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Title:	The Mystery of the Matter in the Universe
Author(s):	Fuyuto, Kaori
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LA-UR-23-

The Mystery of the Matter in the Universe

Kaori Fuyuto

Los Alamos National Laboratory

KF, W. S. Hou and E. Senaha, PLB 776, 402 (2018),
KF, W. S. Hou and E. Senaha, PRD 101 (2020) 011901
J. de Vries, P. Draper, **KF**, J. Kozaczuk and D. Sutherland, PRD99 (2019)015042
J. de Vries, P. Draper, **KF**, J. Kozaczuk and B. Lillard, RD104 (2021) 055039

April 26, 2023
LANL P-3 Seminar

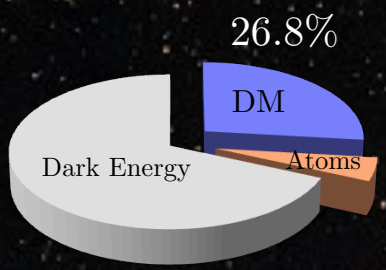
The Standard Model is the most well-tested theory of elementary particles.

The particle content was completed by the discovery of the Higgs boson.

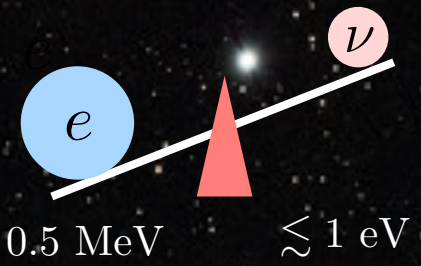
The Standard Model is the most well-tested theory of elementary particles.

However, it does not explain the complete picture.

What is Dark Matter?



What is the origin of tiny neutrino mass ?



The origin of
the present Universe

Why is there more matter than antimatter? $\dfrac{n_b - n_{\bar{b}}}{n_\gamma} = 6.1 \times 10^{-10}$

Physics Beyond the Standard Model (BSM Physics)

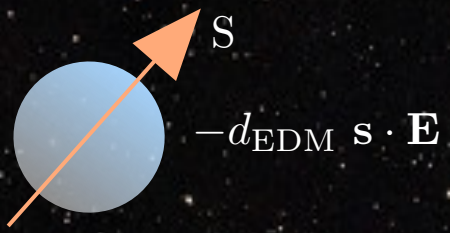
Key approach : Fundamental symmetry tests

Ex) Search for CP violation, Lepton Flavor and Lepton-Number Violation

(C : Charge, P : Parity)

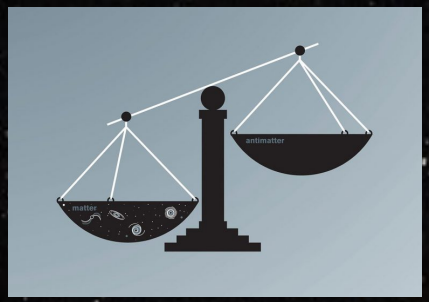
Key approach : Fundamental symmetry tests

Electric Dipole Moments



The origin of
the present Universe

Matter-antimatter asymmetry



Ex) Search for CP violation, Lepton Flavor and Lepton-Number Violation

(C : Charge, P : Parity)

Outline

1. Matter-Antimatter Asymmetry

2. Baryogenesis * Electroweak Baryogenesis

3. Testability by Electric Dipole Moments

   + Importance of multi-species EDM searches

   KF, W. S. Hou and E. Senaha, PLB 776, 402 (2018),
   KF, W. S. Hou and E. Senaha, PRD 101 (2020) 011901
   J. de Vries, P. Draper, **KF**, J. Kozaczuk and D. Sutherland, PRD99 (2019)015042
   J. de Vries, P. Draper, **KF**, J. Kozaczuk and B. Lillard, RD104 (2021) 055039

4. Summary

Matter-antimatter asymmetry


One simple question :
Why do we exist?
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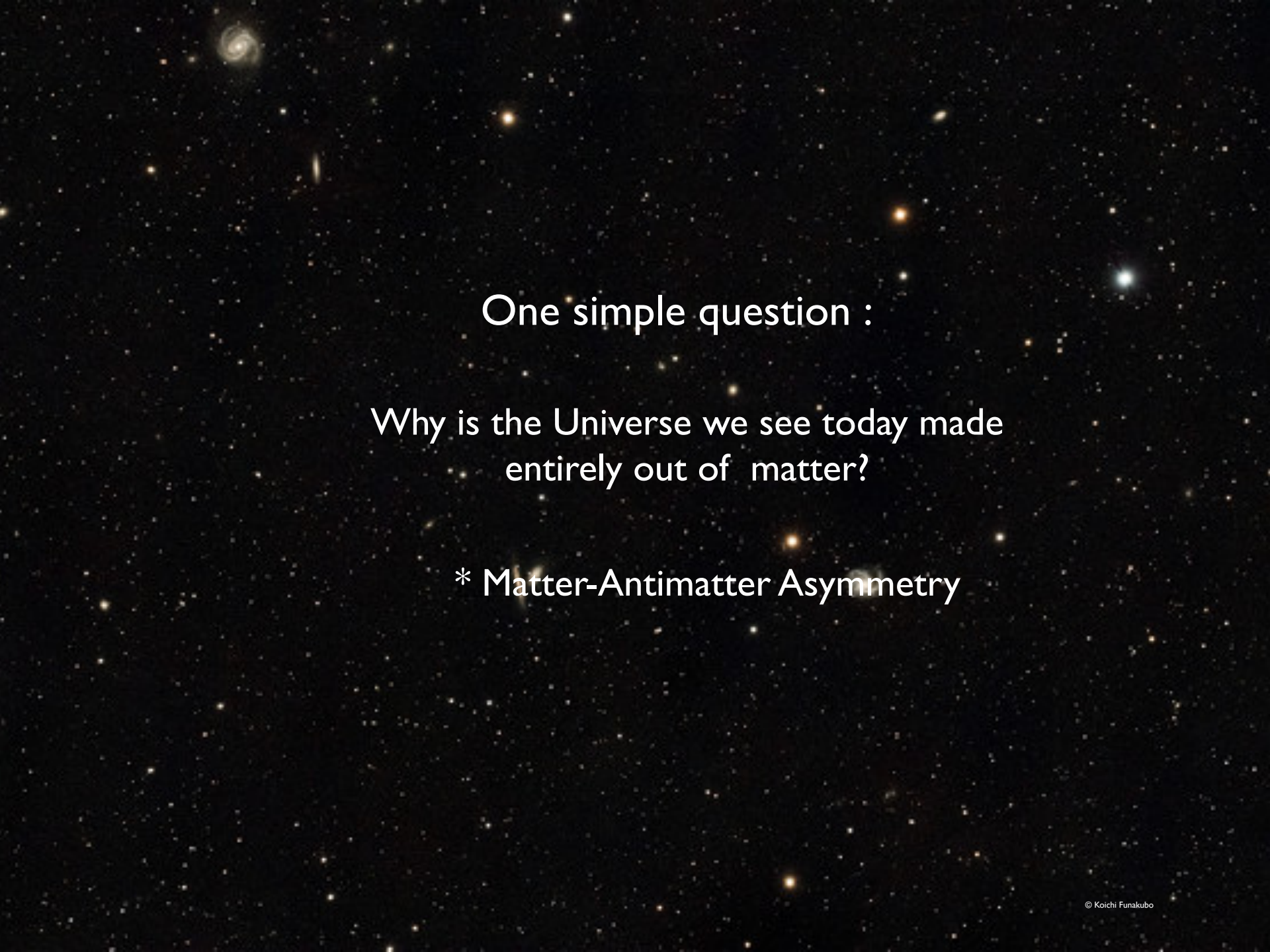
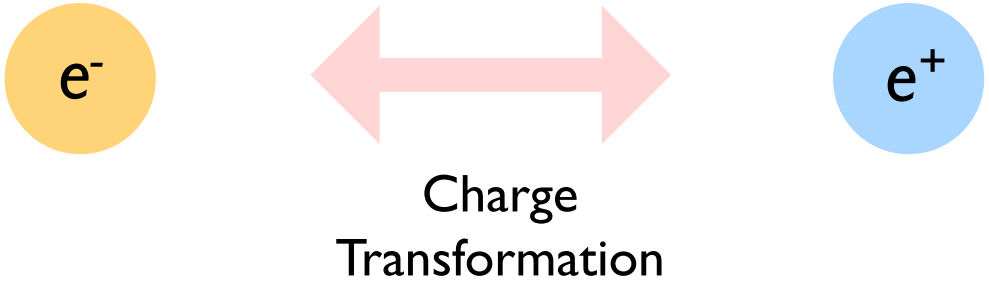

One simple question :
Why is the Universe we see today made entirely out of matter?
* Matter-Antimatter Asymmetry
© Koichi Funakubo

Particle and Antiparticle

Antiparticle : an opposite electric charge to particle

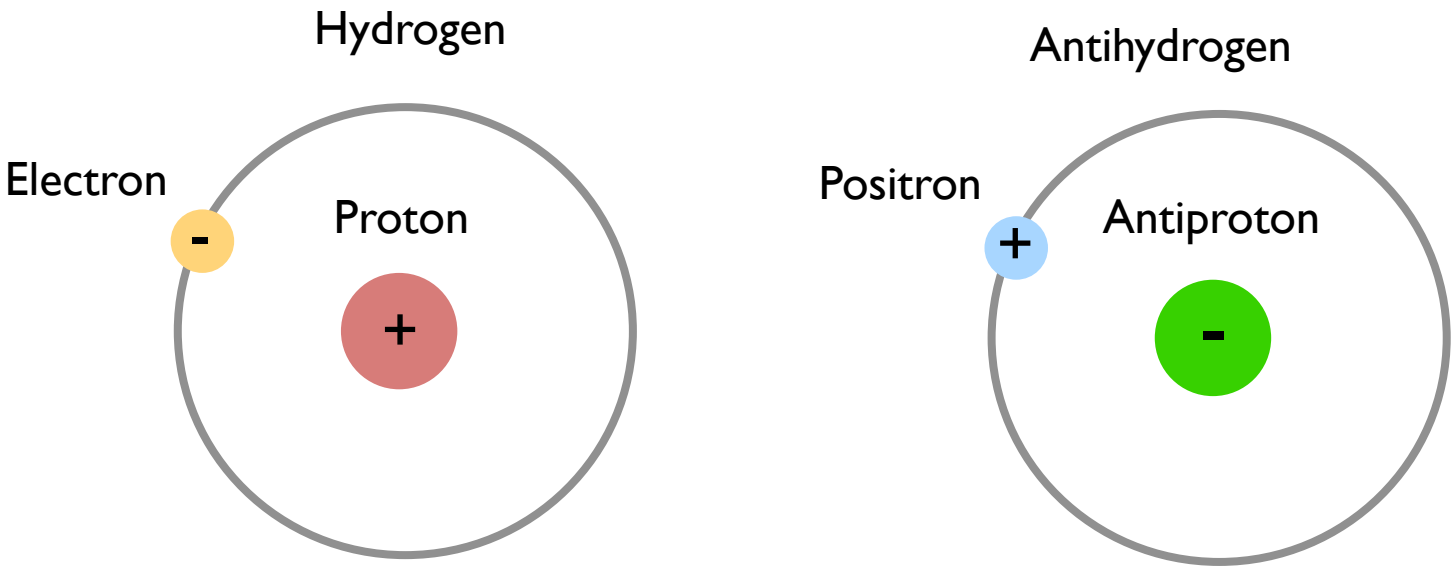
(or internal quantum numbers)

Ex) Electron Positron



Particle and Antiparticle

Antiparticle : an opposite electric charge to particle



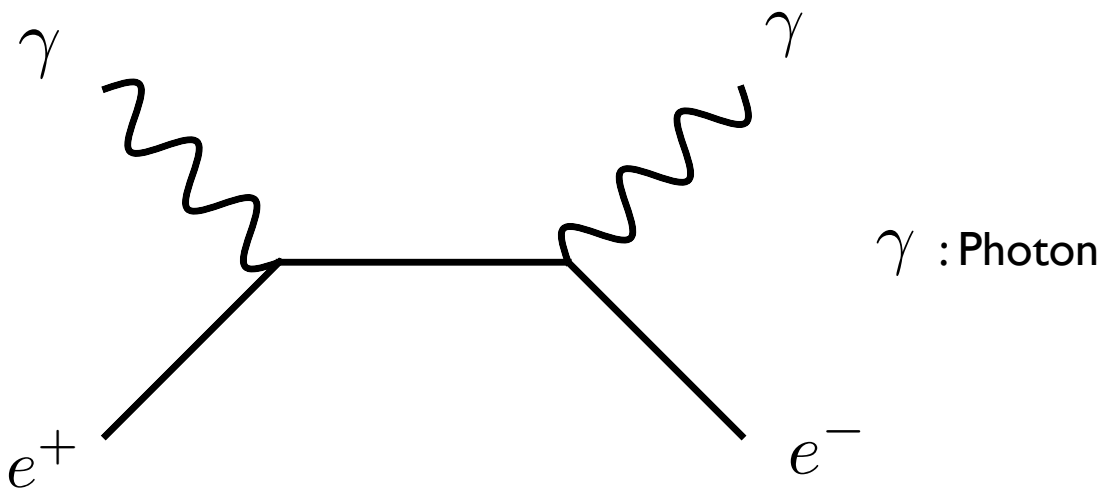
Antimatter is composed of antiparticles.

* We are made of matter.

Particle and Antiparticle

Antiparticle : an opposite electric charge to particle

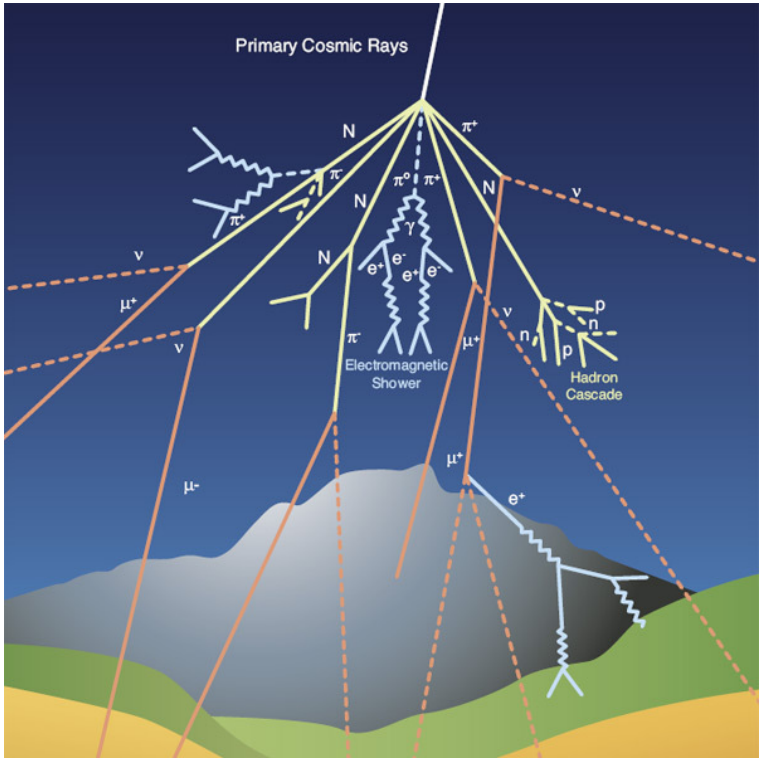
* Feynman diagram



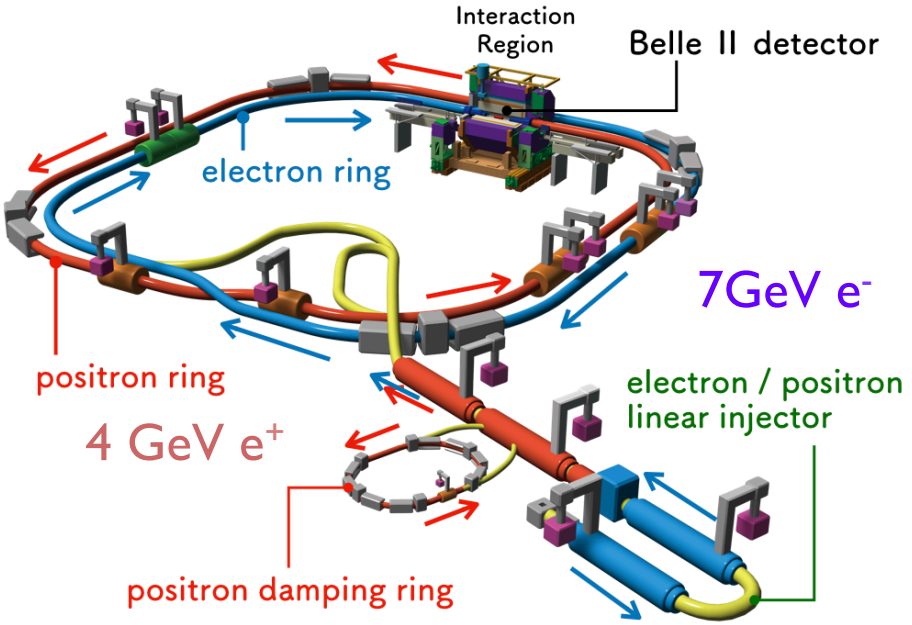
One key process : Annihilation of particle and antiparticle

