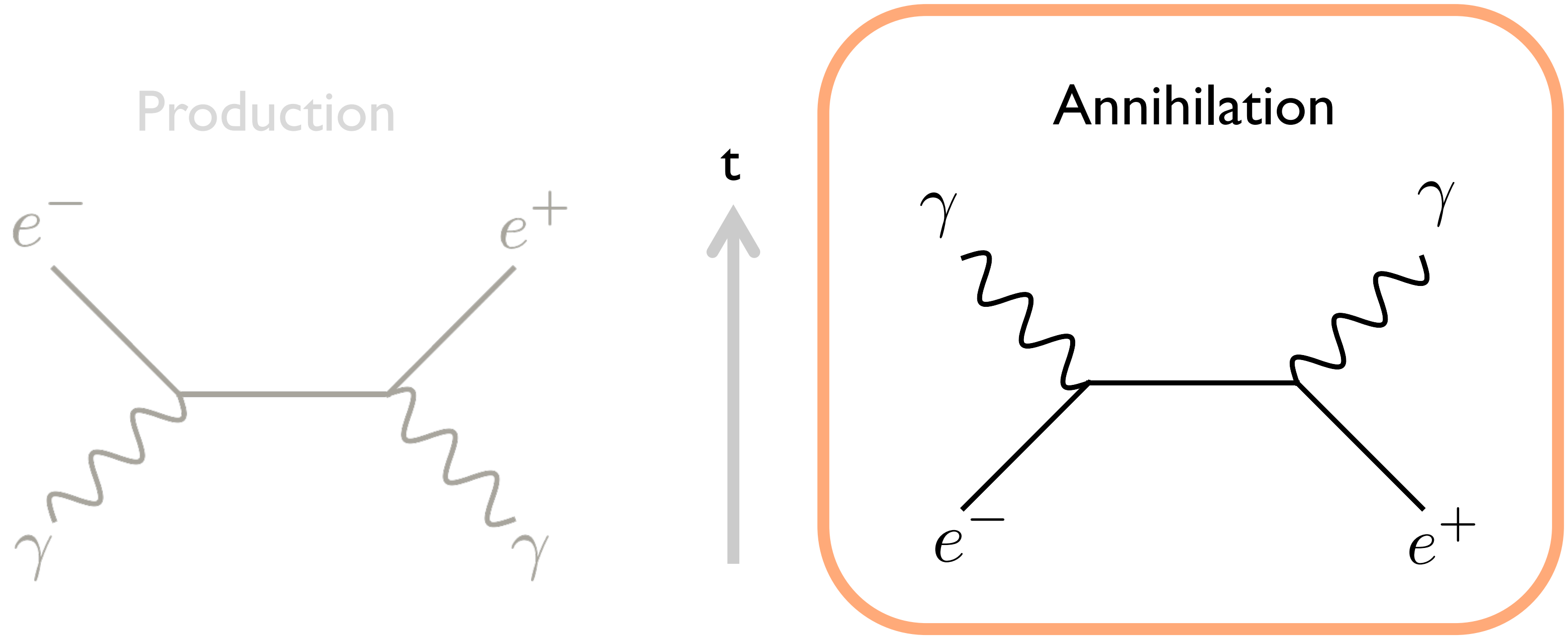


As the Universe expands, it cools down.

The energy of photon decreases, then the production process stops.

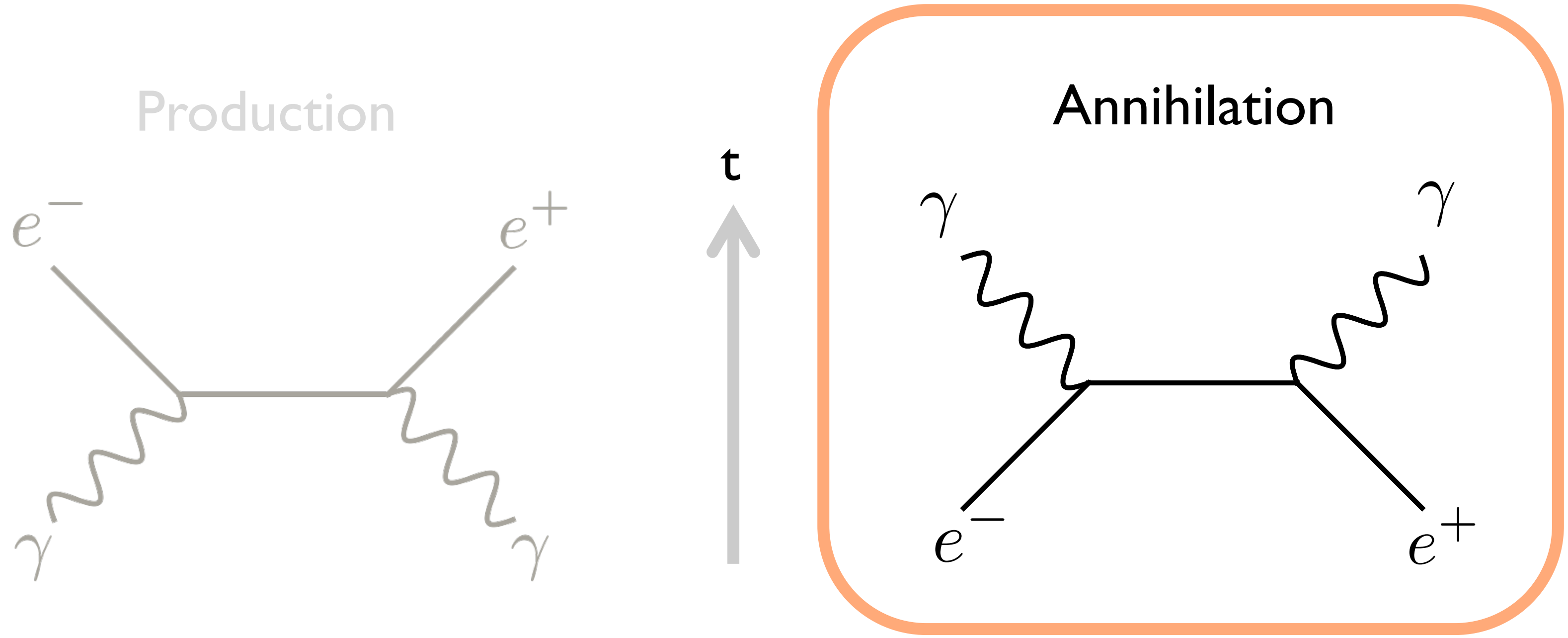
$$E = mc^2$$

Early Universe



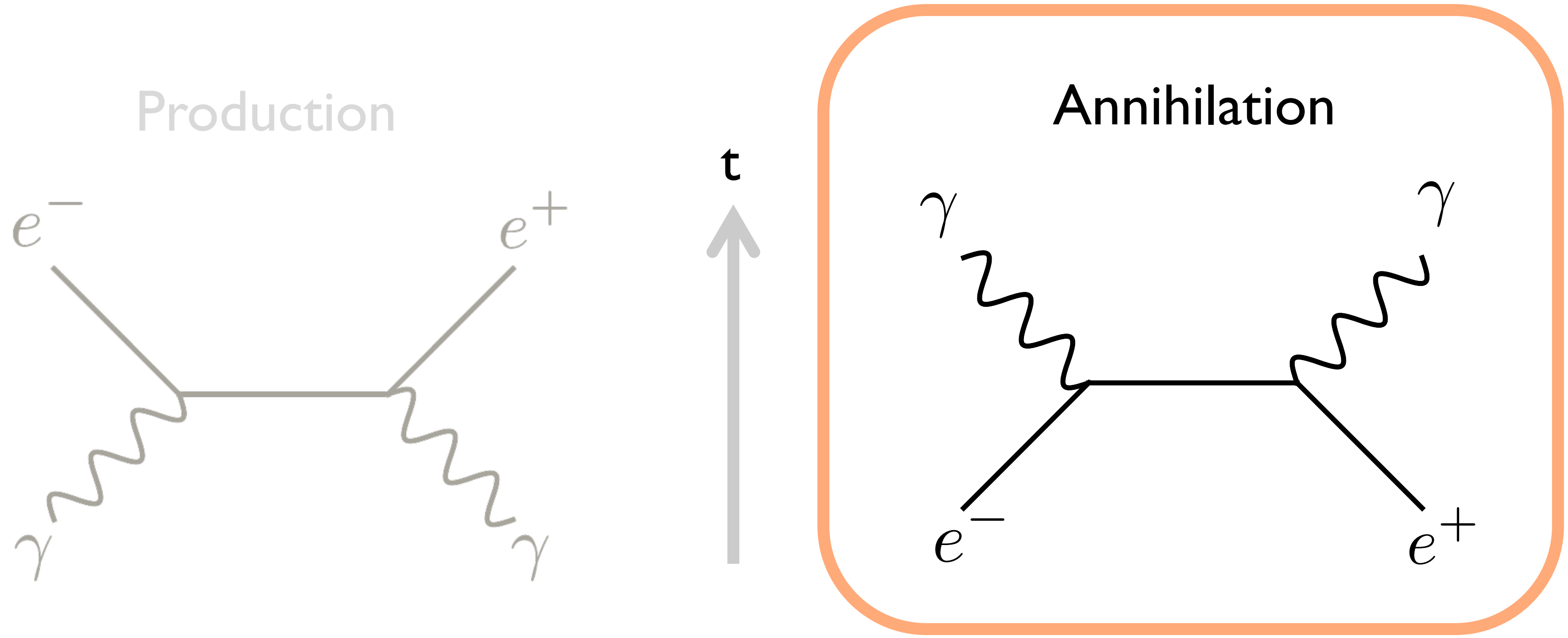
Only the annihilation continues.

Early Universe



If the total numbers of particle and antiparticle are same, is it possible for particles to be left in the present Universe?

Early Universe



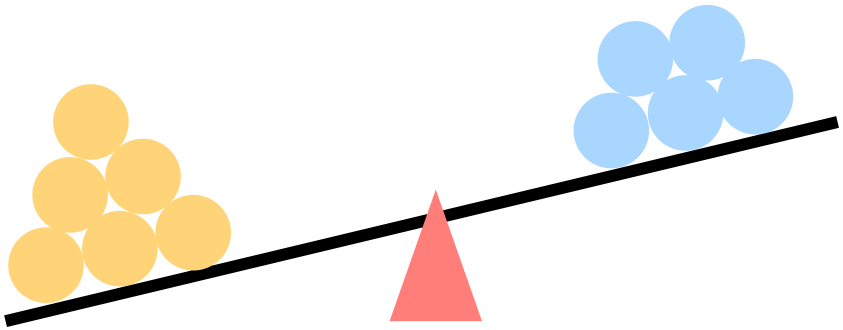
If the total numbers of particle and antiparticle are same,
is it possible for particles to be left in the present Universe?

NO! We do NOT exist today.

Matter-antimatter asymmetry

A tiny imbalance of particle and antiparticle is needed before the annihilation ends.

Particle : $10^{10} + 1$ Antiparticle : 10^{10}



Matter-antimatter asymmetry

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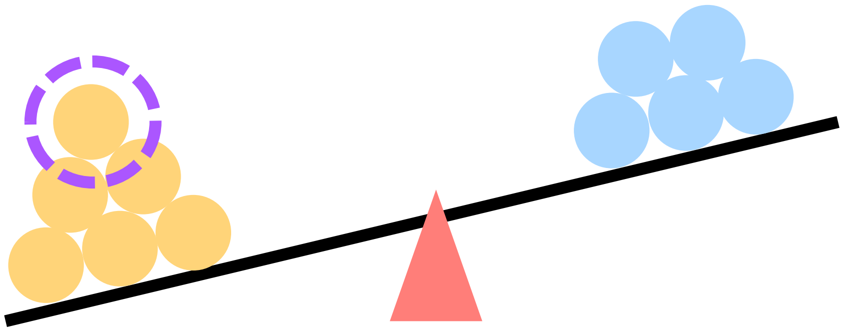


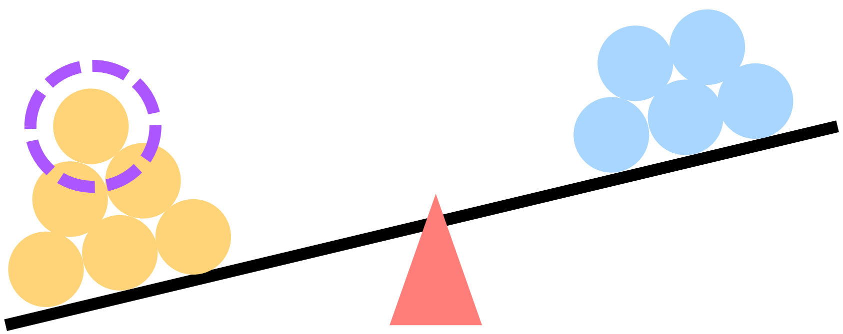
The tiny asymmetry creates the current Universe.

But how?

Matter-antimatter asymmetry

A tiny imbalance of particle and antiparticle is needed before the annihilation ends.

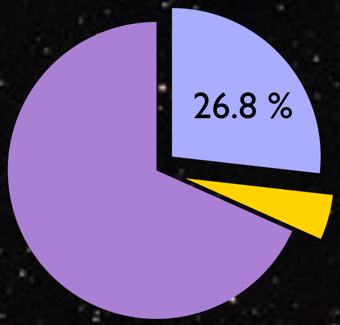
Particle : $10^{10} + 1$ Antiparticle : 10^{10}



Baryogenesis : Mechanisms to create the asymmetry

* Baryon ~ composite particle like proton and neutron

What is Dark Matter ?



Why is neutrino mass so tiny?

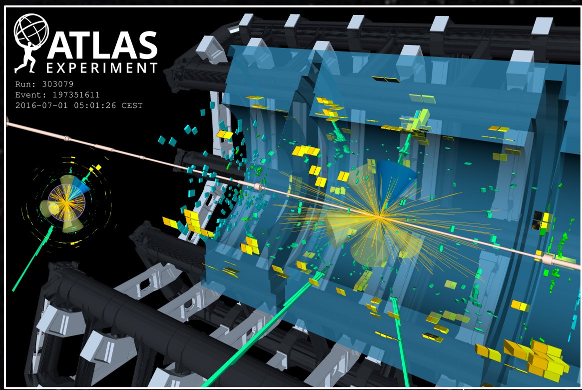
The origin of
the present Universe

Why is there more matter than antimatter?

We don’t know much about our Universe.

Various approaches from particle and nuclear physics

What is Dark Matter ?



C-W. Chiang, G. Cottin, Y. Du, K. Fuyuto, M. Ramsey-Musolf, JHEP01(2021)198

The origin of
the present Universe

Why is neutrino mass so tiny?

W. Dekens, J de Vries, K.Fuyuto, E. Mereghe
G. Zhou, JHEP06(2020)097

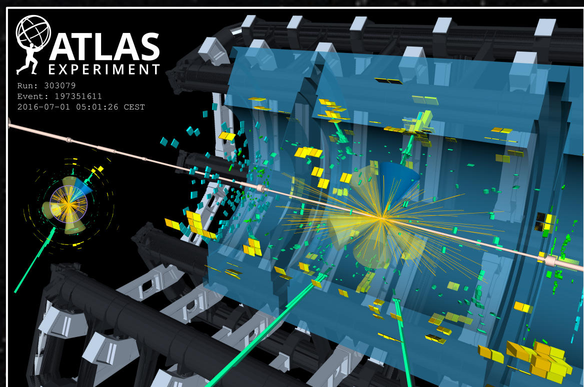
Neutrinoless double beta

Nucleus

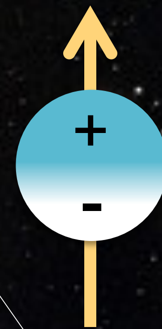
Why is there more matter than antimatter?

