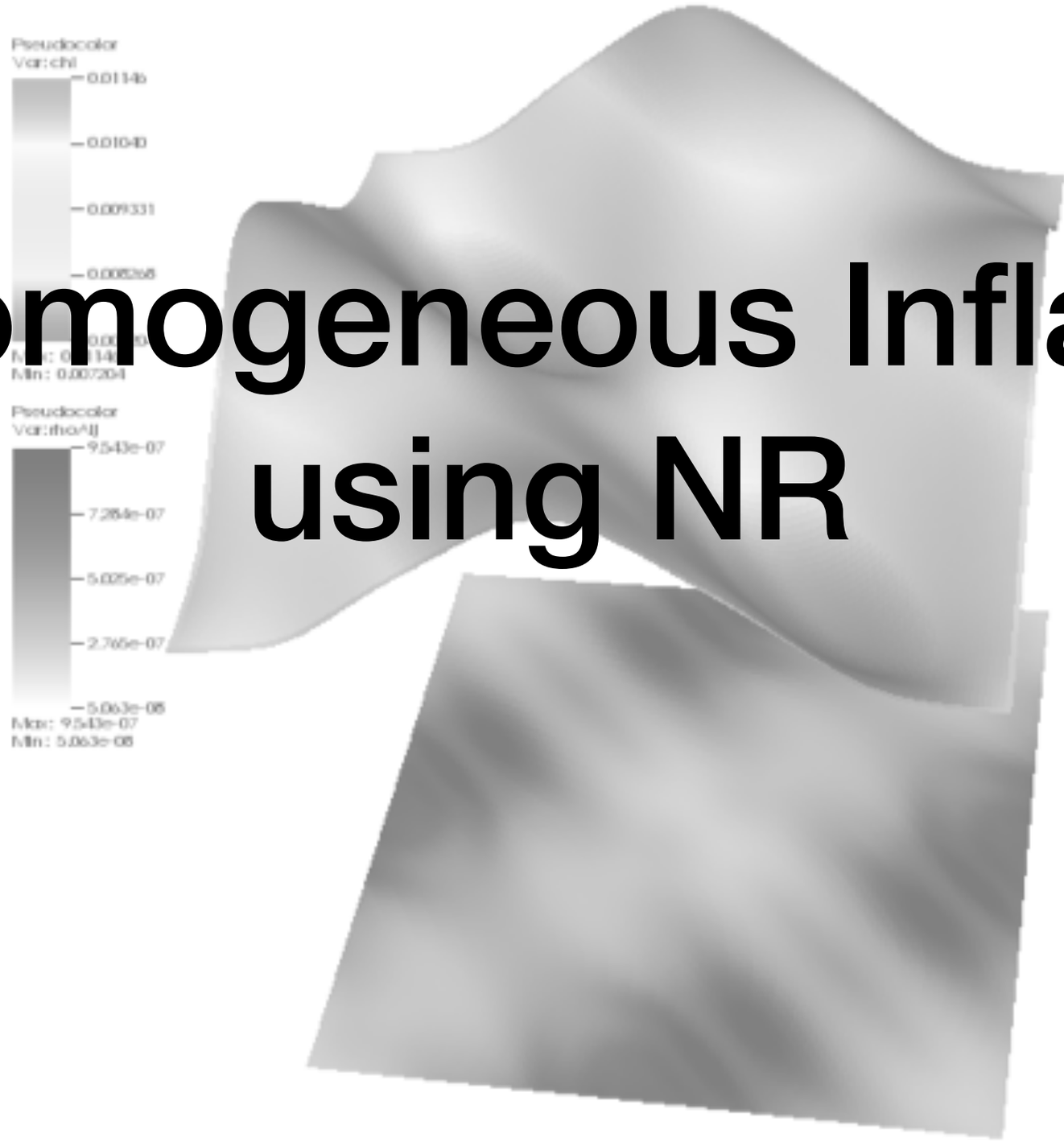
GEORG-AUGUST-UNIVERSITÄT
GÖTTINGEN

www.grchombo.org
kaclough.github.io



Inhomogeneous Inflation using NR

CENTRO DE CIENCIAS
DE BENASQUE
PEDRO PASCUAL

Numerical Relativity beyond GR

Plan for the talk

- The initial condition problem for inflation
- Studying inhomogeneous inflation using NR
- Challenges / Opportunities for NR in inflation

The initial condition problem for inflation

Inflation

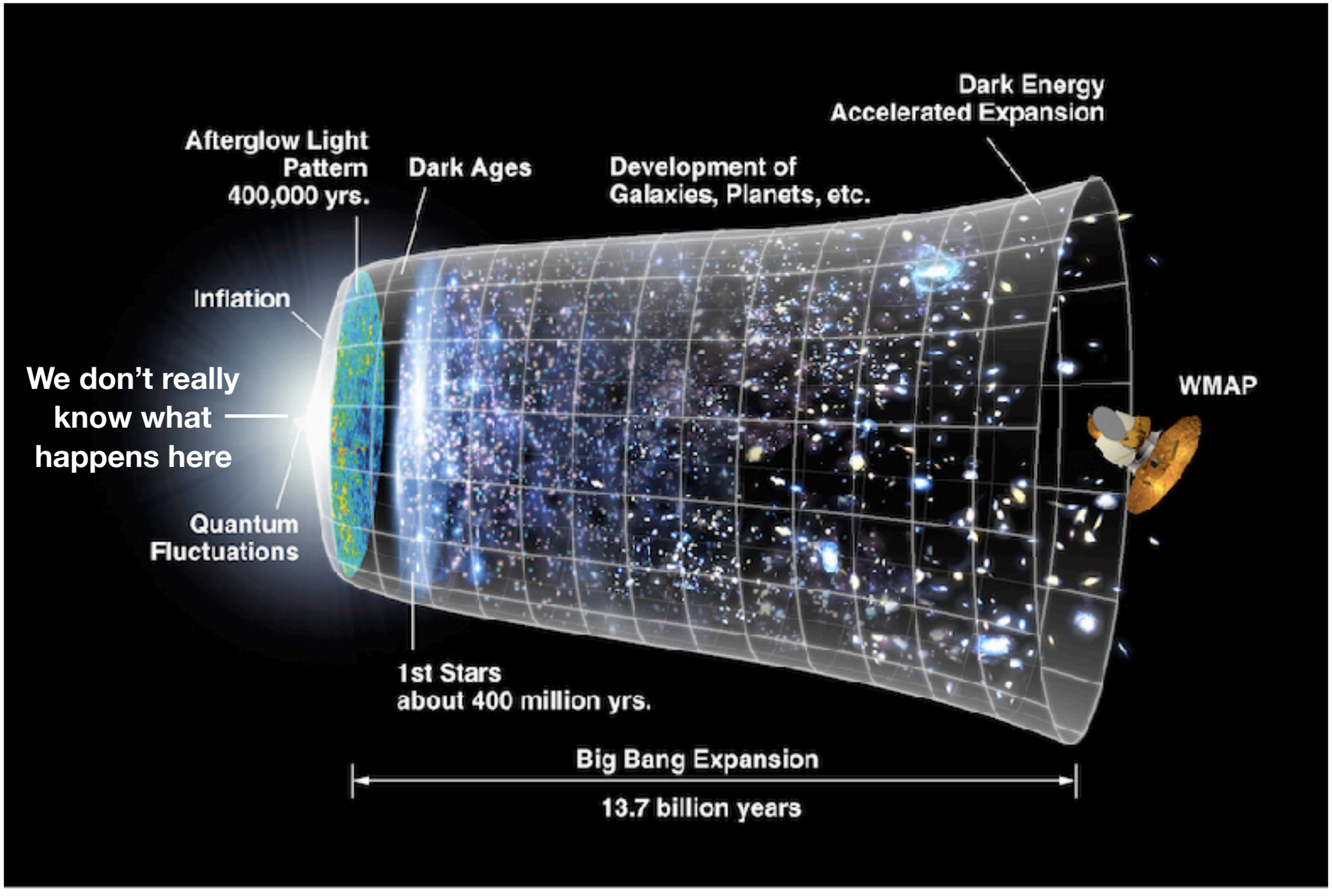


Image NASA/WMAP

Inflation

Why does the universe look the same in all directions?

