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

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Standard cosmological dynamics

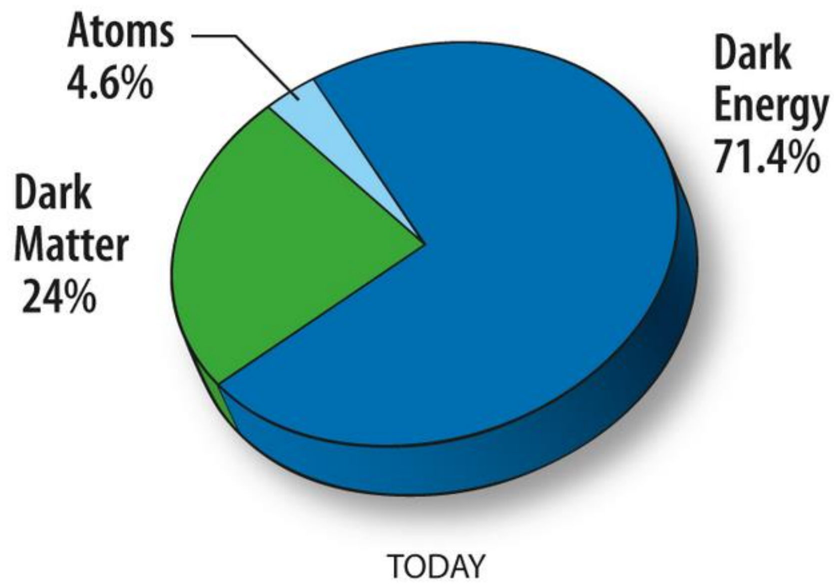
$$G_{\mu\nu} + \Lambda g_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu}$$

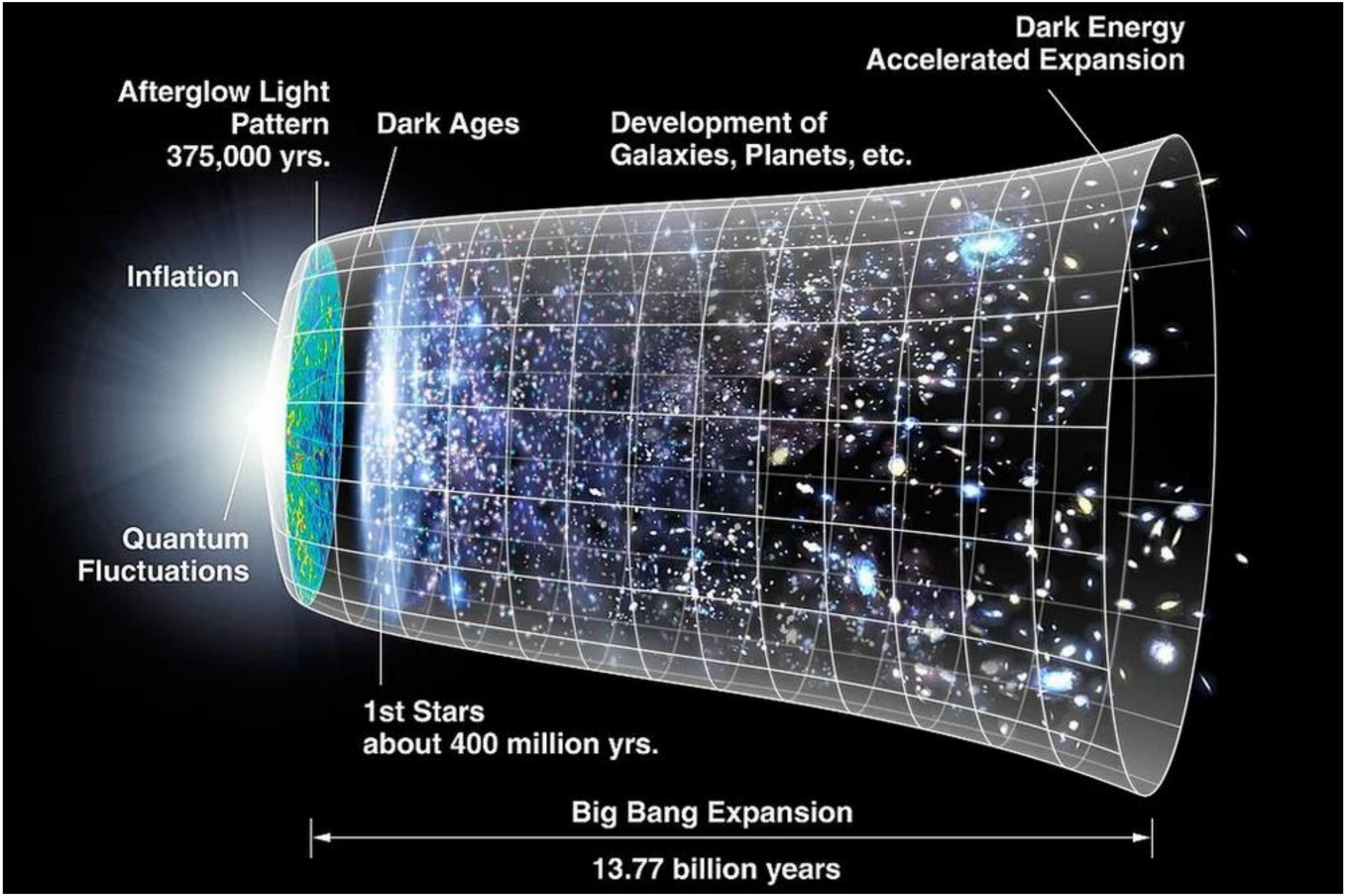
$$ds^2 = c^2 dt^2 - a^2(t)\left[\frac{dr^2}{1 - kr^2} + r^2 d\Omega^2\right]$$

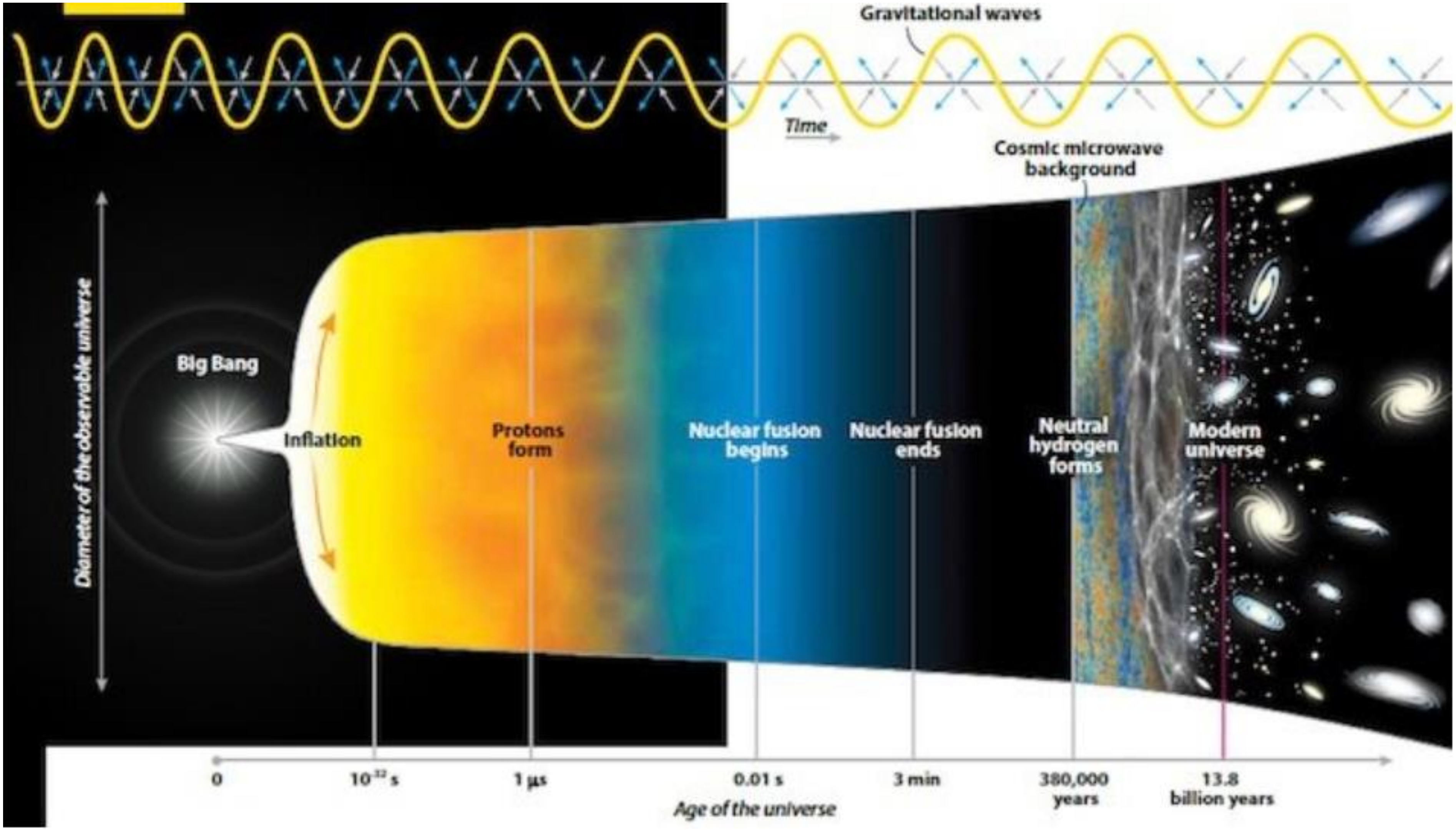
$$\frac{\ddot{a}}{a} = -\frac{4\pi G}{3}\left(\rho + \frac{3p}{c^2}\right) + \frac{\Lambda c^2}{3}$$

