INFLATION FROM WRAPPED BRANES

Sarah Shandera
Columbia University

Based on: M. Becker, L. Leblond, S. S. (arXiv:0709:1170); M. LoVerde, A. Miller, S.S., L. Verde (arXiv:0711.4126): R. Bean, S.S., H. Tye, J. Xu (hep-th/0702107)

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Can string theory suggest
cosmologically interesting ideas?

\- or -

Is there a useful discriminating feature
of inflation models?

\- or -

Could there be *distinctive* signatures
of string theory in inflation?

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GOALS:

I. Why care? (DBI as a pheno model: non-Gaussianity, tensor/scalar ratio)

II. The wrapped brane inflaton (Relating observables to microphysics and extending the field range)

III. Matching observations with a wrapped brane

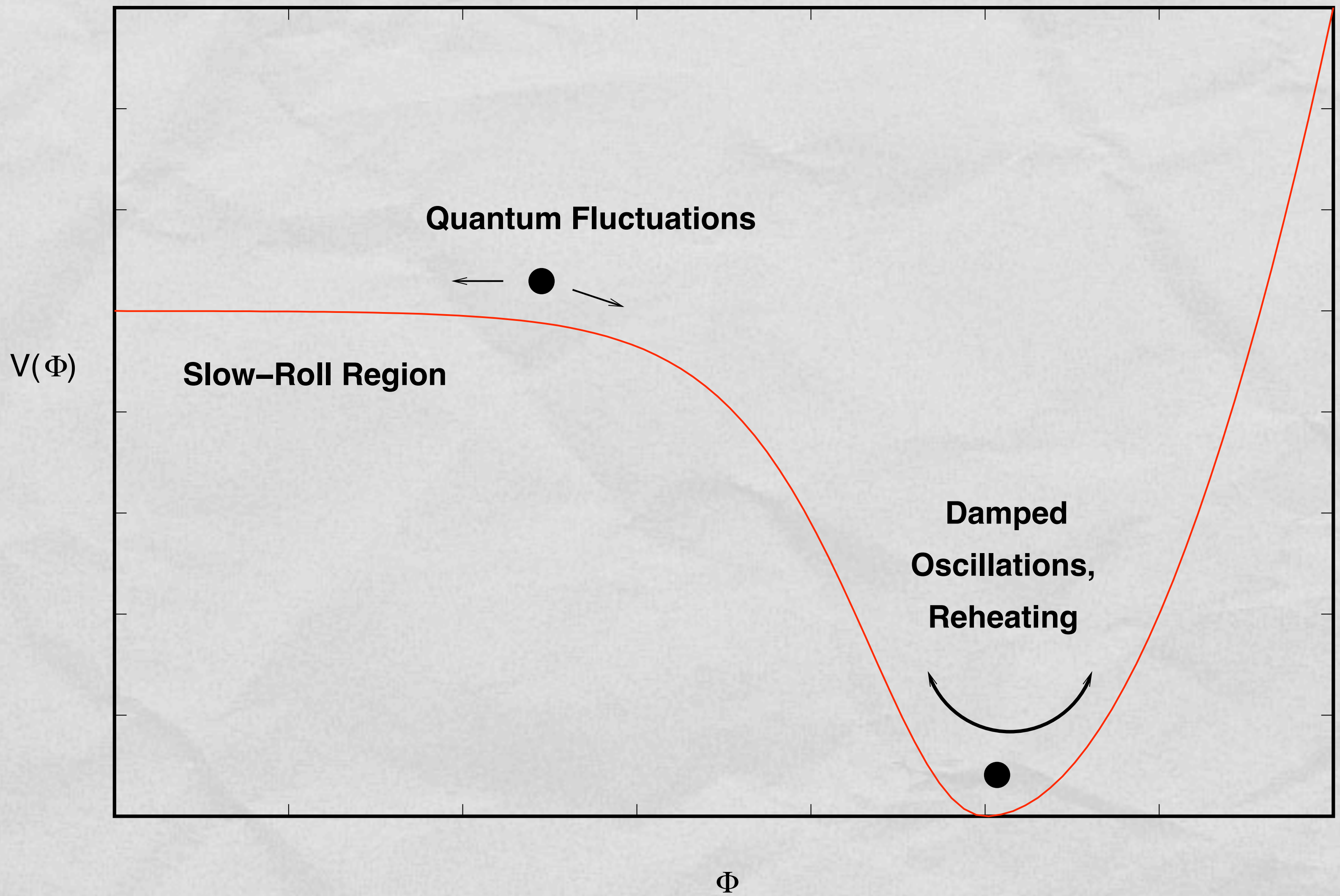
IV. Consistency?

I. WHY DBI?

WHAT DO WE WANT FROM INFLATION?

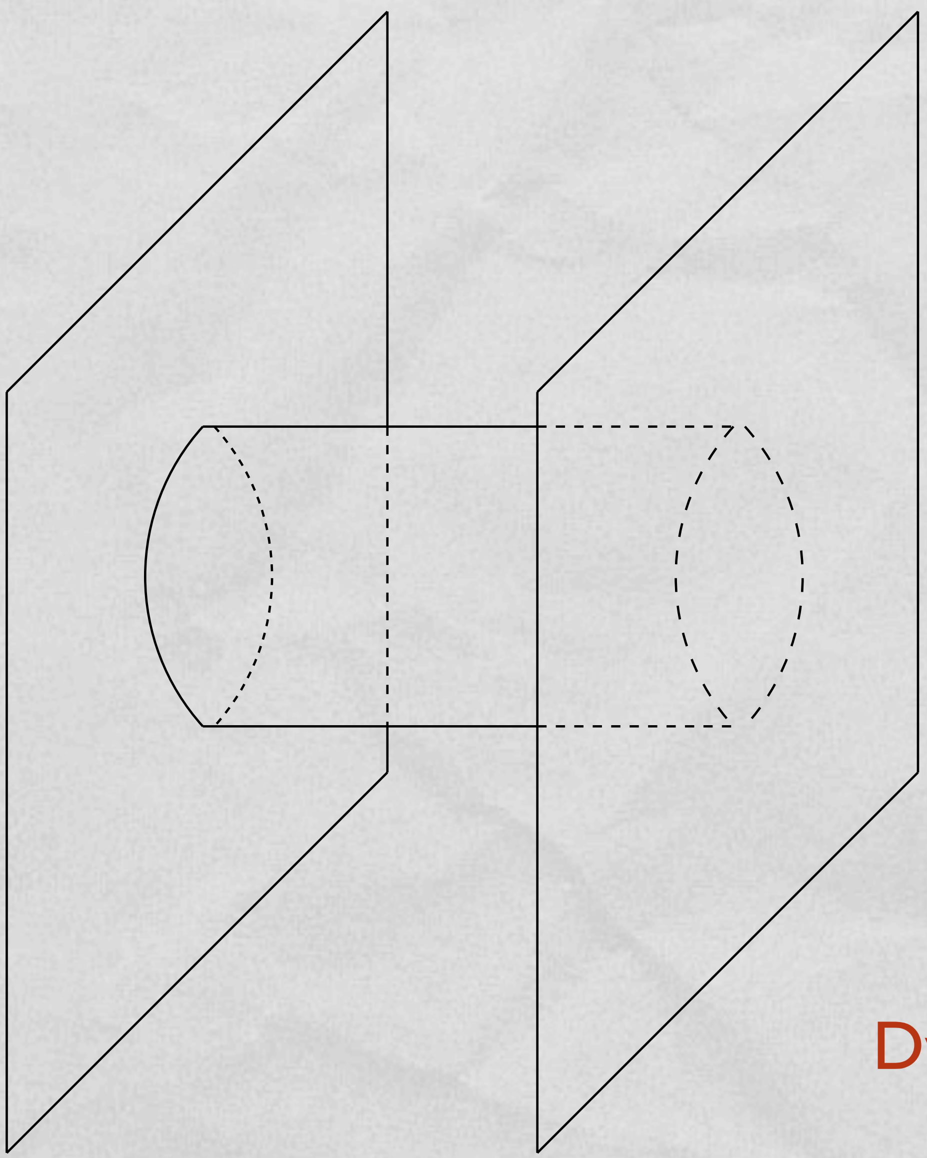
- Enough e-folds (flat potential?)
- Spectrum of primordial fluctuations (amplitude, scale-dependence, correlation functions)
- Other observables?

