~~The axion landscape~~

ultra-ultra-light Axions

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March 23 2015
ultra-light Frontier Workshop

*supported by the New Frontiers Program by the Austrian Academy of Sciences

Plan

Dark Axions

1. An "Axiverse" solution to the cosmological "why-now"* problem

M. Kamionkowski, JP, D.Walker PRL 2014

2. A more quantitative look at the scenario

R. Emami, D. Grin, M. Kamionkowski, JP, A. Raccanelli, *in prep.*

*why did the Universe cool ~30 orders of magnitude in temperature from M_P, before entering an accelerated state

Strong CP problem and QCD axions

CP violating term is introduced 1) by chiral phase rotations to make the quark mass matrix real and 2) through QCD itself

$$S_\Theta = \frac{\bar{\Theta}}{32\pi^2}\int d^4x\, G\widetilde{G} \qquad \bar{\Theta} = \Theta_{\rm QCD} + \arg\det M_{\rm quark}$$

$$\downarrow$$

$\mathbf{E}\cdot\mathbf{B}$ polar times axial vector is CP odd

=> neutron EDM is generated $|d_n| \approx |\bar{\Theta}| \times 10^{-16}\, e$ cm

observational limit $|\bar{\Theta}| \lesssim 10^{-10}$

Strong CP problem, QCD axions

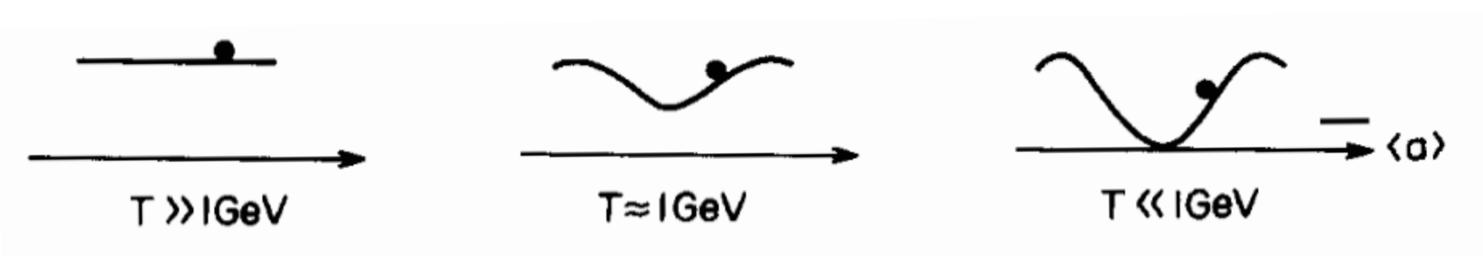
Solution: global, chiral U(1) symmetry, spontaneously broken at f_a
with Goldstone mode $a(x)$ with shift-symmetry $a(x) \to a(x) + const$

$$\int d^4x\, [\bar{\Theta} + a(x)] G\widetilde{G} \quad \text{minimized by} \quad \langle a \rangle = -\bar{\Theta}$$

=> CP violation dynamically turned off (no neutron EDM)

=> expansion around the minimum is the axion
(amounts to promoting $\bar{\Theta}$ to a dynamic variable.)

QCD provides potential for the axion for $T \lesssim \Lambda_{\rm QCD}$



$$V = \Lambda^4_{\rm QCD}\left[1 - \cos\frac{a}{f_a}\right]$$

The many axions of string theory

Topological richness of string compactifications may yield a multitude of axion-like particles—they are the low-energy messengers of these highest energy scales.

KK zero modes of antisymmetric tensor fields; they come in plentitude! $O(100) - O(10^5)$ fields

e.g. Douglas, Kachru 2007

=> Notion of the "Axiverse"

Srvcek, Witten 2006;
Arvanitaki et al 2009,
Cicoli et al 2012, …

The many axions of string theory

The KK zero modes are fundamentally massless (gauge invariance of higher dimensional antisymmetric tensor fields)

The tensor fields have Chern–Simons couplings, necessary for Green–Schwarz mechanism of anomaly cancellation => axion-like couplings to gauge fields => provides periodic potential Witten 1984

NOTE: explicit constructions yield high-scale axions

$$f_a = \alpha M_P, \qquad 10^{-3} \lesssim \alpha \lesssim 1$$

see e.g. Svrcek, Witten 2006
and references therein

Parameterization of the Axiverse

$$\mathcal{L}_a = -\frac{f_a^2}{2}(\partial_\mu \theta_a)^2 - \Lambda_a^4 U(\theta_a), \quad U(\theta) = 1 - \cos\theta, \qquad \theta_a \equiv \phi_a / f_a$$

$$\Lambda_a^4 = \mu^4 e^{-S_a}, \qquad f_a = \alpha M_P,$$

see e.g. also Arvanitaki et al 2009

$$m_a = \frac{\Lambda_a^2}{f_a} \simeq H_0 \frac{\mu_{12}^2}{\alpha_{0.1}} e^{-(\beta a - 223.1)/2} \qquad a = 1, 2, 3, \ldots \qquad S_a = \beta a$$

Our assumptions:

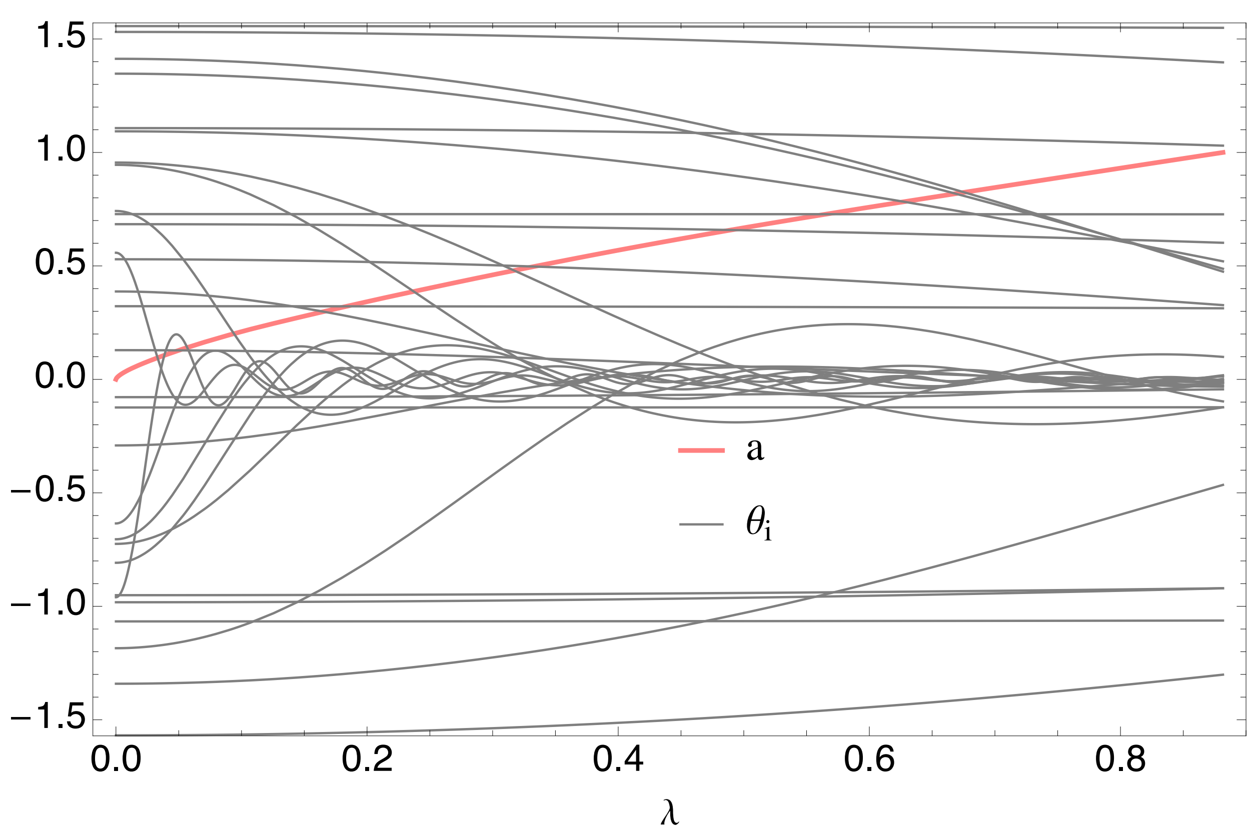
High-scale f_a; axion-mass scanned (uniformly in log m)

Initial angle uniformly distributed $\theta_a \in [-\pi, \pi]$

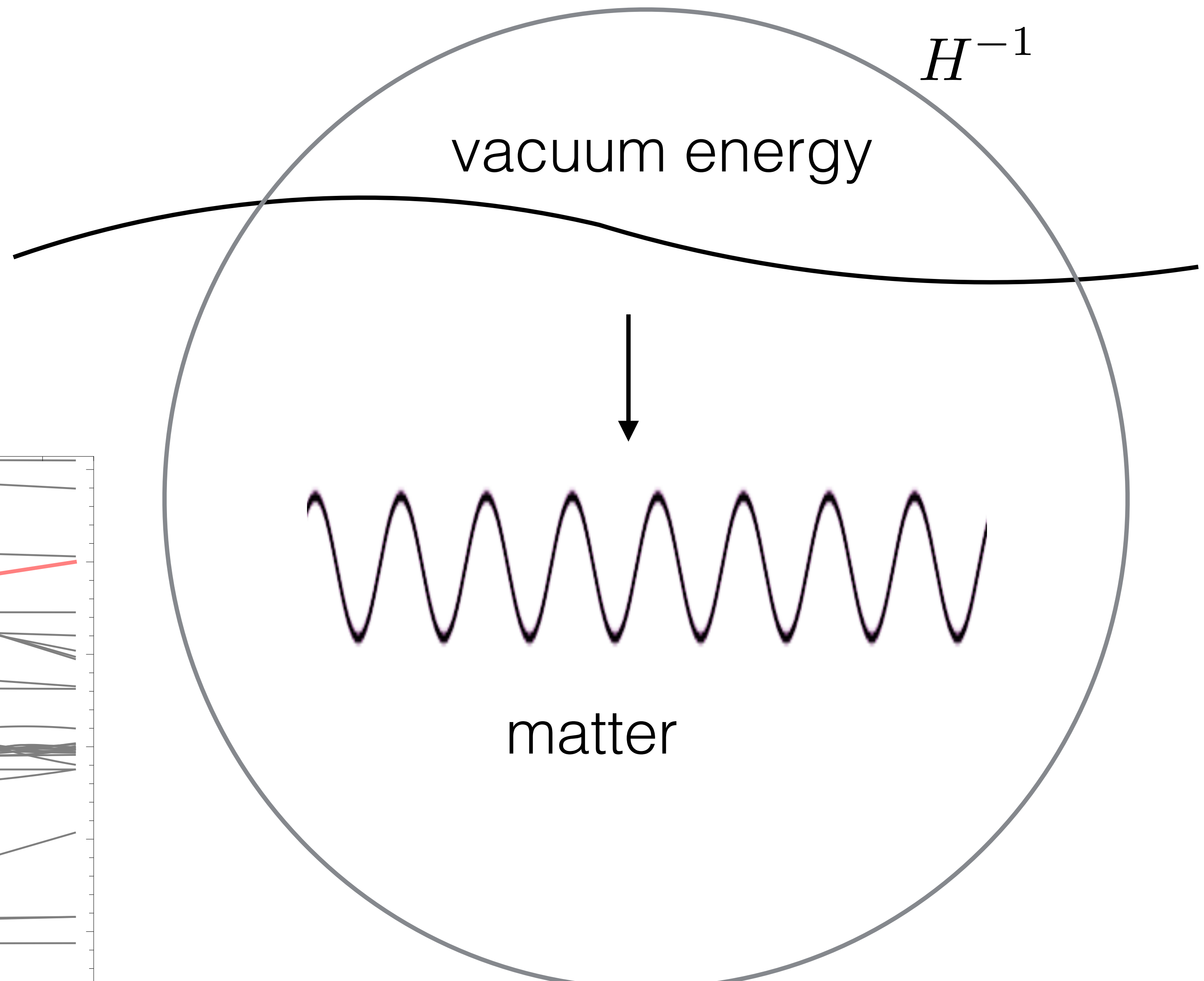
Evolution of axions

$$\ddot{\theta}_a + 3H\dot{\theta}_a + m_a^2 \sin(\theta_a) = 0$$

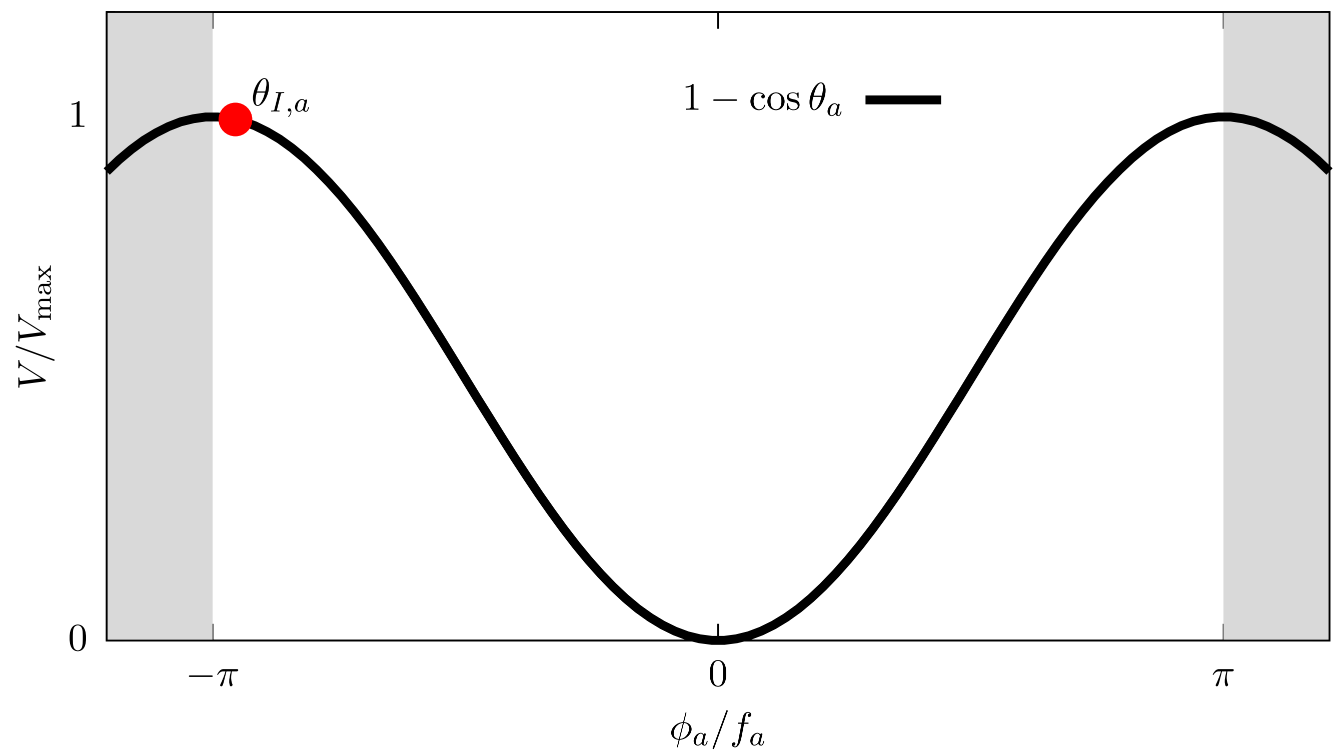
Once axions enter the horizon, $m_a \sim H$, they become dynamical



cosmic time in units of $1/H_0$



A simple observation



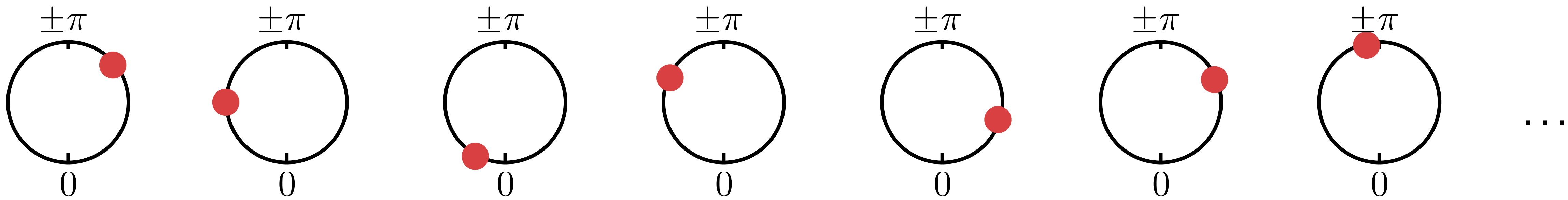
If the field is close enough to the maximum, it slow rolls

$$\epsilon = (M_P^2/2)(V'/V)^2 < 1$$

the equation of state becomes negative $w_a = p_a/\rho_a < -1/3$

and field may come to dominate the energy density and drive a period of accelerated expansion.

