Minimal dissipative extensions of the Standard Cosmological Model

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in collaboration with W. Zimdahl and I. Costa

Phys.Rev.D 104 (2021) 6, 063507

Early-time thermalization of cosmic components? A hint for solving cosmic tensions

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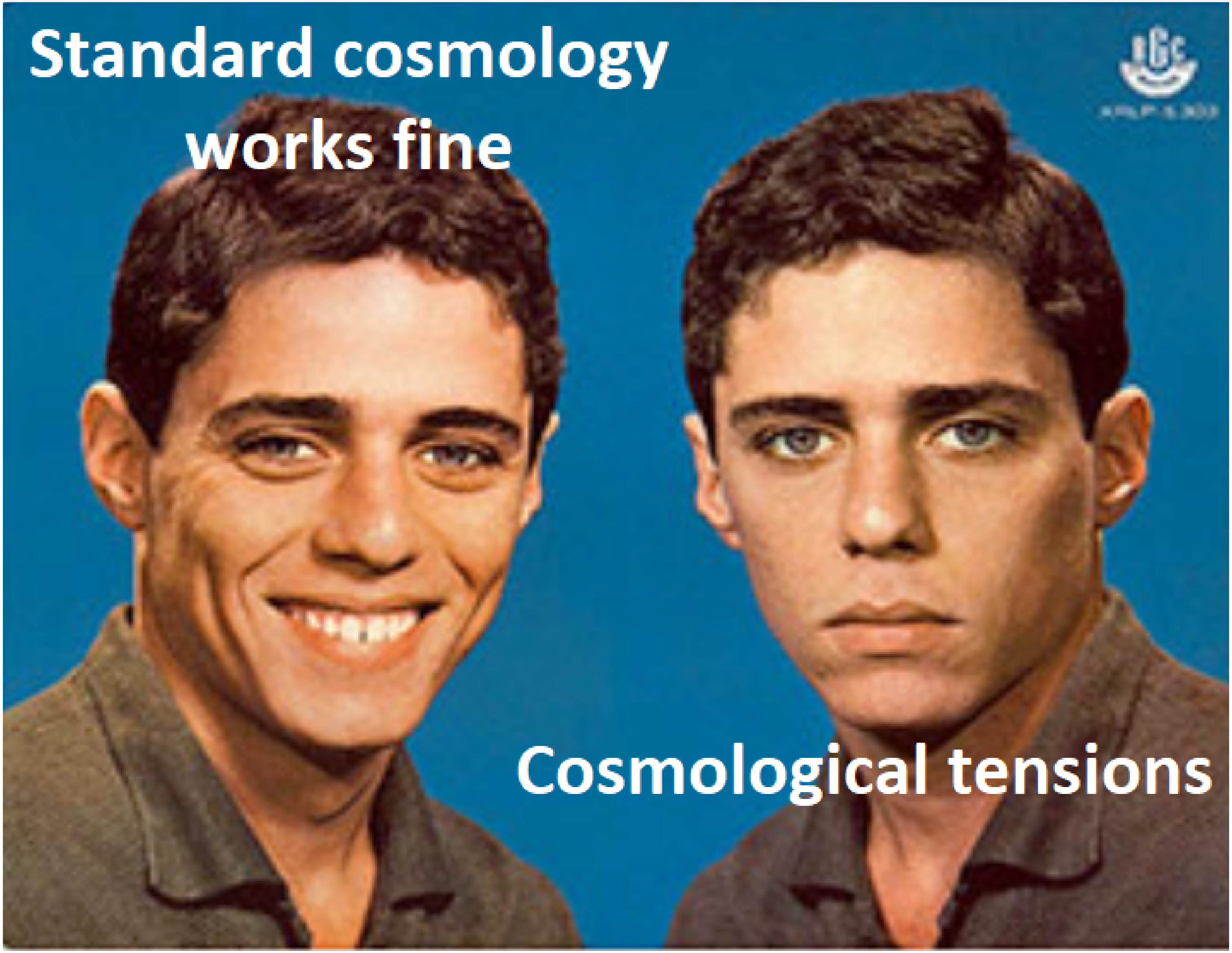

Standard cosmology
works fine
Cosmological tensions

Standard cosmological dynamics

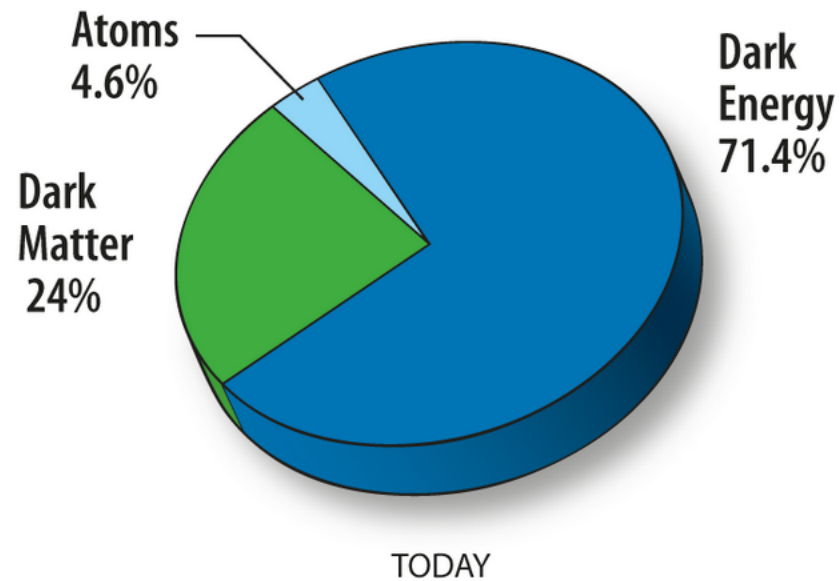
$$G_{\mu\nu} + \Lambda g_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu}$$

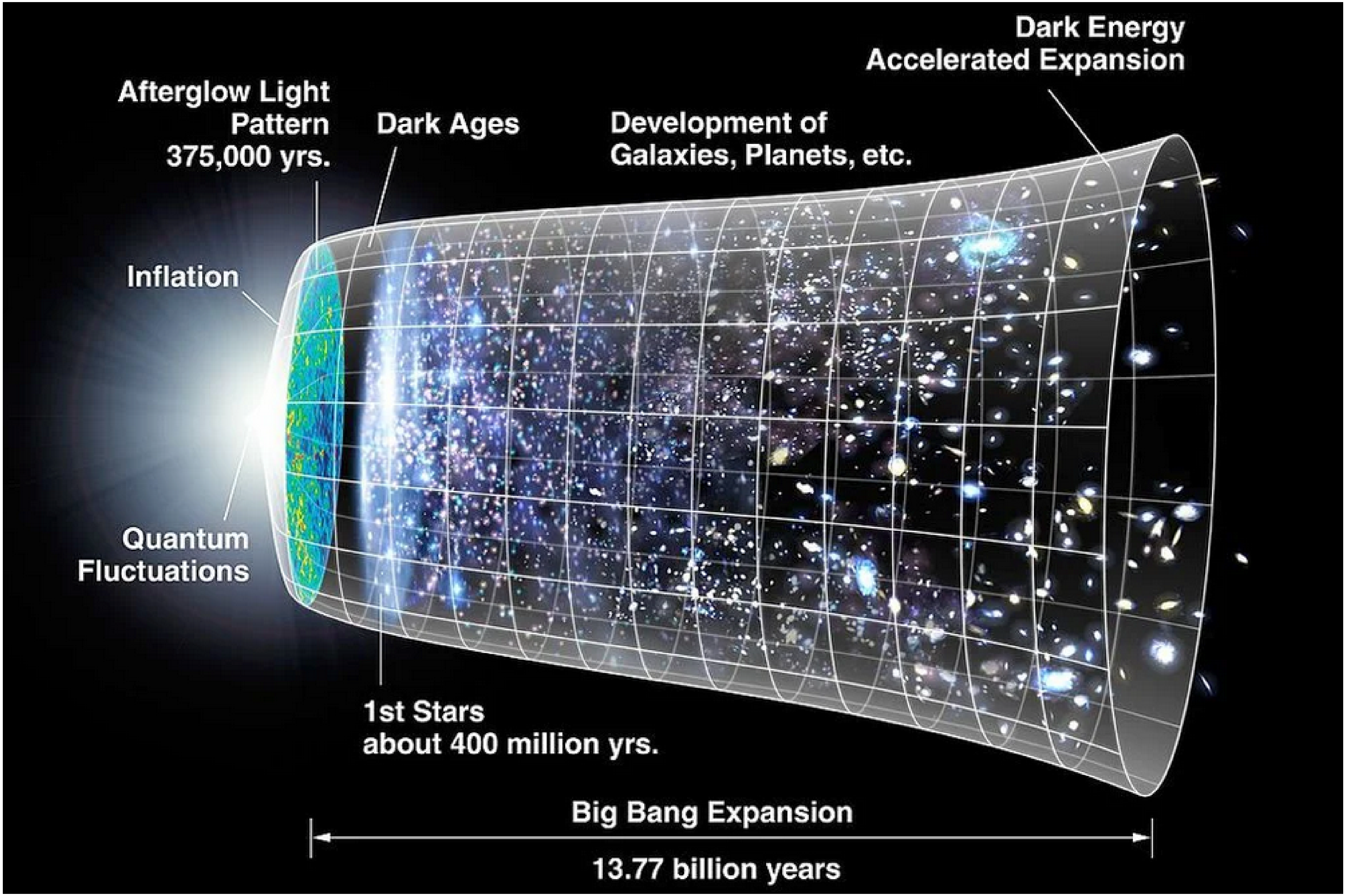
$$ds^2 = c^2 dt^2 - a^2(t)\left[\frac{dr^2}{1-kr^2} + r^2 d\Omega^2\right]$$

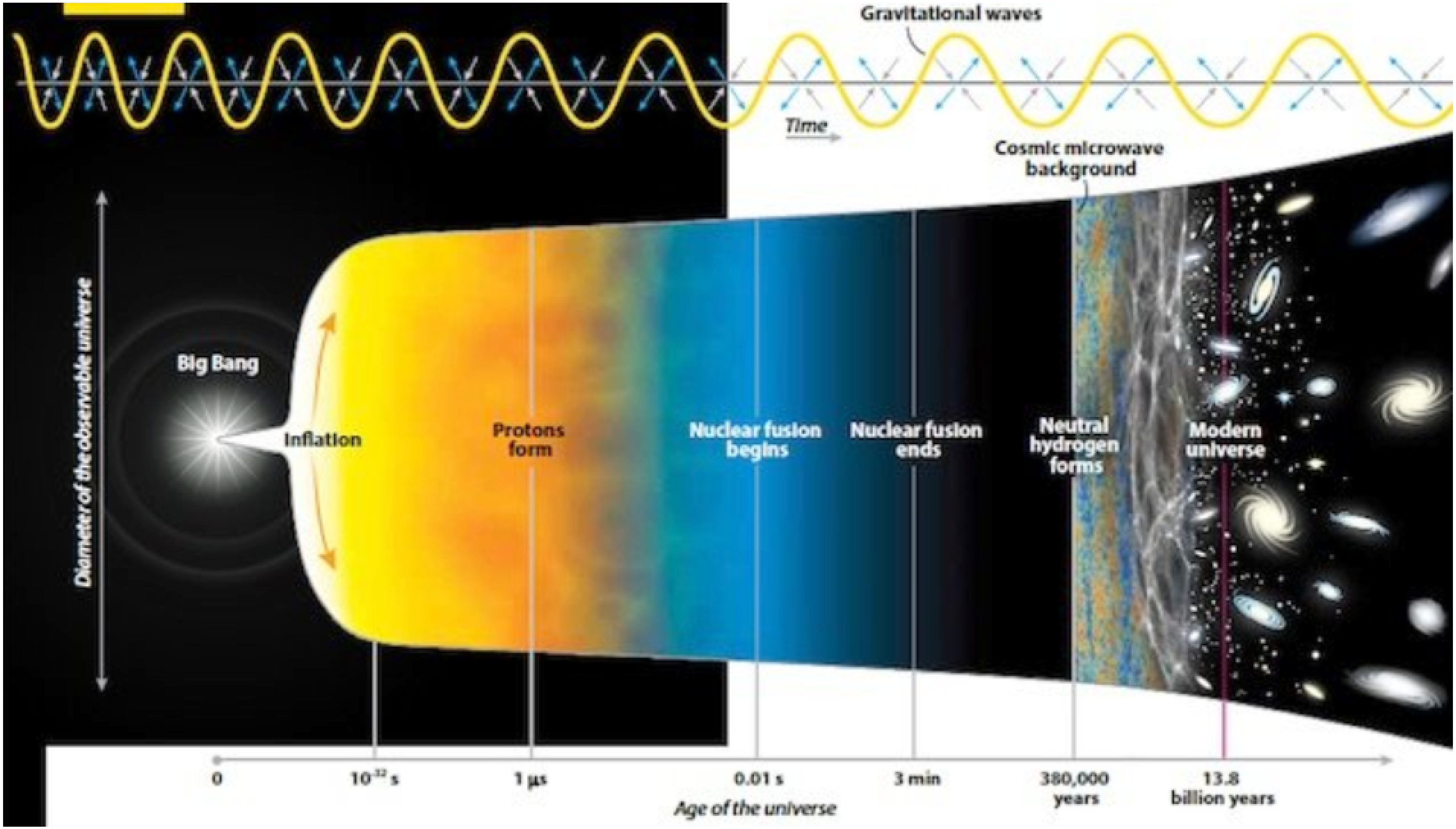
$$\frac{\ddot{a}}{a} = -\frac{4\pi G}{3}\left(\rho + \frac{3p}{c^2}\right) + \frac{\Lambda c^2}{3}$$

