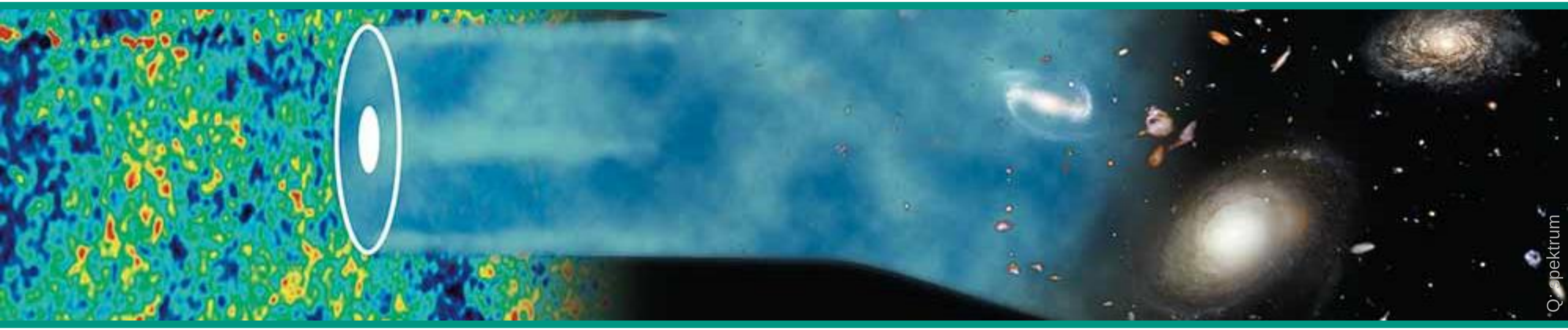
Introduction to Cosmology

Winter term 22/23 Lecture 8 Dec. 20, 2022



Recap of Lecture 7

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- **Primordial Nucleosynthesis: comparing BBN results with CBM data**

  - mass fraction of primordial ^4He: $Y_p = 0.245 \pm 0.003$ from blue compact dwarfs

  - primordial deuterium d from Lyman-α –lines (´forest´) at high-z gas clouds

  - difficult assessment of ^7Li –abundance from halo stars (´ ^7Li –anomaly ´)

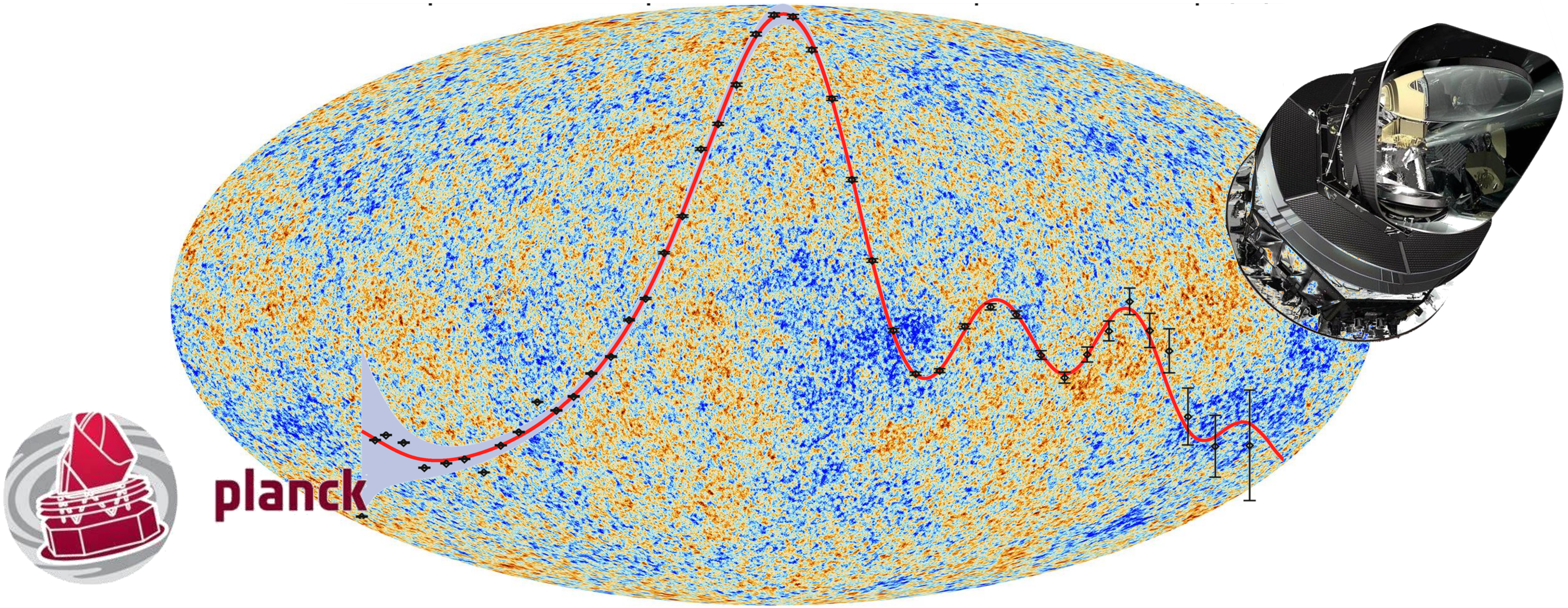
  - BBN light element yields: measurement of baryon density $\Omega_B = 0.042 \ldots 0.048$

  - comparison of ^4He – value (Y_p) from BBN with value of Ω_B from the CMB

  - number of light ν –generations: $N_\nu = 2.92 \pm 0.36$ agrees with SM (3.045)

3.2 Cosmic microwave background radiation: essentials

- **The earliest view: thermal universe pictured at a time $t = 380\,000\ yrs$**

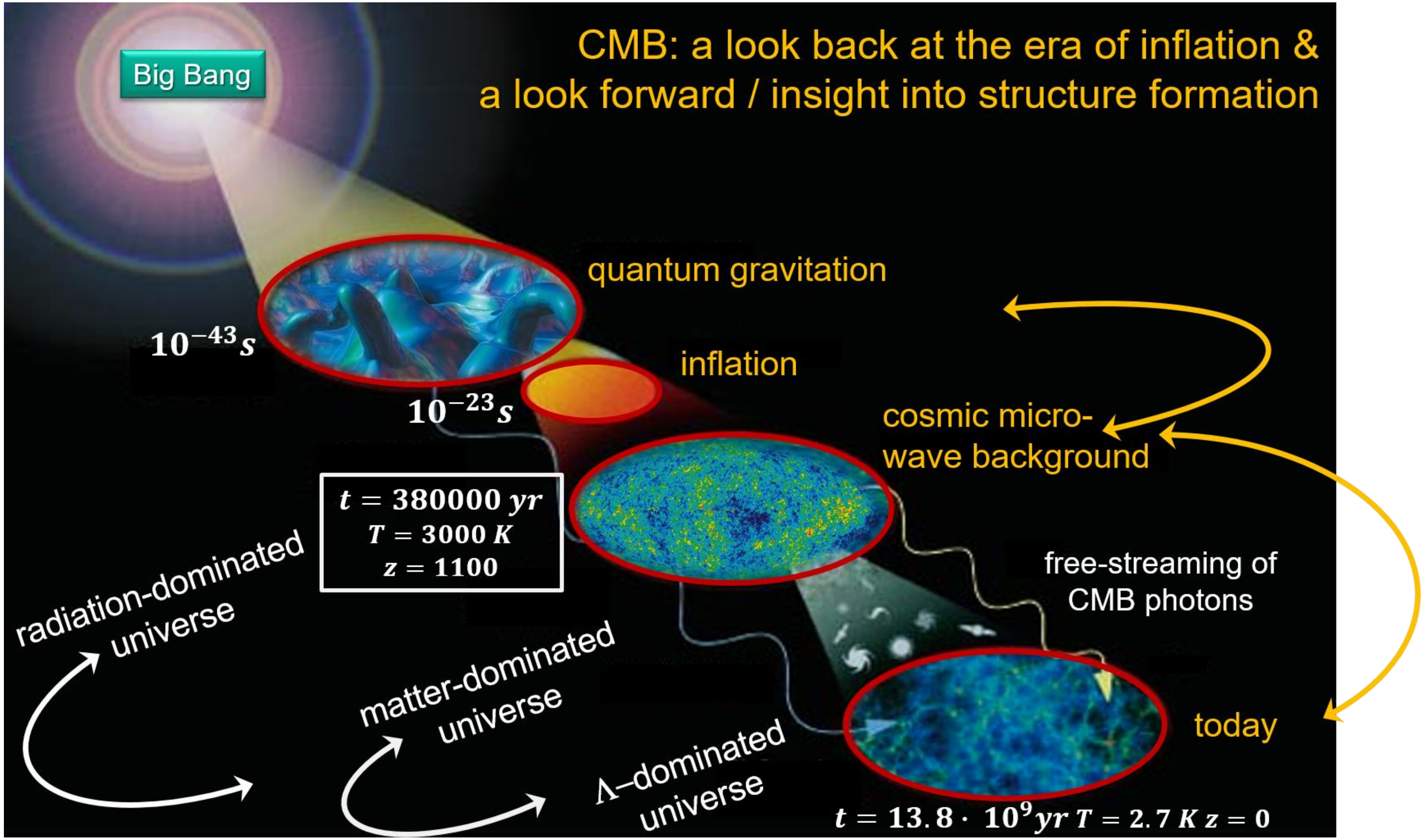


CMB: classification & cross connections

- **overview**

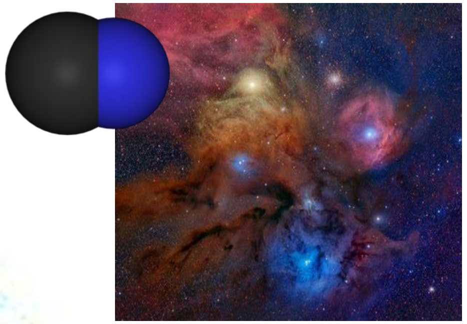
- T –fluctuations: seeded in the era of quantum gravity at $t \sim 10^{-43} s$

- photon-freestreaming: over $t \sim 13.8 \cdot 10^{9}\ yr$, up to present era of dark energy



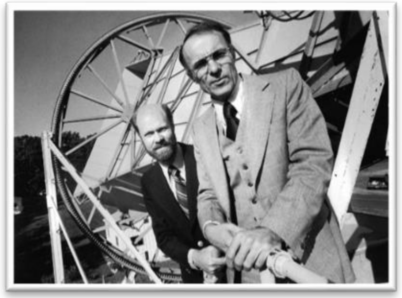
Cosmic microwave background: history

- **The ´classical´ phase up to the mid-1960s: speculation & first detection**



1941: (then unexplained) observation of excitation of interstallar $\boldsymbol{CN}$ molecules from the direction of gas cloud ζ *Ophiuchi* (⇨ rotational bands of CN)

1946: **G. Gamow** *et al.* – hot Big Bang should have resulted in a **cosmic microwave background radiation** (today: $\boldsymbol{T \sim 5\ K}$)



1964: **A. Penzias** & **R. Wilson** – **detection** of the CMB at Holmdel at $\boldsymbol{\lambda = 7\ cm}$ (**Nobel prize 1978**)

Cosmic microwave background: history

- **The ´intermediate´ phase up to the end of the millenium: gearing up!**

1989: start of the NASA satellite mission ***COBE***
- measurement of the spectral form of the CMB with FIRAS (**J. Mather**): is it really a thermal spectrum?

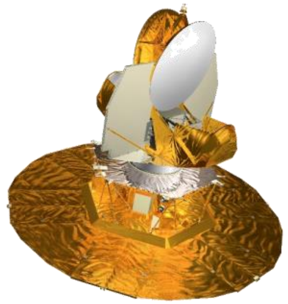
1992 : $4\ yr$ measurement with NASA satellite mission ***COBE***
- detection of tiny fluctuations of the CMB temperature T with DMR (**G. Smoot**): is there a seed of galaxies?

1968: first detection of fluctuations of the CMB temperature T at small scales: what is the topology of the universe?

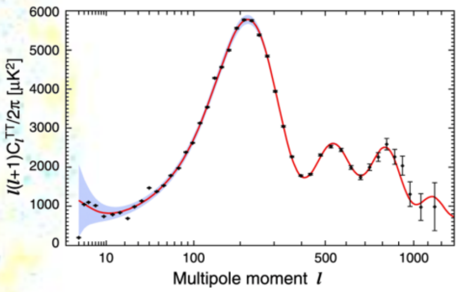
Cosmic microwave background: history

- **The ´intermediate´ phase since the end of the millenium: further gearing up!**

2001: start of the NASA satellite mission ***WMAP***
- first detection of the CMB-**polarization** (DASI)



2003 : first analysis of data from NASA satellite ***WMAP***
- **start of the precision age of cosmology**



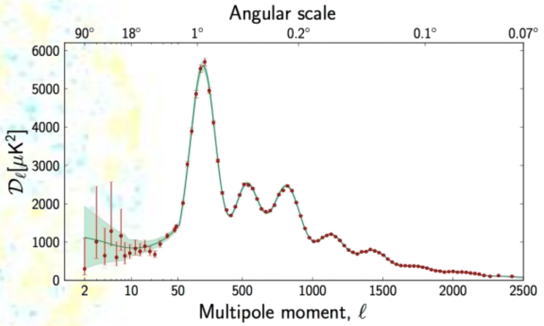
2006: Nobel prize for **J. Mather** and **G. Smoot**

Cosmic microwave background: history

- **The ´present´ phase in the last decade: further gearing up with Planck!**

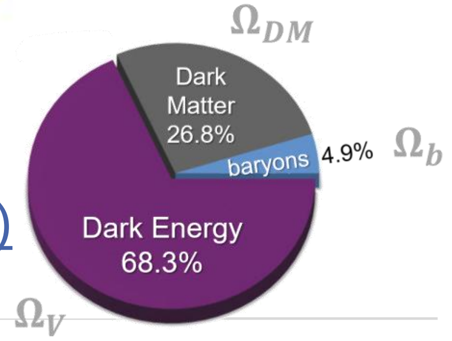
2009: start of the ESA satellite mission ***Planck***

- aim: ´ultimate´ precision via bolometers



2013 : improved analysis of data from ESA satellite ***Planck***

- **extension of multipole down to small angles**



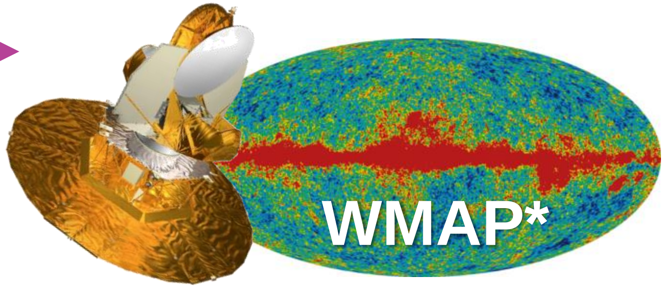
2020: final data from Planck published at

[Planck 2018 results - V. CMB power spectra and likelihoods (aanda.org)]

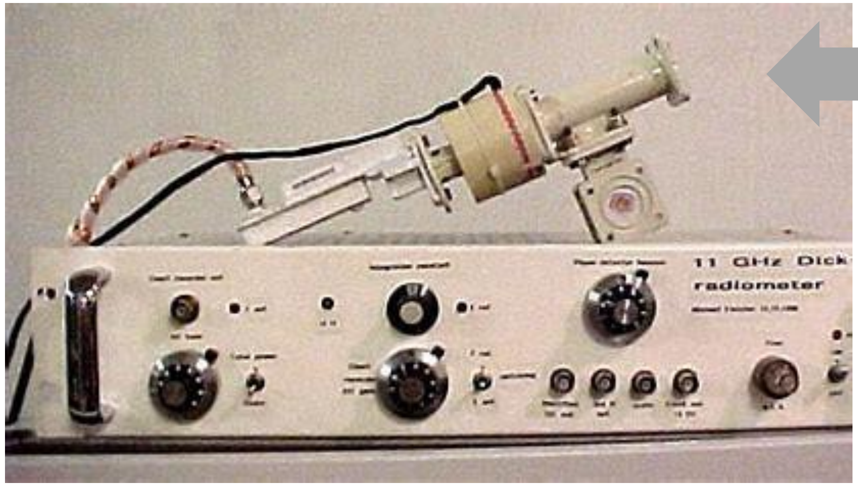
CMB – an unintended, accidential detection

- **Robert Dicke & David Wilkinson at work in Princeton, NJ (1964)**

- 1964: **R.H. Dicke** & D. Wilkinson (Princeton) perform a *dedicated* search for the CMB at microwave-ranges, based on ´CMB re-invented´ by J. Peebles & him



´I have long believed that an experimentalist should not be unduely inhibited by theoretical untidiness´



Dicke radiometer

Dicke-switch (s. COBE)

*WMAP = Wilkinson Microwave Anisotropy Probe

CMB – an unintended, accidential detection

- **Arno Penzias & Robert Wilson at work in Holmdel, NJ (1964/65) in $\boldsymbol{d = 50\ km}$**

  - A. Penzias & R. Wilson (Bell Labs) are testing a new antenna at Holmdel (NJ) for satellite-based communication (US-Europe) at $\boldsymbol{\lambda = 7.35\ cm}$ / $\nu = 4\ GHz$

  - **excess noise signal: it is isotropic**

  - remove ´dielectric white material´ from dish

  - Princeton group explains it to them as the **signal of CMB** they were searching for

CMB – an unintended, accidential detection

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- **Groups (Holmdel: discovery, Princeton:explanation) publish joint papers**

- **Nobel prize 1978** for Penzias & Wilson

- Nobel prize 2019 for J. Peebles (theory)

- R. Dicke

´Boys, we've been scooped.´

A MEASUREMENT OF EXCESS ANTENNA TEMPERATURE AT 4080 Mc/s

Measurements of the effective zenith noise temperature of the 20-foot horn-reflector antenna (Crawford, Hogg, and Hunt 1961) at the Crawford Hill Laboratory, Holmdel, New Jersey, at 4080 Mc/s have yielded a value about 3.5° K higher than expected. This excess temperature is, within the limits of our observations, isotropic, unpolarized, and

⋮

No. 1, 1965 LETTERS TO THE EDITOR 421

Note added in proof.—The highest frequency at which the background temperature of the sky had been measured previously was 404 Mc/s (Pauliny-Toth and Shakeshaft 1962), where a minimum temperature of 16° K was observed. Combining this value with our result, we find that the average spectrum of the background radiation over this frequency range can be no steeper than $\lambda^{0.7}$. This clearly eliminates the possibility that the radiation we observe is due to radio sources of types known to exist, since in this event, the spectrum would have to be very much steeper.