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

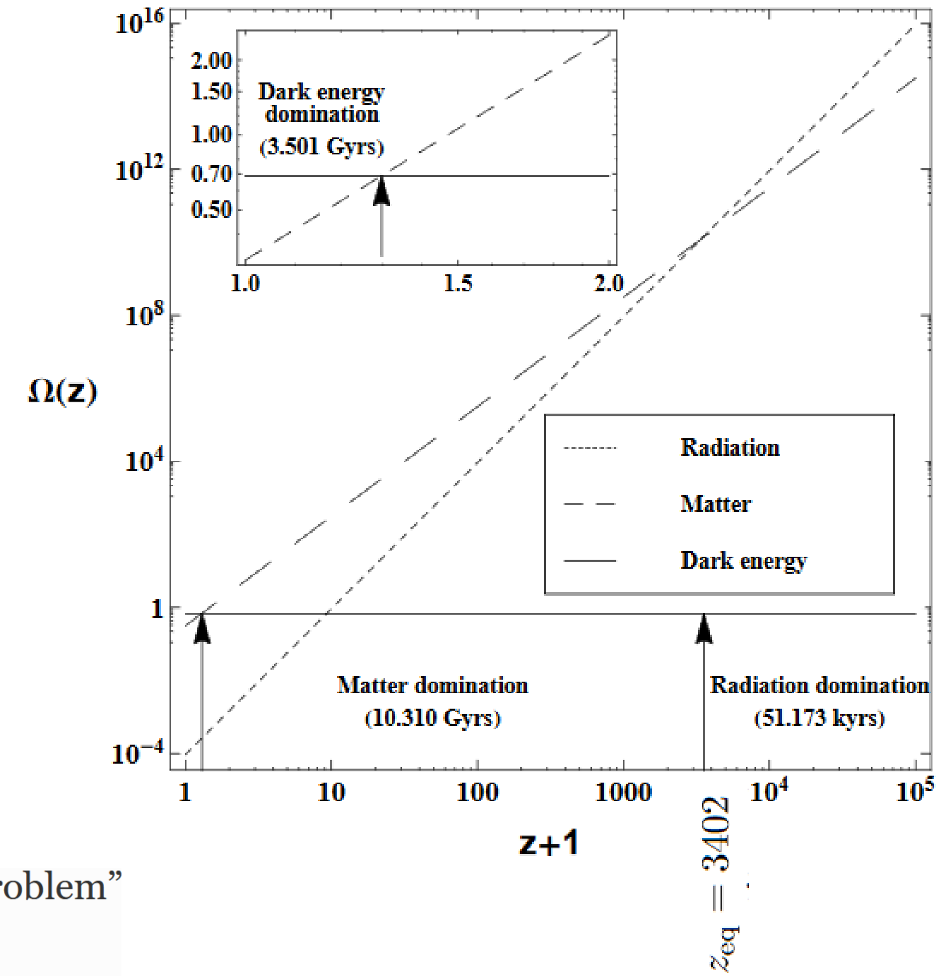

Gravitational waves
Time
Cosmic microwave background
Diameter of the observable universe
Big Bang
Inflation
Protons form
Nuclear fusion begins
Nuclear fusion ends
Neutral hydrogen forms
Modern universe
0
10^{-32} s
1 μs
0.01 s
3 min
380,000 years
13.8 billion years
Age of the universe

Background history

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

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

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

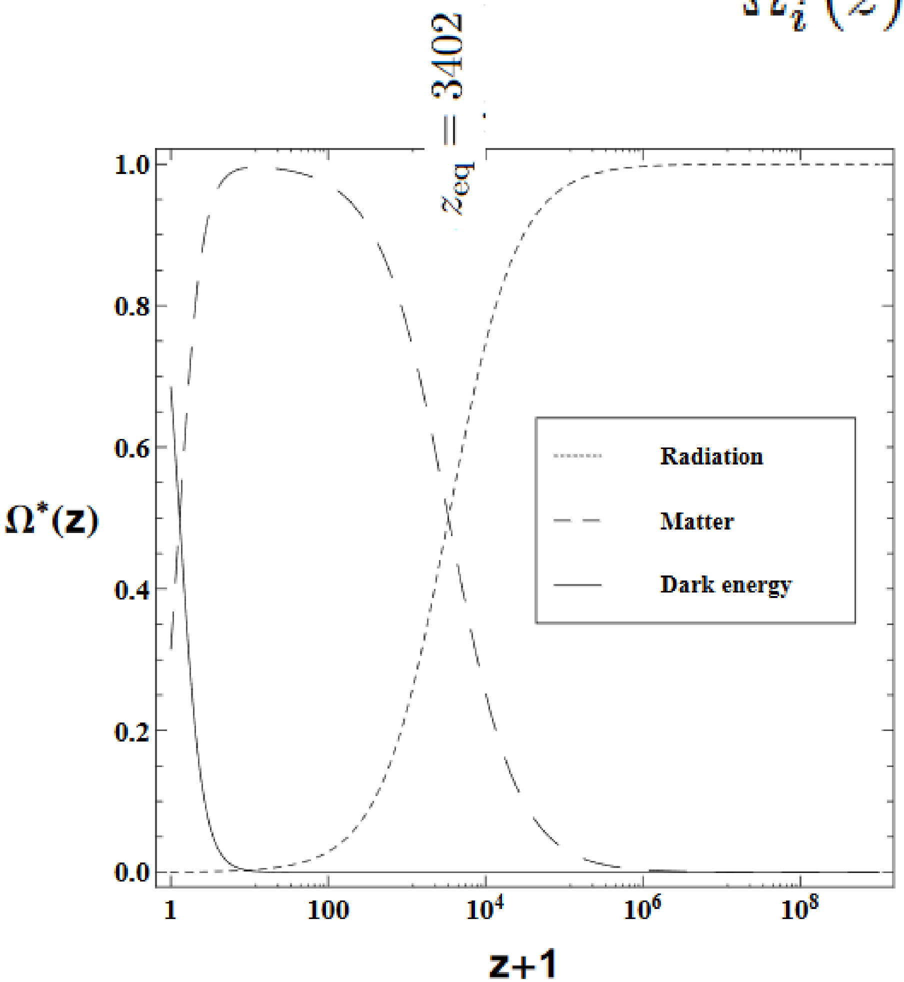


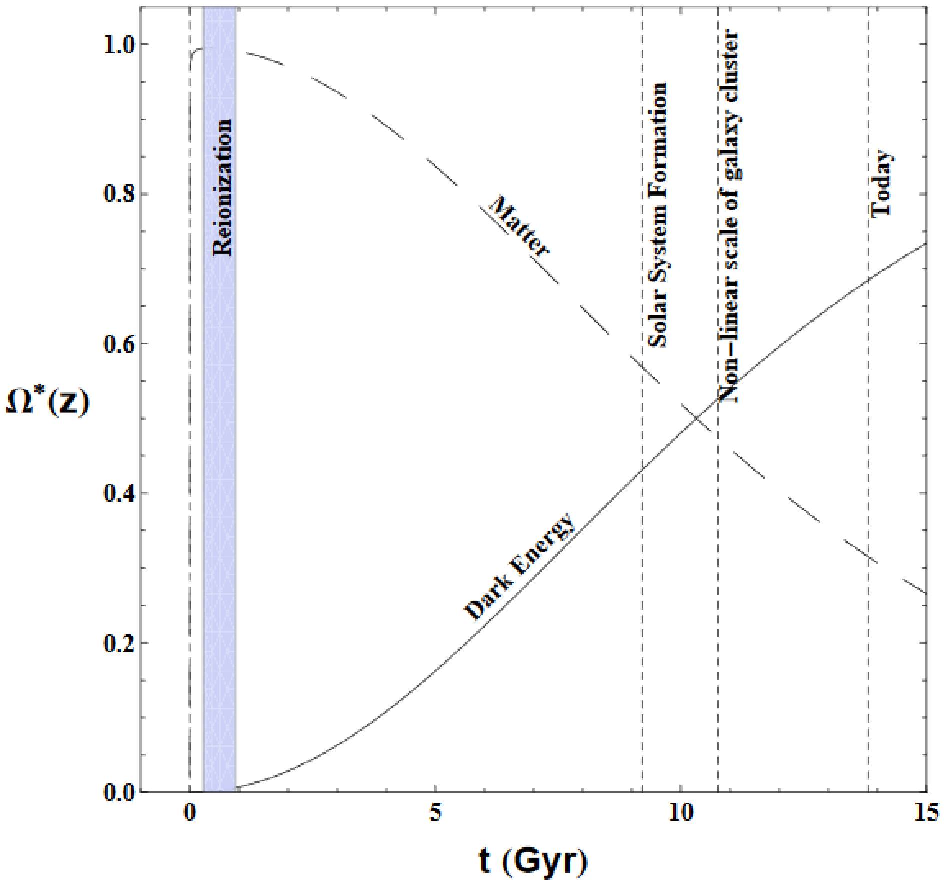
Aspects of the cosmological "coincidence problem"

