Cosmo$\mathcal{L}$attice school:

Lesson 5: Lattice simulations of U(1) gauge theories

Daniel G. Figueroa
IFIC UV/CSIC, Spain

Adrien Florio
Stony Brook U., USA

Francisco Torrenti
U. Basel, Switzerland

CosmoLattice – School 2022

Day 1 (Monday 5th)
- Lesson 1: What is a Lattice?
- Lesson 2: Inflation and post-inflationary dynamics
- Lesson 2b: Primer on Lattice simulations
- Practice

Day 2 (Tuesday 6th)
- Lesson 3: Evolution algorithms ODE
- Lesson 4: Interacting scalar fields in an expanding background
- Topical 1: Gravitational non-minimally coupled scalar fields
- Practice

Day 3 (Wednesday 7th)
- Topical 2: Gravitational waves
- Practice
- Lesson 5: Lattice U(1) gauge theories
- Lesson 6: Lattice SU(2) gauge theories

Day 4 (Thursday 8th)
- Topical 3: Non-linear dynamics of axion inflation
- Lesson 7: Parallelization techniques in CosmoLattice
- Topical 4: Plotting 3D data with CosmoLattice
- Overview + Practice

Introduction to non-linear gauge field dynamics

WHY DO WE WANT TO SIMULATE GAUGE FIELDS IN THE LATTICE?

- **Realistic** physics models must include gauge fields (e.g. the Standard Model).

- Gauge fields can be **significantly excited** in the early universe (both during and after inflation).
  - *Example 1:* Broad parametric resonance of gauge fields coupled to oscillating complex scalars [TODAY!]
  - *Example 2:* Gauge field production during axion inflation [TOMORROW!]

- When $\mathbf{n_k \gg 1}$, gauge fields behave as **classical**, and we can capture their non-linear dynamics with **lattice simulations**.

- **CAVEAT:** Gauge theories must be discretized with **links and plaquettes** in order to preserve **gauge invariance in the lattice** (like in lattice QCD).

Models with gauge fields

Model 1: Gauge fields coupled to charged scalars (SM-like)

$$S = -\int d^4x\sqrt{-g}\left\{(D_\mu\varphi)^*(D^\mu\varphi) + \frac{1}{4}F_{\mu\nu}F^{\mu\nu} + V(|\varphi|)\right\}$$

$$D_\mu \equiv \partial_\mu - ig_A Q_A A_\mu$$
$$F_{\mu\nu} \equiv \partial_\mu A_\nu - \partial_\nu A_\mu$$

+ self-consistent expansion

e.g.: Figueroa, García-Bellido & F.T.: PRD 92 (2015) 8, 083511
Enqvist, Nurmi, Rusak, Weir.: JCAP 02 (2016) 057

TODAY: Lessons 5 [U(1), by me] and 6 [SU(2), by Adrien]

Model 2: Gauge fields coupled to axions (during inflation)

$$S = -\int d^4x\sqrt{-g}\left\{\frac{1}{2}(\partial_\mu\phi)^2 + \frac{1}{4}F_{\mu\nu}F^{\mu\nu} + \frac{\alpha}{4f}\phi F_{\mu\nu}\tilde{F}^{\mu\nu} + V(\phi)\right\}$$

$$F_{\mu\nu} \equiv \partial_\mu A_\nu - \partial_\nu A_\mu$$
$$\tilde{F}_{\mu\nu} \equiv \epsilon_{\mu\nu\alpha\beta}F^{\alpha\beta}$$

+ self-consistent expansion

e.g.: Caravano, Komatsu, Lozanov, Weller: arXiv: 2204.12874
Figueroa, Lizarraga, Urio, Urrestilla: in preparation

TOMORROW: Topical lecture by Joanes and Ander

Table of contents

➤ $\boxed{\text{Equations of motion in the continuum}}$

➤ Gauge invariance in the lattice: links and plaquettes

➤ Implementation in CosmoLattice

- Program variables
- Discretization and evolution algorithms
- Initialization

➤ Example: Abelian-Higgs model

U(1) gauge-invariant action

- We are going to learn how to simulate in the lattice the following action:

POTENTIAL

$$\boxed{S = -\int d^4x\sqrt{-g}\left\{\frac{1}{2}\partial_\mu\phi\partial^\mu\phi + (D_\mu^A\varphi)^*(D_A^\mu\varphi) + \frac{1}{4}F_{\mu\nu}F^{\mu\nu} + V(\phi,|\varphi|)\right\}}$$

g_A **Gauge coupling**

Q_A **Abelian charge**

- **Scalar singlet:** $\phi \in \mathscr{Re}$
- **Complex scalar:** $\varphi \equiv \frac{1}{\sqrt{2}}(\varphi_0 + i\varphi_1)$

  $\varphi_0, \varphi_1 \in \mathscr{Re}$

Scalar sector

- **Covariant derivative:** $D_\mu^A \equiv \partial_\mu - ig_A Q_A A_\mu$
- **Field strength:** $F_{\mu\nu} \equiv \partial_\mu A_\nu - \partial_\nu A_\mu$
  - $\mathscr{E}_i \equiv F_{0i}$ **Electric field**
  - $\mathscr{B}_i \equiv \frac{1}{2}\epsilon_{ijk}F^{jk}$ **Magnetic field**

U(1) gauge sector

- **Fields:** $\{\phi, \varphi_0, \varphi_1, A_1, A_2, A_3\}$ **(we work in the temporal gauge $A_0 = 0$)**

Equations of motion (flat spacetime)

$$\boxed{S = -\int d^4x\sqrt{-g}\left\{\frac{1}{2}\partial_\mu\phi\partial^\mu\phi + (D^A_\mu\varphi)^*(D^\mu_A\varphi) + \frac{1}{4}F_{\mu\nu}F^{\mu\nu} + V(\phi, |\varphi|)\right\}}$$

- **EOM (flat spacetime):** $\delta S = 0$

  - **Scalar singlet:** $\partial^\mu\partial_\mu\phi = \dfrac{\partial V}{\partial\phi}$
  - **Complex scalar:** $D^\mu_A D^A_\mu\varphi = \dfrac{1}{2}\dfrac{\partial V}{\partial|\varphi|}\dfrac{\varphi}{|\varphi|}$
  - **U(1) gauge field:** $\partial_\nu F^{\mu\nu} = J^\mu_A \qquad J^\mu_A \equiv 2g_A Q_A \mathcal{I}m[\varphi^*(D^\mu_A\varphi)]$

    U(1) current

- **Action and EOM are invariant under the following gauge transformations:**

$$\phi(x) \longrightarrow \phi(x)$$
$$\varphi(x) \longrightarrow e^{-ig_A Q_A \alpha(x)}\varphi(x)$$
$$A_\mu(x) \longrightarrow A_\mu(x) - \partial_\mu\alpha(x)$$

$$F_{\mu\nu}(x) \longrightarrow F_{\mu\nu}(x)$$

field strength is gauge invariant

Equations of motion (with expansion)

- **FLRW metric:** $ds^2 = -a^{2\alpha}(\eta)d\eta^2 + a^2(\eta)\delta_{ij}dx^i dx^j$ $\quad d\eta \equiv a^{-\alpha}dt$

- **Dynamical EOM in an expanding background:**

$$\begin{cases} \phi'' - a^{-2(1-\alpha)}\nabla^2\phi + (3-\alpha)\dfrac{a'}{a}\phi' = -a^{2\alpha}V_{,\phi} \\ \varphi'' - a^{-2(1-\alpha)}D_A^2\varphi + (3-\alpha)\dfrac{a'}{a}\varphi' = -\dfrac{a^{2\alpha}V_{,|\varphi|}}{2}\dfrac{\varphi}{|\varphi|} \\ \partial_0 F_{0i} - a^{-2(1-\alpha)}\partial_j F_{ji} + (1-\alpha)\dfrac{a'}{a}F_{0i} = a^{2\alpha}J_i^A \end{cases}$$

U(1) current:

$$J_A^\mu \equiv 2g_A Q_A \mathcal{I}m[\varphi^*(D_A^\mu\varphi)]$$

$$\ddot{A}_i - a^{-2(1-\alpha)}\nabla^2 A_i + \partial_j\partial_i A_j + (1-\alpha)\frac{a'}{a}A_i' = a^{2\alpha}J_i^A$$

- **Gauss constraint:** it must be preserved at all times

$$\partial_i F_{0i} = a^2 J_0^A \longrightarrow \boxed{\nabla\cdot\vec{E} = a^2 J_0^A(\vec{x})} \longrightarrow \int_S \vec{E}\cdot \mathrm{d}\vec{S} = a^2 \underbrace{\int_V \mathrm{d}^3\vec{x}\, J_0^A(\vec{x})}_{:=\,Q\text{ (electric charge)}} = 0$$

V = Lattice

Stress-energy tensor

- **Stress-energy tensor:**

$$T_{\mu\nu} = -\frac{2}{\sqrt{g}}\frac{\delta(\sqrt{g}\mathscr{L})}{\delta g^{\mu\nu}} = g_{\mu\nu}\mathscr{L} - 2\frac{\delta\mathscr{L}}{\delta g^{\mu\nu}} = +\left[2\mathrm{Re}\{(D^A_\mu\varphi)^*(D^A_\nu\varphi)\} + (\partial_\mu\phi)(\partial_\nu\phi)\right] + g^{\alpha\beta}F_{\mu\alpha}F_{\nu\beta}$$
$$-g_{\mu\nu}\left(g^{\alpha\beta}\left[(D^A_\alpha\varphi)^*(D^A_\beta\varphi) + \frac{1}{2}(\partial_\alpha\phi)(\partial_\beta\phi)\right] + \frac{1}{4}g^{\alpha\delta}g^{\beta\lambda}F_{\alpha\beta}F_{\delta\lambda} + V\right)$$

$$\downarrow \quad \bar{\rho} = a^{-2\alpha}\bar{T}_{00} \qquad \bar{p} = \frac{1}{3a^2}\sum_j \bar{T}_{jj}$$

