

# **FIZIČKA KOZMOLOGIJA** **znanost o razvoju svemira**

**Dario Hrupec**

Odjel za fiziku Sveučilišta Josipa Jurja Strossmayera Osijek

Matica hrvatska, Zagreb  
2. ožujka 2023.

**Fizička kozmologija  
je prirodna znanost!**

Nije filozofija!

Nije spekulacija!

Nije “tek privremena”!

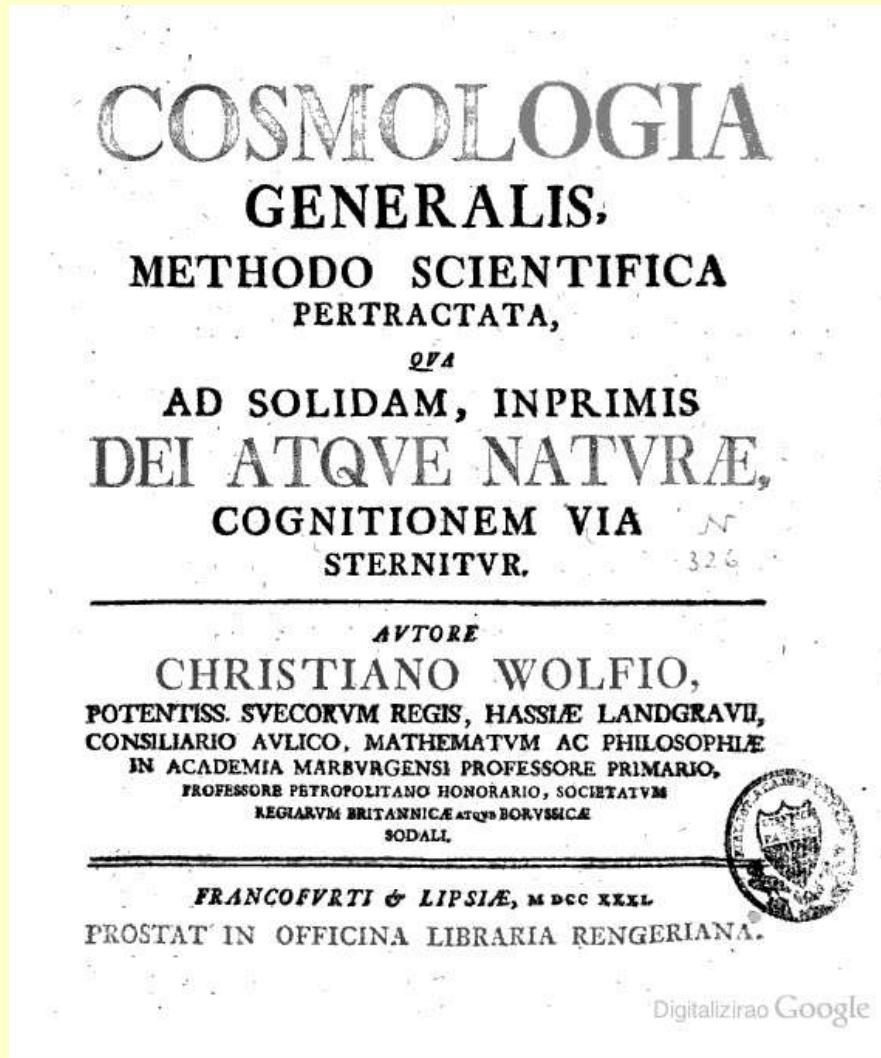
Nije “samo jedan model”!

# Što je kozmologija?

- (1) tumačenje postanka i razvoja svijeta  
**mitologijska (ili religijska) kozmologija**  
≈ 5000 godina
- (2) znanost o podrijetlu, razvoju, strukturi i dinamici svemira  
**fizička kozmologija**  
≈ 50 godina



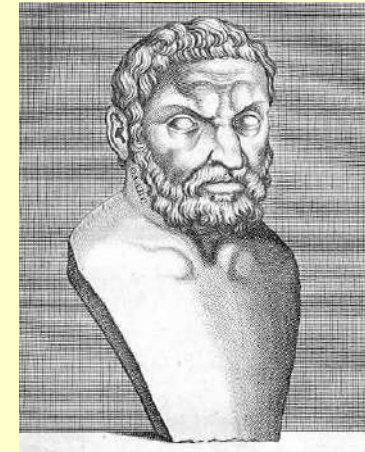
# Naziv kozmologija



Christian Wolff  
njemački filozof  
*Cosmologia generalis* (1731)

**svjetoslovlje**

“filozofijsko učenje o cjelini  
materijalnog svijeta”  
postojalo je još od antike



# Kozmologija vs kozmogonija



postanak svijeta

**svjetorođe**

grčki: **kósmos** (svijet, svemir) + **gonía** (rađanje, postanak)



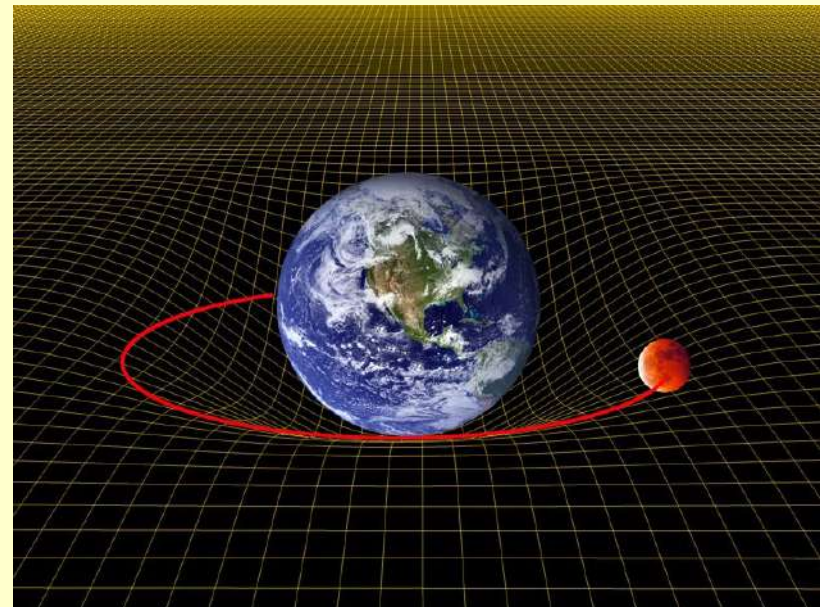
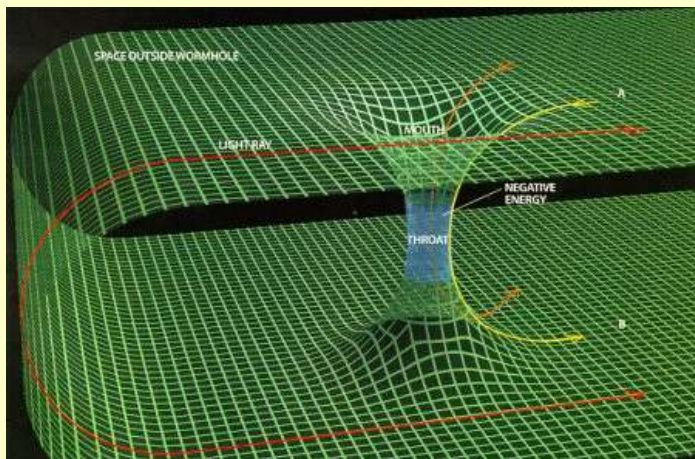
# Matematičko polazište za kozmološke teorije

opća teorija relativnosti

Einstein, 1915.

