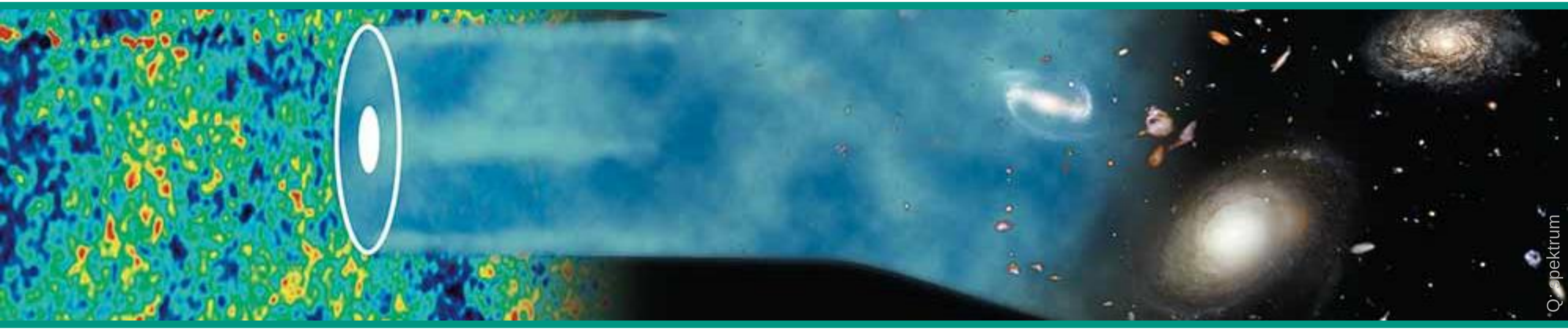
Introduction to Cosmology

Winter term 23/24 Lecture 7 Dec. 5, 2023



Recap of Lecture 6

- **Primordial Nucleosynthesis: formation of light elements during first 3 $min.$**

  - **thermodynamical equilibrium** between p, n due weak interaction by ν´s

  - ν – decoupling (**freeze–out**) at $T = 1\ MeV$ & $t = 1\ s$ (➩ free–streaming of ν´s)

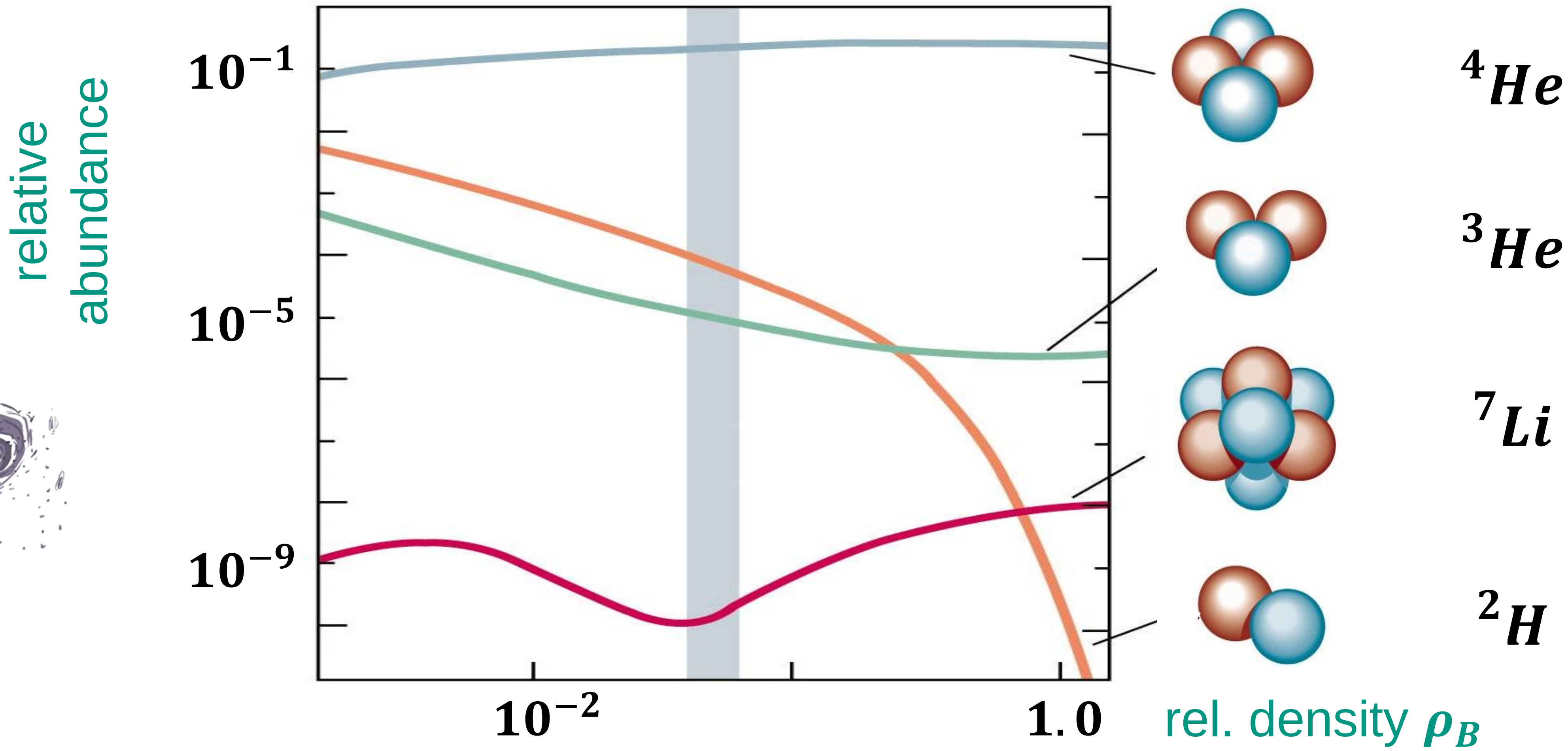
  - (n, p) – ratio $1:6$ at $t = 1\ s$, no element synthesis due to **intense heat bath**

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

  - light element synthesis primarily to ^4He with small traces of d, ^3He, ^7Li : can be used to determine **baryon density** Ω_b

Recap of Lecture 6

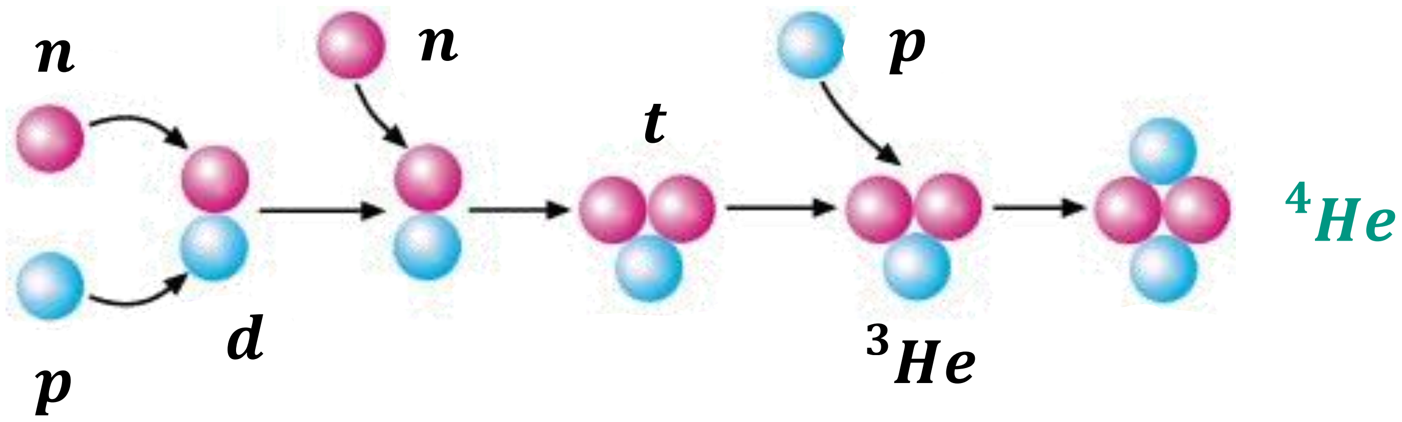
- **Primordial Nucleosynthesis:** light element yield as a function of ρ_B

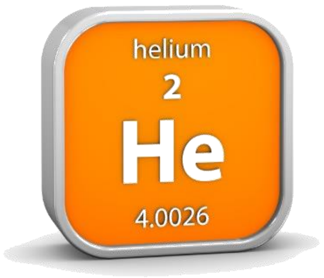


Primordial nucleosynthesis & yield of ^4He

- **Synthesis of light elements essentially stops at ^4He**
  - fusion beyond ^4He is difficult: this is a **very stable** (double magic) **nucleus**
  - ^4He is **difficult to destroy**, also tiny cross–sections for capture of p, n, d
  - almost all neutrons are incorporated into ^4He (⇨ available n limits its formation)
  - usual parameter in literature: primordial ^4He – **mass fraction Y_p**

one of many BBN **reaction pathways** to ^4He – formation





Primordial nucleosynthesis & yield of ^4He

- **A quick estimate on the ^4He – mass fraction Y_p as function of (n, p) ratio**

- we start with the calculated (n, p) – ratio of $1 : 7$ at the onset of BBN

- we then form ^4He via the initial ratio out of $(2n + 2p) + 12\,p = {}^4He + 12\,p$

$$\underbrace{2p) + 12\,p}_{} \quad 2\,n \;:\; 14\,p$$

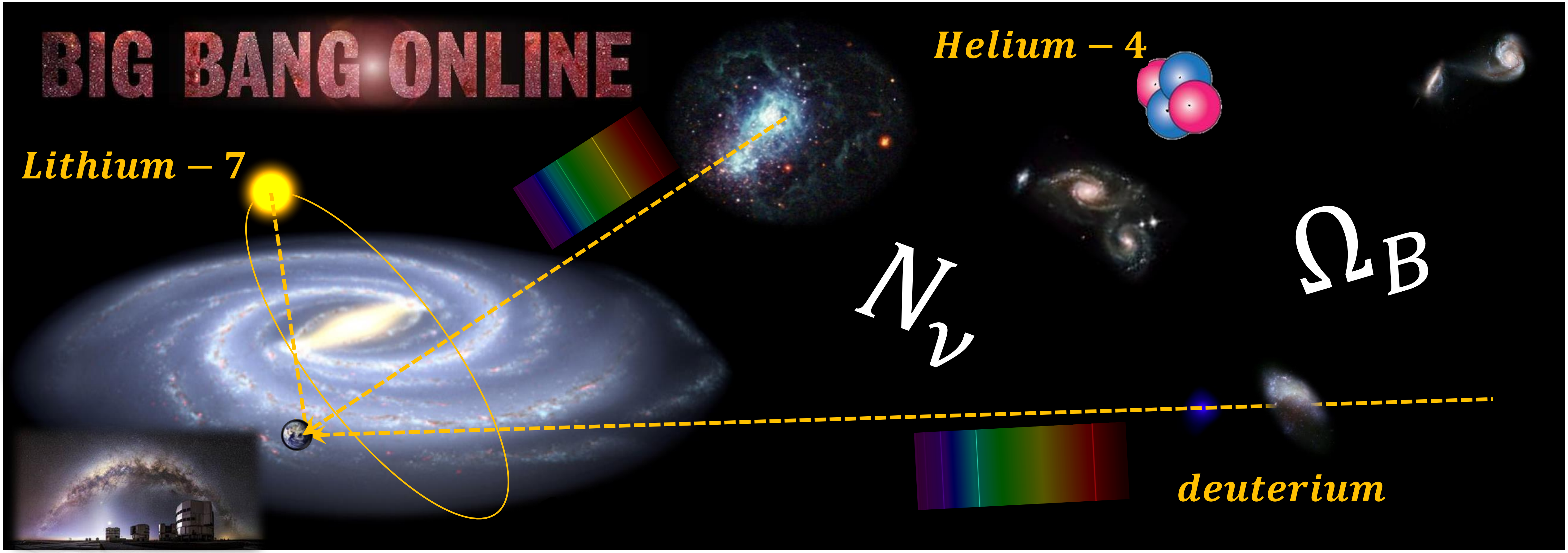
- we now calculate the ^4He mass fraction $Y_p = {}^4He/(2\,n + 14\,p)$

with $m_n = m_p = m_{nucl}$ we have $= 4\,m_{nucl}\,/\,16\,m_{nucl} = 0.25$

- for the (n, p) – ratio of $1 : 7$ we expect a ^4He mass fraction $Y_p = 0.25$

Preview of this Lecture: light element yields

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



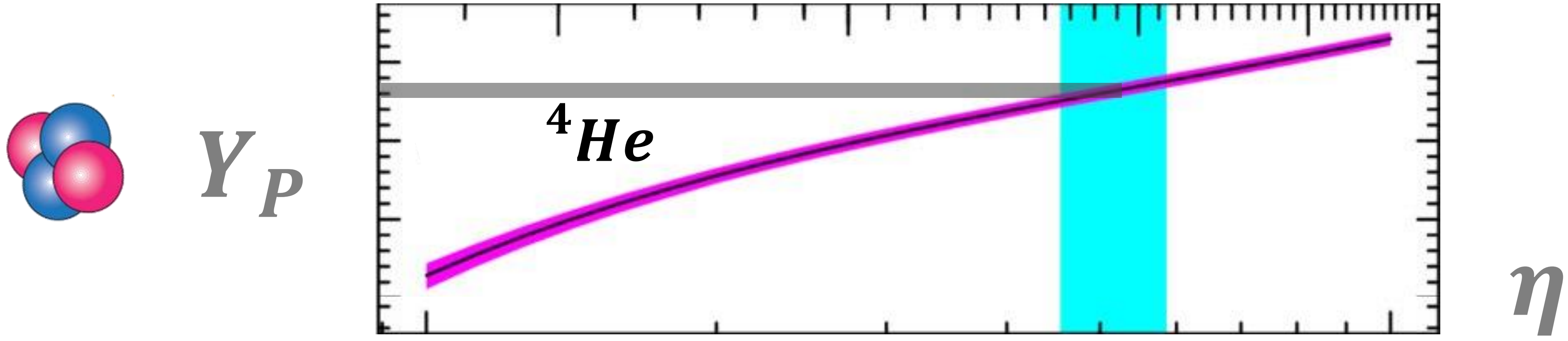
Light element yields as function of parameter η

- **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, thus we have a **larger value of Y_P**

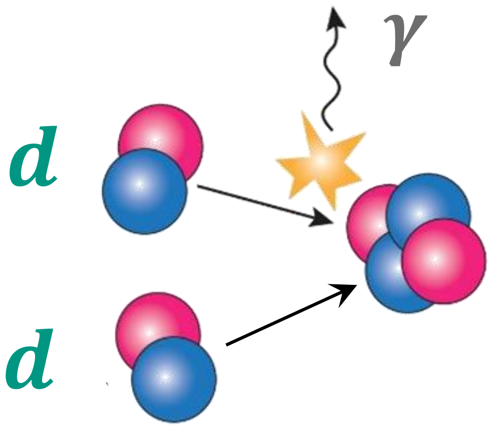


Light element yields as function of parameter η

- **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

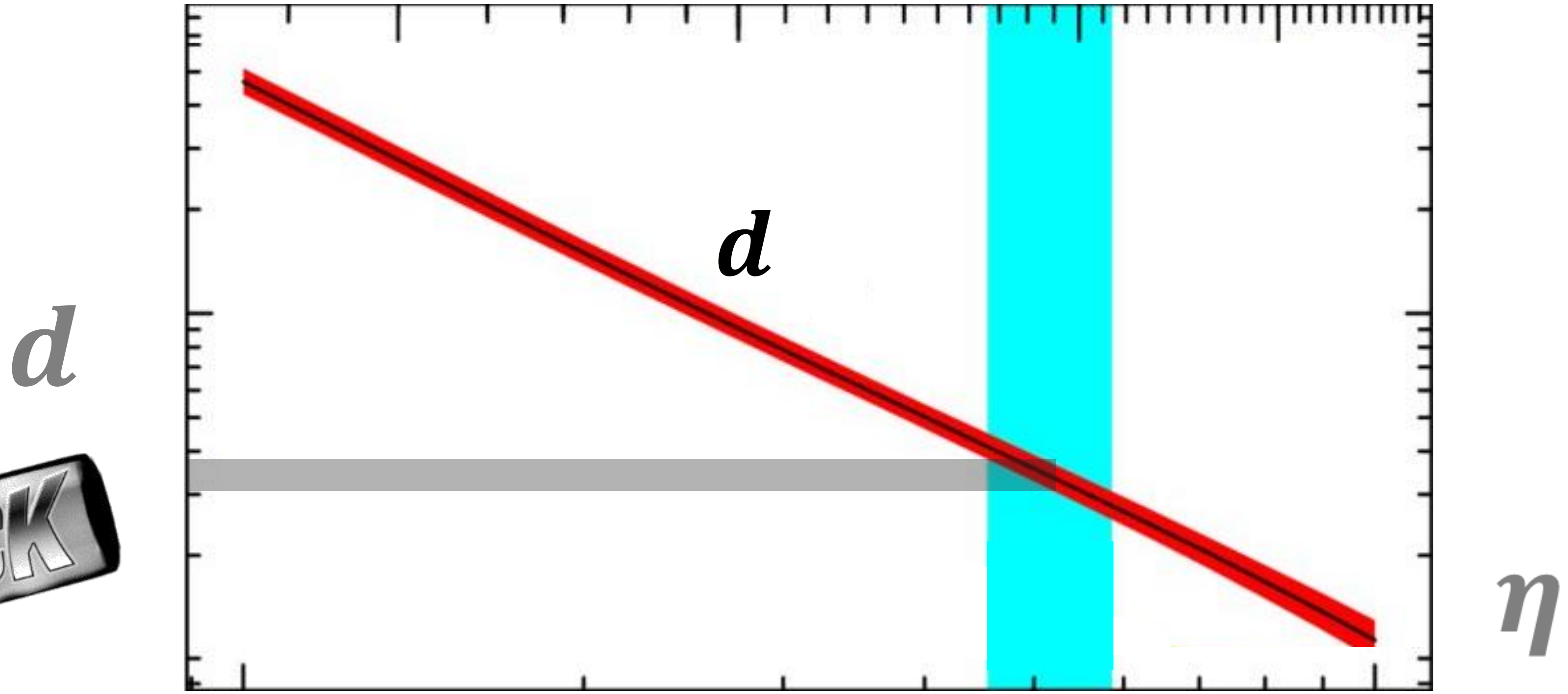
  - for increasing values of η we have more p, n relative to γ´s from heat bath
    ⇨ more baryons due to **higher density ρ_B** ⇨ **less deuterium d**
    it ends up more efficiently in primordial ^4He



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 baryon density Ω_B



Light element yields as function of parameter η

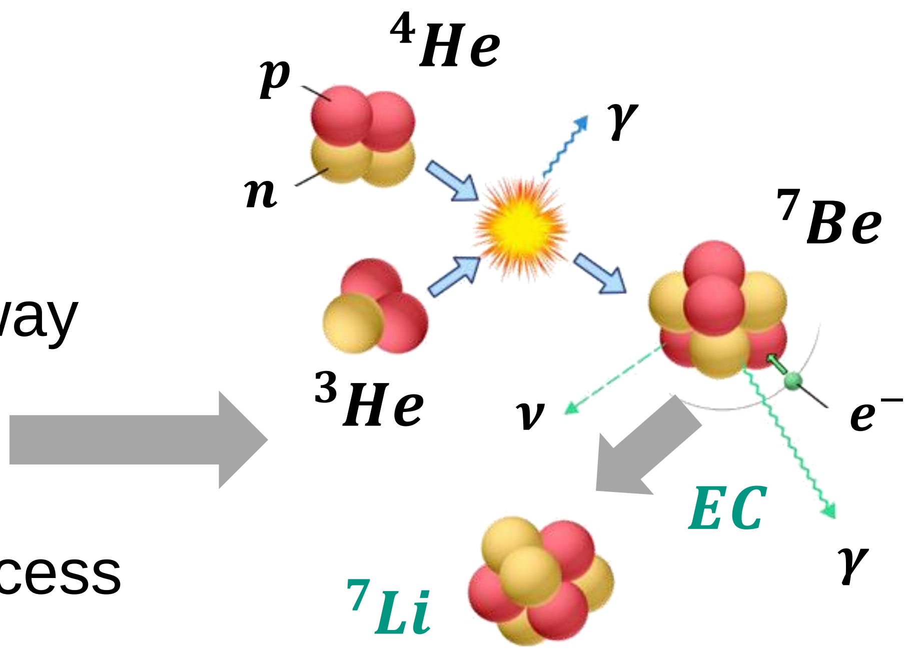
- **Impact of baryon asymmetry η on abundance of primordial lithium ^{7}Li**

