Title: Exploring extra dimensions with cosmic acceleration

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Abstract: The standard cosmological model features two periods of accelerated expansion: an inflationary epoch at early times, and a dark energy dominated epoch at late times. These periods of accelerated expansion can lead to surprisingly strong constraints on models with extra dimensions. I will describe new mathematical results which enable one to reconstruct features of a higher-dimensional theory based on the behaviour of the accelerating four-dimensional cosmology. When applied to inflation, these results pose several interesting questions for the construction of concrete models. When applied to dark energy, they provide a new technique to combine measurements of dark energy parameters and constraints on variation of Newton's constant. This technique can transform near-future dark energy surveys into become powerful probes of extra dimensional physics.

Exploring extra dimensions with cosmic acceleration

Daniel Wesley
(Cambridge)

extra dimensions

(Kaluza-Klein, superstrings)

"cosmic acceleration"

$$\ddot{a} > 0$$

(inflation, dark energy)

- Review of classical energy conditions (null, strong)
- In compactified models, reduction of Einstein equations and energy condition(s) to

$$a\frac{\mathrm{d}\zeta}{\mathrm{d}a} \geq \alpha_0 + \alpha_1\zeta + \alpha_2\zeta^2$$

$$\zeta^2 \leq F$$

resulting in e-folding bounds for accelerated expansion.

- Implications for inflation
- Implications for dark energy -- new technique to combine dark energy and G_N variation constraints to probe extra dimensions

Strong energy condition (SEC)

$R_{MN}\, t^M t^N \geq 0$ where t^M is timelike or null

This condition ensures that geodesics converge, and hence that "gravity is attractive."

Null energy condition (NEC)

$R_{MN}\, n^M n^N \geq 0$ where n^M is null

This is the weakest of the energy conditions, and ensures lightlike observers always see a positive energy density.

Strong $R_{MN}\, t^M t^N \geq 0$	Null $R_{MN}\, n^M n^N \geq 0$
Satisfied by	
• $\rho + P \geq 0$ and $\rho + 3P \geq 0$ • Scalars with $V(\varphi) \leq 0$ • ... classical 11D SUGRA + others • anti-de Sitter $\Lambda<0$ • dust and radiation	• $\rho + P \geq 0$ • Scalars with any $V(\varphi)$ and positive kinetic energy terms • D-branes • Implied by all other energy conditions
Violated by	
• Scalars with $V(\varphi) >0$ anywhere • de Sitter $\Lambda>0$ • D-branes	• Casimir energy (...unless averaged) • Negative tension (orientifold planes) • ghost condensates

Why do we need the NEC?

Causality violations

"warp drives," traversable wormholes, time machines, CTCs

Morris, Thorne *Am. J. Phys.* **56** (1988) 395 ; Visser, Kar, Dadhich *Phys. Rev. Lett.* **90** (2003) 201102 ; Alcubierre *Class. Quant. Grav.* **11** (1994) L73 ; Krasnikov *Phys. Rev. D* **57** (1998) 4760 ; Morris, Thorne, Yurtsever *Phys. Rev. Lett.* **61** (1988) 1446 ; Hawking *Phys. Rev. D* **46** (1992) 603

Quantum instabilities

non-unitarity, ghosts, vacuum decay

(many references...)

Classical instabilities

Big Rips, Big Bounces, gradient instabilities ...

Cline, Jeon, Moore *Phys. Rev. D* **70** (2004) 043543 ; Hsu, Jenkins, Wise *Phys. Lett. B* **597** (2004) 270 ; Buniy, Hsu, Murray *Phys. Rev. D* **74** (2006) 063518 ; Caldwell *Phys. Lett. B* **545** (2002) 23 ; Caldwell, Kamionkowski, Weinberg *Phys. Rev. Lett.* **91** (2003) 071301 (many others...)

Breakdown of gravitational thermodynamics

perpetuum mobile, apparent second law violations

Dubovsky, Gregoire, Nicolis, Rattazzi *JHEP* **0603** (2006) 025 ; Arkani-Hamed, Dubovsky, Nicolis, Trincherini, Villadoro *JHEP* **05** (2007) 055 ; Dubovsky, Sibiryakov *Phys. Lett. B* **638** (2006) 509

(Gibbons '84, Maldacena/Nunez '01)

One cannot obtain a four-dimensional de Sitter universe from a higher-dimensional theory with static extra dimensions that satisfies the **strong** energy condition.*

Proof: $M_n = M_4 \times B$

$$ds^2 = g_{mn}(y)\mathrm{d}y^m\mathrm{d}y^n + W(y)^2 g_{\alpha\beta}\mathrm{d}X^\alpha\mathrm{d}X^\beta$$

$${}^{(n)}R_{\alpha\beta} = {}^{(4)}R_{\alpha\beta} - \frac{1}{4}\nabla_m\nabla^m(W^{-1/4})g_{\alpha\beta}$$

$$\int_B W^{-1/4\,(n)}R_{00}g^{00} = \int_B W^{-1/4\,(4)}R_{00}g^{00} + \int_B(\partial W^{-1/4})^2$$

SEC requires $R_{00} \geq 0 \quad \Lambda > 0 \implies {}^{(4)}R_{00} < 0$

* Fine print: Einstein gravity, closed/compact extra dimensions, finite 4D Newton constant

areas for improvement:

- present-day universe is not de Sitter - what about equations of state differing from $w=-1$?
- extra dimensions could be dynamical - can this allow one to escape from the no-go?
- many higher-dimensional theories violate the SEC - can the energy condition be weakened?

(here w is the ratio of pressure to energy density, $w = P/\rho$)

New theorems

A family of results which pair an energy condition and a general feature of the extra-dimensional spacetime metric.*
Here is an example with one pair:

If the higher-dimensional spacetime is warped and Ricci-flat, and the higher-dimensional theory satisfies the Null Energy Condition, then *the four-dimensional w is different than -1, is time-varying, or both*. In fact, *w cannot remain close to -1 for more than a few e-foldings*.

Furthermore, if the four-dimensional universe is accelerating, then *Newton's constant varies (in both instantaneous and secular senses).*

* Fine print: Einstein gravity, closed/compact extra dimensions, finite 4D Newton constant

4D universe with constant w embedded with k Ricci-flat extra dimensions, evolve by breathing mode only, with no other matter.

$$\mathrm{d}s_4^2 = a(\eta)^2\left(-\mathrm{d}\eta^2 + \mathrm{d}x_3^2\right)$$

$$a(\eta) \sim \eta^{2/(1+3w)}$$

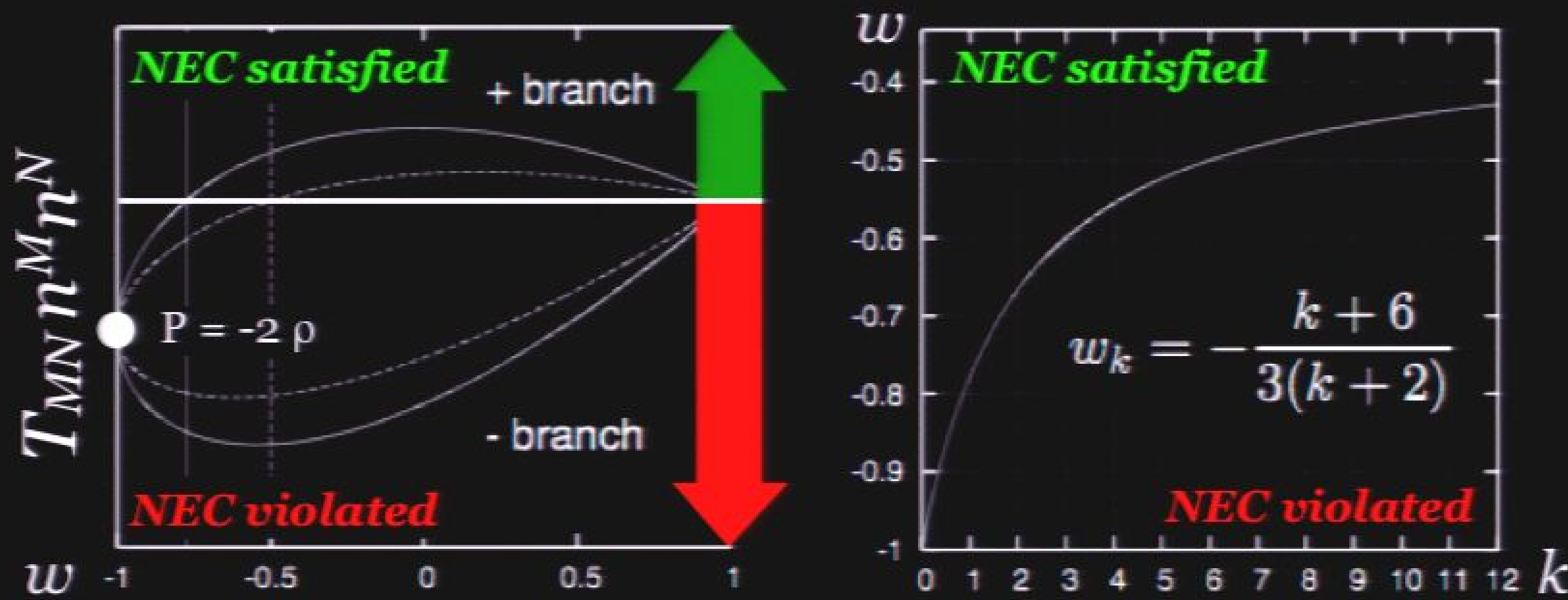
$$\rho + P = 3(1+w)\frac{(a')^2}{a^4} = \frac{(\psi')^2}{a^2}$$

$$V(\psi) = V_0 e^{\pm\sqrt{3(1+w)}\psi} \qquad \psi(\eta) = \mp\left(\frac{1+w}{1+3w}\right)\ln\eta^6 + \psi_0$$

$$c = \sqrt{\frac{2k}{k+2}} \qquad a(\eta) = e^{c\psi/2}A(\eta)$$

$$\mathrm{d}s_{4+k}^2 = A(\eta)^2\left(-\mathrm{d}\eta^2 + \mathrm{d}x_3^2\right) + \exp\left[\frac{2c}{k}\psi(\eta)\right]\mathrm{d}s_k^2$$

