Baryogenesis from matter based CP violation

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Motivation

- We observe a universe that is full of matter but not anti-matter
- Our universe has a net baryon number
- Why do we have to explain this number?
  - Arbitrary initial condition
  - Inflation inflates away any original asymmetry

Motivation

- Sakharov's three conditions
  - C and CP violation : need to favor particles over anti-particles
  - B violation : Need to generate baryon number from a state with no baryon number
  - Out of thermal equilibrium : Nothing happens in thermal equilibrium, detailed balance

Motivation

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CP violation

- “Standard” implementation : CP violating, Baryon number violating decay
- CP violation and Baryon number linked
- How is CP violation related to baryogenesis in general?

CP violation

- CP violating parameter in the Lagrangian
    - Dirac Leptogenesis
    - Spontaneous Baryogenesis
    - Affleck-Dine baryogenesis
    - EW baryogenesis
    - Particle - Anti-particle oscillations
    - …

CP violation

- Most examples all have CP violation in the Lagrangian
- Is this required?

CP violation

- No!
- Affleck-Dine baryogenesis
    - CP violating initial conditions for a scalar
- Inflation yields random walk for scalars
    - Also a random walk for scalar baryon number!

$$\langle n_B \rangle = 0 \qquad \langle n_B^2 \rangle \neq 0$$

CP violation

- Presence of more baryons than anti-baryons is itself a breaking of CP
    - Origin of why baryogenesis is needed
- CP preserving couplings in the presence of CP breaking matter

CP violation

- Matter
  - Gauge fields
  - Gravity waves
  - Dark matter
  - From bubble walls
- Present day abundances can be asymmetric! Testable!

CP violation

- When implementing baryogenesis, CPT and Unitarity are important
- Baryon number production can cancel as a results of them
- CP violation from matter has a distinct advantage
  - Q is odd under CPT
  - Particle anti-particle energy levels are different : in the background of an electron, electron and positron have different energies

Upcoming

- Dark matter as CP violation : Couplings
- Dark matter as CP violation : Kinematics
- Bubble Walls as CP violation

Dark matter as CP violation

- CP violating couplings between dark matter and SM
    - Lagrangian coupling
- Dark matter asymmetric
    - Use dark matter to make an otherwise CP invariant process CP breaking

