Cosmological structure formation in ΛCDM and beyond: Testing ΛCDM with N-body simulations and advanced statistical methods

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The Concordance Model of Cosmology

Hypotheses

- Gravity described by General Relativity (GR)
- Isotropy and homogeneity
- Inflation in the early Universe, nearly scale-invariant power-law primordial power spectrum

The concordance ΛCDM model

- Solution of the Einstein equations: FLRW metric
- Flat Universe
- Universe dominated by dark energy (Λ) and cold dark matter (CDM)
- Observationally supported by different datasets
- But what are dark energy and dark matter?
- Is gravity correctly described by GR?

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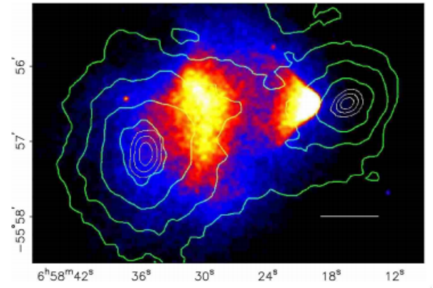
Observational evidence

Dark Universe

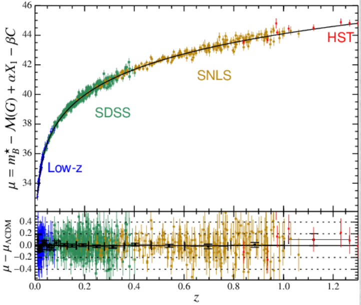
Dark Matter



Clowe et al. (2006)

- Zwicky (1937): velocity dispersion in the Coma cluster is too high: *dunkle Materie* (dark matter)
- Rubin 1970: rotation curve of Andromeda doesn't follow the light distribution
- Cosmological microwave background (CMB): dark matter is needed
- Gravitational lensing, bullet cluster, ...

Dark Energy



JLA, Betoule et al. (2014)

- Einstein (1917): static solution, introduces Λ to make the universe static.
- After the discovery of the expansion: Λ removed
- Perlmutter et al. (1998), Riess et al. (1998): Supernovae show the expansion is accelerated!
- Supported by CMB experiments (WMAP, Planck)

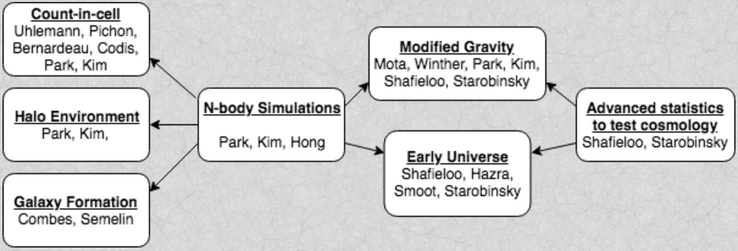
Dark energy problem

Einstein equation:

$$R_{\mu\nu} - \frac{1}{2}Rg_{\mu\nu} + \Lambda g_{\mu\nu} = \frac{8\pi G}{c^4}T_{\mu\nu} \tag{1}$$

- Simplest form: dark energy (DE)$= \Lambda$
- But measured value $\ll$ prediction
- If not Λ, what is DE?
  - Fluid with equation of state w (quintescence, ...)
  - Dynamical dark energy $w(z)$
- Or gravity is not GR? $\rightarrow$ *Modified gravity* (MG)
  - GR is the only 2nd order, 4-dimensional, local metric theory

Falsifying the concordance model of cosmology



Observations ↔ Simulations ↔ Theory

My approach

- Non-linear regime: N-body simulations
- Model-independent methods: look for unexpected features in the data
- Complementary approaches to test the concordance model

Falsifying the concordance model of cosmology

- Non-linear structure formation: N-body simulations
- Parametric approaches
  - simpler (model fitting)
  - Smaller contours
  - Bound by the model
- Non-parametric approaches
  - Can be more difficult
  - May find unexpected features
- Need both!

Initial conditions

Lagrangian perturbation theory

$$\mathbf{x}(\mathbf{q}, z) = \mathbf{q} + \Psi(\mathbf{q})$$

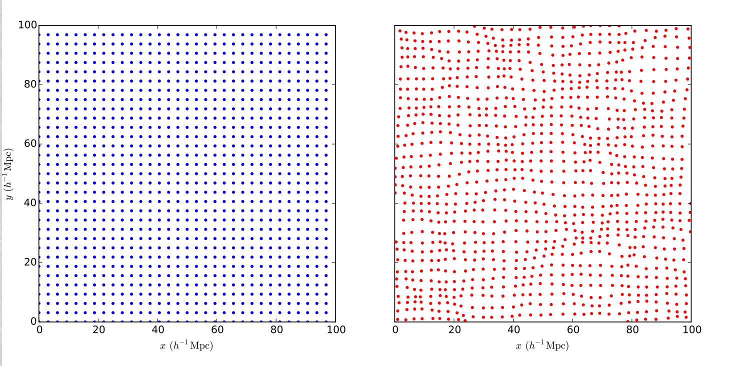
$$\mathbf{v}(\mathbf{q}, z) = \dot{\Psi}(\mathbf{q}, z)$$

