The Dark Energy trajectories in the post-EUCLID era

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Outline

Introduction

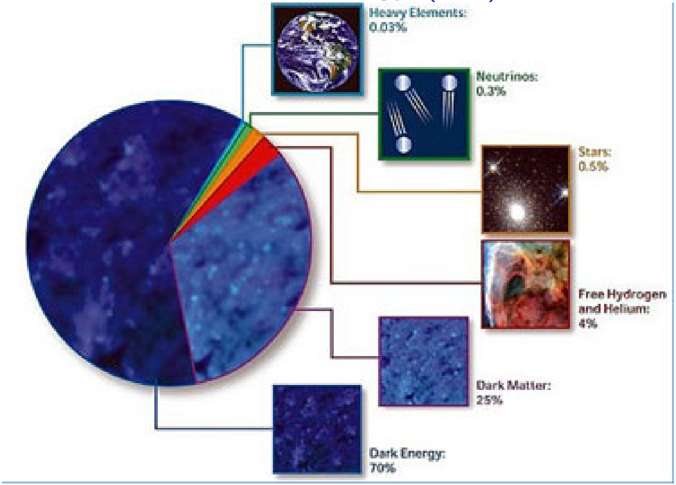
Parameterizing Dark Energy: beyond the phenomenological w_0-w_a

Observational Constraints

- current data: SNLS3yr and the latest H_0 measurment
- The future observations: Planck CMB + EUCLID LSS (+ 21cm + SN)

Conclusion

Cosmic Pie and Dark Energy (DE)



NASA, http://en.wikipedia.org/wiki/File:Cosmological_composition.jpg

Cosmological Constant

$$S = \int \sqrt{-g} d^4x \left[\frac{M_p^2}{2} (R - 2\Lambda) + \mathcal{L}_{\rm matter}(g^{\mu\nu}, \psi_m) \right]$$

$$\rho_{\rm DE} = \text{constant}$$

The equation of state (EOS):

$$w_{\rm DE} \equiv \frac{P_{\rm DE}}{\rho_{\rm DE}} = -1$$

Parameterizing the DE EOS

If not $w_{\rm DE} = -1$, how to parameterize DE?
The oft-used options: constant $w_{\rm DE} = w_0$ or linear $w_{\rm DE} = w_0 + w_a(1 - a)$.

- Too many DE models $\Rightarrow$ difficult to do a model-by-model selection.
- These are good low-redshift approximations for a variety of models.

The take-home message of this talk:
For a wide class of DE models, we have a better choice.

Dark Energy Candidates

A general framework with an extra scalar d.o.f ϕ (scalar-tensor theory)

$$S = \int \sqrt{-g} d^4x \left[\frac{M_p^2}{2} A(\phi; R) + \frac{1}{2} B(\phi) \partial^\mu \phi \partial_\mu \phi - V(\phi) + \mathcal{L}_{\mathrm{matter}} \left(g^{\mu\nu} e^{2\alpha(\phi)}, \psi_m \right) \right]$$

Only two free functions are physical:

- Jordan Frame : $\alpha(\phi) = 0$, $B(\phi) = \pm 1$.
- Einstein Frame : $A(\phi) = R$, $B(\phi) = \pm 1$.

Examples: quintessence; phantom; Brans-Dick theory; $f(R)$ gravity; ...

Dark Energy Candidates

If the coupling between ϕ and matter is negligible:

$$S = \int \sqrt{-g} d^4x \left[\frac{M_p^2}{2} R \pm \frac{1}{2} \partial^\mu \phi \partial_\mu \phi - V(\phi) + \mathcal{L}_{\mathrm{matter}} \left(g^{\mu\nu}, \psi_m \right) \right] .$$

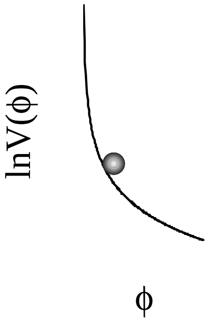
$+$: quintessence.

$-$: phantom.

- These are the simplest alternatives to Λ.
- Many concrete models: Ratra & Peebles 1988; Wetterich 1988; Frieman et al. 1995; Binetruy 1999; Barreiro et al. 2000; Brax & Martin 1999; Copeland et al. 2000; de La Macorra & Stephan-Otto 2001; Carroll et al. 2003; Caldwell 2002; Caldwell et al. 2003; Linder 2006; Copeland et al. 2006; Huterer & Peiris 2007; Linder 2008 ...