FRIEDMANN EQUATIONS

$$\frac{\dot{a}^2 + kc^2}{a^2} = \frac{8\pi G\rho + \Lambda c^2}{3}$$




Dark Energy
Accelerated Expansion
Afterglow Light
Pattern
375,000 yrs.
Dark Ages
Development of
Galaxies, Planets, etc.
Inflation
Quantum
Fluctuations
1st Stars
about 400 million yrs.
Big Bang Expansion
13.77 billion years



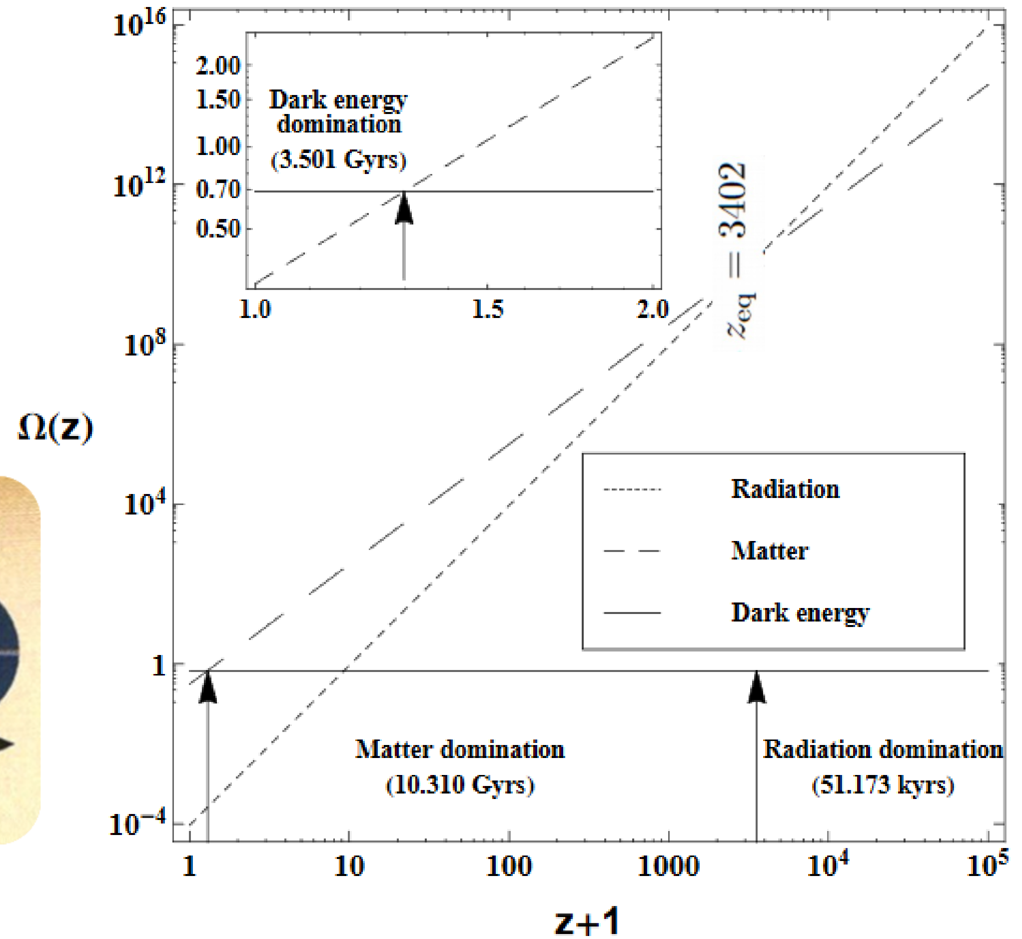
Gravitational waves
Time
Cosmic microwave background
Diameter of the observable universe
Big Bang
Inflation
Protons form
Nuclear fusion begins
Nuclear fusion ends
Neutral hydrogen forms
Modern universe
0
10⁻³² s
1 µs
0.01 s
3 min
380,000 years
13.8 billion years
Age of the universe

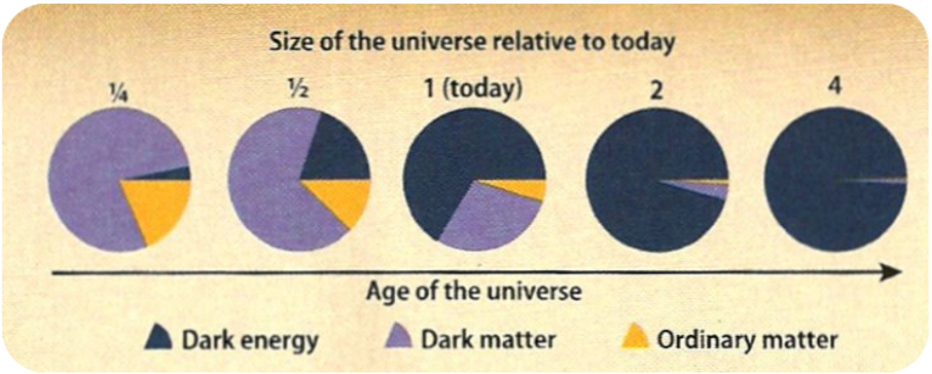
Background history

$$H^2(z) = H_0^2 \left[\Omega_{r0}(1+z)^4 + \Omega_{m0}(1+z)^3 + \Omega_{k0}(1+z)^2 + \Omega_{\Lambda 0}\right]$$

$$\Omega_{m0} = 0.315,\ \Omega_{\Lambda 0} = 0.685 \text{ and } H_0 = 67.3 \text{ km s}^{-1}\text{ Mpc}^{-1}$$

$$\Omega_i(z) = \frac{\rho_i(z)}{\rho_{c0}}$$

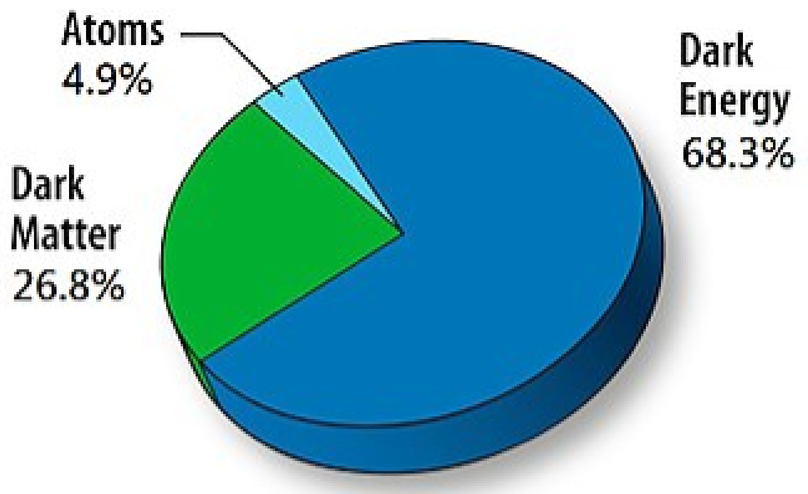




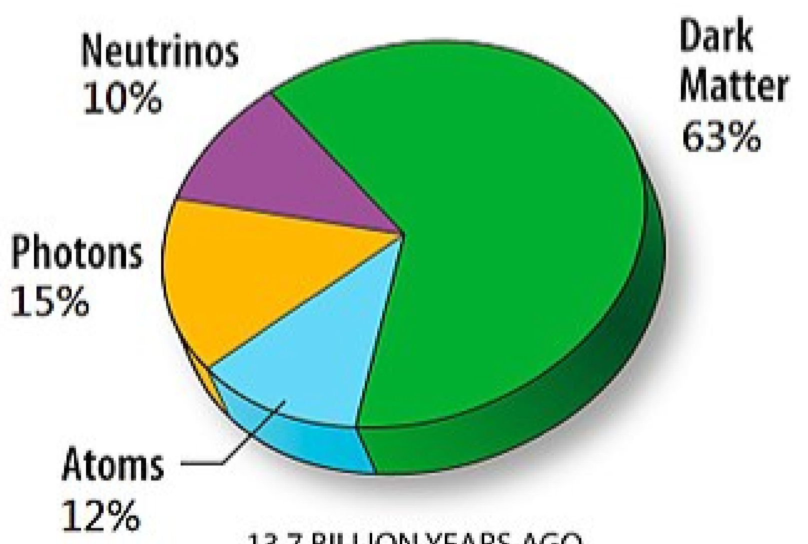
Aspects of the cosmological "coincidence problem"

H. E. S. Velten, R. F. vom Marttens & W. Zimdahl

The European Physical Journal C **74**, Article number: 3160 (2014) | Cite this article

