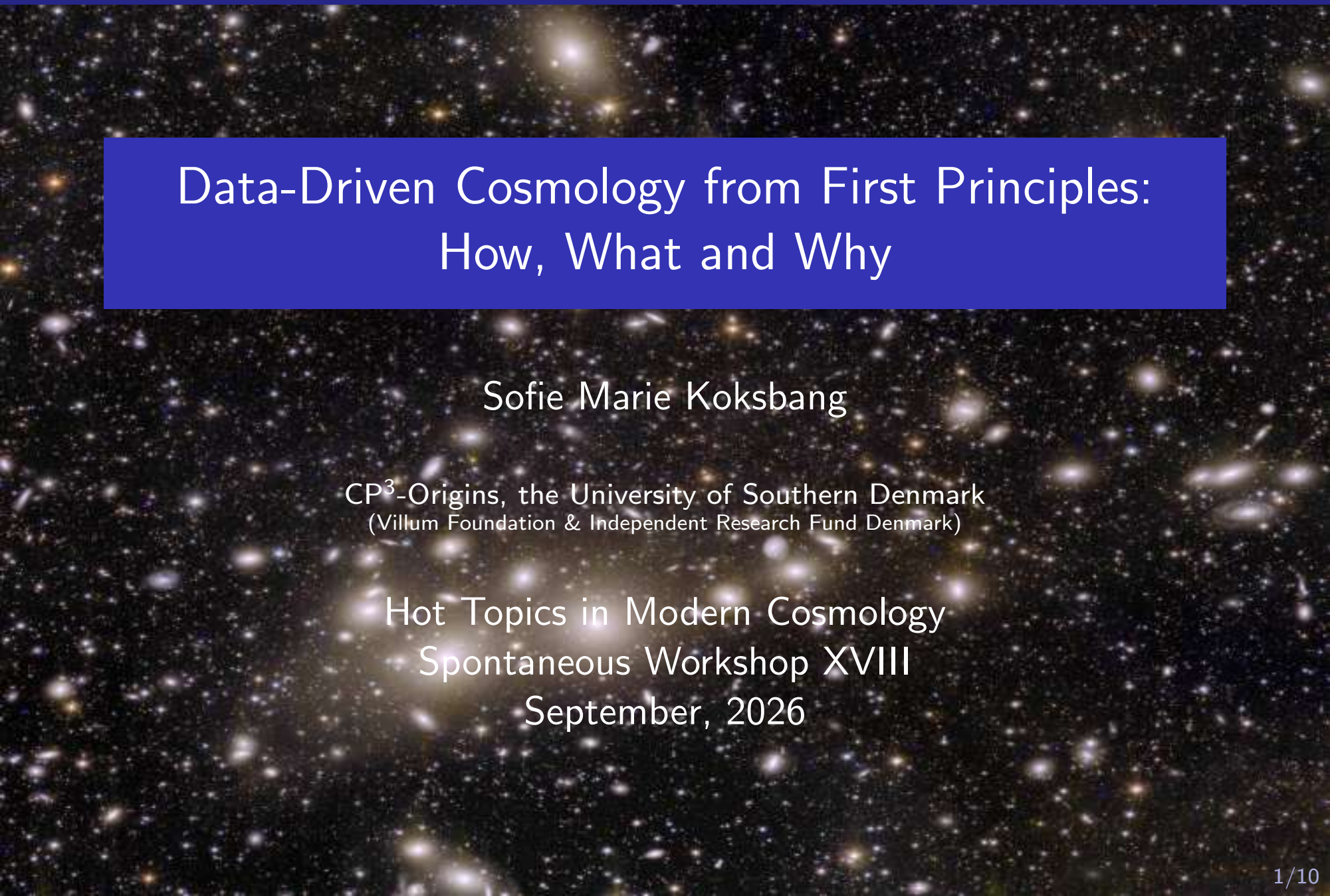


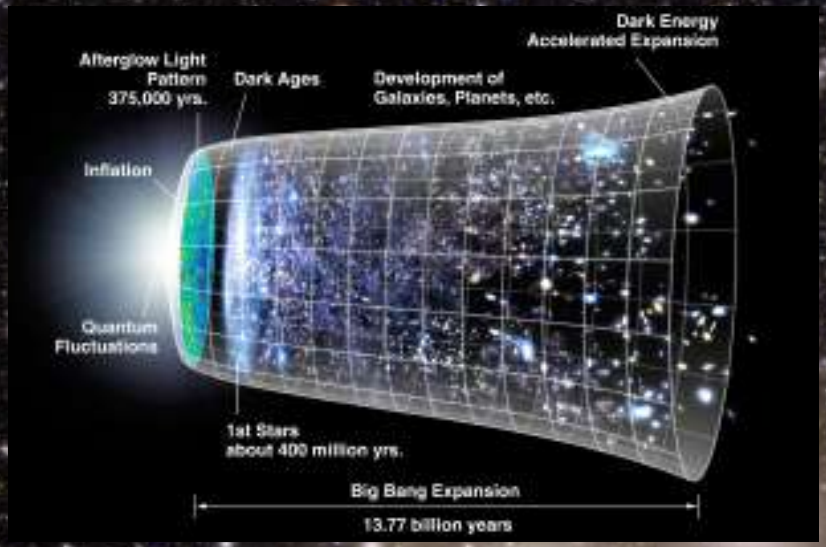
Data-Driven Cosmology from First Principles: How, What and Why