K. Fuyuto, J. Hisano, N. Nagata, PRD87(2013), K. Fuyuto, J. Hisano, N. Nagata, K. Tsumura, JHEP12(2013)010
K.Fuyuto, E. Senaha, PRD90(2014) 015015, K.Fuyuto, E. Senaha, PLB(2015)152
K. Fuyuto, E. Senaha, J, Hisano, PLB755(2016)491, K. Fuyuto, E. Senaha, CW. Chiang, PLB762(2013)315
K, Fuyuto, M. Ramsey-Musolf, PLB781(2018)492, K. Fuyuto, M. Ramsey-Musolf, T. Shen, PLB788(2019)52
K. Fuyuto, WS. Hou, and E. Senaha, PLB 776 (2018) 402
K. Fuyuto, WS. Hou, and E. Senaha, PRD101(2020)011901
J. De Vries, P. Draper, K. Fuyuto, J. Kozaczuk, B. Lillard, PRD104(2021)055039

Electric Dipole Moment

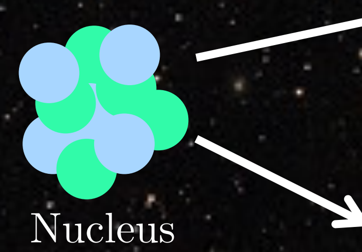


The origin of
the present Universe



Electric Dipole Momen

Neutrinoless double beta

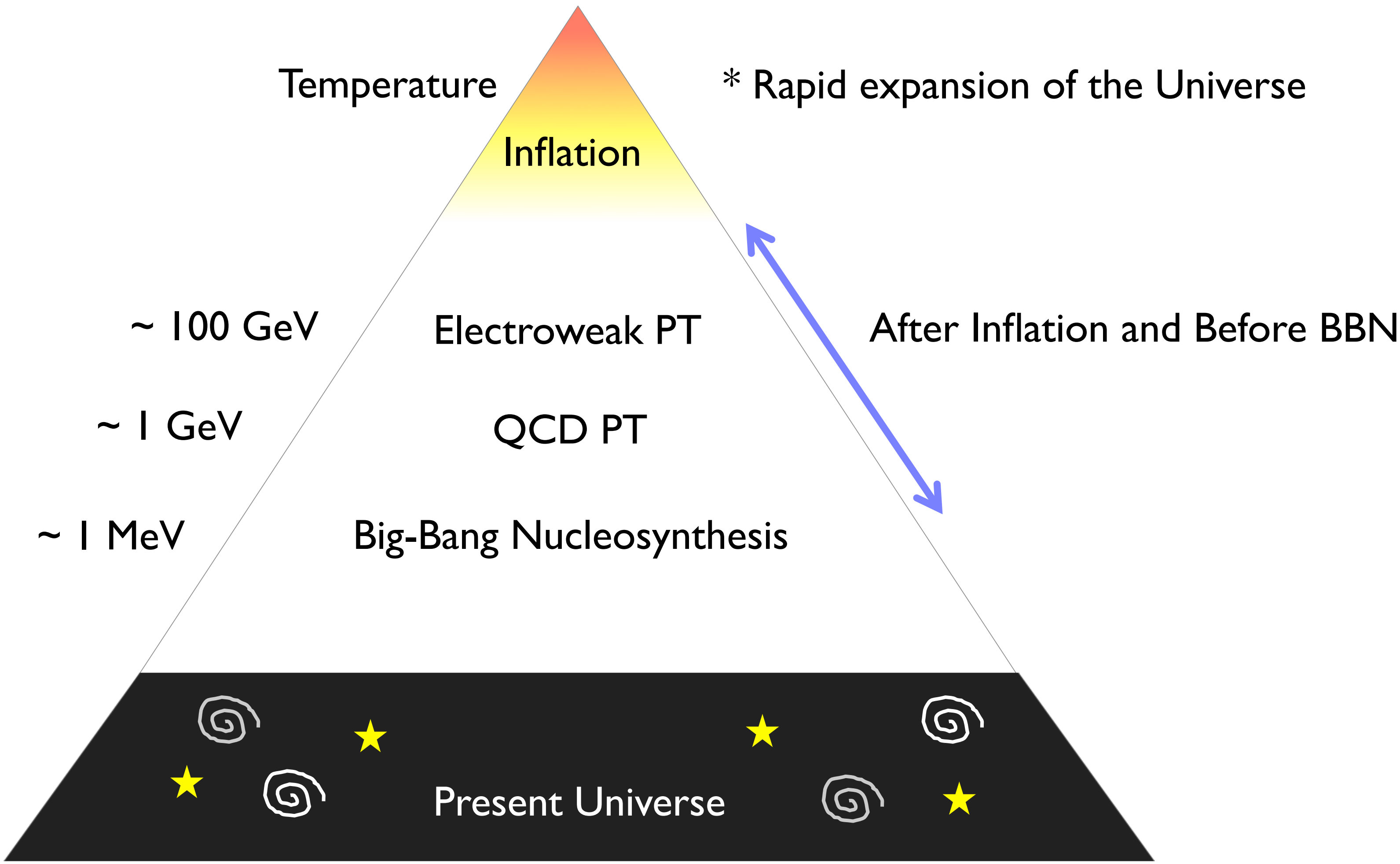


Today : Matter Antimatter Asymmetry

Probe of hypotheses in Particle and Nuclear physics experiment

Baryogenesis

Baryogenesis



Need mechanisms to "dynamically" create the asymmetry

Sakharov's criteria

To create the asymmetry, any mechanisms must satisfy

(1) Baryon number violation

(2) C and CP violation

C : charge, P : parity

(3) Out of equilibrium

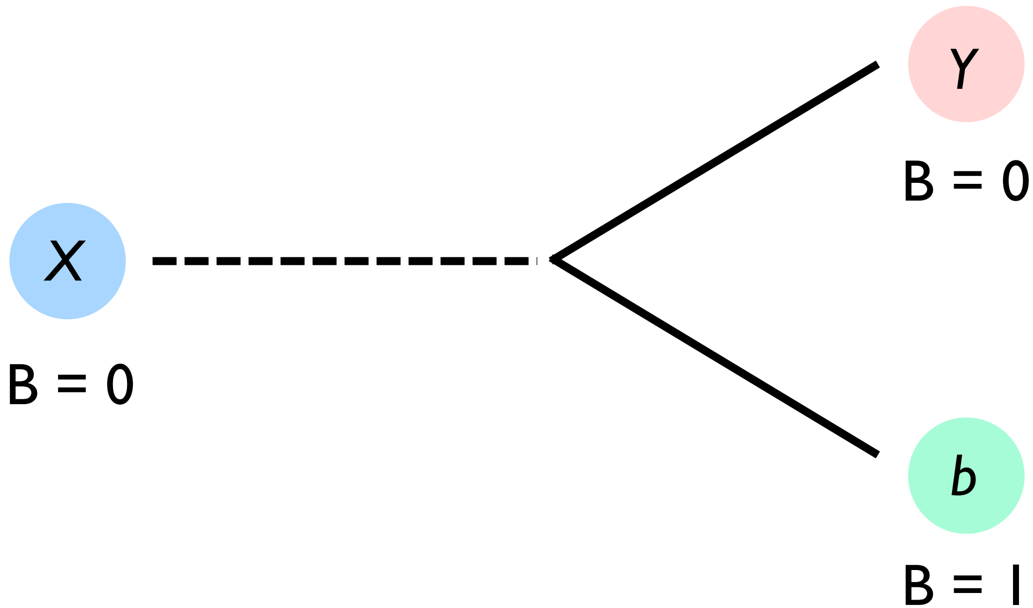
Sakharov

A. D. Sakharov, Pisma Zh. Eksp. Teor. Fiz. 5, 32 (1967)

Sakharov's criteria

(1) Baryon number violation

To have a nonzero baryon number : B

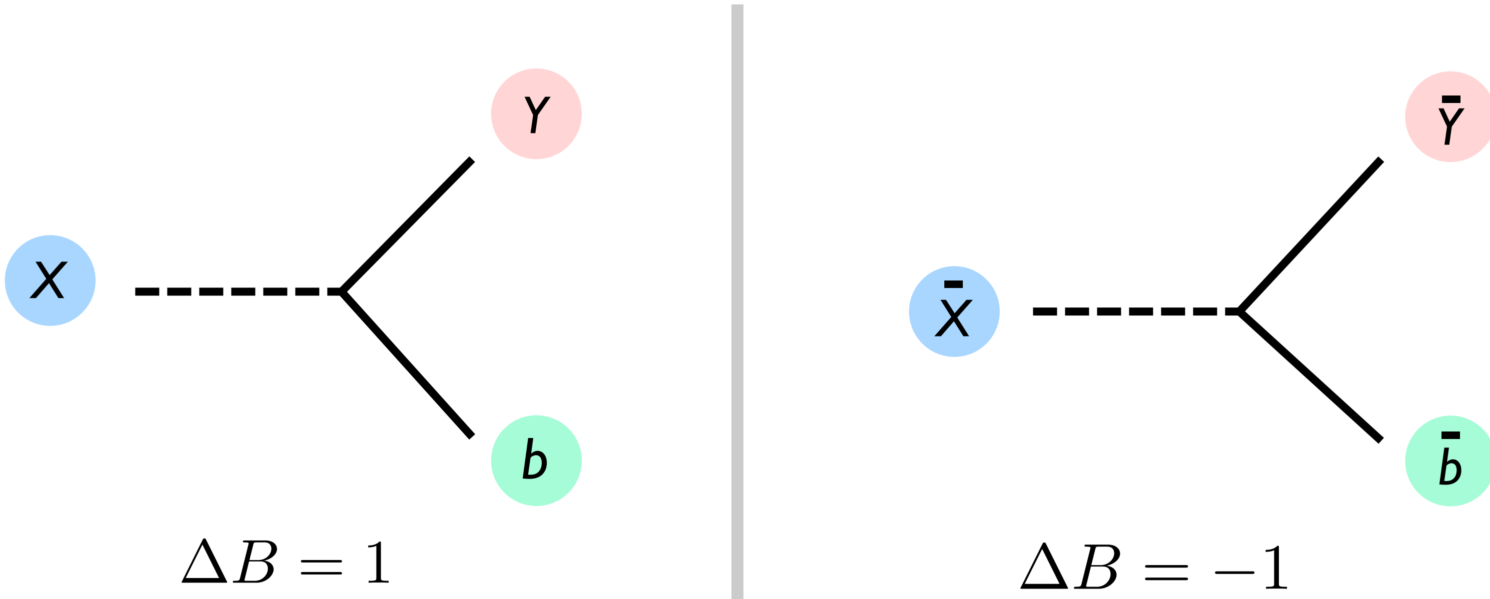


$$\Delta B = 1$$

Sakharov's criteria

(II) C and CP violation (Ā : antiparticle)

To distinguish baryon from anti-baryon production



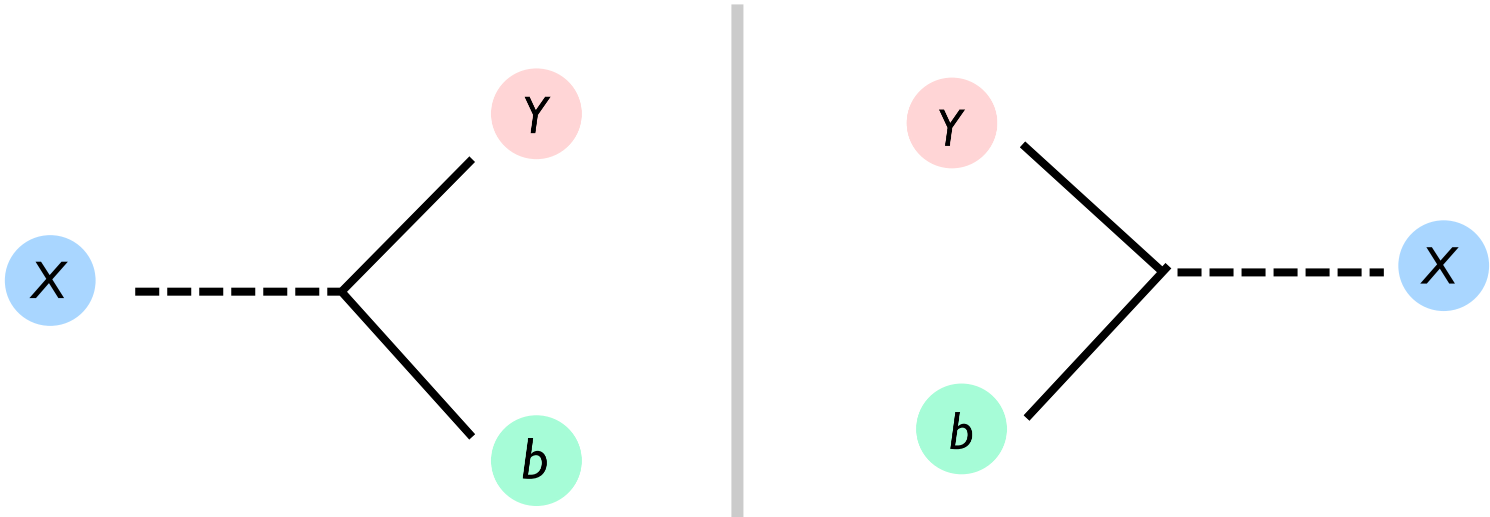
$\Delta B = 1$ $\Delta B = -1$

$$\Gamma\left(X \to Y + b\right) \neq \Gamma\left(\bar{X} \to \bar{Y} + \bar{b}\right)$$

Sakharov's criteria

(III) Out of equilibrium $(\bar{A}$: antiparticle)

To leave produced baryon numbers



$\Delta B = 1$ $\Delta B = -1$

$$\Gamma\left(X \to Y + b\right) \neq \Gamma\left(Y + b \to X\right)$$

Baryogenesis

M. Shaposhnikov, J. Phys. Conf. Ser. 171 (2009) 012005

1. GUT baryogenesis. 2. GUT baryogenesis after preheating. 3. Baryogenesis from primordial black holes. 4. String scale baryogenesis. 5. Affleck-Dine (AD) baryogenesis. 6. Hybridized AD baryogenesis. 7. No-scale AD baryogenesis. 8. Single field baryogenesis. 9. Electroweak (EW) baryogenesis. 10. Local EW baryogenesis. 11. Non-local EW baryogenesis. 12. EW baryogenesis at preheating. 13. SUSY EW baryogenesis. 14. String mediated EW baryogenesis. 15. Baryogenesis via leptogenesis. 16. Inflationary baryogenesis. 17. Resonant leptogenesis. 18. Spontaneous baryogenesis. 19. Coherent baryogenesis. 20. Gravitational baryogenesis. 21. Defect mediated baryogenesis. 22. Baryogenesis from long cosmic strings. 23. Baryogenesis from short cosmic strings. 24. Baryogenesis from collapsing loops. 25. Baryogenesis through collapse of vortons. 26. Baryogenesis through axion domain walls. 27. Baryogenesis through QCD domain walls. 28. Baryogenesis through unstable domain walls. 29. Baryogenesis from classical force. 30. Baryogenesis from electrogenesis. 31. B-ball baryogenesis. 32. Baryogenesis from CPT breaking. 33. Baryogenesis through quantum gravity. 34. Baryogenesis via neutrino oscillations. 35. Monopole baryogenesis. 36. Axino induced baryogenesis. 37. Gravitino induced baryogenesis. 38. Radion induced baryogenesis. 39. Baryogenesis in large extra dimensions. 40. Baryogenesis by brane collision. 41. Baryogenesis via density fluctuations. 42. Baryogenesis from hadronic jets. 43. Thermal leptogenesis. 44. Nonthermal leptogenesis.

Which one is phenomenologically motivated ?

experimentally testable?