Reconstruct (4+k)D metric and use Einstein equations to compute stress-energy tensor



$$V(\psi) = V_0 e^{\mp\sqrt{3(1+w)}\psi}$$

This unusual (even pathological) behavior is completely invisible from 4D

For a more general case...

- Extra dimensions could distort
  - Anisotropically
  - Inhomogeneously
- Warped extra dimensions
- Non-Ricci-flat extra dimensions
- Scalar field might not be breathing mode
- Metric moduli may not act like quintessence
- Completely different scalar could drive accel.
- ... *etc*

Assumptions

- Higher-dimensional action has Einstein-Hilbert form
  ...includes *g(φ)R* and *F(R)* models

$$S_{(4+k)} = \frac{1}{2\kappa^{2+k}} \int \left[R(g) + \mathcal{L}_m^{(4+k)}\right] \sqrt{-g}\, \mathrm{d}^{4+k}X$$

- All four-dimensional statements refer to the Einstein frame metric and its associated cosmology.

$$S_{4\mathrm{D}} = \frac{1}{2\ell_4^2} \int R(g)\sqrt{-g}\, \mathrm{d}^4x + \text{other terms}$$

- *M* closed and compact, or a quotient of such, as *M =M'/G*

$$g_{MN}^{(4+k)} \mathrm{d}X^M \mathrm{d}X^N = e^{2\Omega(t,y)} h_{\mu\nu}^{(4)}(t)\mathrm{d}x^\mu \mathrm{d}x^\nu + g_{\alpha\beta}^{(k)}(t,y)\mathrm{d}y^\alpha \mathrm{d}y^\beta$$

- Arbitrary other matter fields may be present in the action

Curved	Ricci-flat	CRF
$\mathcal{R} \neq 0$ on $\mathcal{M}$	$\mathcal{R} = 0$ on $\mathcal{M}$	$ds^2 = e^{2\Omega} ds_4^2 + e^{-2\Omega} ds_k^2$
Non-Abelian continuous isometries** ... includes models which obtain 4D gauge symmetries by KK reduction Rugby-ball SLED ** We only know these cannot be Ricci-flat, which is a stronger condition than "curvature-free."	Special holonomy *Sp(n)* *Spin(7)* *SU(n) (Calabi-Yau)* *G_2 (M theory)* One-dimensional Original Kaluza-Klein Randall-Sundrum Tori R^n / Z^n *with* $R \geq 0$	Klebanov-Strassler warped throat Giddings-Kachru-Polchinski flux solutions

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	Curved	Ricci-flat	CRF
dS	Strong (Gibbons *et. al.*)	Null	Null
$w>-1$	Strong *(transient)*	Null *(transient)*	Null *(transient)*

Some tools

Decomposition of metric deformations

$$\frac{1}{2}\frac{\mathrm{d}}{\mathrm{d}t}g^{(k)}_{\alpha\beta} = \frac{1}{k}\xi g^{(k)}_{\alpha\beta} + \sigma_{\alpha\beta}$$

A-Averaging

$$\langle Q(t, y^\alpha)\rangle_A = \left(\int e^{A\Omega}\, Q \det\left(e_{\mathcal{M}}\right) \mathrm{d}^k y\right)\left(\int e^{A\Omega} \det\left(e_{\mathcal{M}}\right) \mathrm{d}^k y\right)^{-1}$$

Weighted integral of Q over the compact space

Weighted volume of the compact space

A useful lemma

For a perfect fluid $T_{\hat{\mu}\hat{\nu}} = \begin{pmatrix} \rho & \\ & P\delta_{\hat{m}\hat{n}} \end{pmatrix}$ if ρ + P < 0 then NEC is violated.

In a Kaluza-Klein spacetime, the most general stress-energy is

$$T_{\hat{A}\hat{B}} = \begin{pmatrix} \rho^D & 0_{\hat{0}\hat{n}} & J^{\hat{b}} \\ 0_{\hat{m}\hat{0}} & P_3^D \delta_{\hat{m}\hat{n}} & 0_{\hat{m}\hat{b}} \\ J^{\hat{a}} & 0_{\hat{a}\hat{n}} & \tau_{\hat{a}\hat{b}} \end{pmatrix} \qquad \begin{gathered} \tau_{\hat{a}\hat{b}} = P_k^D \delta_{\hat{a}\hat{b}} + \pi_{\hat{a}\hat{b}} \\ \delta^{\hat{a}\hat{b}} \pi_{\hat{a}\hat{b}} = 0 \quad P_k^D = k^{-1} \delta^{\hat{a}\hat{b}} \tau_{\hat{a}\hat{b}} \end{gathered}$$

If either $\begin{gathered} \rho^D + P_3^D < 0 \\ \rho^D + P_k^D < 0 \end{gathered}$ then NEC violated

Dynamical metric hinders satisfying NEC

$$n^2 e^{-\phi}\langle e^{2\Omega}(\rho^D + P_3^D)\rangle_A = n^2(\rho_T + P_T) - \frac{k+2}{2k}\xi_{0|A}^2 - \frac{k+2}{2k}\langle \xi_{\perp|A}^2\rangle_A - \langle\sigma^2\rangle_A$$

Must be non-negative to satisfy NEC

4D energy density and pressure

$$n^2 e^{-\phi}\langle e^{2\Omega}(\rho^D + P_k^D)\rangle_A = \frac{n^2}{2}(\rho_T + 3P_T) + 2\left(\frac{A}{4} - 1\right)\frac{k+2}{2k}\langle \xi_{\perp|A}^2\rangle_A$$
$$- \frac{k+2}{2k}\xi_{0|A}^2 - \langle\sigma^2\rangle_A$$
$$+ \left[\left(\frac{4}{k} - 1\right)(A+2) + \left(4 - \frac{4}{k}\right)\right]\langle e^{2\Omega}(\partial\Omega)^2\rangle_A$$
$$+ \frac{k+2}{2k}\frac{n}{a^3}\frac{\mathrm{d}}{\mathrm{d}t}\left(\frac{a^3}{n}\xi_{0|A}\right)$$

Dynamical metric helps to satisfy NEC

$$\zeta = \frac{\xi_{0|A}}{H(t)}$$ = fractional increase in volume per Hubble time