Antimatter on the Earth

1. Cosmic rays



2. In laboratories

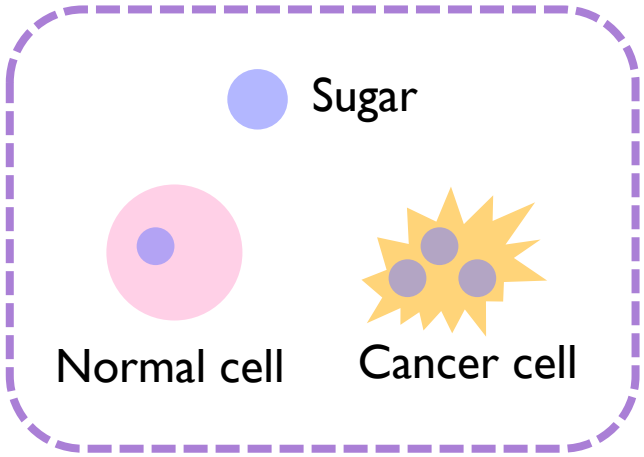


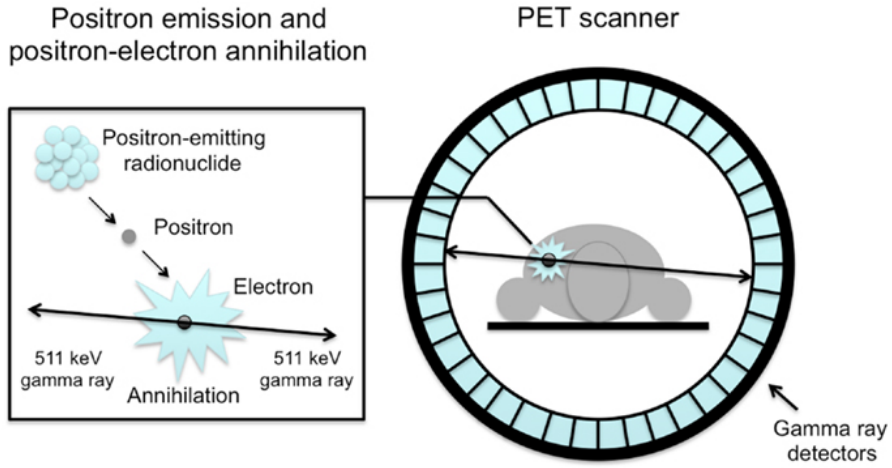
Ex) e^+e^- collider : SuperKEKB

Antimatter on the Earth

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

Positron Emission Tomography

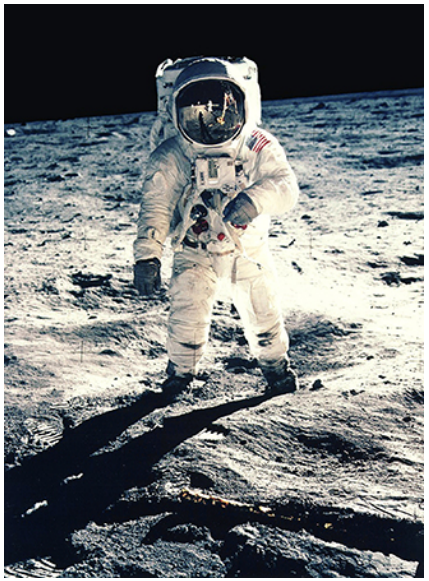




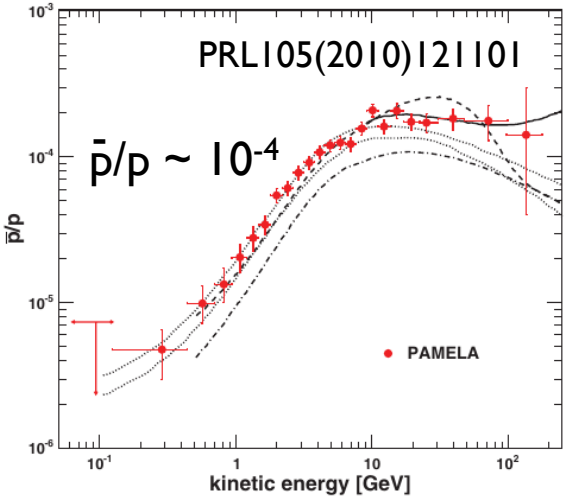
Inject sugar with radioactive isotope (positron emitter)

What about in the Universe?

1) Solar system



2) Our galaxy



Secondary production by the interactions of cosmic rays

3) Beyond our galaxy

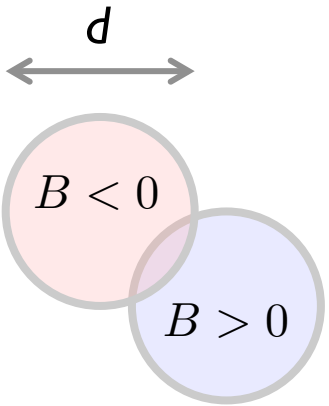
No observation of proton-antiproton annihilation from nearby clusters of galaxies

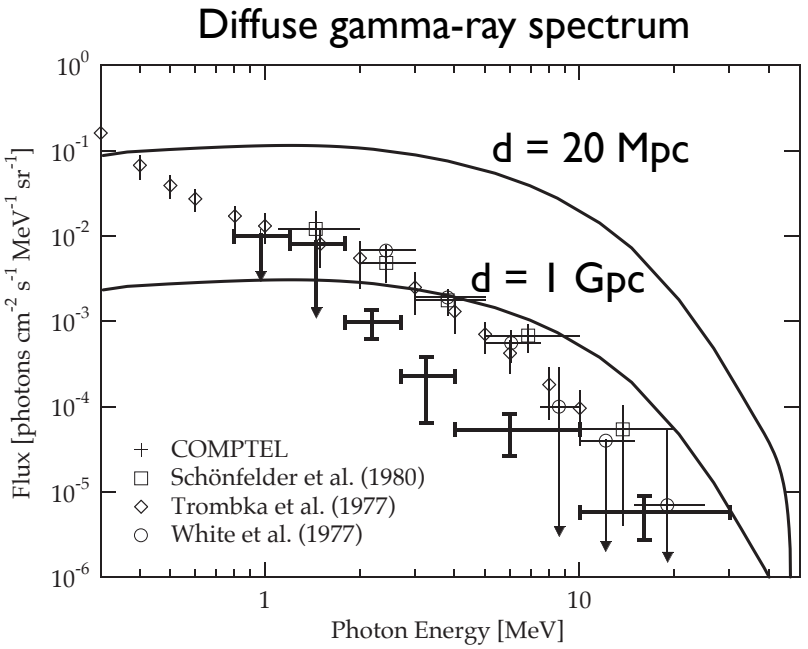
e.g., the Virgo cluster

What about in the Universe?

4) Gamma ray from boundary between matter and antimatter domains

Cohen, De Rujula and Glashow (1997), 9707087 and 9705045





If the domains exist, they must be separated, i.e., d > 1Gpc

~ the size of the visible universe

What about in the Universe?

5) Cosmic Microwave Background

$$\frac{n_B}{n_\gamma} = (6.105 \pm 0.055) \times 10^{-10}$$

PDG: PTEP(2020)083C01

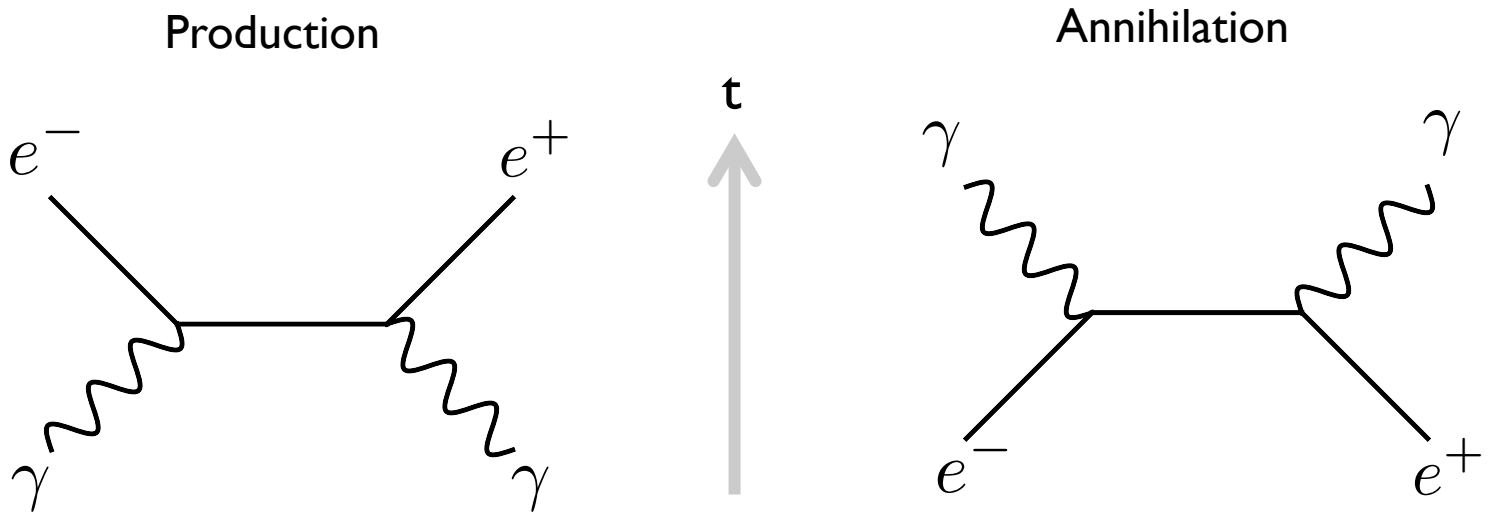
$n_B = n_b - n_{\bar{b}}$ n_γ : Photon density

$n_{b(\bar{b})}$: (Anti−) Baryon number density

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

Why is there more matter than antimatter?

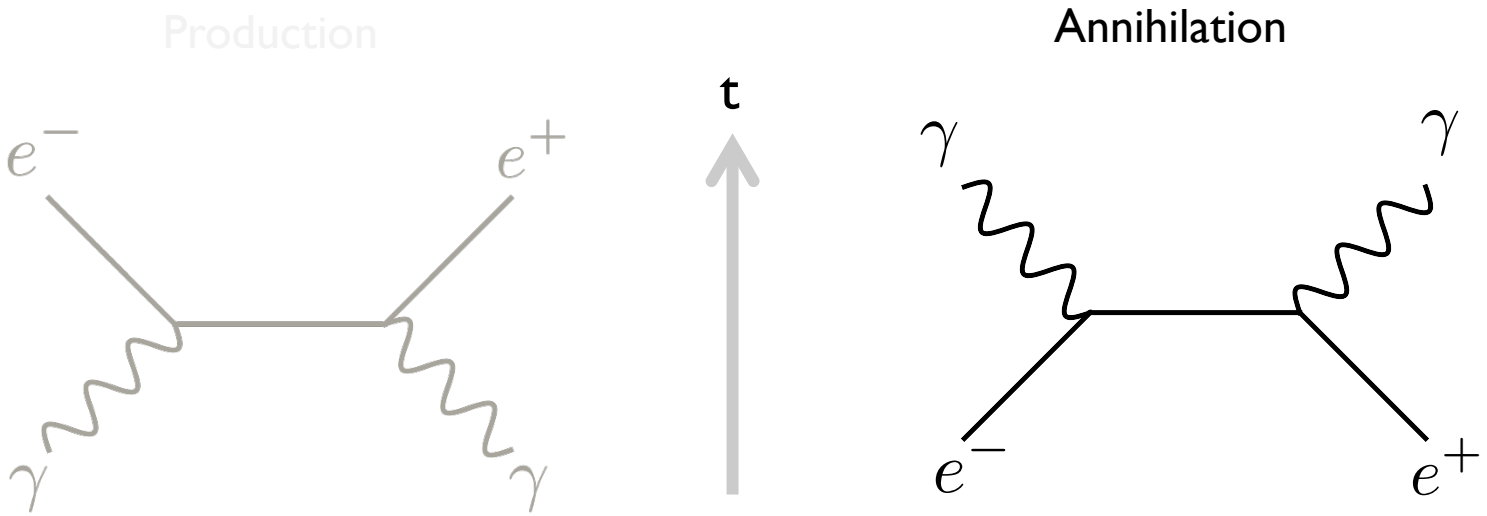
Early Universe



In the early Universe, both production and annihilation occur.

Photon energy E_γ ~ Temperature of the Universe T

Early Universe

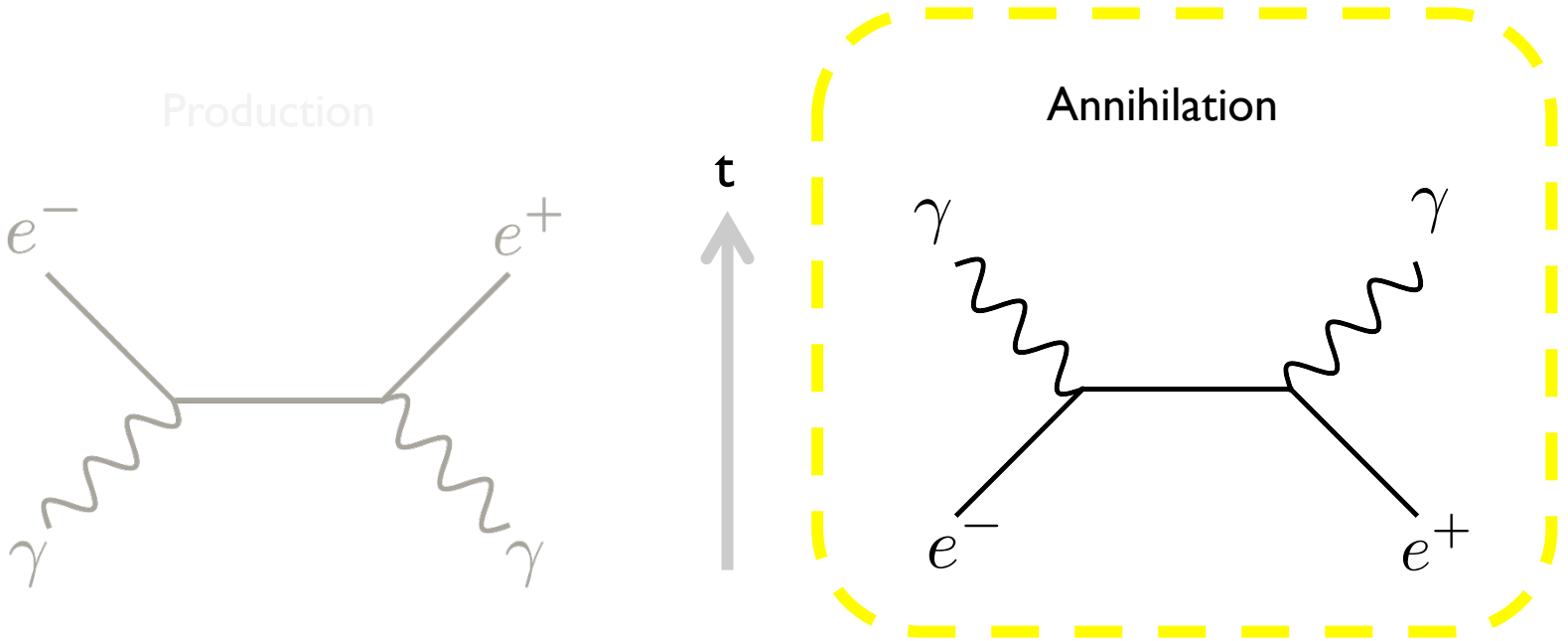


As the Universe expands, it cools down.

