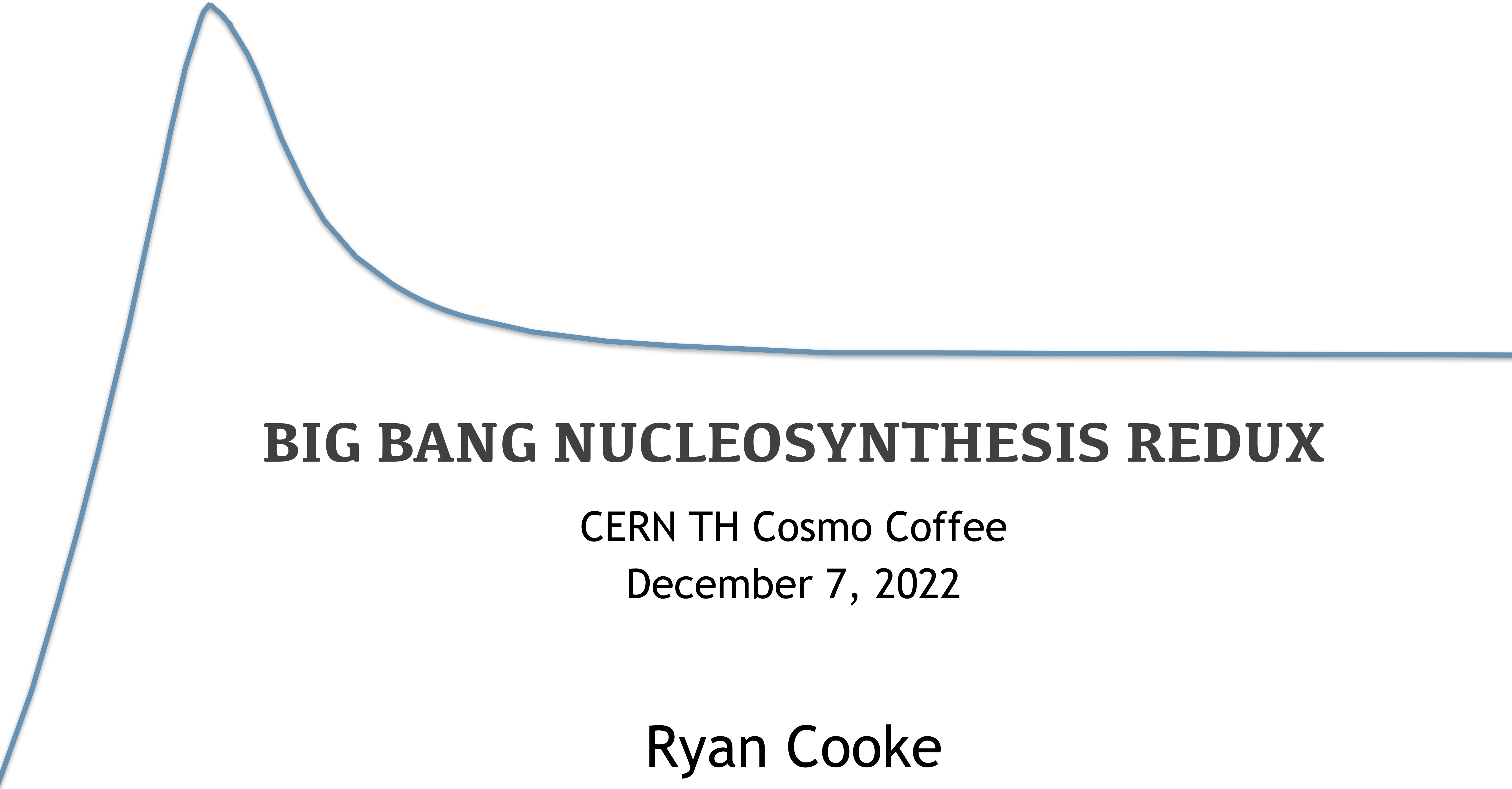
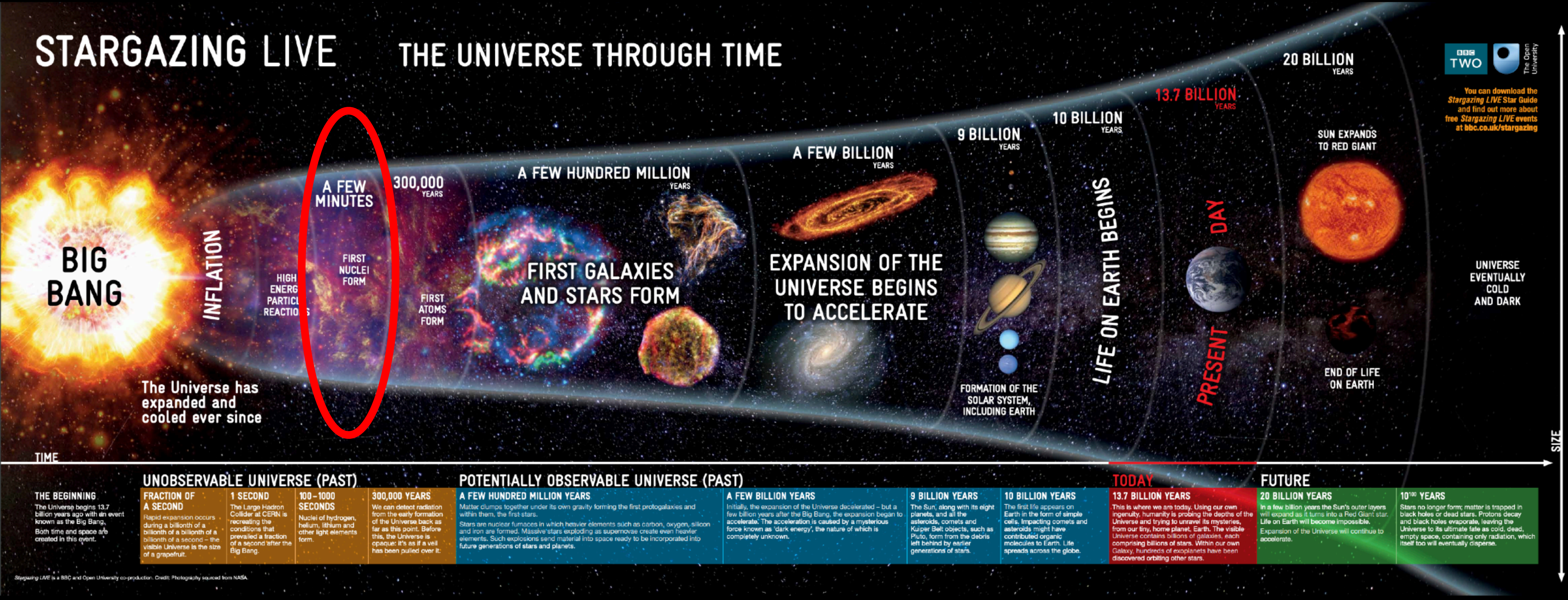


BIG BANG NUCLEOSYNTHESIS REDUX

CERN TH Cosmo Coffee
December 7, 2022

Ryan Cooke

Chronology of the Universe



STARGAZING LIVE

THE UNIVERSE THROUGH TIME

The Universe has expanded and cooled ever since

You can download the *Stargazing LIVE* Star Guide and find out more about free *Stargazing LIVE* events at bbc.co.uk/stargazing

	THE BEGINNING	The Universe begins 13.7 billion years ago with an event known as the Big Bang. Both time and space are created in this event.
UNOBSERVABLE UNIVERSE (PAST)	**FRACTION OF A SECOND**	Rapid expansion occurs during a billionth of a billionth of a billionth of a billionth of a second – the visible Universe is the size of a grapefruit.
	1 SECOND	The Large Hadron Collider at CERN is recreating the conditions that prevailed a fraction of a second after the Big Bang.
	100–1000 SECONDS	Nuclei of hydrogen, helium, lithium and other light elements form.
	300,000 YEARS	We can detect radiation from the early formation of the Universe back as far as this point. Before this, the Universe is opaque: it's as if a veil has been pulled over it.
POTENTIALLY OBSERVABLE UNIVERSE (PAST)	**A FEW HUNDRED MILLION YEARS**	Matter clumps together under its own gravity forming the first protogalaxies and within them, the first stars. Stars are nuclear furnaces in which heavier elements such as carbon, oxygen, silicon and iron are formed. Massive stars exploding as supernovae create even heavier elements. Such explosions send material into space ready to be incorporated into future generations of stars and planets.
	A FEW BILLION YEARS	Initially, the expansion of the Universe decelerated – but a few billion years after the Big Bang, the expansion began to accelerate. The acceleration is caused by a mysterious force known as 'dark energy', the nature of which is completely unknown.
	9 BILLION YEARS	The Sun, along with its eight planets, and all the asteroids, comets and Kuiper Belt objects, such as Pluto, form from the debris left behind by earlier generations of stars.
	10 BILLION YEARS	The first life appears on Earth in the form of simple cells. Impacting comets and asteroids might have contributed organic molecules to Earth. Life spreads across the globe.
TODAY	**13.7 BILLION YEARS**	This is where we are today. Using our own ingenuity, humanity is probing the depths of the Universe and trying to unravel its mysteries, from our tiny, home planet, Earth. The visible Universe contains billions of galaxies, each comprising billions of stars. Within our own Galaxy, hundreds of exoplanets have been discovered orbiting other stars.
FUTURE	**20 BILLION YEARS**	In a few billion years the Sun's outer layers will expand as it turns into a Red Giant star. Life on Earth will become impossible. Expansion of the Universe will continue to accelerate.
	10^{100} YEARS	Stars no longer form; matter is trapped in black holes or dead stars. Protons decay and black holes evaporate, leaving the Universe to its ultimate fate as cold, dead, empty space, containing only radiation, which itself too will eventually disperse.

Stargazing LIVE is a BBC and Open University co-production. Credit: Photography sourced from NASA.