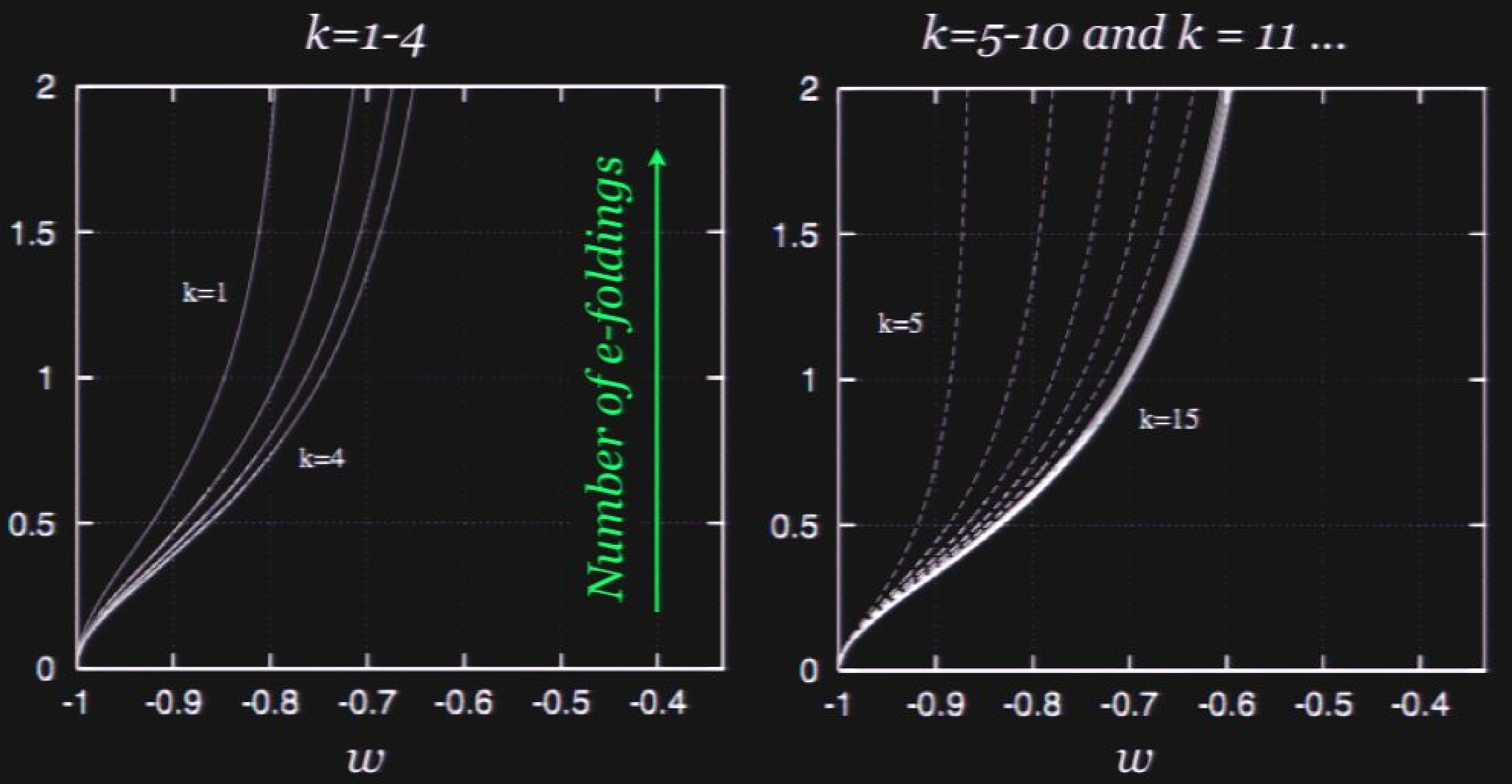
Einstein equations and energy conditions cast as two simple inequalities

(1) $$a\frac{\mathrm{d}\zeta}{\mathrm{d}a} \geq \alpha_0 + \alpha_1\zeta + \alpha_2\zeta^2$$

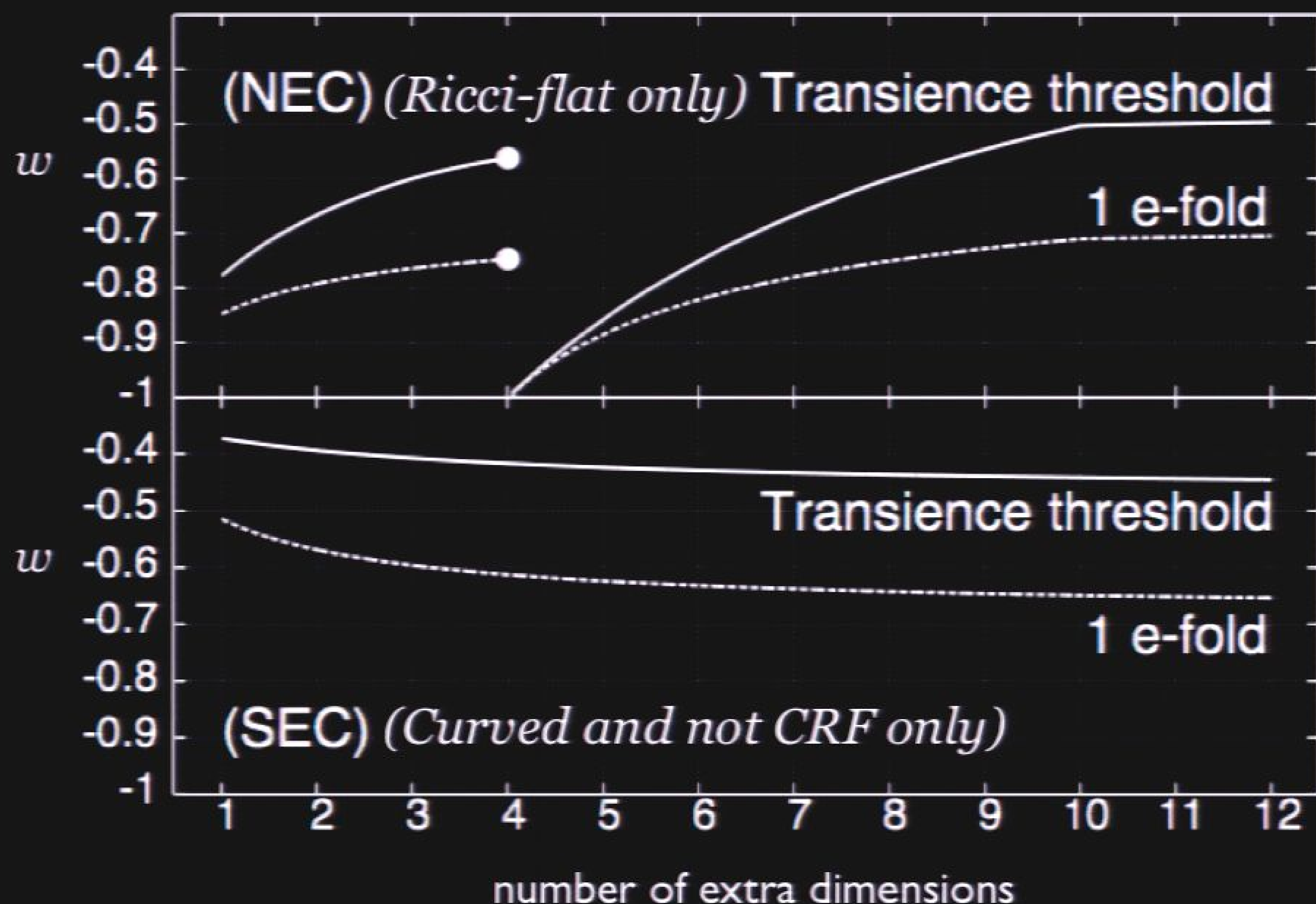
(2) $$\zeta^2 \leq F$$

α_0, α_1, α_2, and F are complicated functions of w, etc. If one cannot solve these equations, then a NEC-satisfying solution does not exist.

The solution with the maximal number of e-foldings consistent with NEC saturates *(1)* with boundary conditions set by *(2)*.



k=1-4
k=5-10 and k = 11 ...
Number of e-foldings
k=1
k=4
k=5
k=15
2
1.5
1
0.5
0
-1
-0.9
-0.8
-0.7
-0.6
-0.5
-0.4
w



(NEC) (Ricci-flat only) Transience threshold
1 e-fold
Transience threshold
1 e-fold
(SEC) (Curved and not CRF only)
w
w
-0.4
-0.5
-0.6
-0.7
-0.8
-0.9
-1
1 2 3 4 5 6 7 8 9 10 11 12
number of extra dimensions

"Loopholes"

1. Curvature of *M*

   Could go either way, either helping or hindering NEC.
   Important question: what metric should we use?

2. Quantum effects

   If we are unable to impose the Einstein equations, how literally should we take the extra dimensions?

3. Higher-derivative corrections to GR

   $$G_{MN} = T_{MN} + \Theta_{MN}[R, R_{AB}, R_{ABCD}]$$

   if effectively NEC-violating, do we avoid usual problems?

4. Negative-tension objects (not really a loophole, these violate NEC)

   braneworld boundaries, O-planes

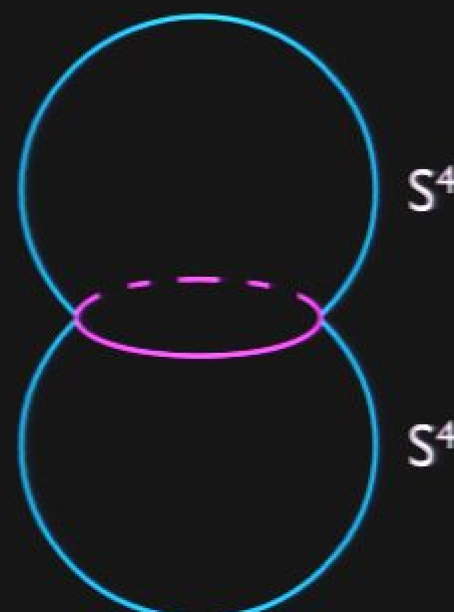
Bubbles of nothing

$$S = S_{\text{matter}} + S_{\text{gravity}} + \sum_i T_i \int_{\partial\mathcal{M}_i} \sqrt{h}\, \mathrm{d}^{d-1}x$$

