Constraining Trajectories of Dark Energy Inflatons @Miami08

Dick Bond @
CITA ICAT Canadian Institute for Theoretical Astrophysics L'institut canadien d'astrophysique theorique
25 years cifar

What is the Universe made of?

NOW: baryons + (cold-ish) dark matter + dark energy/inflaton + tiny curvature energy (+light neutrinos+photons). ??a bit of strings/textures/PBHs??

THEN: coherent inflaton /**"vacuum" energy + zero-point fluctuations** in all fields & then preheat via mode coupling to incoherent cascade to thermal equilibrium soup

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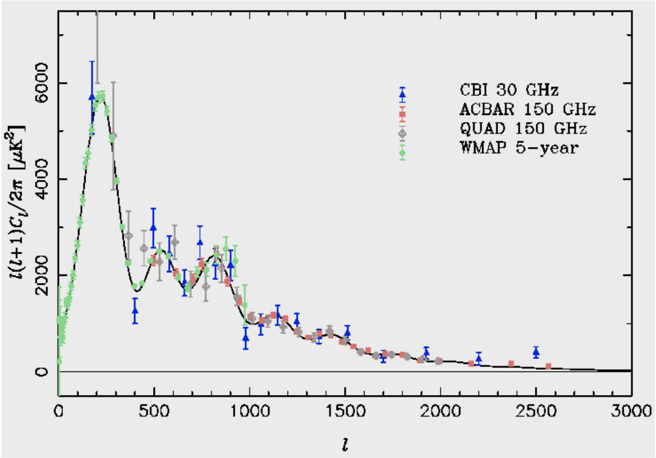
very early U early to middle to now U **very late U**

string theory/landscape/higher dimensions

inflation cyclic baryogenesis dark matter BBN γdec **dark energy**

$V_{eff}(\psi_{inf})$?

$K_{eff}(\psi_{inf})$?



$V_{eff}(\psi_{inf})$?

$K_{eff}(\psi_{inf})$?

cosmic mysteries

n_b/n_γ ρ_{dm}/ρ_b z_{eq}/z_{rec} ρ_{curv} ρ_{de}/ρ_{dm} $\rho_{de} \sim H^2 M^2_{Planck}$ $\rho_{m\nu}/\rho_{stars}$

Standard Parameters of Cosmic Structure Formation

$\Omega_b h^2$ $\Omega_{dm} h^2$ Ω_Λ Ω_k τ_c

$\ln A_s$ n_s $r = A_t/A_s$ $dn_s/d\ln k$ n_t

$1+w_0$, w_a $\theta \sim \ell_s^{-1}$ $n_e(a)$ $\sim \ln \sigma_8^2$

New Parameters of Cosmic Structure Formation: early-inflaton & late-inflaton trajectories (& reionization histories)

$\epsilon_\phi = (1+w(a)) \times 3/2 = -d\ln\rho_\phi/d\ln a/2$

$\epsilon_s f(a/a_{\Lambda eq}; a_s/a_{\Lambda eq}; \zeta_s)$

$\ln P_s(\ln k)$ & $r(k_p)$ & $\ln P_t(\ln k)$

$\epsilon_\phi(\ln k)$, $k \sim Ha$ & $\ln H(k_p)$

Blind trajectory analysis cf. data, then & now

expand $\epsilon(\ln k)/\epsilon_\phi(\ln a)$ in localized mode fns

e.g., **Chebyshev/B-spline coefficients ϵ_b**

ϵ_b-measures: "theory prior"=*informed prior?*

+ subdominant

isocurvature/ cosmic string/ tSZ ...

dark matter abundance Ω_m=0.268 +.012 -.012

	January 2000	January 2002	June 2002	January 2003	March 2003
$\Omega_{cdm}h^2$	$0.198^{+0.088}_{-0.080}$	$0.130^{+0.031}_{-0.028}$	$0.124^{+0.026}_{-0.025}$	$0.125^{+0.021}_{-0.022}$	$0.111^{+0.010}_{-0.010}$

CMB-only history (weak-h prior). LSS-then drove to near current

$\Omega_{dm}h^2$ **0.1145 +-0.0023 CMBall+WL+LSS+SN+Lya**

$\Omega_b h^2$ **0.0233 +- 0.0005**

$\rho_{dm}/\rho_b = 5.1$

Ω_Λ	$0.34^{+0.28}_{-0.24}$	$0.52^{+0.17}_{-0.20}$	$0.53^{+0.17}_{-0.19}$	$0.57^{+0.14}_{-0.19}$	$0.73^{+0.06}_{-0.10}$

CMB-only history (weak-h prior). LSS-then drove to near current value

dark energy abundance Ω_Λ=0.736 +.012 -.012

& H_0 = 72 +-1 CMBall+WL+LSS+SN+Lya

$\rho_m/\rho_{de} = .30$

ε=-dlnH/dlna=1+q: now =3/2[Ω_{m0} +(1+w)(1-Ω_{m0})] **~0.40?, to 0?**

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– Dick Bond

CIAR

25 years cifar

Constraining Trajectories of Dark Energy Inflatons

Inflation Now $\varepsilon_\phi(a) = \varepsilon_s f(a/a_{\Lambda eq}; a_s/a_{\Lambda eq}; \zeta_s)$

$\varepsilon_\phi = -d\ln\rho_\phi / d\ln a / 2$ ~0 now, to $\varepsilon = -d\ln\rho_{tot} / d\ln a / 2$ ~0 to 2, 3/2, ~.4

cf. w(a): w0,wa; w in z-bands or z-modes; $\varepsilon(a)$: in modes, jerk

~1 good e-fold. only ~2 params. priors matter

Inflation Then $\varepsilon(k) = (1+q)(a)$ **= mode expansion in resolution (lnHa ~ lnk)**

~r/16 (Tensor/Scalar Power & gravity waves) ~ 10 good e-folds CMB+LSS

Cosmic Probes Now CMB(Apr08), CFHTLS SN(Union 307),WL, LSS/BAO, Lyα

Cosmic Probes Then JDEM-SN + DUNE-WL + Planck1

Zhiqi Huang, Bond & Kofman 09 ε_s=-0.03+-0.28 now, inflaton (potential gradient)^2

to +-0.07 then Planck1+JDEM SN+DUNE WL, weak a_s < 0.36 now <0.21 then

Measuring $w(a)=p/\rho$ (SNe+CMB+WL+LSS+Lya)

$w(a)=w_0$

$1+w_0 = -0.0 \pm 0.06$

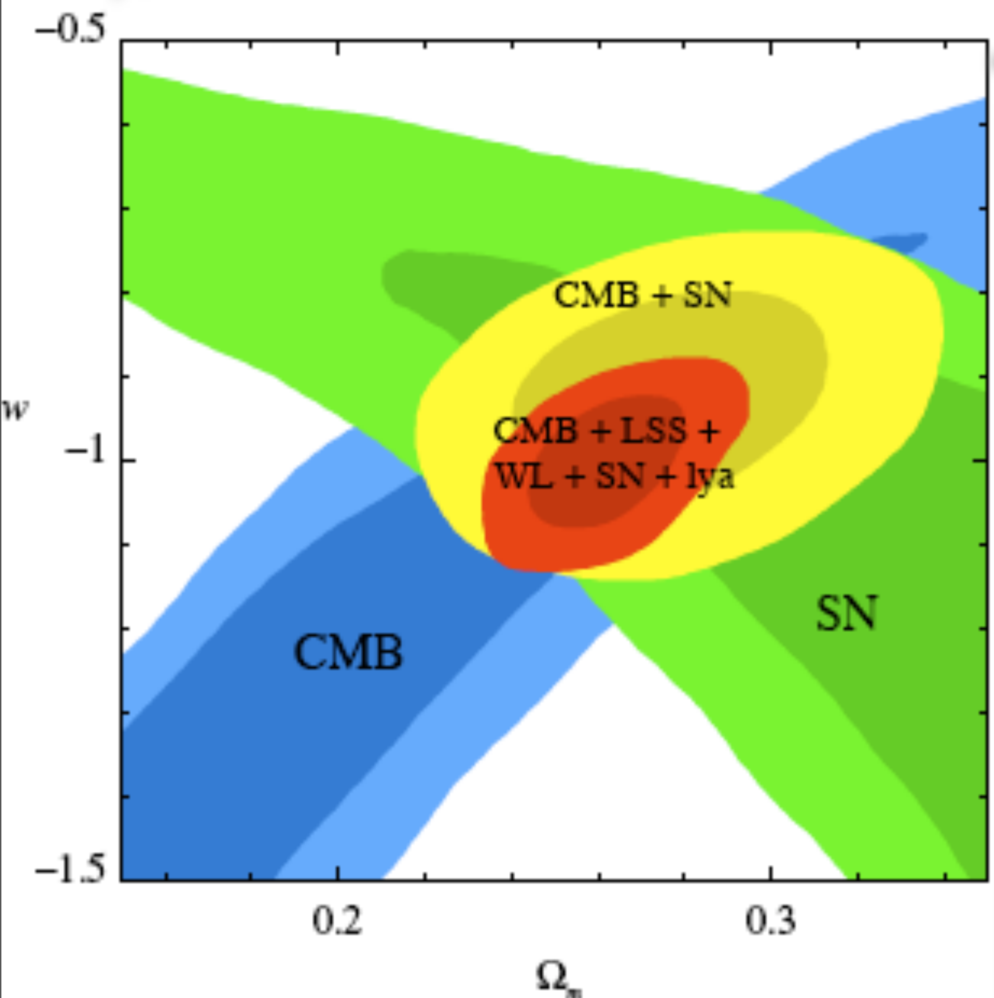
- $\epsilon_{\phi 0} = 3(1+w_0)/2 = 0.0 \pm 0.09$ if constant

