Lost in the Cosmological Swampland

Marco Raveri

University of Genova

Scalar fields in cosmology

Scalar fields have a very special place in cosmologists' hearth

In cosmology everything depends on time

⇩

Scalar fields are clocks (…inflation…)

When we need to fix cosmology a scalar field is our first choice

Scalar fields in cosmology

When we need to fix cosmology a scalar field is our first choice

Dark Energy

Early Dark Energy

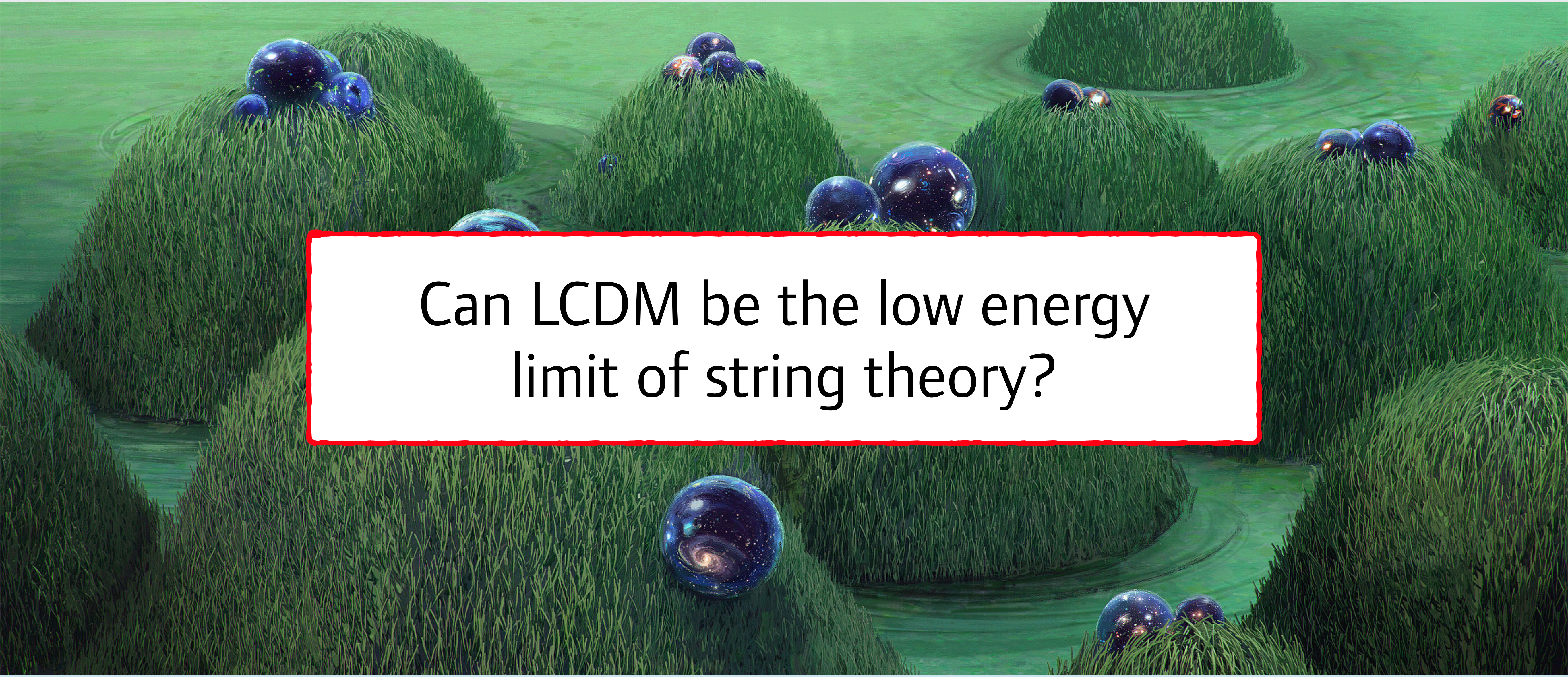
Inflation

Technical note: due to the symmetries of the cosmological background everything acquires a scalar mode

GR being the exception, extra vector and tensor fields would have a scalar component + we cannot really observe vector and tensor modes in the data…

The string theory swampland

Not every consistent Quantum Field Theory can arise as a low energy limit of string theory



Can LCDM be the low energy limit of string theory?

(G.Obied, H.Ooguri, L.Spodyneiko, C.Vafa, arXiv:1806.08362; Image: Maciej Rebisz for Quanta Magazine)

The string theory swampland

Limited field excursion

$$\Delta\phi < M_P$$

the potential cannot be too flat

$$\lambda = \frac{|V'|}{V} \sim O(1)$$

Is this consistent with the (possibly) 2 scalar fields epochs we have: inflation & DE domination

(G.Obied, H.Ooguri, L.Spodyneiko, C.Vafa, arXiv:1806.08362; Image: Maciej Rebisz for Quanta Magazine)

Lambda and the swampland

Lambda in LCDM can be modeled very well by a scalar field

$$w_{\rm DE} \equiv \frac{P_{\rm DE}}{\rho_{\rm DE}} \equiv \frac{\frac{1}{2a^2}\dot{\phi}^2 - V}{\frac{1}{2a^2}\dot{\phi}^2 + V}$$

$$\ddot{\phi} + 2\mathscr{H}\dot{\phi} + a^2\frac{\partial V}{\partial \phi} = 0$$

…stuck on a flat potential…

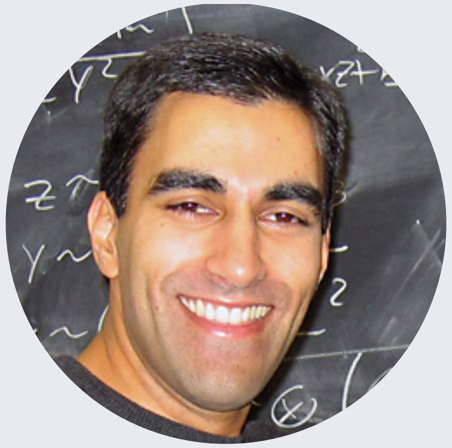
Lambda and the swampland

Not consistent with swampland requirements

Some indication that Lambda is a solid theoretical expectation

Initial constraints on string swampland

Wayne Hu (Chicago)



Savdeep Sethi (Chicago)

Condition:	Globally saturated by:
C1.1: $M_P \frac{\|V'\|}{V} \equiv \lambda \gtrsim O(1)$	$V(\phi) = A \exp(-\lambda \phi)$
C1.2: $-M_P^2 \frac{V''}{V} \equiv c^2 \gtrsim O(1)$	$V(\phi) = B \cos(c\phi)$

(MR, Wayne Hu, Savdeep Sethi, arXiv:1812.10448)

Initial constraints on string swampland

Throw in all cosmological data we have

CMB | **SN** | **LSS**

↓

Mainly constraining cosmological distances

(MR, Wayne Hu, Savdeep Sethi, arXiv:1812.10448)