Big Bang Nucleosynthesis (BBN) Ingredients

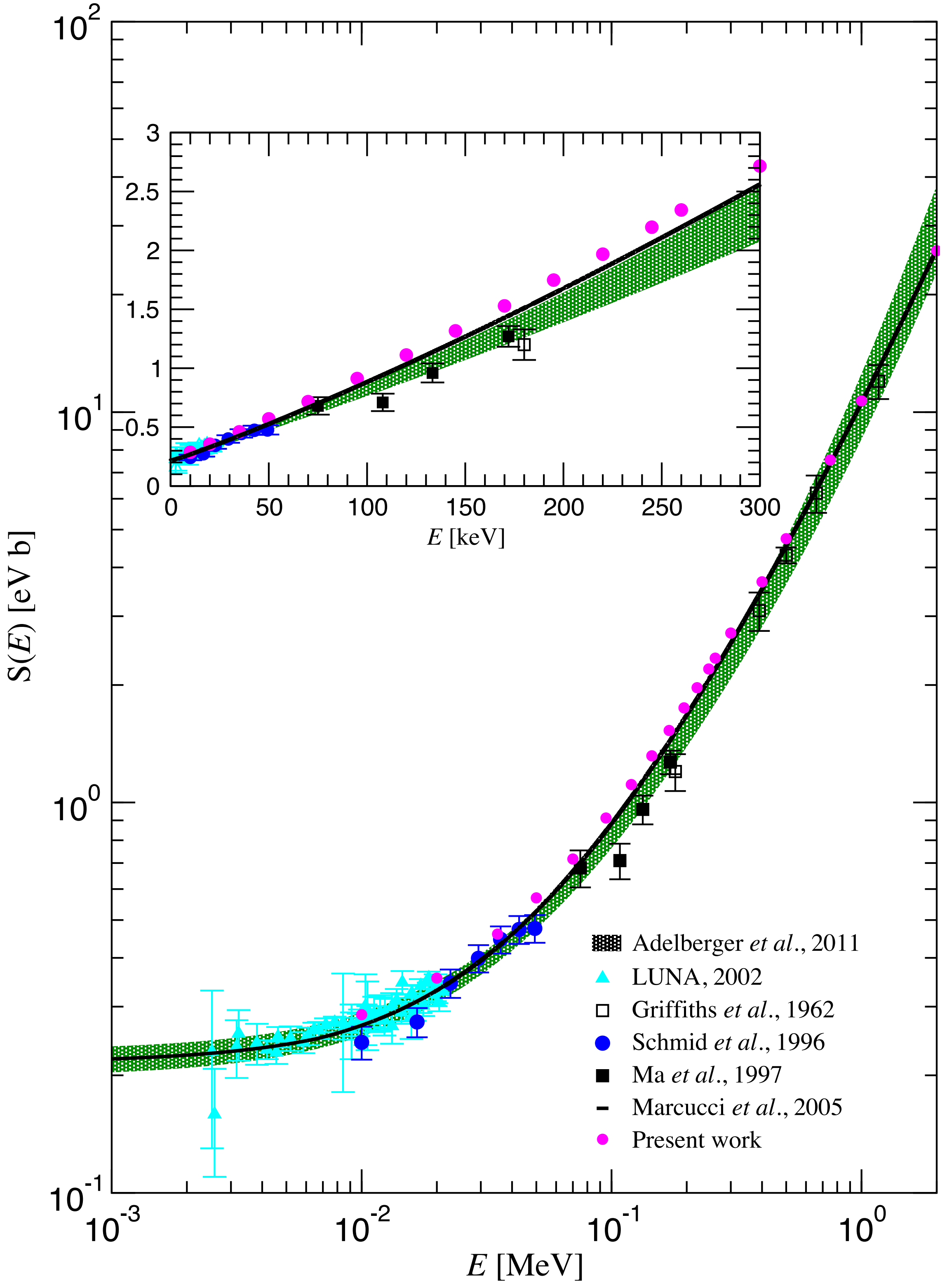
Input parameters

- The expansion rate of the Universe
- Baryon density parameter
- Neutrino Degeneracy (i.e. lepton asymmetry)

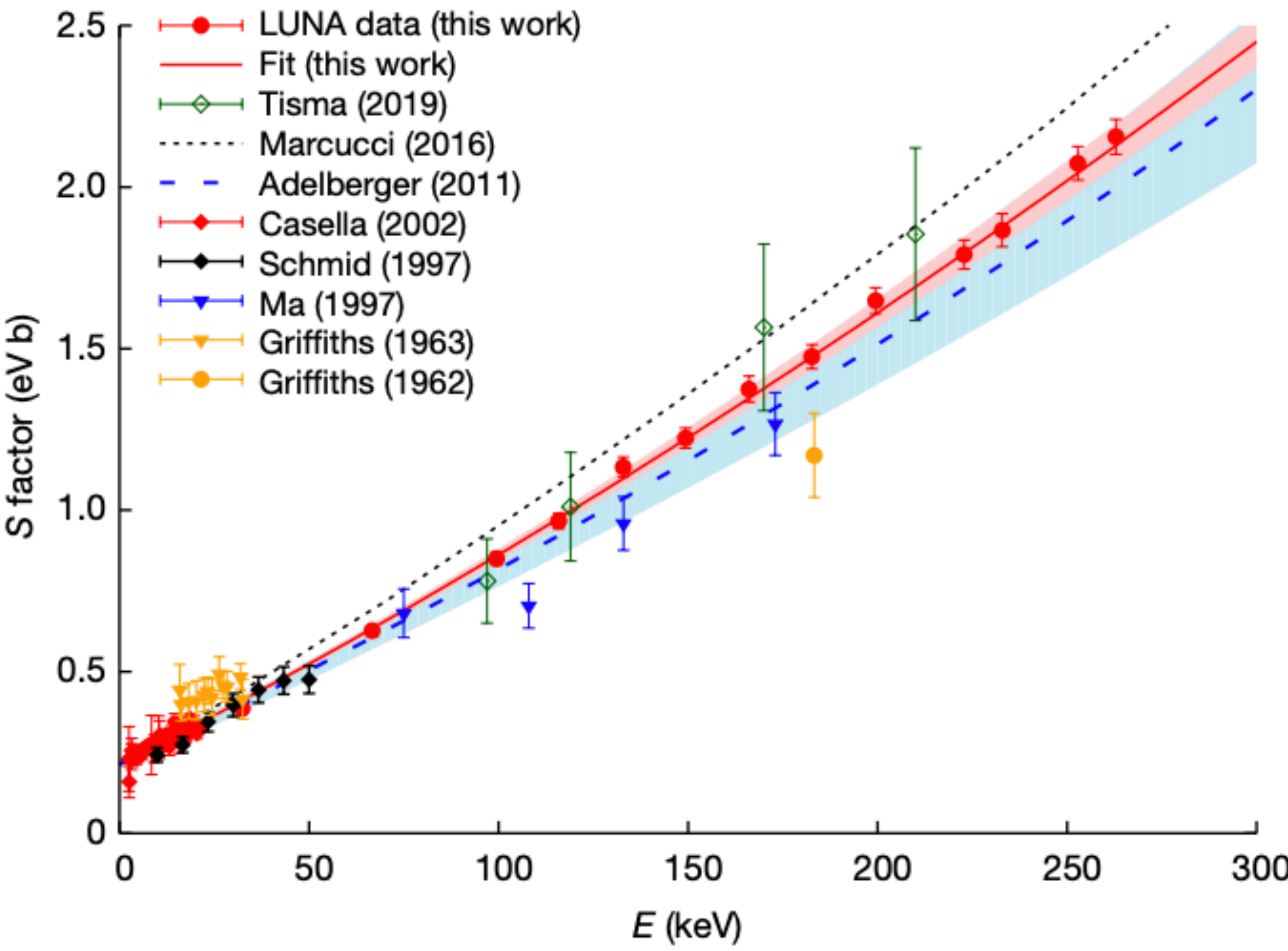
Standard Model Assumptions

- Laboratory measured reaction cross-sections
- General Relativity (i.e. the Friedmann equations)
- 3 families of neutrinos
- No lepton asymmetry

