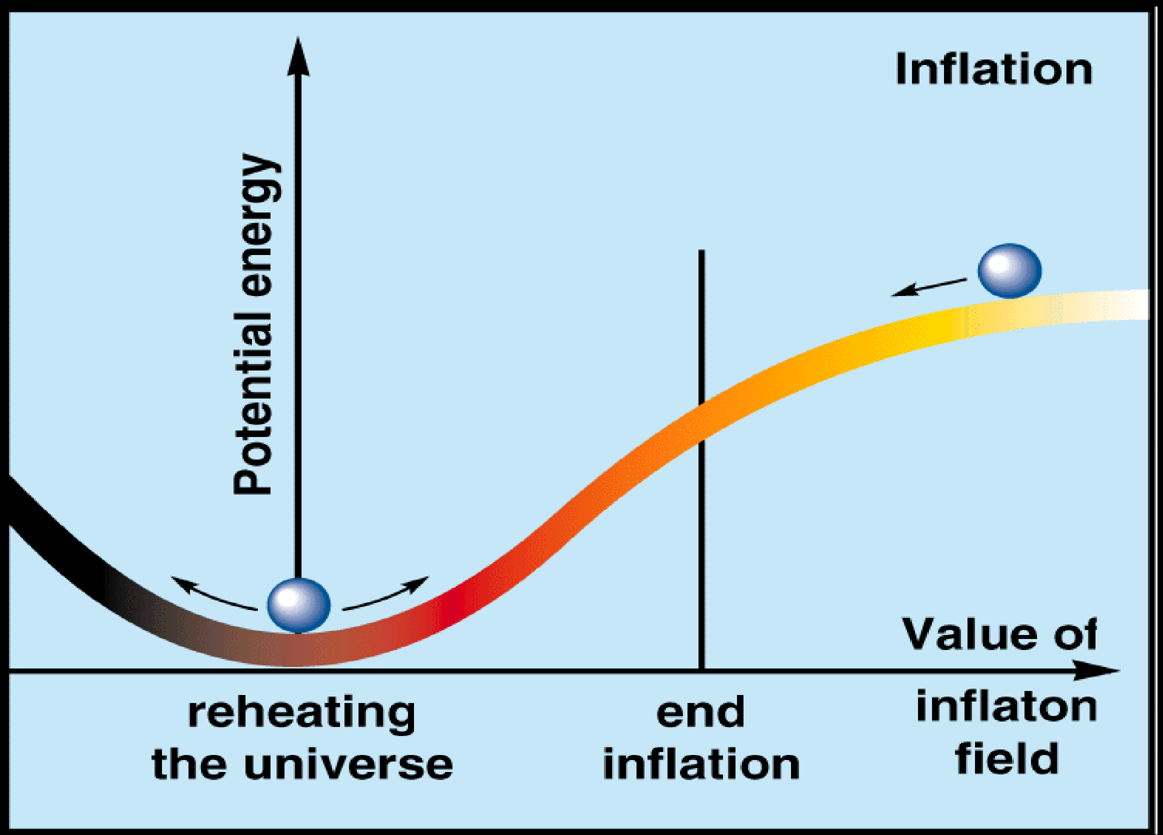
Status of Inflation



DSU2006, Madrid
21st June 2006

Juan García-Bellido
Física Teórica UAM

MSSM Inflation

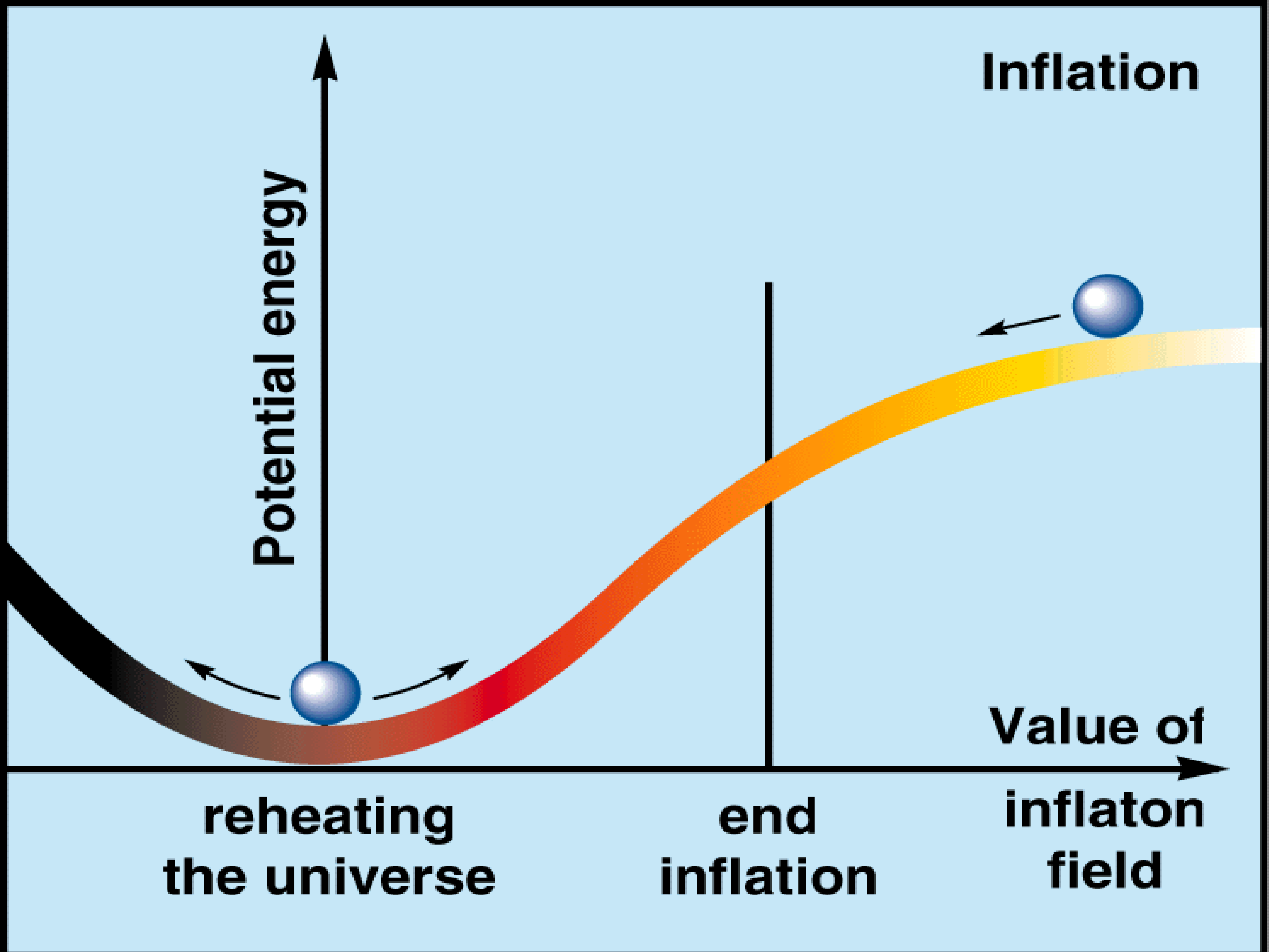
J. G.-B.
Kary Enqvist
Anupam Mazumdar
Rouzbeh Allahverdi

