Quintessential Relaxation of Hubble Puzzle

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Hubble Discrepancy Important

Era of precision cosmology

- Detailed measurements
  - CMBR, BAO, SN, local (GAIA),…
- ΛCDM works incredibly well
- New physics can show up only in small deviations
    - Or on unexplored scales
  - Many glitches will go away
  - But worth paying attention to
  - As a model builder have to ask what it could mean
  - And how should we look further
- Hubble discrepancy direct probe of late time cosmology
  - Reason we do these measurements: does model work?
  - Or is there something we are missing?
- Whether or not it remains, an opportunity to find what we learn from more detailed measurements
- And to think about which measurements could be useful in the future

In Brief: Measurements and Parameters

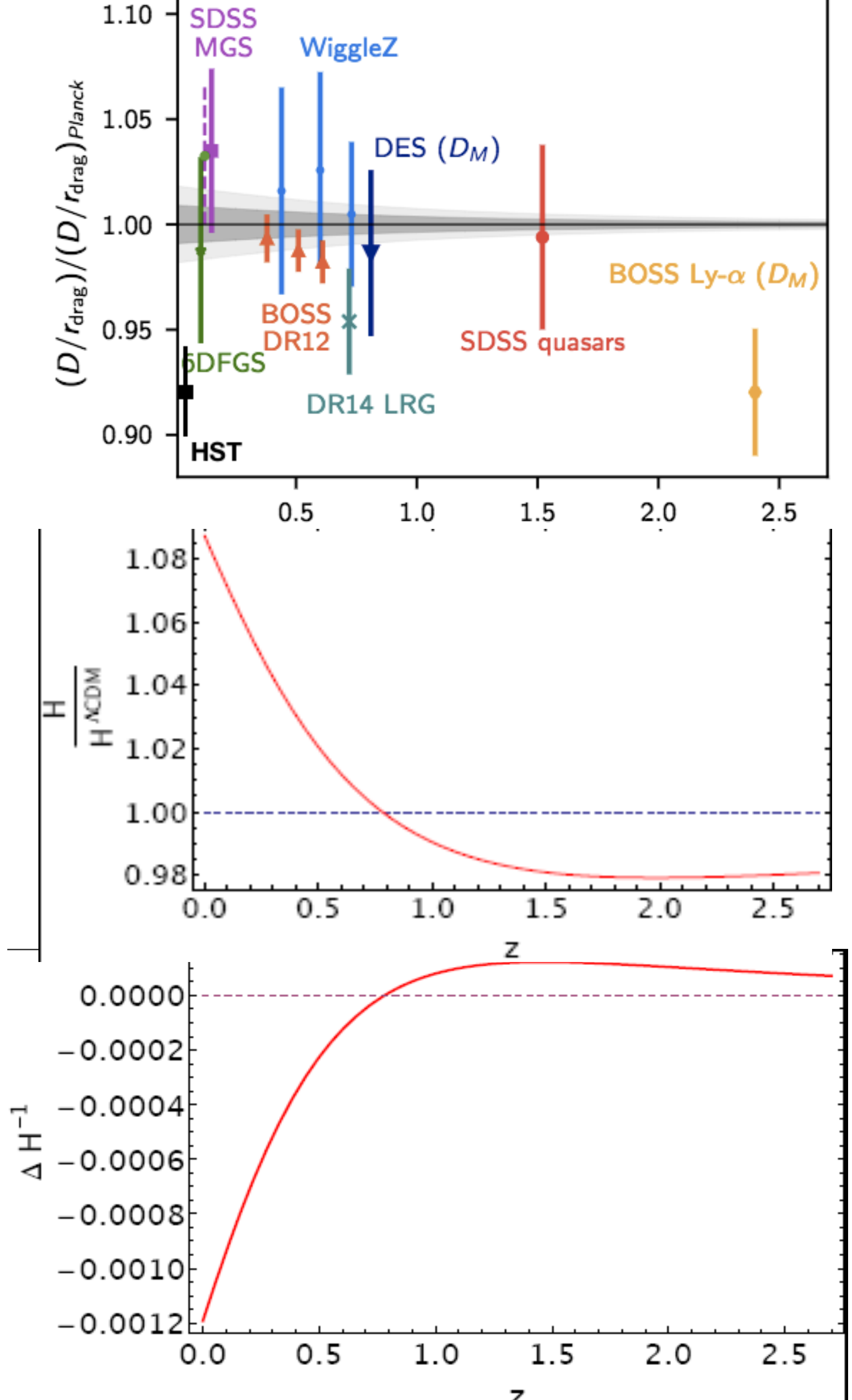
- Measurements:
  - CMBR: Planck
  - BAO: BOSS,…
  - Lensing (Planck,…)
  - SN: SHoES, (JLA, PANTHEON)
    - H_0=73.24 +/- 1.74 km/sec/Mpc
    - Vs Planck with ΛCDM H0=68.29 +/- .49 (TT, lensing, BAO, ShoES)
    - Planck (TT, pol, lensing, BAO) 67.66 +/-.42

- When fitting: CMBR Extremely Well-Measured Parameters: drives fits
- BAO, H0 measurements tugs
- But any model has to accommodate:
  - $z_{\_eq}$
  - $\theta_S = r_{\_s}/D_{\_A}$ ***drives a lot for us
  - $\theta_D = r_{D(amping)})/D_A$ "CMB"Diffusion in High l modes
  - ρ_b/ρ_{DM} amplitude odd vs even peaks
  - Also (BAO) $\theta_{d(rag)}$-=r_d/D_A ***drives also

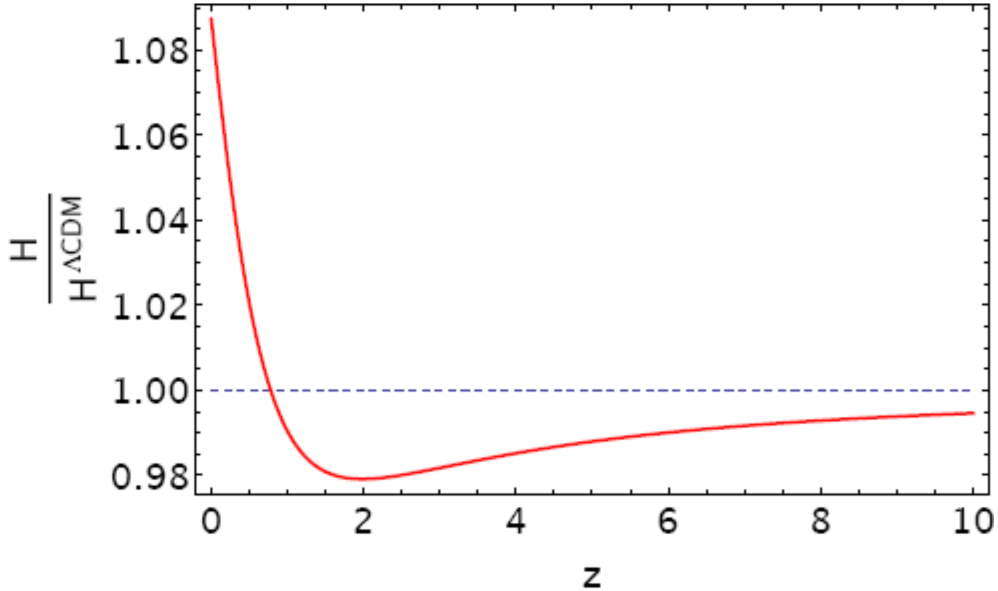
What does large $\mathbf{H_0}$ for fixed angular size of **sound horizon** at recombination (and BAO) tell us?