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

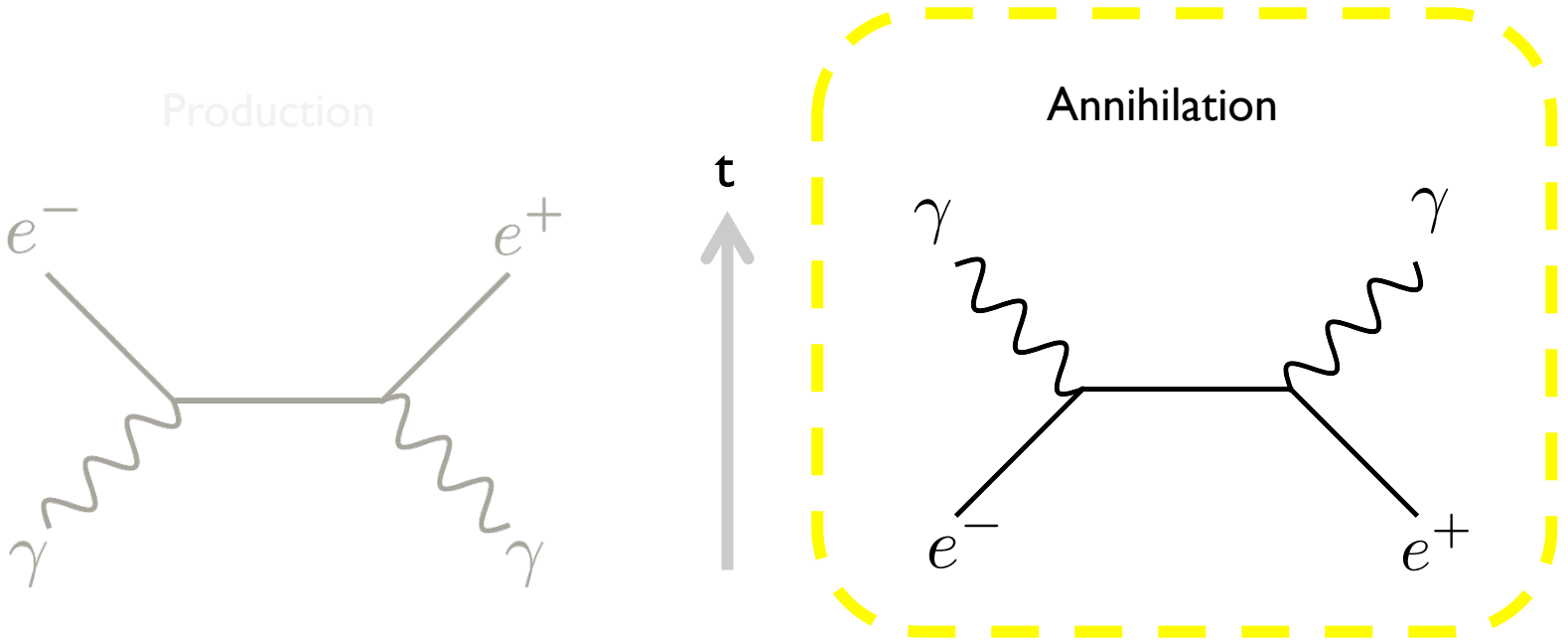
$$E = mc^2$$

Early Universe



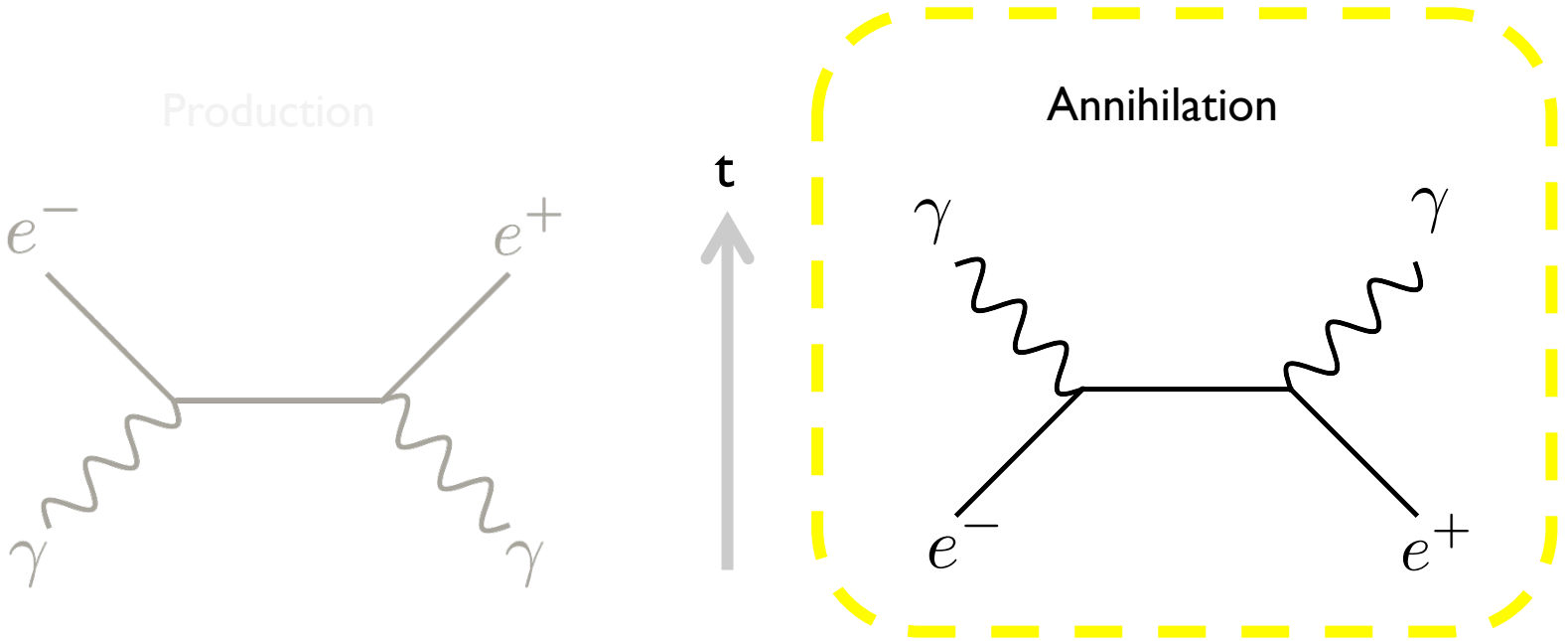
Only the annihilation continues.

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



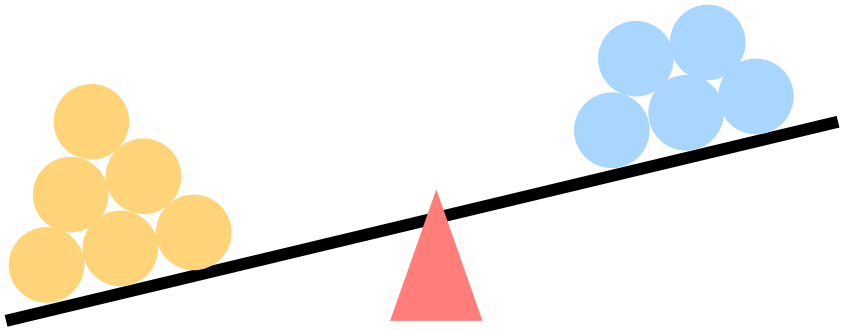
If the total numbers of particle and antiparticle are same,
is it possible for particles to be left in the present Universe?

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}



$$\frac{n_b - n_{\bar{b}}}{n_\gamma} = (6.105 \pm 0.055) \times 10^{-10}$$

PDG: PTEP(2020)083C01

Matter-antimatter asymmetry

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

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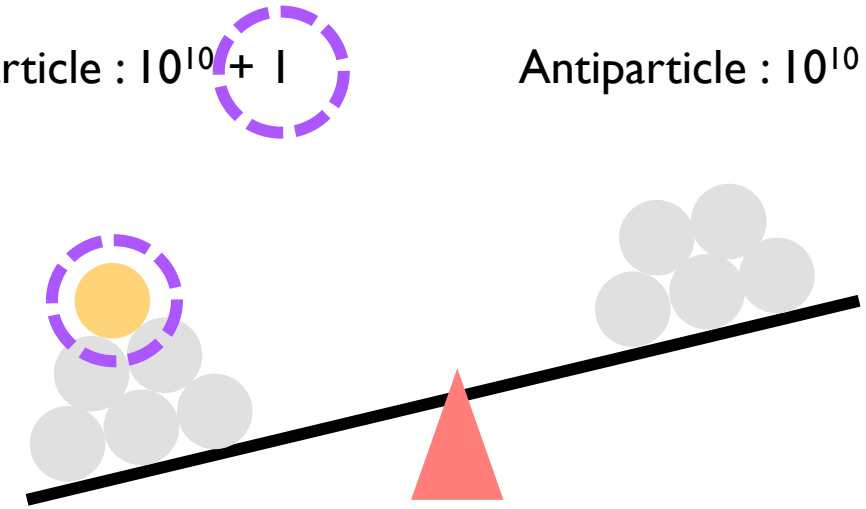


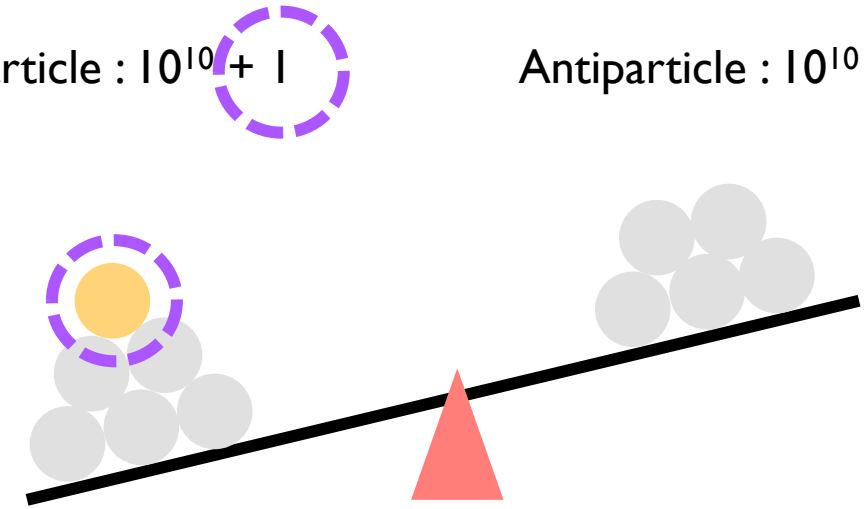
The tiny asymmetry creates the current Universe.

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}

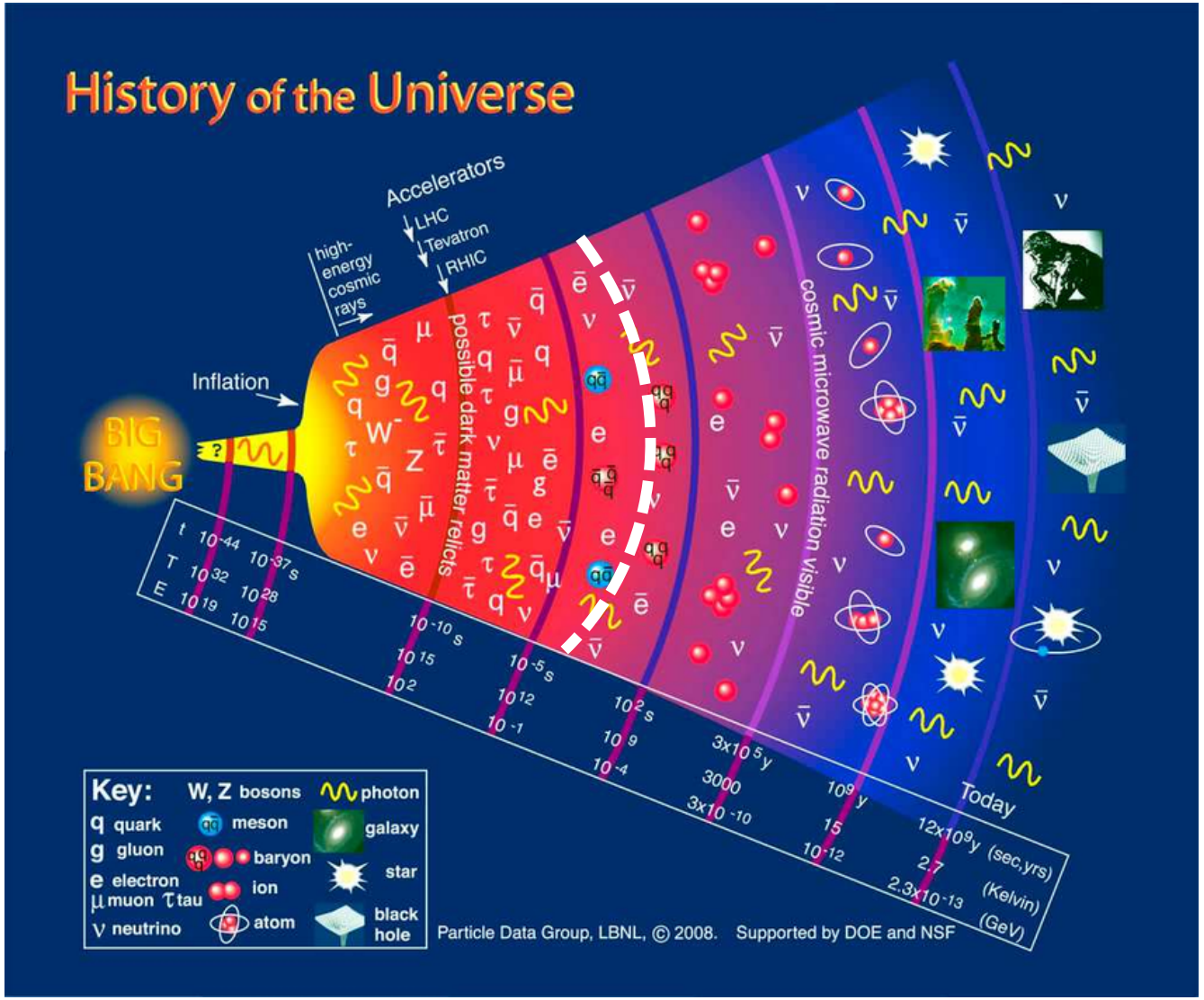


Baryogenesis : Mechanisms to dynamically create the asymmetry

Baryogenesis

Baryogenesis

*After Inflation and Before BBN (~ O(1) MeV)