  - **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

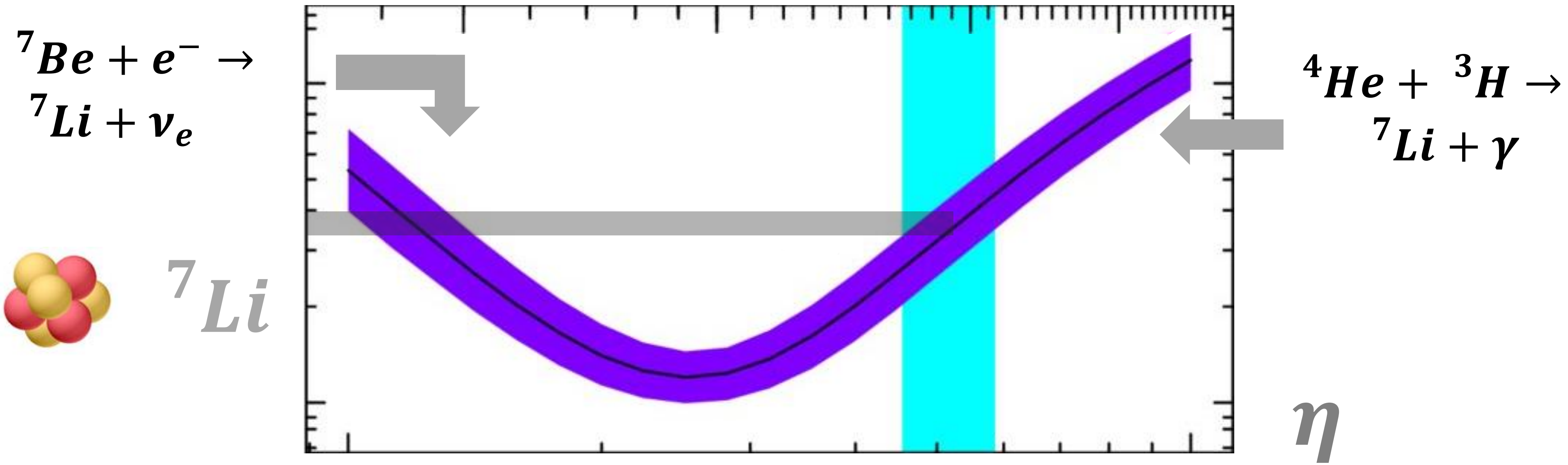


Light element yields as function of parameter η

- **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



Light element yields & future e –mobility

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

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

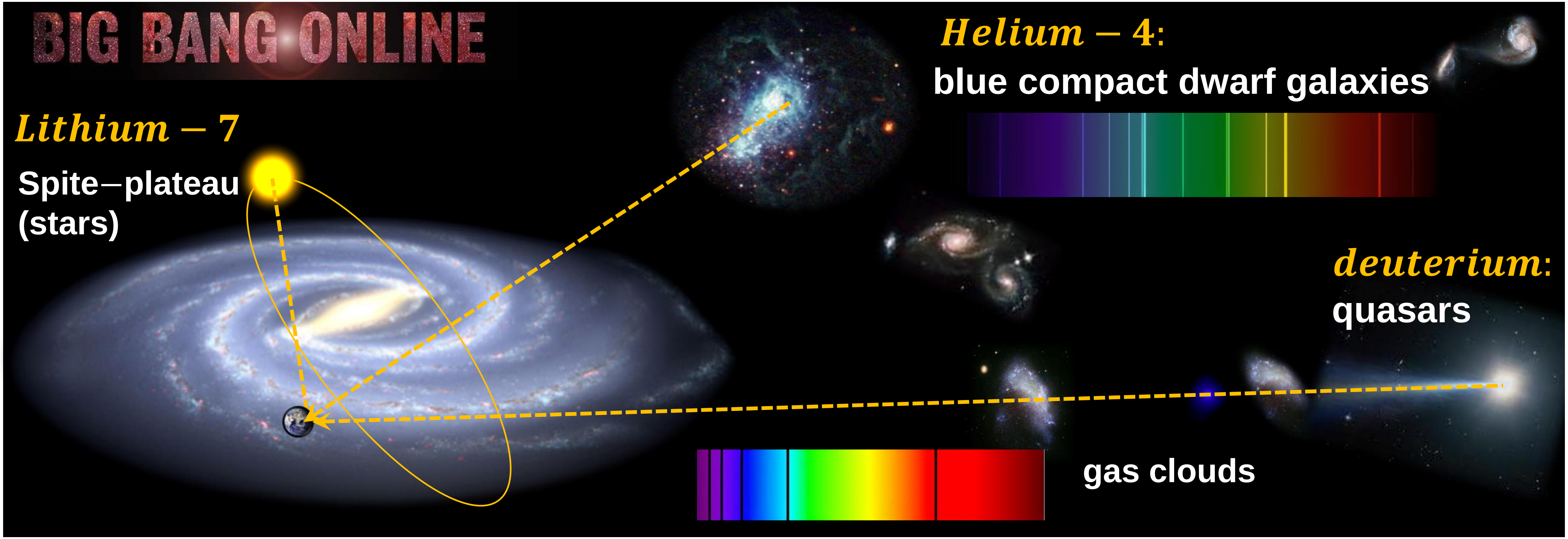
  - **lithium**: very important for the

powered by BBN

^7Li

Light element yields: spectroscopic results

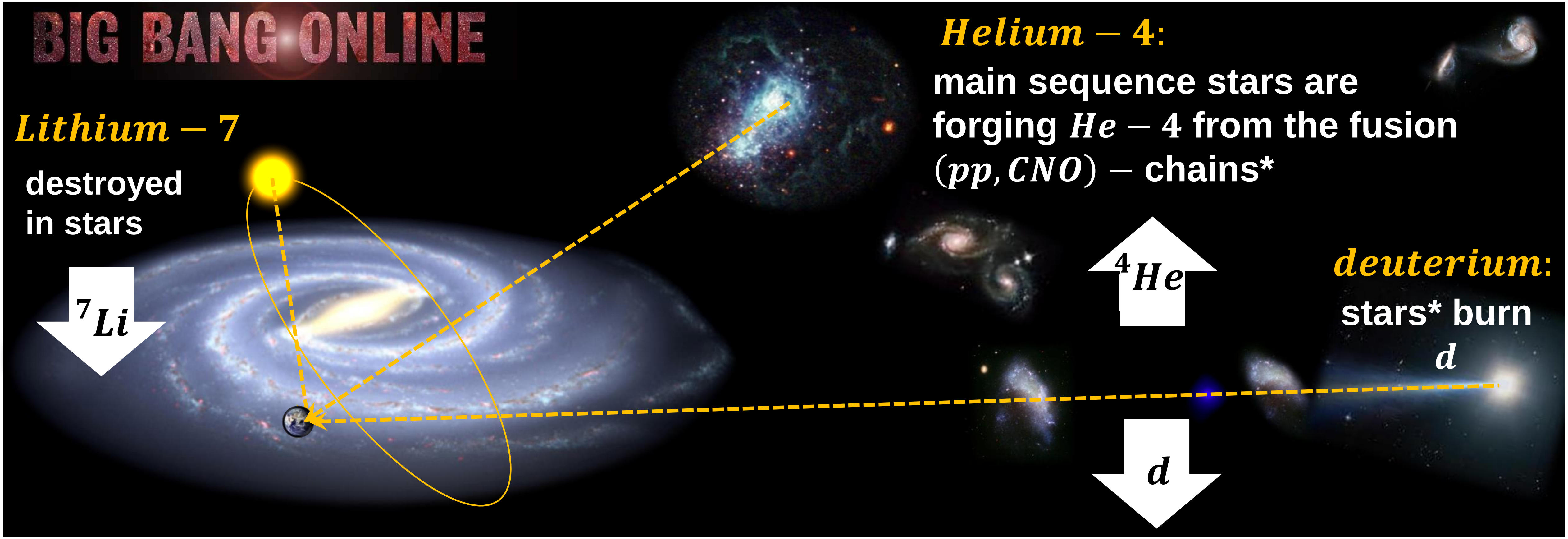
- We want to determine the light element yields of BBN in the universe today!
  - each element is identified by its **characteristic** emission / absorption lines



Light element yields: spectroscopic results

- **How can we determine the light element yields of BBN in the universe today?**

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

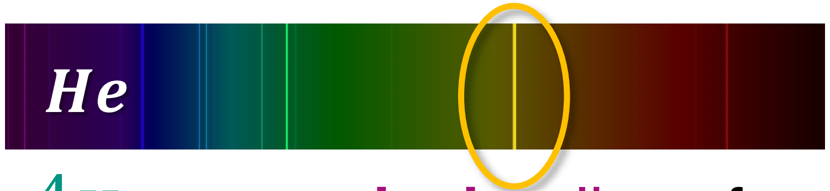


*see $ATP - II$ (summer term 2024)

Light element yields: atomic physics as basis

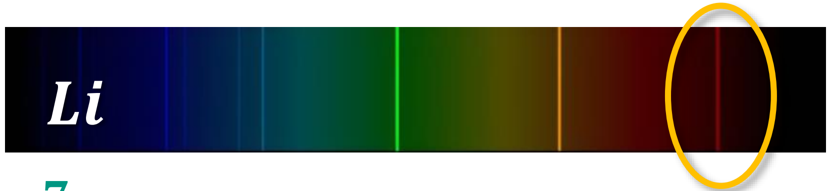
Karlsruhe Institute of Technology

- **Spectroscopy of the three light BBN elements** d, ^4He, ^7Li



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

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

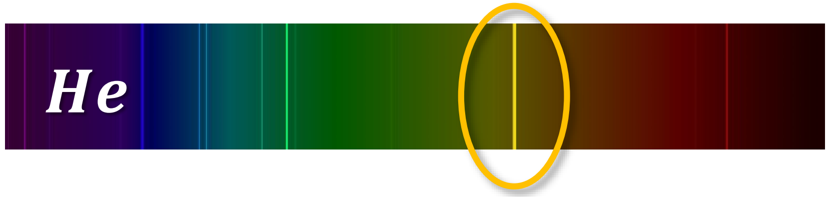


^7Li: **absorption** lines of ^7Li in **atmospheres of stars** in halo (**Spite plateau**)

*clouds of **singly ionised** hydrogen atoms

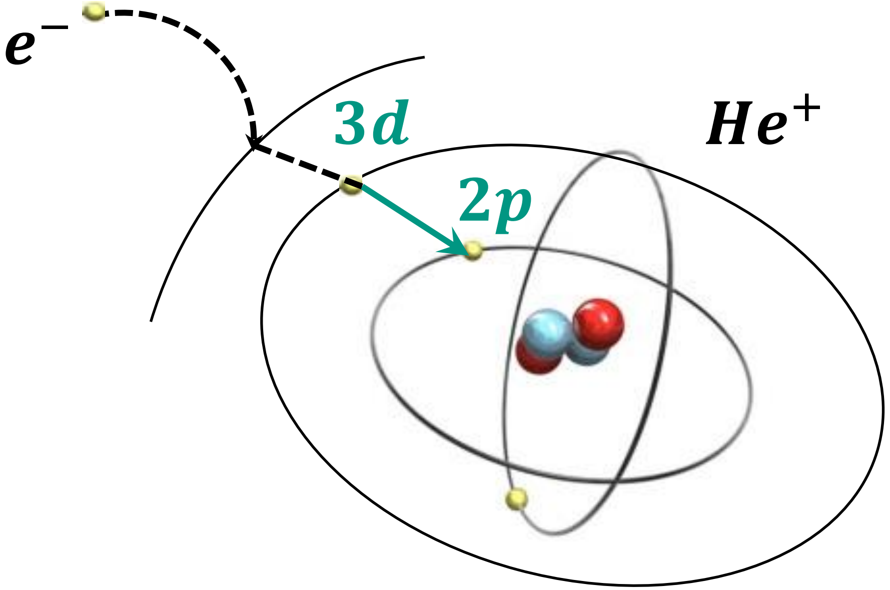
Measuring the ^{4}He – abundance with the VLT

- **Using high–precision spectroscopy to measure the primordial ^{4}He yield**



$\lambda = 587.6\ nm$

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



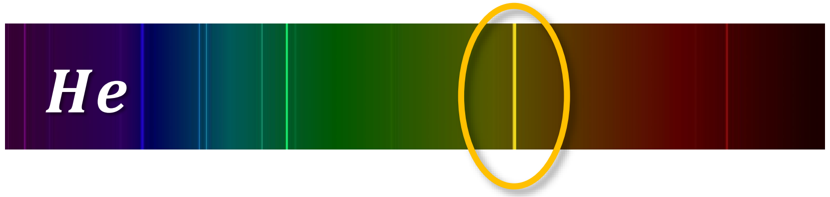
VLT – Very Large Telescope

$$1s\ 3d\ (23.07\ eV) \rightarrow 1s\ 2p\ (20.96\ eV)$$

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

Measuring the ^4He – abundance with the VLT

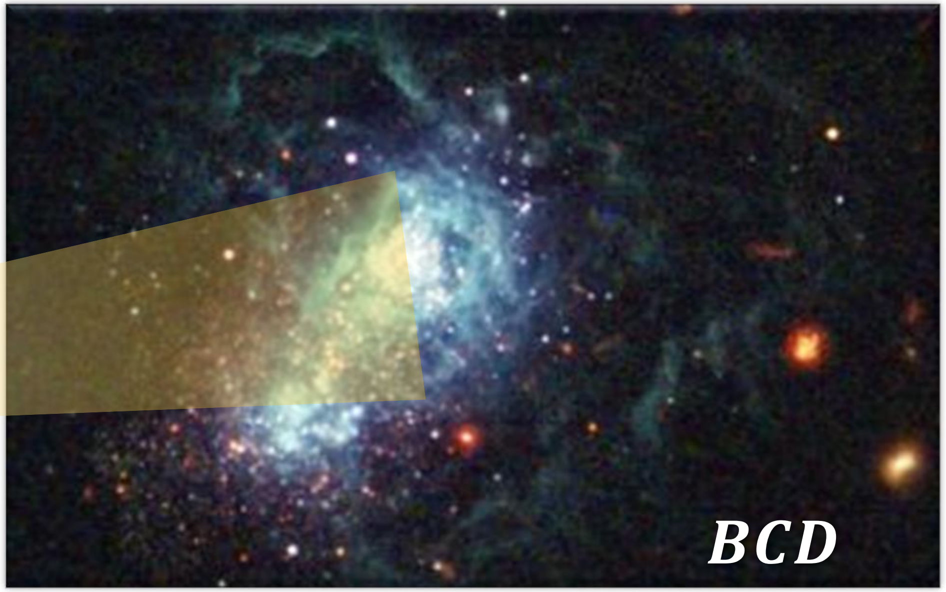
- Observing ***B***lue ***C***ompact ***D***warf (BCD)–galaxies with the VLT spectrograph



$\lambda = 587.6\ nm$

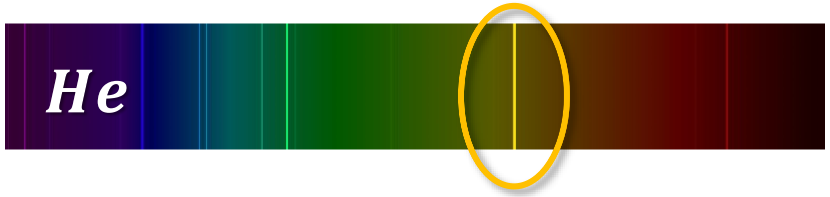
- BCDs: rich in gas ⇨ large **star–forming regions** ⇨ gas is ionised (He^+) by UV – **light of very massive stars**

- BCDs: small galaxies – poor in ´metals´
  ⇨ small previous reaction rates of stellar fusion



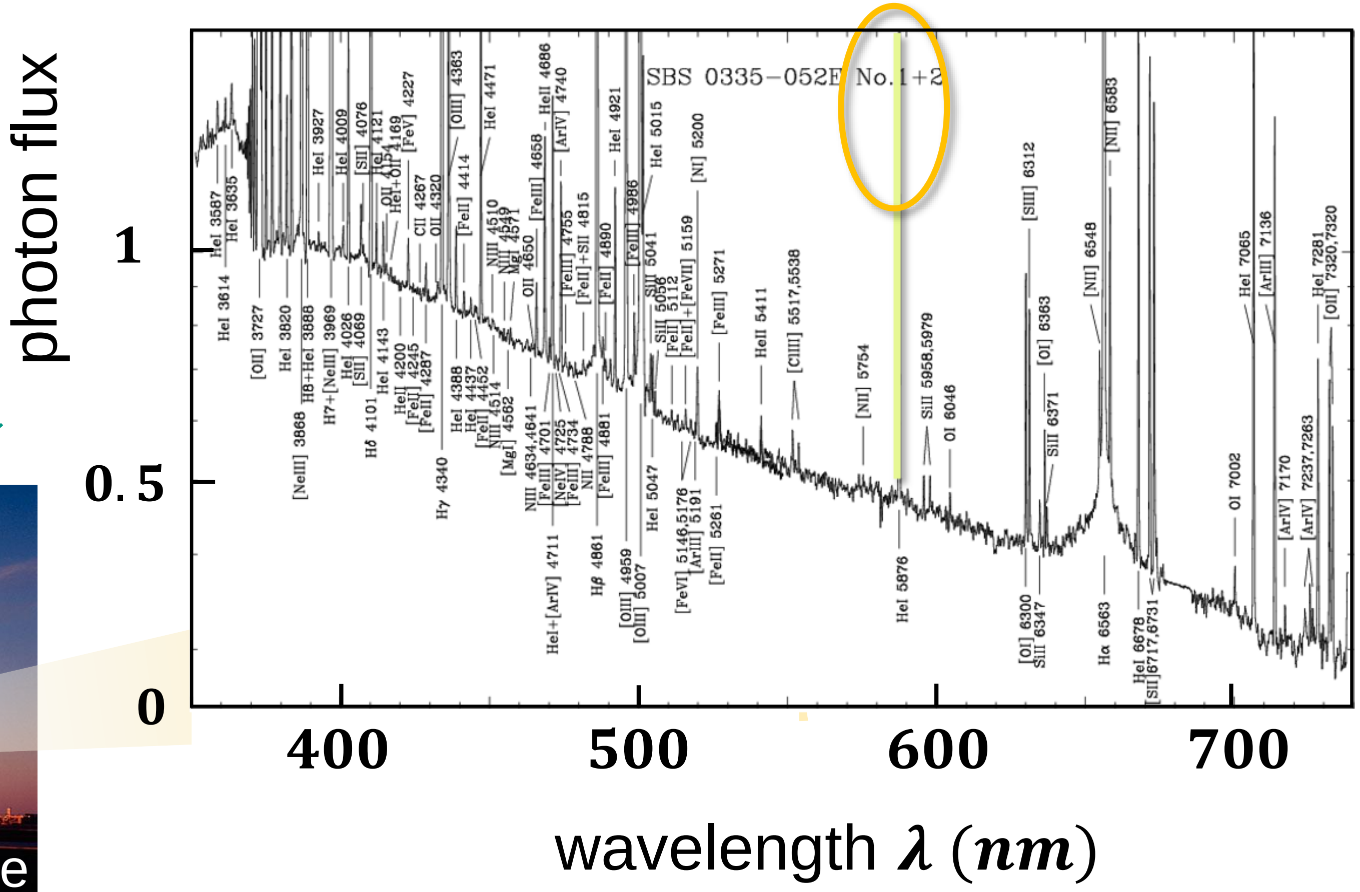
Measuring the ^4He – abundance

- **Observing *B*lue *C*ompact *D*warf (*BCD*)−galaxies with the *VLT* spectrograph**



$\lambda = 587.6\ nm$

- ***BCD*s: many line emissions visible, we analyse peak height at $587.6\ nm$**



VLT – *V*ery *L*arge *T*elescope

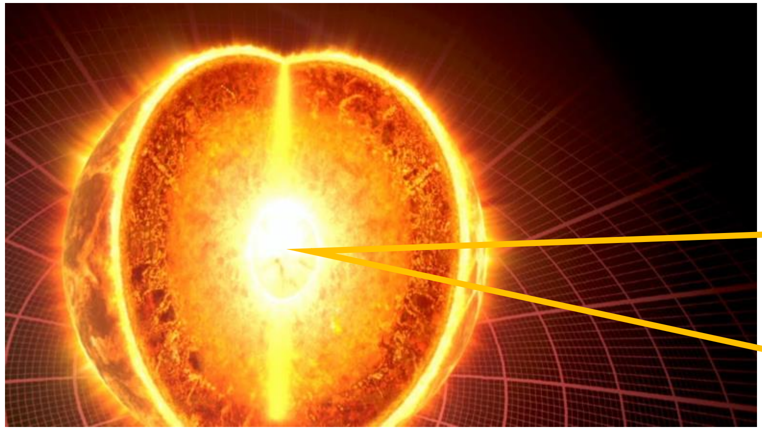
Measuring the ^4He − abundance: systematics

