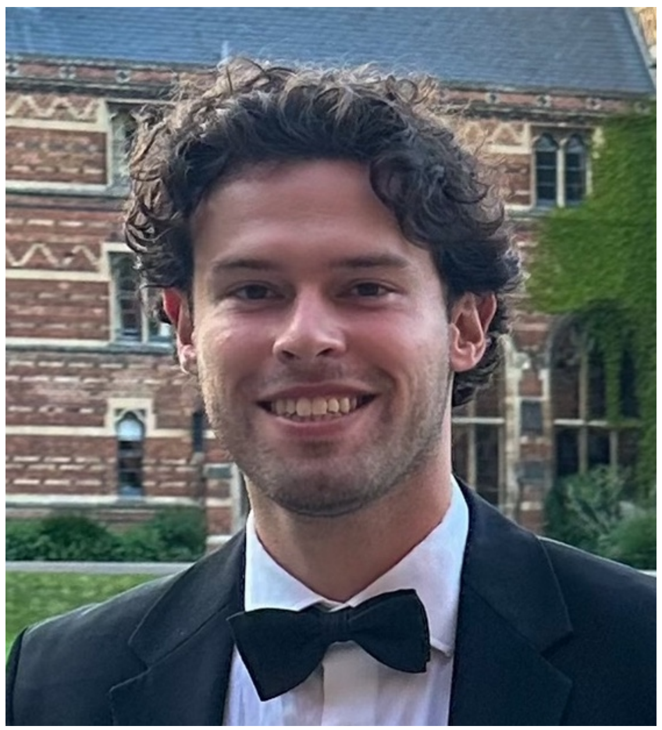
The battle against the underdetermination of dark energy

Pedro G. Ferreira

UNIVERSITY OF OXFORD

June 2025

Based on work done with



William Wolf

Carlos Garcia Garcia

Deaglan Bartlett

Theo Anton

Based on the following papers:

“Underdetermination of Dark Energy” - 2310.07482

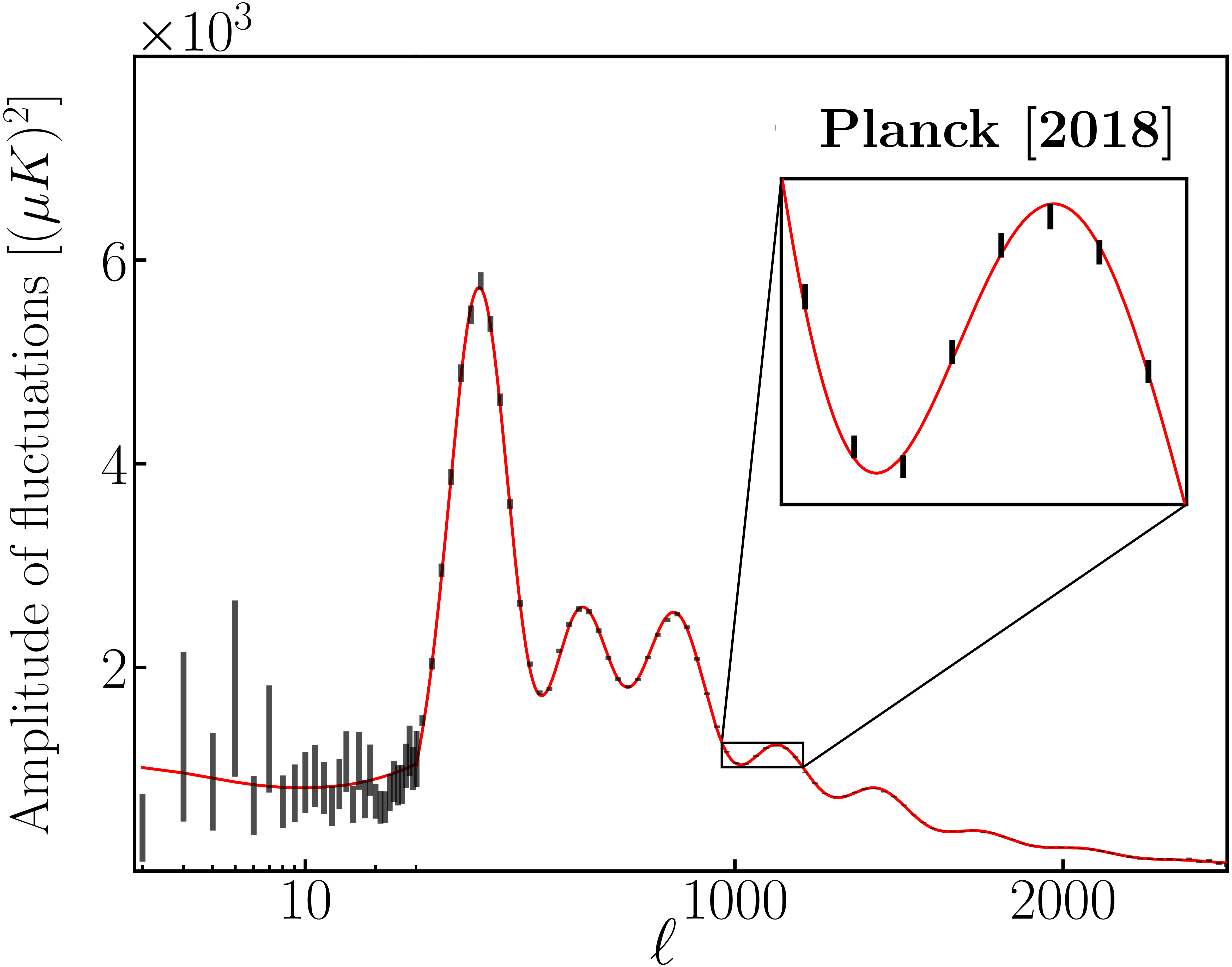
“Scant evidence for thawing quintessence” - 2408.17318

“Matching current observations with non-minimally coupled dark energy” 2409.17019

“The Spectre of Underdetermination in Cosmology” - 2501.06095

“Robustness of Dark Energy phenomenology against different parametrizations” - 2502.04929

“The cosmological evidence for non-minimal coupling” - 2504.07679



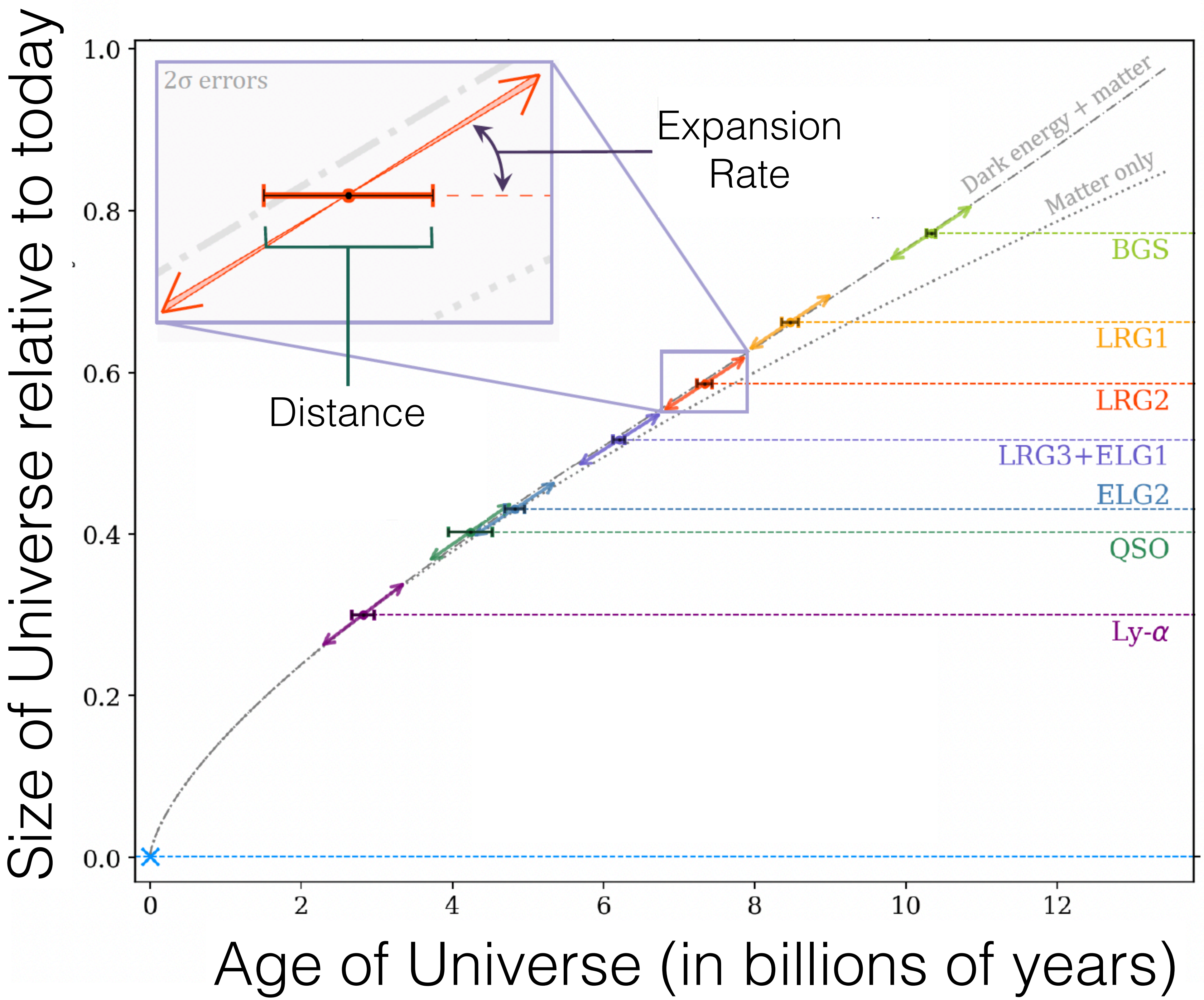
$\times 10^3$
Amplitude of fluctuations $[(\mu K)^2]$
6
4
2
10
1000
2000
ℓ
Planck [2018]

Parameter	TT+lowE 68% limits	TE+lowE 68% limits	EE+lowE 68% limits	TT,TE,EE+lowE 68% limits	TT,TE,EE+lowE+lensing 68% limits	TT,TE,EE+lowE+lensing+BAO 68% limits
$\Omega_b h^2$	0.02212 ± 0.00022	0.02249 ± 0.00025	0.0240 ± 0.0012	0.02236 ± 0.00015	0.02237 ± 0.00015	0.02242 ± 0.00014
$\Omega_c h^2$	0.1206 ± 0.0021	0.1177 ± 0.0020	0.1158 ± 0.0046	0.1202 ± 0.0014	0.1200 ± 0.0012	0.11933 ± 0.00091
$100\theta_{MC}$	1.04077 ± 0.00047	1.04139 ± 0.00049	1.03999 ± 0.00089	1.04090 ± 0.00031	1.04092 ± 0.00031	1.04101 ± 0.00029
τ	0.0522 ± 0.0080	0.0496 ± 0.0085	0.0527 ± 0.0090	$0.0544^{+0.0070}_{-0.0081}$	0.0544 ± 0.0073	0.0561 ± 0.0071
$\ln(10^{10} A_s)$	3.040 ± 0.016	$3.018^{+0.020}_{-0.018}$	3.052 ± 0.022	3.045 ± 0.016	3.044 ± 0.014	3.047 ± 0.014
n_s	0.9626 ± 0.0057	0.967 ± 0.011	0.980 ± 0.015	0.9649 ± 0.0044	0.9649 ± 0.0042	0.9665 ± 0.0038
H_0 [km s^{-1} Mpc^{-1}] . .	66.88 ± 0.92	68.44 ± 0.91	69.9 ± 2.7	67.27 ± 0.60	67.36 ± 0.54	67.66 ± 0.42
Ω_Λ	0.679 ± 0.013	0.699 ± 0.012	$0.711^{+0.033}_{-0.026}$	0.6834 ± 0.0084	0.6847 ± 0.0073	0.6889 ± 0.0056
Ω_m	0.321 ± 0.013	0.301 ± 0.012	$0.289^{+0.026}_{-0.033}$	0.3166 ± 0.0084	0.3153 ± 0.0073	0.3111 ± 0.0056
$\Omega_m h^2$	0.1434 ± 0.0020	0.1408 ± 0.0019	$0.1404^{+0.0034}_{-0.0039}$	0.1432 ± 0.0013	0.1430 ± 0.0011	0.14240 ± 0.00087
$\Omega_m h^3$	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
σ_8	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
$S_8 \equiv \sigma_8(\Omega_m/0.3)^{0.5}$	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
$\sigma_8 \Omega_m^{0.25}$	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
z_{re}	7.50 ± 0.82	$7.11^{+0.91}_{-0.75}$	$7.10^{+0.87}_{-0.73}$	7.68 ± 0.79	7.67 ± 0.73	7.82 ± 0.71
$10^9 A_s$	2.092 ± 0.034	2.045 ± 0.041	2.116 ± 0.047	$2.101^{+0.031}_{-0.034}$	2.100 ± 0.030	2.105 ± 0.030
$10^9 A_s e^{-2\tau}$	1.884 ± 0.014	1.851 ± 0.018	1.904 ± 0.024	1.884 ± 0.012	[illegible]	[illegible]
Age [Gyr]	13.830 ± 0.037	13.761 ± 0.038	$13.64^{+0.16}_{-0.14}$	13.800 ± 0.024	[illegible]	[illegible]
z_*	1090.30 ± 0.41	1089.57 ± 0.42	$1087.8^{+1.6}_{-1.7}$	1089.95 ± 0.27	[illegible]	[illegible]
r_* [Mpc]	144.46 ± 0.48	144.95 ± 0.48	144.29 ± 0.64	144.39 ± 0.30	144.43 ± 0.26	144.57 ± 0.22
$100\theta_*$	1.04097 ± 0.00046	1.04156 ± 0.00049	1.04001 ± 0.00086	1.04109 ± 0.00030	1.04110 ± 0.00031	1.04119 ± 0.00029
z_{drag}	1059.39 ± 0.46	1060.03 ± 0.54	1063.2 ± 2.4	1059.93 ± 0.30	1059.94 ± 0.30	1060.01 ± 0.29
r_{drag} [Mpc]	147.21 ± 0.48	147.59 ± 0.49	146.46 ± 0.70	147.05 ± 0.30	147.09 ± 0.26	147.21 ± 0.23
k_D [Mpc^{-1}]	0.14054 ± 0.00052	0.14043 ± 0.00057	0.1426 ± 0.0012	0.14090 ± 0.00032	0.14087 ± 0.00030	0.14078 ± 0.00028
z_{eq}	3411 ± 48	3349 ± 46	3340^{+81}_{-92}	3407 ± 31	3402 ± 26	3387 ± 21
k_{eq} [Mpc^{-1}]	0.01041 ± 0.00014	0.01022 ± 0.00014	$0.01019^{+0.00025}_{-0.00028}$	0.010398 ± 0.000094	0.010384 ± 0.000081	0.010339 ± 0.000063
$100\theta_{s,eq}$	0.4483 ± 0.0046	0.4547 ± 0.0045	0.4562 ± 0.0092	0.4490 ± 0.0030	0.4494 ± 0.0026	0.4509 ± 0.0020

Ω_Λ . . . . 0.679 ± 0.013

measured at 52 σ !!

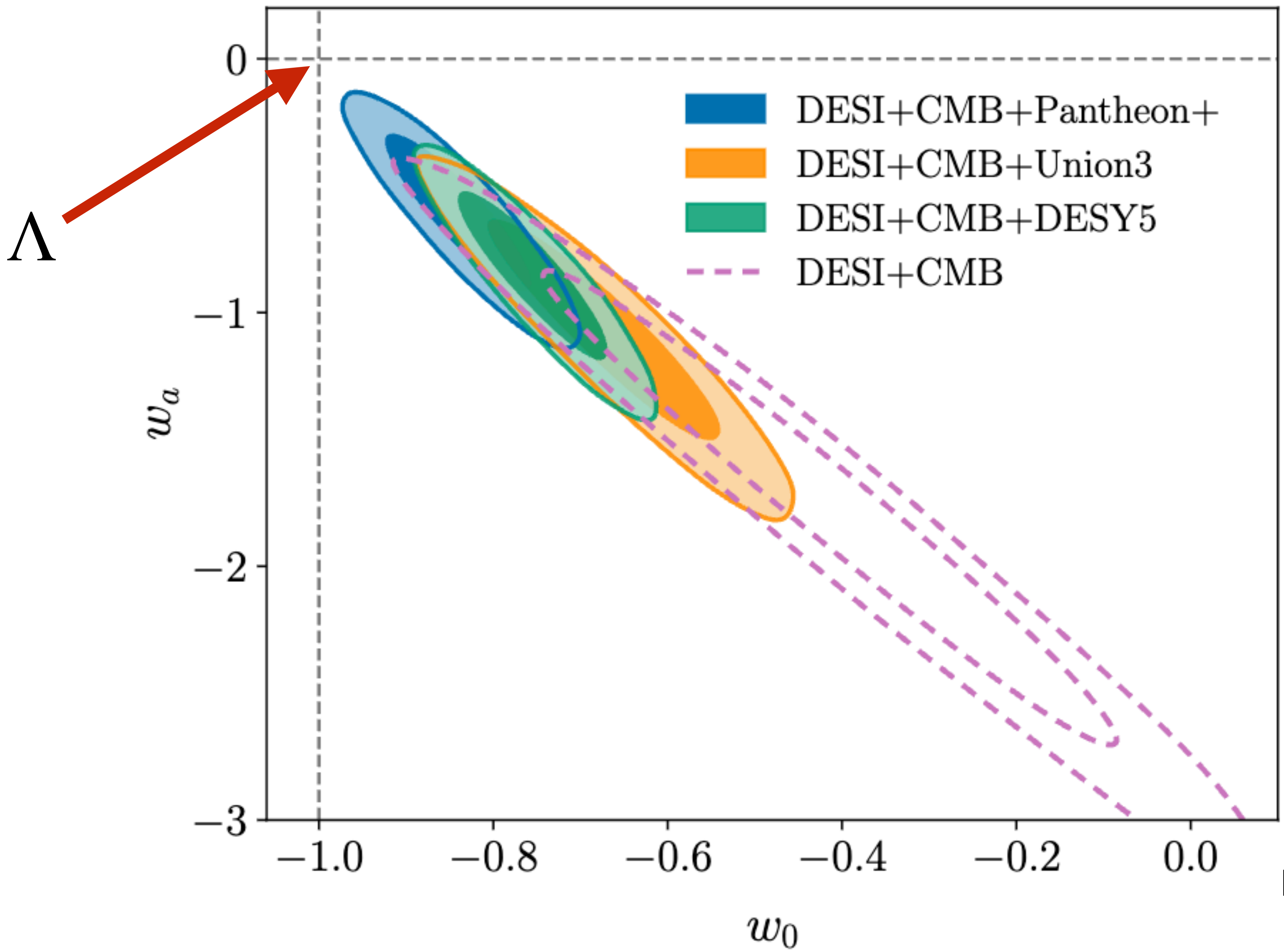
Planck 2015



Size of Universe relative to today
Age of Universe (in billions of years)
2σ errors
Expansion Rate
Distance
Dark energy + matter
Matter only
BGS
LRG1
LRG2
LRG3+ELG1
ELG2
QSO
Ly-α
1.0
0.8
0.6
0.4
0.2
0.0
0
2
4
6
8
10
12

