5 December, TeVPA 2019

Probing the history of dark sector interactions

Lawrence Dam
Sydney Institute for Astronomy
The University of Sydney

with K. Bolejko, G. Lewis; arxiv:1908.01953

THE UNIVERSITY OF SYDNEY

Dark sector interactions

- Experimental searches for particle DM
- No experimental search for DE
  - DM candidates motivated by theory (WIMPs, axions, sterile neutrinos, etc)
  - DM-DE interactions?
- Probing dark sector interaction in the lab a non-starter
- However…

… the question of DM-DE interaction can (only?) be investigated from cosmological observations

Interacting DE models

- DM and DE generically coupled
- Dynamical DE model + coupling have been studied for over two decades
  - elaborate models; weak observational constraints
  - alleviates ‘coincidence problem’
- Recent work focussed on interaction itself
  - minimal extension to ΛCDM
  - fluid description of DE

Interaction in fluid approximation

- Conservation of total energy-momentum given by

$$\nabla_\mu (T_b^{\mu\nu} + T_c^{\mu\nu} + T_{de}^{\mu\nu} + T_\gamma^{\mu\nu} + T_\nu^{\mu\nu} + \cdots) = 0$$

- Relax the ΛCDM assumption $\nabla_\mu T_c^{\mu\nu} = 0, \quad \nabla_\mu T_{de}^{\mu\nu} = 0$:

$$\nabla_\mu T_c^{\mu\nu} = -Q^\nu$$

$$\nabla_\mu T_{de}^{\mu\nu} = +Q^\nu$$

but still have total conservation of EM

- Decompose wrt CDM 4-velocity $Q^\mu(t, \mathbf{x}) = Q(t)u_c^\mu + f^\mu$
- Restrict to energy exchange only ($f^\mu = 0$):

$$Q^\mu(t, \mathbf{x}) = Q(t)u_c^\mu$$

- Q typically chosen for simplicity but no theoretical basis

This work: Probe DM-DE interaction using a data-driven, model-independent approach

Reconstruction method

- Take agnostic approach: let data decide best form of Q

- Define dimensionless interaction strength

$$\boxed{q(a) := Q(a)/(H\rho_{de})}$$

- $q(a)$ has infinite DoF. We reconstruct a discretized representation

$$q(a) = \sum_{i=1}^{n_{\rm bins}} q_i T_i(a) \implies \text{define a vector } \mathbf{q} = (q_1, \ldots, q_{n_{\rm bins}})^T$$

$$T_i(a) = \begin{cases} 1, & a_{i-1} \leq a \leq a_i \\ 0, & \text{otherwise} \end{cases}$$

Smoothing prior

Bayes' theorem: $p(\mathbf{q}\,|\,\text{data}) \propto p(\text{data}\,|\,\mathbf{q})\, p(\mathbf{q})$

- Too much freedom, degeneracies abound
- Restrict to subspace of smooth reconstructions

Assign informative prior to $\mathbf{q}$

$$p(\mathbf{q}) = \frac{1}{\sqrt{\det 2\pi C}} \exp\left(-\frac{1}{2} (\mathbf{q}^{fid} - \mathbf{q})^T C_{prior}^{-1} (\mathbf{q}^{fid} - \mathbf{q}) \right)$$

$$\mathbf{q}^{fid} = (q_1^{fid}, \ldots, q_{n_{\text{bins}}}^{fid})^T$$

- reconstruction regresses to $\mathbf{q}^{fid}$ in the absence of data
- key to smoothness lies in C_{prior}

Specifying correlations

- Bin-bin correlations $C_{ij} = \langle (q_i - \bar{q}_i)(q_j - \bar{q}_j) \rangle$
- Discretize:

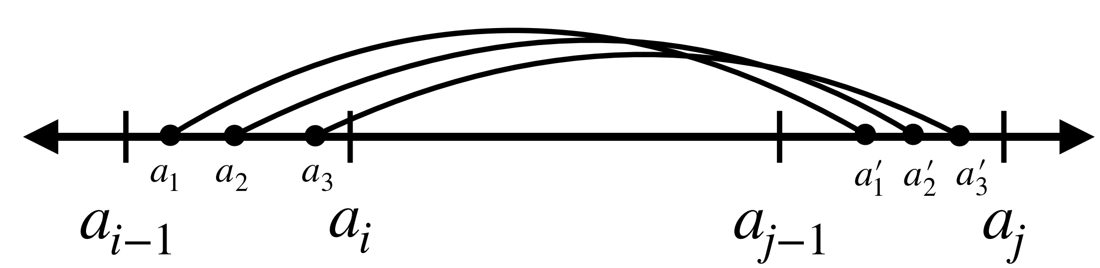
$$q(a) \rightarrow q_i = \int_0^1 da\, W_i(a)\, q(a)$$

$$C_{ij} = \int_0^1 da\, W_i(a) \int_0^1 da'\, W_j\left(a'\right)\, \xi(|a - a'|)$$

where

$$\xi(|a - a'|) := \left\langle (q(a) - q^{fid}(a))(q(a') - q^{fid}(a')) \right\rangle$$