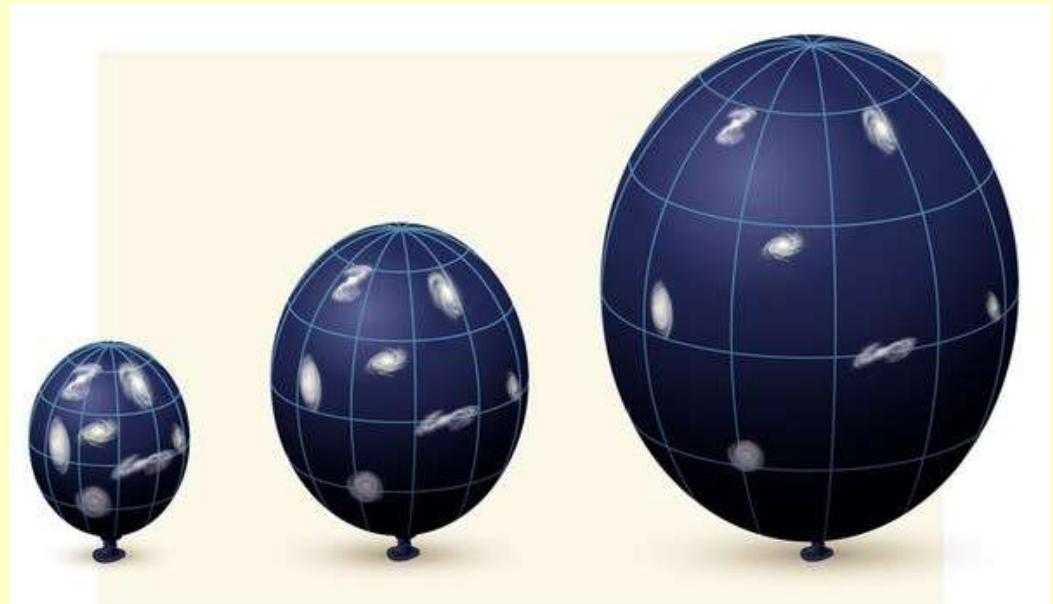
masaenergija zakrivljuje prostorvrijeme

širenje svemira, gravitacijski valovi, crne rupe, crvotočine



# Pretpostavke za model velikog praska

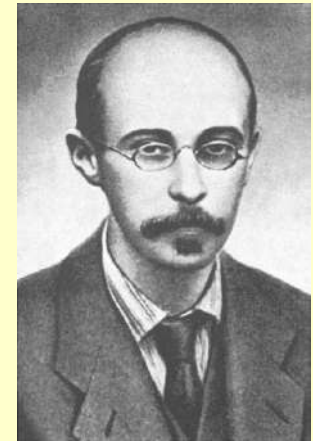
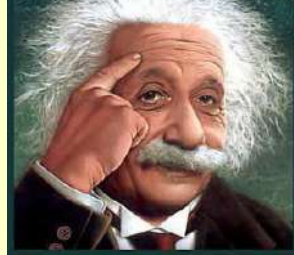
- (1) univerzalnost fizičkih zakona (isti su svugdje i uvijek)
- (2) kozmološko načelo (svemir je približno homogen i izotropan u prostoru, ali ne i u vremenu)
- (3) kopernikansko načelo (ne opažamo svemir iz nekog povlaštenog položaja)





# Predviđanja modela velikog praska

“the biggest blunder of my career”



Alexander Friedmann (1888.-1925.)

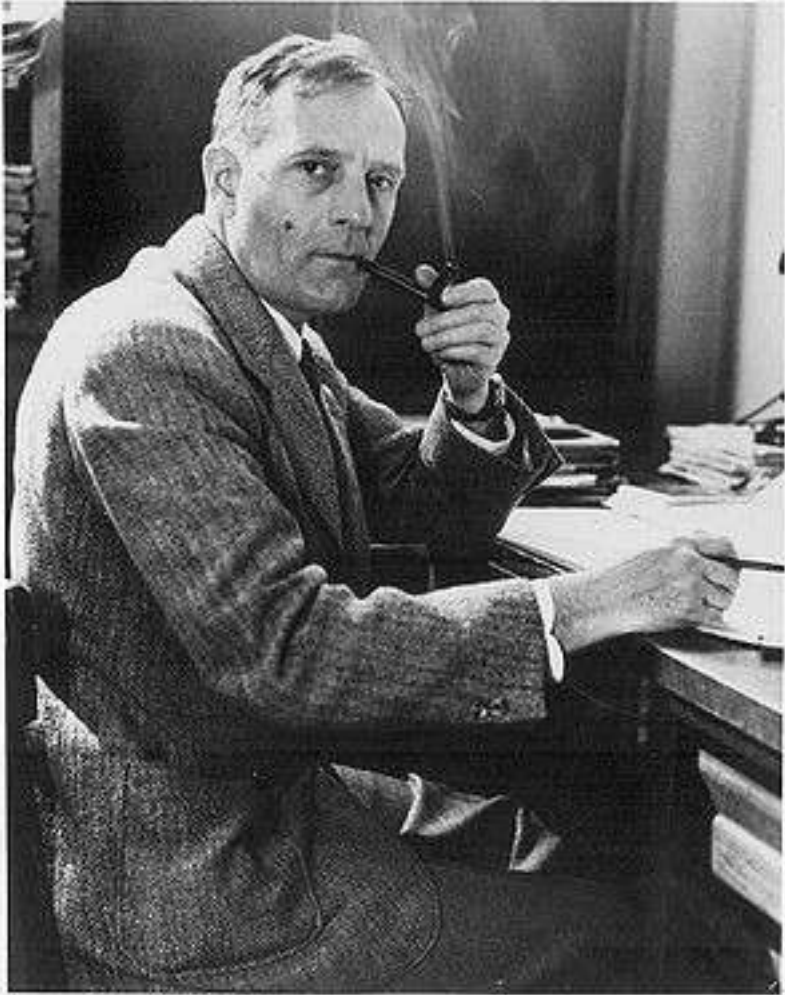
(1) širenje svemira

(2) vruće, gusto stanje **u početku**

(3) nastanak lakih elemenata u ranoj fazi razvoja svemira  
(nukleosinteza)