Initial constraints on string swampland

Mainly constraining cosmological distances

⇩

Integrals of the expansion rate $\mathscr{H}^2 \sim V$

⇩

C1.1 is a second derivative of data
C1.2 is a third derivative

(MR, Wayne Hu, Savdeep Sethi, arXiv:1812.10448)

Initial constraints on string swampland

Field excursion is better constrained:

$$\Delta\phi = -\int_{-\infty}^{0} dN \frac{e^{-3N}}{H} \int_{-\infty}^{N} d\tilde{N} \frac{e^{3\tilde{N}}}{H} \frac{dV}{d\phi}$$

Same order as data

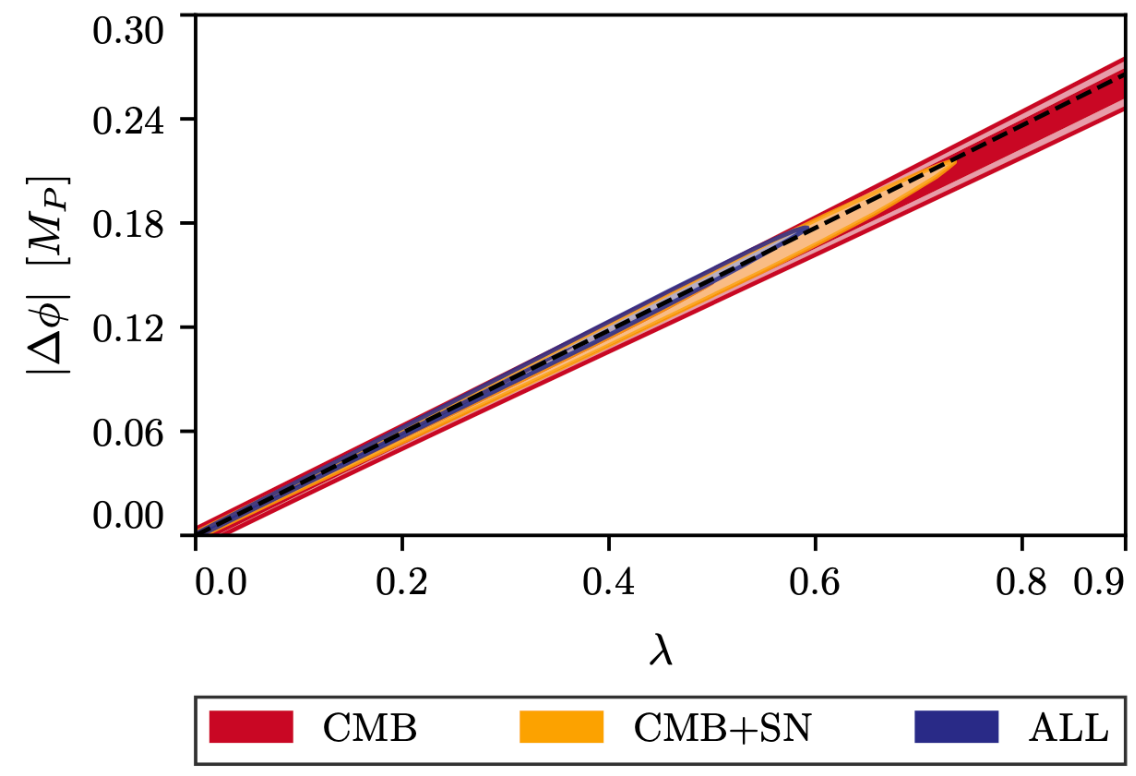
(MR, Wayne Hu, Savdeep Sethi, arXiv:1812.10448)

Initial constraints on string swampland

Hierarchy of constraints

Data set	λ 68% (95%) C.L.	$\lvert\Delta\phi\rvert$ $[M_P]$ 68% (95%) C.L.
CMB	$\lambda < 1.1\,(1.9)$	$\lvert\Delta\phi\rvert < 0.33\,(0.52)$
CMB + SN	$\lambda < 0.38\,(0.64)$	$\lvert\Delta\phi\rvert < 0.11\,(0.19)$
CMB + H_0	$\lambda < 0.29\,(0.56)$	$\lvert\Delta\phi\rvert < 0.08\,(0.16)$
ALL	$\lambda < 0.28\,(0.51)$	$\lvert\Delta\phi\rvert < 0.08\,(0.15)$

Data set	c 68% (95%) C.L.
CMB	$c < 2.3\,(3.1)$
CMB + SN	$c < 0.25\,(1.4)$
CMB + H_0	$c < 0.17\,(0.84)$
ALL	$c < 0.16\,(0.73)$



(MR, Wayne Hu, Savdeep Sethi, arXiv:1812.10448)

Can we do better than that?

Swampland conjectures are fairly generic, can we match?

$$S_\phi \equiv \int d^4x \sqrt{-g} \left(\frac{1}{2} \nabla_\mu \phi \nabla^\mu \phi - V(\phi) \right)$$

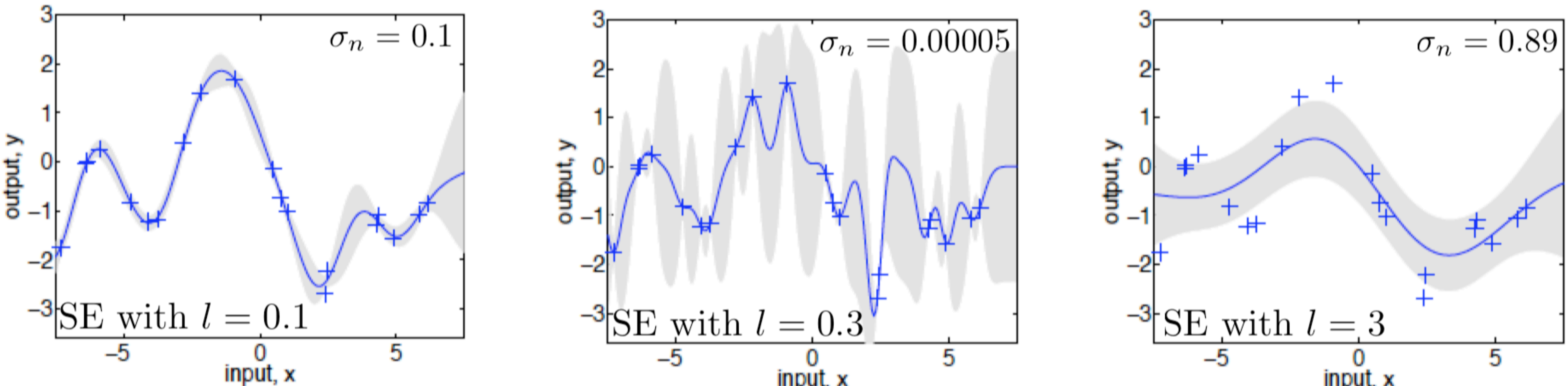
Scalar field with
standard kinetic term
$\Lambda(a) \leftrightarrow V(\phi)$
one-to-one correspondence with a time-dependent cosmological constant

(Minsu Park, MR, Bhuvnesh Jain, arXiv:2101.04666, PRD editor suggestion)

Learning from the data: how to

Estimating functions of time from the data?