THE (FIELD THEORY) PICTURE



(ORIGINAL) BRANE INFLATION

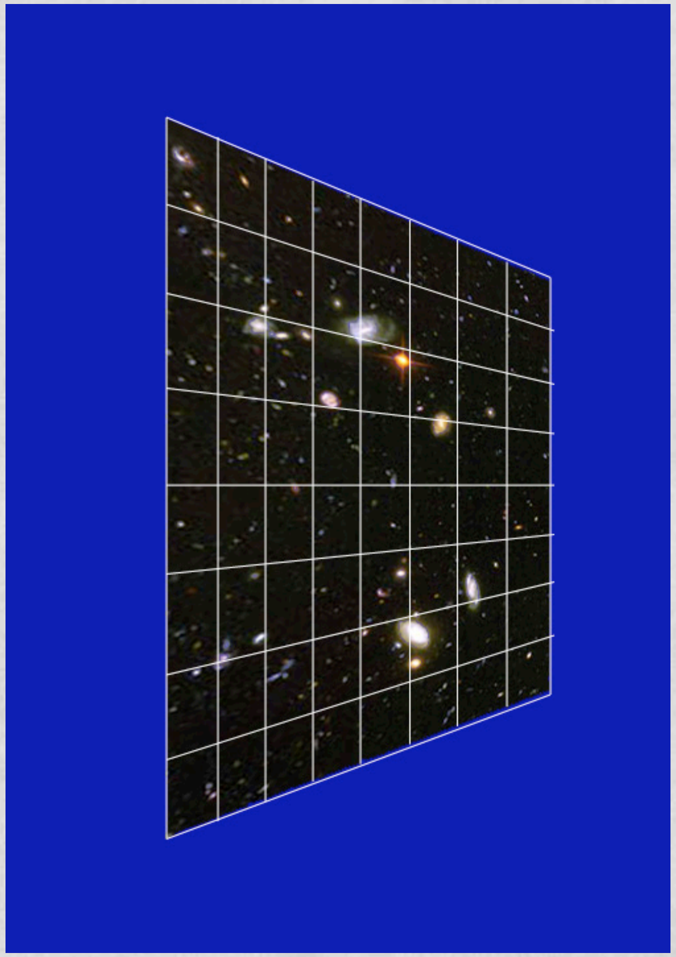
Inflaton ~ Brane separation



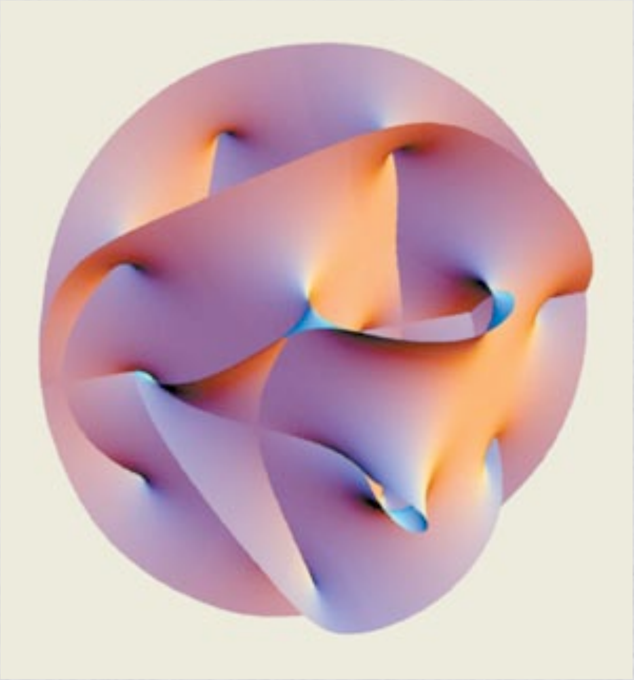
- Brane/anti-brane potential from closed string exchange
- Reheating and cosmic strings from brane annihilation

Dvali and Tye; Garcia-Bellido, Rabadan, Zamora; Burgess et al.

THE BIG PICTURE...



X

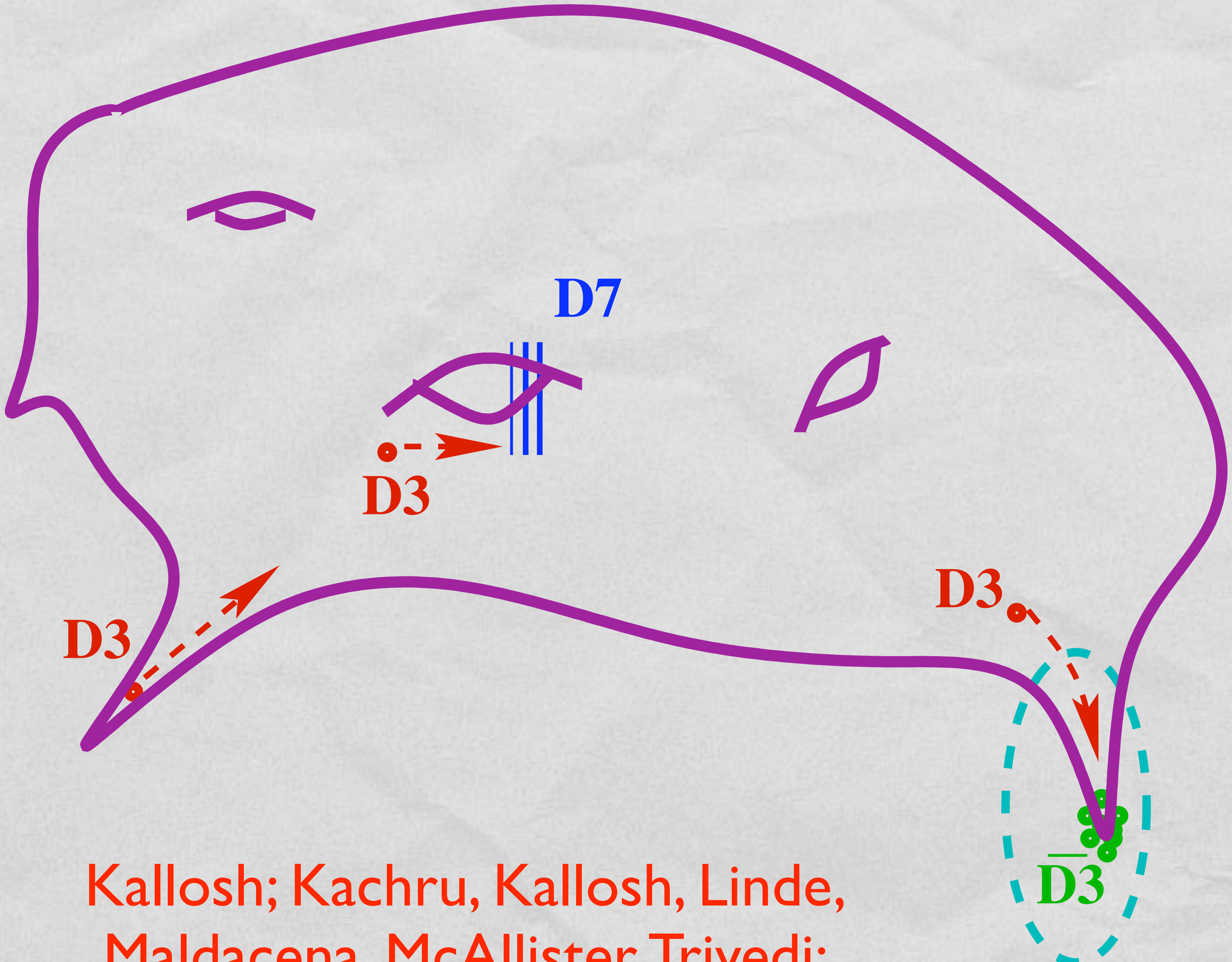


3 + 1 dimensions (us)

X

6 compact dimensions

CARTOON GUIDE TO BRANE INFLATION (IN IIB)



Kallosh; Kachru, Kallosh, Linde, Maldacena, McAllister, Trivedi; X. Chen; Dasgupta, Herdeiro, Hirano,

Features:

- Mobile D3s
- KS throats
- anti-D3s in throats
- Wrapped D7s

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WHY USE THE THROAT?

- Warping helps flatten the brane/anti-brane potential
- Metric is known
- Details of the bulk can be largely ignored
- Warping gives interesting features

THE DBI ACTION

- Dynamics (Silverstein, Tong, Alishahiha)

$$S = -\int d^4x\, a(t)^3 f(\phi)^{-1}\sqrt{1 - f(\phi)\dot{\phi}^2} + V(\phi)$$

- Geometry (Klebanov, Strassler)

$$ds^2 = h^{-1/2}(r)\eta_{\mu\nu}dx^\mu dx^\nu + h^{1/2}(r)(dr^2 + r^2 ds^2_{T^{1,1}})$$

$$f(\phi) = S^{-1}h(\phi) = T_3^{-1}h(\phi)$$

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Assume quadratic

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normalization

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normalization

D3 brane

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DBI FEATURES

- From the DBI action, there is an effective speed limit set by the warping:

$$\boxed{\begin{gathered}\dot{\phi}^2 < f(\phi)^{-1} = Sh(\phi)^{-1} \\ h \approx \frac{R^4}{r^4} = \frac{R^4 T_3^2}{\phi^4}\end{gathered}}$$

- Lorentz factor:

$$\boxed{\gamma(\phi) = \frac{1}{\sqrt{1 - f(\phi)\dot{\phi}^2}}}$$

FRAMEWORK FOR CALCULATING OBSERVABLES

* modified Hubble slow roll parameters

$$\varepsilon_D \equiv \frac{2M_p^2}{\gamma}\left(\frac{H'(\phi)}{H(\phi)}\right)^2$$

$$\eta_D \equiv \frac{2M_p^2}{\gamma}\left(\frac{H''(\phi)}{H(\phi)}\right)$$

$$\kappa_D \equiv \frac{2M_p^2}{\gamma}\left(\frac{H'}{H}\frac{\gamma'}{\gamma}\right)$$

$$\frac{\ddot{a}}{a} = H^2(1-\varepsilon_D)$$

$$\dot{\phi} = -\frac{2M_p^2 H'}{\gamma}$$

SOME OBSERVABLES

- scalar index

$$\boxed{n_s - 1 \approx -4\varepsilon + 2\eta - 2\kappa}$$

- tensor index

$$\boxed{n_t = \frac{-2\varepsilon}{1-\varepsilon-\kappa}}$$

- tensor/scalar ratio

$$\boxed{r = \frac{16\varepsilon}{\gamma}}$$

$$n_t = -\frac{r}{8}\left(\frac{\gamma}{1-\varepsilon-\kappa}\right)$$

RELATION BETWEEN DEFINITIONS

$$\varepsilon_D = -\frac{\dot{H}}{H^2} \to \varepsilon_{SR}$$

$$\eta_D \to \eta_{SR} - \varepsilon_{SR}$$

$$\kappa_D = \frac{\dot{c}_s}{c_s H} = s$$

$$\tilde{\eta} = \frac{\dot{\varepsilon}}{\varepsilon H} = 2\varepsilon_D - 2\eta_D + \kappa$$

CONSTRAINTS

- 55 e-folds in the throat
- Inflation ends when brane separation is small (or expansion parameters become > 1)
- Throat is smaller than bulk (volume bound)
- COBE normalization matched

*explore non-Gaussianity, tensor-scalar ratio, etc.