A. A. Penzias
R. W. Wilson

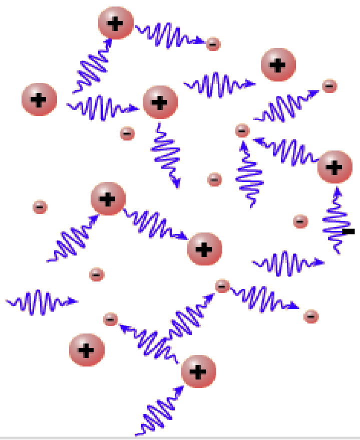
May 13, 1965
Bell Telephone Laboratories, Inc
Crawford Hill, Holmdel, New Jersey

CMB – a (perfect?) thermal black body radiation

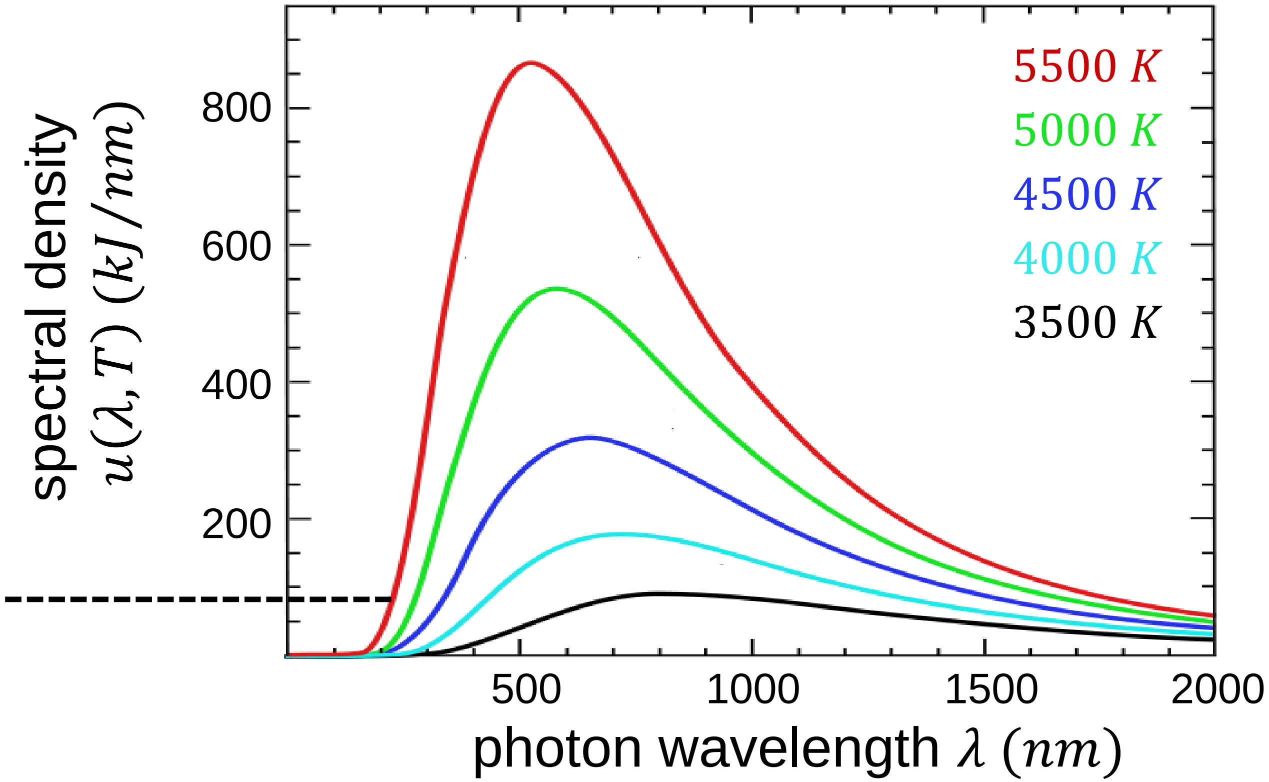
- **Photons released after neutralization of the primordial plasma**

  - initial phase ($t < 380000\ yr$): photon interactions with *free* e^- of hot plasma
    ⇨ **thermodynamical equilibrium**

  - **Thomson scattering**:
    elastic scattering of photons
    off electrons ($h \cdot \nu \ll m_e \cdot c^2$)

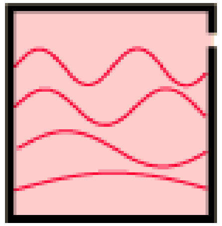


plasma



CMB – a (perfect?) thermal black body radiation

- **Photons released after neutralization of the primordial plasma**



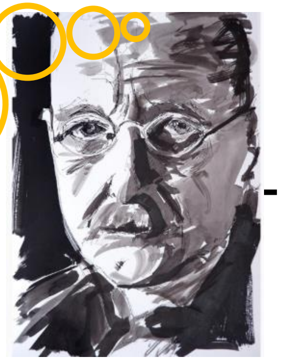
  - RECAP: Planck distribution of a perfect black body has 1 free parameter only

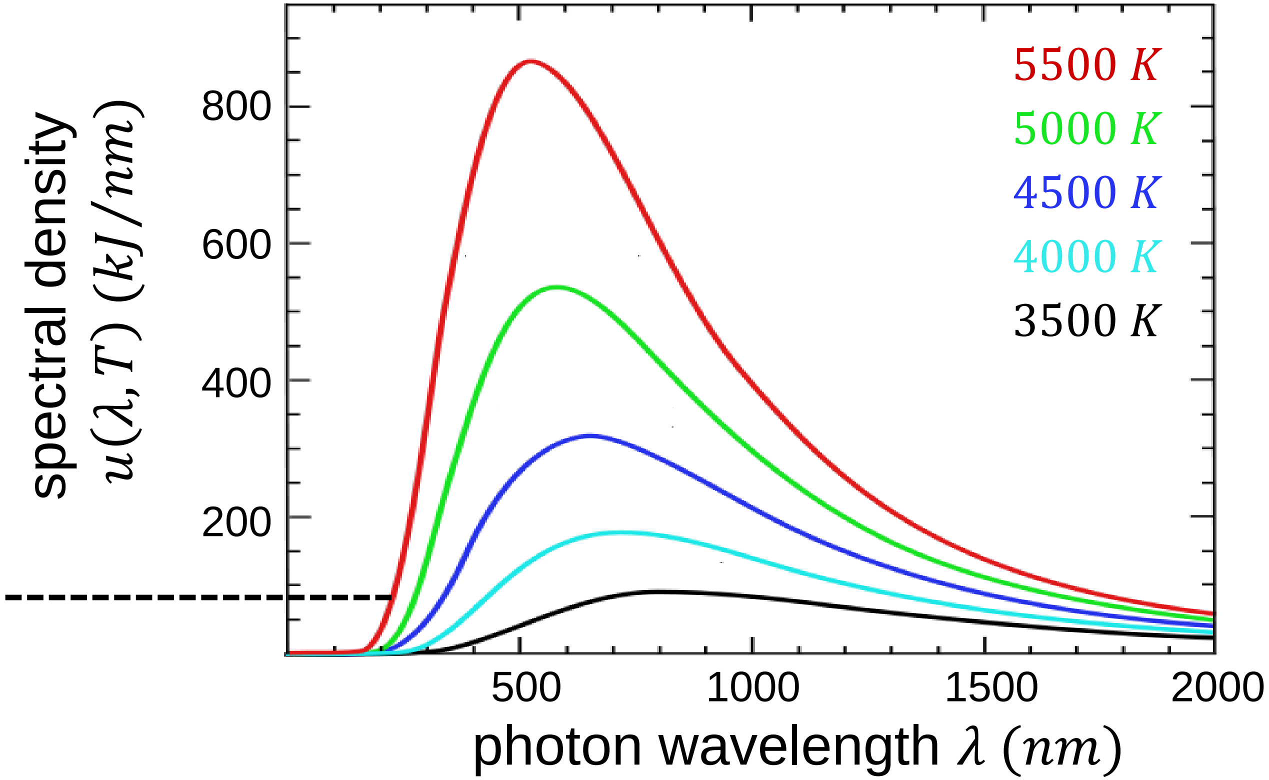
absolute temperature T

↓

spectral energy density $u(\nu,T)$

$$u(\nu,T)=\frac{4\pi}{c}I(\nu,T)$$
$$=\frac{8\pi h\nu^3}{c^3}\cdot\frac{1}{e^{h\nu/kT}-1}$$





CMB – a (perfect?) thermal black body radiation

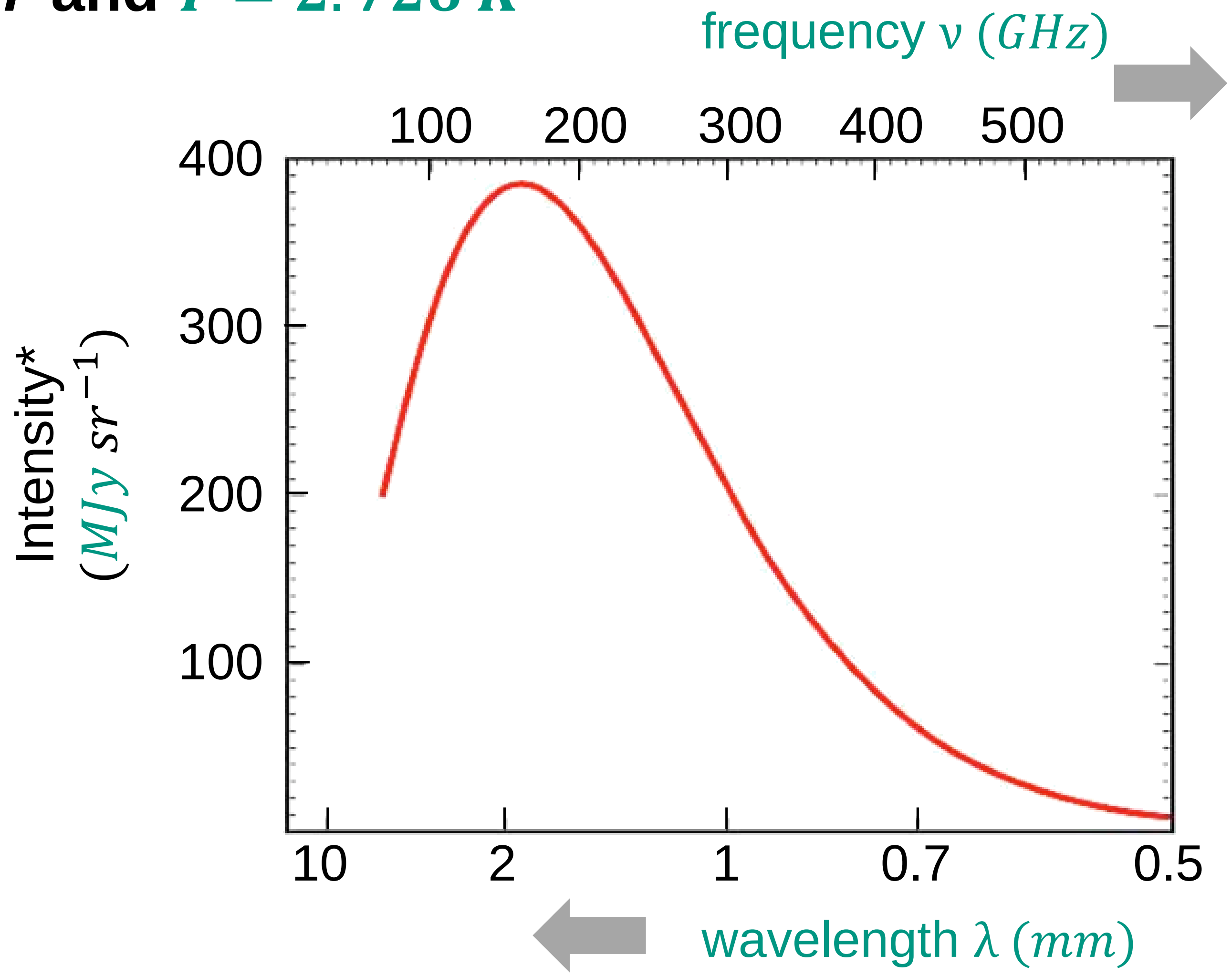
- **CMB parameters at $t = 13.8 \cdot 10^9\ yr$ and $T = 2.726\ K$**

  - cosmological expansion since decoupling of photons shifts CMB to *microwave-band*

  - wavelength: $\lambda = 0.5 \ldots few\ \boldsymbol{mm}$

  - frequency: $\nu = 10 \ldots few \cdot 10^2\ \boldsymbol{GHz}$

we used $\lambda = 7.35\ cm$
with our Horn antenna!



*unit Jansky $(1\ Jy = 10^{-26}\ W\ m^{-2}\ Hz^{-1})$

CMB – a (perfect?) thermal black body radiation

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CMB parameters vs. commercial frequencies

- CMB at $10 \ldots few \cdot 10^2 \; \boldsymbol{GHz}$

- **WLAN:**
  $\mathbf{2.4} \; \boldsymbol{GHz}, 5 \; GHz, 6 \; GHz, 60 \; GHz$

- **Bluetooth:**
  $\mathbf{2.4 \ldots 2.48} \; \boldsymbol{GHz}$

- **UHF:**
  $\mathbf{0.3 \ldots 3} \; \boldsymbol{GHz}$

- **radar:**
  $\mathbf{0.3 \ldots 300} \; \boldsymbol{GHz}$
  example: M-band $\sim 80 \; GHz$ for ´automotive radar´

CMB – a (perfect?) thermal black body radiation

- **CMB parameters at $t = 13.8 \cdot 10^9\, yr$ and $T = 2.726\, K$**

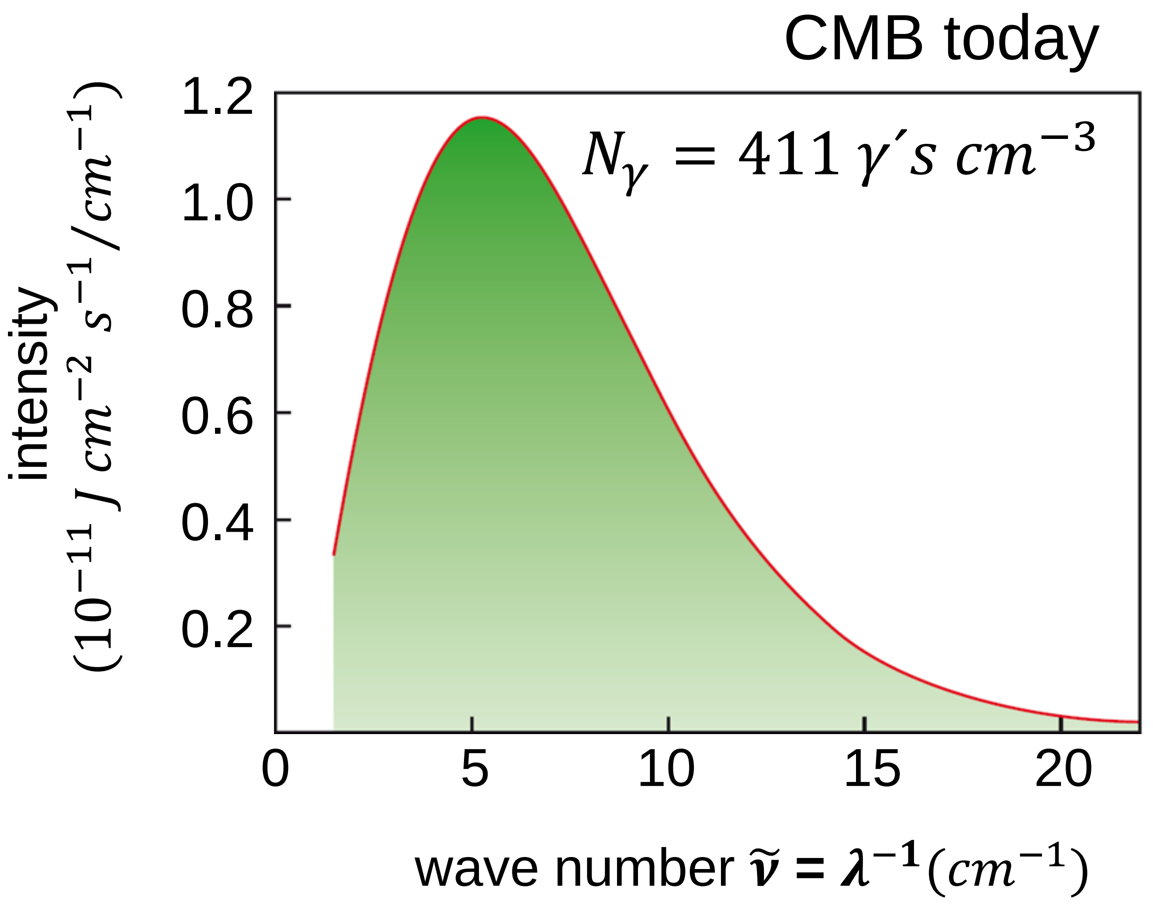
energy density of CMB today

$$u_\gamma = 4.39 \cdot 10^{-14}\, J/m^3$$

$$\rho_\gamma = u_\gamma/c^2 = 4.65 \cdot 10^{-31}\, kg/m^3$$

$$\rho_\gamma \cdot c^2 = 0.261\, MeV/m^3$$

$$\Omega_\gamma = 5.05 \cdot 10^{-5}$$



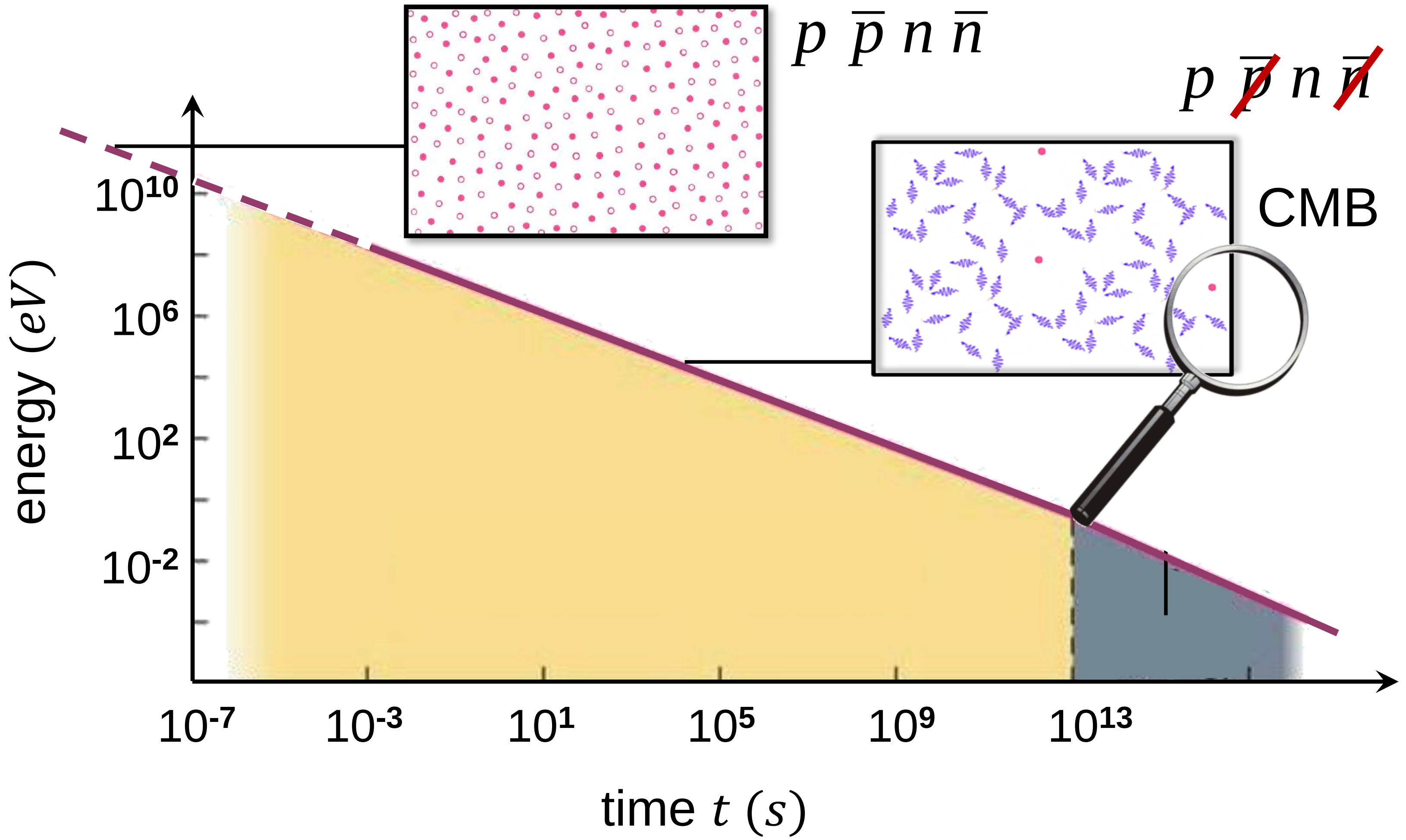
CMB origin: matter – antimatter annihilation

- **annihilation* of nucleons: $\boldsymbol{p, n, \bar{p}, \bar{n}}$**

- at $T \sim 150\ MeV$: QCD-phase transition to bound quarks (nucleons)

- annihilation processes (at somewhat later t): ⇨ observed **baryon-asymmetry $\boldsymbol{\eta}$** of the universe