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

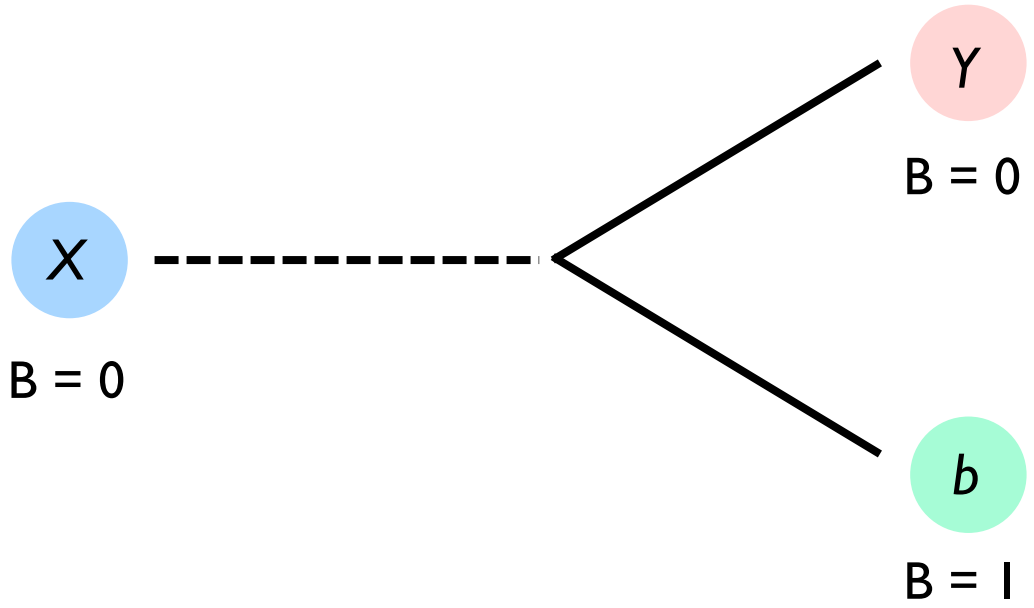
Sakharov

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

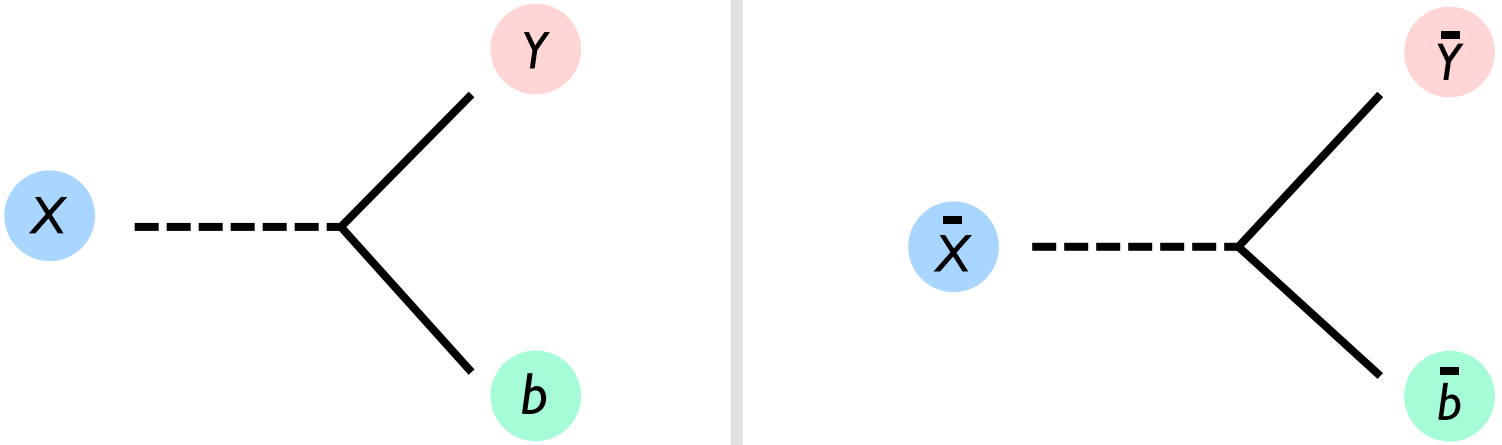


$$\Delta B = 1$$

Sakharov's criteria

(II) C and CP violation ($\bar{A}$: antiparticle)

To distinguish baryon from anti-baryon production



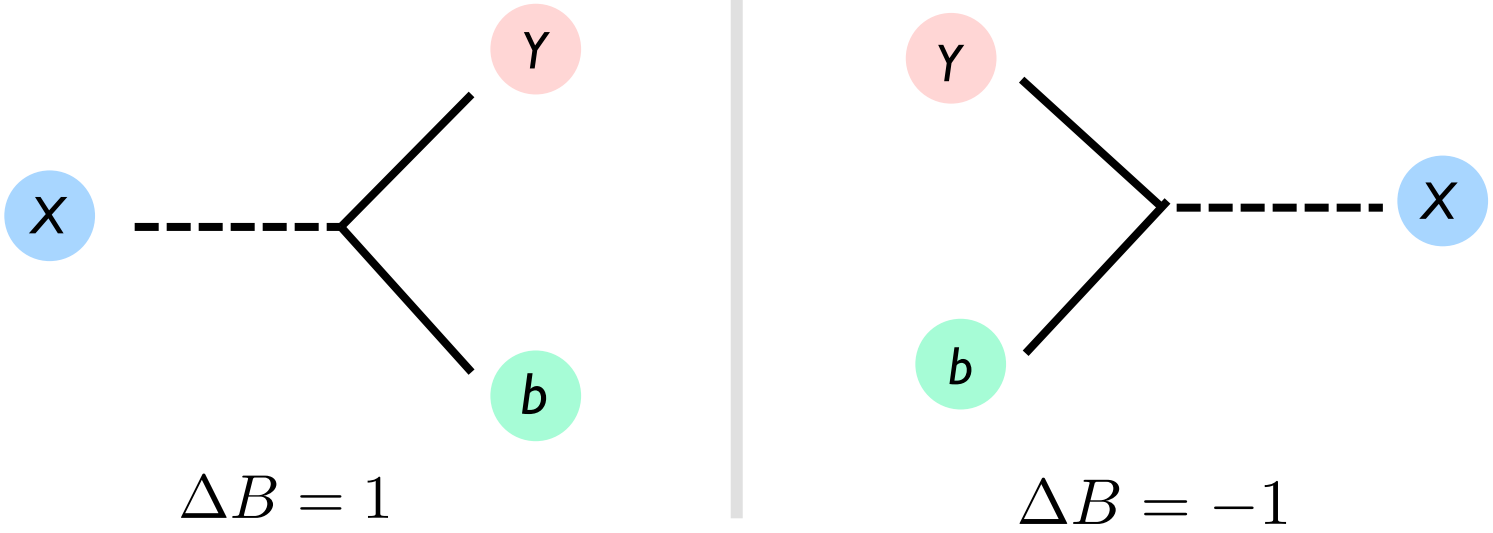
$\Delta B = 1$ $\Delta B = -1$

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

Sakharov's criteria

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

To leave produced baryon numbers



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

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 ?

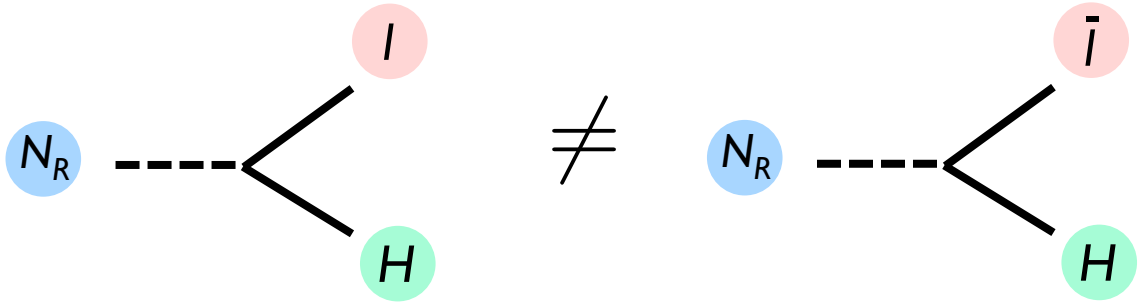
experimentally testable?

Baryogenesis

Leptogenesis

Fukugita and Yanagida, PLB174(1986)45

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



Thermal leptogenesis

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

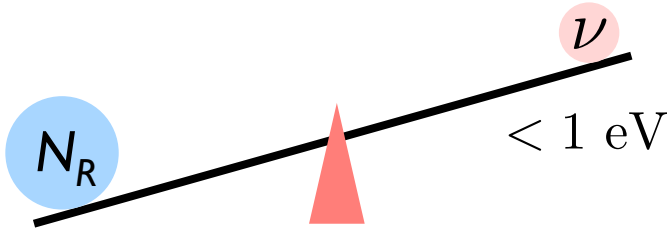
Sphaleron Process

Baryogenesis

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.

Thermal leptogenesis

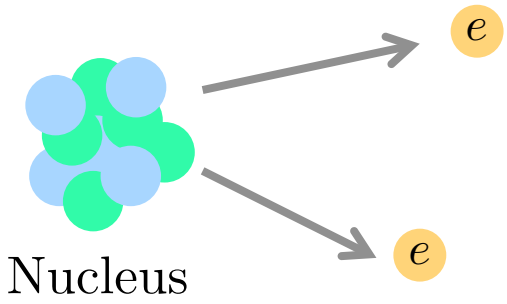
$$N_R \sim 10^{14}\ \text{GeV} \gg \begin{matrix} m_p \sim 1\ \text{GeV} \\ m_e \sim 0.5\ \text{MeV} \end{matrix} \quad \Big| \quad m_\nu \sim \frac{Y_\nu^2 v^2}{M_R} \qquad v = 246\ \text{GeV}$$

Baryogenesis

Leptogenesis

Fukugita and Yanagida, PLB174(1986)45

Predict neutrinoless double beta deacy



$$\Delta L = 2$$

Thermal leptogenesis

$N_R \sim 10^{14}$ GeV

Too heavy to produce in collider experiments…

Baryogenesis

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

Electroweak (EW) baryogenesis

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

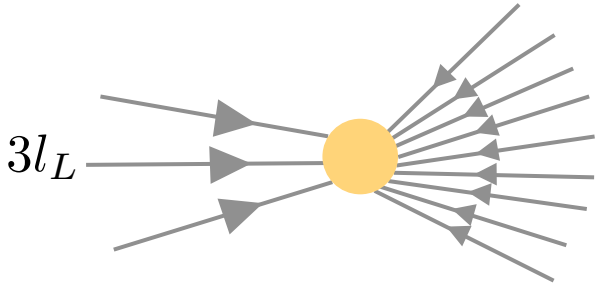
Electroweak Baryogenesis

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

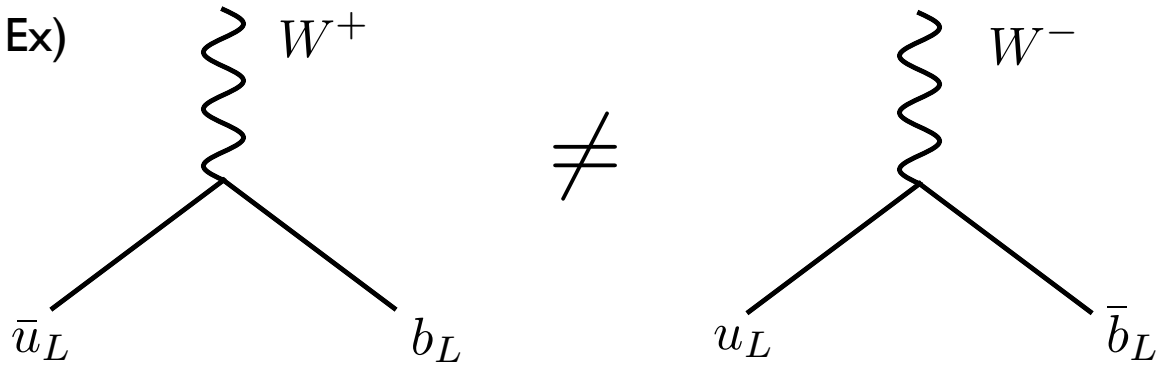
(2) C and CP violation

Chiral gauge theory and CP phase

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

Chiral interaction and CP phase in CKM Matrix

Ex)

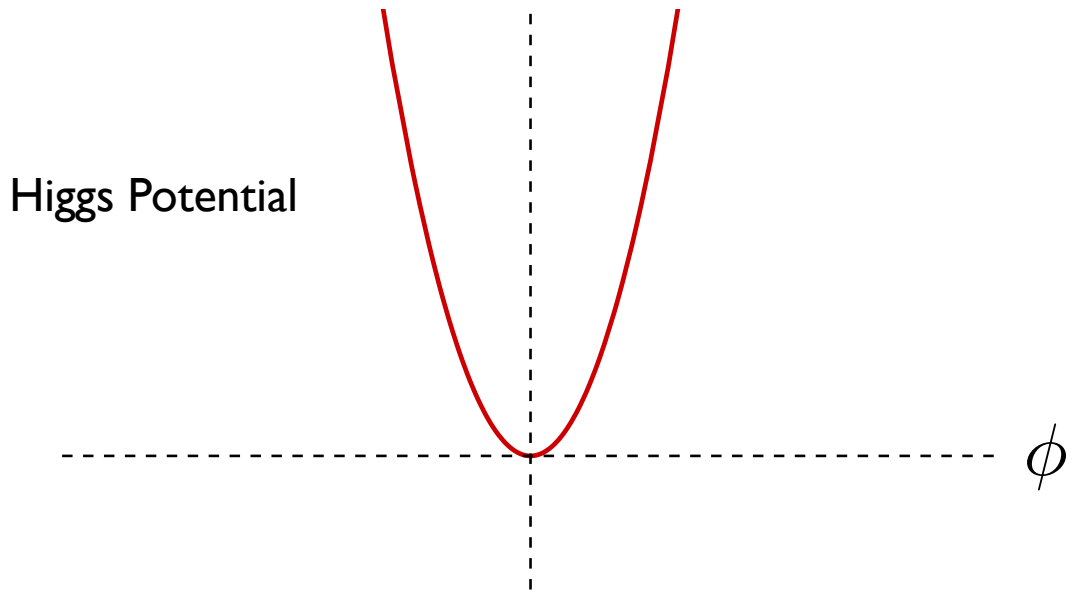


Electroweak Baryogenesis

(3) Out of equilibrium

First order electroweak phase transition (EWPT)

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

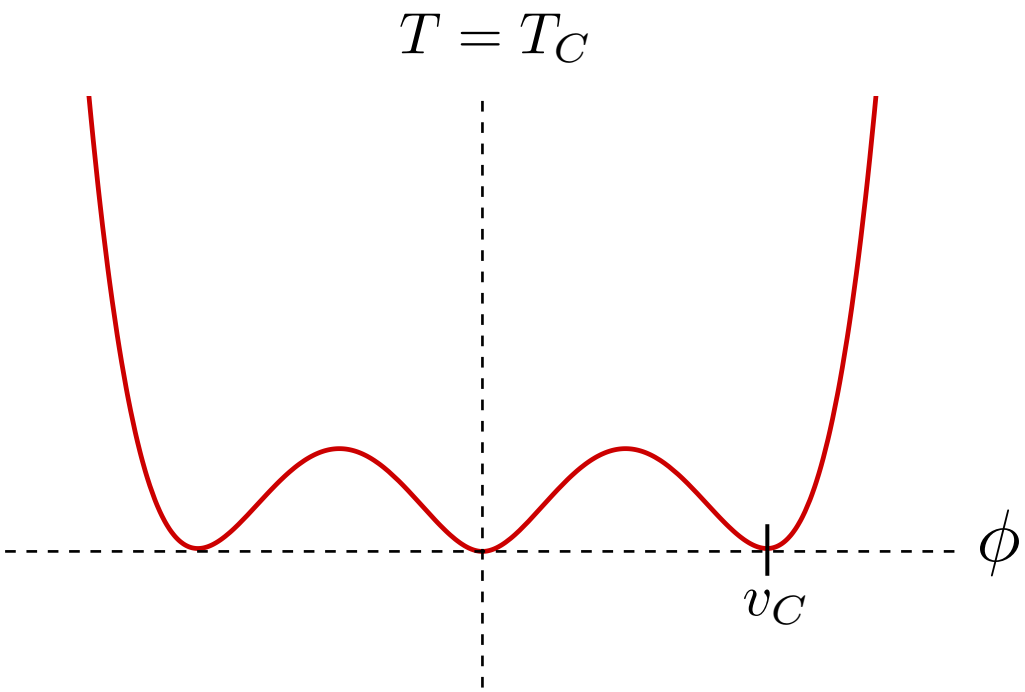


Electroweak Symmetry is unbroken : $\mathcal{L}_Y \supset y_e \bar{L} H e_R$

Electroweak Baryogenesis

(3) Out of equilibrium

First order electroweak phase transition (EWPT)