NON-GAUSSIANITY

NON-GAUSSIANITY

- Higher order correlations have more information!
  - Size (Slow-roll or not? DBI: "f_{NL}" ~ γ^{-2})
  - Sign (More or less structure? DBI has less)
  - Shape
  - Scale-dependence

(What kind of physics?)

THE LOCAL MODEL

- A simple ansatz:

$$\boxed{\zeta(x) = \zeta_g(x) + f_{NL}\left[\zeta_g^2(x) - \langle \zeta_g^2(x) \rangle\right]}$$

- Then in Fourier space:

$$\begin{aligned} \langle \zeta_{NG}(k_1)\zeta_{NG}(k_2)\rangle &= \langle \zeta_G(k_1)\zeta_G(k_2)\rangle + O(f_{NL}^2) \\ &\approx (2\pi)^3\delta(k_1+k_2)\frac{2\pi^2\mathcal{P}^{\zeta_G}(k)}{k^3} \end{aligned}$$

$$\begin{aligned} \langle \zeta_{NG}(k_1)\zeta_{NG}(k_2)\zeta_{NG}(k_3)\rangle = f_{NL}\frac{(2\pi)^7}{2}\delta^3(k_1+k_2+k_3)\left(\frac{\mathcal{P}^{\zeta_G}(k_1)\mathcal{P}^{\zeta_G}(k_2)}{k_1^3k_2^3} + \text{perm.}\right) \\ + O(f_{NL}^3) \end{aligned}$$

HOW NON-GAUSSIAN? (SMOOTH MODELS)

- Slow-roll (squeezed limit): $f_{NL} \sim -(n_s - 1)$ (Maldacena)
- EFT suggests adding higher derivative terms gives $f_{NL} \sim 1$
  (Creminelli; 'equilateral model')
- DBI: Observationally limited (saturates CMB bound)
  (Silverstein, Tong)

✱ Surprisingly large: the square root sums an infinite number of powers of the derivative; similar effect found in tachyon actions (Barnaby, Cline)

DBI NON-GAUSSIANITY

- DBI is a subset of small sound speed models,

$$\boxed{c_s^2 = \frac{\partial p}{\partial \dot{\phi}} \Big/ \frac{\partial \rho}{\partial \dot{\phi}} = \frac{1}{\gamma^2}}$$

(Seery, Lidsey; Chen, Huang, Kachru, Shiu)

- DBI 3-point is largest in the equilateral limit (local is largest in squeezed limit)

- Current CMB bound:

$$f_{NL}^{eff}(k_1 = k_2 = k_3)$$
$$-256 < f_{NL}^{eq} < 332$$

(Creminelli et al.)

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SCALE-DEPENDENCE

For DBI: $c_s(k) = c_s^{pivot}\left(\frac{k}{k_{pivot}}\right)^{\kappa}$

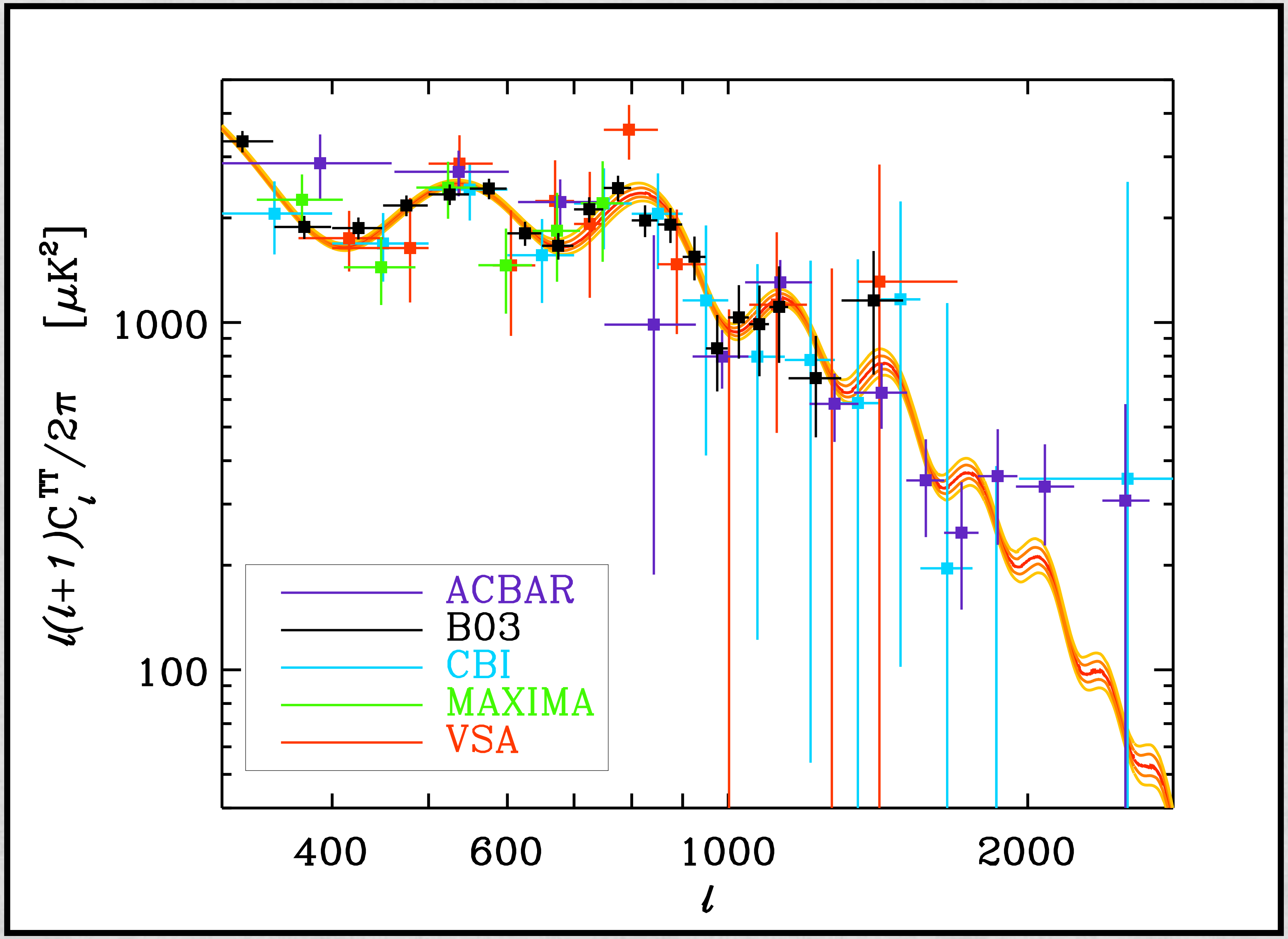
- Defining an effective f_{NL} from the equilateral limit:

$$f_{NL}^{c} = -\frac{35}{108}3^{2(n_s-1)}\left(\frac{1}{c_s^2}-1\right)$$

- We can use the DBI case to suggest an ansatz, with κ a free parameter

$$f_{NL}^{eq}(k) = f_{NL,\,pivot}^{eq}\left(\frac{k}{k_{pivot}}\right)^{-2\kappa}$$

THE CMB IS ONLY THE BEGINNING...



(WMAP 3, Spergel et al.)

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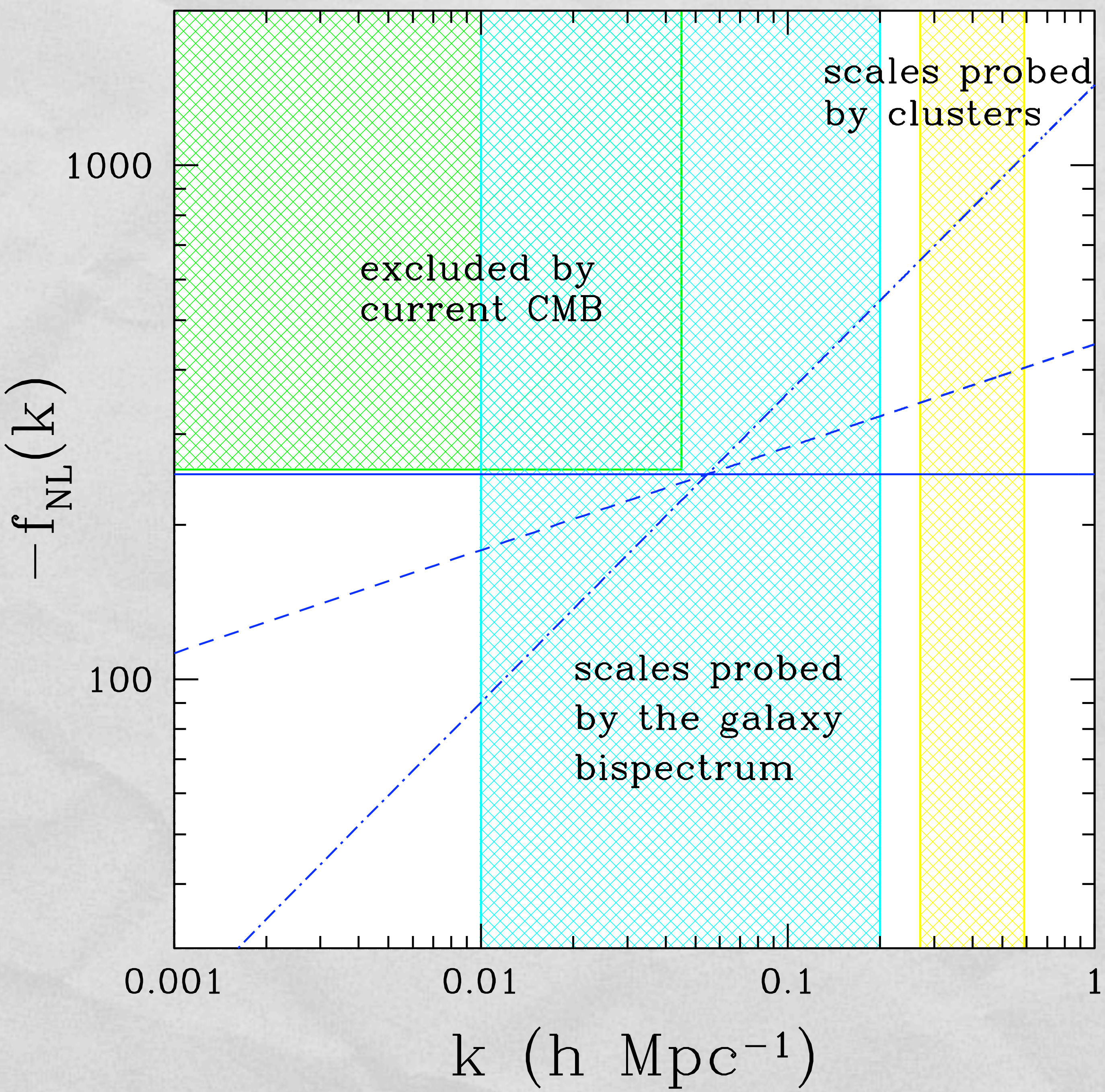
RELEVANT OBSERVATIONS