´baryogenesis´

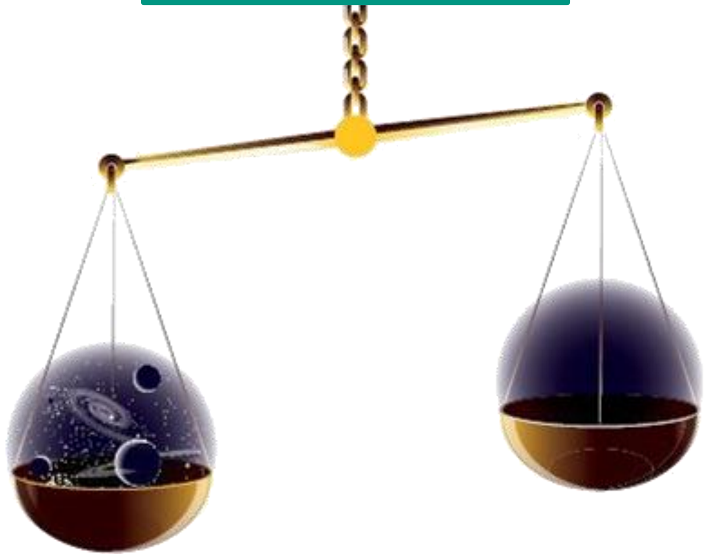


*see also lecture #5, pages 26-30

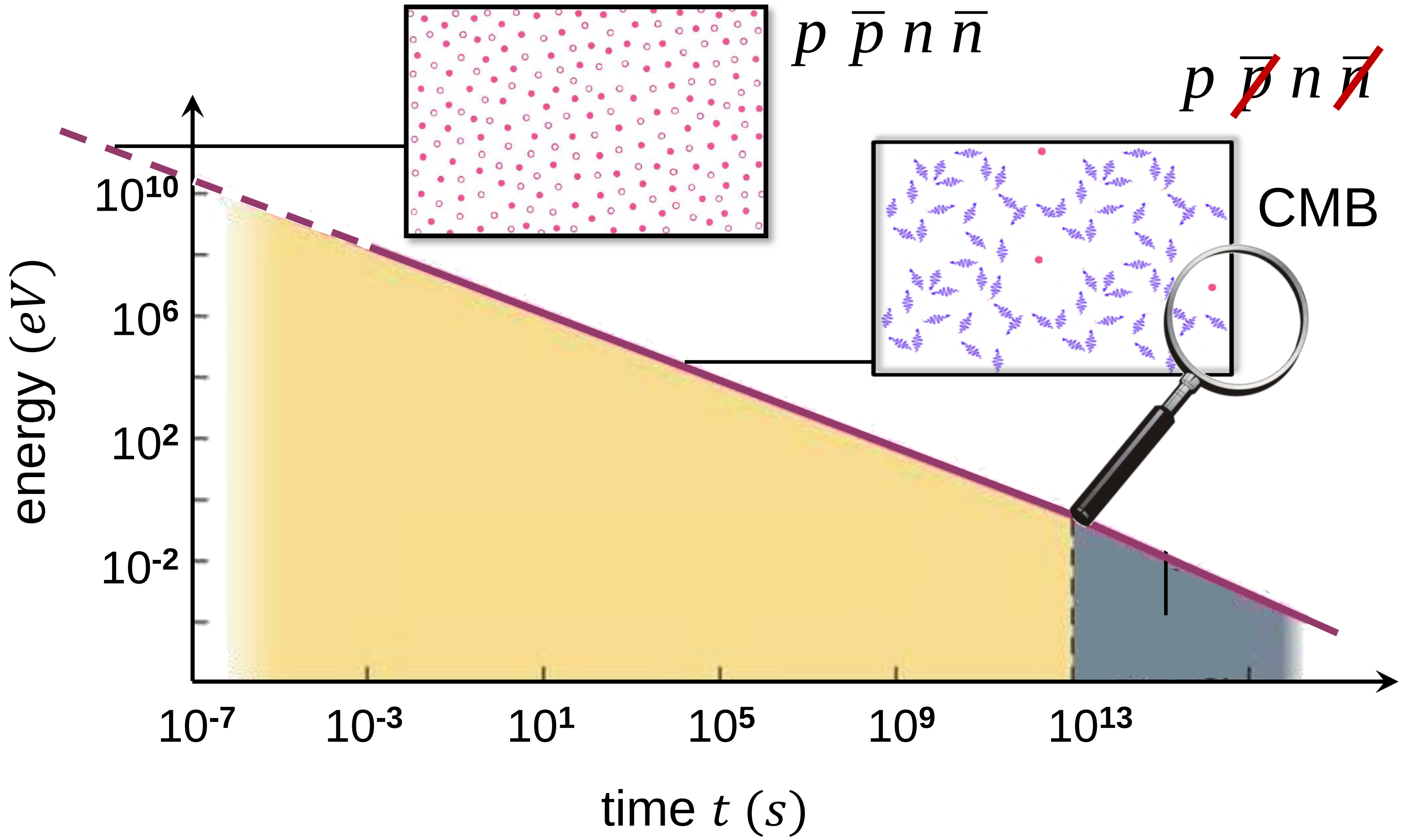
CMB origin: matter – antimatter annihilation

- **annihilation of nucleons: $p, n, \bar{p}, \bar{n}$**

$$\boxed{\eta = \frac{n_B - n_{\bar{B}}}{n_\gamma}}$$



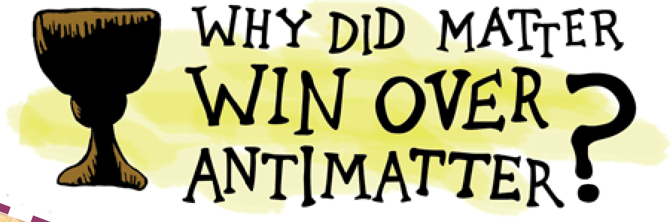
$\eta = (6.14 \pm 0.24) \cdot 10^{-10}$

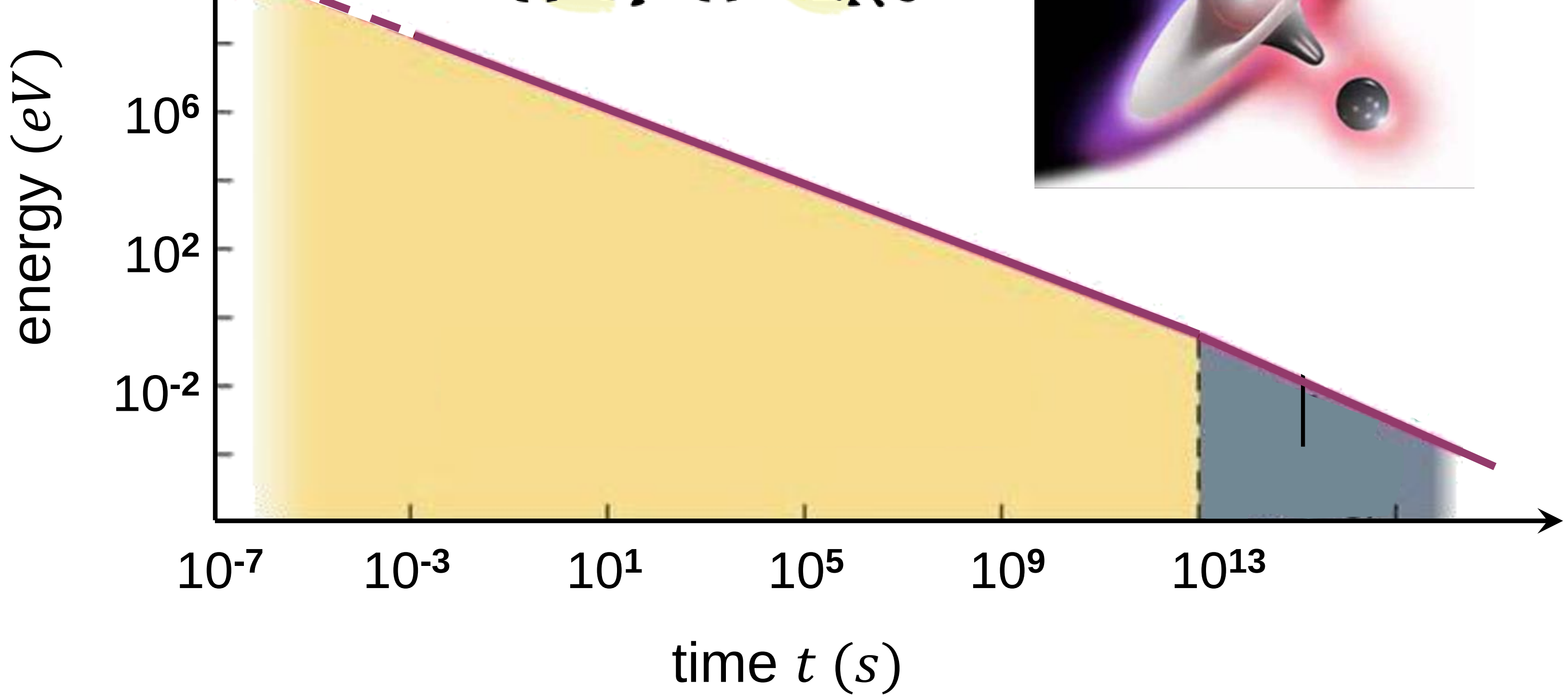


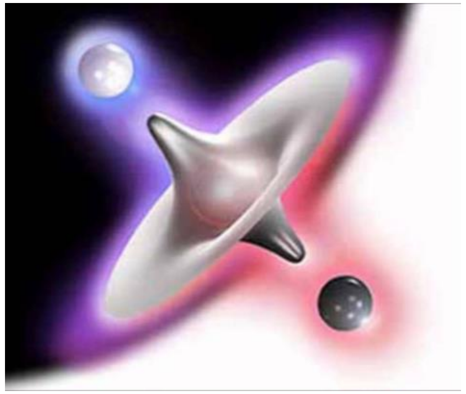
CMB origin: matter – antimatter annihilation

- **We need to explain the asymmetry between matter and anti-matter**

  - 3 necessary conditions for successful baryogenesis







CMB origin: matter – antimatter annihilation

- **3 Sakharov conditions for successful baryogenesis**

#1: CP – and C – violating processes

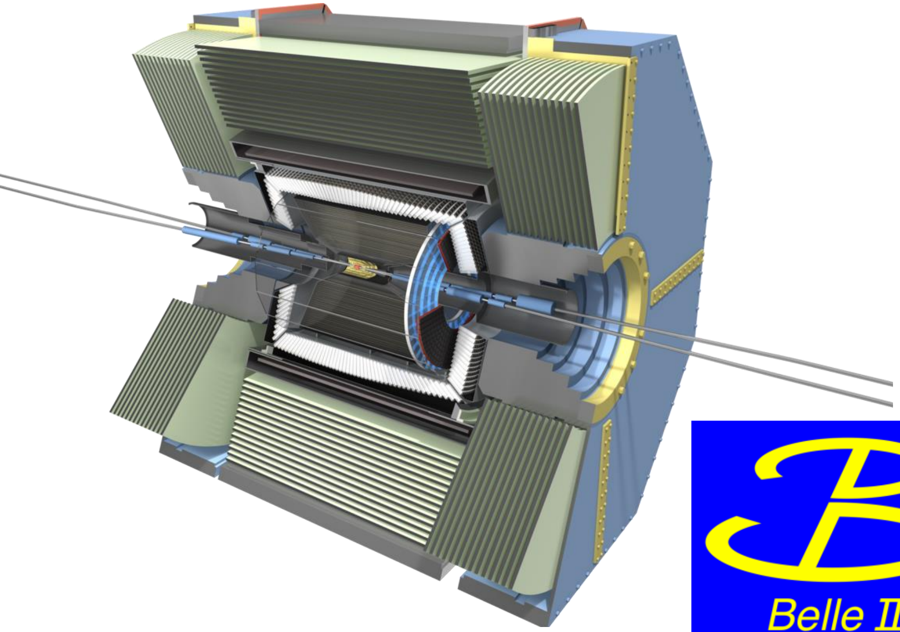
#2: processes which are violating baryon-number conservation ($\Delta B \neq 0$)

#3: no thermodynamic equilibrium

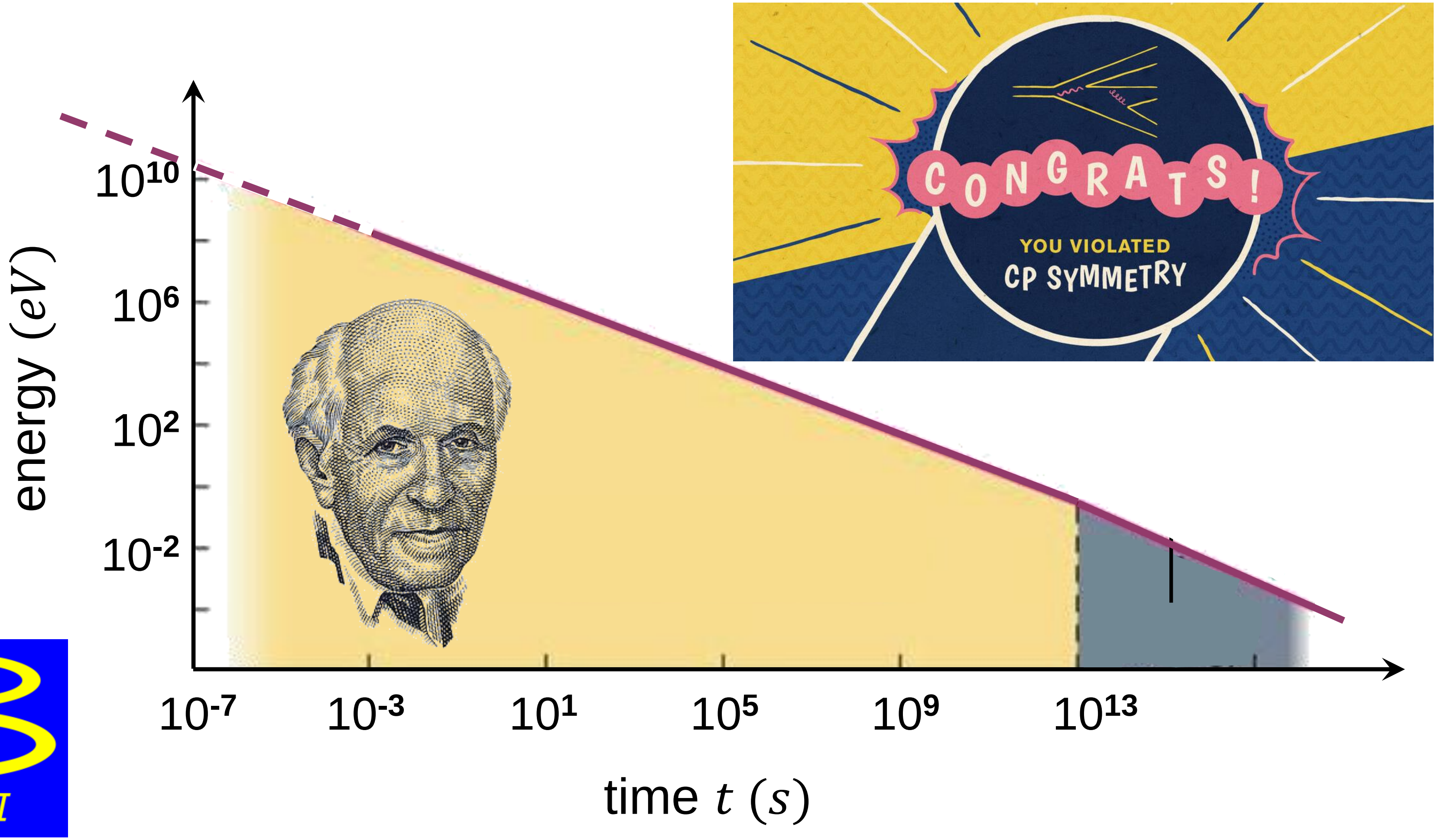
CMB origin: matter – antimatter annihilation

- **Sakharov condition #1: CP – and C – violating processes (origin??)**

  - hadronic origin?
    decay amplitudes of
    kaons, b – quarks

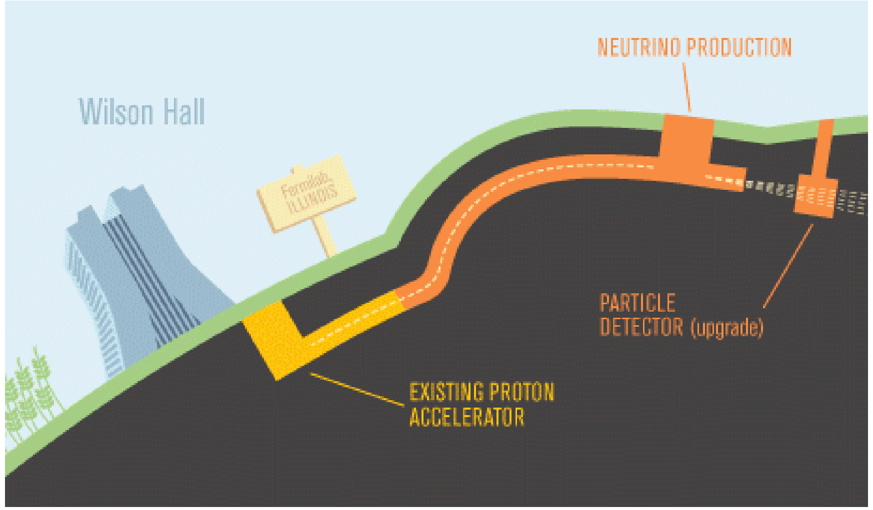


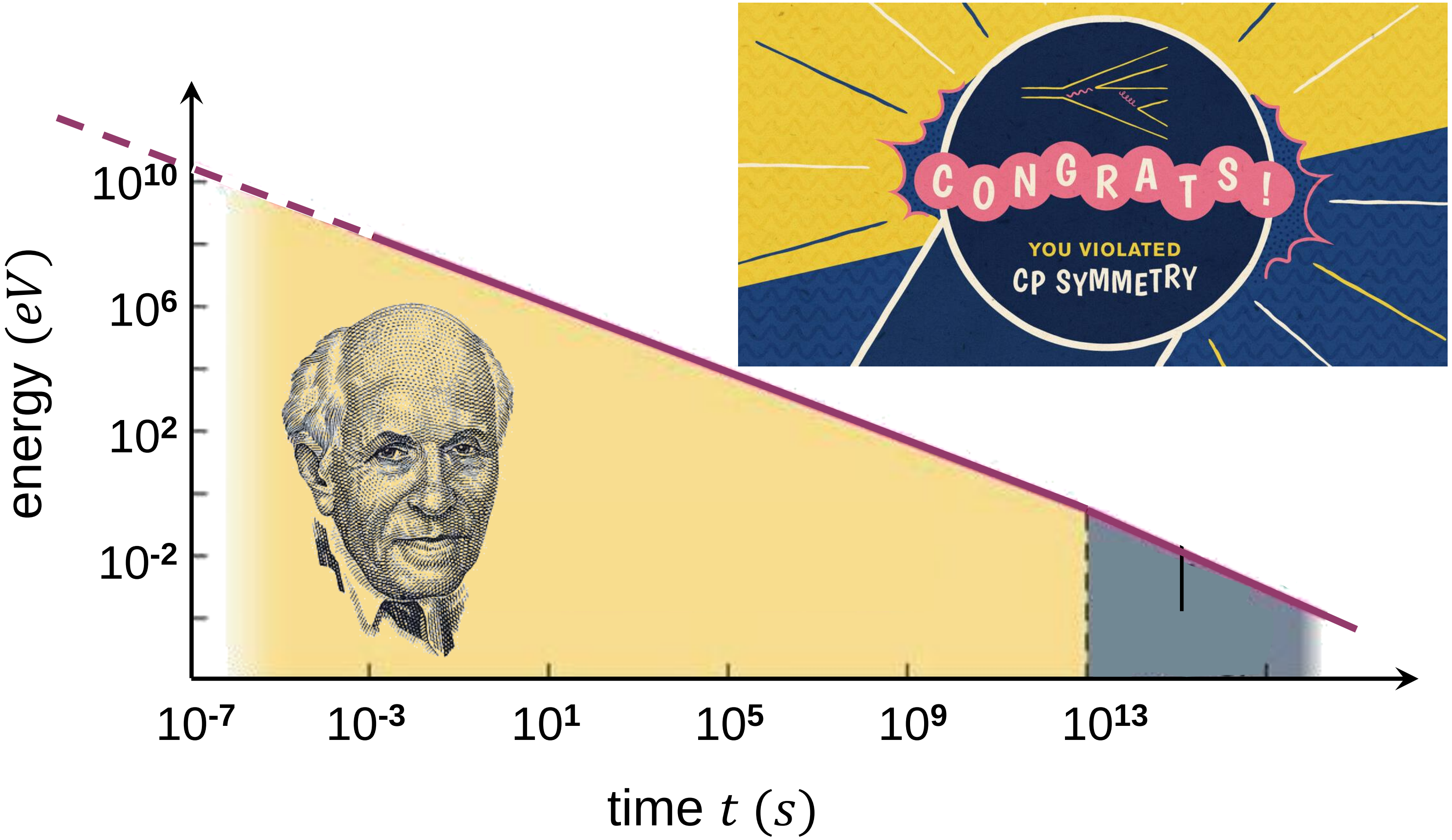
Belle II



CMB origin: matter – antimatter annihilation

- **Sakharov condition #1: CP – and C – violating processes (origin??)**
  - leptonic origin? decay amplitude of heavy neutrinos, neutrino mixing…