Reaction rates

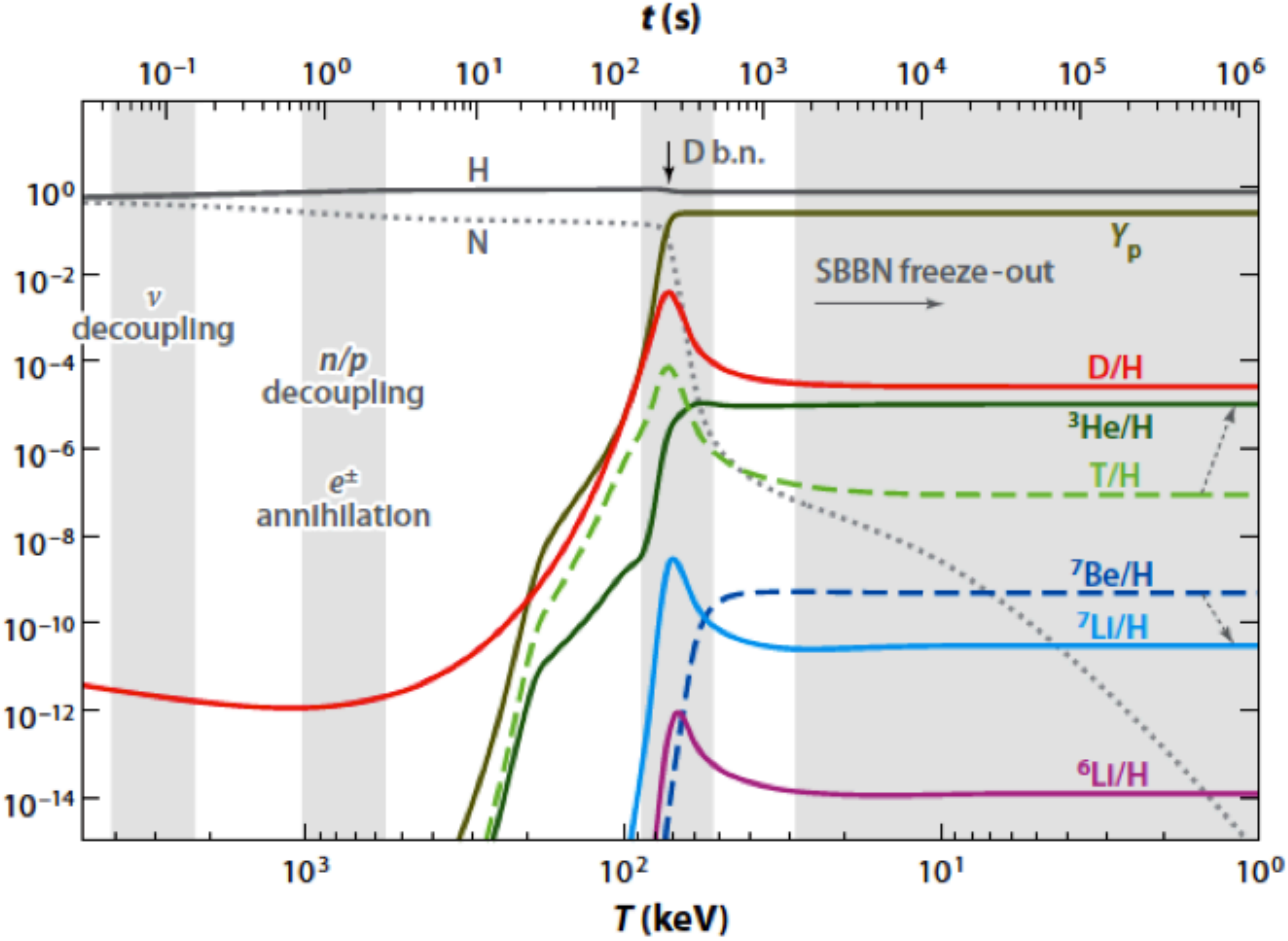


Marcucci et al. (2016), Phys. Rev. L, 116, 2501



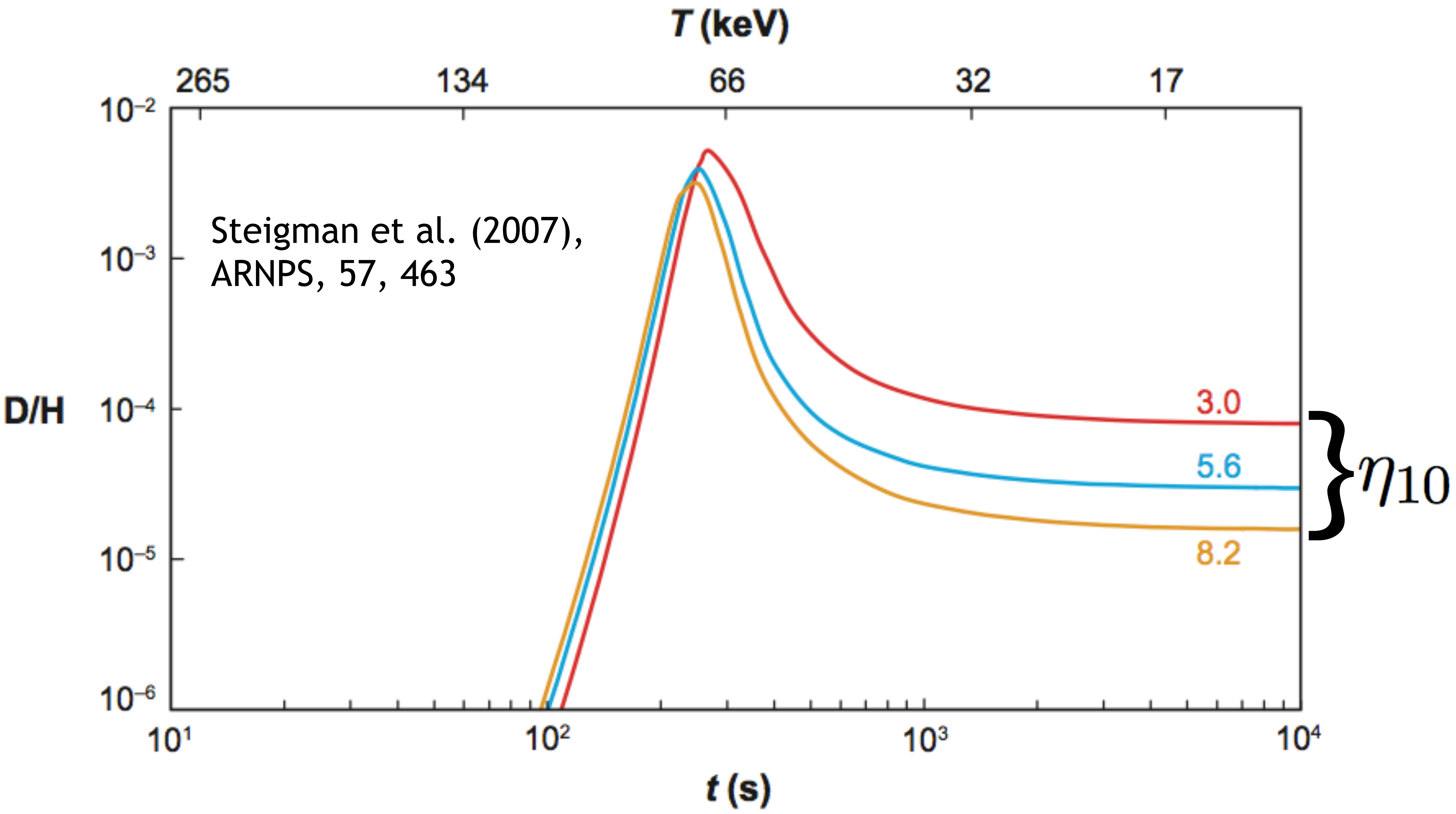
LUNA collaboration, 2020, Nature, 587, 210

Timeline of Big Bang Nucleosynthesis



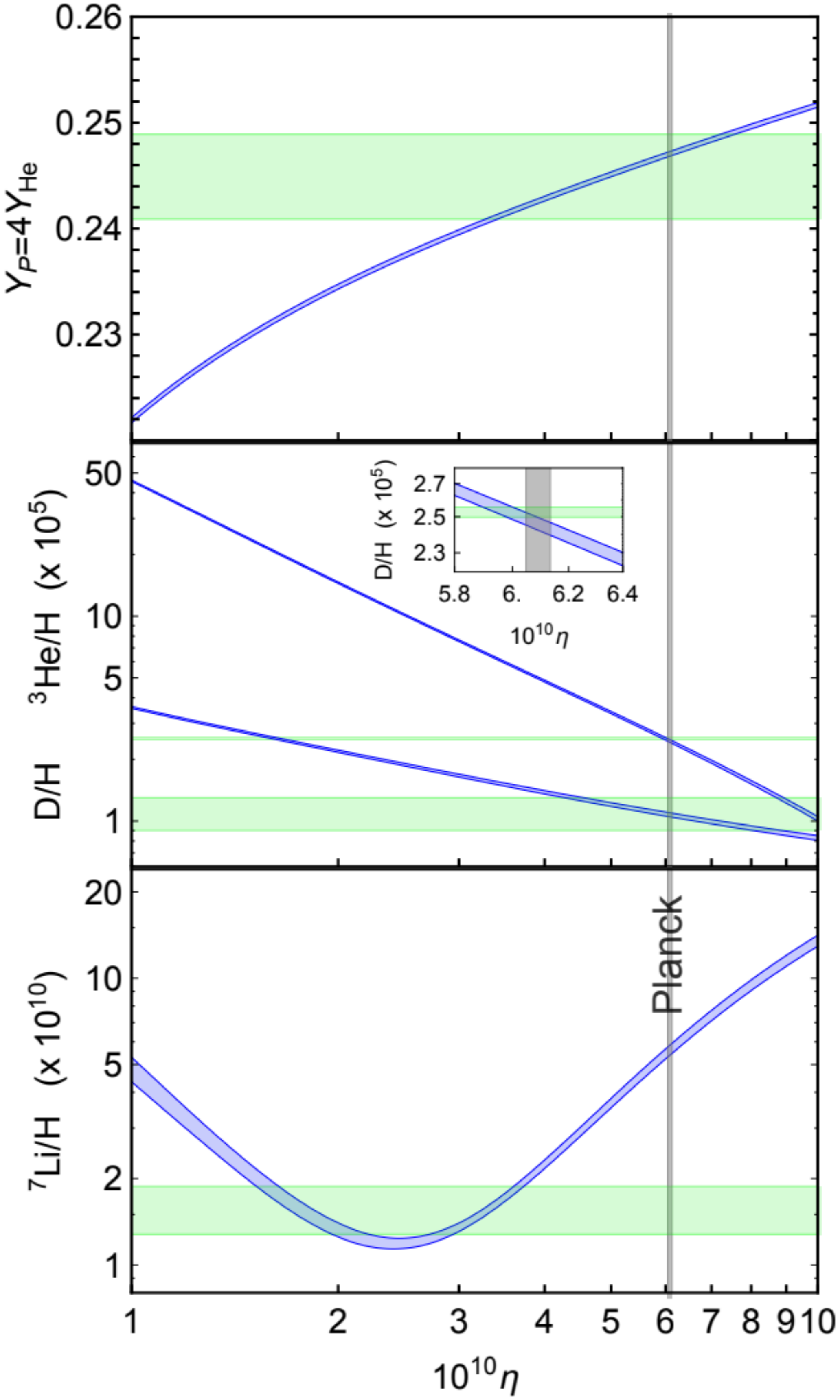
Variation with baryon-to-photon ratio

$$\boxed{\eta_{10} = \frac{\text{density of baryons}}{\text{density of photons}} \times 10^{10}} \longrightarrow \boxed{\Omega_{B,0} \propto \eta_{10}}$$