$\kappa = -0.3$

$\kappa = -0.1$

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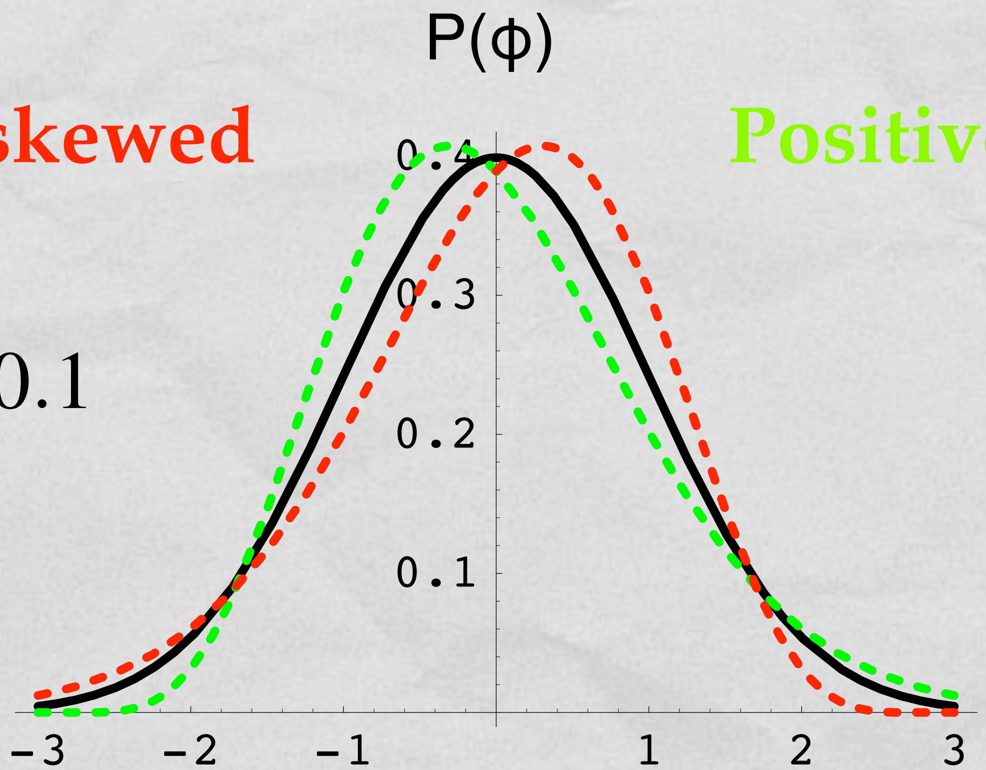
PHYSICALLY (LOCAL MODEL)...

Negatively skewed

Positively skewed



$$f_{NL} = \pm 0.1$$

$$\sigma^2 = 1$$

$$k^2\zeta = 4\pi G a^2 \delta\rho.$$

$+f_{NL}$=more clusters

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OBSERVABLES

- CMB
- Cluster number counts
- Galaxy bispectrum

Analysis on the next slide from
arXiv:0711.4126,
M. LoVerde, A. Miller, L. Verde, S.S.

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SO HOW WELL CAN WE DO?

Info.	Fiducial Model	σ_{Ω_m}	σ_h	σ_{σ_8}	$\sigma_{f_{NL}}$	σ_κ
WMAP		0.0264	0.029	0.046	150	–
WMAP + dN/dz	$f_{NL}^{eq} = 38 \quad \kappa = 0$	0.0080	0.029	0.026	150	1.69
"	$f_{NL}^{eq} = 38 \quad \kappa = -0.3$	0.011	0.029	0.032	150	1.20
"	$f_{NL}^{eq} = -256 \quad \kappa = 0$	0.0076	0.029	0.022	150	0.17
"	$f_{NL}^{eq} = -256 \quad \kappa = -0.3$	0.0089	0.029	0.022	149	0.14
"	$f_{NL}^{eq} = 332 \quad \kappa = 0$	0.010	0.029	0.034	150	0.40
"	$f_{NL}^{eq} = 332 \quad \kappa = -0.3$	0.011	0.029	0.034	150	0.23
Planck		0.0084	0.011	0.015	40	–
Planck + dN/dz	$f_{NL}^{eq} = 38, \quad \kappa = 0.0$	0.0058	0.011	0.014	40	1.00
"	$f_{NL}^{eq} = 38 \quad \kappa = -0.3$	0.0070	0.011	0.015	40	0.47
"	$f_{NL}^{eq} = -256 \quad \kappa = 0$	0.0053	0.011	0.013	40	0.09
"	$f_{NL}^{eq} = -256 \quad \kappa = -0.3$	0.0061	0.011	0.013	40	0.09
"	$f_{NL}^{eq} = 332 \quad \kappa = 0$	0.0066	0.011	0.015	40	0.19
"	$f_{NL}^{eq} = 332 \quad \kappa = -0.3$	0.0068	0.011	0.015	40	0.11

$(\Omega_m = 0.24, h = 0.73, \sigma_8 = 0.77, \kappa = 0)$

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$(\Omega_m = 0.24, h = 0.73, \sigma_8 = 0.77, \kappa = 0)$

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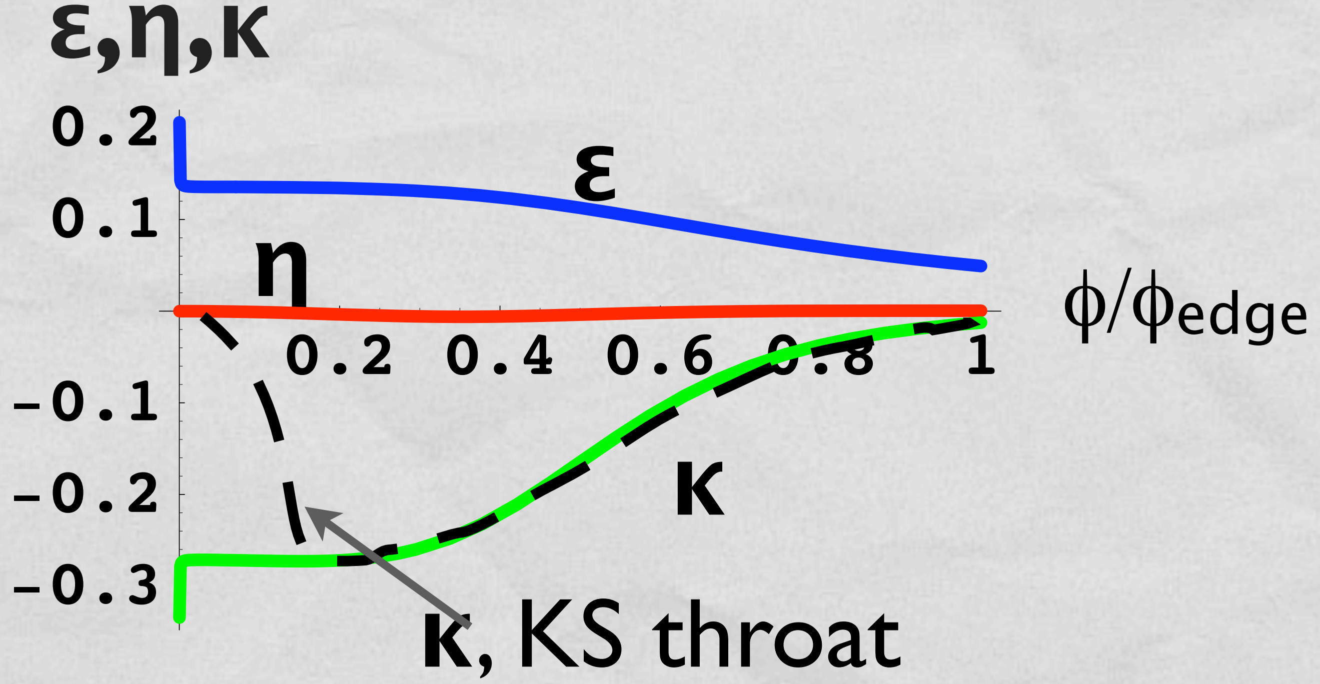
ASPECTS NG MAY TEST

- UV (NG increases on small scales) vs. IR (NG decreases on small scales)
- Deformed conifold: $\kappa = 0$
- Features (bumps in the potential or the warp factor)
- Deviations from Bunch-Davies? (Holman, Tolley)

* All scale-dependent

MAPPING THE WARP FACTOR



Here κ is a slow-roll parameter; can consider larger $|\kappa|$ if spectrum is computed numerically

IN THE FUTURE...