Negative-tension
"Coleman-de Luccia instantons"

$$S = \int P(X) - V(\phi)$$

$$X = -\frac{1}{2}(\partial\phi)^2$$



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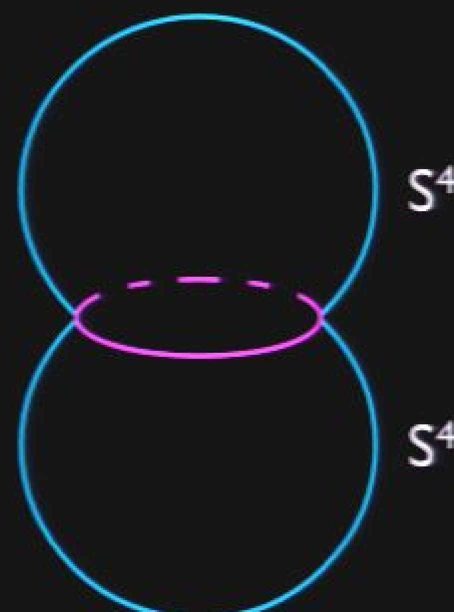

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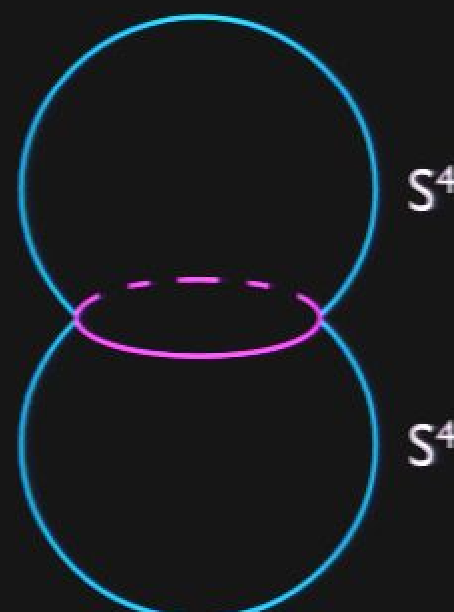
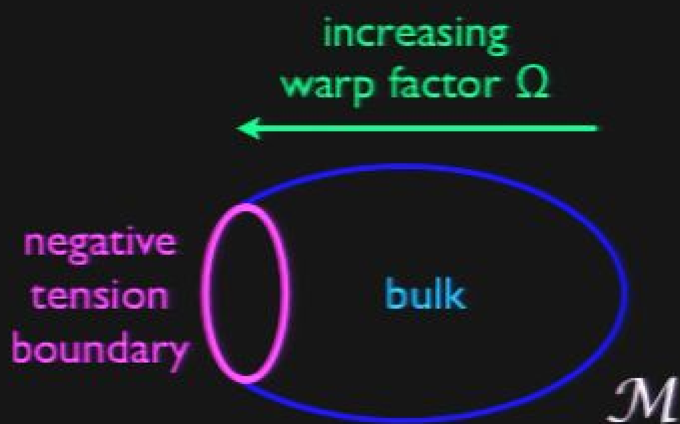
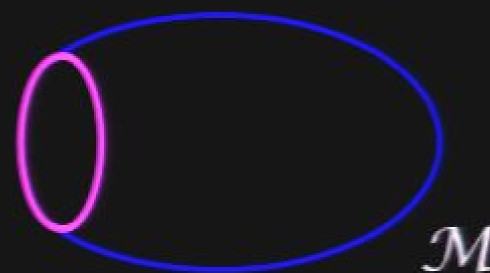


Accelerating to decelerating transition after inflation





inflating

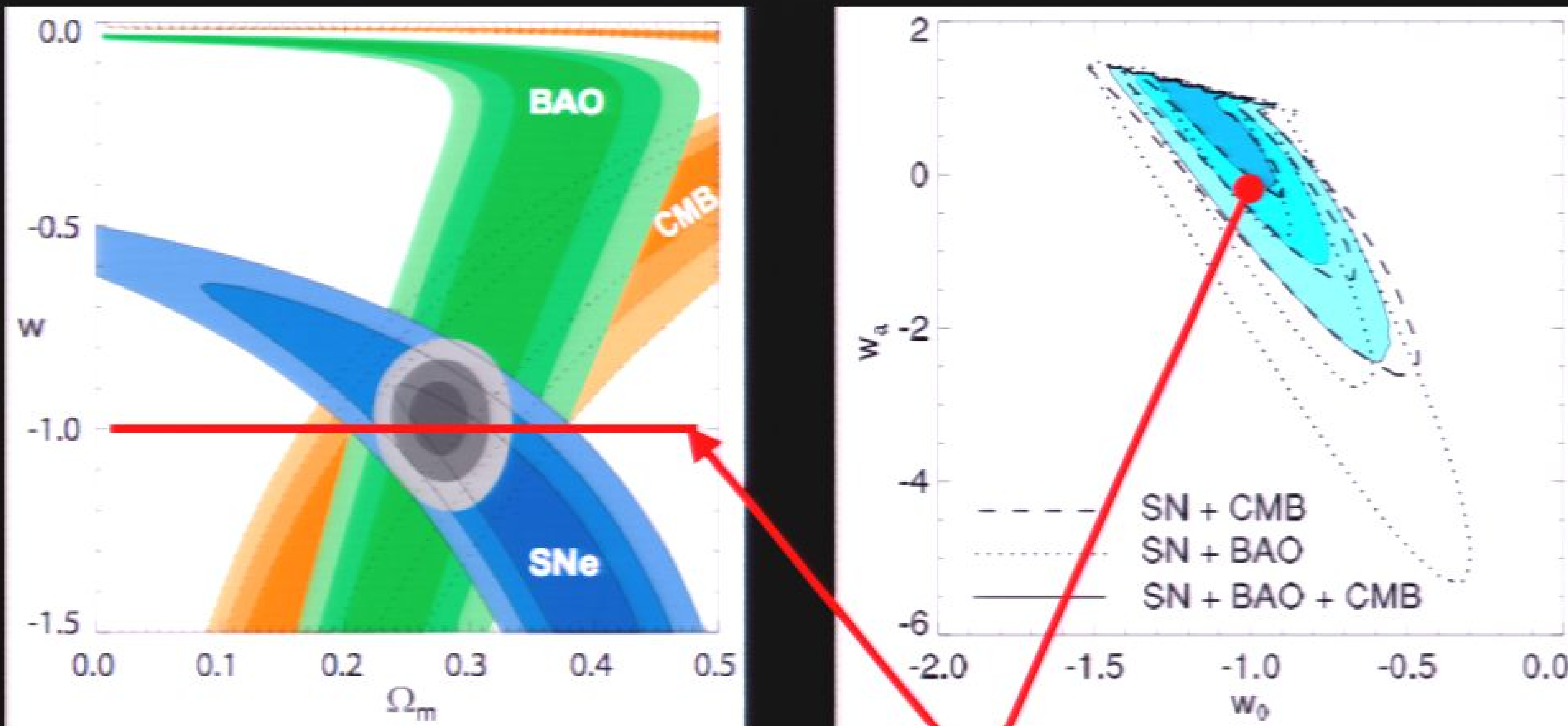
$$\langle \rho^D + P_k^D \rangle < 0$$

radiation dominated

$$\langle \rho^D + P_k^D \rangle > 0$$

Additional sources of NEC violation may be required,
in addition to the negative tension boundaries.

Applications to future dark energy surveys



figures from Kowalski *et al.* 0804.4142

data is consistent with a cosmological constant

Problem 1: easy to construct models which give w very close to -1

Slow-roll scalar field with potential

$$3H\dot{\varphi} = -\frac{\mathrm{d}V(\varphi)}{\mathrm{d}\varphi}$$

$$w = \frac{\frac{1}{2}\dot{\varphi}^2 - V(\varphi)}{\frac{1}{2}\dot{\varphi}^2 + V(\varphi)} \sim -1 + \frac{M_{\mathrm{Pl}}^2}{3}\left(\frac{V'}{V}\right)^2$$

Extremely ambitious space missions may get $w_{dark} \lesssim -0.955$ at 3σ, which requires $\left|\frac{V'}{V}\right| \lesssim \frac{0.37}{M_{\mathrm{Pl}}}$

∴ Easy to choose parameters such that we can never distinguish this simple model from Λ.

Problem 2: What will confirming de Sitter tell us?

The "inverse problem"

How can we use the observed properties of dark energy to learn about its origin?

Example: suppose a reliable source informs us that $w_{dark} = -1$ and constant.

Possibility I:

A simple cosmological constant Λ.

Possibility II:

Metastable de Sitter string vacuum

... one of 10^{300} choices given choice of Calabi-Yau (or other manifold) configuration of D/anti-D branes, O-planes, flux winding numbers, etc.

Observational prospects

(work-in-progress with Paul Steinhardt)

More precise measurements of w(a), combined with bounds on variation of fundamental constants, can provide surprisingly powerful probes of extra-dimensional physics.

