Testing the cosmological model with the large-scale structure

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CIEMAT

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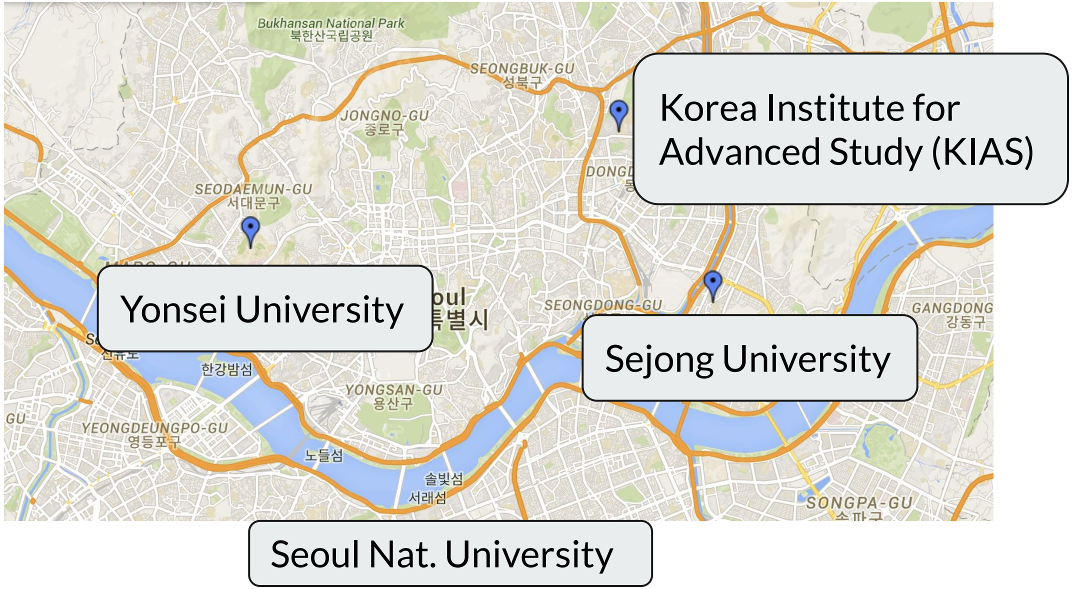
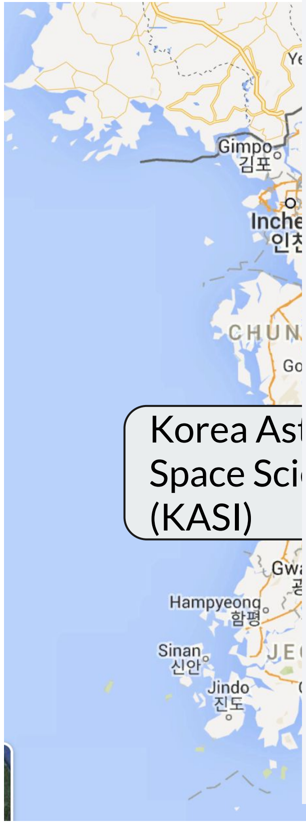
Astronomy & Cosmology in Korea (a totally biased picture!)



KASI & KIAS cosmology groups:
Members of DESI

Astronomy & Cosmology in Korea (a totally biased picture!)

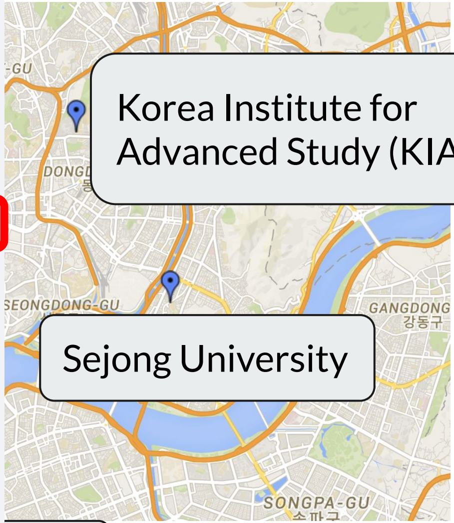


Korea Ast
Space Sci
(KASI)

All Countries and Economies

Country	Most Recent Year	Most Recent Value
Israel	2018	4.95
Korea, Rep.	2018	4.81
Switzerland	2017	3.37
Sweden	2018	3.34
Japan	2018	3.26
Austria	2018	3.17
Germany	2018	3.09
Denmark	2018	3.06
United States	2018	2.84

Source: World Bank (2018)



Korea Institute for Advanced Study (KIAS)

Sejong University

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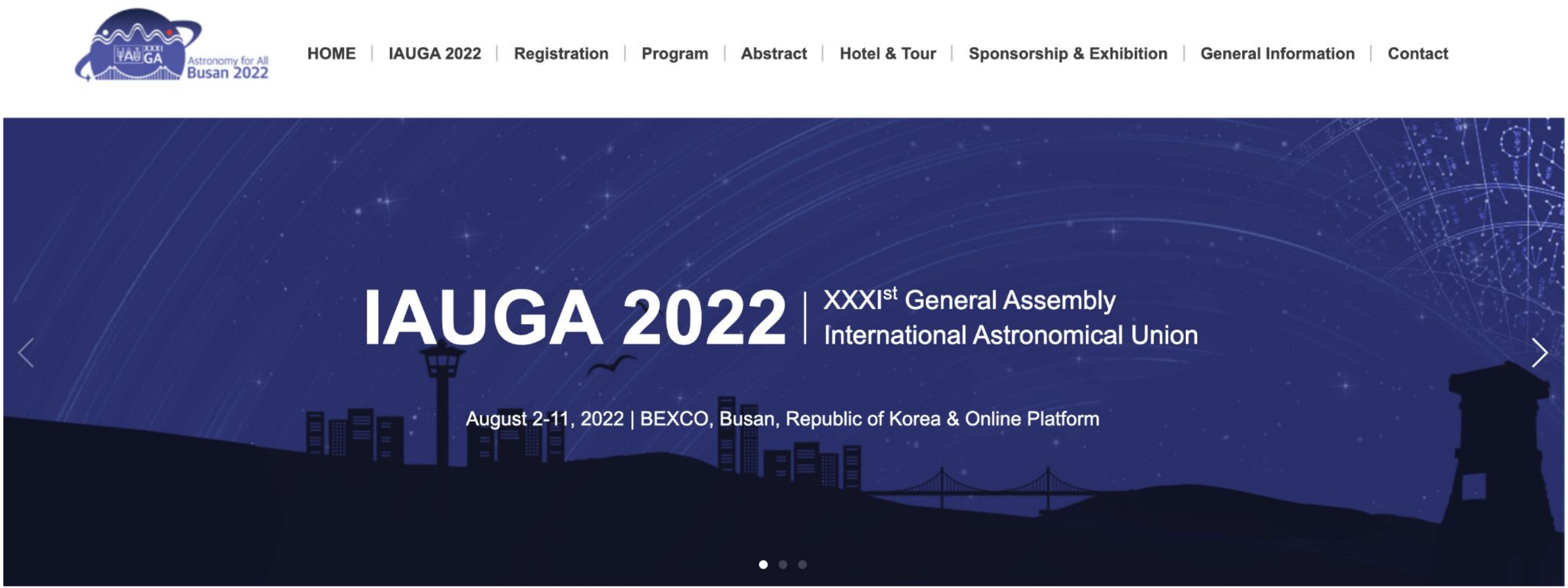
ps:

Astronomy & Cosmology in Korea (a totally biased picture!)



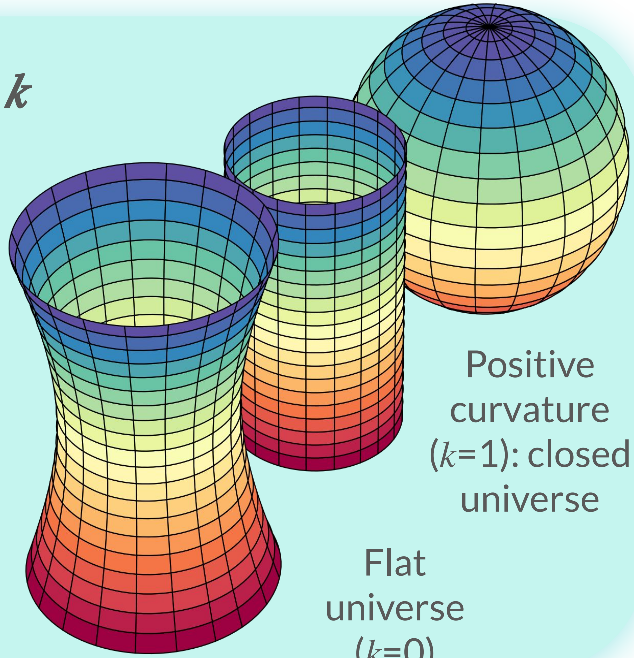
The Concordance Model

The concordance model of cosmology: the FLRW metric

- *Isotropy & Homogeneity* → *FLRW metric*

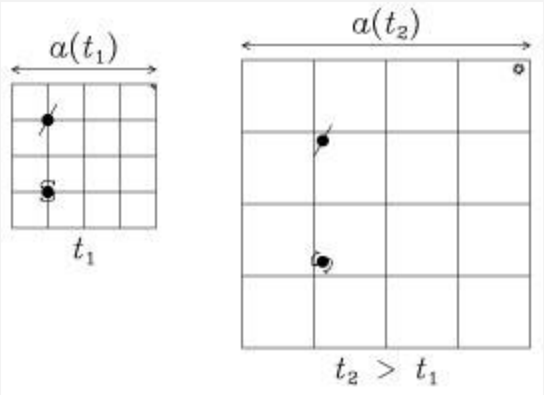
$$ds^2 = g_{\mu\nu}dx^\mu dx^\nu = c^2dt^2 - a^2(t)\left(\frac{dr^2}{1-kr^2} + r^2 d\Omega^2\right)$$