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

$1+w_0 = -0.01 \pm 0.19$

$w_a = 0.0 +0.6-0.8$

- $\epsilon_{\phi 0} = -0.015 \pm 0.3$ if a-linear model



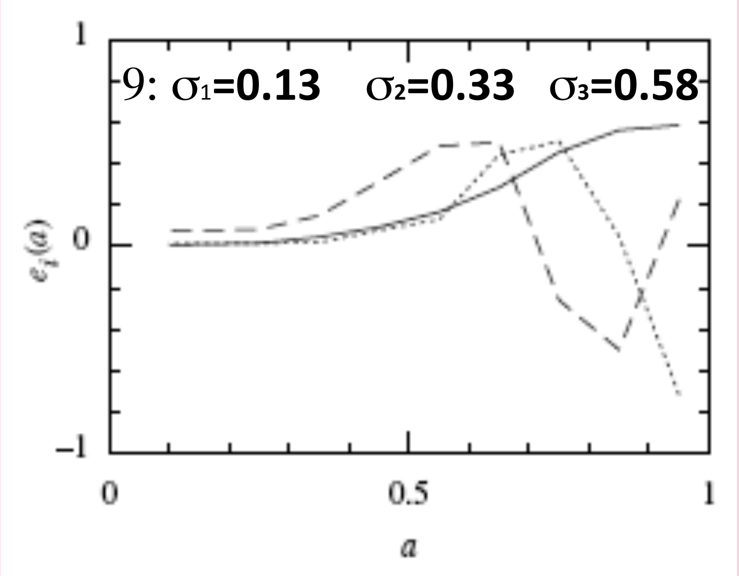
piecewise parameterization

4,9,40 modes in redshift

9 & 40 into Parameter eigenmodes

data cannot determine >2 EOS parameters

DETF Albrecht etal06, Crittenden etal06, hbk08



40: $\sigma_1=0.15$ $\sigma_2=0.36$ $\sigma_3=0.61$

- **Cosmological Constant (w=-1)**
- **Quintessence**

$V(\psi)$ **($-1 \le w \le 1$)**

- **Phantom field**

KE < 0 & $V(\psi)$ ($w \le -1$)

- **Tachyon fields ($-1 \le w \le 0$)**
- **K-essence: KE not quadratic**

$V \sim \exp[..\psi]$, ratra, peebles 88, ...

$\psi^{-p=1,2,4..}$, $V_0 + ..\psi^{p=1,2,4..}$,

$V_{pNGB} \sim \sin^2\psi/2f$, kaloper, sorba 05, 08 dutta, sorbo 06

$V \sim \exp[..\psi^2]\,\psi^{-p}$, brax, martin 99

V_{holes}, V_{branes},

$(V_0 + ..[\psi - \psi_0]^2)$, ..

& much more

$\varepsilon_\phi(a) = (1+w)2/3$ $= -d\ln\rho_\phi / d\ln a \,/2$ $\varepsilon_V(a) = (d\ln V/d\psi)^2/4$	partial blind search constrain eigenmodes map ε_ϕ-trajectories for varying V onto eigenmodes	informed but non-exhaustive search $\varepsilon_s = (d\ln V/d\psi)^2/4$ @pivot a_{eq} yes $\zeta_s = \pm 1.001\, d^2\ln V/d\psi^2/4$ @a_{eq} no $\zeta_s = d\ln\varepsilon_s/d\ln a$ x1/2 @a_{eq}

Old view: **Theory prior = delta function of THE correct one and only theory**

New: Theory prior = probability distribution of **late-flows** on an **energy LANDSCAPE**

6/7 tiny extra dimensions

1980

R^2-inflation

Old Inflation

Chaotic inflation

New Inflation

Double Inflation

Power-law inflation

SUGRA inflation

Radical BSI inflation

variable M_P inflation

Extended inflation

1990

Natural pNGB inflation

Hybrid inflation

Assisted inflation

SUSY F-term inflation

SUSY D-term inflation

Brane inflation

2000

SUSY P-term inflation

Super-natural Inflation

K-flation

2003 KKLT

N-flation

ekpyrotic/ cyclic

DBI inflation

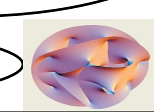
$D3-D7$ inflation

Warped Brane inflation

Tachyon inflation

Racetrack inflation

Roulette inflation Kahler moduli/axion



3-parameter formula

$$\ddot{\phi} + 3H\dot{\phi} + V'(\phi) = 0$$

+ Friedmann Eqn+DM+B

$$\theta \equiv \begin{cases} \sin^{-1} \frac{\dot{\phi}}{\sqrt{2\rho_\phi}} \\ \sinh^{-1} \frac{\dot{\phi}}{\sqrt{2\rho_\phi}} \end{cases}$$

$$w(a) = -1 + \frac{2\epsilon_s}{3}\Big\{\frac{(\frac{a_s}{a})^{3-3.6a_s|\epsilon_s|(1-\Omega_{m0})}}{\sqrt{1+\frac{\epsilon_s}{3|\epsilon_s|}(\frac{a_s}{a})^{6-7.2a_s|\epsilon_s|(1-\Omega_{m0})}}}\frac{1}{\sqrt{|\epsilon_s|}}$$
$$+[\sqrt{1+(\frac{a_{eq}}{a})^3} - (\frac{a_{eq}}{a})^3 \ln((\frac{a}{a_{eq}})^{\frac{3}{2}} + \sqrt{1+(\frac{a}{a_{eq}})^3})](1-\zeta_s)$$
$$+0.36\varepsilon_s(1-\Omega_{m0})\frac{(\frac{a}{a_{eq}})^2}{1+(\frac{a}{a_{eq}})^4}[0.9 - 0.7\frac{a}{a_{eq}} - 0.045(\frac{a}{a_{eq}})^2]$$
$$+\frac{2\zeta_s}{3}[\sqrt{1+(\frac{a}{a_{eq}})^3} - 2(\frac{a_{eq}}{a})^3(\sqrt{1+(\frac{a}{a_{eq}})^3} - 1)]\Big\}^2$$

accurate fits to **slow-to-moderate roll** & even wild rising baroque late-inflaton trajectories + **thawing & freezing** trajectories.
non-oscillating

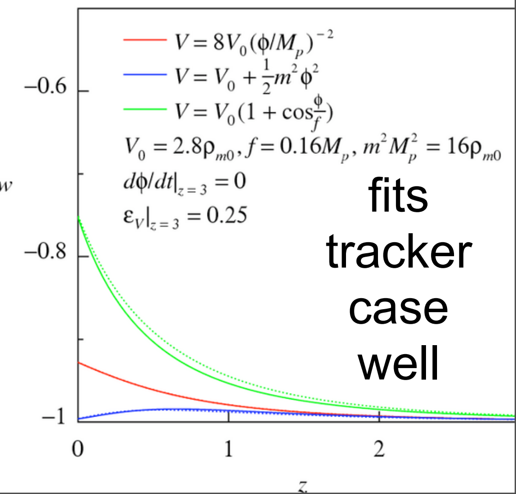
where

$$a_{eq} \equiv (\frac{\Omega_{m0}}{1-\Omega_{m0}})^{\frac{1}{3[1-0.36\varepsilon_s(1-\Omega_{m0})]}}$$