A simple observation



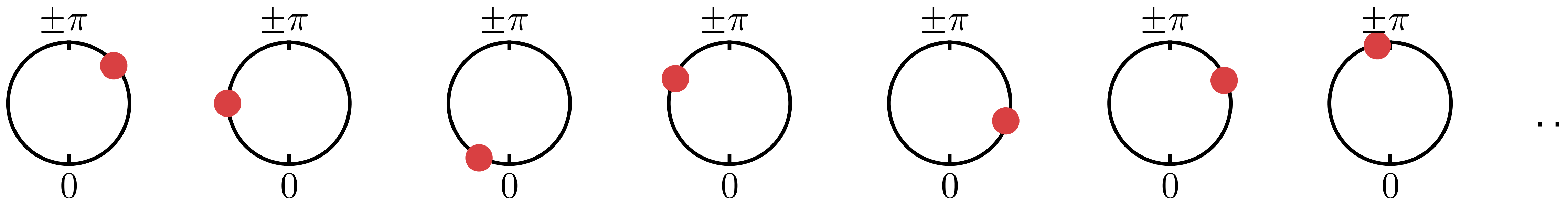
Slow roll for $\pi > |\theta_{a,I}| \gtrsim \pi - 2\sqrt{2} f_a/M_p = \pi - 2\sqrt{2}\alpha$

The probability for one field to slow roll is $\sim 2\sqrt{2}\alpha/\pi \simeq \alpha$, and the probability that the a-th field drives accelerated expansion is

$$P(a) = \alpha\,(1-\alpha)^{a-1}$$

There is a slowly decreasing probability per logarithmic interval in cosmic time or scale factor, or redshift, or cosmic temperature for the Universe to become dark-energy dominated!

Late time acceleration



The axion field that describes cosmic acceleration in *our* Universe has

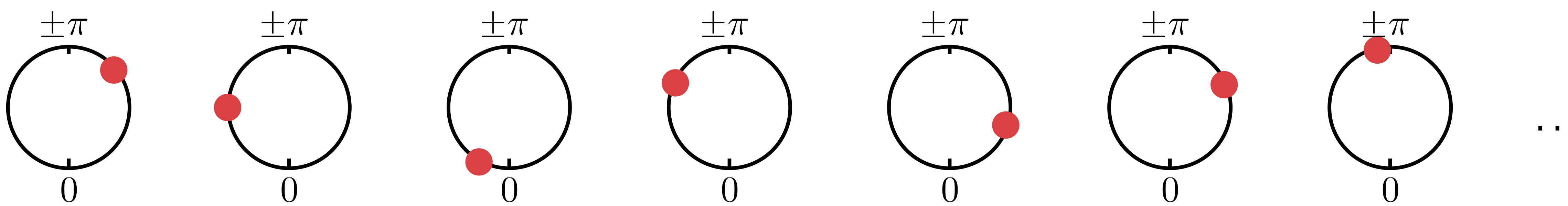
$$2m_a^2 f_a^2 \simeq \Omega_\Lambda \rho_c \simeq 0.7\,(3\,H_0^2 M_P^2)$$

In a simple toy model $S_a = \beta a$, $f_a = \alpha M_P$, with $\alpha = 0.1$, $\beta = 9$, and $\mu_{12} = 1$, this is met for $a = 24$ and

$$m_a = 2H(R_a)$$

is met for at redshift $z \simeq 2$. Probability is $O(0.01) - O(0.001)$

Late time acceleration



$m_{18} \sim 10^{12} H_0$ $m_{20} \sim 10^{8} H_0$ $m_{22} \sim 10^{4} H_0$ $m_{24} \sim H_0$

1. The fact that the axion mass is scanned, makes it little surprising that there is a field with m ~ H_0;

2. The high-scale f_a as encountered in string realizations ensures that the field indeed comes to dominate the energy

3. The probability for slow roll for the critical field is not too small

=> “Axiverse-solution” to the “why-now” problem.

Of course, all this was cursory,

but asking the right questions, will allow to derive PDFs for their answers in concrete examples.

Most immediate issue: high scale axion models suffer severe constraints from their contribution to the matter density

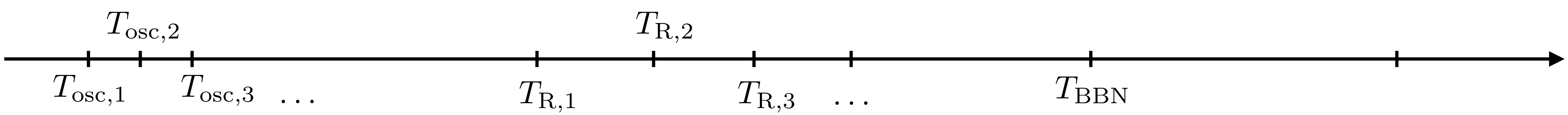
Ways out while maintaining solution to the “why now” problem?

- A low inflationary scale would ameliorate the most stringent matter limits
- Heavy axions that enter horizon early (those are the most dangerous ones) could decay
- Can there be some dynamical selection of field values during inflation?
- Are there “better” potentials than 1-cos(x)?

Axion decays

axions enter horizon,
redshift like matter

visible energy injections
strongly constrained



thermal bath (re)created
by axion decays, if visible

$$T_{\mathrm{R,a}} \sim \sqrt{\Gamma_a M_P} \qquad Y_a^{(k)} = Y_a \prod_{i=1}^{k} \frac{1}{\Delta_i} \qquad \Delta_a = \frac{m_a Y_a}{T_{R,a}} \prod_{i=1}^{a-1} \frac{1}{\Delta_i}$$

If only a few of the heaviest states decay before BBN,dilutes all other axions that have entered before BBN

$$\left.\frac{\rho_{\mathrm{m,axions}}}{\rho_R}\right|_{T_{R,a_{\mathrm{out}}-1}} \sim \sum_{a=a_{\mathrm{out}}}^{a_{\mathrm{in}}} \frac{m_a}{m_{a_{\mathrm{out}}-1}} \frac{Y_a}{Y_{a_{\mathrm{out}}-1}} \simeq \frac{U(\theta_{I,a_{\mathrm{out}}})}{U(\theta_{I,a_{\mathrm{out}}-1})} e^{-\beta/4}$$

abundance after reheating
independent of Γ

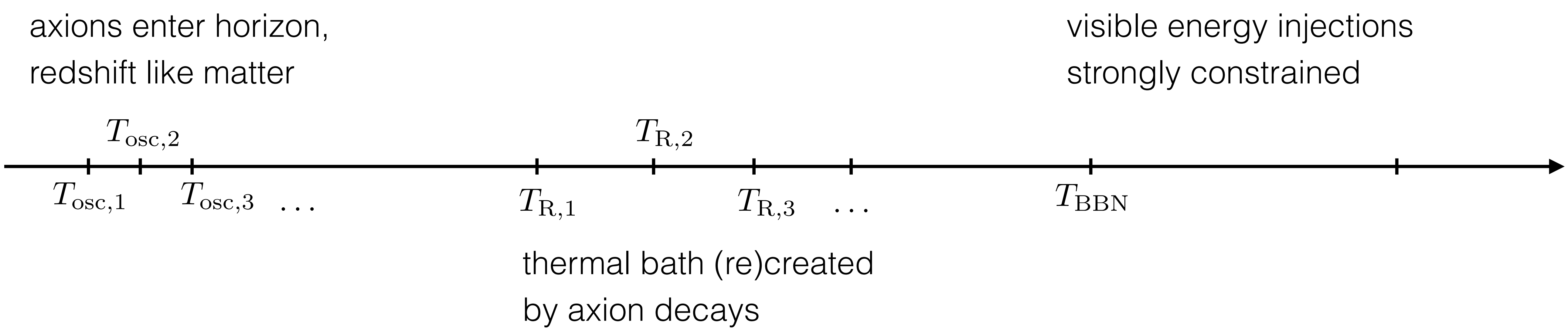
$$\left.\frac{\rho_{\mathrm{m,axions}}}{\rho_R}\right|_{T_{R,a_{\mathrm{out}}}} \sim \frac{U(\theta_{I,a_{\mathrm{out}}})}{U(\theta_{I,a_{\mathrm{out}}-1})} \begin{cases} e^{+\beta/2} & (\Gamma_a \sim m_a^3/f_a^2 m) \\ 1 & (\Gamma_a \sim m_a m_\psi^2/f_a^2). \end{cases}$$

abundance prior to next decay

Residual decays inject an energy/baryon $\left.\dfrac{m_a Y_a^{(a-1)} s}{n_B}\right|_{T_{R,a}} \simeq \dfrac{m_a Y_a^{(a-1)}}{\eta_B}$

(unpublished)

Axion decays



Tuning of ~ one in 10^5 is required, to evade constraints if energy injection/ baryon is visible, or, likewise, to maintain z of matter-radiation equality

Such scenario leaves open many questions: concrete realization of axion-matter couplings, origin of baryon abundance, …

What is the probability that there is no axion field entering between $[H_{\rm eq}, H_{\rm BBN}]$?

$$\mathrm{Pr} = 1 - \sum_{k=0}^{m} \frac{(kx-\mu)^k e^{-kx}}{k!}\left(1 + \frac{k}{\mu - kx}\right) \sim 10^{-4}$$

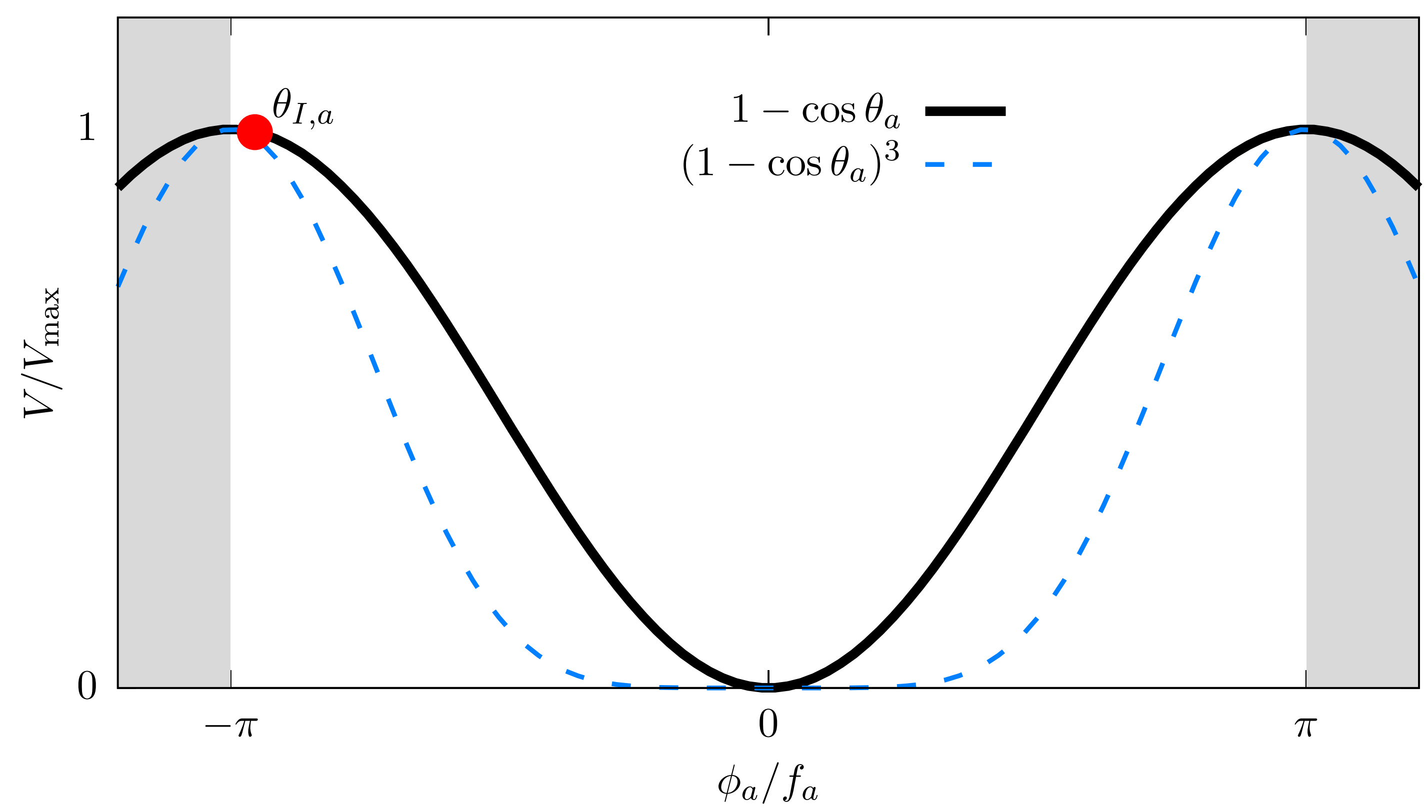
A modified potential

Oscillation around a minimum $V(\phi) \simeq \phi^6$

Matter contribution with e.o.s. $w = 1/2$

Energy density redshifts faster than radiation: $\rho_\phi \sim R^{-9/2}$

Field has no mass, but amplitude-dep. oscillation frequency that decreases slower than H
=> field keeps oscillating



No overclosure or isocurvature constraints for the modified potential

Price to pay: Stricter requirement on initial displacement for the field to slow-roll