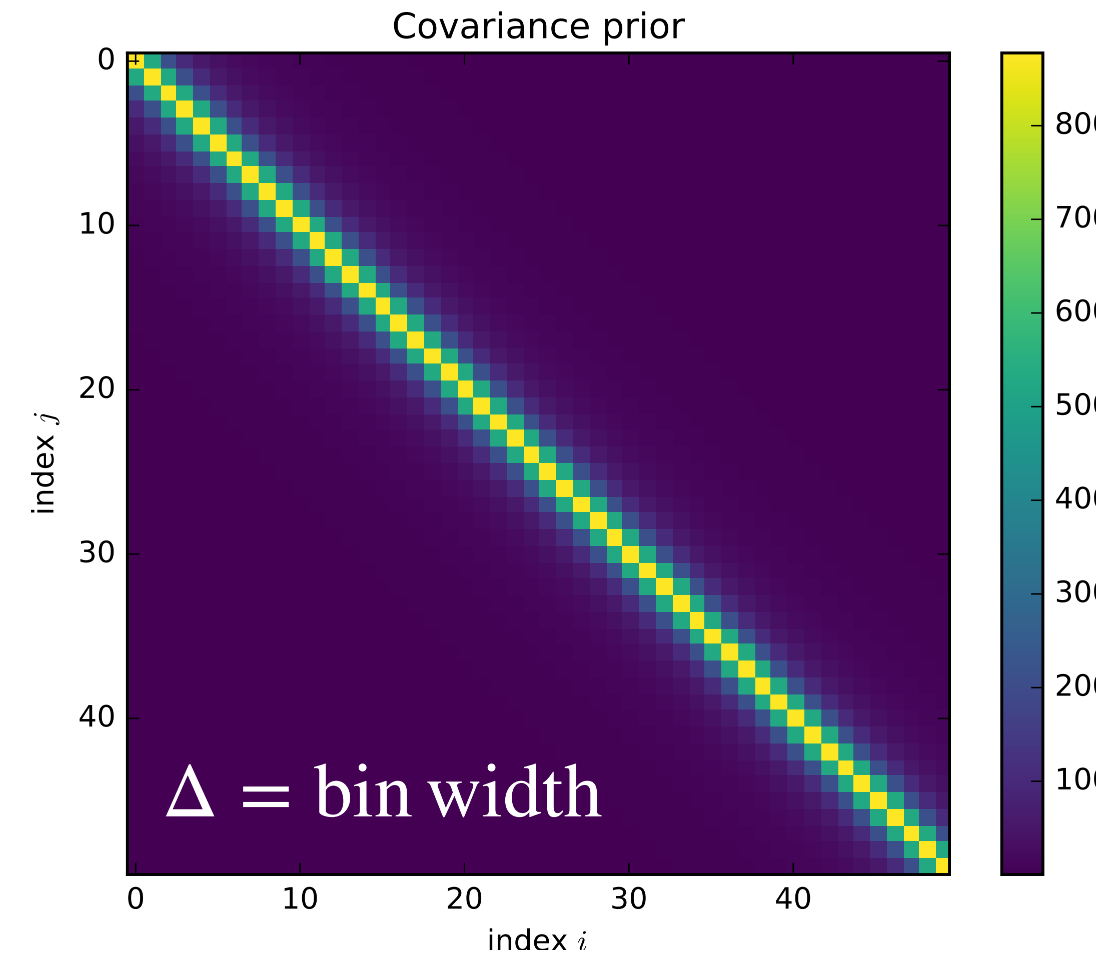
- To compute C_{ij} sum all pairwise correlations between bin i and bin j