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

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

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





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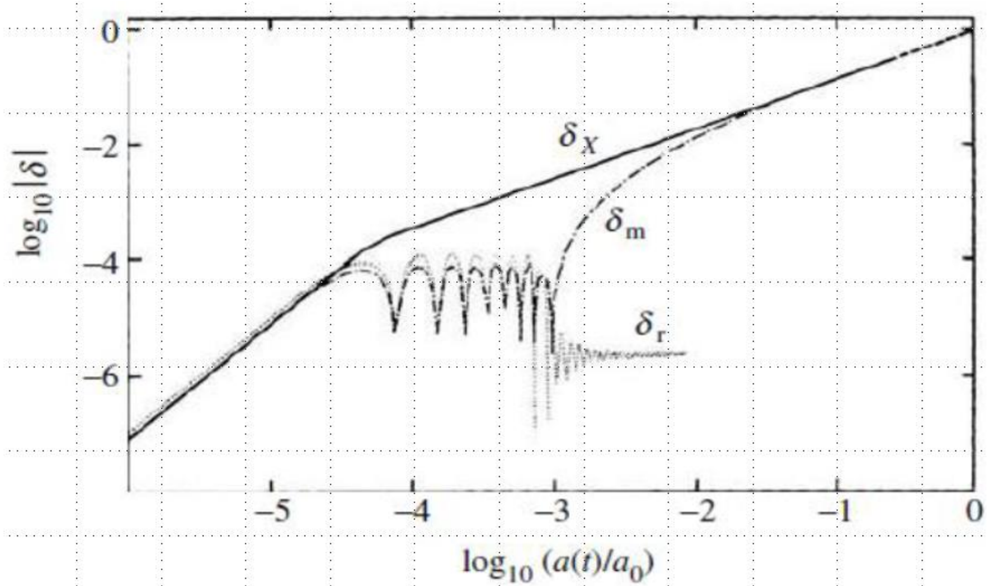
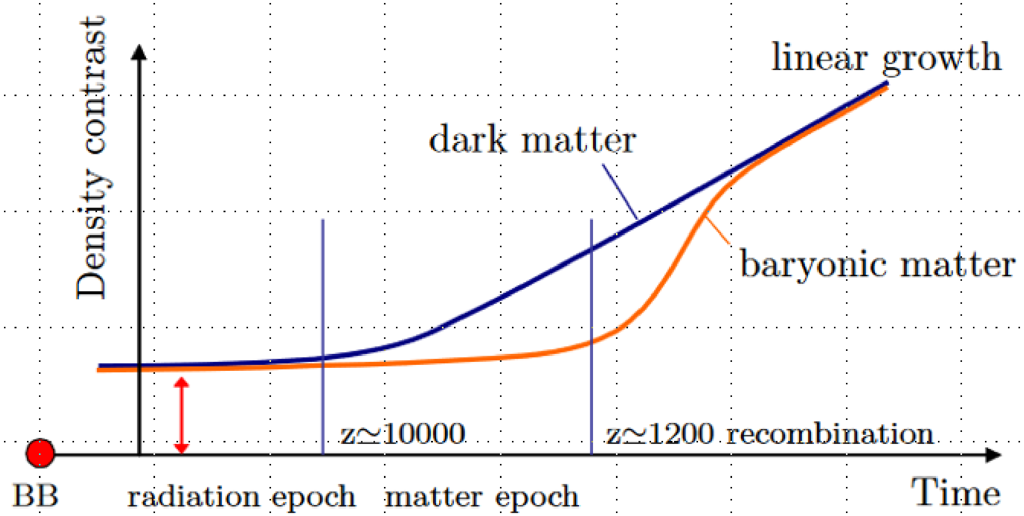
Growth of matter overdensities





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
- ...

Motivation of this work

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

'Understanding' cosmological bulk viscosity

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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 $(A = 1, 2)$

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

$$T_{A;k}^{ik} = 0,$$

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):

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

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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 (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 $\eta_0 + \tau$

$$\rho_{A'}(\eta_0 + \tau) = \rho_A(\eta_0) + \tau\dot{\rho}_A(\eta_0) + \ldots$$

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

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

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 find 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

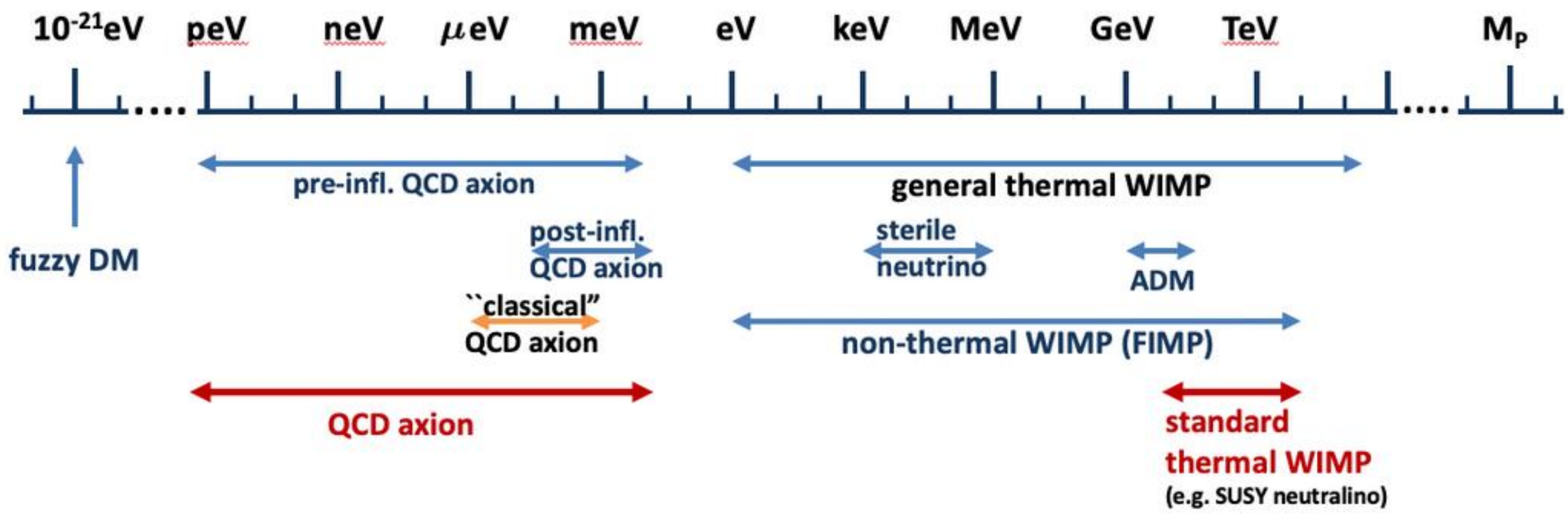
Radiation: $p_r = n_r k_B T_r, \quad \rho_r = 3 n_r k_B T_r,$

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: heaky and slow (prevailing view)
Warm dark matter: something between Hot and Cold e Hot!



