Constraints on Modified Gravity

A.C. Davis
DAMTP, Cambridge

Screened Modified Gravity

consider the action

$$S = \int d^4x\sqrt{-g}\left(\frac{R}{16\pi G_N} - \frac{(\partial\phi)^2}{2} - V(\phi)\right) + S_m(\psi_i, A^2(\phi)g_{\mu\nu})$$

gives the effective potential

$$V_{\text{eff}}(\phi) = V(\phi) - (A(\phi) - 1)T$$

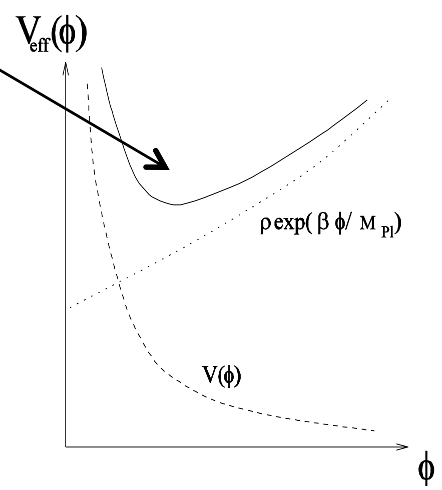
This should give fifth forces, but these are screened. Two types of screening.
Chameleons - the mass depends on the environment; dilatons and symmetrons - the coupling to matter depends on the environment.
Both are considered. They have been constrained by solar system and lab tests.

The effect of the environment

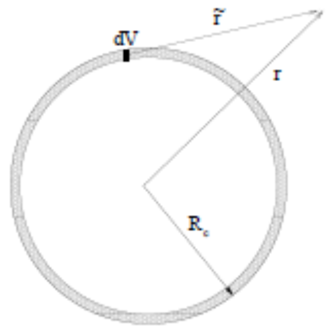
When coupled to matter, scalar fields have a matter dependent effective potential

$$V_{eff}(\phi) = V(\phi) + \rho_m A(\phi)$$

Environment dependent minimum

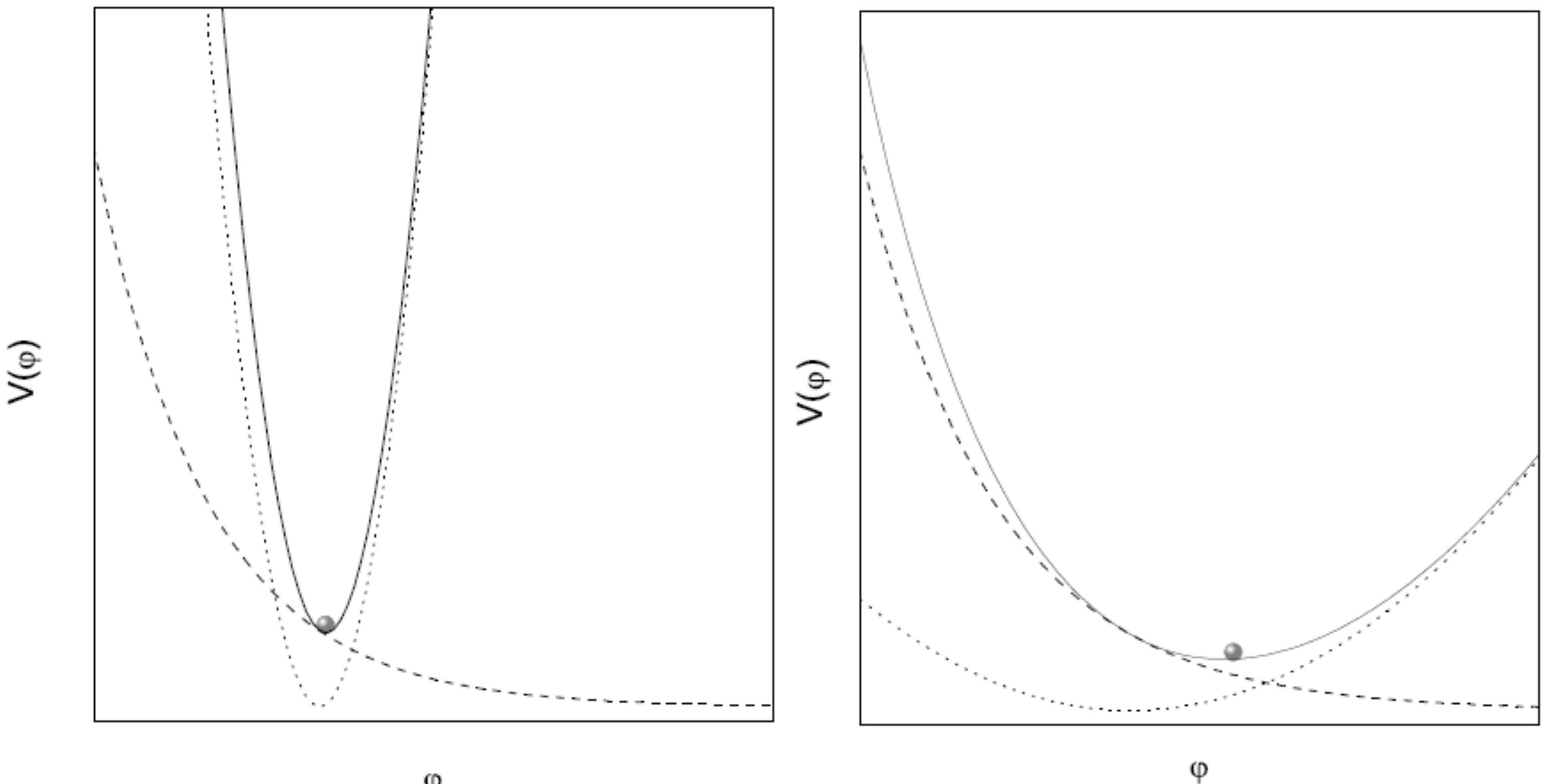


$$\beta(\phi) = m_{\rm Pl} \frac{d \ln A(\phi)}{d\phi}$$



The field generated from deep inside is Yukawa suppressed. Only a thin shell radiates outside the body. Hence suppressed scalar contribution to the fifth force.

$$F_\phi \propto \Delta R / R \Phi_N$$



Dilaton

$$V(\phi) = V_0 e^{-\phi/m_{\rm Pl}}, \quad A(\phi) = 1 + \frac{A_2}{2m_{\rm Pl}^2}(\phi - \phi_\star)^2$$

Formalism applies also to f(R) gravity: chameleon mechanism.

f(R) is totally equivalent to an effective field theory with gravity and scalars!

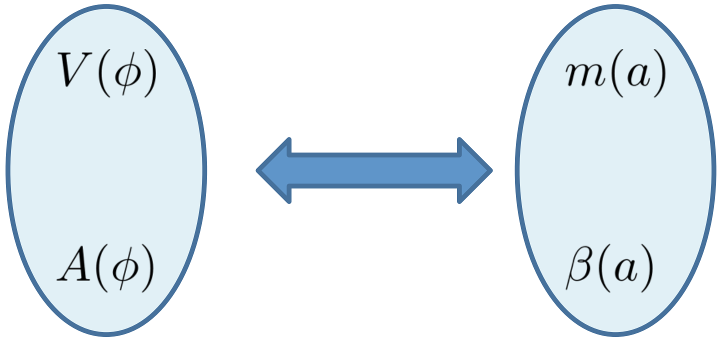
$$S=\int d^4x\sqrt{-g}\left(\frac{1}{16\pi G_N}R-\frac{1}{2}(\partial\phi)^2-V(\phi)+\mathcal{L}_m(\psi_m,e^{2\phi/\sqrt{6}m_{\rm Pl}}g_{\mu\nu})\right)$$

The potential V is directly related to f(R)

Crucial coupling between matter and the scalar field

$$V(\phi)=m_{\rm Pl}^2\frac{Rf'-f}{2f'^2},\quad f'=e^{-2\phi/\sqrt{6}m_{\rm Pl}}$$

Tomography

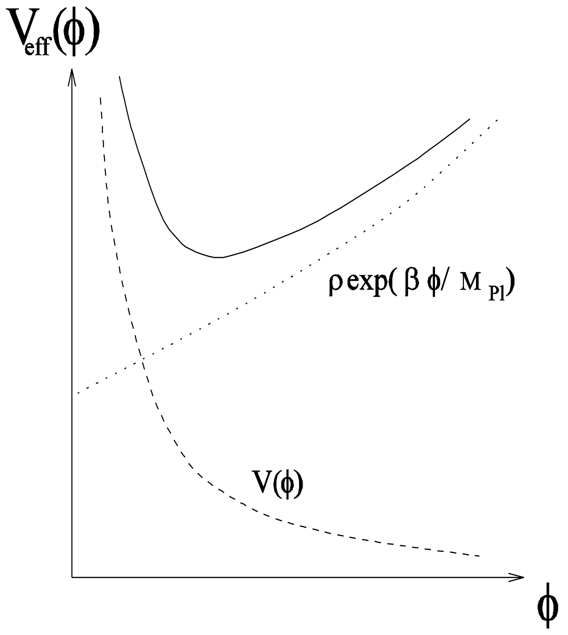


Applies to all models considered

All these models can be entirely characterised by 2 time dependent functions. The non-linear potential and coupling of the model can be reconstructed using:

Works for chamelons, dilatons, symmetrons etc…

$$\phi(a) = \phi_i + \frac{3}{m_{Pl}} \int_{a_i}^{a} da \frac{\beta(a)\rho(a)}{am^2(a)}$$
$$V(a) = V_i - \frac{3}{m_{Pl}} \int_{a_i}^{a} da \frac{\beta^2(a)\rho^2(a)}{am^2(a)}$$