(4) postojanje kozmičkog mikrovalnog pozadinskog  
zračenja

# Edwin Hubble



1924. godine  
“maglice” su druge galaksije

1929. godine  
pomak prema crvenome  
raste s udaljenošću

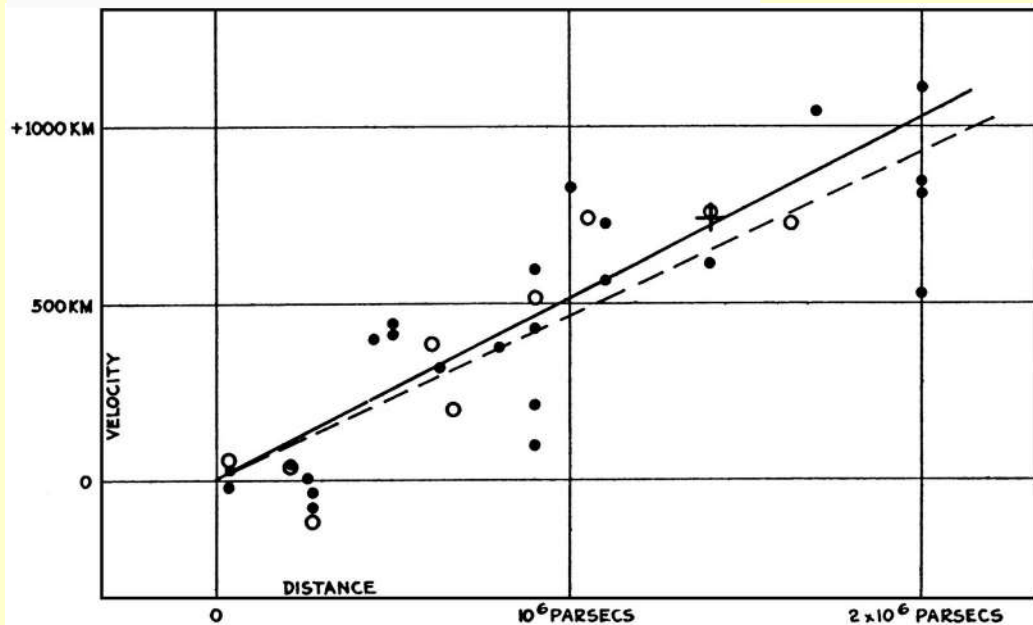
# Arno Penzias i Robert Wilson

1964. godine  
opažanje kozmičkog  
mikrovalnog pozadinskog  
zračenja

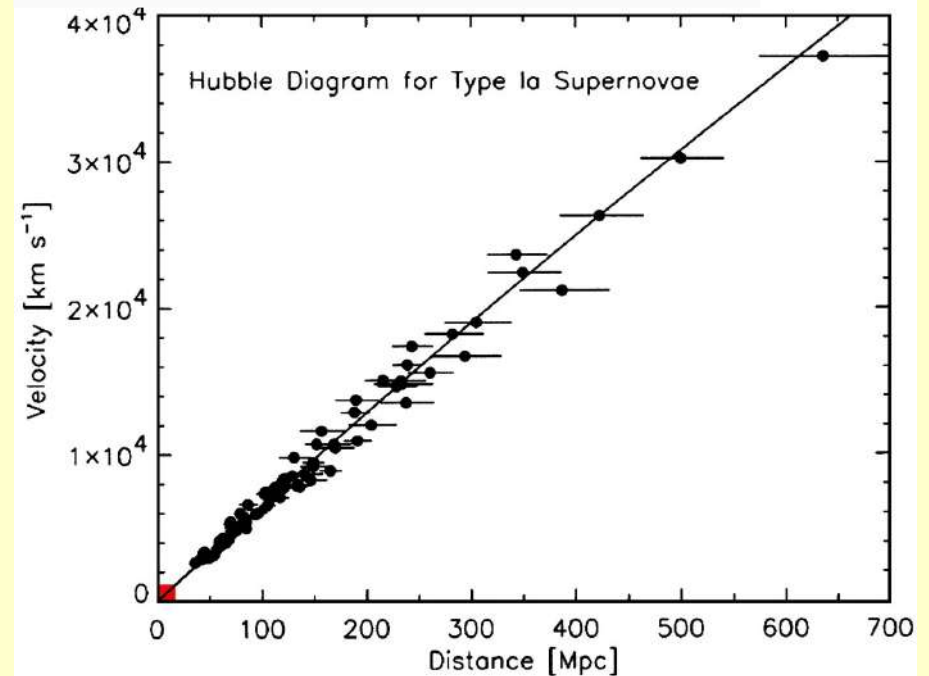


# Potvrde modela velikog praska: (1) udaljavanje galaksija

Hubble, E. P. (1929) Proc. Natl. Acad. Sci. USA 15, 168–173.