As dark energy surveys provide ever-more stringent constraints on the dark energy equation-of-state, we can progressively rule out families of extra-dimensional models - even if the measurements are consistent with Λ

Einstein equations and energy conditions cast as two simple inequalities

$$a\frac{\mathrm{d}\zeta}{\mathrm{d}a} \geq \alpha_0 + \alpha_1\zeta + \alpha_2\zeta^2$$

$$\zeta^2 \leq F$$

Where ζ measures the rate-of-change of extra-dimensional volume, and α_0, α_1, α_2, and F are complicated functions of w, etc.

4D Newton constant $$G_N^{(4)} = \frac{G_N^{(4+k)}}{\mathrm{Vol}(M)}$$

$$\frac{\dot{G}_N}{G_N} = -H(t)\zeta \qquad \frac{G_N(t_1)}{G_N(t_0)} = \exp\int_{a(t_1)}^{a(t_0)} \zeta(a)\,\frac{\mathrm{d}a}{a}$$

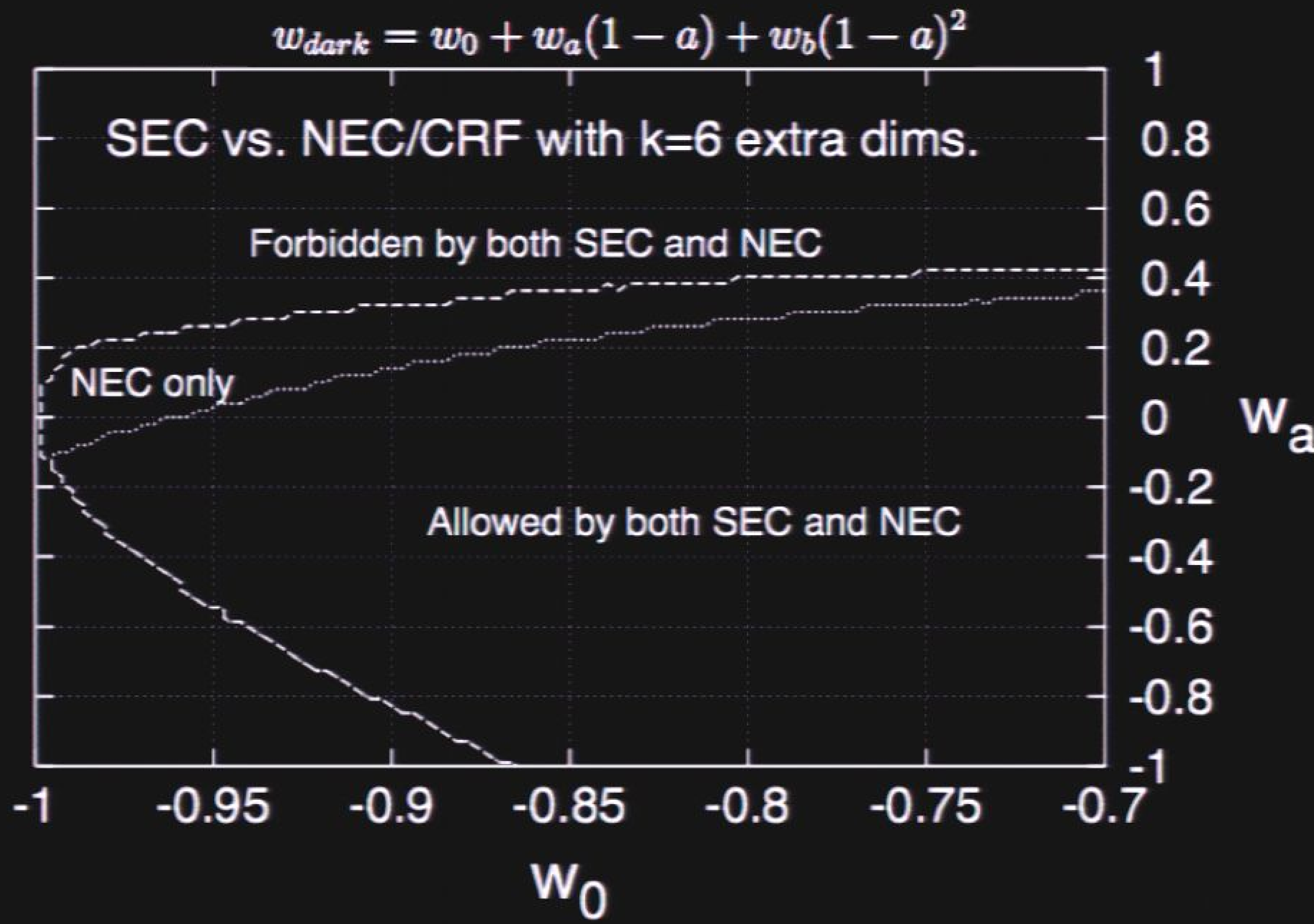
Dark energy parameterization

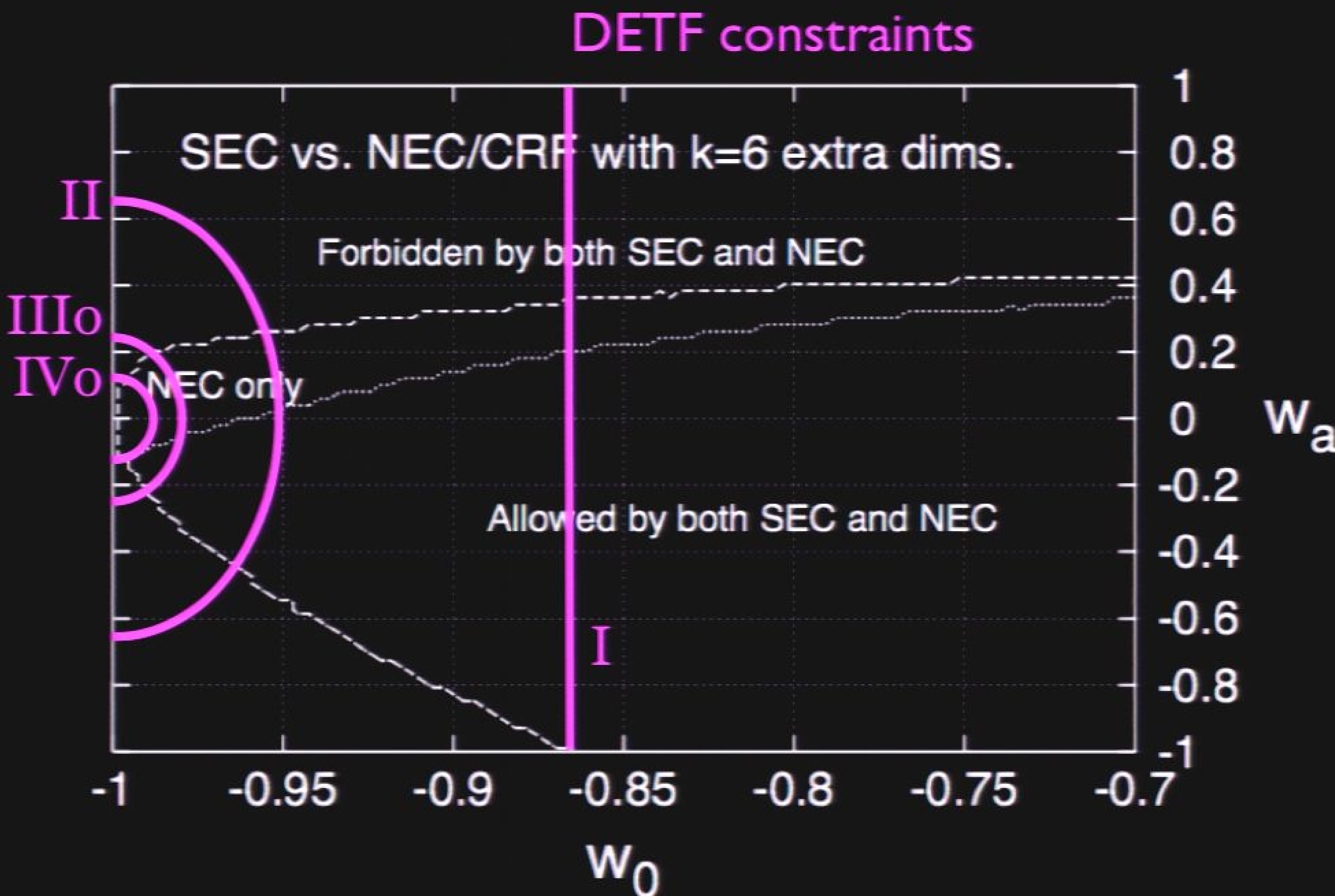
$$w_{dark} = w_0 + w_a(1-a) + w_b(1-a)^2$$

DETF linear parameterization

This term allows us to ensure $w_{dark} > -1$ even when the scale factor is significantly different from unity

We explored model space by running many different realizations of dark energy models and ζ evolution on Cosmos, the UK national cosmology supercomputer


$w_{dark} = w_0 + w_a(1-a) + w_b(1-a)^2$
SEC vs. NEC/CRF with k=6 extra dims.
Forbidden by both SEC and NEC
NEC only
Allowed by both SEC and NEC
1
0.8
0.6
0.4
0.2
0
-0.2
-0.4
-0.6
-0.8
-1
wa
-1
-0.95
-0.9
-0.85
-0.8
-0.75
-0.7
w0