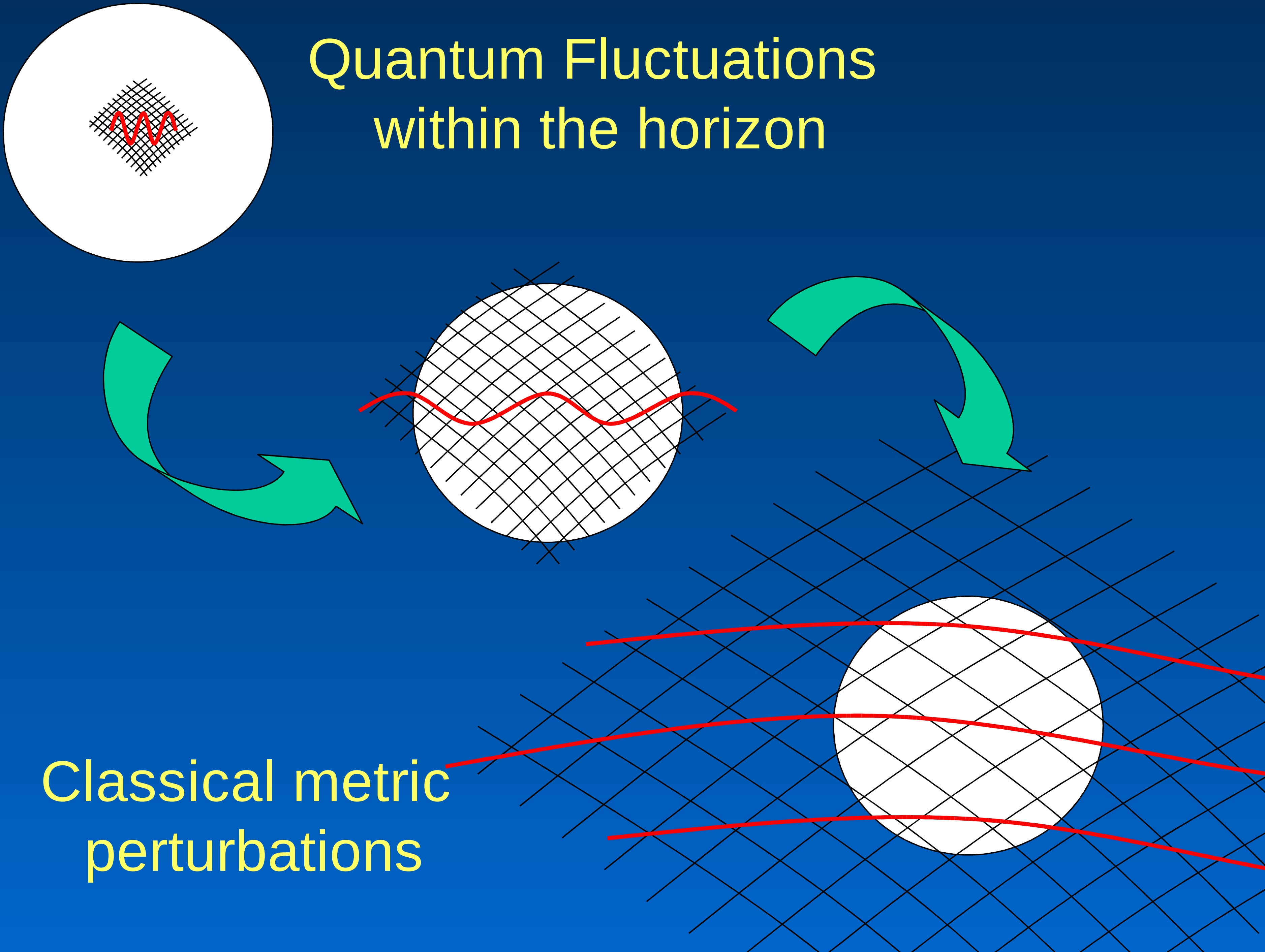
hep-ph/0605035

DSU 2006, Madrid
21st June, 2006

Inflation is a healthy 25 year old baby

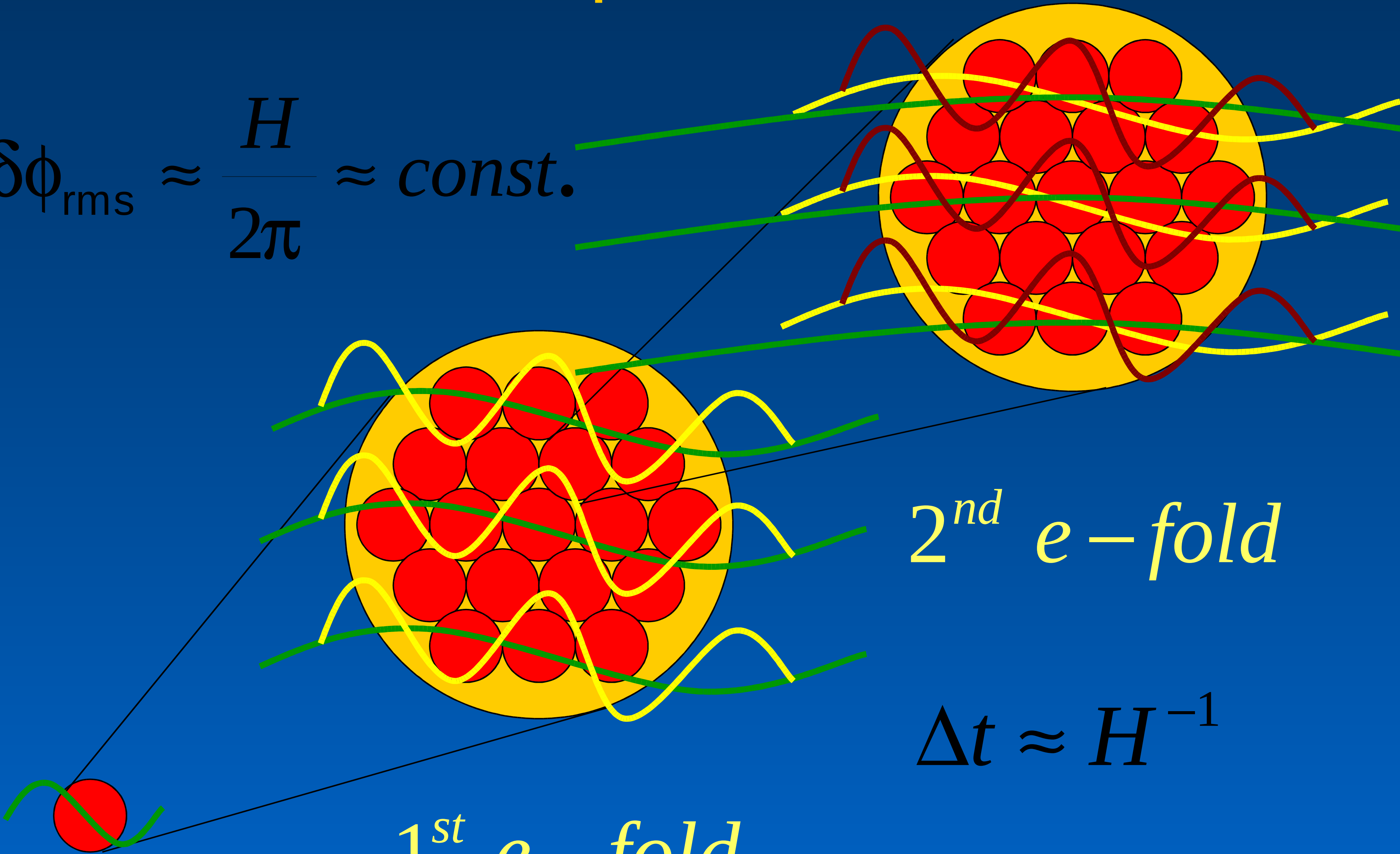
- Well established paradigm
- Basic predictions confirmed by experiments
- New phenomenology from preheating
- In need of a particle physics realization


Inflation
Potential energy
Value of
inflaton
field
reheating
the universe
end
inflation


Quantum Fluctuations
within the horizon
Classical metric
perturbations

Scale Invariant Spectrum

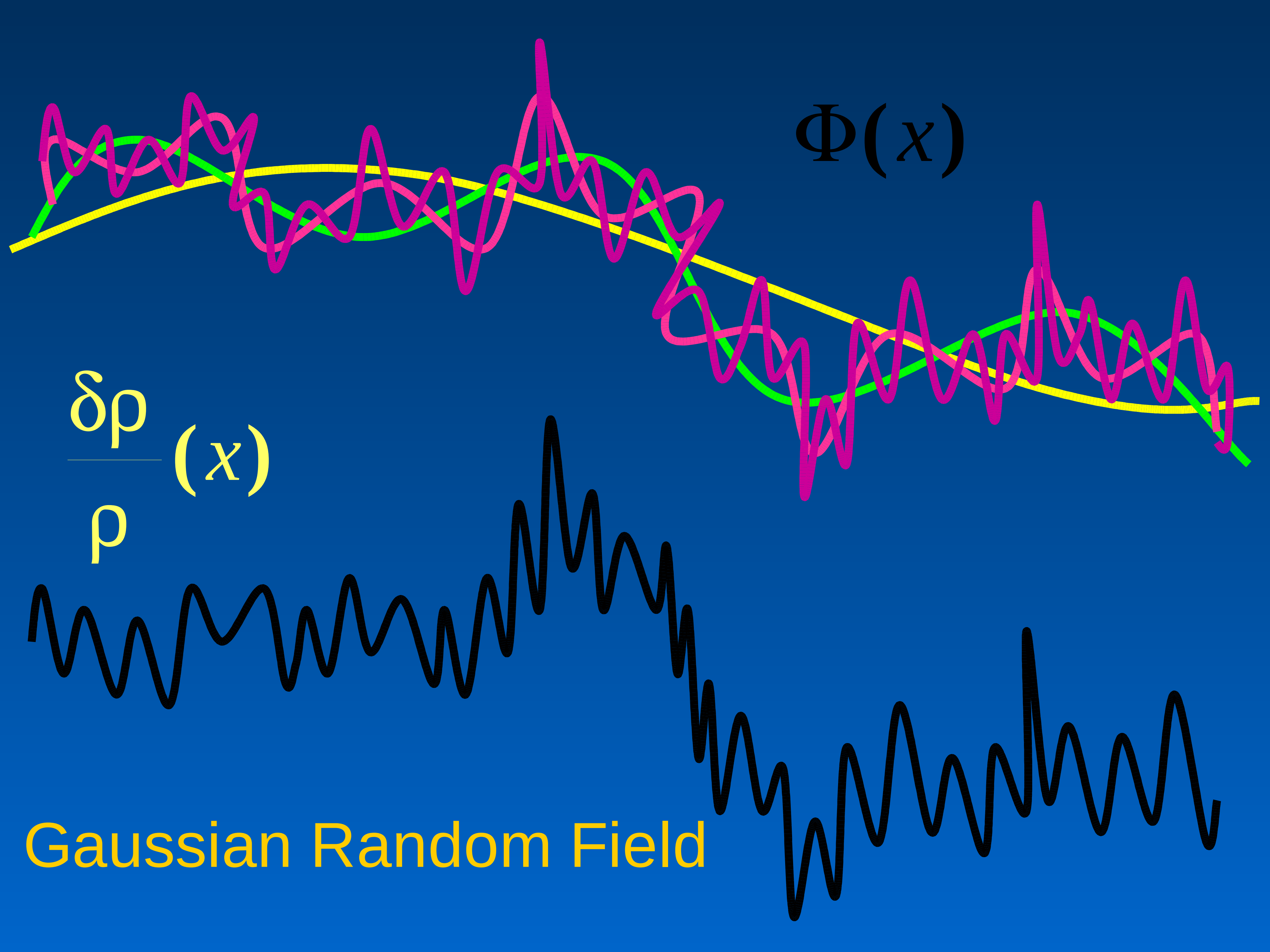
$$\delta\phi_{\mathrm{rms}} \approx \frac{H}{2\pi} \approx const.$$