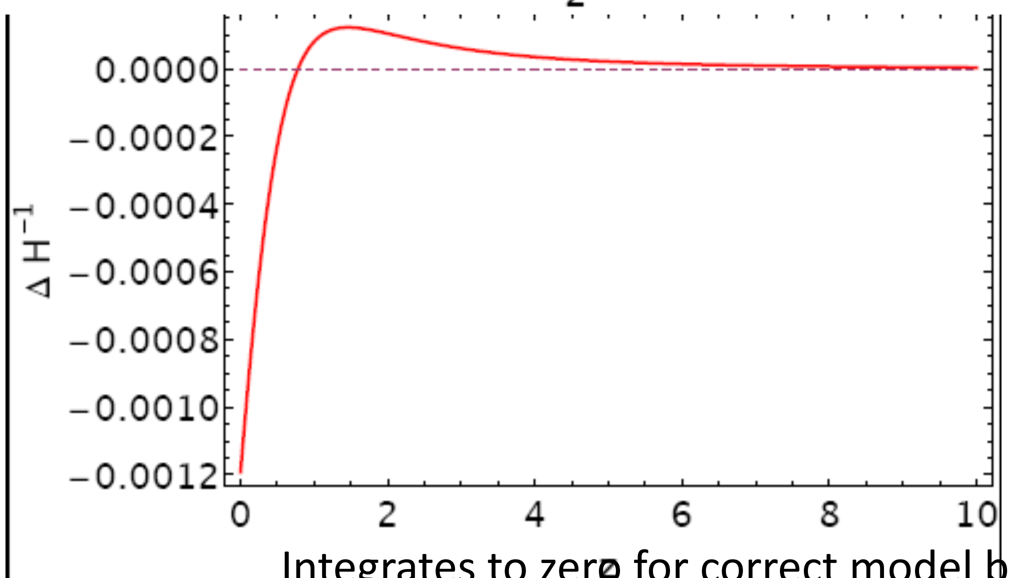
- Fixed $\theta_s \equiv \frac{r_s(z_*)}{D_A(z_*)}$ $r_s \equiv \int_0^{a_*} \frac{c_s da}{a^2 H(a)}$ $D_A \equiv a_* \int_{a_*}^1 \frac{da}{a^2 H(a)}$.
  - If you don´t change r_s (change H before or around CMB)
  - Need to balance + and - changes in H
    - so that D_A stays at same value
  - This can work
    - But BAO would then generally changes if r_D fixed
  - For most models you can raise H at one time and lower at another (eg decaying dark matter, N_{eff})
    - But one turnaround point as function of z
    - Can be hard to accommodate more than 2 data points (diff z)
  - Will see can only work to some extent because θ_d from BAO is a bit higher than ΛCDM predicts

Schematic: Try to change D_A
By changing H_0
Also changes D_A BAO
But in right direction
This is made up
Can't get both to work



Required Behavior (Toy)





Integrates to zero for correct model but wont' work for both CMB and BAO

How Do We See This in a Model?

- Why Model?
- Model allows you to see full effect
  - Background cosmology H(z), w(z)
  - But also Fluctuations

- General spline for H(z) or w(z) useful
- But don’t necessarily get model-independent bounds
  - Bound really can depend on many parameters to implement the spline
  - Generally affects details, not only background cosmology
- And of course you want to know the physics
  - Model gives idea how parameters can be implemented

Some "models" proposed so far

- Late time models
  - Change after z_{eq}, z_{rec}
- Converting non-relativistic dark matter to radiation (decaying DM) Bringmann, Kahlhoefer, Schmidt-Hoberg, Walia

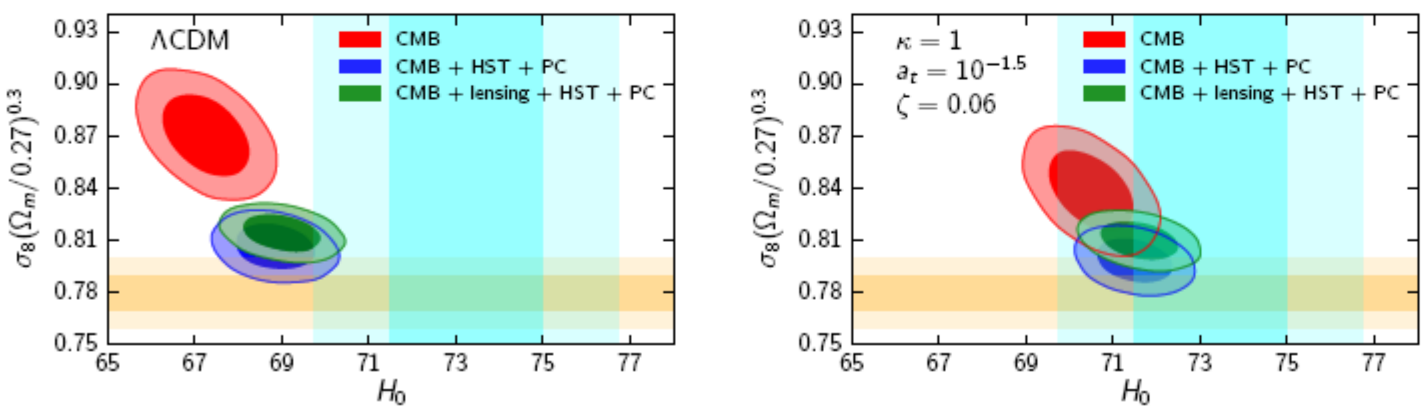
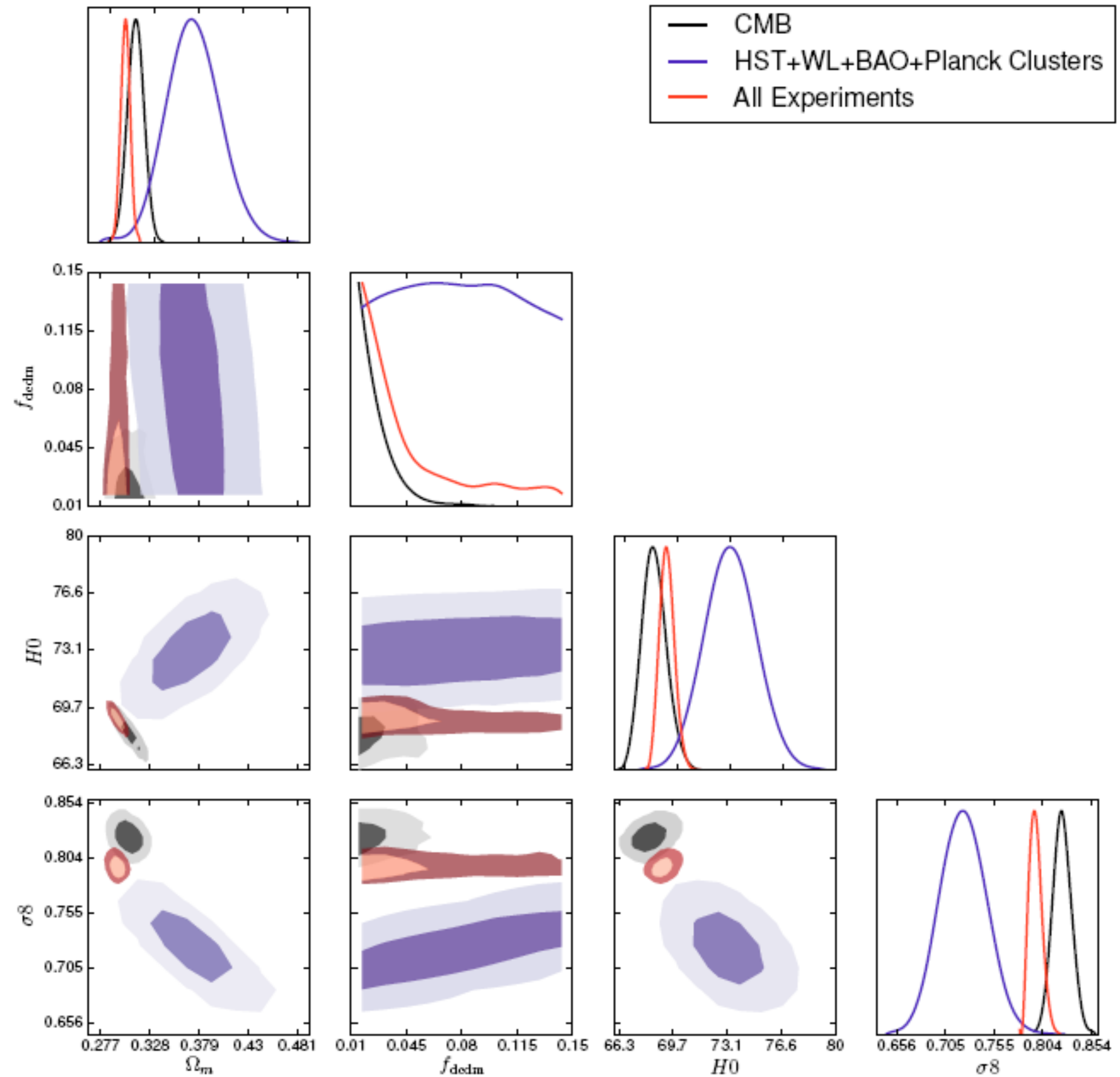


