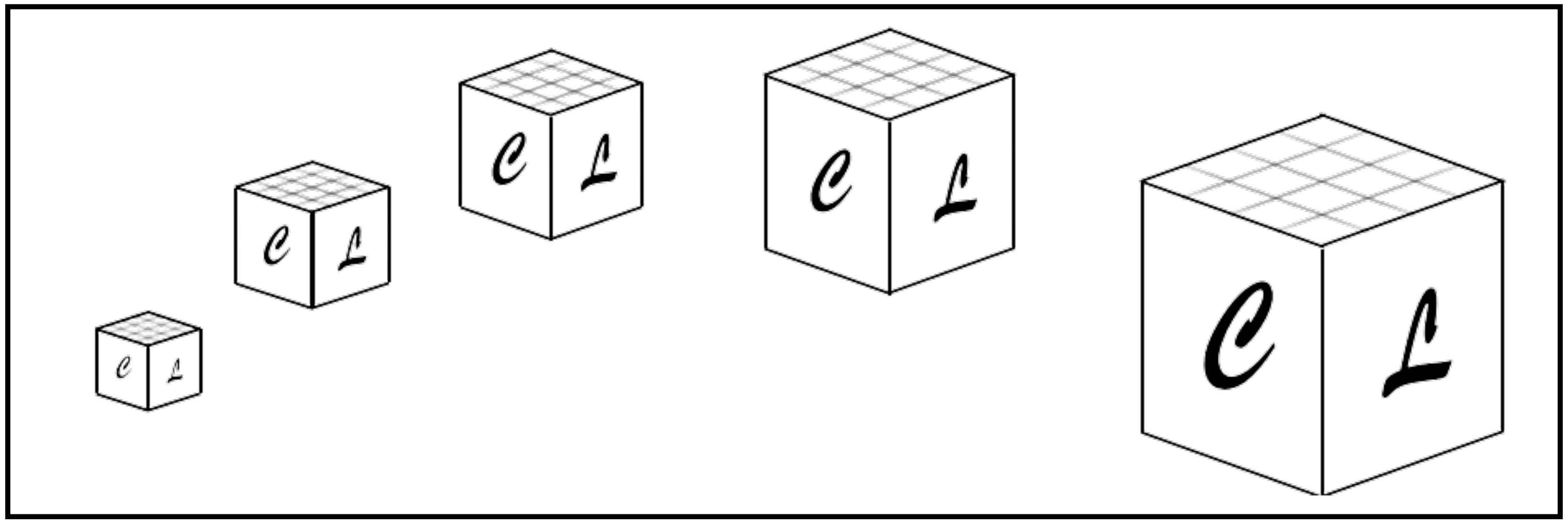
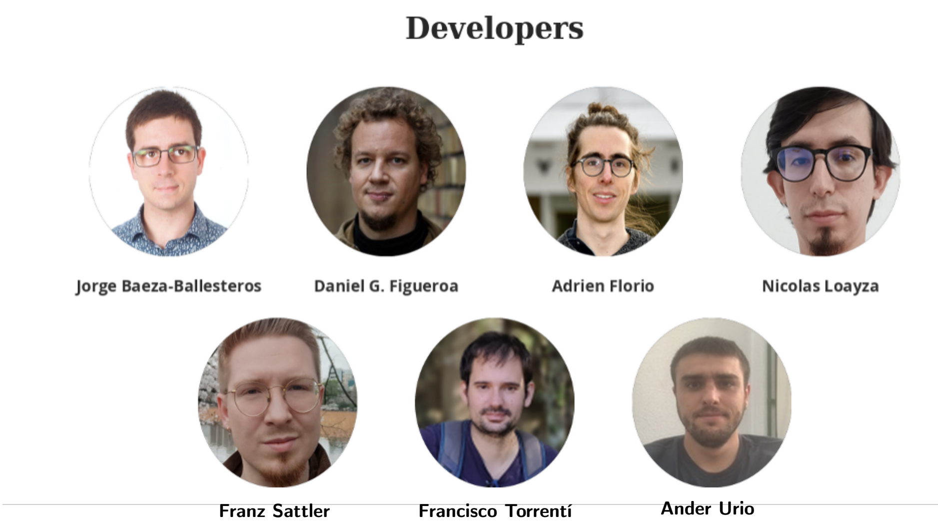


New features of CosmoLattice v2.0

Francisco Torrentí

U. Carlos III, Madrid

Based on slides prepared by Franz Sattler



CosmoLattice 2.0

Preliminary "alpha" of **CosmoLattice 2.0** available in GitHub:

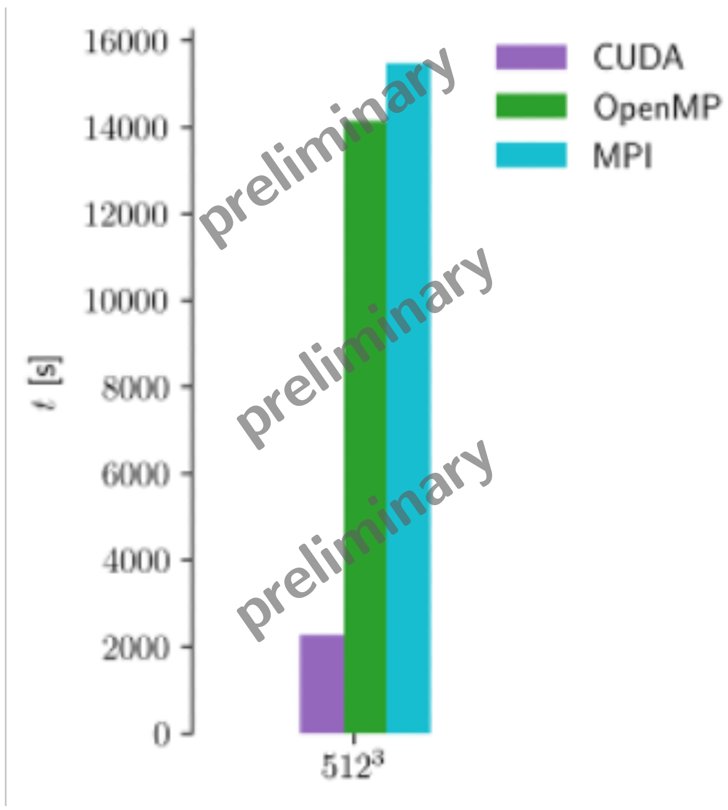
git checkout CLV2.0Alpha

- Doesn't include everything planned for the final version.
- It contains bugs $\longrightarrow$ **use at your own discretion!!**
- Undocumented $\longrightarrow$ **please do not write us e-mails**
- If you find a critical error $\longrightarrow$ **let us know!**