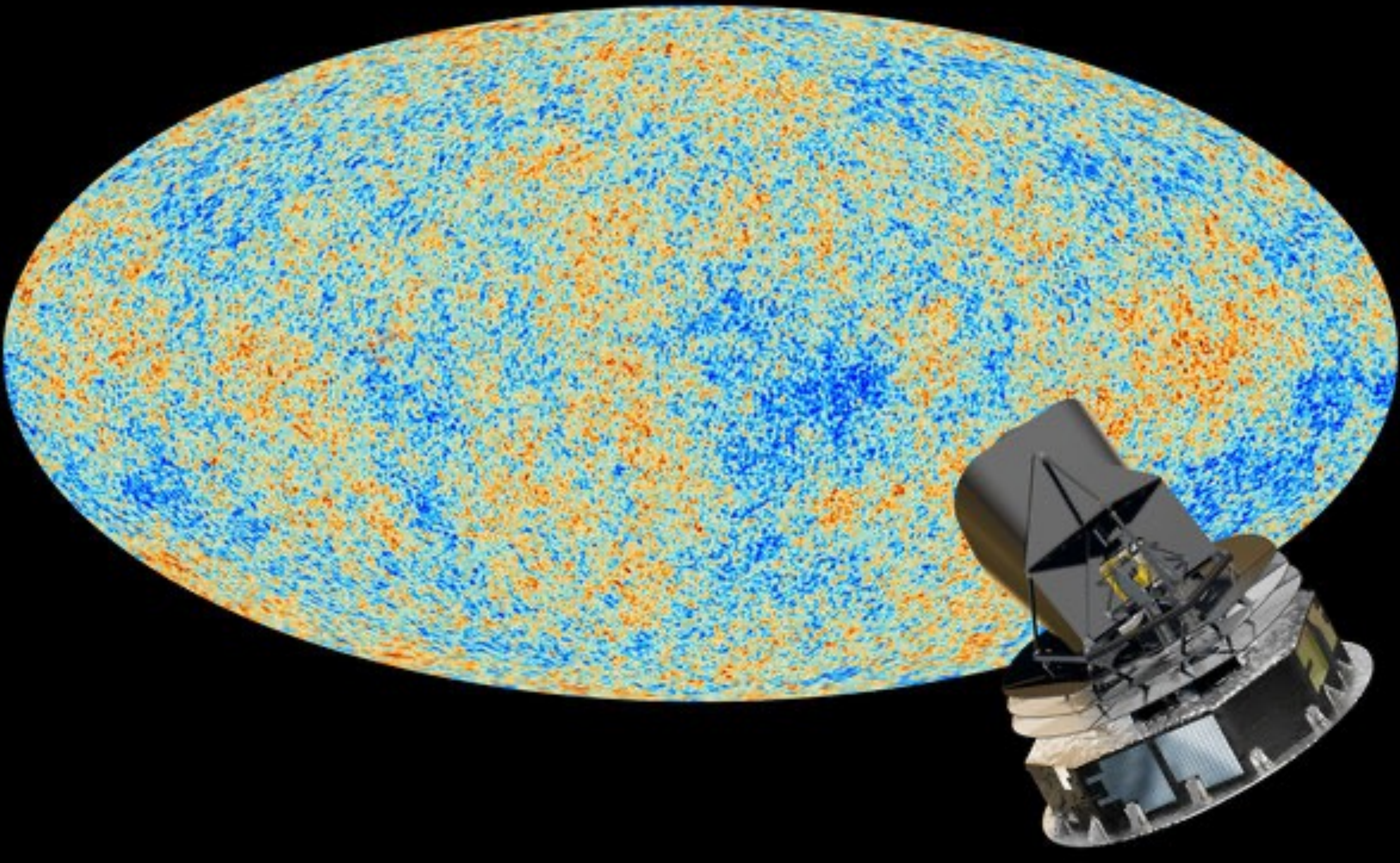
Steigman et al. (2007), ARNPS, 57, 463

Variation with baryon-to-photon ratio

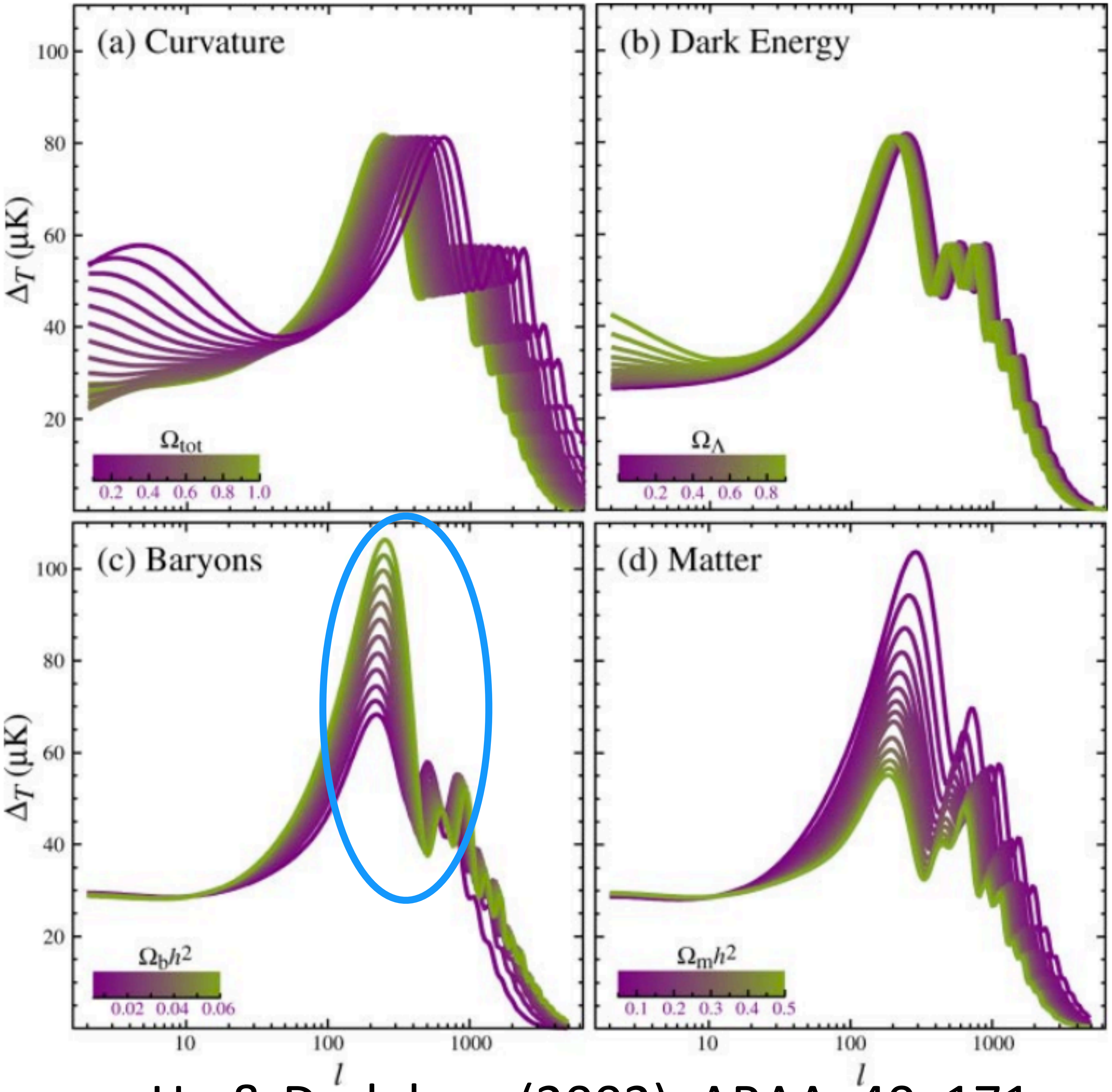


Pitrou et al. (2018), arXiv:1801.08023

Planck



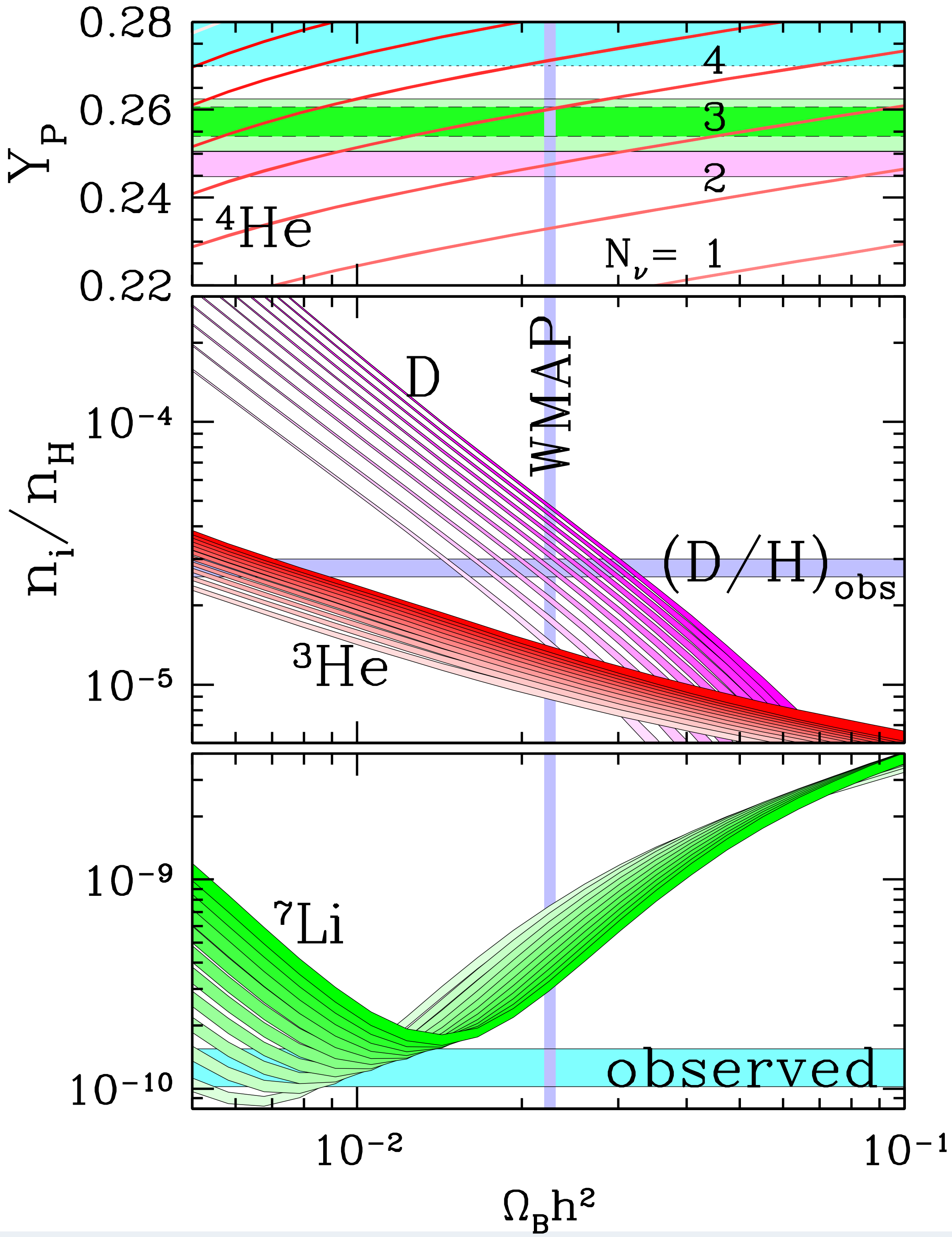
CMB Baryon Density



Hu & Dodelson (2002), ARAA, 40, 171

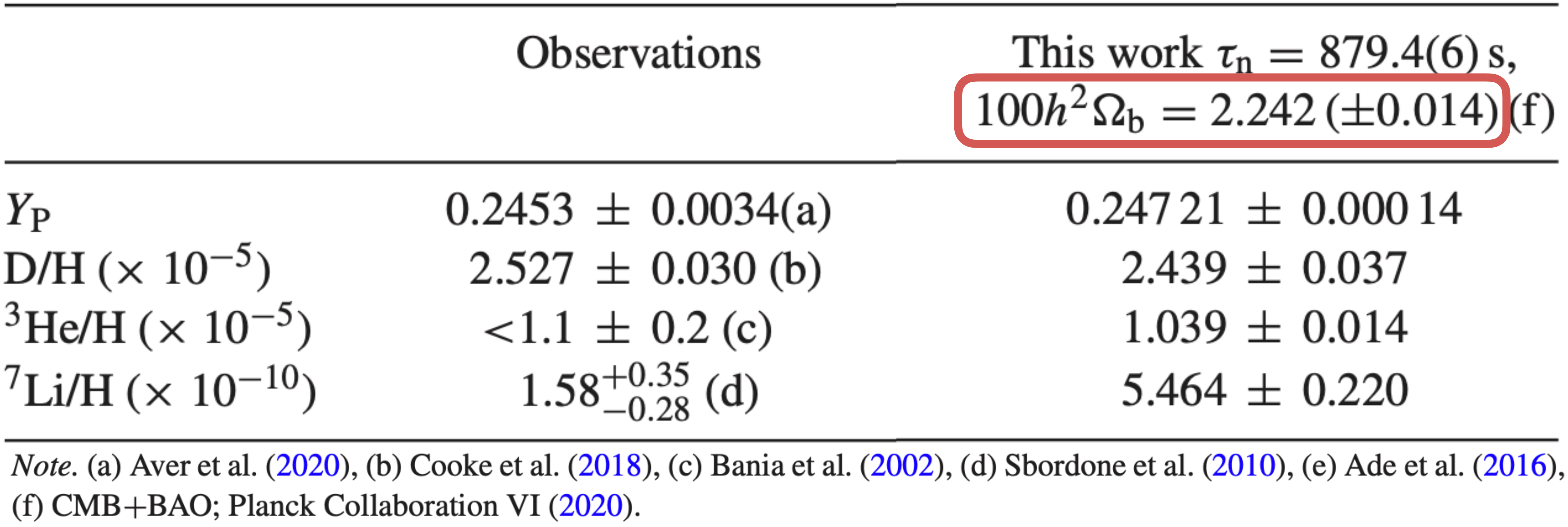
BBN - Beyond the Standard Model

Nollett & Holder (2011), arXiv: 1112.2683



- 4He/H is commonly thought of as being the most sensitive to Neff
- D/H offers tightest bound on the baryon density, but is also very sensitive to Neff
- Lithium-7 disagrees with the Standard Model by 6σ
- Helium-3 doesn't currently have a good primordial estimate

