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 plus zero point fluctuations in all fields. & then preheat through mode coupling to incoherent cascade to thermal equilibrium.

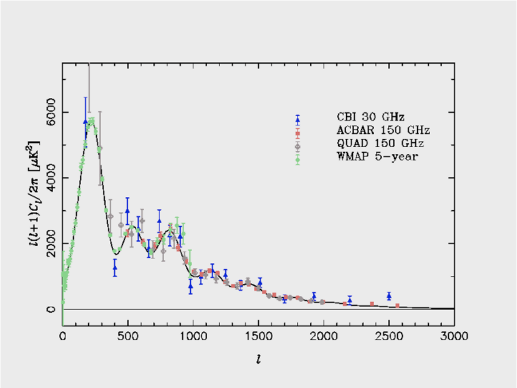
very early U early to middle to now U **very late U**

string theory/landscape/higher dimensions

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

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

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



ρ_{curv} n_b/n_γ

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

Standard Parameters of Cosmic Structure Formation

$\theta \sim \ell_s^{-1}$ $\sim \ln \sigma_8^2$

Ω_k $\Omega_b h^2$ $\Omega_{dm} h^2$ Ω_Λ τ_c $\ln A_s$ n_s $r = A_t/A_s$

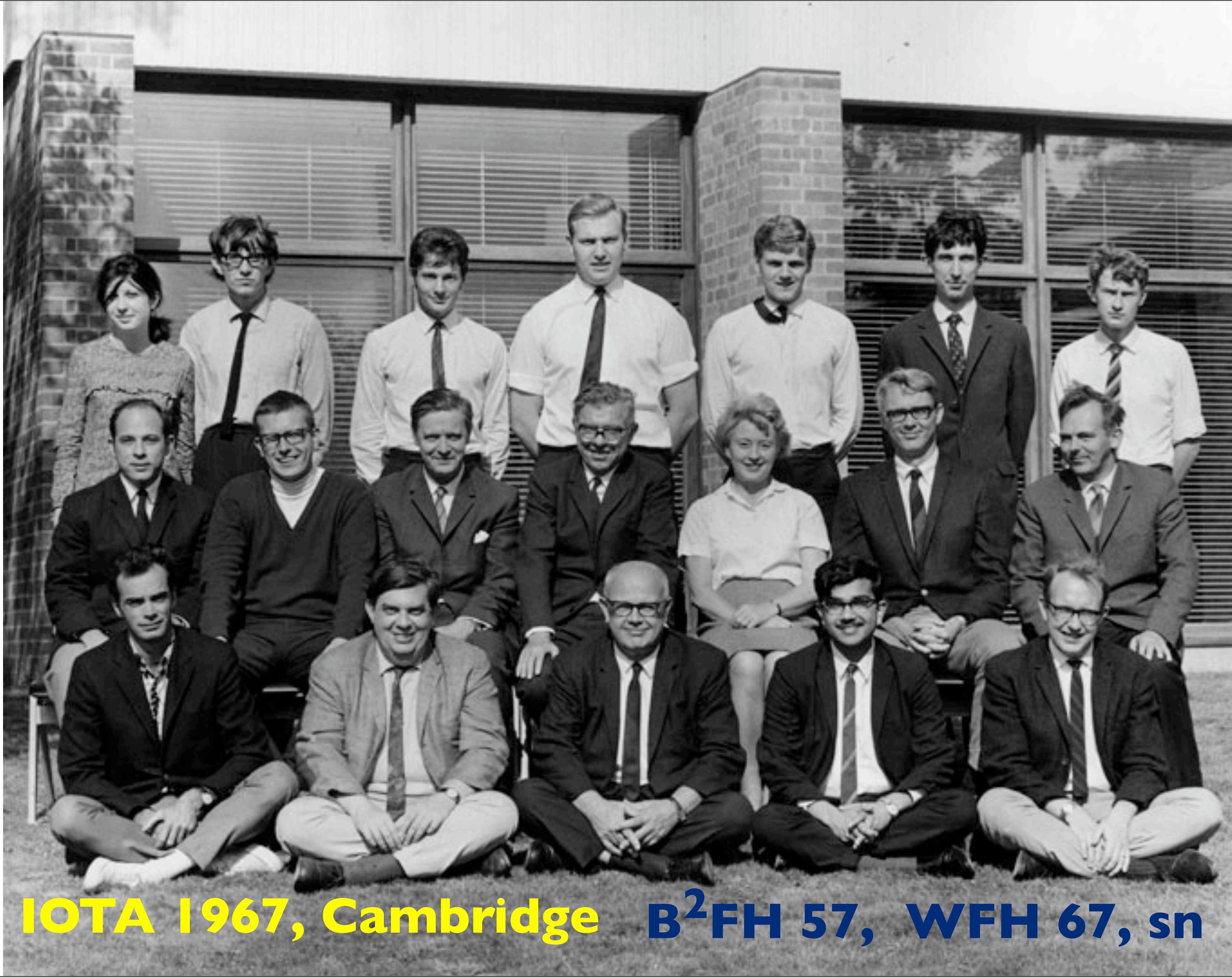
$1+w_0$, w_a $dn_s/d\ln k$ n_t

New Parameters of Cosmic Structure Formation: early-inflaton & late-inflaton trajectories

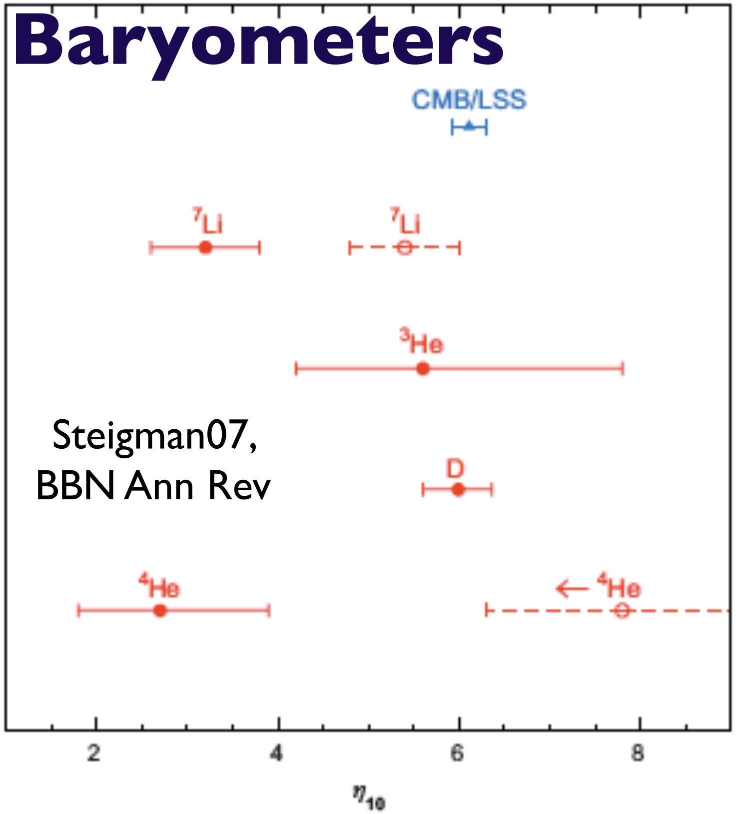
$\varepsilon_\phi = (1+w(a)) \times 3/2$ $\epsilon(k), \quad k \approx Ha$ $\ln H(k_p)$

$\varepsilon_s f(a/a_{\Lambda eq}; a_s/a_{\Lambda eq}; \zeta_s)$ $\ln P_s(k)$ $\ln P_t(k)$

+ subdominant isocurvature/cosmic string/ tSZ ...


IOTA 1967, Cambridge
B^{2}FH 57, WFH 67, sn

Baryometers



Nobel Prize 84 Willy Fowler + Chandra -sekhar

$$\eta_{10} \equiv 10^{10}(n_{\rm B}/n_\gamma) \equiv 274\ \Omega_{\rm B}h^2$$

	January 2000	January 2002	June 2002	January 2003	March 2003
$\Omega_{\rm b}h^2$	$0.0339^{+0.0443}_{-0.0246}$	$0.0222^{+0.0025}_{-0.0021}$	$0.0221^{+0.0024}_{-0.0020}$	$0.0221^{+0.0023}_{-0.0018}$	$0.0233^{+0.0013}_{-0.0013}$
	boom98: Apr00/01/dasi		**cbi1: Jun02**	**acbar1: Dec02**	**WMAP1: Feb03**

0.0223 ± 0.0007

0.0226 +- 0.0006 wmap3+acbar+cbi+... LSS

0.0233 +- 0.0005 wmap5+acbar+cbi+b03+.+WL+LSS+SN1+Lya

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

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

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

0.1145 +-0.0023 CMBall+WL+LSS+SN+Lya

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

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?**

CITA ICAT Canadian Institute for Theoretical Astrophysics L'institut canadien d'astrophysique theorique

– 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-bins, w in modes, $\varepsilon(a)$: in modes, jerk

~1 good e-fold. only ~2 params

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

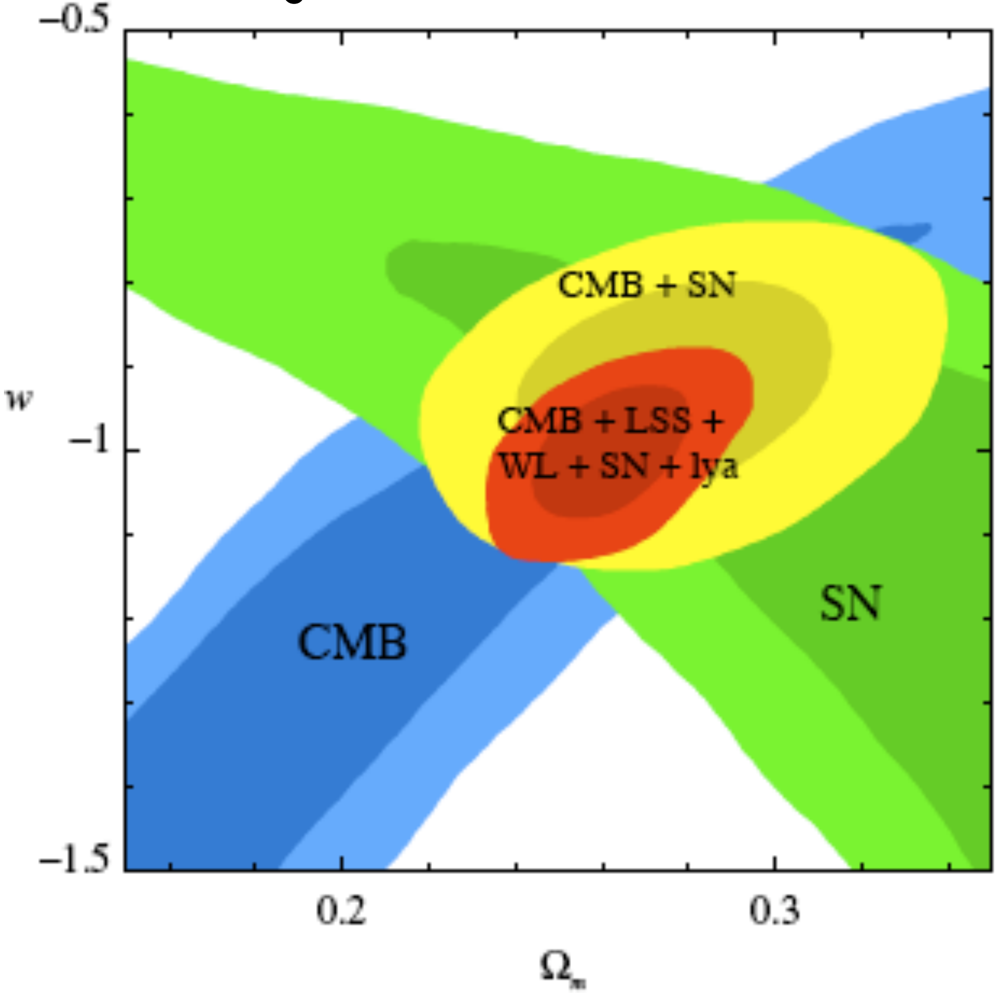
Zhiqi Huang, Bond & Kofman 08 ε_s=-0.03+-0.28 now, inflaton (potential gradient)^2