Numerical Study

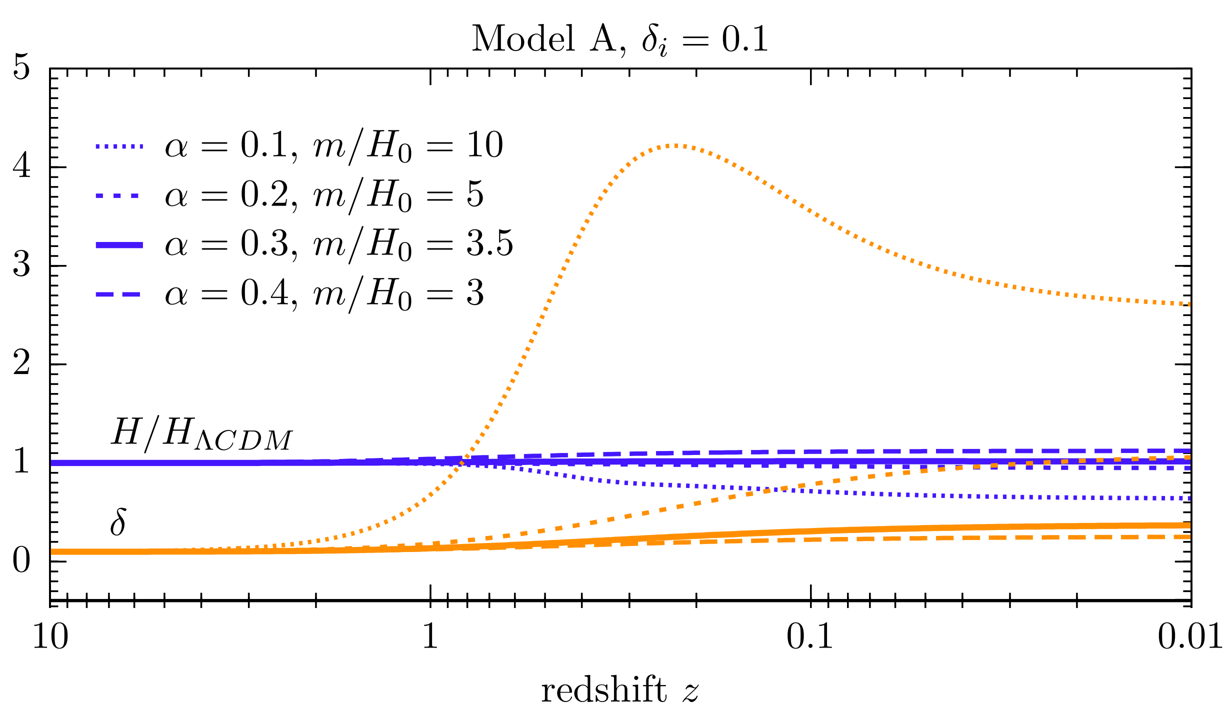
R. Emami, D. Grin, M. Kamionkowski, JP, A. Raccanelli, *in preparation*

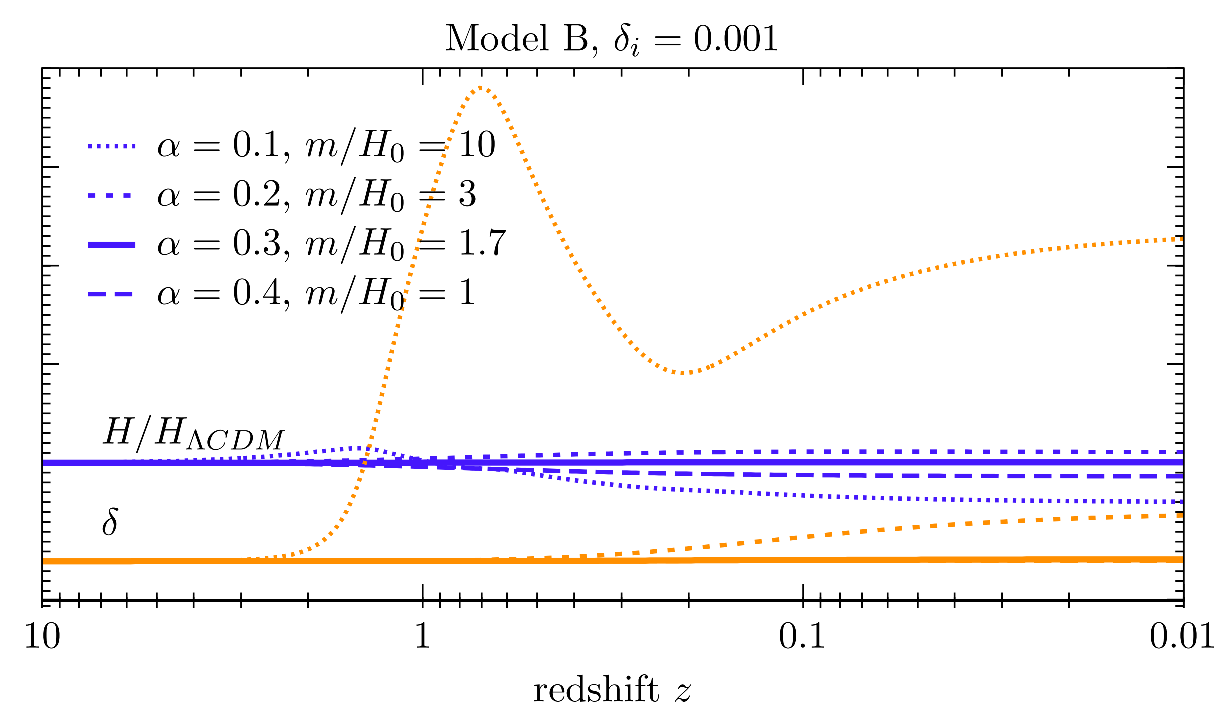
Model A

$$V(\phi) = \Lambda^4 \left[1 - \cos(\phi/f)\right]$$

Model B

$$V(\phi) = \Lambda^4 \left[1 - \cos(\phi/f)\right]^3$$





Picking a prospective axion field, we study late-time behavior by varying axion-mass, PQ scale f_a, and initial displacement from π, δ.

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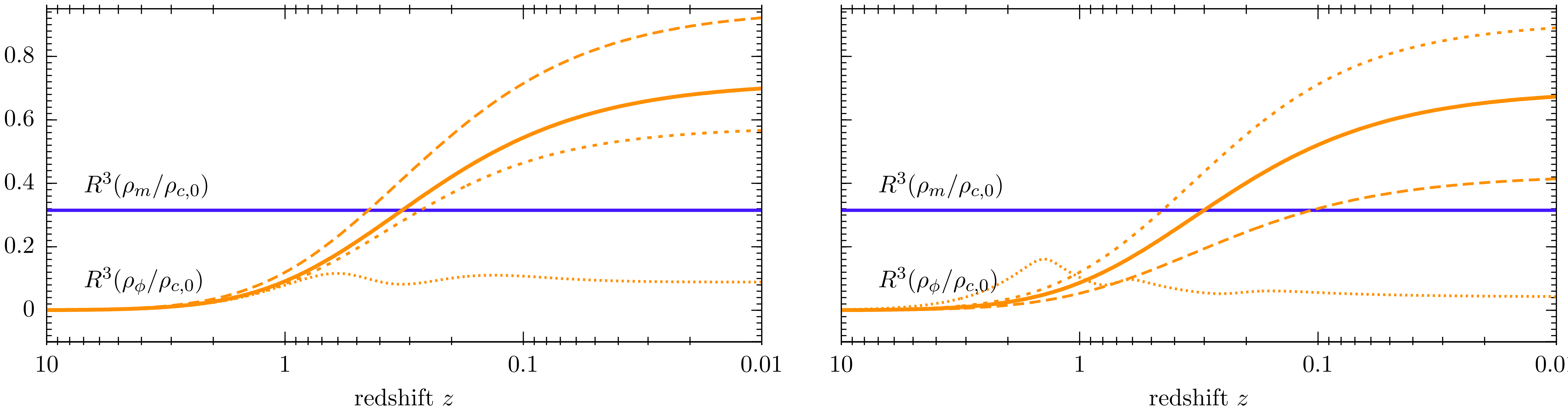

Prospective solution requires the field to start dominating the energy budget at z ~ 1; “matter-Λ equality”

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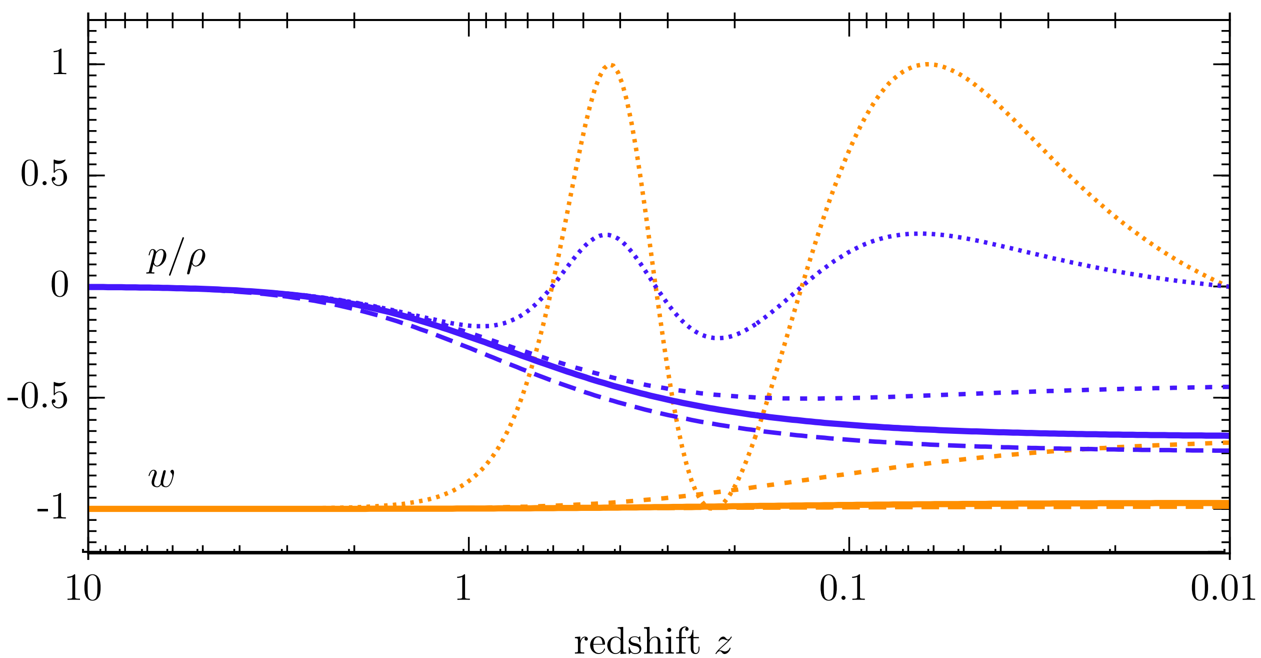

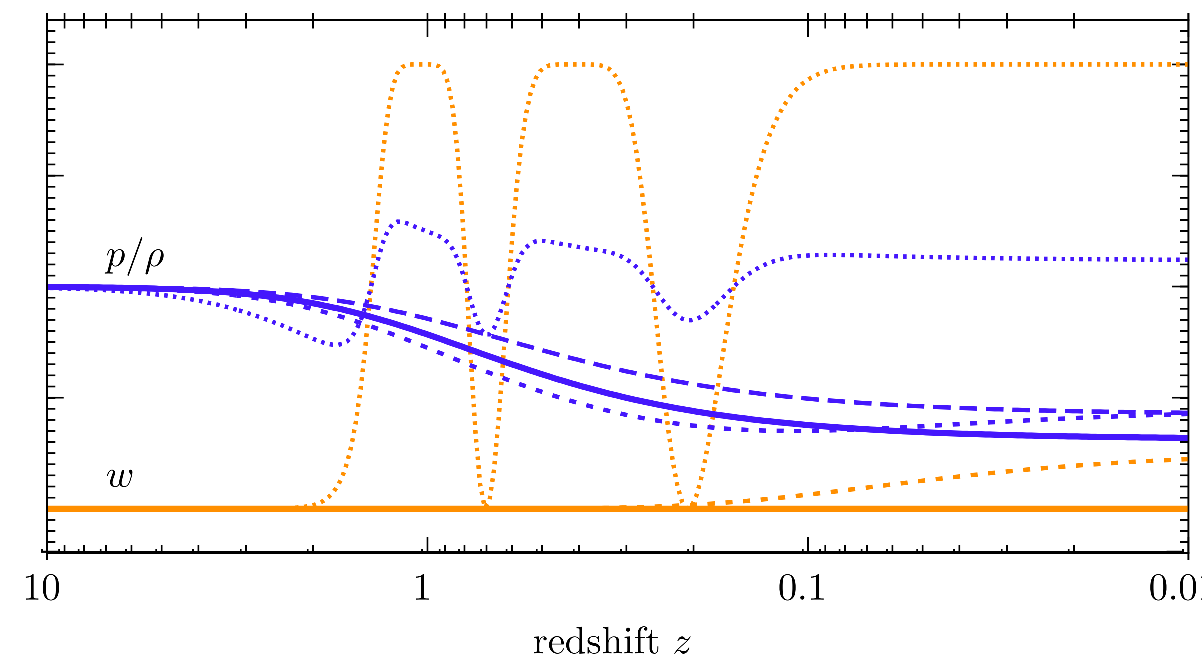

Equation of state of the axion $w = p_a/\rho_a$ informs us on the matter-vs.-dark energy character of the field (cosmological constant w = -1)

Numerical Study

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=> Prospective parameter space for late time accelerated expansion:

$$-1 < w < -0.7 \quad \text{and} \quad 0.7 < \Omega_\phi < 0.6$$

	Model A		Model B	
α	$\delta_i^{\max}$	m/H_0	$\delta_i^{\max}$	m/H_0
0.1	3.5×10^{-3}	9.5–10.5	5×10^{-6}	4.7–5.3
0.2	0.12	4.7–5.5	5×10^{-3}	2.38–2.68
0.3	0.4	3.1–3.9	0.04	1.57–1.83
0.4	0.65	2.4–3.2	0.12	1.20–1.30

δ_i is a direct measure of the probability to obtain a late-time accelerated solution [up to O(1)-factor]

Numerical Study

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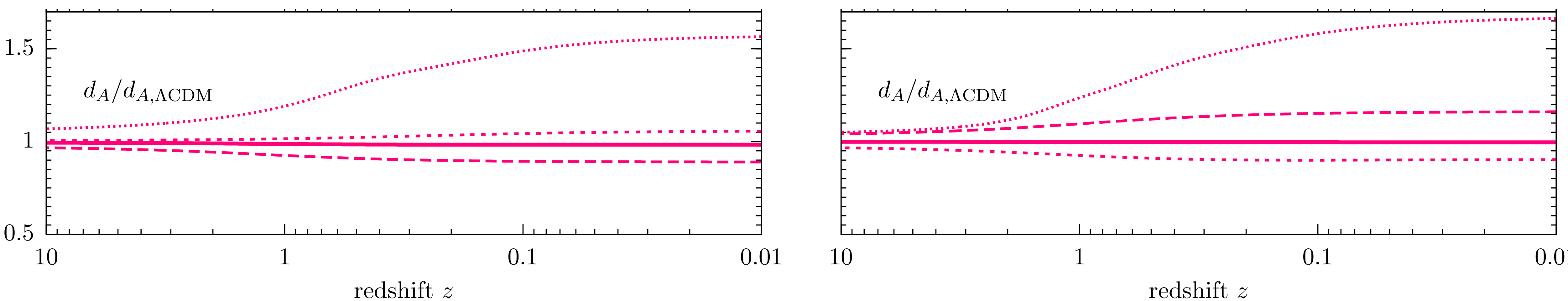
Potential observables for the prospective parameters, e.g.



