Theory of dark energy

Almost 100 years

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Meeting on Fundamental Cosmology

eman ta zabal zazu

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1. Intro..
2. Model
   - Parametrizations
   - Model independence
   - Ingredients
3. Probes
   - Supernovae
   - CMB distance priors
   - H(z)
   - Redshift drift
   - Growth factor

Intro...

Universe's gravitational look $\neq$ Universe's optical look

Dark components explain it $\begin{cases} \text{dark matter} \\ \text{dark energy} \end{cases}$

- slowly redshifting
- weakly clustering

- GR: best candidate on solar system tests
  - Homogeneous and isotropic GR universe
  - acceleration if $p < -\rho/3$

∘ Λ term: $p = -\rho$

but if "dark energy" is a catch-all term ....

- Modified gravity (study perturbations)
  - $\mathcal{R} \to F(\mathcal{R})$
    ⋆ matter era?
    ⋆ solar system challenges
  - Gravity leaking off the brane → acceleration
    - DGP scenario ∘ deprecated
    - offsprings: Galileon, ... [Ferreira & Skordis 2013]

- Two biggest questions:

  1. Repulsive component or GR breakdown ?
  2. Constant energy density or dynamics?

Model

- Basic playground:
  - FRW with scale factor a and Hubble function $H = \dot{a}/a$

$$H^2 + \frac{k}{a^2} = \rho_{tot}$$

tot = matter,dark energy, radiation,neutrinos,...

$$\Omega_i = \frac{\rho_i}{3H^2}, \quad w = p_{de}/\rho_{de}$$

$$\dot{\rho}_m + 3H\rho_m = 0$$

$$\dot{\rho}_{de} + 3H(1+w)\rho_{de} = 0$$

(interaction $\Rightarrow$ rhs $\neq 0$)

$$\text{Begin with} \begin{cases} H \text{ or } \Omega_{de} \\ w \\ q = -\ddot{a}a/\dot{a}^2 \end{cases}$$

Parametrizations

- Most popular route:
  - $w(z) =$ your favourite choice

same expression at all redshifts

- how to guess?
- needs: flexibility despite smoothness
- no more than two parameters

[Linder & Huterer 2005, Sarkar et al. 2008]

- Integration → smoothing

$$\Omega_{de} = \exp\left(\int_0^z \frac{3(1+w(z))}{1+z} dz\right)$$

CPL

- “Canonical case”: linear equation of state

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

[Chevallier & Polarski, 2001; Linder, 2003]

$$w_a \equiv w_1$$

- too simple?
- flexible even for (underlying) fast transitions
- degeneracy at $w_0 + w_1 = 0$ (healing priors needed)

○ DETF Figure of Merit (how good is the survey?)

$$FoM \propto \frac{1}{\sigma_0 \sigma_1}$$

Pivoted CPL

- New parameter in the game

$$w(a) = w_p + w_a(a_p - a)$$

- guess a_p pivot to reduce correlation
- better figure of merit

  Wang $\Rightarrow$ $\boxed{z_p = 0.5}$

◦ Wang Figure of Merit (more rigorous)

$$FoM \propto \frac{1}{\sqrt{\det \mathbf{C}}}$$

Freezing or thawing?

[Caldwell and Linder 2005]

- Scalar field rolling down a potential
  - **Thawing:** initially $w \sim -1, \quad dw/dz > 0$
  - **Freezing:** initially $w > -1, \quad dw/dz < 0$
- Key problem: measure w_1

3yrs James Webb ST $\sim$ 36 SN ($1.5 < z < 3.5$) +

HST/6yrs $\sim$ 28 SN ($1. < z < 2.5$)

25% better error in w_1

$$\sigma_{w_0} \sim 0.17 \quad \sigma_{w_1} \sim 1.1$$

[Salzano,Rodney,Sendra,Lazkoz,Riess et.al 2013]

Error in w_1

EUCLID 10 times smaller

JPAS 4 times smaller

Other choices I

- Early time blow-up
  - [Cooray and Huterer, 1999]

$$w = w_0 + w_1 z$$

  - [Efstathiou, 2000]

$$w = w_0 + w_1 \log(1 + z)$$

- Same w at early and late times
  - [Jassal, Bagla, Padmanabhan,2004]

$$w = w_0 + w_1 \frac{z}{(1 + z)^2}$$

Other choices II

- Polynomial around ΛCDM (early time blow-up)
    - [Weller and Albrecht, 2000]

$$w = -1 + c_1(1+z) + c_2(1+z)^2$$

- CPL-like but faster
    - [Barboza and Alcaniz, 200]

$$w = w_0 + w_1 \frac{z(1+z)}{1+z^2}$$

Other choices III

- Early dark energy

$$\Omega_{de}(a) = \text{early} \neq 0$$

[Pettorino,Amendola, Wetterich 2013]

  - one of their examples

$$\Omega_{de}(a) = \frac{\Omega^0_{de} - \Omega_e(1 - a^{-3w_0})}{\Omega^0_{de} + \Omega^0_m a^{3w_0}} + \Omega_e(1 - a^{-3w_0})$$

