Resolving Cosmological Tensions with Unparticles

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"Tensions in Cosmology" Workshop
Corfu, September 2023

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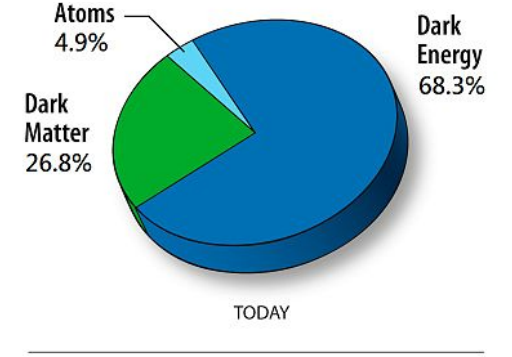
1912.10532, 2010.20998, 2111.09946, 2302.00067+WiP

Outline

- Introduction
- Beyond the scalar field paradigm
- Banks-Zaks Cosmology
- Emergent Unparticles DE Model and the tensions
- Phenomenological fluid approach (WiP)
- Conclusions

COSMOLOGY CRASH SLIDE



- Consider the FLRW metric with no spatial curvature. Define the critical density

$$\rho_c = \frac{3H_0^2}{8\pi G}, \quad \Omega_{0i} = \frac{\rho}{\rho_c}, \quad w_i = \frac{p_i}{\rho_i}, \quad EOS$$

$$H(z)^2 = H_0^2 \sum_i \Omega_{0i}(1+z)^{3+3w_i}, \quad \dot{H} = -H_0^2 \sum_i \frac{3+3w_i}{2}\Omega_{0i}(1+z)^{3+3w_i}$$

- For z<3400 (equality of matter and radiation), equations simplify further:

$$H(z)^2 \simeq H_0^2 \left[\Omega_{m0}(1+z)^3 + 1 - \Omega_{m0}\right], \quad \dot{H} \simeq -\frac{3}{2}H_0^2\Omega_{m0}(1+z)^3$$

- LCDM model ~1% accuracy (CMB) $H_0 = 67.4 \pm 0.5, \quad \Omega_{m0} = 0.315 \pm 0.007$

$$H_0, \Omega_b, \Omega_c, \tau, \sigma_8, n_s; \quad \Omega_{m0} = \Omega_b + \Omega_c; \quad \Omega_{m0} + \Omega_{\Lambda 0} = 1$$

Fundamental Problems in Cosmology

- Big Bang Singularity - Artymowski, IBD, Kumar JCAP 2019 +WiP.
- Early Universe - Inflation/Bounce? Which model? Connection with SM Artymowski, IBD, Thattarampilly JCAP 2020, IBD, Thattarampilly 2308.00256
- Nature of present acceleration - CC? Dark Energy? Modified gravity? Which model?

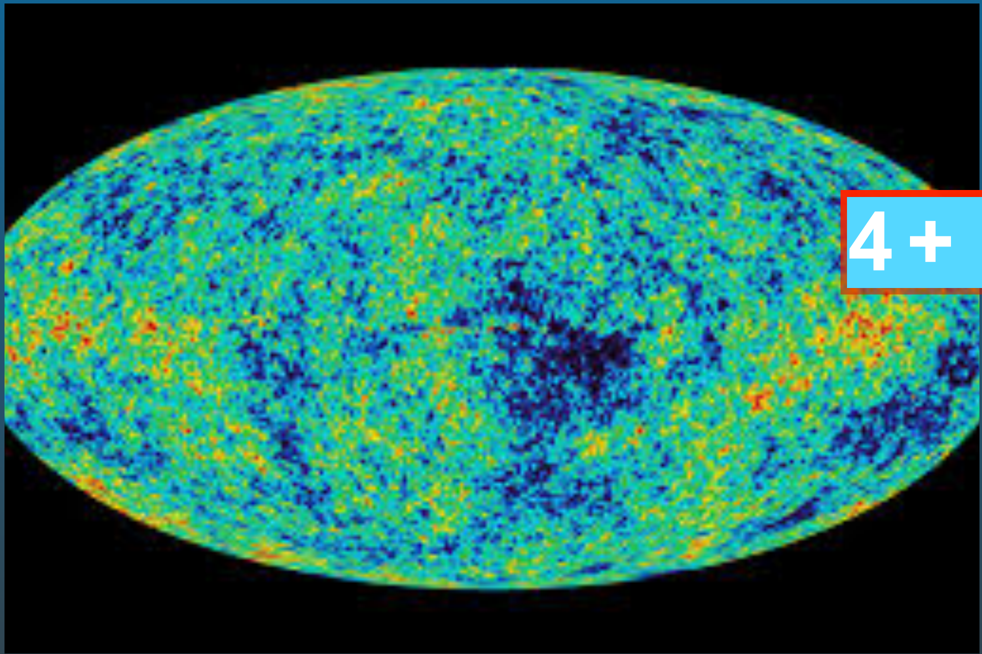
Scalar Fields!