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Hot Topics in Modern Cosmology
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Standard cosmology is based on FLRW models



$$H^2 = \left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi G}{3}\rho - \frac{\kappa}{R_0^2 a^2} + \frac{\Lambda}{3}$$

$$\frac{\ddot{a}}{a} = -\frac{4\pi G}{3}(\rho + 3P) + \frac{\Lambda}{3}$$

The FLRW metric

$$ds^2 = a^2 \left[-d\eta^2 + dr^2 + f_K^2(r) d\Omega^2 \right]$$

$$f_K(r) = \begin{cases} K^{-1/2} \sin(K^{1/2} r) & (K > 0) \\ r & (K = 0) \\ |K|^{-1/2} \sinh(|K|^{1/2} r) & (K < 0) \end{cases}$$

When has data outgrown FLRW?

- Evidence for anisotropies in the Hubble diagram has accumulated in recent years

  Representative studies: arXiv:2605.18470, 2411.10838, 2411.14758, 2406.14827, 2402.17741, 2305.12819, 2309.11320, 2212.13569, 2212.10328, 1911.06456, 1808.04597

- Bulk flow too large for ΛCDM: 2512.03168 and refs. therein
- Large-scale anisotropy? 2505.23526 (but see also 2608.30914)
- Spatial variations in cosmological parameters from Planck: 2207.05765
- Cosmological observations may now be too precise to neglect the effects of nonlinear structure formation

