CITA ICAT Canadian Institute for Theoretical Astrophysics L'institut canadien d'astrophysique theorique – **Dick Bond**

CIAR 25 years cifar

Constraining Inflationary Histories, now & then

Inflation Now $1+w(a)= \varepsilon_s f(a/a_{\Lambda eq}; a_s/a_{\Lambda eq}; \zeta_s)$

goes to $\varepsilon(a)$ x3/2 = 3(1+q)/2 ~1 good e-fold. only ~2params

ε=-dlnH/dlna ~0 to 2 to 3/2 to ~.4 now, on its way to 0?

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

Inflation Then $\varepsilon(k)=(1+q)(a)$ = mode expansion in resolution (lnHa ~ lnk)
~r/16 (Tensor/Scalar Power & gravity waves)

Cosmic Probes Now CMB(Apr08), CFHTLS SN(192),WL(Apr07), LSS/BAO, Lyα

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

Zhiqi Huang, Bond & Kofman 08 ε_s=-0.06+-0.20 now, inflaton (potential gradient)^2

to +-0.07 then Planck1+JDEM SN+DUNE WL, weak a_s < 0.3 now <0.21 then

INFLATION NOW

PROBES NOW

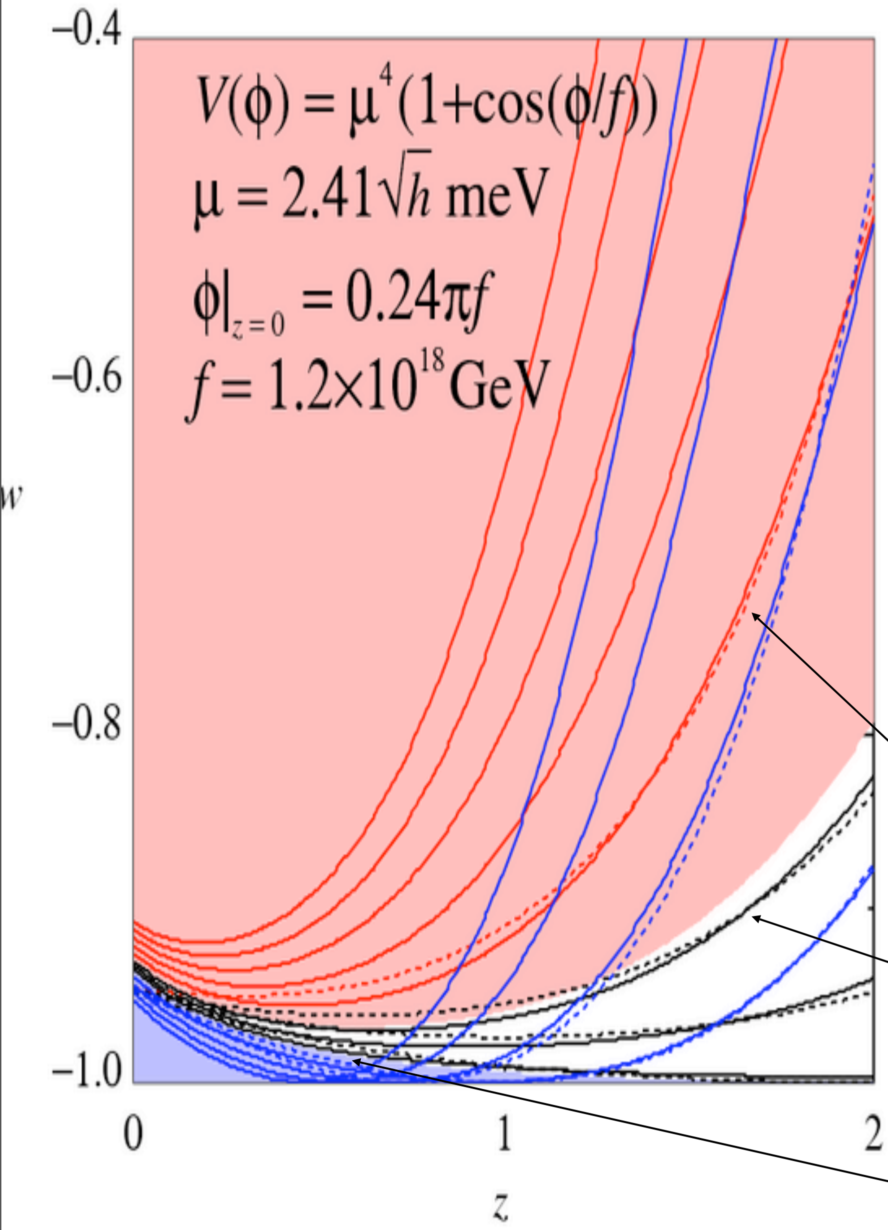
- **Cosmological Constant (*w*=-1)**
- **Quintessence**

(-1≤*w*≤1)

- **Phantom field (*w*≤-1)**
- **Tachyon fields (-1 ≤ *w* ≤ 0)**
- **K-essence**

(no prior on *w*)

w-trajectories for V(ϕ): pNGB example e.g.sorbo et07



For a given quintessence potential V(ϕ), we set the "initial conditions" at z=0 and evolve backward in time.

w-trajectories for $\mathbf{\Omega_m}$ (z=0) = 0.27 and $(V'/V)^2/(16\pi G)$ (z=0) = 0.25, ~ the 1-sigma limit, varying the initial kinetic energy $w_0 = w(z=0)$

Dashed lines: 2-param approximation

Wild rise solutions

Slow-to-medium-roll solutions

Complicated scenarios: roll-up then roll-down

Approximating Quintessence for Phenomenology

Zhiqi Huang, Bond & Kofman 08

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

quintessence

$$\begin{cases} d\theta/dN = \sqrt{3\epsilon_V \Omega_\phi}\cos\theta - \frac{3}{2}\sin 2\theta, \\ d\Omega_\phi/dN = 3\Omega_\phi(1-\Omega_\phi)\cos 2\theta, \\ d\epsilon_V/dN = -\sqrt{12\epsilon_V\Omega_\phi}(\eta_V - 2\epsilon_V)\sin\theta, \end{cases}$$

$1 + w = 2\sin^2\theta$

phantom

$$\begin{cases} d\theta/dN = \sqrt{-3\epsilon_V \Omega_\phi}\cosh\theta - \frac{3}{2}\sinh 2\theta, \\ d\Omega_\phi/dN = 3\Omega_\phi(1-\Omega_\phi)\cosh 2\theta, \\ d\epsilon_V/dN = \sqrt{-12\epsilon_V\Omega_\phi}(\eta_V - 2\epsilon_V)\sinh\theta, \end{cases}$$

Include a w<-1 phantom field, via a negative kinetic energy term

$1 + w = -2\sinh^2\theta$

$$\theta \equiv \begin{cases} \sin^{-1}\frac{\dot{\phi}}{\sqrt{2\rho_\phi}} & \text{for quintessence,} \\ \sinh^{-1}\frac{\dot{\phi}}{\sqrt{2\rho_\phi}} & \text{for phantom.} \end{cases}$$

$$\Omega_\phi \equiv \frac{8\pi G\rho_\phi}{3H^2}, \epsilon_V \equiv \frac{\beta}{16\pi G}\left(\frac{V'}{V}\right)^2, \eta_V \equiv \frac{\beta}{8\pi G}\frac{V''}{V}$$

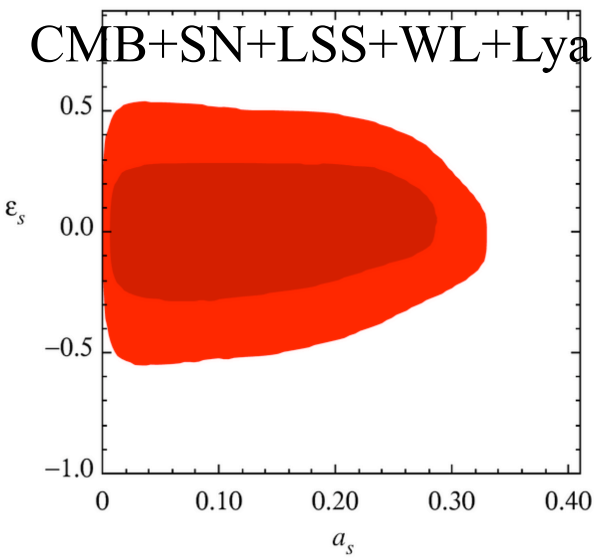
slow-to-moderate roll conditions

$$\begin{cases} \frac{1}{2}\dot{\phi}^2 \ll V(\phi), \\ \varepsilon_s \lesssim 1, \\ \eta_s \lesssim 1, \end{cases} \quad \text{at} \quad 0 < z < 2.$$

1+w< 0.3 (for 0<z<10) gives a 2-parameter model (a_s and ε_s):

$$a_{eq} \equiv (\frac{\Omega_{m0}}{\Omega_{\Lambda 0}})^{\frac{1}{3}} \sim 0.7,$$

$$w(a) = -1 + \frac{2\varepsilon_s}{3}\{\frac{1}{\sqrt{|\varepsilon_s|}}(\frac{a_s}{a})^3 + \sqrt{1+(\frac{a_{eq}}{a})^3} - (\frac{a_{eq}}{a})^3 \ln[(\frac{a}{a_{eq}})^{\frac{3}{2}} + \sqrt{1+(\frac{a}{a_{eq}})^3}]\}^2 + O(\theta^3),$$



Early-Exit Scenario: scaling regime info is lost by Hubble damping, i.e.small **a_s**

1+w< 0.2 (for 0<z<10) and gives a 1-parameter model (a_s<<1):

$$w(a) = -1 + \frac{2\varepsilon_s}{3}\{\sqrt{1+(\frac{a_{eq}}{a})^3} - (\frac{a_{eq}}{a})^3 \ln[(\frac{a}{a_{eq}})^{\frac{3}{2}} + \sqrt{1+(\frac{a}{a_{eq}})^3}]\}^2.$$

3-parameter parameterization

next order corrections:

Ω_m (a) (depends on ε_s redefines a_{eq})

$\varepsilon_V = \varepsilon_s$ (a) (adds new ζ_s parameter)

enforce asymptotic kinetic-dominance w=1 (add a_s power suppression)

refine the fit to encompass even baroque trajectories.

