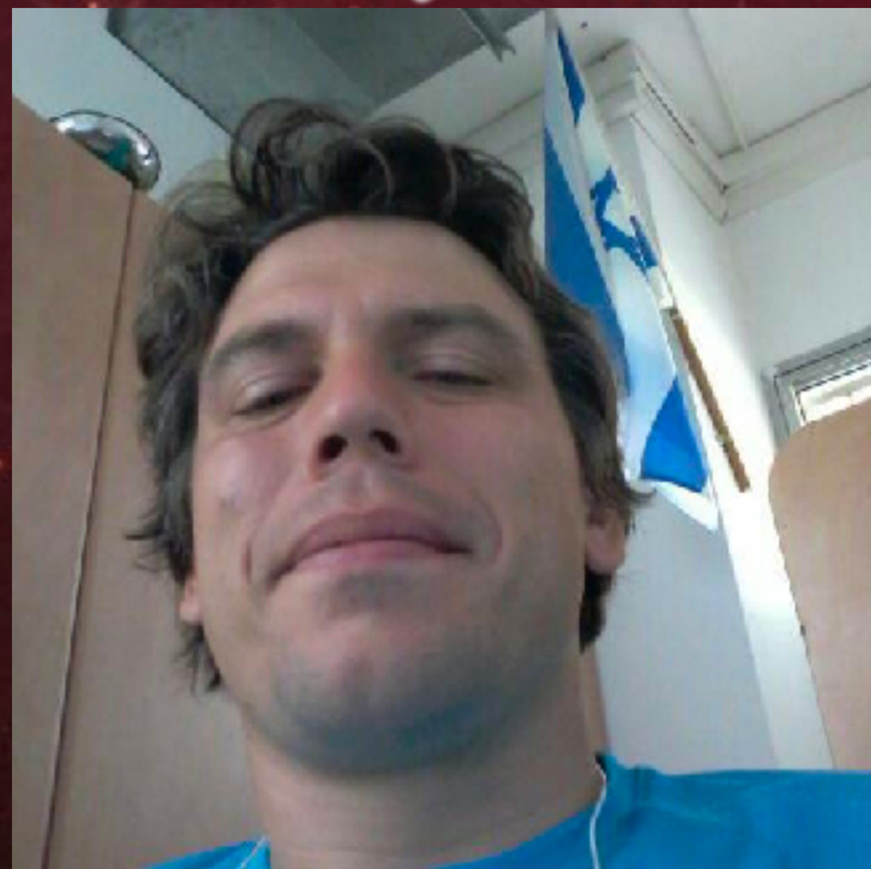
Beyond Scalar Field Cosmology

Ido Ben-Dayan
Ariel University, UC Berkeley
Pheno 2022 Symposium

Utkarsh Kumar

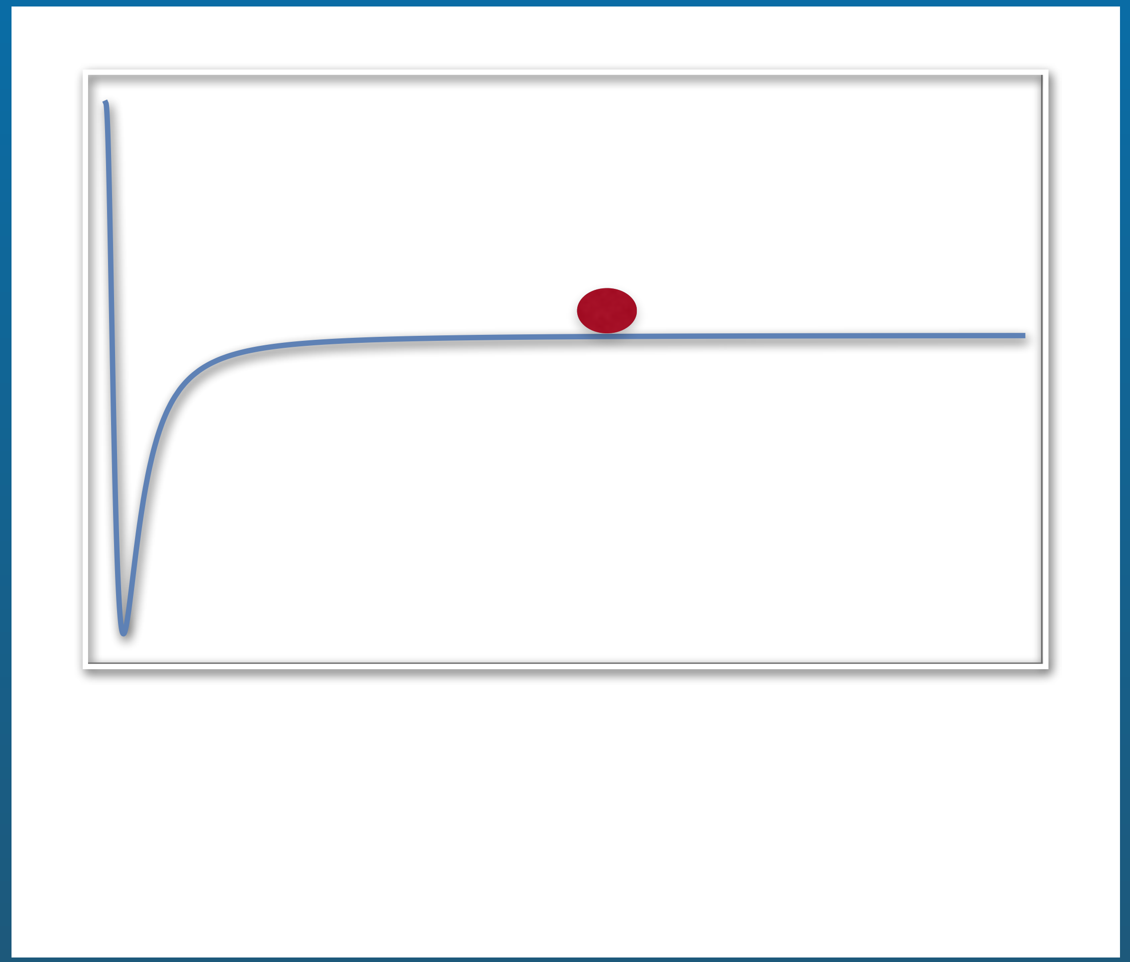
Michal Artymowski



Outline

- “Problems” with scalar fields
- Collective Emergent Phenomena - “Unparticles”
- Unparticles as Dark Energy and the Hubble tension.
- Summary

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…
- Big Bang singularity.
- The Swampland Conjecture - in QG potentials are steep (see however, IBD, PRD 2018 “Draining the Swampland” and endless others)

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

PROBLEMS WITH PRESENT ACCELERATION (CC/DE)

- CC is the simplest parametrization of the observed acceleration.