Curvature k



Wikipedia

Scale Factor a



Cosmology = study of a(t)

The concordance model of cosmology: Gravity

- ***Gravity:*** *General Relativity*
- ***Einstein Equations:*** $R_{\mu\nu} - \frac{1}{2}Rg_{\mu\nu} + \Lambda g_{\mu\nu} = \frac{8\pi G}{c^4}T_{\mu\nu}$

Geometry

Cosmological constant

Energy

- *Solve for the FLRW metric: obtain the* ***Friedmann Equations***

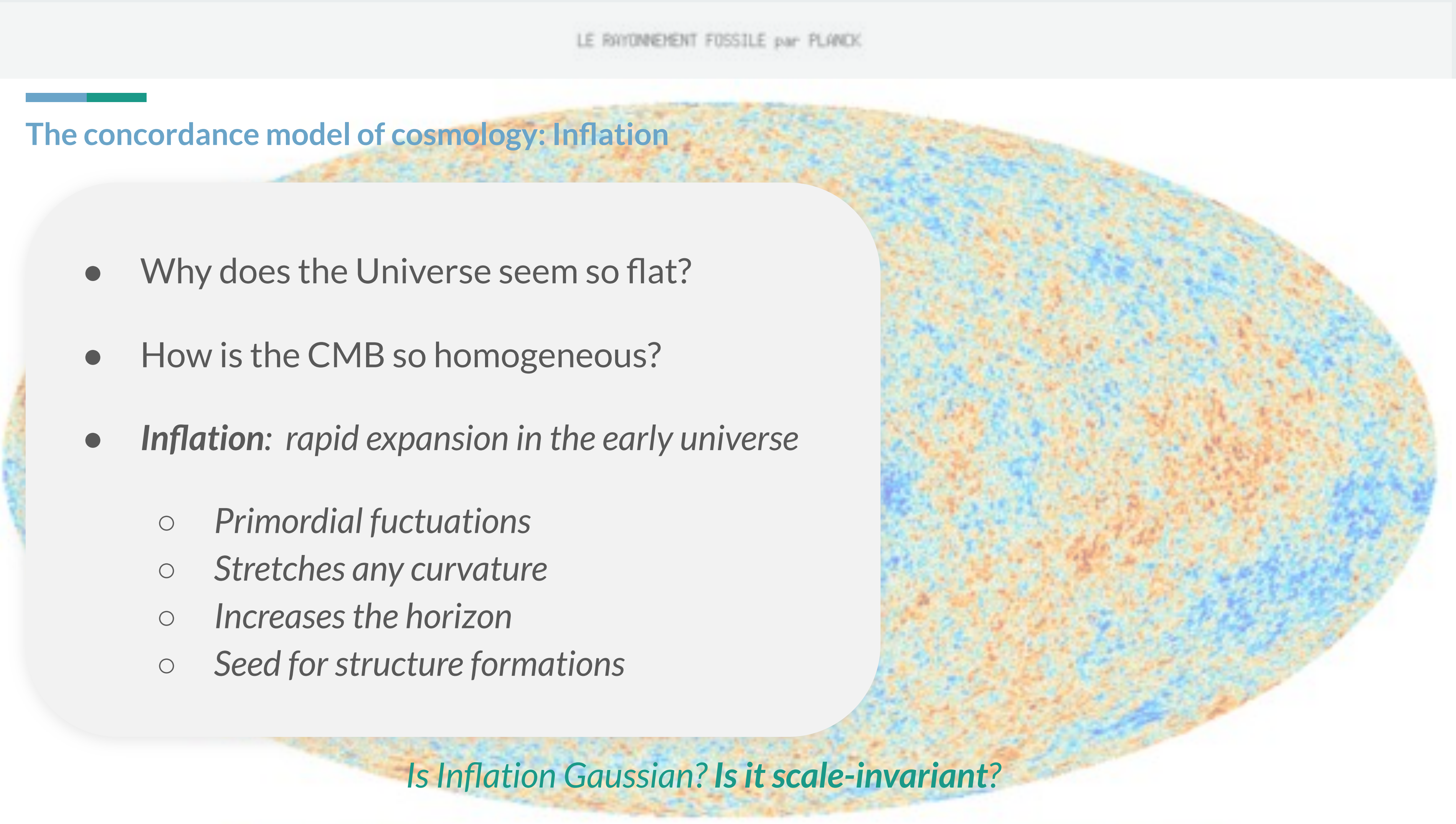
$$\left(\frac{\dot{a}}{a}\right)^2 = H^2 = \frac{8\pi G}{3}\rho - \frac{kc^2}{a^2} + \frac{\Lambda c^2}{3}$$

$$\frac{\ddot{a}}{a} = -\frac{4\pi G}{3}\left(\rho + \frac{3p}{c^2}\right) + \frac{\Lambda c^2}{3}.$$

Matter: density ρ, pressure p

Curvature k

Cosmological constant Λ



The concordance model of cosmology: Inflation

- Why does the Universe seem so flat?
- How is the CMB so homogeneous?
- ***Inflation**: rapid expansion in the early universe*
    - *Primordial fuctuations*
    - *Stretches any curvature*
    - *Increases the horizon*
    - *Seed for structure formations*

*Is Inflation Gaussian? **Is it scale-invariant**?*

The concordance model of cosmology

Isotropy & Homogeneity
FLRW metric

A theory of gravity
General relativity

Initial conditions
Inflation

- *Flat Universe dominated by dark energy & dark matter*
- *Concordance: CMB, BAO, SNIa*
- *But… tensions*

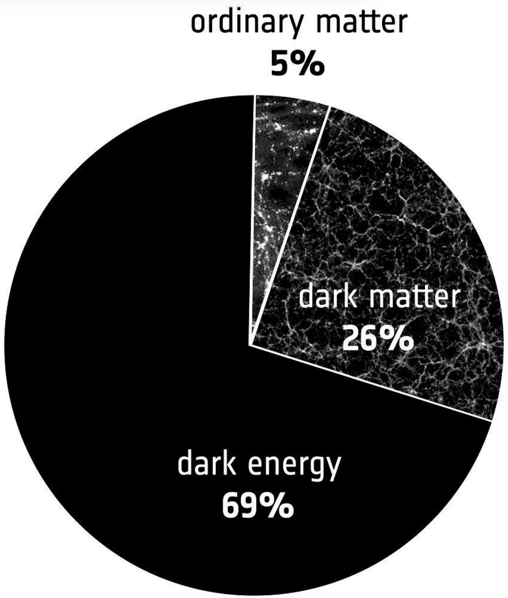


Image Credit:
Science/AAAS

The large scale structure hold valuable information

Advanced Statistical Methods

Model-dependent Methods

- *Widely used; more straightforward (model-fitting), "easier"*
- *More constraining power*
- ***Bias towards the (assumed) model***

MCMC, Nested sampling

vs.

Model-independent Methods

- *Less straightforward; overfitting problem*
- *Less constraining power*
- *More flexibility*
- ***No bias towards any model***
- ***Can detect unexpected features in the data***

Gaussian process, iterative smoothing,
Crossing statistics, …

Both approaches ***can*** and ***should*** be used **together**

The Linear Regime

The concordance model of cosmology

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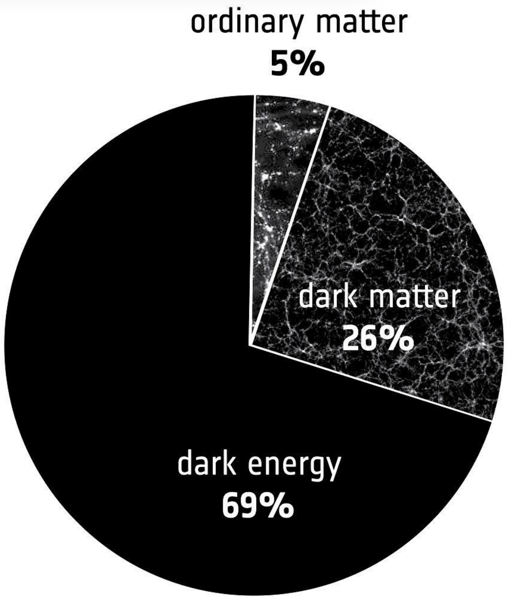

Image Credit:
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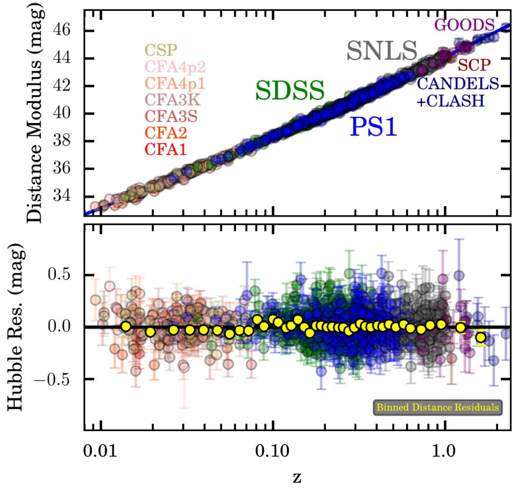
» *The large scale structure hold valuable information*

