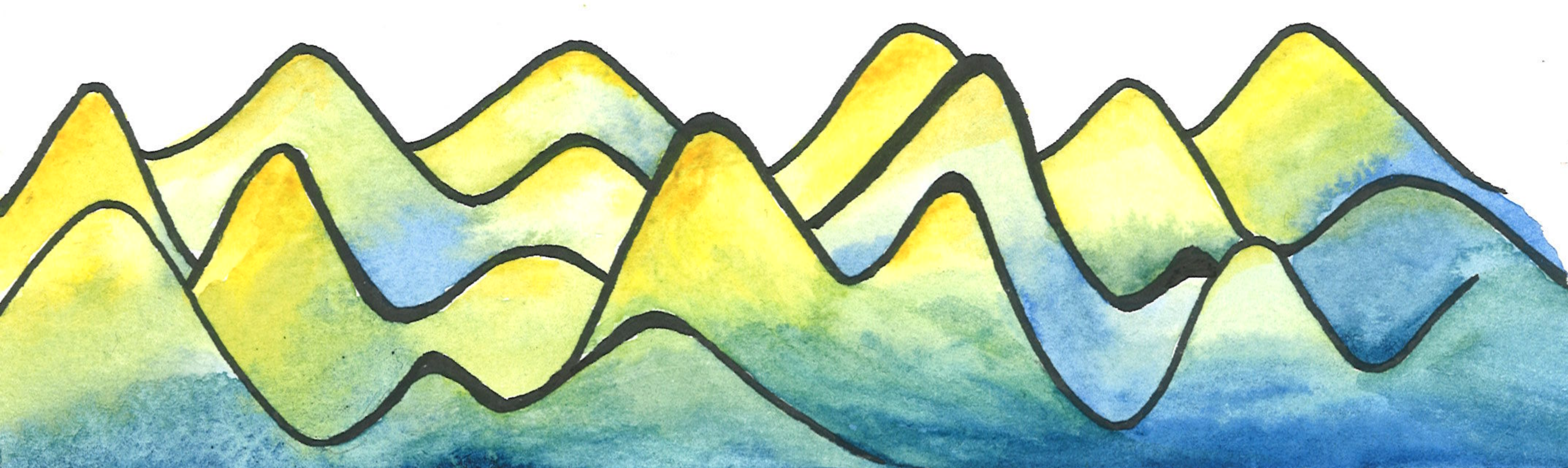
Mafalda Dias

room 308 mafalda.dias@desy.de

Early Universe/ Inflation

- Model independent computation of observable predictions
- String pheno/ SUGRA model building
- Statistical tools for complex systems

Complexity in inflation



Inflation and the tantalizing idea of using cosmological observations as a lab for high energy physics

Fundamental physics

↑

Observations / Phenomenology:
Single field Slow Roll inflation?

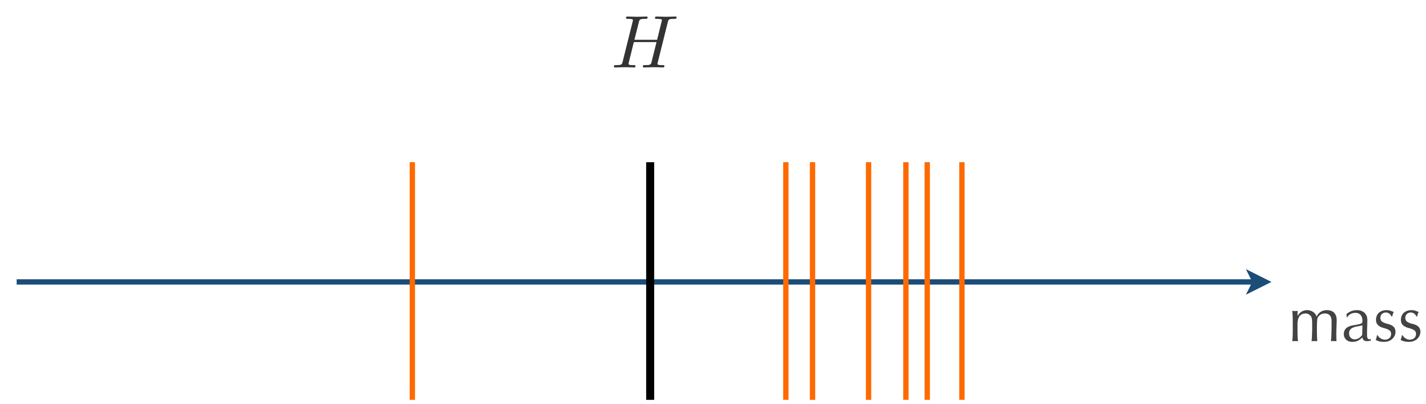
Inflation and the tantalizing idea of using cosmological observations as a lab for high energy physics

Fundamental physics

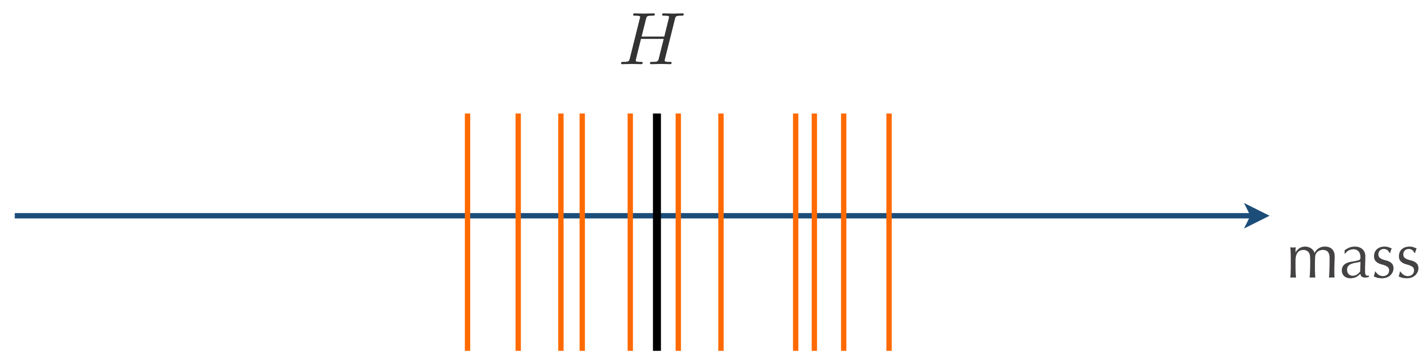
↓

Observations / Phenomenology

Inflation and the tantalizing idea of using cosmological observations as a lab for high energy physics



single field inflation



multifield inflation

INFLATION AND THE TANTALIZING IDEA OF USING COSMOLOGICAL OBSERVATIONS AS A LAB FOR HIGH ENERGY PHYSICS

Fundamental physics

↓

COMPLEXITY
EMERGENCE

↓

Observations

- many fields
- complex potentials
- curved field-space metrics
- dependence on initial conditions

Inflation in the presence of many fields

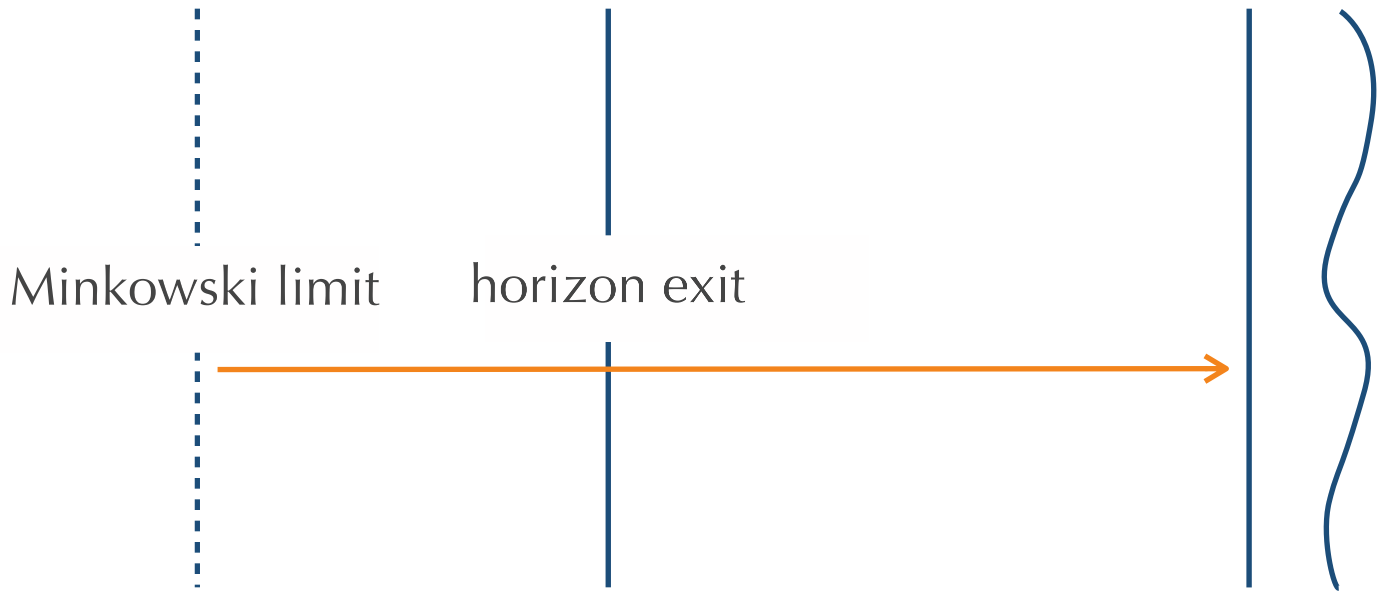
Superhorizon evolution of observables

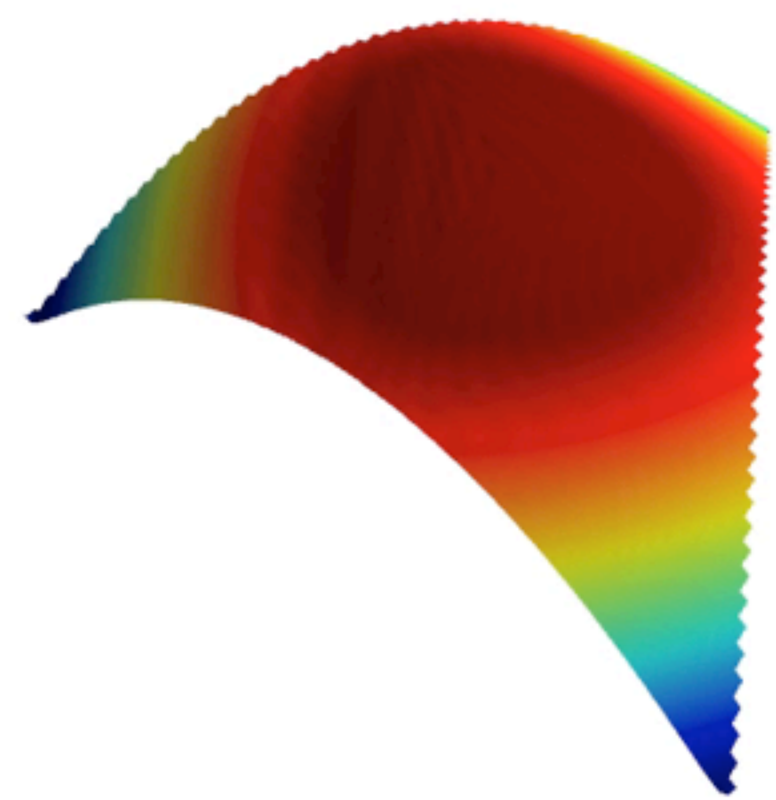
- Compute observables beyond horizon exit
- Account for interference effects at horizon exit

Non-gaussianity

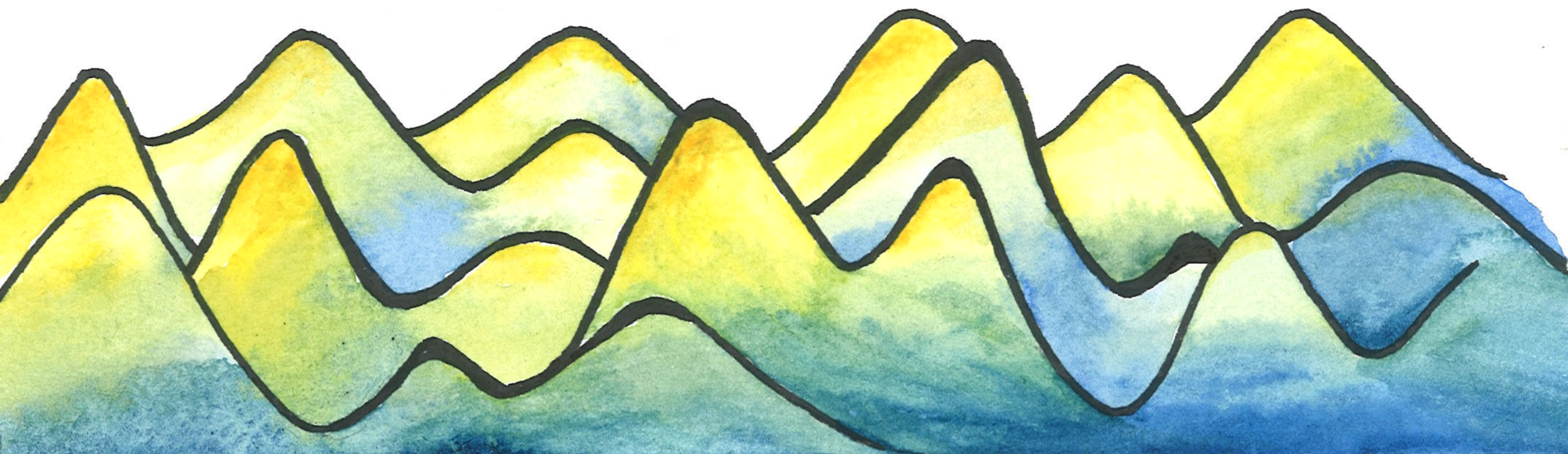
- Local type, but for most models not observable
- Massive modes: quasi-single field effects and particle production

