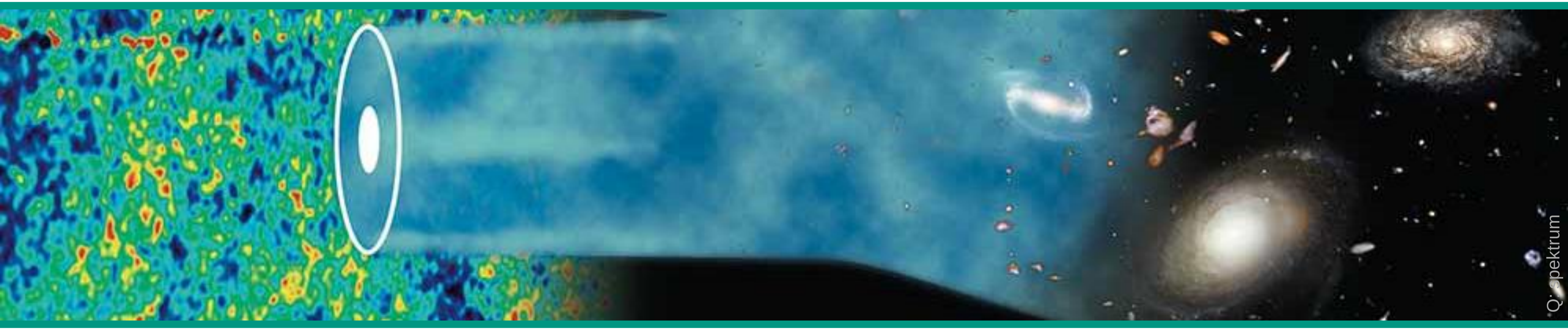
Karlsruhe Institute of Technology

Introduction to Cosmology

Winter term 22/23 Lecture 7 Dec. 13, 2022



Recap of Lecture 6

- **Primordial Nucleosynthesis: formation of light elements during first 3 $\boldsymbol{min}$.**

  - thermodynamical equilibrium between $\boldsymbol{p, n}$ due weak interaction by ν´s

  - neutrino decoupling (freeze-out) at $T = 1\ MeV$ and $t = 1\ s$ (free-streaming ν´s)

  - (n, p) – ratio $1{:}\,6$ at $t = 1\ s$, no element synthesis due to intense heat bath

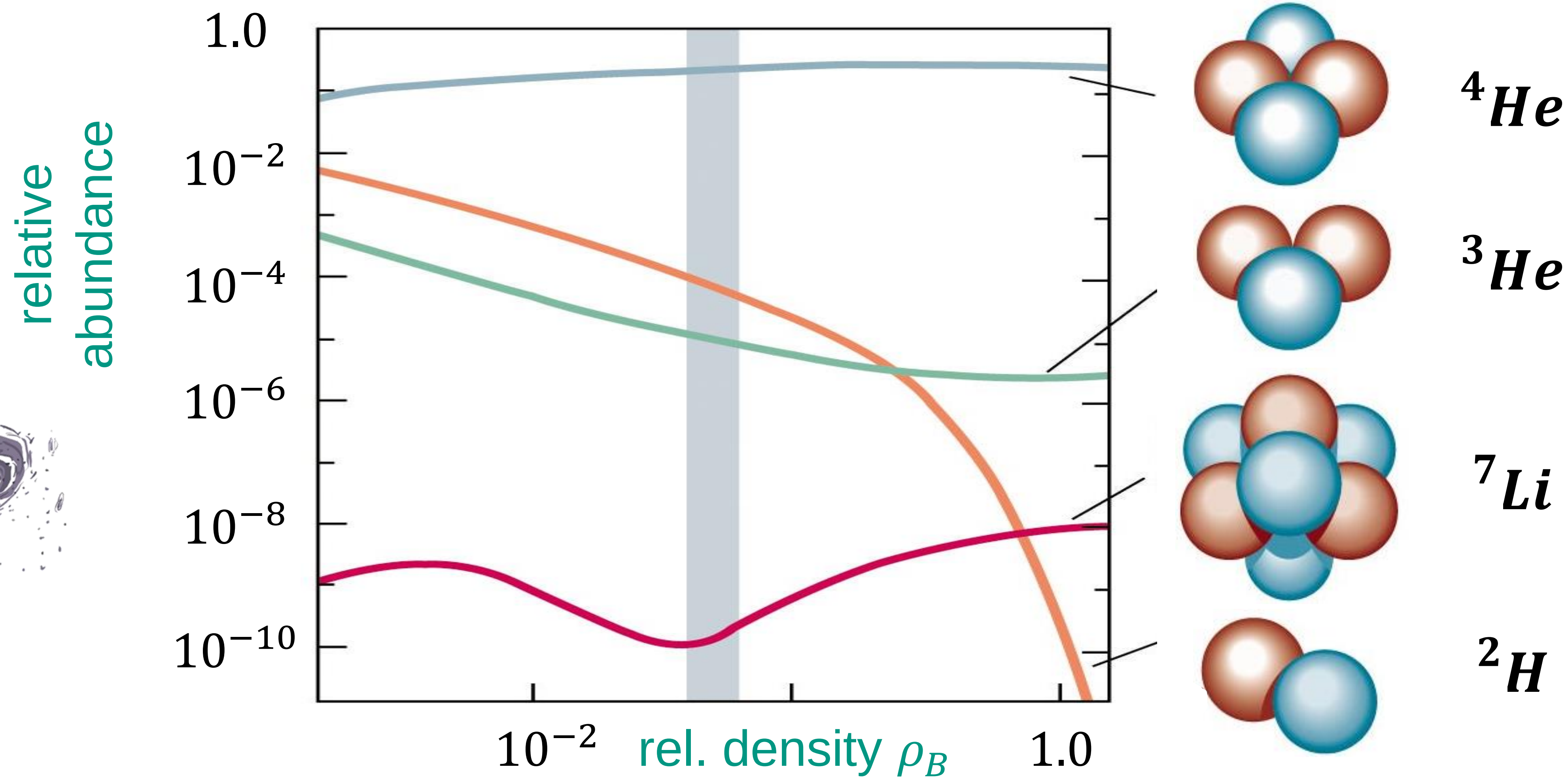
  - fusion only starts at $t \approx 1\ \mathrm{min.}$ due to $\boldsymbol{d}$ – **bottleneck**, then (n, p) – ratio $1{:}\,7$

  - light element synthesis primarily to $\boldsymbol{{}^4He}$ with traces of d, ${}^3He$, ${}^7Li$

  - BBN-prediction of primordial ${}^4He$ mass fraction $Y_p = \frac{2(n/p)}{1+(n/p)} \approx 0.25$

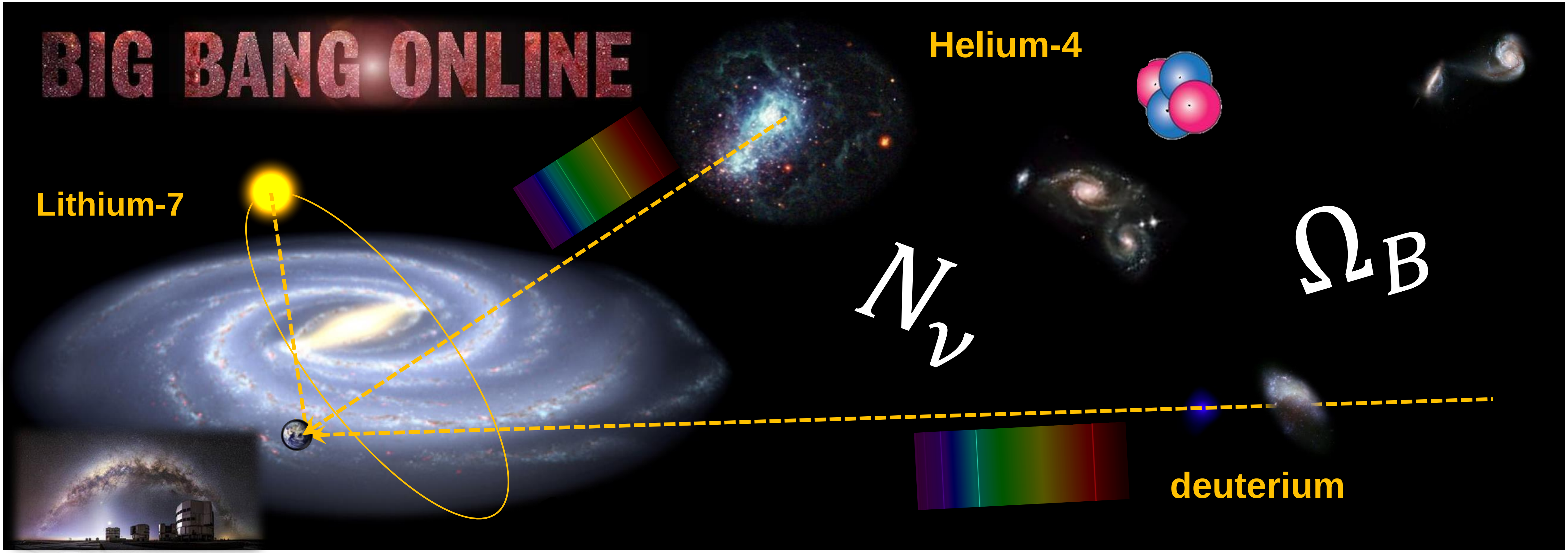
Recap of Lecture 6

- **Primordial Nucleosynthesis: light element yield as a function of ρ_B**



Preview of this Lecture: light element yields

- Determining the abundance of the light elements d, ${}^4He$, ${}^7Li$ for Ω_B & N_ν



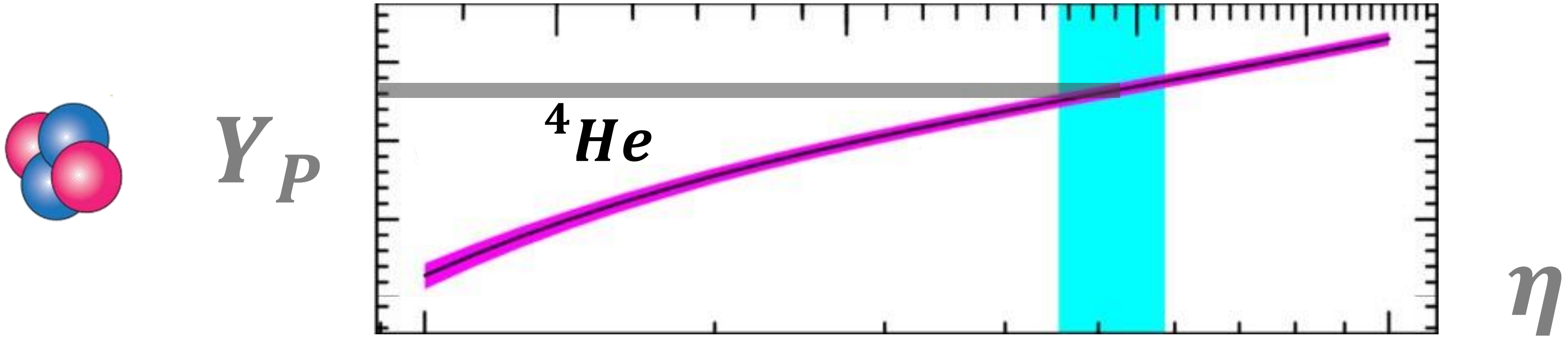
Light element yields as function of parameter η

- **Impact of baryon asymmetry η on abundance of primordial ^4He**

  - for increasing values of η we have more p, n relative to γ´s from heat bath

    ⇨ nucleosynthesis starts earlier at higher values of T_{fr}

    ⇨ larger (n, p) – ratio: more deuterium d is fused, which then ends up as primordial ^4He and a **larger value of Y_P**

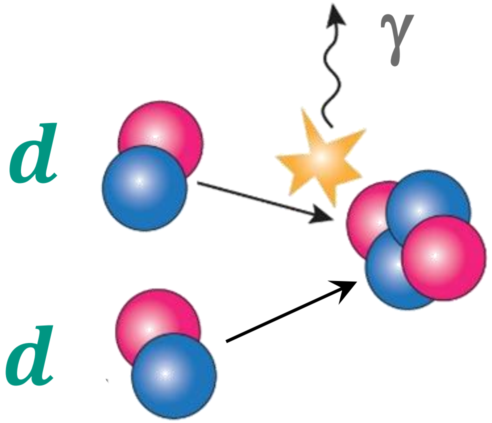


Light element yields as function of parameter η

- **Impact of baryon asymmetry η on abundance of primordial deuterium d**

  - deuterium is THE bottleneck of light element synthesis (small $E_B = 2.2\ MeV$) thus it is most strongly affected by parameter η

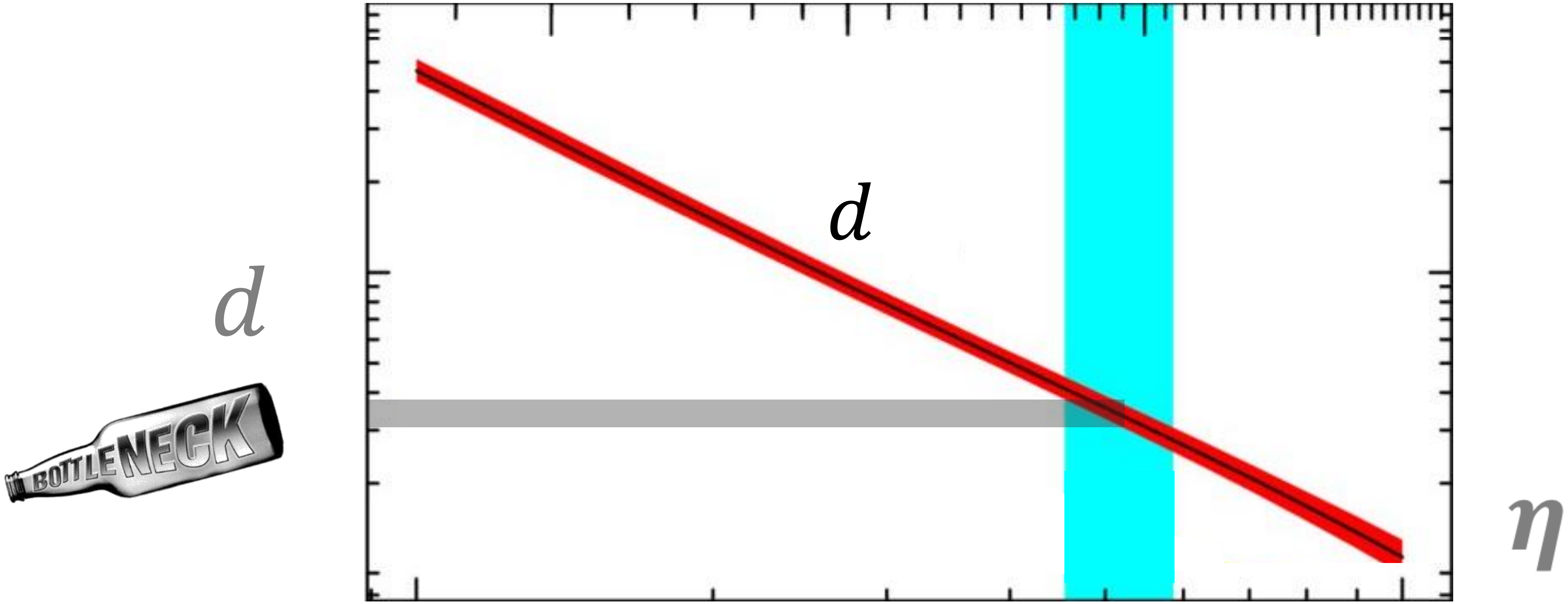
  - for increasing values of η we have more p, n relative to γ´s from heat bath ⇨ more baryons due to higher density ρ_B ⇨ less deuterium d (it ends up more efficiently in primordial ^4He



Light element yields as function of parameter η

- **Impact of baryon asymmetry η on abundance of primordial deuterium d**

  - deuterium is THE bottleneck of light element synthesis (small $E_B = 2.2\ MeV$) thus it is **best suited to deduce the baryon density Ω_B**



Light element yields as function of parameter η

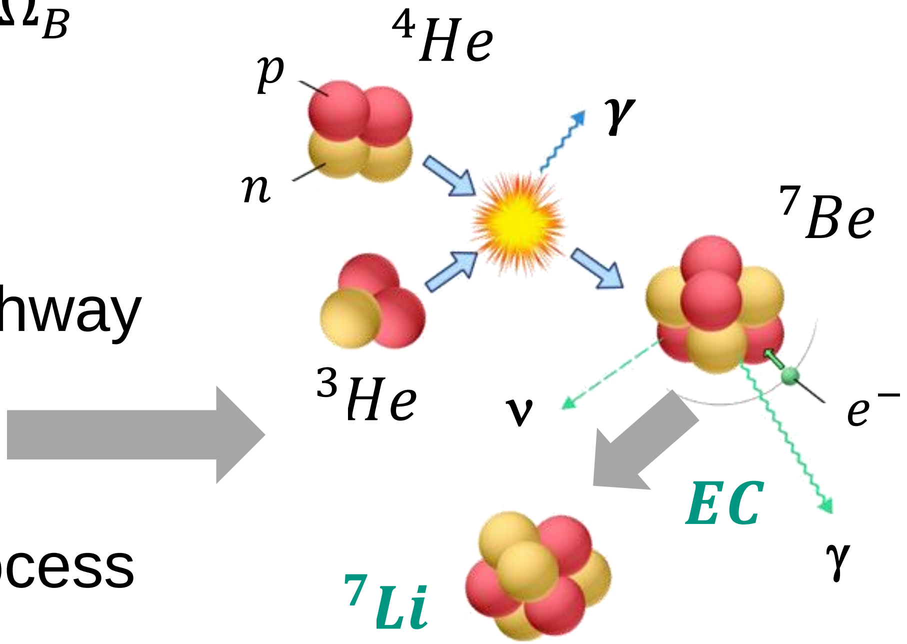
- **Impact of baryon asymmetry η on abundance of primordial lithium ^{7}Li**

- lithium has a **very small** primoridal abundance & mass fraction $< 10^{-7}$

- major challenge in measuring baryon density Ω_B with the abundance of ^{7}Li arises due to two reaction pathways:

a) for *smaller values* of η the EC reaction pathway $^{7}Be + e^{-} \rightarrow {}^{7}Li + \nu_e$ is dominant

b) for *larger values* of η the (t,γ)-capture process $^{4}He + {}^{3}H \rightarrow {}^{7}Li + \gamma$ is dominant



Light element yields as function of parameter η

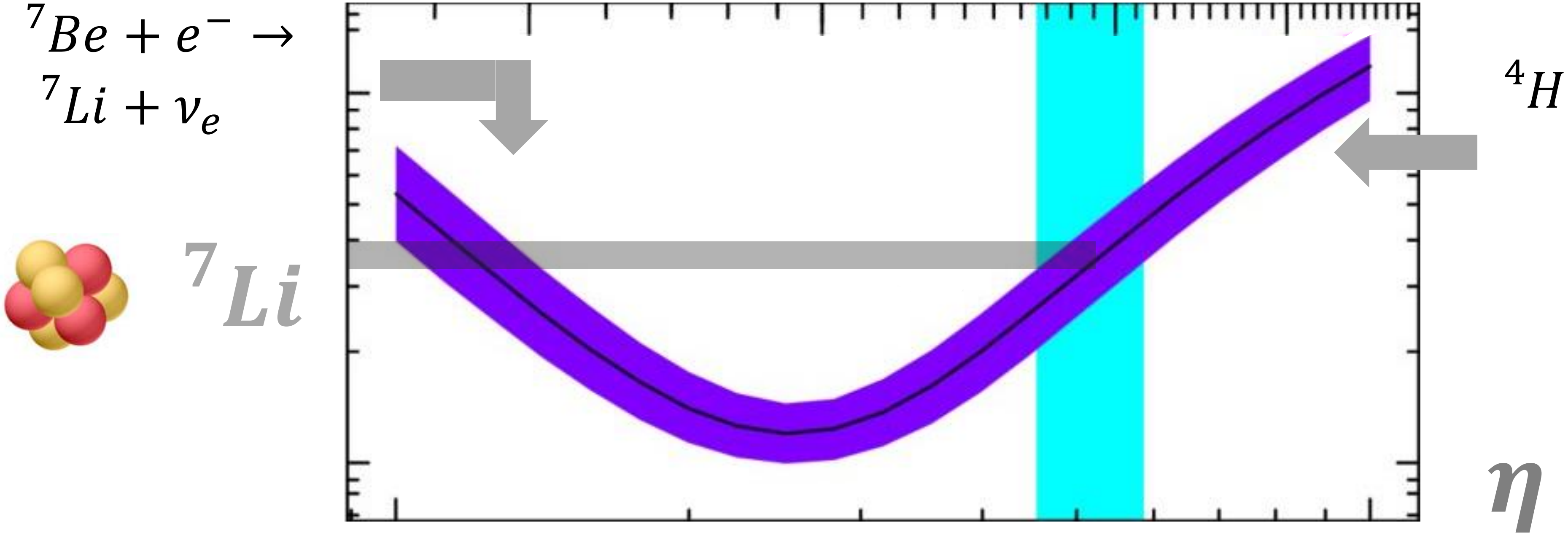
- **Impact of baryon asymmetry η on abundance of primordial lithium ^7Li**