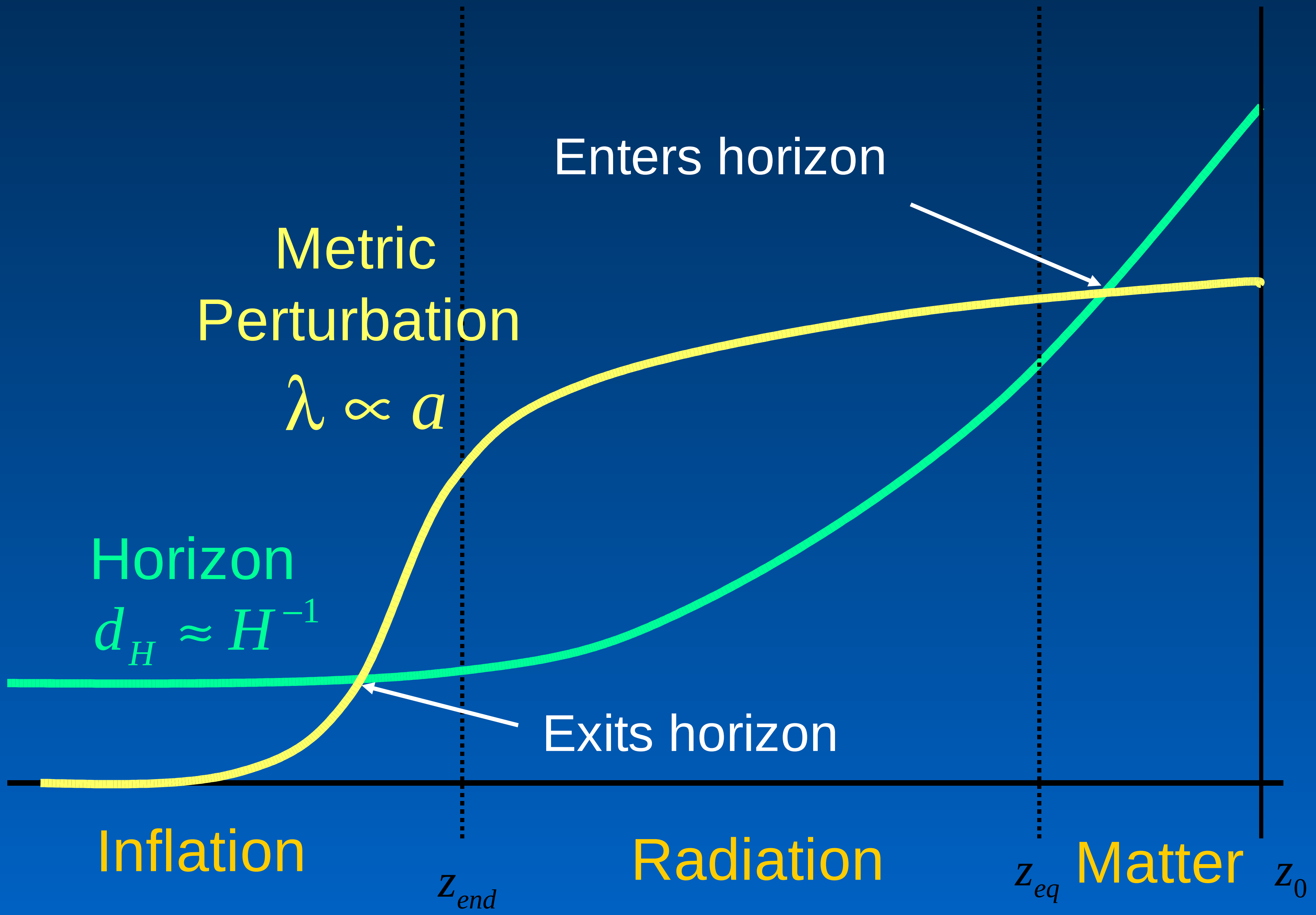


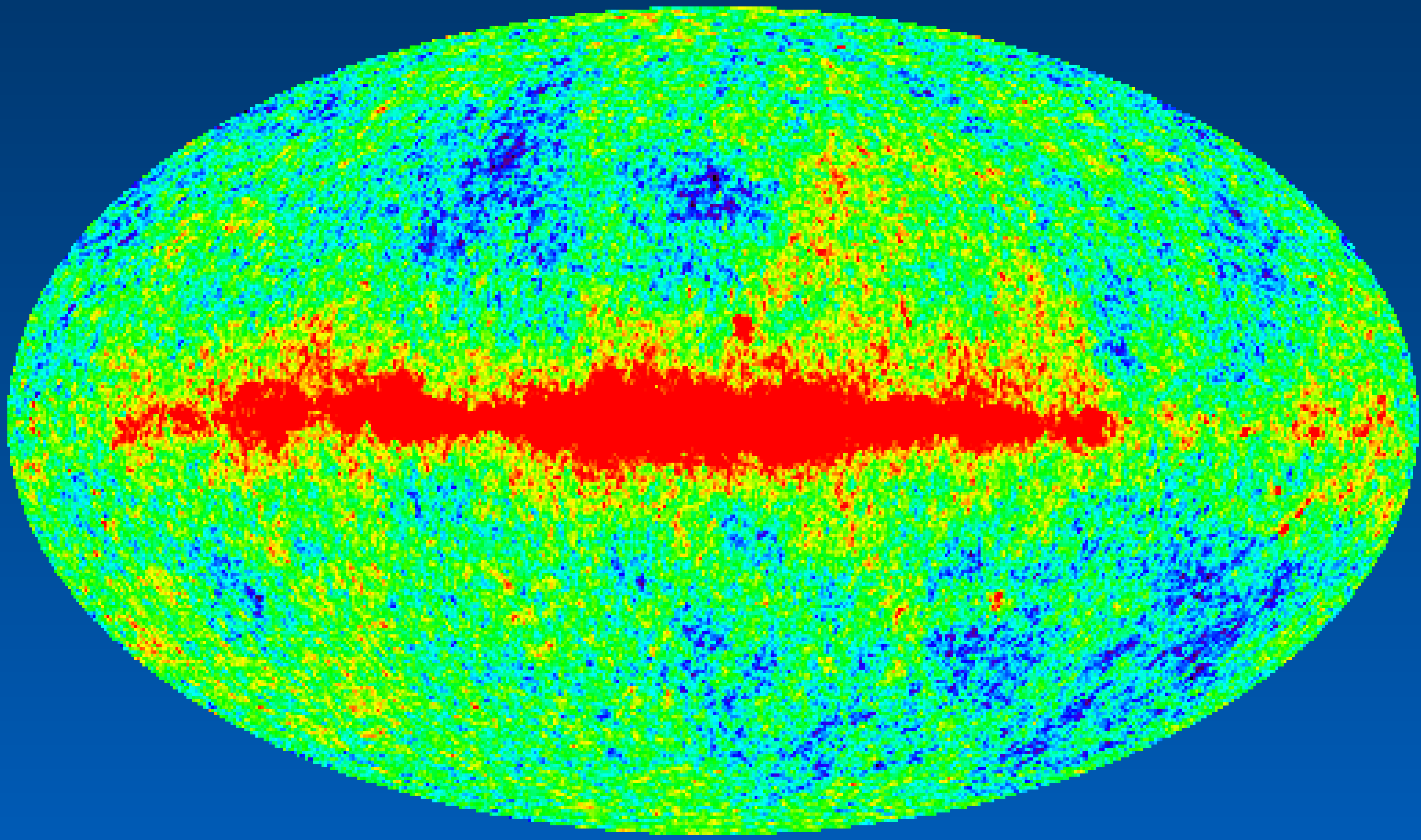
$$2^{nd}\ e - fold$$

$$\Delta t \approx H^{-1}$$

$$1^{st}\ e - fold$$


$\Phi(x)$
$\frac{\delta\rho}{\rho}(x)$
Gaussian Random Field


Enters horizon
Metric
Perturbation
$\lambda \propto a$
Horizon
$d_H \approx H^{-1}$
Exits horizon
Inflation
z_{end}
Radiation
z_{eq}
Matter
z_0



$z \approx 1100$ CMB Anisotropies

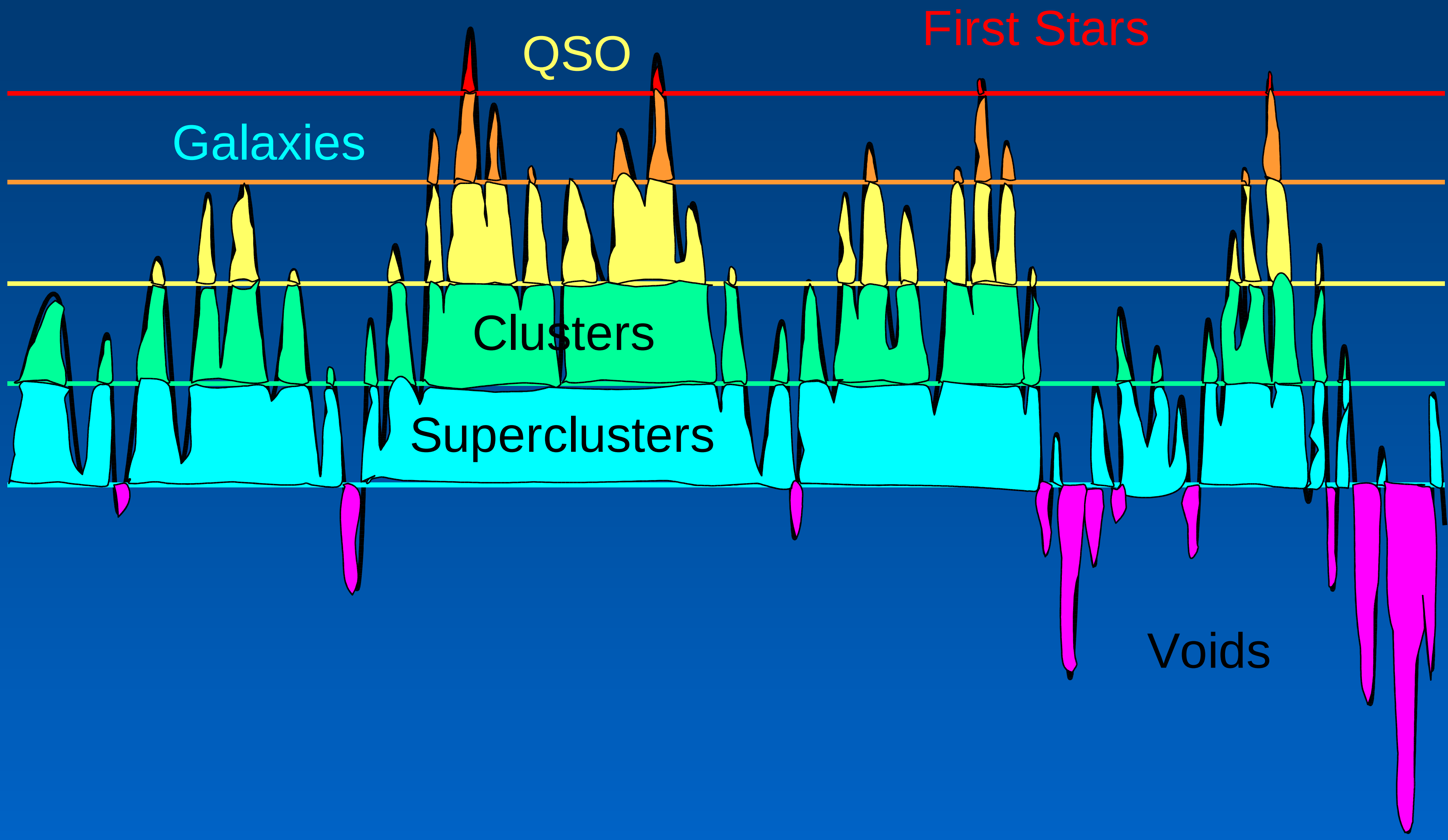
$z \approx 100$ Dark ages

$z \approx 20$ First stars

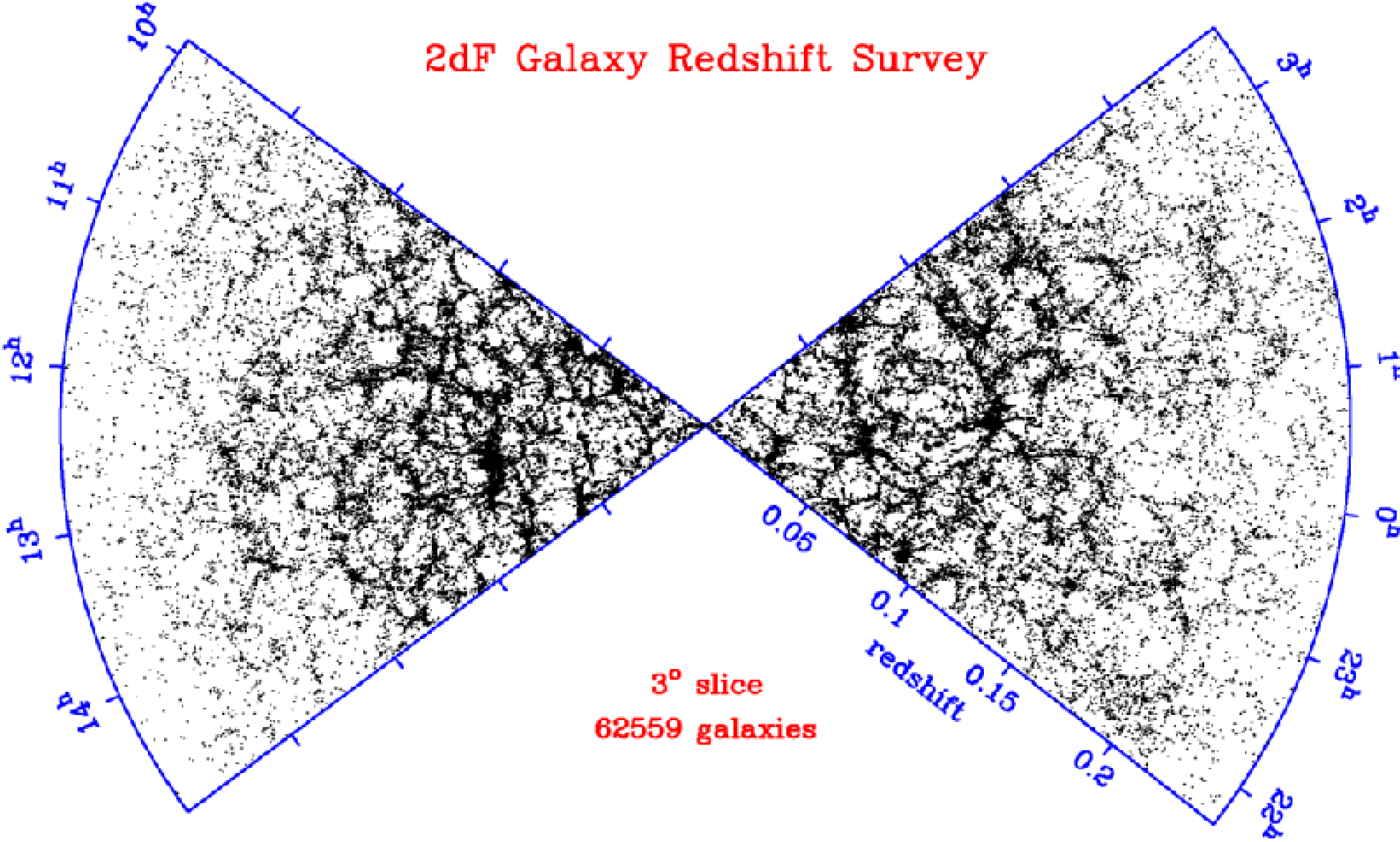
$z \approx 10$ Galaxies & Quasars

$z \approx 1$ Clusters & Superclusters

Density Contrast Thresholds



Cone diagram: 3-degree slice



Basic Inflationary Predictions

Geometry and matter:

- Homogeneity (acausal origin)
- Flat spatial sections (exp. growth)
- No appreciable topology (exp. growth)
- Origin matter & radiation (reheating)

Metric Perturbations:

- Gaussian spectrum (ground state)
- Aprox. scale invariant (slow roll condition)
- Adiabatic density fluctuations (single fluid)
- Gravitational waves (tensor metric pert.)
- No vector perturbations (no defects)

What do we ignore about Inflation?