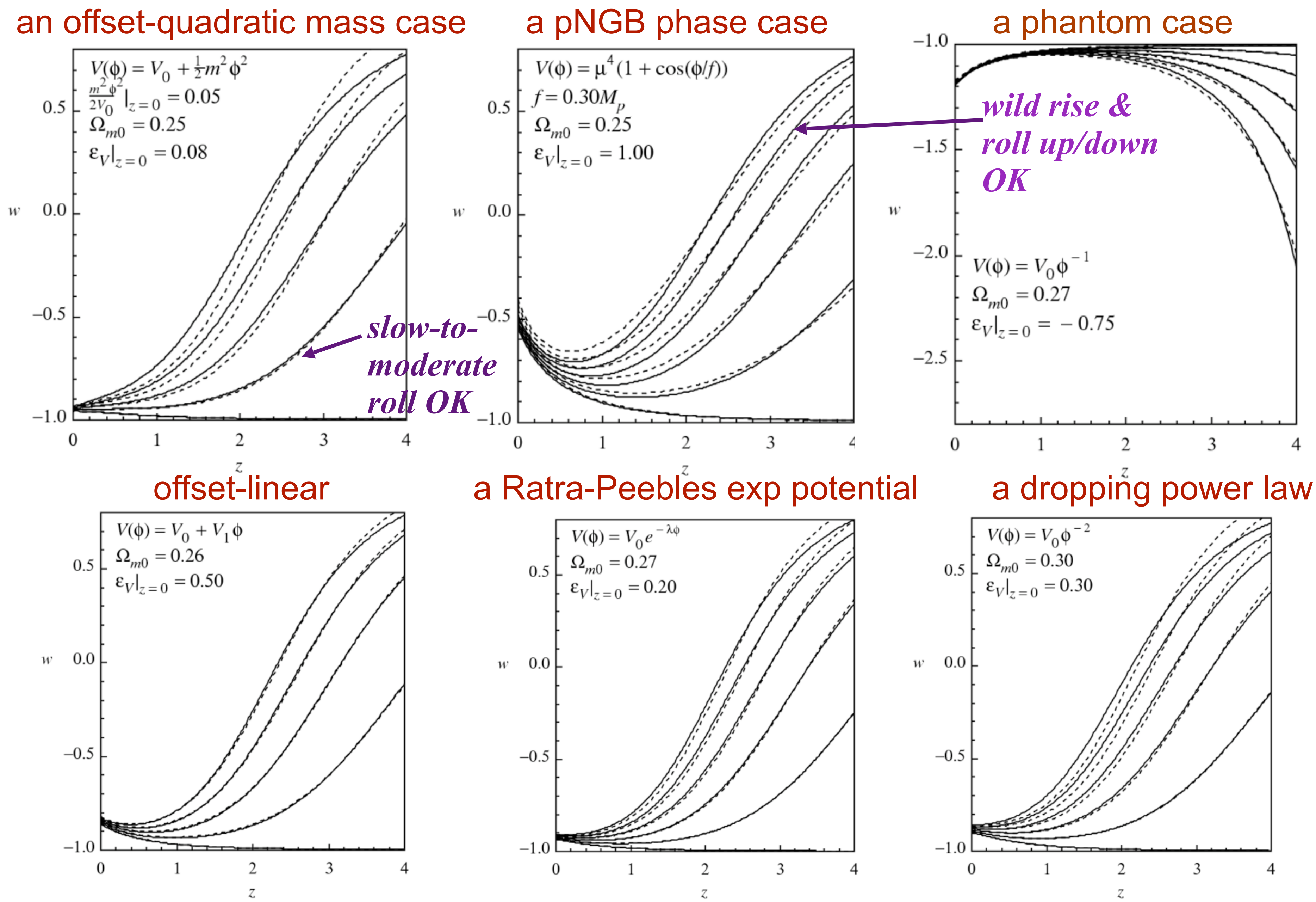
$$a_s \geq 0$$

- ~15% thawing, 8% freezing, with flat priors

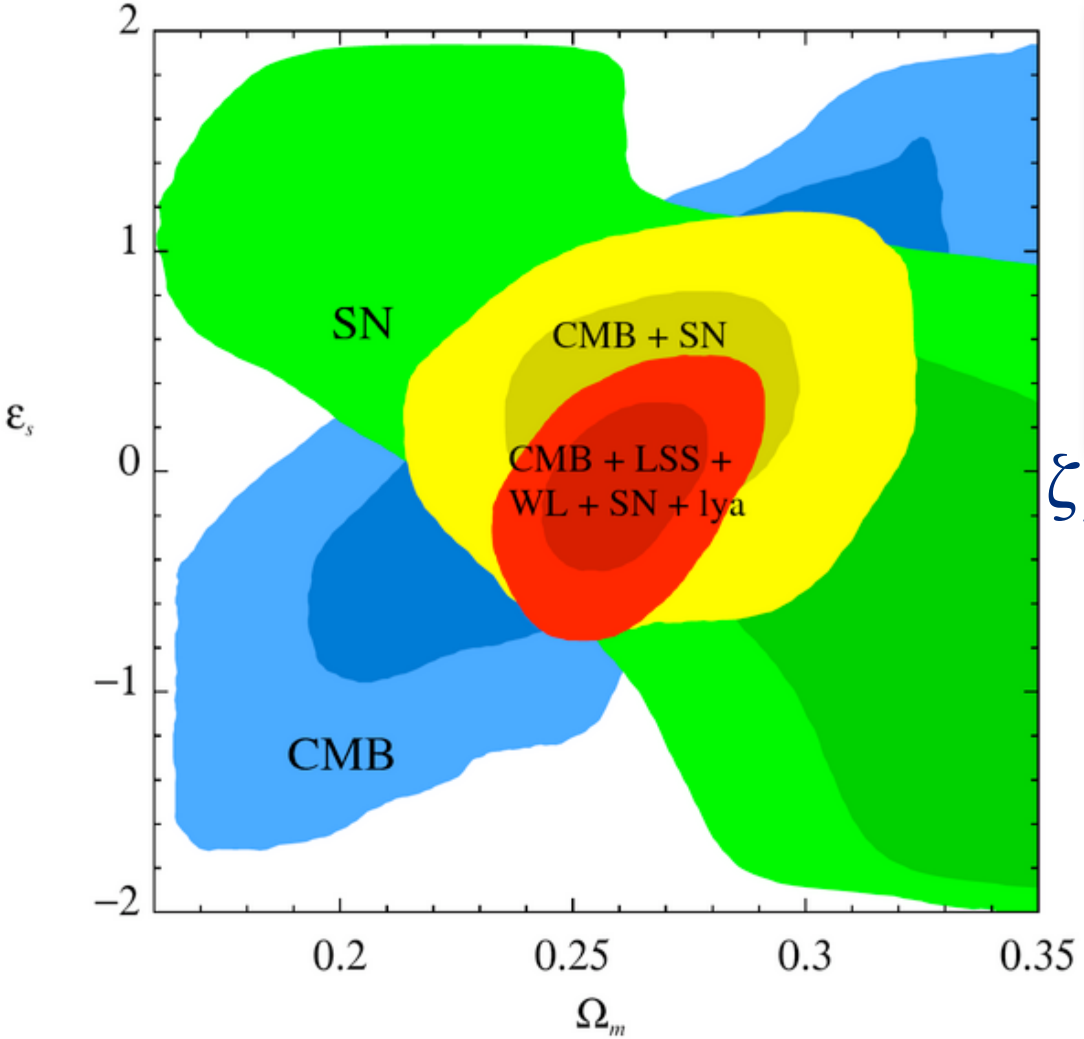
$$\sqrt{|\epsilon_V|} = \sqrt{|\epsilon_s|}[1 + \zeta_s((\frac{a}{a_{eq}})^{\frac{3}{2}} - 1)] \quad -1 < \zeta_s < 1$$



sample w(z)-trajectories for $V(\psi)$, back-integrate now to then



measuring ε_s ζ_s a_s=0 tracking (SNe_{union}+CMB $_{wmap5+acbar+cbi5yr+b03+}$+$WL_{cfhtls+cosmos}$+$LSS_{sdssRG+2dF}$+Lya)



ε_s= $(d\ln V/d\psi)^2/4$ @pivot a_{eq}

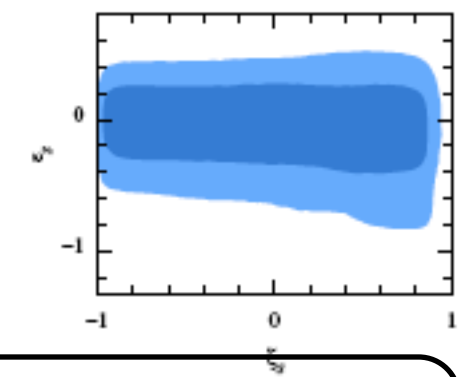
ε_s	$.01 + .25 -.28$	1
	$-.03 + .21 -.25$	3
	$-.03 + .26 -.30$	**2**

