On the realization of the supersymetric Starobinsky inflation with higher order corrections

based on: arXiv:1405.6732, in collaboration with J. Yokoyama (U Tokyo)

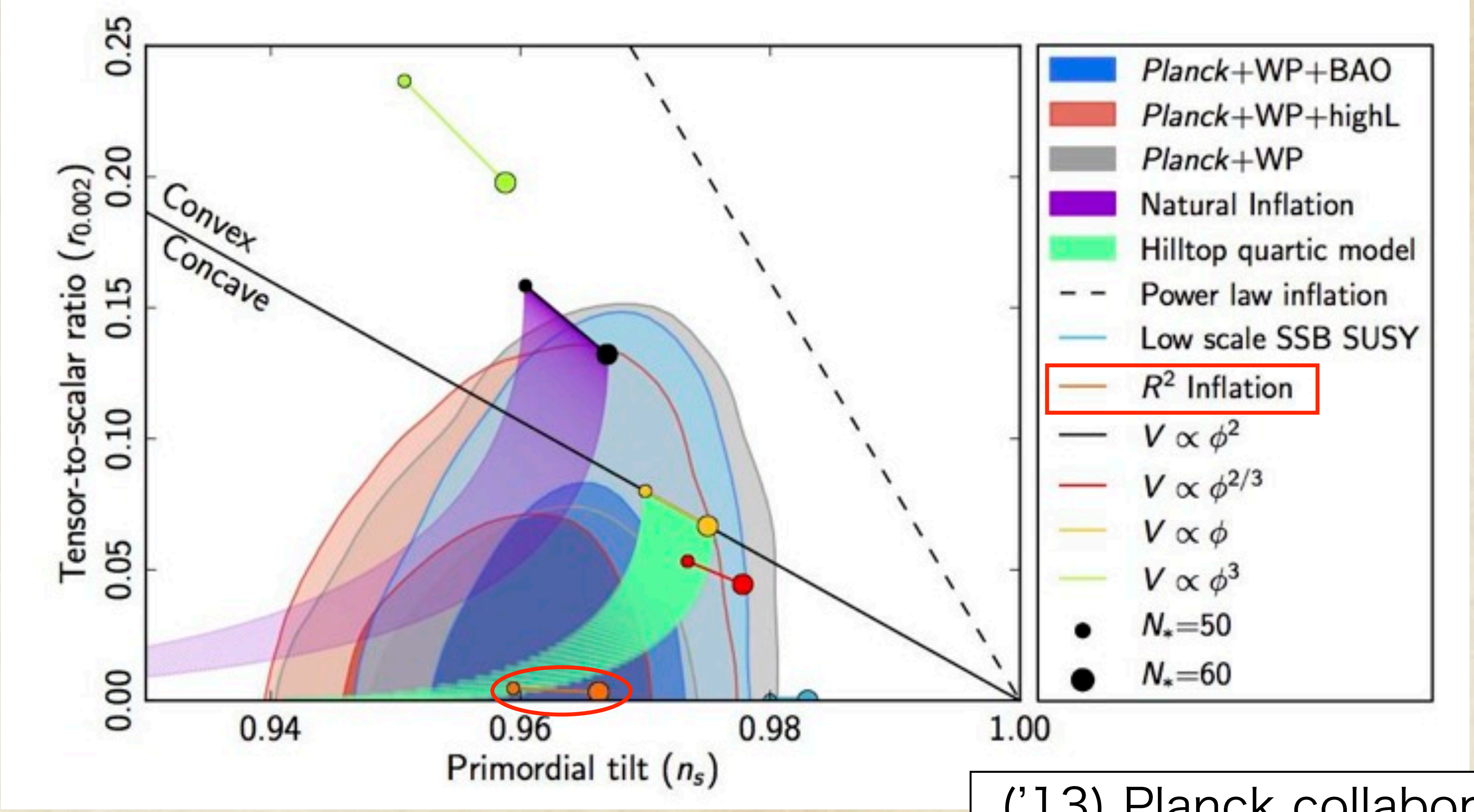
Kohei Kamada
(EPFL, ITP, LPPC)

Planck 2014, 29/5/2014 @ Institut des Cordeliers, Paris

Courtesy H.Oide

CMB observation by Planck

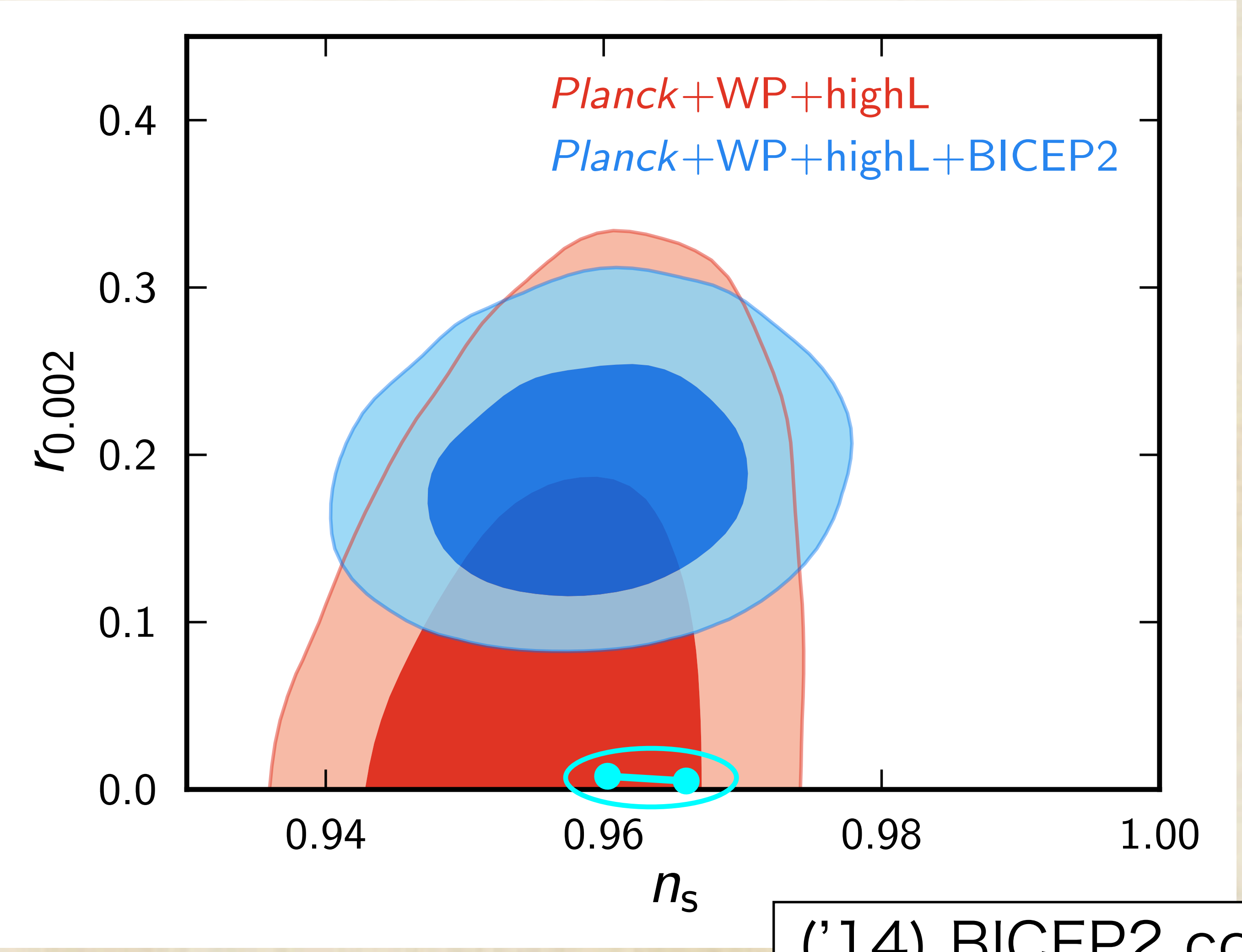
seems to be support Starobinsky's R^2 inflation model...