Angular diameter distance $d_A(z) = (1+z)^{-1} \int_{t(z)}^{t_0} \frac{dt}{R}$

Numerical Study - Predictions

Model A

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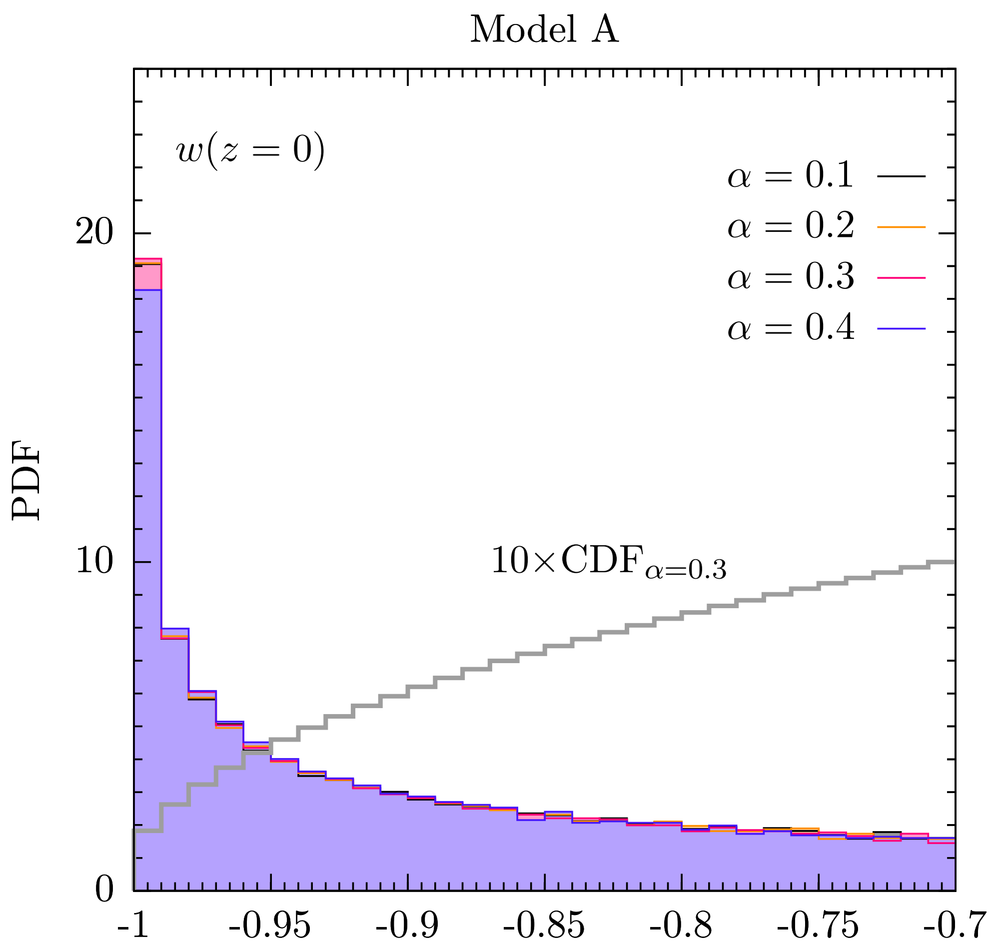

Model B

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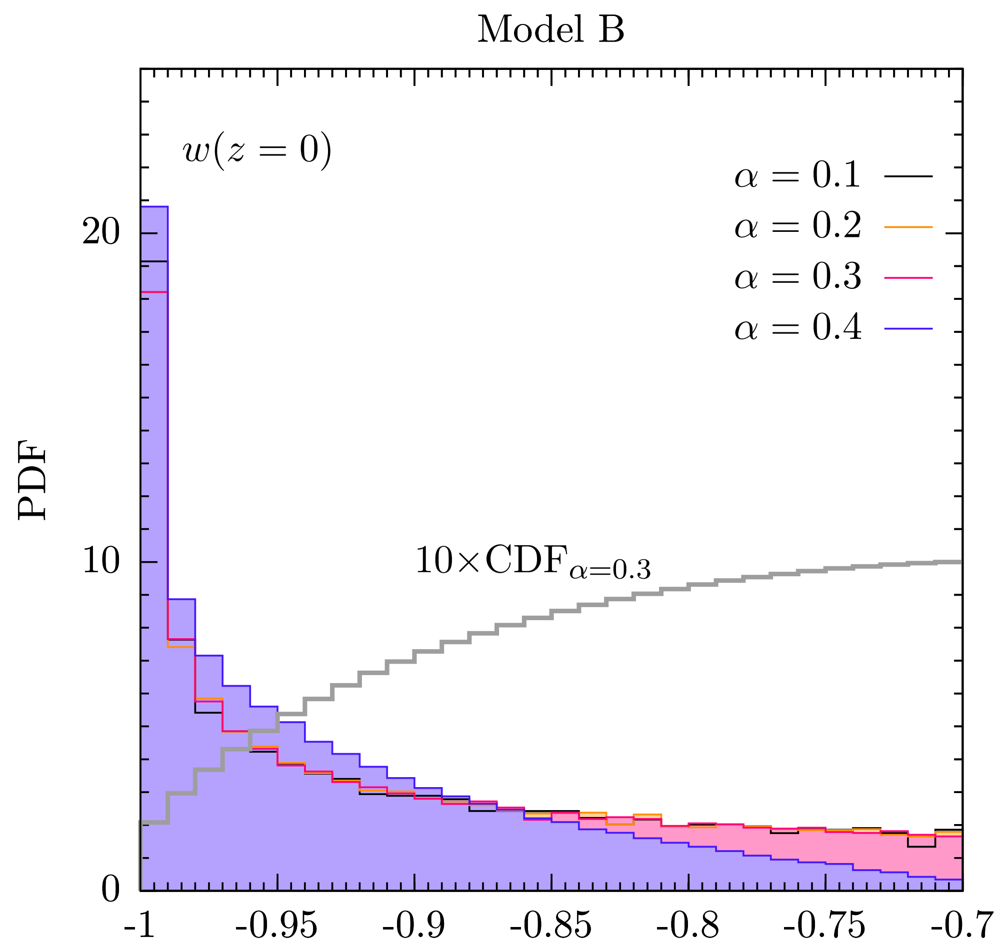

If observations on w continue to converge to an ever smaller range around w = −1, the string-axiverse scenario becomes less attractive in the sense that the scenario does not single itself out with a prediction w > -1

Numerical Study - Predictions

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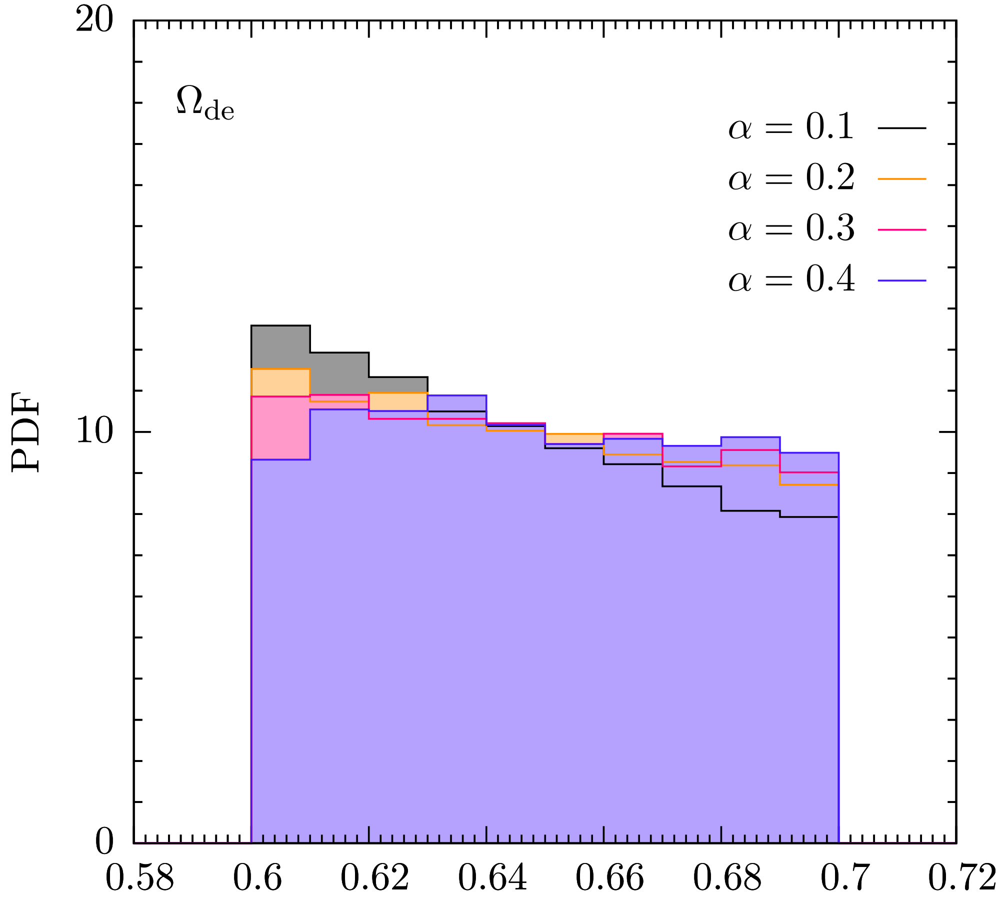

Model B

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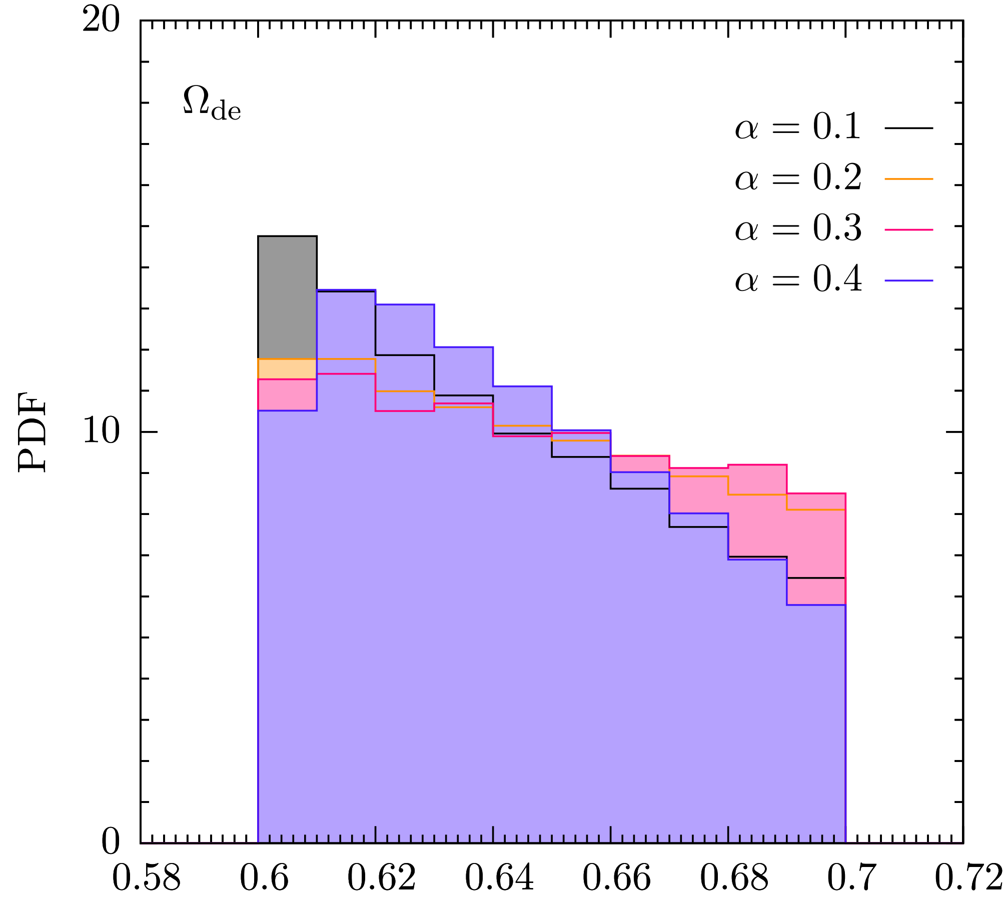

For a given α, all dark energy candidate solutions have approximately the same mass m that is small enough that little evolution of the field has yet occurred, but big enough to yield dark energy dominance => $\rho_\phi \propto (2 - \delta_i^2/2) m^2 \alpha^2$ => PDF of ρ_ϕ is logarithmic for fixed α, m

Numerical Study - Predictions

Model A

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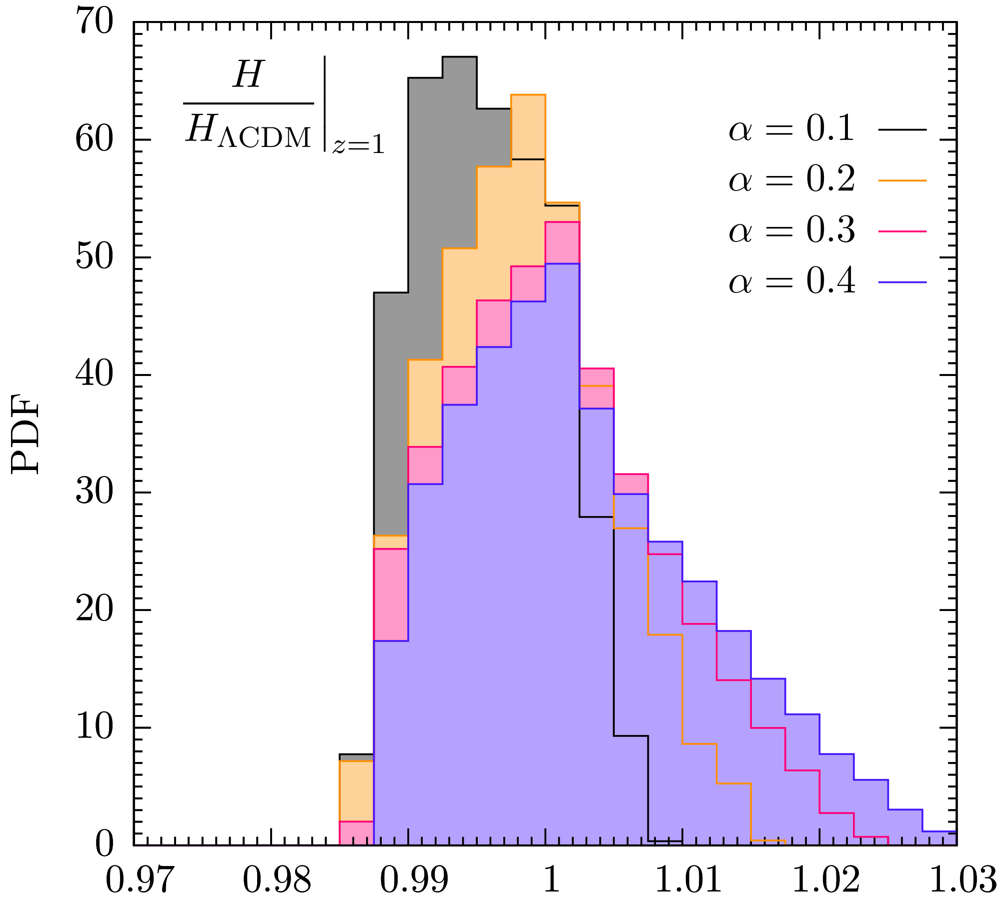