- Biggest hierarchy problem in fundamental physics - *The Cosmological Constant Problem*

  $\rho_\Lambda^{\text{obs.}} \sim 10^{-10}\text{erg/cm}^3, \quad \text{M}_{\text{QCD}} \sim 10^{36}\,\text{erg/cm}^3, \quad \text{M}_{\text{EW}} \sim 10^{47}\,\text{erg/cm}^3, \quad \text{M}_{\text{pl}} \sim 10^{110}\text{erg/cm}^3.$

- Why now? The coincidence problem $\frac{\rho_m}{\rho_\Lambda} \sim 1$

- Requires fine-tuned initial conditions in the early universe. Especially for scalar fields.

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

- Trace of the energy momentum tensor: $\theta^{\mu}_{\mu} = \frac{\beta(g)}{2g} N[F^{a}_{\mu\nu} F_{a\,\mu\nu}]$
- β vanishes in the conformal limit.
- The thermal average gives: $\theta^{\mu}_{\mu} = \rho - 3p \propto T^{\delta}$
  $\rho = \sigma T^4 + BT^{4+\delta}$
- $p = \frac{1}{3}\sigma T^4 + \frac{B}{\delta + 3} T^{4+\delta}$
- Gravitational coupling to matter and radiation.

BANKS-ZAKS COSMOLOGY

- Very general, based on dimensional analysis, any broken CFT $\theta^{\mu}_{\mu} \sim \left(\frac{T}{\Lambda_{\mathcal{U}}}\right)^{4+\delta}$
- The equation of state is not (nearly) constant anymore
$$w \equiv \frac{p}{\rho} = \frac{1}{3}\frac{\sigma + \frac{3B}{3+\delta}T^{\delta}}{\sigma + BT^{\delta}}$$
- The unparticles are a ‘clock’ of the universe.

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.

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

- Can have a limiting temperature - an effective CC!

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

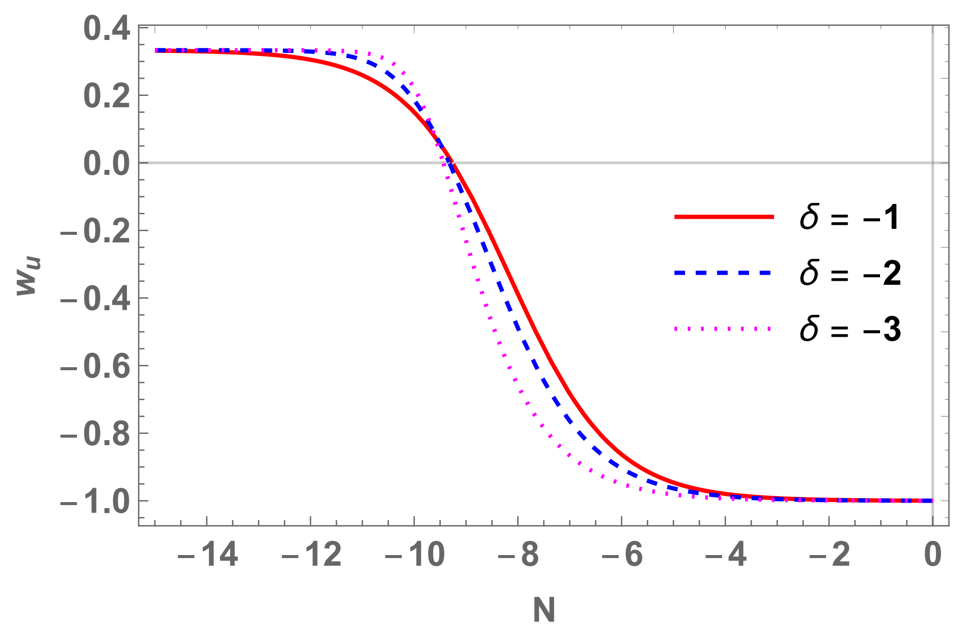
$$If\, B < 0,\ -3 < \delta < 0 \Rightarrow \dot{\rho}_u = -3H(\rho_u + p_u)\,|_{T \to T_c} \to 0$$

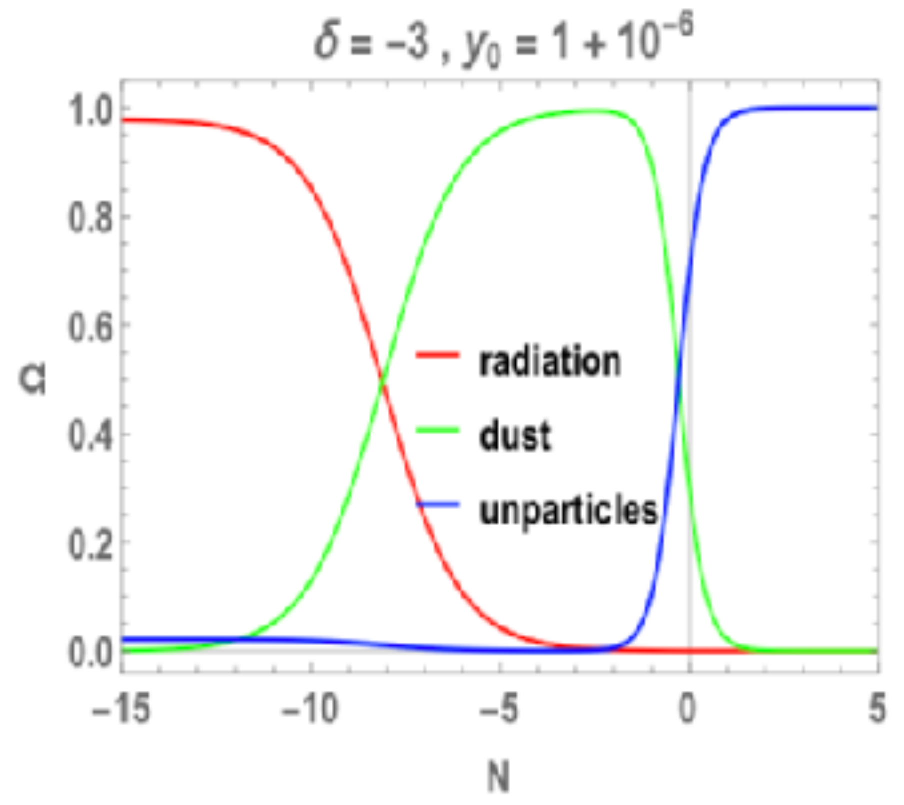
- The limiting temperature is due to the dynamical evolution of the Friedmann/continuity equation

UNPARTICLES AS DARK ENERGY

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

- No NEC violation, @ high T, w=1/3 -radiation. @ low T, limiting temperature T_c. Dim-less temperature $y=T/T_c$
- $$-3 < \delta < 0, \quad B < 0 \Rightarrow \quad T > T_c = \left[\frac{4(\delta+3)}{3(\delta+4)}\left(-\frac{\sigma}{B}\right)\right]^{\frac{1}{\delta}}$$
- 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. Transition quickly at some point after decoupling.
- Deviations can only come from higher loop corrections of the beta function.