- Nature of Dark Matter

- The Hubble Tension
- The LSS (S_8) Tension

- H_0 is the most important cosmological measurement and is relevant for fundamental physics as well.

z>1



$$H_0 = 67.4 \pm 0.5\, km/sec/Mpc$$
$$H_0 = 67.4 \pm 1.2\, km/sec/Mpc$$

4+ SIGMA!

z<1

$$H_0 = 73 \pm 1\, km/sec/Mpc$$

69.8+-1.9
73.6+-3.9
73.3+-1.8
74.8+-3.1
76.5+-4.0

THE LSS S_8 TENSION

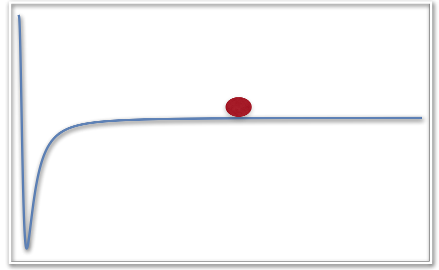
- Measurements of matter fluctuations on large scales is given by $S_8 = \sigma_8 \sqrt{\frac{\Omega_{m0}}{0.3}}$

2-3 SIGMA!

- σ_8 are the linear matter fluctuations smoothed over 8h Mpc
- Ω_{m0} is the relative matter energy density.
- CMB (Planck measurement) $S_8 = 0.834 \pm 0.016$
- (Also KiDs …) DES $S_8 = 0.776 \pm 0.017$

Most attempts to reduce one tension result in increasing the other!

SCALAR FIELDS IN COSMOLOGY



- Daily practice in theoretical physics T(t,x)
- A single DOF, with a flat potential - everyone can do that!
- Abundant in String Theory and extensions of the SM
- Fine-tuned models? organizing principle?
- Field Theory is much richer - confinement, strong interactions, topological defects, conformal symmetry…
- The Swampland Conjecture - in QG potentials are steep (see however, IBD, PRD 2018 "Draining the Swampland")

$$\Delta\phi \lesssim 1, \quad \frac{V'}{V} \gtrsim 1 \quad OR \quad \frac{V''}{V} \gtrsim 1$$

PROBLEMS WITH PRESENT ACCELERATION (CC/DE)

- CC is the simplest parametrization of the observed acceleration
- The CC is related to zero point vacuum fluctuations of fields and respects Lorentz inv., for a cutoff M, we expect $\rho_\Lambda \sim M^4$
- For any fundamental energy scale M, we find a CC much smaller than expected - *The Cosmological Constant Problem*
  $\rho_\Lambda^{\text{obs.}} \sim 10^{-10}\text{erg/cm}^3, \quad M_{QCD} \sim 10^{36}\text{erg/cm}^3, \quad M_{EW} \sim 10^{47}\text{erg/cm}^3, \quad M_{pl} \sim 10^{110}\text{erg/cm}^3.$

WHY NOW?

- Energy Density of matter ~ a^{-3}, radiation ~ a^{-4}, CC ~a^{0}.
- Completely different scaling which is why we had a radiation dominated universe followed by after domination.
- Why do we have today $\frac{\rho_m}{\rho_\Lambda} \sim 1$?
- Requires fine-tuned initial conditions in the early universe. Especially for scalar fields.

BEYOND SCALAR FIELDS IN COSMOLOGY

- Daily practice in theoretical physics T(t,x) ✓
- ~~A single DOF, with a flat potential - everyone can do that!~~
  Emergent single DOF with an equation of state - everyone can do that! ✓
- Abundant in String Theory and extensions of the SM ✓
- ~~Fine-tuned models? organizing principle?~~
- Field Theory is much richer - confinement, strong interactions, topological defects, conformal symmetry… ✓
- ~~The Swampland Conjecture - in QG potentials are steep~~

BANKS-ZAKS COSMOLOGY

- Consider a sector with conformal symmetry (SU(3) with N_f massless fermions) weakly coupled to the SM (suppressed by $\Lambda_{\mathcal{U}}$).
- At high temperature ($T \gg \Lambda_{\mathcal{U}}$) conformal symmetry is restored and the sector behaves like radiation.
- At low temperature the coupling to SM breaks the symmetry - “unparticles” with anomalous scaling T^{δ}.

BANKS-ZAKS COSMOLOGY - UNPARTICLES

- Theory with conformal symmetry, slightly displaced from its conformal fixed point. β function vanishes in the conformal limit.
- Very general, based on dimensional analysis, any broken CFT $\theta^{\mu}_{\mu} \sim \left(\frac{T}{\Lambda_{\mathcal{U}}}\right)^{4+\delta}$
- The thermal average gives: $\theta^{\mu}_{\mu} = \rho - 3p \propto T^{\delta}$
- $\rho = \sigma T^4 + BT^{4+\delta}$
- $p = \frac{1}{3}\sigma T^4 + \frac{B}{\delta + 3}T^{4+\delta}$
- The equation of state is not (nearly) constant anymore $w \equiv \frac{p}{\rho} = \frac{1}{3}\frac{\sigma + \frac{3B}{3+\delta}T^{\delta}}{\sigma + BT^{\delta}}$

BANKS-ZAKS COSMOLOGY - CONSEQUENCES W(T)

- Naturally behaves as different fluids at different epochs
- Can temporarily violate the Null Energy Condition (NEC) - No Big Bang singularity without QG or non-canonical Lagrangians
- Can have a limiting temperature - an effective CC!