ζ_s= +-1.001$d^2\ln V/d\psi^2$ /4 @pivot a_{eq}

ζ_s =$d\ln\varepsilon_s$ /$d\ln a$ x1/2 @pivot a_{eq}

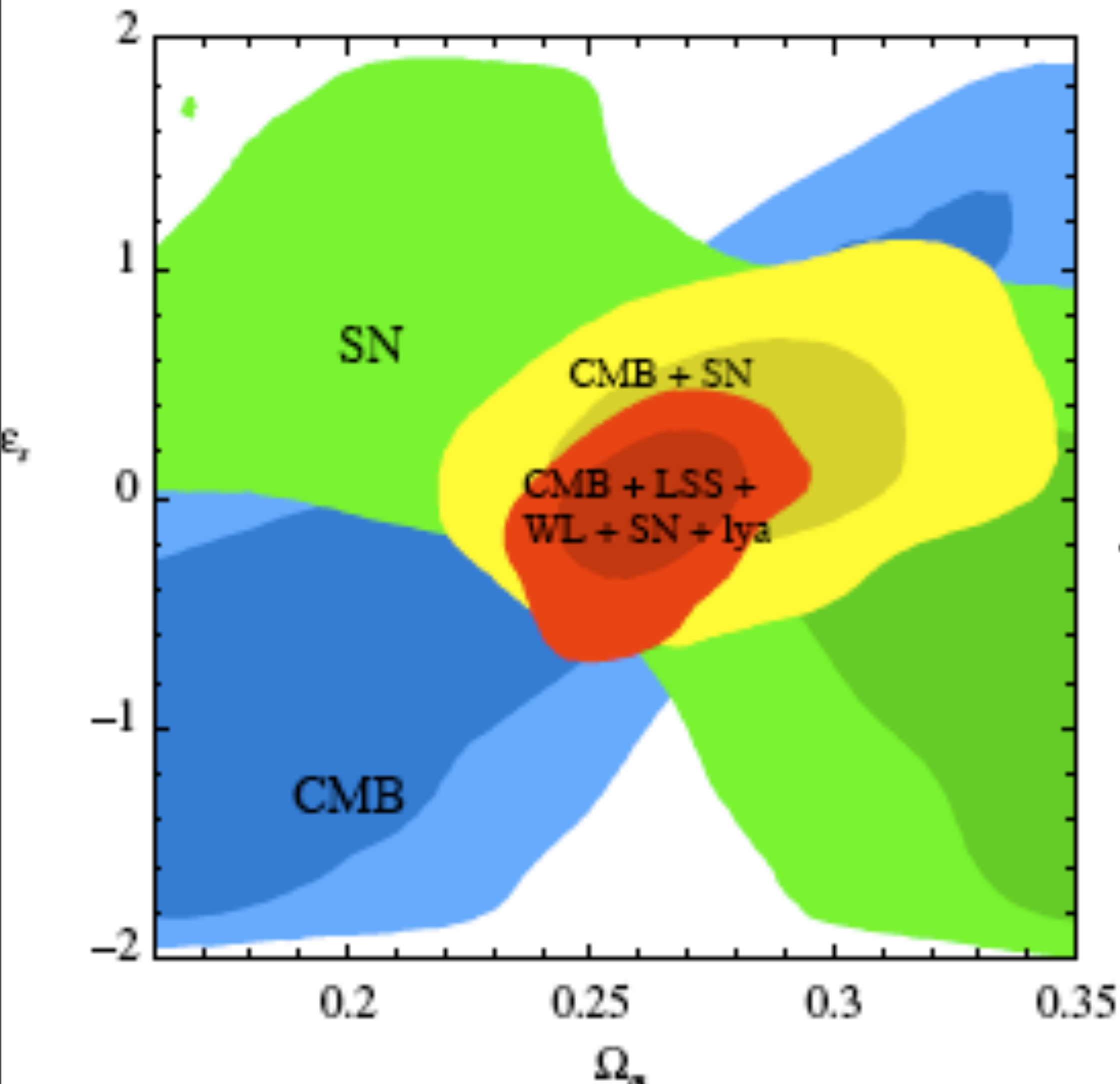
ill-determined now

$0.1^{+0.6}_{-0.7}$



cannot reconstruct the quintessence potential, just the slope ε_s & ~hubble drag

measuring ε_s a_s ζ_s scaling+tracking SNe$_{union}$+CMB$_{wmap5+acbar+cbi5yr+b03+}$+WL$_{cfhtls+cosmos}$+LSS$_{sdssRG+2dF}$+Lya)



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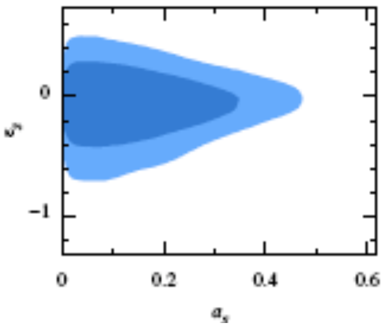
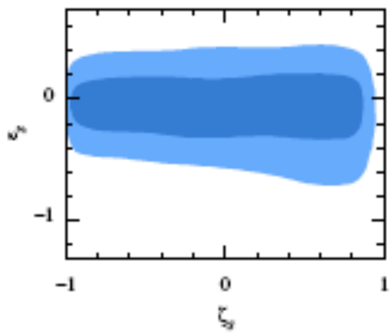


$0.000^{+0.192+0.364}$

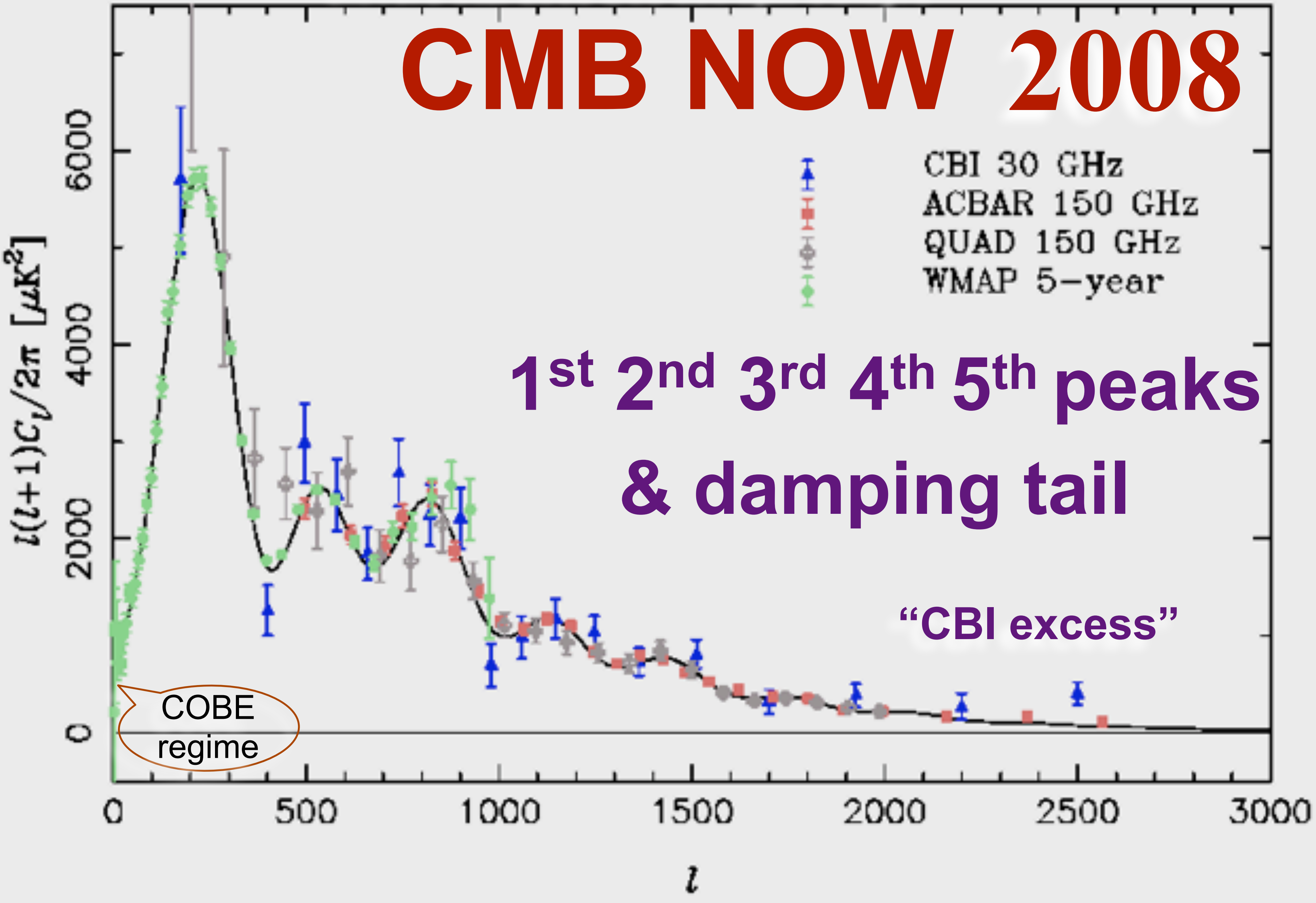


$0.0^{+0.7}_{-0.7}$

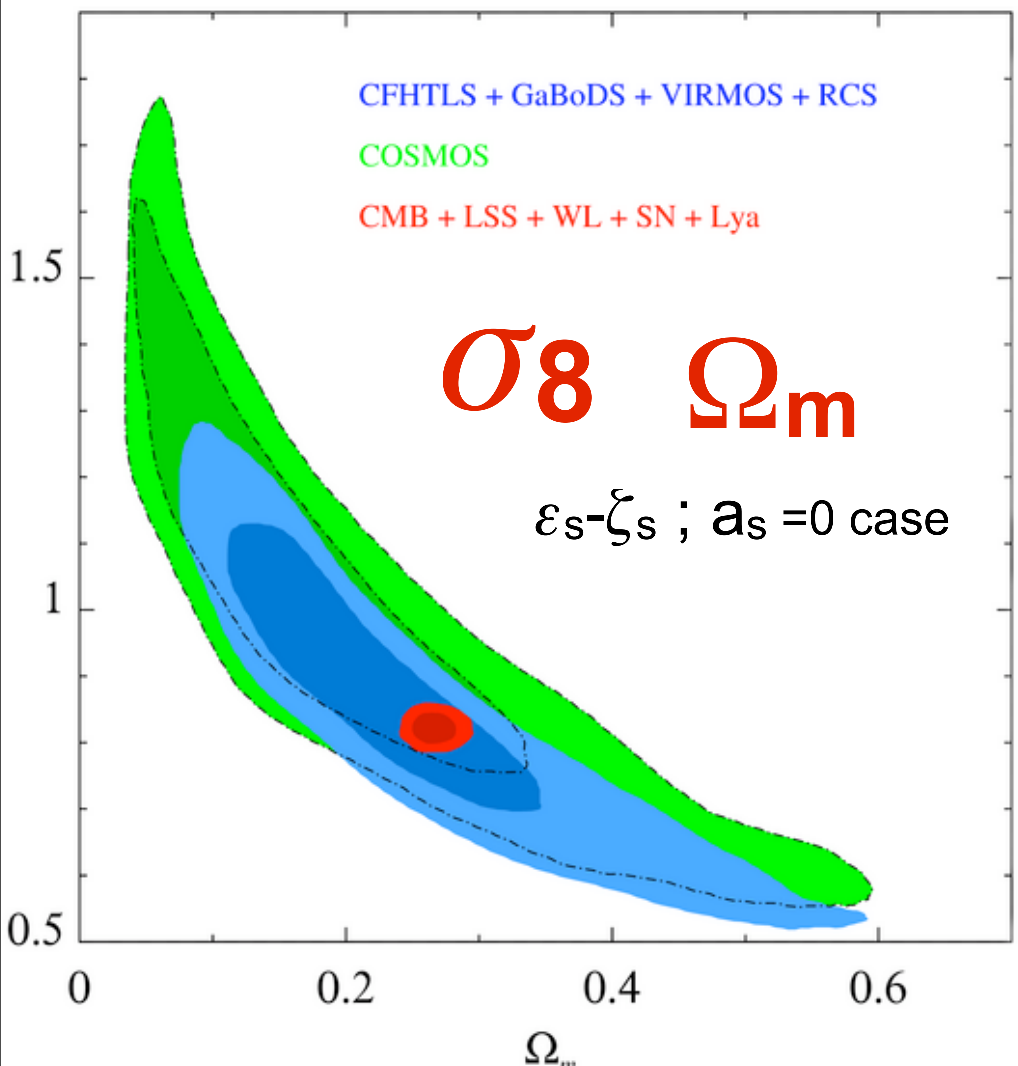
modified CosmoMC with Weak Lensing, SZ, SN,CMB, bias & w(a) slow-to-moderate-roll trajectories & various priors

cannot reconstruct the quintessence potential, just the slope ε_s & ~hubble drag

Sievers etal 2008 Dec astroph CBI5yrs



Weak Lens now: CFHTLS-wide(22sq deg)+GaBoDS (13) +Virmos-Descart(8)+RCS1(53) Apr07+ & COSMOS07



case	Ω_m	σ_8
LCDM	0.265+-.011	0.828+-.015
w0	0.265+-.013	0.829+-.025
w0-wa	0.265+-.014	0.831+-.027
ε_s-ζ_s	0.265+-.013	0.829+-.024
ε_s-ζ_s-a_s	0.265+-.013	0.832+-.025

recent weak lensing "alone"