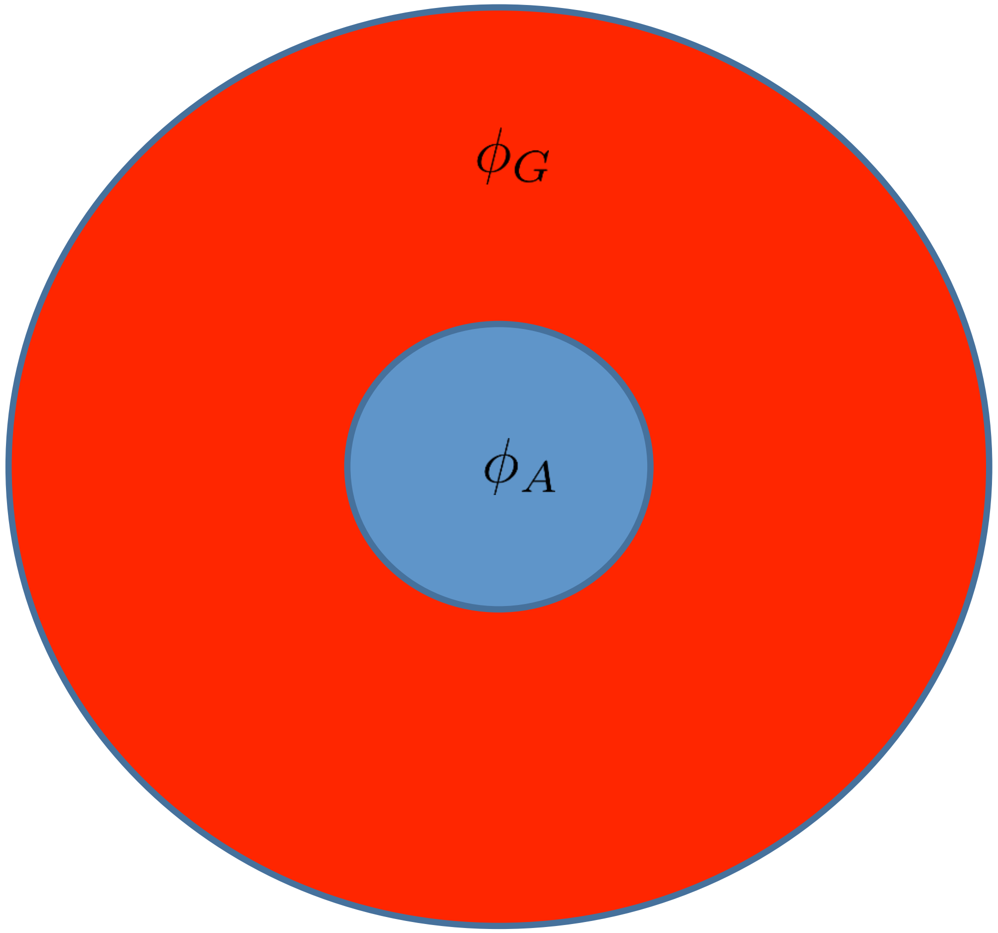


tomography

$m(a)$
$\beta(a)$
↔
$m(\rho)$
$\beta(\rho)$

$$\rho(a) = \frac{\rho_0}{a^3}$$

The m(a)-β(a) parameterisation is useful to express the screening criterion for an object BLUE embedded in a larger region RED:



Scalar charge: $$Q_A = \frac{|\phi_G - \phi_A|}{2 m_{\rm Pl} \Phi_A}$$

$$Q_A \leq \beta_G$$

Self screening: large Newton potential

Blanket screening: due to the environment G

Φ_A Newton's potential at the surface

The Milky Way must be screened

For chameleons, dilatons and large curvature models:

$$\beta(a) = \beta_0 a^{-s}, \quad m(a) = m_0 a^{-r}$$

3/2<r<3, s=0 : chameleons

r>3, s=0 : large curvature

r=3/2, s=-3: dilaton

Self-screening of the Milky Way:

$$\frac{m_0^2}{H_0^2} \geq \frac{9\Omega_{m0}}{2(2r-3-s)} 10^6$$

This bounds the range of the scalar interaction to be less than a few Mpc's on cosmological scales

Cosmology

Modified gravity can evade detection in the solar system, but this doesn’t mean there is no effect on cosmology.

There is a long range field of gravitational strength. It adds an extra force cosmologically

For example, there could be affect the clustering of matter to form galaxies.

At the linear level, CDM perturbations grow differently from GR in chameleon, dilaton, symmetron models:

$$\delta_c'' + \mathcal{H}\delta_c' - \frac{3}{2}\Omega_m\mathcal{H}^2\left(1 + \frac{2\beta(a)^2}{1 + \frac{m(a)^2a^2}{k^2}}\right)\delta_c = 0$$

Linear perturbations solely determined by the m(a)-β(a) parameterisation !

Inside the Compton wavelength k<<m(a)a, anomalous growth depending on the coupling to matter β(a).

$$\delta \sim a^{\frac{\nu}{2}}, \quad \nu = \frac{-1 + \sqrt{1 + 24(1 + 2\beta_c^2)}}{2}$$

Outside the Compton wavelength, growth is not modified: $\delta \sim a$

N-Body Simulations

dilatons

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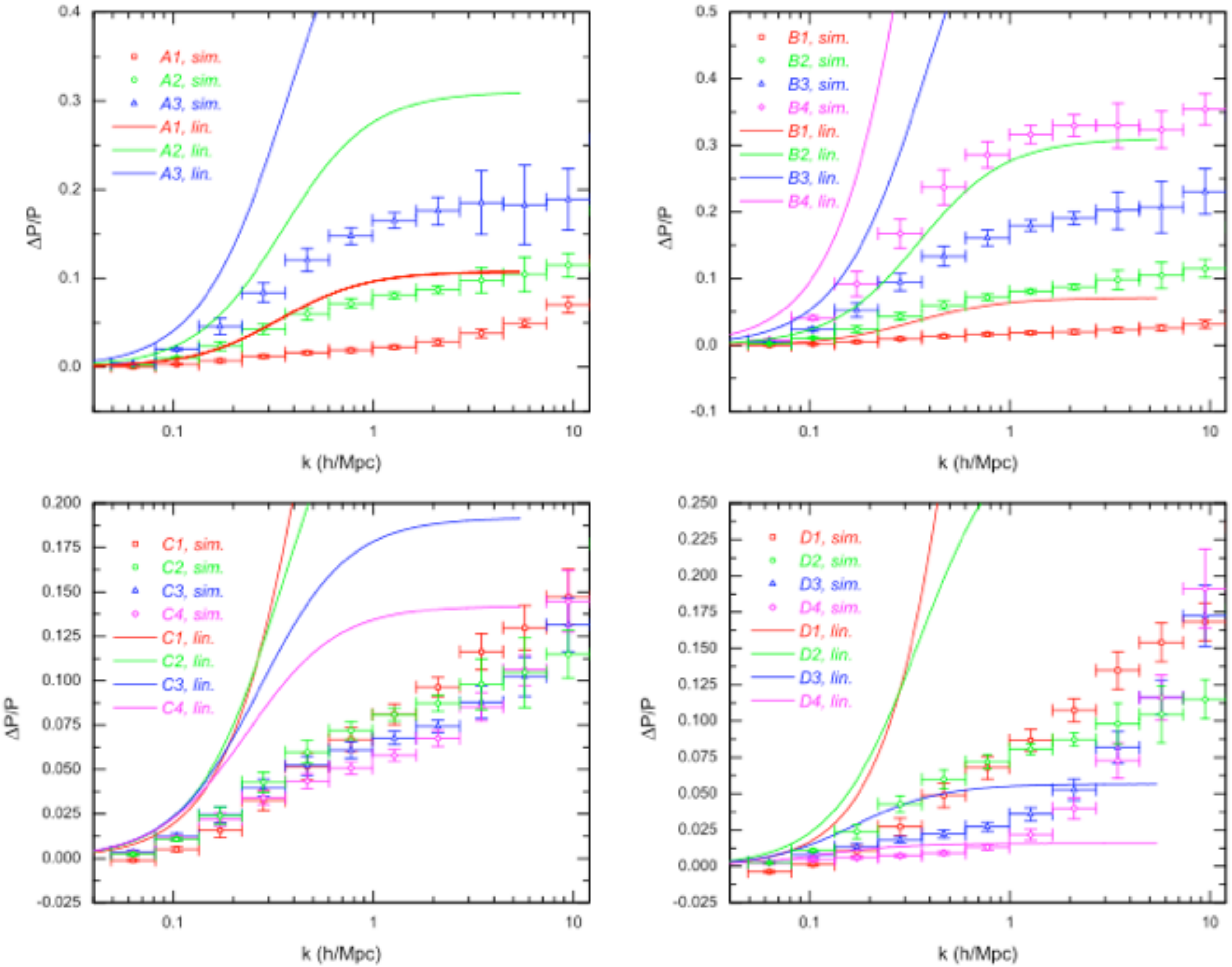
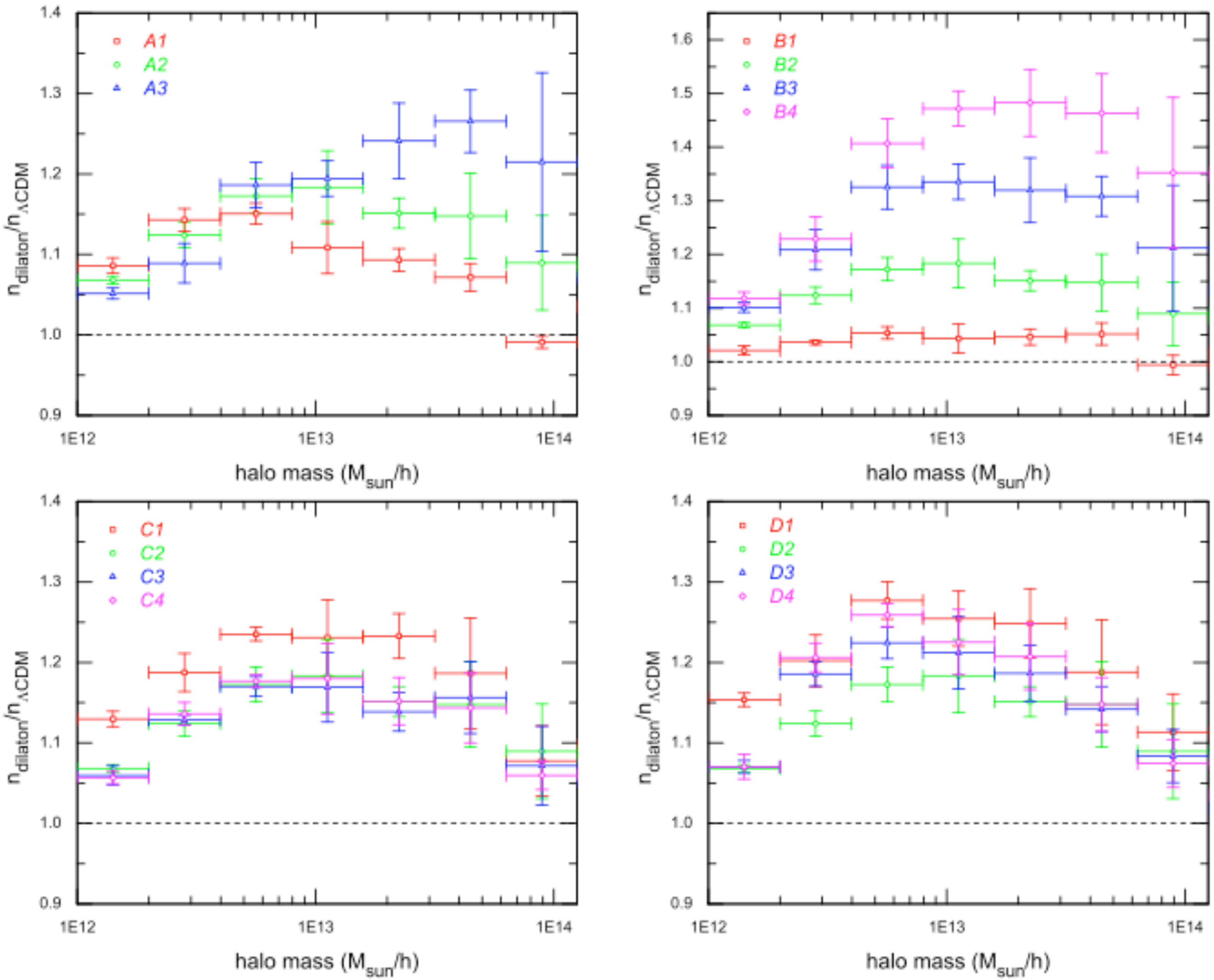


ECOSMOG simulations using a modification of the RAMSES code.
Full use of the m(a)-β(a) parameterisation.



