Asymmetries in the early universe

Valerie Domcke
CERN

Invisibles23 Workshop
31.08.2023, Göttingen

Asymmetries in the early universe

Valerie Domcke
CERN

Invisibles23 Workshop
31.08.2023, Göttingen

postdoc application deadline September 3 !

Asymmetries in the early universe

Valerie Domcke
CERN

Invisibles23 Workshop
31.08.2023, Göttingen

primordial B and L asymmetries

baryon asymmetry at BBN (~ 1 MeV) and CMB decoupling (~ eV) : $\frac{n_B}{s} \simeq 8.7 \times 10^{-11}$

In SM, B – L and B + L are conserved below EWPT / sphaleron freeze-out (~ 100 GeV).
Above, sphaleron processes drive B + L = 0.

→ lepton asymmetry at 100 GeV: $\frac{|n_L|}{s} \lesssim 10^{-10}$

primordial B and L asymmetries

baryon asymmetry at BBN (~ 1 MeV) and CMB decoupling (~ eV) : $\frac{n_B}{s} \simeq 8.7 \times 10^{-11}$

In SM, B – L and B + L are conserved below EWPT / sphaleron freeze-out (~ 100 GeV). Above, sphaleron processes drive B + L = 0.

→ lepton asymmetry at 100 GeV: $\frac{|n_L|}{s} \lesssim 10^{-10}$

spontaneous CP violation the early Universe is very small

primordial B and L asymmetries

baryon asymmetry at BBN (~ 1 MeV) and CMB decoupling (~ eV) : $\frac{n_B}{s} \simeq 8.7 \times 10^{-11}$

In SM, B – L and B + L are conserved below EWPT / sphaleron freeze-out (~ 100 GeV).
Above, sphaleron processes drive B + L = 0.

→ lepton asymmetry at 100 GeV: $\frac{|n_L|}{s} \lesssim 10^{-10}$

spontaneous CP violation the early Universe is very small

However:

B + L asymmetry can be much larger at earlier times

B – L asymmetry can be much larger if B – L violation introduced

Pastor, Pinto, Raffelt `08,
Mangano et al `11,
Castorina et al `12, ...
Pitrou et al `18, ...
Escudero, Ibarra, Maura `22

Asymmetries in electron neutrinos from BBN, CMB:
(charged particles constrained by charge neutrality) $\frac{|n_{\nu_e} - n_{\bar{\nu}_e}|}{s} \sim \frac{|\mu_{\nu_e}|}{T} \lesssim 10^{-2}$

Due to neutrino oscillations, large μ_{ν_α} with $\Sigma \mu_{\nu_\alpha} = 0$ only constrained to: $|\mu_{\nu_\alpha}|/T \lesssim \mathcal{O}(1)$

or not ?

primordial B and L asymmetries

Observationally,
O(1) lepton flavour asymmetries
are not excluded

Hints from BBN (helium anomaly)
and CMB (polarization)
for large CP violation
Burns, Tait, Valli `22, Minami, Komatsu `20

Implications for baryogenesis,
CP-violating BSM physics,
thermal phase transitions,….

primordial B and L asymmetries

Observationally,
O(1) lepton flavour asymmetries
are not excluded

Hints from BBN (helium anomaly)
and CMB (polarization)
for large CP violation
Burns, Tait, Valli `22, Minami, Komatsu `20

Implications for baryogenesis,
CP-violating BSM physics,
thermal phase transitions,….

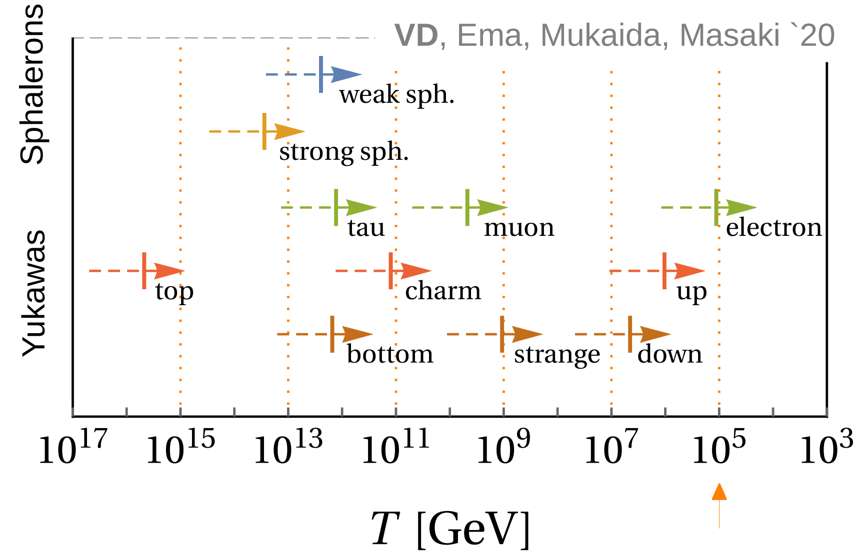
Outline of this talk:

- implications of large spontaneous CP violation in the early universe
- new bounds on lepton flavour asymmetries
- implications for baryogenesis

SM interactions and conserved charges

- exactly conserved charges: $B/3 - L_\alpha \, , \, Y$

(lepton flavour, hypercharge)