Background Expansion: Observables

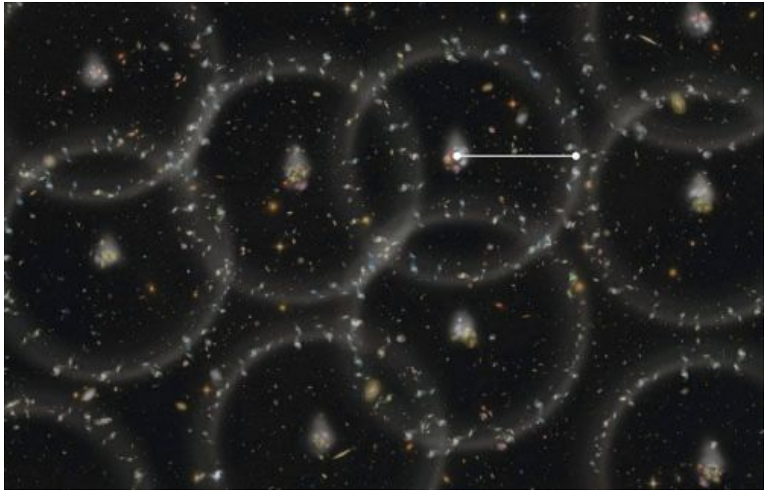
Type Ia Supernovae (SNIa): *standard candles*



Known luminosity → *Luminosity Distance*

$$\mu(z) = 5\log_{10} d_L(z) + cst$$

Baryon acoustic oscillations (BAO): *standard ruler*

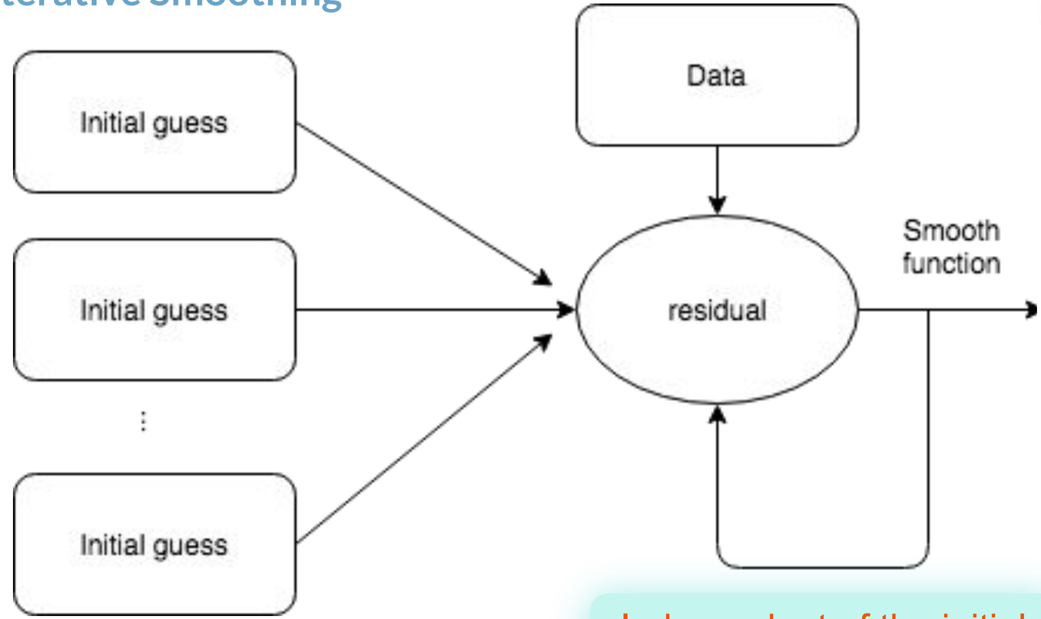


Known size → *Angular Diameter Distance, Hubble Parameter*

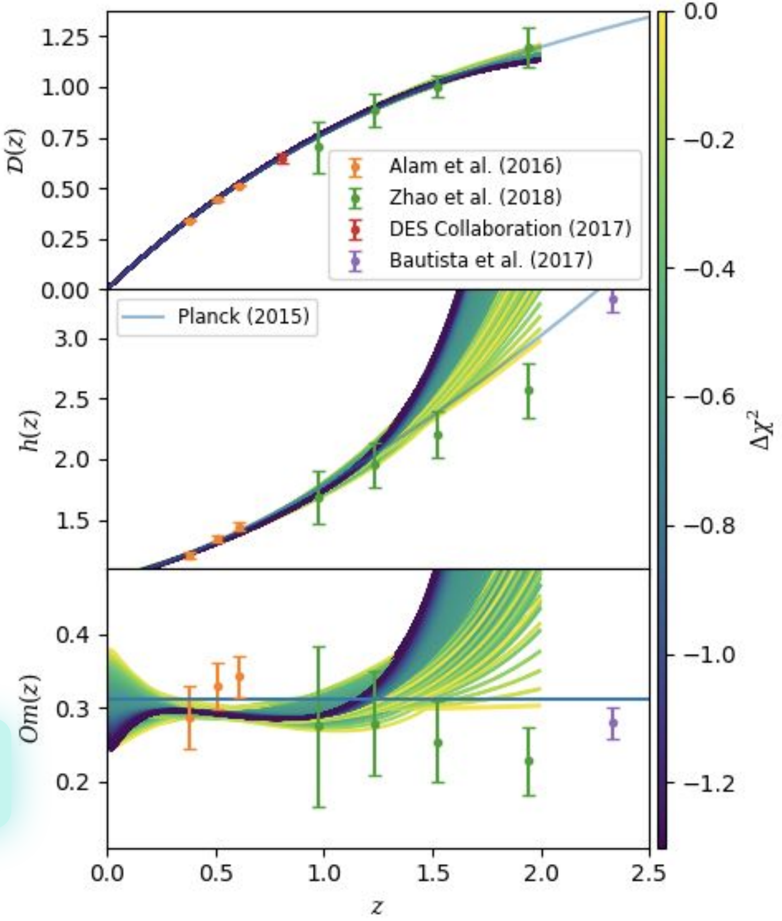
$d_A(z)/r_d$, $H(z)\, r_d$

$$r_d = \frac{c}{H_0\sqrt{3}} \int_0^{1/(1+z_d)} \frac{da}{a^2 h(a)\sqrt{1+\frac{3\Omega_b}{4\Omega_r}a}}$$

Direct reconstruction of the Expansion History: Iterative Smoothing



Independent of the initial guess!



Shafieloo et al. (2006), Shafieloo (2007)
BL & Shafieloo (2017)
Shafieloo, BL, Starobinsky (2018)

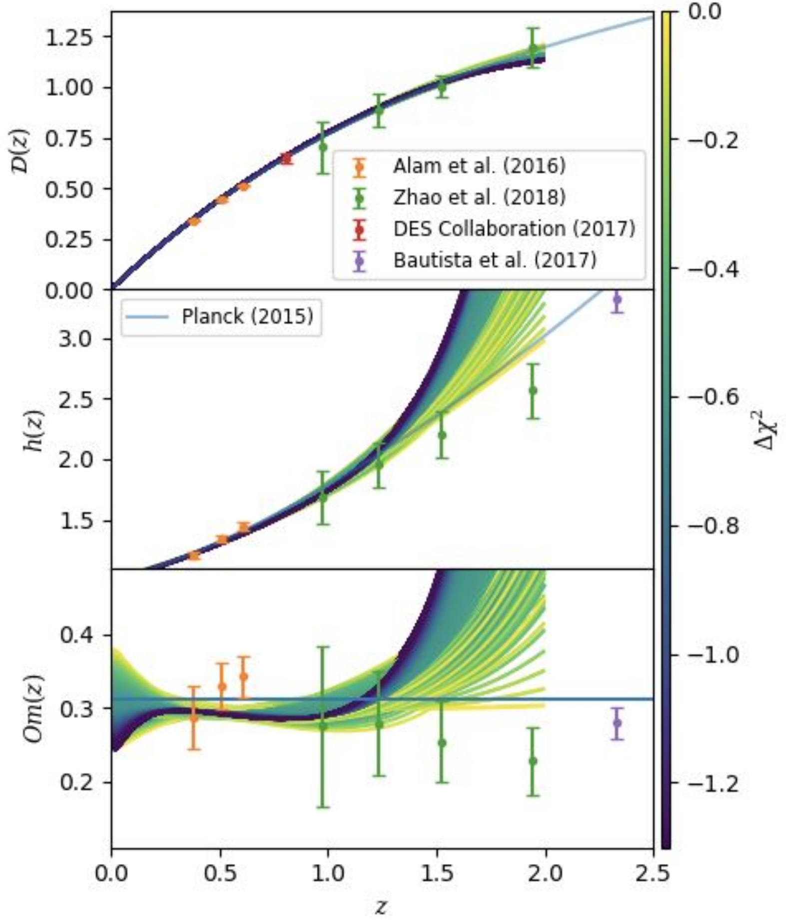
Testing Flat-ΛCDM

Consistent with Flat-ΛCDM at z < 1.5

Hints of tension at z>1.5 (cf. Sahni et al. 2014, Zhao et al. 2017)

Om diagnostics (Sahni et al. 2008):

$$Om(z) = \frac{h^2(z)-1}{(1+z)^3-1} \overset{\text{flat-}\Lambda\text{CDM}}{\equiv} \Omega_{m,0}$$