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

Measuring w (SNe+CMB+WL+LSS+Lya)

$$w(a) \equiv \frac{p(a)}{\rho(a)}$$

$1+\mathbf{w_0} = -0.0 \pm 0.06$



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

$1+\mathbf{w_0} = -0.01 \pm 0.19$

$\mathbf{w_a} = 0.0 +0.6-0.8$

piecewise parameterization

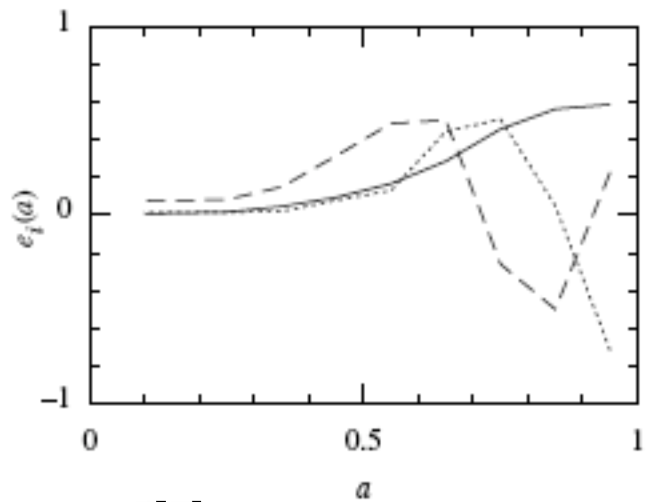
4,9,40 modes in redshift

9 & 40 into Parameter eigenmodes

data cannot determine >2 EOS parameters

DETF Albrecht etal06, Crittenden etal06, hbk08

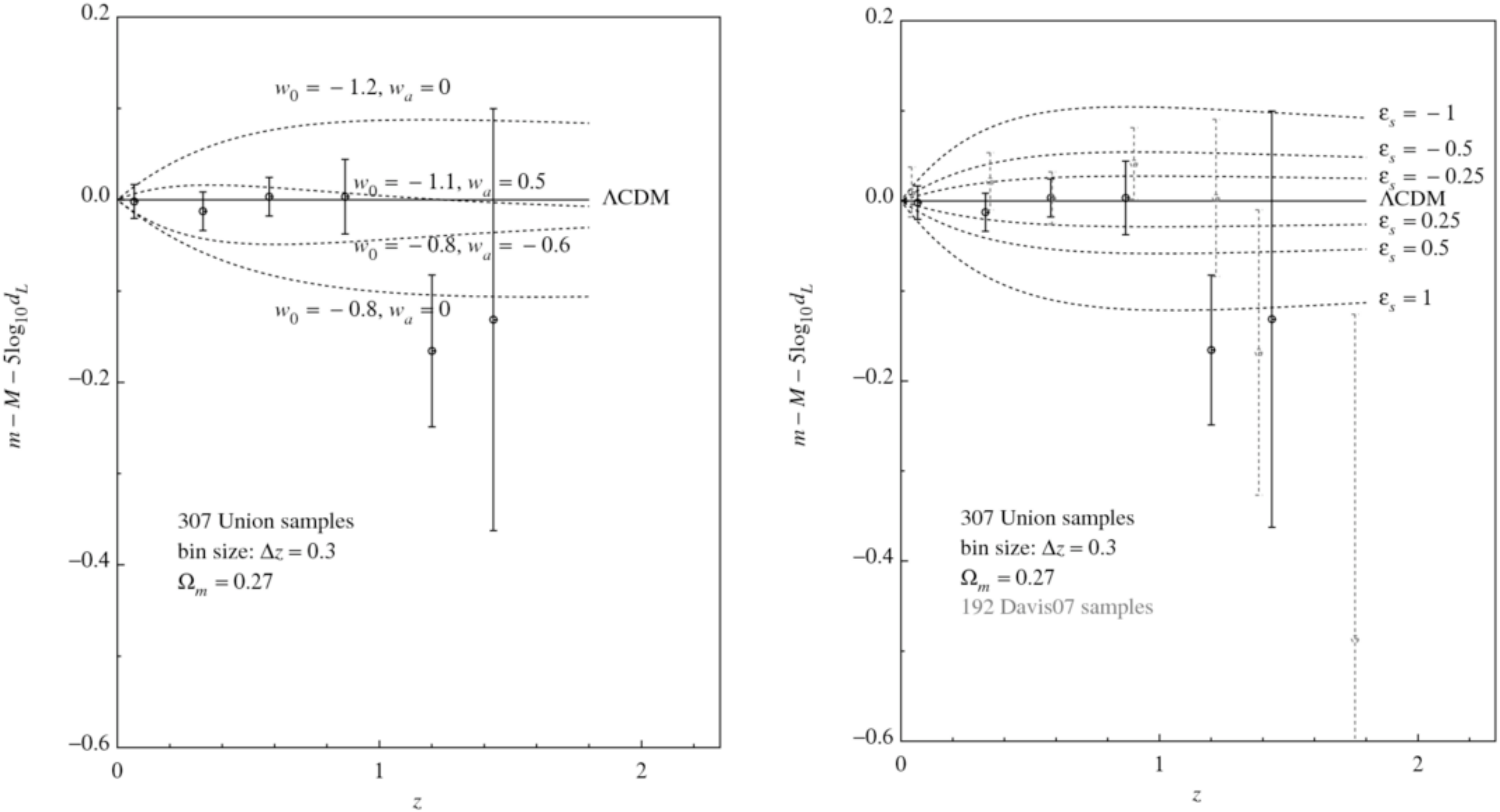
σ_1=0.13 σ_2=0.33 σ_3=0.58



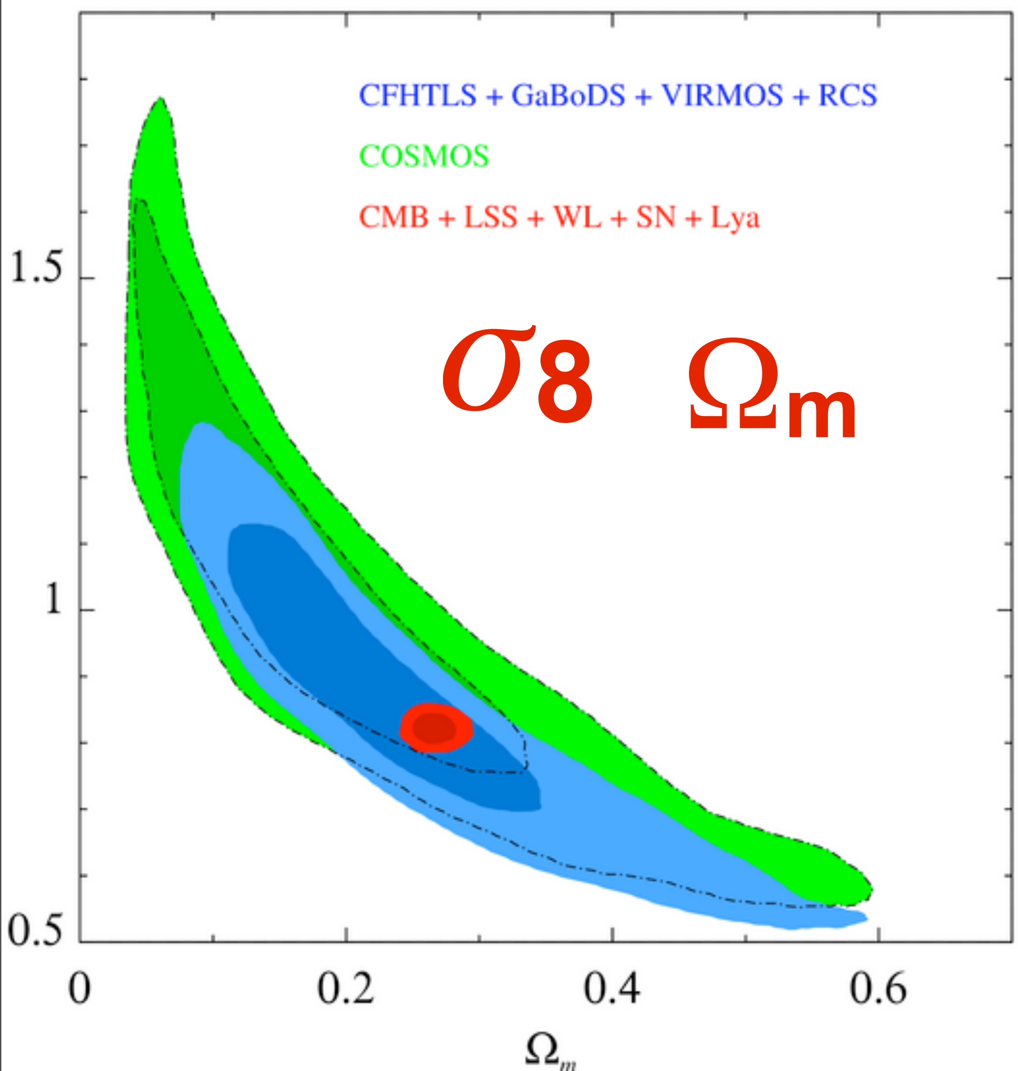
. $\varepsilon_{\phi 0}$ = 0.0 +/- 0.09 if constant, $\varepsilon_{\phi 0}$ = -0.015 +/- 0.3 if a-linear model

SN1a now: Union sample 307 Apr08, partially unified.