UNPARTICLES AS DARK ENERGY- UDE

- @ high T, w=1/3 -radiation. @ low T, limiting temperature T_c. Dim-less temperature **y=T/T$_c$**

$$w \equiv \frac{p}{\rho} = \frac{1}{3} \frac{\sigma + \frac{3B}{3+\delta} T^\delta}{\sigma + BT^\delta}$$

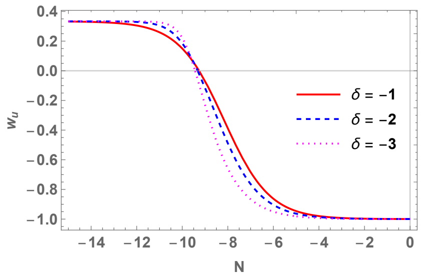
- $$-3 < \delta < 0, \quad B < 0 \Rightarrow \quad T > T_c = \left[\frac{4(\delta+3)}{3(\delta+4)} \left(-\frac{\sigma}{B} \right) \right]^{\frac{1}{\delta}}$$

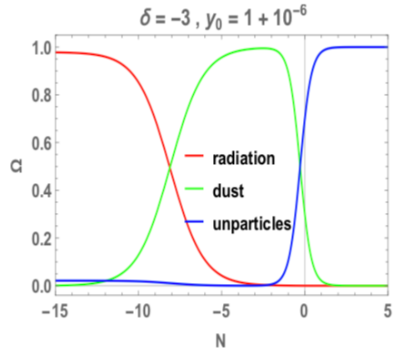
- The dynamical evolution starts from high T and asymptotes to T_c.

- Unparticles start as radiation and as they asymptote to T_c they behave as a CC.

- Deviations can only come from higher loop corrections of the beta function.

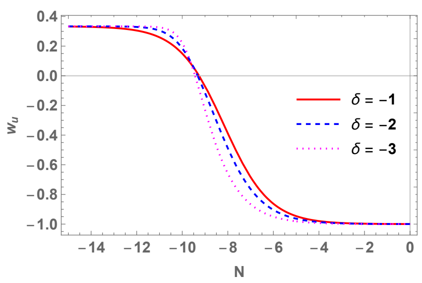
Artymowski, IBD, Kumar PRD 2021, 2022, IBD, Kumar 2023

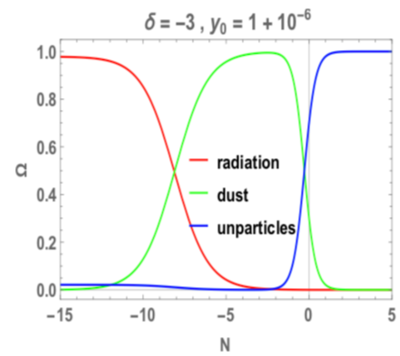




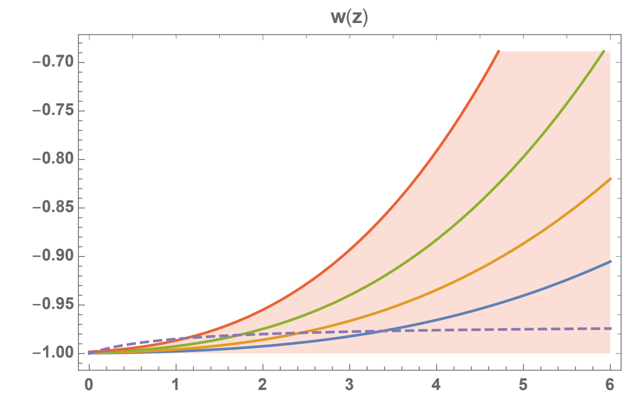
UDE- PROS.

- No fine-tuning of initial conditions. Radiation and CC behavior are predictions.
- No “Swampland conjectures”, no scalar fields, no modified gravity.
- B is fixed by present day DE density. We are very close to the critical temperature $y_0 - 1 \lesssim 10^{-4}$





UDE - PREDICTIONS



- Special redshift dependence of w:
  $w_u \simeq -1 + 4(\delta + 4)\left(y_0 - 1\right)(1 + z)^3$

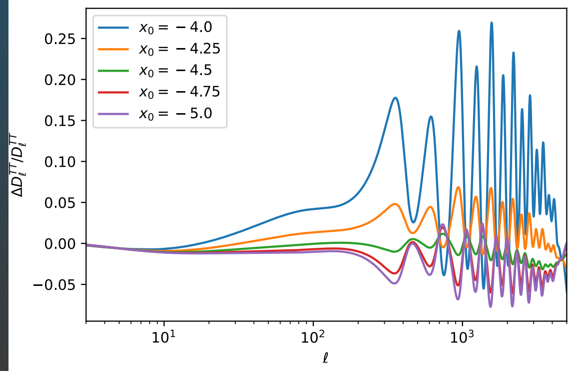
- Contributes to N_{eff}, consistency condition, current limits $\Delta N_{eff} \lesssim 0.19$:

$$w_u(z) \simeq -1 + 0.58\,(1 + z)^3 \left(-1 - \frac{4}{\delta}\right)^{1/4} \left[\frac{\Omega_{r0}}{\Omega_{u0}} \Delta N_{eff}\right]^{3/4}$$