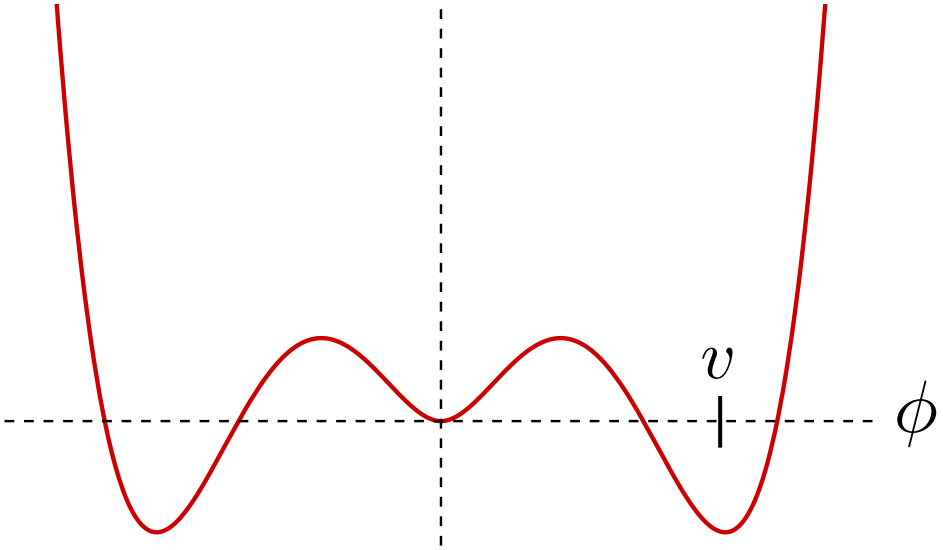
Another minimum at T_C: $\phi = v_C$

Electroweak Baryogenesis

(3) Out of equilibrium

First order electroweak phase transition (EWPT)

Present Universe $T = 0$



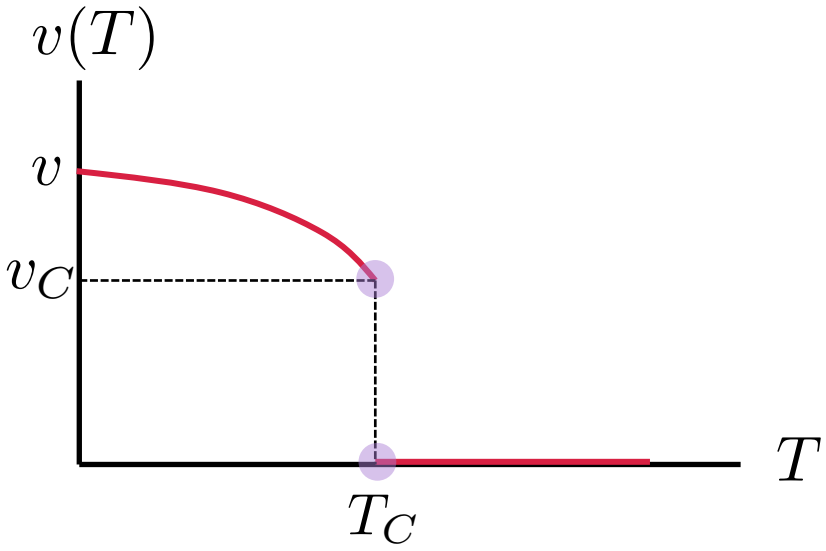
$m_e \neq 0$

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)



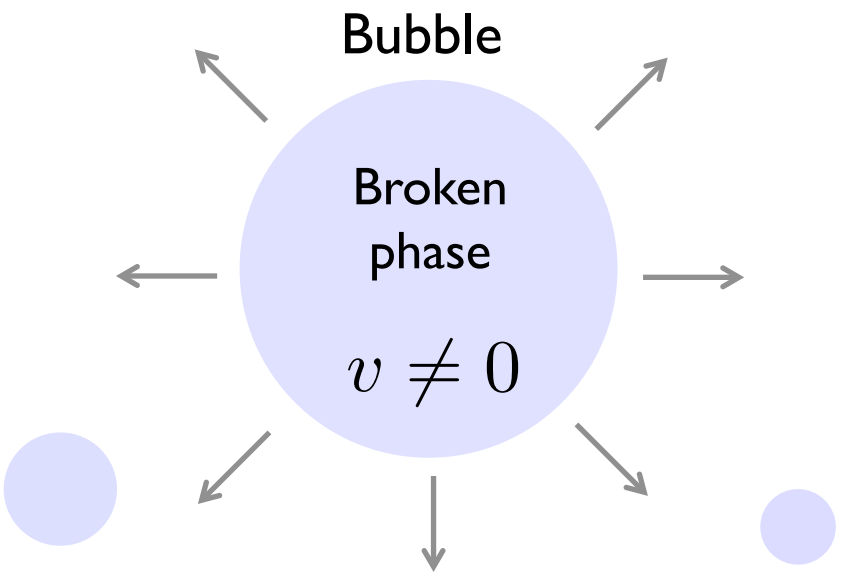
T_C : Critical Temperature

v_C : Higgs VEV at T_C

First order EWPT : discontinuity of the Higgs VEV

Electroweak Baryogenesis

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



Electroweak Baryogenesis

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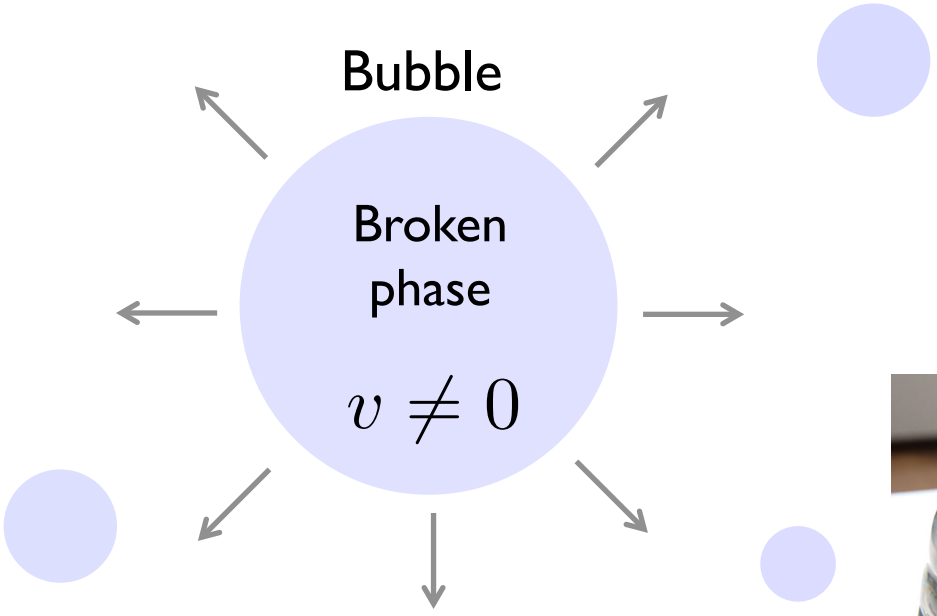
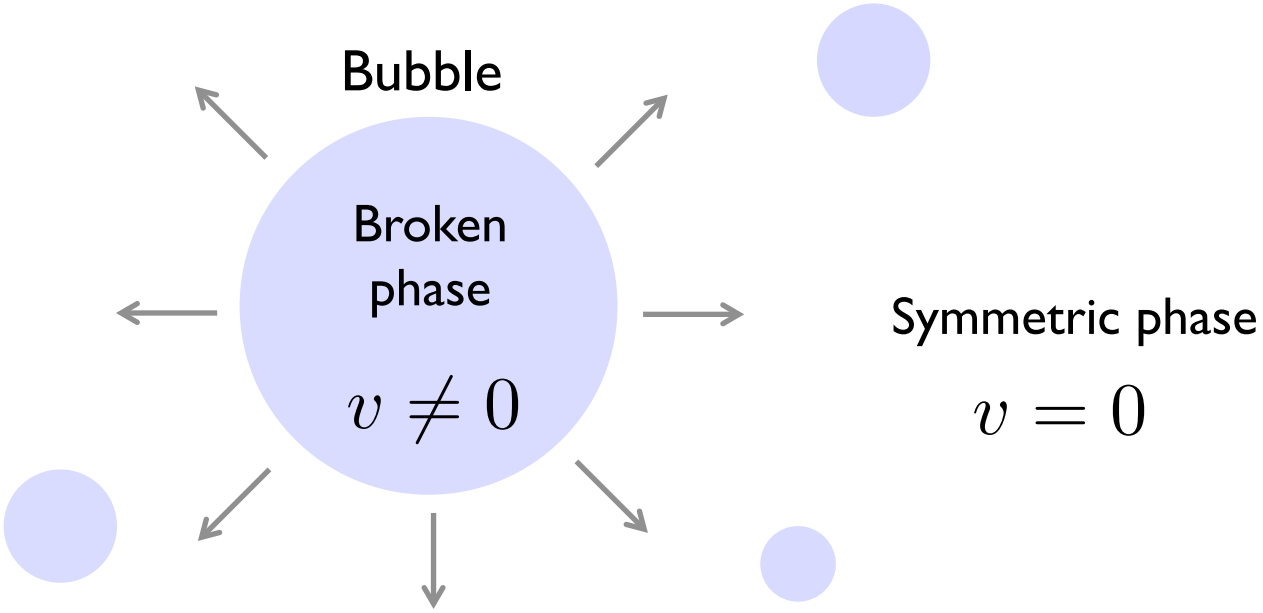


Boiling water

Electroweak Baryogenesis

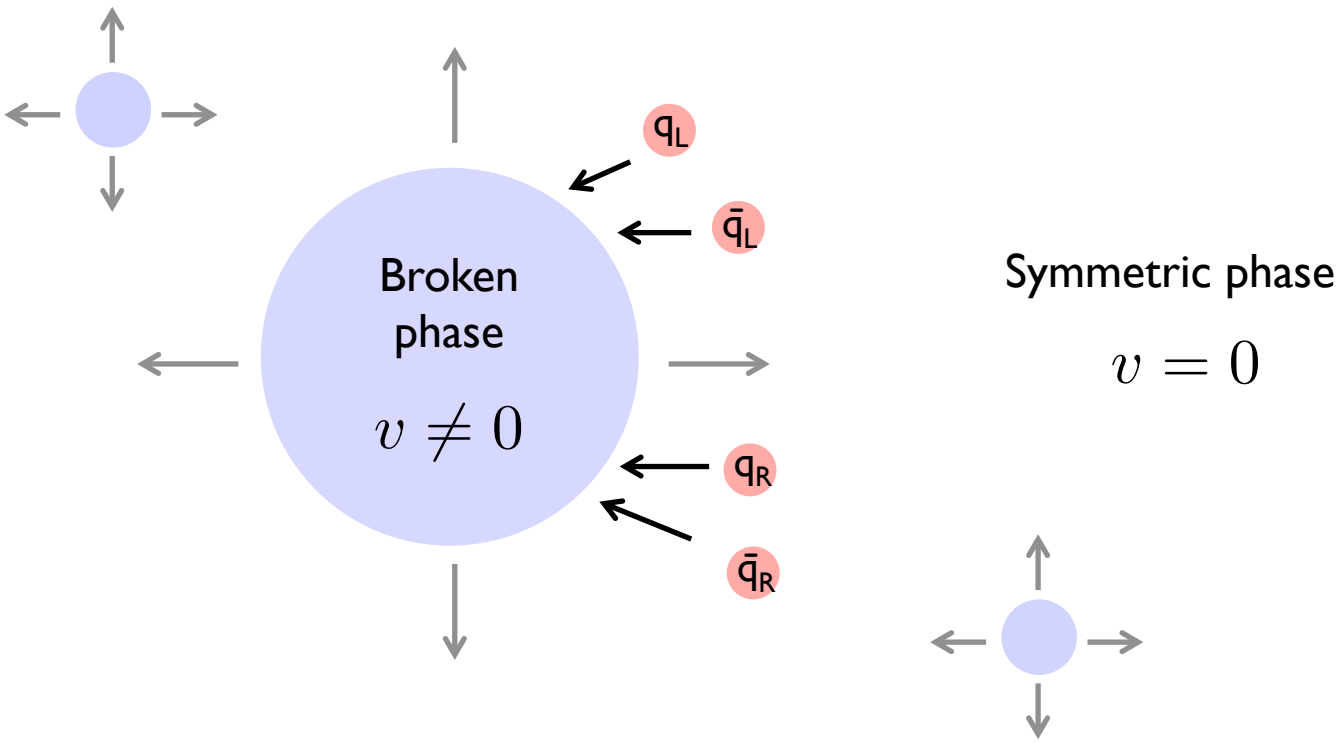
If the 1st order EWPT occurs, bubbles can be nucleated around at T_C.



EWPT ends when the Universe is filled with bubbles.

Electroweak Baryogenesis

Particle and antiparticle interact with bubble wall.



Electroweak Baryogenesis

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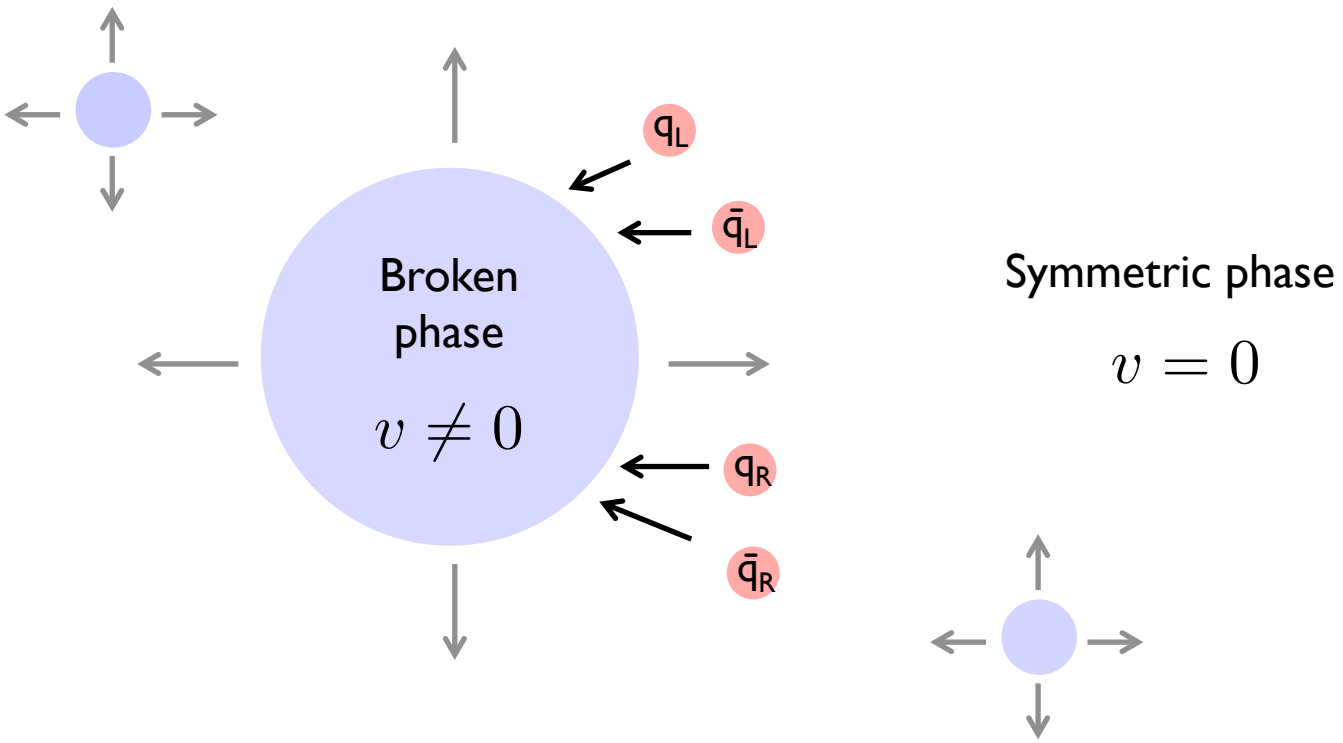
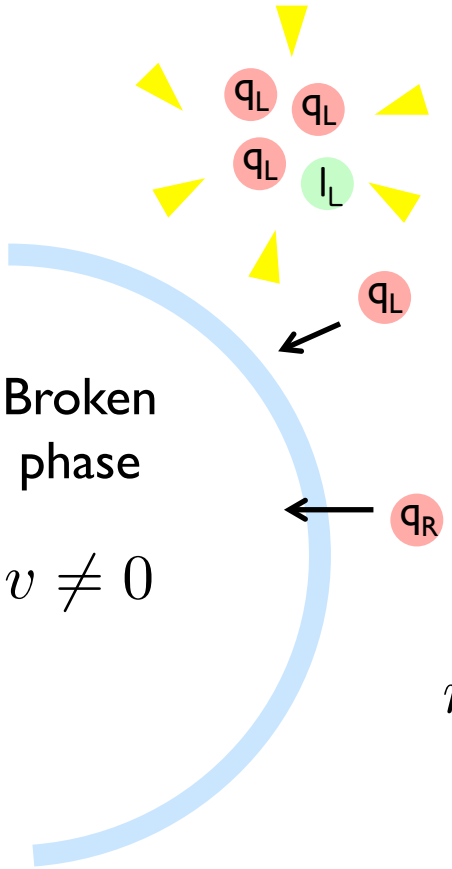


Under CP violation $n_B = \underbrace{n_b^L - n_{\bar{b}}^L}_{\neq 0} + \underbrace{n_b^R - n_{\bar{b}}^R}_{\neq 0}$

Electroweak Baryogenesis

Sphaleron process changes the number of left-handed particles.