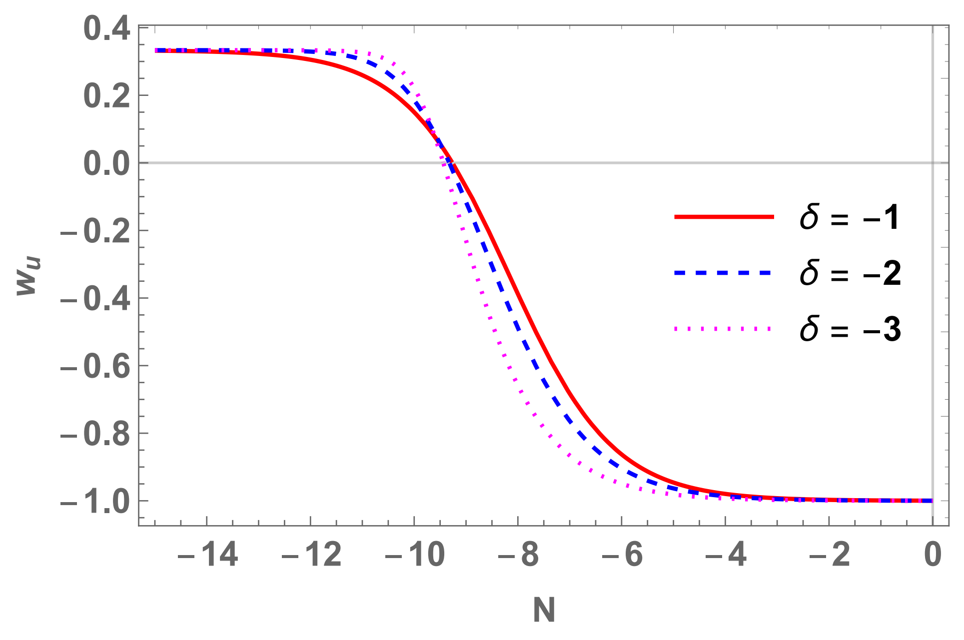
Artymowski, IBD, Kumar PRD 2021 +2111.09946

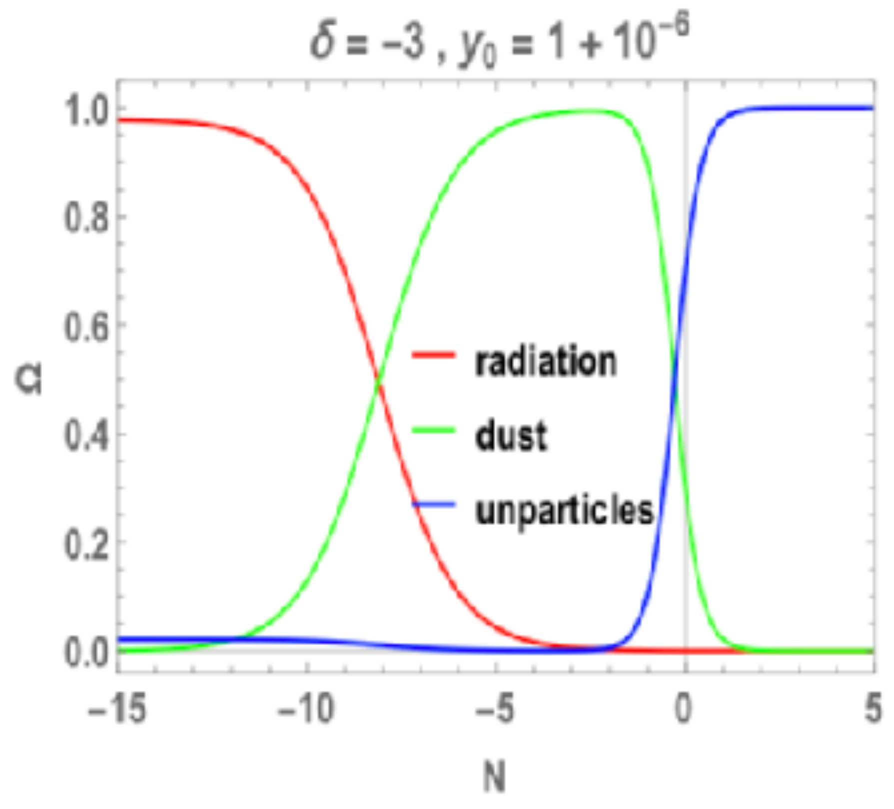
UNPARTICLES AS DARK ENERGY- PROS.

- No fine-tuning of initial conditions. Radiation and CC behavior are predictions.

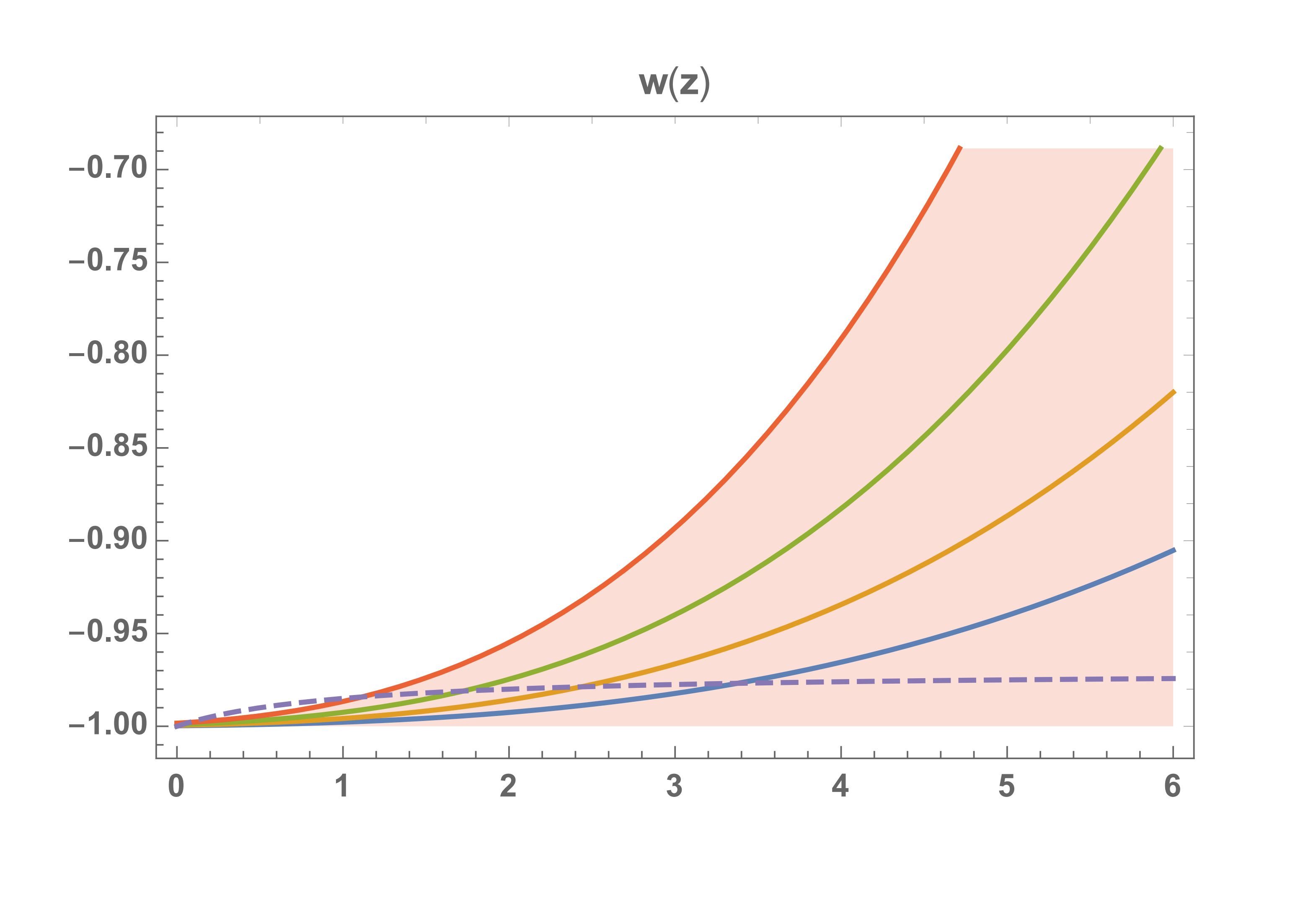
- No "Swampland conjectures", no scalar fields, no modified gravity.