The fluid description employed here is valid as long as

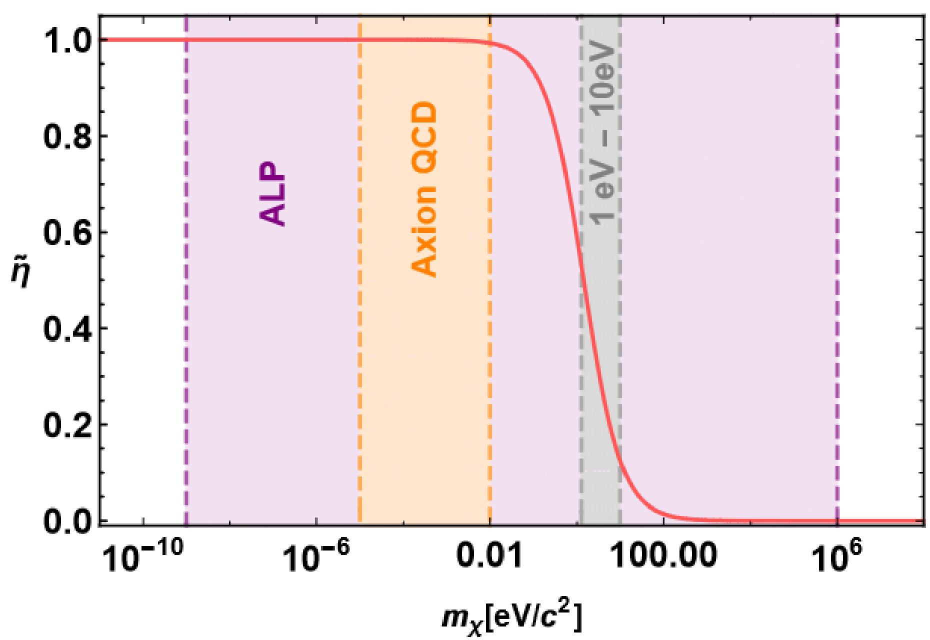
$$\tau << H^{-1}$$

Definition:

$$\xi = \tau \frac{n_r k_B T}{3} \frac{n_\chi}{2n_r + n_\chi} = \frac{\rho_r}{9}\tilde{\eta}\tau, \qquad \tilde{\eta} \equiv \frac{\eta_{\chi r}}{2+\eta_{\chi r}}, \quad \eta_{\chi r} \equiv \frac{n_\chi}{n_r}.$$

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

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



Interesting mass regime:

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

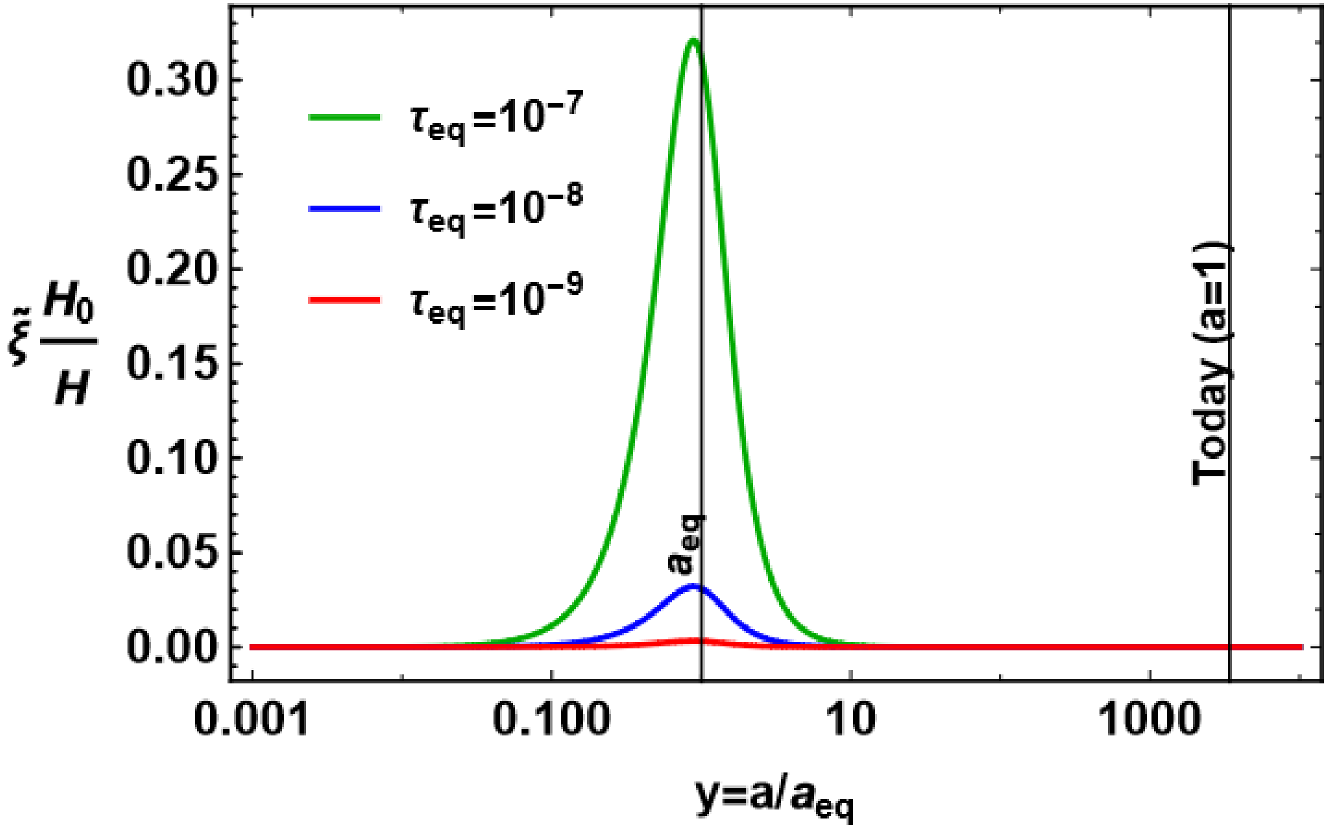
Below 1eV the particle becomes too relativistic; T(eq) ~ 0.6 eV

Above 10eV the effect vanishes

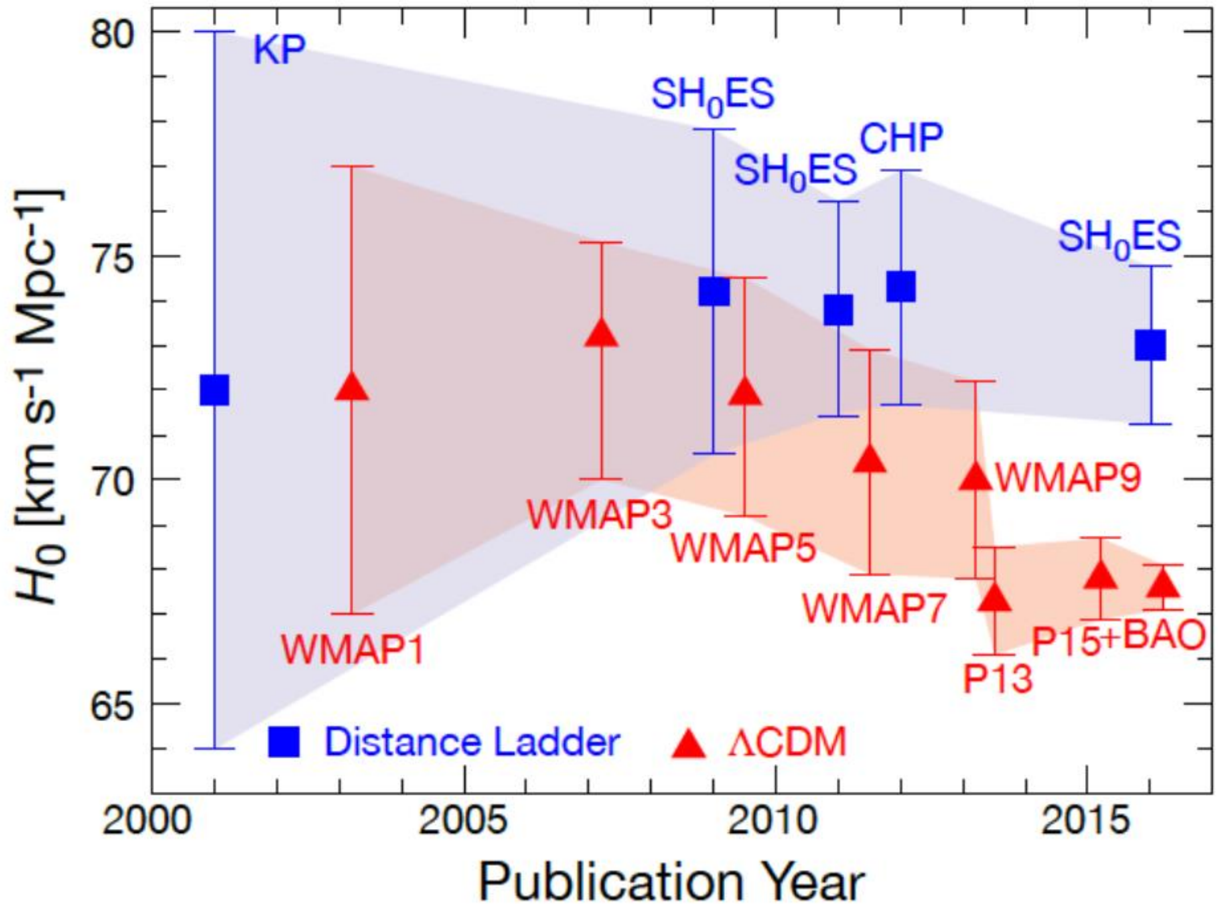
Magnitude of the effect (fixing 1 eV)