Standard Model values



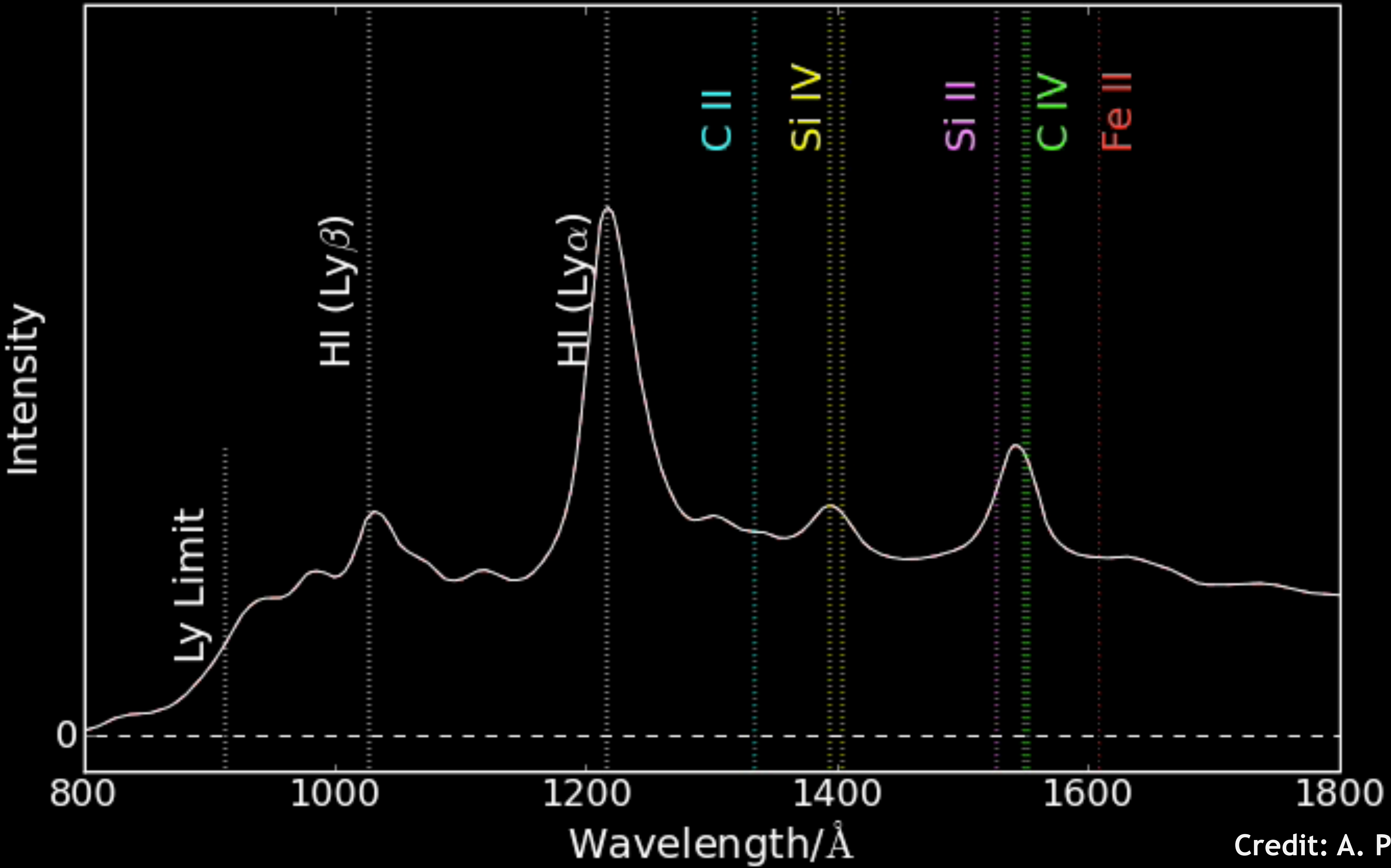
	Observations	This work $\tau_n = 879.4(6)$ s, $\boxed{100h^2\Omega_b = 2.242\,(\pm 0.014)}$ (f)
Y_P	0.2453 ± 0.0034(a)	$0.247\,21 \pm 0.000\,14$
D/H ($\times 10^{-5}$)	2.527 ± 0.030 (b)	2.439 ± 0.037
^{3}He/H ($\times 10^{-5}$)	$<1.1 \pm 0.2$ (c)	1.039 ± 0.014
^{7}Li/H ($\times 10^{-10}$)	$1.58^{+0.35}_{-0.28}$ (d)	5.464 ± 0.220

Note. (a) Aver et al. (2020), (b) Cooke et al. (2018), (c) Bania et al. (2002), (d) Sbordone et al. (2010), (e) Ade et al. (2016), (f) CMB+BAO; Planck Collaboration VI (2020).

Pitrou et al. (2021), MNRAS, 502, 2474

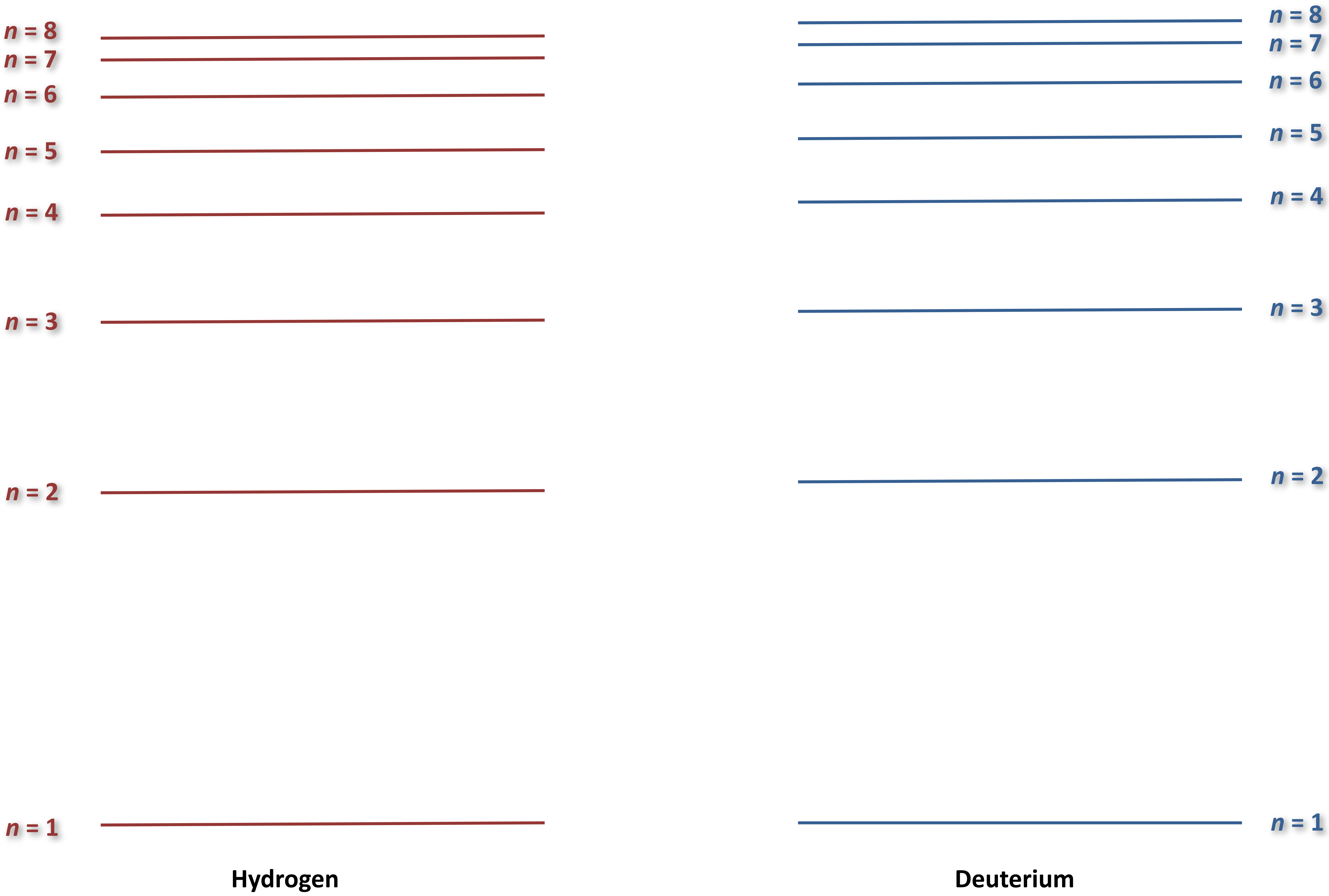
(PRIMAT code)