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

this choice is analytic. The correction on w is only ~ 0.01

3-parameter parameterization

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

where

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

$$a_s \geq 0$$

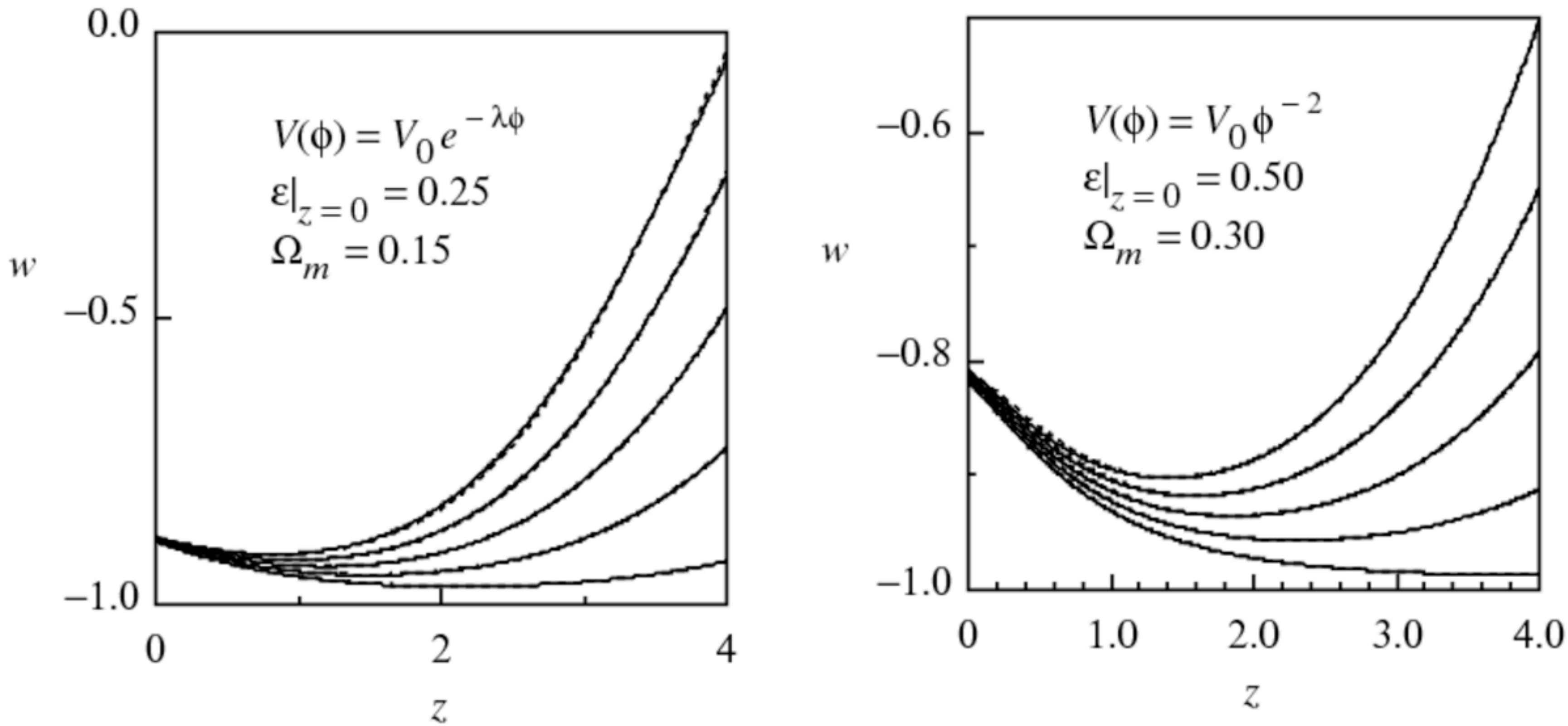
$$-1 < \zeta_s < 1$$

3-parameter fitting

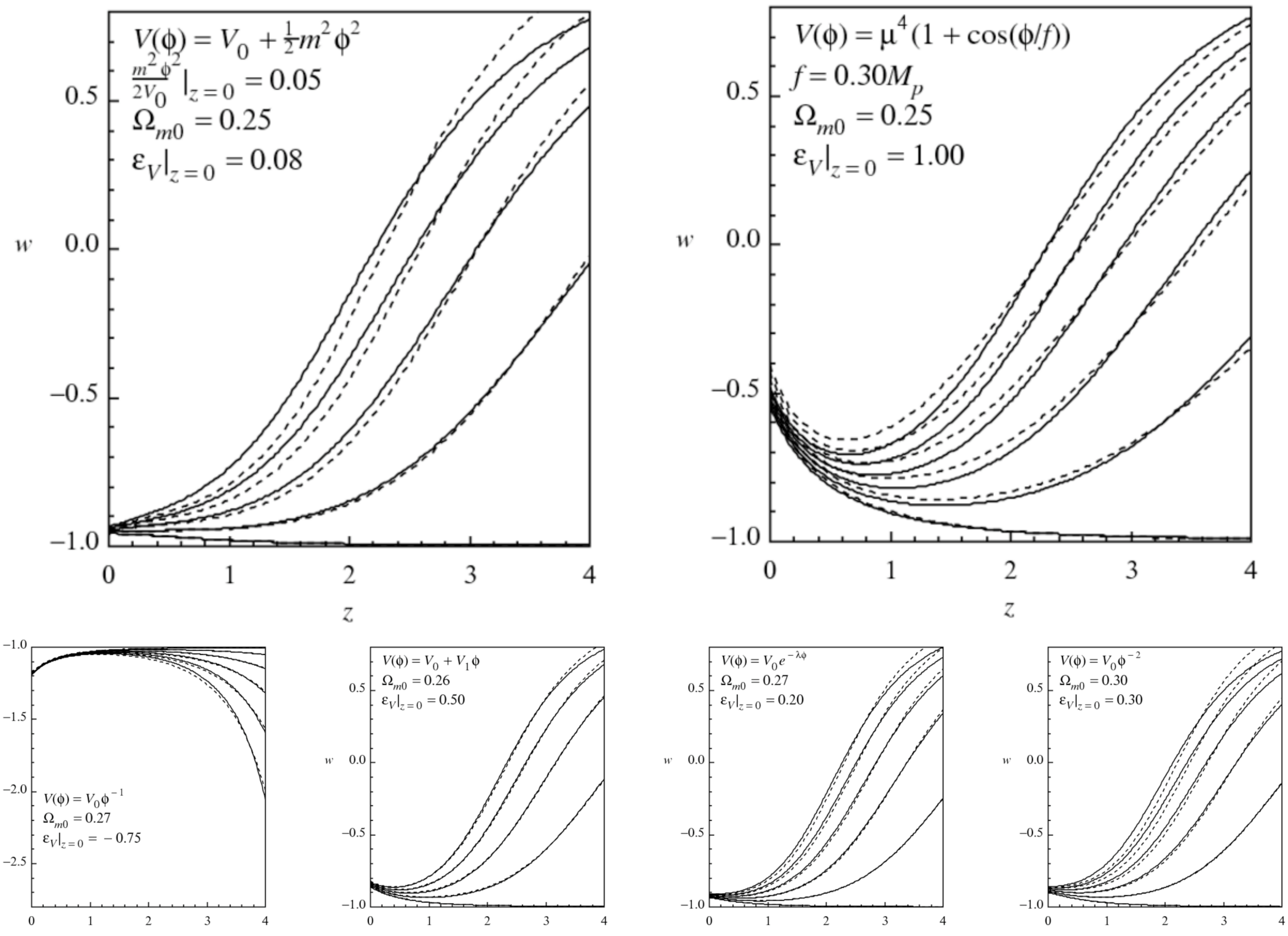
ε_s & ζ_s calculated from ε trajectory (linear least square)

a_s is χ^2 -fit

- **Perfectly fits slow-to-moderate roll**



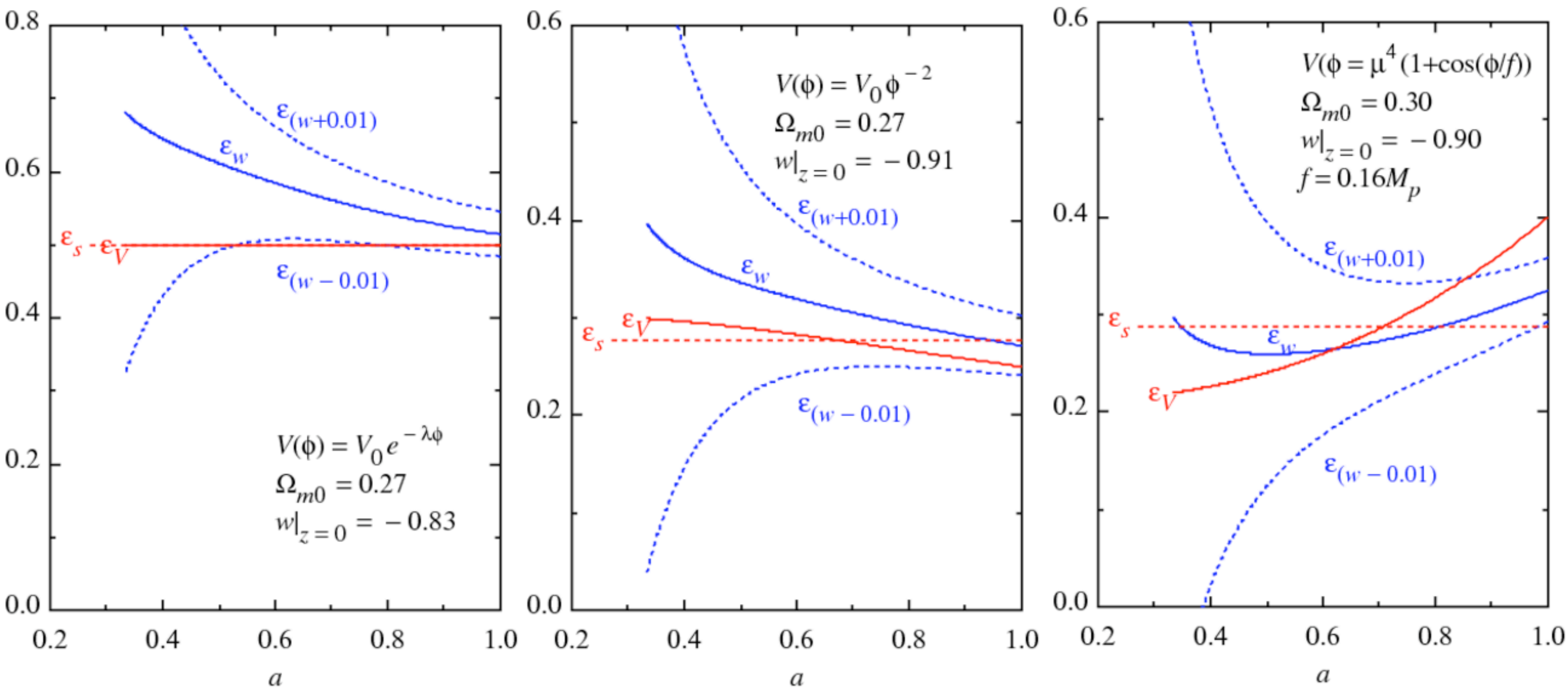
fits wild rising trajectories



ε_v trajectories are slowly varying: why the fits are good

Dynamical ε_w= (1+w)(a)/f(a) cf. shape ε_V= (V'/V)^2 (a) /(16πG)

ε_s= ε_v uniformly averaged over 0<z<2 in a.

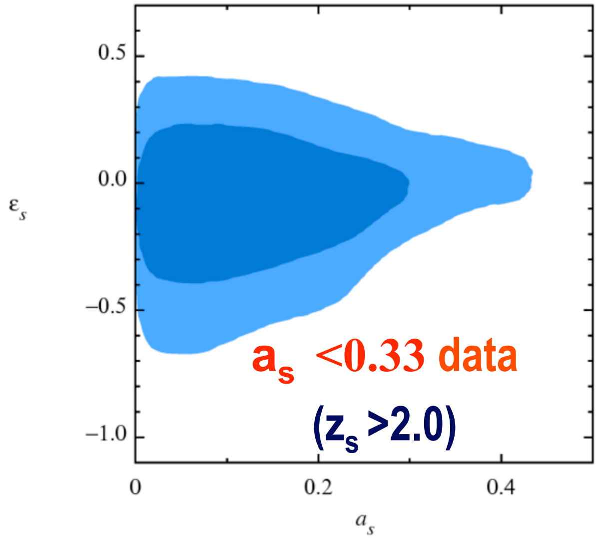


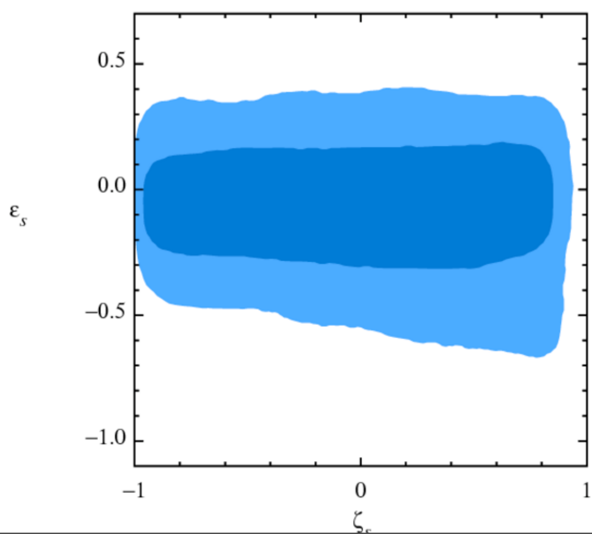
Measuring the 3 parameters with Apr08 data

