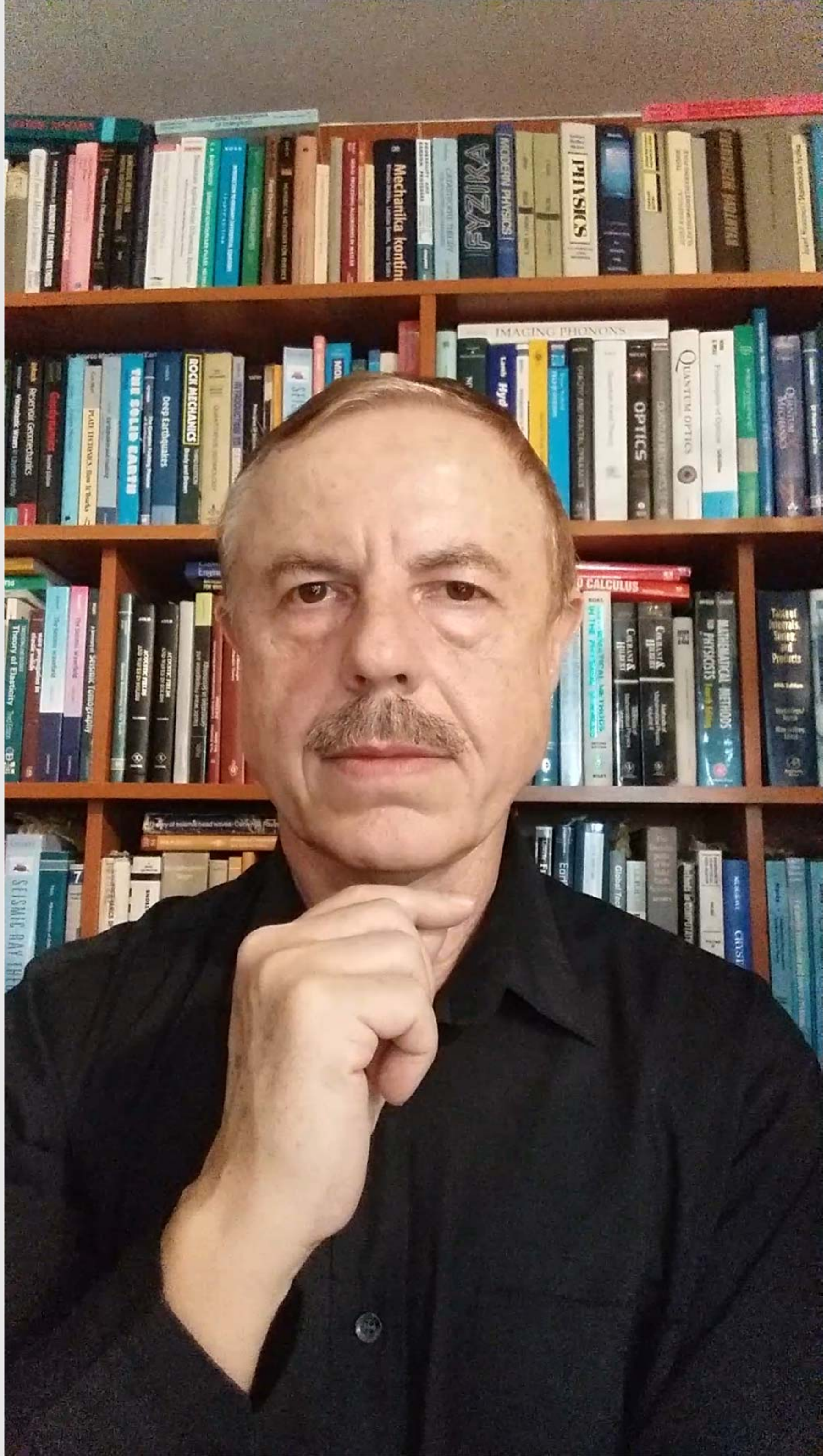
Is
cosmic microwave background
relic radiation of Big Bang
or
thermal radiation
of cosmic dust?

Václav Vavryčuk

The Czech Academy of Sciences
Institute of Geophysics

www: https://www.ig.cas.cz/en/contact/staff/vaclav-vavrycuk/
video: https://youtu.be/DVejwsJGOK8



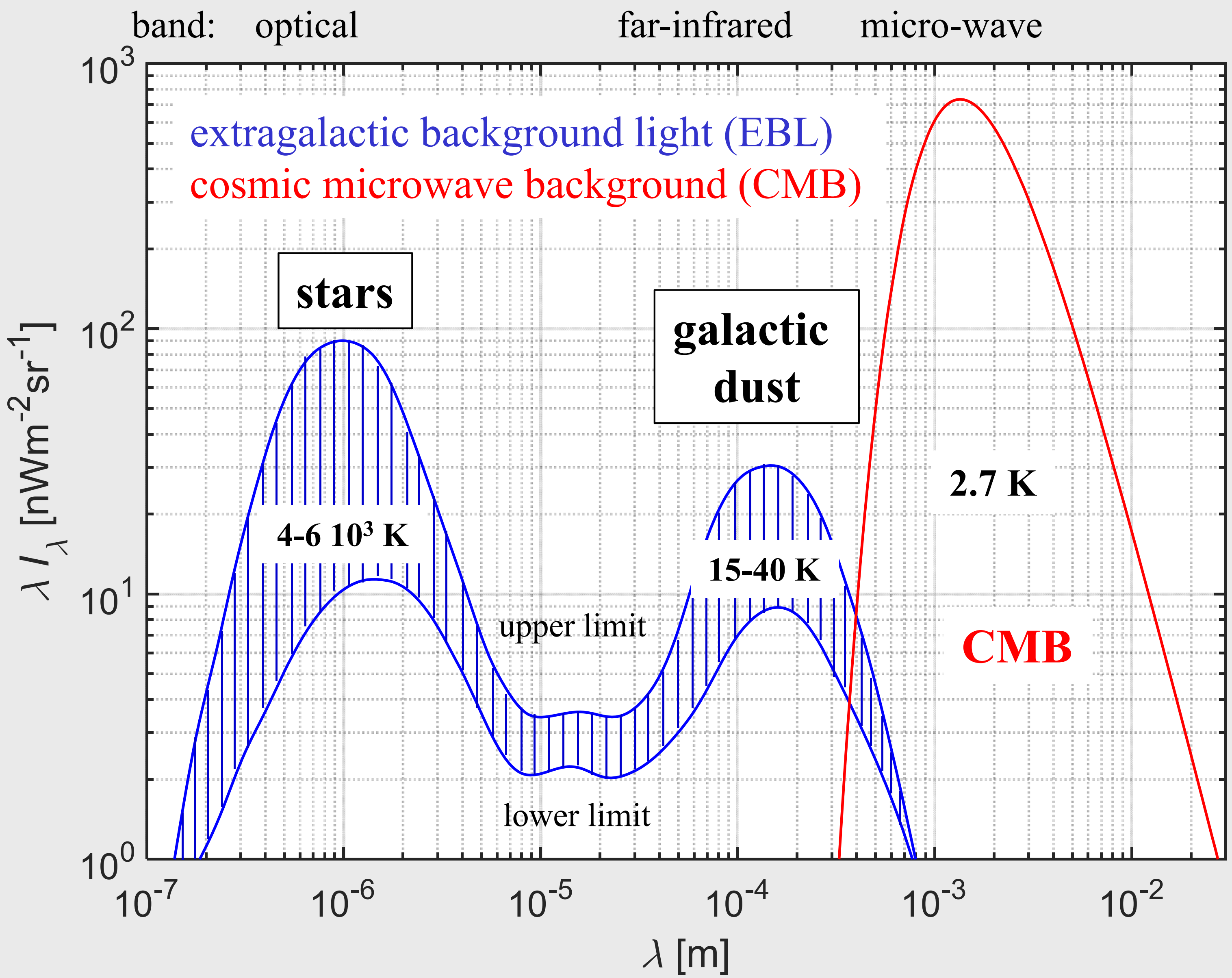
Cosmic microwave background (CMB) – history

Theoretical predictions and observations

- Ralph Alpher & Robert Herman (1948) – the existence of 'relic radiation' as radiation remaining form the hot Big Bang, the blackbody temperature estimated to 5 K
- George Gamov (1952, 1956) – temperature estimates 7 and 6 K
- Yakov Zel'dovich and Robert Dicke in the early 1960s – rediscoveries and re-estimates of the CMB temperature
- Arno Penzias & Robert Wilson (1965) – discovery of strong microwave radiation from all directions, the blackbody temperature of ~3 K, <u>Nobel prize in 1978</u>
- Robert Dicke et al. (1965) – proposed to interpret the CMB as blackbody radiation originated in the hot Big Bang
- George Smoot & John Mather, 1992 – FIRAS on the COBE satellite, discovery of the CMB anisotropy, <u>Nobel prize in 2006</u>
- **CMB experiments**: COBE, BOOMERANG, DASI, WMAP, Planck

Light coming from the Universe

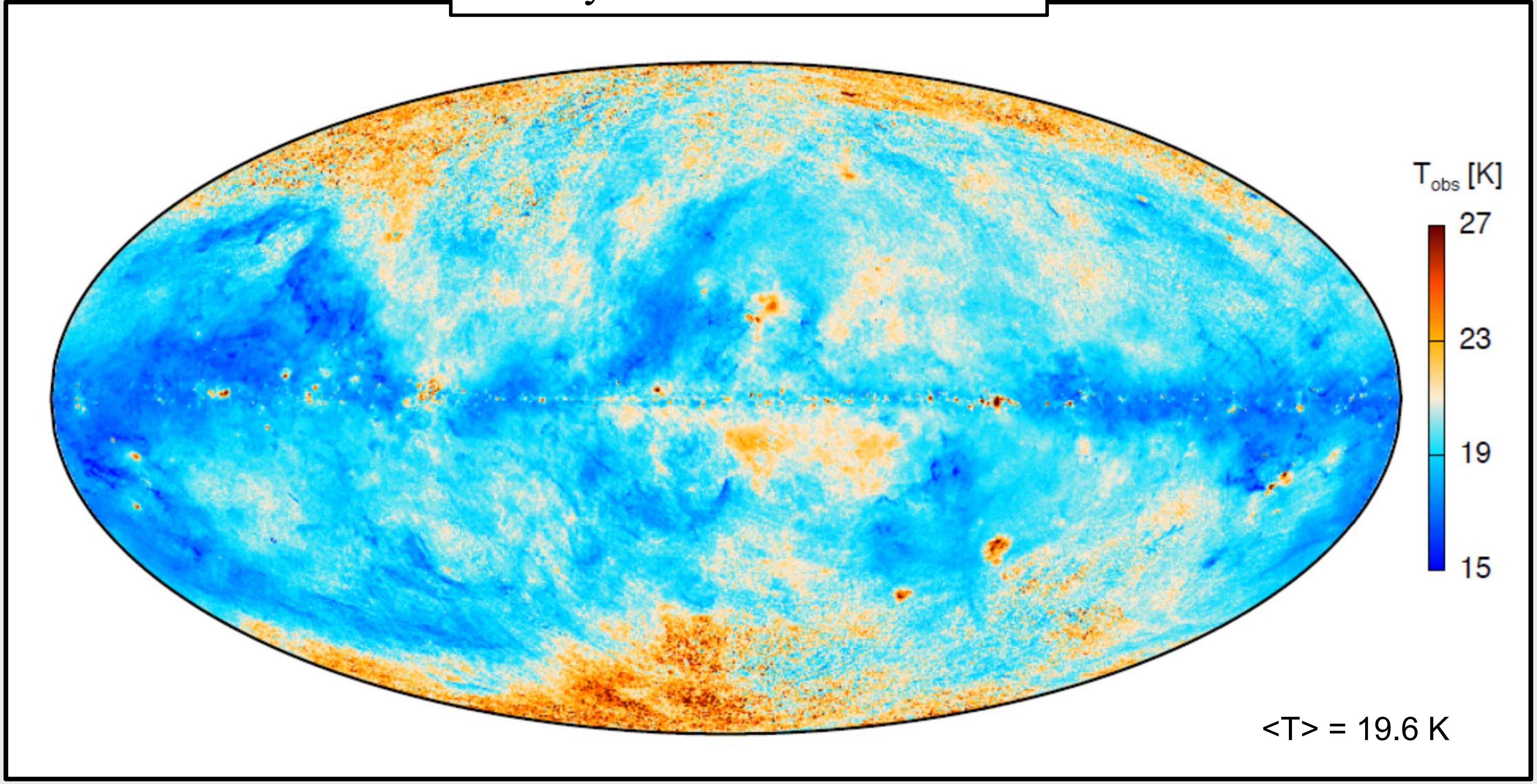
Origin of observed light: stars, galactic dust, intergalactic dust, Big Bang