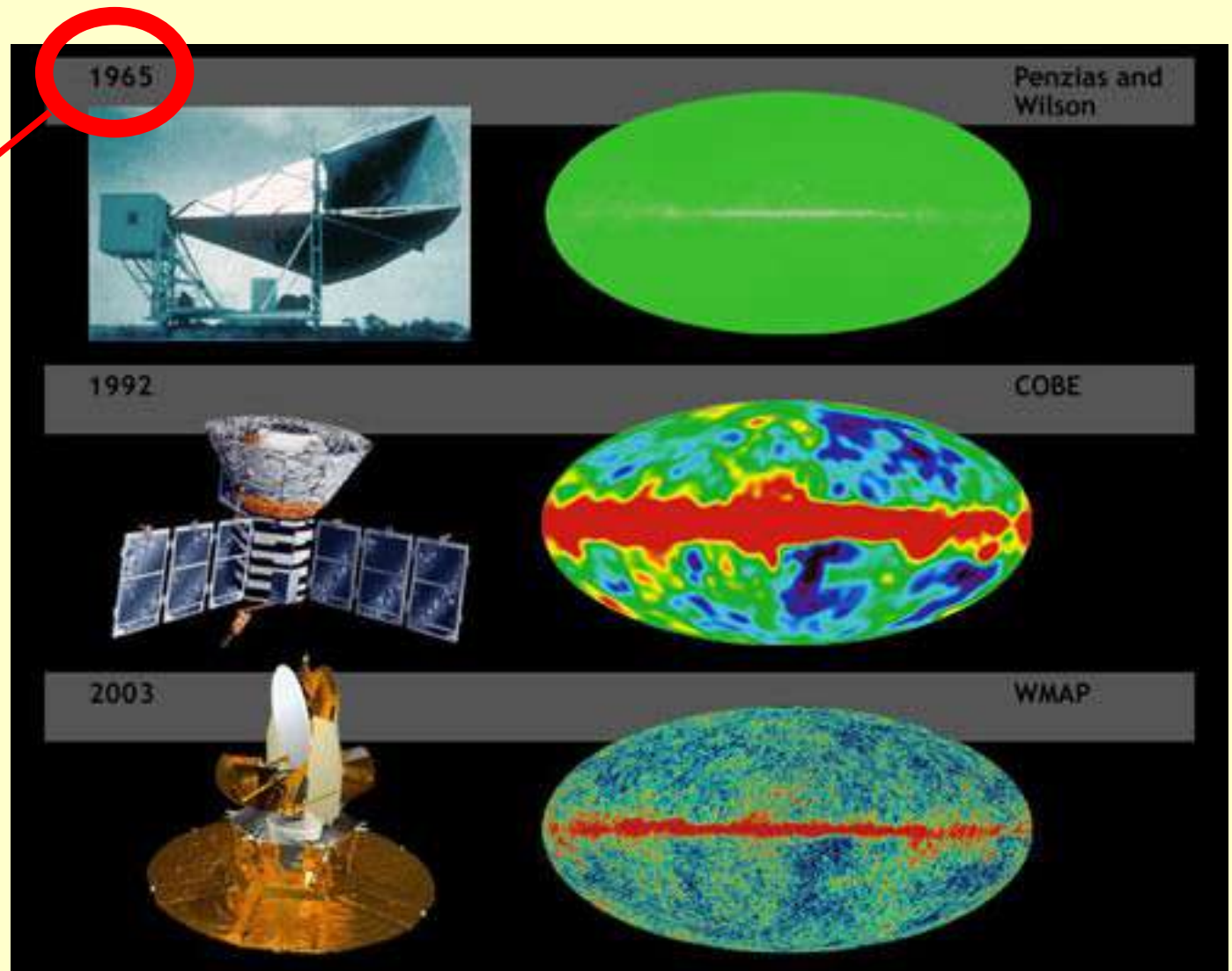


Jha, S. (2002) Ph.D. thesis (Harvard Univ., Cambridge, MA).