- Perturbation observables $(\gamma, f\sigma_8)$ - as LCDM to 0.1%

$$\delta'_u = -(1 + w_u)\,(\theta_u - 3\,\Phi') - \frac{a'}{a}\left(\frac{\delta p_u}{\delta \rho_u} - w_u\right)\delta_u\,,$$

$$\theta'_u = -\frac{a'}{a}\,(1 - 3\,w_u)\,\theta_u - \frac{w'_u}{1 + w_u}\,\theta_u + \frac{\frac{\delta p_u}{\delta \rho_u}}{1 + w_u}\,k^2\,\delta_u + k^2\,\Phi$$



UDE AND LCDM - LIKELIHOOD ANALYSIS

- Perform likelihood analysis of UDE and compare to LCDM

- Consider various data sets, each time removing one that is causing the tension.

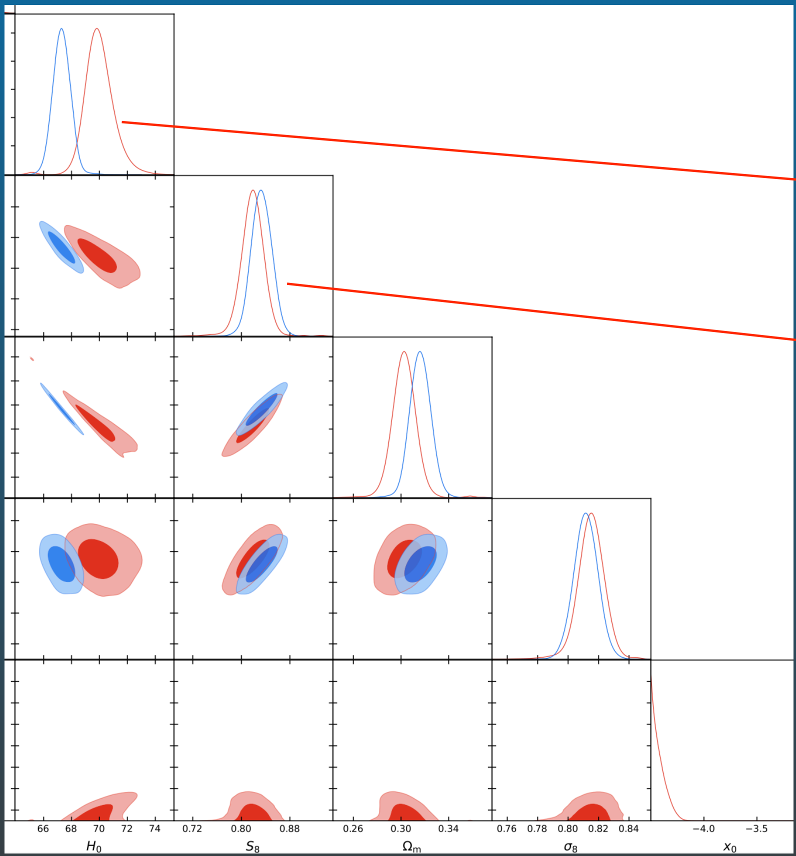
- For UDE fix $\delta = -3$, data is insensitive to the exact value.

- Flat priors for the different parameters
  $H_0, \Omega_b, \Omega_c, \tau, \sigma_8, n_s; \quad y_0 = 1 + 10^{x_0}, \quad x_0 \in [-6, -3]$

- Model mostly changes the Early Universe z>1.

