

Cosmology with pseudo Nambu-Goldstone Bosons

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with M. Anber, K. Dutta, N. Kaloper

A **COSMOLOGICAL CONSTANT** $\Lambda \cong (10^{-3} \text{ eV})^4$

is the simplest candidate
for the current phase of cosmic acceleration

(and even in excellent agreement with data!)

...but **Quintessence**
remains as a logical possibility

QUINTESSENCE

A couple of problems...

- Radiative stability of the potential?
- Long Range forces?

Same problem as for the cosmological constant, just much worse:


- for the c.c., need to justify one small number
- for quintessence, many parameters must be small

(e.g.: not only the height of the potential, but also its slope + couplings to matter)

A “good” model of quintessence

Quantum corrections are the enemy:

To protect ourselves against them, we invoke
symmetries



A field φ has a **shift symmetry** if the theory that describes it is invariant under the transformation

$$\varphi \rightarrow \varphi + c$$

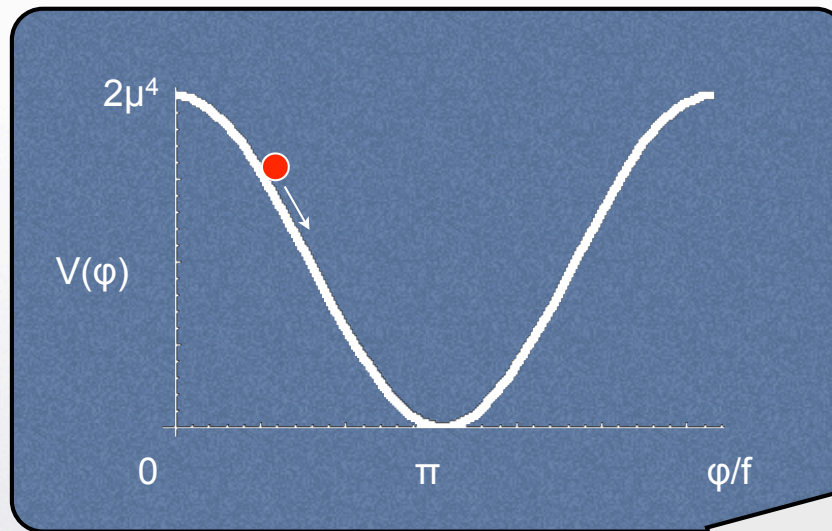
If this symmetry is exact, the only possible potential for φ is $V(\varphi)=\text{constant}$

(i.e. a cosmological constant...)

now let us break the shift symmetry a little bit...
the potential for φ changes to

$$V(\varphi) = \mu^4 [\cos(\varphi/f) + 1]$$

Frieman et al 1995
(<1998!)



PSEUDO-NAMBU-GOLDSTONE BOSON
PNGB

two parameters:

- f associated to normalization of φ



flat potential in limit $f \rightarrow \infty$

- μ related to breaking of global $U(1)$ symmetry

typically

$$\mu^4 \cong M_P^4 e^{-S}$$

instanton action

$$\mu \cong 10^{-3} \text{ eV} \Rightarrow S \cong 280$$

Because of its radiative stability,

*A pNGB is an extremely well motivated (the best?)
model of quintessence
from the point of view of effective field theory*

What about long range forces?

Usually dangerous operators of the form

$$\delta\mathcal{L} \sim \beta \frac{\phi}{M_P} \bar{\psi} \langle h \rangle \psi$$

The diagram shows the equation $\delta\mathcal{L} \sim \beta \frac{\phi}{M_P} \bar{\psi} \langle h \rangle \psi$ with a large red 'X' over it. An arrow points from the ϕ to a box containing the text "Forbidden by shift symmetry and ϕ pseudoscalar!". Another arrow points from the $\langle h \rangle$ to the text "Higgs vev \propto mass of particle". Below the crossed-out equation, the text "Allowed term" is written.

Forbidden by shift symmetry and ϕ pseudoscalar!
 Must be smaller than $\sim 10^{-4}$!

Higgs vev \propto mass of particle

Allowed term

$$\delta\mathcal{L} \sim \beta' \frac{\partial_\mu \phi}{M_P} \bar{\psi} \gamma^\mu \gamma^5 \psi$$

With no serious constraints (because of γ^5) on β'

...but parity is broken by the vev of φ ...
...and shift symmetry is broken by the potential of φ !

Possible new operators of the form

$$\delta\mathcal{L} \sim e^{-S'} \cos(\phi/v) \bar{\psi}\langle h\rangle\psi$$

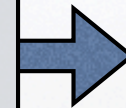
can be dangerous unless S' is large enough.

*...but, since S has to be very large,
we can expect also S' to be large enough*

How many parameters do we need to describe pNGB quintessence?

In principle three parameters: μ, f and φ_0 (initial value of φ)

Only two independent parameters left when we require that today the energy of the pNGB is $\sim 70\%$ of the total (as required by observations)



f

φ_0

Requirements from strings

String Theory appears to require

Banks, Dine, Fox and Gorbатов 03

$$0 < f \lesssim M_P$$

since also $0 < \varphi_0 < 2\pi f$,

the parameter
space of the model
is compact:

We can hope to exclude the whole model!