Baryogenesis

M. Shaposhnikov, J. Phys. Conf. Ser. 171 (2009) 012005

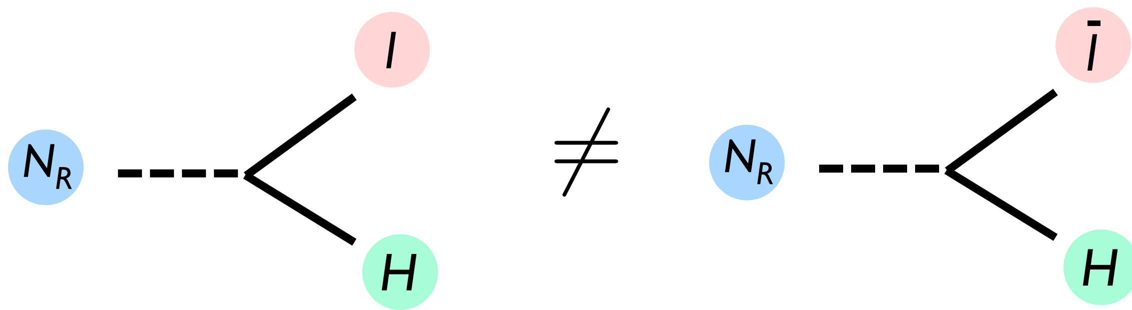
1. GU… prin… Hyb… 9. E… …esis. 12. EW… …genesis. 15. … …18. Spo… …Defect me… …hort cos… …f vor… …ain wal… …e. 30. Bar… …king. 33. Ba…

Monopole baryog… …induced baryogenesis. 37. Gravitino induced baryogenesis. 38. Radion induced …genesis. 39. Baryogenesis in large extra dimensions. 40. Baryogenesis by brane collision… …Baryogenesis via density fluctuations. 42. Baryogenesis from hadronic jets. 43. Thermal leptogenesis. 44. Nonthermal leptogenesis.

Leptogenesis

Fukugita and Yanagida, PLB174(1986)45

Decay of a heavy particle (N_R) leads to the asymmetry.



Nonzero lepton number : $\Delta L \neq 0$ → $\Delta B \neq 0$

Sphaleron Process

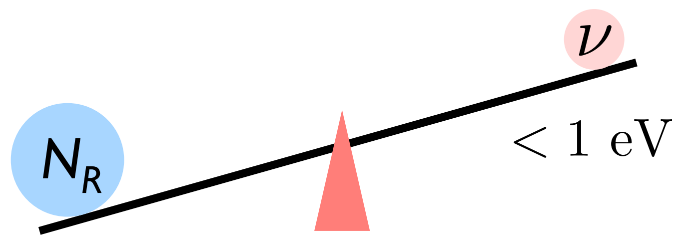
Baryogenesis

M. Shaposhnikov, J. Phys. Conf. Ser. 171 (2009) 012005

Leptogenesis

Fukugita and Yanagida, PLB174(1986)45

Decay of a heavy particle (N_R) leads to the asymmetry.



Tiny neutrino mass is explained by seesaw mechanism.

Monopole baryog… …induced baryogenesis. 37. Gravitino induced baryogenesis. 38. Radion induced …genesis. 39. Baryogenesis in large extra dimensions. 40. Baryogenesis by brane collision 41. Baryogenesis via density fluctuations. 42. Baryogenesis from hadronic jets. 43. Thermal leptogenesis. 44.Nonthermal leptogenesis.

$$N_R \sim 10^{14}\ \text{GeV} \gg \begin{array}{l} m_p \sim 1\ \text{GeV} \\ m_e \sim 0.5\ \text{MeV} \end{array}$$

$$m_\nu \sim \frac{Y_\nu^2 v^2}{M_R} \qquad v = 246\ \text{GeV}$$

Baryogenesis

M. Shaposhnikov, J. Phys. Conf. Ser. 171 (2009) 012005

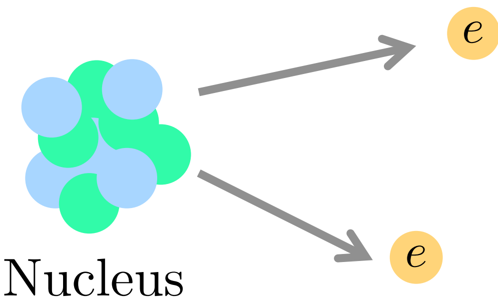
1. GU… prin… Hyb… esis. 12. 9. E… genesis. EW… 18. 15. … Defect Spo… hort me… f cos… nain vor… e. 30. wal… king. Bary… 33. Ba… Monopole baryog… induced baryogenesis. 37. Gravitino induced baryogenesis. 38. Radion induced …genesis. 39. Baryogenesis in large extra dimensions. 40. Baryogenesis by brane collision… Baryogenesis via density fluctuations. 42. Baryogenesis from hadronic jets. 43.

Thermal leptogenesis. 44.Nonthermal leptogenesis.

Leptogenesis

Fukugita and Yanagida, PLB174(1986)45

Predict neutrinoless double beta deacy



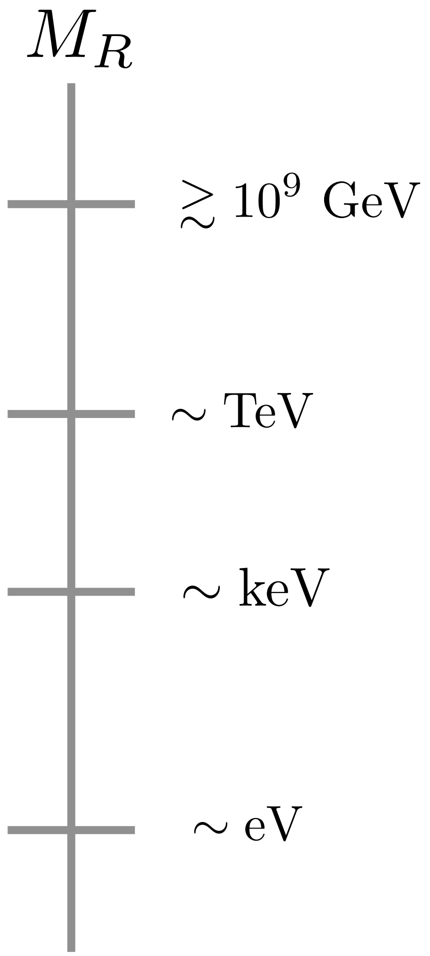
$$\Delta L = 2$$

$N_R \sim 10^{14}$ GeV Too heavy to produce in collider experiments…

Various motivations

For more details, see
M. Drewes, 1303.6912

Other phenomenological aspects of N_R:



Wide mass range!

BAU

Thermal Leptogenesis

W. Buchmuller, et al, Ann.Rev.Nucl.Part.Sci. 55 (2005)311,

Resonant Leptogenesis

E. K. Akhmedov, et al, PRL81(1998)1359

DM

DM candidate

S. Dodelson, L. M. Widrow, PRL72(1994)17

Anomalies

Short-baseline neutrino oscillation

LSND : PRD64(2001)112007
MiniBooNE : PRL110(2013)161801
Reactor anomaly : PRD83(2011)073006

$\bar{\nu}_\mu \to \bar{\nu}_e$

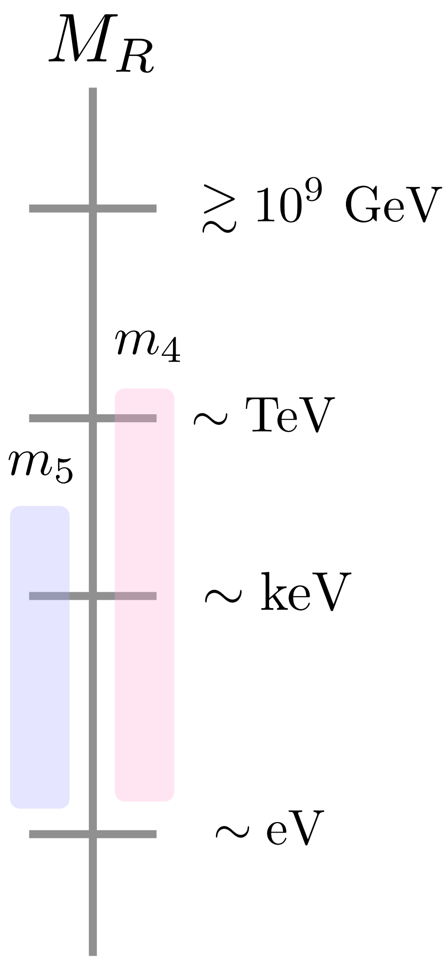
MiniBooNE : PRL121(2018)221801
PRL102(2009)101802

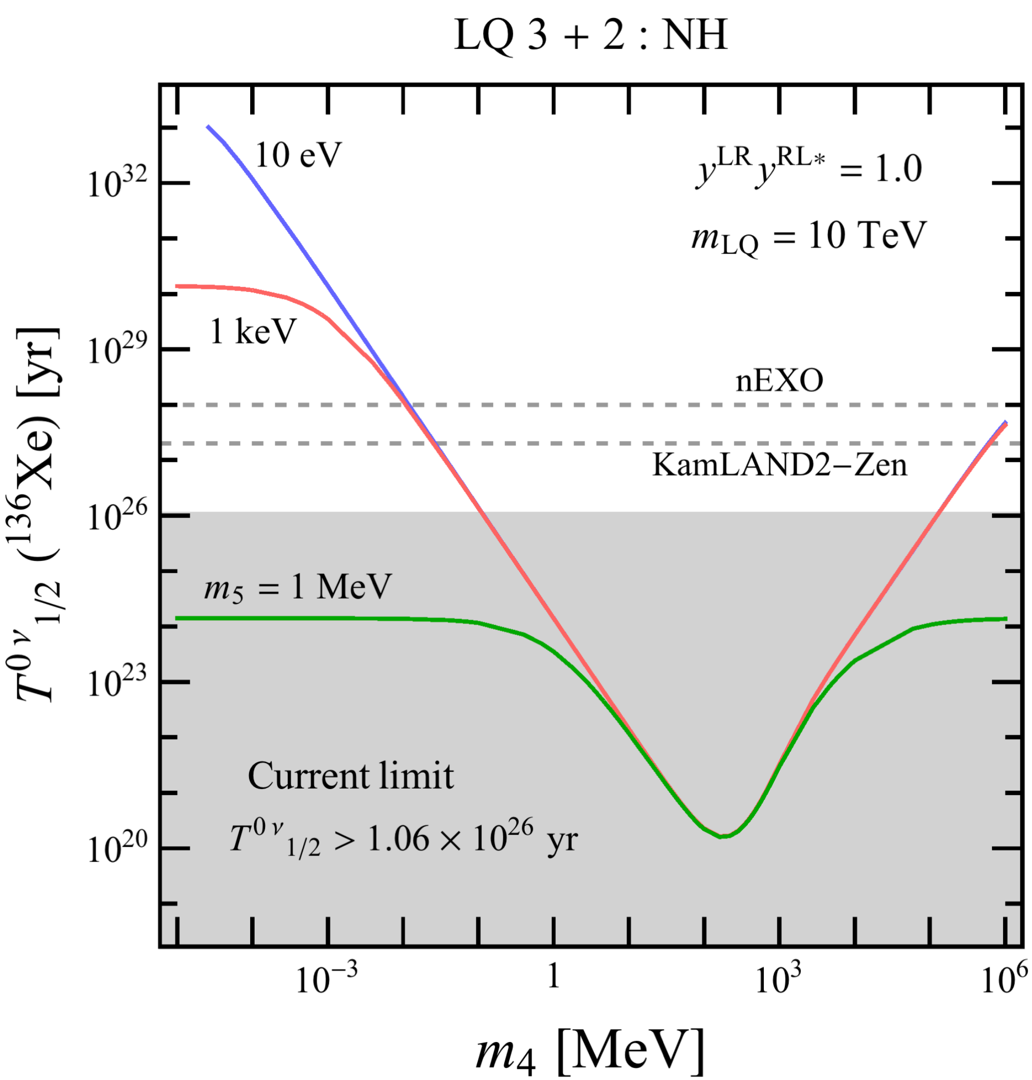
$\nu_\mu \to \nu_e$

Various motivations

W. Dekens, J de Vries, K. Fuyuto, E. Mereghetti, G. Zhou
JHEP06(2020)097

Analysis of 0N2B depending on N_R mass in a model-independent way





Baryogenesis

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Hybridized AD baryogenesis. 7. No-scale AD baryogenesis. 8. Single field baryogenesis.
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Spontaneous baryog... 19. Coherent baryogenesis. 20. Gravitational baryogenesis. 21. Defect
mediated baryogene... ...ryogenesis from long cosmic strings. 23. Baryogenesis from short
cosmic strings. 24. B... ...from collapsing loops. 25. Baryogenesis through collapse of
vortons. 26. Baryog... ...xion domain walls. 27. Baryogenesis through QCD domain
walls. 28. Baryogene... ...le domain walls. 29. Baryogenesis from classical force. 30.
Baryog... ...breaking.
33. Ba... ...
Mono... ...enesis. 38.
Radio... ...esis by
brane... ...c jets. 43.
Therr...

Electroweak Baryogenesis

The BAU is produced during EW phase transition.

✦ Testable scenario

in Particle and Nuclear Physics experiments

Electroweak Baryogenesis

Kuzmin, Rubakov, Shaposhnikov, PLB155, 36 (1985)

Sakharov's conditions are satisfied as follows:

(1) Baryon number violation

Sphaleron process

(2) C and CP violation

Chiral gauge theory and CP phase

(3) Out of equilibrium

First order electroweak phase transition

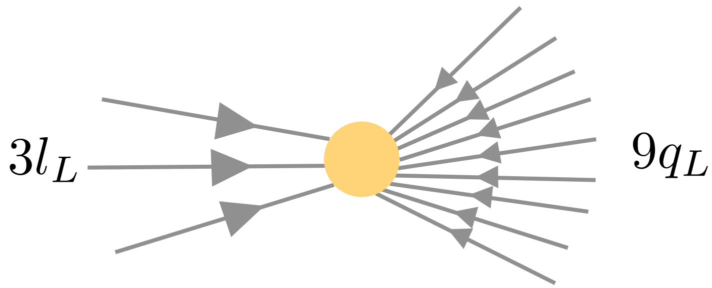
Electroweak Baryogenesis

Manton, Phys. Rev. D28 (1983) 2019
Klinkhammer and Manton, Phys. Rev. D30 (1984)

(1) Baryon number violation

Sphaleron process

(B + L) non-conserved process due to quantum effect



Only left-handed particles

$$\sim \Pi_i (q_{Li} q_{Li} q_{Li} l_{Li})$$

This process is active at finite temperature but suppressed at T=0.

$$\Gamma^{(s)}_{\rm sph} \simeq \kappa (\alpha_W T)^4$$

$$\Gamma^{(b)}_{\rm sph} \simeq T^4 e^{-E_{\rm sph}/T}$$

$E_{\rm sph}$: Energy of sphaleron

Electroweak Baryogenesis

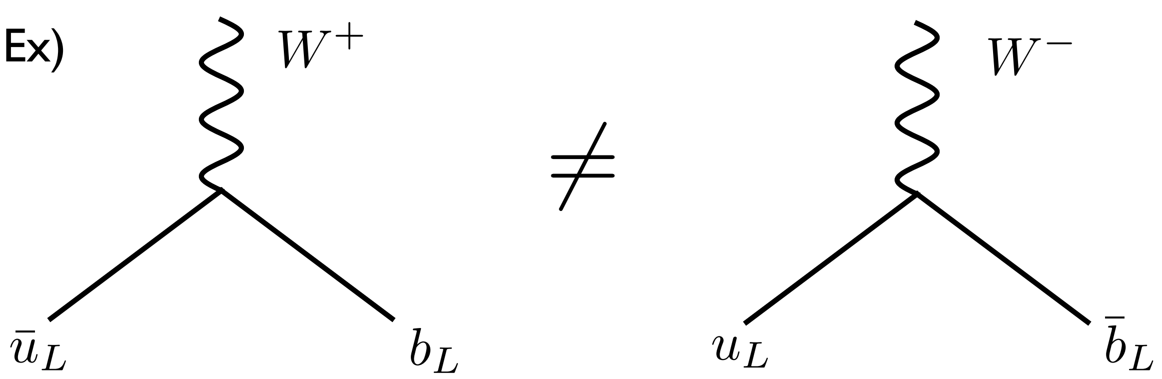
(2) C and CP violation

Chiral gauge theory and CP phase

$$\mathcal{L}_{\rm cc} = \frac{g_2}{\sqrt{2}} \begin{pmatrix} \bar{u}_L & \bar{c}_L & \bar{t}_L \end{pmatrix} \gamma^\mu W_\mu^+ V_{\rm CKM} \begin{pmatrix} d_L \\ s_L \\ b_L \end{pmatrix} \qquad V_{\rm CKM} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