('13) Planck collaboration

Courtesy H.Oide

Recent BICEP2 B-mode data ruled out R^2 inflation?



('14) BICEP2 collaboration

Courtesy H.Oide

However...

Towards an Understanding of Foregrounds in the BICEP2 Region

Raphael Flauger

in collaboration and discussion with:

Steve Choi, Aurelien Fraisse, Colin Hill,
Lyman Page, Suzanne Staggs, and David Spergel

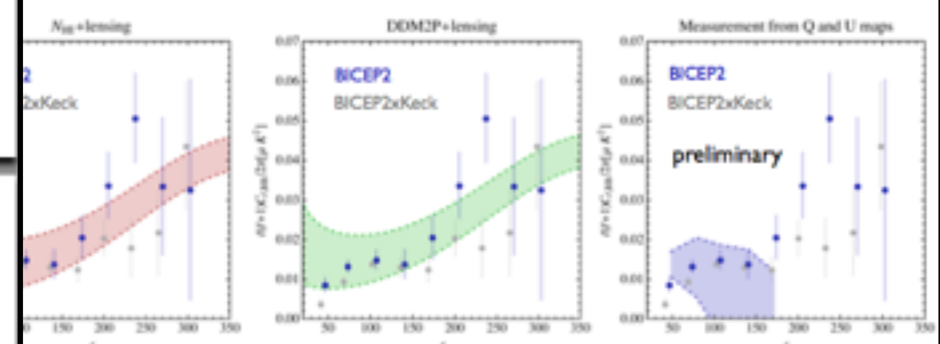
PCTS, Princeton, May 15, 2014

BICEP2

index and seems to have been ignored

Conclusions

- CEP has provided us with the deepest maps of any patch of e sky at 150 GHz and has detected degree scale B-modes
- ccording to all estimates, foregrounds may be small enough to tect a (large) primordial signal at 150 GHz without reground subtraction, but the uncertainty on foregrounds is rge and measurements at other frequencies (especially above 0 GHz e.g. from Planck) seem important for a definitive easurement



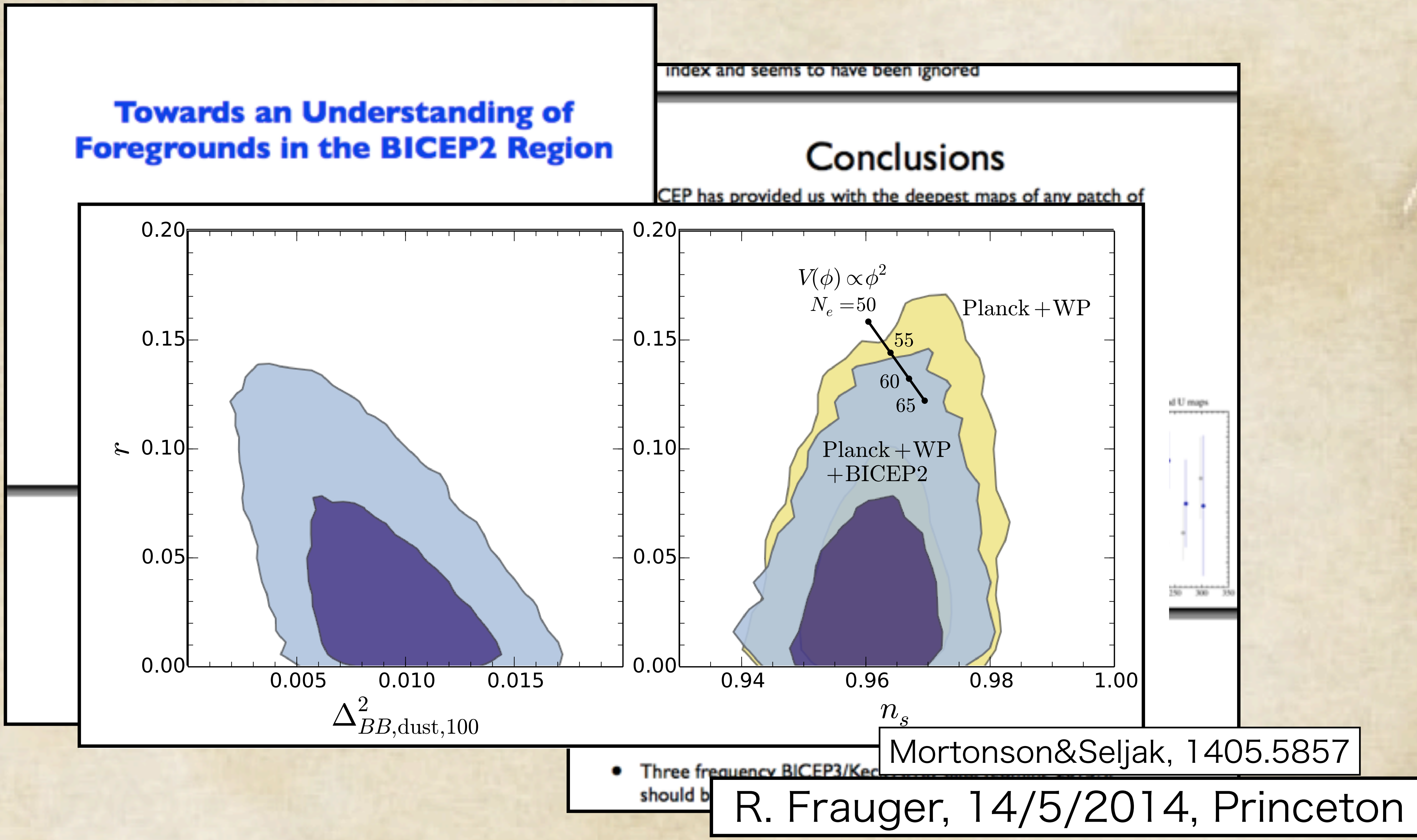
Conclusions

- 100 GHz Keck Array data will be available soon
- Three frequency BICEP3/Keck Array data (coming 2015?) should b

R. Frauger, 14/5/2014, Princeton

Courtesy H.Oide

However...



