Evidence for the History of Cosmic Expansion

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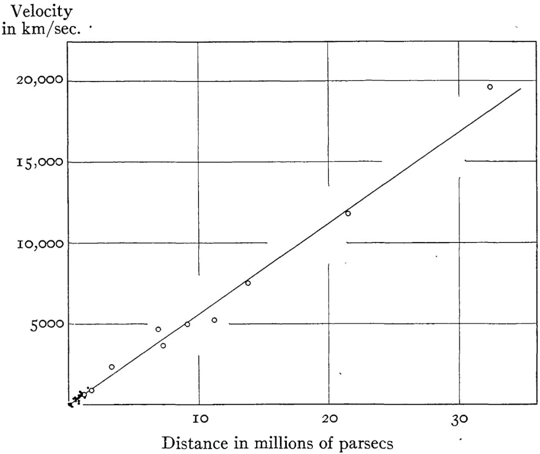
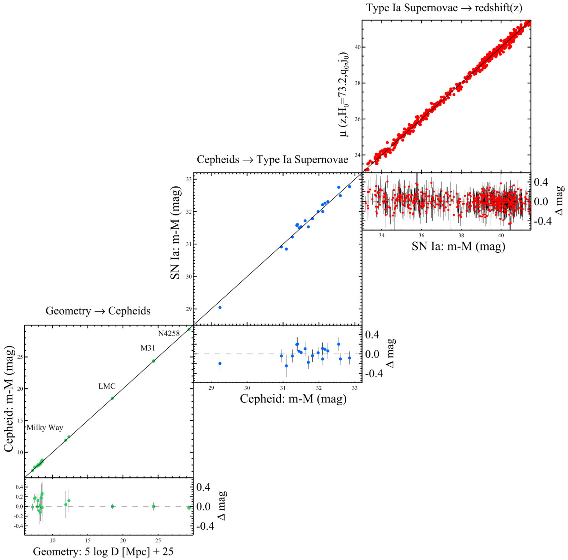
Expansion Law



$$v = \frac{d}{1790} = 558 \text{ km/sec. per million parsecs.}$$

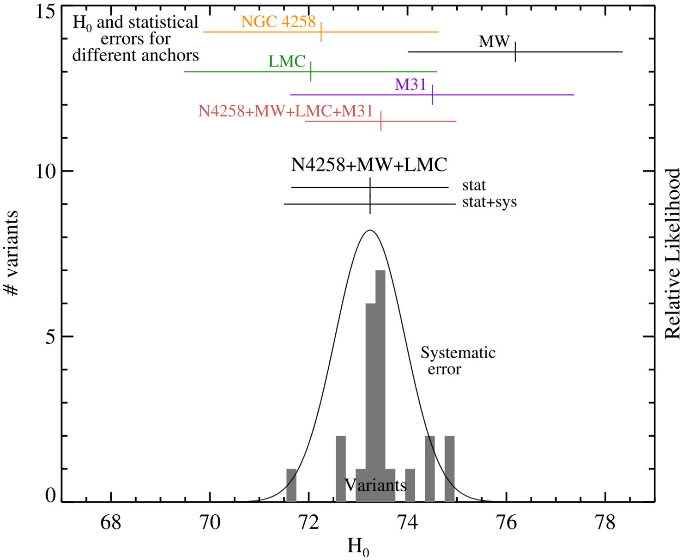
Hubble & Humason 1931

Expansion Law



Riess et al. 2016

Expansion Law



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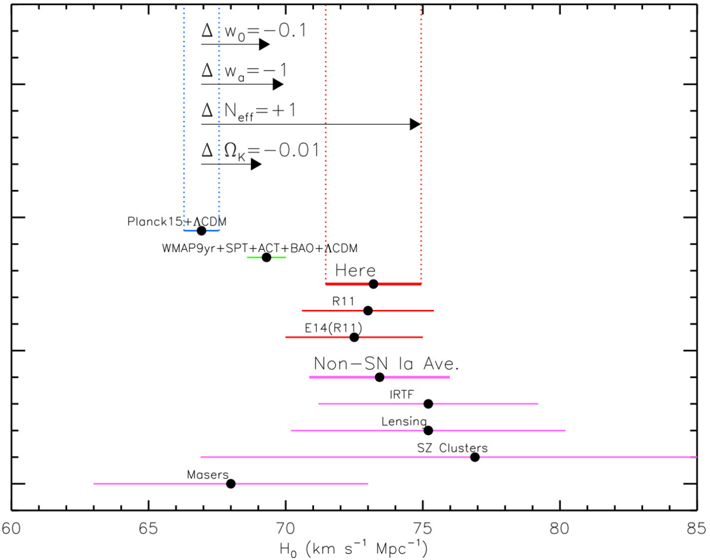

