String Cosmology

BIRS meeting, Fall 2021

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1891

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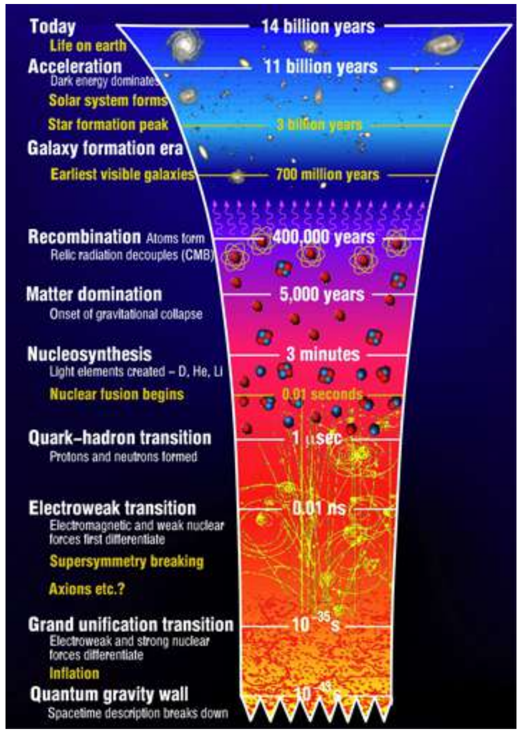
As one of the two discussion leaders, I was invited to prepare a few minutes of remarks about what I see as central questions at the interface of cosmology and string theory. (Needless to say, a few minutes is not enough!)

To my thinking, there are three categories of obvious such questions:

What about dark energy? →



← What came before BBN (inflation, reheating)?

How did the Universe originate? →

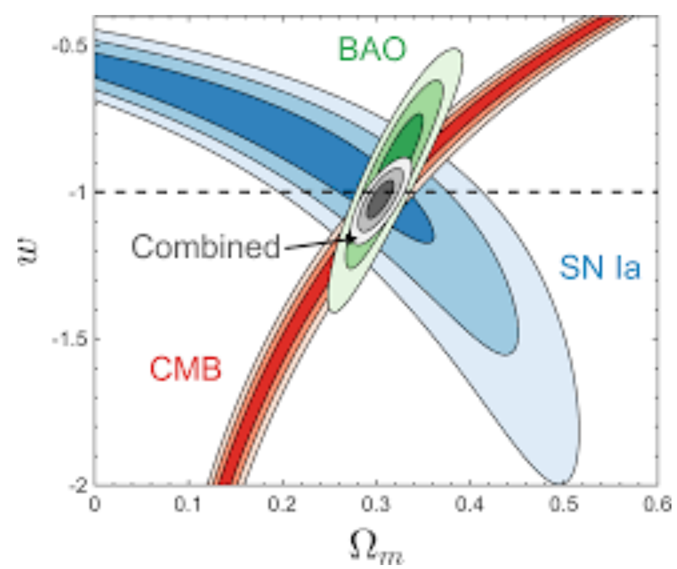
Each is (at least naively) very sensitive to UV physics; there is a "reason" string theory may be relevant.

I will work in reverse chronological order.

What do we know about dark energy?

$$p = w\rho$$

$$w < -\frac{1}{3} \rightarrow$$ **accelerated expansion**



Constraints from data ever more strongly favor w close to -1.

Therefore, I'll restrict attention to a cosmological constant.

The maximally symmetric solution of Einstein's equations in the presence of (positive) cosmological term, is de Sitter space.

Some interesting questions:

— how do you make de Sitter solutions in string theory? Is there mathematical structure in the space of such solutions?

— What is non-perturbative string theory in de Sitter space? (For a satisfactory answer to this kind of question, see the answer with flipped sign of the cosmological term.)

I'll focus on the first, not because I think it is more interesting, but because it seems to be a subject of frequent discussion in this community.

A prototype example of a simple solution could be Freund-Rubin solutions that give AdS space. E.g. starting from 6d Einstein-Maxwell theory:

$$S = \int d^6x \sqrt{-G_6}\left(\mathcal{R}_6 - |F_2|^2\right),$$

$$ds^2 = \eta_{\mu\nu}dx^\mu dx^\nu + R^2 g_{mn}(y)dy^m dy^n$$

compactify on two-sphere

$$\int_{S^2} F_2 = N$$

thread it with N units of flux

$$V(R) \sim \frac{N^2}{R^6} - \frac{1}{R^4}$$

resulting 4d "radion" potential

Exhibits AdS solutions which have R ~ N; reliable at large N.