$$\Psi(\mathbf{q}) = \Psi^{(1)}(q) + \Psi^{(2)}(q) + \cdots$$

$\mathbf{q}$: Lagrangian (initial) position

Ψ: displacement field

$\nabla\Psi^{(1)}(\mathbf{q}) \propto -\delta(\mathbf{q})$



Before : Lagrangian position

After: Comoving position

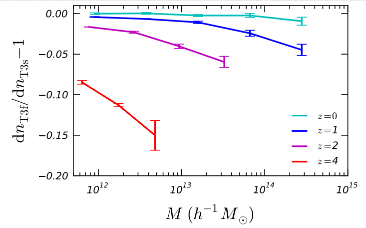
Redshift evolution of the mass function

BL, Park & Kim, New Astron. 30, 79 (2014)

How does the order of the Lagrangian Perturbation Theory (LPT) affect the evolution?

- At $z > 0$, the mass function is underestimated in 1LPT simulations

$z_{\rm ini} = 100$

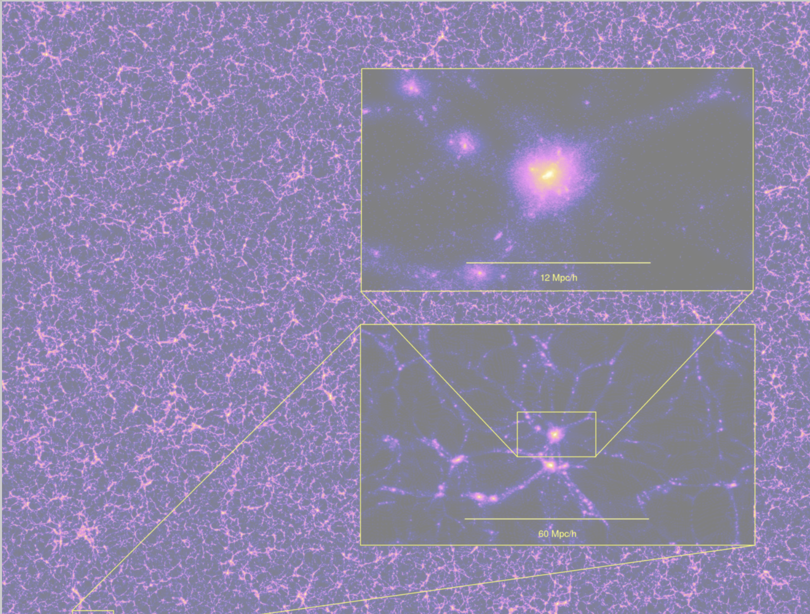


Mass function: 1LPT/2LPT

- The underestimation is larger at high mass
- Need for at least ≈ 100 expansion factors
- Need to *carefully choose the starting redshift*

Horizon Run 4

Kim, Park, BL, Hong, JKAS 48, 213 (2015)



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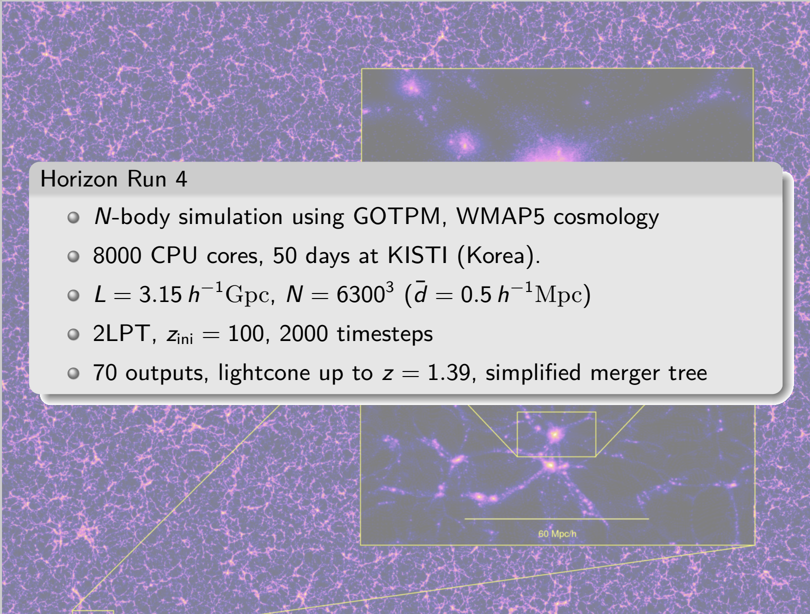
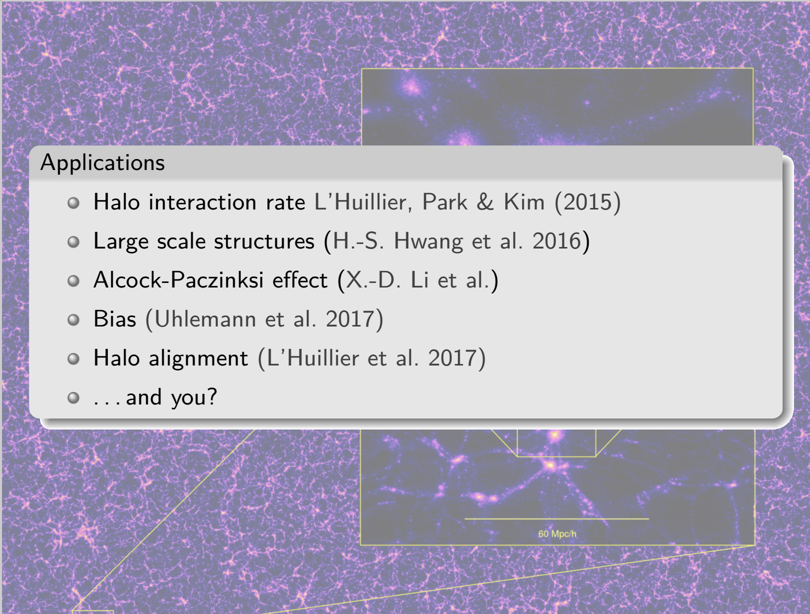