The differences are subtle, but could be detected in the next generation of experiments

Compare $m(a), \beta(a)$ parametrisation with data to extract parameters

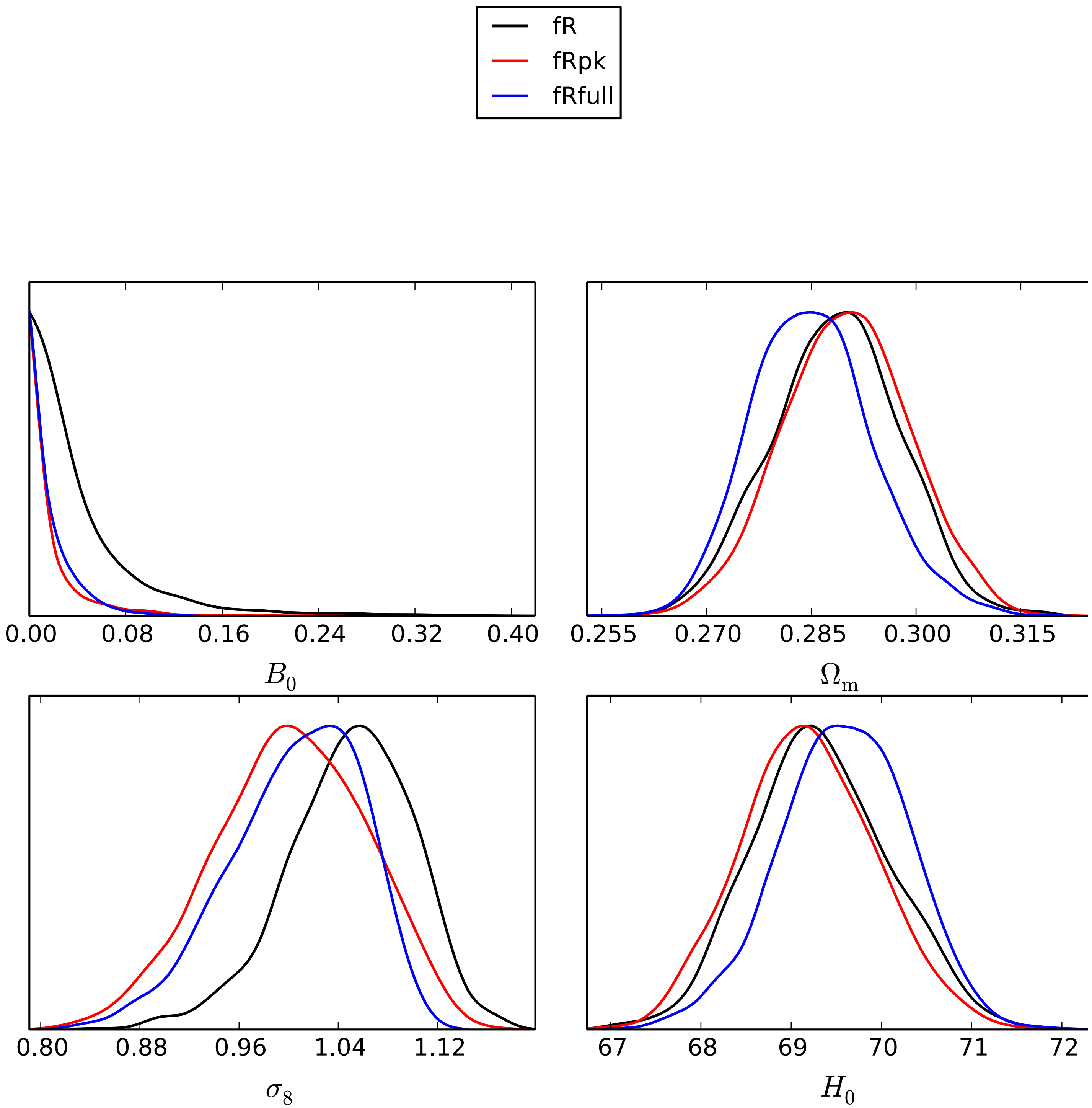
Can rewrite usual parametrisation in this notation

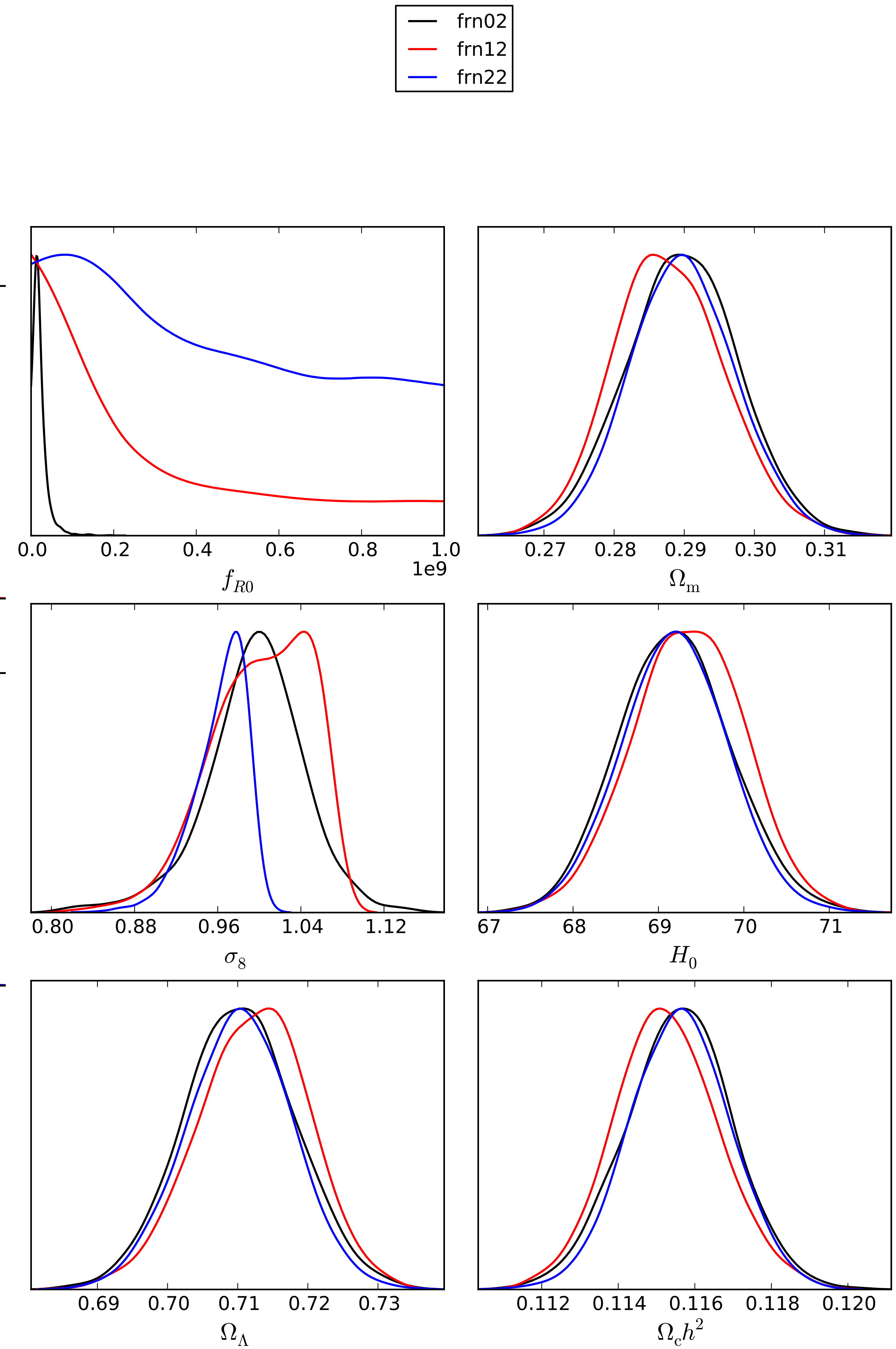
$$\mu(k,a) = \frac{(1+2\beta^2)k^2 + m^2a^2}{k^2 + m^2a^2},$$

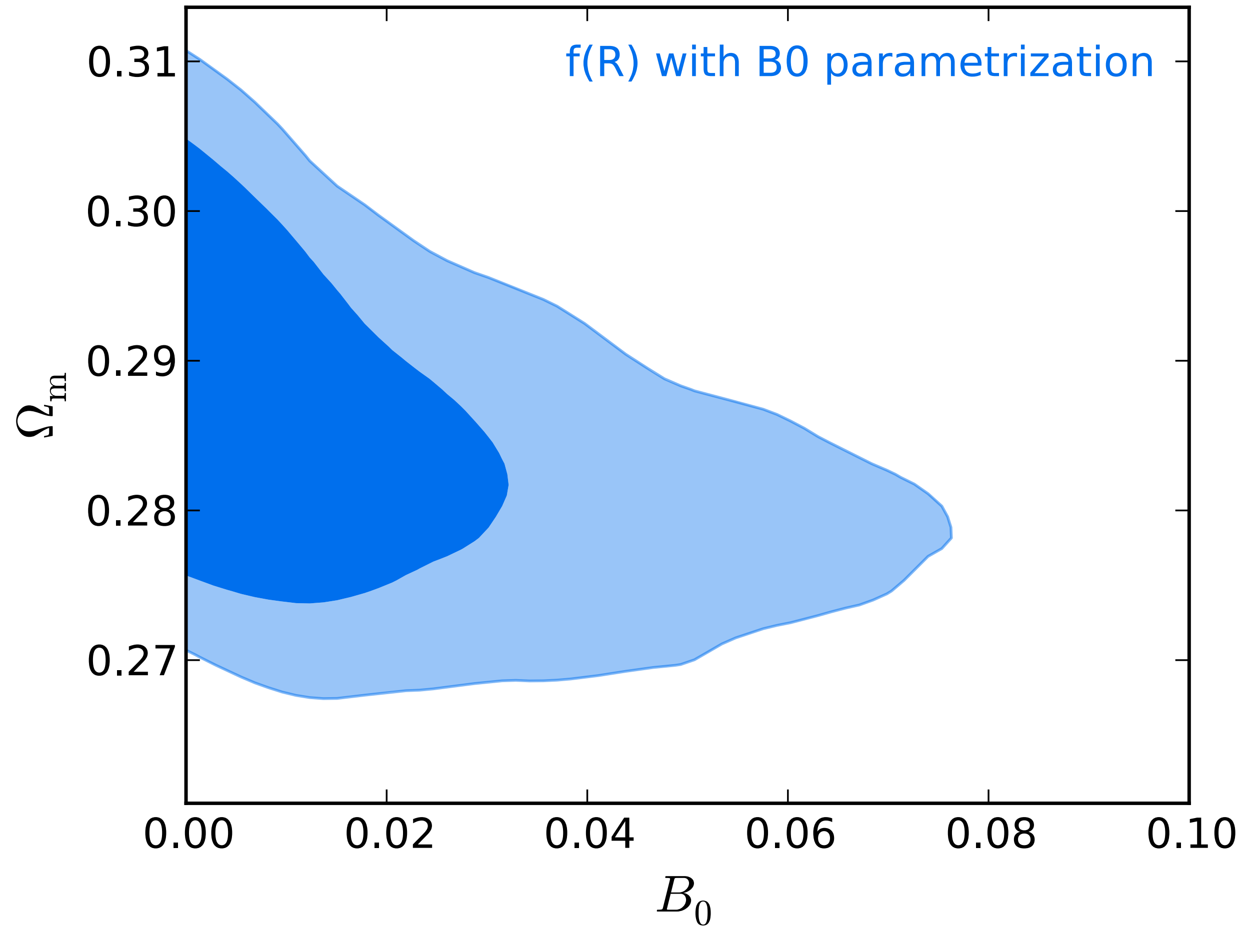
$$\gamma(k,a) = \frac{(1-2\beta^2)k^2 + m^2a^2}{(1+2\beta^2)k^2 + m^2a^2}$$