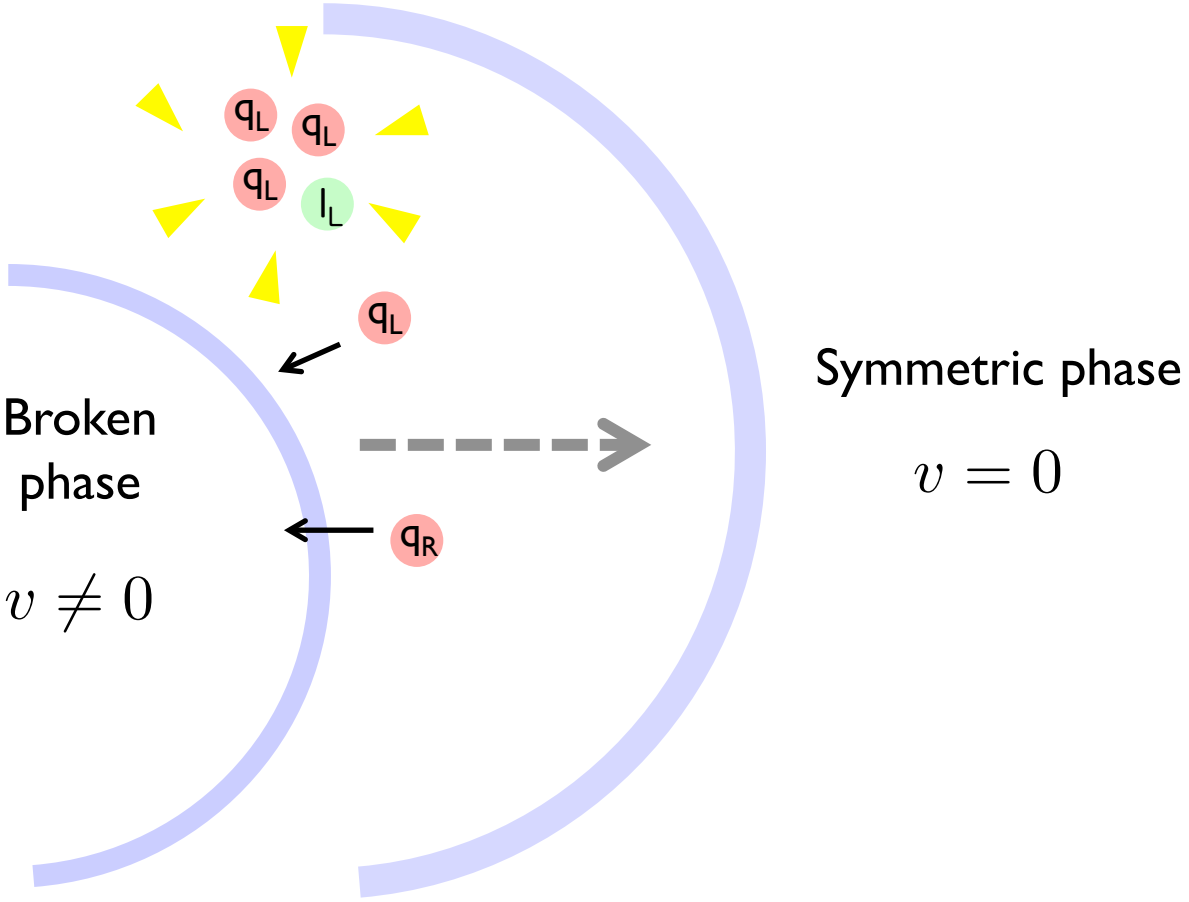
Symmetric phase

$$v = 0$$

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

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

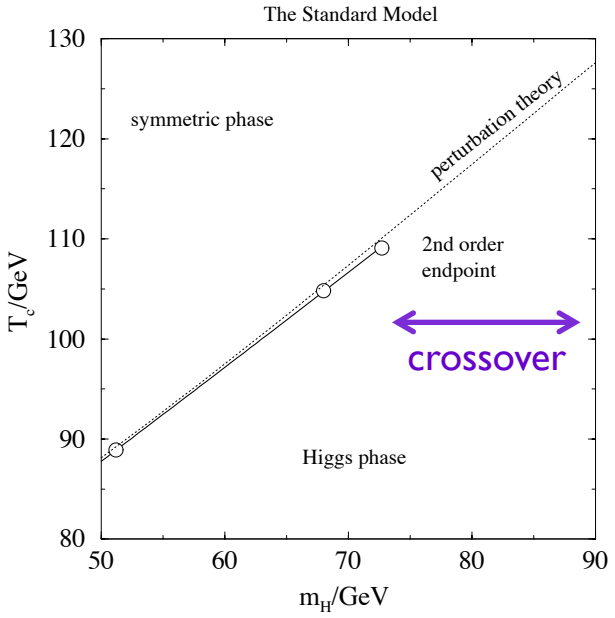
~ Electric Dipole Moment

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 Nelson, PRD51, 379 (1995)

The SM EWBG was ruled out.

1) EWPT is crossover for $m_H > 73$ GeV.



Measured value

$$m_H = 125.09 \pm 0.24 \text{ GeV}$$

ATLAS and CMS Coolaborations
Phys. Rev. Lett. 114 (2015) 191803

Lattice Study :
M. Laine, et al, Nucl. Phys. B Proc. Suppl. 73 (1999)180

Testability

Kajantie et al, PRL77, 2887 (1996), Rummukainen et al, NPB 542, 283 (1998)
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The SM EWBG was ruled out.

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

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

CP violation at T = 0

$$A_{\mathrm{CP}} = (m_t^2 - m_c^2)(m_t^2 - m_u^2)(m_c^2 - m_u^2)(m_b^2 - m_s^2)(m_b^2 - m_d^2)(m_s^2 - m_d^2)J$$

$$J = \mathrm{Im}\,(V_{ud}V_{cb}V_{ub}^*V_{cd}^*) \simeq 3 \times 10^{-5}$$

T ≠ 0

$$\delta_{\mathrm{CP}} \simeq \frac{A_{\mathrm{CP}}}{T_C^{12}} \simeq 10^{-20} \qquad T_C \simeq 100\ \mathrm{GeV}$$

$$B \propto \delta_{\mathrm{CP}} \ll 10^{-10}$$

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)
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Next possibility for EWBG ：BSM Physics

First order EWPT

New CP violation

✔ Collider experiments

Higgs Physics

✔ Search for new CP violation

Electric Dipole Moments

Testability

Kajantie et al, PRL77, 2887 (1996), Rummukainen et al, NPB 542, 283 (1998)
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Electric Dipole Moments

Electric Dipole Moments

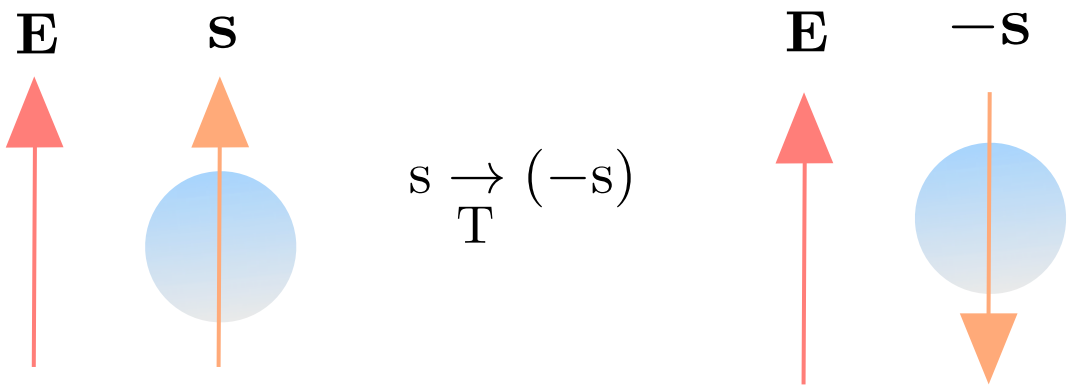
Electric Dipole Moment is CPV quantity :

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

$\mathbf{E}$: Electric field $\mathbf{s}$: Spin

Violation of Time-reversal symmetry

CP violation under CPT theorem



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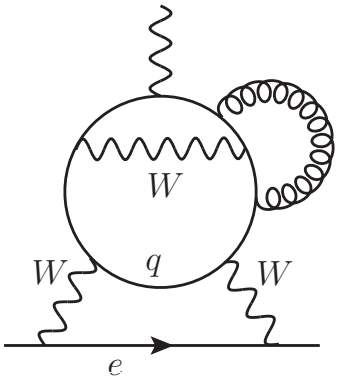
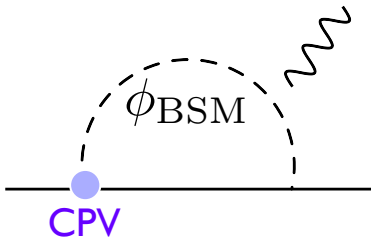


Ex) Electron EDM in the SM (4 loop)

$$d_e^{\mathrm{CKM}} \sim O(10^{-44})\ e\ \mathrm{cm}$$

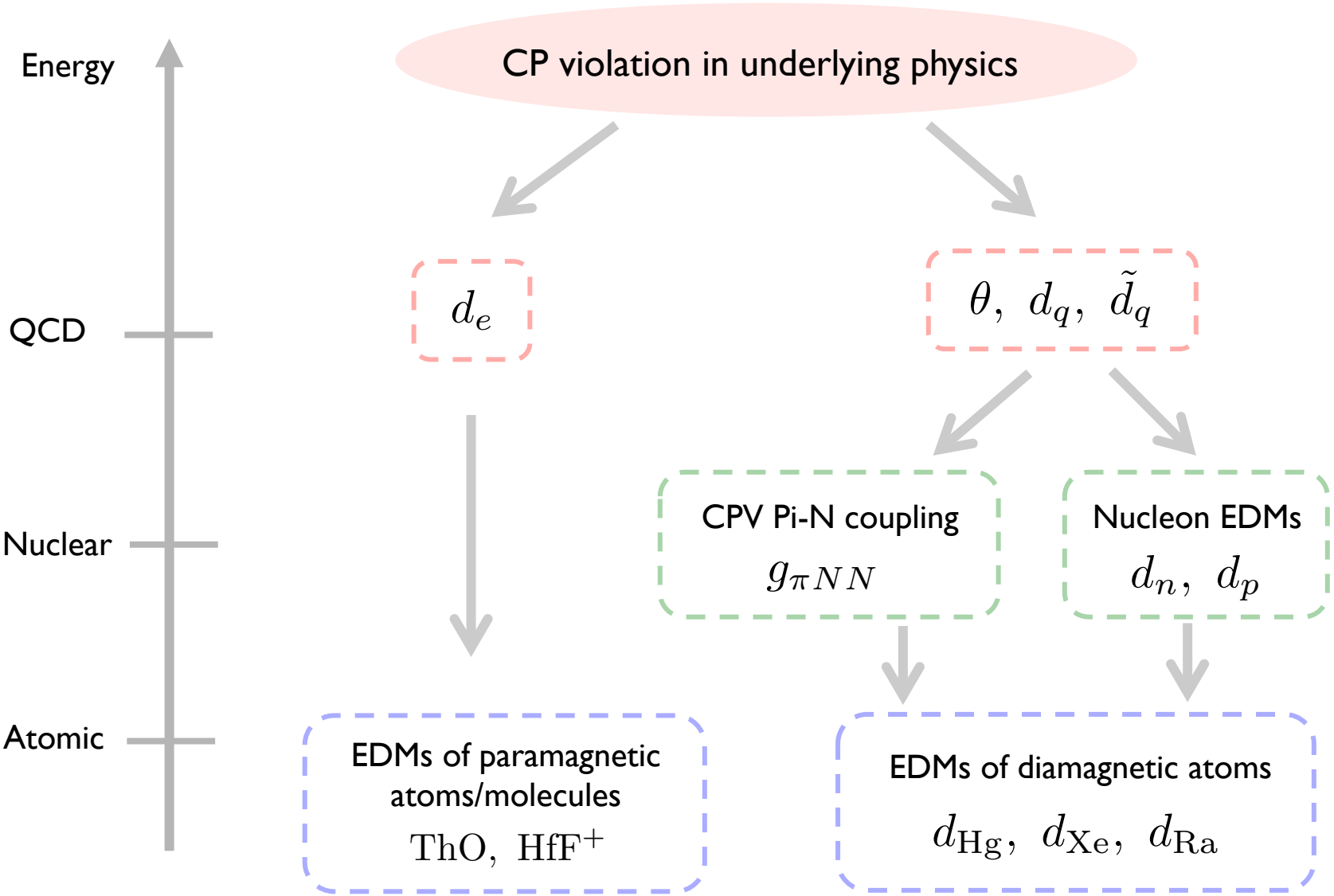
E. P. Shabalin, Sov. J. Nucl. Phys. 28, 75 (1978)
M. Pospelov, I.B. Khriplovich, SJNP53(1991)638, Yad. Fiz. 53(1991)1030
D. Ng, J. Ng, Mod. MPLA11(1996)211, W. Bernreuther, M. Suzuki, RMP63(1991)313
M. Pospelov and A. Ritz, PRD89(2014)056006



$$d_e^{\mathrm{BSM}} \gg d_e^{\mathrm{CKM}}$$

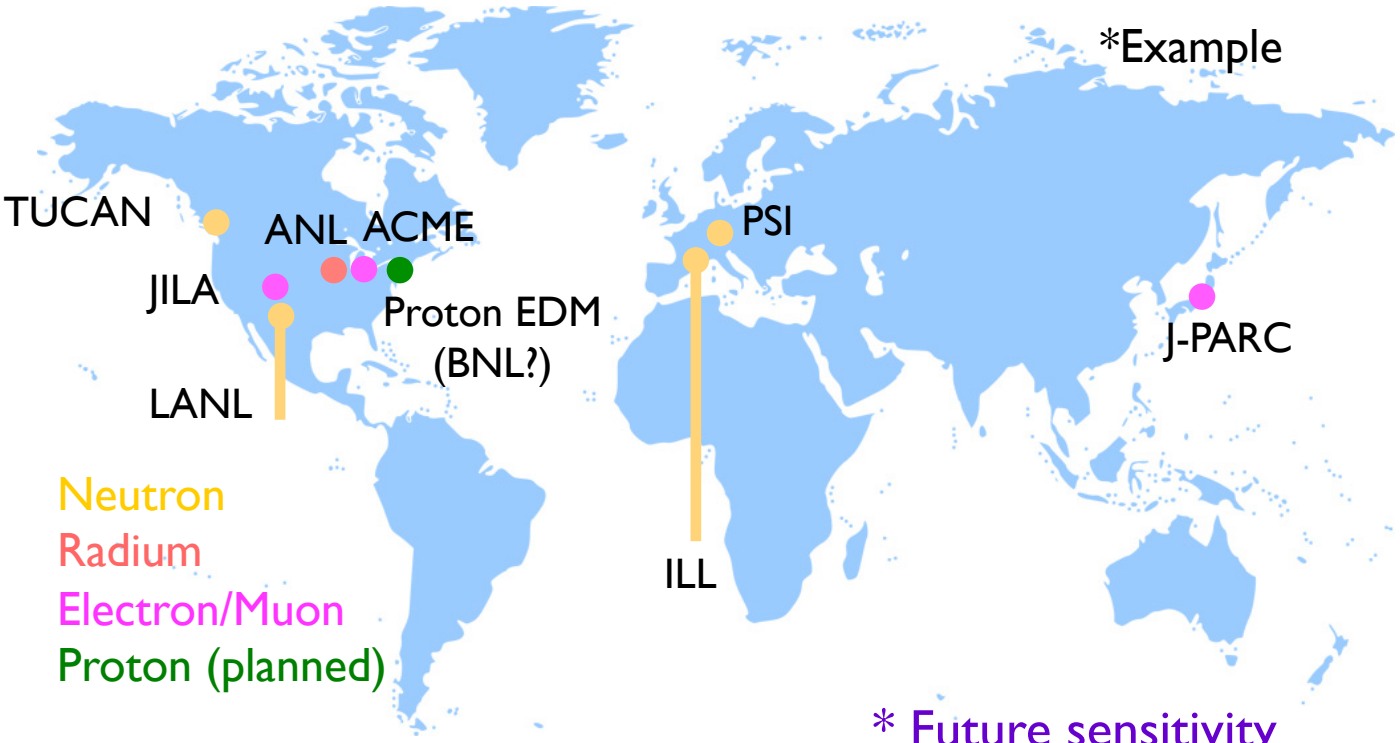
Electric Dipole Moments

Pospelov and Ritz: 0504231



Searches for EDMs

Worldwide race is ongoing !