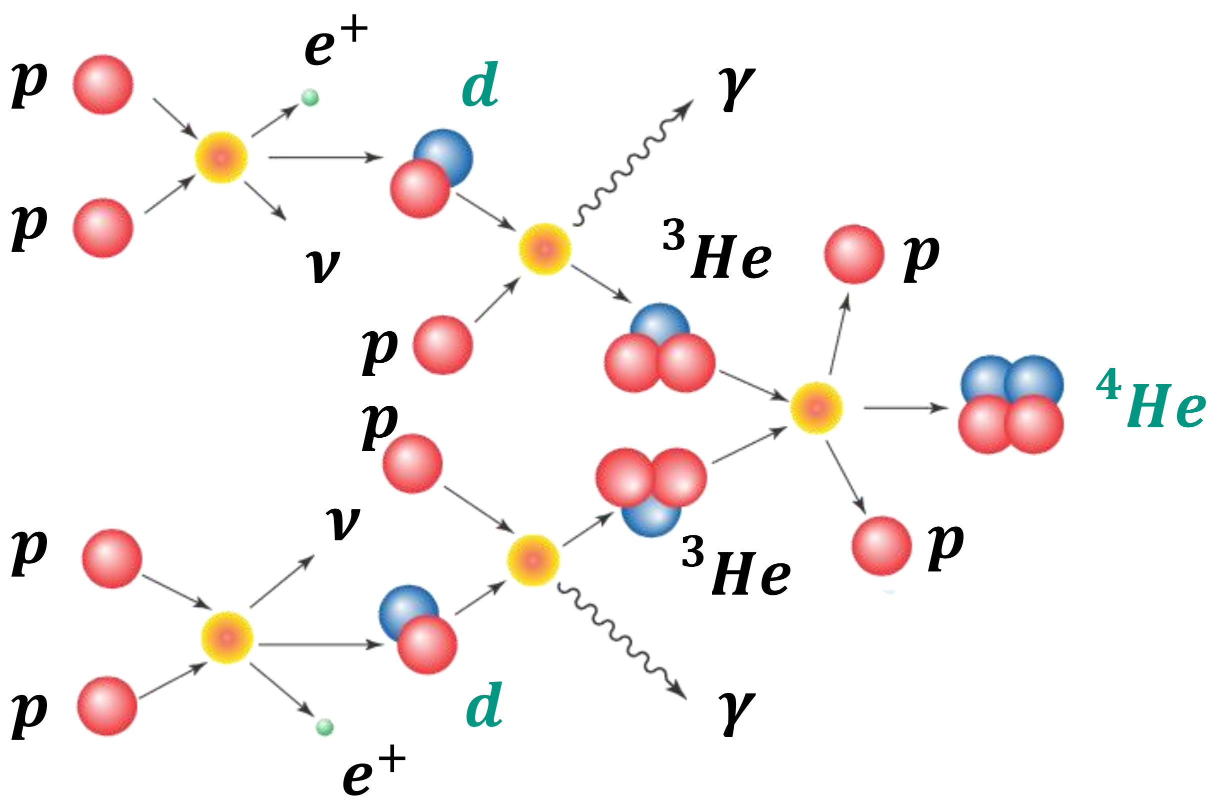
- **Abundance of ^4He in the universe continually increases due to fusion**

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

  - pp −
  - CNO −

  $$4\,p + 2e^- \rightarrow \, ^4He + 2\nu_e$$





⇨ search for **metal−poor*** regions

*metallicity in astrophysics defined as **ratio O/H**

Measuring the ^4He – abundance: systematics

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

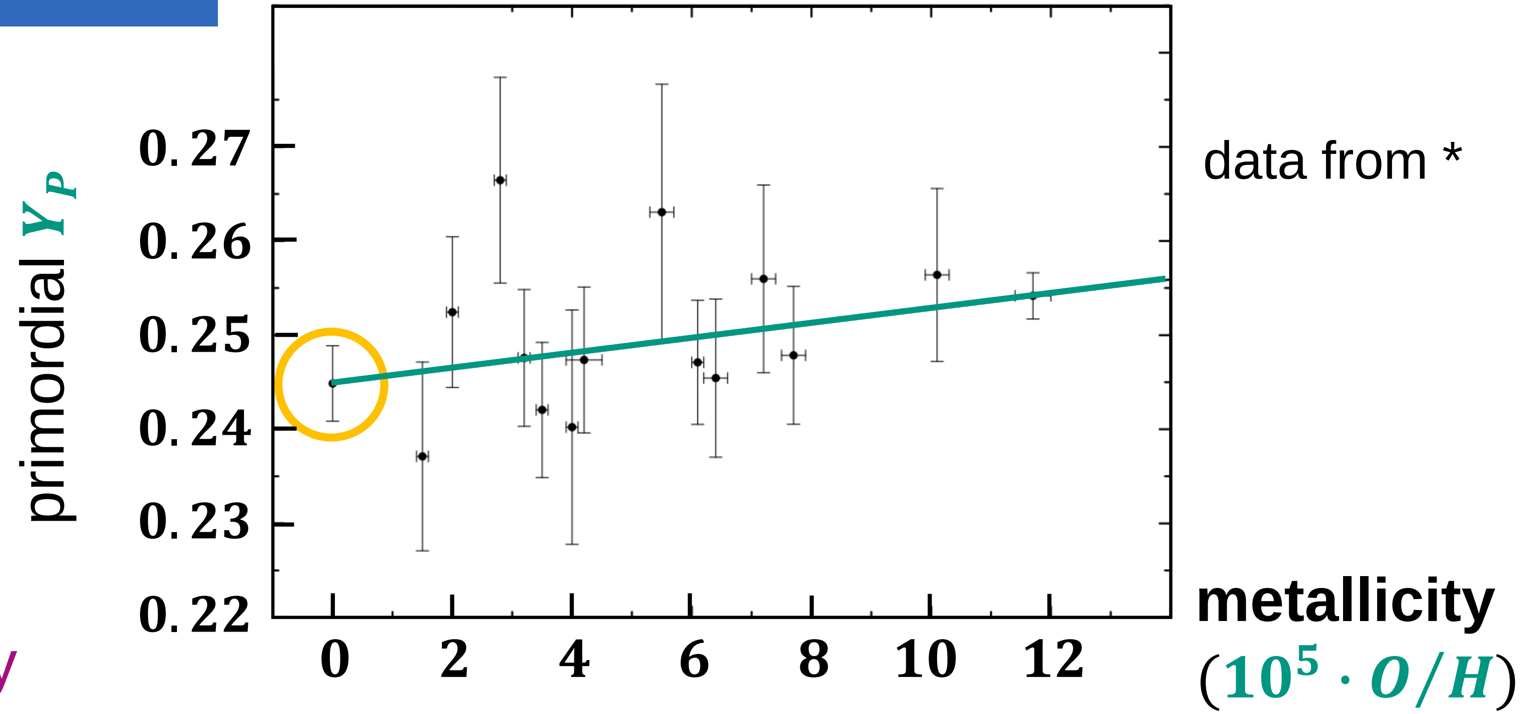
$Y_p(^4\text{He})$	$\pm 1\sigma_{\text{stat}}$	$\pm 1\sigma_{\text{sys}}$	$\pm 1\sigma_{\text{tot}}$	# systems
0.2453	0.0034			16
0.2451	0.0019	0.0018	0.0026	1
0.243	0.005			16
0.2462	0.0022			120
0.2436	0.0040			54
0.2448	0.0027	0.0018	0.0033	7

2022 values

PDG particle data group

mass fraction of ^4He

$Y_P = 0.245 \pm 0.003$



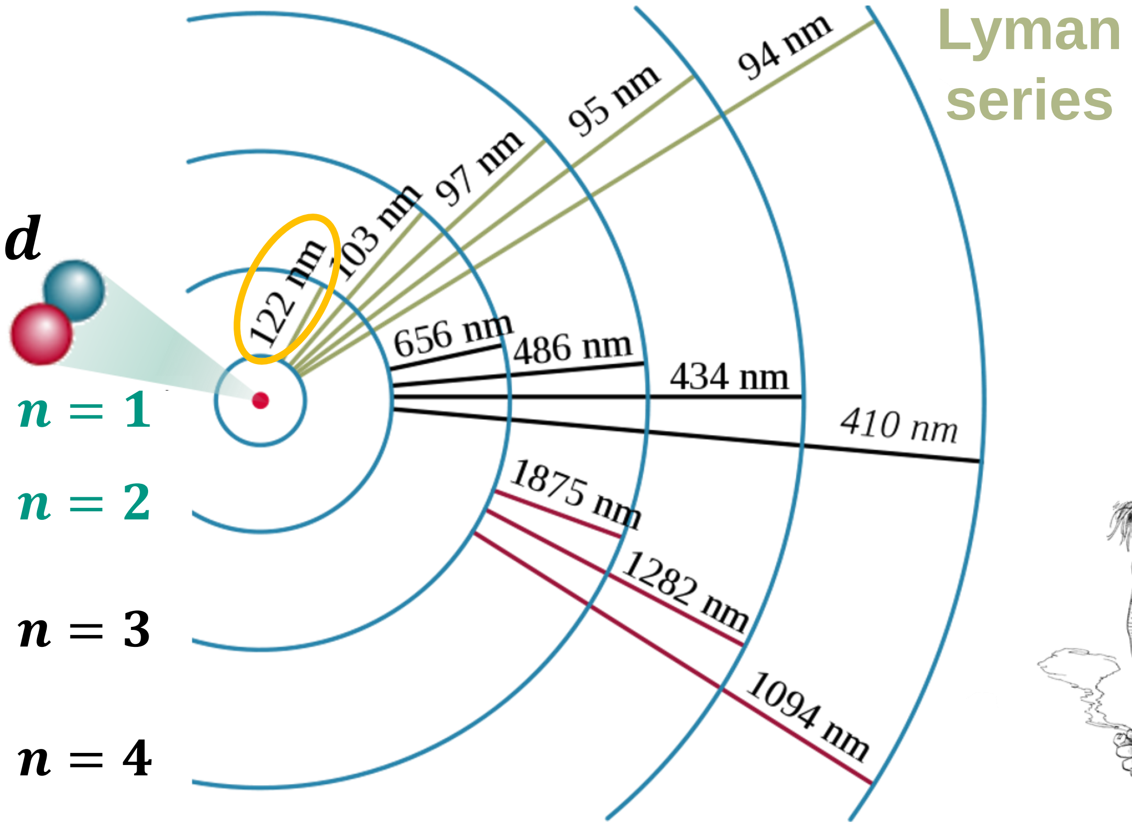
- good agreement with BBN theory

* 1503.08146.pdf (arxiv.org)

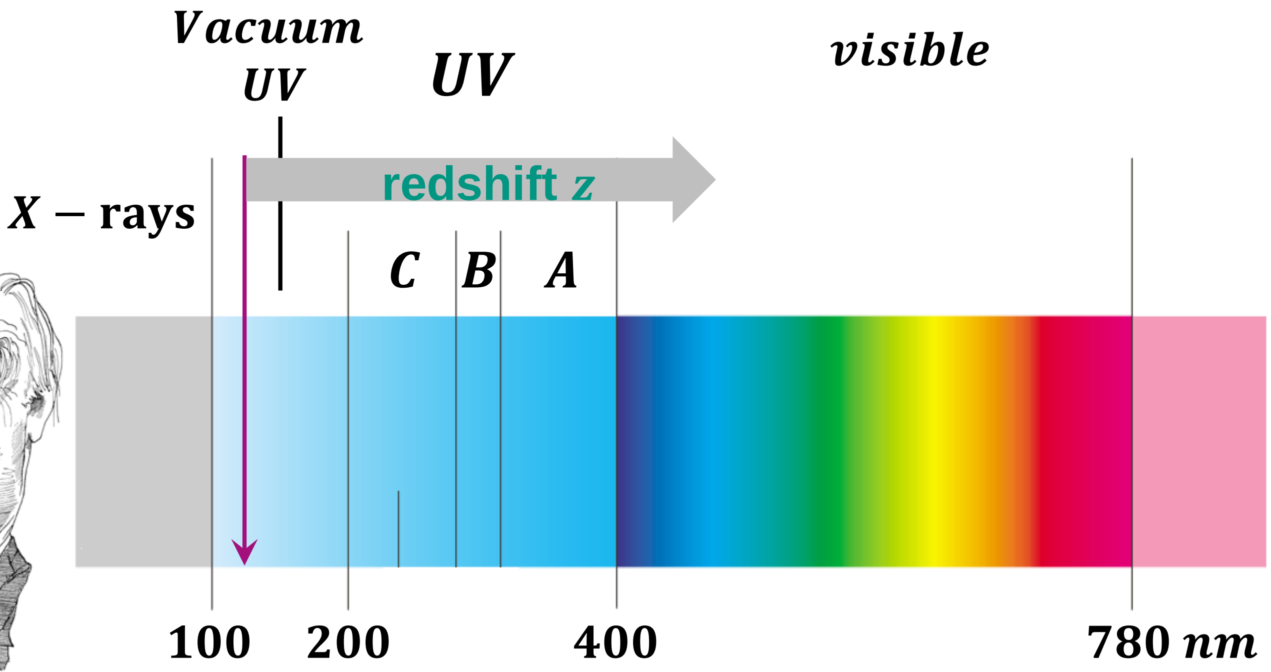
deuterium–abundance: $Ly-\alpha$ absorption lines

- 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 a distant source is shifting $Ly-\alpha$ line from VUV to visible spectrum

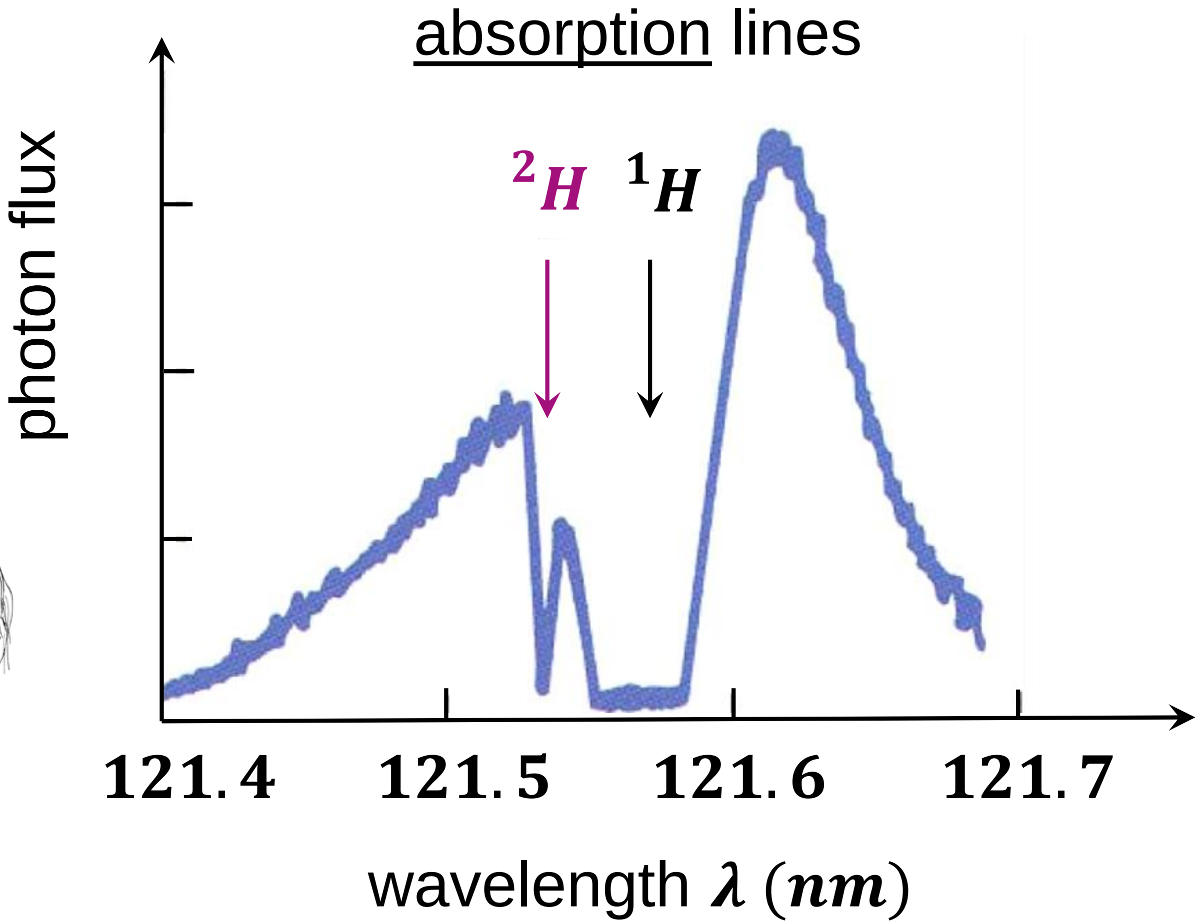


deuterium–abundance: $Ly - \alpha$ absorption line

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

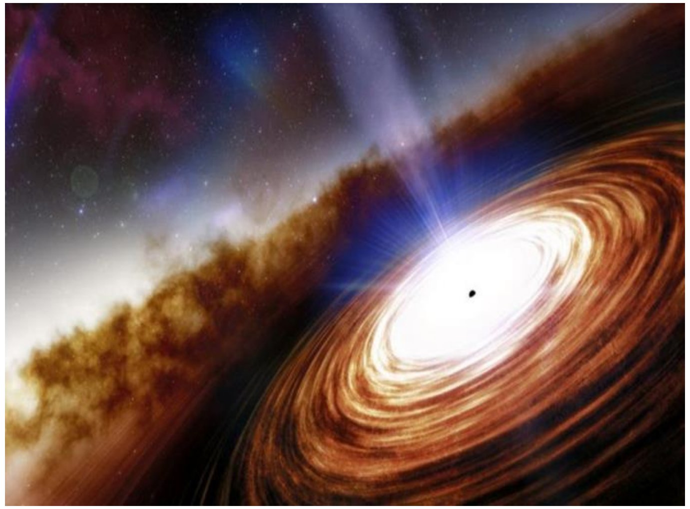
- spectroscopic challenge #**1**:
  the $\boldsymbol{Ly - \alpha}$ – **lines** of ^2H & ^1H
  lie very close together (only **reduced mass** $\boldsymbol{\mu = (m_1 \cdot m_2)/(m_1 + m_2)}$ differs
  ⇨ need resolution $\boldsymbol{\Delta E/E \approx 2.7 \cdot 10^{-4}}$

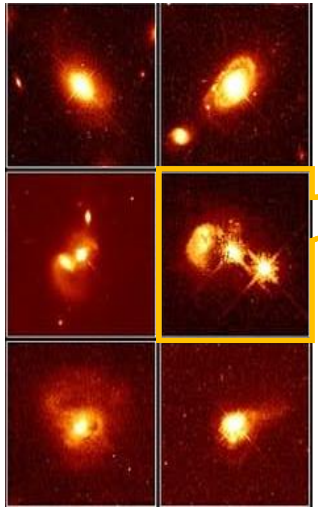
- spectroscopic challenge #**2**:
  the $\boldsymbol{Ly - \alpha}$ – **lines** of ^2H & ^1H
  differ by a huge amount in their **intensity** (flux ratio $\sim 10^{-5}$)
  ⇨ ^1H – **line is often saturated**

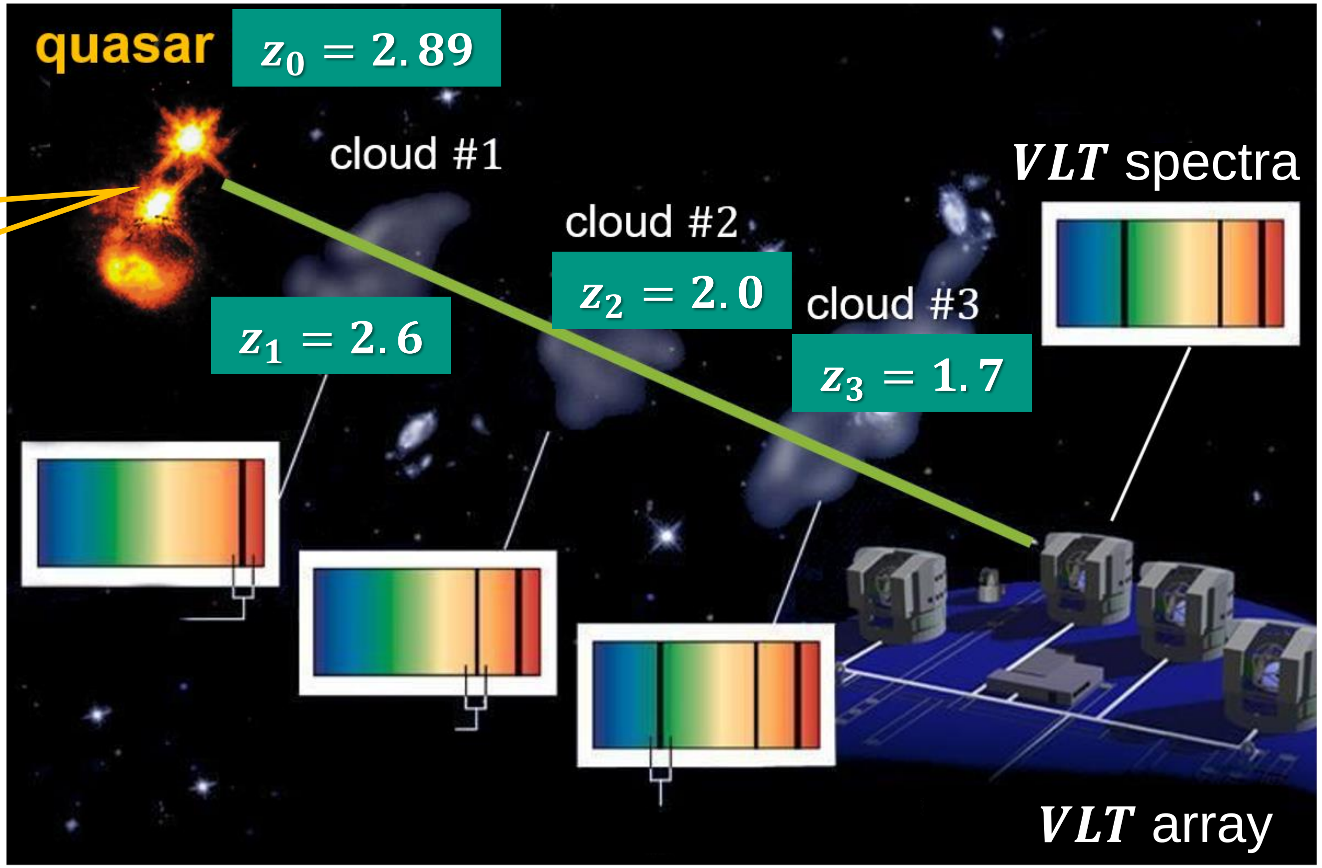


deuterium–abundance: $Ly - \alpha$ forest

- Observing the absorption lines of gas clouds illuminated by quasars







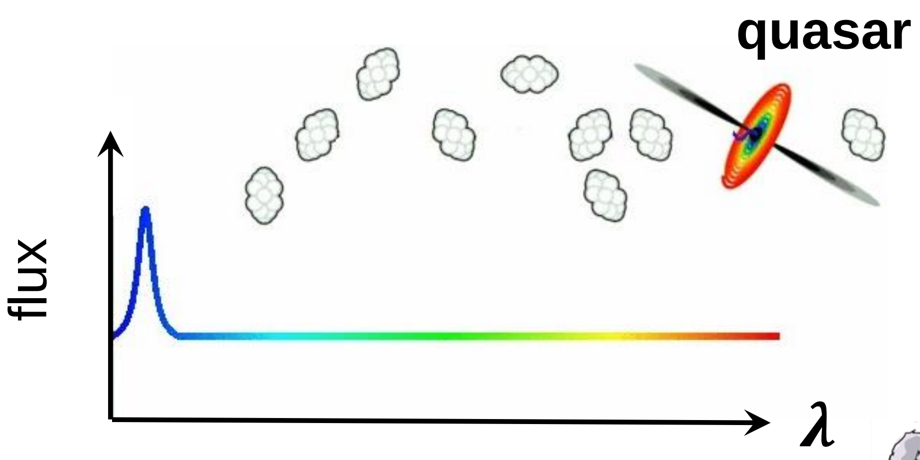
$Ly - \alpha$ absorption lines λ_i of extragalactic clouds