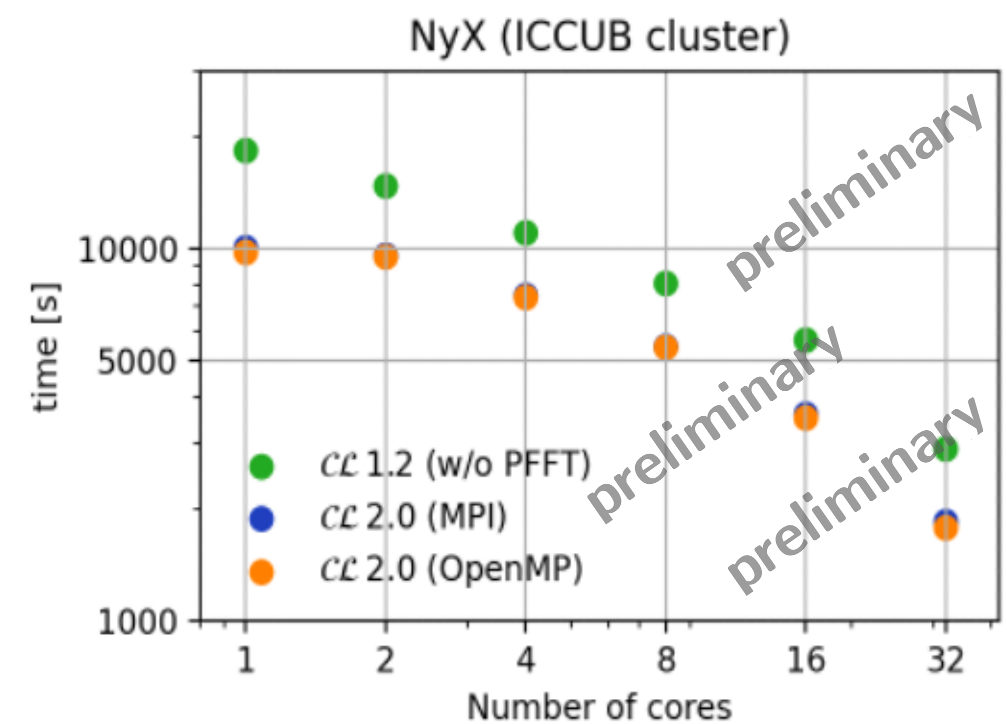
Expected public release in Summer 2026

CosmoLattice 2.0 performance

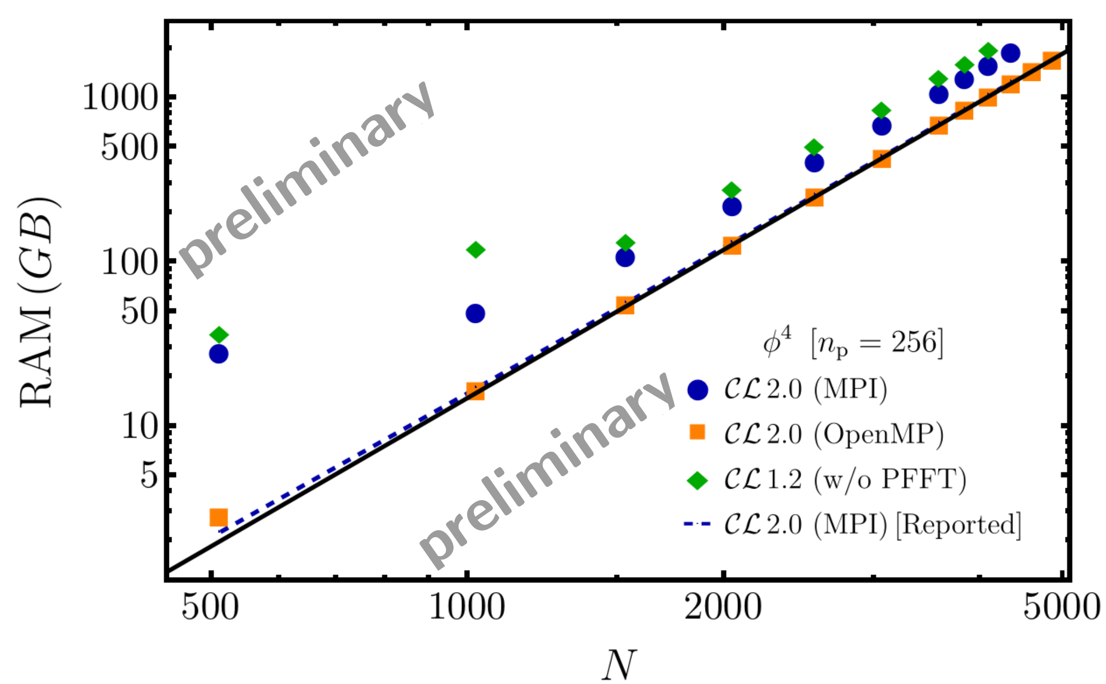
Significant speedups by using GPUs



Improved CPU-only performance



Less memory consumption



Axion-gauge interactions

$$\mathscr{L} = \partial_\mu\phi\partial^\mu\phi + V(\phi) + \frac{1}{4}F^{\mu\nu}_{\mu\nu} - \boxed{\frac{\alpha_\Lambda}{4}\frac{\phi}{m_{\rm pl}}F_{\mu\nu}\tilde{F}^{\mu\nu}}$$

$$\left.\begin{array}{rcll}
\ddot{\phi} &=& -3H\dot{\phi} + \frac{1}{a^2}\vec{\nabla}^2\phi - V_{,\phi} + \frac{\alpha_\Lambda}{a^3 m_p}\vec{E}\cdot\vec{B}\,, & \\
\dot{\vec{E}} &=& -H\vec{E} - \frac{1}{a^2}\vec{\nabla}\times\vec{B} - \frac{\alpha_\Lambda}{a m_p}\left(\dot{\phi}\vec{B} + \vec{\nabla}\phi\cdot\vec{E}\right), & \\
\ddot{a} &=& -\frac{a}{3m_p^2}\left(2\rho_{\rm K} - \rho_{\rm V} + \rho_{\rm EM}\right)\,, & \\
\vec{\nabla}\cdot\vec{E} &=& -\frac{\alpha_\Lambda}{a m_p}\vec{\nabla}\phi\cdot\vec{B}\,, & \texttt{[Gauss law]} \\
H^2 &=& \frac{1}{3m_p^2}\left(\rho_{\rm K} + \rho_{\rm G} + \rho_{\rm V} + \rho_{\rm EM}\right)\,, & \texttt{[Hubble law]}
\end{array}\right\}$$