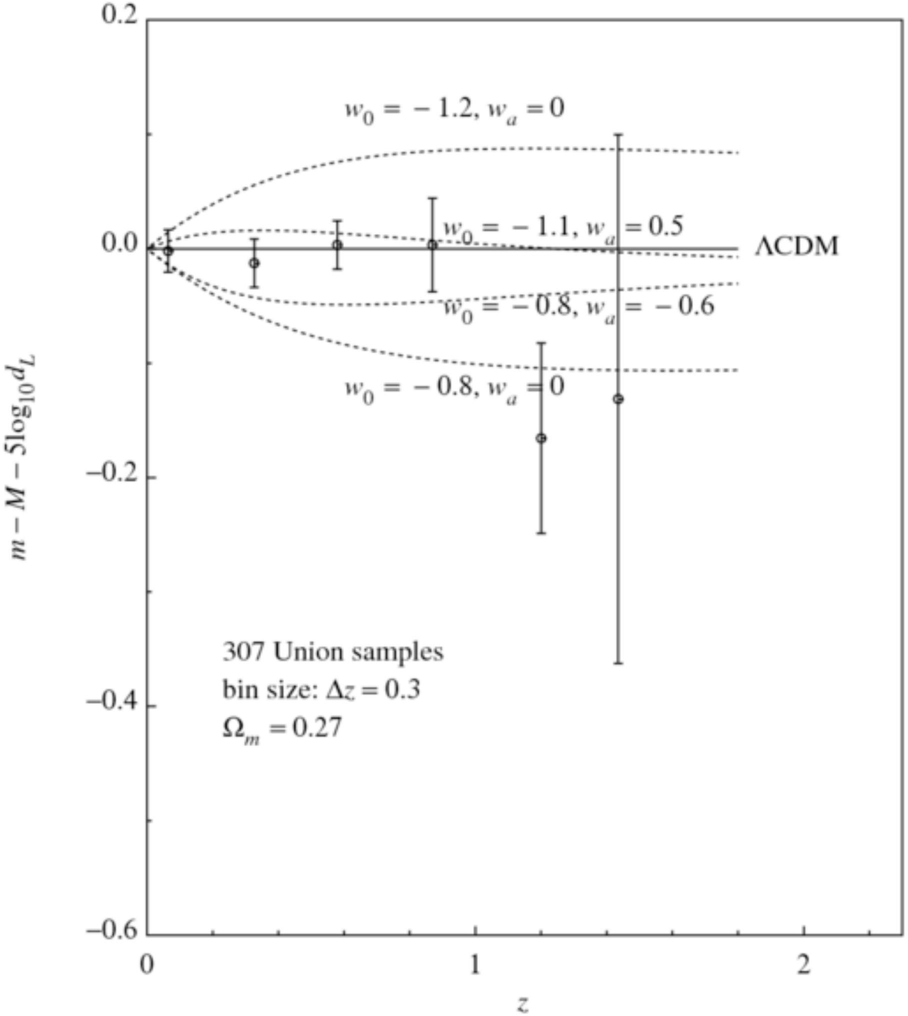
CFHTLS	0.26+	0.83+.04-.05
	cf.	0.80+.05-.05
COSMOS	0.26+	0.88+-.07-.08
cf.		0.87+-.074

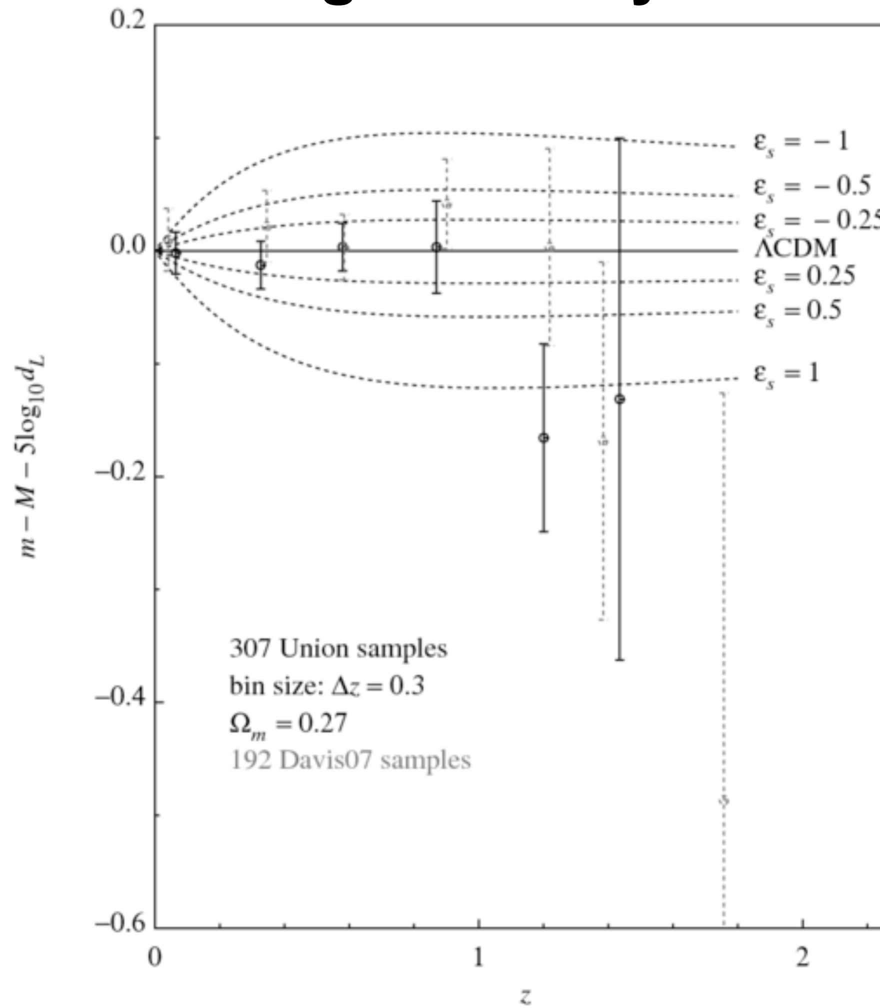
recent SZ CBIexcess **"cmb-alone"**

CBI+Acbar+Bima σ_8**SZ** ~.95+-.05 +-.05

planck1+jdem+dune .260+-.004 .809+-.004
ε_s-ζ_s case a_s-indep & ε_s =-0.00+.07-.06

SN1a now: Union sample 307 Apr08, partially unified. CFHT SNLS3 ~Jan09, ~4 x SNLS1, calibrated, systematic errors included. Low z from Carnegie in ~0.5yr