now constrain parameters with data using posterior probability of parameters

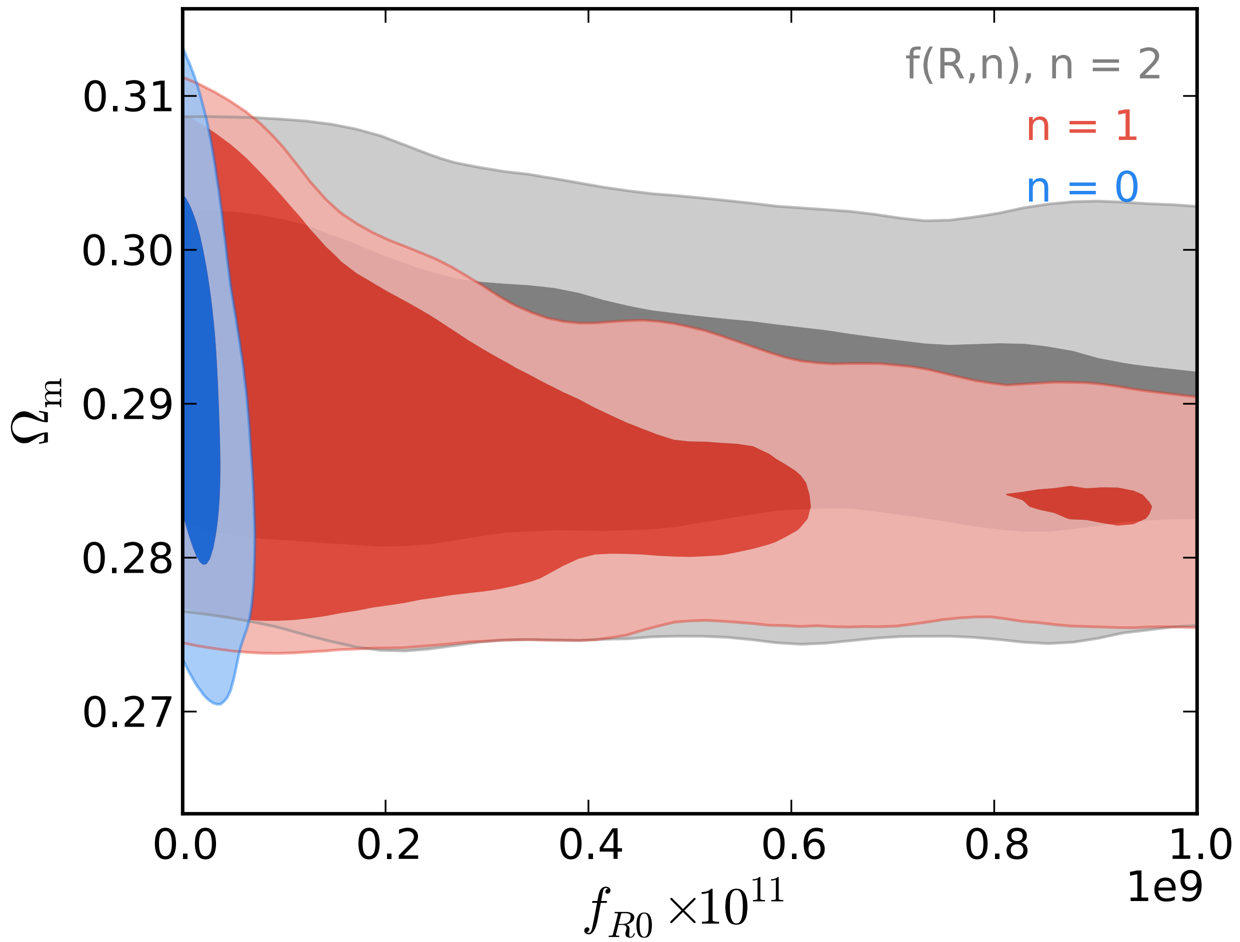
with Philippe Brax, Alireza Hojjati, Aaron Plahn and Levon Pogosian


fR
fRpk
fRfull
0.00 0.08 0.16 0.24 0.32 0.40
B_0
0.255 0.270 0.285 0.300 0.315
Ω_m
0.80 0.88 0.96 1.04 1.12
σ_8
67 68 69 70 71 72
H_0


frn02
frn12
frn22
0.0 0.2 0.4 0.6 0.8 1.0
1e9
f_{R0}
0.27 0.28 0.29 0.30 0.31
Ω_m
0.80 0.88 0.96 1.04 1.12
σ_8
67 68 69 70 71
H_0
0.69 0.70 0.71 0.72 0.73
Ω_Λ
0.112 0.114 0.116 0.118 0.120
$\Omega_c h^2$

