Summer Institute 2011 @ Fujiyoshida

August 5, 2011

ASPECTS OF D-BRANE INFLATION IN STRING COSMOLOGY

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TODAY'S PLAN

- Cosmic Inflation and String Theory

- D-Brane Inflation and its Difficulties

arXiv:0708.4285 with Shunichiro Kinoshita and Shinji Mukohyama

- Inflation from Rapid-Rolling D-Branes

arXiv:0810.0810 with Shinji Mukohyama

arXiv:0905.1752 with Shinji Mukohyama and Brian A. Powell

- Curvatons in Warped Throats

arXiv:0905.2835 with Shinji Mukohyama

arXiv:1107.6011 with Masahiro Kawasaki and Fuminobu Takahashi

COSMIC INFLATION

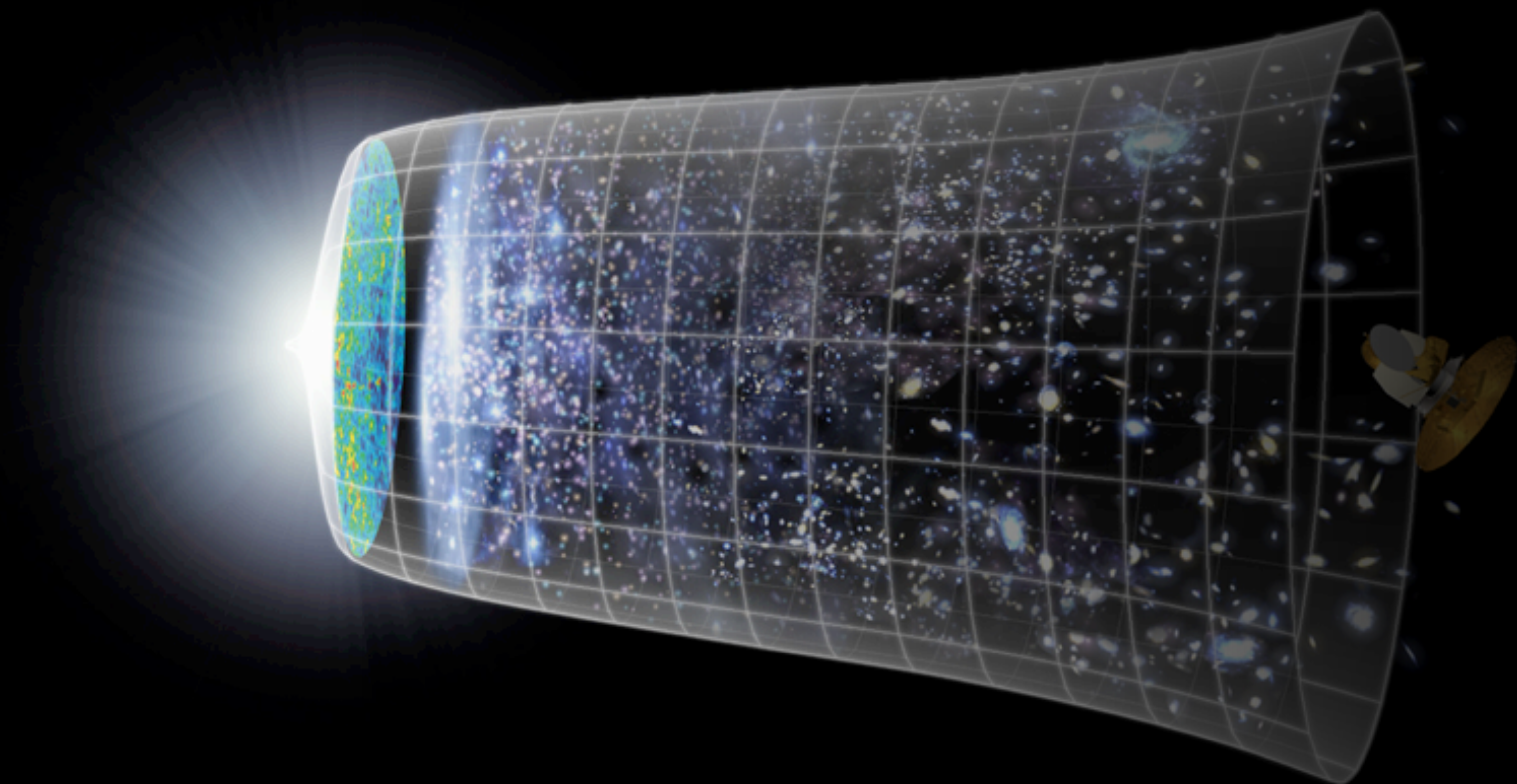

image: NASA/WMAP Science Team

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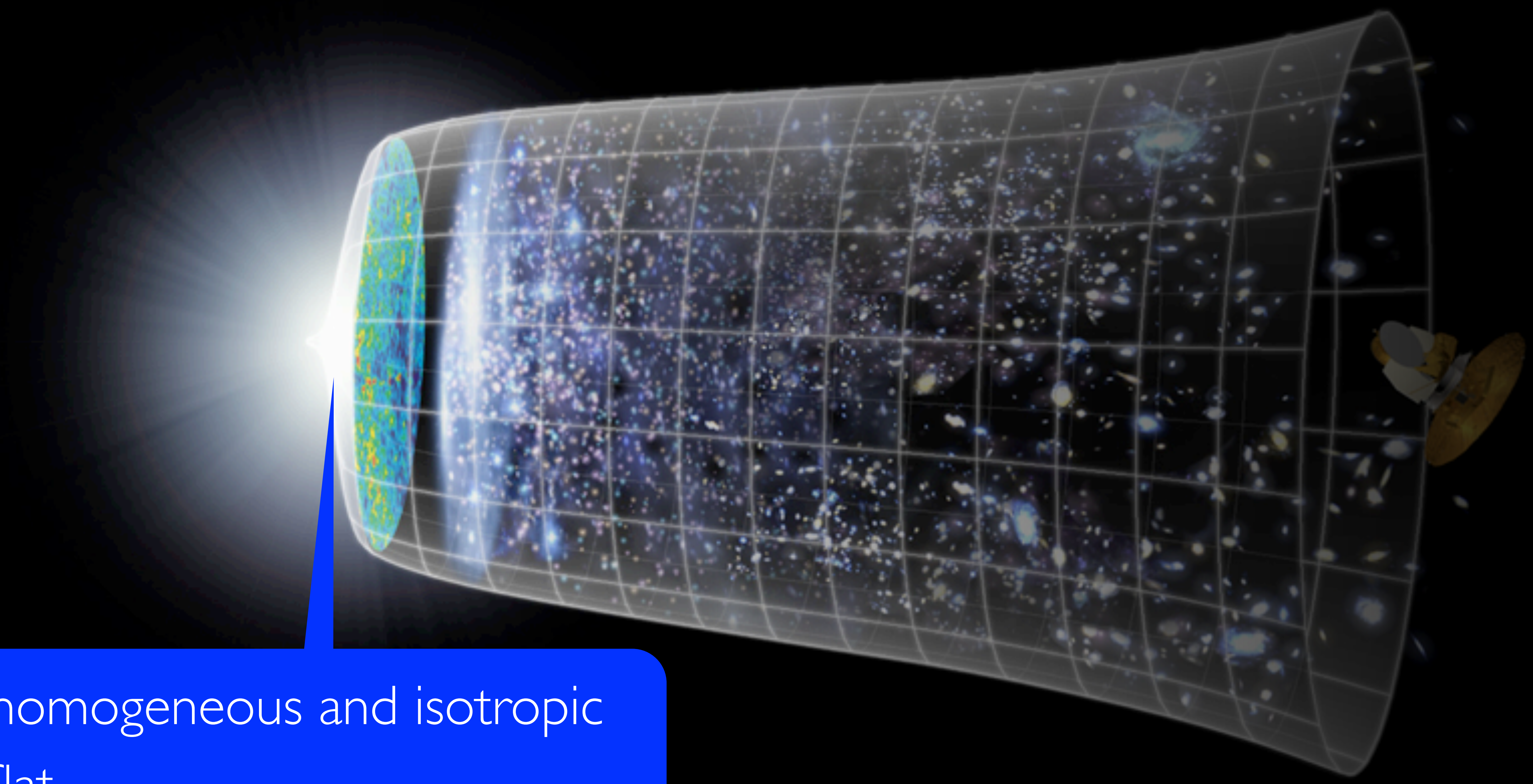
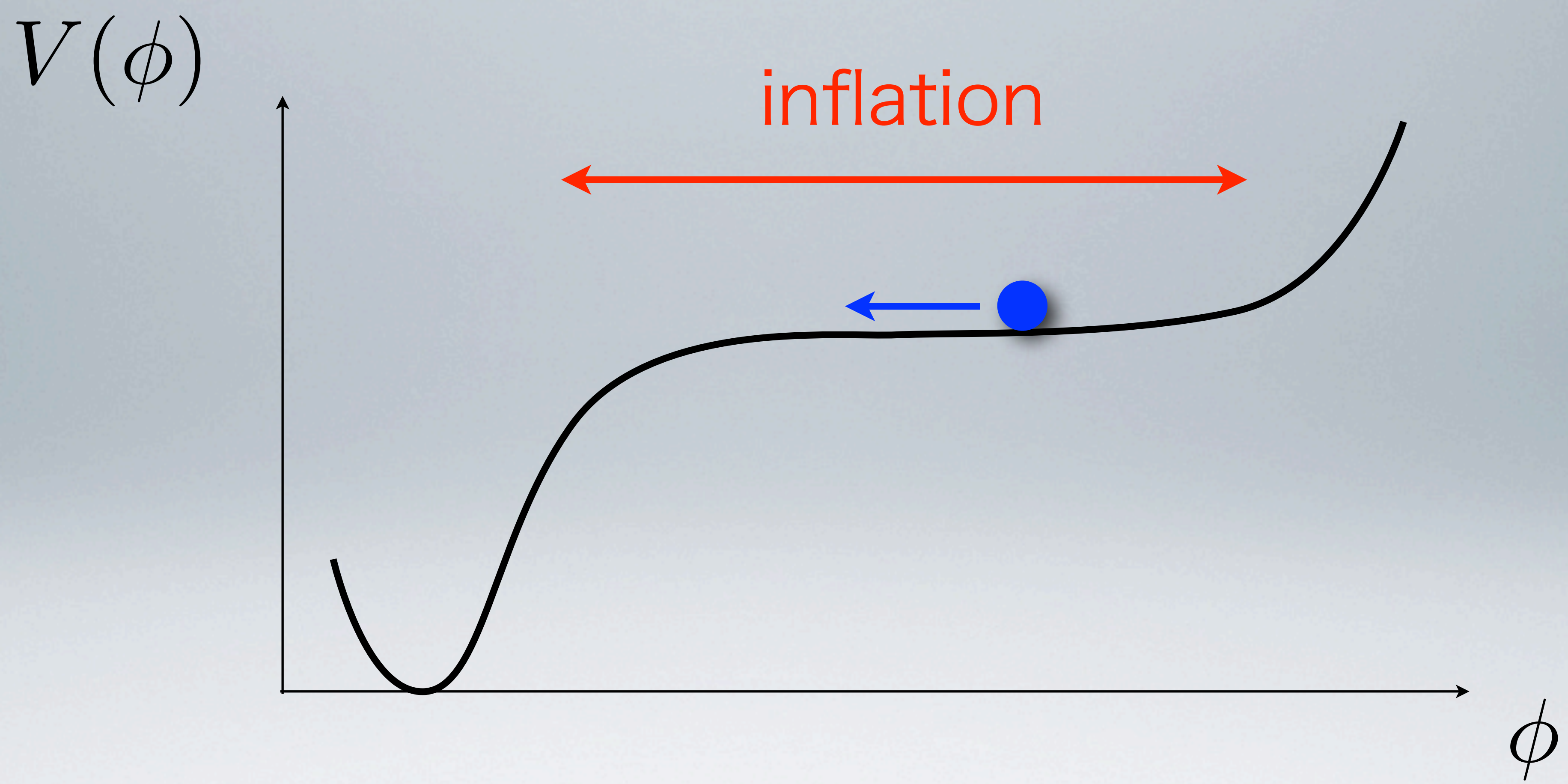


- homogeneous and isotropic
- flat
- without unwanted relics
- tiny inhomogeneities

image: NASA/WMAP Science Team

TOWARDS MICROSCOPIC REALIZATION

Inflaton : a scalar field which acts like vacuum energy



slow-roll conditions: $\epsilon \equiv \frac{M_p^2}{2}\left(\frac{V'}{V}\right)^2, \quad |\eta| \equiv \left|M_p^2 \frac{V''}{V}\right| \ll 1$

FUNDAMENTAL QUESTIONS

- What is the inflaton?
- What microphysics governed the inflationary universe?

- UV-sensitivity of inflationary cosmology

- How valid is the effective field theory description?

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- How valid is the effective field theory description?

String Theory may help!

STRING COSMOLOGY

Good things for Cosmology

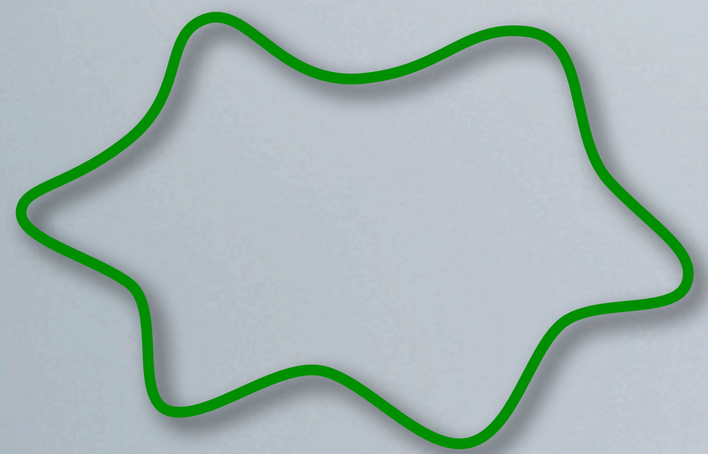
- allows description of the universe at high energy
- provides new ideas, new ingredients, and new ways of thinking about the early universe

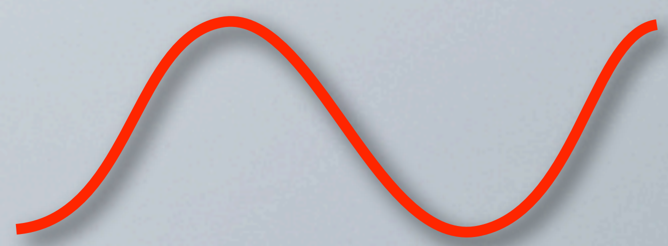
Good things for String Theory

- may provide tests of string theory through cosmological observables

STRING THEORY

- quantum gravity candidate based on closed / open strings





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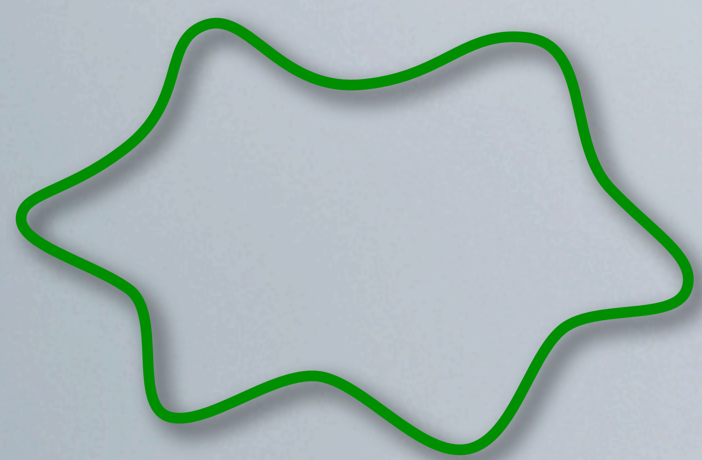

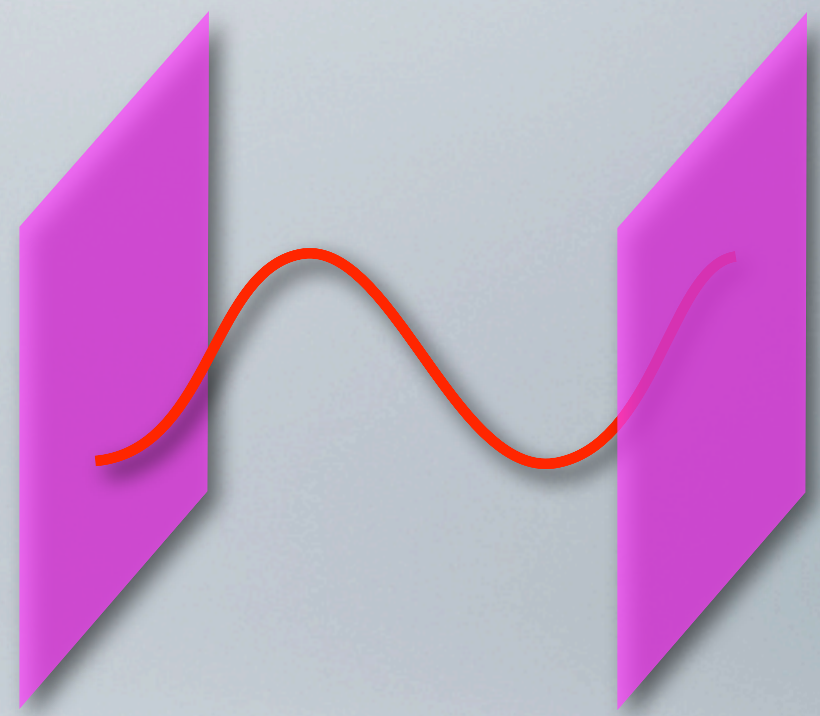

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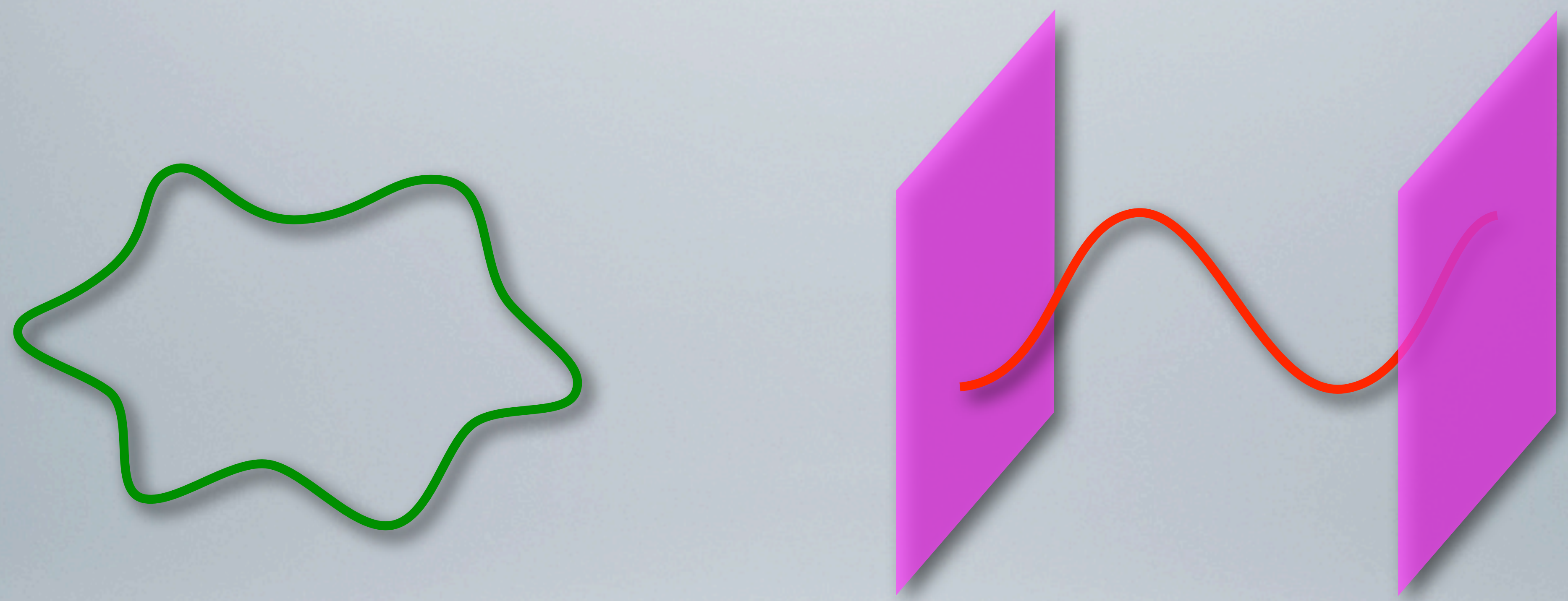