- **Energy density:** $\rho = K_\phi + K_\varphi + G_\phi + G_\varphi + K_{U(1)} + G_{U(1)} + V$
- **Pressure density:** $p = K_\phi + K_\varphi - \frac{1}{3}(G_\phi + G_\varphi) + \frac{1}{3}(K_{U(1)} + G_{U(1)}) - V$

$$K_\phi = \frac{1}{2a^{2\alpha}}\phi'^2 \qquad K_\varphi = \frac{1}{a^{2\alpha}}(D^A_0\varphi)^*(D^A_0\varphi)$$

(Kinetic-scalar)

$$G_\phi = \frac{1}{2a^2}\sum_i(\partial_i\phi)^2 \qquad G_\varphi = \frac{1}{a^2}\sum_i(D^A_i\varphi)^*(D^A_i\varphi)$$

(Gradient-scalar)

$$K_{U(1)} = \frac{1}{2a^{2+2\alpha}}\sum_i F^2_{0i} \qquad G_{U(1)} = \frac{1}{2a^4}\sum_{i,j<i}F^2_{ij}$$

(Electric & Magnetic)

Friedmann equations

- **Friedmann equations:**

$$\left(\frac{a'}{a}\right)^2 = \frac{a^{2\alpha}}{3m_p^2}\langle K_\phi + K_\varphi + G_\phi + G_\varphi + K_{U(1)} + G_{U(1)} + V\rangle$$

$$\frac{a''}{a} = \frac{a^{2\alpha}}{3m_p^2}\langle(\alpha-2)(K_\phi + K_\varphi) + \alpha(G_\phi + G_\varphi) + (\alpha+1)V + (\alpha-1)(K_{U(1)} + G_{U(1)})\rangle$$

Table of contents

- Equations of motion in the continuum
- Gauge invariance in the lattice: links and plaquettes
- Implementation in CosmoLattice
    - Program variables
    - Discretization and evolution algorithms
    - Initialization
- Example: Abelian-Higgs model

Discretization of gauge theories

- In Lesson 4, we discretize the EOM of the scalar fields by **approximating the derivatives in the continuum** by **finite differences in the discrete**.

Example: $\partial_\mu \varphi(\mathbf{n})$

$$\Delta^+_\mu \varphi \equiv \frac{\varphi_{+\mu} - \varphi}{\delta x^\mu} = \partial_\mu \varphi + \mathcal{O}(\delta x^2)$$

$$\Delta^-_\mu \varphi \equiv \frac{\varphi - \varphi_{-\mu}}{\delta x^\mu} = \partial_\mu \varphi + \mathcal{O}(\delta x^2)$$

- CAN WE DO THE SAME FOR **GAUGE FIELDS**? **No.**

- WHY? **This formulation does not preserve gauge invariance in the lattice (and propagates spurious degrees of freedom).**

Gauge invariance in the discrete

$$S = \int d^4x \mathscr{L} \qquad \boxed{-\mathscr{L} = (D_\mu\varphi)^* D^\mu\varphi + \frac{1}{4}F_{\mu\nu}F^{\mu\nu} + V(\varphi^*\varphi)} \qquad e \equiv g_A Q_A$$

➤ **Gauge transformation in the continuum:** $\begin{cases} \varphi(x) \rightarrow e^{-ie\alpha(x)}\varphi(x) \\ A_\mu(x) \rightarrow A_\mu(x) - \partial_\mu\alpha(x) \end{cases}$

$$\boxed{\begin{aligned} (D_\mu\varphi) \equiv \partial_\mu\varphi - ieA_\mu\varphi \quad &\longrightarrow \quad \partial_\mu(e^{-ie\alpha(x)}\varphi(x)) - ie(A_\mu - \partial_\mu\alpha(x))\varphi e^{-ie\alpha(x)} = \\ &= e^{-ie\alpha(x)}\Big(\partial_\mu\varphi(x) - \cancel{ie(\partial_\mu\alpha)\varphi(x)} - ieA_\mu + \cancel{ie\partial_\mu\alpha(x)\varphi(x)}\Big) = e^{-ie\alpha(x)}D_\mu\varphi \end{aligned}}$$

➤ **Gauge transformation in the discrete** **(naive discretization)** $\begin{cases} \varphi(x) \rightarrow e^{-ie\alpha(x)}\varphi(x) \\ A_\mu(x) \rightarrow A_\mu(x) - \Delta_\mu^+\alpha(x) \end{cases}$

$$\boxed{(D_\mu\varphi) \equiv \Delta_\mu^+\varphi - ieA_\mu\varphi \quad \longrightarrow \quad \Delta_\mu^+(e^{-ie\alpha(x)}\varphi(x)) - ie(A_\mu - \Delta_\mu^+\alpha(x))\varphi e^{-ie\alpha(x)} \neq e^{-ie\alpha(x)}D_\mu\varphi}$$

[The Leibniz rule $(fg)' = fg' + f'g$ does not hold for finite difference operators]

Links and plaquettes

We must discretize the theory with links and plaquettes in order to preserve GAUGE INVARIANCE in the lattice.

- **Parallel transporter:** Connects two points of spacetime $dx^\mu = (d\eta, dx^i)$

$$V(x,y) = \mathrm{Pexp}\left(-ie\int_x^y dx^\mu A_\mu(x)\right)$$

Gauge transformation:

$$V(x,y) \longrightarrow V(x,y)e^{-ie(\alpha(x)-\alpha(y))}$$

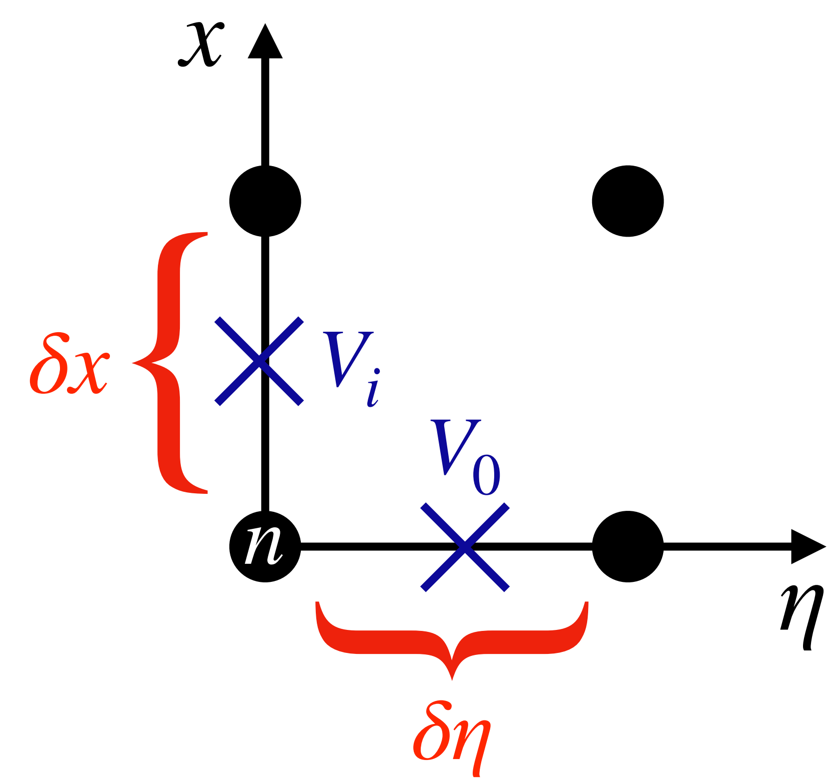
$[A_\mu(x) \to A_\mu(x) - \partial_\mu\alpha(x)]$

- **Links:** (minimal connectors)

$$V_{0,n} \equiv \exp\left\{-ie\int_{x(n)}^{x(n+\hat{0})} d\eta' A_0\right\} \approx e^{-ie\delta\eta A_0}$$

$$V_{i,n} \equiv \exp\left\{-ie\int_{x(n)}^{x(n+\hat{i})} dx' A_i\right\} \approx e^{-ie\delta x A_i}$$

gauge fields and links live in points $n + \hat{\mu}/2$



- **Notation:** $V_\mu \equiv V_\mu(n + \frac{1}{2}\hat{\mu})$ $\quad V_{-\mu} \equiv V^*_{\mu,-\mu}$