DESI 2025

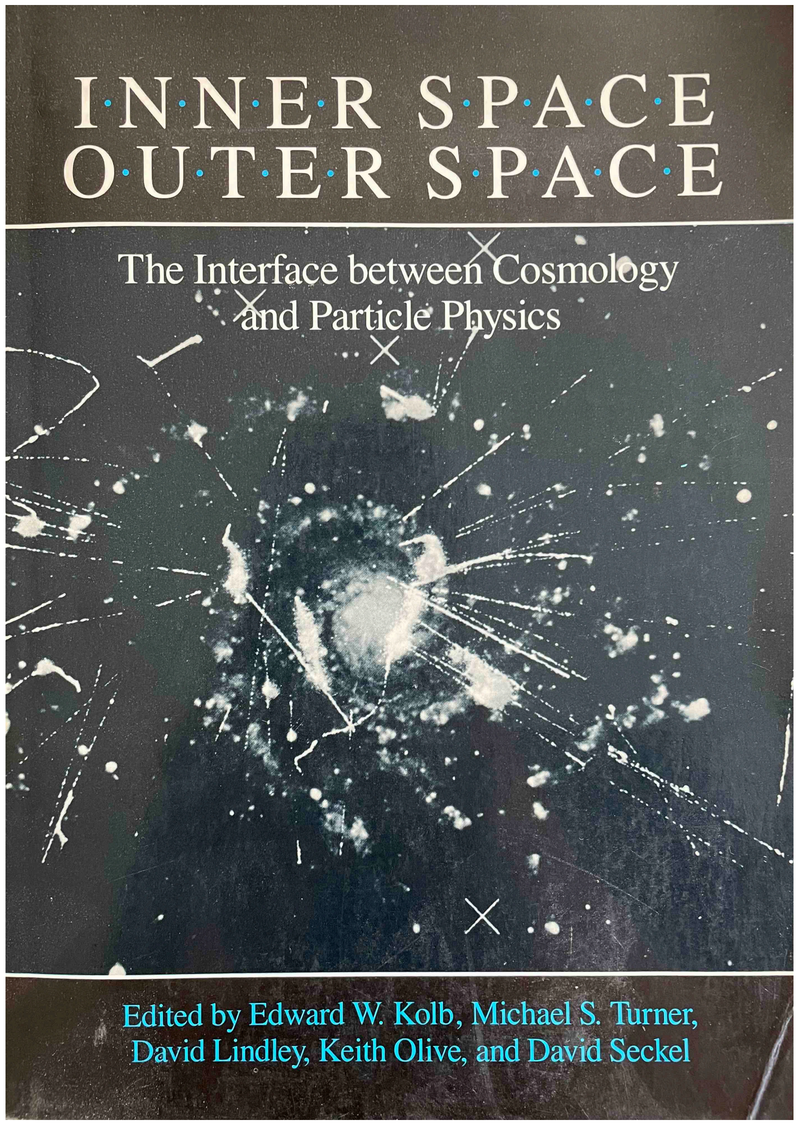
Preference for Dynamical Dark Energy

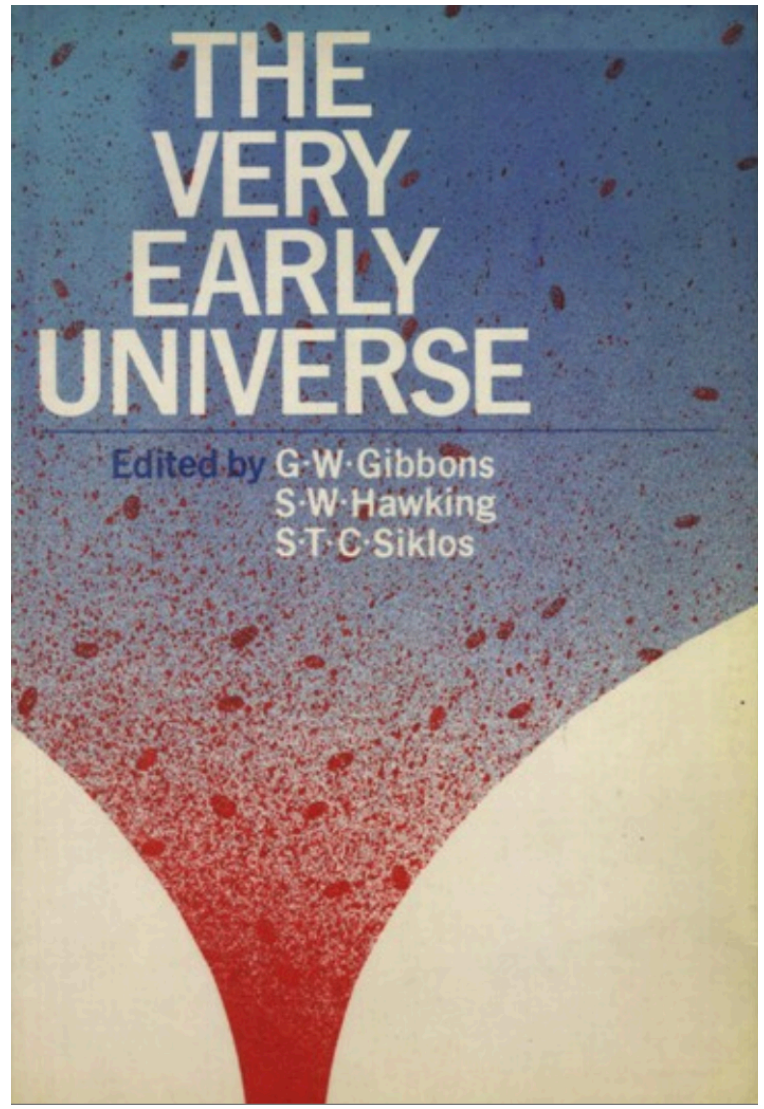


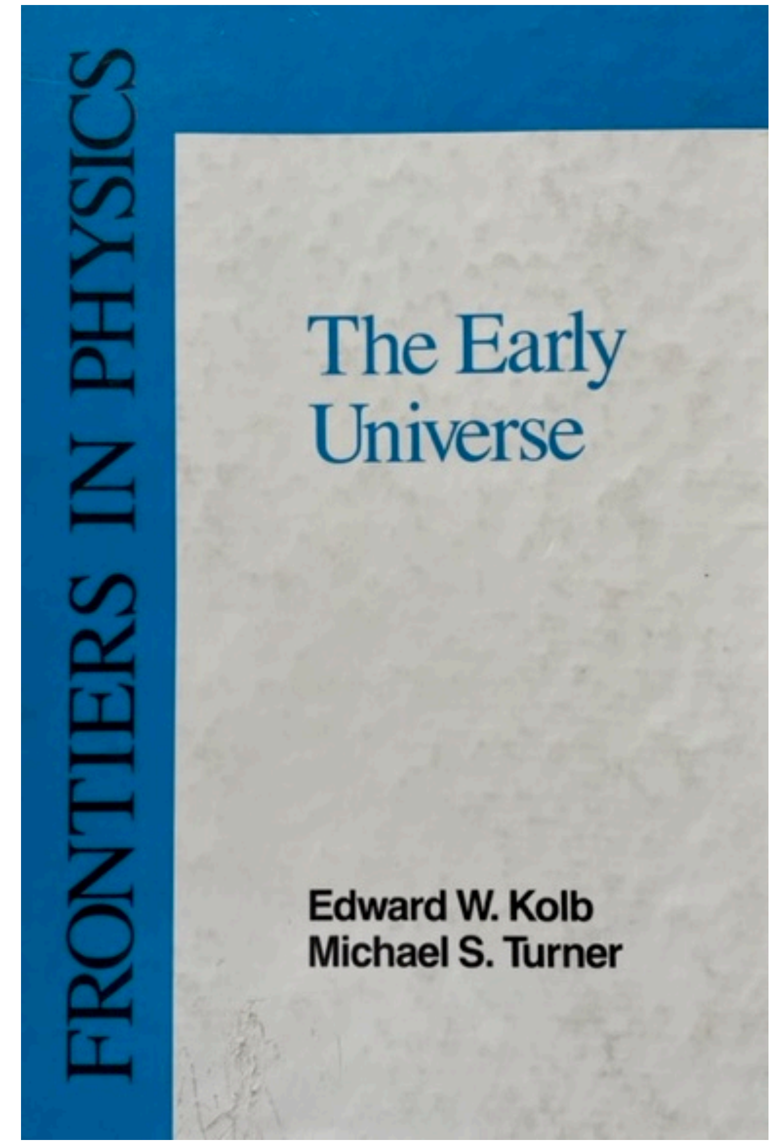
DESI (2025)

E.g. $w(a) \simeq w_0 + w_a(1-a)$

The Rise of “Particle” Cosmology







Inflation, dark matter, dark energy …

The Standard Model
(the physics we know)

Quantum physics Spacetime Gravity Forces

$$W = \int DgDAD\psi D\Phi \exp\{ \int d^4x\sqrt{-g}[\frac{M_P^2}{2}R - \frac{1}{4}F^a_{\mu\nu}F^{a\mu\nu}$$

$$+ i\bar{\psi}^i\gamma^\mu D_\mu\psi^i + (\bar{\psi}^i_L V_{ij}\Phi\psi^j_R + \mathrm{h.c.}) - |D_\mu\Phi|^2 - V(\Phi)]\}$$

Matter

Higgs

The New Standard Model

$$W = \int DgDAD\psi D\Phi \exp\{ \int d^4x\sqrt{-g}[\frac{M_P^2}{2}R - \frac{1}{4}F^a_{\mu\nu}F^{a\mu\nu}$$

$$+i\bar{\psi}^i\gamma^\mu D_\mu\psi^i + (\bar{\psi}^i_L V_{ij}\Phi\psi^j_R + \mathrm{h.c.}) - |D_\mu\Phi|^2 - U(\Phi)$$

\+ "something"

What is the microphysics of "something"?

For example: $-\frac{1}{2}\partial_\mu\phi\partial^\mu\phi - V(\phi) + \cdots$?

E.g for dark energy …

Λ
Saltatory dark energy
Self-tuning Λ
Fluid dark energy
Chaplygin gas
Generalized Chaplygin gas
Coupled dark energy
Quintessence
Natural quintessence
Axion quintessence
Pseudo-Nambu-Goldstones quintessence
Supergravity quintessence
String- inspired quintessence
Kahler quintessence
Phantom quintessence
Coupled quintessence
K-essence
Tachyon field
Dilatonic dark energy
Scale invariant models
Holographic dark energy
Sequestered dark energy
Horndeski gravity
Kinetic braiding gravity
Galileon gravity
Fab-four gravity
Emergent dark energy
Massive gravity
Bigravity
Einstein-Aether gravity
Causal sets Λ
Varying neutrino mass dark energy
Hu-Sawicki $F(R)$ gravity
Battye $F(R)$ gravity
$f(\mathcal{T})$ gravity
Bulk-brane dark energy
DGP gravity
$+\cdots$

Can we tell them apart?

The British Journal for the Philosophy of Science

VOLUME IV FEBRUARY, 1954 NO. 16

IS PHYSICAL COSMOLOGY A SCIENCE?

A Discussion

G. J. WHITROW and H. BONDI

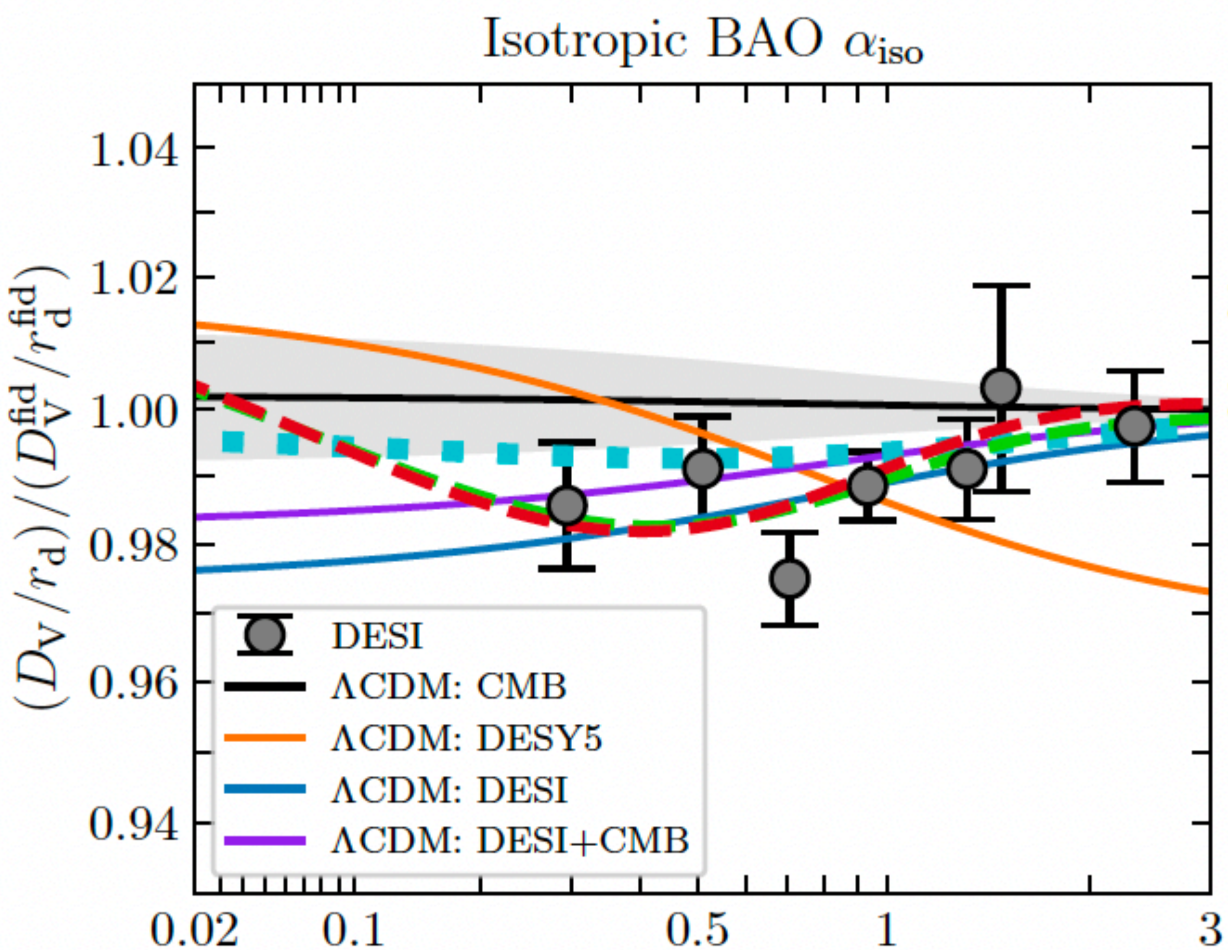
21st Century update:

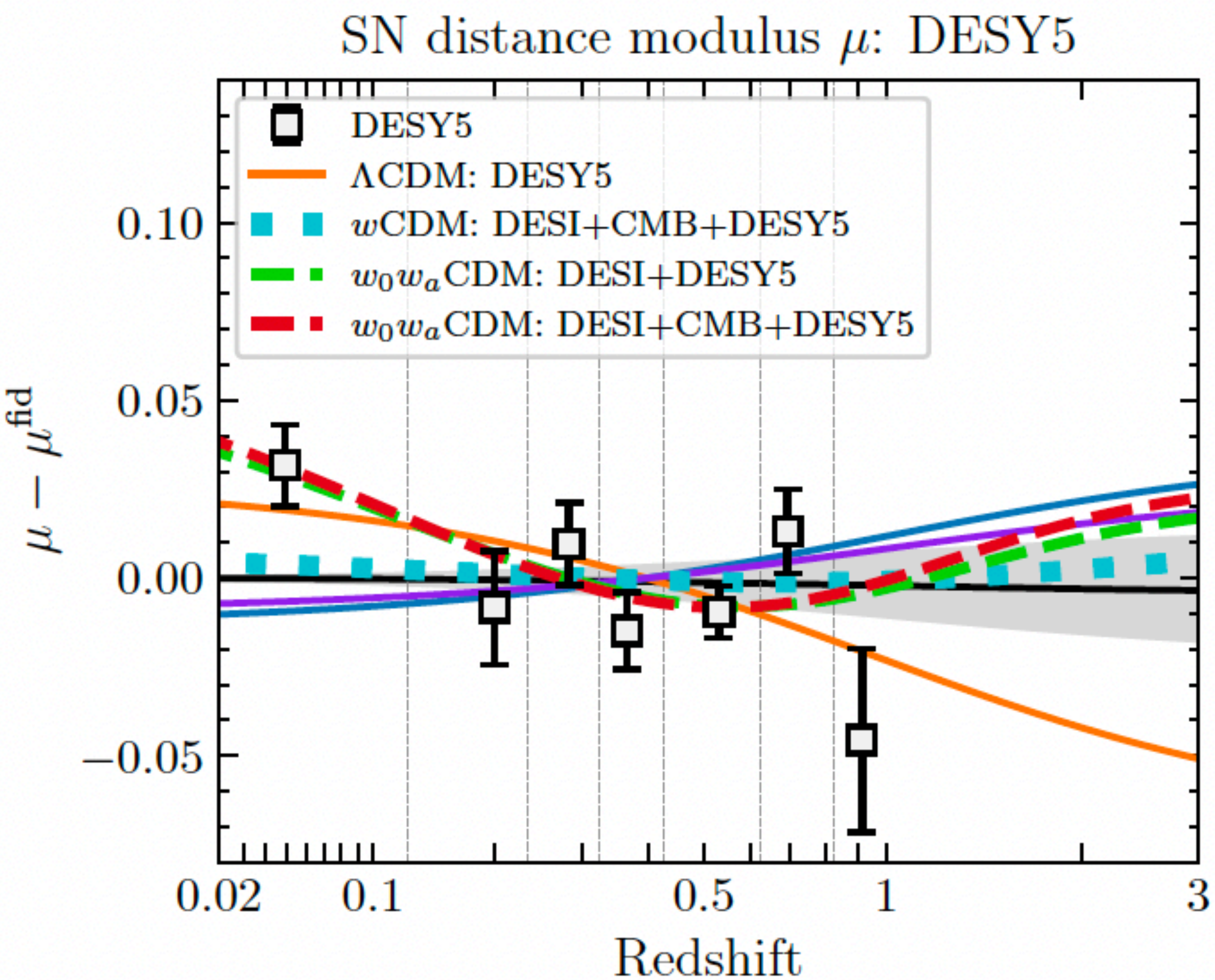
IS PARTICLE COSMOLOGY A SCIENCE?

A Discussion

Specifically, can we go beyond “opinion” in figuring out the nature of dark energy?

The Data





DESI DR2 2025

The critics say …

Beware of supernovae data :
- Inconsistency between DES and Pantheon analysis
- Role of low-z sample

Efstathiou & Cortês/Liddle

Note: need to consider selection function of each survey & wait for the new low-Z surveys (ZTF, etc)

Beware of DESI data: inconsistency of with SDSS

Efstathiou

Note: inconsistency small (2.8σ) but there …

DESI 2025

“w-ology”

In practice we compress the data.

We <u>assume</u> that the Hubble expansion is of the form

$$H^2(a) = H_0^2\left[\Omega_{\rm m}a^{-3} + (1-\Omega_{\rm m})e^{3w_a(a-1)}a^{-3(1+w_0+w_a)}\right]$$

We <u>measure</u> μ, D_A, D_V which are all functions of $H(a)$

We <u>estimate</u> the (w_0, w_a) that best fit the data.