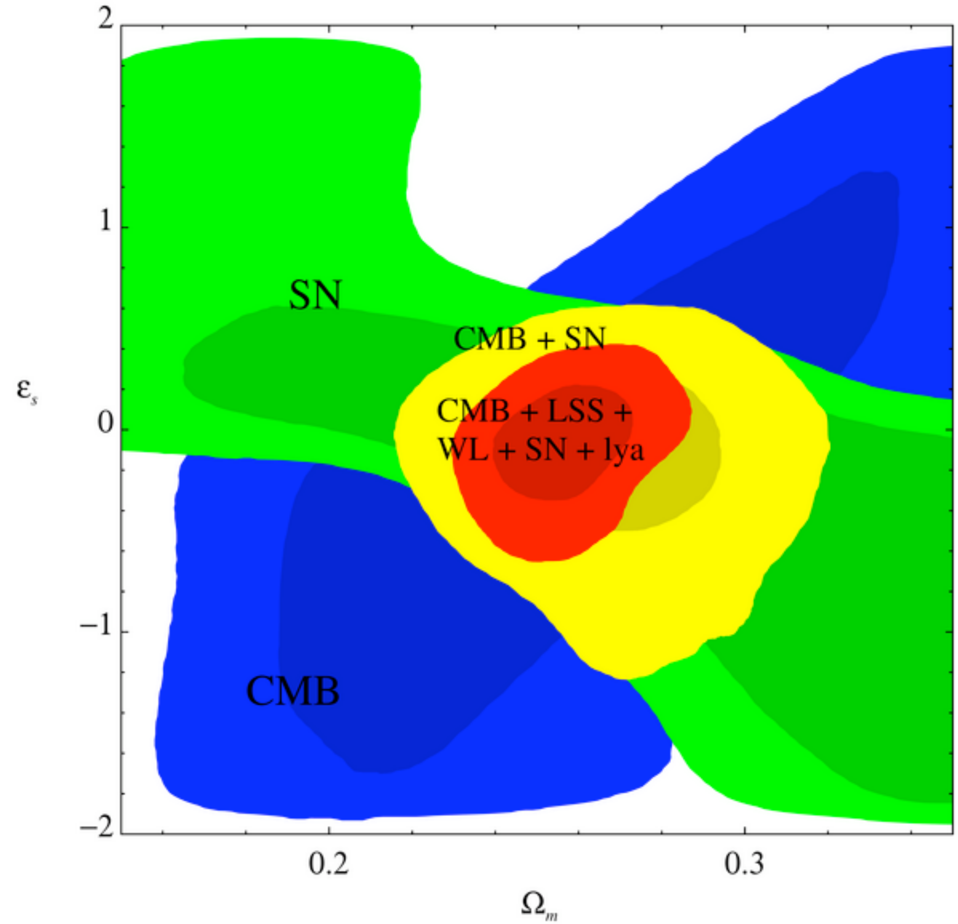
- Use 3-parameter formula over 0<z<4 & $w(z>4)=w_h$

ε_s = -0.00 +0.20 -0.20 1params

ε_s = -0.06 +0.19 -0.21 3params







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+w0, wa

$dn_s/d\ln k$ n_t

New Parameters of Cosmic Structure Formation

1+w(a)

$\epsilon(k), \quad k \approx Ha$ $\ln H(k_p)$

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

$\ln P_s(k)$ $\ln P_t(k)$

+ subdominant isocurvature/cosmic string/ tSZ

CMB/LSS Phenomenology

CITA/CIfAR there

- Mivelle-Deschenes (IAS)
- Pogosyan (U of Alberta)
- Myers (NRAO)
- Holder (McGill)
- Hoekstra (UVictoria)
- van Waerbeke (UBC)

CITA/CIfAR here

- Bond
- Contaldi
- Lewis
- Sievers
- Pen
- McDonald
- Majumdar
- Nolta
- Iliev
- Kofman
- Vaudrevange
- Huang

Prokushkin

- Dalal
- Dore
- Kesden
- MacTavish
- Pfrommer
- Shirokov

UofT here

- Netterfield
- Carlberg
- Yee

& Exptal/Analysis/Phenomenology Teams here & there

- Boomerang03 (98)
- Cosmic Background Imager1/2
- Acbar07
- WMAP (Nolta, Dore)
- CFHTLS – WeakLens
- CFHTLS - Supernovae
- RCS2 (RCS1; Virmos-Descart)

Parameter data now: CMBall_pol

SDSS P(k), BAO, 2dF P(k)

Weak lens (Virmos/RCS1, CFHTLS, RCS2) ~100sqdeg Benjamin etal. aph/0703570v1

Lya forest (SDSS)

SN1a “gold”(192,15 z>1 to 242+) CFHTLS

then: ACT (SZ), Spider, Planck, 21(1+z)cm GMRT,SKA

COSMIC PARAMETERS NOW & THEN

The Parameters of Cosmic Structure Formation

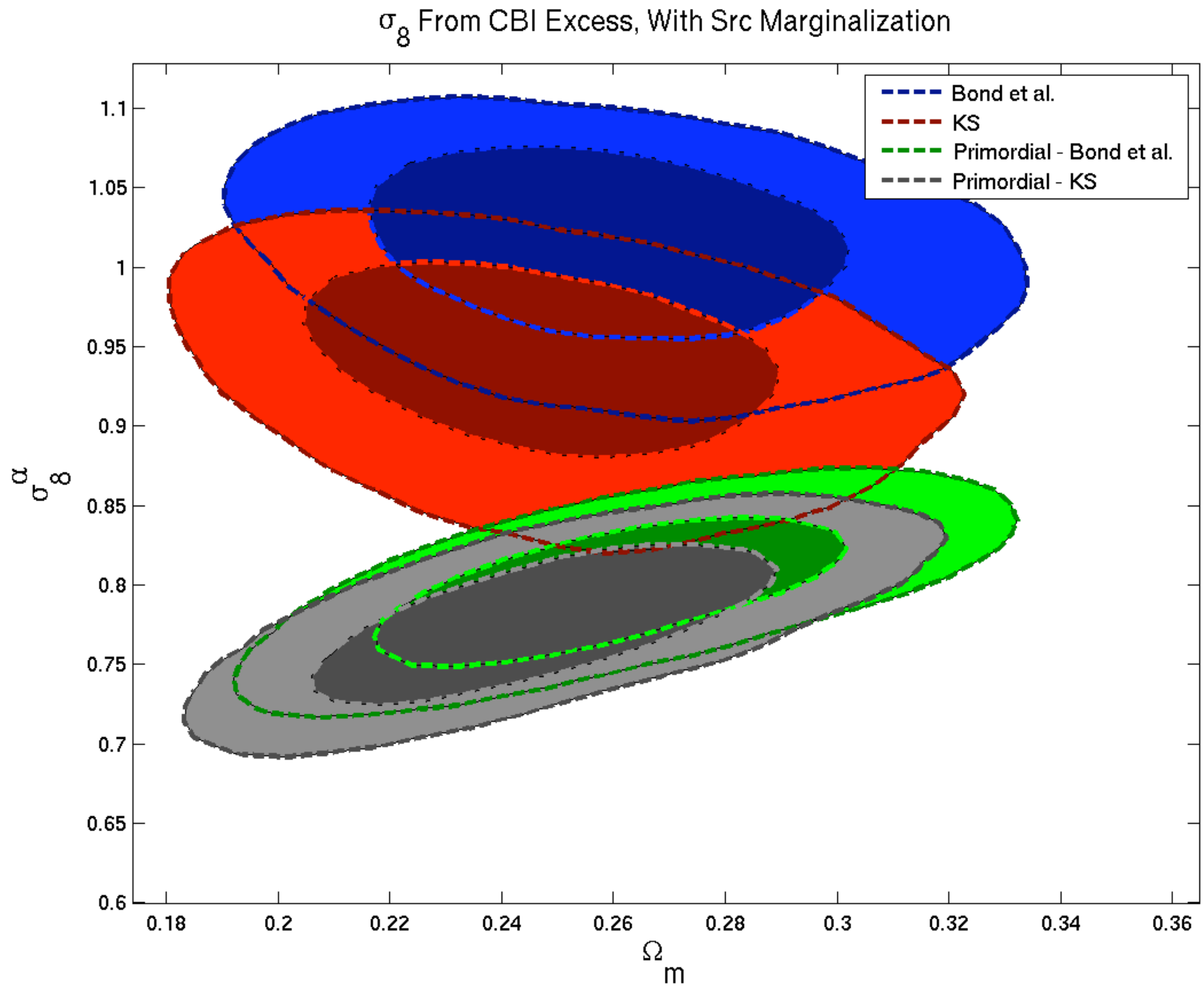
Cosmic Numerology: april08 cmb +LSS/WL/SN wmap5

n_s = .976 +- .011 (+-.005 Planck1)

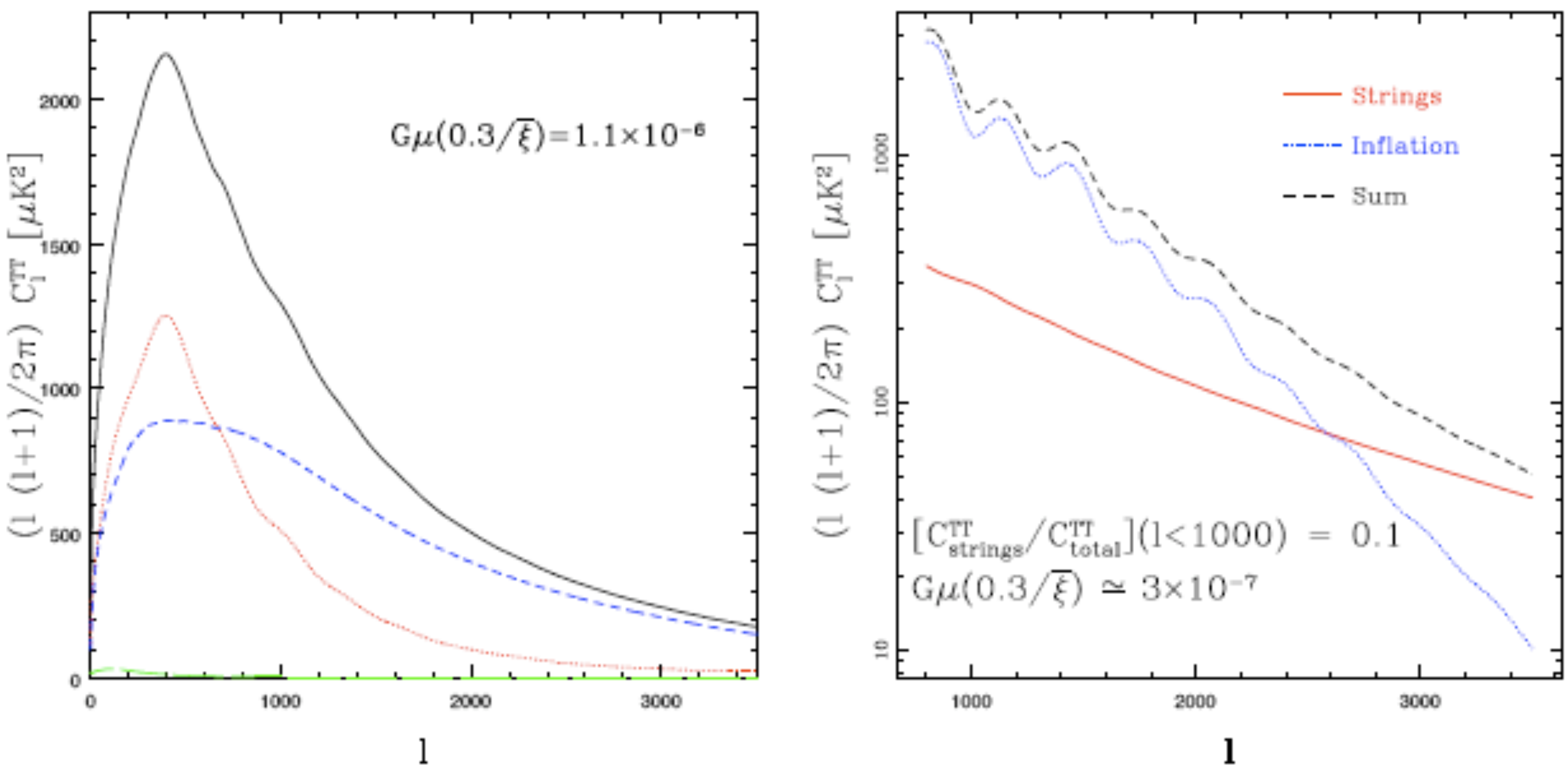
$r = A_t / A_s < 0.33_{cmb}$ 95% CL (+-.03 P1)

$-9 < f_{NL} < 111$ (+-
5-10 P1)

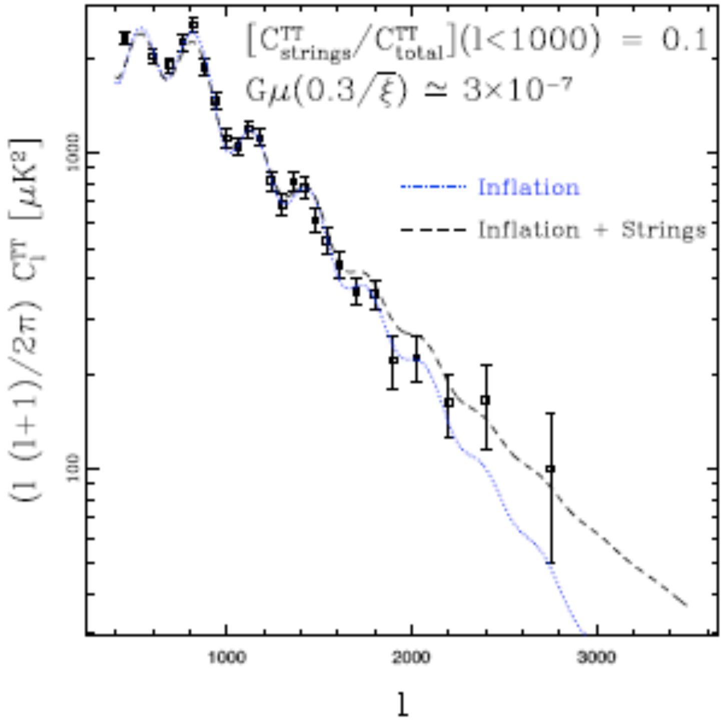
CBI/BIMA/Acbar Excess Issue. Thermal SZ explanation requires modified CL templates over that given by adiabatic hydro simulations and by simple semi-analytic calculations