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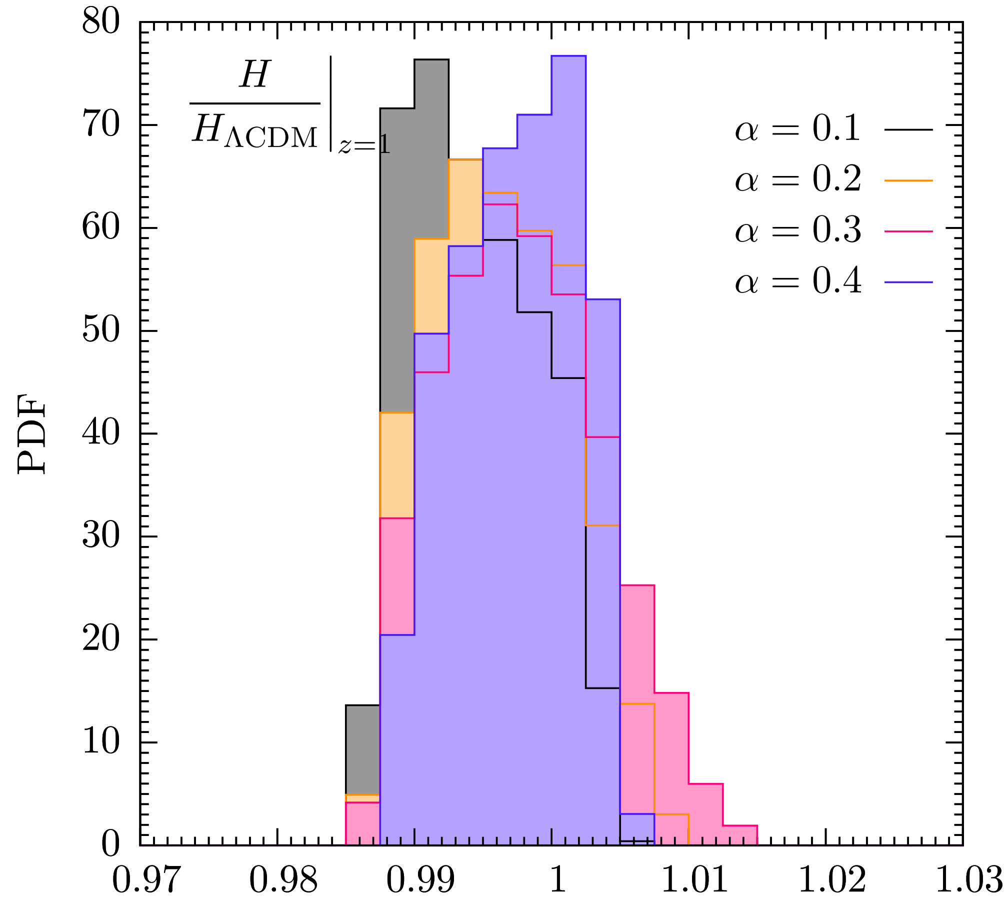

Observables: PDFs inform us about the required observational accuracy of DE surveys; here 2% deviation from LCDM at most

Numerical Study - Predictions

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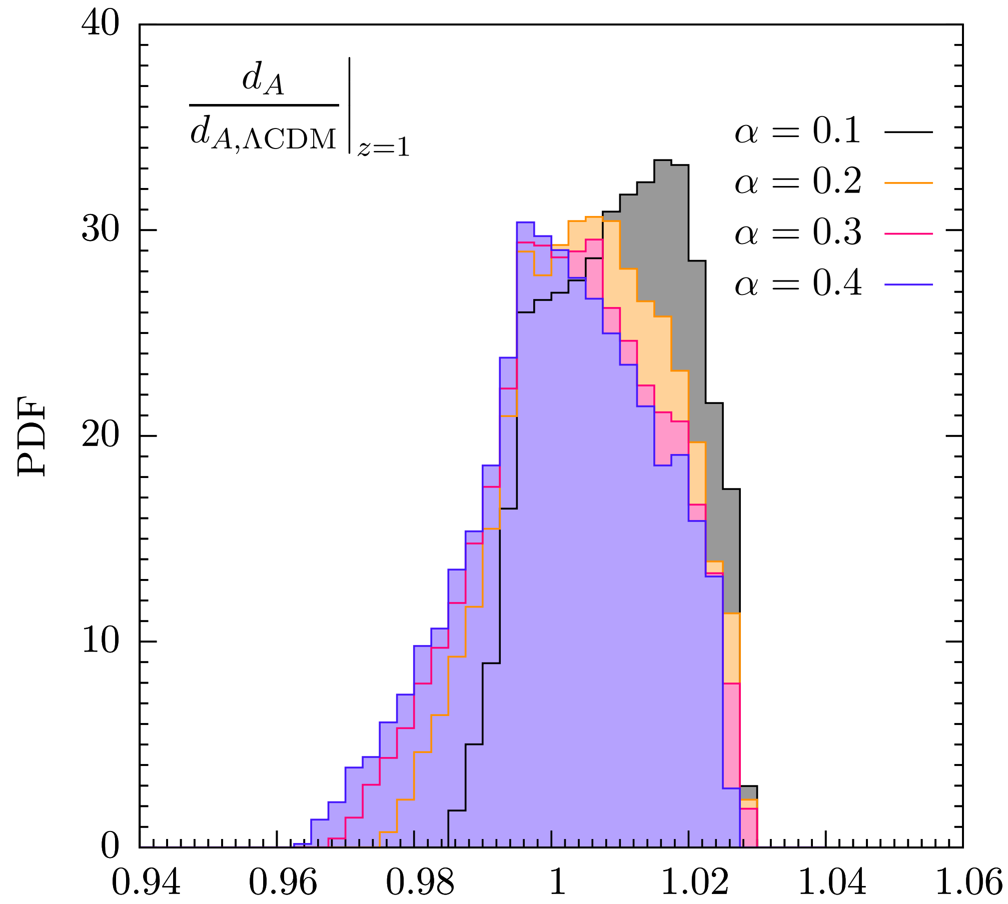

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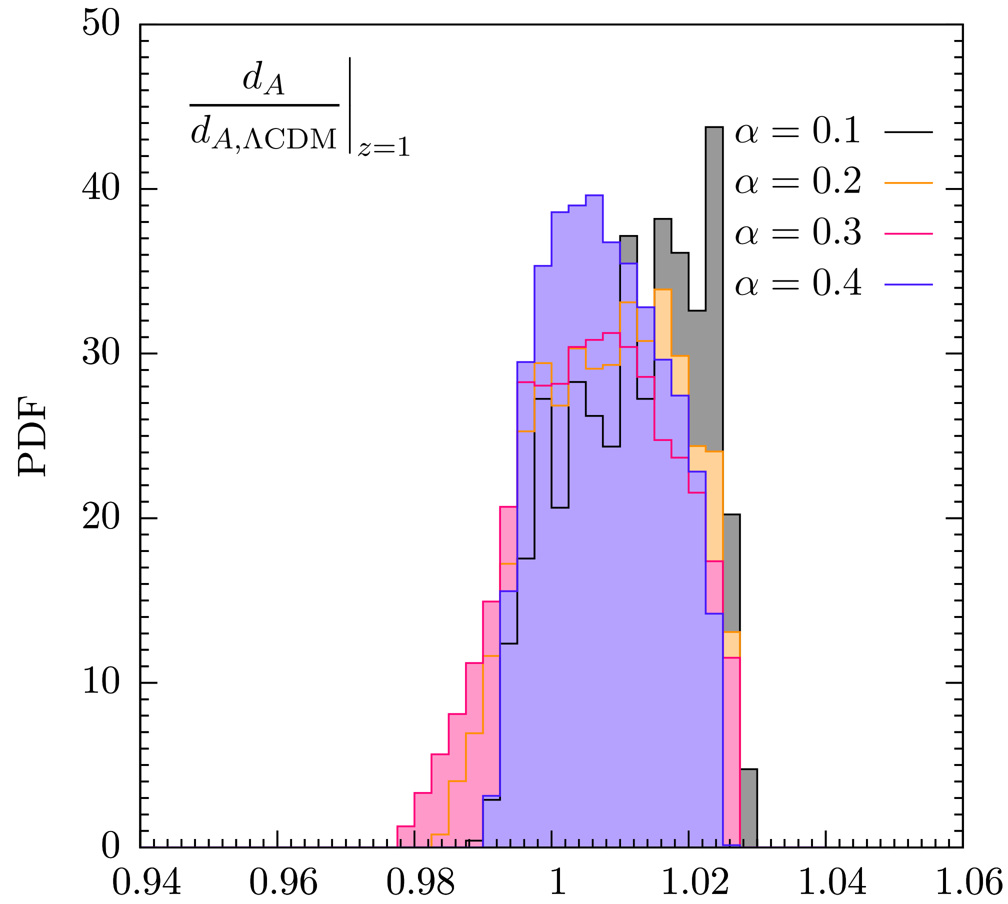

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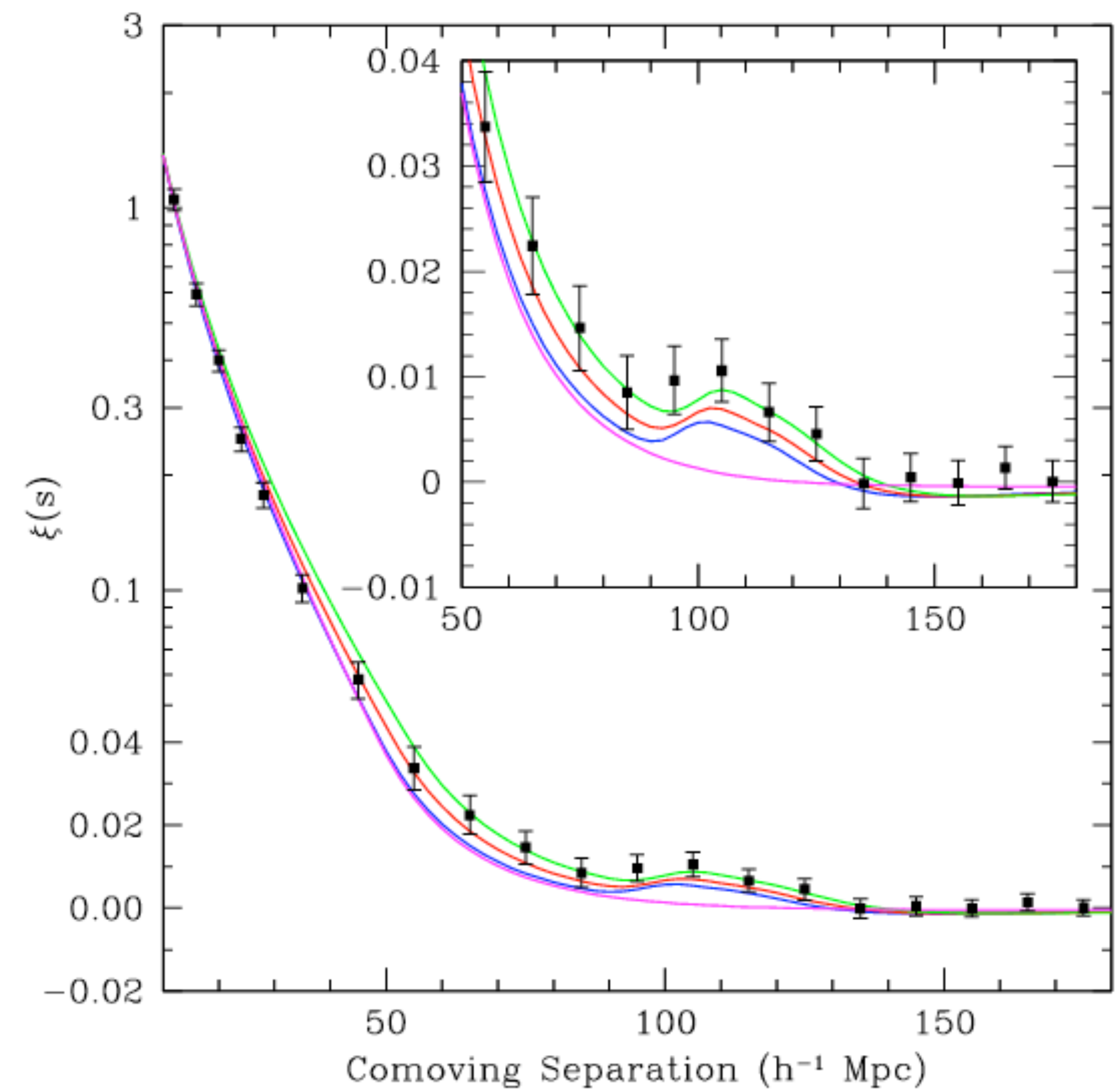
BAO Standard Ruler

Initial overdensity=overpressure (in DM & gas) launches a sound wave (travels at ~60% of speed of light)

When pressure-providing photons decouple, sound speed plummets and wave stalls at $r_s \sim 150\,\mathrm{Mpc}$

Overdensity in shell (gas) and in the original center (DM) both seed the formation of galaxies; their separation: 150 Mpc