FIG. 8. Best fit regions for ΛCDM (*left panel*) and our model with $\kappa = 1$, $\zeta = 0.06$ and $a_t = 10^{-1.5}$ (*right panel*). The orange and cyan bands indicate the direct measurements of $\sigma_8(\Omega_m/0.27)^{0.3} = 0.78 \pm 0.01$ [55] and $H_0 = 73.24 \pm 1.74$ [49] respectively.

Mechanism?

- Work by trading off matter against dark energy to keep D_A fixed at CMB
- Lower energy density during matter domination; lower H
- Then more energy due to greater dark energy at CC domination
  - Dark energy “replacing” matter for same H_0 leads to smaller H at all earlier times implying larger D_A
  - To avoid this need to have larger H_0
  - Requisite negative and positive changes to H

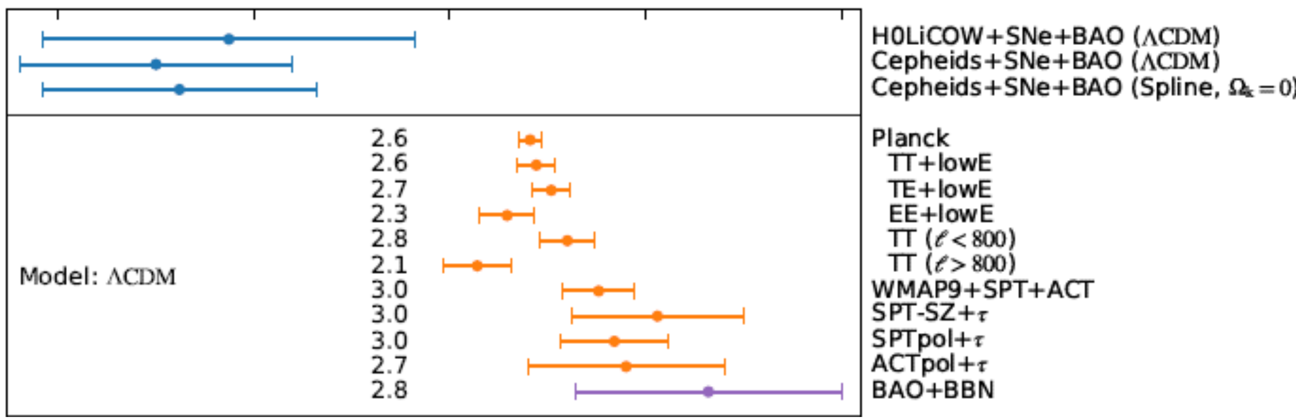
- This paper didn’t include BAO
- You can’t fix both without an extra lever



Vivian Poulin,[a,b] Pasquale D. Serpico,[a,b] Julien Lesgourgues[b]

No ONLY late time model works

Kevin Aylor,[1] Mackenzie Joy,[2] Lloyd Knox,[1] Marius Millea,[3,4,5] Srinivasan Raghunathan,[6,7] and W. L. Kimmy Wu[8]



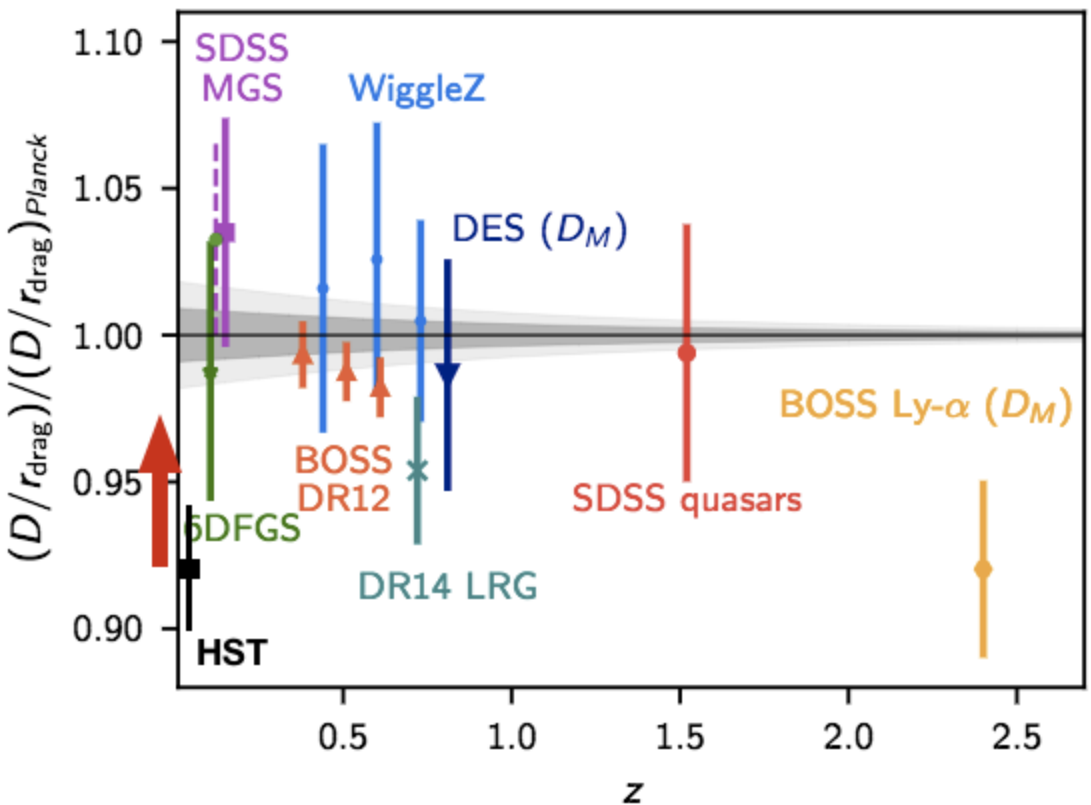
H determined by Reiss and BAO disagrees with value from Planck

Alternatively fix rs from CMB and can't fit H from both BAO and Reiss

To Accommodate BAO

Need Extra lever at "early" time: r_s:

- Changing r_s makes it more feasible to accommodate both BAO and SHoES
- Extract bigger H values from CMB and BAO
- Easier to accommodate SHoES



Alternative: Early Time Models: just change r_s Early Dark Energy?

