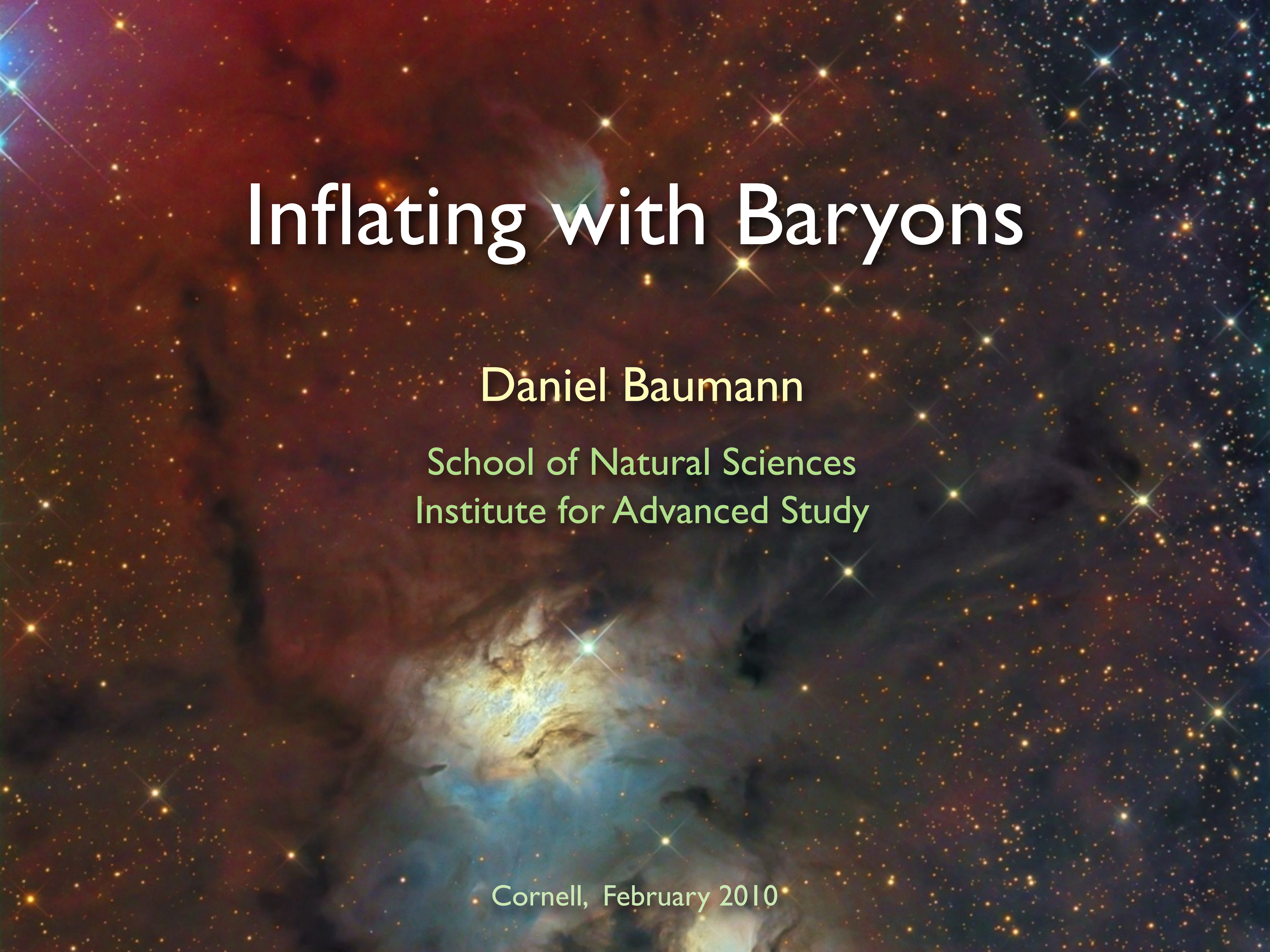

Inflating with Baryons

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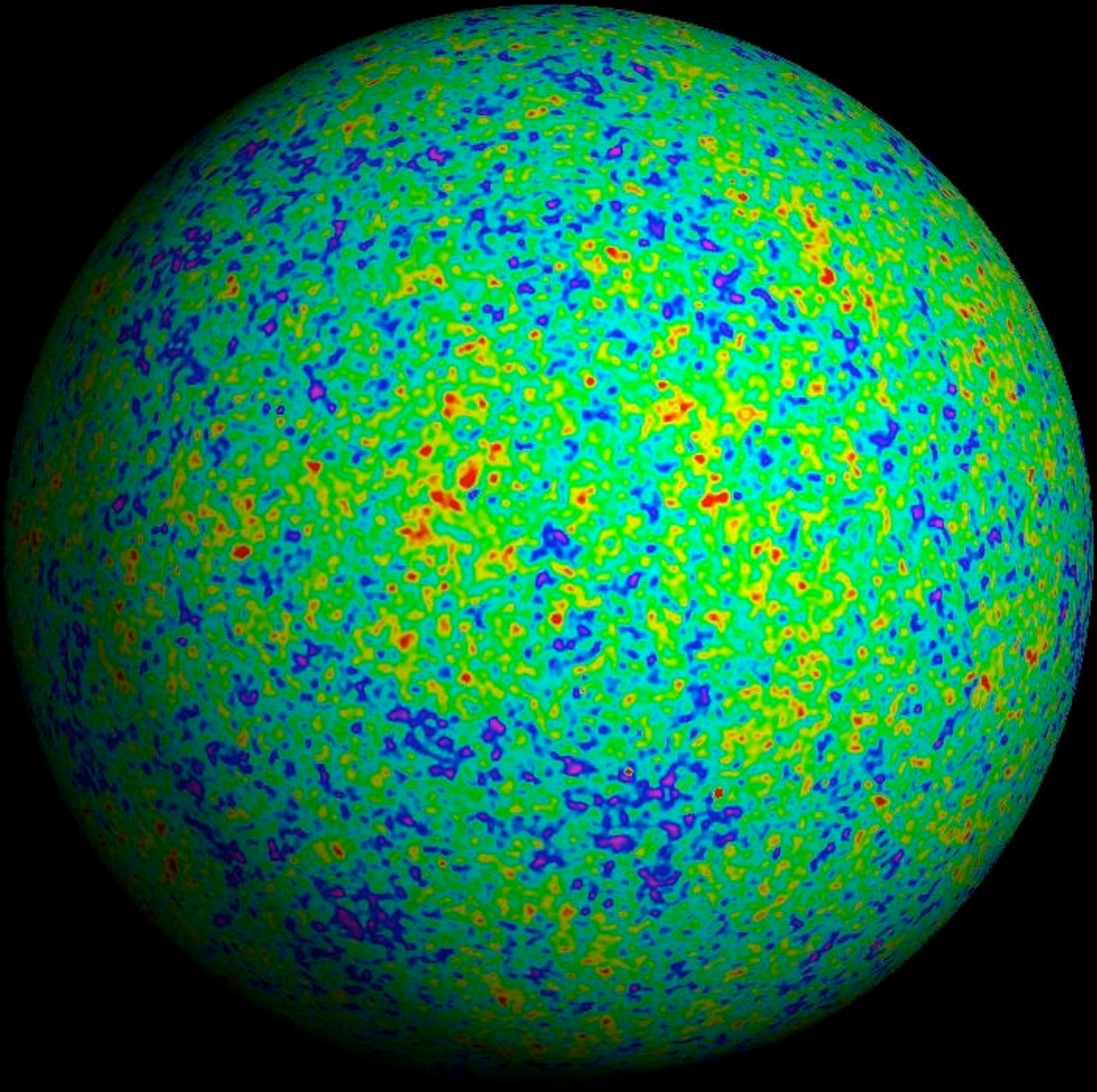
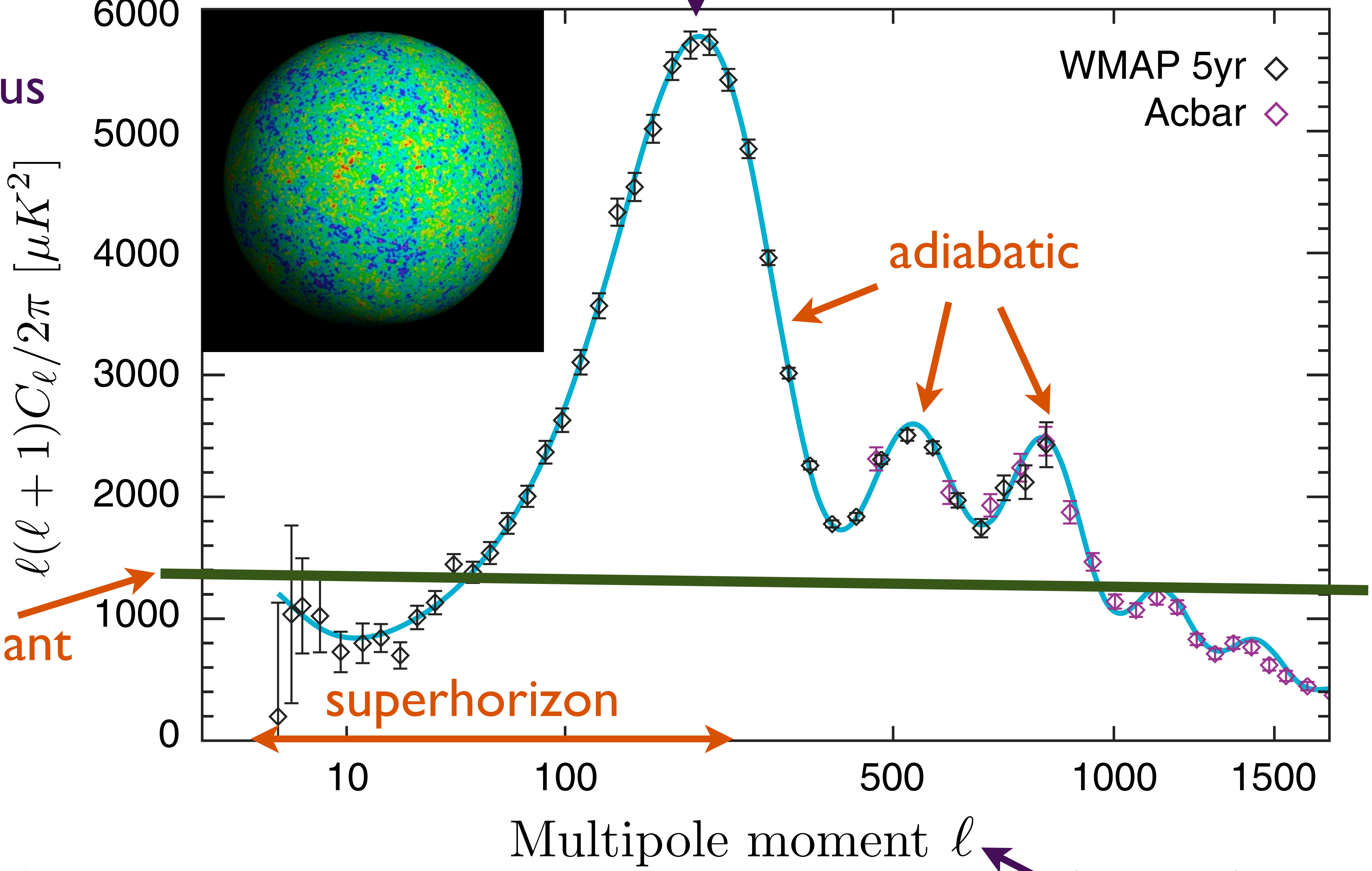
Cornell, February 2010



Inflation is an elegant explanation for the data:

Guth (1980)



flat

homogeneous

adiabatic

Gaussian

scale-invariant

superhorizon

isotropic

BUT:

What is the physics of inflation ?