- Recent analysis finds a NG signal in CMB (Yadav, Wandelt, f_{NL}~90)
- No matter the eventual fate of that result, NG is such a powerful discriminator that it should continue to be probed at all possible scales

FIELD RANGE AND OBSERVABLES

LYTH BOUND

- Field range is related to tensor/scalar ratio:

$$\boxed{\frac{1}{M_p}\frac{d\phi}{dN_e} = \sqrt{\frac{r}{8}}}$$

- Sub-planckian field range implies $r < 0.01$ (barely detectable) if *r* is constant
- Can be larger if *r* changes rapidly (e.g., if sound speed decreases)

REMINDER: CHAOTIC INFLATION

- Usually, quadratic potential requires trans-Planckian field range

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

$$\boxed{\varepsilon < 1 \Rightarrow \frac{\phi}{M_p} > \sqrt{2}}$$

$$\boxed{H(\phi) = h_n\phi^n}$$

$$\boxed{\varepsilon = \frac{2M_p^2}{\gamma}\left(\frac{H'}{H}\right)^2 < 1\,, \Rightarrow \frac{\phi}{M_p} > n\sqrt{\frac{2}{\gamma}}}$$

FUNDAMENTAL QUANTITIES AND OBSERVABLES

- Field Range: canonical inflaton, 4D Planck mass:

$$\boxed{\frac{\phi}{M_p}}$$

- Relating the modulus field to the canonical inflaton:

$$\boxed{\phi = \sqrt{S}\rho}$$

- Volume and Planck mass:

$$\boxed{M_p^2 = \frac{V_6^w}{\kappa_{10}^2} = \frac{2V_6^w}{(2\pi)^7 g_s^2 \alpha'^4}}$$

THROAT DETAILS

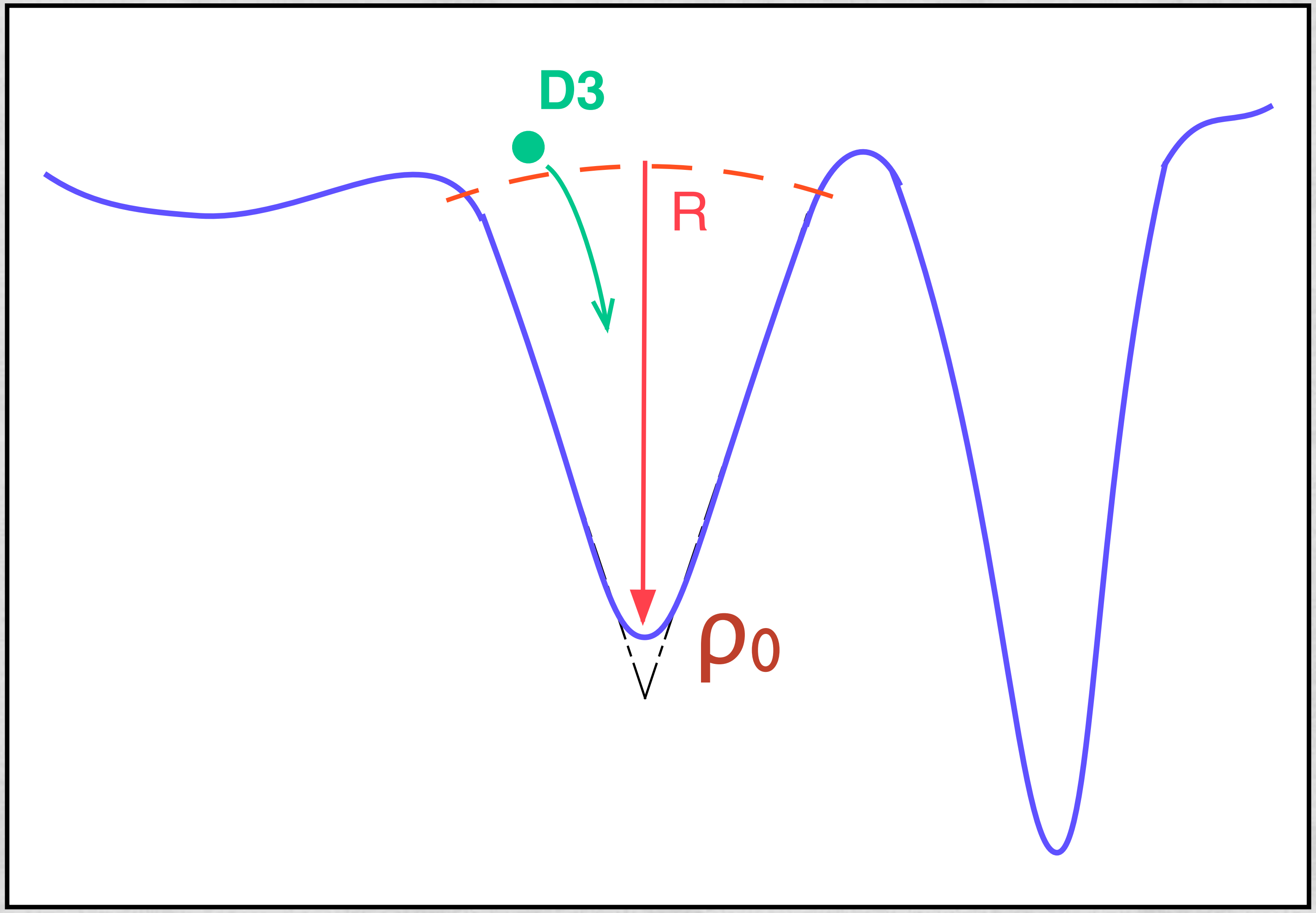
$$\boxed{AdS_5 \times X_5}$$

- Background D3 charge N

$$R^4 = \frac{4\pi g_s N \pi^3 \alpha'^2}{v}$$

$$v = Vol(X_5)$$

- Cut-off scale ρ_0



THE D3 BRANE FIELD RANGE PROBLEM

- The smallest possible compact volume is the throat volume:

$$\boxed{\begin{aligned} V_6^w \sim V_6^{throat} &= \int_0^{\rho_{UV}} d\rho\, \rho^5 h(\rho) \int d\Omega_{X_5} \\ &= 2\pi^4 g_s N^2 \rho_{UV}^2 \end{aligned}}$$

- Then, the field range is:

$$\boxed{\left(\frac{\Delta\phi}{M_p}\right)_{max} < \frac{2}{\sqrt{N}}}$$

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CONFLICT WITH OBSERVATION?

- Non-Gaussianity and the tensor/scalar ratio:

$$\boxed{\left(\frac{\Delta\phi}{M_p}\right)^2 = \frac{32}{r\gamma^2}}$$

$$\boxed{N \lesssim 38}$$

- COBE normalization: $\boxed{N \gtrsim 10^8 Vol(X_5)}$
- Need small background charge, large orbifolding:

$$\boxed{Vol(X_5) \sim (\pi)^3 \to 10^{-7}}$$

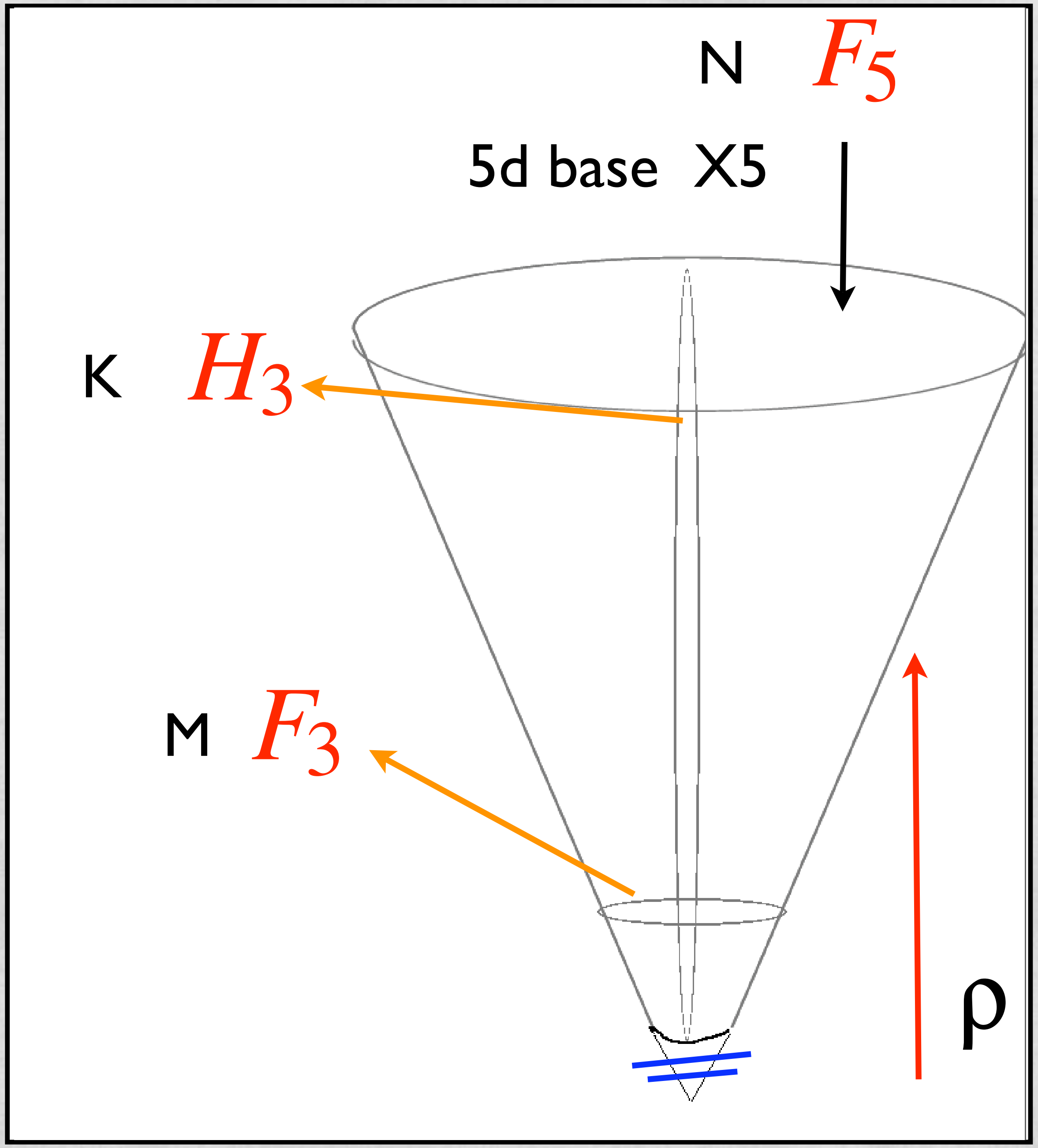
(Baumann, McAllister)

SUMMARY SO FAR...