Note: different BBN codes currently produce different results

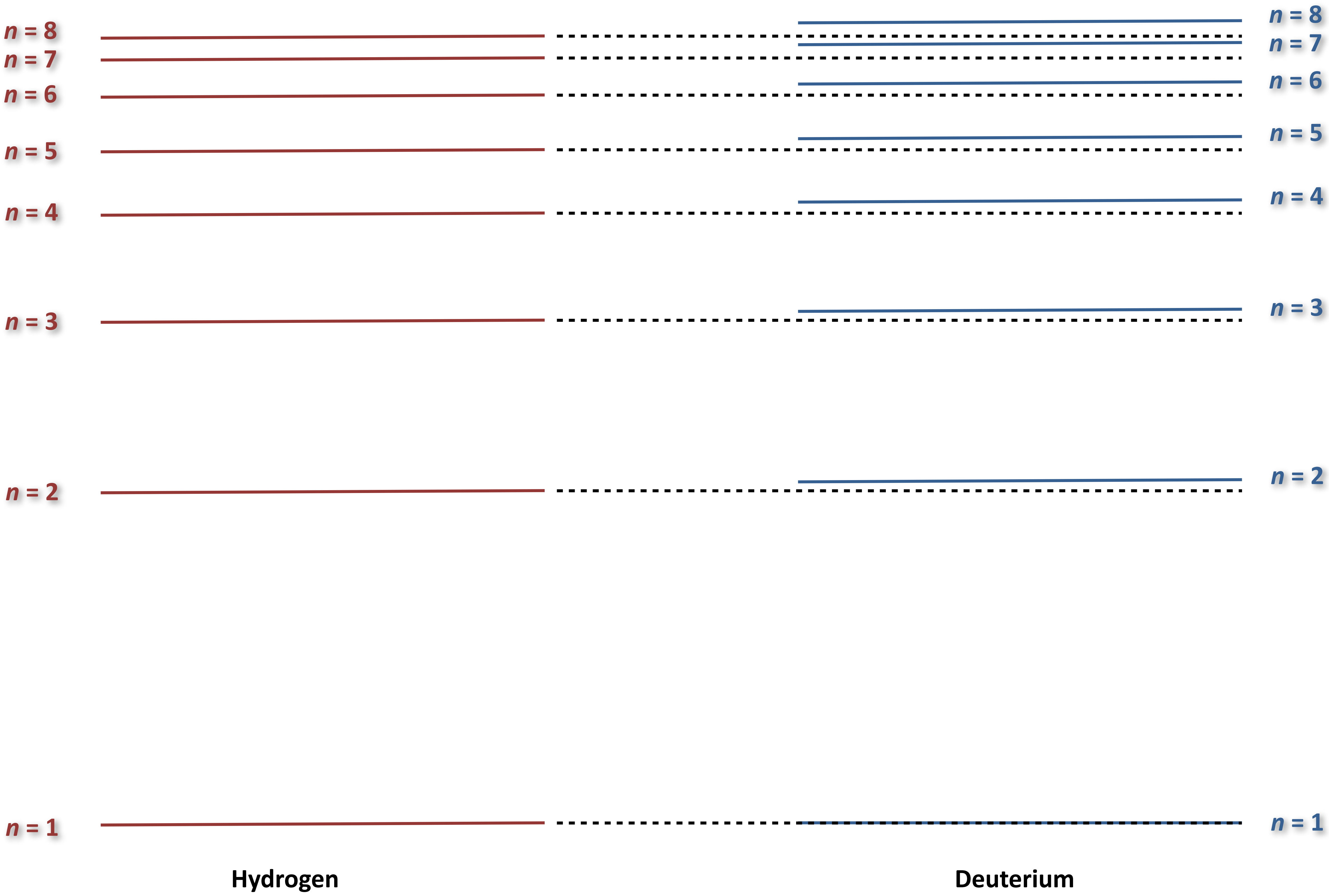


Credit: A. Pontzen

Energy levels of hydrogen and deuterium



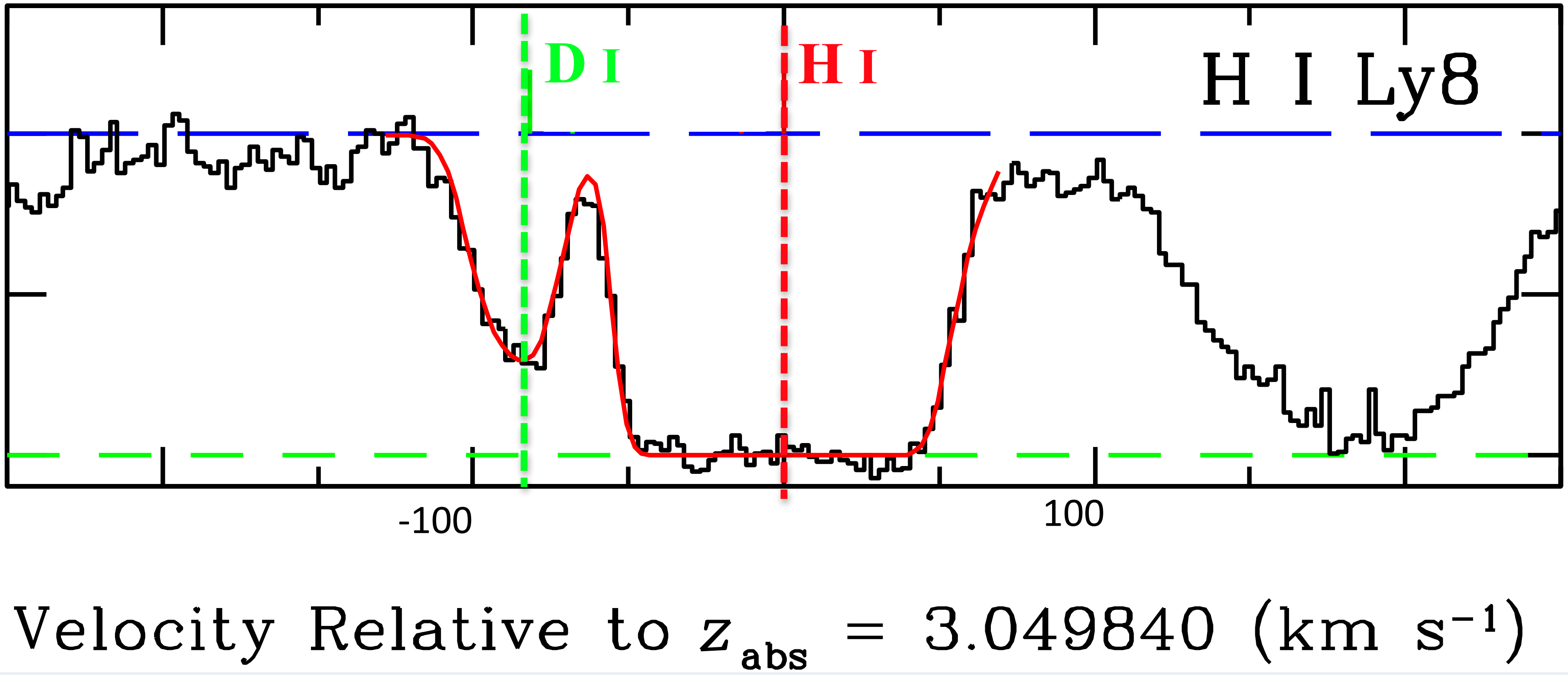
Energy levels of hydrogen and deuterium



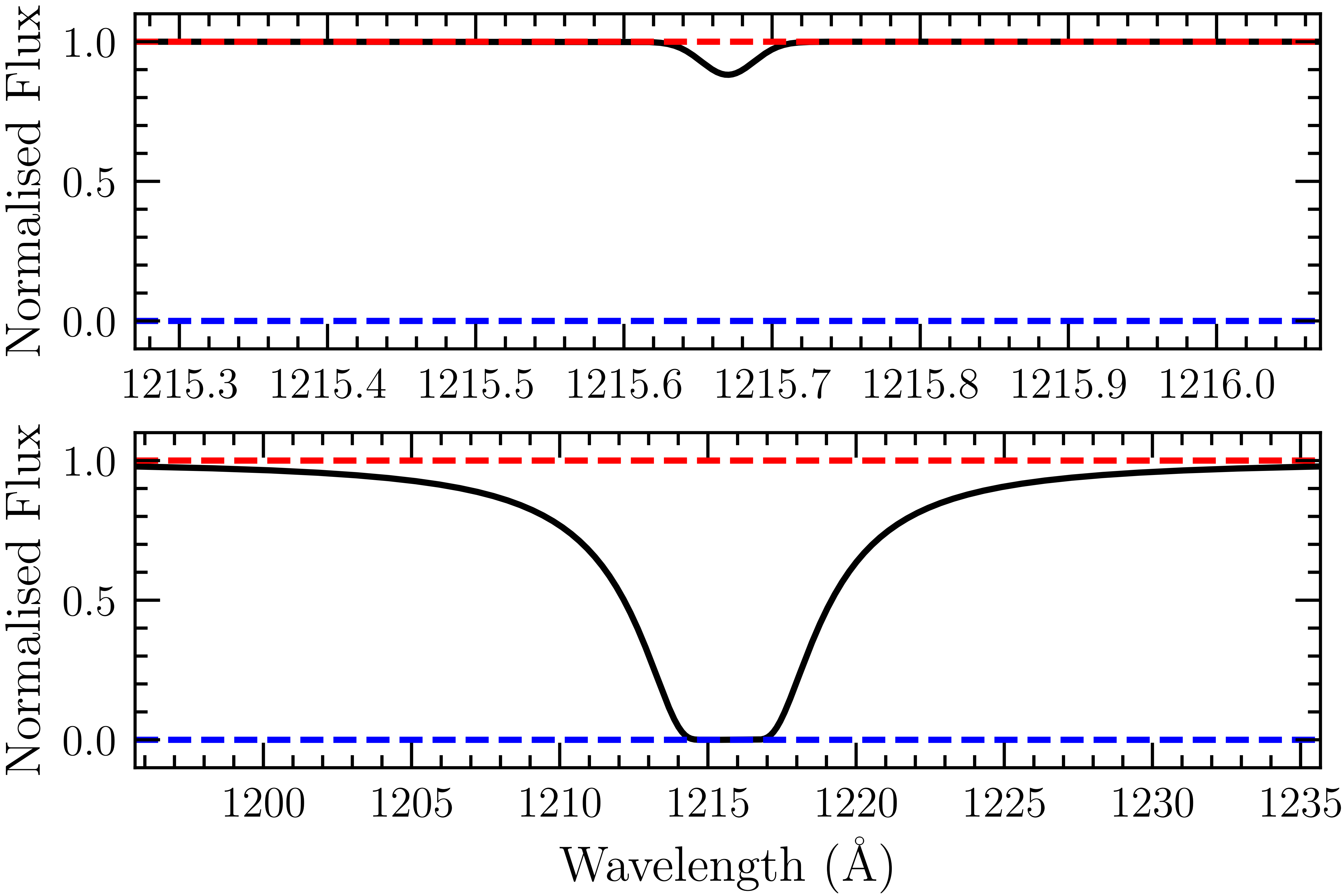
How to precisely measure D/H

Potentially the best systems are the most metal-poor DLAs

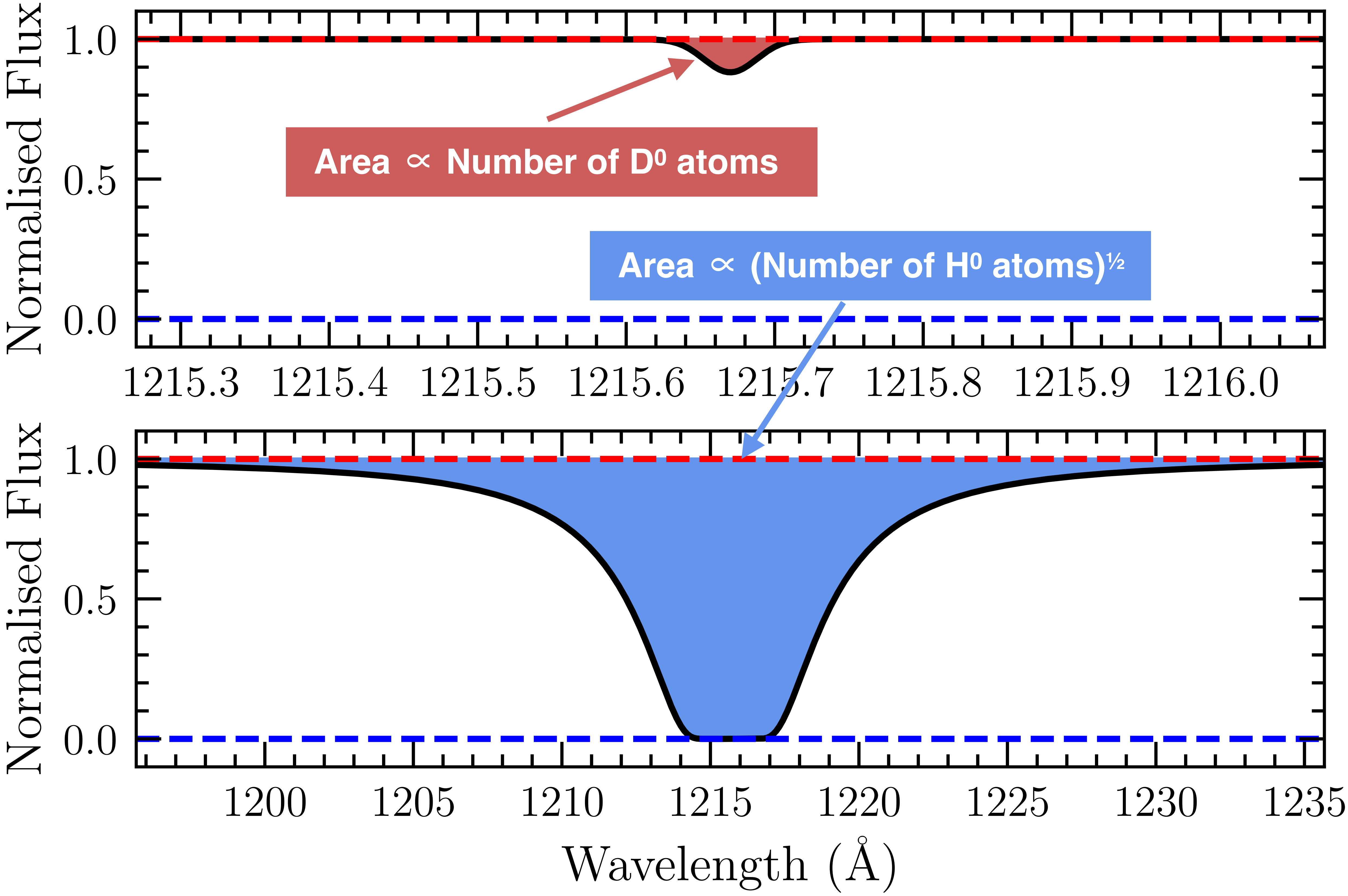
- Ease of measuring the H I column density from the wings of the damped Lyman-α line.
- Many transitions available for the D I Lyman series to measure deuterium column density
- Low metallicity implies negligible D astration
- Quiescent kinematics help to resolve the 82 km/s isotope shift