CFHT SNLS3 ~Jul08, ~4 x SNLS1, calibrated. Low z ~0.5yr



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	0.265+-.013	0.829+-.024
ε_s-a_s-ζ_s	0.265+-.013	0.832+-.025

recent weak lensing "alone"

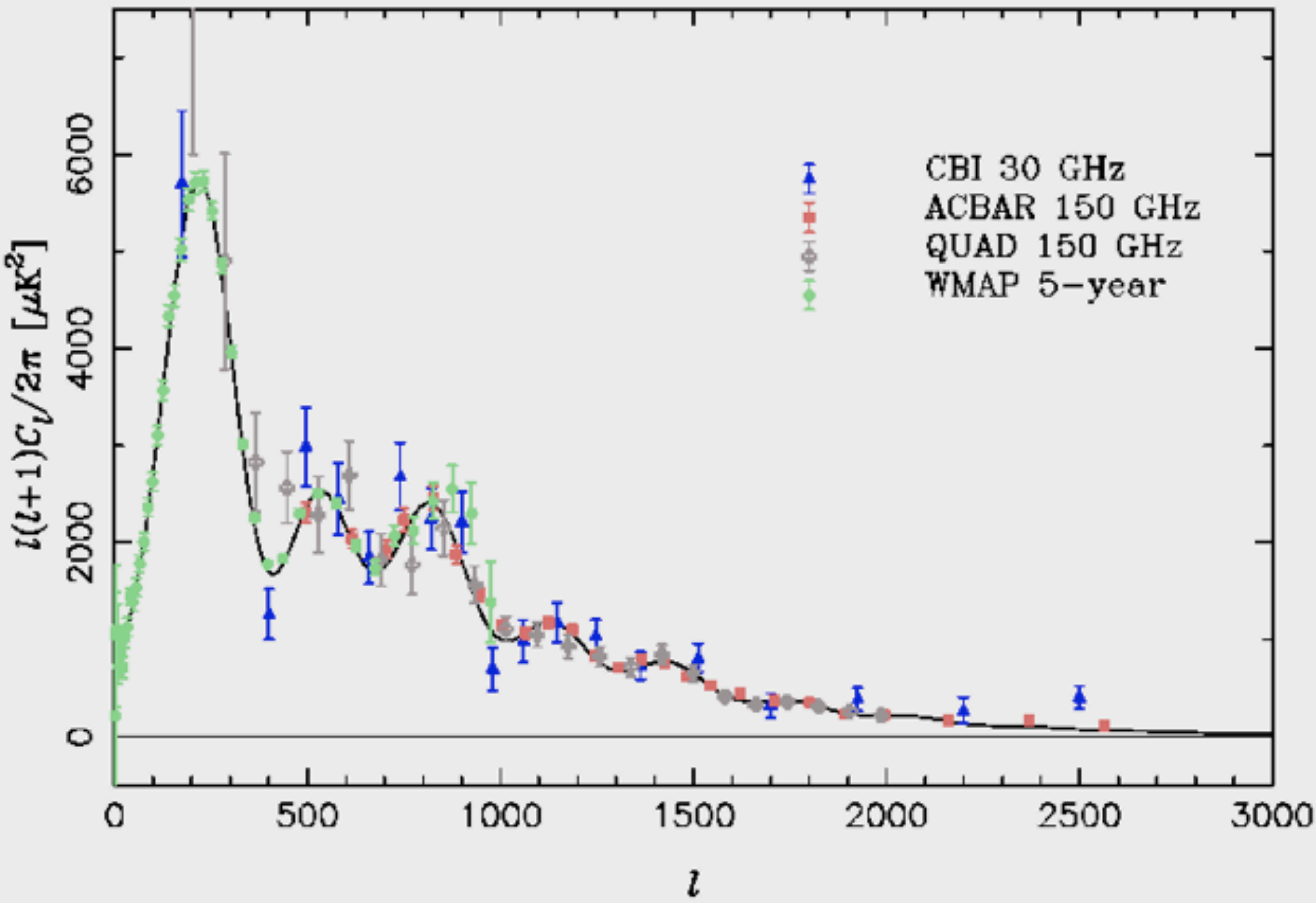
CFHTLS	0.26+	0.83+.04-.05
	cf.	0.80+.05-.05
COSMOS	0.26+	0.88+-.07-.08
cf.		0.87+-.074

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

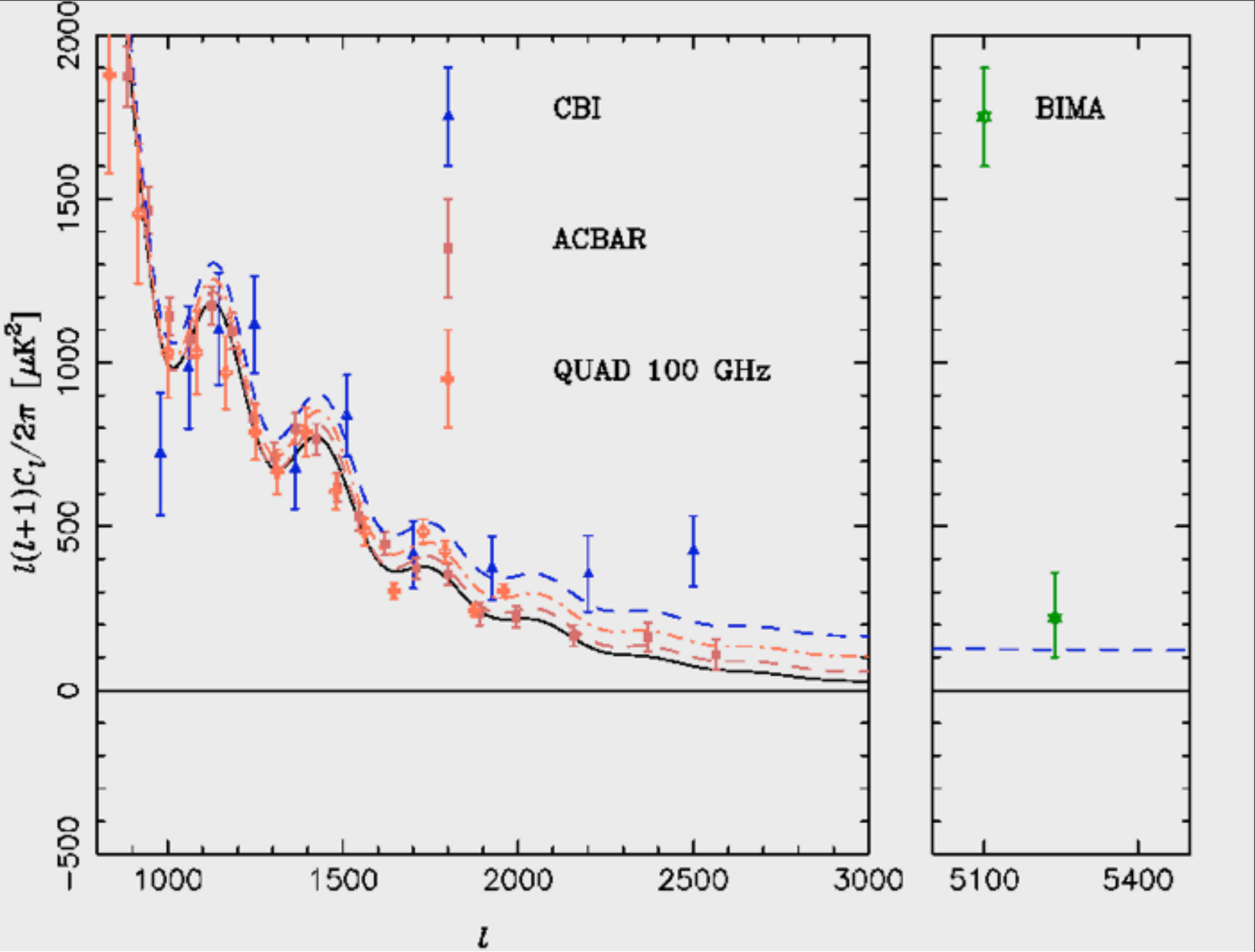
CBI+Acbar+Bima σ_8**SZ** ~.95+-.05 +-.05

planck1+jdem+dune .260+-.004 .850+-.005

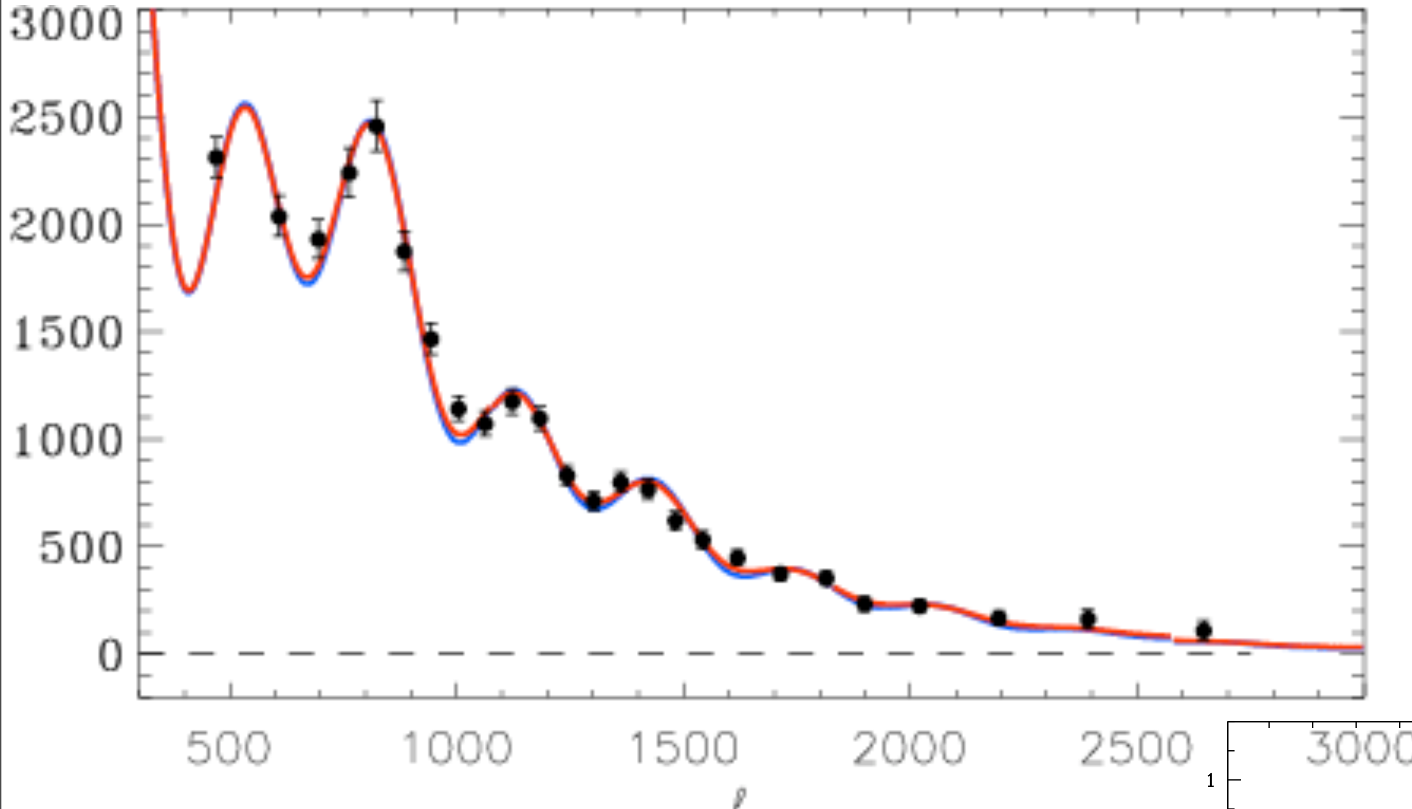
ε_s-a_s-ζ_s case ε_s =.02+.07-.06



CBI 30 GHz
ACBAR 150 GHz
QUAD 150 GHz
WMAP 5-year
$l(l+1)C_l/2\pi$ [μK^2]
0
2000
4000
6000
0
500
1000
1500
2000
2500
3000
l



CBI
ACBAR
QUAD 100 GHz
BIMA
$l(l+1)C_l/2\pi$ [μK^2]
l
2000
1500
1000
500
0
−500
1000
1500
2000
2500
3000
5100
5400