Temperature of galactic dust in the Milky Way

- Dust temperature *T* varies between 15 K and 30 K
- *T* depends on the dust density and light emitted from nearby stars

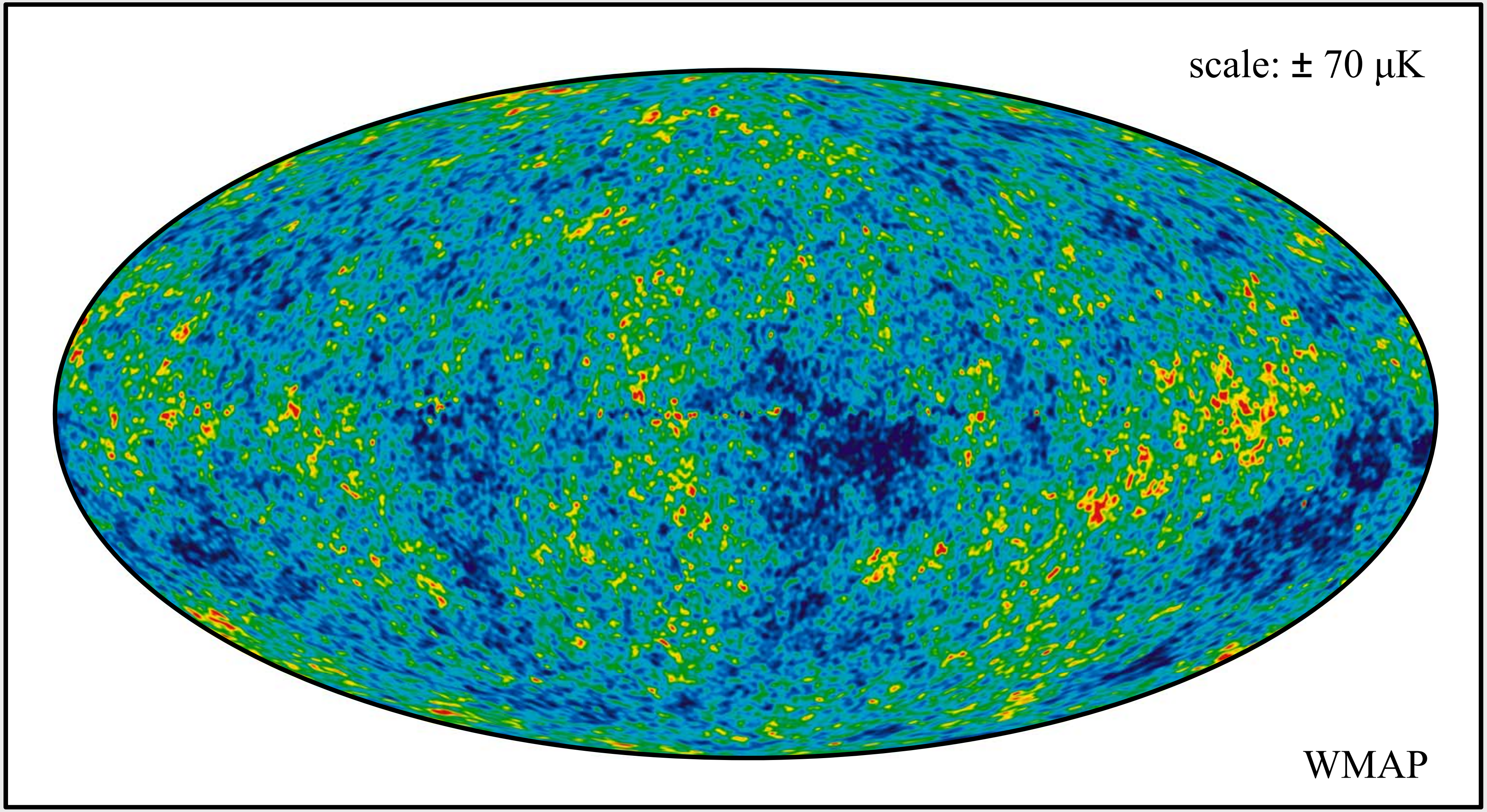
All-sky thermal dust emission



Planck 2013 Results

CMB temperature anisotropy

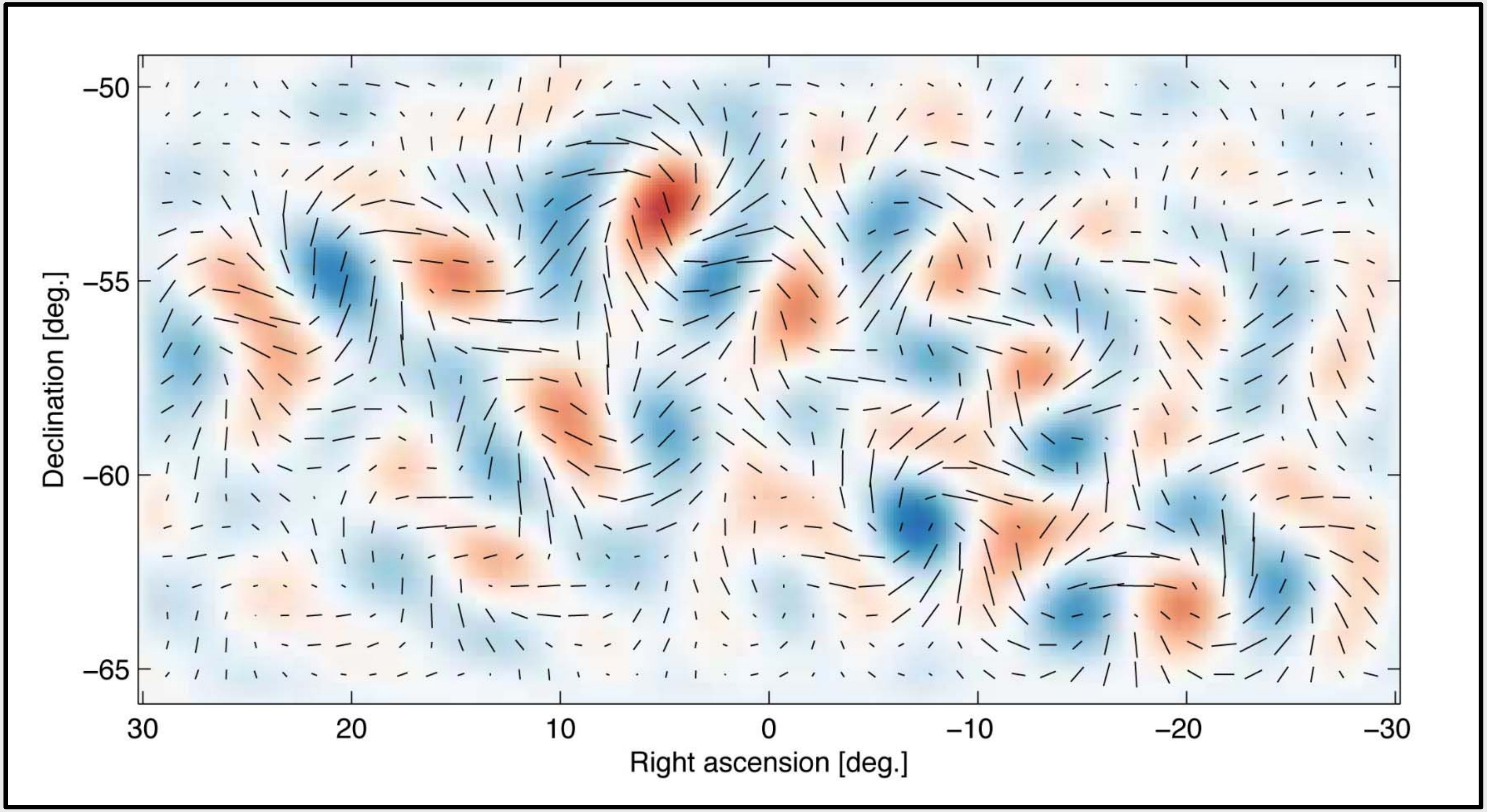
- The CMB temperature is quite stable and uniform **$T = 2.72548 \pm 0.00057$ K**
- Still it displays some fluctuations called the temperature anisotropies



https://map.gsfc.nasa.gov/media/

CMB polarization anisotropy

- The CMB is linearly polarized with two types of polarization (E-modes, B-modes)
- Polarization anomalies correlate with the temperature anisotropies



https://www.cfa.harvard.edu/~cbischoff/cmb/

CMB as relic radiation of Big Bang

Commonly accepted origin of the CMB

CMB as relic radiation:

- Radiation produced at very high redshifts (z ~1100, last scattering surface)
- Radiation is cooling due to adiabatic expansion of the Universe
- Temperature anisotropies: reflect density and velocity fluctuations at z ~1100
- Polarization anisotropies: Thomson scattering in a heterogeneous plasma

Difficulties and open questions:

- Unexpected features at large angular scales
  - non-Gaussianity of the CMB anisotropies (Vielva et al., 2004)
  - violation of statistical isotropy and scale invariance (Planck 2014)

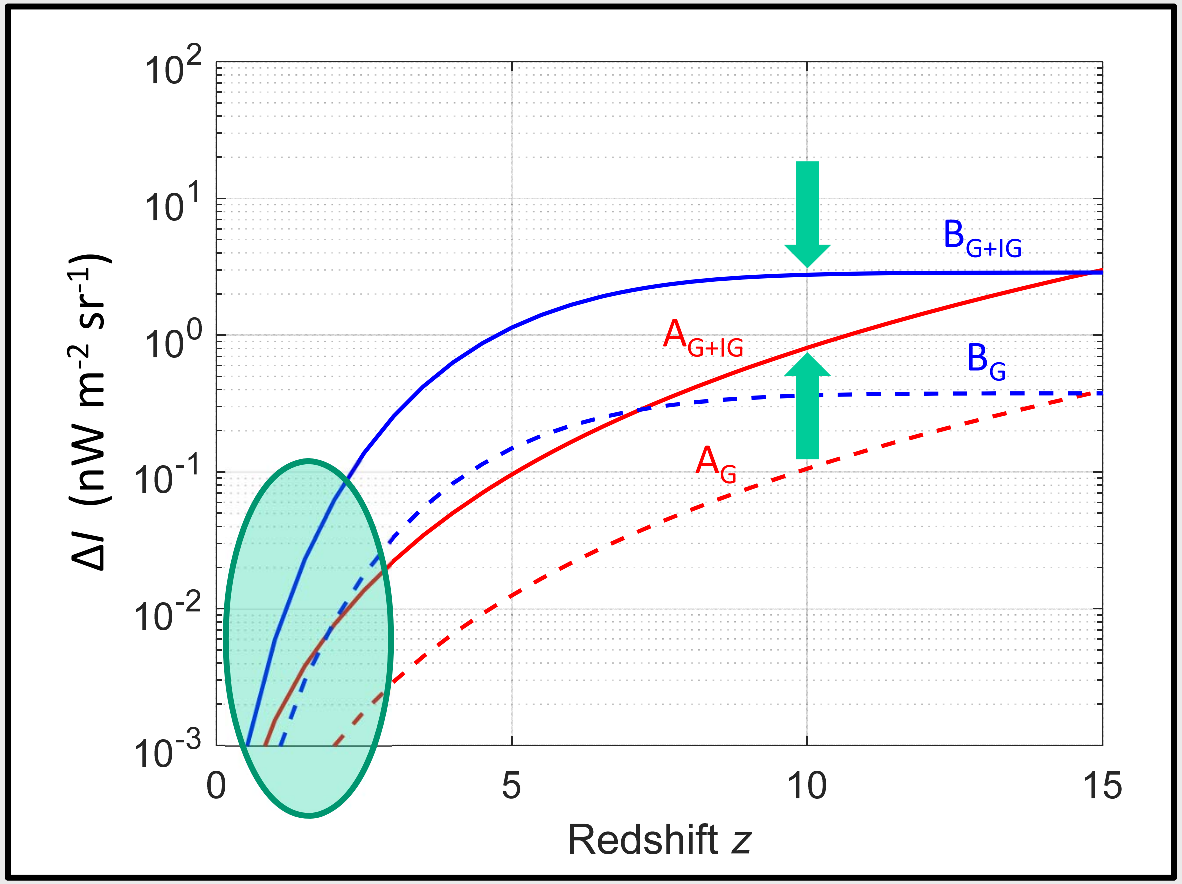
- Light from the very early Universe should be distorted in later epochs (Vavryčuk, 2017)
  - due to absorption by galactic dust
  - due to absorption by intergalactic dust