Geometry and matter:

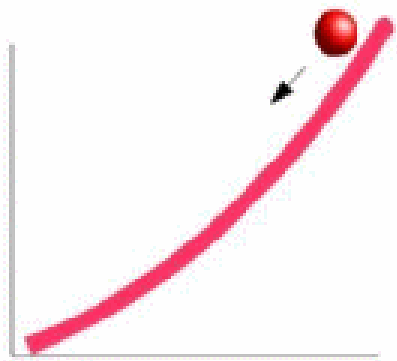
- Scale of Inflation (GUT vs EW)
- Nature of Inflaton (effective vs fundamental)
- Couplings to matter (reheating)
- Quantum backreaction (Planckian effects)

Metric Perturbations:

- Gravitational waves (tensor metric pert.)
- Non-Gaussianities spectrum (self-couplings)
- Deviations scale invariance (non-slow roll)
- Isocurvature fluctuations (multiple fluids)
- Possible vector perturbations (cosmic strings)

Model Building

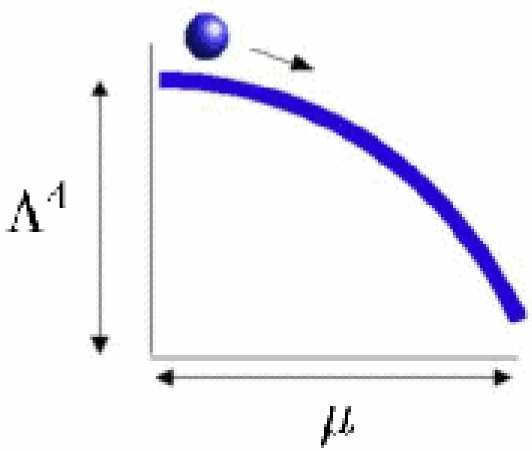
single field inflation



Large field

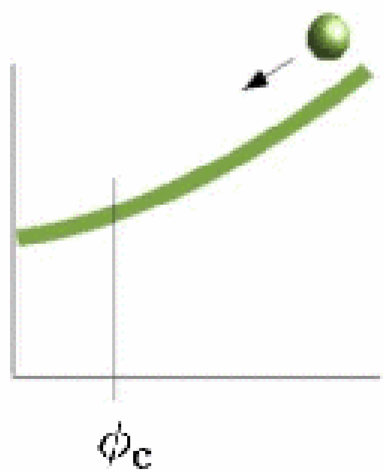
$$V(\phi) = \Lambda^4 (\phi/\mu)^p$$

$$V(\phi) = \Lambda^4 e^{\phi/\mu}$$



Small field

$$V(\phi) = \Lambda^4 \left[1 - (\phi/\mu)^p\right]$$



Hybrid

$$V(\phi) = \Lambda^4 \left[1 + (\phi/\mu)^p\right]$$

Single dynamical quantity:

$$V(\phi) \rightarrow H(\phi) \approx const.$$

$$\left.\begin{array}{l} S \approx \left(H \dfrac{\delta\phi}{\dot{\phi}} \right)^2 = \dfrac{\kappa^2}{2\varepsilon} \left(\dfrac{H}{2\pi} \right)^2 \\[2ex] T \approx \left(2\sqrt{2}\,\kappa\,\delta\phi \right)^2 = 8\kappa^2 \left(\dfrac{H}{2\pi} \right)^2 \end{array}\right\} \; r = \frac{T}{S} = 16\varepsilon$$

Slow roll parameters   Observables

$$\varepsilon = \frac{1}{2\kappa^2}\left(\frac{V'(\phi)}{V(\phi)}\right)^2 << 1$$

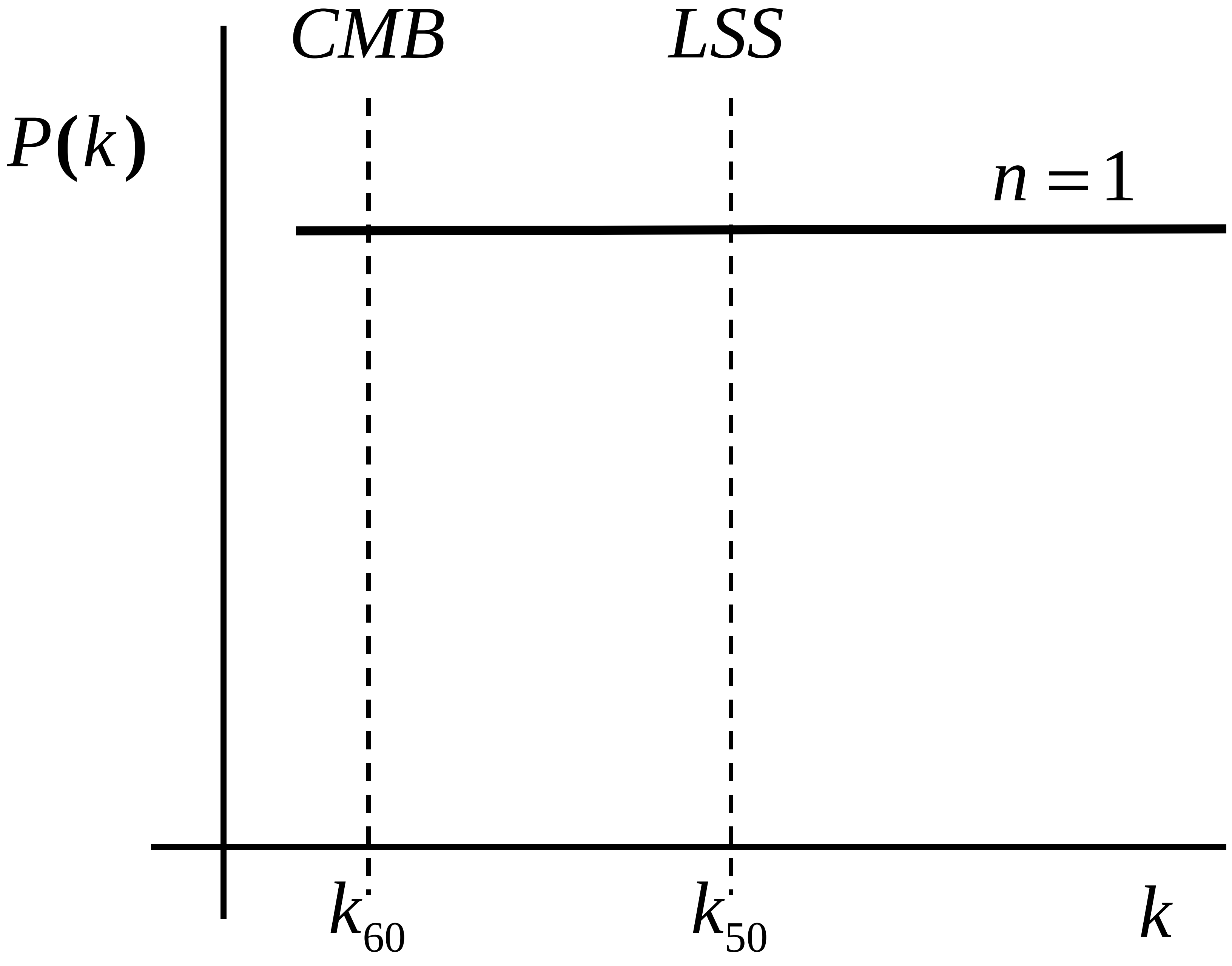
$$\eta = \frac{1}{2\kappa^2}\left(\frac{V''(\phi)}{V(\phi)}\right) << 1$$

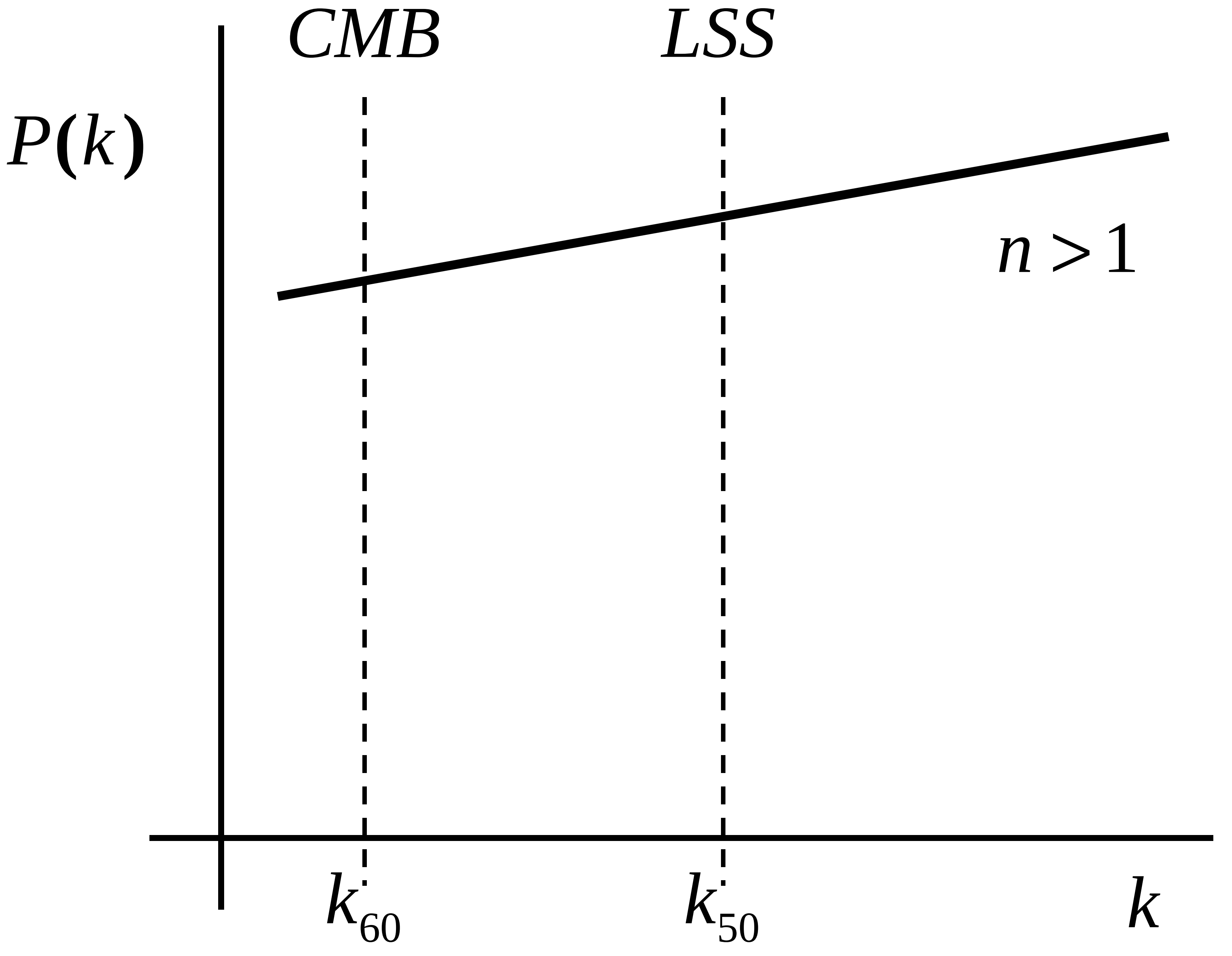
$$\xi^2 = \frac{1}{\kappa^4}\left(\frac{V'(\phi)V'''(\phi)}{V^2(\phi)}\right)$$