On the right:

1) Backreaction after end of inflation
2) Backreation during end of slow-roll
3) Backreaction during slow-roll

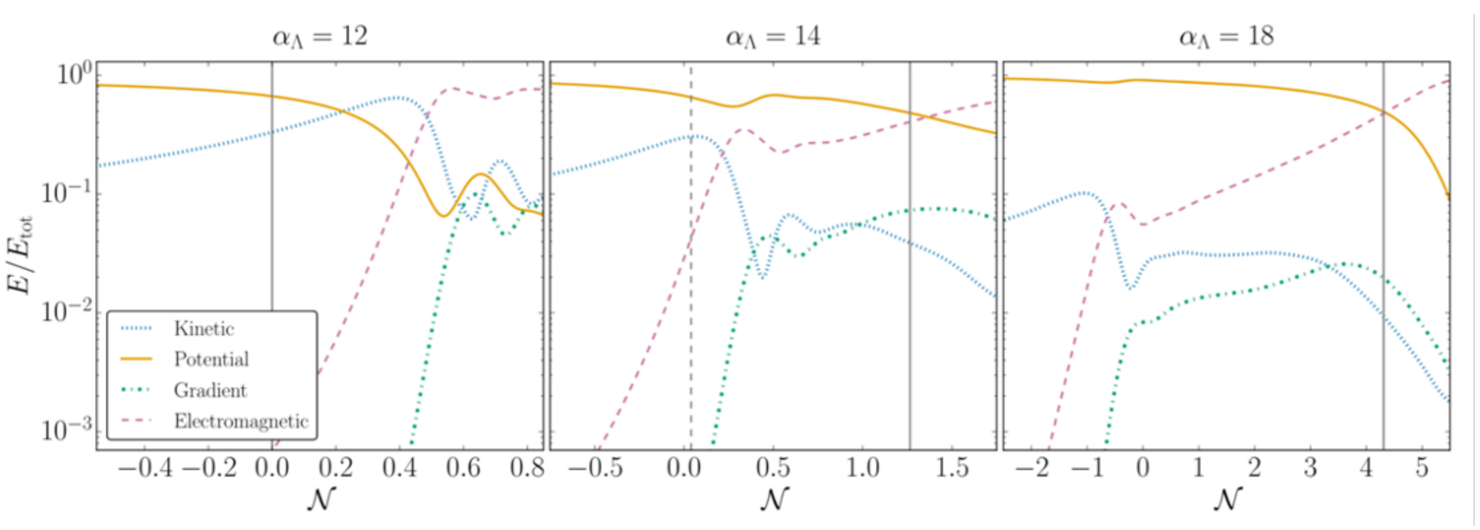


Figure: Figueroa, Lizarraga, Loayza, Urio, Urrestilla; Phys.Rev.D 111 (2025) 6, 063545

Non-minimal couplings to curvature

$$S = \int d^4x\sqrt{-g}\left(\frac{1}{2}m_{\rm pl}^2 R - \boxed{\frac{1}{2}\xi R\phi^2} - \frac{1}{2}g^{\mu\nu}\partial_\mu\phi\partial_\nu\phi + \dots\right)$$

$$[\texttt{Minimally coupled}]\begin{cases} \varphi_m' = a^{\alpha-3}\pi_{\varphi_m}\,, \\ \pi_{\varphi_m}' = a^{1+\alpha}\,\nabla^2\varphi - a^{3+\alpha}V_{,\varphi_m}\,, \end{cases}$$

$$[\texttt{Non-minimally coupled}]\begin{cases} \phi' = a^{\alpha-3}\pi_\phi\,, \\ \pi_\phi' = a^{1+\alpha}\,\nabla^2\phi - a^{3+\alpha}\left(\xi R\phi + V_{,\phi}\right)\,, \end{cases}$$

$$[\texttt{Expanding background}]\begin{cases} a' = a^{\alpha-1}\pi_a\,, \\ \pi_a' = \frac{a^{2+\alpha}}{6}R\,, \end{cases}$$