You may be tempted to assign physical meaning to (w_0, w_a)

Indeed $w(a) = \dfrac{P_{\rm DE}}{\rho_{\rm DE}} \simeq w_0 + w_a(1-a)$

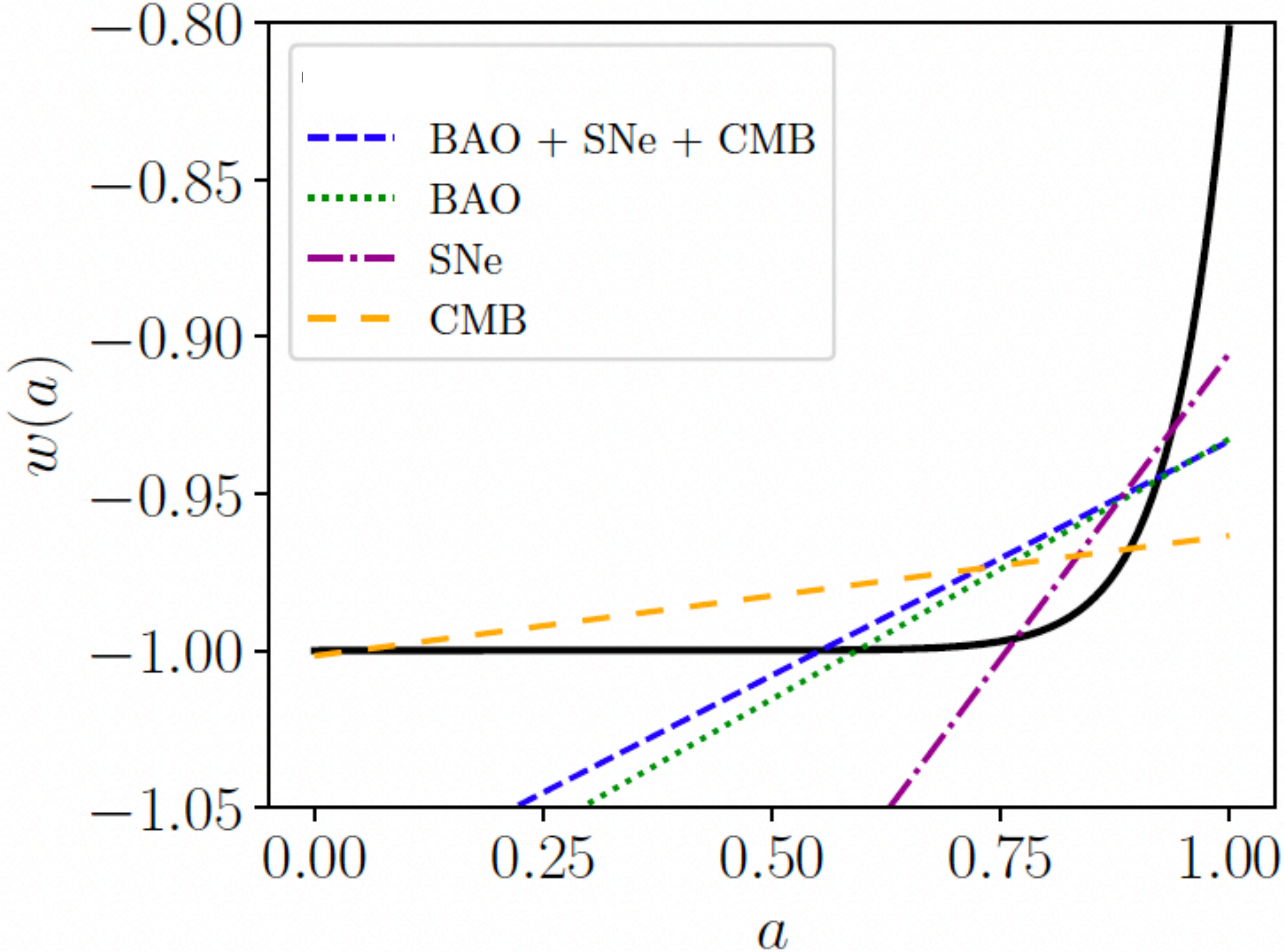
And $w(a) = -1$ is Λ and $w(a) < -1$ is "unphysical"…

But <u>don't</u>!

The results are dependent on survey characteristics (depth, redshift dependence, etc).

(w_0, w_a) is a (useful) form of data compression

(w_0, w_a) depends on the survey



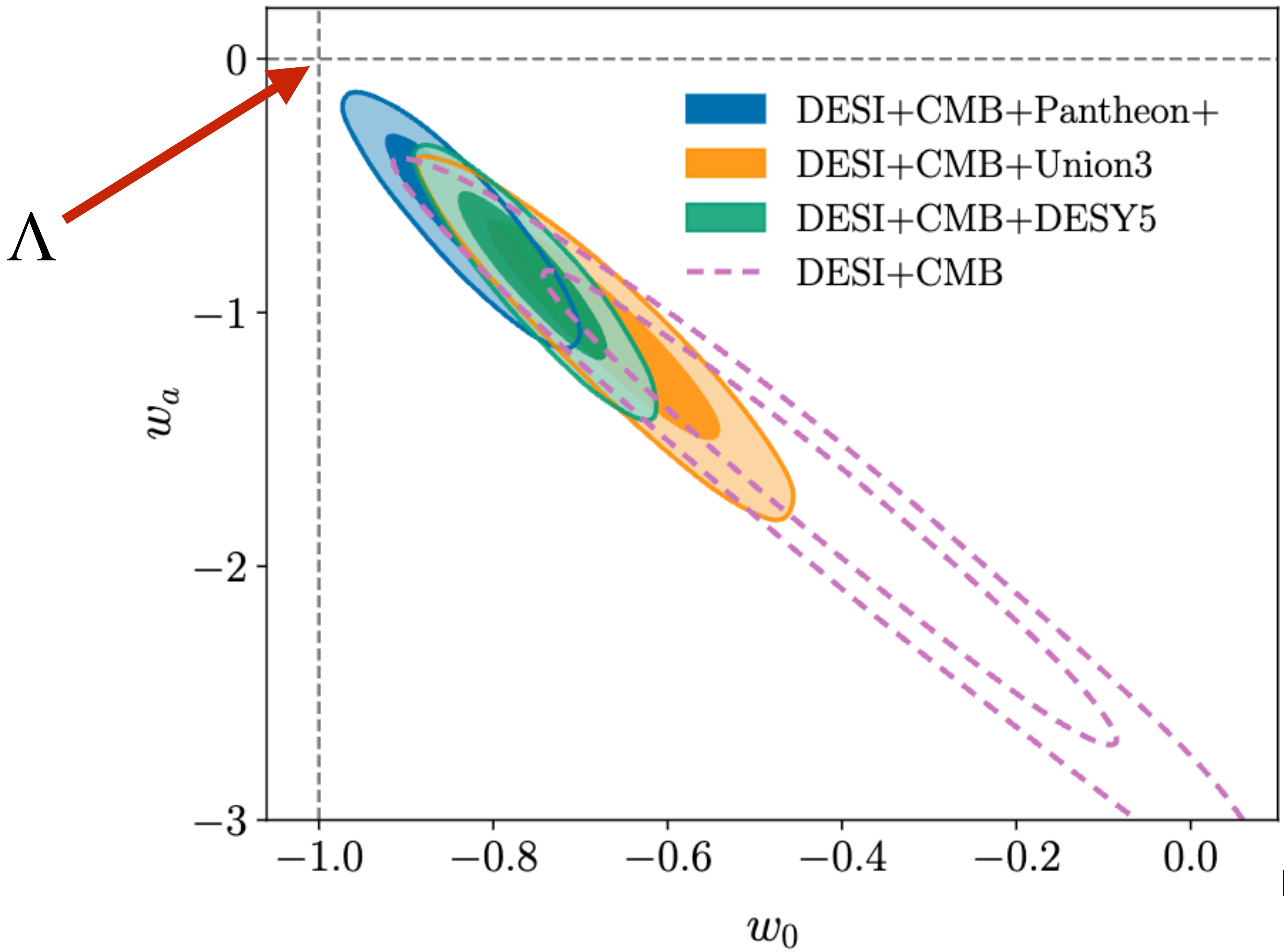
There is no unique value of (w_0, w_a)!

Assume $w_a = 0$

Model/Dataset	Ω_m	H_0 [km s^{-1} Mpc^{-1}]	$10^3\Omega_\mathrm{K}$	w or w_0	w_a
wCDM					
CMB	$0.203^{+0.017}_{-0.060}$	85^{+10}_{-6}	—	$-1.55^{+0.17}_{-0.37}$	—
DESI	0.2969 ± 0.0089	—	—	-0.916 ± 0.078	—
DESI+Pantheon+	0.2976 ± 0.0087	—	—	-0.914 ± 0.040	—
DESI+Union3	0.2973 ± 0.0091	—	—	-0.866 ± 0.052	—
DESI+DESY5	0.2977 ± 0.0091	—	—	-0.872 ± 0.039	—
DESI+CMB	0.2927 ± 0.0073	69.51 ± 0.92	—	-1.055 ± 0.036	—
DESI+CMB+Pantheon+	0.3047 ± 0.0051	67.97 ± 0.57	—	-0.995 ± 0.023	—
DESI+CMB+Union3	0.3044 ± 0.0059	68.01 ± 0.68	—	-0.997 ± 0.027	—
DESI+CMB+DESY5	0.3098 ± 0.0050	67.34 ± 0.54	—	-0.971 ± 0.021	—

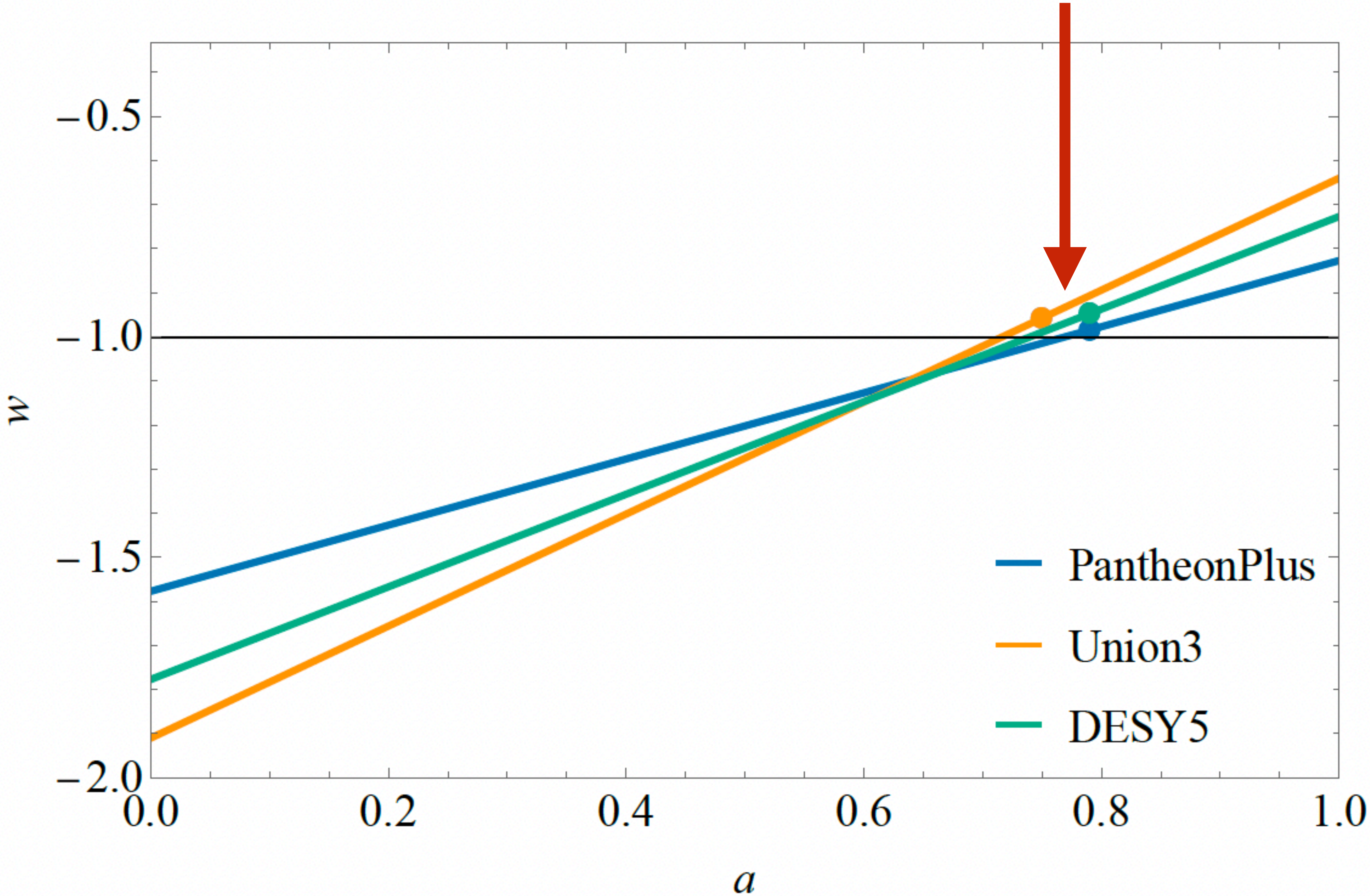
$$w_0 \simeq -1$$

Preference for Dynamical Dark Energy

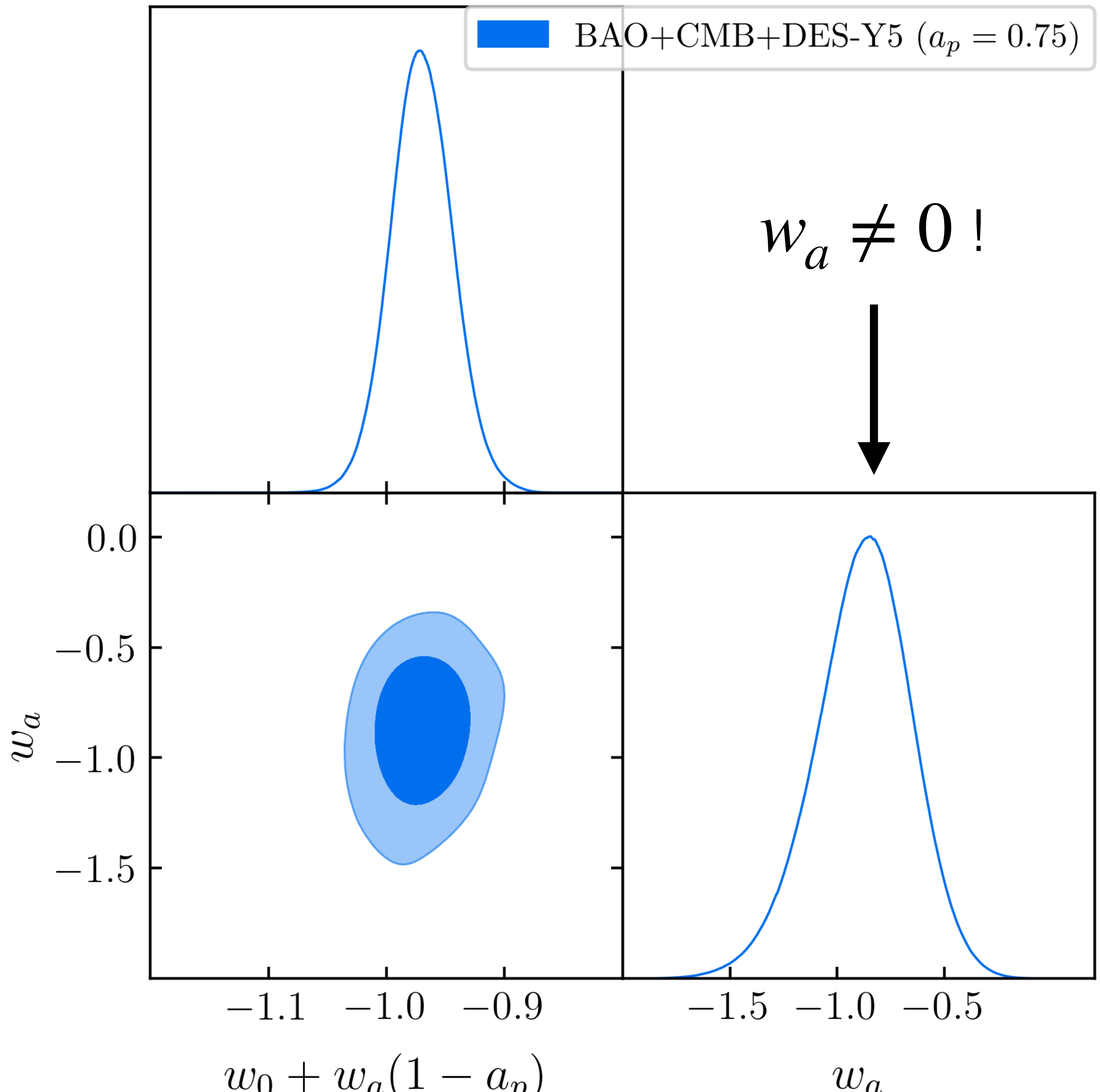


DESI (2025)

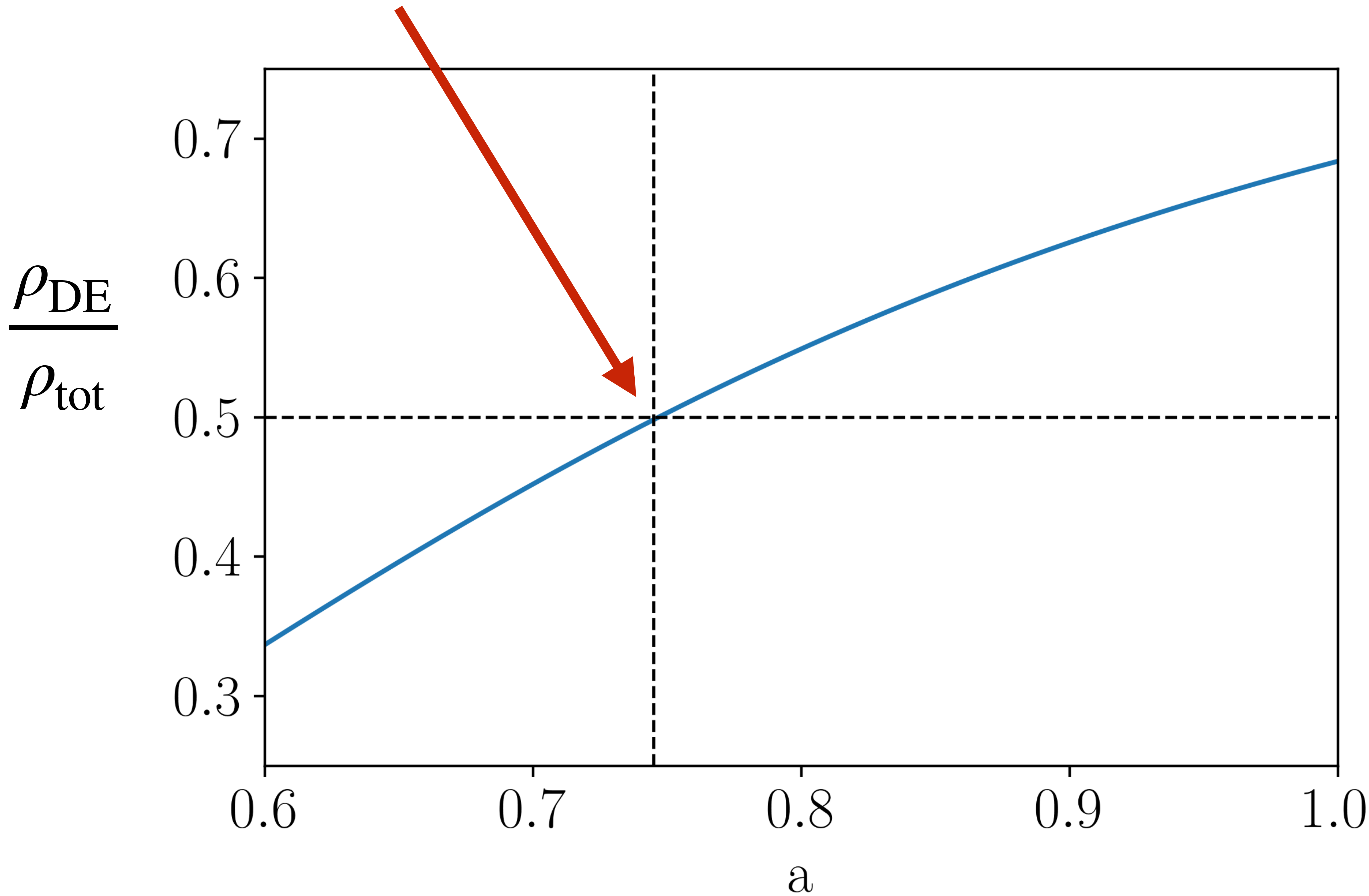
Coincidence?