Analysis of the parameter space of the model

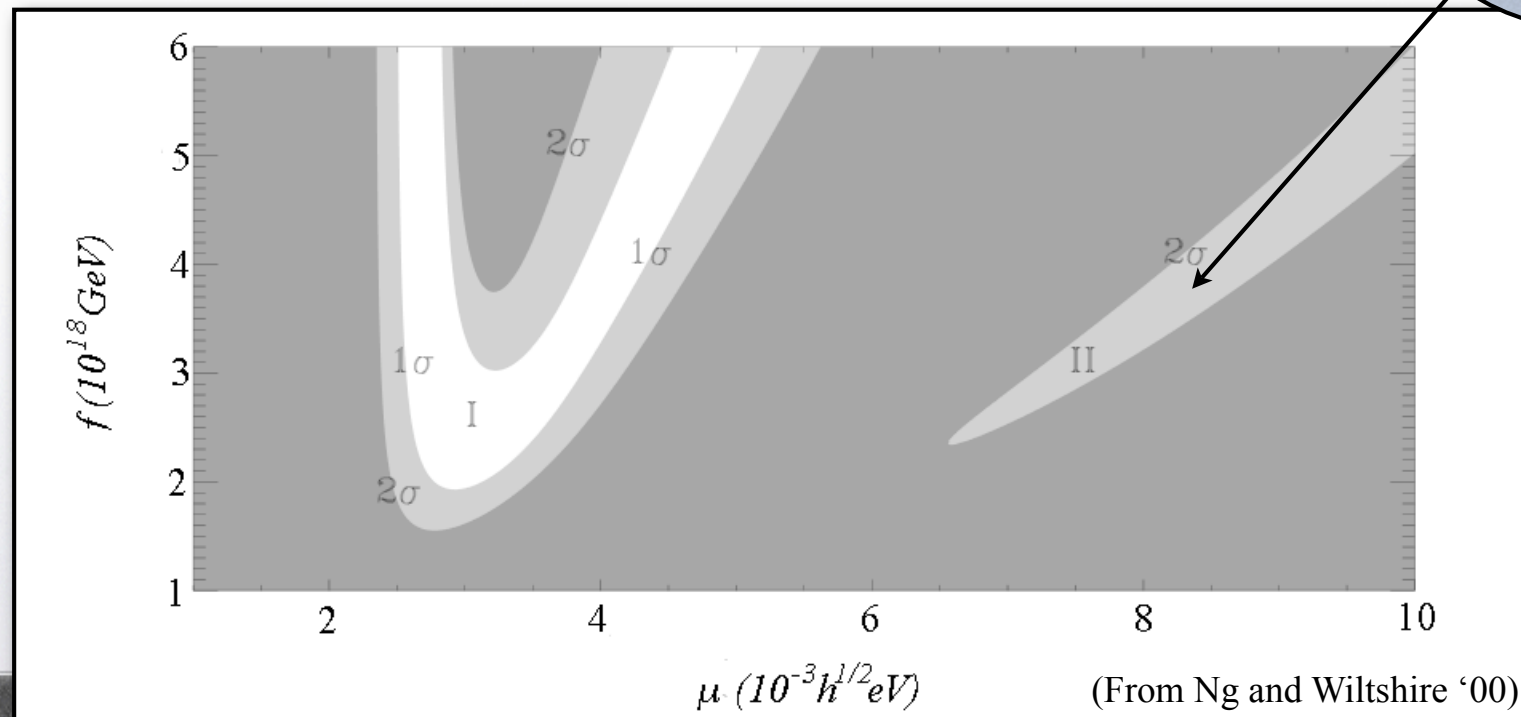
(K. Dutta, LS 2007)

Previous literature: Frieman and Waga (2000)
Ng and Wiltshire (2000)