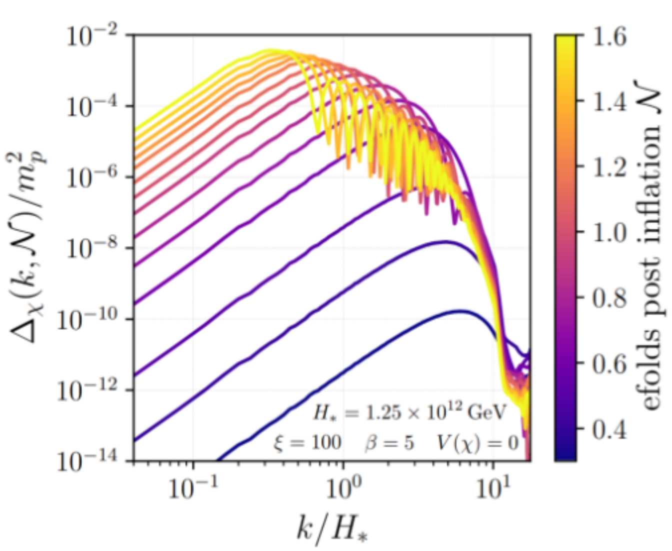
with

$$R = \frac{1}{m_p^2}\left[\frac{2\,(1-6\xi)\,\left(E_G^\phi - E_K^\phi\right) + 4\langle V\rangle - 6\xi\langle\phi V_{,\phi}\rangle + (\rho_{\rm m} - 3p_{\rm m})}{1 + (6\xi-1)\,\xi\langle\phi^2\rangle/m_p^2}\right],$$

Example: Ricci-Reheating, with

$$\mathscr{L} = \frac{1}{2}(\partial\phi)^2 - V_1(\phi) - \frac{1}{2}(\partial\chi)^2 - \frac{1}{2}\xi R\chi^2 - V(\chi)$$

R < 0 $\longrightarrow$ Tachyonic instability



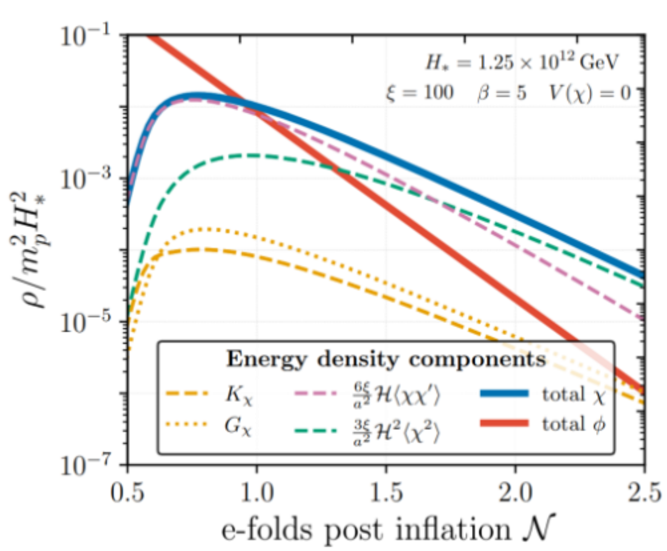
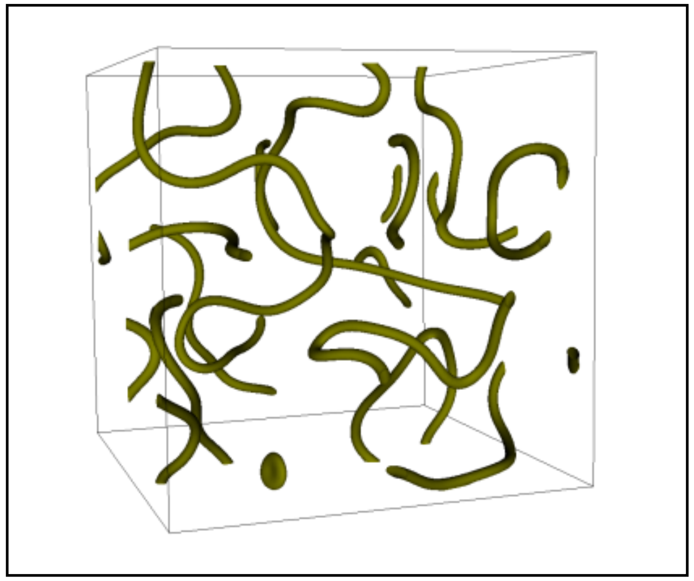