THE TRANSPORT METHOD





Emergence in complex potentials



Random Potential using RMT

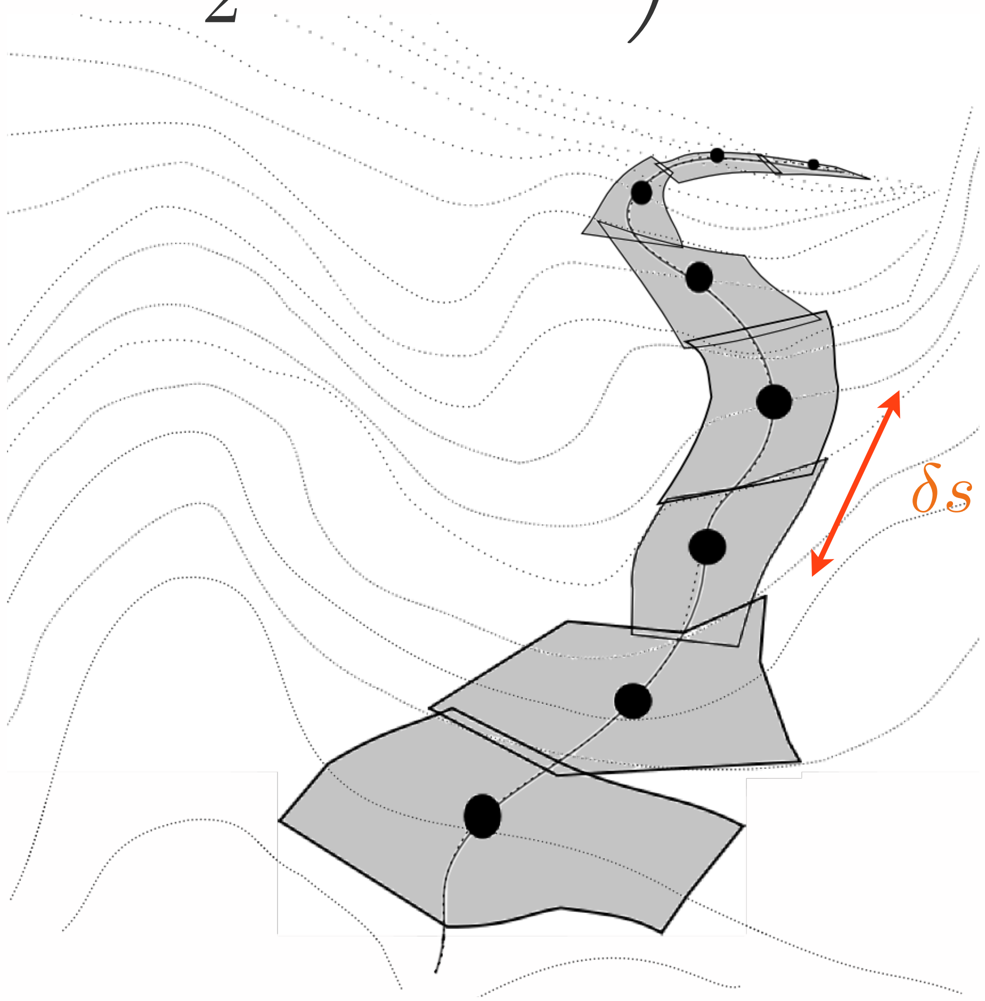
A local approach:

$$V\Big|_{p_0} = \Lambda_{\rm v}^4 \sqrt{N_f} \left(v_0|_{p_0} + v_a|_{p_0} \tilde{\phi}^a + \frac{1}{2} v_{ab}|_{p_0} \tilde{\phi}^a \tilde{\phi}^b \right)$$

$$v_0|_{p_1} = v_0|_{p_0} + v_a|_{p_0} \delta s^a$$

$$v_a|_{p_1} = v_a|_{p_0} + v_{ab}|_{p_0} \delta s^b$$

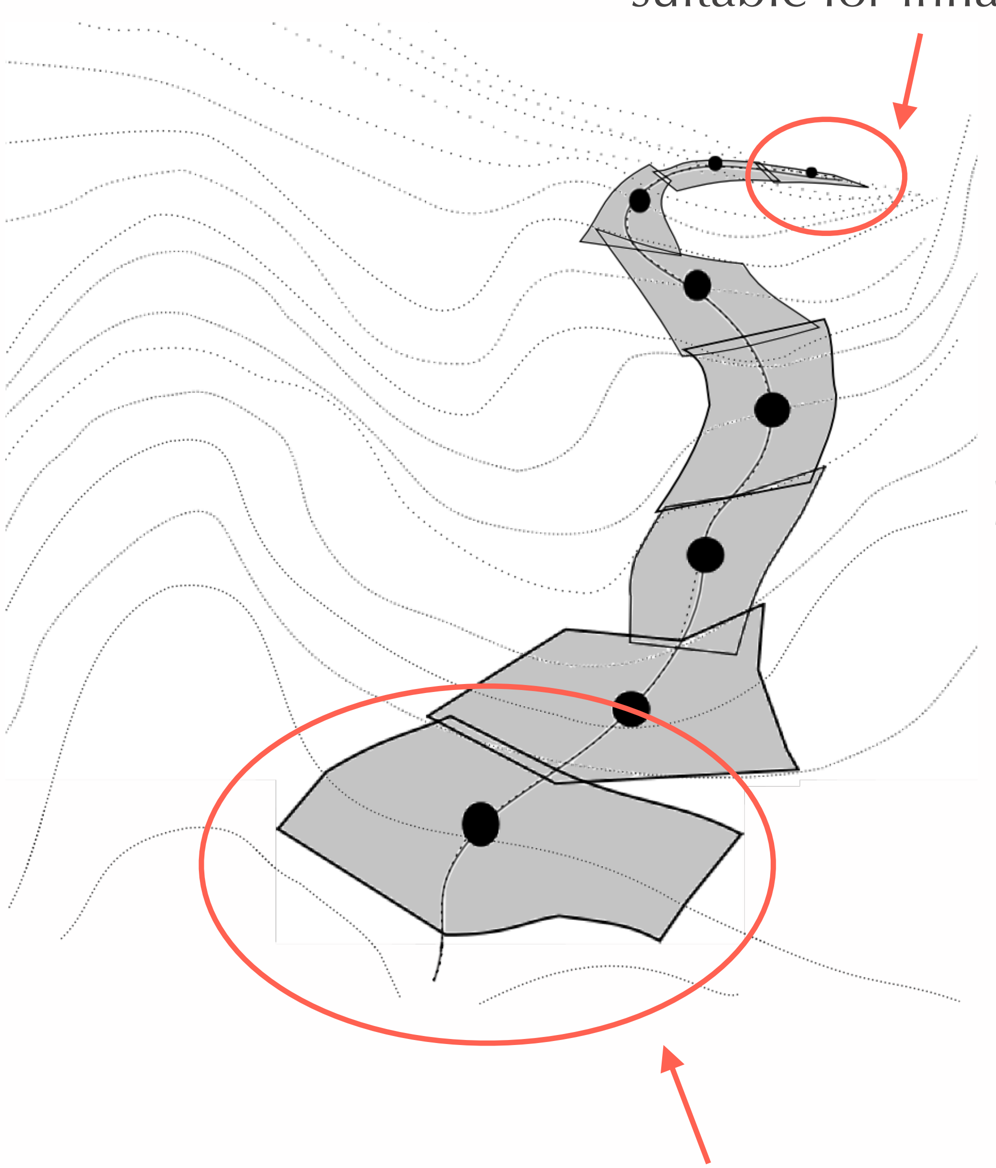
$$v_{ab}|_{p_1} = v_{ab}|_{p_0} + \underbrace{\delta v_{ab}|_{p_0 \to p_1}}_{?}$$



$\tilde{\phi}^a \equiv \phi^a / \Lambda_{\rm h}$

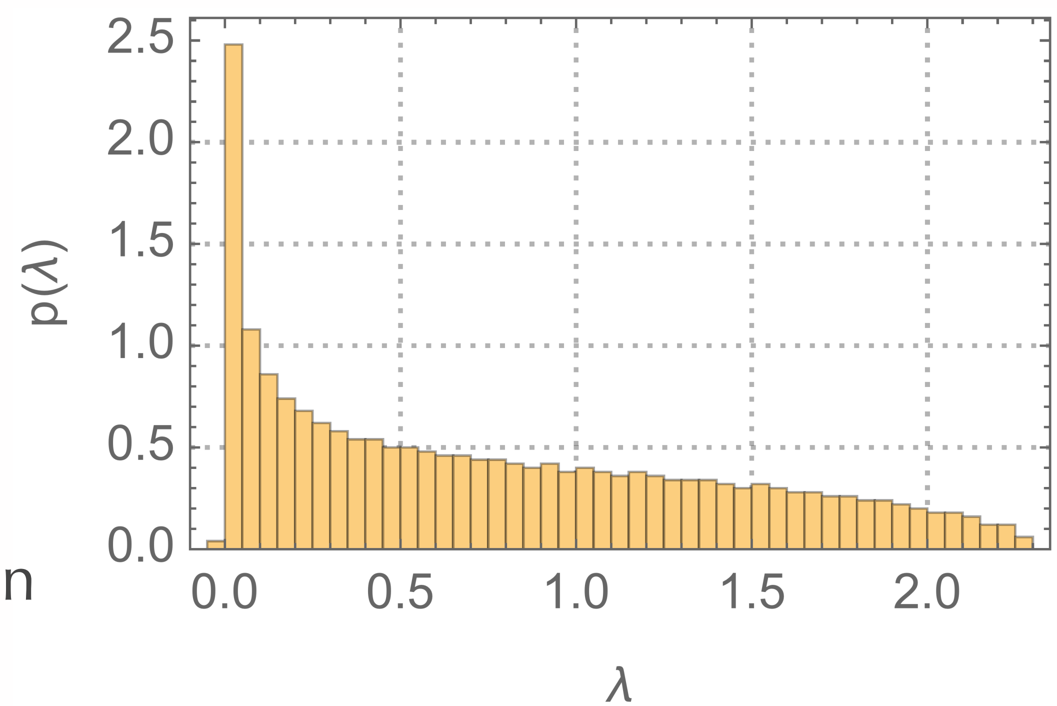
Random Potential using RMT

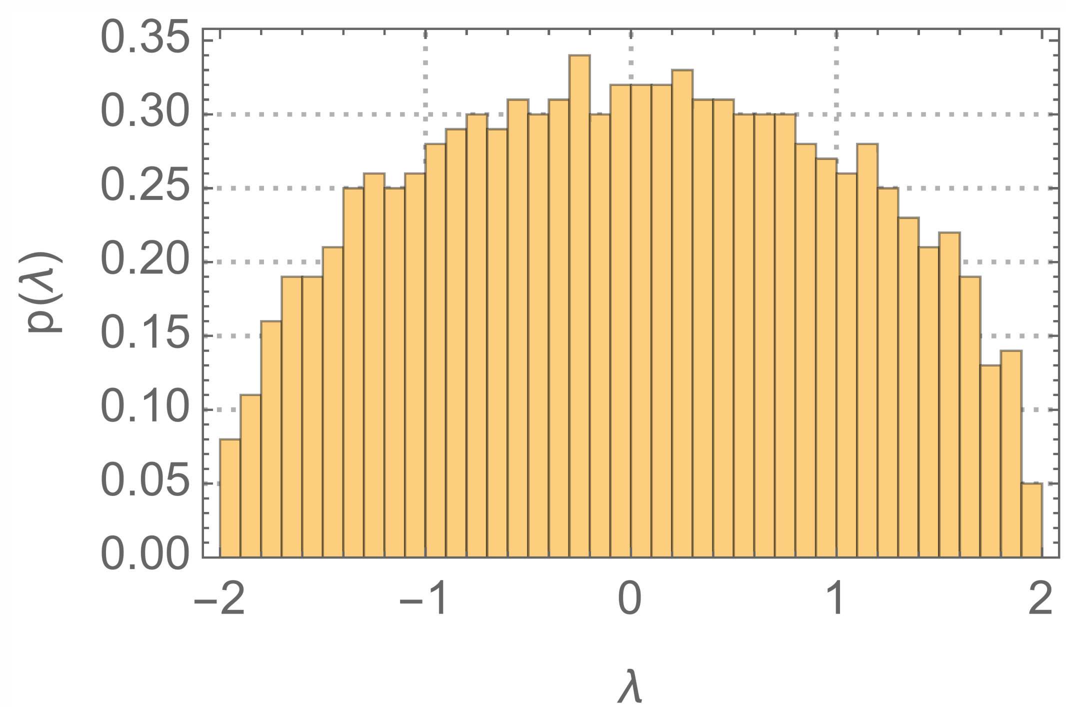
Rare, fluctuated spectrum, suitable for inflation