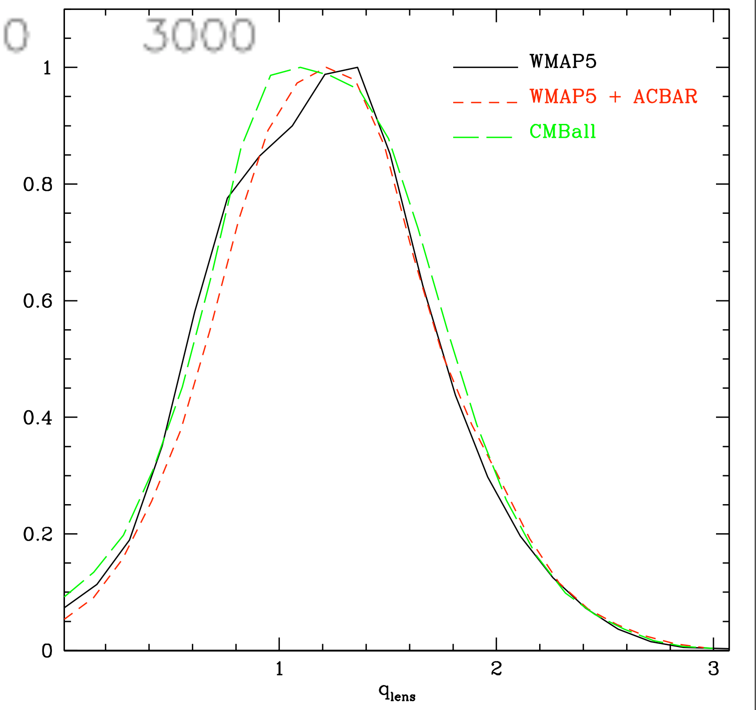
$$C_\ell^{\mathrm{lens}} = C_\ell^{\mathrm{no-lens}} + q_{\mathrm{lens}} \Delta C_\ell^{\mathrm{lens}}$$

wmap5+ acbar

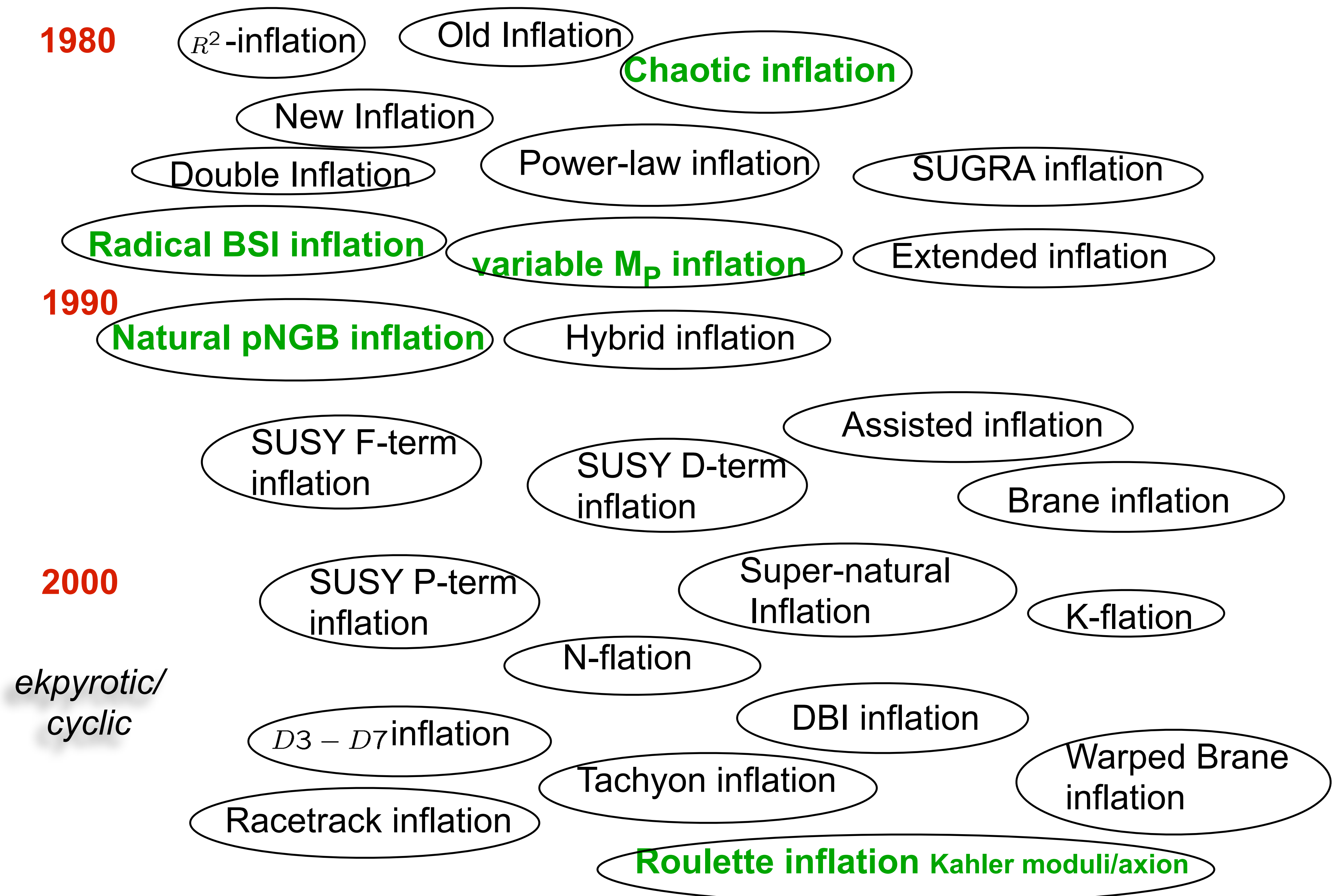
$$q_{\mathrm{lens}} = 1.23^{+0.22(+0.83)}_{-0.23(-0.76)}$$

CMBall

$$q_{\mathrm{lens}} = 1.20^{+0.24(+0.84)}_{-0.24(-0.77)}$$



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



- **Cosmological Constant (*w*=-1)**
- **Quintessence** $V(\psi)$ **(-1≤*w*≤1)**
- **Phantom field** **KE < 0 &** $V(\psi)$ **(*w*≤-1)**
- **Tachyon fields (-1 ≤ *w* ≤ 0)**
- **K-essence: KE not quadratic**
-

$$V\sim \exp[..\psi],$$

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

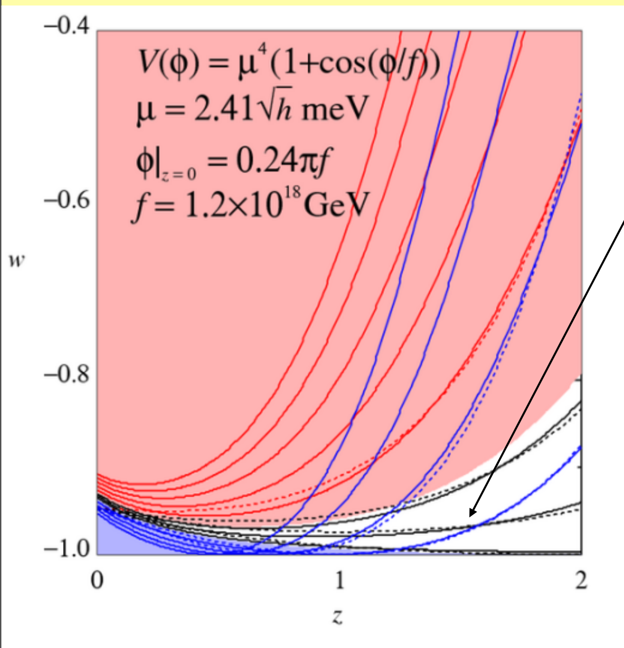
$$\mathbf{V_{pNGB} \sim sin^2..\psi,\ V_{holes},\ V_{branes},}$$

$$(V_0+..[\psi-\psi_0]^2)..$$ & much more

Late-Inflaton $\varepsilon_\phi(a) = \varepsilon_s f(a/a_{\Lambda eq}; a_s/a_{\Lambda eq}; \zeta_s)$

3-param formula accurately fits slow-to-moderate roll & even wild rising baroque late-inflaton trajectories, as well as thawing & freezing trajectories. but not oscillating DE

Cosmic Probes Now CFHTLS SN(Union~300),WL,CMB,BAO,LSS,Lyα



slow-to-moderate roll OK

wild rise & roll up/down OK

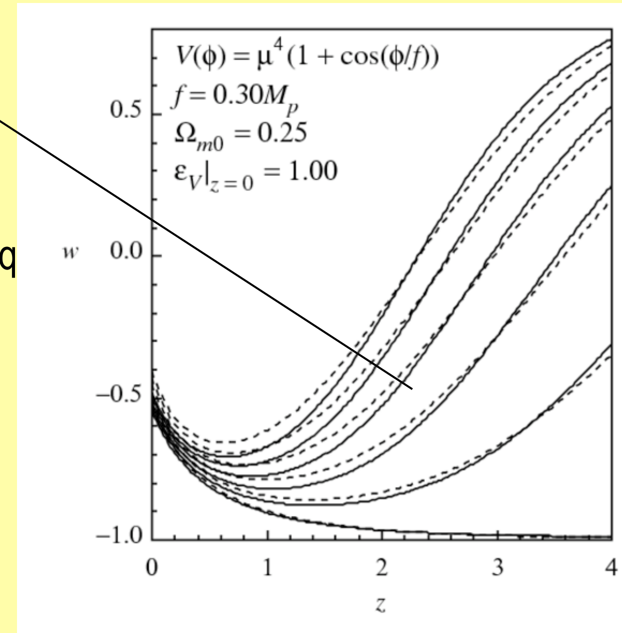
$\varepsilon_v = (d\ln V/d\psi)^2/4$ @pivot a_{eq}

$\varepsilon_s = -0.03 \pm 0.25$ now

$a_s < 0.36$ ($z_s > 2.3$) now

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

ill-determined now



ε_s to ± 0.07 then

Planck1+JDEM SN+DUNE WL,

weak a_s <0.21 then, (z_s >3.7)

3rd param ζ_s ill-determined then

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

(late-inflaton field < Planck mass, but sometimes not by a lot)

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

+ Friedmann Equation + DM+B

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

where

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

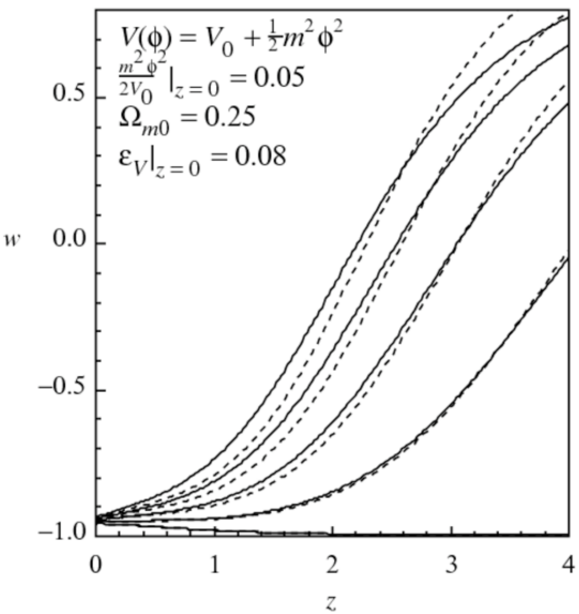
$$a_s \geq 0$$

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

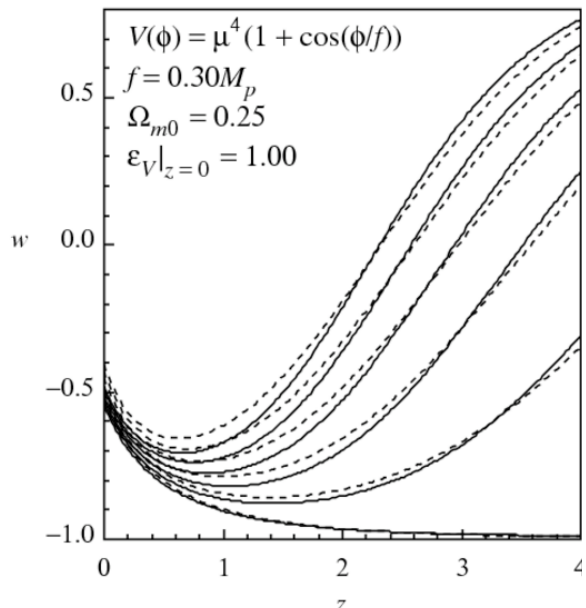
- ~15% thawing, 8% freezing, with flat priors