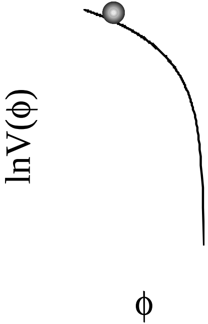
Quintessence: two classes of models

tracking:



early-universe: fast-roll
late-universe: slow-roll

thawing:



early-universe: frozen
late-universe: slow-roll

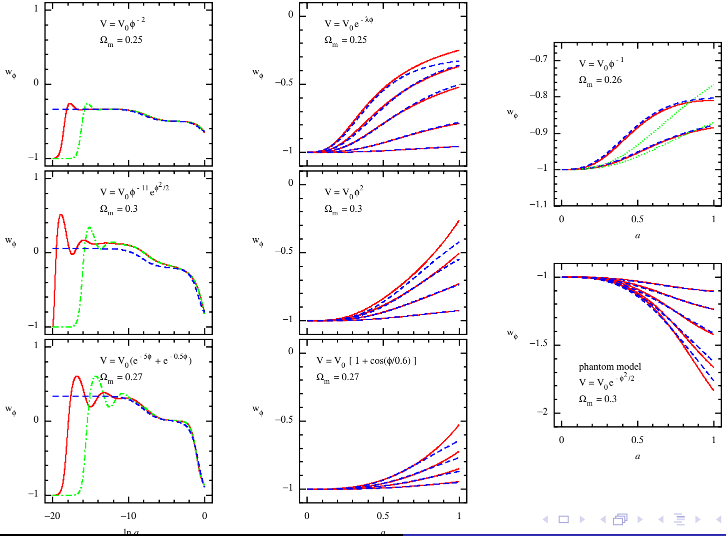
The quintessence/phantom $w_{\rm DE}$ recipe

$$w_{\rm DE} = w_\phi = F\left(a; \Omega_m, \epsilon_s, \epsilon_{\phi,\infty}, \zeta_s\right)$$

- The slope parameter $\epsilon_s \equiv \pm\frac{M_p^2}{2}(\frac{d\ln V}{d\phi})^2$ at low redshift ('+' for quintessence, '-' for phantom).
- The tracking parameter $\epsilon_{\phi,\infty} \sim |1 + w_\phi|$ at high redshift.
- The running parameter ζ_s is related to $|d\phi/dt|$ and $\frac{d^2\ln V}{d\phi^2}$ at low redshift (for thawing models $\zeta_s \propto \frac{d^2\ln V}{d\phi^2}$).

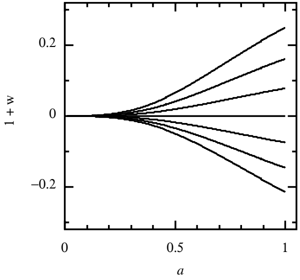
For the explicit expression of F and more details see *Huang, Bond, Kofman*, 2011 (ApJ).

Comparing our $w_{\rm DE}$ formula with the exact solutions.



The thawing models with slow rolling.

Slow-roll thawing models: only ϵ_s is relevant.



from bottom to top:

$$\epsilon_s = -0.75, -0.5, ..., 0.75$$

The degeneracy between w_0 and w_a (defined as $\frac{dw}{da}|_{a=1}$).

$$1+w_0+w_a(0.264+\frac{0.132}{\Omega_{m0}}) = 0 \; .$$

Cosmological Data Sets

- Cosmic Microwave Background (**CMB**): WMAP7(2010), ACT(2010), Acbar (2009), QUAD (2009), BICEP (2009), CBI (2008), Boomerang (2006), VSA (2004), MAXIMA (2000)
- Type Ia Supernova (**SN**): 472 SNs (123 low-z + 242 SNLS3yr + 93 SDSS1yr + 14 HST)
- Weak Lensing (**WL**): COSMOS + CFHTLS-wide + RCS + VIRMOS + GaBoDS.
- Large Scale Structure (**LSS**): SDSS-DR7 LRG (2009).
- Lya Forest (**Ly**α): SDSS (P. McDonal 2005, 2006).
- HST constraint $H_0 = 73.8 \pm 2.4 \mathrm{km\,s^{-1}\,Mpc^{-1}}$. (Riess et al 2011)

SNLS3yr

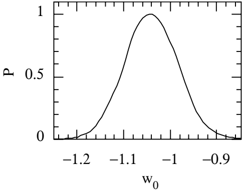
Table 2. Cosmological results assuming a flat universe and constant w for the SNLS3 sample plus BAO and WMAP7