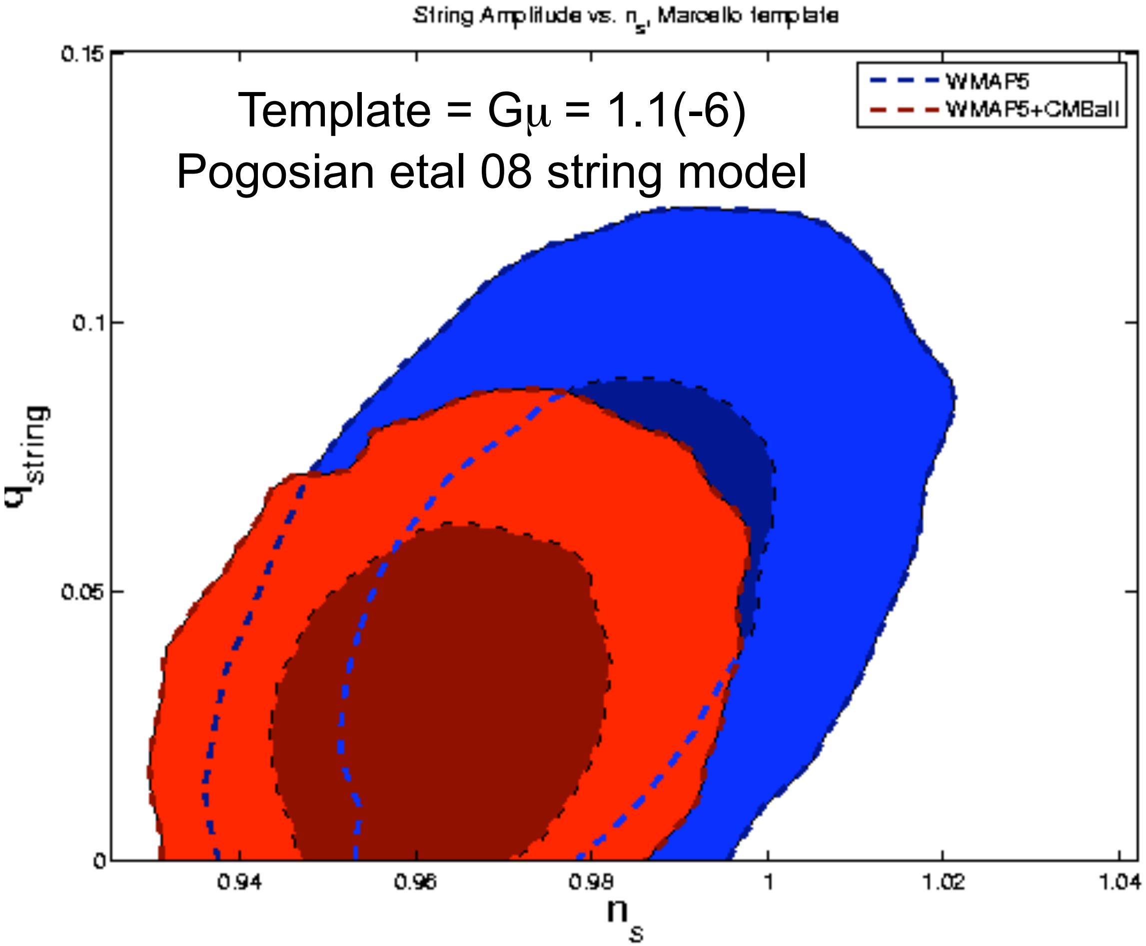


COSMIC STRING CONSTRAINTS Pogosian etal 08 semi-analytic models (cf. numerical string models Bevis 07)



COSMIC STRING CONSTRAINTS Pogosian etal 08 semi-analytic models (cf. numerical string models Bevis 07)