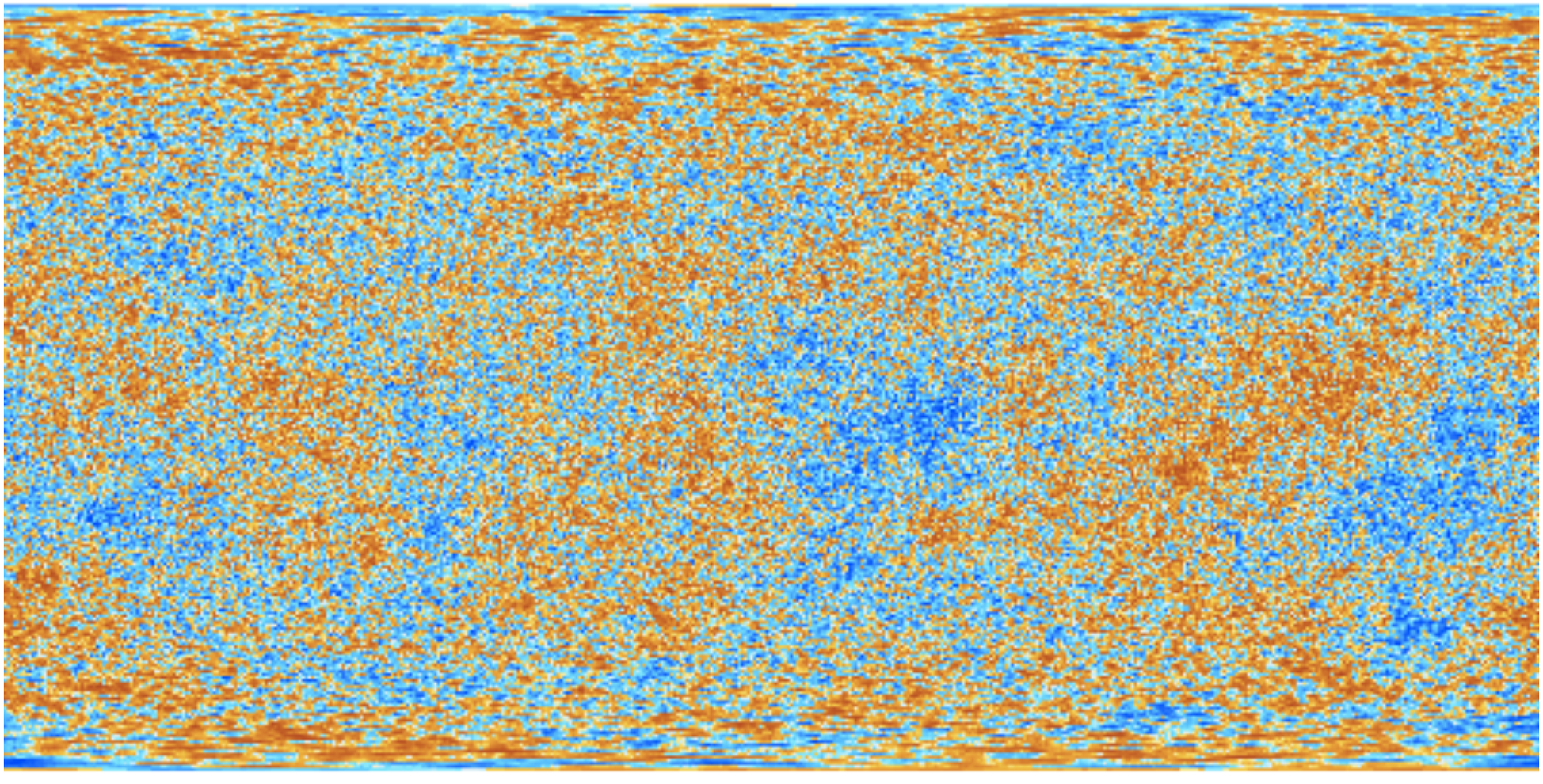
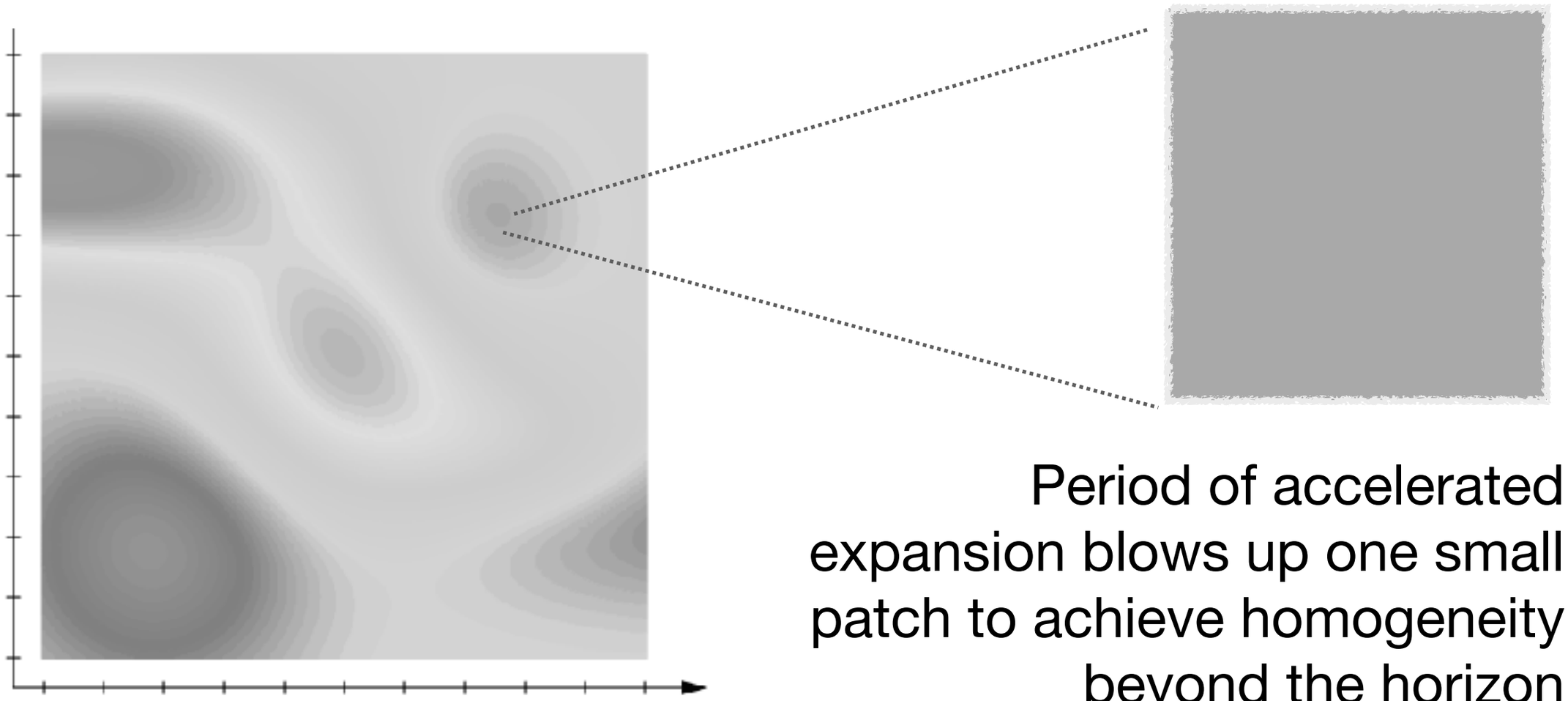


Image ESA/Planck

Inflation

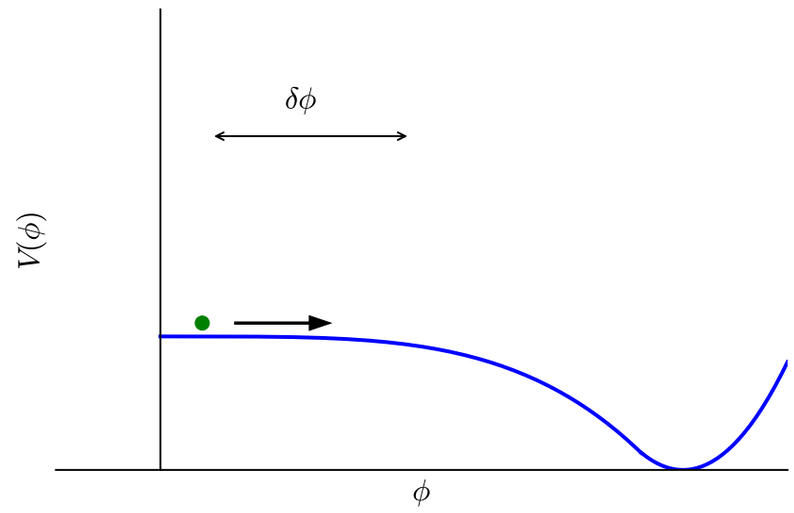


Period of accelerated expansion blows up one small patch to achieve homogeneity beyond the horizon