Riess et al. 2016

Friedmann's Equation

Metric (spatially homogeneous and isotropic)

$$ds^2 = -c^2 dt^2 + a^2(t) \left[dw^2 + f_K^2(w) d\Omega^2 \right]$$

Scale factor $a(t)$, $f_K(w) = w$ for $K = 0$

Friedmann's Equation

Hubble constant H_0, Hubble function $H(a)$

$$\left(\frac{\dot{a}}{a}\right)^2 = H^2(a) = H_0^2\, E^2(a)$$

Expansion function $E(a)$

Friedmann's Equation

Expansion function $E(a)$

$$E(a) = \left(\Omega_{r0}a^{-4} + \Omega_{m0}a^{-3} + \Omega_{K0}a^{-2} + \Omega_{\Lambda 0}\right)^{1/2}$$

Friedmann's Equation

Expansion function $E(a)$

$$E(a) = \left(\Omega_{r0}a^{-4} + \Omega_{m0}a^{-3} + \Omega_{K0}a^{-2} + \Omega_{Q0}a^{-3(1+w)}\right)^{1/2}$$

Equation-of-state parameter w

Friedmann's Equation

Expansion function $E(a)$

$$E(a) = \left(\Omega_{r0}a^{-4} + \Omega_{m0}a^{-3} + \Omega_{K0}a^{-2} + \Omega_{Q0}e^{-3\int_a^1 (1+w)\mathrm{d}\ln a'}\right)^{1/2}$$

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Expansion function $E(a)$

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Equation-of-state parameter w

Chevallier-Polarski-Linder (CPL) parameterisation:

$$w(a) = w_0 + (1 - a)w_a$$

Distances

Light propagation, $\mathrm{d}s = 0$, from the metric:

$$c|\mathrm{d}t| = a(t)\mathrm{d}w$$

Distances

Light propagation, $\mathrm{d}s = 0$, from the metric:

$$w(a) = \frac{c}{H_0} \int_a^1 \frac{\mathrm{d}x}{x^2 E(x)}$$

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Angular-diametre distance ($K = 0$)

$$D_{\mathrm{ang}}(a) = \frac{\text{length scale}}{\text{angle spanned}} = a\, w(a)$$

Luminosity distance

$$D_{\mathrm{lum}}(a) = \frac{\text{luminosity}}{\text{flux}} = \frac{w(a)}{a}$$

Etherington relation, independent of cosmological model

Structure Growth

Euler-Poisson system, linearised, Fourier modes δ_k of density contrast, sound speed c_s

$$\ddot{\delta}_k + 2H\dot{\delta}_k = \left(4\pi G\bar{\rho} - \frac{c_\mathrm{s}^2 k^2}{a^2}\right)\delta_k$$

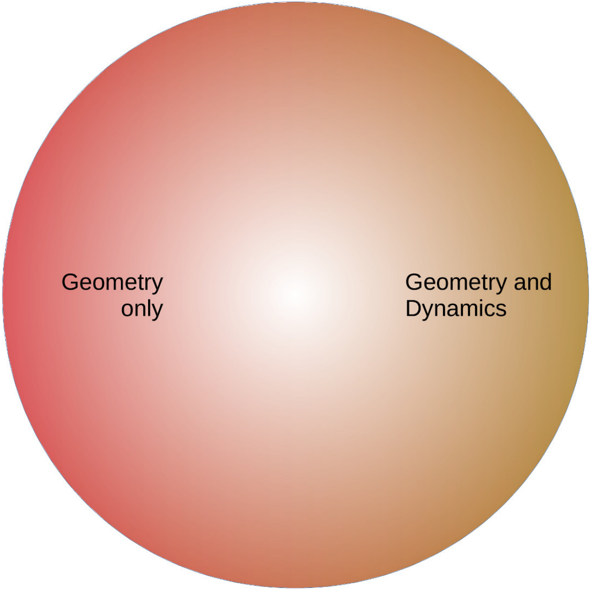
dark matter: $c_\mathrm{s} = 0$

$$\ddot{\delta}_k + 2H\dot{\delta}_k = 4\pi G\bar{\rho}\,\delta_k$$

(growing) solution: linear growth factor $D_+(a)$

baryonic matter: $c_\mathrm{s} \approx c/\sqrt{3} > 0$, oscillations on small scales