CMB origin: matter – antimatter annihilation

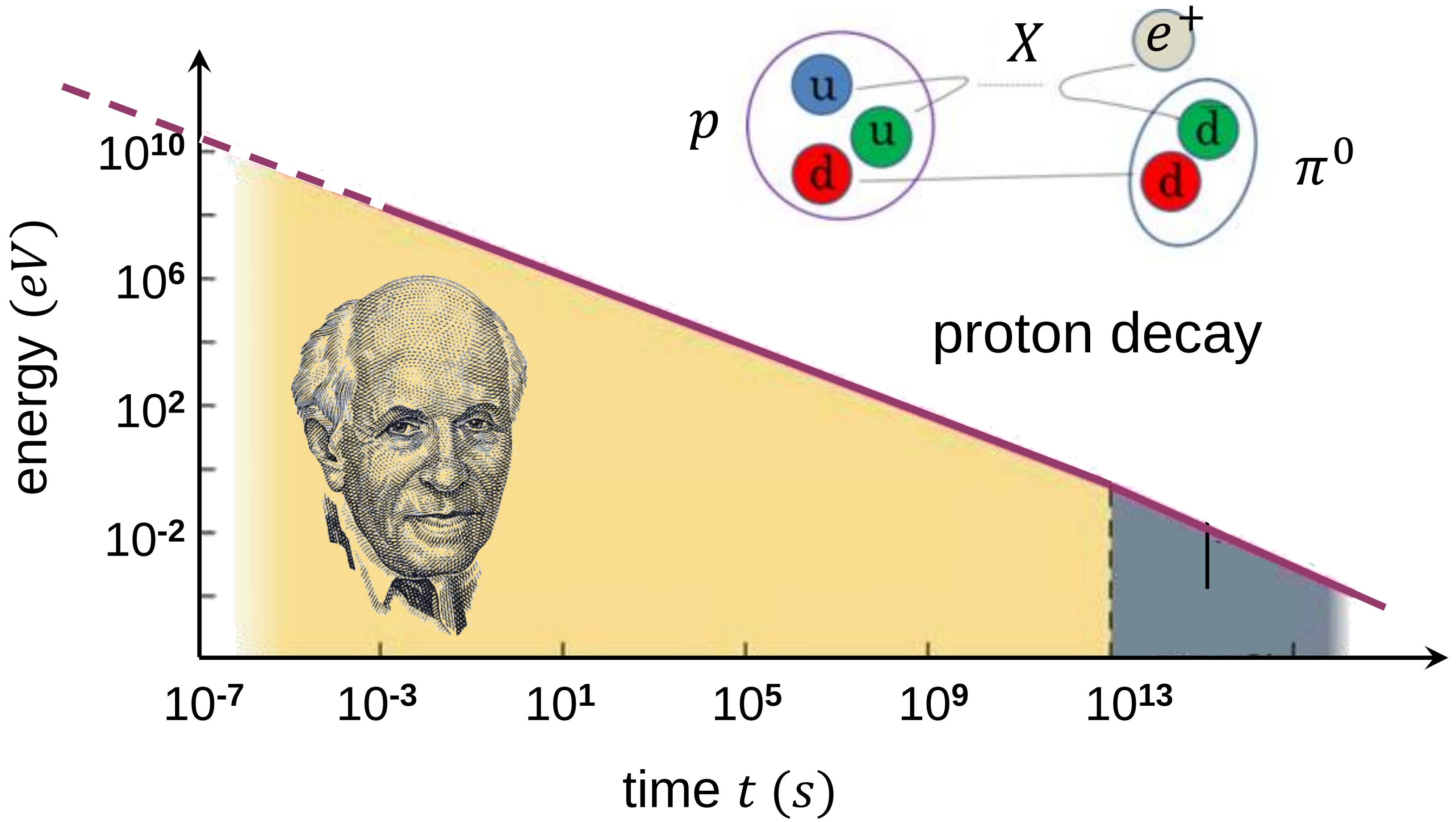
- **Sakharov condition #2: B – violating processes**

- GUT*-scenarios predict violation of B (while they are conserving $(B-L)$)

baryon number

$$\boxed{B = \frac{1}{3}\cdot[N(q) - N(\bar{q})\ ]}$$

$N(q), N(\bar{q})$: number of quarks/ antiquarks

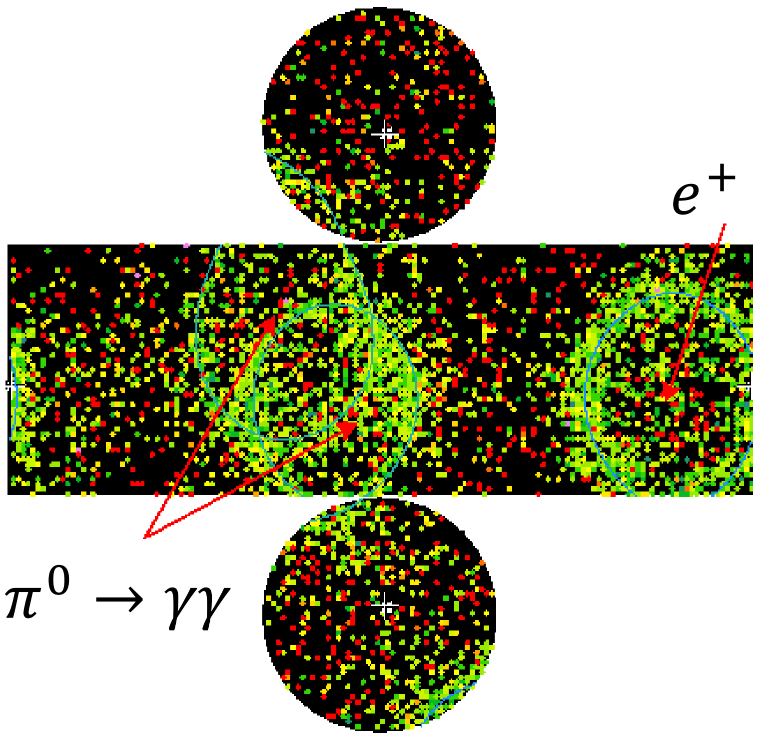


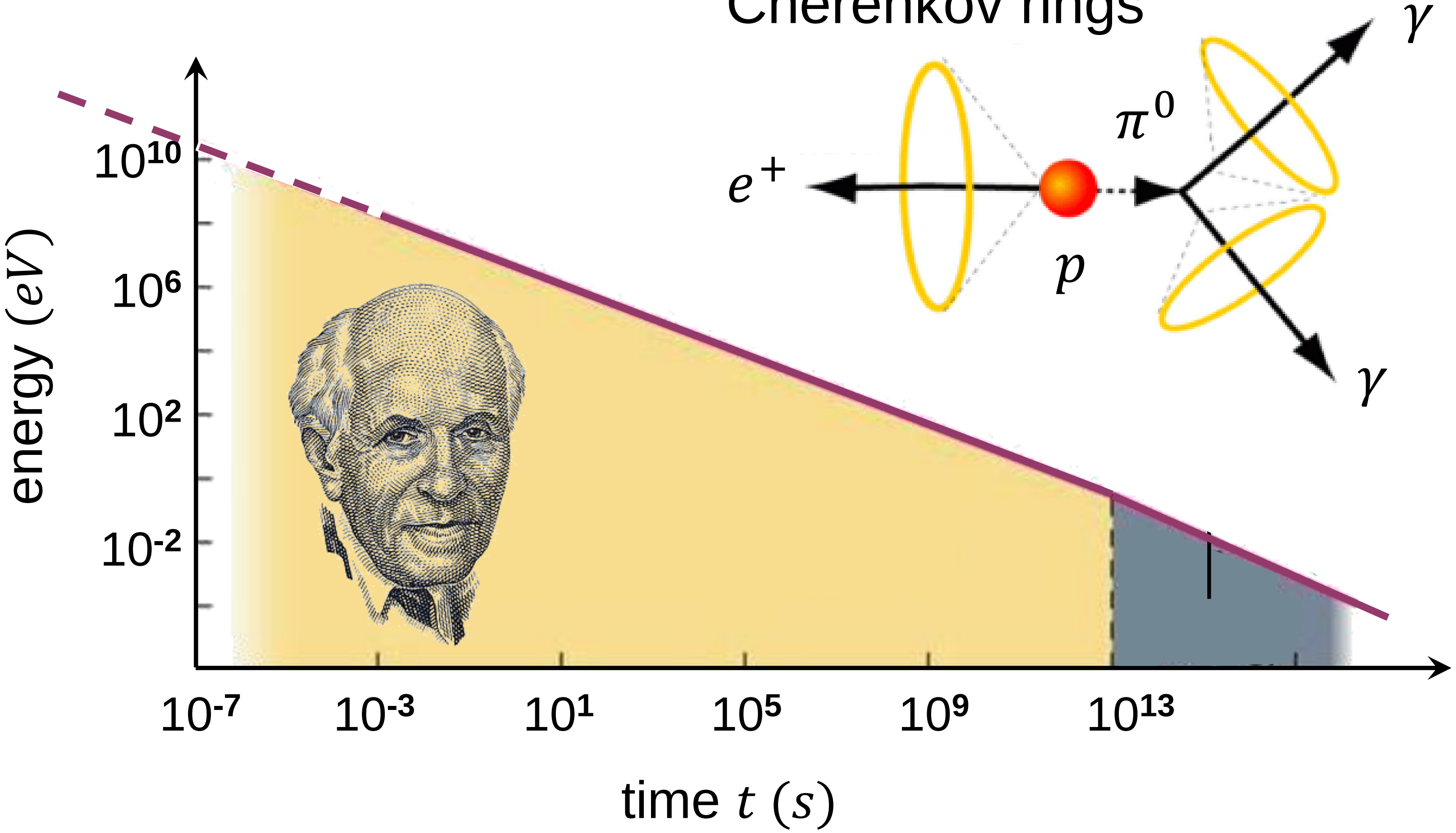
*Grand Unified Theory

CMB origin: matter – antimatter annihilation

- **Sakharov condition #2: B – violating processes**

- *simulated* p – decay in Super-Kamiokande

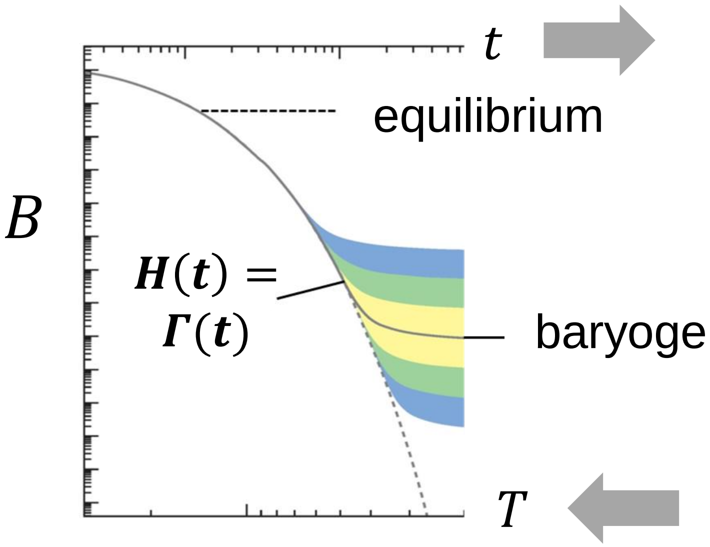


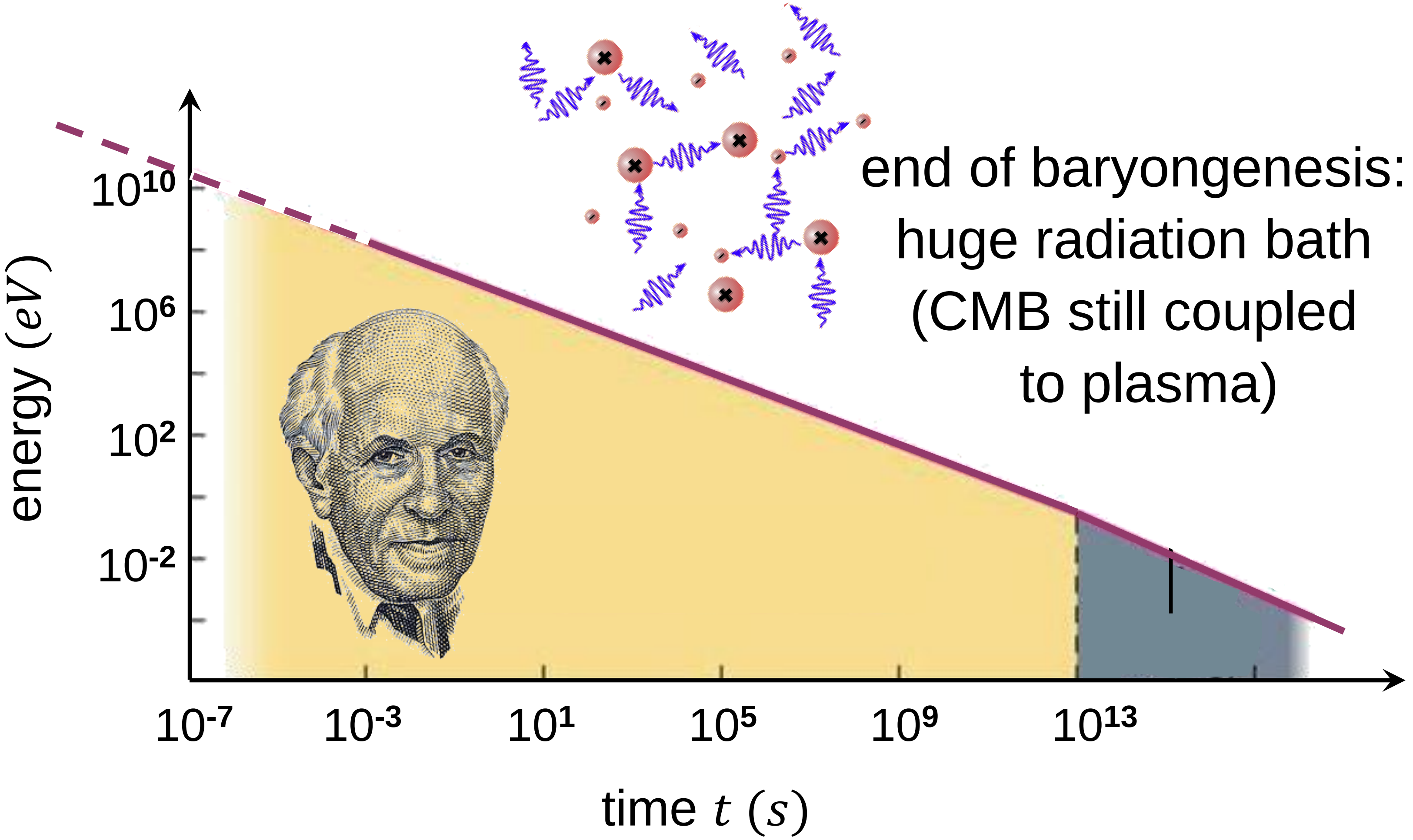


CMB origin: matter – antimatter annihilation

- **Sakharov condition #3: interactions out of thermal equilibrium***

  - expansion rate $H(t)$ is larger than reaction rate $\Gamma(t)$ responsible for $B-$ violation





end of baryongenesis: huge radiation bath (CMB still coupled to plasma)

*see also lecture #5, pages 43-48

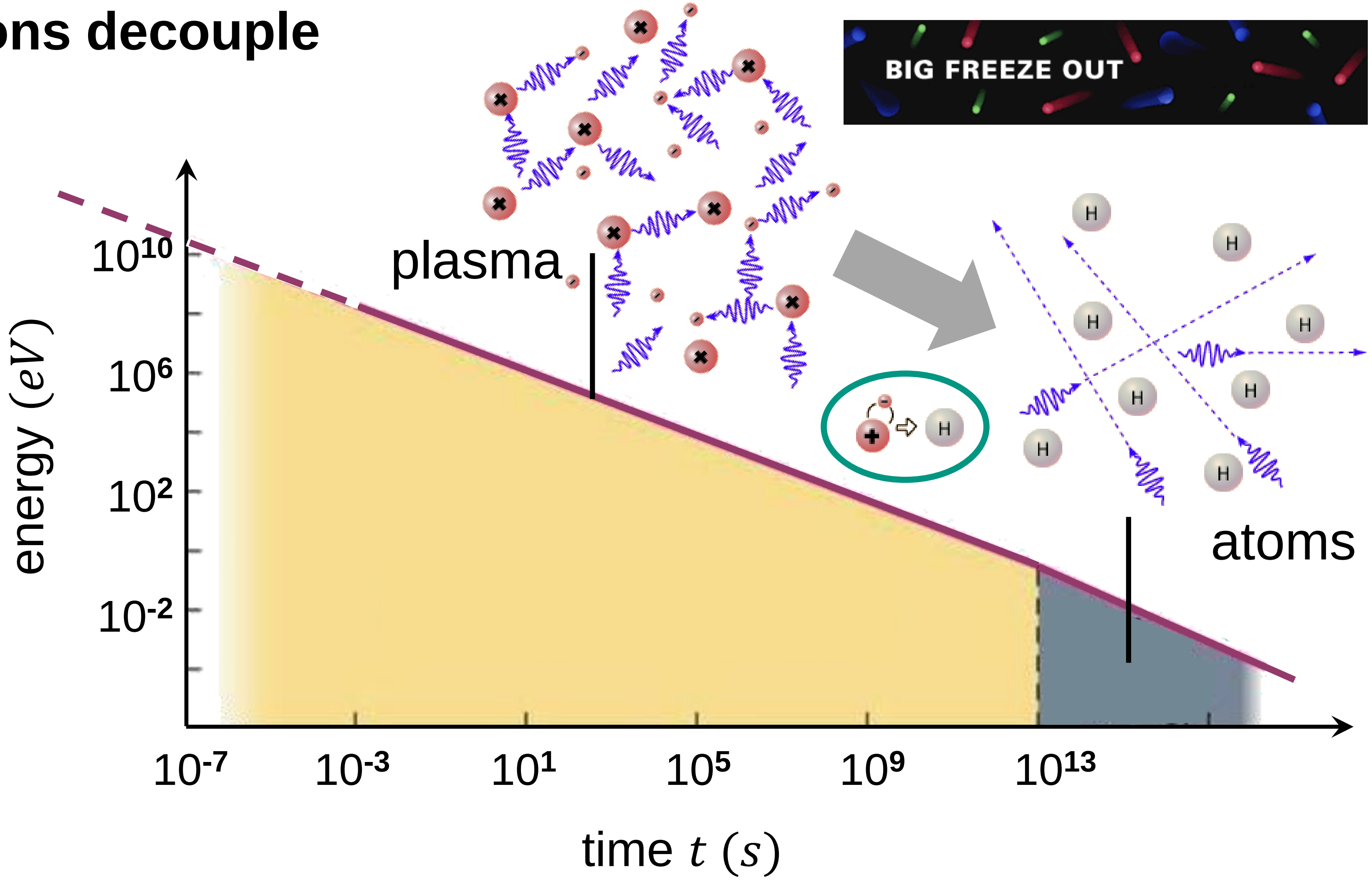
Freeze-out of the thermal radiation: much later!

- **Phase transition: photons decouple**

  - at $T_{dec} = 3000\ K\ (eV)$
  at $\boldsymbol{t_{dec} = 378\,000\ yr}$
  (redshift $z_{dec} = 1100$)
  plasma → atoms
  ⇨ neutral atoms form
  different opacity for γ´s

$$\boxed{\Gamma(t) = H(t)}$$

photon scattering
rate off e^- in plasma



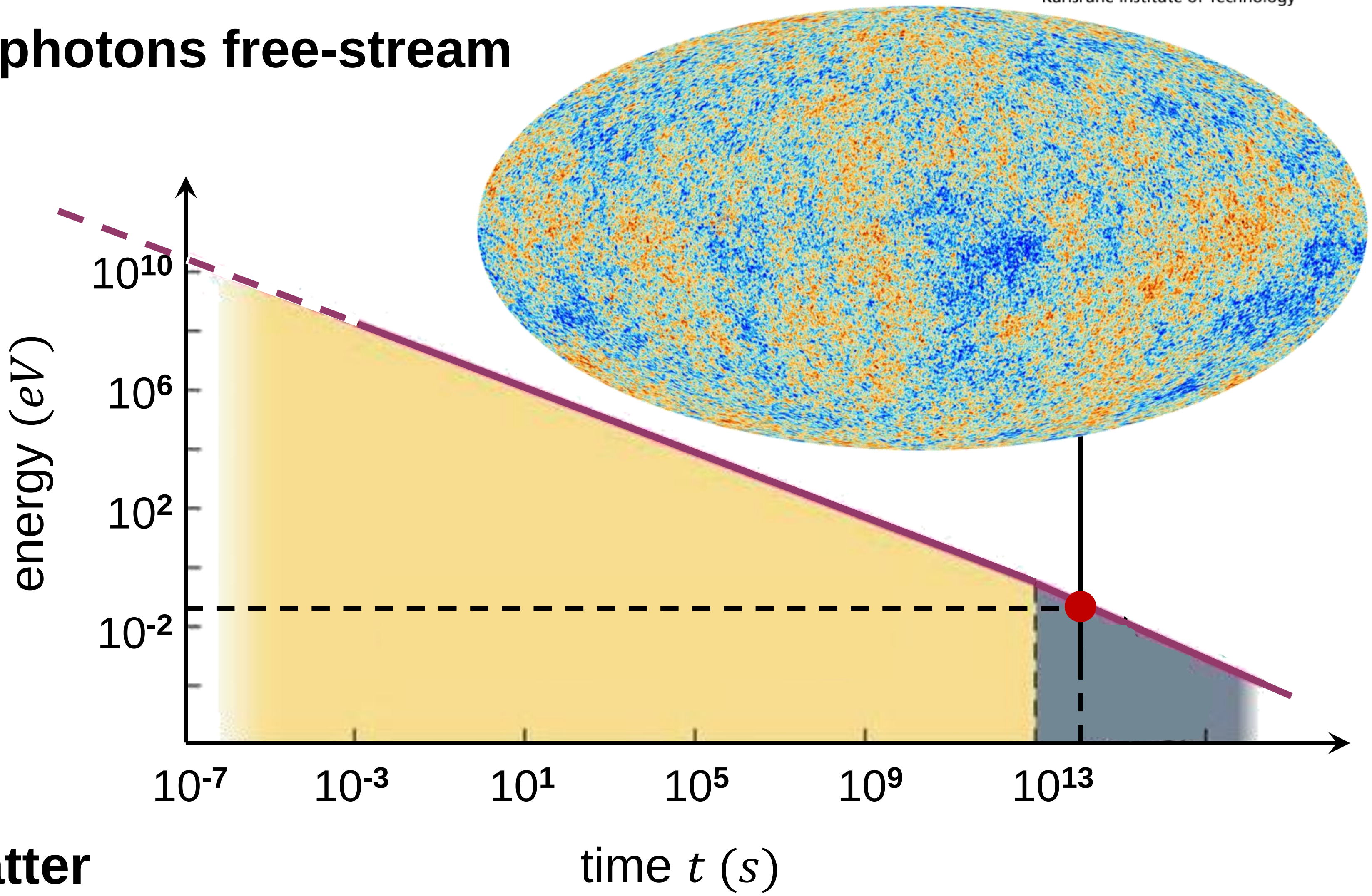
Freeze-out of the thermal radiation

- **Phase transition: CMB photons free-stream**

- at $T_{dec} = 3000\ K\ (eV)$
  at $\boldsymbol{t_{dec} = 378\,000\ yr}$
  (redshift $z_{dec} = 1100$)
  universe = transparent
  to photons (radiation)

$$\boldsymbol{p + e^- \rightarrow H + \gamma}$$

- matter & radiation are
  no longer coupled via
  Thomson scattering:
  only gravity acts on matter