The initial condition problem for inflation

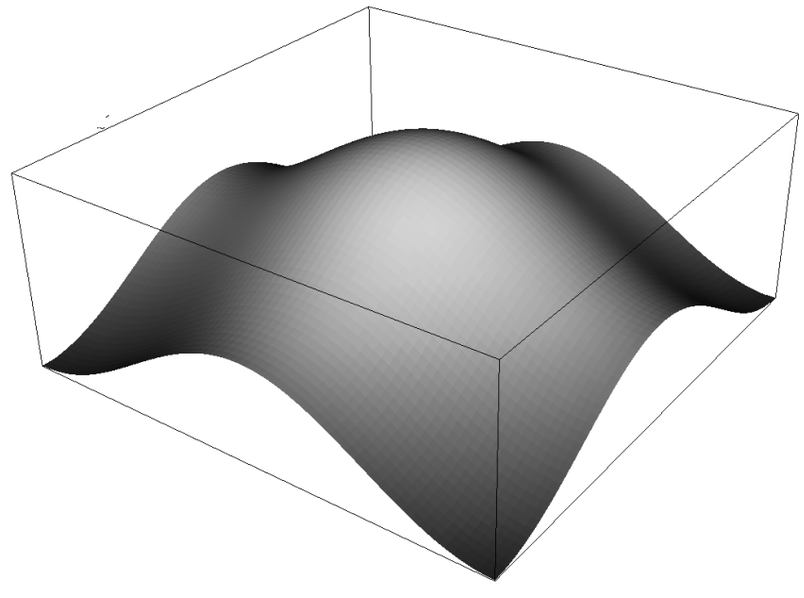
Spacetime pre inflation is homogeneous

inflation not needed



inflation (potentially) does not work

Spacetime pre inflation is inhomogeneous

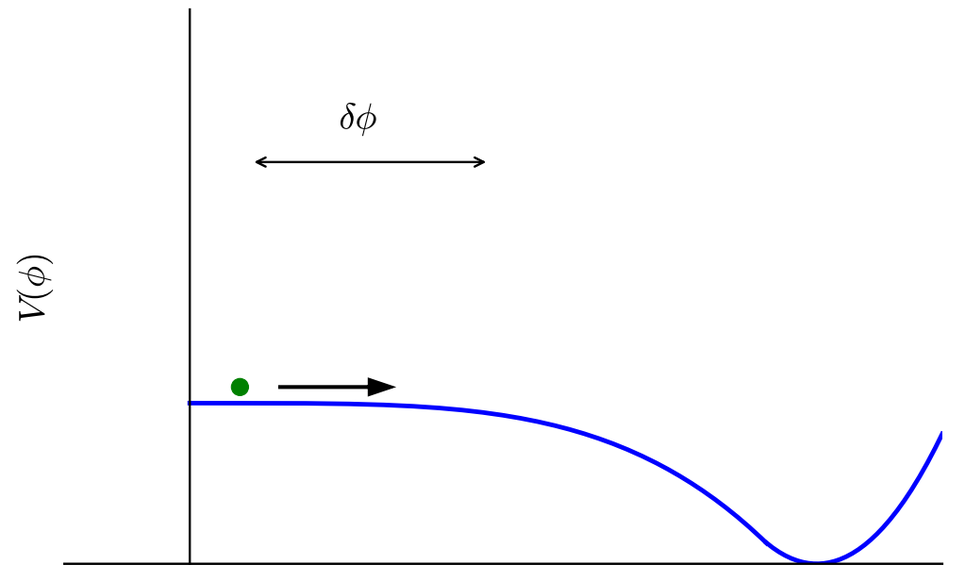


Modify inflationary / early universe model?

Modify gravity?

Small field versus large field models

- Small field $\delta\phi \ll M_{pl}$
- Large field $\delta\phi \gg M_{pl}$



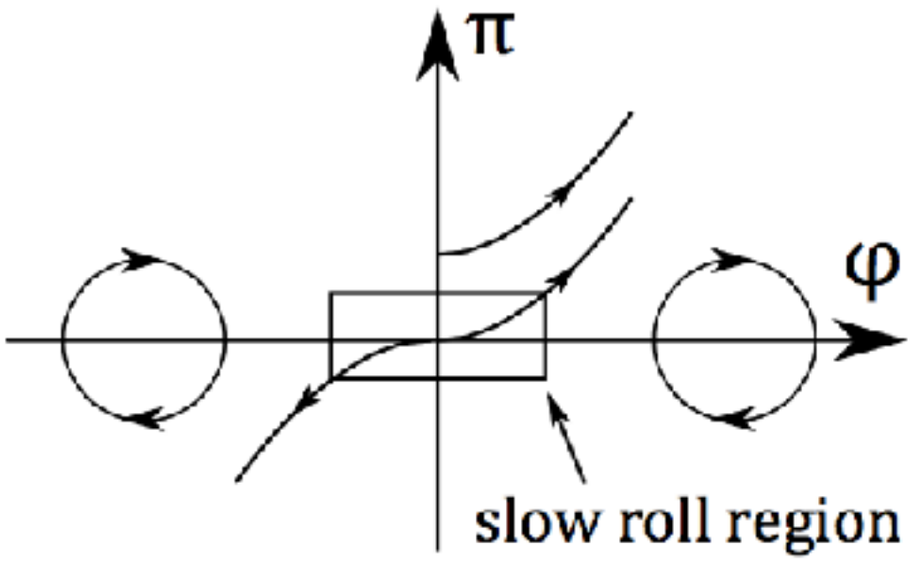


Diagram from:
Initial Conditions for Inflation: A Short Review
Robert Brandenberger, arXiv 1601.01918

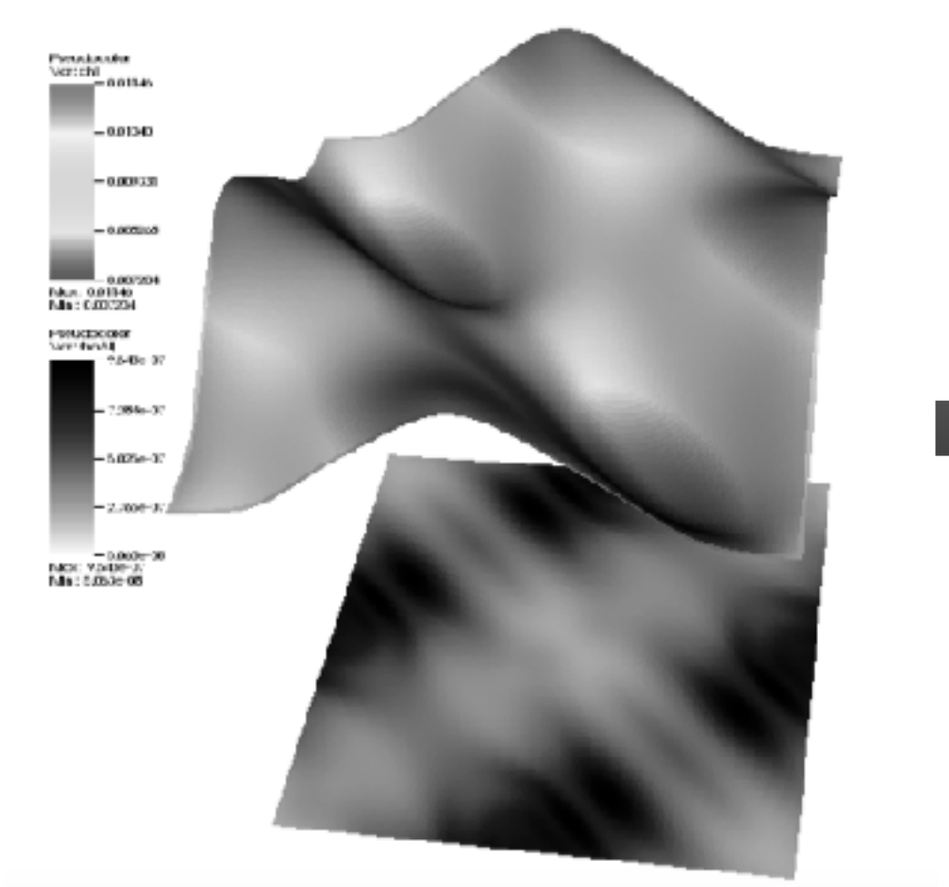
Small field fits better into an effective theory, but is not an attractor in field space