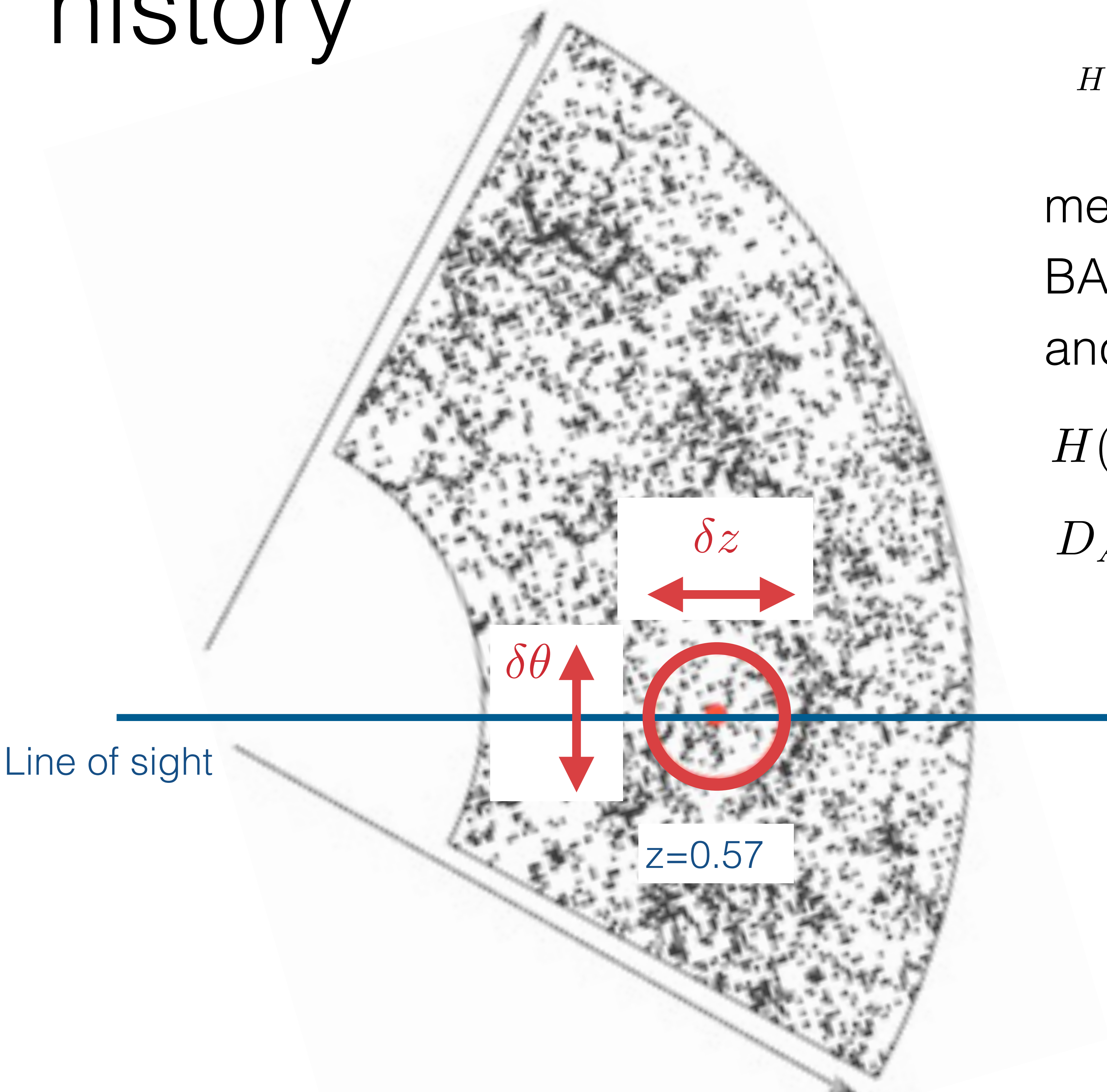
=> ~1% bump in the correlation function $\xi(s)$

Eisenstein et al 2005

Measuring the expansion history

$$D_A(z) = (1+z)^{-1} \int_{t(z)}^{t_0} \frac{dt}{R}$$

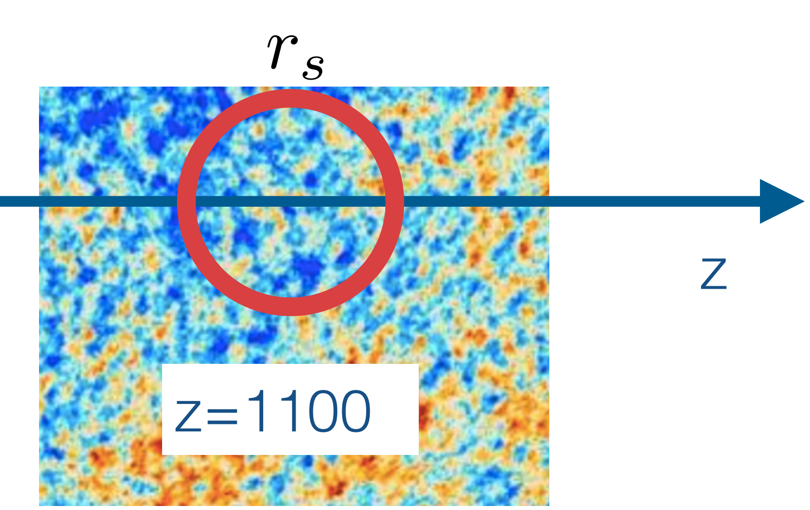
$$H^2(z) \simeq H_0^2 \left[\Omega_m (1+_z)^3 + \Omega_\phi^{3(1+w(z))} \right]$$



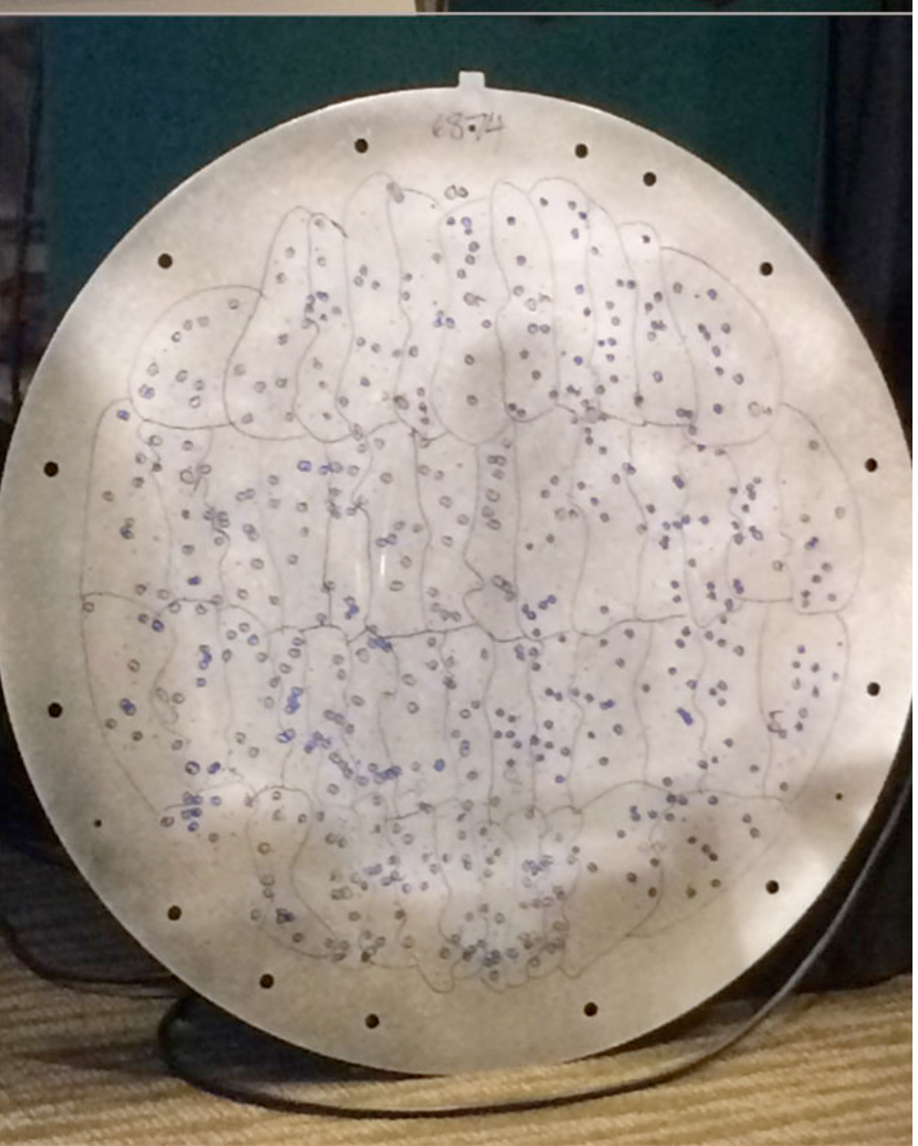
measurement of anisotropic BAO allows extraction of H and D_A

$$H(z)/c = \delta z / r_s$$

$$D_A(z) = r_s / \delta\theta$$



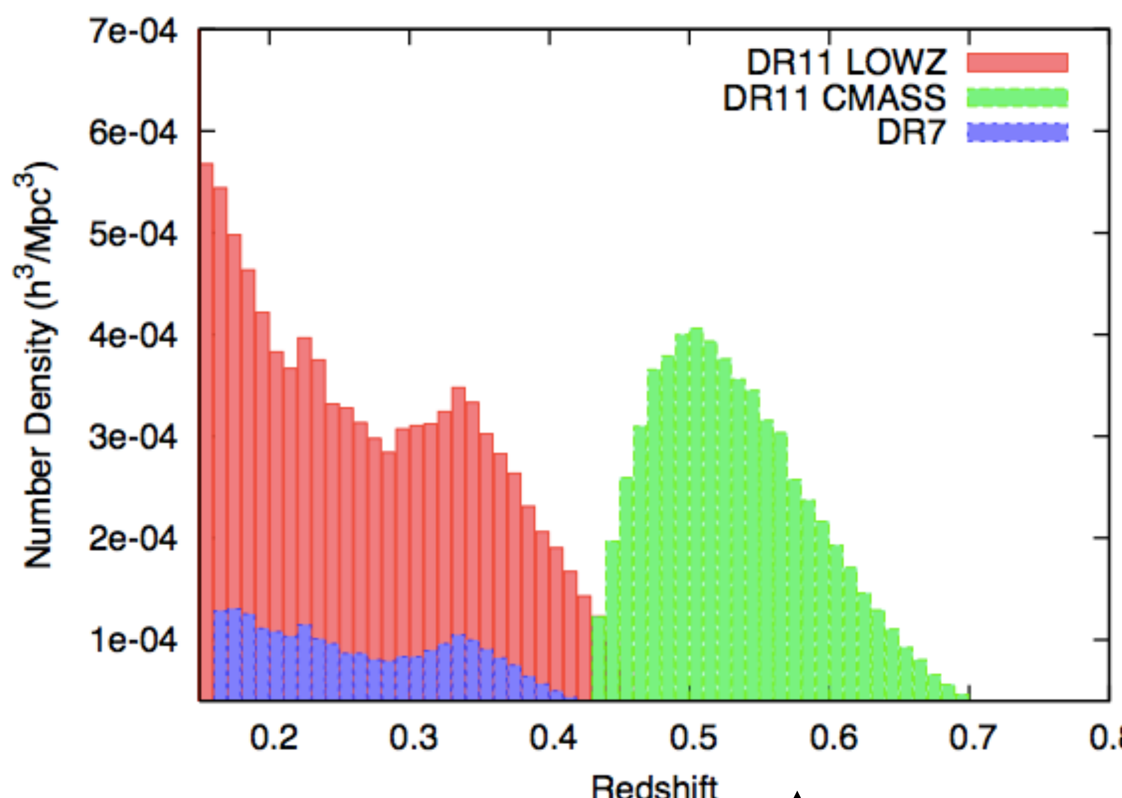
CMB, decoupling



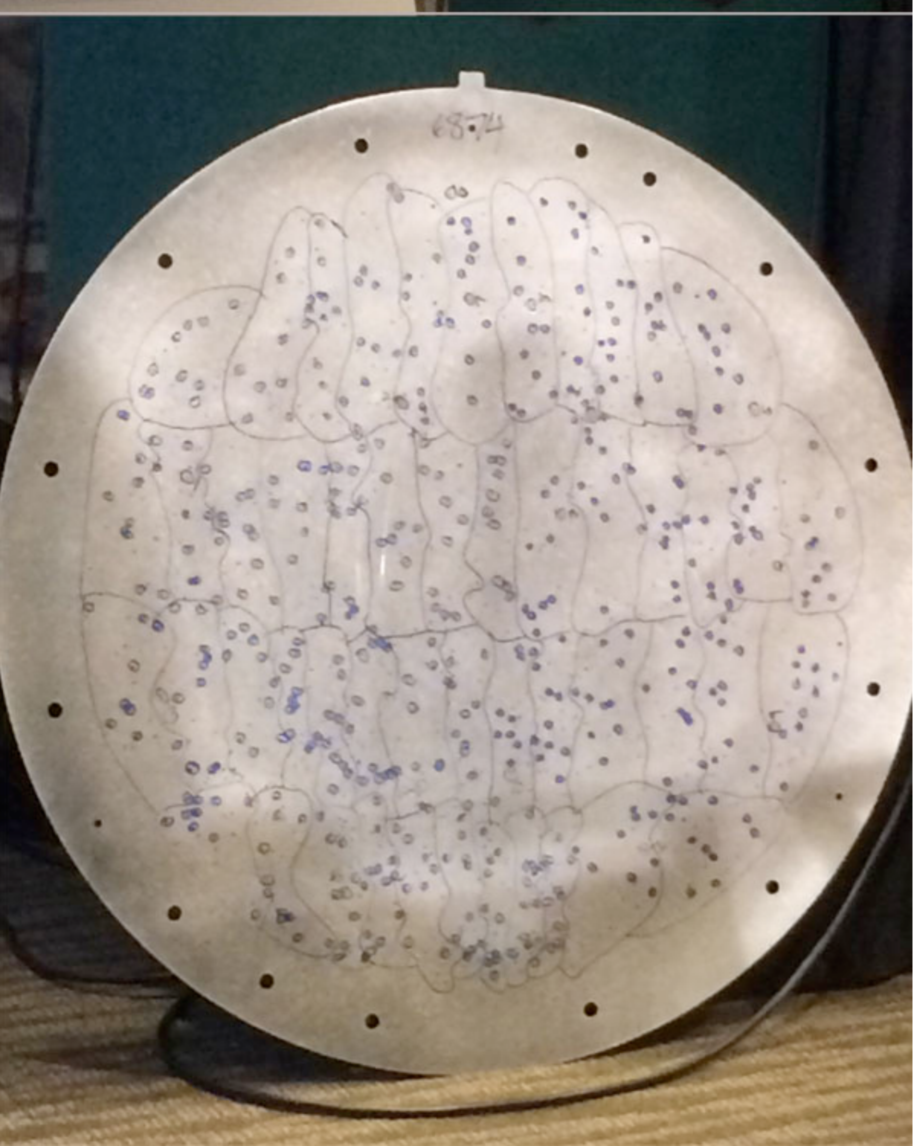
SDSS-BOSS results

Anderson et al 2014

BOSS mapped 10.000 square deg
(~25% of the sky) over 7yr
1.4 Mio Galaxies, 300k Quasars