$|d_e| < 4.1 \times 10^{-30}\ e\ \mathrm{cm}$

JILA Collaboration : 2212.11841

$|d_n| < 1.8 \times 10^{-26}\ e\ \mathrm{cm}$

nEDM Collaboration, PRL124(2020)081803

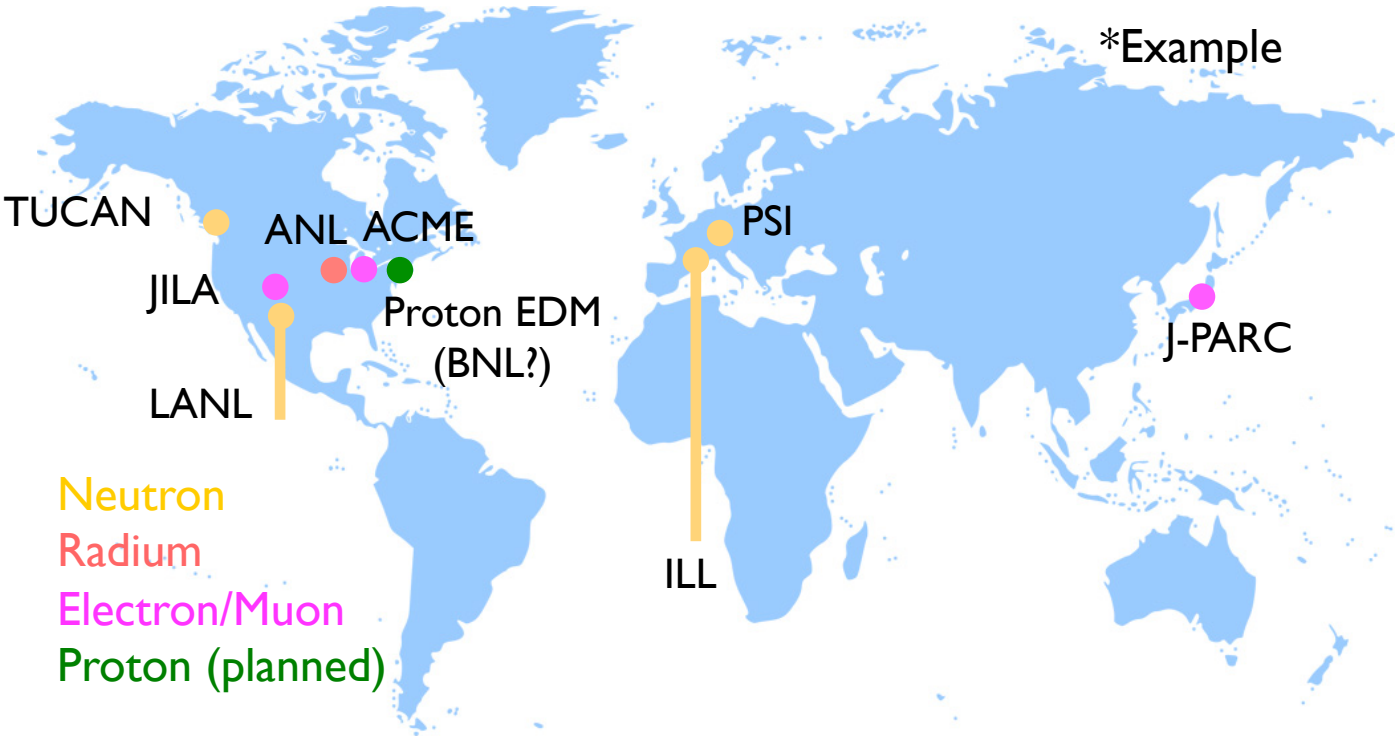
* Future sensitivity

$\sim 10^{-30}\ e\ \mathrm{cm}$

$\sim 10^{-(27-28)}\ e\ \mathrm{cm}$

Searches for EDMs

Worldwide race is ongoing !



One example of BSM model for EWBG

Two Higgs Doublet Model

Two Higgs Doublet Model

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

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

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

Two Higgs Doublet Model

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

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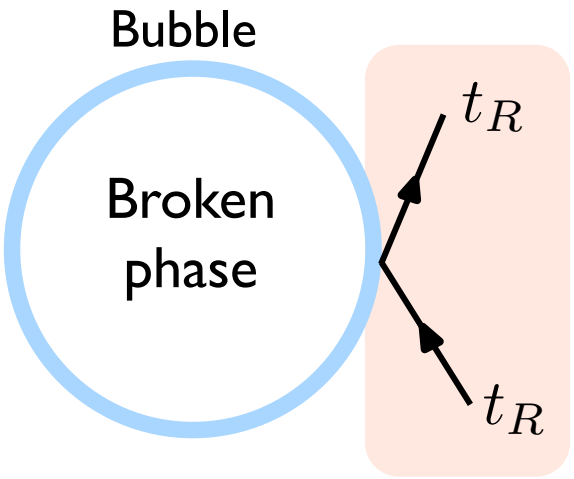
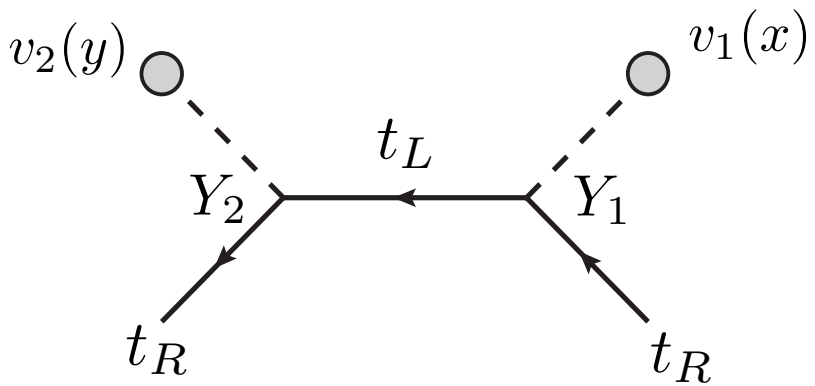




* Focus on top quark

Two Higgs Doublet Model

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

Two doublets H_1 and H_2

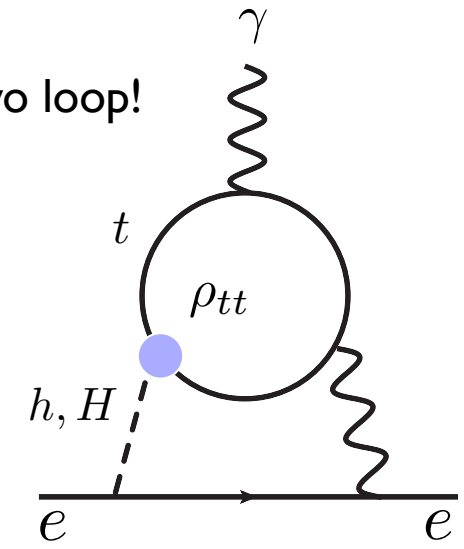
Yukawa interactions :

CPV : $|\rho_{tt}|e^{i\phi_{tt}}$

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

Yukawa : m_t/v

Two loop!



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

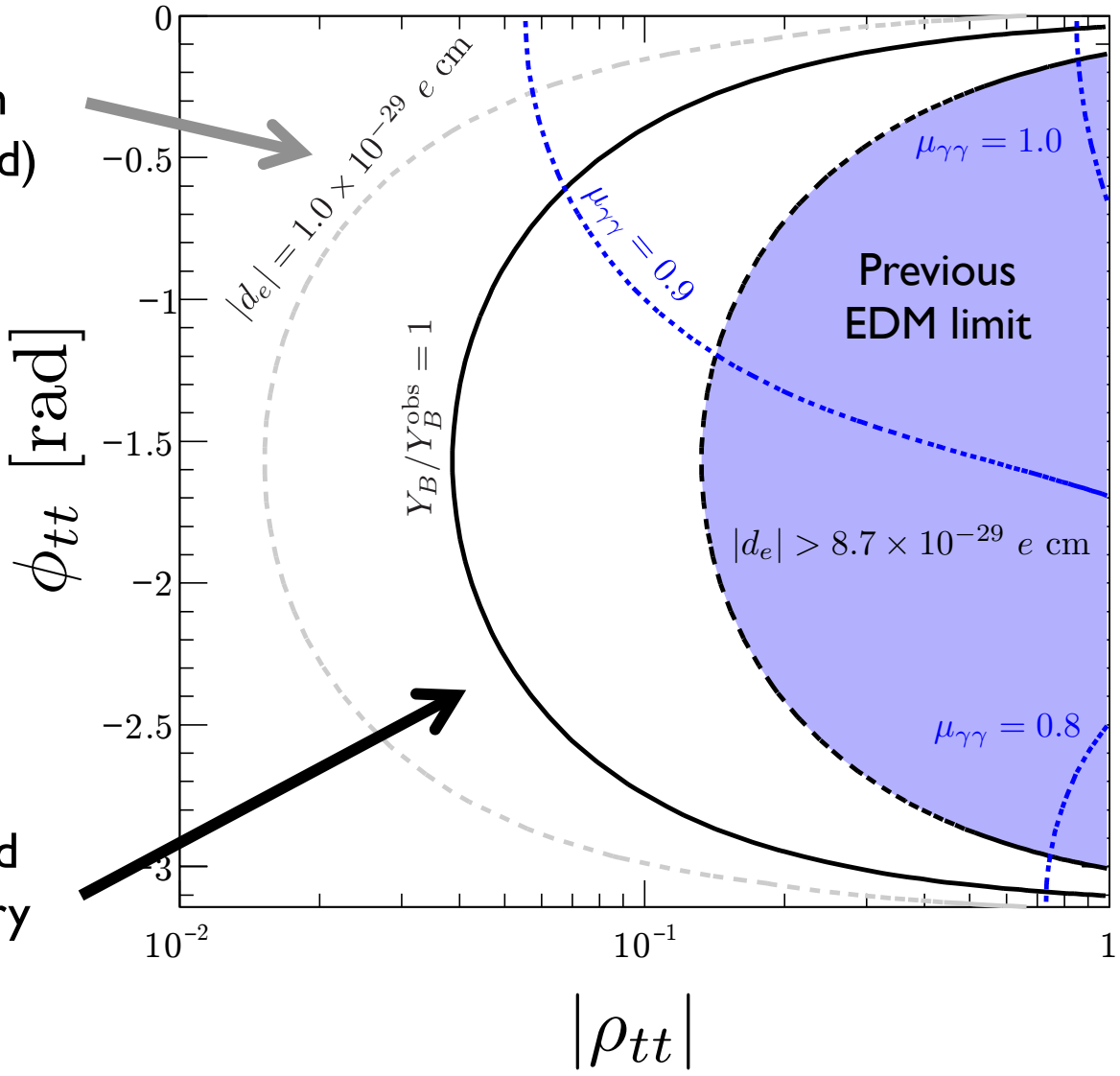
EDM : $d_e \propto |\rho_{tt}| \sin\phi_{tt}$

Probed by EDM experiments !

Two Higgs Doublet Model

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

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



Observed
asymmetry
(Black)

Two Higgs Doublet Model

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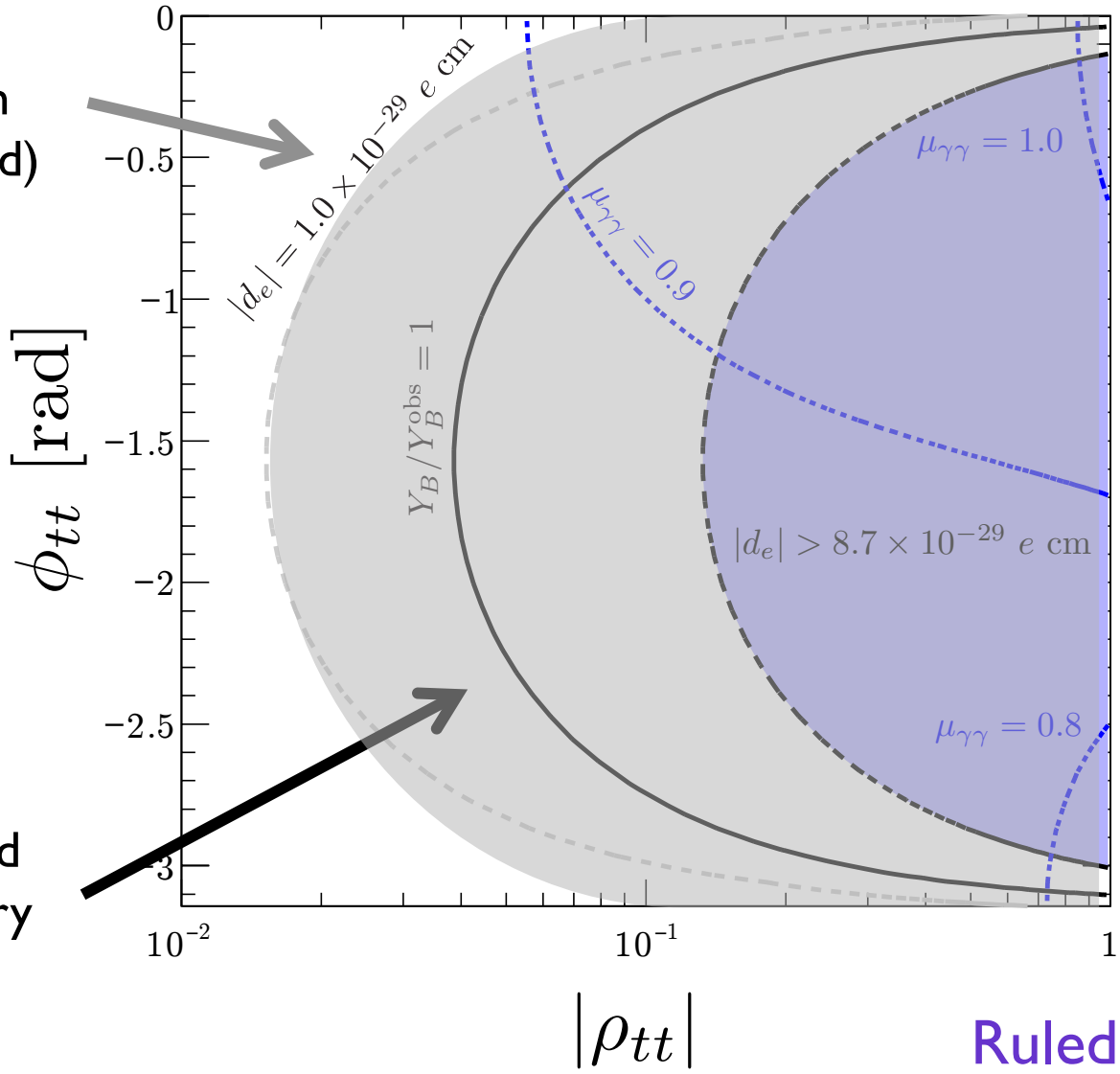

Observed
asymmetry
(Black)

Ruled out!