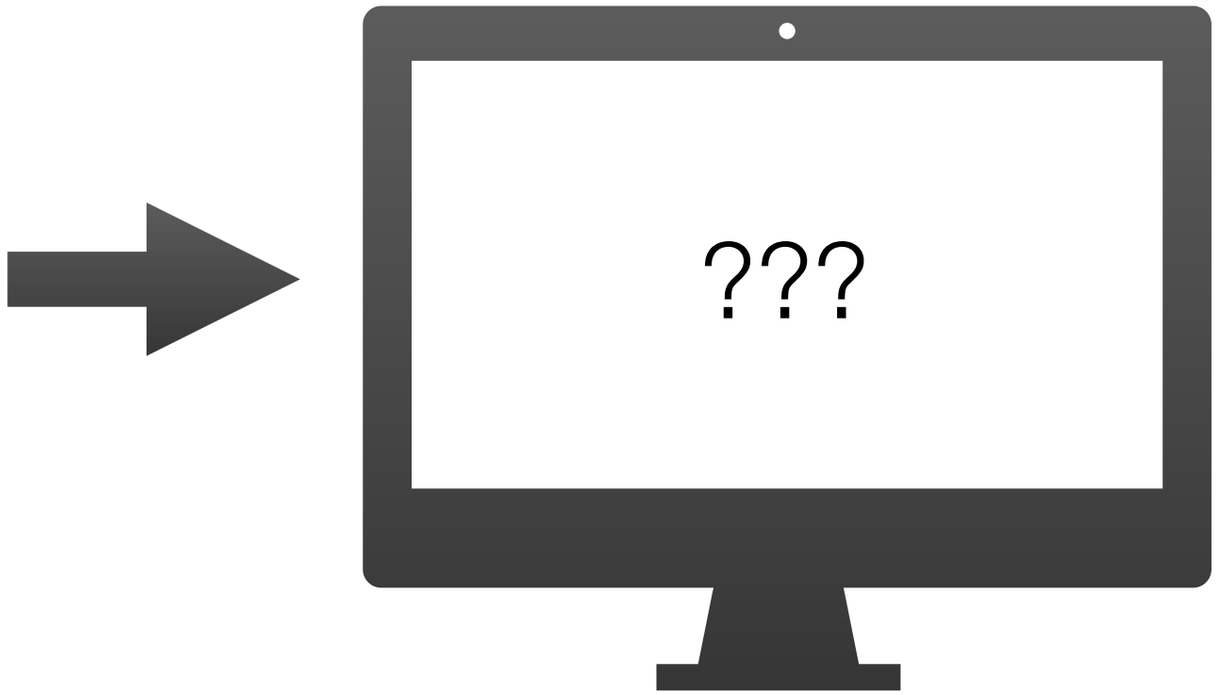
Studying inhomogeneous inflation using NR

Numerical simulations of inflation in full GR

- Dalia S. Goldwirth and Tsvi Piran
  - Inhomogeneity and the onset of inflation
    Phys. Rev. Lett. 64, 2852 (1990)
- P. Laguna, H. Kurki-Suonio, and R. A. Matzner
  - Inhomogeneous Inflation: Numerical Evolution
    Phys.Rev. D48 (1993) 3611-3624
- William E. East, Matthew Kleban, Andrei Linde and Leonardo Senatore
  - Beginning Inflation in an inhomogeneous universe
    JCAP 1609 (2016) no.09, 010
- Katy Clough, Raphael Flauger, Eugene A. Lim, Brandon S. DiNunno, Willy Fischler, Sonia Paban
  - Robustness of Inflation to Inhomogeneous Initial Conditions
    JCAP 1709 (2017) no.09, 025
  - Robustness of Inflation to Large Tensor Perturbations
    JCAP 1805 (2018) no.05, 065

Aim: develop our intuition for the failure of slow roll inflation using time domain evolutions of inhomogeneous initial conditions





Metric

- Decompose the 4D spacetime metric as:

$$ds^2 = -(\alpha^2 - \beta^k \beta_k)dt^2 + 2\beta^i dx_i dt + \gamma_{ij} dx^i dx^j$$

- Compare to FRLW:

$$ds^2 = -a^2(\tau)d\tau^2 + a^2(\tau)\delta_{ij} dx^i dx^j$$

The extrinsic curvature

- Related to the time derivative of the spatial metric

$$K_{ij} \sim -\frac{\partial_t \gamma_{ij}}{2\alpha}$$

- Usually decomposed into its trace and trace free parts

$$K_{ij} = \frac{1}{\chi}(\tilde{A}_{ij} + \frac{1}{3}\tilde{\gamma}_{ij}K)$$

- (In FRW the trace K is $K = -3H$)

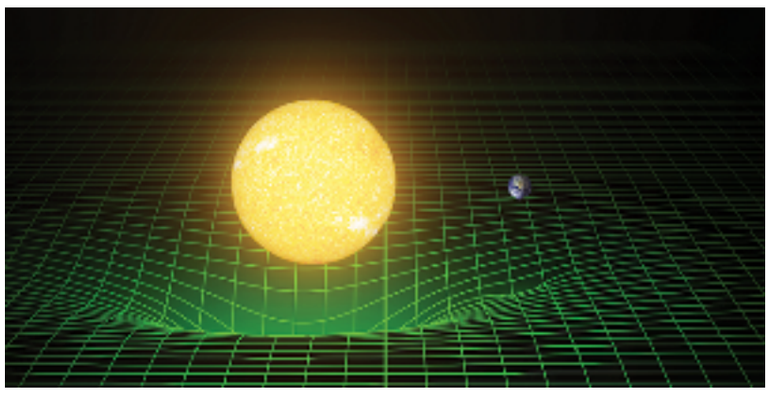
Inhomogeneous inflation - initial conditions

Scalar perturbations in the inflaton field (+ in the metric)

$$\phi = f(x,y,z) \quad \dot{\phi} = 0$$

$$\chi = g(x,y,z) \quad K = const$$

✔ Done



Tensor perturbations in metric

$$A_{ij}^{TT} \neq 0 \quad A_{ij}^{L} = 0$$

✔ Done

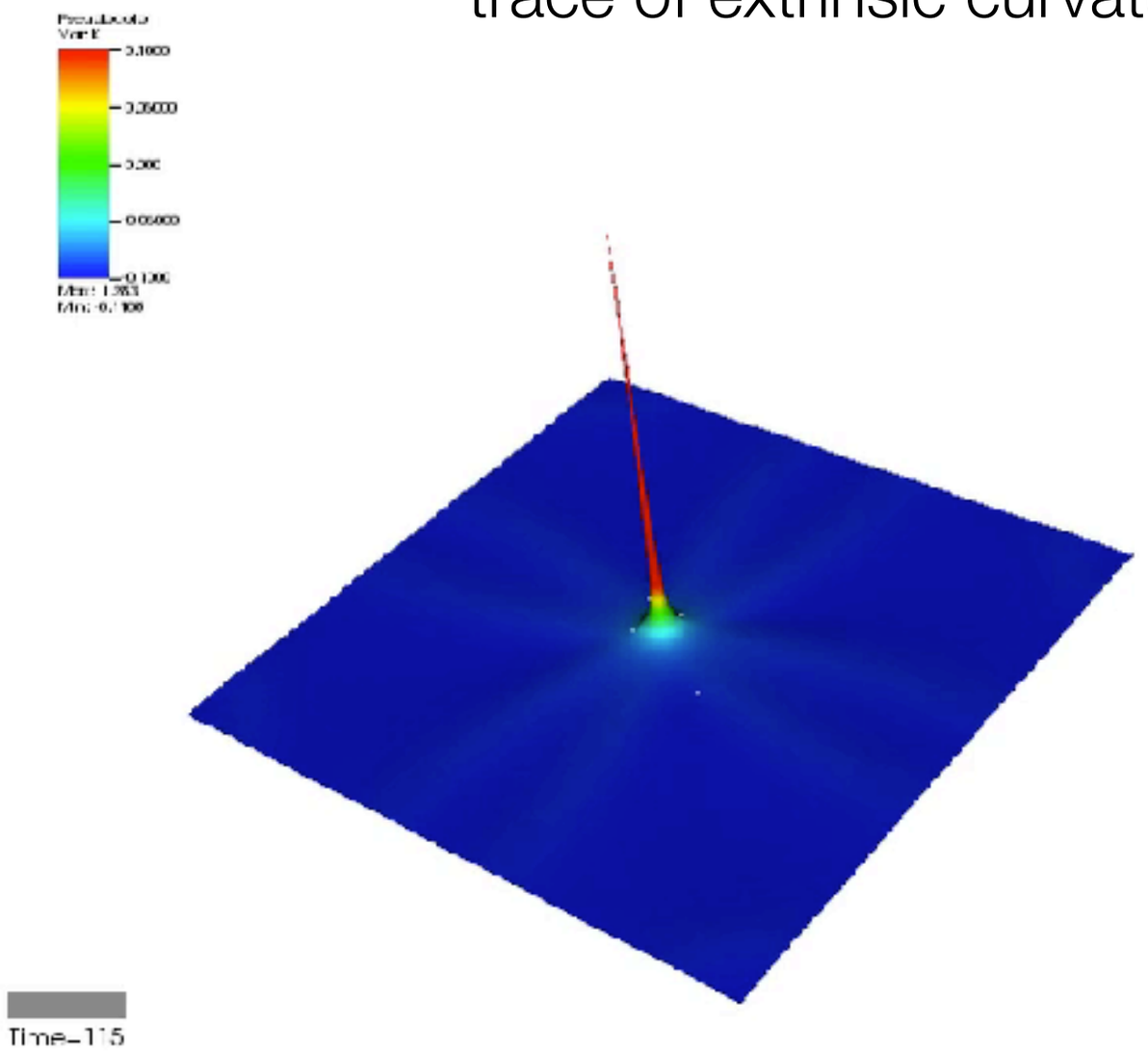
$$A_{ij}^{TT} \neq 0 \quad A_{ij}^{L} \neq 0$$