- open strings end on Dp-branes, i.e. physical objects with p spatial dimensions

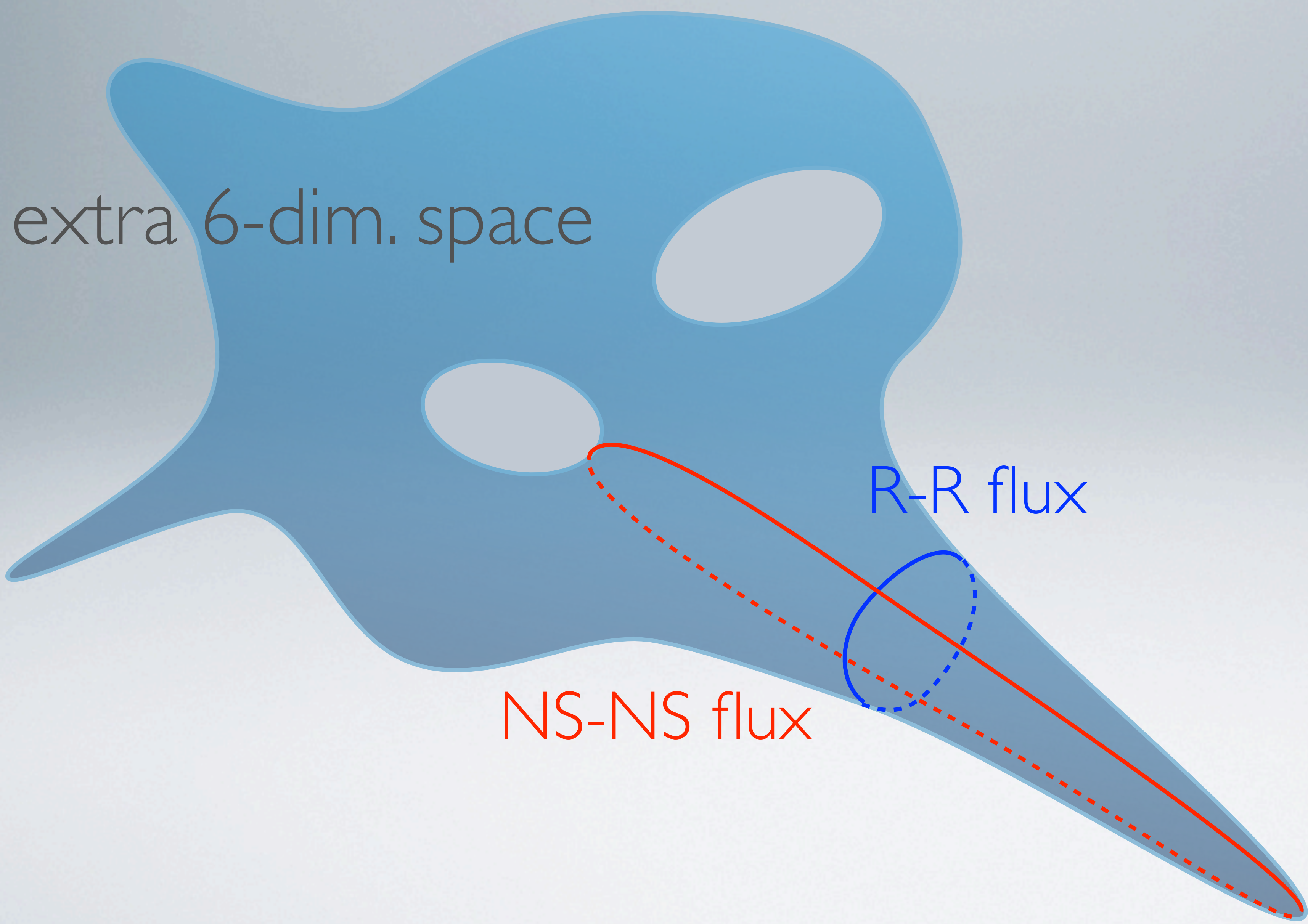
- string theory predicts 10 (or 11) spacetime dimensions

  → the extra 6 (or 7) dimensions need to be compactified

COMPACTIFICATION OF TYPE IIB STRING THEORY

Klebanov, Strassler '00 Gidding, Kachru, Polchinski '02 Kachru, Kallosh, Linde, Trivedi '03

warped compactification to 4-dim. dS with all moduli fixed via fluxes, brane sources, and nonperturbative effects



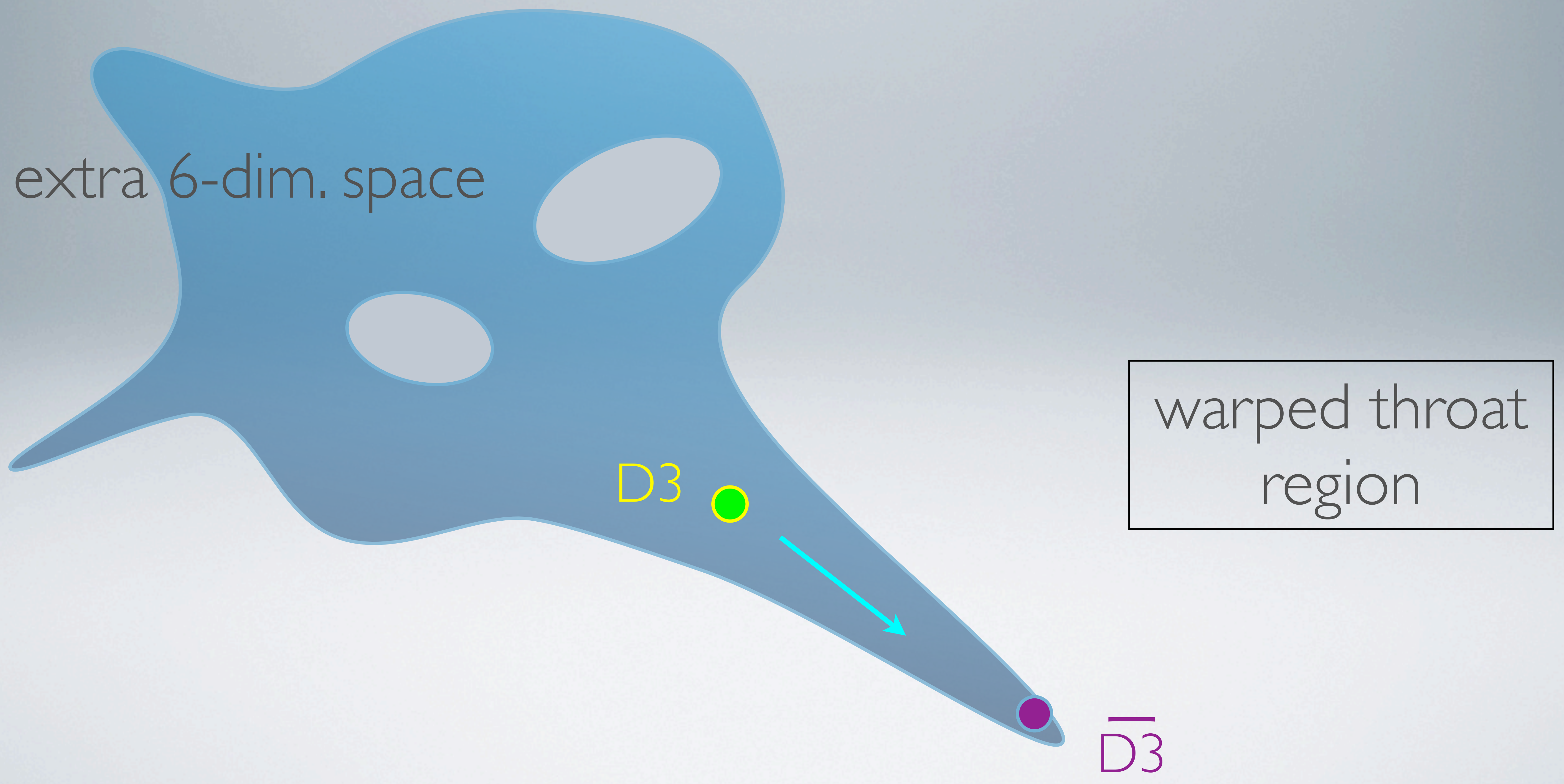
warped throat region

$$ds^2 = h(y)^2 g^{(4)}_{\mu\nu} dx^\mu dx^\nu + h(y)^{-2} g^{(6)}_{mn} dy^m dy^n$$

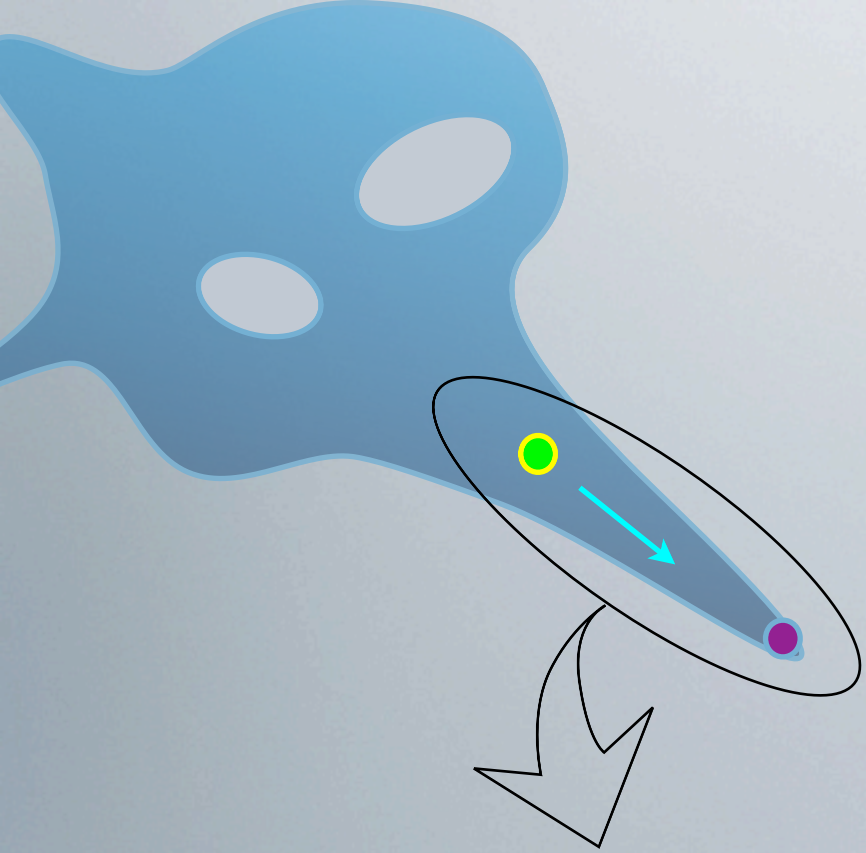
D-BRANE INFLATION IN A WARPED THROAT

Kachru, Kallosh, Linde, Maldacena, McAllister, Trivedi '03

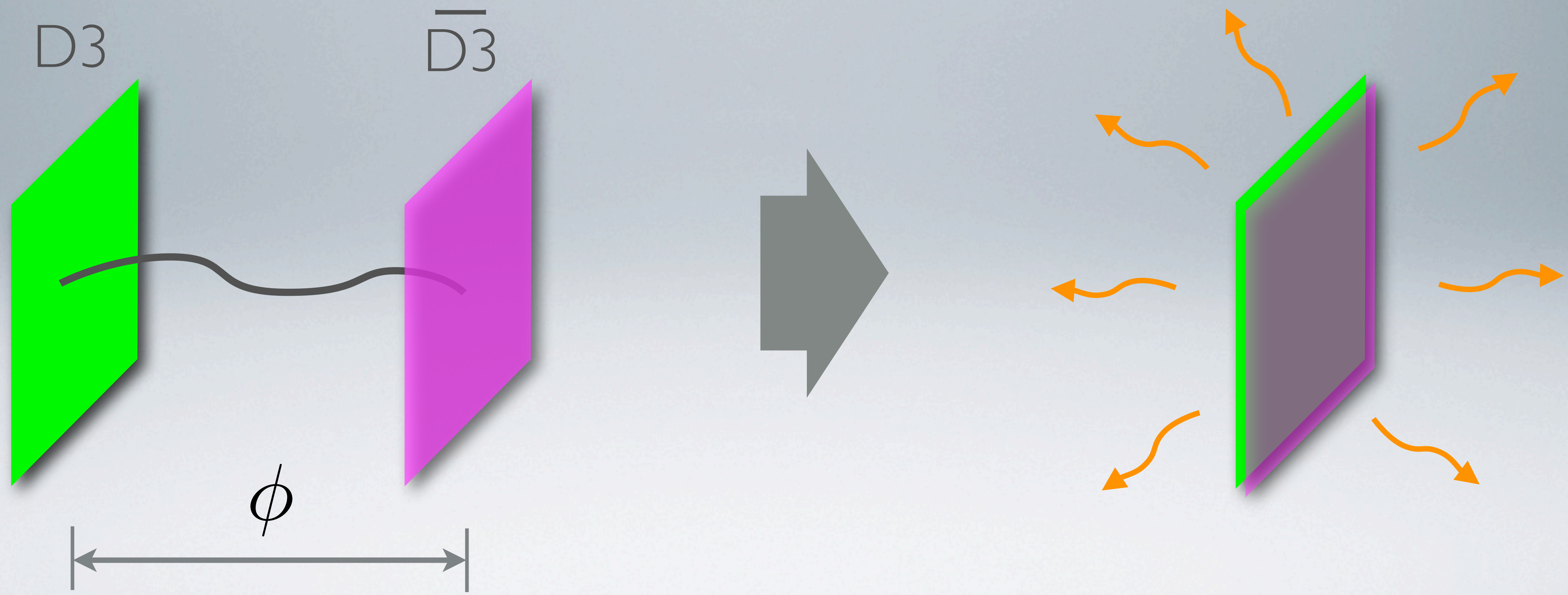
A brane-antibrane pair drives inflation.



D-BRANE INFLATION : A CLOSER LOOK



inflaton ϕ : radial position of the D3



Coulomb interaction

D3-$\overline{\text{D3}}$ annihilation

INFLATON POTENTIAL

ϕ : (normalized) D3 position

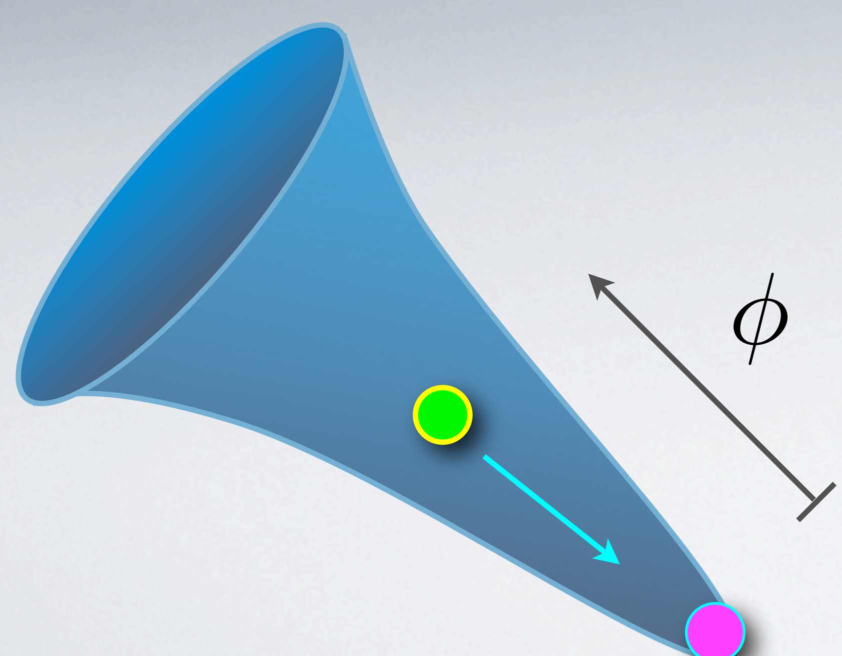
h_0 : warp factor at the throat tip

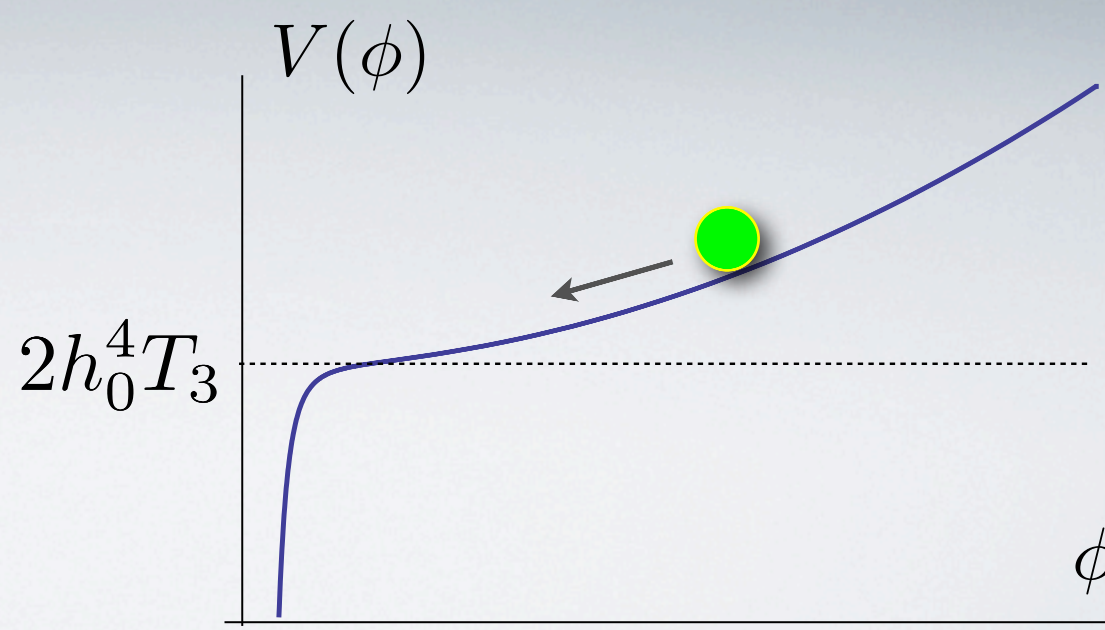
$$V(\phi) = 2h_0^4 T_3 \left(1 - \frac{\mu^4}{\phi^4}\right) + H^2\phi^2 + \cdots$$

$\overline{\text{D3}}$-tension

Coulomb interaction

from moduli stabilization





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Coulomb interaction

from moduli stabilization

$$H^2 \simeq \frac{V}{3M_p^2} \longrightarrow \eta = M_p^2 \frac{V''}{V} \simeq \frac{2}{3}$$

η-problem

~~slow-roll inflation~~

(unless delicate fine-tuning)

Baumann et al. '06 - '10

ALTERNATIVE APPROACH: DBI INFLATION

Silverstein, Tong '04

Inflation from D-branes moving with relativistic velocities.

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Throat too short for a relativistically moving D3-brane to drive sufficient inflation.

Baumann, McAllister '06   Lidsey, Huston '07

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Not only for D3-branes,
but also for higher-dimensional wrapped branes (D5 and D7).

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Relaxation of constraints by multi-field/Galileon extensions?
(talks by Tsutomu & Shuntaro yesterday)

SUMMARY SO FAR FOR D-BRANE INFLATION

Slow-Roll Inflation

- suffers from the **η**-problem (i.e. Hubble size mass)

DBI Inflation (relativistic limit)

- suffers from geometrical constraints

INFLATION FROM RAPID-ROLLING D-BRANES

Kofman, Mukohyama '07 TK, Mukohyama '08 TK, Mukohyama, Powell '09

- An inflationary attractor solution DOES exist even for $\eta \sim \mathcal{O}(1)$.
- This corresponds to D-branes moving rapidly, but non-relativistically.
- The inflaton is quickly decelerating / accelerating. ($\longleftrightarrow$ slow-roll inf.)