Vivian Poulin1 , Tristan L. Smith2 , Daniel Grin3 , Tanvi Karwal1 , and Marc Kamionkowski1

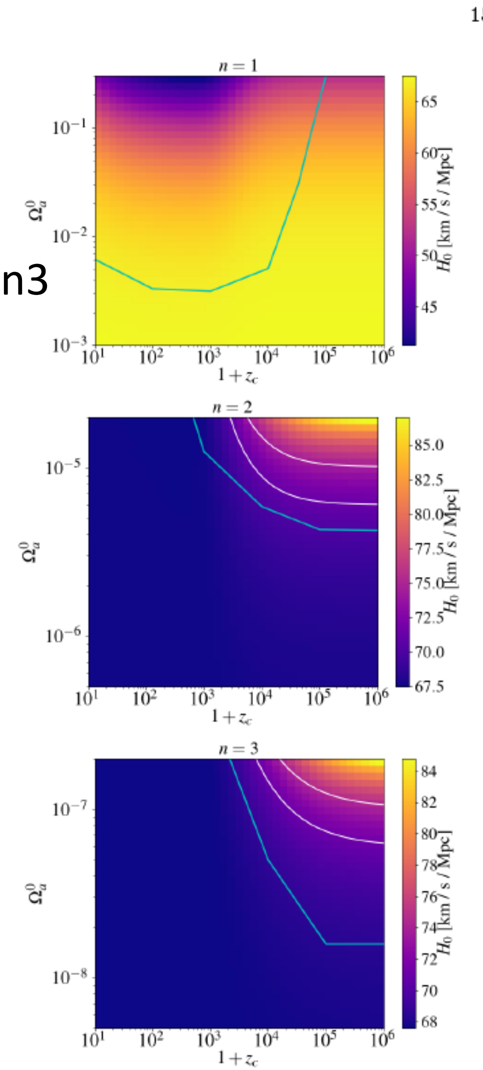
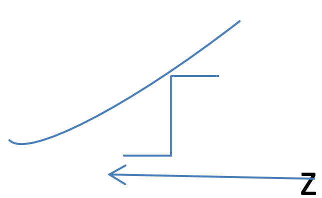


Figure 8: Hubble parameter H_0 for various values of Ω_a^0 and z_c, for the $n = 1$ (top panel), $n = 2$ (middle panel) and $n = 3$ case (bottom panel). The cyan line represents the constraints shown in Fig. 6. The white contours show the 1σ contour on the H_0 value measured by SH0ES.

- Early dark energy to raise H and hence sound horizon
- Rapid elimination
- Potential of form

$$V_n(\phi) = \Lambda^4(1 - \cos\phi/f)^n,$$

- But not enough change in H for any n
- Best is n=2
- CMB rules out model for ShoES values
- Energy vs z



Early Time Models: N_{eff}

- Zeq In ΛCDM, this is $\frac{\rho_{m,0}}{\rho_{\text{rad},0}} - 1$.
  - Change radiation and DM
  - Both can contribute to changing rs
    - Radiation ha sound speed1/
    - Interacting radiation has sou
    - Zero sheer from interactions

Manuel A. Buen-Abad and Martin Schmaltz*

Parameter mean values and 68%CL confidence interval (or 95%CL upper limit), lin. priors			
Parameters	ΛCDM	WI limit	DP limit
$100\omega_b$	$2.245^{+0.013}_{-0.014}$	$2.249^{+0.018}_{-0.019}$	$2.242^{+0.017}_{-0.019}$
n_s	$0.9656^{+0.0038}_{-0.0037}$	$0.9708^{+0.0044}_{-0.0041}$	$0.9701^{+0.0038}_{-0.0042}$
τ_{reio}	$0.04887^{+0.008}_{-0.008}$	$0.05915^{+0.0082}_{-0.0078}$	$0.06118^{+0.0093}_{-0.0086}$
H_0	$68.67^{+0.41}_{-0.46}$	$70.01^{+1.1}_{-1.2}$ (95% CL: 72.21)	$69.13^{+0.76}_{-1.3}$ (95% CL: 71.32)
$\ln 10^{10} A_s$	$3.023^{+0.015}_{-0.015}$	$3.05^{+0.017}_{-0.017}$	$3.056^{+0.022}_{-0.019}$
$\omega_{\text{dm}}^{\text{tot}}$	$0.1168^{+0.001}_{-0.00089}$	$0.126^{+0.0032}_{-0.0039}$	$0.1235^{+0.0017}_{-0.0033}$
ΔN_{fluid}	0	$0.369^{+0.17}_{-0.19}$ (95% CL: ≤ 0.6657)	≤ 0.5064 (95% CL)
$10^7\Gamma_0$	0	$1.097^{+0.32}_{-0.32}$	$\Gamma_0 \gg H_0$
f	0	1	$0.01387^{+0.0052}_{-0.0046}$
$100\theta_s$	$1.042^{+0.00028}_{-0.0003}$	$1.043^{+0.00035}_{-0.00037}$	$1.043^{+0.00036}_{-0.00038}$
σ_8	$0.7933^{+0.0052}_{-0.0054}$	$0.7721^{+0.01}_{-0.01}$	$0.7734^{+0.011}_{-0.012}$
Ω_m	$0.2968^{+0.0057}_{-0.0053}$	$0.3043^{+0.0067}_{-0.0053}$	$0.3067^{+0.0074}_{-0.007}$

TABLE III: Parameter mean values and 68%CL confidence interval (or 95%CL upper limit), in the W and DP cases, with linear priors on all parameters.

Early Models

- Don’t get far enough with H
- Limited because CMBR well-measured!
- And you are messing with Universe near CMB time
  - Harder to pin down precise failure mode
  - Depends on details

Agrawal, Cyr-Racine, Pinner, Randall

New Model: automatically combines early and late time solutions

$$-\mathcal{L} \supset \frac{1}{2}(\partial_\mu \phi)^2 + \frac{1}{2}(\partial_\mu \chi)^2 + \frac{1}{2}m^2\chi^2\left(1 + y\frac{\phi}{M_{\rm pl}}\right) + V_\phi,$$

- Rolling scalar field Φ; X is dark matter
  - Motivated by quintessence models
  - Requisite dark energy at the end

$$V_\phi \equiv V_1 e^{-\lambda_1 \phi/M_{\rm pl}} + V_2 e^{-\lambda_2 \phi/M_{\rm pl}}.$$

- We choose large λ_1 to get tracker solution
- See Shinji Tsujikawa review
- y coupling changes dark matter mass
- Small λ_2 to get flat potential today—essentially cc at the end