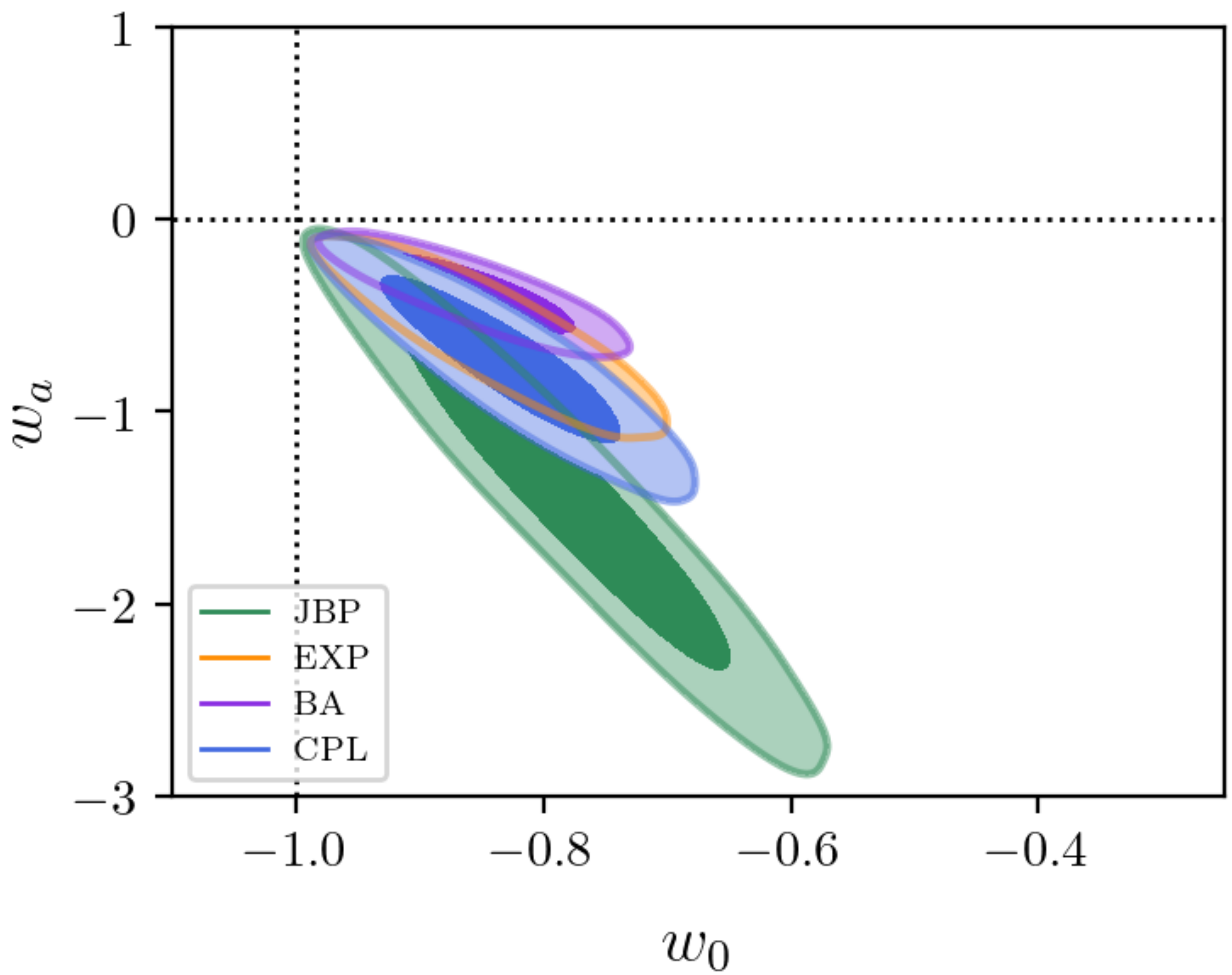
Cortês & Liddle 2024


BAO+CMB+DES-Y5 ($a_p = 0.75$)
$w_a \neq 0$!
0.0
−0.5
−1.0
−1.5
w_a
−1.1
−1.0
−0.9
$w_0 + w_a(1 - a_p)$
−1.5
−1.0
−0.5
w_a

Another coincidence?



Does it depend on the parametrisation?



Wolf et al 2025

Inspired by Giaré et al 2024

JBP: $w_0 + w_a \times a(1-a)$

Dimakis et al 2016

EXP: $(w_0 - w_a) + w_a \times \exp(1-a)$

Jassal et al 2005

BA: $w_0 + w_a \times \dfrac{1-a}{a^2 + (1-a)^2}$

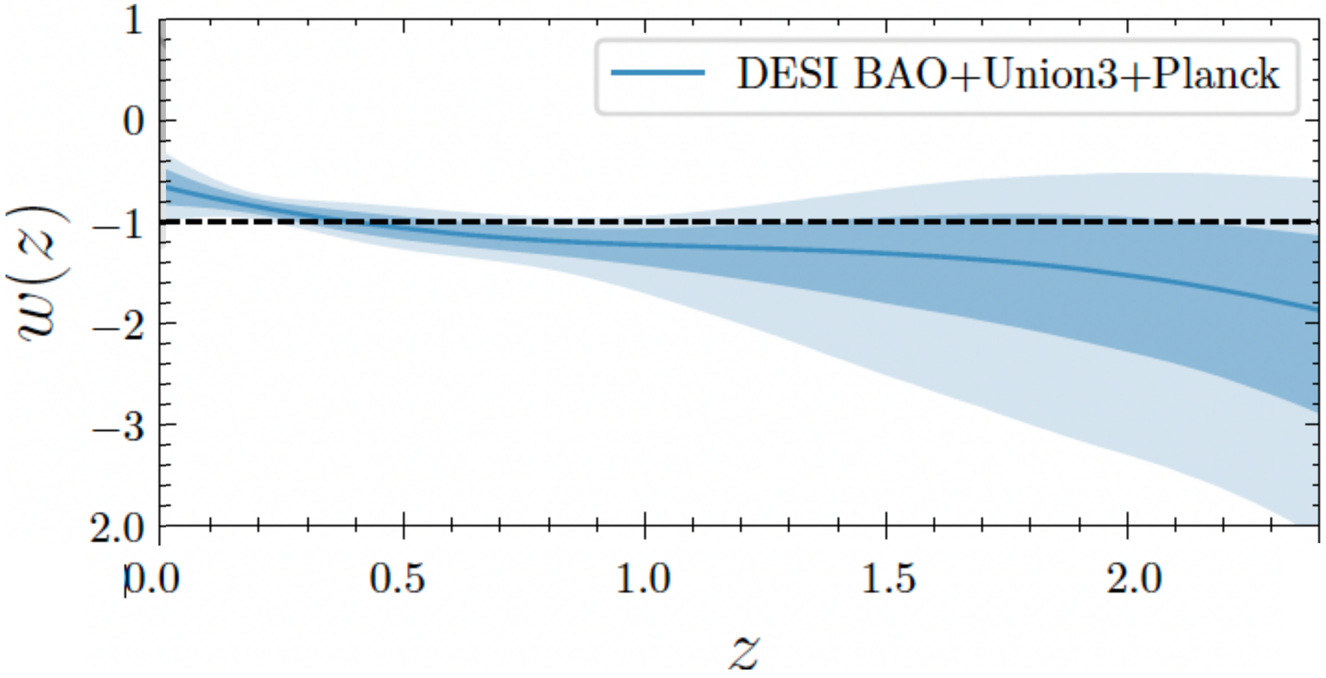
Barboza et al 2008

CPL: $w_0 + w_a \times (1-a)$

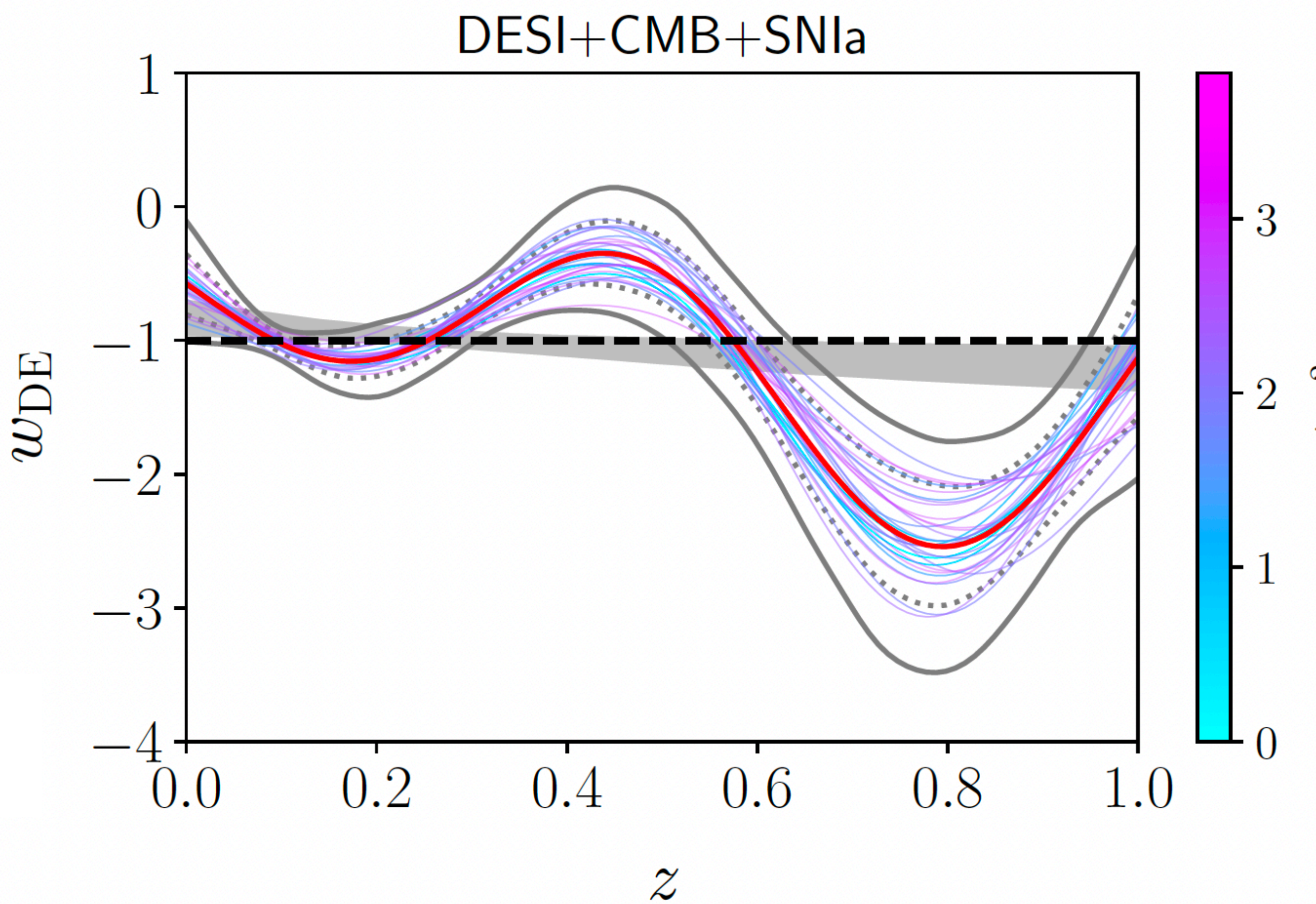
Chevalier et al 2001

Beyond quintessence …

Phantom: $w(a) < -1$



Calderon et al 2024



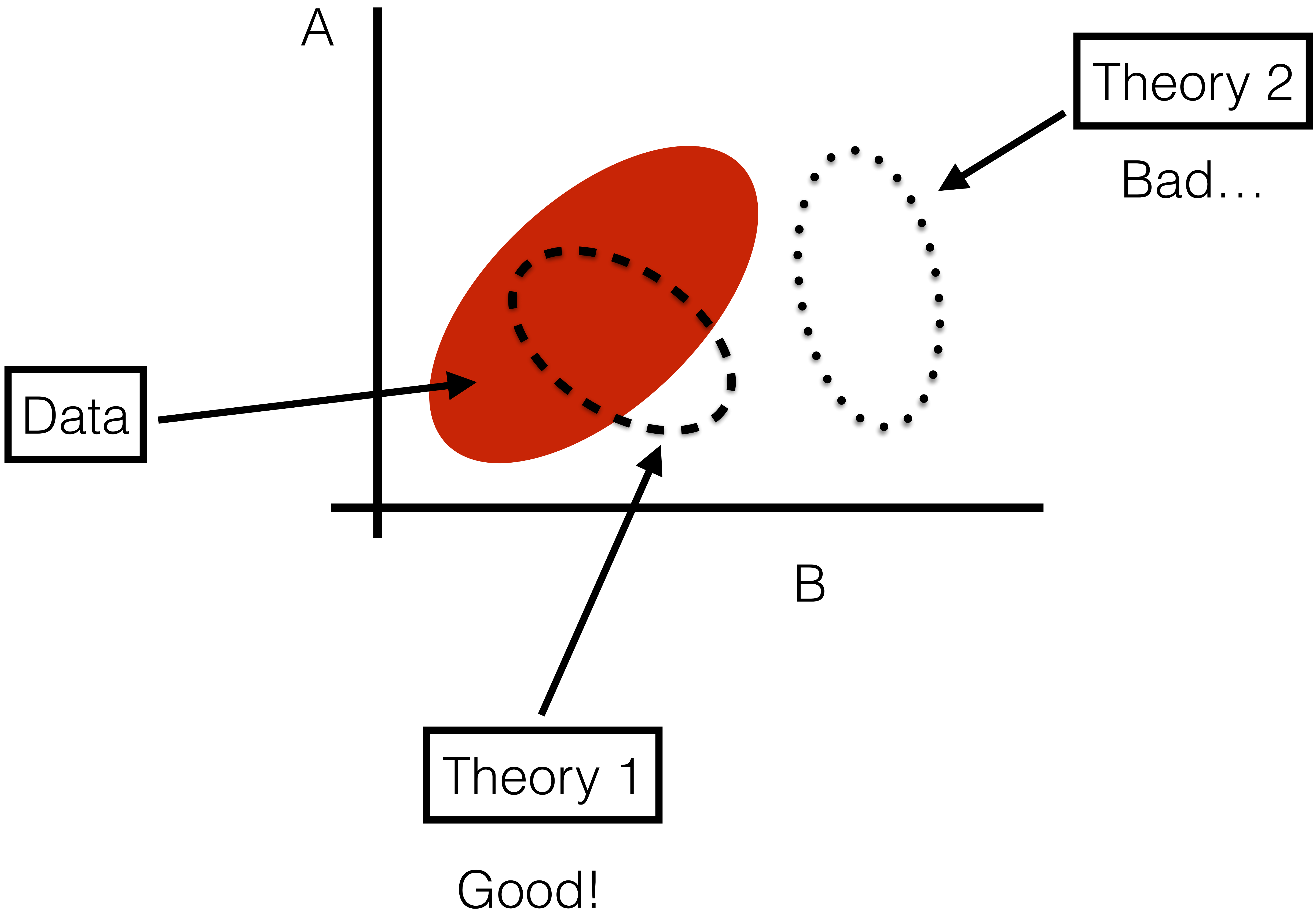
Ye et al, 2024

Disclaimer!

From now on

I will assume the data is correct

and is fit for cosmological analysis!


A
Theory 2
Bad…
Data
B
Theory 1
Good!

How do we compare with “theory”?

- Fields $(\varphi, \psi, \cdots)$
- Parameters $(\alpha, \beta, \cdots)$
- I.C. $(\varphi_i, \dot{\varphi}_i, \cdots)$

predict

- $H(a)$
- $D_A(a)$
- $D_V(a)$
- μ

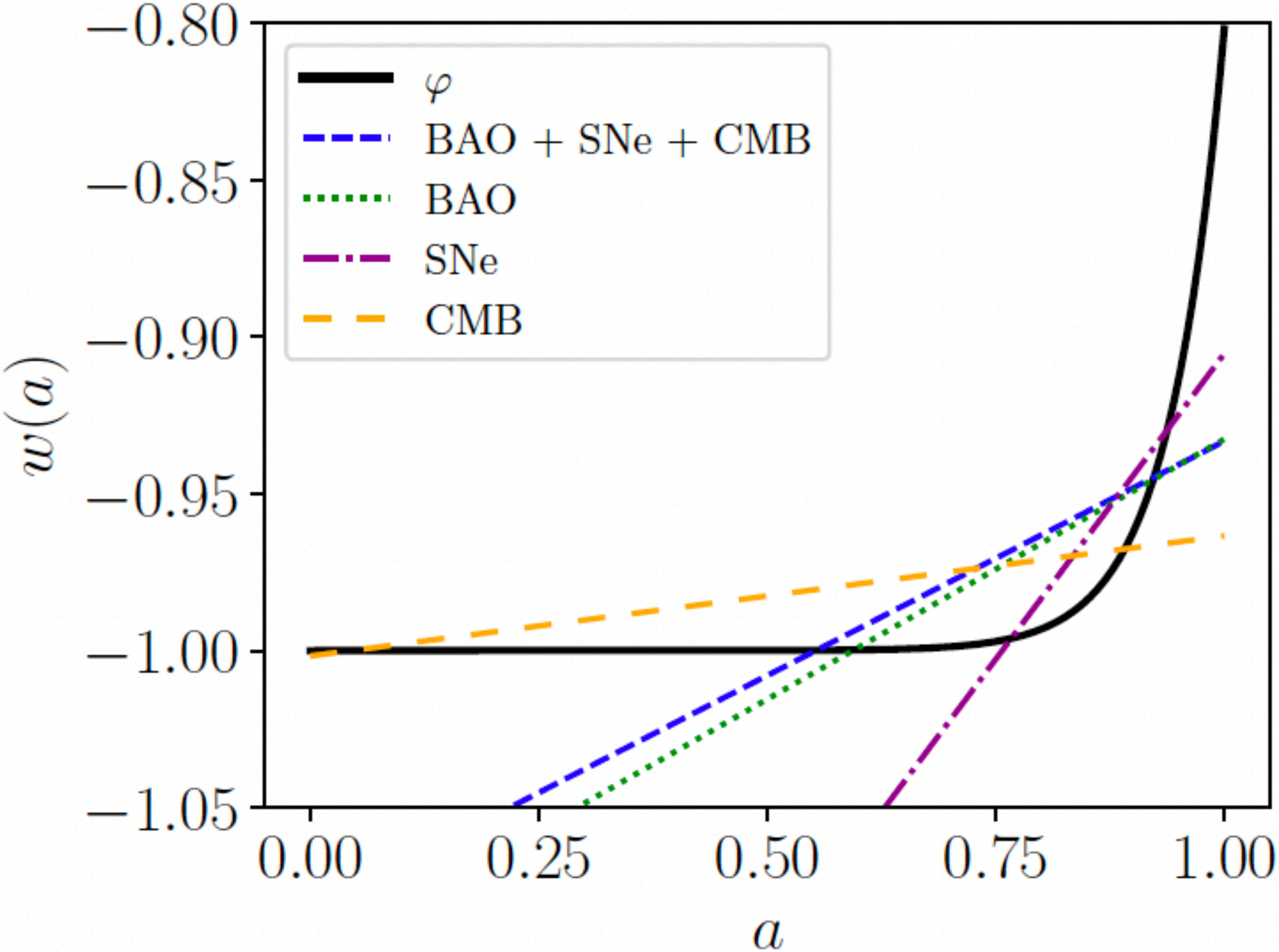
- Redshift range
- Uncertainties
- Covariances

fit

(w_0, w_a)

Result: Priors on (w_0, w_a)

(w_0, w_a) depends on the survey



Theory does not uniquely predict (w_0, w_a)!