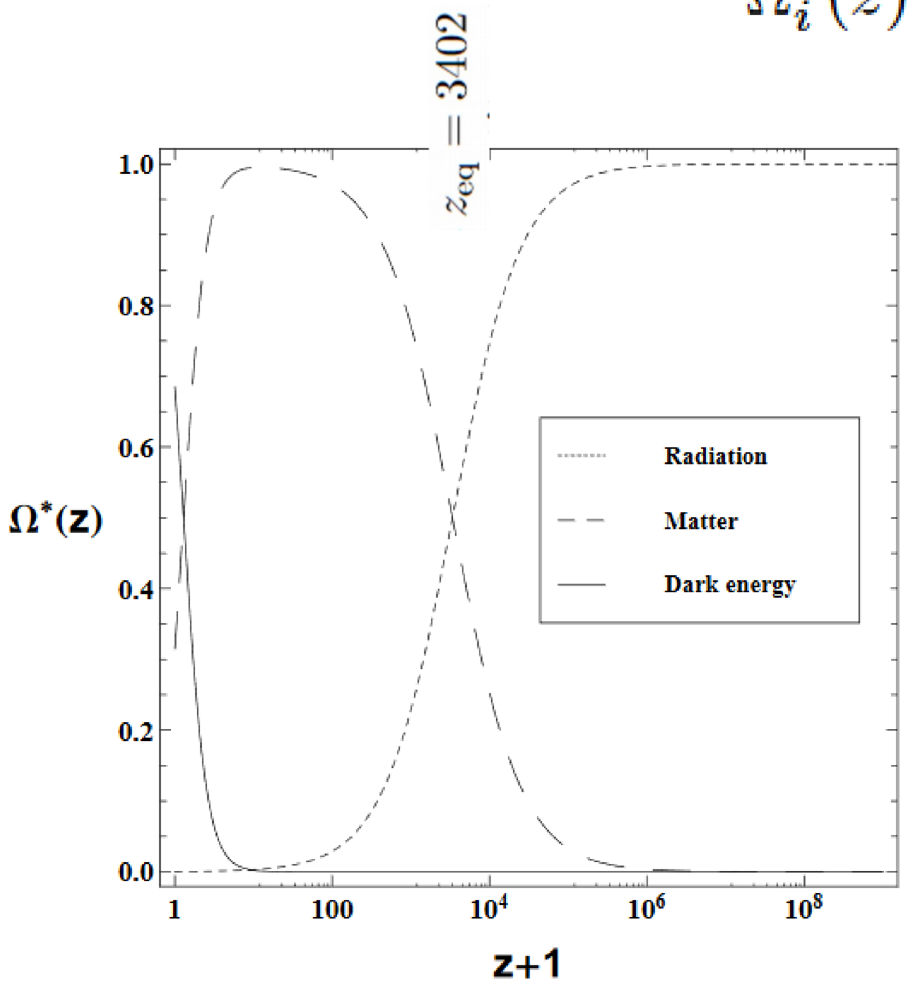


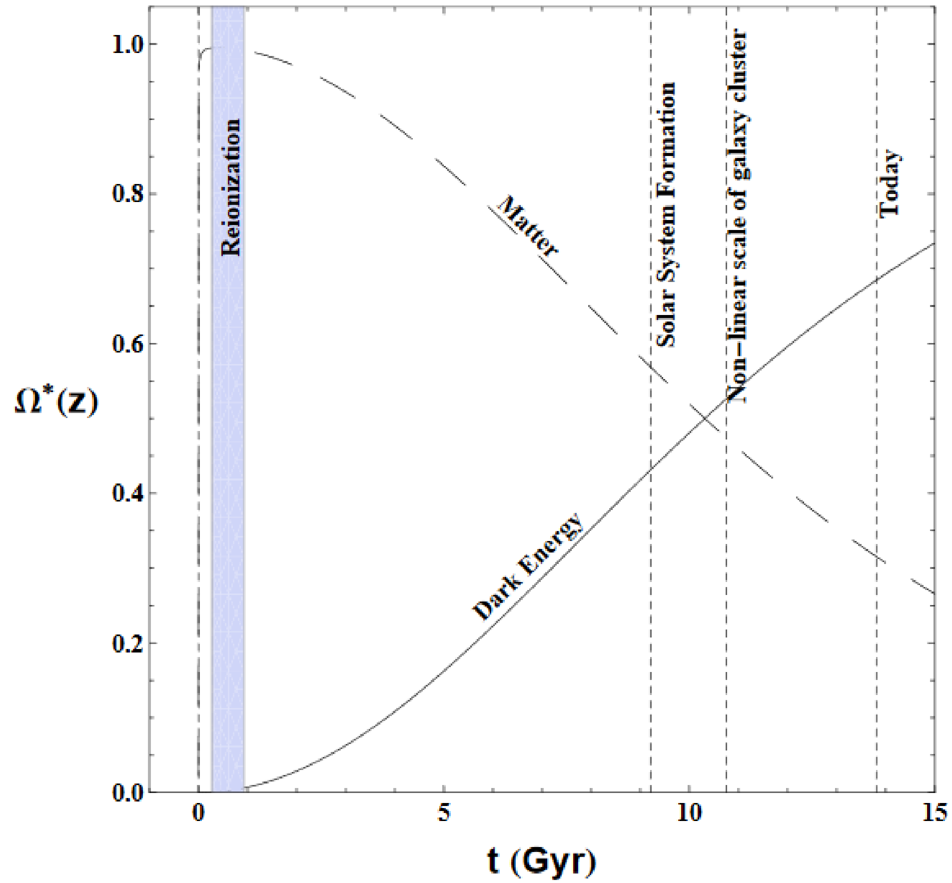
TODAY



13.7 BILLION YEARS AGO
(Universe 380,000 years old)

$$\Omega_i^\star(z) = \frac{\rho_i(z)}{\rho_c(z)}$$





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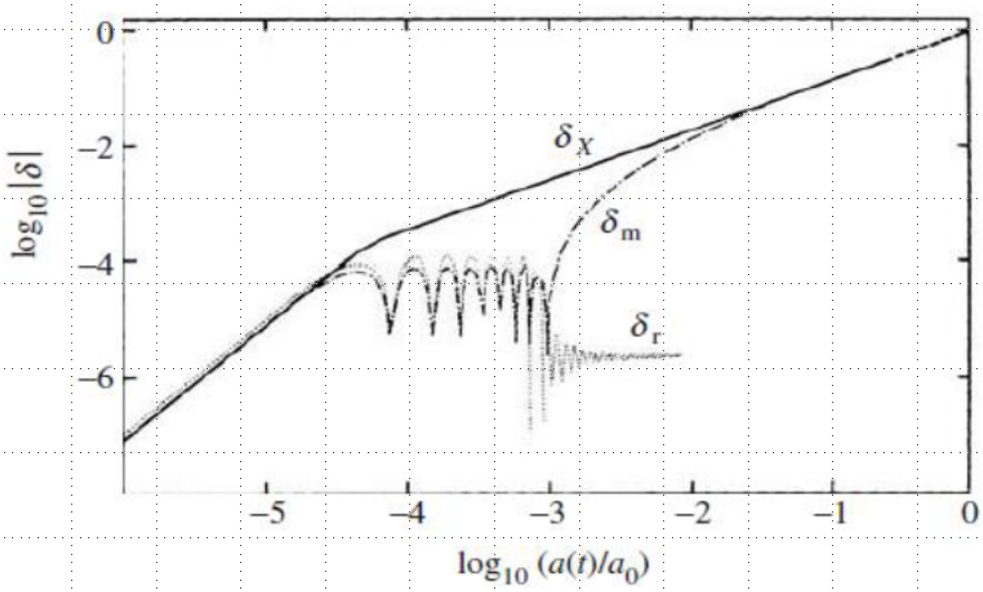
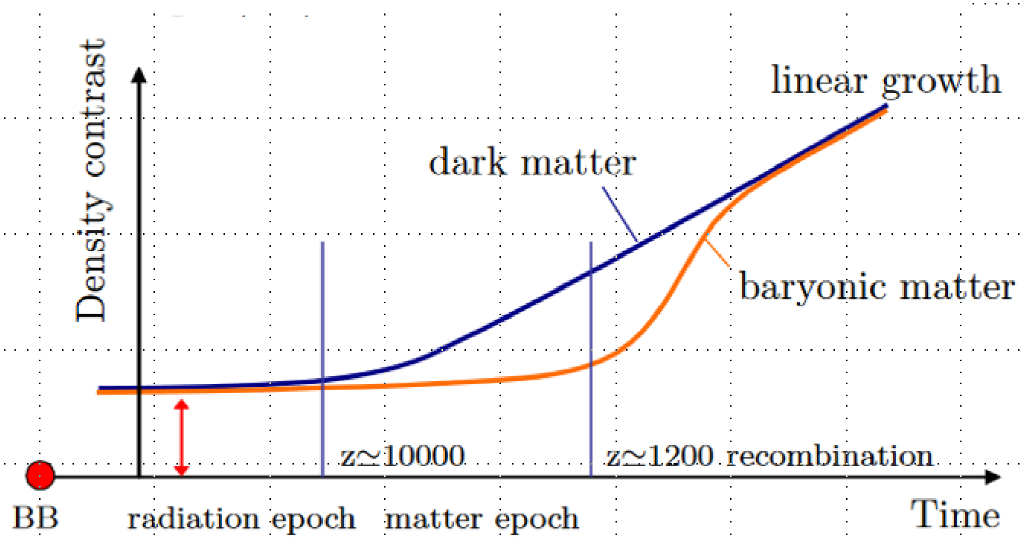
Growth of matter overdensities



