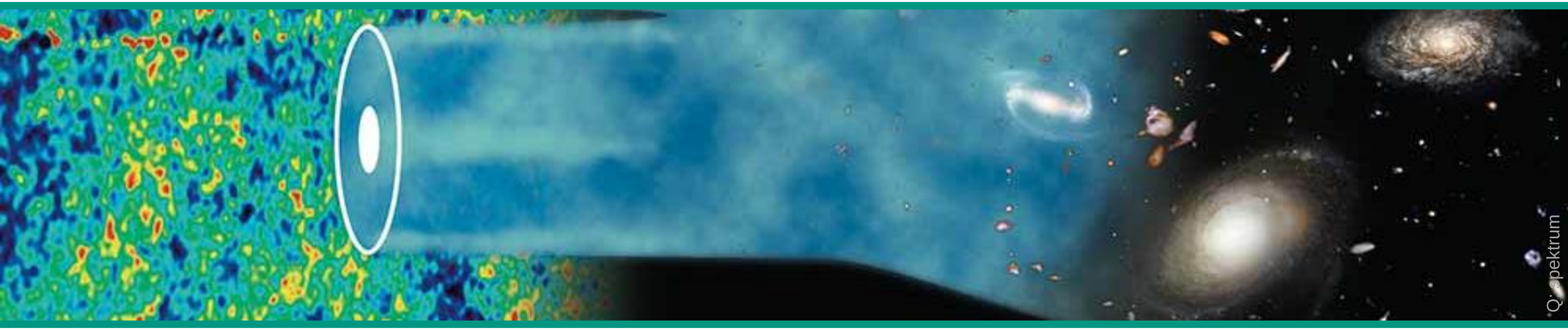
Karlsruhe Institute of Technology

Introduction to Cosmology

Winter term 23/24 Lecture #5 Nov. 21, 2023



Recap of Lecture 4

- **Friedmann equation for expanding universe**

  - cosmological constant $\Lambda \neq 0$ ($3.6\ GeV/m^3$ $vs.$ $10^{121}\ GeV/m^3$)

  - integration of acceleration eq.: $H^2(t) = \left(\frac{\dot{a}(t)}{a(t)}\right)^2 = \frac{8}{3} \cdot \pi \cdot G \cdot \rho_{m,\gamma}(t) + \frac{\Lambda c^2}{3}$

  - universe appears to be **flat**: **curvature $k = 0$** (brief inflationary epoch?)

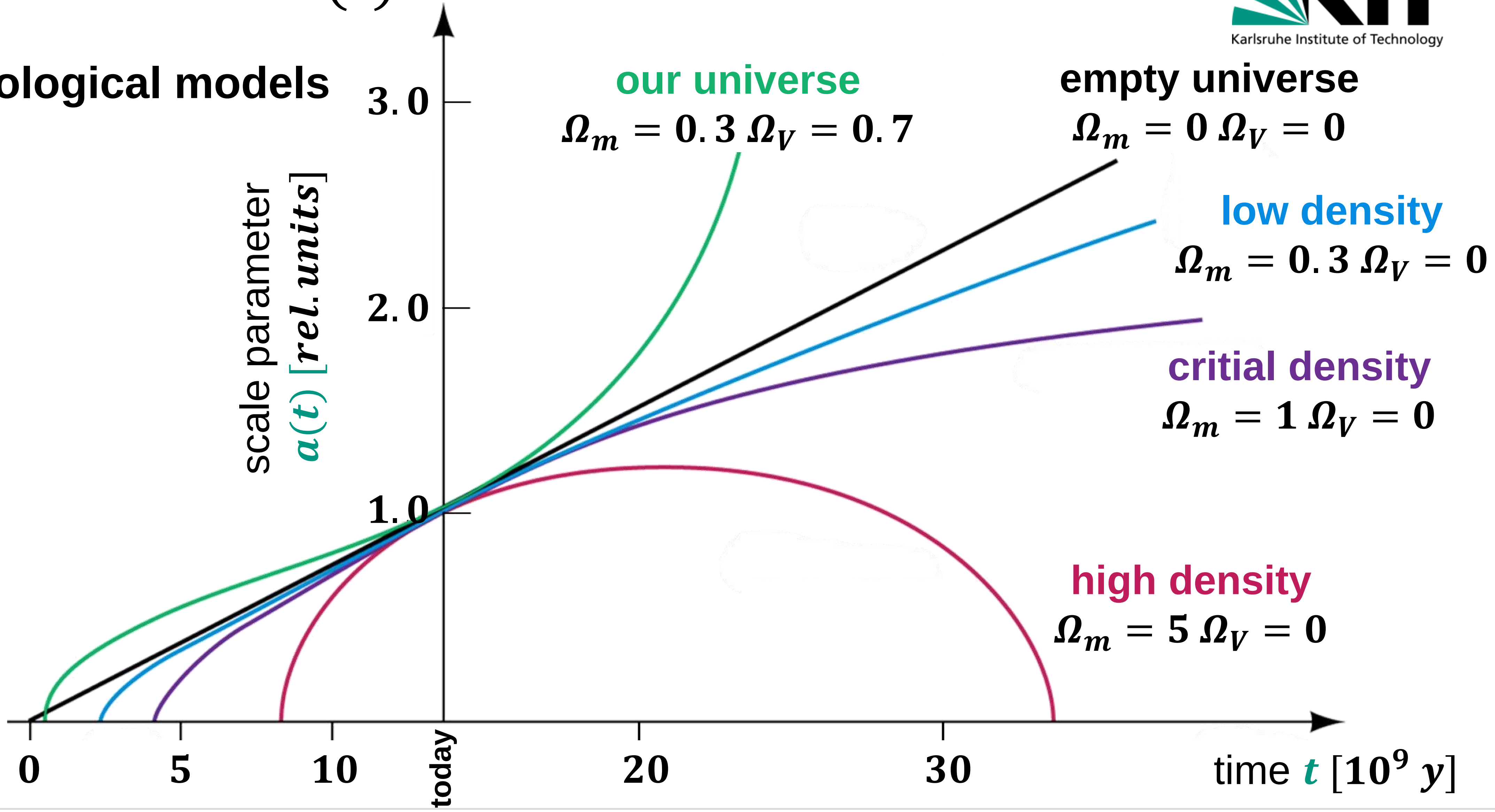
  - three cosmological epochs: **radiation** / **matter** / **vacuum**

  - total energy density $\Omega_{tot} = \Omega_\gamma + \Omega_m + \Omega_V + \Omega_k$ ($\equiv 1$, if critical density)

  - definition of **Hubble time $t_H = (H_0)^{-1}$** $= 13.8 \cdot 10^9\ yr$ (uniform expansion)

Scale parameter $a(t)$ for different models

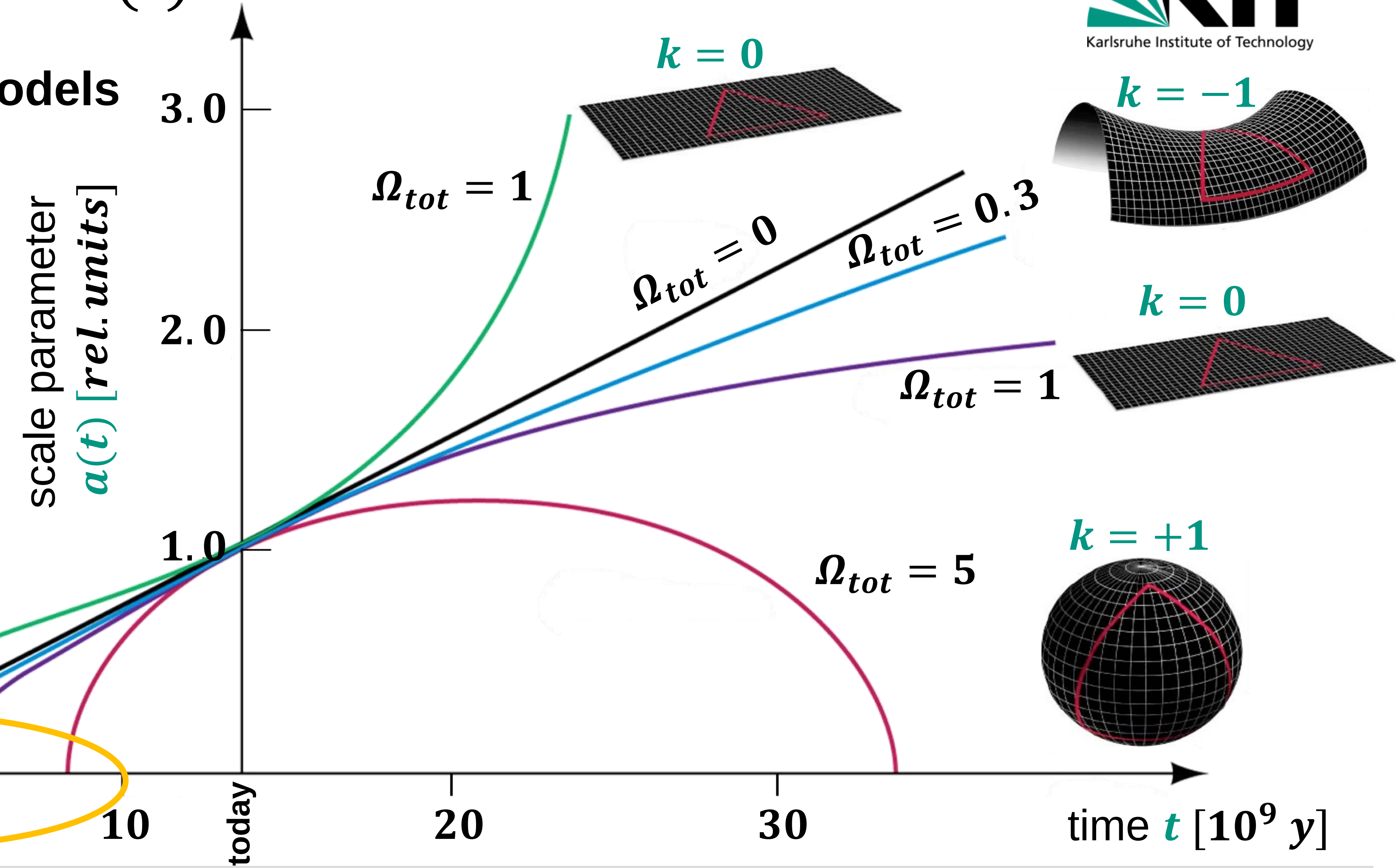
- Cosmological models



Scale parameter $a(t)$ for different models

- **Cosmological models**

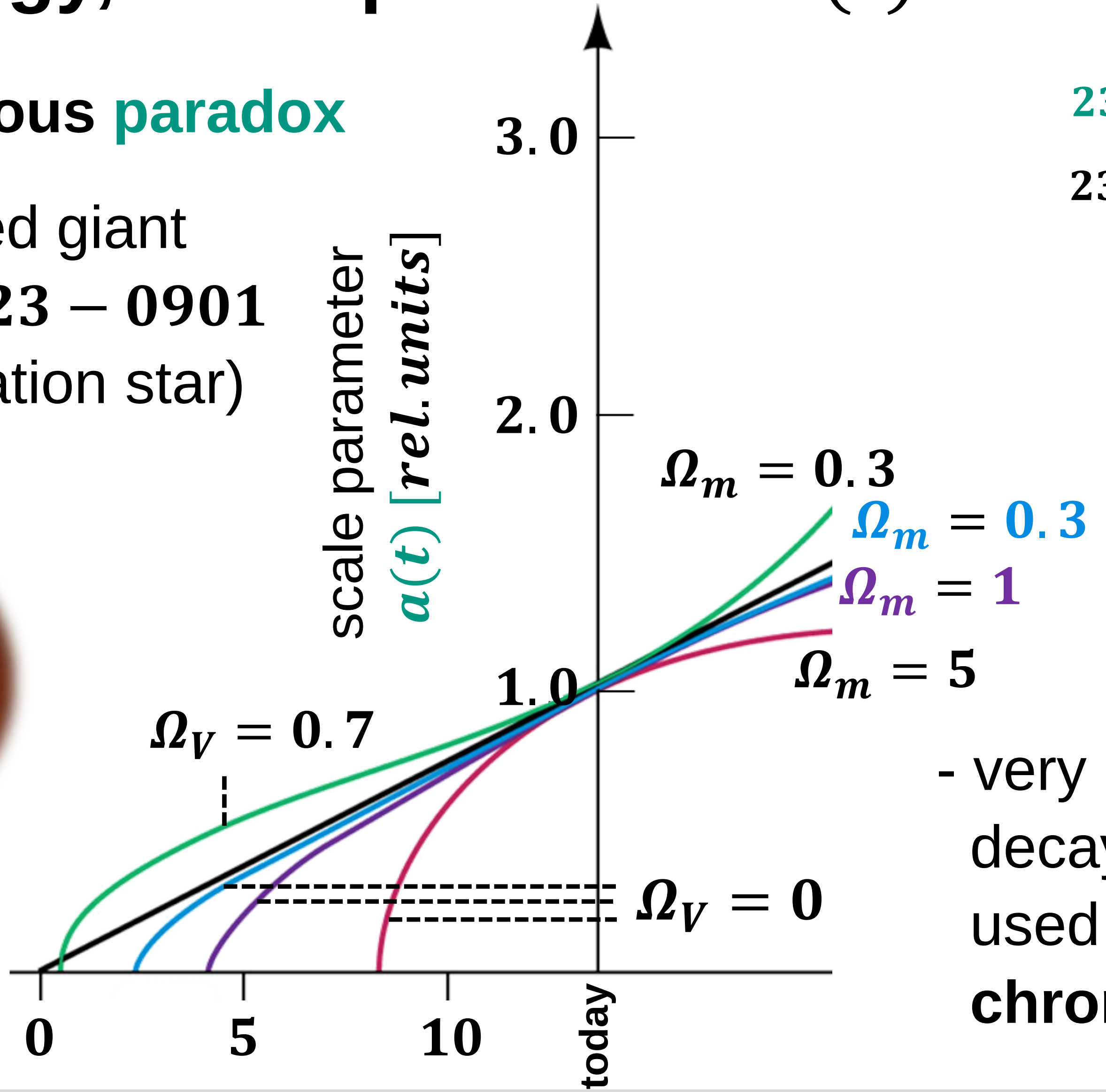
can we use a
cosmological clock
to cross–check??

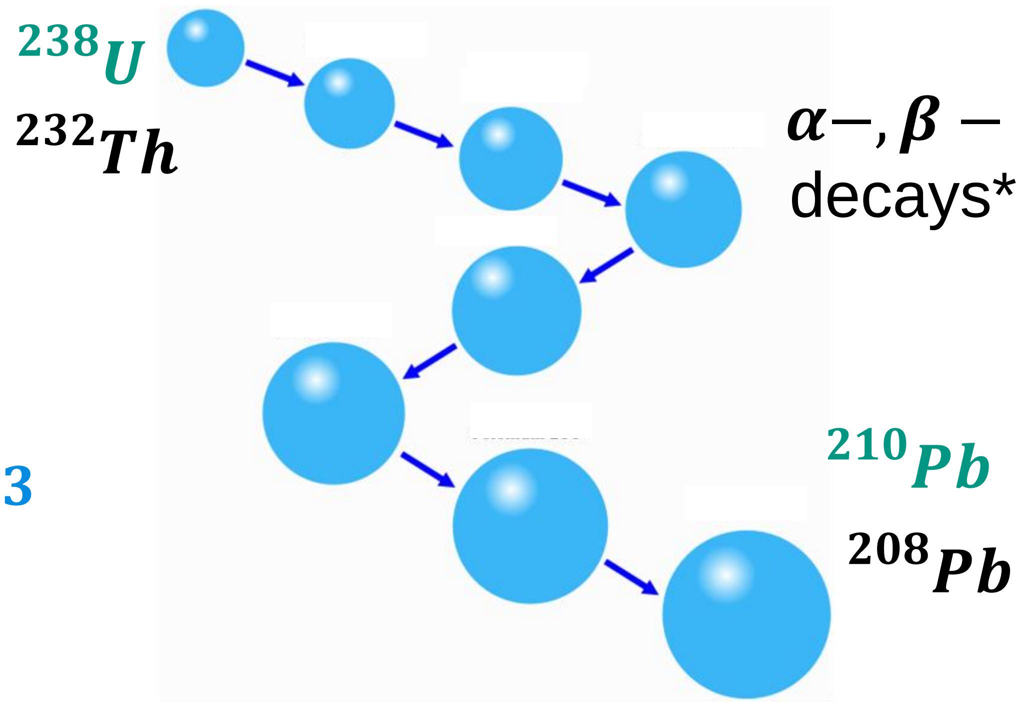


Topology, scale parameter $a(t)$ & the oldest stars

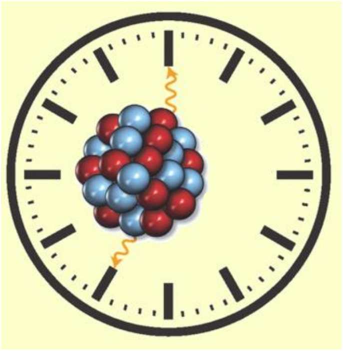
- A famous paradox

example: red giant star $HE\ 1523-0901$ (2^{nd} generation star)





- very long–lived nuclear decays (U, Th) can be used as **cosmo–chronometers**



*see $ATP-I$

Topology, scale parameter $a(t)$ & the oldest stars

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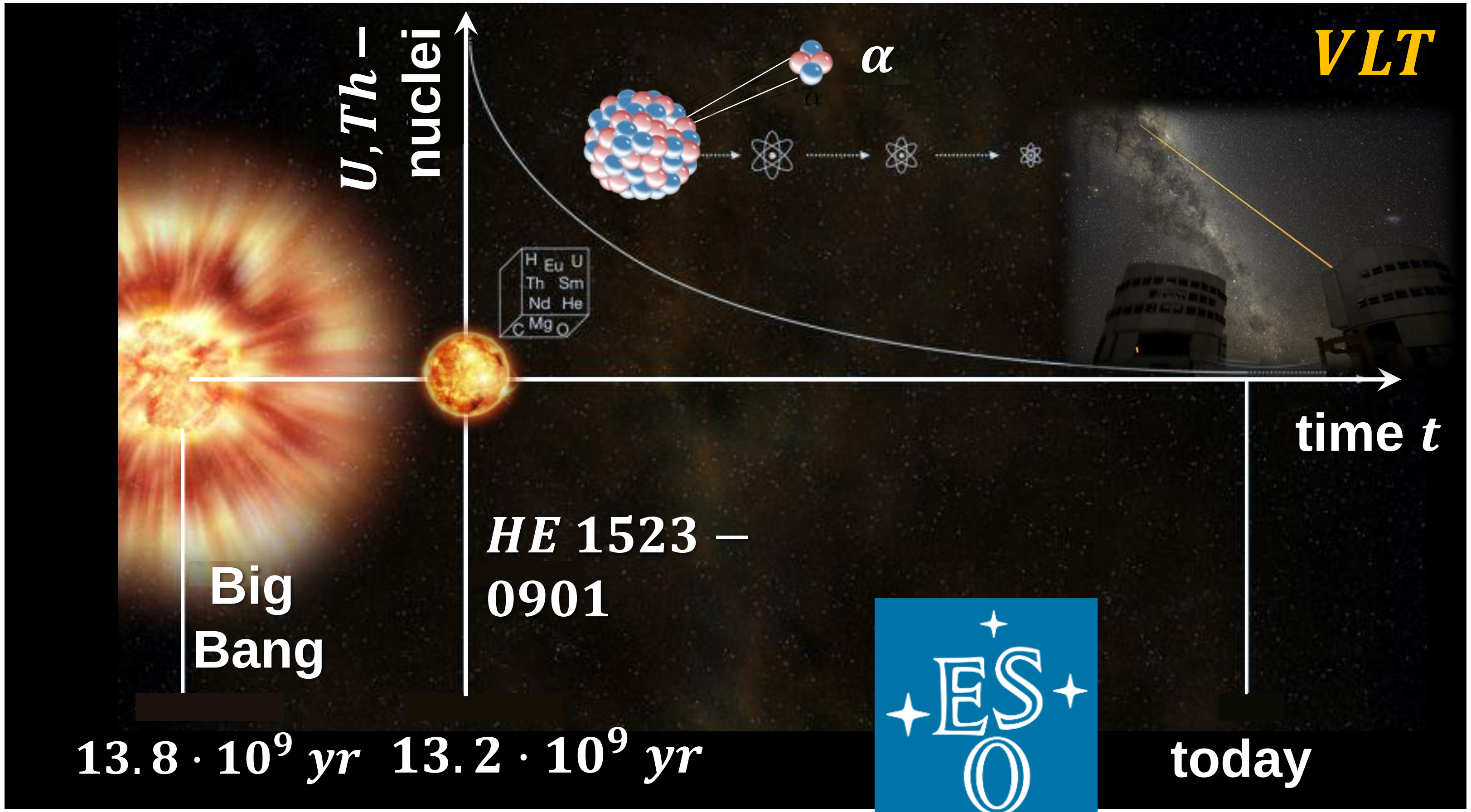
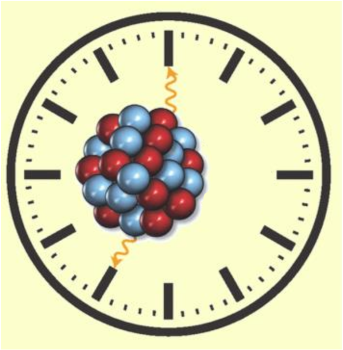
- A famous **paradox**: nuclear clocks observed in star $HE\ 1523-0901$



- **nuclear & particle physics**: radioactive dating is a very important method for cosmology



Topology, scale parameter $a(t)$ & the oldest stars

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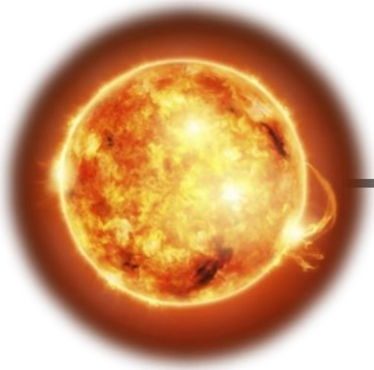
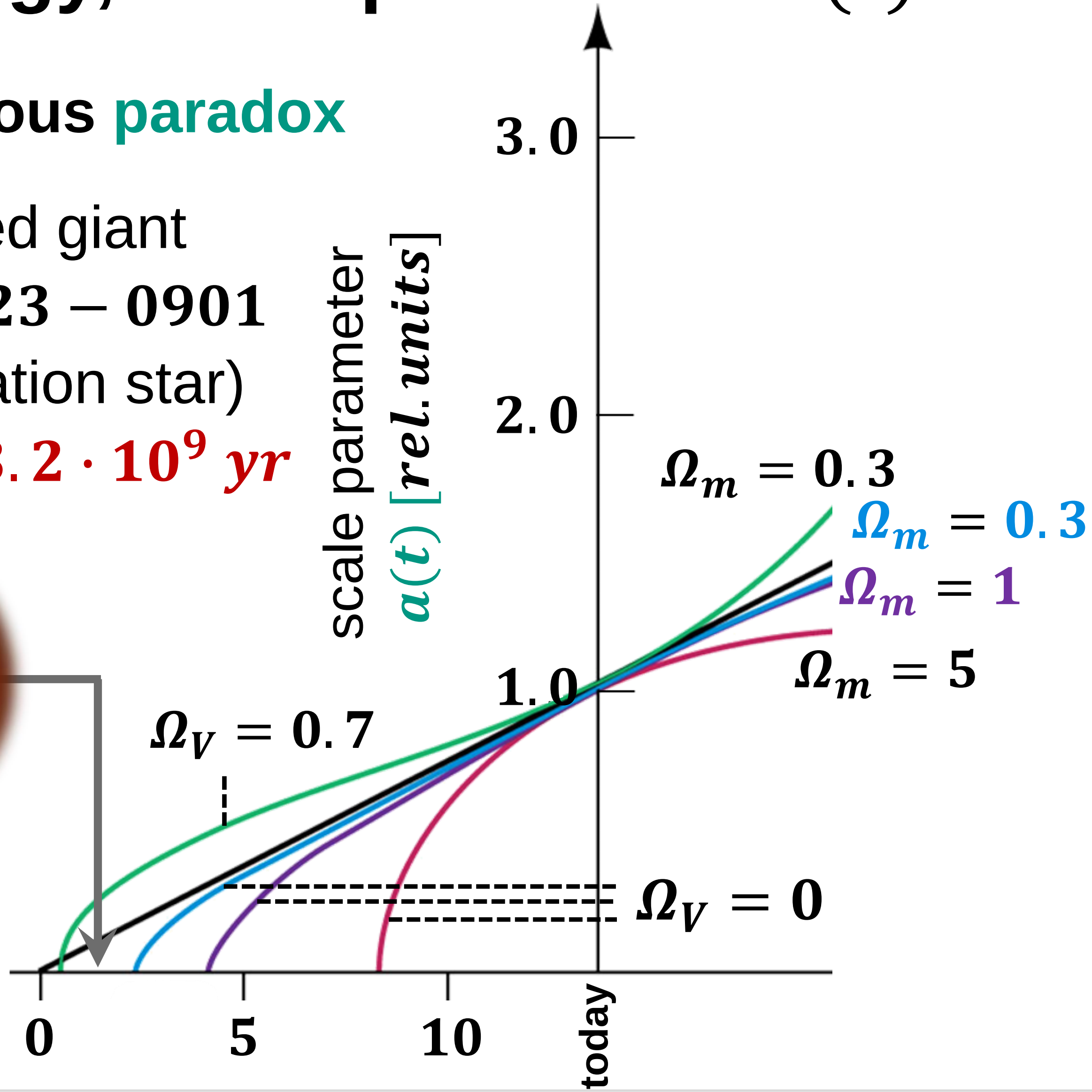
- **A famous paradox**

example: red giant star $\boldsymbol{HE\ 1523-0901}$ (2^{nd} generation star)

age: $t = 13.2 \cdot 10^9\ yr$





- a universe with $\Omega_m = 1$ (or with $\Omega_m = 0.3$) only: it would be younger than the oldest stars (age by ´nuclear clocks´)

apparently a paradox

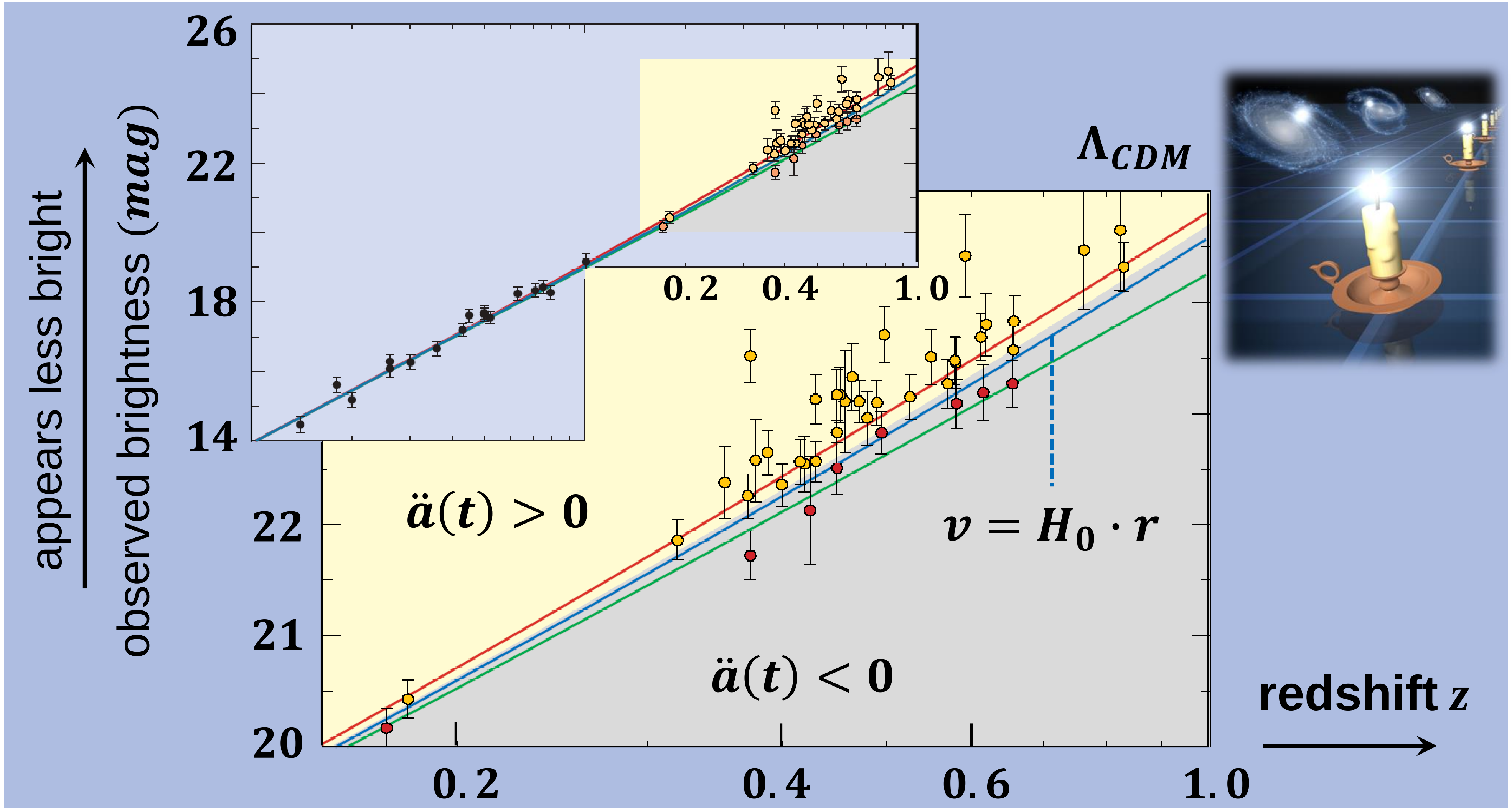
further hint for $\Lambda \neq 0$

Evidences for $\Lambda \neq 0$ & expansion with $\ddot{a}(t) > 0$

- **Observed brightness of distant $SNae$: dimmer than one expects** (thus $\Lambda \neq 0$)