Total distortion of the CMB by dust absorption

- The total CMB intensity should be declined
- The distortion is at least 1 nWm^{-2} sr^{-1}, well above the sensitivity of the COBE/FIRAS, WMAP or Planck

Model A: constant proper dust density with redshift

Model B: proper dust density is related to the global stellar mass density



G – distortion by dust in galaxies

IG – distortion by intergalactic dust

Vavryčuk (MNRAS, 2017)

CMB as thermal radiation of intergalactic dust

Alternative origin of the CMB: dust in the Universe

CMB as thermal radiation of dust:

- Dust is thermalized by absorbing light of stars and emits thermal radiation
- Galactic dust produces thermal radiation at FIR wavelengths (EBL)
- Intergalactic dust is colder than galactic dust and emits CMB
- Proposed and discussed by: Wright (1982), Pan (1988), Bond et al. (1991), Peebles (1993), Aguirre (2000), Narlikar et al. (2003)

Difficulties and open questions:

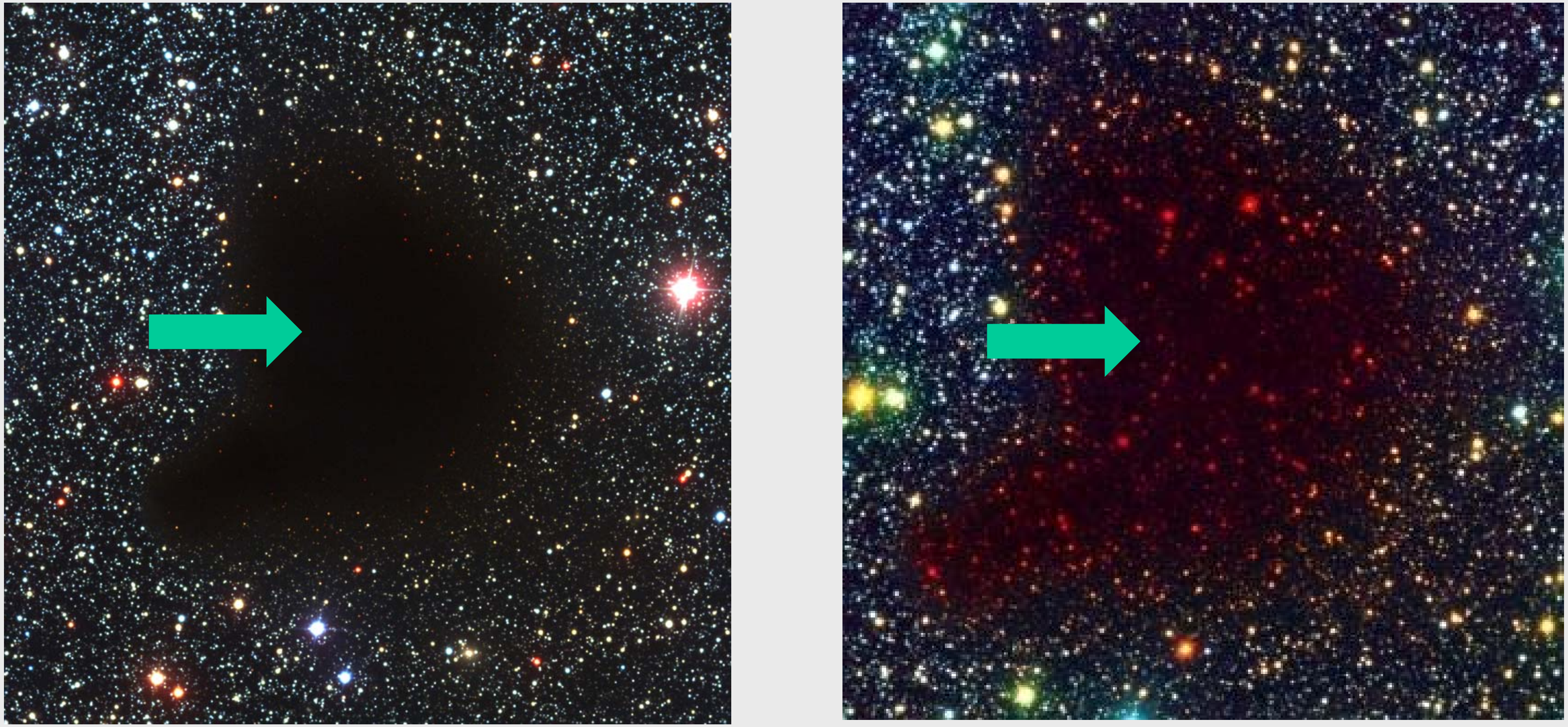
- Why the CMB radiation is so uniform and isotropic, although dust distribution is very likely quite heterogeneous?
- Why the CMB is not affected by a variety of redshifts of radiating dust grains? We should observe a mix of differently redshifted spectra.
- What is the origin of the CMB polarization anisotropies?
- Why the CMB temperature and polarization fluctuations are correlated?

abandoned

Dust theory – revisited

Alternative origin of the CMB: dust in the Universe

- **Universe is not transparent but partially opaque due to light absorption by dust**
- **Dust grains are warming up and emit thermal radiation:**
  - galactic dust produces the EBL at FIR wavelengths (T ~ 15 - 40K)
  - intergalactic dust produces the CMB (T ~ 3K) ???



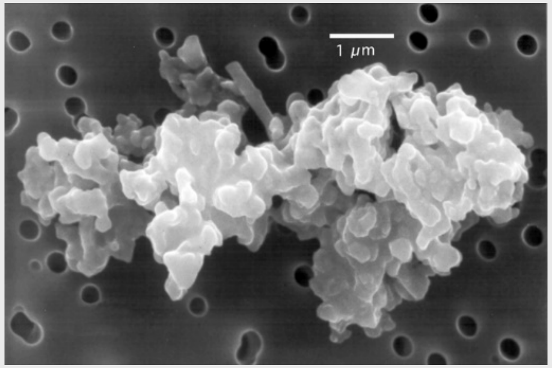
example of reddening

Precollapse Black Cloud B68, ESO

Origin, size, composition and properties of dust

- **Size and shape**

  typically ~ 1 µm, needle-shaped or elongated dust grains, complex fluffy aggregates



Jessberger et al. (2001)

- **Origin**

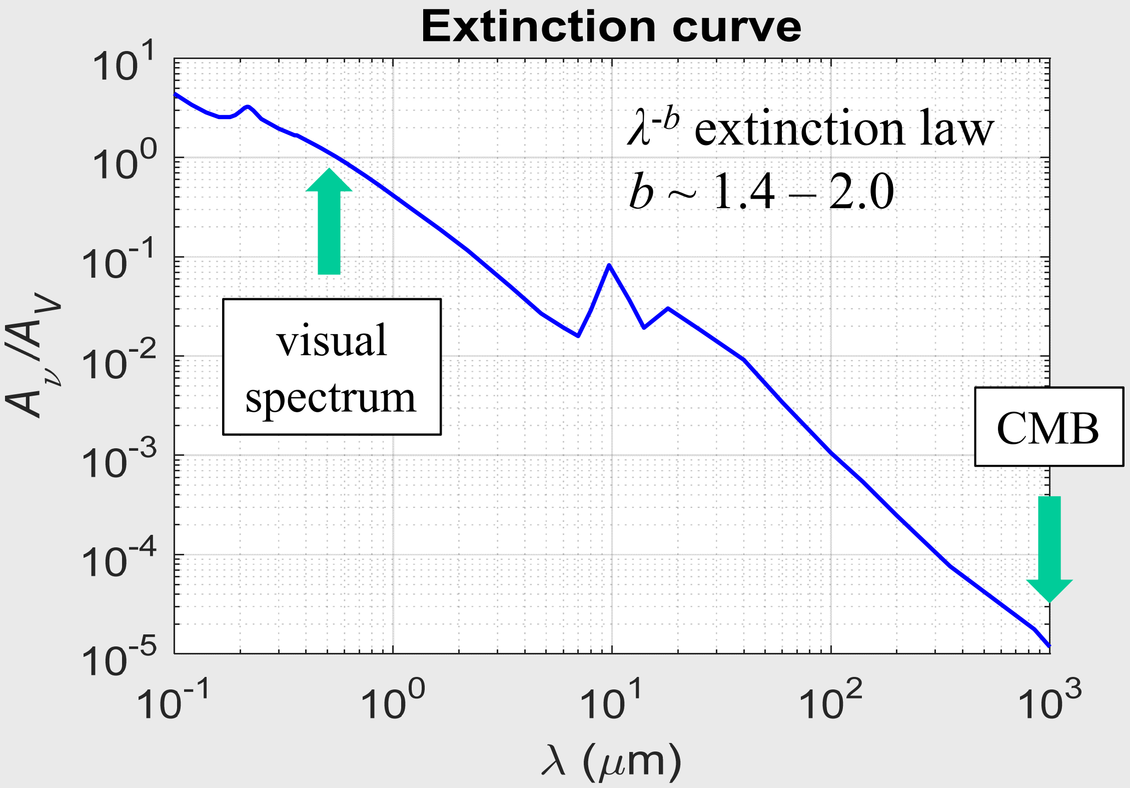
  supernovae collapses – outflow of material into the space

- **Composition**

  graphite, silicates, metals

- **Properties**

  - electrical conductivity
  - wavelength-dependent light absorption



λ^{-b} extinction law

$b \sim 1.4 – 2.0$

Mathis (1990), Draine (2011)

Galactic and intergalactic opacities

Galactic opacity & type of a galaxy

(Calzetti 2001, Holwerda et al, 2005)

elliptical galaxies:	0.04-0.08 mag
Sa-Sab:	0.5-075 mag
Sb-Scd:	0.65-0.95 mag
irregular galaxies:	0.3-0.4 mag

Mean value A_V over type and occurrence:

0.15-0.30 mag

Intergalactic opacity

(Menard et al. 2010, Xie et al. 2015)

- dust in the IGM, damped Lyman absorbers
- near galaxies and in intracluster space
- studied by quasar composite spectra which show a systematic variance with redshift
- strongly redshift dependent

Mean local value A_V: ~ **0.02 mag Gpc^{-1}**

elliptical galaxy

ESO

spiral galaxy

ESO

Dust extinction versus hydrogen density

Hydrogen column densities

Studied by the Lyman-α absorption lines of dampled Lyman absorbers (DLAs)

N_{H} versus colour excess:

$$N_{\mathrm{H}} / \left(A_B - A_V\right) = 5.8 \text{ x } 10^{21}\,\mathrm{cm}^{-2}\,\mathrm{mag}^{-1}$$