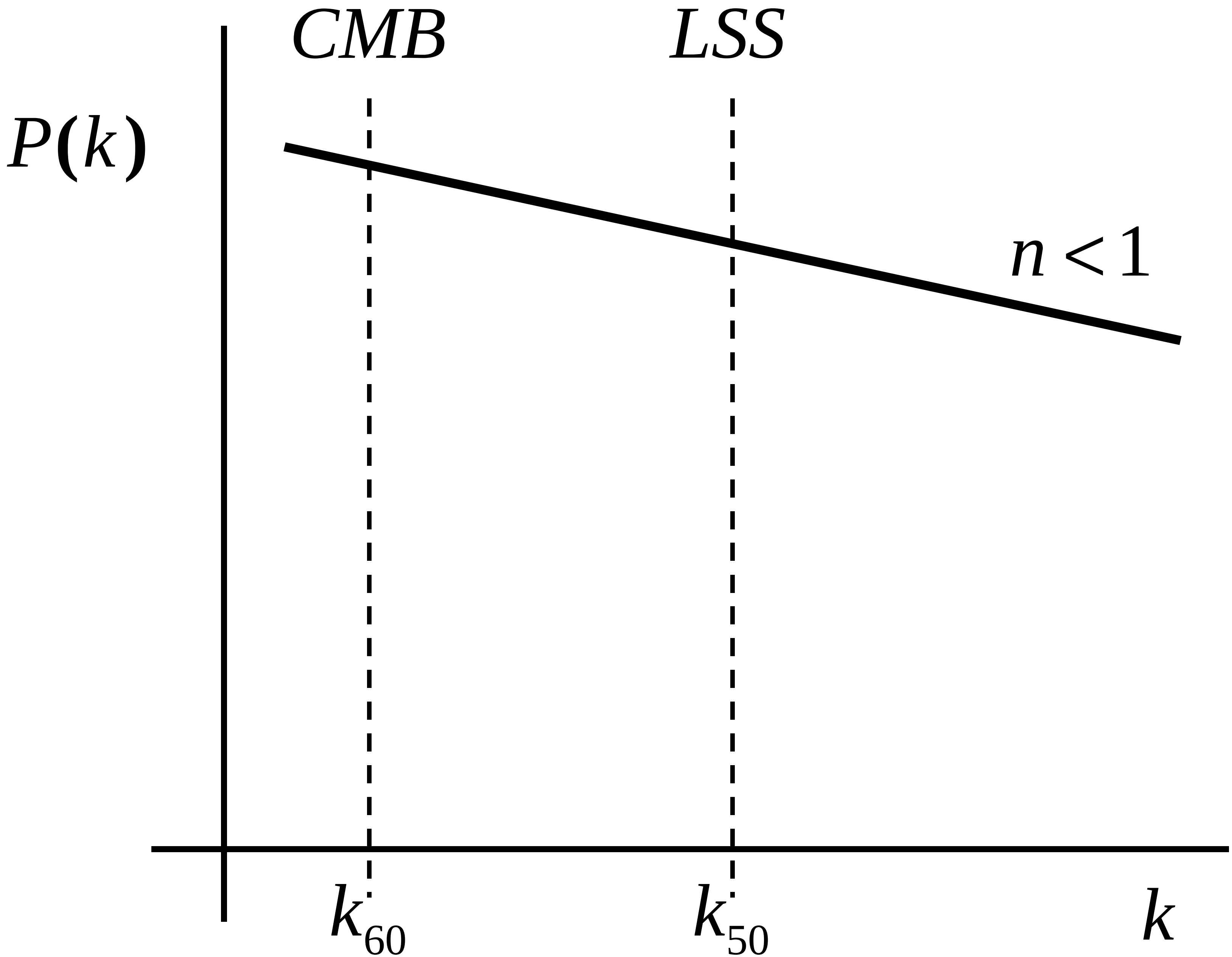
$$n_s = 1 - 6\varepsilon + 2\eta$$

$$n_t = -2\varepsilon$$

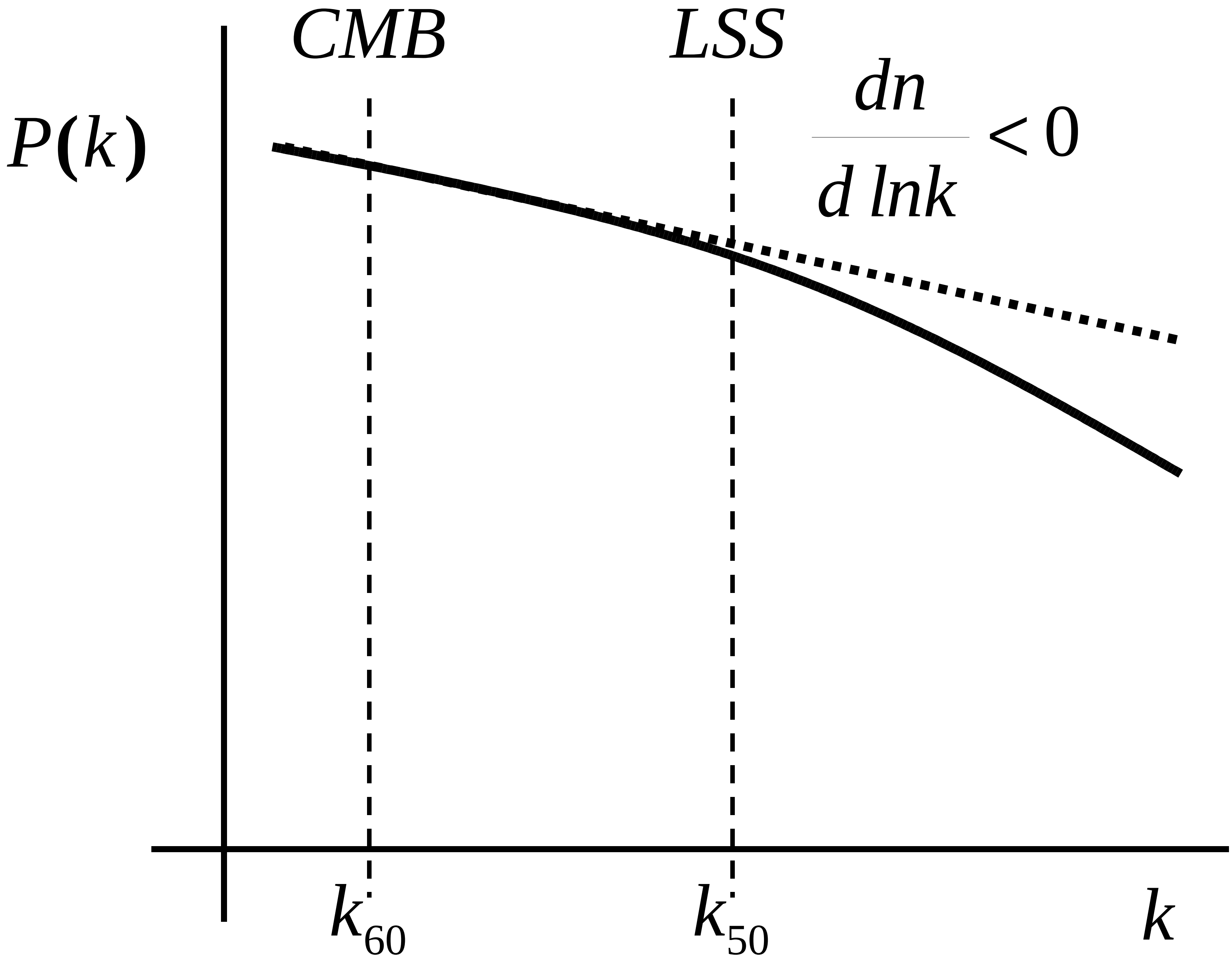
$$\frac{dn_s}{d\ln k} = 2\xi^2 + 24\varepsilon^2 - 16\varepsilon\eta$$