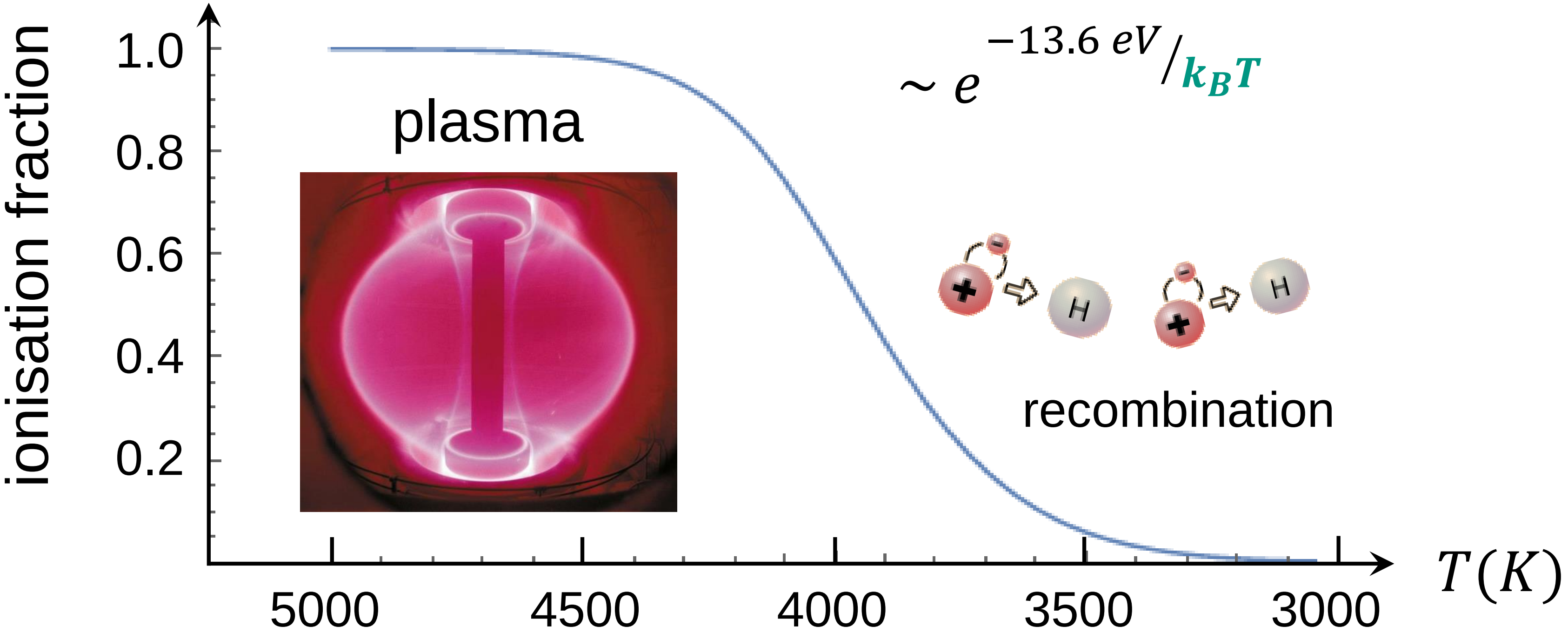
Decoupling of radiation from matter

A closer look with M. Saha on the transition from plasma to neutral state

- Saha ionisation equation: describes the fraction of ionised atoms (H, He) as function of the temperature $k_B T$ of the universe

M. Saha

- universe became transparent at a temperature $T \sim 3000\ K\ (z = 1100)$



Before the freeze-out: a transition from Ω_γ to Ω_M

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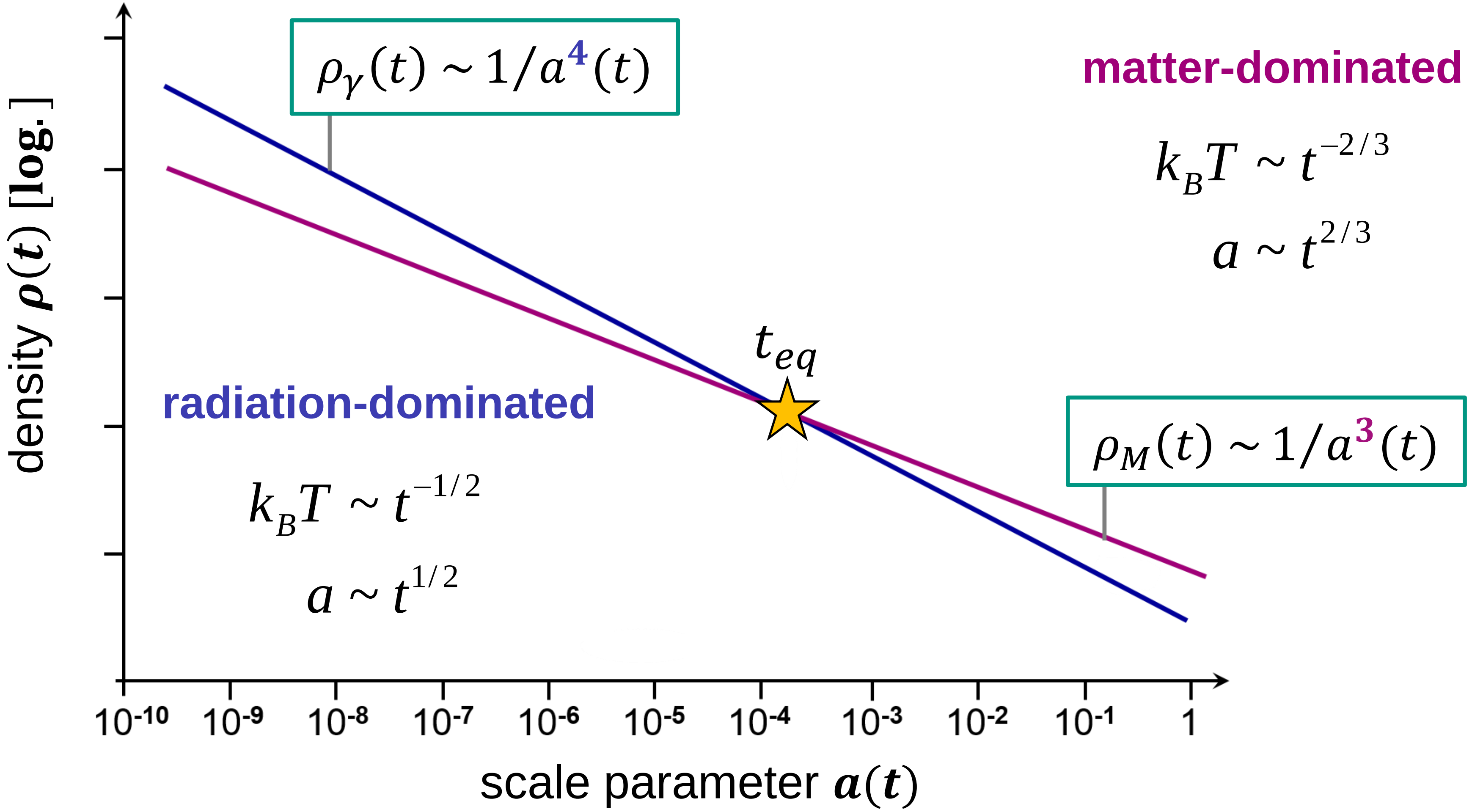
- From a radiation-dominated (Ω_γ) to a matter-dominated (Ω_M) universe

- time t_{eq} of equality
  $\boldsymbol{\rho_\gamma(t) = \rho_M(t)}$
  (radiation – matter

$$t_{eq} \approx 30000\, yr$$
$$z_{eq} \approx 1500$$

- decoupling of matter & radiaiton at $t = 378000\, yr$ occurs later!



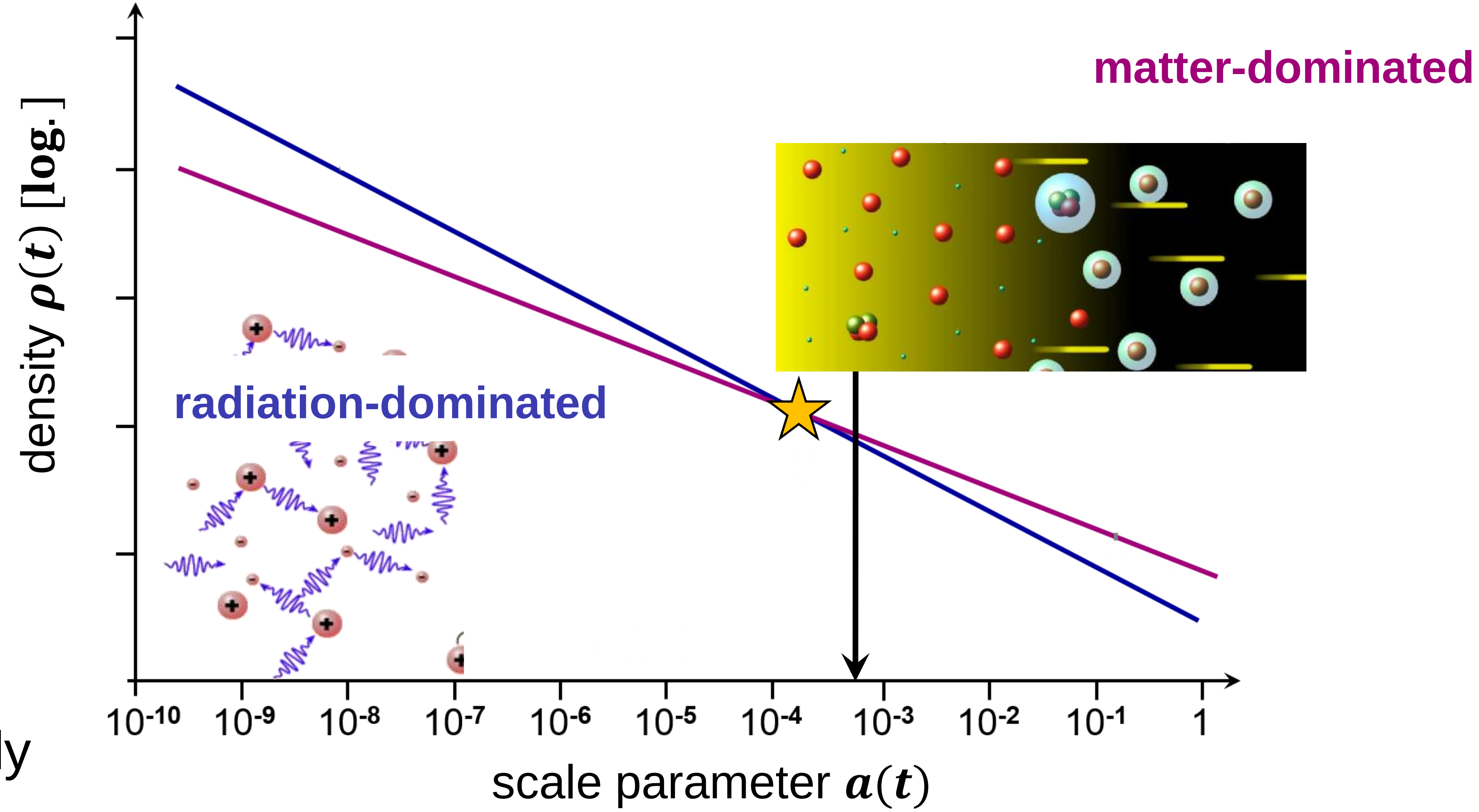
Before the freeze-out: a transition from Ω_γ to Ω_M

- **From a radiation-dominated (Ω_γ) to a matter-dominated (Ω_M) universe**

- after decoupling matter can (finally) clump together

$$t_{dec} = 378000\ yr$$
$$z_{dec} \approx 1100$$

- also important: speed of sound (density waves) changes considerably



Radiation- and matter- dominated universe

- **Properties of the phase transition from a plasma to neutral atoms**

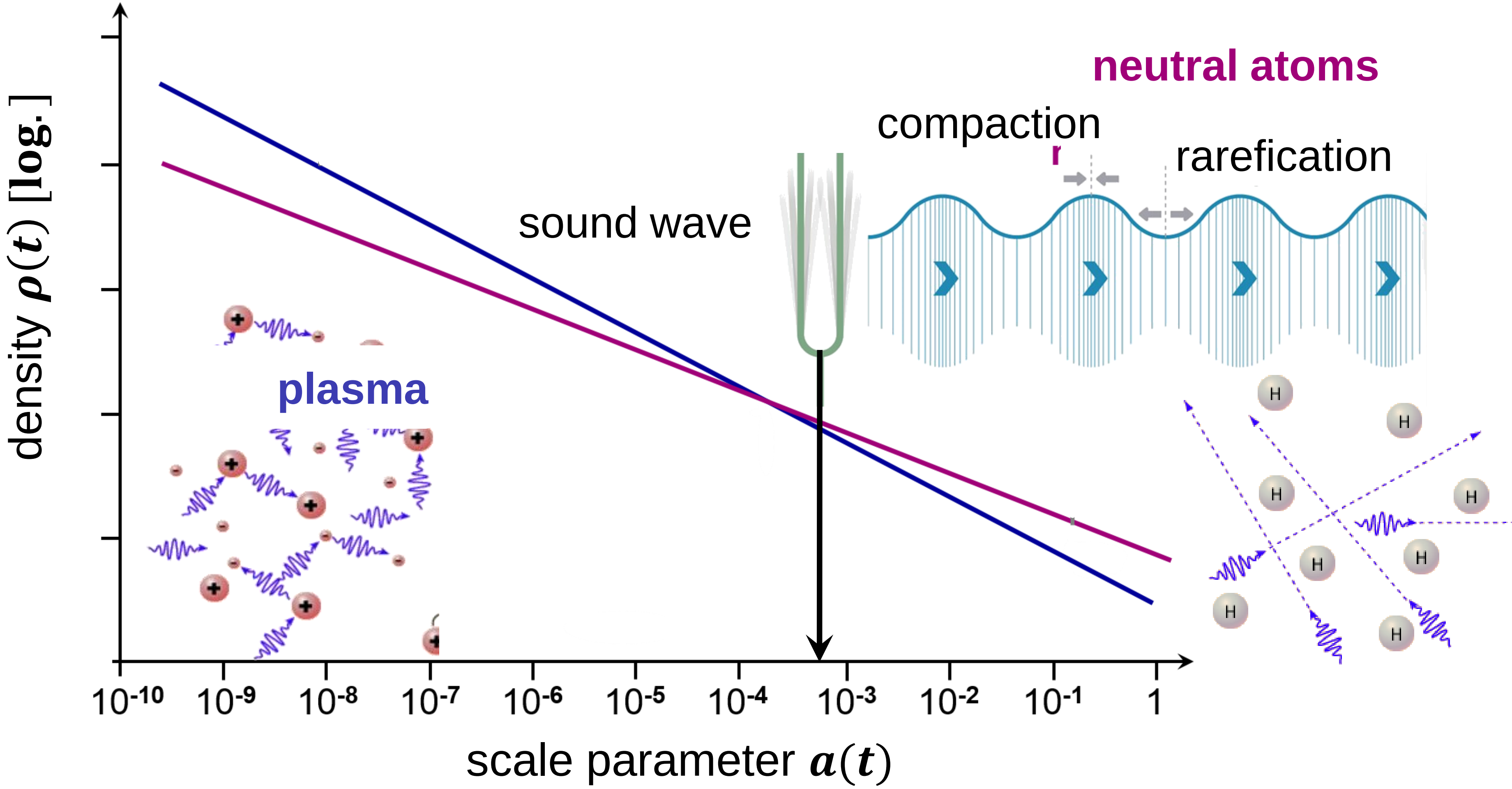
- **sound speed v_S** before (plasma) & after (neutral atoms) recombination:

- plasma: very fast!

$$v_S^2 = \frac{\partial p}{\partial \rho} = \frac{c^2}{3}$$

- neutral matter:

$$v_S^2 \approx 0$$

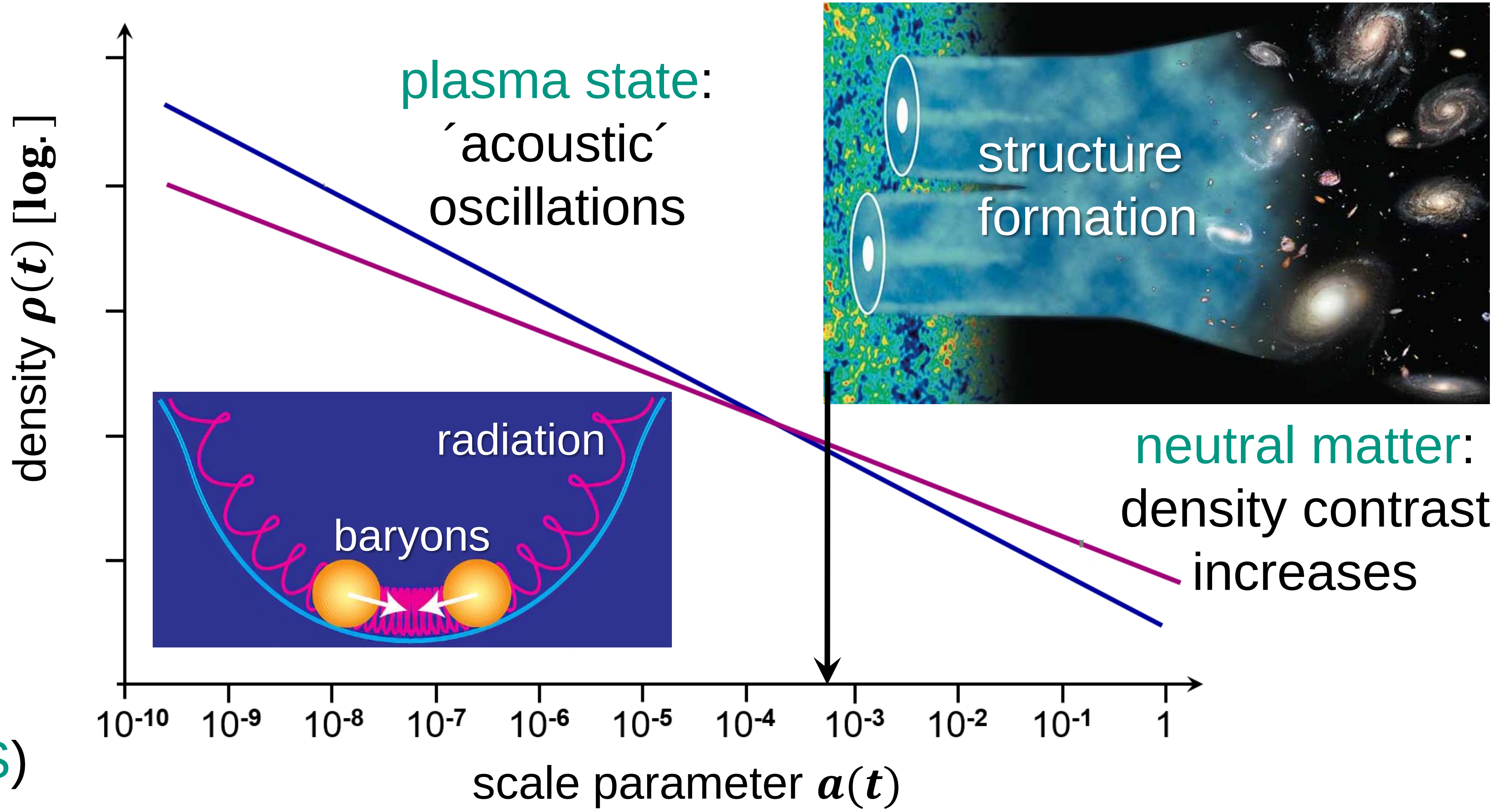


Radiation- and matter- dominated universe

- **Decoupling of radiation from matter: structure formation starts!**

- plasma:
  small fluctuations
  $\Delta T/T$ ⇨ (BAO)
  ´Baryon Acoustic
  Oscillations´

- neutral matter:
  gravity amplifies
  local overdensities
  to the current Large-
  Scale Structures (LSS)