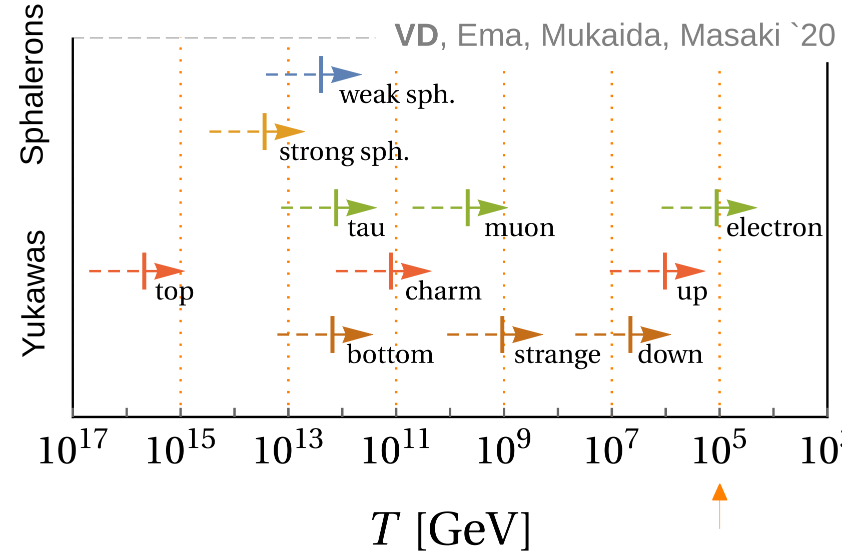
- in the early Universe, SM interactions cannot keep up with expansion

→ additional approximately conserved charges $q_X = n_X - n_{\bar{X}} = \mu_X T^2/6$:

SM interactions and conserved charges

- exactly conserved charges: $B/3 - L_\alpha\,,\,Y$

  (lepton flavour, hypercharge)



- in the early Universe, SM interactions cannot keep up with expansion

→ additional approximately conserved charges $q_X = n_X - n_{\bar{X}} = \mu_X T^2/6$:

	T [GeV]	y_e	y_{ds}	y_d	y_s	y_{sb}	y_μ	y_c	y_τ	y_b	WS	SS	y_t
(v)	$(10^5, 10^6)$	q_e	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
(iv)	$(10^6, 10^9)$	q_e	$q_{2B_1-B_2-B_3}$	q_{u-d}	✓	✓	✓	✓	✓	✓	✓	✓	✓
(iii)	$(10^9, 10^{11-12})$	q_e	$q_{2B_1-B_2-B_3}$	q_{u-d}	q_{d-s}	$q_{B_1-B_2}$	q_μ	✓	✓	✓	✓	✓	✓
(ii)	$(10^{11-12}, 10^{13})$	q_e	$q_{2B_1-B_2-B_3}$	q_{u-d}	q_{d-s}	$q_{B_1-B_2}$	q_μ	q_{u-c}	q_τ	q_{d-b}	q_B	✓	✓
(i)	$(10^{13}, 10^{15})$	q_e	$q_{2B_1-B_2-B_3}$	q_{u-d}	q_{d-s}	$q_{B_1-B_2}$	q_μ	q_{u-c}	q_τ	q_{d-b}	q_B	q_u	✓

conserved charges + # equilibrated interactions = # particle species = 16

asymmetries are redistributed across different species

chiral plasma instability

chiral magnetohydrodynamics (MHD) : hyper gauge fields, plasma w asymmetries

classical Maxwell eqs with $J_Y = \sigma_Y (E_Y + v \times B_Y) + \frac{2\alpha_Y}{\pi} \mu_{Y,5} B_Y$

conductivity

fluid velocity
→ inverse cascade

chiral magnetic effect
→ chiral plasma instability

$$\mu_{Y,5} = \sum_i \varepsilon_i g_i Y_i^2 \mu_i$$

chiral chemical potential

chiral plasma instability

chiral magnetohydrodynamics (MHD) : hyper gauge fields, plasma w asymmetries

classical Maxwell eqs with $J_Y = \sigma_Y (E_Y + v \times B_Y) + \frac{2\alpha_Y}{\pi} \mu_{Y,5} B_Y$

conductivity

fluid velocity
→ inverse cascade

chiral magnetic effect
→ chiral plasma instability

$$\mu_{Y,5} = \sum_i \varepsilon_i g_i Y_i^2 \mu_i$$

chiral chemical potential

neglecting
fluid velocity

helicity: $$\partial_\eta h_k = -\frac{2k^2}{\sigma_Y} h_k + \frac{4\alpha_Y}{\pi} \frac{\mu_{Y,5}}{\sigma_Y} \rho_{B,k}$$

magn. energy density: $$\partial_\eta \rho_{B,k} = -\frac{2k^2}{\sigma_Y} \rho_{B,k} + \frac{\alpha_Y}{\pi} \frac{\mu_{Y,5}}{\sigma_Y} k^2 h_k$$

diffusion — chiral magnetic effect

modes of one helicity with $k < k_{\rm CPI} \equiv \alpha_Y |\mu_{Y,5}|/\pi$ become tachyonically unstable for $|\mu_{Y,5}| \neq 0$

chiral plasma instability

chiral magnetohydrodynamics (MHD) : hyper gauge fields, plasma w asymmetries

classical Maxwell eqs with $$J_Y = \sigma_Y (E_Y + v \times B_Y) + \frac{2\alpha_Y}{\pi} \mu_{Y,5} B_Y$$

conductivity

fluid velocity
→ inverse cascade

chiral magnetic effect
→ chiral plasma instability

$$\mu_{Y,5} = \sum_i \varepsilon_i g_i Y_i^2 \mu_i$$

chiral chemical potential

neglecting fluid velocity

helicity: $$\partial_\eta h_k = -\frac{2k^2}{\sigma_Y} h_k + \frac{4\alpha_Y}{\pi} \frac{\mu_{Y,5}}{\sigma_Y} \rho_{B,k}$$

magn. energy density: $$\partial_\eta \rho_{B,k} = -\frac{2k^2}{\sigma_Y} \rho_{B,k} + \frac{\alpha_Y}{\pi} \frac{\mu_{Y,5}}{\sigma_Y} k^2 h_k$$

diffusion — chiral magnetic effect

modes of one helicity with $k < k_{\rm CPI} \equiv \alpha_Y |\mu_{Y,5}|/\pi$ become tachyonically unstable for $|\mu_{Y,5}| \neq 0$