Chiral interaction and CP phase in CKM Matrix

Ex)

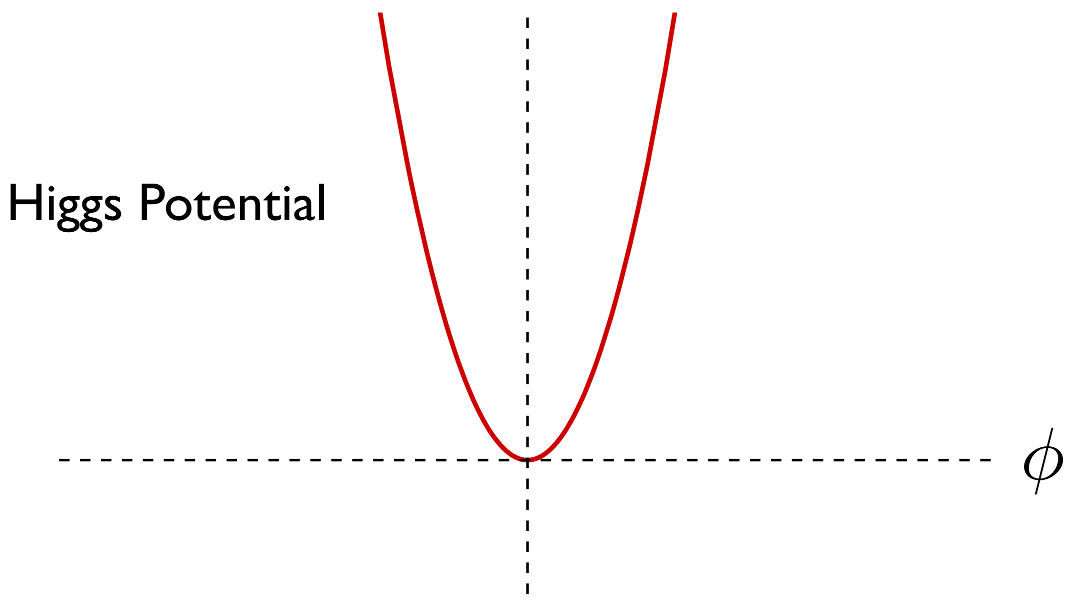


Electroweak Baryogenesis

(3) Out of equilibrium

First order electroweak phase transition (EWPT)

Early Universe $T \gg O(100)\ \mathrm{GeV}$

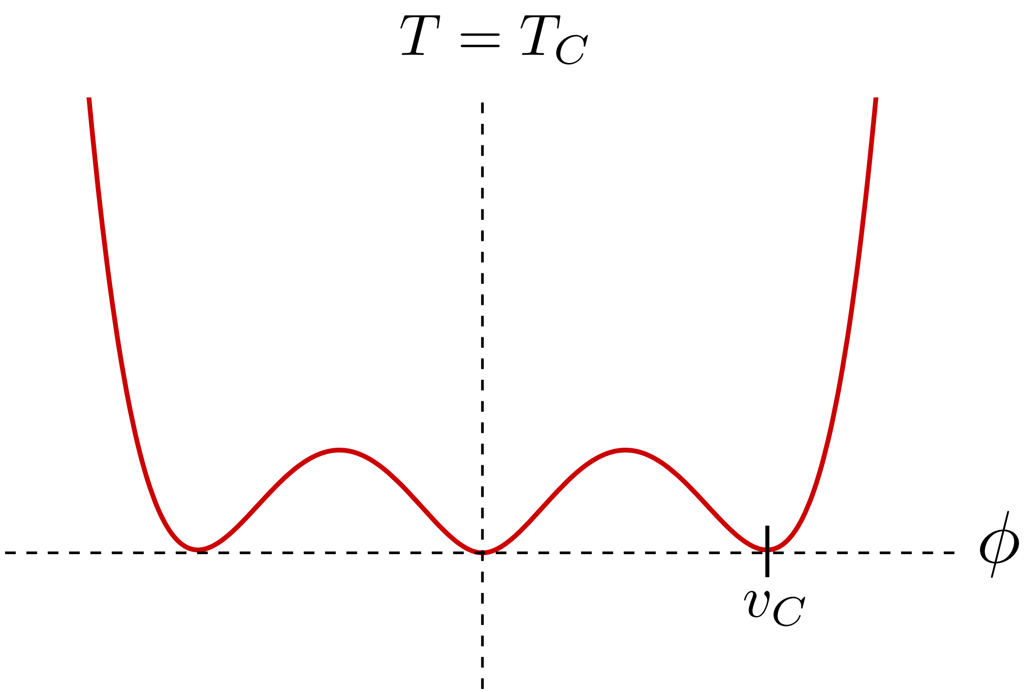


Electroweak Symmetry is unbroken : $\mathcal{L}_Y \supset y_e \bar{L} H e_R$

Electroweak Baryogenesis

(3) Out of equilibrium

First order electroweak phase transition (EWPT)



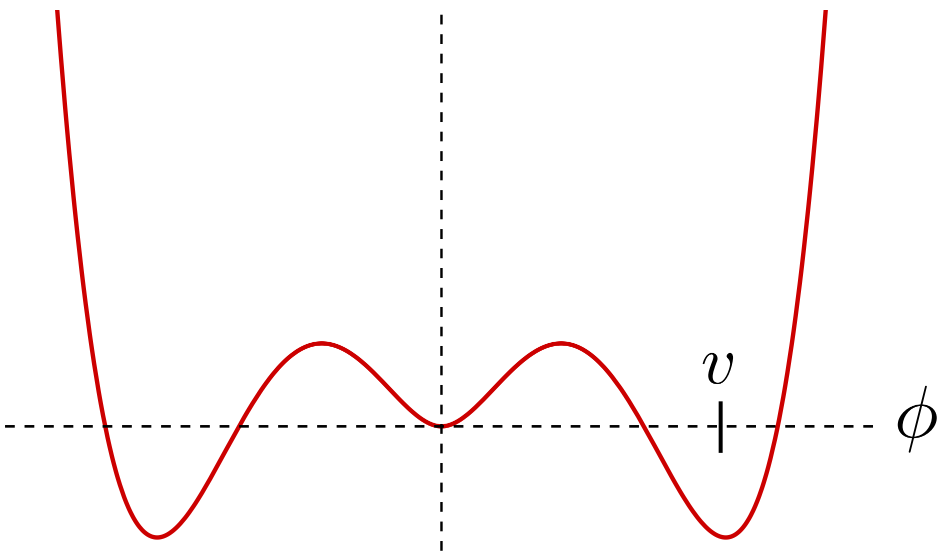
Another minima at T_C : $\phi = v_C$

Electroweak Baryogenesis

(3) Out of equilibrium

First order electroweak phase transition (EWPT)

Present Universe $T = 0$



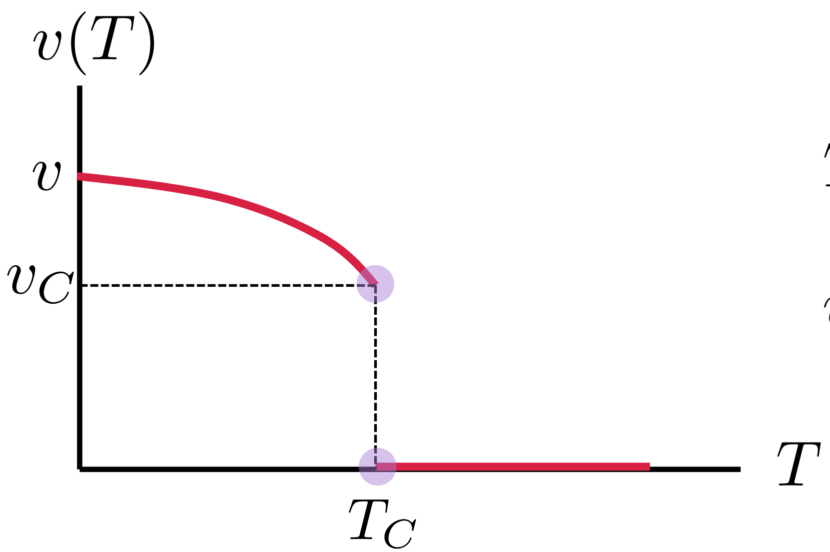
$m_e \neq 0$

Electroweak Symmetry is broken : $\mathcal{L}_Y \supset y_e v \bar{e}_L e_R$

Electroweak Baryogenesis

(3) Out of equilibrium

First order electroweak phase transition (EWPT)



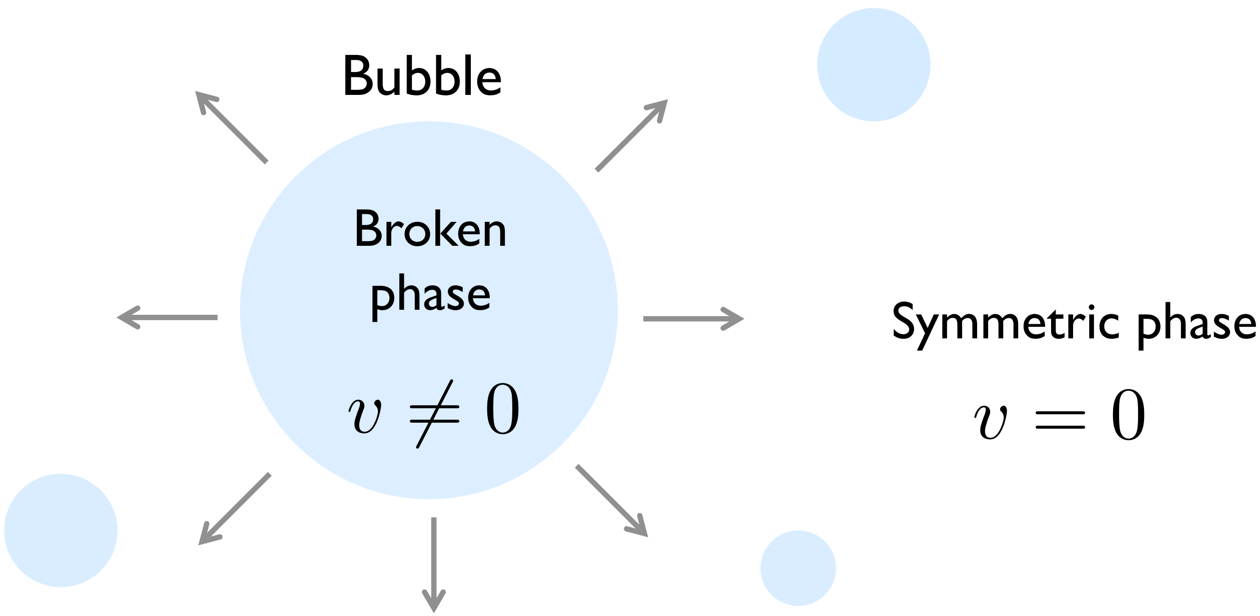
T_C : Critical Temperature

v_C : Higgs VEV at T_C

First order EWPT : discrete change of the Higgs VEV

Electroweak Baryogenesis

If the 1st order EWPT occurs, bubbles can be nucleated around at T_C.



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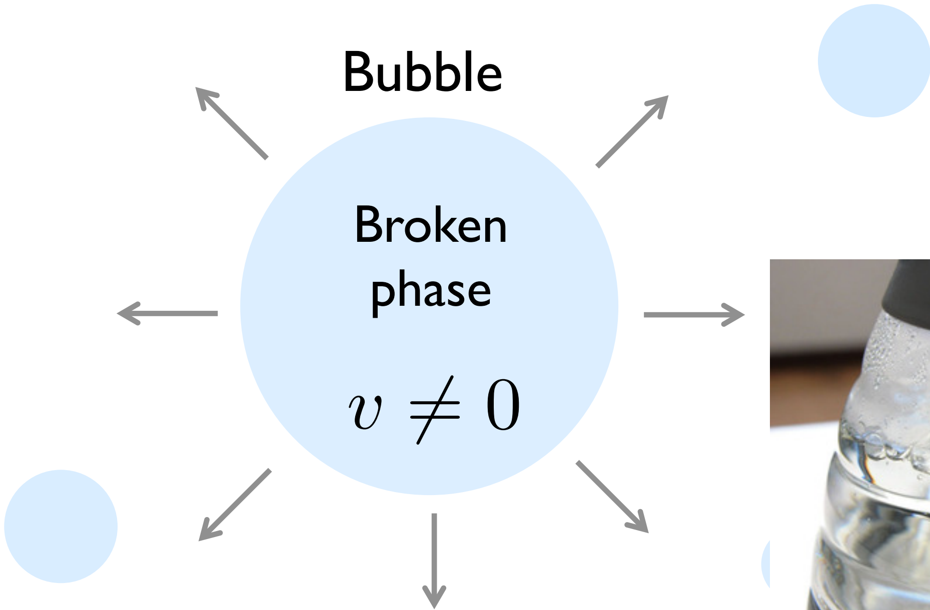