- DBI brane inflation suggests an alternative to requiring a flat potential; worthwhile to try to realize DBI inflation
- This comes along with large, scale-dependent non-Gaussianity and maybe observable gravitational waves
- DBI with a D3 brane struggles(!) to match data
- Regardless of the viability of DBI, suggests interesting ways to distinguish inflation scenarios

II. THE WRAPPED BRANE INFLATON

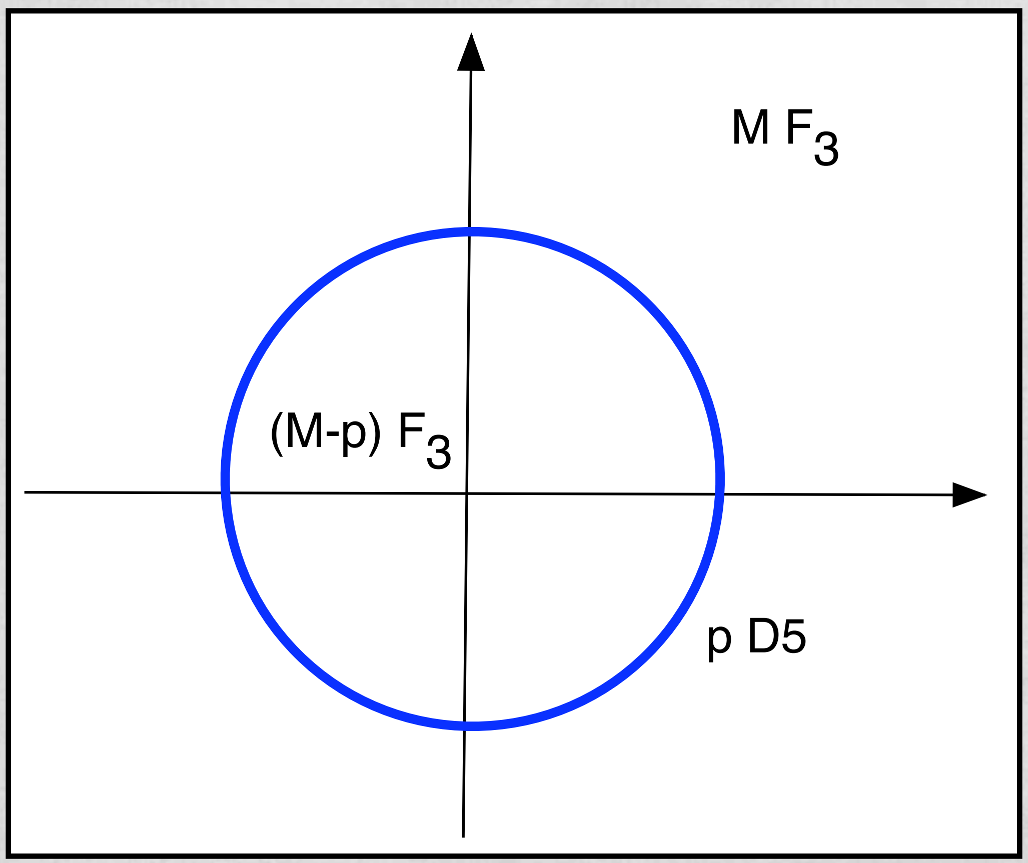
THE WARPED DEFORMED CONIFOLD

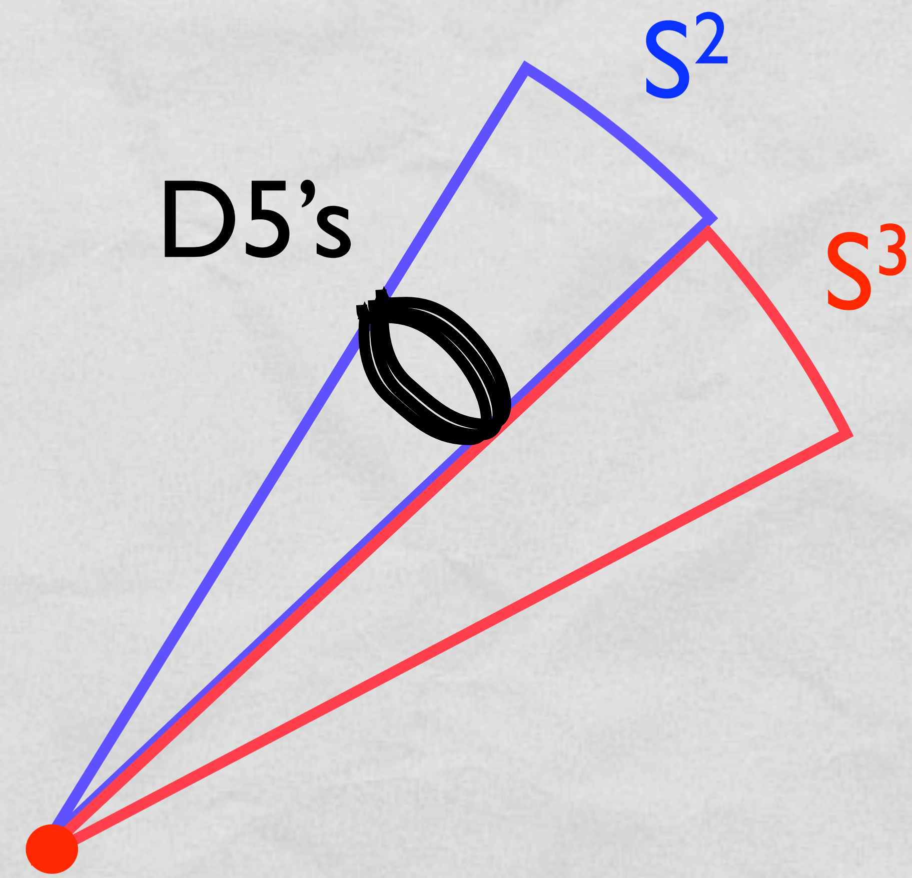


- In the UV (away from the tip) $\boxed{X_5 = T^{1,1}}$
- In the IR, S^2 shrinks to zero size; S^3 finite volume
- warp factor approaches a constant:

$$\boxed{h(r_0) = \frac{R^4}{r_0^4} = e^{8\pi K/(3g_s M)}}$$

WRAPPING A D5-BRANE





(Kobayashi, Mukohyama, Kinoshita; Becker, Leblond, S.S.)

EXTENDING THE FIELD RANGE

- Orbifolding S2 or S3:

$$\int_{S^2} d\Omega_2 \to \frac{1}{a}\int_{S^2} d\Omega_2$$

- Wrapping number p
- Then the normalization is

$$S = \frac{4\pi R^2}{3}\frac{p}{a}T_5$$

- Field range:

$$\left(\frac{\Delta\phi}{M_p}\right)^2 \leq \frac{2^3\pi}{3}\frac{p}{a}\left(\frac{g_s}{N\nu}\right)$$

III. MATCHING OBSERVATIONS

THREE DIMENSIONLESS VARIABLES

- Inflaton mass: $\boxed{A \equiv H' = \frac{m}{\sqrt{6}M_p}}$
- Field range: $\boxed{B \equiv \frac{\phi}{M_p}}$
- Normalization: $\boxed{C \equiv R^4 S}$

OBSERVATIONAL CONSTRAINTS

- Power spectrum normalization:

$$\boxed{P_S = \frac{H^4\gamma^2}{16\pi^2 M_p^4 H'^2} = \frac{A^4 C}{4\pi^2} \sim 2\times 10^{-9}}$$