$$\tilde{\xi}\frac{H_0}{H} = \tau(y)\frac{H_0^2}{H}\Omega_r\,\tilde{\eta}$$

$$\tau(y) = \tau_{\rm eq}\frac{H_{\rm eq}}{H}\left(\frac{2y^2}{1+y^4}\right)$$

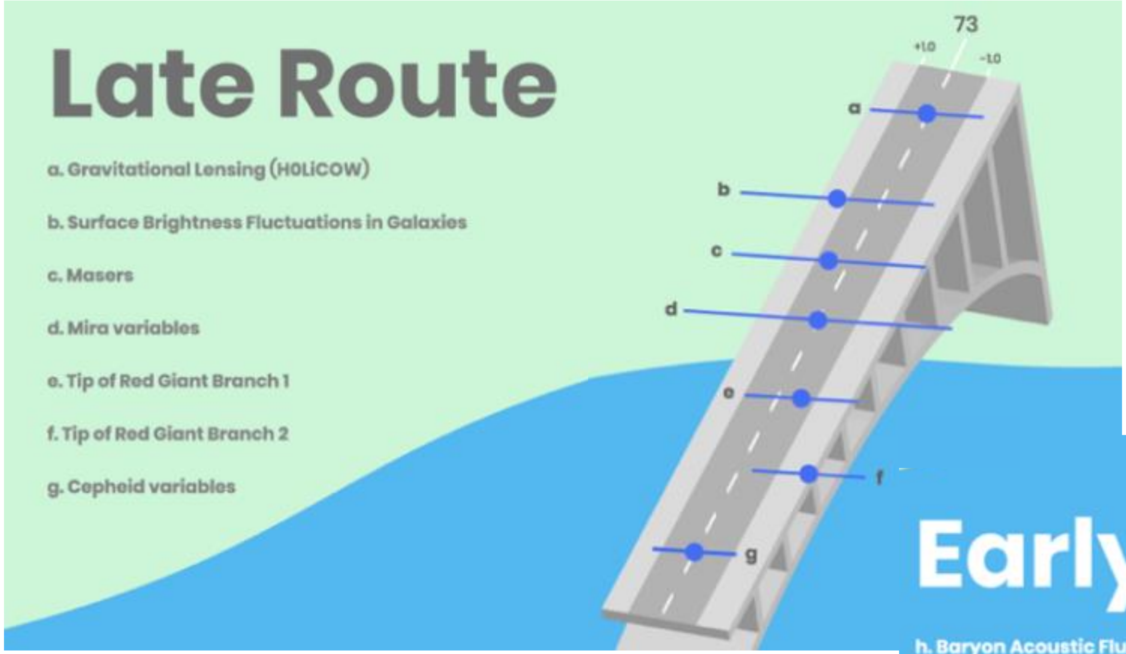


INTRODUCING THE COSMIC TENSION ON H0



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

Introducing the cosmic tension on H0



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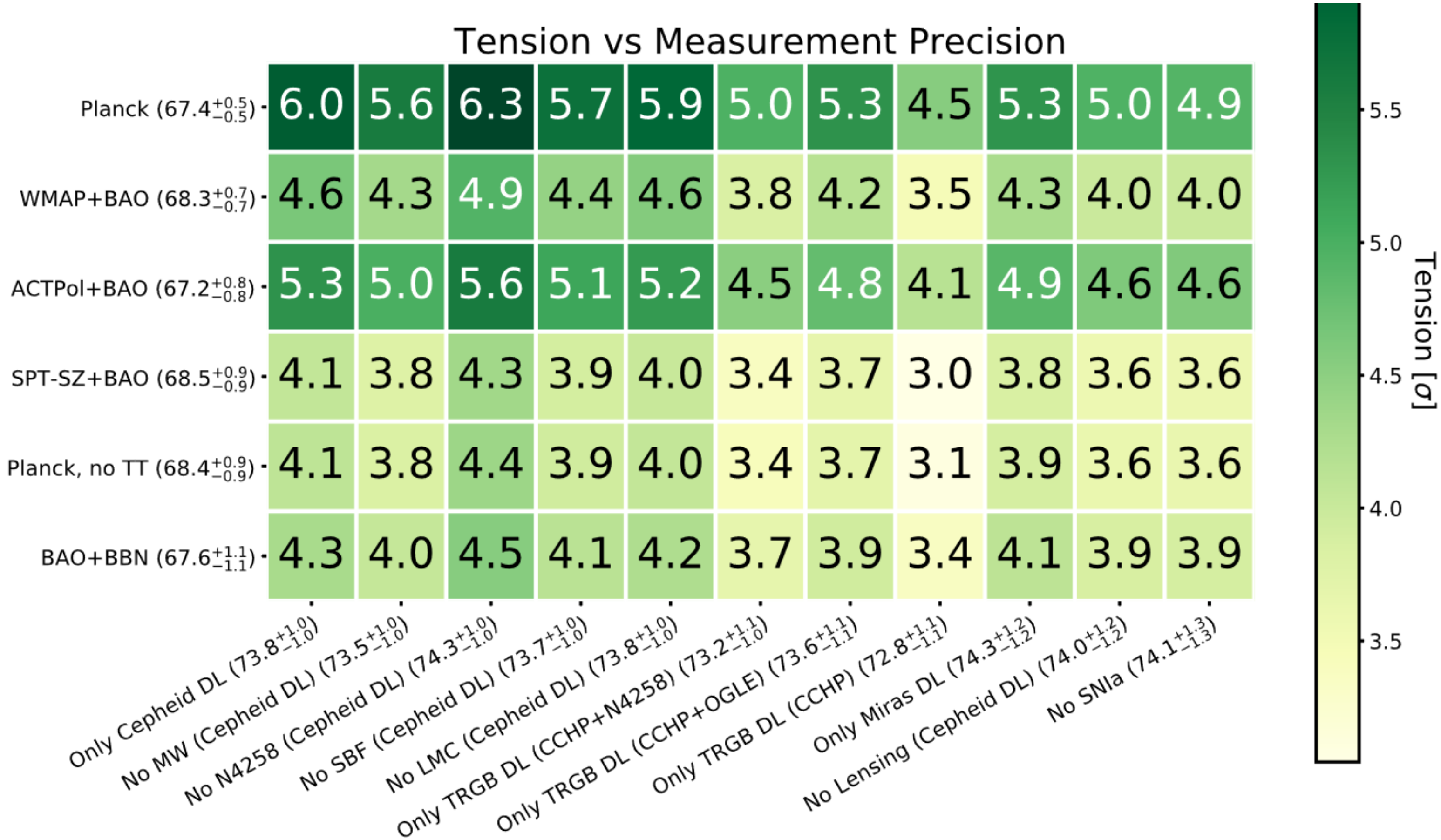
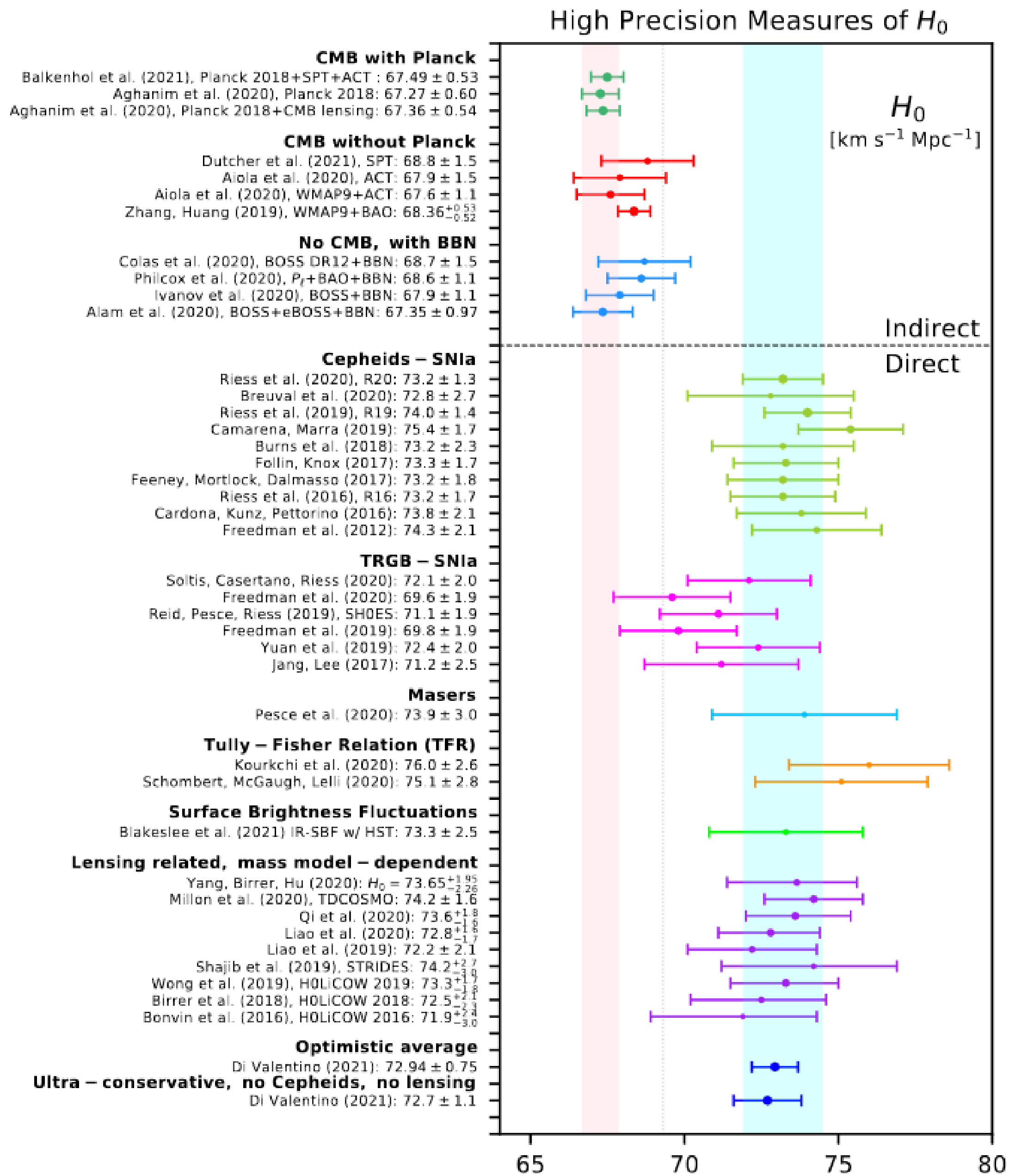