Fit	α^{a}	β^{a}	M_B^1	M_B^2	Ω_m	w
Marginalization fits						
Stat only	$1.450^{+0.112}_{-0.105}$	$3.164^{+0.096}_{-0.094}$	-19.164	-19.227	$0.276^{+0.016}_{-0.013}$	$-1.043^{+0.054}_{-0.055}$
Stat + sys	$1.367^{+0.086}_{-0.084}$	$3.179^{+0.101}_{-0.099}$	-19.175	-19.220	$0.274^{+0.019}_{-0.015}$	$-1.068^{+0.080}_{-0.082}$

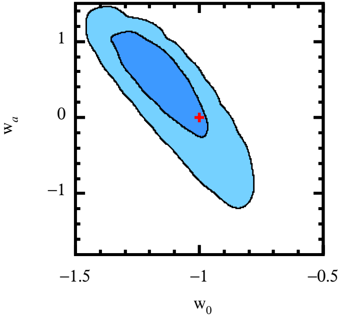
The updated phenomenological w_{DE}

constant w_{DE}:

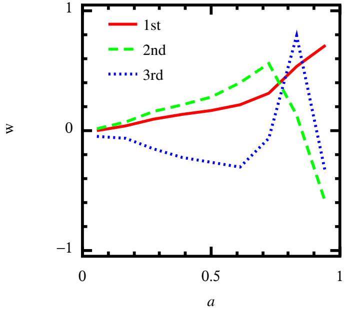
$$w = -1.040^{+0.056}_{-0.056}$$



w_0-w_a:

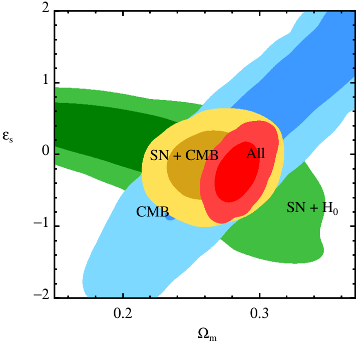


The eigen modes

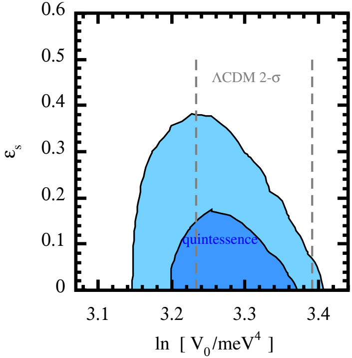


9 uniform bins $a \in [0, 1]$.
basis: top-hat functions.
$\sigma_1 = 0.12$
$\sigma_2 = 0.22$
$\sigma_3 = 0.41$

ϵ_s and $\ln V_0$.

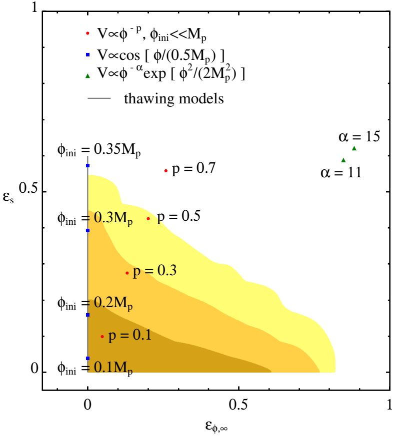


Slow-roll thawing case; assuming $\epsilon_{\phi,\infty} = 0$ and $\zeta_s = 0$.

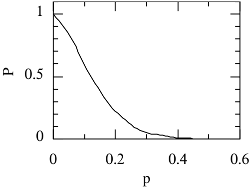


General quintessence; Uniform priors on $\Omega_b h^2$, $\Omega_c h^2$ and θ.

Quintessence models on the ϵ_s-$\epsilon_{\phi,\infty}$ plane.

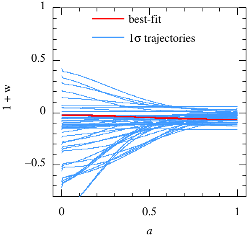


Direct constraint on the $V \propto \phi^{-p}$ tracking model is $p < 0.43$ (3-σ).