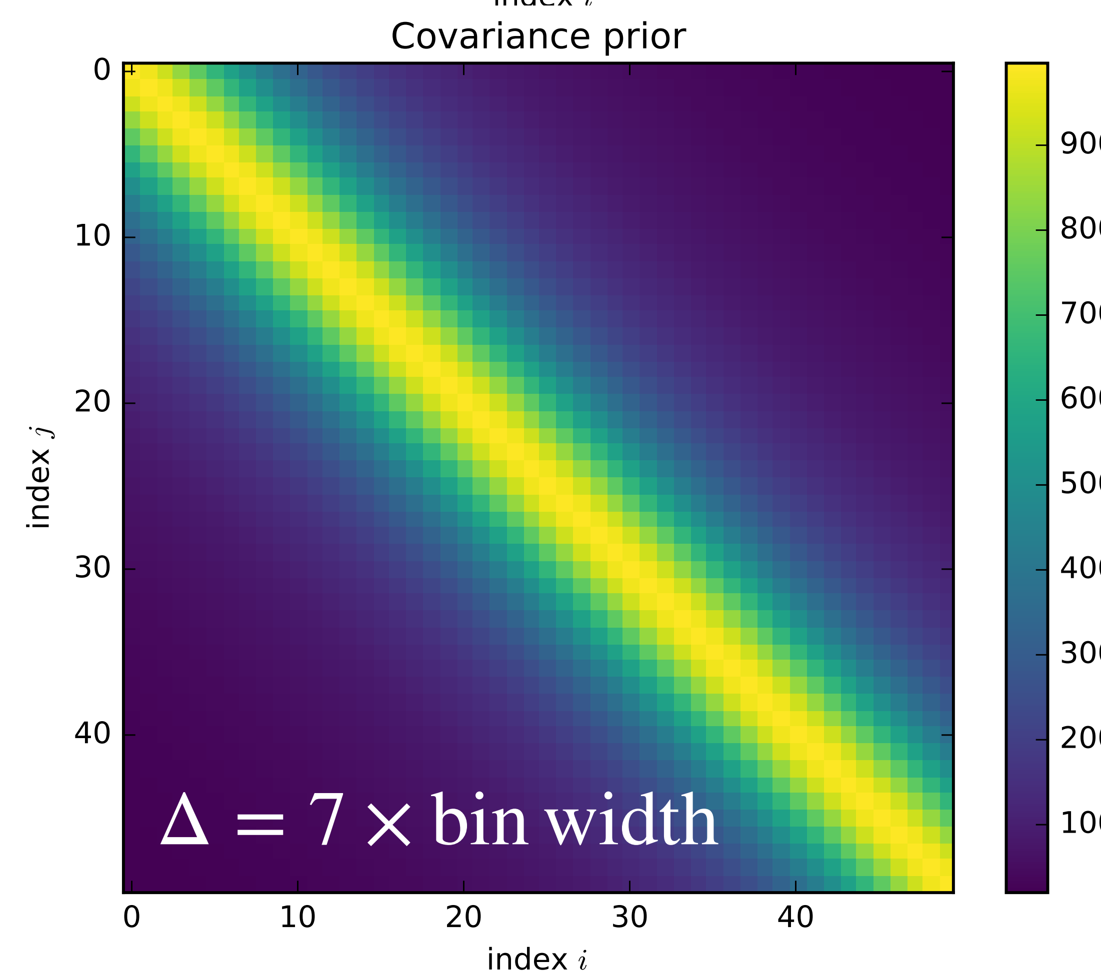


- For **smoothness** we want bins to be **positively** correlated. We adopt the correlation function (astro-ph/0510293)

$$\xi(|a - a'|) = \frac{\sigma^2}{1 + (|a - a'|/\Delta)^2}$$

  - σ controls strength of correlations
  - Δ controls characteristic scale of correlations