RAPID-ROLL INFLATION

$$\frac{\mathcal{L}}{\sqrt{-g}} = -\frac{1}{2} g^{\mu\nu} \partial_\mu \phi \partial_\nu \phi - V(\phi)$$

$$\epsilon \equiv \frac{M_p^2}{2} \left(\frac{V'}{V} \right)^2 \qquad \eta \equiv M_p^2 \frac{V''}{V}$$

Hubble eq. $$3 M_p^2 H^2 = \frac{\dot{\phi}^2}{2} + V$$

EOM $$\ddot{\phi} + 3H\dot{\phi} = -V'$$

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conditions $\epsilon \ll 1$ $\eta < \frac{3}{4}$

Hubble eq. $3M_p^2 H^2 = \frac{\dot{\phi}^2}{2} + V \longrightarrow 3M_p^2 H^2 \simeq V$

EOM $\ddot{\phi} + 3H\dot{\phi} = -V' \longrightarrow cH\dot{\phi} \simeq -V'$

where $c = \frac{3 + \sqrt{9 - 12\eta}}{2}$

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slow-roll recovered upon η → 0

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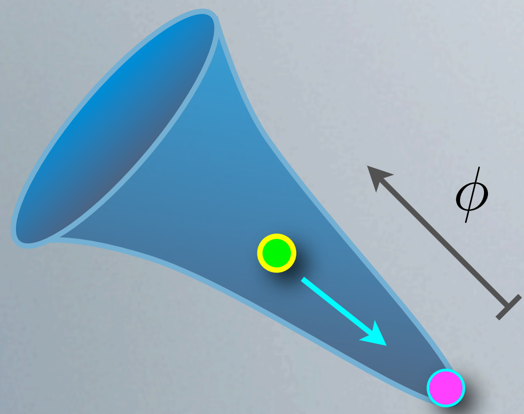
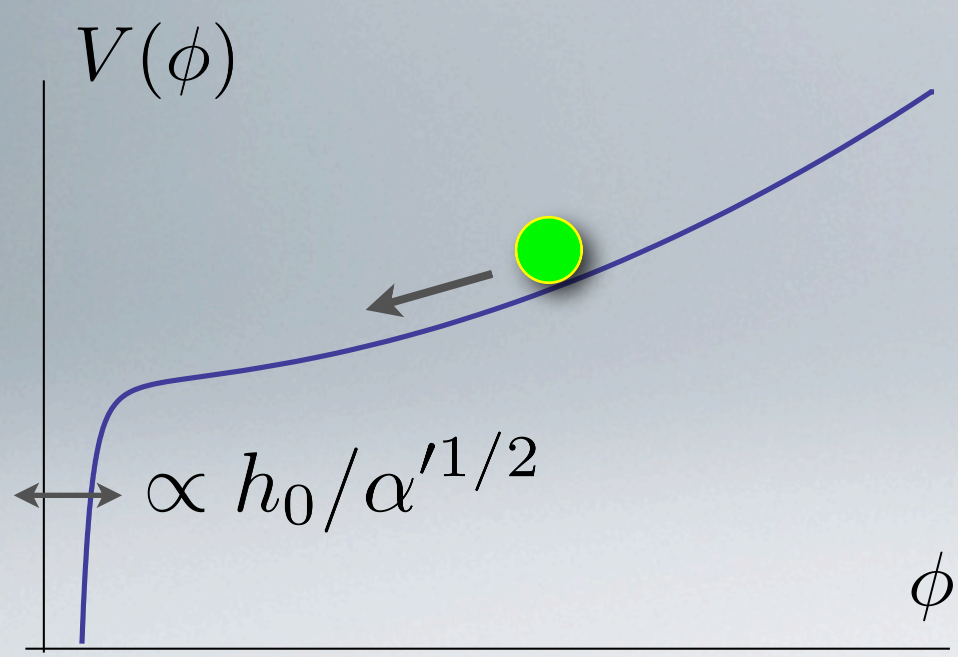


$$\frac{\mathcal{L}}{\sqrt{-g}} = -\frac{1}{2} g^{\mu\nu}\partial_\mu\phi\partial_\nu\phi - V_0\left\{1 + \mathcal{O}(1)\times\frac{\phi^2}{M_p^2} - \frac{\mu^4}{\phi^4}\right\}$$



inflationary attractor

$$\frac{\dot\phi}{H} \simeq -\frac{6\eta}{3+\sqrt{9-12\eta}}\phi$$

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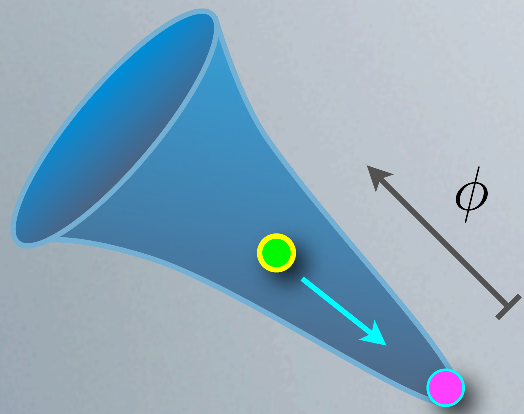

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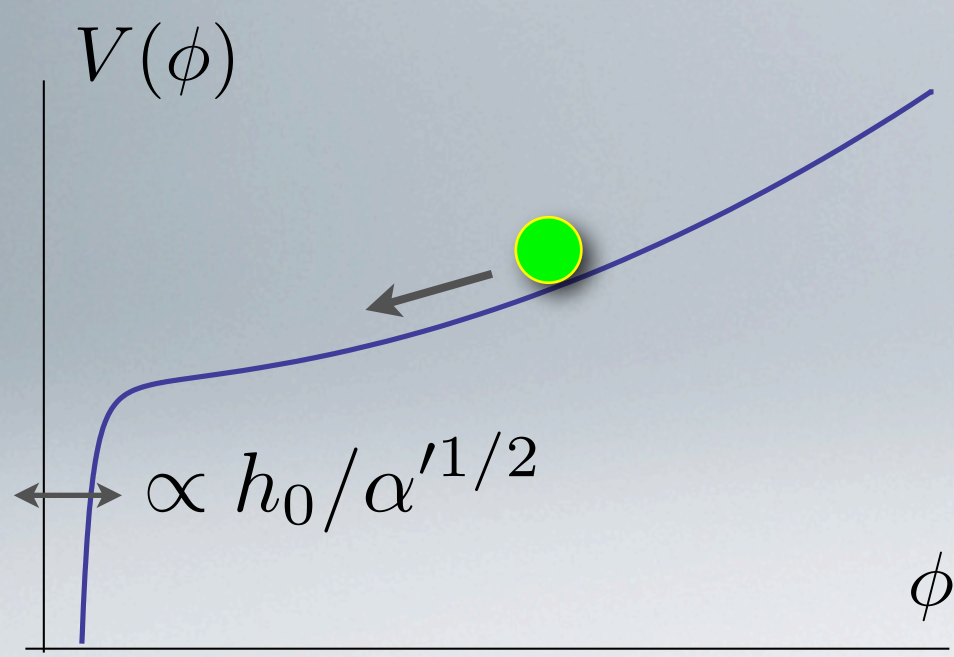

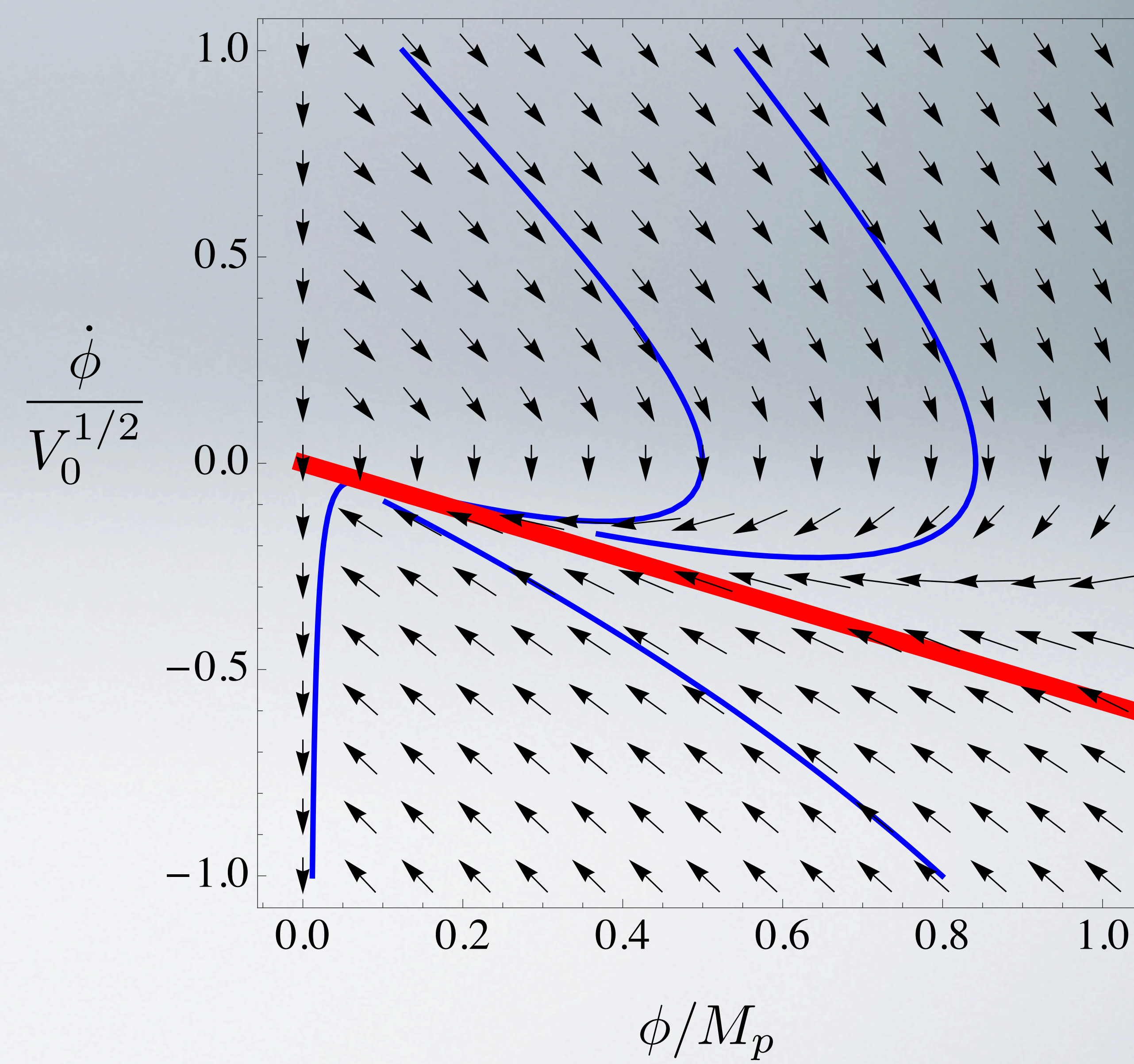

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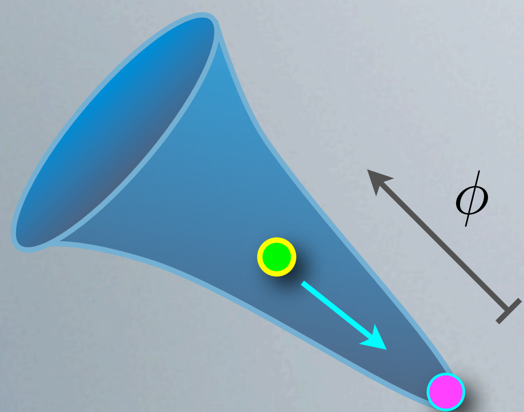

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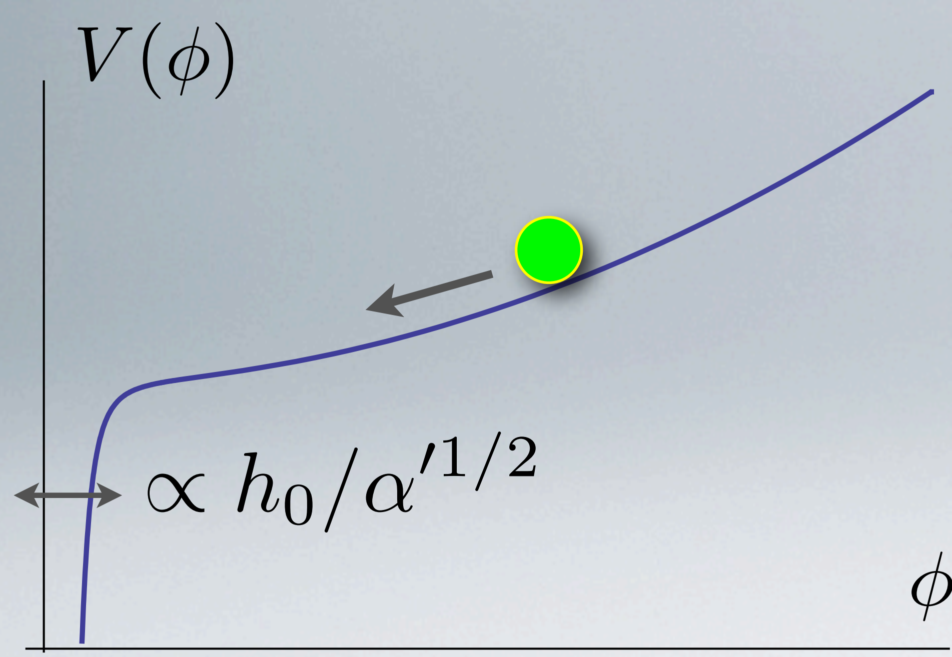
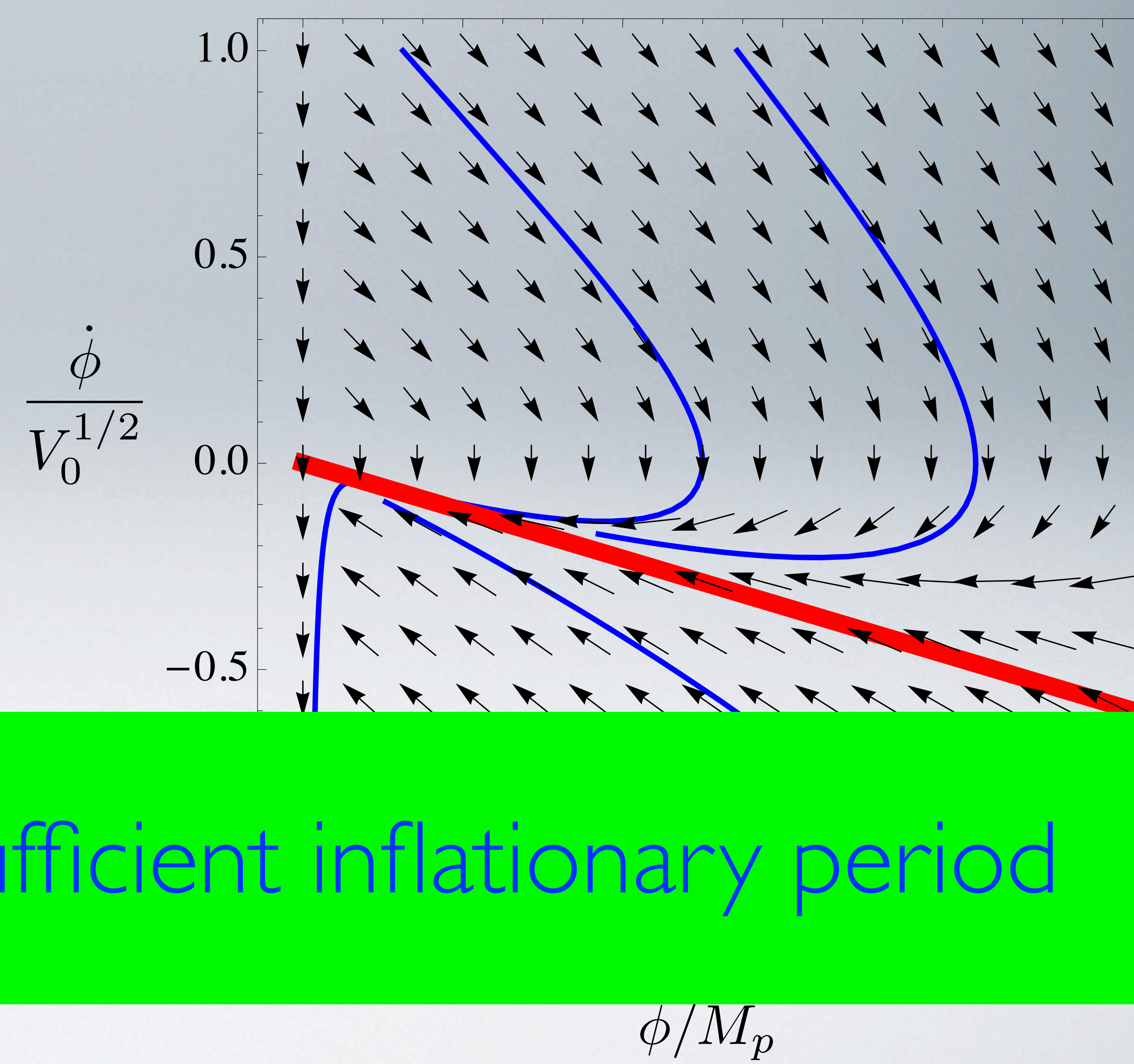




strong warping gives sufficient inflationary period

$H \quad 3+\sqrt{9-12\eta}$

INFLATION FROM RAPID-ROLLING D3-BRANE

- D3-$\overline{\text{D3}}$ system in a warped geometry can give rise to rapid-roll inflation

- no need to cancel the Hubble size mass

  → remedy to the η-problem

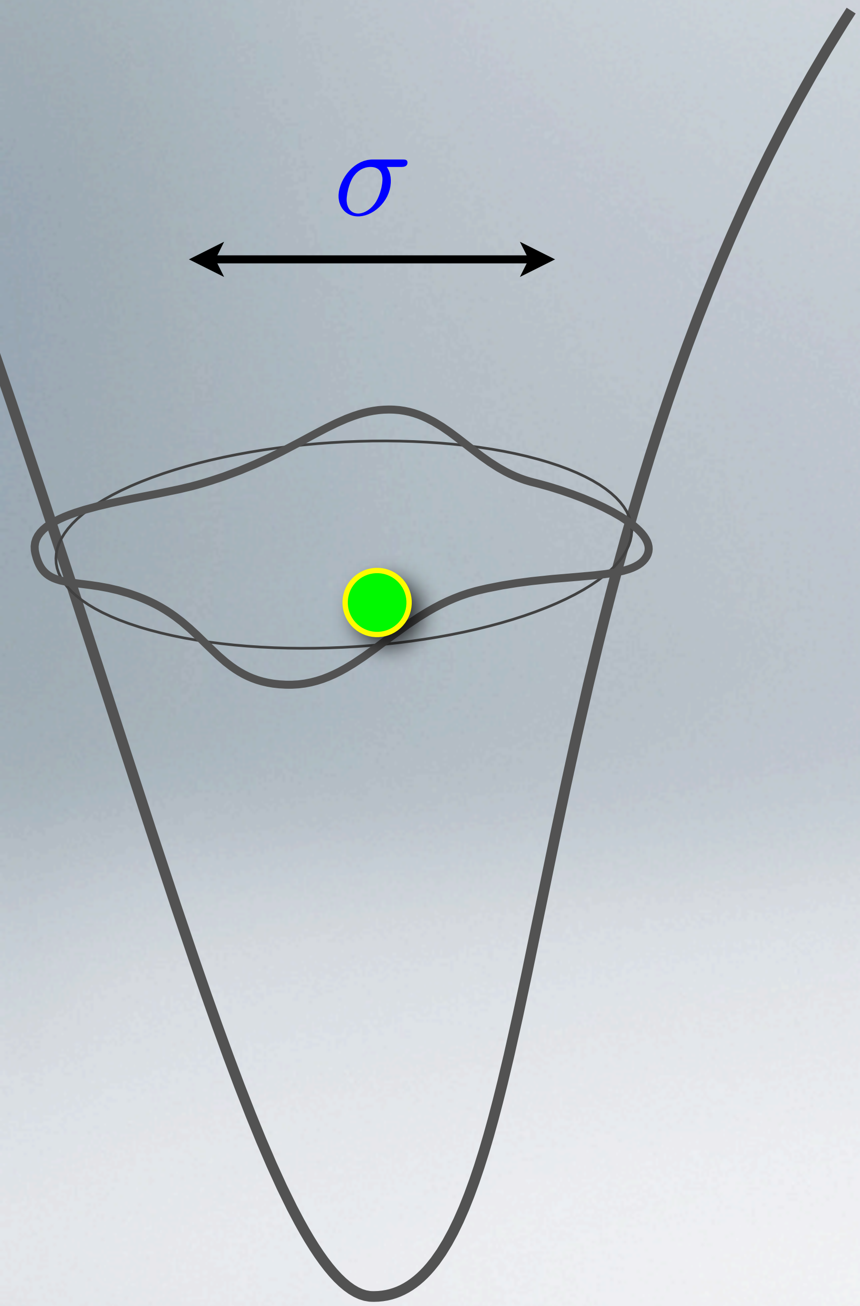
- sufficient inflationary expansion can be obtained in a single throat

  → geometrical constraints circumvented

- However, the inflaton itself cannot produce scale-invariant density perturbations.