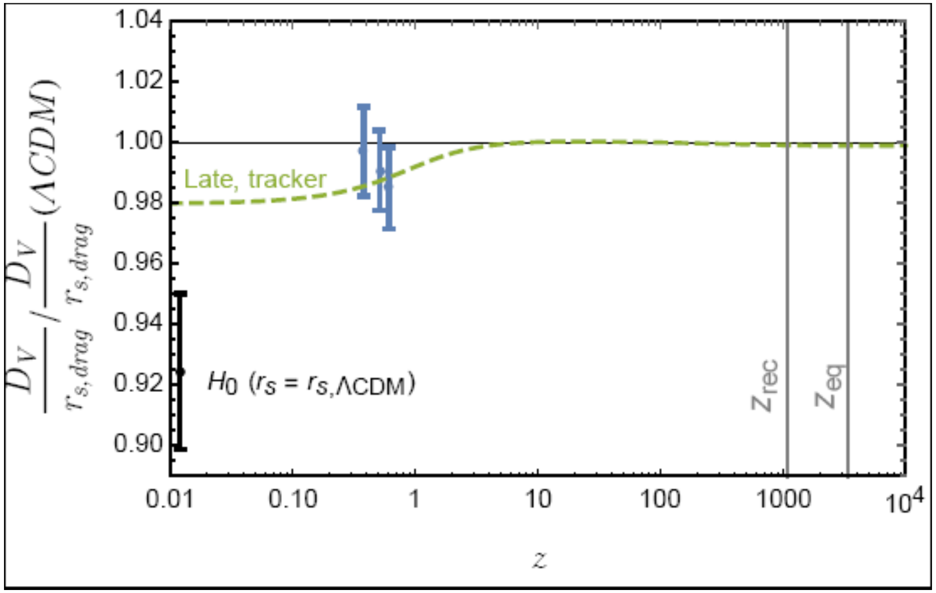
Scalar Model

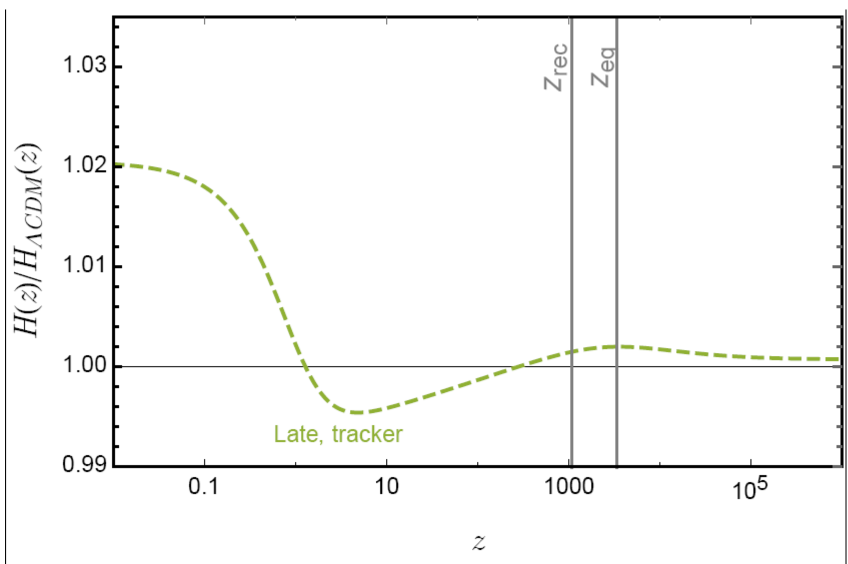
- Allows us to systematically investigate separate effects
- Tracker interesting in that it is like
  - Radiation early, matter intermediate, dark energy late
- Model automatically has ingredients in late and early universe
- Key to late time solution is removing dark matter between CMB and today (like decaying dm) but here by changing dark matter mass
- To keep D_A constant need additional dark energy
  - This is what raises H in the end
- At early time we have additional $V(\Phi)$ energy
- Will raise r_s
  - But only for low λ_1

Dark Matter (Late Time) Evolution

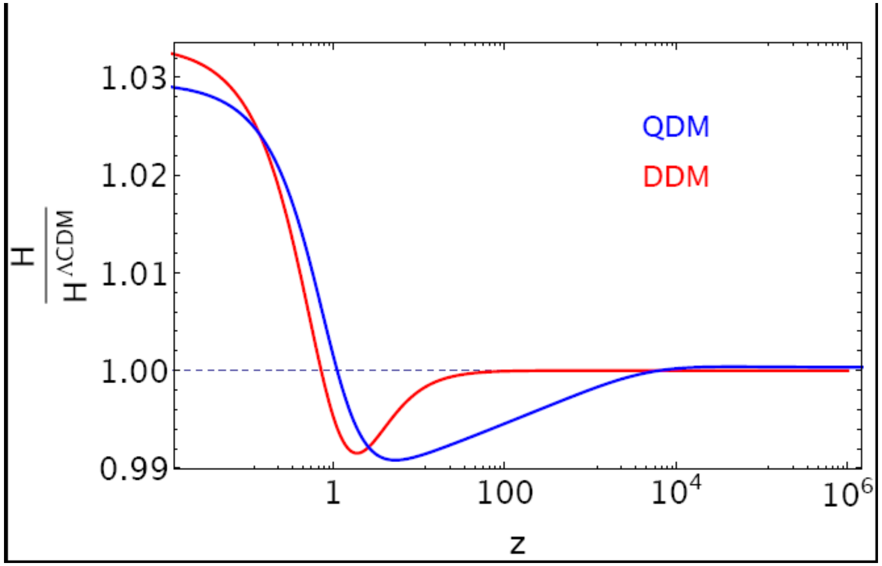
- Dark matter energy changes relative to ordinary model by
  - Late time evolution after CMB
- $y\ \Delta\Phi/M_p$
  - $\Delta\Phi$ will be from tracker solution
  - $\Delta\Phi$ from z_{eq} to z_0 is about
  - $25\ M_p/\lambda_1$
  - Net change (follows from tracker energy) $25\ y/\ \lambda_1$
  - Often about 8% in best fit
  - ~3% change to H

Late time (large λ_1 result)





Just late time similar to decaying dark matter



Good but not enough for SHoES

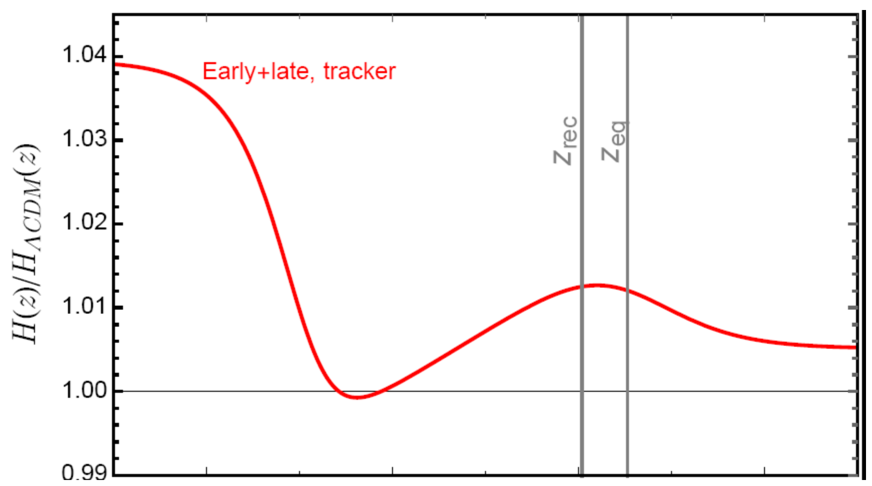
Adjust r_s: Add early time with small λ_1 Intuition on Tracker Solution

- Energy in Φ at early times
- $4/\lambda_1^2\ \rho$
- Early time: additional contribution to H
  - For sufficiently small λ_1 can get reduction in rs
- Automatically allows early AND late time modules
  - Seems to be necessary