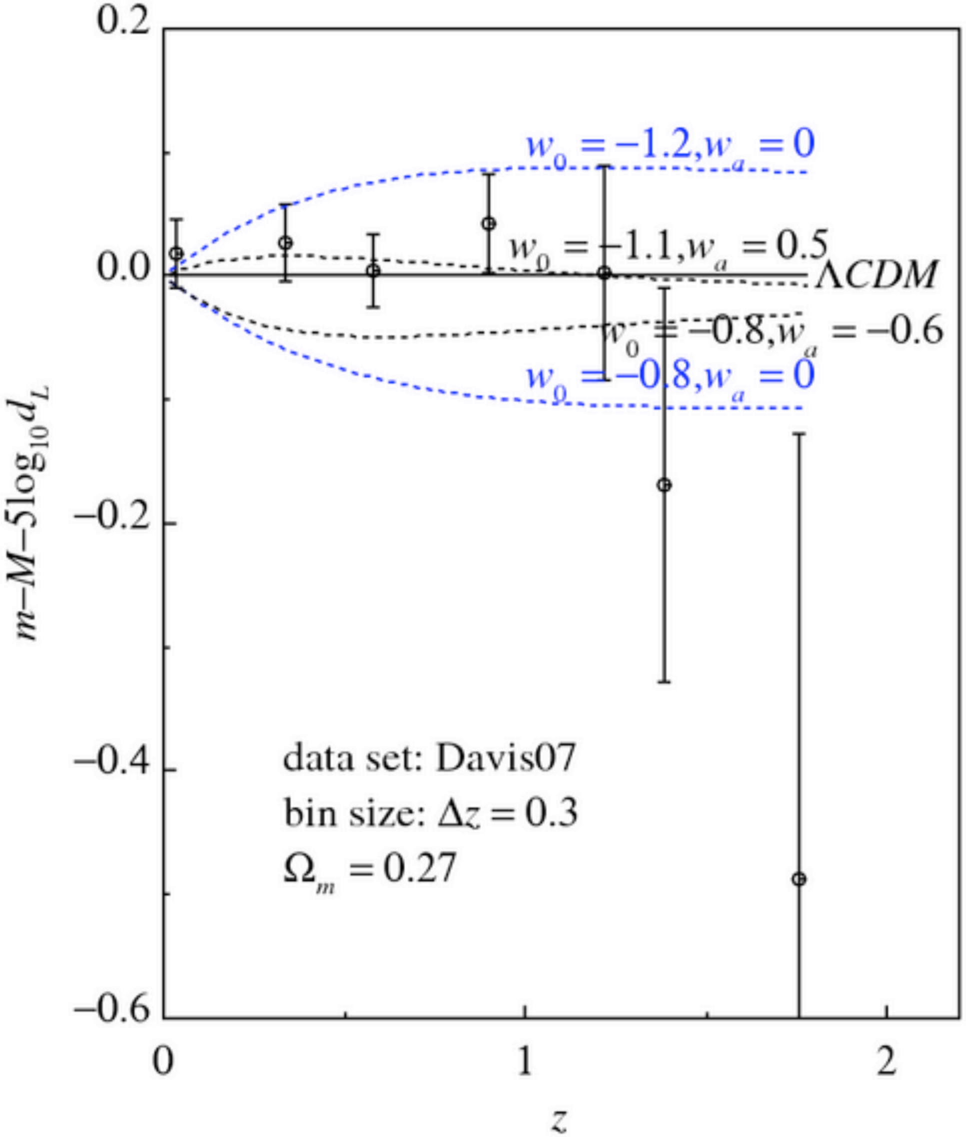




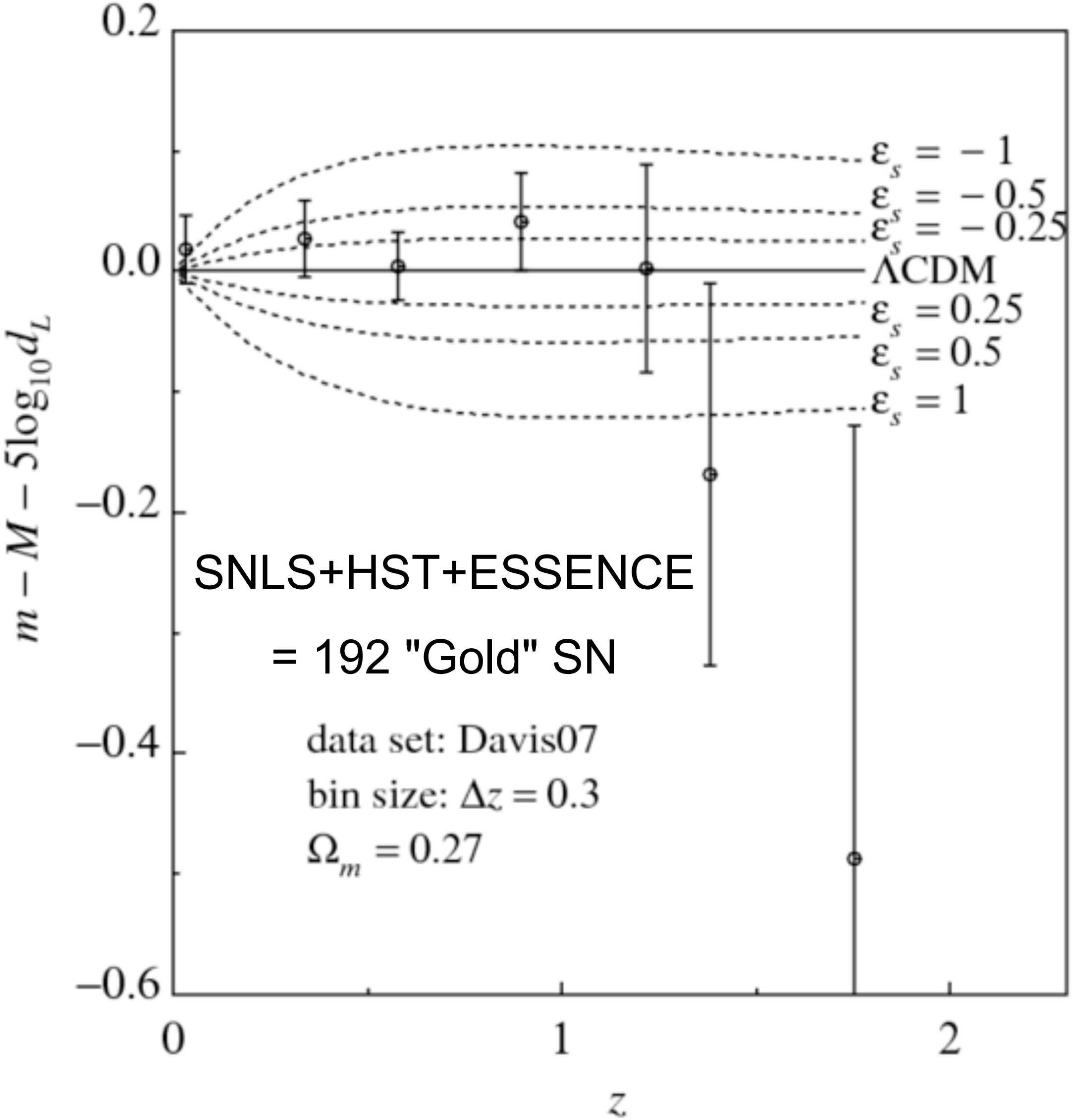
$w(a)=w_0+w_a(1-a)$ models

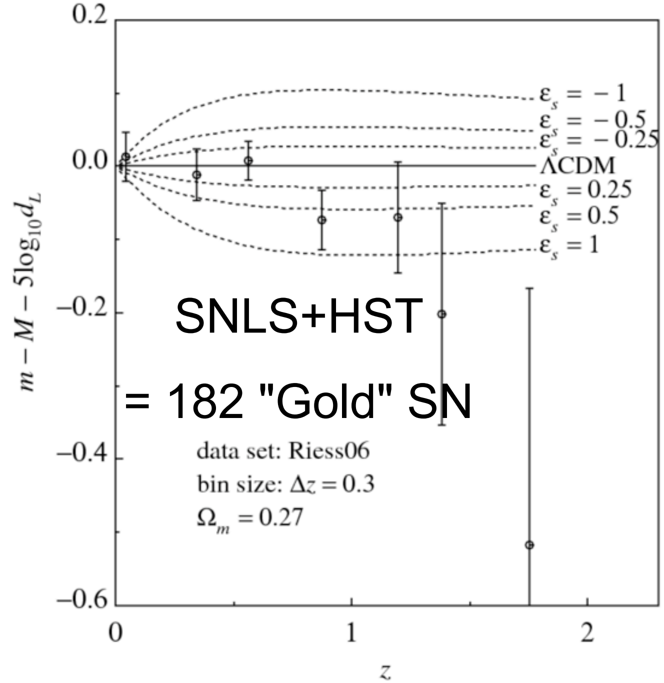
cf. SNLS+HST+ESSENCE = 192 "Gold" SN

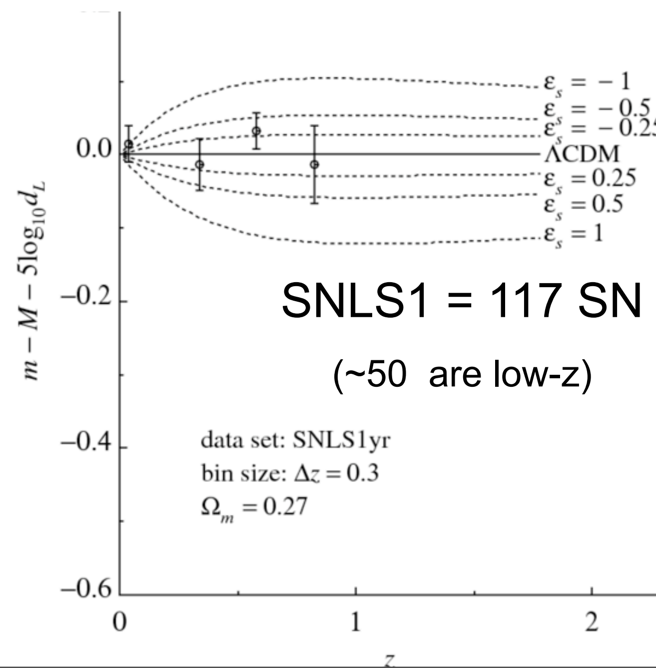
illustrates the near-degeneracies of the contour plot



45 low-z SN + ESSENCE SN + SNLS 1st year SN
+ Riess high-z SN, all fit with MLCS



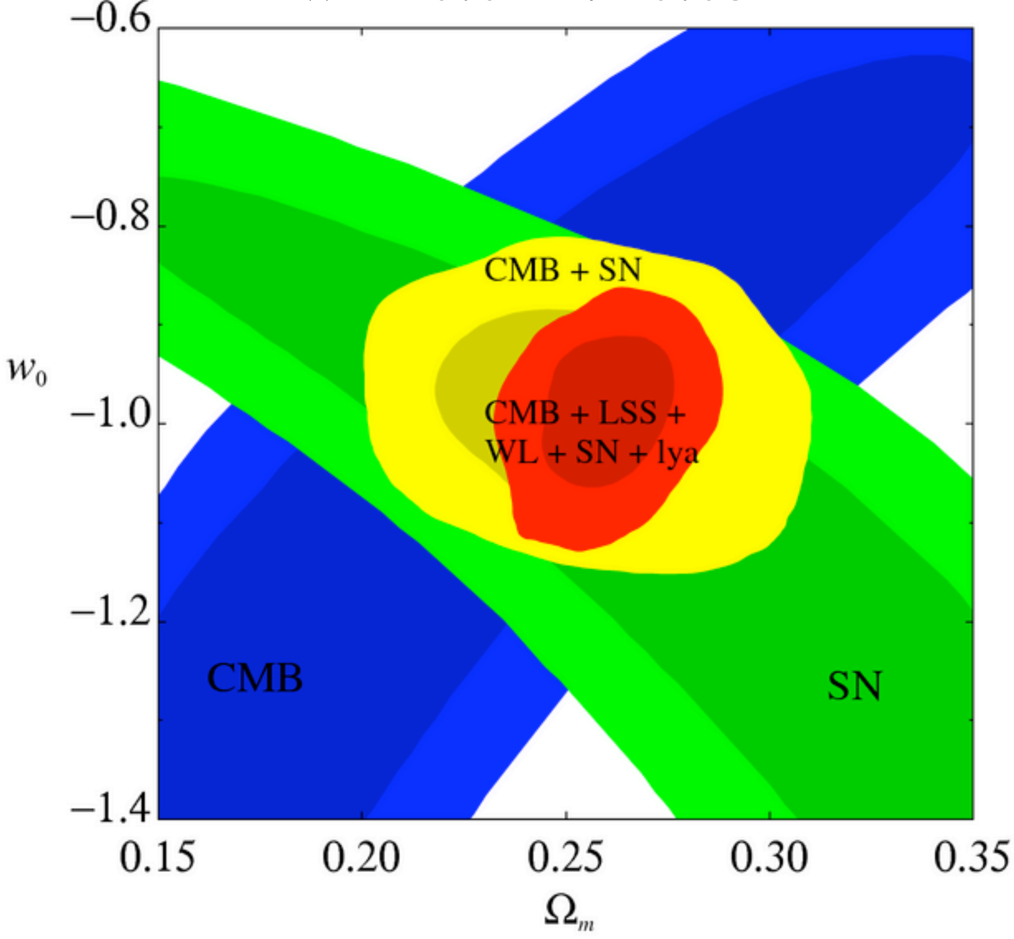




Measuring w (Apr07 SNe+CMB+WL+LSS)

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

1+w = 0.02 +/- 0.05

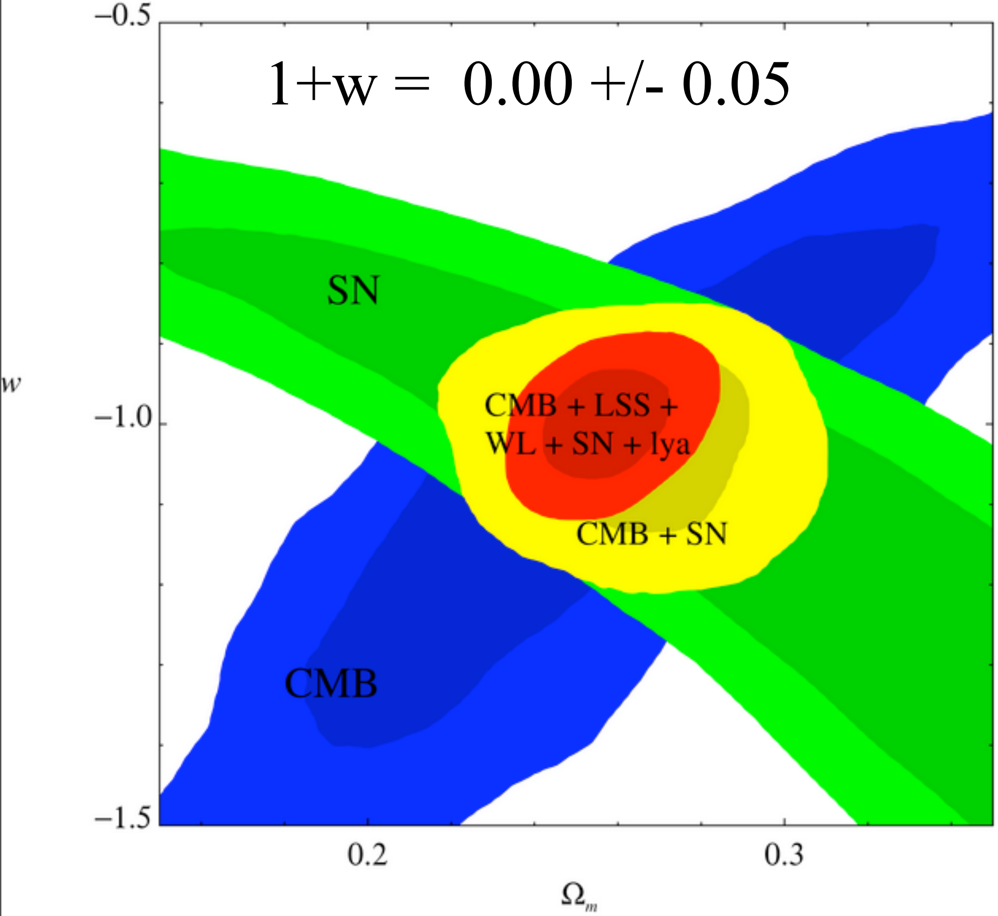


Measuring w (Apr08 SNe+CMB+WL+LSS)

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

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

$1+w0 = -0.11 \pm .14$, $wa=0.4 \pm 0.4$



piecewise parameterization

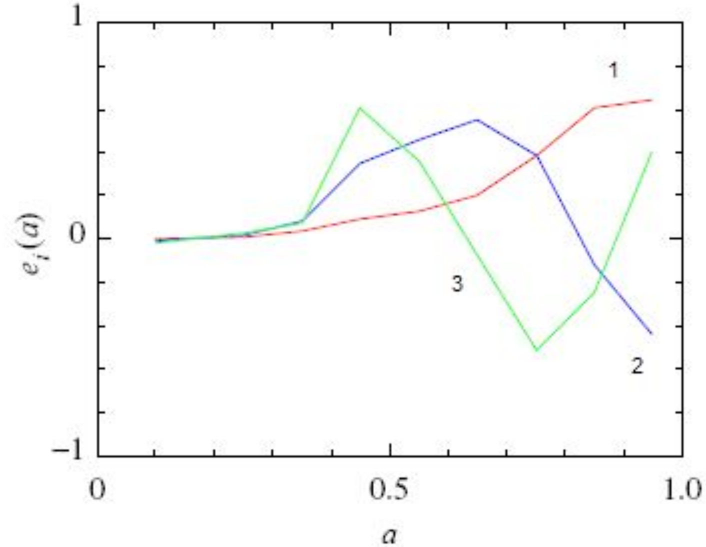
4,9,40 modes in redshift

9 & 40 into Parameter eigenmodes

data cannot determine >2 EOS parameters

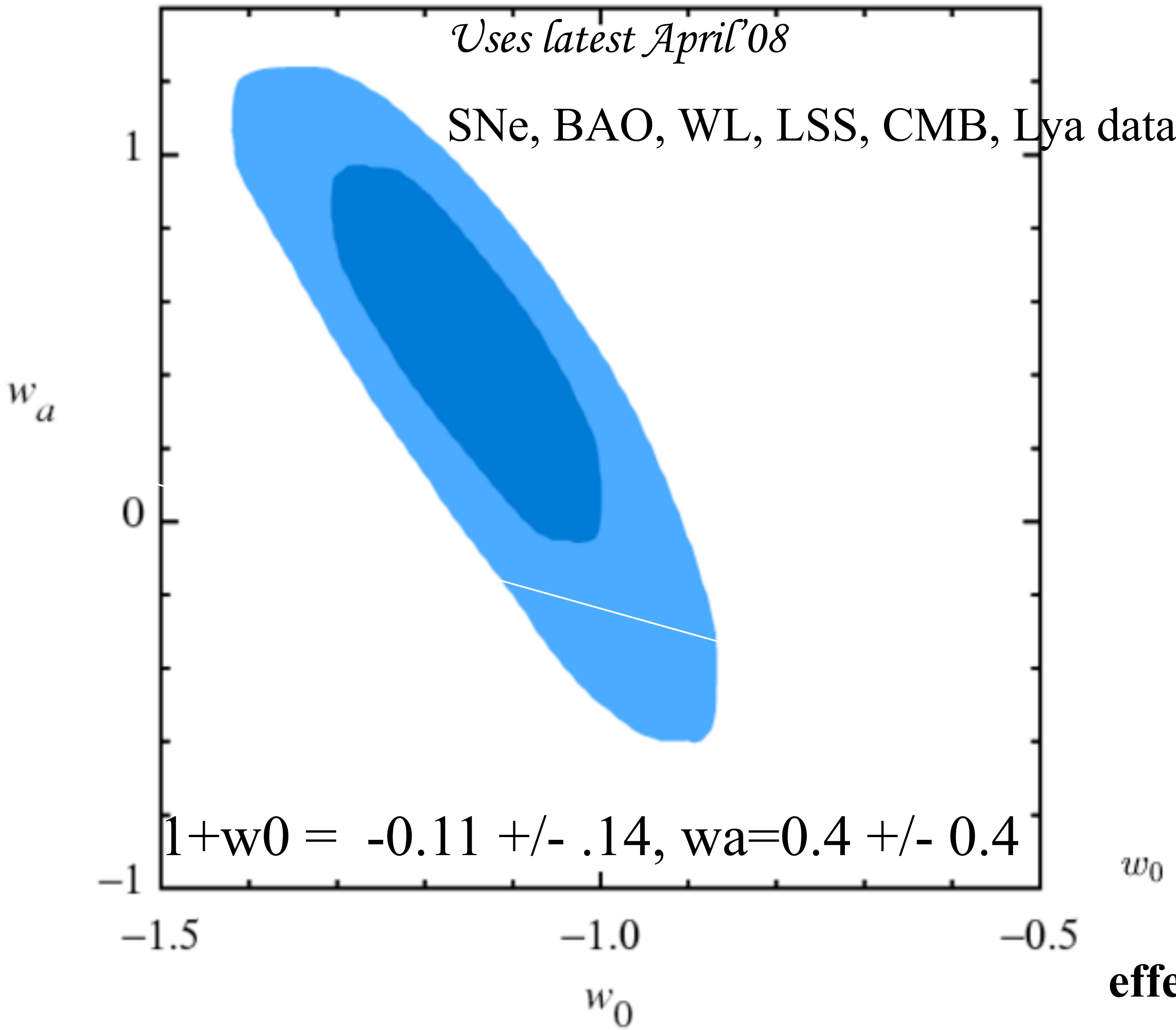
DETF Albrecht etal06, Crittenden etal06, hbk07