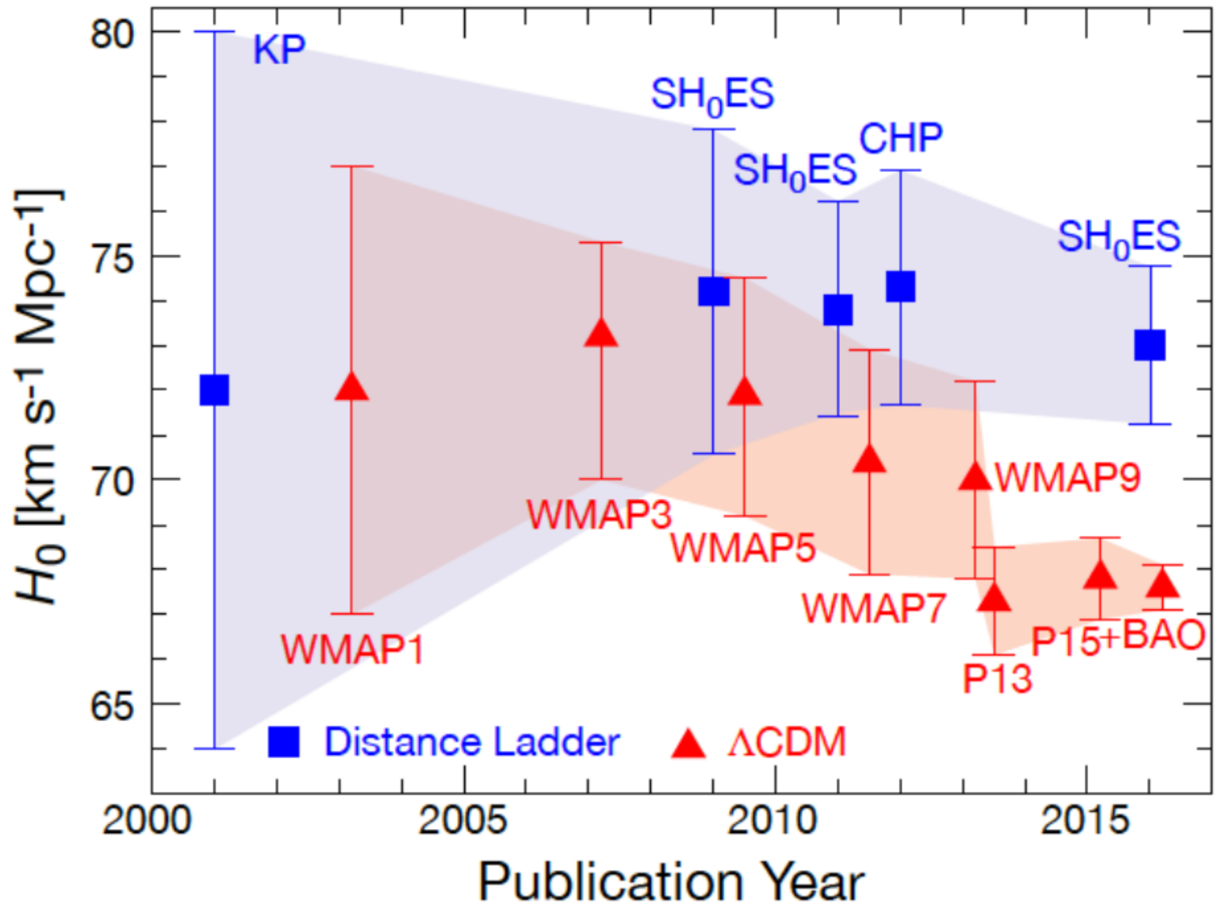


Matter = Dark Matter + Baryonic

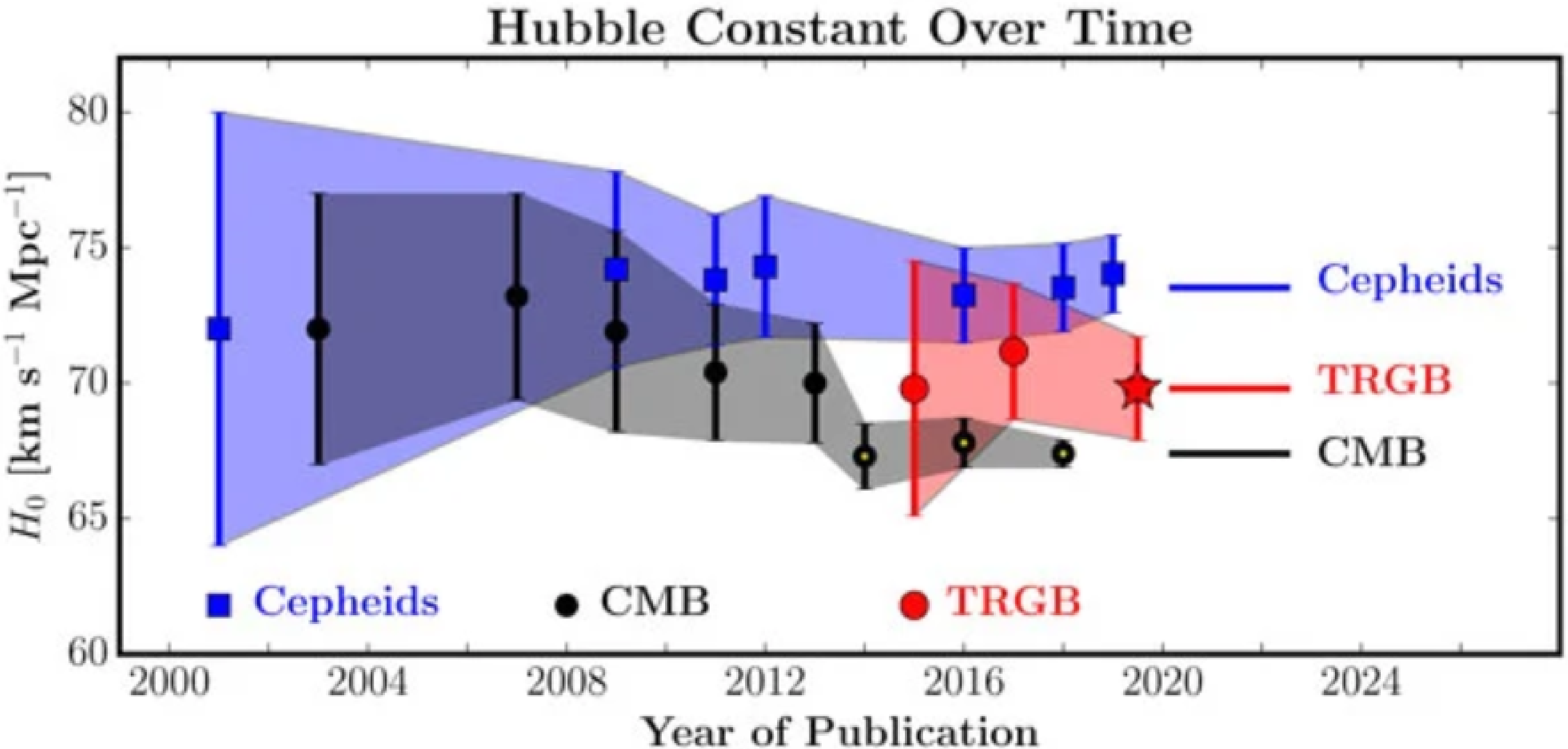
Pillars of the standard cosmology

- Theoretical:
- 1) Cosmological Principle
- 2) GR
- 3) Perfect fluid description of cosmic fluids
- ...
- Observational:
- 1) Expansion (Lemaitre-Hubble law)
- 2)CMB
- 3) BBN
- ...

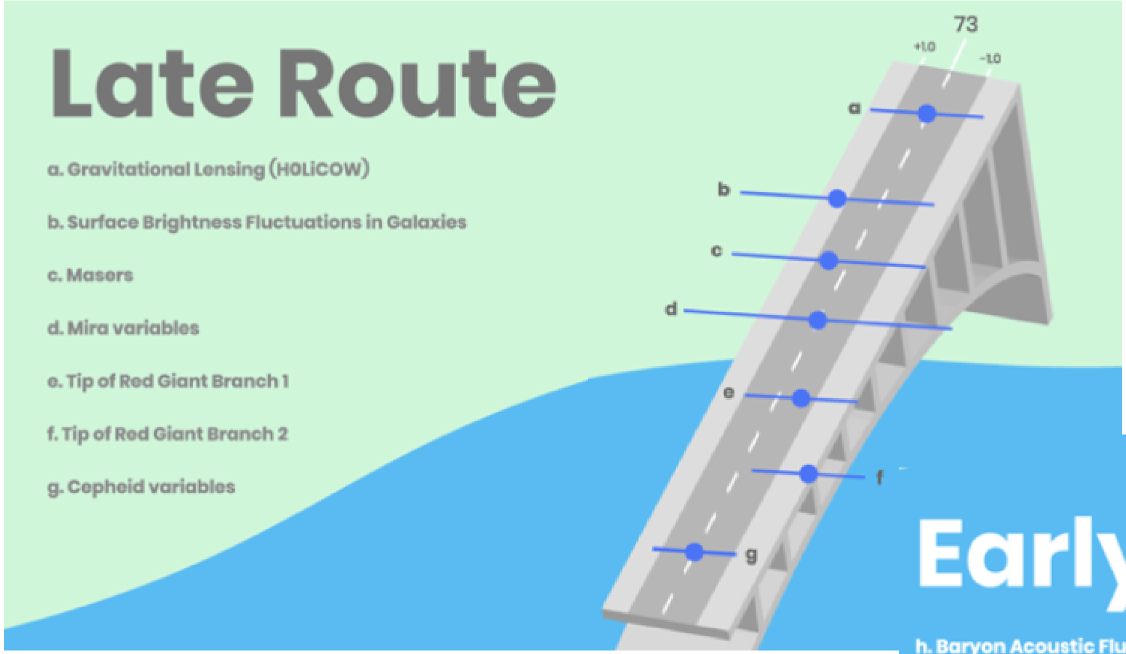
INTRODUCING THE COSMIC TENSION ON H0



Wendy L. Freedman *Nature Astronomy* **1**, Article number: 0121 (2017)

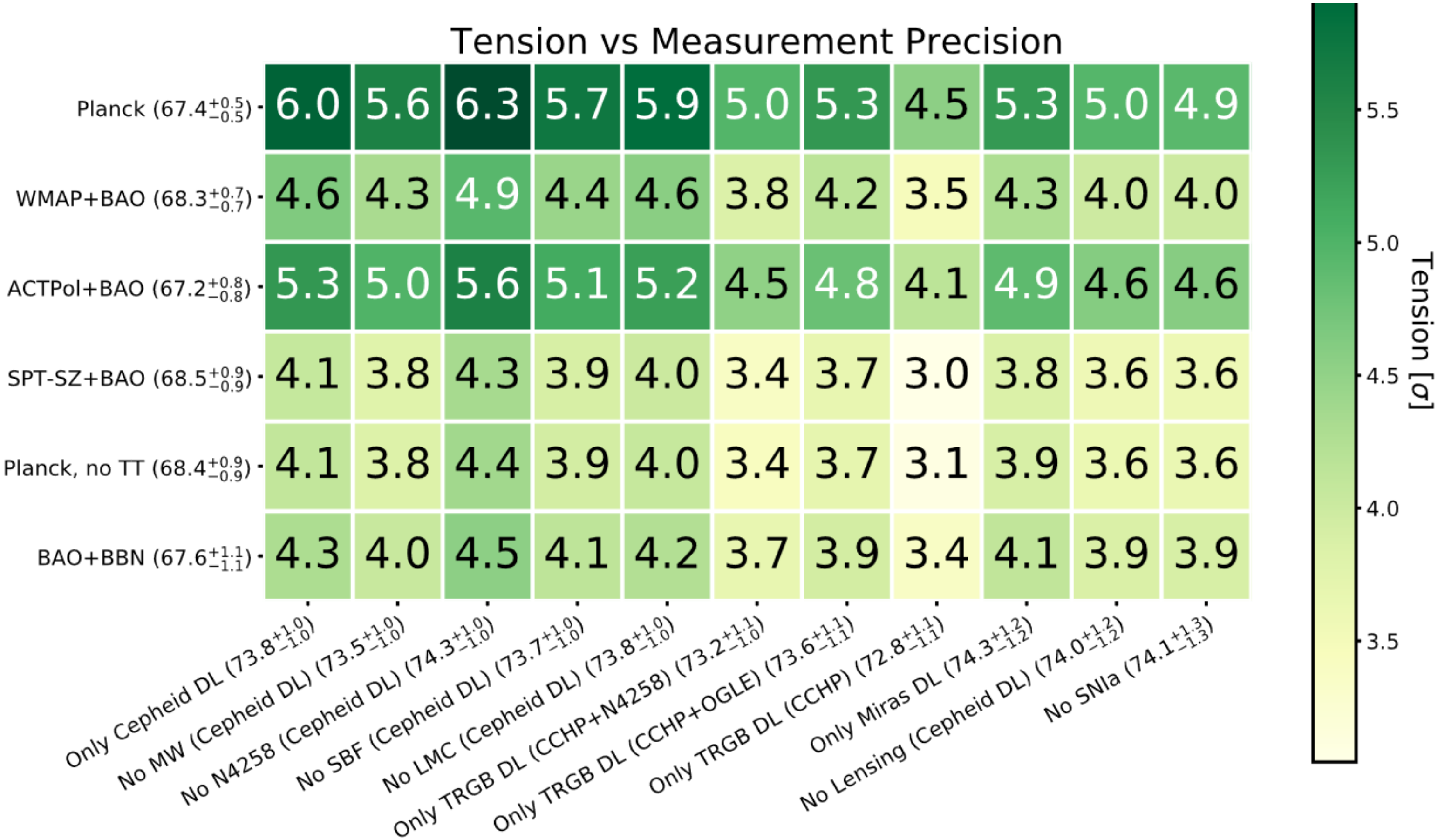

Hubble Constant Over Time
80
75
70
65
60
H_0 [km s^{-1} Mpc^{-1}]
2000
2004
2008
2012
2016
2020
2024
Year of Publication
Cepheids
TRGB
CMB
Cepheids
CMB
TRGB