Analysis using type Ia SNe and gravitationally lensed quasars

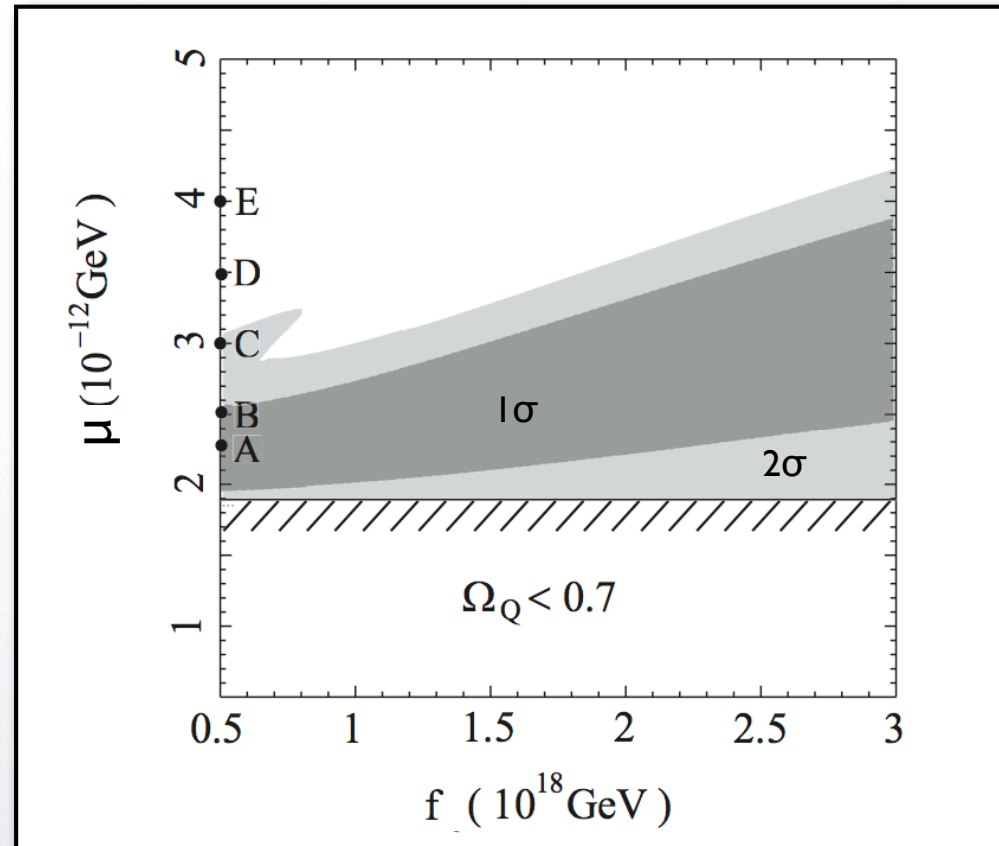
Both impose the constraint $\varphi_0 = 1.06 M_P$

pNGB
“climbing
the hill”



More previous literature: [Kawasaki, Moroi, Takahashi \(2001\)](#):

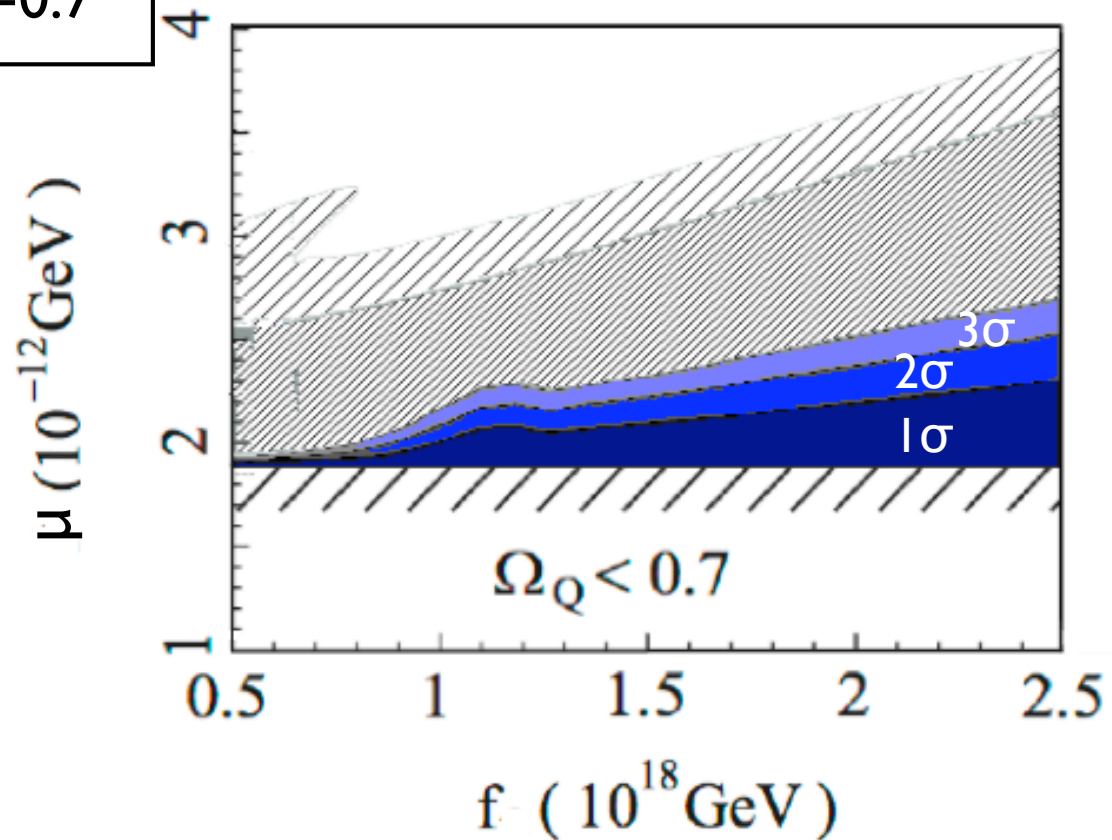
Constraints from CMB only
(pre-WMAP data):