Dark matter as CP violation

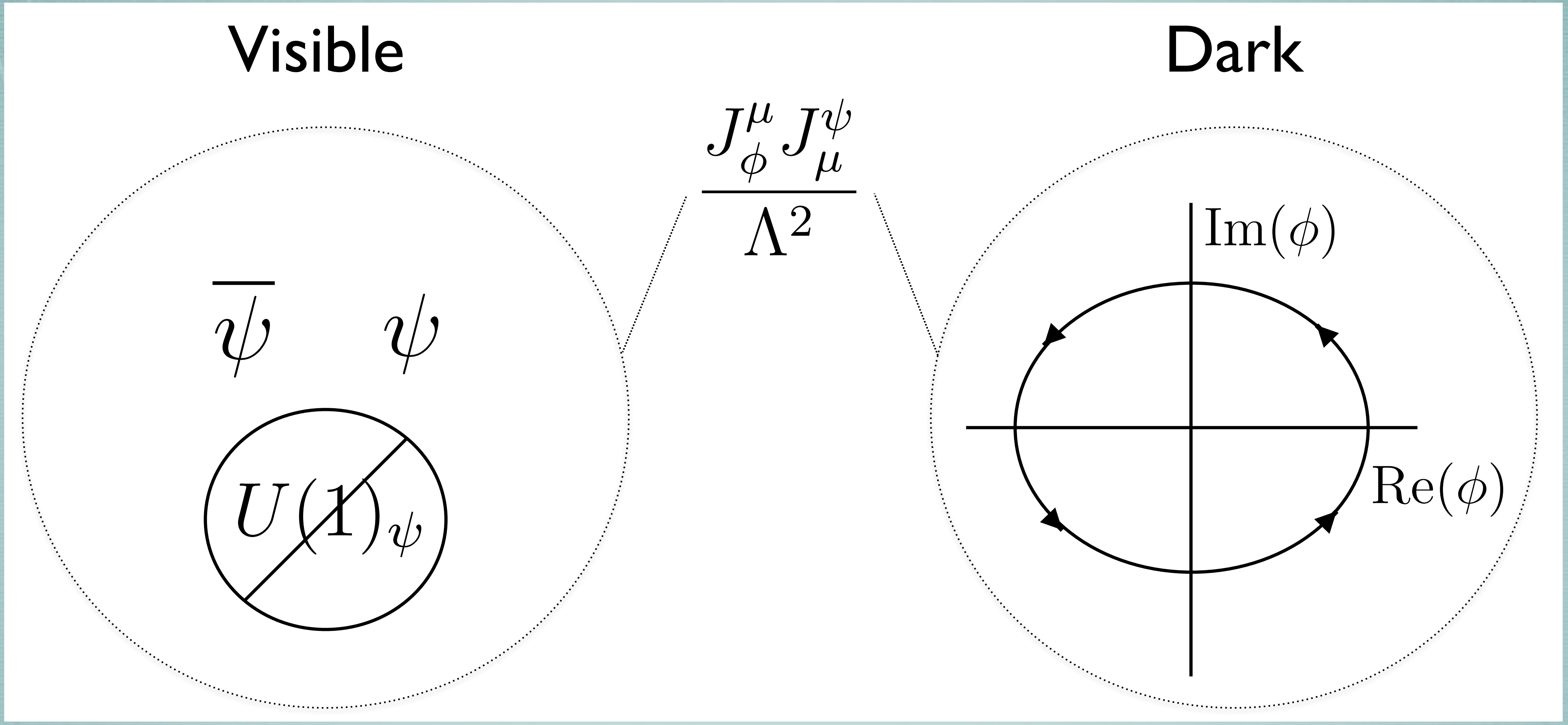
- Use the asymmetry in dark matter as the CP violation needed to implement baryogenesis
  - Couplings
  - Kinematics
- Asymmetry implies that $J_D^0 \neq 0$ so use J_D^0 to make a CP violating coupling in the Lagrangian
  - Just like Higgs vev allows one to write down SU(2) violating couplings

DM : Couplings

$$\mathcal{L} \supset \frac{J_D^\mu J_\mu^{B+L}}{\Lambda^2}$$

- Spontaneous baryogenesis implemented via asymmetric dark matter
  - Usual case : scalar field evolving in field space

A simple model



- Two sectors connected by a higher dimensional operator
- Dark sector is a classical field

A simple model

$$\ddot{\phi} + m_\phi^2 \phi = 0$$

$$\phi \sim a e^{-iEt} + b^\dagger e^{iEt}$$

- A classical field with an asymmetry

$$\phi(t) = \phi_0 e^{i m_\phi t}$$

A simple model

$$\rho_0 = 2m_\phi^2 |\phi_0|^2$$

- Assume we've measured the energy density of the dark sector at some later time

$$\mathcal{L} \supset \frac{\rho_0}{m_\phi \Lambda^2} \frac{T^3}{T_0^3} \left(\overline{\psi}\gamma_0\psi\right) \equiv \mu \left(\overline{\psi}\gamma_0\psi\right) = \mu \left(n_\psi - n_{\overline{\psi}}\right)$$

- Spontaneous baryogenesis!