  - lithium has a **very small** primoridal abundance & mass fraction $< 10^{-7}$

  - major challenge in measuring baryon density Ω_B

$^7Be + e^- \rightarrow$
$^7Li + \nu_e$

$^4He + {}^3H \rightarrow$
$^7Li + \gamma$



Light element yields & future e-mobility

- **Impact of baryon asymmetry η on abundance of primordial lithium ^{7}Li**

  - lithium has a **very small** primoridal abundance & mass fraction $< 10^{-7}$

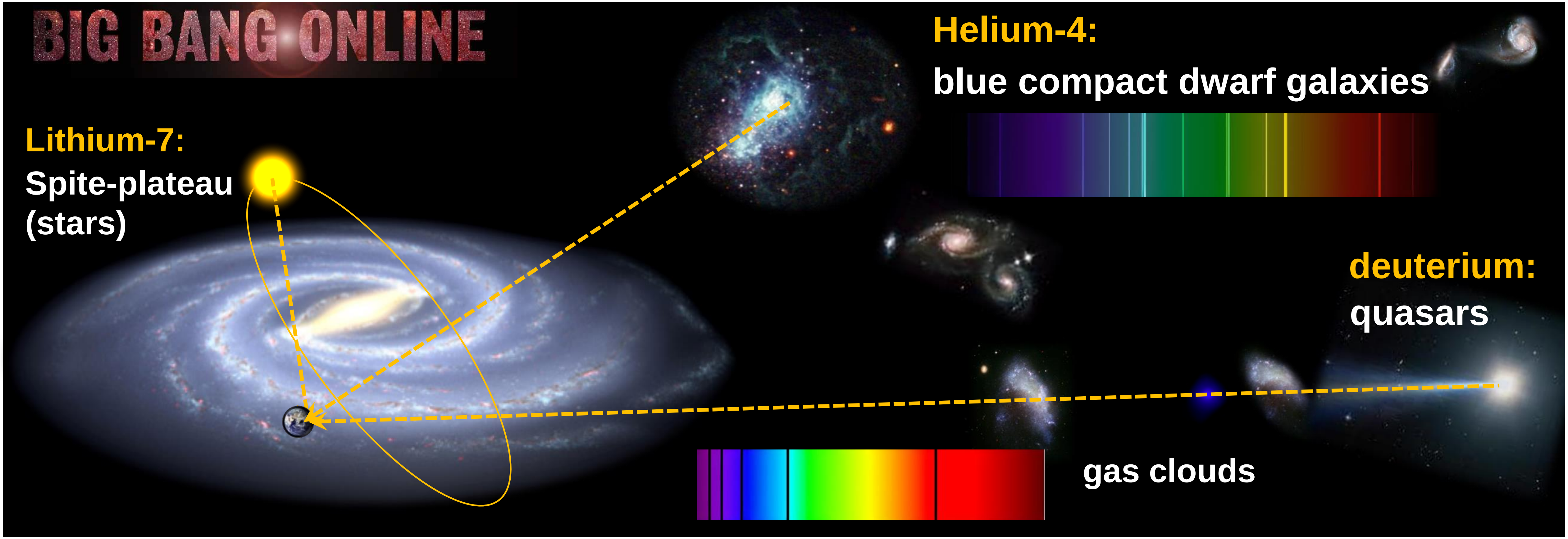
  - lithium is very important for the

powered by BBN

^{7}Li

Light element yields: spectroscopic results

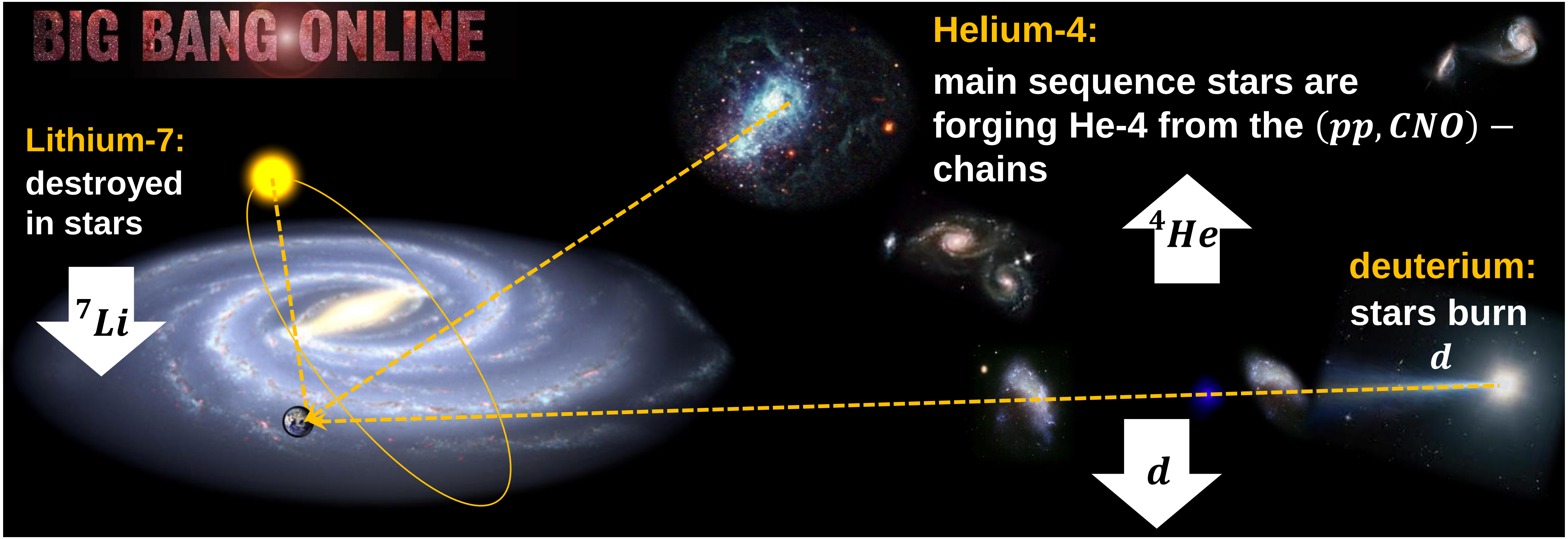
- **We want to determine the light element yields of BBN in the universe today!**
  - each element is identified by its characteristic emission/absorption lines



Light element yields: results & systematics

- **Do we determine the correct light element yields of BBN in the universe?**

  - each element abundance is **modified** by $13.8 \cdot 10^9\ yrs$ of stellar processes!



Lithium-7:
destroyed in stars

Helium-4:
main sequence stars are forging He-4 from the $(pp, CNO)-$chains

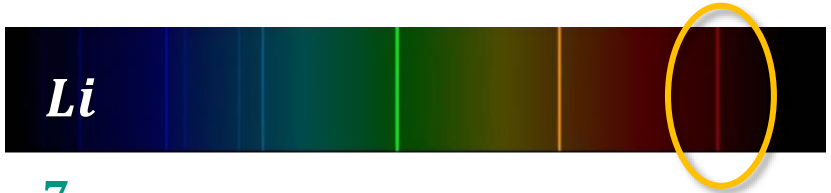
deuterium:
stars burn d

Light element yields: atomic physics as basis

- **Spectroscopy of the three light BBN elements $\boldsymbol{d}$, $\boldsymbol{{}^4He}$, $\boldsymbol{{}^7Li}$**

$\boldsymbol{{}^4He}$: emission lines from **recombination** processes of $\boldsymbol{He^+}$**- ions** in galactic $H{-}II$ - regions* and in Blue Compact Dwarf (BCD) galaxies

$\boldsymbol{{}^2H}$: absorption lines of ${}^2H(Ly-\alpha$ line) in extragalactic clouds along the line-of-sight of distant quasars (which provide a ´back-illumination´)



$\boldsymbol{{}^7Li}$: absorption lines of ${}^7Li$ in atmospheres of stars in halo (**Spite plateau**)

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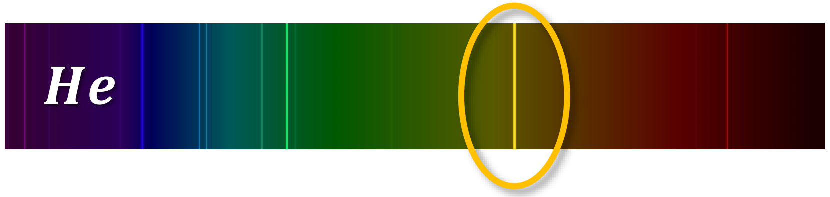
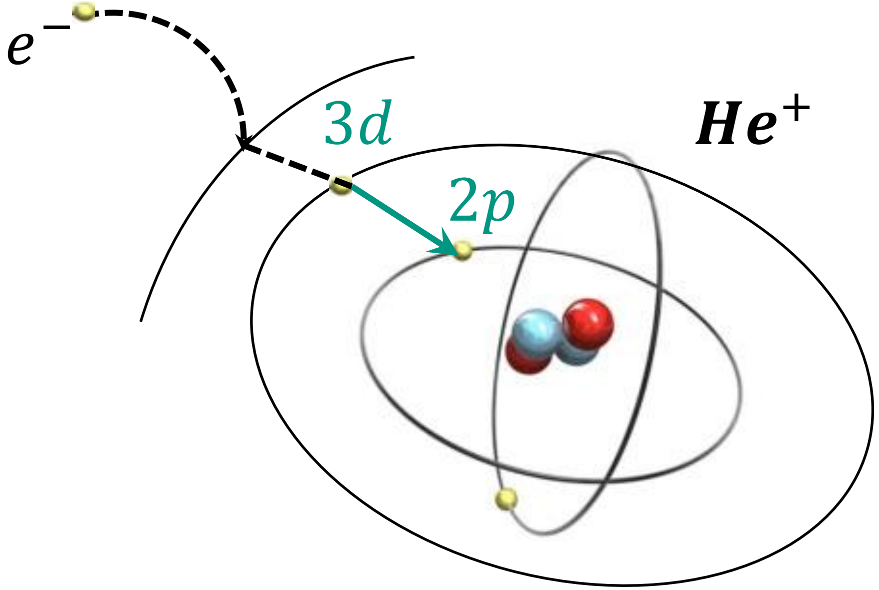
* clouds of singly ionised hydrogen atoms

Measuring the ^4He –abundance

- Using high-precision spectroscopy to measure the primordial ^4He yield



$\lambda = 587.6\ nm$



- transition $3d \rightarrow 2p$: strongest optical transition ideally suited for high-precision spectrographs

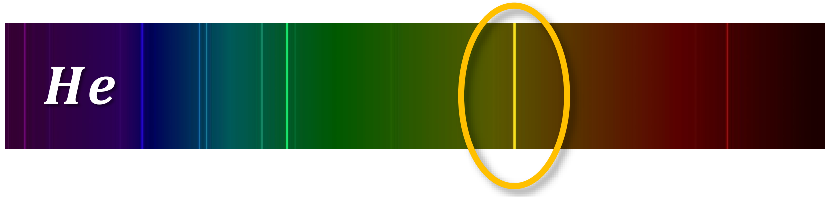

VLT – Very Large Telescope

$$1s\ \mathbf{3d}\ (23.07\ eV) \rightarrow 1s\ \mathbf{2p}\ (20.96\ \mathrm{eV})$$

$$\Delta E = 2.11\ eV\ (\lambda = 587.6\ nm, \text{ yellow line})$$

Measuring the ^{4}He –abundance

- **Observing Blue Compact Dwarf galaxies at the VLT spectrograph**

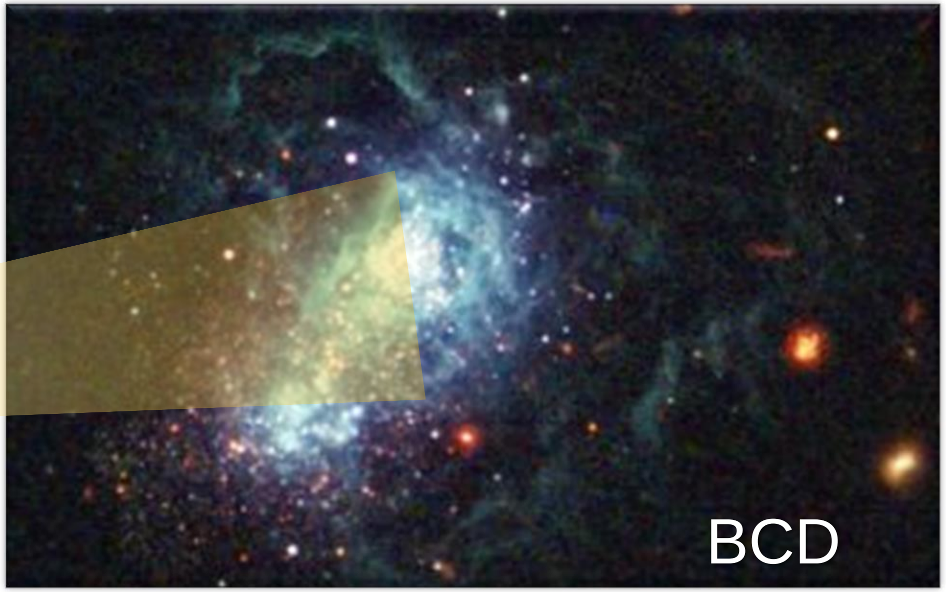


$$\lambda = 587.6\,nm$$

- BCDs: rich in gas – large star-forming regions ⇨ gas is ionised (He^{+}) by UV – light of very massive stars

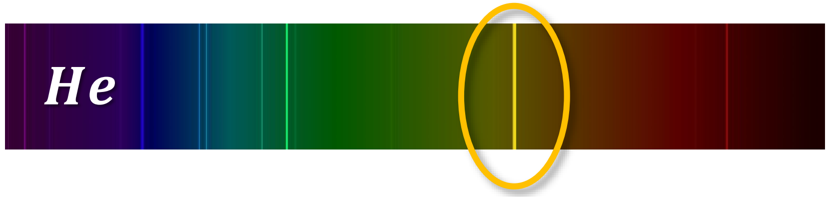
- BCDs: small galaxies – poor in ´metals´ ⇨ few stellar fusion reactions


VLT – Very Large Telescope


BCD

Measuring the ^4He −abundance

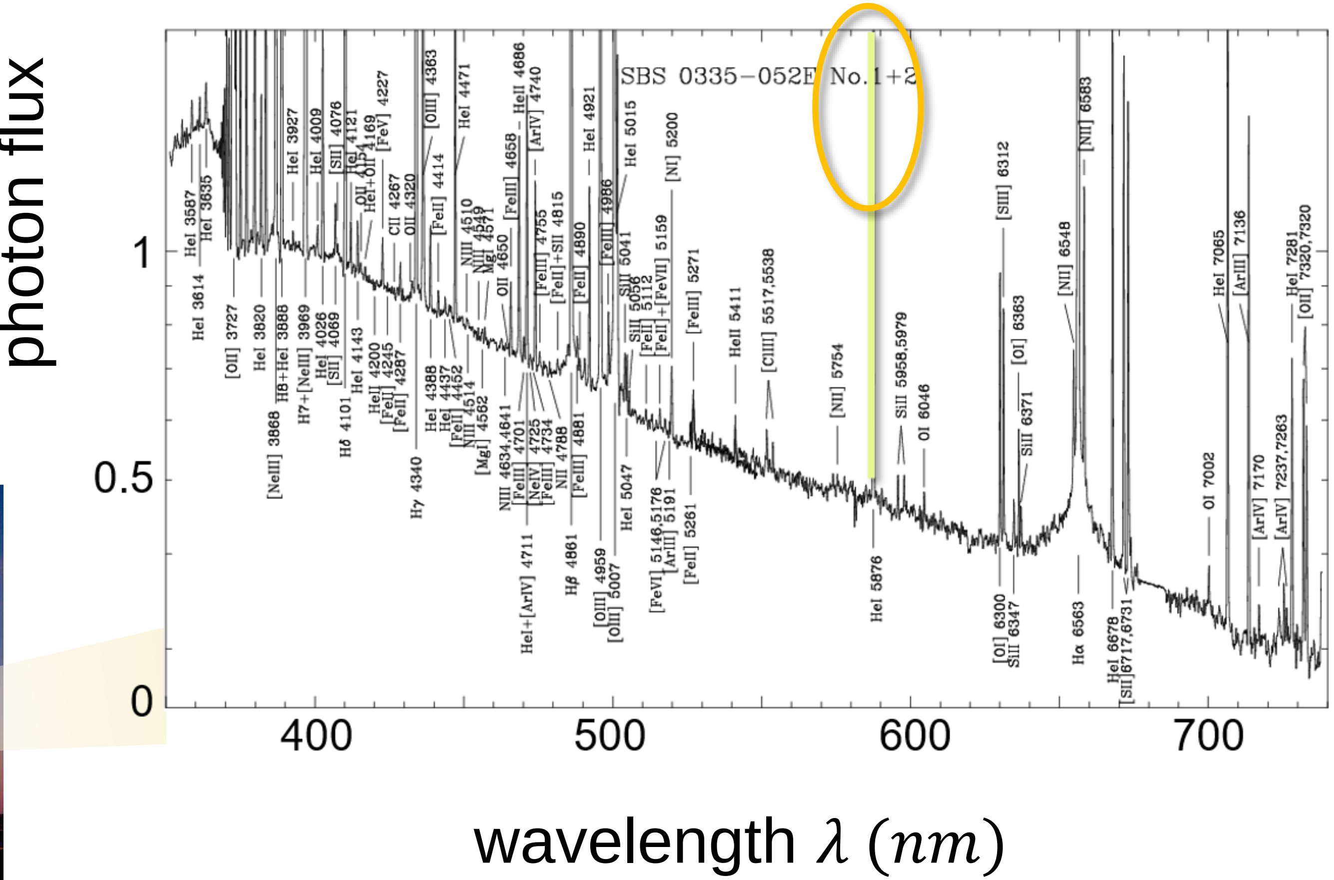
- **Observing Blue Compact Dwarf galaxies at the VLT spectrograph**



$$\lambda = 587.6\, nm$$

- BCDs: many line emissions visible, we analyse peak height at 587.6 nm


VLT – Very Large Telescope

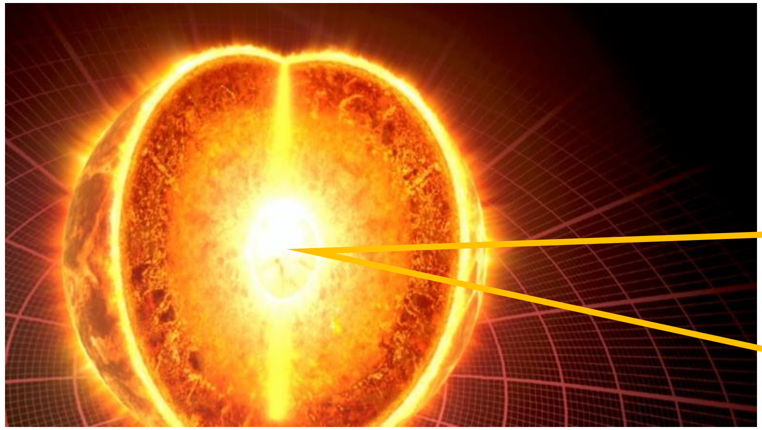


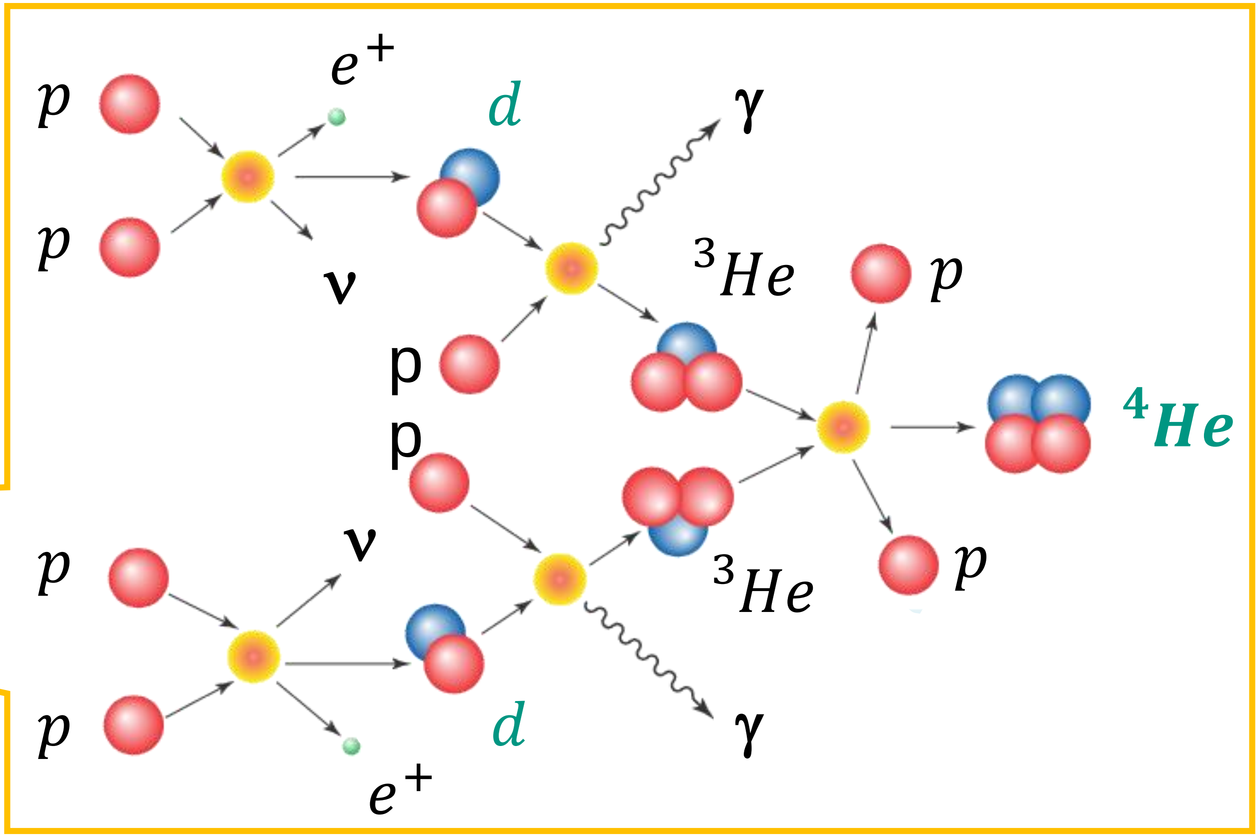
Measuring the ^4He –abundance: systematics