$$\dot{\phi} = f(x,y,z)$$

? In progress

Large field inflation - very robust

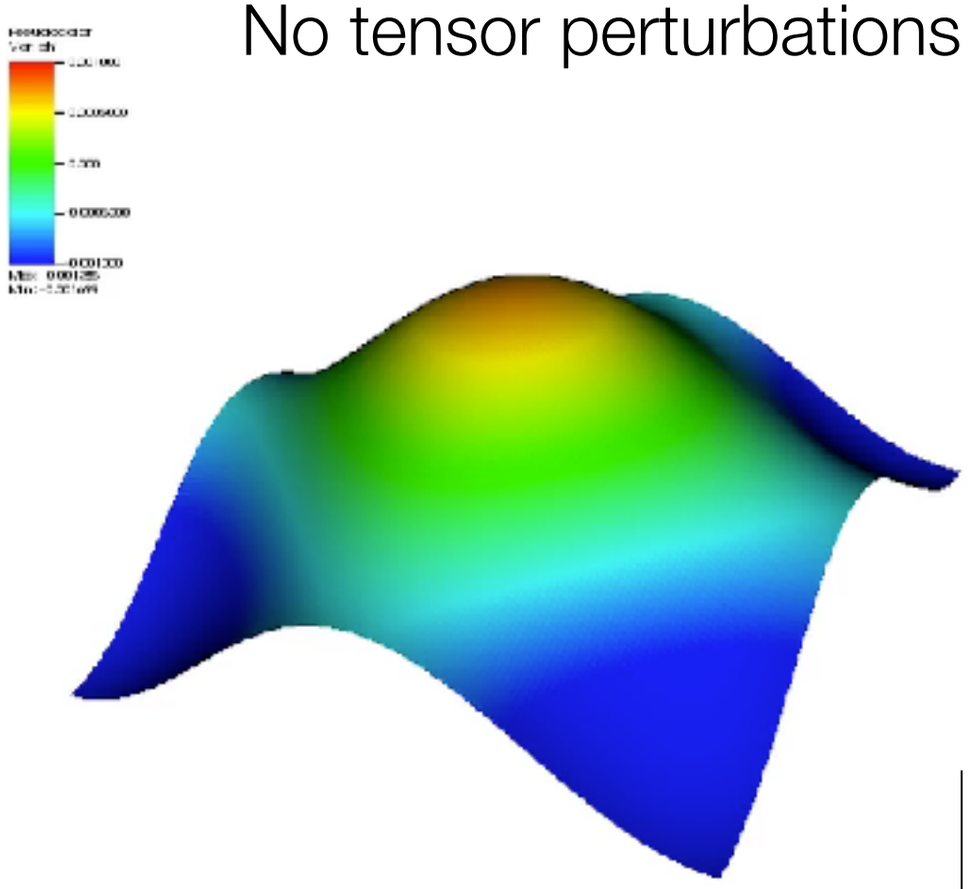
trace of extrinsic curvature K on spatial slice



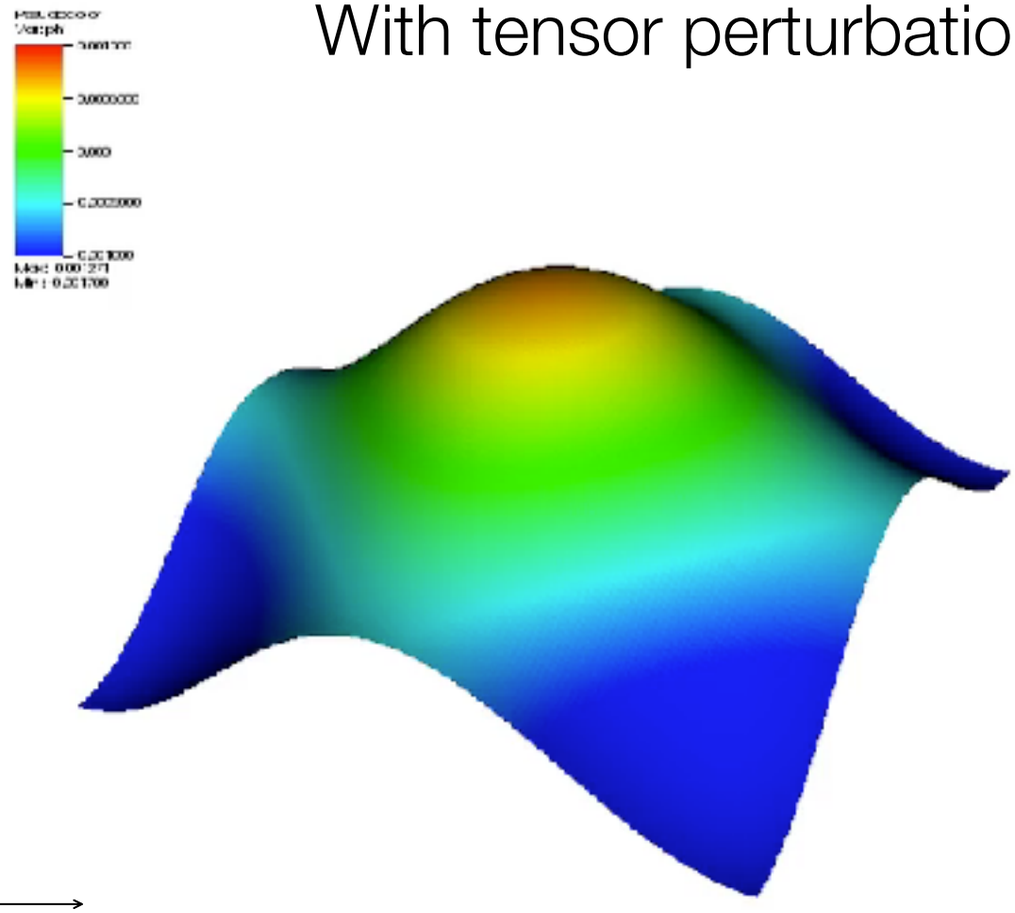
(as first shown in) East et al.
JCAP 1609 (2016) no.09, 010