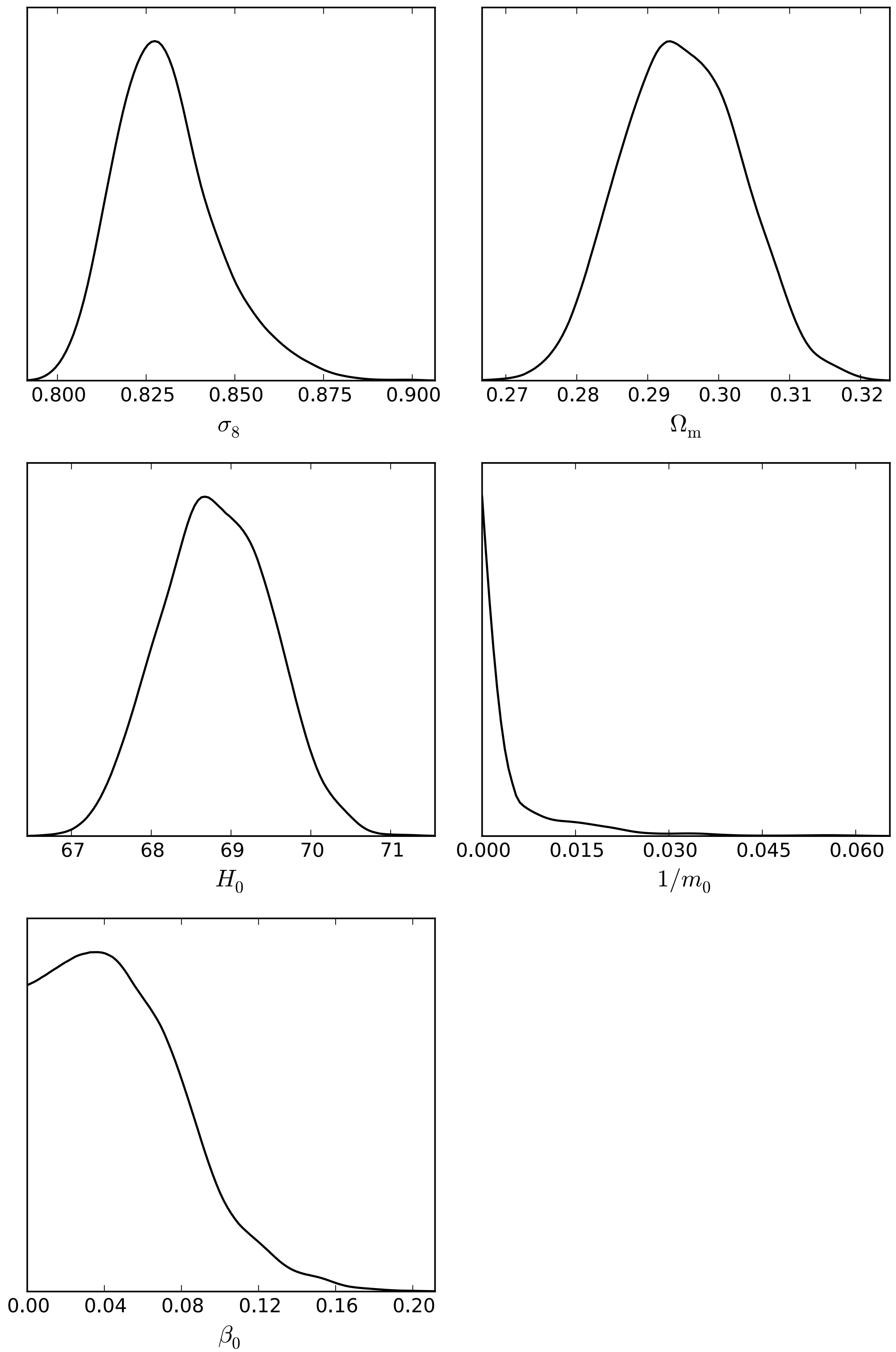


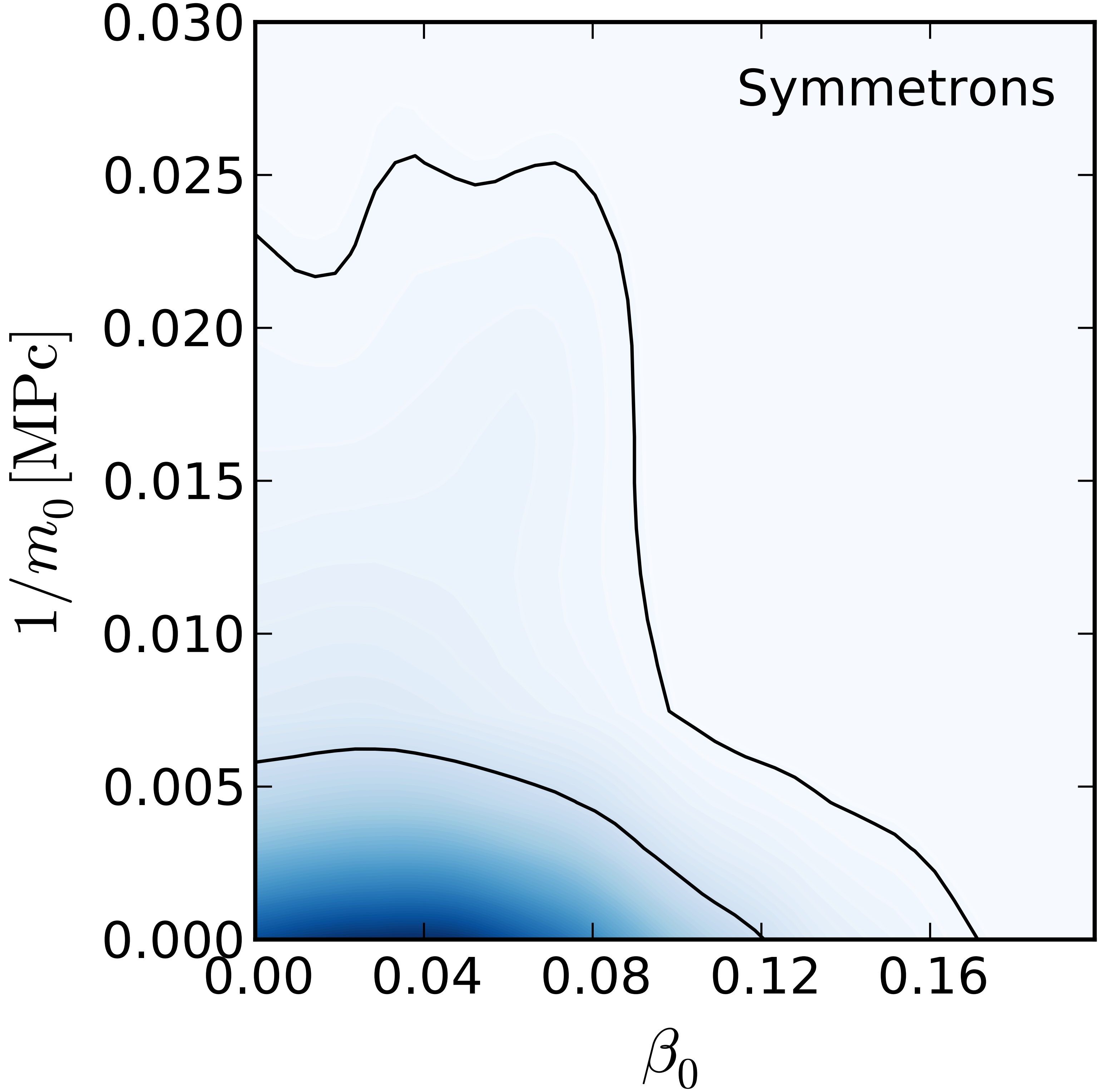
f(R) with B0 parametrization
0.31
0.30
0.29
0.28
0.27
Ω_m
0.00
0.02
0.04
0.06
0.08
0.10
B_0



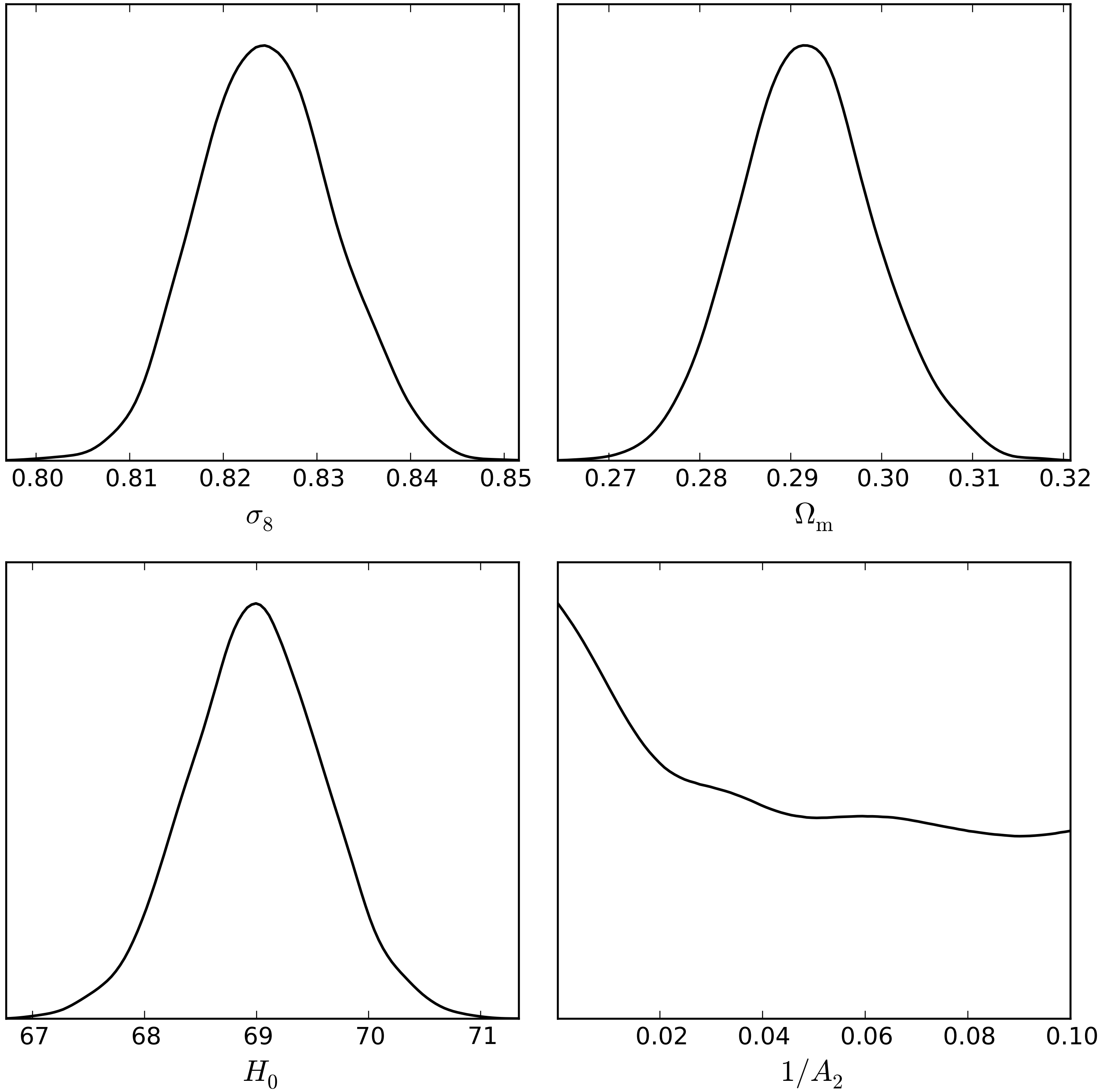
f(R,n), n = 2
n = 1
n = 0
0.31
0.30
0.29
0.28
0.27
Ω_m
0.0
0.2
0.4
0.6
0.8
1.0
1e9
$f_{R0} \times 10^{11}$

Symmetrons

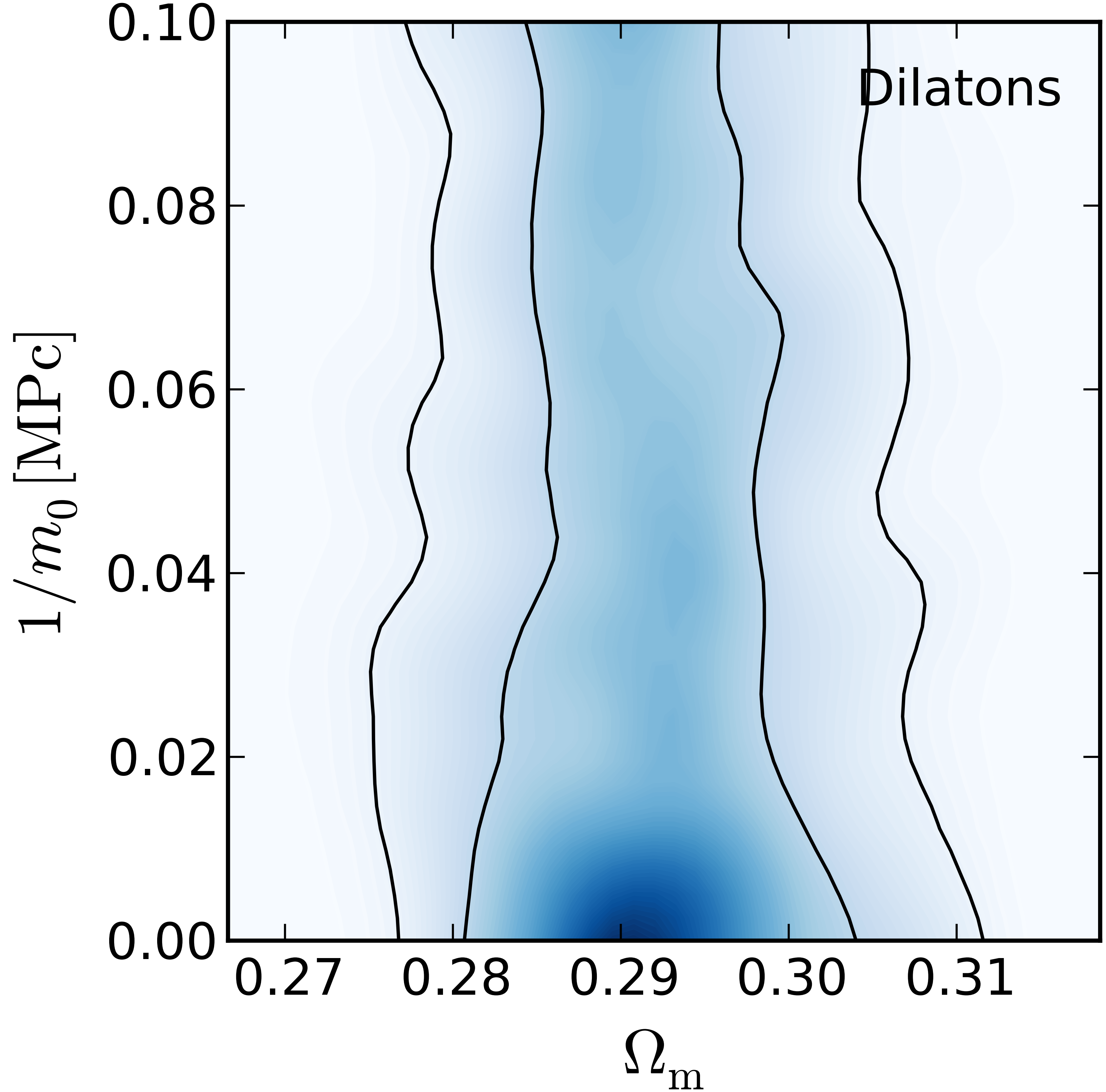

0.800 0.825 0.850 0.875 0.900
σ_8
0.27 0.28 0.29 0.30 0.31 0.32
Ω_m
67 68 69 70 71
H_0
0.000 0.015 0.030 0.045 0.060
$1/m_0$
0.00 0.04 0.08 0.12 0.16 0.20
β_0


Symmetrons
0.030
0.025
0.020
0.015
0.010
0.005
0.000
$1/m_0[\mathrm{MPc}]$
0.00
0.04
0.08
0.12
0.16
β_0

Dilatons



0.80
0.81
0.82
0.83
0.84
0.85
σ_8
0.27
0.28
0.29
0.30
0.31
0.32
$\Omega_{\rm m}$
67
68
69
70
71
H_0
0.02
0.04
0.06
0.08
0.10
$1/A_2$



Dilatons
0.10
0.08
0.06
0.04
0.02
0.00
0.27
0.28
0.29
0.30
0.31
$1/m_0\,[\mathrm{MPc}]$
Ω_{m}

Next we want to make forecasts for future experiments.