Cosmography without FLRW

$$D_L(z) = D_L^{(1)} z + D_L^{(2)} z^2 + D_L^{(3)} z^3 + \mathcal{O}(z^4)$$

$$D_L^{(1)} = \frac{c}{H_0}$$

Hubble scale

$$D_L^{(2)} = \frac{c}{H_0} \frac{1 - q_0}{2}$$

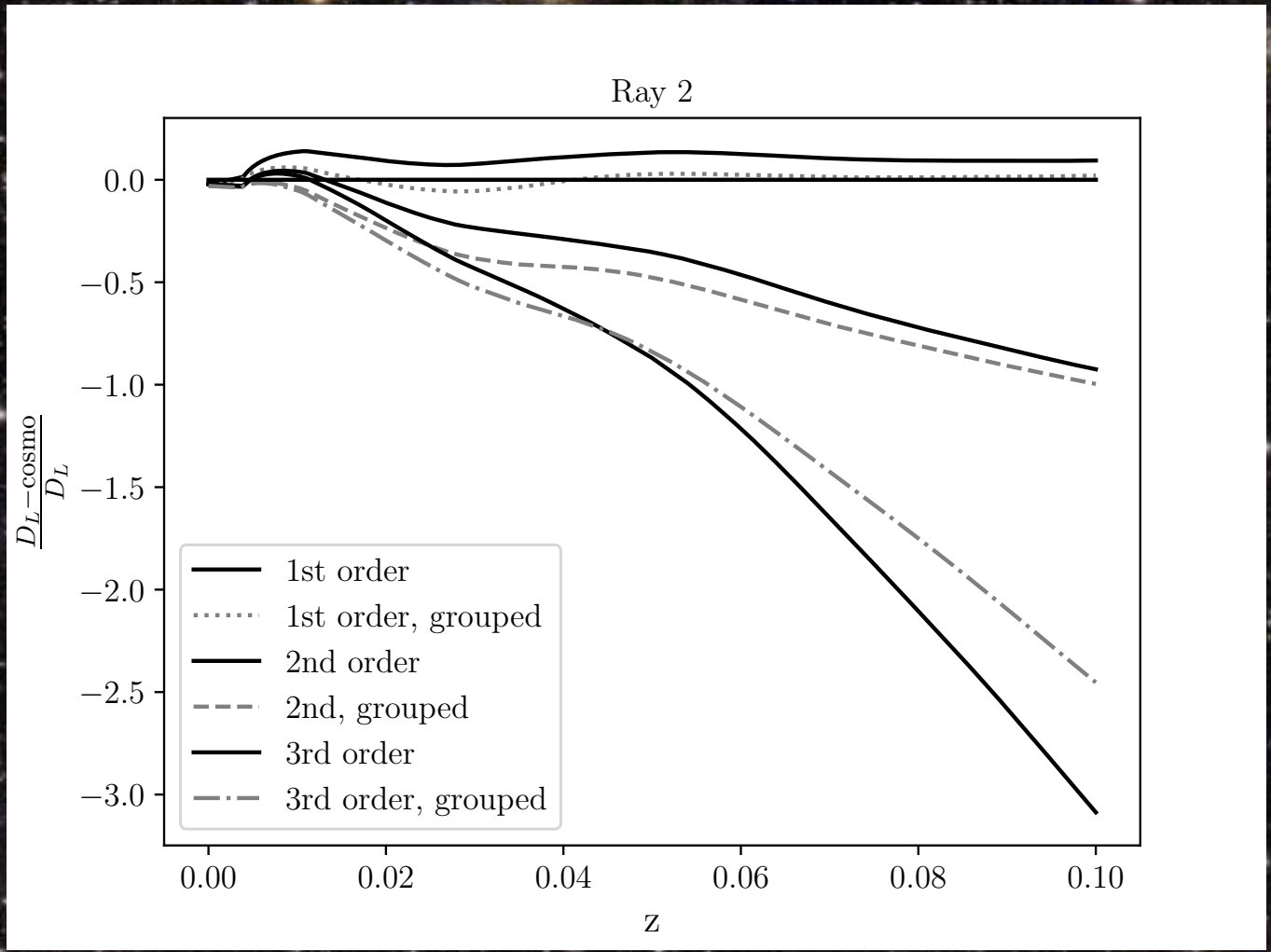
deceleration

$$D_L^{(3)} = \frac{c}{H_0} \frac{-1 + 3q_0^2 + q_0 - j_0 + \mathcal{R}_0}{6}$$

jerk + curvature

2312.09875, 2401.12291, 2408.04333, 2010.06534, PhD thesis Umeh 2013, astro-ph/0006273

But general cosmographic expansions don't converge...



arXiv:2412.12637

Cosmography centered at arbitrary redshift

$$d'_A = -\frac{\hat{\theta}}{2(1+z)^2 E_o \mathcal{H}} d_A$$

$$d''_A = \frac{d_A}{2(1+z)^2 E_o \mathcal{H}} \left[\frac{2\hat{\theta}}{1+z} + \frac{\hat{\theta}\mathcal{H}'}{\mathcal{H}} - \frac{2|\hat{\sigma}|^2 + k^\mu k^\nu R_{\mu\nu}}{(1+z)^2 E_o \mathcal{H}} \right].$$

$$d'''_A = \frac{d_A}{2(1+z)^2 E_o \mathcal{H}} \left[\frac{3\left(2|\hat{\sigma}|^2 + k^\mu k^\nu R_{\mu\nu}\right)}{(1+z)^2 E_o \mathcal{H}} \left(\frac{2}{1+z} + \frac{\mathcal{H}'}{\mathcal{H}} \right) - \frac{\hat{\theta}\mathcal{H}''}{\mathcal{H}} - \frac{2\hat{\theta}\mathcal{H}'^2}{\mathcal{H}^2} - \frac{4\hat{\theta}\mathcal{H}'}{(1+z)\mathcal{H}} - \frac{6\hat{\theta}}{(1+z)^2} \right.$$
$$\left. - \frac{\left(k^\mu k^\nu R_{\mu\nu}\right)'}{(1+z)^2 E_o \mathcal{H}} - \frac{\hat{\theta}\left(2|\hat{\sigma}|^2 + k^\mu k^\nu R_{\mu\nu}\right) - 4\left(2\hat{\theta}|\hat{\sigma}|^2 + k^\alpha k^\beta C_{\mu\alpha\nu\beta}\hat{\sigma}^{\mu\nu}\right)}{2(1+z)^4 E_o^2 \mathcal{H}^2} \right].$$

arXiv:2608.07008

Sachs equations

$$\hat{\theta} = \frac{1}{D_A}\frac{dD_A}{d\lambda}$$

$$\frac{d\hat{\theta}}{d\lambda} + \hat{\theta}^2 + |\hat{\sigma}|^2 = -\frac{1}{2}R_{\alpha\beta}k^\alpha k^\beta$$

$$\frac{d\hat{\sigma}}{d\lambda} + 2\hat{\theta}\hat{\sigma} = -\frac{1}{2}C_{\alpha\beta\gamma\delta}\epsilon^{*\alpha}k^\beta\epsilon^{*\gamma}k^\delta$$