Horizon Run 4

- *N*-body simulation using GOTPM, WMAP5 cosmology
- 8000 CPU cores, 50 days at KISTI (Korea).
- $L = 3.15\,h^{-1}\mathrm{Gpc}$, $N = 6300^3$ ($\bar{d} = 0.5\,h^{-1}\mathrm{Mpc}$)
- 2LPT, $z_{\rm ini} = 100$, 2000 timesteps
- 70 outputs, lightcone up to $z = 1.39$, simplified merger tree

Horizon Run 4

Kim, Park, BL, Hong, JKAS 48, 213 (2015)

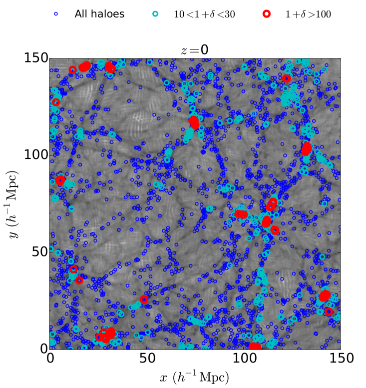


Applications

- Halo interaction rate L'Huillier, Park & Kim (2015)
- Large scale structures (H.-S. Hwang et al. 2016)
- Alcock-Paczinksi effect (X.-D. Li et al.)
- Bias (Uhlemann et al. 2017)
- Halo alignment (L'Huillier et al. 2017)
- . . . and you?

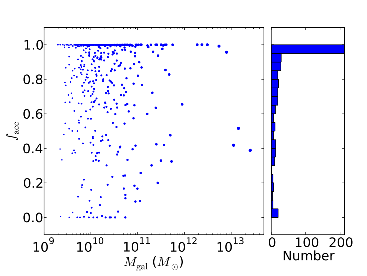
Galaxies and their environment

Interaction rate of haloes within the LSS (HR4)



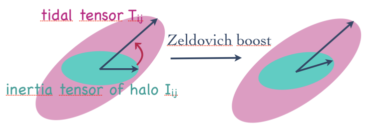
BL, Park & Kim, MNRAS 451, 527 (2015)

Mass assembly of galaxies: hydro zoom-in simulations



Dominated by smooth accretion (BL, Combes & Semelin A&A 544, A68 (2012))

How do galaxies get their orientations?



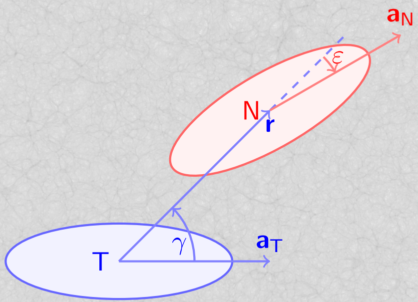
Codis et al. (2015)

Tidal Torque Theory (White 1984)

- Initial angular momentum: misalignment between inertia tensor of the proto-galaxy and the tidal field
- Subsequent evolution: non-linear (mergers). Does it still stand? Not so much (Porciani et al. 2002)

- Studying galaxy orientation is important for understanding their formation
- Intrinsic alignment is a systematic for lensing surveys (EUCLID)
- 2 types of alignments:
  - Large-scale (with the LSS)
  - Small-scale: central-satellite, satellite-satellite

Shape alignment

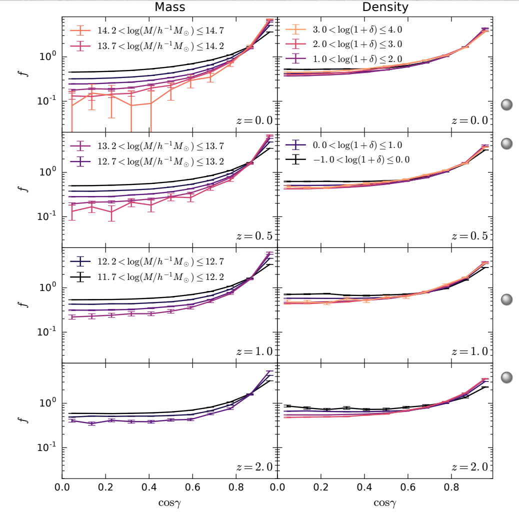


$\gamma = (\mathbf{a}_\mathrm{T}, \mathbf{r})$: angle between major axis (target) and direction neighbour