DETF constraints
SEC vs. NEC/CRF with k=6 extra dims.
Forbidden by both SEC and NEC
NEC only
Allowed by both SEC and NEC
II
IIIo
IVo
I
1
0.8
0.6
0.4
0.2
0
-0.2
-0.4
-0.6
-0.8
-1
w_a
-1
-0.95
-0.9
-0.85
-0.8
-0.75
-0.7
w_0

G_N variation constraints

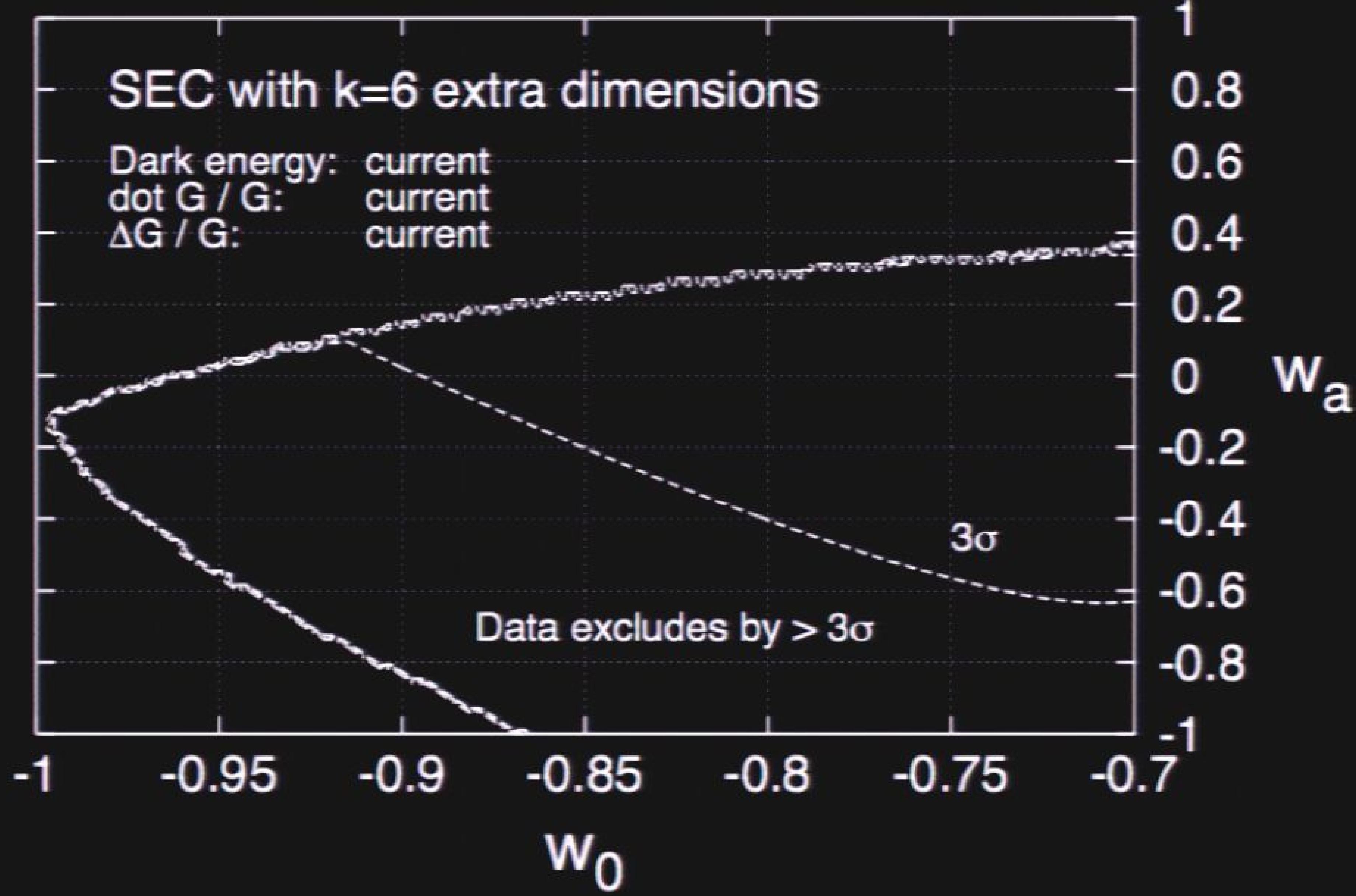
BBN constraints using WMAP Ω_b and HEP N_ν
Copi, Davis, Krauss, PRL 92 171301 (2004)

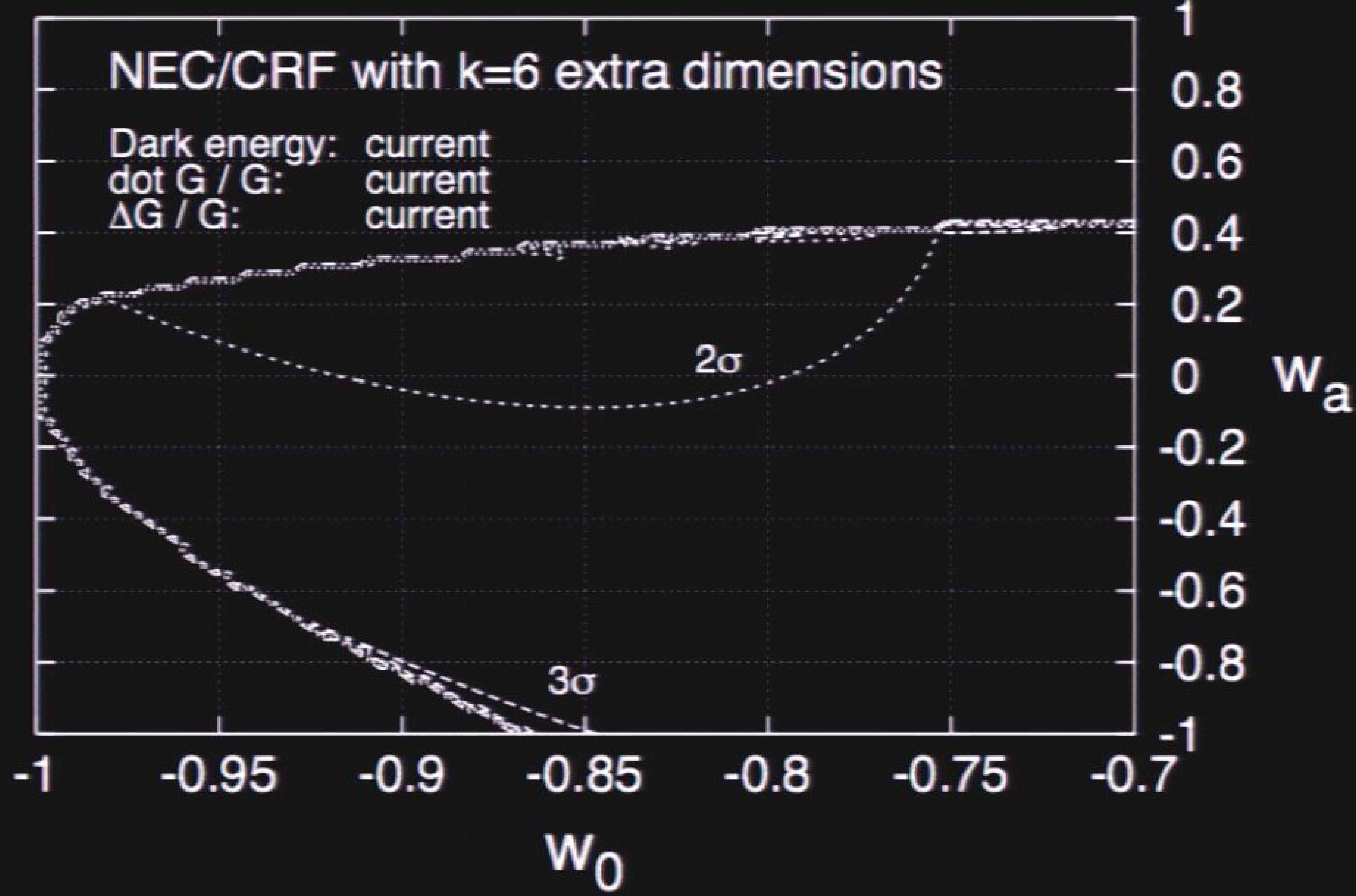
$$\frac{G_{BBN}}{G_0} = 1.01^{+0.20}_{-0.16}$$

Radar ranging data from Mariner 10, Mercury and Venus $\quad \dot{G}/G = (0 \pm 2) \times 10^{-12}\ \mathrm{yr}^{-1}$