Chemical potentials

$$\begin{aligned}\mathcal{L} &= i\overline{\psi}(\partial\!\!\!/ - i\mu\gamma^0)\psi \\ &= i\overline{e^{-i\mu t}\psi}\partial\!\!\!/(e^{-i\mu t}\psi)\end{aligned}$$

Decompose into creation and annihilation operators

$$\psi \sim a e^{-i(E+\mu)t} + b^\dagger e^{i(E-\mu)t}$$

particles and anti-particles have their energy shifted differently

Spontaneous Baryogenesis

$$
\begin{aligned}
n_\psi - n_{\overline{\psi}} &= 2\int \frac{d^3p}{(2\pi)^3}\left(\frac{1}{e^{(p-\mu)/T}+1} - \frac{1}{e^{(p+\mu)/T}+1}\right) \\
&\approx \left(\frac{\mu^3}{3\pi^2} + \frac{\mu T^2}{3}\right) \approx \frac{\mu T^2}{3}, \quad T \gg \mu\,.
\end{aligned}
$$

- Thermal equilibrium carries charge
- Equilibrium number abundances proportional to each other

$$
Y_\psi \equiv \frac{n_\psi - n_{\overline{\psi}}}{s} \approx \frac{n_{\overline{\phi}} - n_\phi}{s}\frac{T_\psi^2}{3\Lambda^2} = Y_\phi \frac{T_\psi^2}{3\Lambda^2}
$$

DM : Couplings

$$\mathcal{L} \supset \frac{J_D^\mu J_\mu^{B+L}}{\Lambda^2}$$

- Asymmetric dark matter can act like the CP violation needed for spontaneous baryogenesis
- All couplings/Lagrangian is CP symmetric

DM : Kinematics

$$\mathcal{L} \supset \frac{\varphi \psi_B \psi_D \varphi_D^\dagger}{\Lambda}$$

- CP violation in kinematics
- Dark matter abundance does not effect Lagrangian
- Final states of particles vs anti-particles are different
    - Pauli exclusion / Bose enhancement
    - If statistics vanish, CP violation vanishes

DM : Kinematics

$$\varphi \Rightarrow \psi_B \psi_D \varphi_D^\dagger$$

$$\varphi \Rightarrow \psi_B^\dagger \psi_D^\dagger \varphi_D$$

- In vacuo, decays of phi are CP preserving, Baryon number breaking, Dark matter number conserving
- More dark matter particles than anti-dark matter particles
  - Pauli exclusion prefers second decay
  - Bose enhancement prefers second decay

DM : Kinematics

$$\mathcal{L} \supset \frac{\varphi\psi_B\psi_D\varphi_D^\dagger}{\Lambda} + A\varphi_D\varphi_D\Phi^\dagger + y\Phi^\dagger\psi_D\psi_D + m\psi_D\psi_D^c + M\psi_B\psi_B^c + \frac{\psi_B u^c d^c d^c}{\Lambda}$$

- Extra terms break additional symmetries

$$\Delta\Gamma = \Gamma(\varphi \to \psi_B\psi_D\varphi_D^\dagger) - \Gamma(\varphi \to \psi_B^\dagger\psi_D^\dagger\varphi_D)$$
$$= -\frac{\mu_{\varphi_D} T_D m_\phi}{16\pi^3\Lambda^2}\ln\left[\frac{m_{\varphi_D}}{T_D}\right] - \frac{\mu_{\psi_D} T_D^2}{8\pi^3\Lambda^2}$$

- As expected, Pauli exclusion and Bose enhancement work in the same direction

DM : Kinematics

$$\Delta\Gamma = \Gamma(\varphi \to \psi_B \psi_D \varphi_D^\dagger) - \Gamma(\varphi \to \psi_B^\dagger \psi_D^\dagger \varphi_D)$$
$$= -\frac{\mu_{\varphi_D} T_D m_\phi}{16\pi^3\Lambda^2} \ln\left[\frac{m_{\varphi_D}}{T_D}\right] - \frac{\mu_{\psi_D} T_D^2}{8\pi^3\Lambda^2}$$

- Linear in chemical potential
    - If chemical potential changes sign, asymmetry needs to change sign
- Log dependence on mass
    - Bosons can condense so mass is relevant
- Proportional to temperature