- B is fixed by present day DE density. We are very close to the critical temperature $y_0 - 1 \lesssim 10^{-4}$ (Dim-less temperature $y=T/T_c$)





UNPARTICLES DARK ENERGY PREDICTIONS



- Special redshift dependence of w, at z<<1000:

$$w_u \simeq -1 + 4(\delta + 4)\left(y_0 - 1\right)(1+z)^3$$

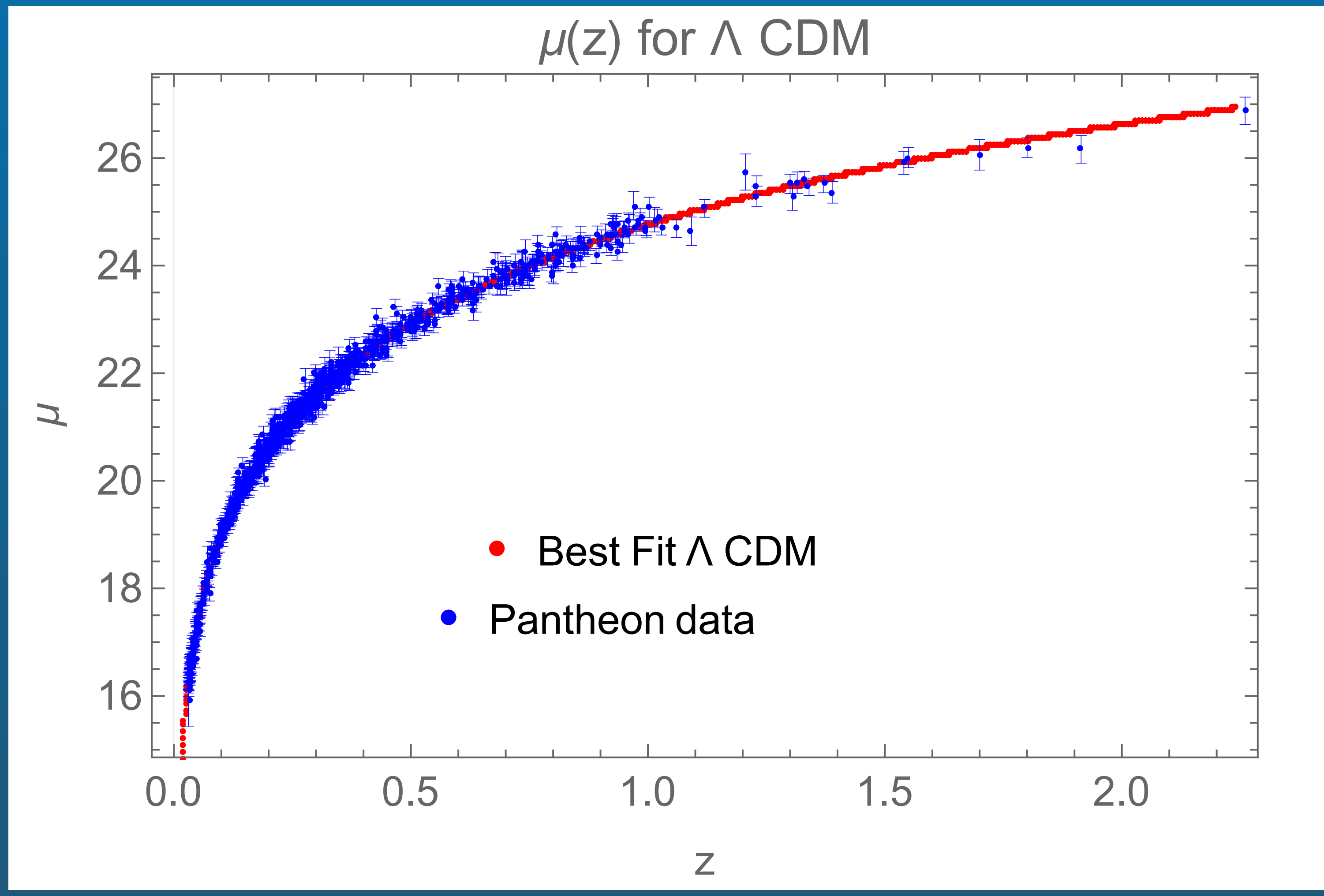
- Contriubutes to Neff, current limits $\Delta N_{eff} \lesssim 0.19$:

$$\frac{\rho_u}{\rho_r} \simeq \frac{\Omega_{u0}}{\Omega_{r0}} 3(\delta+4)(-\delta)^{1/3}(y_0 - 1)^{4/3} = \frac{7}{8}\left(\frac{4}{11}\right)^{4/3} \Delta N_{eff}$$

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

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

UNPARTICLE DARK ENERGY AND THE HUBBLE TENSION



- SNIa data is now good enough for model inference, fitting all SNIa at once to H_0 and Ω_{m0}, (953 SN from Pantheon sample, z>0.03, now Pantheon+ ~1500 SN)