Constraints



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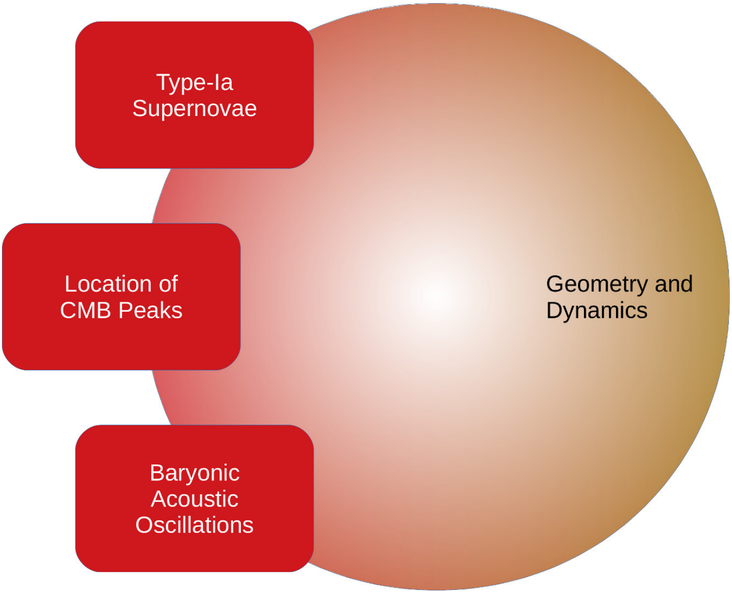

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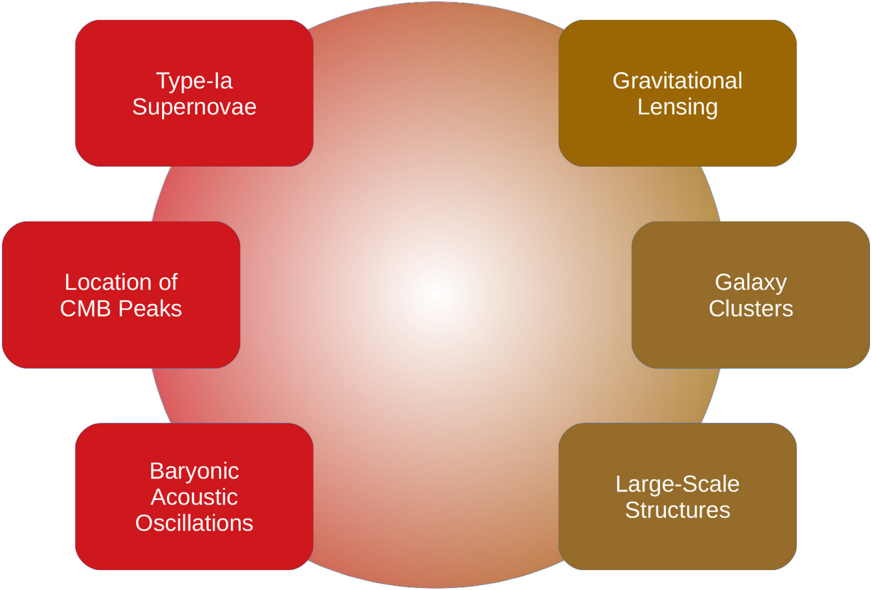
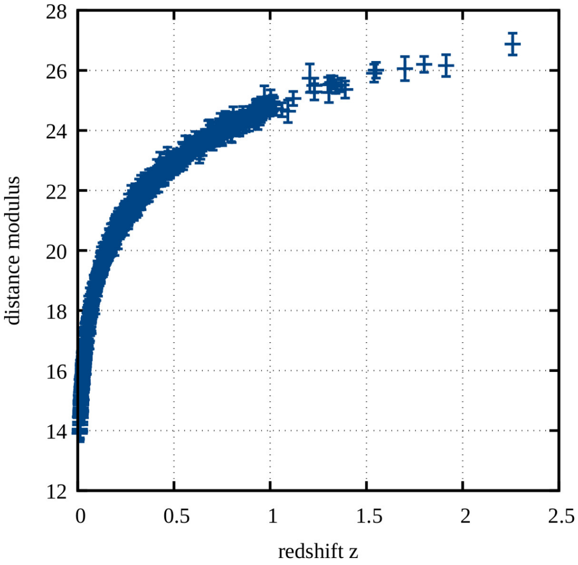
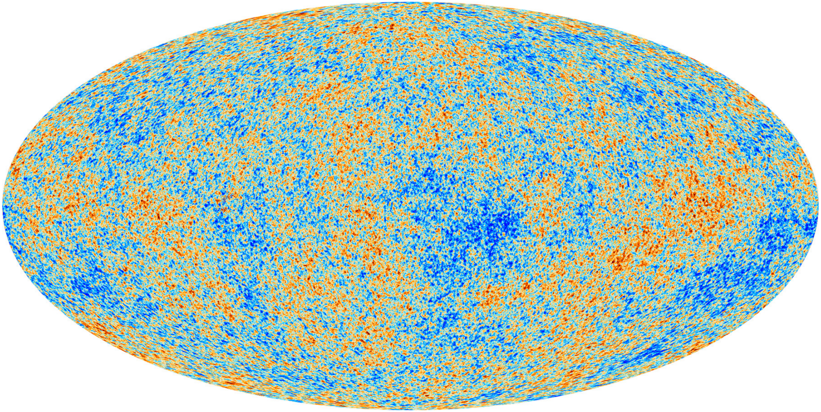