Perlmutter Reiss Schmidt

Nobel prize **2011**



Evidences for $\Lambda \neq 0$ & existence of dark energy

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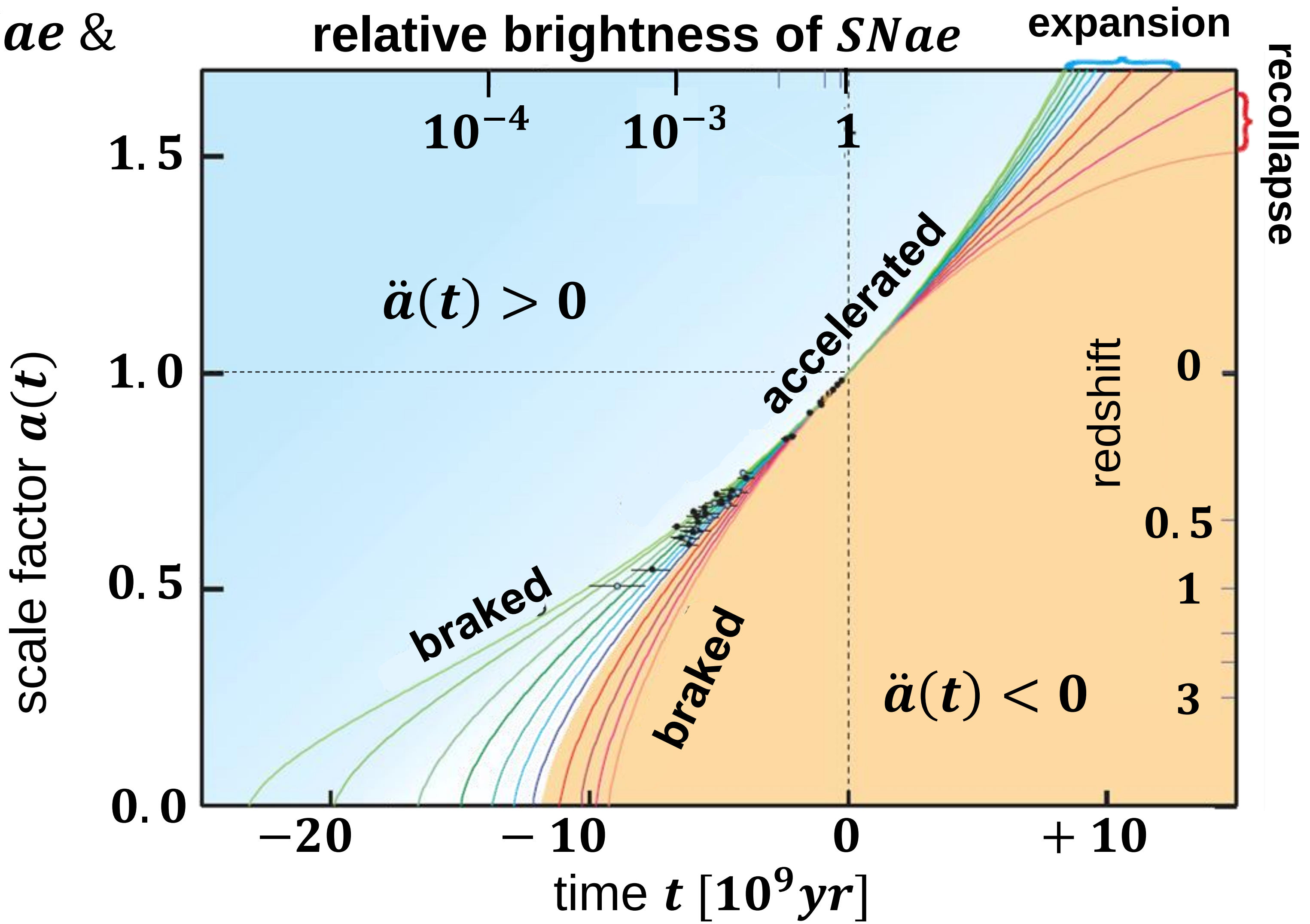
- **Observed brightness of $SNae$ & evolution of the scale parameter $a(t)$**

- $SNae\ type\ Ia$: observed up to large **redshifts $z = 1$** [$a(t) \sim 0.5$] via precision spectroscopy of atomic lines

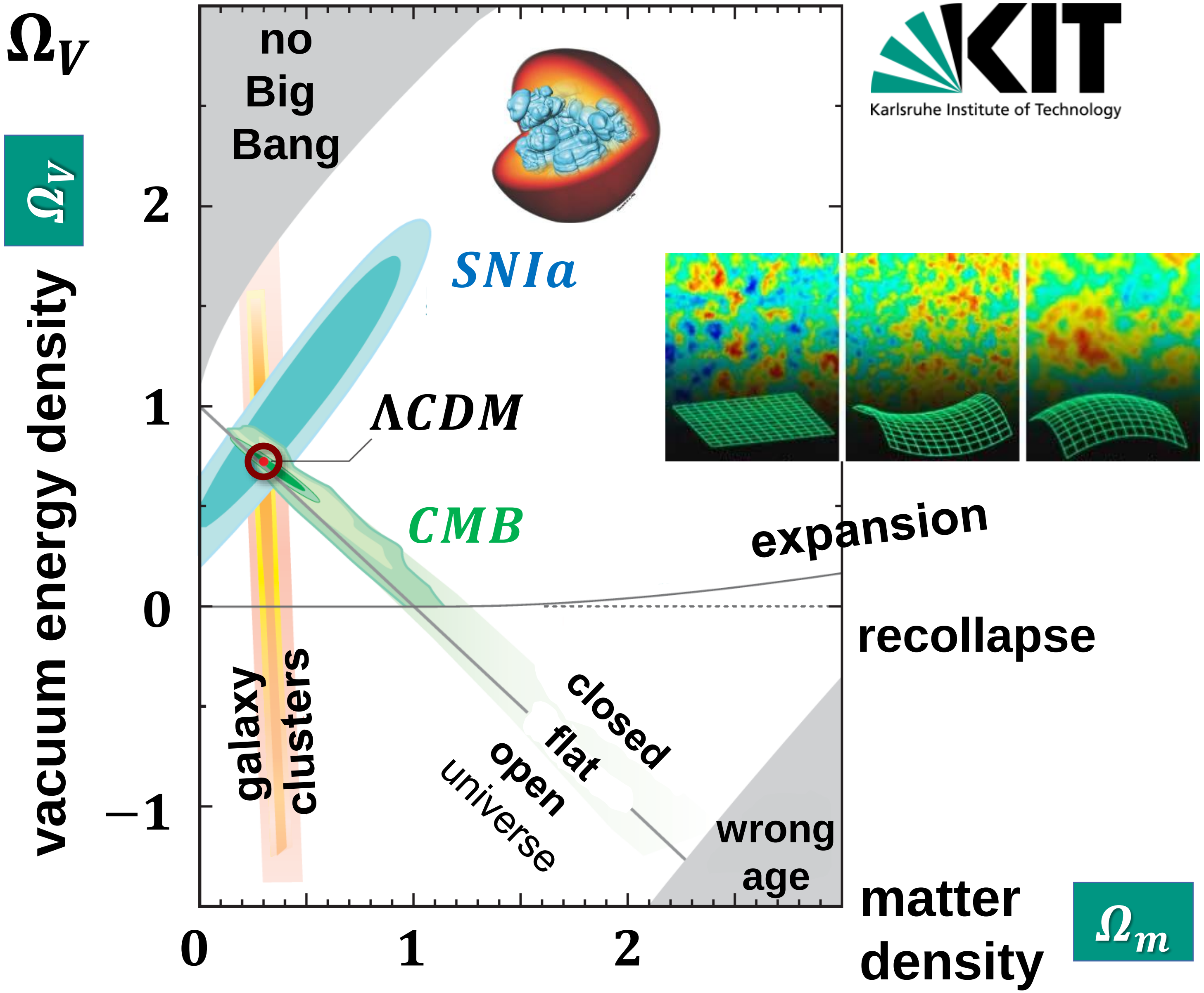
- comparison of the absolute SN – brightness M with apparent brightness m
  ⇨ distance modulus $m - M$
  ⇨ sensitivity to SN – distance r



Global data set for Ω_m & Ω_V

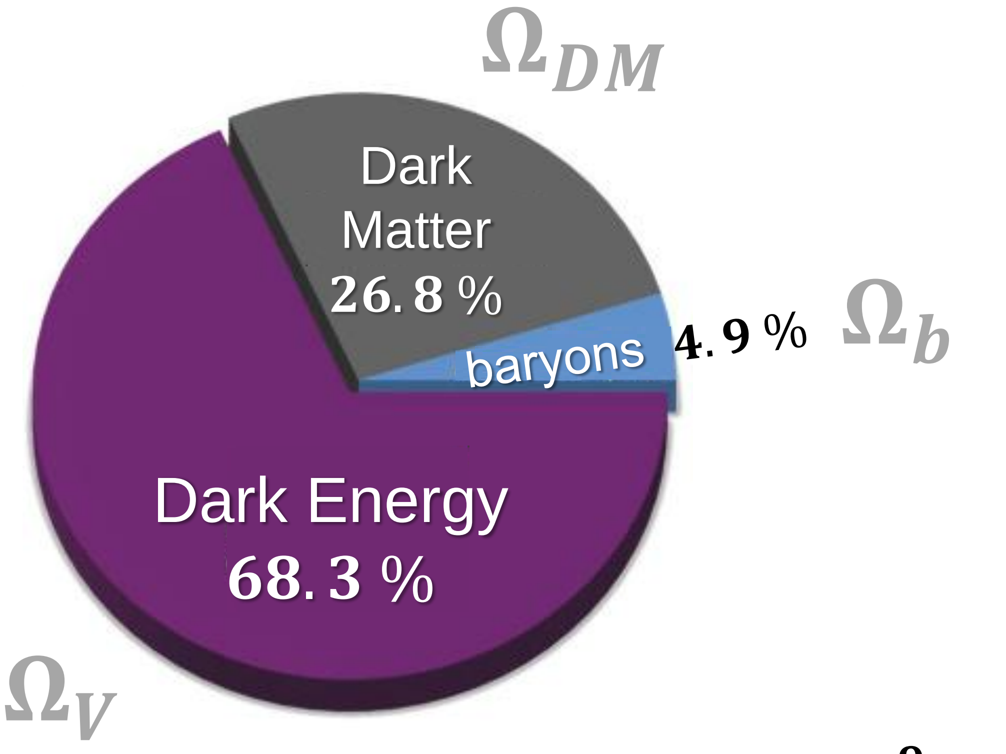
■ **Actual best fit values**

- **combining** data sets using:
  - $SNIa$ brightness data
  - CMB analyses
  - galaxy clusters
- ´**orthogonal**´ methods:
  - CMB analyses $(3\ K)$: sensitive to $\Omega_{tot} = \Omega_V + \Omega_m$
  - $SNae$ – brightness: sensitive to value $\Omega_V - \Omega_m$

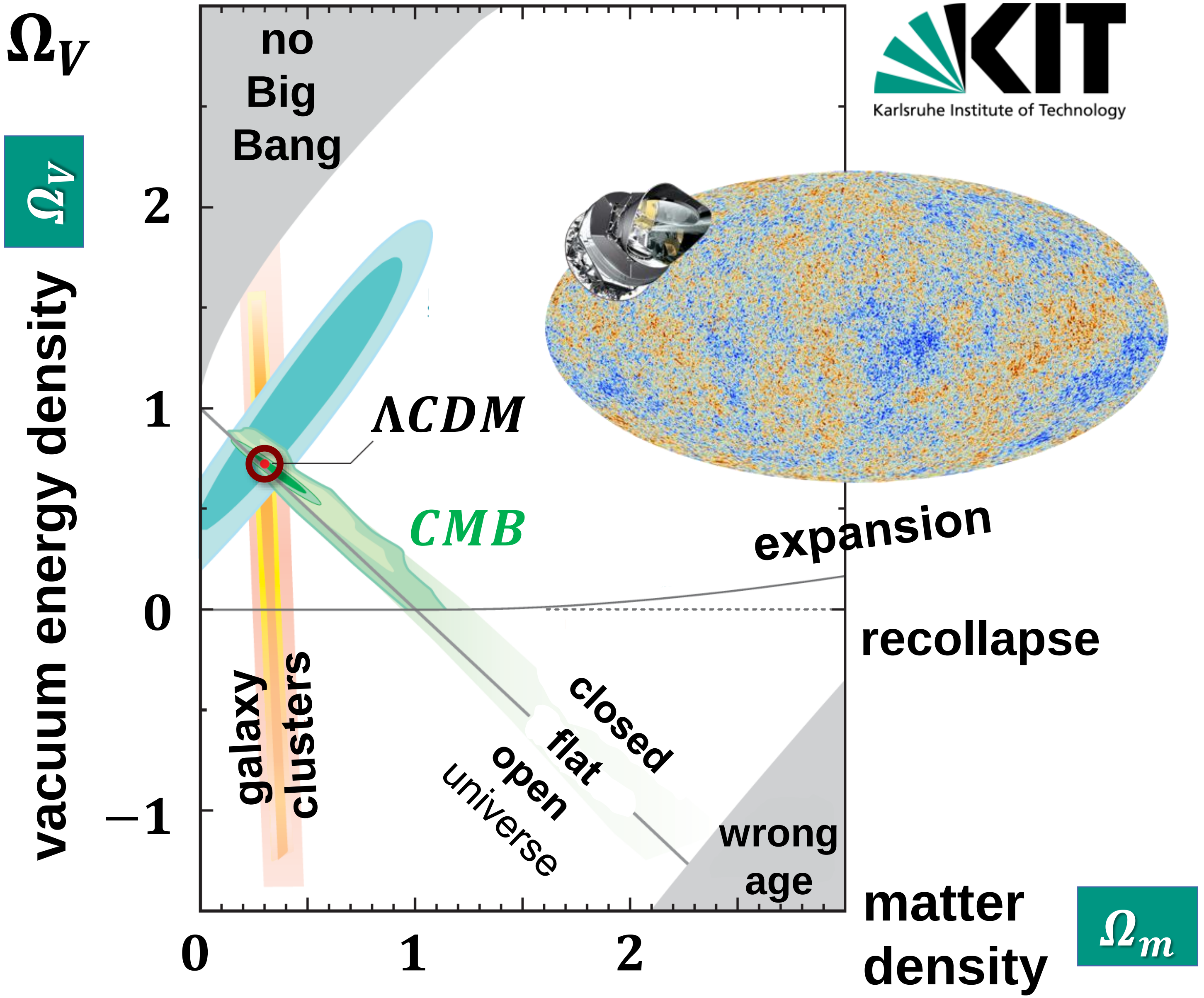


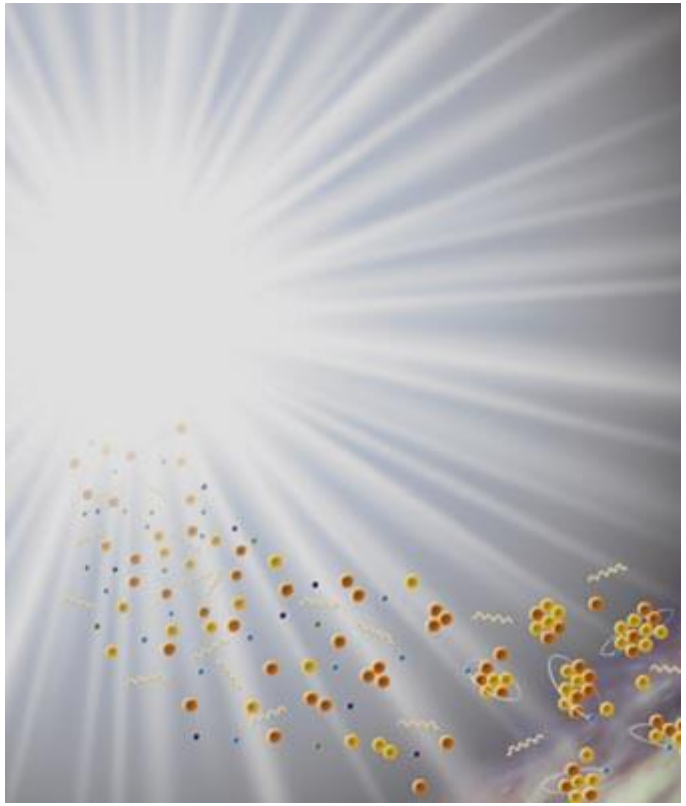
Global data set for Ω_m & Ω_V

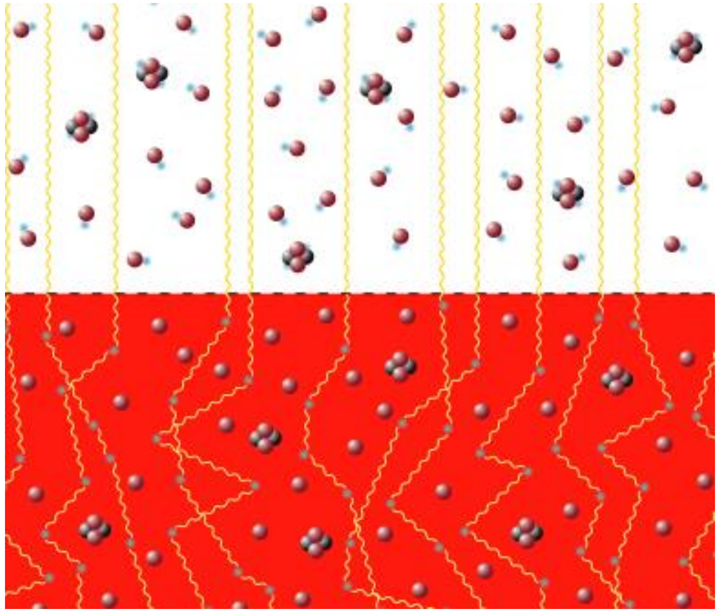
- ΛCDM concordance model of cosmology

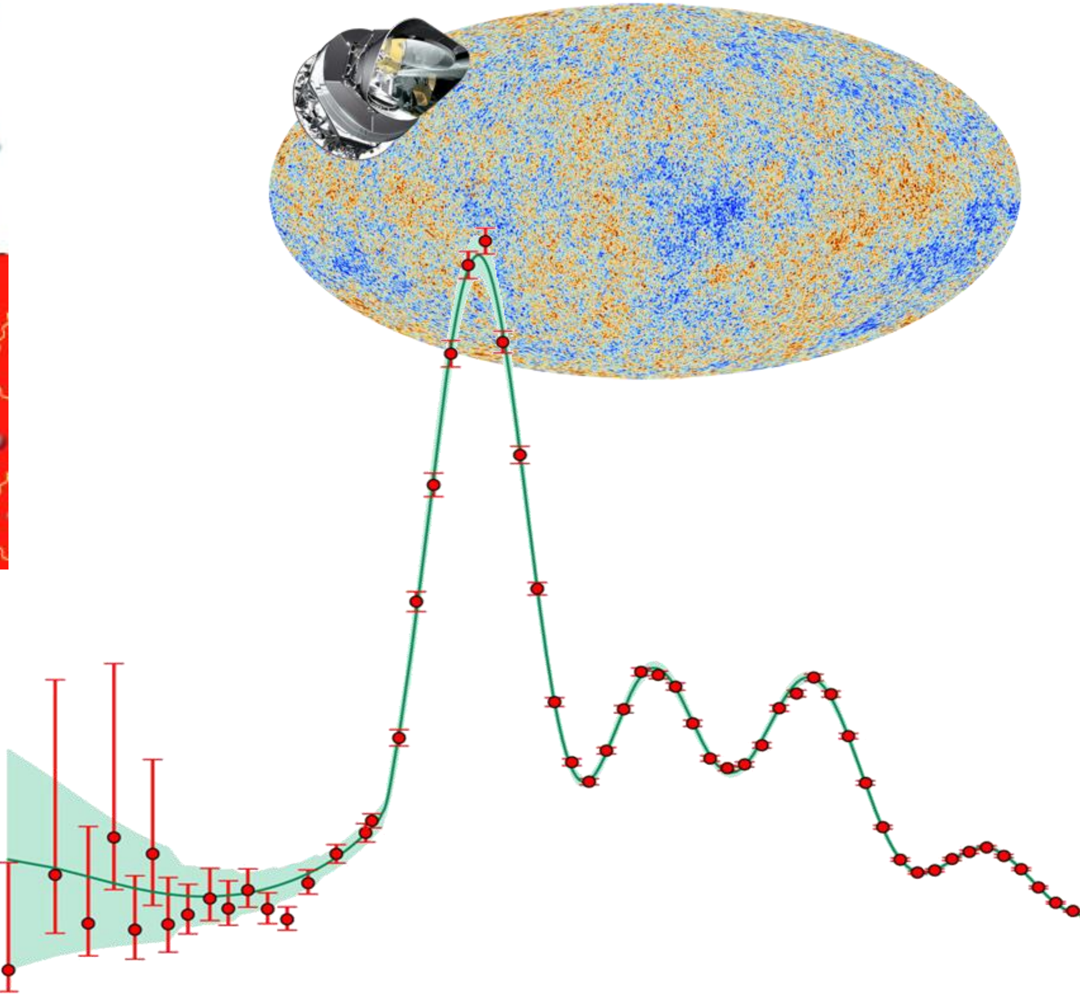


$T_0 = 13.73 \cdot 10^9 yr$









CHAPTER 3 – THERMAL UNIVERSE

Overview: thermal history of the universe

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- **An expanding universe necessarily is cooling down**