Electroweak Baryogenesis

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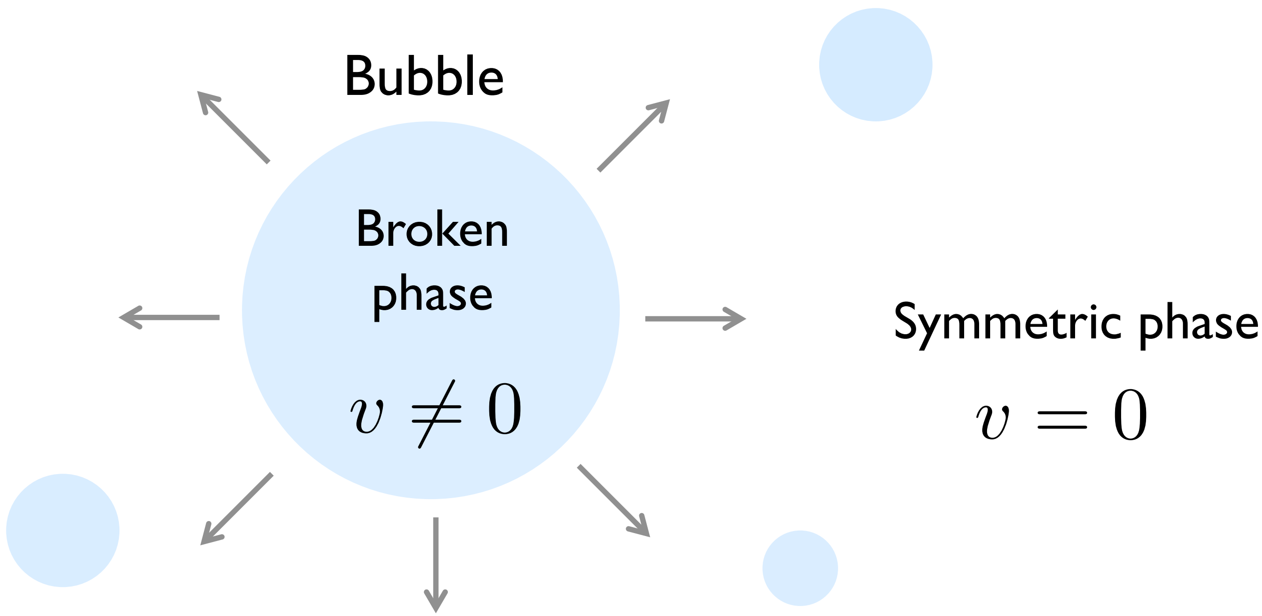
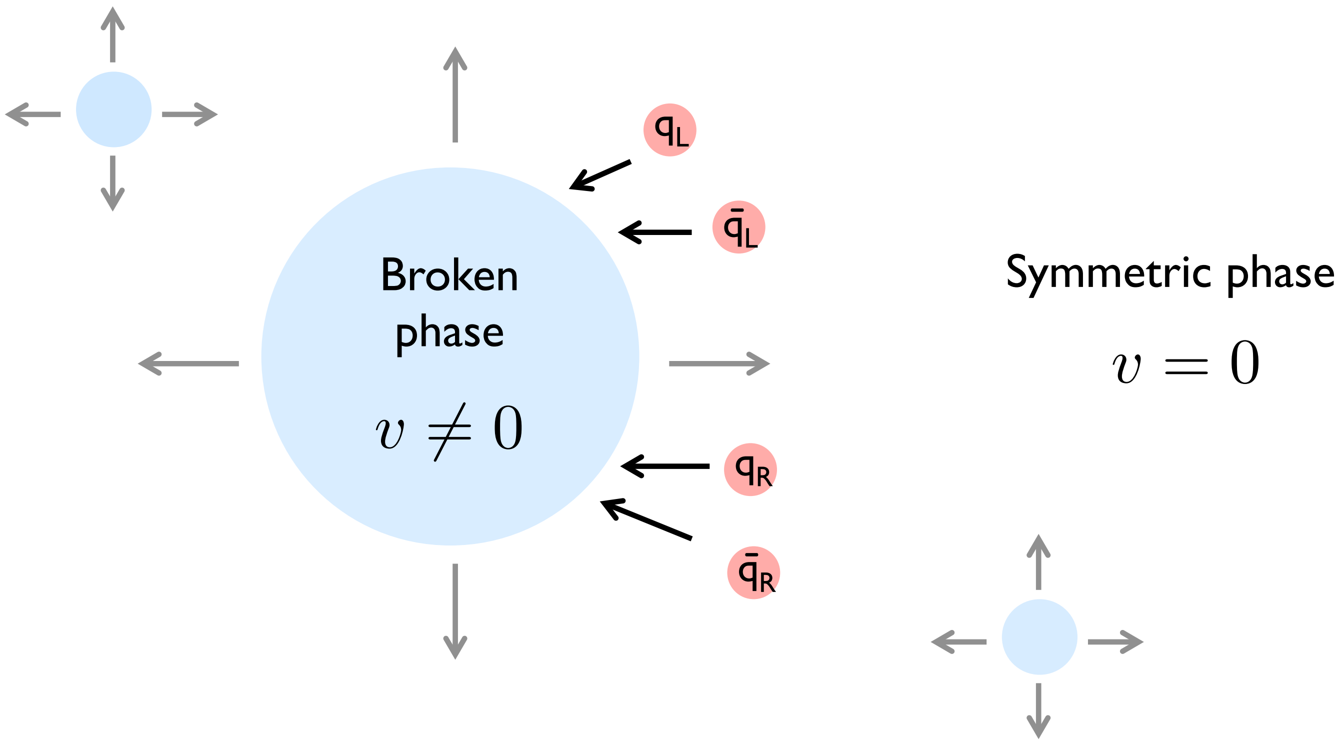


EWPT ends when the Universe is filled with bubbles.

Electroweak Baryogenesis

Particle and antiparticle interact with bubble wall.



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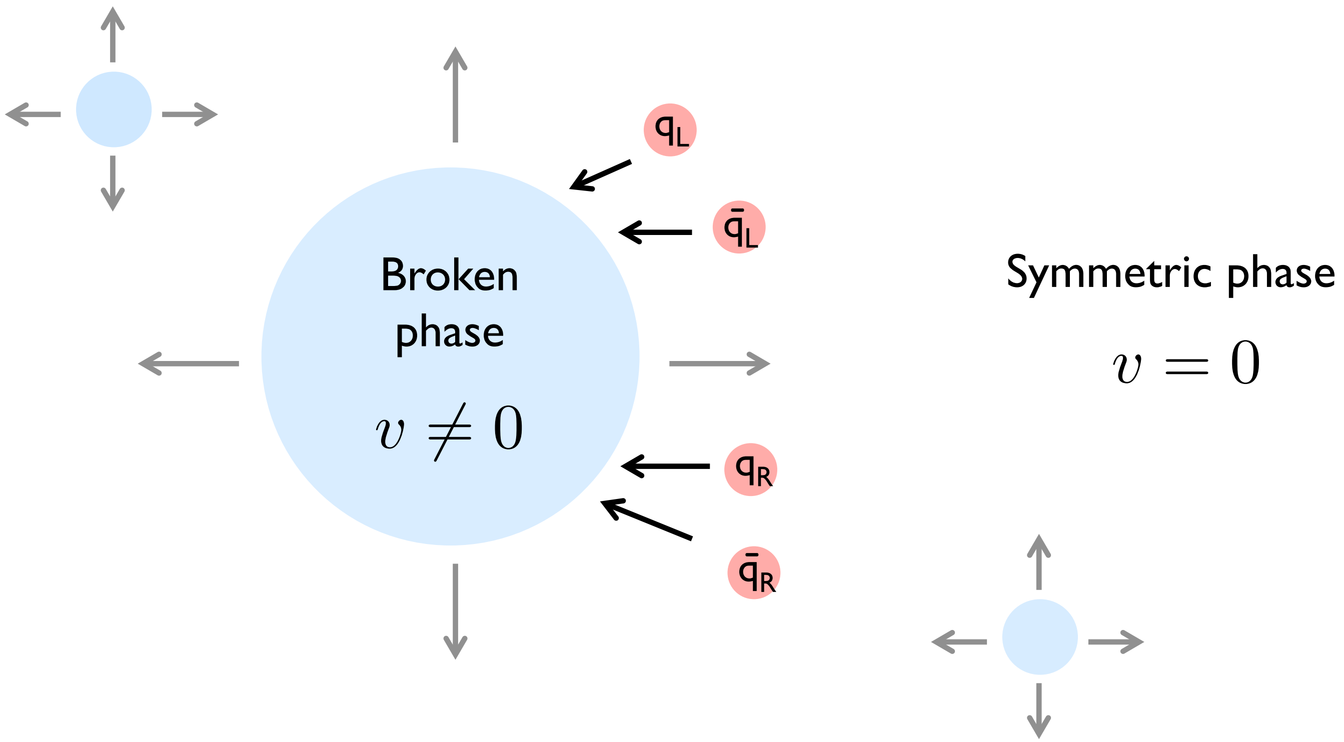
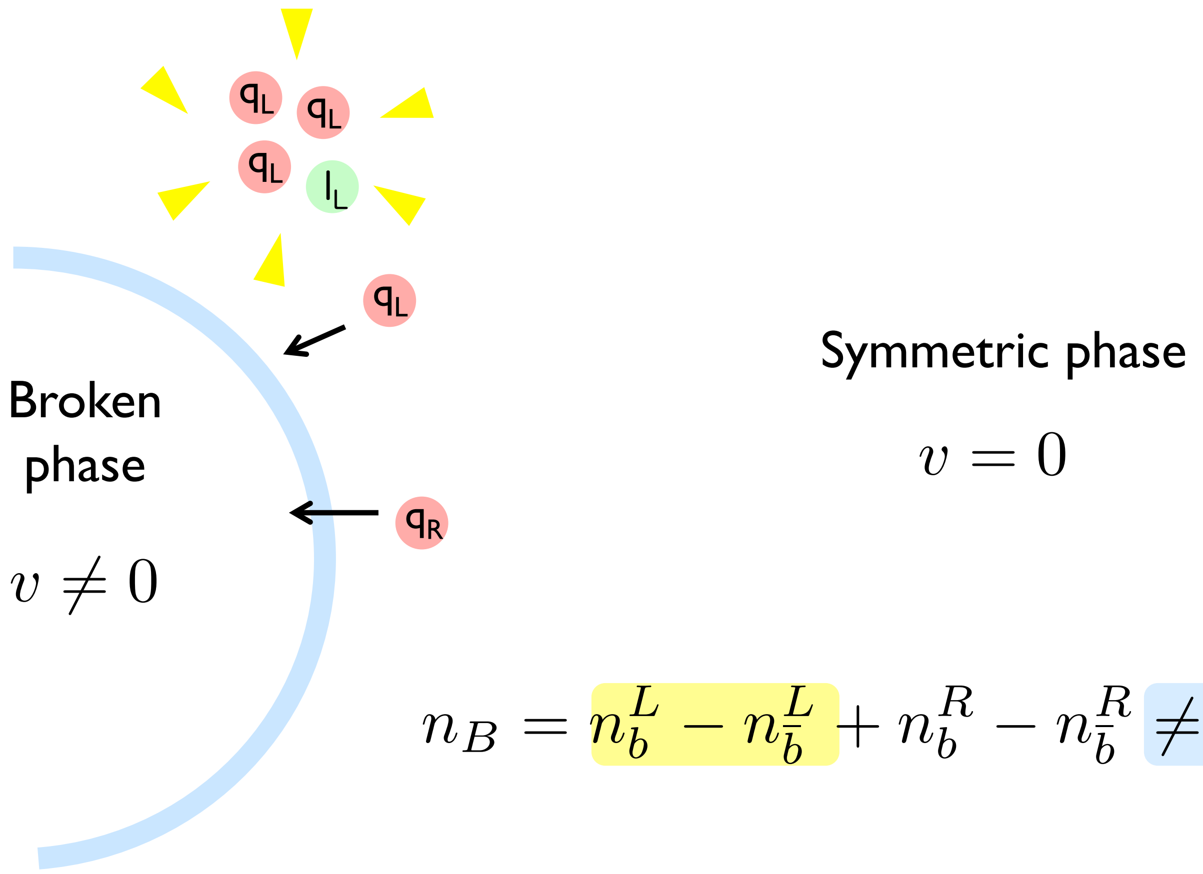


Under CP violation $$n_B = \underbrace{n_b^L - n_{\bar{b}}^L}_{\neq 0} + \underbrace{n_b^R - n_{\bar{b}}^R}_{\neq 0} = 0$$

Electroweak Baryogenesis

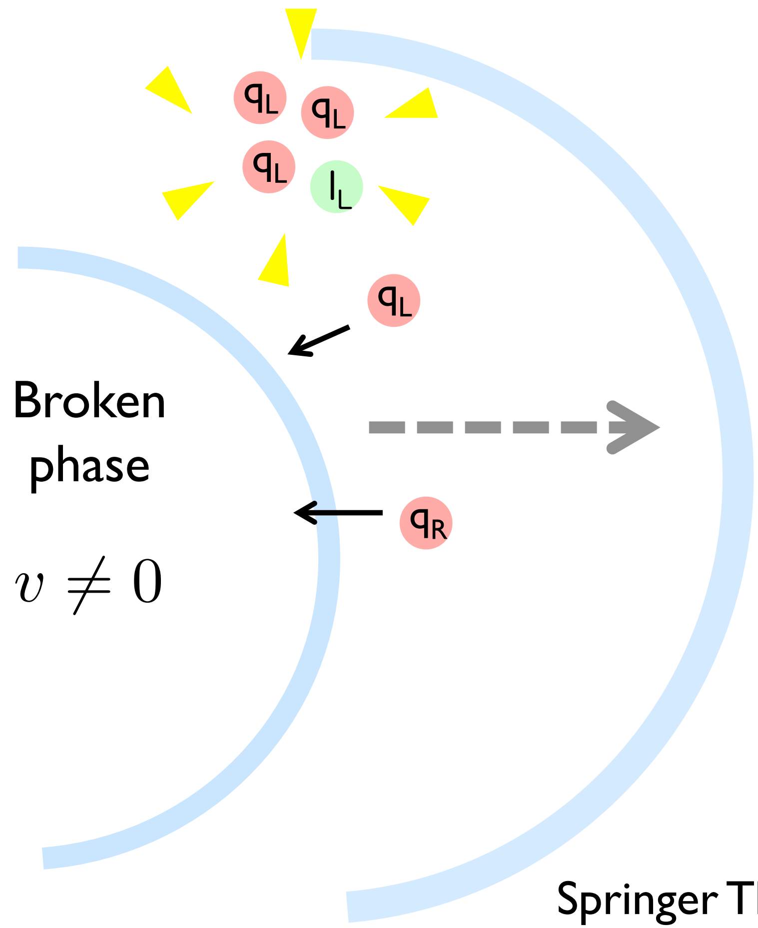
Sphaleron process changes the number of left-handed particles.



$$n_B = n_b^L - n_{\bar{b}}^L + n_b^R - n_{\bar{b}}^R \neq 0$$

Electroweak Baryogenesis

With the expansion of bubble, $n_B \neq 0$ can be included in it.



Springer Theses Book by K. Fuyuto
"Electroweak Baryogenesis and Its Phenomenology"

Testability

Testability

Kajantie et al, PRL77, 2887 (1996), Rummukainen et al, NPB 542, 283 (1998)
Csikor et al, PRL 82, 21 (1999), Aoki et al, PRD 60, 013001 (1999), Laine et al, NPB 73, 180 (1999)
Gavela et al, NPB430, 382 (1994) ; Huet and Nelsen, PRD51, 379 (1995)

The SM EWBG was ruled out.

1) EWPT is crossover for $m_H > 73\ \mathrm{GeV}$.

Measured value
$m_H = 125\ \mathrm{GeV}$

2) KM phase is not enough to generate the observed BAU.