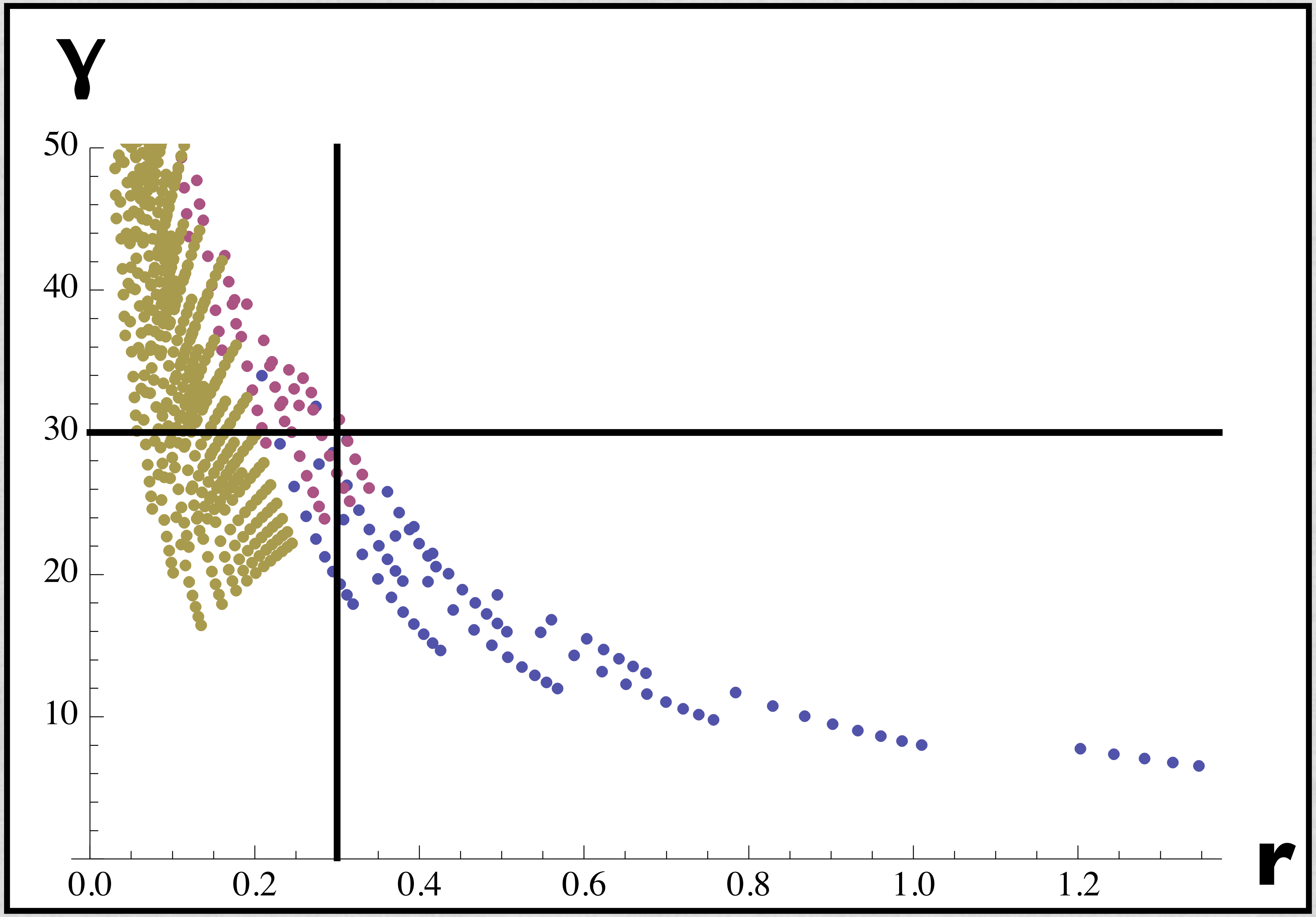
- Non-Gaussianity:

$$\boxed{|f_{NL}^{eq.}| < 256 \qquad \gamma \sim 2M_p^2 f(\phi)^{1/2} H' = \frac{2\sqrt{C}A}{B^2} < 30}$$

- Tensor/Scalar ratio:

$$\boxed{r = \frac{32M_p^2}{\gamma^2\phi^2} = \frac{8B^2}{CA^2} < 0.3}$$

CONSTRAINTS ON FUNDAMENTAL PARAMETERS



$$\frac{N}{v} > 10^5 g_s^{-1/3} \left(\frac{a}{p}\right)^{2/3}$$

$$Nv < 6 \times 10^3 \left(\frac{p}{a}\right)^2 g_s$$

$$p \sim a$$
$$g_s = 1/10$$

Example point: N~ 10^4, v=1/40; γ=25, r=0.29

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LYTH BOUND REVISITED

- Observationally, Lidsey and Huston find

$$r>0.002$$

- For a D3, the result was

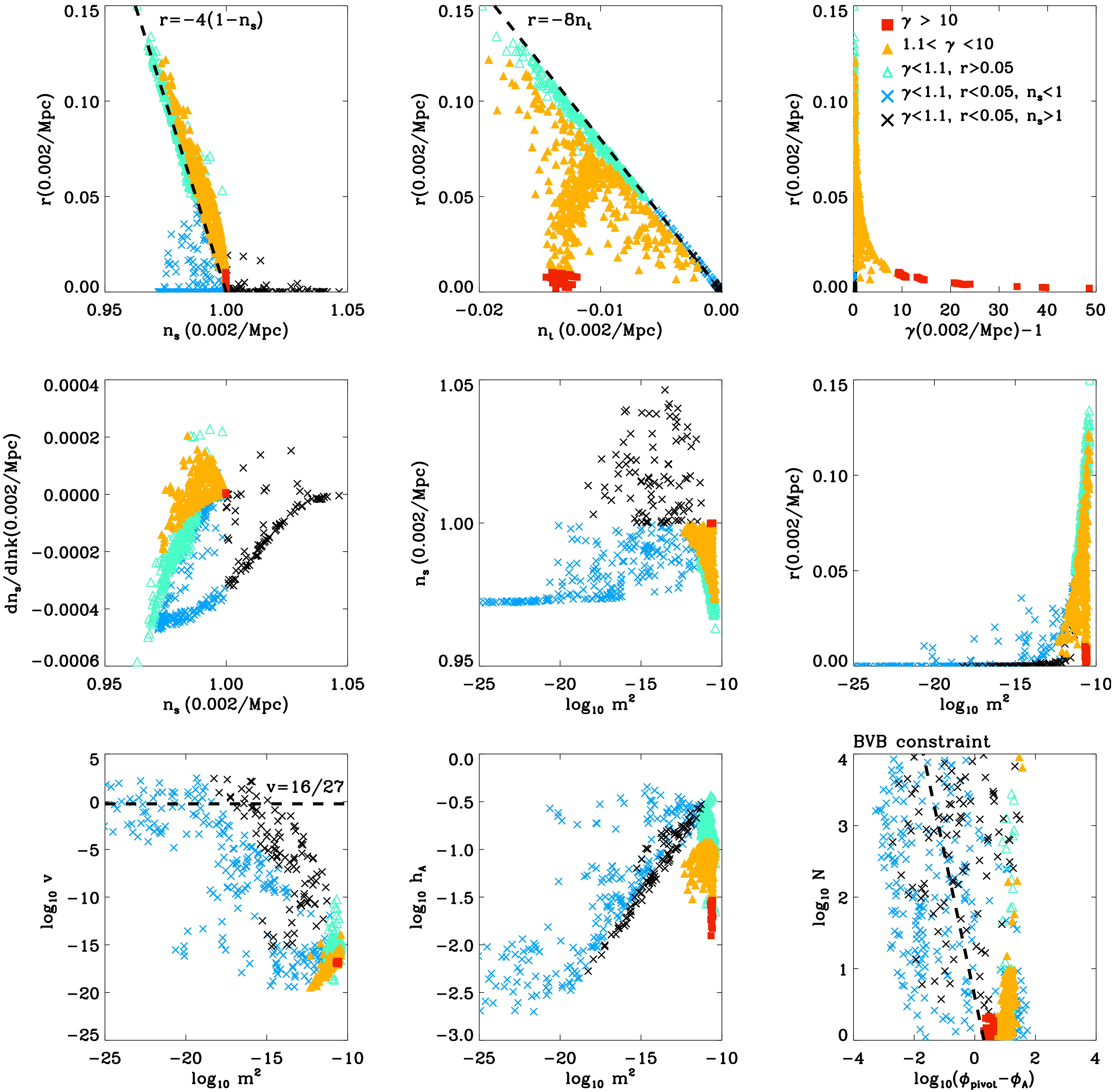
$$r<10^{-7}$$

- Assuming that r is constant on the scale of roughly 1 e-fold, the Lyth bound with a wrapped D5 gives

$$r<0.04$$

CLUES FROM THE D3 CASE?

- Lots of caveats:
  - Haven't computed number of e-folds
  - Haven't considered realistic throat geometry
- Monte-Carlo for D3 brane case, ***without*** imposing volume constraint (there are other ways to extend the field range) (hep-th/0702107, R. Bean, S.S., H. Tye, J. Xu)



r=-4(1-n_s)
r=-8n_t
γ > 10
1.1< γ <10
γ<1.1, r>0.05
γ<1.1, r<0.05, n_s<1
γ<1.1, r<0.05, n_s>1
r(0.002/Mpc)
n_s (0.002/Mpc)
n_t (0.002/Mpc)
γ(0.002/Mpc)-1
dn_s/dlnk(0.002/Mpc)
n_s (0.002/Mpc)
log10 m²
v=16/27
log10 v
log10 h_A
BVB constraint
log10 N
log10(φ_pivot-φ_A)

IV. CONSISTENCY ISSUES

SOME POINTS OF CONCERN

- What is the potential really?
- Back-reaction of the brane on the geometry?
- Is this a good “low” energy description?

SOME POSSIBLE POTENTIALS

- Chern-Simons term:

$$\boxed{S_{CS} = \mu_5 \int P[C_6 + C_4 \wedge (B_2 + 2\pi F)]}$$

$$\boxed{= \mu_5 2\pi \int d^4x \left(\frac{3M}{4h} + \frac{1}{g_s h} (3 g_s M \ln(\phi/\phi_0) + 2\pi q) \right)}$$

$$\boxed{H(\phi) = h_n \phi^n}$$

- Other power laws?
  - n=2 inflates for smaller field range
  - n>3 require trans-planckian field range

SIMPLISTIC BACKREACTION

- Examining the perturbation to the radial warp factor due to the brane:

$$\frac{p\gamma}{a} \ll \sqrt{\frac{Nv}{g_s}}$$

- With bounds from data, this gives:

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And for D3:

$$\boxed{\begin{gathered}\gamma T_3 < N T_3 \\ \Rightarrow \gamma \ll 36\end{gathered}}$$

KK MODES

- We would like to ignore all fields except the inflaton:

$$\boxed{m_{KK}^{w} > H}$$

- KK modes at the bottom of the throat have warped masses

$$\boxed{\frac{1}{R}\frac{\phi_{IR}}{\phi_{UV}} > H_{max} = A\phi_{max}} \qquad \boxed{h_{IR}^{-1/4} > A\sqrt{S}R^2 = A\sqrt{C}}$$

- Number of e-folds?

$$\boxed{N_e = A\sqrt{C}\log(h_{IR}^{1/4})}$$

CONCLUSIONS

- Fundamental moduli space translates to constraints on canonical inflaton field range (matches expectations from EFT)
- For brane inflation, the relationship depends on the dimensionality
- DBI with a wrapped brane can match observational data in the most optimistic case, but:
  - Many concerns other than field range

SOME FINAL OPTIMISM...