Introducing the cosmic tension on H0



Credits: ADAM RIESS, Nature Review Physics 2019

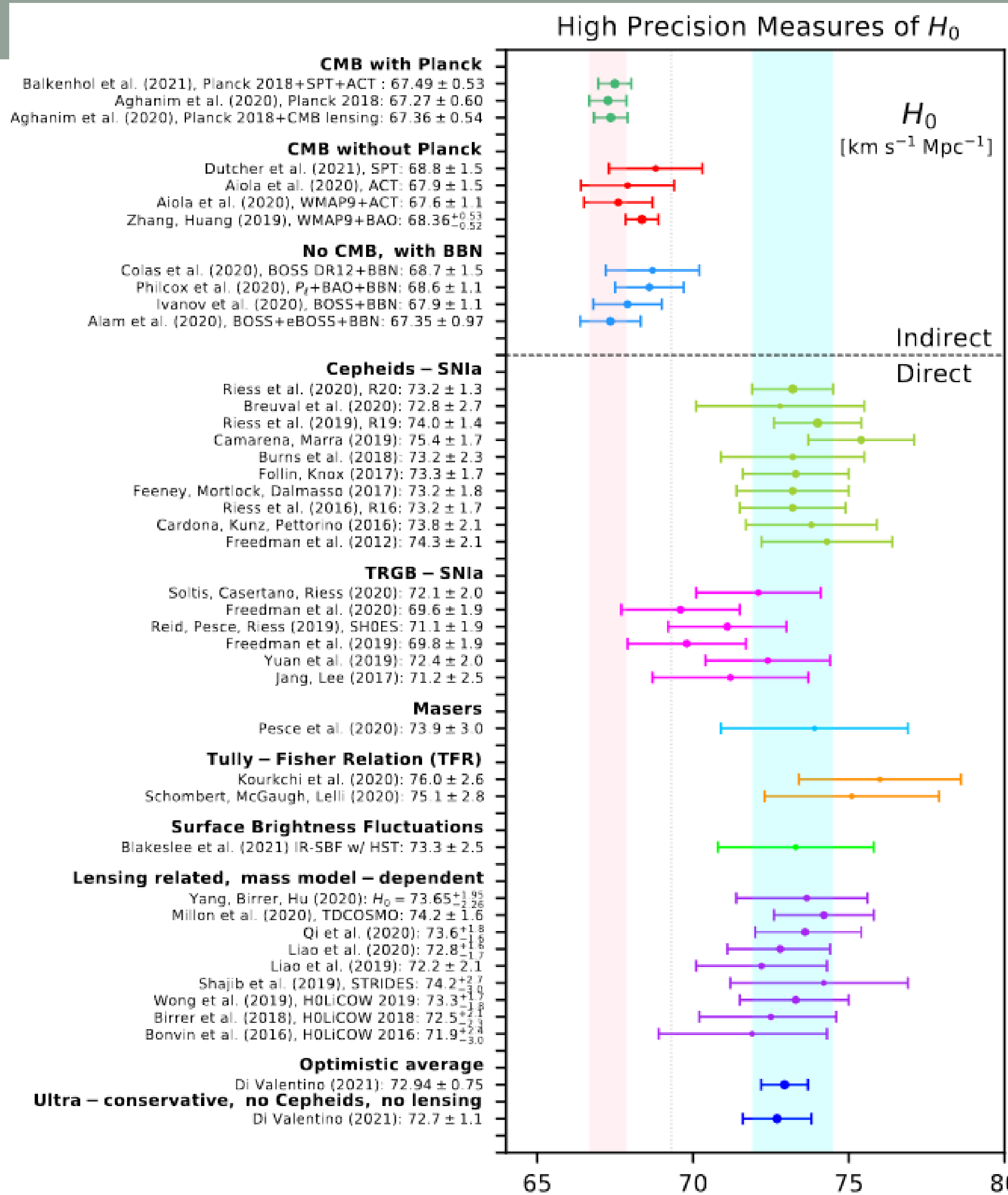
Introducing the cosmic tension on H0



Credits: ADAM RIESS, Nature Review Physics 2019

In the Realm of the Hubble tension – a Review of Solutions †

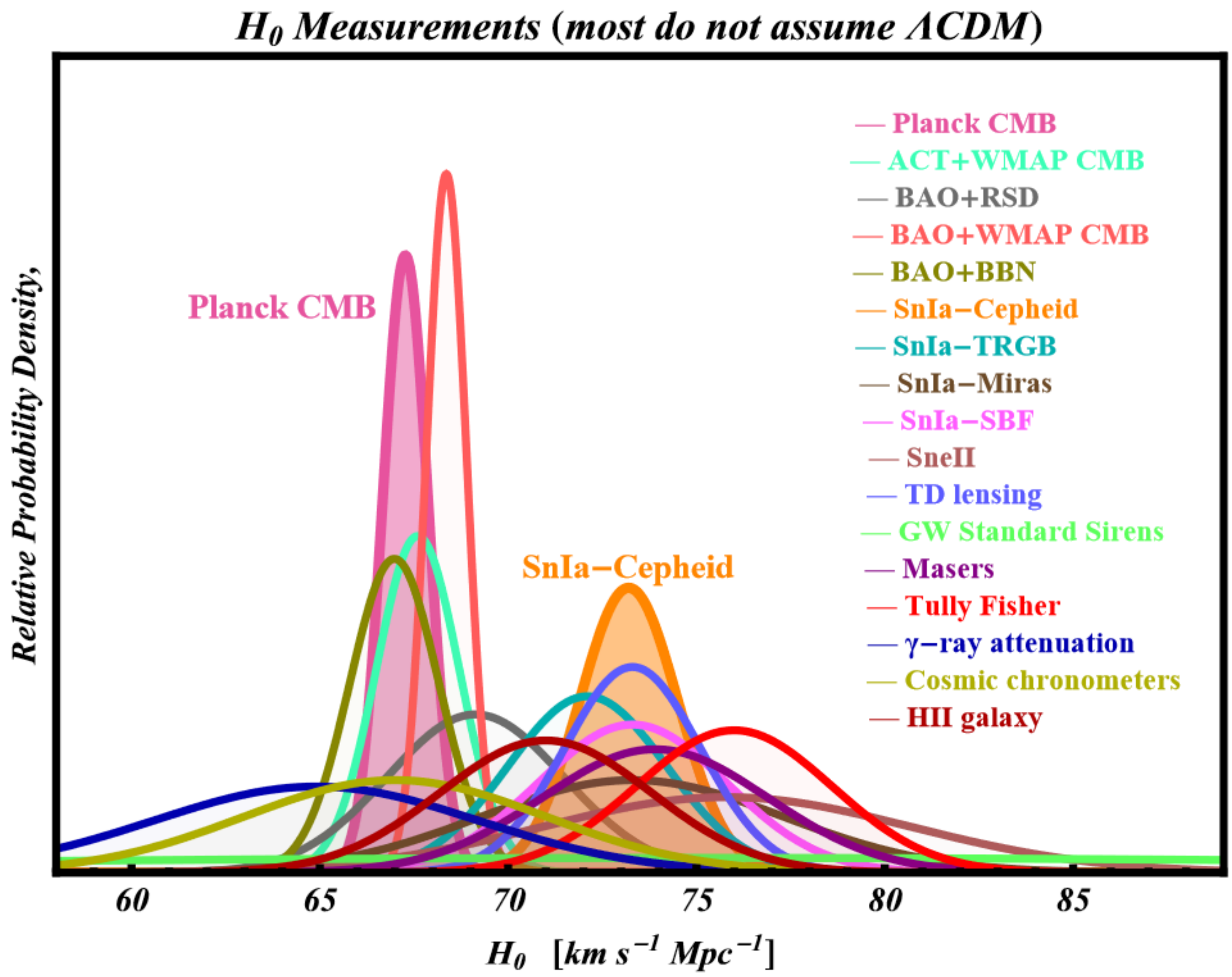
Eleonora Di Valentino[1*], Olga Mena[2], Supriya Pan[3], Luca Visinelli[4], Weiqiang Yang[5], Alessandro Melchiorri[6], David F. Mota[7], Adam G. Riess[8,9], Joseph Silk[8,10,11]



Challenges for ΛCDM : An update

arXiv:2105.05208

L. Perivolaropoulos[1,*] and F. Skara[1,†]
[1]Department of Physics, University of Ioannina, 45110 Ioannina, Greece
(Dated: May 20, 2021)



Early time modifications preferred over late time ones?

To H_0 or not to H_0?

George Efstathiou

Monthly Notices of the Royal Astronomical Society, Volume 505, Issue 3, August 2021, Pages 3866–3872, https://doi.org/10.1093/mnras/stab1588

Published: 05 June 2021 **Article history** ▾

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ABSTRACT

This paper investigates whether changes to late-time physics can resolve the 'Hubble tension'. It is argued that many of the claims in the literature favouring such solutions are caused by a misunderstanding of how distance ladder measurements actually work and, in particular, by the inappropriate use of a distance ladder H_0 prior. A dynamics-free inverse distance ladder shows that changes to late-time physics are strongly constrained observationally and cannot resolve the discrepancy between the SH0ES data and the base ΛCDM cosmology inferred from *Planck*. We propose a statistically rigorous scheme to replace the use of H_0 priors.

It is, therefore, unlikely that changes to the late time expansion history can resolve the 'Hubble tension'. …

Ruling Out New Physics at Low Redshift as a solution to the H_0 Tension

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KASI Campus, University of Science and Technology,
217 Gajeong-ro, Yuseong-gu, Daejeon 34113, Korea
(Dated: June 20, 2022)

We make the case that there can be no low-redshift solution to the H_0 tension. To robustly answer this question, we use a very flexible parameterization for the dark energy equation of state such that every cosmological distance still allowed by data exists within this prior volume. To then answer whether there exists a satisfactory solution to the H_0 tension within this comprehensive parameterization, we constrained the parametric form using different partitions of the Planck cosmic microwave background, SDSS-IV/eBOSS DR16 baryon acoustic oscillation, and Pantheon supernova datasets. When constrained by just the cosmic microwave background dataset, there exists a set of equations of state which yields high H_0 values, but these equations of state are ruled out by the combination of the supernova and baryon acoustic oscillation datasets. In other words, the constraint from the cosmic microwave background, baryon acoustic oscillation, and supernova datasets together does not allow for high H_0 values and converges around an equation of state consistent with a cosmological constant. Thus, since this very flexible parameterization does not offer a solution to the H_0 tension, there can be no solution to the H_0 tension that adds physics at only low redshifts.

To fit both the H_0 and CMB constraints, a successful model that adds physics at low redshift must have a faster-than-ΛCDM expansion history at low redshift and a slower-than-ΛCDM expansion history at high redshift.

Pillars of the standard cosmology

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- ...
- Observational:
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- 2)CMB
- 3) BBN
- ...

Motivation of this work

Mon. Not. R. Astron. Soc. **280,** 1239–1243 (1996)

'Understanding' cosmological bulk viscosity

Winfried Zimdahl[1,2]

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ABSTRACT

A universe consisting of two interacting perfect fluids with the same 4-velocity is considered. A heuristic mean free time argument is used to show that the system as a whole cannot also be perfect, but necessarily implies a non-vanishing bulk viscosity. A new formula for the bulk viscosity is derived and compared with corresponding results of radiative hydrodynamics.

Key words: hydrodynamics – radiative transfer – relativity – cosmology: theory.

Mon. Not. R. Astron. Soc. **280**, 1239–1243 (1996)

It is the aim of this paper to show that *different cooling rates for two perfect fluids are sufficient for the existence of a non-vanishing bulk viscosity of the system as a whole.* No additional concept, such as that of a heat flux over inter-molecular distances, is required. The basic idea is to study a universe of two different interacting perfect fluids and to seek the conditions under which an effective one-fluid description is possible. It turns out that this one-fluid universe is necessarily dissipative.

TWO-FLUID DYNAMICS

$$T^{ik} = T_1^{ik} + T_2^{ik},$$

with $(A = 1, 2)$

$$T_A^{ik} = \rho_A u^i u^k + p_A h^{ik}$$

$$T^{ik}_{A;k} = 0,$$

implying the energy balances

$$\dot{\rho}_A = -\Theta(\rho_A + p_A),$$

$$p_A = p_A(n_A, T_A)$$

$$\rho_A = \rho_A(n_A, T_A),$$

$$\frac{\partial \rho_A}{\partial n_A} = \frac{\rho_A + p_A}{n_A} - \frac{T_A}{n_A}\frac{\partial p_A}{\partial T_A};$$

Mon. Not. R. Astron. Soc. **280**, 1239–1243 (1996)

EFFECTIVE ONE-FLUID DYNAMICS

Assumption: Fluids are allowed to interact

Total effective fluid characterized by the total particle number and equilibrium temperature:

$$n = n_1 + n_2$$

equilibrium temperature T.

$$p = p(n, T) \qquad \rho = \rho(n, T)$$

Definition of the equilibrium temperature set by energy conservation (extensive variable):

$$\rho_1(n_1, T_1) + \rho_2(n_2, T_2) = \rho(n, T)$$

Mon. Not. R. Astron. Soc. **280**, 1239–1243 (1996)

For pressure (intensive thermodynamical variable) :

$$p_1(n_1, T_1) + p_2(n_2, T_2) \neq p(n, T)$$

For perfect fluids 1 and 2 the difference between both sides of the above inequality is the viscous pressure

$$\pi = p_1(n_1, T_1) + p_2(n_2, T_2) - p(n, T)$$

All effects of dissipation thus show up as contributions to $\Delta T^{\alpha\beta}$. Our task is now to construct the most general possible dissipative tensor $\Delta T^{\alpha\beta}$ allowed by Eq. (2.11.8) and by the second law of thermodynamics.

$$U^\alpha U^\beta \Delta T_{\alpha\beta} = 0$$

S.Weinberg, Gravitation and cosmology: principles and applications of GR, John Wiley and Sons, 1972

Mon. Not. R. Astron. Soc. **280**, 1239–1243 (1996)

Assumption: Let τ ( ) be the characteristic mean free time for the interaction between both components.