N_{H} versus extinction:

$$N_{\mathrm{H}} / A_V \approx 1.87 \text{ x } 10^{21}\,\mathrm{cm}^{-2}\,\mathrm{mag}^{-1} \quad \text{for } R_V = 3.1$$

DLA properties

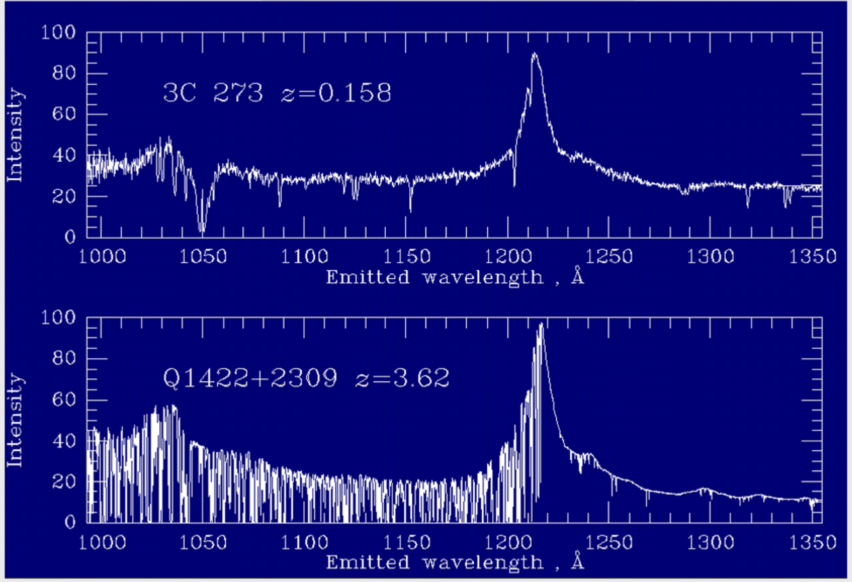
mean cross-section density ~10^{-5} Mpc^{-1}
column density N_{HI} ~ 10^{21} cm^{-2}

Intergalactic extinction

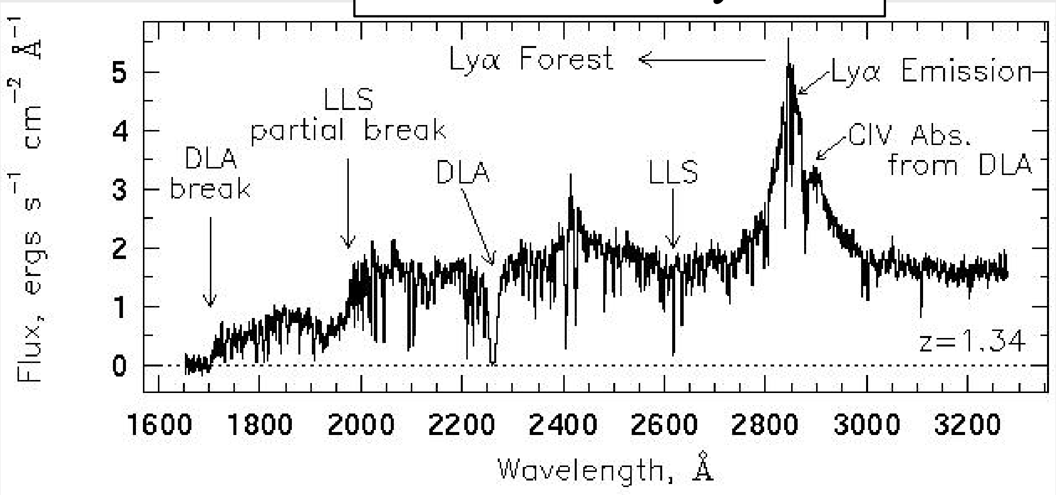
$$\boxed{A_V \sim 0.02 \text{ mag Gpc}^{-1}}$$

(Bohlin et al., 1978, Rachford et al., 2002; Zwaan et al, 2005)

Lyman-α forest



LLS and DLA systems



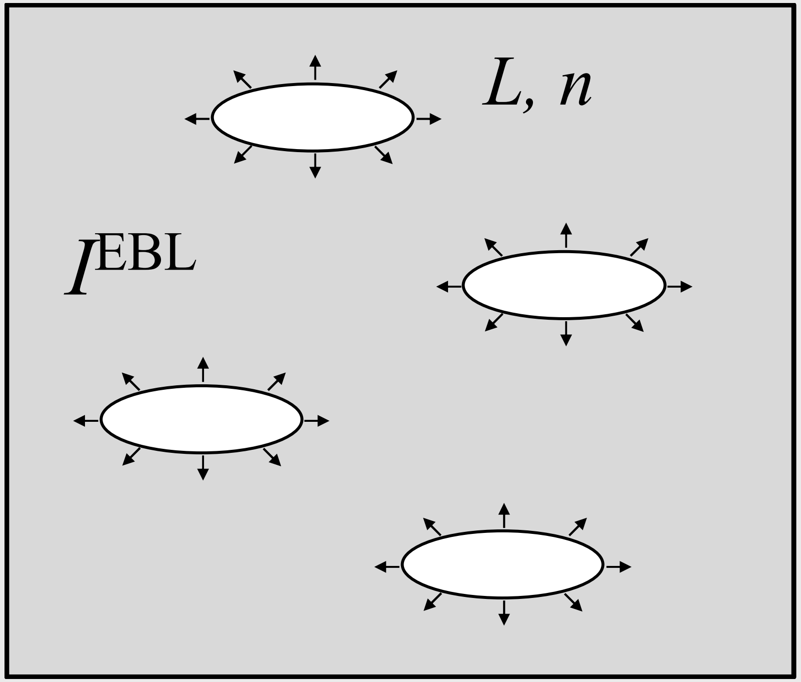
Charlton & Churchill (2000)

Light in dusty universe

How opacity affects the light in the Universe?

EBL – light summed from all galaxies

$$I_0^{\mathrm{EBL}} = \frac{1}{4\pi}\int_0^{z_{\max}} \frac{j(z)}{(1+z)^2}\,\boxed{e^{-\tau(z')}}\,\frac{c}{H_0}\frac{dz}{E(z)}$$



$j(z) = nL$ – luminosity density (in W m^{-3})

L – galaxy luminosity (in W)

n – galaxy number density (in m^{-3})

H_0 – Hubble constant

$E(z)$ – dimensionless Hubble parameter

$\tau(z)$ – **optical depth**, decrease of amplitude

$$\boxed{\tau_\nu(z) = \frac{c}{H_0}\int_0^z \left(\frac{\kappa_\nu}{\gamma_0}+\lambda_{\nu 0}\right)(1+z')^2\,\frac{dz'}{E(z')}}$$

$$\gamma_0 = \frac{1}{n_0 \pi a^2}$$

λ_0 – intergalactic opacity (~ 0.02 Gpc^{-1})

κ – mean galactic opacity (~ 0.22)

γ_0 – the galaxy mean free path (~ 160 Gpc)

Vavryčuk (2017)

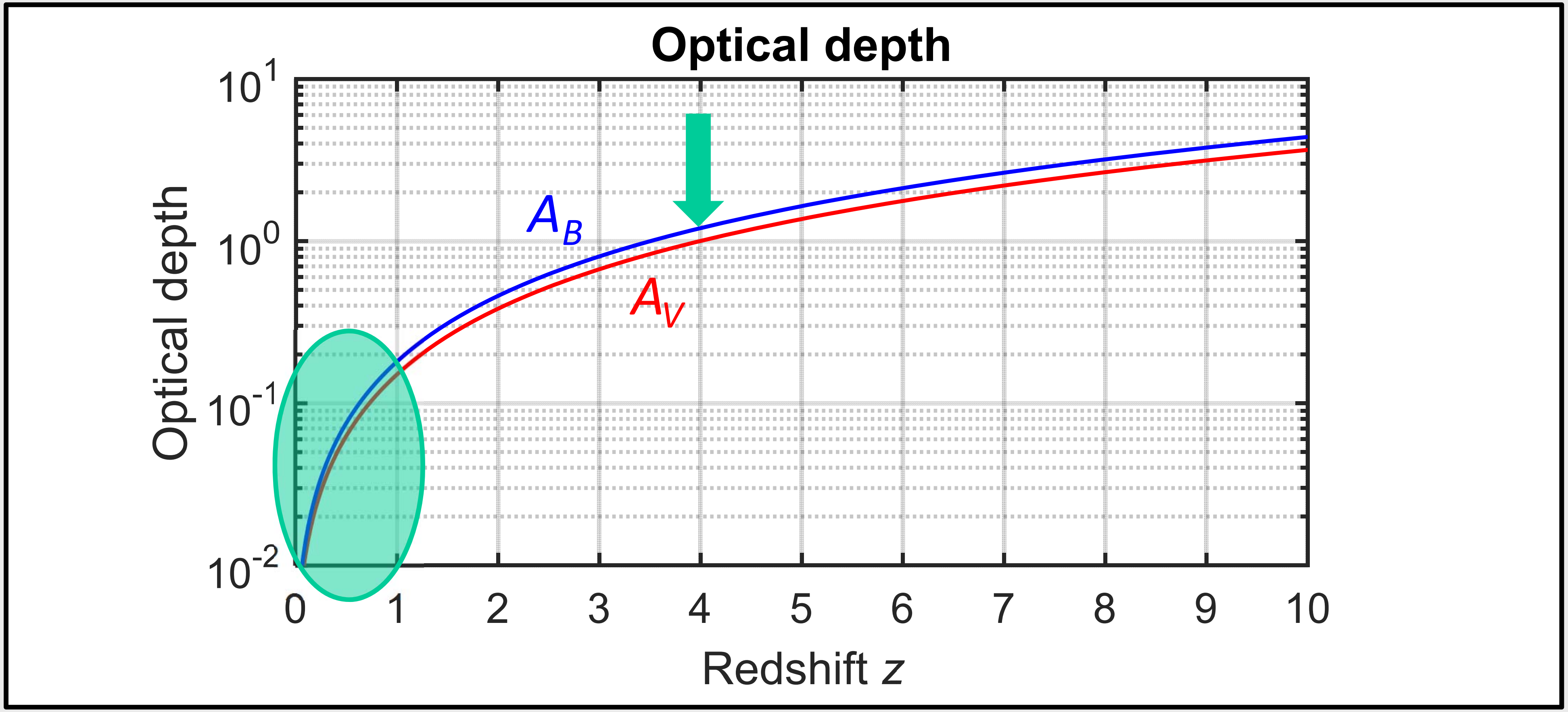
Redshift-dependent opacity

Universe occupied a small volume in previous epochs:

- high dust density
  (small distances between dust grains)
- high galaxy number density
- high frequencies of light due to redshift

→

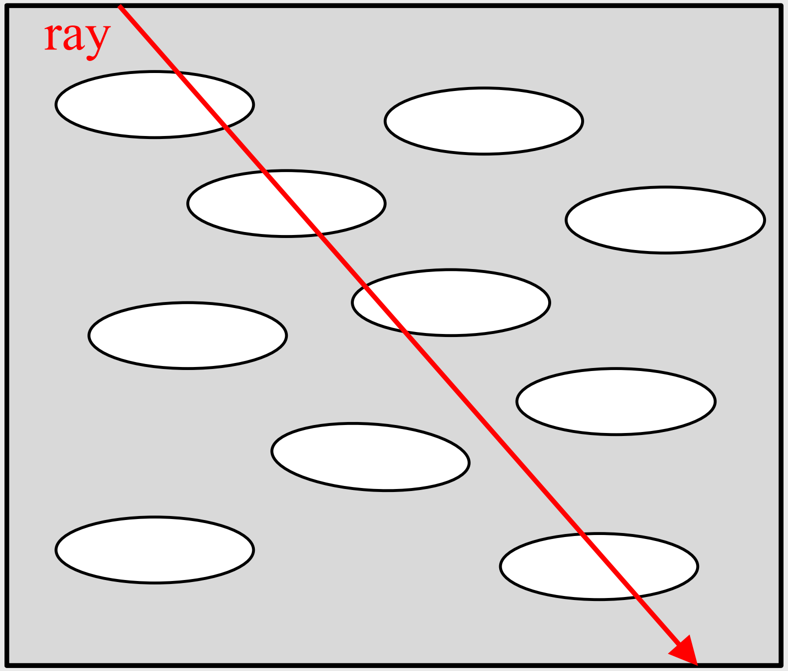
dust absorption
strongly increases
with redshift!