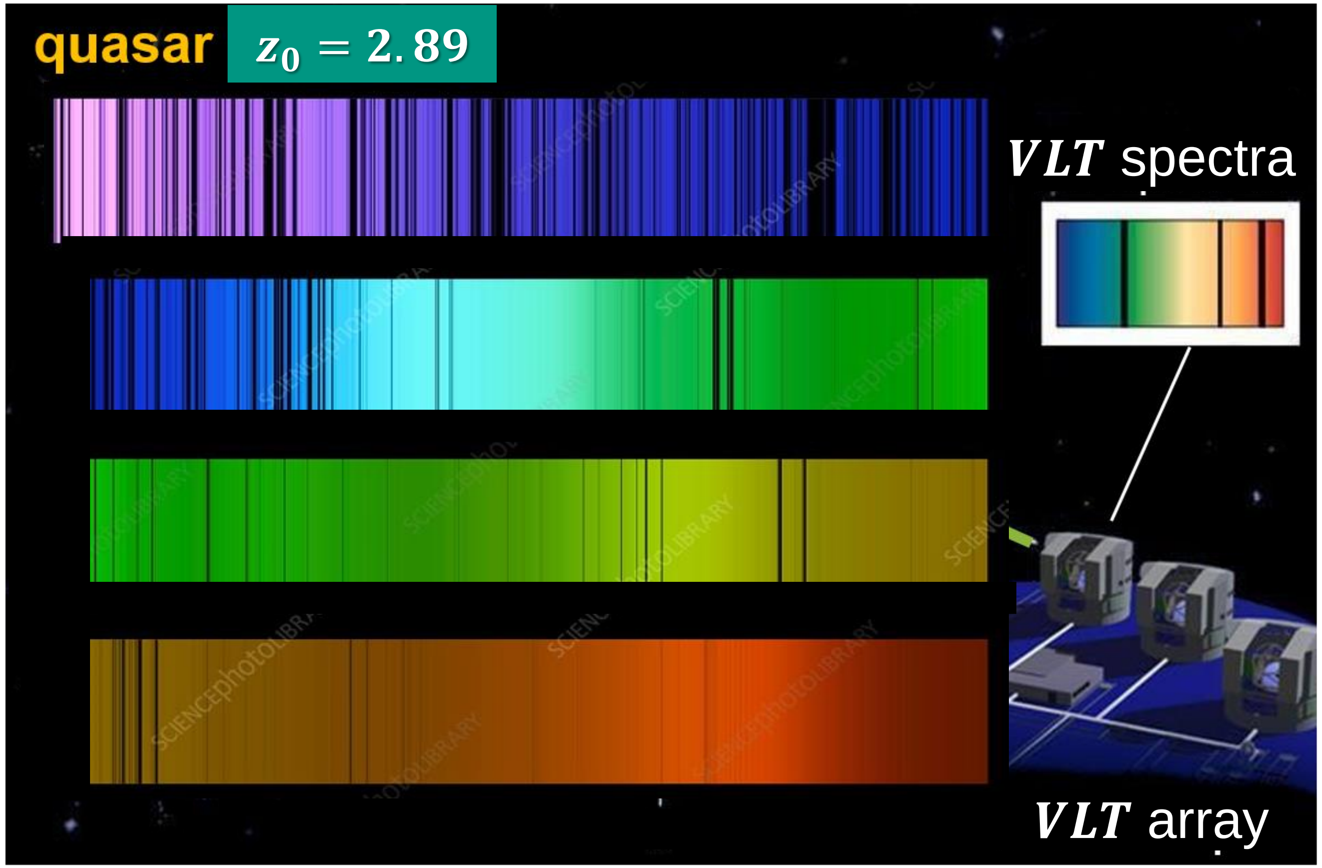
- quasar (supermassive black hole) at center of a galaxy acts as very bright beacon located far away, illuminating gaseous clouds with ^2H and ^1H at the **line–of–sight**

deuterium–abundance: $Ly - \alpha$ forest

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

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

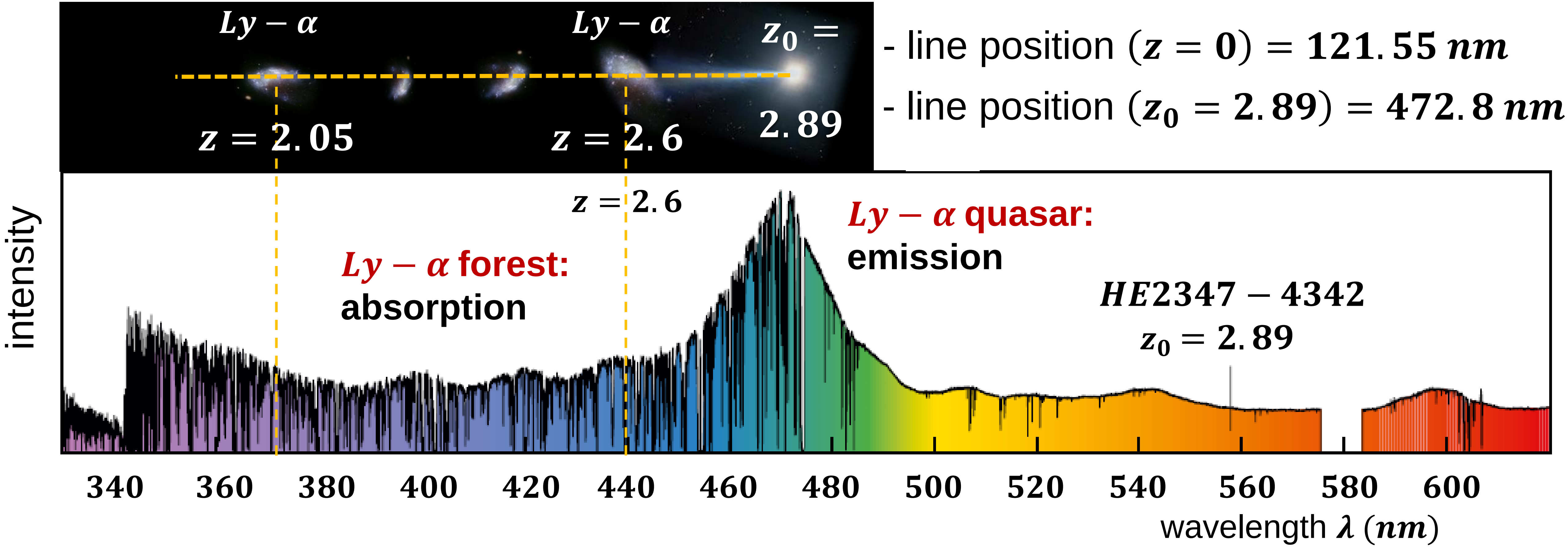




$Ly - \alpha$ absorption lines λ_i of extragalactic clouds

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

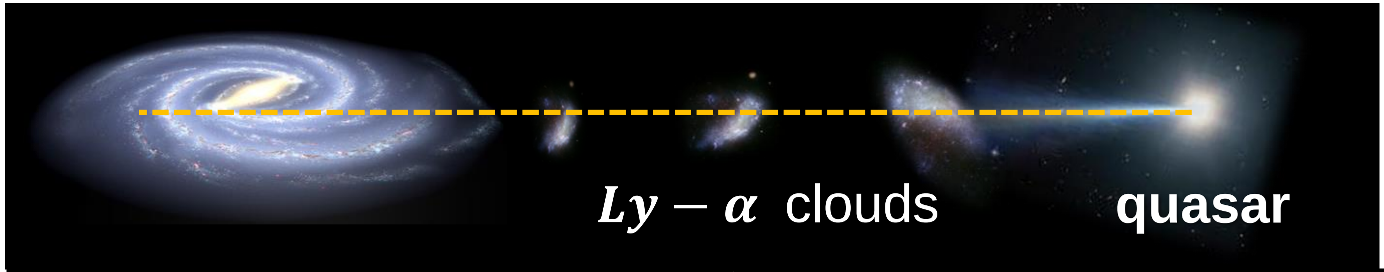


- line position $(z = 0) = 121.55\, nm$
- line position $(z_0 = 2.89) = 472.8\, nm$

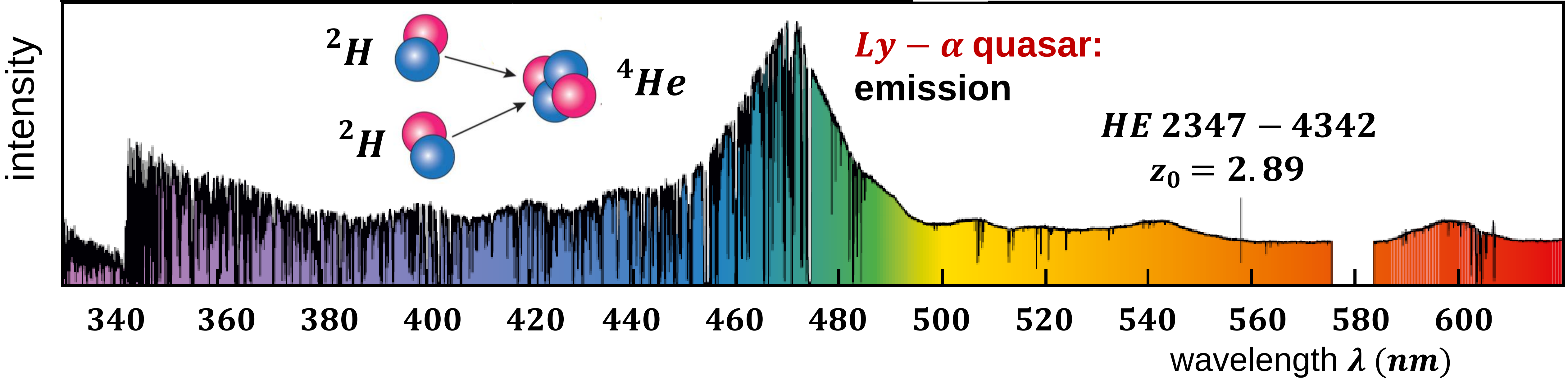
$^{*}z = (\lambda_{obs}/\lambda_{emit}) - 1$

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

- **Deuterium is destroyed by fusion ($pp-, CNO-$ chains) inside sellar cores**
  - identify the **largest value** of $^2H/\,^1H$ along the **line–of–sight**



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

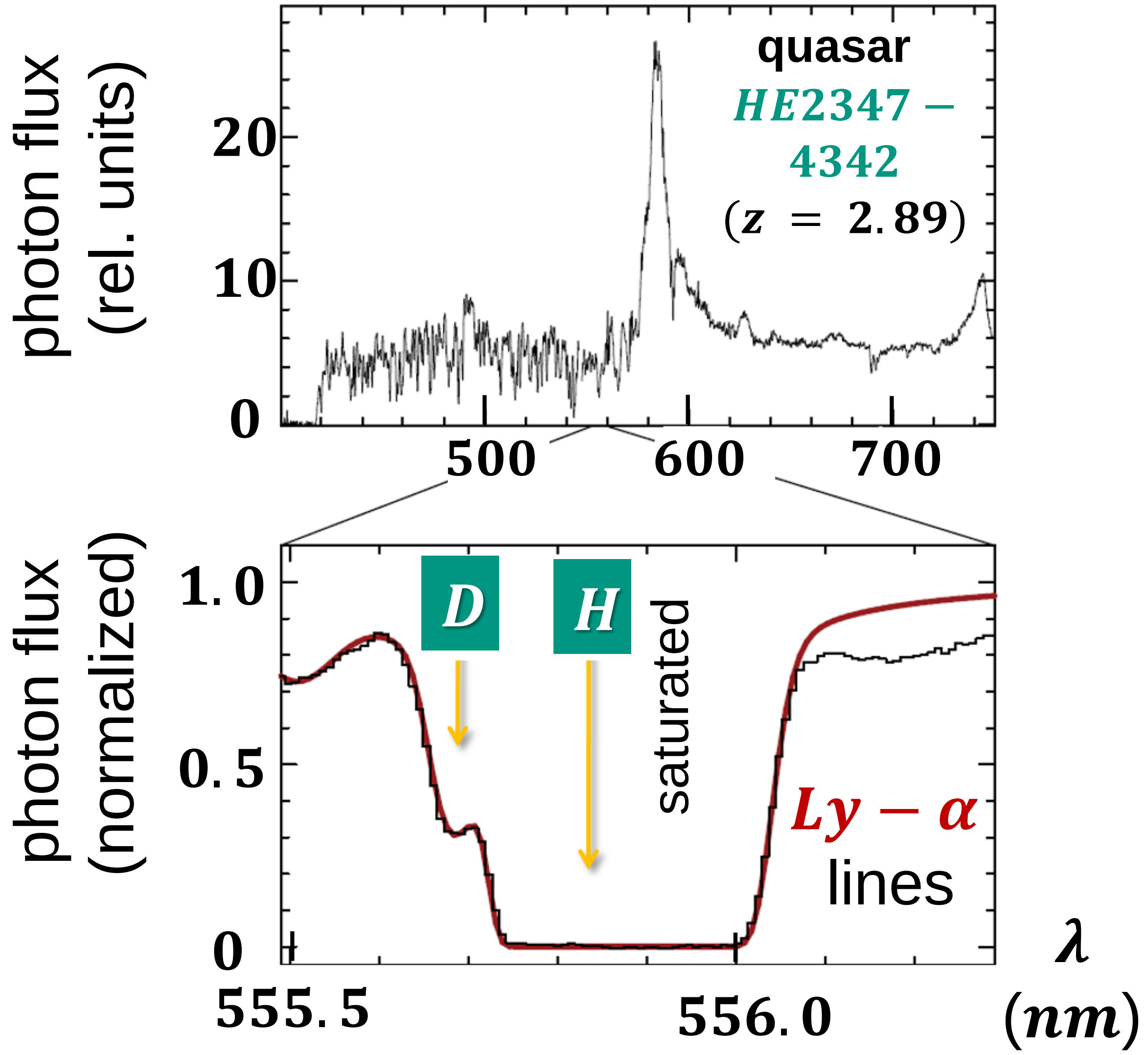


deuterium–abundance: results

- **Analysis of line profiles and intensity ratios: challenges**
  - extragalactic clouds can be rotating ⇨ **lines are Doppler–broadened**
  - saturation of main ^{1}H – **line** ⇨ **rely on other (weaker) lines**
  - present (2023) PDG – value* :

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

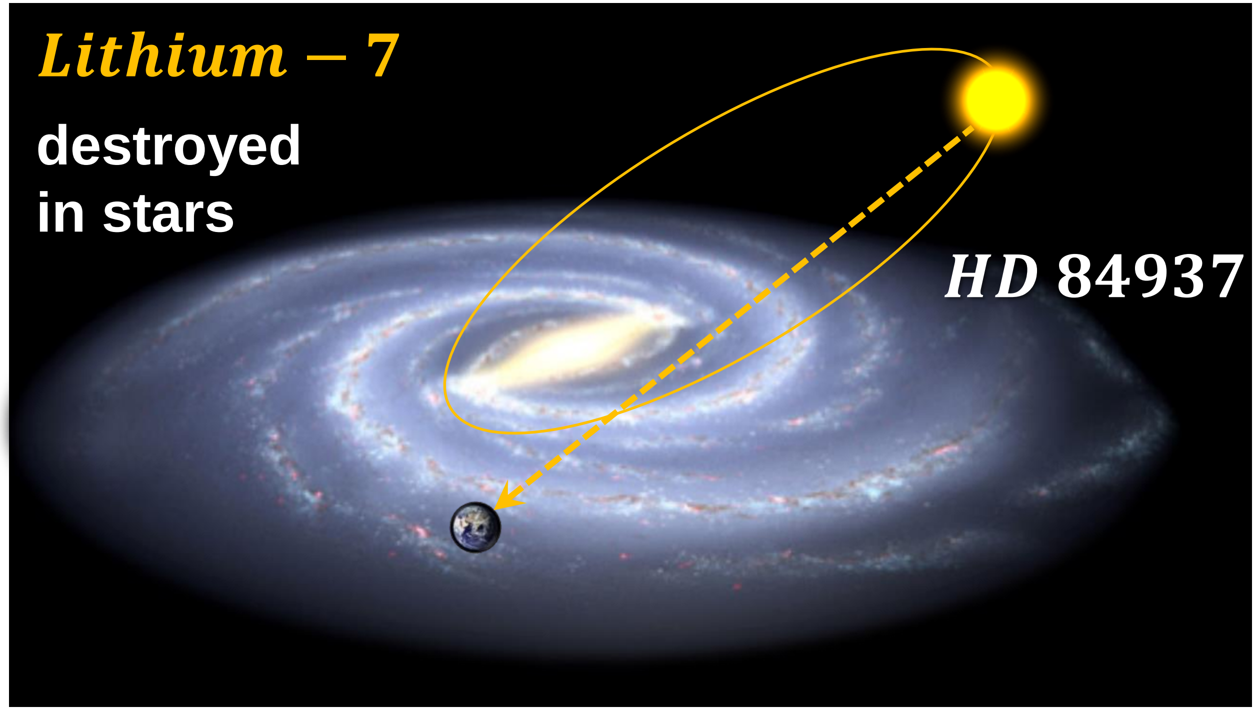
stat. + syst.