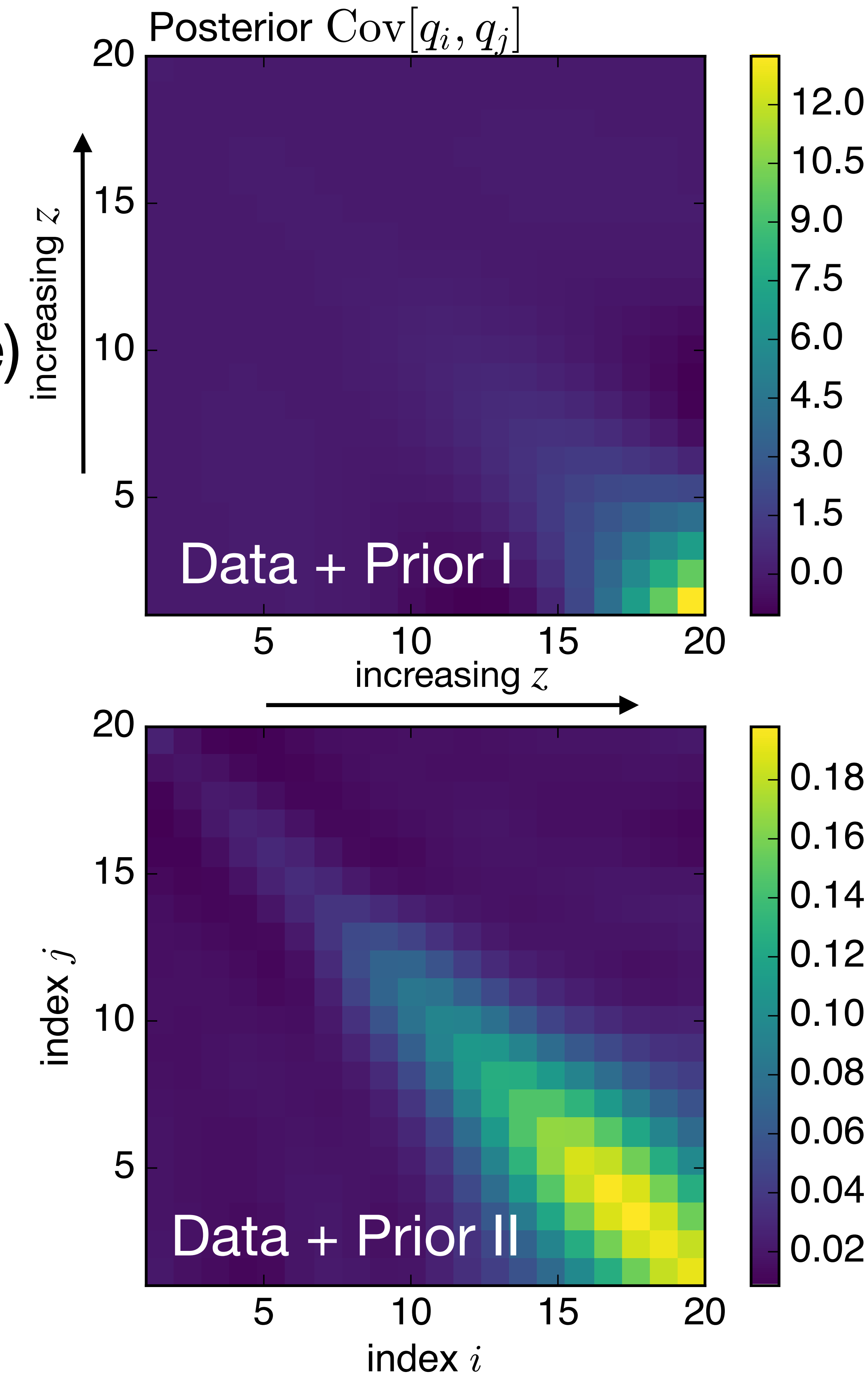
Specifying fiducial model

- Consider two fiducial models:

  Prior I: $\mathbf{q}^{fid} = A\mathbf{q}$ (running average)

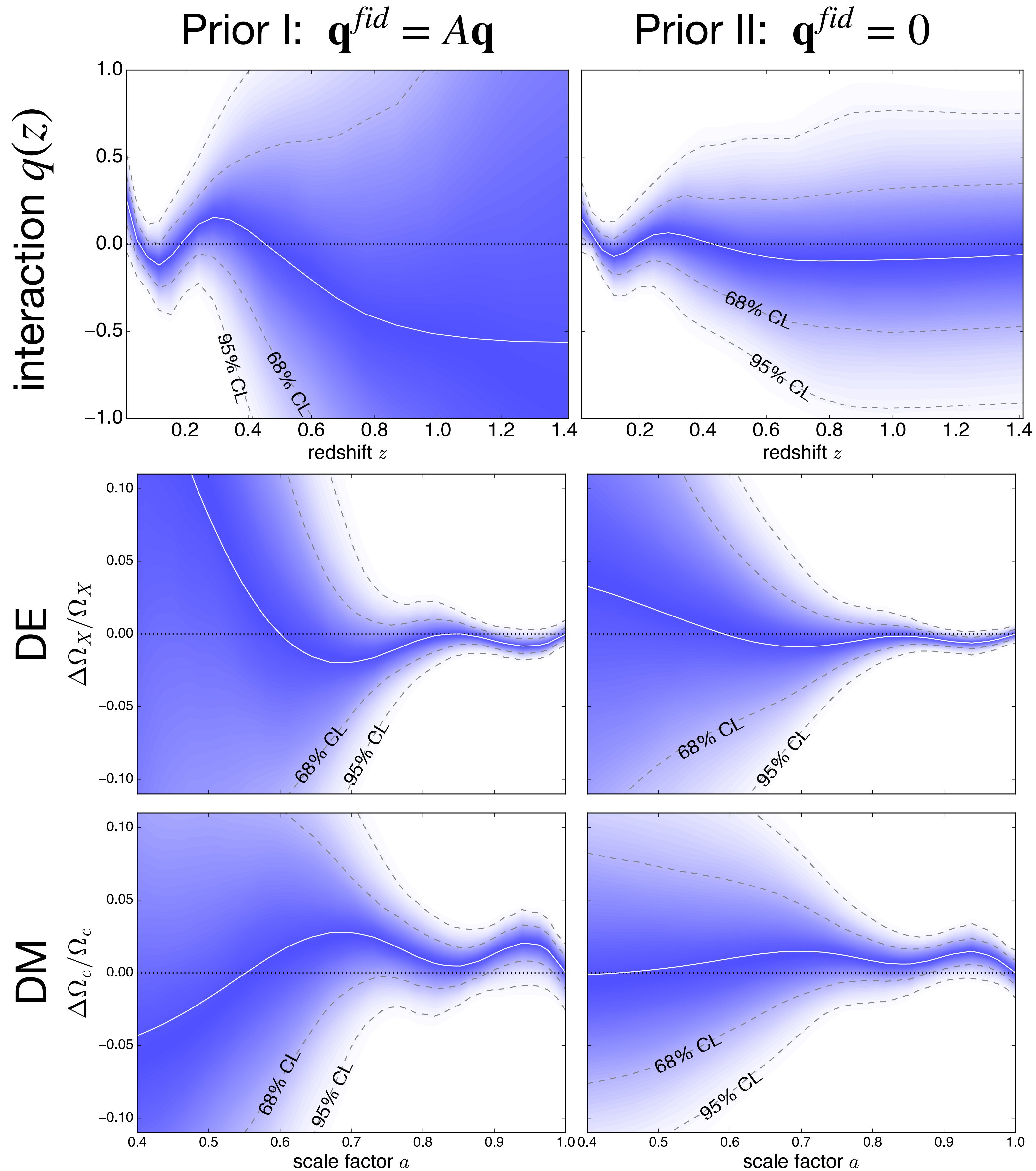
  Prior II: $\mathbf{q}^{fid} = 0$ (conservative)

- Data more informative at low-z, uncertainties in q_i increase with i



Full reconstruction

- Data = BAO+CMB+RSD+SN+ $H(z)$
- Interaction consistent with zero at $z > 0.2$
- Slight feature at $z \lesssim 0.2$ robust to two different priors
- Consistent with zero but lots of redundancy. Want optimal description of $q(z)$