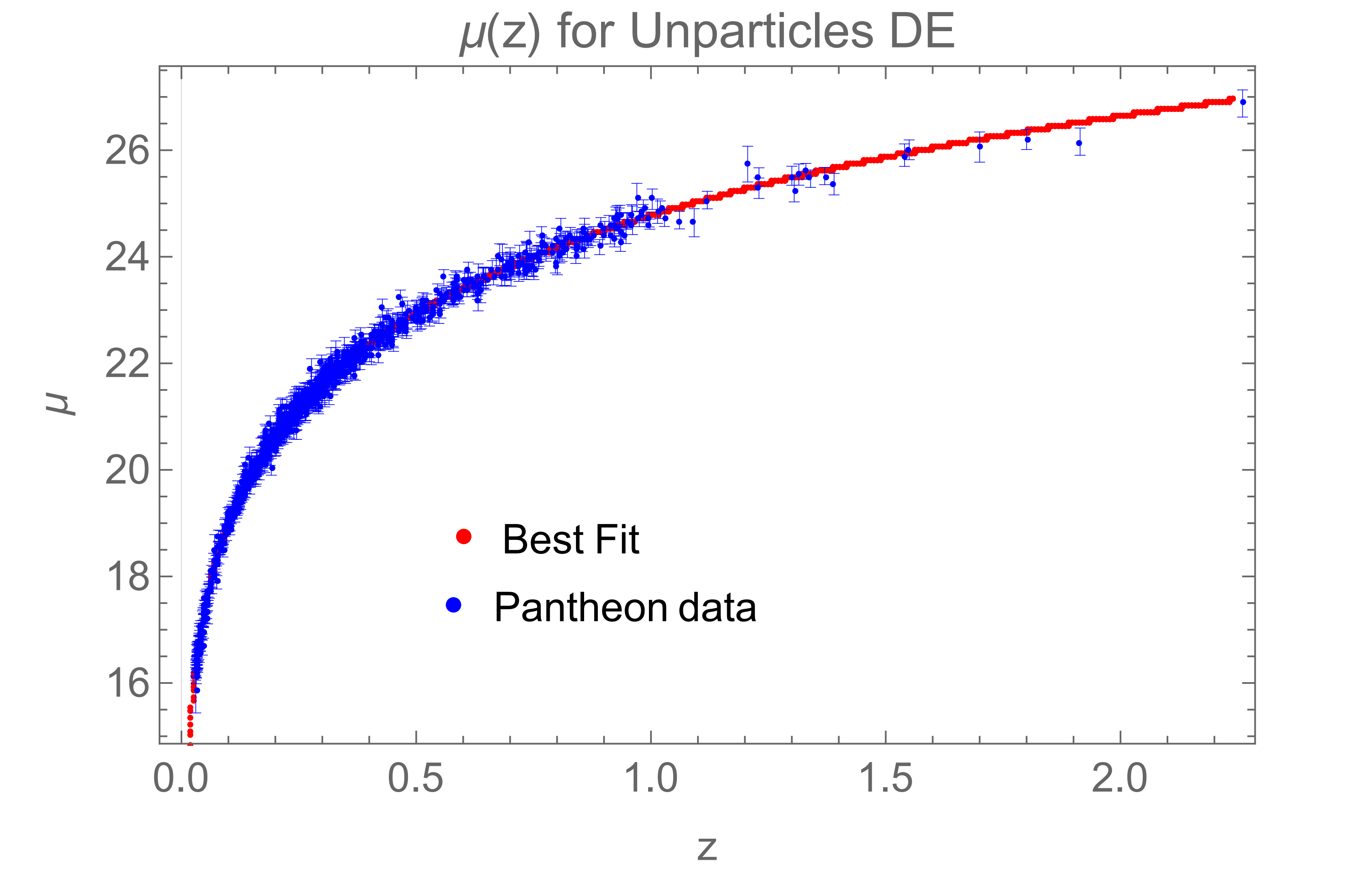
- Better quantification of the tension. Inferred parameters according to maximal likelihood.

- Fit the distance modulus, Hubble is degenerate with absolute magnitude,"external" M_B=-19.3

$$\mu = 5\, Log_{10}\, d_L(H_0\,, \Omega_{m_0}, \delta, \Delta\, N_{eff}) + 25 + M_B$$

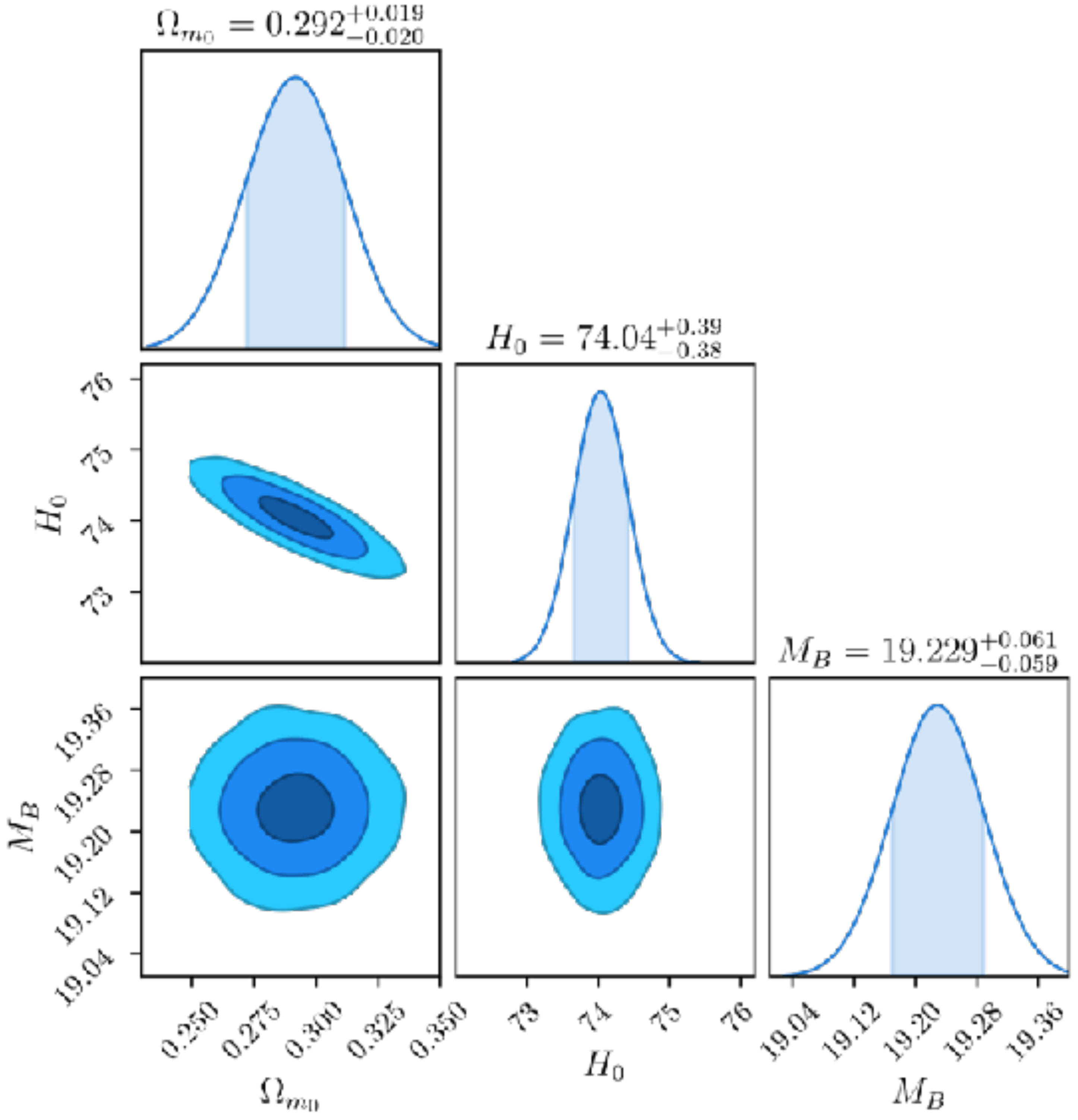
$$H_0 = 71.6 \pm 0.2 \quad km/sec/Mpc, \quad \Delta N_{eff} = 0.2 \pm 0.11 \quad (stat.)$$