  → perturbations need to be generated by something else

Angular directions of warped throats can generate curvature perturbations



during inflation

TK, Mukohyama '10 and work in progress

- as multi-field inflation
- light fields modulating rapid-roll inflation can generate scale-invariant perturbations

after inflation (as curvatons)

TK, Mukohyama '09

- D-branes oscillating in warped throats can be curvatons

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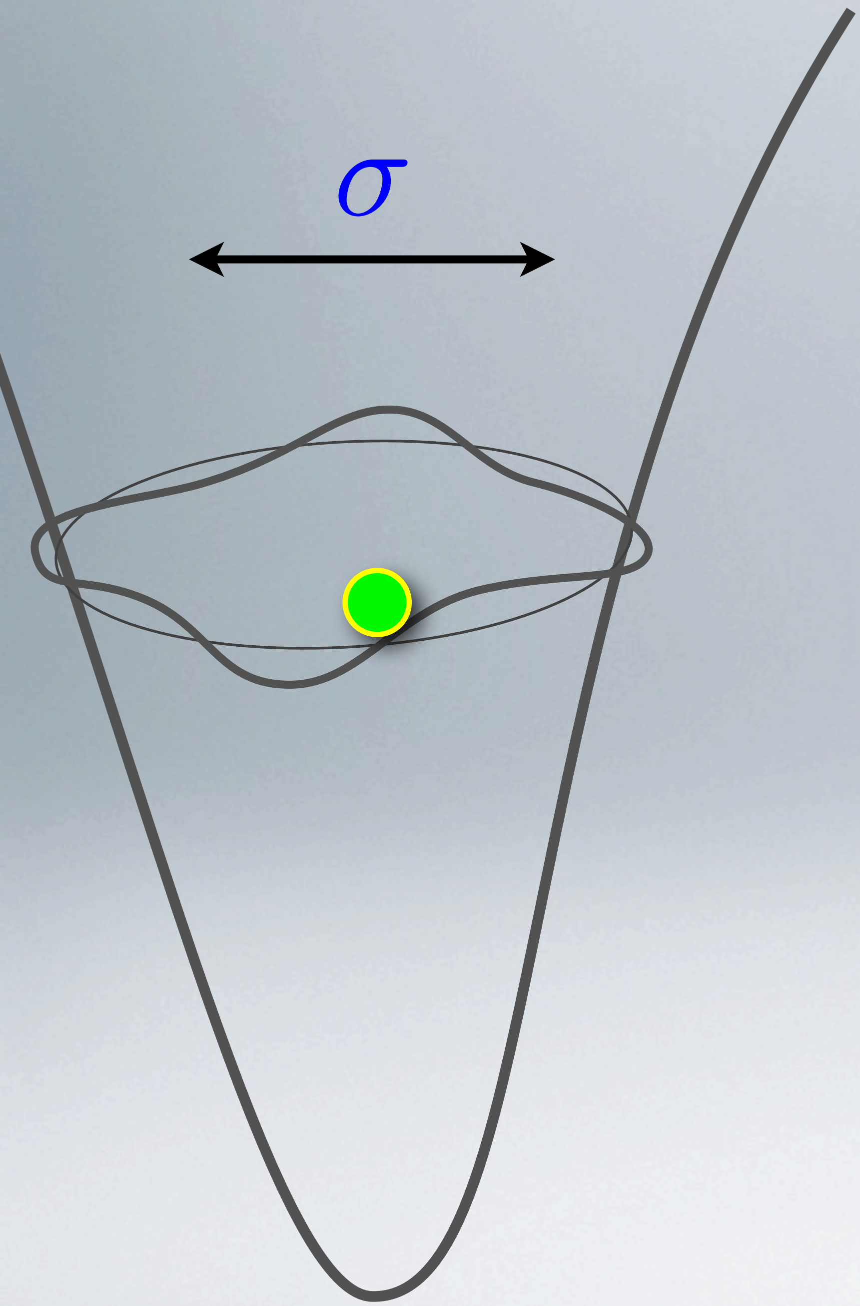

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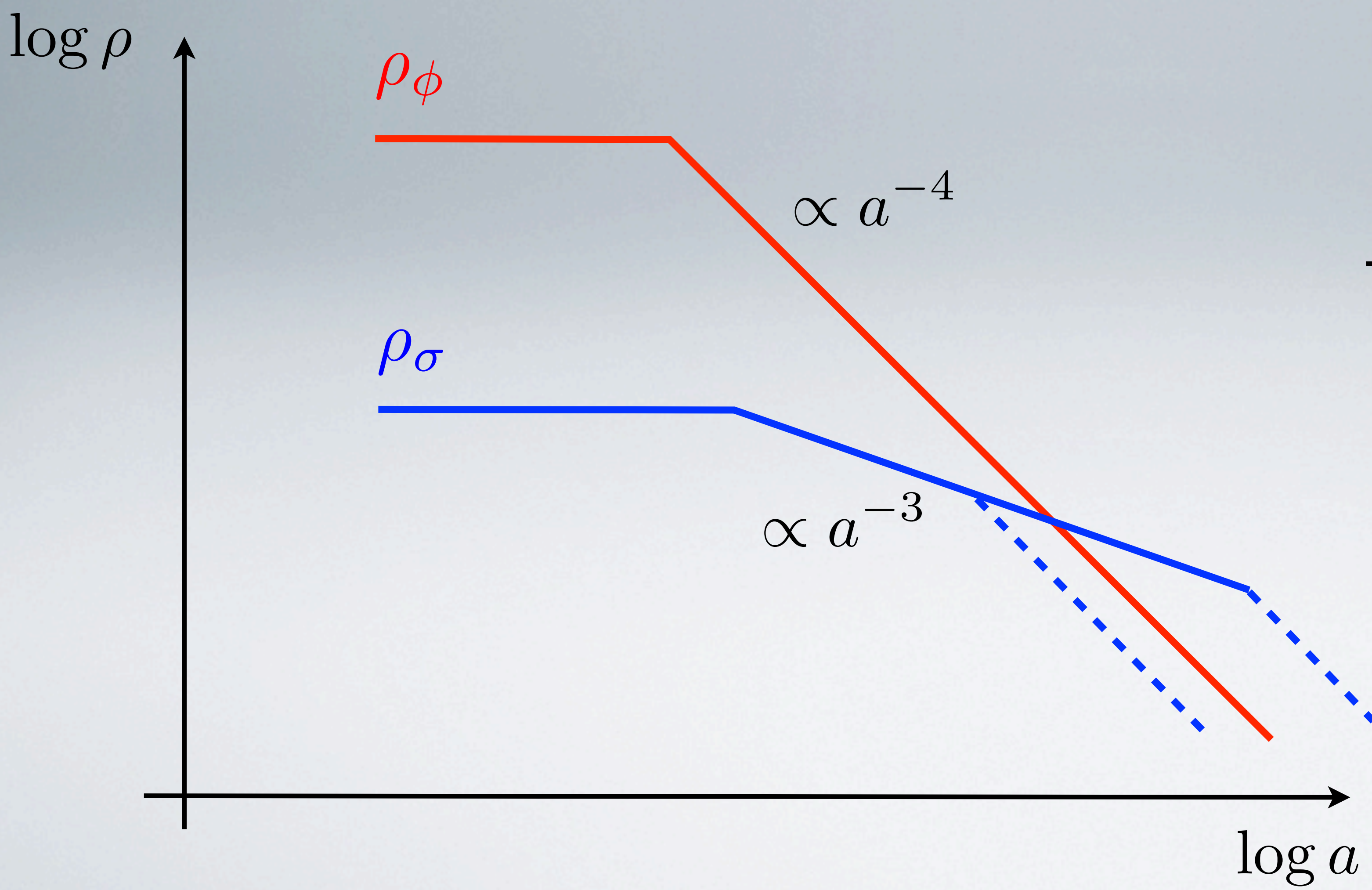
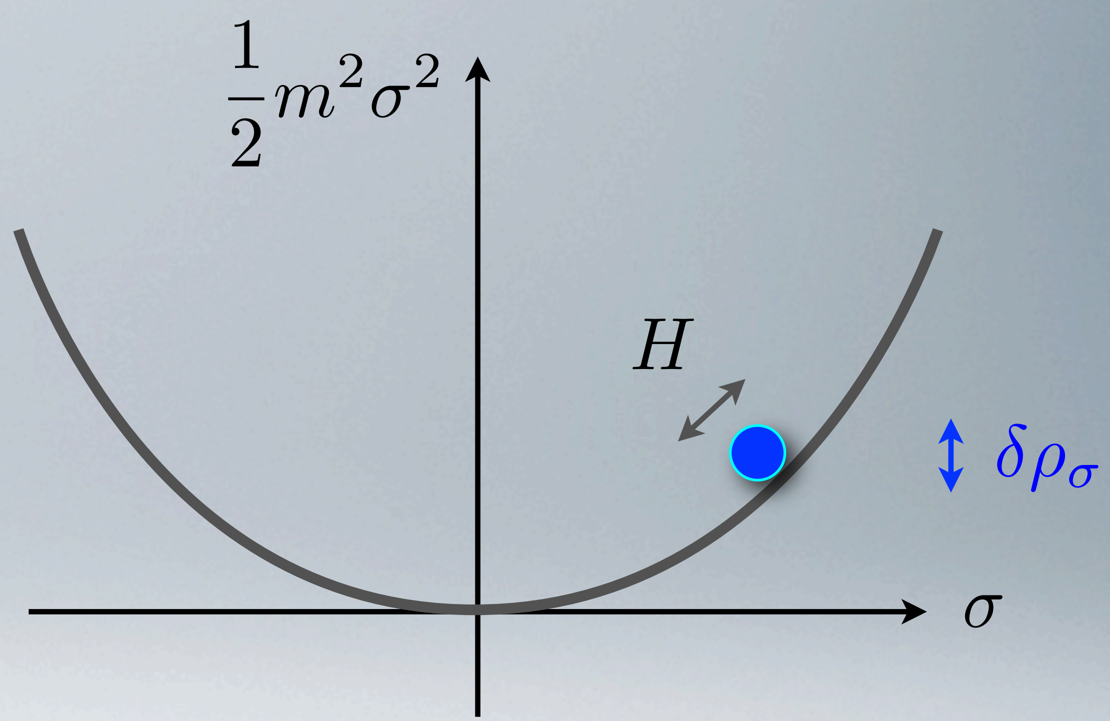
CURVATON MECHANISM

Linde, Mukhanov '97
Enqvist, Sloth '01
Lyth, Wands '01
Moroi, Takahashi '01

curvaton : a light field (i.e. $m^2 \ll H^2$) which generates density perturbations after inflation





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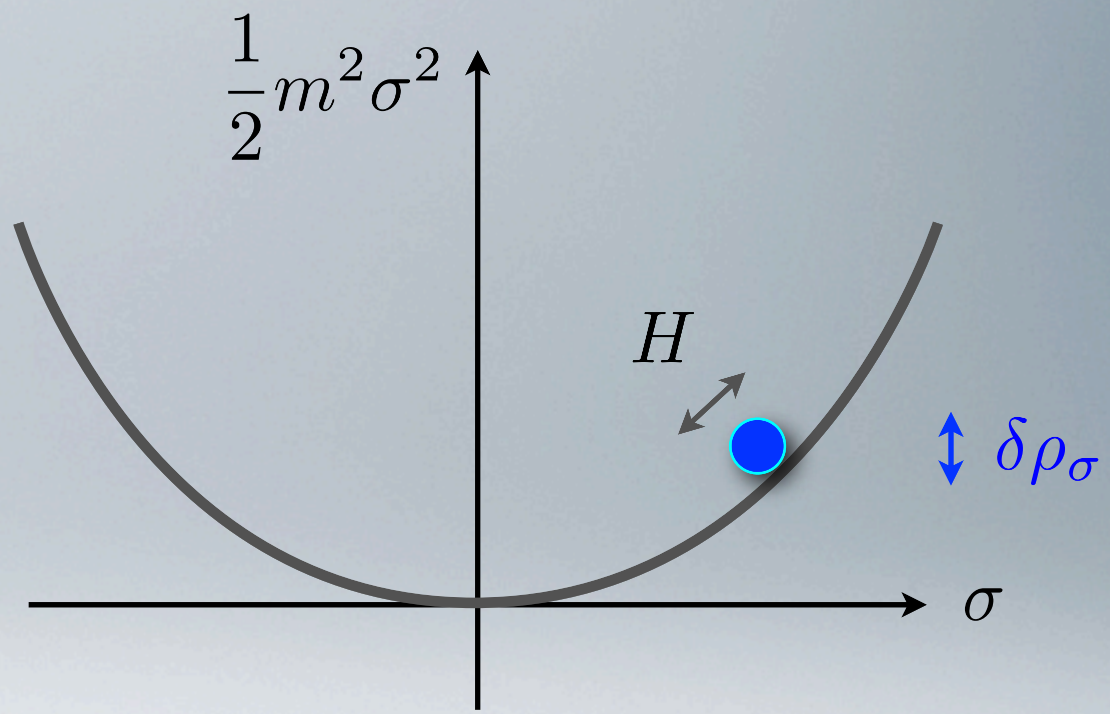