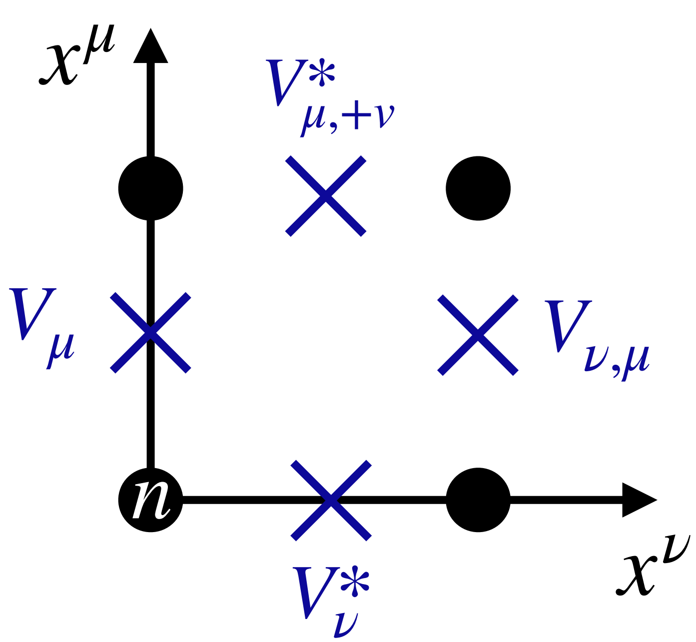
Links and plaquettes

- **Gauge covariant derivative:**

$$\left.\begin{aligned}\varphi &\longrightarrow e^{ie\alpha(x)}\varphi\\ A_\mu &\longrightarrow A_\mu - \Delta_\mu^+\alpha\\ V_{\pm\mu} &\longrightarrow V_{\pm\mu}e^{ie(\alpha_{\pm\mu}-\alpha)}\end{aligned}\right\} \Rightarrow \boxed{(D_\mu^\pm\varphi)(\mathbf{l}) = \pm\frac{1}{\delta x^\mu}(V_{\pm\mu}\varphi_{\pm\mu}-\varphi)} \qquad \hat{\mathbf{l}} = \hat{\mathbf{n}} + \frac{1}{2}\hat{\mu}$$

- *Expansion:* $(D_\mu^\pm\varphi)(\mathbf{l}) = (D_\mu\varphi)(\mathbf{l}) + \mathcal{O}(\delta x^2)$
- *Gauge transform.:* $D_\mu^\pm\varphi \to e^{ie\alpha}(D_\mu^\pm\varphi)$

- **Plaquettes:** $\boxed{V_{\mu\nu} \equiv V_\mu V^*_{\mu,+\nu}V_{\nu,+\mu}V^*_\nu \simeq e^{-ie\delta x_\mu\delta x_\nu[F_{\mu\nu}+\mathcal{O}(\mathrm{dx})]}}$



- *Expansion:*

$$\mathscr{Re}\{V_{\mu\nu}\} \longrightarrow 1 - \frac{1}{2}\delta x_\mu^2\delta x_\nu^2 e^2F_{\mu\nu}^2 + \mathcal{O}(\delta x^5)$$

$$\mathscr{Im}\{V_{\mu\nu}\} \longrightarrow -\,\delta x_\mu\delta x_\nu eF_{\mu\nu} + \mathcal{O}(\delta x^3) \qquad \mathbf{l} = \mathbf{n} + \frac{1}{2}\hat{\mu} + \frac{1}{2}\hat{\nu}$$

- *Gauge transform.:* $V_{\mu\nu} \longrightarrow V_{\mu\nu}$

Compact and non-compact formulations

Two formulations for U(1) gauge fields:

$$\begin{cases} \text{Non-compact: based on gauge field amplitudes } A_\mu \\ \text{Compact: based on links } V_\mu \end{cases}$$

U(1) toolkit:

$$\text{Links}: V_\mu \equiv e^{-ig_AQ_A\delta x_\mu A_\mu} = \cos(g_AQ_A\delta x_\mu A_\mu) - i\sin(g_AQ_A\delta x_\mu A_\mu);\quad V_{-\mu}\equiv V^*_{\mu,-\mu};\quad V^*_\mu V_\mu = 1\,;$$

$$\text{Plaquettes}: V_{\mu\nu}\equiv V_\mu V_{\mu,+\mu}V^*_{\mu,+\nu}V^*_\nu \simeq e^{-ig_AQ_A\delta x_\mu\delta x_\nu[F_{\mu\nu}+\mathcal{O}(\delta x)]};\quad V^*_{\mu\nu} = V_{\nu\mu}\,;$$

$$\text{Covariant Derivs.}: (D^\pm_\mu\varphi)(\mathbf{l}) = \pm\frac{1}{\delta x^\mu}(V_{\pm\mu}\varphi_{\pm\mu}-\varphi)\,,\quad \mathbf{l} = \mathbf{n}\pm\frac{1}{2}\hat\mu$$

$$\text{Expansions}: \begin{cases} (D^\pm_\mu\varphi)(\mathbf{l}) \longrightarrow (D_\mu\varphi)(\mathbf{l}) + \mathcal{O}(\delta x^2) & \mathbf{l}=\mathbf{n}\pm\frac{1}{2}\hat\mu \\ \mathcal{R}e\{V_{\mu\nu}\} \longrightarrow 1-\frac{1}{2}\delta x_\mu^2\delta x_\nu^2 g_A^2Q_A^2F^2_{\mu\nu} + \mathcal{O}(\delta x^5)\,, & \mathbf{l}=\mathbf{n}+\frac{1}{2}\hat\mu+\frac{1}{2}\hat\nu \\ \mathcal{I}m\{V_{\mu\nu}\} \longrightarrow -\delta x_\mu\delta x_\nu g_AQ_AF_{\mu\nu} + \mathcal{O}(\delta x^3)\,, & \mathbf{l}=\mathbf{n}+\frac{1}{2}\hat\mu+\frac{1}{2}\hat\nu \end{cases}$$

$$\text{Expressions}: \begin{cases} \left.\begin{array}{l} \sum_n \frac{1}{4}F^2_{\mu\nu} \cong -\frac{1}{2}\sum_n \frac{\mathcal{R}e\{V_{\mu\nu}\}}{\delta x_\mu^2\delta x_\nu^2 g_A^2Q_A^2} = -\frac{1}{4}\sum_n\frac{(V_{\mu\nu}+V^*_{\mu\nu})}{\delta x_\mu^2\delta x_\nu^2g_A^2Q_A^2} + \mathcal{O}(\delta x^2) \\ \sum_n\frac{1}{4}F^2_{\mu\nu}\simeq\sum_n\frac{1}{4}\frac{\mathcal{I}m^2\{V_{\mu\nu}\}}{\delta x_\mu^2\delta x_\nu^2g_A^2Q_A^2} = -\sum_n\frac{1}{4}\frac{(V_{\mu\nu}-V^*_{\mu\nu})^2}{\delta x_\mu^2\delta x_\nu^2g_A^2Q_A^2}+\mathcal{O}(\delta x^2)\end{array}\right] & (\texttt{Compact}) \\ \sum_n\frac{1}{4}F^2_{\mu\nu}\simeq\frac{1}{4}\sum_n(\Delta^+_\mu A_\nu - \Delta^+_\nu A_\mu)^2 + \mathcal{O}(\delta x^2)\ ] & (\texttt{Non-Compact}) \end{cases}$$

$$\text{Gauge Trans.}: \left\{\begin{array}{lcl} \phi & \longrightarrow & e^{+ig_AQ_A\alpha}\phi \\ A_\mu & \longrightarrow & A_\mu - \Delta^+_\mu\alpha \\ V_{\pm\mu} & \longrightarrow & V_{\pm\mu}e^{ig_AQ_A(\alpha_{\pm\mu}-\alpha)} \end{array}\right] \Longrightarrow \begin{cases} D^\pm_\mu\phi \longrightarrow e^{ig_AQ_A\alpha}(D^\pm_\mu\phi) \\ V_{\mu\nu} \longrightarrow V_{\mu\nu}\ \text{(gauge inv.)}\end{cases}$$

NOTE: SU(2) theories can only be formulated with a compact formulation [see Lesson 6]

Table of contents

Gauge EOM in program variables

- **Program variables:**

$$d\tilde{\eta} \equiv a^{-\alpha}\omega_* dt \qquad d\tilde{x}^i \equiv \omega_* dx^i$$

$$\tilde{\varphi} \equiv \frac{1}{f_*}\varphi \qquad \widetilde{A}_\mu \equiv \frac{1}{\omega_*}A_\mu$$

Link:

$$V_\mu = e^{-i\delta x_\mu A^\mu} = e^{-i\delta\tilde{x}_\mu \tilde{A}^\mu}$$

Program potential:

$$\tilde{V}(|\tilde{\varphi}|) = \frac{1}{f_*^2\omega_*^2}V(f_*|\varphi|)$$

$$\widetilde{F}_{\mu\nu} \equiv F_{\mu\nu}/\omega_*^2$$
$$\widetilde{D}_\mu \equiv D_\mu/\omega_*$$
$$\tilde{J}^\mu_A \equiv 2g_A Q_A \mathcal{I}m[\tilde{\varphi}^*(\tilde{D}^\mu\tilde{\varphi})]$$

- **Field equations (in the continuum):**

$$(a^{3-\alpha}\tilde{\varphi}')' - a^{1+\alpha}\overrightarrow{\widetilde{D}}^2\tilde{\varphi} = -a^{\alpha+3}\widetilde{V}_{,|\tilde{\varphi}|}\frac{\tilde{\varphi}}{2|\tilde{\varphi}|}$$

$$\tilde{\partial}_0(a^{1-\alpha}\widetilde{F}_{0i}) - a^{\alpha-1}\partial_j\widetilde{F}_{ji} = a^{1+\alpha}\tilde{J}^A_i$$