CMB
LSS
$P(k)$
$n = 1$
k_{60}
k_{50}
k

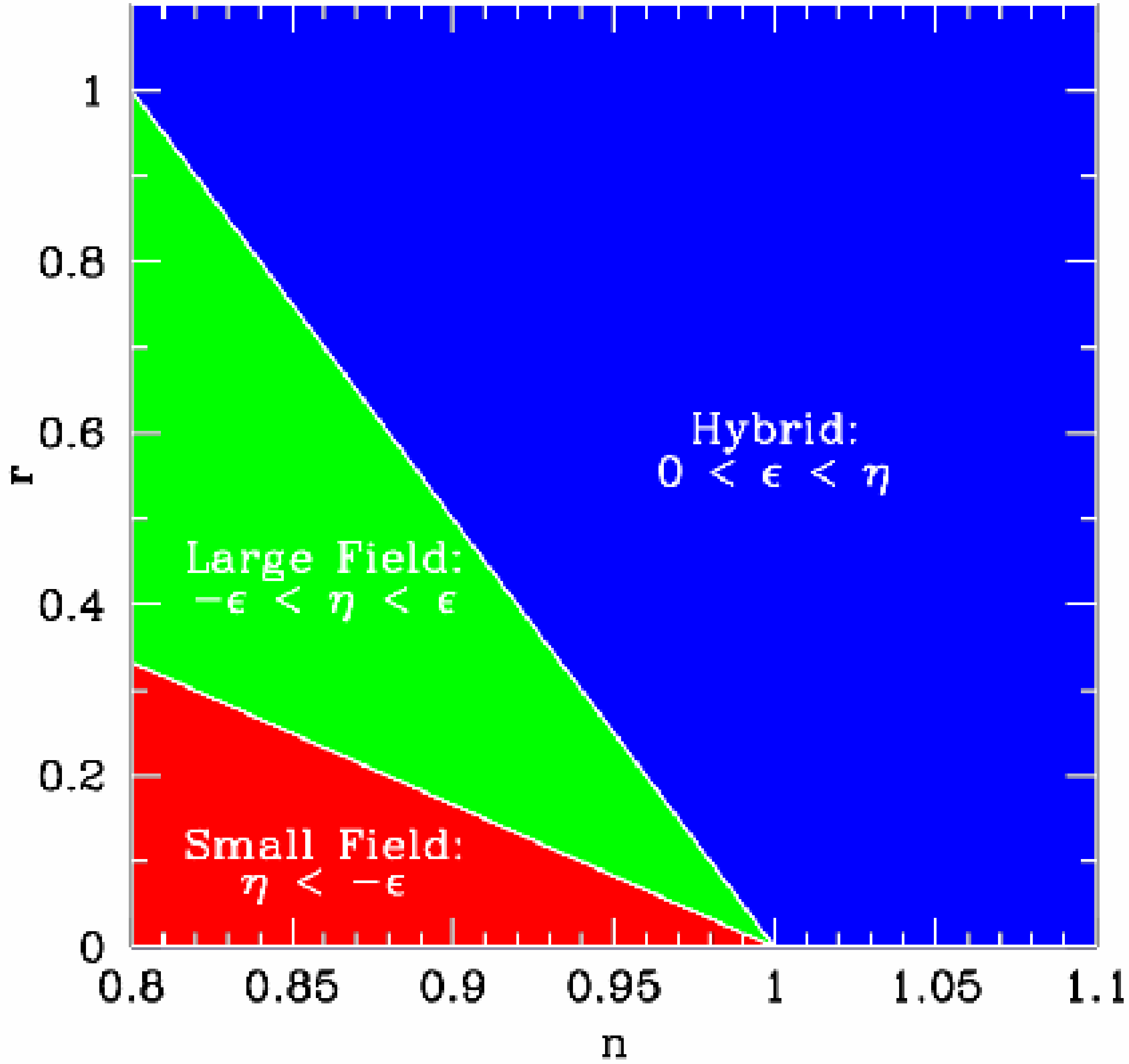

CMB
LSS
P(k)
n > 1
k60
k50
k



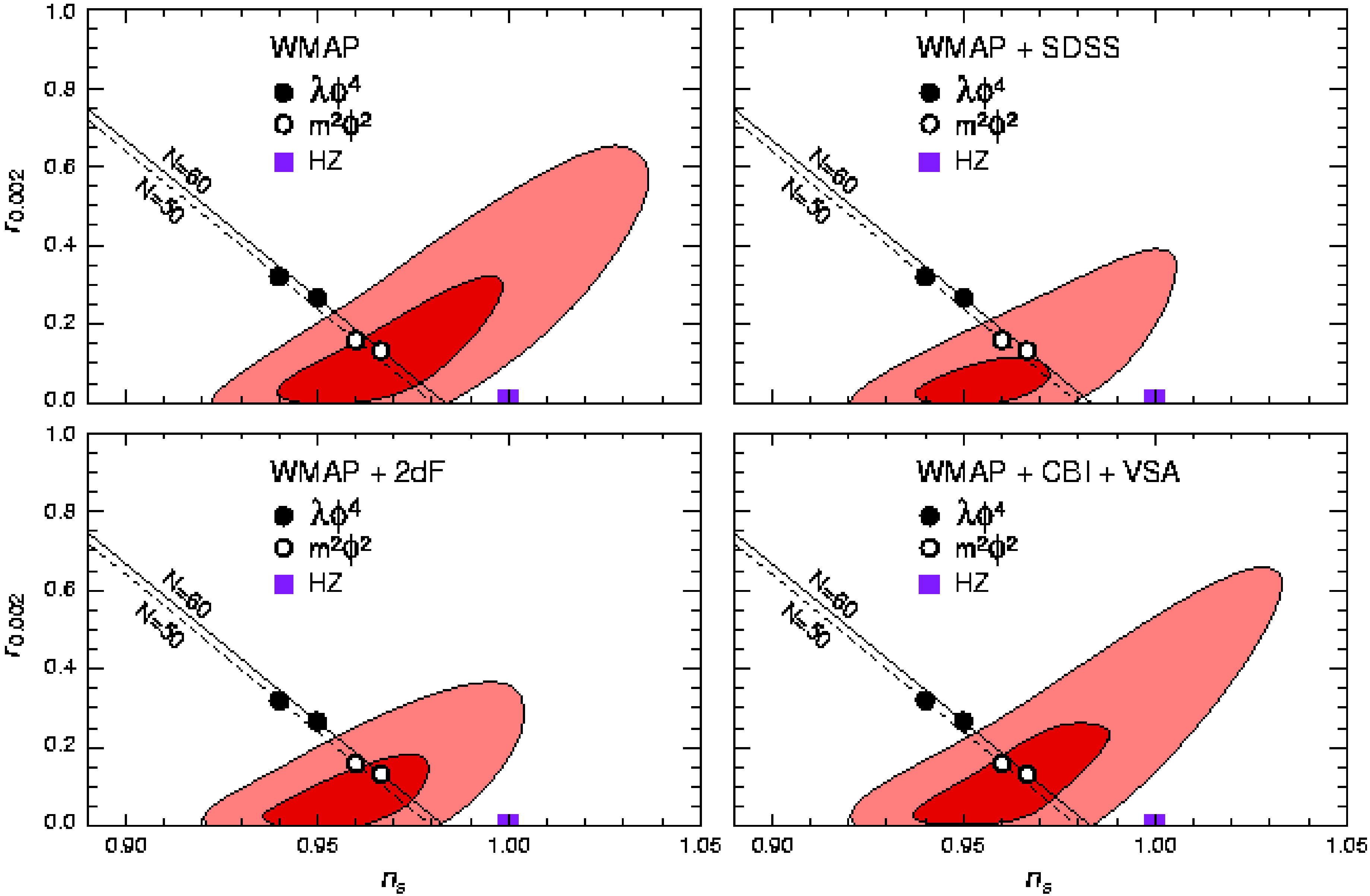
CMB
LSS
P(k)
n<1
k60
k50
k


CMB
LSS
$\frac{dn}{d\ln k} < 0$
$P(k)$
k_{60}
k_{50}
k

single field inflation



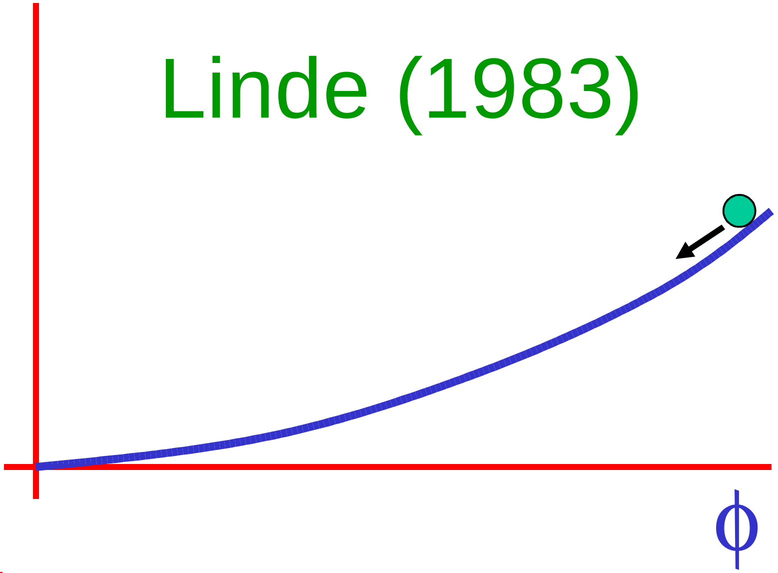
WMAP 3-year (2006)



Large Field

Linde (1983)

$$V(\phi) = \frac{1}{2} m^2 \phi^2$$



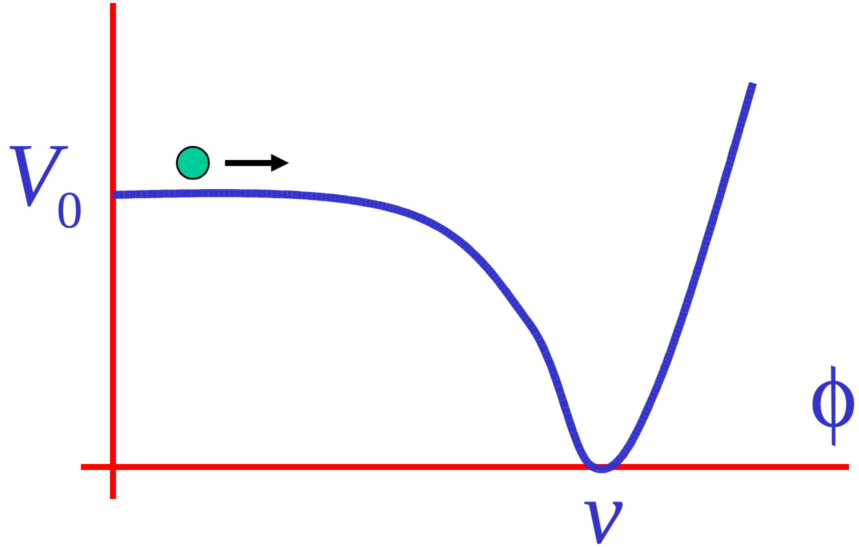
$$\varepsilon = \frac{2}{\kappa^2 \phi^2} = \frac{1}{2N}, \quad \eta = \frac{1}{2N}, \quad \xi^2 = 0$$

$$n_S - 1 = -\frac{2}{N} < 0 \qquad \frac{dn_S}{d\ln k} = -\frac{4}{N^2} = -(n_S - 1)^2$$

$$n_T = -\frac{1}{N} < 0 \qquad r = \frac{8}{N} = 0.13$$

Small Field

$$V(\phi) = \frac{\lambda}{4}(\phi^2 - v^2)^2$$



$$\varepsilon = \frac{m^2}{\kappa^2 V_0}\frac{m^2\phi^2}{2V_0} \ll \eta = -\frac{m^2}{\kappa^2 V_0}, \quad \xi^2 = \frac{12\lambda}{\kappa^4 V_0}\frac{m^2\phi^2}{2V_0}$$

$$n_S - 1 = -\frac{m^2}{\kappa^2 V_0} < 0 \qquad \frac{dn_S}{d\,lnk} = -8\kappa^2\phi^2(1-n_S)^3$$

$$N = \frac{1}{\eta}\, ln\frac{\phi}{\phi_{end}} \qquad r = 16\varepsilon \ll (1-n_s)$$

If the physics of Inflation is at the GUT scale, then

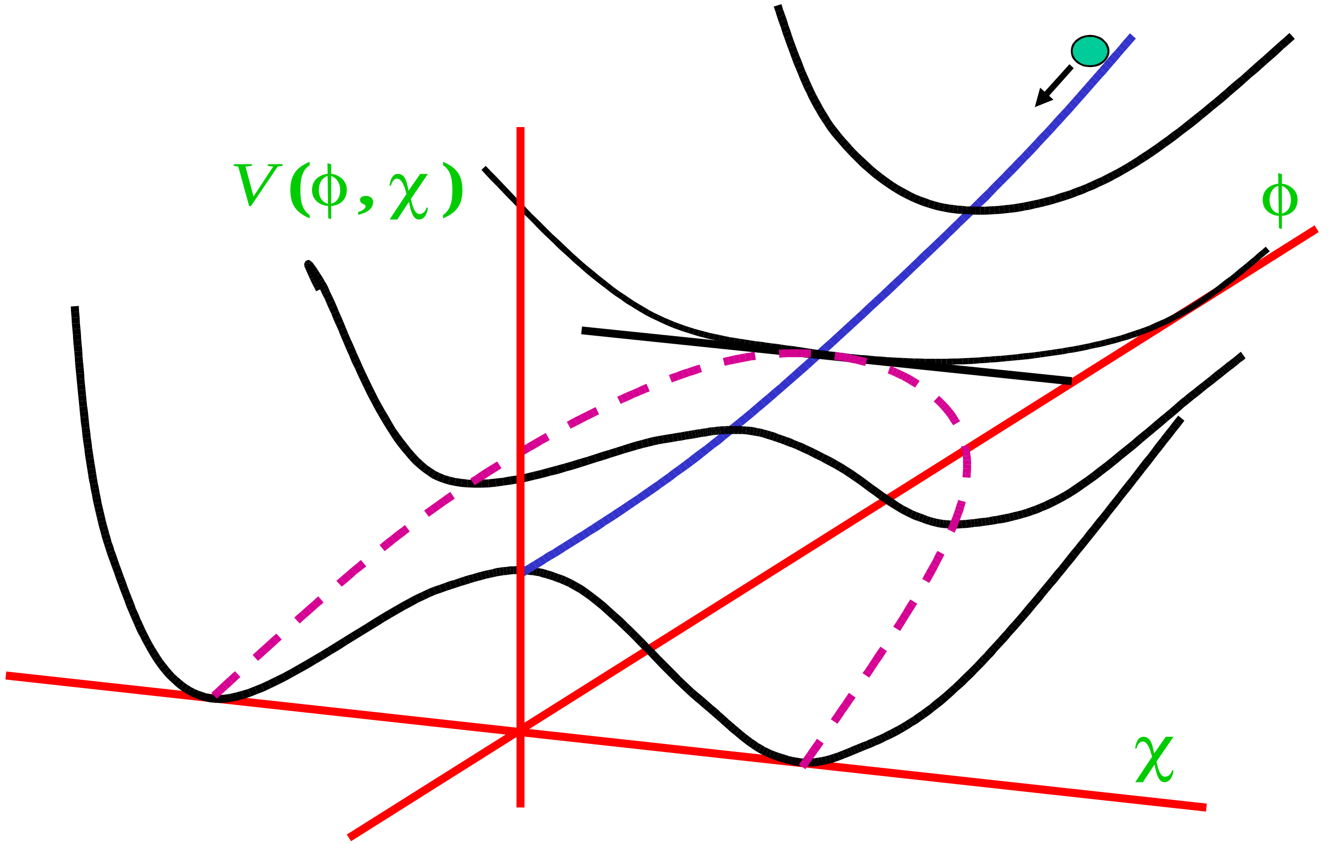
$$M_{\mathbf{inf}} \approx 10^{16}\ GeV \Rightarrow \varepsilon \approx 0.1$$

We should see gravitational waves in the CMB polarization field (e.g. with Planck) or with GW Observatories like LISA

Hybrid Inflation

Linde (2001)

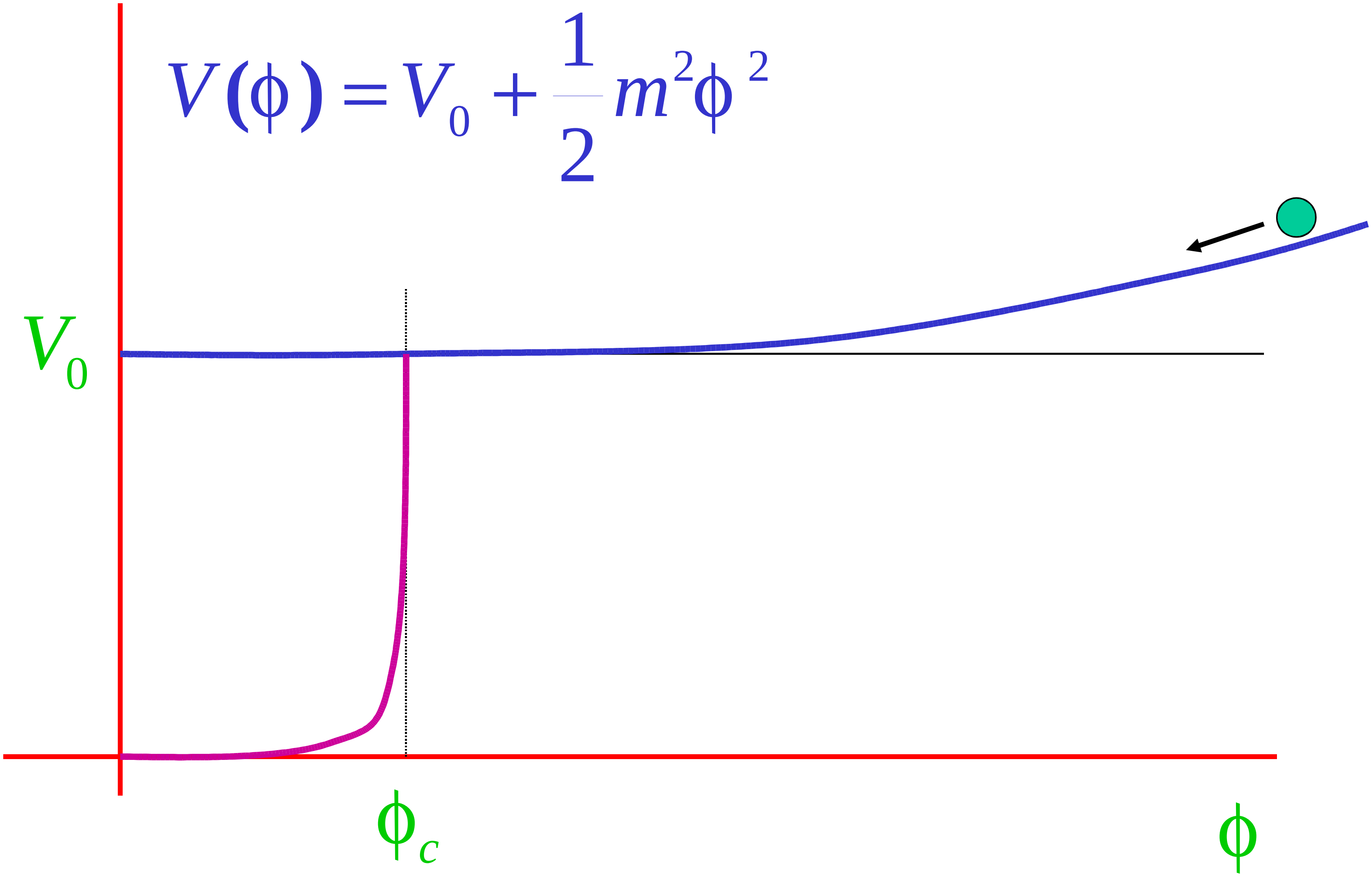
$$V(\phi,\chi)=\frac{\lambda}{4}(\chi^2-v^2)^2+\frac{1}{2}g^2\chi^2\phi^2+\frac{1}{2}m^2\phi^2$$