Are there analogues of Freund-Rubin that just use the classical energetics exhibited by fluxes and branes, and yield de Sitter space?

$$\Delta V = \int \sqrt{-g} g^{\mu_1 \nu_1} ... g^{\mu_p \nu_p} F_{\mu_1 ... \mu_p} F_{\nu_1 ... \nu_p} \sim \frac{1}{R^{6+2p}}$$

energetics of p-form flux

$$\Delta V \sim \pm \frac{1}{R^{12-q}}$$

energetics of brane wrapping q-cycle

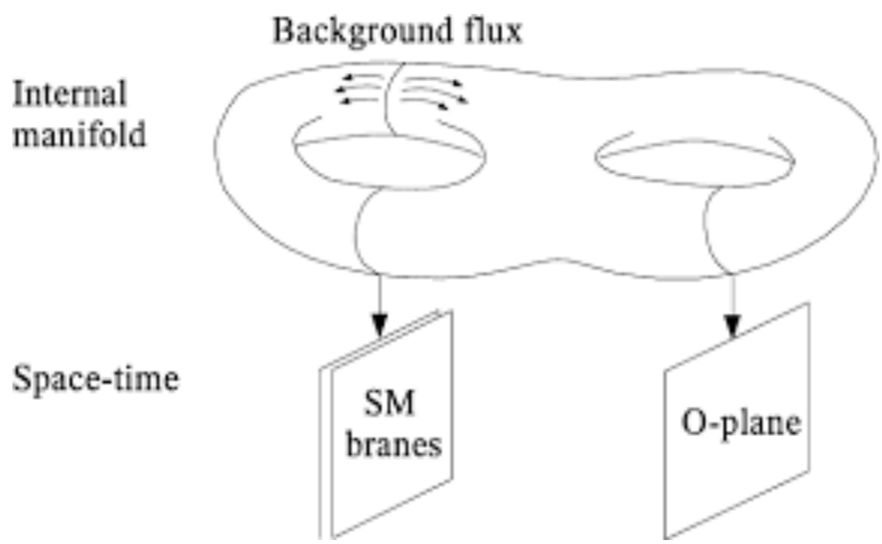
With just D-branes, O-planes, and RR and NS fluxes, the answer (in the critical dimension) seems to be negative from a variety of no-go theorems.

de Wit, Hari Dass; Maldacena, Nunez; Hertzberg, SK, Taylor, Tegmark; ...

Including also curvature and NS-branes, I believe there is no known obstruction to such solutions, and there are proposed examples.

c.f. Dong, Horn, Silverstein, Torroba 2010

Another class of solutions has been proposed that uses ingredients familiar to the class of vacua used in various studies of (4d N=1 supersymmetric) string phenomenology.



Setting: IIB string theory on Calabi-Yau orientifold of D3/D7 type, with 3-form fluxes

…; Giddings, SK, Polchinski; …

— Potentials for complex structure moduli (can) arise from fluxes:

$$W_{\rm classical} = \int_X (F - \tau H) \wedge \Omega \ .$$

Gukov, Vafa, Witten

— Potentials for Kahler moduli (can) arise from Euclidean branes or similar effects:

$$\Delta W \sim \sum_D e^{-{\rm vol}(D)} + \cdots$$

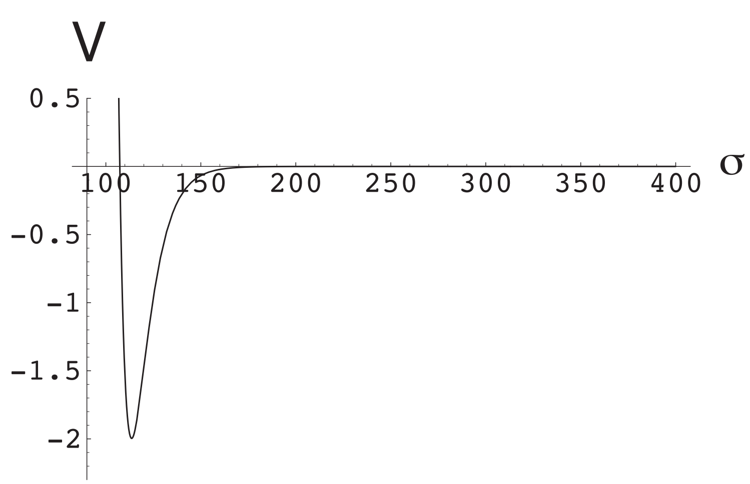
Witten '96; …

It was proposed in various papers that different regimes of parameters in (some) such models, can yield de Sitter solutions.