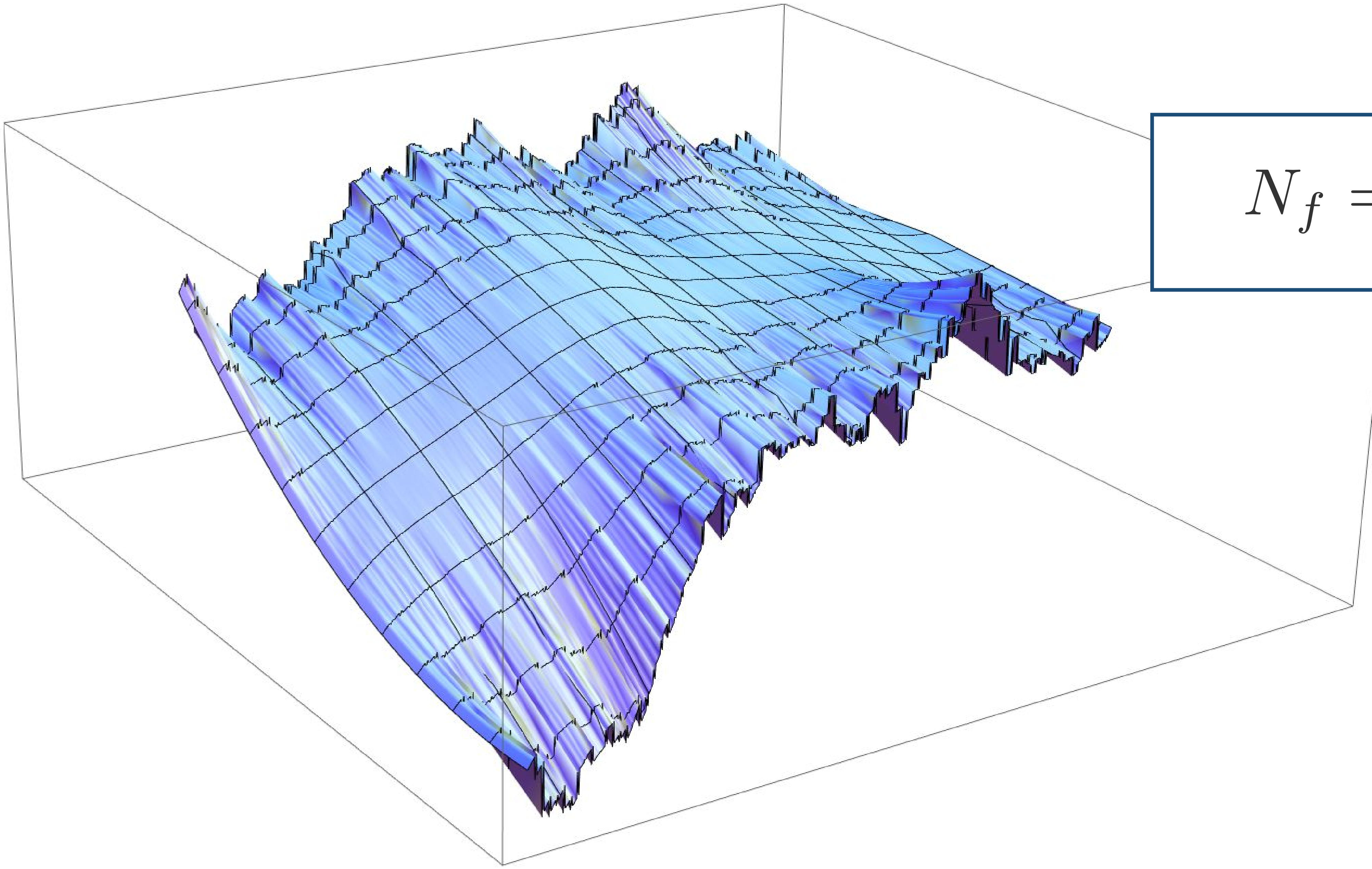
Typical configuration, not suitable for inflation