Hybrid Inflation

Linde (2001)

$$V(\phi) = V_0 + \frac{1}{2} m^2 \phi^2$$



Hybrid Inflation

Linde (2001)

$$V(\phi,\chi)=\frac{\lambda}{4}(\chi^2-v^2)^2+\frac{1}{2}g^2\chi^2\phi^2+\frac{1}{2}m^2\phi^2$$

$$\varepsilon=\frac{m^2}{\kappa^2 V_0}\frac{m^2\phi^2}{2V_0}\ll\eta=\frac{m^2}{\kappa^2 V_0},\quad \xi^2=0$$

$$n_S-1=\frac{m^2}{\kappa^2 V_0}>0 \qquad \frac{dn_S}{d\,lnk}=-8\kappa^2\phi^2(n_S-1)^3$$

$$N=\frac{1}{\eta}ln\frac{\phi}{\phi_c} \qquad r=16\varepsilon\ll(n_S-1)$$

If the scale of Inflation is due to EW physics then

$$M_{\mathbf{inf}} \approx 10^3\, GeV \Rightarrow \varepsilon << 1$$

We will never see gravitational waves in the CMB polarization field nor in GW observatories like LISA

Low scale inflation is difficult to test

Perhaps via reheating (new phenomena):

- EW baryogenesis
- Primordial magnetic fields
- Primordial gravitational waves
- Non-thermal ph. trans. & cosmic strings
- Particle Dark Matter off equilibrium

Is low-scale inflation difficult to test?

We hope that the scale is sufficiently low that inflation can be tested at accelerators

So far it has been difficult to come up with a viable version of EW scale inflation and/or a connection with extensions of Standard Model

In the rest of ½ talk I will try to convince you that there is at least some hope to test the idea of inflation at the LHC in the near future

GUIDING PRINCIPLE: FLAT DIRECTIONS

Around 300 gauge invariant flat directions in the MSSM made up of squarks, sleptons and Higgses. Only 2 are valid directions.

Potentials vanish in the supersymmetric limit. Lifted by soft SUSY breaking mass terms and trilinear couplings A, as well as non-renorm. Planck-suppressed superpotential corrections

$$W = \frac{\lambda}{n} \frac{\Phi^n}{M_P^{n-3}} \qquad n = 6$$

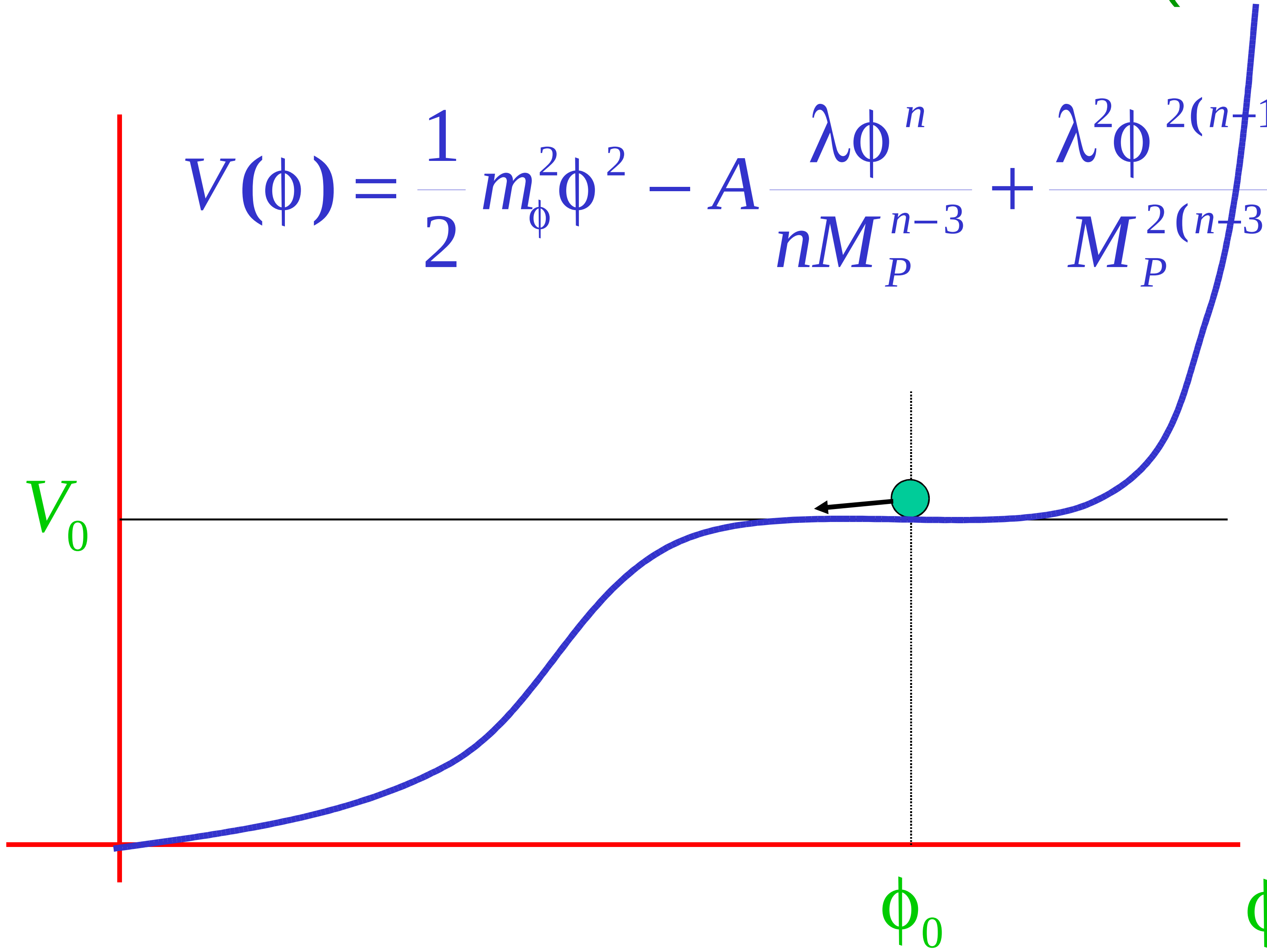
$$\Phi = L_i L_j e_k$$

$$\Phi = u d_i d_j$$

MSSM Inflation

Allahverdi et al. (2006)

$$V(\phi) = \frac{1}{2} m_\phi^2 \phi^2 - A \frac{\lambda \phi^n}{n M_P^{n-3}} + \frac{\lambda^2 \phi^{2(n-1)}}{M_P^{2(n-3)}}$$



MSSM Inflation

Allahverdi et al. (2006)

$$V(\phi) = \frac{1}{2} m_\phi^2 \phi^2 - A \frac{\lambda \phi^n}{n M_P^{n-3}} + \frac{\lambda^2 \phi^{2(n-1)}}{M_P^{2(n-3)}}$$

$$V'(\phi) = m_\phi^2 \phi \left(1 - \frac{A}{m_\phi^2} \frac{\lambda \phi^{n-2}}{M_P^{n-3}} + 2(n-1) \frac{\lambda^2 \phi^{2(n-2)}}{m_\phi^2 M_P^{2(n-3)}} \right)$$

$$V''(\phi) = m_\phi^2 \left(1 - (n-1) \frac{A}{m_\phi^2} \frac{\lambda \phi^{n-2}}{M_P^{n-3}} + 2(n-1)(2n-3) \frac{\lambda^2 \phi^{2(n-2)}}{m_\phi^2 M_P^{2(n-3)}} \right)$$

$$V'''(\phi) = (n-1)(n-2) \frac{m_\phi^2}{\phi} \left(- \frac{A}{m_\phi^2} \frac{\lambda \phi^{n-2}}{M_P^{n-3}} + 4(2n-3) \frac{\lambda^2 \phi^{2(n-2)}}{m_\phi^2 M_P^{2(n-3)}} \right)$$

MSSM Inflation

Allahverdi et al. (2006)

Saddle Point:

$$A = 8(n-1)m_\phi^2$$

$$V'(\phi_0) = V''(\phi_0) = 0$$

$$\phi_0 = \left(\frac{m_\phi M_P^{n-3}}{\lambda\sqrt{2n-2}} \right)^{1/(n-2)}$$

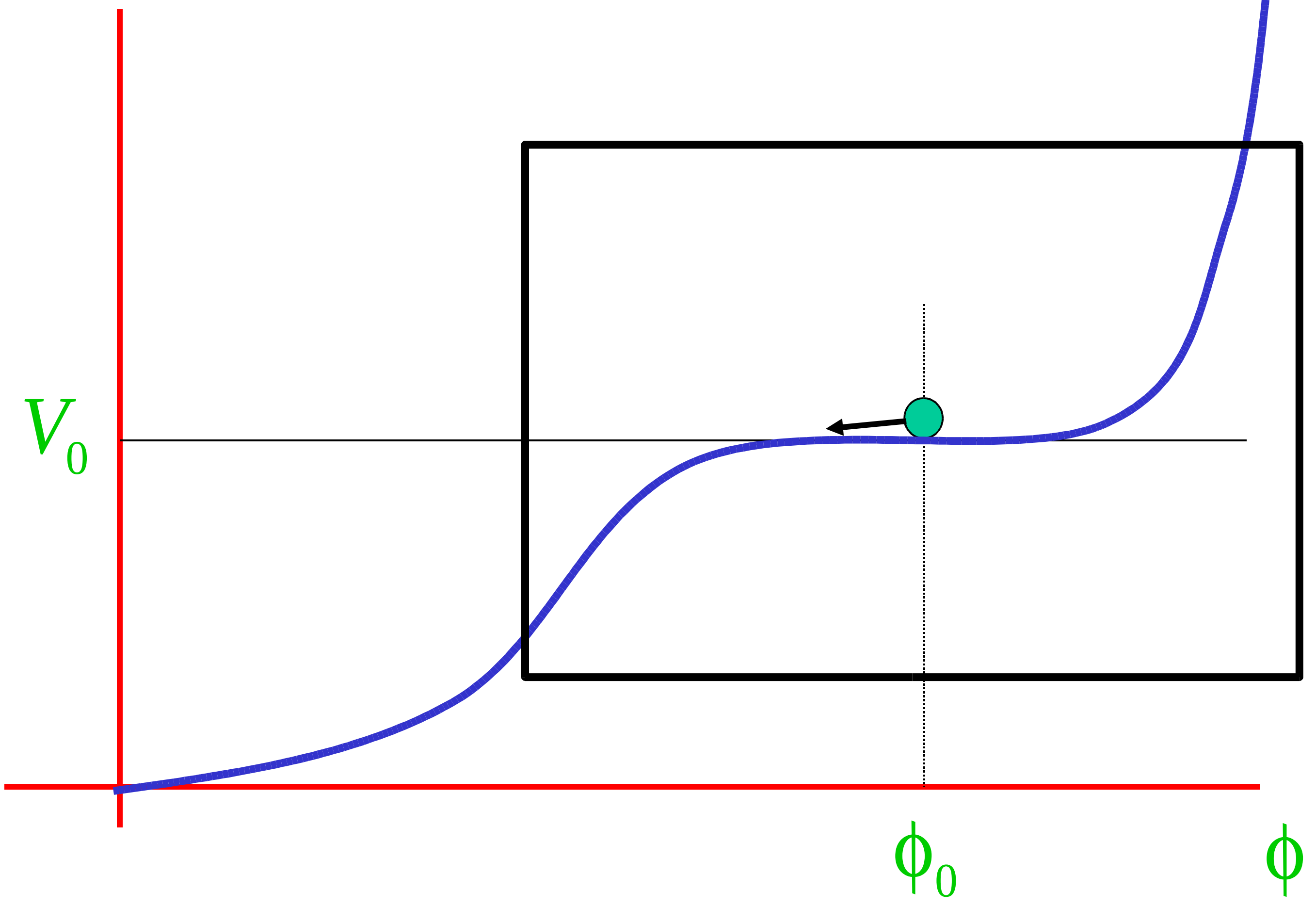
$$V(\phi_0) = \frac{(n-2)^2}{2n(n-1)} m_\phi^2 \phi_0^2$$

$$V'''(\phi_0) = 2(n-2)^2 \frac{m_\phi^2}{\phi_0}$$

MSSM Inflation

Allahverdi et al. (2006)

$$V(\phi) = V(\phi_0) + \frac{1}{3!}V'''(\phi_0)(\phi - \phi_0)^3$$



MSSM Inflation

Observable ranges

self-reproduction

$$\frac{H_{\mathbf{inf}}}{2\pi} < \frac{\dot{\phi}}{H_{\mathbf{inf}}} \quad \Rightarrow \quad \frac{\phi_0 - \phi}{\phi_0} \geq \left(\frac{m_\phi \phi_0^2}{M_P^3} \right)^{1/2}$$