S.K., Kallosh, Linde, Trivedi; Balasubramanian, Berglund, Conlon, Quevedo

In the first proposal, the small parameter necessary to exhibit a controlled solution (analogous to the "large N" of Freund-Rubin) is a small value of the flux superpotential:

$$W = W_0 \ll 1 \ .$$



A theory with such small classical superpotential and generic further corrections to the low-energy effective theory exhibits an AdS minimum.

At this level, we can ask:

Do there exist Calabi-Yau models that have the necessary non-perturbative effects, and/or the small classical superpotential, required for this discussion?

Partial answers to these questions existed for many years.

...; Denef, Douglas, Florea, Grassi, SK; Lust, Reffert, Schulgin, Stieberger; ...

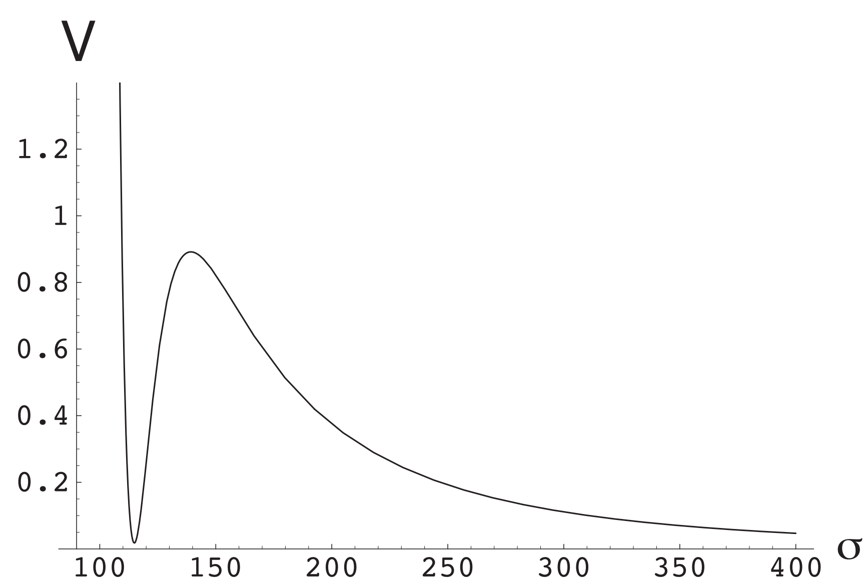
Most recently, very beautiful work by the Cornell group has developed techniques to analyze many toric Calabi-Yau hyper-surfaces and complete intersections. They can find models with

$$|e^{K/2} W_{\rm classical}| < 10^{-100} \ .$$

Demirtas, Kim, McAllister, Moritz, Rios-Tascon

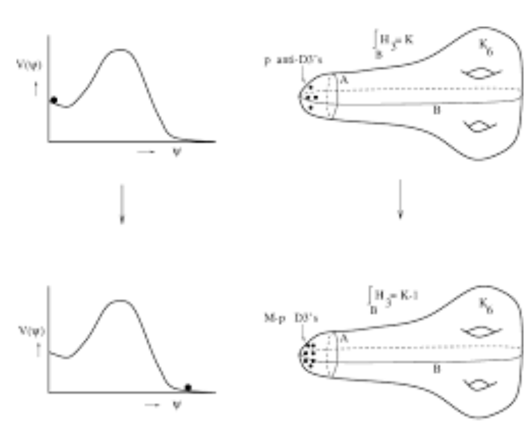
(And, with small string coupling.) As this is classical (tree-level) physics, one can only ask if they made a mistake computing period integrals, which can be tested.

These models are also chosen to exhibit the requisite instanton effects (with "enough effects" to generate potentials spanning the directions in the Kahler cone).