DM : Kinematics

$$Y_B = \frac{g_{\star,\rho}^{1/4}}{192 \times 2^{3/4} \times 5^{1/4}\pi^4}(\frac{\sqrt{M_p m_\varphi}}{\Lambda})^3 Y_D = \frac{8\pi^2 g_{\star,\rho}}{5 \times 3^{1/4}}\frac{T^3}{m_\phi^3}Y_D$$

- If late time decays give a small entropy dump, easy calculation of baryon number asymmetry
- Reasonable choices of parameters can give the observed asymmetry

DM : Kinematics

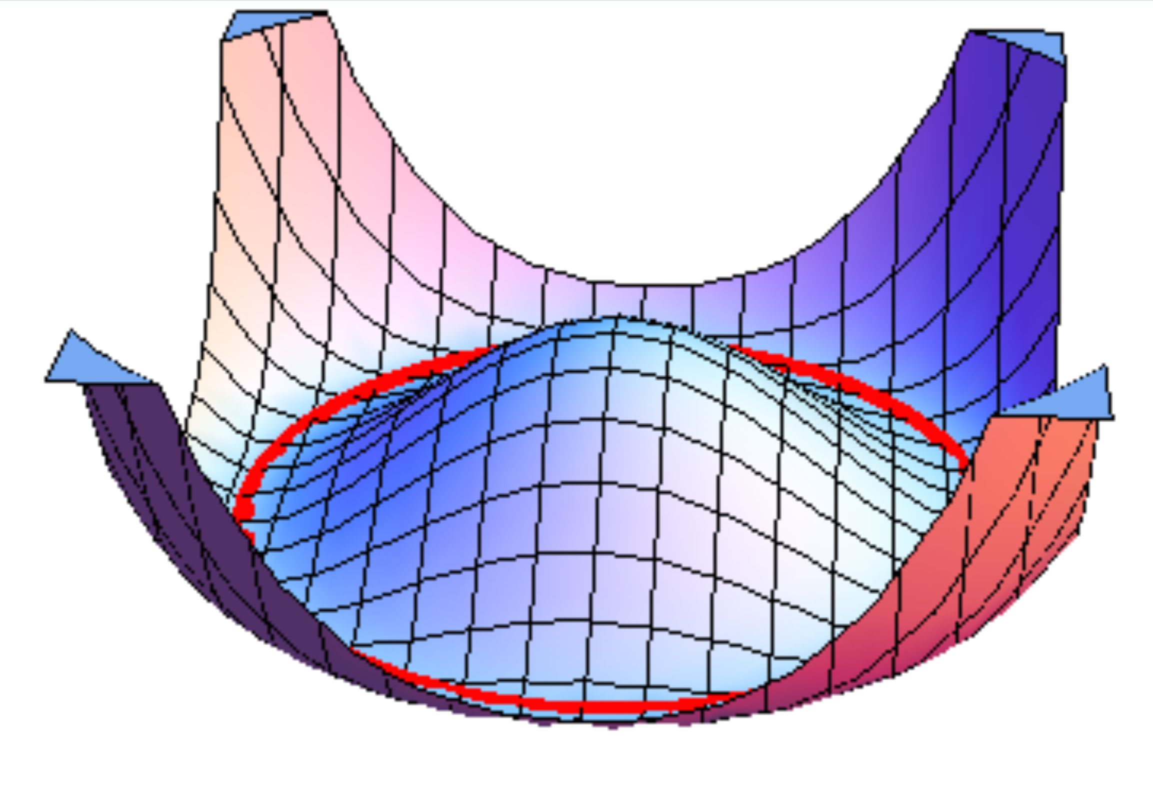
- Amusing example that illustrates two facts
    - Quantum statistics can be critical in a mechanism of baryogenesis
    - The CP violation necessary for baryogenesis might not be seen in the Lagrangian

Work in progress, keep your eyes out!