$\varepsilon = (\mathbf{a}_\mathrm{N}, \mathbf{r})$: angle major between the major axis of the neighbour and the direction of the target

Alignment major axis – neighbour

BL, Park, Kim MNRAS 466, 4875 (2017)



- $\gamma = (\mathbf{a}_\mathrm{T}, \mathbf{r})$
- Position of the neighbour aligned with the major axis of the target
- Alignment increases with mass
- Little dependence on the large-scale density

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DM haloes in modified gravity

BL, Winther, Mota, Park, Kim MNRAS 468, 3174 (2017)

Studing DM Haloes in MG

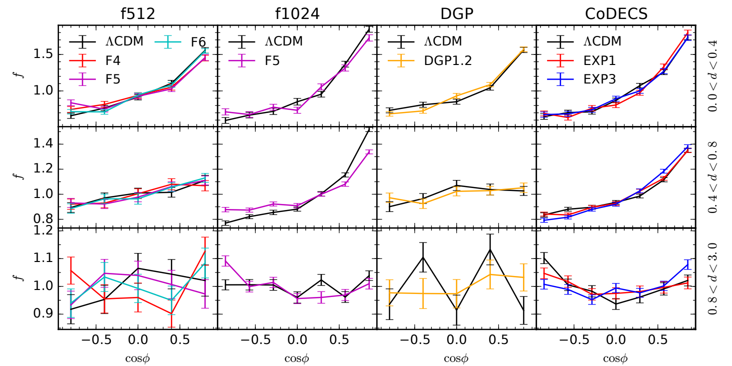
- GR or modified gravity (MG)?
- How do haloes form in MG?
- Can the alignment tell us something about MG?

Simulations

- $f(R)$ (10^{-4}, 10^{-5}, 10^{-6}): $256\,h^{-1}\mathrm{Mpc}, 512^3$, and $1\,h^{-1}\mathrm{Gpc}, 1024^3$
- DGP ($r = 1.2$): $250\,h^{-1}\mathrm{Mpc}, 512^3$
- Coupled DE (Baldi et al 2012): $1\,h^{-1}\mathrm{Gpc}, 1024^3$

Alignment of interacting pairs

BL, Winther, Mota, Park, Kim MNRAS 468, 3174 (2017)



- ϕ: angle between the spins of interacting pairs
- $f(R)$: weaker alignment in low-density
- Dynamical DE: slightly stronger alignment in low-density
- Overall: very weak effect

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Planck 2018 cosmology

Parameter	Plik best fit	Plik [1]	CamSpec [2]	([2] − [1])/σ_1	Combined
$\Omega_b h^2$	0.022383	0.02237 ± 0.00015	0.02229 ± 0.00015	−0.5	0.02233 ± 0.00015
$\Omega_c h^2$	0.12011	0.1200 ± 0.0012	0.1197 ± 0.0012	−0.3	0.1198 ± 0.0012
$100\theta_{MC}$	1.040909	1.04092 ± 0.00031	1.04087 ± 0.00031	−0.2	1.04089 ± 0.00031
τ	0.0543	0.0544 ± 0.0073	$0.0536^{+0.0069}_{-0.0077}$	−0.1	0.0540 ± 0.0074
$\ln(10^{10} A_s)$	3.0448	3.044 ± 0.014	3.041 ± 0.015	−0.3	3.043 ± 0.014
n_s	0.96605	0.9649 ± 0.0042	0.9656 ± 0.0042	+0.2	0.9652 ± 0.0042
$\Omega_m h^2$	0.14314	0.1430 ± 0.0011	0.1426 ± 0.0011	−0.3	0.1428 ± 0.0011
H_0 [km s^{-1}Mpc^{-1}]	67.32	67.36 ± 0.54	67.39 ± 0.54	+0.1	67.37 ± 0.54
Ω_m	0.3158	0.3153 ± 0.0073	0.3142 ± 0.0074	−0.2	0.3147 ± 0.0074
Age [Gyr]	13.7971	13.797 ± 0.023	13.805 ± 0.023	+0.4	13.801 ± 0.024
σ_8	0.8120	0.8111 ± 0.0060	0.8091 ± 0.0060	−0.3	0.8101 ± 0.0061
$S_8 \equiv \sigma_8(\Omega_m/0.3)^{0.5}$	0.8331	0.832 ± 0.013	0.828 ± 0.013	−0.3	0.830 ± 0.013
z_{re}	7.68	7.67 ± 0.73	7.61 ± 0.75	−0.1	7.64 ± 0.74
$100\theta_*$	1.041085	1.04110 ± 0.00031	1.04106 ± 0.00031	−0.1	1.04108 ± 0.00031
r_{drag} [Mpc]	147.049	147.09 ± 0.26	147.26 ± 0.28	+0.6	147.18 ± 0.29

- Precision cosmology

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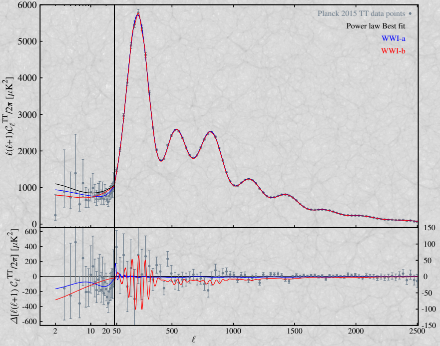
- Precision cosmology
- *But this is model-dependent*: What if the primordial power spectrum is *not* a power law?