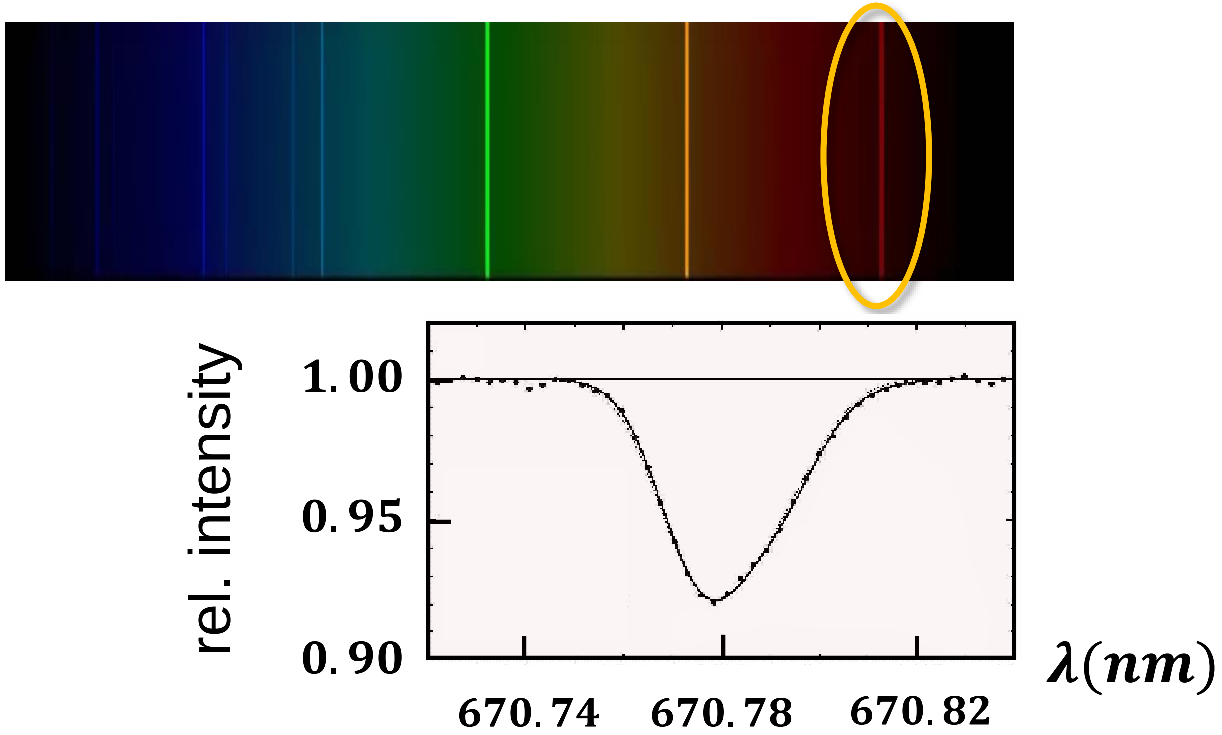


 * rpp2022-rev-bbang-nucleosynthesis.pdf (lbl.gov)

abundance of ^7Li – the 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 old, **metal–poor stars**



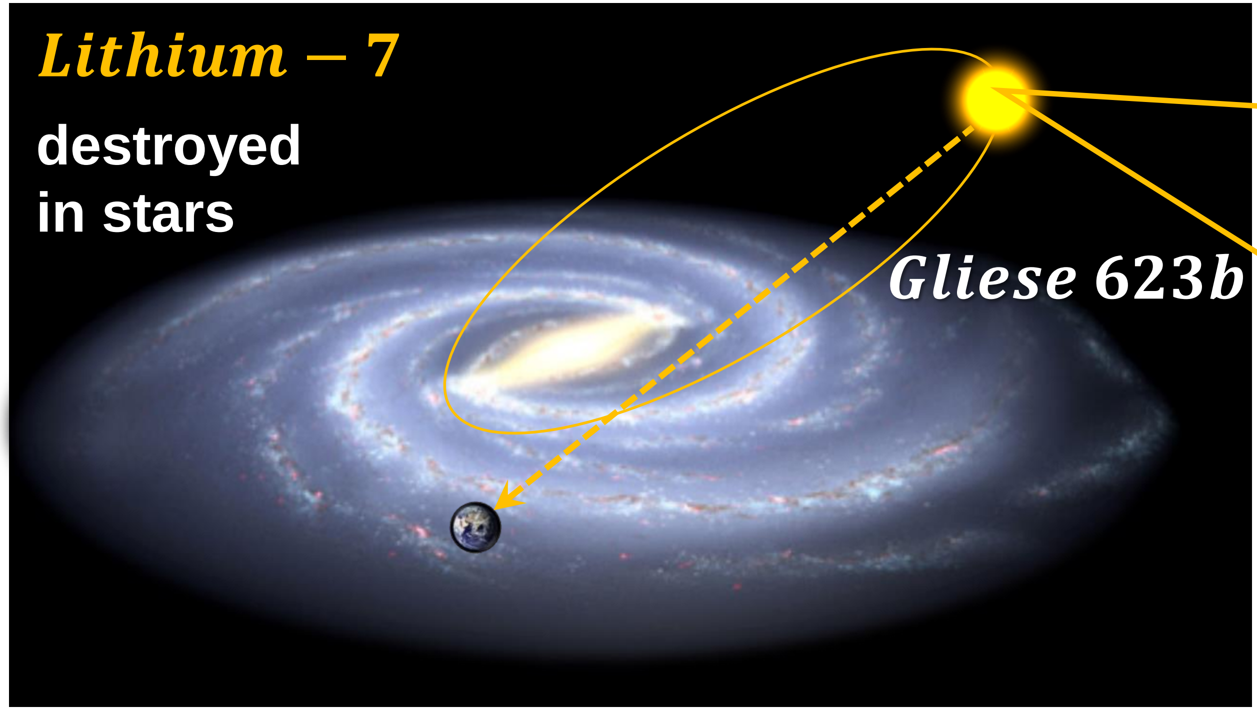


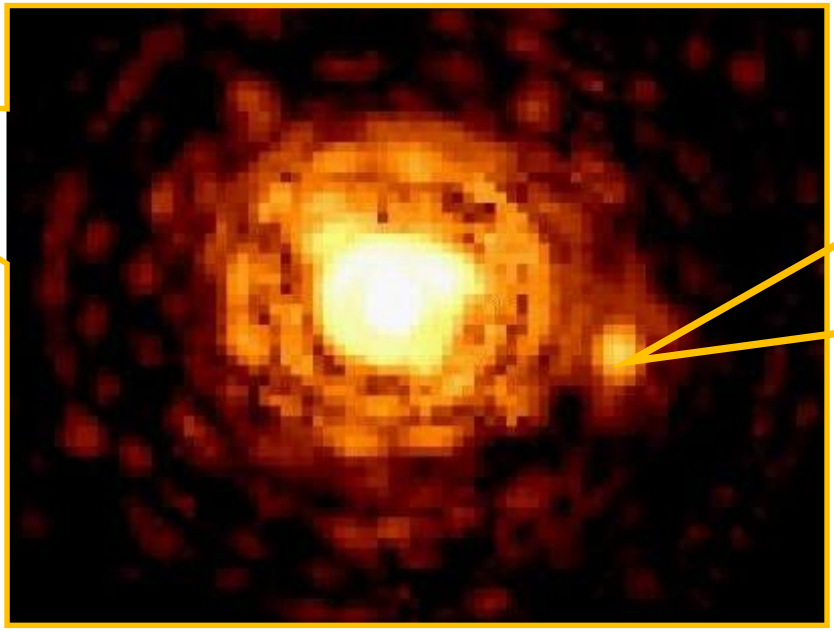
abundance of ^7Li – the Spite plateau

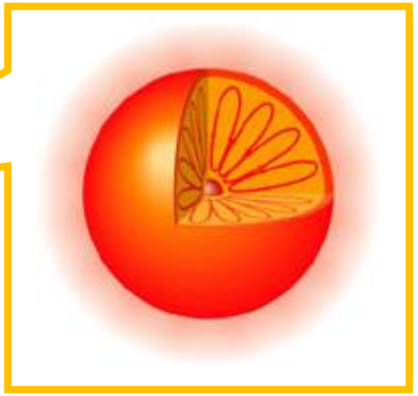
- **Observation of absorption line from ^7Li: select old, metal–poor stars**

  - low–mass $(m \sim 0.1\, M_{\odot})$ stars in our galactic halo: **small fusion rates**

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



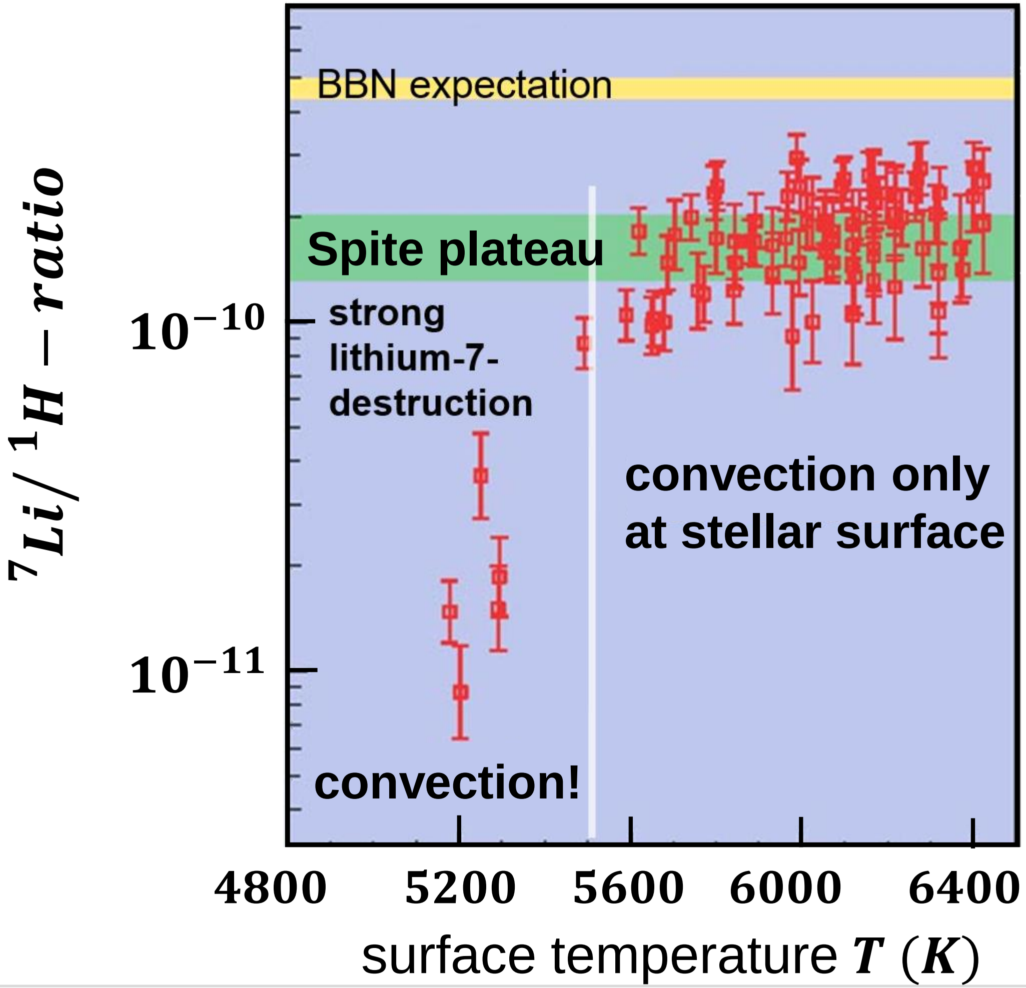




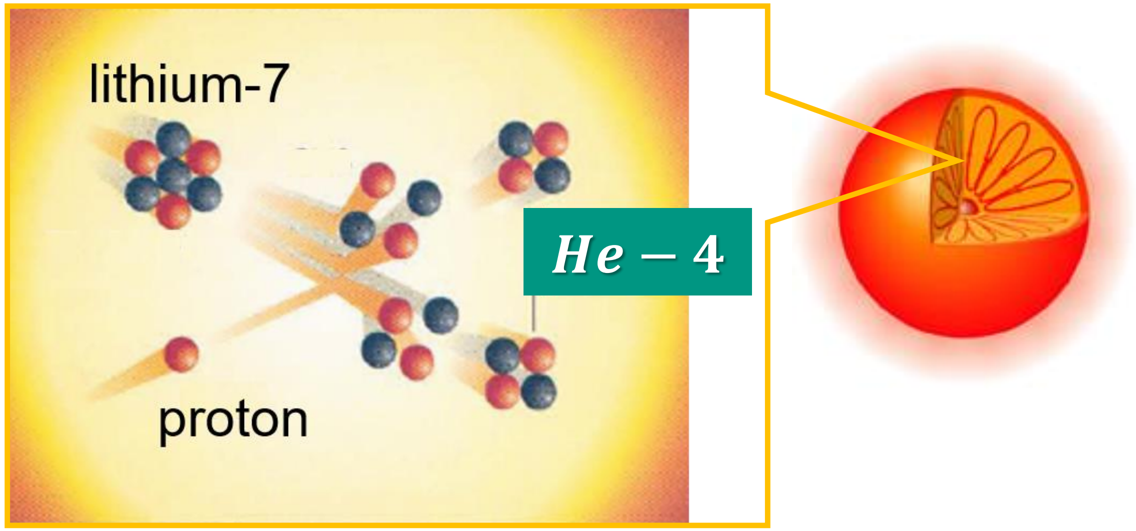
Gliese 623b – example of a low–mass star

abundance of ^7Li – the Spite plateau

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

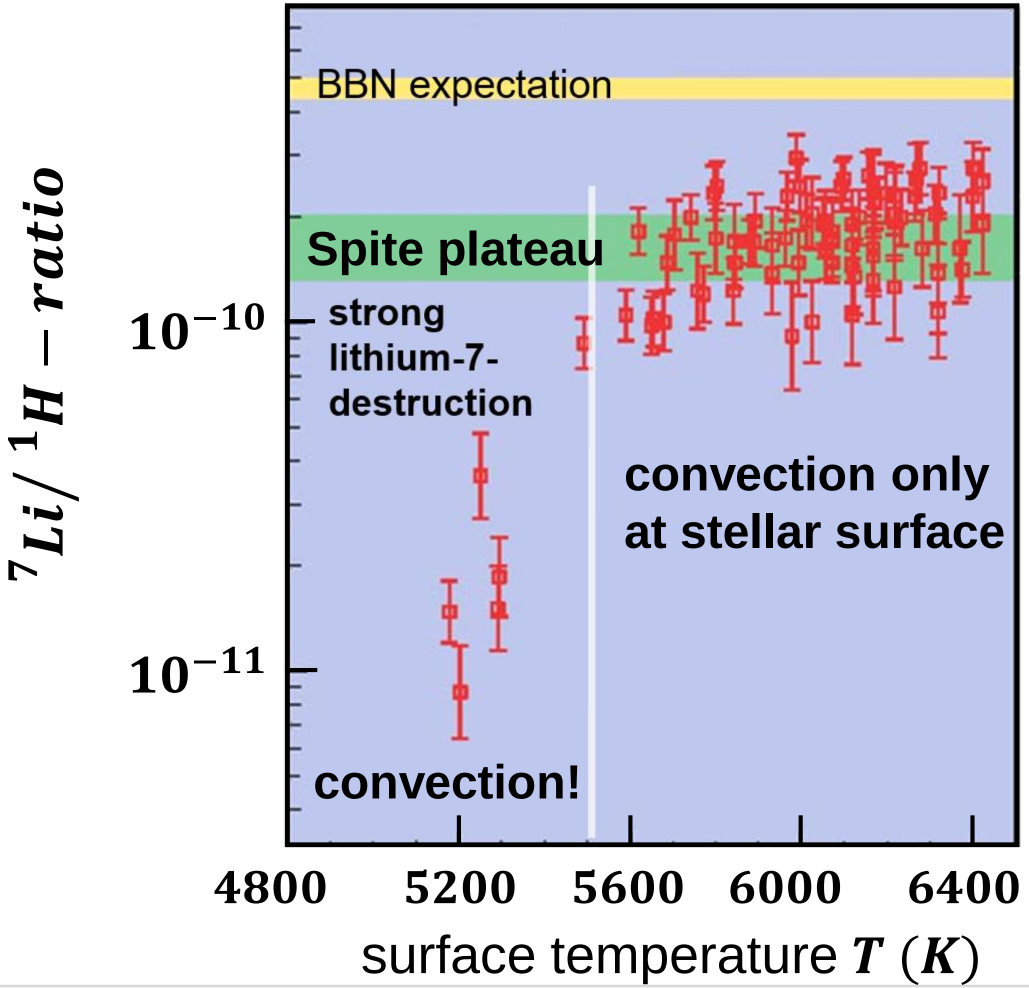


- stars with **high surface temperature T**:
  minimum surface convection
  ⇨ **reduces** dangerous **burning of ^7Li** which decreases the primordial yield



abundance of ^7Li – the ´anomaly´

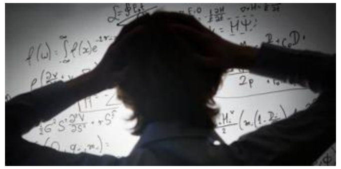
- **Observation of absorption line from ^7Li: a systematic effect unexplained**



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

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

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



Observed light element yields & baryon density

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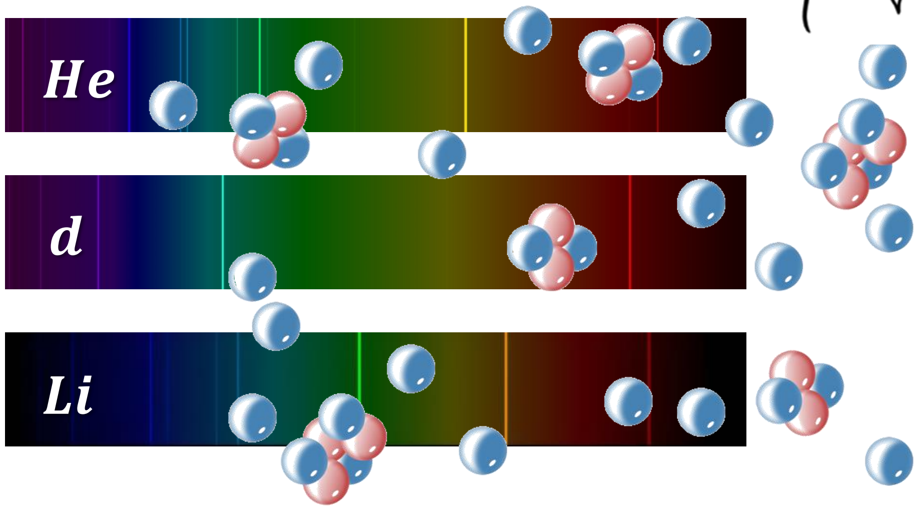
- **Combining results for ^4He, ^2H, ^7Li and comparison with Ω_B from the CMB**

- deriving Ω_B from

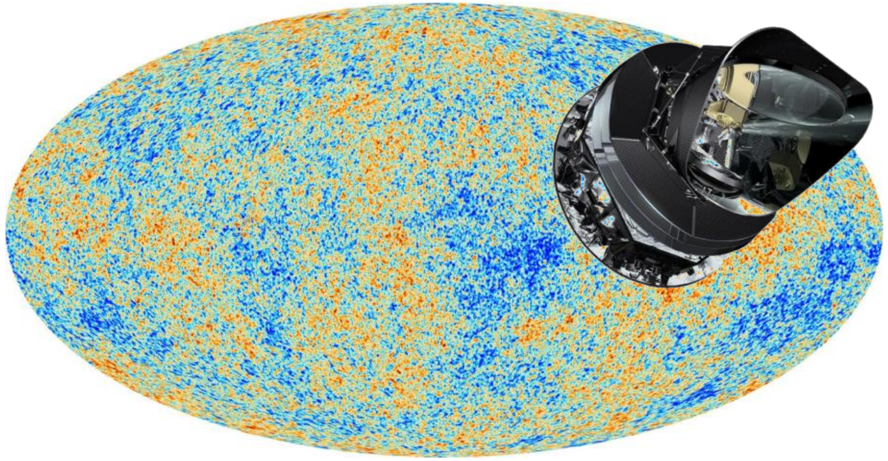
measurements of light element yields $(3\ min.)$

