Cosmology with pseudo Nambu-Goldstone Boson quintessence

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with K. Dutta, N. Kaloper

Several candidates for the current phase of acceleration...

Prime candidate: a **COSMOLOGICAL CONSTANT** Λ

many virtues:

- it is the energy of the vacuum
- it has no dynamics
- it predicts w=-1
- in excellent agreement with data

Several candidates for the current phase of acceleration...

First candidate: a **COSMOLOGICAL CONSTANT** Λ

a couple of vices:

- observationally boring
- 60-120 orders of magnitude smaller than expected

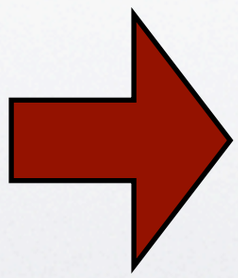
Let us see if there is another possibility...

- some unknown mechanism fixes the vacuum energy to zero
- the Universe accelerates because of some fluid that has not relaxed to its vacuum yet

QUINTESSENCE

Typically modeled as a scalar field φ with potential $V(\varphi)$

$$\rho = \dot{\varphi}^2/2 + V(\varphi)$$
$$p = \dot{\varphi}^2/2 - V(\varphi)$$



acceleration if $V(\varphi)$ is sufficiently flat

QUINTESSENCE

Pro

- Answers the question "why the Universe is accelerating even if the cosmological constant vanishes?"

- Observationally more exciting: $w \neq -1$ is a prediction that differentiates it from a cosmological constant

- Huge impact for Physics: a new form of matter!

QUINTESSENCE

Contra

The quintessence field is slowly evolving

Its potential must be extremely flat

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

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

why quantum effects do not modify such a delicate potential?

(e.g.: the coefficients in Taylor expansion of the potential)

QUINTESSENCE

Contra

quintessence is slowly evolving and does not cluster

its mass is tiny (typically $m \sim H_0 \sim 10^{-33}$eV!)

effectively behaves as a massless particle

can mediate long range forces!

unless its coupling to matter is
~1000 times weaker than gravity

QUINTESSENCE

Contra

an infinity of potentials

impossible to analyze all of them

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

$$\varphi \longrightarrow \varphi + c$$

If this symmetry is exact, the only possible potential for φ is V(φ)=constant

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

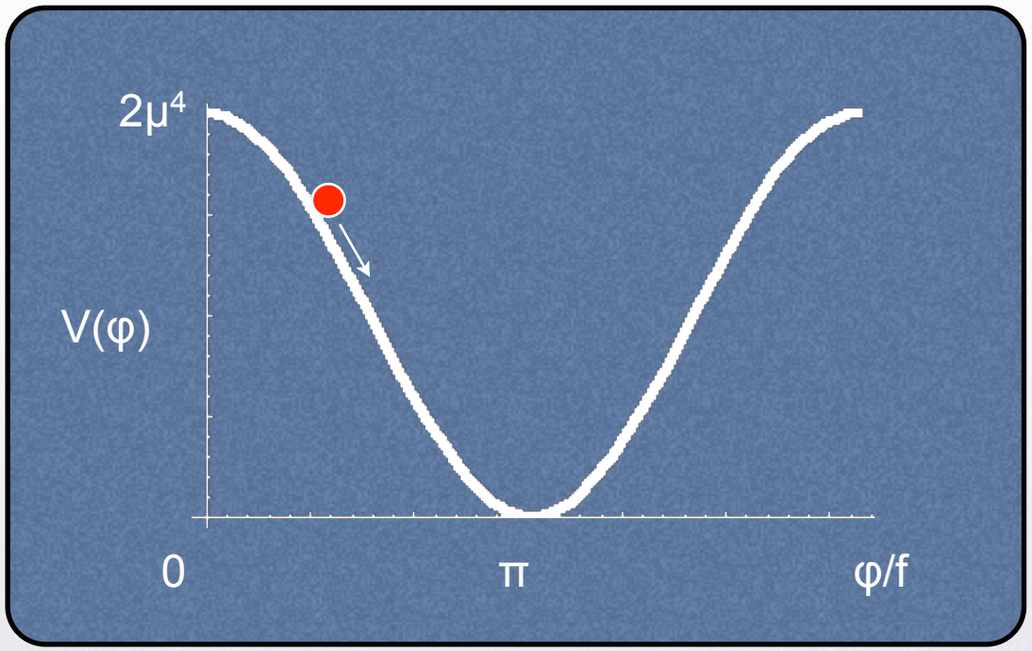
now let us break the shift symmetry a little bit...
the potential for φ changes to

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

Frieman et al 1995
(<1998!)

f measures the breaking
of the shift symmetry

in the limit $f \to \infty$
the symmetry is restored



The cosine potential: where does it come from?

- Theory with a spontaneously broken global U(1)

$$\mathcal{L} = \partial_\mu H^* \, \partial^\mu H - \lambda \left(|H|^2 - v^2 \right)^2$$

- Decompose $H = (v + \delta H) \, e^{i\phi/v}$

  where δH is massive and φ is a massless Goldstone boson *(pseudoscalar)*

- The global U(1) is broken e.g. by gravitational instantons

$$\delta\mathcal{L} = e^{-S} \, M_P^3 \, (H + H^*) + \ldots$$

(S = instanton action, $\propto M_P^2$)

- A potential is generated:

$$\delta V \sim e^{-S} M_P^3 \, v \, \cos(\phi/v)$$

Pseudo-Nambu-Goldstone boson
PNGB

Because of its radiative stability,

A pNGB is an extremely well motivated (the best?)
model of quintessence
from the point of view of particle physics

What about long range forces?