Gaussian processes and machine learning



Rasmussen & Williams 2006

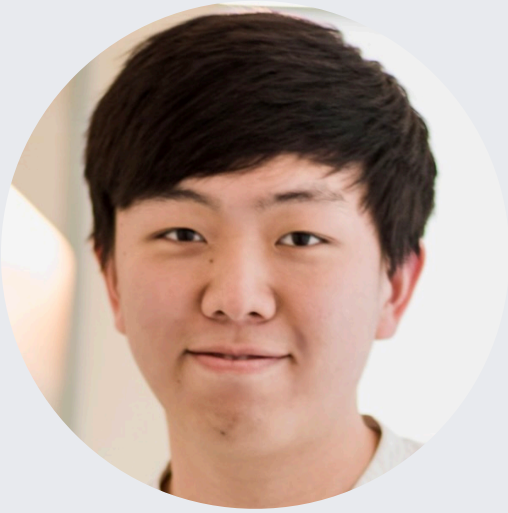
In our case **non-Gaussian** processes
(Gaussian data but non-linear model)

(MR et al. arXiv:2107.12990 and arXiv:2107.12992)

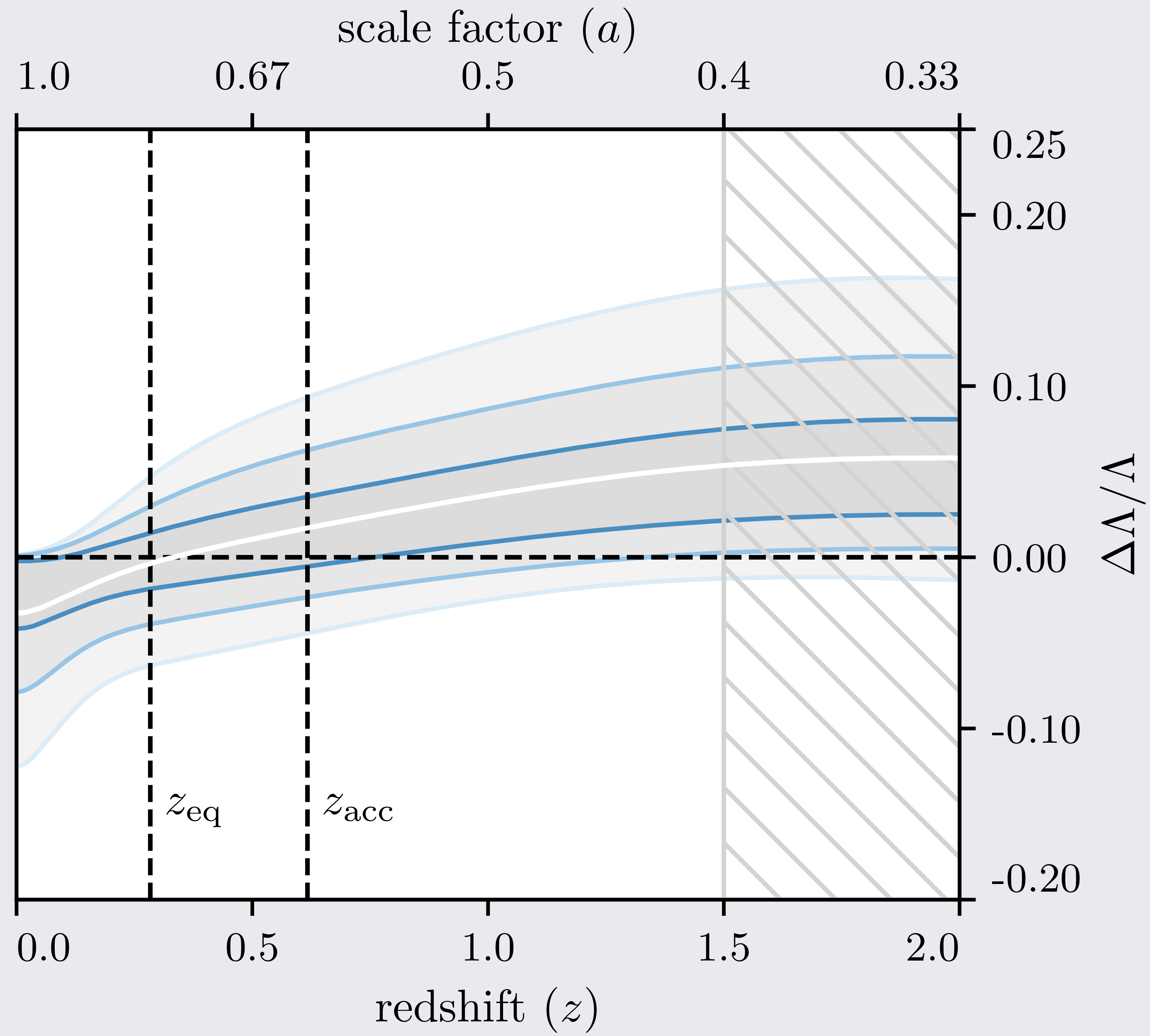
Quintessence reconstruction

Scalar field with standard kinetic term

$\Lambda(a) \leftrightarrow V(\phi)$



Minsu Park (UPenn)