- deriving Ω_B from

measurement* of matter–photon oscillations $(380\,000\ yrs)$



baryon density

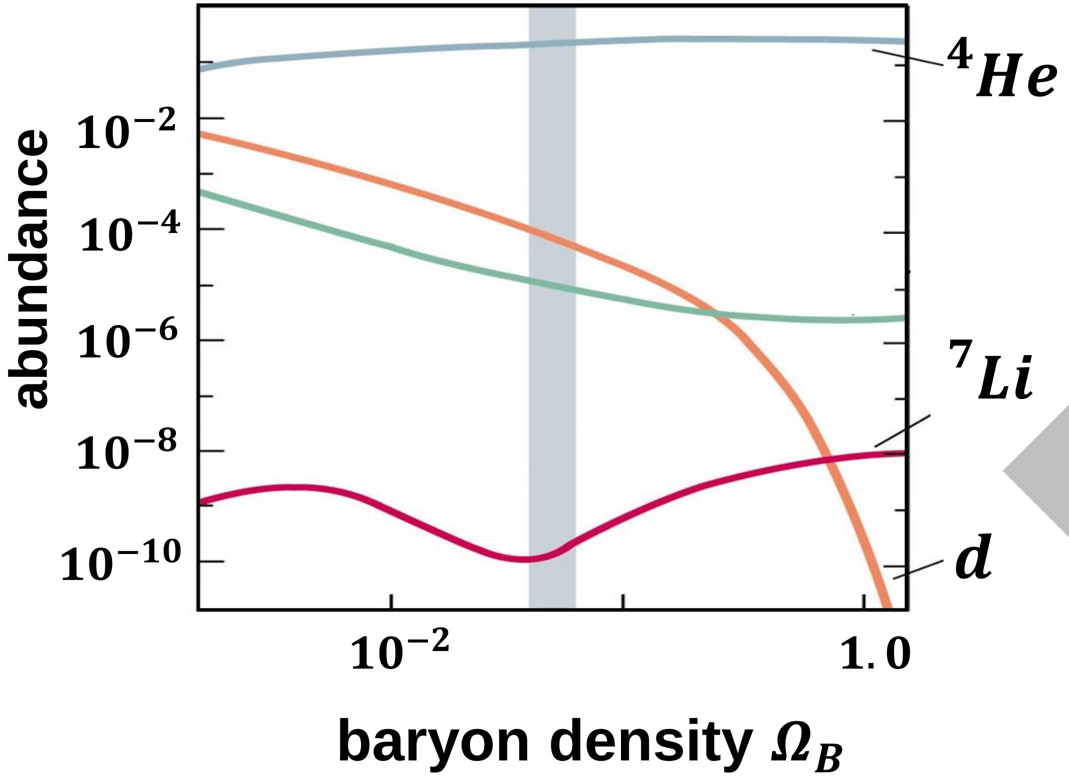


*see next chapter

Observed light element yields & baryon density

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

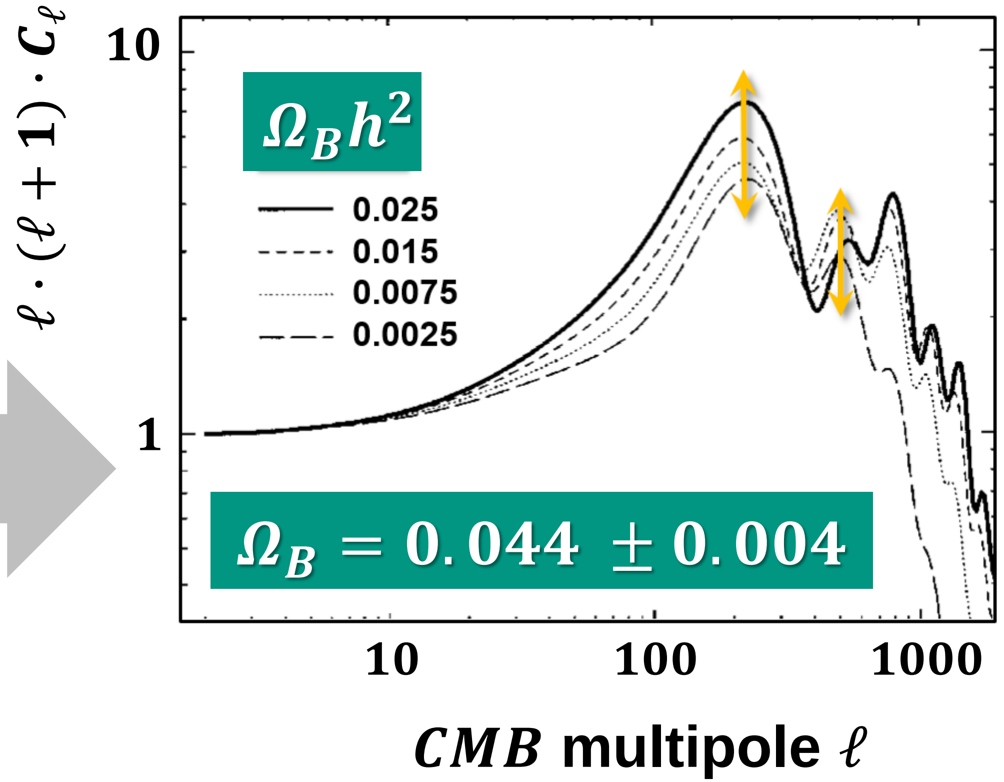
- deriving Ω_B from



Ω_B

baryon density

- deriving Ω_B from



Schramm plot for BBN

- **Comparison of BBN & CMB**

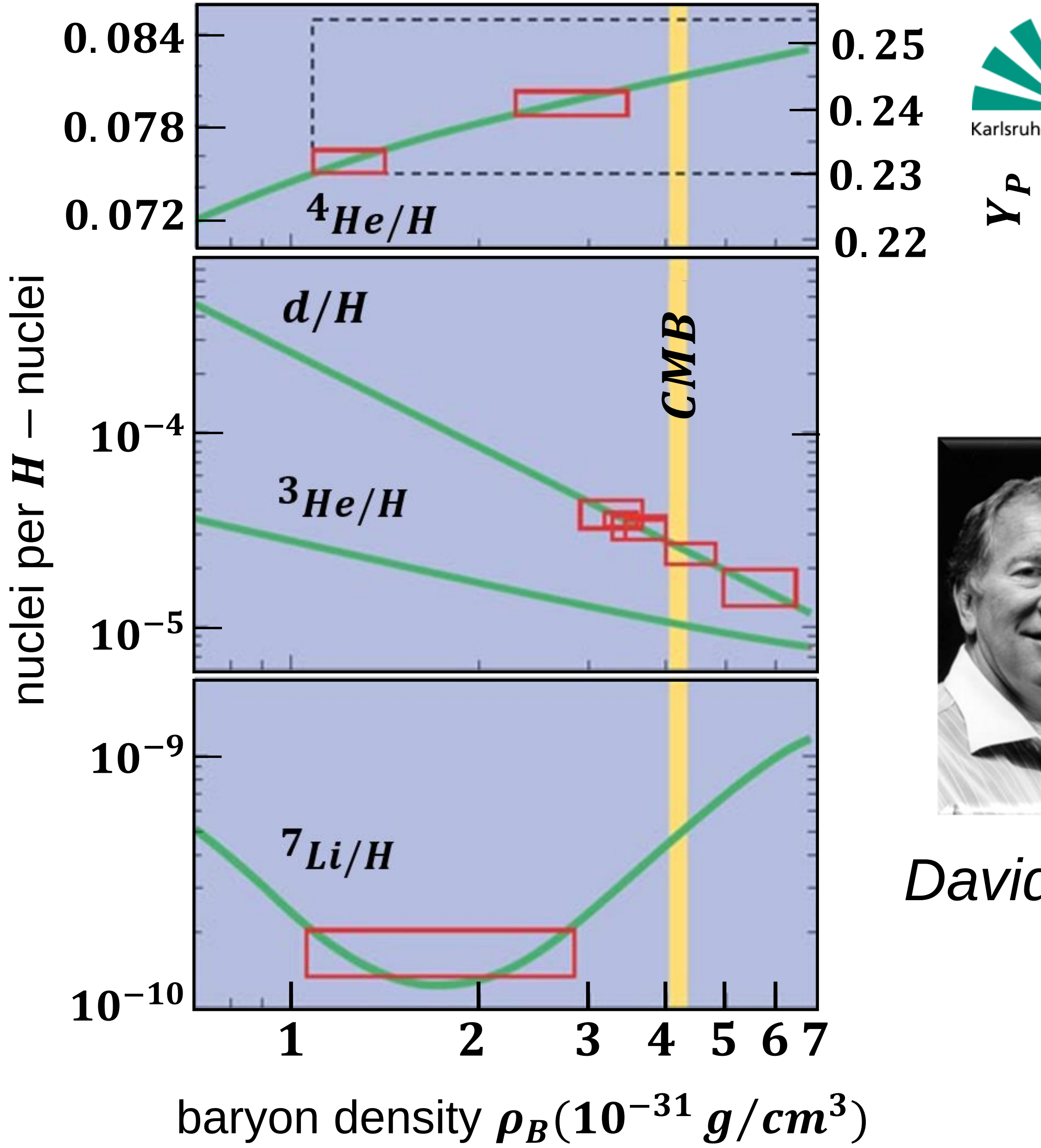
- observed **BBN light element yields** are broadly consistent with precise CMB results, but **systematics remains**

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

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

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

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



David Schramm

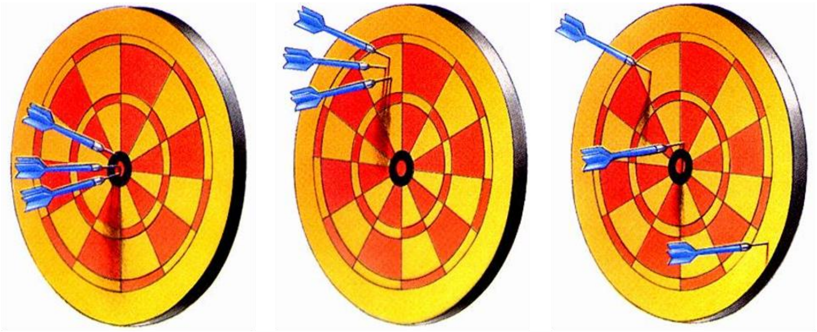
* η_{10} = baryon–asymmetry in units of 10^{-10}

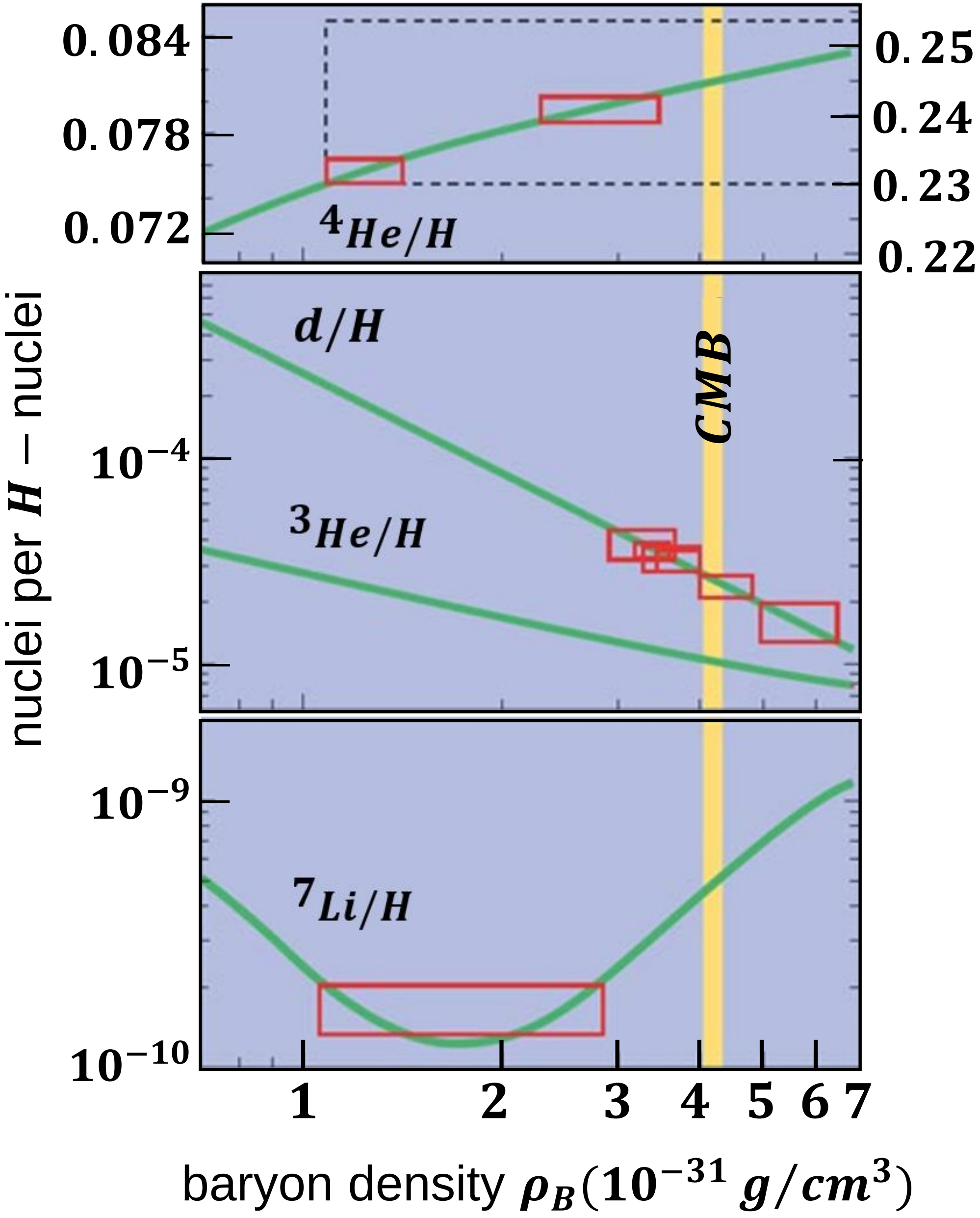
Schramm plot for BBN

- **Comparison of BBN & CMB**

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

- keywords for observations: accuracy, trueness, precision

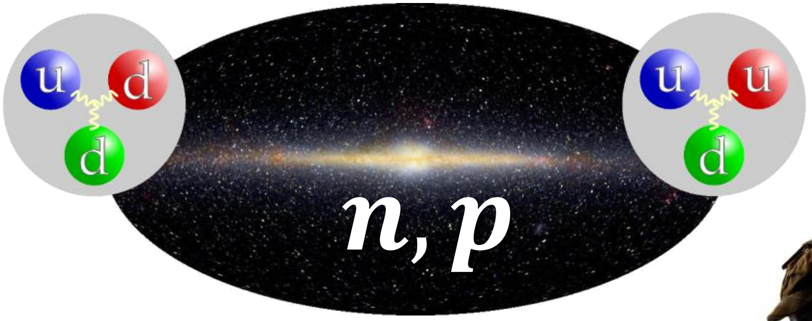




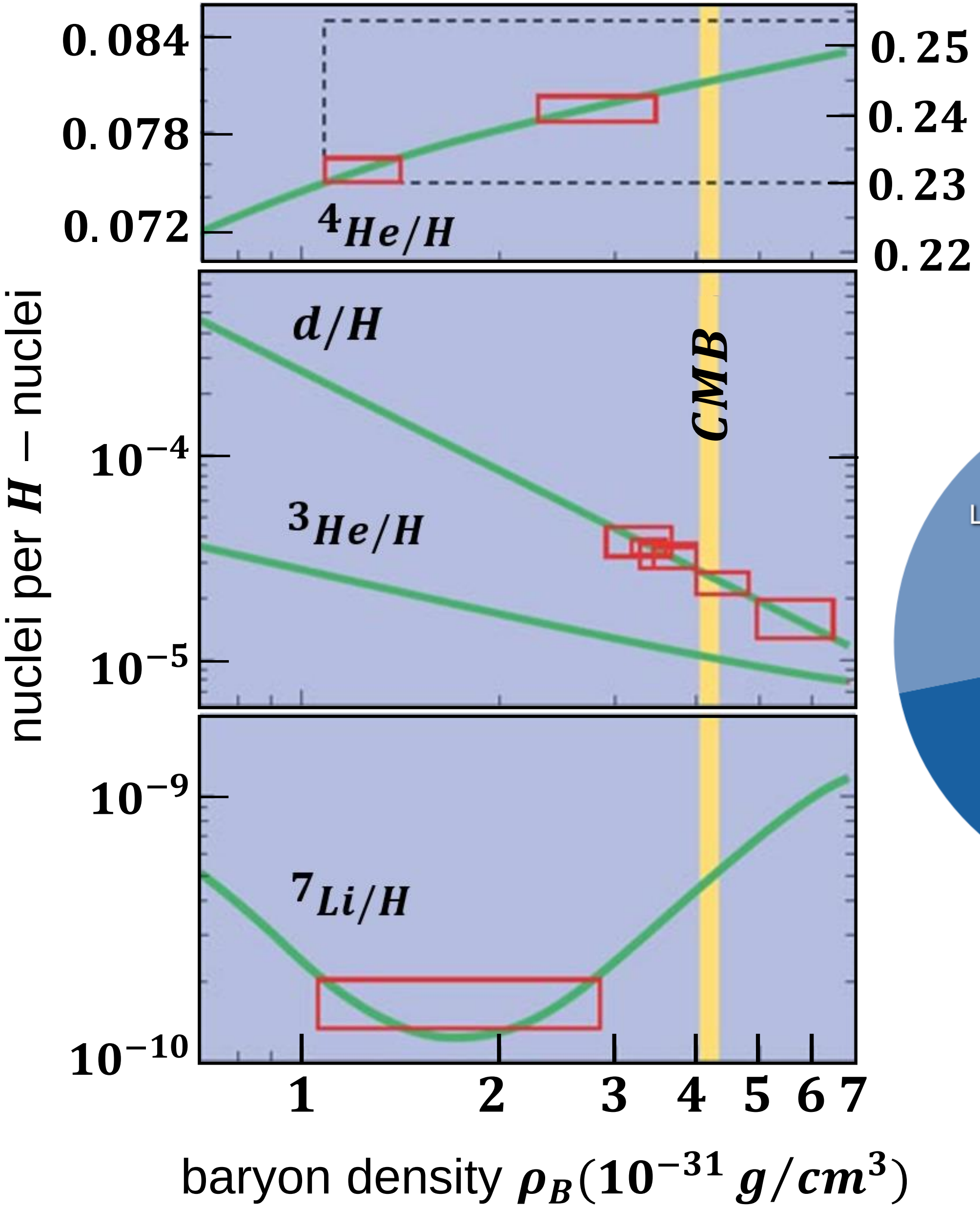
BBN & missing baryons

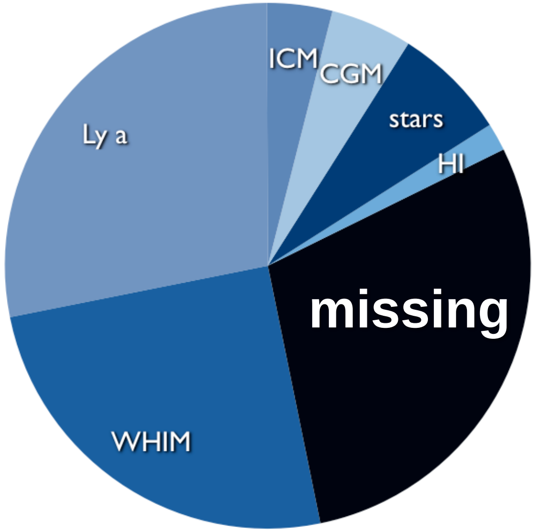
- **Case of ´missing baryons´**

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



where have the baryons gone…?





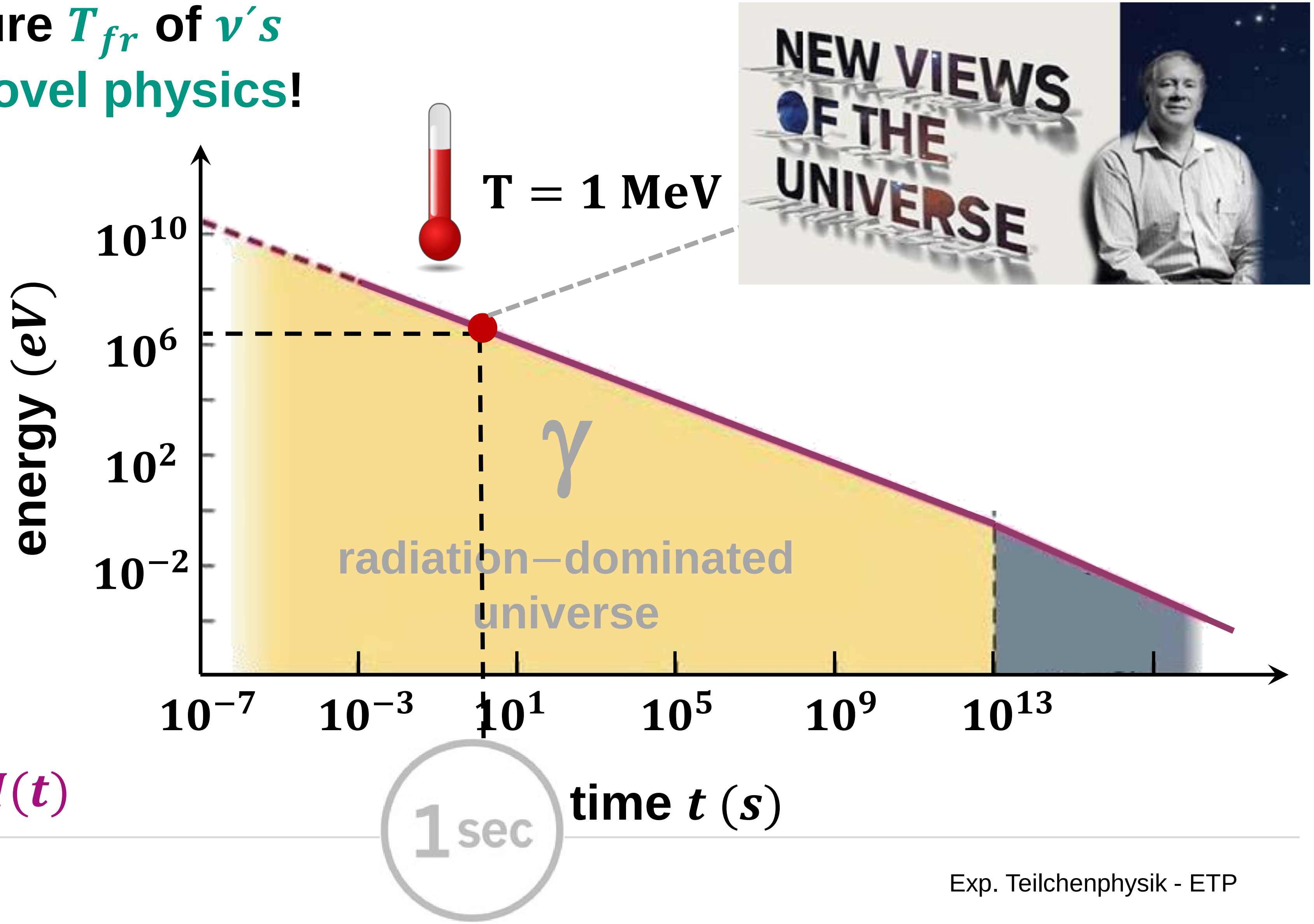
Schramm´s idea: $\boldsymbol{BBN}$ as tool for particle physics