Usually dangerous operators of the form

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

Higgs vev
∝ mass of particle

Must be smaller than ~10^{-4}!

Forbidden by shift symmetry and ϕ pseudoscalar!

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

$$\delta\mathcal{L} \sim e^{-S'} \frac{H + H^*}{M_P} \bar{\psi}\langle h\rangle\psi$$

can be dangerous unless S' is large enough.

...but, since S has to be very large,
we DO expect also S' to be large enough!

(more about this later...)

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 ~70% of the total (as required by observations)

Requirements from strings

String Theory appears to require $0<f\lesssim M_P$

Banks, Dine, Fox and Gorbatov 2003

Factors of 2, π etc not considered. They typically go in the direction of making the bound more stringent

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

the parameter space of the model is compact:

We can hope to exclude the whole model!

...so let us see how close it is to getting excluded!

Analysis of the parameter space of the model

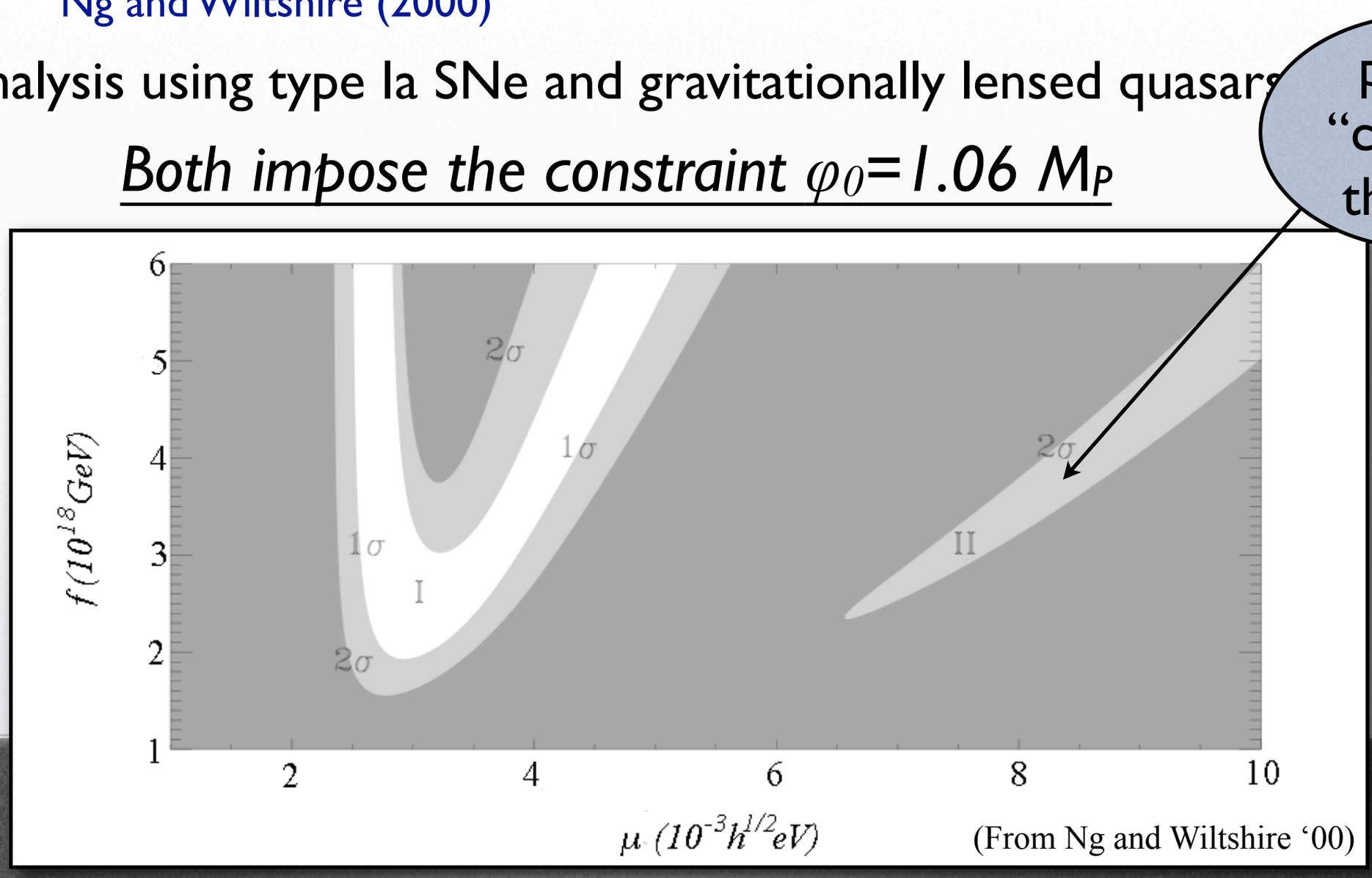
(K. Dutta, LS 2007)