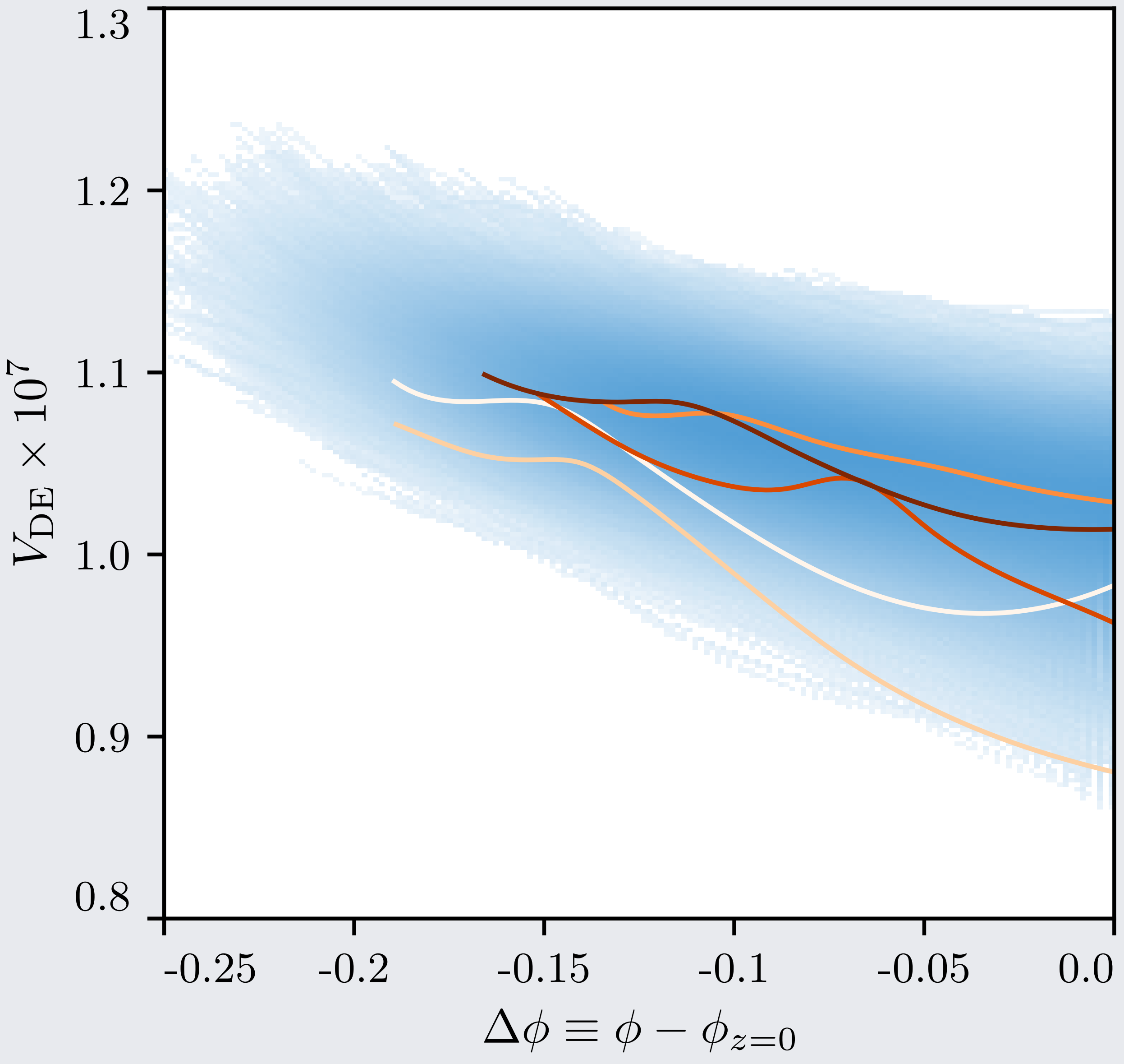


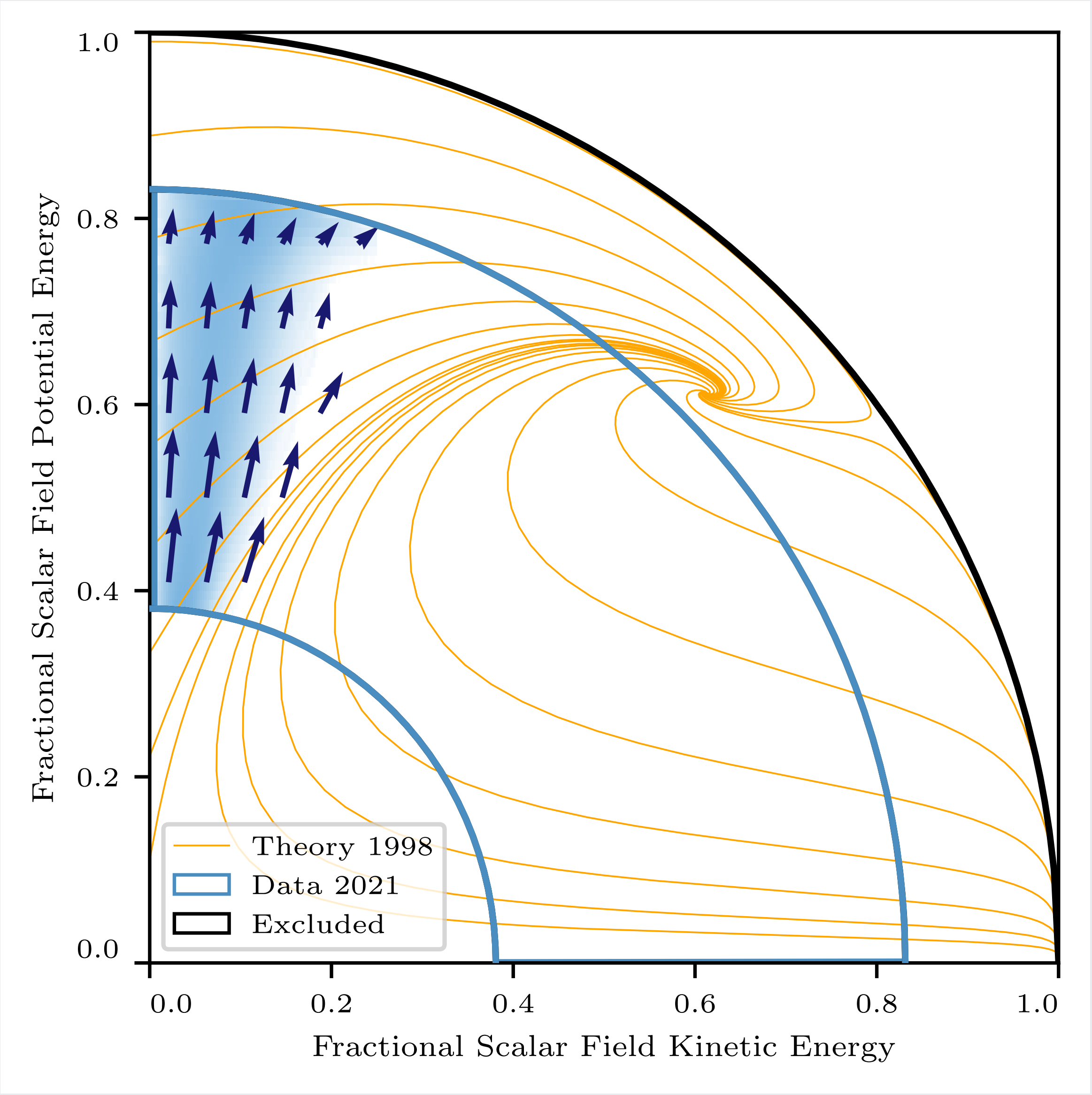
(Minsu Park, MR, Bhuvnesh Jain, arXiv:2101.04666, PRD editor suggestion)

Quintessence reconstruction

Scalar field potential

Dark Energy phase space





(Minsu Park, MR, Bhuvnesh Jain, arXiv:2101.04666, PRD editor suggestion)