Type-Ia Supernovae



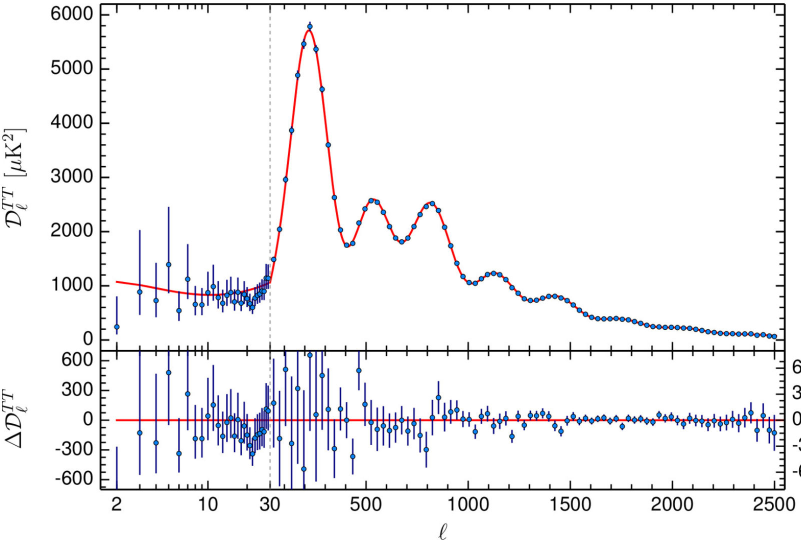
Pantheon sample, Scolnic et al. 2018

Location of CMB Peaks



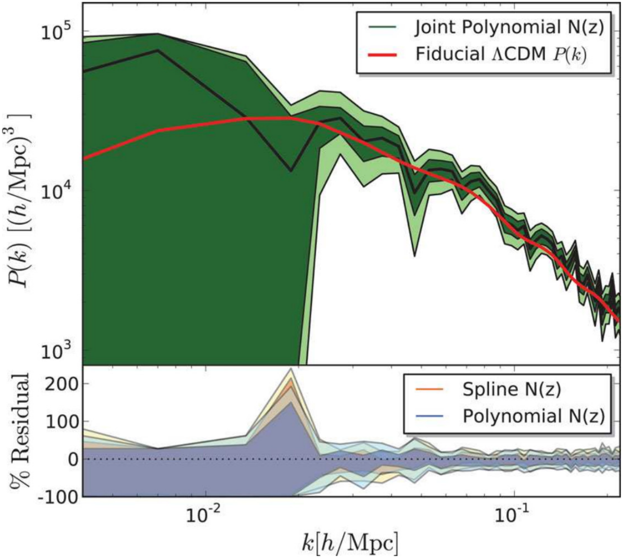
Planck 2015

Location of CMB Peaks

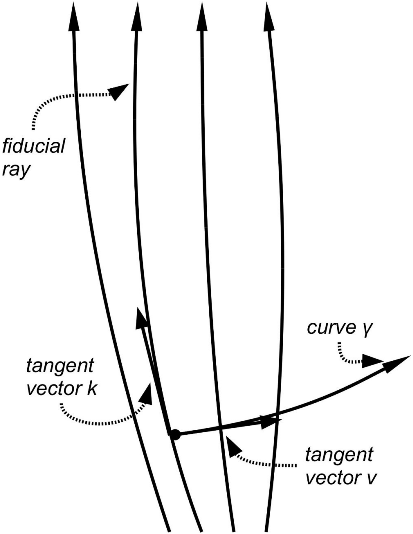


Planck 2015

Baryonic Acoustic Oscillations



WiggleZ, Poole et al.