→ chiral chemical potential converted into helical gauge fields $h = \pi T^2/\alpha_Y \, c_5(T) \, \mu_{Y,5}^{\rm ini}$ at

$$T_{\rm CPI} \sim 10^5 \text{ GeV} \left(\frac{10^2}{g_*}\right)^{\frac{1}{2}} \left(\frac{\alpha_Y}{0.01}\right)^2 \left(\frac{10^2 T}{\sigma_Y}\right) \left(\frac{\mu_{Y,5}/T}{2\cdot 10^{-3}}\right)^2 \Bigg|_{T_{\rm CPI}}$$

T_{Y_e}

particle asymmetries can be converted to helical gauge fields

Kamada `18

inverse cascade

Brandenburger et al `17
Schober et al `18

neglecting the fluid velocity, diffusion will erase helical gauge fields on short scales.

fluid velocity introduces non-linear mode coupling, free energy is minimized when helicity stored in long-wave length modes → inverse cascade

For sufficiently large helical fields (ie Reynolds number > 1) inverse cascade is triggered and helicity is protected from diffusion

helical gauge fields can survive even after chemical potentials are erased

baryogenesis from decaying hypermagnetic fields

At EW phase transition, hypermagnetic helicity converted to EM helicity

→ generation of B+L asymmetry due to ABJ anomaly — Joyce, Shaposhnikov `97

Sphaleron wash-out decouples at EW phase transition

→ final B+L asymmetry sensitive to detailed time evolution of EW PT

Baryon asymmetry today estimated as: — Kamada, Long `16

$$\frac{n_B^h}{s} = c_B^{\rm dec} \frac{\alpha_Y}{2\pi} \frac{h}{n_\gamma} \sim 10^{-6} h/T^3 \sim 10^{-4} (\mu_{Y,5}/T)_{T_{\rm CPI}}$$

for $|\mu| \gtrsim 10^{-6}$ danger of massive overproduction of baryon asymmetry in SM EW PT !

summary and outline

- **implications of large spontaneous CP violation in the early universe**
  - SM interactions re-shuffle particle asymmetries
  - chiral plasma instability: $\mu \mapsto h$
  - helicity can survive until EW PT and generate (large) baryon asymmetry

- **new bounds on lepton flavour asymmetries**
- **implications for baryogenesis**

a bound on lepton flavour asymmetries

e.g. at T ~ $10^{5..6}$ GeV

Domcke, Kamada, Mukaida, Schmitz, Yamada `22

$$\frac{\mu_{Y,5}}{T} = \frac{711}{481}\frac{\mu_e}{T} + \frac{5}{13}\frac{\mu_{\Delta_e}}{T} - \frac{4}{37}\frac{\mu_{\Delta_{\mu+\tau}}}{T}\,,$$

$$\Delta_\alpha = B/3 - L_\alpha$$

all SM interactions
in equilibrium
except electron Yukawa

a bound on lepton flavour asymmetries

Domcke, Kamada, Mukaida, Schmitz, Yamada `22

e.g. at T ~ $10^{5..6}$ GeV

$$\frac{\mu_{Y,5}}{T} = \frac{711}{481}\frac{\mu_e}{T} + \frac{5}{13}\frac{\mu_{\Delta_e}}{T} - \frac{4}{37}\frac{\mu_{\Delta_{\mu+\tau}}}{T}\,, \qquad \Delta_\alpha = B/3 - L_\alpha$$

all SM interactions
in equilibrium
except electron Yukawa

consider only B-L conserving lepton flavour asymmetries $\mu_e^{\text{ini}} = 0\,, \quad \sum_\alpha \mu_{\Delta_\alpha} = 0$

$$\rightarrow \mu_{Y,5} \sim \mu_{\Delta_\alpha} \neq 0$$

a bound on lepton flavour asymmetries

e.g. at T ~ 10^5..6 GeV

Domcke, Kamada, Mukaida, Schmitz, Yamada `22

$$\frac{\mu_{Y,5}}{T} = \frac{711}{481}\frac{\mu_e}{T} + \frac{5}{13}\frac{\mu_{\Delta_e}}{T} - \frac{4}{37}\frac{\mu_{\Delta_{\mu+\tau}}}{T}\,, \qquad \Delta_\alpha = B/3 - L_\alpha$$

all SM interactions
in equilibrium
except electron Yukawa

consider only B-L conserving lepton flavour asymmetries $\mu_e^{\rm ini} = 0\,, \quad \sum_\alpha \mu_{\Delta_\alpha} = 0$

$$\rightarrow \mu_{Y,5} \sim \mu_{\Delta_\alpha} \neq 0$$

last SM coupling (electron Yukawa) comes into equilibrium

overproduction of baryon asymmetry if

$$T_{\rm CPI} \gtrsim 10^5 \text{ GeV} \quad \rightarrow \quad \left|\frac{\mu_{\Delta_e}}{T}\right| = \left|\frac{\mu_{\Delta_\mu} + \mu_{\Delta_\tau}}{T}\right| > 0.01$$

and

$$\frac{n_B}{s} > 10^{-10} \quad \rightarrow \quad |\mu_{\Delta_\alpha}/T| \gtrsim 10^{-5}$$

a bound on lepton flavour asymmetries

Domcke, Kamada, Mukaida, Schmitz, Yamada `22

e.g. at T ~ $10^{5..6}$ GeV

$$\frac{\mu_{Y,5}}{T} = \frac{711}{481}\frac{\mu_e}{T} + \frac{5}{13}\frac{\mu_{\Delta_e}}{T} - \frac{4}{37}\frac{\mu_{\Delta_{\mu+\tau}}}{T}\,,$$