RESULTS

Planck Only

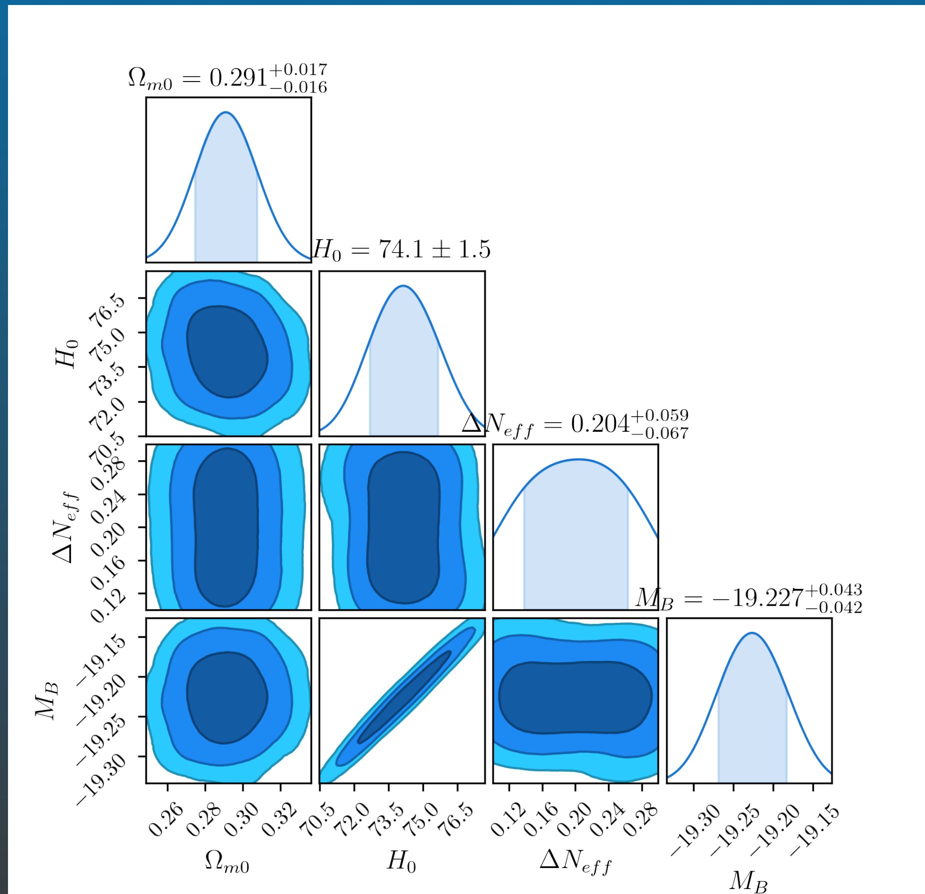


Hubble is shifted Towards SN value!

S_8 is reduced towards DES value!

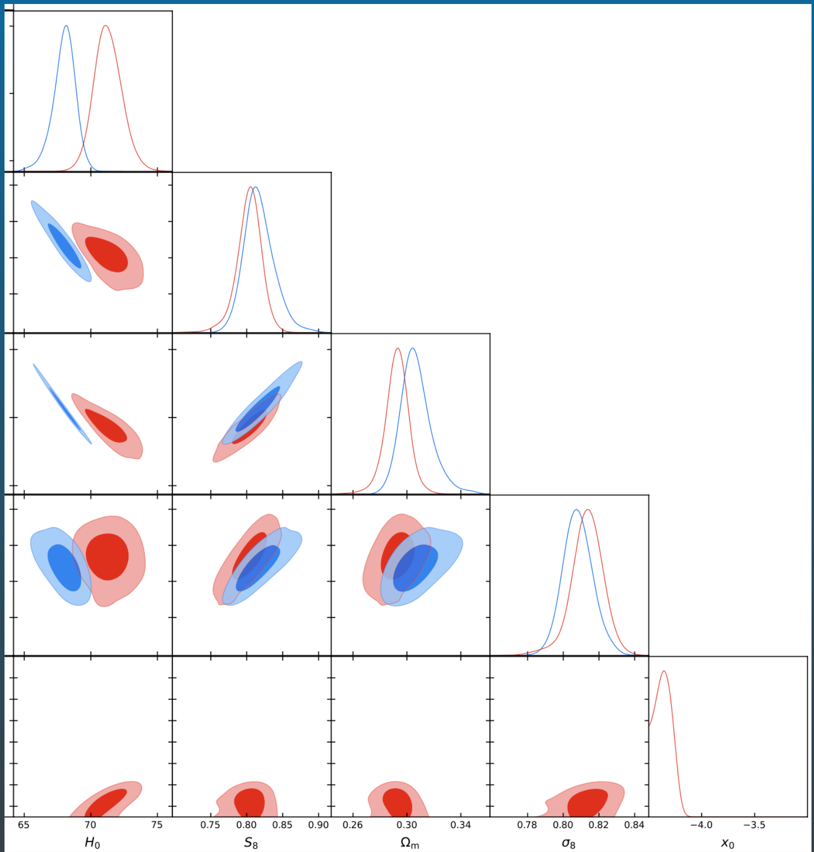
$\Delta\chi^2 = 2.14$: – (

SN Only



RESULTS

Planck+Pantheon+SH0ES



Hubble is shifted
Towards SN value!

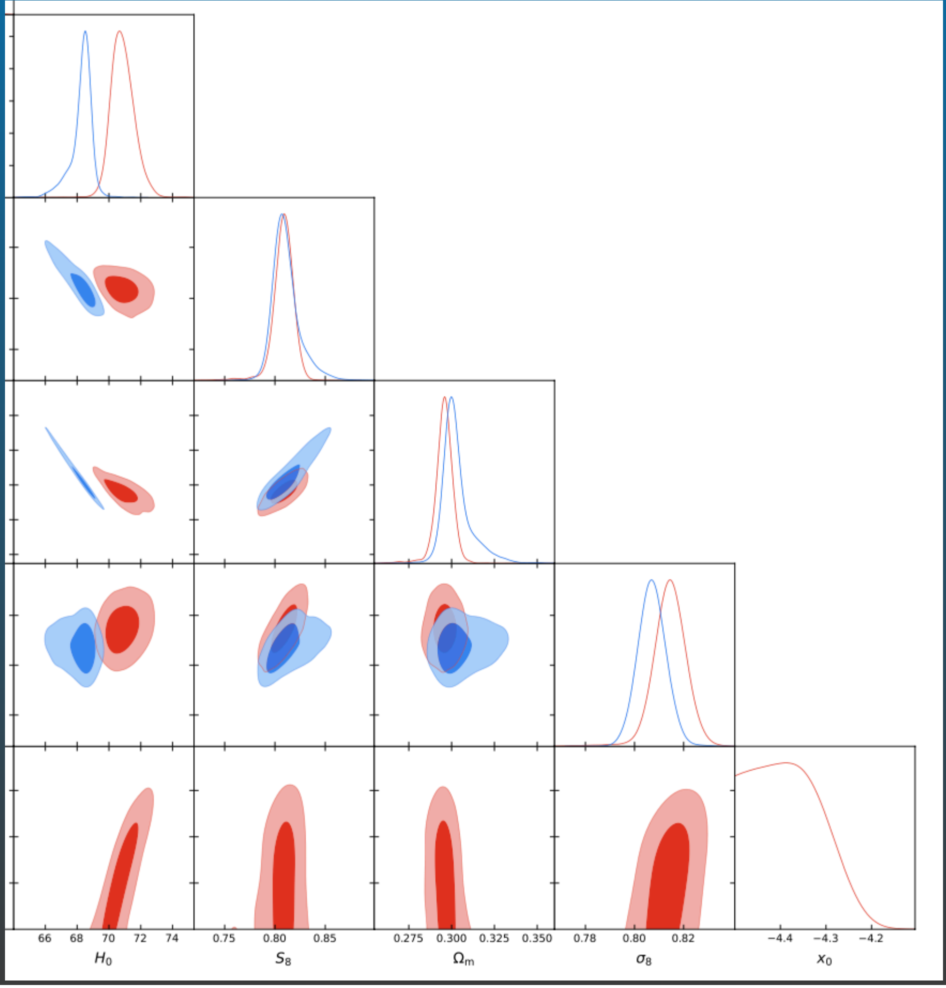
S_8 is reduced
towards DES value!