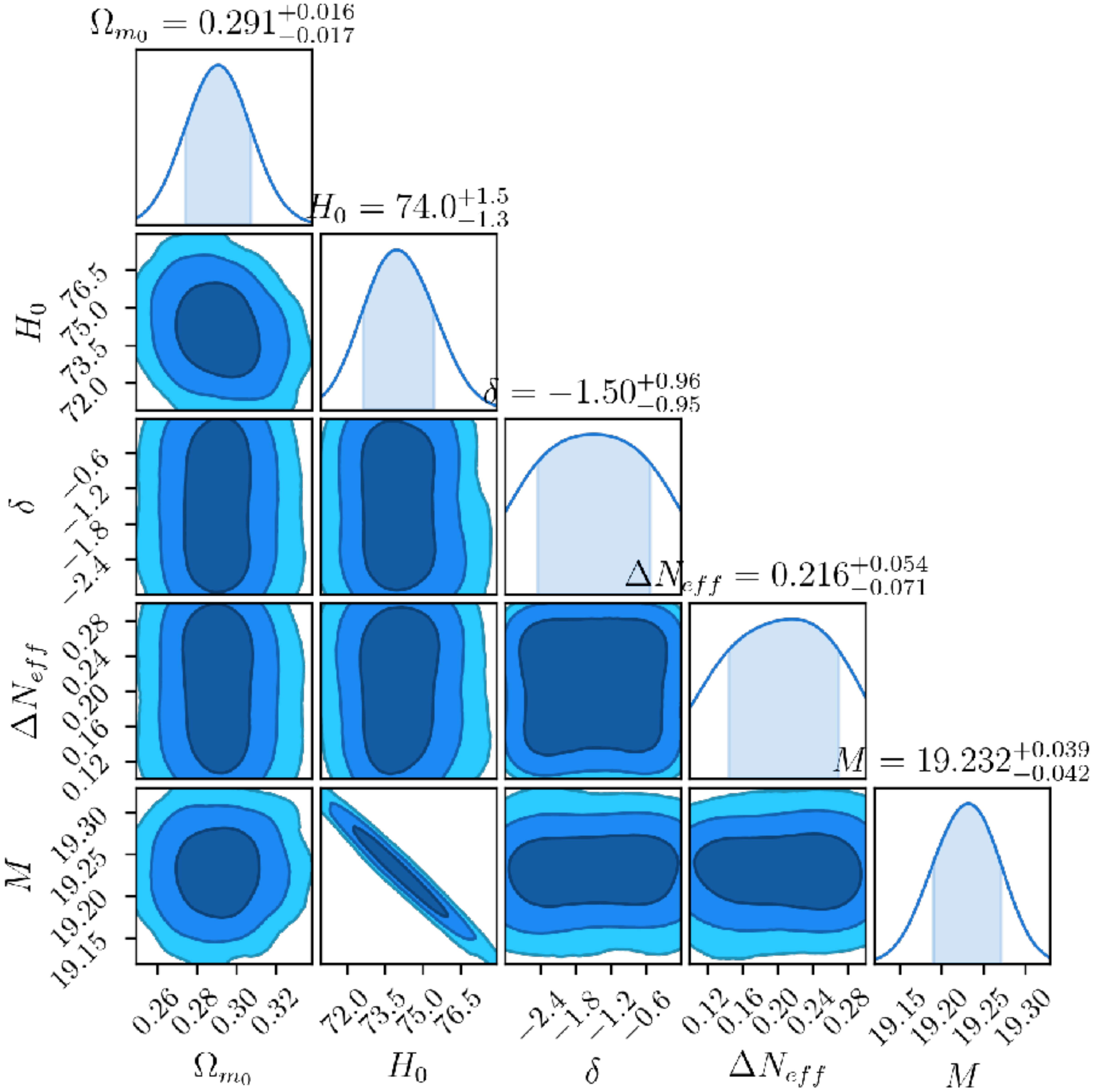
$$\Omega_{m0} = 0.291 \pm 0.013, \quad H_0 = 71.5 \pm 0.3 \quad km/sec/Mpc \quad (stat.)$$