Number e-folds

$$N(\phi) = \int \frac{H d\phi}{\dot{\phi}} \approx \frac{\phi_0^3}{M_P^2 (\phi_0 - \phi)} \leq \left(\frac{\phi_0^2}{m_\phi M_P} \right)^{1/2}$$

End Inflation

$$\frac{(\phi_0 - \phi)}{\phi_0} \approx \left(\frac{\phi_0}{M_P} \right)^{1/2}$$

MSSM Inflation

CMB anisotropies

metric fluctuations

$$\delta_H \approx \frac{1}{5\pi}\frac{H^2_{\mathbf{inf}}}{\dot\phi} \approx \frac{m_\phi M_P}{\phi_0^2} N^2_{COBE} \approx 10^{-5}$$

tilt

$$n_s = 1 - \frac{4}{N_{COBE}} \approx 0.93$$

scale-dep.

$$\frac{d\, n_s}{d\ln k} \approx -\frac{4}{N^2_{COBE}} \approx -0.002$$

gravitational waves

$$r = 16\varepsilon << 1$$

MSSM Inflation

Energy scales

Sub-Planckian vev's

$$m_\phi \approx 1-10\, TeV \qquad A = \sqrt{40}\, m_\phi$$

$$\phi_0 \approx 1-3\times 10^{14}\, GeV \qquad \lambda \approx 1$$

Low-scale inflation

$$M_{\mathbf{inf}} \approx 1-3\times 10^{9}\, GeV$$

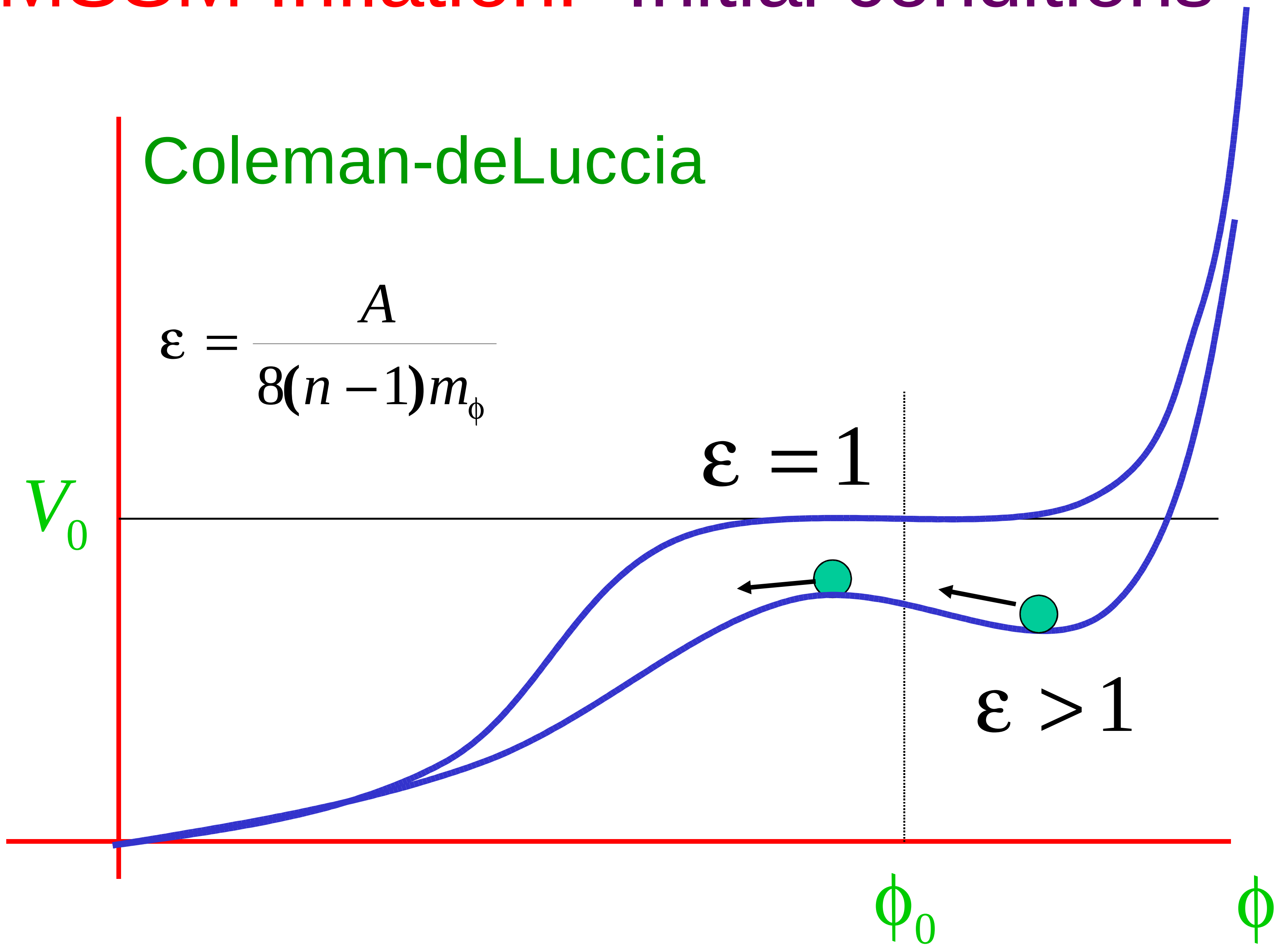
$$H_{\mathbf{inf}} \approx 1-10\, GeV$$

$$T_{rh} \approx 1-10\, TeV$$

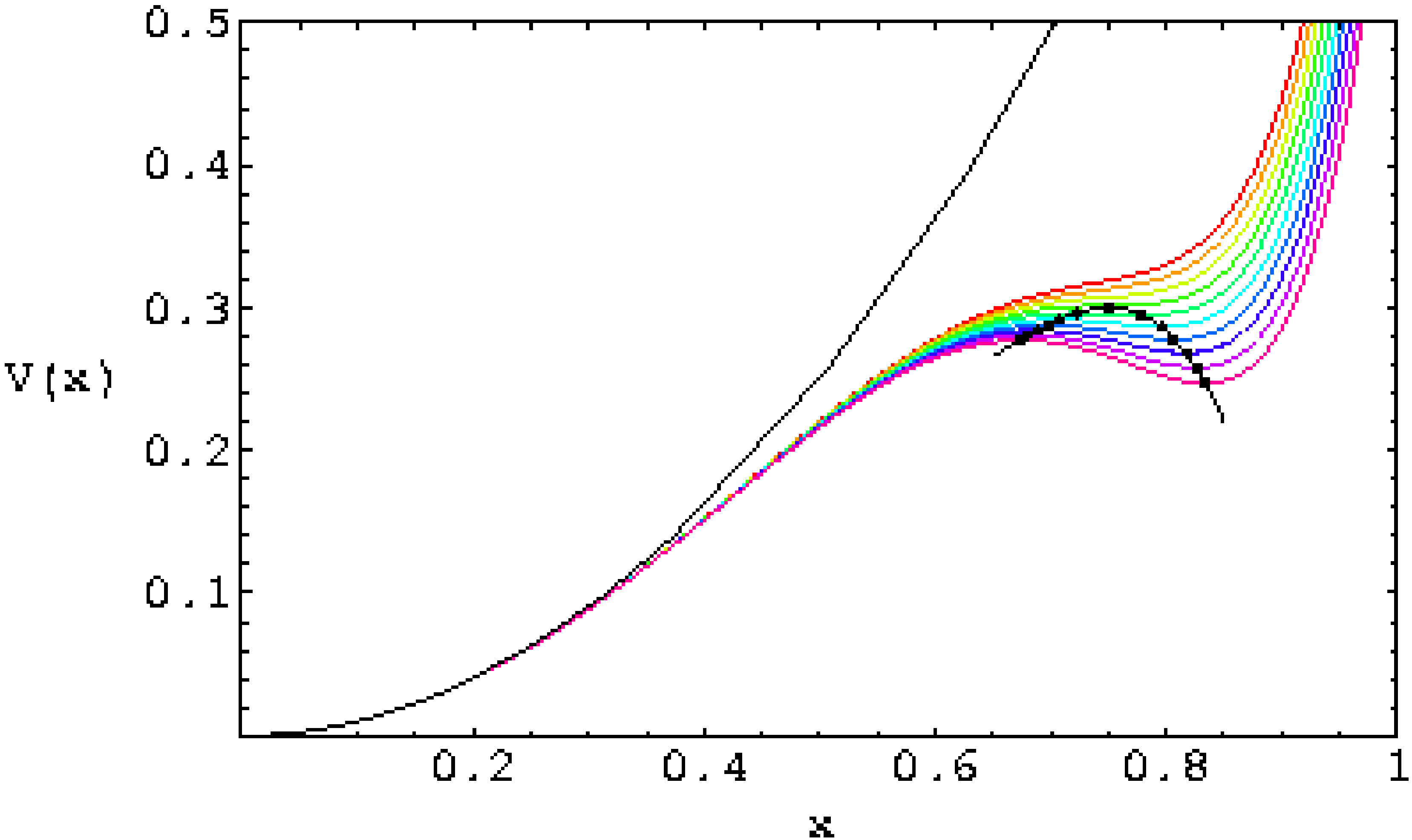
Enough e-folds

$$N_e \leq N_{SR} = \left(\frac{\phi_0^2}{m_\phi M_P}\right)^{1/2} \approx 10^3$$

MSSM Inflation: Initial conditions



$$\varepsilon = \frac{A}{8(n-1)m_\phi} = 0.95, \ldots, 1.09$$



MSSM Inflation

Radiative corrections

mass

$$m_R^2 = m_0^2\left(1 + K_1 \mathbf{log}\left(\frac{|\phi|^2}{\mu^2}\right)\right)$$

A-term

$$A_R = A_0\left(1 + K_2 \mathbf{log}\left(\frac{|\phi|^2}{\mu^2}\right)\right)$$

coupling

$$\lambda_R = \lambda_0\left(1 + K_3 \mathbf{log}\left(\frac{|\phi|^2}{\mu^2}\right)\right)$$

RGE flow helps initial conditions at minimum

Conclusions

- The inflationary paradigm provides a general framework in which one can describe all cosmological observations

- The standard model of single field inflation works OK, for the moment. We might need to add small amount isocurvature, tensors, non-gaussianity and perhaps topological def.

- Great time: sufficiently concrete to make predictions that can be tested soon, and phenomenologically rich (preheating), so there is room for imagination/speculation.

The future looks promising

- New observations:
  Planck & CMBPol (CMB)
  SZE & Grav. Lensing (CMB+LSS)
  SDSS Lyman alpha (LSS)
  2dFGRS QSO (LSS)
  SNAP & DES (SNIa)
  MAGIC & GLAST (Dark Matter+Cosmic Rays)
- New theoretical ideas on the nature of vacuum energy (e.g. modified gravity?)
- New models of inflation based on fundamental physics (e.g. susy, strings/branes)