$\Delta\chi^2 \simeq -11$!

	LCDM	UDE
H_0	$68.00^{+0.92}_{-0.70}$ (68.46)	$71.29^{+0.96}_{-1.1}$ (71.18)
σ_8	$0.8082^{+0.0079}_{-0.0088}$ (0.8045)	$0.8132^{+0.0093}_{-0.0078}$ (0.813)
S_8	$0.817^{+0.017}_{-0.023}$ (0.8045)	$0.803^{+0.018}_{-0.014}$ (0.806)
Ω_m	$0.3069^{+0.0088}_{-0.013}$ (0.3005)	$0.2926^{+0.0087}_{-0.0077}$ (0.295)

RESULTS

Planck+Lensing+BAO+DES+Pantheon+SH0ES



Hubble is shifted Towards SN value!

S_8 is reduced towards DES value!

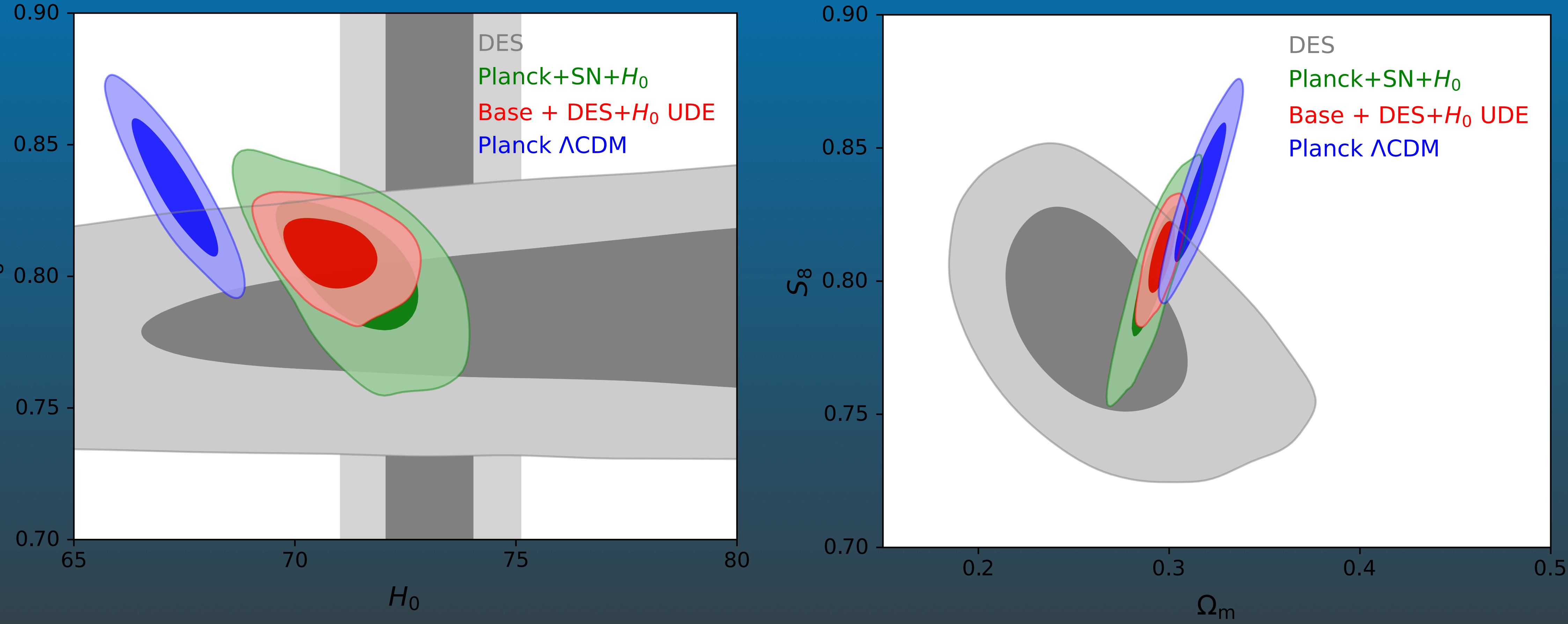
$\Delta\chi^2 = -7.24$!