$$\hat{\theta} := \frac{1}{2}k^\alpha_{;\alpha}$$

$$\hat{\sigma} := \frac{1}{2}k_{\alpha;\beta}\epsilon^{*\alpha}\epsilon^{*\beta}$$

$$\sigma_{\alpha\beta} = Re(\hat{\sigma}\epsilon_\alpha\epsilon_\beta)$$

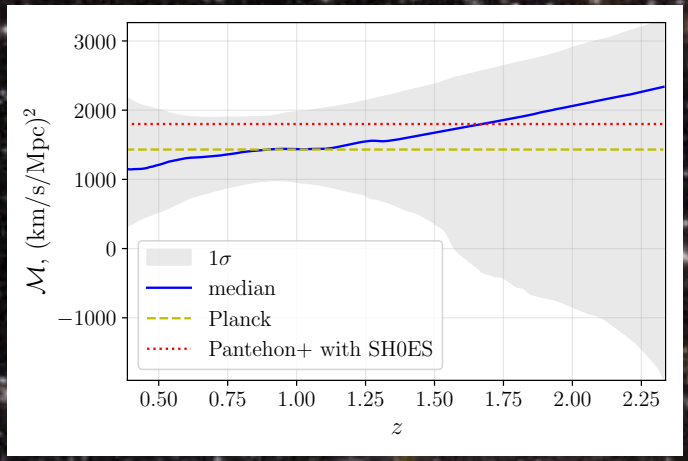
$$|\hat{\sigma}| := \frac{1}{2}\sigma_{\alpha\beta}\sigma^{\alpha\beta}$$

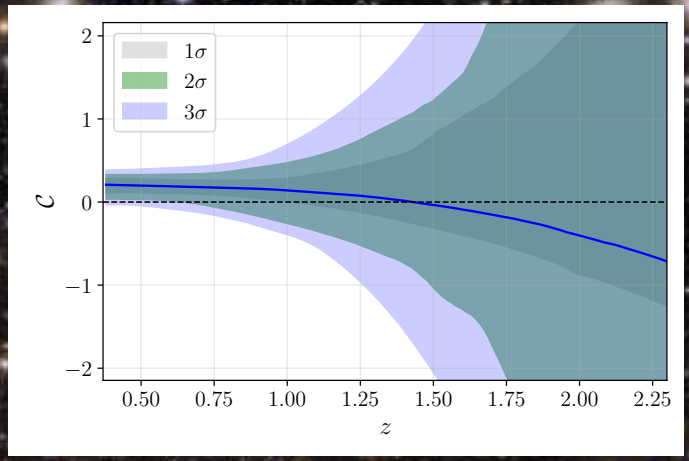
Data-driven cosmology with first-principles

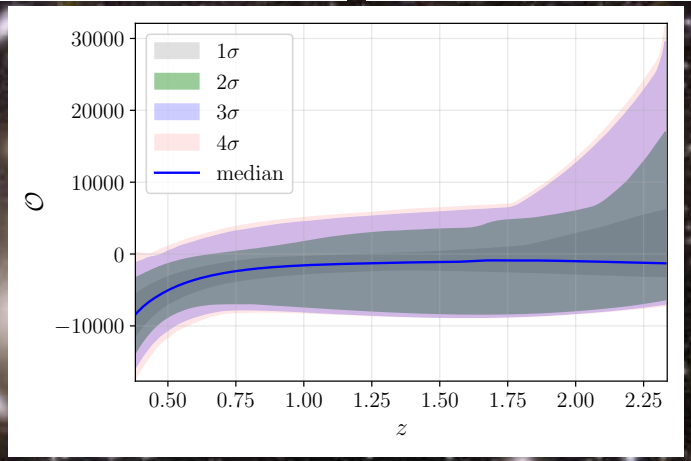
$$
\begin{aligned}
\mathcal{M} :=& -\frac{2\mathcal{H}^2}{3d_A(1+z)}\left(d_A'\left[\frac{2}{1+z}+\frac{\mathcal{H}'}{\mathcal{H}}\right]+d_A''\right) \\
=& \frac{2|\hat{\sigma}|^2 + R_{\mu\nu}k^\mu k^\nu}{3(1+z)^5} \\
\underset{\text{perfect fluid}}{=}& \frac{2|\hat{\sigma}|^2}{3(1+z)^5} + \frac{8\pi G}{3(1+z)^3}(\rho+p) \\
\underset{\Lambda\text{CDM}}{=}& \Omega_{m,0}H_0^2.
\end{aligned}
$$

arXiv:2604.05836, 2604.05822

First results







arXiv:2604.05836, 2604.05822