Conjugate momenta:

$$\tilde{\pi}_\varphi \equiv a^{3-\alpha}\tilde{\varphi}'$$

$$(\tilde{\pi}_A)_i \equiv a^{1-\alpha}\widetilde{F}_{0i} = a^{1-\alpha}A_i'$$

$$(\tilde{\pi}_\varphi)' = \mathcal{K}_\varphi[a,\tilde{\varphi},\widetilde{A}_j] \qquad \mathcal{K}_\varphi[a,\tilde{\varphi},\widetilde{A}_j] \equiv -a^{\alpha+3}\widetilde{V}_{,|\tilde{\varphi}|}\frac{\tilde{\varphi}}{2|\tilde{\varphi}|} + a^{1+\alpha}\overrightarrow{\widetilde{D}}^2\tilde{\varphi}$$

$$(\pi_A)_i' = \mathcal{K}_{A_i}[a,\tilde{\varphi},\widetilde{A}_j] \qquad \mathcal{K}_{A_i}[a,\tilde{\varphi},\widetilde{A}_j] \equiv a^{1+\alpha}\tilde{J}^A_i + a^{\alpha-1}\tilde{\partial}_j\widetilde{F}_{ji}$$

$$\tilde{\varphi}' = a^{\alpha-3}\tilde{\pi}_\varphi$$

$$A_i' = a^{\alpha-1}(\tilde{\pi}_A)_i$$

Gauge EOM in program variables

- **Second Friedmann equation (dynamical):** $b \equiv a' = da/d\tilde{\eta}$

$$b' = \mathcal{K}_a\left[a, \widetilde{E}^{\varphi}_K, \widetilde{E}^{\varphi}_G, \widetilde{E}^{\varphi}_V, \widetilde{E}^{A}_K, \widetilde{E}^{A}_G\right]$$

$$\mathcal{K}_a\left[a, \widetilde{E}^{\varphi}_K, \widetilde{E}^{\varphi}_G, \widetilde{E}^{\varphi}_V, \widetilde{E}^{A}_K, \widetilde{E}^{A}_G\right] \equiv \frac{a^{2\alpha+1}}{3}\frac{f_*^2}{m_p^2}\left[(\alpha-2)\widetilde{E}^{\varphi}_K + \alpha\widetilde{E}^{\varphi}_G + (\alpha+1)\widetilde{E}_V + (\alpha-1)(\widetilde{E}^{A}_K + \widetilde{E}^{A}_G)\right]$$

- **First Friedmann equation (constraint):**

$$b^2 = \frac{1}{3}\left(\frac{f_*}{m_p}\right)^2 a^{2(\alpha+1)}\left[\widetilde{E}^{\varphi}_K + \widetilde{E}^{\varphi}_G + \widetilde{E}_V + \widetilde{E}^{A}_K + \widetilde{E}^{A}_G\right]$$

with:

$$\widetilde{E}^{\varphi}_K = \frac{1}{a^6}\left\langle \tilde{\pi}^2_{\varphi}\right\rangle \qquad \widetilde{E}^{A}_K = \frac{1}{2a^4}\frac{\omega_*^2}{f_*^2}\sum_{i=1}^{3}\left\langle(\tilde{\pi}_A)^2_i\right\rangle$$

$$\widetilde{E}^{\varphi}_G = \frac{1}{a^2}\langle \sum_i (\widetilde{D}^A_i\varphi)^*(\widetilde{D}^A_i\widetilde{\varphi})\rangle \qquad \widetilde{E}^{A}_G = \frac{1}{2a^4}\frac{\omega_*^2}{f_*^2}\sum_{i,j<i}\langle \widetilde{F}^2_{ij}\rangle \qquad \widetilde{E}_V = \left\langle \widetilde{V}(\tilde{\varphi},\ldots)\right\rangle$$

(Complex scalar: Kinetic and gradient) *(Electric and magnetic)* *(Potential)*

Table of contents

Discretization of gauge field equations

➤ We can discretize the field equations by using the U(1) toolkit (non-compact):

<u>CONTINUOUS</u> <u>DISCRETE</u>

- *Kernels:*

$$\mathscr{K}_{\varphi}[a,\tilde{\varphi},\widetilde{A}_j] = -a^{\alpha+3}\widetilde{V}_{,|\tilde{\varphi}|}\frac{\tilde{\varphi}}{2|\tilde{\varphi}|} + a^{1+\alpha}\overrightarrow{\widetilde{D}}^2\tilde{\varphi} \longrightarrow \mathscr{K}_{\varphi}[a,\tilde{\varphi},\widetilde{A}_i] = -a^{\alpha+3}\frac{\widetilde{V}_{,|\tilde{\varphi}|}}{2}\frac{\tilde{\varphi}}{|\tilde{\varphi}|} + a^{1+\alpha}\sum_i \widetilde{D}_i^-\widetilde{D}_i^+\tilde{\varphi}$$

$$\mathscr{K}_{A_i}[a,\tilde{\varphi},\widetilde{A}_j] = 2a^{1+\alpha}g_AQ_A\mathscr{I}m[\tilde{\varphi}^*(\tilde{D}_i\tilde{\varphi})] + a^{\alpha-1}\tilde{\partial}_j\widetilde{F}_{ji} \longrightarrow \mathscr{K}_{A_i}[a,\tilde{\varphi},\widetilde{A}_j] = a^{1+\alpha}\left(\frac{2g_AQ_A}{\delta\tilde{x}}\frac{f_*^2}{\omega_*^2}\mathscr{I}m[\tilde{\varphi}^*e^{-i\delta x\tilde{A}^i}\tilde{\varphi}]\right) + a^{\alpha-1}\sum_j\left(\tilde{\Delta}_j^-\tilde{\Delta}_j^+\widetilde{A}_i - \tilde{\Delta}_j^-\tilde{\Delta}_i^+\widetilde{A}_j\right)$$

- *Energies:*

$$\widetilde{E}_G^{\varphi} = \frac{1}{a^2}\langle\sum_i(\widetilde{D}_i^A\varphi)^*(\widetilde{D}_i^A\widetilde{\varphi})\rangle \longrightarrow \widetilde{E}_G^{\varphi} = \frac{1}{a^2}\sum_i\left\langle(\tilde{D}_i^+\tilde{\varphi})^*(\tilde{D}_i^+\tilde{\varphi})\right\rangle$$

$$\widetilde{E}_G^{A} = \frac{1}{2a^4}\frac{\omega_*^2}{f_*^2}\sum_{i,j<i}\langle\widetilde{F}_{ij}^2\rangle \longrightarrow \widetilde{E}_G^{A} = \frac{1}{2a^4}\frac{\omega_*^2}{f_*^2}\sum_{i,j<i}\left\langle(\tilde{\Delta}_i^+\widetilde{A}_j - \tilde{\Delta}_j^+\widetilde{A}_i)^2\right\rangle$$

And now we solve them with an appropriate evolution algorithm!

Evolution algorithms for gauge theories

(Non-compact) Staggered leapfrog algorithm

- *Initial conditions:* $\left\{a, \tilde{\varphi}, \widetilde{A}_i\right\}$ at $\tilde{\eta}_0$, $\left\{b_{-1/2}, (\tilde{\pi}_\varphi)_{-1/2}, (\tilde{\pi}_A)_{i,-1/2}\right\}$ at $\tilde{\eta}_0 - \frac{\delta\tilde{\eta}}{2}$.

- *Evolution:*

$$\begin{aligned}
(\tilde{\pi}_\varphi)_{+1/2} &= (\tilde{\pi}_\varphi)_{-1/2} + \delta\tilde{\eta}\mathcal{K}_\varphi[a, \tilde{\varphi}, \widetilde{A}_i]\,, \\
(\tilde{\pi}_A)_{i,+1/2} &= (\tilde{\pi}_A)_{i,-1/2} + \delta\tilde{\eta}\mathcal{K}_{A_i}[a, \tilde{\varphi}, \widetilde{A}_j]\,, \\
b_{+1/2} &= b_{-1/2} + \delta\tilde{\eta}\mathcal{K}_a\left[a, \overline{\widetilde{E}_K^\varphi}, \widetilde{E}_G^\varphi, \widetilde{E}_V^\varphi, \overline{\widetilde{E}_K^A}, \widetilde{E}_G^A\right]\,, \\
a_{+0} &= a + \delta\tilde{\eta} b_{+1/2}\,, \\
a_{+1/2} &= (a_{+0} + a)/2\,, \\
\tilde{\varphi}_{+0} &= \tilde{\varphi} + \delta\tilde{\eta} a_{+1/2}^{-(3-\alpha)} (\tilde{\pi}_\varphi)_{+1/2}\,, \\
\widetilde{A}_{i,+0} &= \widetilde{A}_i + \delta\tilde{\eta} a_{+1/2}^{-(1-\alpha)} (\tilde{\pi}_A)_{i,+1/2}\,,
\end{aligned}$$

- *Hubble constraint:* $b^2 = \frac{1}{3}\left(\frac{f_*}{m_p}\right)^2 a^{2(\alpha+1)}\left[\overline{\widetilde{E}_K^\varphi} + \widetilde{E}_G^\varphi + \widetilde{E}_V + \overline{\widetilde{E}_K^A} + \widetilde{E}_G^A\right]$

Evolution algorithms for gauge theories

(Non-compact) Velocity-Verlet algorithm

- *Initial conditions:* $\left\{a, b, \tilde{\varphi}, \tilde{\pi}_\varphi, \widetilde{A}_i, (\tilde{\pi}_A)_i\right\}$ at η_0.