$\sigma_1=0.12$ $\sigma_2=0.32$ $\sigma_3=0.63$



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

w(a)=w$_0$+w$_a$(1-a)



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

effective constraint eq.

z-modes of w(z)

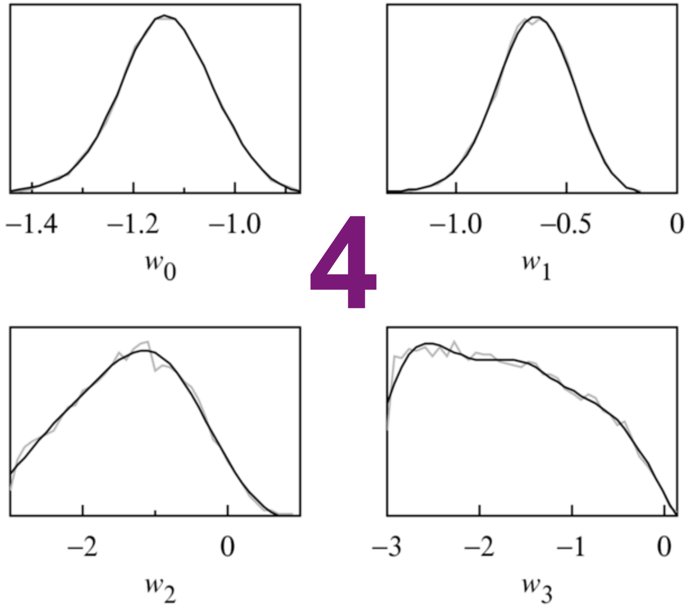
piecewise parameterization **4,9,40**

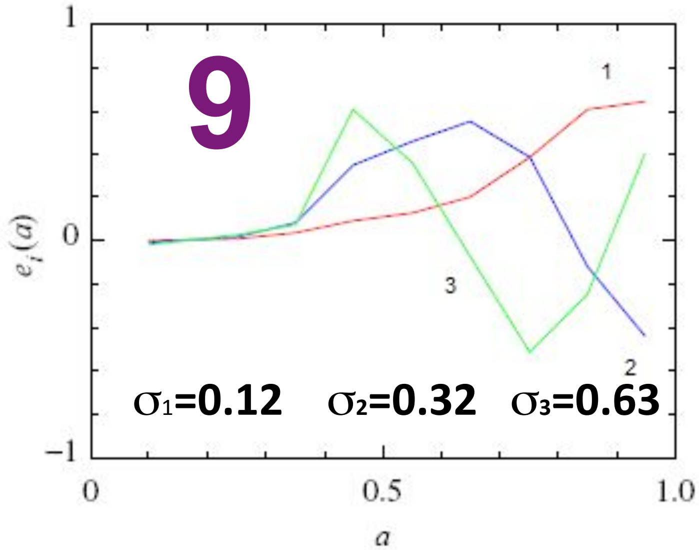
Higher Chebyshev expansion is not useful:

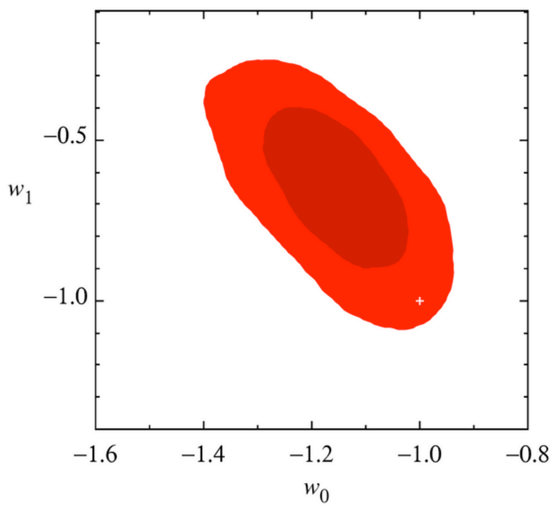
data cannot determine >2 EOS parameters

9 & 40 into Parameter eigenmodes

DETF Albrecht etal06, Crittenden etal06, hbk07



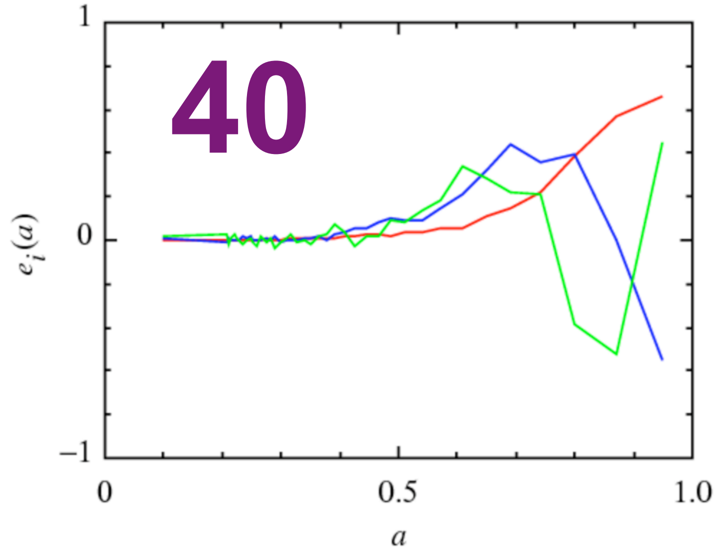




Data used 07.04:

CMB+SN+WL

+LSS+Lya

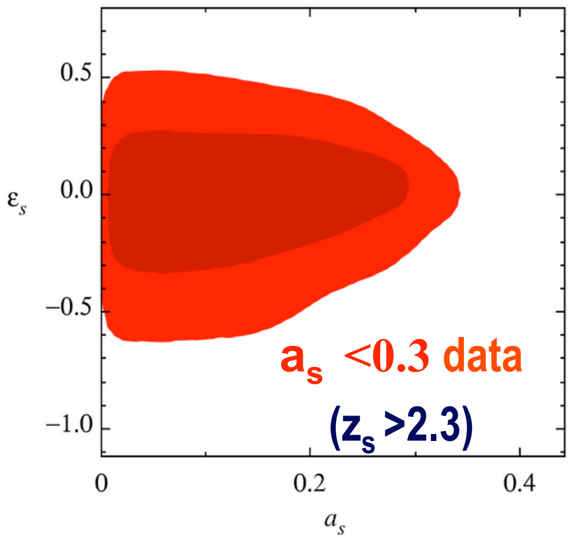


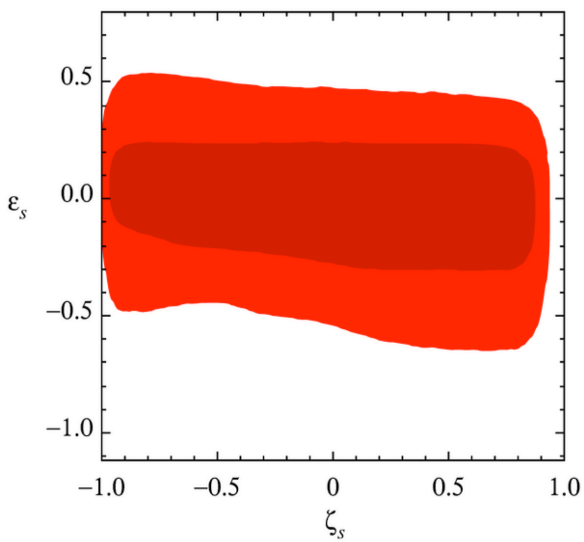
Measuring the 3 parameters with Apr07 data

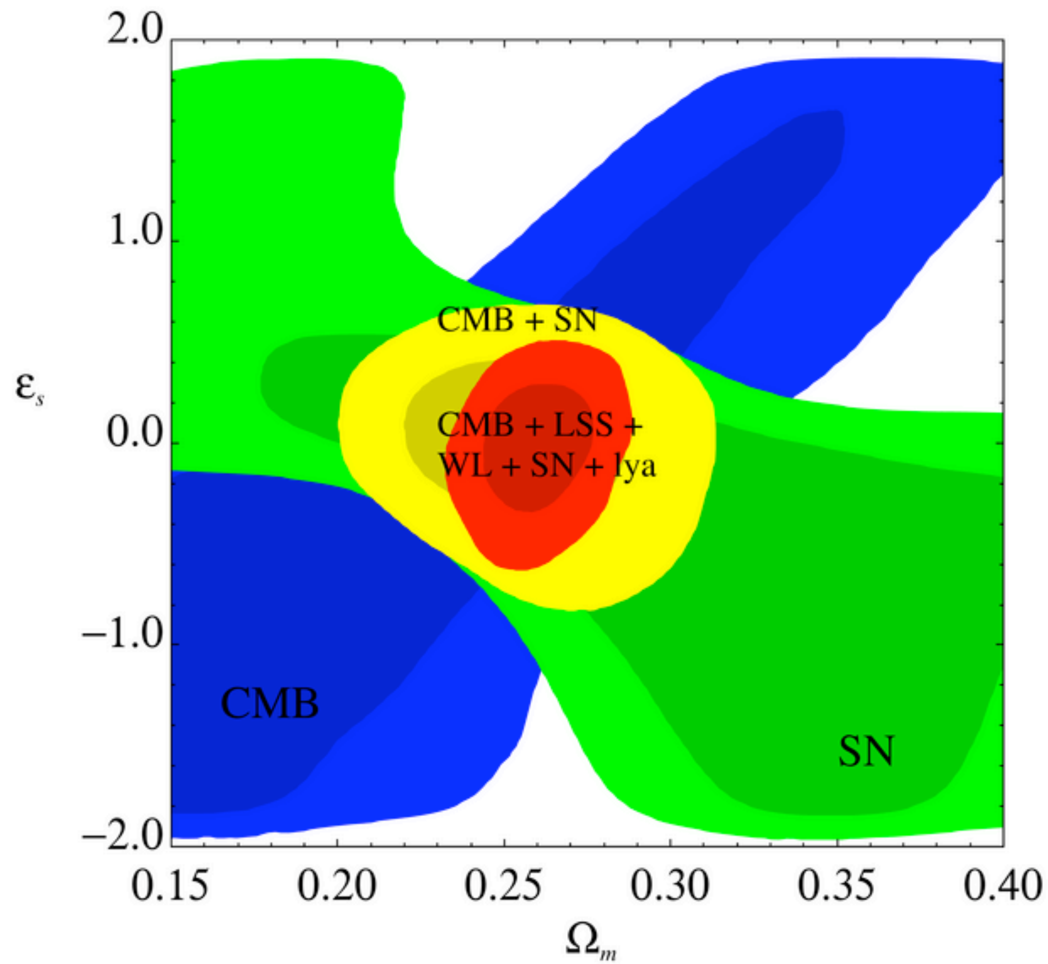
- Use 3-parameter formula over $0<z<4$ $w(z>4)=w_h$