Courtesy H.Oide

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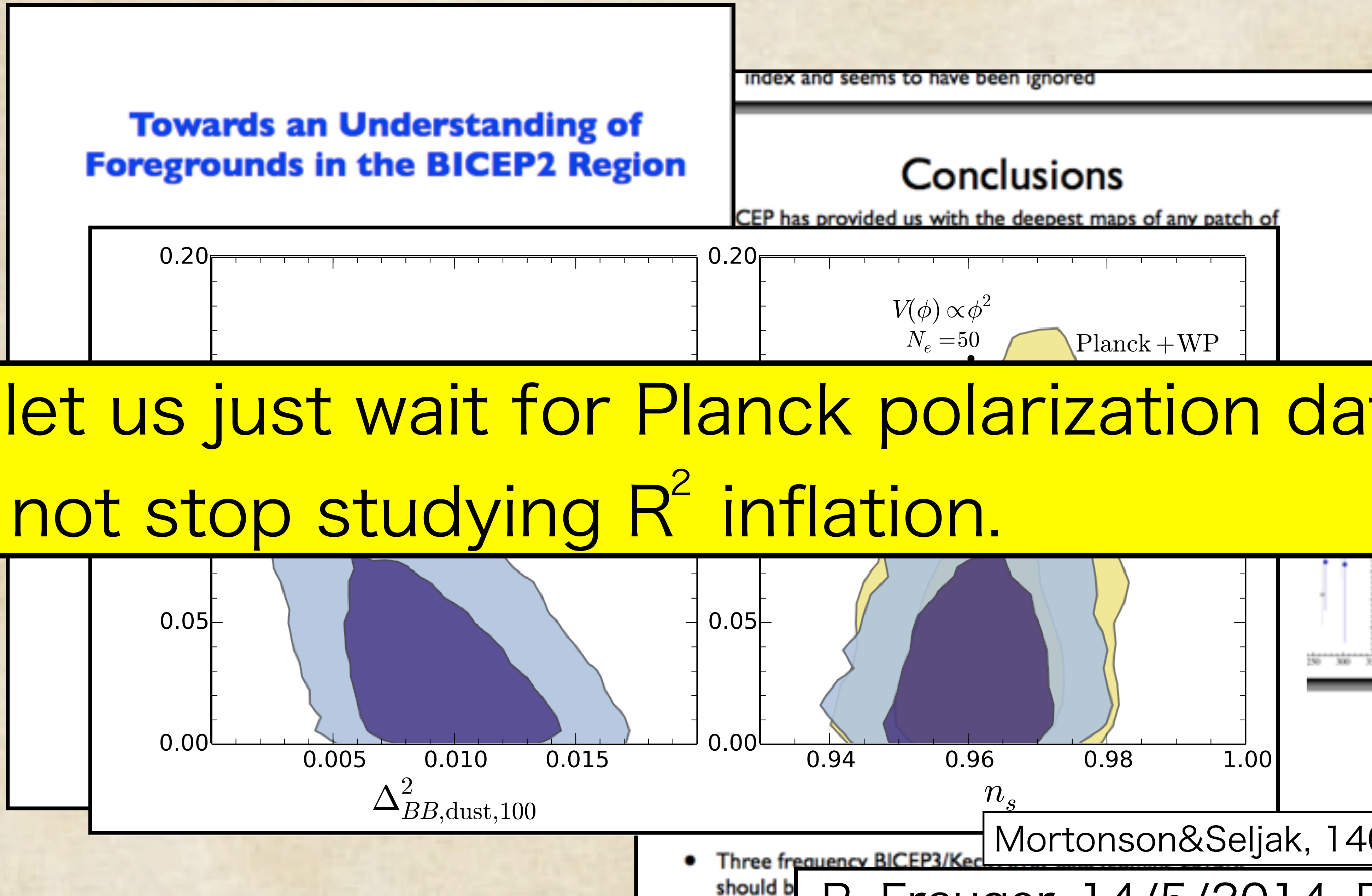


OK, let us just wait for Planck polarization data, and not stop studying R^2 inflation.

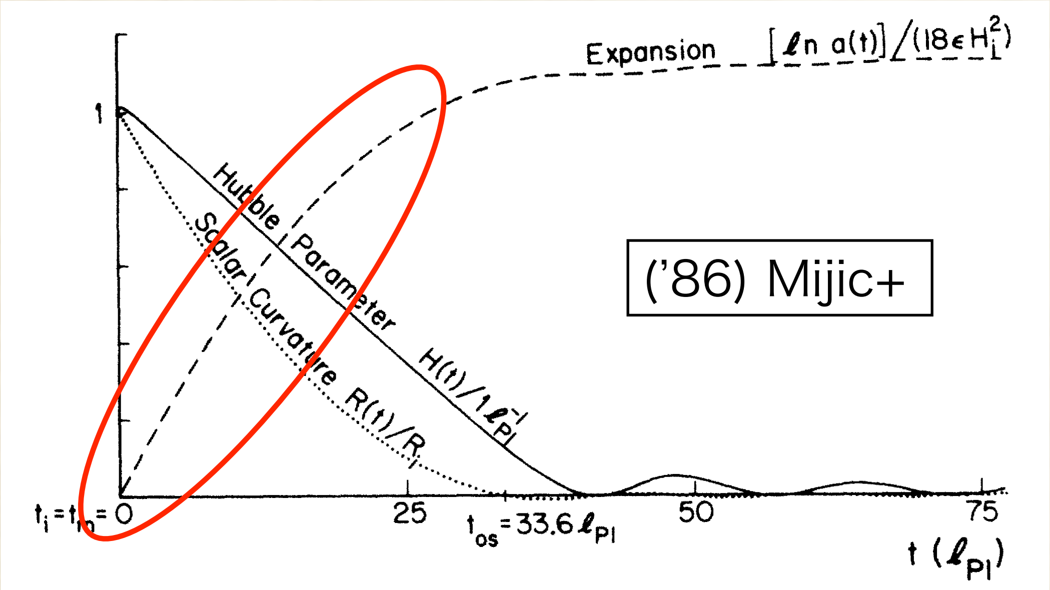
Mortonson&Seljak, 1405.5857

R. Frauger, 14/5/2014, Princeton

Courtesy H.Oide

R^2 inflation (('80) Starobinsky)

...inflation model from modified gravity

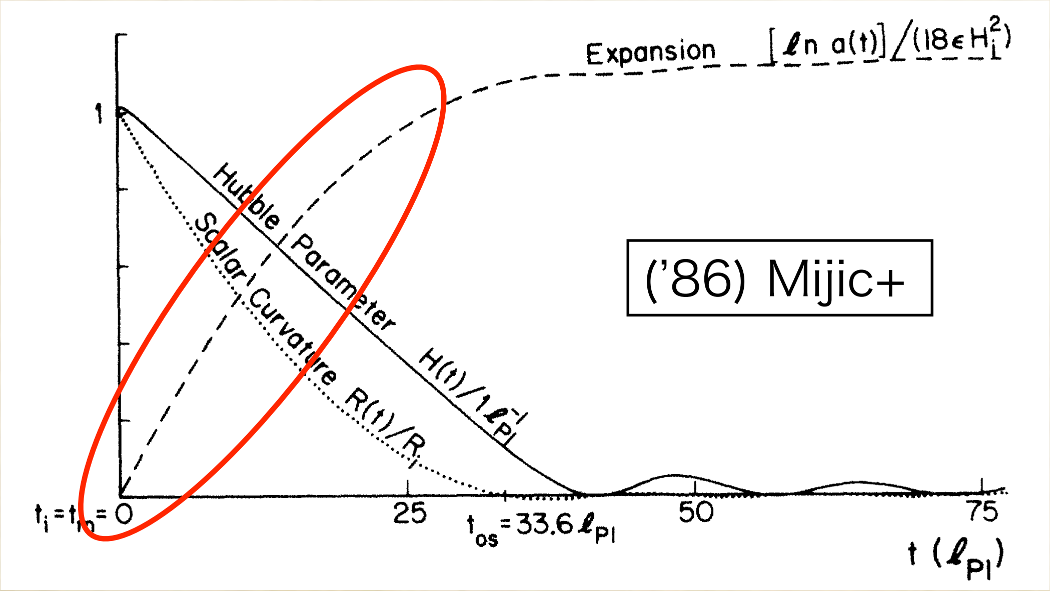


$$S = \int d^4x\sqrt{-g}\frac{M_{\rm Pl}^2}{2}\left[-R + \frac{R^2}{6M^2}\right]$$

Courtesy H.Oide

R^2 inflation (('80) Starobinsky)

...inflation model from modified gravity



$$S = \int d^4x \sqrt{-g} \frac{M_{\rm Pl}^2}{2} \left[-R + \frac{R^2}{6M^2} \right]$$

It has a dual theory of scalar field (scalaron) with minimal coupling to gravity via introducing auxiliary field and performing conformal transformation,

$$S = \int d^4x \sqrt{-\tilde{g}} \frac{M_{\rm Pl}^2}{2} \left[-\tilde{R} - \frac{1}{2}(\partial_\mu \tilde{\varphi})^2 - \frac{3}{4} M^2 M_{\rm Pl}^2 \left(1 - \exp\left[-\sqrt{\frac{2}{3}} \frac{\tilde{\varphi}}{M_{\rm Pl}} \right] \right)^2 \right]$$