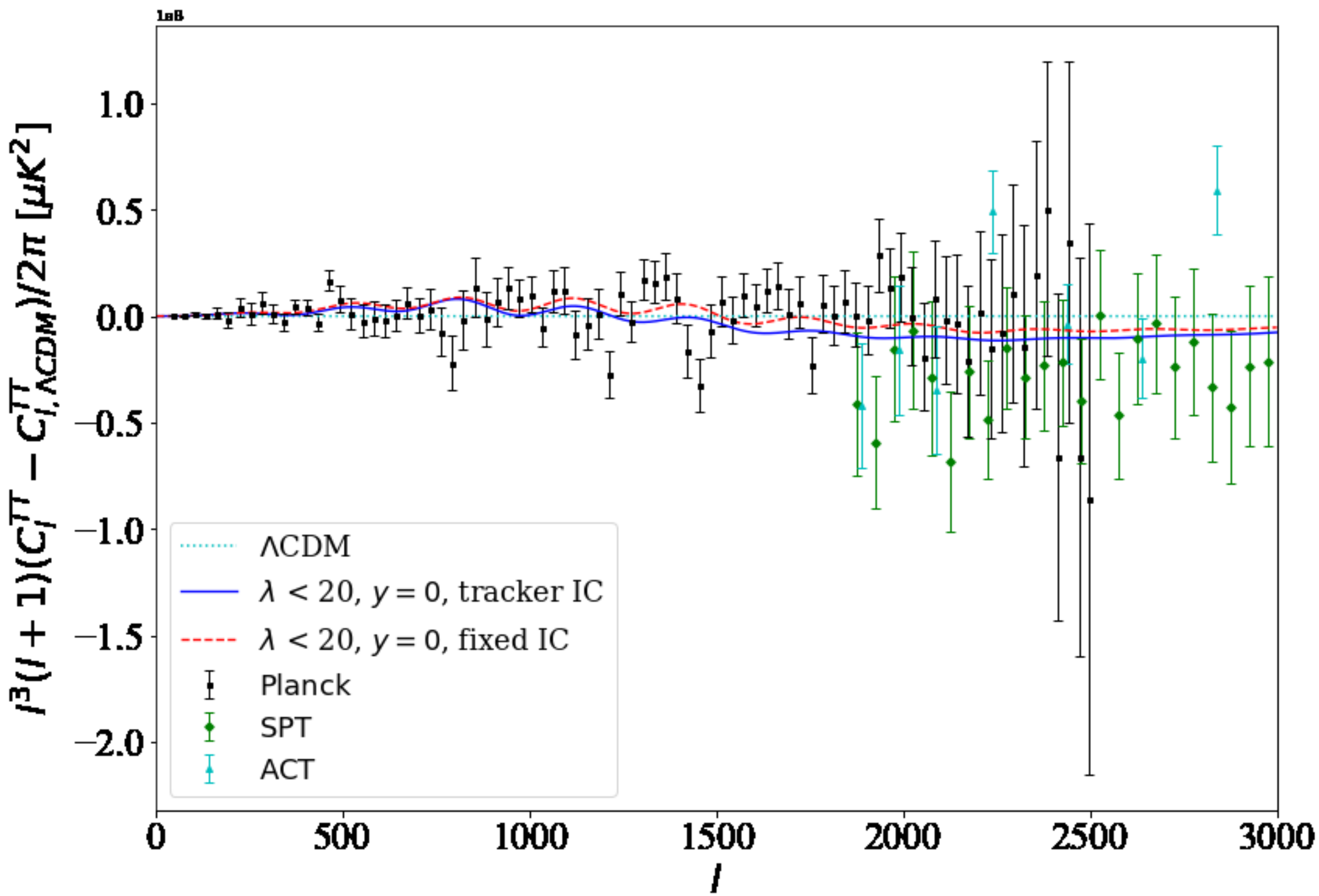
Turns out still not enough

- Early tracker stage tracking radiation
- Too much “radiation” in early stages
- Damps high l contribution