Opacity ratio

What is more important:

galactic or intergalactic opacity?



Opacity ratio R_κ - average ratio between attenuation caused by intergalactic dust vs galaxies

$$\boxed{R_\kappa = \frac{\lambda_0 \gamma_0}{\kappa} \quad \sim 13.5}$$

n_0 – the galaxy number density (0.02 Mpc^{-3})
a – the galaxy radius (10 kpc)

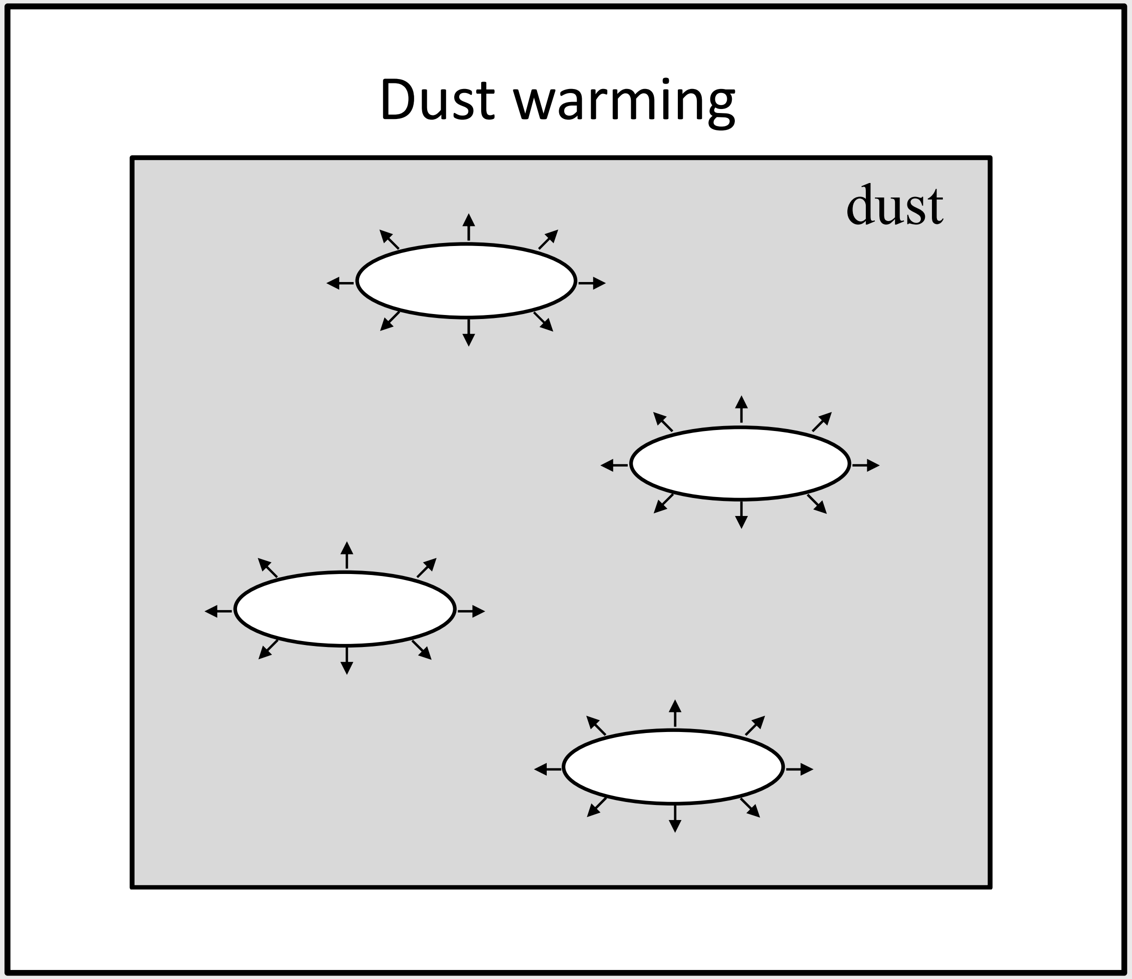
λ_0 – intergalactic opacity (~ 0.02 mag Gpc^{-1})
κ – mean galactic opacity (~ 0.22)
γ_0 – the galaxy mean free path (~ 160 Gpc)

$$\boxed{\gamma_0 = \frac{1}{n_0 \pi a^2}}$$

Intergalactic opacity is higher by more than one order than galactic opacity!

Energy balance of intergalactic dust and galaxies I

- Galaxies produce light
- Light is absorbed by dust and dust is heated up
- The dust temperature **continuously** increases

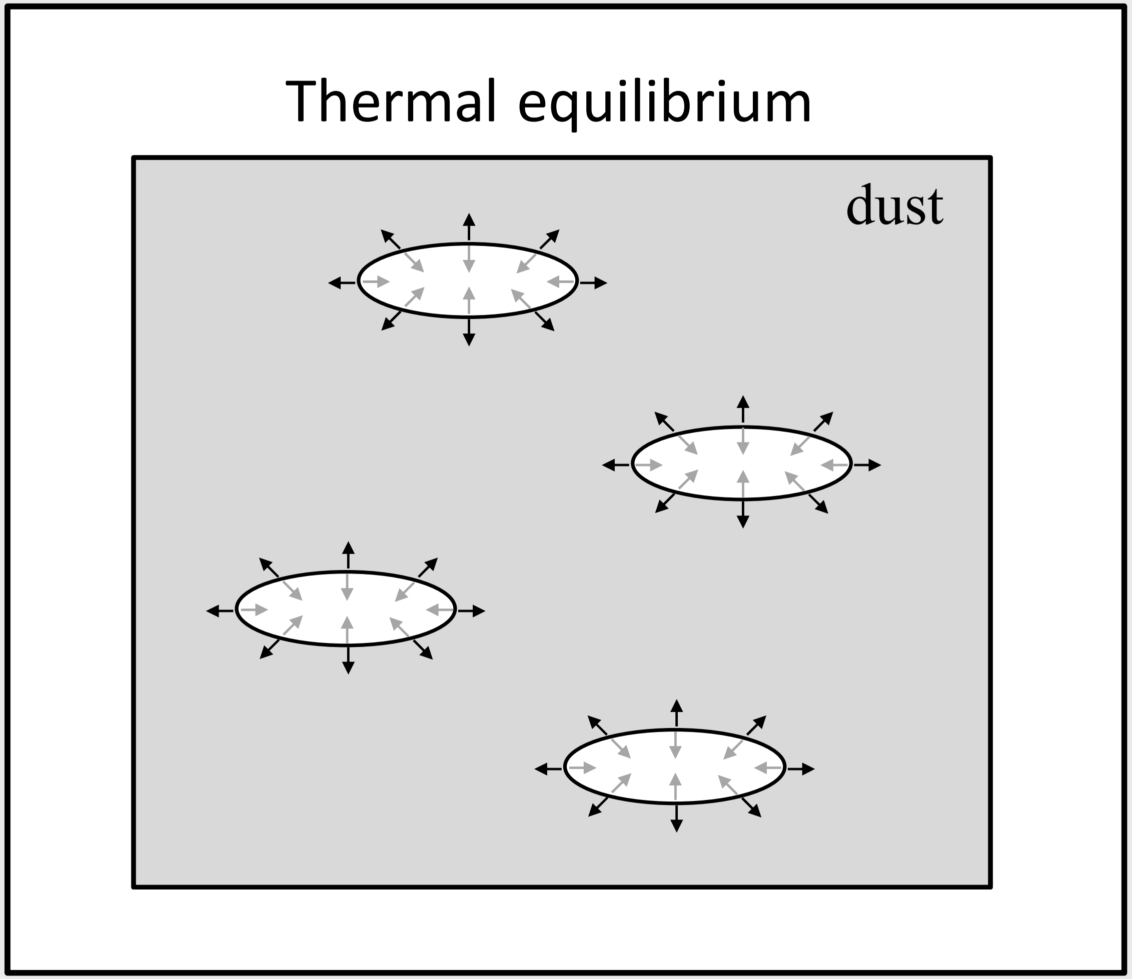


Thermal catastrophe

(known from the Olbers' paradox)

Energy balance of intergalactic dust and galaxies II

- Dust is heated up due to absorption of light from galaxies
- Dust emits thermal radiation, radiation is partly absorbed by galaxies
- Dust and galaxies are in energy balance → temperature is **stable**



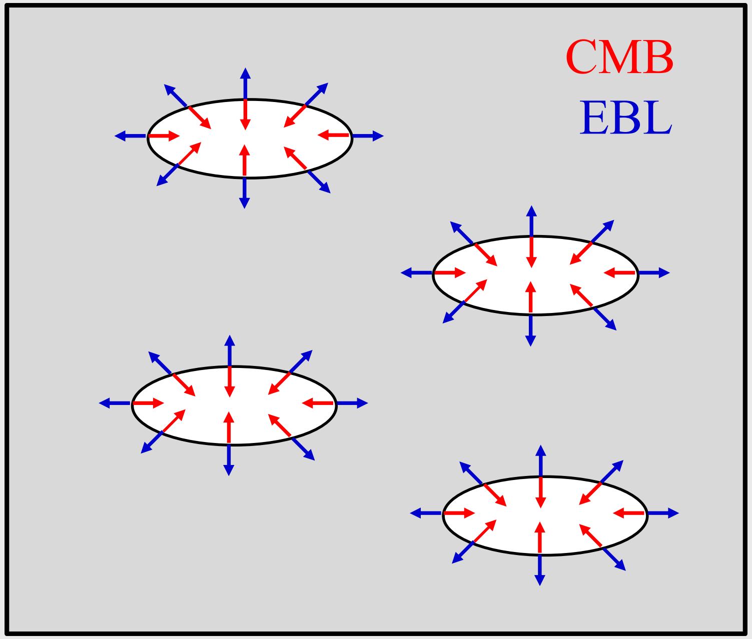
Dust temperature remains low and constant!