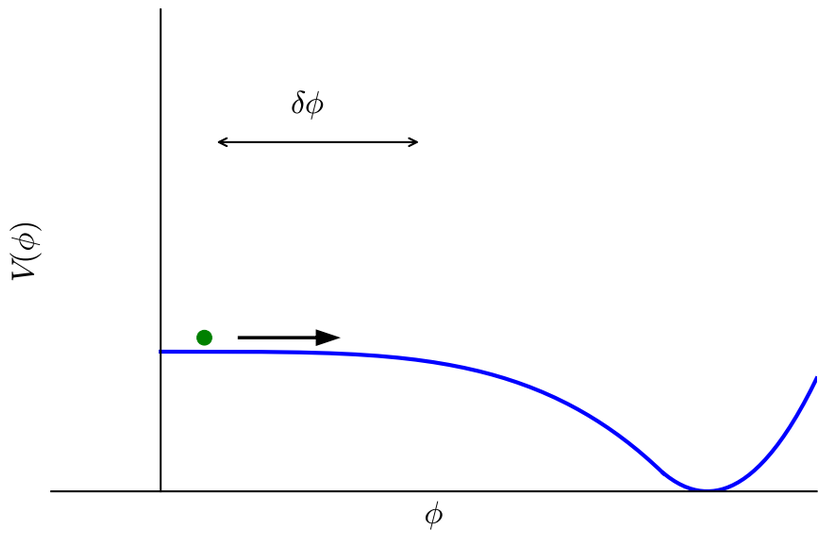
Small field inflation - not very robust

No tensor perturbations



With tensor perturbations

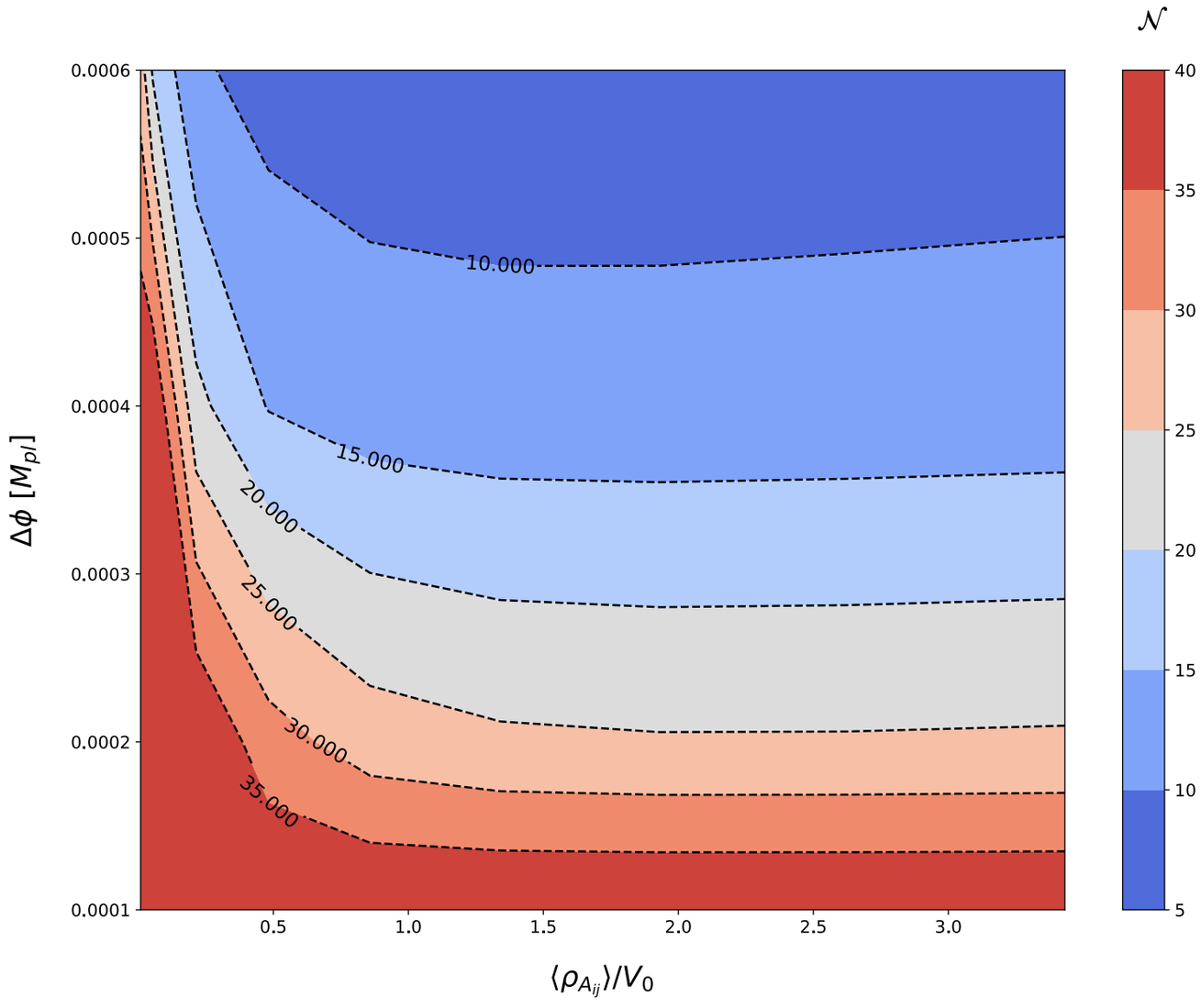




Clough et al.
JCAP 1709 (2017) no.09, 025
JCAP 1805 (2018) no.05, 065

Small field inflation - not very robust

amplitude of scalar field fluctuations



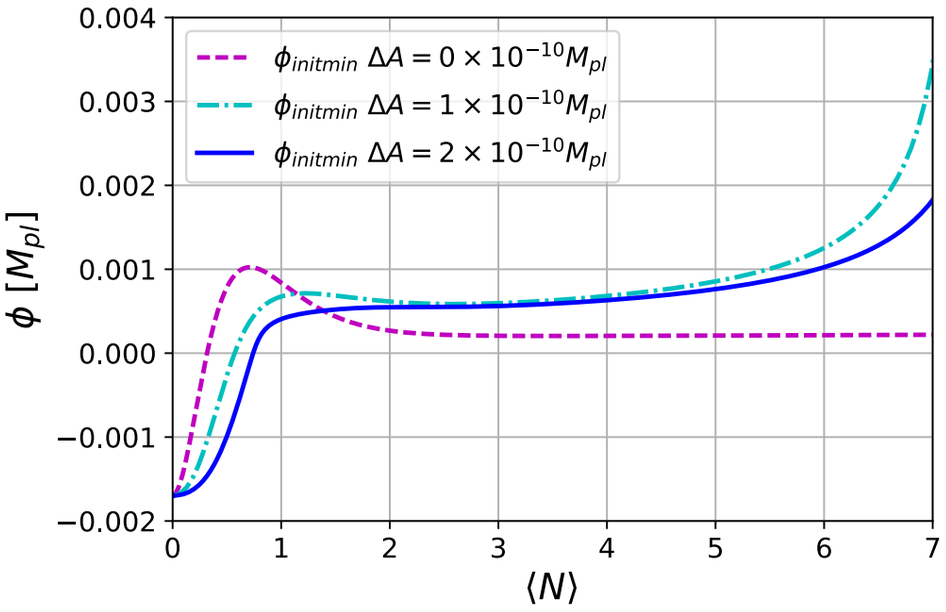
e-folds

amplitude of metric/tensor fluctuations

Clough et al.
JCAP 1709 (2017) no.09, 025
JCAP 1805 (2018) no.05, 065

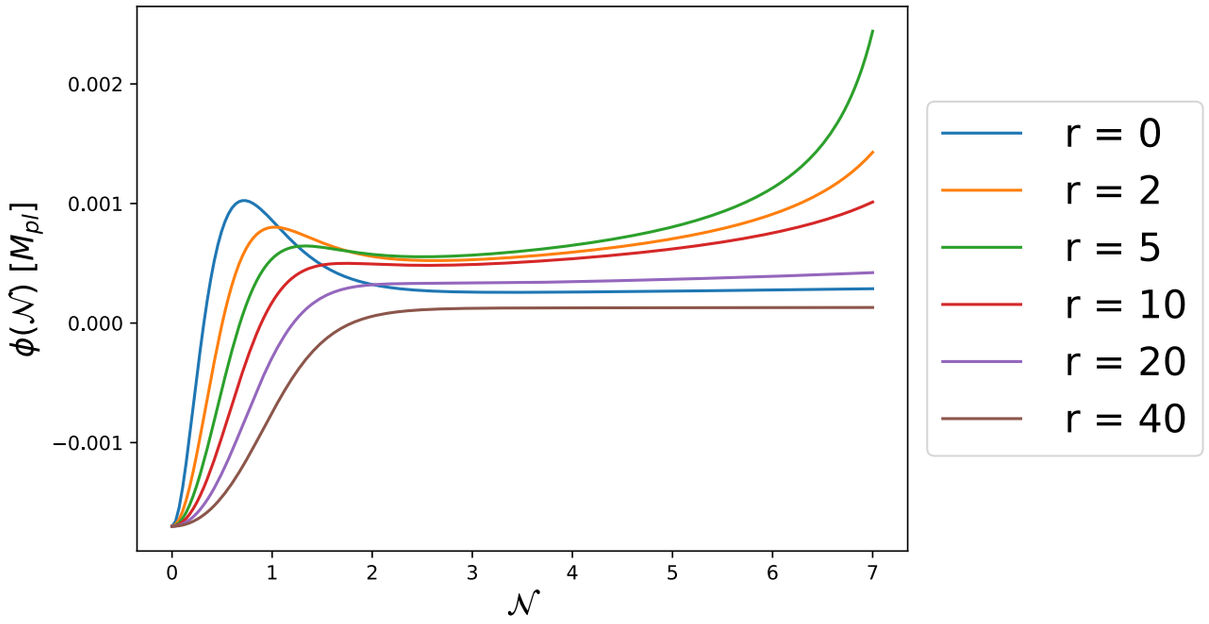
Small field inflation - not very robust

inflaton field (simulation)



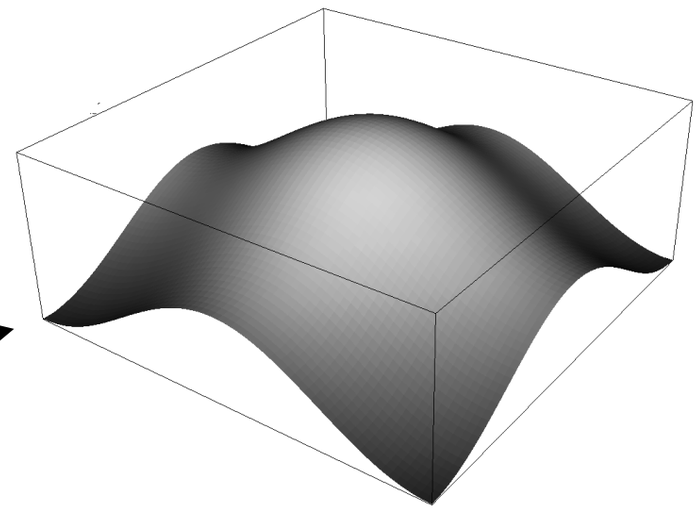
e-folds

inflaton field (toy model)



