Creating the Baryon Asymmetry from Lepto-Bubbles

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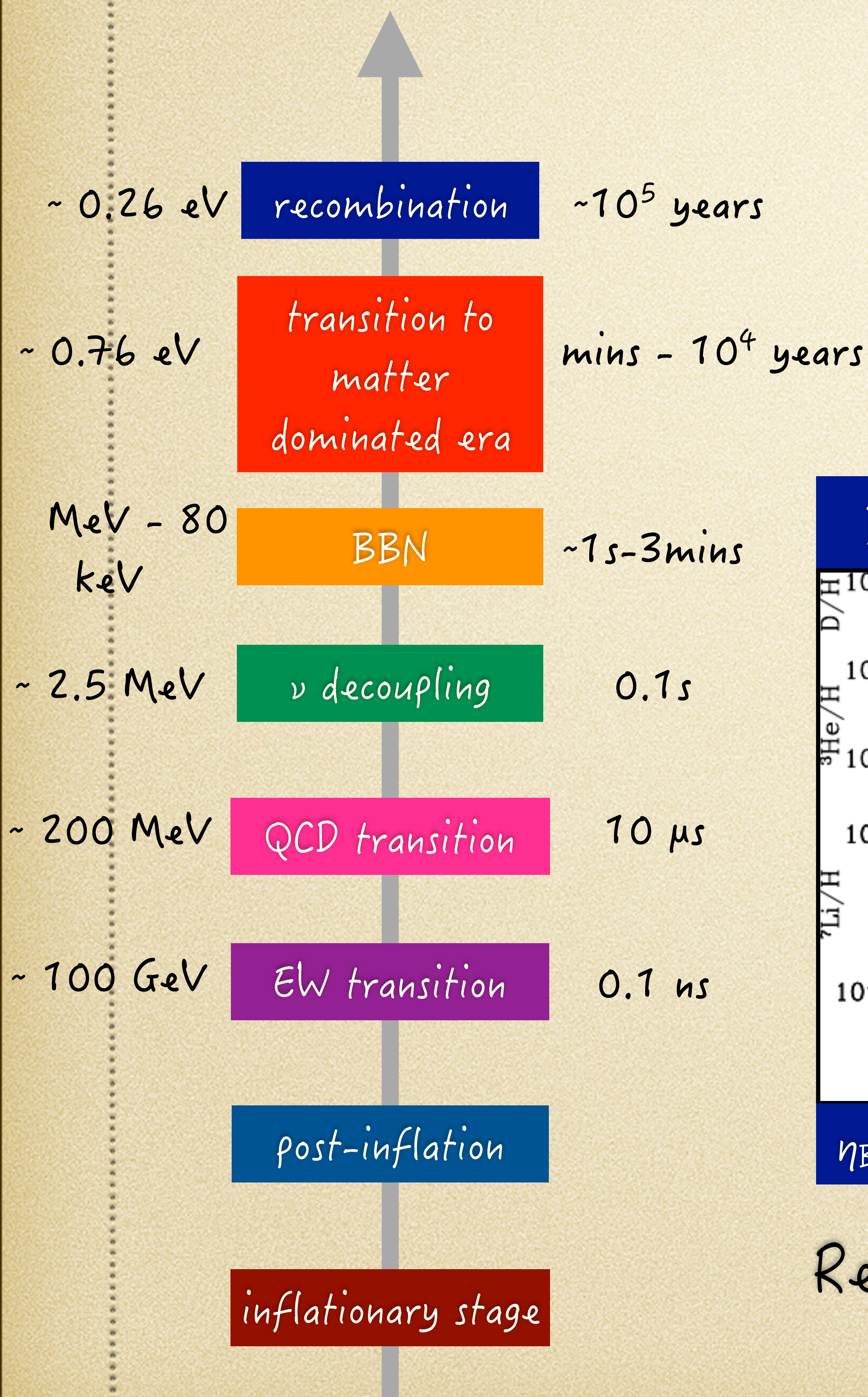
Work in collaboration with Silvia Pascoli and Ye-Ling Zhou

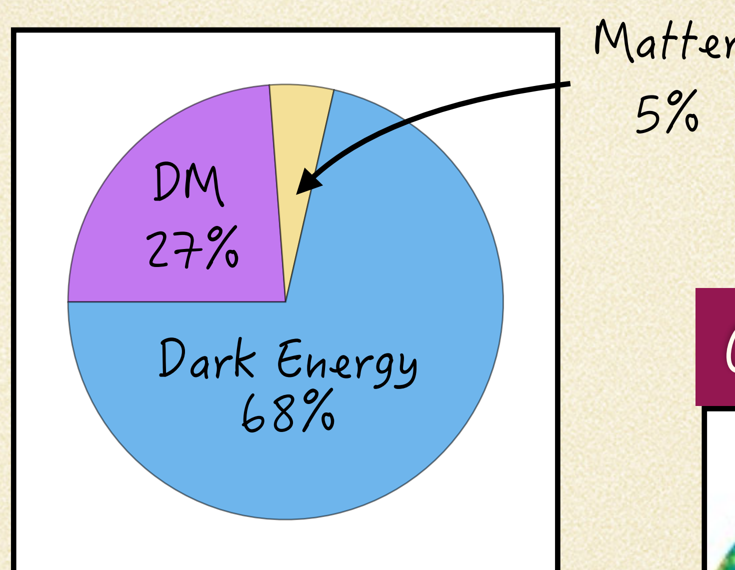
1609.07969

Outline

- Baryon Asymmetry Measurement
- Sakharov's Conditions
- What are lepto-bubbles?!
- Non-eq QFT/ finite temp QFT (sorry)
- Results