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Next candidate for EWBG ：Physics beyond the SM

First order EWPT

New CP violation

✔ Collider experiments

Higgs Physics

✔ Search for new CP violation

Electric Dipole Moments

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Real singlet model

SM + Real singlet scalar (S)

Higgs potential :

$$V \supset -\mu_H^2 H^\dagger H + \lambda_H (H^\dagger H)^2$$

$$+\mu_{HS} H^\dagger H S + \frac{\lambda_{HS}}{2} H^\dagger H S^2$$

Relevant interactions to cause different EWPT from the SM

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$$V \supset -\mu_H^2 H^\dagger H + \lambda_H (H^\dagger H)^2$$

$$+\mu_{HS} H^\dagger H S + \frac{\lambda_{HS}}{2} H^\dagger H S^2$$

Higgs - Gauge : $\kappa_V = \frac{g_{hVV}^{\rm rSM}}{g_{hVV}^{\rm SM}}$ Higgs - Fermion : $\kappa_F = \frac{g_{hff}^{\rm rSM}}{g_{hff}^{\rm SM}}$

$$\kappa_V = \kappa_F = \cos\alpha \equiv \kappa$$

Mixing Angle

Baryon number conservation condition

In order to leave the BAU after EWPT,

Baryon number conservation condition : $\Gamma_B^{(b)} < H$

$\Gamma_B^{(b)}$: B-number changing rate in broken phase

H : Hubble constant

* Known as the strong first order EWPT

Rough Criterion : $\dfrac{v_C}{T_C} \gtrsim 1$

$\mathrm{Ex)} \sim 1.1 - 1.2\ (\mathrm{rSM})$

K, Fuyuto and E. Senaha, PRD 90, 015015 (2014)

$\sim 1.2\ (\mathrm{2HDM})$

K.Fuyuto, E. Senaha, PLB(2015)152

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$$\frac{v_C}{T_C} > \zeta_{\rm sph}(E_{\rm sph}(T_C))$$

More precise predictions of the Higgs couplings

Baryon number conservation condition

In order to leave the BAU after EWPT,

Strong 1st order EWPT : $\dfrac{v_C}{T_C} > \zeta_{\rm sph}(E_{\rm sph}(T_C))$

First precise estimation in rSM K, Fuyuto and E. Senaha, PRD 90, 015015 (2014)

1) Find v_C and T_C with the finite-temperature 1-loop effective potential

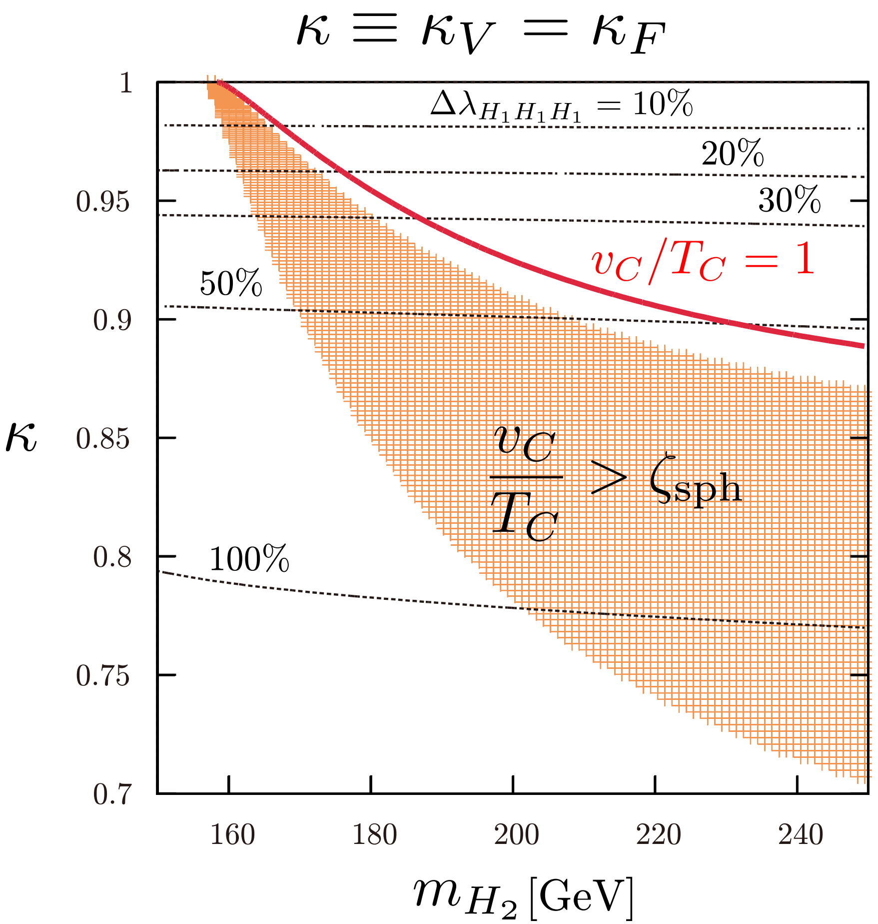
$$V_{\rm eff} = V_0 + V_1(T=0) + V_1(T \neq 0)$$

2) Estimate $\zeta_{\rm sph}(T_C)$ by solving equations of motion for the sphaleron solutions

3) Predict the Higgs couplings to gauge boson and fermion

EWPT and Higgs couplings

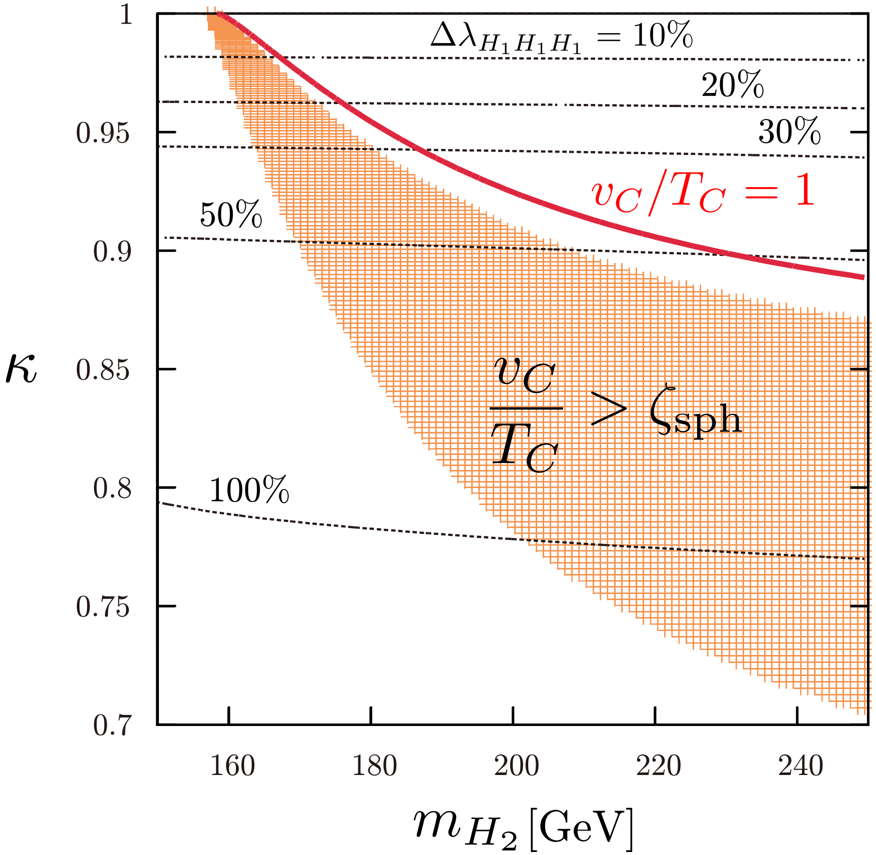
K, Fuyuto and E. Senaha, PRD 90, 015015 (2014)



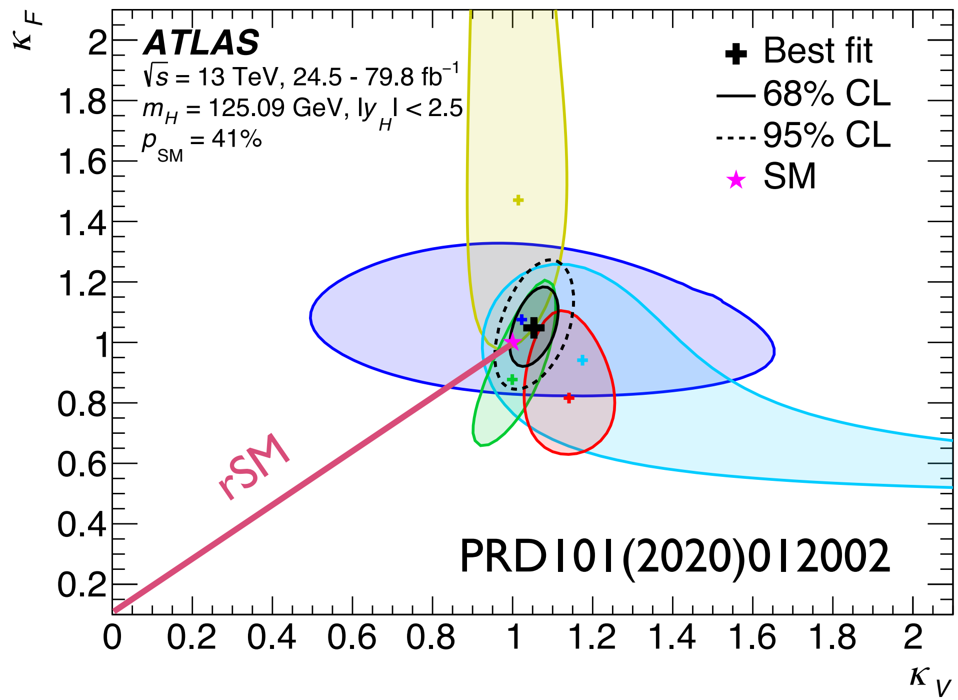
EWPT and Higgs couplings

K, Fuyuto and E. Senaha, PRD 90, 015015 (2014)

$\kappa \equiv \kappa_V = \kappa_F$



Higgs coupling measurements @ATLAS



$$\kappa_V = 1.05 \pm 0.04$$
$$\kappa_F = 1.05 \pm 0.09$$

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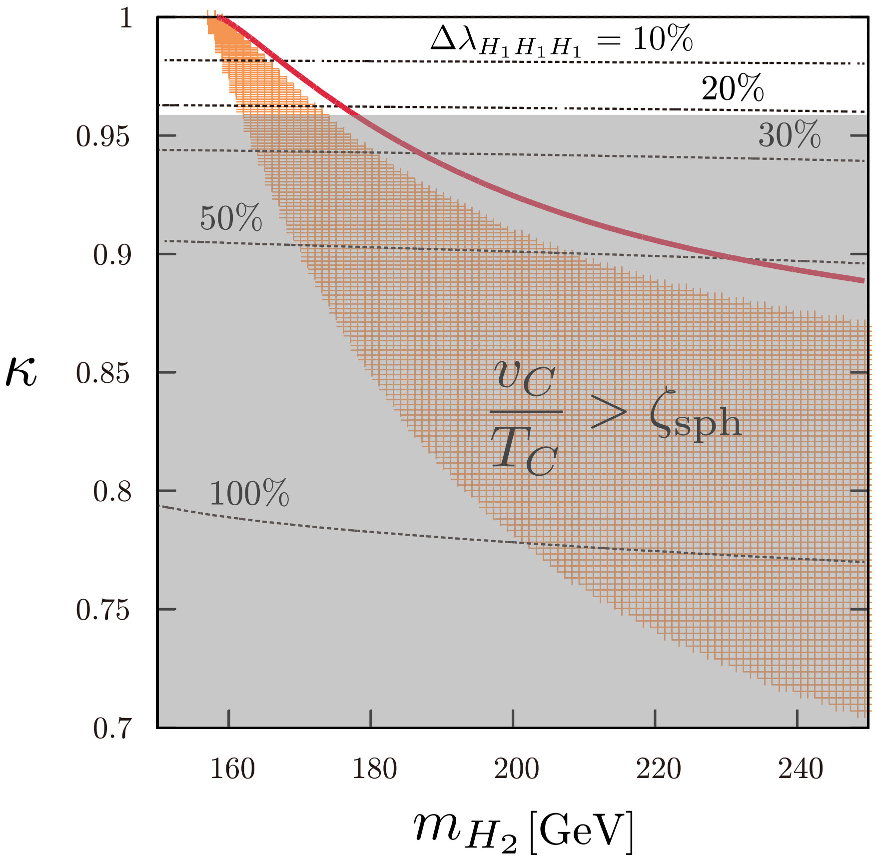

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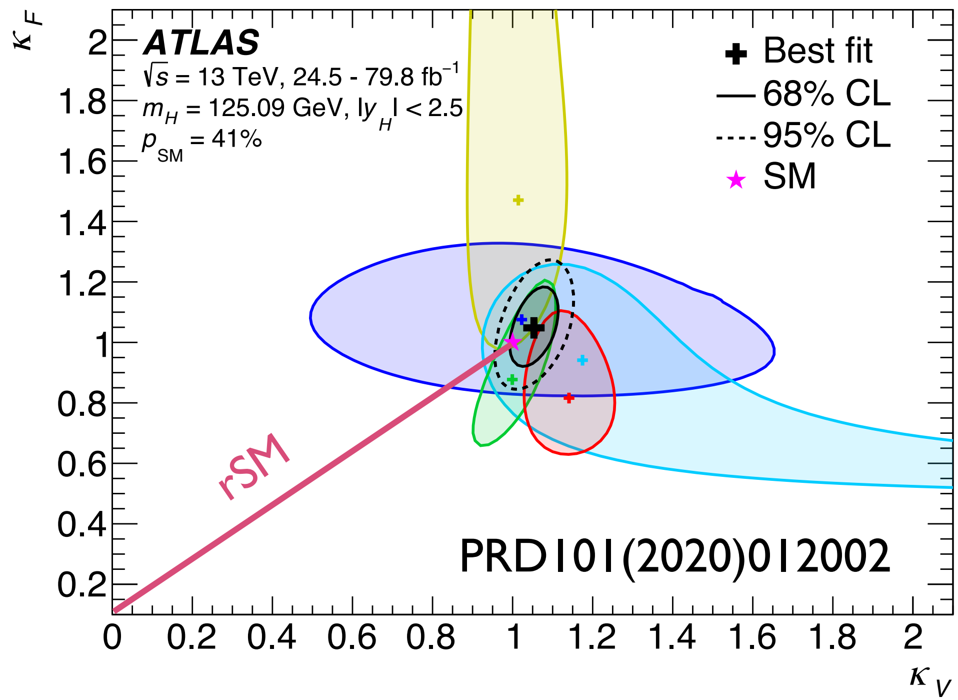

160 GeV $\lesssim m_{H_2} \lesssim$ 180 GeV

$$\kappa_V = 1.05 \pm 0.04$$
$$\kappa_F = 1.05 \pm 0.09$$

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✔ Search for new CP violation

Electric Dipole Moments

Electric Dipole Moments

Net displacement of charge along spin (s) axis

$$H_{\mathrm{EDM}} = -d\frac{\mathbf{s}}{|\mathbf{s}|} \cdot \mathbf{E}$$

$\mathbf{E}$: Electric field

Nonzero *d* : Violation of Time-reversal symmetry

CP violation under CPT theorem

Electric Dipole Moments

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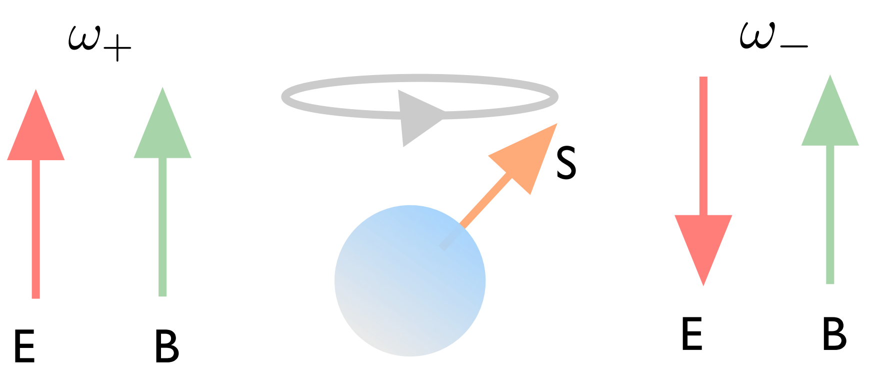
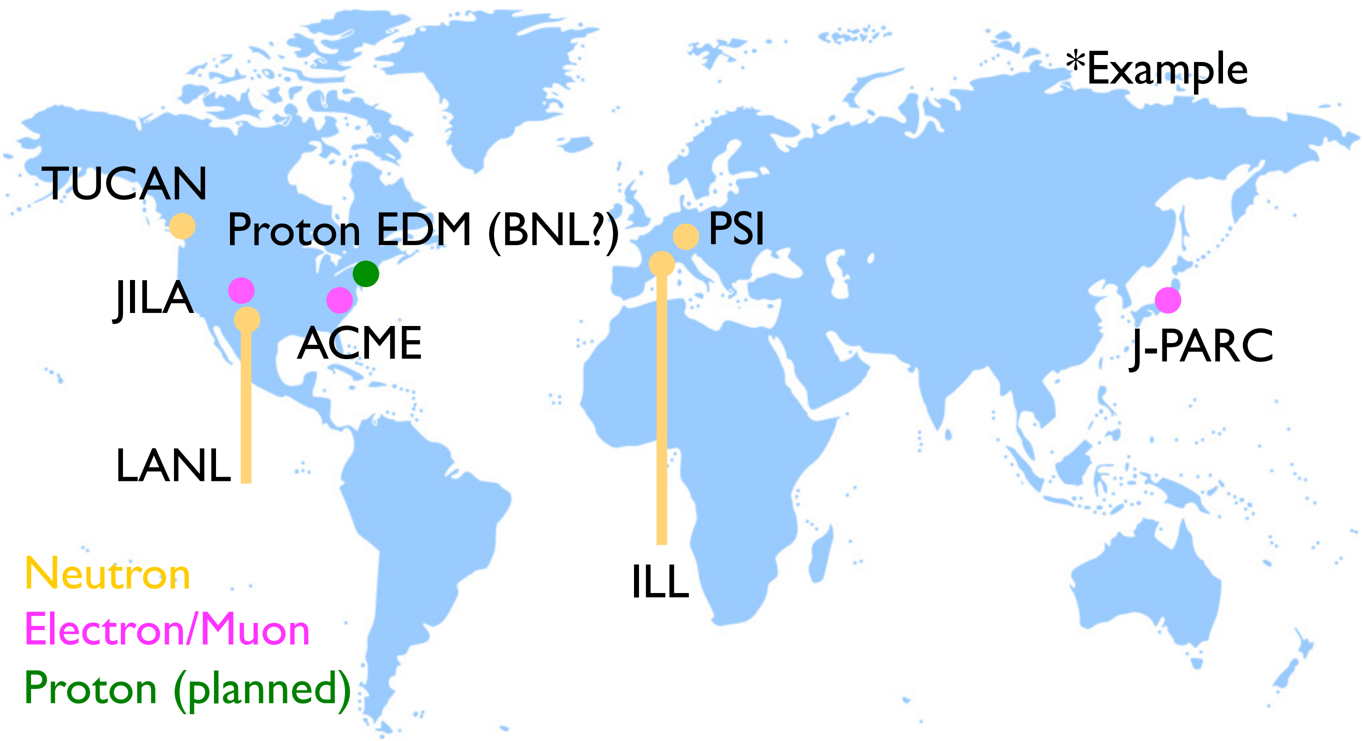