- **Abundance of ^4He in the universe continually increases due to fusion**

  - hydrogen burning: fusion cycles generate non-negligible amounts of ^4He

$$\left.\begin{array}{l}\text{- } pp - \\ \text{- } CNO - \end{array}\right\} 4\,p + 2e^- \to {}^4He + 2\nu_e$$



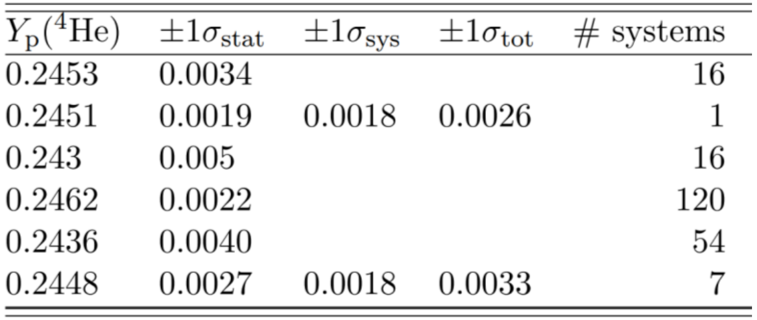


⇨ search for metal-poor* regions

*metallicity in astrophysics: ratio O/H

Measuring the ^4He –abundance: systematics

- Abundance of ^4He in the universe continually increases due to fusion



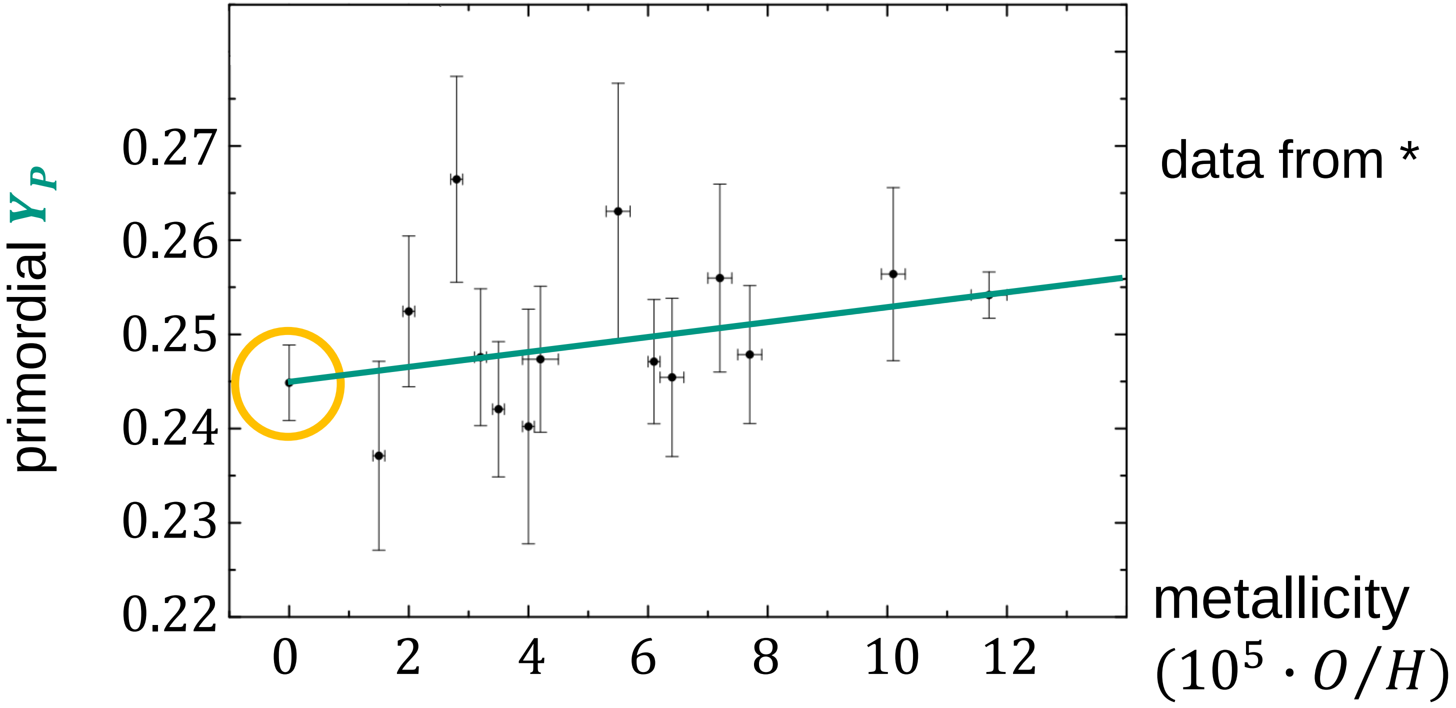
$Y_p(^4\mathrm{He})$	$\pm1\sigma_{\mathrm{stat}}$	$\pm1\sigma_{\mathrm{sys}}$	$\pm1\sigma_{\mathrm{tot}}$	# systems
0.2453	0.0034			16
0.2451	0.0019	0.0018	0.0026	1
0.243	0.005			16
0.2462	0.0022			120
0.2436	0.0040			54
0.2448	0.0027	0.0018	0.0033	7

2022 values

- good agreement with BBN theory

mass fraction of ^4He

$$Y_P = 0.245 \pm 0.003$$



data from *

*1503.08146.pdf (arxiv.org)

evaluation period – Dec. 5 – 16, 2022

- **Please take your time to evaluate the cosmo lectures & exercises/tutorials**

lectures: QR-code & link

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https://onlineumfrage.kit.edu/evasys/public/online/index/index?online_php=&p=AGFKD&ONLINEID=58057111675834557075727718326824247031928

exercises & tutorials: QR-code & link

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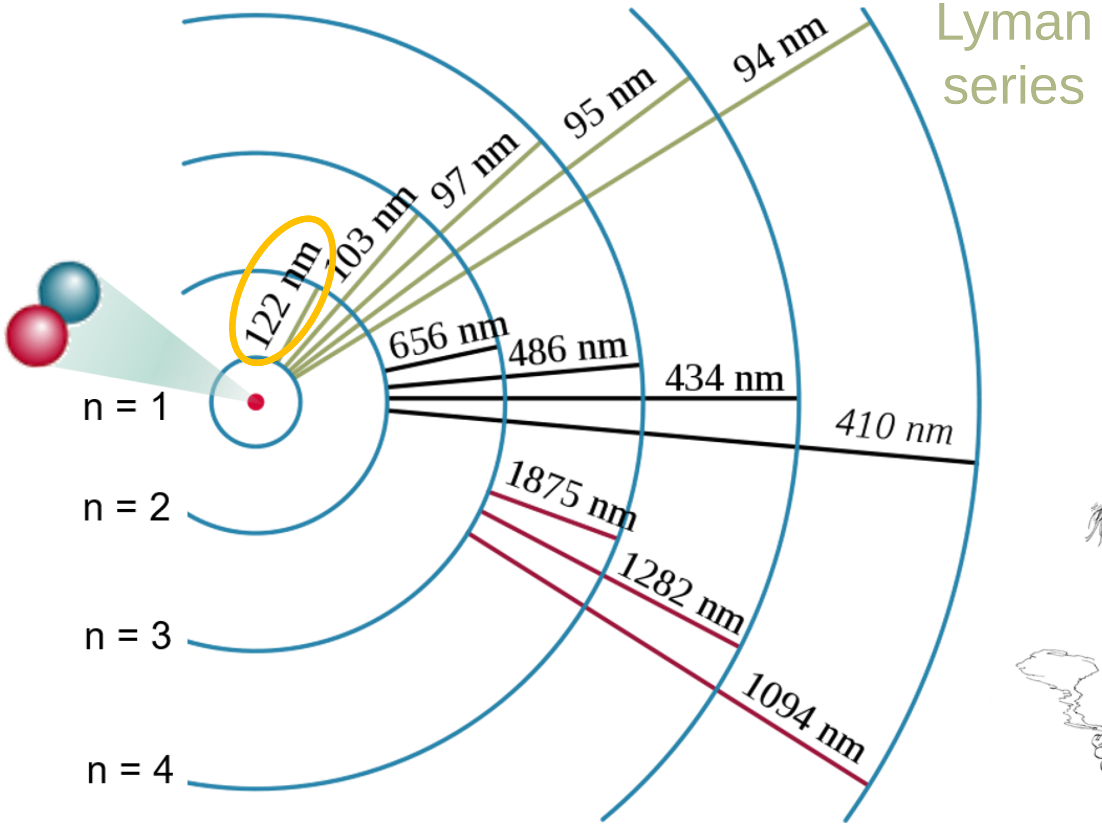
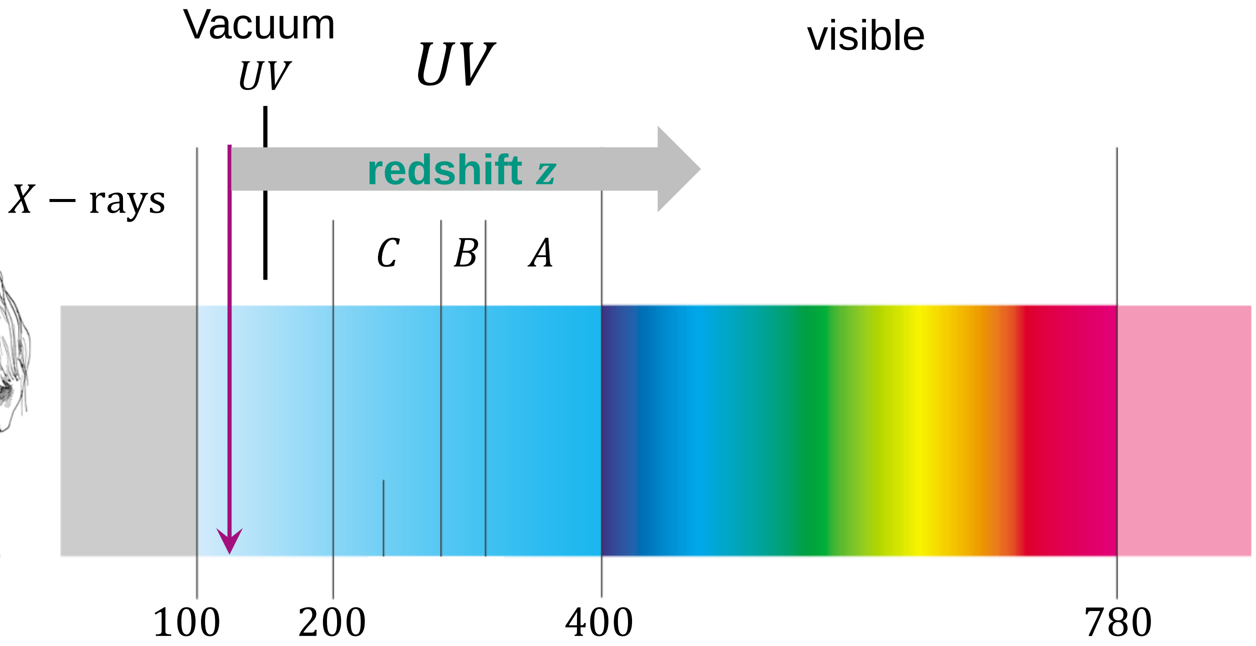
deuterium–abundance: $Ly - \alpha$ absorption line

- **We use the Lyman–α transition at $\lambda = 121.55\ nm$ to observe $d\ (\,^2H\,)$**

- Lyman–α line from $n = 2$ to $n = 1$

- redshift z from distant source will shift $Ly - \alpha$ line from VUV to visible spectrum



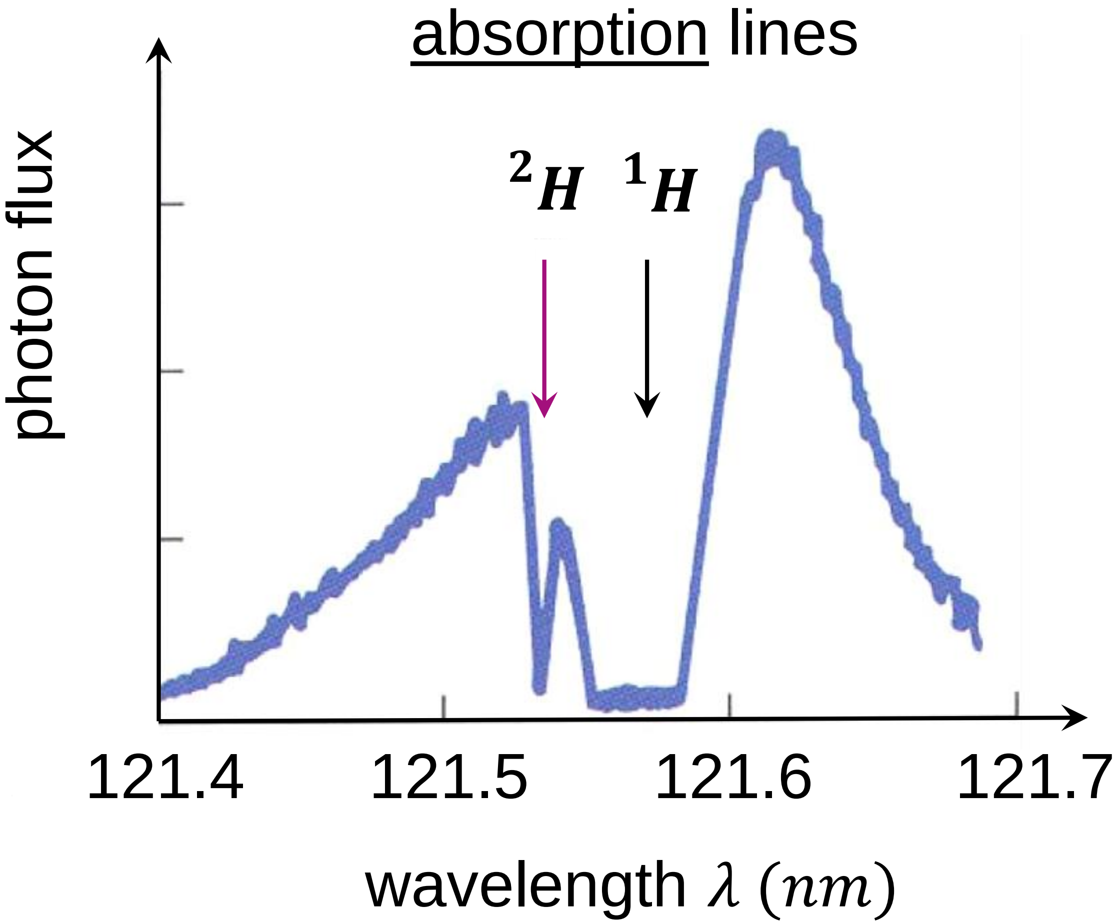


deuterium−abundance: $Ly-\alpha$ absorption line

- **Spectroscopic challenges to separate hydrogen isotope ^2H from ^1H**

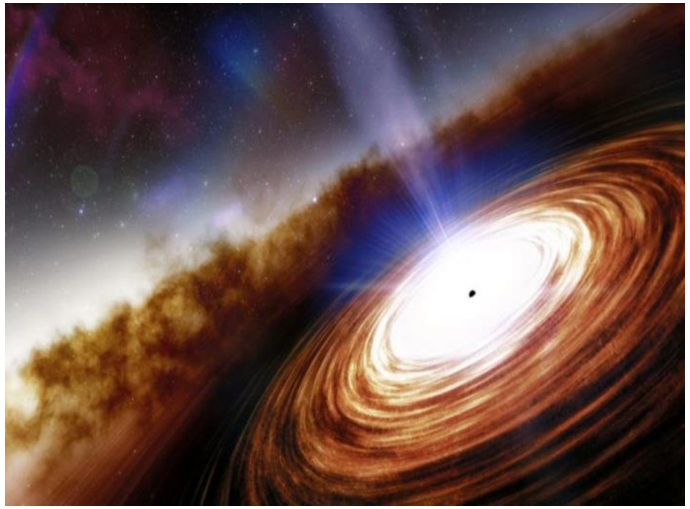
\- spectroscopic challenge #1:
the $Ly-\alpha$ −lines of ^2H and ^1H
lie very close together (only reduced
mass $\mu = (m_1 \cdot m_2)/(m_1+m_2)$ differs
⇨ resolution $\Delta E/E \approx 2.7 \cdot 10^{-4}$ needed

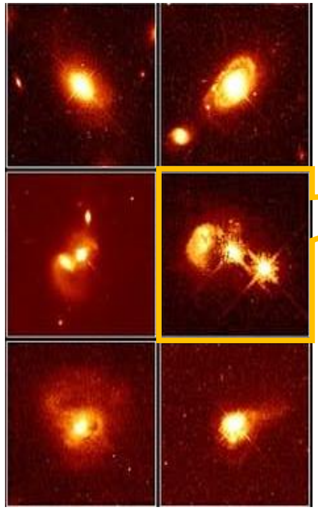
\- spectroscopic challenge #2:
the $Ly-\alpha$ −lines of ^2H and ^1H
differ by a huge amount in their
intensity (flux ratio ~ 10^{-5})
⇨ ^1H – line often saturated