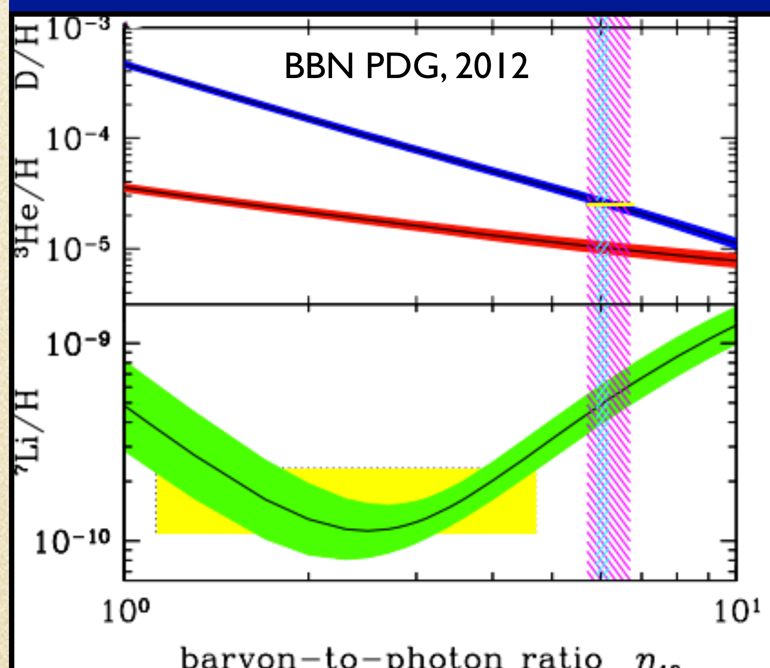
Measuring the Baryon Asymmetry





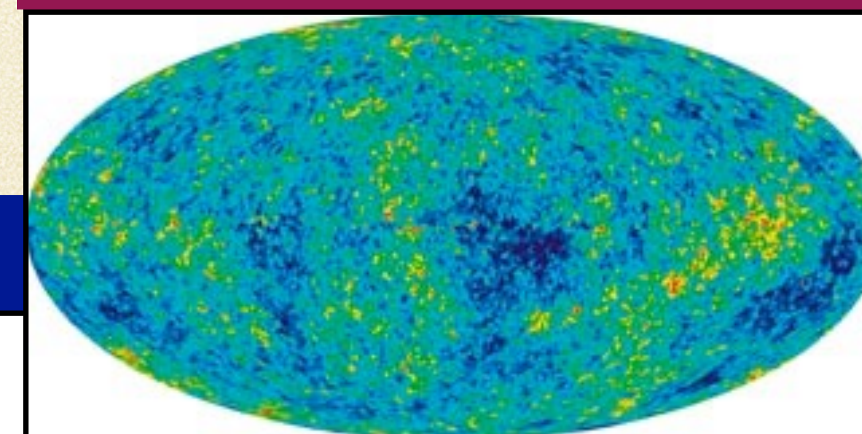
$$\eta = \frac{n_B - n_{\overline{B}}}{n_\gamma}$$

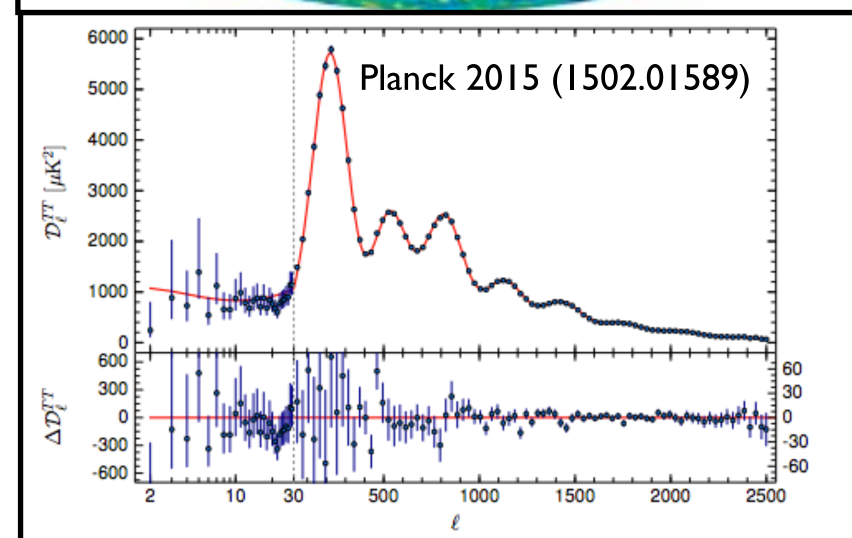
Big-Bang Nucleosynthesis



$\eta_{BBN} = (6.08 \pm 0.06) \times 10^{-10}$

Cosmic Microwave Background





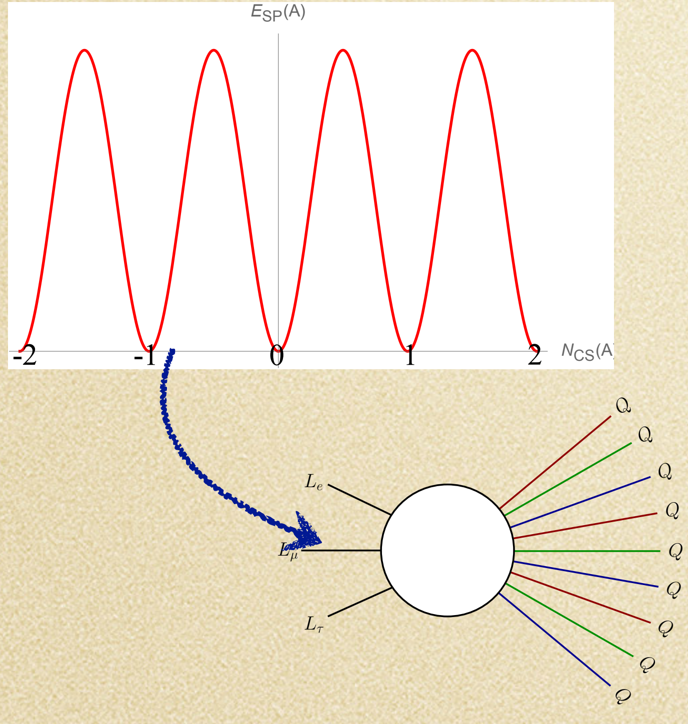
$\eta_{CMB} = (6.23 \pm 0.17) \times 10^{-10}$

Remarkable agreement between η_{CMB} and η_{BBN}

Sakharov's Conditions

B/L Violation

- $T > T_{EW}$ transitions between different vacua can occur: B+L violating sphaleron.