From now on I will solely focus on scalar field models for dark energy.

Lowest order Effective Field Theory

$$S = \int d^4x\sqrt{-g}\left[\frac{M_{\mathrm{Pl}}^2}{2}F(\varphi)R + G(\varphi)X - V(\varphi)\right] + S_{\mathrm{m}}$$

Note: this is not about building models.

Thawing Models

$$S = \int d^4x \sqrt{-g} \left[\frac{1}{2} M_{\mathrm{Pl}}^2 R + X - V(\varphi) \right] + S_{\mathrm{m}}$$

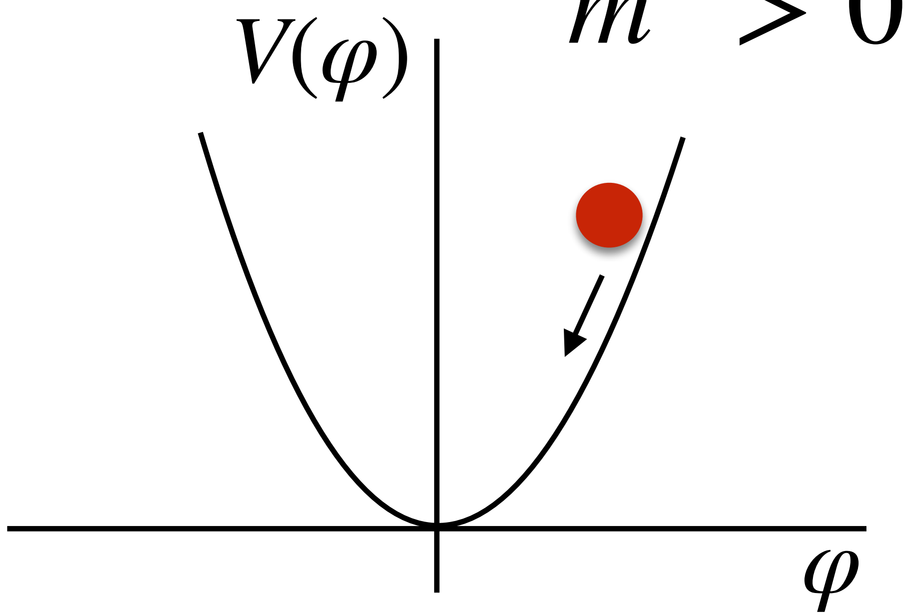
with $X = -\dfrac{1}{2}\partial^\mu \varphi \partial_\mu \varphi$ and $w_a < 0$.

Most general thawing model

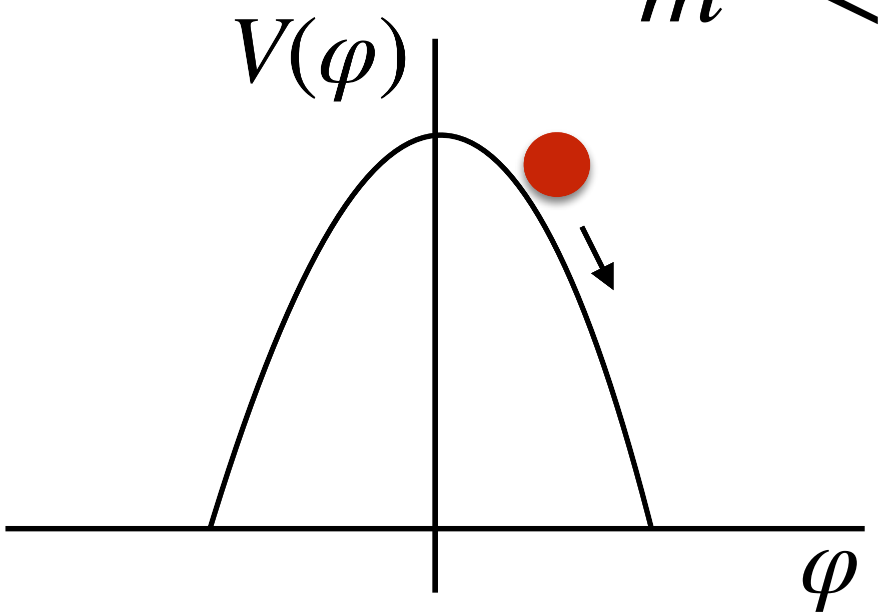
Most generic potential for (minimally coupled) thawing:

$$V(\varphi) = V_0 + \frac{1}{2}m^2\varphi^2$$

$m^2 > 0$



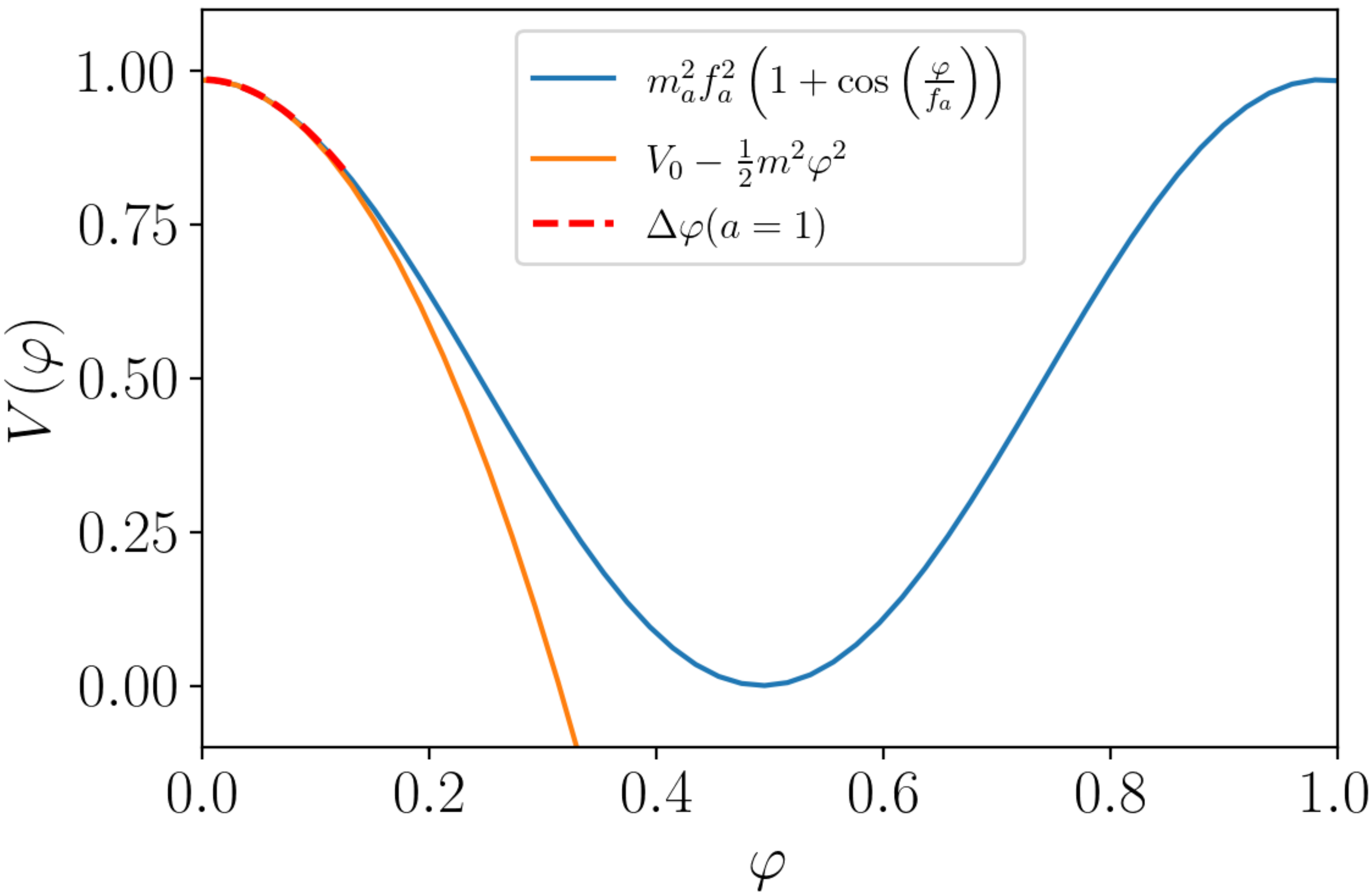
$m^2 < 0$



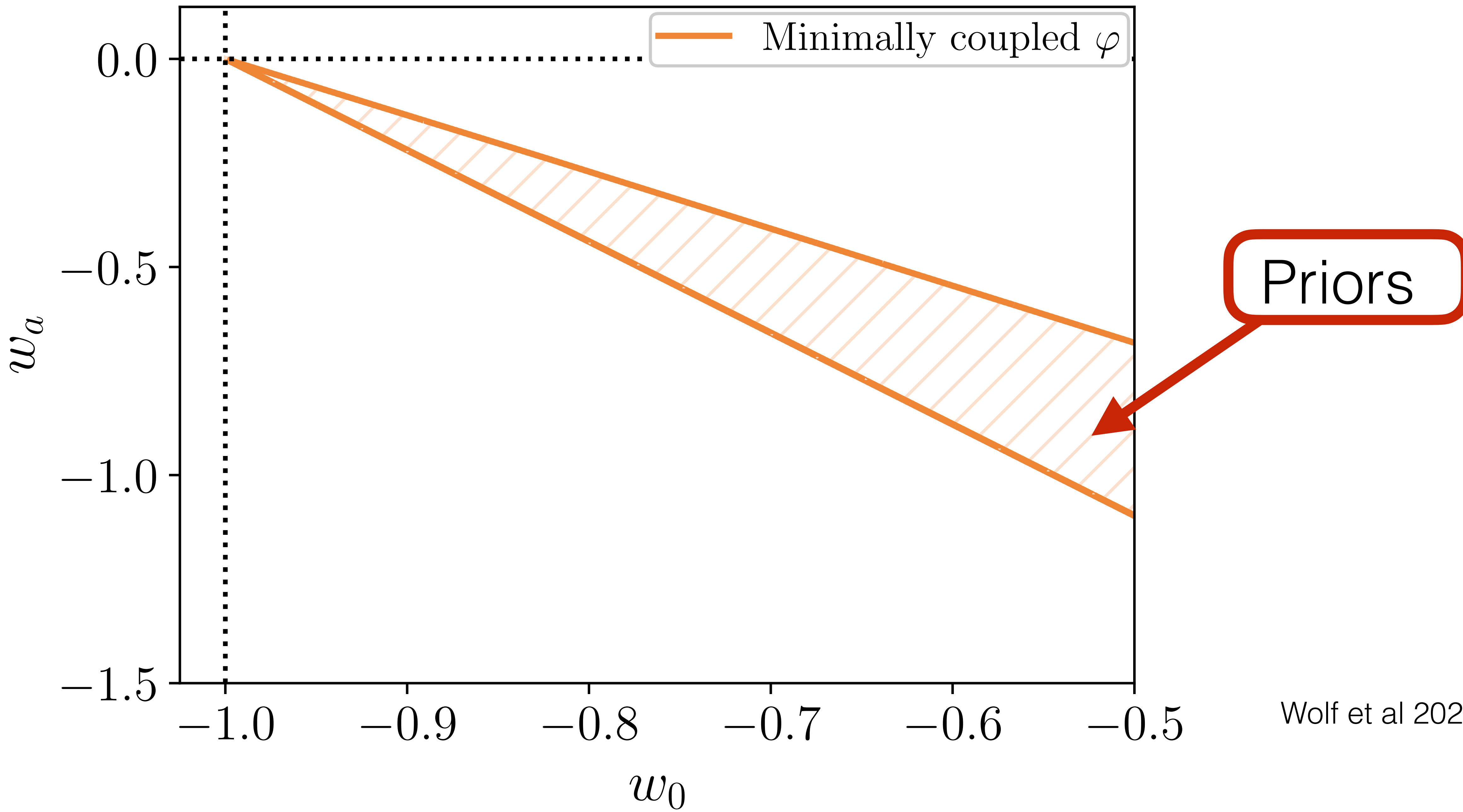
Note: $V_0 \sim M_{\rm Pl}^2 H_0^2$ and $m^2 \sim H_0^2$

Excellent approximation because $\Delta\varphi/M_{\rm Pl}$ is small

e.g. an axion potential (but true for any potential)

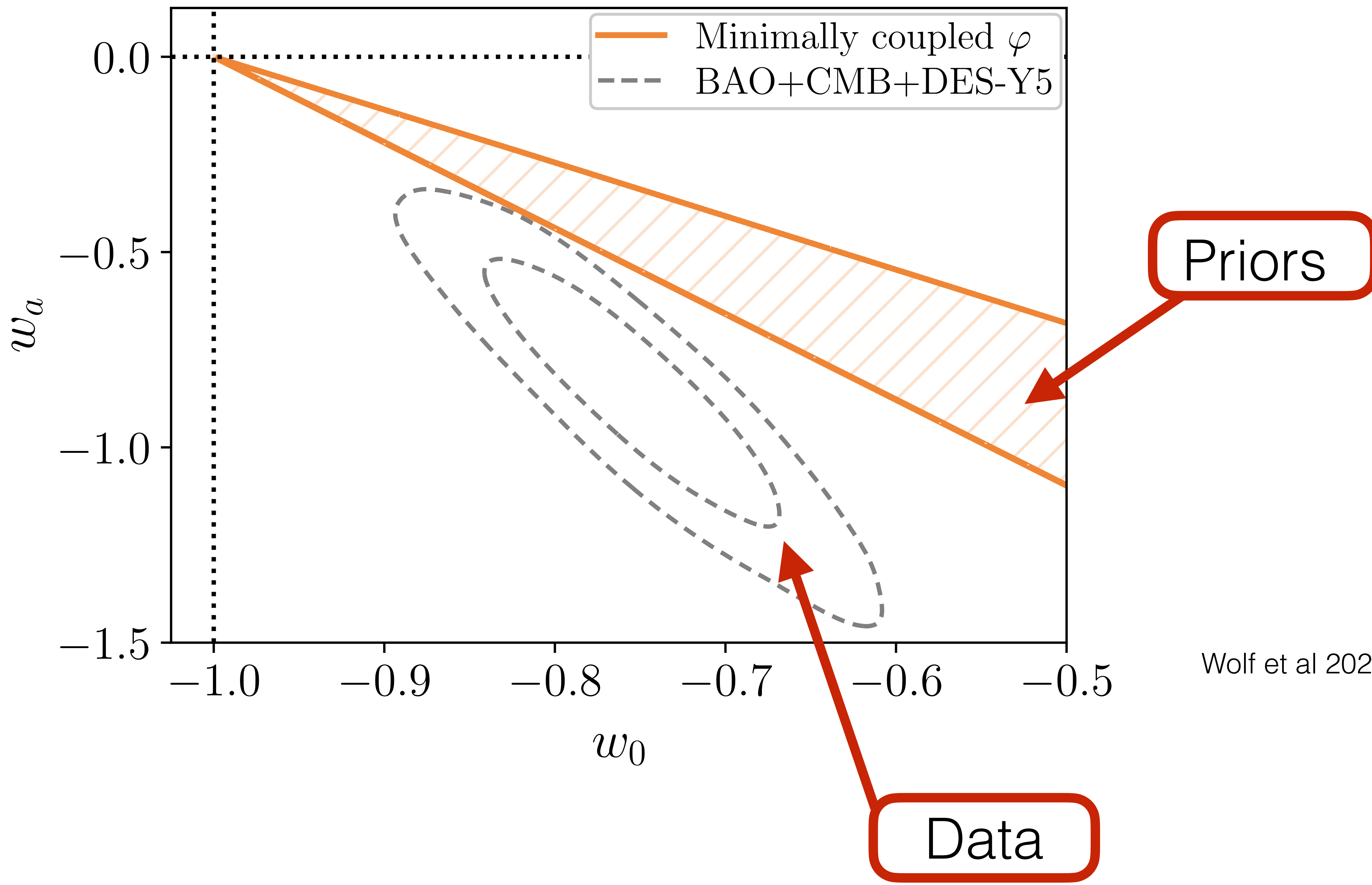


Most general thawing model

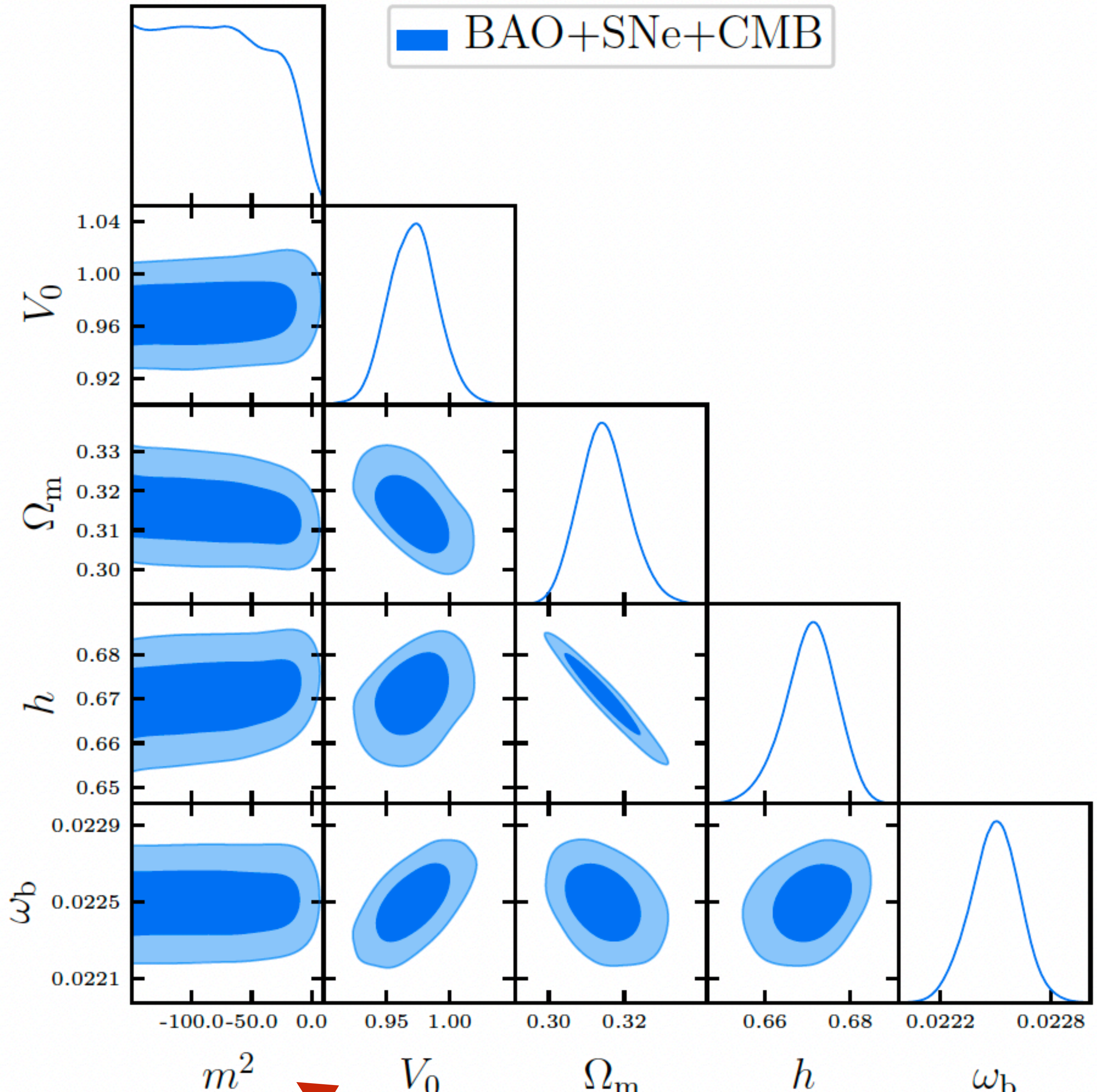


Wolf et al 2023

Most general thawing model



Wolf et al 2023



Hill top models ($m^2 < 0$) strongly favoured.