Our results

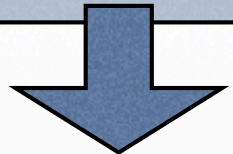
Enforcing
 $\Omega_\phi=0.7$

constraints from the
182 supernovae of
the *gold* sample of
Riess et al, 2006



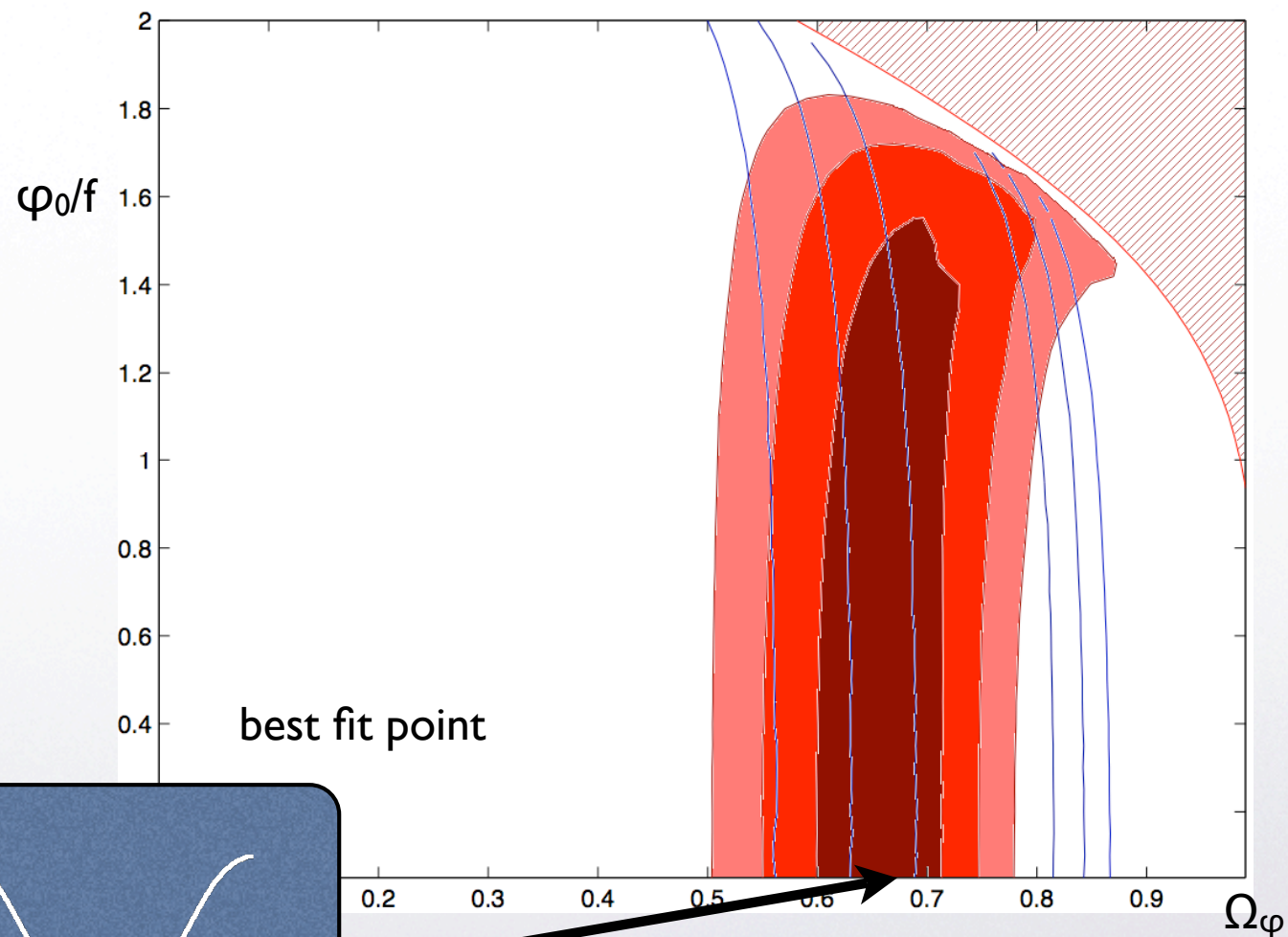
Our results (cont'd)

Without
assumption
 $\Omega_\phi=0.7$



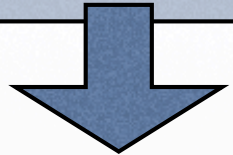
One more
variable (Ω_ϕ)

Parameter space allowed for $f=M_P$,
constraints from SNe



Our results (cont'd)