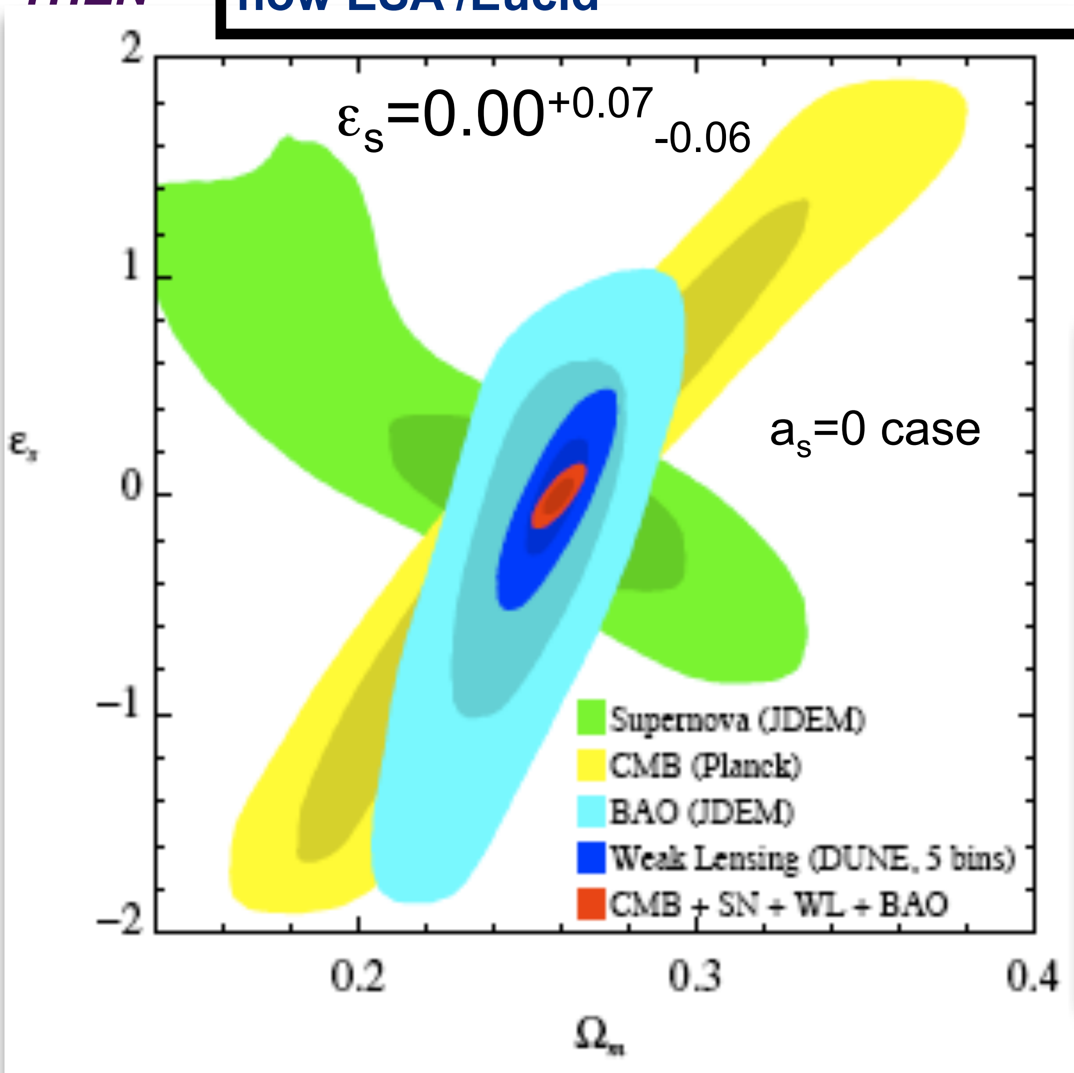
INFLATION NOW PROBES THEN

Beyond Einstein panel: LISA+JDEM

Forecast: **JDEM-SN** (2500 hi-z + 500 low-z) + **DUNE-WL** (50% sky, gals @z = 0.1-1.1, 35/min^2) + **Planck1yr**

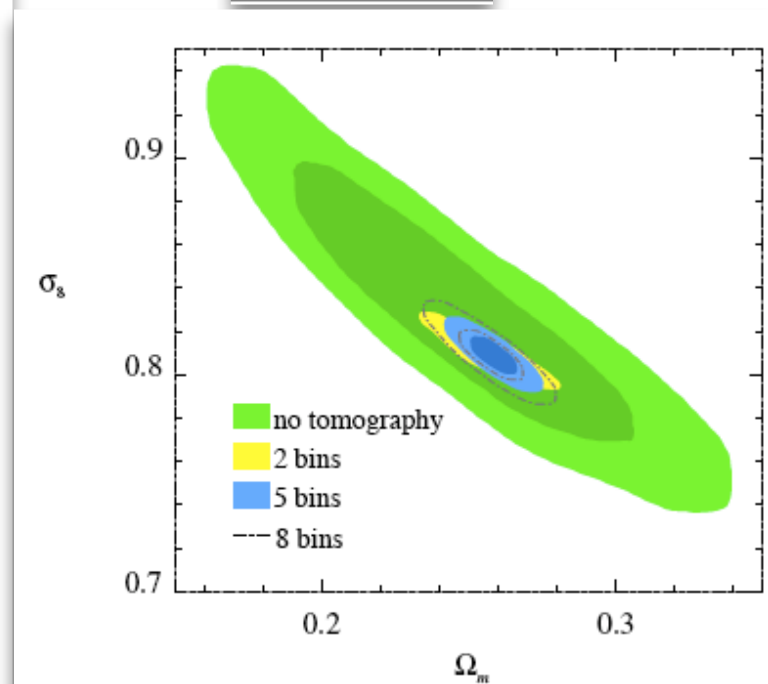
now ESA /Eucid

ESA (+NASA/CSA)



ζ_s ~dlnε_s /dlna /2 ill-determined

$0.1^{+0.6}_{-0.7}$



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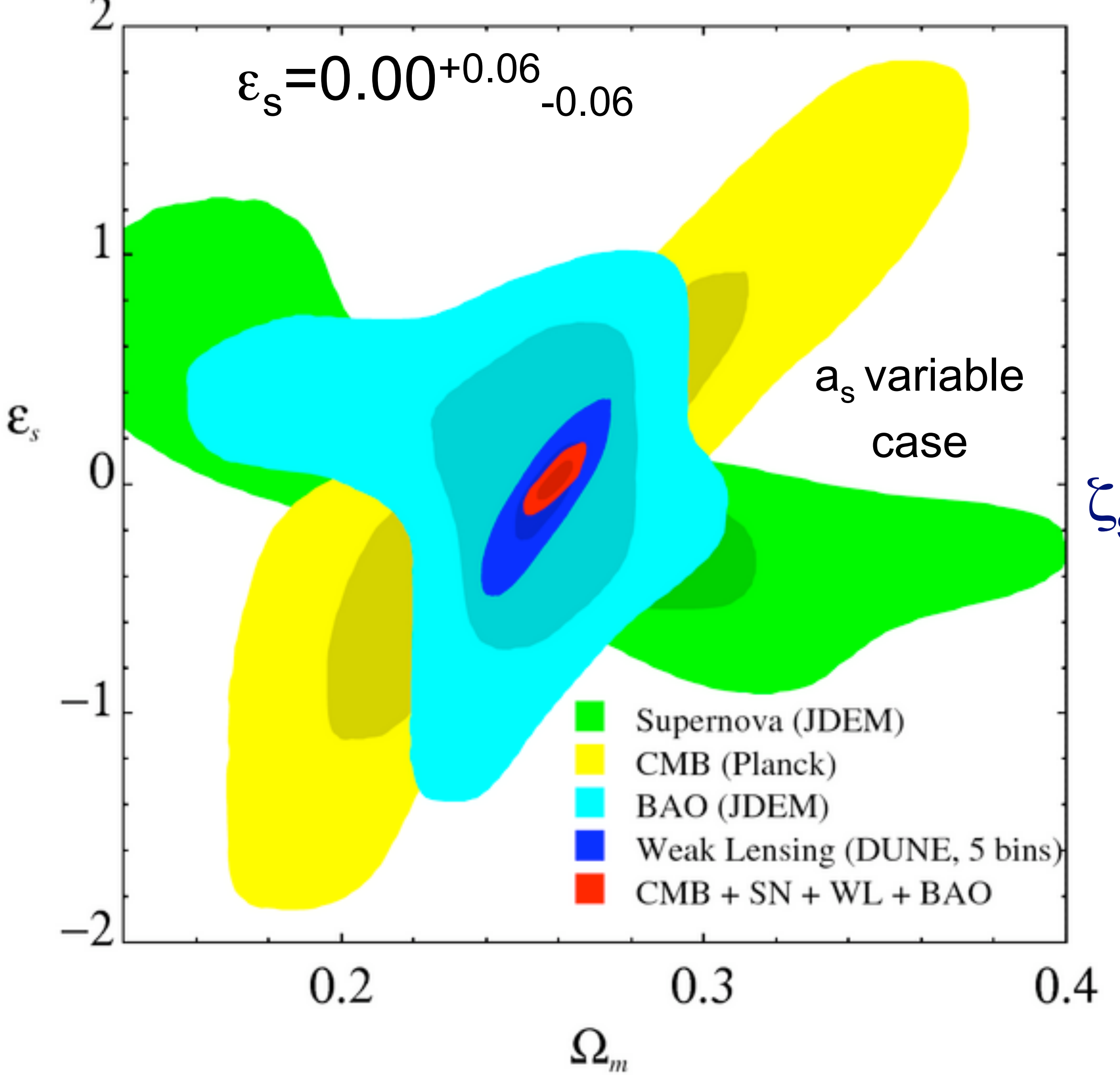
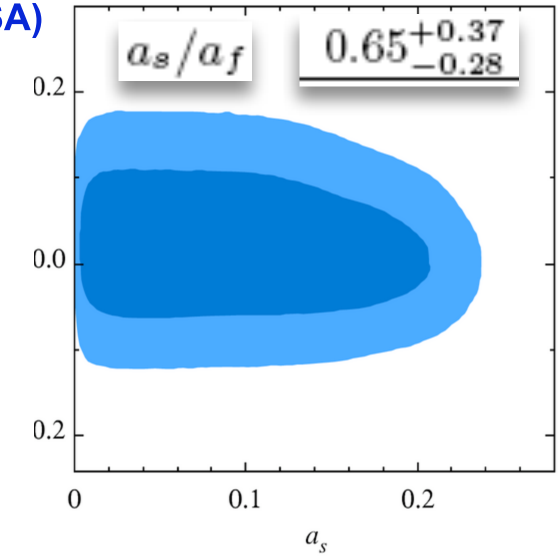
ESA (+NASA/CSA)





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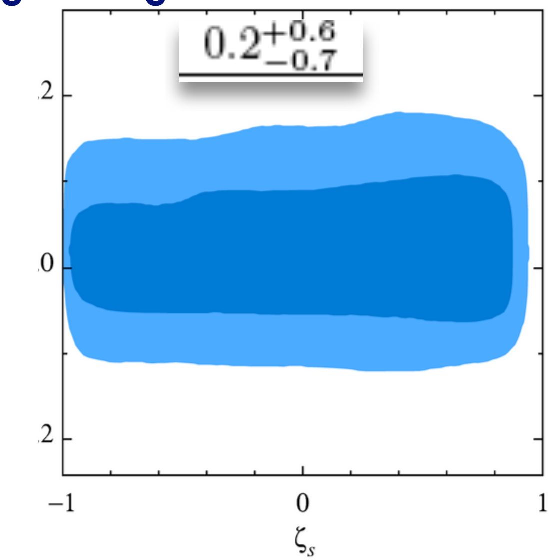


very early U early to middle to now U **very late U**

inflation *string theory/landscape/higher dimensions* **dark energy**

$V_{eff}(\psi_{inf})$? partial shape reconstruction reconstruct gradient $V_{eff}(\psi_{inf})$?