Wiggly-whipped inflation

Hazra, Shafieloo, Smoot & Starobinsky (2014ab, 2016)



- WWI: class of models with features in the PPS
- Step in the potential → wiggles in the power spectrum
- Better fit than power law
- at the expense of (a few) extra parameters

- CMB alone cannot distinguish the model
- 2D (CMB) → 3D (LSS)
- Can we use the LSS to distinguish these models?

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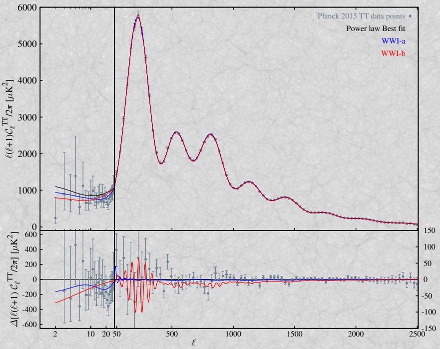

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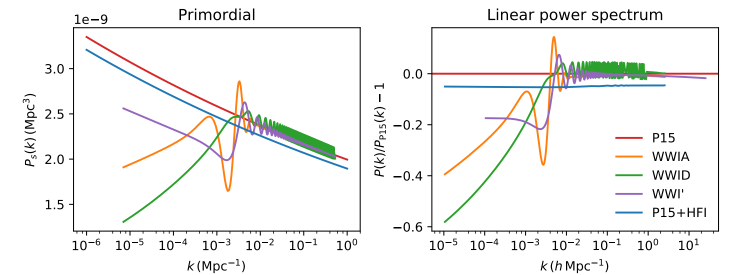
- **Can we use the LSS to distinguish these models?**

Primordial power spectrum

BL, Shafieloo, Hazra, Smoot, Starobinsky MNRAS 477, 2503 (2018)



- Reference model: Planck 2015 TTTEEE (P15)
- Wiggly-whipped inflation (Hazra et al. 2014ab, 2016): WWIA, WWID, WWI'
- Planck 2015 TTTEEE+HFI (P15+HFI)
- The WWI models give better fit to the CMB data than power law: indistinguishable
- **Can we use the LSS to distinguish these models?**

The simulations

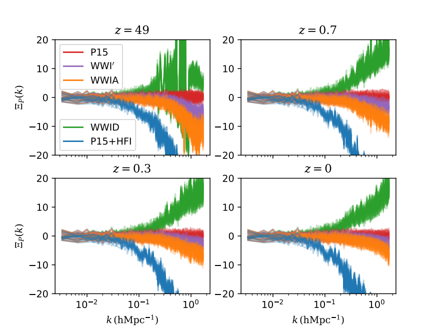
BL, Shafieloo, Hazra, Smoot, Starobinsky MNRAS 477, 2503 (2018)

- *N*-body simulations with GADGET-2 Springel 2005
- 5 models × 15 random realizations
- Volume: $L = 1.89\,h^{-1}\mathrm{Gpc}$, $N = 1024^3$ (DESI survey)

Model	Ω_m	H_0 ($\mathrm{km\,s^{-1}\,Mpc^{-1}}$)	σ_8	n_s
P15	0.317	67.05	0.836	0.9625
WWIA	0.320	66.86	0.834	-
WWID	0.318	67.01	0.842	-
WWI'	0.317	67.04	0.834	-
P15+HFI	0.319	66.93	0.816	0.9619

Matter power spectrum

BL, Shafieloo, Hazra, Smoot, Starobinsky MNRAS 477, 2503 (2018)



Normalized difference:

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

$$\delta(\mathbf{x}) = (\rho(\mathbf{x}) - \bar{\rho})/\bar{\rho},$$

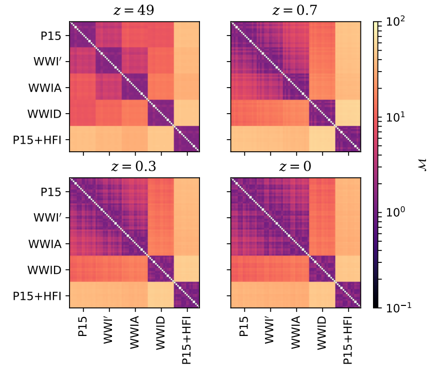
$$P(k) = \frac{1}{V}\left\langle|\delta(\mathbf{k})|^2\right\rangle_{|\mathbf{k}|=k}.$$

- Power spectrum calculated by ComputePk (L'Huillier 2014)
- Features vanish in the non-linear regime.
- WWID and P15+HFI can be distinguished, but not WWIA,

Matter power spectrum

BL, Shafieloo, Hazra, Smoot, Starobinsky MNRAS 477, 2503 (2018)

- Separability Matrix M: r.m.s. of the normalized difference between two simulations: 75×75 matrix