$$\Delta_\alpha = B/3 - L_\alpha$$

all SM interactions in equilibrium except electron Yukawa

consider only B-L conserving lepton flavour asymmetries $\mu_e^{\text{ini}} = 0\,, \quad \sum_\alpha \mu_{\Delta_\alpha} = 0$

$$\rightarrow \mu_{Y,5} \sim \mu_{\Delta_\alpha} \neq 0$$

last SM coupling (electron Yukawa) comes into equilibrium

overproduction of baryon asymmetry if

$$T_{\text{CPI}} \gtrsim 10^5 \text{ GeV} \quad \rightarrow \quad \left|\frac{\mu_{\Delta_e}}{T}\right| = \left|\frac{\mu_{\Delta_\mu} + \mu_{\Delta_\tau}}{T}\right| > 0.01$$

and

$$\frac{n_B}{s} > 10^{-10} \quad \rightarrow \quad |\mu_{\Delta_\alpha}/T| \gtrsim 10^{-5}$$

bound on LFAs,
two orders of magnitude
stronger than BBN bound

a bound on lepton flavour asymmetries

Domcke, Kamada, Mukaida, Schmitz, Yamada `22

$$|\mu_{\Delta_\alpha}|/T < 0.01$$

- applies also for B-L = 0 → in that case factor 100 stronger than BBN bound
- applies at T > 10^5 GeV → constraint on primordial asymmetries
- disfavours leptoflavourgenesis   Mukaida, Schmitz, Yamada `21
- if marginally fulfilled, provides a viable (though tuned) baryogenesis mechanism
- sensitive to CPI dynamics, not sensitive to EW PT dynamics
- non-perturbative SU(2) processes (sphalerons) + η_B^{obs} → bound on B-L
  non-perturbative U(1) processes (CPI) + η_B^{obs} → bound on LFAs

implications for baryogenesis

models with temporarily large (lepton) asymmetries in the early Universe can lead to large baryon asymmetries

Axiogenesis [Co, Domcke, Harigaya `22]

Axion inflation [VD, Kamada, Mukaida, Schmitz, Yamada `22]

algebraic framework for tracking evolution of chemical potentials

VD, Kamada, Mukaida, Schmitz, Yamada `20,`22

Summary

- (spontaneous) CP violation in the early universe can trigger chiral plasma instability, inverse cascade and baryogenesis
- new bound on primordial B-L conserving lepton flavour asymmetries, $|\mu_{\Delta_\alpha}|/T < 0.01$
- framework to constrain or obtain observable predictions for models with large primordial asymmetries

Summary

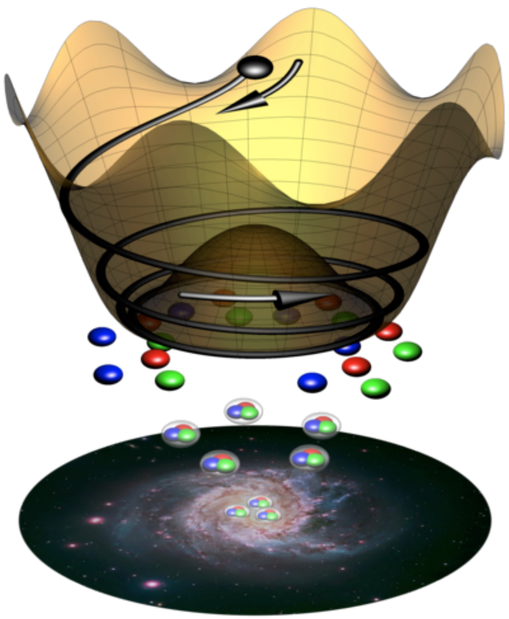
- (spontaneous) CP violation in the early universe can trigger chiral plasma instability, inverse cascade and baryogenesis
- new bound on primordial B-L conserving lepton flavour asymmetries, $|\mu_{\Delta_\alpha}|/T < 0.01$
- framework to constrain or obtain observable predictions for models with large primordial asymmetries

Thank you!

backup slides

implications for axiogenesis

Kinetic misalignment & axiogenesis [Co, Hall, Harigaya `19; Co, Harigaya `19]



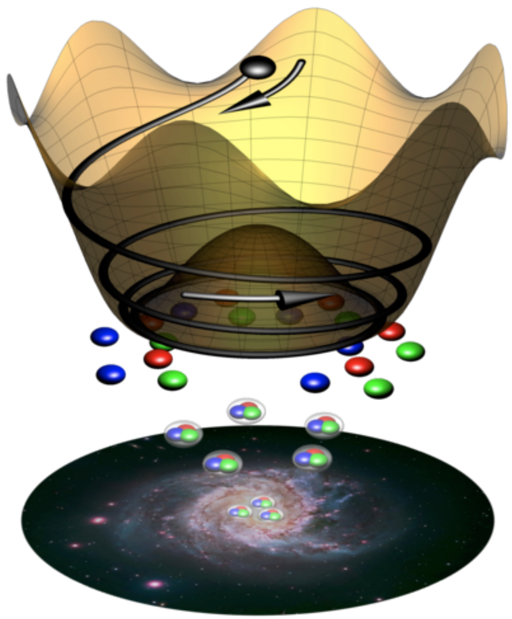
rotating PQ field

→ axion DM via kinetic misalignment

→ baryon asymmetry from via spontaneous baryogenesis
(but in simplest model insufficient to explain BAU)

implications for axiogenesis

Kinetic misalignment & axiogenesis [Co, Hall, Harigaya `19; Co, Harigaya `19]



rotating PQ field

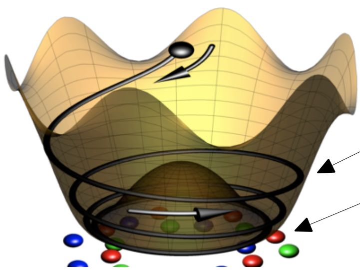
→ axion DM via kinetic misalignment

→ baryon asymmetry from via spontaneous baryogenesis
(but in simplest model insufficient to explain BAU)