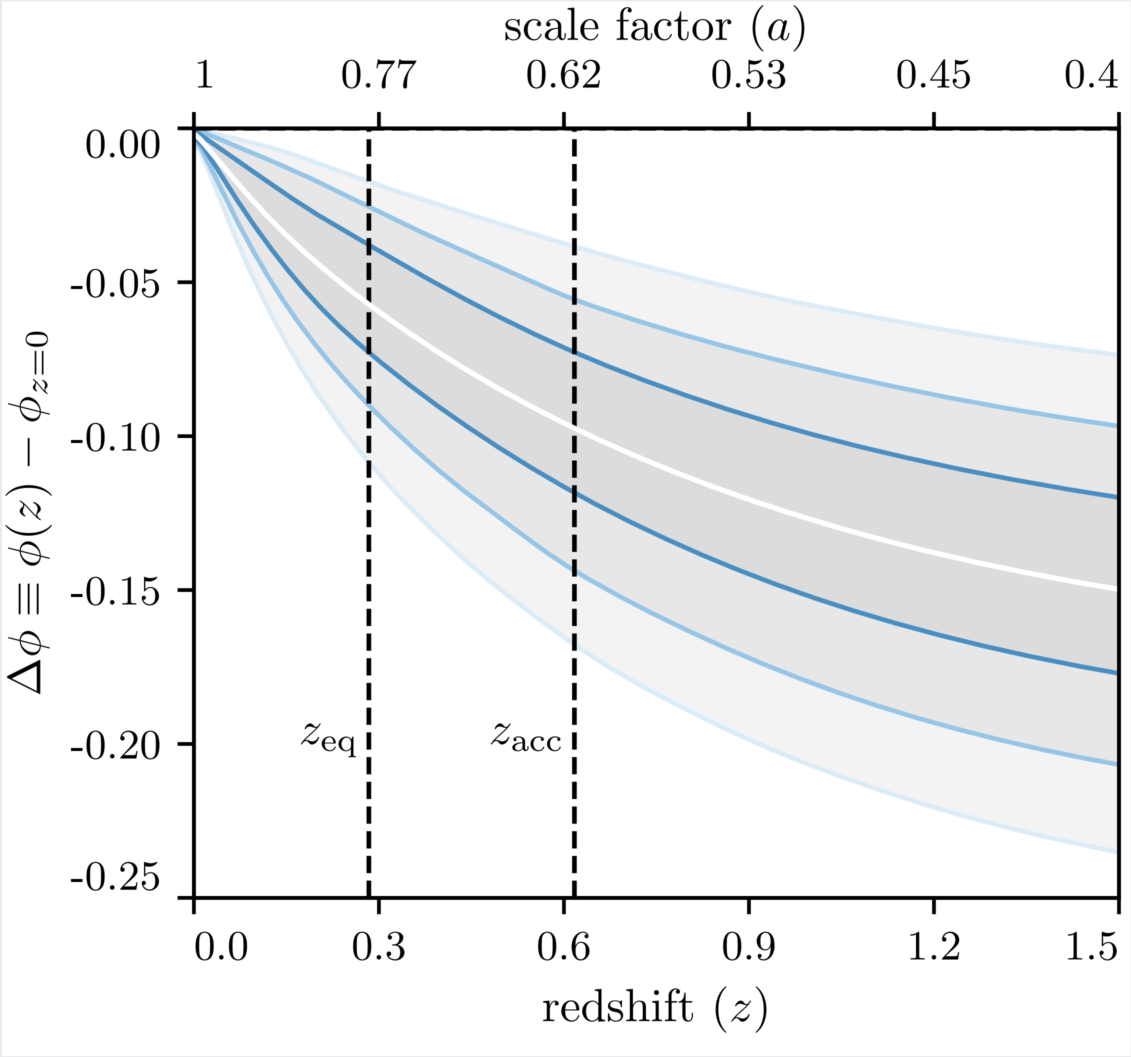
The string theory swampland reconstructed