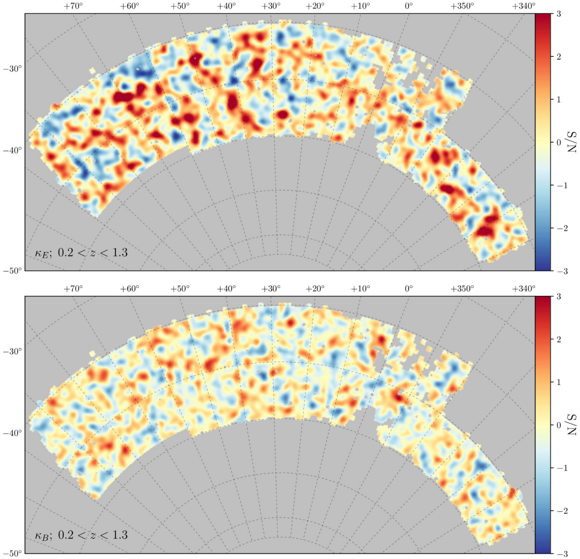
From Jacobi equation:

$$\left(\mathrm{d}_w^2 + K\right) x^i = -2\partial^i \Phi$$

Astigmatism, image distortions γ, correlation function:

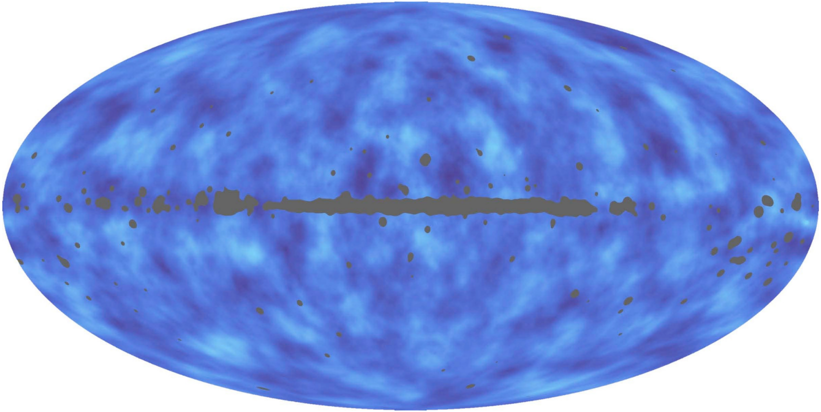
$$C_\ell^\gamma = \frac{9}{4}\left(\frac{H_0}{c}\right)^4 \Omega_{\mathrm{m0}}^2 \int_0^{w_\mathrm{s}} \mathrm{d}w \underbrace{\left(\frac{w_\mathrm{s} - w}{a w_\mathrm{s}}\right)^2}_{E(a)} \underbrace{P_\delta\left(\frac{\ell}{w}\right)}_{D_+(a)}$$

Gravitational Lensing



DES, Chang et al. 2017

Gravitational Lensing



Planck 2015

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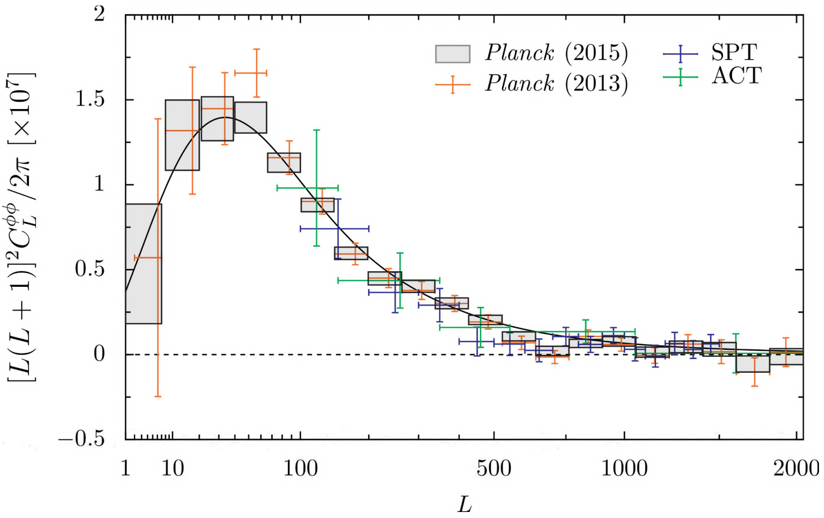
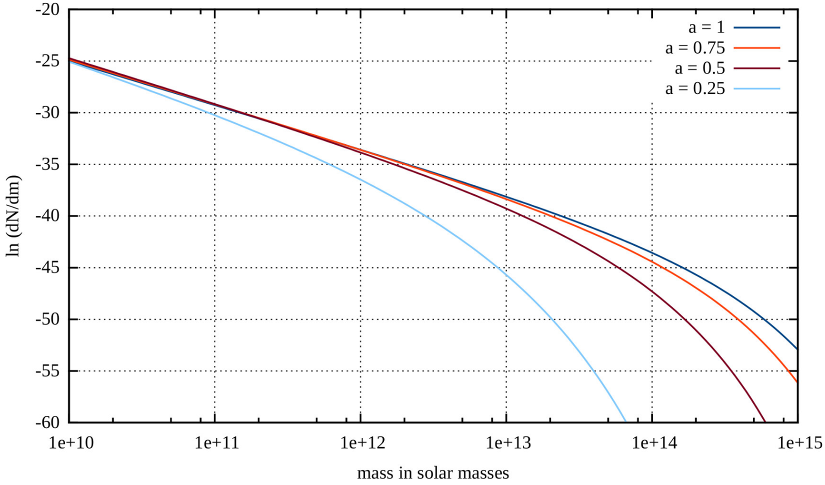