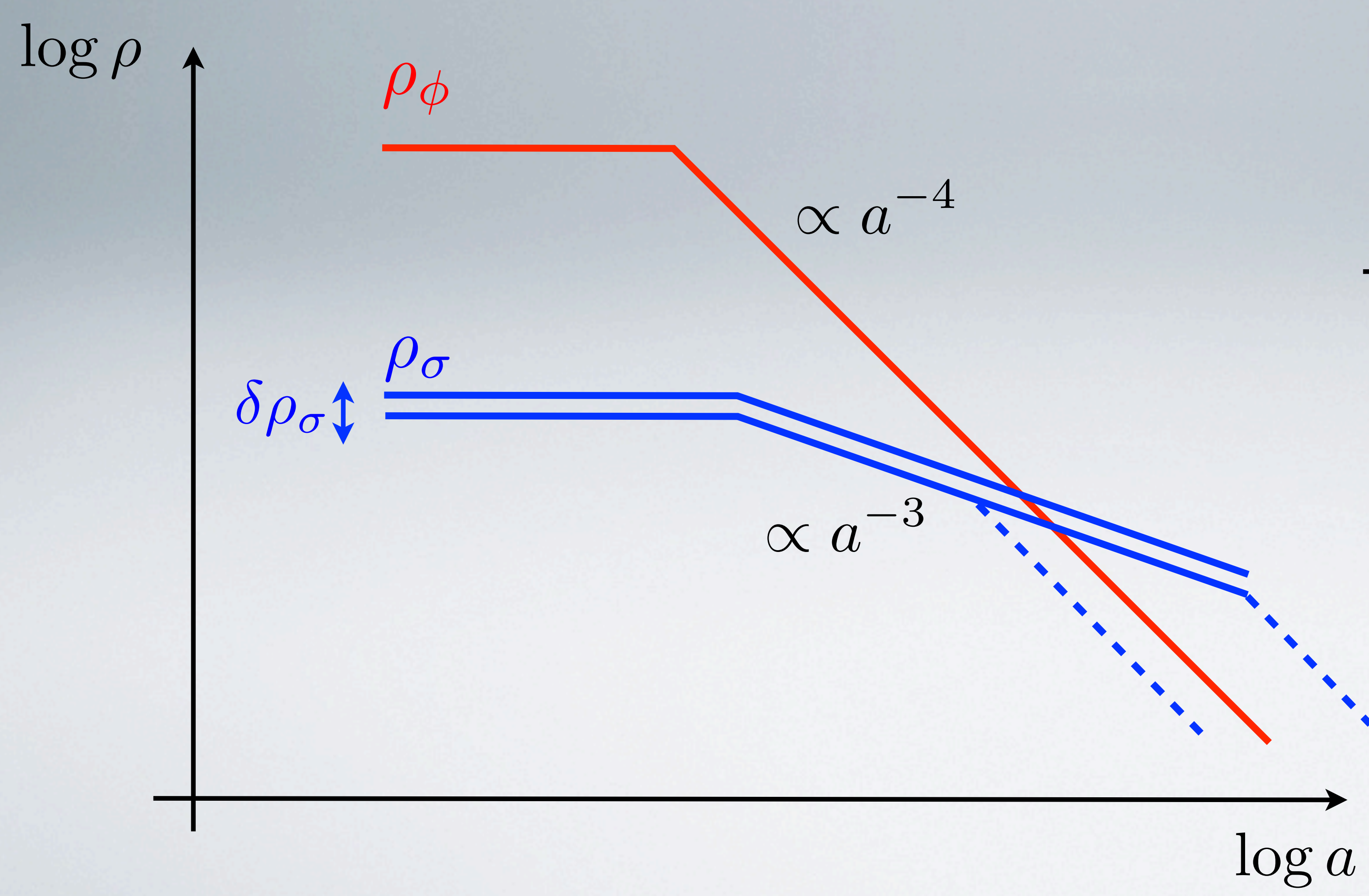

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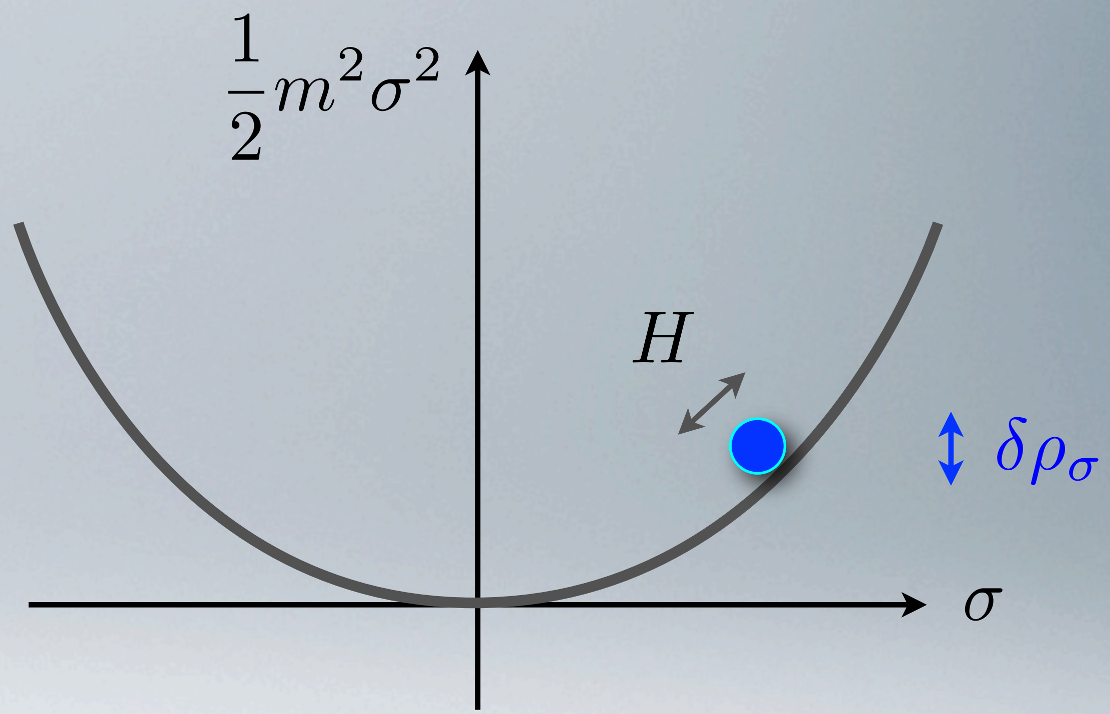
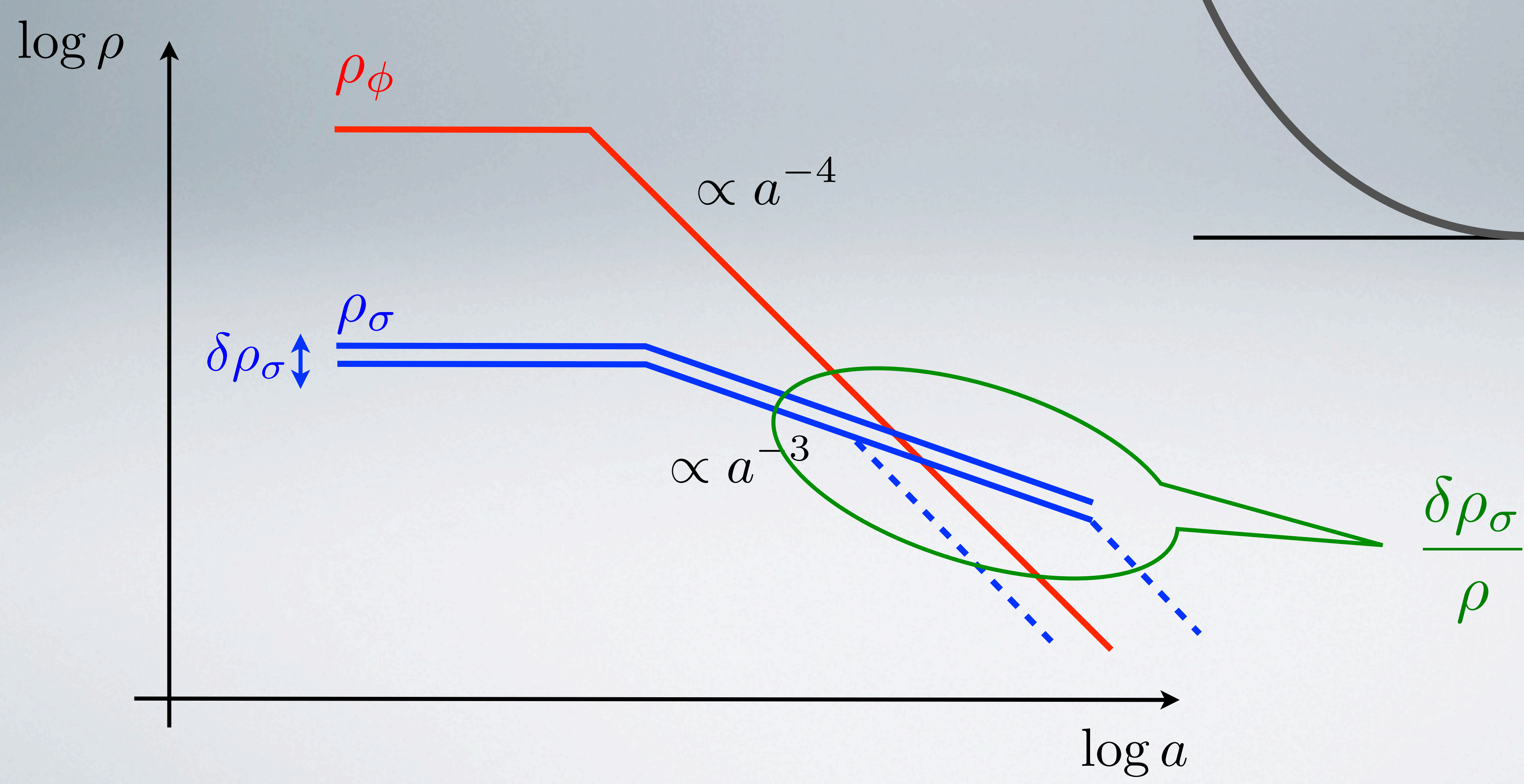
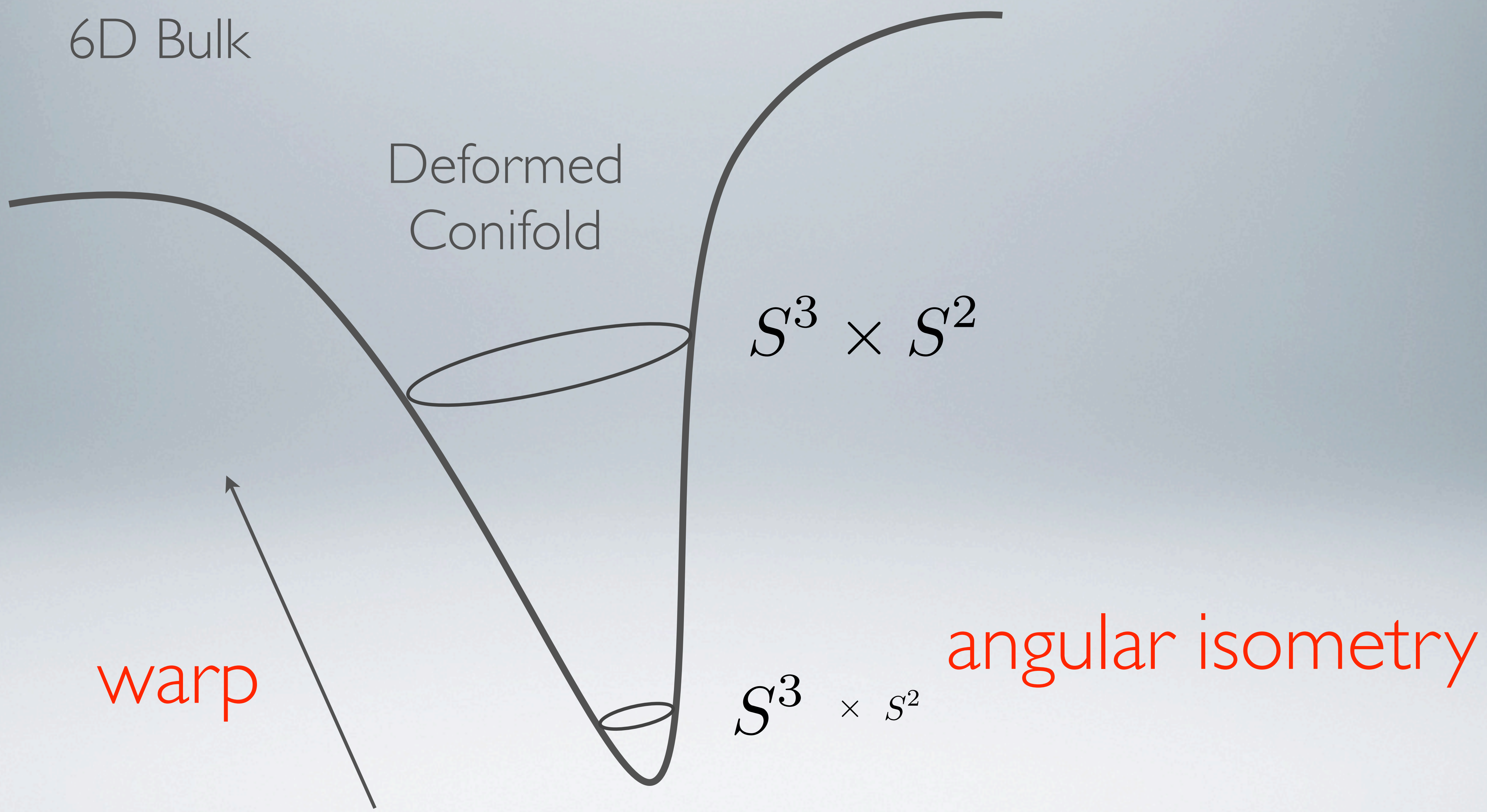




CURVATONS IN A WARPED THROAT



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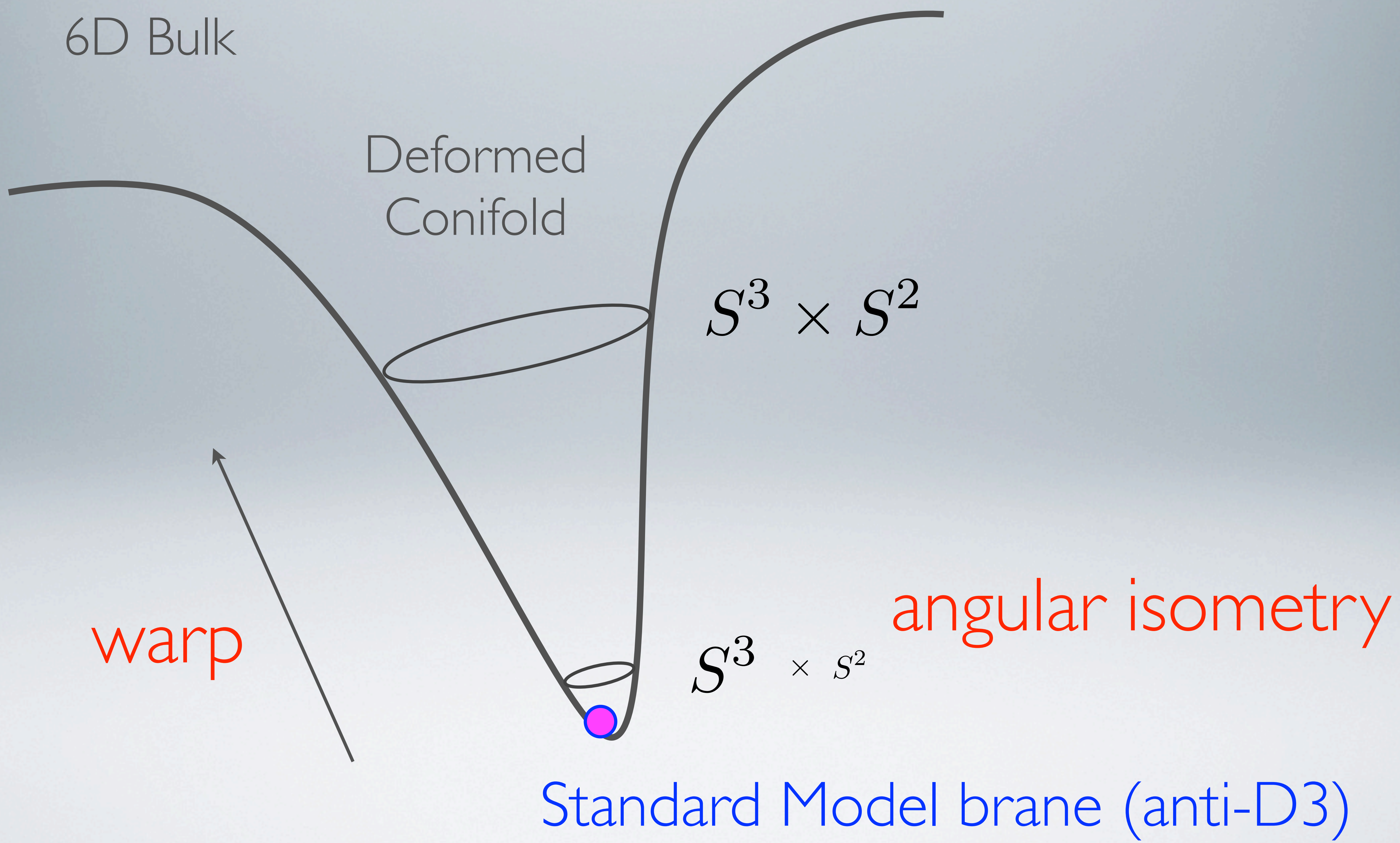
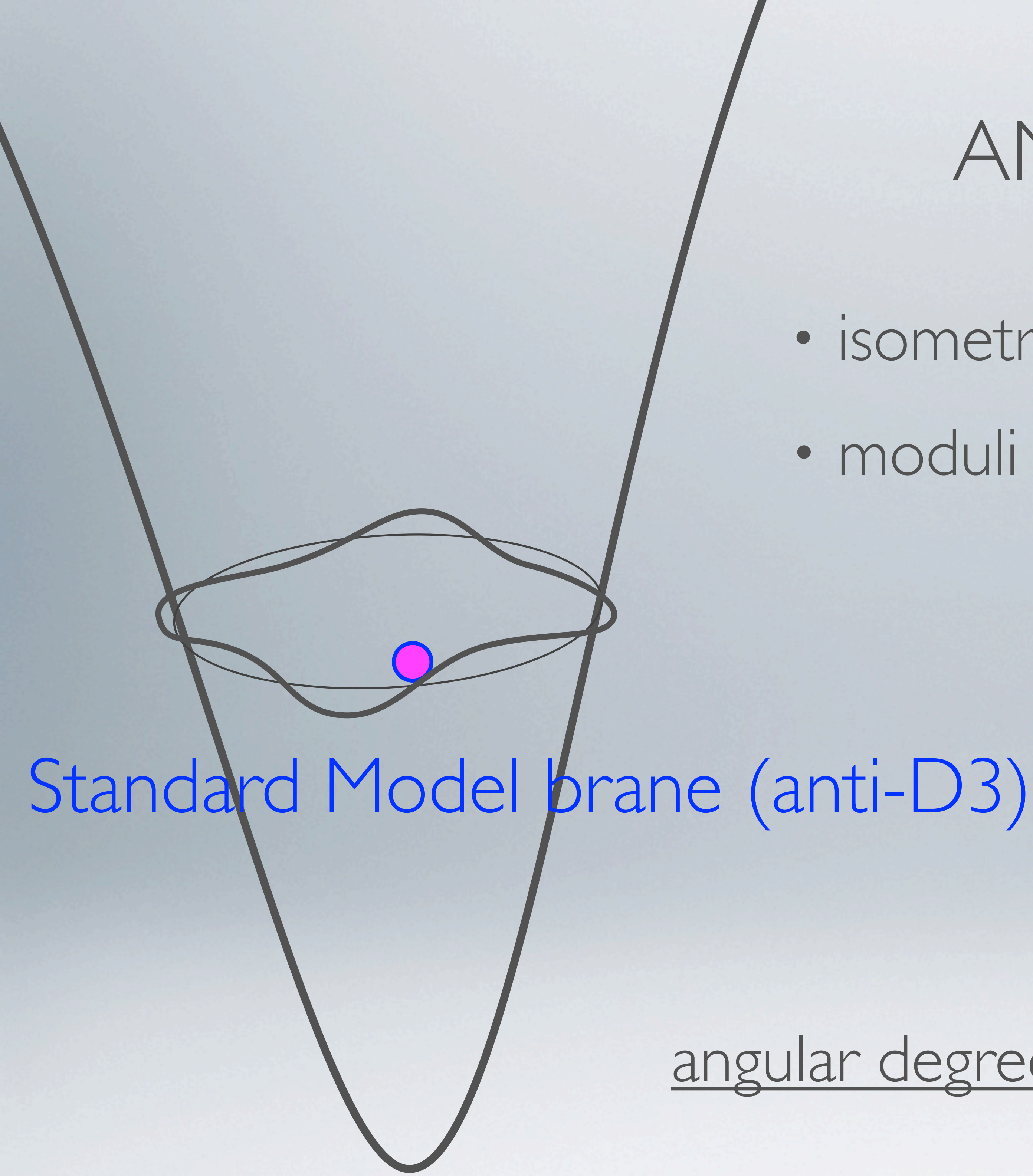


ANGULAR POTENTIAL



- isometry breaking bulk effects
- moduli stabilizing non-perturbative effects

↓ + warping

small mass to the
<u>angular degrees of freedom</u> of the SM brane

||

CURVATON $\boldsymbol{\sigma}$

→ eventually decays into other open string modes (reheating)

ACTION

$$S = -T_3 \int d^4\xi \sqrt{-\det G_{\mu\nu}} \left(1 - \bar{\Psi} i \not{D} \Psi\right) - T_3 \int C_4$$

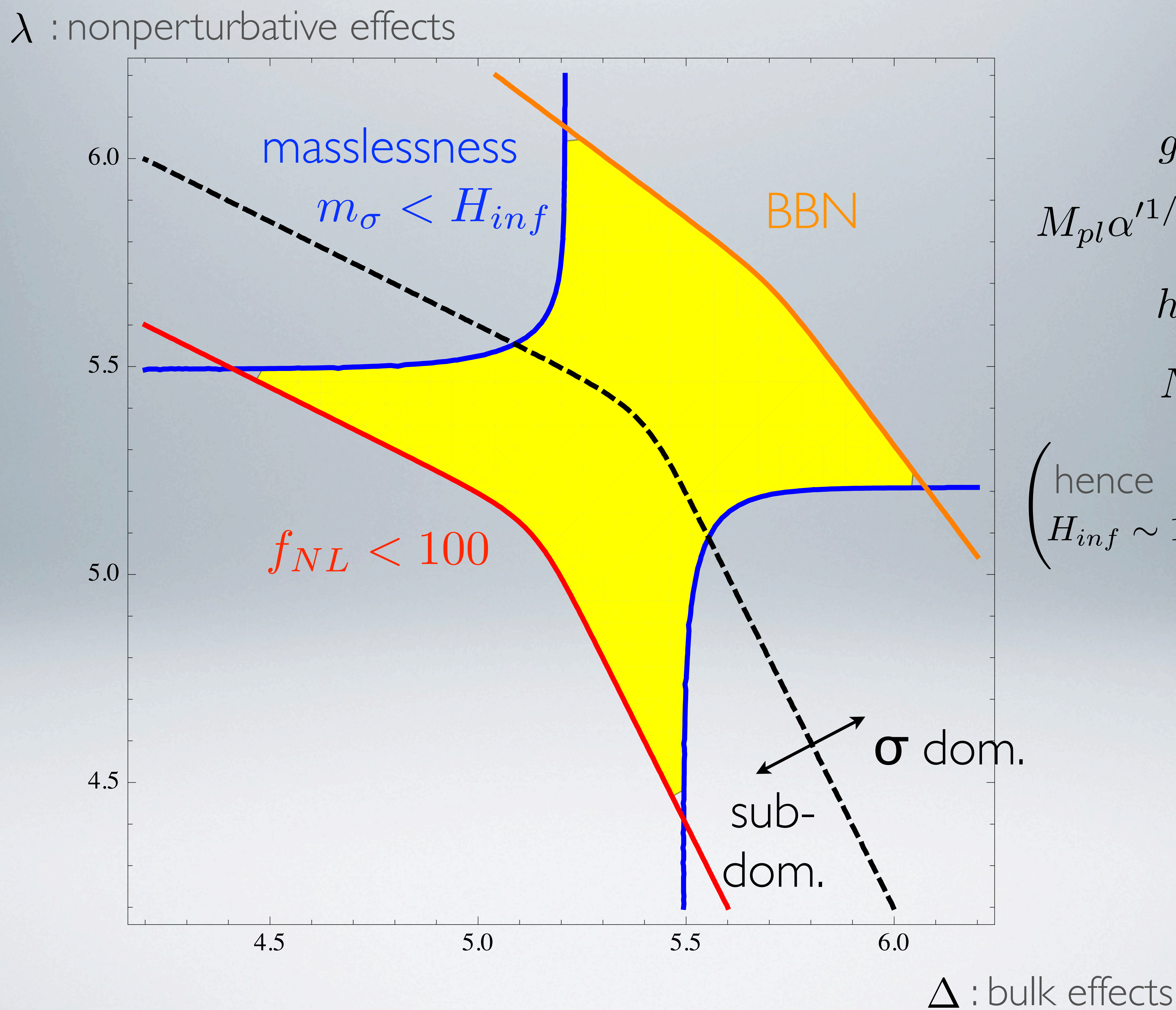
$$\sim \int d^4x \sqrt{-g^{(4)}} \Big[-(\partial\sigma)^2 + \bar{\psi} i \not{D} \psi$$
$$- (m_{\text{bulk}}^2 + m_{\text{np}}^2)\sigma^2 + \frac{g_s M^{1/2} \alpha'^{3/2}}{h_0^3} \frac{m_{\text{bulk}}^2 m_{\text{np}}^2}{m_{\text{bulk}}^2 + m_{\text{np}}^2} \sigma \bar{\psi} i \not{D} \psi + \cdots \Big]$$

$$m_{\text{bulk}}^2 = \frac{h_0^{\Delta-2}}{g_s M \alpha'}$$: bulk effects

$$m_{\text{np}}^2 = \frac{h_0^{\lambda-2}}{g_s M \alpha'}$$: nonperturbative effects

h_0 : warp factor at the tip $\left(ds^2 = h^2 g_{\mu\nu}^{(4)} dx^\mu dx^\nu + h^{-2} g_{mn}^{(6)} dx^m dx^n \right)$

PARAMETER CONSTRAINTS



$$g_s = 0.1$$

$$M_{pl}\alpha'^{1/2} = 300$$

$$h_0 = 10^{-5}$$

$$N = 50000$$

(hence $H_{inf} \sim 10^{-11} f_{\rm NL} M_{pl}$)