Courtesy H.Oide

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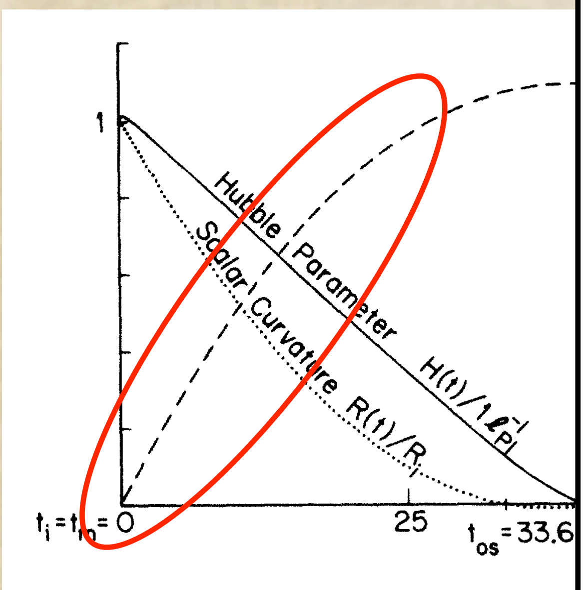

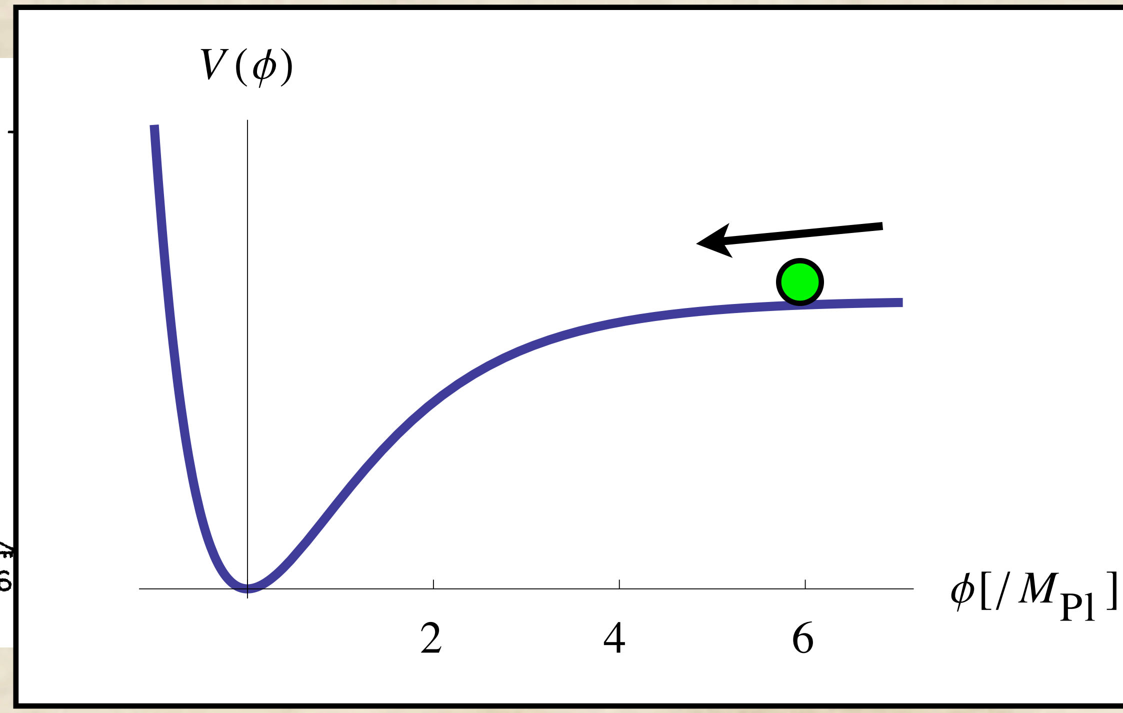

$$g\,\frac{M_{\rm Pl}^2}{2}\left[-R+\frac{R^2}{6M^2}\right]$$

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i.e. inflation with a very flat potential

Courtesy H.Oide

Observational predictions of R^2 inflation

...can be seen easily in the scalaron picture

Scalar powerspectrum

$$A_s = \frac{H^2}{8\pi^2 \epsilon M_{\rm Pl}^2} \quad \text{with} \quad \epsilon \equiv \frac{M_{\rm Pl}^2}{2}\left(\frac{V'}{V}\right)^2$$

⇨ $A_s^{\rm obs} \simeq 2.2 \times 10^{-9}$ requires $M \sim 3 \times 10^{13}$ GeV

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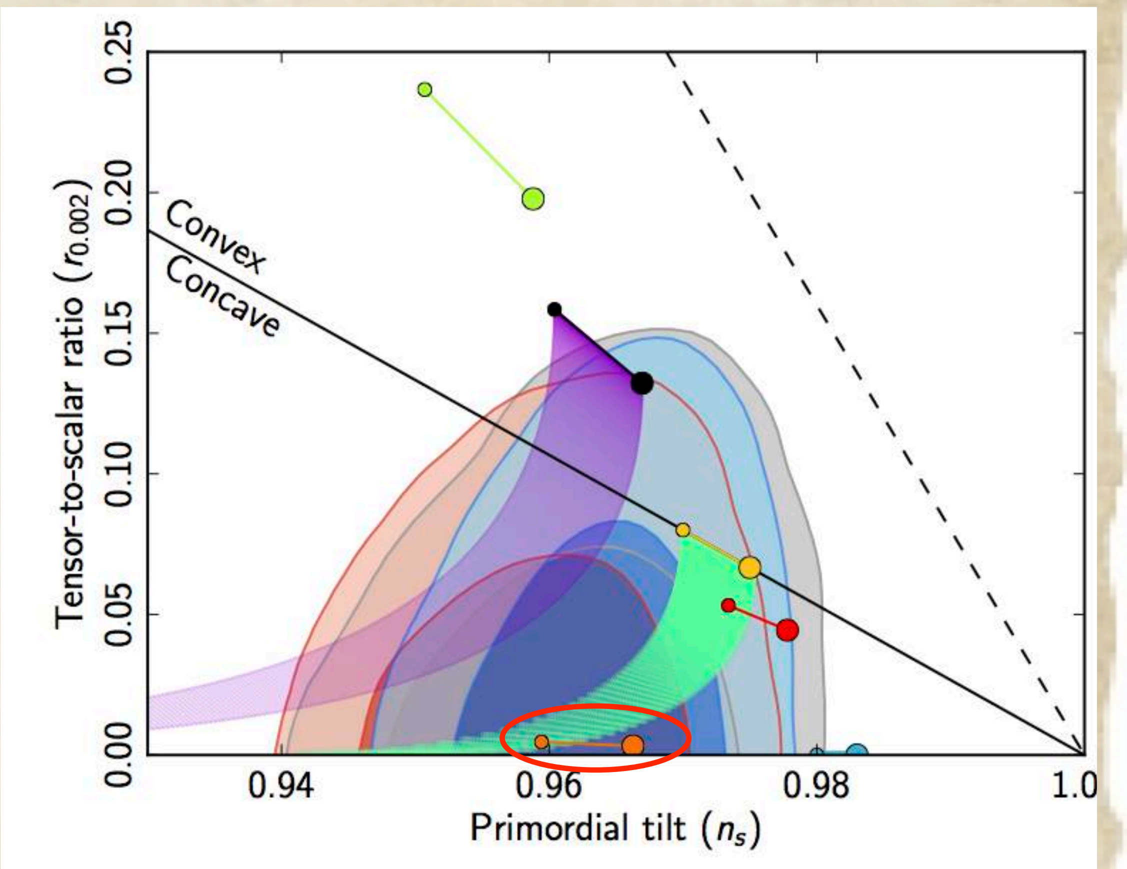
This determines other observables;

Scalar spectral index: $n_s \simeq 0.960 - 0.966$

Tensor-to-scalar ratio: $r \simeq 3 \times 10^{-3}$

Good agreement with Planck data



Courtesy H.Oide

Some issues in R^2 inflation

- How to explain the origin of R^2 term?