	LCDM	UDE
H_0	$68.28^{+0.71}_{-0.31}$ (68.47)	$70.87^{+0.61}_{-0.79}$ (70.76)
σ_8	0.8071 ± 0.0059 (0.8069)	0.8142 ± 0.0073 (0.8140)
S_8	$0.8111^{+0.0080}_{-0.015}$ (0.8075)	$0.808^{+0.010}_{-0.0078}$ (0.8093)
Ω_m	$0.3030^{+0.0038}_{-0.0091}$ (0.3004)	$0.2956^{+0.0049}_{-0.0041}$ (0.2965)

Improvement in the likelihood persists for all other combinations of data sets by at least $|\Delta\chi^2| > 2.1$

Both tensions are reduced to less than 1 STD w.r.t SH0ES and DES!

RESULTS



Clear improvement in concordance and likelihood!

PHENOMENOLOGICAL FLUID WITH "TRACKER MECHANISM"

- Could unparticle behavior be more robust?
- Any DE model needs a "tracker mechanism" - DE "tracks" the matter or radiation to avoid fine tuning.
- Possibility of measuring the spatial curvature. *Leonard et al. 2016* -need theoretical insights.
- Could some of the tensions be just parametrization issues?
- Parametrize a relatively sudden transition.

PHENO. FLUID DE

- Theoretical priors:
- 1) Fulfill the Null Energy Condition w>=-1
- 2) Today w~-1
- 3) At early times w=1/3 (or 0) for tracker mechanism
- Speed of sound $c_s^2 = 1$ or 0 or open $0 \leq c_s^2 \leq 1$ and adiabatic speed of sound:

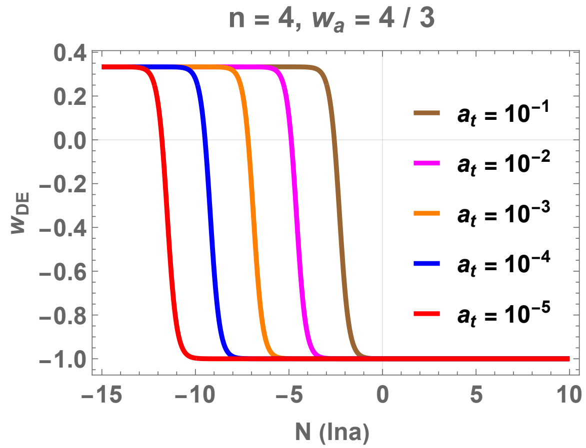
$$c_a^2 = w_{DE}(1 - \frac{n}{4}) + \frac{n}{12}$$

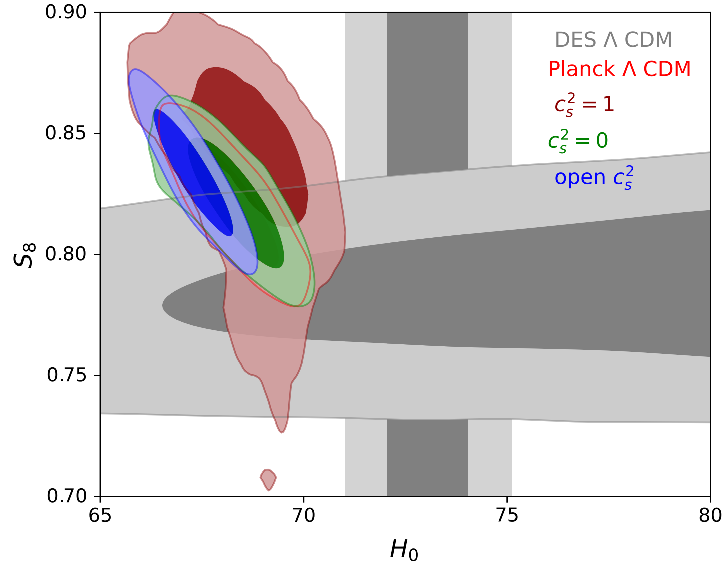
- a_t transition redshift.