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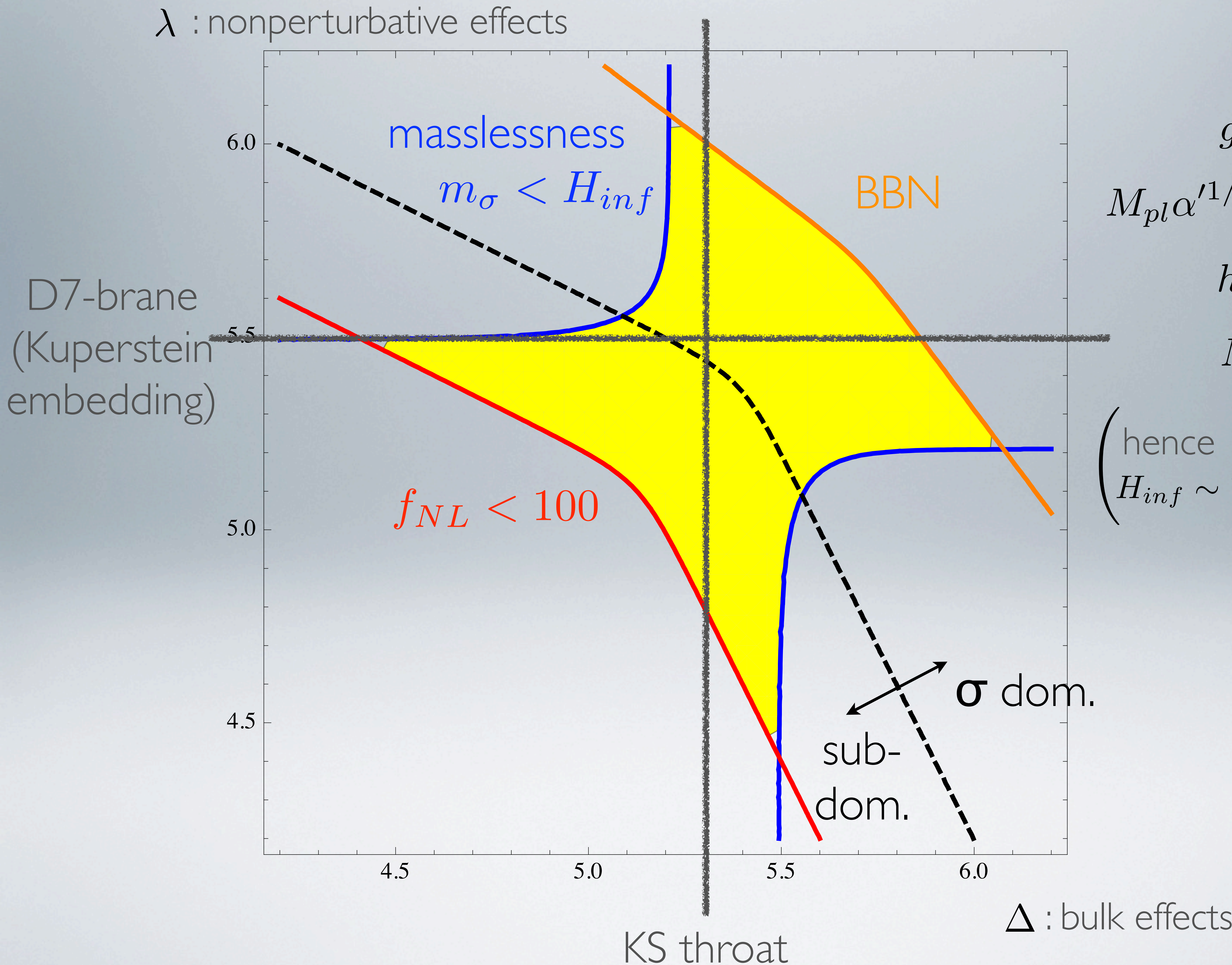

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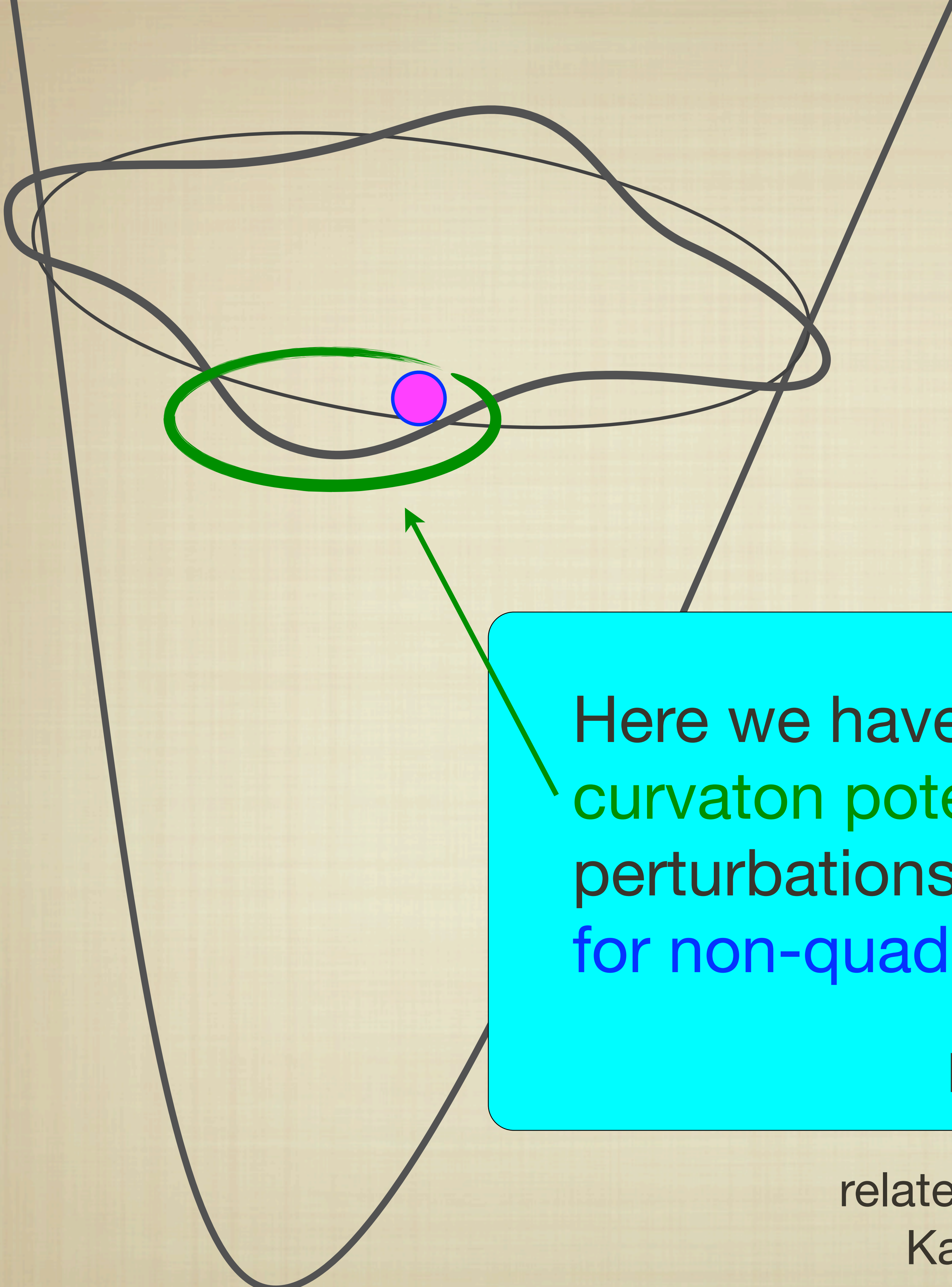

Here we have considered quadratic curvaton potentials, but density perturbations can be quite different for non-quadratic potentials.

Kawasaki, TK, Takahashi ’11

related works by Enqvist, Takahashi ’08
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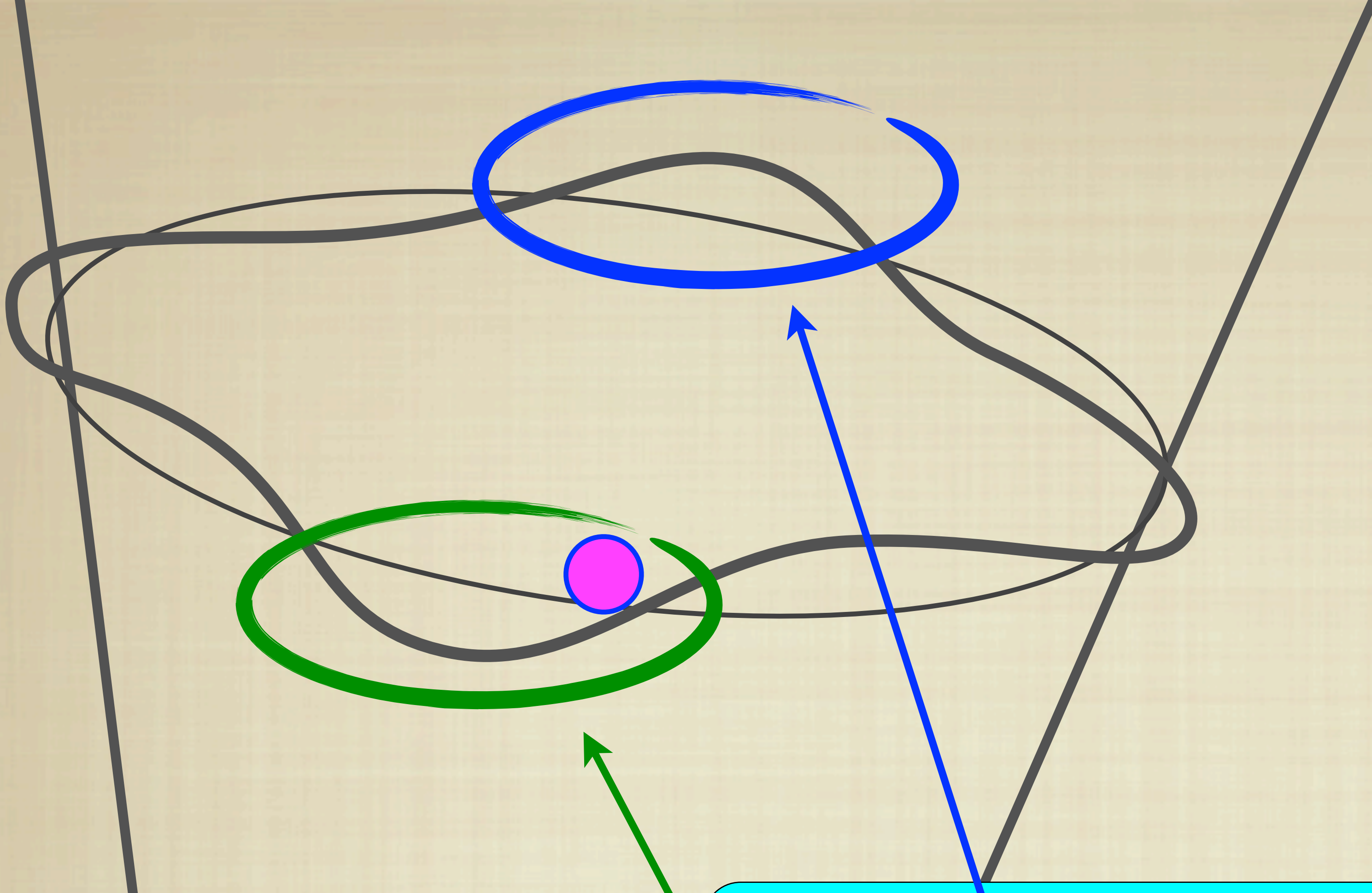

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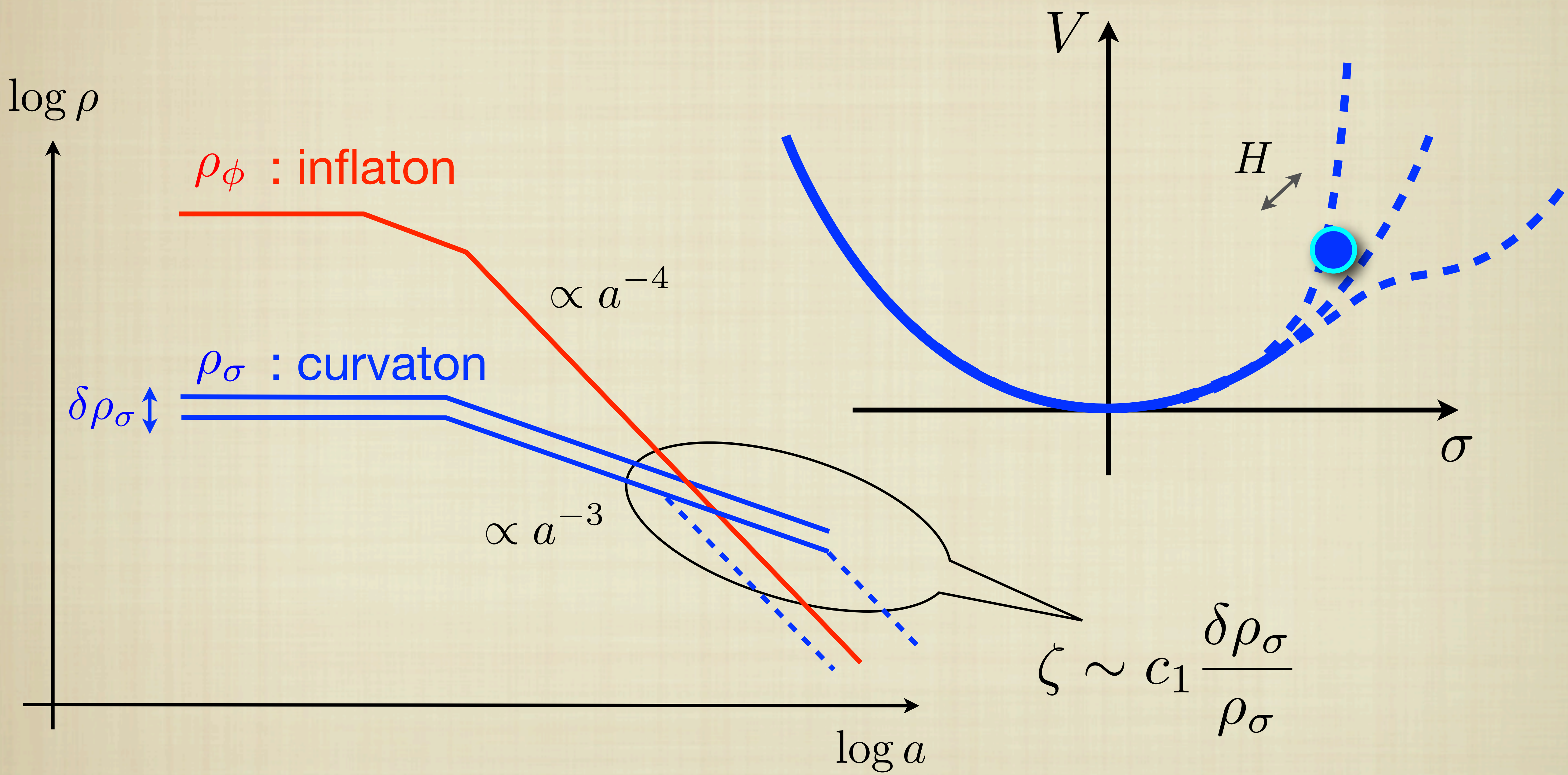
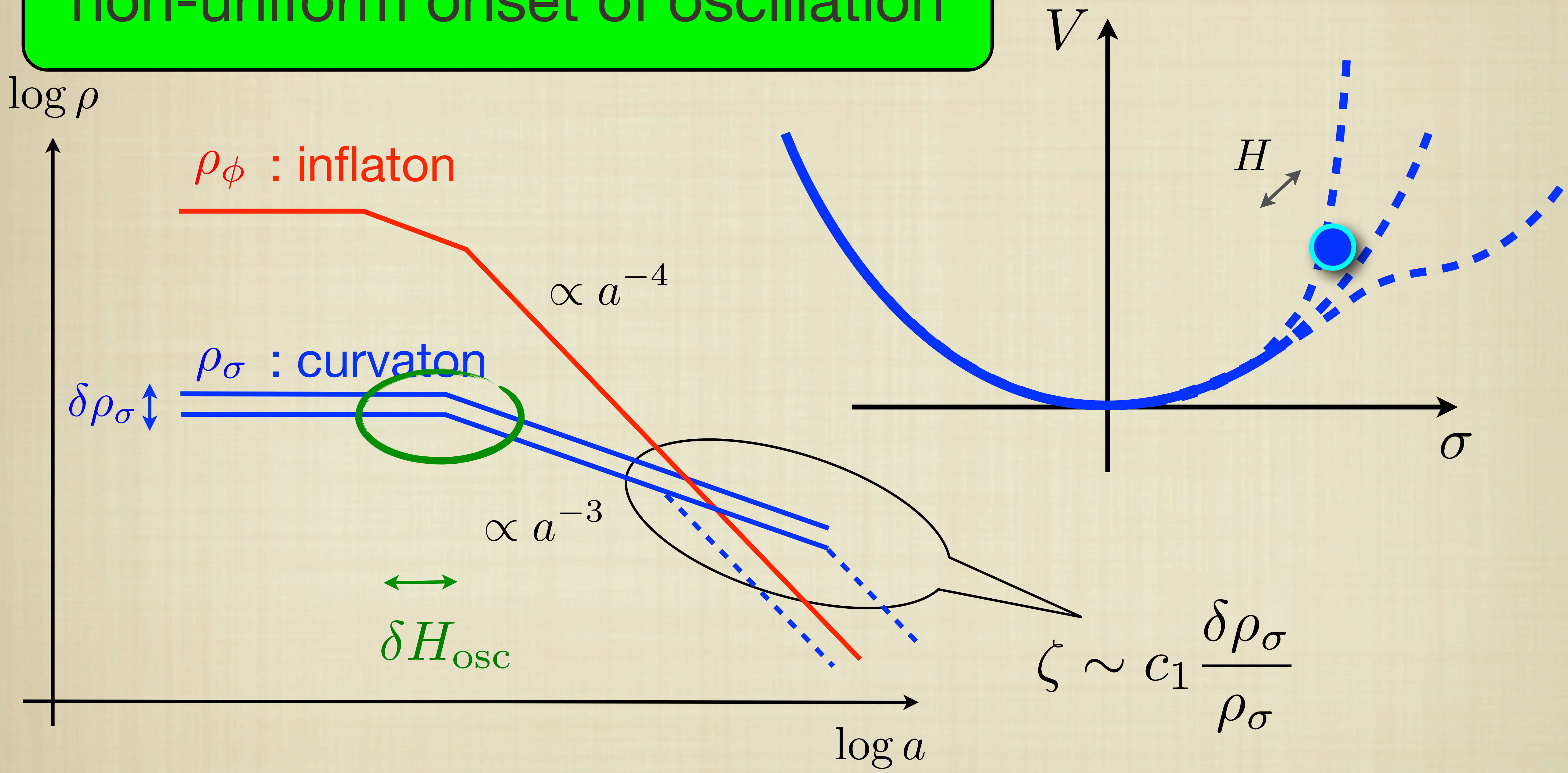