# Potvrde modela velikog praska: (2) kozmičko mikrovalno pozadinsko zračenje

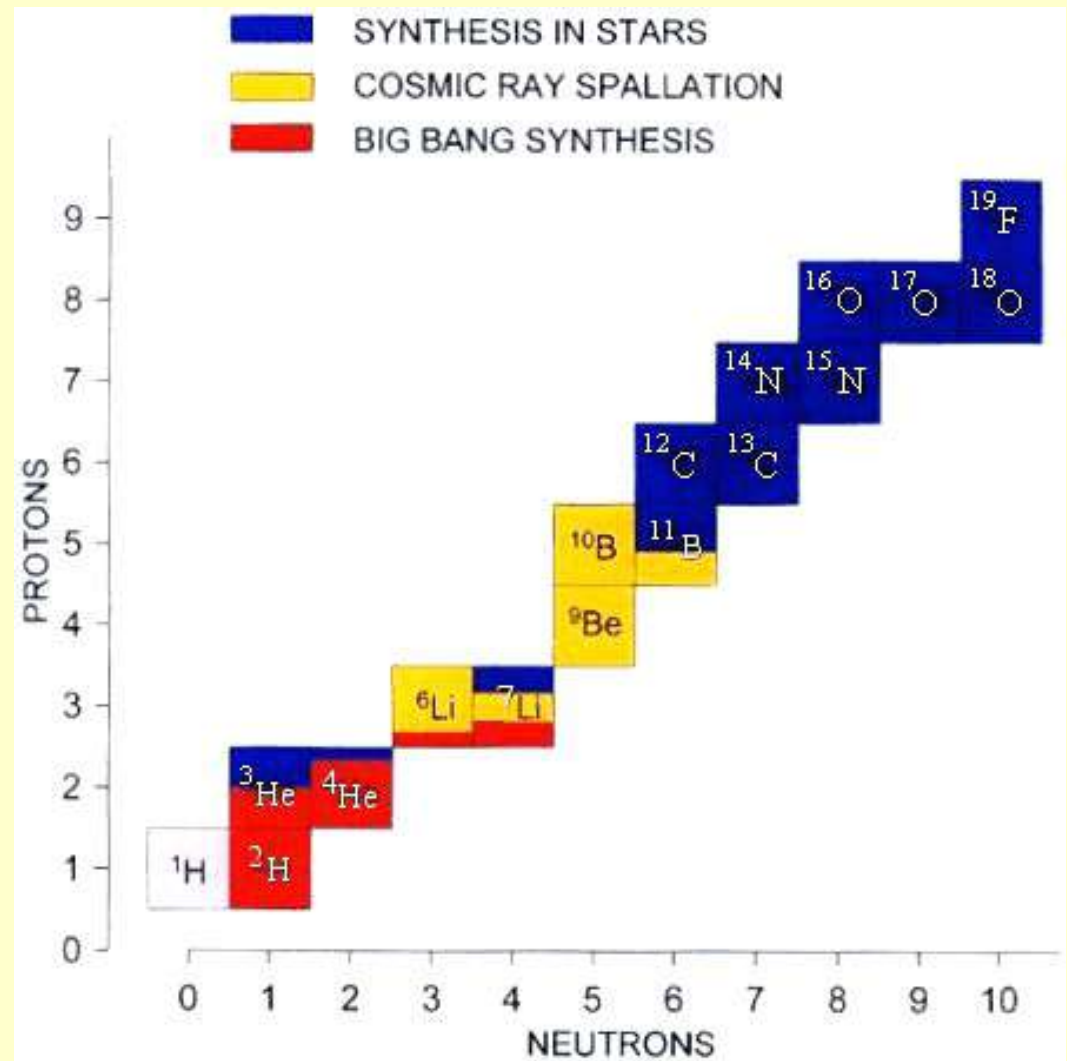
kozmiologija  
postaje znanost



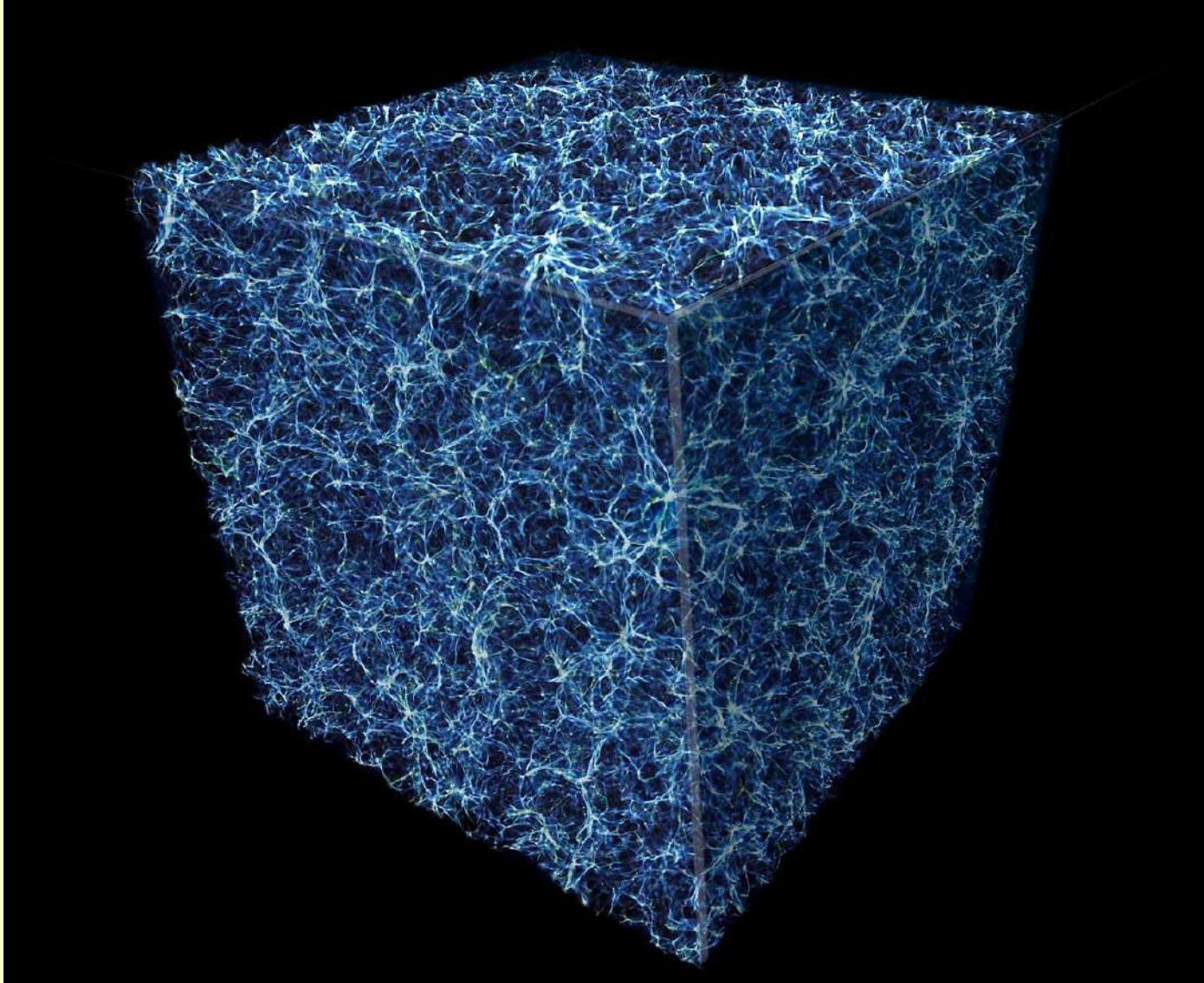


# Potvrde modela velikog praska: (3) udjeli primordijalnih elemenata

astronomska opažanja  
H, D,  $^3\text{He}$ ,  $^4\text{He}$ ,  $^7\text{Li}$   
u dalekim oblacima  
primordijalnog plina  
**potvrdila** su proračune  
modela velikog praska



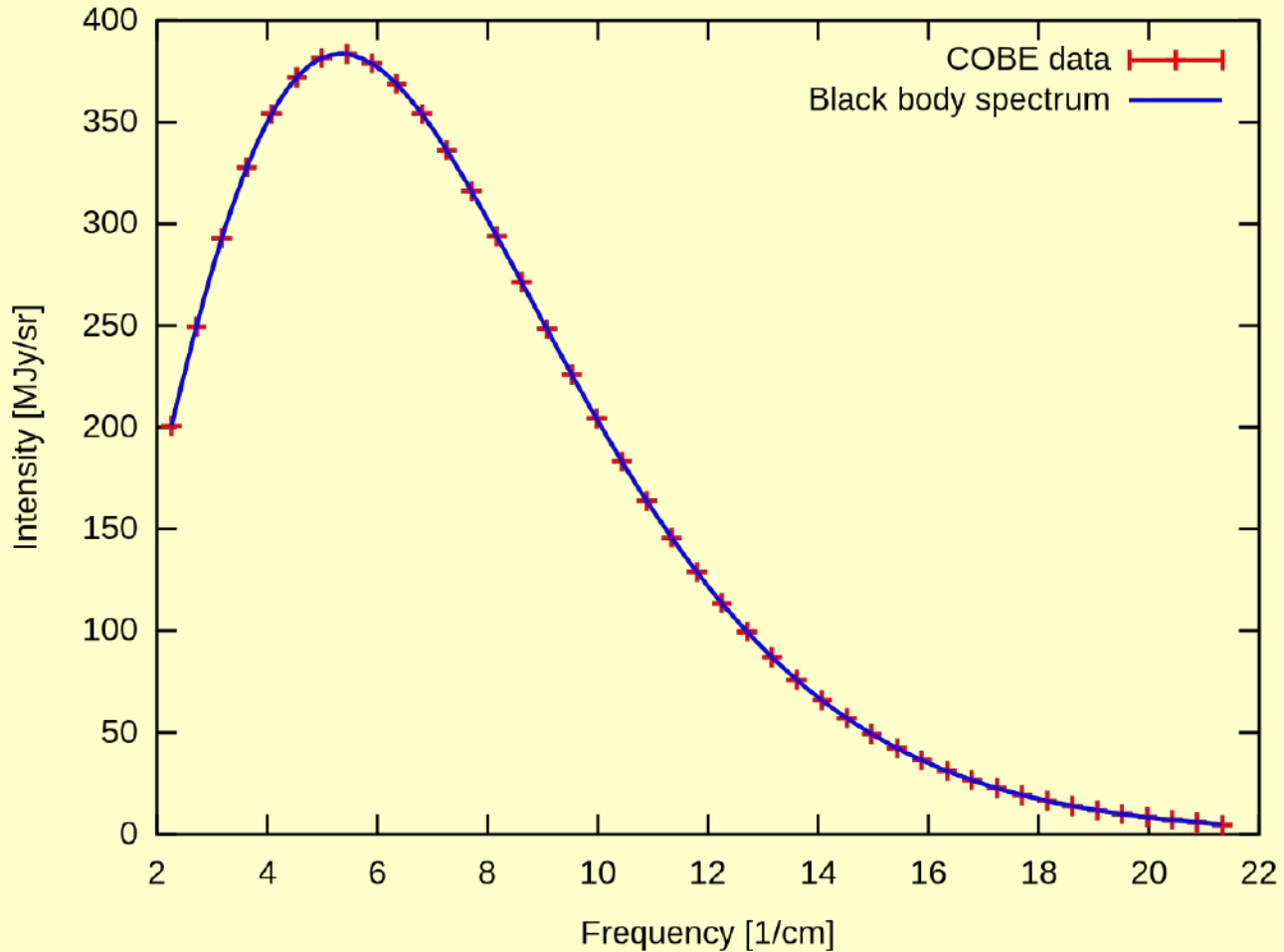
# Potvrde modela velikog praska: (4) struktura svemira na najvećoj skali