- *Evolution:*

$$
\begin{aligned}
(\tilde{\pi}_\varphi)_{+1/2} &= \tilde{\pi}_\varphi + \frac{\delta\tilde{\eta}}{2}\mathcal{K}_\varphi[a, \tilde{\varphi}, \widetilde{A}_j]\,,\\
(\tilde{\pi}_A)_{i,+1/2} &= (\tilde{\pi}_A)_i + \frac{\delta\tilde{\eta}}{2}\mathcal{K}_{A_i}[a, \tilde{\varphi}, \widetilde{A}_j]\,,\\
b_{+1/2} &= b + \frac{\delta\tilde{\eta}}{2}\mathcal{K}_a\left[a, \widetilde{E}_K^\varphi, \widetilde{E}_G^\varphi, \widetilde{E}_V^\varphi, \widetilde{E}_K^A, \widetilde{E}_G^A\right],\\
a_{+0} &= a + \delta\tilde{\eta} b_{+1/2}\,,\\
a_{+1/2} &= \frac{a_{+0} + a}{2}\,,\\
\tilde{\varphi}_{+0} &= \tilde{\varphi} + \delta\tilde{\eta}\frac{(\tilde{\pi}_\varphi)_{+1/2}}{a_{+1/2}^{3-\alpha}}\,,\\
\widetilde{A}_{i,+0} &= \widetilde{A}_i + \delta\tilde{\eta}\frac{(\tilde{\pi}_A)_{+1/2}}{a_{+1/2}^{1-\alpha}}\,,\\
(\tilde{\pi}_\varphi)_{+0} &= (\tilde{\pi}_\varphi)_{+1/2} + \frac{\delta\tilde{\eta}}{2}\mathcal{K}_\varphi[a_{+0}, \tilde{\varphi}_{+0}, \widetilde{A}_{j,+0}]\,,\\
(\tilde{\pi}_A)_{i,+0} &= (\tilde{\pi}_A)_{i,+1/2} + \frac{\delta\tilde{\eta}}{2}\mathcal{K}_{A_i}[a_{+0}, \tilde{\varphi}_{+0}, \widetilde{A}_{j,+0}]\,,\\
b_{+0} &= b_{+1/2} + \frac{\delta\tilde{\eta}}{2}\mathcal{K}_a\left[a_{+0}, \widetilde{E}_{K,+0}^\varphi, \widetilde{E}_{G,+0}^\varphi, \widetilde{E}_{V,+0}^\varphi, \widetilde{E}_{K,+0}^A, \widetilde{E}_{G,+0}^A\right],
\end{aligned}
$$

Generalization to VV4 - VV10 implemented in CosmoLattice (and explained in the "Art")

- *Hubble constraint:* $b^2 = \frac{1}{3}\left(\frac{f_*}{m_p}\right)^2 a^{2(\alpha+1)}\left[\widetilde{E}_K^\varphi + \widetilde{E}_G^\varphi + \widetilde{E}_V + \widetilde{E}_K^A + \widetilde{E}_G^A\right]$

Table of contents

Initial conditions for complex scalars

- **Initial condition for complex scalars:**

$$\varphi \equiv \frac{1}{\sqrt{2}}(\varphi_0 + i\varphi_1) \quad \longrightarrow \quad \boxed{\begin{aligned} \varphi_n(\mathbf{x}, t_*) &\equiv |\varphi_*| + \delta\varphi_{n_*}(\mathbf{x}) \\ \dot{\varphi}_n(\mathbf{x}, t_*) &\equiv |\dot{\varphi}_*| + \delta\dot{\varphi}_{n*}(\mathbf{x}) \end{aligned}} \qquad n = 0,1$$

Homogeneous mode

Fluctuations

- For **complex scalars** we **try** to set the same spectrum of initial fluctuations as for scalar singlets (see **Lesson 2**):

$$\boxed{\begin{aligned} \delta\tilde{\varphi}_n(\tilde{\mathbf{n}}) &= \frac{1}{\sqrt{2}}\left(|\delta\tilde{\varphi}_n^{(l)}(\tilde{\mathbf{n}})|\, e^{i\theta_n^{(l)}(\tilde{\mathbf{n}})} + |\delta\tilde{\varphi}_n^{(r)}(\tilde{\mathbf{n}})|\, e^{i\theta_n^{(r)}(\tilde{\mathbf{n}})}\right) \\ \delta\tilde{\varphi}_n{}'(\tilde{\mathbf{n}}) &= \frac{1}{a^{1-\alpha}}\left[\frac{i\tilde{\omega}_{k,\varphi_n}}{\sqrt{2}}\left(|\delta\tilde{\varphi}_n^{(l)}(\tilde{\mathbf{n}})|\, e^{i\theta_n^{(l)}(\tilde{\mathbf{n}})} - |\delta\tilde{\varphi}_n^{(r)}(\tilde{\mathbf{n}})|\, e^{i\theta_n^{(r)}(\tilde{\mathbf{n}})}\right)\right] - \tilde{\mathcal{H}}\,\delta\tilde{\varphi}_n(\tilde{\mathbf{n}}) \end{aligned}}$$

$|\delta\tilde{\phi}^{(l,r)}(\tilde{\mathbf{n}})|$: Rayleigh distribution with expected **(*)**

$\theta^{(l,r)}(\tilde{\mathbf{n}})$: Random phase in range [0,2π]

$$\tilde{\omega}_{k,\varphi_n} \equiv \sqrt{\tilde{k}^2 + a^2(\partial^2\tilde{V}/\partial\tilde{\varphi}_n^2)}$$

$$\tilde{\mathcal{H}} \equiv a^\alpha H/\omega_*$$

(in principle)
8 random functions

Initial conditions for gauge fields

- For **gauge fields** we only set fluctuations to the time-derivative:

$$\boxed{\begin{aligned} A_i(\mathbf{x}, t_*) &\equiv 0 \\ \dot{A}_i(\mathbf{x}, t_*) &\equiv \delta \dot{A}_{i*}(\mathbf{x}) \end{aligned}}$$

→ **Initially we have some electric field, but zero magnetic field**

- But the fluctuations must preserve the **Gauss constraint**:

$$\partial_i \dot{A}_i(\mathbf{x}) = J_0^A(\mathbf{x}) \xrightarrow{\text{Fourier transform}} k^i \dot{A}_i(\mathbf{k}) = J_0^A(\mathbf{k}) \longrightarrow \boxed{\dot{A}_i(\mathbf{k}) = i\frac{k_i}{k^2} J_0^A(\mathbf{k})}$$

$$J_0^A(\mathbf{x}) \equiv 2 g_A Q_A^{(\varphi)} \mathcal{I}m[\varphi^* \varphi']$$

Initial spectrum for electric field

- In the discrete:

$$\sum_i \Delta_i^- \Delta_0^+ A_i(\mathbf{n}) = J_0^A(\mathbf{n}) \longrightarrow \Delta_0^+ A_i(\tilde{\mathbf{n}}) = i \frac{k^-_{\mathrm{Lat},i}}{(k^-_{\mathrm{Lat},i})^2} J_0^A(\tilde{\mathbf{n}})$$

$$k^-_{\mathrm{Lat},i} = \frac{\sin(2\pi \tilde{n}_i/N)}{\delta x} - i \frac{1 - \cos(2\pi \tilde{n}_i/N)}{\delta x}$$

Initial conditions for gauge fields

- We want zero electric charge in the lattice, so we require:

$$Q = J_0^A(\mathbf{k}=\mathbf{0}) = \int d^3\mathbf{x} J_0^A(\mathbf{x}) \propto \int d^3\mathbf{k}\,\mathscr{R}e[\varphi_0^*(\mathbf{k})\varphi_1'(\mathbf{k}) - \varphi_0'(\mathbf{k})\varphi_1^*(\mathbf{k})] \overset{!}{=} 0$$

3 constraints:

$$|\delta\varphi_0^{(l)}(\mathbf{k})| = |\delta\varphi_0^{(r)}(\mathbf{k})|$$

$$|\delta\varphi_1^{(l)}(\mathbf{k})| = |\delta\varphi_1^{(r)}(\mathbf{k})|$$

$$\theta_1^{(r)}(\mathbf{k}) = \theta_0^{(r)}(\mathbf{k}) + \theta_1^{(l)}(\mathbf{k}) - \theta_0^{(l)}(\mathbf{k})$$

Table of contents

Example: Abelian-Higgs model

- As an example, we are going to simulate an **Abelian gauge model:**

$$\boxed{S = -\int d^4x\sqrt{-g}\left\{(D_\mu^A\varphi)^*(D_A^\mu\varphi) + \frac{1}{4}F_{\mu\nu}F^{\mu\nu} + V(|\varphi|)\right\}}$$

+ self-consistent expansion

$$\boxed{V(|\varphi|) = \lambda|\varphi|^4 = \frac{\lambda}{4}(\varphi_0 + \varphi_1)^4}$$

$$\varphi \equiv \frac{1}{\sqrt{2}}(\varphi_0 + i\varphi_1)$$

- We chose **program variables** analogously to scalar model:

$$f_* = |\varphi_*|$$
$$\omega_* = \sqrt{\lambda}\,|\varphi_*|$$
$$\alpha = 1$$

PROGRAM POTENTIAL:

$$\tilde{\varphi} \equiv \varphi/f_*$$

$$\boxed{\tilde{V}(|\tilde{\varphi}|) \equiv \frac{1}{f_*^2\omega_*^2}V(f_*|\varphi|) = |\tilde{\varphi}|^4}$$