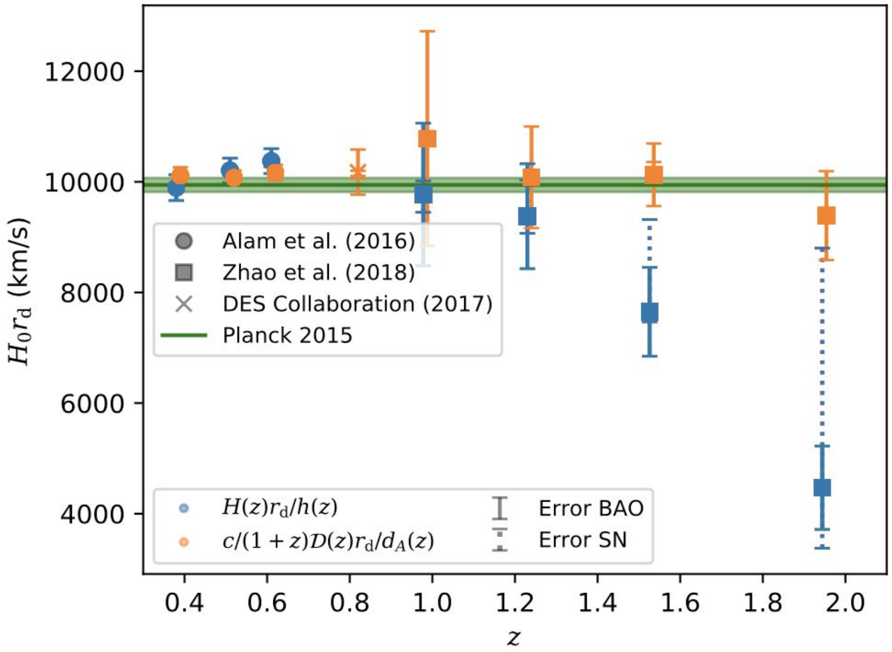
BL & Shafieloo (2017)
Shafieloo, BL, Starobinsky (2018)

Model-independent Measurement of $H_0 r_d$

SNIa: Pantheon $\rightarrow$ $H_0 d_L(z)/c$

BAO: (e)BOSS $\rightarrow$ $H(z) r_d$, $d_A(z)/r_d$

$$H_0 r_d = \frac{H(z) r_d}{h(z)} = \frac{c}{1+z} \frac{\mathcal{D}(z) r_d}{d_A(z)}$$



Consistent with Planck 2015: $H_0 r_d$ = (9944.0 +/- 127.4) km s^{-1}

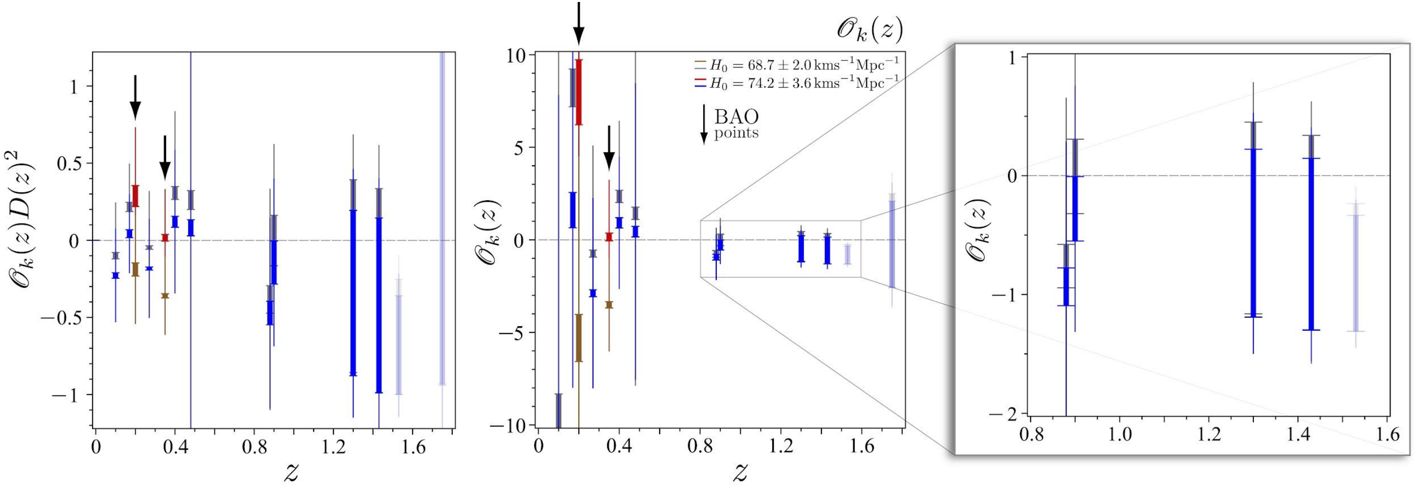
BL & Shafieloo (2017)
Shafieloo, BL, Starobinsky (2018)

Model-independent test of FLRW metric & curvature

Clarkson et al. (2008):

$$\mathcal{D}(z) = \frac{1}{\sqrt{-\Omega_k}} \sin\left(\sqrt{-\Omega_k}\int_0^z \frac{\mathrm{d}x}{h(x)}\right)$$

$$\mathcal{O}_k(z) = \frac{(h(z)\mathcal{D}'(z)^2 - 1)}{\mathcal{D}^2(z)} = \frac{\left(\frac{H(z)\mathcal{D}'(z)}{H_0}\right)^2 - 1}{\mathcal{D}^2(z)} \overset{\text{FLRW}}{\equiv} \Omega_k$$



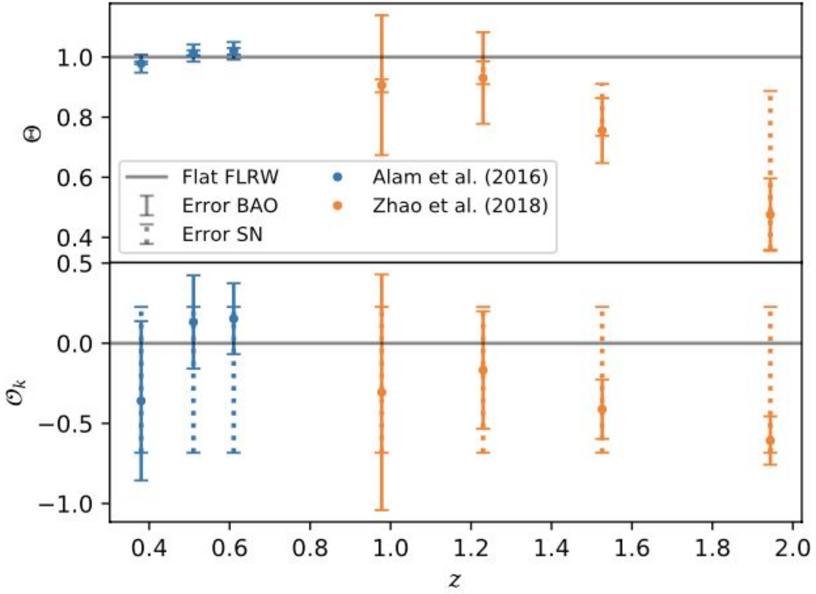
Shafieloo & Clarkson (2010)

Model-independent test of FLRW metric & curvature

New formulation:

$$\Theta(z) = h(z)\mathcal{D}'(z) = \frac{(1+z)}{c} H(z) r_d \frac{d_A(z)}{r_d} \frac{\mathcal{D}'(z)}{\mathcal{D}(z)} = F_{AP}(z) \frac{\mathcal{D}'(z)}{\mathcal{D}(z)} \overset{\text{flat-FLRW}}{\equiv} 1$$

$$\mathcal{O}_k(z) = \frac{\Theta^2(z) - 1}{\mathcal{D}^2(z)} \overset{\text{FLRW}}{\equiv} \Omega_k$$