Dyson Brownian Motion



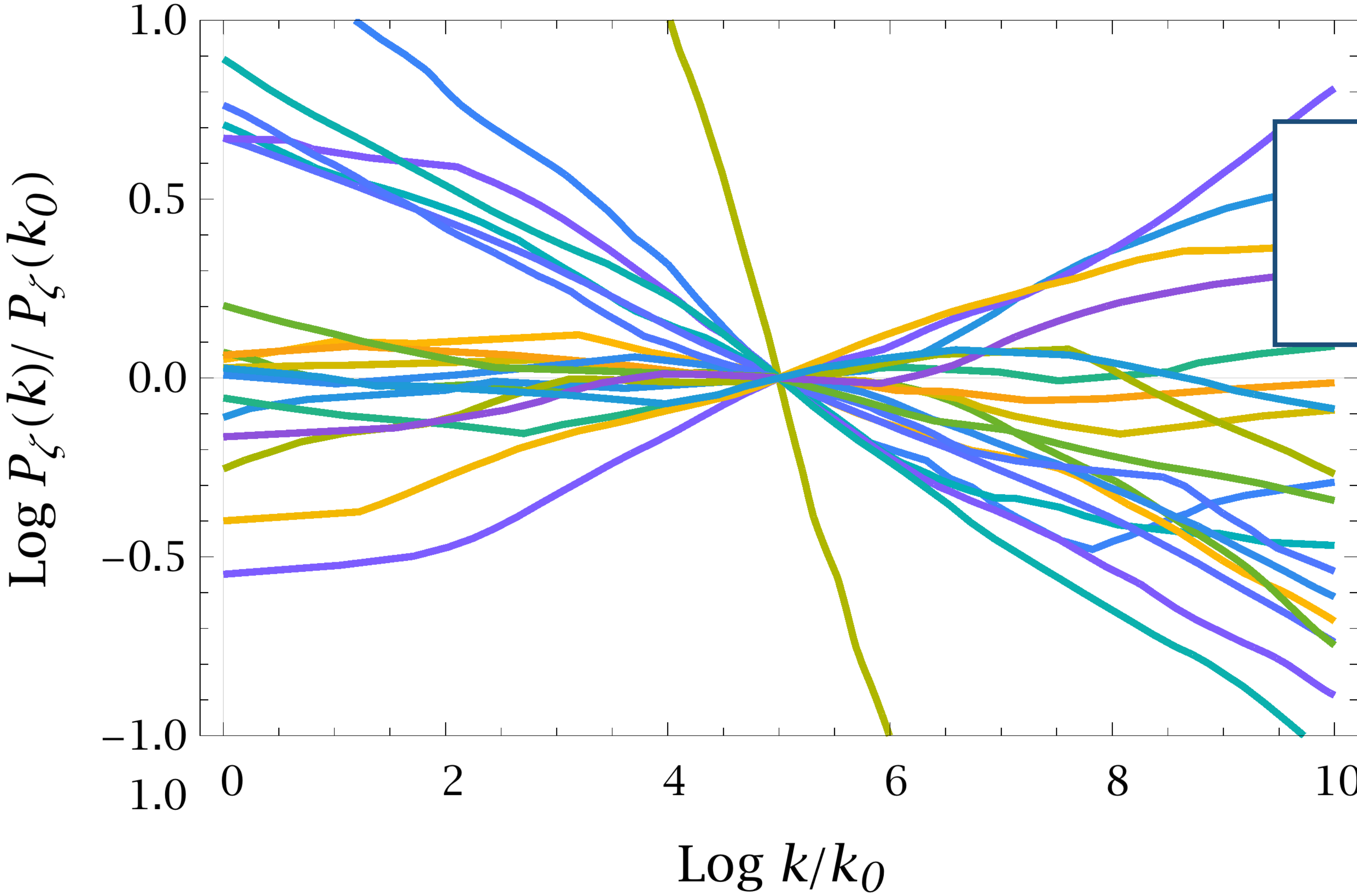


Random Potential using RMT



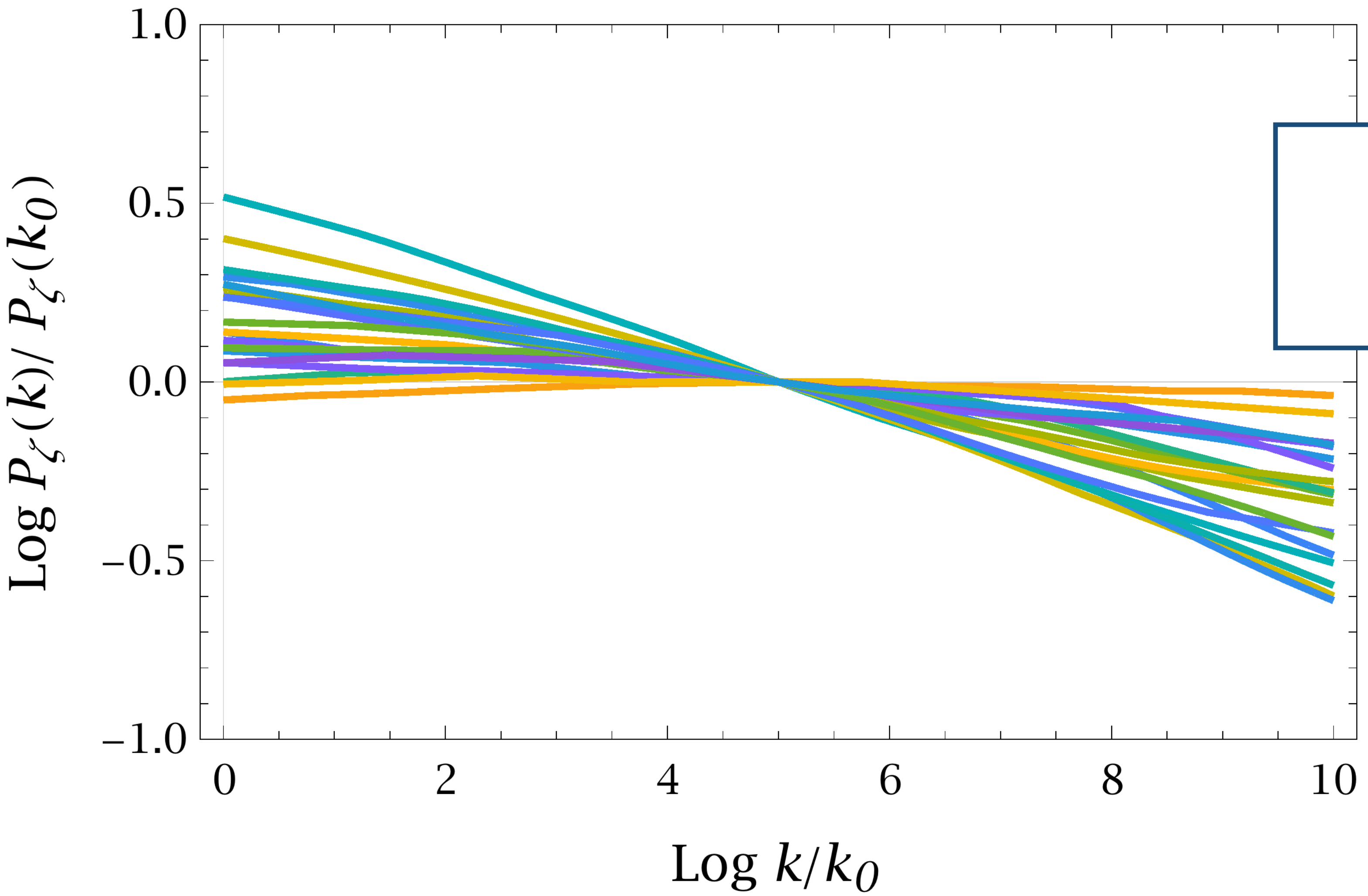
$N_f = 2$

Random Potential using RMT



$N_f = 2$

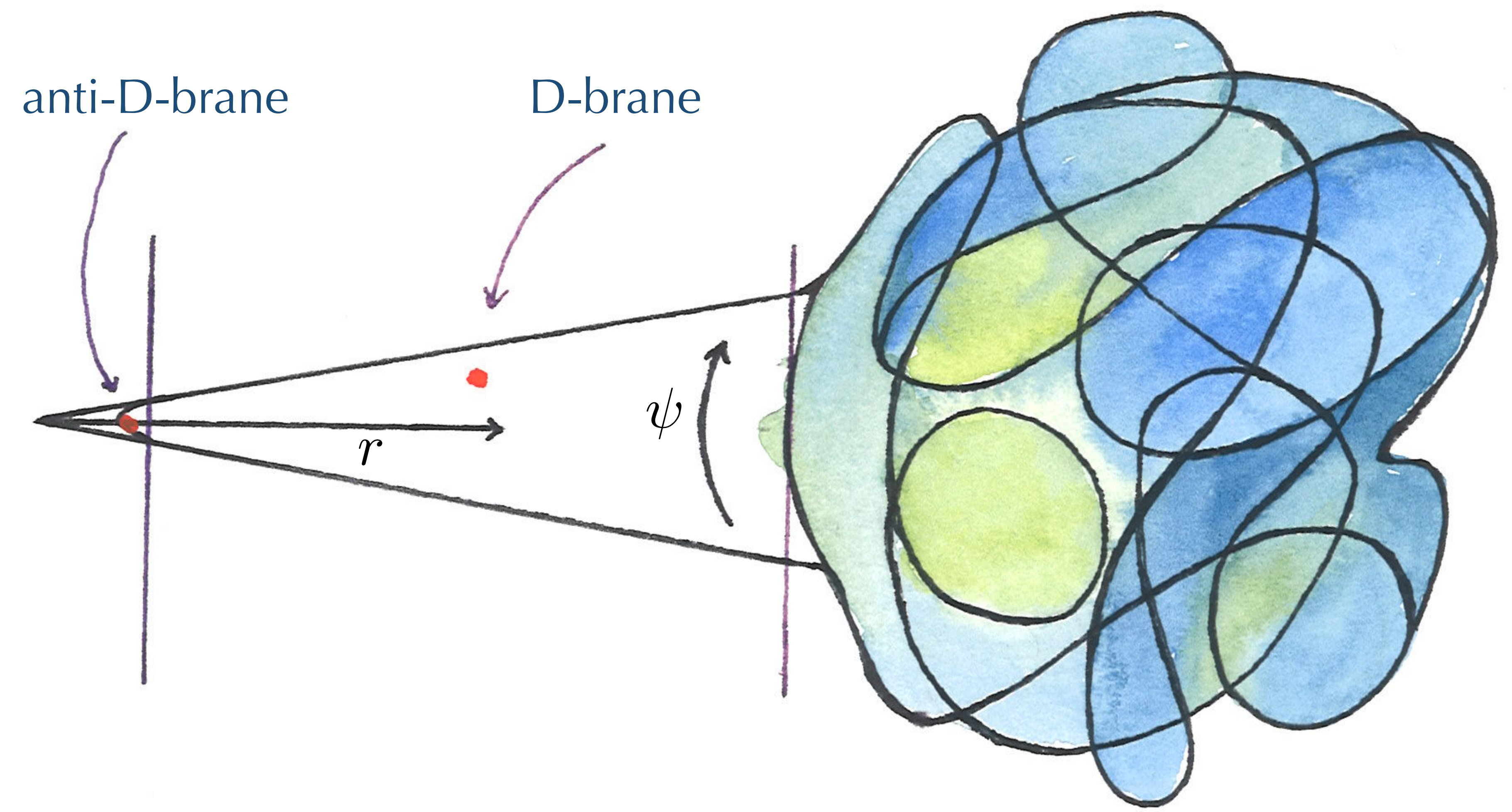
Random Potential using RMT



$N_f = 50$

Smoother and more predictive spectra

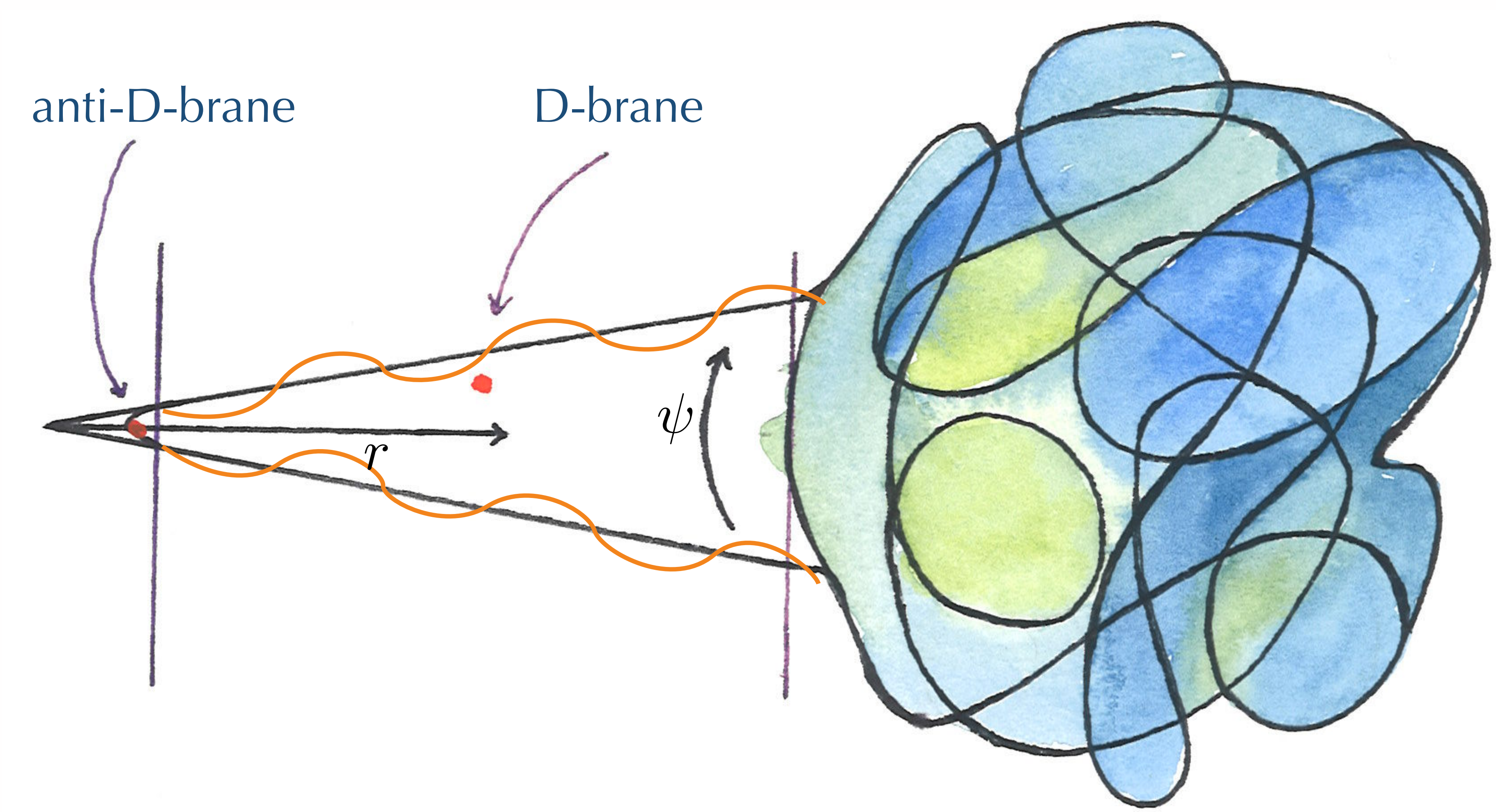
D-BRANE INFLATION



$$V = V_{\text{Coulomb}} + V_{\text{mass}} \qquad V_{\text{Coulomb}} \propto 1/r^4 \quad V_{\text{mass}} \propto r^2$$

no successful inflation

D-brane Inflation



$$V = V_{\text{Coulomb}} + V_{\text{mass}} + V_{\text{bulk}}$$

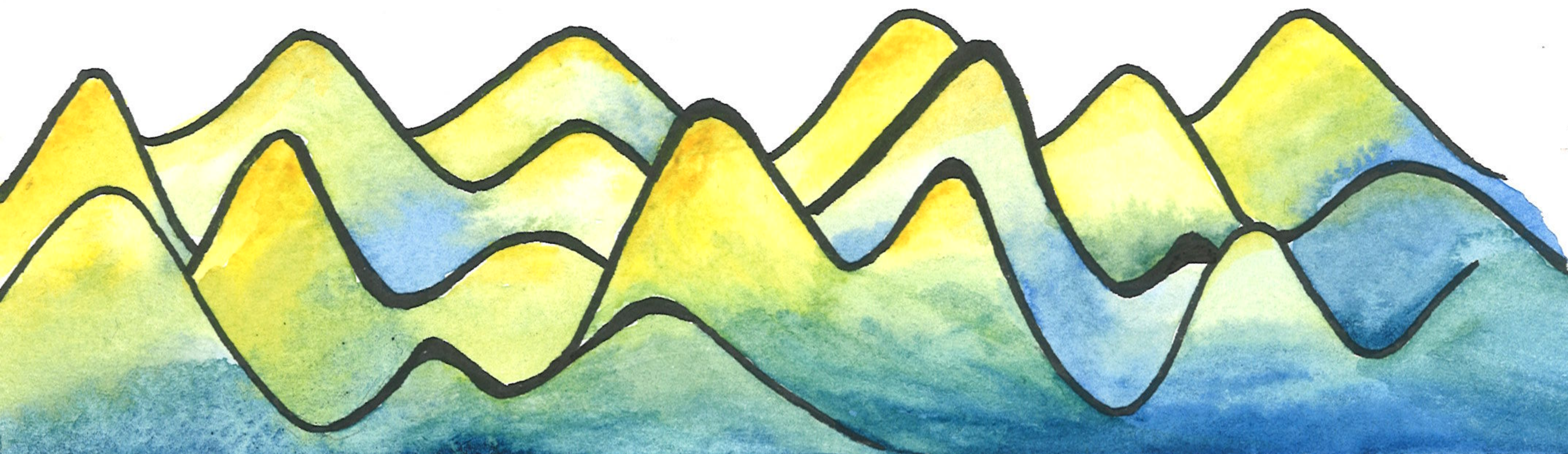
$$V_{\text{bulk}} \propto \sum_{LM} C_{LM} r^{\Delta(L)} Y_{LM}(\psi)$$

C_{LM}: stochastic Wilson coefficients

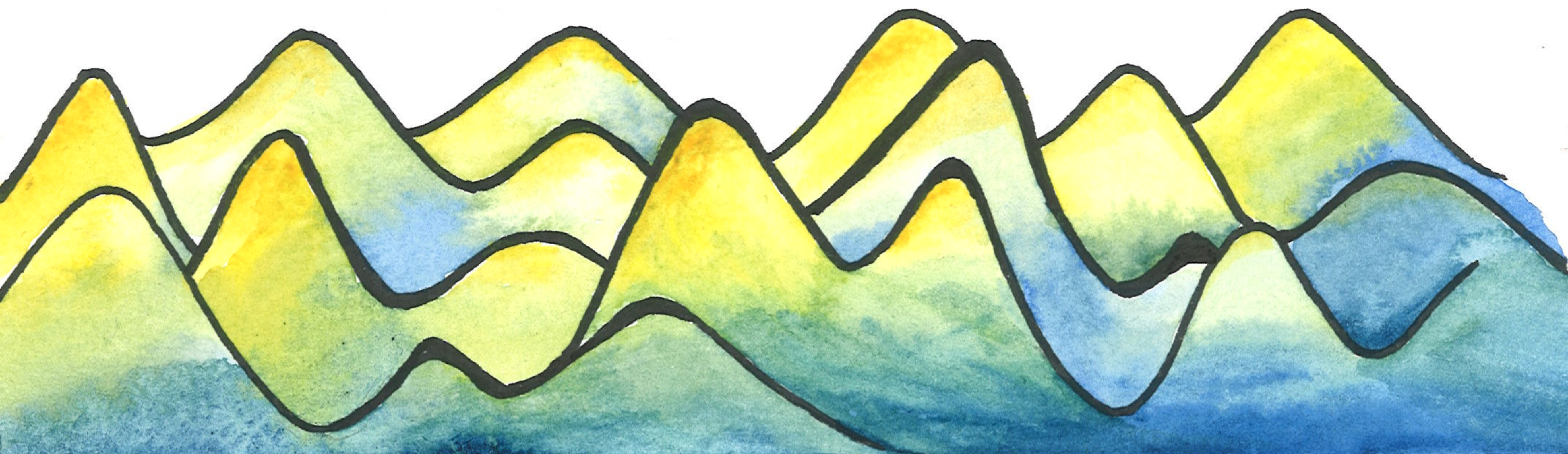
$Y_{LM}(\psi)$: harmonic eigenfunction

SUMMARISING:

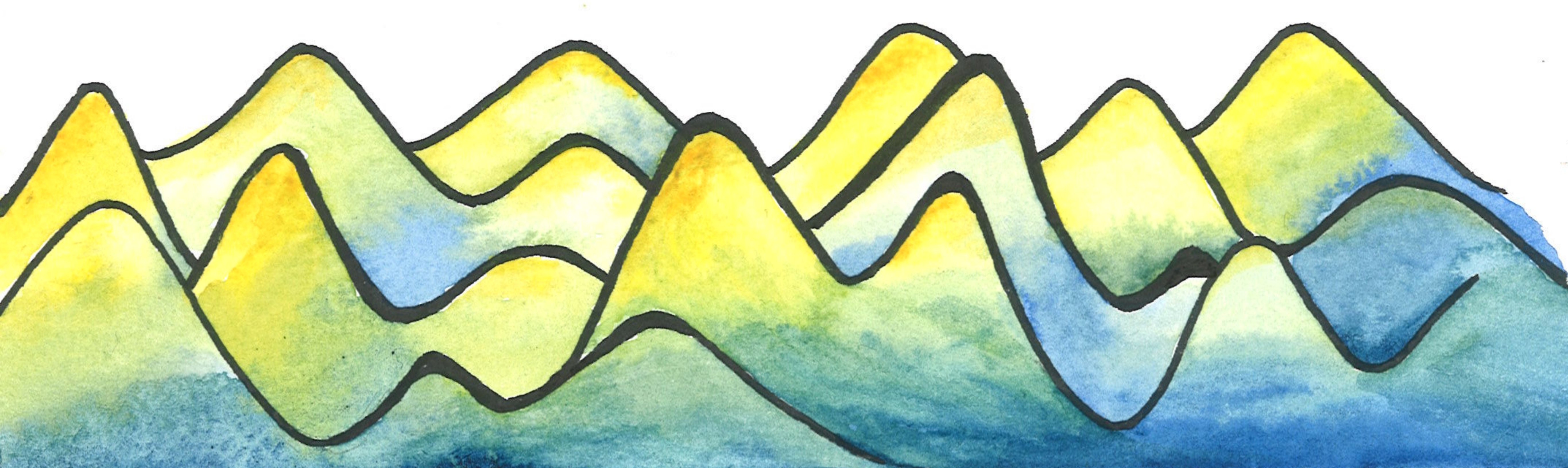
- High energy physics suggests a complex picture for inflation.
- This complexity can have important phenomenological consequences, and certainly implies computational difficulties -- transport method.
- This complexity can give rise to emergent predictive behaviour, which can be explored using stochastic tools in model building.



Extra slides



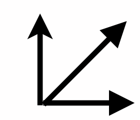
Complex field-space metrics: N-flation



N-flation example

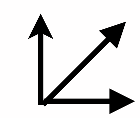
N-Axions potential:

$$V = K^{ij}\partial\theta_i\partial\theta_j + \sum_i \Lambda_i(1 - \cos\theta_i)$$



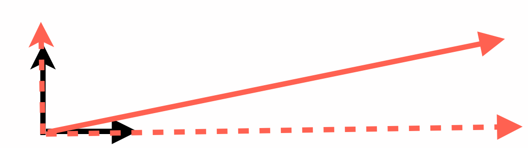
$\pi\sqrt{2}$

$$V = \mathrm{Diag}[f_i]\ \partial\theta_i\partial\theta_j + \sum_i \Lambda_i(1 - \cos\theta_i)$$



$\pi\sqrt{2}$

$$V = \partial\theta_i\partial\theta_j + \sum_i \Lambda_i(1 - \cos\theta_i/f_i)$$

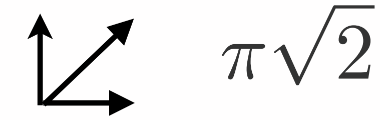


$\pi\sqrt{f_1^2 + f_2^2}$

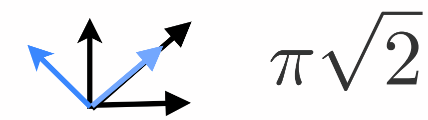
N-FLATION EXAMPLE

N-AXIONS POTENTIAL:

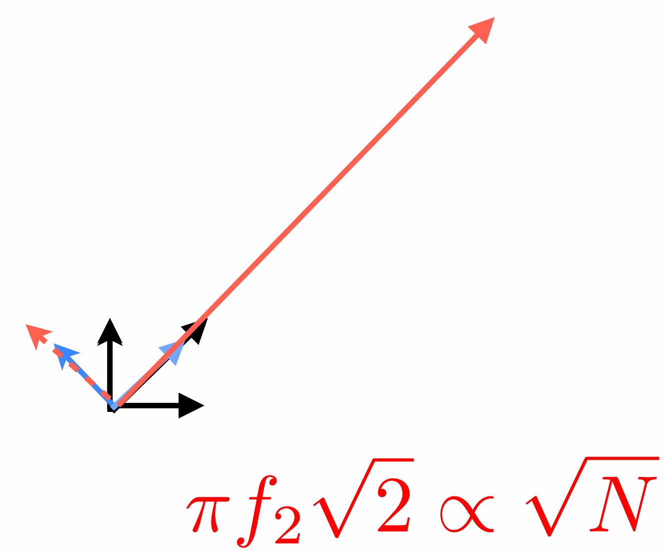
$$V = K^{ij}\partial\theta_i\partial\theta_j + \sum_i \Lambda_i(1 - \cos\theta_i)$$



$$V = \mathrm{Diag}[f_i]\ \partial\tilde{\theta}_i\partial\tilde{\theta}_j + \sum_i \Lambda_i(1 - \cos\tilde{\theta}_i)$$

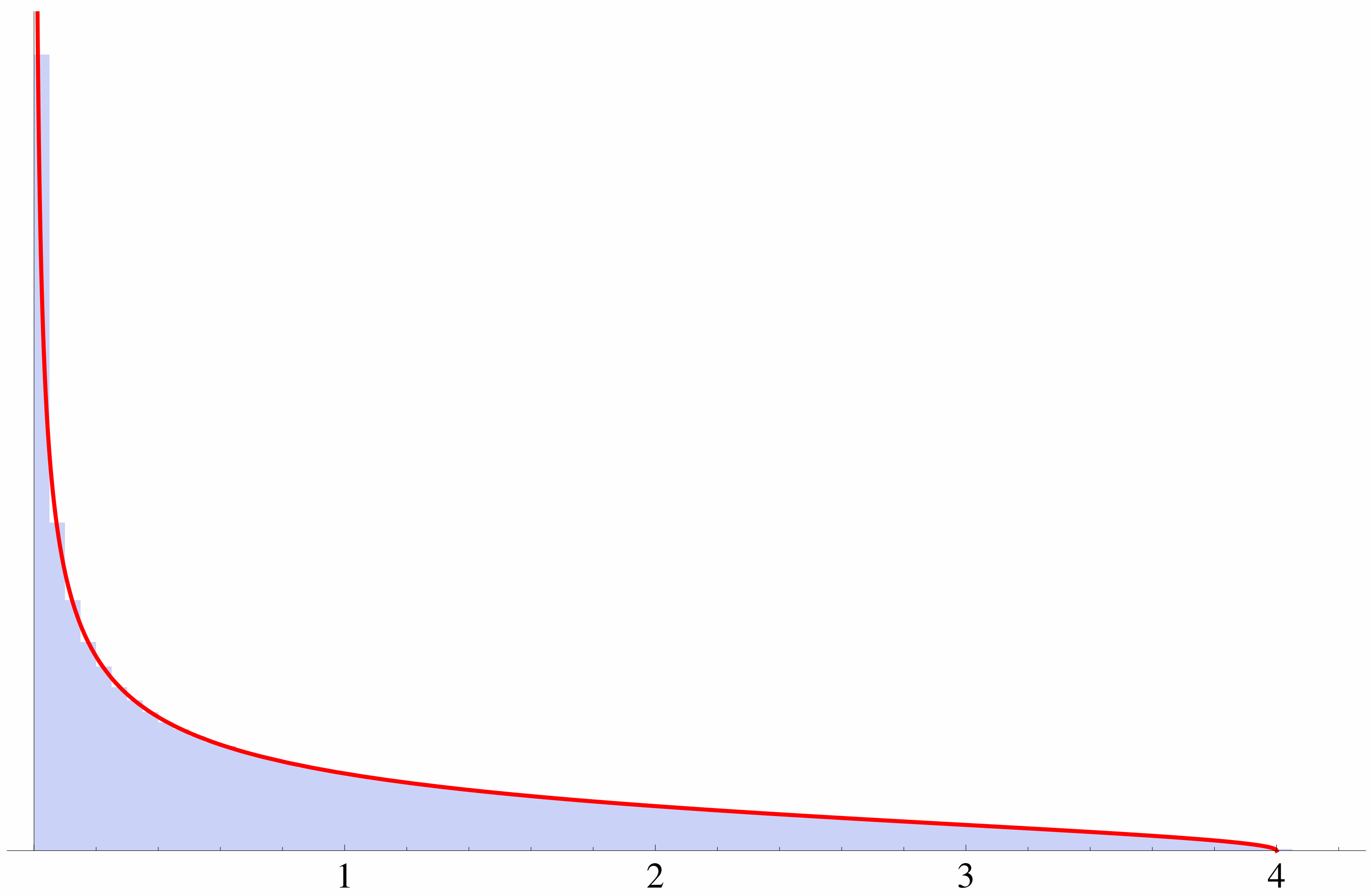


$$V = \partial\theta_i\partial\theta_j + \sum_i \Lambda_i(1 - \cos\theta_i/f_i)$$



N-flation example

K^{ij} ⟶ Positive definite ⟶ Wishart ensemble



THE TRANSPORT METHOD

$$\frac{d\delta\phi_\alpha}{dN} = u_{\alpha\beta}\delta\phi_\beta + \frac{1}{2}u_{\alpha\beta\gamma}\delta\phi_\beta\delta\phi_\gamma + \cdots$$

$$\hat{\mathcal{H}} = \hat{\mathcal{H}}_0 + \hat{\mathcal{H}}_{\text{int}} \longrightarrow \boxed{\left[\delta\hat{\varphi}_\alpha, \hat{\mathcal{H}}_0\right] = iu_{\alpha\beta}\delta\hat{\varphi}_\beta} \quad \boxed{\left[\delta\hat{\varphi}_\alpha, \hat{\mathcal{H}}_{\text{int}}\right] = iu_{\alpha\beta\gamma}\delta\hat{\varphi}_\beta\delta\hat{\varphi}_\gamma}$$

$$\frac{d\Sigma_{\alpha\beta}}{dN} = \left\langle \frac{d\delta\phi_\alpha}{dN}\delta\phi_\beta + \delta\phi_\alpha\frac{d\delta\phi_\beta}{dN} \right\rangle = u_{\alpha\gamma}\Sigma_{\gamma\beta} + u_{\beta\gamma}\Sigma_{\alpha\gamma} + \cdots$$

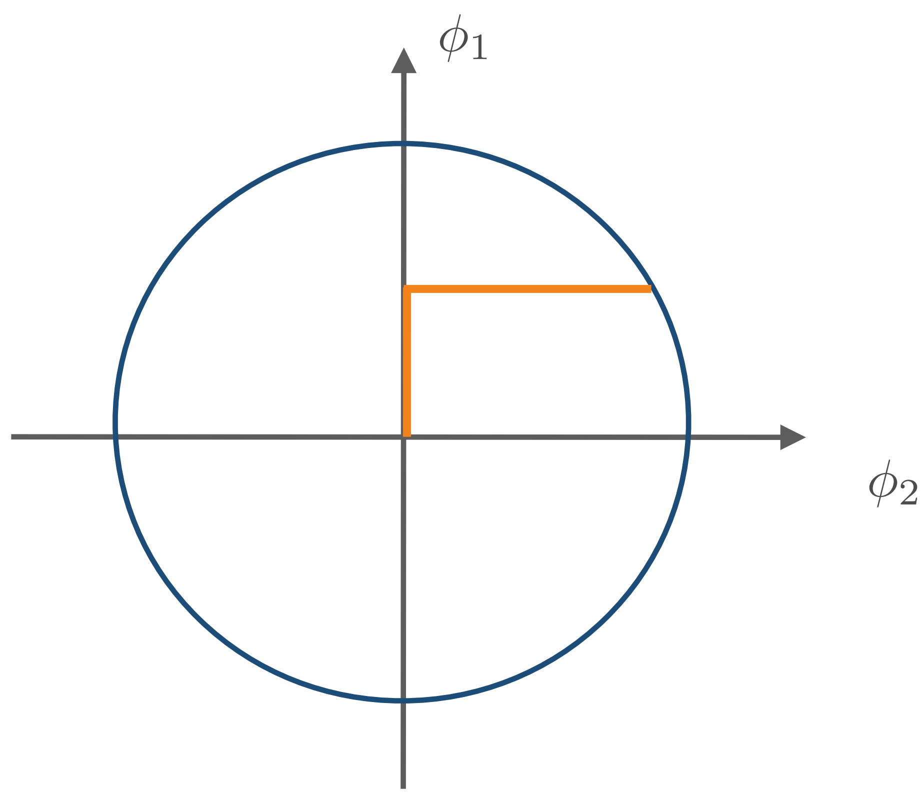
$$\frac{d\alpha_{\alpha\beta\gamma}}{dN} = u_{\alpha\lambda}\alpha_{\lambda\beta\gamma} + u_{\alpha\lambda\mu}\Sigma_{\lambda\beta}\Sigma_{\mu\gamma} + \text{cyclic }(\alpha \to \beta \to \gamma) + \cdots$$