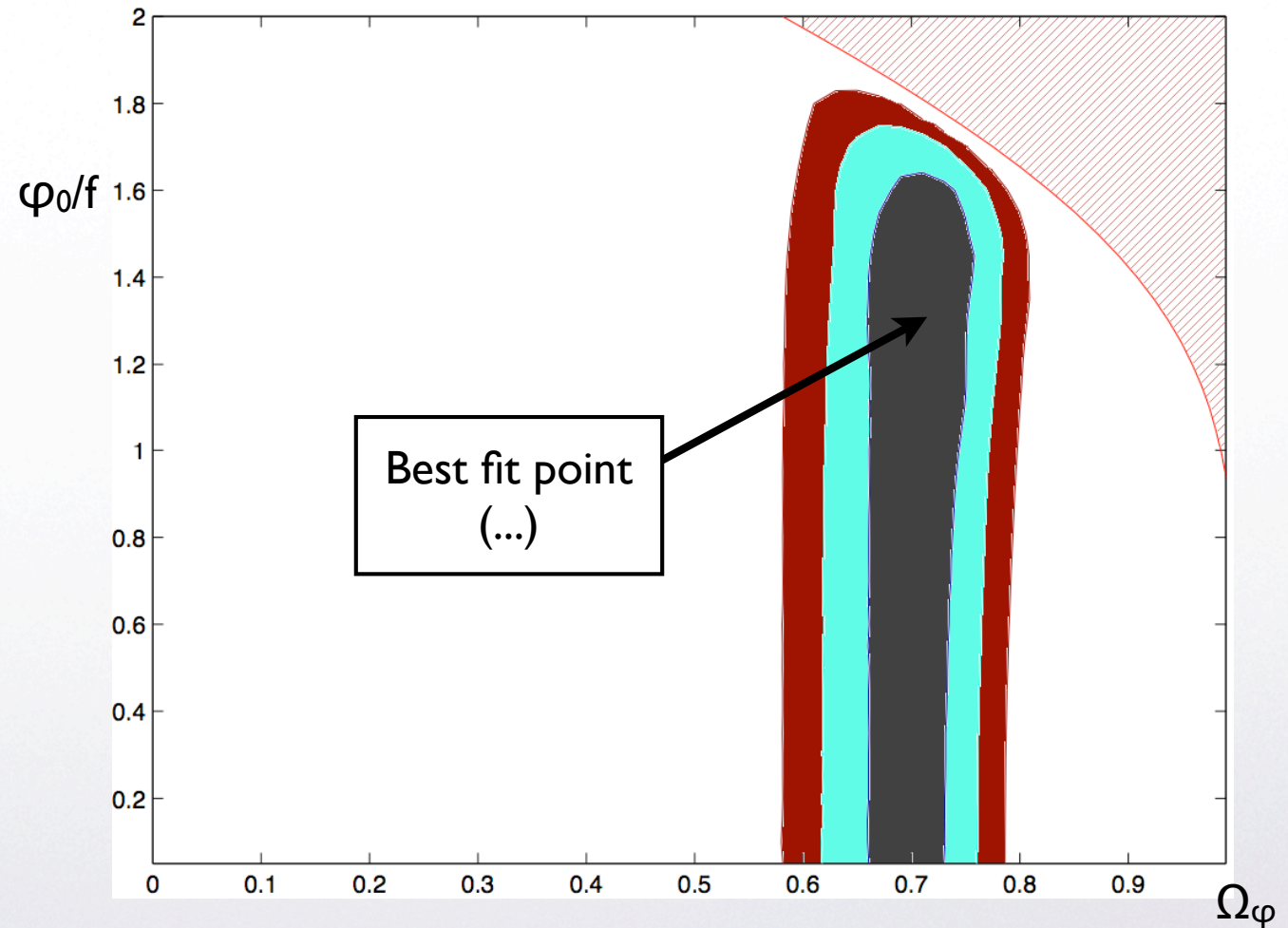
Without
assumption
 $\Omega_\phi = 0.7$



One more
variable (Ω_ϕ)

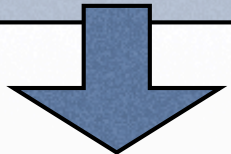
Parameter space allowed for $f=M_P$,
adding CMB (shift parameter)

Bond, Efstathiou Tegmark 97
Wang Mukherjee 06



Our results (cont'd)

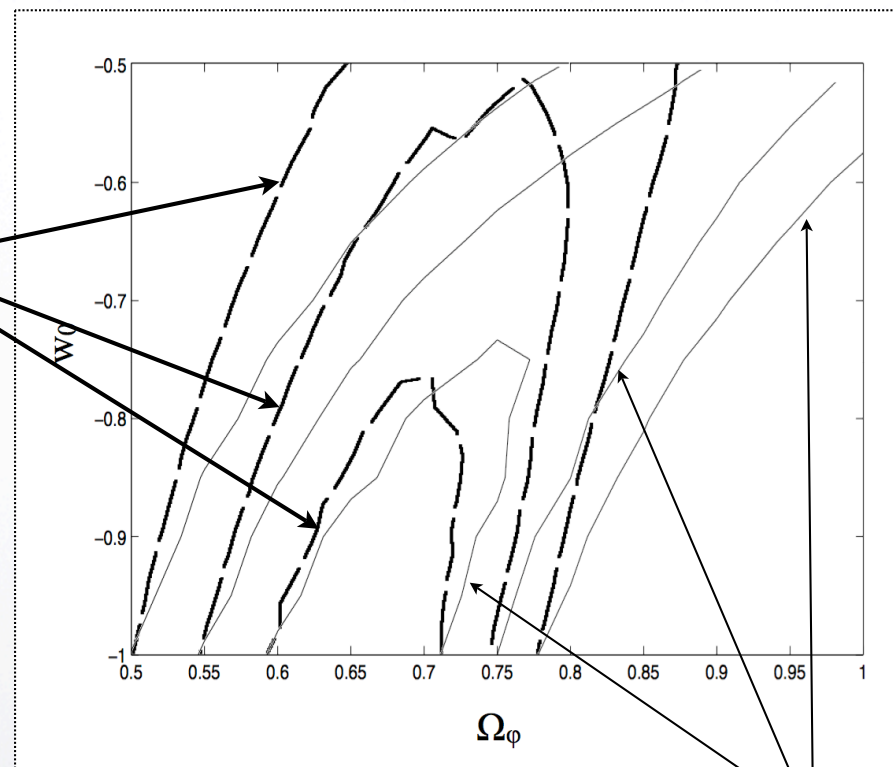
Without
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One more
variable (Ω_ϕ)