- rotating PQ field induces large CP violation → can trigger chiral plasma instability
- rotation of PQ field lasts until QCD PT → CPI possible below 10^5 GeV

[Co, Domcke, Harigaya `22]

implications for axiogensis



$T > T_S$ inspiral phase

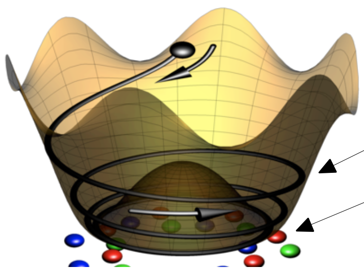
$T < T_S$ rotation in local minimum of Mexican hat potential

DM production: $(T < T_{\rm QCD} < T_S)$

$r|\dot{\theta}|^2/s$

$$\Omega_a h^2 = \Omega_{\rm DM} h^2 \times c_\Omega \left(\frac{10^9\ \text{GeV}}{f_a}\right)\left(\frac{Y_\theta}{73.3}\right)$$

implications for axiogensis



$T > T_S$ inspiral phase

$T < T_S$ rotation in local minimum of Mexican hat potential

DM production: $(T < T_{\rm QCD} < T_S)$

$r|\dot\theta|^2/s$

$$\Omega_a h^2 = \Omega_{\rm DM} h^2 \times c_\Omega \left(\frac{10^9\ \text{GeV}}{f_a}\right)\left(\frac{Y_\theta}{73.3}\right)$$

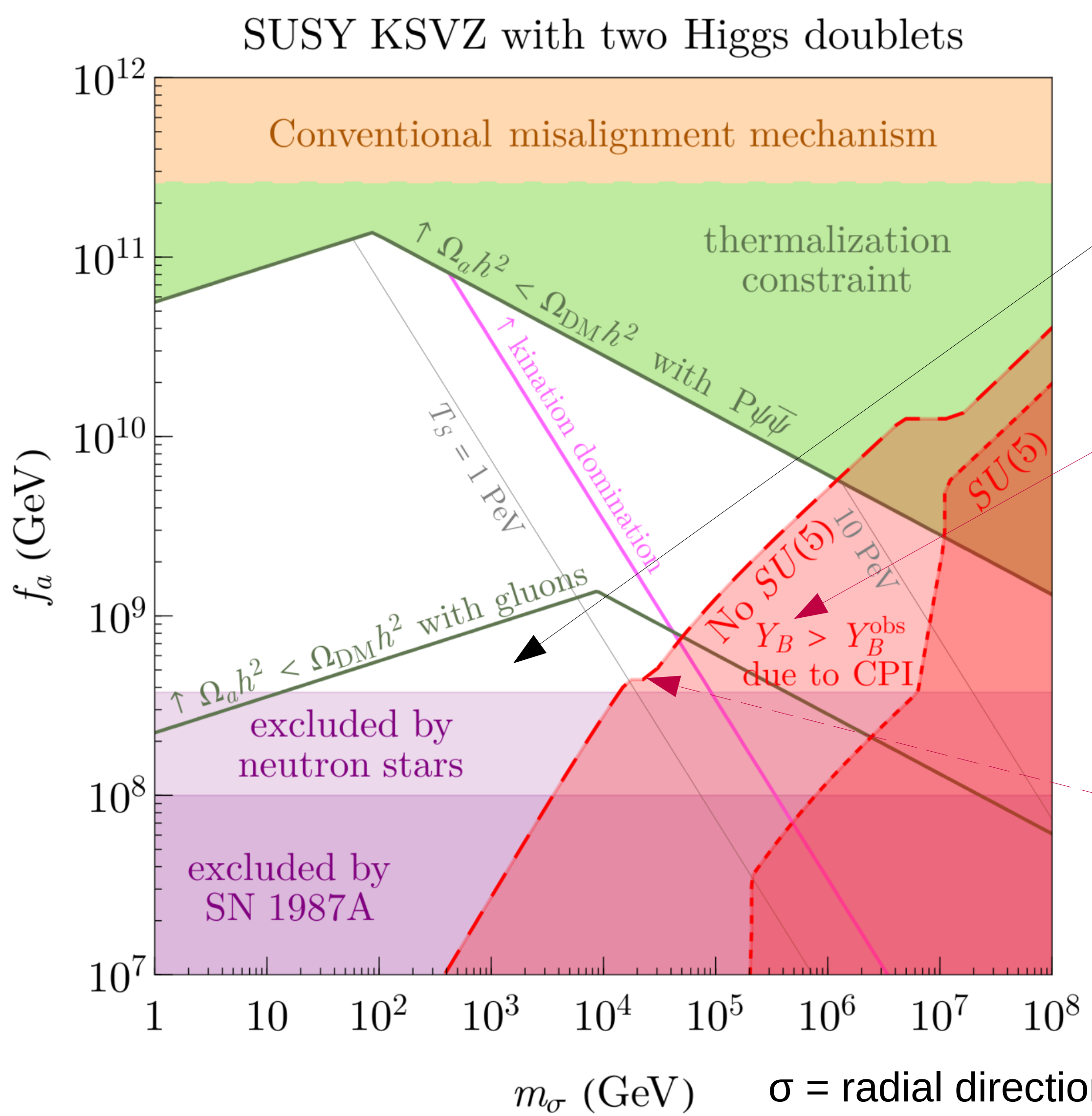
chiral plasma instability: $(T_{\rm CPI} > T_S)$