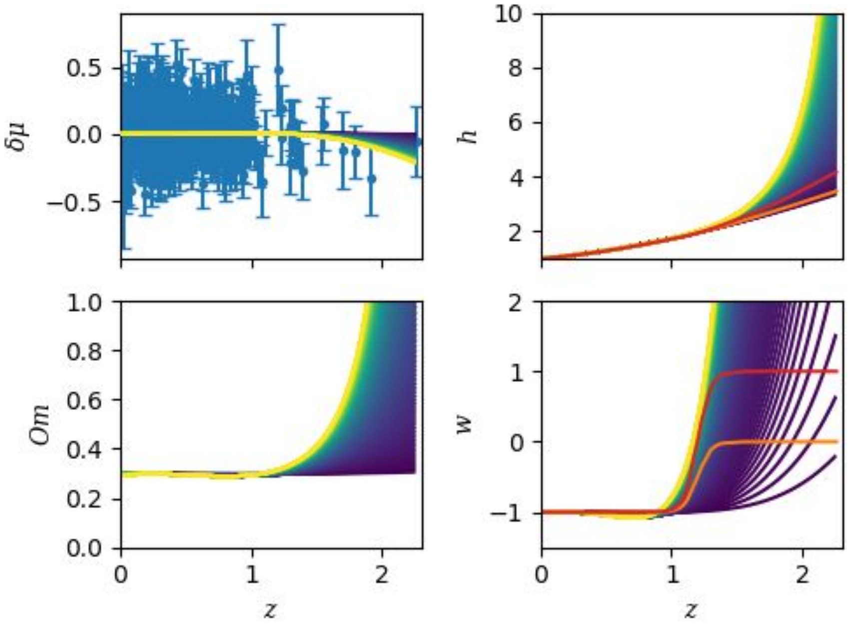
Consistent with flat FLRW

Consistency BAO ↔ SNIa

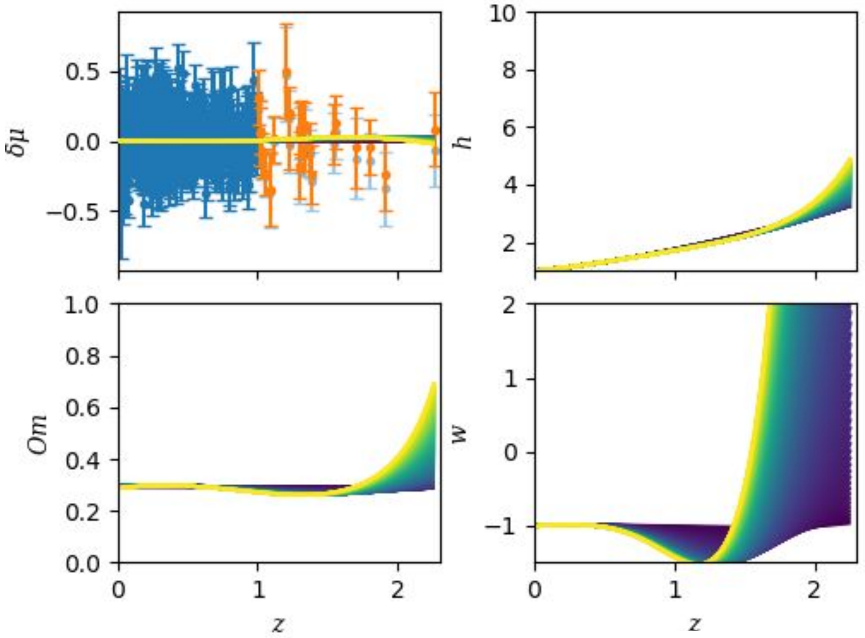
Hints of deviations at high-z?

BL & Shafieloo (2017)
Shafieloo, BL, Starobinsky (2018)

High-z SNIa: cosmology or systematics?



Possible deviation from LCDM at high-z
Difficult to reproduce by dark energy models



Malmquist-like correction: $\mu \to \mu + A(z-1)$
Om better behaved
Not statistically significant

BL, Shafieloo, Linder, Kim (2019)

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Isotropy & Homogeneity
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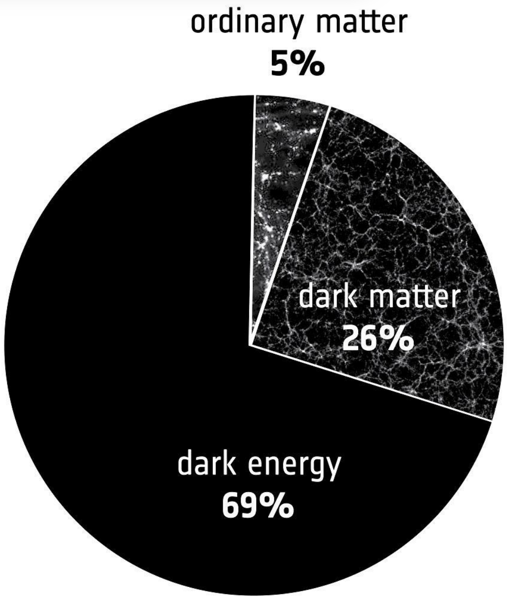


Image Credit:
Science/AAAS

» ***The large scale structure hold valuable information***

Redshift-space Distortion

Expansion (background)

Modified Gravity

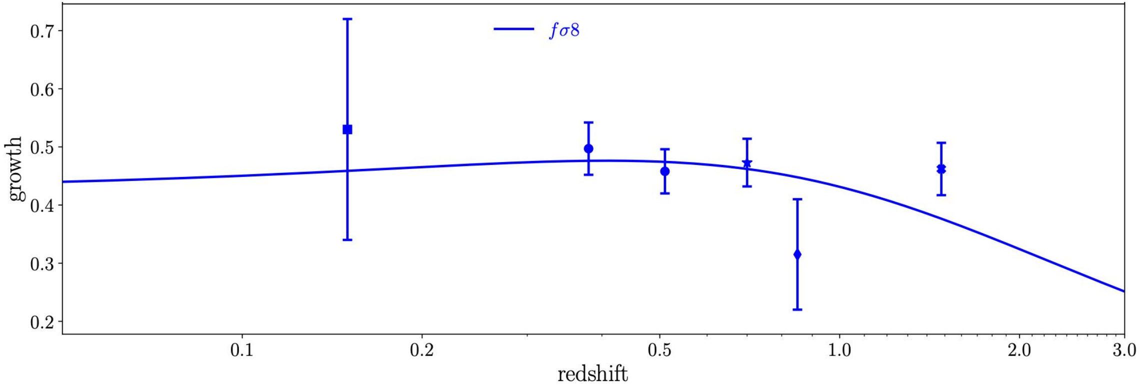
Linear growth of perturbations:

$$\ddot{\delta} + 2H\dot{\delta} = \frac{3}{2}\Omega_{\rm m} H^2 \frac{G_{\rm eff}}{G_{\rm N}}\delta \longrightarrow D(z)$$

Growth rate:

$$f = \frac{\mathrm{d}\ln D}{\mathrm{d}\ln a} \simeq \Omega_m^{\gamma}$$

σ_8 : *rms of the fluctuations* δ



eBOSS final results (2007.08991)

Reconstructing Expansion from Growth

$$f\sigma_8 = \sigma_{8,0}\,\Omega_{\rm m}^{\gamma}\,\exp\left(-\int_a^1 \Omega_{\rm m}^{\gamma}\,{\rm d}\ln a\right)$$

BL et al. (2018), Shafieloo, BL & Starobinsky (2018)

EXPANSION ⇄ *GROWTH*

Starobinsky (1998) exact formula (in GR):

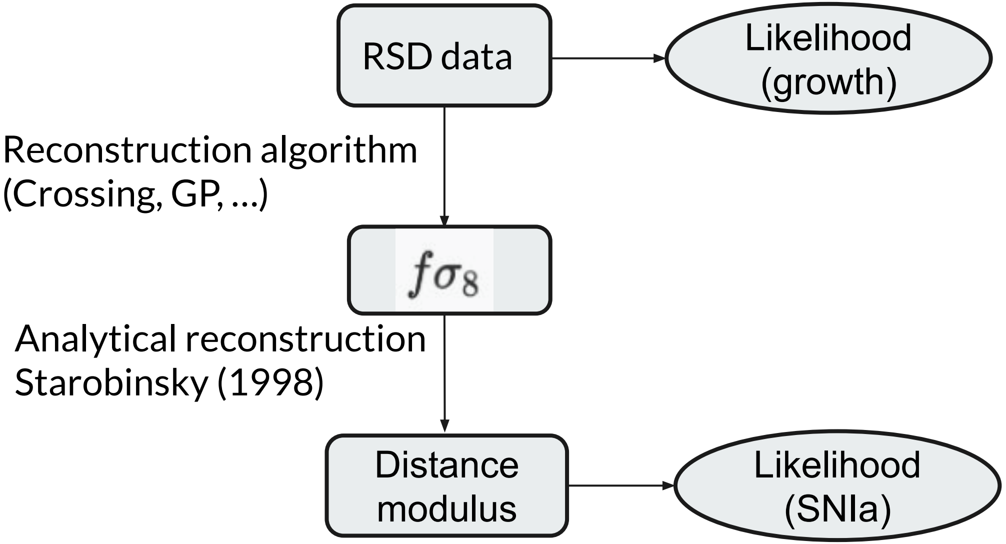
$$h^2(z) = \left(\frac{1+z}{\delta'(z)}\right)^2 \left(\delta_0'^2 - 3\Omega_{\rm m0}\int_0^z \delta(u)|\delta'(u)|\frac{{\rm d}u}{1+u}\right)$$

"Only" dependent on

$(\Omega_{\rm m0}\,,\,\sigma_{8,0}\,,\,\delta(z))$

** Independent of Dark Energy!*

Reconstructing Expansion from Growth



BL, Shafieloo, Polarski, Starobinsky (2020)

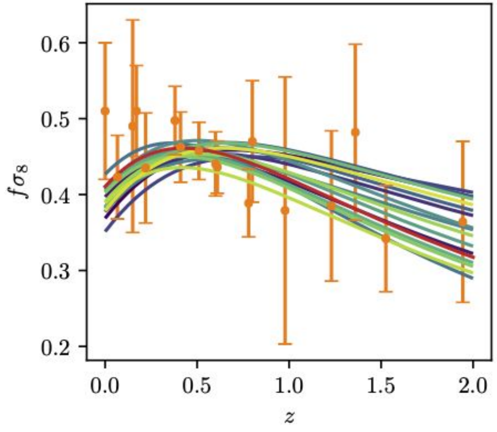
Reconstructing Expansion from Growth: Crossing statistics

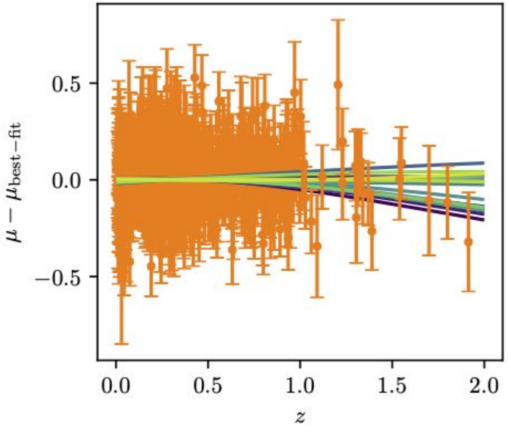
Crossing statistics (Shafieloo 2011,2012):
"How consistent is the considered model with the data?"

- ➔ Mean function ("what we want to test"): best-fit LCDM

Multiply by hyperfunction (Chebyshev polynomials with coeffs. C_i)

What is the posterior distribution of C_i? Deviation from the mean function?