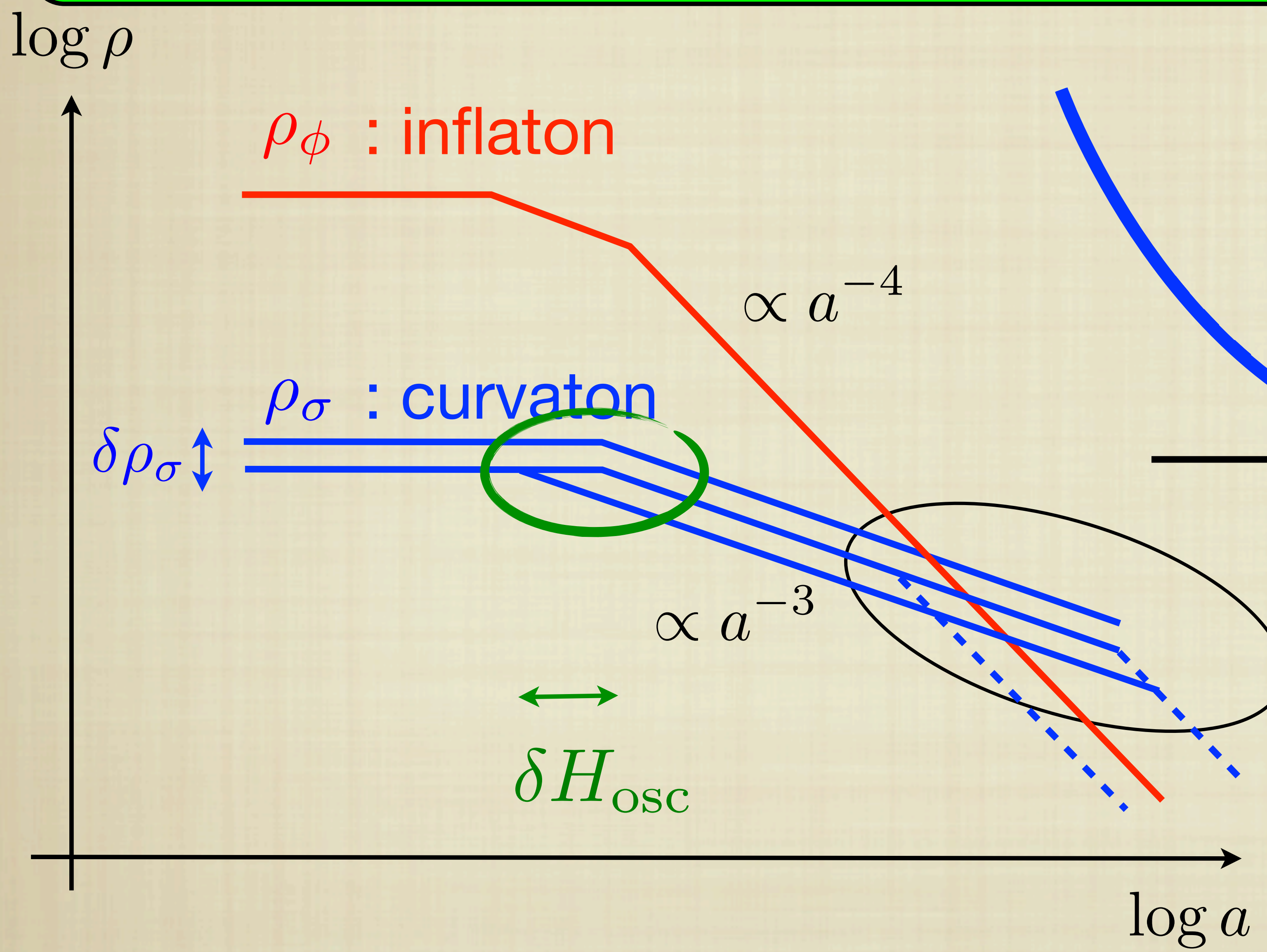
Curvatons with Non-Quadratic Potentials

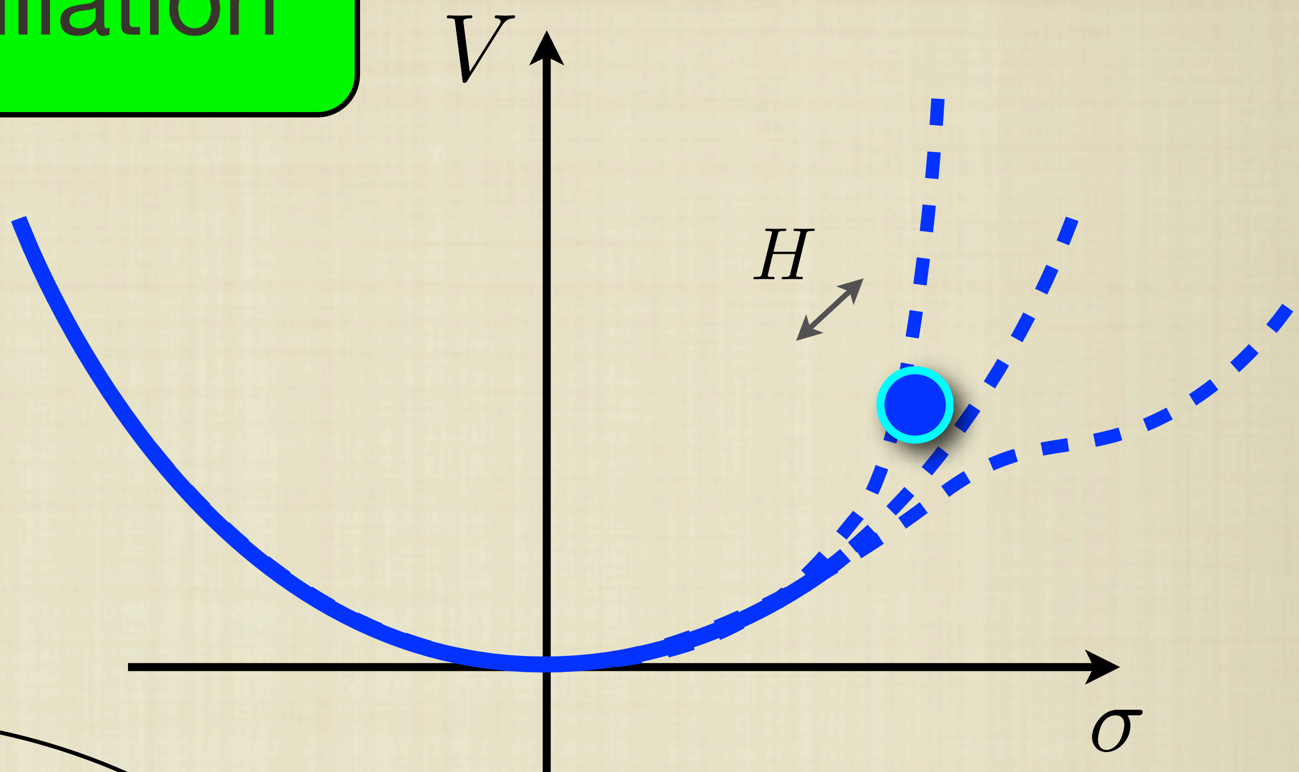
non-uniform onset of oscillation



Curvatons with Non-Quadratic Potentials

non-uniform onset of oscillation





$$\zeta \sim c_1 \frac{\delta\rho_\sigma}{\rho_\sigma} - c_2 \frac{\delta H_{\rm osc}}{H_{\rm osc}}$$

Additional contributions to the density perturbations!

Density Perturbations

$$\mathcal{P}_\zeta = \left(\frac{\partial \mathcal{N}}{\partial \sigma_*} \frac{H_*}{2\pi} \right)^2$$

$$\frac{\partial \mathcal{N}}{\partial \sigma_*} = \frac{r}{4+3r} (1 - X(\sigma_{\rm osc}))^{-1} \left\{ \frac{V'(\sigma_{\rm osc})}{V(\sigma_{\rm osc})} - \frac{3X(\sigma_{\rm osc})}{\sigma_{\rm osc}} \right\} \frac{V'(\sigma_{\rm osc})}{V'(\sigma_*)}$$

$r \equiv \frac{\rho_\sigma}{\rho_r}$ @ curvaton decay

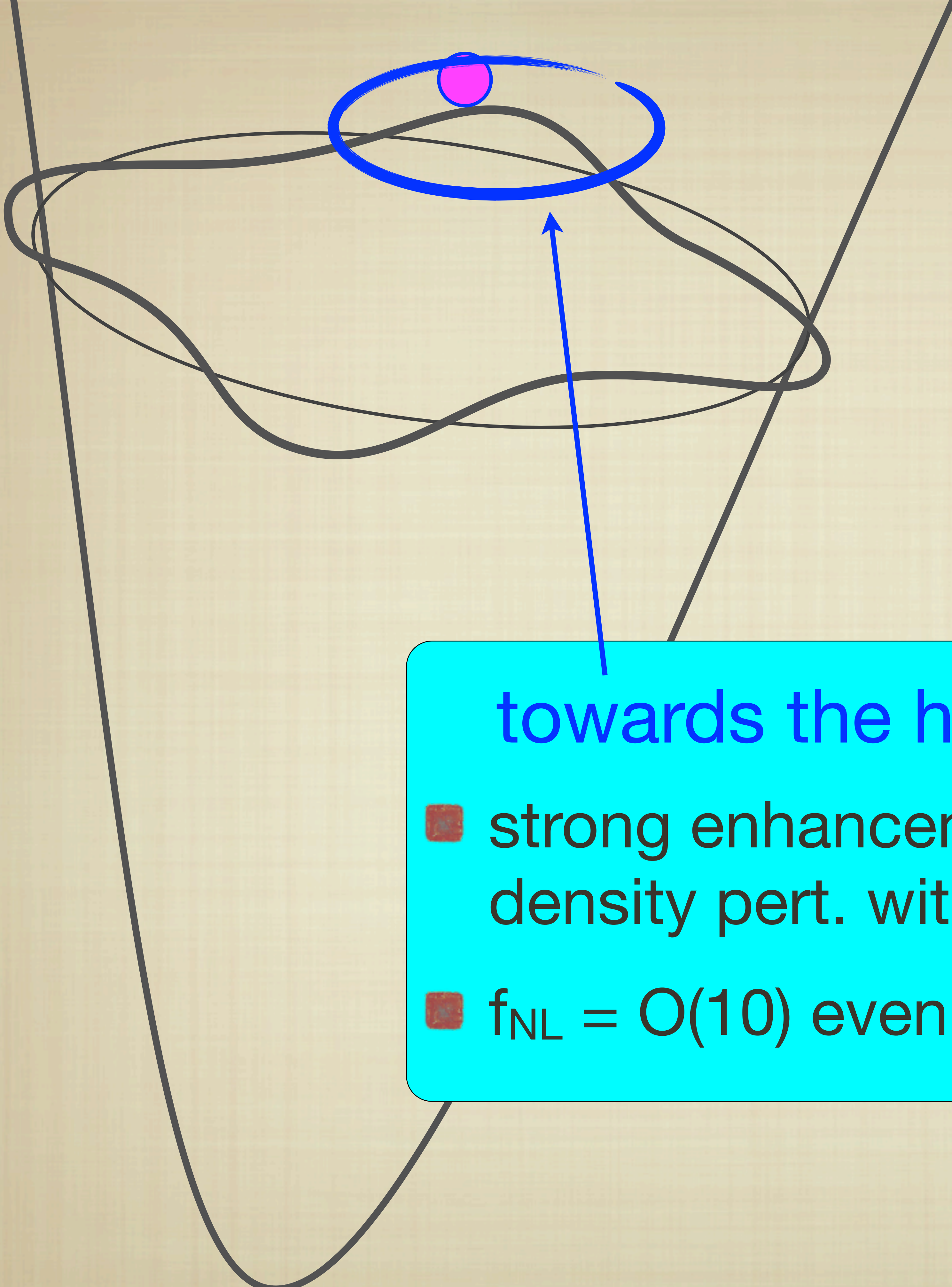
$*$: @ horizon exit

osc : @ onset of curvaton oscillation

$$X(\sigma_{\rm osc}) \equiv \frac{1}{2(c-3)} \left(\frac{\sigma_{\rm osc} V''(\sigma_{\rm osc})}{V'(\sigma_{\rm osc})} - 1 \right)$$

: effects due to non-uniform onset of oscillation

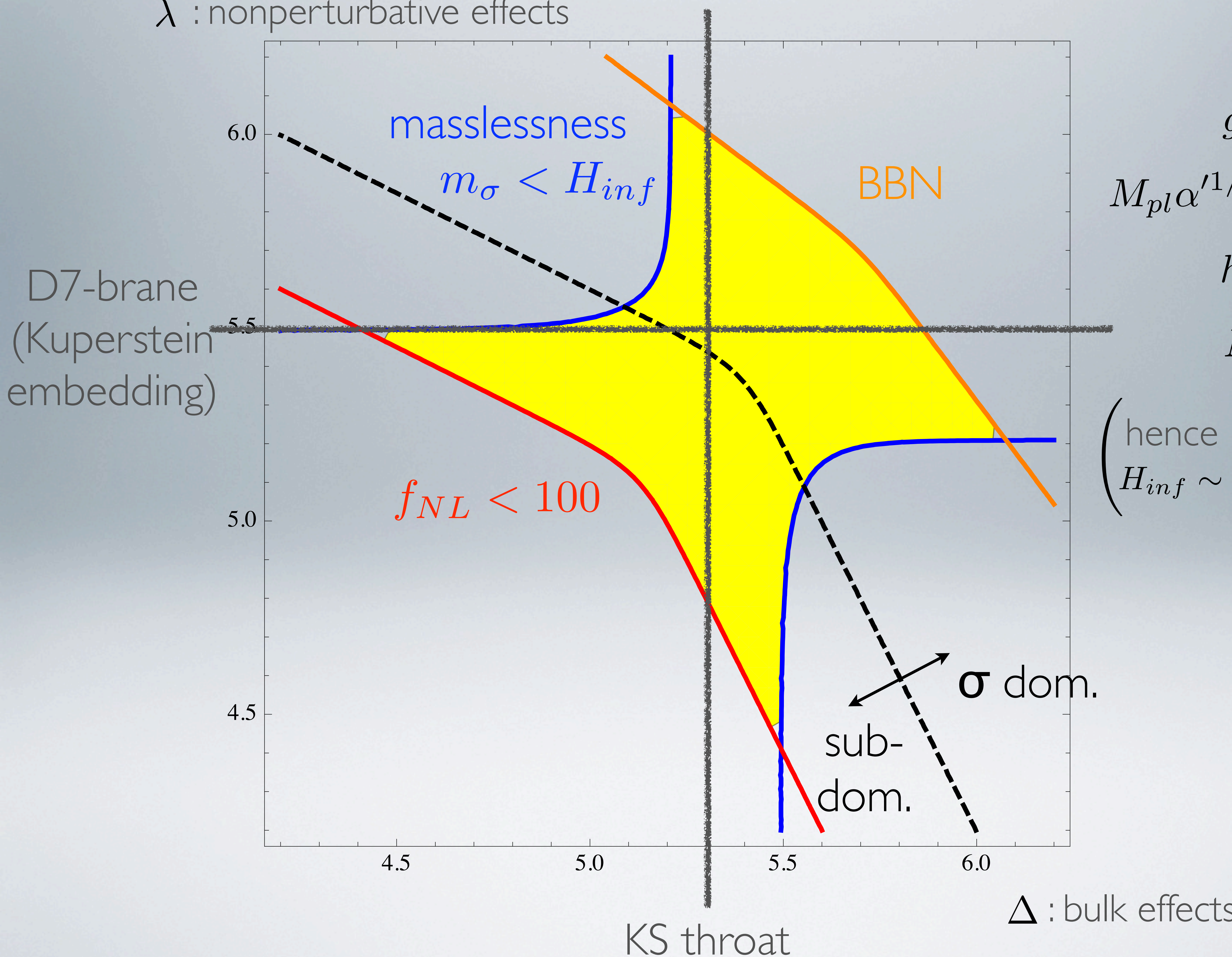
Non-Gaussianity f_{NL} also modified.



towards the hilltop:

- strong enhancement of linear-order density pert. with mild increase of f_{NL}
- $f_{NL} = O(10)$ even for a dominant curvaton

PARAMETER CONSTRAINTS



$g_s = 0.1$

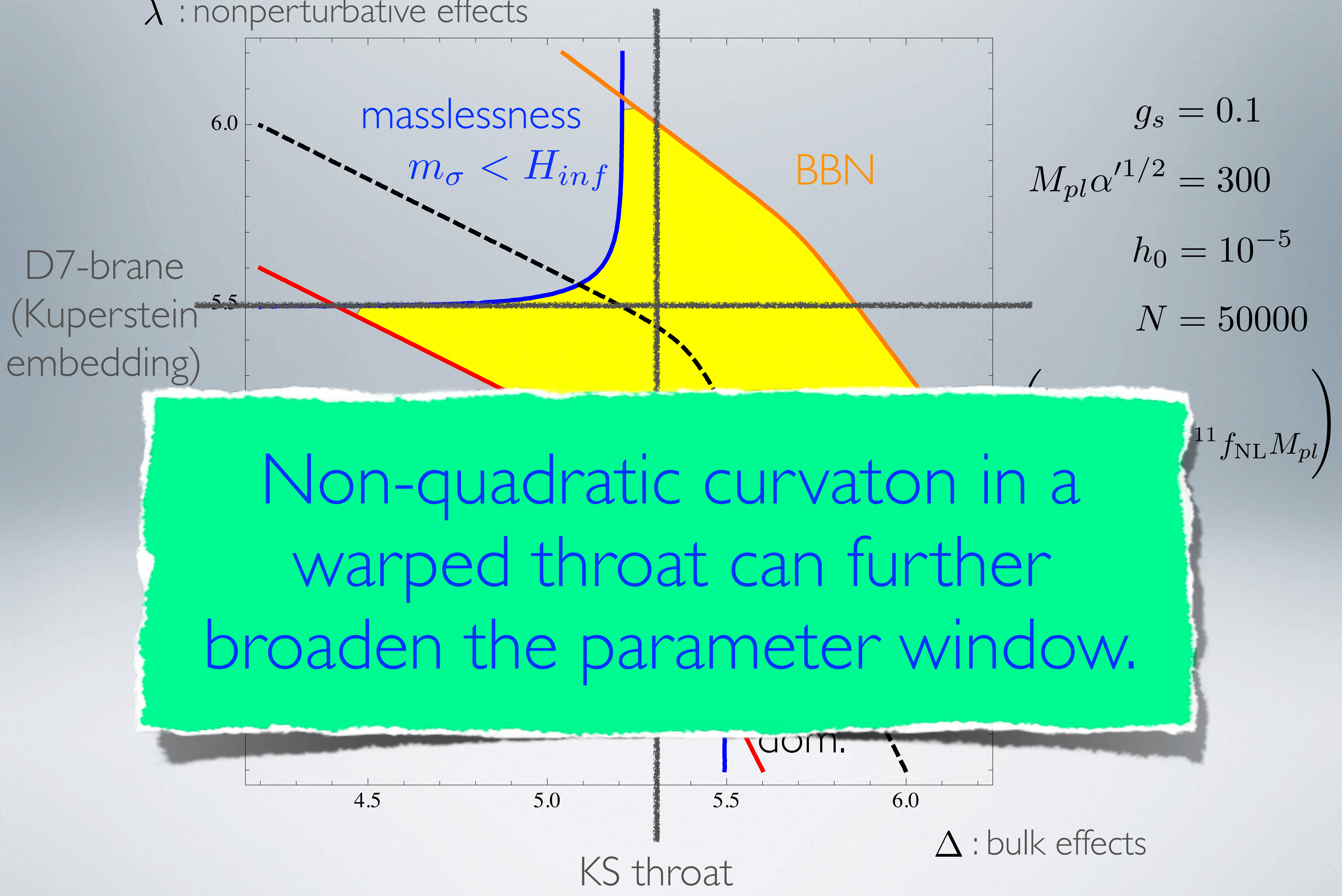
$M_{pl}\alpha'^{1/2} = 300$

$h_0 = 10^{-5}$

$N = 50000$

(hence $H_{inf} \sim 10^{-11} f_{\rm NL} M_{pl}$)

PARAMETER CONSTRAINTS



Non-quadratic curvaton in a warped throat can further broaden the parameter window.