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

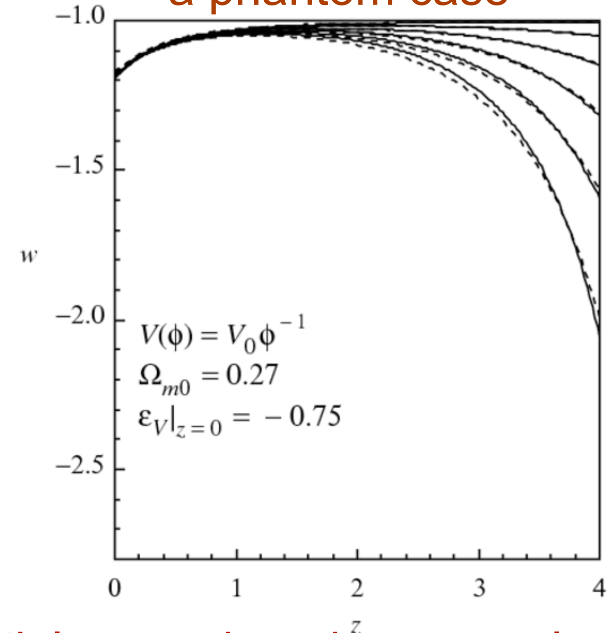
a offset-quadratic mass case



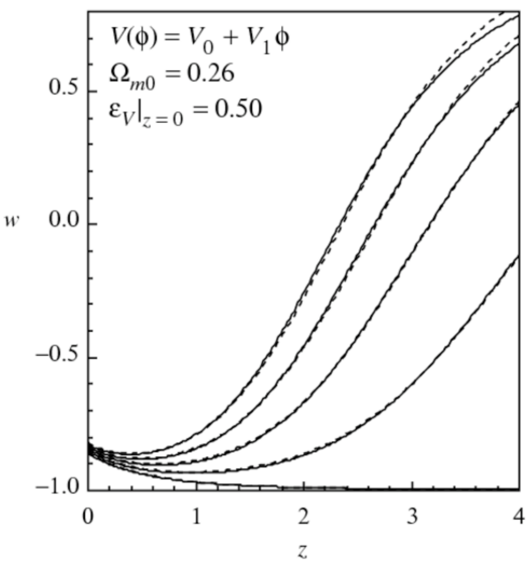
a pNGB phase case



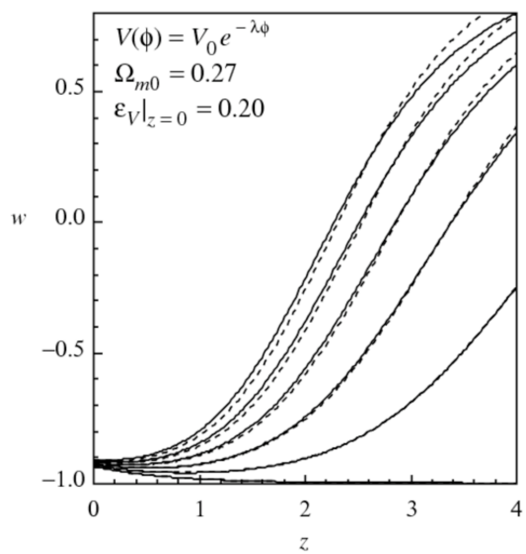
a phantom case



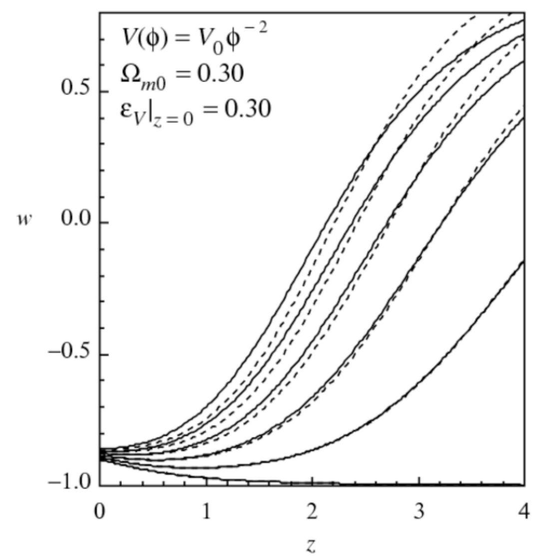
offset-linear



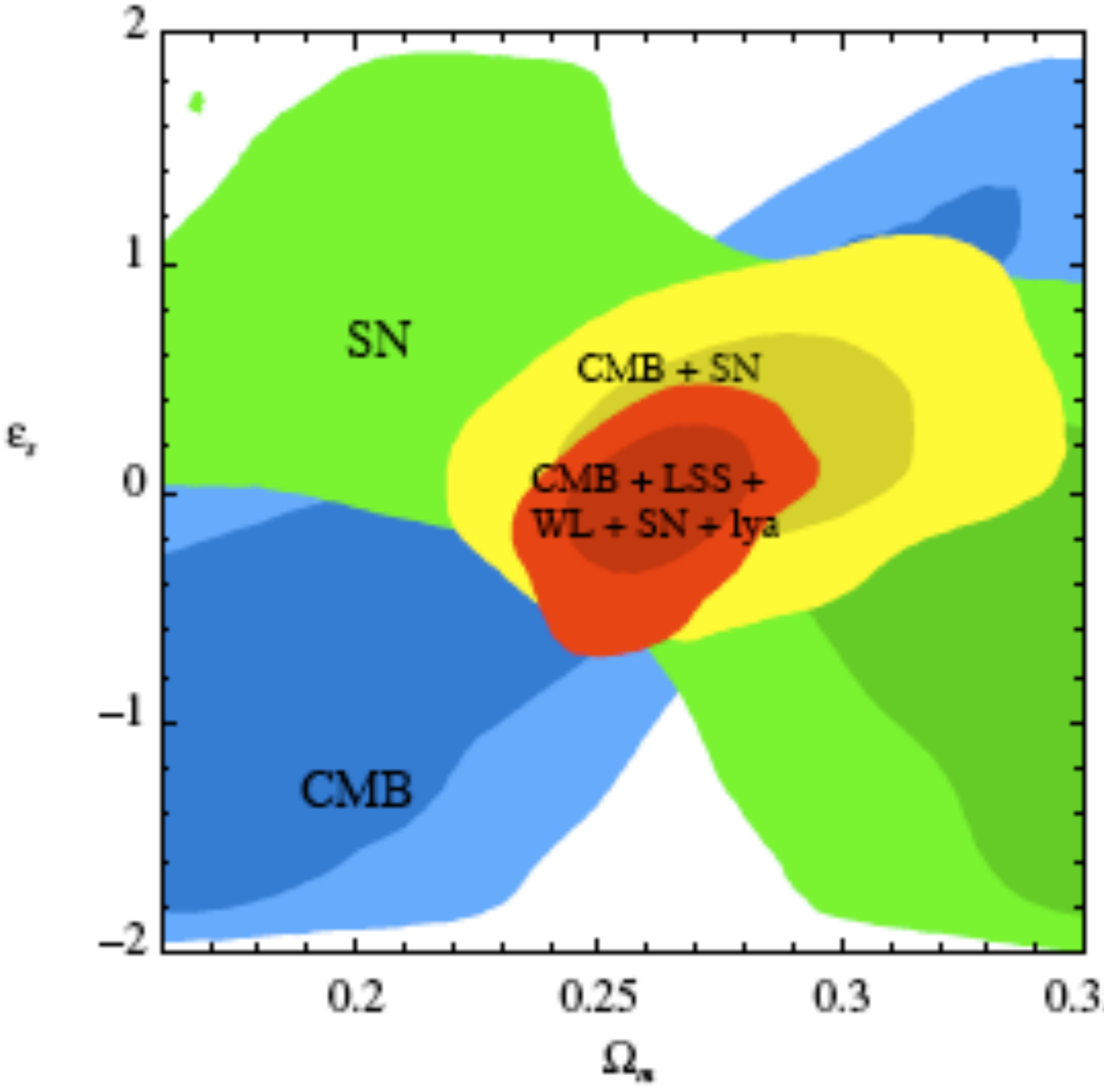
a Ratra-Peebles exp potential



a dropping power law



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

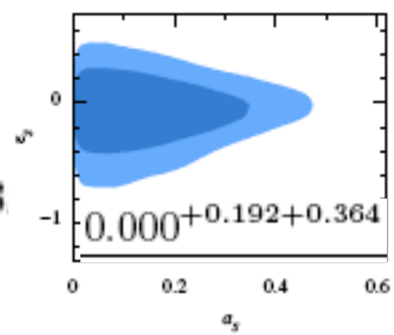


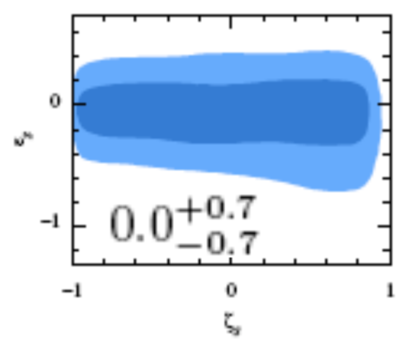
modified CosmoMC with Weak Lensing, SZ, SN,CMB, bias & w(a) slow-to-moderate-roll trajectories with various priors