LIKELIHOOD RESULTS OF SNIA

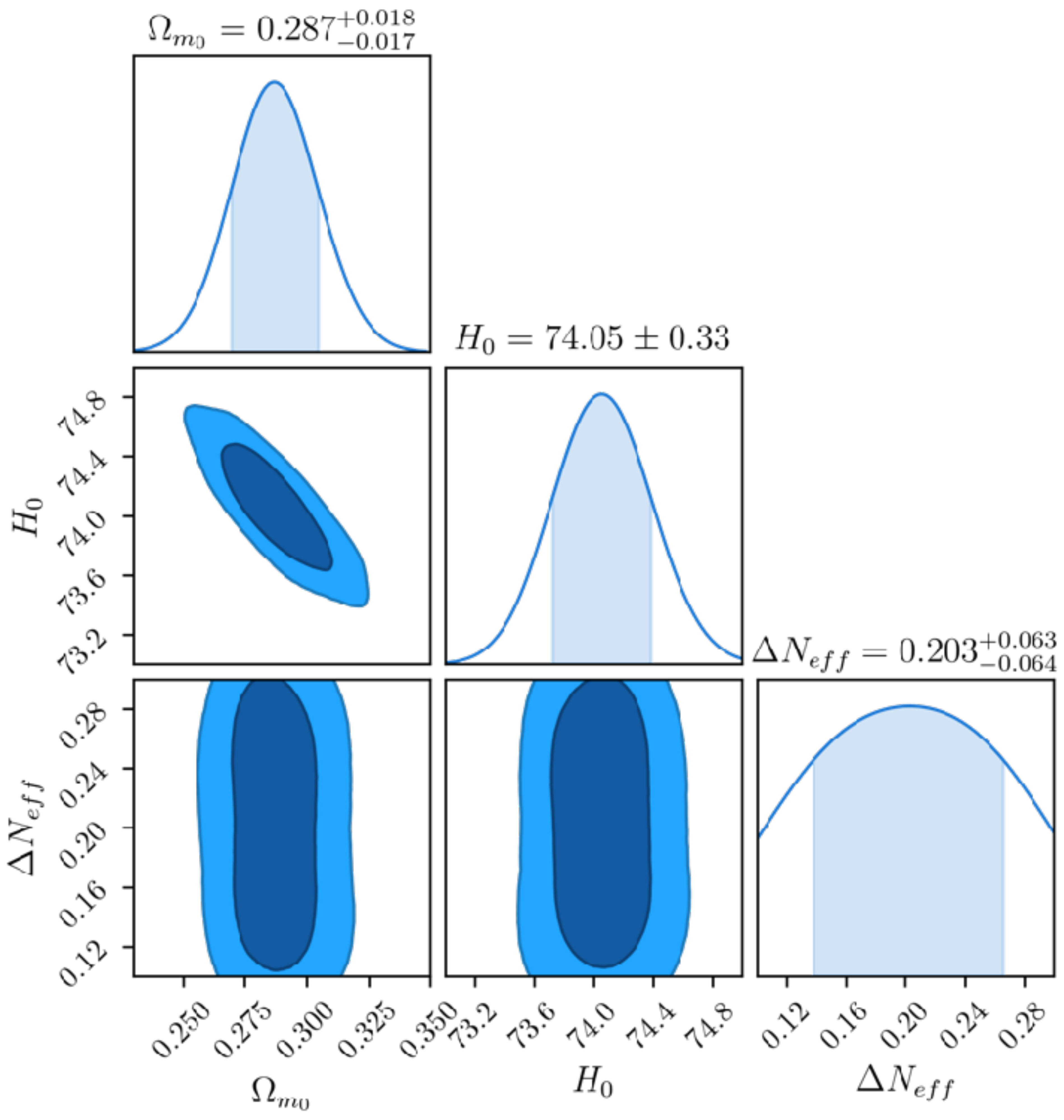
- Hubble degenerate with absolute magnitude- need to marginalize.

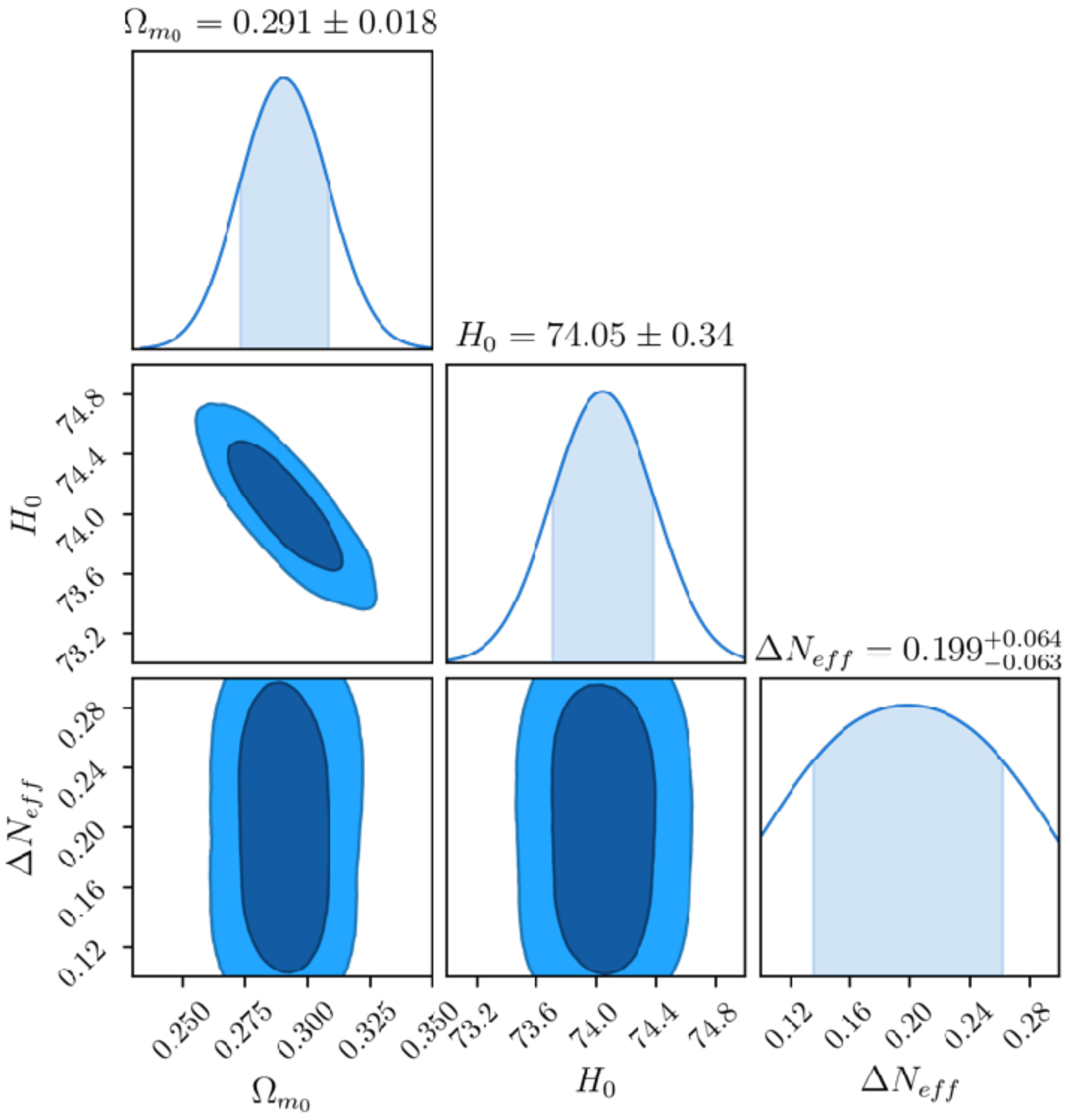




LIKELIHOOD RESULTS OF SNIA

- Fixing delta and M_B





SUMMARY

- 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 in Cosmology - Big Bang singularity, Swampland, CC… and for practical ones - Hubble tension, N_{eff}, …
- Highly predictive, consistency condition - detected within a decade or bound consistency approaching LCDM.
- Novel approach to the Hubble tension.

FUTURE PROSPECTS

- Full likelihood analysis including CMB, systematic errors.
- Further model building - early dark energy, transition between BBN and last scattering.
- Early Universe Physics - Artymowski, IBD, Kumar JCAP 2019 +WiP
- Theory - closer inspection of other CFTs and their thermal behavior, higher loop corrections.