- shortly after Big Bang:

$$t \sim 10^{-36}\ s$$

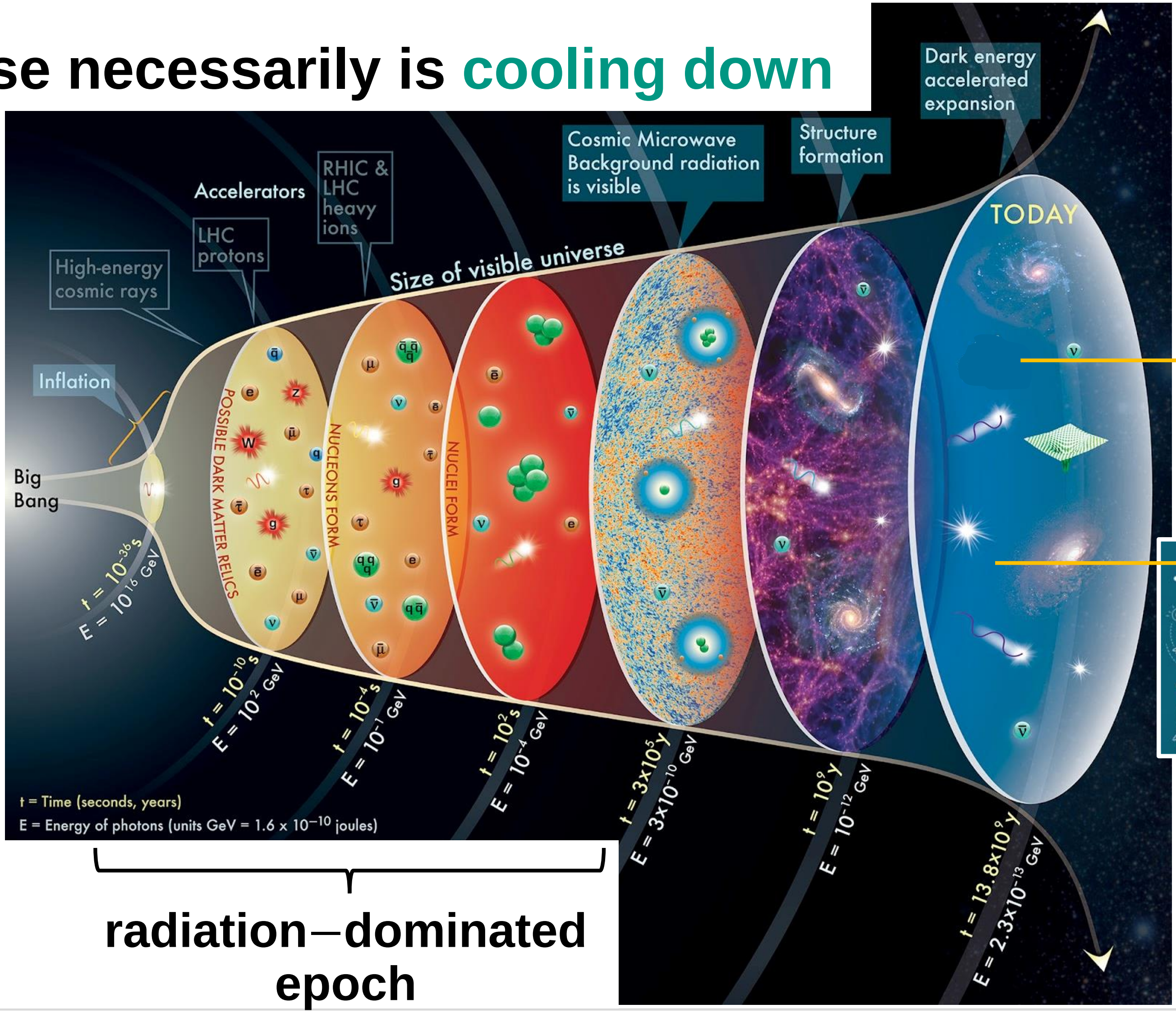
$$T \sim 10^{25}\ eV$$

- present universe:

$$t \sim 13.8 \cdot 10^{9}\ yr$$

$$T \sim 10^{-3}\ eV$$

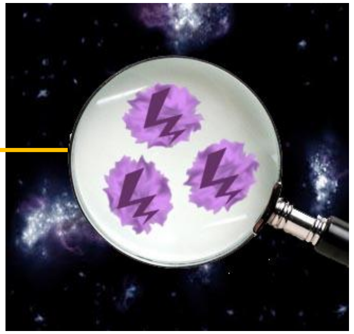
- here: focus on ***radiation–dominated universe***, up to $t \sim 47\,000\ yr$



radiation–dominated epoch

Λ

Dark Energy



Dark Matter

CDM

Q: LBL/PDG

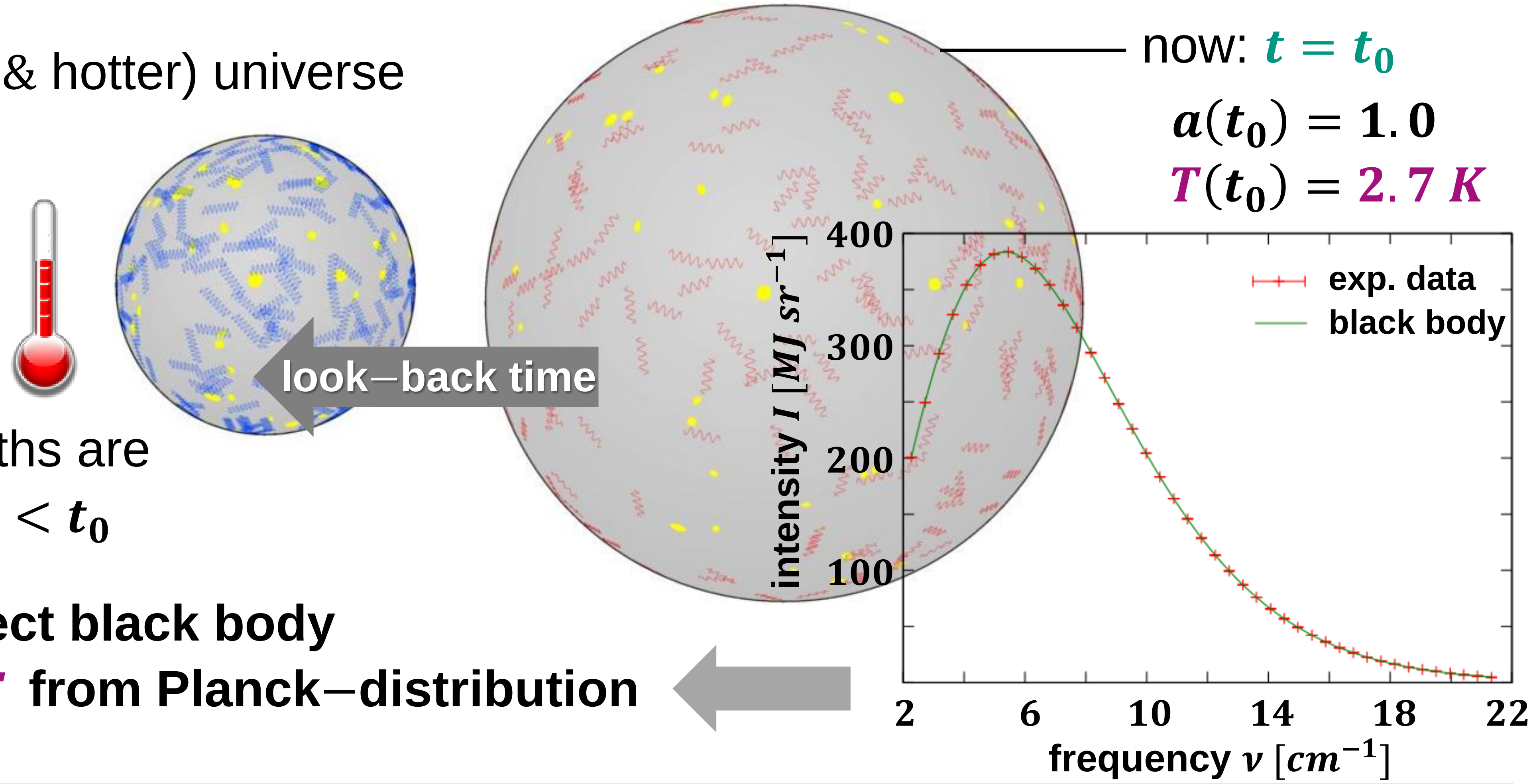
Evolution of temperature T in expanding cosmos

- **What is the relation between the scale factor $a(t)$ & temperature T ?**

earlier (smaller & hotter) universe

$a(t_1) = 0.5$

$T(t_1) = \ ?$



- photon wavelengths are blue–shifted for $t < t_0$

- **universe ≡ perfect black body**
  ⇨ **temperature T from Planck–distribution**

Evolution of temperature T in expanding cosmos

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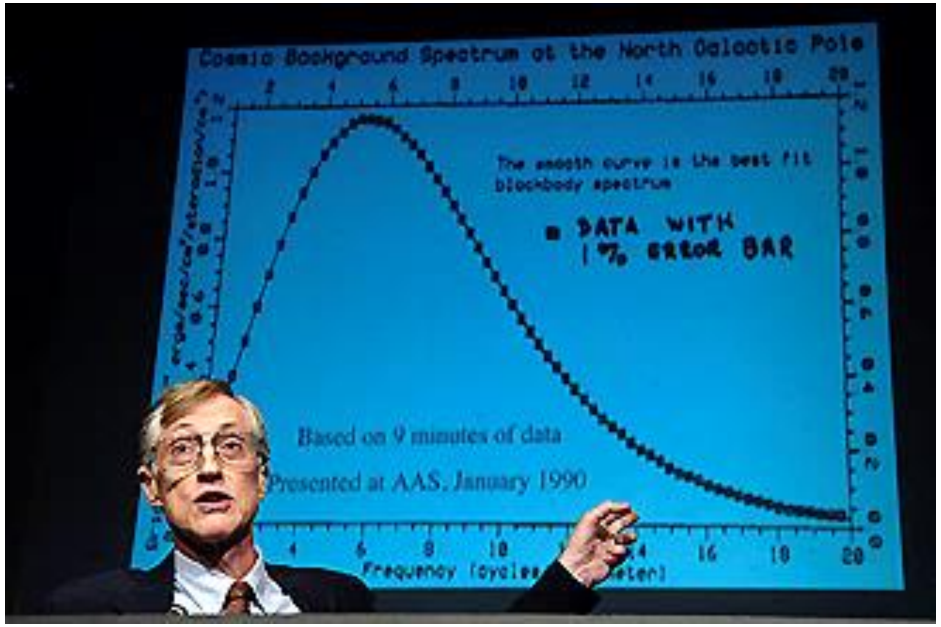
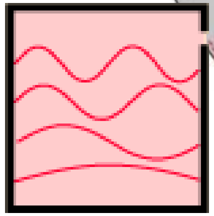
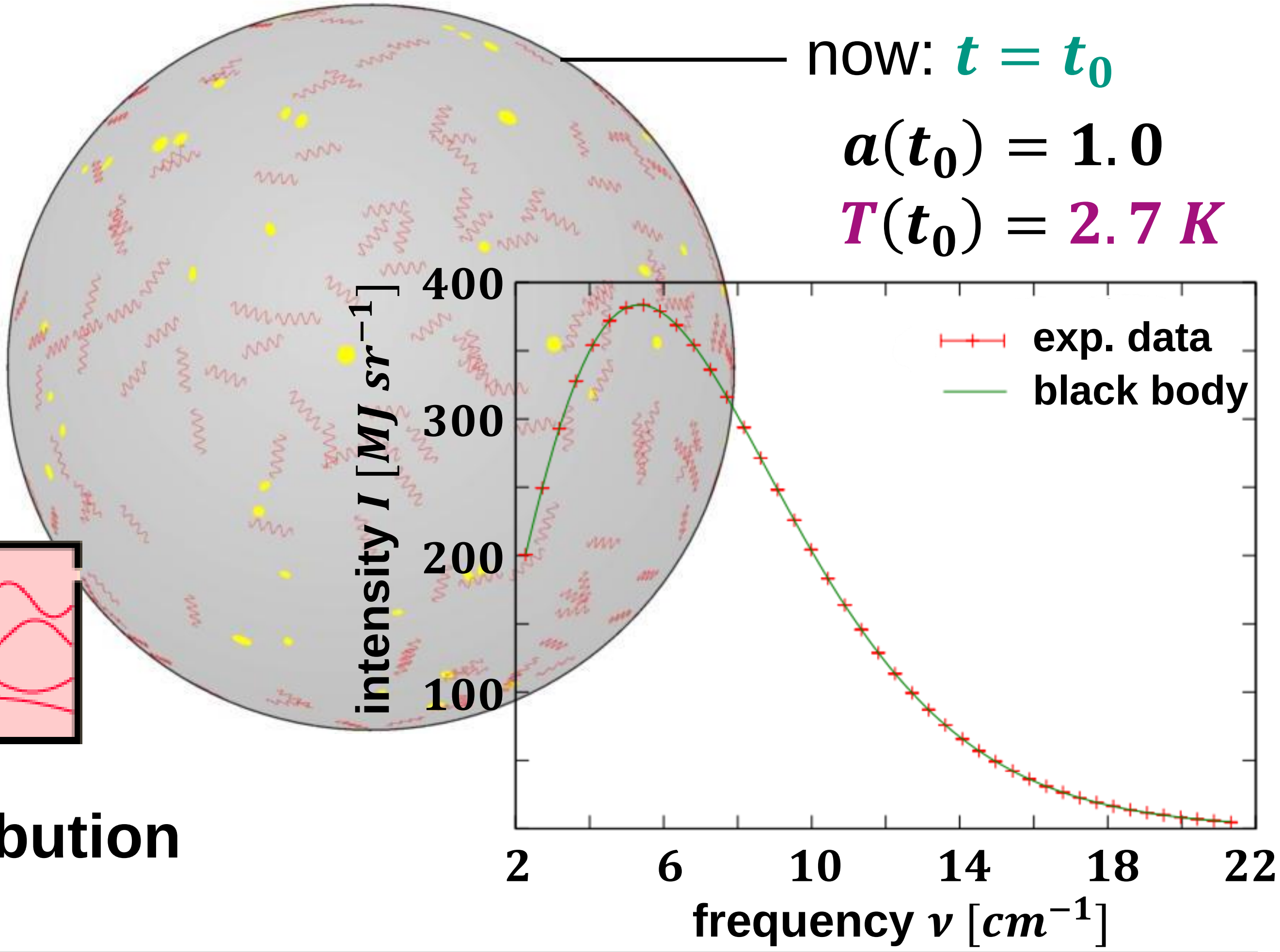
- **What is the relation between the scale factor $a(t)$ & temperature T ?**

Q: NASA







- universe ≡ perfect black body

⇨ temperature T from Planck–distribution

Evolution of temperature T: Wien´s law

■ **Wien´s displacement law and the Cosmic Microwave Background (CMB)**

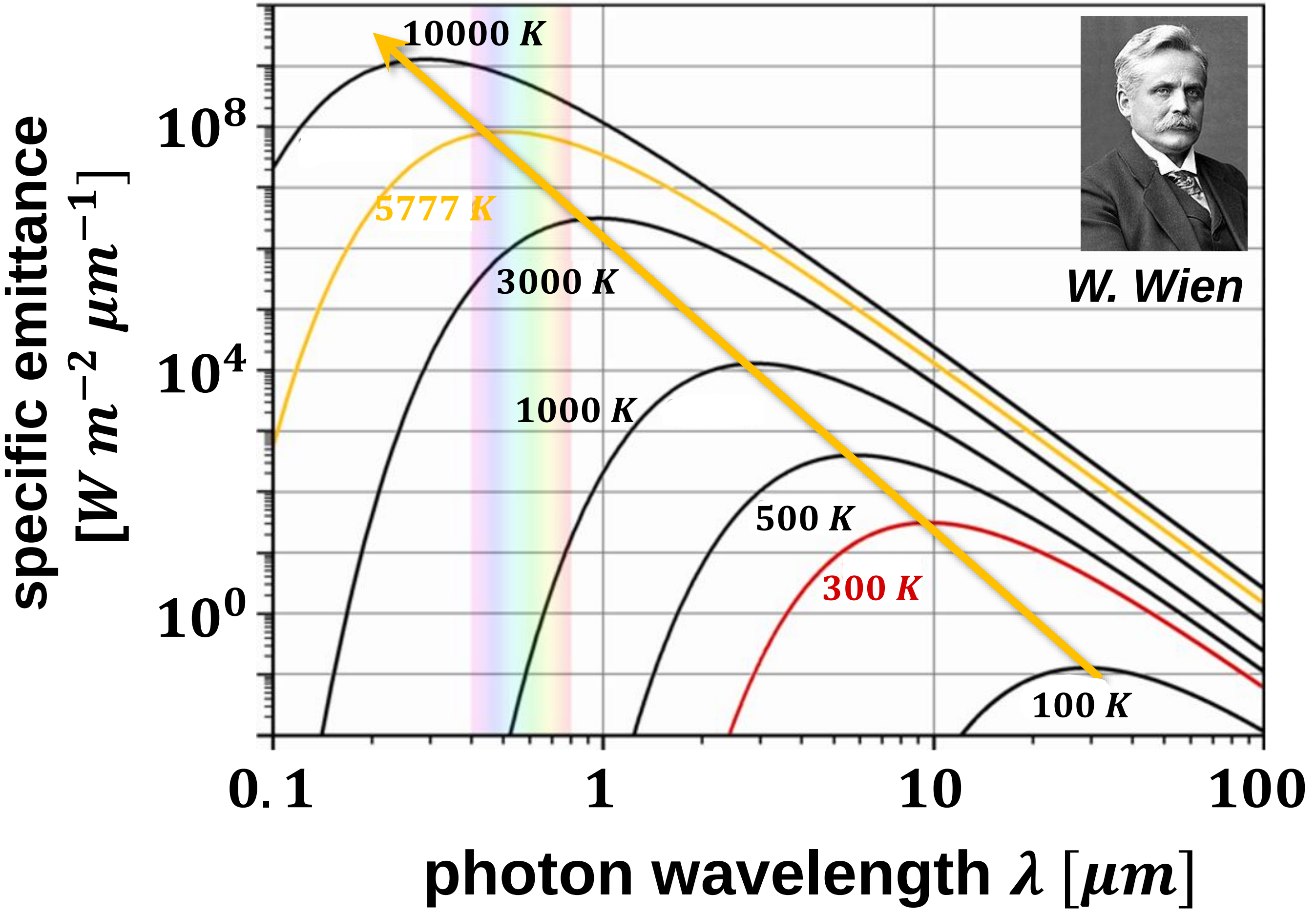
- relation between **temperature** T & **maximum emittance** λ_{max} of a thermal radiation bath (Planck)

$$\lambda_{max} \cdot T = 2.8978\, mm\, K$$

- adiabatic expansion of cosmos (z) & CMB – photons of **frequency** ν

$$T_\gamma(z) = T_\gamma\,(z = 0) \cdot (1 + z)$$

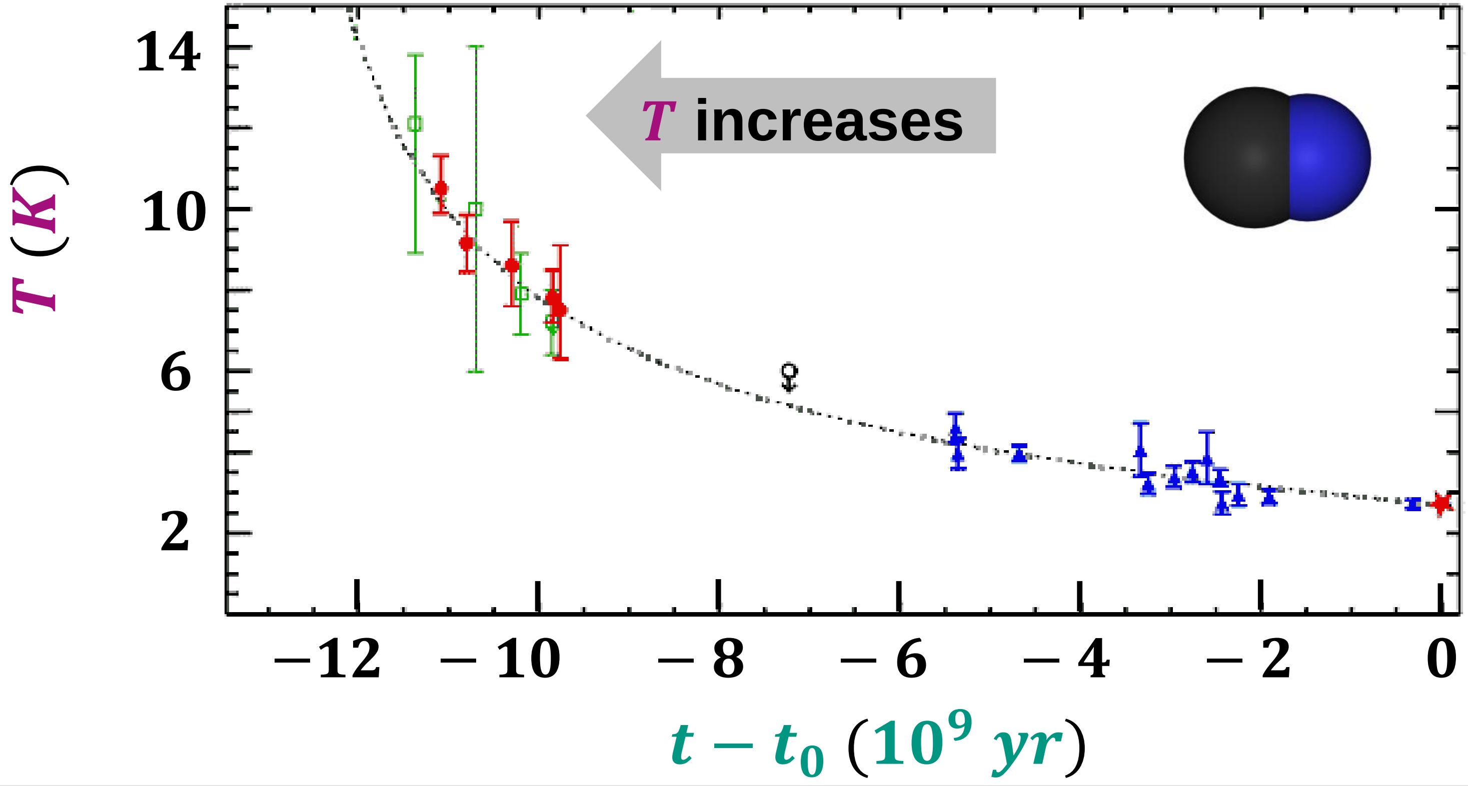
$$h\nu(z) = h\nu(z = 0) \cdot (1 + z)$$

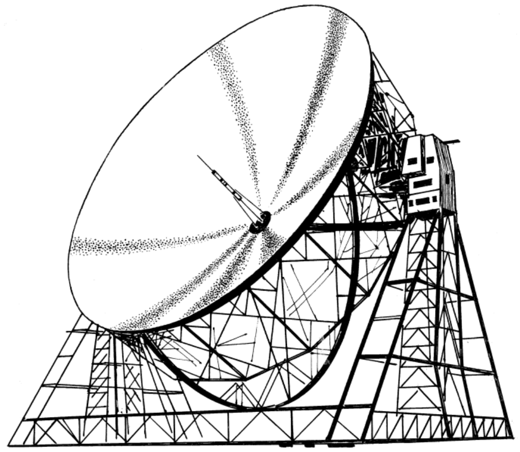


Evolution of temperature T: experimental data

- **Observational evidence for an increase in temperature T at earlier times t**

  - effect: **thermal excitation of Cyan (CN) molecules** due the early, much hotter **CMB radiation** (⇨ more intense molecular excitation)

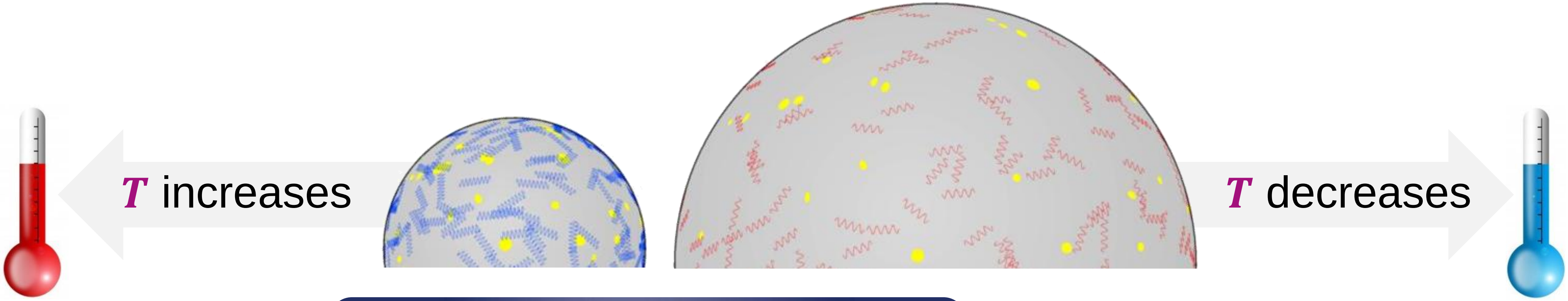




radio−astronomical observations of $T(t)$ using distant CN clouds

Evolution of temperature T & energy conservation

- **A cornerstone of cosmology: adiabatic expansion process**



A. Einstein

adiabatic cosmological expansion

J. Stefan

L. Boltzmann

Evolution of temperature T as function of t & $a(t)$

- **Connecting two descriptions: photon bath & thermodynamical ensemble**

time t

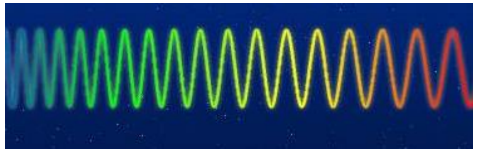
$$\rho_\gamma(t) = N_\gamma(t) \cdot E_\gamma(t)$$

temperature T

$$\rho_\gamma(T) = \frac{\pi^2}{15\, h^3 c^3} \cdot (k_B \cdot T)^4$$

A. Einstein

photon bath: photons are elementary particles



ensemble: photons act as thermodynamical ensemble

J. Stefan

L. Boltzmann

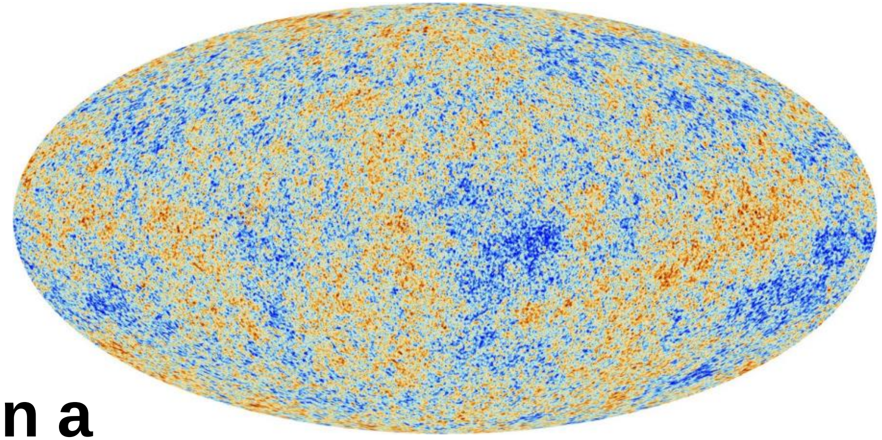
Evolution of temperature T as function of t & $a(t)$

- **Connecting two descriptions: photon bath & thermodynamical ensemble**

$$\rho_\gamma(t) = N_\gamma(0) \cdot a(t)^{-3} \cdot E_\gamma(0) \cdot a(t)^{-1}$$

$$\rho_\gamma(t) \sim a(t)^{-4} \quad \Longleftrightarrow \quad \rho_\gamma(T) \sim T(t)^4$$

$$T(t) \sim \frac{1}{a(t)} \sim \frac{1}{\sqrt{t}}$$



evolution of temperature T in a radiation–dominated universe

Properties of the radiation−dominated universe

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■ **Temperature scale $T(t)$ and energy scale $E(t)$ of CMB photons**

- important **conversion factor**:

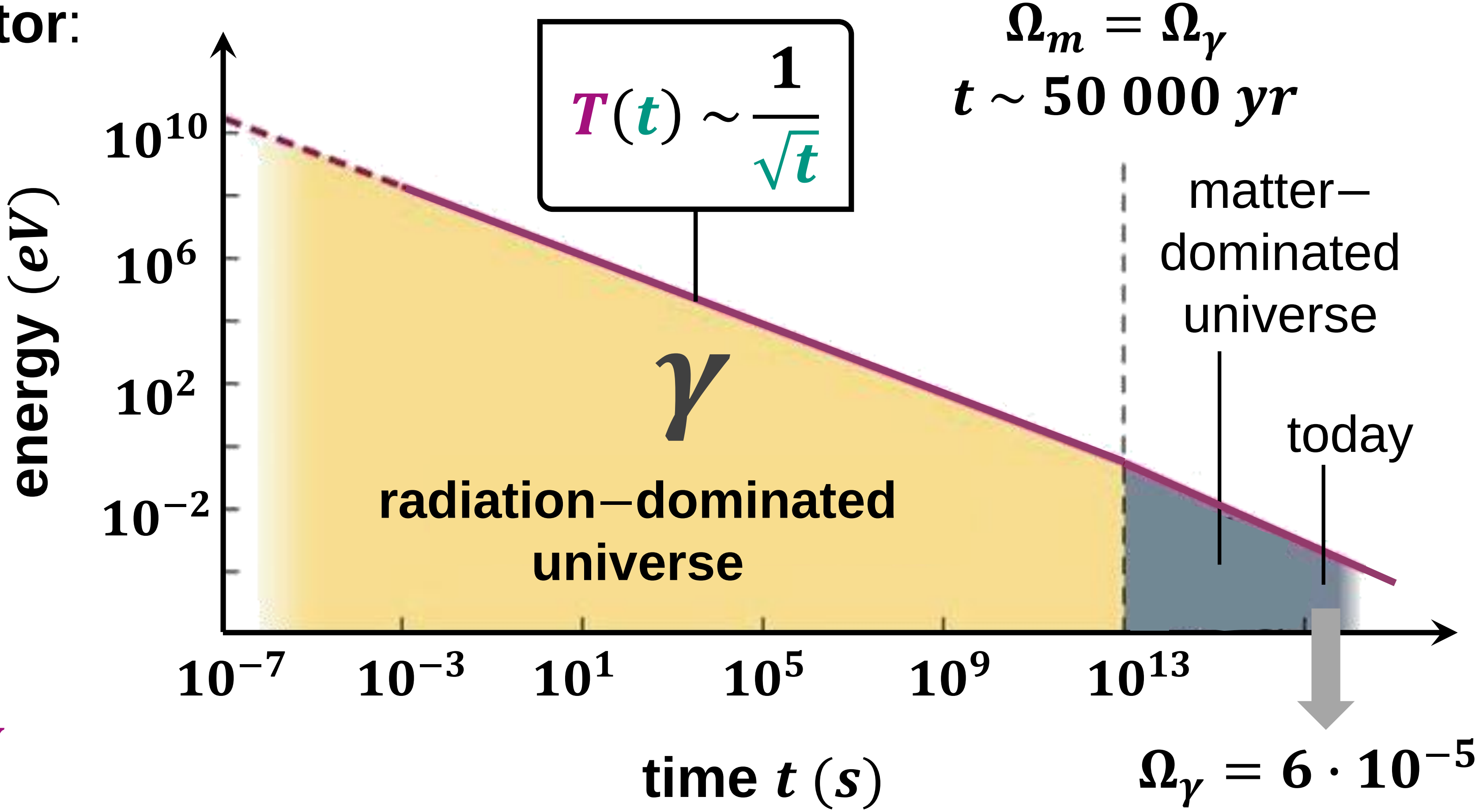
$$10^4\ K \leftrightarrow 1\ eV$$

$(11\,605\ K)$

$$T(t) \cong \sim \frac{10^{10} K}{\sqrt{t\ [s]}}$$

$$\cong \sim \frac{1\ MeV}{\sqrt{t\ [s]}}$$

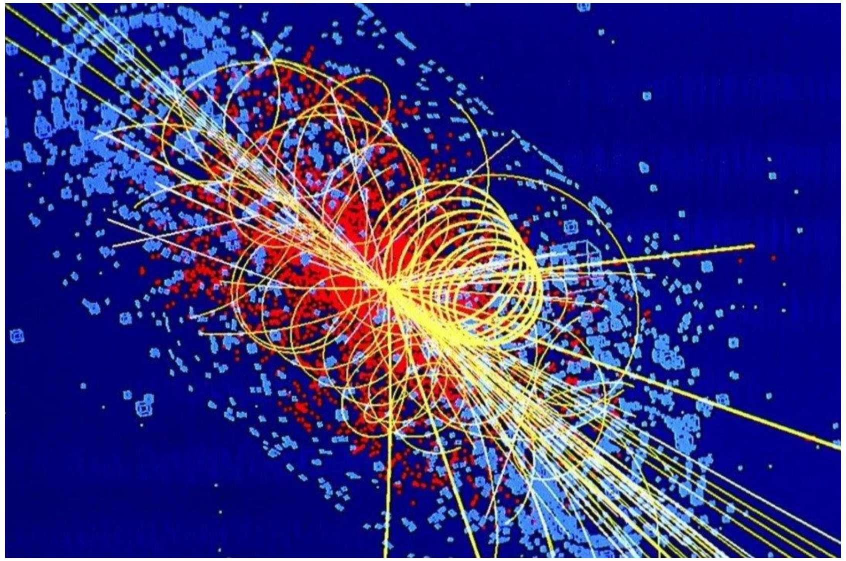
at $t = 1\ s \leftrightarrow T = 1\ MeV$

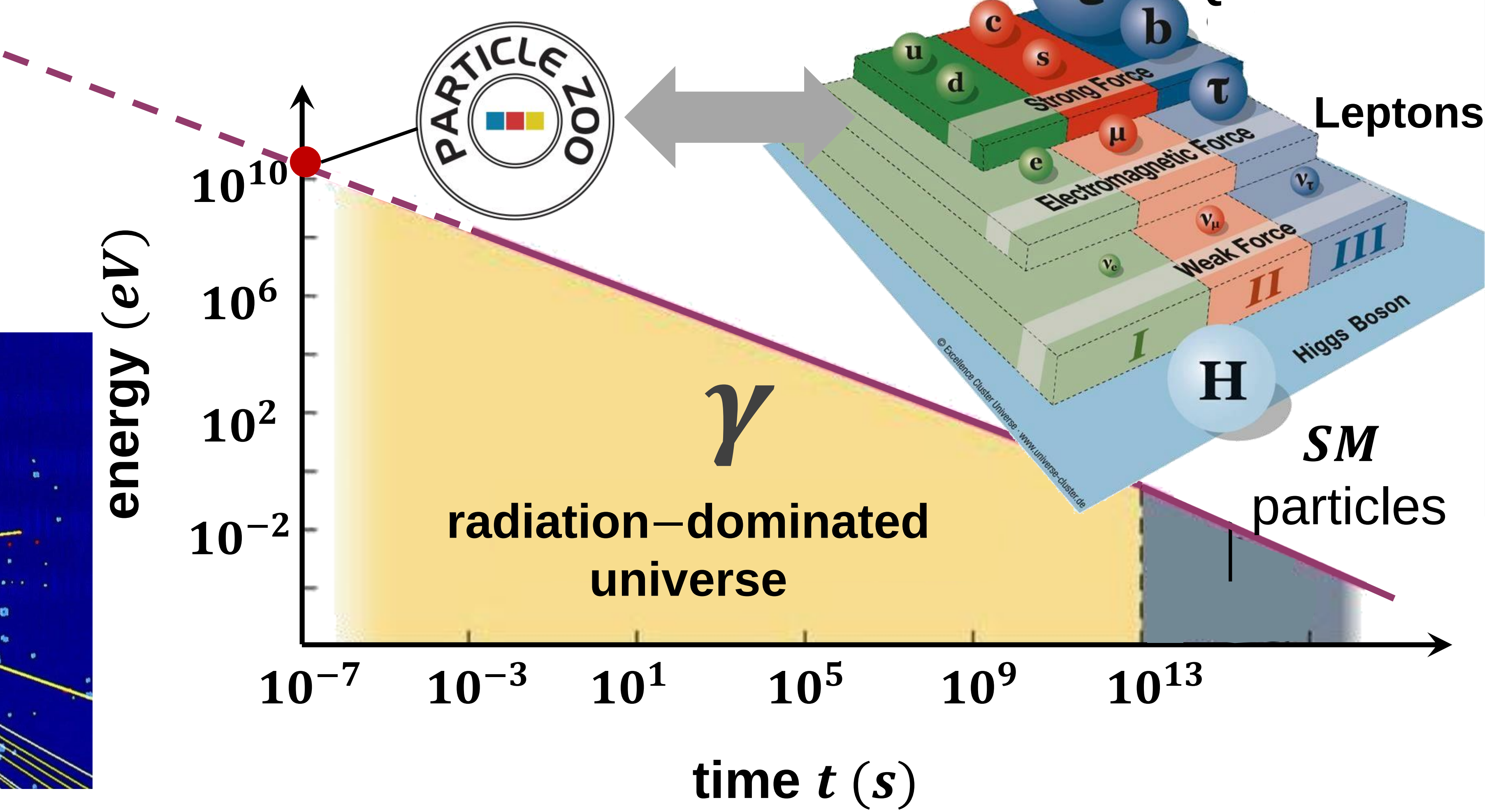


Thermal production of the ´Particle Zoo´

- **Big Bang: Particle production due to thermal processes**

\- **heat bath**:
particle interactions
via strong & electro–
weak interactions



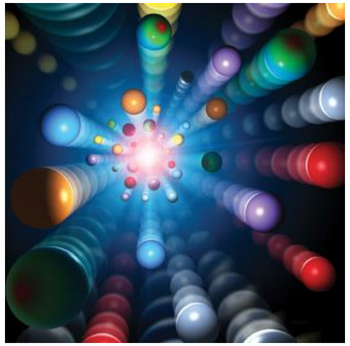


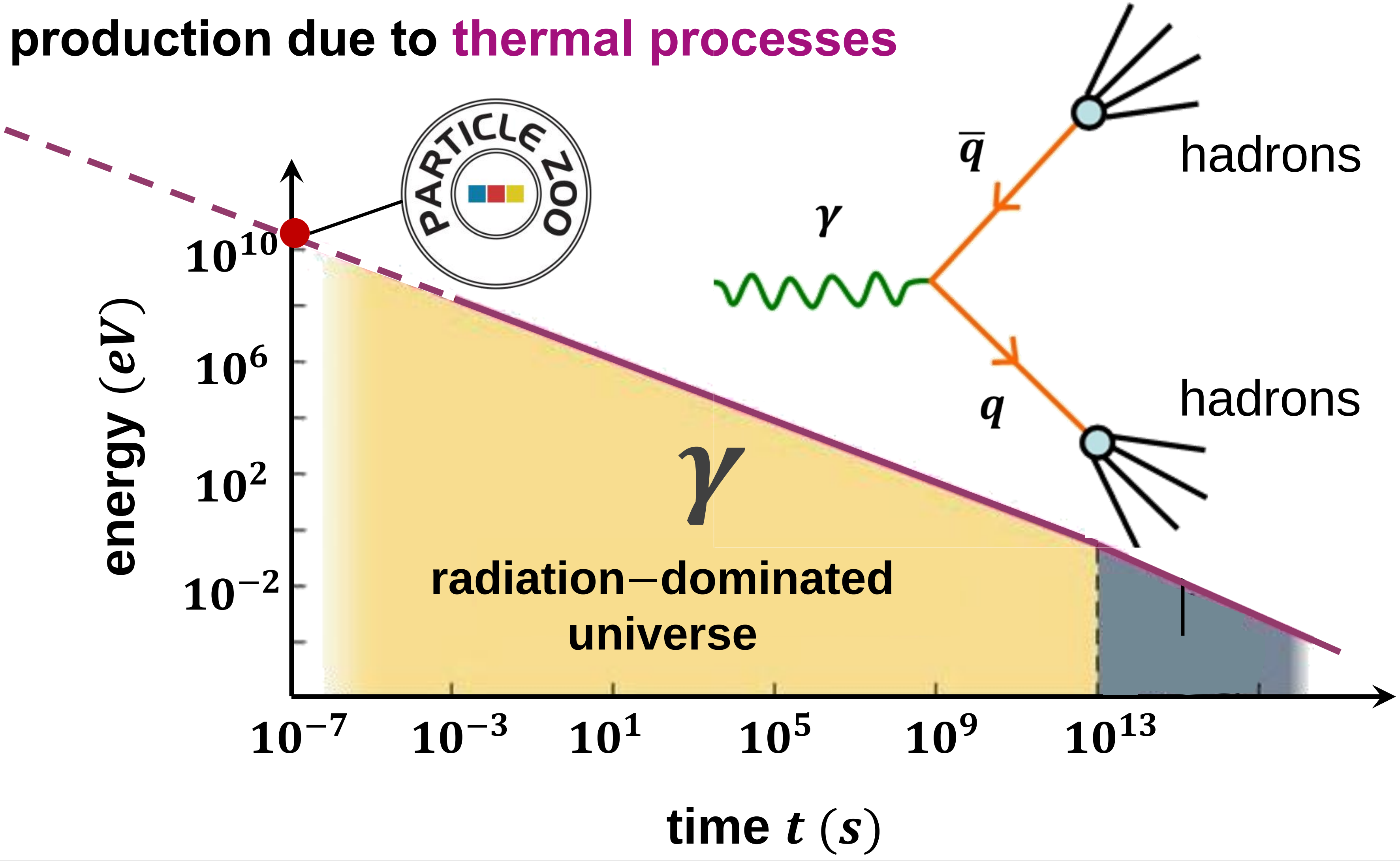
Thermal production of the ´Particle Zoo´

- **Big Bang: Particle production due to thermal processes**

- **heat bath**:
  particle interactions via strong & electro–weak interactions

- **thermal production**
- annihilation
- decay





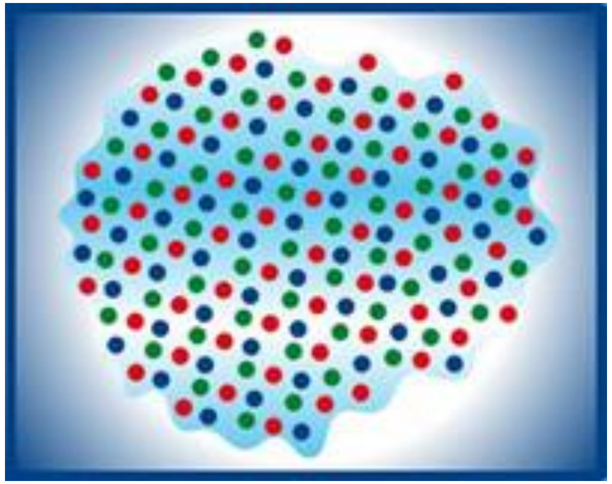
Radiation–dominated universe: Particle Zoo

- **Particle production during the Big Bang**

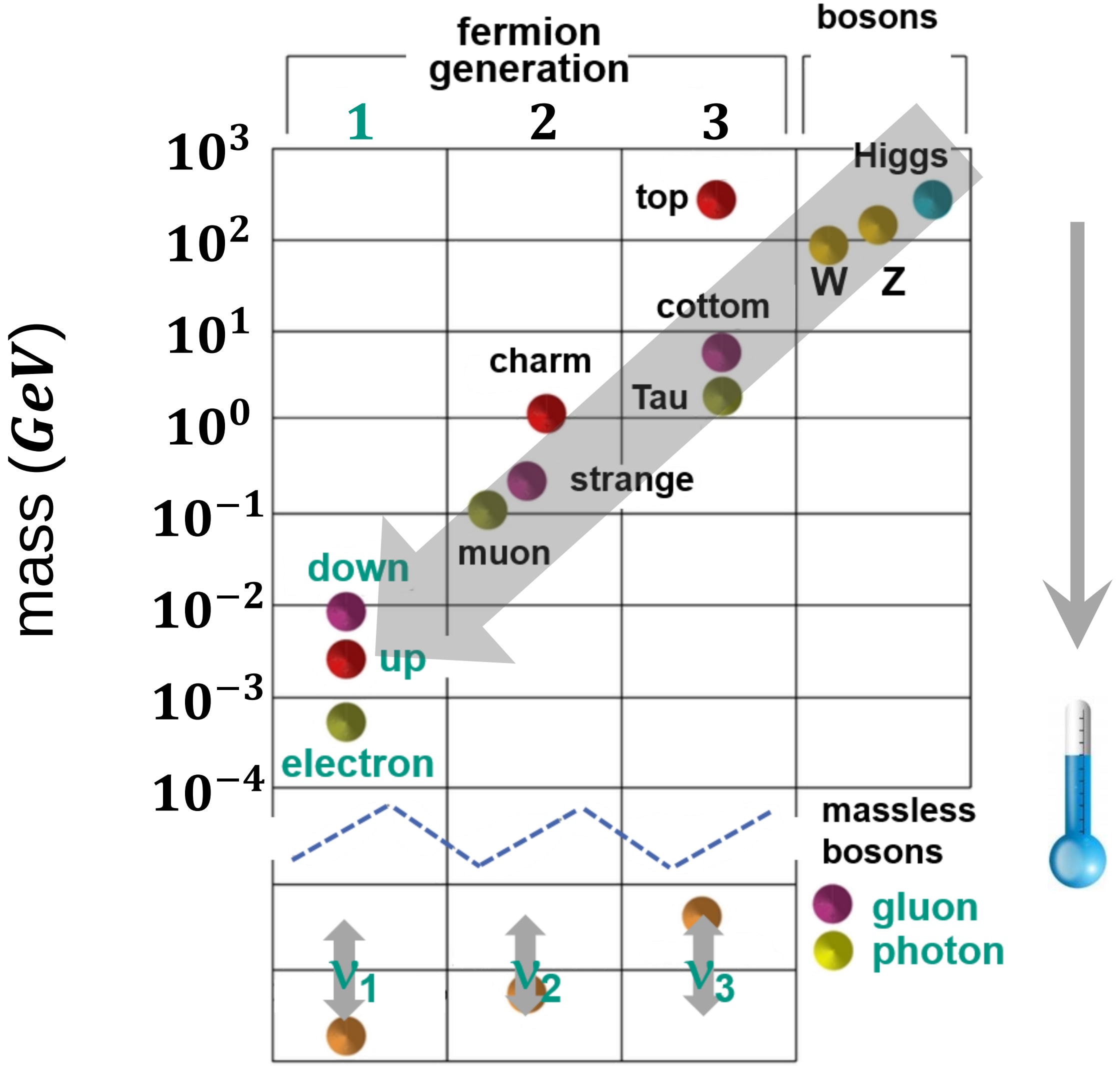
Leptons:

$e^+ \quad e^- \quad \nu_{e,\mu,\tau} \quad \bar{\nu}_{e,\mu,\tau}$

Quarks: $u \quad \bar{u} \quad d \quad \bar{d}$



Quark-Gluon plasma



Production of particles & phase transitions

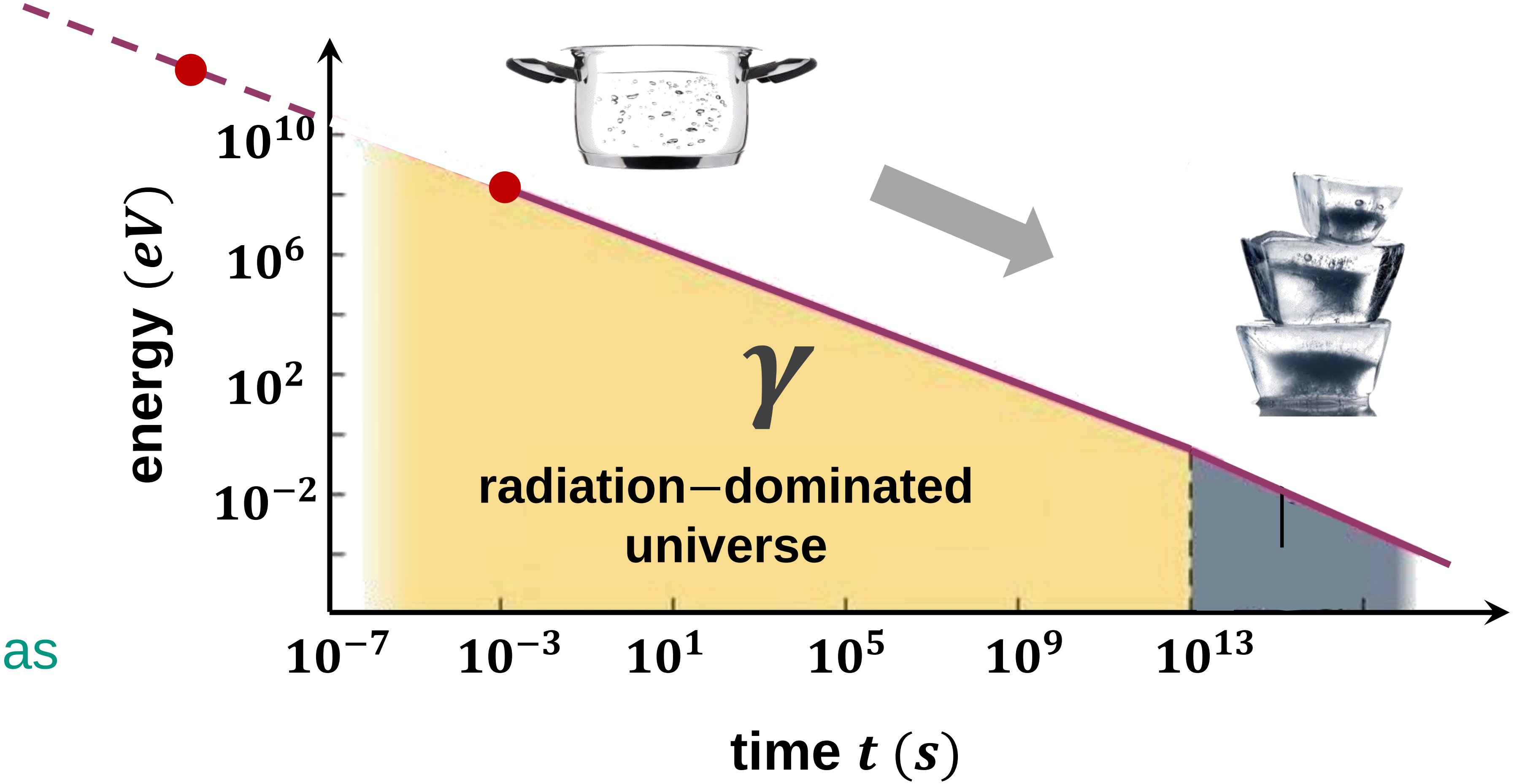
- **During expansion & cooling of universe:** phase transitions

  - many examples:

    Higgs mechanism

    QCD transition

    plasma to atomic gas

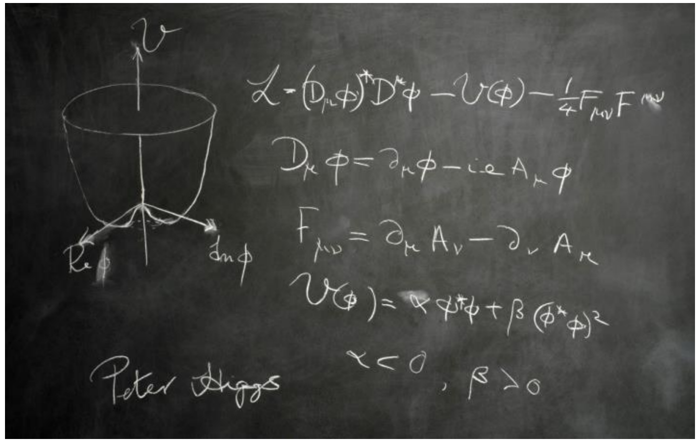


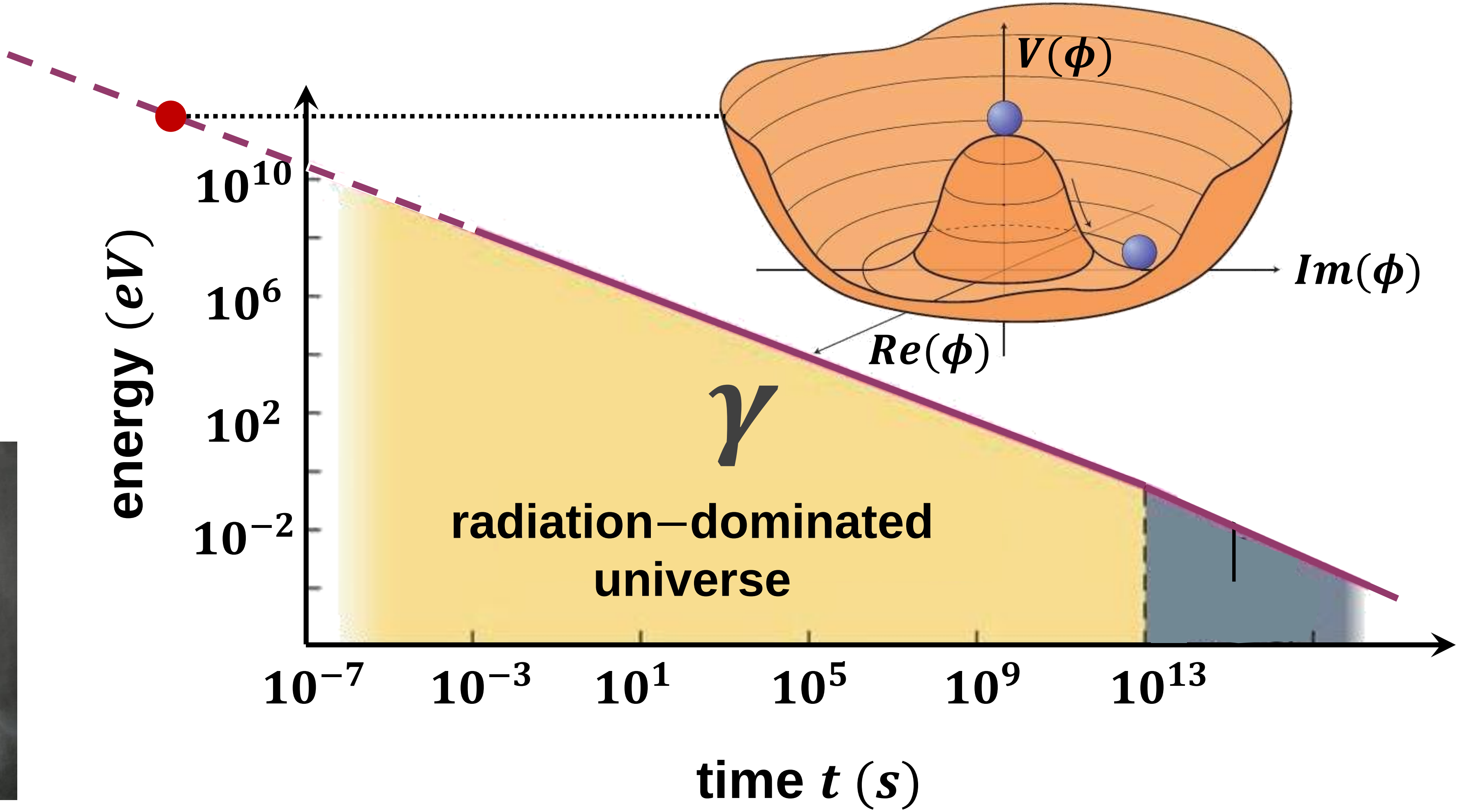
Production of particles & phase transitions

■ **During expansion & cooling of universe: electroweak phase transition**

- example:

Higgs mechanism





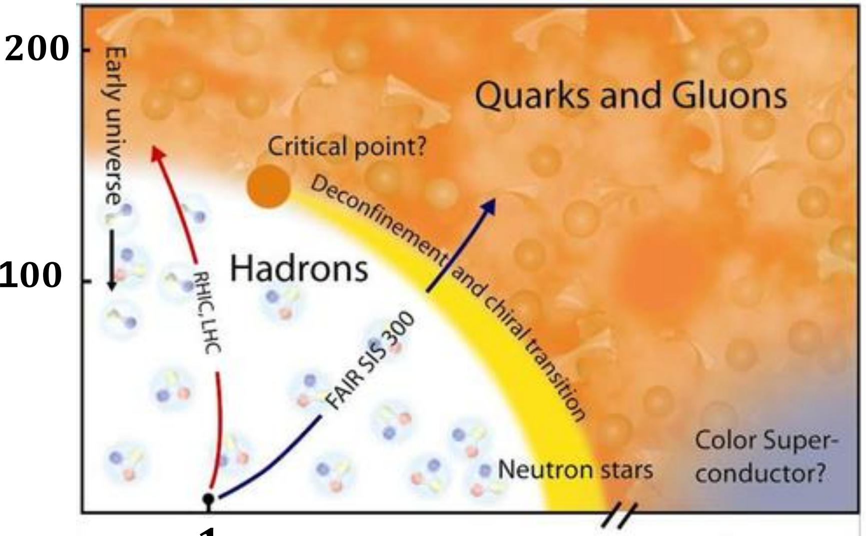
Production of particles & phase transitions

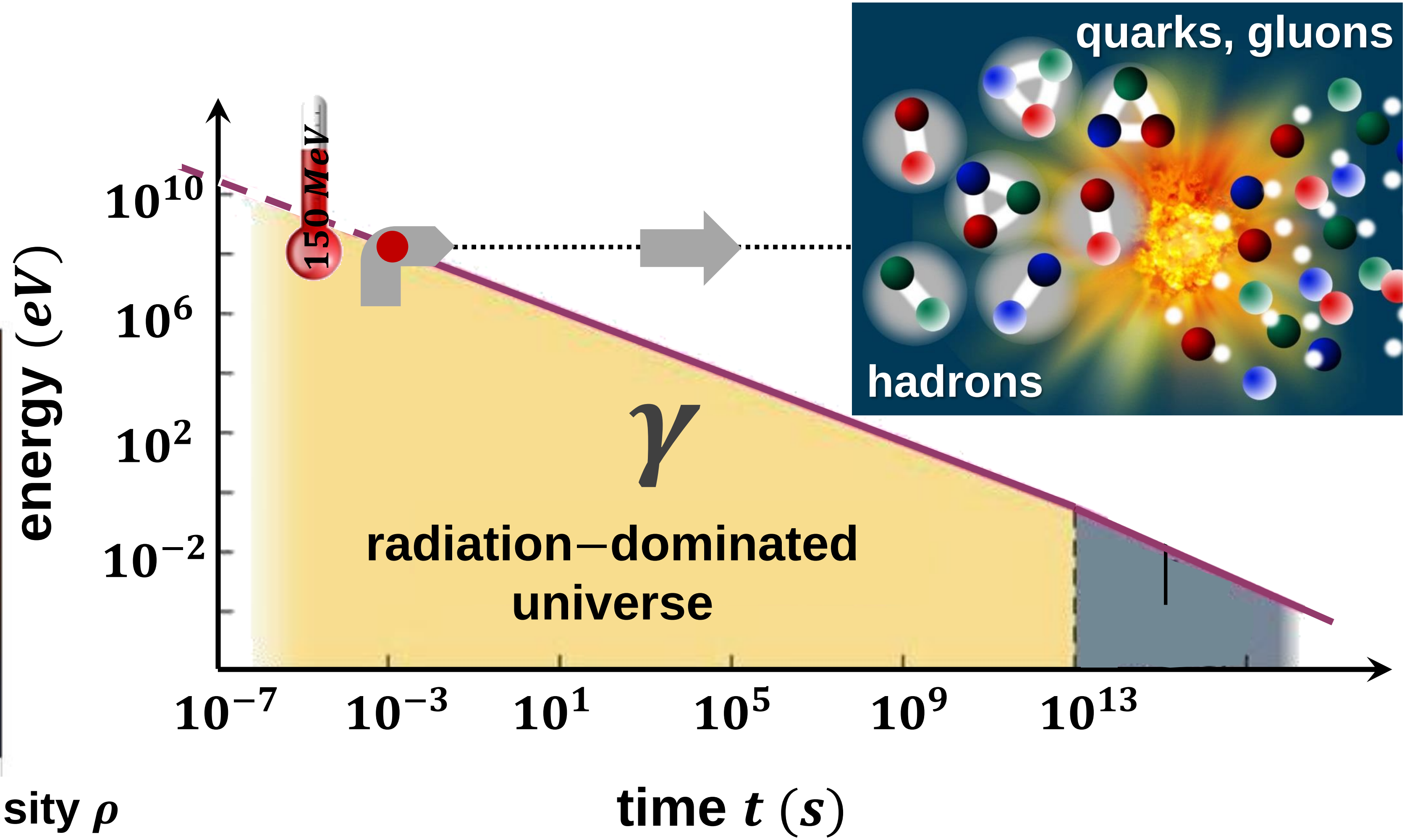
- **During expansion & cooling of universe: QCD phase transition**

  - example:

    QCD at $T = 150\ MeV$:

    quarks ⇒ hadrons

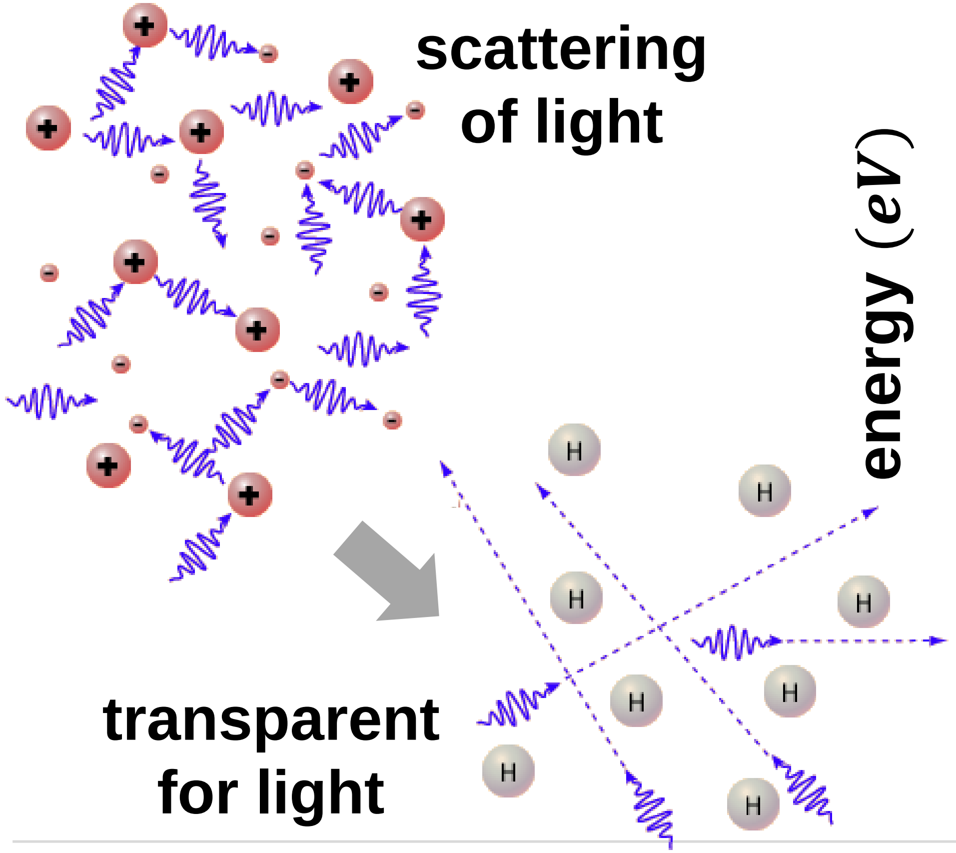


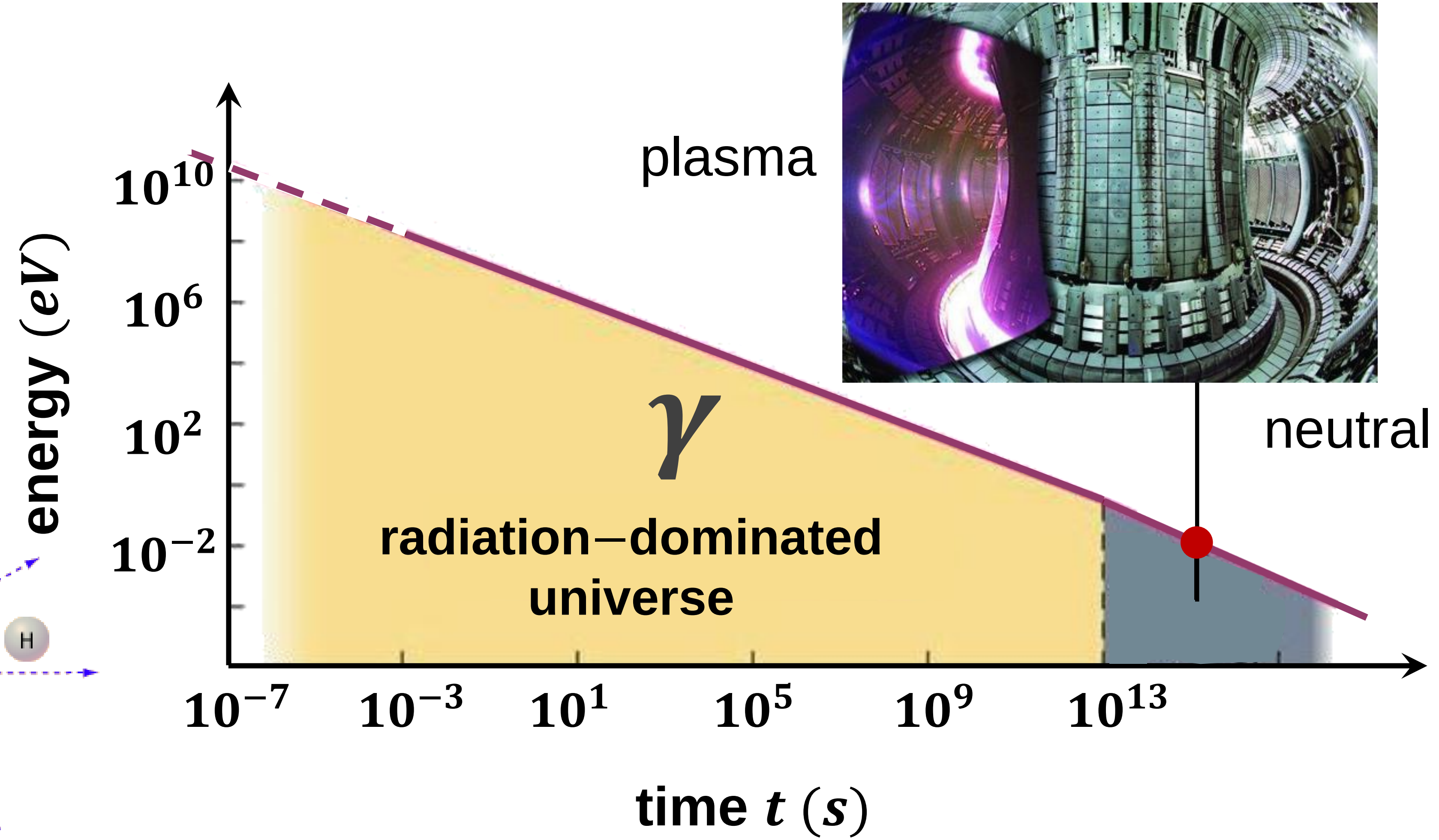


Production of particles & phase transitions

- During expansion & cooling of universe: transition plasma ⇨ neutral atoms

- example:

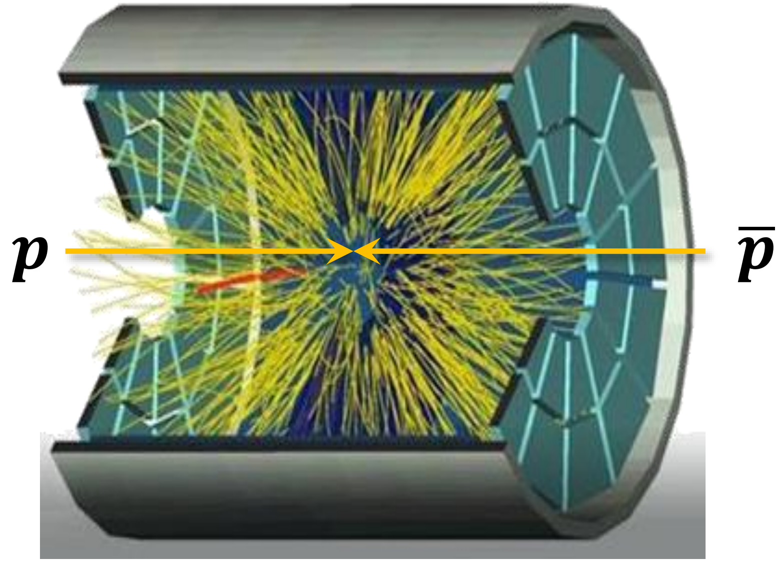


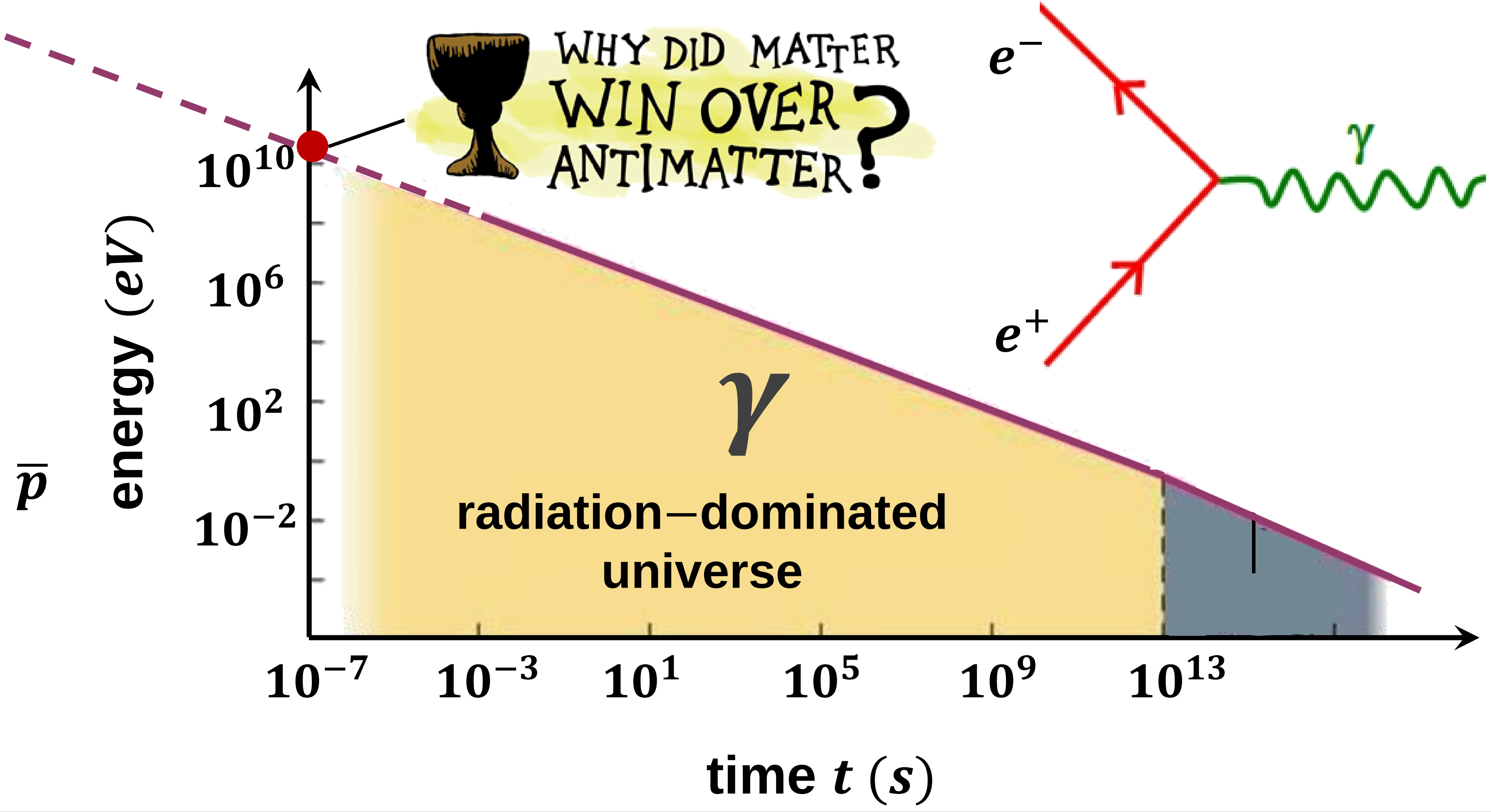


Annihilations within the ´Particle Zoo´

- **Particle annihilations** **will dominate in case of falling temperatures**

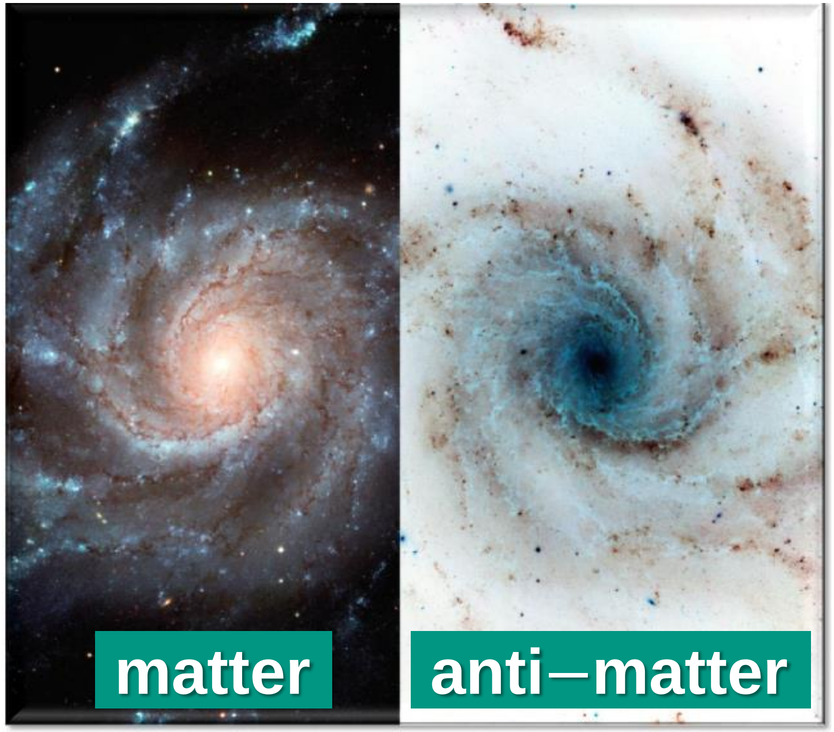
- in case of **perfect CP symmetry**: no baryons left in the universe



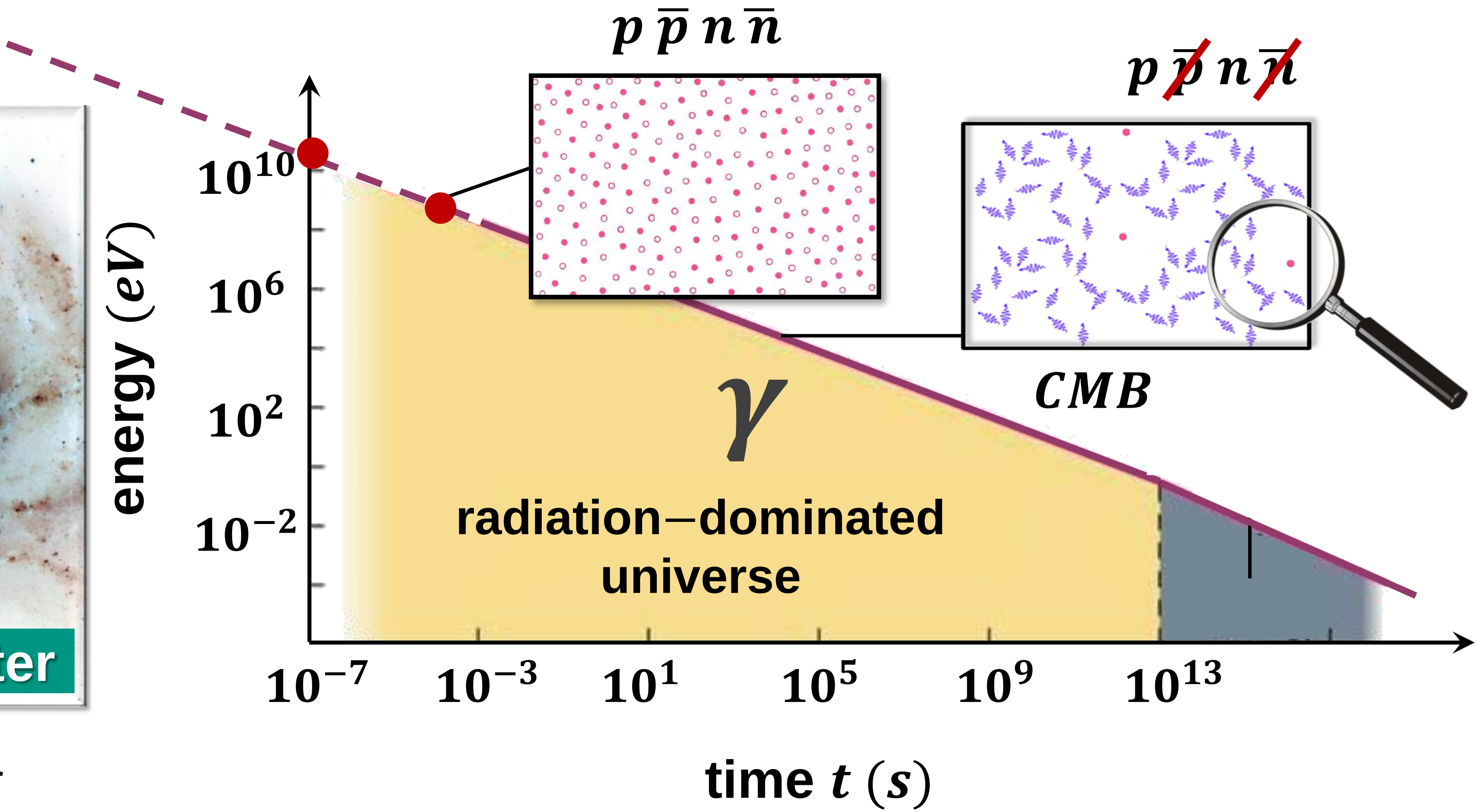


Annihilations within the ´Particle Zoo´

- **Particle annihilations: tiny preference for matter particles due to $\not{C}\not{P}$**