Izvor: NASA, ESA, and E. Hallman (University of Colorado, Boulder)

# Odabrani rezultati: COBE

Cosmic microwave background spectrum (from COBE)



[https://lambda.gsfc.nasa.gov/product/cobe/firas\\_monopole\\_get.html](https://lambda.gsfc.nasa.gov/product/cobe/firas_monopole_get.html)

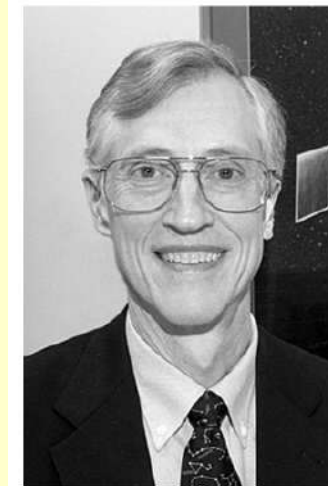


Photo: P. Izzo  
John C. Mather



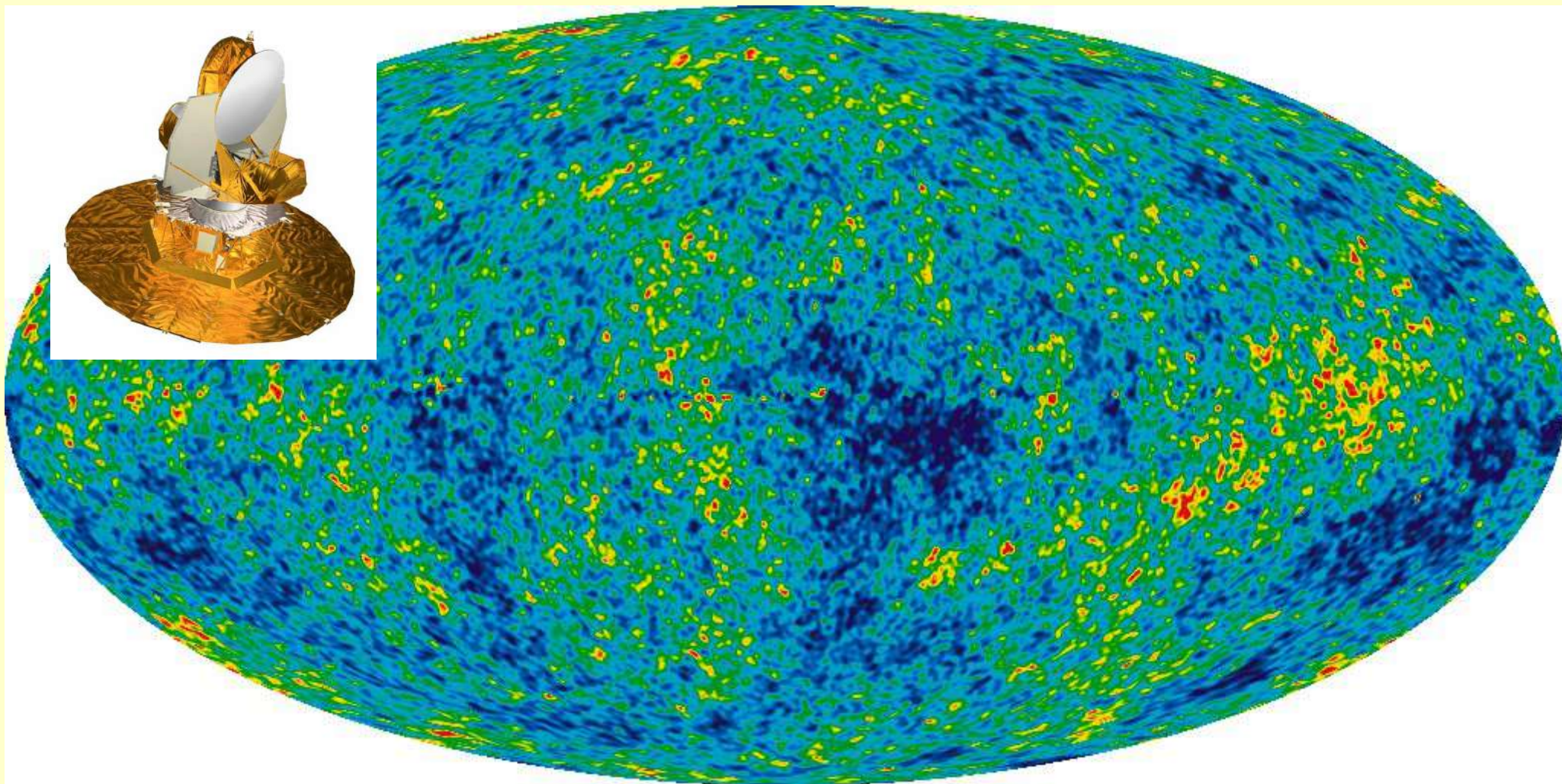
Photo: J. Bauer  
George F. Smoot

**George Smoot i John Mather, Nobelova 2006.**

"the COBE-project can also be regarded as the starting point for cosmology as a precision science"



# Odabrani rezultati: WMAP



**Wilkinson Microwave Anisotropy Probe  
devet godina opažanja  
fluktuacije koje odgovaraju začetku formiranja galaksija**