At the level of analyzing effects of small changes to such a potential, a range of tunably small perturbations to the radion potential can change the AdS minimum to a dS minimum.

In high energy theory, "tunably small perturbations to the potential" were proposed for years in phenomenology, in the guise of (dynamical) supersymmetry breaking (DSB).



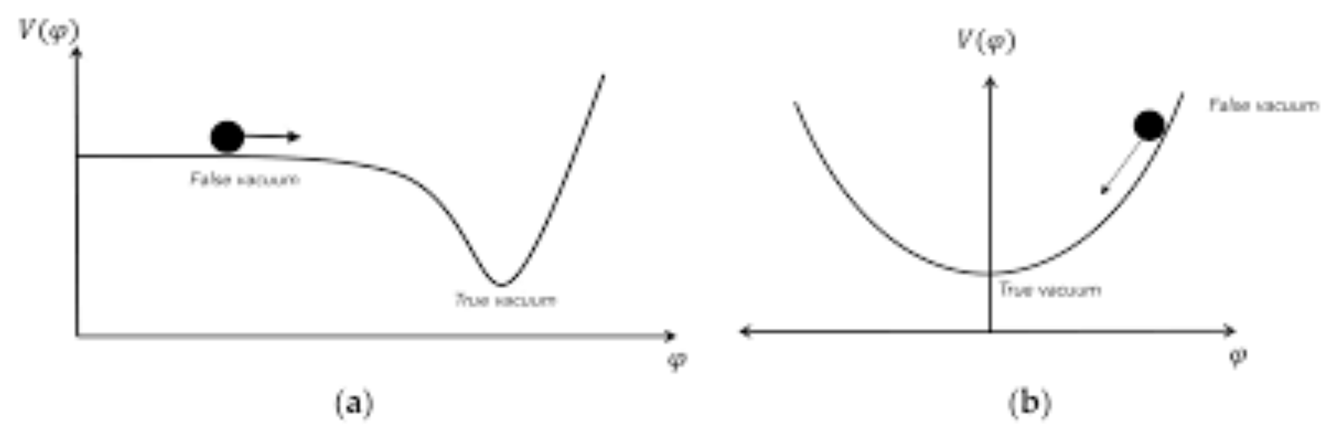
One of many possible examples in this context involves supersymmetry breaking states with anti-D3 branes in a warped, deformed conifold geometry.

Local constructions can be completely controlled. Gluing into a compact Calabi-Yau can (and likely will) be studied in greater detail.

Klebanov, Strassler; SK, Pearson, Verlinde

What came before BBN: inflation in string theory?

Cosmic inflation is a great idea that may well explain the "bigness" of space and the perturbations that eventually collapse to form galaxies.



Guth; Linde; Albrecht, Steinhardt

In my mind, its main a priori merit is the genericity of the ingredients involved: one or a few scalar fields, and a positive potential with a region of small slope.

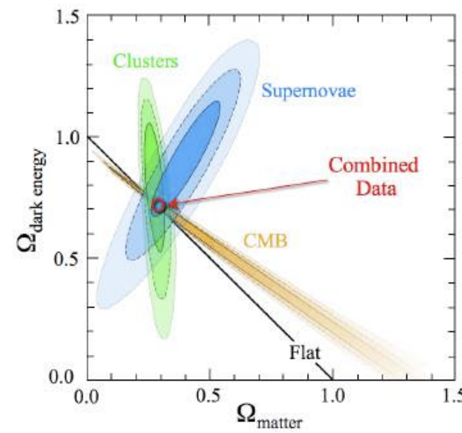
Creminelli, Senatore Vasy '19

Unlike many aspects of our field, inflation is clearly sensitive to "very UV" physics:

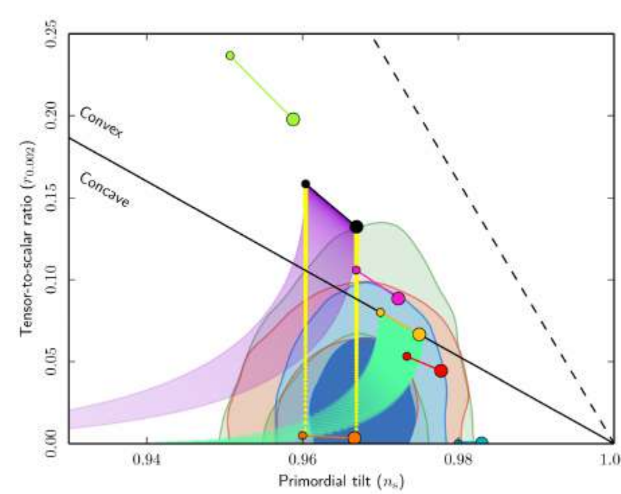
$$\epsilon = \frac{1}{2} M_P^2 (\frac{V'}{V})^2, \quad \eta = M_P^2 \frac{V''}{V} \rightarrow$$ **O(1) shifts from Planck-suppressed operators**

Semi-quantitative predictions already verified include:

— $\Omega_{\rm tot} \simeq 1$ **(predicted at a time when this seemed far from likely to be true)**

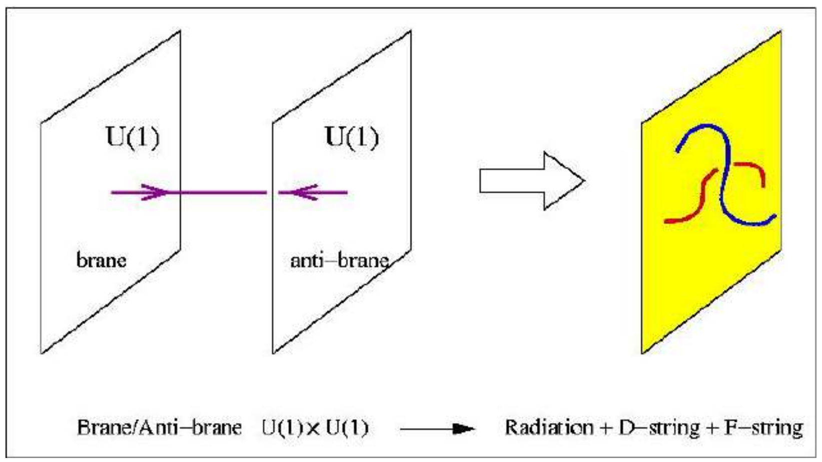


— **Harrison-Zeldovich spectrum of perturbations with slight deviations from scale invariance.**



— **Collapse of super-horizon modes back into the horizon to produce the visible density perturbations. (c.f. acoustic peaks, qualitatively…)**

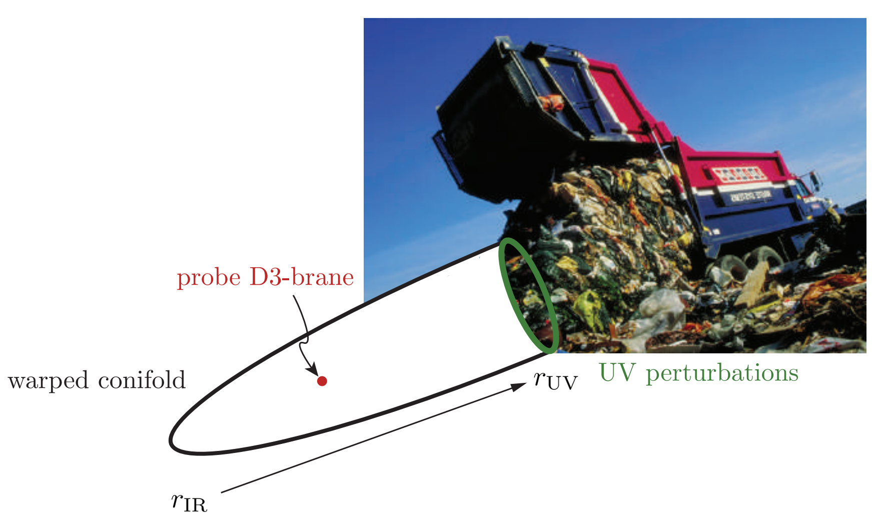
There are two classes of string models that I think deserve special mention. Further work on the robustness of each would certainly be merited, and I see strategies for research on both.



Brane dynamics in a compactification can release a "waterfall" of energy coming from, e.g., brane annihilation.