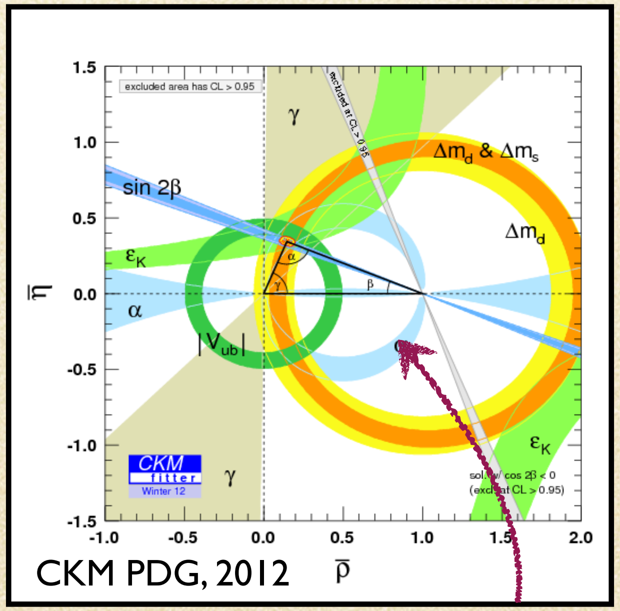


Transitions between vacua
L-asymmetry → B-asymmetry

CP Violation

- Not enough CPV in SM quark sector to produce η_B.

$$\frac{n_B - n_{\overline{B}}}{n_\gamma} \propto \frac{J \times \Delta m_{tcu}{}^2 \times \Delta m_{dsb}{}^2}{T_{EW}^{12}} \sim 10^{-17}$$



measured from b and kaon system

- Requires new sources of CPV.

Out of Equilibrium

- $\Gamma_{process} \equiv \Gamma_{inverse}$
- Interaction rate of a process drops below the expansion rate of the Universe, the process can come out of equilibrium: $\Gamma < H$.
- For our mechanism: phase transition.

LeptoBubbles
a new mechanism

Silvia Pascoli, JT, Ye-Ling Zhou, arXiv:1609.07969

Basic Mechanism: CPPT

Assume ν masses come from dim-5 op that violates L by 2 units

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

λ time-dependent and CPV

No need to specify UV-completion

λ associated to SM-singlet scalar Φ. $\langle\Phi\rangle \Rightarrow$ leptonic masses and mixing.

↓

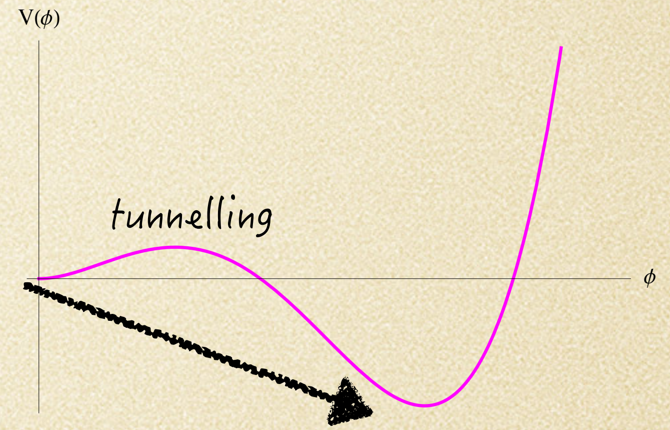
The finite temperature scalar potential of Φ can undergo P.T.

↓

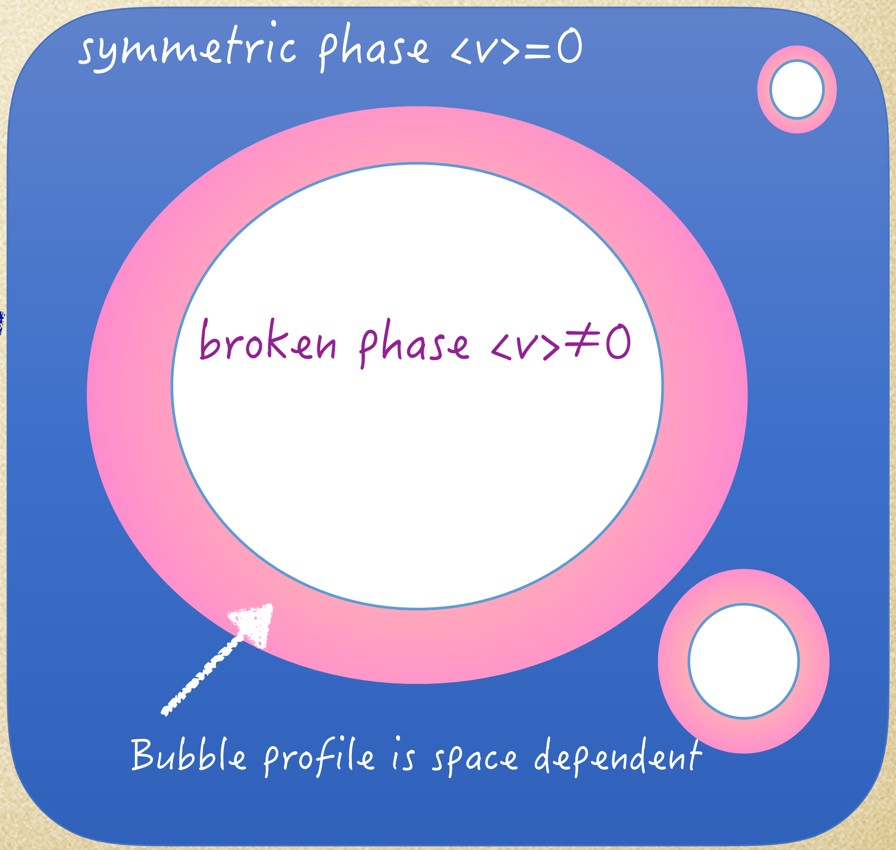
Bubbles of leptonically CPV broken phase nucleate