Bubble walls

$$V = \frac{\lambda}{4}(\phi^\dagger \phi - \frac{v^2}{2})^2$$

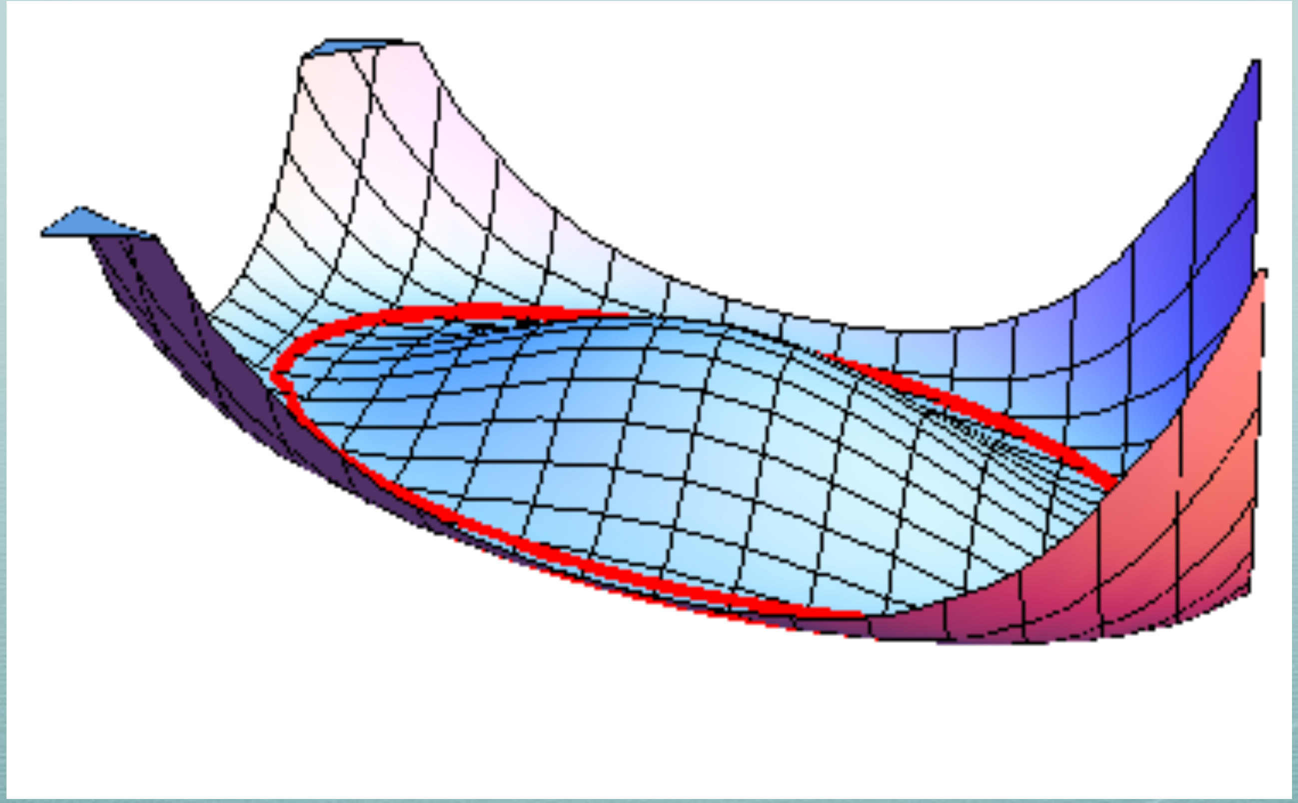
- Bubbles in a CP preserving theory can break CP



Bubble walls

$$V = \frac{\lambda}{4}(\phi^\dagger\phi - \frac{v^2}{2})^2 + \mu^3(\phi + \phi^\dagger)$$