Temperature of intergalactic dust

Energy balance between galaxies and intergalactic dust:

$$I^D = R_\kappa I^{EBL}$$

E absorbed by galaxies → $$\frac{I^D}{R_\kappa} = I^{EBL}$$ ← *E* radiated by galaxies



I^D – intensity of intergalactic dust radiation (in nWm^{-2}sr^{-1})

R_κ – opacity ratio (~13.5)

I^{EBL} – intensity of the EBL radiation (~80 nWm^{-2}sr^{-1})

Predicted dust temperature

$$T^D = \left(\frac{I^D}{\pi\sigma}\right)^{\frac{1}{4}} = 2.776\ \mathrm{K}$$

σ – Stefan-Boltzmann constant

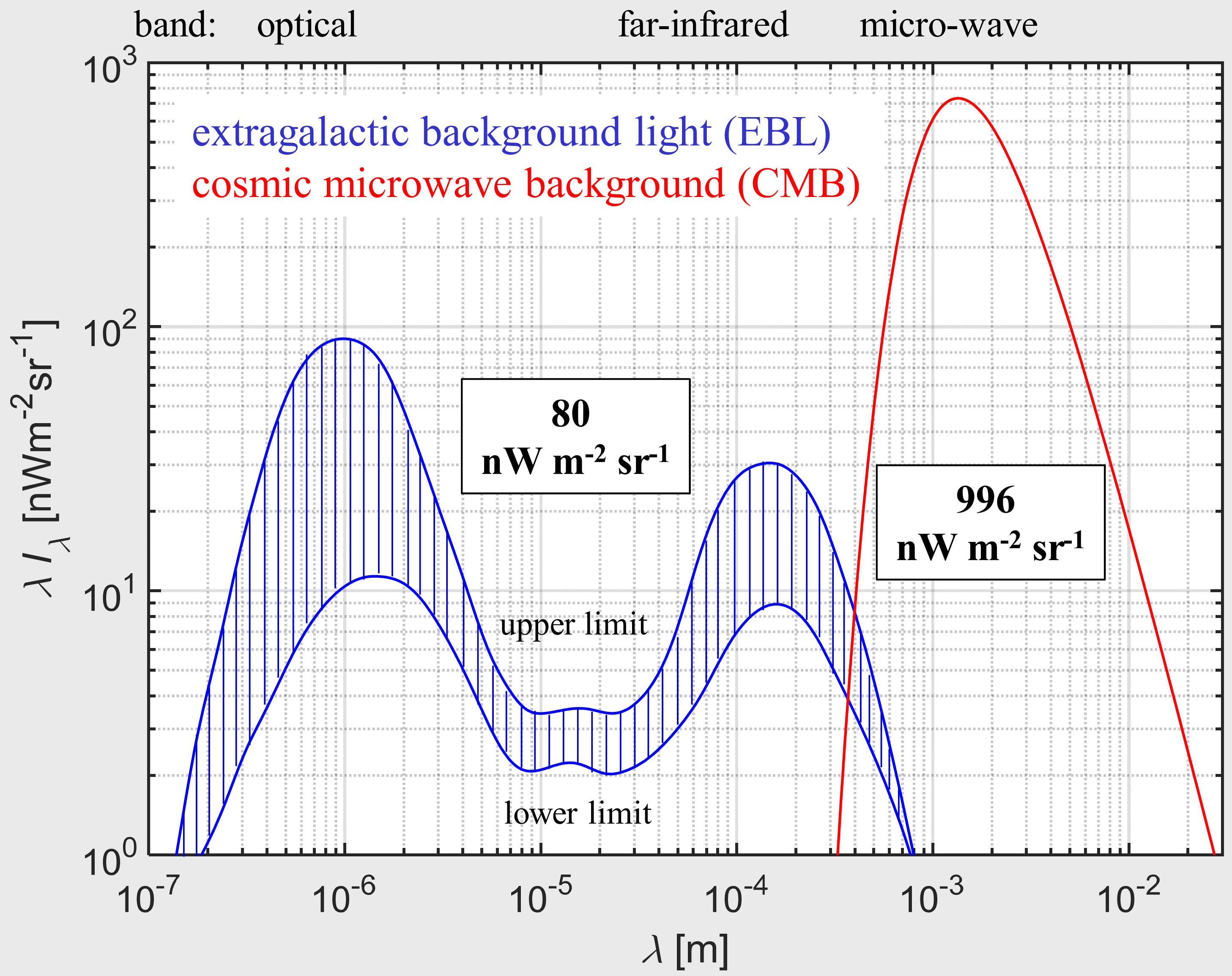
Observed CMB temperature

$$T^{\mathrm{obs}} = 2.725\ \mathrm{K}$$

T error < 2%

Relation between EBL and CMB

- **The total intensities of the EBL and CMB are not independent!**
- **The multiplication factor is the opacity ratio R_κ**



Evolution of dust radiation with redshift

Evolution of dust temperature with redshift

- **Transparent universe**

  equation of radiative transfer for adiabatic expansion:

$$\frac{d}{dt}I_\nu + 3HI_\nu = 0 \quad \rightarrow \quad \boxed{\begin{aligned} I^{\text{relic}} &= I_0^{\text{relic}}(1+z)^4 \\ T^{\text{relic}} &= T_0^{\text{relic}}(1+z) \end{aligned}}$$

H – Hubble parameter, ν – frequency

- **Opaque universe**

  equation of radiative transfer for adiabatic expansion:

$$\frac{d}{dt}I_\nu + 3HI_\nu = \frac{c}{4\pi}j_\nu - c\kappa_\nu I_\nu \overset{!}{=} 0 \quad \rightarrow \quad \boxed{\begin{aligned} I^{\text{dust}} &= I_0^{\text{dust}}(1+z)^4 \\ T^{\text{dust}} &= T_0^{\text{dust}}(1+z) \end{aligned}}$$

sources = losses

j_ν – luminosity density, c – light speed, κ_ν – opacity

balance between sources and losses

Why the radiation is not distorted by redshift?

Increase of T^{dust} with z exactly compensates change of wavelengths!

Evolution of galaxies and intergalactic dust with redshift

Assumption of the model:

The number of galaxies and the amount of dust are time independent!

Is such assumption physically reasonable?

No light from the early universe
is evidenced by:

decline of the luminosity density with *z*

decline of the global stellar mass with *z*

Dark or opaque early universe?

Darkness vs. opacity of the early universe (z ~ 5-20)

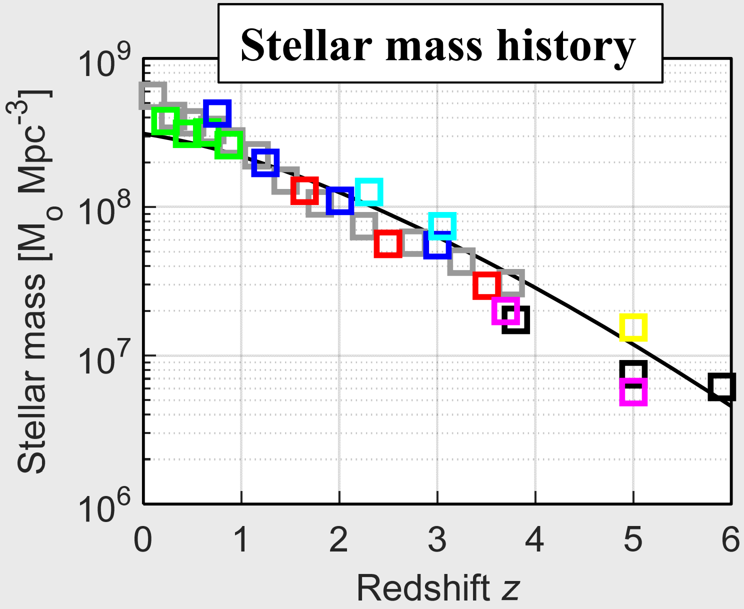
Decreasing amount of observed light with increasing redshift

transparent universe

opaque universe

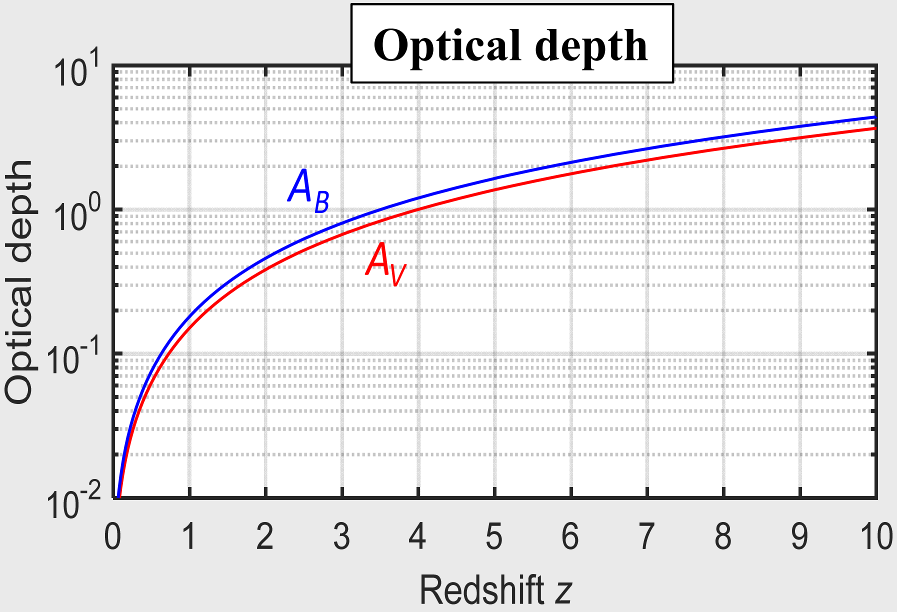
stellar mass decreases with z

intergalactic opacity increases with z



Stellar mass history

colors – measurements of different authors



Optical depth

dust density increases as $(1+z)^3$

Redshift-dependent luminosity density

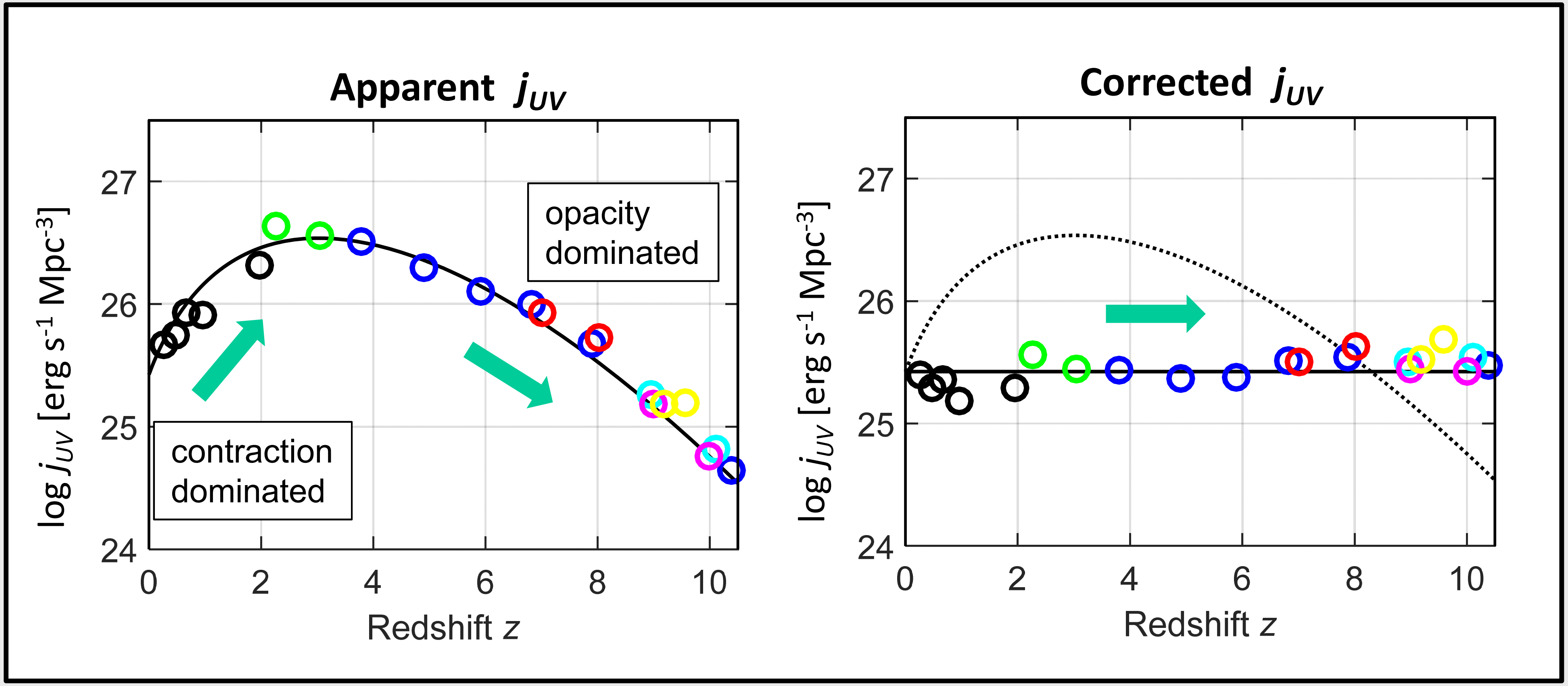
Luminosity density *j* - volume energy density of light in the Universe (Wm^{-3})

- increases from $z = 0$ to $z = 3$
- decreases for $z > 3 – 4$

$$\boxed{j_{UV}^{A} = j_{UV}(z)(1+z)^{3}e^{-\tau(z)}}$$

Transparent universe: *j* reflects evolution of number of galaxies, unknown origin