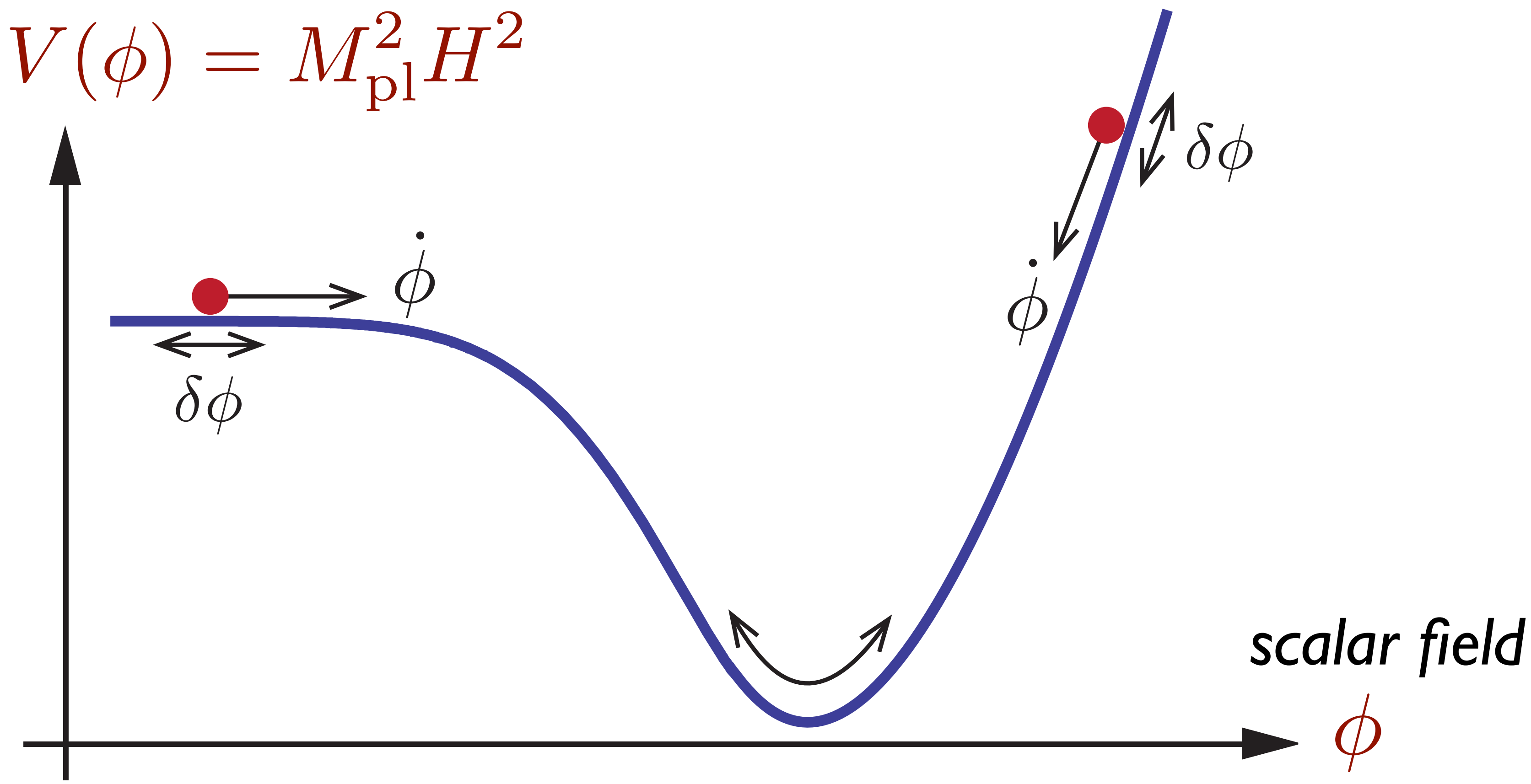
Outline

1. The Eta Problem

2. A Field Theory Solution

with Daniel Green

The Eta Problem



slow-roll inflation:

$$\varepsilon = \frac{M_{\rm pl}^2}{2}\left(\frac{V'}{V}\right)^2 \ll 1$$

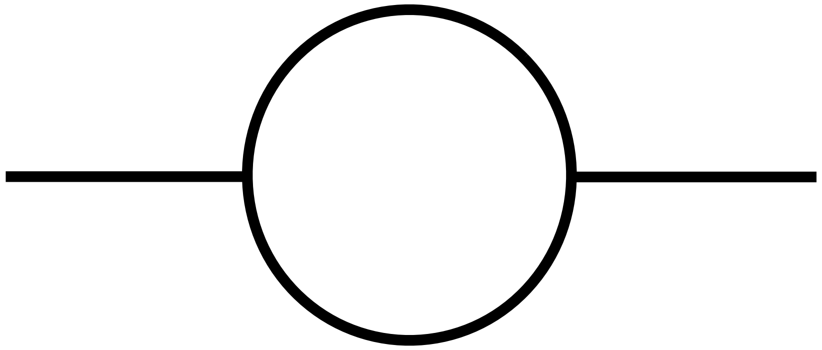
$$\eta = M_{\rm pl}^2 \frac{V''}{V} \ll 1$$

Why is the inflaton so light ?