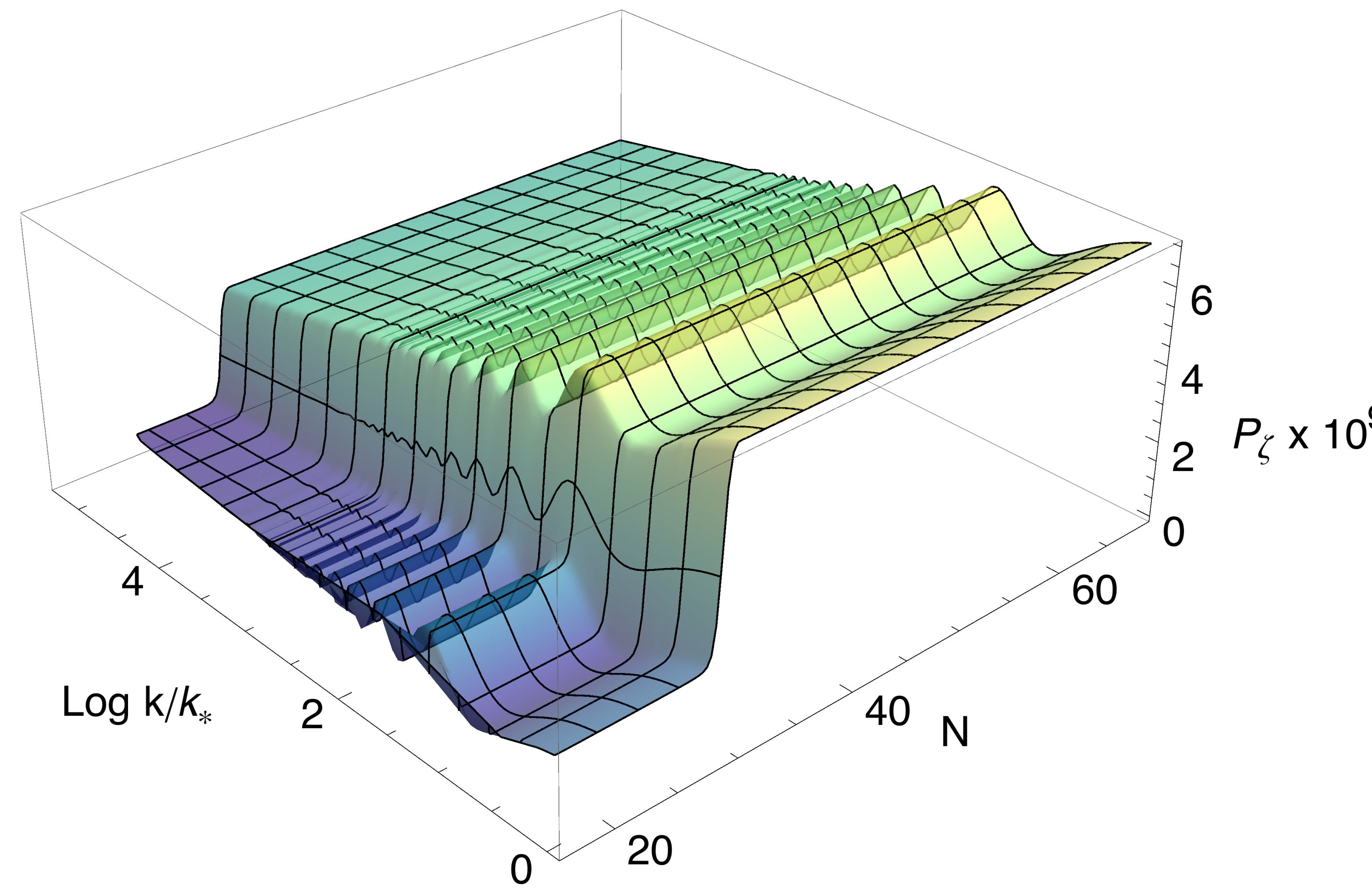
system of ODEs

$$\Sigma_{\alpha\beta} \equiv \langle\delta\phi_\alpha\delta\phi_\beta\rangle$$

$$\alpha_{\alpha\beta\gamma} \equiv \langle\delta\phi_\alpha\delta\phi_\beta\delta\phi_\gamma\rangle$$

Inflation in the presence of many fields





$$V = \frac{1}{2}\sum_{\alpha=1}^{3} m_\alpha^2 \phi_\alpha^2 \qquad G^{\alpha\beta} = \begin{pmatrix} 1 & \Gamma & 0 \\ \Gamma & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

Inflation and the tantalizing idea of using cosmological observations as a lab for high energy physics

$$g_{ij} = a^2(t) e^{\zeta(\mathbf{x},t)} \gamma_{ij}(\mathbf{x})$$

$a^2(t)$ → scale factor

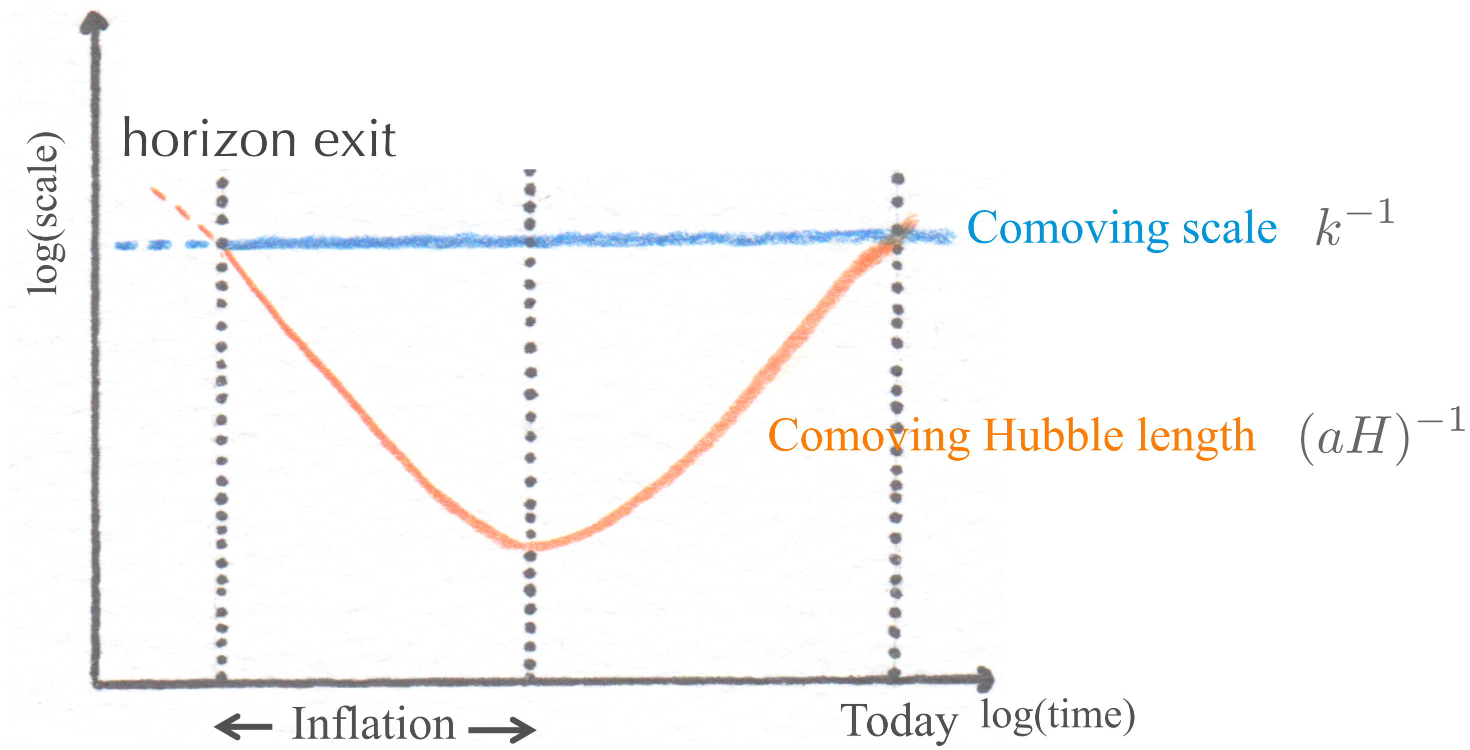
$\zeta(\mathbf{x},t)$ → scalar mode:

ζ curvature perturbation

$\gamma_{ij}(\mathbf{x})$ → tensor modes

Field perturbation $\delta\phi$ → Curvature perturbation ζ → P_ζ: $\langle\zeta\zeta\rangle$; n_s: $\frac{\mathrm{d}\langle\zeta\zeta\rangle}{\mathrm{d}\ \ln k}$; f_{NL}: $\langle\zeta\zeta\zeta\rangle$

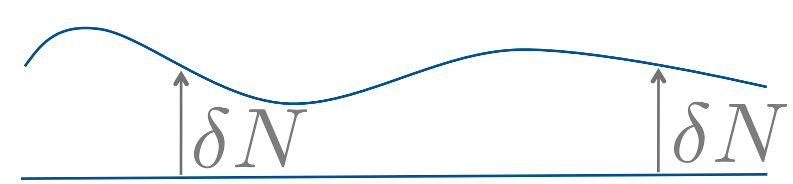
INFLATION IN THE PRESENCE OF MANY FIELDS