Planck 2015

Galaxy Clusters

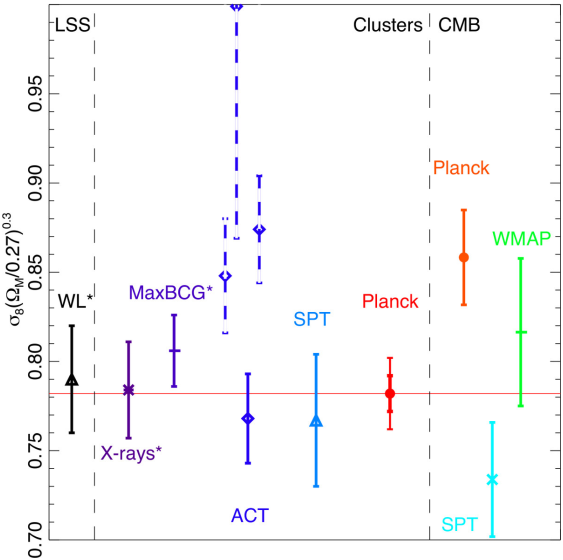
MACS 1206.2–0847

Galaxy Clusters



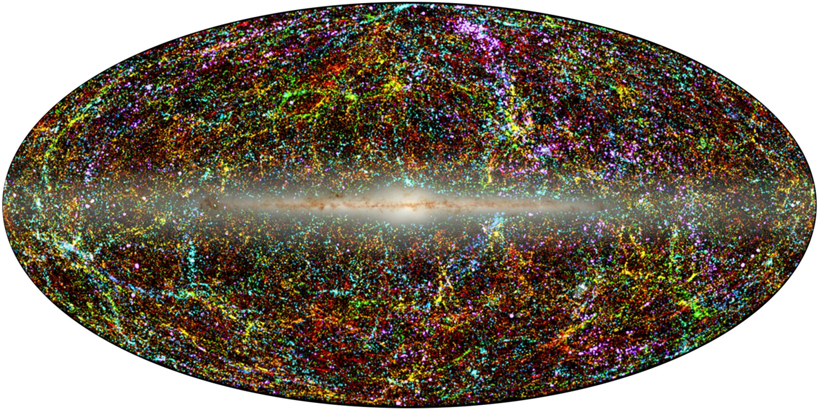
volume: $E(a)$, structure growth: $D_+(a)$

Galaxy Clusters



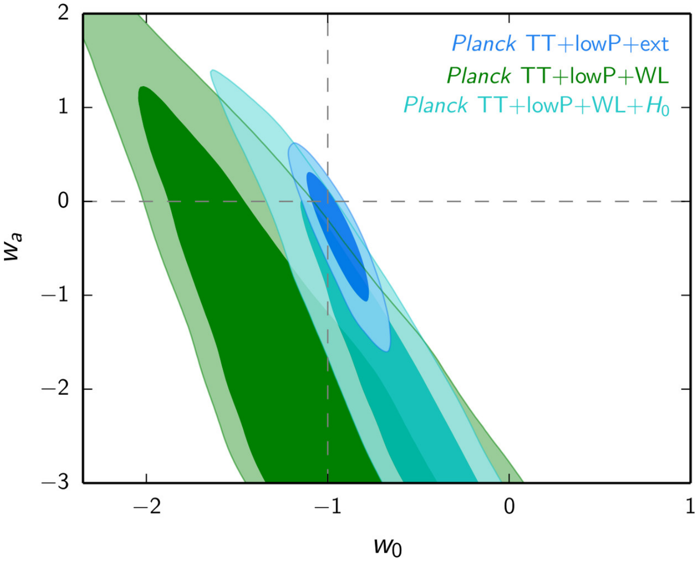
Planck 2015

Large-Scale Structures



2-Micron All-Sky Survey (2mass)