$$\eta \approx \frac{m_\phi^2}{H^2} \ll 1$$

The Eta Problem

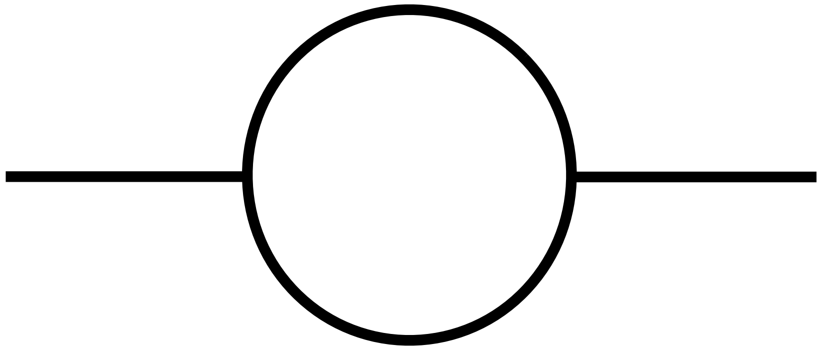
like the Higgs ***hierachy problem***



$$m_\phi^2 \sim \Lambda_{\rm uv}^2 \gg H^2$$

The Eta Problem

like the Higgs ***hierachy problem***



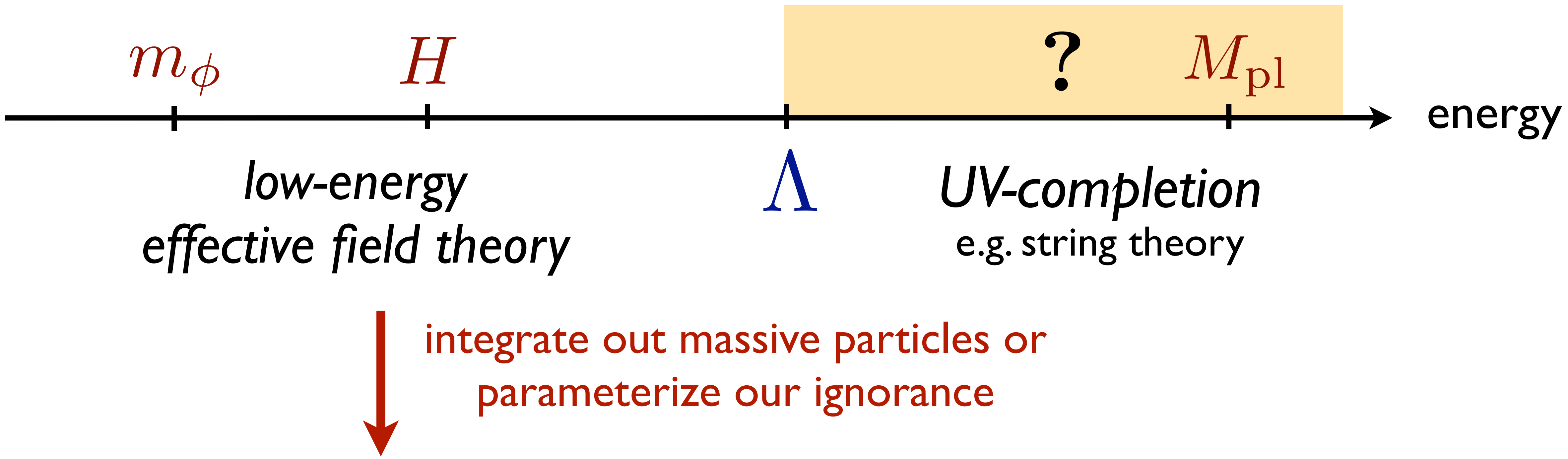
$$m_\phi^2 \sim H^2$$

supersymmetry ameliorates the problem,
but ***doesn't solve it***.

↓

need ***fine-tuning*** or ***additional symmetry***

The Eta Problem



m_ϕ H $?$ $M_{\rm pl}$

energy

Λ

low-energy effective field theory

UV-completion

e.g. string theory

integrate out massive particles or parameterize our ignorance

non-renormalizable interactions

$$\Delta\mathcal{L} = \sum_\delta \frac{\mathcal{O}_\delta(\phi)}{\Lambda^{\delta-4}}$$

In inflation, even Planck-suppressed interactions cannot be ignored!

The Eta Problem

Inflation is sensitive to

dimension-6 Planck-suppressed operators

$$\Delta V = V_0 \frac{\phi^2}{M_{\rm pl}^2}$$

Can we forbid corrections with a ***symmetry*** ?