- **Initial conditions:** We distribute the complex scalar amplitude equally between its components:

$$\varphi_0 = \varphi_1 = \phi_*/\sqrt{2} \qquad \dot{\varphi}_0 = \dot{\varphi}_1 = \dot{\phi}_*/\sqrt{2}$$

amplitude for the end of inflation in $\lambda\varphi^4$ potential

Example: Abelian-Higgs model

<u>This model is implemented in the file `lphi4U1.h` of CosmoLattice.</u>

- **In the model file (`lphi4U1.h`):**

```
struct ModelPars : public TempLat::DefaultModelPars{
    static constexpr size_t NScalars = 0;
    static constexpr size_t NCScalars = 1;
    static constexpr size_t NU1Flds = 1;
    static constexpr size_t NSU2Doublet = 0;
    static constexpr size_t NSU2Flds = 0;
    static constexpr size_t NPotTerms = 1;

    // Coupling managers:  they deal with the different couplings between
    // the gauge fields and complex scalars/SU2 doublets
    //  --> If a type of interaction is not present, comment the corresponding line
    typedef TempLat::CouplingsManager<NCScalars, NU1Flds,true> CsU1Couplings;
  // typedef TempLat::CouplingsManager<NSU2Doublet, NU1Flds, true> SU2DoubletU1Couplings;
  // typedef TempLat::CouplingsManager<NSU2Doublet, NSU2Flds,true> SU2DoubletSU2Couplings;
};
```

Number of fields for each species

Coupling managers (sets which complex scalars are coupled to the U(1) gauge sector)

Example: Abelian-Higgs model

➤ **In the parameter file** (lphi4U1.in)**:**

```
#IC
kCutOff = 6
initial_amplitudes = 0
initial_momenta = 0
cmplx_field_initial_norm = 5.25151e18     # homogeneous amplitudes in GeV
cmplx_momentum_initial_norm = -4.45258e30 # homogeneous amplitudes in GeV2

#Gauge couplings and effectiveCharges
CSU1Charges = 1
gU1s = 1.11037e-05

#Model Parameters
lambda = 9e-14
```

$\rightarrow |\varphi_*|, |\dot{\varphi}_*|$

$\rightarrow Q_A, g_A$

$\rightarrow \lambda$

➤ **In the model file** (lphi4U1.h)**:**

```
// COMPLEX SCALAR NORM: initial homogeneous amplitude and derivative
double normCmplx0 = parser.get<double>("cmplx_field_initial_norm");
double normPiCmplx0 = parser.get<double>("cmplx_momentum_initial_norm");

// We distribute the norm equally between the two components using the "Complexify" function
fldCS0(0_c) = Complexify(normCmplx0 / sqrt(2.0), normCmplx0 / sqrt(2.0));
piCS0(0_c)  = Complexify(normPiCmplx0 / sqrt(2.0), normPiCmplx0 / sqrt(2.0));
```

→ Reads initial homogeneous modes from input file

→ Sets the initial values for complex scalars: $\varphi = \left(\frac{|\varphi_*|}{\sqrt{2}}, \frac{|\varphi_*|}{\sqrt{2}}\right)$ $\dot{\varphi} = \left(\frac{|\dot{\varphi}_*|}{\sqrt{2}}, \frac{|\dot{\varphi}_*|}{\sqrt{2}}\right)$

Example: Abelian-Higgs model

- In the model file (`lphi4U1.h`):

```
alpha = 1;
fStar = normCmplx0;
omegaStar = sqrt(lambda) * normCmplx0;
```

$\rightarrow f_* = |\varphi_*|, \quad \omega_* = \sqrt{\lambda}\,|\varphi_*|, \quad \alpha = 1$

```
auto potentialTerms(Tag<0>) // Term 0: Qua
{
    return  pow<4>(norm(fldCS(0_c)));
}
```

$\rightarrow \tilde{V}(|\tilde{\varphi}|) = |\tilde{\varphi}|^4$

```
auto potDerivNormCS(Tag<0>) // Derivative
{
    return 4 * pow<3>(norm(fldCS(0_c)));
}
```

$\rightarrow \tilde{V}_{,|\tilde{\varphi}|}(|\tilde{\varphi}|) = 4|\tilde{\varphi}|^3$

```
auto potDeriv2NormCS(Tag<0>) // 2nd derivati
{
    return  12 * pow<2>(norm(fldCS(0_c)));
}
```

$\rightarrow \tilde{V}_{,|\tilde{\varphi}||\tilde{\varphi}|}(|\tilde{\varphi}|) = 12|\tilde{\varphi}|^2$

Generic model with multiple fields

➤ Consider a model with **Np potential terms, Ns scalar singlets** and **Nc complex scalars**:

$$\boxed{\tilde{V} = \tilde{V}(\tilde{\phi}_0, \ldots, \tilde{\phi}_{N_s}, |\tilde{\varphi}_0|, \ldots, |\tilde{\varphi}_{N_c}|) = \tilde{V}^{(0)}(\ldots) + \ldots + \tilde{V}^{(Nt)}(\ldots)}$$

your model file must have:

- **Np potentialTerms functions:** $\{\tilde{V}^{(0)}, \ldots, \tilde{V}^{(N_t)}\}$
- **Ns potDeriv functions:** $\{\tilde{V}_{,\tilde{\phi}_0}, \ldots, \tilde{V}_{,\tilde{\phi}_{N_s}}\}$
- **Ns potDeriv2 functions:** $\{\tilde{V}_{,\tilde{\phi}_0\tilde{\phi}_0}, \ldots, \tilde{V}_{,\tilde{\phi}_{N_s}\tilde{\phi}_{N_s}}\}$
- **Nc potDerivNormCS functions:** $\{\tilde{V}_{,|\tilde{\varphi}_0|}, \ldots, \tilde{V}_{,|\tilde{\varphi}_{N_c}|}\}$
- **Nc potDerivNorm2CS functions:** $\{\tilde{V}_{,|\tilde{\varphi}_0||\tilde{\varphi}_0|}, \ldots, \tilde{V}_{,|\tilde{\varphi}_{N_c}||\tilde{\varphi}_{N_c}|}\}$

Output from CosmoLattice

- `average_norm_cmplx_scalar_[nfld].txt`: $\tilde{\eta}$, $\langle|\tilde{\varphi}|\rangle$, $\langle|\tilde{\varphi}'|\rangle$, $\langle|\tilde{\varphi}|^2\rangle$, $\langle|\tilde{\varphi}'|^2\rangle$, $\mathrm{rms}(|\tilde{\varphi}|)$, $\mathrm{rms}(|\tilde{\varphi}'|)$
- `average_[Re/Im]_cmplx_scalar_[nfld].txt`: $\tilde{\eta}$, $\langle\tilde{\varphi}_n\rangle$, $\langle\tilde{\varphi}'_n\rangle$, $\langle\tilde{\varphi}^2_n\rangle$, $\langle\tilde{\varphi}'^2_n\rangle$, $\mathrm{rms}(\tilde{\varphi}_n)$, $\mathrm{rms}(\tilde{\varphi}'_n)$
- `average_norm_[U1]_[nfld].txt`: $\tilde{\eta}$, $\langle|\vec{\tilde{\mathcal{E}}}|\rangle$, $\langle|\vec{\tilde{\mathcal{B}}}|\rangle$, $\langle|\vec{\tilde{\mathcal{E}}}|^2\rangle$, $\langle|\vec{\tilde{\mathcal{B}}}|^2\rangle$, $\mathrm{rms}(|\vec{\tilde{\mathcal{E}}}|)$, $\mathrm{rms}(|\vec{\tilde{\mathcal{B}}}|)$

- `average_energies.txt`:

$$\tilde{\eta},\ \tilde{E}_K^{(\phi,0)},\ \tilde{E}_G^{(\phi,0)},\ \dots\ ,\ \tilde{E}_K^{(\phi,N_s-1)},\ \tilde{E}_G^{(\phi,N_s-1)},\ \tilde{E}_K^{(\varphi,0)},\ \tilde{E}_G^{(\varphi,0)},\ \dots\ ,\ \tilde{E}_K^{(\varphi,N_c-1)},\ \tilde{E}_G^{(\varphi,N_c-1)},$$
$$\tilde{E}_K^{(\Phi,0)},\ \tilde{E}_G^{(\Phi,0)},\ \dots\ ,\ \tilde{E}_K^{(\Phi,N_d-1)},\ \tilde{E}_G^{(\Phi,N_d-1)},\ \tilde{E}_K^{(A,0)},\ \tilde{E}_G^{(A,0)},\ \dots\ ,\ \tilde{E}_K^{(A,N_{u1}-1)},\ \tilde{E}_G^{(A,N_{u1}-1)},$$
$$\tilde{E}_V^{(0)},\ \dots,\ \tilde{E}_V^{(N_p-1)},\ \langle\tilde{\rho}\rangle$$

- `average_gauss_[U1/SU2]_[nfld].txt`: $\tilde{\eta}$, $\frac{\langle\sqrt{(\mathrm{LHS}-\mathrm{RHS})^2}\rangle}{\langle\sqrt{(\mathrm{LHS}+\mathrm{RHS})^2}\rangle}$, $\langle\sqrt{(\mathrm{LHS}-\mathrm{RHS})^2}\rangle$, $\langle\sqrt{(\mathrm{LHS}+\mathrm{RHS})^2}\rangle$.
- `spectra_norm_cmplx_scalar_[nfld].txt`: $\tilde{k}$, $\widetilde{\Delta}_{\tilde{\varphi}}(\tilde{k})$, $\widetilde{\Delta}_{\tilde{\varphi}'}(\tilde{k})$, $\tilde{n}_{\tilde{k}}$, Δn_{bin}
- `spectra_norm_[U1/SU2]_[nfld].txt`: $\tilde{k}$, $\widetilde{\Delta}_{\tilde{\mathcal{E}}}(\tilde{k})$ $\widetilde{\Delta}_{\tilde{\mathcal{B}}}(\tilde{k})$, Δn_{bin}