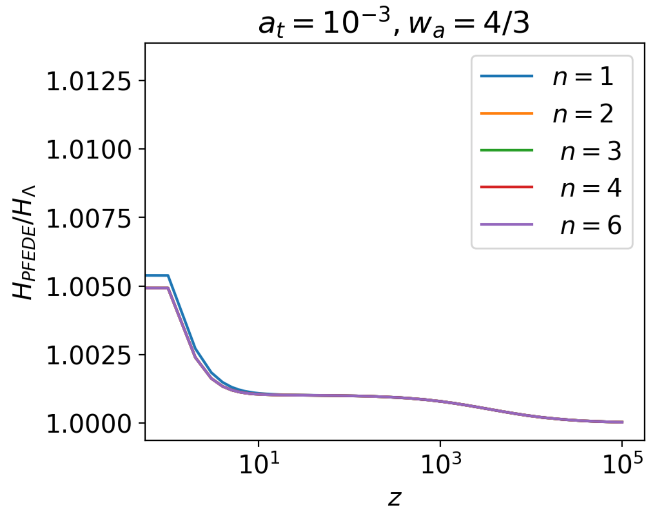
$$w_{DE}(a) = -1 + \frac{4/3}{1 + \left(a/a_t\right)^n}$$

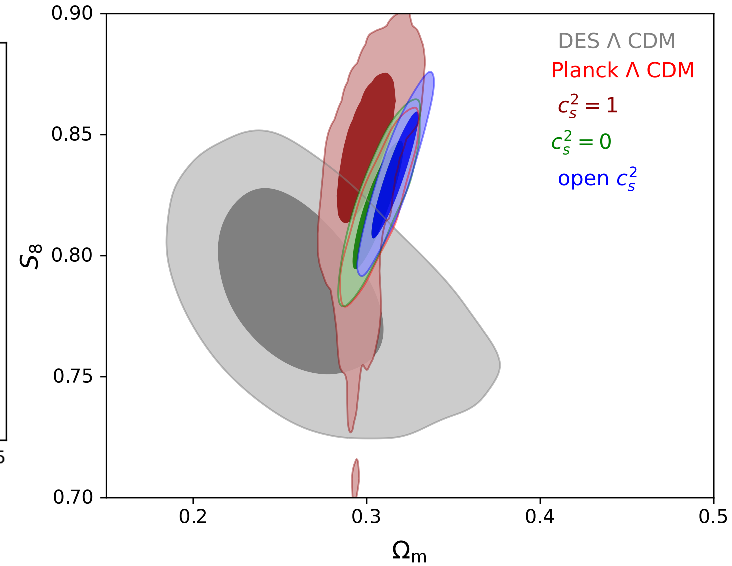
RESULTS

- Slight reduction in H0 and S8 tension. H0~69, S8~0.81.
- Less statistically significant.
- $\Delta\chi^2 \simeq -2.7$
- n>3 preferred
- In all cases, z_t~30.









BEYOND SCALAR FIELD SUMMARY

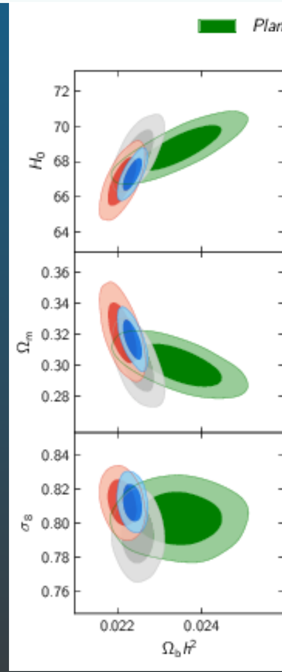
- Within UDE cosmological concordance is largely restored for both Hubble and S_8 tension
- Pheno. Fluid approach not as successful. Still z_t~30
- Going beyond weakly coupled scalar fields opens a new model space with different problems and opportunities.
- Generic arguments about conformal symmetry and dim. analysis.
- Useful for fundamental problems - Big Bang singularity, Swampland, CC… and for practical ones - Hubble tension, S_8 tension, N_{eff}, …
- Highly predictive, consistency condition - detected within a decade or bound consistency approaching LCDM.
- Future directions - interactions with CMB, $N_{eff,}$ growth of fluctuations

BACKUP: HUBBLE TENSION REVISITED

- <u>**SNIa:**</u> do not assume a model except isotropic redshift.
- Consider only low redshift SNIa, z<<1.

$$d_L(z) = \frac{1+z}{H_0}\int_0^z \frac{dz'}{\sqrt{\Omega_m(1+z')^3+1-\Omega_m}} \underset{z<<1}{\approx} \frac{z}{H_0}\left[1+\left(1-\frac{3}{4}\Omega_m\right)z\right]$$

- <u>Measure</u> Hubble $H_0^{SN,obs.} = 73 \pm 1\, km/sec/Mpc$
- Use Hubble and high redshift z~1 for matter density Ω_{m0}, CC etc.
- <u>**CMB:**</u> Take all possible data. Assume a model (like LCDM)
- <u>Infer</u> the model parameters from a likelihood analysis



BACKUP 2: EARLY UNIVERSE

- Consider unparticles+fluid.

$$H(z)^2 = H_0^2 \sum_i \Omega_{0i}(1+z)^{3+3w_i}, \quad \dot{H} = -H_0^2 \sum_i \frac{3+3w_i}{2}\Omega_{0i}(1+z)^{3+3w_i}$$

- Violates NEC near the Bounce.

- New stable solutions- de Sitter Bounce, standard Bounce, cyclic universe.

- Analysis of the different phases

$$\rho = \sigma T^4 + BT^{4+\delta}$$

$$p = \frac{1}{3}\sigma T^4 + \frac{B}{\delta+3}T^{4+\delta}$$

- Calculation of the primordial spectra and stability of the cyclic/bounce scenarios.

Artymowski, IBD, Kumar JCAP 2019 +WiP