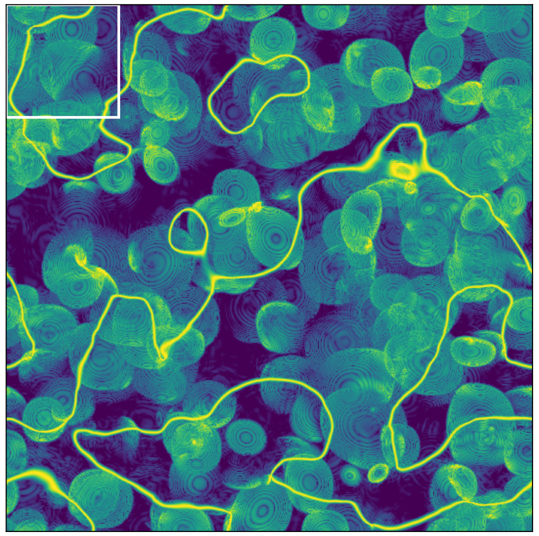
Figure: Baeza-Ballesteros, Figueroa, Florio, Lizarraga, Loayza, Marschall, Opferkuch, Stefanek, Torrentí, Urio, 2512.1562

Topological defects

Figure: Baeza-Ballesteros, Copeland, Figueroa, Lizarraga, PRD 110, 043522 (2024)



String Networks



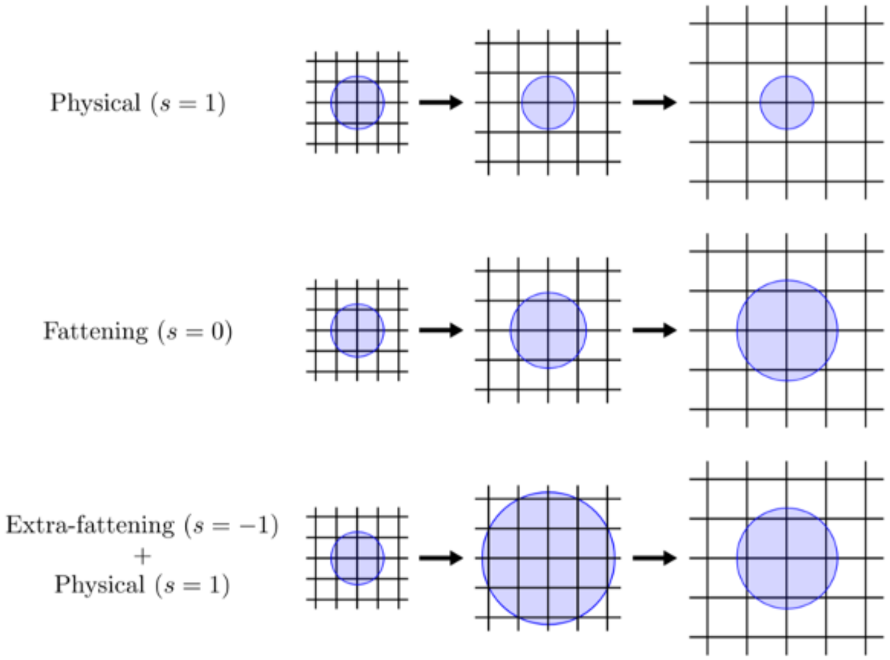
Domain walls (2D slices)

Figure: Notari, Rompineve & F.T, JCAP 07 (2025) 049

- Topological defects can be **generated dynamically** in CosmoLattice 1.X.

- **Challenges**:
  - Loss of resolution at late times.
  - Slow approach to scaling.

- **In CosmoLattice 2.0:**
  - Fattening/extra-fattening (PRS method)
  - Initialization routines (e.g. diffusion)
  - Specific observables (e.g. string width, DW area)



Magneto Hydro-dynamics (MHD)

$$T^{\mu\nu} = (p+\rho)U^\mu U^\nu - p g^{\mu\nu}$$

$$D_\nu T^{\mu\nu} = \partial_\nu T^{\mu\nu} + \Gamma^\mu_{\sigma\nu} T^{\sigma\nu} + \Gamma^\nu_{\nu\sigma} T^{\mu\sigma} = \frac{1}{\sqrt{-g}} \partial_\nu (\sqrt{-g}\, T^{\mu\nu}) = 0,$$

$$\boxed{\begin{aligned} \partial_\eta \tilde{T}^{00} + \partial_i \tilde{T}^{0i} &= \tilde{S}^0[\phi, A_k, \{\tilde{T}_{lk}\}]\,, \\ \partial_\eta \tilde{T}^{0i} + \partial_j \tilde{T}^{ij} &= \tilde{S}^i[\phi, A_k, \{\tilde{T}_{lk}\}]\,, \end{aligned}}$$

Later public release

Theory review in Summer 2026

Kenneth MARSCHALL

Daniel FIGUEROA

Antonino S. MIDIRI

Alberto ROPER POL

Other new features

Runge-Kutta Solvers

Necessary for non-symplectic EoMs, e.g. axion couplings or non-minimal couplings. We provide low-storage Runge-Kutta of orders 2 and 4.