- Strong (CMB) constraints

$$\Omega^{early}_{de}(a) < 4\%$$

Selfie

- [Sendra and Lazkoz, 2012]

$$w(z) = -1 + c_1\left(1+\frac{z}{1+z}\right) + c_2\left(1+\frac{z}{1+z}\right)^2$$

$$w(z) = -1 + c_1 T_1\left(1+\frac{z}{1+z}\right) + c_2 T_2\left(1+\frac{z}{1+z}\right) \qquad T \equiv \text{Chebyshev}$$

- c_1 and c_2 expressed in terms of w_0 and $w_{0.5}$

FoM **six times larger** than (standard) CPL

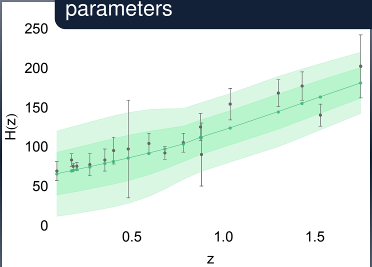
Model independent tracks

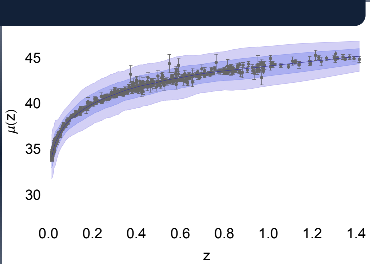
Approaches

- Principal Components Analysis
- Nonlinear Inverse Approach
- Dipole of the Luminosity Distance method
- Smoothing Method
- Gaussian Processes
- Nodal Reconstruction
- Genetic Algorithms
- Loess+Simex

- **Problems**
  - prior, fiducial cosmological model or initial guess model
  - bins sharing data points
  - low efficiency at high z (few data points)
  - Error underestimation or overestimation
  - Computational cost

Loess+Simex reconstructions of H(z) and $\mu(z)$ with optimal regression parameters





Montiel et al. 2014

Dark energy potential

- Intepretation: DE as quintessence (ϕ)

$$(H/H_0)^2 = (1-\Omega_m/3)(1+z)^6 + (\Omega_m/3)(1+z)^3 - 2(1+z)^6 \int_0^z (V(x)/H_0^2)(1+z)^{-7} dx$$

$$\phi(z) - \Phi(0) = \pm \int_0^z \frac{\sqrt{6(H/H_0)^2 - 2\Omega_m(1+z)^3 - 2V(z)/H_0^2}}{(1+z)H/H_0}$$

Chimento & Jakubi 1996

$$V(z) = \sum_{i=1}^{N} \lambda_n T_n(2\frac{z}{z_{max}} - 1)$$

Martínez & Verde 2008

Key ingredients

1. Hubble parameter
   - Planck+WP $\sim 67\, km/s/Mpc$ vs HST $\sim 74\, km/s/Mpc$
   - $\sum m_\nu \downarrow \rightarrow H_0 \uparrow$ CMB and HST reconciled
   - H_0 from gravitational time delays closer to CMB ~ 69 [Sereno & Paraficz, 2013]
2. Ω_m and Ω_k
   - affect $H(z)$ and $D_{L,C,A}(z)$
   - CMB+BAO+SN$\rightarrow \Omega_k \sim 0$ our assumption
   - Precise (independent) $\Omega_m h^2$ from CMB peaks
3. Sound horizon r_s
   - affects the physical scale of the CMB peaks and the BAO feature
4. Matter overdensity fluctuation $\sigma_8(z)$
   - affects growth measures

Main attack line: geometry

- ⋆ Luminosity distance (SN)
- ⋆ Comoving distance and matter density (CMB shift, BAO)
- ⋆ Hubble function (BAO and Hubble data)
- ⋆ Redshift drift

Type Ia SN

- Revolution: 1998 discovery of acceleration [Riess et. al 1998, Perlmutter et al 1998]
- "Standardizable candles"

standarity issues
- *explosion mechanism details*
- *systematic errors (photometry, host, lensing, etc.)*

- Luminosity distance data:

$$D_L = (1+z)\int_0^z \frac{cdx}{H(x)}$$

- Theoretical inputs

$$\mu_{th} = 5\log_{10} D_L + 25$$

Current immense precision $\rightarrow$ systematics become important $(\%1 - \%2)$

CMB (distance priors)

- Efficient summary of CMB data [Wang & Wang 2013]

$$R = \sqrt{\Omega_m H_0^2}\, r(z_\star) \qquad l_a = \pi r(z_\star)/r_s(z_\star)$$

- Parameter degeneracy reduction
  - $R \rightarrow$ amplitude of the acoustic peaks
  - $l_a \rightarrow$ peak structure

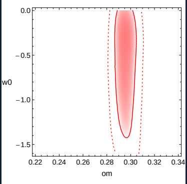
$z_\star$ redshift at last scattering surface

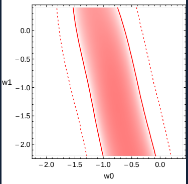
$r = D_C = D_L/(1+z)$ comoving distance

r_s sound horizon

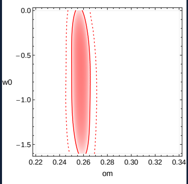
CMB shift constraints

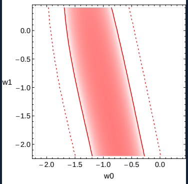
$H_0 = 69.$





$H_0 = 73.8$





- $H_0 \uparrow \Rightarrow$ less matter, more phantom, smaller dw/da
- ΛCDM with 1σ, more compliance for larger H_0

Hubble data (BAO and ...)