- **Freeze–out temperature T_{fr} of ν´s may be changed by novel physics!**

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

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

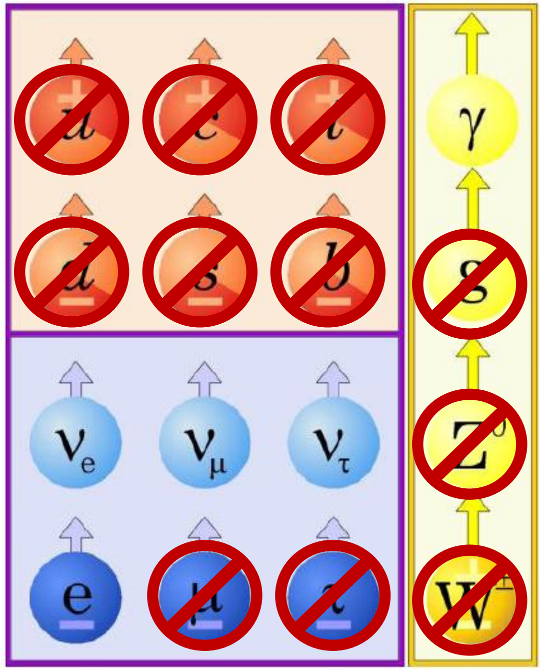
idea: the number N_ν of ν – generations impacts $H(t)$

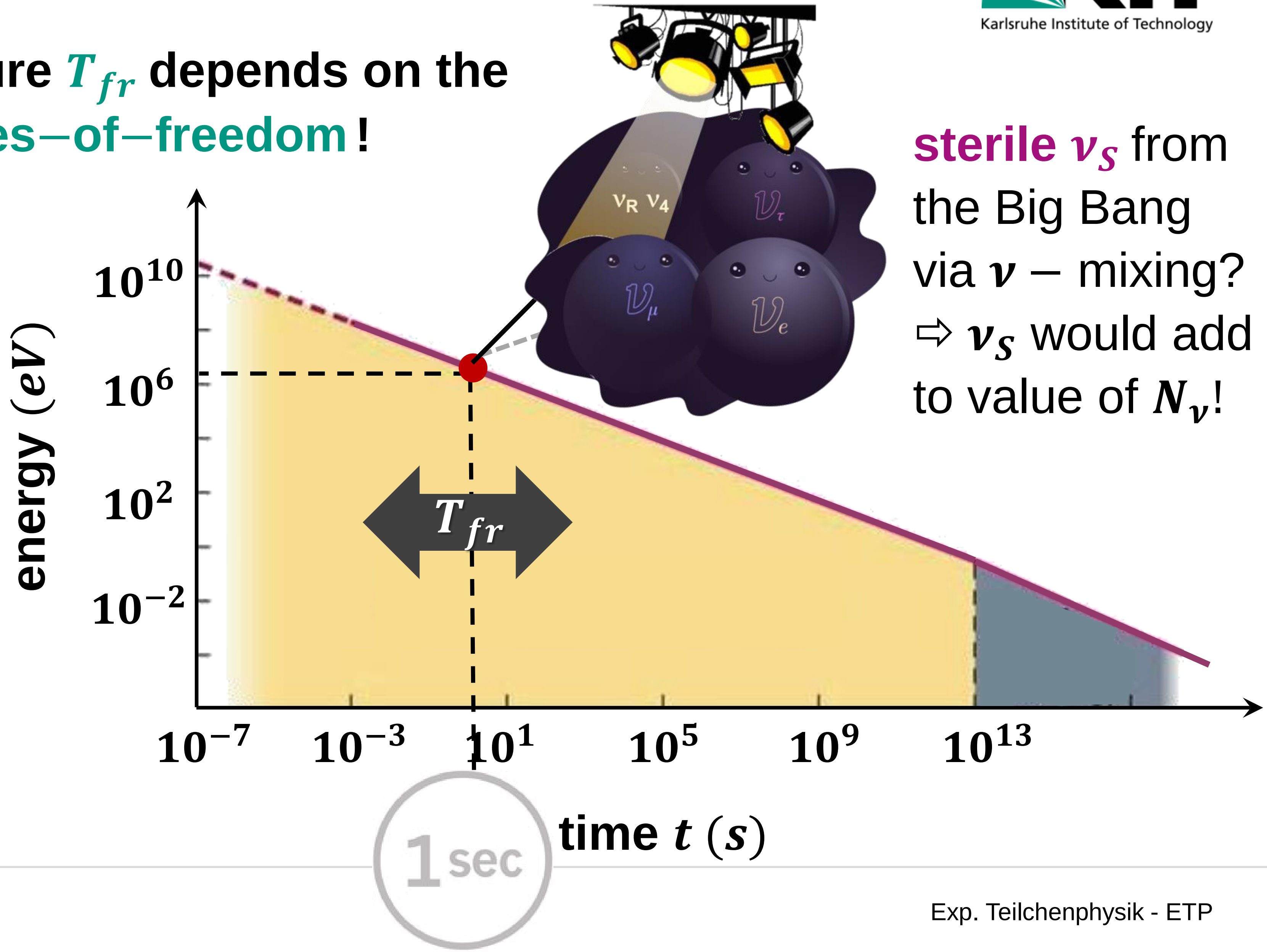


BBN as tool for novel particle physics at $t = 1\ s$

- **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 $E = 1\,MeV$ & $t = 1\,s$ *

γ: ☑ **boson**

factor = 1

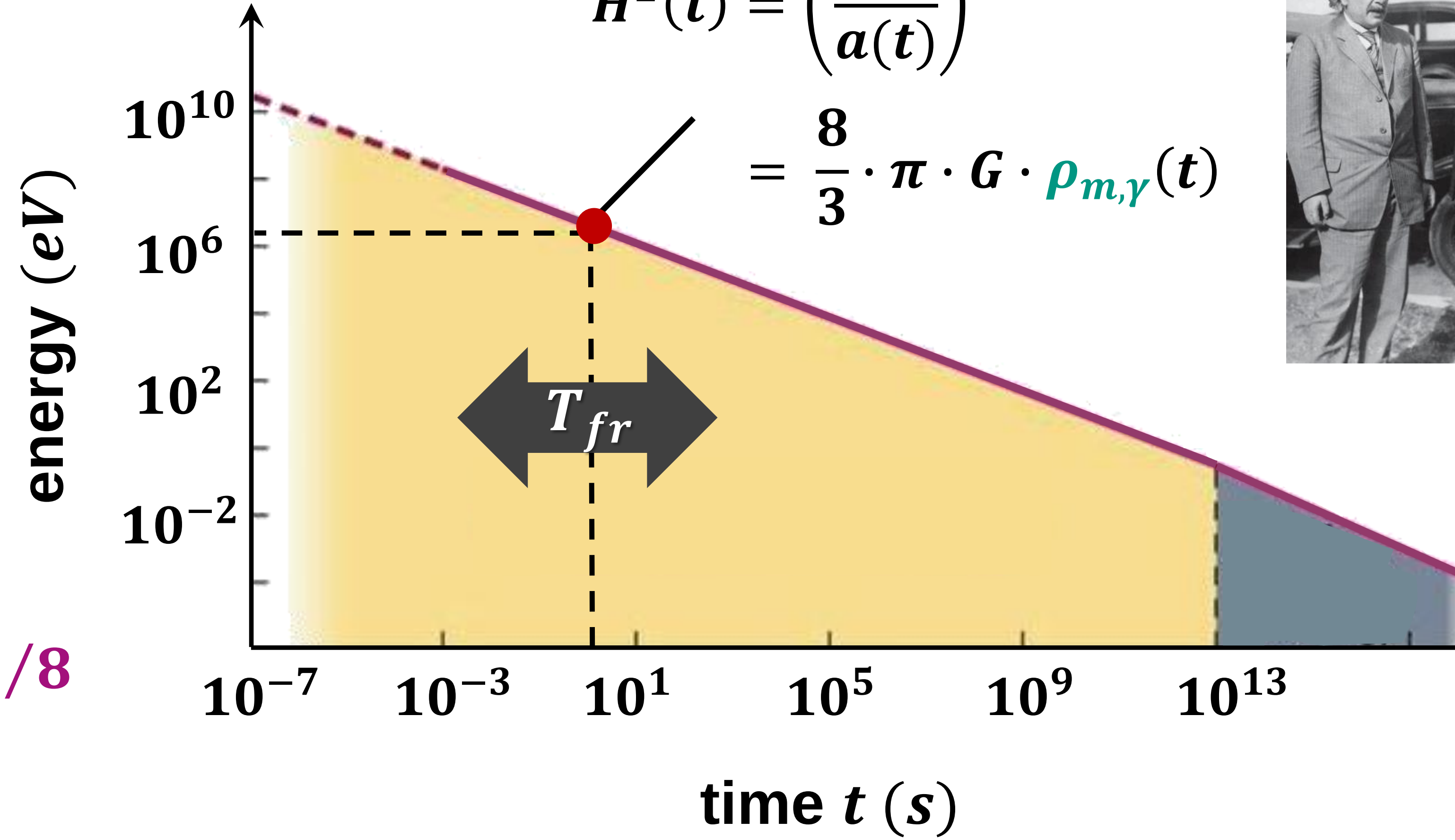
$\nu_e\,\nu_\mu\,\nu_\tau$: ☑

e: ☑

fermions

factor = 7/8

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

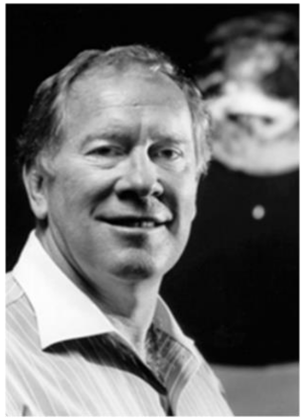


* μ, τ have already all decayed

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

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

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



- **relativistic particles** with contributions from

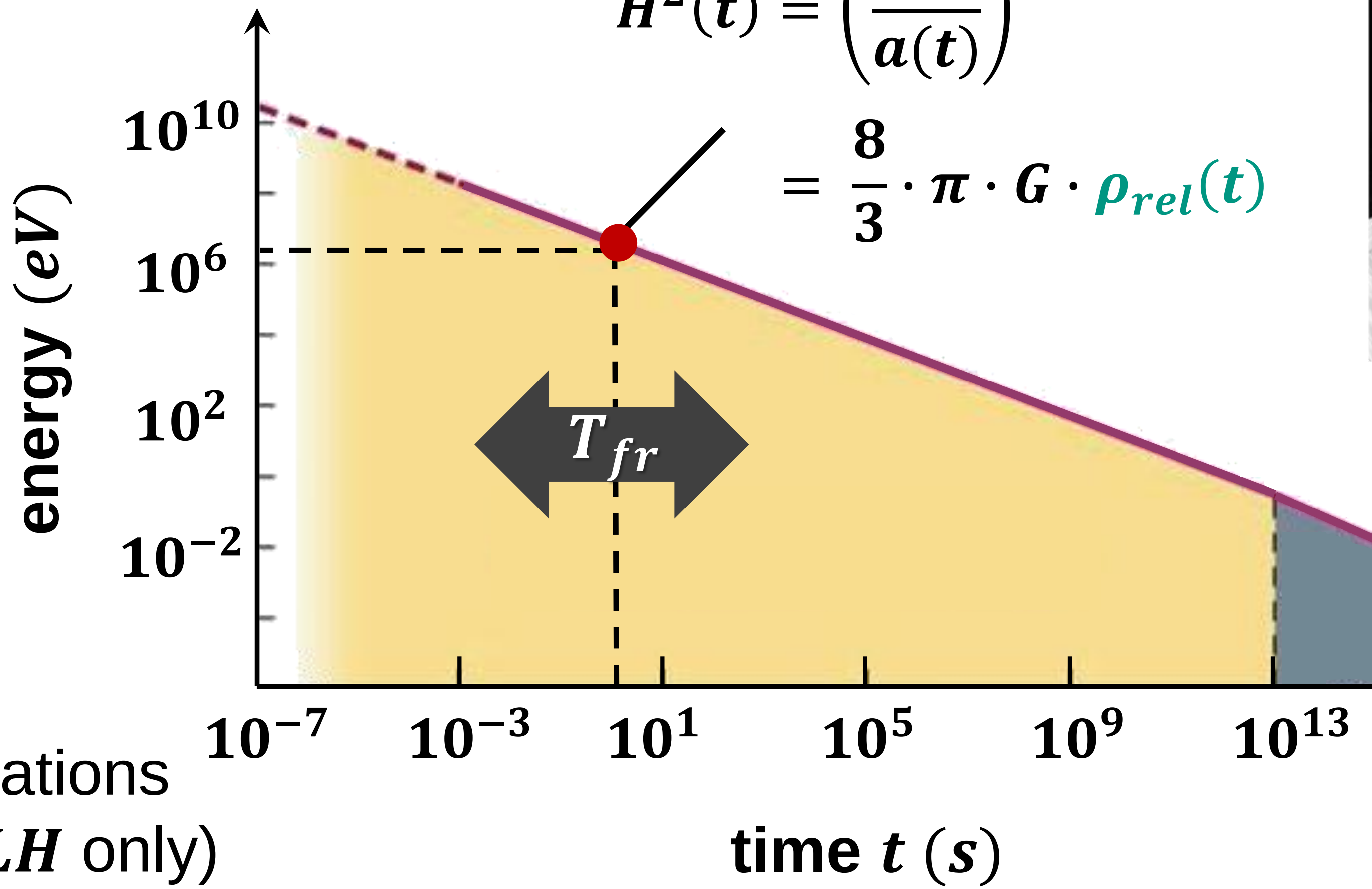
bosons: fermions:

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

γ´s

1 generation of e^- $(LH + RH)$

3 generations of ν´s $(LH$ only)



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

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

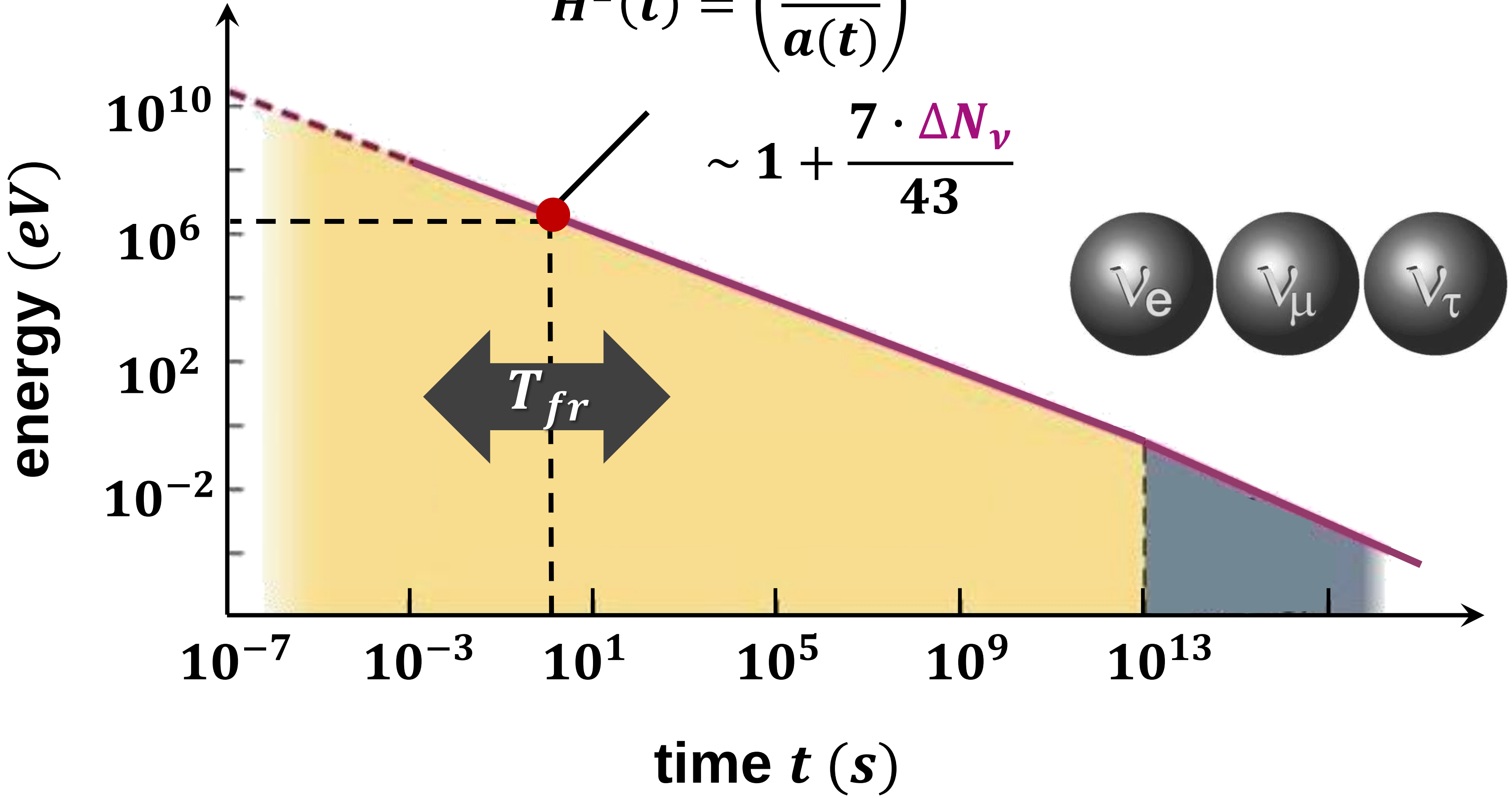
- **relativistic particles** normalized to $\rho_\gamma(t)$

$$\rho_{rel}(t) = \frac{43}{8} \cdot \rho_\gamma(t)$$

- each **additional ν – generation** would lead to an increase of $H(t)$ & thus modify T_{fr} via $\rho_{rel}(t)$

$$H^2(t) = \left(\frac{\dot{a}(t)}{a(t)}\right)^2$$

$$\sim 1 + \frac{7 \cdot \Delta N_\nu}{43}$$



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

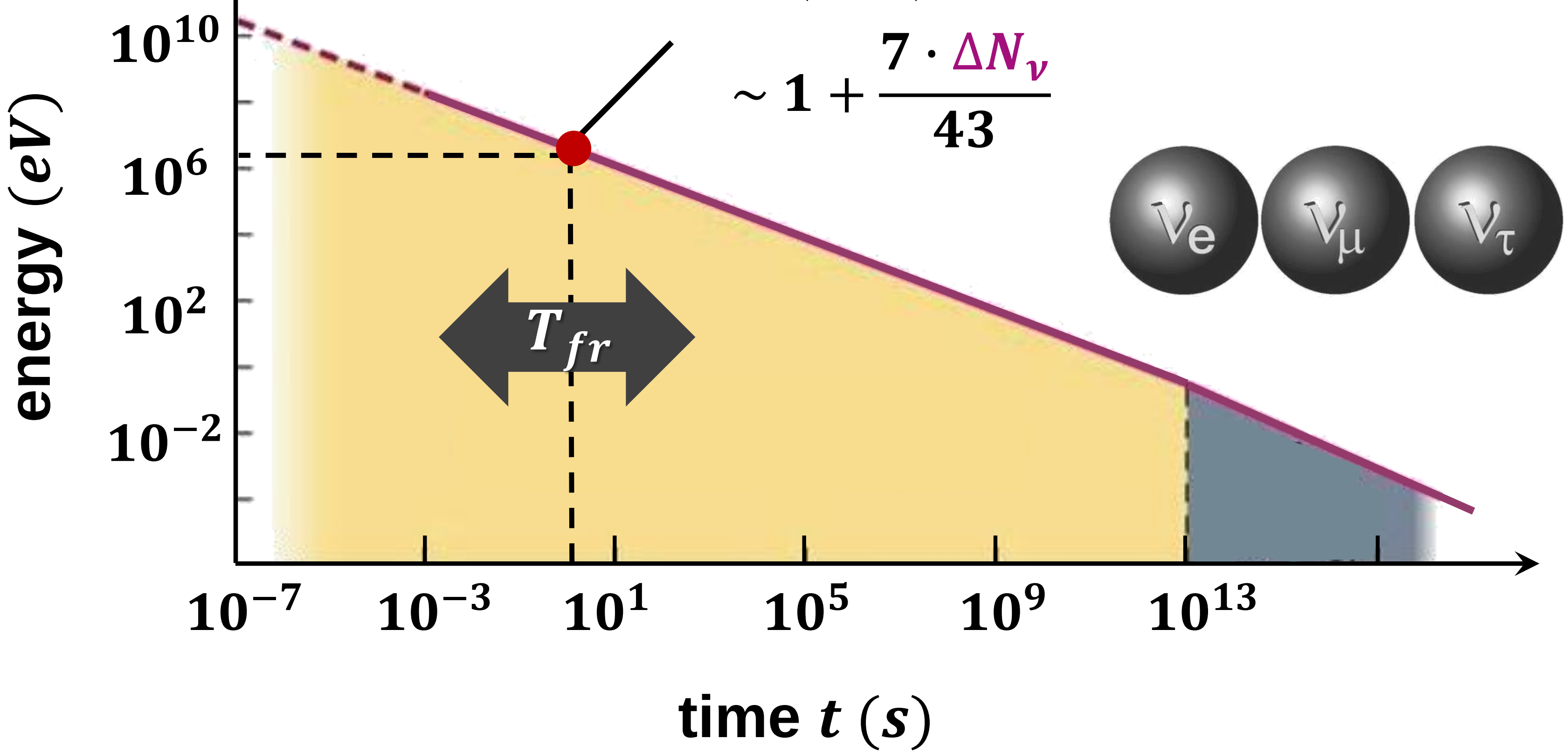
- **Freeze–out temperature T_{fr} depends on the # of relativistic degrees–of–freedom!**