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

Analysis using type Ia SNe and gravitationally lensed quasars

Both impose the constraint $\varphi_0 = 1.06\ M_P$

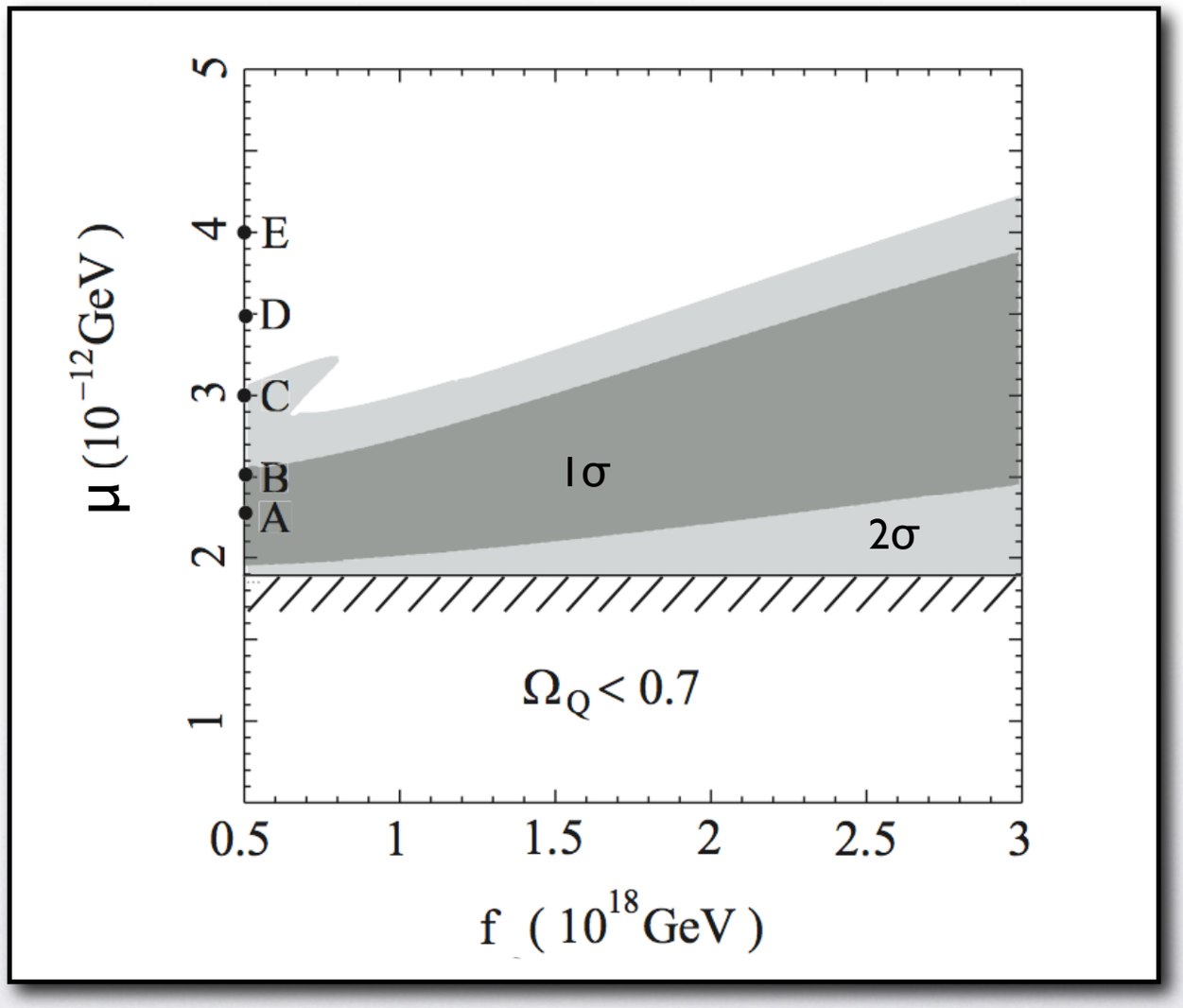
pNGB "climbing the hill"



(From Ng and Wiltshire '00)

More previous literature: Kawasaki, Moroi, Takahashi (2001):