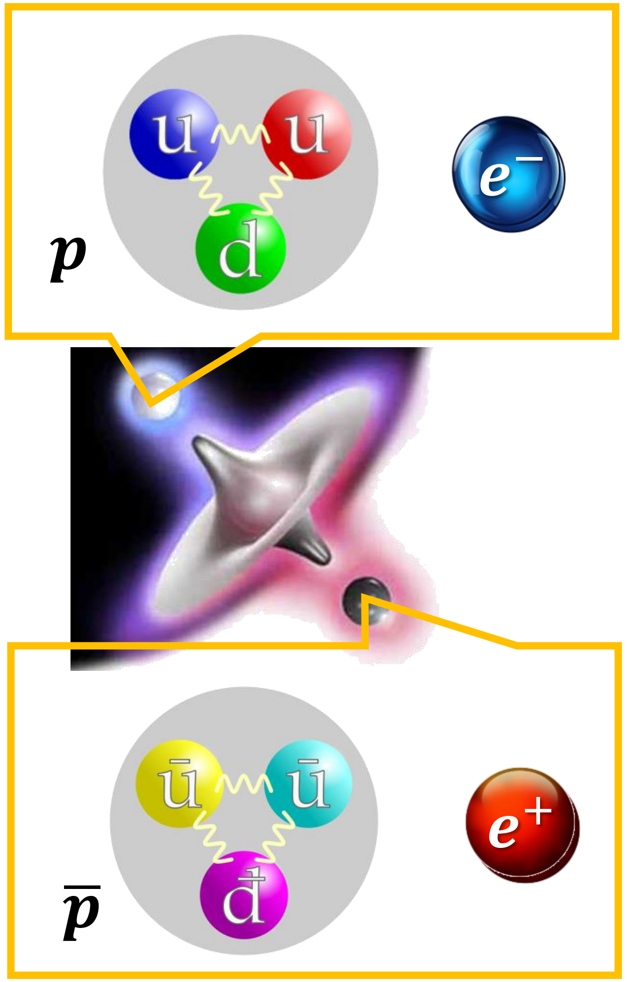


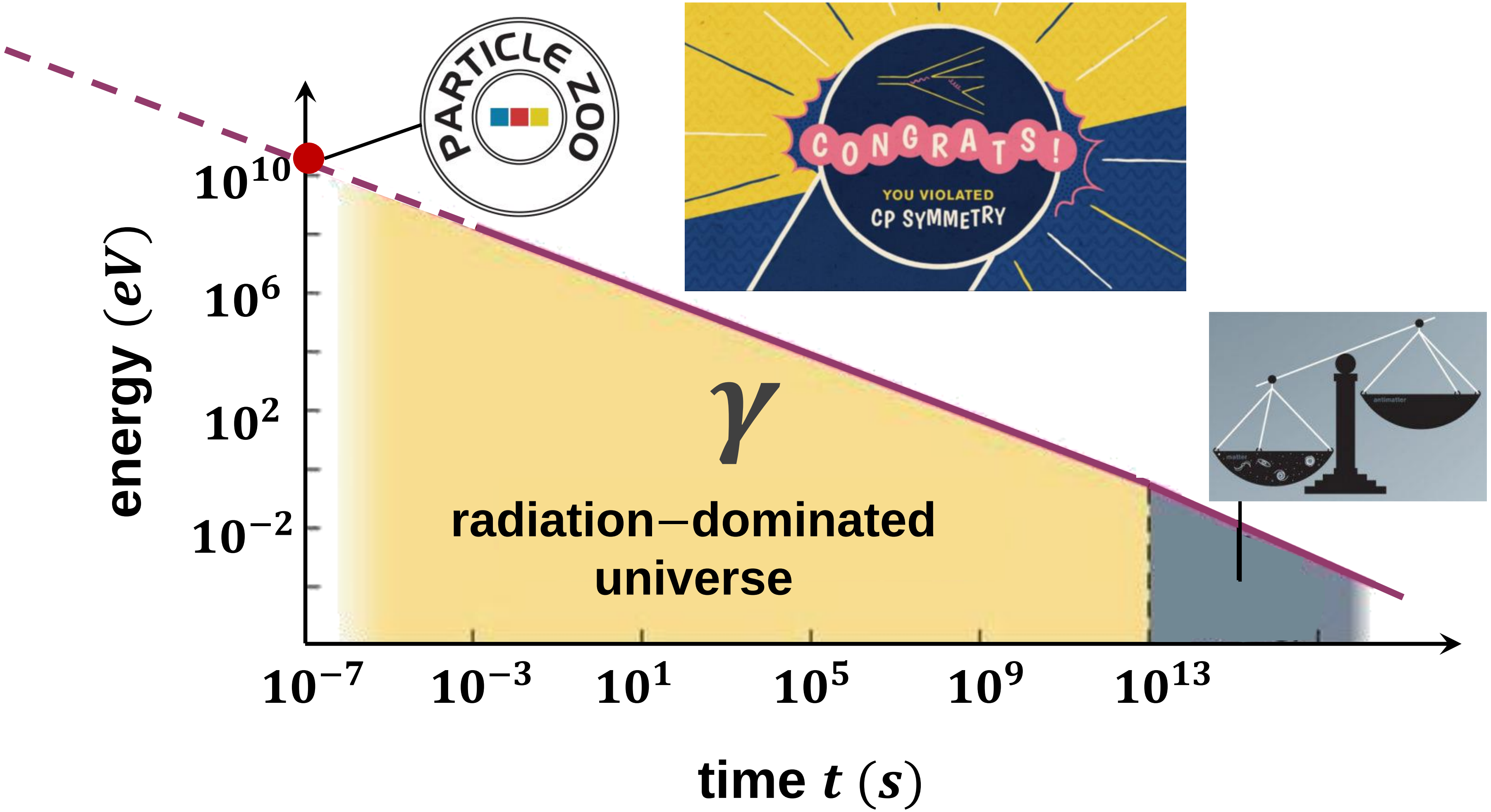
3 Sacharov–criteria



Annihilations within the ´Particle Zoo´

- **Particle annihilations: an extremely tiny preference for matter particles…**



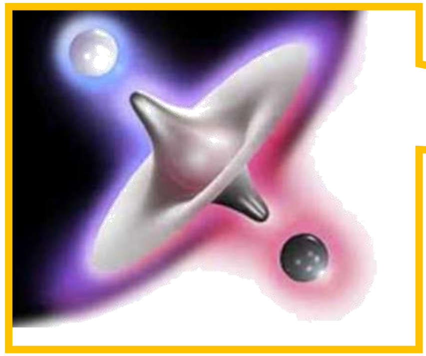


Annihilations within the ´Particle Zoo´

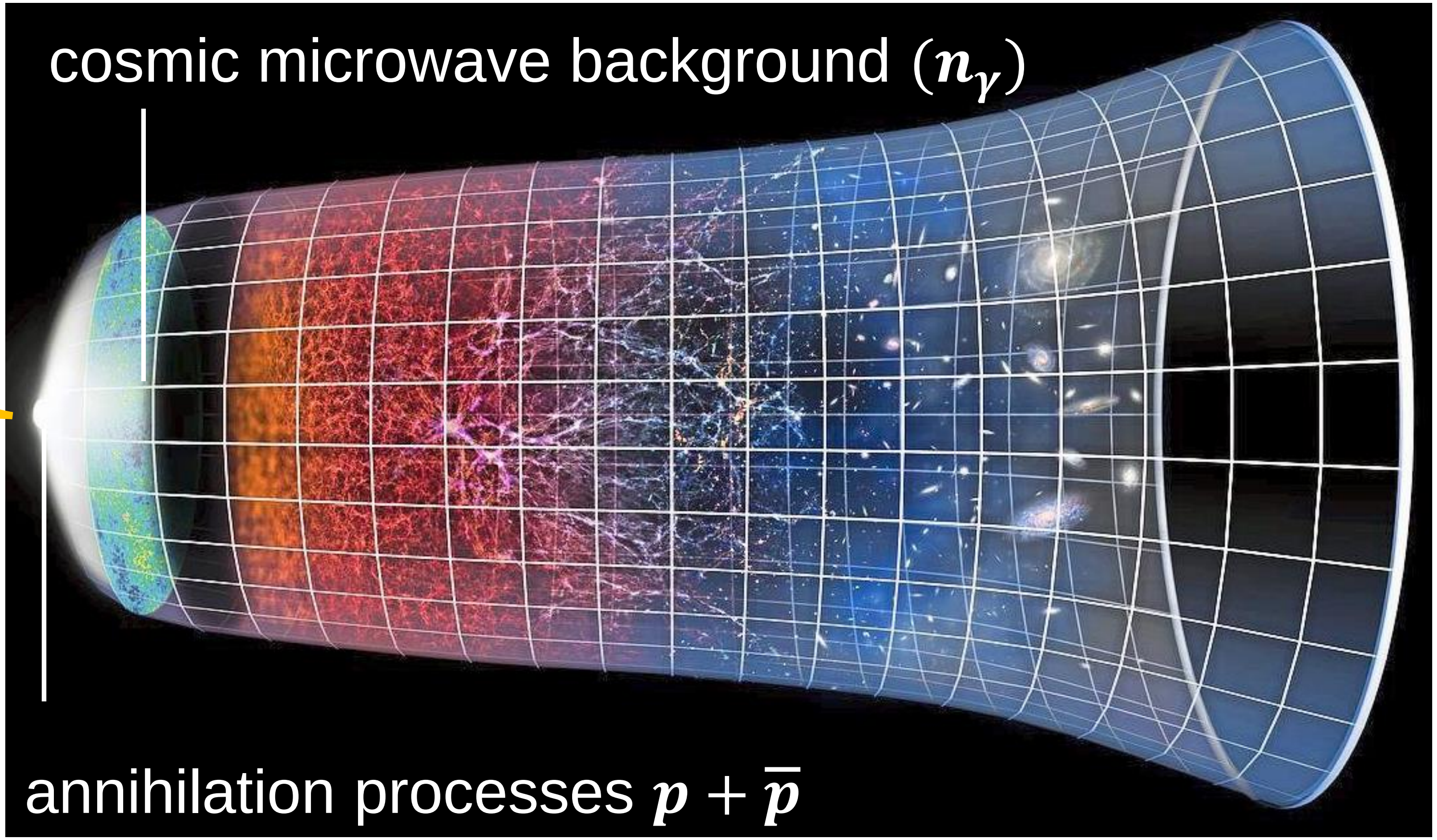
- **Particle annihilations after the Big Bang** & **origin of baryon number violation**

  - universe with a net **baryon asymmetry η**

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



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



Further processing of baryons: nucleosynthesis!

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- **Nuclear reactions produce the light elements in the universe**

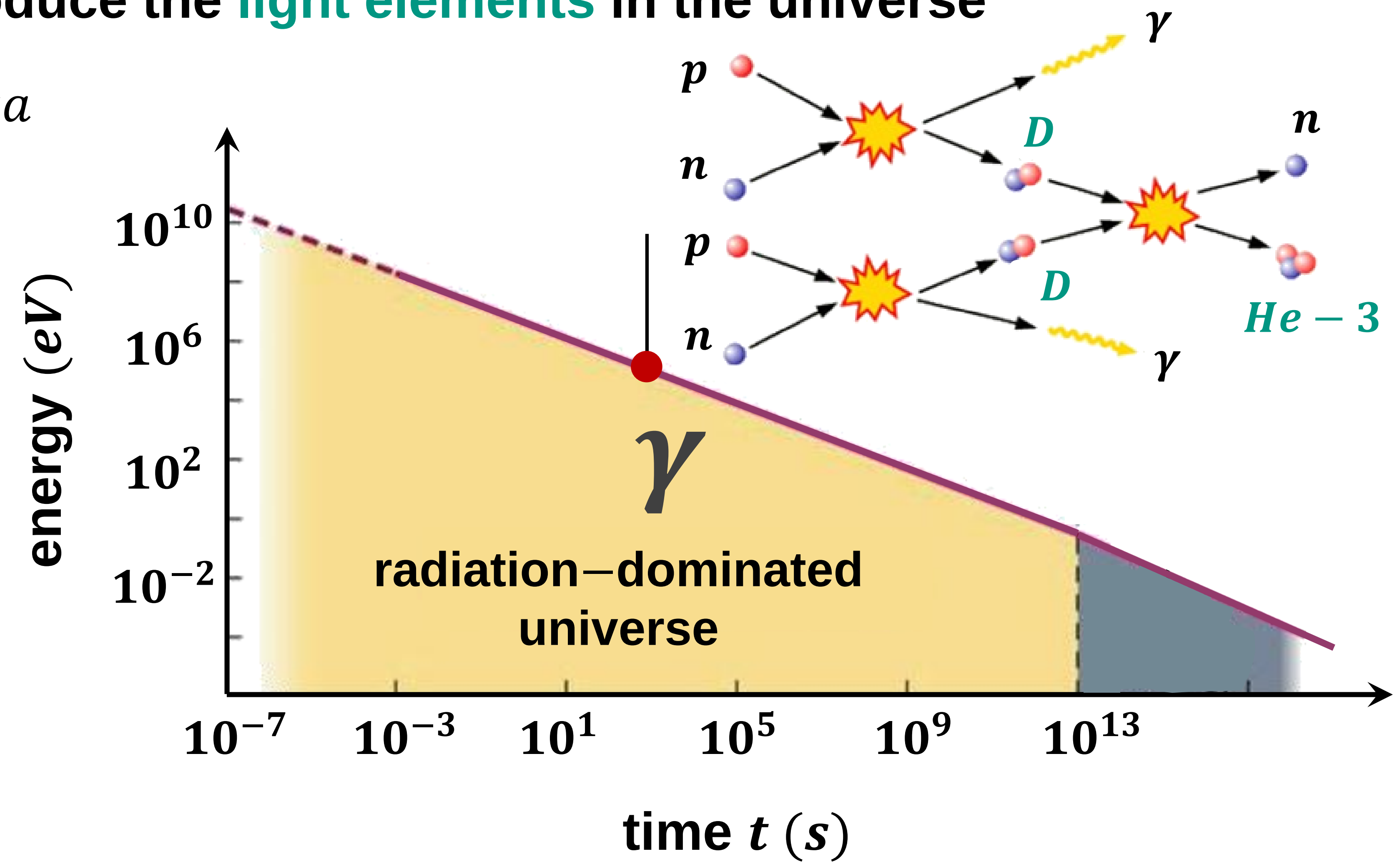
- during a short interval *aka*
  ´the first 3 minutes´

$t = 1 \dots 3\ min$

$T \approx 10^8 K$

$E \approx few\ keV$

- fusion of **light isotopes**:
  $D,\ ^3He,\ ^4He,\ ^7Li,\ \dots$



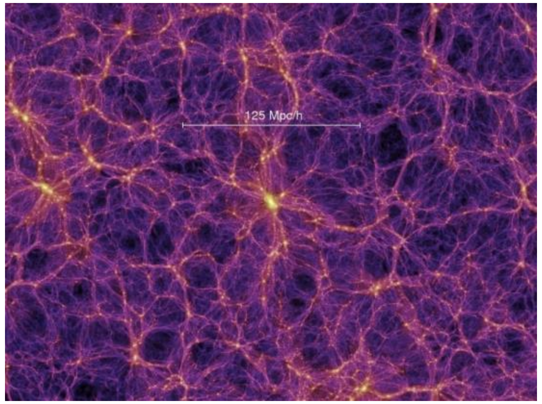
Properties of the matter–dominated universe

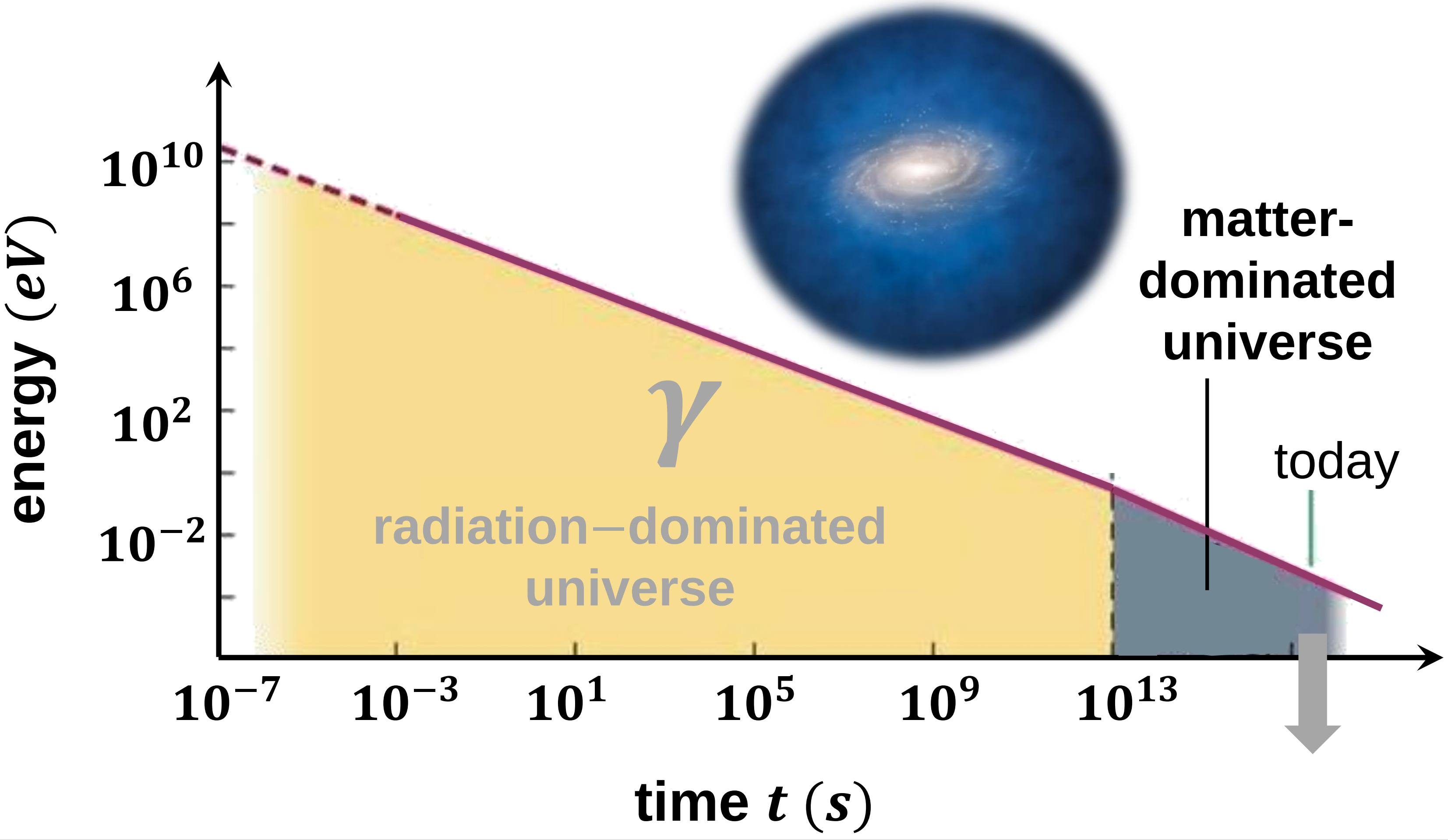
- **After $t \sim 50\,000\ yr$: evolution is dominated by matter (dark matter, baryons)**

- two key players today:

Dark Matter:
gravitational attraction

Dark Energy:
anti–gravity

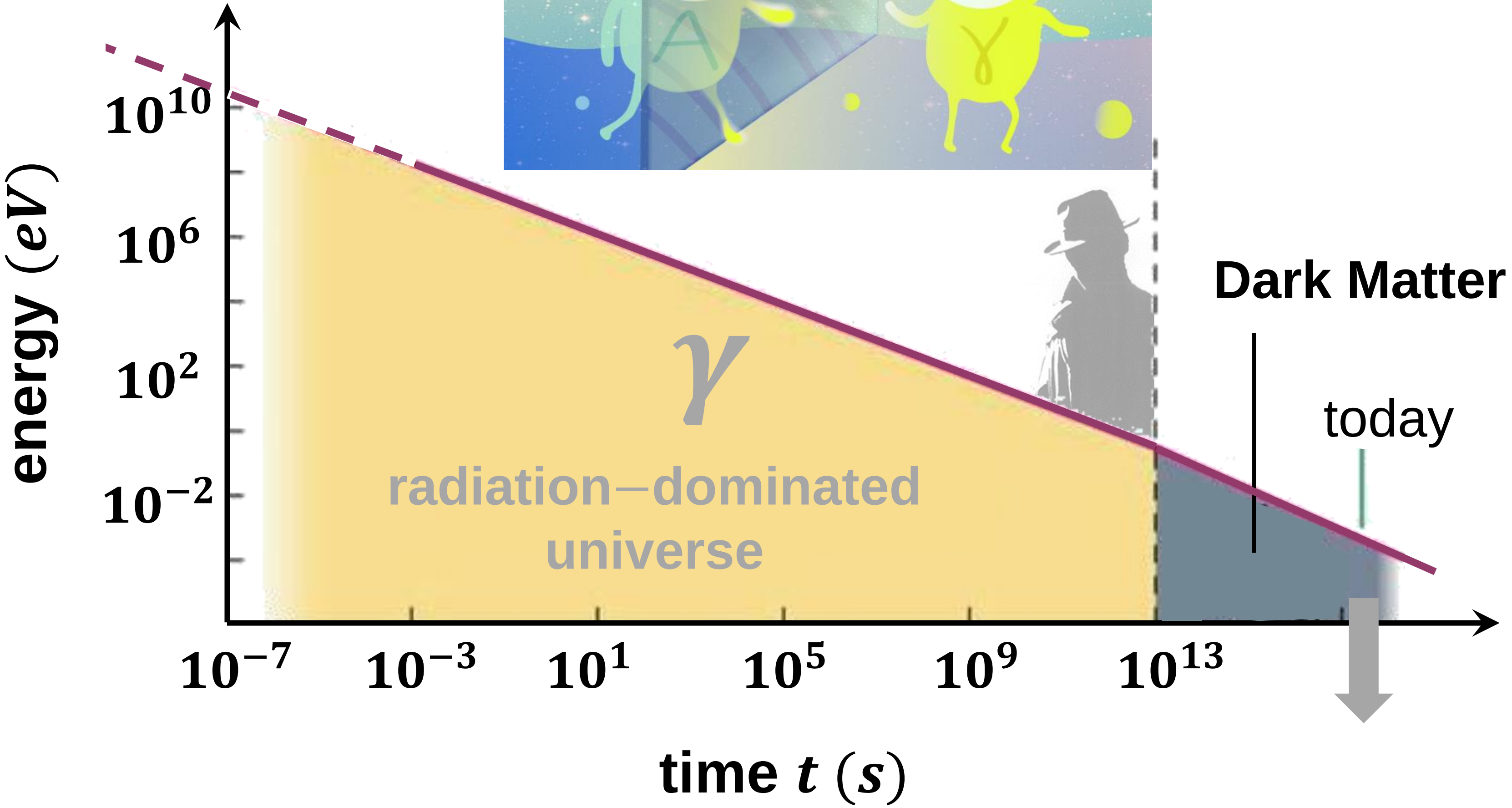


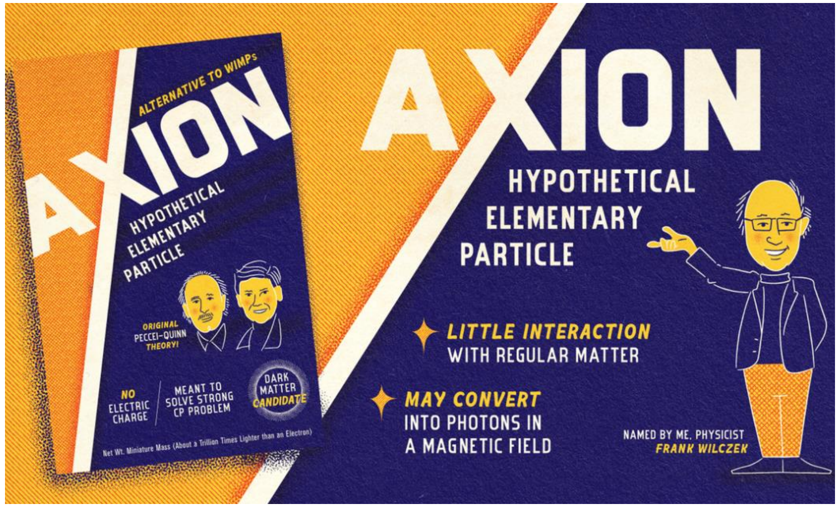


Properties of the matter–dominated universe

- **Non–thermal processes: axions**

- particles **without** coupling to heat bath*: production via **breaking** of specific (Peccei–Quinn) symmetry



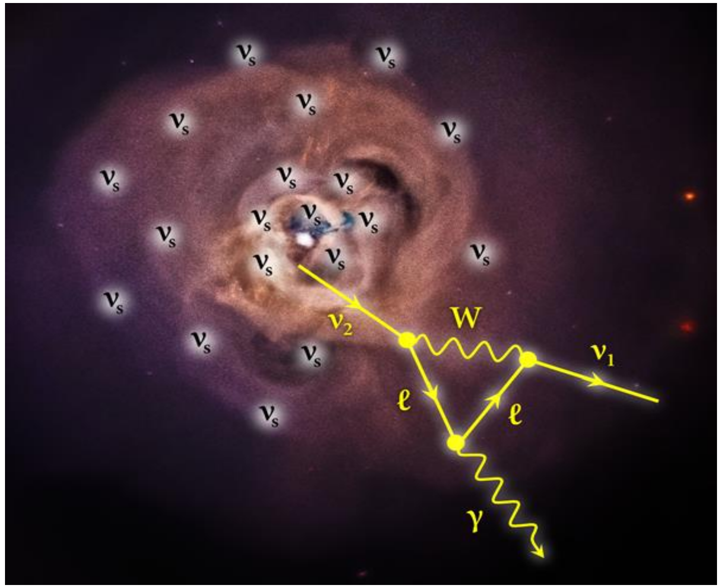


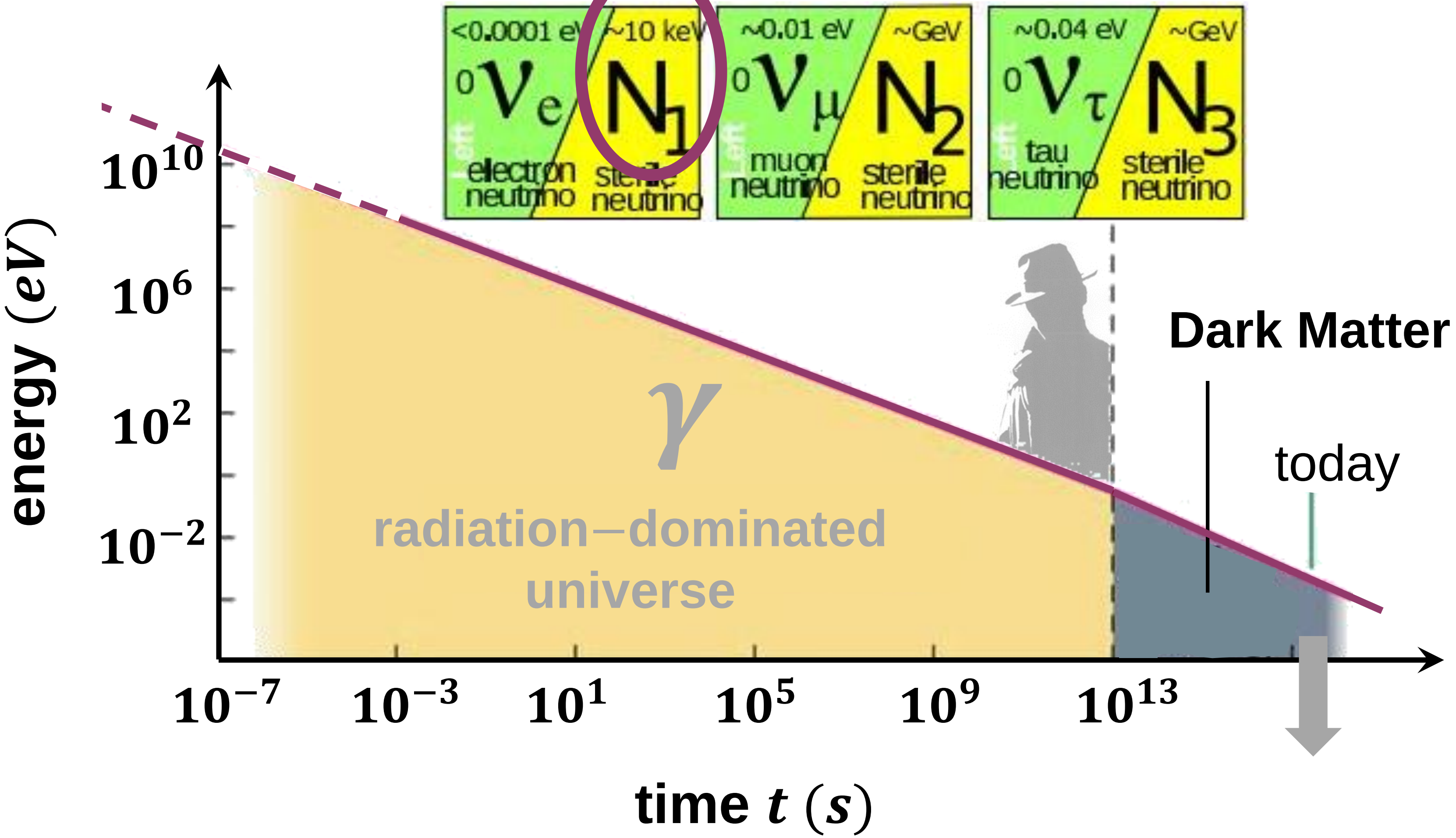
*details see $ATP-I$

Properties of the matter−dominated universe

- **Non−thermal processes: sterile neutrinos**

- particles **without** coupling to heat bath*: production via oscillations in case of sterile ($\boldsymbol{RH}$) neutrinos