2+1D and 1+1D support

Simulations with reduced dimensionality, to capture the late-time evolution.

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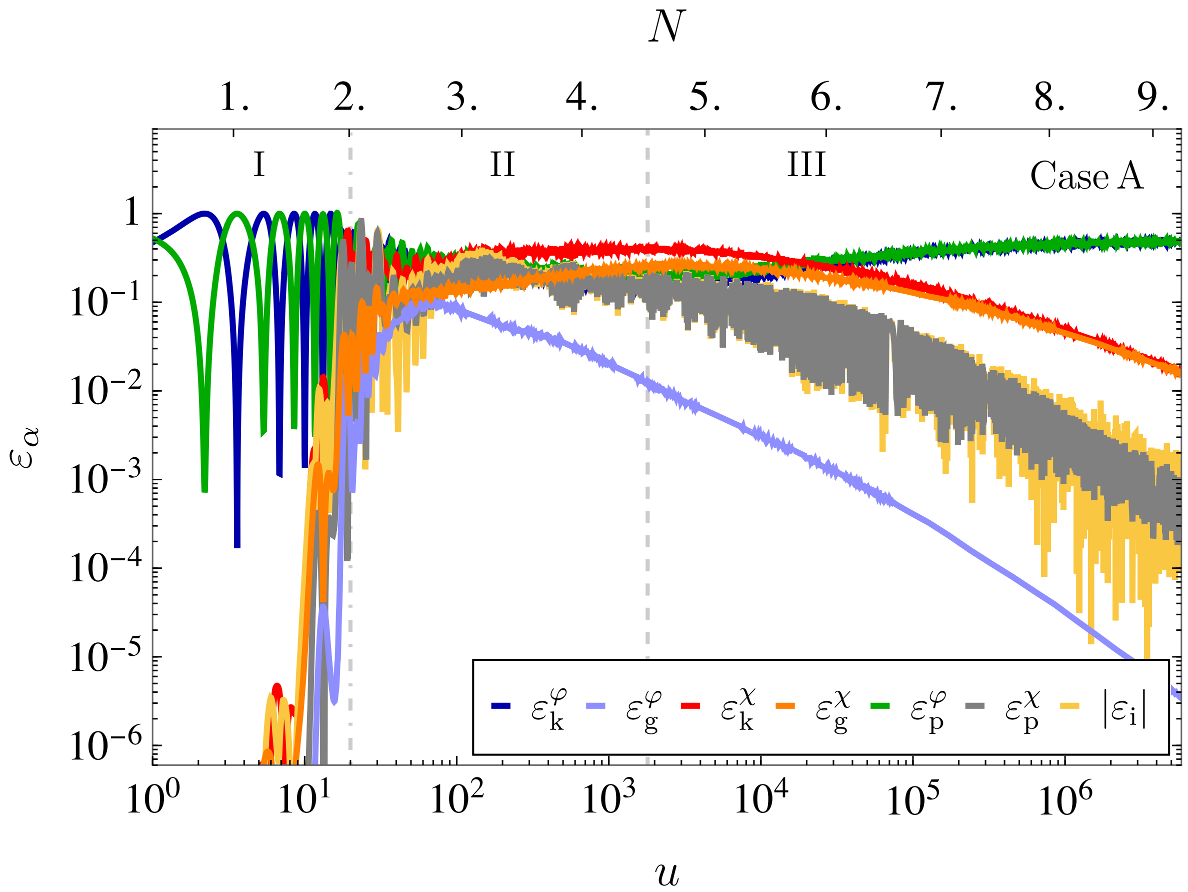

Antusch, Marschall & F.T.; JCAP 11 (2025) 002.

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Feed in arbitrary power spectra for scalar fields, and for U(1) fields via chirality decomposition.

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For simulation with very large number of points

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Required RAM

Scalar+GWs	Double	Single
N=2000	0.7 TB	0.35 TB
N=4000	5.6 TB	2.8 TB
N=8000	**45 TB**	**22 TB**
N=16000	**360 TB**	**180 TB**

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Improved snapshots
Allows to plot small regions of the lattice and/or to skip points.