↓

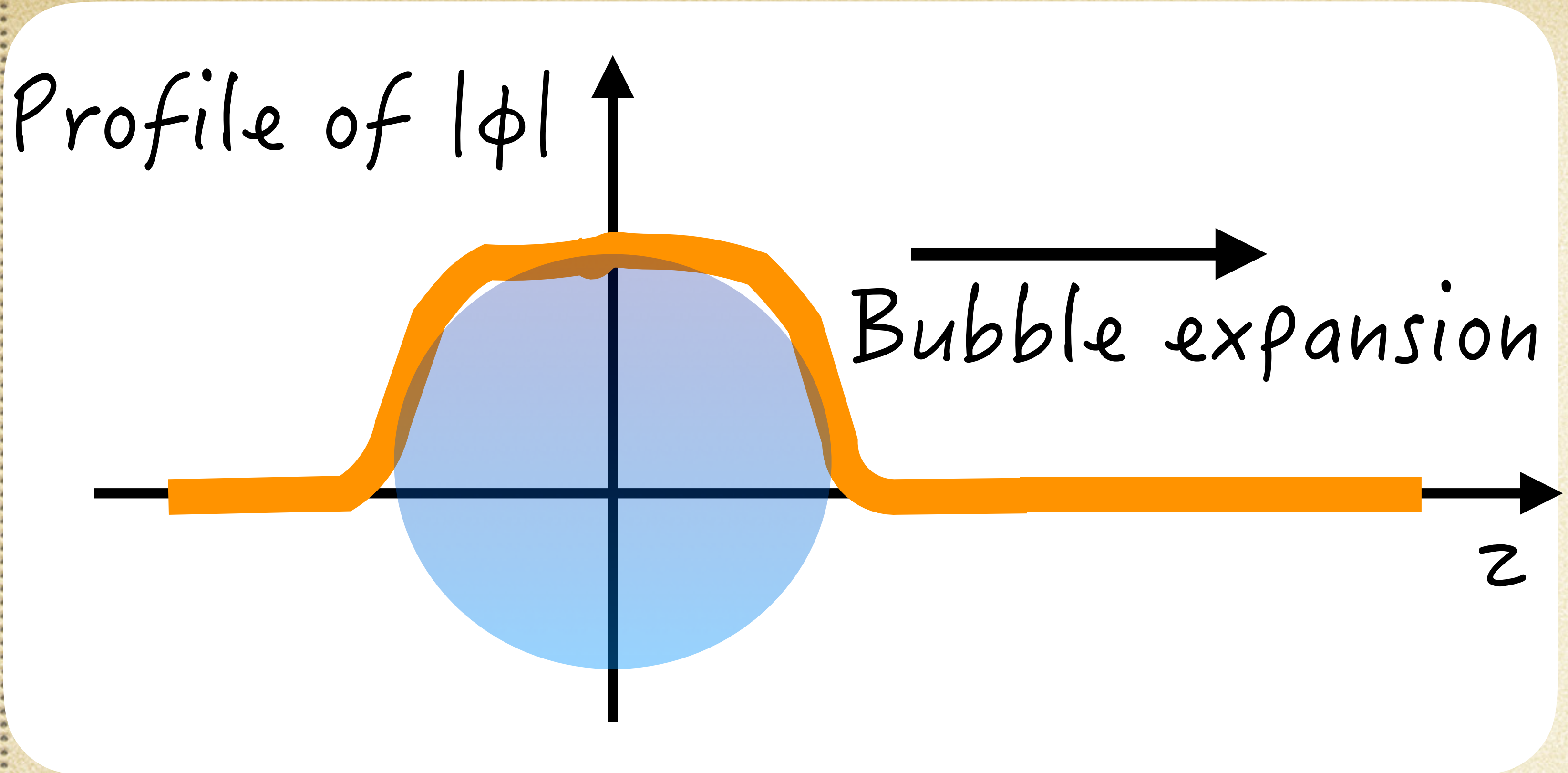
Around bubble walls, λ, time-dependent. Interference of Weinberg op at different times creates lepton asymmetry.



A leptobubble is born!



Thanks to Ye-Ling Zhou for figure

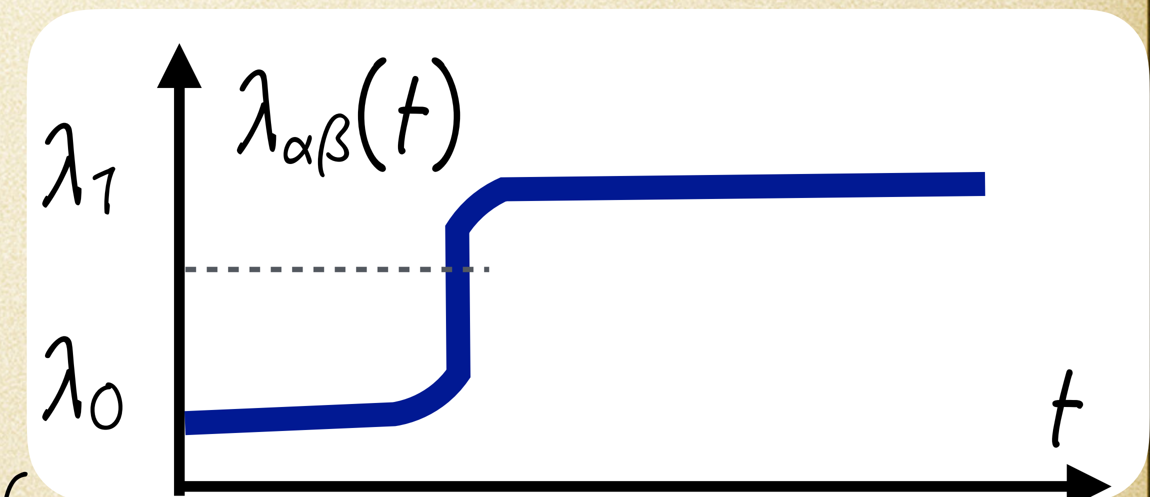


$$\lambda_{\alpha\beta} = \lambda^0_{\alpha\beta} + \lambda^1_{\alpha\beta}\frac{\langle\phi\rangle}{v_\phi}$$