e-folds

You are here

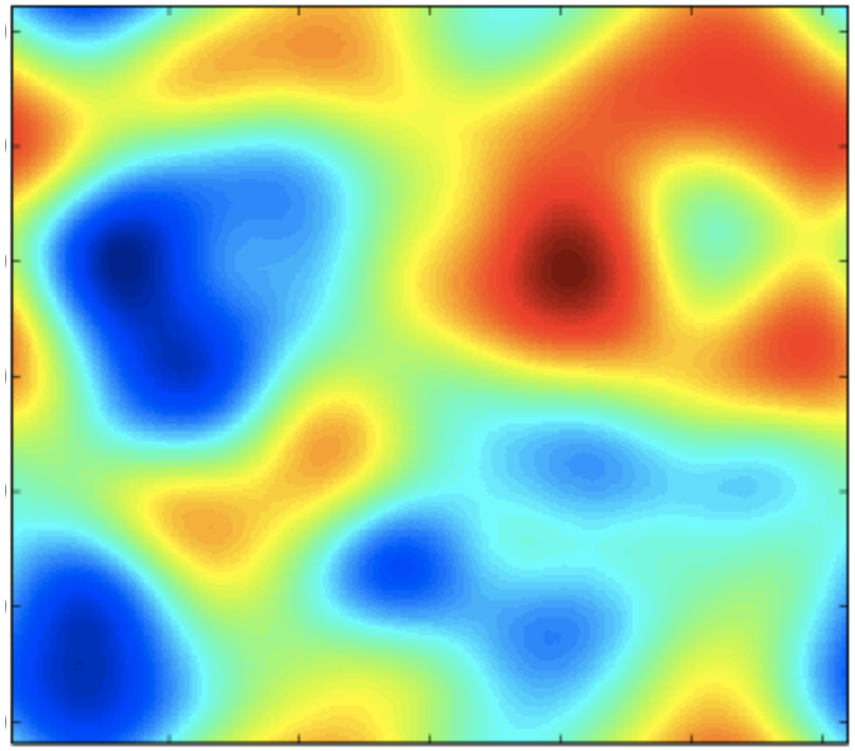


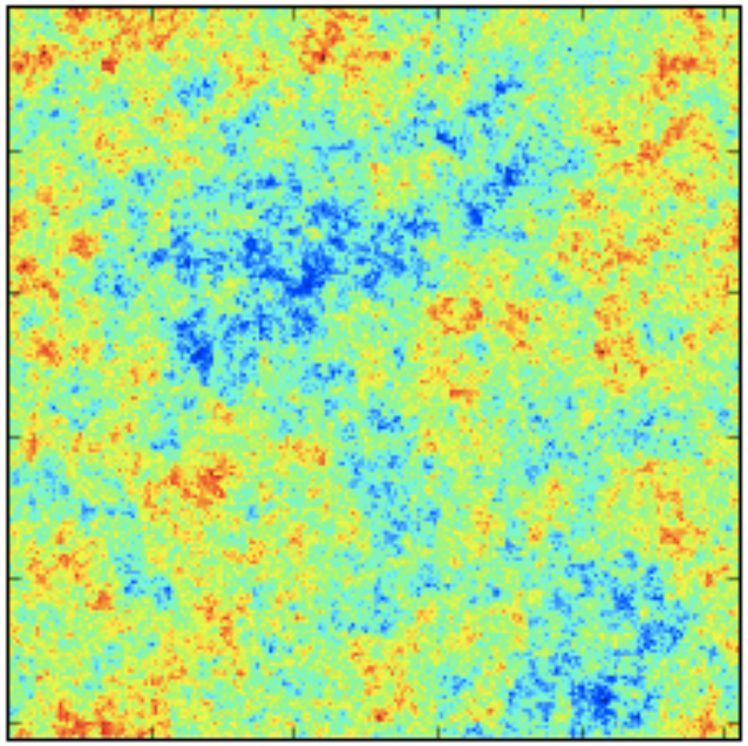
Clough et al.
JCAP 1709 (2017) no.09, 025
JCAP 1805 (2018) no.05, 065

Challenges / Opportunities for studying early universe physics with NR

Challenges / Opportunities

- Resolution required for power spectra



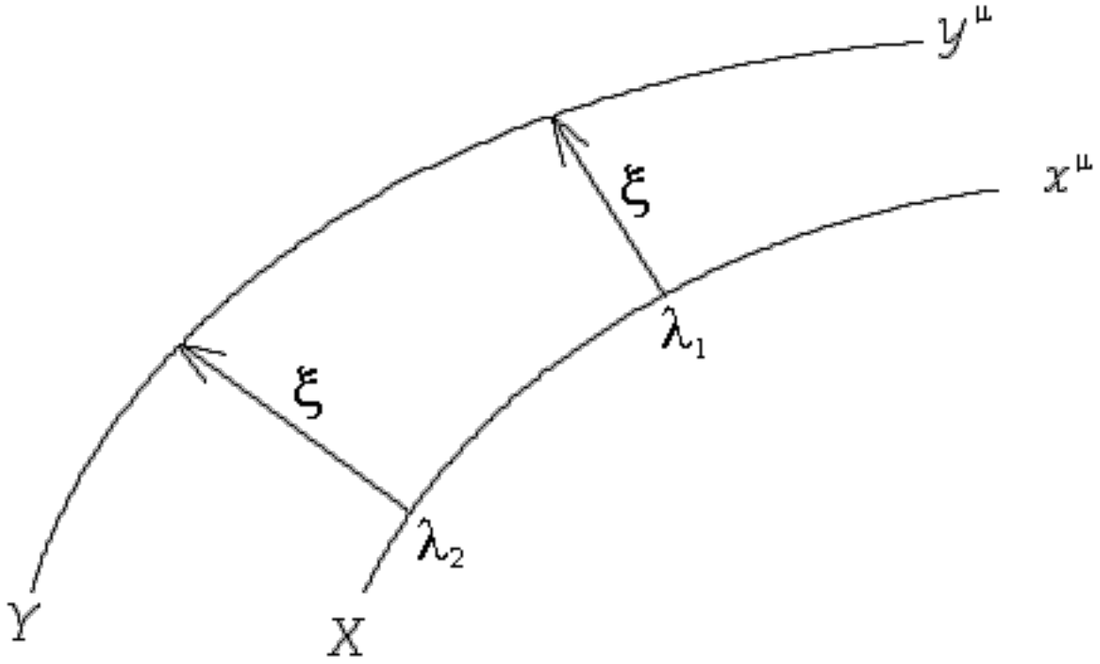


Giblin et al.
Departures from the Friedmann-Lemaitre-Robertston-Walker Cosmological Model in an Inhomogeneous Universe
PRL 116 251301

Challenges / Opportunities

- Interpretation of results / observables

$$ds^2 = a^2(\tau)\left[(1+2A)d\tau - 2B_i dx^i d\tau - (\delta_{ij}+h_{ij})\,dx^i dx^j\right]$$

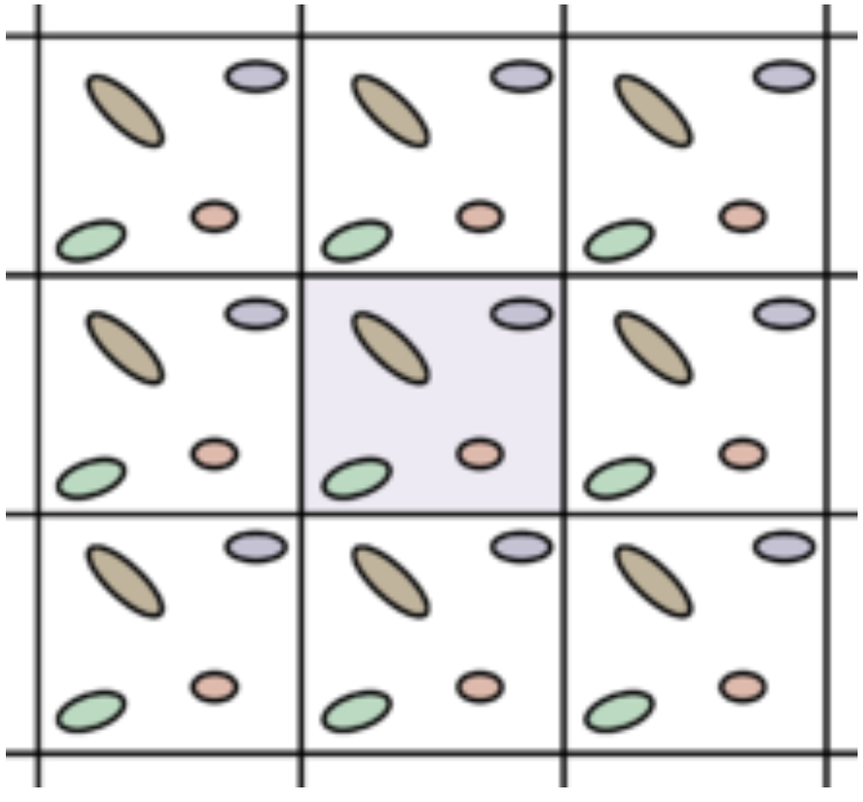


East et al.
Comparing Fully General Relativistic and Newtonian Calculations of Structure Formation
Phys.Rev. D97 (2018) no.4, 043509