# Odabrani rezultati: satelit Planck

	Description	Symbol	Value-2015 <sup>[94]</sup>	Value-2018 <sup>[95]</sup>
Independent parameters	Physical baryon density parameter <sup>[a]</sup>	$\Omega_b h^2$	$0.02230 \pm 0.00014$	$0.0224 \pm 0.0001$
	Physical dark matter density parameter <sup>[a]</sup>	$\Omega_c h^2$	$0.1188 \pm 0.0010$	$0.120 \pm 0.001$
	Age of the universe	$t_0$	$(13.799 \pm 0.021) \times 10^9$ years	$(13.787 \pm 0.020) \times 10^9$ years <sup>[98]</sup>
	Scalar spectral index	$n_s$	$0.9667 \pm 0.0040$	$0.965 \pm 0.004$
	Curvature fluctuation amplitude, $k_0 = 0.002 \text{ Mpc}^{-1}$	$\Delta_R^2$	$2.441^{+0.088}_{-0.092} \times 10^{-9}$ <sup>[99]</sup>	?
	Reionization optical depth	$\tau$	$0.066 \pm 0.012$	$0.054 \pm 0.007$
Fixed parameters	Total density parameter <sup>[b]</sup>	$\Omega_{\text{tot}}$	1	?
	Equation of state of dark energy	$w$	-1	$w_0 = -1.03 \pm 0.03$
	Tensor/scalar ratio	$r$	0	$r_{0.002} < 0.06$
	Running of spectral index	$dn_s/d \ln k$	0	?
	Sum of three neutrino masses	$\sum m_\nu$	$0.06 \text{ eV}/c^2$ <sup>[c][92]:40</sup>	$0.12 \text{ eV}/c^2$
	Effective number of relativistic degrees of freedom	$N_{\text{eff}}$	$3.046$ <sup>[d][92]:47</sup>	$2.99 \pm 0.17$
Calculated values	Hubble constant	$H_0$	$67.74 \pm 0.46 \text{ km s}^{-1} \text{ Mpc}^{-1}$	$67.4 \pm 0.5 \text{ km s}^{-1} \text{ Mpc}^{-1}$
	Baryon density parameter <sup>[b]</sup>	$\Omega_b$	$0.0486 \pm 0.0010$ <sup>[e]</sup>	?
	Dark matter density parameter <sup>[b]</sup>	$\Omega_c$	$0.2589 \pm 0.0057$ <sup>[f]</sup>	?
	Matter density parameter <sup>[b]</sup>	$\Omega_m$	$0.3089 \pm 0.0062$	$0.315 \pm 0.007$
	Dark energy density parameter <sup>[b]</sup>	$\Omega_\Lambda$	$0.6911 \pm 0.0062$	$0.6847 \pm 0.0073$
	Critical density	$\rho_{\text{crit}}$	$(8.62 \pm 0.12) \times 10^{-27} \text{ kg/m}^3$ <sup>[g]</sup>	?
	The present root-mean-square matter fluctuation averaged over a sphere of radius $8h^{-1} \text{ Mpc}$	$\sigma_8$	$0.8159 \pm 0.0086$	$0.811 \pm 0.006$
	Redshift at decoupling	$z_*$	$1089.90 \pm 0.23$	$1089.80 \pm 0.21$
	Age at decoupling	$t_*$	$377700 \pm 3200$ years <sup>[99]</sup>	?
	Redshift of reionization (with uniform prior)	$z_{\text{re}}$	$8.5^{+1.0}_{-1.1}$ <sup>[100]</sup>	$7.68 \pm 0.79$

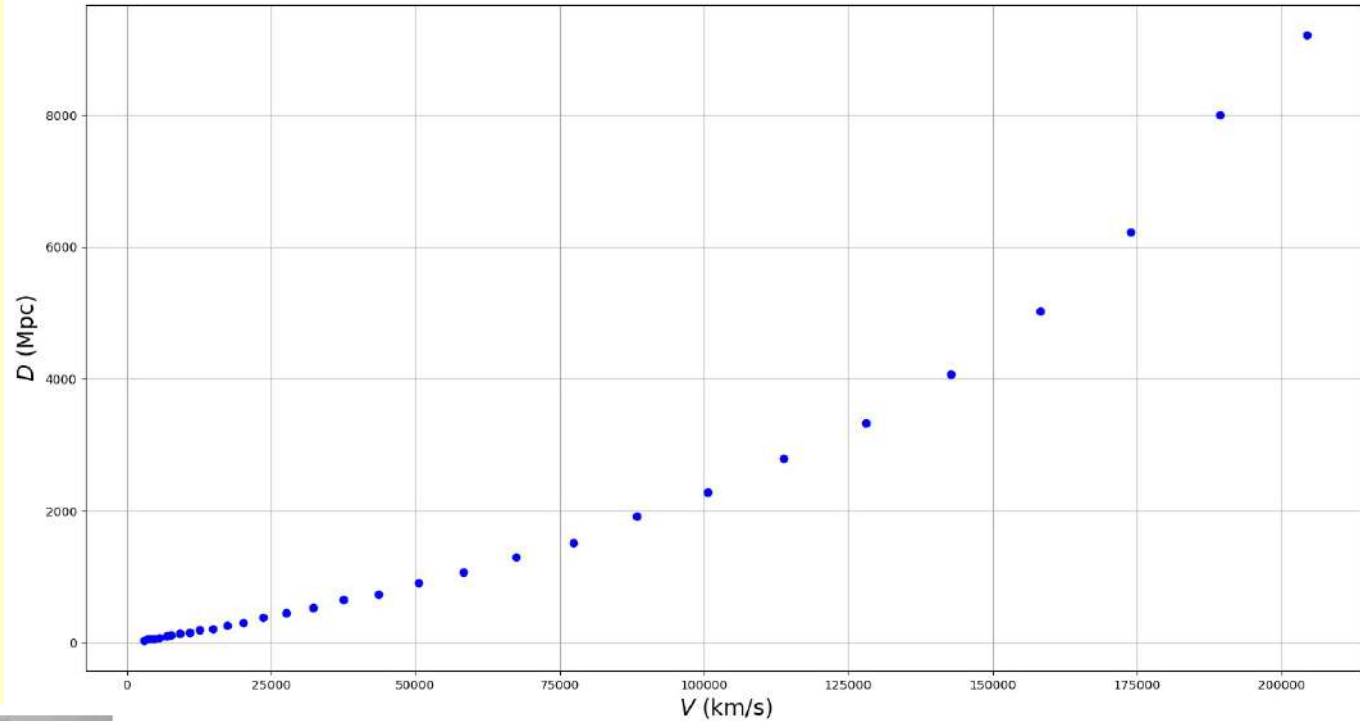
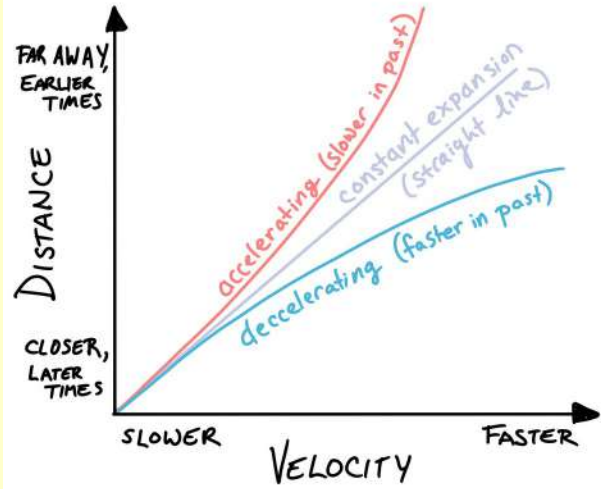