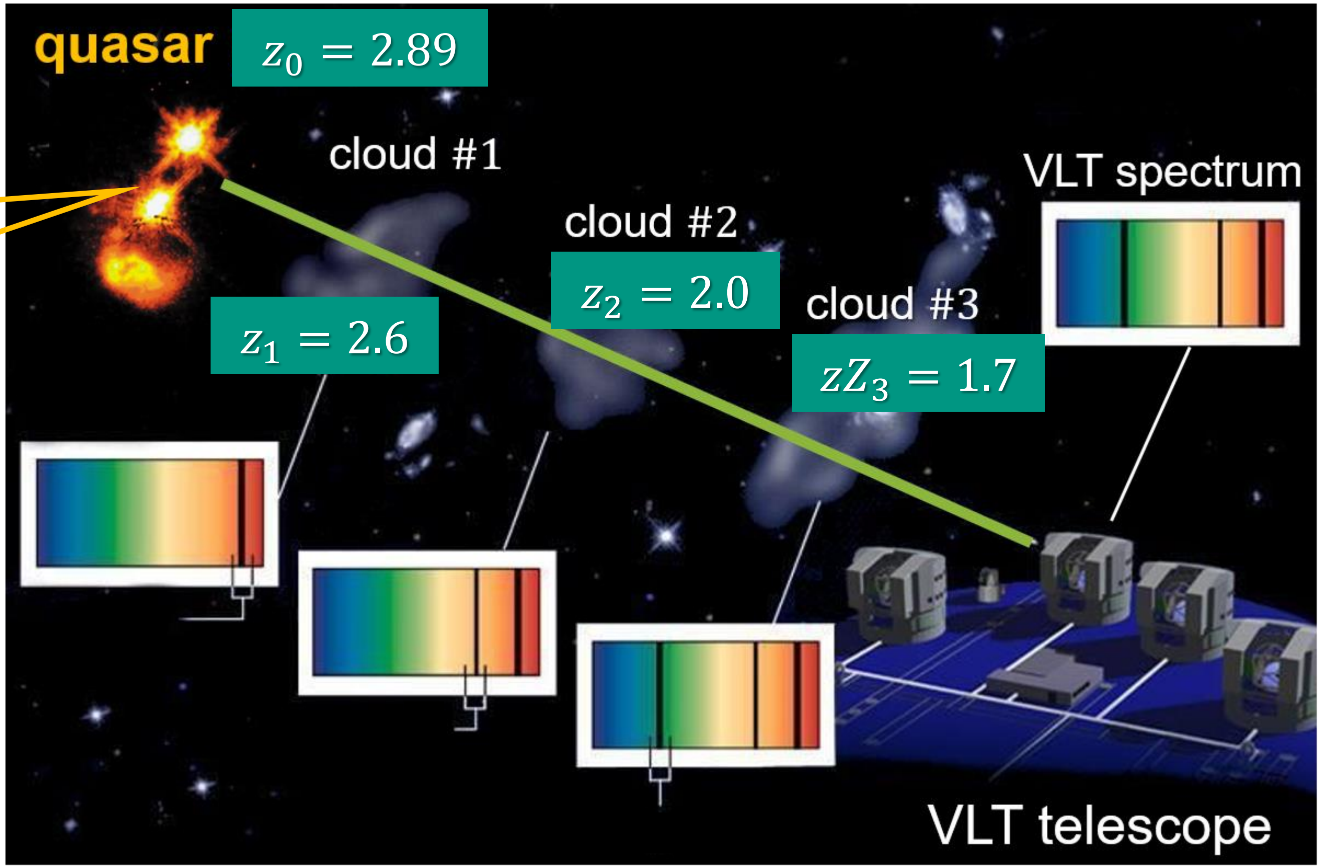
deuterium–abundance: $Ly - \alpha$ forest

- **Observing the absorption lines of gas clouds illuminated by quasars**





- quasar (supermassive black hole) at center of a galaxy acts as very bright beacon located far away, illuminating gaseous clouds with ^2H and ^1H on the line-of-sight

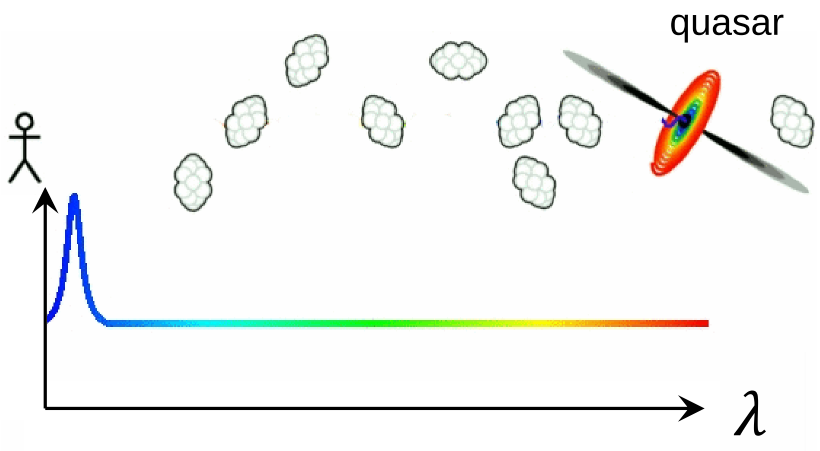


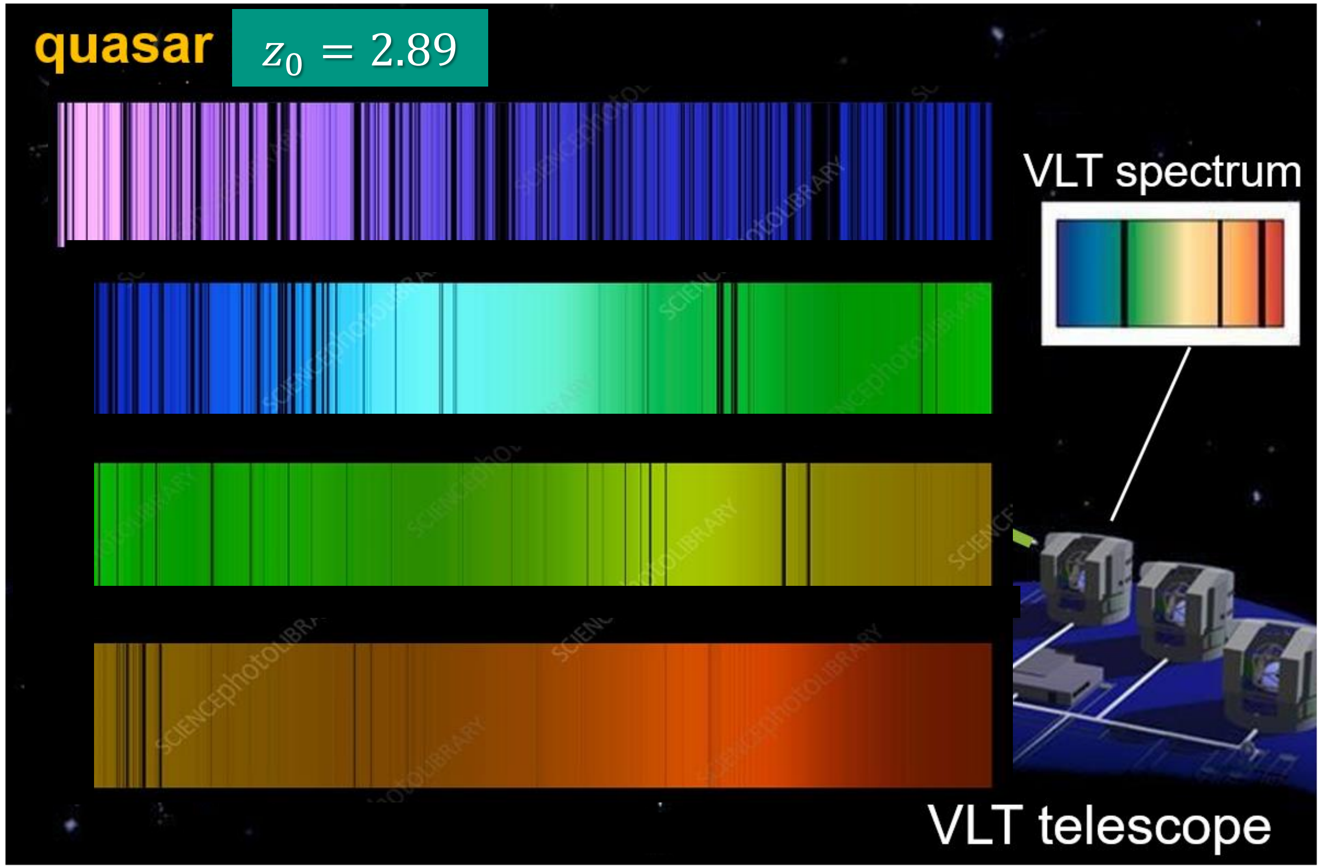
$Ly - \alpha$ absorption lines λ_i of extragalactic clouds

deuterium–abundance: $Ly - \alpha$ forest

- **Observing the absorption lines of gas clouds illuminated by quasars**

- each gas cloud absorbs quasar light at ist individual **cosmological distance z_i**
  ⇨ **the Lyman–α –forest**

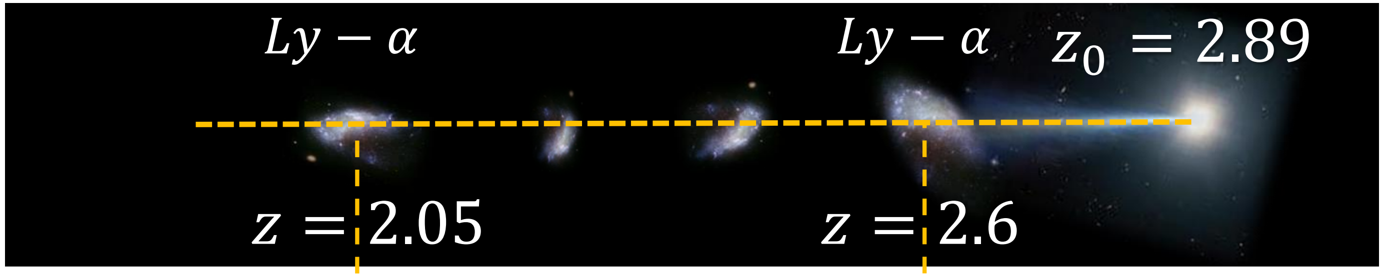




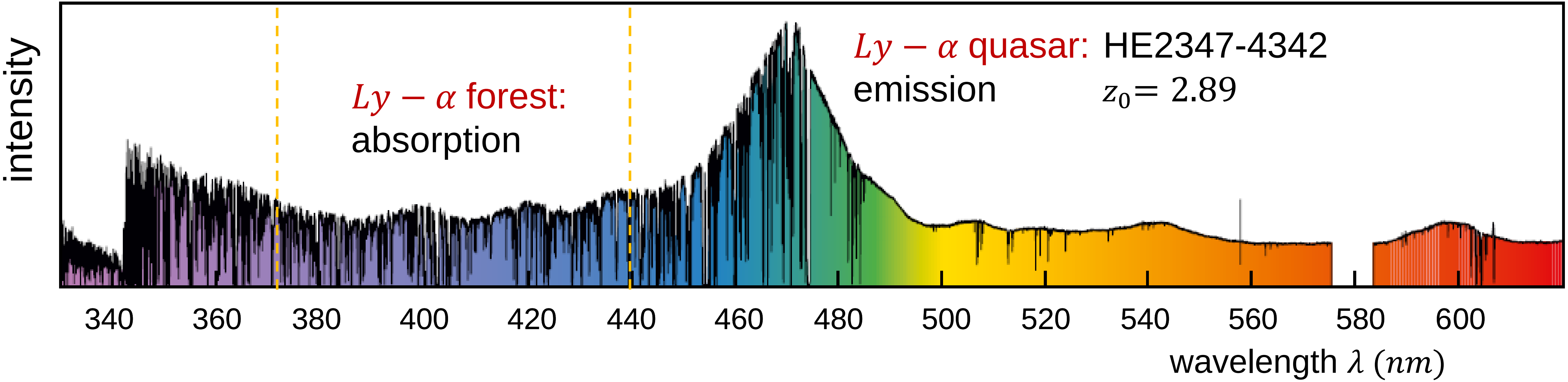
$Ly - \alpha$ absorption lines λ_i of extragalactic clouds

deuterium–abundance: $Ly-\alpha$ forest

- **Observing the absorption lines of gas clouds illuminated by quasars**
  - identify all lines that belong to a specific cloud at smaller redshifts* z_i



- line position $(z = 0) = 121.55\,nm$
- line position $(z_0 = 2.89) = 472.8\,nm$

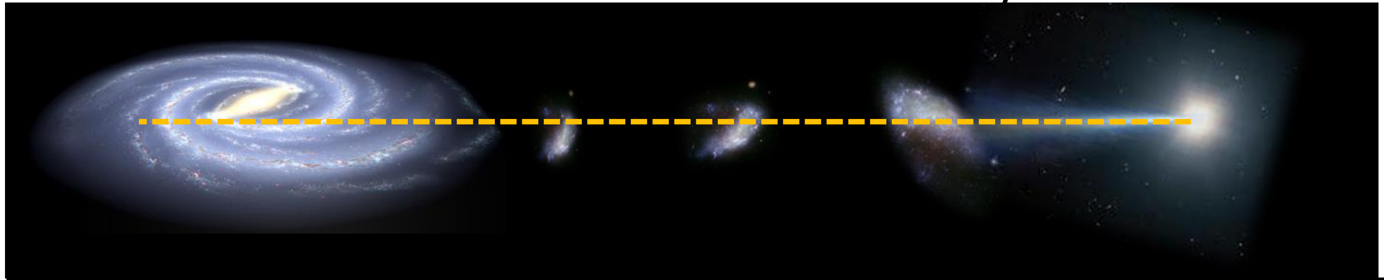


$^*z = (\lambda_{obs}/\lambda_{emit}) - 1$

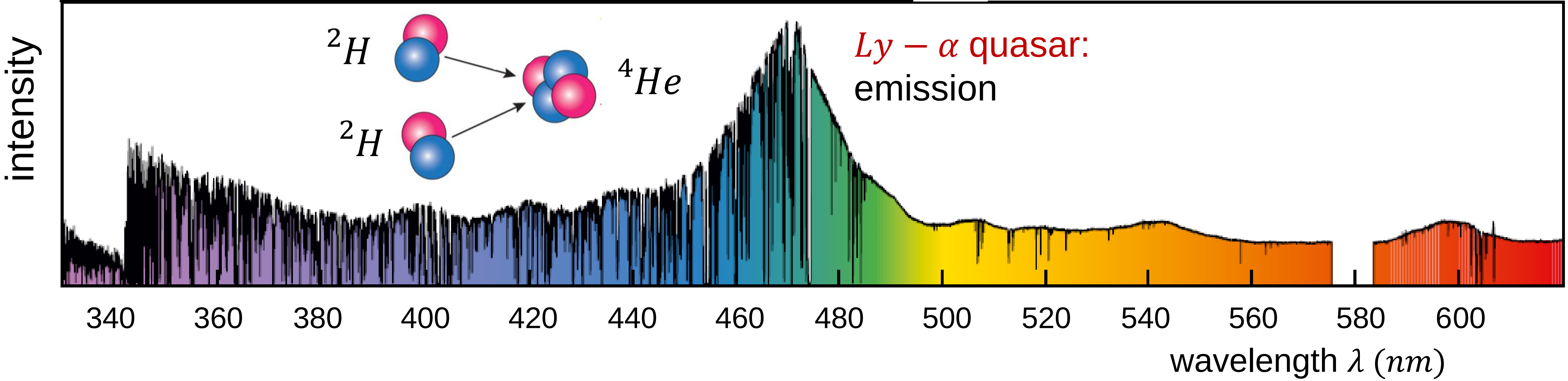
deuterium−abundance: $Ly - \alpha$ forest systematics

- **Deuterium is destroyed by fusion $(pp-, CNO -$chains$)$ due to stars**

  - identify the largest value of $^2H/\,^1H$ along the line-of-sight



- oldest objects: smaller systematics
- fusion: primordial d burned to ^4He



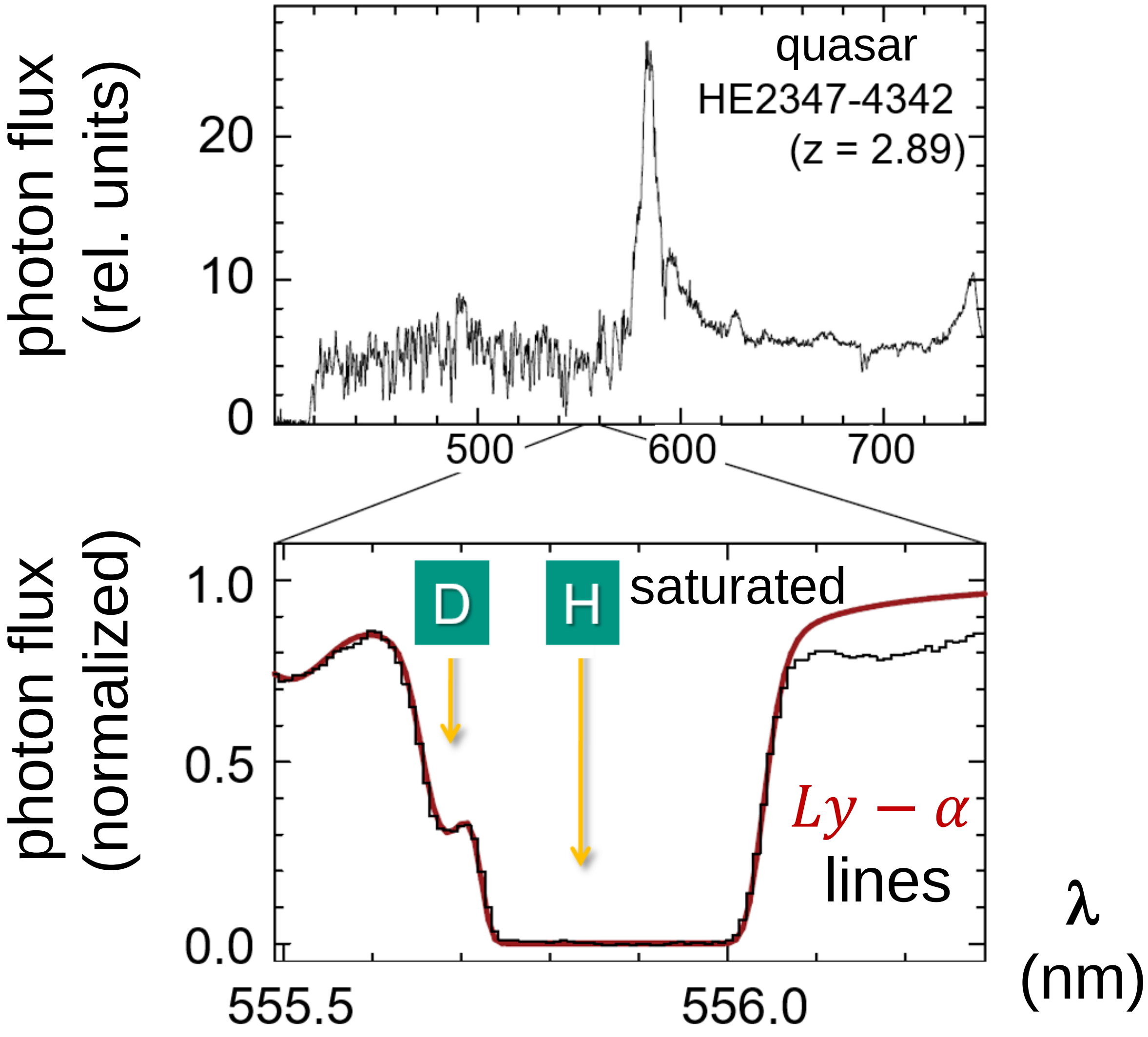
$^*z = (\lambda_{obs}/\lambda_{emit}) - 1$

deuterium−abundance: results

- **Analysis of line profiles and intensity ratios**
  - further challenges: extragalactic clouds can be rotating ⇨ lines are Doppler-broadened
  - further challenges: saturation of ^{1}H – line ⇨ use of other lines
  - present (2022) PDG-value:

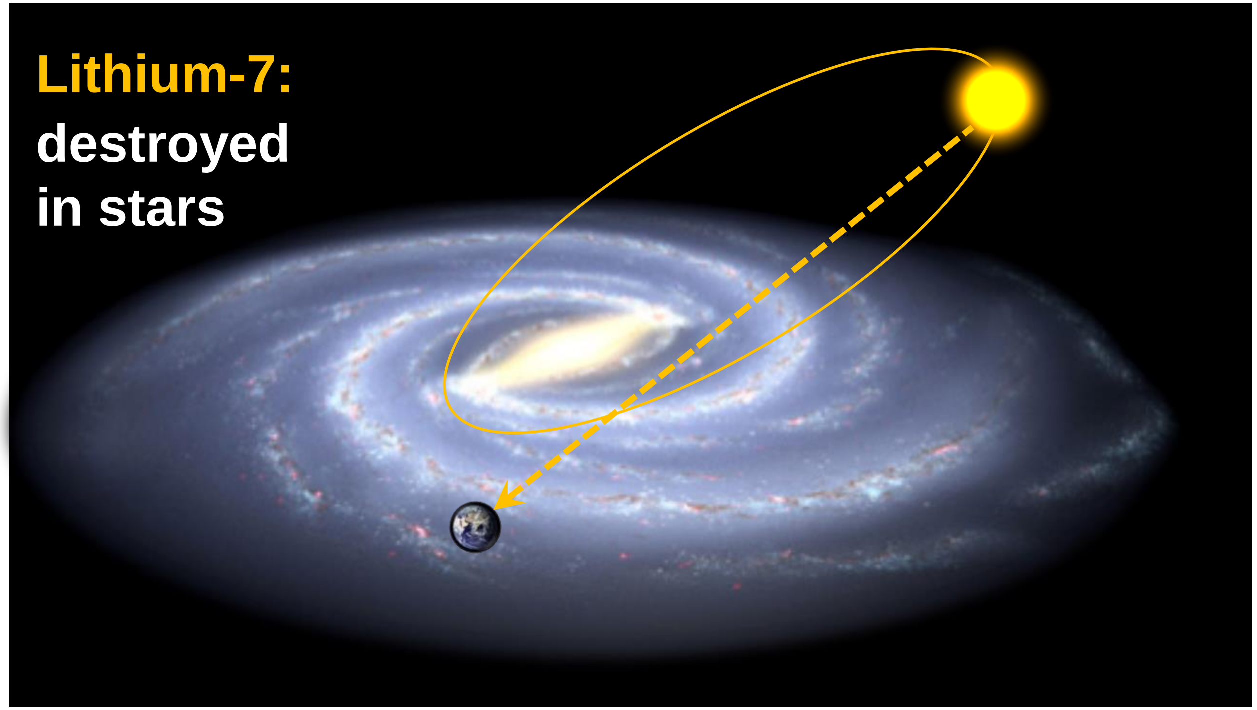
$$\boxed{\frac{D}{H} = (25.47 \pm 0.25) \cdot 10^{-6}}$$

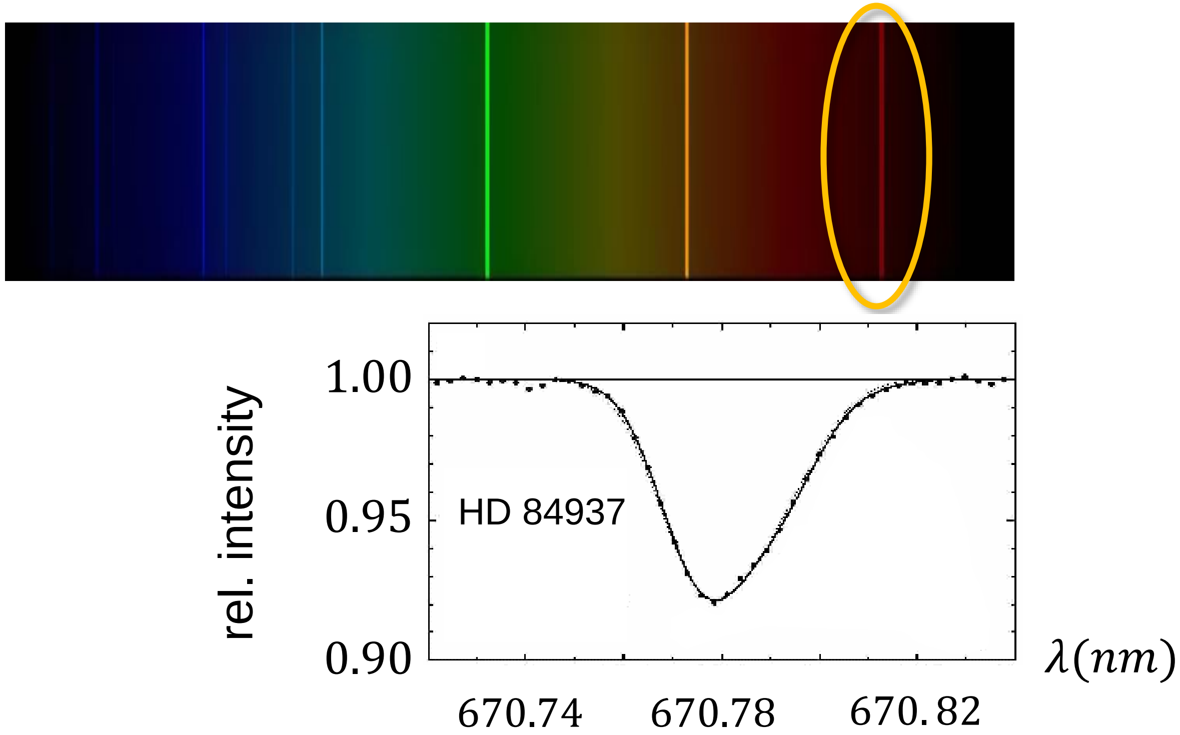
stat. + syst.



abundance of ^7Li – Spite plateau

- **Observation of absorption line from ^7Li: select old, metal-poor stars**
  - absorption (doublet-) line of ^7Li at deep red wavelength $\lambda = 670.7\,nm$
  - primordial ^7Li located in the atmosphere of the old, metal-poor star



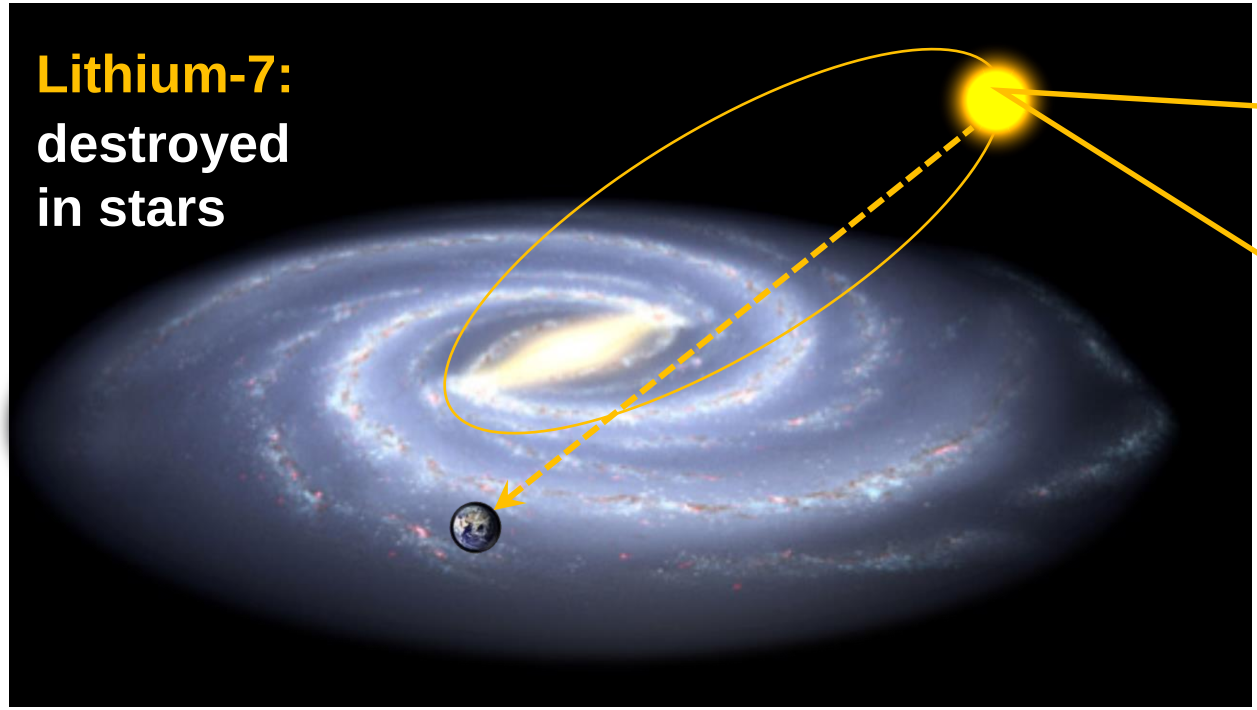


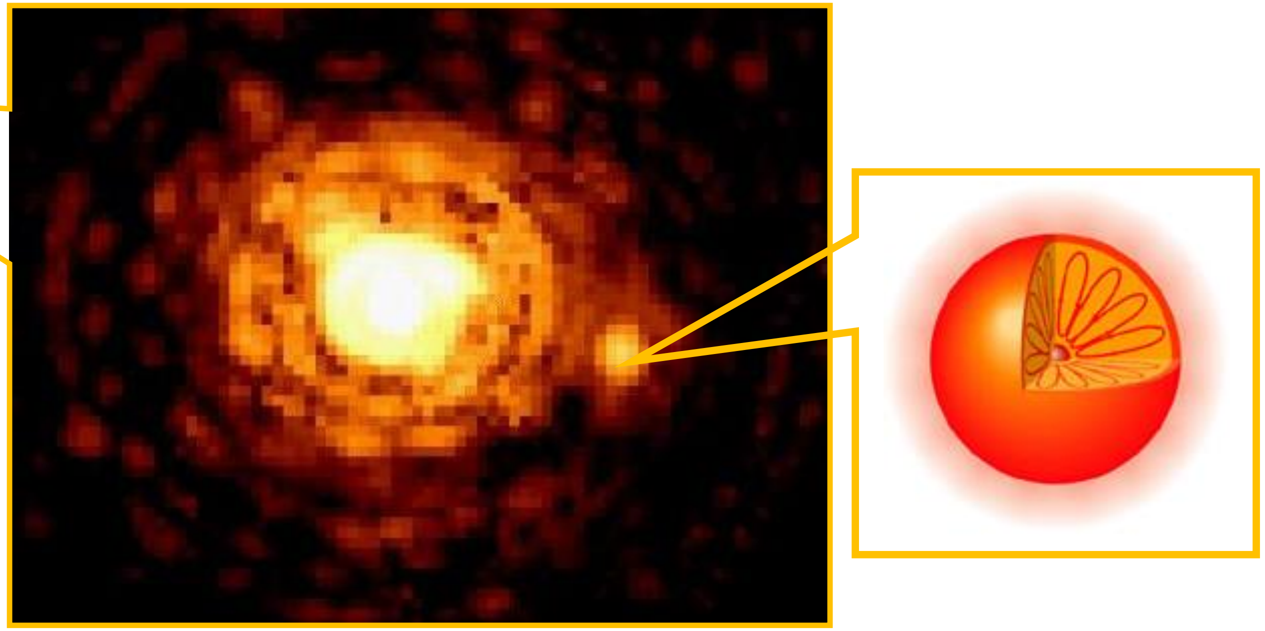
abundance of ^{7}Li – Spite plateau

- **Observation of absorption line from ^{7}Li: select old, metal-poor stars**

  - low-mass $\left(m \sim 0.1\ M_{\odot}\right)$ stars in the galactic halo: small fusion rates

  - stars with high surface temperature T: minimum amount of surface convection

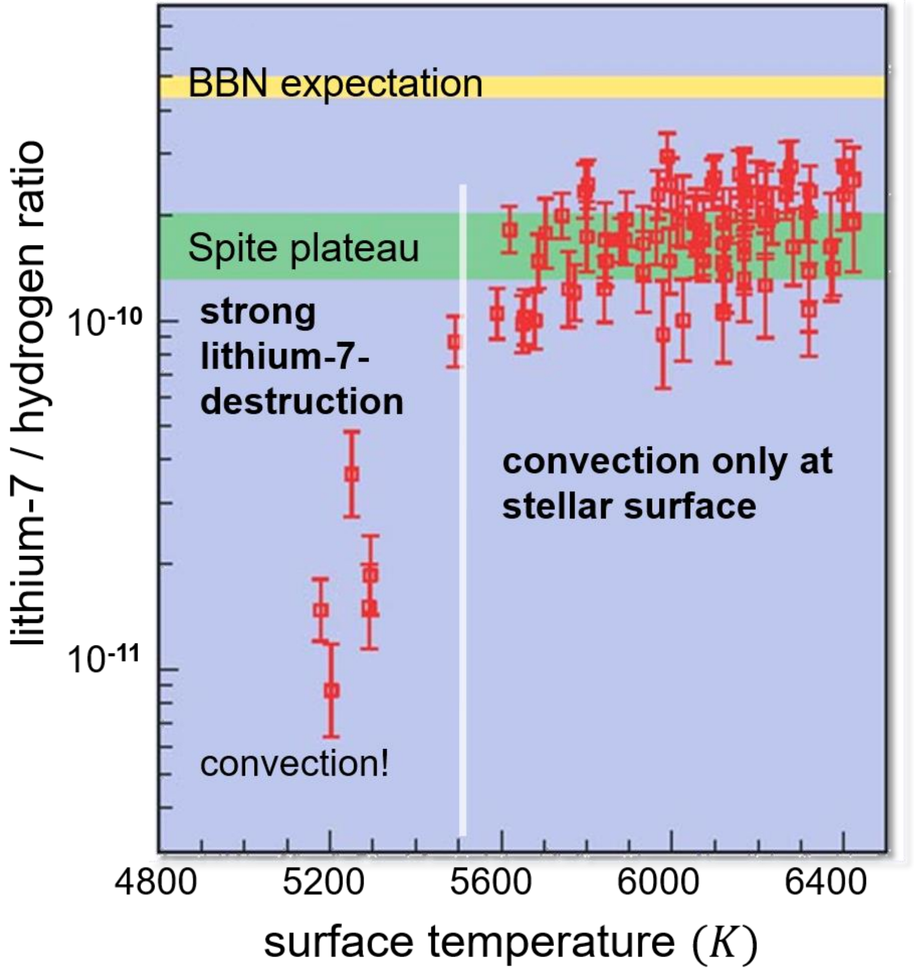




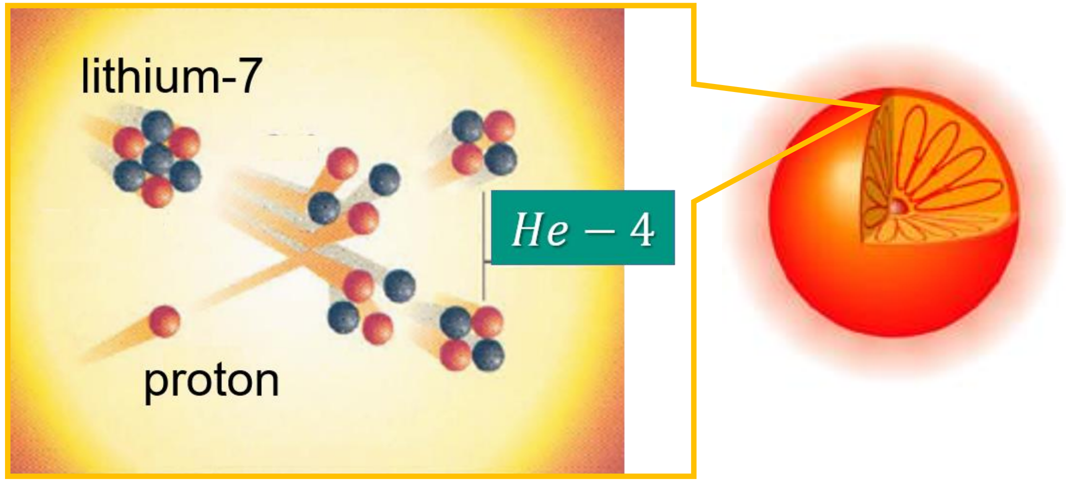
Gliese 623b – example of a low-mass star

abundance of ^7Li – Spite plateau

- **Observation of absorption line from ^7Li: select old, metal-poor stars**

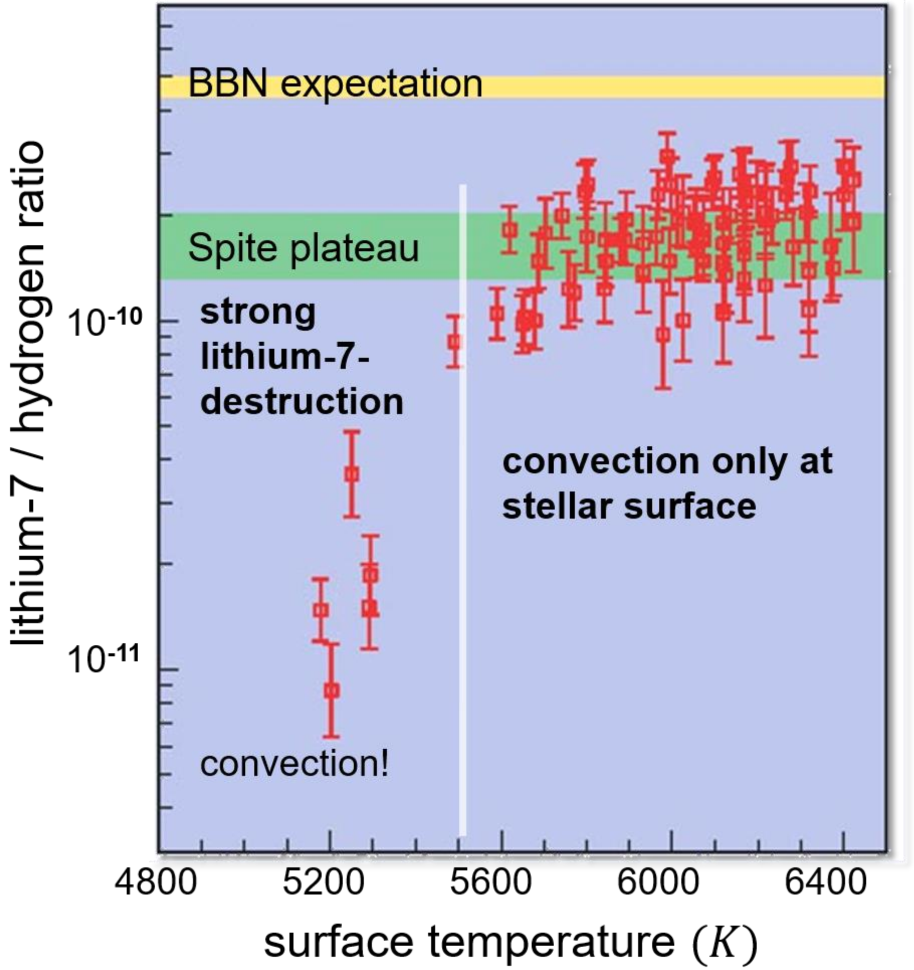


- stars with high surface temperature T:
  minimum surface convection
  ⇨ reduces dangerous buring of ^7Li
  which decreases the primordial yield



abundance of ^7Li – the ´anomaly´

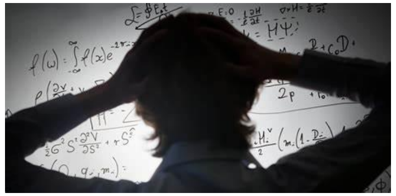
- **Observation of absorption line from ^7Li: a systematic effect unexplained**



- observed values of ^7Li below the BBN expectation: the ^7Li –anomaly manifests even in stars with high surface temperature (´Spite plateau´) ⇨ **missing lithium**

$$\boxed{\frac{Li}{H} = (1.6\ \pm 0.3) \cdot 10^{-10}}$$

- (wild?) speculations: is this due to time-varying natural constants or decaying dark matter??