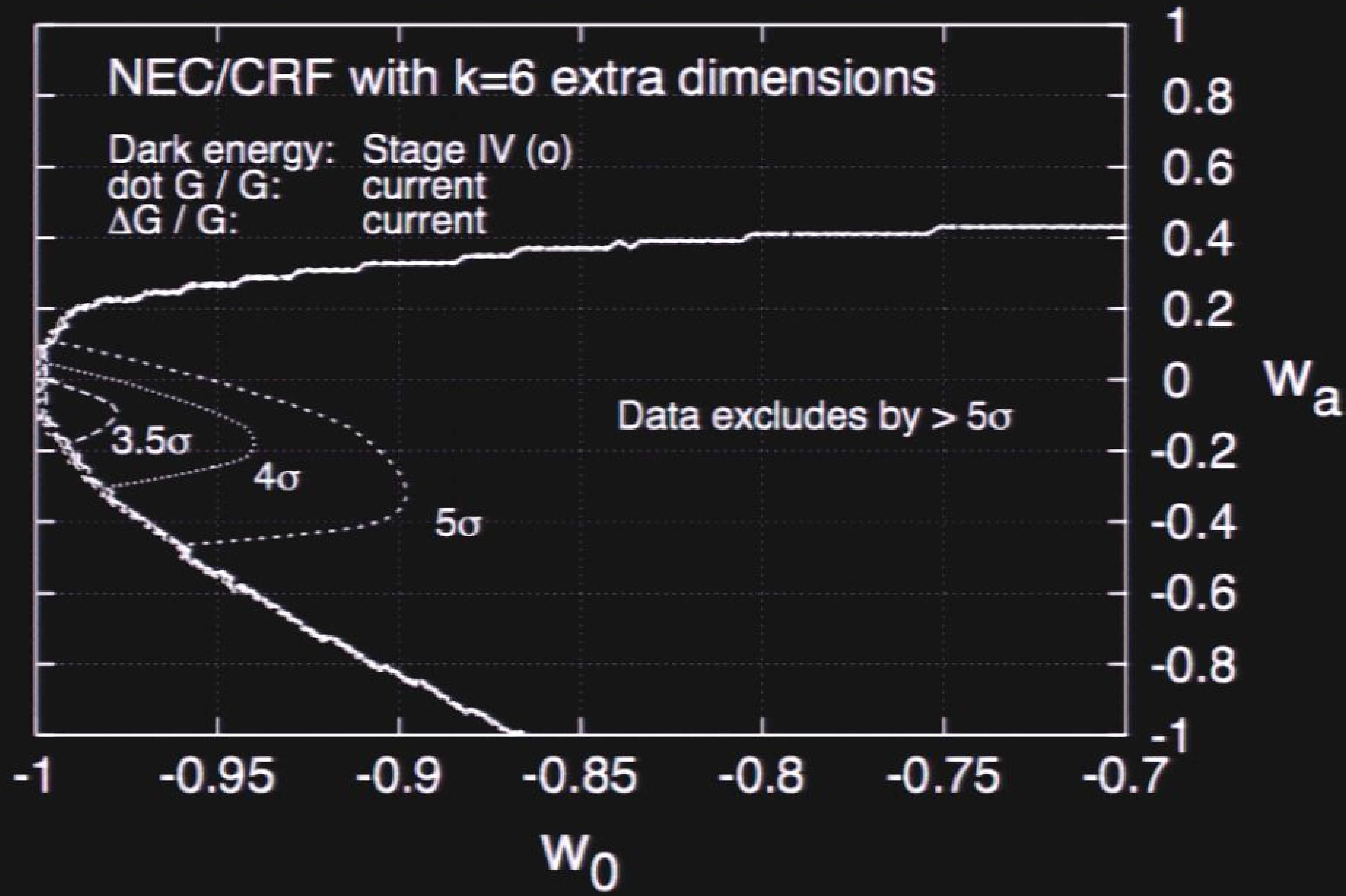
PSR 1913+16 $\quad \dot{G}/G = (4 \pm 5) \times 10^{-12}\ \mathrm{yr}^{-1}$

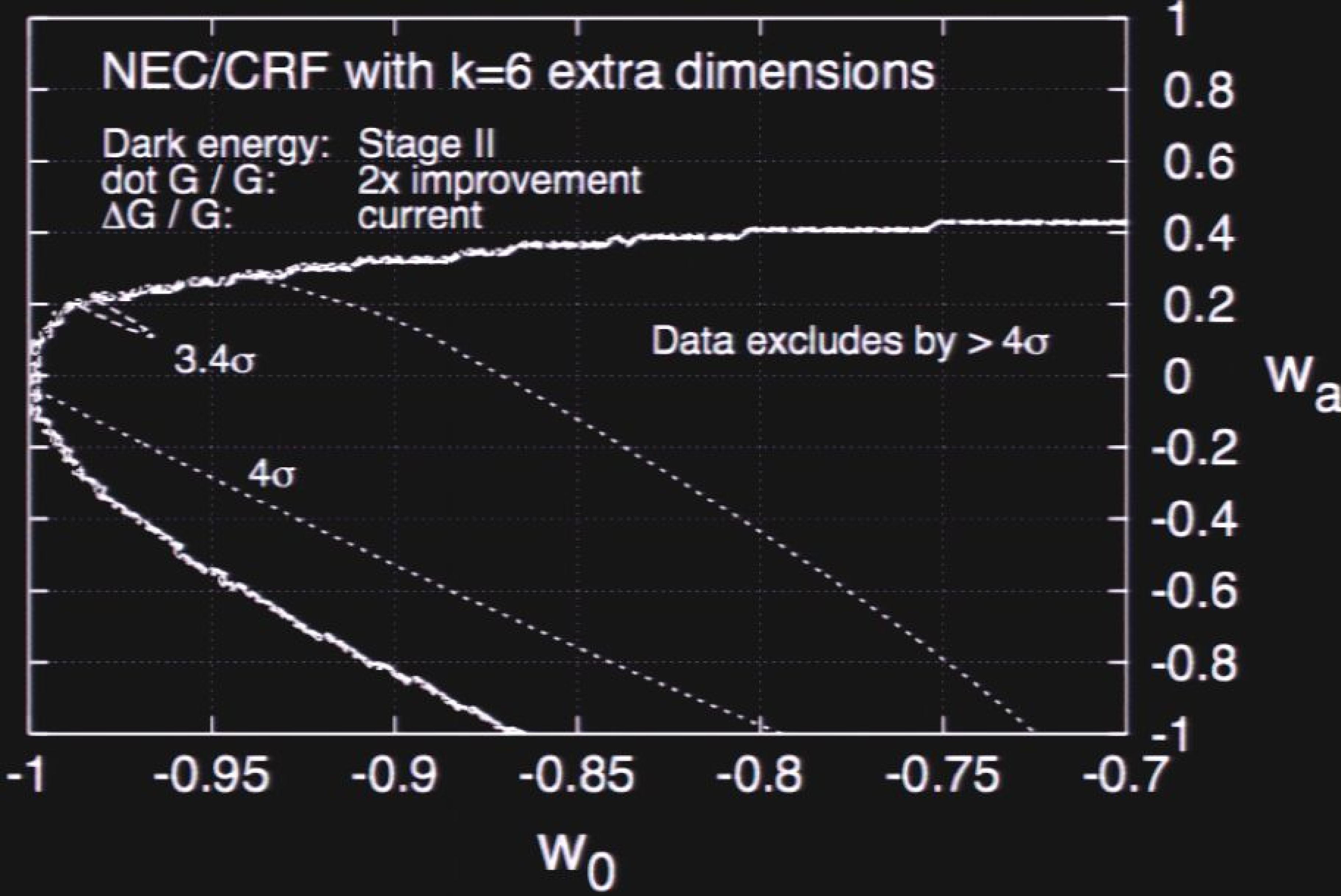
$$\frac{\dot{G}}{G} = (0 \pm 5) \times 10^{-12}\ \mathrm{yr}^{-1}$$