λ^0 initial value of λ before flavon PT

Time-dependent coupling Ansatz

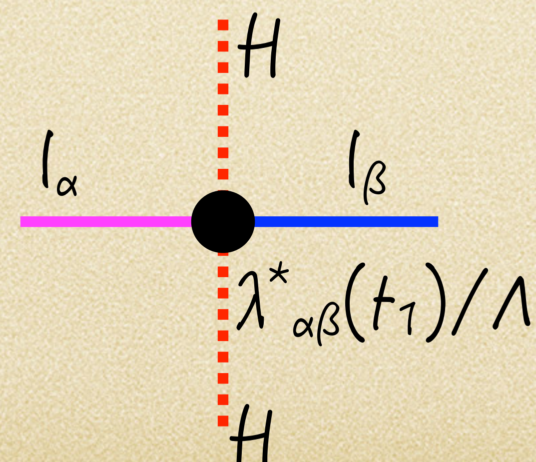
$$\lambda(t) = \lambda_0 + \frac{\lambda_1}{2}\left[1 + \tanh\left(\frac{z - v_w t}{L_w}\right)\right]$$



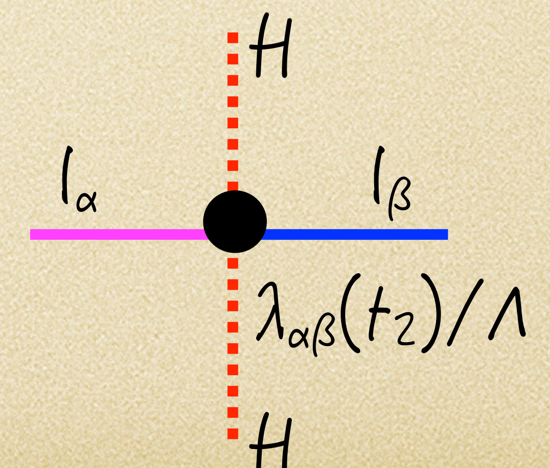
Lepton Asymmetry generated by interference of Weinberg operator at different times

$\lambda_{\alpha\beta}(t_1) \neq \lambda_{\alpha\beta}(t_2)$

$\Delta n_l \propto \mathrm{Im}\,\{$



$\times$



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Lepton Asymmetry

Lepton Asymmetry from KB equation

$$i\partial\!\!\!/ S^{<,>} - \Sigma^H \odot S^{<,>} - \Sigma^{<,>} \odot S^H = \frac{1}{2}\left[\Sigma^> \odot S^< - \Sigma^< \odot S^>\right]$$

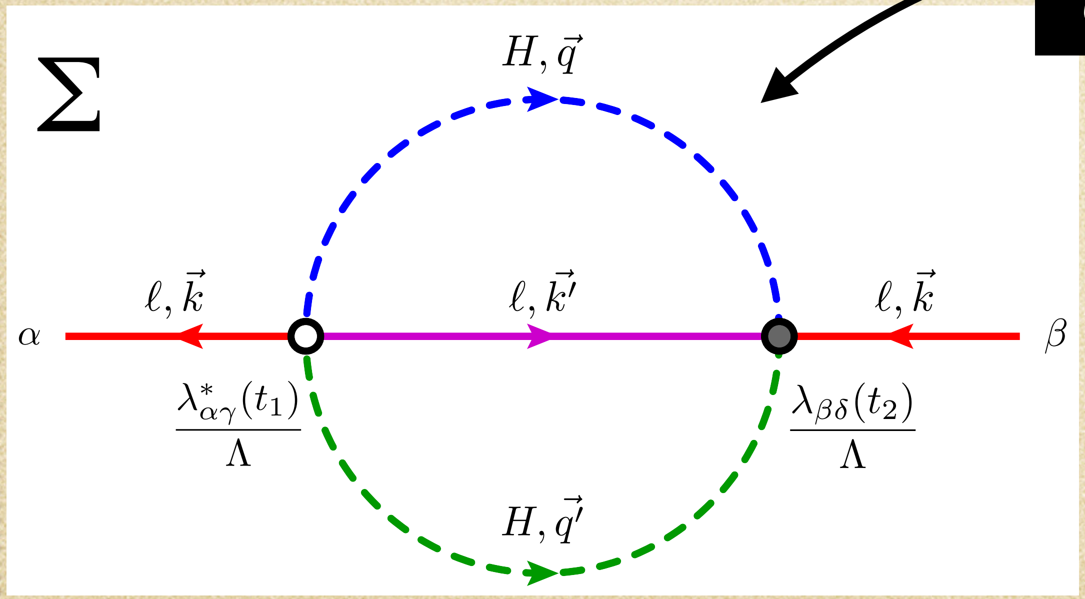
Lepton Asymmetry | Self-energy correction | Dispersion Relation | Collision Term

CPV-source

ignore these ones for now

$$L_{\vec{k}} = -\int_{t_i}^{t_f} dt_1 \int_{t_i}^{t_f} dt_2 \mathrm{tr}\Big[\Sigma^>_{\vec{k}}(t_1,t_2) S^<_{\vec{k}}(t_2,t_1) - \Sigma^<_{\vec{k}}(t_1,t_2) S^>_{\vec{k}}(t_2,t_1)\Big]$$

Lepton Self-Energy



Assume Higgs and lepton in thermal equilibrium

$$L_{\vec{k}\alpha\beta} = \sum_{\gamma\delta} \frac{12}{\Lambda^2} \int_{t_i}^{t_f} dt_1 \int_{t_i}^{t_f} dt_2 \mathrm{Im}\{\lambda^*_{\alpha\gamma}(t_1)\lambda_{\beta\delta}(t_2)\}$$