The Eta Problem

shift symmetry

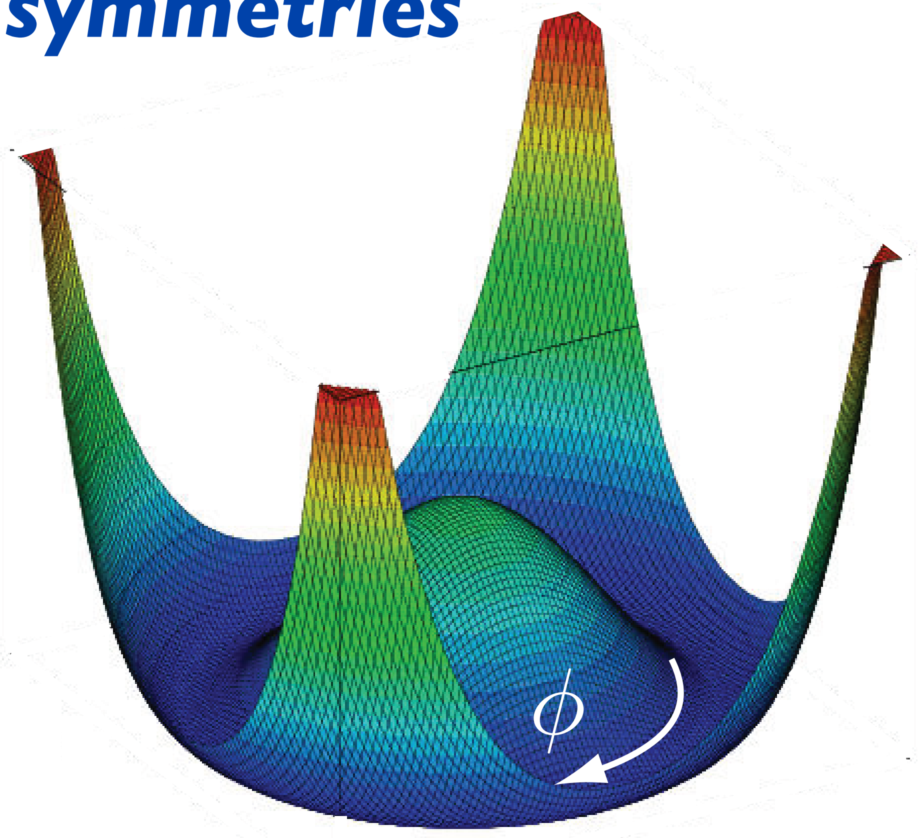
$$\phi \to \phi + const.$$

$$\xcancel{V_0 \frac{\phi^2}{M_{\rm pl}^2}}$$

↕

spontaneous breaking of global symmetries

Many models implement this solution in supergravity.



The Eta Problem

BUT:

“Quantum gravity breaks global symmetries.”

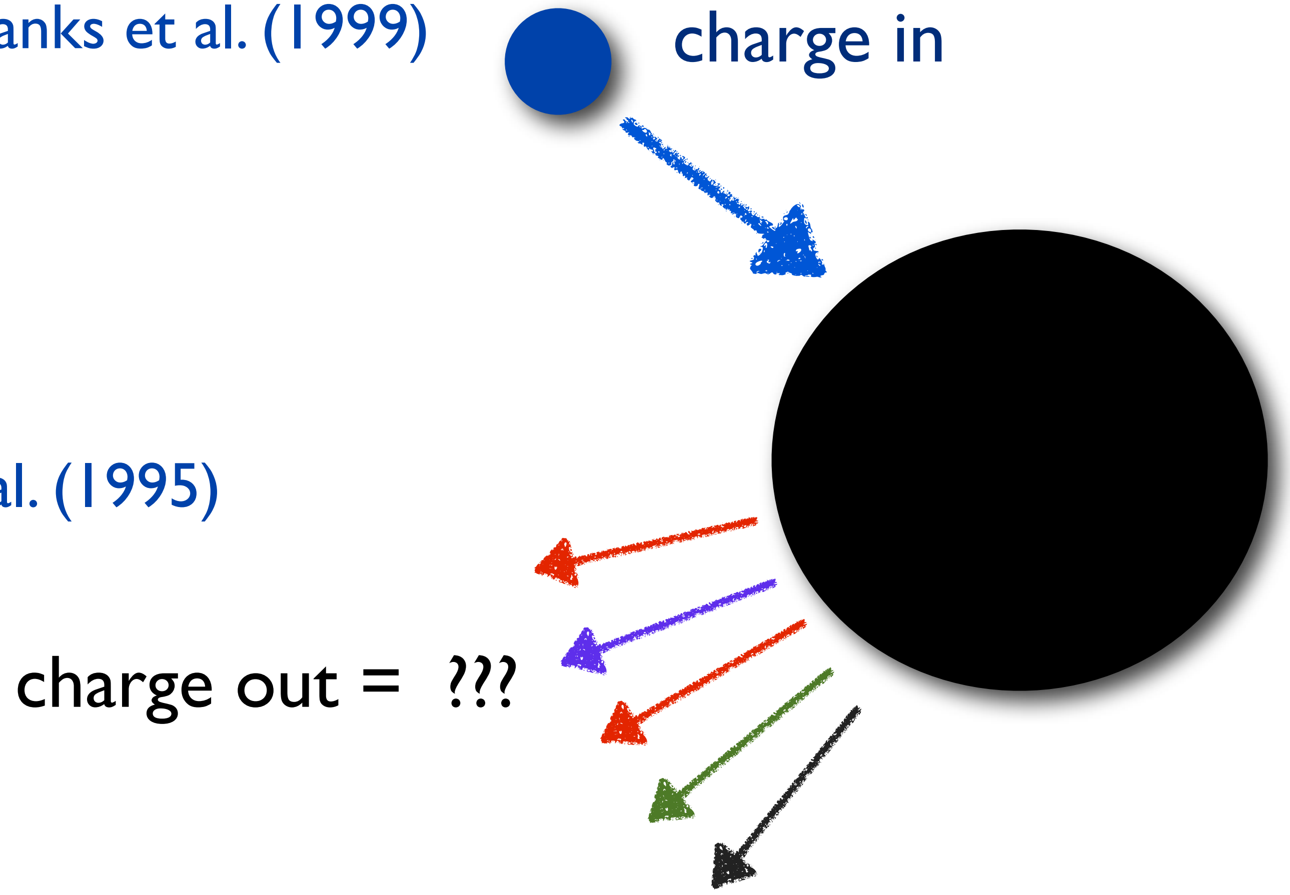
This is a theorem in perturbative string theory

Banks et al. (1999)

More generally:

Black hole evaporation
breaks global symmetries

e.g. Kallosh et al. (1995)



Planck-suppressed operators reintroduce the eta problem !

$$V_0 \frac{\phi^2}{M_{\rm pl}^2}$$

The Eta Problem

“Quantum gravity breaks global symmetries.”

protecting the inflaton from this is the real challenge:

1. compute the symmetry breaking effects in ***string theory***

2. find a sufficiently powerful symmetry in ***field theory***

Inflating with Baryons

with Daniel Green

arXiv:1009.3032

Proton Decay in the SM

experimental fact:

the proton has a very long lifetime

"I can feel it in my bones."
Wigner (1943)

imagine we didn't know about quarks and treated the proton as fundamental :

dimension-5 Planck-suppressed operators:

$$\frac{p\,\mathcal{O}}{M_{\rm pl}} \longrightarrow$$

induce rapid proton decay

$$\Gamma \sim \frac{m_p^3}{M_{\rm pl}^2} \sim 10^{-13}\,{\rm s}^{-1}$$

Proton Decay in the SM

experimental fact: the proton has a very long lifetime

explanation:

the Standard Model has an

"accidental" baryon number symmetry

gauge symmetries and particle content of the SM forbid renormalizable interactions that violate baryon number

in fact, there aren't even dimension-5 operators →

leading operators are dimension-6

$$\boxed{\frac{qqq\,\ell}{M_{\rm pl}^2}}$$

consistent with limits on proton decay.

Can we solve the eta problem
in a similar way ?

A New Solution to the Eta Problem

↓

Find a theory with an accidental global symmetry because its gauge symmetries and field content forbid symmetry-breaking operators with dimensions less than 7

existence proof:

baryons in SUSY QCD

baryon

$$\underset{\text{baryon}}{\mathcal{B}} = \underbrace{qq\cdots q}_{\text{quarks}}$$

quarks

no dangerous Kähler and superpotential corrections !!

PNGBs in SUGRA

Supergravity Eta Problem

Copeland et al.

$$V = e^{K/M_{\rm pl}^2}\left[K^{\Phi\bar{\Phi}} D_\Phi W \overline{D_\Phi W} - \frac{3}{M_{\rm pl}^2}|W|^2\right]$$

F-term vacuum energy drives inflation:

$$D_X W = \mu^2$$

$$V = \left(1 + \frac{K}{M_{\rm pl}^2} + \cdots\right)\mu^4$$

tied to kinetic term

$$K = \Phi^\dagger \Phi \xrightarrow[\varphi \equiv |\Phi|]{} \eta = 1 + \cdots$$

extra terms from $W(\Phi)$

can lead to (fine-tuned) cancellations

cf. brane inflation

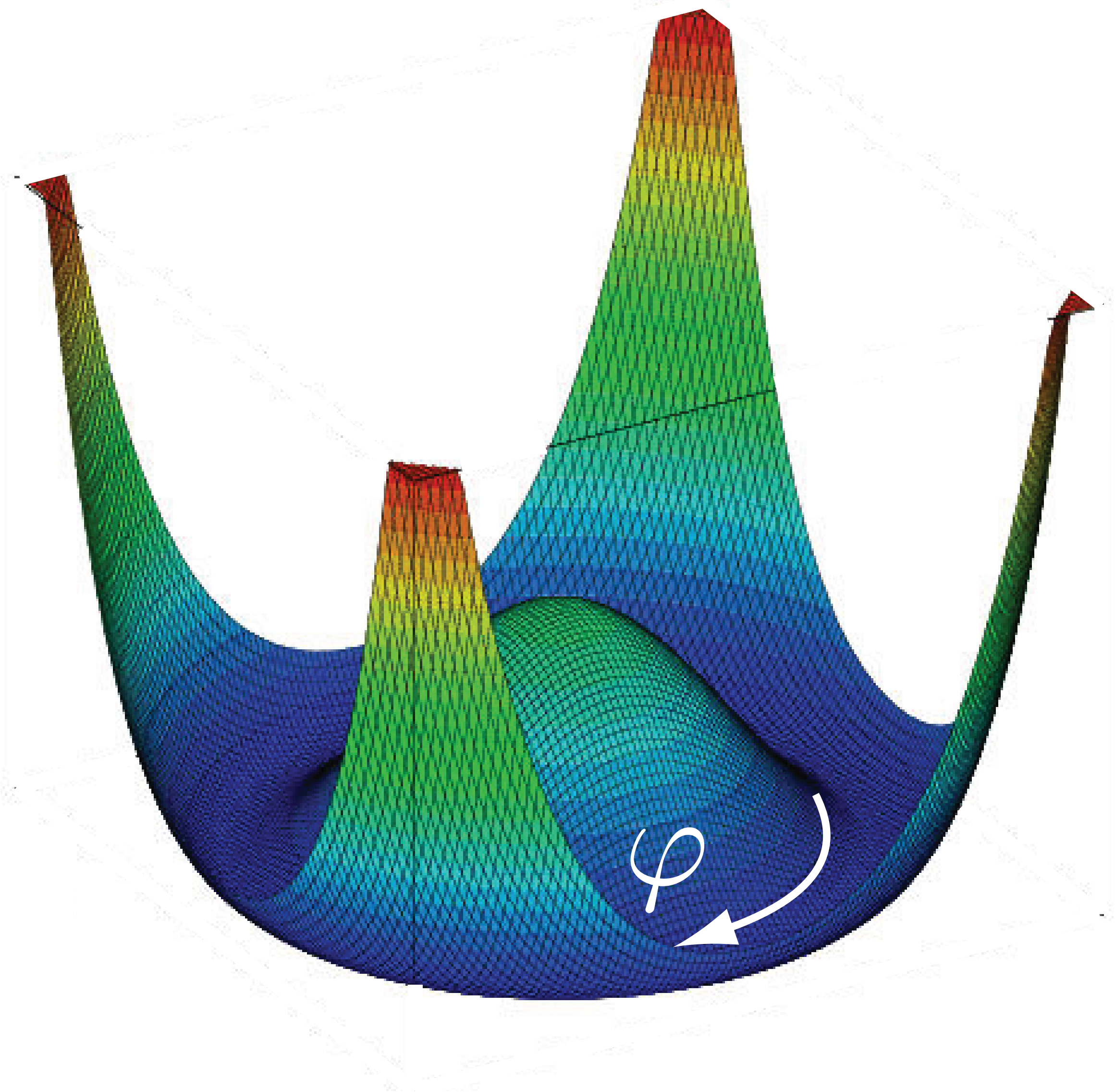
PNGBs in SUGRA

$$\Phi = f e^{\phi} \longrightarrow K = \Phi^\dagger \Phi = f^2 e^{\phi + \phi^\dagger}$$

$$\downarrow$$

no mass for

$$\varphi \equiv f \, \mathrm{Im}(\phi)$$



"a Goldstone boson coupled to gravity is a Goldstone boson"