Observed light element yields & baryon density

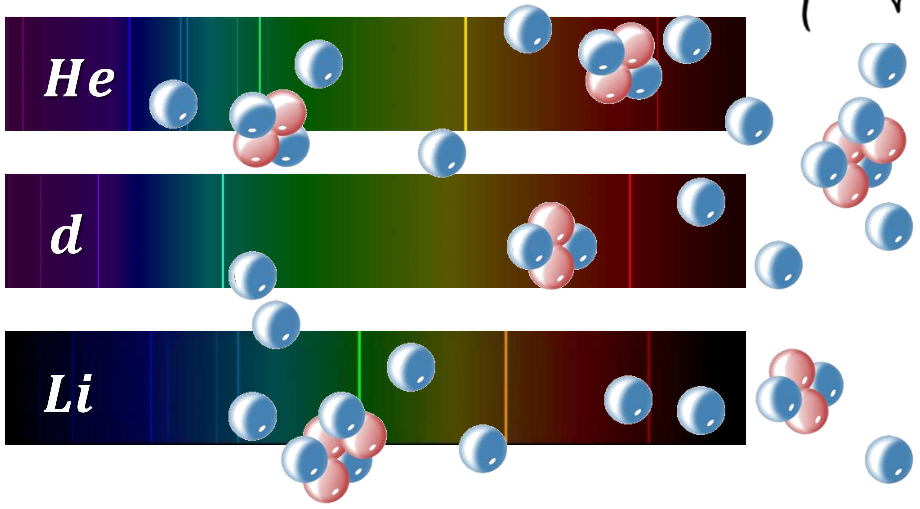
- **Combining results for ^4He, ^2H, ^7Li and comparison with Ω_B from the CMB**

- deriving Ω_B from

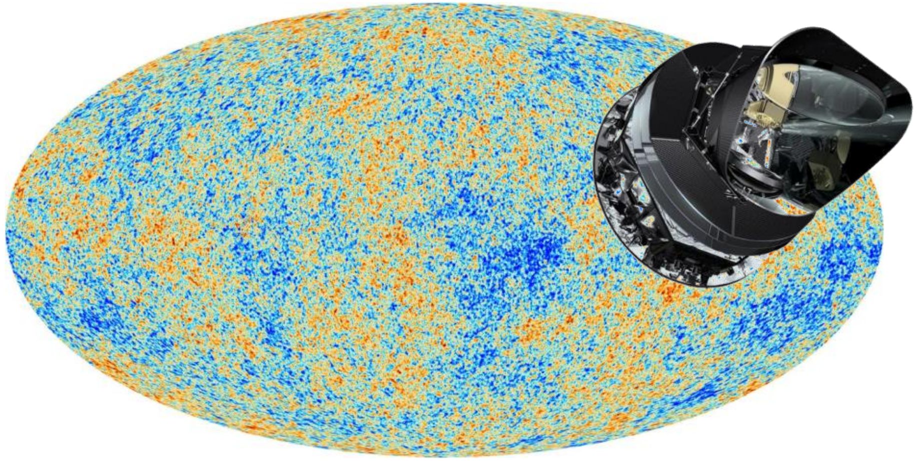
measurements of light element yields $(3\ min.)$

- deriving Ω_B from

measurement* of matter-photon oscillations $(380\ 000\ \text{yrs})$



baryon density



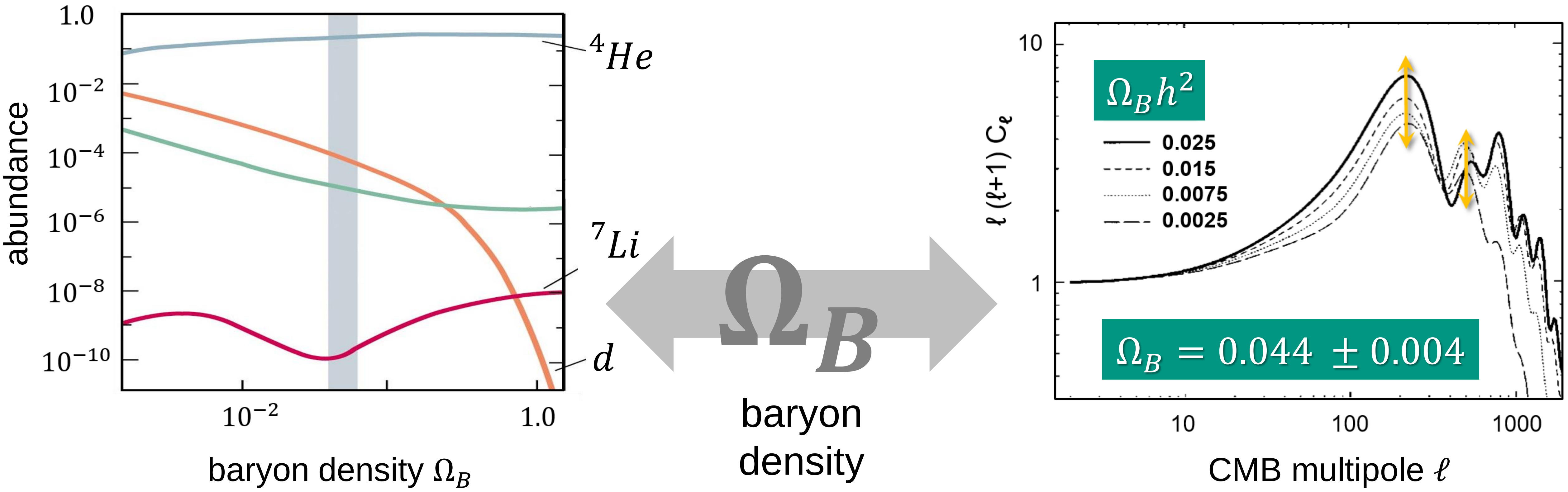
*see next chapter

Observed light element yields & baryon density

- **Combining results for ^4He, ^2H, ^7Li and comparison with Ω_B from the CMB**

- deriving Ω_B from

- deriving Ω_B from



Schramm plot for BBN

- **Comparison of BBN & CMB**

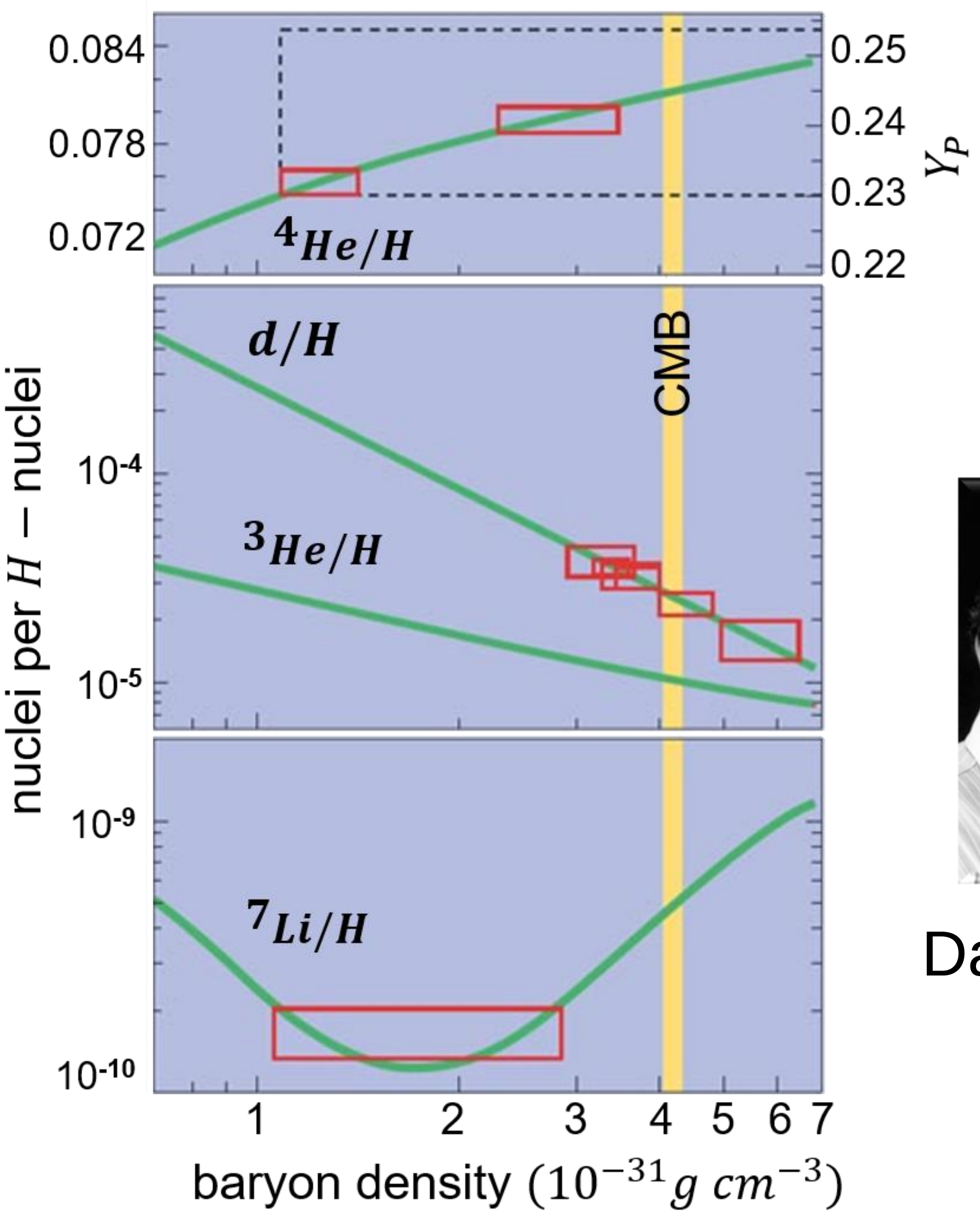
  - observed BBN light element yields are broadly consistent with precise CMB results, but **systematics remains**

  - with $N(\gamma)$ from CMB we have*

$$5.8 \le \eta_{10} \le 6.5 \; (95\% \; CL)$$

and thus $(h^2 \cong 0.5)$

$$0.021 \le \Omega_B h^2 \le 0.024 \; (95\% \; CL)$$



David Schramm

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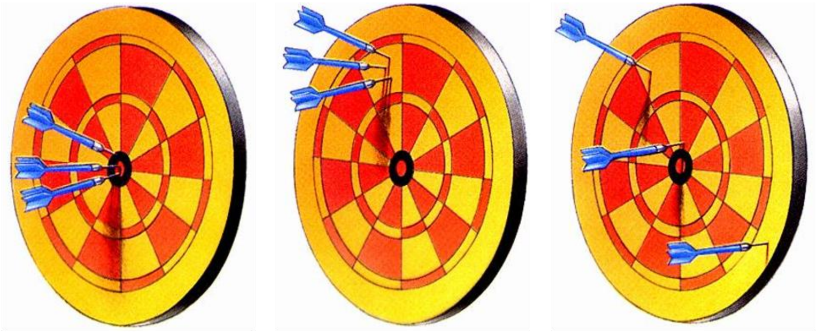
* η_{10} = baryon-asymmetry in units of 10^{-10}

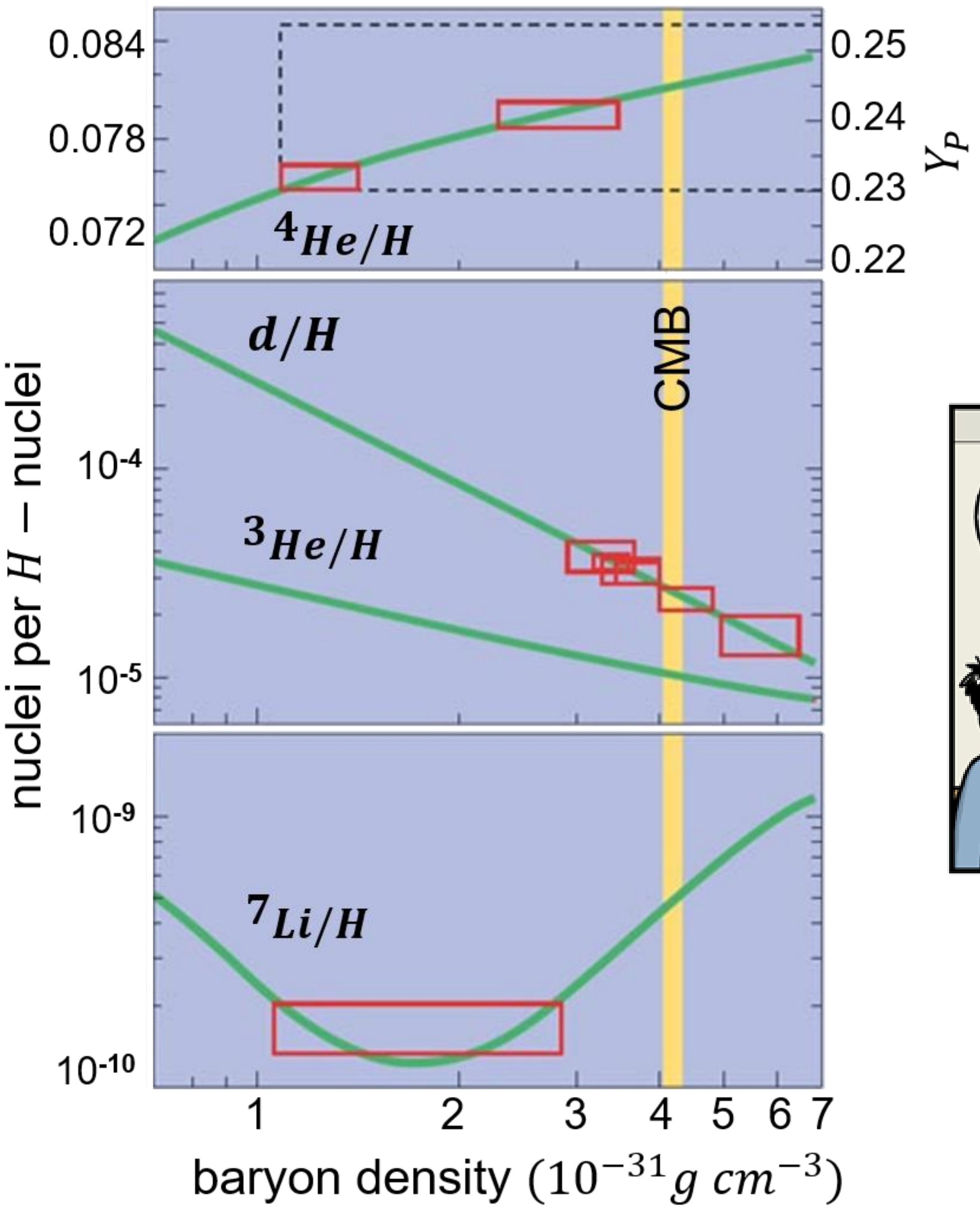
Schramm plot for BBN

- **Comparison of BBN & CMB**

- observed BBN light element yields are broadly consistent with precise CMB results, but **systematics remains**

- accuracy, trueness, precision

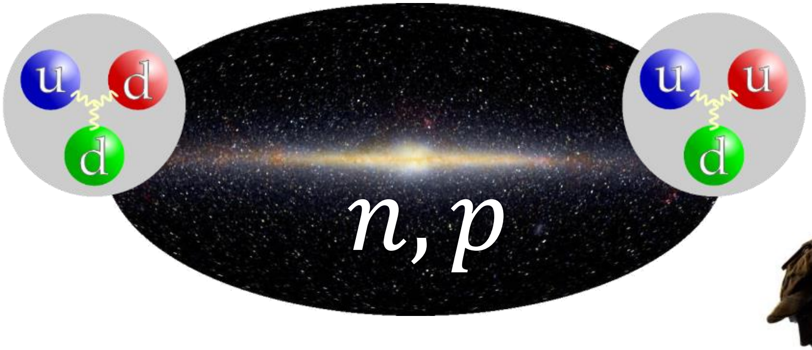




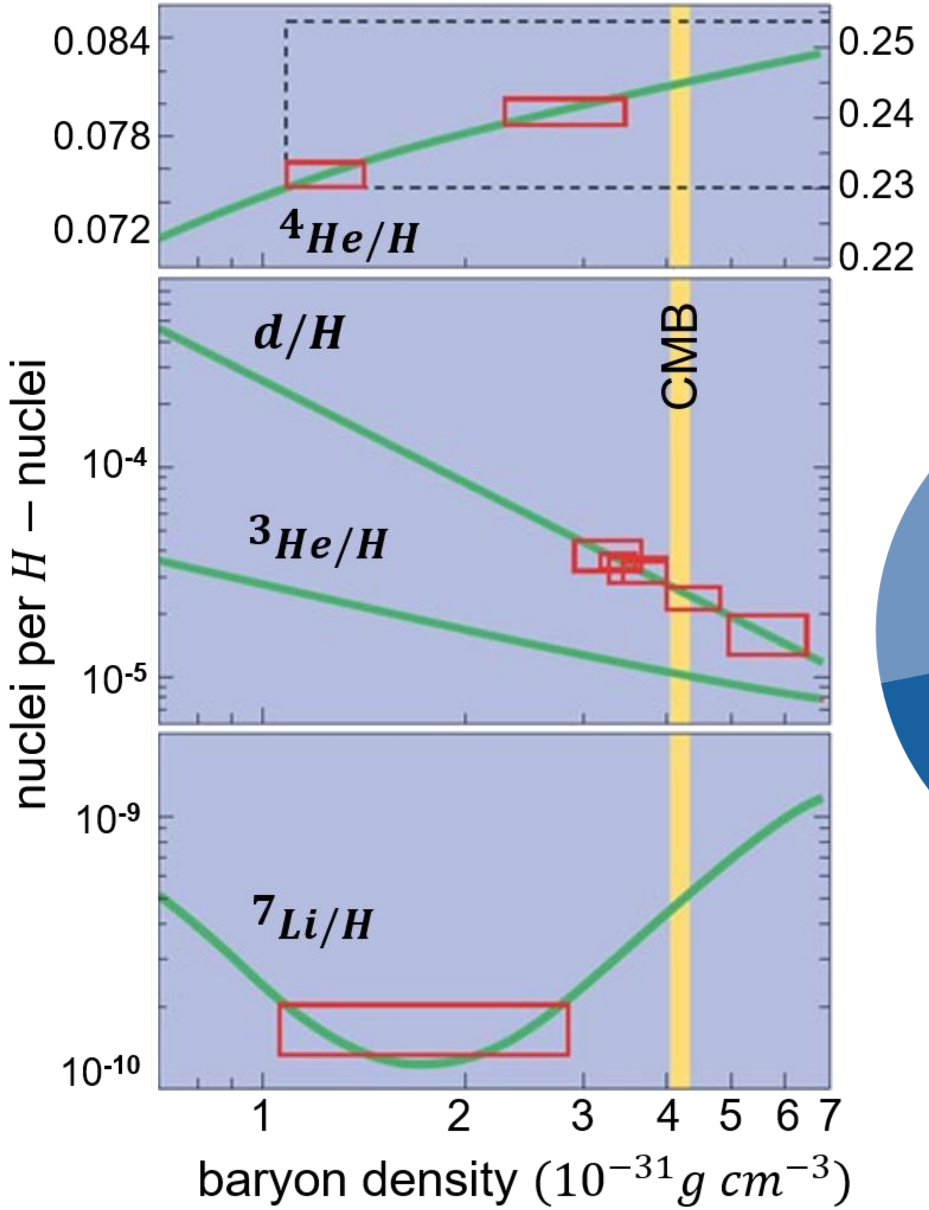
BBN & missing baryons

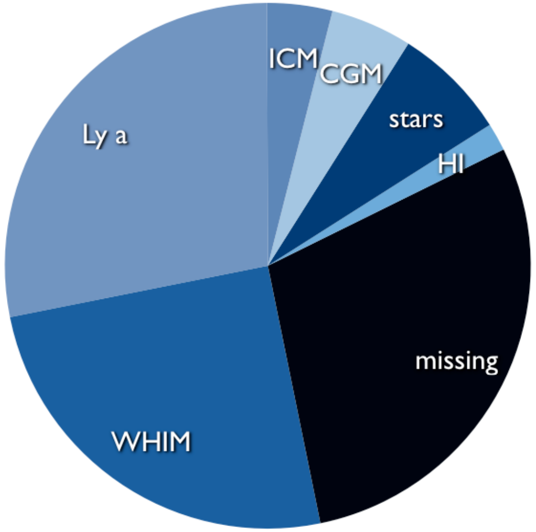
- **Case of ´missing baryons´**

  - observed, luminous baryons (galaxies & stars, cold gas, plasma, intergalactic medium) 30% less than expected from the *BBN* value



where have the baryons gone…?