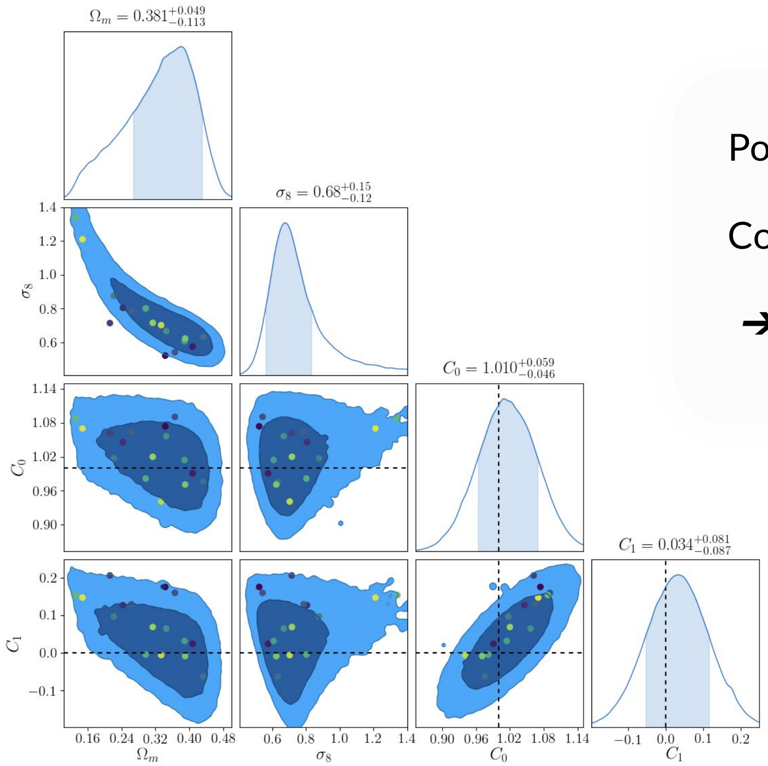




Deformations of the mean function (best-fit, red)

BL, Shafieloo, Polarski, Starobinsky (2020)

Reconstructing Expansion from Growth: Crossing statistics



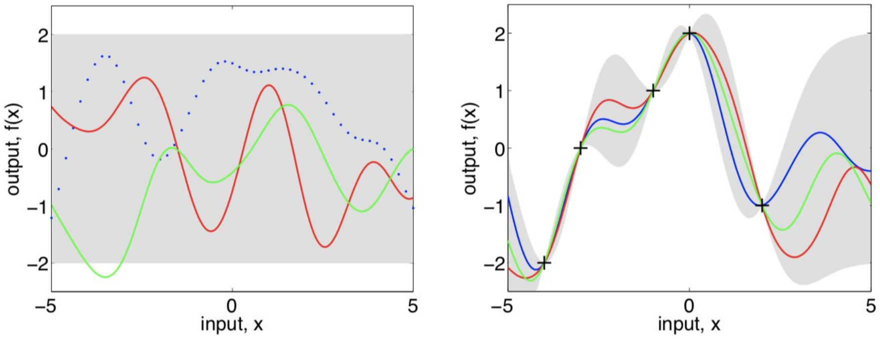
Posterior distribution of C_i:

Consistent with $C_0 = 1, C_i = 0$:

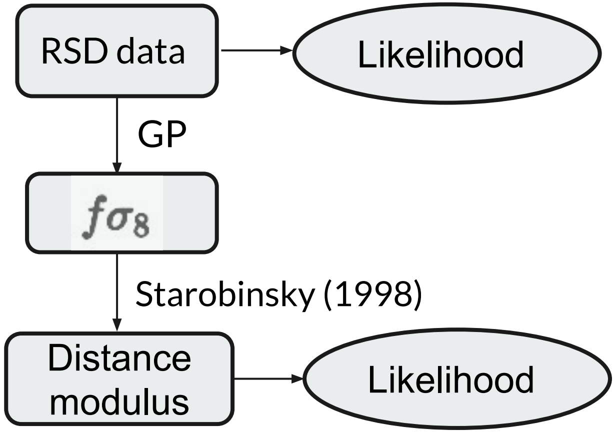
➔ *The data does not require deviation from ΛCDM+GR*

<u>*BL, Shafieloo, Polarski, Starobinsky (2020)*</u>

Reconstructing Expansion from Growth: Gaussian Process



(a), prior (b), posterior



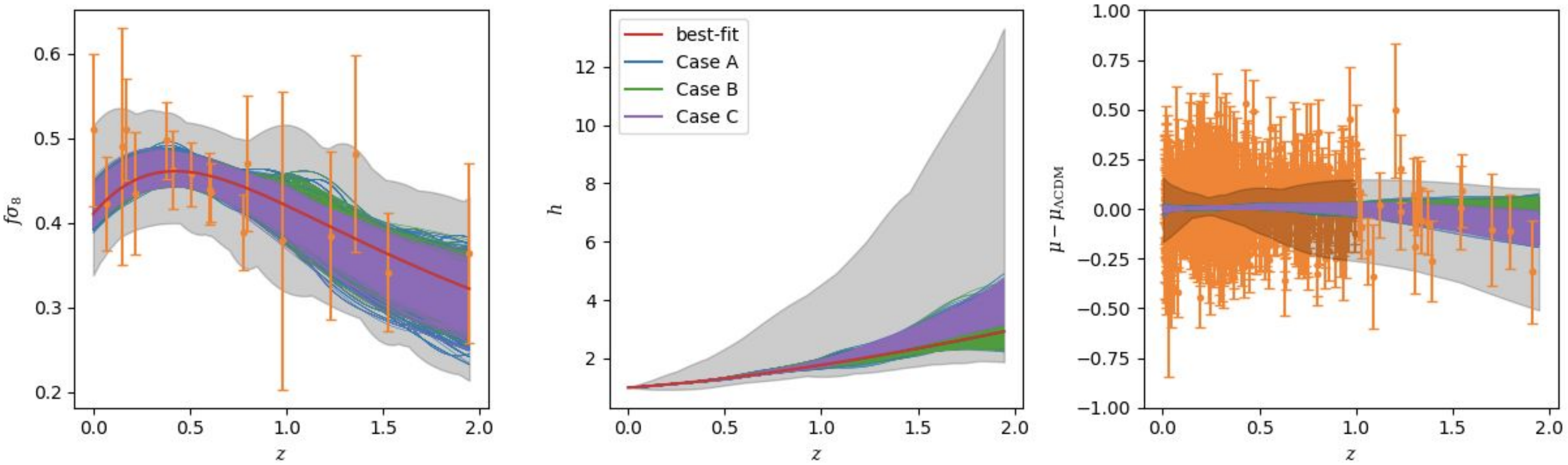
Observations y_i reconstruct f(z)?

Ansatz: (y_i, f(z_j)) are jointly Gaussian, with an input-covariance

The hyper-parameters of the GP are trained on the data

BL, Shafieloo, Polarski, Starobinsky (2020)

Reconstructing Expansion from Growth: Gaussian Process



Consistent with GR+LCDM

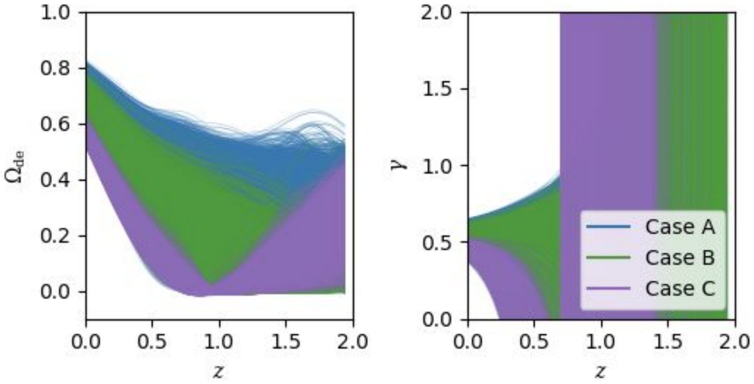
DE energy density is not guaranteed to be positive!

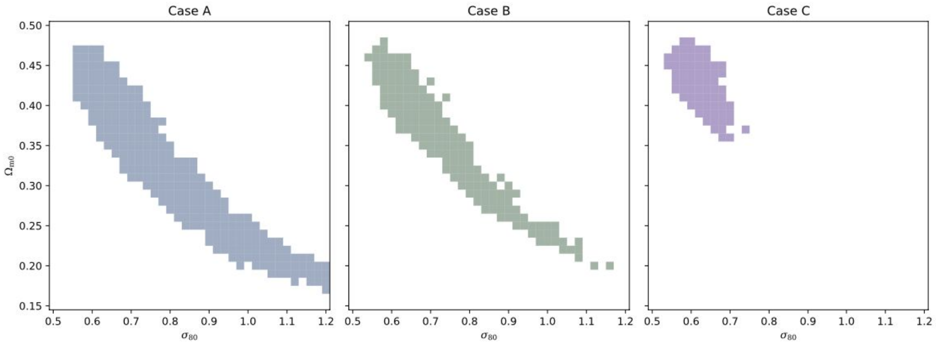
$$\Omega_{DE}(z) = 1 - \frac{\Omega_{m0}(1+z)^3}{h^2(z)}$$

- Case A: $\Omega_{DE}(z < 2) > 0$
- Case B: $\Omega_{DE}(z < 1) > 0$
- Case C: $\Omega_{DE}(z < 0.7) > 0$

BL, Shafieloo, Polarski, Starobinsky (2020)

Negative DE Energy Density?