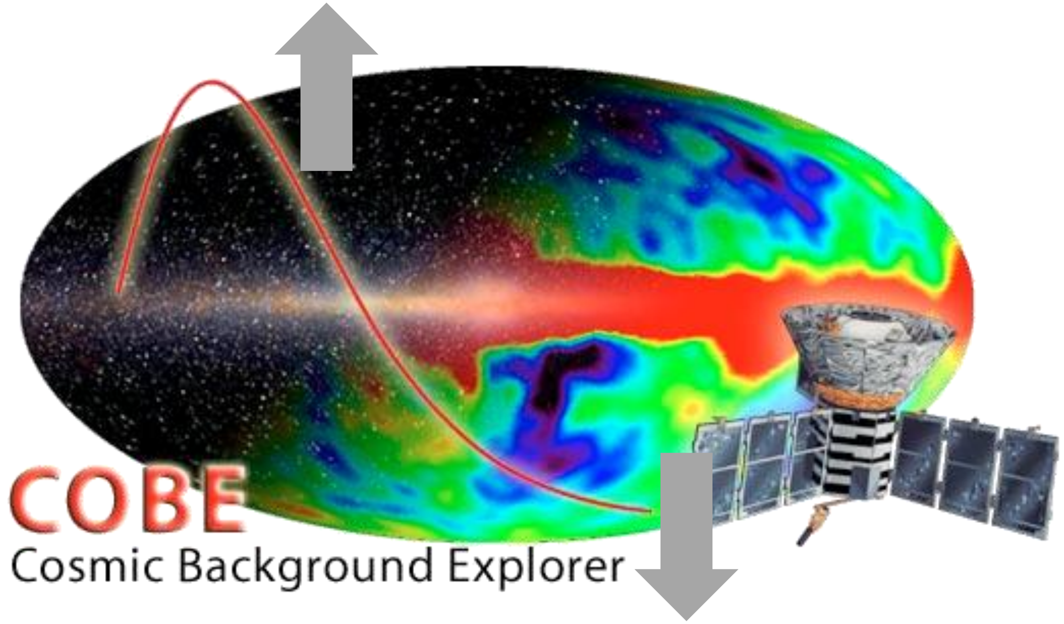


3.3 Cosmic Microwave Background: experiments

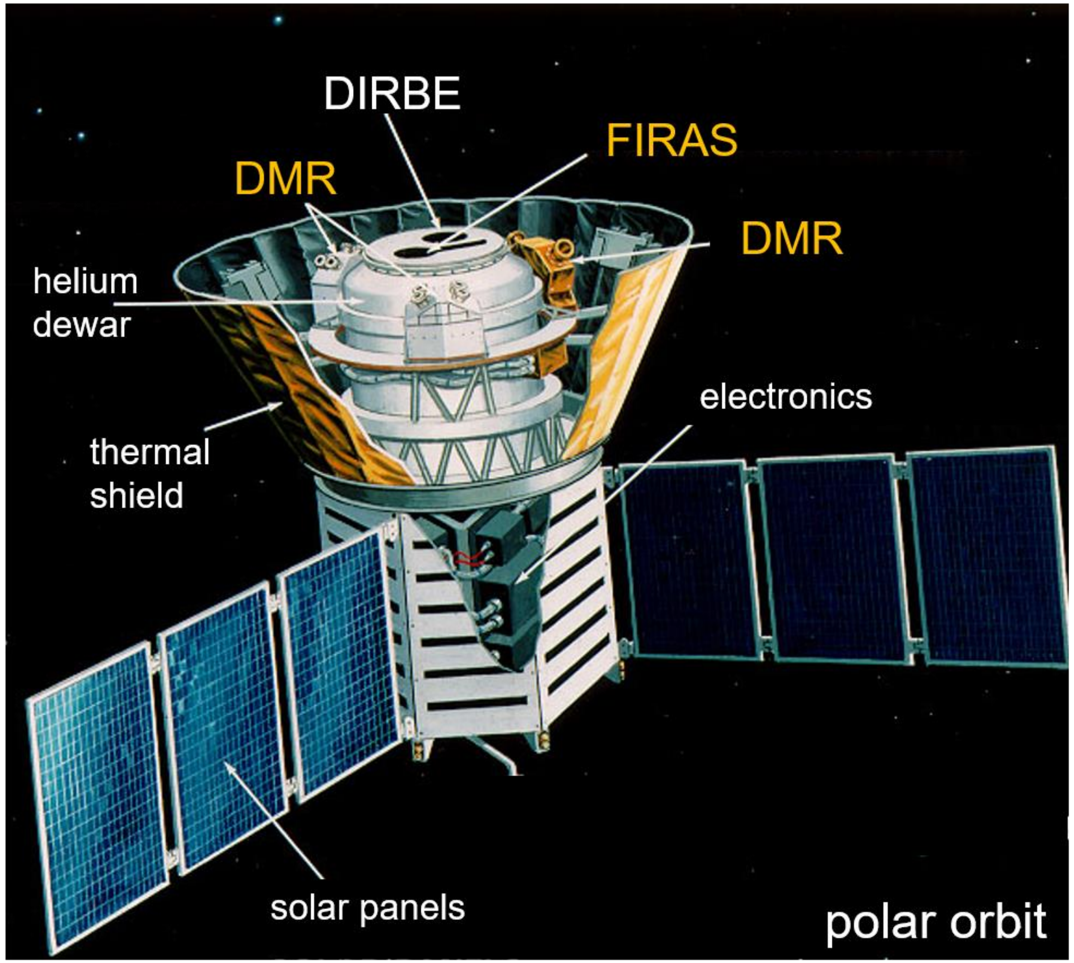
- **The first space-based CMB mission: COsmic Background Explorer (COBE)**

- NASA mission 1989-1993, two goals:

- is CMB a **perfect black body** spectrum?



- does CMB exhibit **fluctuations** $\Delta T/T$?



COBE mission: the FIRAS instrument

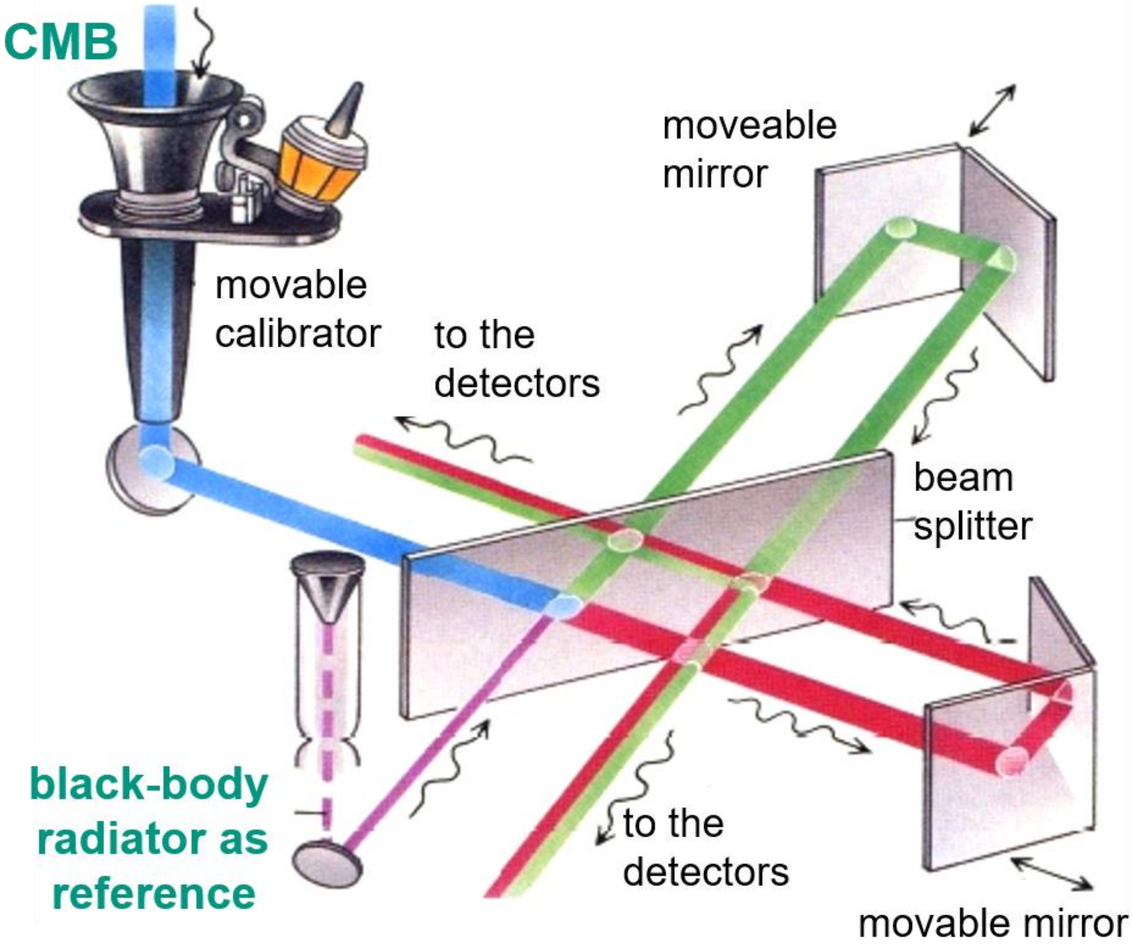
- John Mather investigates the spectral form of the CMB with FIRAS

- Far InfraRed Absolute Spectrophotometer (**FIRAS**)

- a classical Michelson-interformeter using LHe – cooled bolometers

FIRAS horn

- **principle**:
compare CMB from horn with 7° opening angle with a LHe – cooled reference black-body radiator

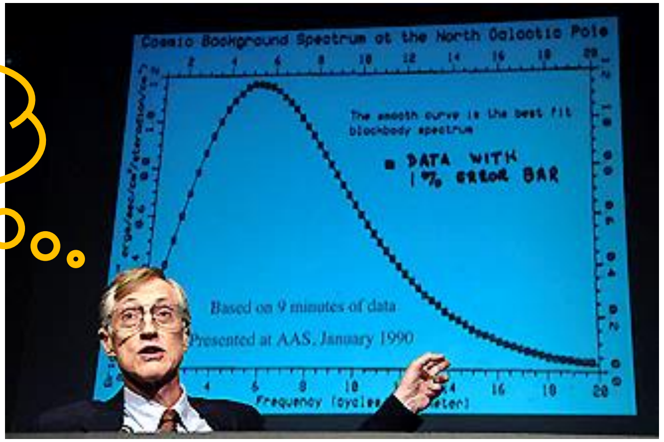


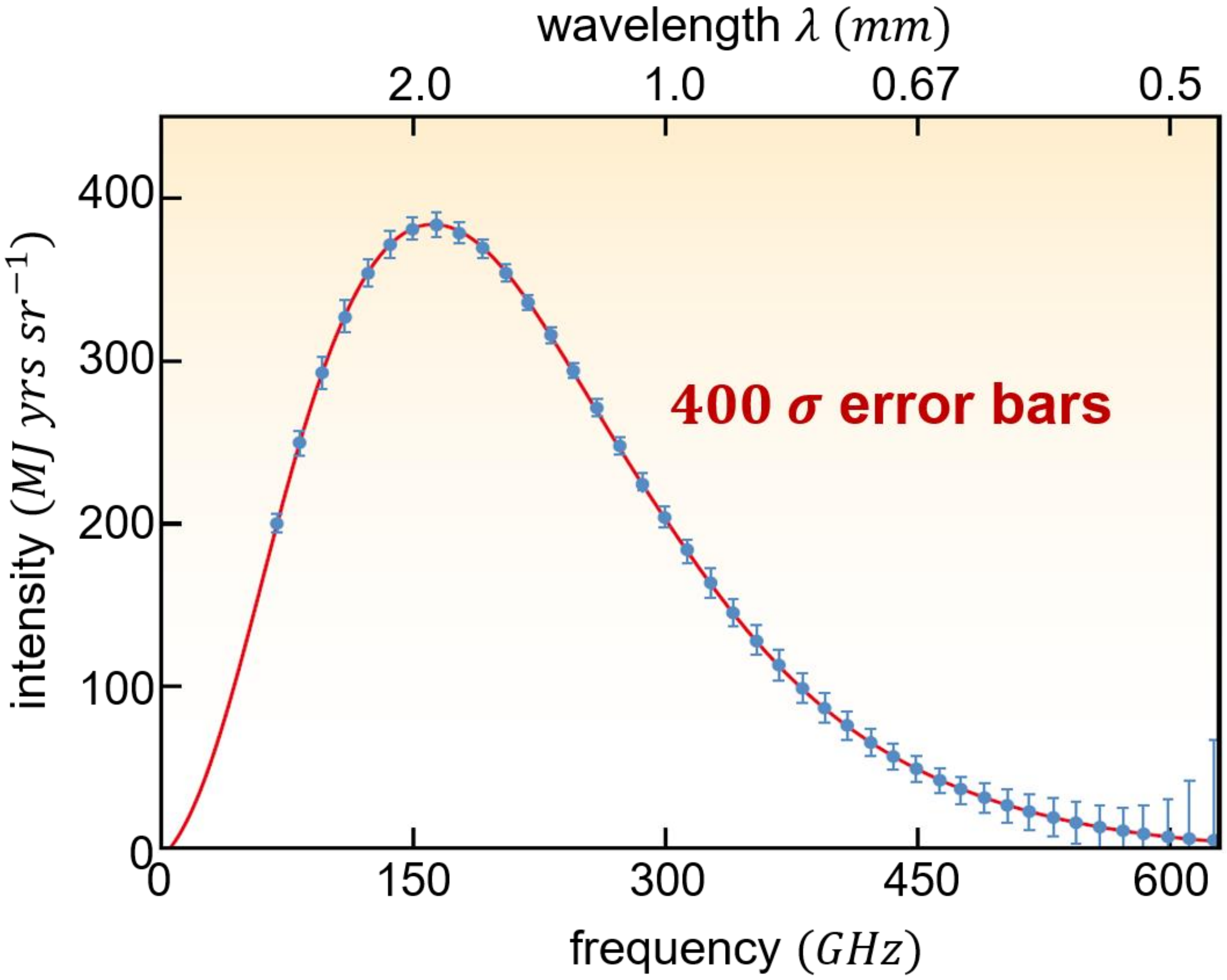
FIRAS: first results already after 9 min.

- **FIRAS reveals: BBR is a perfect black-body radiator**

  - FIRAS operation ended when $650\ \ell\ LHe$ – dewar was empty (1990)

9 min. for my Nobel





$$T(CMB) = (2.72548 \pm 0.00057)K$$

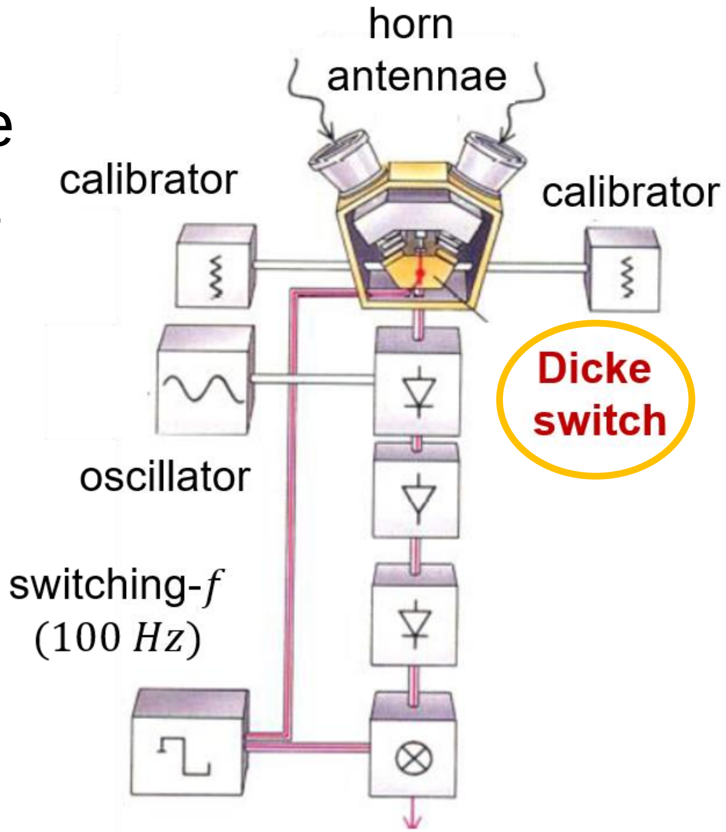
COBE mission: the DMR instrument

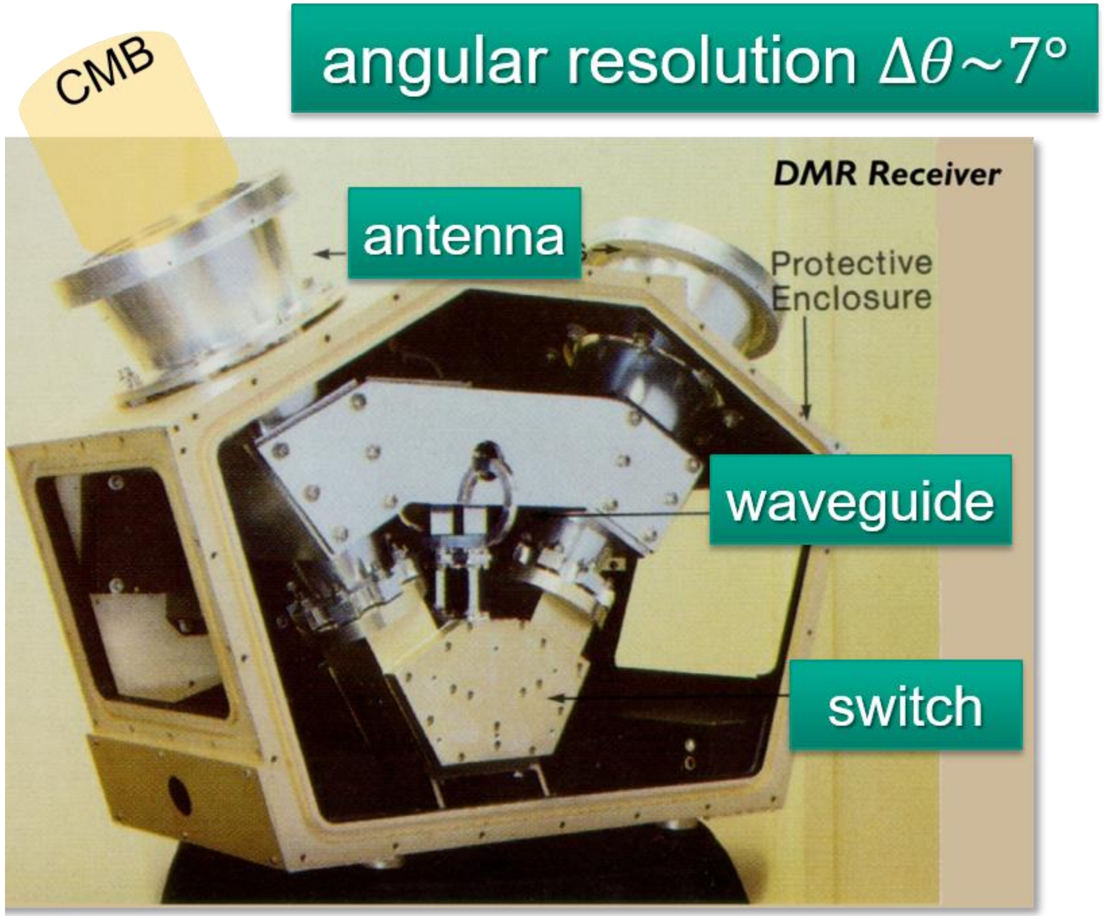
- **George Smoot is hunting tiny CMB temperature fluctuations $\Delta T/T$ with DMR**

- **D**ifferential **M**icrowave **R**adiometer - **DMR**

- **principle**:
  compare $\Delta T/T$ of the CMB from 2 spots at 60° relative to each other with two horn antenna integrating over a 7° opening angle of the sky

- **key to success**:
  Dicke switch*





*oups, Dicke scooped again…

DMR: stat. significant results only after $4\ yrs$.