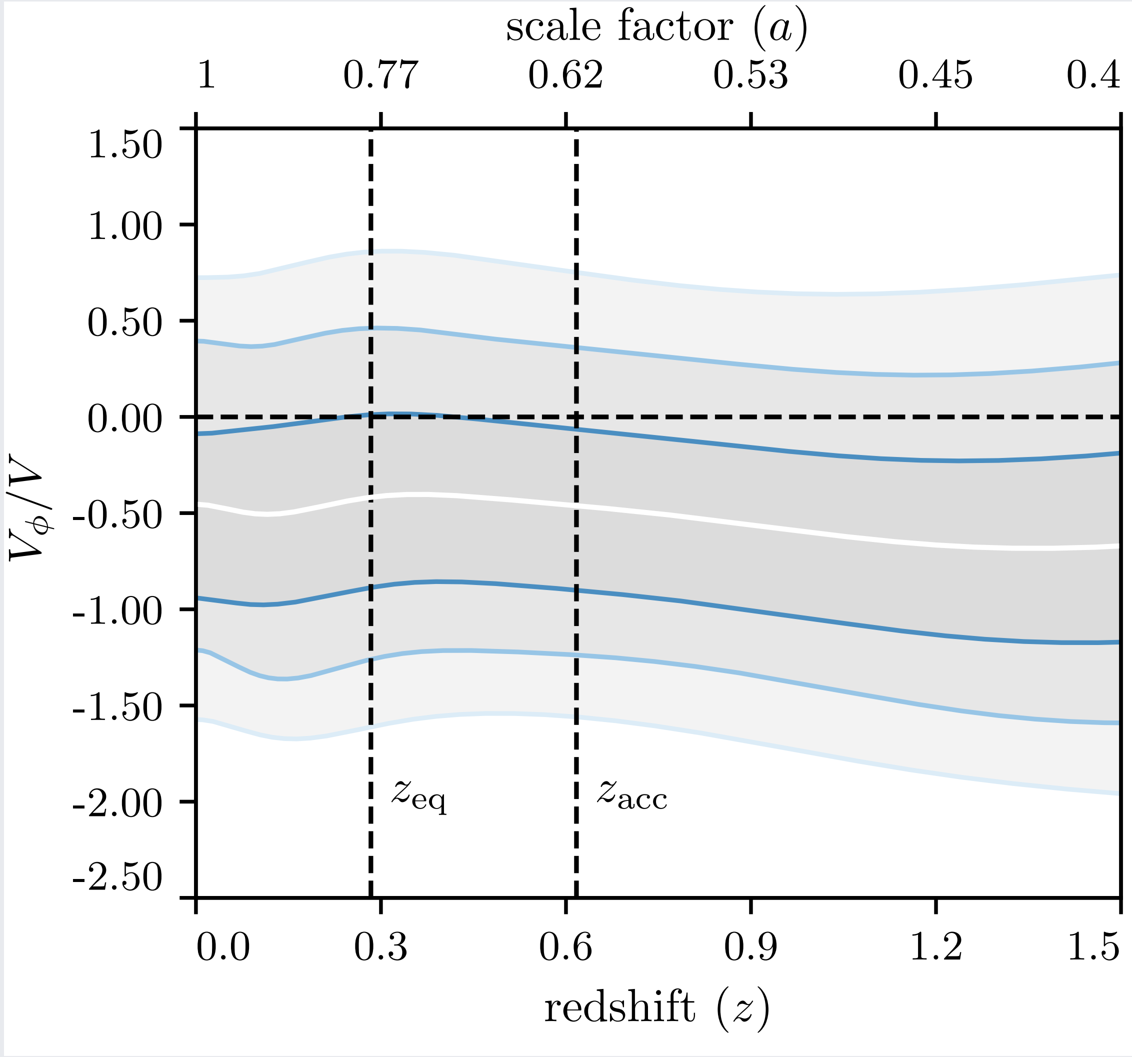
Limited field excursion

$$\Delta\phi < M_P$$

the potential cannot be too flat

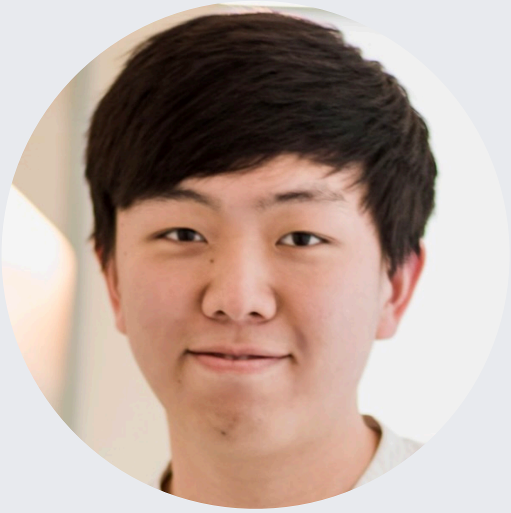
$$\lambda = \frac{|V'|}{V} \sim O(1)$$





(Minsu Park, MR, Bhuvnesh Jain, arXiv:2101.04666, PRD editor suggestion)

Can we do even better than that?



Minsu Park (UPenn)

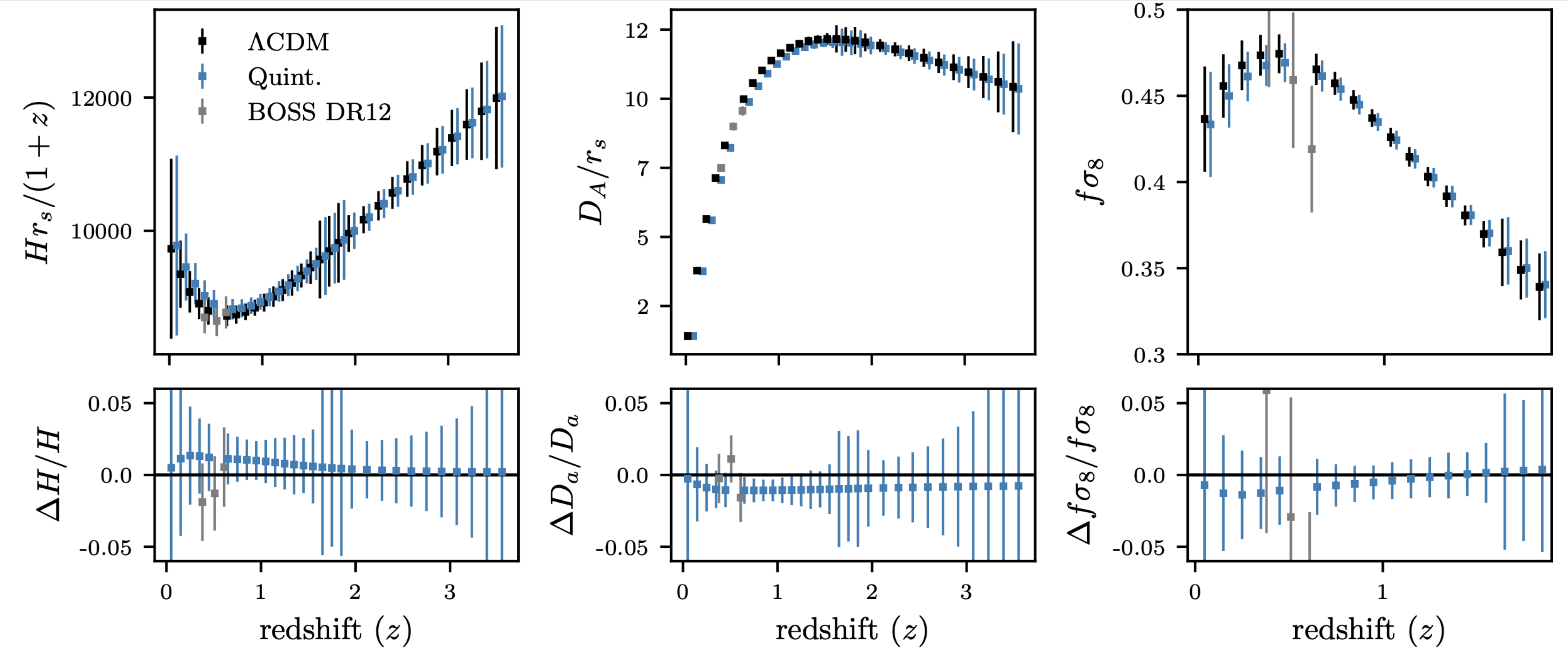
Sam Goldstein (Columbia)

Will future experiments improve significantly these constraints?

(Samuel Goldstein, Minsu Park, MR, Bhuvnesh Jain, and Lado Samushia, arXiv:2207.01612)

Can we do even better than that?