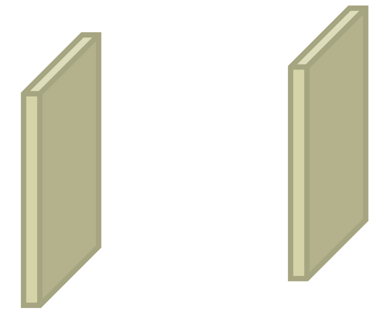
This is in progress

Casimir Force Experiments

Brax et al PRD76(07)124034

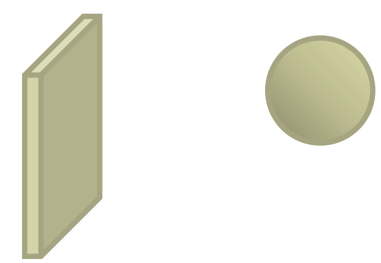
The scalar force could be detected in Casimir type experiments

force between parallel plates



$$F_{cas} \approx d^{-4}$$

force between a plate and a sphere



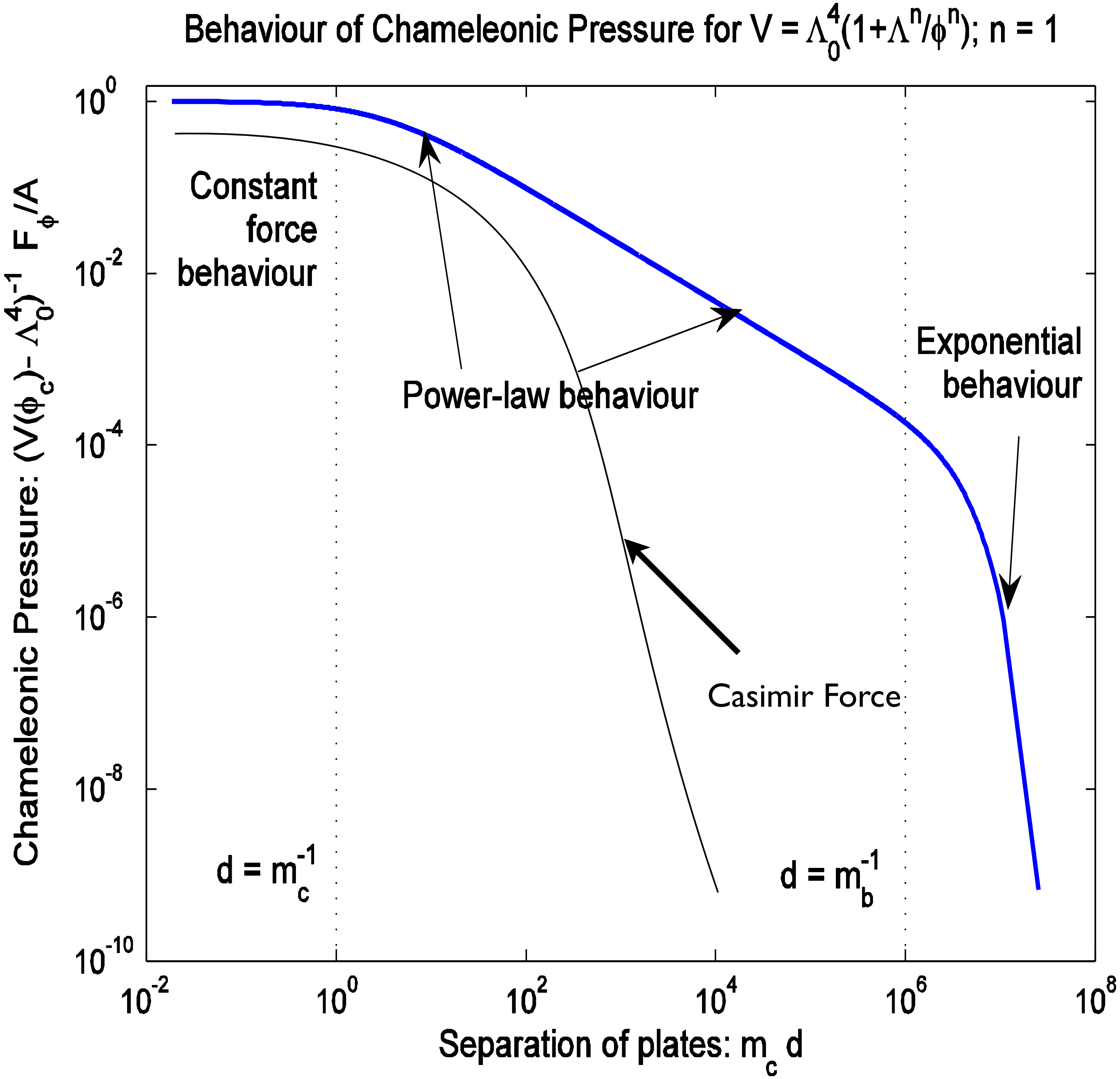
chameleonic force

$$\frac{F_\phi}{A} \sim \Lambda^4 (\Lambda d)^{-\frac{2n}{n+2}}$$

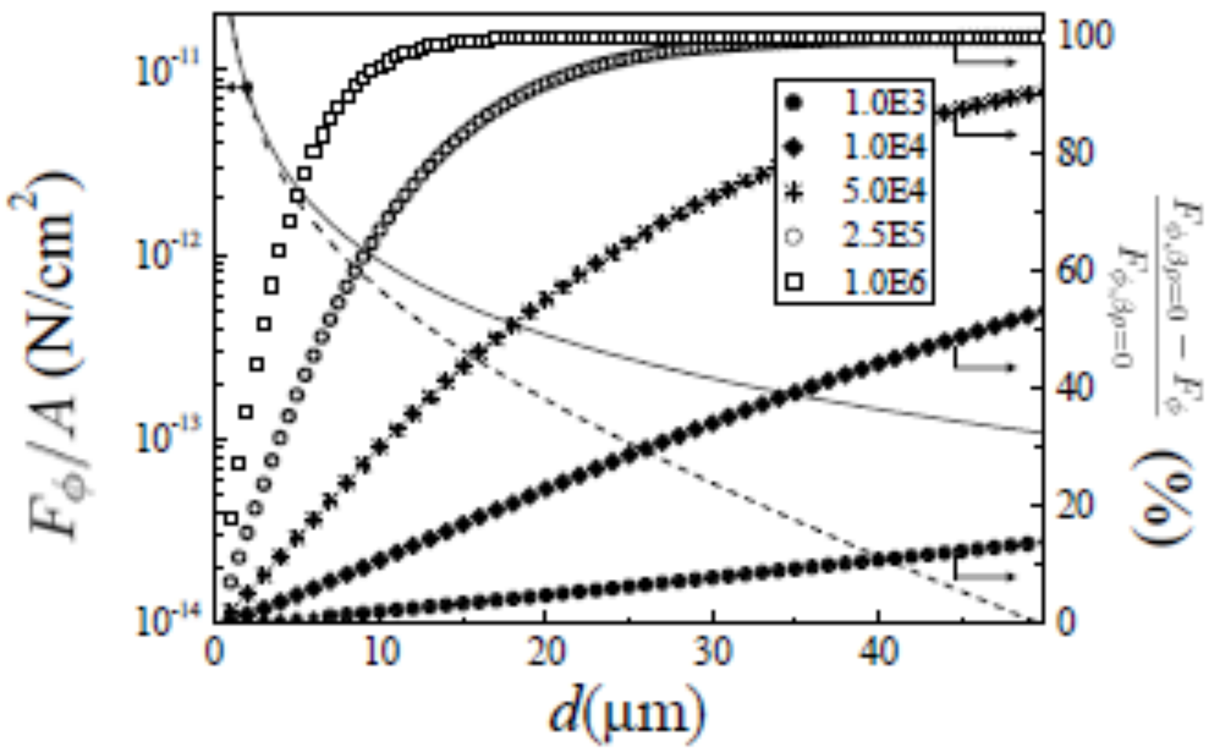
$$\frac{F_\phi}{F_{\text{cas}}} \sim \frac{240}{\pi^2} (\Lambda d)^{\frac{2(n+4)}{n+2}}$$

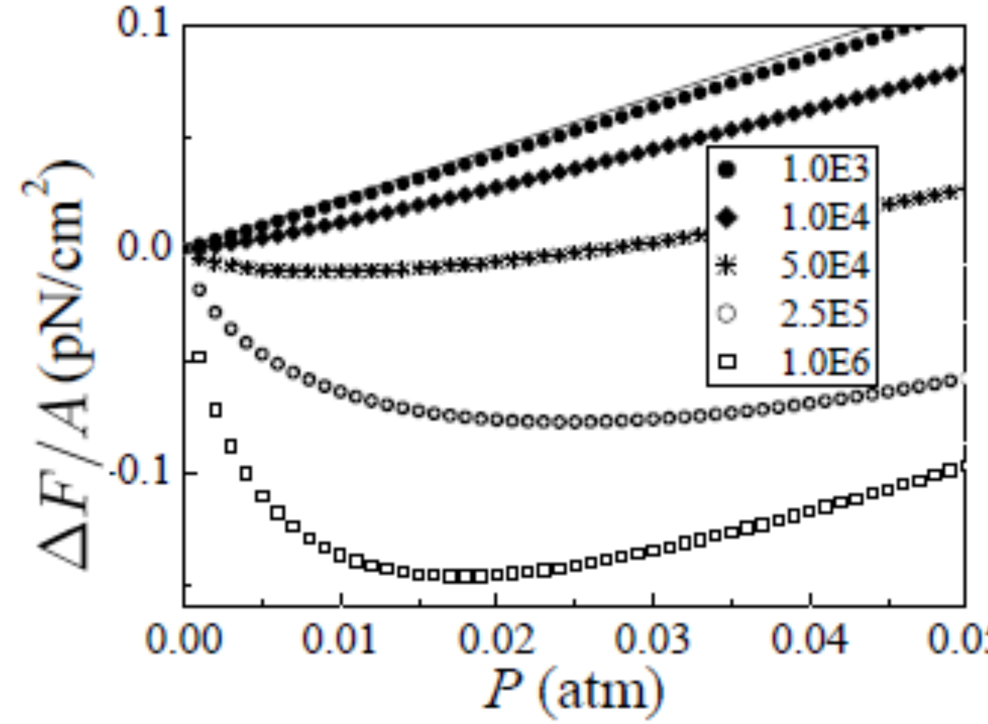
dark energy scale is

$$\Lambda^{-1} \sim 82 \mu m$$



Behaviour of Chameleonic Pressure for V = $\Lambda_0^4(1+\Lambda^n/\phi^n)$; n = 1
Chameleonic Pressure: $(V(\phi_c) - \Lambda_0^4)^{-1}\ F_\phi/A$
Separation of plates: $m_c\ d$
Constant force behaviour
Power-law behaviour
Exponential behaviour
Casimir Force
$d = m_c^{-1}$
$d = m_b^{-1}$
10^0
10^{-2}
10^{-4}
10^{-6}
10^{-8}
10^{-10}
10^{-2}
10^0
10^2
10^4
10^6
10^8