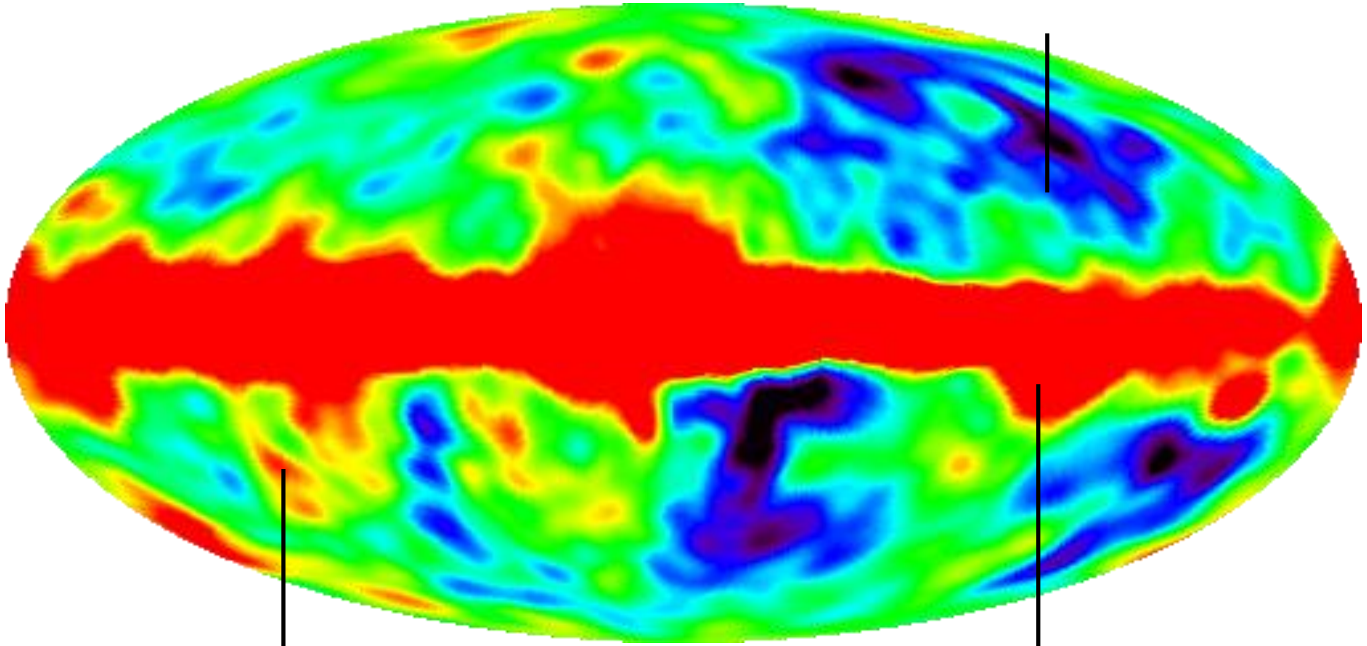
- **DMR reveals: BBR shows tiny fluctuations temperature $\Delta T/T$**

- DMR operation ended in 1993 (data do not depend on cooling by LHe-dewar)

4 yrs. for my Nobel

we had to integrate the data over four years…

few μK colder



few μK warmer

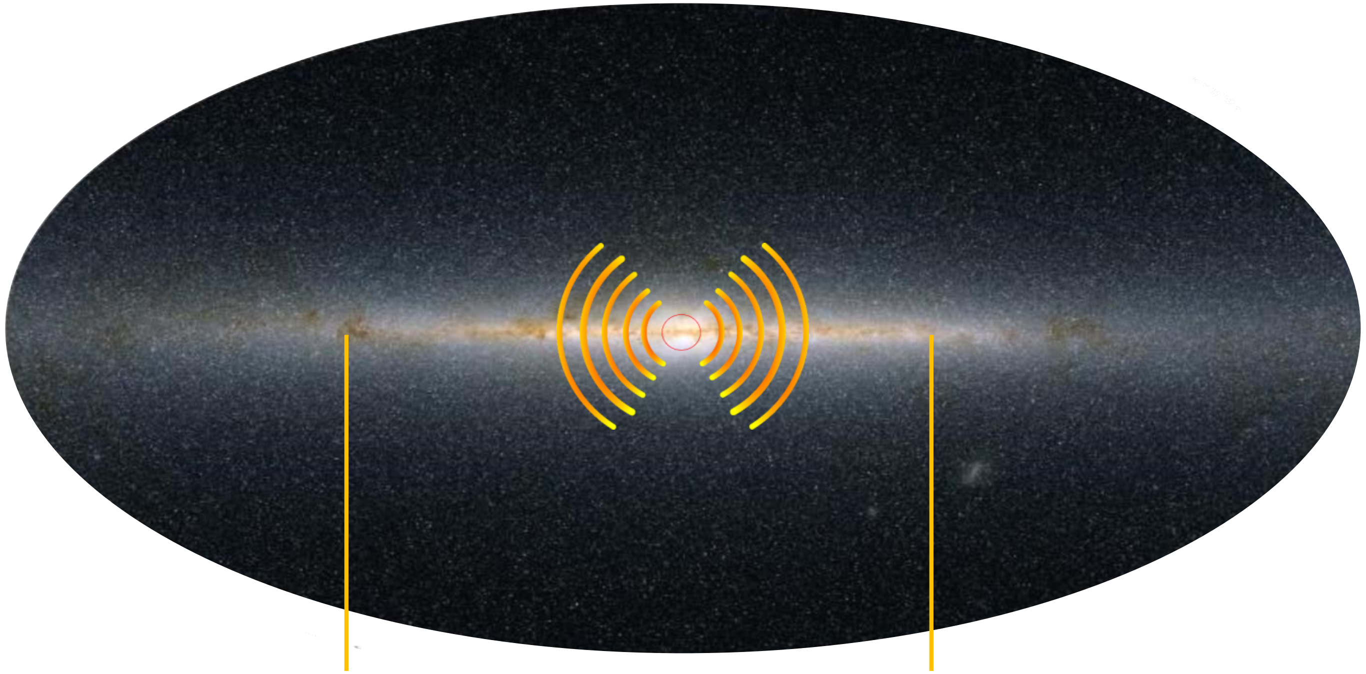
galactic emission: a noise signal

DMR: stat. significant results only after $4\ yrs$.

- **DMR r signaleveals: BBR signal needs to be separated from the galactic noise via their respective frequency dependence**

  - galactic plane is a strong radio source: noise signal for CMB

we had to cut out the galactic plane …



DMR: stat. significant results only after $4\ yrs$.

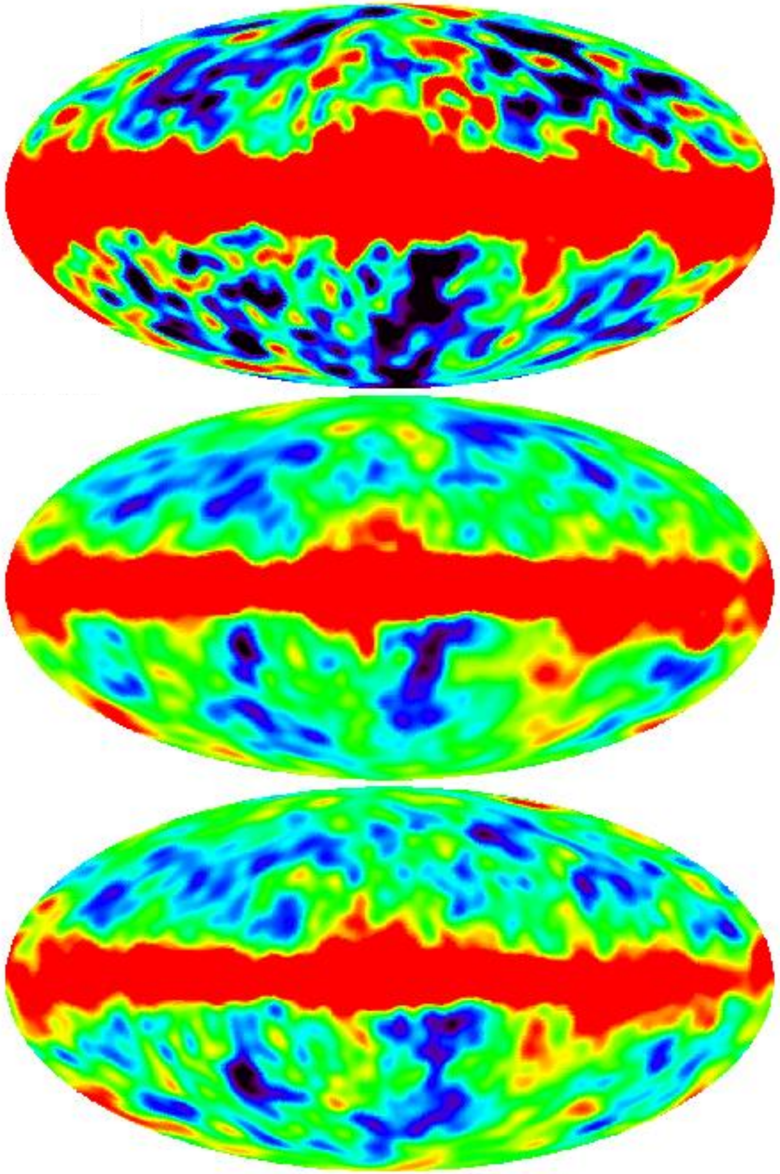
- **DMR reveals: BBR shows tiny fluctuations temperature $\Delta T/T$**

 - DMR operated at 3 different frequencies: $31.5\ - 53 - 90\ GHz$

consistent results!!

$-100\ \mu K$ $+100\ \mu K$

we had to compare hot & cold spots at 3 frequencies: good match!



$31.5\ GHz$

$35\ GHz$

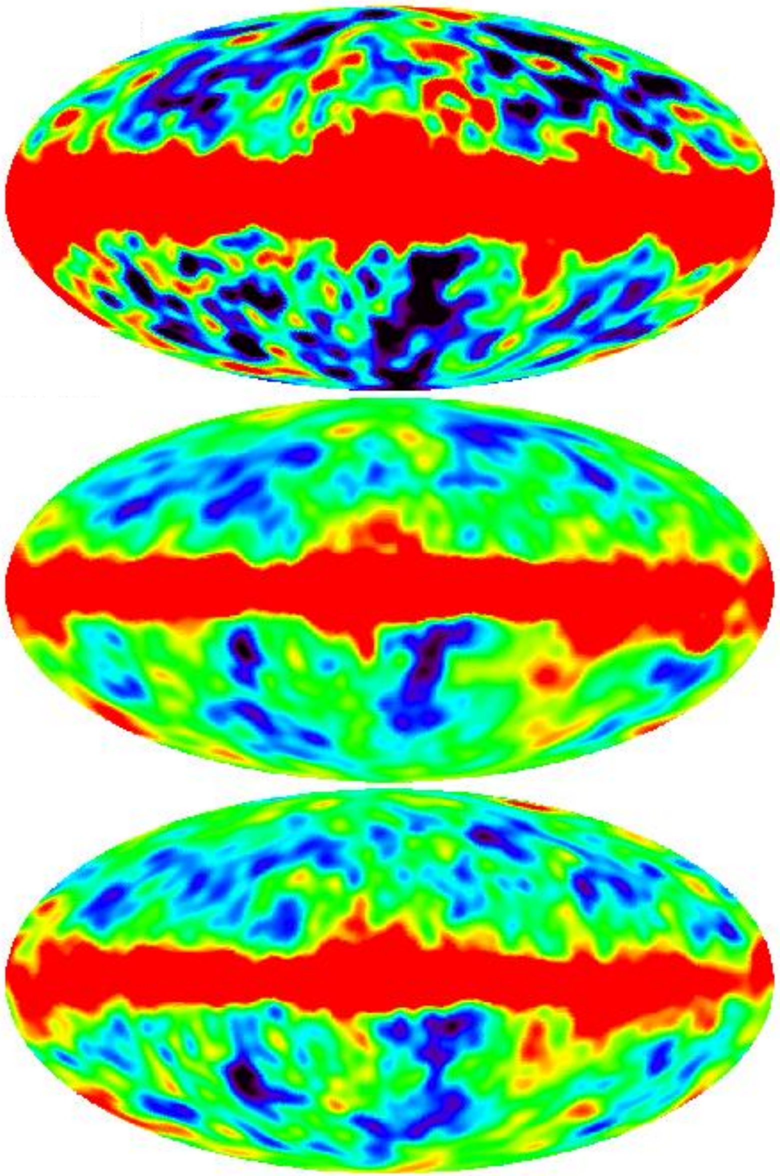
$90\ GHz$

DMR: stat. significant results only after $4\ yrs$.

- **DMR reveals: BBR shows tiny fluctuations temperature $\Delta T/T$**

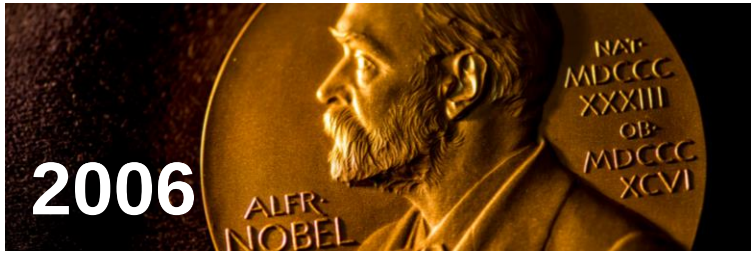
  - DMR operated at 3 different frequencies: $31.5\ - 53 - 90\ GHz$

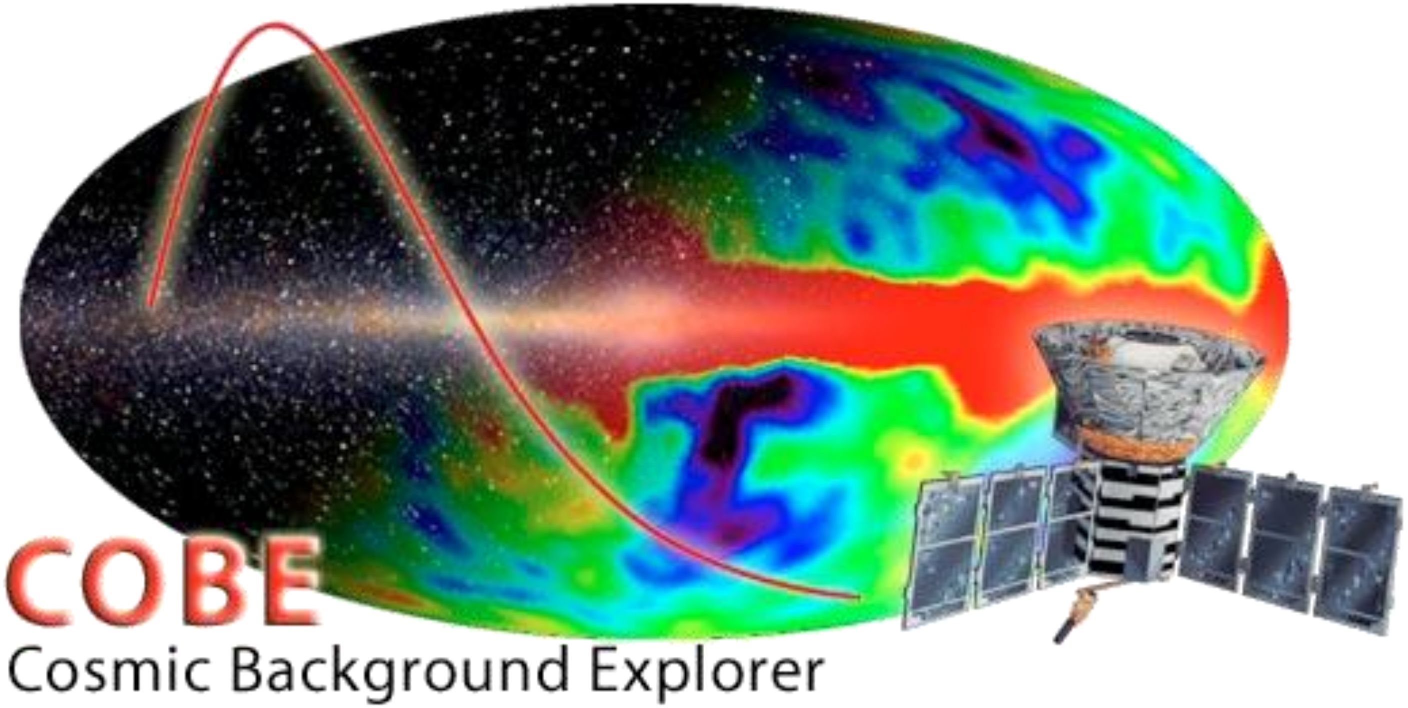
Dr. Sheldon Cooper, ok?



COBE mission: important CMB results

- **J. Mather and G. Smoot are awarded the Nobel prize in physics in 2006**





"for their discovery of the blackbody form and anisotropy of the cosmic microwave background radiation."

Scientific legacy of COBE for cosmology

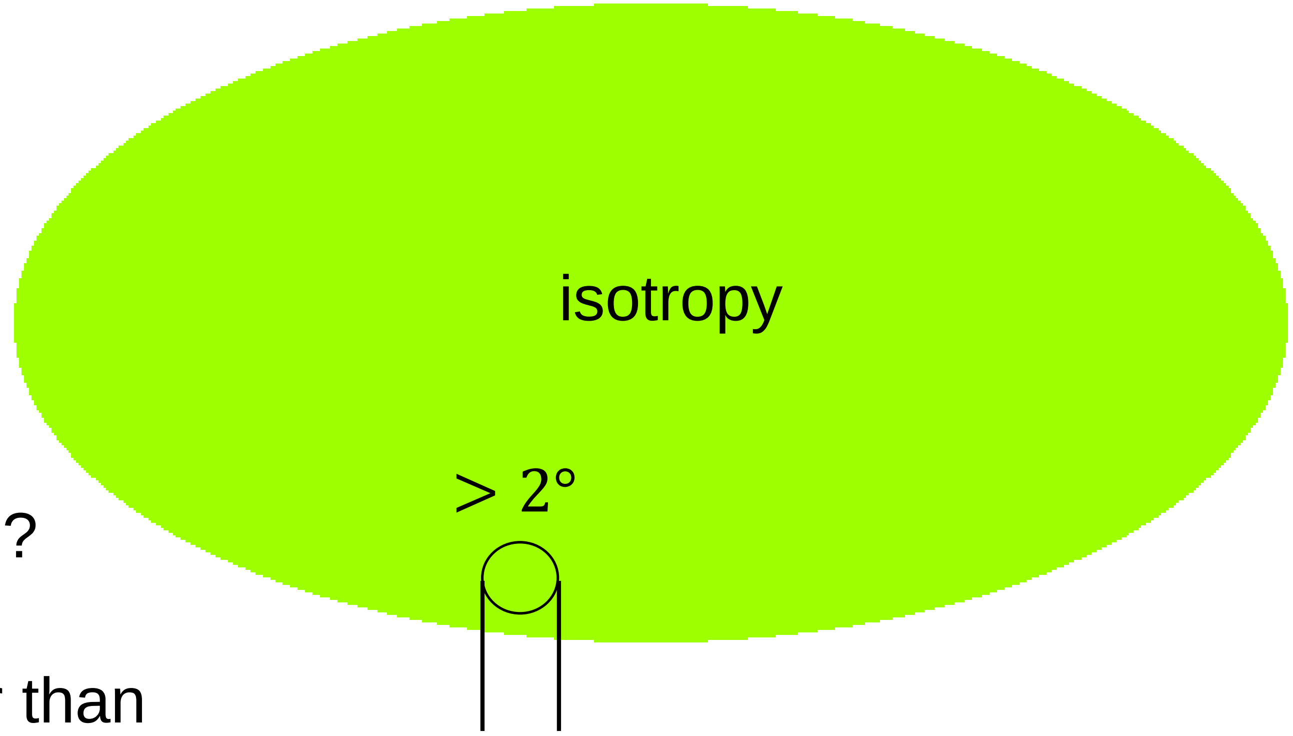
- **Legacy #1: to first order at the $sub-K$ –scale, the universe is isotropic**

- homogenous & isotropic universe
  with **Robertson-Walker metrics**

- **cosmological origin** of CMB

- what is the origin of the isotropy
  of the CMB on the $sub-K$ – scale?

- **horizon problem**: all scales larger than
  $2°$ have never been in causal contact!