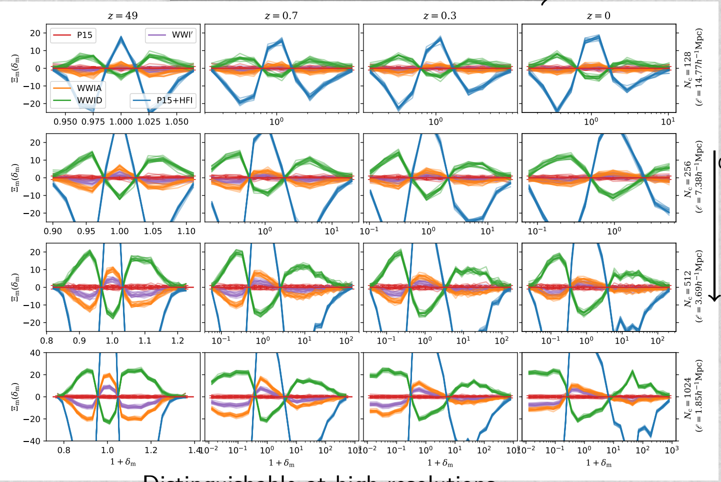
- At $z = 49$: all models well distinguished
- By $z = 0$: WWID and P15+HFI well distinguished, but P15, WWI′, WWIA are not

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

Matter density

BL, Shafieloo, Hazra, Smoot, Starobinsky MNRAS 477, 2503 (2018)

Lower redshifts →



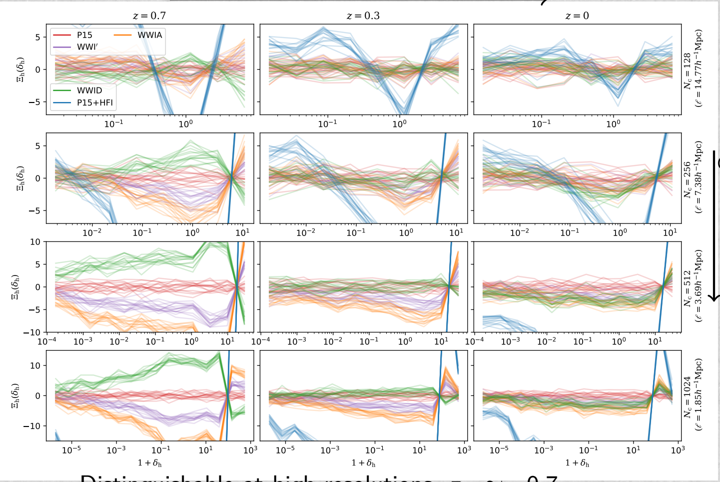
Higher resolutions ↓

Distinguishable at high-resolutions

Halo mass density

BL, Shafieloo, Hazra, Smoot, Starobinsky MNRAS 477, 2503 (2018)

Lower redshifts



Higher resolutions

Distinguishable at high-resolutions, $z \simeq 0.7$

Summary

- Alignment in modified gravity: small effect, hard to detect
- Not too important for weak lensing?
- Features in the PPS: $P(k)$ may not be sufficient
- Count-in-cell: large statistics allow to distinguish
- What about baryons?
- Next generation survey: Euclid, DESI, LSST, can probe these scales
- **Important to be ready for the next generation**

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Background expansion

Expansion for dark energy as a fluid with EOS $w(z)$:

$$h^2(z) = \Omega_\mathrm{m}(1+z)^3 + \Omega_k(1+z)^2 + (1-\Omega_k-\Omega_\mathrm{m})\exp\left(\int_0^z \frac{1+w(x)}{1+x}\mathrm{d}x\right) \tag{2}$$

- Type Ia supernovae (SNIa): Pantheon (Scolnic et al. 2018): 1048 SNIa up to $z = 2.3$: $\mu(z) \propto \log_{10} d_\mathrm{L}(z) + \mathrm{cst}$.
- Baryon Acoustic Oscillations from BOSS DR12 (Alam et al. 2017) and eBOSS DR 14Q (Zhao et al. 2018): $H(z)r_\mathrm{d}, d_\mathrm{A}(z)/r_\mathrm{d}$.
  - r_d: Sound horizon at drag epoch

Direct Reconstruction of the Expansion History

BL & Shafieloo JCAP 01, 17 (2017), Shafieloo, BL & Starobinsky 1804.04320

- Iterative smoothing: Direct reconstruction from the data, no cosmological assumption Shafieloo et al. (2006), Shafieloo (2007),...
- New matrix formulation for correlated data (Shafieloo, L'Huillier & Starobinsky 2018):

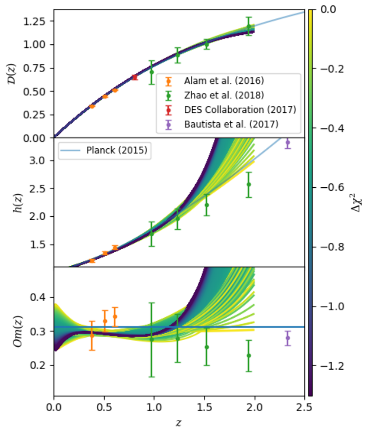
$$\hat{\mu}_{n+1}(z) = \hat{\mu}_n(z) + \frac{\delta\mu_n^{\mathrm{T}}(z)\mathbf{C}^{-1}\mathbf{W}(z)}{(1,\cdots,1)\mathbf{C}^{-1}\mathbf{W}(z)}; \tag{3}$$

where

$$\mathbf{W}_i(z) = \exp\left(-\frac{\ln^2\left(\frac{1+z}{1+z_i}\right)}{2\Delta^2}\right) \tag{4}$$