$$T_{\rm CPI}^{\rm MD} \simeq 3.0\ \text{PeV}\,|c_5|^{4/5}\,c_\Omega^{1/5}\left(\frac{10}{c_{\rm CPI}}\,\frac{50\,T}{\sigma_Y}\right)^{\frac{2}{5}}\left(\frac{N_{\rm DW}\,m_\sigma}{10^5\ \text{GeV}}\right)^{\frac{3}{5}}\left(\frac{10^9\ \text{GeV}}{f_a}\right)^{\frac{1}{5}}\left(\frac{g_{\rm MSSM}}{g_*(T_{\rm CPI}^{\rm MD})}\right)^{\frac{1}{5}}$$

- CPI is avoided only if $T_{\rm CPI} < T_S$
- If CPI occurs, overproduction of BAU in entire parameter space viable for DM

implications for axiogenesis

[Co, Domcke, Harigaya `22]



σ = radial direction of PQ field

viable parameter space (axion DM)

overproduction of baryon asymmetry through CPI

(contour determined by $\mu_{Y,5}(T)/\dot{\theta}$ ie particle content and couplings)

observed value for BAU reproduced on boundary

(CPI marginally efficient)

[baryogenesis from axion inflation]

‘axion’ inflation, a minimal setup for SM + inflation:

Domcke, Kamada, Mukaida, Schmitz, Yamada `22

axion with scalar potential

(hyper charge) U(1) gauge field

massless (SM) fermions

axion gauge field coupling

$$\mathcal{L} = \sqrt{-g}\left[\frac{1}{2}\partial^\mu\phi\partial_\mu\phi - V(\phi)\right] - \frac{1}{4}F_{\mu\nu}F^{\mu\nu} + \sum_\alpha \bar{\psi}_\alpha(i\partial\cdot\gamma - gQA\cdot\gamma)\psi_\alpha + \frac{\alpha\phi}{4\pi f_a}F_{\mu\nu}\tilde{F}^{\mu\nu}$$

$$(\partial_\mu\phi)\bar{\psi}\gamma^\mu\gamma^5\psi$$

[baryogenesis from axion inflation]

'axion' inflation, a minimal setup for SM + inflation:

Domcke, Kamada, Mukaida, Schmitz, Yamada `22

axion with scalar potential — (hyper charge) U(1) gauge field — massless (SM) fermions — axion gauge field coupling

$$\mathcal{L} = \sqrt{-g}\left[\frac{1}{2}\partial^\mu\phi\partial_\mu\phi - V(\phi)\right] - \frac{1}{4}F_{\mu\nu}F^{\mu\nu} + \sum_\alpha \bar\psi_\alpha(i\partial\cdot\gamma - gQA\cdot\gamma)\psi_\alpha + \frac{\alpha\phi}{4\pi f_a}F_{\mu\nu}\tilde F^{\mu\nu}$$

$$(\partial_\mu\phi)\bar\psi\gamma^\mu\gamma^5\psi$$

→ exponential production of helical gauge fields through tachyonic instability for $\dot\phi \neq 0$

chemical potentials for fermions

[baryogenesis from axion inflation]

'axion' inflation, a minimal setup for SM + inflation:

Domcke, Kamada, Mukaida, Schmitz, Yamada `22

axion with scalar potential

(hyper charge) U(1) gauge field

massless (SM) fermions

axion gauge field coupling

$$\mathcal{L} = \sqrt{-g}\left[\frac{1}{2}\partial^\mu\phi\partial_\mu\phi - V(\phi)\right] - \frac{1}{4}F_{\mu\nu}F^{\mu\nu} + \sum_\alpha \bar{\psi}_\alpha(i\partial\cdot\gamma - gQA\cdot\gamma)\psi_\alpha + \frac{\alpha\phi}{4\pi f_a}F_{\mu\nu}\tilde{F}^{\mu\nu}$$

$$(\partial_\mu\phi)\bar{\psi}\gamma^\mu\gamma^5\psi$$

→ exponential production of helical gauge fields through tachyonic instability for $\dot{\phi} \neq 0$

chemical potentials for fermions

→ two contribution to final baryon asymmetry:

$$\chi = \frac{q_{CS}}{2T^3}\Big|_{\rm rh}$$

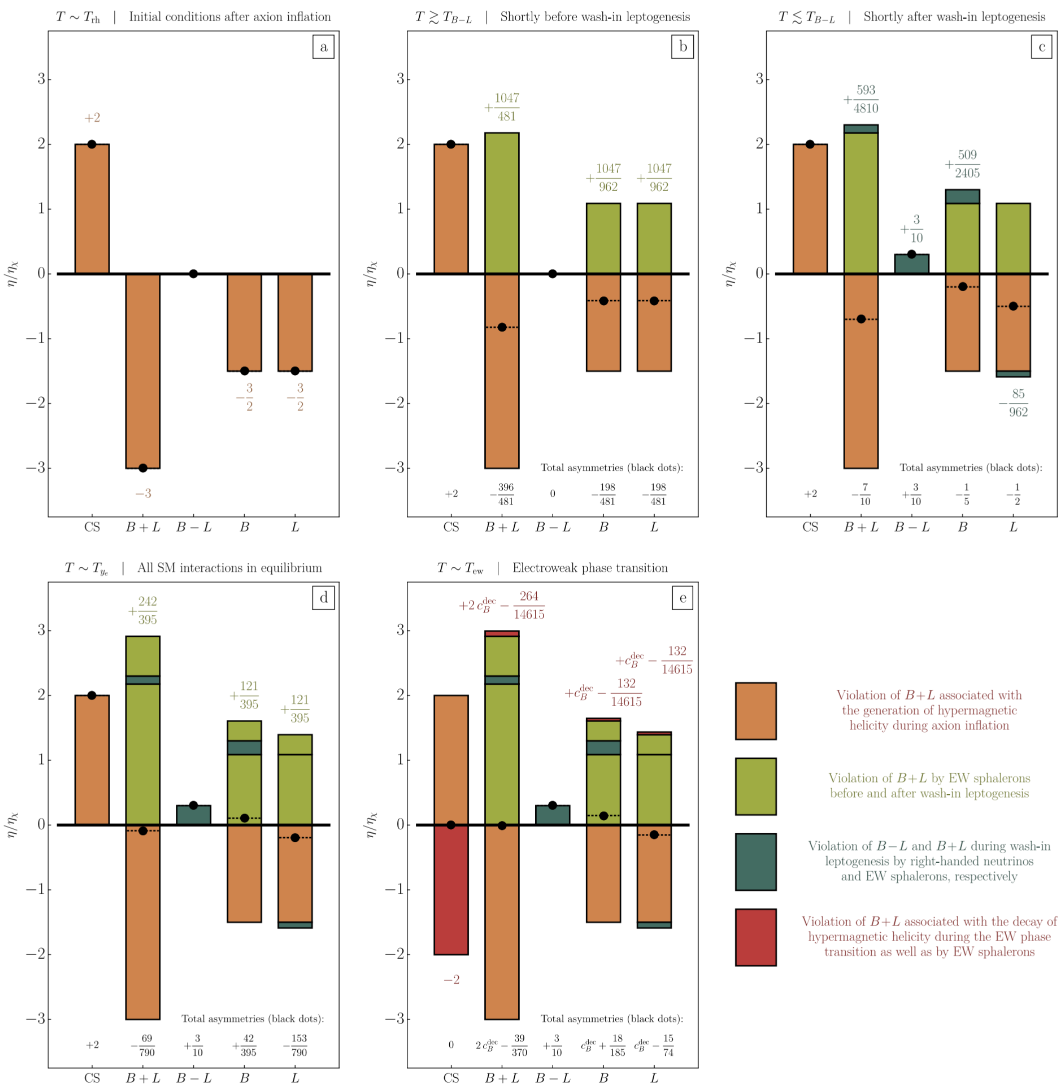
$$\eta_B^h \simeq 7.5\cdot 10^{-3}\left(\frac{c_B^{\rm dec}}{0.05}\right)\chi$$

from decaying helical hypermagn. gauge fields

$$\eta_B^{\rm N} \simeq 0.01\left(\frac{c_B^{\rm N}}{0.1}\right)\chi$$

from re-shuffling chemical potentials if right-handed neutrinos included (B-L) = wash-in leptogenesis

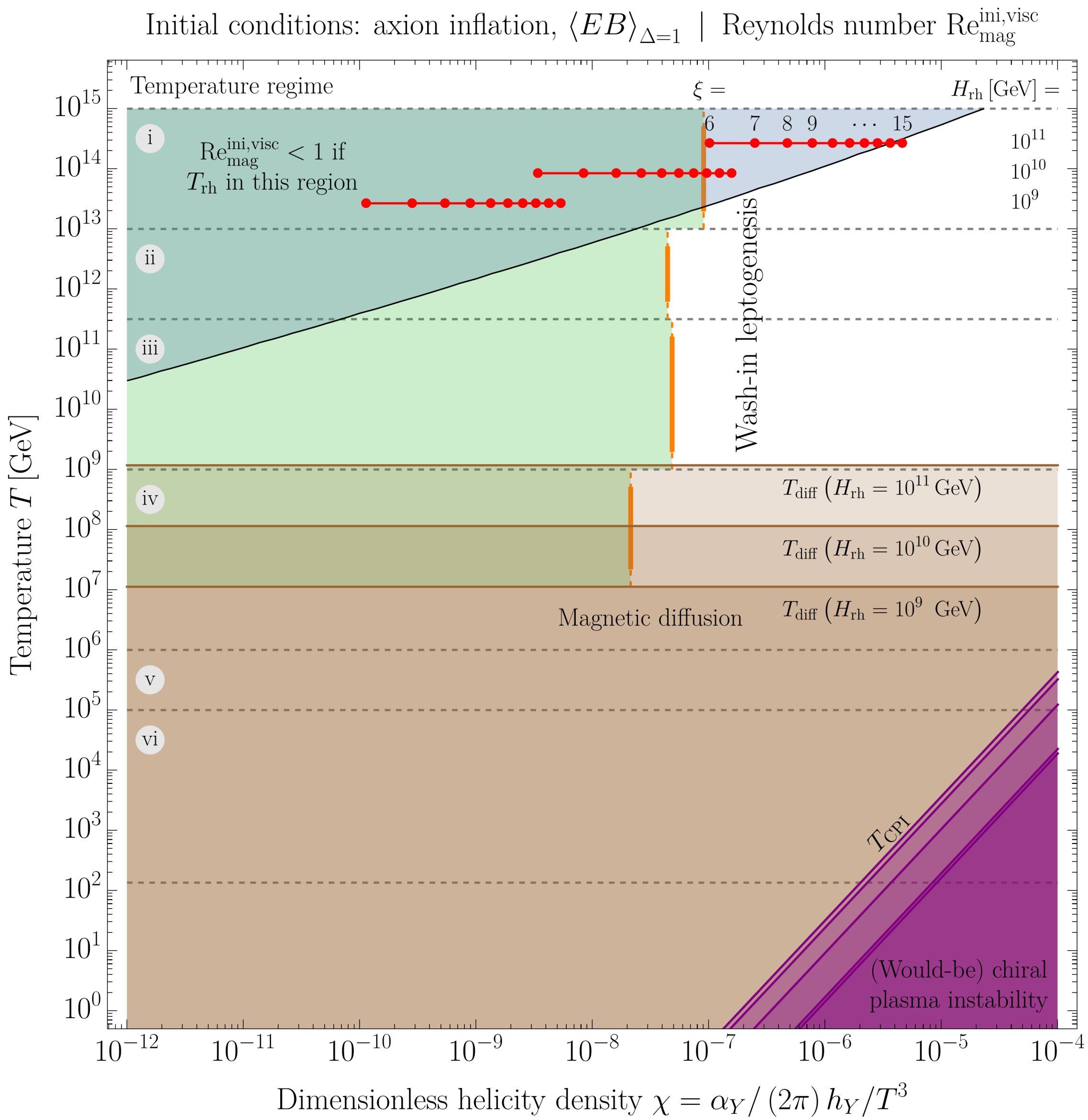
[baryogenesis from axion inflation]