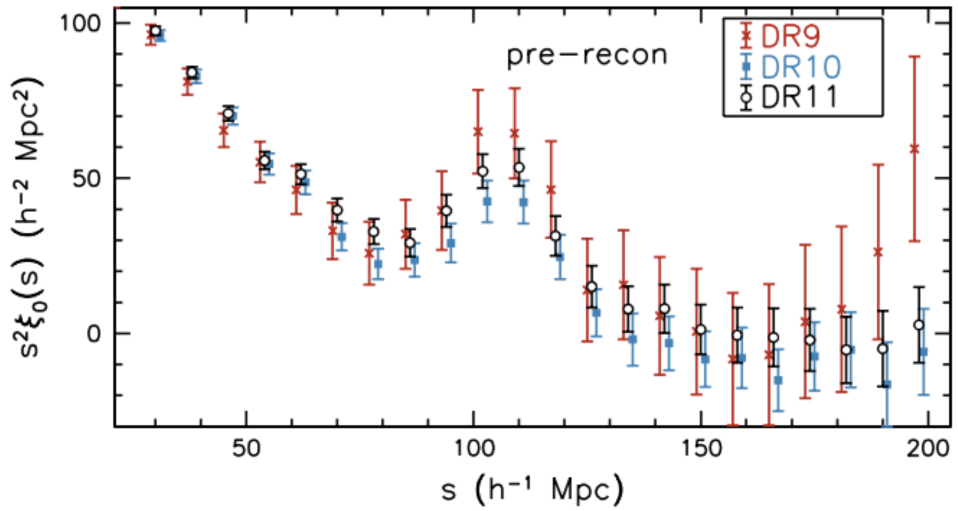


mean z = 0.57



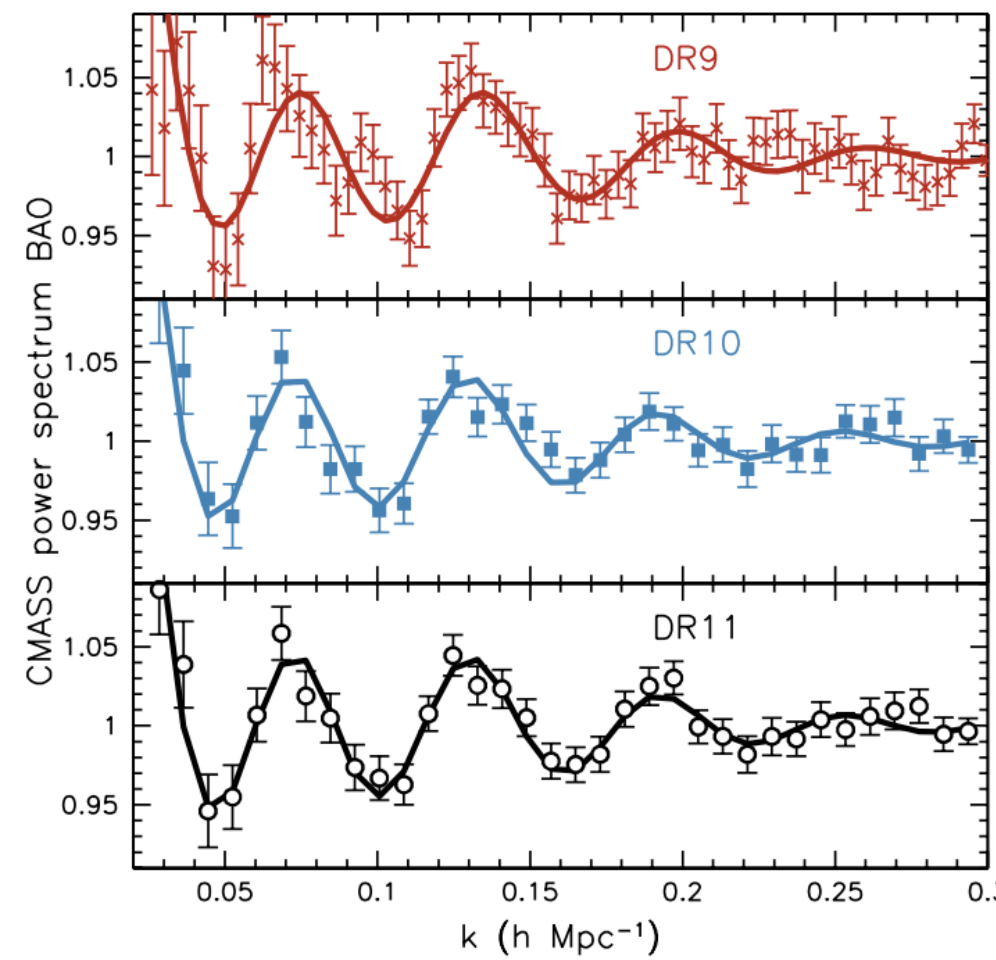
SDSS-BOSS results

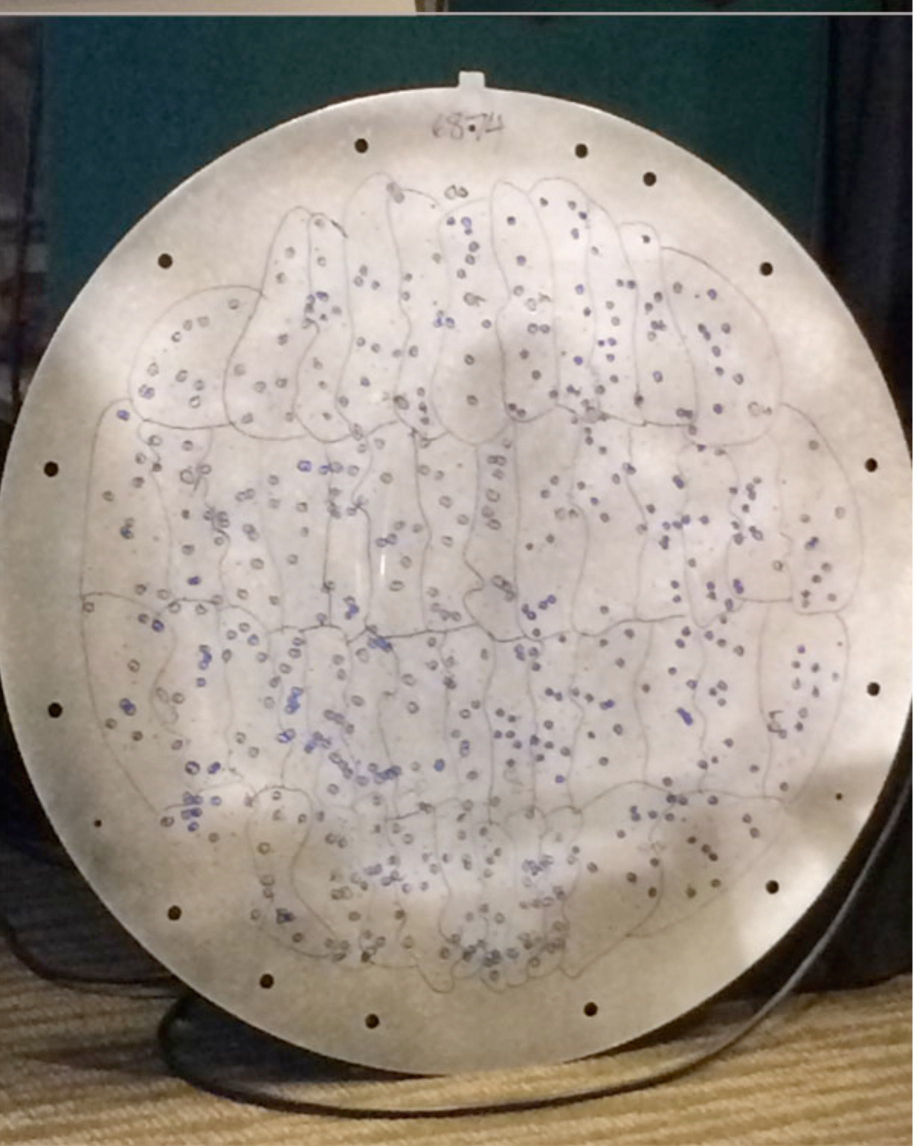
Anderson et al 2014



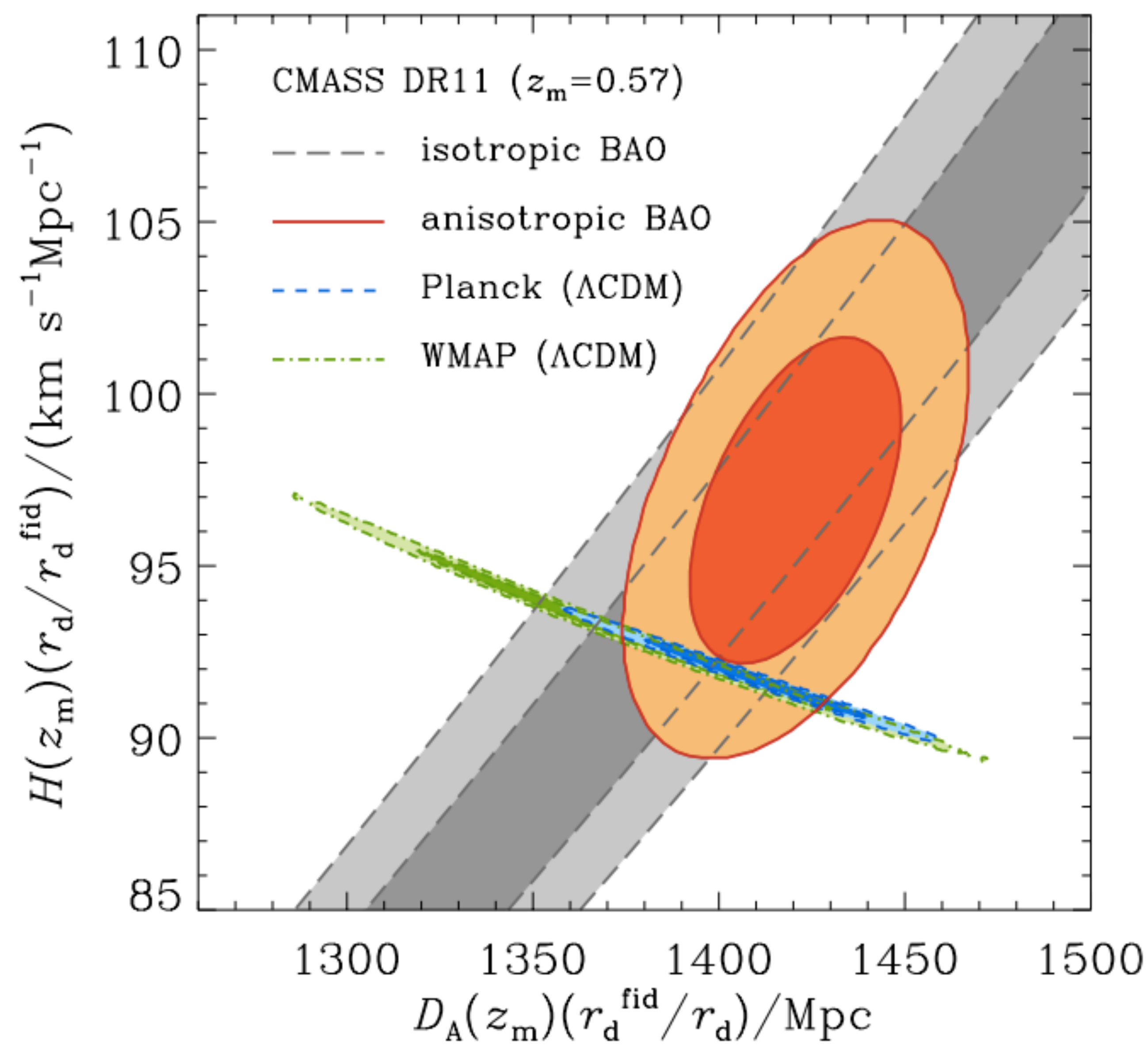
Bump in the spatial correlation function at 150 h Mpc…