Example: Abelian-Higgs model

Source term

$$\ddot{A}_i - a^{-2(1-\alpha)}\nabla^2 A_i + \partial_j\partial_i A_j + (1-\alpha)\frac{a'}{a}A_i' = \overbrace{a^{2\alpha}J_i^A}$$

$$J_A^i \equiv 2g_AQ_A\mathcal{I}m[\varphi^*(\partial_i\varphi - ig_AQ_AA_i\varphi)]$$

contains

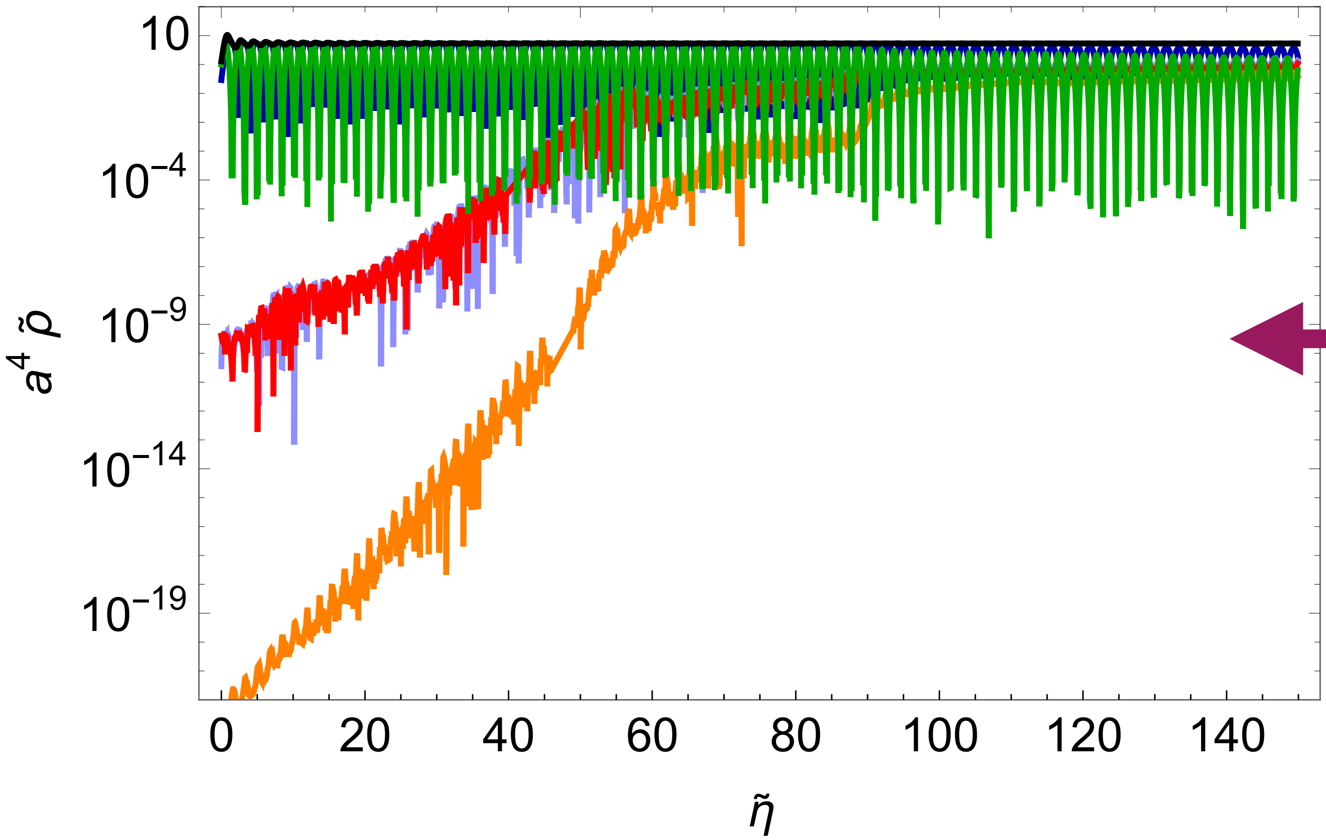
Similar to the source term
of the analogous scalar equation

$$g_AQ_A|\varphi|^2A_i$$

Gauge fields coupled to charged scalars with a monomial potential
experience parametric resonance
(similar to the scalar case seen in Lesson 2)

Explicit comparison between scalar and gauge simulations:
D.G. Figueroa, J. García-Bellido and F.T.: **PRD 92 (2015) 8, 083511**

Example: Abelian-Higgs model



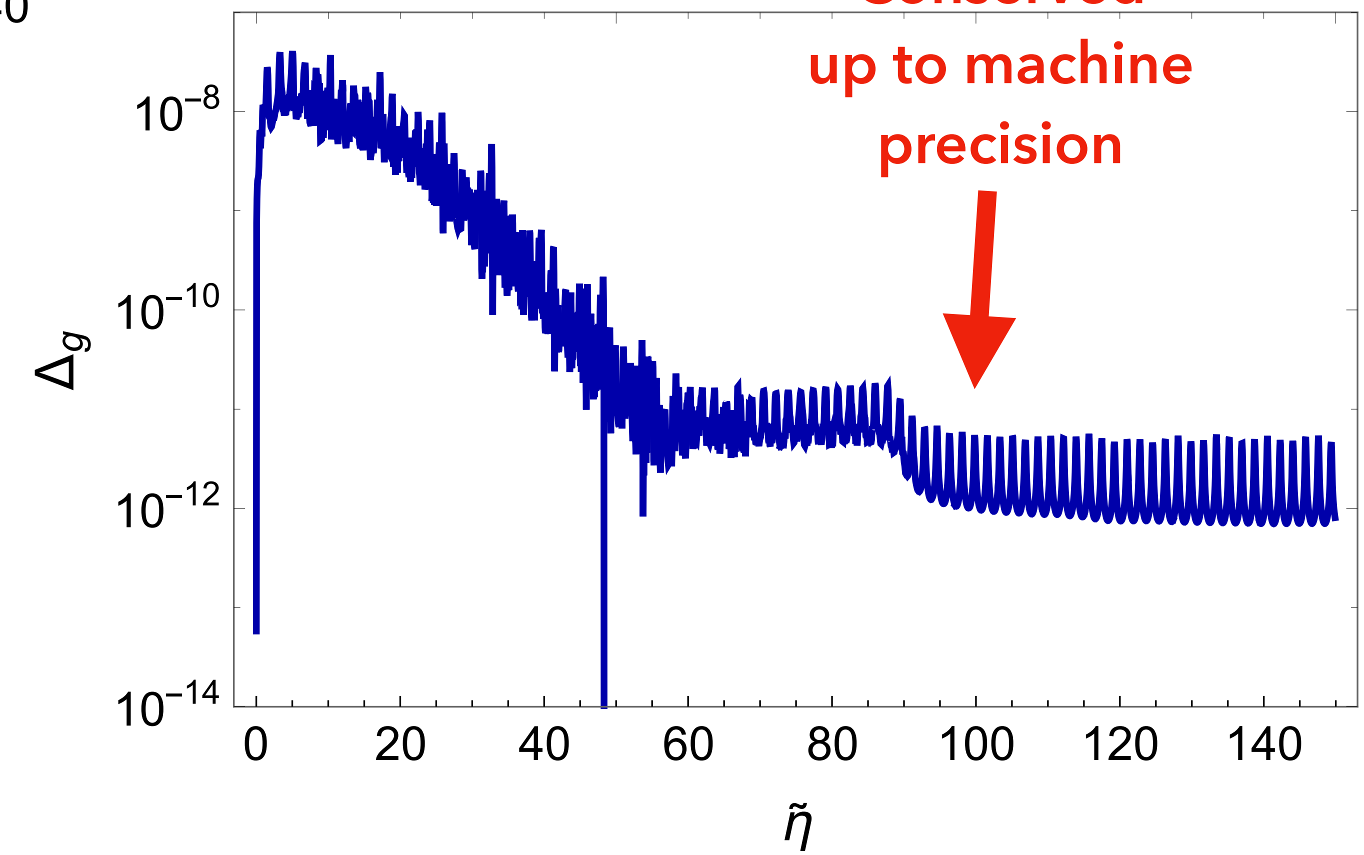
Energy density:

$$\tilde{\rho} = \frac{1}{f_*^2\omega_*^2}\left(\widetilde{E}_K^{\varphi} + \widetilde{E}_G^{\varphi} + \widetilde{E}_K^{A} + \widetilde{E}_G^{A} + \widetilde{E}_V\right)$$