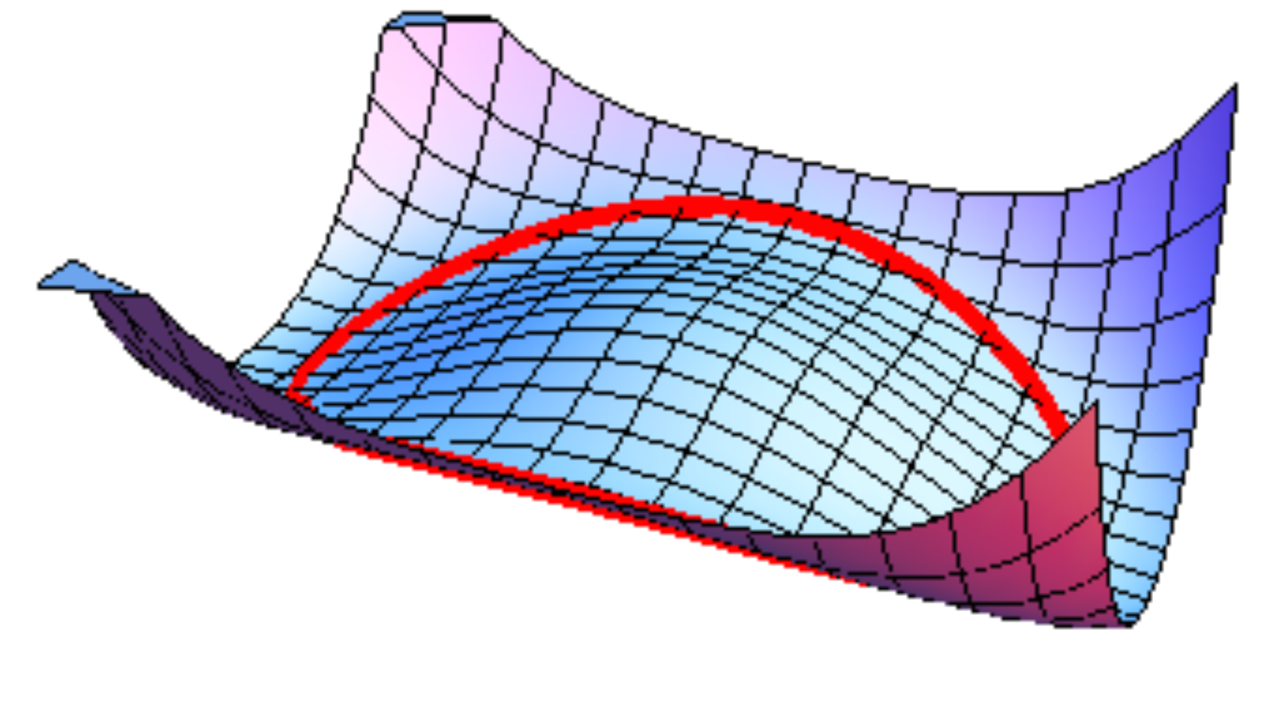
- CP invariant is reflection across x-axis