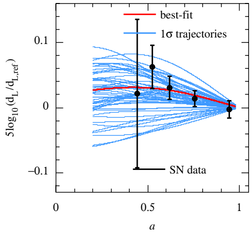


Marginalized over ζ_s and other cosmological parameters.

reconstructed $1 + w_{\rm DE}$ trajectories:



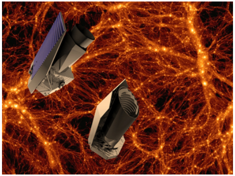
the distance moduli:



Forecasts Mock Data

- **CMB**: **Planck2.5yr**, using 3 channels (70GHz, 100GHz, 143GHz), assuming 5% foreground residual (synchrotron + dust), $f_{\rm sky} = 3/4$, $l_{\rm max} = 2500$.
- **LSS**: **EUCLID** spectroscopic redshift survey; $f_{\rm sky} = 0.5$, $0.5 < z < 2.1$.
- **SN**: **JDEM**, 500 LOWZ ($z < 0.03$) + 2500 HIGHZ ($0.03 < z < 1.7$)
- **21-cm** survey **CHIME** 200m×200m cylinder radio telescope, 4000 receivers integrated 4 yrs; $f_{\rm sky} = 0.36$.

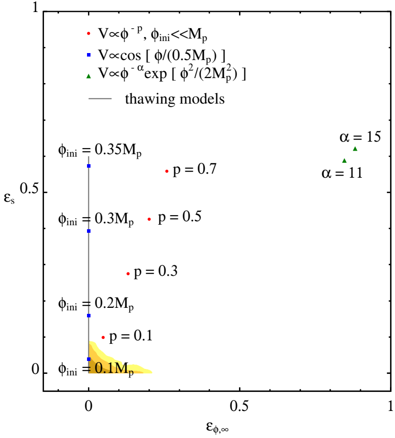
The EUCLID LSS survey

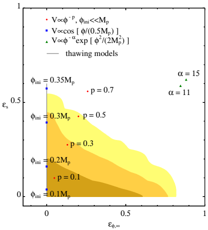


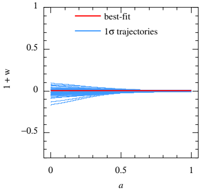
$$P_g(k, z, \mu) = \left(b + \frac{d \ln D}{d \ln a}\mu^2\right)^2 D^2(z) P_m(k, z = 0) e^{-k^2\mu^2\sigma^2} .$$

8 redshift bins $\times$ 30 k bins $\times$ 20 μ bins
marginalize over 16 nuisance parameters: b_1, b_2, ..., b_8; σ_1, σ_2, ..., σ_8.
cut-off at quasi nonlinear scales ($k \sim 0.2\,\mathrm{Mpc}^{-1}$).

DE EOS in the post-EUCLID era

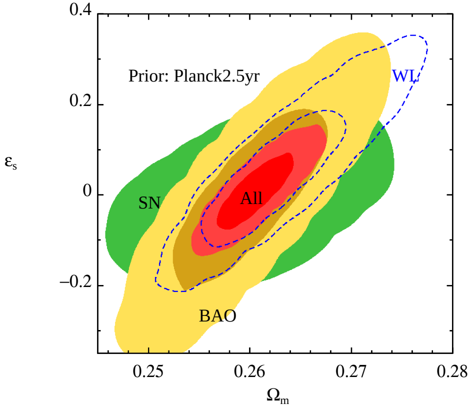






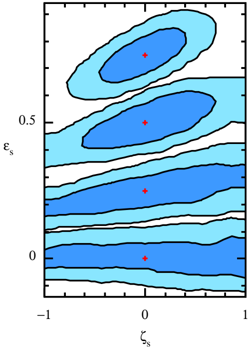
Marginalized over ζ_s and other cosmological parameters.

Comparison between different probes



- BAO can be achieved with less expensive experiments such as CHIME.
- LSS and WL are correlated; Simulatenous treatment requires extra work.

How about the "running" parameter ζ_s?



A slowly rolling field does not "feel" the curvature of the potential.

Conclusion

- Both quintessence and phantom models are consistent with current observations. The best-fit model is in the proximity of Λ.
- The constraints on the slope parameter ϵ_s and tracking parameter $\epsilon_{\phi,\infty}$ can be improved by a factor of about 5 by the future observations.
- The running parameter (in thawing case, the second derivative of $\ln V$ at low redshift) is not measured today, and will not be measurable in the near-future observations, unless the true model significantly deviates from Λ.
- The ϵ_s-$\epsilon_{\phi,\infty}$ space is complementary to the standard w_0-w_a space.