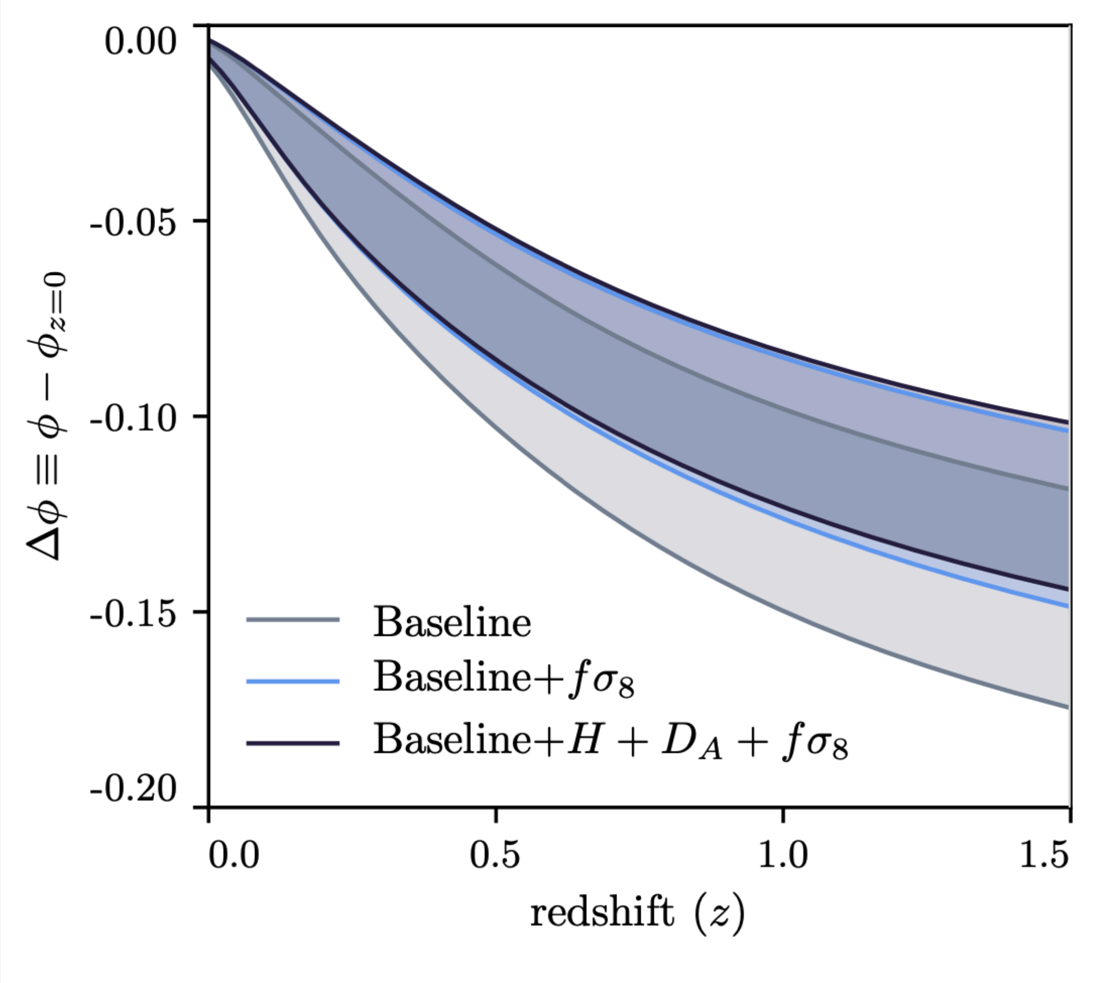
String swampland conjectures
→ derivatives of cosmological data
→ need accurate tomography
→ DESI (Dark Energy Spectroscopic Instrument)



(Samuel Goldstein, Minsu Park, MR, Bhuvnesh Jain, and Lado Samushia, arXiv:2207.01612)

Can we do even better than that?

Roughly 30% improvement on field excursion, not so much on other conjectures (constraining power from CMB arm dominates)



(Samuel Goldstein, Minsu Park, MR, Bhuvnesh Jain, and Lado Samushia, arXiv:2207.01612)

Next? Physical learning

Restrict to (possibly weird) scalar field models

symmetries of the Universe

Large cosmological scales

Gravity and DE models at linear scales:
one extra scalar
at most two derivatives (no Lorentz violations)
universal and minimal coupling to matter (WEP)

(arXiv:1907.03150 for a review)

Physical learning

…a complicated geometry exercise…

Write down all that is allowed by homogeneity and isotropy

Intrinsic curvature $R^{(3)}$

Extrinsic curvature $K_{\mu\nu}$

Lapse δg_{00}

Regular matter

$$S = \int d^4x \sqrt{-g} \left\{ \frac{m_0^2}{2} [1 + \Omega(\tau)] R + \Lambda(\tau) - a^2 c(\tau) \delta g^{00} \right.$$
$$+ \frac{M_2^4(\tau)}{2} (a^2 \delta g^{00})^2 - \frac{\bar{M}_1^3(\tau)}{2} a^2 \delta g^{00} \delta K^\mu_\mu - \frac{\bar{M}_2^2(\tau)}{2} (\delta K^\mu_\mu)^2 - \frac{\bar{M}_3^2(\tau)}{2} \delta K^\mu_\nu \delta K^\nu_\mu$$
$$\left. + \frac{a^2 \hat{M}^2(\tau)}{2} \delta g^{00} \delta R^{(3)} + m_2^2(\tau) (g^{\mu\nu} + n^\mu n^\nu) \partial_\mu (a^2 g^{00}) \partial_\nu (a^2 g^{00}) \right\} + S_m[g_{\mu\nu}]$$

(arXiv:1907.03150 for a review)

Physical learning

Gravity and DE models at linear scales:
one extra scalar
at most two derivatives (no Lorentz violations)
universal and minimal coupling to matter (WEP)