Nice reviews: Quevedo '02; Baumann, McAllister book; Silverstein, '16

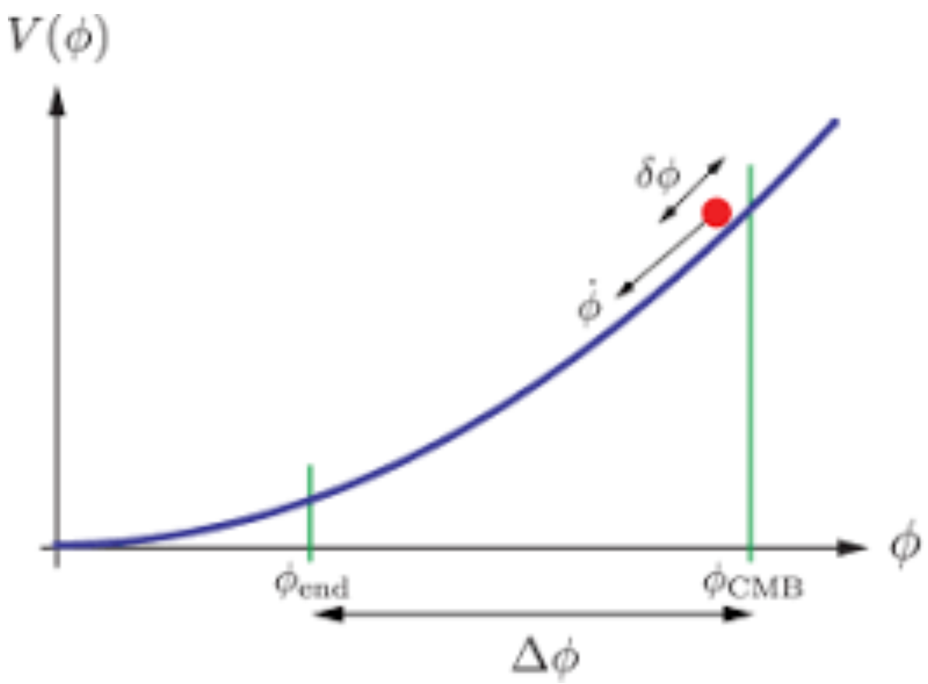
In local models of (non-conformal) holography, such as the warped conifold, one can precisely parametrize the sets of operators and coefficients needed to make inflation occur or not, as well as their effects on inflationary parameters.



By general principles, "gluing" into a bulk (= coupling to quantum gravity) can only induce such operators, with estimable coefficients.

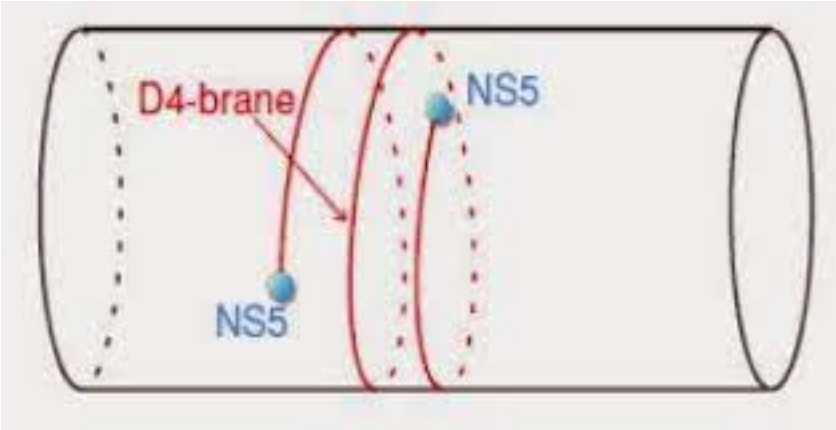
…; Baumann, Dymarsky, S.K., Klebanov, McAllister '08,'10

A second class which, I think, deserves added attention is large field inflation, arising from branes (e.g. axion monodromy) or axion fields in string theory.



Here, the main interest is that the models which generate observable tensor to scalar ratio r (at least for near term experiments) exhibit Planckian or super-Planckian field ranges.

Lyth '97



Examples of models based on axion monodromy or other dynamics of axions exist, and refining them will become extremely interesting if BICEP or its successors detect r.

e.g. McAllister, Silverstein, Westphal '08; ...

Thanks for your attention!