ε_s .01 + .25 -.28 1

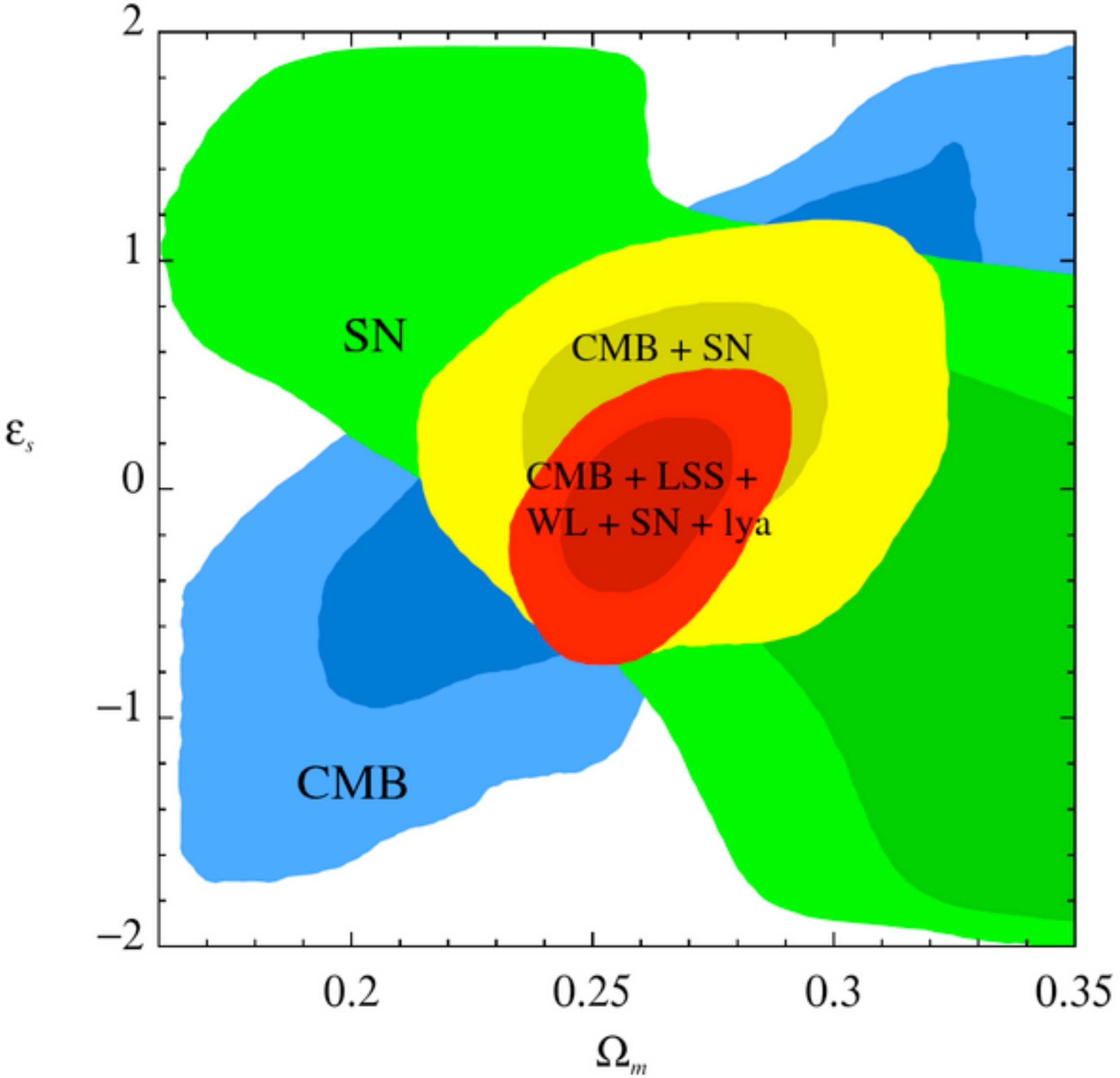
-.03 + .21 -.25 3

-.03 + .26 -.30 2





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



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

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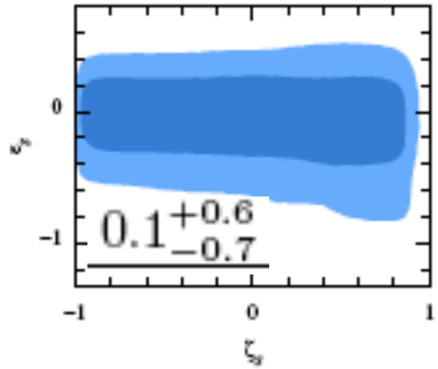
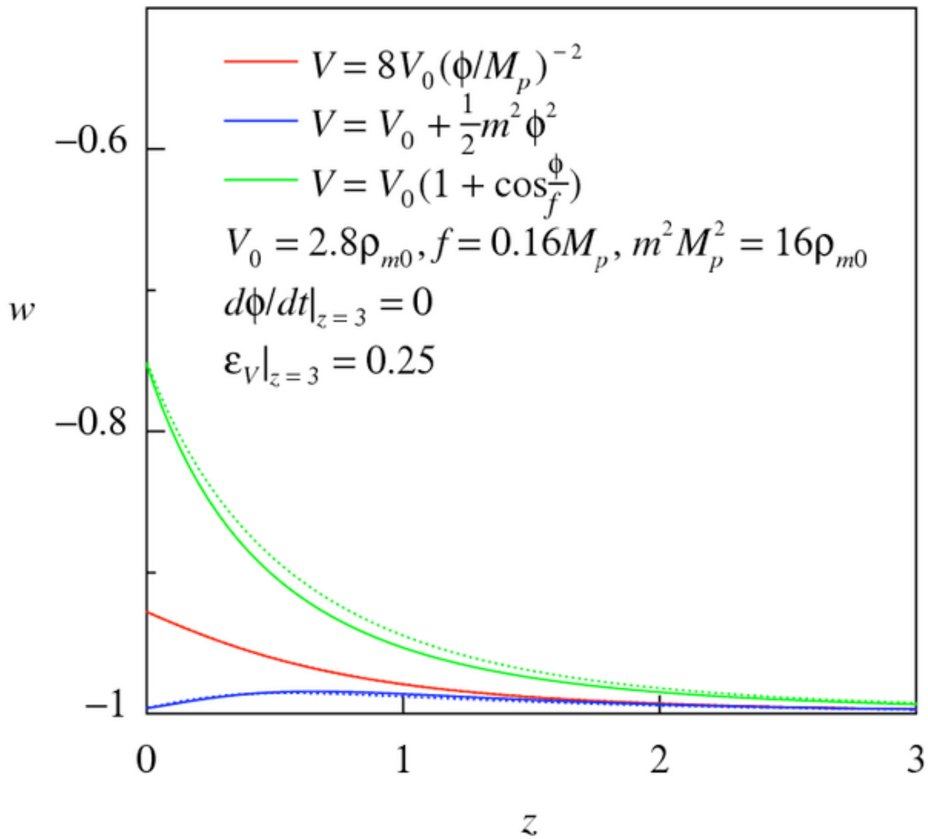
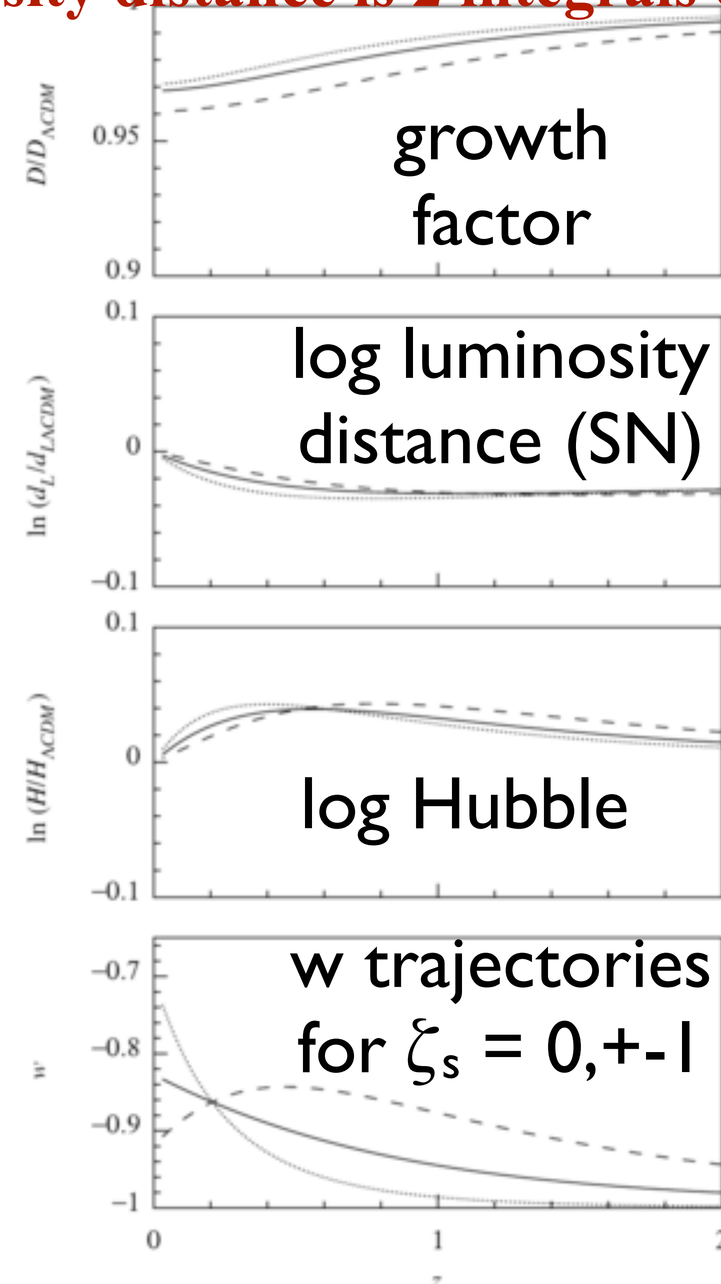


Why can't we measure the change of the slope, i.e., the effective mass of the potential? **w changes but the luminosity distance is 2 integrals of it.**

we fit w(z) for tracker potentials very well

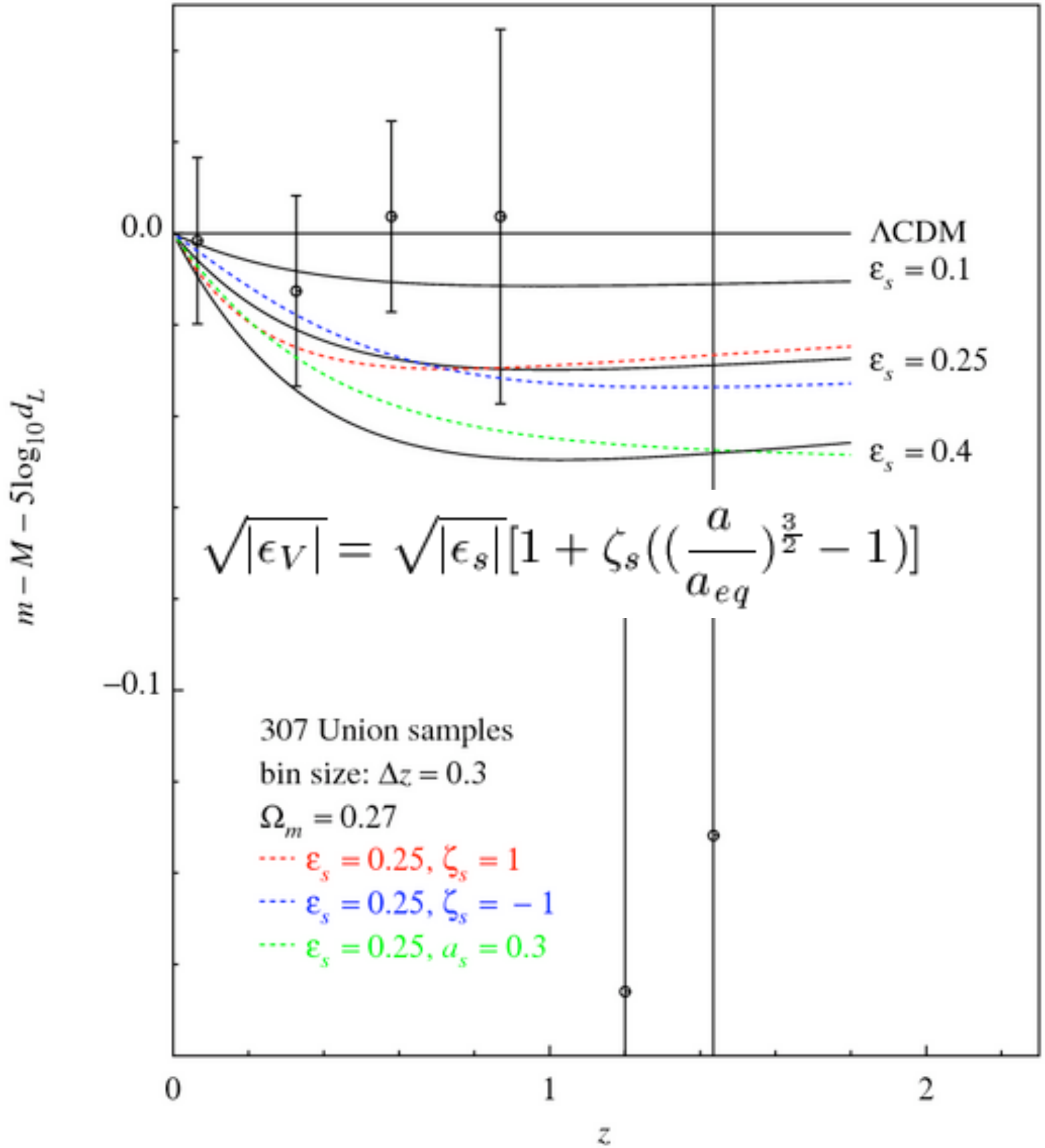
$$\sqrt{|\epsilon_V|} = \sqrt{|\epsilon_s|}[1 + \zeta_s((\frac{a}{a_{eq}})^{\frac{3}{2}} - 1)]$$