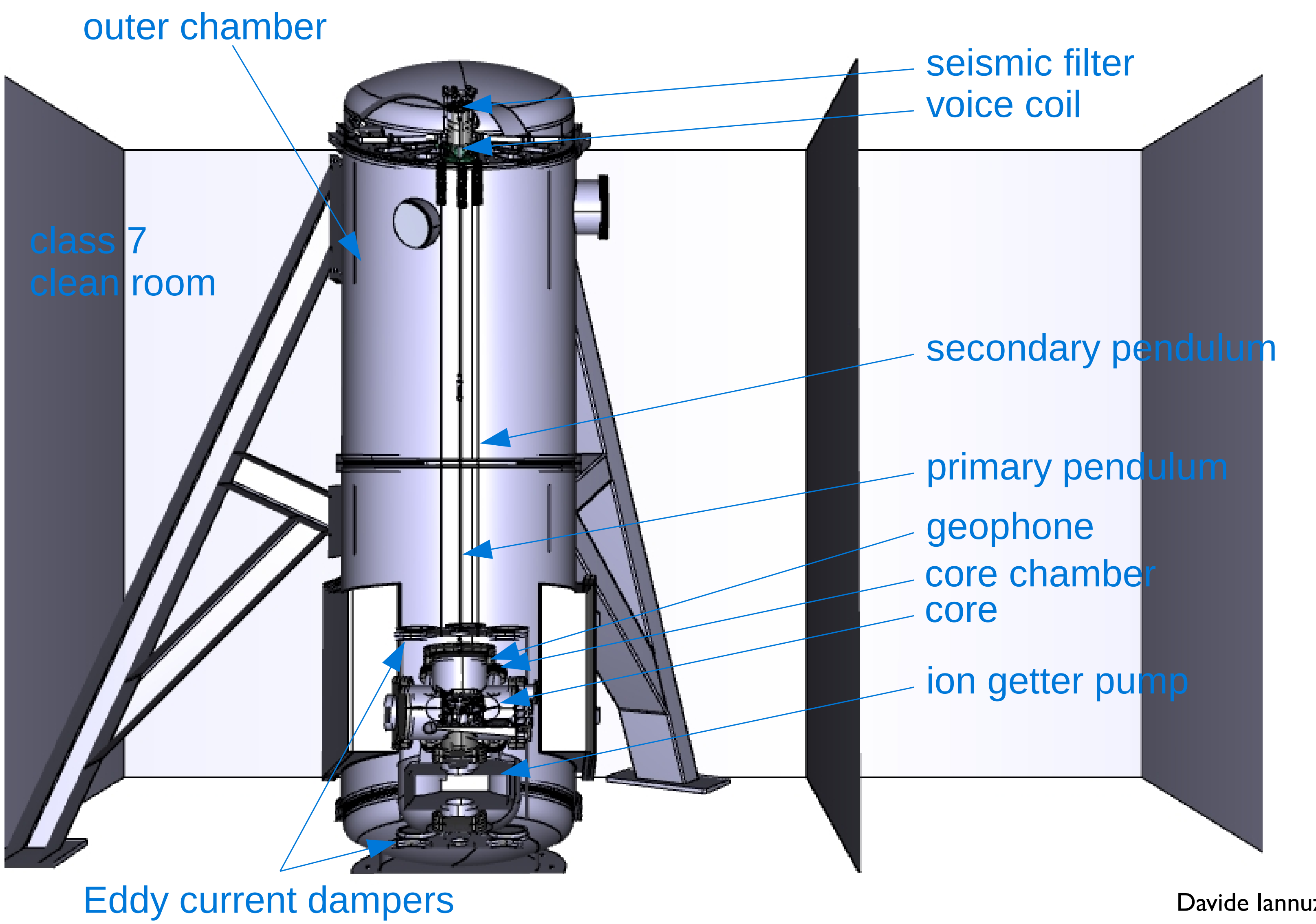




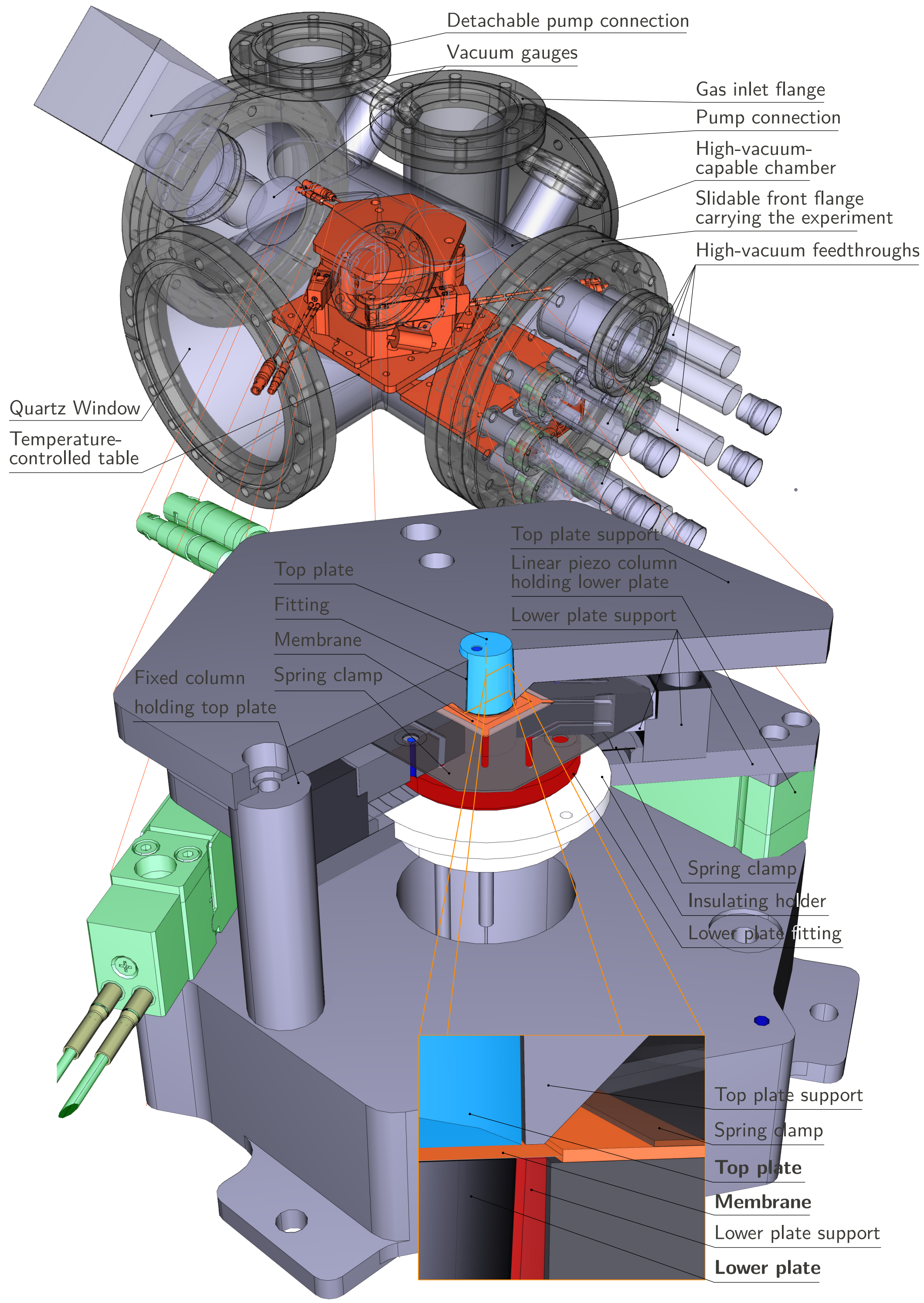
by changing the density between plates the chameleonic force is screened

for plate separation of 30 microns, inject gas at different pressures could determine the coupling to matter

with Davide Iannuzzi
PRL104(10)241101



Davide Iannuzzi, Rene Sedmik et al



Detachable pump connection
Vacuum gauges
Gas inlet flange
Pump connection
High-vacuum-
capable chamber
Slidable front flange
carrying the experiment
High-vacuum feedthroughs
Quartz Window
Temperature-
controlled table
Top plate support
Linear piezo column
holding lower plate
Lower plate support
Top plate
Fitting
Membrane
Spring clamp
Fixed column
holding top plate
Spring clamp
Insulating holder
Lower plate fitting
Top plate support
Spring clamp
Top plate
Membrane
Lower plate support
Lower plate

Can we do More?