flat/ constant curvature gauge $\delta\phi$

constant density gauge ζ

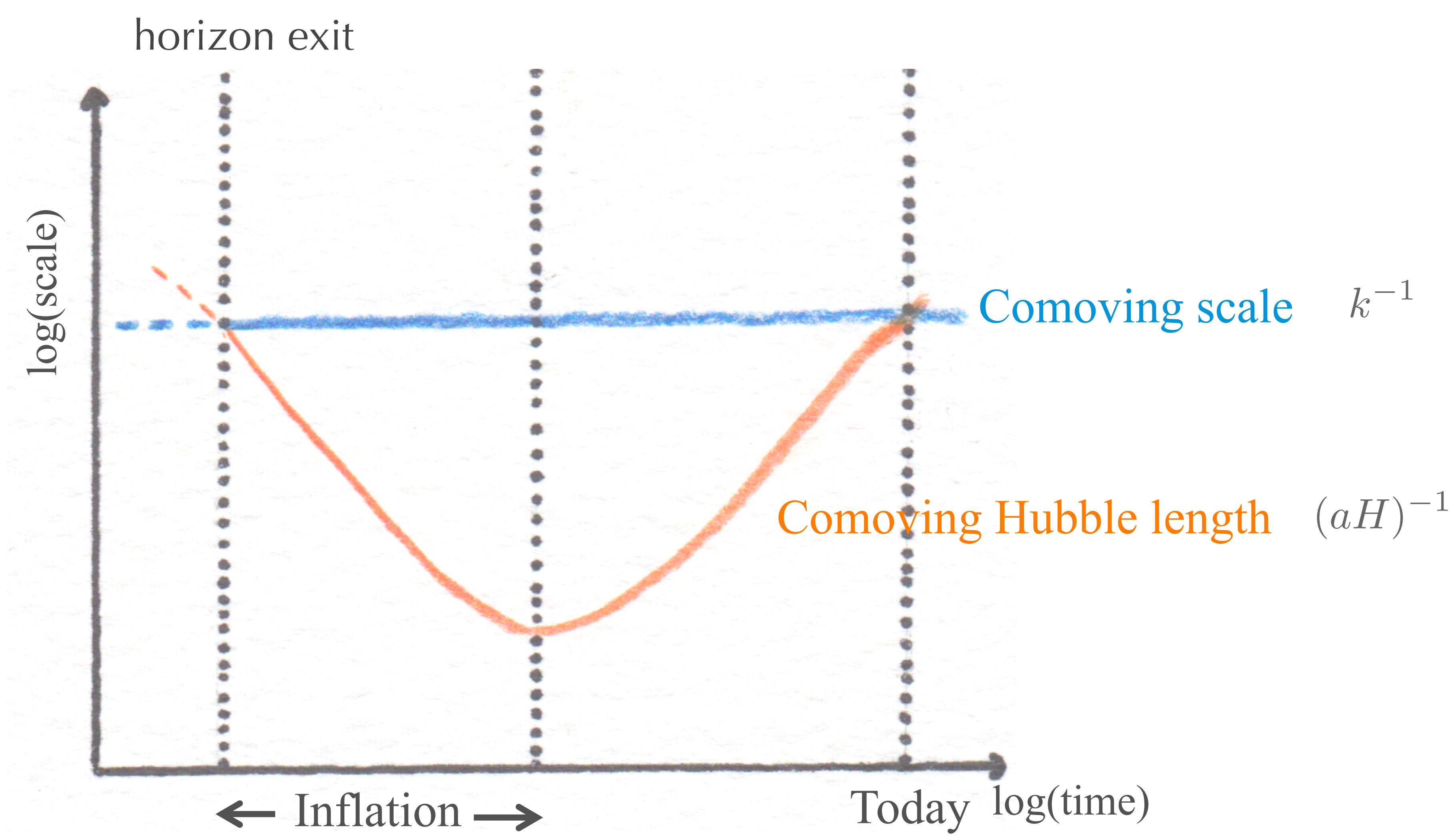
constant ρ



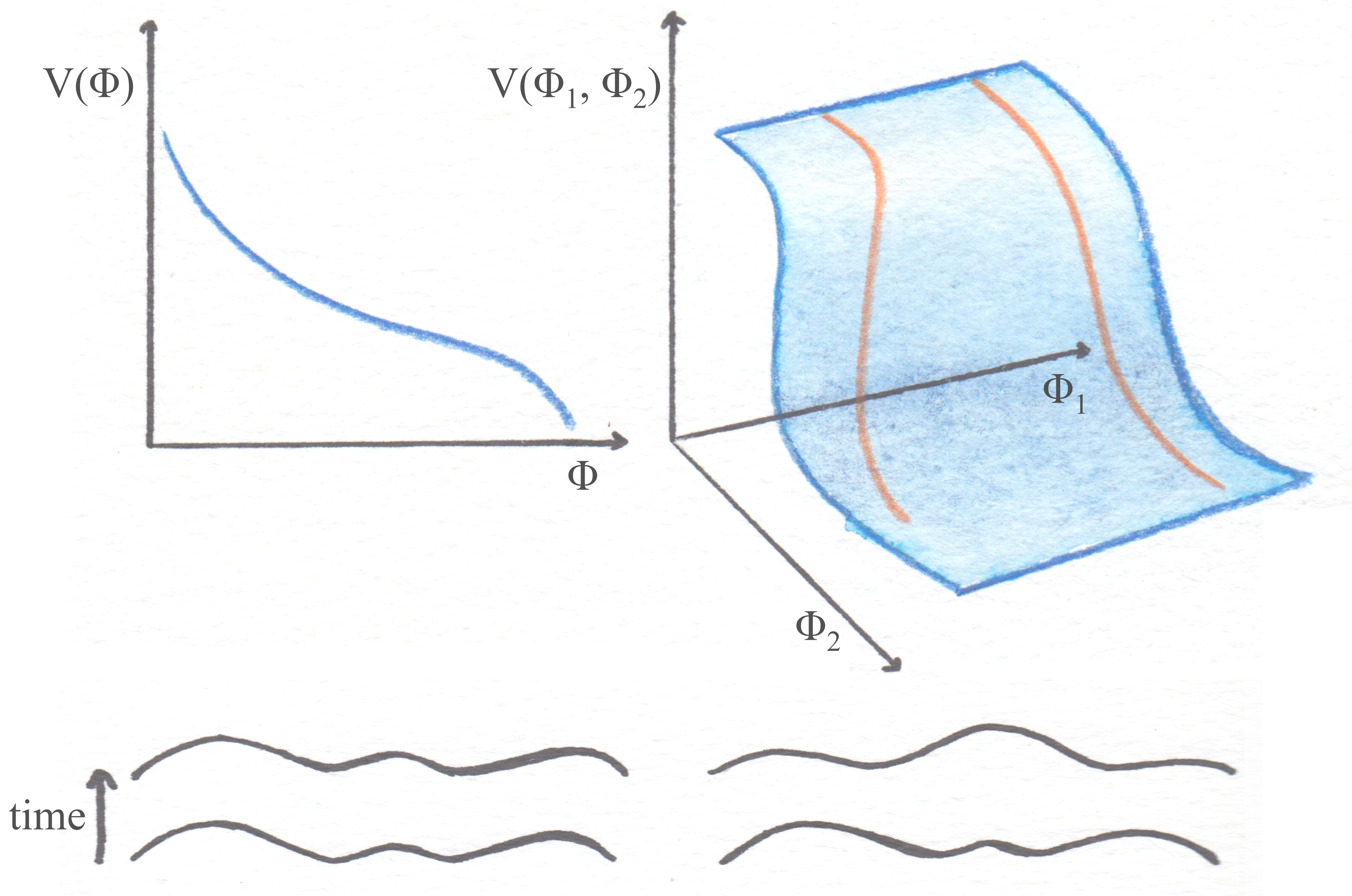
flat

$$\zeta = \delta N$$

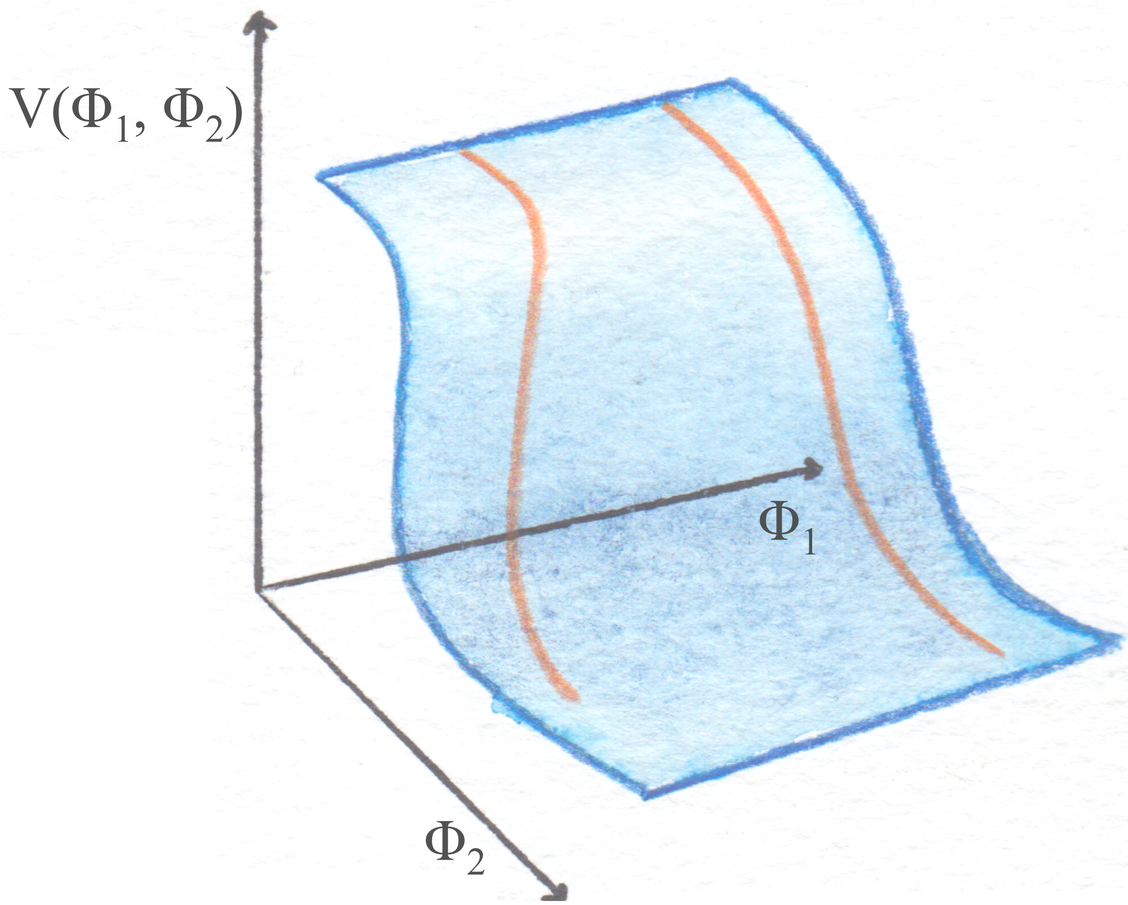
Inflation in the presence of many fields



INFLATION IN THE PRESENCE OF MANY FIELDS

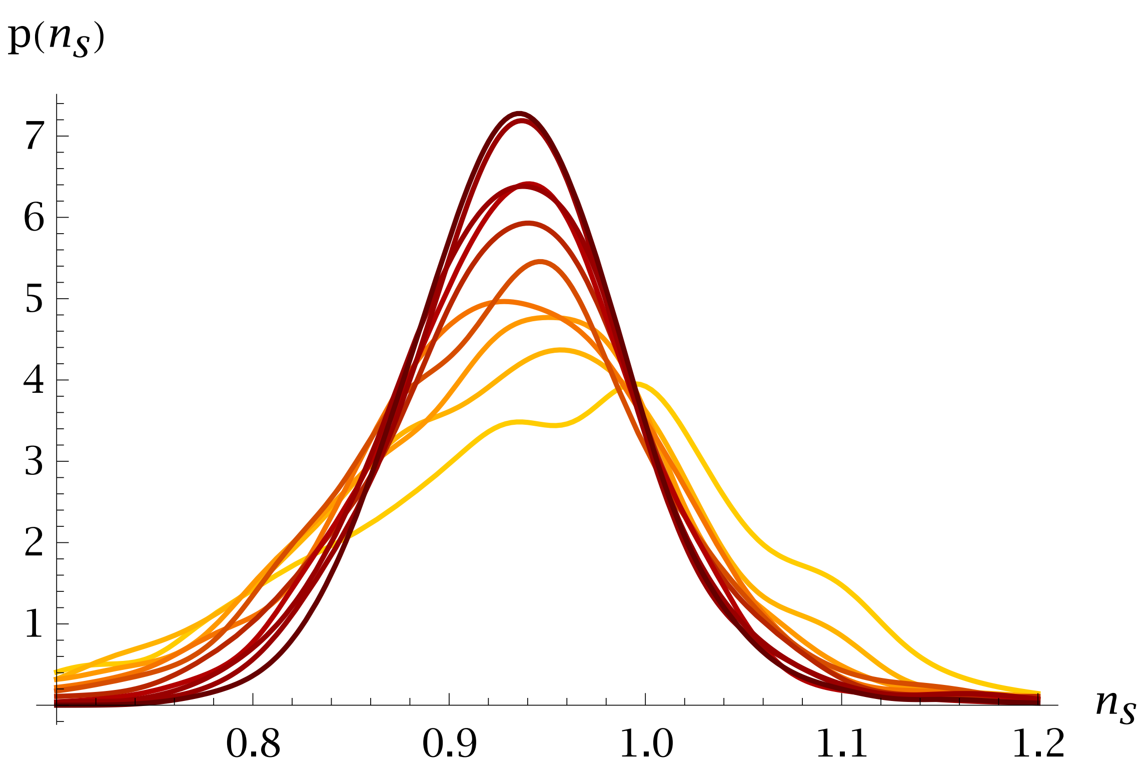


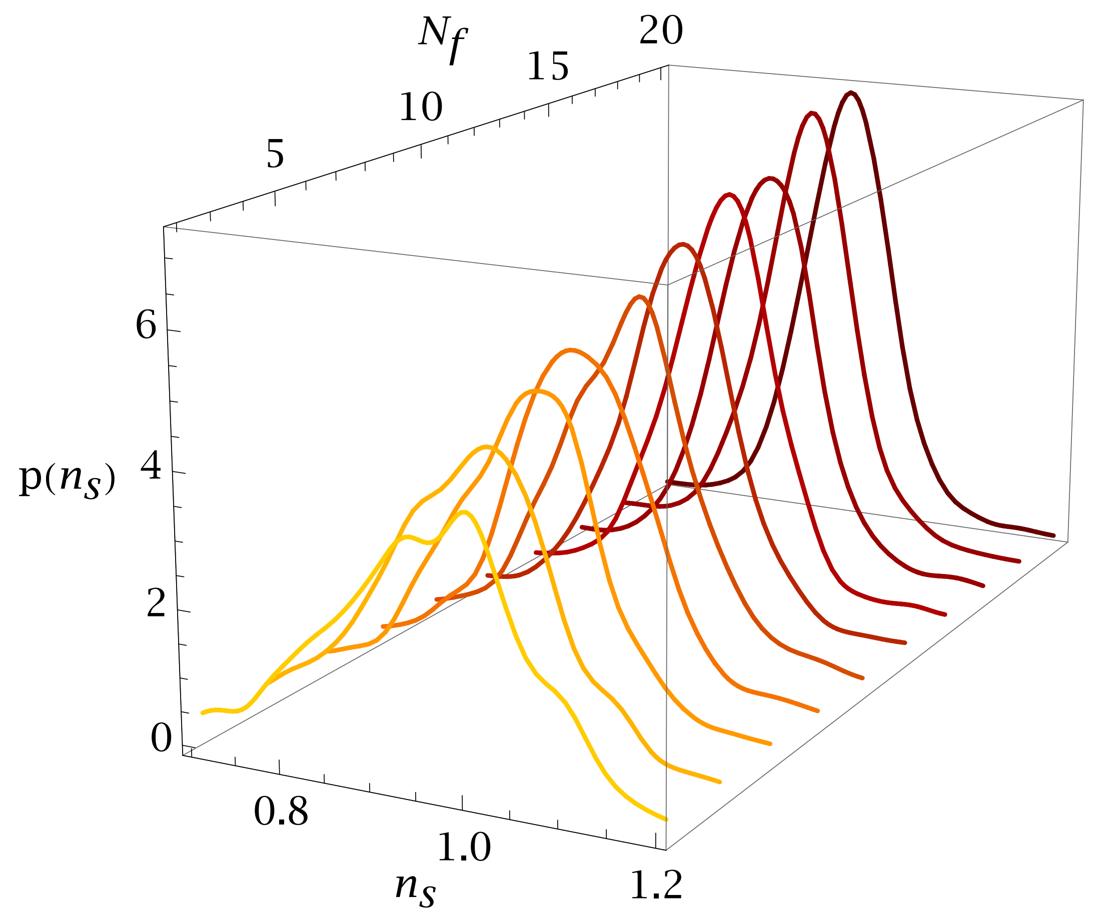
INFLATION IN THE PRESENCE OF MANY FIELDS