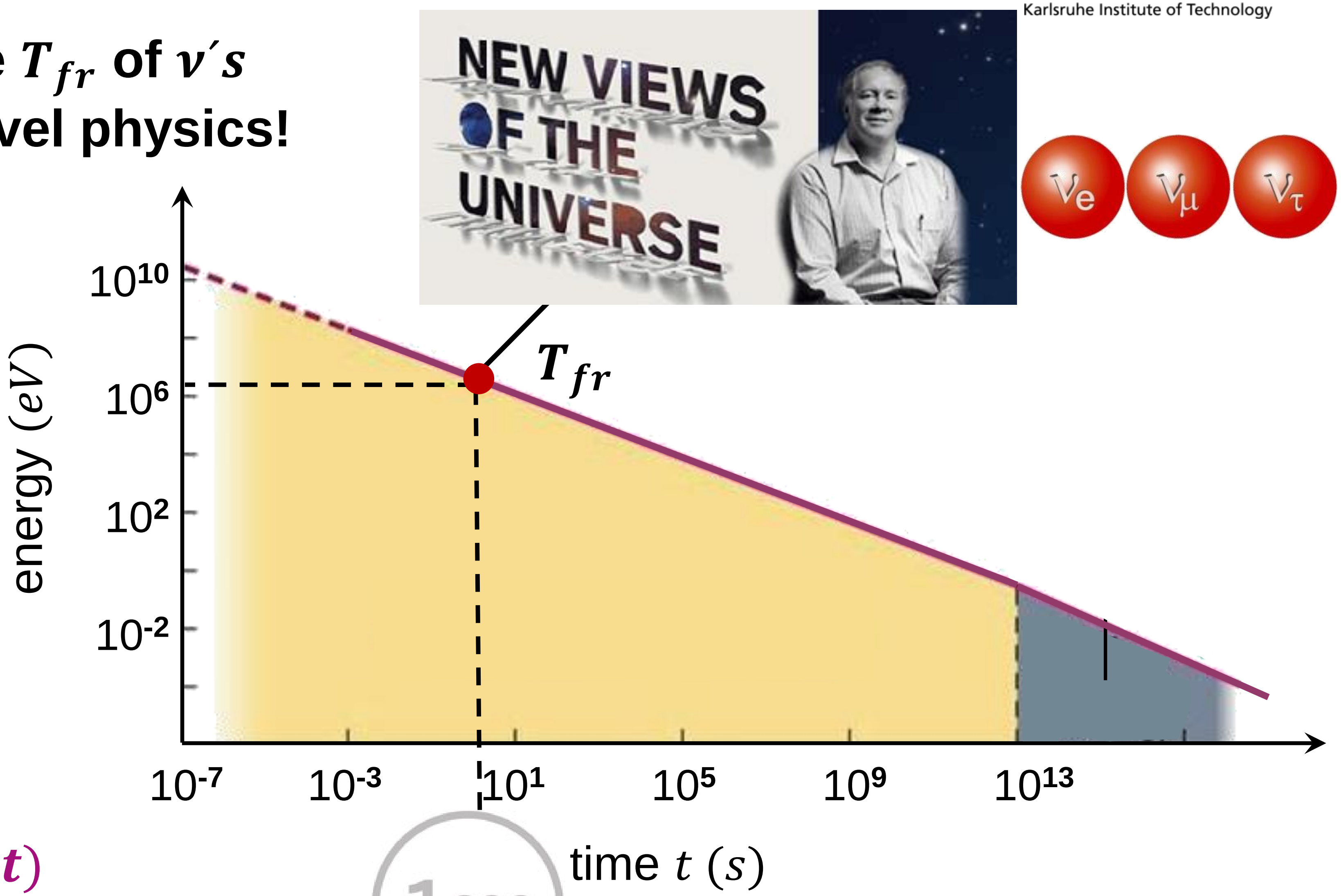
Schramm´s idea: *BBN* as tool for particle physics

- **Freeze-out temperature T_{fr} of $\nu´s$ may be changed by novel physics!**

  - RECAP: an important time stamp for BBN is when $\nu´s$ decouple at $t = 1\ s$ and $T = 1\ MeV$

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

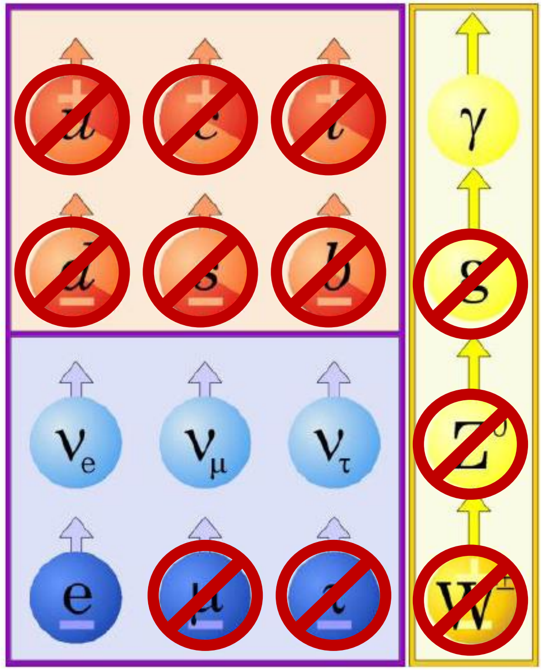
idea: the number N_ν of $\nu -$ generations impacts $H(t)$

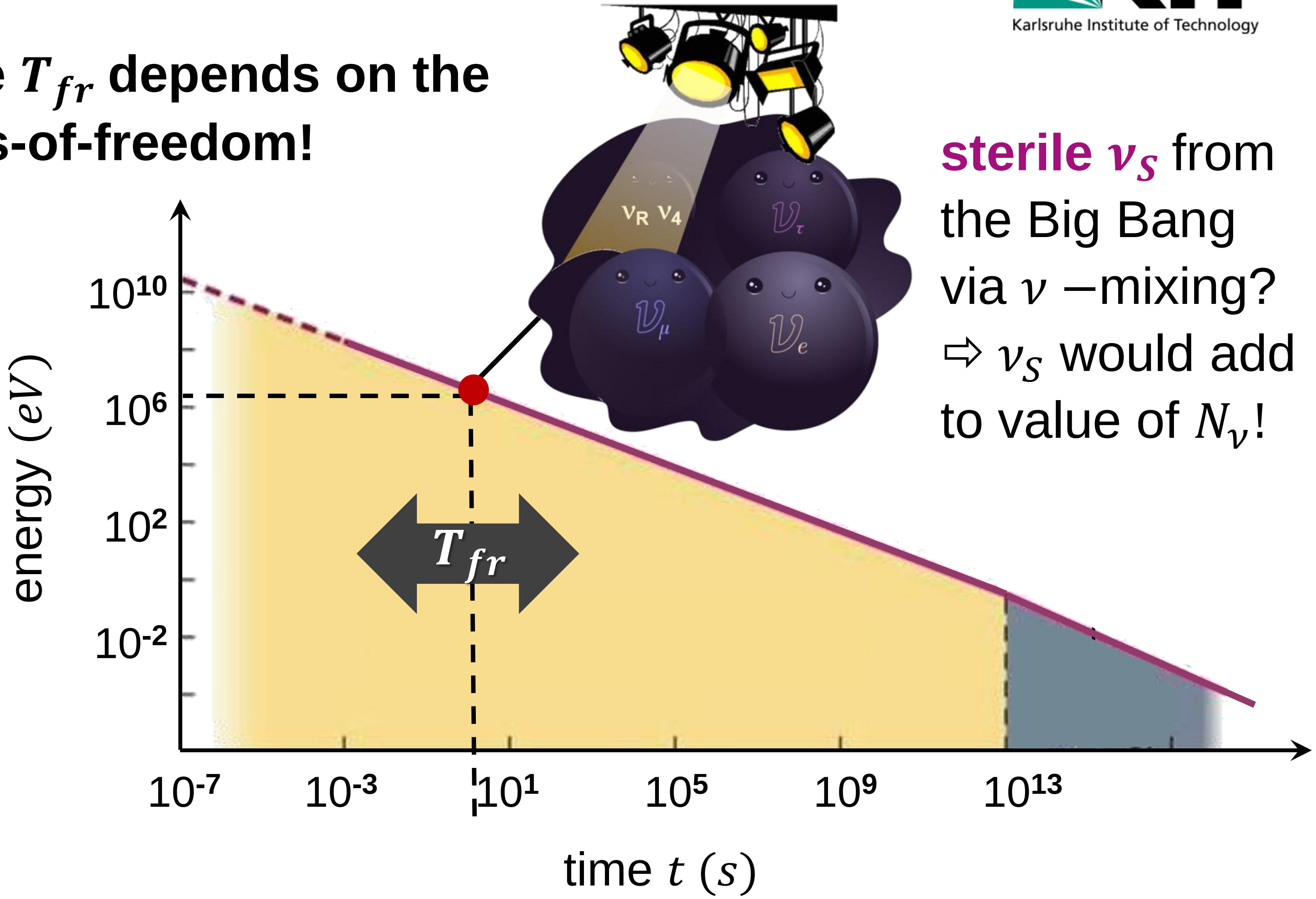


BBN as tool for novel particle physics at $t = 1\ s$

- **Freeze-out temperature T_{fr} depends on the # of relativistic degrees-of-freedom!**

  - **relativistic particles** at $E = 1\ MeV$ & $t = 1\ s$





sterile ν_S from the Big Bang via ν –mixing?
⇨ ν_S would add to value of N_ν!

BBN as tool for novel particle physics at $t = 1\ s$

- **Freeze-out temperature T_{fr} depends on the # of relativistic degrees-of-freedom!**

\- **relativistic particles**

at $E = 1\ MeV$ & $t = 1\ s$

$\boldsymbol{\gamma}$: ☑ boson

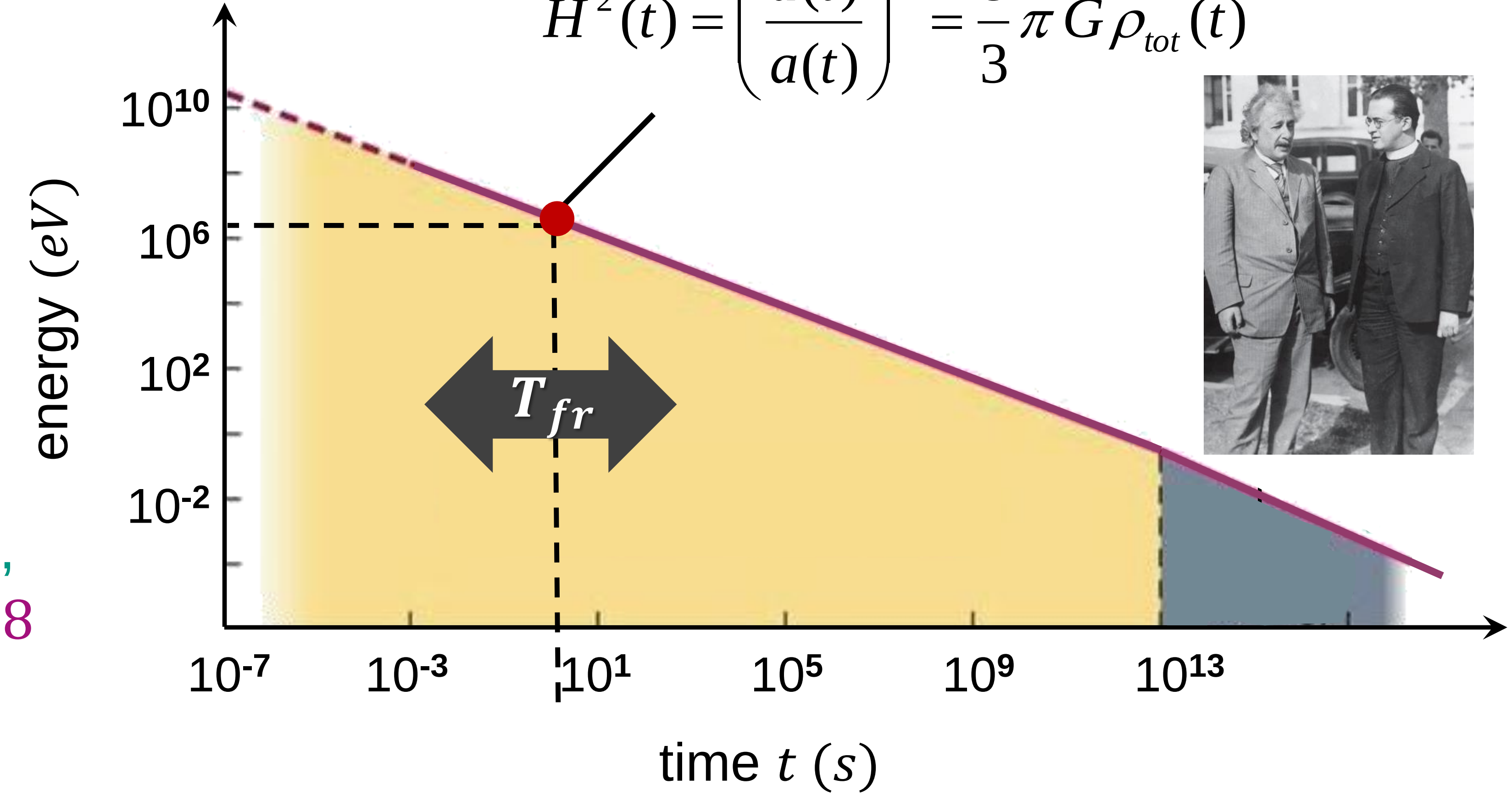
factor = 1

$\boldsymbol{\nu_e\,\nu_\mu\,\nu_\tau}$: ☑

$\boldsymbol{e}$: ☑

fermions, factor $7/8$

$$H^2(t) = \left(\frac{\dot{a}(t)}{a(t)}\right)^2 = \frac{8}{3}\pi G \rho_{tot}(t)$$



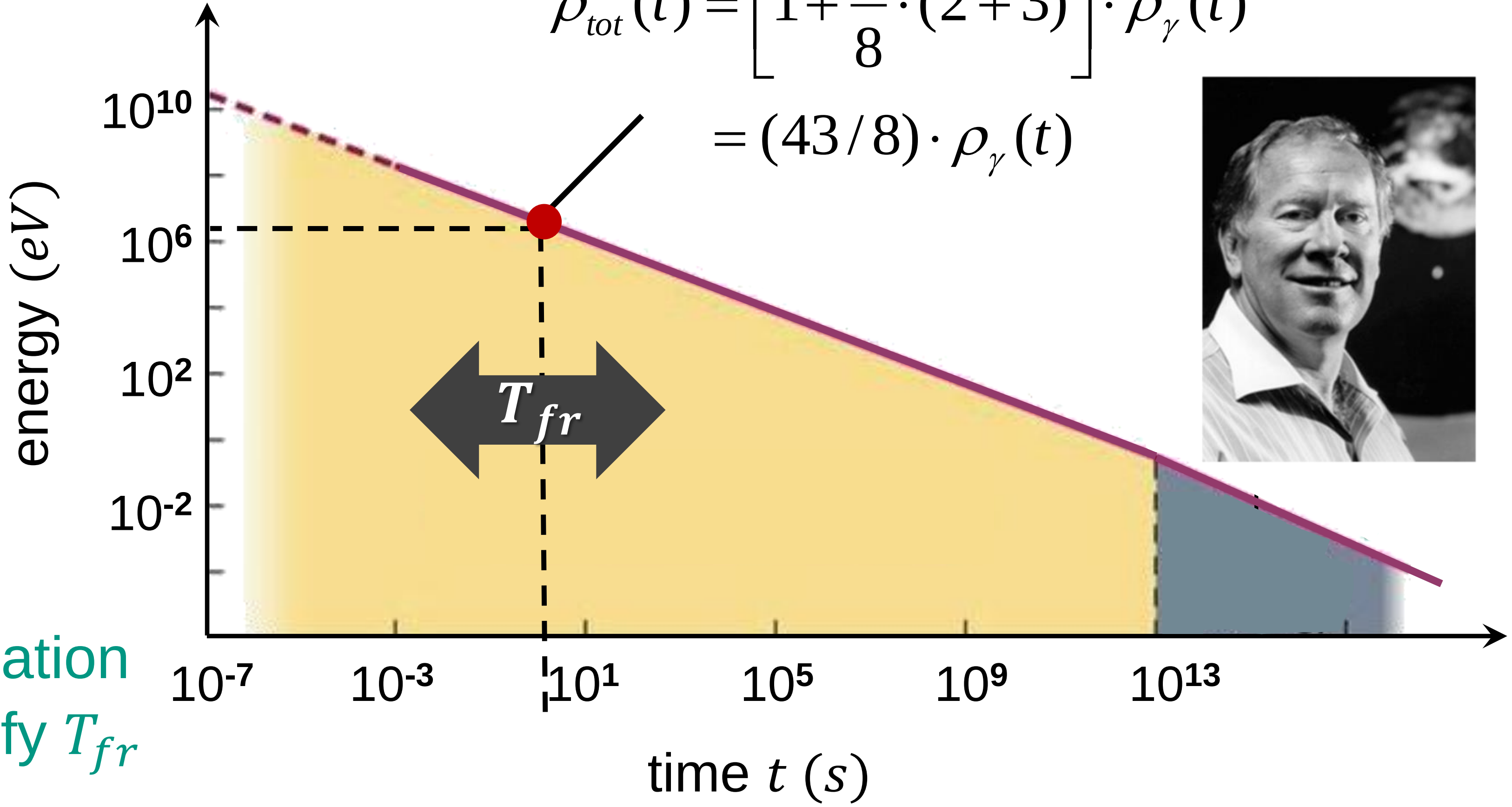
BBN as tool for extra neutrino generations

- **Freeze-out temperature T_{fr} depends on the # of relativistic degrees-of-freedom!**

- **impact of extra relativ. degrees of freedom**: new ν –generations ΔN_ν

$$\boxed{\left(\frac{\dot{H}(t)}{H(t)}\right)^2 \sim 1+\frac{7\Delta N_\nu}{43}}$$

- each additional ν –generation will increase $H(t)$ & modify T_{fr}



$$\rho_{tot}(t)=\left[1+\frac{7}{8}\cdot(2+3)\right]\cdot\rho_\gamma(t)$$

$$=(43/8)\cdot\rho_\gamma(t)$$

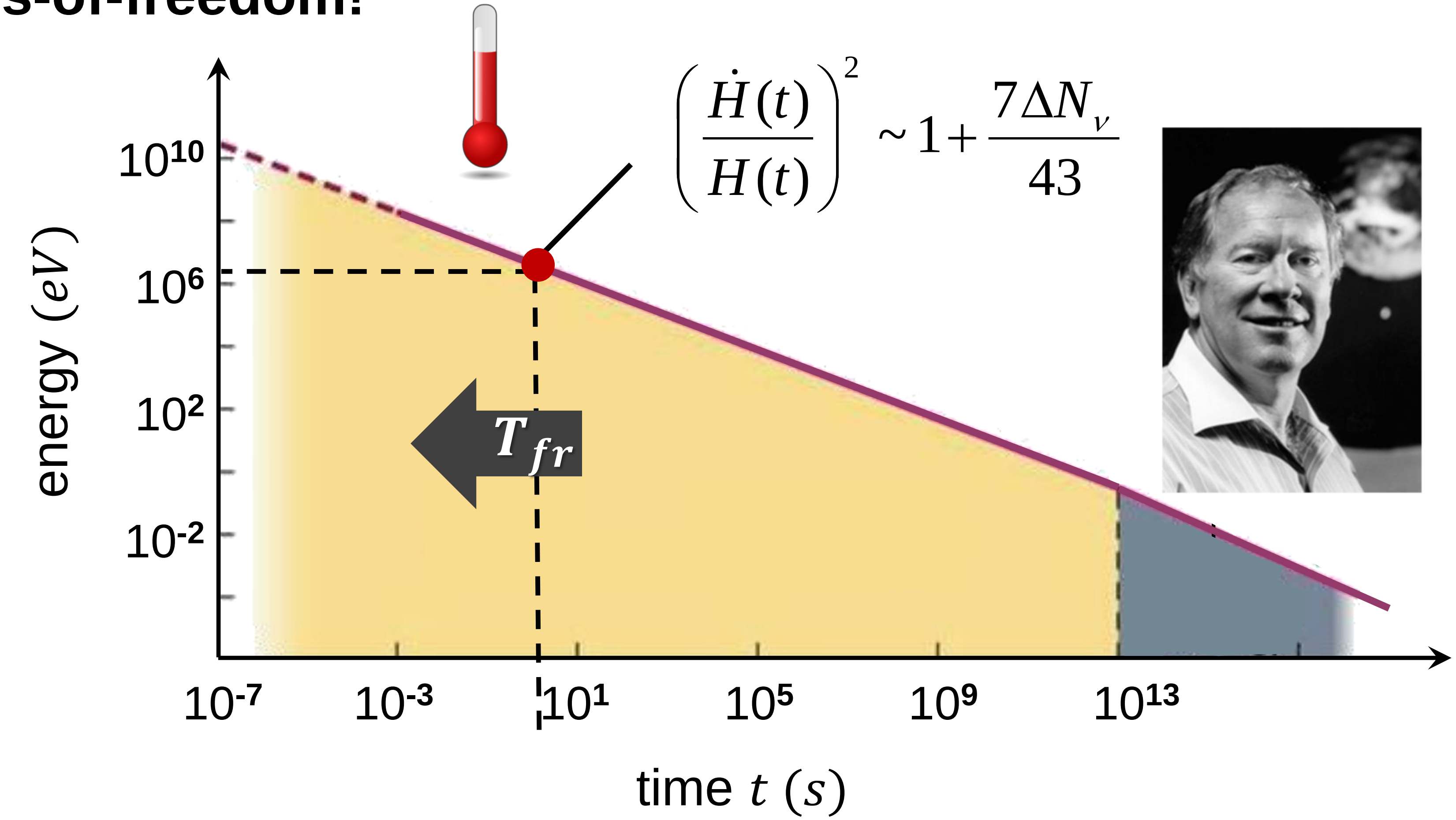
BBN as tool for extra neutrino generations