ε_s = -0.01 +0.23 -0.24 1params

ε_s = -0.00 +0.20 -0.24 1params





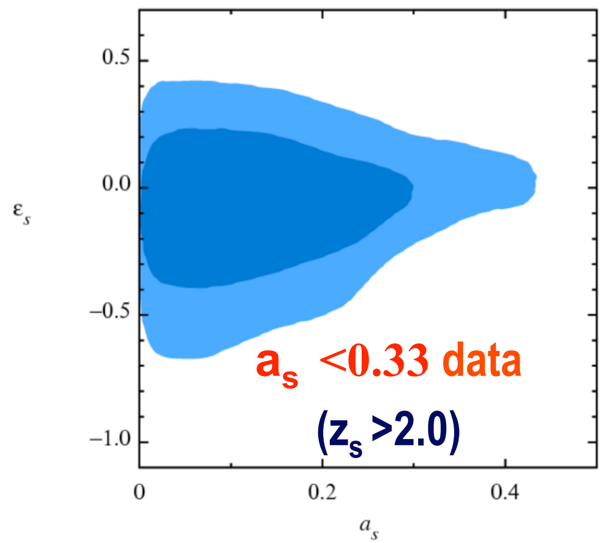


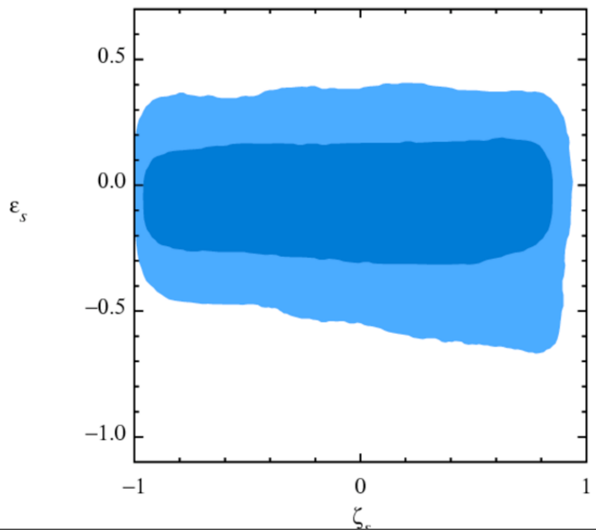
Measuring the 3 parameters with Apr08 data

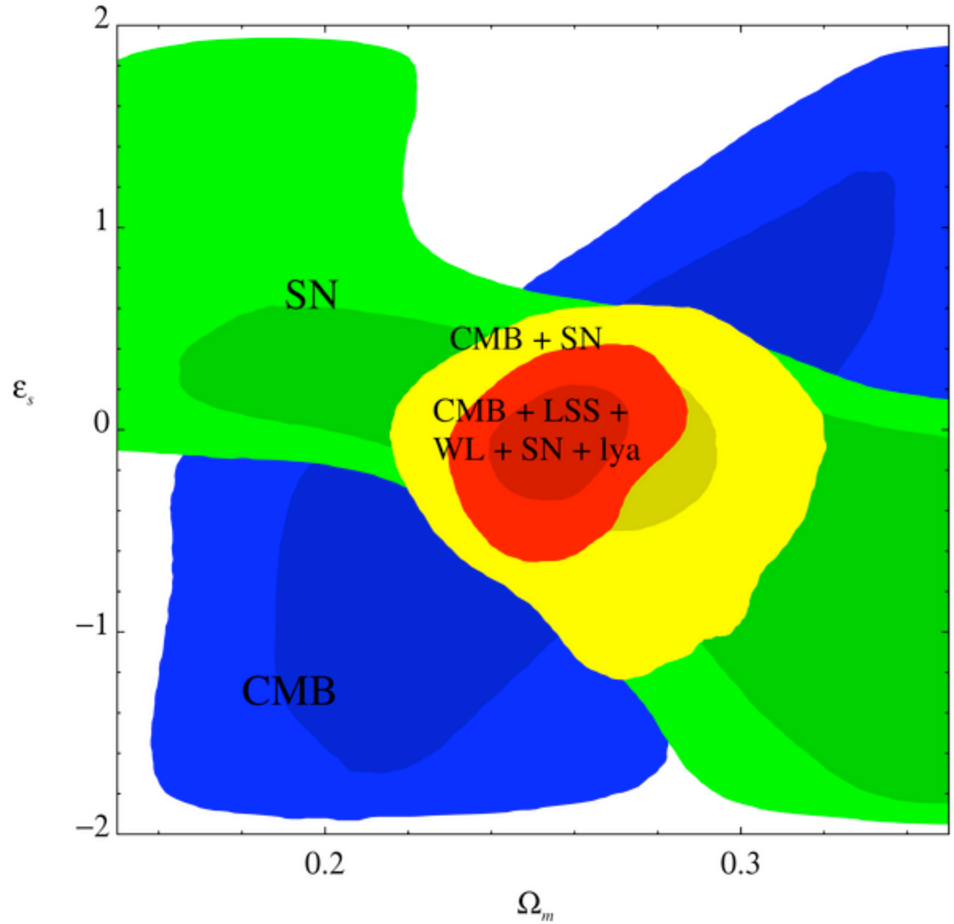
- Use 3-parameter formula over $0<z<4$ & $w(z>4)=w_h$

$\varepsilon_s = -0.00\ +0.20\ -0.20$ 1params

$\varepsilon_s = -0.06\ +0.19\ -0.21$ 3params





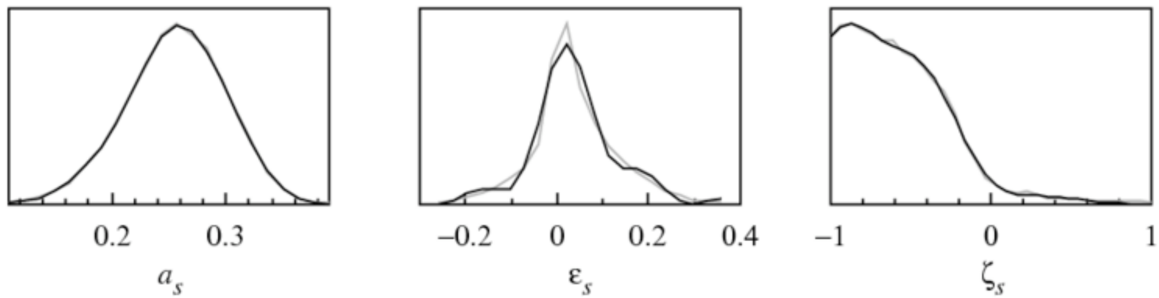


Thawing, freezing or non-monotonic?

- *Thawing*: 1+w monotonic up as z decreases
- *Freezing*: 1+w monotonic down to 0 as z decreases
- ~15% thaw, 8% freeze, most non-monotonic with flat priors

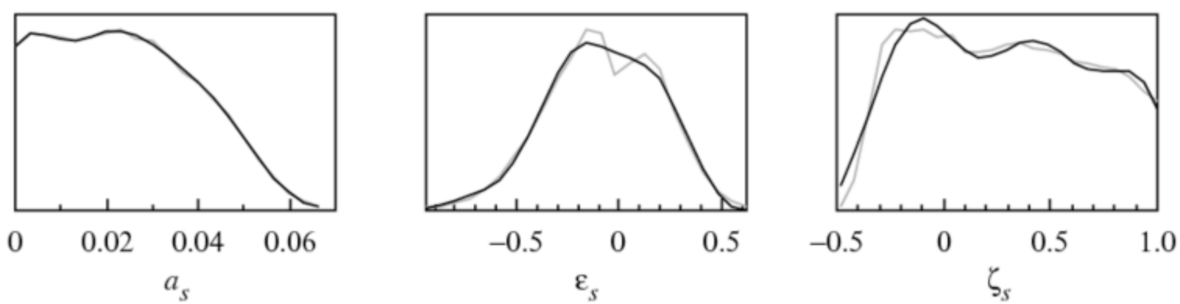
With freezing prior:

$$\epsilon_s = -0.02^{+0.10}_{-0.06}$$

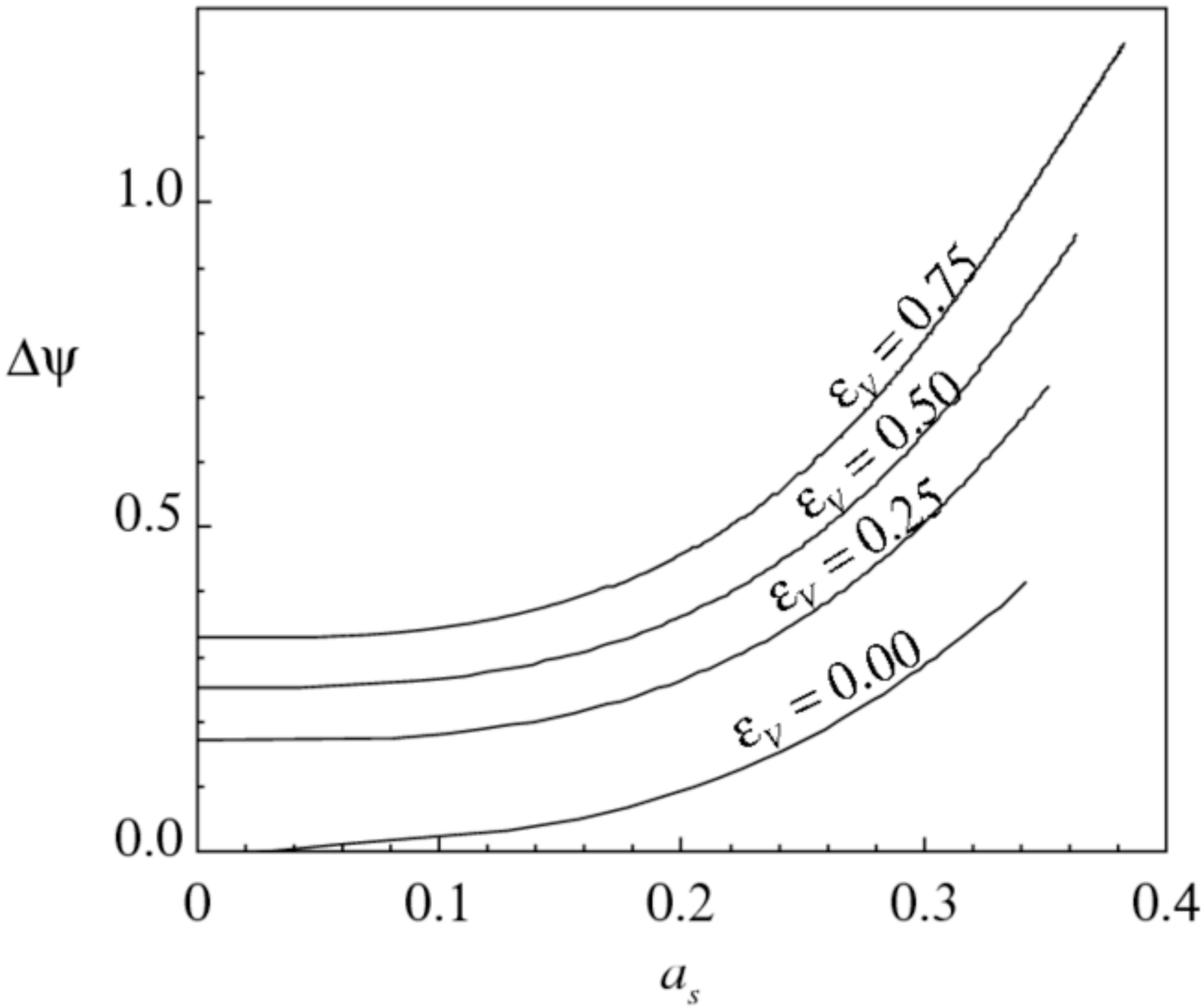


With thawing prior:

$$\epsilon_s = -0.08^{+0.29}_{-0.27}$$



the quintessence field is below the reduced Planck mass



INFLATION NOW

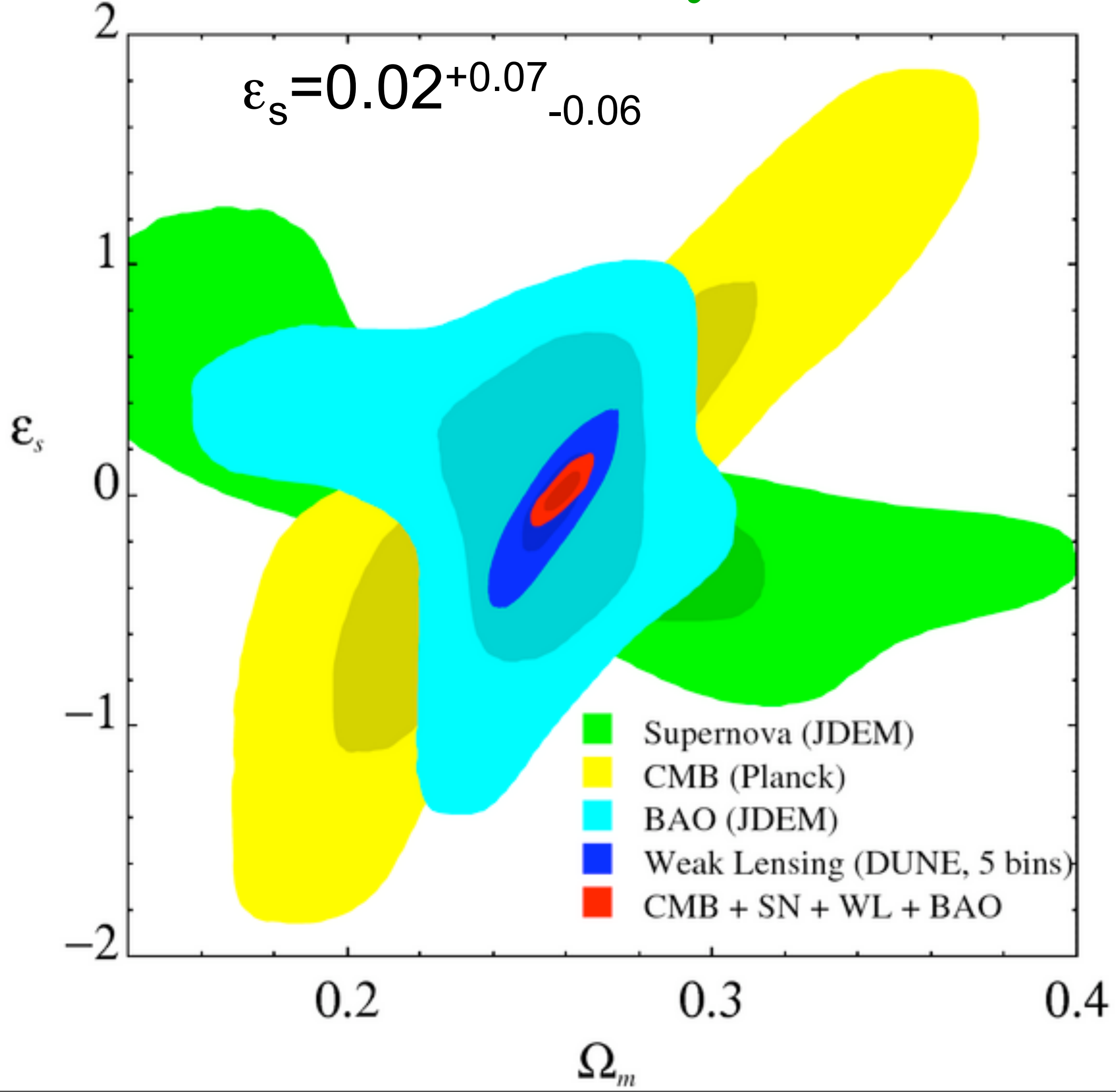
PROBES THEN

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/min²) + Planck1yr

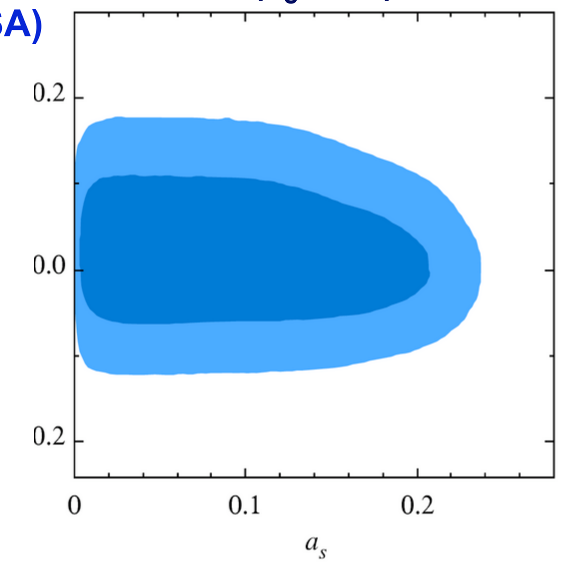
ESA (+NASA/CSA)

$\varepsilon_s=0.02^{+0.07}_{-0.06}$

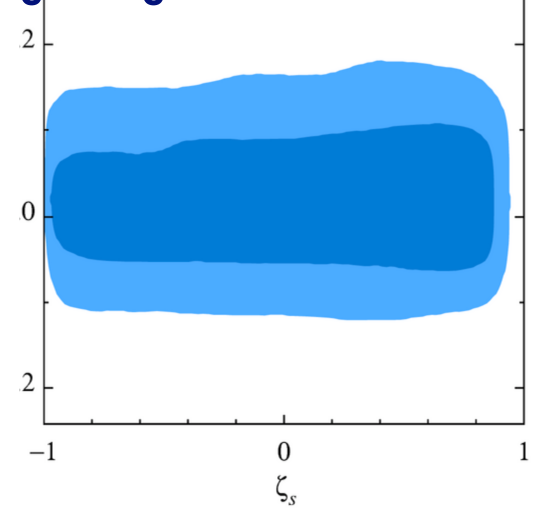


$a_s<0.21$ (95%CL)

($z_s>3.7$)



ζ_s ($\sim d\varepsilon_s/d\ln a$) ill-determined



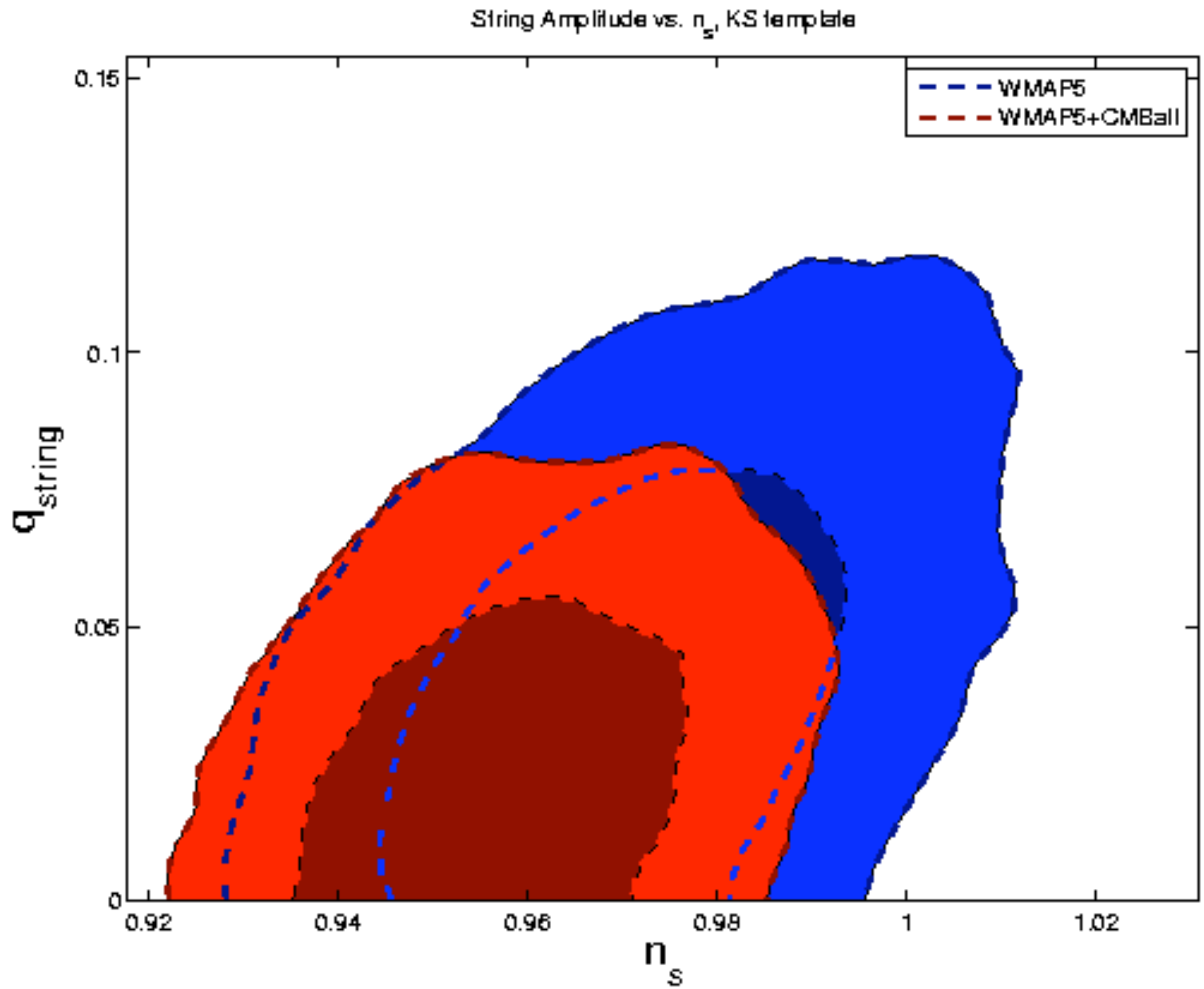
Inflation now summary

- 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 HBK07: 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 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 $\Omega_Q(a)$ at z_dec and z_bbn
- For general slow-to-moderate rolling one needs 2 "dynamical parameters" (a_s, ε_s) & Ω_Q to describe w to a few % for the not-too-baroque w-trajectories. A 3rd param ζ_s, ($\sim d\varepsilon_s/d\ln a$) is ill-determined now & in a Planck1yr-CMB+JDEM-SN +DUNE-WL future.
- $1+w(a)=\varepsilon_s f(a/a_{\Lambda eq};a_s/a_{\Lambda eq};\zeta_s)$
- ?? extension to $\varepsilon_s<0$ – phantom energy, eg negative kinetic energy

- In the early-exit scenario, the information stored in a_s is erased by Hubble friction over the observable range & w can be described by a single parameter ε_s.
- a_s is < 0.33 current data ($z_s>2.0$) to <0.21 ($z_s>3.7$) in Planck1yr-CMB+JDEM-SN+DUNE-WL future
- current observations are well-centered around the cosmological constant $\varepsilon_s=-0.06\pm0.20$
- in Planck1yr-CMB+JDEM-SN+DUNE-WL future ε_s to ±0.07
- but one cannot reconstruct the quintessence potential, just the slope ε_s & hubble drag info
- late-inflaton field is < Planck mass, but not by a lot

END

COSMIC PARAMETERS NOW & THEN


String Amplitude vs. n_s, KS template
WMAP5
WMAP5+CMBall
0.15
0.1
0.05
0
0.92
0.94
0.96
0.98
1
1.02
q_{string}
n_s

The Parameters of Cosmic Structure Formation

Cosmic Numerology: aph/0801.1491 – our Acbar paper on the basic 7+; bchkv07

WMAP3modified+B03+CBIcombined+Acbar08+LSS (SDSS+2dF) + DASI (incl polarization and CMB weak lensing and tSZ)

n_s = .962 +- .014 (+-.005 Planck1)

.93 +- .03 @0.05/Mpc run&tensor

$r = A_t / A_s < 0.47_{cmb}$ 95% CL (+-.03 P1)

<.55 CMB+LSS ε prior 5-pivot B-spline

< .22 CMB+LSS ln ε prior 5-pivot B-spline

$dn_s / d\ln k$ = -.04 +- .02 (+-.005 P1)

CMB+LSS run&tensor prior change?<#(1-n_s)

f_{NL}=87+-60?! (+-5-10 P1)

A_s = 22 +- 2 x 10^{-10}

1+w = 0.02 +/- 0.05

'phantom DE' allowed?!

$\epsilon_s = 0.00^{+0.20}_{-0.24}$ +-.07 then

$\Omega_b h^2$ = .0226 +- .0006

$\Omega_c h^2$ = .116 +- .005

Ω_Λ = .72 +.02- .03

h = .704 +- .022

Ω_m = .27 + .03 -.02

z_{reh} = 11.7 +2.1- 2.4

The Parameters of Cosmic Structure Formation

Cosmic Numerology: wmap5+acbar08 wmap5

n_s = .964 +- .014 (+-.005 Planck1)

$r=A_t / A_s$ < 0.54cmb 95% CL (+-.03 P1)

<

<

dn_s /dln k=-.048 +- .027* (+-.005 P1)

WMAP5+ACBAR08 run&tensor

A_s = 24 +- 1.1 x 10^{-10}

-9< f_{NL} <111 (+- 5-10 P1)

$\Omega_b h^2$ = .0227 +- .0006

$\Omega_c h^2$ = .110 +- .005

Ω_Λ = .74 +.03- .03

h = .72 +- .027

Ω_m = .26 + .03 -.03

z_{reh} = 11.0 +1.5- 1.4