$$\int_{q,q'} M_{\alpha\beta\gamma\delta}(t_1, t_2, k, k', q, q')$$

Finite T Matrix Element

Final Expression for Lepton Asymmetry

Loop Factor

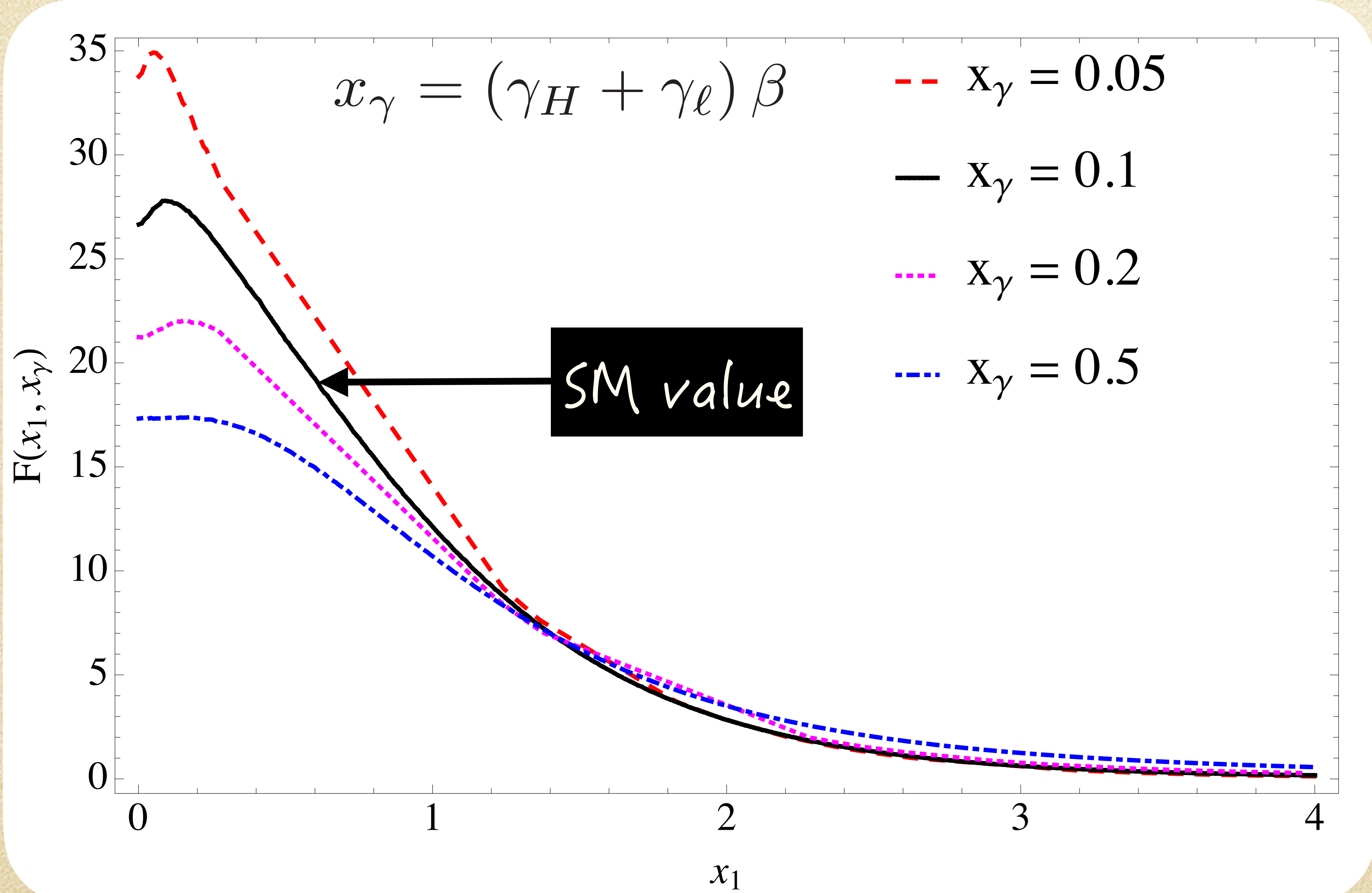
$$L_{\vec{k}} = \frac{3\,\mathrm{Im}\left\{\mathrm{tr}\left[m_\nu^0 m_\nu^*\right]\right\} T^2}{(2\pi)^4\, v_H^4} F\left(x_1, x_\gamma\right)$$

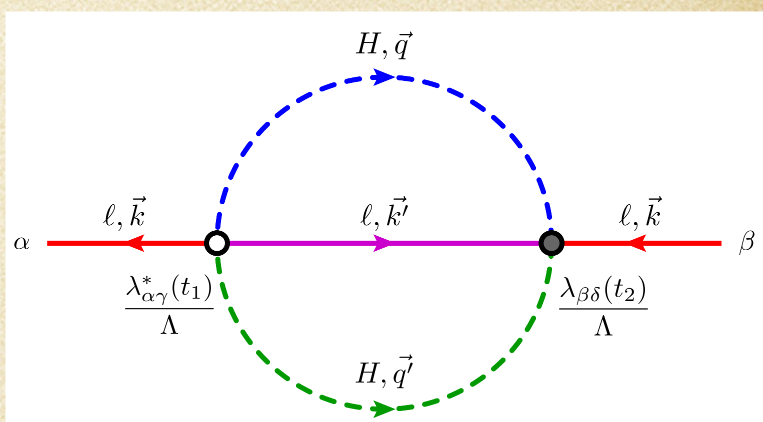
$$F\left(x_1, x_\gamma\right) = \frac{1}{2x_1}\int_0^{+\infty} dx \int_0^{+\infty} x_2 dx_2 \int_{|x_1-x|}^{|x_1+x|} dx_3 \int_{|x_2-x|}^{|x_2+x|} dx_3 \sum_{\eta_2,\eta_3,\eta_4=\pm 1}\left[1 - \frac{\left(x_1^2+x^2-x_3^2\right)\left(x_2^2+x^2-x_4^2\right)}{4\eta_2 x_1 x_2 x^2}\right]$$

$$\times \frac{X_{\eta_2\eta_3\eta_4} x_\gamma \sinh X_{\eta_2\eta_3\eta_4}}{\left(X_{\eta_2\eta_3\eta_4}^2 + x_\gamma^2\right)^2 \cosh x_1 \cosh x_2 \sinh x_3 \sinh x_4}$$

$$x_1 = k\beta/2, \quad x_2 = k'\beta/2, \quad x_3 = q\beta/2, \quad x_4 = q'\beta/2,$$

$$x = p\beta/2 \quad X_{\eta_2\eta_3\eta_4} = x_1 + \eta_2 x_2 + \eta_3 x_3 + \eta_4 x_4$$





Loop provides O(10) enhancement to lepton asymmetry

Final Expression for Lepton Asymmetry

O(10) enhancement

$$L_{\vec{k}} = \mathrm{Im}\left(m_\nu^0 m_\nu^*\right) \frac{3T^2}{(2\pi)^4 v_H^4} F\left(x_1, x_\gamma\right)$$