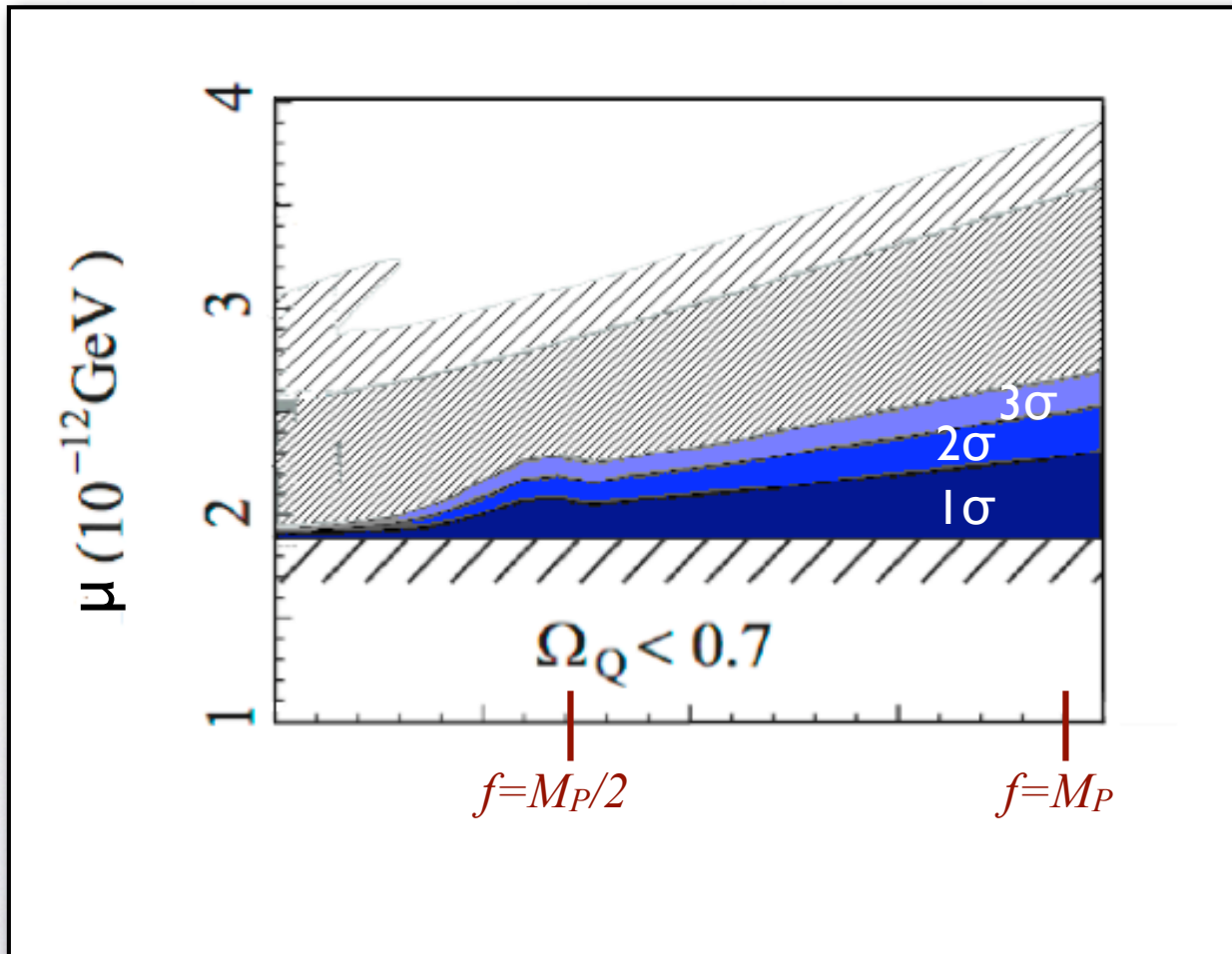
Parameter space in plane (Ω_ϕ, w_0)