- **Freeze-out temperature T_{fr} depends on the # of relativistic degrees-of-freedom!**

- **impact of ΔN_ν**:
  ⇨ larger value of $H(t)$
  ⇨ increase of T_{fr}

- more $n´s$ are available

- primordial ^4He mass fraction Y_P **increases**



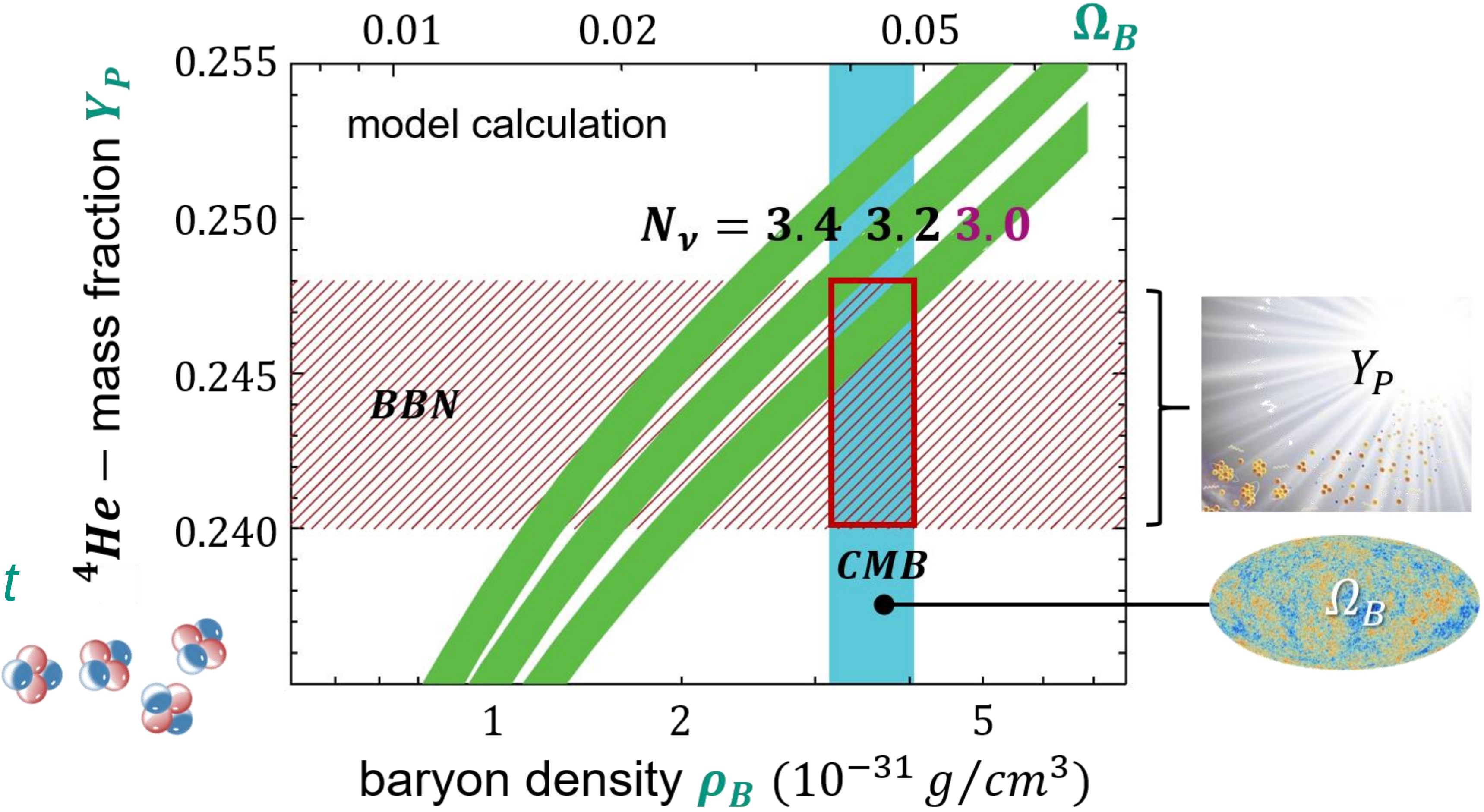
$$\left(\frac{\dot{H}(t)}{H(t)}\right)^2 \sim 1 + \frac{7\Delta N_\nu}{43}$$

BBN results need to be combined with CMB data

- Primordial ^{4}He mass yield Y_P combined with baryon density Ω_B from CMB

- BBN:
  Y_P value is *dependent* on N_ν

- CMB:
  Ω_B value *independent* on N_ν

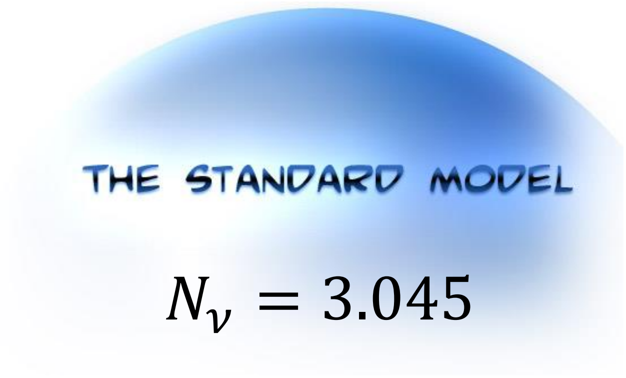


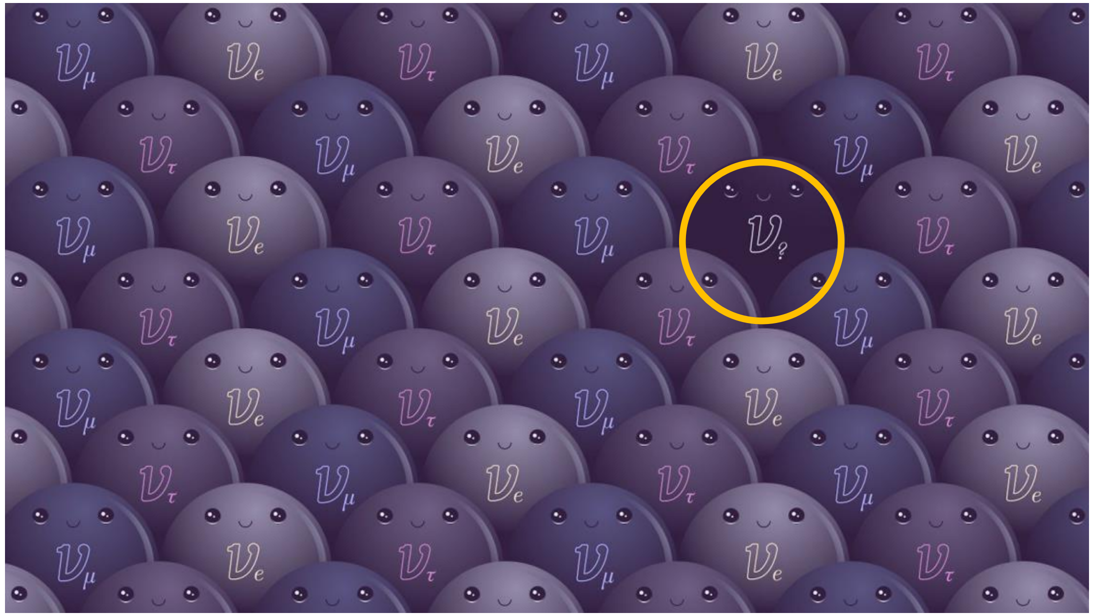
BBN results need to be combined with CMB data

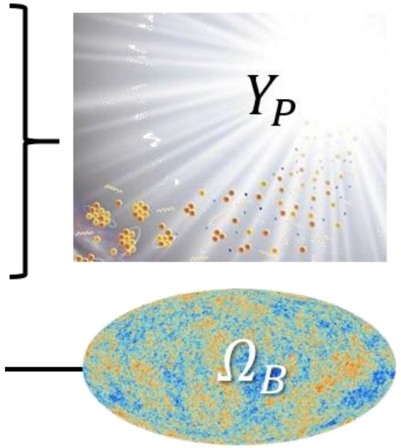
- **Primordial ^4He mass yield Y_P combined with baryon density Ω_B from CMB**

  - cetailed calculation gives SM-expectation of $N_\nu = 3.045$ for 3 generations, resulting from the finite time interval for ν-decoupling

  - if observation provides $N_\nu \gg 3.045$: there are eV … keV – scale extra-ν´s or dark radiation (MeV)







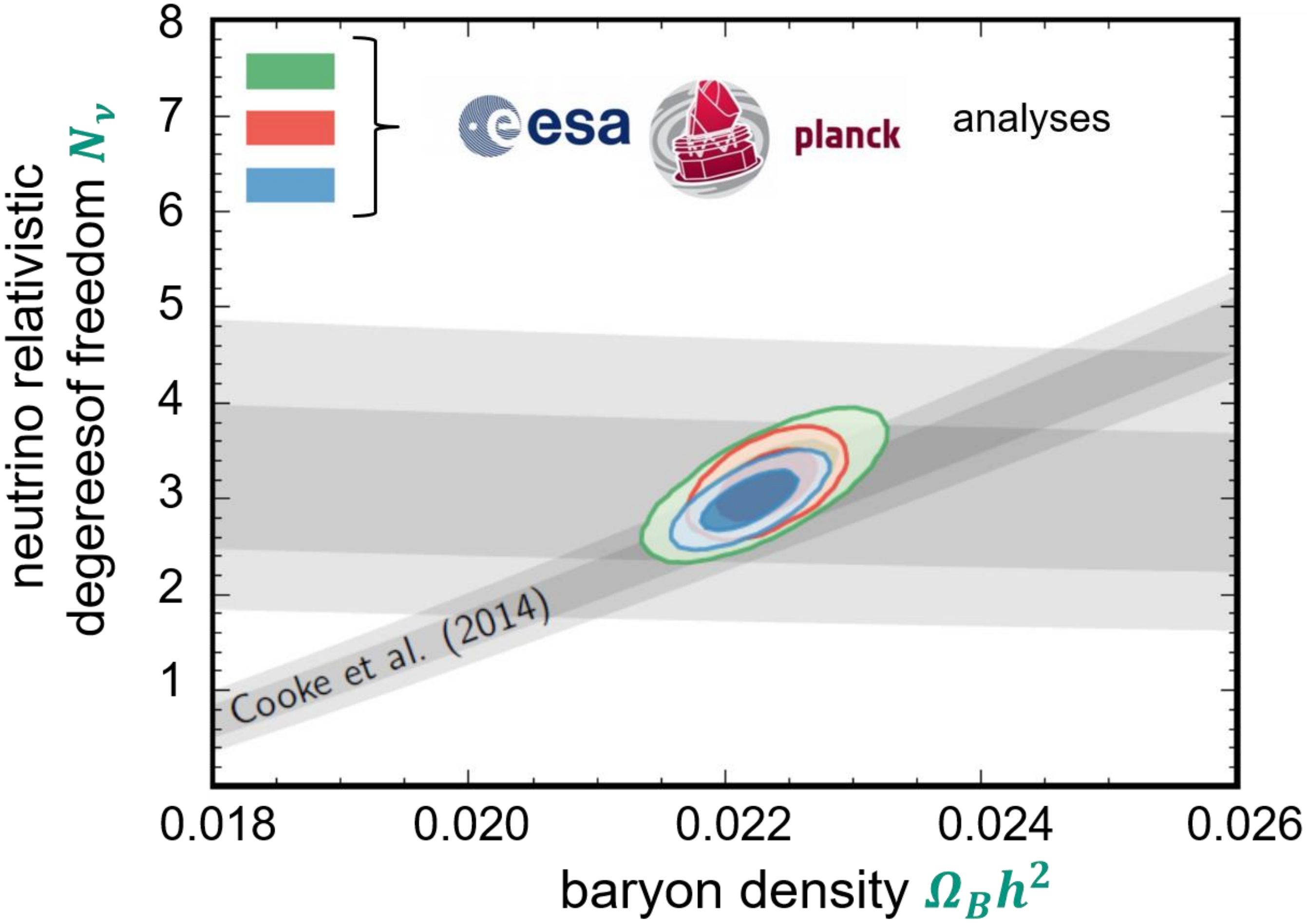
BBN results need to be combined with CMB data

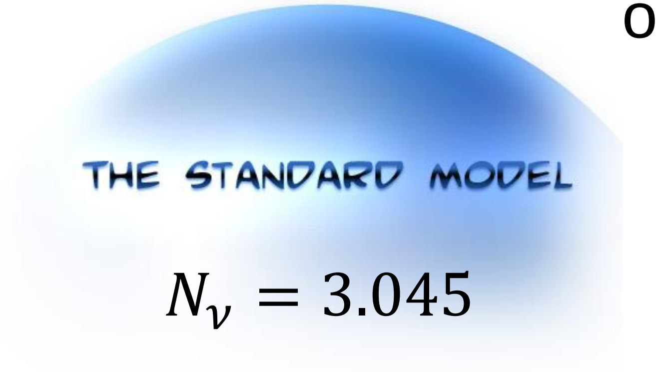
- **Primordial ^4He mass yield Y_P combined with baryon density Ω_B from CMB**

  - latest data from BBN & CMB (Planck 2018) give a result of

$$\boxed{N_\nu = 2.92 \pm 0.36}$$

  - **no evidence of light ν_S** or other dark radiation (gravitinos,…) or metastable $(Z^0)´$





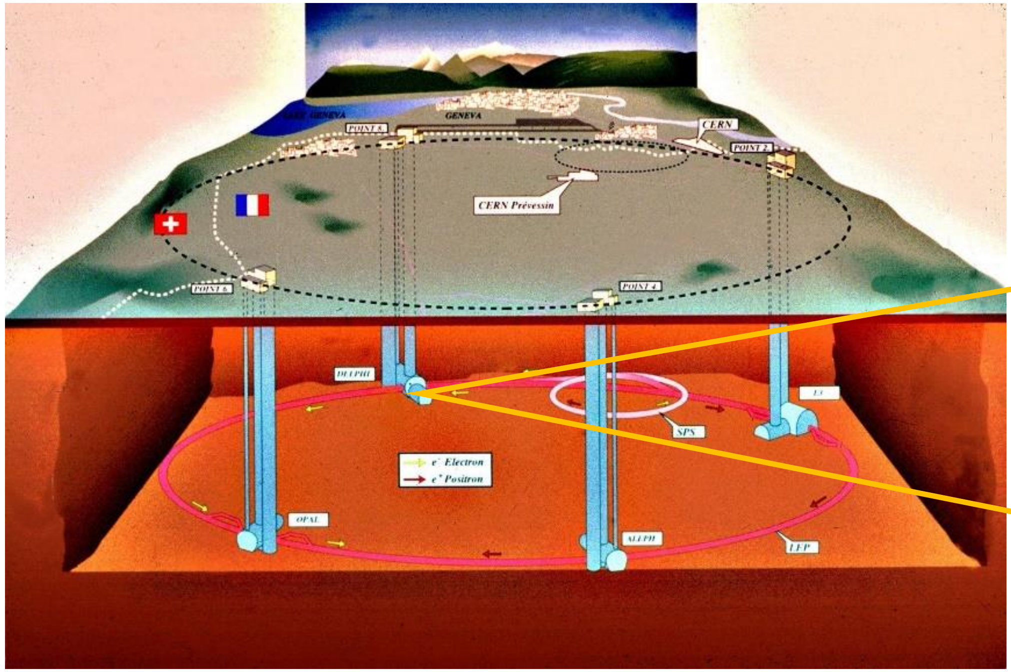
$$N_\nu = 3.045$$

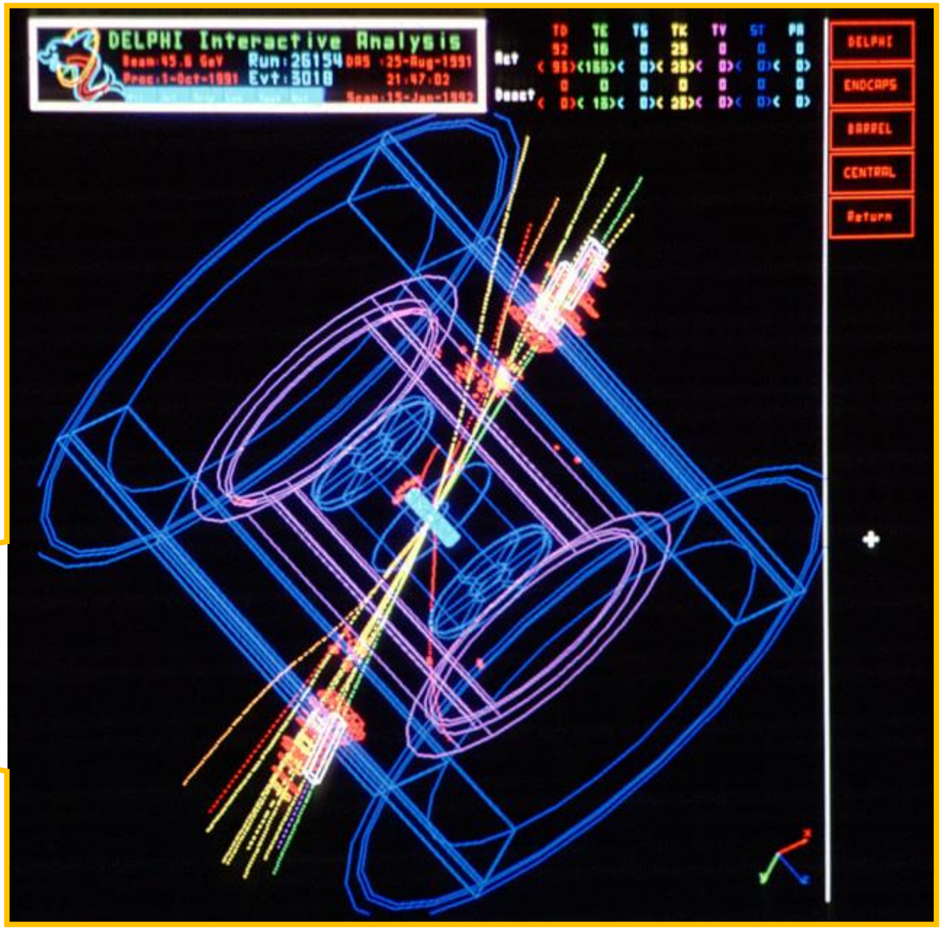
INSERTION: compare N_ν to measurements at *LEP*

- **How do these results relate to the much earlier results at CERN´s *LEP*?**

***L**arge*
***E**lectron*
***P**ositron*
Collider

- *LEP* experiments performed a precision measurement of the **invisible width Γ_{inv} of the Z^0**





INSERTION: investigating the Z^0 invisible width

- **The invisible width Γ_{inv} of the Z^0**

***L**arge*
***E**lectron*
***P**ositron*
Collider

- $\Gamma_{inv} = \Gamma_{tot} - \Gamma_{hadr} - 3 \cdot \Gamma_{lept,ch}$

$$\Gamma_{inv} = \Gamma_{tot} - \underbrace{\Gamma_{hadr}}_{\text{hadronic}} - 3 \cdot \underbrace{\Gamma_{lept,ch}}_{\text{leptonic } e}$$

- SM fits to entire *LEP*-data:

$$\boxed{N_\nu = 2.994 \pm 0.012}$$

- **but: Z^0** – bosons <u>only</u> couple to LH, active neutrinos (**not to ν_S**!)