Credits: ADAM RIESS, Nature Review Physics 2019

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

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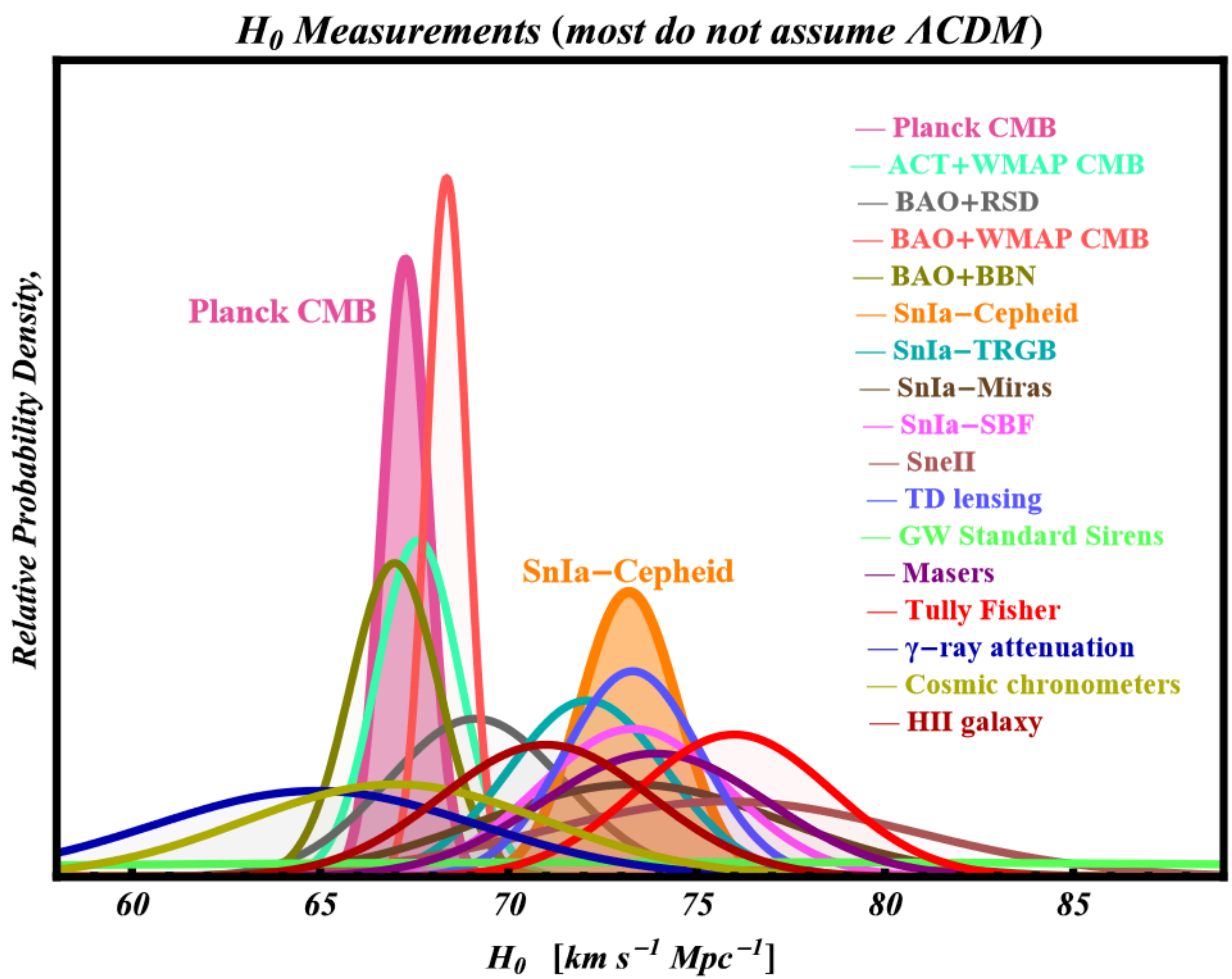
[1] Department of Physics, University of Ioannina, 45110 Ioannina, Greece
(Dated: May 20, 2021)



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

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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.

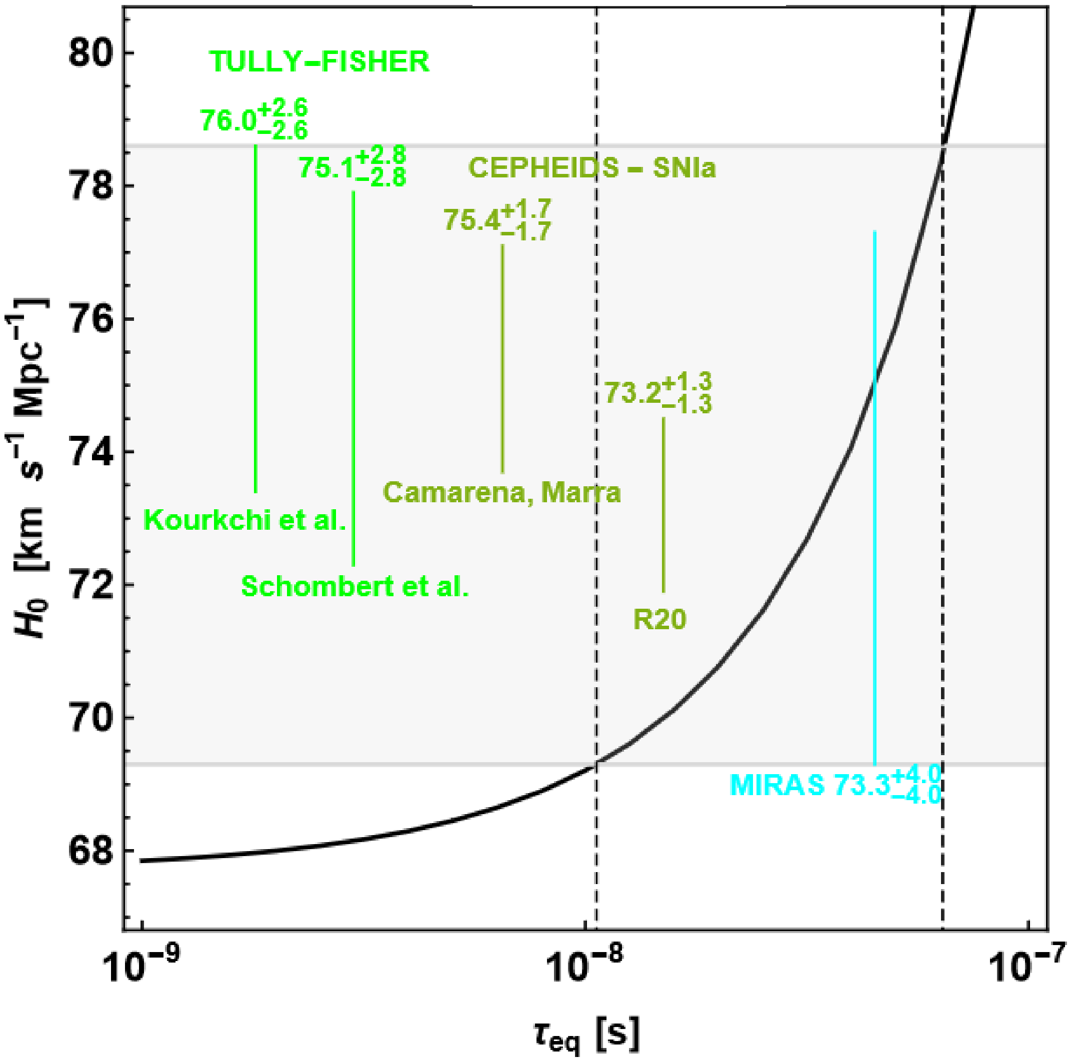
It is, therefore, unlikely that changes to the late time expansion history can resolve the 'Hubble tension'. …