- 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

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

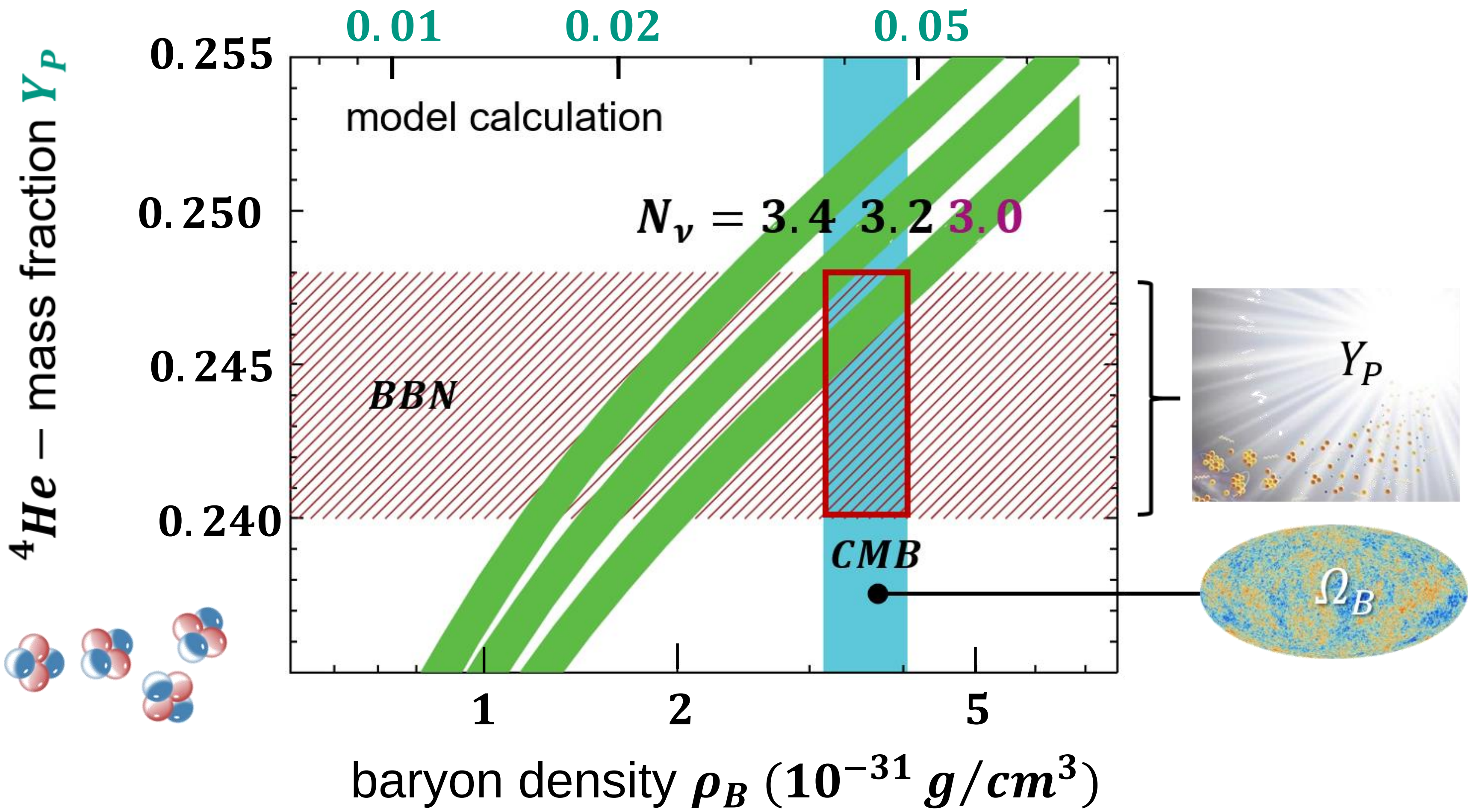


BBN results can be combined with CMB data

- Primordial ^4He 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 is *independent* of N_ν

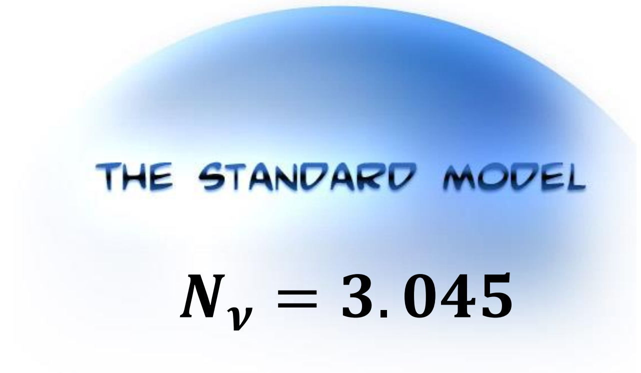


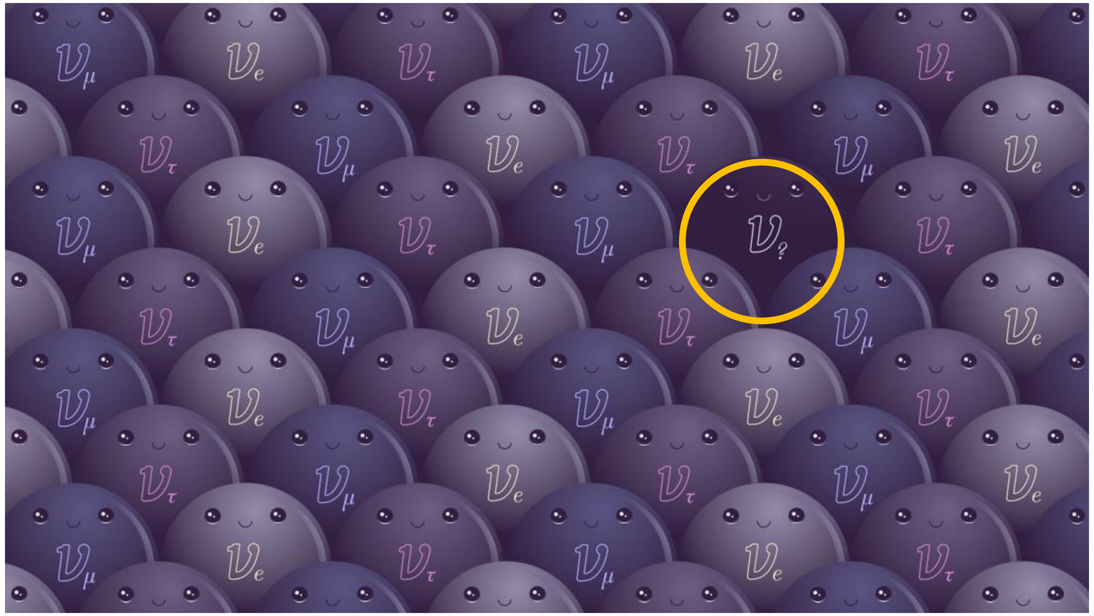
BBN results can be combined with CMB data

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

  - detailed calculation gives SM – expectation of $N_\nu = 3.045$ for **3** ν – generations (non–integer value due to finite **time interval for ν – decoupling**)

  - should observations provide conclusive values of $N_\nu \gg 3.045$:
  evidence for $eV \ldots keV$ – scale
  extra–ν´s or other forms of socalled
  dark radiation (MeV)





BBN results can be combined with CMB data

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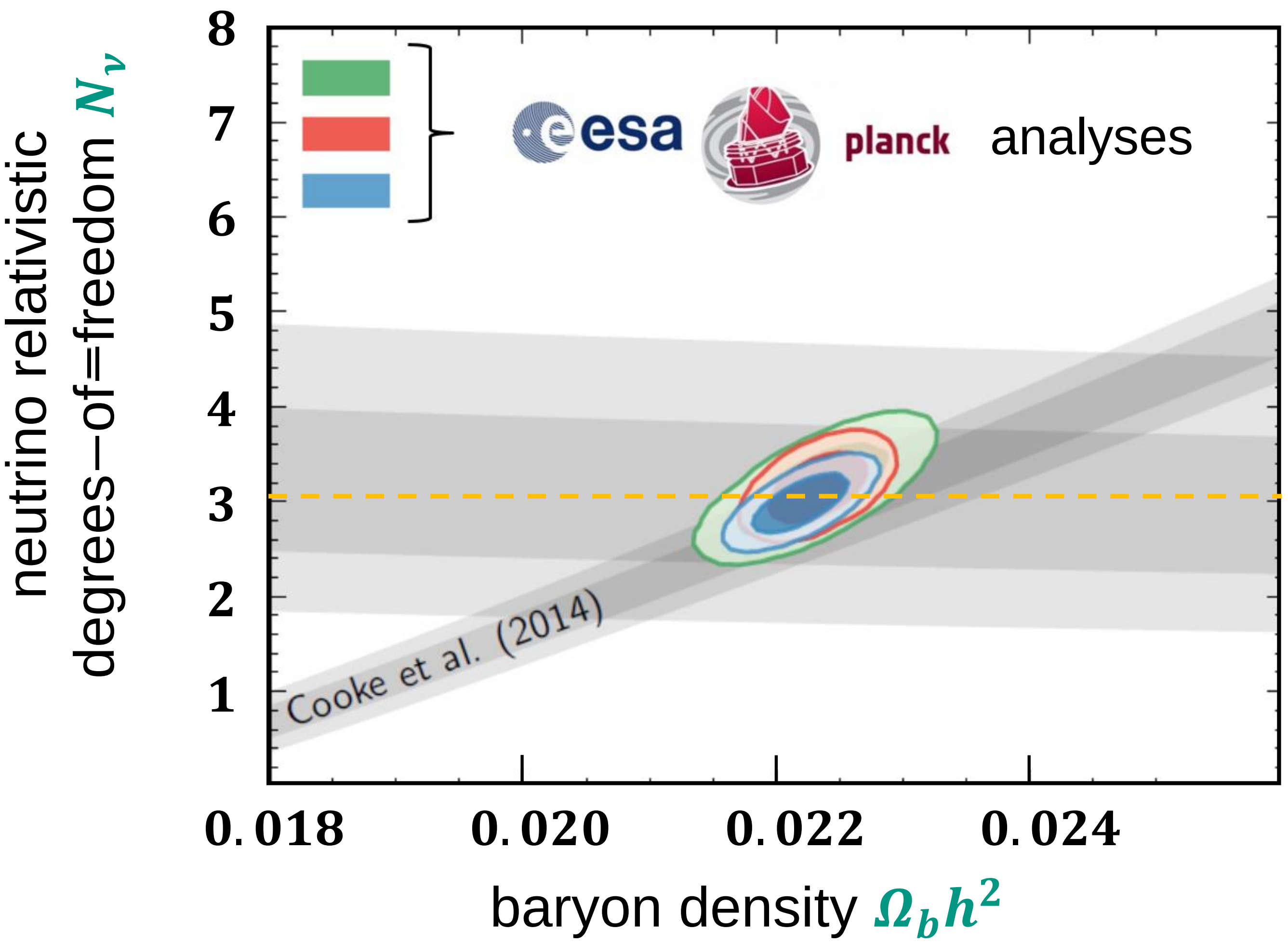
- **Primordial ^4He mass yield Y_P combined with baryon density Ω_B from CMB**

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

$$N_\nu = 2.92 \pm 0.36$$

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

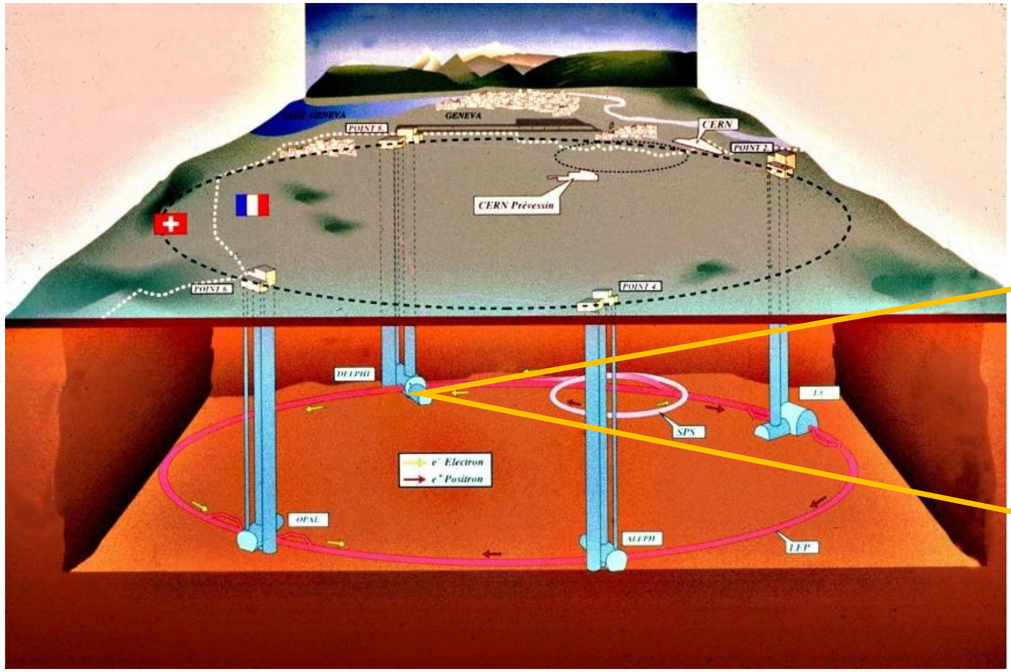


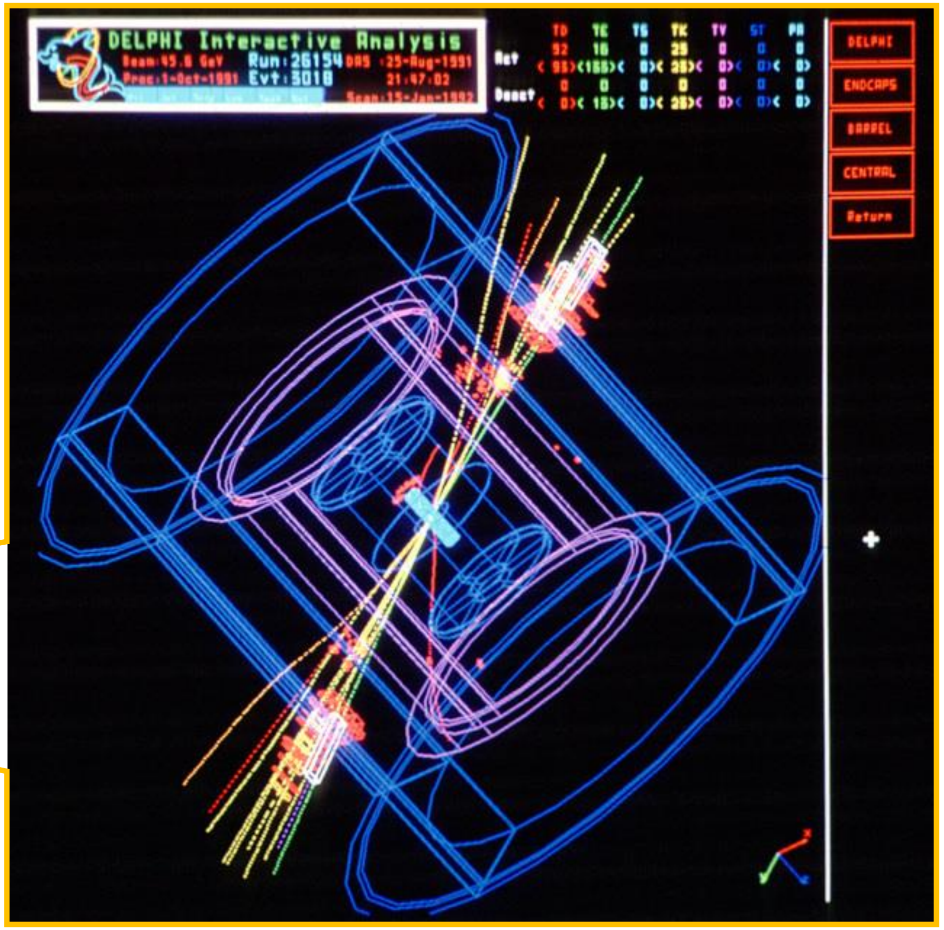
Let´s compare N_ν to older measurements at LEP

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

$\boldsymbol{L}$*arge*
$\boldsymbol{E}$*lectron*
$\boldsymbol{P}$*ositron*
Collider

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





LEP: investigating the Z^0 invisible width

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

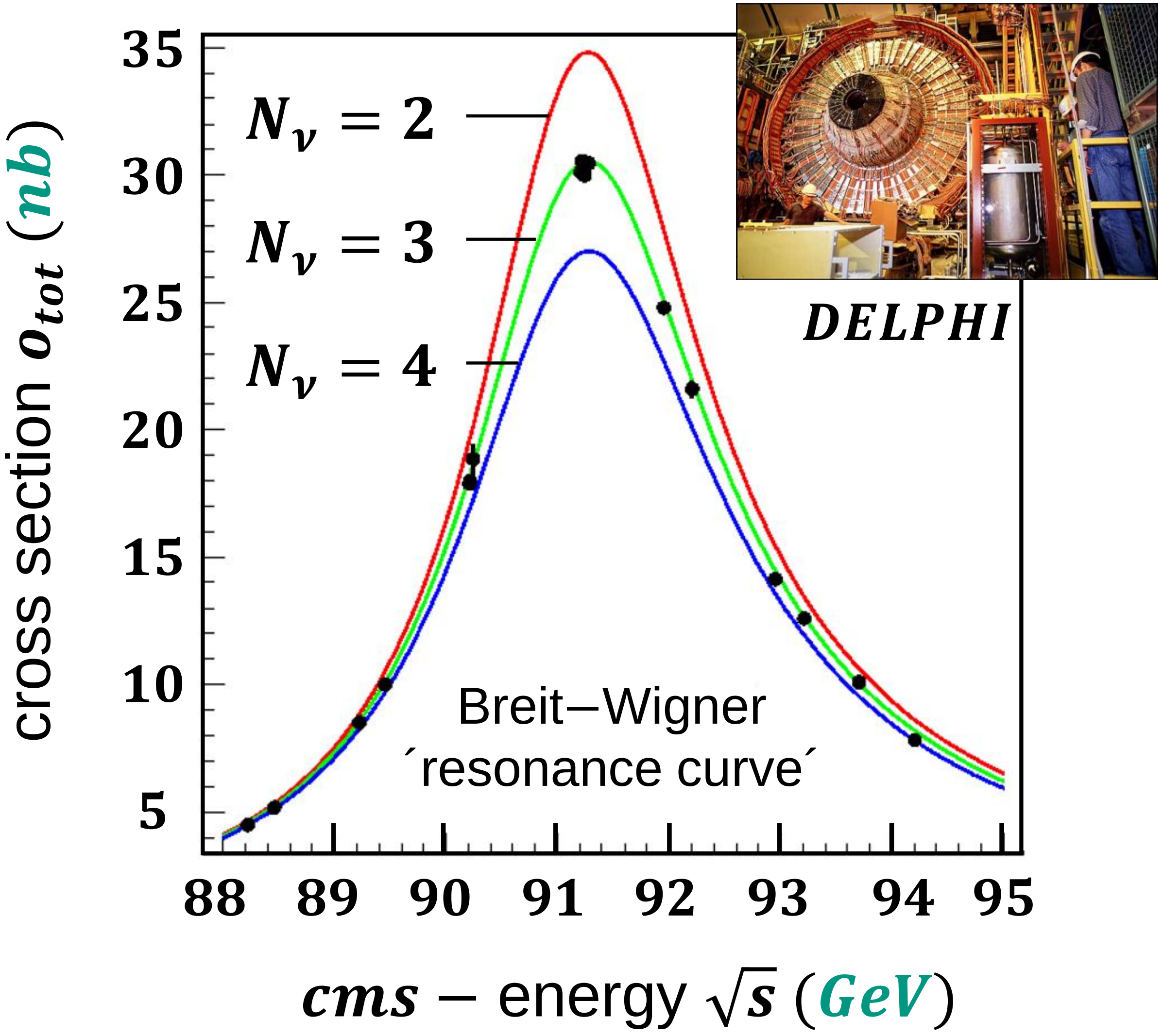
  - $\Gamma_{inv} = \Gamma_{tot} - \Gamma_{hadr} - 3 \cdot \Gamma_{lept,ch}$

    (Γ_{hadr}: hadronic; $\Gamma_{lept,ch}$: leptonic e)

  - SM fits to entire LEP – data:

$$N_\nu = 2.994 \pm 0.012$$

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



DELPHI

evaluation period – Dec. $4 - 16, 2023$

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- **Please evaluate the cosmo lectures & exercises/tutorials**

lectures: QR – code & link

https://onlineumfrage.kit.edu/evasys/online.php?p=34SFX

exercises & tutorials: QR – code & link

https://onlineumfrage.kit.edu/evasys/online.php?p=L45YG