- Case A: $\Omega_{DE}(z < 2) > 0$
- Case B: $\Omega_{DE}(z < 1) > 0$
- Case C: $\Omega_{DE}(z < 0.7) > 0$

High $\Omega_{m,0}$ and low $\sigma_{8,0}$ allowed by the data

BL, Shafieloo, Polarski, Starobinsky (2020)

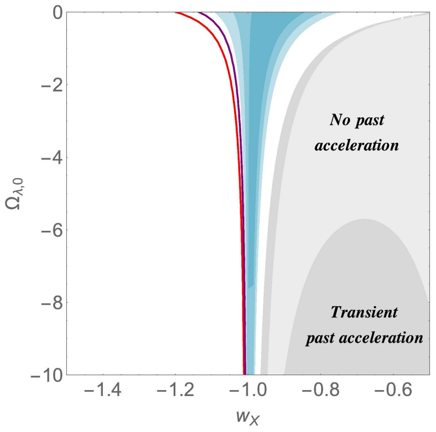
Negative DE Energy Density?

Toy model: Negative cosmological constant

Two DE components X and λ:

Constant λ<0

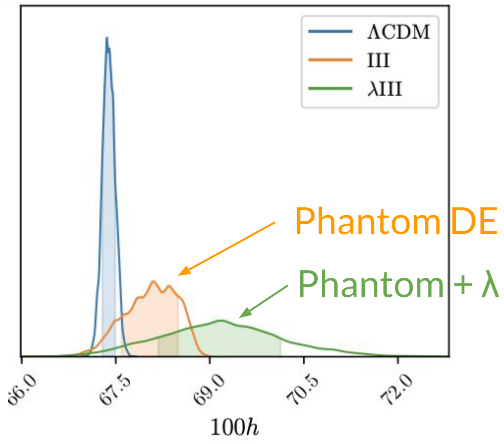
X: Phantom behaviour: $w_X(0.1 < z < 1) < -1$



Interesting transient acceleration in the past

Not excluded by the data (similar Bayesian evidence as LCDM)

Can mitigate the H_0 tension

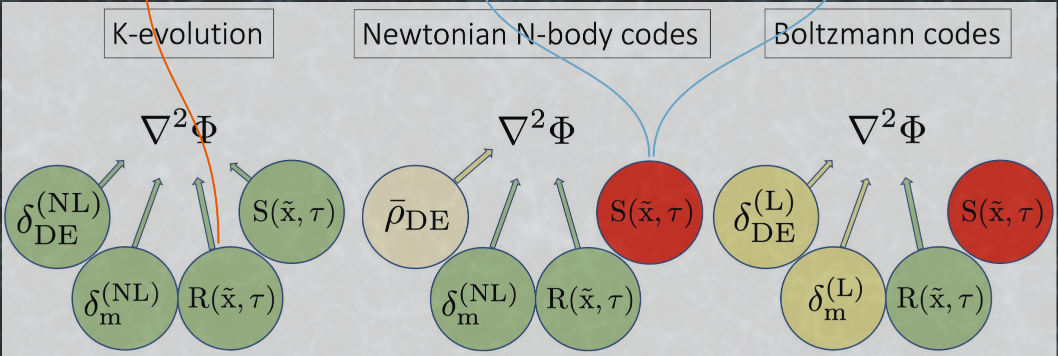


Calderón, Gannouji, BL, Polarski (2021)

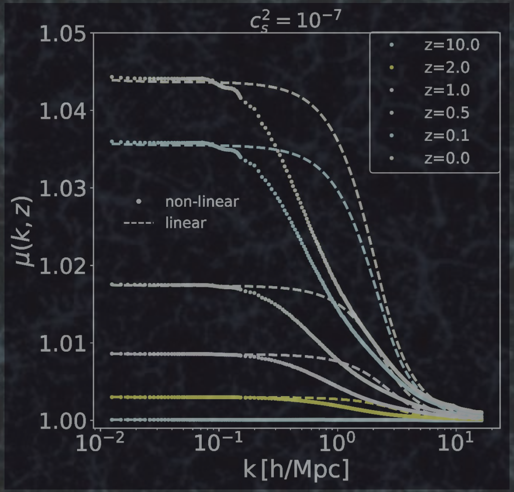
The non-linear Regime:
N-body Simulations

Parametrizing Nonlinear DE Perturbations

$$\nabla^2\Phi = 3\mathcal{H}\Phi' + 3\mathcal{H}^2\Psi + \frac{1}{2}\delta^{ij}\Phi_{,i}\Phi_{,j} + 4\pi G_N a^2(1-2\Phi)\sum_X \bar{\rho}_X\delta_X\ ,$$



- Relativistic N-body code k-evolution (Hassani et al)
  - Effects of **non-linearity**
  - **Non-Λ Dark Energy** (k-essence)



Deviation from GR (μ ≡ 1)

Hassani, BL+(2020)

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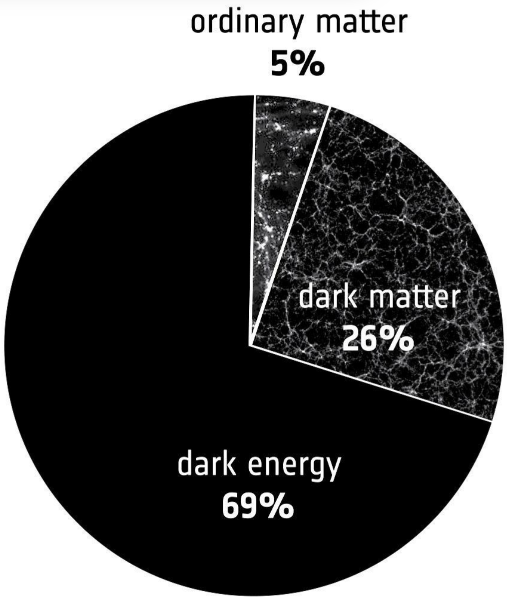


Image Credit:
Science/AAAS

» ***The large scale structure hold valuable information***

Planck 2018 constraints: power law

Parameter	Plik best fit	Plik [1]
$\Omega_b h^2$	0.022383	0.02237 ± 0.00015
$\Omega_c h^2$	0.12011	0.1200 ± 0.0012
$100\theta_{MC}$	1.040909	1.04092 ± 0.00031
τ	0.0543	0.0544 ± 0.0073
$\ln(10^{10} A_s)$	3.0448	3.044 ± 0.014
n_s	0.96605	0.9649 ± 0.0042