Spin precession

$$d = \frac{\omega_+ - \omega_-}{4E}$$

Electric Dipole Moments

Various searches for EDMs are ongoing and planned.



$$|d_e| < 1.1 \times 10^{-29} \; e \; \mathrm{cm}$$ ACME Collaboration : Nature 562(2018)7727

$$|d_n| < 1.8 \times 10^{-26} \; e \; \mathrm{cm}$$ nEDM Collaboration, PRL124(2020)081803

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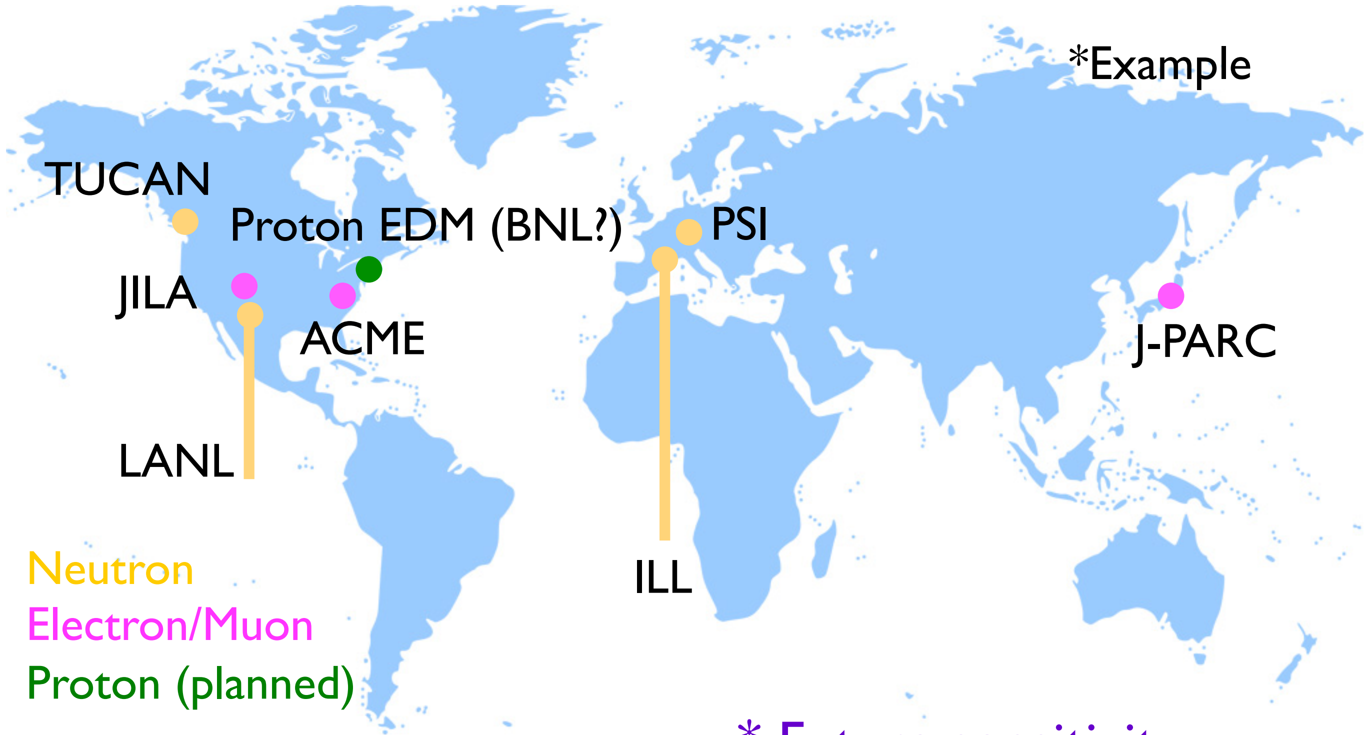

* Future sensitivity

$$|d_e| < 1.1 \times 10^{-29}\ e\ \mathrm{cm} \qquad \sim 10^{-30}\ e\ \mathrm{cm}$$

$$|d_n| < 1.8 \times 10^{-26}\ e\ \mathrm{cm} \qquad \sim 10^{-(27-28)}\ e\ \mathrm{cm}$$

Two Higgs Doublet Model

Two doublets H_1 and H_2

Yukawa interactions :

$$-\mathcal{L}_Y = \bar{q}_L \left(Y_1 \tilde{H}_1 + Y_2 \tilde{H}_2 \right) u_R + \text{h.c.}$$

$Y_1, \ Y_2$: Complex numbers

$$H_{1,2} = \begin{pmatrix} \phi_i^+ \\ \frac{1}{\sqrt{2}}(v_i + h_i + i a_i) \end{pmatrix}$$

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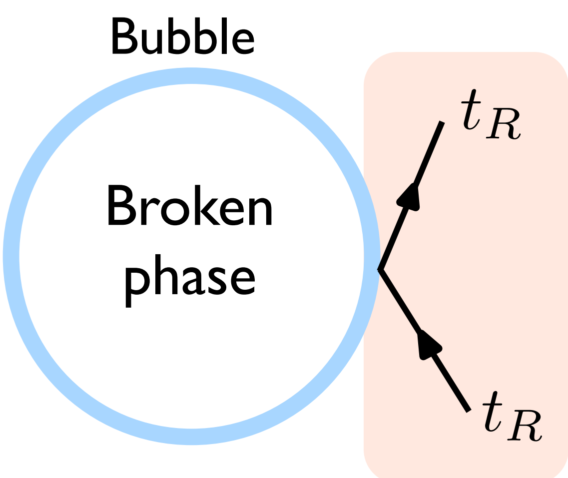

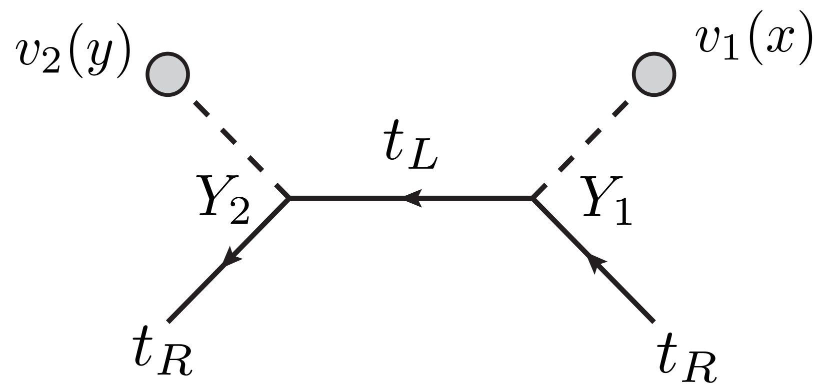

* Focus on top quark

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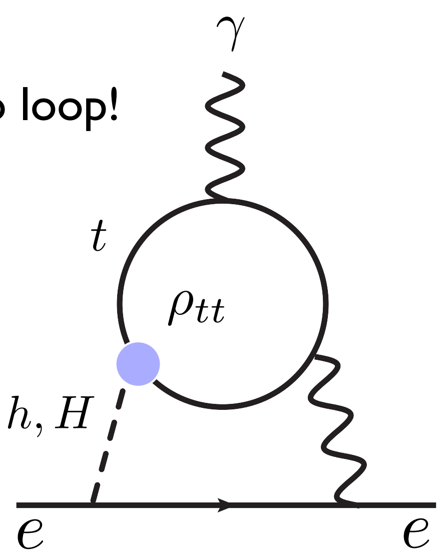
Yukawa interactions :   Complex : $|\rho_{tt}|e^{i\phi_{tt}}$

$$-\mathcal{L}_Y = \bar{t}_L \left[\frac{y_t}{\sqrt{2}} s_\alpha + \frac{1}{\sqrt{2}} \rho_{tt} c_\alpha \right] t_R h + \text{h.c.}$$

Two loop!



BAU : $n_B \propto y_t |\rho_{tt}| \sin\phi_{tt}$

EDM : $d_e \propto |\rho_{tt}| \sin\phi_{tt}$

Probed by EDM experiments !

Two Higgs Doublet Model

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$$-\mathcal{L}_Y = \bar{t}_L \left[\frac{y_t}{\sqrt{2}} s_\alpha + \frac{1}{\sqrt{2}} \rho_{tt} c_\alpha \right] t_R h + \text{h.c.}$$

1. Estimate the BAU by solving quantum Boltzmann equations

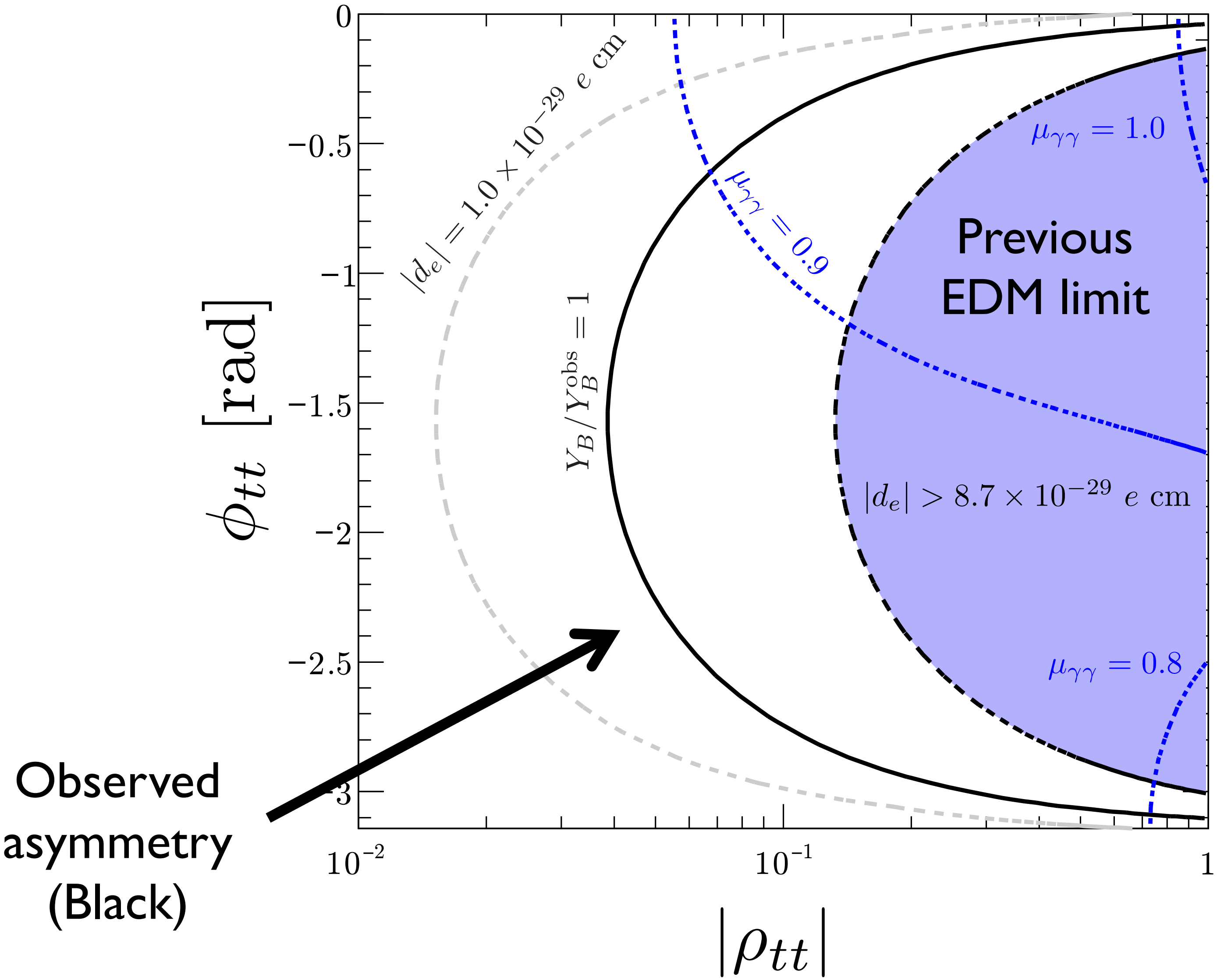
$$\partial_t n_a + \nabla \cdot j_a = \sum_b \Gamma_{ab} n_b + S_a^{\mathrm{CPV}}$$

n_a : number density

2. Predict electric dipole moments generated by ρ_{tt}

Two Higgs Doublet Model

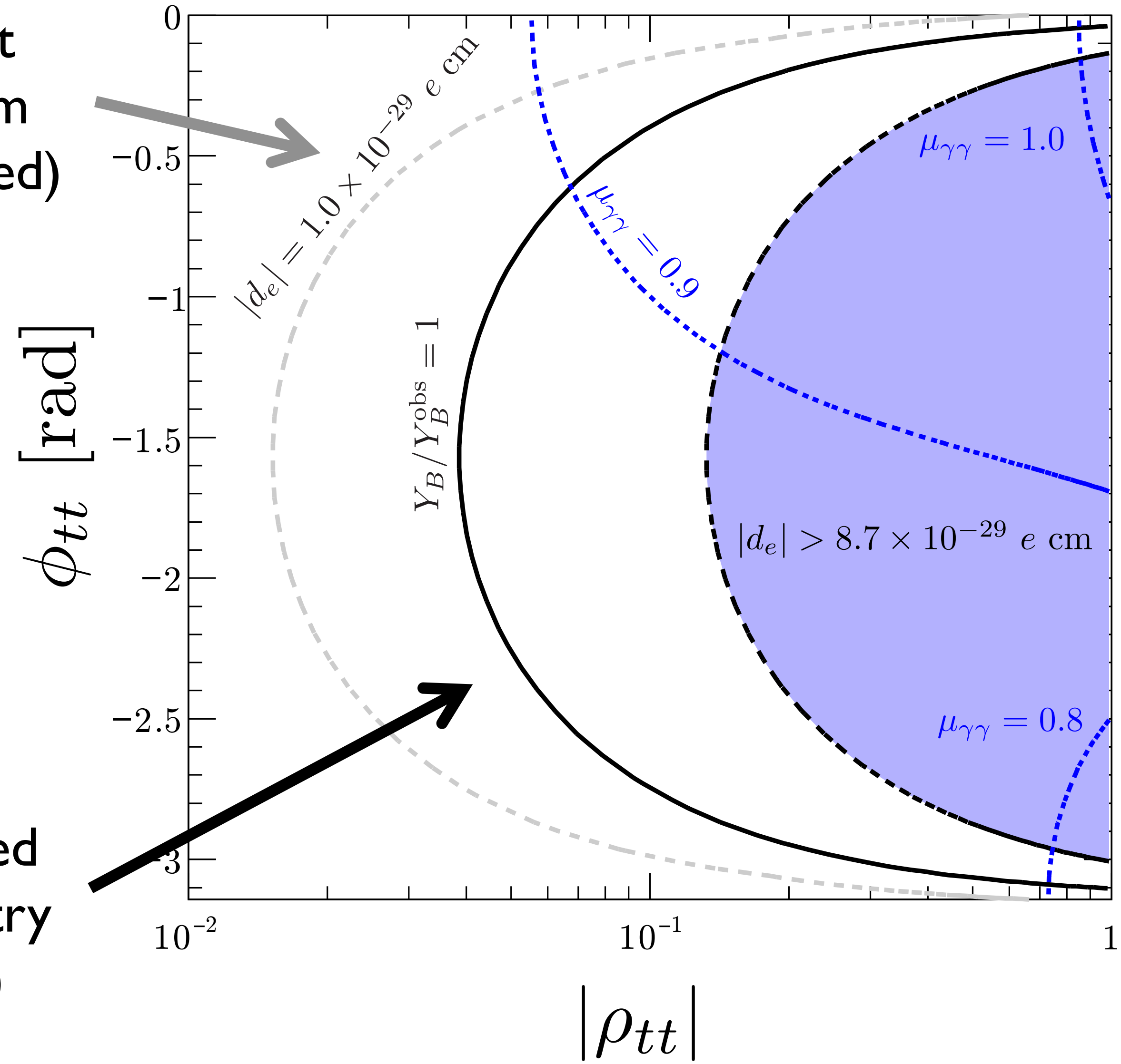
K. Fuyuto, WS. Hou, and E. Senaha
PLB 776 (2018) 402