- Are there any higher order terms?
  How they affect if ever?

- Initial condition problem?

Courtesy H.Oide

Some issues in R^2 inflation

- How to explain the origin of R^2 term?

  Induce from high energy theories. (1st step) *Embed in Supergravity.*

- Are there any higher order terms?

  How they affect if ever?

  Consider the terms expected in Supergravity and compare with observation.

- Initial condition problem?

  Relatively small potential energy requires large homogeneous region that satisfies $(\partial_i \phi)^2 \ll V (\ll M_{\rm Pl}^4)$ *for inflation to start.*

  chaotic initial condition does not work.

Courtesy H.Oide

Embedding R^2 inflation in old minimal supergravity

('87) Cecotti, ('13) Farakos+

Start from D-term Lagrangian in super conformal theory

$$\mathcal{L} = -3[S_0\bar{S}_0]_D + 3\lambda_1[\mathcal{R}\bar{\mathcal{R}}]_D$$

$$[V]_D \equiv \int d^2\Theta \mathcal{E} P[V] + \mathrm{h.c.}$$

$$\mathcal{R} \equiv \frac{1}{2} S_0^{-1} P[\bar{S}_0]$$

Einstein-Hilbert action

R^2 term

After gauge fixing, $S_0 = 1$
the system leads to the supersymmetric R^2 system.

Courtesy H.Oide

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Einstein-Hilbert action   *R^2 term*

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Once more, it is easy to see the system in terms of the scalaron picture.

$$\mathcal{L} = -3[S_0 \bar{S}(T + \bar{T} - C\bar{C})]_D + \frac{6}{\sqrt{\lambda_1}} \left[S_0^3 C \left(T - \frac{1}{2} \right) \right]_F + \text{h.c.}$$

C: goldstiono; T: scalaron

Courtesy H.Oide

$$\mathcal{L} = -3[S_0\bar{S}(T+\bar{T}-C\bar{C})]_D + \frac{6}{\sqrt{\lambda_1}}\left[S_0^3 C\left(T-\frac{1}{2}\right)\right]_F + \text{h.c.}$$

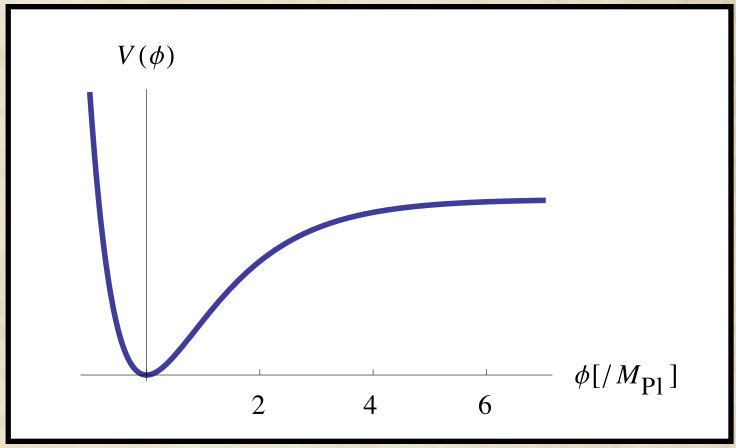
This is just the system with

Kähler potential: $K = T + T - C\bar{C}$

Superpotential: $W = C\left(T - \frac{1}{2}\right)$

By rewriting scalaron multiplet as

$$T = \frac{1}{2}\exp[\sqrt{2/3}\phi] + ib$$



and setting $C = b = 0$,

canonically normalized scalaron with a potential

$$V = \frac{6}{\lambda_1}\left(1 - \exp\left[-\sqrt{\frac{2}{3}}\frac{\phi}{M_{\rm Pl}}\right]\right)^2$$

is obtained.

Surely supersymmetrization of R^2 model !!

('13) Farakos+

Courtesy H.Oide

Higher order corrections ('13) Farakos+

Lowest order correction that modifies scalaron potential is...

$$\xi\left[\nabla^\alpha(\mathcal{R}/S_0)\nabla_\alpha(\mathcal{R}/S_0)\bar{\nabla}_{\dot\alpha}(\bar{\mathcal{R}}/\bar{S}_0)\bar{\nabla}^{\dot\alpha}(\bar{\mathcal{R}}/\bar{S}_0)\right]_D$$

In terms of scalaron picture, the full Lagrangian leads to

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$$+\frac{\xi}{\lambda_1^2}\left[\nabla^\alpha C\nabla_\alpha C\bar{\nabla}_{\dot\alpha}\bar{C}\bar{\nabla}^{\dot\alpha}\bar{C}\right]_D$$

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$$+\frac{\xi}{\lambda_1^2}\left[\nabla^\alpha C\nabla_\alpha C\bar{\nabla}_{\dot{\alpha}}\bar{C}\bar{\nabla}^{\dot{\alpha}}\bar{C}\right]_D$$

or in more familier expression,

$$\mathcal{L} = \int d^2\Theta 2\mathcal{E}\left[\frac{3}{8}\left(\bar{\mathcal{D}}\bar{\mathcal{D}}-8\mathcal{R}\right)e^{-K/3}+W\right]+\text{h.c.}$$
$$-\frac{\xi}{\lambda_1^2}\int d^2\Theta 2\mathcal{E}\left[\frac{1}{8}\left(\bar{\mathcal{D}}\bar{\mathcal{D}}-8\mathcal{R}\right)\mathcal{D}^\alpha C\mathcal{D}_\alpha C\bar{\mathcal{D}}^{\dot{\alpha}}\bar{C}\bar{\mathcal{D}}_{\dot{\alpha}}\bar{C}\right]$$

with the same Kähler/superpotential

Courtesy H.Oide

Additional term modifies the F-term of C field, and the resultant potential for scalaron ϕ is, now,

$$V(\phi) = \frac{3\lambda_1^2}{16\xi} e^{-2\sqrt{2/3}\phi} X(X-1)$$

with

$$X = \begin{cases} \cosh m & \text{for} \quad \xi > 0, \\ \cos \tilde{m} & \text{for} \quad \xi < 0 \end{cases}$$

$$m = \frac{1}{3} \cosh^{-1} \left[144 s((e^{\sqrt{2/3}\phi} - 1)^2 + 4b^2) + 1 \right]$$

$$\tilde{m} = \frac{1}{3} \cos^{-1} \left[144 s((e^{\sqrt{2/3}\phi} - 1)^2 + 4b^2) + 1 \right]$$

$$s \equiv \frac{\xi}{\lambda_1^3}.$$

This is just the supersymmetrization of R^4 correction!