$\boldsymbol{T = 2.726\ K}$, without causal contact

Scientific legacy of COBE for cosmology

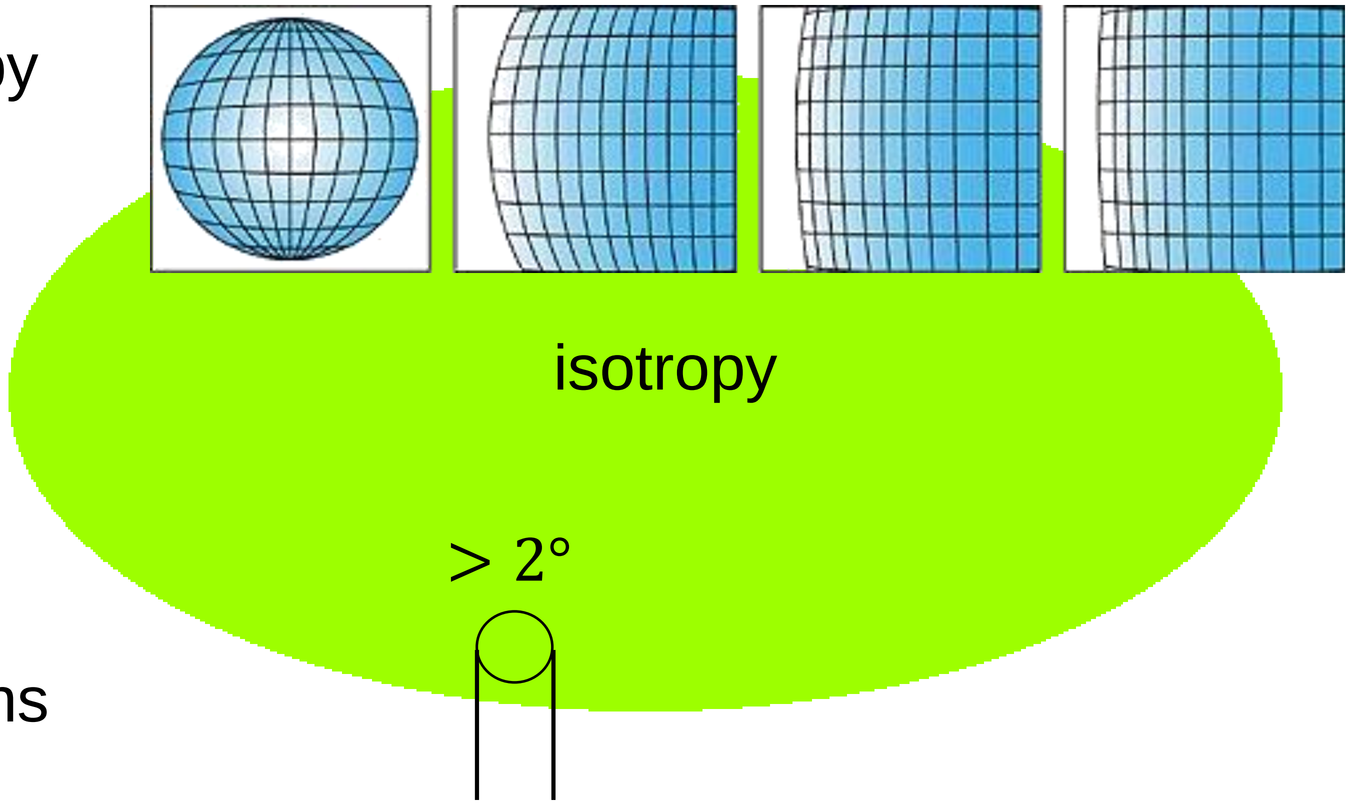
- **Legacy #1: to first order at the $sub-K$ –scale, the universe is isotropic**

- inflationary theory addresses this by an **exponential growth of $a(t)$** at $t = 10^{-36} \dots 10^{-32} s$

- expansion driven by inflaton field

- increase of scale factor $a(t)$ by more than $\mathbf{10^{22}}$ (or e^{60} – fold)

- inflation would smooth out variations in the T –distribution of the CMB (down to the 10^{-5} level observed)

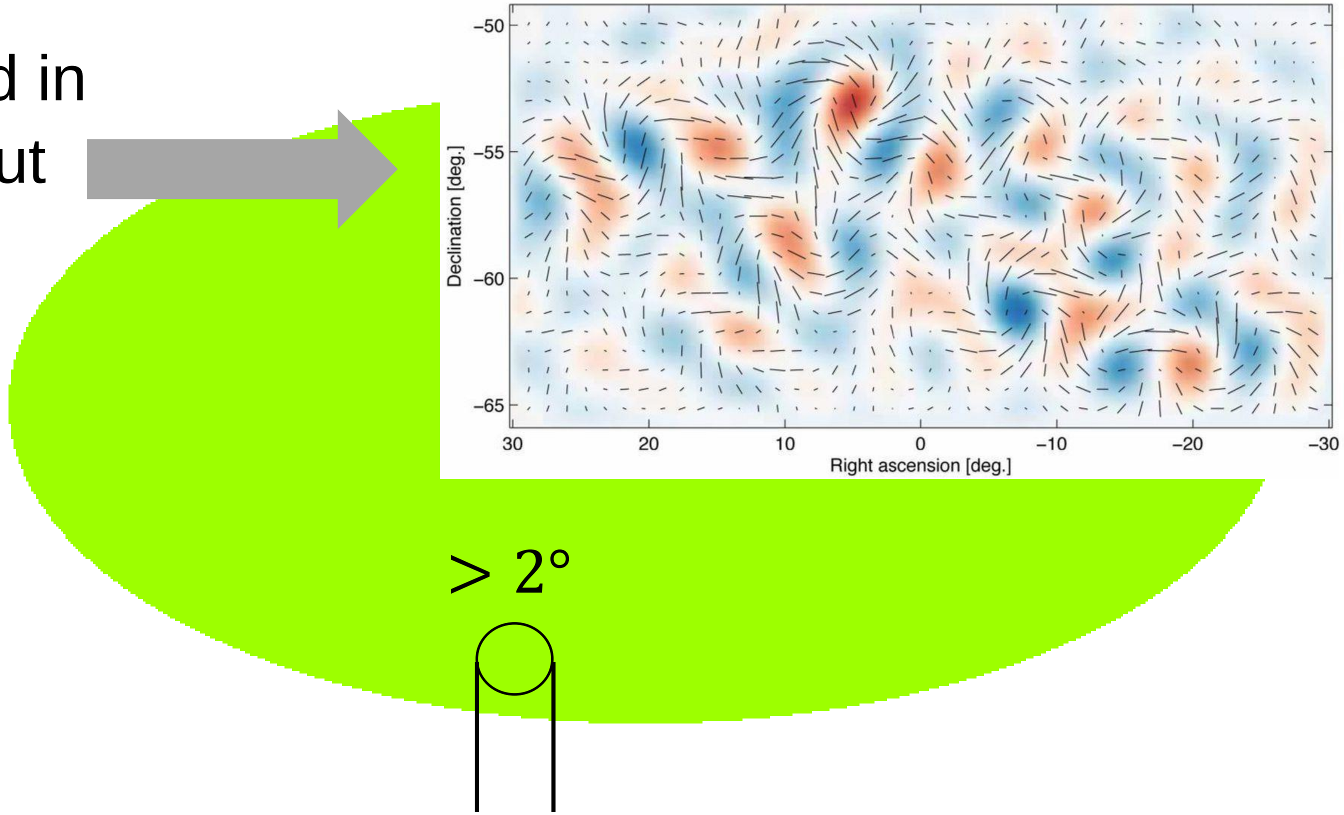


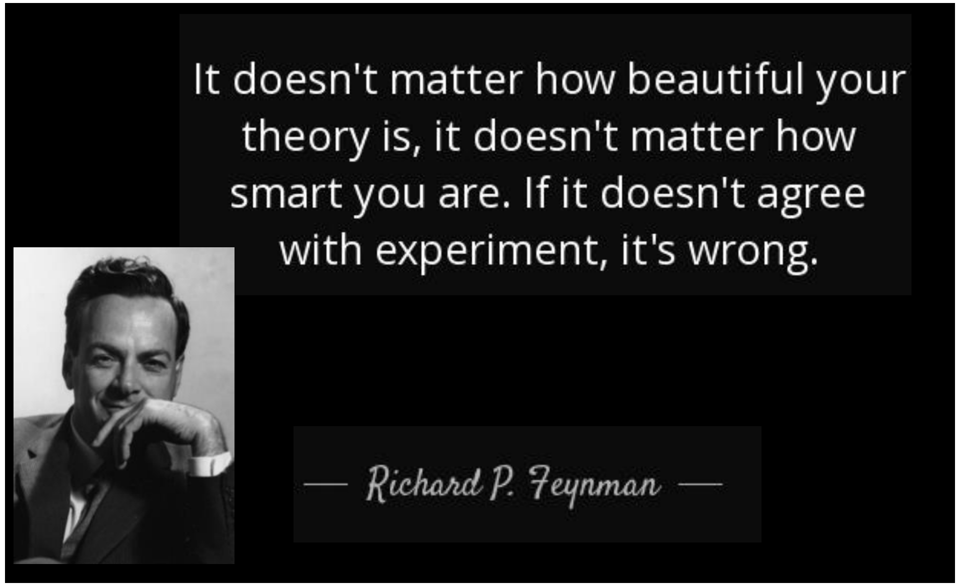
$\boldsymbol{T = 2.726\ K}$, without causal contact

Scientific legacy of COBE for cosmology

- **Legacy #1: to first order at the** $sub - K$ **–scale, the universe is isotropic**

- rapid expansion should have resulted in the emission **gravitational waves**, but no signal has been measured* (yet?)





$T = 2.726\ K$, without causal contact

*see ATP-2 in summer 2023

Scientific legacy of COBE for cosmology

- **Legacy #2: at the mK –scale, the dipole anisotropy manifests**

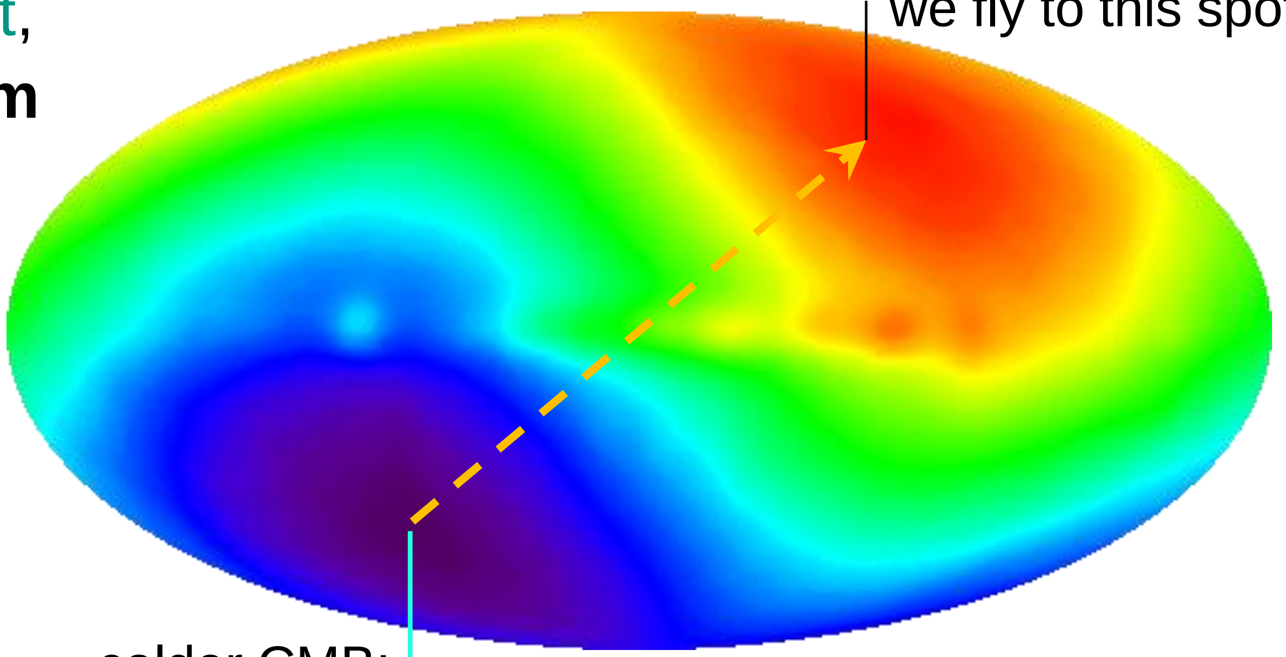
  - Dipole anisotropy: a Doppler effect, caused by **motion of solar system** relative to CMB radiation field

  - Doppler amplitude:

$$\Delta T(\theta) = T_0 \cdot \left(1 + \frac{v}{c} \cdot \cos\theta\right)$$
$$= (3.365 \pm 0.0275) mK$$
$$\Rightarrow v = 371 \; km/s$$

  - CMB is an absolute reference system, but not distinguished in SR*

hotter CMB:
we fly to this spot



colder CMB:
we fly away from this spot

$-3.3\ mK$  $+3.3\ mK$

*Special Relativity

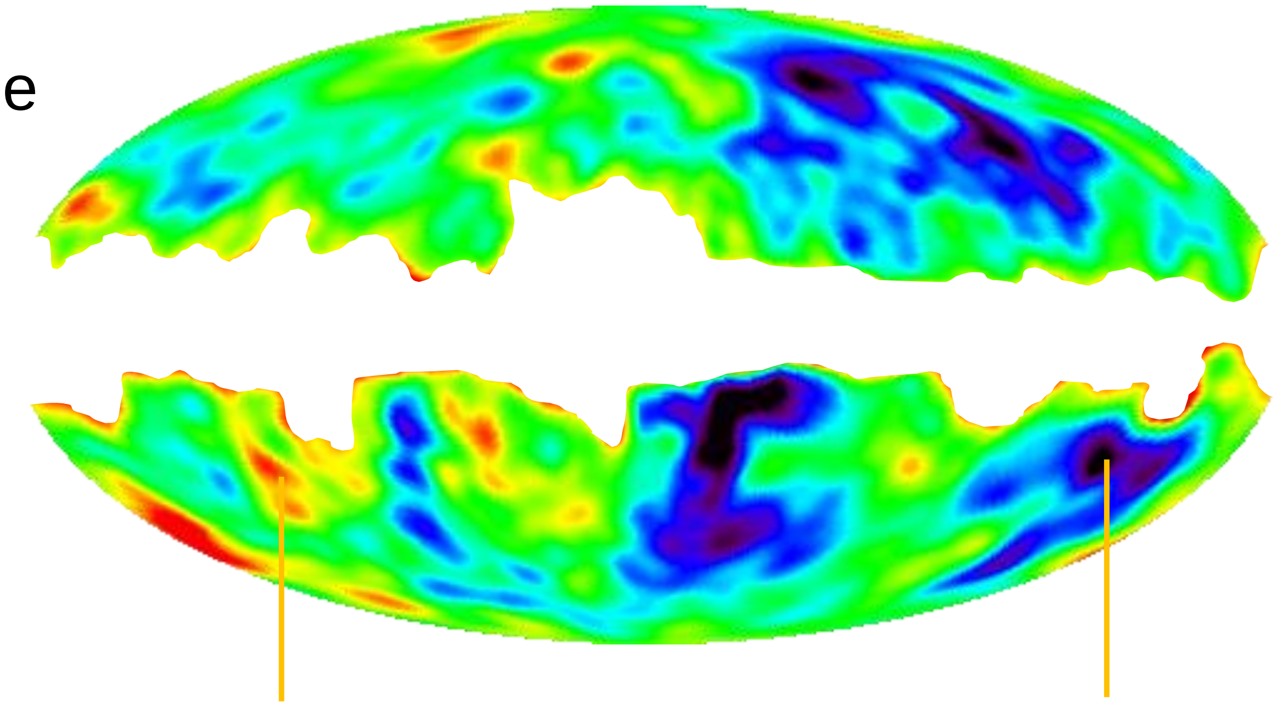
Scientific legacy of COBE for cosmology

- **Legacy #3: at the μK –scale, temperature fluctuations $\Delta T/T$ manifest**

- temperature fluctuations $\Delta T/T$ are **anti-correlated** to fluctuations of the density $\Delta\rho/\rho$ of specific regions

$$\boxed{\frac{\Delta T}{T} = -\frac{\Delta\rho}{\rho}}$$

- amplitude at the level $\sim 10^{-5}$ $(10 \ldots 20\ \mu K)$: agrees with inflation

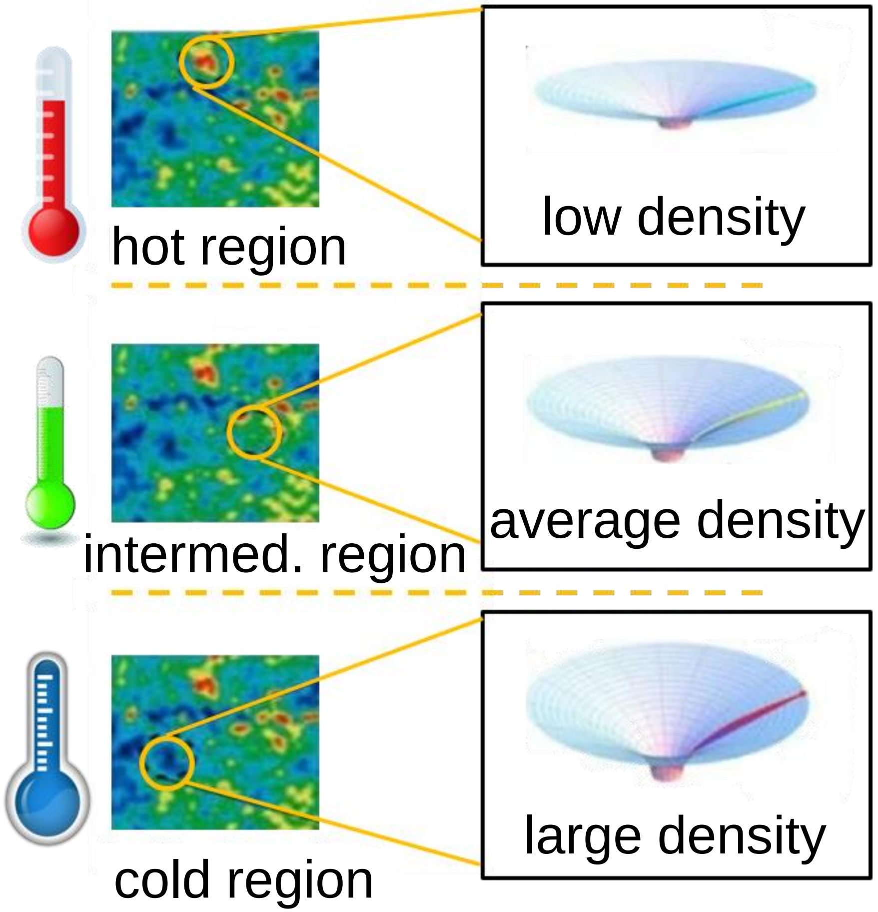


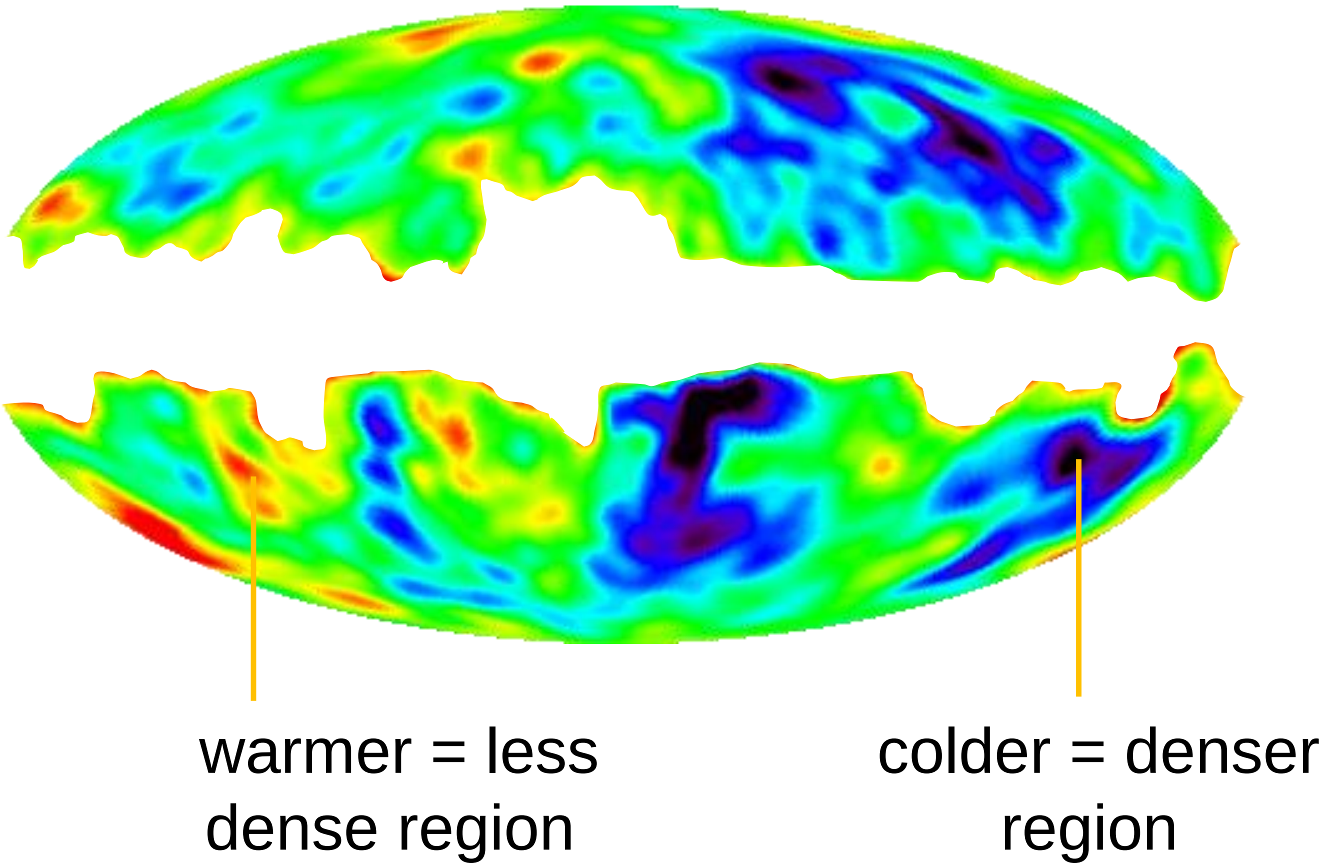
warmer = less dense region

colder = denser region

Scientific legacy of COBE for cosmology

- **Legacy #3: fluctuations $\Delta T/T$ as seeds for (much later) structure formation**





Legacy of cosmology

- Happy Holidays & a happy New Year 2023

FROHE FESTTAGE UND EIN GUTES NEUES JAHR