$K_{eff}(\psi_{inf})$? $K_{eff}(\psi_{inf})$?

$1-n_s \sim 2\varepsilon_s + 4\zeta_s$ **x.999 &** $r \sim 16\varepsilon_s$ **slow roll**

2 solutions: nearly uniform acceleration & small ζ_s

$\varepsilon_s \sim .017 +- .007$; $\varepsilon_s < .025$ 95% from r

\

low energy inflation with tiny ε_s

$2\zeta_s \sim .017 +- .007$

errors go to $+-$ .0012 Planck+JDEM+DUNE

$\varepsilon_s = (d\ln V/d\psi)^2/4$ @a_{eq}

$\varepsilon_s \sim$ **-.03 + .26 -.30**

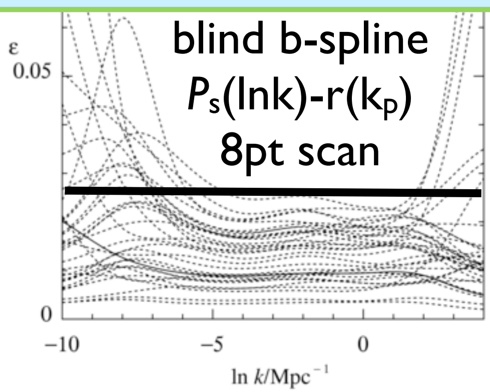
to $+-$ .07 Planck+JDEM+DUNE

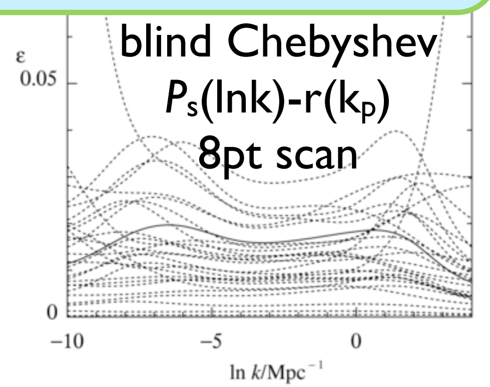
$\zeta_s = +- 1.001\, d^2\ln V/d\psi^2/4$ @a_{eq}

$\zeta_s \sim$ **0.1 +.6 -.7**

to +.6−.7 Planck+JDEM+DUNE **LCDM**

to +.3−.3 steep-ish exp[−ψ]





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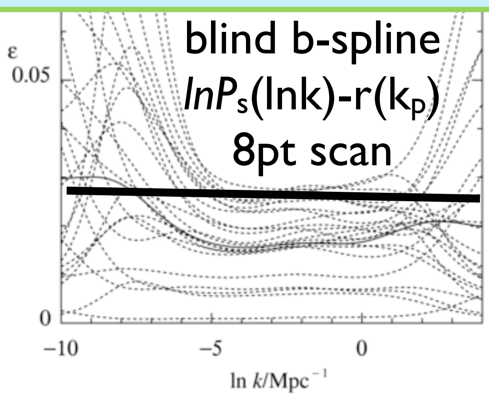
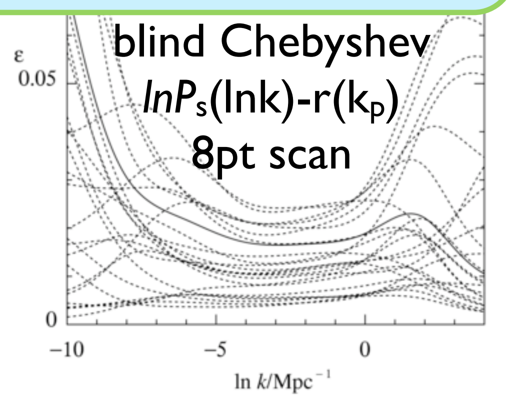




$\varepsilon_s = (d\ln V/d\psi)^2/4$ @a_{eq}

$\varepsilon_s \sim -.03 +.26 -.30$

to $\pm .07$ Planck+JDEM+DUNE

$\zeta_s = \pm 1.001\, d^2\ln V/d\psi^2/4$ @a_{eq}

$\zeta_s \sim 0.1 +.6 -.7$

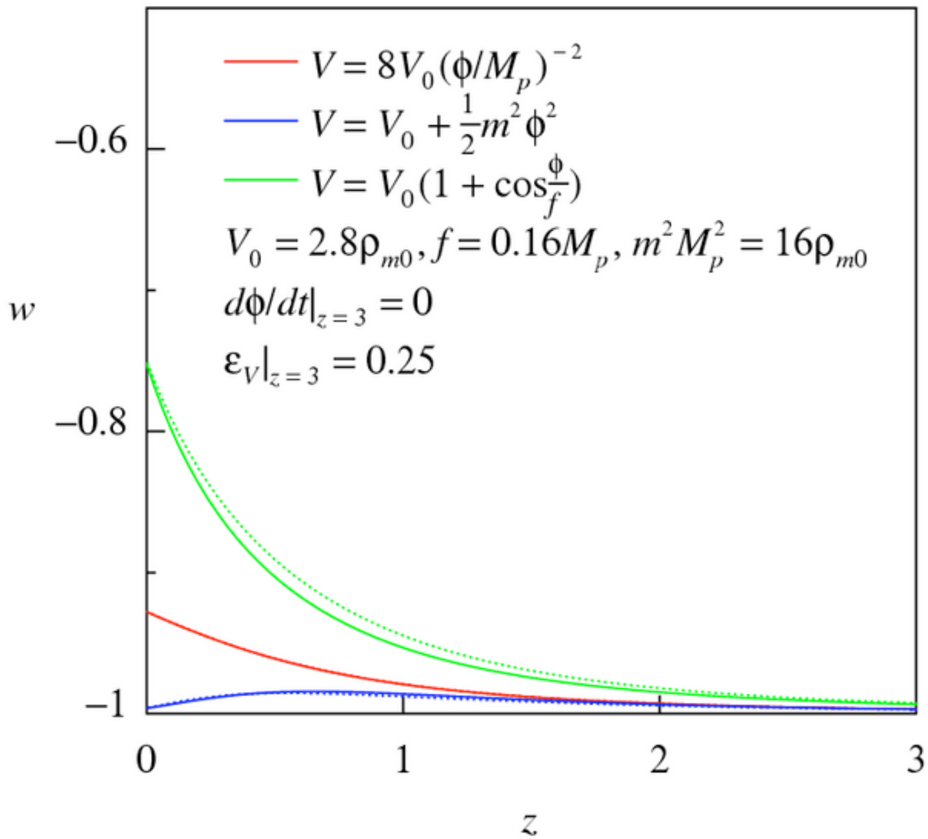
to $+.6 -.7$ Planck+JDEM+DUNE **LCDM**

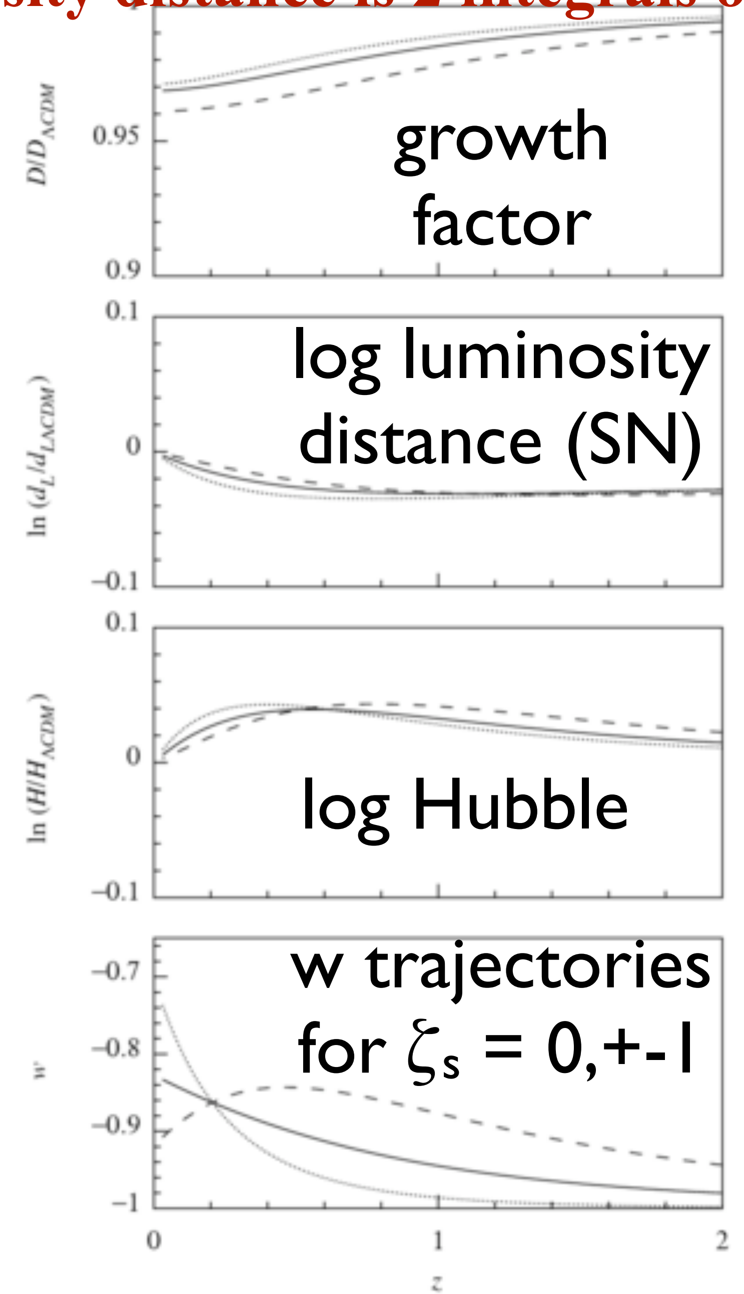
to $+.3 -.3$ steep-ish $\exp[-\psi]$

Why can't we measure the change of the slope, i.e., the effective mass of the potential? **w changes but the luminosity distance is 2 integrals of it.**