- Less smearing (avoids one integral)
  - age differences of old passively evolving galaxies

[Jiménez, Verde et al. (several years)]

$$H(z) = -dz/(dt(1+z))$$

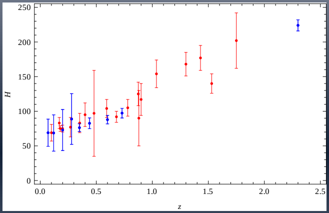
$$+$$

BAO data

$$r_s(z_d) = c\Delta z_{BAO}/H(z)$$

z_d redshift at drag epoch

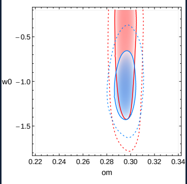
H(z) observations

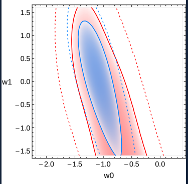


- $z > 0.3$, error $< 10\%$ [Sloan, Wiggle-z]
- $z = 2.3$, error $\sim 3.5\%$ [Boss]

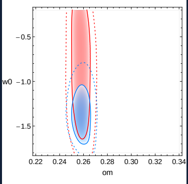
CMB (shift)+H(z)

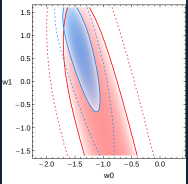
$H_0 = 69.$





$H_0 = 73.8$

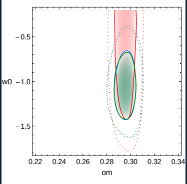


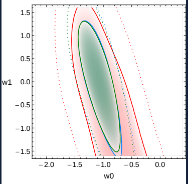


- Low H_0 close up around ΛCDM
- High H_0 phantom favoured

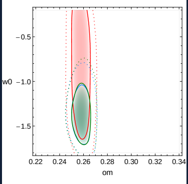
(smoothed bineed SN)+CMB (shift)+H(z)

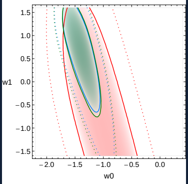
$H_0 = 69.$





$H_0 = 73.8$





- Close up around ΛCDM for both H_0 values
- Constraints improve for low $H0$, worsened for high H_0

Redshift drift

- Monitor over time a good spectral line: "detectable effect"

$$\Delta v = c\Delta z_2/(1 + z_s)$$

z_s: redshift between emission and reception

- Link to expansion history

$$\frac{\Delta v}{c} = H_0 \Delta t \,(1 - H(z_s)/(H_0(1 + z_s)))$$

- [Liske et al. 2008]
  - Next generation of Extremely Large Telescopes 42-m ELT
  - 4000 hours of integration, 20 year period

“Go beyond attack line”: perturbations

⋆ Growth factor

Growth factor

- Evolution of matter perturbations in a late universe with DE

$$\ddot{\delta}_m + 2H\dot{\delta}_m = 4\pi G_{eff}\,\rho_m \delta_m$$

$$\rho_m \equiv \text{matter density} \quad \delta_m = (\rho_m - \bar{\rho}_m)/\bar{\rho}_m$$

- Parametrize as

$$f = \Omega_m(a)^{\gamma(a)}$$

  and solve approximately
- Weak w – dependence of $\gamma \Rightarrow$

  separable background and fluctuation growth

- Some γ values:
  - GR with $w = const.$

$$\gamma \simeq \frac{3(w-1)}{6w-5}$$

  - GR with *Lambda*CDM

$$\gamma \simeq \frac{6}{11}$$

  - DGp

$$\gamma \simeq \frac{11}{16}$$

- Cosmological observable: $f\sigma_8$

  typical error $> 10\%$

- Usually

$$\gamma = \gamma_0 + \gamma_1 y(z)$$

$$y(z) = \boxed{\text{your favourite choice}}$$

- Alternatively expand in powers of
  - $(1 - \Omega_m)$
  - $\ln \Omega_m$ ✓ [Steigerwald et al. 2014]

- Treat $F(\mathcal{R})$ theories as a deviation from ΛCDM

$$f(\mathcal{R}) = \mathcal{R} - 2\Lambda y(\mathcal{R}, b)$$

$b \equiv$ deviation rate
ΛCDM recovered for $b \to 0$

- [Basilakos et al. 2013]
  - γ_0 close to GR, ΛCDM
  - $\gamma_1 < 0.2$, error $> 100\%$
  - $b < 0.3$, error $> 100\%$

In brief

- Acceleration: observationally confirmed
- Model?? Theoretical background ??
- Constraints improving