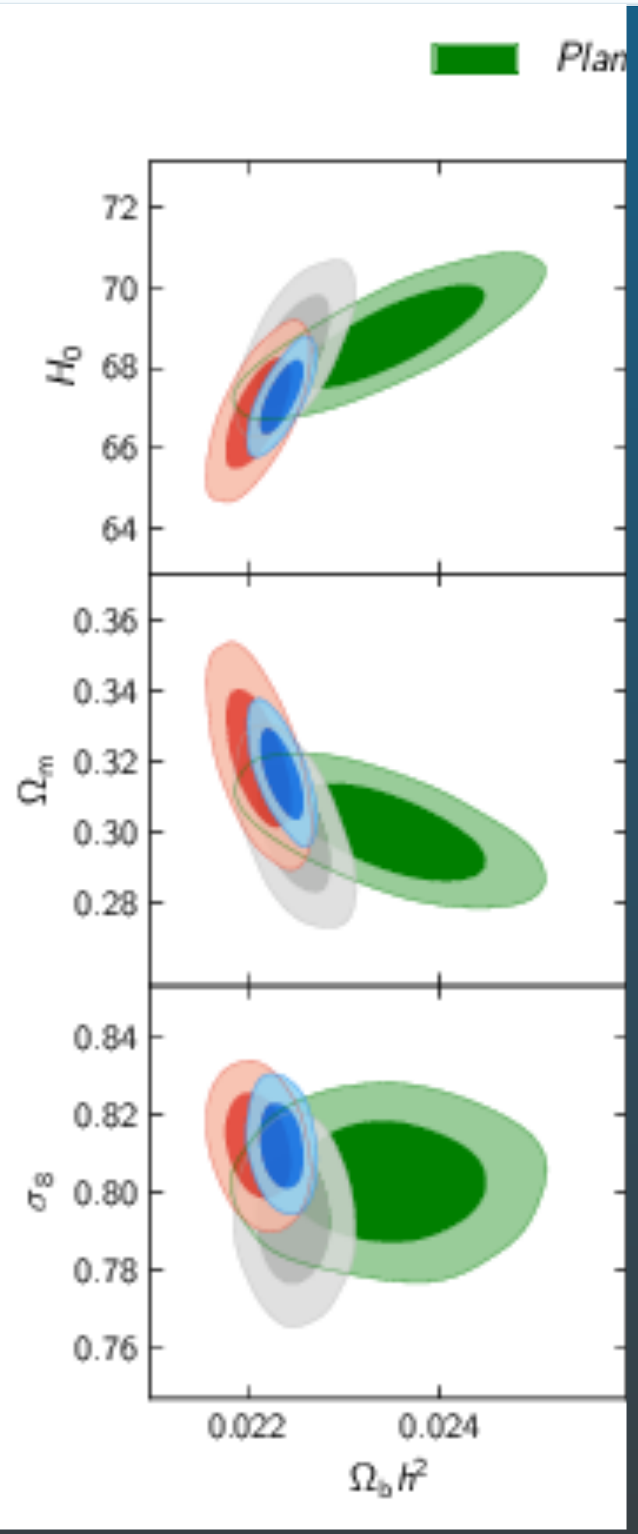
Backup Slides

HUBBLE TENSION REVISITED

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

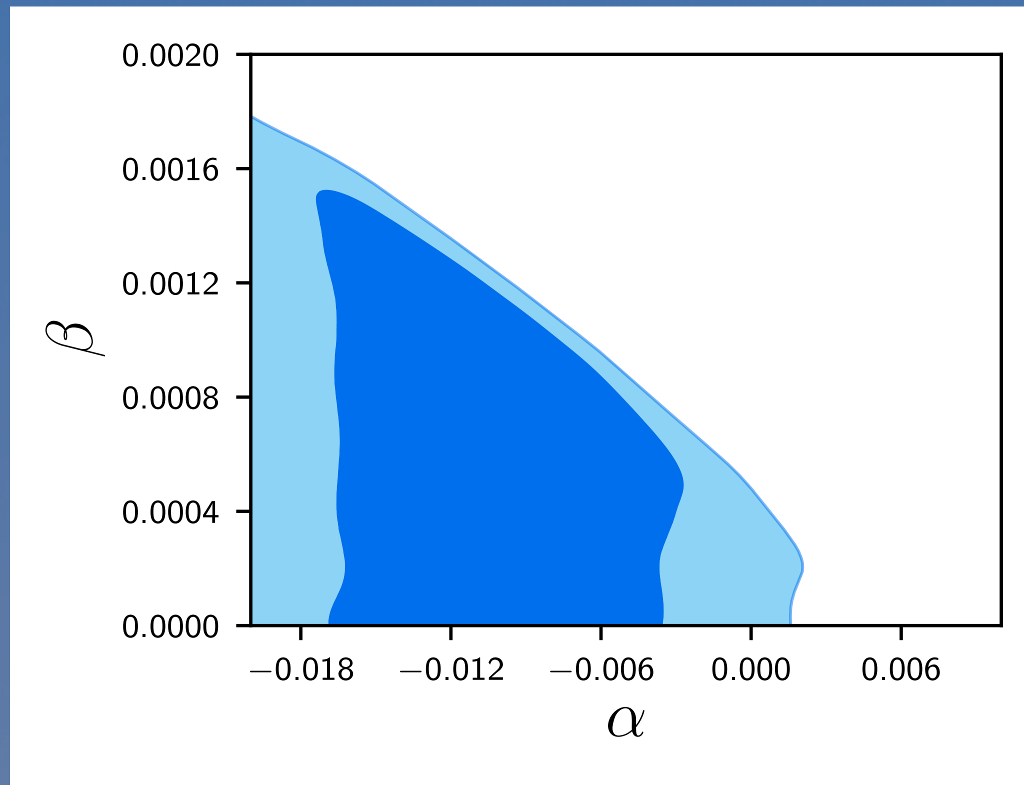
$$d_L(z) = \frac{1+z}{H_0}\int_0^z \frac{dz'}{\sqrt{\Omega_m(1+z')^3+1-\Omega_m}} \underset{z<<1}{\approx} \frac{z}{H_0}\left[1+\left(1-\frac{3}{4}\Omega_m\right)z\right]$$

- <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



N_{EFF} - # RELATIVISTIC DOF AT DECOUPLING

- SM prediction (neutrinos and photons) - N_{eff}=3.046, Current measurements N_{eff}=2.99+-0.19
- Constrains DM models, and in general additional particles beyond the SM.
- Can be used to constrain primordial density and GW spectra (IBD, Keating, Leon, Wolfson, JCAP 2019)
- Very popular way of resolving the Hubble tension (Neff>3.046)



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?~~ Symmetry
- Field Theory is much richer - confinement, strong interactions, topological defects, conformal symmetry…
- No Big Bang singularity Artymowski, IBD, Kumar JCAP 2019 +WiP
- ~~The Swampland Conjecture - in QG potentials are steep~~
- Relevant for the Hubble tension. Predictions for Neff and w(z)

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

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

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

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

Artymowski, IBD, Kumar JCAP 2019 +WiP