ν mass matrix **BEFORE CPPT** dependent upon flavour model

ν mass matrix **AFTER CPPT** dependent upon low-energy observables

CPPT Temperature

Assuming $(m_\nu^0)^2 \sim m_\nu^2 \sim (0.1\ \mathrm{eV})^2$

$$T \sim 10 \sqrt{L_{\vec{k}} \frac{v_H^2}{m_\nu}}$$

using $L_{\vec{k}} = 6.19 \times 10^{-10}$

$$\Longrightarrow \; T \sim 10^{11}\mathrm{GeV}$$

To-do List

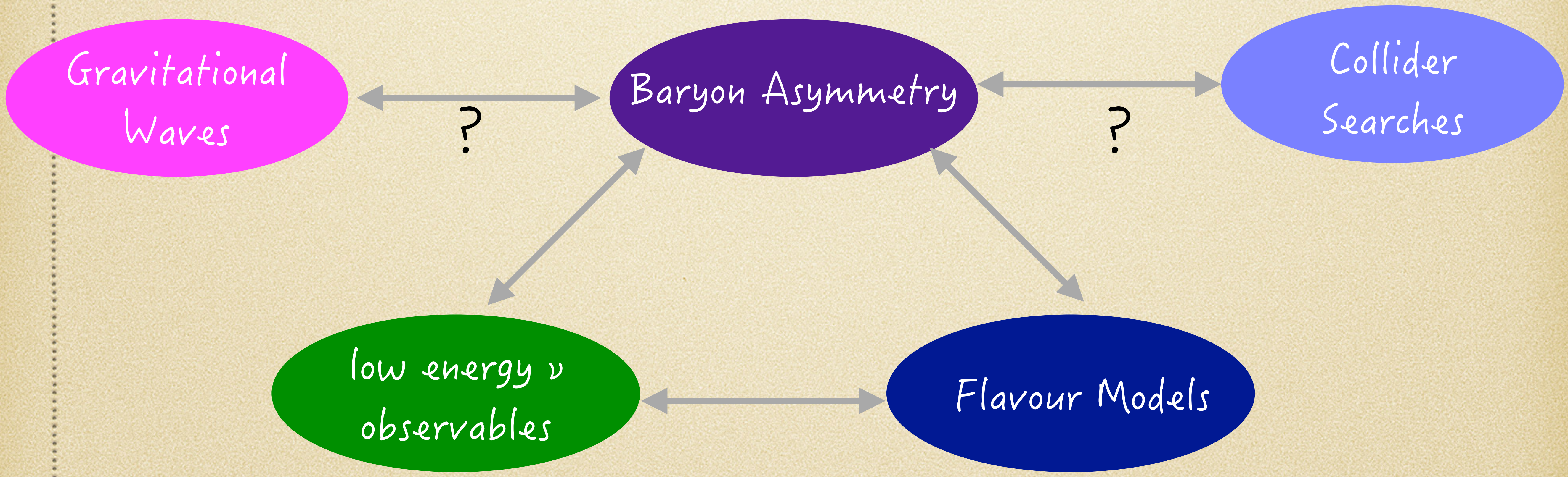
Similar calculation as in "Quantum Leptogenesis" 1012.5821 (Buchmuller etal)

- This estimate accounts for initial asymmetry and not the full evolution.
- Thermal width of lepton flavours treated the same. We are in the temperature regime where tau is out of equilibrium: need to include flavour effects.

Conclusions

- Leptobubbles is a **new** mechanism to generate the BAU
- Two **major differences** from conventional leptogenesis

1. ν masses come from Weinberg op. But no need to specify the UV-completion (seesaw, loop effects etc)
2. CP-violation occurs below ν mass generation scale.



Thank You for Listening

Calculation Tool
CTP Formalism

Motivation for CTP Formalism

$$\frac{\partial \rho}{\partial t} = \{H, \rho\}$$

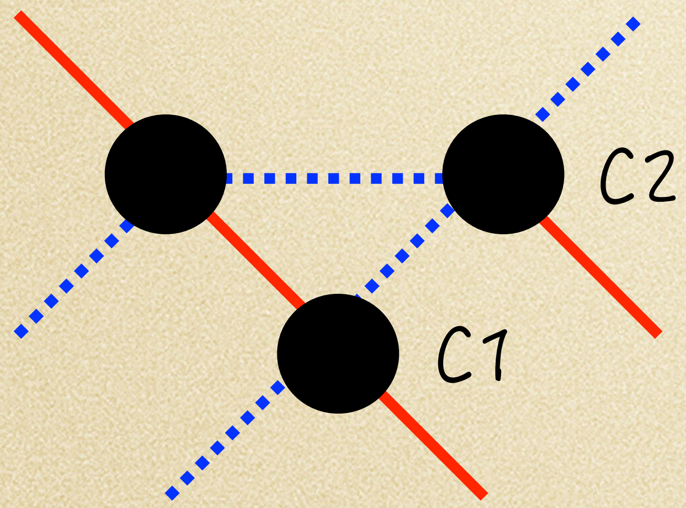
Quantum Liouville Equation

↓ BBGKY

Classical

$$\frac{\partial \rho}{\partial t} + 3H\rho = \frac{1}{(2\pi)^3}\frac{1}{\omega}C[\rho]$$

Quantum: from S-matrix typically calculated at T=0



Many systems in cosmology use semi-classical Boltzmann equations.

↓

BEs assume **dilute gas.**
Collision 2 does not "remember" collision 1

↓

Early Universe is hot dense plasma: dilute gas is not a good assumption. Plasma is everywhere and the particles feel its presence

↓

S-matrix calculation in T=0 assumes asymptotically free states (LSZ-reduction). Not necessarily good approximation high T, finite density, out of equilibrium environment.