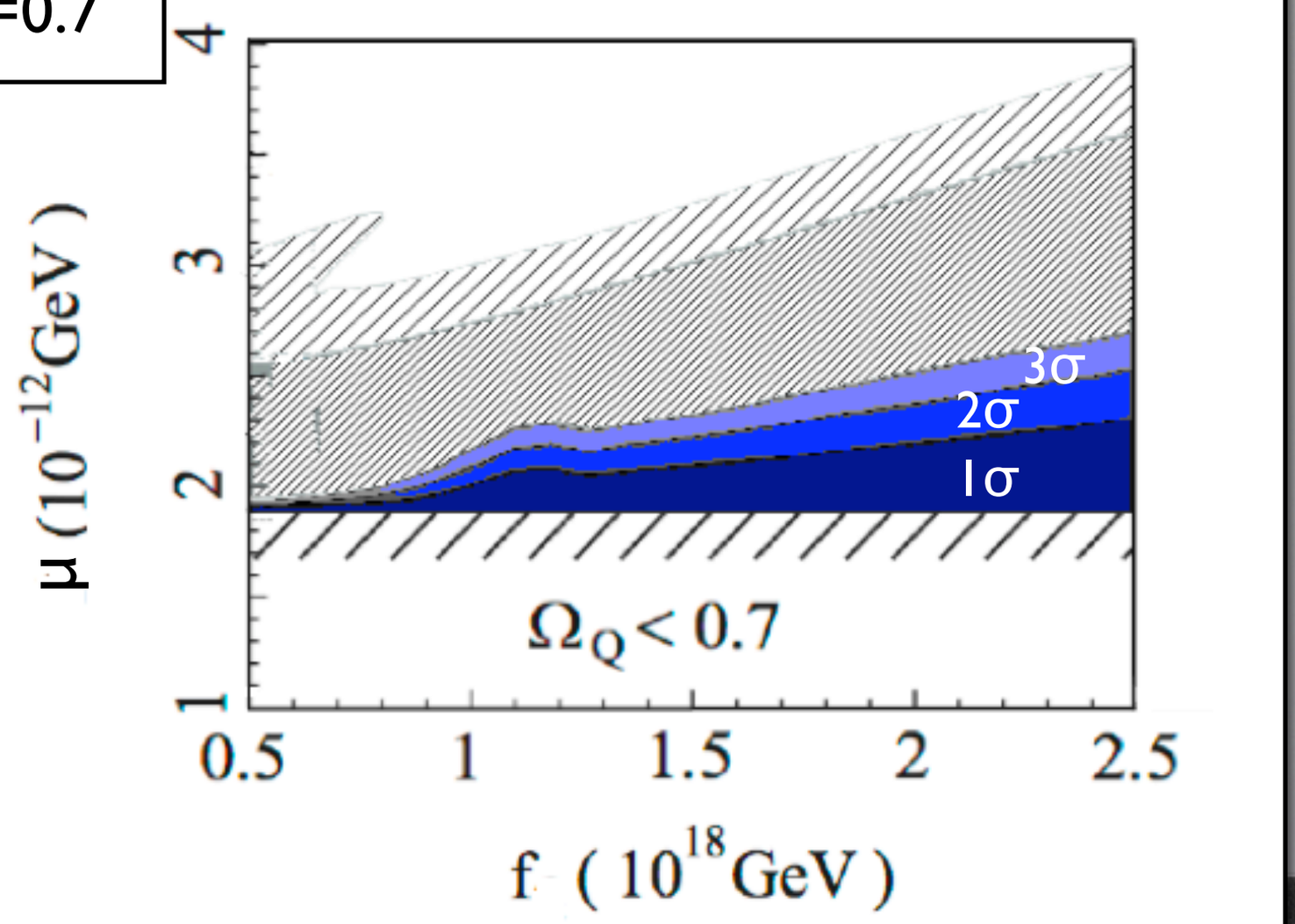
Constraints from CMB only (pre-WMAP data):