# Odabrani rezultati: ubrzano širenje

moj plot s podacima iz rada M. Betoule et al. A&A 568, A22 (2014)

crtež Jessie Muir

<https://www.jessiemuir.com/2021-12-08-hubble-diagram/>



© The Nobel Foundation. Photo: U. Montan



© The Nobel Foundation. Photo: U. Montan  
Saul Perlmutter



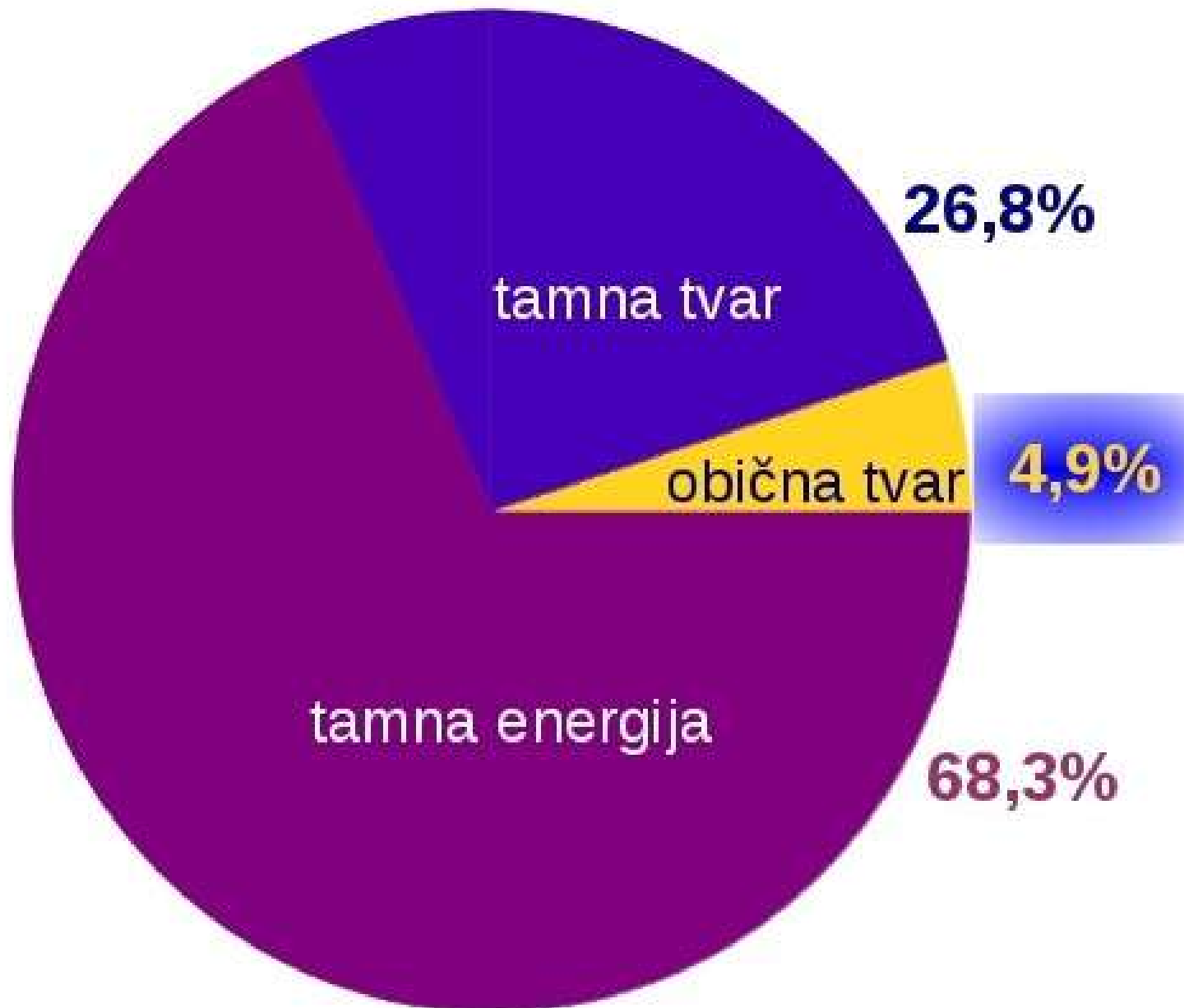
© The Nobel Foundation. Photo: U. Montan  
Brian P. Schmidt



© The Nobel Foundation. Photo: U. Montan  
Adam G. Riess

**Saul Perlmutter, Brian Schmidt i Adam Riess, Nobelova 2011.**

# Odabrani rezultati: “5% svemira”



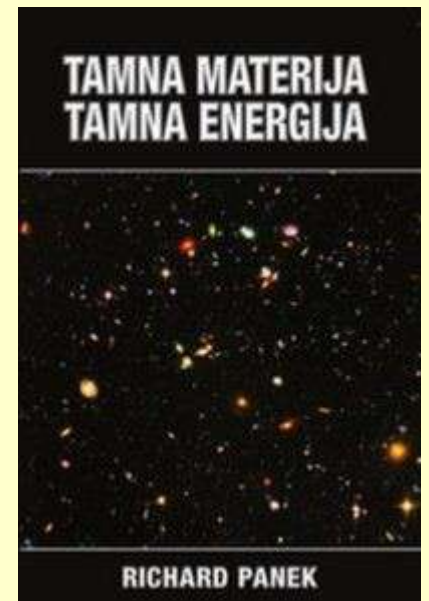
# Odabrani rezultati: Nobelova 2019.



Izvor: Juan Diego Soler

**James Peebles**

za "teorijska otkrića u fizičkoj kozmologiji"



**Fizička kozmologija  
je prirodna znanost!**