An element of the cosmic fluid is at equilibrium at a proper time η_0

$$T(\eta_0) = T_1(\eta_0) = T_2(\eta_0)$$

During the following time interval τ, that is, untill a subsequent "collision" the subsystems move freely according to their internal dynamics. Then, at $\eta_0 + \tau$

$$\rho_A(\eta_0 + \tau) = \rho_A(\eta_0) + \tau\dot{\rho}_A(\eta_0) + \dots$$

$$T(\eta_0 + \tau) \neq T_1(\eta_0 + \tau) \neq T_2(\eta_0 + \tau) \neq T(\eta_0 + \tau)$$

$$T_A(\eta_0 + \tau) = T_A(\eta_0) + \tau\dot{T}_A(\eta_0) + \dots$$

Mon. Not. R. Astron. Soc. 280, 1239–1243 (1996)

Finally, by assuming that the bulk viscous pressure is given by the Eckart theory

$$\pi = -\zeta\Theta$$

And applying well known thermodynamical relations one finds the bulk viscous coefficient

$$\zeta = -\tau T \frac{\partial\rho}{\partial T}\left(\frac{\partial p_1}{\partial\rho_1} - \frac{\partial p}{\partial\rho}\right)\left(\frac{\partial p_2}{\partial\rho_2} - \frac{\partial p}{\partial\rho}\right)$$

Let us apply the previous formula for the bulk viscous pressure to the system: Matter + Radiation

Radiation: $p_r = n_r k_B T_r, \quad \rho_r = 3 n_r k_B T_r,$

Matter: $p_\chi = n_\chi k_B T_\chi, \quad \rho_\chi = n_\chi m_\chi c^2 + \frac{3}{2} n_\chi k_B T_\chi,$

The dark matter particle

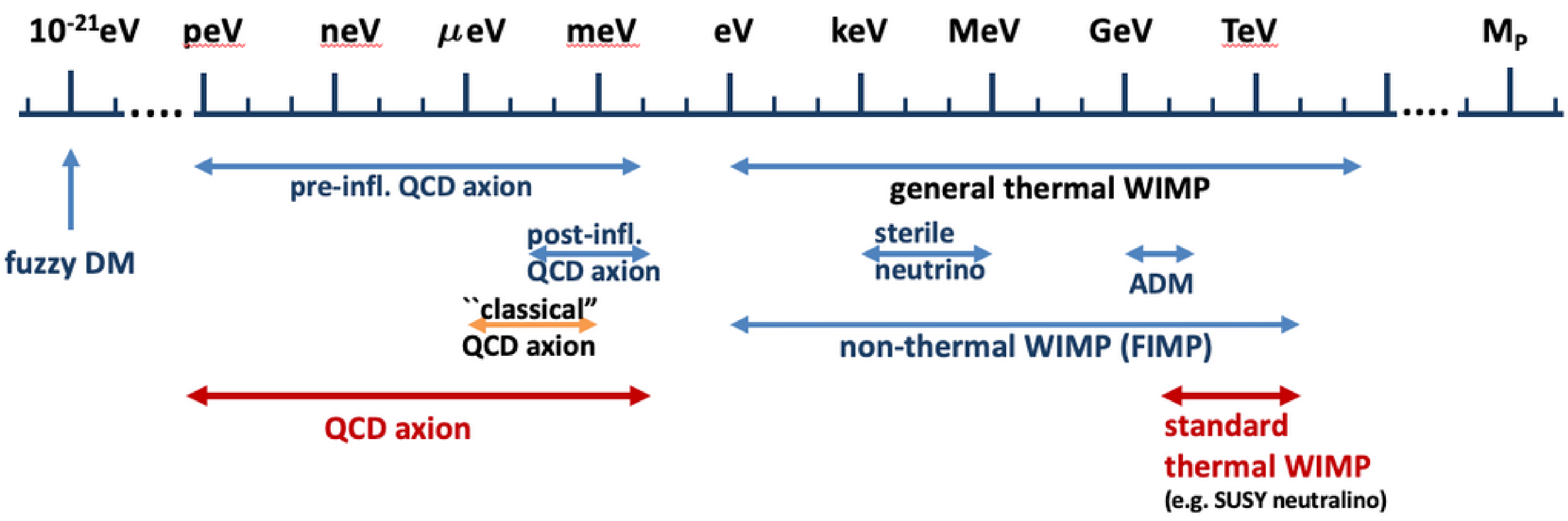
Minimum requirements for such particle candidate

1) To Interact gravitationally;
2) Electrically neutral, otherwise it had already been detected;
3) Very small cross section (explains the lack of positive direct detection results);

Hot dark matter: light and fast (non competitive models)

Cold dark matter: heavy and slow (prevailing view)

Warm dark matter: something between Hot and Cold e Hot!



The fluid description employed here is valid as long as

$$\tau << H^{-1}$$

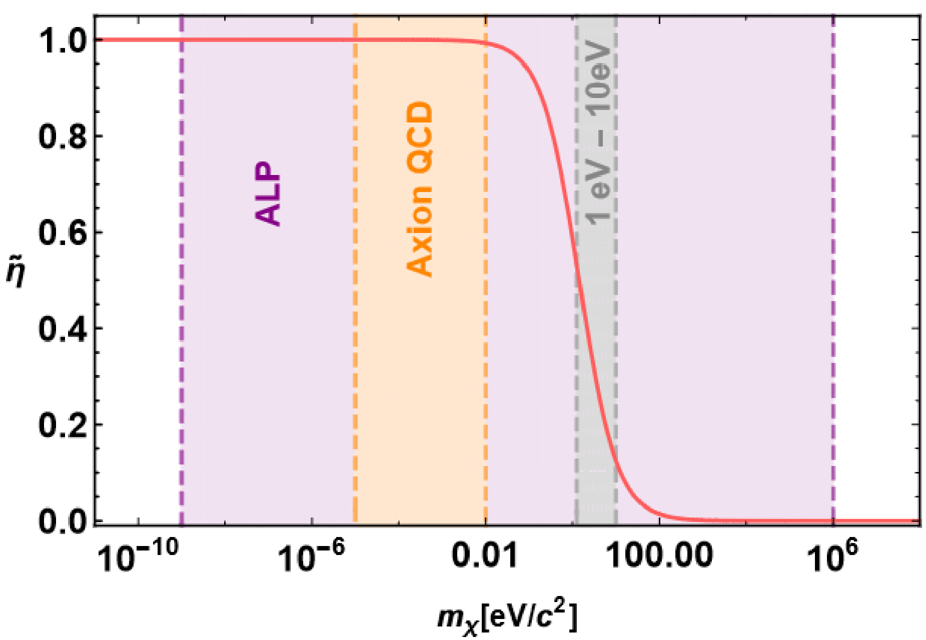
Definition:

$$\xi = \tau \frac{n_r k_B T}{3} \frac{n_\chi}{2n_r + n_\chi} = \frac{\rho_r}{9}\tilde{\eta}\tau,$$

$$\tilde{\eta} \equiv \frac{\eta_{\chi r}}{2 + \eta_{\chi r}}, \quad \eta_{\chi r} \equiv \frac{n_\chi}{n_r}.$$

$$\eta_{\chi r} = \frac{n_\chi}{n_r} = \frac{n_B}{n_r}\frac{n_\chi}{n_B} \approx \frac{n_B}{n_r}\frac{\rho_\chi/m_\chi}{\rho_B/m_B}$$

$$\approx 5\frac{n_B}{n_r}\frac{m_B}{m_\chi} \approx \frac{2.9}{m_\chi}[eV/c^2].$$



Interesting mass regime:

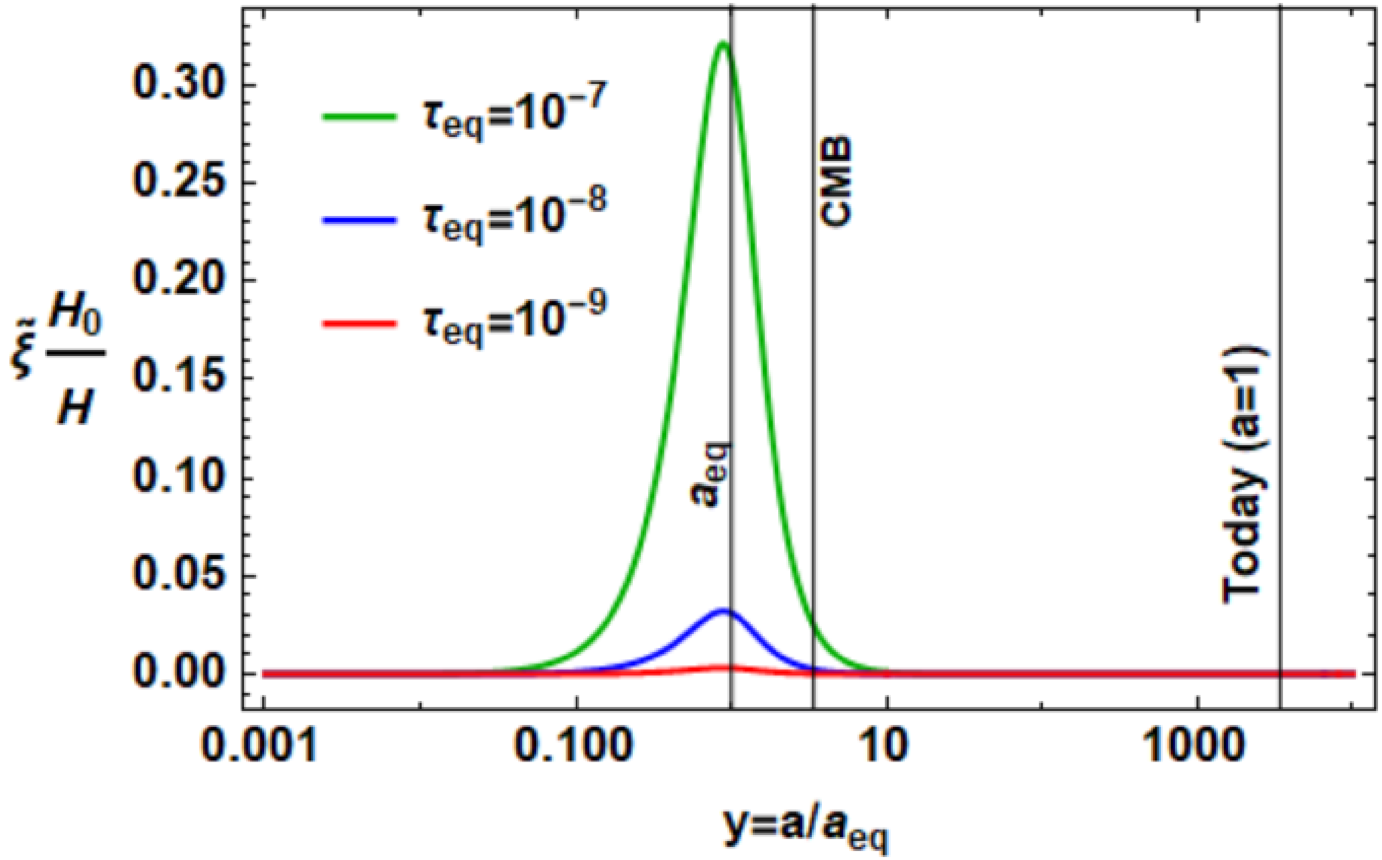
$$1\text{eV} \lesssim m_\chi \lesssim 10\text{eV}$$

Below 1eV the particle becomes too relativistic; T(eq) ~ 0.6 eV

Above 10eV the effect vanishes

Magnitude of the effect (fixing dark matter mass = 1 eV)

$$\tilde{\xi}\frac{H_0}{H} = \tau(y)\frac{H_0^2}{H}\Omega_r\,\tilde{\eta} \qquad \tau(y) = \tau_{eq}\frac{H_{eq}}{H}\left(\frac{2y^2}{1+y^4}\right)$$



The background expansion is modified well before CMB!