Berges, Anisimov, Garbrecht, Drewes, Millington

The CTP Formalism

generating functional T=0

T=0, in-out formalism

$$Z[J] = \langle \phi_{vac_{in}} | \phi_{vac_{out}} \rangle = \int D\phi e^{i\int d^4x (\mathcal{L} + J\phi(x))}$$

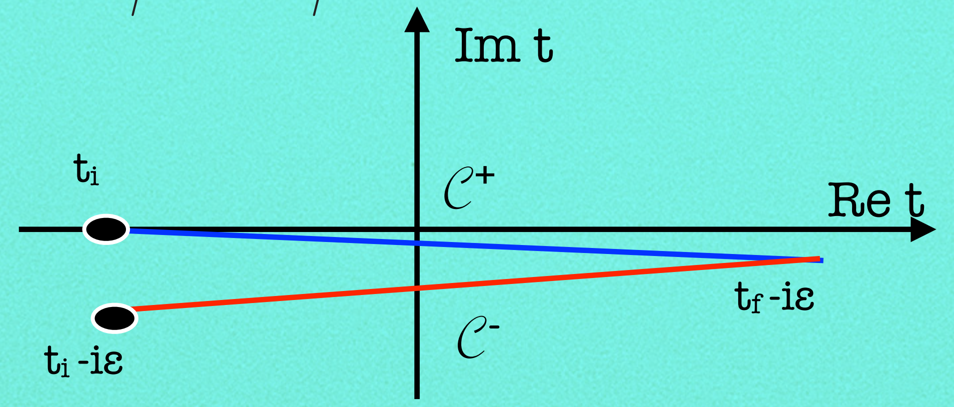
$$\langle T[\phi(x)\phi(y)] \rangle = -\frac{\delta^2}{\delta J(x) \delta J(y)} \log Z[J]$$

generating functional T≠0

T≠0, in-in formalism

$$Z[J_+, J_-] = \int D\Psi D\phi^-_{in} D\phi^-_{in} \langle \phi_{in} | \Psi, t_f \rangle \langle \Psi, t_f | \phi^+_{in} \rangle \langle \phi^-_{in} | \rho | \phi^-_{out} \rangle$$

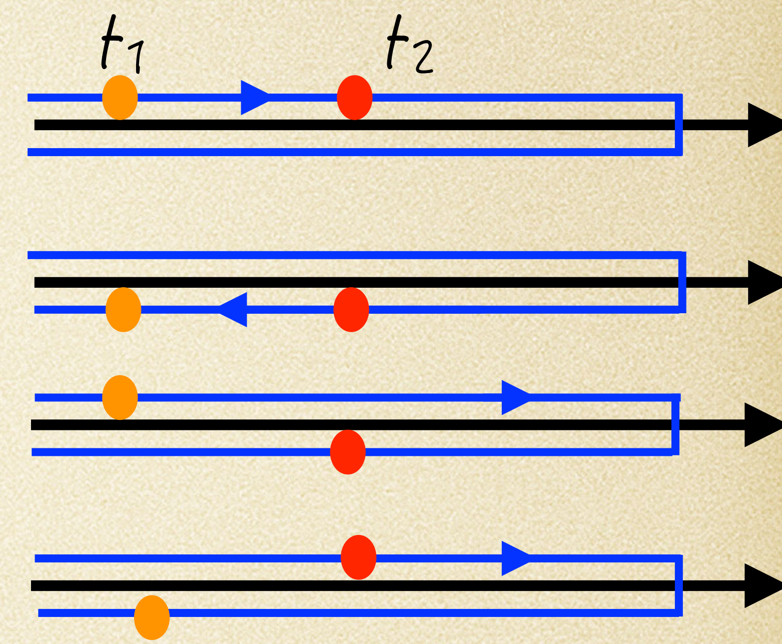
$$= \int D\phi^+ D\phi^- e^{i\int \left(\mathcal{L}[\phi^+] + J_+ \phi^+ - \mathcal{L}[\phi^-] - J_- \phi^- \right)}$$



$$i\Delta^{ab}_\phi(x,y) = -\frac{\delta^2}{\delta J_a(x) J_b(y)} \log Z[J_+, J_-] = i\langle \mathcal{C}[\phi^a(x)\phi^b(y)] \rangle$$

Green's Functions

$$x = (t_1, \vec{x}) \quad y = (t_2, \vec{y})$$



Feynman Propagator

$$i\Delta^T(x,y) = \langle T[\phi(x)\overline{\phi}(y)]\rangle$$

Dyson Propagator

$$i\Delta^{\overline{T}}(x,y) = \langle \overline{T}[\phi(x)\overline{\phi}(y)]\rangle$$

Wightman Propagators

$$i\Delta^<(x,y) = -\langle \phi(y)\phi(x)\rangle$$

$$i\Delta^>(x,y) = \langle \phi(x)\phi(y)\rangle$$

T=0 bit

Heaviside function

distribution function

$$i\Delta^T(x,y) = \frac{i}{p^2 - m^2 + i\epsilon} + 2\pi\delta(p^2 - m^2)[\theta(p_0)f(\vec{p}) + \theta(-p_0)f(-\vec{p}))]$$

$$i\Delta^{\overline{T}}(x,y) = \frac{i}{p^2 - m^2 - i\epsilon} + 2\pi\delta(p^2 - m^2)[\theta(p_0)f(\vec{p}) + \theta(-p_0)f(-\vec{p}))]$$

$$i\Delta^<(x,y) = 2\pi\delta(p^2 - m^2)[\theta(p_0)f(\vec{p}) + \theta(-p_0)(1 + \overline{f}(-\vec{p}))]$$

$$i\Delta^>(x,y) = 2\pi\delta(p^2 - m^2)[\theta(p_0)(1 + f(\vec{p})) + \theta(-p_0)\overline{f}(-\vec{p})]$$

Schwinger-Dyson Equation

a,b CTP indices

$$\Delta^{ab} = \Delta^{(0)ab} + cd\Delta^{(0)cd} \odot \Sigma^{db} \odot \Delta^{db}$$

Kadanoff Baym equations are the <,> parts of SD equations

$$i\partial\!\!\!/ S_\ell^{<,>} - \Sigma^H \odot S_\ell^{<,>} - \Sigma^{<,>} \odot S_\ell^H = \frac{1}{2}\left[\Sigma^{>} \odot S_\ell^{<} - \Sigma^{<} \odot S_\ell^{>}\right]$$

lepton asymmetry — self-energy correction — dispersion relation — collision term → CPV source

$$S^T_{\alpha\beta}(x,y) = \langle T[\ell_\alpha(x)\overline{\ell_\beta}(y)]\rangle, \quad S^H = S^T - \frac{1}{2}\left(S^{>} + S^{<}\right), \quad \Sigma^H = \Sigma^T - \frac{1}{2}\left(\Sigma^{>} + \Sigma^{<}\right)$$