Our results

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

Enforcing $\Omega_\varphi = 0.7$

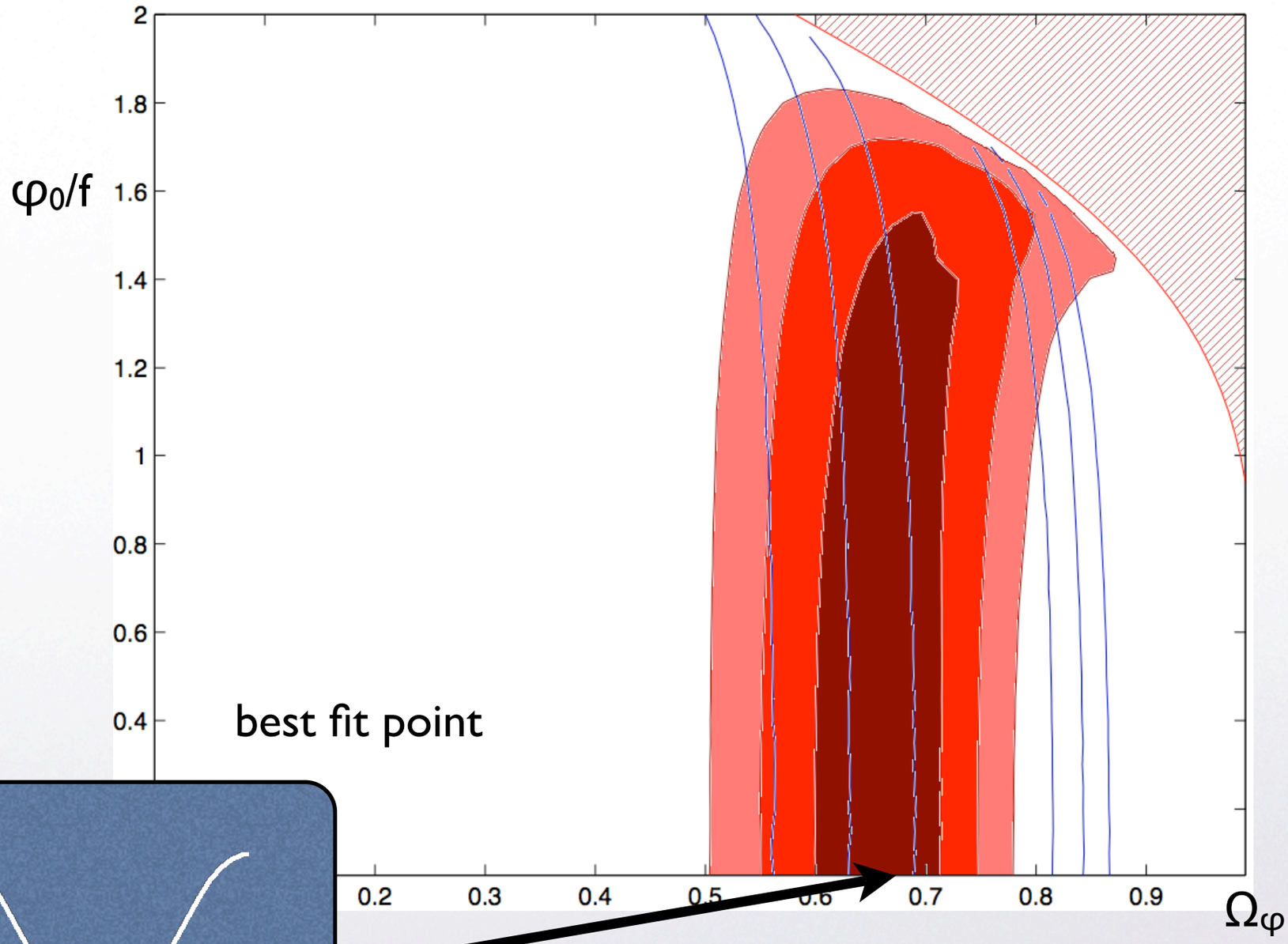


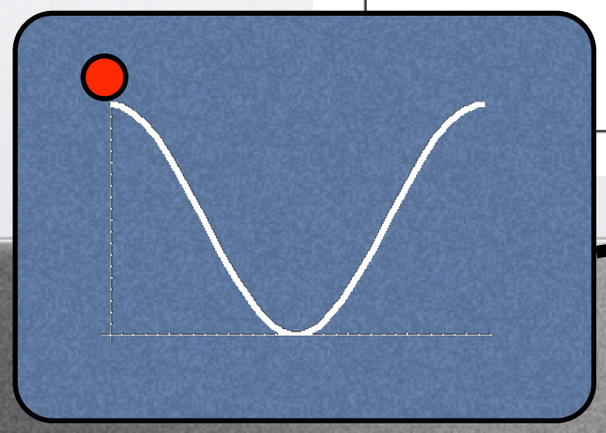
Our results (cont'd)

Without assumption $\Omega_\varphi=0.7$

One more variable (Ω_φ)

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





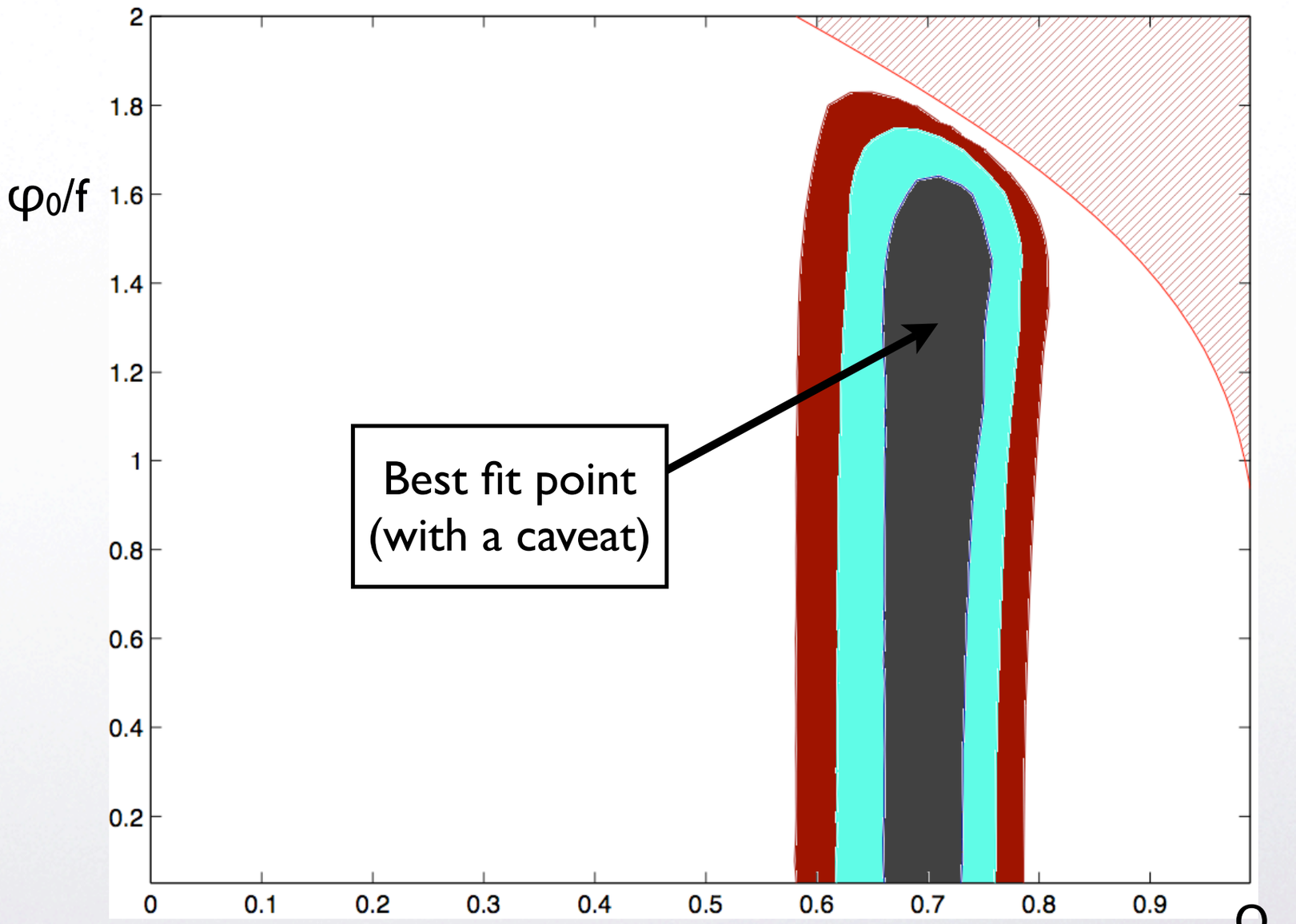
Our results (cont'd)