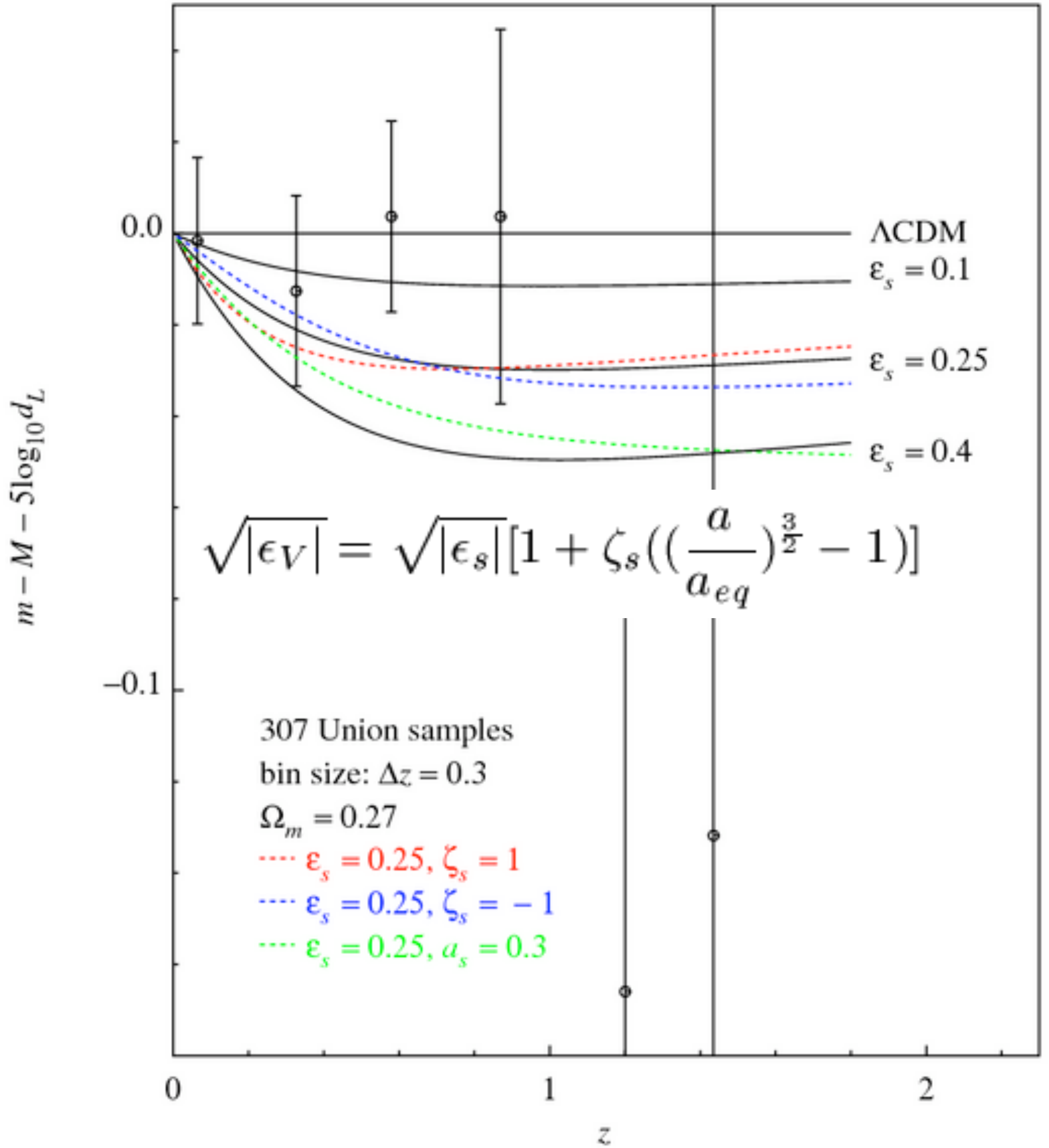
we fit w(z) for tracker potentials very well

$$\sqrt{|\epsilon_V|} = \sqrt{|\epsilon_s|}[1 + \zeta_s((\frac{a}{a_{eq}})^{\frac{3}{2}} - 1)]$$





Why we can measure the 1st but not the 2nd derivative of the log-potential in the Supernova 1a case => potential reconstruction very partial



DE interaction & 5th force?

e.g., action ~ $F(\phi,R)+L_m$, Jordan frame, cf. Einstein frame action $F=M_P^2/2\ R$,

Jordan-Brans-Dicke/scalar-tensor $F=f(\phi)R/2 + d\phi d\phi/2 - V(\text{phi})$, dilaton $f=e^{2\phi/M_P}$

conformal transformation $\Omega^{-2}= dF\ /\ d(M_P^2/2\ R)$ to Einstein frame

order parameter field ψ=-sqrt(6) ln Ω (replaces ϕ if $\Omega^{-2}(\phi)$ only)

ψ couples to $\rho_m - 3p_m$

chameleon is the dilaton-motivated one (**Khoury and Weltman 04,..., Kaloper 07)**

general dilaton-motivated coupling $\exp(2\beta_i\,\psi)L_{mi}$

phantom mimic: ρ_m has a correction to a^{-3}, interpret it as an addition to DE w, which can give an apparent $w < -1$

solar system tests are an issue. strong constraints on β_i

$m_i\ (\psi)$ (modified mass, dynamical (very low energy) higgs + std one). couples to ρ_m

very early U early to middle to now U **very late U**

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$V_{eff}(\psi_{inf})$? partial shape reconstruction reconstruct gradient $V_{eff}(\psi_{inf})$?

$K_{eff}(\psi_{inf})$? $K_{eff}(\psi_{inf})$?

$1-n_s \sim 2\varepsilon_s + 4\zeta_s$ x.9999 & $r \sim 16\varepsilon_s$ slow roll

2 solutions: nearly uniform acceleration & small ζ_s

$\varepsilon_s \sim .017 +- .007$; $\varepsilon_s < .025$ 95% from r \

low energy inflation with tiny ε_s

$2\zeta_s \sim .017 +- .007$

errors go to +− .0012 Planck+JDEM+DUNE

$\varepsilon_s = (d\ln V/d\psi)^2/4$ @a_{eq}

$\varepsilon_s \sim -.03 + .26 - .30$

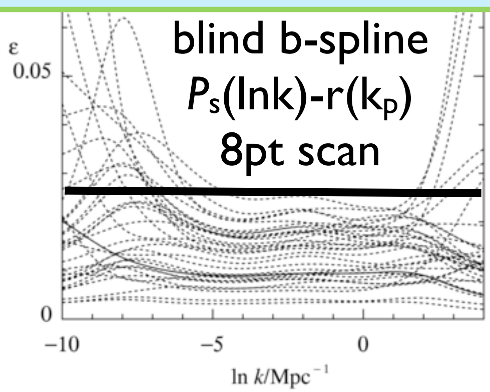
to +− .07 Planck+JDEM+DUNE

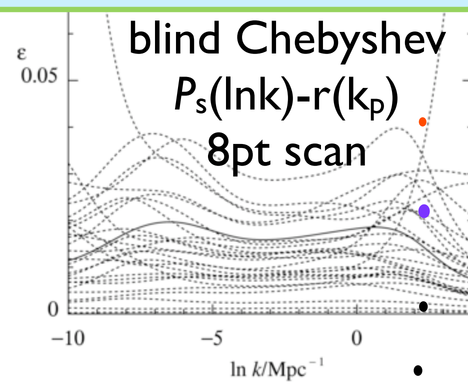
$\zeta_s =_{+-} 1.001\, d^2\ln V/d\psi^2/4$ @a_{eq}

$\zeta_s \sim 0.1 +.6 -.7$

to +.6-.7; +-.3 Planck+JDEM+DUNE

$a_s < 0.36$ ($z_s > 2.0$) • to a_s to <0.21 ($z_s > 3.7$)





we ignore z_dec and z_bbn constraints on Ω_Q (a)
much further trajectory extrapolation needed.

prior sensitivity sqrt(ε): ε=0.00 +.09-.13 &
ε>0 (since phantom is ~ baroque): ε=0.00+.20

late-inflaton field is < Planck mass

coupled-DE 5th force constraints are strong

end