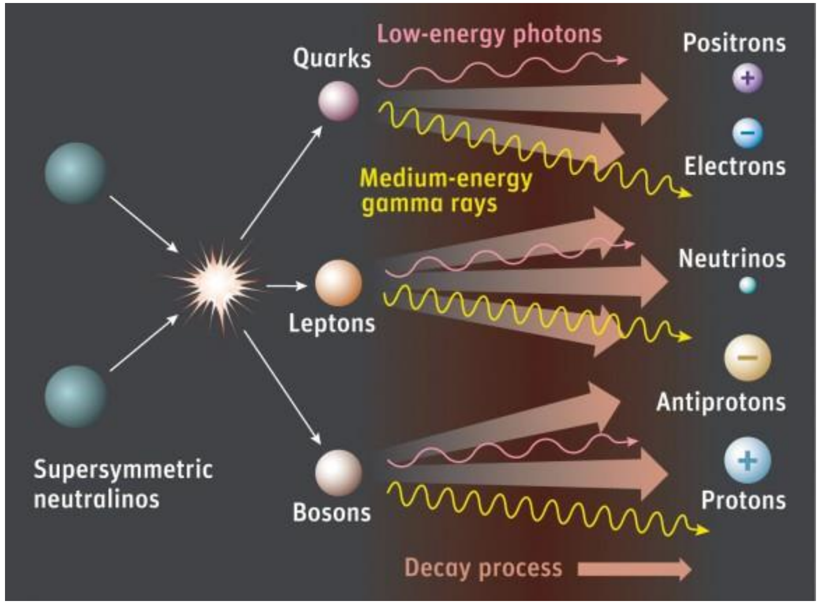


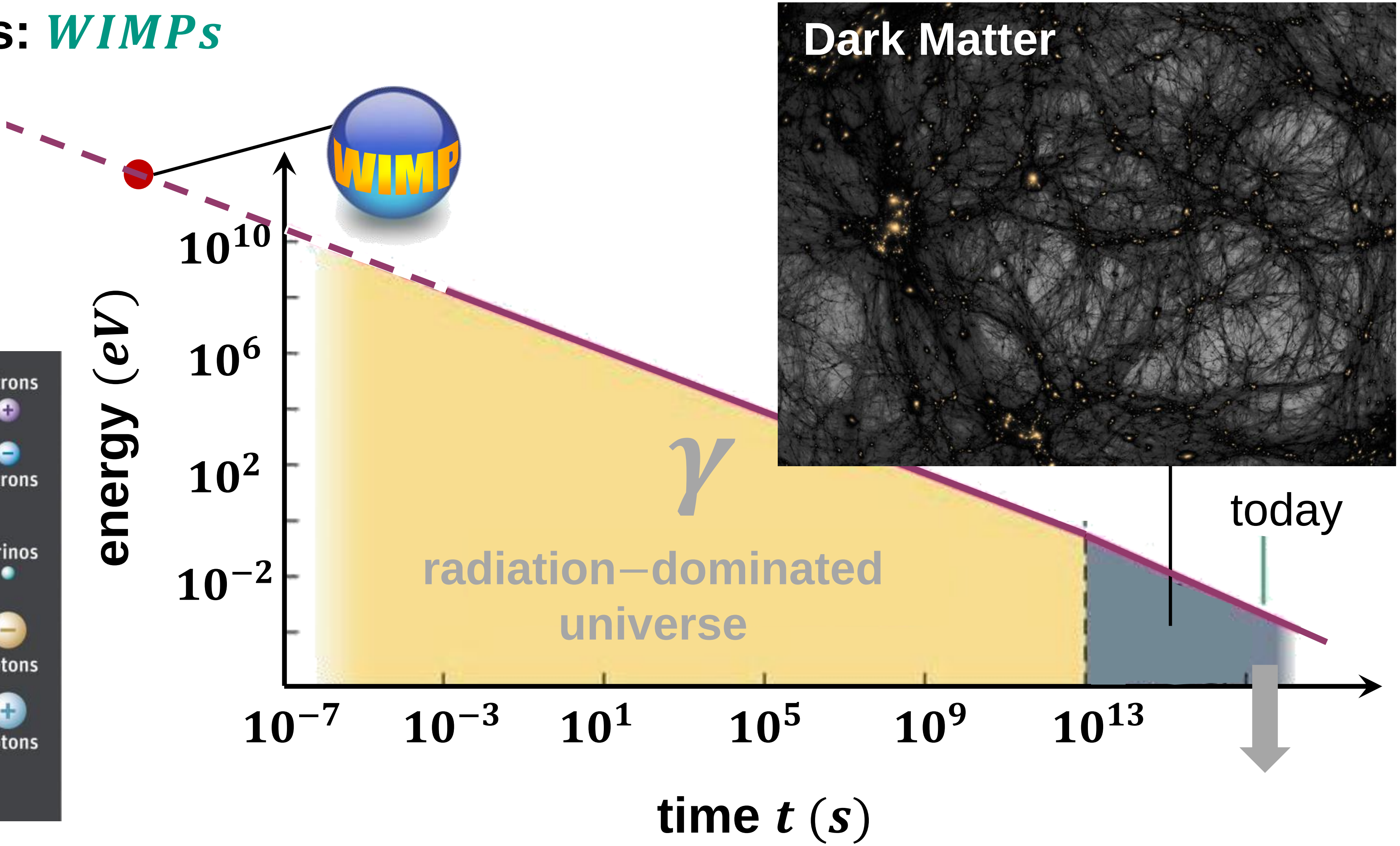
*details see $\boldsymbol{ATP-II}$

Properties of the matter−dominated universe

- **Thermal processes:** ***WIMPs***

- coupling to heat bath:
  particle interactions
  generate dark matter



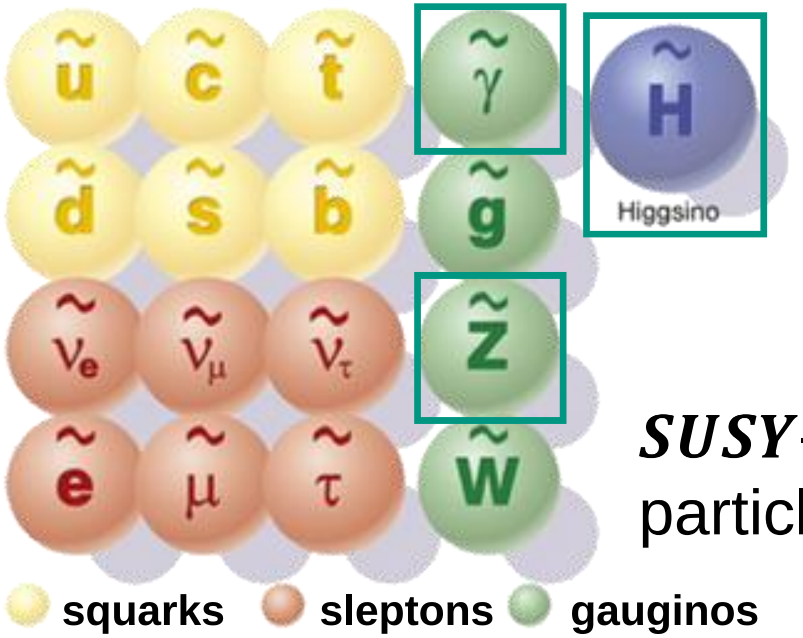


*W*eakly *I*nteracting *M*assive *P*article

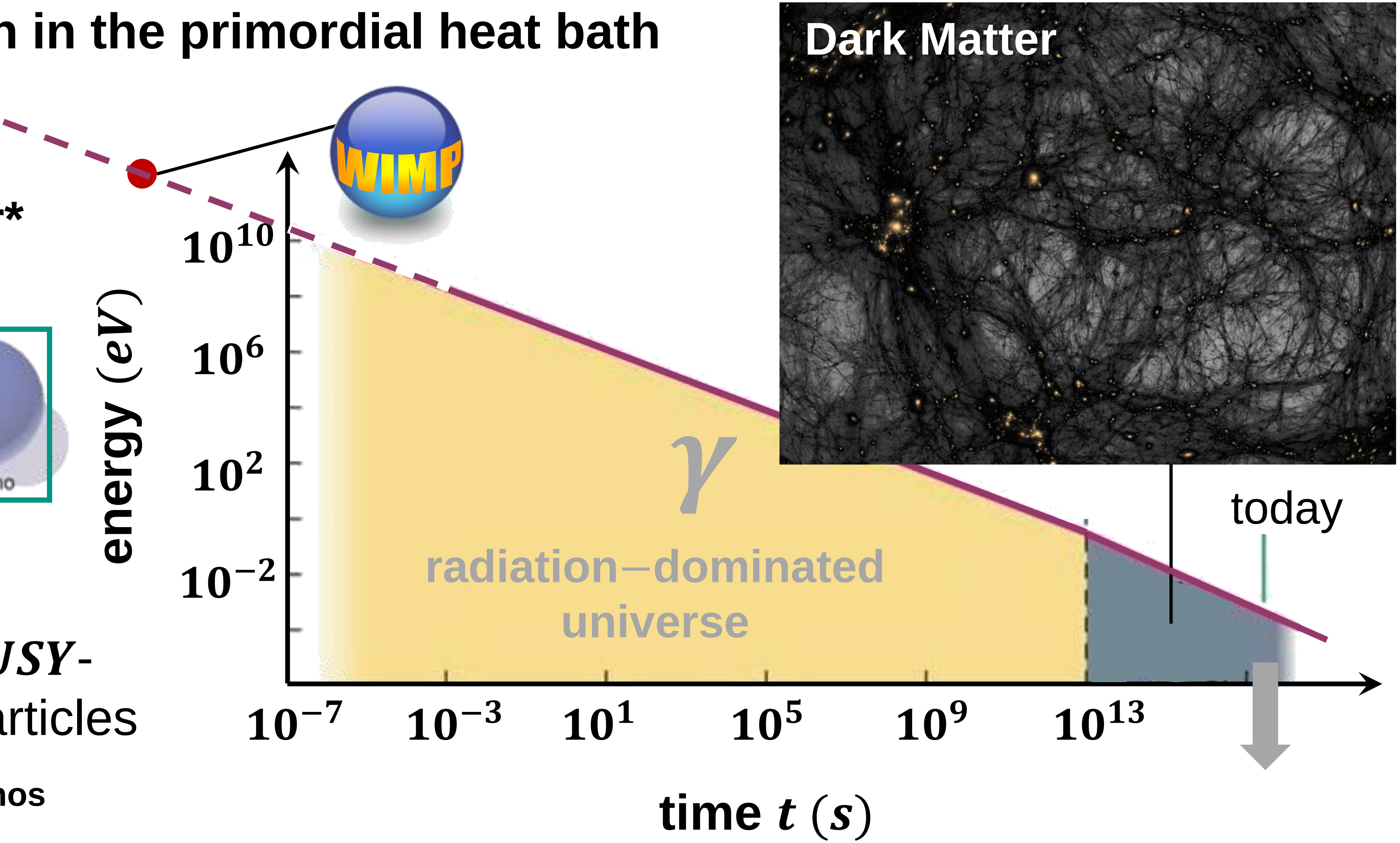
Thermal particle production: case of $WIMPs$

- Particle production in the primordial heat bath

- particle interactions generate dark matter*



$SUSY$-particles



*details see $ATP - I$

Thermal particle production: key processes

- **During expansion of universe: three key processes are of relevance**

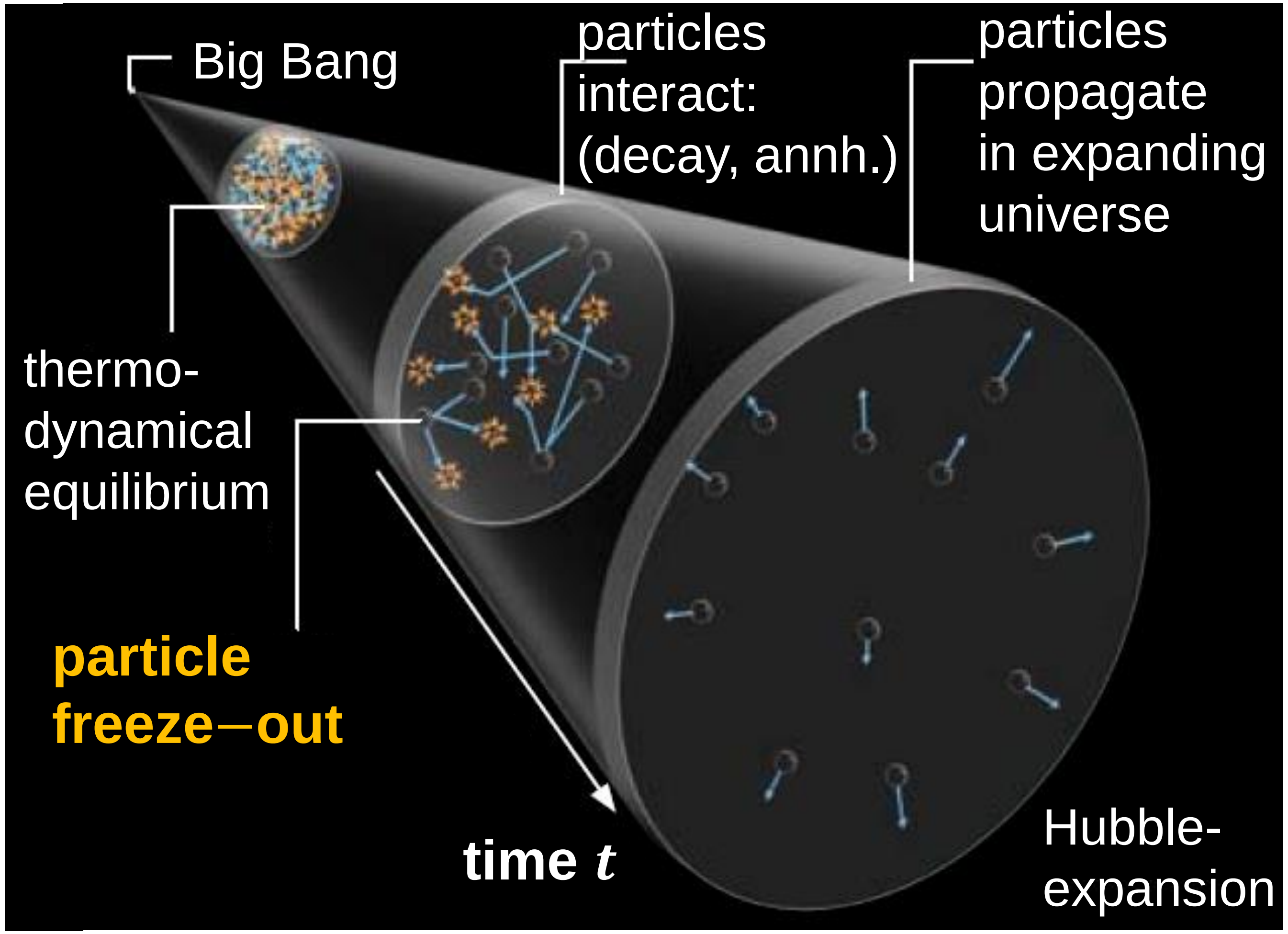
characteristic thermal phases:

- 1 : thermodynamical equilibrium:
  Boltzmann-distribution

- interactions with neighbours

- **freeze–out** & **de–coupling**

- free propagation

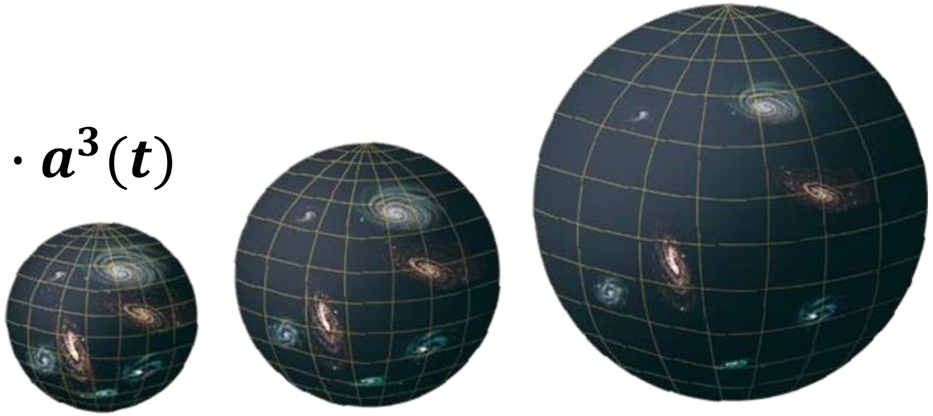


Thermal particle production: key processes #1

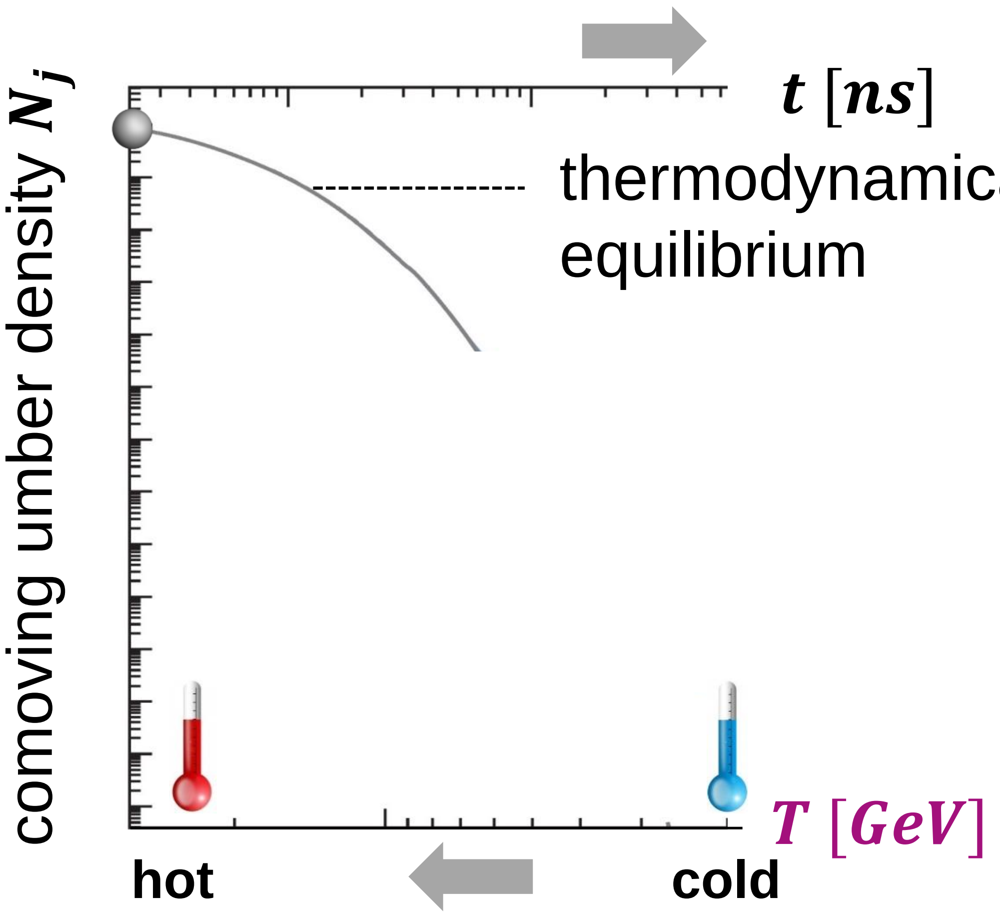
■ **During expansion of universe: phase 1 – thermal equilibrium**

- all particle number densities in **comoving coordinates $\vec{x}$**
  ⇨ density decrease due to the expansion of the universe thus taken into account

$$\rho_0 = \rho(t) \cdot a^3(t)$$



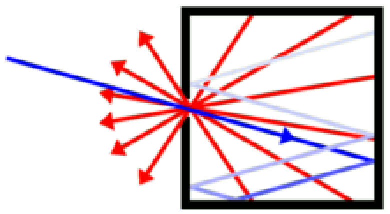
$$\vec{r}(t) = a(t) \cdot \vec{x}$$



Thermal particle production: key processes #1

- **During expansion of universe: phase 1 – Boltzmann distribution**

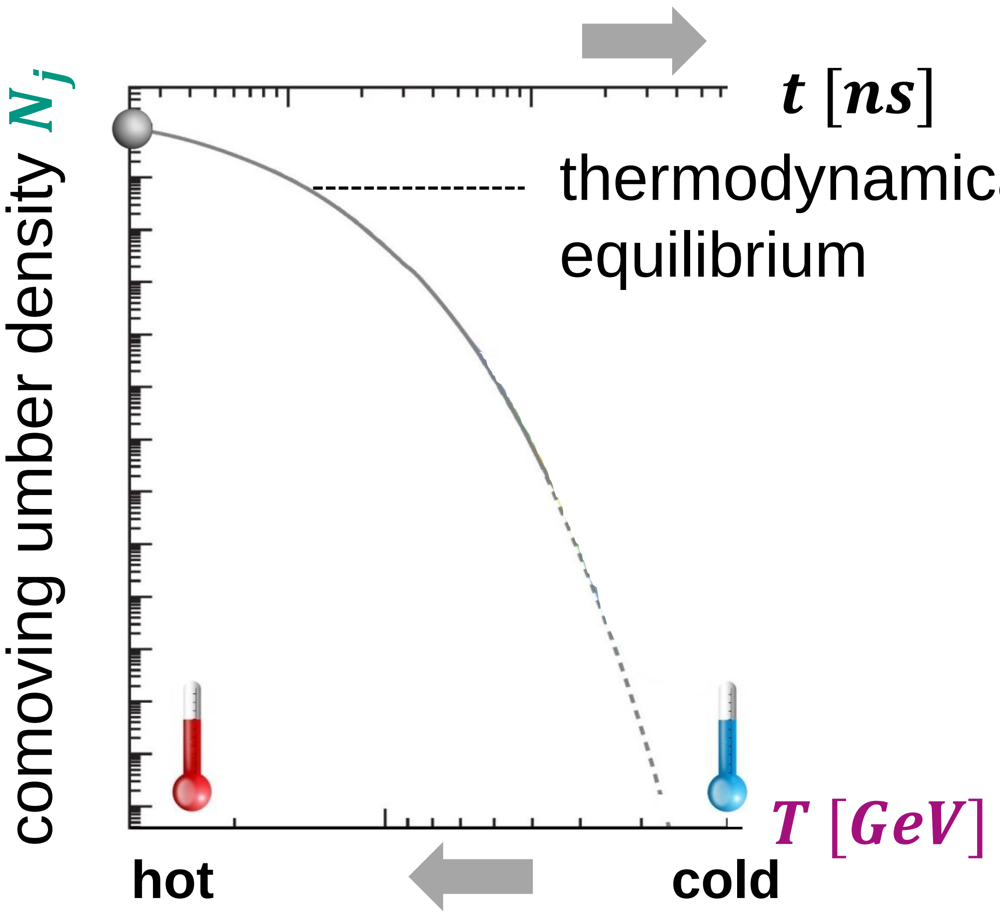
  - particle species: **production** & **annihilation** (thermal heat bath)



  - particle number density N_j defined by **2 free parameters**:

    particle energy (mass) $E_j = M_j \cdot c^2$

    temperature heat bath $E_\gamma = k_B \cdot T$



Thermal particle production: key processes #1

- **During expansion of universe: phase 1 – Boltzmann distribution**

- evolution of **number density** N_j

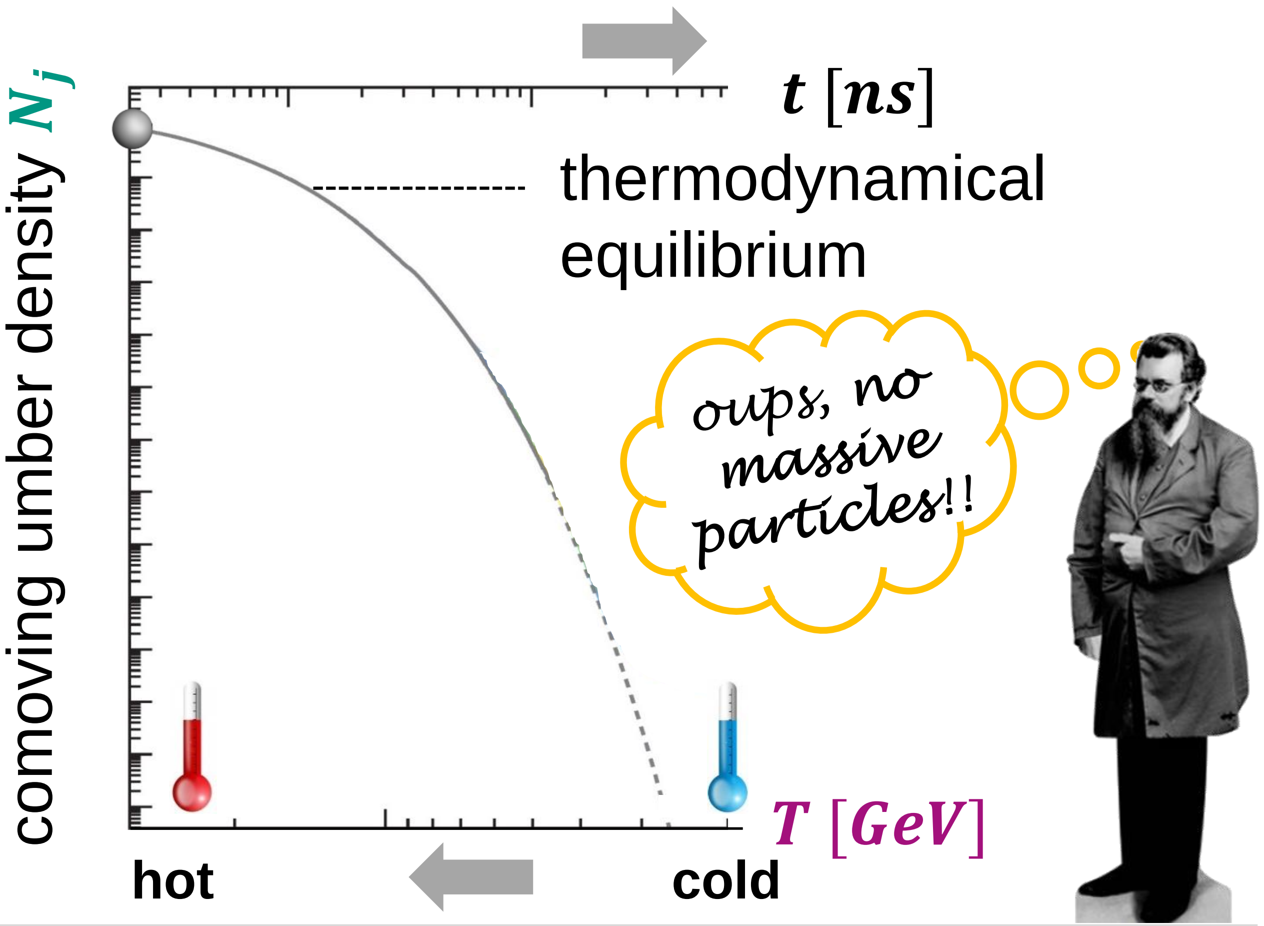
$$N_j = N_0 \cdot g_j \cdot e^{-E_j/k_B T}$$

N_0: primary particle number density

N_j: actual particle number density at temperature T (energy E_j)

g_j: intrinsic degree of degeneracy (fermions, bosons)