Additional features can show up on the spectral tilt when the inflationary background is given by rapid-roll inflation.

$$\frac{\delta\rho}{\rho} \propto H_{\rm inf}$$

SPECTRAL TILT IN RAPID-ROLL INFLATION

The Hubble parameter in rapid-roll inflation does NOT possess a hierarchy amongst its higher-order time derivatives:

$$\left|\frac{1}{H}\frac{d}{dt}\ln H\right| \sim \left|\left(\frac{1}{H}\frac{d}{dt}\right)^2 \ln H\right| \sim \left|\left(\frac{1}{H}\frac{d}{dt}\right)^3 \ln H\right| \sim \cdots$$

(cf. SLOW-ROLL INFLATION:

$$\left|\frac{1}{H}\frac{d}{dt}\ln H\right| \gg \left|\left(\frac{1}{H}\frac{d}{dt}\right)^2 \ln H\right| \gg \left|\left(\frac{1}{H}\frac{d}{dt}\right)^3 \ln H\right| \gg \cdots$$

)

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⟶ The resulting curvature perturbation spectrum can have large running (and its running, and so on).

$$\frac{d}{d\ln k}\ln\left(\frac{\delta\rho}{\rho}\right), \quad \frac{d^2}{d(\ln k)^2}\ln\left(\frac{\delta\rho}{\rho}\right), \quad \frac{d^3}{d(\ln k)^3}\ln\left(\frac{\delta\rho}{\rho}\right), \quad \cdots$$

CONSTRAINTS ON RAPID-ROLL INFLATION

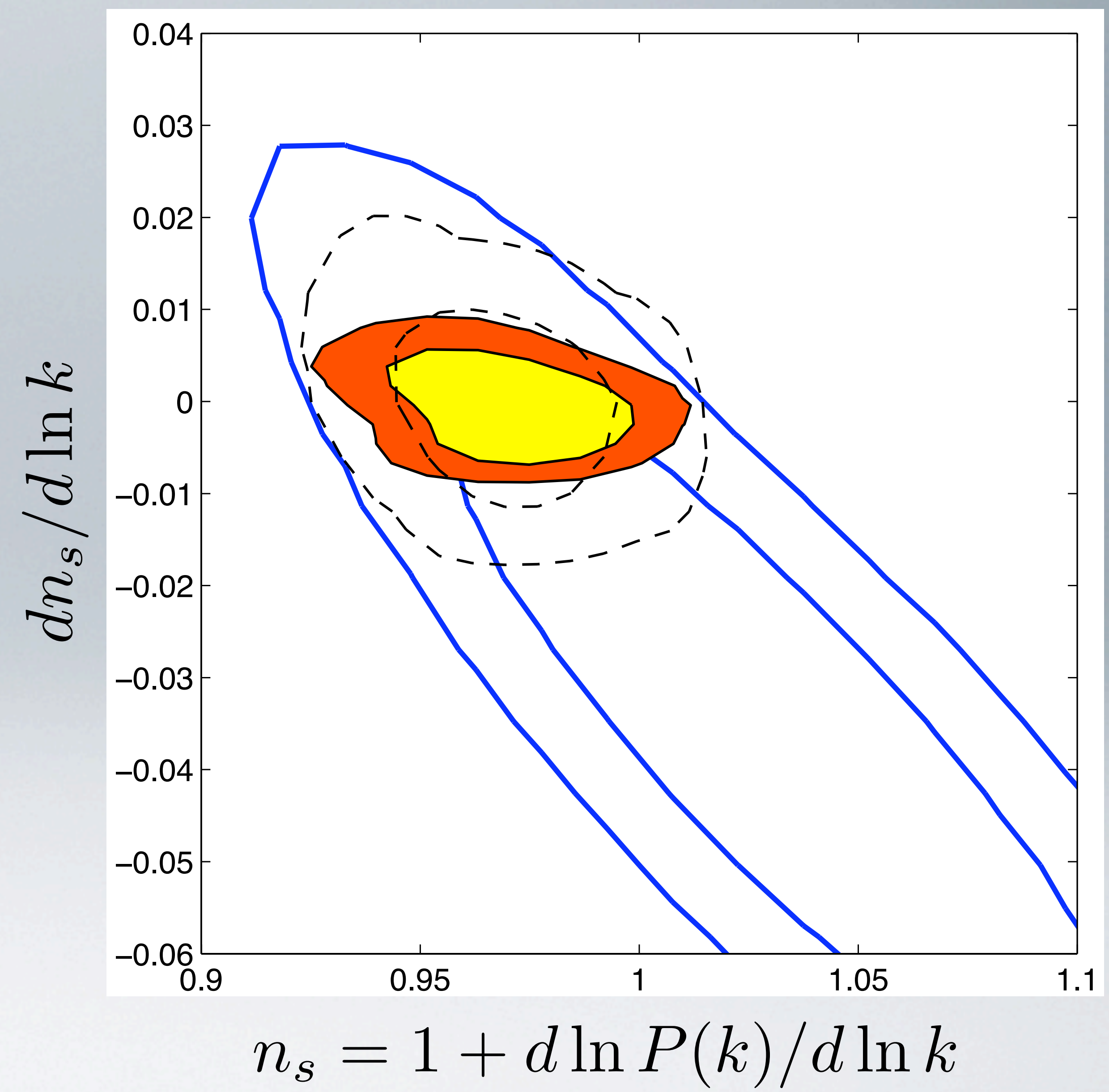
TK, Mukohyama, Powell '09

When $P(k) \propto H^2$,

$$P(k) = \frac{P(k_0)}{1+A}\left[1 + A\left(\frac{k}{k_0}\right)^{-B}\right]$$

$$n_s(k_0) - 1 = -\frac{AB}{1+A}$$

$$\frac{dn_s}{d\ln k}(k_0) = \frac{AB^2}{(1+A)^2}$$



Tightly constrained by CMB & LSS data.

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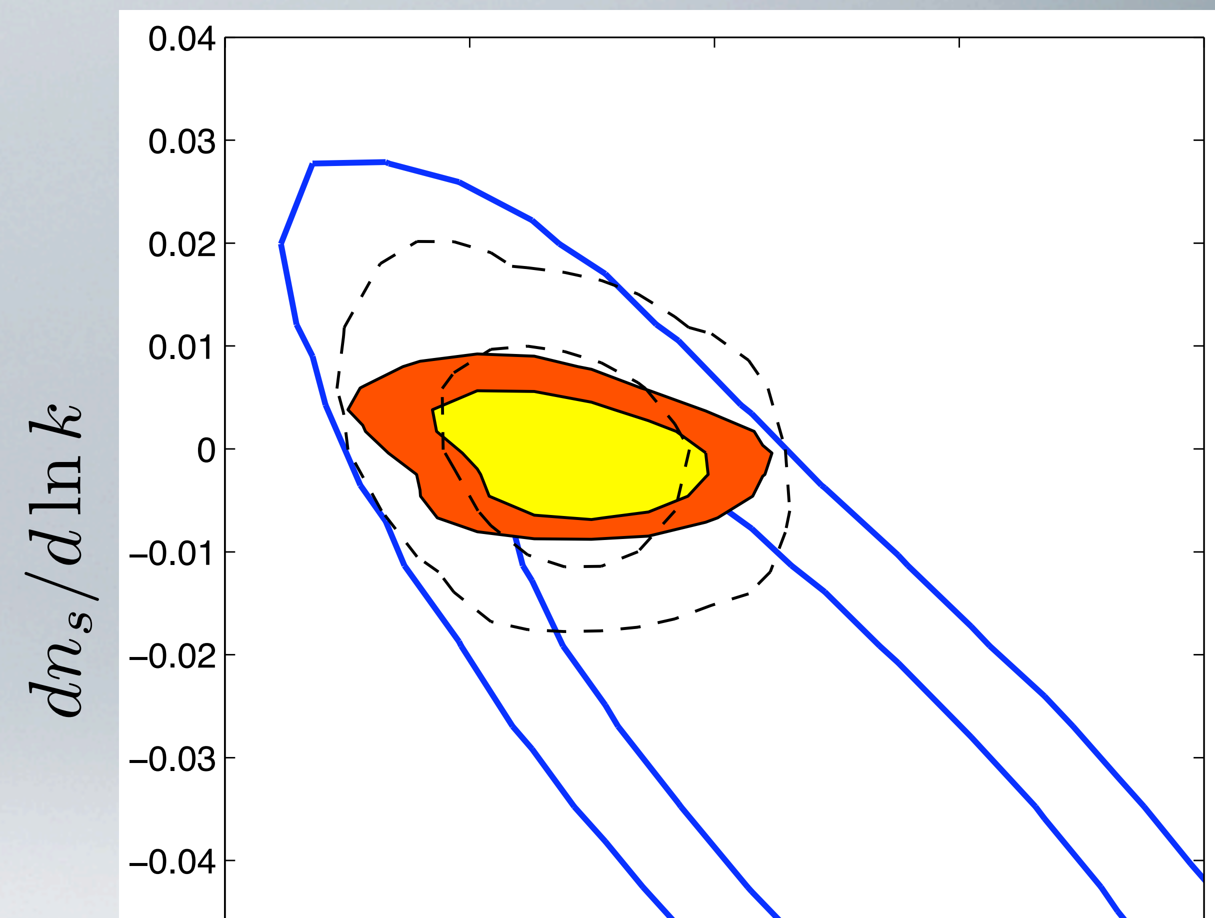
$$\frac{dn_s}{}(k_0) \quad AB^2$$



distinguishing features especially at small scales

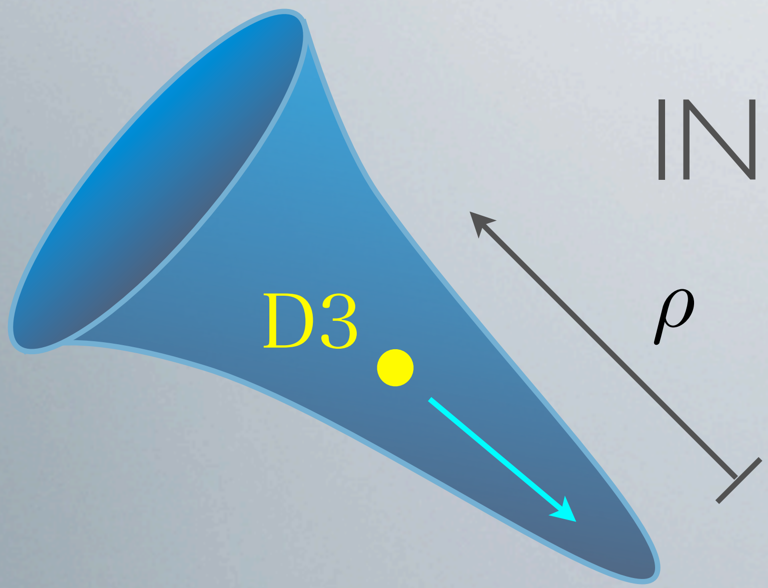
CMB & LSS data.

SUMMARY

- Slow-roll and relativistic limits of D-brane inflation suffer from the η-problem and geometrical constraints, respectively.
- Rapid-rolling D-branes exhibit stable inflationary attractors, as well as provide sufficient inflationary expansions.
- Rapid-roll inflationary backgrounds give rise to density perturbation spectra with running spectral index.
- Angular oscillations of D-branes at throat tips can source the primordial density perturbations through the curvaton mechanism.
- Various roles in inflationary cosmology can be shared by the many degrees of freedom that show up in string theory.

BACKUP SLIDES

INFLATON KINETIC TERM



throat geometry

$$ds^2 = h(\rho)^2 g^{(4)}_{\mu\nu} dx^\mu dx^\nu + h(\rho)^{-2}(d\rho^2 + \rho^2 d\Sigma^2_{X_5})$$

DBI action

$$\begin{aligned} S_{\rm DBI} &= -T_3 \int d^4x \sqrt{-\det(G_{\mu\nu})} \\ &= -T_3 \int d^4x \sqrt{-g^{(4)}} h^4 \sqrt{1 + h^{-4} g^{(4)\alpha\beta}\partial_\alpha\rho\partial_\beta\rho} \\ &\simeq -T_3 \int d^4x \sqrt{-g^{(4)}} \left(h^4 + \frac{1}{2} g^{(4)\alpha\beta}\partial_\alpha\rho\partial_\beta\rho\right) \\ &= \int d^4x \sqrt{-g^{(4)}} \left(-T_3 h^4 - \frac{1}{2} g^{(4)\alpha\beta}\partial_\alpha\phi\partial_\beta\phi\right) \end{aligned}$$

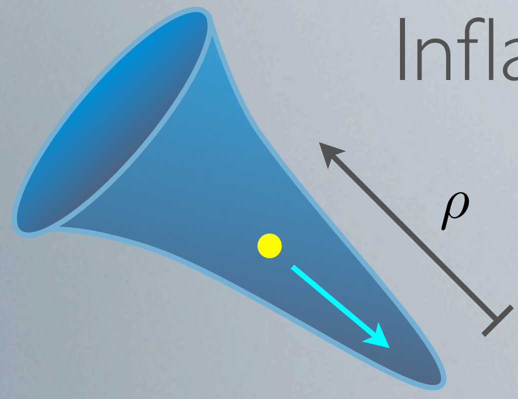
inflaton

$$d\phi = \sqrt{T_3}\, d\rho$$

ALTERNATIVE APPROACH: DBI INFLATION

Silverstein, Tong '04

Inflation driven by D-branes moving with relativistic velocities.



$$ds^2 = h(\rho)^2 g^{(4)}_{\mu\nu} dx^\mu dx^\nu + h(\rho)^{-2}(d\rho^2 + \rho^2 d\Sigma^2_{X_5})$$

$$\begin{aligned} S_{\mathrm{DBI}} &= -T_3 \int d^4x \sqrt{-\det(G_{\mu\nu})} \\ &= -T_3 \int d^4x \sqrt{-g^{(4)}} h(\rho)^4 \sqrt{1 - \frac{\dot{\rho}^2}{h(\rho)^4}} \end{aligned}$$

The warping of the throat enforces the D-brane to slow down, regardless of the potential.

$$\frac{\dot{\rho}^2}{h(\rho)^4} < 1$$

DBI INFLATION

$$\frac{\mathcal{L}}{\sqrt{-g^{(4)}}} = -T(\phi)\sqrt{1 - \frac{\dot{\phi}^2}{T(\phi)}} + T(\phi) - V(\phi)$$

$$T(\phi) \equiv T_3 h(\phi)^4$$

- inflation can occur for some $T(\phi)$, $V(\phi)$

  → a new stringy inflation mechanism

- a remedy to the η-problem (no need for slow-roll)

- produces large non-Gaussianity

  → can be tested in future experiments

NEW DIFFICULTIES: GEOMETRICAL CONSTRAINTS ON FIELD RANGE

Baumann, McAllister '06 Lidsey, Huston '07

- DBI inflation generates (too) large non-Gaussianity. In order to suppress non-Gaussianity down to a level consistent with WMAP data, the inflaton need to travel at least some field range $\Delta\phi$.

- On the other hand, the inflaton field range is geometrically restricted by the throat length, which is restricted by the Planck mass.

$$M_p^2 = \frac{2V_6}{(2\pi)^7 g_s^2 \alpha'^4} > \frac{2\mathrm{Vol}(X_5)(\Delta\phi)^6}{(2\pi)^7 g_s^2 \alpha'^4 h_*^4 T_3^3}$$

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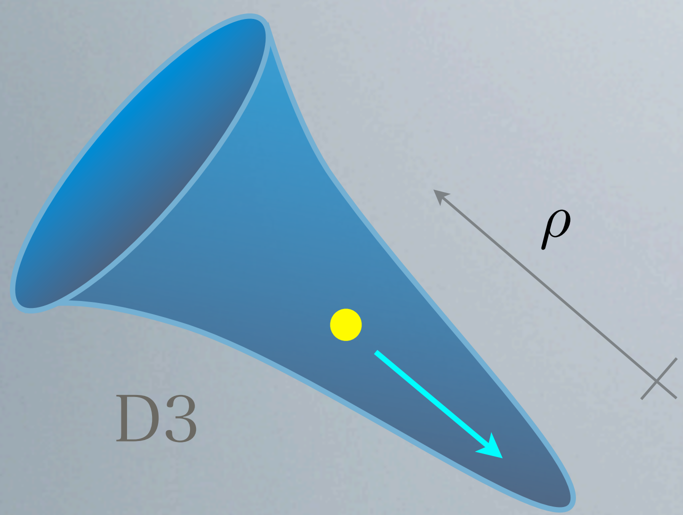
CONTRADICTION!

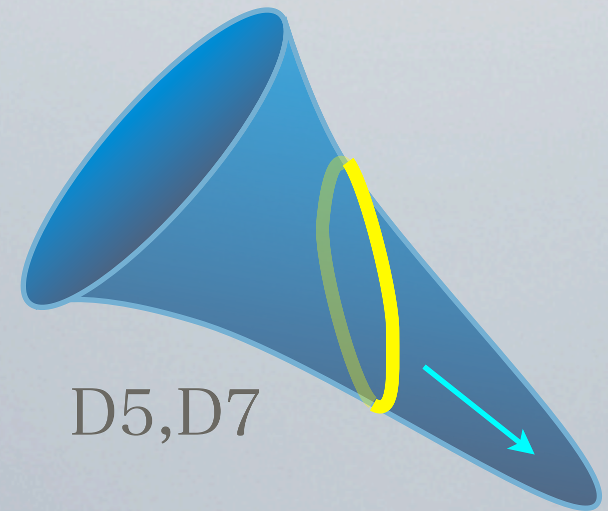
Throat too short for a relativistically moving D3-brane to drive sufficient inflation.

WRAPPED BRANES

TK, Mukohyama, Kinoshita '07

Becker, Leblond, Shandera '07





D3-brane

$$d\phi \equiv T_3^{1/2}\, d\rho$$

D(3+2n)-brane

$$d\phi \equiv T_{3+2n}^{1/2} \left\{ \int d^{2n}\xi \sqrt{\det(G_{kl} - B_{kl})} \right\}^{1/2} d\rho$$

$\sim$volume of the wrapped cycle

effective field range increased for wrapped branes

→ Geometrical constraint for DBI inflation can be solved!

BACKGROUND CHARGE

A long throat is sufficient in any case.

→ Large flux number required.

tadpole-cancellation condition $$N = \frac{\chi}{24}$$

χ : Euler number of a Calabi-Yau fourfold

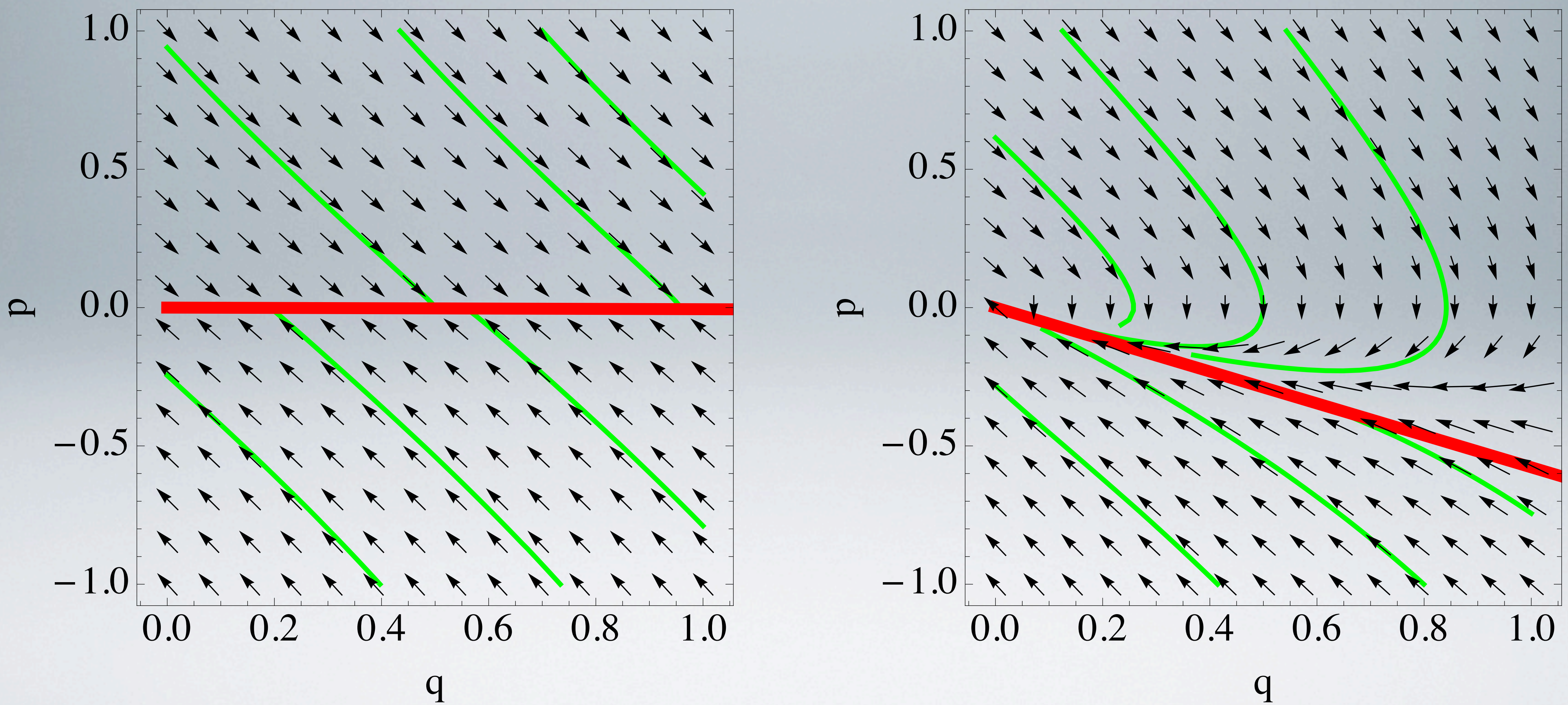
The large flux number required exceeds the largest known Euler number for a CY 4-fold $\chi = 1820448$

Klemm, Lian, Roan, Yau 1998

SLOW-ROLL AND RAPID-ROLL INFLATIONS

$$V(\phi) = V_0 \left(1 + \mu \frac{\phi^2}{M_p^2}\right)$$

$$p = \frac{\dot{\phi}}{V_0^{1/2}} \qquad q = \frac{\phi}{M_p}$$



$\mu = 1/200$ $\mu = 1/3$

COSMOLOGICAL CONSTRAINTS ON RAPID-ROLL