PNGB
Quintessence



Constant w_0

Let us go back to the (f, μ) plane

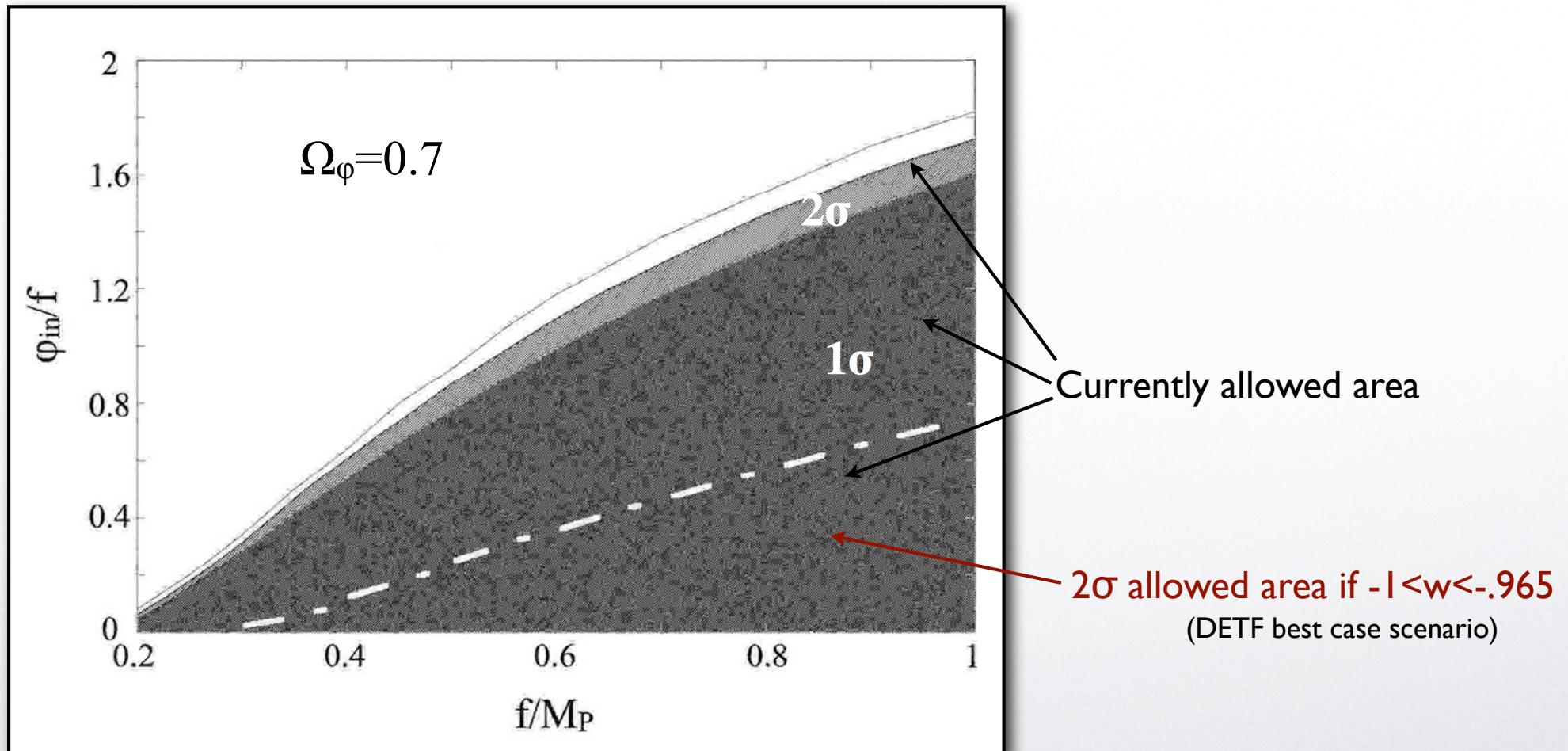


For $f \lesssim M_P/3$,
the parameter
space is
very narrow

If we require $f < M_P$
the model is under
some pressure by data

Future measurements
will constrain
even more strongly
this parameter space.
HOW MUCH?

The allowed parameter space:



Current constraint: $f \gtrsim M_P/3$

Future constraint: $f \gtrsim M_P/2$

What about theory?

- Is it possible to obtain $f \sim M_P$ in String Theory?
- Phenomenological problems if scalar moduli get same mass as pseudoscalars

Kalosh talk

- Conjectured stronger constraint $f \lesssim M_P/S \cong M_P/300$

Arkani-Hamed et al 06, Svrcek 06

What if $f \sim M_P$ is impossible in String Theory?

Kaloper and LS 05

We consider *many* pNGBs: **qui**N**essence**

Start from N pNGBs:

$$\mathcal{L} = -\sqrt{-g} \sum_{i=1}^N \left\{ \frac{1}{2} (\partial\phi_i)^2 + \Lambda_i^4 [1 + \cos(\phi_i/f_i)] \right\}$$

a low-scale version
of N-flation

Dimopoulos et al 05

pNGB version of
assisted inflation

Liddle et al 98

Assume that all the ϕ_i , all the f_i and all the Λ_i are equal:

$$\mathcal{L} = -\sqrt{-g} \left\{ \frac{N}{2} (\partial\phi)^2 + N \Lambda^4 [1 + \cos(\phi/f)] \right\}$$

Canonically normalized field $\Phi = \sqrt{N} \phi$

$$\mathcal{L} = -\sqrt{-g} \left\{ \frac{1}{2} (\partial\Phi)^2 + N \Lambda^4 \left[1 + \cos \left(\frac{\Phi}{\sqrt{N} f} \right) \right] \right\}$$

Can be $> M_P$
even if $f < M_P$!