Use tomography to consider generalised chameleons, symmetrons and dilatons

Expect chameleons to be detected or ruled out by Amsterdam experiment. Constraints on other models are less strong

in progress with Philippe Brax

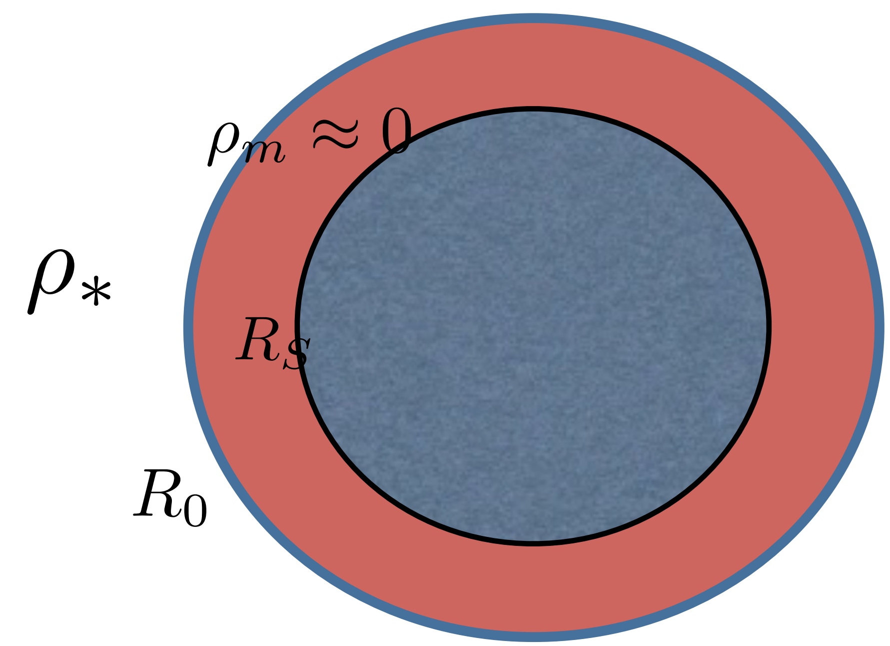
Screened ‘Hair’ on a Black Hole

Consider the effect of screened modified gravity in the strong gravity regime, for instance in a the presence of a black hole. There is a ‘no scalar hair’ theorem for black holes, but this is for idealised conditions where there is no matter and the scalar field is constant. This is not the case in screened modified gravity.

$$R_S \equiv 2M_{BH}M_{Pl}^{-2}$$

In the absence of the scalar field the region I is vacuum $\quad R_S < r < R_0$

with a constant matter density in region II $\quad \rho_* \quad r > R_0$

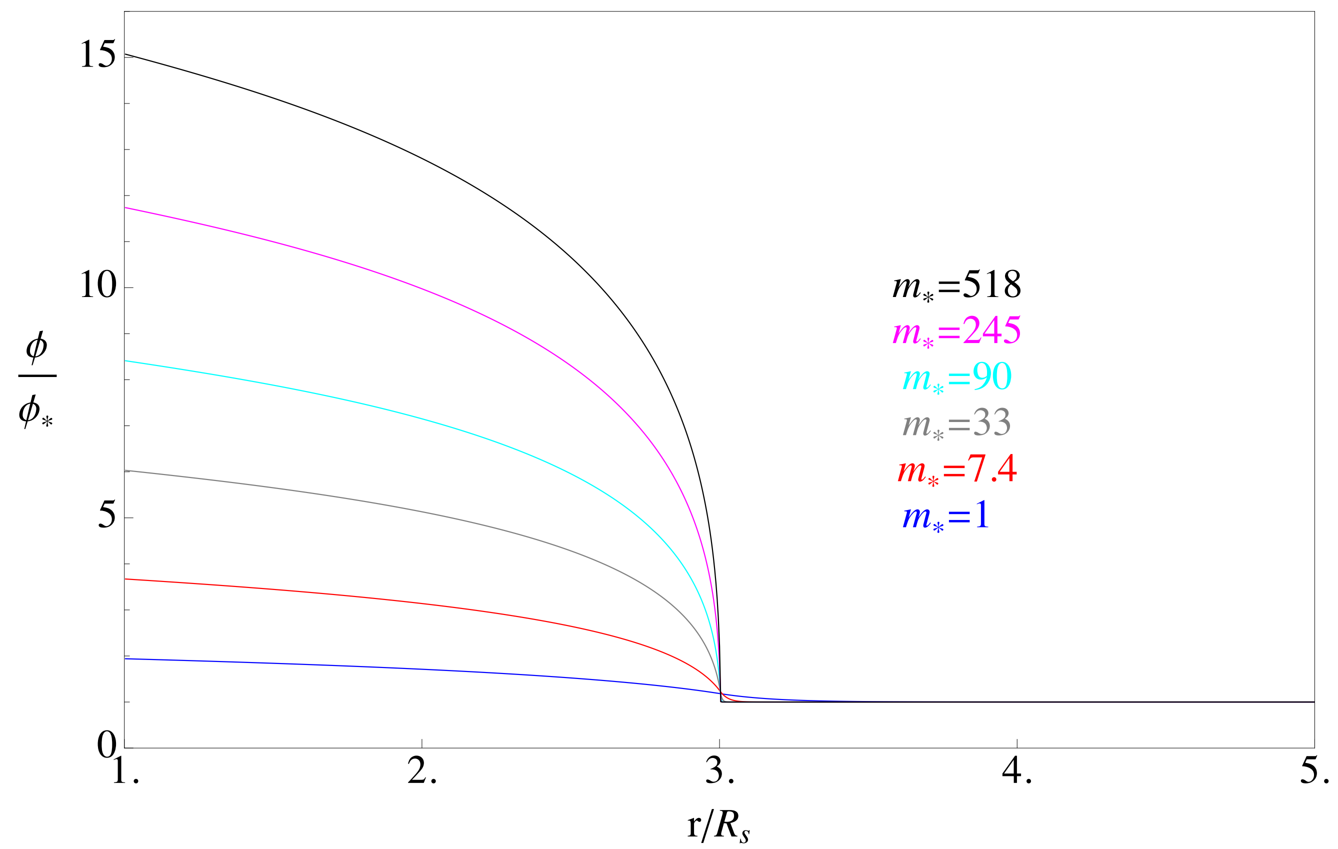


with Ruth Gregory and Rahul Jha

In the thin shell limit we find

$$\phi_h \approx \left[\frac{nV_0R_o^2}{6}\right]^{\frac{1}{n+2}}$$

the value of the scalar field at the black hole horizon



The ratio of scalar to gravitational force is

$$\frac{|F_\phi|}{|F_N|} \approx \left(\frac{r}{R_s}\right)^2 \beta(\phi)|\vec{\nabla}\phi|\frac{M_{BH}}{M_p^3}$$

Comparing scalar radiation to quadrupole radiation for supermassive black hole

$$\left|\frac{\dot{\mathcal{E}}_\phi}{\dot{\mathcal{E}}_{GR}}\right| \sim 10^{-23+\frac{2(n+3)}{(n+1)(n+2)}} \left(\frac{M_{BH}}{M_\odot}\right)^2 \approx 10^{-11} - 10^{-5}$$

Now consider realistic accretion disk

in Weyl form:

$$ds^2 = e^{2\lambda}dt^2 - e^{2(\nu-\lambda)}(d\rho^2 + d\zeta^2) - \alpha^2 e^{-2\lambda}d\phi^2$$

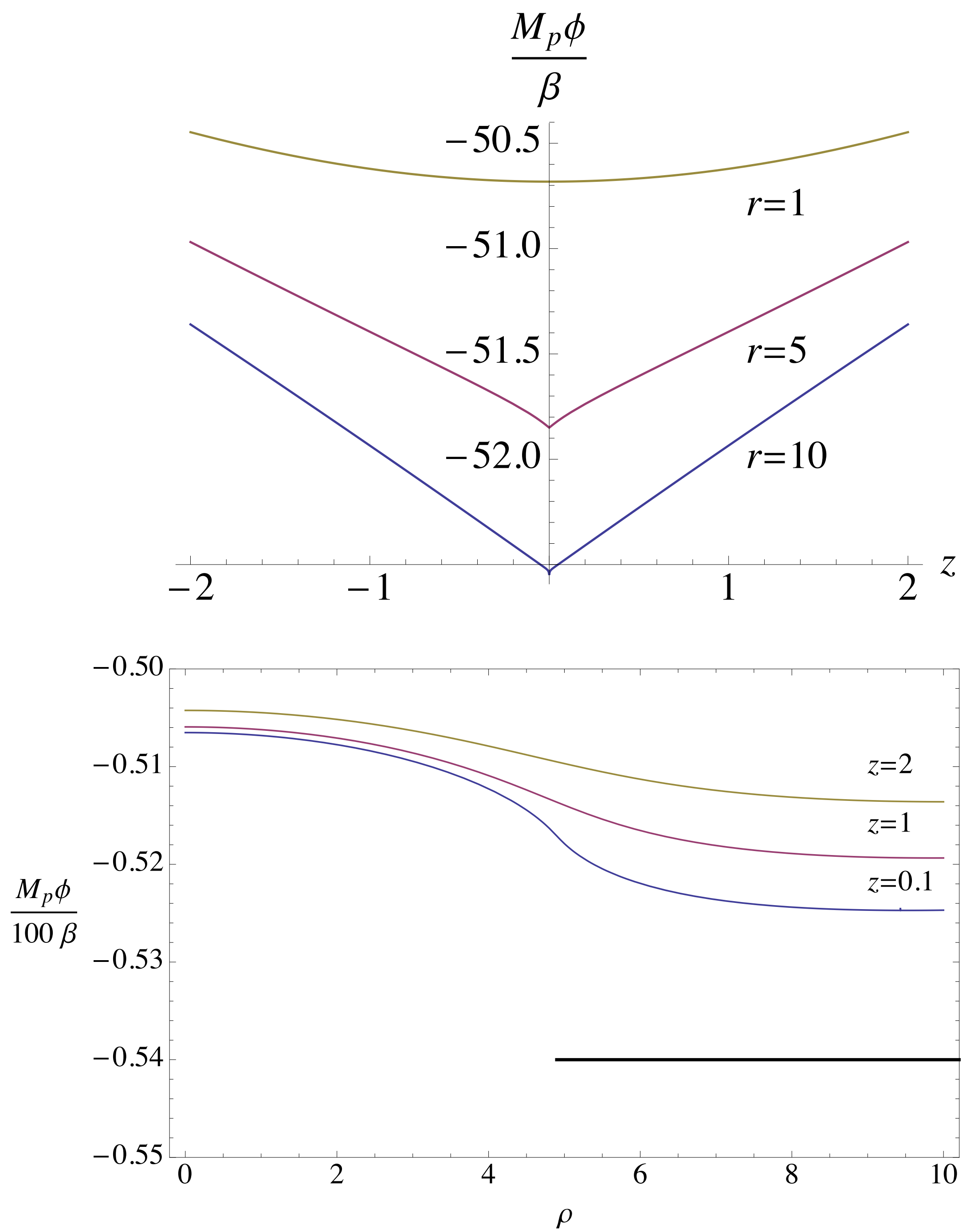
where

$$\alpha \equiv \rho \ , \qquad \lambda = \frac{1}{2}\ln\frac{R_+ - \zeta_+}{R_- - \zeta_-} \ , \qquad \nu = \frac{1}{2}\ln\frac{(R_+R_- + \zeta_+\zeta_- + \rho^2)}{2R_+R_-}$$

and

$$\zeta_\pm = \zeta \pm GM \qquad , \qquad R_\pm^2 = \rho^2 + \zeta_\pm^2$$

Solve as before



Kerr black holes treated similarly -
numerics in progress

The Future

Forecasts for future experiments for all generalised models — underway

Detailed predictions for all lab experiments for generalsed models —underway

Predictions for scalar radiation from Kerr black holes — in progress

Thank you!