Benefits of absorption lines



Benefits of absorption lines

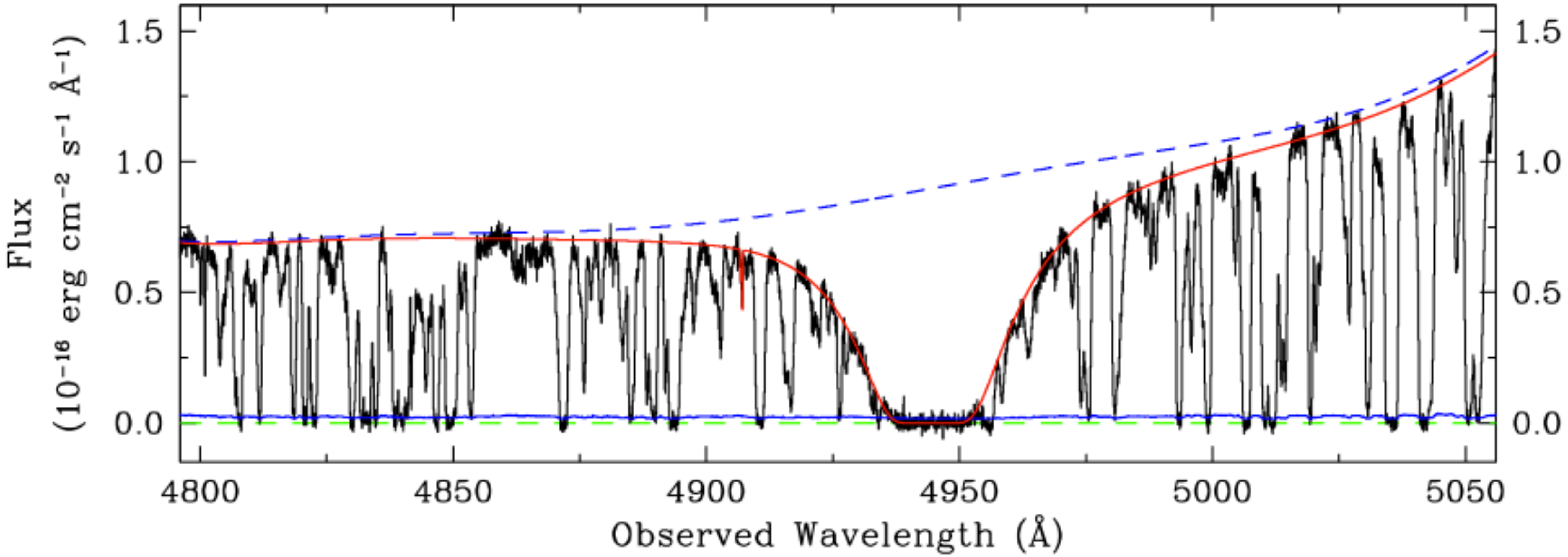


Area ∝ Number of D^0 atoms

Area ∝ (Number of H^0 atoms)^{½}

High precision D/H measures

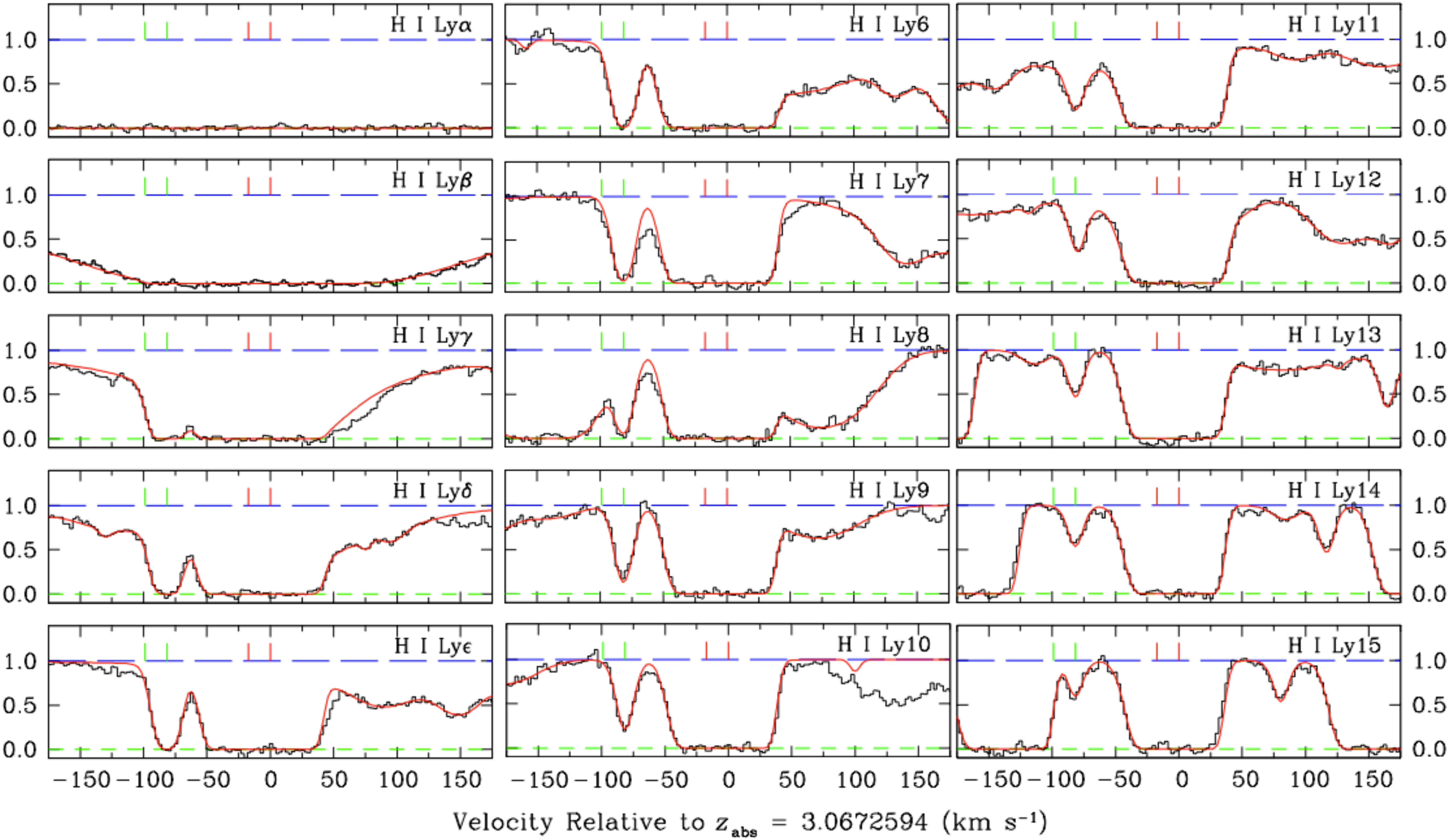
Cooke et al. (2014) ApJ, 781, 31



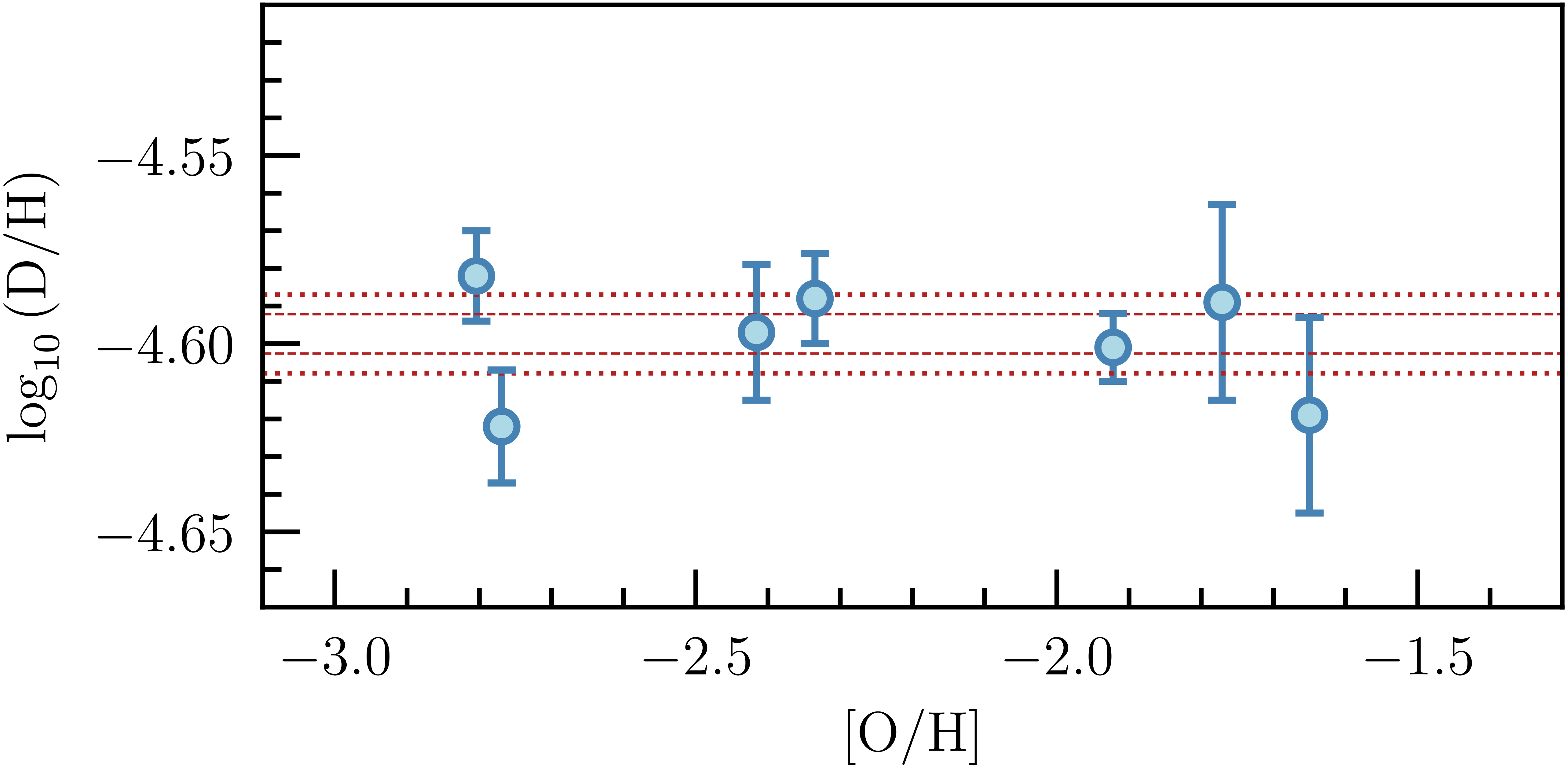
log N(H I)/cm^{-2} = 20.495 ± 0.008