Without assumption Ω_φ=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



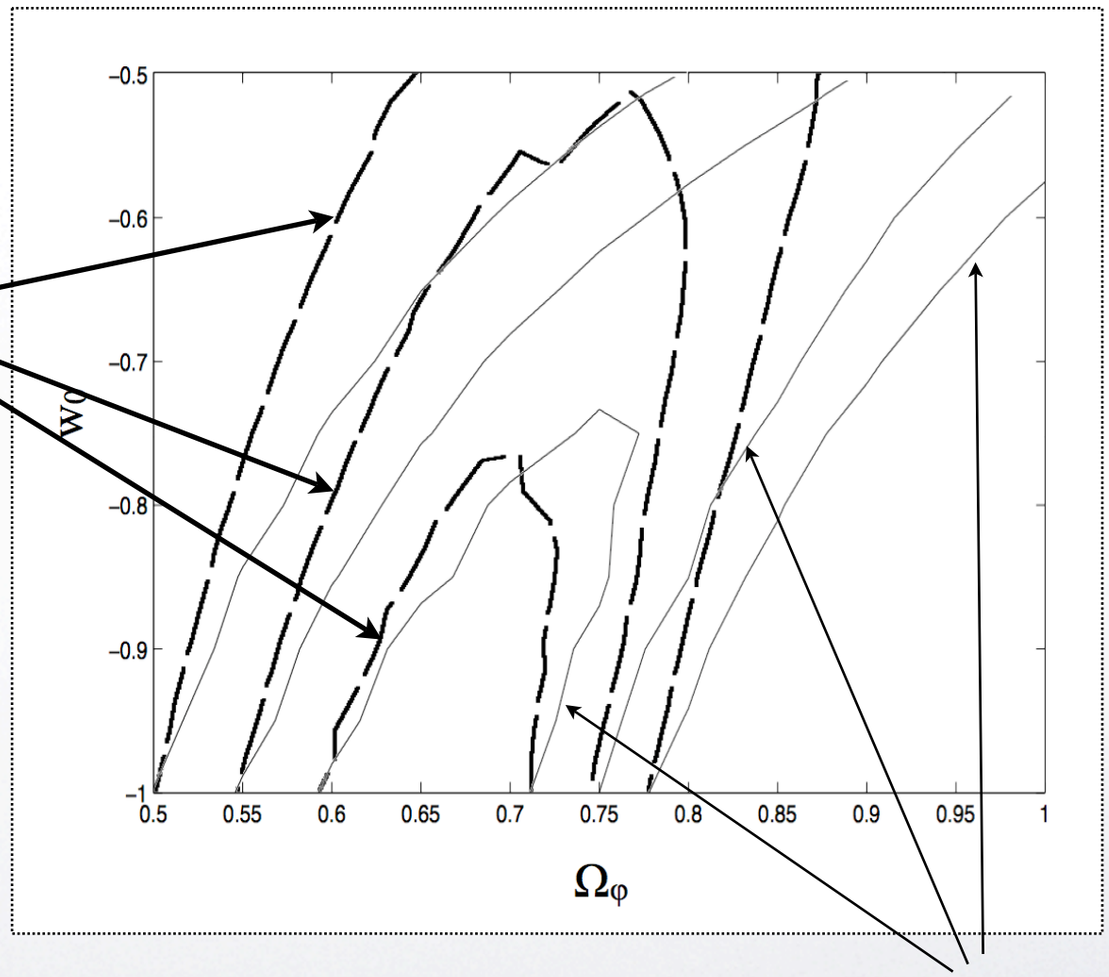
Our results (cont'd)

Without assumption $\Omega_\varphi=0.7$

One more variable (Ω_φ)