SIMULATING THE EARLY UNIVERSE
A Hands-On CosmoLattice Workshop
Nonlinear dynamics
Gauge fields
Reheating
Gravitational waves
Speakers
N. Loayza · K. Marschall · J. Rubio · F. Torrenti
7-8 May 2026
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REGISTER NOW!
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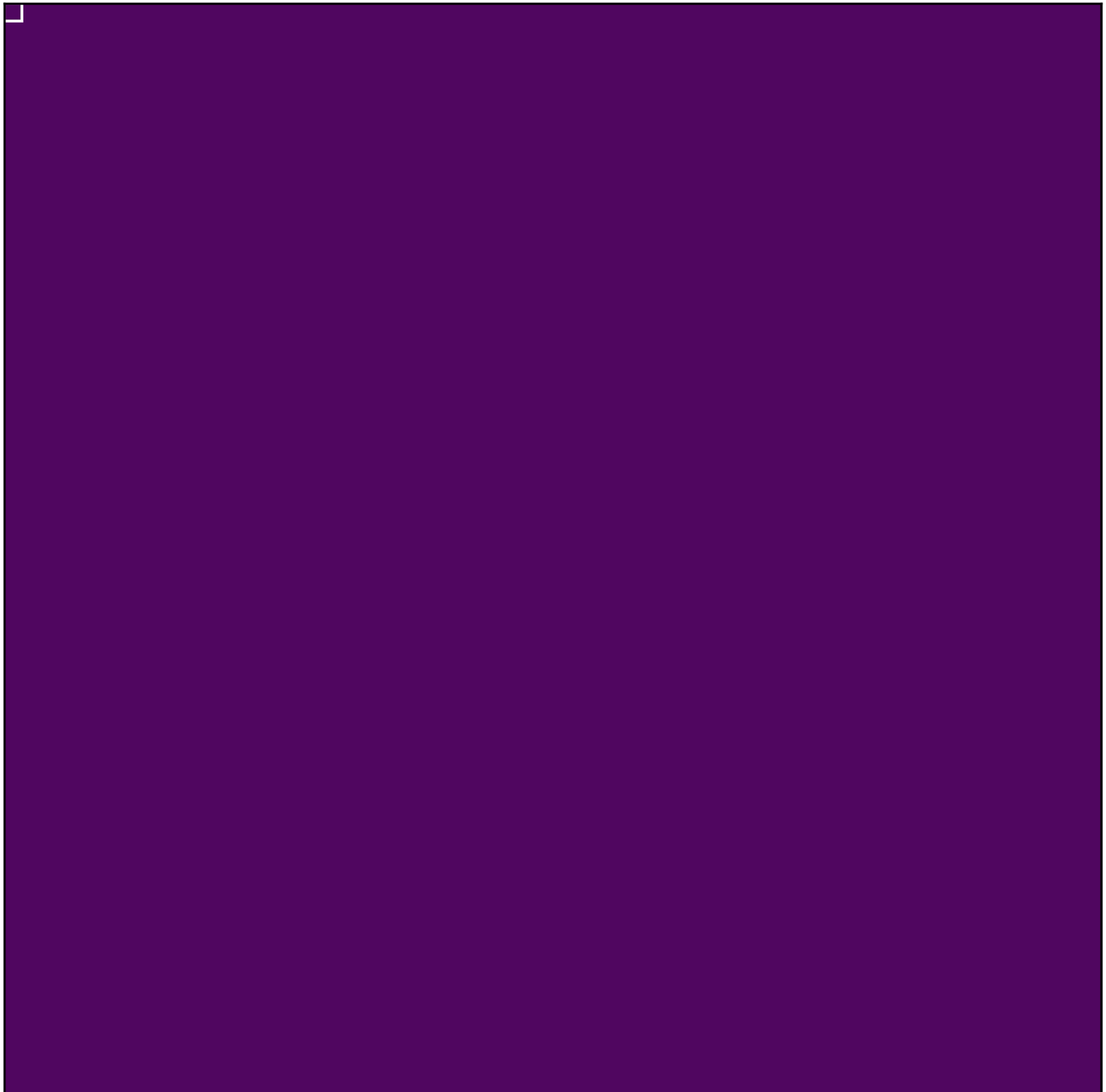

Notari,
Rompineve &
F.T (JCAP'25)


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THANK YOU!

Thank you!

Investigación confinanciada por la Comunidad de Madrid en el marco de la convocatoria correspondiente al año 2025 de las ayudas a la atracción de talento investigador “César Nombela” (**2025-T1/COM-36104**).