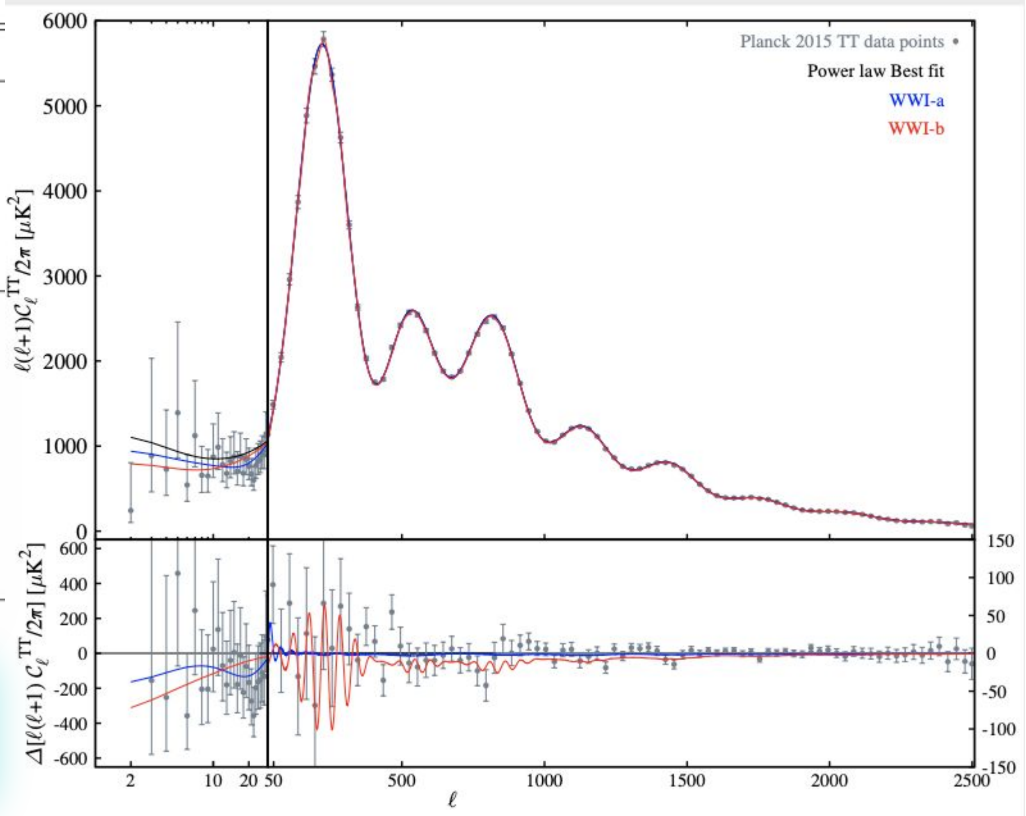
Power-law fits very well

But features still allowed at $\ell < 500$

Example: wiggly whipped inflation

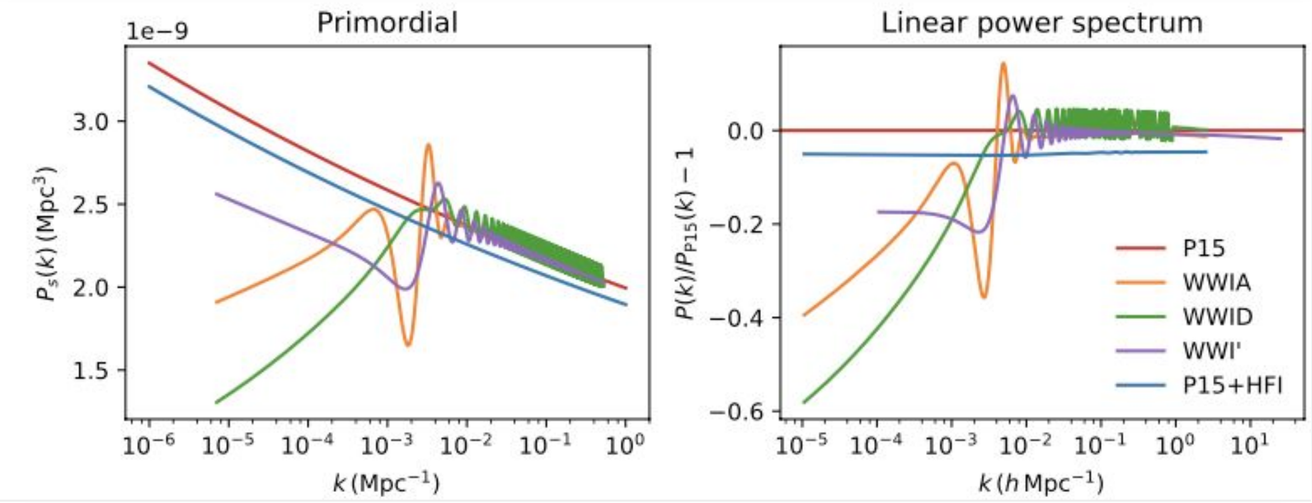
CMB: 2D info only

Can the LSS break the degeneracy?



Primordial Power Spectrum

BL, Shafieloo, Hazra, Smoot, Starobinsky (2018)



N-body simulations

15 realizations x 5 models

L=1.89 Gpc/h

N=1024^3

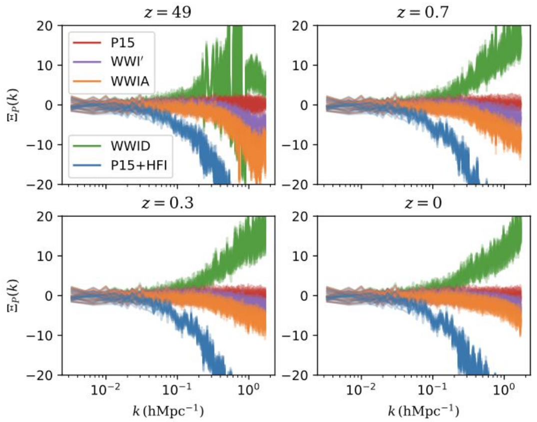
Reference model: Planck 2015 TTTEEE (P15)

Wiggly-whipped inflation (Hazra et al. 2014ab, 2016): WWIA, WWID, WWI’

Planck 2015 TTTEEE+HFI (P15+HFI)

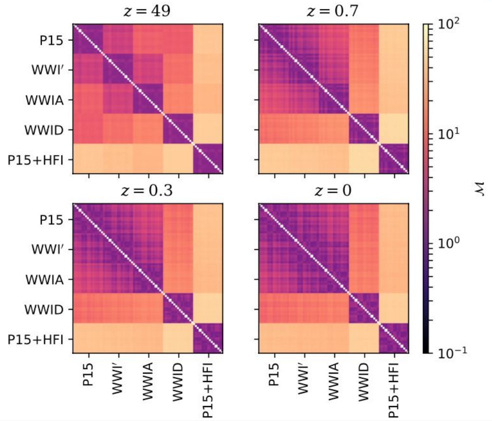
Matter Power Spectrum

BL, Shafieloo, Hazra, Smoot, Starobinsky (2018)



$$\Xi(k) = \frac{(P(k) - \langle P_{\mathrm{P15}}(k)\rangle)}{\sigma_P(k)}$$

$$M_{P,i,j}(k) = \sqrt{\frac{1}{N_k}\sum_k\left(\frac{P_i(k)-P_j(k)}{\sigma_P(k)}\right)^2}$$



Initial conditions: features visible

Features disappear in the non-linear regime

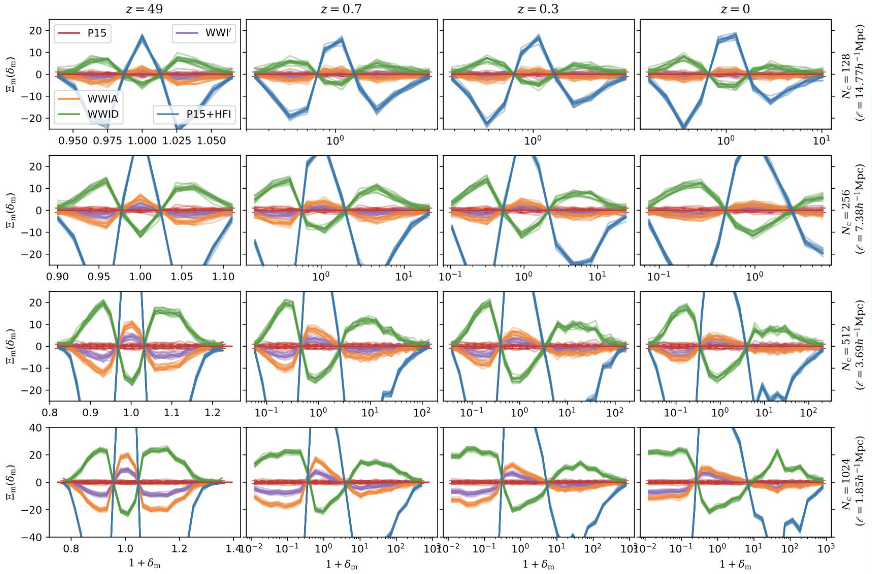
WWID, P15+HFI can be distinguished till z=0

WWIA, WWI' cannot be distinguished

Power spectrum may not be sufficient

Count-in-cell: Matter density

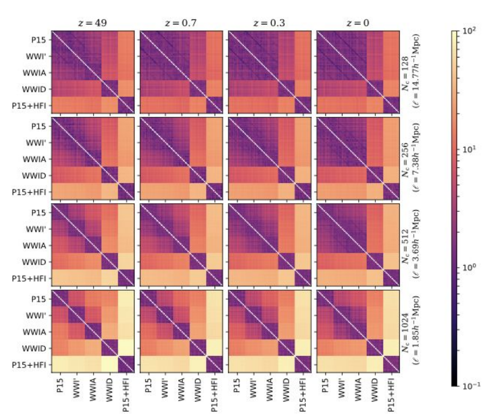
BL, Shafieloo, Hazra, Smoot, Starobinsky (2018)



Can distinguish between models!

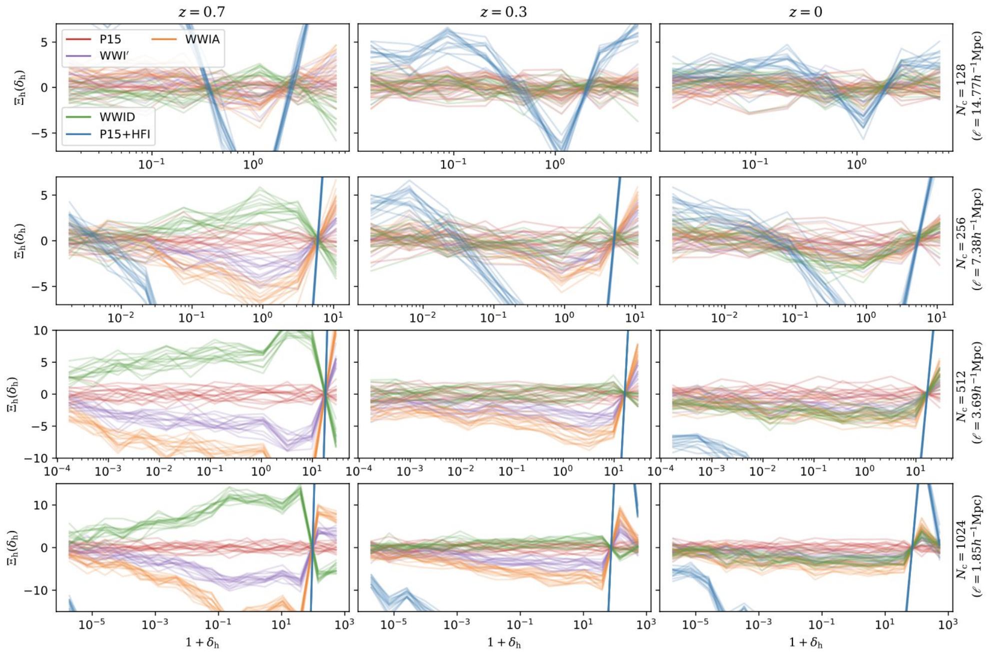
From 1D P(k) to 3D count-in-cell

Non-linear regime: P(k) does not capture all the information



Count-in-cell: Haloes

BL, Shafieloo, Hazra, Smoot, Starobinsky (2018)



Still holds!

But by z=0, difficult to distinguish

Summary

- Current data are consistent with Flat FLRW, Λ as dark energy, GR as gravity, but room for deviation
- Modeling the non-linear regime with N-body simulations beyond ΛCDM
  - Relativistic simulations of DE: quantifying and parametrizing the deviation from ΛCDM
  - LSS can help constraining the early Universe: 3 dimensional info
- Future surveys (DESI) will help

- ¡Gracias! -

- 감사합니다 -