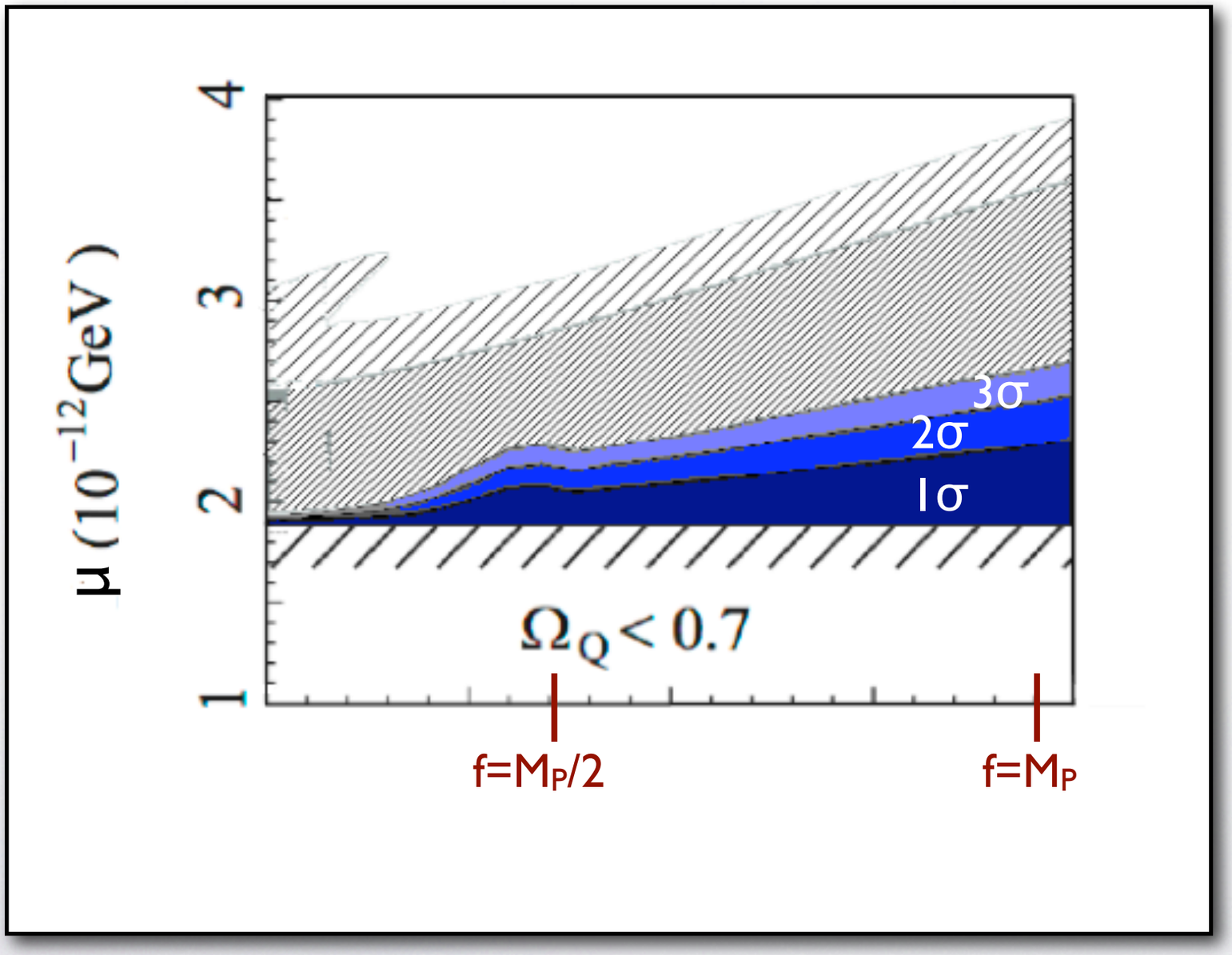
Parameter space in plane (Ω_φ, w_0)