Background effects

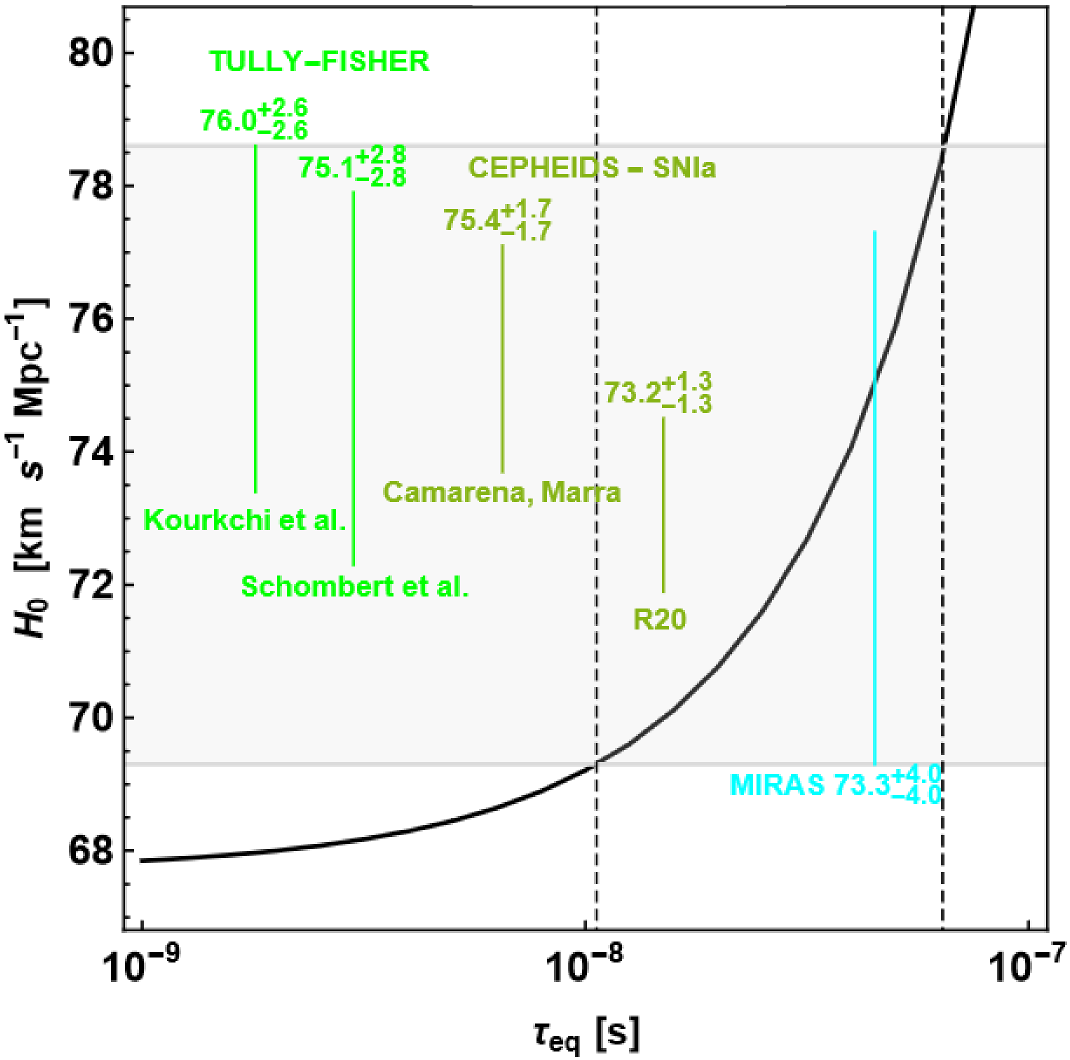
$$2Ea\frac{dE}{da}+3E^2\left(1-\frac{\tilde{\xi}}{3E}\right)+\frac{\Omega_{r0}}{a^4}-3(1-\Omega_{r0}-\Omega_{m0})=0. \qquad E(a_i)=\frac{H_\Lambda(a_i)}{H_0^{cmb}},$$

Steps:

1) Starting with H_0= 67.4 km/s/Mpc;
2) Integrate back in time assuming standard LCDM dynamics;
3) Find H(z_i), let us say, z_i = 100000;

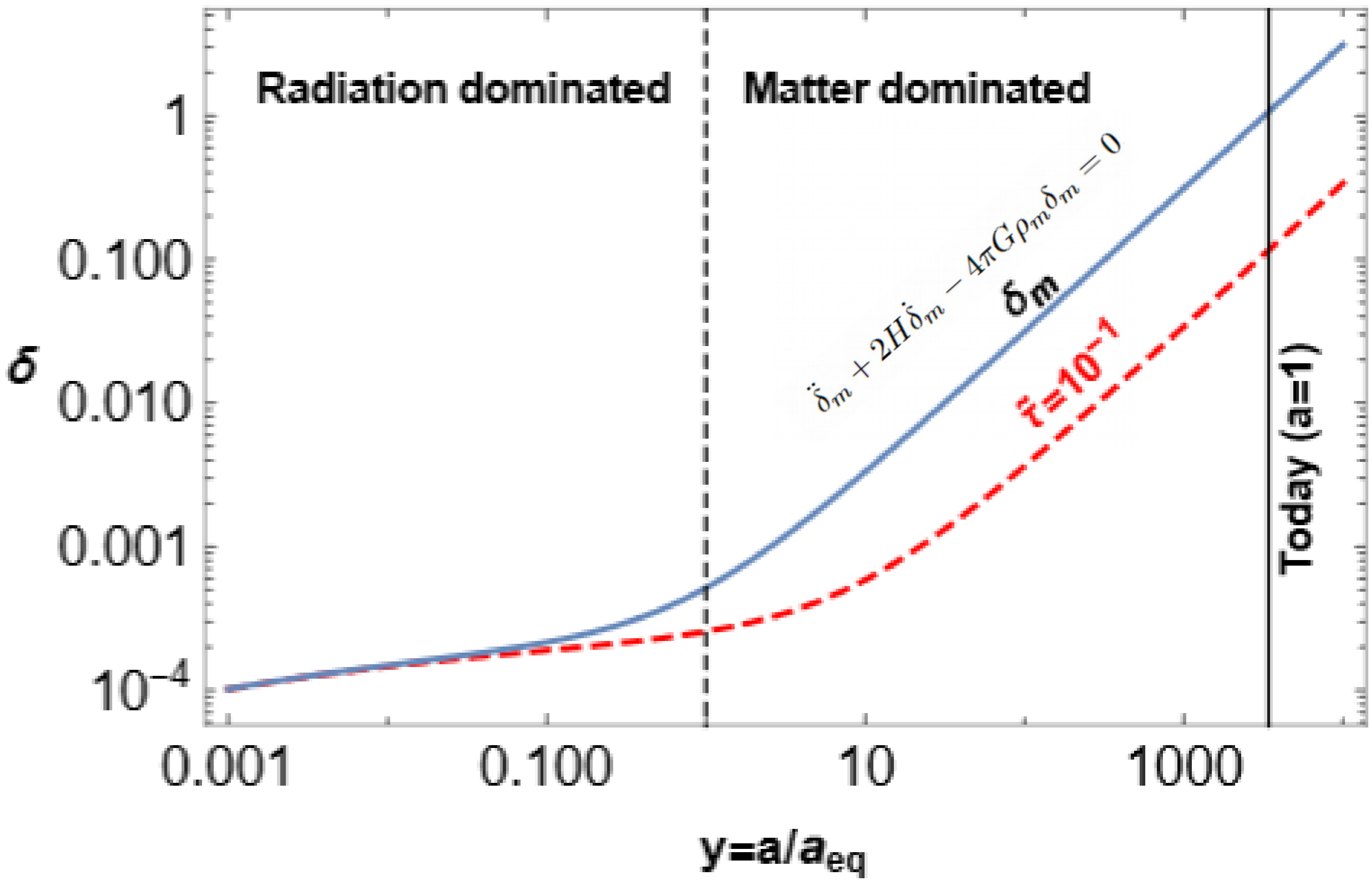
4) Assume the new background dynamics takes into account the bulk viscous pressure around equality only;
5) Integrate the new dynamics from the starting point H(z_i) until z=0.
6) Find new H_0 value as a function of the interacting time scale at equality.

Physical interpretation: While the bulk viscous coefficient is positive, the bulk viscous pressure is negative. Then this yields to an extra "push off" on the expansion around equality.



Large scale structure effects

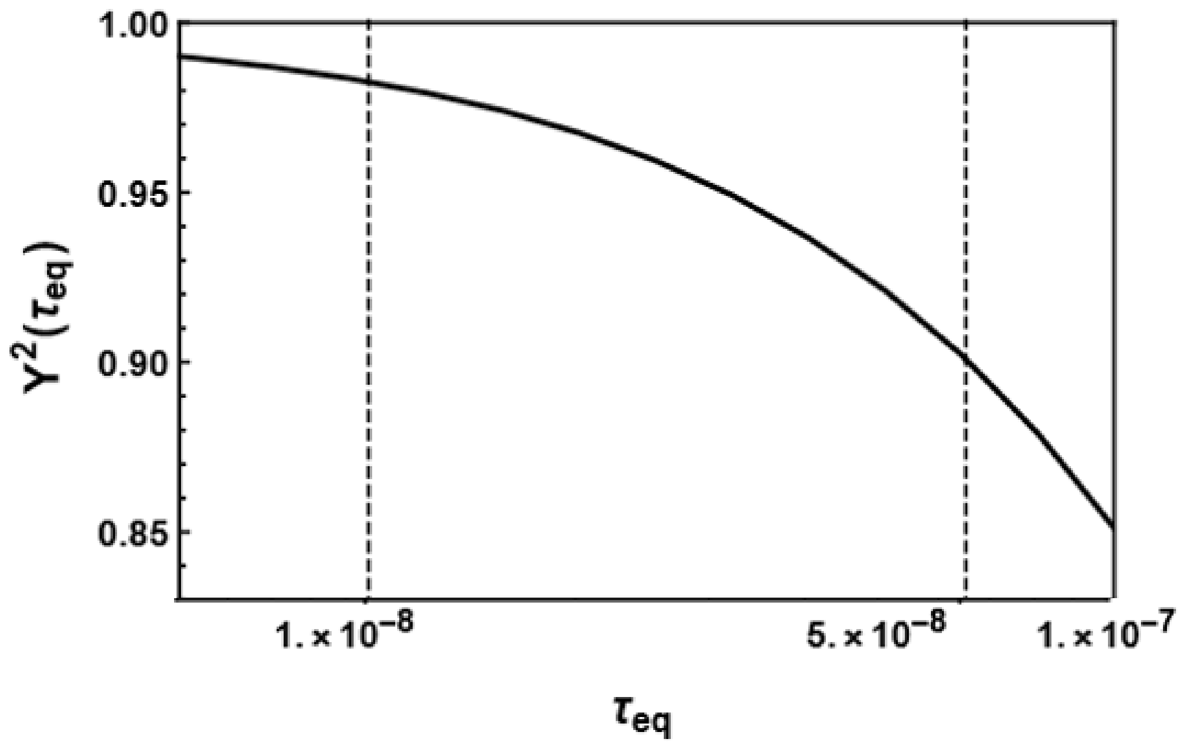
$$\frac{d^2\delta_m}{dy^2} + \left[\frac{(2+3y)}{2y\,(1+y)} + \frac{\tilde{\xi}}{2y}\frac{H_0}{H}\right]\frac{d\delta_m}{dy} - \frac{3}{2y\,(1+y)}\delta_m = 0.$$



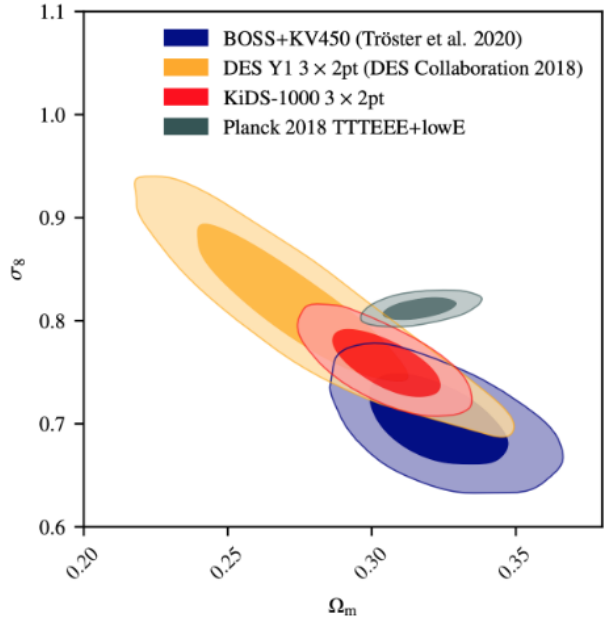
Growth suppression mechanism

A new "transfer function-like Y" contribution to the matter power spectrum P(k)