Two Higgs Doublet Model

K. Fuyuto, WS. Hou, and E. Senaha
PLB 776 (2018) 402

New limit
~10^{-29} e cm
(Gray dashed)



Observed
asymmetry
(Black)

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PLB 776 (2018) 402

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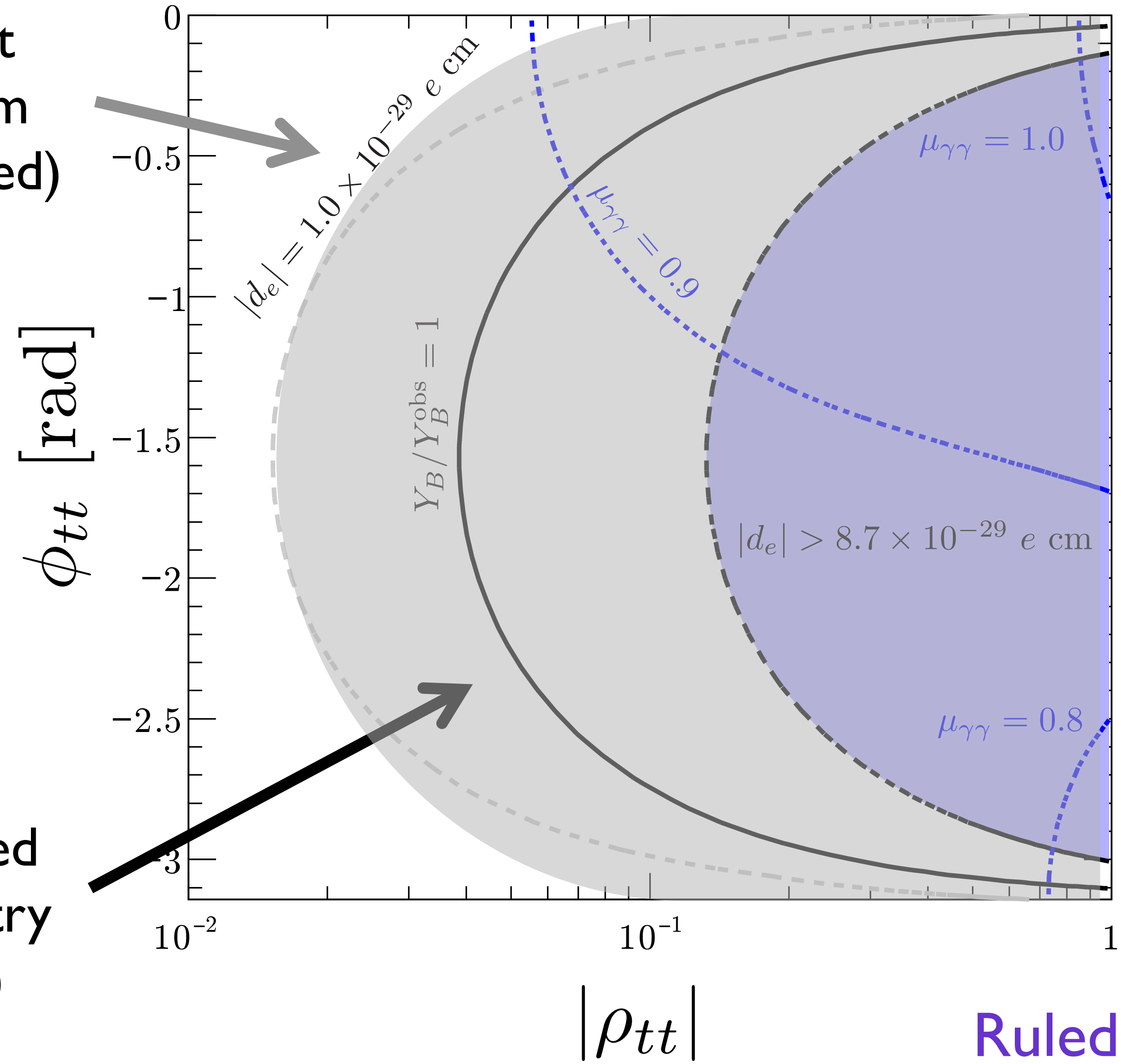

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Ruled out!

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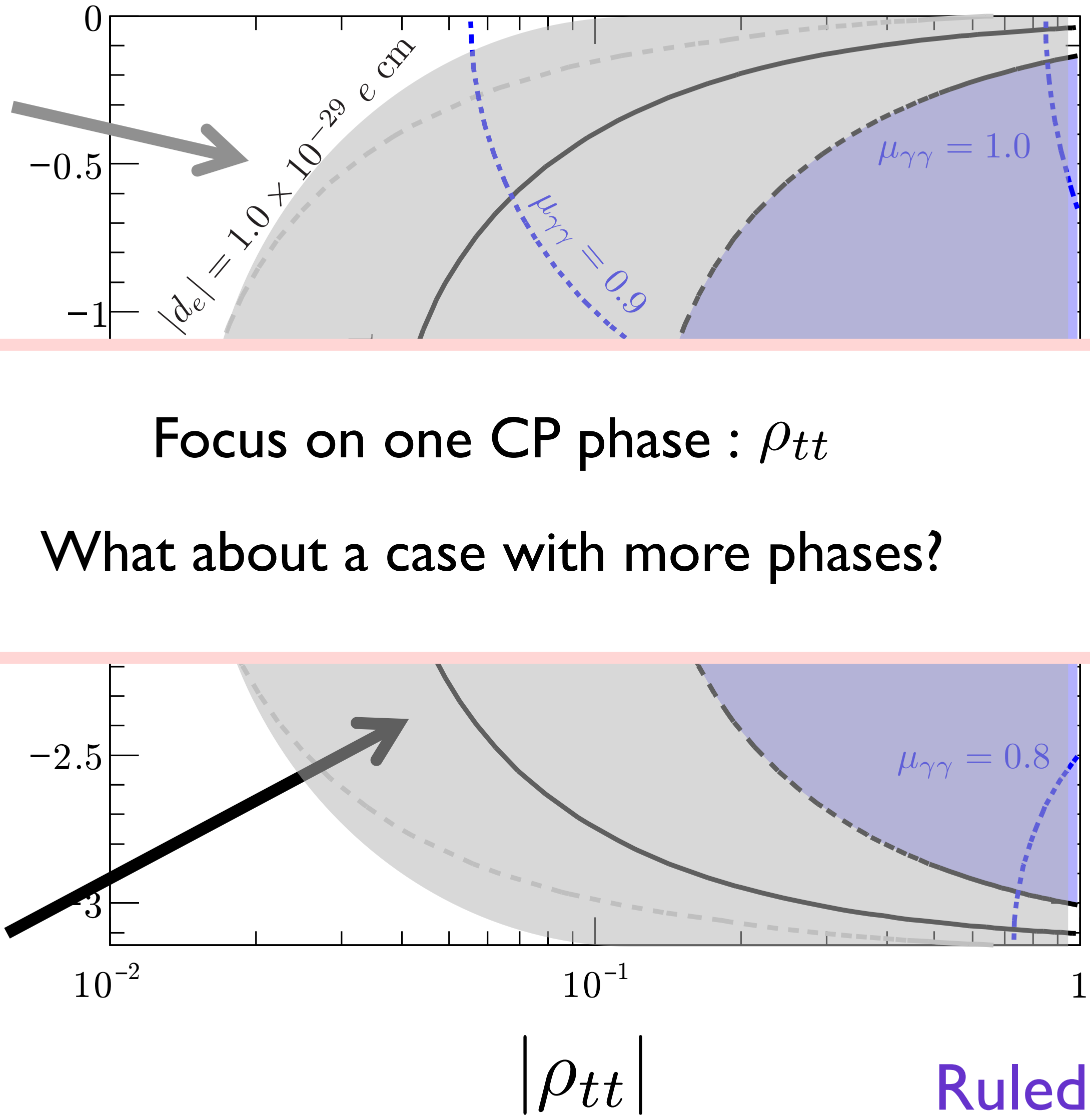


Focus on one CP phase : ρ_{tt}

What about a case with more phases?

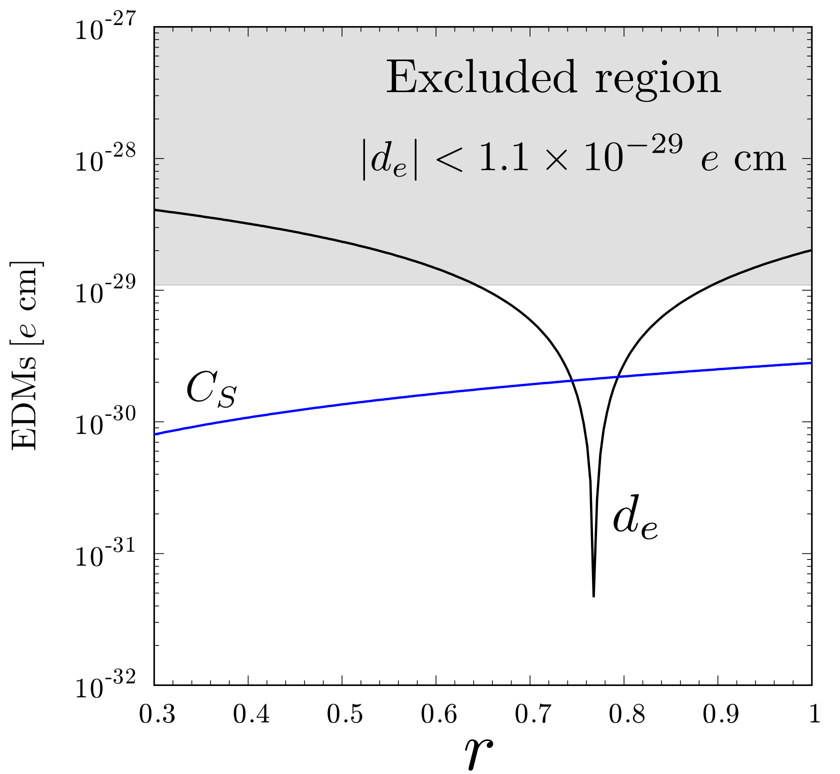
Observed
asymmetry
(Black)

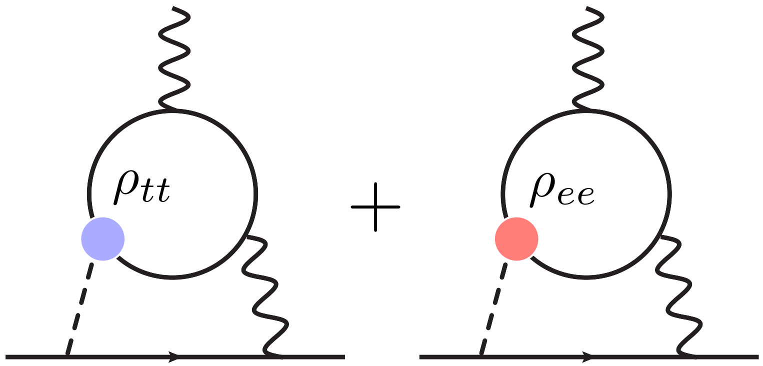
Ruled out!

Two Higgs Doublet Model

K. Fuyuto, WS. Hou, and E. Senaha
PRD101(2020)011901

Case with two phases : $\rho_{tt}, \; \rho_{ee}$





Cancellation occurs!

2HDM EWBG is still viable.

Multi-species searches, e.g. nucleon EDMs, are necessary

Future direction

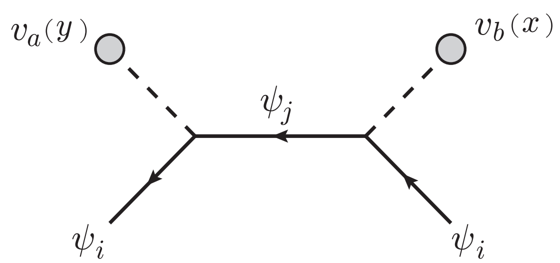
✔ Investigation of any possibility of CP violation

- CPV in various models beyond the Standard Model
- Multiple searches for new CP violation, e.g. collider experiments

✔ Improvement of theoretical uncertainties

- Estimations of the asymmetry

  Beyond the lowest order in powers of v/T



- Nucleon EDMs

  ~ 50% uncertainties from quark chromo EDMs

  * Expect lattice QCD calculations

Future plan : $d_p \sim 10^{-29}\ e\ \mathrm{cm}$ $\quad d_n \sim 10^{-28}\ e\ \mathrm{cm}$

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LANL T2

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LANL nEDM experiment

Approach to the Matter-Antimatter Asymmetry from broad fields

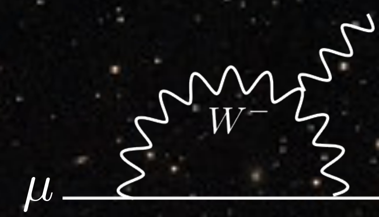
Cosmology & Astrophysics

- Gravitational waves
- Early-universe observables
- X-ray observation

Dark Matter

Nuclear Physics

- EDM
- LNV and LFV



Neutrino Ma

The origin of
the present Universe

Particle Physics

- Higgs precision measurements
- Direct collider search for new particles
- Neutrino oscillation experiments

Conclusion

- Solving the mystery of the matter-antimatter asymmetry is one of the serious challenges in modern science.
- In theoretical physics, various mechanisms have been invented.
- Expect further progresses from broad approaches.

Today : Electroweak Baryogenesis

High testability in particle and nuclear physics experiments

Probing one possibility is a "significant" step
to understand the reason why we exist.

Thank you very much!