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:

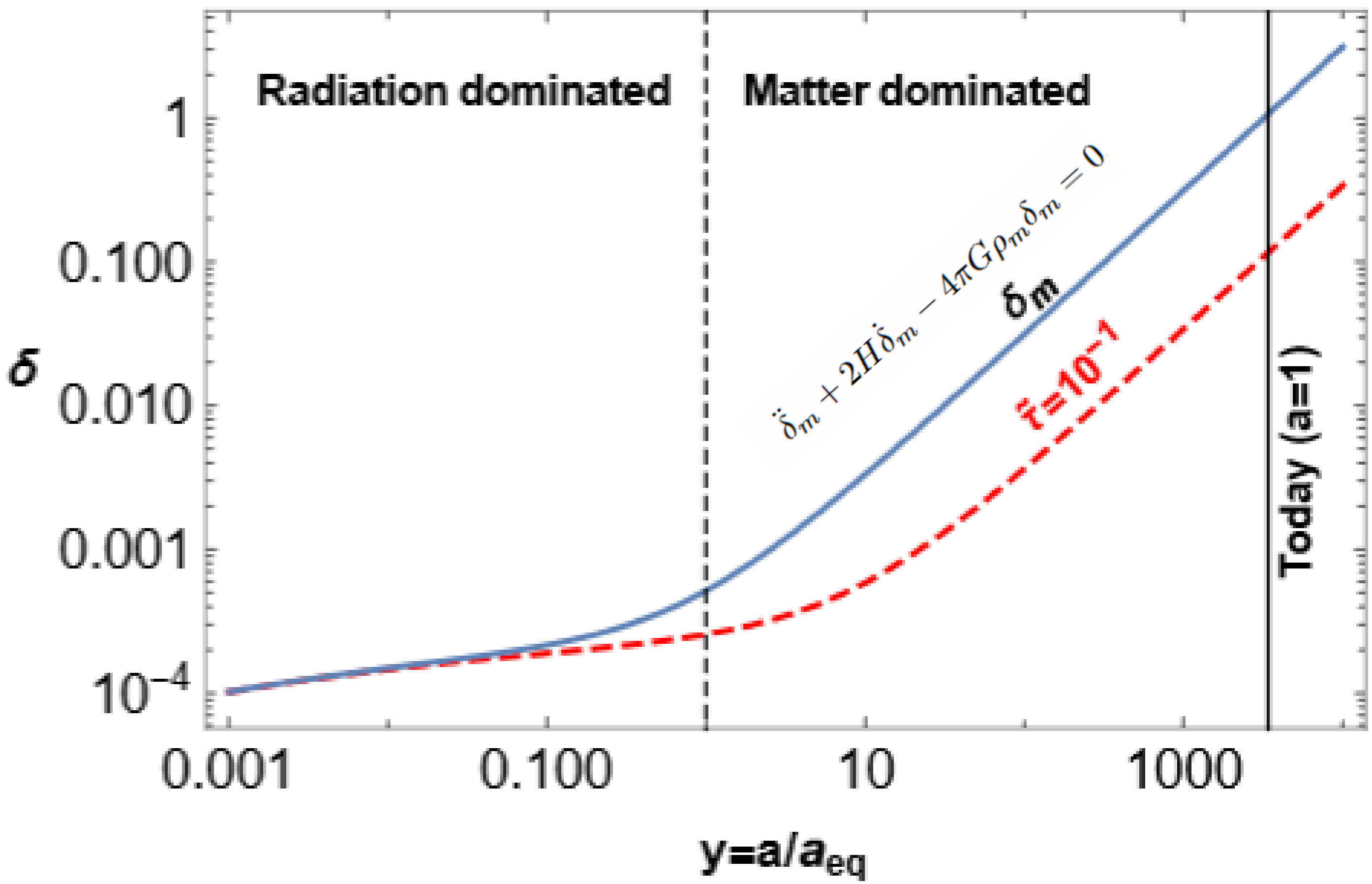
1) Starting with H_0= 67.4 km/s/Mpc;
2) Integrate back in time assuming standard LCDM dynamics;
3) Find H(z_i), let us say, z_i = 100000;
4) Assume the new background dynamics takes into account the bulk viscous pressure around equality only;
5) Integrate the new dynamics from the starting point H(z_i) 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 a na extra “push off” on the expansion around equality.

Large scale structure effects

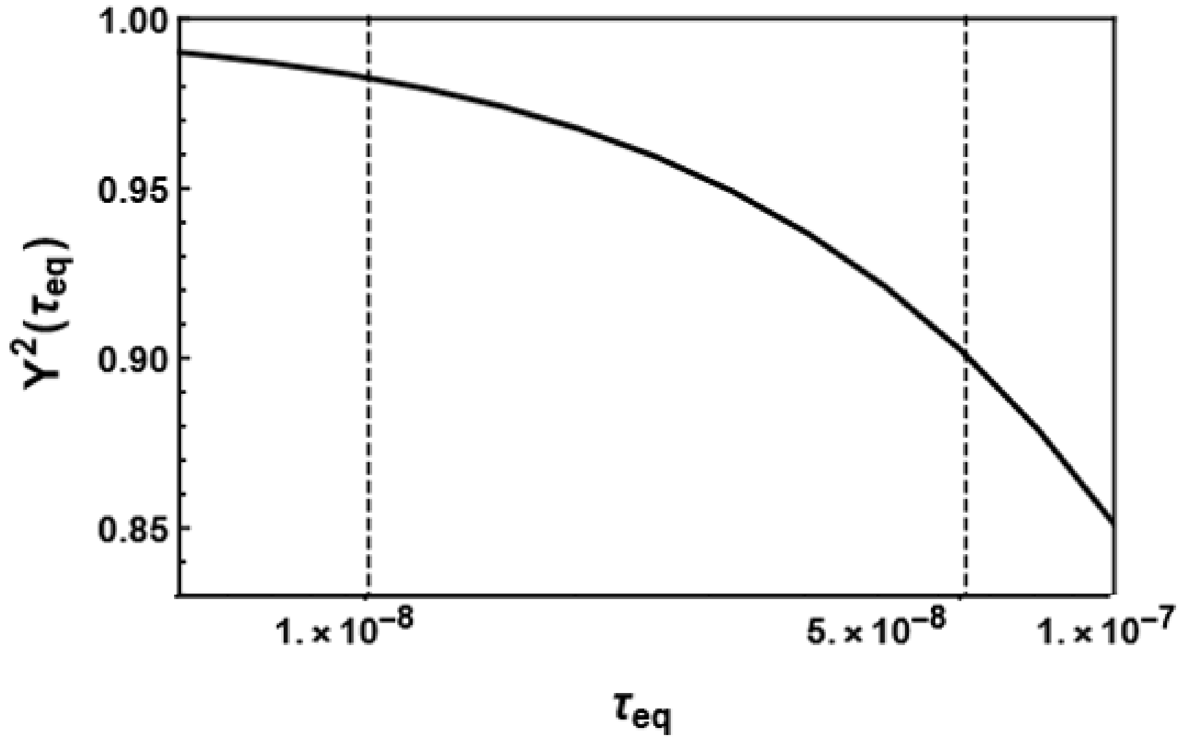
$$\frac{d^2\delta_m}{dy^2} + \left[\frac{(2+3y)}{2y\,(1+y)} + \frac{\tilde{\xi}}{2y}\frac{H_0}{H}\right]\frac{d\delta_m}{dy} - \frac{3}{2y\,(1+y)}\delta_m = 0.$$