Is there evidence for thawing?

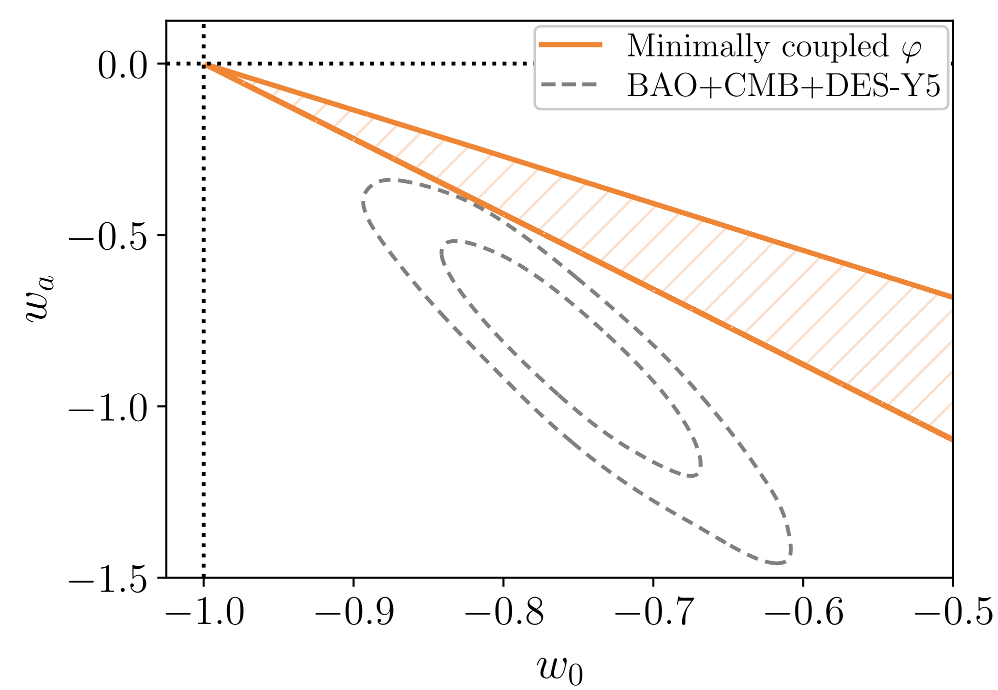
Compare to ΛCDM: $\Delta\chi^2 \simeq -14$

Bayesian Evidence: $\log B \simeq 3.46 \pm 0.57$

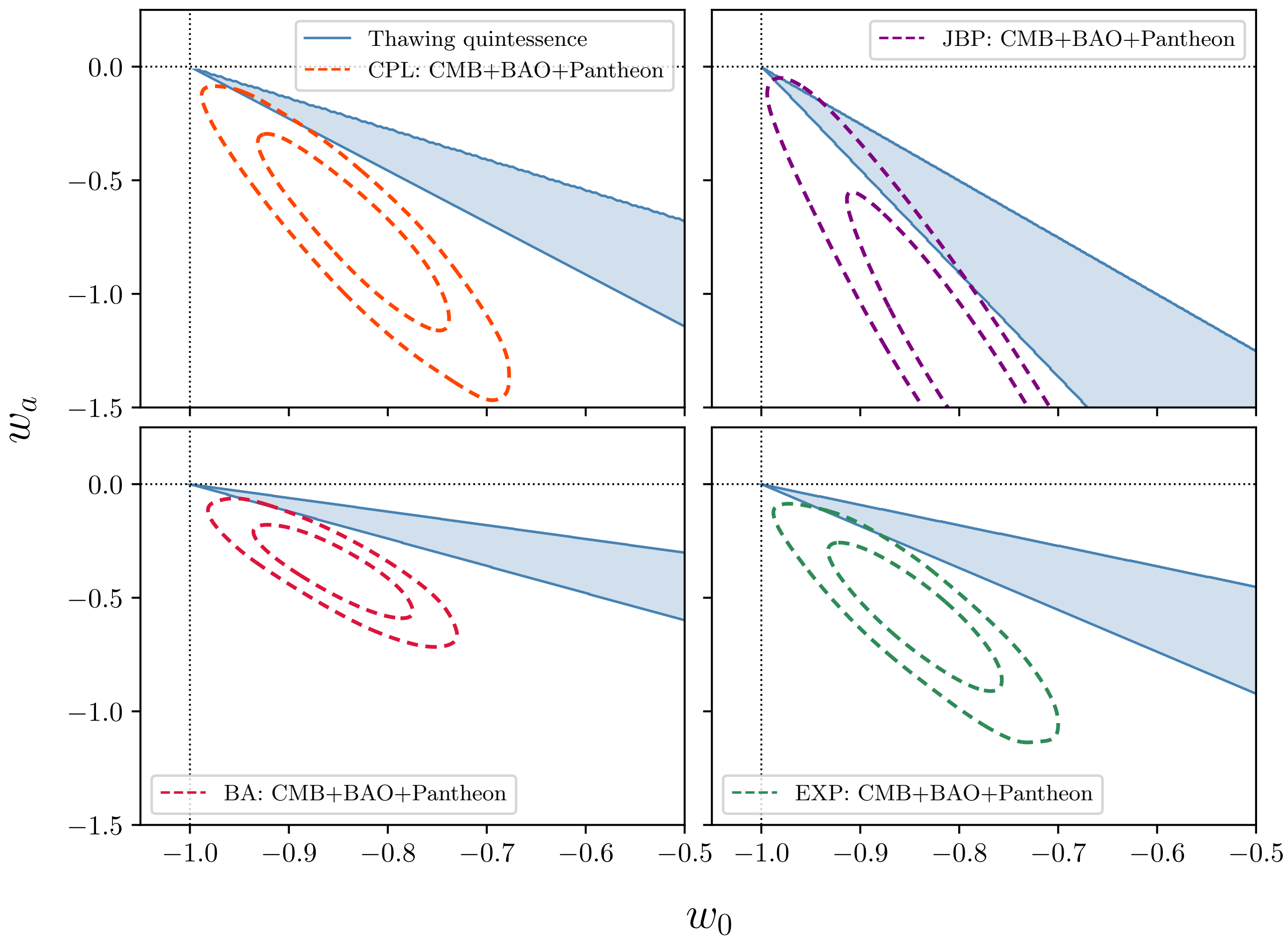
$1-2.5$	positive
$2.5-5$	moderate
>5	strong

Mildly better than ΛCDM but inconclusive

Scant evidence for thawing



Does it depend on the parametrisation?



Wolf et al in progress 2024

Not really …

JBP: $w_0 + w_a \times a(1-a)$

Dimakis et al 2016

EXP: $(w_0 - w_a) + w_a \times \exp(1-a)$

Jassal et al 2005

BA: $w_0 + w_a \times \dfrac{1-a}{a^2 + (1-a)^2}$

Barboza et al 2008

CPL: $w_0 + w_a \times (1-a)$

Chevalier et al 2001

Non-minimal coupling

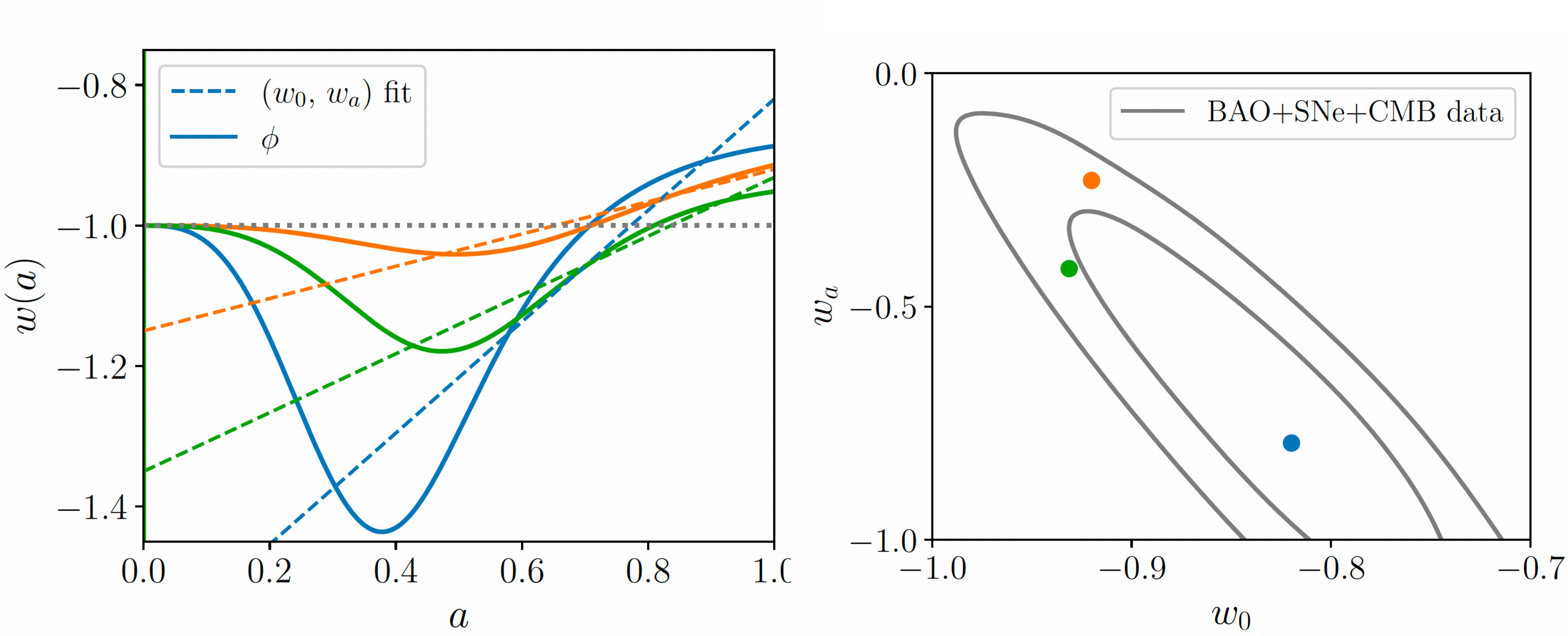
Non-minimal coupling:

$$S = \int d^4x\sqrt{-g}\left[\frac{1}{2}\left(M_{\mathrm{P}}^2 - \xi\varphi^2\right)R + X + V(\varphi)\right]$$

$$V(\varphi) = V_0 + \beta\varphi + \frac{1}{2}m^2\varphi^2$$

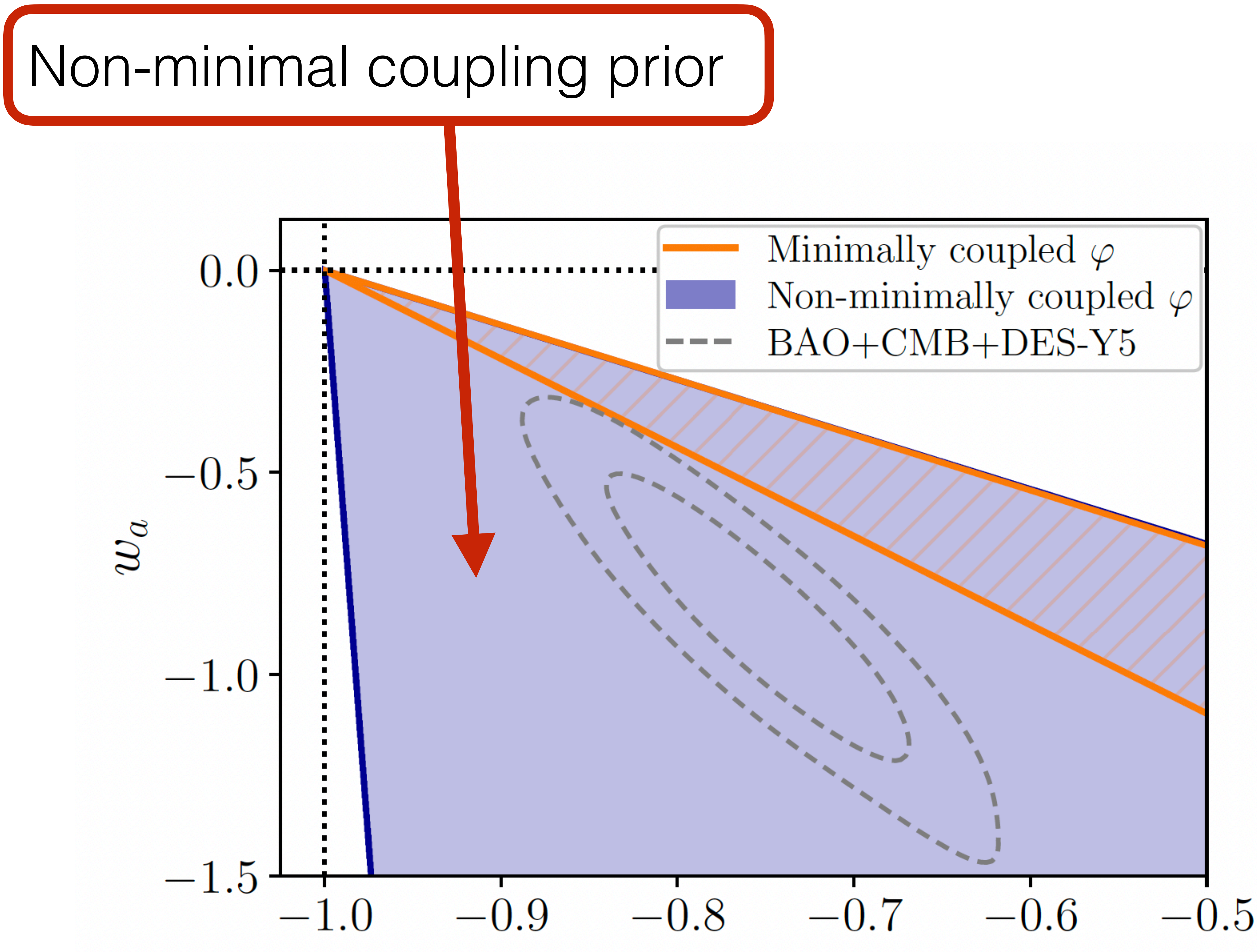
Non-minimal coupling

Non-minimal coupling:



Wolf et al 2024

Non-minimal coupling



Wolf et al 2025

Non-minimal coupling

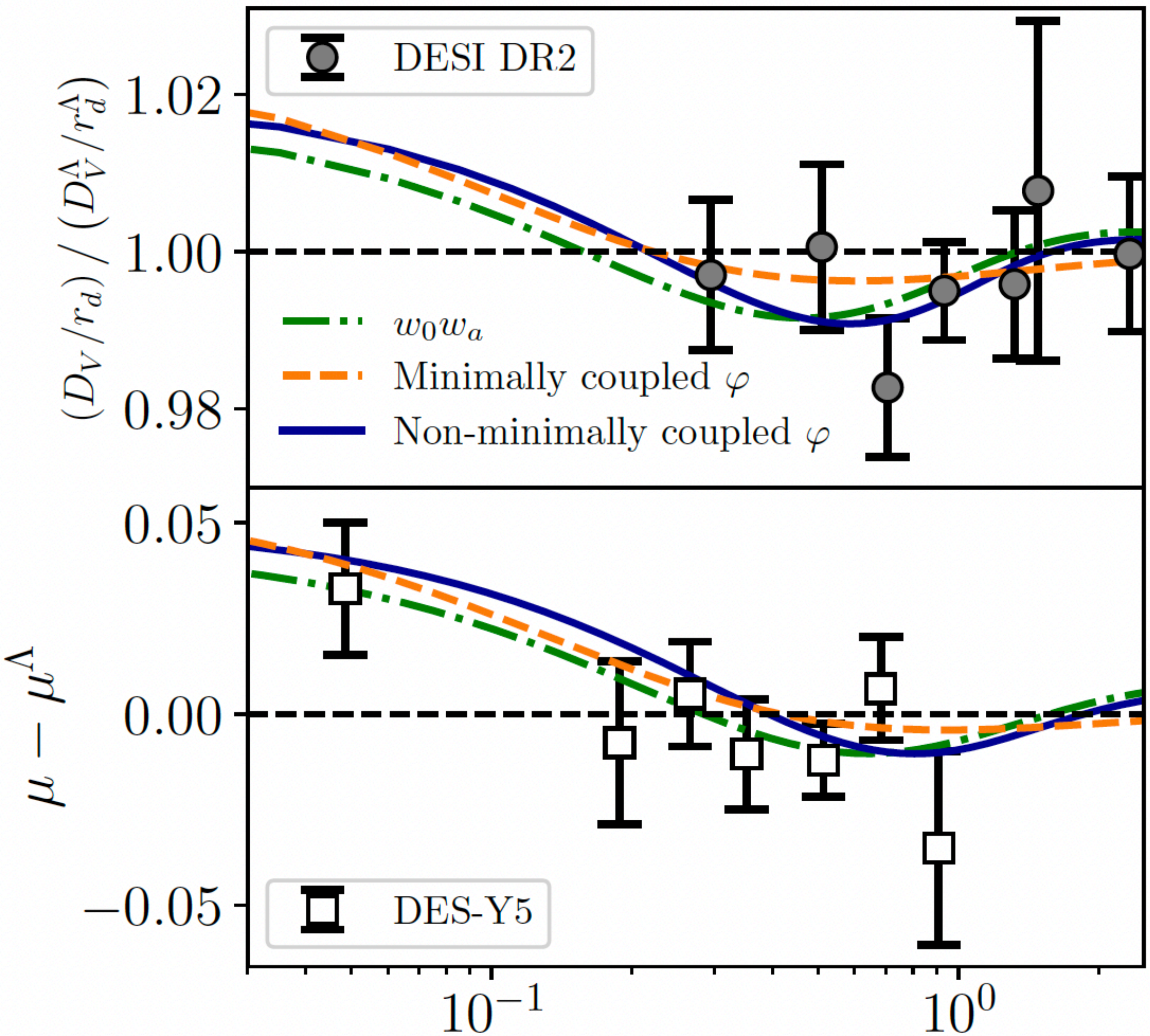
Compare to ΛCDM:

$$\Delta\chi^2 \simeq -24$$

$1 - 2.5$	positive
$2.5 - 5$	moderate
> 5	strong

Bayesian Evidence: $\log B \simeq 7.34 \pm 0.6$

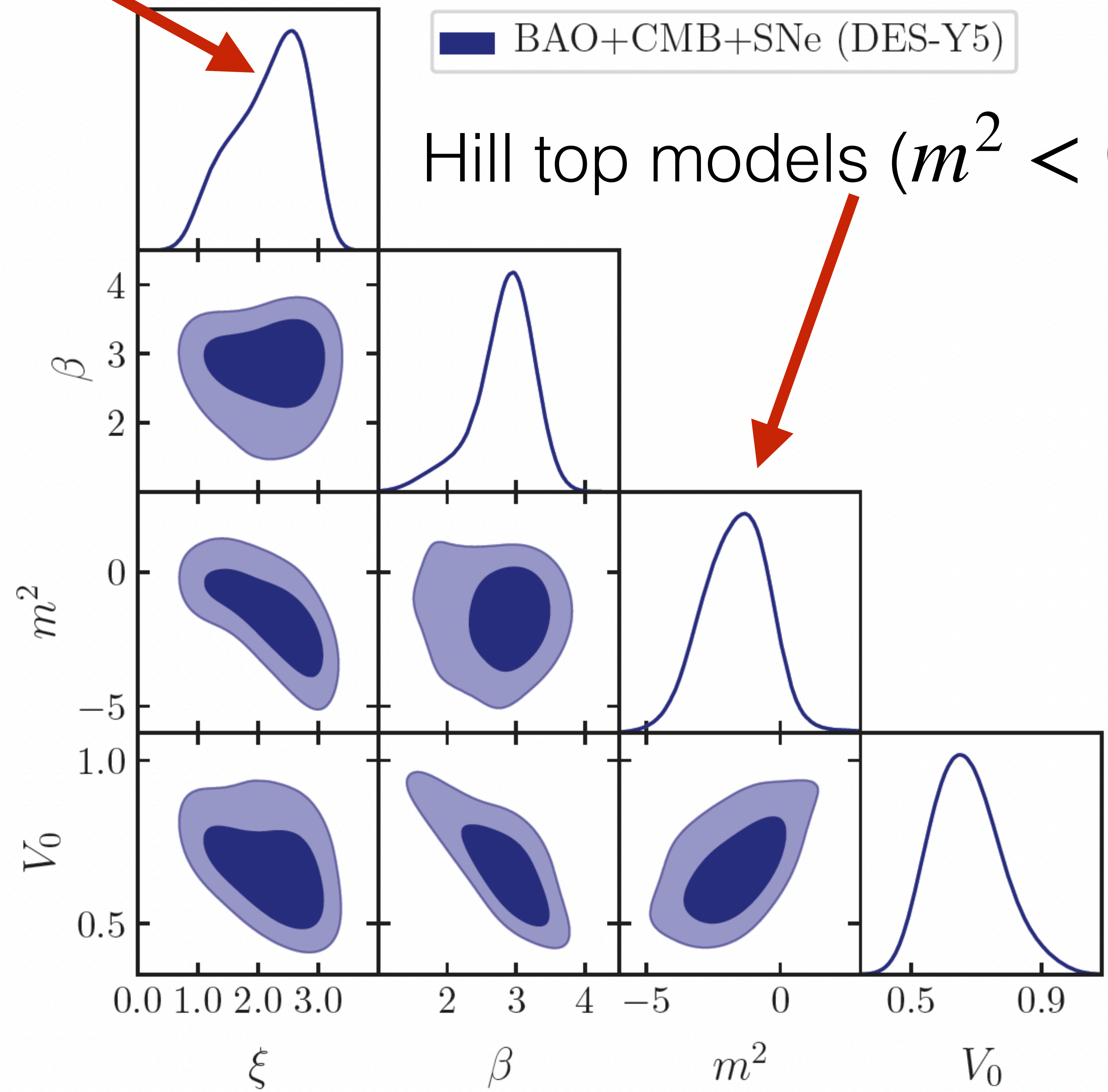
Overwhelming evidence for non-minimal coupling.



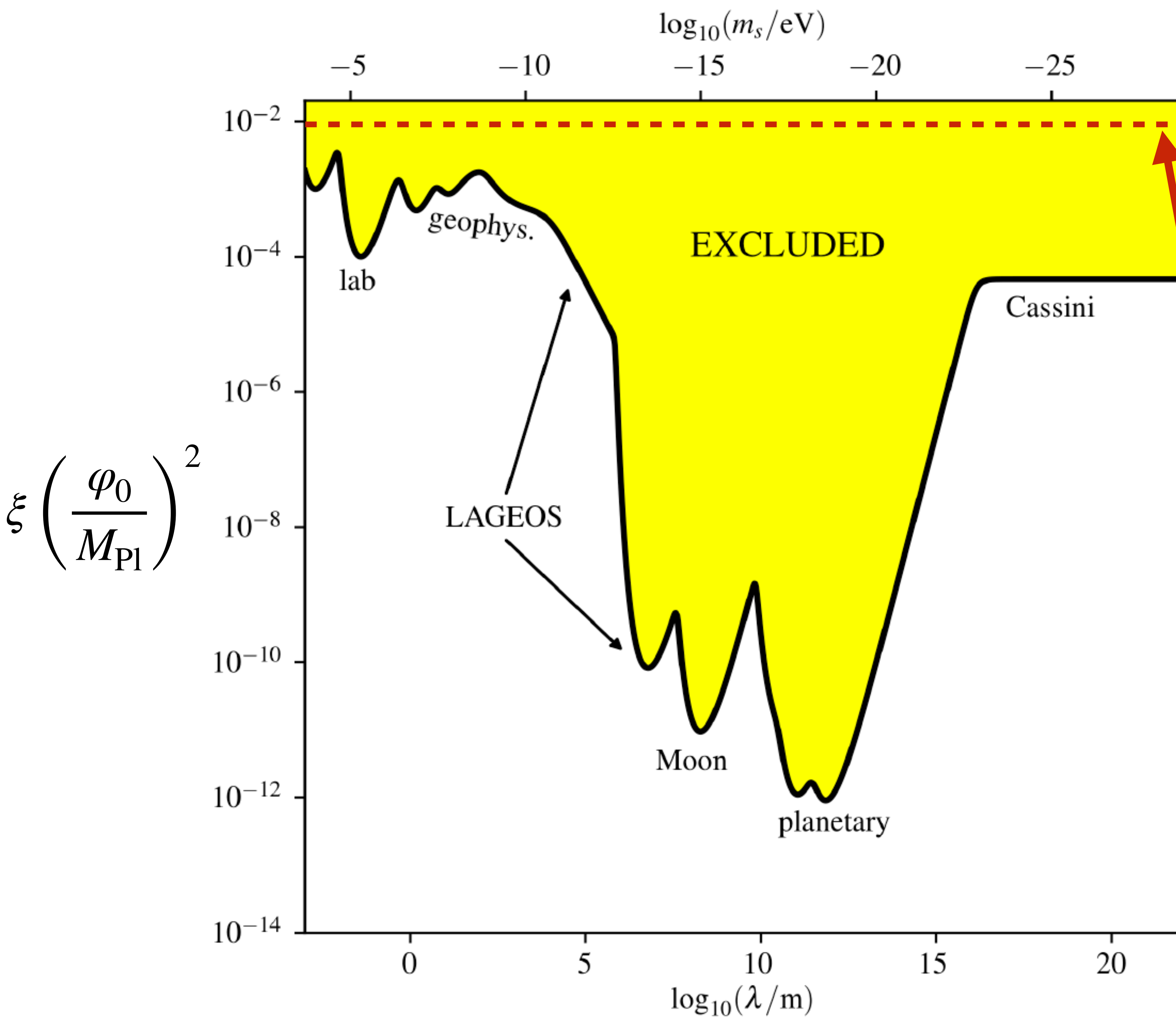
Wolf et al 2025

$\xi \sim \mathcal{O}(1)$

Hill top models ($m^2 < 0$) favoured.



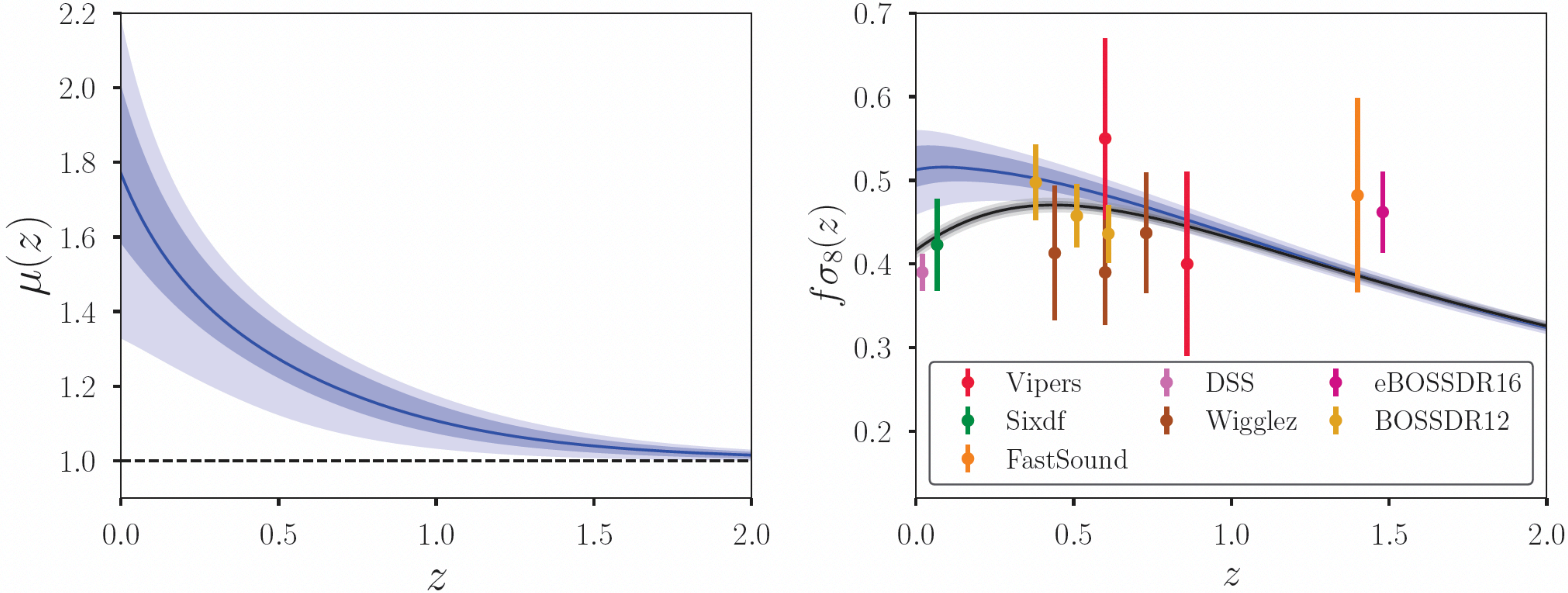
The Problem of Fifth Forces



…but cosmology give us: $\xi\left(\frac{\varphi_0}{M_{\mathrm{Pl}}}\right)^2 \sim 0.01 - 0.1$

The Problem of Fifth Forces

Growth rate of structure



Modified Newton Poisson: $\nabla^2\Phi = 4\pi G\mu\rho_{\mathrm{M}}$

Screening?

$$S = \int d^4x \sqrt{-g} \left[\frac{1}{2} \left(M_{\rm P}^2 - \xi \varphi^2 \right) R + X + \boxed{\frac{1}{\Lambda^4} X^2} - V(\varphi) \right] + S_{\rm m}$$

Next term in EFT

Vainshtein Screening: $\frac{F_5}{F_N} \propto \left(\frac{r}{r_V} \right)^{4/3}$ with $r_V = \left(\frac{M}{16\pi \Lambda^2 M_{\rm Pl}} \right)^{1/2}$

Note: different scaling from cubic Galileon

But: $\Lambda < 10^{-2}\mathrm{eV}$…

Different non-minimal coupling

Not all non-minimal coupled theories are equal

Simplest, non-trivial, shift symmetric scalar tensor:

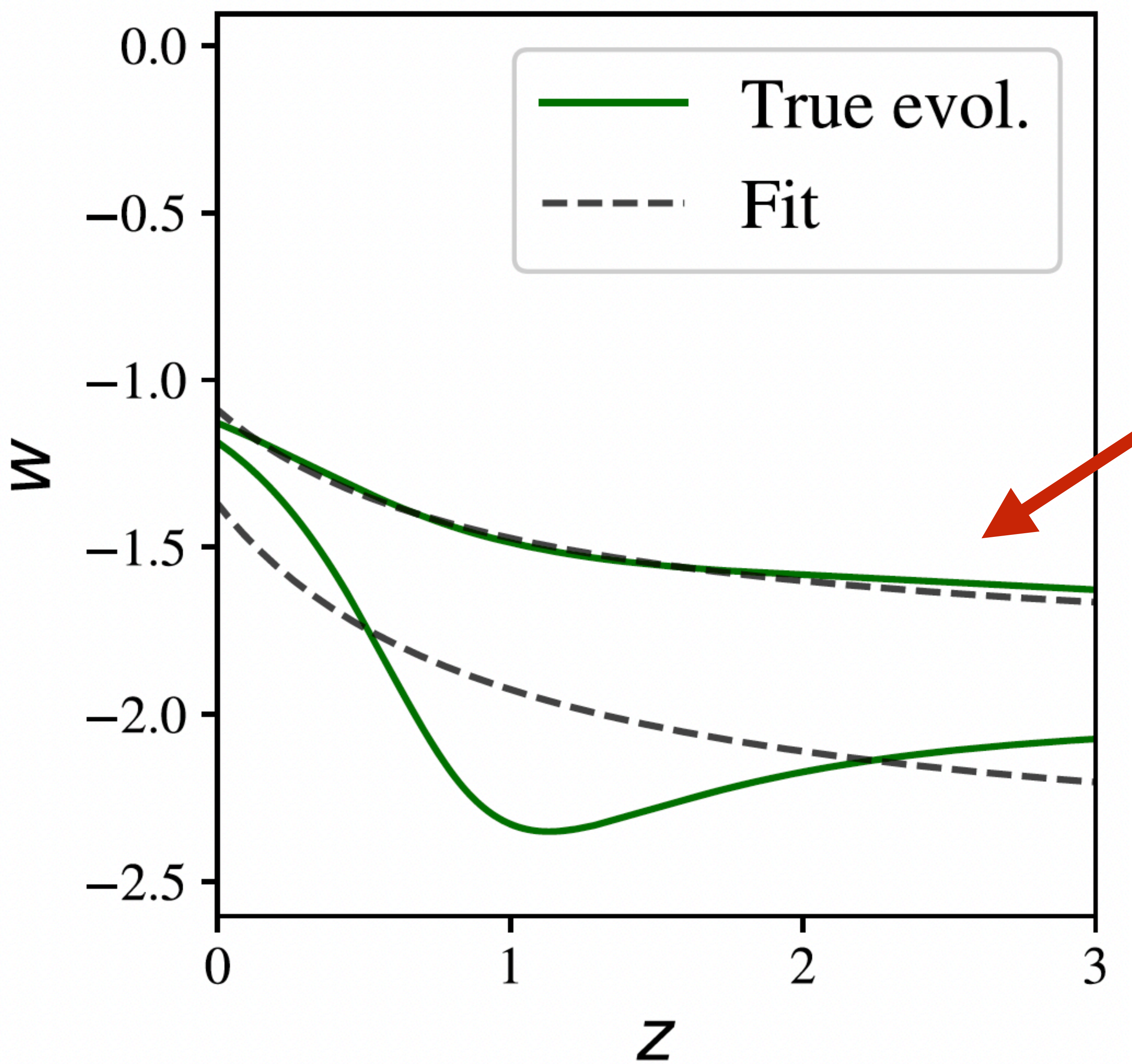
$$S = \int d^4x\sqrt{-g}\left[\frac{1}{2}M_{\mathrm{P}}^2 R - X + \alpha X^2 + \Box\phi\left(\gamma X + \zeta X^2\right)\right]$$