Dusty universe: *j* reflects expansion and dust absorption



Redshift-dependent stellar mass density

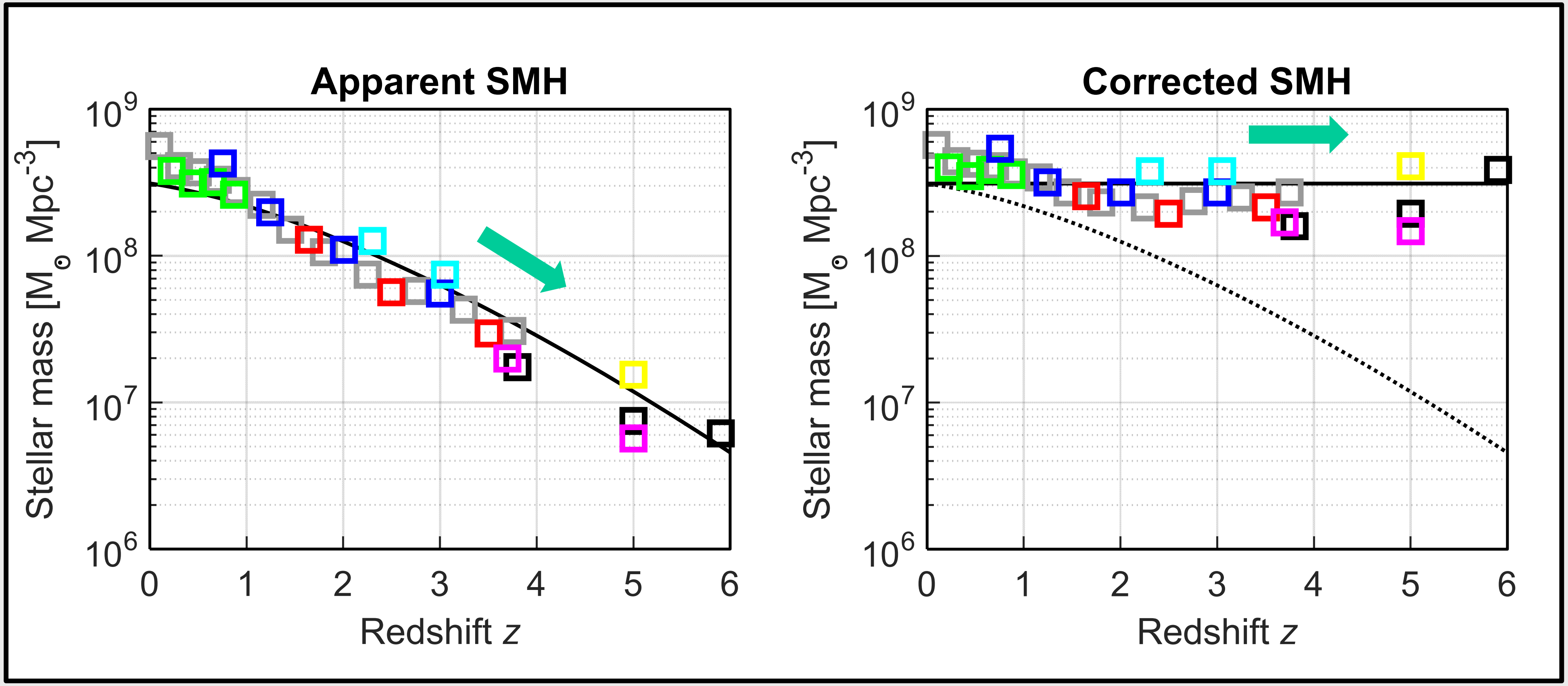
Stellar mass density *ρ* – number of stars per volume (in M_{sun} Mpc^{-3})

- apparent stellar mass density ρ^A increases with time

$$\boxed{\rho^A(z) = \rho(z)\, e^{-\tau_V(z)}}$$

Transparent universe: stellar mass density increases with time, the rate decreases

Dusty universe: stellar mass density is constant in time



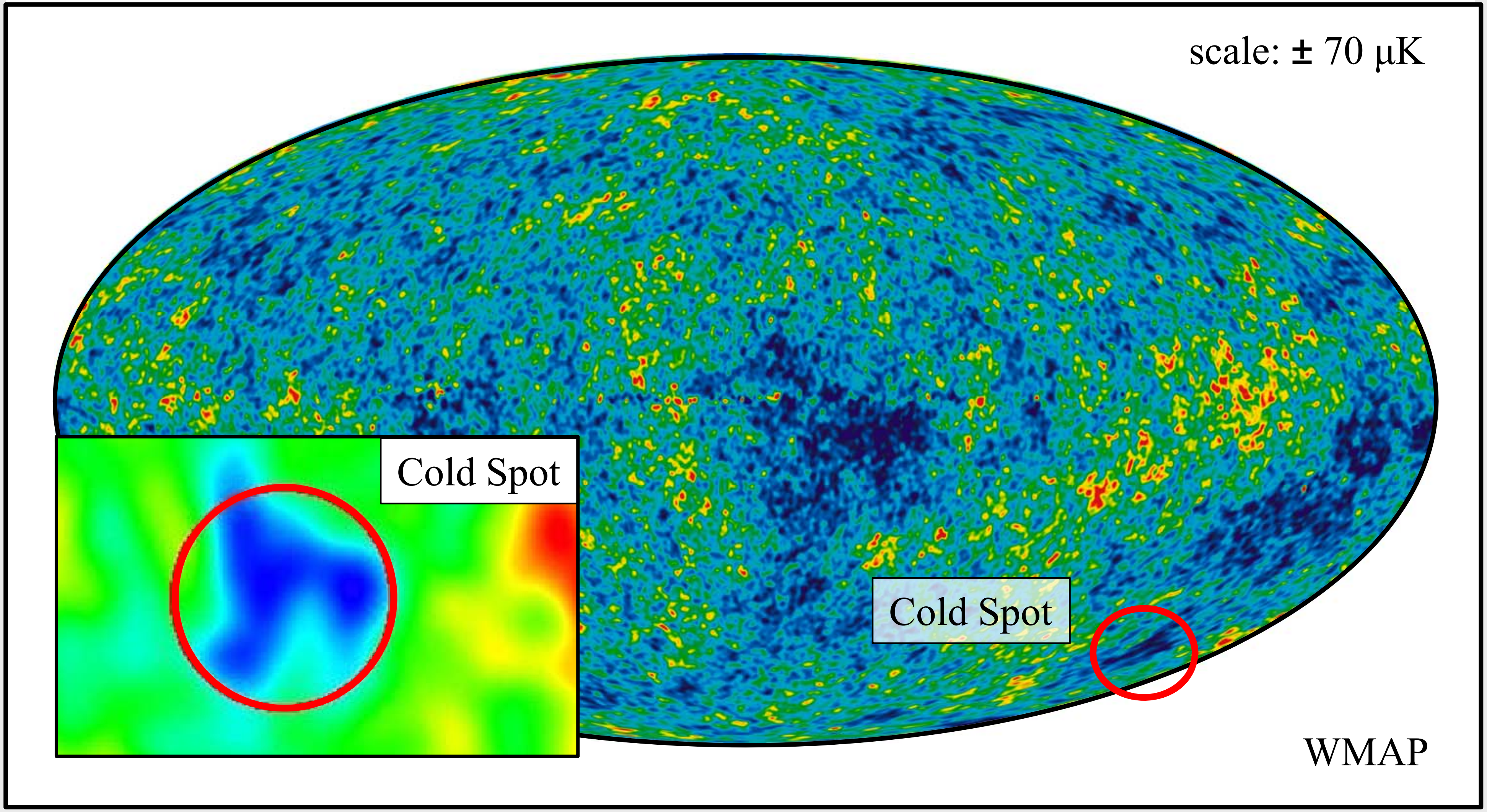
Temperature and polarization anisotropies of CMB

Temperature anisotropy of CMB

CMB fluctuations are caused by the EBL fluctuations due to clusters and voids

Correlation between CMB fluctuations and voids and clusters (Kovács et al. 2017)

Cold Spot – related to Eridanus Supervoid (Szapudi et al, 2015)

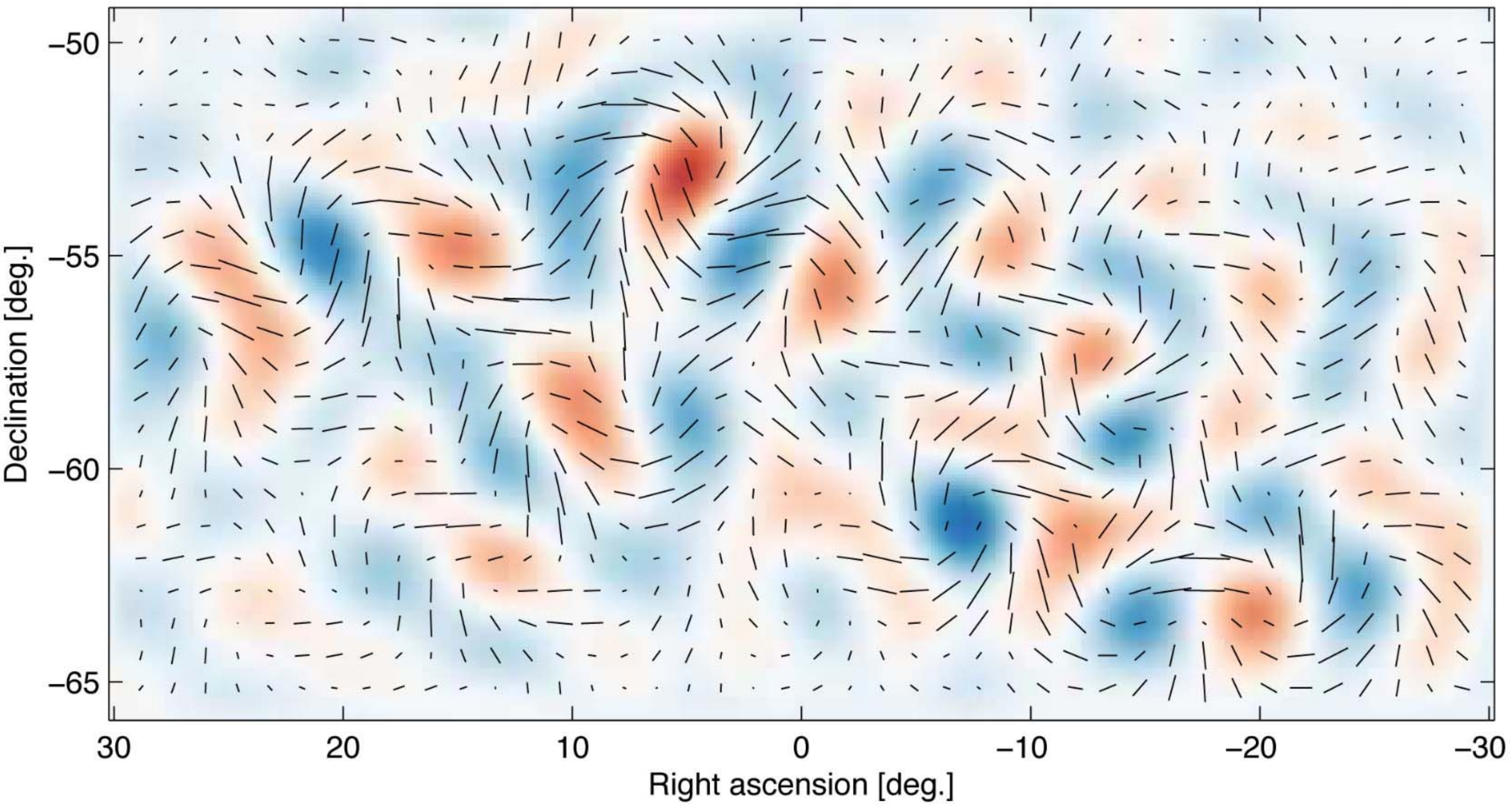


https://map.gsfc.nasa.gov/media/

Polarization anisotropy of CMB

The CMB is linearly polarized with two types of polarization (E-modes, B-modes)