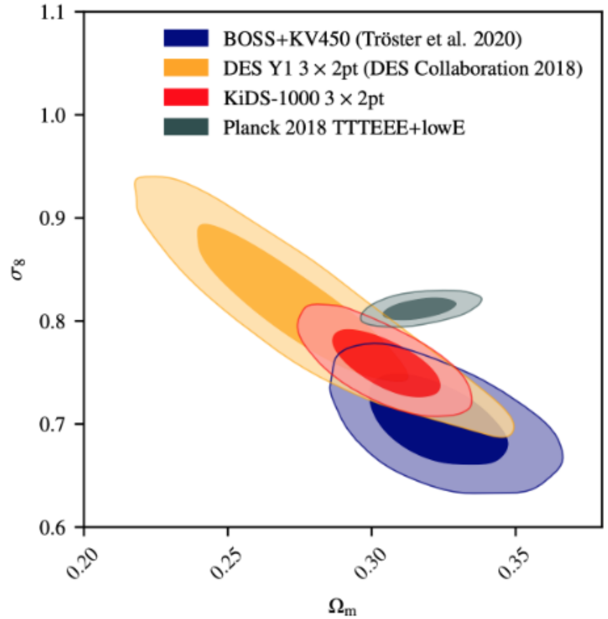


Growth suppression mechanism

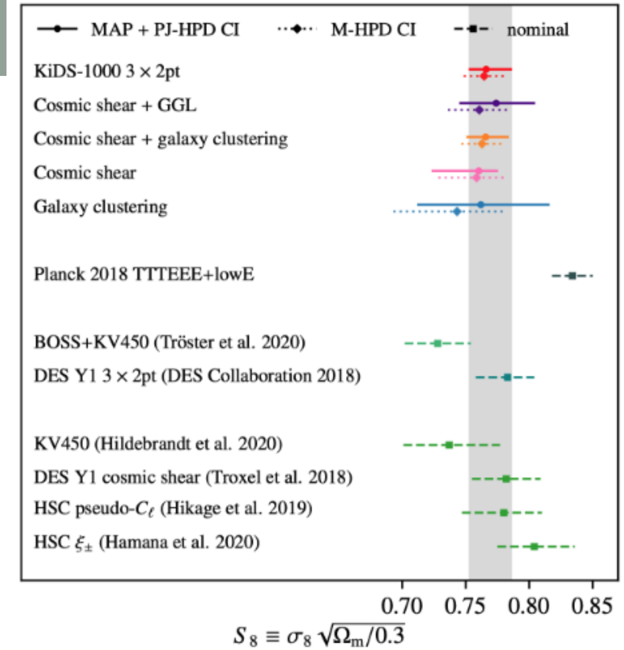
A new “transfer function-like Y” contribution to the matter power spectrum P(k)

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



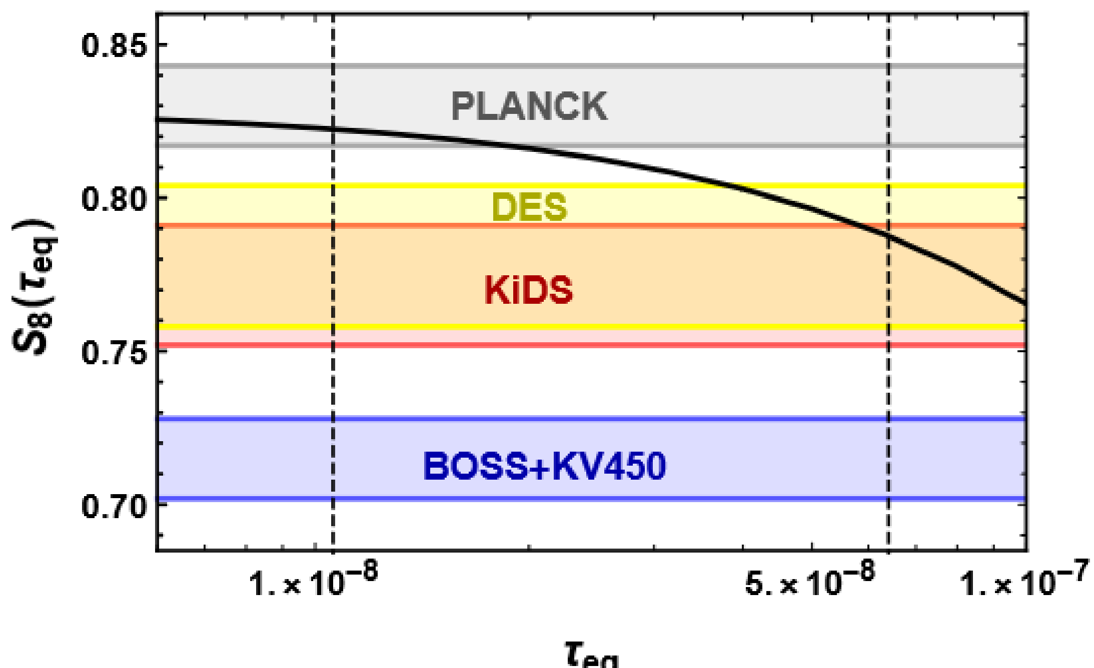


Snowmass2021 (2008.11285)



S8 tension

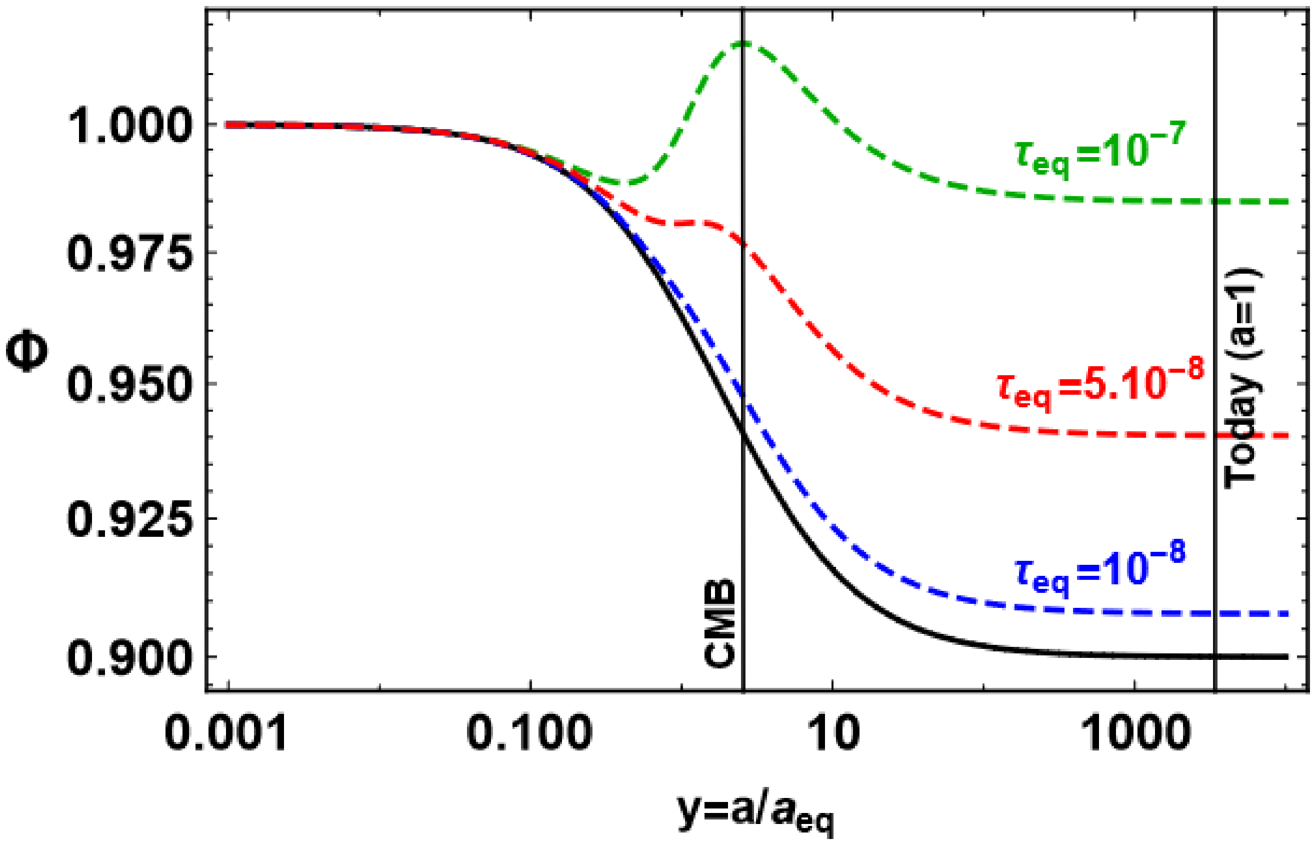
$$S_8 = \sigma_8 \left(\frac{\Omega_{m0}}{0.3}\right)^{1/2}$$



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/free streamin/silk damping...