Courtesy H.Oide

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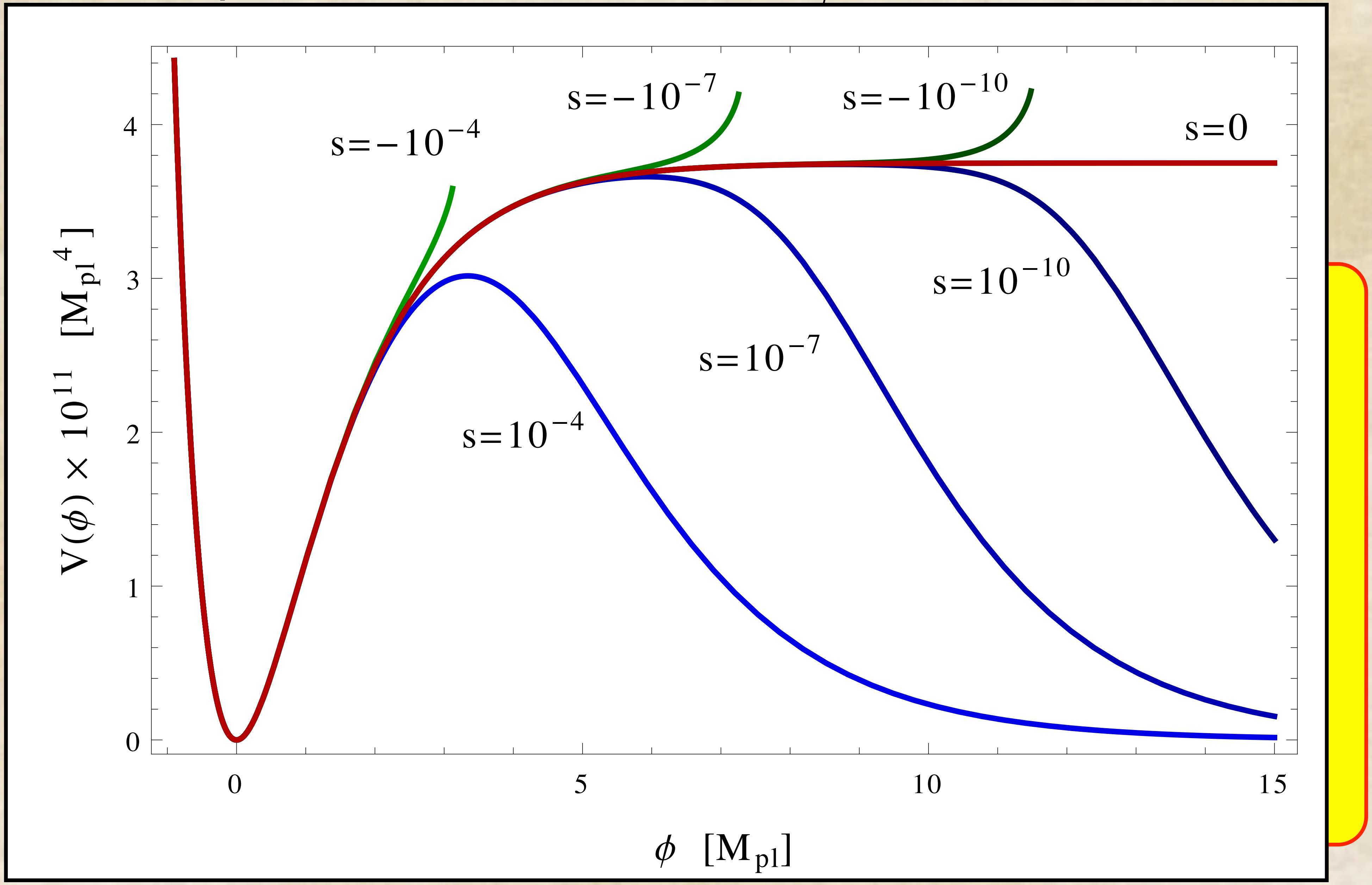

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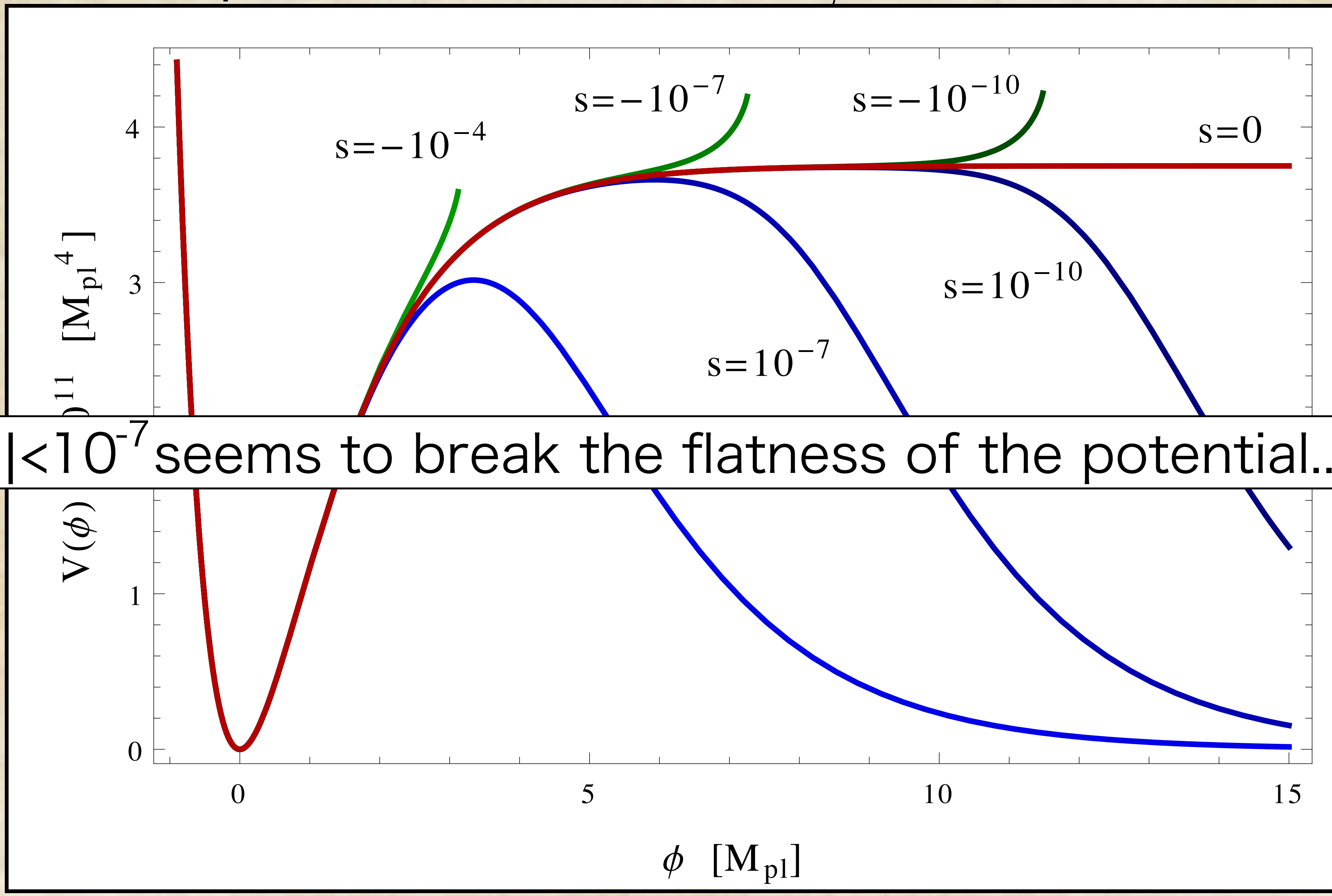