Two Higgs Doublet Model

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

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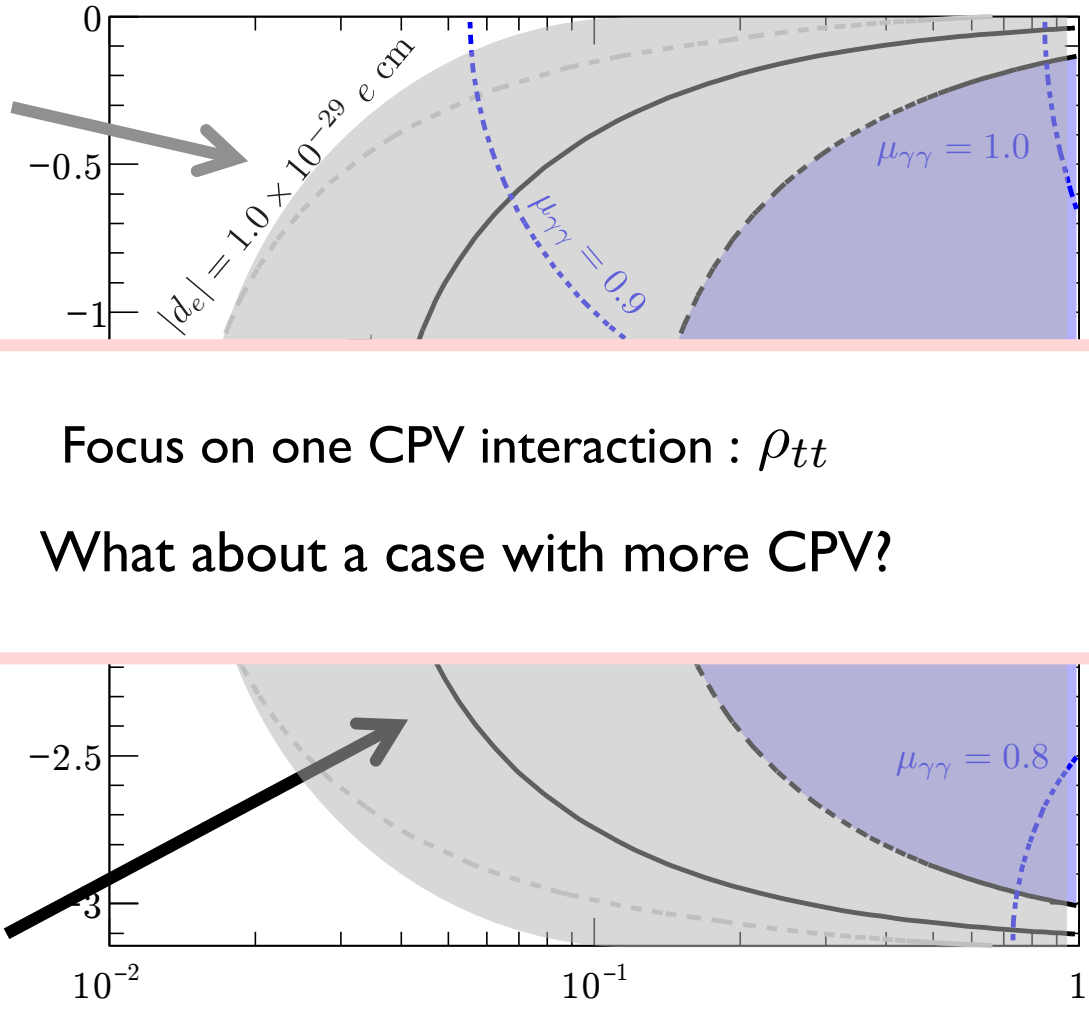


Focus on one CPV interaction : ρ_{tt}

What about a case with more CPV?

Observed
asymmetry
(Black)

Ruled out!

Two Higgs Doublet Model

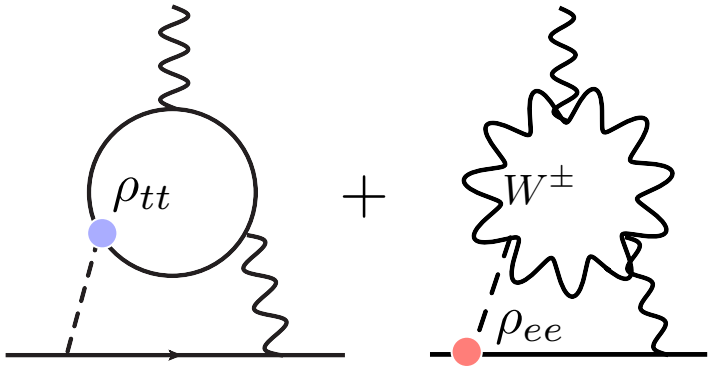
KF, WS. Hou, and E. Senaha, PLB 776 (2018) 402

Case with two CPV sources : ρ_{tt}, ρ_{ee}

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

$$+\bar{e}_L \left[\frac{y_e}{\sqrt{2}} s_\alpha + \frac{1}{\sqrt{2}} \rho_{ee} c_\alpha \right] e_R h + \text{h.c.}$$

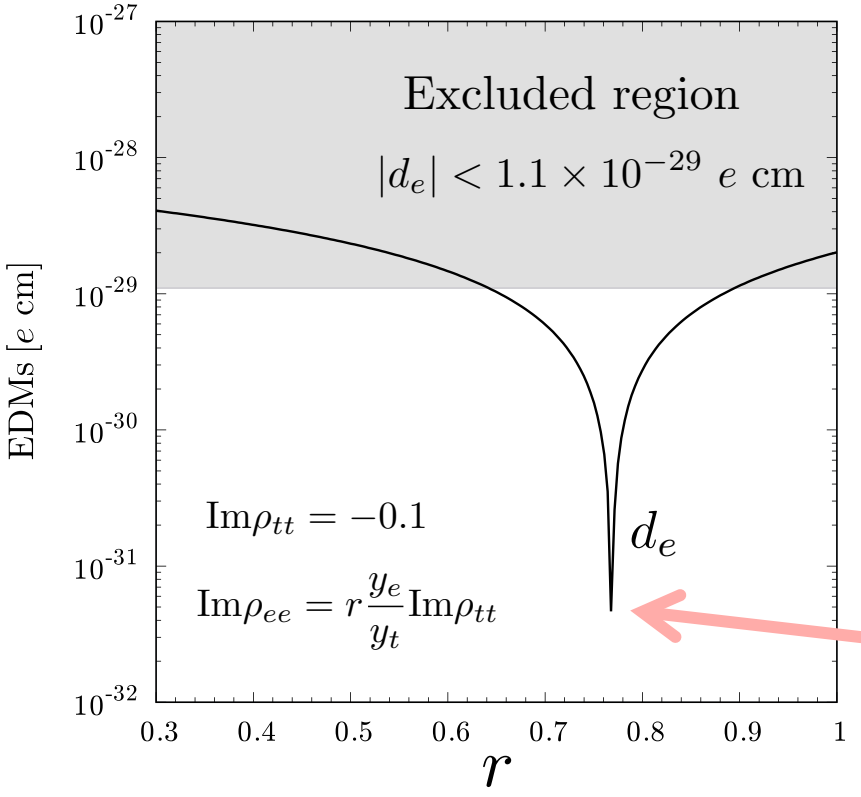
Electron EDMs

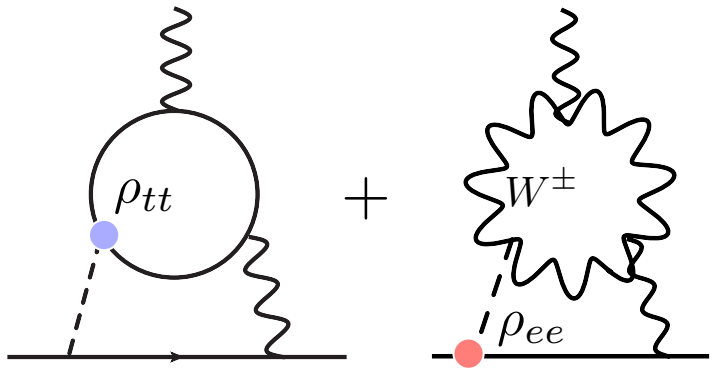


Two Higgs Doublet Model

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

Case with two CPV sources : ρ_{tt}, ρ_{ee}





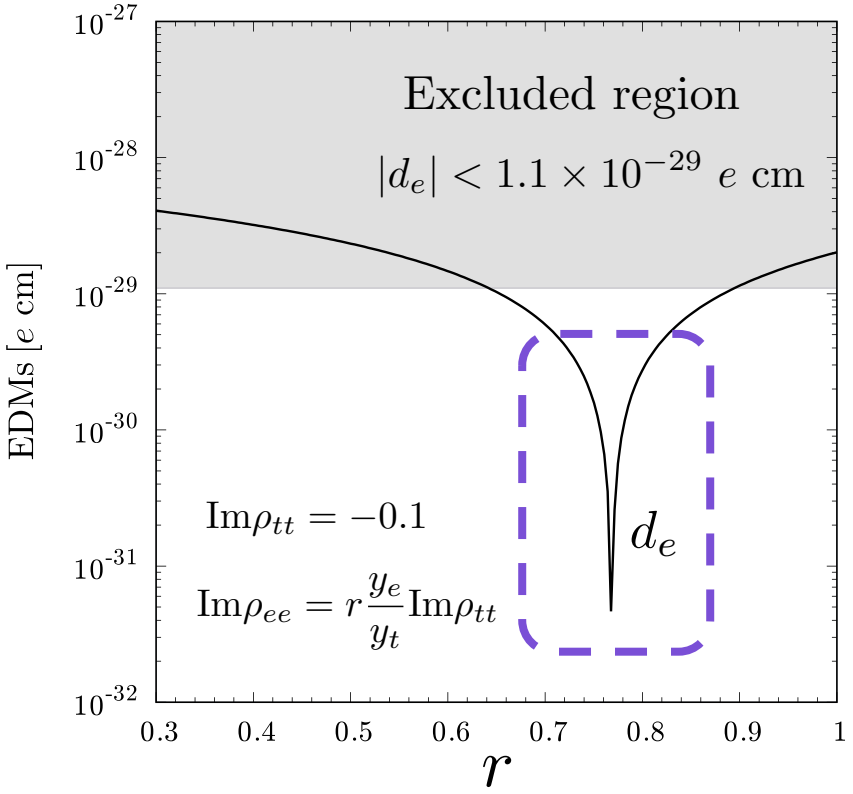
Cancellation occurs.
2HDM EWBG is still viable.

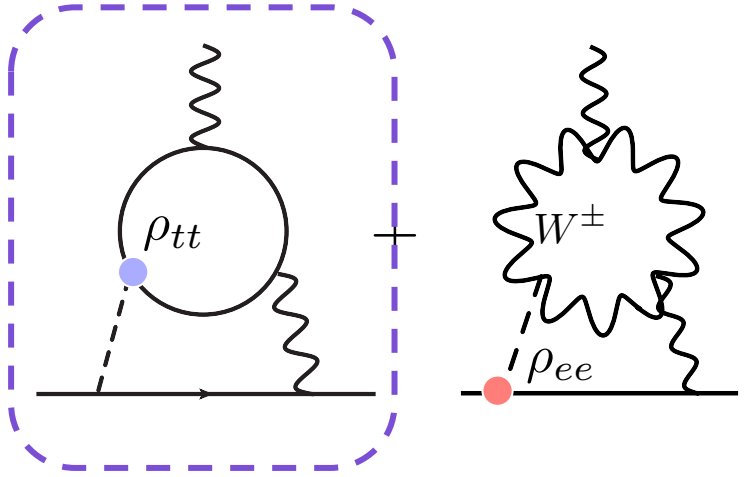
$$d_e^{\mathrm{total}} = d_e^t + d_e^W = 0$$

Two Higgs Doublet Model

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

Case with two CPV sources : ρ_{tt}, ρ_{ee}





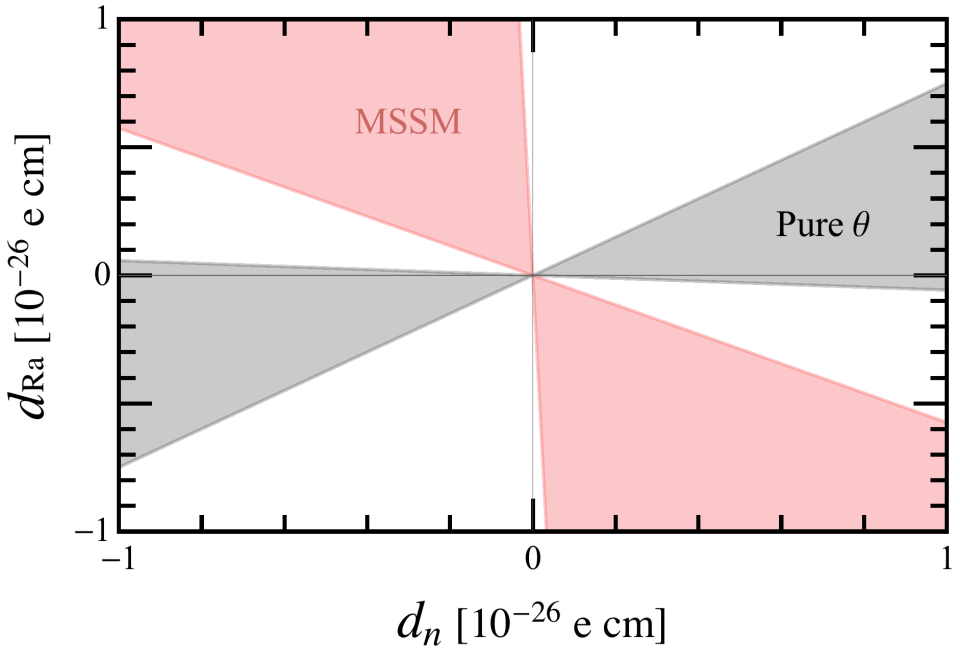
$d_{n,p} \propto d_q^t \neq 0$

Multi-species EDM searches, e.g. nucleon/atomic EDMs, are necessary!

Importance of multi-species EDM searches

Multi-species EDM searches can disentangle CPV sources in underlying physics.

Ex) QCD theta term VS SUSY



QCD theta term

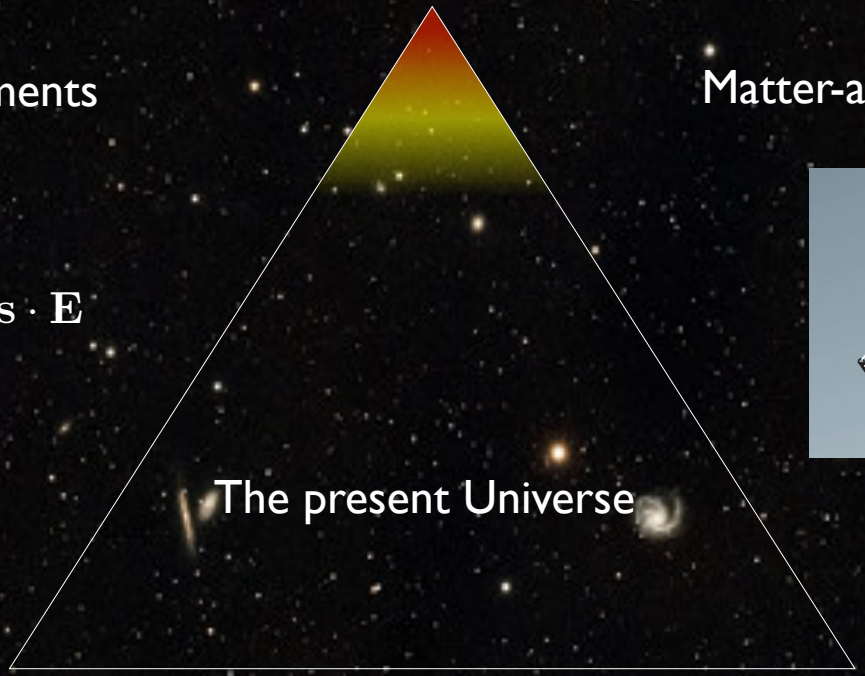
SUSY with new CPV sources

The prediction of d_{Ra}/d_n is different from pure theta case.

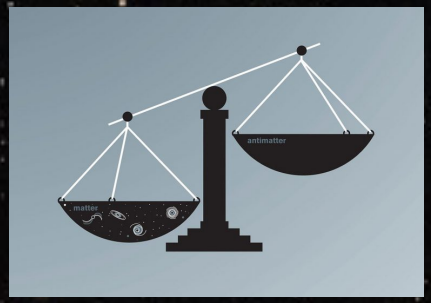
Conclusion

We still don't know much about our Universe.

Electric Dipole Moments



Matter-antimatter asymmetry



Search for EDMs are essential to reveal the origin of the Universe

Importance of multi-species EDM searches