…makes wiggles in the power spectrum





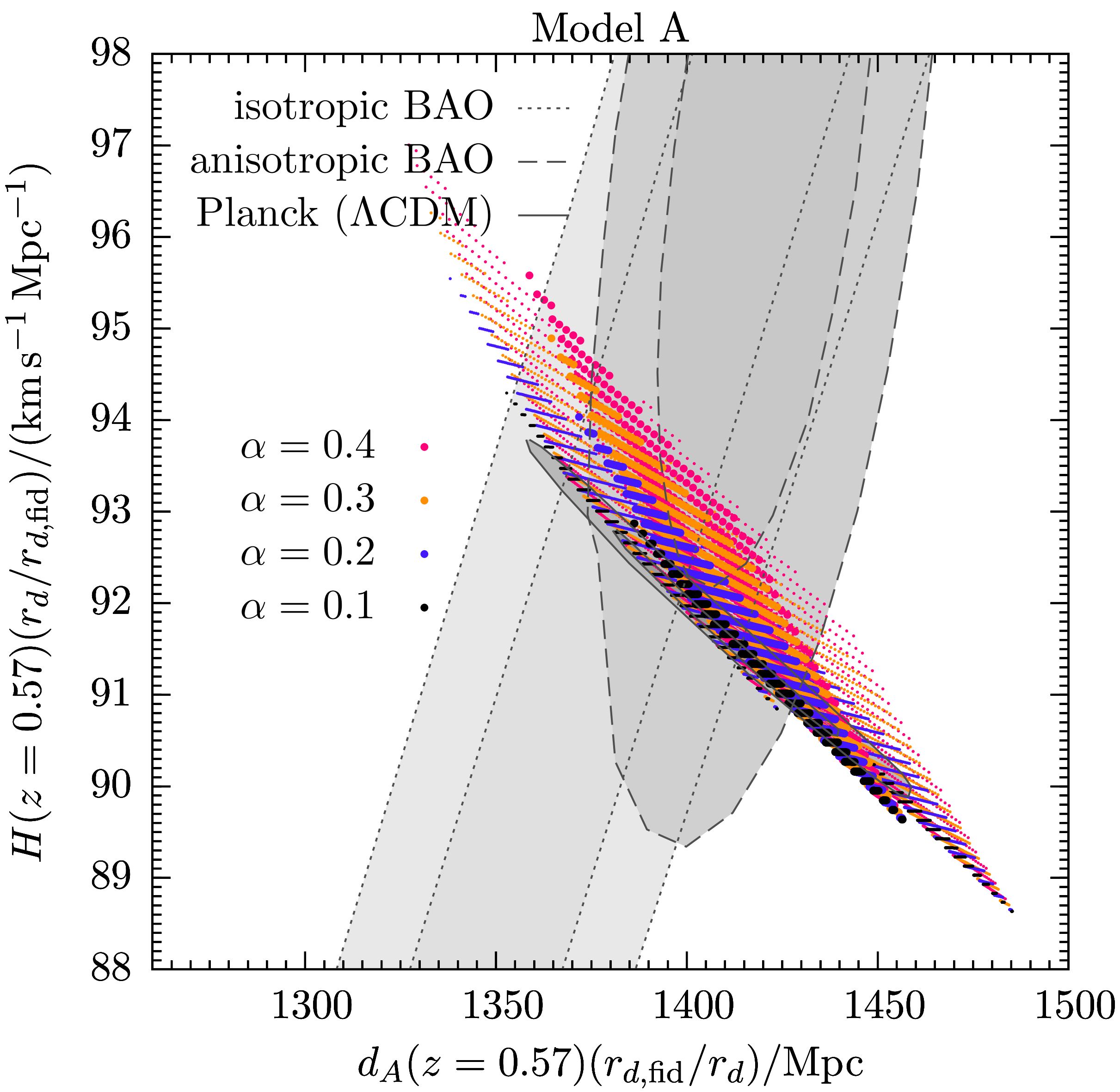
BAO measurement

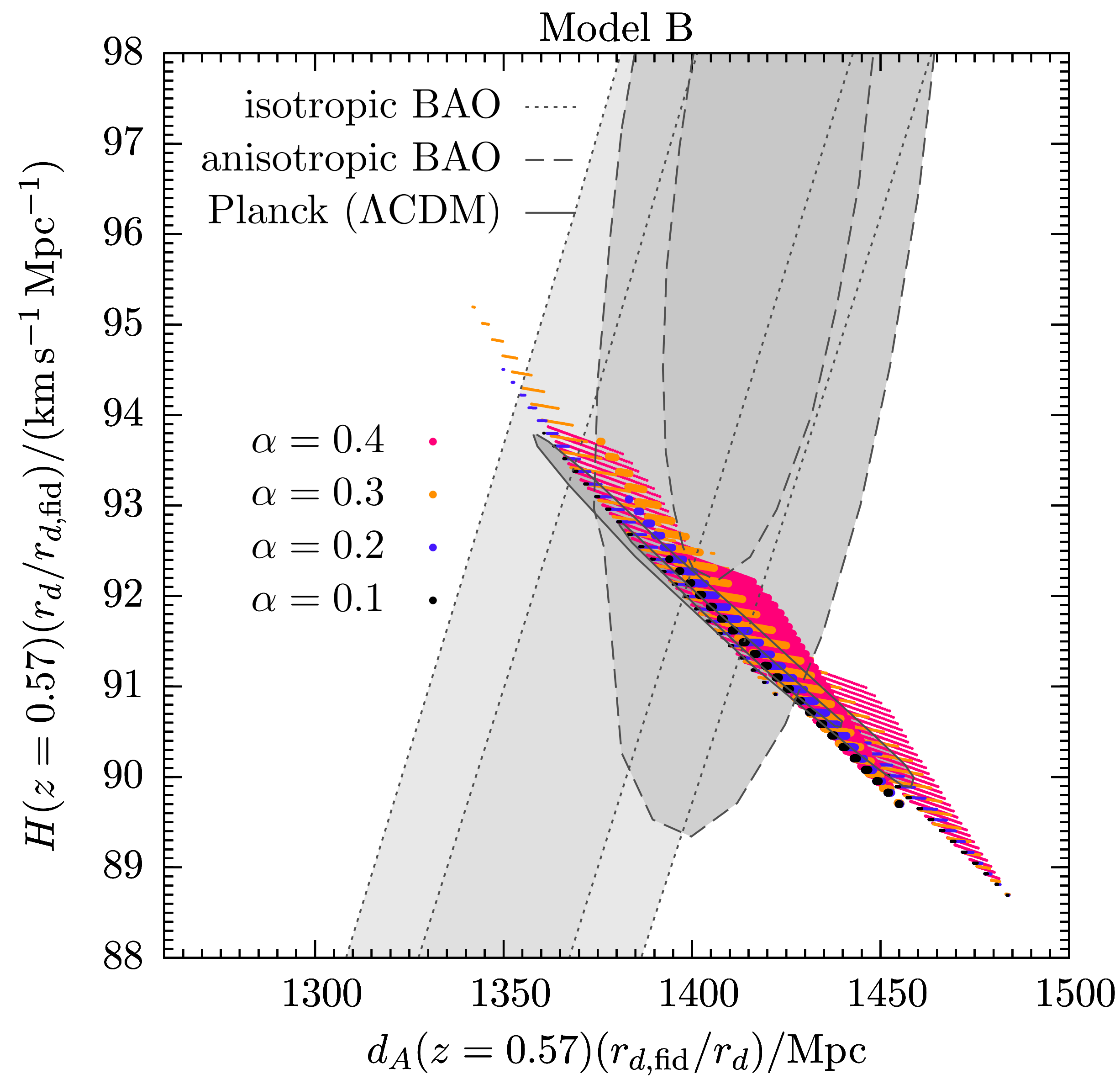


everything is relative to
a fiducial cosmology

Anderson et al 2014

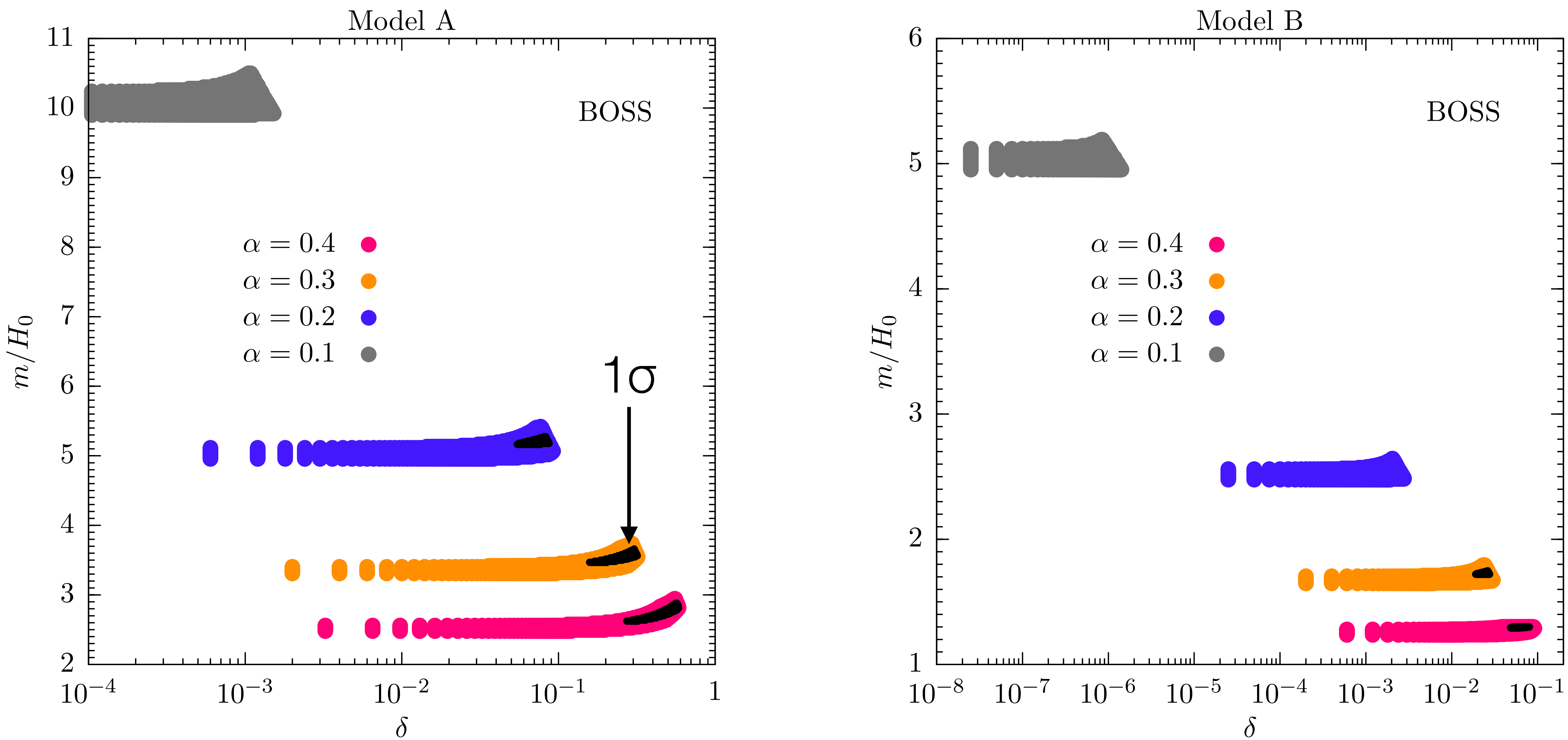
Predictions vs current sensitivity from BOSS





each colored point provides late-time acceleration in the axiverse;
light dots: h is varied, while keeping physical densities fixed.

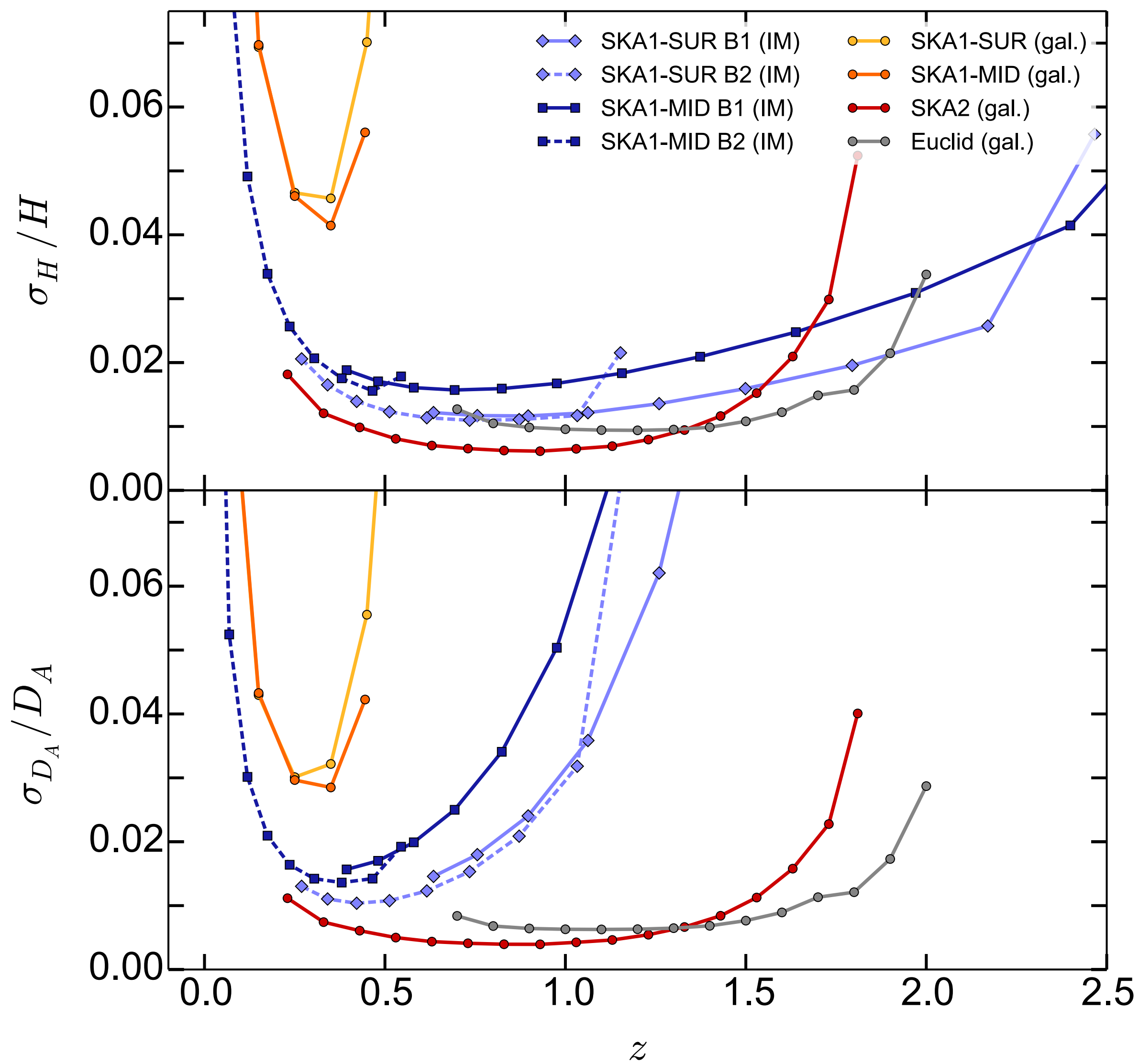
Constraints from BAO



Smaller α (i.e. smaller f_a requires higher mass, putting a stricter requirement on δ for the field to remain overdamped until $z \sim 1$.

NB: $\delta = 0$ (cosmological constant) is always allowed for at 2σ BOSS; scan has poor resolution.

Future sensitivity - example SKA



Bull et al. 2015

future SKA BAO observations from galaxy redshift and intensity mapping of 21cm promise (sub)% level insight into H and D_A

Utilizing future sensitivity on H and D_A from SKA, Euclid,.. are currently being worked out => sensitivity to dynamical dark energy may be established

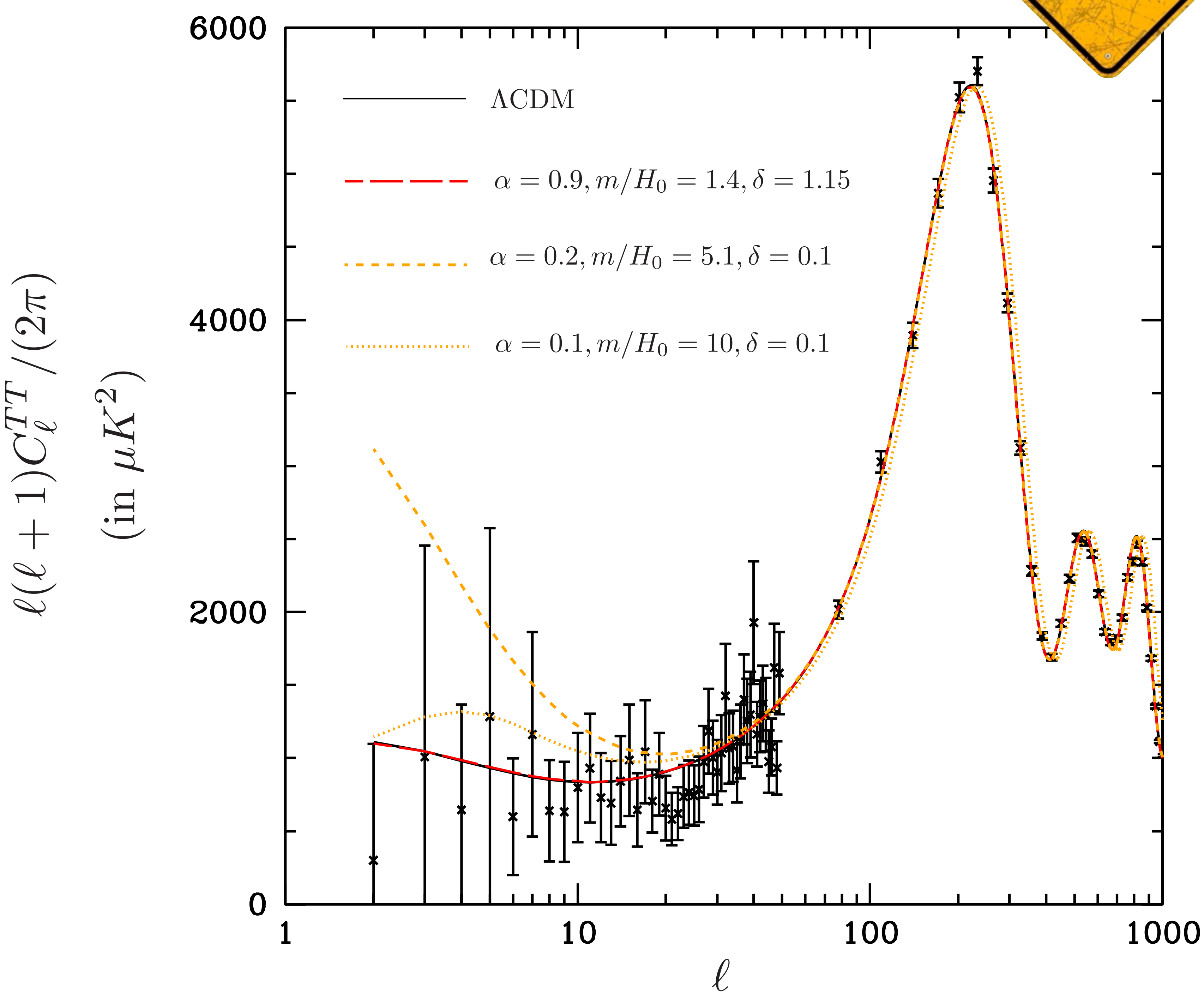
CMB observables

2 principal effects for homogeneous axion field:

modified angular diameter distance to LSS; shifts peaks
$\theta_s = r_s(z_*)/D_A(z_*)$

modified late-time ISW because w(z)

[builds on Dan's work Hlozek et al 2014]



Summary

Stringy axions when they come in multitude offer the possibility that the Universe enters stages of accelerated expansion during its lifetime.

Large $f_a \sim M_{GUT}$ - M_P ("dark axions") may endow the field with sufficient potential energy to have the Universe dominated by it at late times; probability that this happened only recently is not too small.

Currently we look into more details regarding the cosmology of the model, set constraints, and look into future probes that may discern the scenario from other quintessence models.