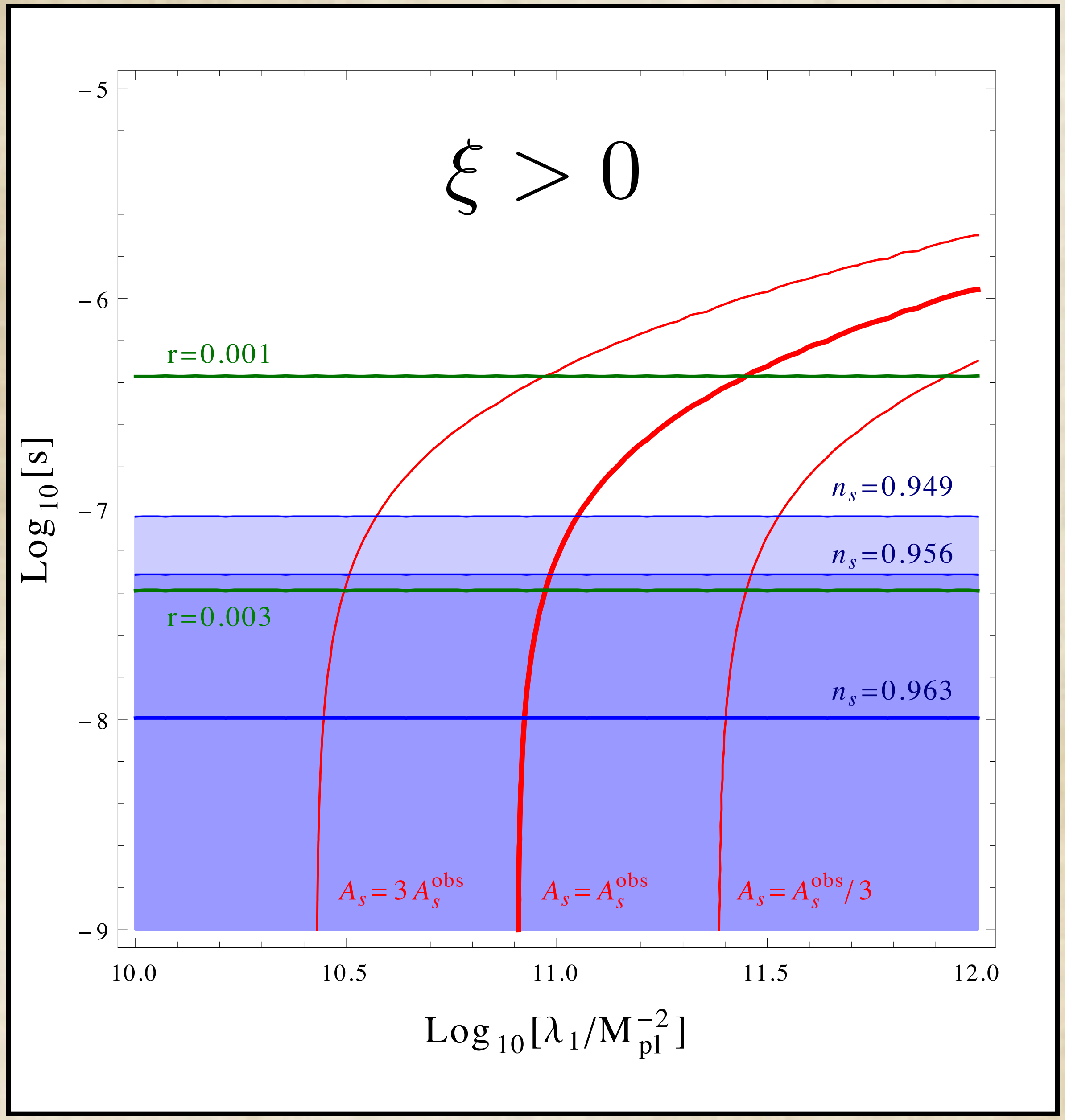
$|s|<10^{-7}$ seems to break the flatness of the potential...

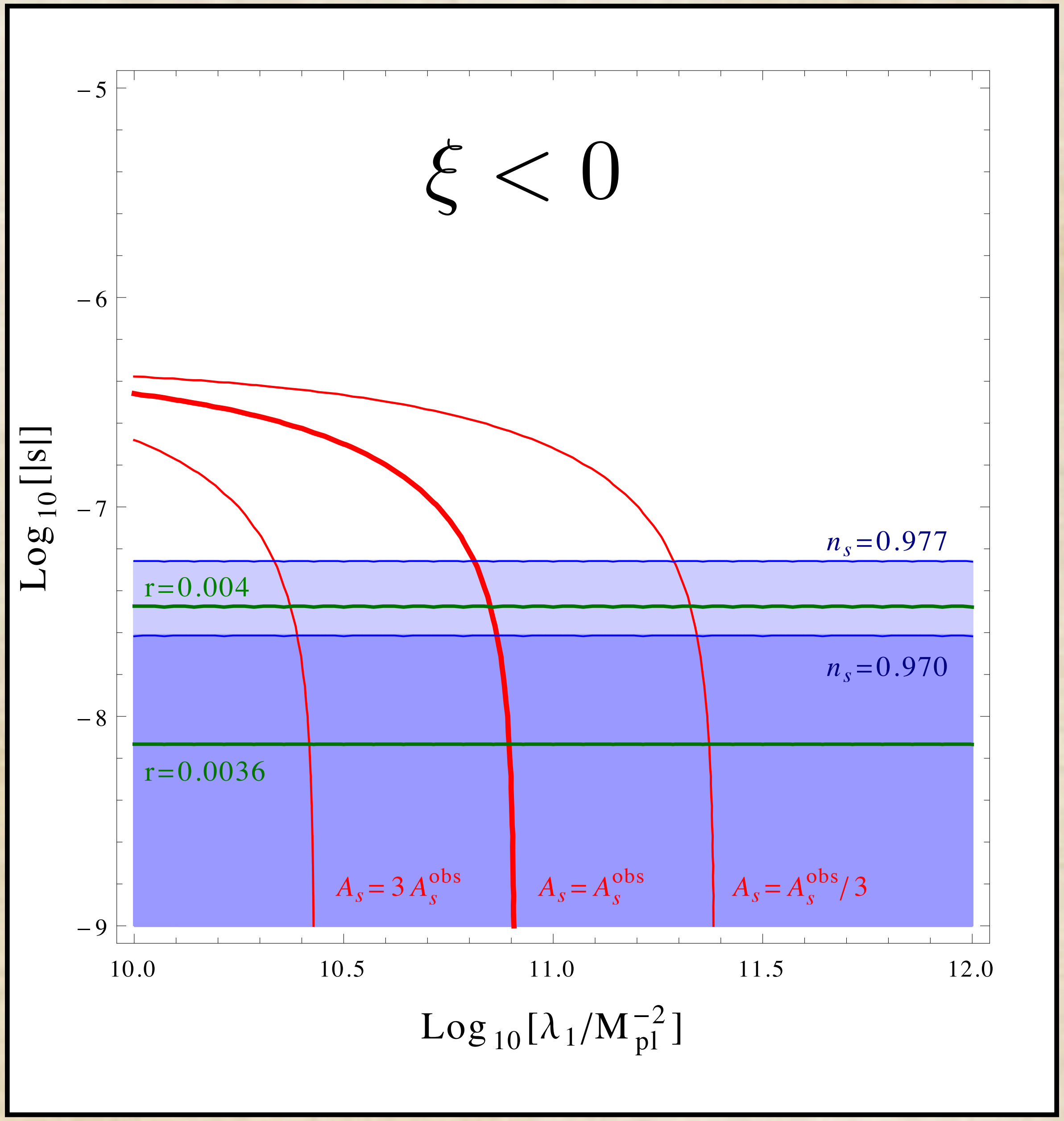
This is just the supersymmetrization of R^4 correction!

Courtesy H.Oide

More quantitatively, look at the observational constraint.

KK, in prep.





Courtesy H.Oide

Tuned initial condition is required?