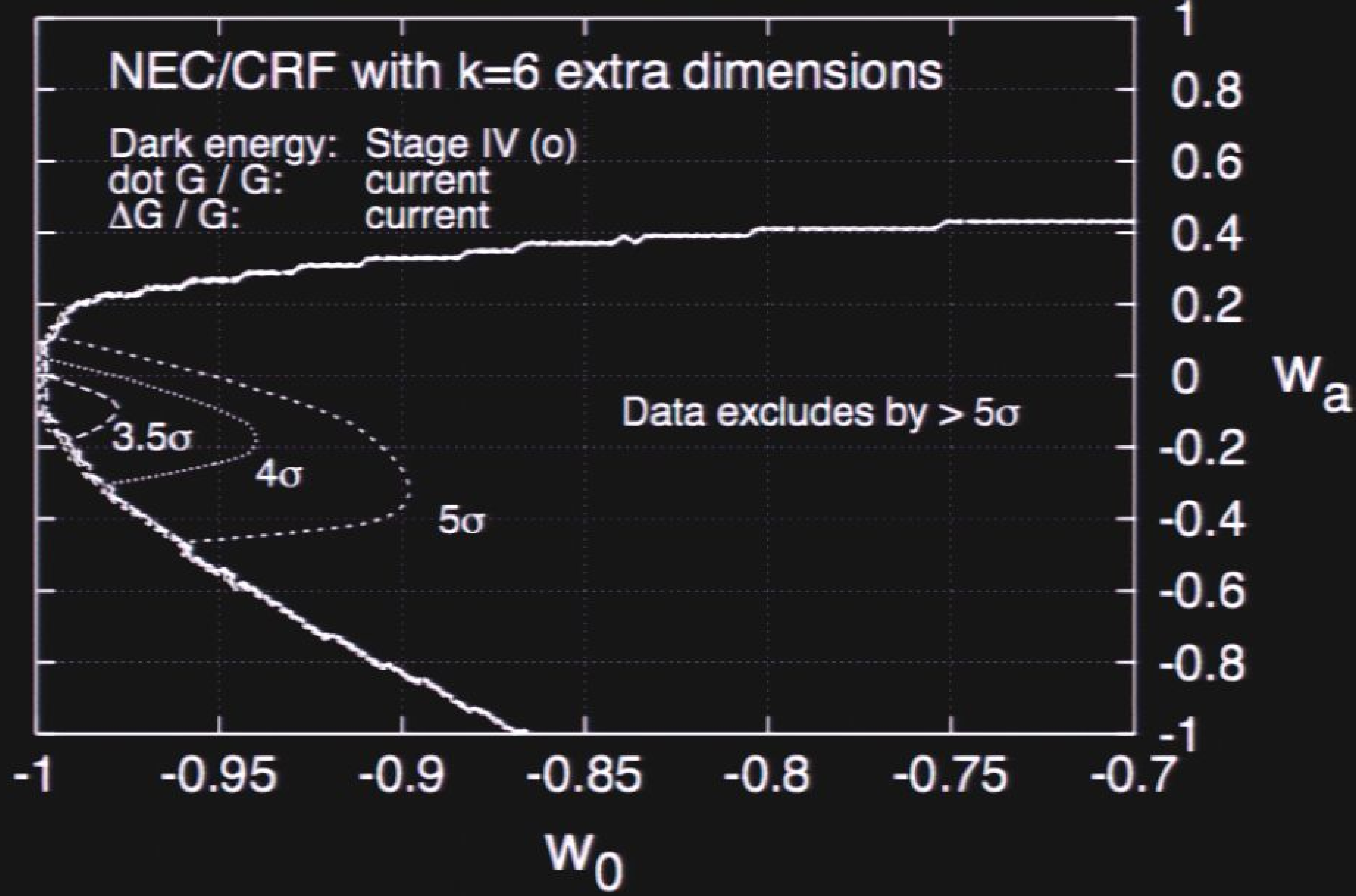

SEC with k=6 extra dimensions
Dark energy: current
dot G / G: current
ΔG / G: current
3σ
Data excludes by > 3σ
1
0.8
0.6
0.4
0.2
0
-0.2
-0.4
-0.6
-0.8
-1
w_a
-1
-0.95
-0.9
-0.85
-0.8
-0.75
-0.7
w_0

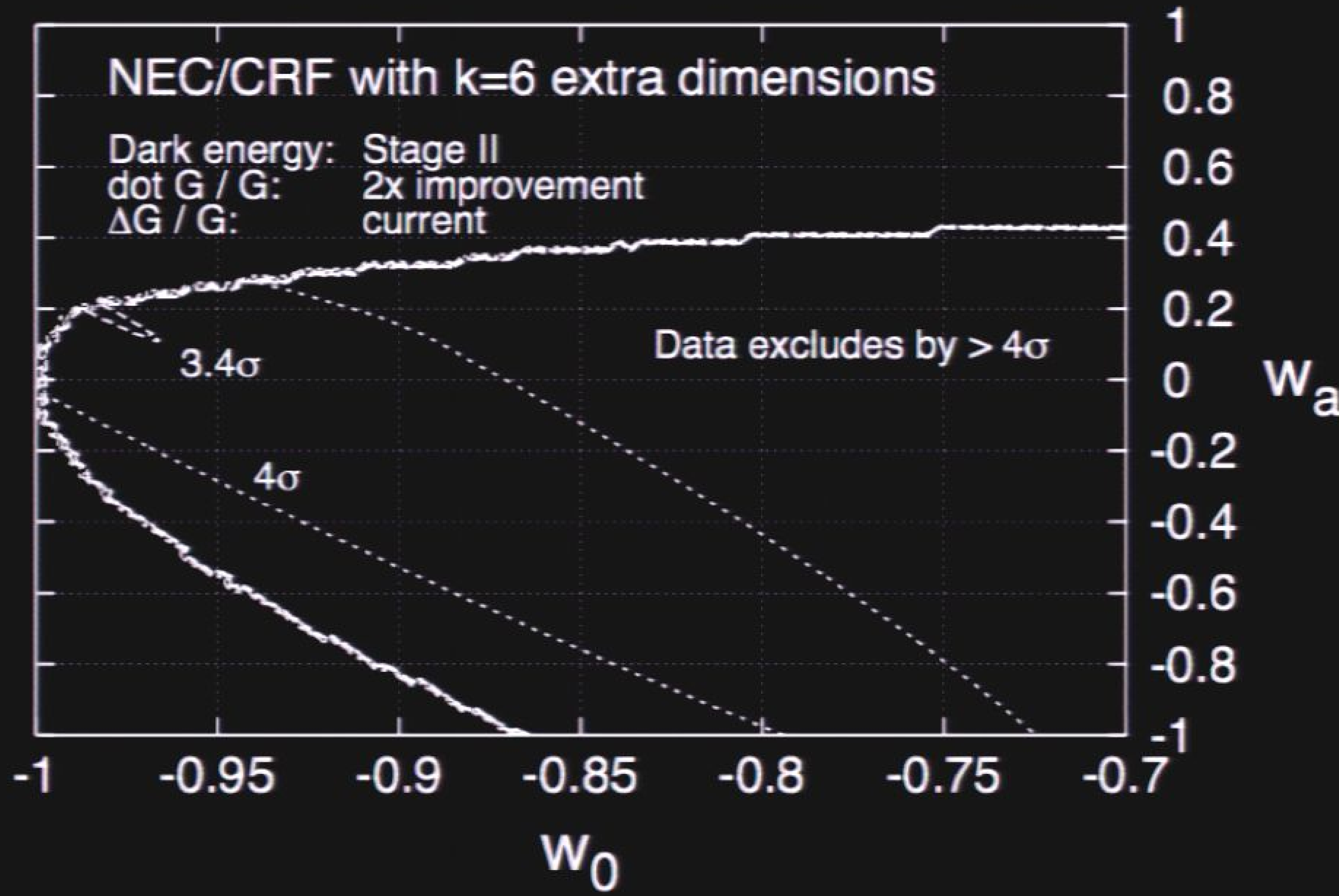


NEC/CRF with k=6 extra dimensions
Dark energy: current
dot G / G: current
ΔG / G: current
2σ
3σ
1
0.8
0.6
0.4
0.2
0
-0.2
-0.4
-0.6
-0.8
-1
w_a
-1
-0.95
-0.9
-0.85
-0.8
-0.75
-0.7
w_0


NEC/CRF with k=6 extra dimensions
Dark energy: Stage IV (o)
dot G / G: current
ΔG / G: current
Data excludes by > 5σ
3.5σ
4σ
5σ
1
0.8
0.6
0.4
0.2
0
-0.2
-0.4
-0.6
-0.8
-1
w_a
-1
-0.95
-0.9
-0.85
-0.8
-0.75
-0.7
w_0


NEC/CRF with k=6 extra dimensions
Dark energy: Stage II
dot G / G: 2x improvement
ΔG / G: current
3.4σ
4σ
Data excludes by > 4σ
1
0.8
0.6
0.4
0.2
0
-0.2
-0.4
-0.6
-0.8
-1
wa
-1
-0.95
-0.9
-0.85
-0.8
-0.75
-0.7
w0


NEC/CRF with k=6 extra dimensions
Dark energy: Stage IV (o)
dot G / G: current
ΔG / G: current
Data excludes by > 5σ
3.5σ
4σ
5σ
1
0.8
0.6
0.4
0.2
0
-0.2
-0.4
-0.6
-0.8
-1
w_a
-1
-0.95
-0.9
-0.85
-0.8
-0.75
-0.7
w_0



NEC/CRF with k=6 extra dimensions
Dark energy: Stage II
dot G / G: 2x improvement
ΔG / G: current
Data excludes by > 4σ
3.4σ
4σ
1
0.8
0.6
0.4
0.2
0
-0.2
-0.4
-0.6
-0.8
-1
w_a
-1
-0.95
-0.9
-0.85
-0.8
-0.75
-0.7
w_0

Conclusions

- Obtaining an accelerating 4D universe puts surprisingly strong constraints on theories with extra dimensions
- Suggests a series of interesting questions about inflationary models, their sources for NEC violation, and the nature of the accelerating/decelerating transition
- A novel technique for leveraging future dark energy constraints with G_N variation constraints, which can provide a powerful probe of extra-dimensional physics.