⇨ for $T \rightarrow 0$ we have $N_j \rightarrow 0$



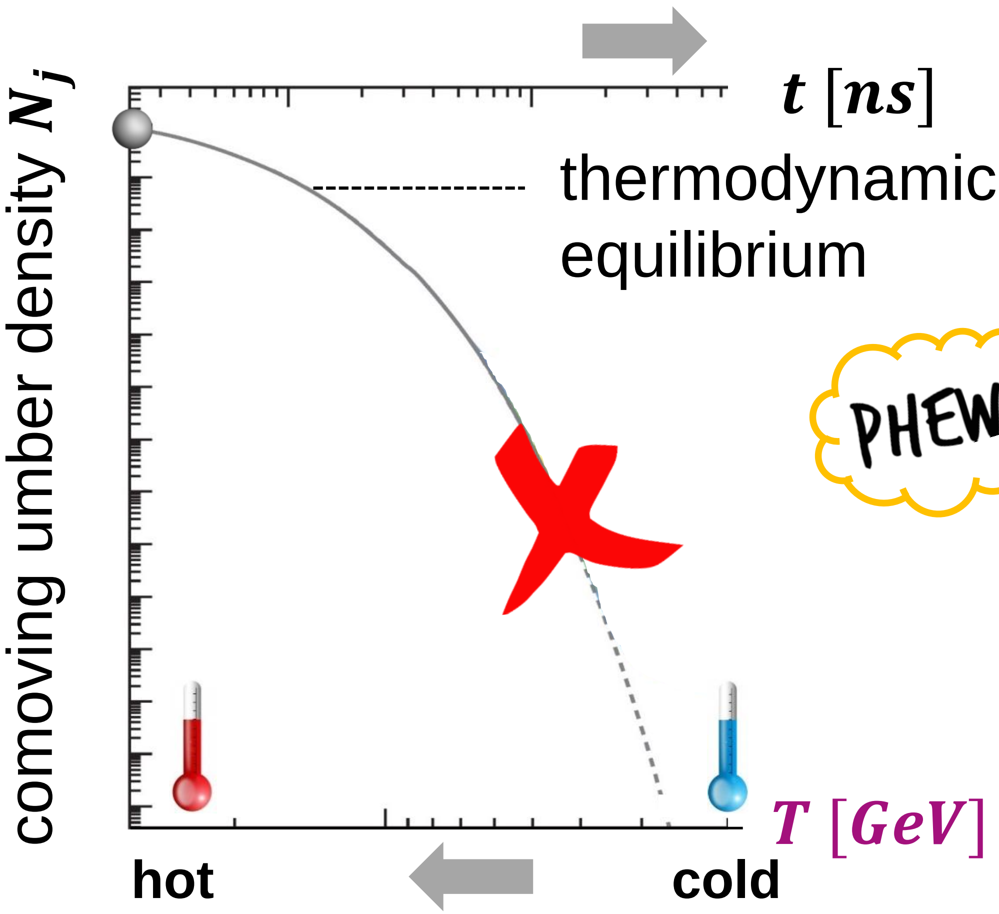
Thermal particle production: key processes #2

■ **During expansion of universe: phase 2 – breaking of thermal equilibrium**

- evolution of number density

$$N_j = N_0 \cdot g_j \cdot e^{-E_j/k_B T}$$

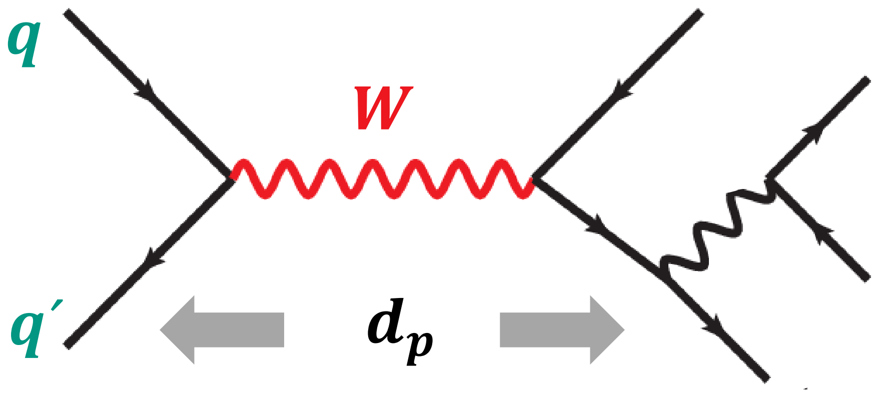
- finite number density $N_j \neq 0$ requires **breaking of thermal equilibrium** (´**decoupling from heat bath**´)



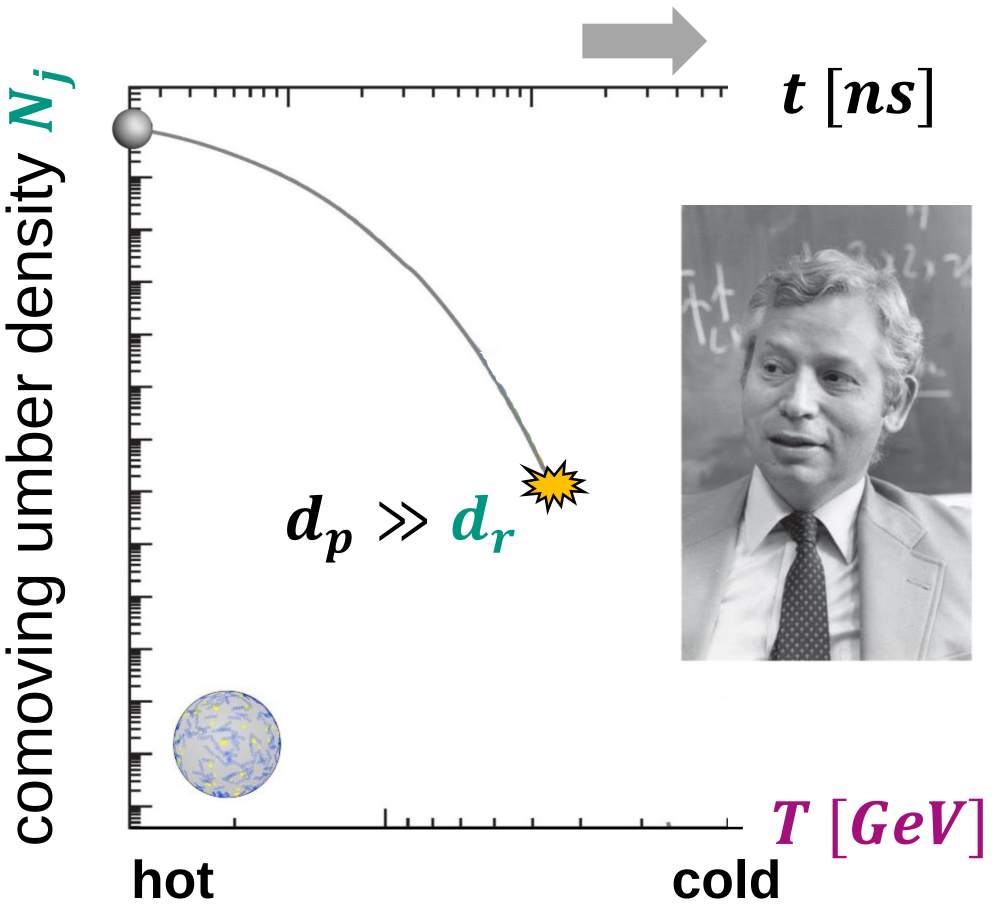
Thermal particle production: key processes #2

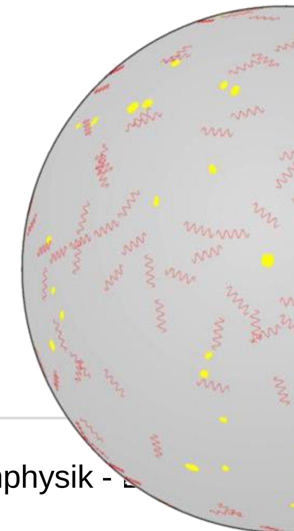
- **During expansion of universe: phase 2 – breaking of thermal equilibrium**

- expansion of the universe takes plase in ´**real**´ **coordinates** $\vec{r}$



- exchange bosons W, Z, g with finite range d_r (or lifetime τ)
- yet: increase of particle distances d_p

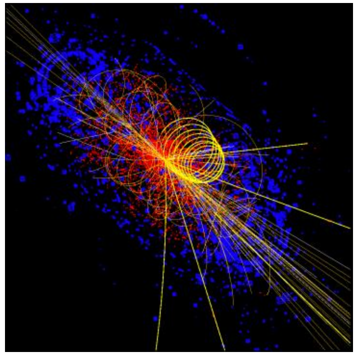




Thermal particle production: key processes #3

- **During expansion of universe:** **phase 3 – freeze–out of particles**

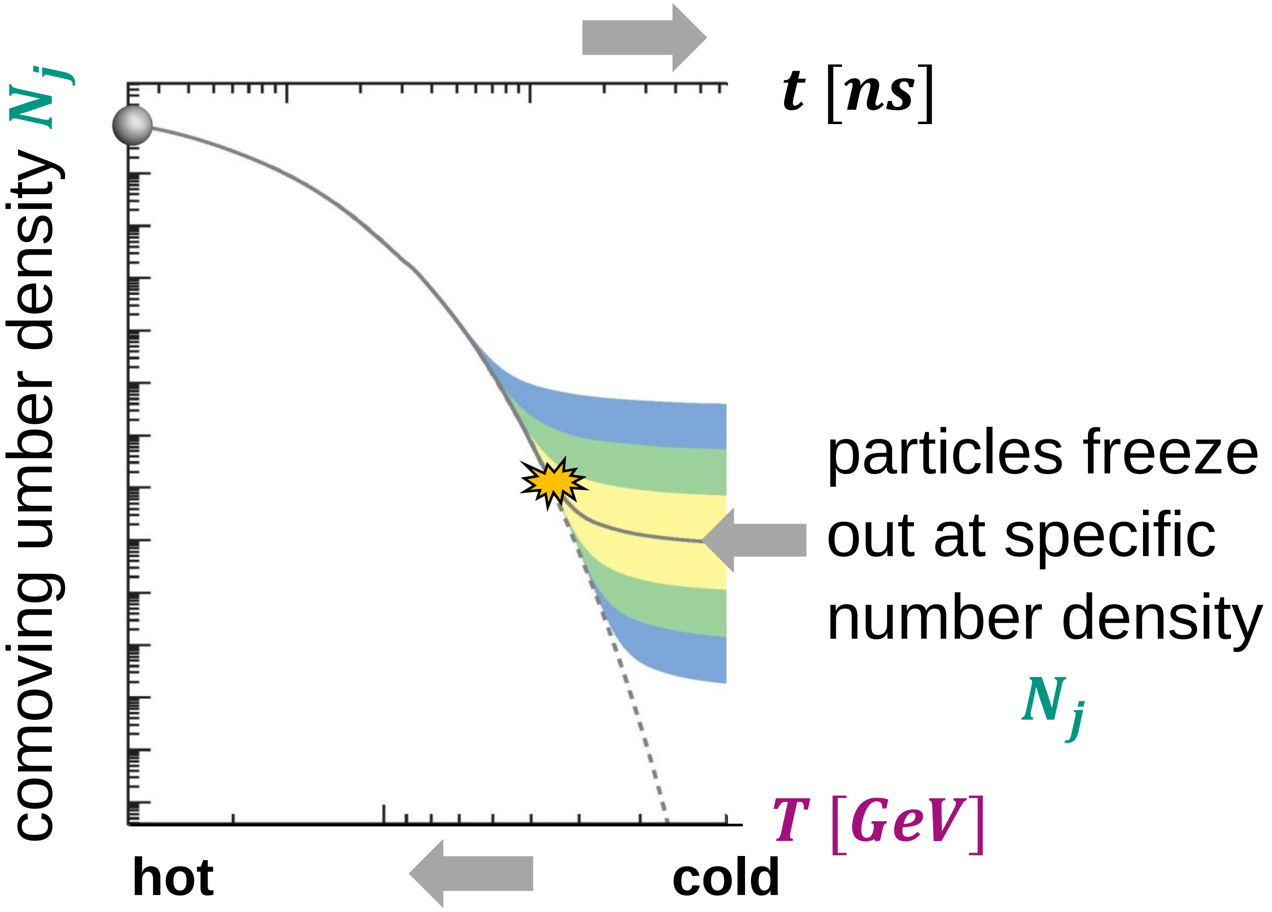
  - **decoupling from heat bath** at a specific **time t** / **temperature T**:



$$\Gamma(t) = H(t)$$

Hubble expansion rate $H(t)$

particle interaction rate $\Gamma(t)$



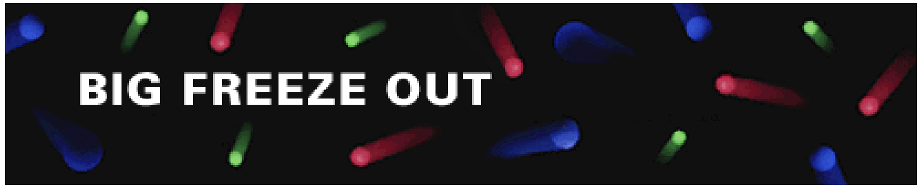
Thermal particle production: key processes #3

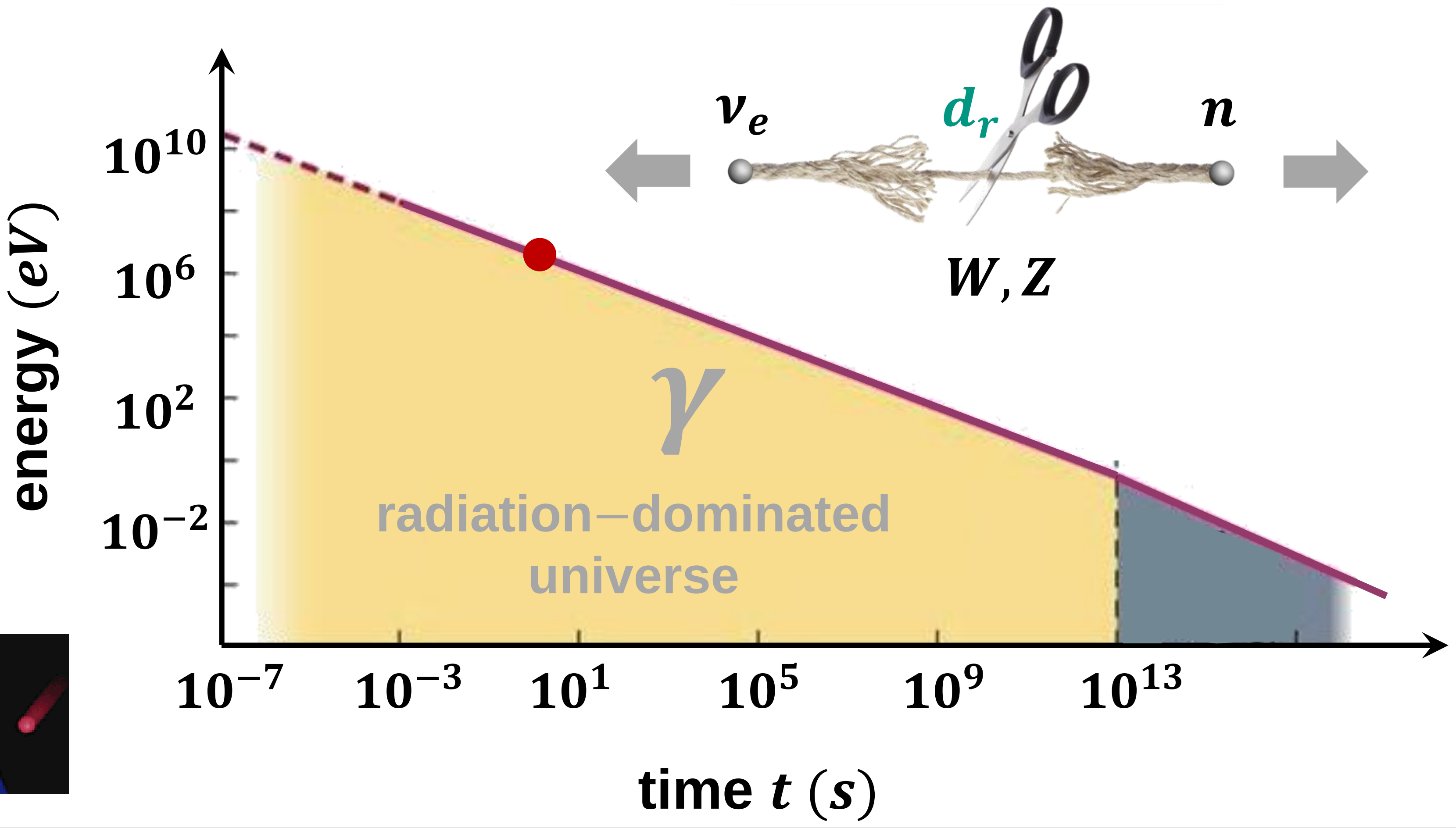
■ **During expansion of universe: freeze−out processes of ν´s are important**

- example:
  neutrinos from Big Bang
  decouple once we have

$$\Gamma_\nu(t) = H(t)$$

Γ_ν: weak interaction cross section





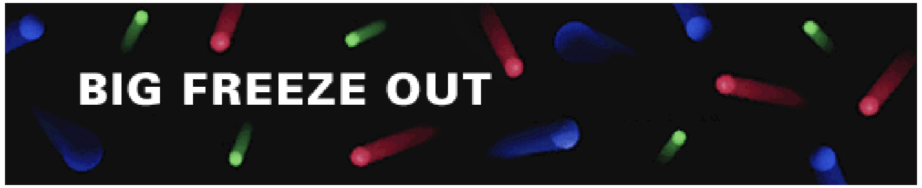
Thermal particle production: key processes #3

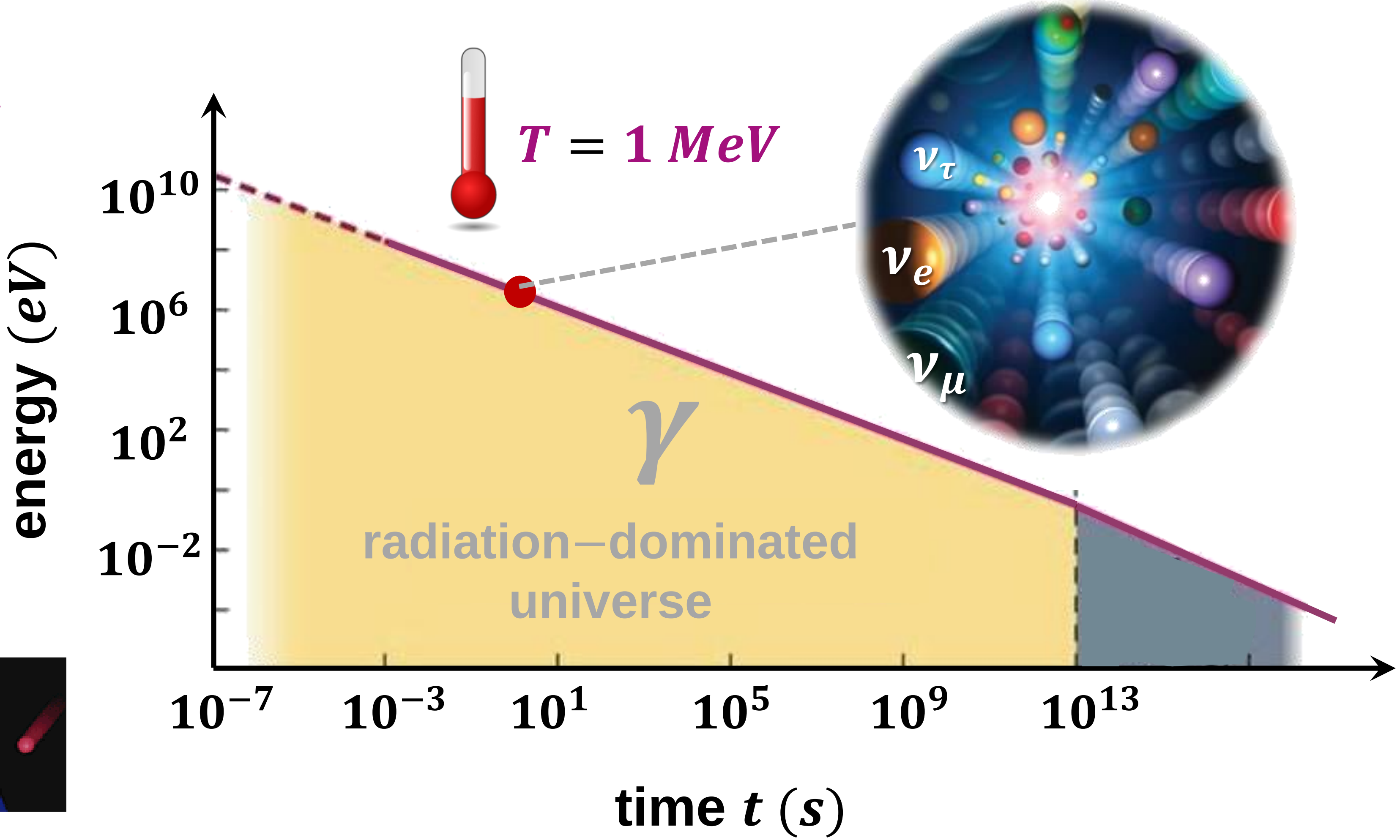
- **During expansion of universe: freeze–out processes of $\nu's$ are important**

$T(t = 1\,s) = 1\,MeV$

$$\Gamma_\nu(t) = H(t)$$

weak interaction cross section



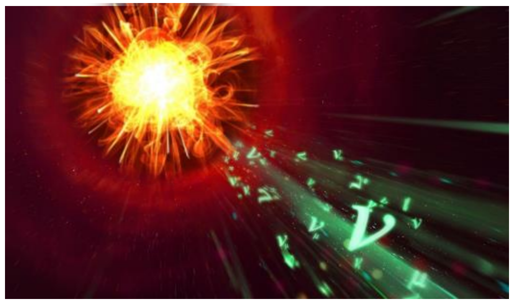


Thermal particle production: key processes #3

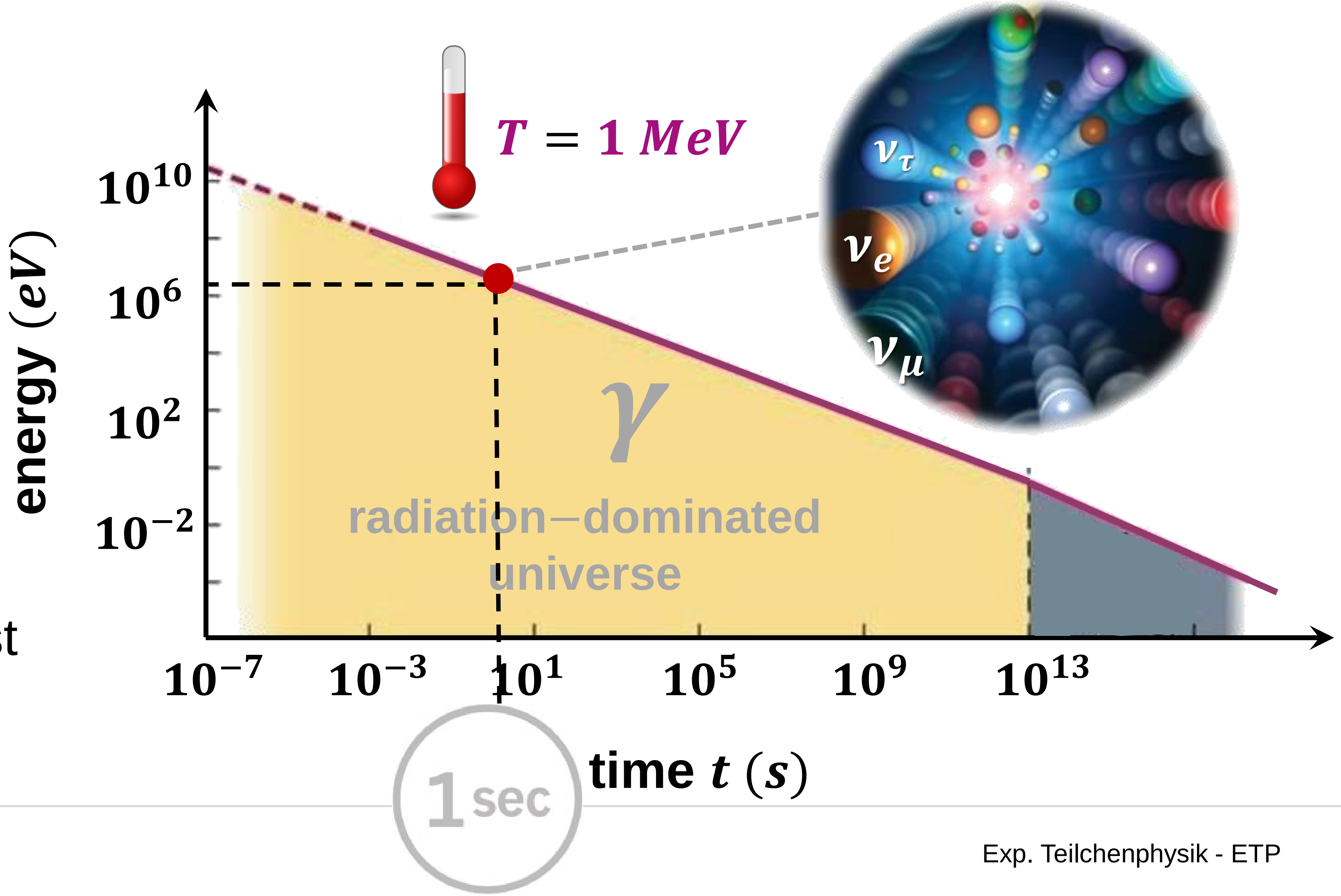
Karlsruhe Institute of Technology

- During expansion of universe: freeze−out processes of ν´s are important

- since $t = 1\ s$ neutrinos from the Big Bang are ´**free−streaming**´



- detection of ´**relic ν´s**´ would allow to take a first picture of the universe already at $t = 1\ s$



Physics Colloquium on a topic in Cosmology

- **A world–leading cosmologist on neutrinos & cosmology – don´t miss it!**

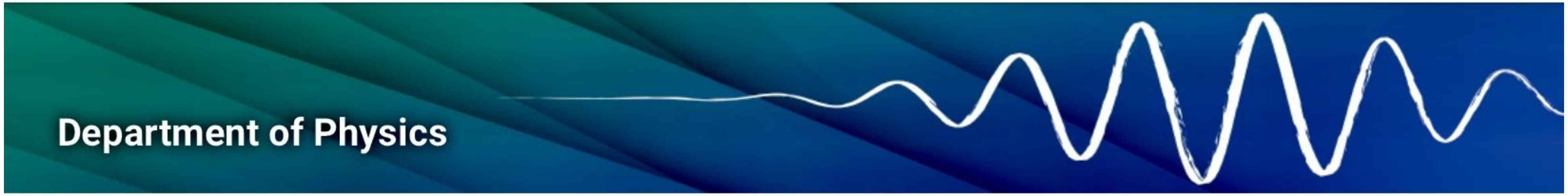
Neutrino mass bounds from cosmology: How strong? How robust?

Friday, 24 November 2023, 15:45-17:15

KIT, Campus Süd
Geb. 30.22, Lehmann-Hörsaal

Speaker
Julien Lesgourgues

RWTH Aachen



Calendar of Events