Karhunen-Loève analysis

$$q(a) = \sum_i q_i T_i(a) = \sum_i \alpha_i e_i(a)$$

KL modes

- Generalizes aspects of PCA

- KL identifies features that are well-determined. Noise dominated features can be filtered out

- Principal component analysis (PCA) not valid since we have non-trivial prior information

    - does not distinguish between prior and data

KL signal-to-noise modes

$$q(a) = \sum_i q_i \, T_i(a) = \sum_i \alpha_i \, e_i(a)$$

- What's important is the information gained from likelihood (data)

$\mathrm{Cov}[\alpha_m, \alpha_n]$ is diagonal, $\{\alpha_i\}$ are uncorrelated variables

$$C_{prior} \, \mathbf{e}_a = \lambda_a \, C_{post} \, \mathbf{e}_a$$

($C_{post} \, \mathbf{e}_a = \lambda_a \, \mathbf{e}_a$ for PCA)

- Unlike PCA $\{\mathbf{e}_1, \mathbf{e}_2, \ldots, \mathbf{e}_{n_{\mathrm{bins}}}\}$ are not orthogonal set. Instead

$$\mathbf{e}_a^T \, C_{post} \, \mathbf{e}_b = \delta_{ab}$$

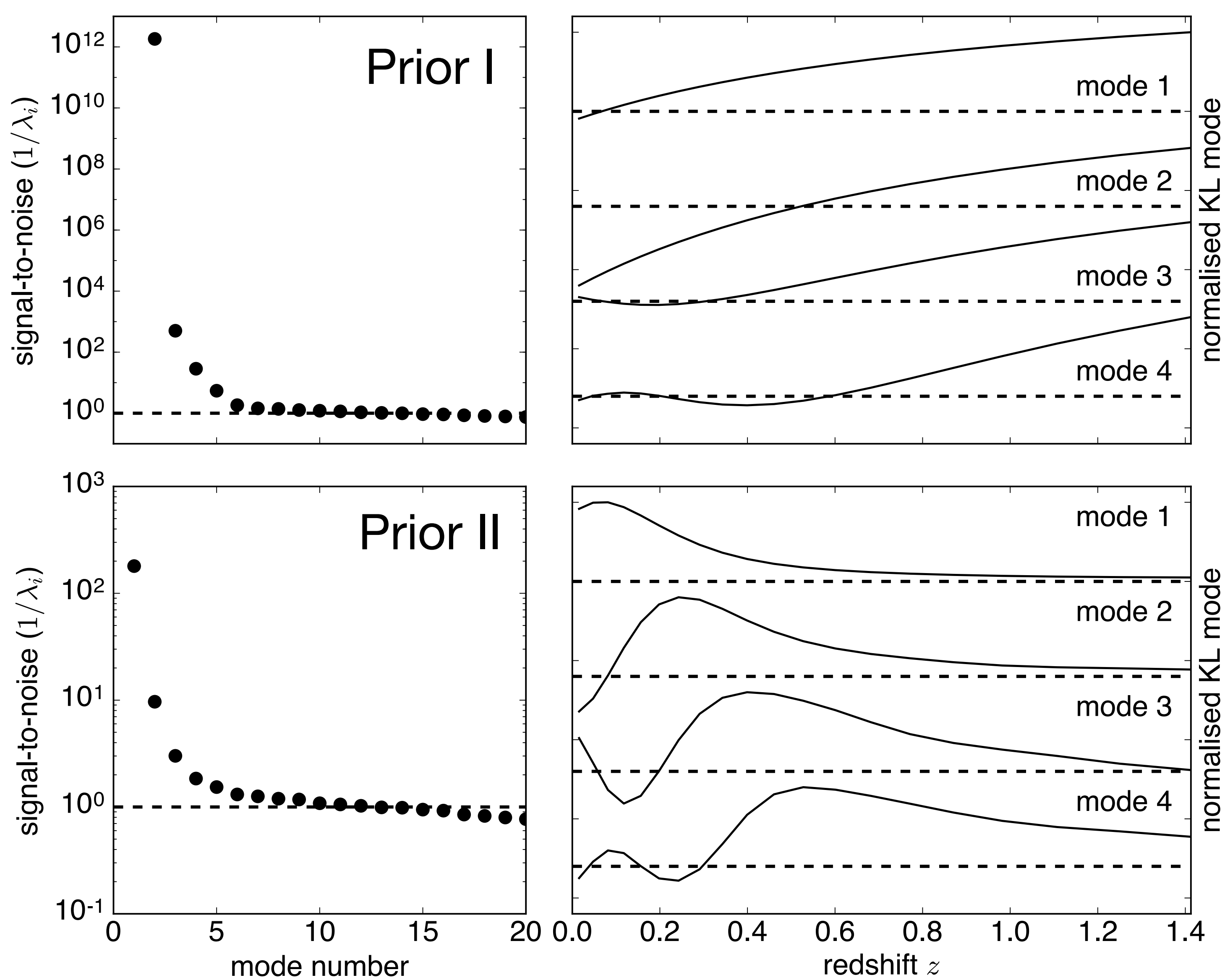
$$\mathbf{e}_a^T \, C_{prior} \, \mathbf{e}_b = \lambda_a \, \delta_{ab}$$