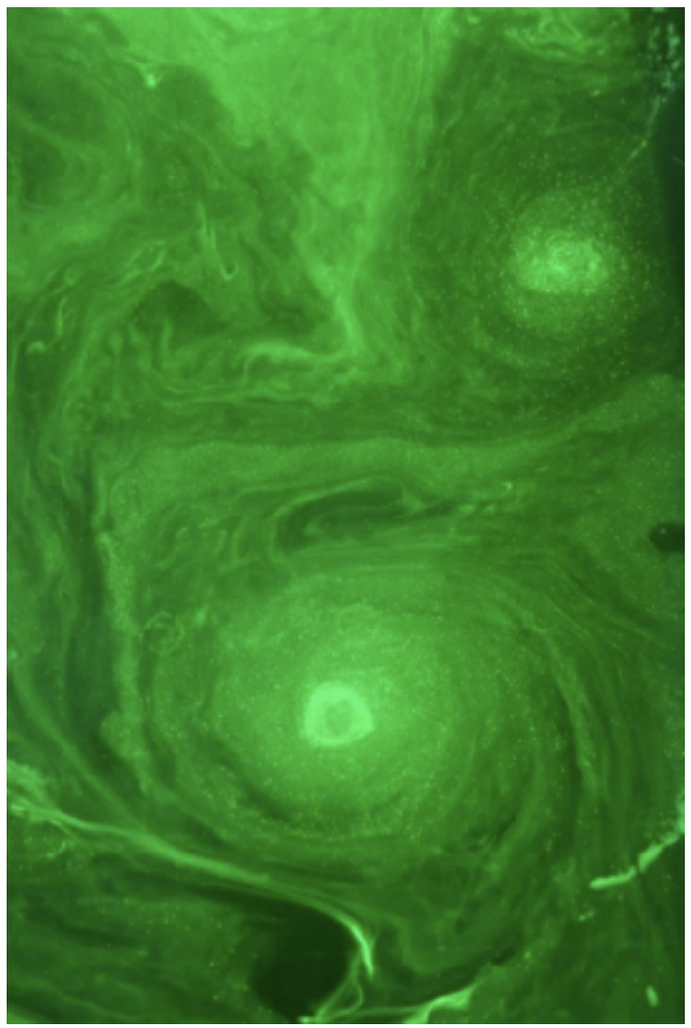
Challenges / Opportunities

- Initial conditions and boundary conditions

$$D^2\chi \sim K^2 - 24\pi G(\rho + \rho_{A_{ij}})$$



Challenges / Opportunities



- Are there preferred initial conditions?

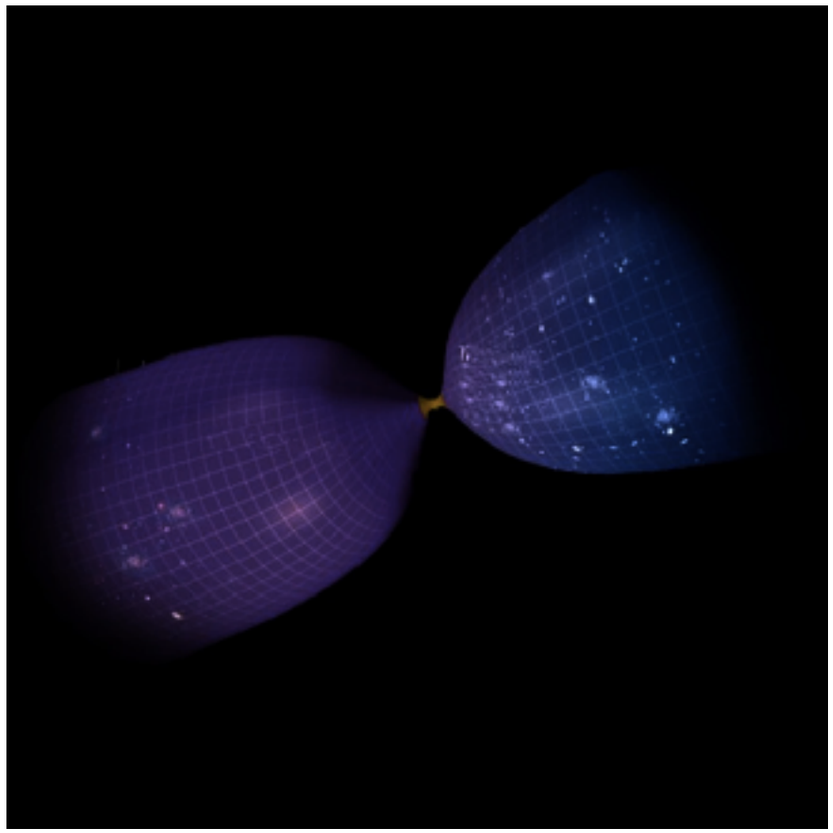
e.g. GW turbulence

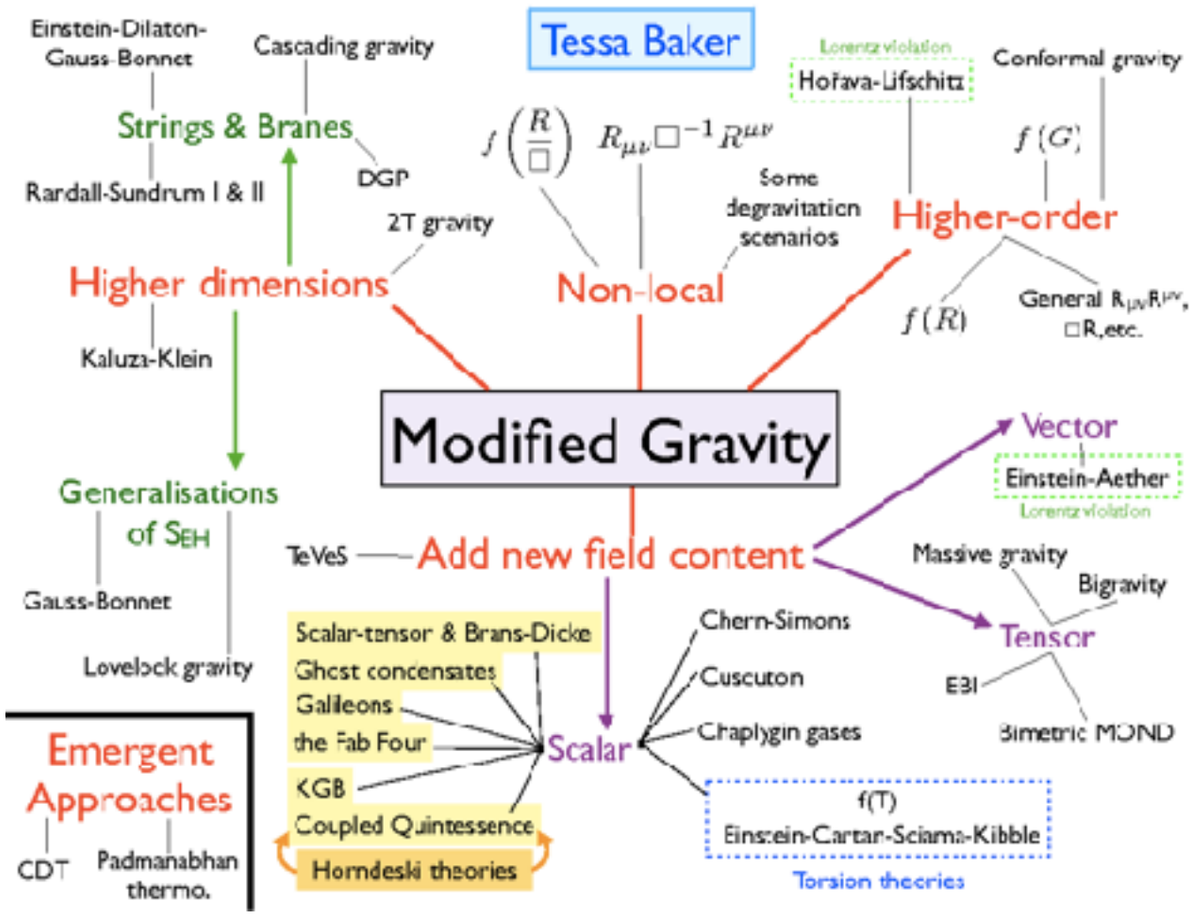
Galtier and Nazarenko
Turbulence of Weak Gravitational Waves in the Early Universe
Phys. Rev. Lett. **119**, 221101

Clough and Niemeyer
On the difficulty of generating gravitational wave turbulence in the early universe
arXiv:1803.10719

Challenges / Opportunities

- New physics / modified gravity





Thank you for listening, any questions?