Early +Late Hubble

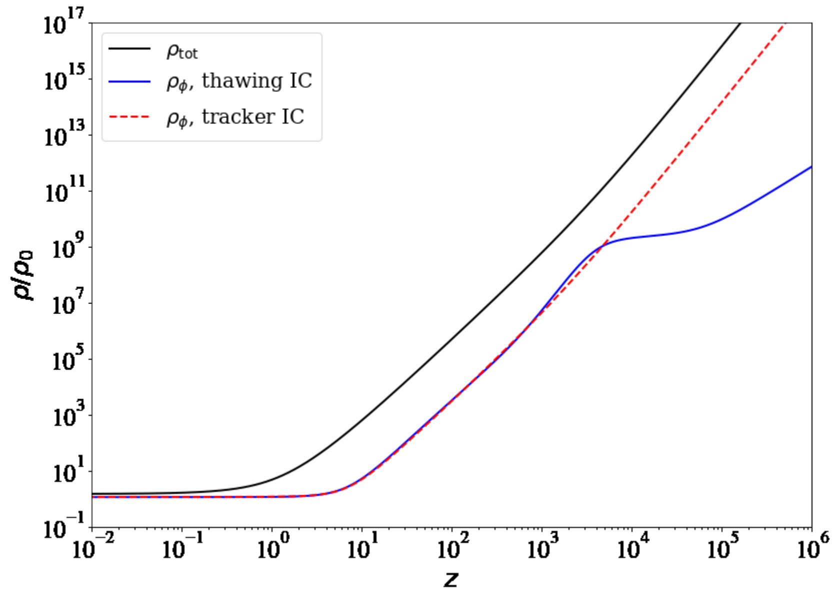


Insight?: CMB Residuals with fixed vs tracking ic

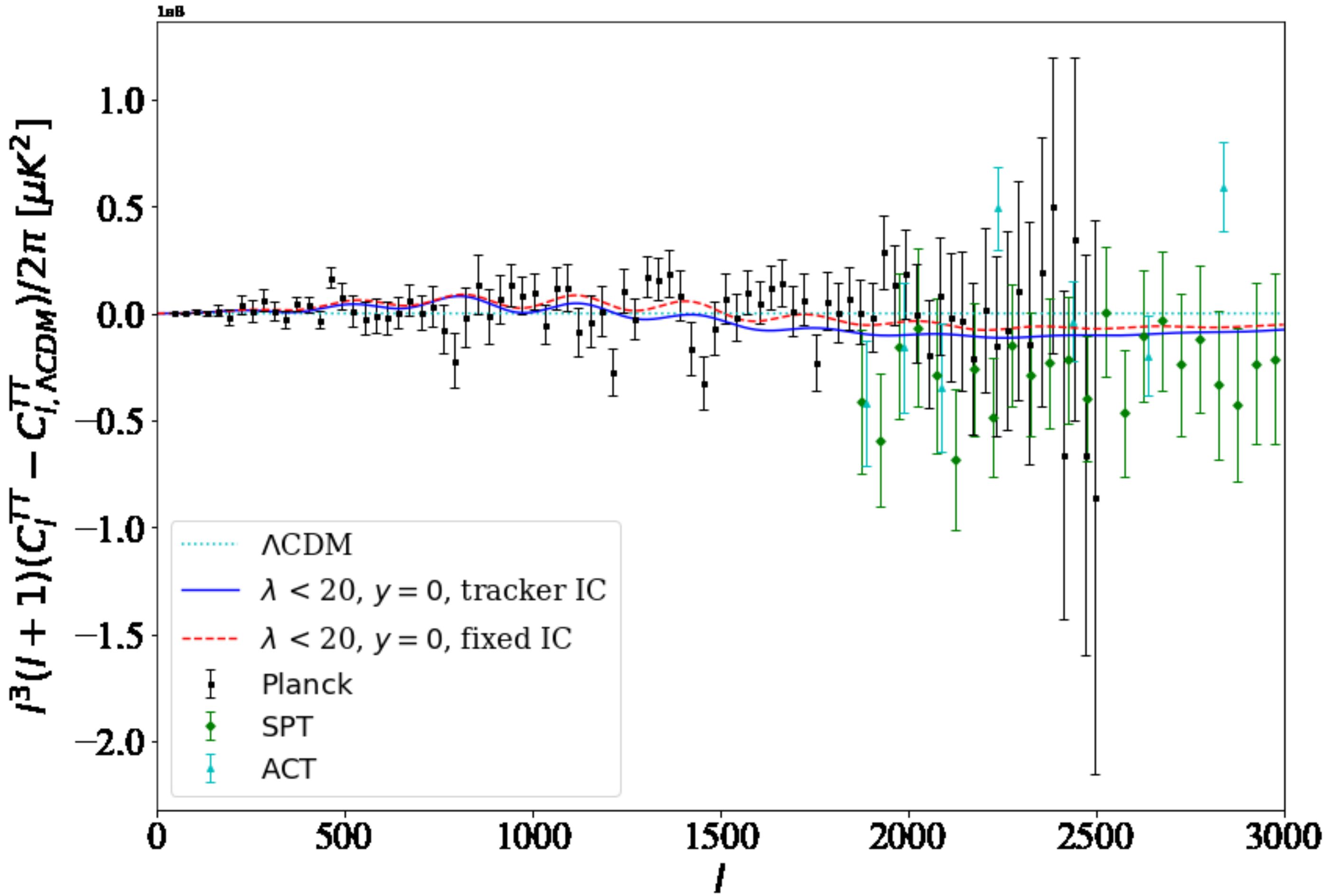


•Change initial condition: Tracker vs Tracker/Thaw

- Hope for better behavior at high l



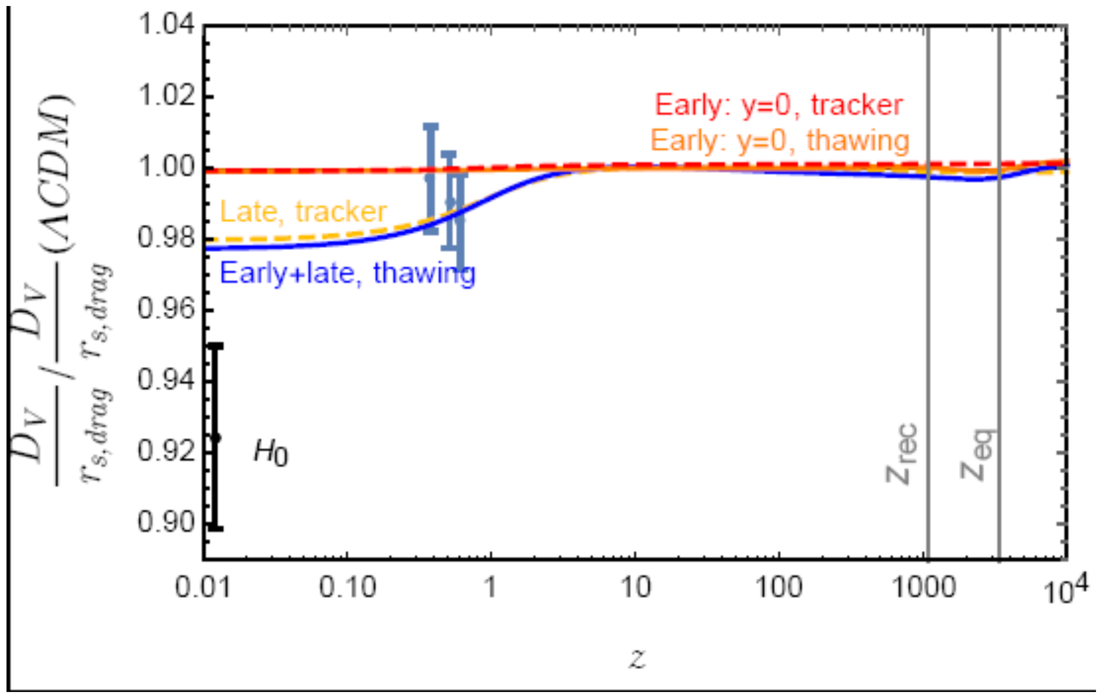
CMB Residuals with fixed vs tracking ic



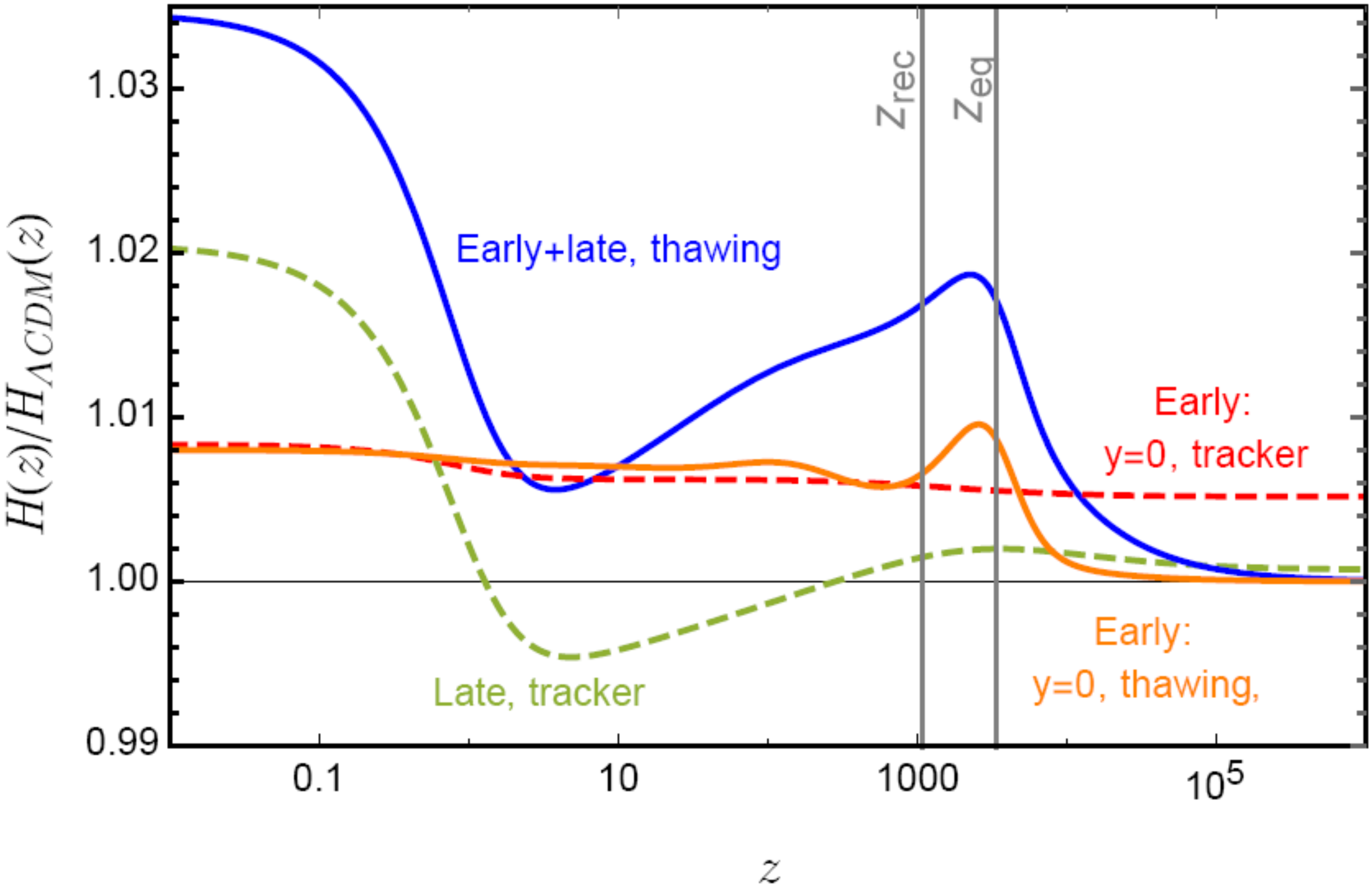
Best Implementation

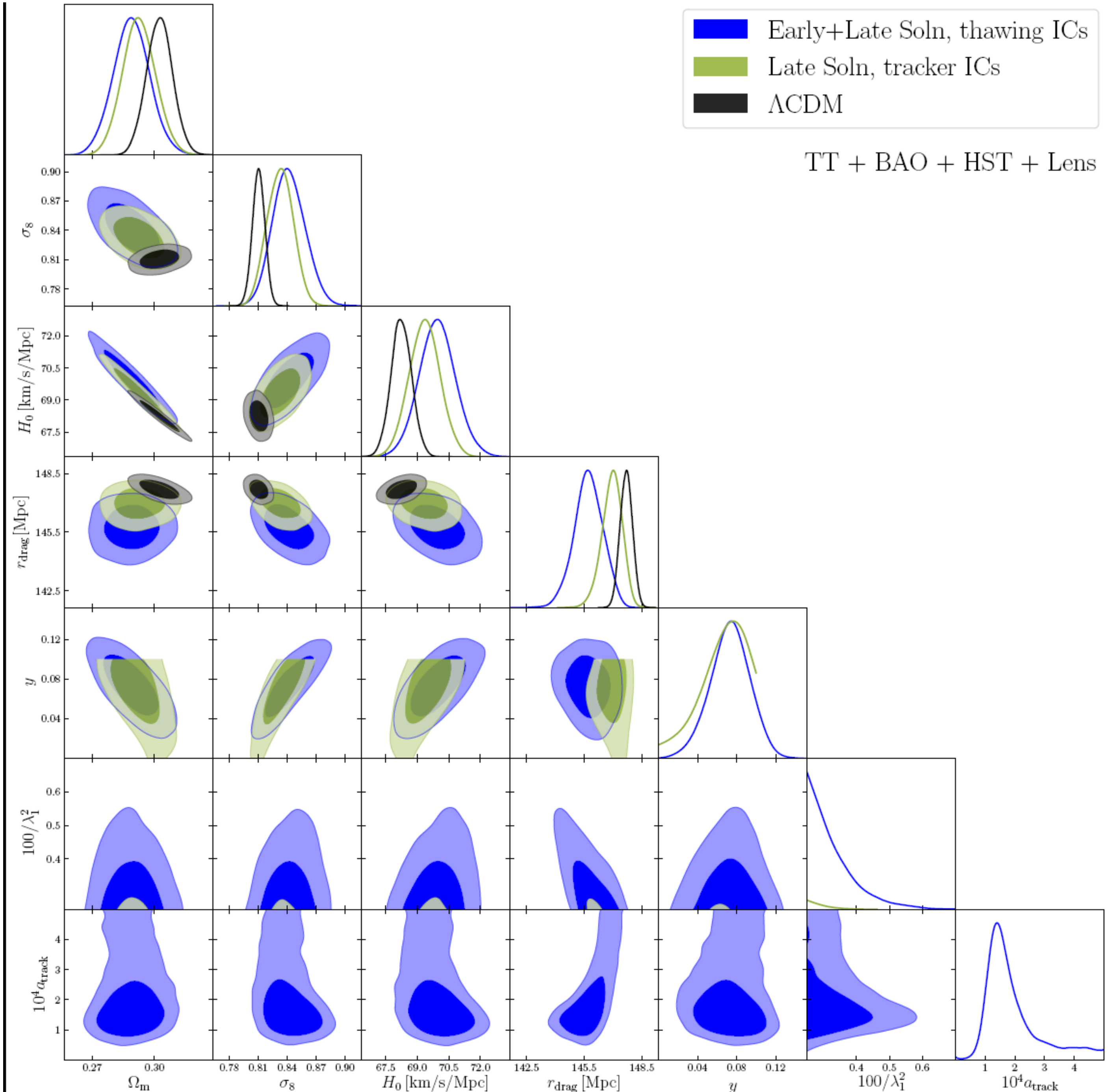
- Large enough y to get late time effect
- Small enough λ_1 to get early time effect
- Late enough tracker initial condition to save high l modes