$$\{\Lambda(t), M_P^2(t), \alpha_K(t), \alpha_B(t), \alpha_T(t)\}$$

Cosmological constant

Gravitational constant

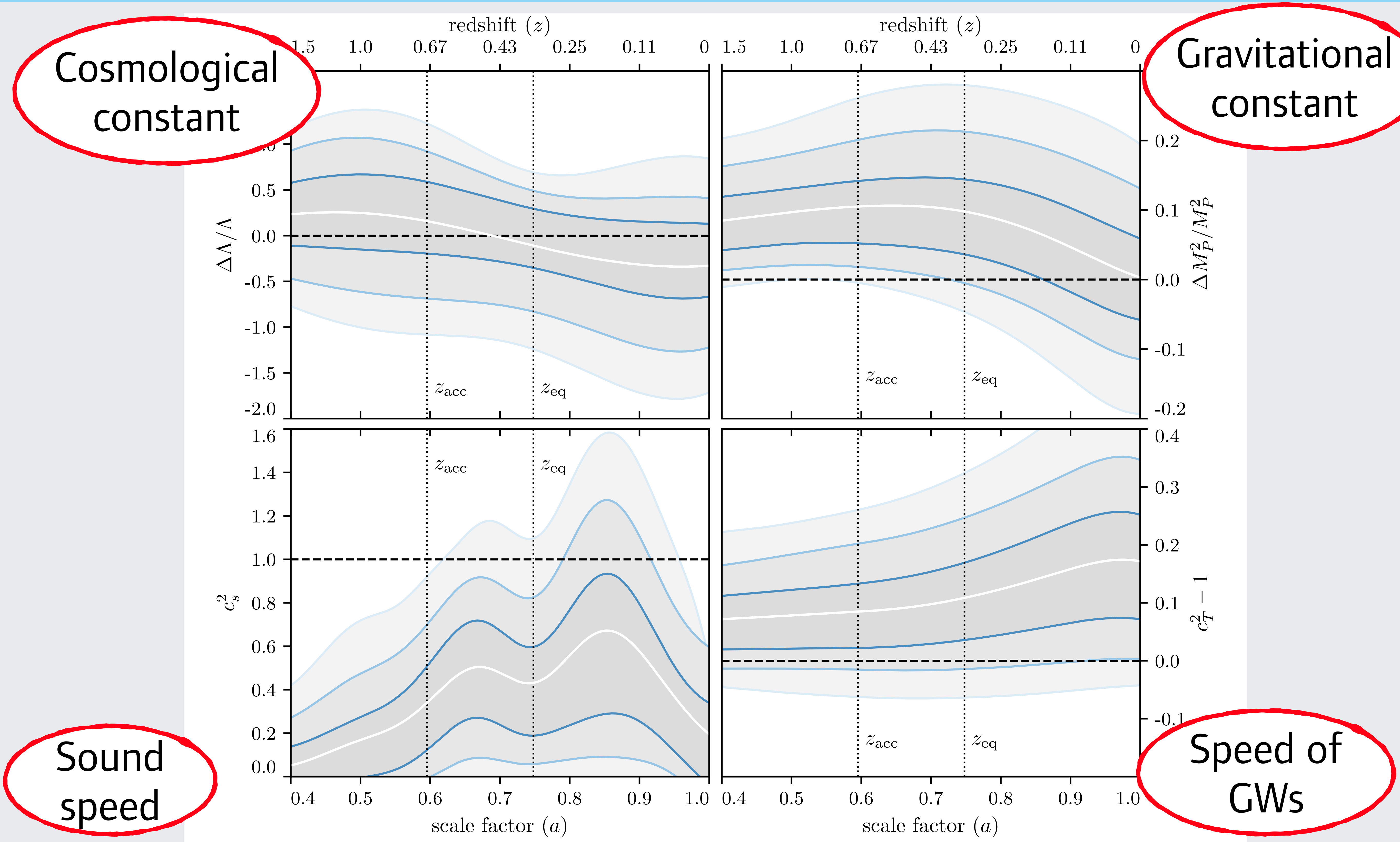
Kinetic energy

Derivative couplings

Speed of GWs

(arXiv:1907.03150 for a review)

Dark Energy and Gravity reconstruction



(MR, arXiv:1902.01366)

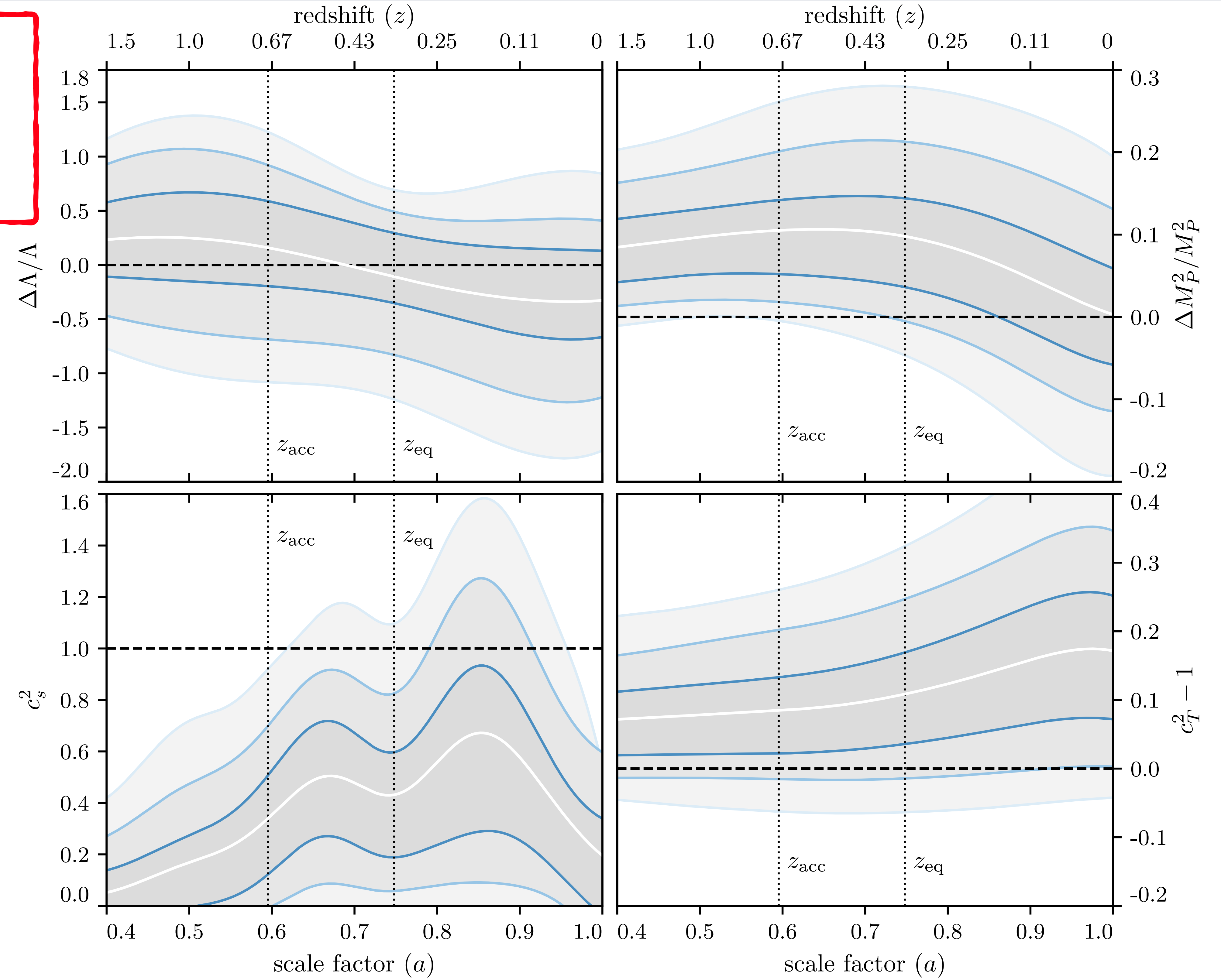
Dark Energy and Gravity reconstruction

Symmetries and data power

$$\left|\frac{\Delta\Lambda}{\Lambda}\right| \lesssim 1.5$$

$$\left|\frac{\Delta M_P}{M_P}\right| \lesssim 0.3$$

$$\left|\frac{\Delta c_T}{c_T}\right| \lesssim 0.4$$



(MR, arXiv:1902.01366)

Outlook

* Swampland conjectures are constrained as a function of time, but unlikely to improve by orders of magnitude in the next years.

* Other quantities are and can be studied. Couplings to matter? Standard kinetic terms?

* Cosmology is in the regime where we can test the theoretical statements you make! (and we are eager to…)

* No matter how general/generic, we have matching data analysis tech and data power