- evolution of primordial asymmetries for axion inflation
- analytical expressions for general initial conditions at all temperature ranges given in

Domcke, Kamada, Mukaida, Schmitz, Yamada \`22

[baryogenesis from axion inflation]



$$\xi = \frac{\alpha_Y \dot{\phi}}{2 H f_a}$$

onset of CPI cancels off
helicity and chemical potentials

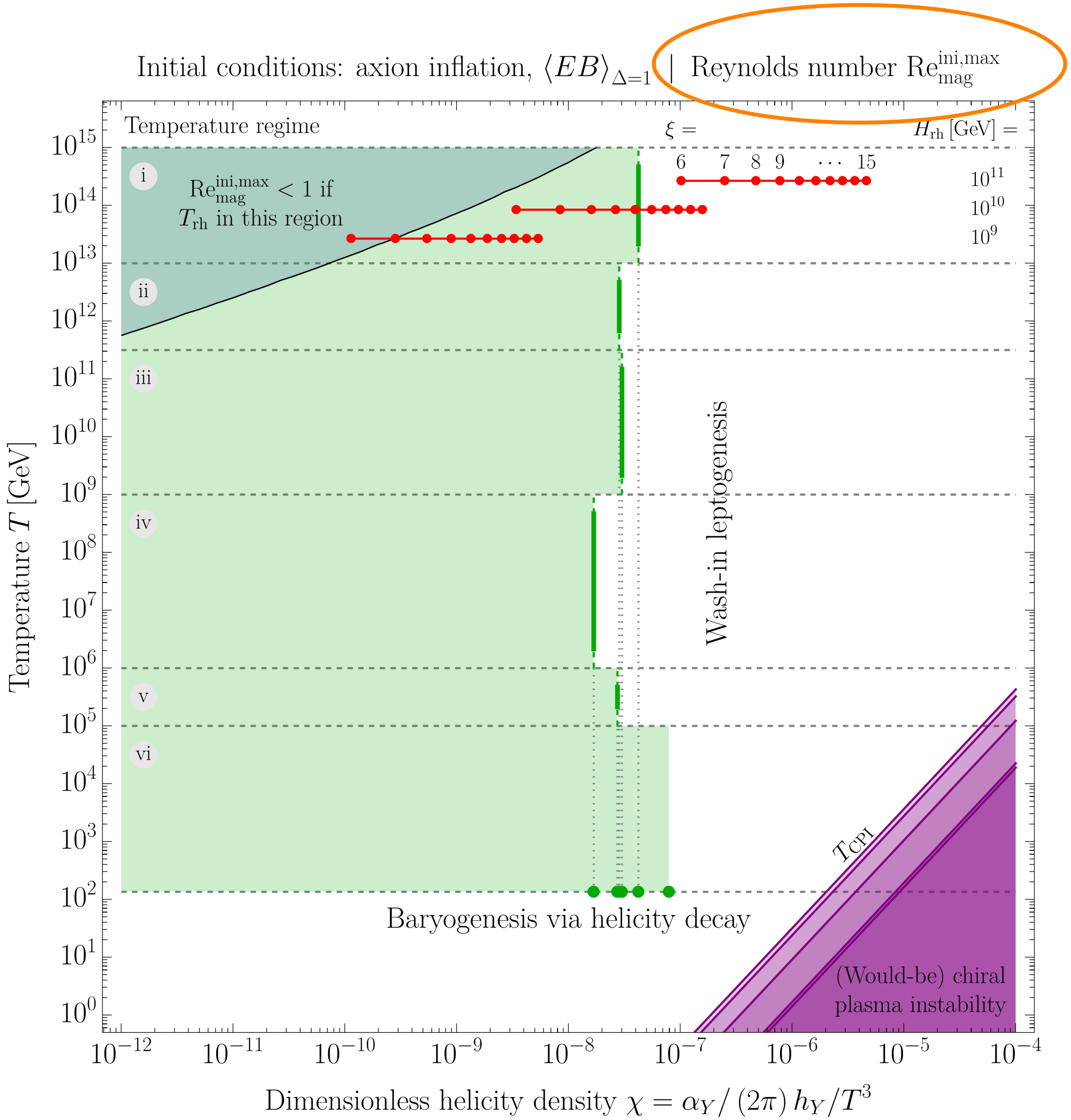
diffusion erases gauge fields
(for conservative estimate of Reynold number)

for RHN mass scale above
diffusion temperature,
successful wash-in leptogenesis

$\chi \sim 10^{-8}$ naturally achieved
in axion inflation

axion inflation can account
for successful baryogenesis

baryogenesis from axion inflation



baryogenesis via helicity decay
and wash-in leptogenesis