Current Constraints



Planck 2015

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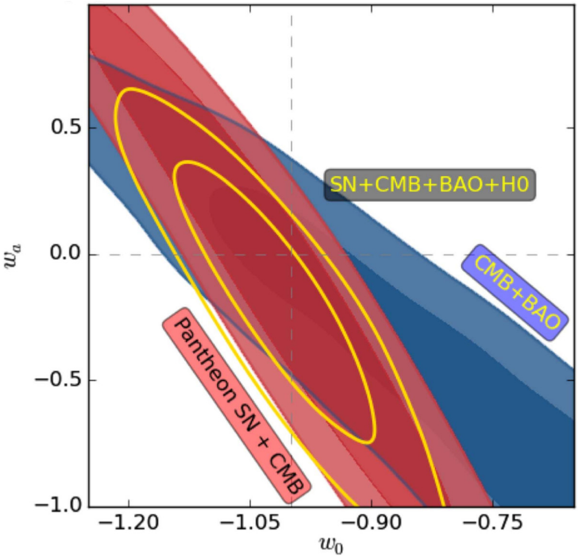

Scolnic et al. 2018

Model-Independent Reconstruction of $E(a)$

Measurement: luminosity distance

$$D_{\text{lum}}(a) = \frac{1}{a}\int_a^1 \frac{\mathrm{d}x}{x^2 E(x)}$$

Representation of $E(a)$:

$$e(a) := [aE(a)]^{-1}\ , \quad e(a) = -a^2 D'_{\text{lum}}(a) + \lambda \int_1^a \frac{\mathrm{d}x}{x}\, e(x)$$

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Representation of $D_{\rm lum}(a)$:

$$D_{\rm lum}(a) = \sum_{j=1}^{M} c_j p_j(a)$$

with (orthonormal) basis functions $p_j(a)$

Mignone & MB, Mignone & Maturi, Benítez Herrera et al., . . .

Model-Independent Reconstruction of $D_+(a)$

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Measurement: luminosity distance

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Representation of $E(a)$:

$$e(a) := [aE(a)]^{-1}\ , \quad e(a) = -a^2D'_{\rm lum}(a) + \lambda\int_1^a \frac{\mathrm{d}x}{x}\,e(x)$$

Reconstruction of $D_+(a)$:

$$D''_+ + \left(\frac{3}{a} + \frac{E'(a)}{E(a)}\right)D'_+ = \frac{3}{2}\frac{\Omega_{\rm m0}}{a^5}D_+$$

Initial conditions:

$$D_+(a_{\rm min}) = 1\ , \quad D'_+(a_{\rm min}) = \frac{D_+(a)}{a}f(a)$$

Model-Independent Reconstruction of $D_+(a)$

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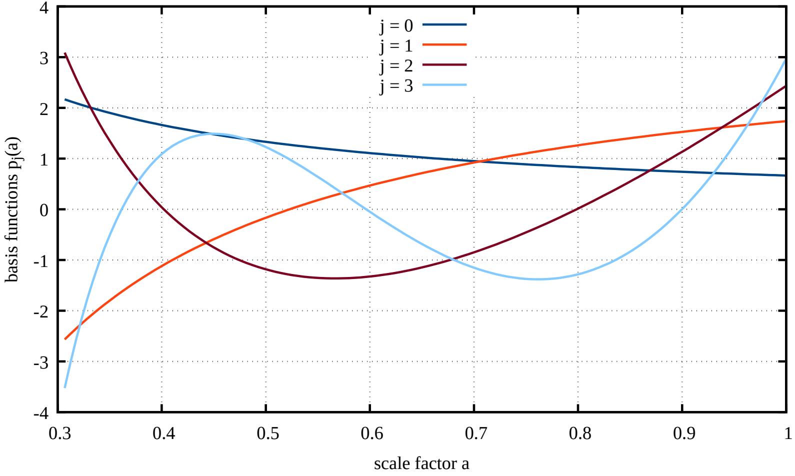