$$P(k) = \Upsilon^2(\tau_{\rm eq}) D_+^2 T^2(k) A k^n .$$

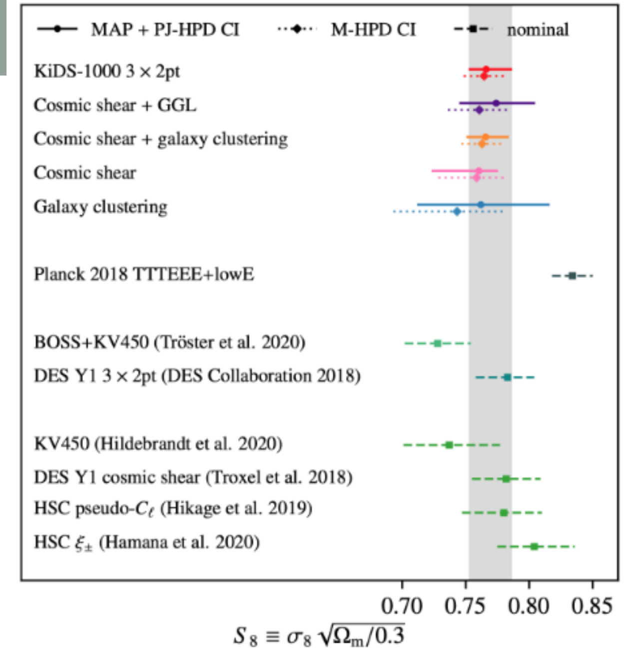


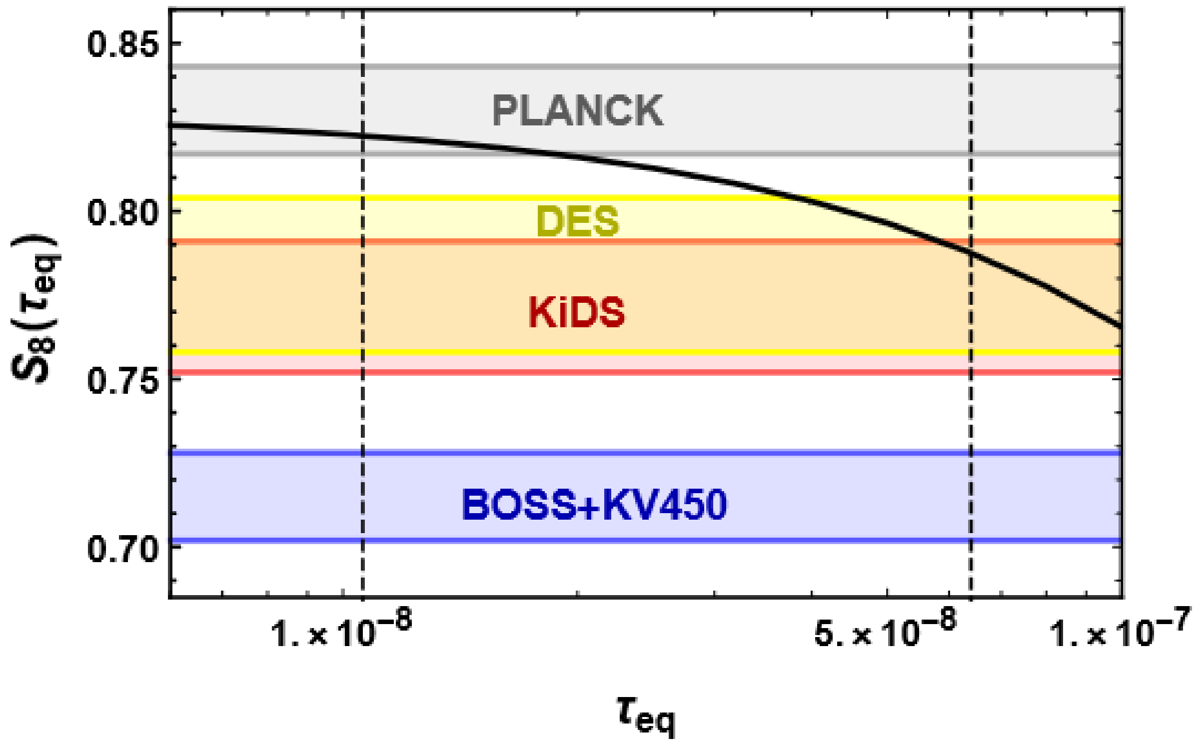
Snowmass2021 (2008.11285)

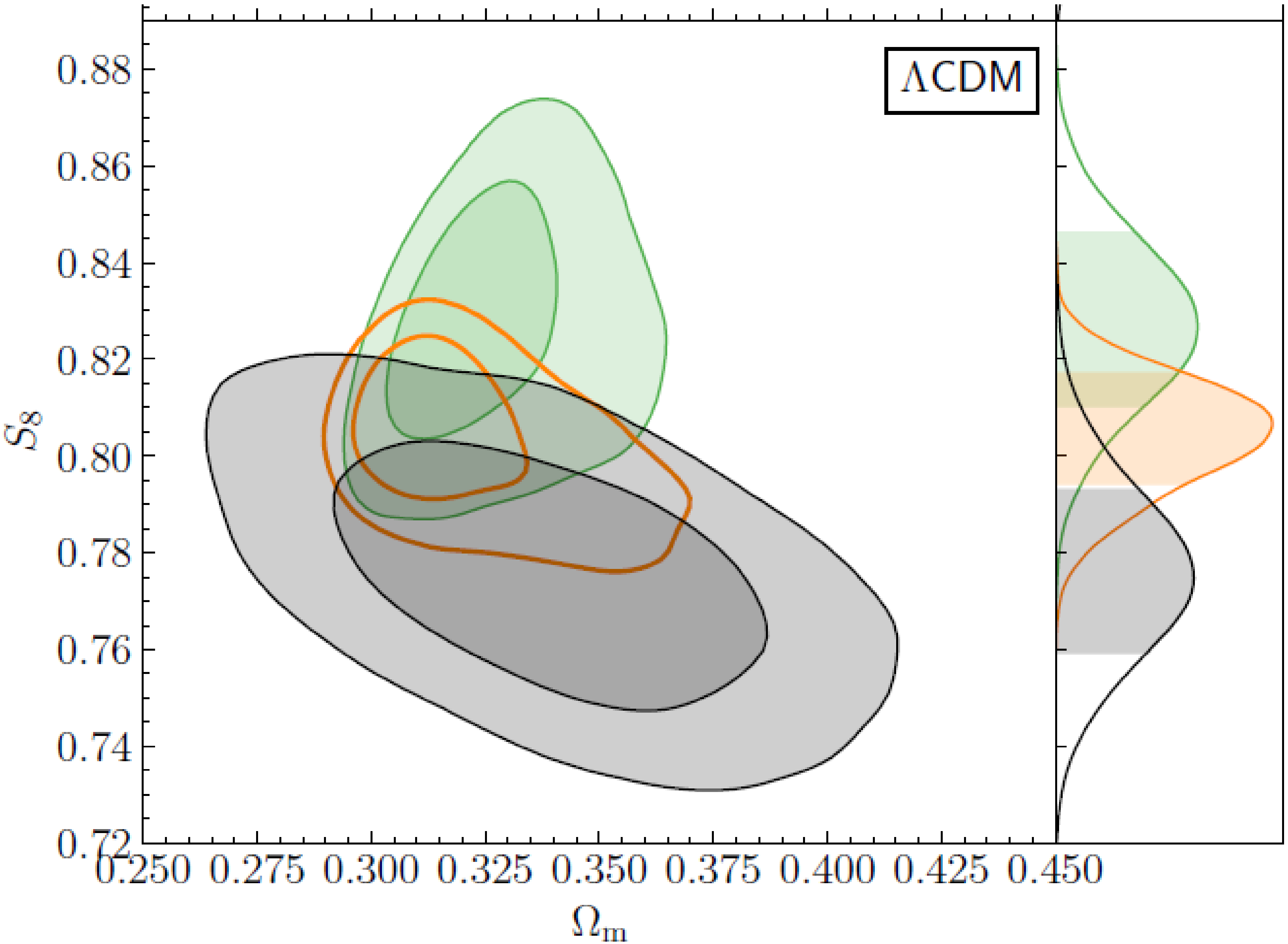


S8 tension

$$S_8 = \sigma_8 \left(\frac{\Omega_{m0}}{0.3} \right)^{1/2}$$





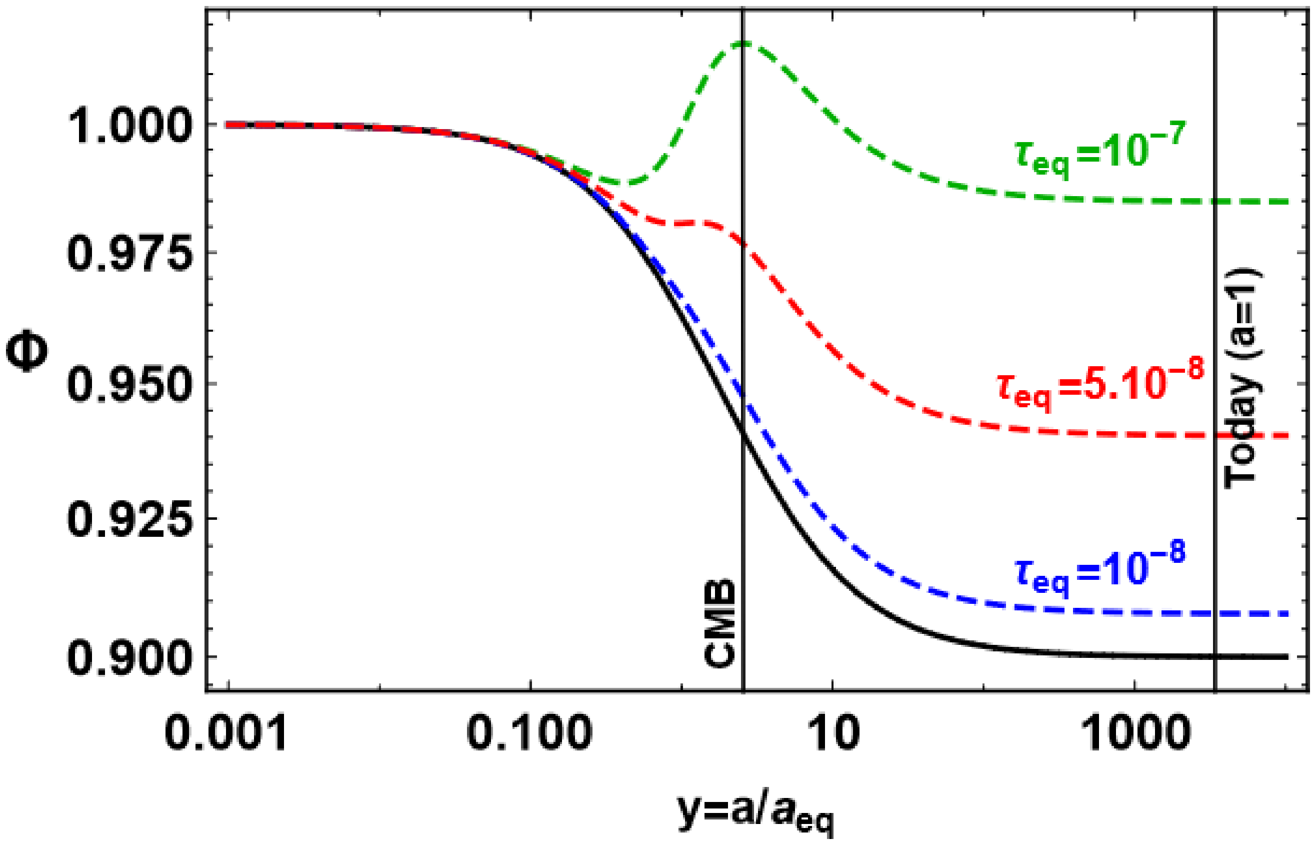


PRD 105 023520 (2022) DES 3Years results

Scales larger than horizon

$$ds^2 = a^2\left[-(1+2\Phi)d\eta^2 + (1+2\Psi)\delta_{ij}dx^i dx^j\right]$$

$$\frac{d^2\Phi}{dy^2} + \left[\frac{21y^2+54y+32}{2y(1+y)(3y+4)}\right]\frac{d\Phi}{dy} + \frac{\Phi}{y(1+y)(3y+4)} = \frac{\tilde{\xi}}{2y^2}\frac{H_0}{H}\Phi + \frac{\tilde{\xi}}{2y}\frac{H_0}{H}\frac{d\Phi}{dy}$$



Summary

- Motivation: Zimdahl MNRAS1995 “An heuristic attempt to clarify the origin of cosmological bulk viscosity”.
- Application to the radiation-matter transition. Due to the multi-fluid nature of the admixture matter + radiation and allowing take interacting takes place the universe experiences the emergence of a cosmological bulk viscosity.
- The net effect: Bulk viscous pressure added to the kinetic pressure of cosmic elements.
- Consequence: Background expansion experiences a “push off” around equality time.
- A possible hint for cosmic tensions?
- NEXT: Actual (detailled) impact on CMB (early ISW effect) and other observables