PNGB Quintessence



Constant w_0

Let us go back to the (f, μ) plane

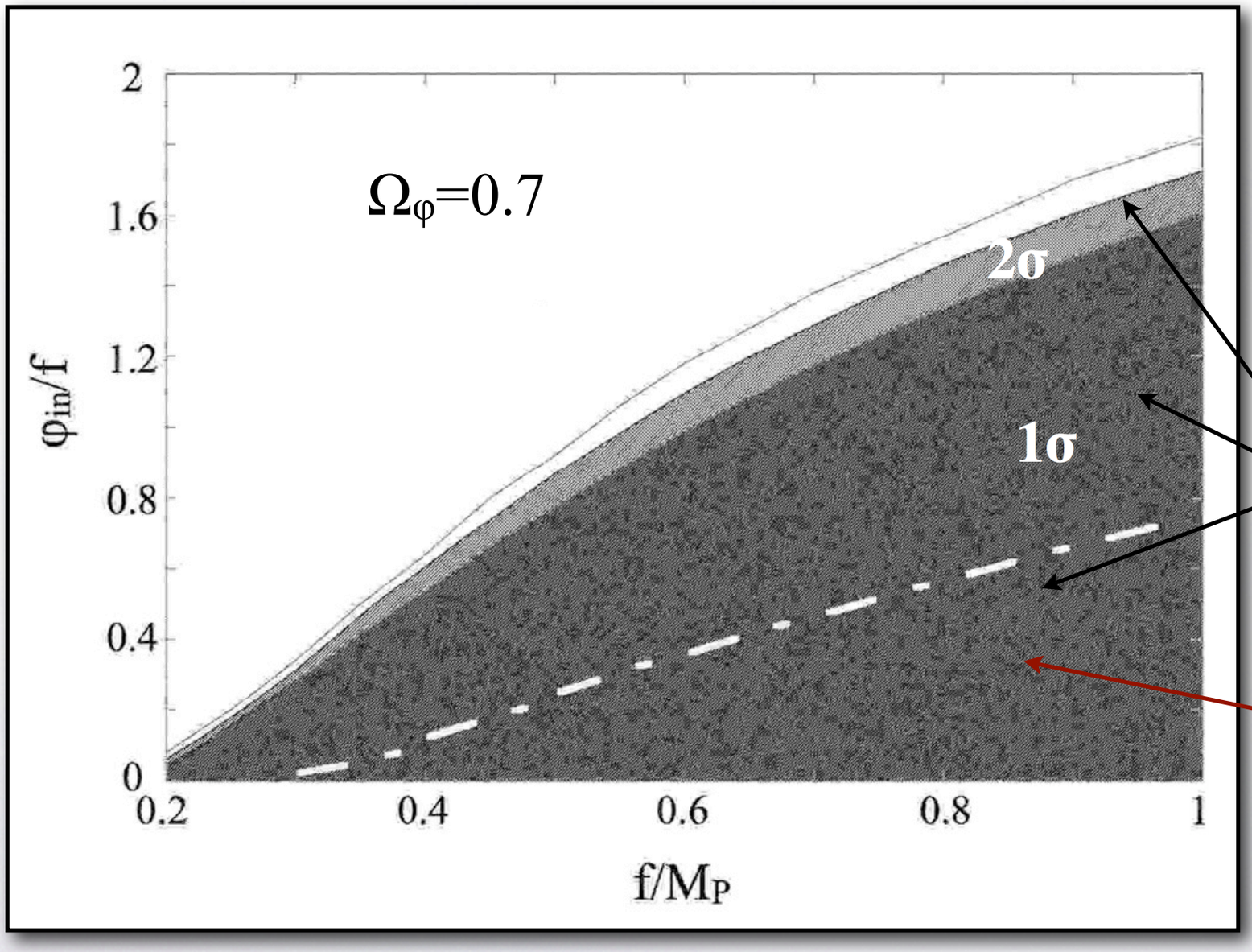


For $f \lesssim M_P/2$,
the parameter
space is
very narrow

If we want to believe in
String Theory
(that requires $f<M_P$)
the model is under
some pressure by data

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

The allowed parameter space:



Currently allowed area

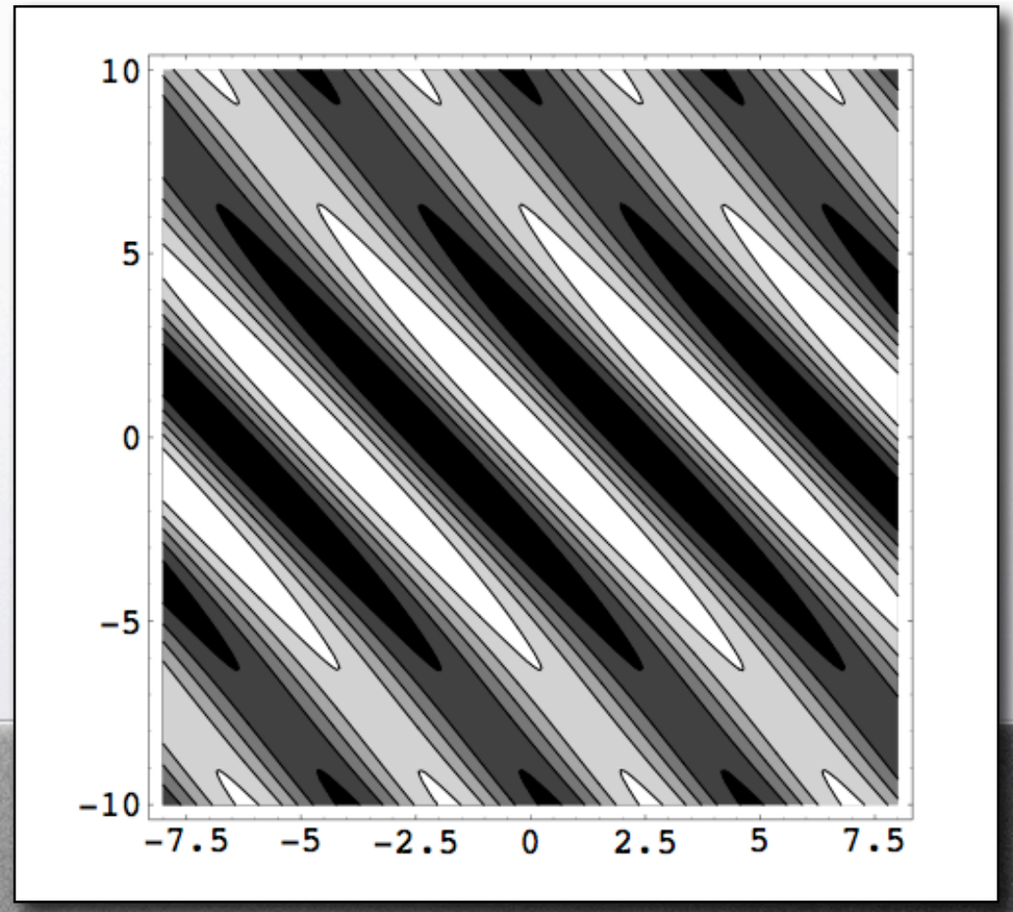
Allowed area if -1<w<-.965

What if observations push f to be *unnaturally* close to M_P?

Kim, Nilles and Peloso 2004

Use *two* pNGBs!

$$V = \Lambda_1^4 \left[1 - \cos\left(\frac{\theta}{f_1} + \frac{\rho}{g_1}\right)\right] + \Lambda_2^4 \left[1 - \cos\left(\frac{\theta}{f_2} + \frac{\rho}{g_2}\right)\right]$$



What if observations push f to be *unnaturally* close to M_P?

Kaloper and LS 2005

We consider *many* pNGBs: quiNtessence

Start from N pNGBs:

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

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

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

Canonically normalized field $\Phi = \sqrt{N}\, \varphi$

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

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

...so possible to get quintessence
in String Theory
without the fine-tuning $f \cong M_P$

Conclusions

- Some models of quintessence more motivated than others
- The pNGB quintessence parameter space has shrunk in the last 6 years
- pNGB quintessence still a (the?) viable model of quintessence in String Theory
- A challenge to theorists...

theory:

$$V \sim e^{-S} M_P^3 v \, \cos\left(\phi/v\right)$$

observations:

$$v \gtrsim M_P/3\,, \quad S \simeq 280$$

this can be difficult

*this can be **very** difficult*

already a problem for QCD axion, where S>200 required

...still some work needed to find a good model of Quintessence in String Theory!