*A couple of (semi-phenomenological)
comments about N-flation*

Comment #1

How large can the N of N -flation be?

Dimopoulos et al 05

$N < 200$ if we want to trust
loop corrections to M_P induced by the pNGBs

How large do we need it to be?

Dimopoulos et al 05

Approximating
 $\cos(x) \cong 1 - x^2/2$

$\left\{ \begin{array}{l} \text{Assuming } f \cong M_P, \varphi_1 = \varphi_2 = \dots = \varphi_N, \quad N \cong 200! \\ \text{Assuming } f \cong M_P, \varphi_i \text{ distributed between } 0 \text{ and } f, N \cong 600 \end{array} \right.$

Liddle, Kim 06

w/o approx
 $\cos(x) \cong 1 - x^2/2$

Assuming $f \cong M_P$, φ_i distributed on $[0, 2\pi f[$, $N \cong 60$ enough!

NOTE1: More realistic to assume a spectrum of f s and μ s

Easter, McAllister 05

NOTE2: If $f < M_P/S$, then $N \cong 10^4$ is needed!

Olsson 07

Comment #2


pNGB-generated magnetic fields

M. Anber, LS 2006

pNGBs will in general be coupled to $U(1)$ gauge fields via

$$\mathcal{L} \supset \sum_{i=1}^N \alpha \frac{\phi_i}{4 M_P} F_{\mu\nu} \tilde{F}^{\mu\nu}$$

$$(\alpha = \mathcal{O}(1))$$



Magnetic fields can be produced
by the rolling pNGBs
at inflation

Cosmological magnetic fields

- Observed with intensities of order μGauss
- Coherence lengths of 10s of kpcs
- ***Unknown origin***

Can be amplified by a *dynamo mechanism*:

Seed field required $\sim 10^{-30}$ G

Davis, Lilley and Tornkvist 1999

studied magnetic field produced by coupling to pNGB:

If the energy in magnetic field during inflation $<$ energy in inflaton condensate

AND

~~**If** after inflation the magnetic field does not evolve
(apart from effects related to expansion of the Universe)~~

THEN

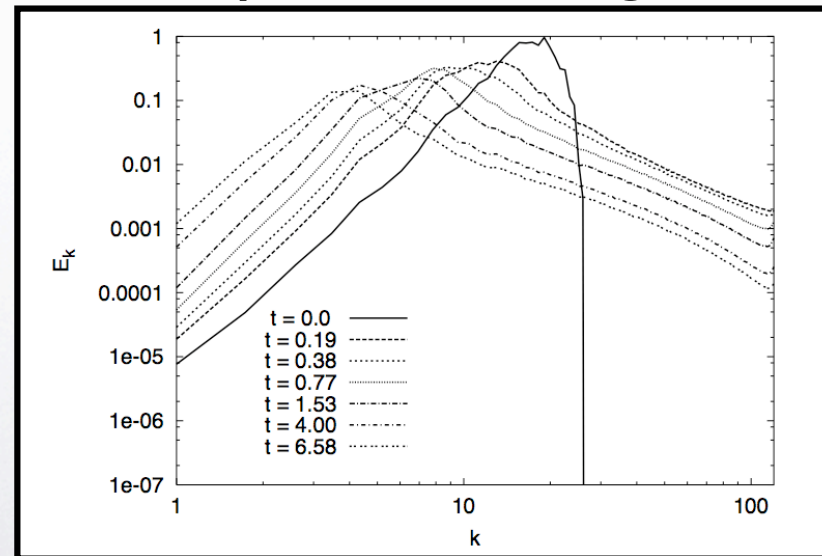
The resulting magnetic field today is too weak
to be the one we observe

Evolving the field in the cosmic plasma

Background
violates parity

→ The magnetic field produced has *maximal helicity*

Magnetohydrodynamic processes (*inverse cascade*)
transfer power to large scales



From Jedamzik and Banerjee 2004

Final value of the magnetic field (before the dynamo)

$$B \simeq 10^{-33} \frac{e^{\pi \xi}}{\xi^{17/12}} \left(\frac{T_{\text{RH}}}{10^9 \text{ GeV}} \right)^{11/36} \left(\frac{l_{\text{phys}}}{10 \text{ kpc}} \right)^{-9/4} \text{ G}$$

$[\xi = \mathcal{O}(1) \alpha]$

$$\alpha \gtrsim 10$$

is sufficient to initiate the dynamo

Conclusions

- Some models of quintessence more motivated than others
- The pNGB quintessence parameter space has shrunk in the last 6 years
- pNGBs emerge naturally when we want to do cosmology with scalar fields - and with String Theory