Traykova et al 2021

Note: Galileon Model

Different non-minimal coupling

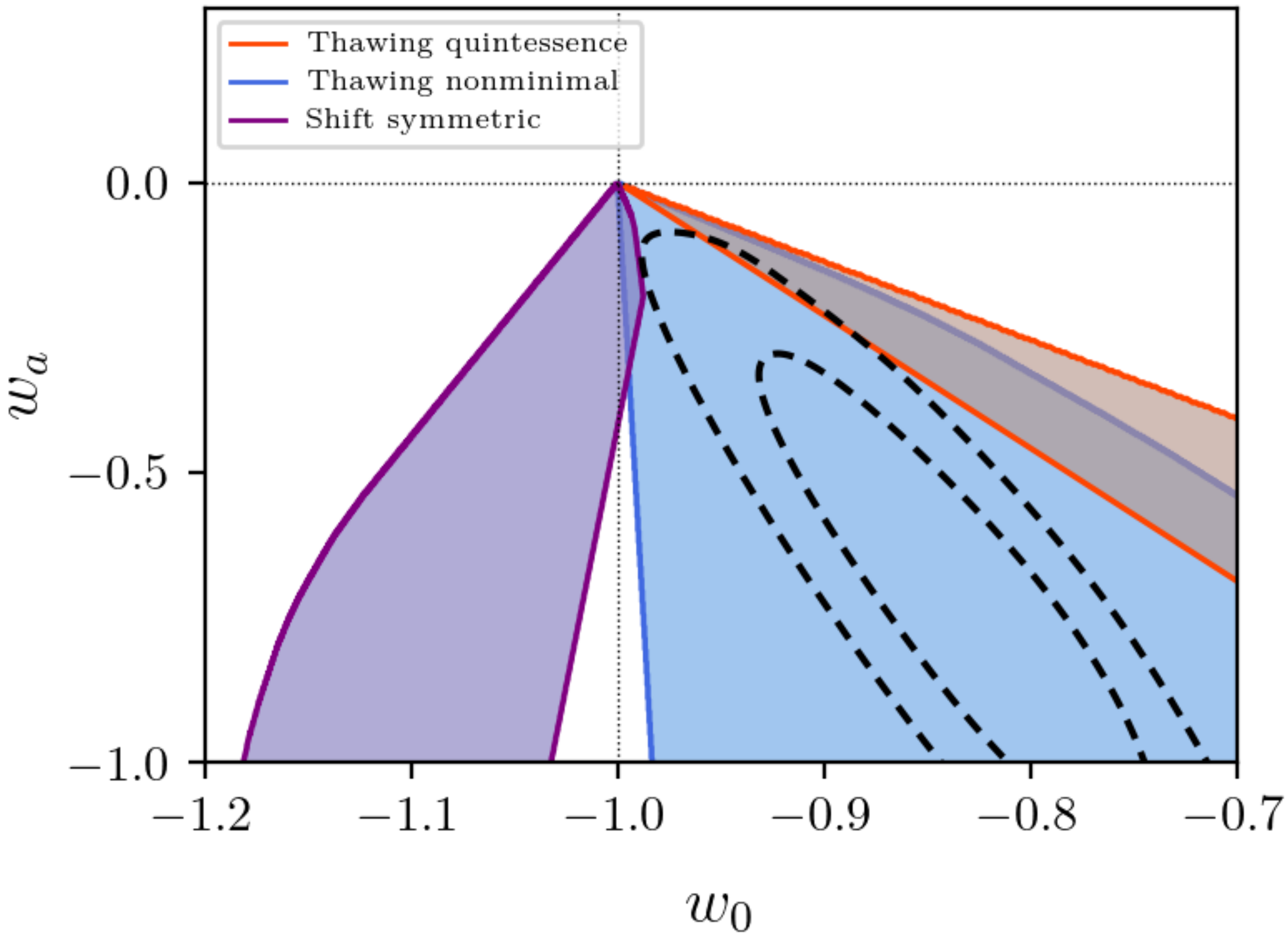
Shift symmetric theories



Always $w(a) < -1$

Traykova et al 2021

Different non-minimal coupling



Wolf et al (in progress) 2024

Different non-minimal coupling

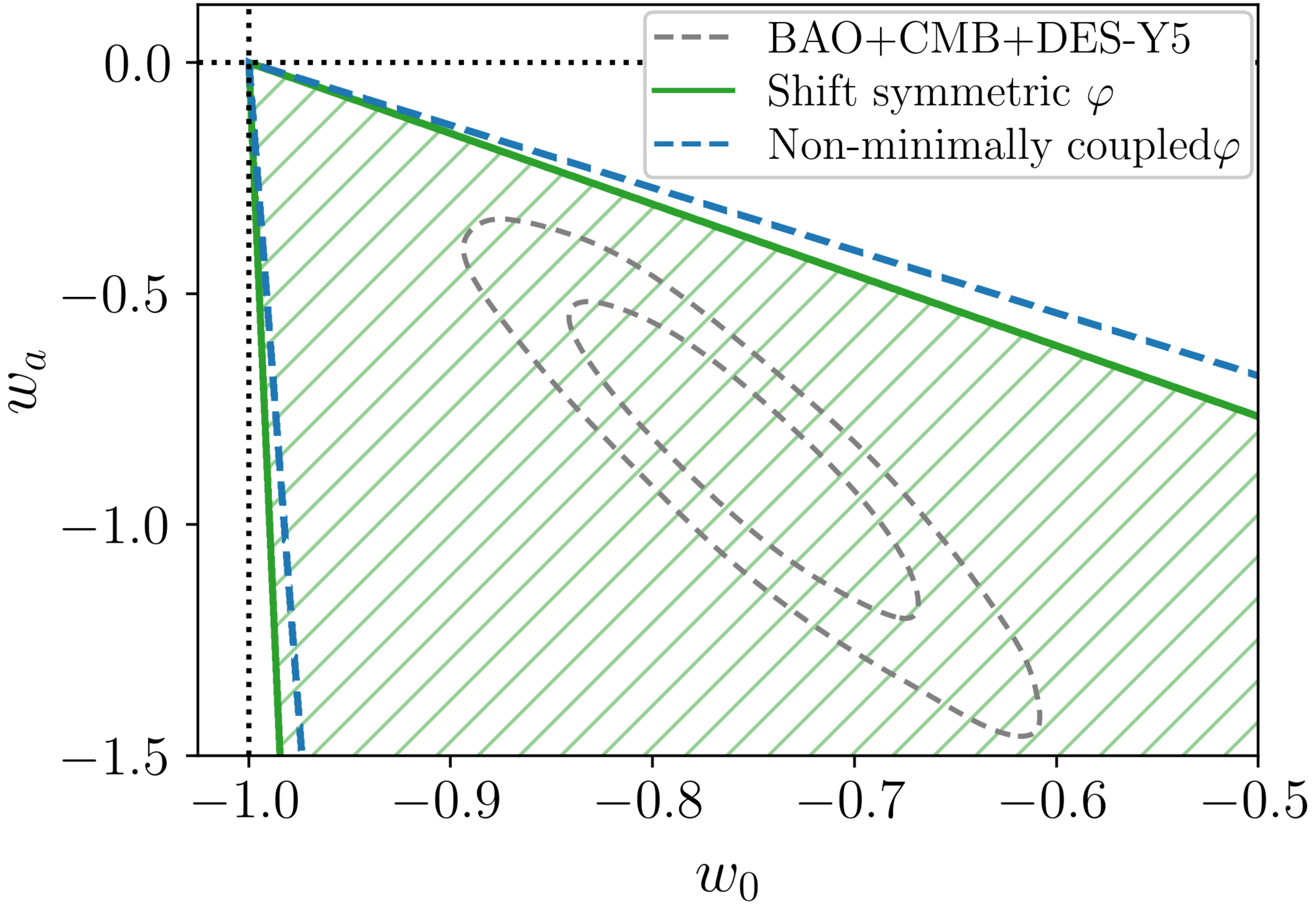
Add a potential

$$S = \int d^4x \sqrt{-g} \left[\frac{1}{2} M_{\mathrm{P}}^2 R - X + \frac{\gamma}{\Lambda^3} X \Box \varphi - V(\varphi) \right]$$

$$V(\varphi) = V_0 + \frac{1}{2} m^2 \varphi^2$$

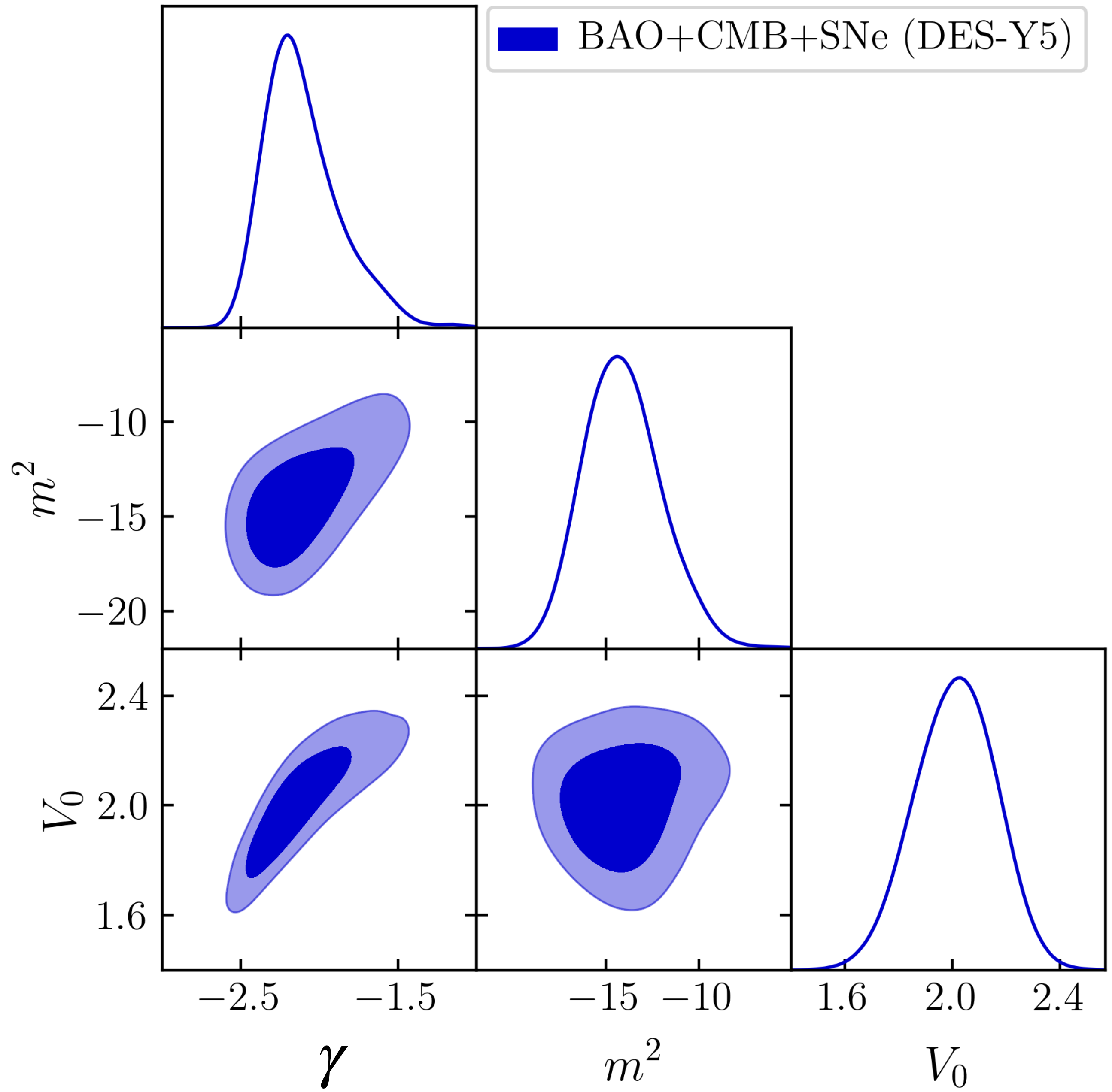
Note: Not shift symmetric

Different non-minimal coupling



Wolf et al (in progress) 2024

Different non-minimal coupling



Wolf et al (in progress) 2024

Different non-minimal coupling

Compare to ΛCDM:

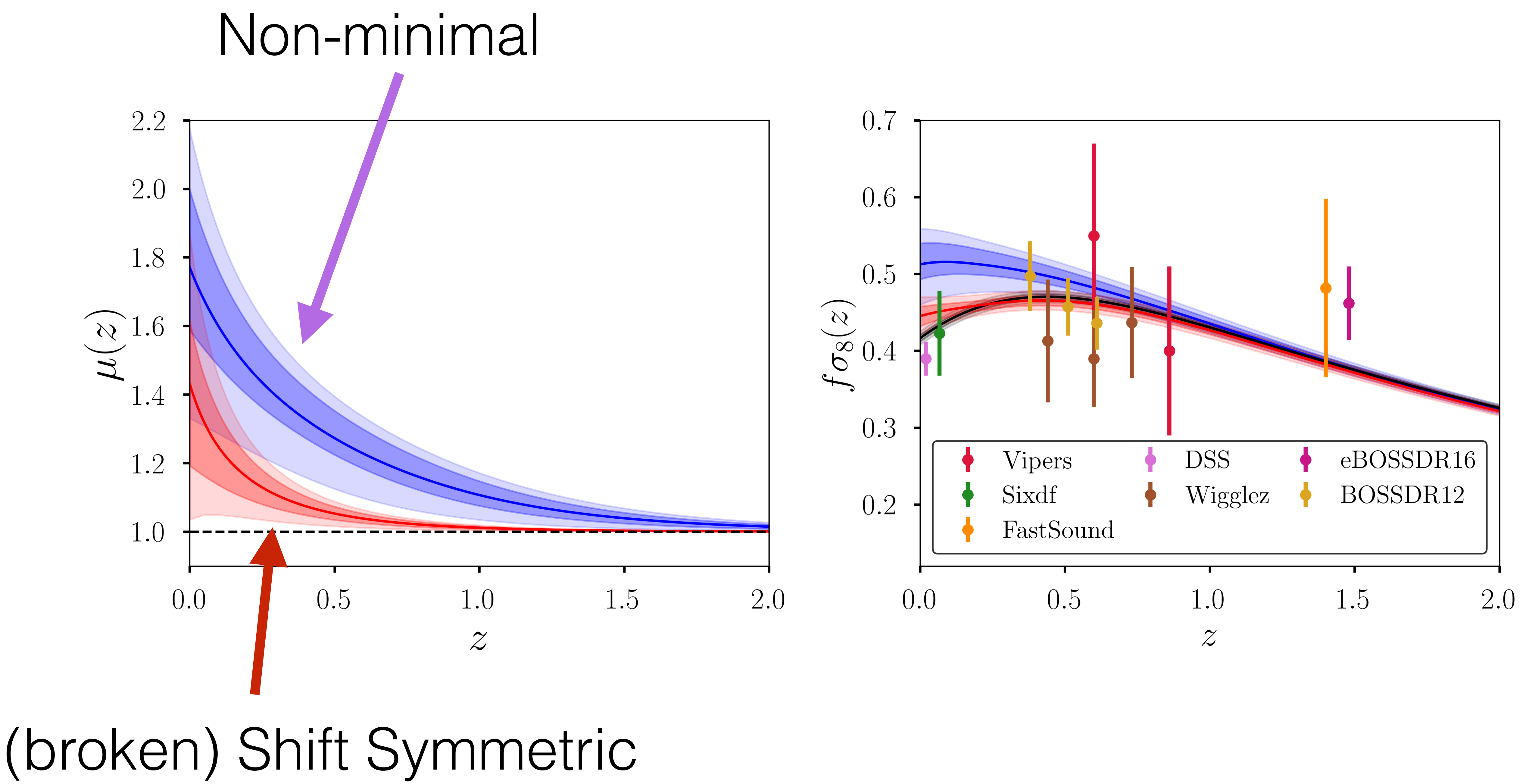
$$\Delta\chi^2 \simeq -20$$

$1-2.5$	positive
$2.5-5$	moderate
>5	strong

Bayesian Evidence: $\log B \simeq 5$

Strong evidence for non-minimal coupling.

Fifth forces



Modified Newton Poisson: $\nabla^2\Phi = 4\pi G\mu\rho_{\mathrm{M}}$

Screening?

$$S = \int d^4x\sqrt{-g}\left[\frac{1}{2}M_{\rm P}^2 R - X + \boxed{\frac{\gamma}{\Lambda^3}X\,\Box\,\varphi} - V_0 - \beta\varphi - \frac{1}{2}m^2\varphi^2\right]$$

Cubic Galileon (Vainshtein) Screening

But same non canonical terms now used for phantom behaviour on cosmological scales *and* screening…

Mismatch of scales…

Alternatives

Some form of non-minimal coupling essential

$\downarrow$

protect from fifth forces.

- Higher order (Galileon) terms?
- Hide fifth forces from baryons $\rightarrow$ Coupled DM/DE?

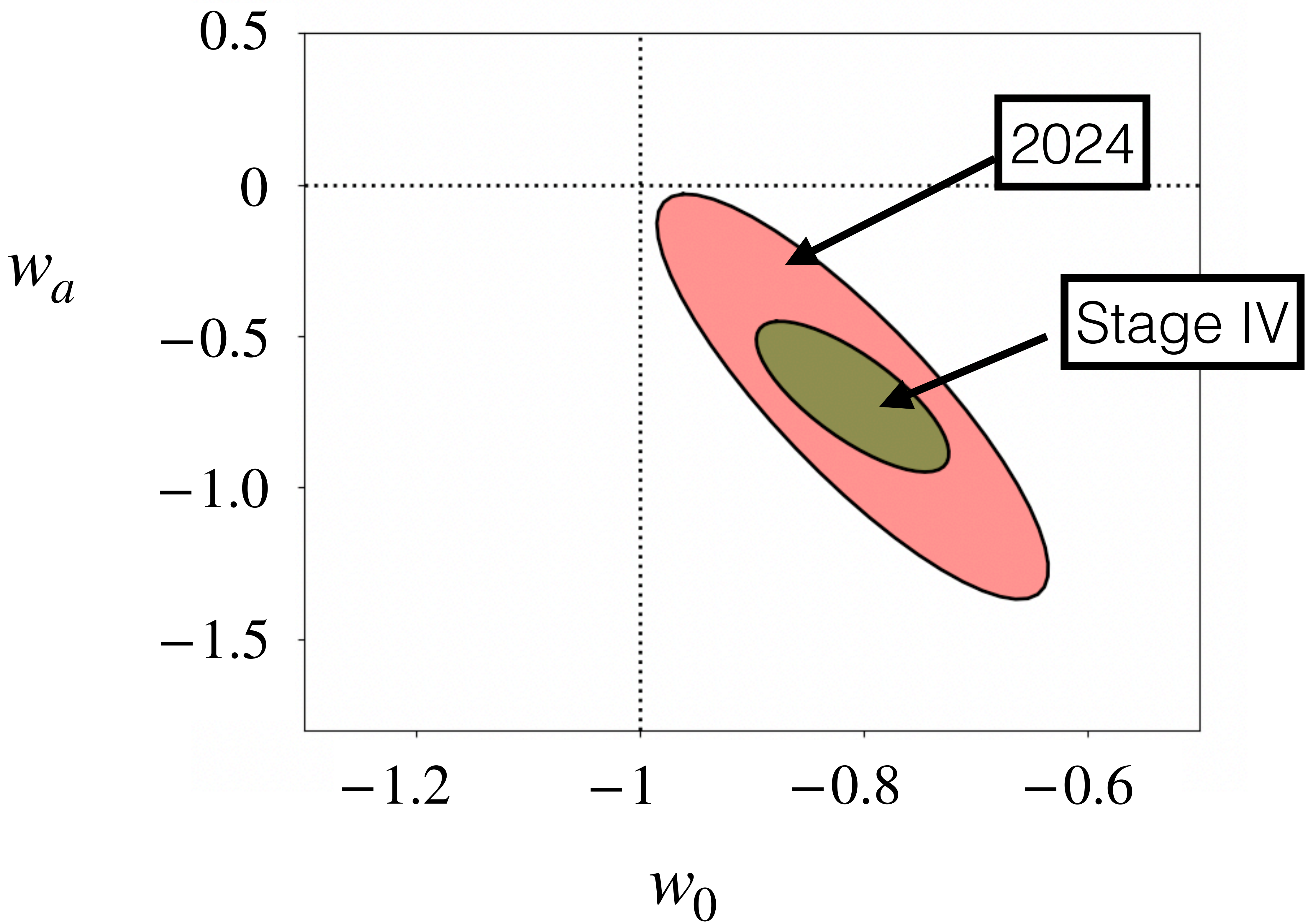
e.g. Amendola, 2000

The Ptolomaic Era of Dark Energy…

Are we adding epicycle upon epicycle in our attempts at constructing a viable model of scalar field dark energy?

Back to “opinions”…

The Future



Is Dark Energy Unknowable?

The Facts

- ΛCDM is a remarkable fit
- There are (non-minimal) quintessence models that can do much better but have ancillary gravitational effects.
- Data will improve constraints by factor of (only) a few in the next ten years
- There are a multitude of models which are effectively indistinguishable

Is Dark Energy Unknowable?

What might happen…

- Constraints will improve to a strange, unique region of model space
- New (as yet unknown) non-cosmological measurement detects dark energy

But …

- Must have unique signature!

yet …

mass scale $m_{\rm DE} \sim 10^{-33}{\rm eV}$

Is Dark Energy Unknowable?

An interesting possibility…

- Could scalar field dark energy be incompatible with the data?
- Revisit the paradigm for cosmic acceleration.

‘Until 1925, most great physicists, including Einstein and Max Planck, had doubted that man could truly grasp the deepest implications of quantum theory. They really felt that man might be too stupid to properly describe quantum phenomena.’

‘… men at the weekly colloquium in Berlin wondered: "Is the human mind gifted enough to extend physics into the microscopic domain - to atoms, molecules, nuclei, and electrons?" Many of those great men doubted that it could.’

Eugene Wigner Recollections

Thank You