Testing Flat-ΛCDM

BL & Shafieloo JCAP 01, 17 (2017), Shafieloo, BL & Starobinsky 1804.04320



Om diagnostics (Sahni et al. 2008)

$$Om(z) = \frac{h^2(z) - 1}{(1+z)^3 - 1} \tag{5}$$

$$\overset{\text{flat-}\Lambda\text{CDM}}{\equiv} \quad \Omega_m \tag{6}$$

- Consistent with flat-ΛCDM,
- Hints of tension at $z \gtrsim 1.5$ (c.f. Sahni et al. (2014), Zhao et al. (2017)

Testing Λ

Zhao et al Nature Astron. 1, 627 (2017)

nature astronomy

LETTERS

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Dynamical dark energy in light of the latest observations

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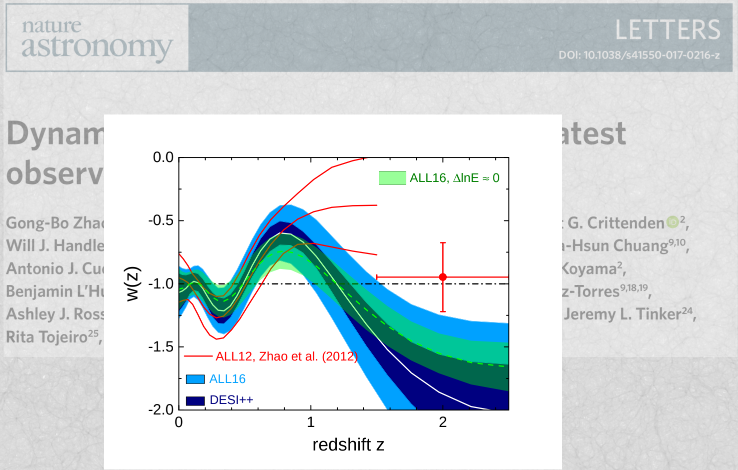
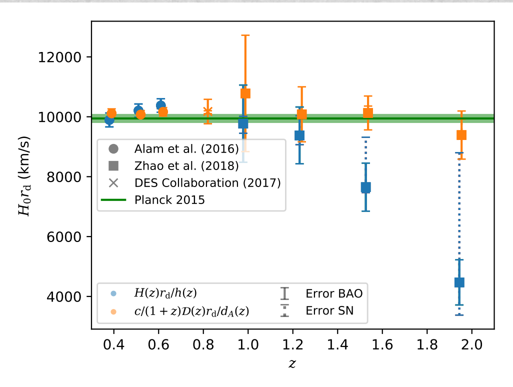
Testing Λ

Zhao et al Nature Astron. 1, 627 (2017)



Model-independent measurement of $H_0 r_d$

BL & Shafieloo JCAP 01, 17 (2017), Shafieloo, BL & Starobinsky 1804.04320

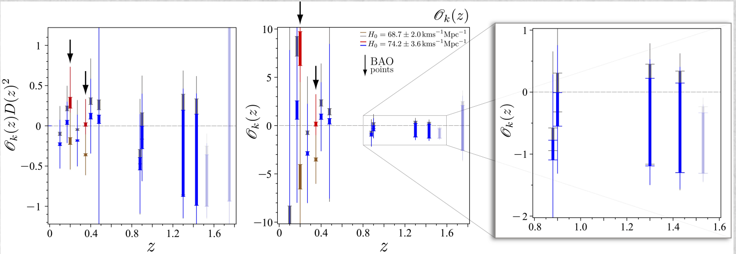


Consistent with Planck 2015: $H_0 r_d = 9944.0(1274)\,\mathrm{km\,s^{-1}}$

FLRW Metric test

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

$$\mathcal{O}_k(z) = \frac{(h(z)\mathcal{D}'(z)^2 - 1)}{\mathcal{D}^2(z)} \overset{\text{FLRW}}{\equiv} \Omega_k (\text{Clarkson et al. 2008})$$



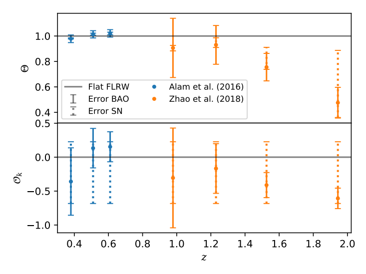
Shafieloo & Clarkson (2010)