…since nonzero higher correction make the inflationary region narrower…

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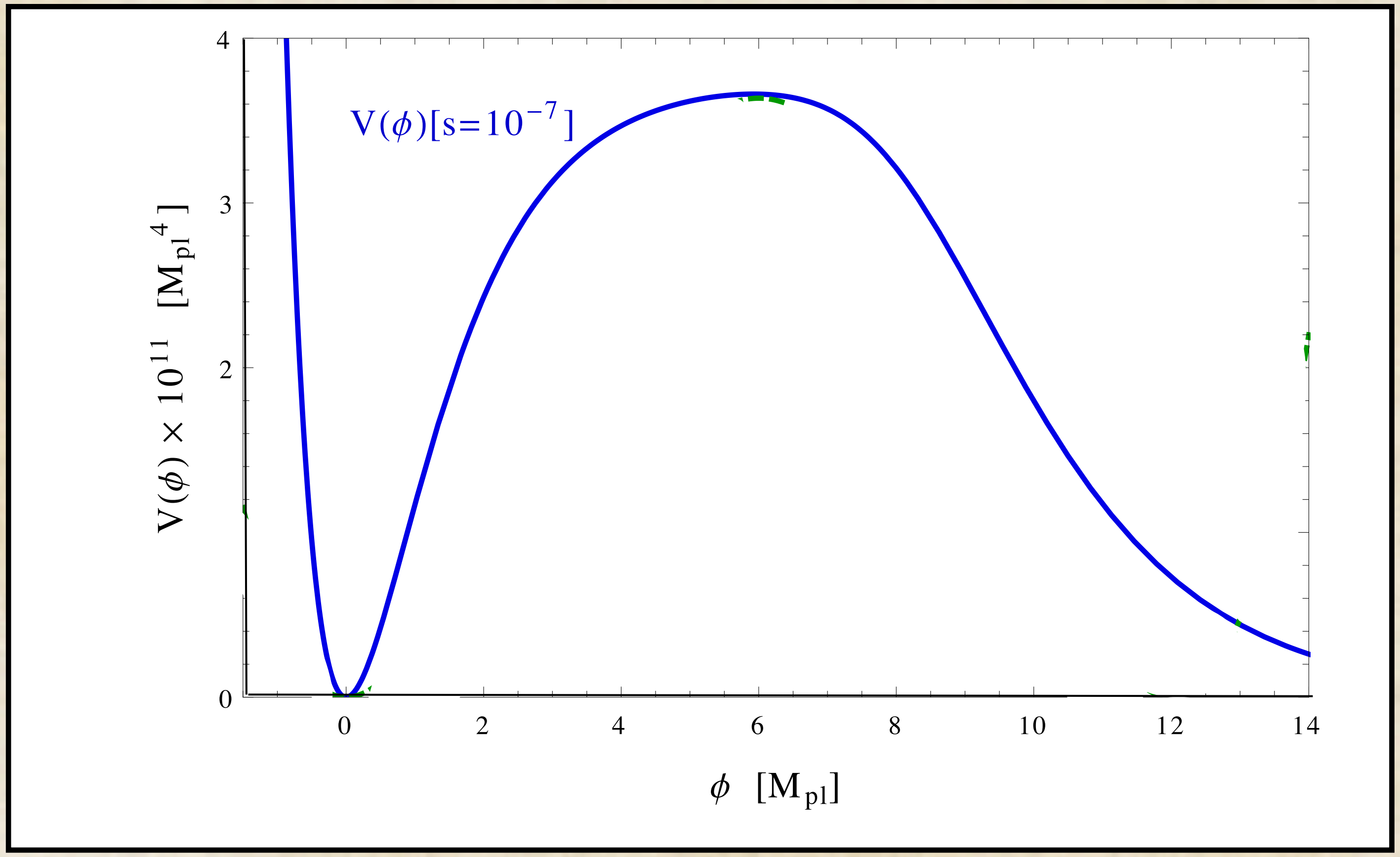
However, in the case $\xi > 0$ there is domain wall solution.



Is topological inflation possinle?

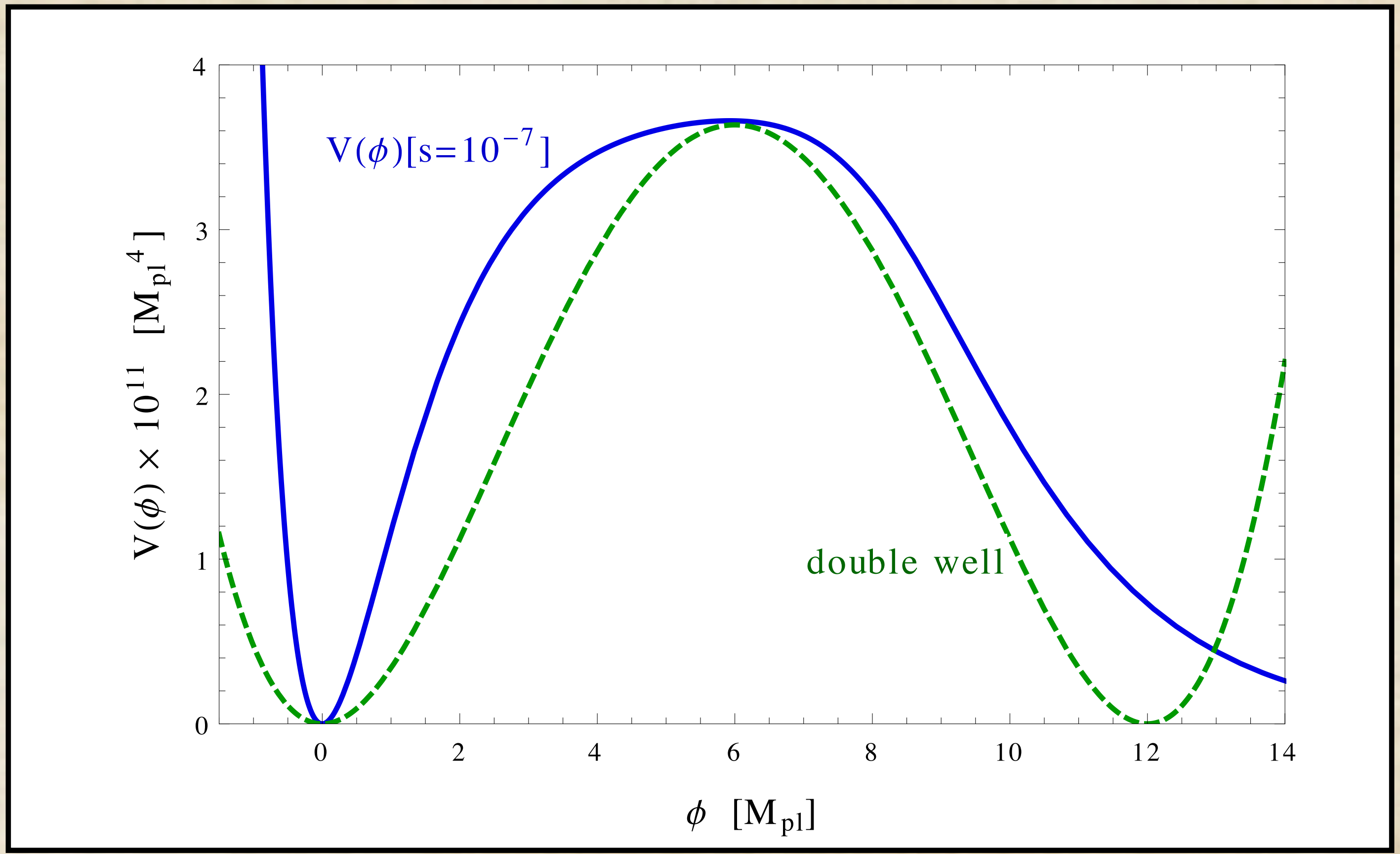
Courtesy H.Oide

It is known that for the double well potential

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

topological inflation, or inflation that starts from inside domain-wall is possible if $v > 1.7 M_{\rm pl}$. ('96)Sakai+

And the present potential is much flatter than double well potential with $\phi_{\rm max} > 6 M_{\rm Pl}$.



Courtesy H.Oide

Estimated thickness of the domain wall is also thick enough, for s>10^{-7}

$$H\delta \simeq 0.22 s^{-1/6}$$

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This circumstantial evidence strongly suggests that topological inflation will take place in this potential if the parameter is small enough to explain the observation.

Courtesy H.Oide

Conclusion

- R^2 inflation is still an interesting inflation model.
- Its supersymmetrization would be the clue to find its origin.
- The lowest correction corresponds to R^4 correction, and Planck observation gives a strong constraint as $|s| < 9\times10^{-8}$, which will be an important information for the physics behind the model.
- But if this constraint is passed, topological inflation is possible and hence there is no initial condition problem.

Courtesy H.Oide