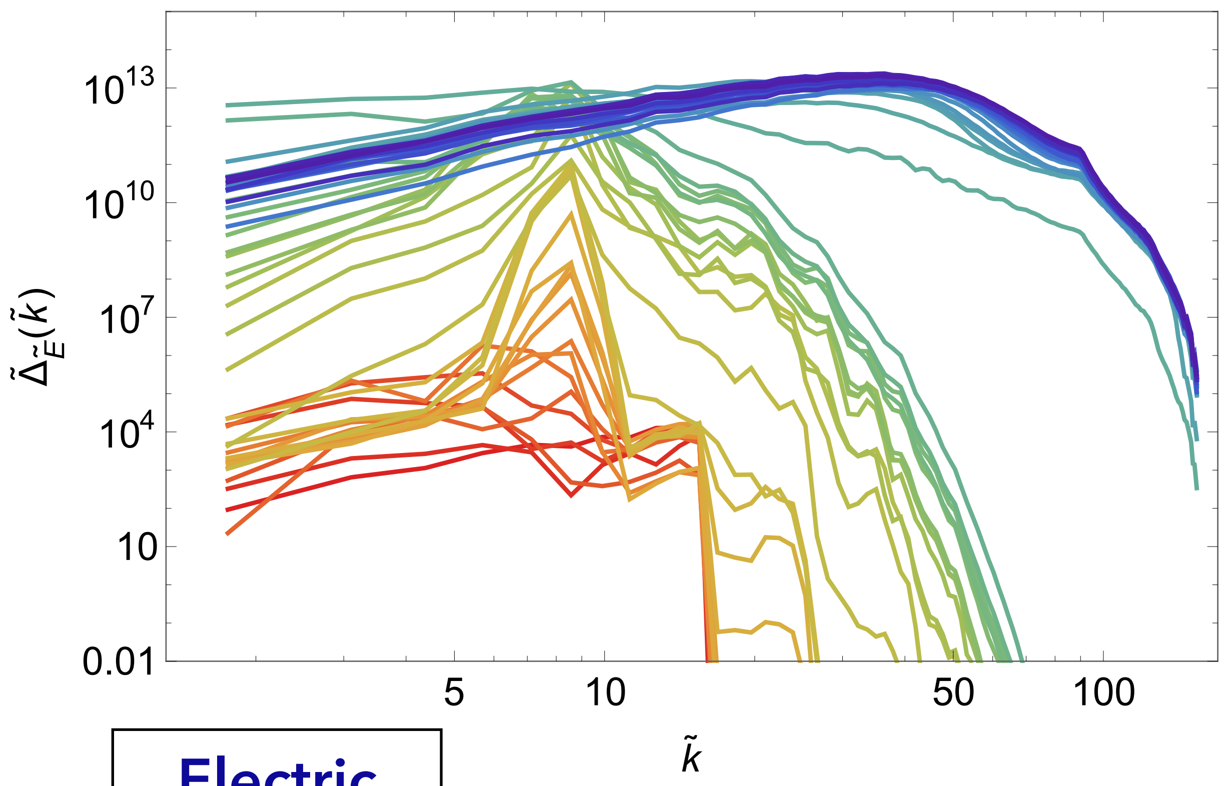
Gauss law conservation:

$$\underset{LHS}{\Delta_i^-\Delta_0^+A_i} = \underset{RHS}{a^2J_0^A}$$

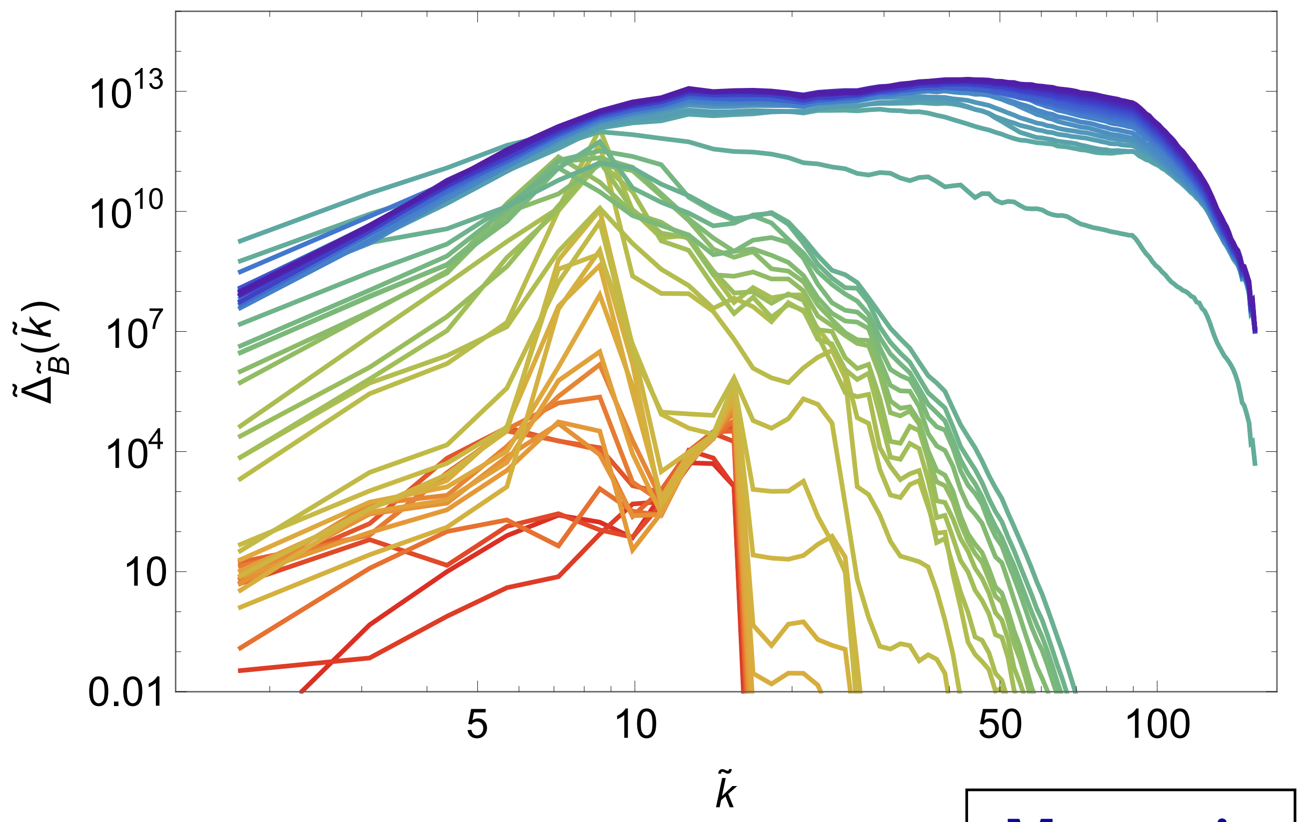
$$\Delta_g \equiv \frac{\langle\sqrt{(LHS-RHS)^2}\rangle}{\langle\sqrt{(LHS+RHS)^2}\rangle}$$



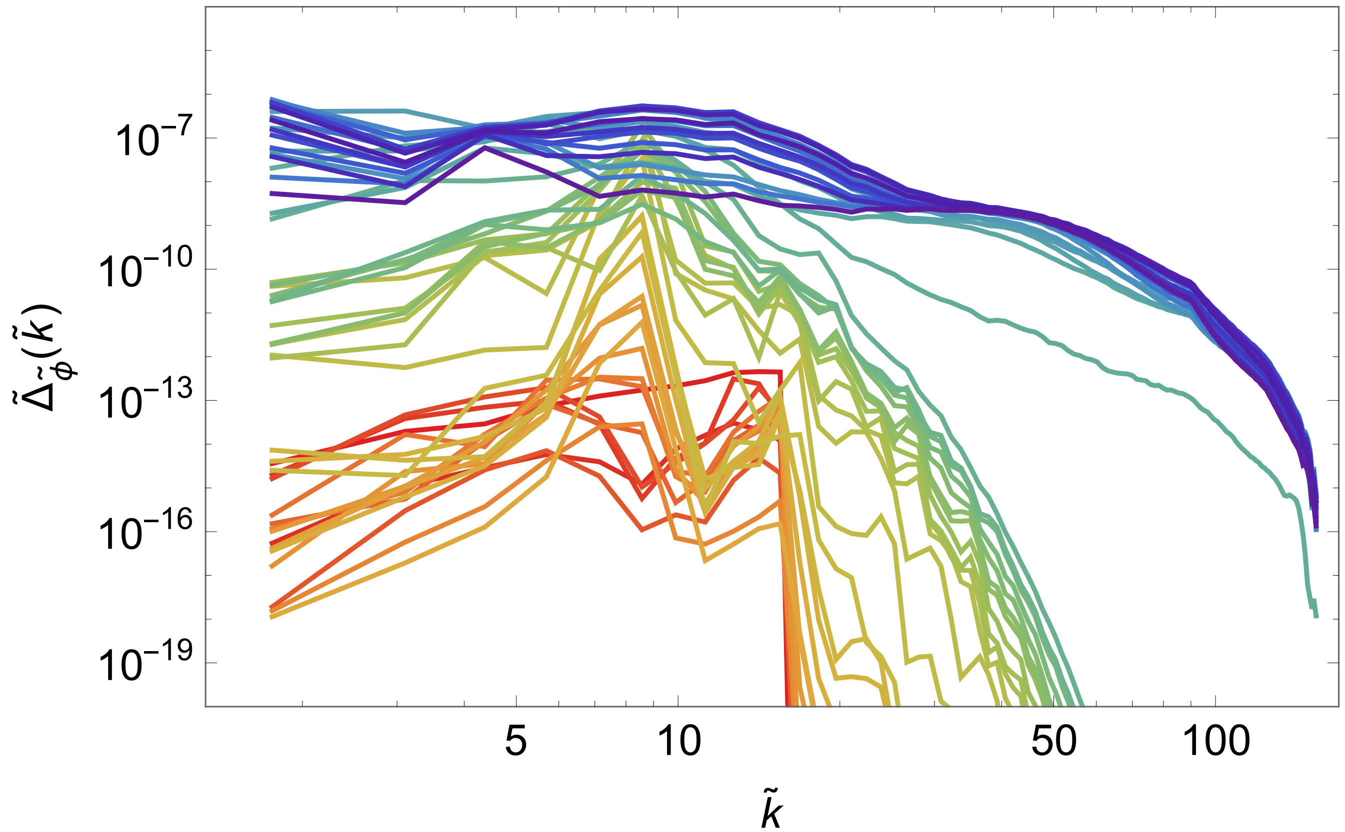
Example: Abelian-Higgs model



Electric spectra



Magnetic spectra



Complex scalar spectra

Thank you!