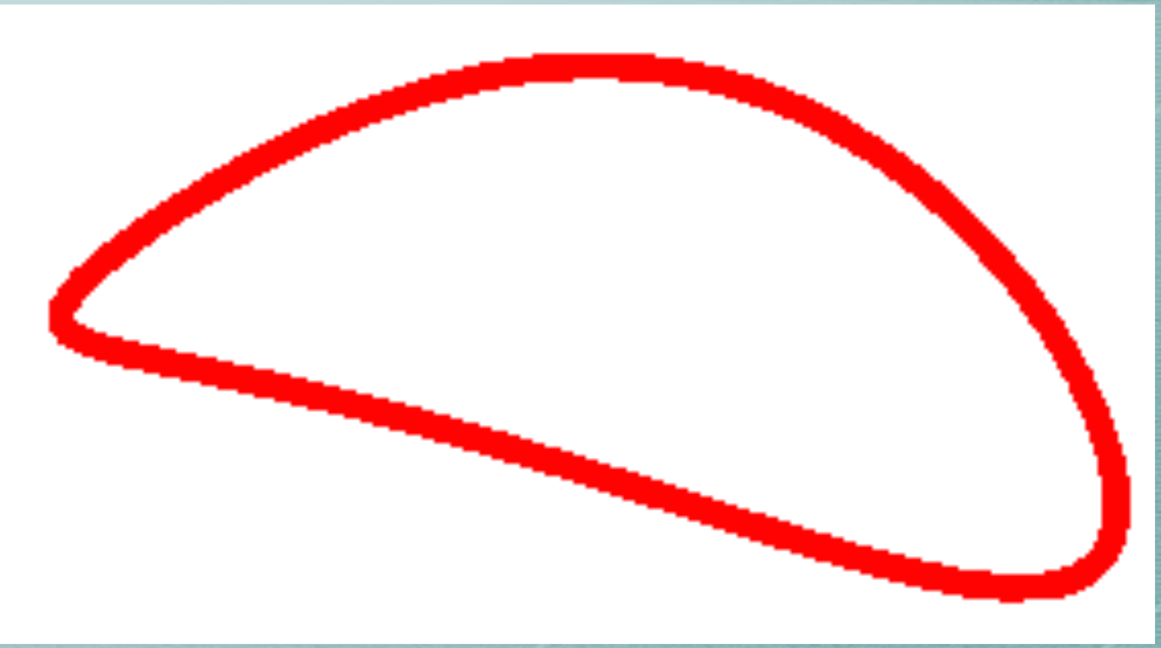


Bubble walls

$$V = \frac{\lambda}{4}(\phi^\dagger\phi - \frac{v^2}{2})^2 + \mu^3(\phi + \phi^\dagger) - \delta m^2(\phi^2 + \phi^{\dagger,2})$$

- Tunneling now CP non-invariant





Bubble walls

- A CP invariant theory with tunneling between CP invariant minima can be CP breaking!
- The bubble walls have large non-zero phases
- Can be used to implement baryogenesis

Bubble walls

- CP invariance = two tunneling paths with equal probability and exactly opposite CP violating angles
    - Universe is a patchwork of baryons and anti-baryons
    - Average gives no baryons
- EW baryogenesis?
    - Observable universe : 10^{42} different tunneling events
    - Almost all of them had to produce baryons

Bubble walls

- Typical solution to homogeneity problem : Inflation
- ϕ inflaton
    - Inflate at the higher minima
    - Tunneling occurs and 60 e-foldings later inflation ends
    - Entire universe sees the same CP violating phase!
- Utilize your favorite way for baryogenesis given these CP violating post inflation conditions

Bubble walls

- Amusing other direction
- Allow for small CP breaking to bias couplings?
    - CP violation in bubble wall can be much larger than CP violation in Lagrangian
    - Large variance in baryon number (isocurvature perturbations)

Work in progress

Conclusion

- CP violation in baryogenesis is typically a Lagrangian parameter
- Can also use non-Lagrangian parameters
    - Dark matter can provide CP violation
        - Amusing example that relies critically on quantum statistics
    - Bubble walls can provide CP violation
        - Leads to a theory which has large variance in final baryon number

CP violation

$$\mathcal{L} \;=\; \partial\phi\partial\phi^\dagger - m^2\phi\phi^\dagger - \frac{\lambda}{4}(\phi\phi^\dagger)^2 - \frac{\delta\lambda}{4}(\phi^4 + \phi^{\dagger,4})$$

- Number preserving Lagrangian up to a small symmetry breaking quartic
- Random walk far away from the origin

$$\langle\phi_r^2(x,t)\rangle = \frac{3H_{\rm inf}^4}{8\pi^2 m^2}$$

CP violation

$$\frac{dn_B}{dt} = -3Hn_B + 2\delta\lambda(\phi_r\phi_i^3 - \phi_i\phi_r^3) \qquad n_B^{\mathrm{eq}} = \frac{2\delta\lambda(\phi_r\phi_i^3 - \phi_i\phi_r^3)}{3H}$$

- Wait long times until equilibrium has been reached
- Baryon number does a random walk too
- Can show that correlation length is large

$$\langle n_B(x) n_B(x) \rangle = \frac{27\,\delta\lambda^2 H_{\mathrm{inf}}^{16}}{256\pi^8 m^8 H^2}$$