Why we can measure the 1st but not the 2nd derivative of the log-potential.

potential reconstruction very partial



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

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 $\Omega^{-2}= dF\ /\ dM_P^2/2\ R$ to Einstein frame

order parameter field ψ=-sqrt(6) ln Ω (replaces ϕ phi 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 beta_i

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

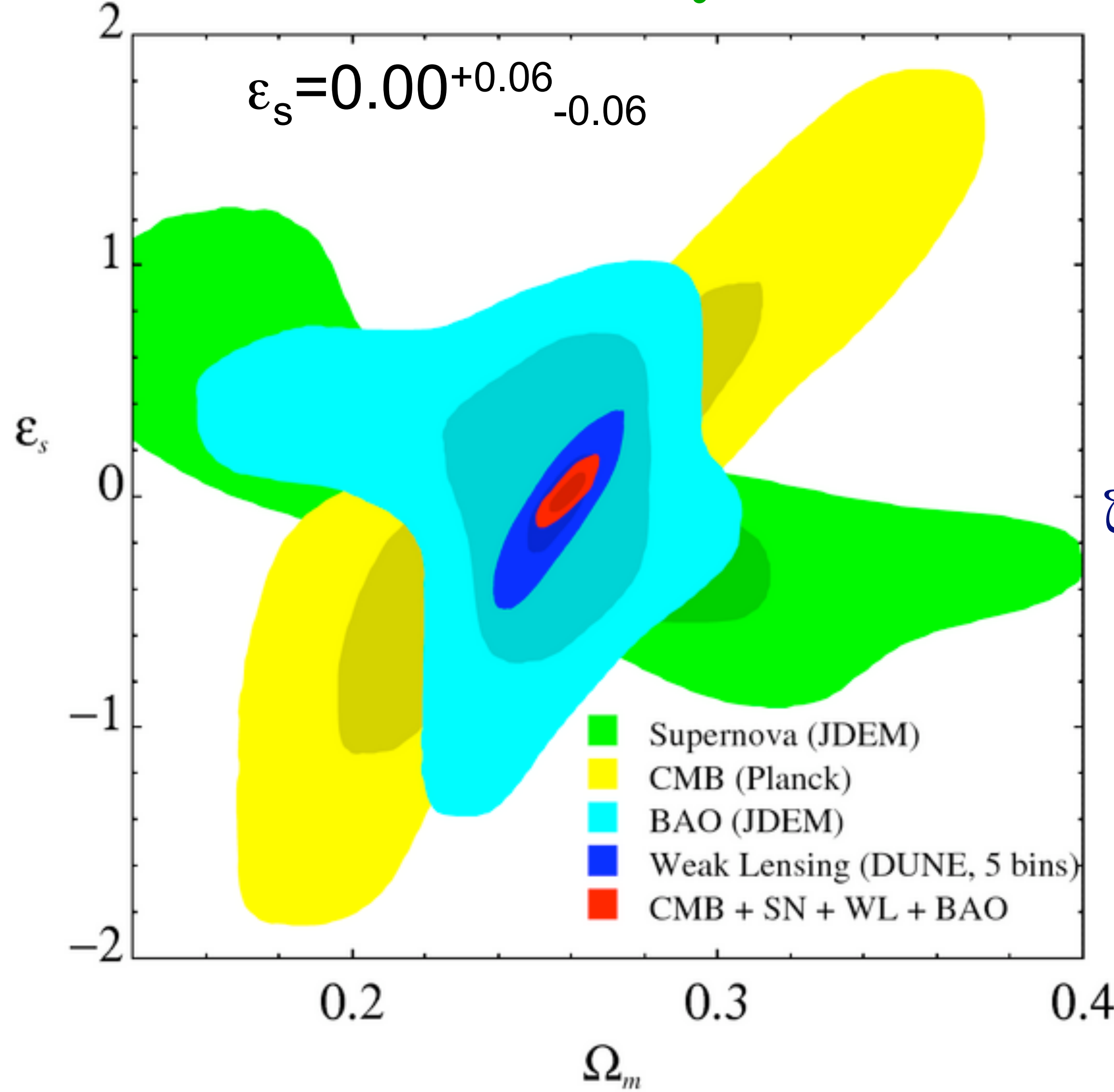
INFLATION NOW

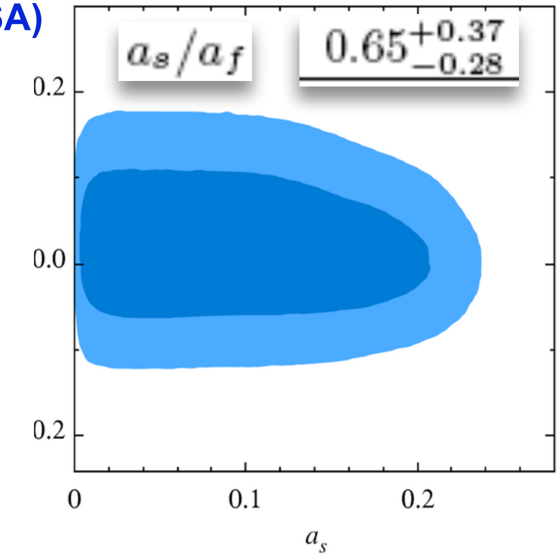
PROBES THEN

Beyond Einstein panel: LISA+JDEM

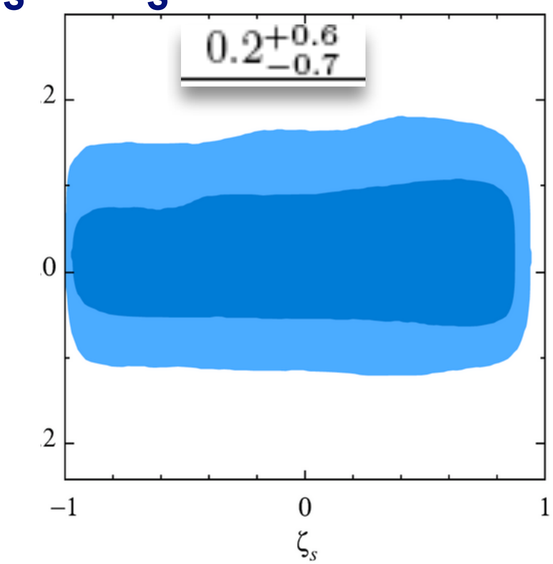
Forecast: JDEM-SN (2500 hi-z + 500 low-z) + DUNE-WL (50% sky, gals @z = 0.1-1.1, 35/min^2) + Planck1yr

ESA (+NASA/CSA)





ζ_s ~dlnε_s /dlna /2 ill-determined



Beyond Einstein panel: LISA+JDEM

Forecast: **JDEM-SN** (2500 hi-z + 500 low-z)

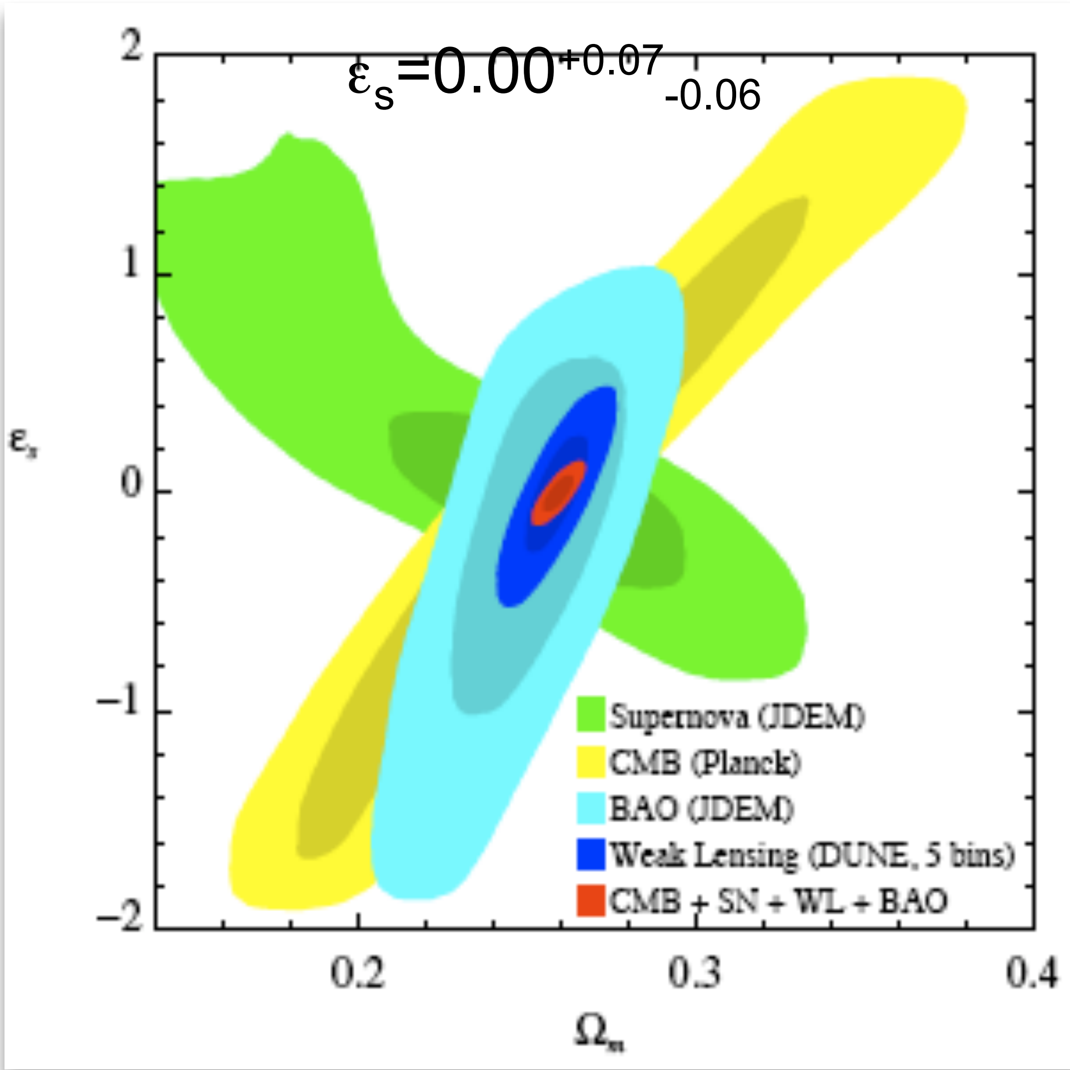
+ **DUNE-WL** (50% sky, gals @z = 0.1-1.1, 35/min^2) +