$1/\lambda_a$ is S/N of a^{th} mode

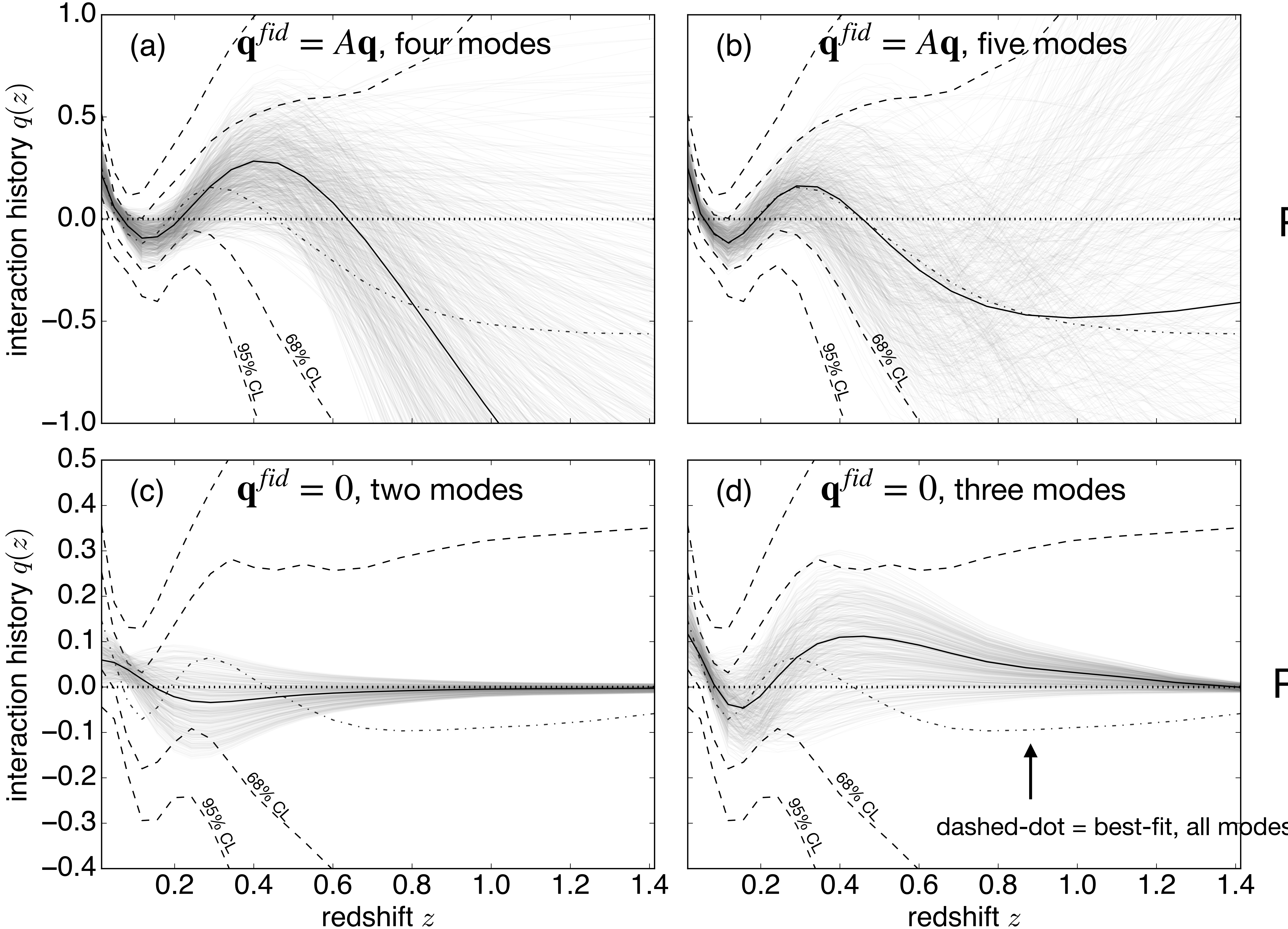
How many KL modes to retain?

- Effective number of q_i parameters

$$n_{\rm eff} = n_{\rm tot} - {\rm tr}(C_{\rm post} C_{\rm prior}^{-1}) = n_{\rm bins} - \sum_{a=1}^{n_{\rm bins}} \lambda_a$$