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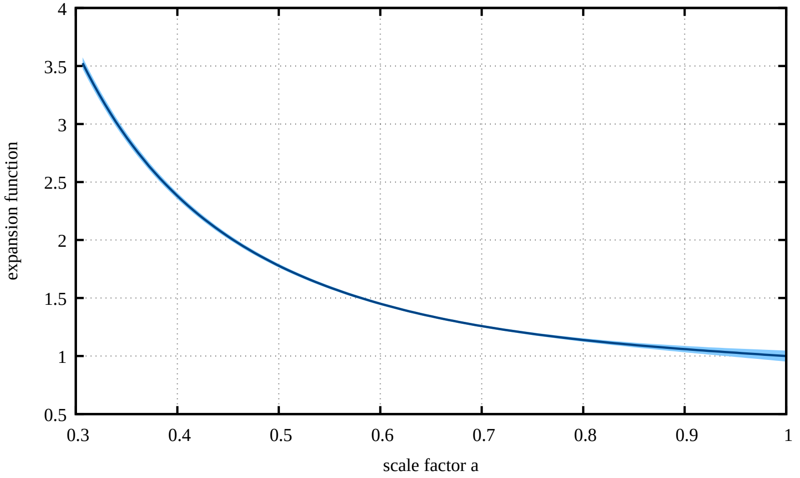

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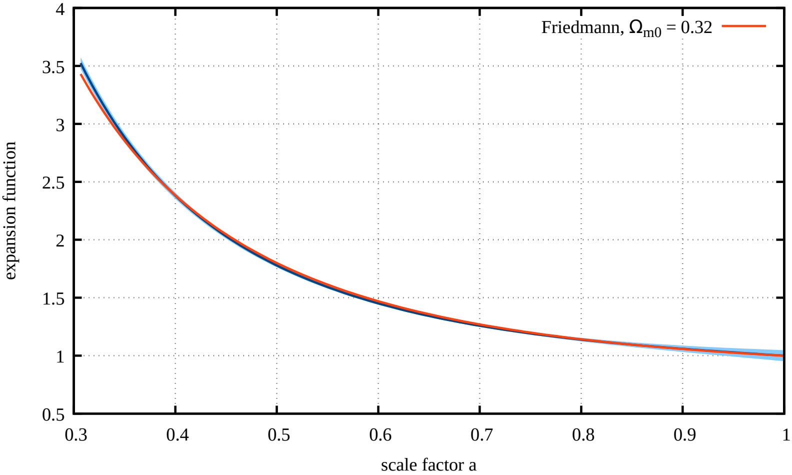
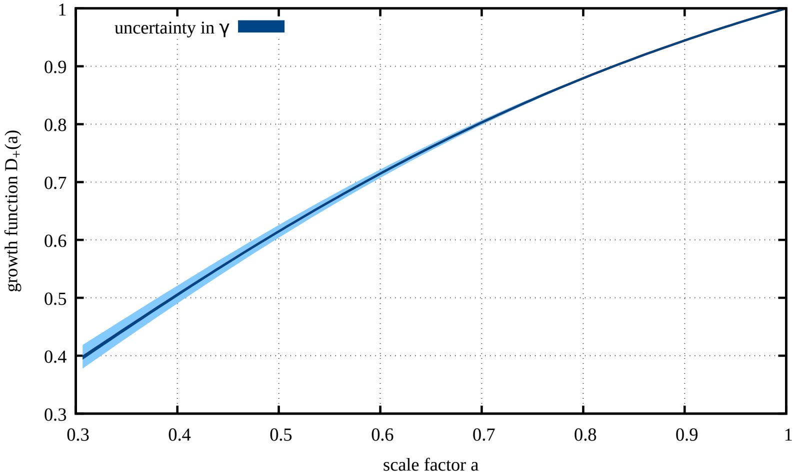


Model-Independent Reconstruction of $D_+(a)$



Haude, Maturi, MB 2019

Summary

- Multitude of cosmological observables is determined by expansion function $E(a)$ and growth function $D_+(a)$
- Constraints within framework of Friedmann models favour cosmological constant
- Model-independent reconstruction of $E(a)$ is possible, result is tightly contrained
- (Almost) model-independent reconstruction of $D_+(a)$ follows
- $E(a)$ and $D_+(a)$ are empirically known within tight limits, based exclusively on metric theory of gravity and symmetry assumptions
- Generalisations of GR need to agree with both

  Heisenberg & MB, in preparation