Polarization anomalies correlate with the temperature anisotropies



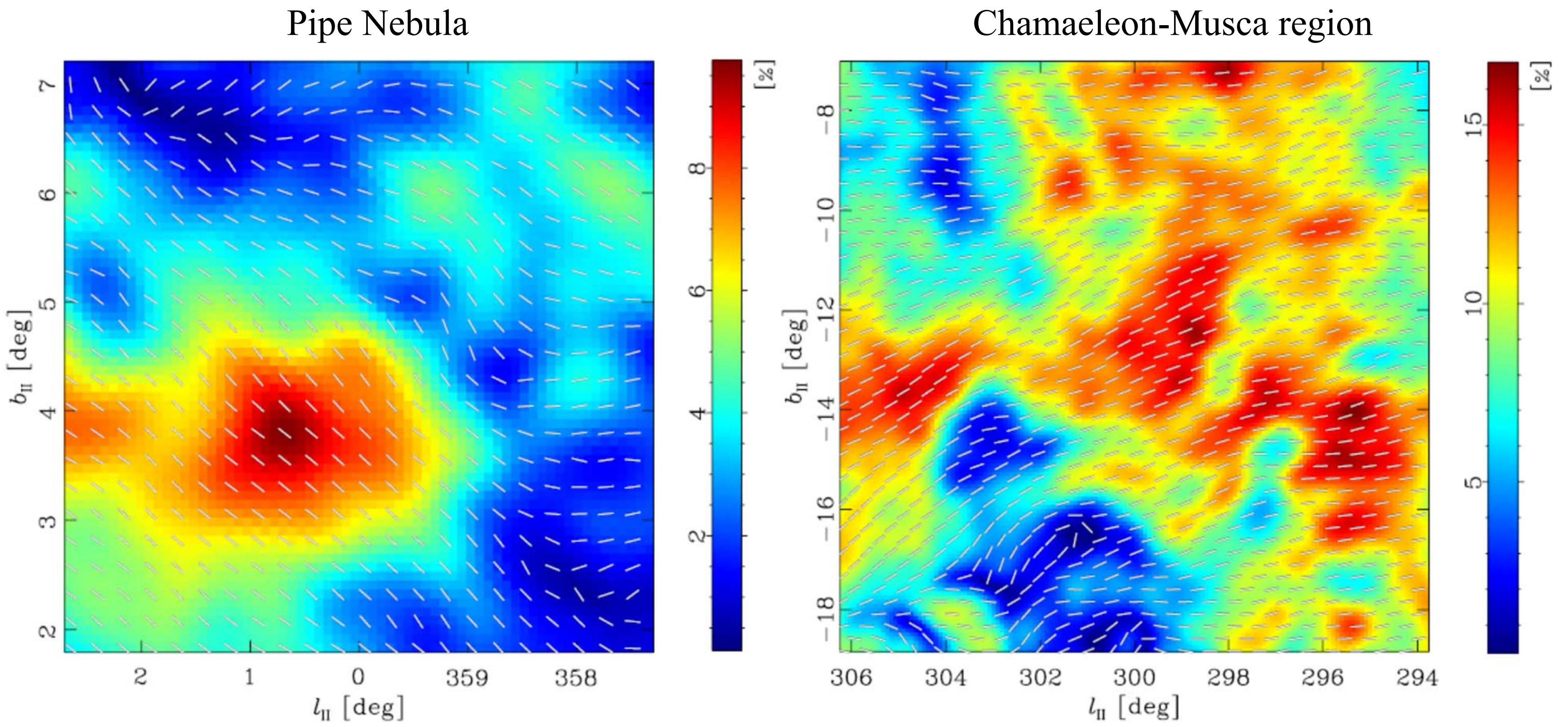
https://www.cfa.harvard.edu/~cbischoff/cmb/

Polarization anisotropy of CMB

Interaction of dust with cosmic magnetic fields:

- Needle-shaped conducting dust grains cause polarized thermal radiation
- **Galactic dust** – polarization anomalies at FIR wavelengths
- **Intergalactic dust** – polarization anomalies at the CMB wavelengths

Tracing of magnetic field by galactic dust


Pipe Nebula

Chamaeleon-Musca region

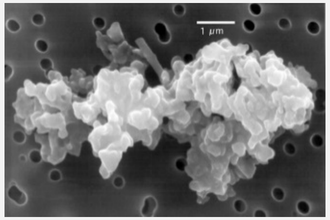
Planck XIX (2015, Fig. 10)

Summary

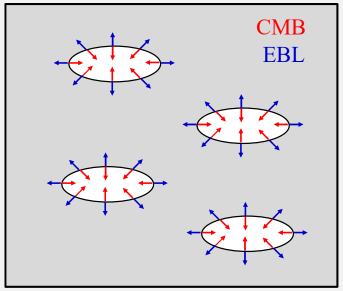
Summary I – origin of the CMB

Dust theory provides a consistent explanation of the CMB origin

- The CMB is thermal radiation of intergalactic dust grains.

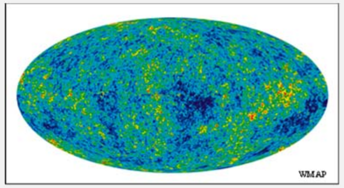


- The temperature of the CMB is controlled by energy balance between galaxies and intergalactic dust.

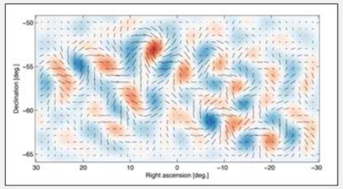


- The CMB temperature is predicted with a high accuracy and it linearly increases with redshift.

- The CMB temperature anisotropies are caused by fluctuations of the EBL related to clusters and voids in the universe.



- The CMB polarization anisotropies are caused by alignment of conducting dust grains in magnetic fields in the universe.

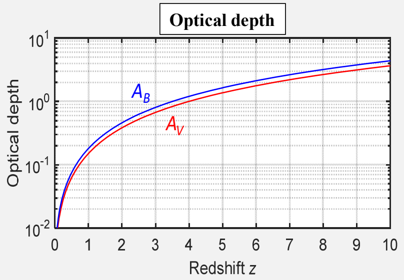


- The CMB temperature and polarization anisotropies are correlated because they have a common origin: large scale structures in the universe.

Summary II – cosmological consequences

Dust theory is incompatible with the Big Bang

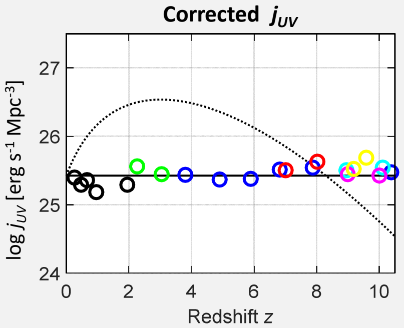
- Opacity strongly increases with redshift.



Optical depth

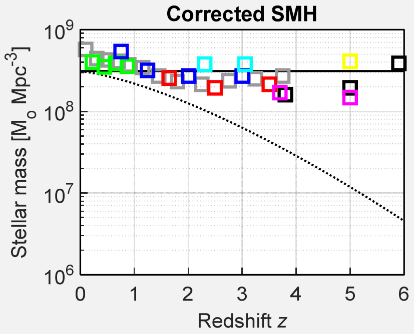
- No light from the early universe is due to its opacity rather than due to its darkness.

- Proper luminosity density corrected for the universe opacity is time independent.



Corrected j_{UV}

- Global stellar mass corrected for the universe opacity is time independent.

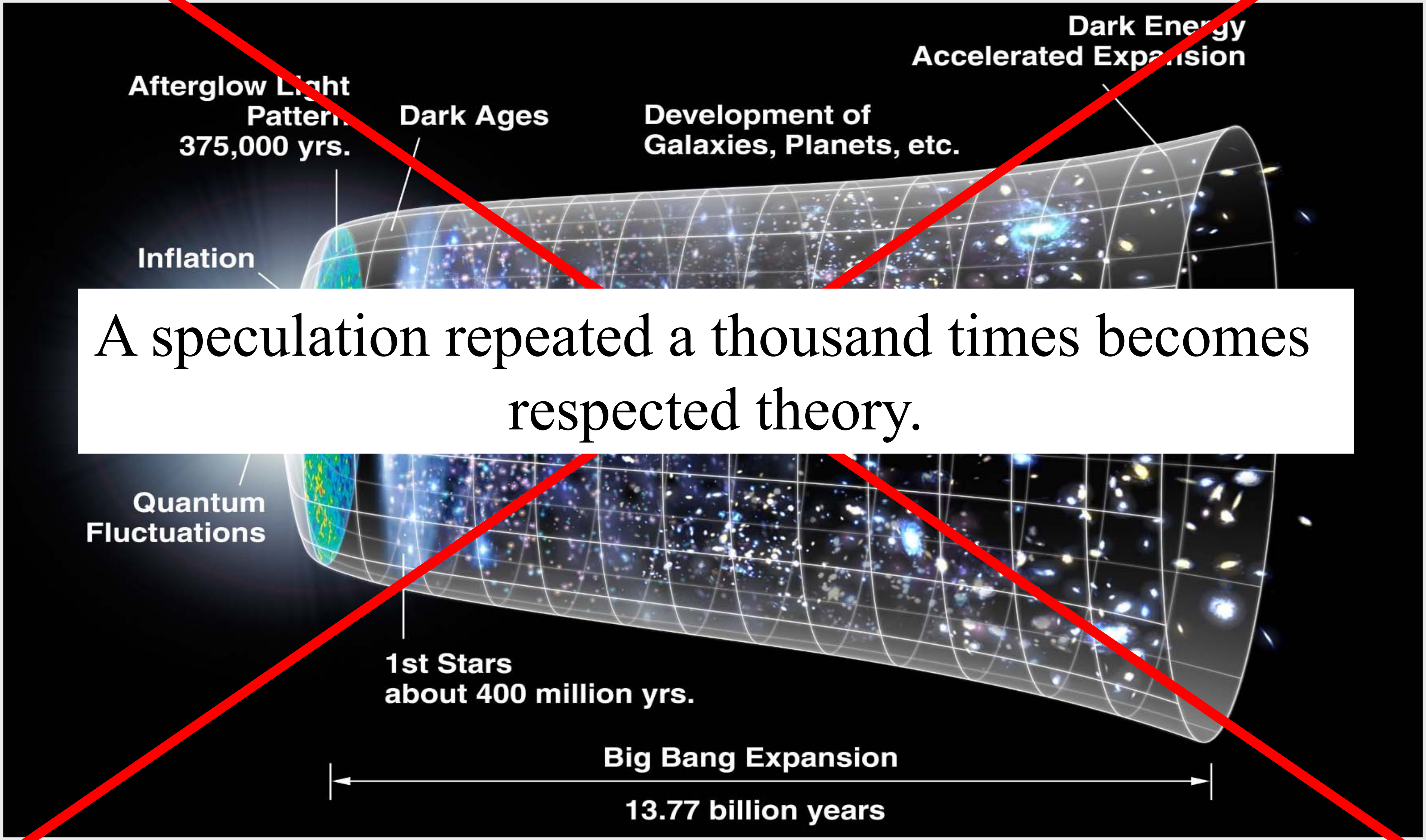


Corrected SMH

Constant number of galaxies and constant amount of dust in the universe point to a cyclic cosmological model rather than to an evolution of the universe from a singularity.

Universe chronology based on the Big Bang theory

- CMB is the only direct observation of the Big Bang
- if CMB is not relic radiation, the Big Bang theory is questioned



A speculation repeated a thousand times becomes respected theory.

NASA/WMAP Science Team

Motto:
Be critical and distinguish between hypotheses
and theories supported by observations.

Thank you for your attention

References:
V. Vavryčuk (2017), Universe opacity and EBL, MNRAS, ***465****, 1532-1542*
V. Vavryčuk (2017), Missing dust signature in the CMB, MNRAS, ***470****, L44-L48*
V. Vavryčuk (2018), Universe opacity and CMB, MNRAS, ***478,*** *283–301*