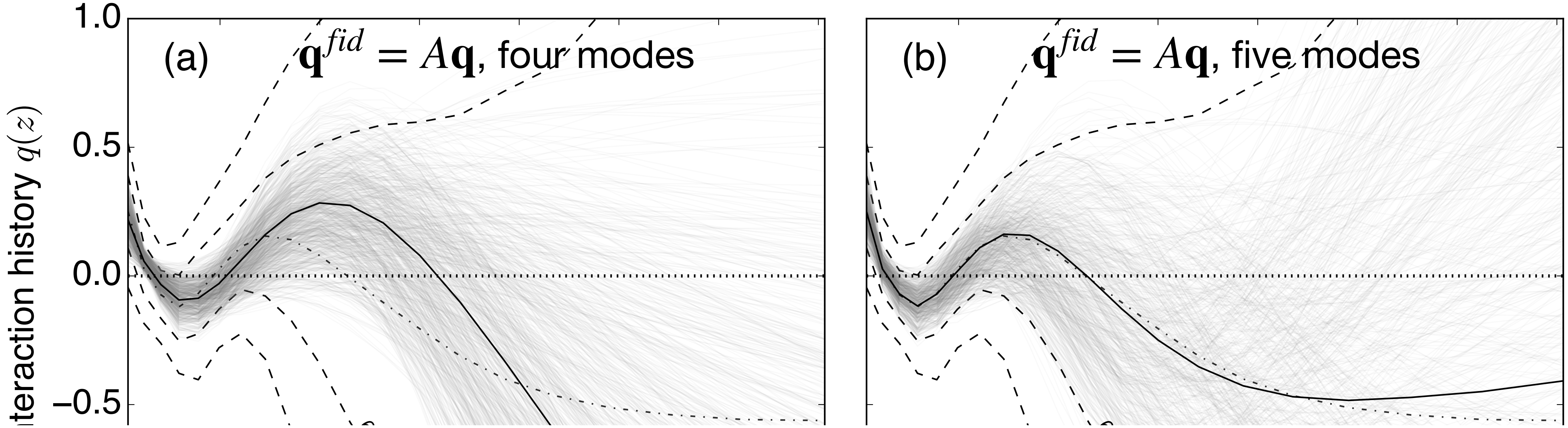
KL reconstruction



Prior I

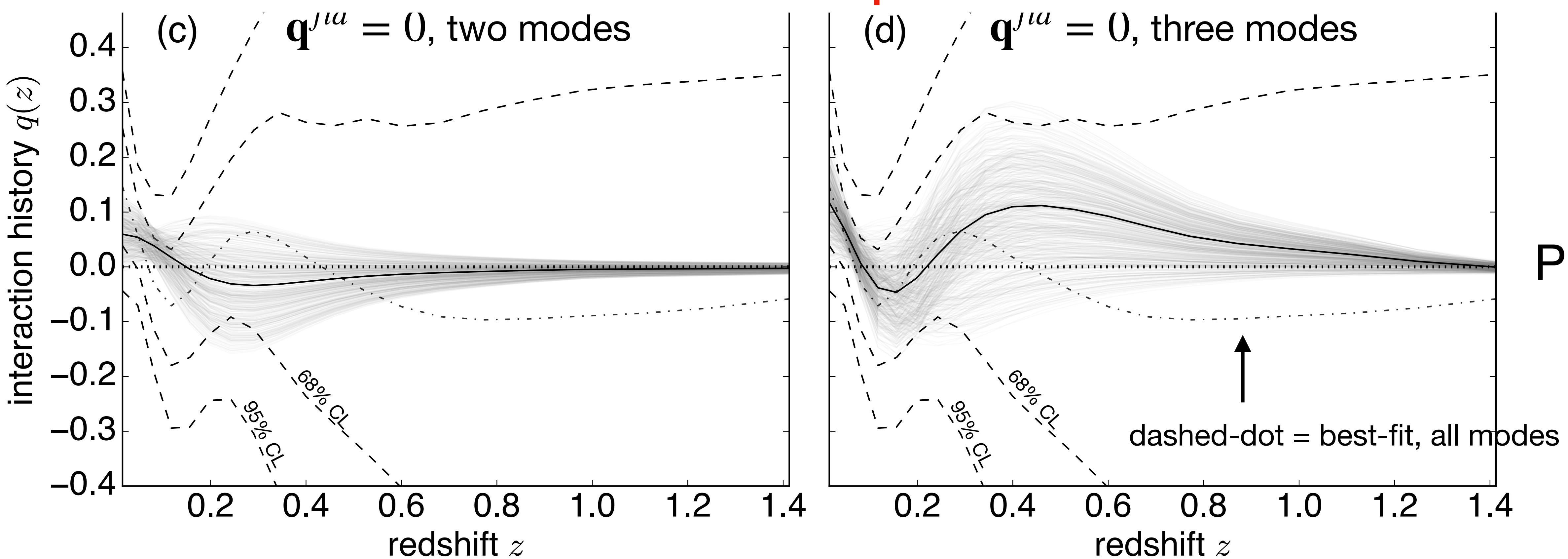
Prior II

KL reconstruction



Prior I

All reconstructions moderately disfavoured by Bayesian model comparison



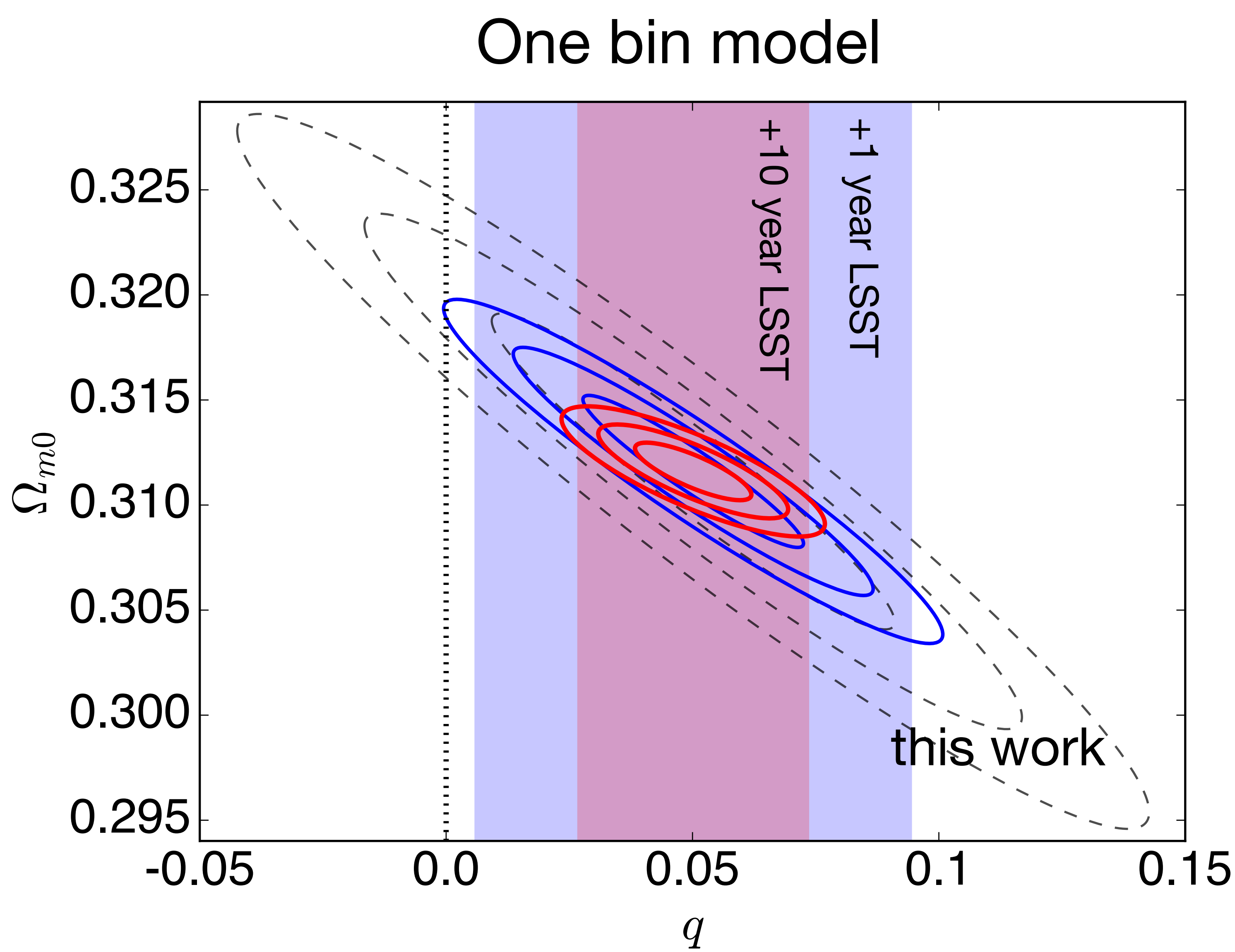
Prior II

Future prospects

- Fisher matrix

$$F_{ij} = -\left\langle \frac{\partial^2 \ln \mathscr{L}}{\partial\theta^i \partial\theta^j} \right\rangle \Bigg|_{\theta_i=\theta_i^{ML}}$$

- What improvements can we expect from DESI (RSD+BAO) and LSST SNIa?
- $> 3\sigma$ constraints on interaction possible with 1 year LSST sample
  - improvements largely come from RSD



$$F_{ij} = F_{ij}^{\mathrm{LSST-SN}} + F_{ij}^{\mathrm{DESI-RSD}} + F_{ij}^{\mathrm{DESI-BAO}} + F_{ij}^{\mathrm{data}}$$

Summary

1. No evidence for late-time interaction in the dark sector

    - Targeted search for DM-DE interaction shows slight $\lesssim 2\sigma$ deviations from ΛCDM at $z < 0.2$

2. KL analysis can be used to isolate data-sensitive modes

    - needed for penalised reconstruction

    - One KL mode well-constrained with current data

3. ΛCDM remains best model in all model comparison tests when range of data considered

Thank you

Extra slides

Interaction or MG?

- In linear perturbation theory $\delta(t, \mathbf{x}) = D(t)\, \delta_i(\mathbf{x})$ i.e. grows uniformly with growth factor $D(t)$
  - relative height of peaks and troughs of density field does not change with time (self-similar)
  - consequence of inverse-square law. More generally

$$\frac{\partial^2 \delta_{\mathbf{k}}}{\partial t^2} + 2\frac{\dot{a}}{a}\frac{\partial \delta_{\mathbf{k}}}{\partial t} = S(k, t)\delta_{\mathbf{k}}$$

$S(k, t) \rightarrow S(t)$ for GR

- Growth rate $f = d \ln D / d \ln a$

$$f(a) \approx \Omega_m(a)^\gamma, \quad \gamma \approx 0.55 \text{ for } \Lambda\text{CDM}$$

  - background expansion history fully determines $f(a)$ (non-local)
- Measurements that differ from $\gamma \approx 0.55$ taken as sign of gravity theory *not* given by GR
  - provides a framework for investigating MG
- Interaction complicates this picture
  - can still have GR and $\gamma \neq 0.55$ with interaction