A Simple Model

$$W = \overset{\text{vacuum energy}}{-\underset{\text{spurion}}{X}\mu^2} + \overset{\text{spontaneous symmetry breaking}}{\underset{\text{singlet}}{S}(\underset{\text{chiral superfields}}{\Phi\tilde{\Phi}} - \underset{\text{breaking scale}}{f}{}^2)}$$

$$\begin{tikzcd}
F_X = \mu^2 \arrow[d] & F_S = 0 \arrow[d] \\
V_0 = \mu^4 & \Phi = f e^{\phi} \quad \tilde{\Phi} = f e^{-\phi}
\end{tikzcd}$$

inflaton = PNGB

$$\varphi = f\,\mathrm{Im}(\phi)$$

A Simple Model

vacuum energy spontaneous symmetry breaking

$$W = -X\mu^2 + S(\Phi\tilde{\Phi} - f^2)$$

add *waterfall fields* to end inflation

$$\Delta W = m(\varphi)\,\psi\tilde{\psi} + y^2 X \psi^2$$

singlet coupling

inflaton-dependent mass

e.g. $m(\varphi) = \Phi + \tilde{\Phi}$

$m(\varphi \approx 0) \gg y\mu$ $V \approx V_0 > 0$

$m(\varphi = \varphi_\star) < y\mu$ $V \to 0$

→ *hybrid inflation*

A Simple Model

Pseudo Natural Inflation

Arkani-Hamed et al.

$$\boxed{W = S(\Phi\tilde{\Phi} - f^2) + \lambda(\Phi + \tilde{\Phi})\,\psi\tilde{\psi} + X(y^2\psi^2 - \mu^2)}$$

symmetry breaking waterfall vacuum energy

Planck-Scale Corrections

Pseudo Natural Inflation

Arkani-Hamed et al.

$$\boxed{W = S(\Phi\tilde{\Phi} - f^2) + \lambda\,(\Phi + \tilde{\Phi})\,\psi\tilde{\psi} + X(y^2\psi^2 - \mu^2)}$$

ΔK

Dimension 5: $c\,\frac{\Phi}{M_{\rm pl}}X^\dagger X \longrightarrow \eta = c\,\frac{M_{\rm pl}}{f} \gg 1$

Dimension 6: $(c_0\,\Phi^\dagger\tilde{\Phi} + c_1\,\Phi^2 + c_2\,\tilde{\Phi}^2)\frac{X^\dagger X}{M_{\rm pl}^2}$

$$\big\downarrow$$

$$\boxed{\eta = c_i \sim 1}$$

ΔW many dangerous corrections.

Goal: Construct a model of inflation that is insensitive to Planck-scale corrections.

↓

baryons in SUSY QCD

Baryon Inflation

SUSY QCD

- Gauge symmetry: $SU(\underset{\text{colors}}{N_c})$
- Matter content:

$\underset{\text{(IR free)}}{N_f > 3N_c}$ flavors of quarks $(q_i)_a$

and anti-quarks $(\tilde{q}_i)^a$

gauge index

flavor index

mesons $\mathcal{M}_{ij} = (q_i)_a (\tilde{q}_j)^a$

baryons $\boxed{\mathcal{B}_{i..k} = \epsilon^{a..d}(q_i)_a..(q_k)_d}$

Baryon Symmetry

$U(1)_B$

		Q_B	Δ
quarks	q_i	$+1$	1
	$\tilde{q}_i$	-1	1
mesons	$\mathcal{M}_{ij}$	0	2
baryons	$\mathcal{B}_{i..k}$	$+N_c$	N_c
	$\tilde{\mathcal{B}}_{i..k}$	$-N_c$	N_c

$N_c \geq 3$ $\longrightarrow$ all baryon symmetry violating operators are irrelevant !

Inflating with Baryons

use the phase of a baryon as the inflaton

vacuum energy spontaneous symmetry breaking

$$W = -X\mu^2 + S^{mn}(q_m\tilde{q}_n - f^2\delta_{mn})$$

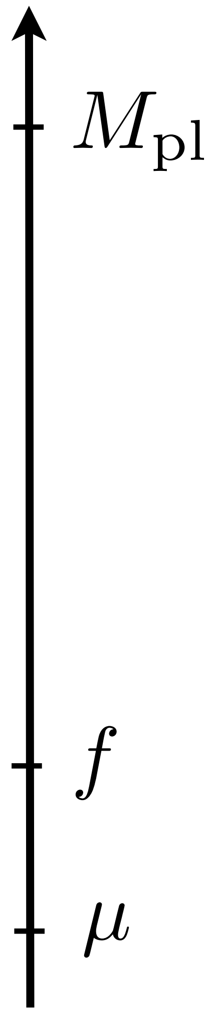
flavor indices
$m, n = 1..N_c$

$$\begin{tikzcd} F_X = \mu^2 \arrow[d] & F_S = 0 \arrow[d] \\ V_0 = \mu^4 & (q_m)_a = f e^{i\frac{\varphi}{f}} \delta_{m,a} \end{tikzcd}$$

$$(\tilde{q}_n)^a = f e^{-i\frac{\varphi}{f}} \delta_n^a$$

quarks get vev's

Absence of the Eta Problem



- ***Kähler Corrections***

$$\Delta K = \frac{\mathcal{B}}{M_{\rm pl}^{N_c}} X^\dagger X \quad \longrightarrow \quad \Delta\eta = \left(\frac{f}{M_{\rm pl}}\right)^{N_c - 2}$$