Comparison
Early+Late Does Better on BAO



Early+Late+Thaw Does Best





Early+Late Soln, thawing ICs
Late Soln, tracker ICs
ΛCDM
TT + BAO + HST + Lens
σ_8
H_0 [km/s/Mpc]
$r_{\rm drag}$ [Mpc]
y
$100/\lambda_1^2$
$10^4 a_{\rm track}$
$\Omega_{\rm m}$

Seems CMB, BAO, H0 requires (at least) two modules

Early: rs

- Neff
- Decaying DE
- Extra "DM" (via Φ)

Late: DA

- Decaying DM ; Add DE
- Remove DM (via Φ) ; Add DE

- Extra "DM" (via Φ with ic)

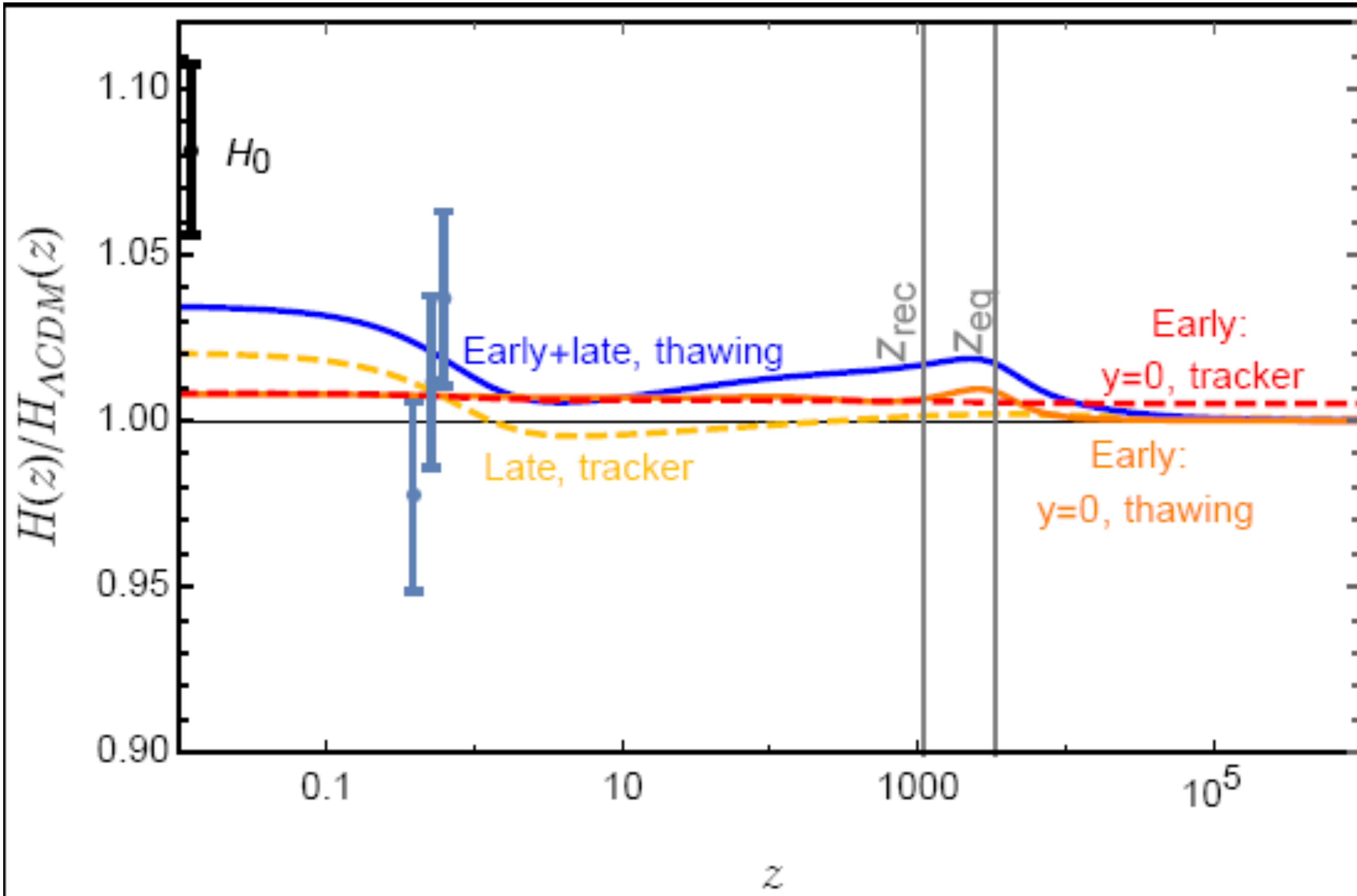
Probably our model better for Planck than Neff at high l
Less energy for given shift in rs which is IR dominated
Extra degrees of freedom suppressed by suppression of radiation contribution to H at CMB time
We have less damping high l tail
Sheerless like interacting Neff so less phase shift potentially too
Plus with ic extra radiation turned off for most high l modes

*Planck clusters artifically eleveated interacting Neff goodness of fit

Model somewhat better at high l (especially with polarization data)

Model	LCDM	LCDM+Neff	Vary IC, 10 < Lambda < 20
(Delta) chi^2	11084.19	-1.8	-1.18
-Planck low l	10494.84	-0.66	1.59
-Planck high l TTTEEE lite	566.67	4.64	1.85
-Planck lensing	9.22	0.3	0.22
-HST	9.02	-5.76	-6.23
-BAO	3.56	-0.04	1.07
-simlow (tau_r)	0.87	-0.27	0.34
H0 (best fit)	68.01	70.1	70.33
H0 (95% CL)	68.82	72.36	71.59
Omega_m	0.305	0.302	0.286
sigma_8	0.812	0.828	0.848
lambda_1			20
y			0.077
z_track			9260
dNeff		0.435	

All Vairiants: still not quite there…



Conclusion

- Discrepancy hard to resolve
  - An awful lot is measured
  - It is difficult to change late time universe in an acceptable way
  - In my experience “too good to be true” is usually not true
- Our model does (at least) as well as any
  - And sheds light on issues
- Could be a discovery of *late time evolution
  - *late includes at or near CMB
- Which of course would be very exciting
- This will be resolved in future:
  - Gravity wave measurements of H
  - Lensing measurments
  - Improved BAO measurements
    - Especially if gets rs as well
  - H(z) from SN eg Pantheon constraining more
  - w(z) measurements !!
    - Models give different energy domination time
  - Release of Planck 2018 will help too
- Hard to reconcile most extreme values: sound speed? Perturbation spectrum?
- Interesting to see what happens with furhter low z measurmeents
  - Not just CMBR dominated
  - Clearly a tradeoff—no perfect match
- Our only ways to explore the late time universe
- Let’s make the most of it