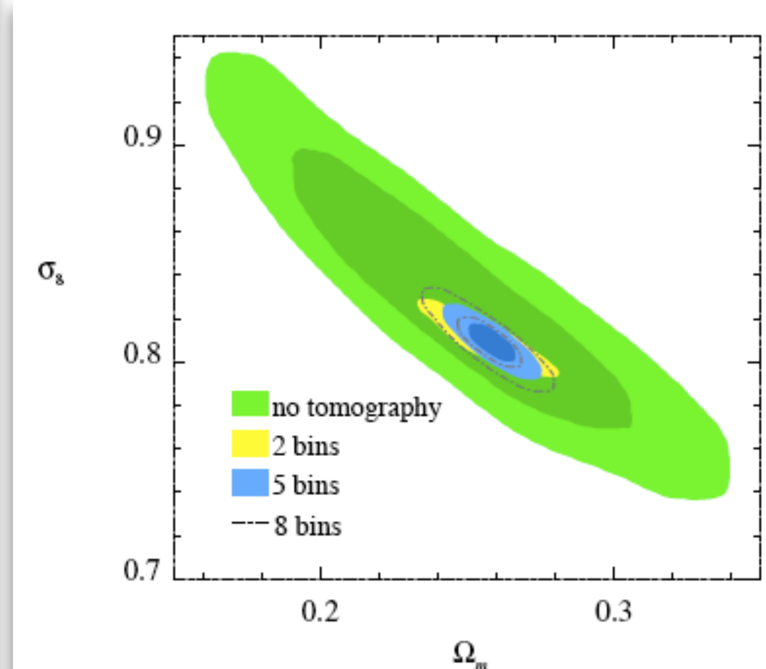
Planck1yr ESA (+NASA/CSA)

a_s=0 case

ζ_s ~dlnε_s /dlna /2 ill-determined

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





Inflation now summary

- the data cannot determine more than 2 w-parameters (+ csound?). general higher order Chebyshev or spline expansion in $1+w$ as for "inflation-then" $\varepsilon=(1+q)$ is not that useful. Parameter eigenmodes show what is probed
- Any w(a) leads to a viable DE model. The $w(a)=w_0+w_a(1-a)$ phenomenology requires baroque potentials
- Philosophy of HBK08: backtrack from now (z=0) all w-trajectories arising from quintessence ($\varepsilon_s>0$) and the phantom equivalent ($\varepsilon_s<0$); use a 3-parameter model $\varepsilon_\phi=(1+w(a))3/2=\varepsilon_s f(a/a_{\Lambda eq};a_s/a_{\Lambda eq};\zeta_s)$ to well-approximate even rather baroque w-trajectories, as well as thawing & freezing trajectories.
- We ignore constraints on Q-density from photon-decoupling and BBN because further trajectory extrapolation is needed. Can include via a prior on Ω_Q (a) at z_dec and z_bbn.
- For general slow-to-moderate rolling 2 "dynamical parameters" (a_s, ε_s) & Ω_Q describe w to a few %. In early-scaling-exit, the information stored in a_s is erased by Hubble drag over the observable range & w can be described by a single parameter ε_s. for baroque w-trajectories, add a 3rd param ζ_s ($d\ln\varepsilon_s/d\ln a/2$) - not-determined now & then. freeze-out w at high z, 4th param $-0.00^{+0.09}_{-0.13}$ $0.00^{+0.20+0.42}$
- prior-dependence e.g. sqrt(ε_s), a_s near 0, $\varepsilon_s>0$ since $\varepsilon_\phi<0$ of phantom energy, negative kinetic energy is baroque
- Apr08 observations well-centered around a cosmological constant $\varepsilon_s=-0.03+-0.28$ $a_s<0.36$ ($z_s>2.0$)

  cf. $\varepsilon_{\phi0}=$ -0.00 +/- 0.09 if constant, $\varepsilon_{\phi0}=$ -0.015 +/- 0.30 if a-linear model
- in Planck1yr-CMB+JDEM-SN+DUNE-WL future ε_s to +-0.07, a_s to <0.21 ($z_s>3.7$)
- cannot reconstruct the quintessence potential, just the slope ε_s & hubble drag info
- late-inflaton field is < Planck mass, but not by a lot
- DE may couple to matter, 5th force constraints are strong, maybe best hope in determining more about DE (chameleon example of dilaton a la Khoury and Weltman 04)

end

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25 years cifar

Inflation Then $\varepsilon(k)$ ~r/16

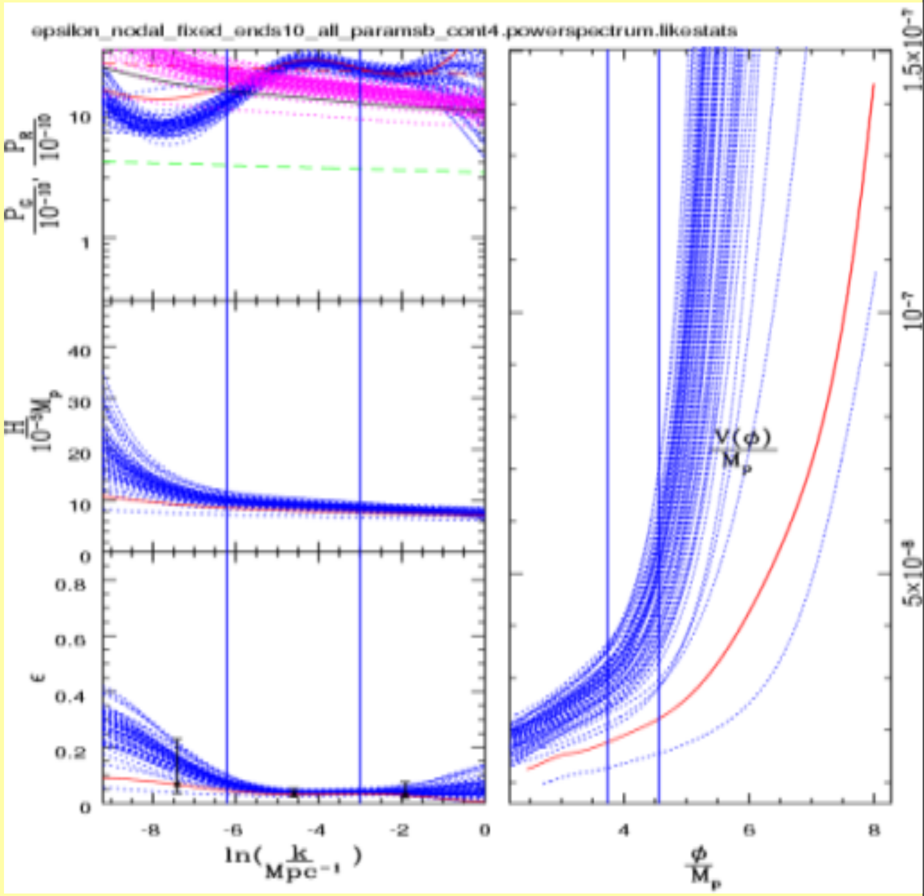
= mode expansion in lnHa ~ lnk

be blind: all $\varepsilon < 1$ *trajectories* give *allowed* potential & kinetic energies

~10 good e-folds k~10^{-4}Mpc^{-1} to ~ 1 Mpc^{-1}

~ 10+ parameters? H(ϕ), V(ϕ)

Bond, Contaldi, Huang, Kofman, Vaudrevange 08



Inflation Now *all* $\varepsilon_\phi < 1$ *trajectories* give *allowed* potential & kinetic energies

but... do not be blind:… ~1 good e-fold. only ~2params

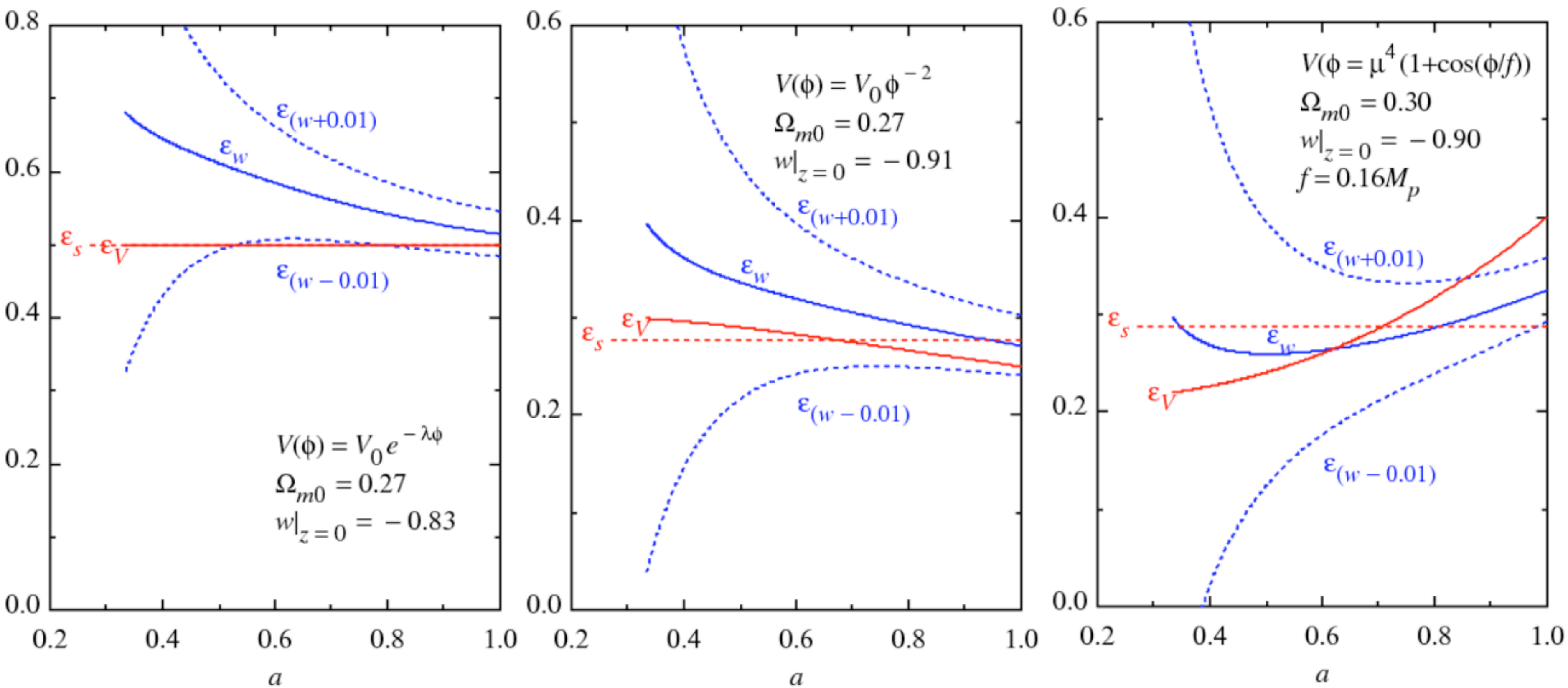
get $\varepsilon_s = (d\ln V/d\psi)^2/4$ @ pivot pt

Huang, Bond & Kofman 08

ε_v trajectories are slowly varying: why the fits are good

Dynamical $\varepsilon_w = \varepsilon_\phi\, \varepsilon_s / \varepsilon_{\phi\text{-approx}}$ cf. shape $\varepsilon_V = (V'/V)^2\ (a)\ /(16\pi G)$

& ε_s is ε_v uniformly averaged over $0<z<2$ in a



the quintessence field is below the reduced Planck mass