- DBI inflation has suggested an alternative to standard slow-roll with observable features
- Non-Gaussianity is especially useful and leads to new ideas for observationally distinguishing models
- DBI emphasizes importance of moduli space
- Inflation is a useful context to investigate warped supersymmetry breaking

GENERAL SOUND SPEED

$$\boxed{\langle\zeta(\vec{k}_1)\zeta(\vec{k}_2)\zeta(\vec{k}_3)\rangle = (2\pi)^7\delta^3(\vec{k}_1+\vec{k}_2+\vec{k}_3)\frac{\mathcal{P}^\zeta(K)^2}{k_1^3k_2^3k_3^3}(\mathcal{A}_\lambda+\mathcal{A}_c+\mathcal{A}_o+\mathcal{A}_\varepsilon+\mathcal{A}_\eta+\mathcal{A}_s)}$$

$$\boxed{K = k_1+k_2+k_3}$$

(Chen, Huang, Kachru, Shiu)

Current CMB bound: $f_{NL}^{eff}(k_1=k_2=k_3)$

$$-256 < f_{NL}^{eq} < 332$$

(Creminelli et al.)

Carnegie Mellon,
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lower order

$$\mathcal{A}^c(k_1,k_2,k_3) = \left(\frac{1}{c_s^2}-1\right)\left(-\frac{1}{K}\sum_{i>j}k_i^2k_j^2+\frac{1}{2K^2}\sum_{i\neq j}k_i^2k_j^3+\frac{1}{8}\sum_i k_i^3\right)$$

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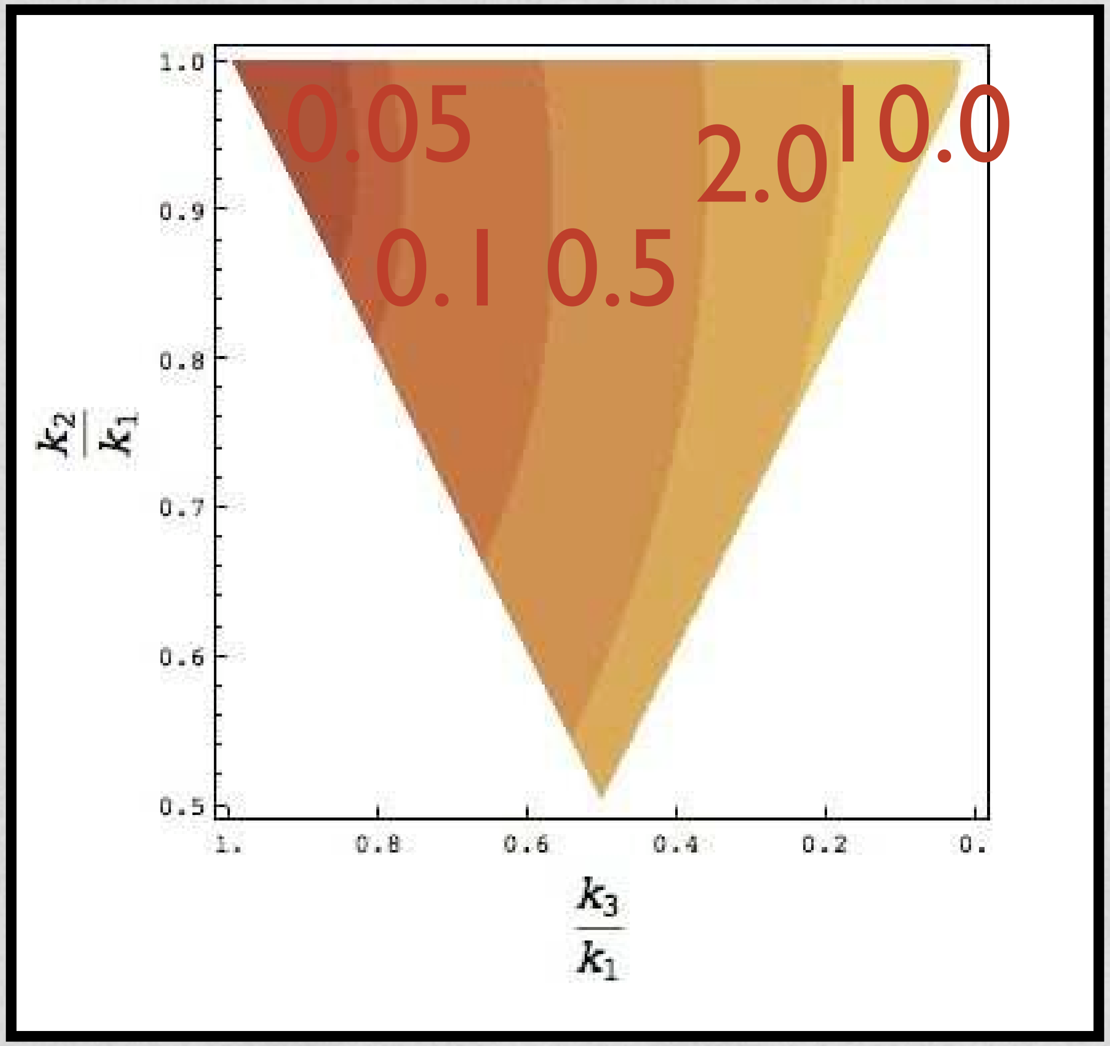
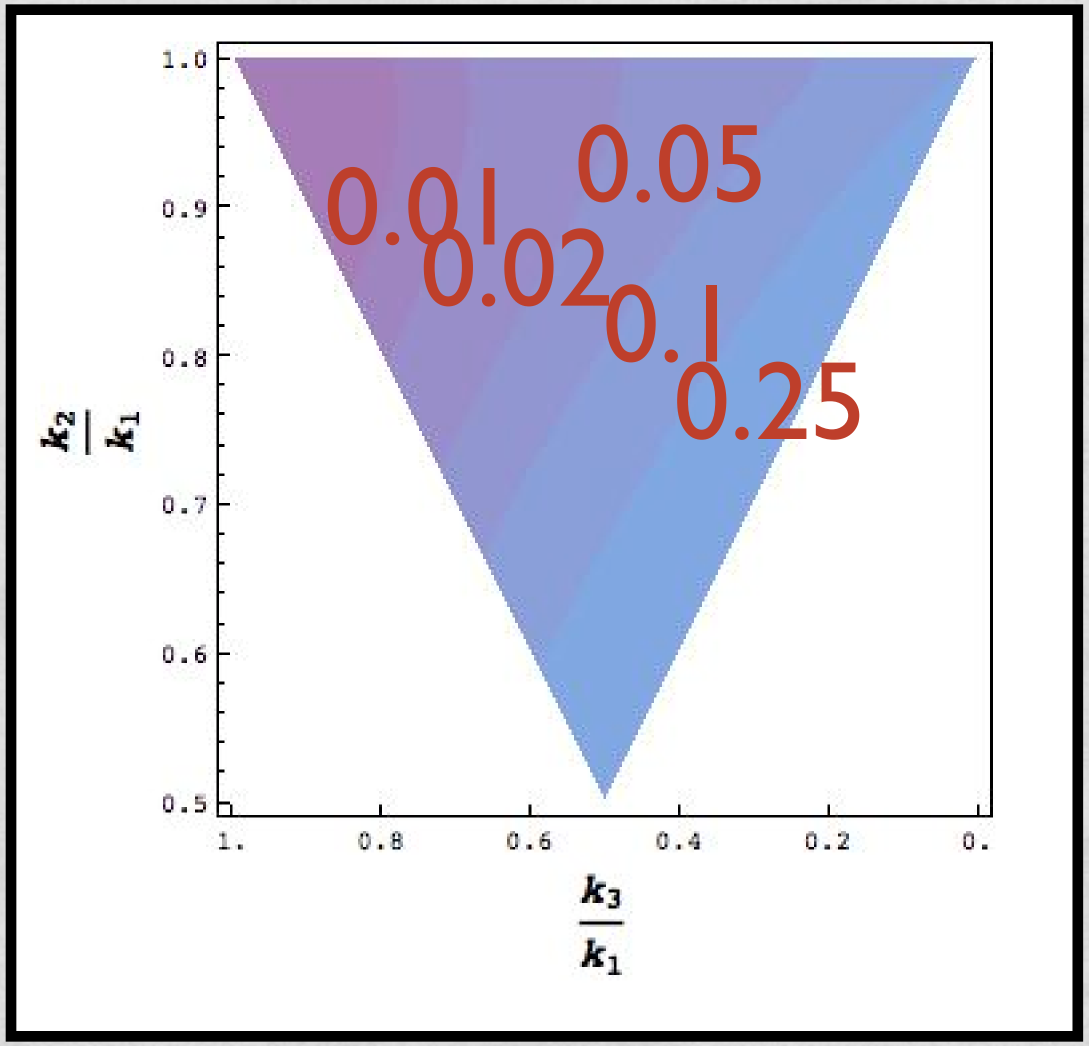
TWO COMPARISONS

$(\mathcal{A}_{local} - \mathcal{A}_c)/\mathcal{A}_c$



$(\mathcal{A}_{equil} - \mathcal{A}_c)/\mathcal{A}_c$



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