- SUPERHORIZON EVOLUTION OF OBSERVABLES
  - also interference effects at horizon exit
- NON-GAUSSIANITY
  - local type, but for most models not observable
  - massive modes: quasi-single field effects and particle production
- ISOCURVATURE
  - non-predictive models if ζ not conserved by reheating

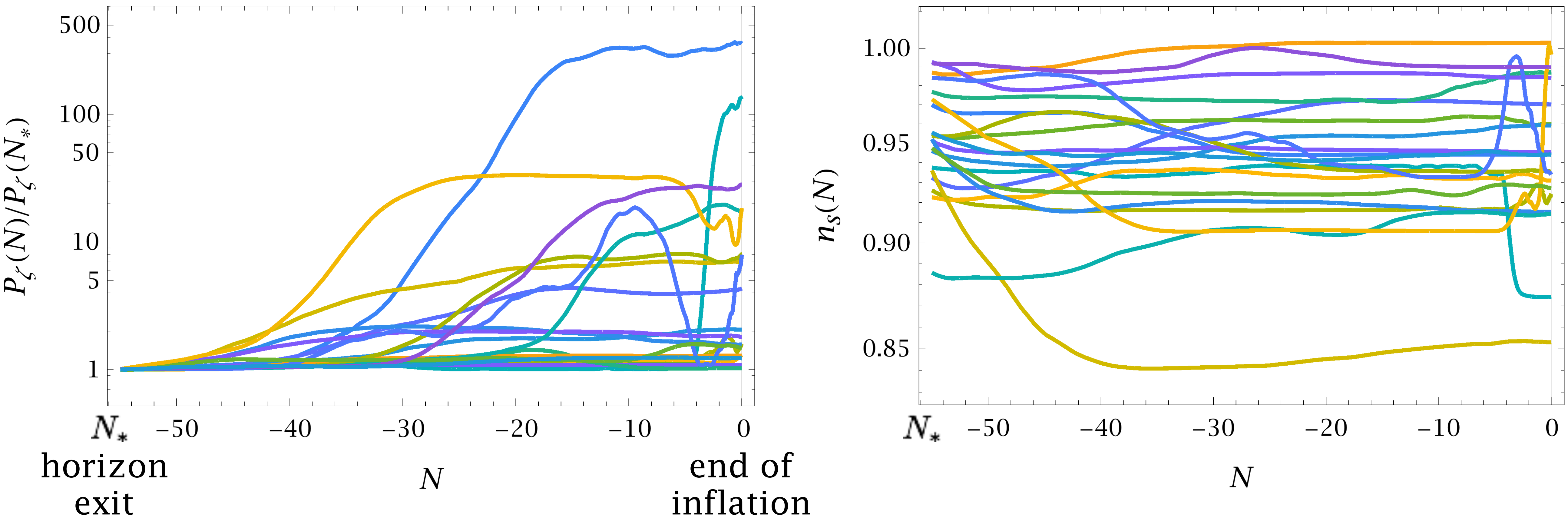
Random Potential using RMT





Smoother and more predictive spectra

Random Potential using RMT



Significant superhorizon evolution of the primordial curvature perturbation, implying the presence of many active fields

THE TRANSPORT METHOD

$\langle \text{in} | \zeta\zeta | \text{in} \rangle$

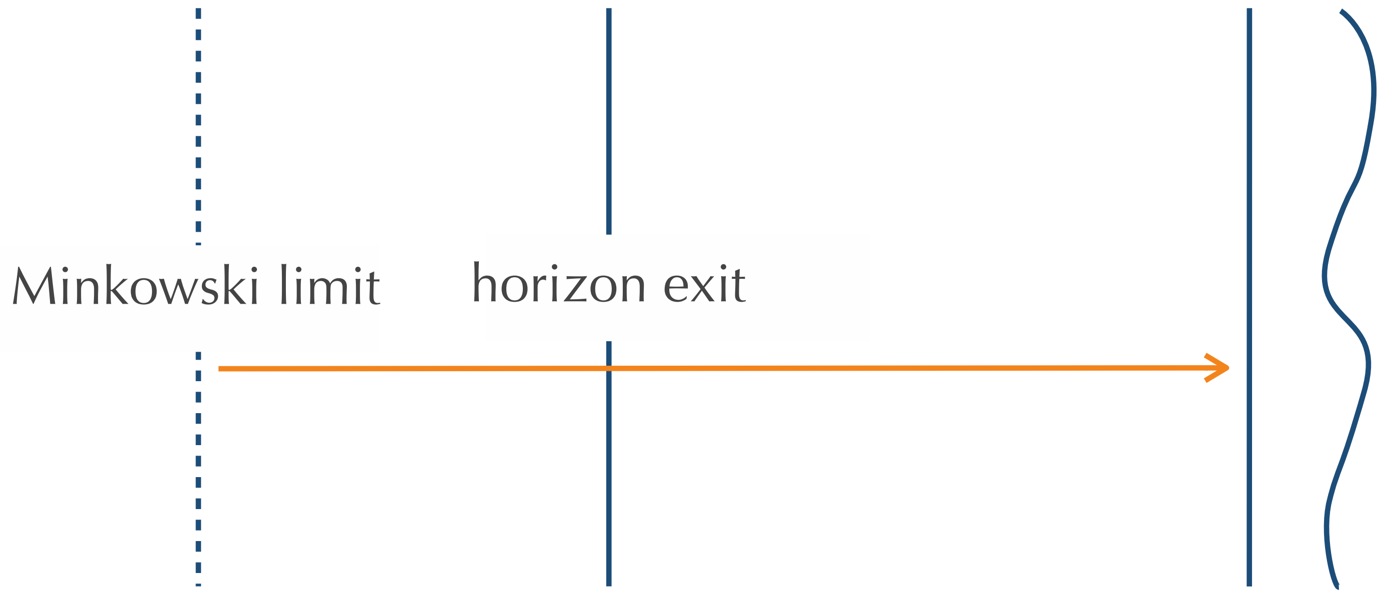
integrable form, nasty for numerics

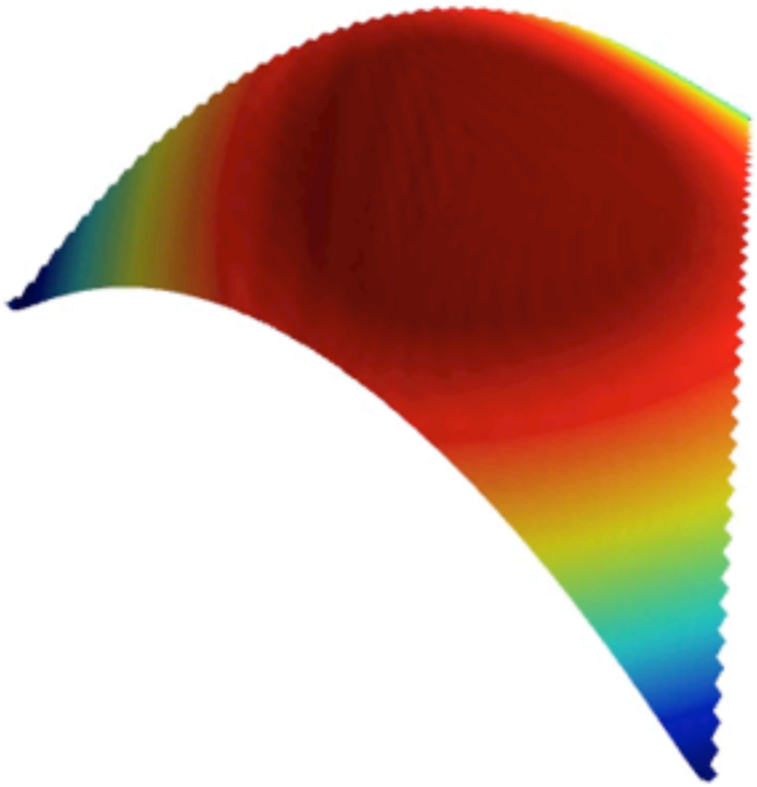
time dependent divergences at large scales

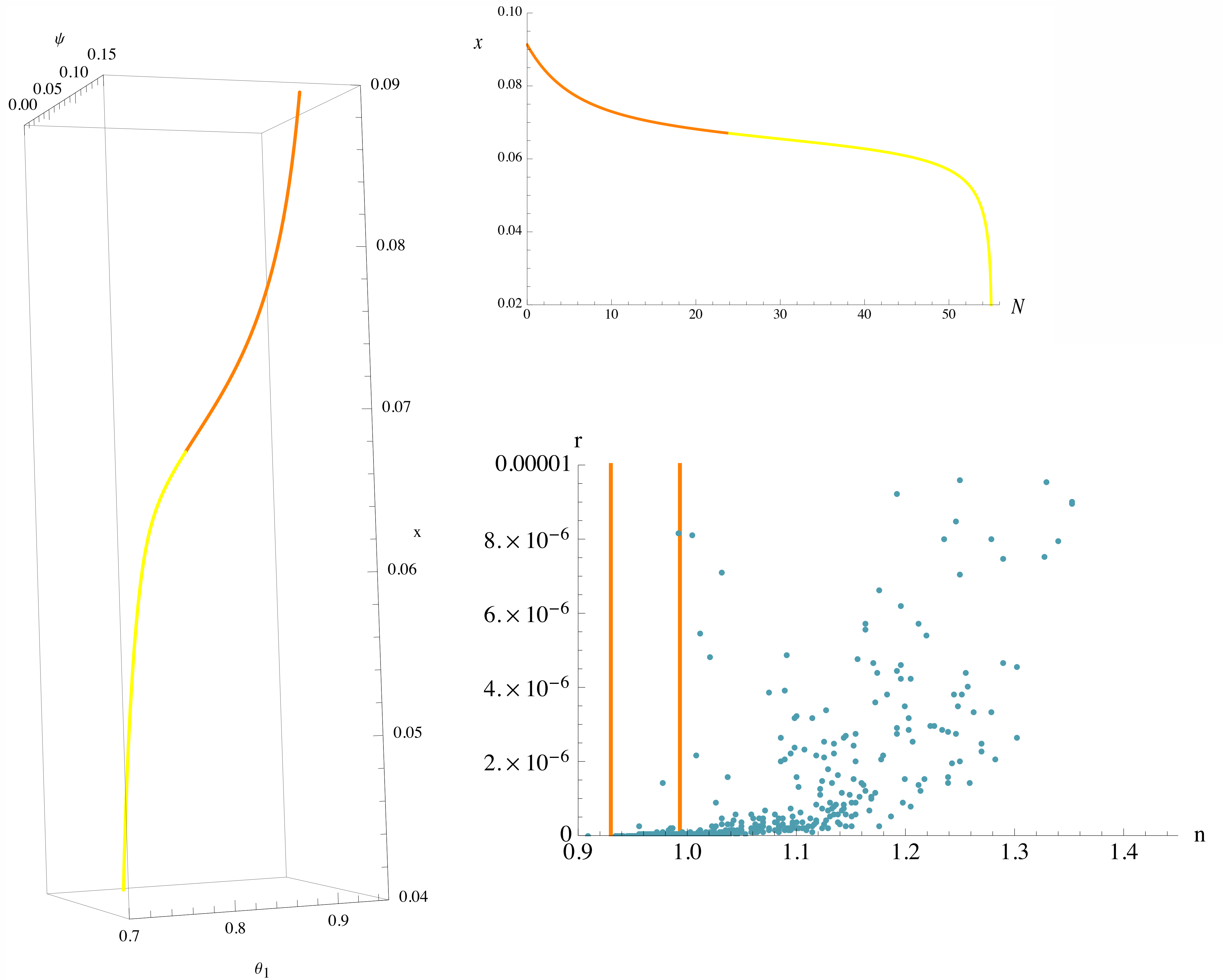
$\zeta = \delta N$

variational form, nasty for numerics

requires an initial condition at horizon exit






ψ
0.15
0.10
0.05
0.00
0.09
0.08
0.07
x
0.06
0.05
0.04
0.7
0.8
0.9
θ1
0.10
x
0.08
0.06
0.04
0.02
0
10
20
30
40
50
N
r
0.00001
8. × 10−6
6. × 10−6
4. × 10−6
2. × 10−6
0
0.9
1.0
1.1
1.2
1.3
1.4
n