FLRW Metric test

BL & Shafieloo JCAP 1, 15 (2017), Shafieloo et al. (1804.04320)

$$\Theta(z) = h(z)\mathcal{D}'(z) = \frac{(1+z)}{c} H(z) r_{\rm d} \frac{d_{\rm A}(z)}{r_{\rm d}} \frac{\mathcal{D}'(z)}{\mathcal{D}(z)} = F_{\rm AP}(z) \frac{\mathcal{D}'(z)}{\mathcal{D}(z)} \quad (7)$$

$$\mathcal{O}_k(z) = \frac{\Theta^2(z) - 1}{\mathcal{D}^2(z)} \overset{\rm FLRW}{\equiv} \Omega_k (\text{Clarkson et al. 2008}) \quad (8)$$



- $H(z)r_{\rm d}, d_{\rm A}(z)/r_{\rm d}$ from BAO
- $\mathcal{D}(z), \mathcal{D}'(z)$ from JLA supernovae
- **Consistent with a flat Universe!**

The Concordance Model of Cosmology

Hypotheses

- **Gravity described by General Relativity (GR)**
- Isotropy and homogeneity
- Inflation in the early Universe, power-law primordial power spectrum

The concordance ΛCDM model

- Solution of the Einstein equations: FLRW metric
- Flat Universe
- **Universe dominated by dark energy (Λ)** and cold dark matter (CDM)
- Observationally supported by different datasets
- But what are dark energy and dark matter?
- **Is gravity correctly described by GR?**

Perturbation level: testing gravity

Linear Growth rate:

$$f(z) = \frac{\mathrm{d}\ln\delta}{\mathrm{d}\ln a} \simeq \Omega_{\mathrm{m}}^{\gamma}(z), \tag{9}$$

where

$$\Omega_{\mathrm{m}}(z) = \frac{\Omega_{\mathrm{m}}(1+z)^3}{h^2(z)}. \tag{10}$$

$$f\sigma_8(z) \simeq \sigma_8(0)\Omega_{\mathrm{m}}^{\gamma}(z)\exp\left(-\int_0^z \Omega_{\mathrm{m}}^{\gamma}(z')\frac{\mathrm{d}z'}{1+z'}\right), \tag{11}$$

$f\sigma_8$ depends on $(\Omega_{\mathrm{m}}, \gamma, \sigma_8)$ and $h(z)$.

- Redshift-space distorsion (from various surveys): $f\sigma_8(z)$, $f = \mathrm{d}\ln\delta/\mathrm{d}\ln a \simeq \Omega_{\mathrm{m}}^{\gamma}(z)$
- In GR, $\gamma \simeq 0.55$: **can test Gravity**

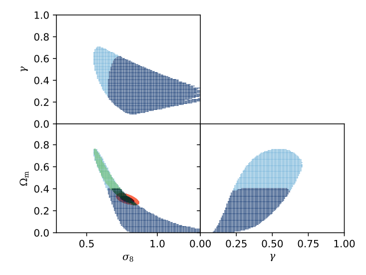
Perturbation level: testing gravity

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

- $f\sigma_8$ depends on $(\Omega_\mathrm{m}, \gamma, \sigma_8)$ and $h(z)$.
- We use our model-independent reconstruction of $h(z)$
- Constrain $(\Omega_\mathrm{m}, \gamma, \sigma_8)$ with growth data
- For GR, $\gamma \simeq 0.55$: test of gravity
- SNIa: model-independent $h(z)$, χ^2_SN
- Minimize the total $\chi^2 = \chi^2_\mathrm{SN} + \chi^2_{f\sigma_8}$.

Cosmological constraints

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



Shafieloo, L'Huillier & Starobinsky (2018)

ΛCDM (1σ,2σ)

Model-independent ($\chi^2 < \chi^2_{\mathrm{min},\Lambda\mathrm{CDM}}$)

Model-independent, $\gamma = 0.55$ (GR)

Dark Blue/Green: $\Omega_{\mathrm{DE}}(z) = h^2(z) - \Omega_{\mathrm{m}}(1+z)^3 > 0$.

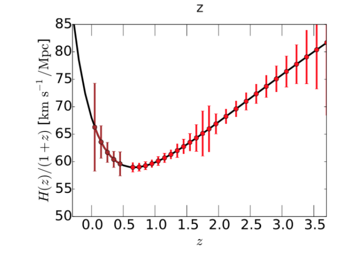
- Model-independent constraints: larger contours than ΛCDM
- Fully consistent with GR+ΛCDM background

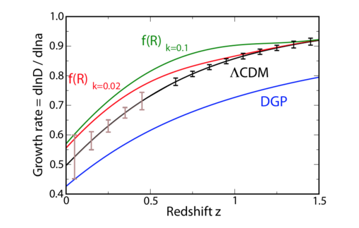
Summary

- Combination of different expertise: *N*-body simulations and background statistics to find the proper pattern of the Universe in connection with the data
- *N*-body simulations to probe the non-linear regime and distinguish between different models (ΛCDM, Gravity, Dark Enegy, Primordial power spectrum, . . .)
- Model-independent approach: look for features in the data beyond expectations from the concordance model
- Next generation survey (DESI, Euclid, LSST, WFIRST, SPHEREx,. . .) will reveal new secrets of the Universe

Perspectives

Future surveys





DESI Collaboration (2016)

- Future surveys will constrain further the expansion and growth
- Can test gravity, dark energy, initial conditions, . . .
- Important to be ready