$\boxed{N_c \geq 3}$ *no Kähler corrections !!*

- ***Superpotential Corrections***

$$\Delta W = \frac{\mathcal{B}}{M_{\rm pl}^{N_c - 2}} X \quad \longrightarrow \quad \Delta\eta = \left(\frac{f}{M_{\rm pl}}\right)^{N_c - 4} \frac{f^2}{\mu^2}$$

$\boxed{N_c \geq 5}$ *everything suppressed !!*

Graceful Exit ?

add *waterfall fields* to end inflation

$$\Delta W \;=\; m(\varphi)\,\psi\tilde{\psi} + y^2 X\,\psi^2$$

singlet

$$m(\varphi) = \lambda\,\frac{\mathcal{B}+\tilde{\mathcal{B}}}{M_{\rm pl}^{N_c-1}} = \lambda\, f\left(\frac{f}{M_{\rm pl}}\right)^{N_c-1}\cos(\varphi/f) \quad ?$$

- ***problem:***

mass of the waterfall can't be bigger than Hubble

$$m \gg H \sim \frac{\mu^2}{M_{\rm pl}} \quad \longleftrightarrow \quad \lambda \gg (\Delta\eta)^{-1}\frac{M_{\rm pl}^2}{f^2} \gg 1$$

Graceful Exit ?

- problem: *mass of the waterfall can't be bigger than Hubble*

- reason: *coupling between the inflaton and the waterfall is irrelevant*

$$\lambda \, \frac{\mathcal{B}+\tilde{\mathcal{B}}}{M_{\rm pl}^{N_c-1}} \, \psi\tilde{\psi}$$

- solution: *mediate the baryon symmetry breaking effects by relevant couplings of quarks to larger representations of SU(N_c)*

I will illustrate this solution to the graceful exit problem with a concrete example:

SU(5) SUSY QCD

An Explicit SU(5) Model

matter content

quarks q

baryons $\mathcal{B}$

waterfall ψ ← singlet

messenger h ← larger representation

$$\mathbf{10} \quad h_{ab}$$

allows couplings to quarks
that break the baryon symmetry

$$qhh \equiv \epsilon^{abcde} q_a h_{bc} h_{de} \qquad \mathbf{5\text{-}10\text{-}10}$$

we will use these couplings to construct marginal
operators that couple the inflaton to the waterfall fields

An Explicit SU(5) Model

$$W \supset m\psi\tilde{\psi} + \lambda\, q_1 h h$$ waterfall mass

$$+ (\psi q_3 + \tilde{q}_2 \cdot h) \cdot \tilde{Q}_6 + (\tilde{\psi} q_5 + \tilde{q}_4 \cdot h) \cdot \tilde{Q}_7$$ mediation

$$\begin{tikzcd}
\tilde{q}_2 \cdot h \arrow[d] & \tilde{q}_4 \cdot h \arrow[d] \\
h_{23} = \psi\, e^{2i\frac{\varphi}{f}} & h_{45} = \tilde{\psi}\, e^{2i\frac{\varphi}{f}}
\end{tikzcd}$$

$$\begin{tikzcd}
 & & \tilde{Q} \arrow[dr, leftrightarrow] & & \\
\varphi \arrow[r, leftrightarrow] & h \arrow[ur, leftrightarrow] & & \psi \arrow[r] & m(\varphi)\,\psi\tilde{\psi}
\end{tikzcd}$$

An Explicit SU(5) Model

$$W \supset m\psi\tilde{\psi} + \lambda\, q_1 hh$$

waterfall mass

$$+ (\psi q_3 + \tilde{q}_2 \cdot h) \cdot \tilde{Q}_6 + (\tilde{\psi} q_5 + \tilde{q}_4 \cdot h) \cdot \tilde{Q}_7$$

mediation

integrate out $\tilde{Q}$

$$h_{23} = \psi\, e^{2i\frac{\varphi}{f}} \qquad h_{45} = \tilde{\psi}\, e^{2i\frac{\varphi}{f}}$$

$$\boxed{W_{\text{eff}} = m\left(1 + d\, e^{5i\frac{\varphi}{f}}\right)\psi\tilde{\psi} + X\left(y^2\psi^2 - \mu^2\right)}$$

This is just our U(1) model,
but with the U(1) now *explained* !

where $d \equiv \dfrac{\lambda f}{m}$

(add Kähler and superpotential corrections as you wish)

Revisiting the Eta Problem

We added extra representations.

Do these introduce new dangerous contributions to eta?

NO

DB and Daniel Green
arXiv:1009.3032

waterfall and mediator fields have ***zero vev's*** during inflation

→ correct the inflaton potential only at ***one-loop***

→ this is sufficient to keep eta small.

Summary

Explained origin of approximate U(1) symmetry !!

Baryon symmetry was only broken by irrelevant operators.

Constructed an explicit inflationary model

SU(5) gauge group

Waterfall fields in 10 + 1 representations

... without an eta problem !

All contributions to eta suppressed
(both Kähler and superpotential)

Conclusions

Generic models of inflation
are Planck-sensitive

*Baryon number can be Planck-**insensitive***

Provides a field theory explanation
for the small inflaton mass

Thank you for your attention!

and thanks to my collaborator:

Daniel Green