High precision D/H measures

Cooke et al. (2014) ApJ, 781, 31



The primordial deuterium abundance

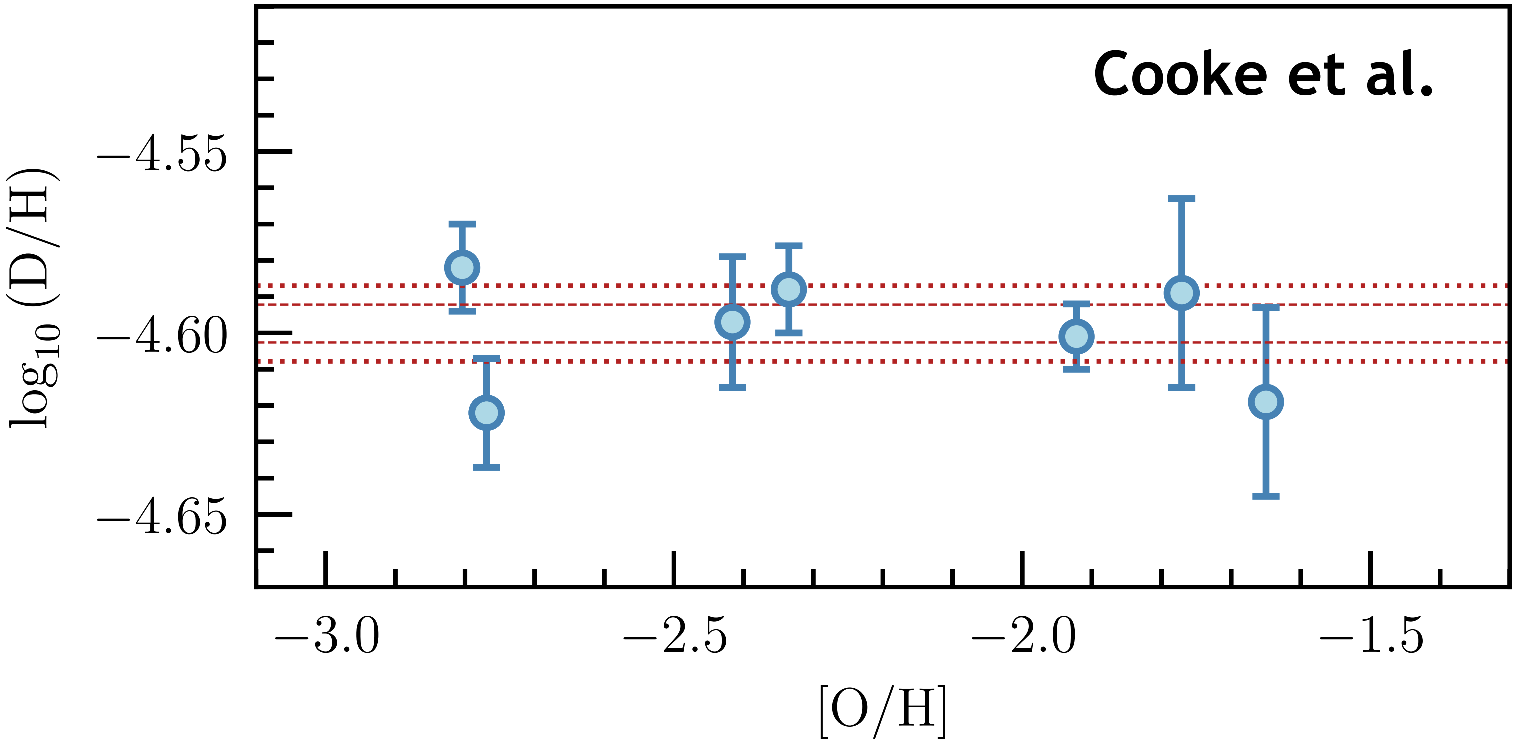


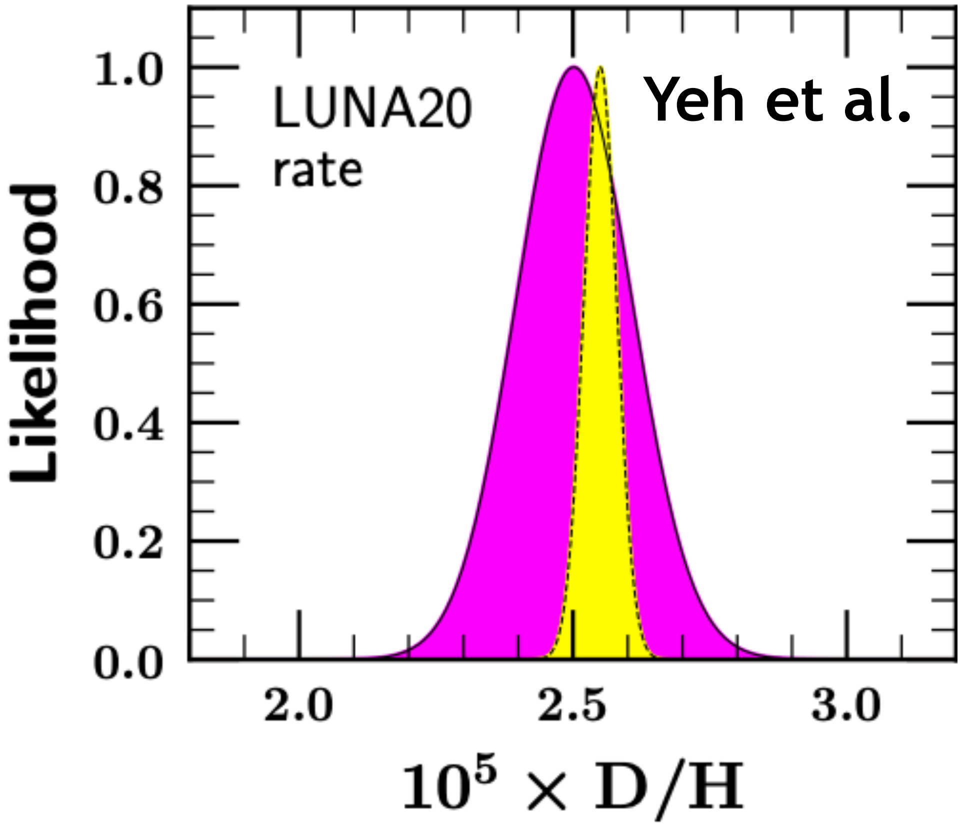
$$\log_{10}(\mathrm{D/H})_{\mathrm{P}} = -4.5974 \pm 0.0052$$

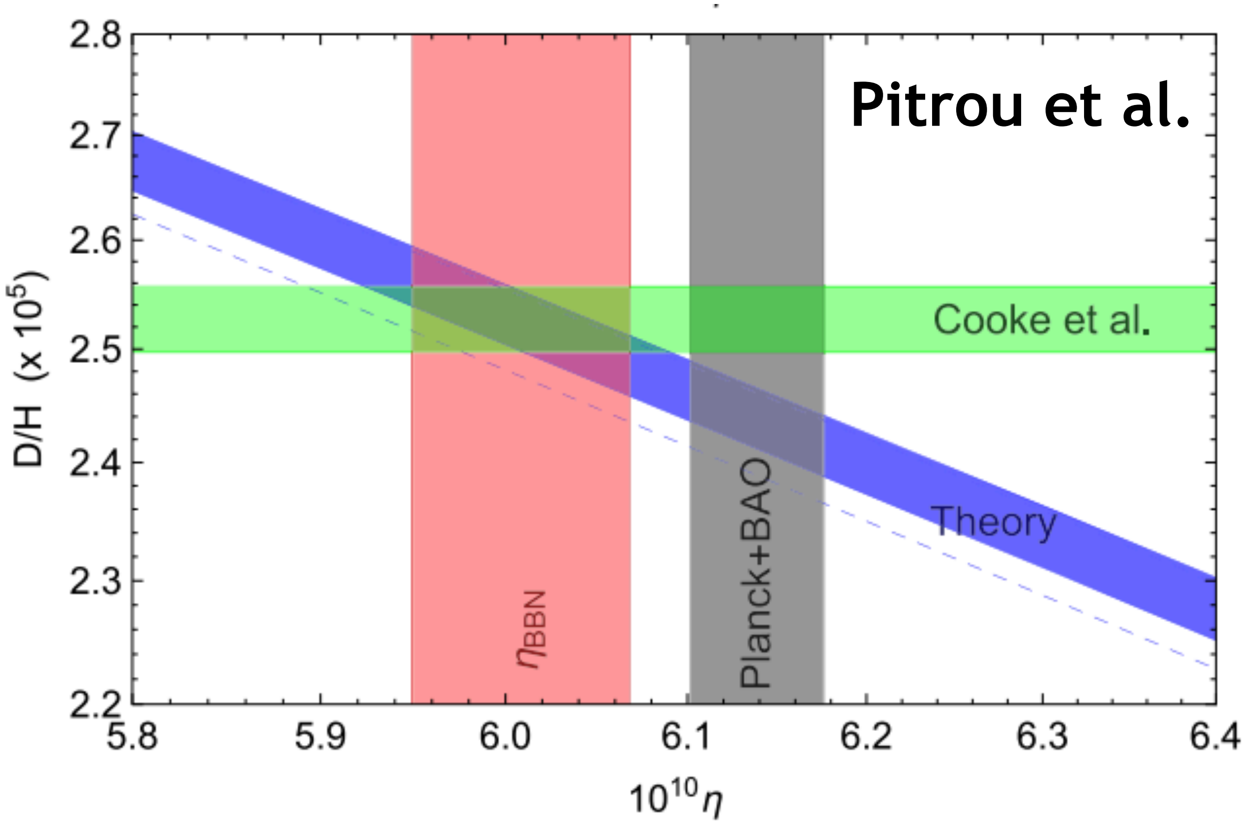
$$10^5(\mathrm{D/H})_{\mathrm{P}} = 2.527 \pm 0.030$$

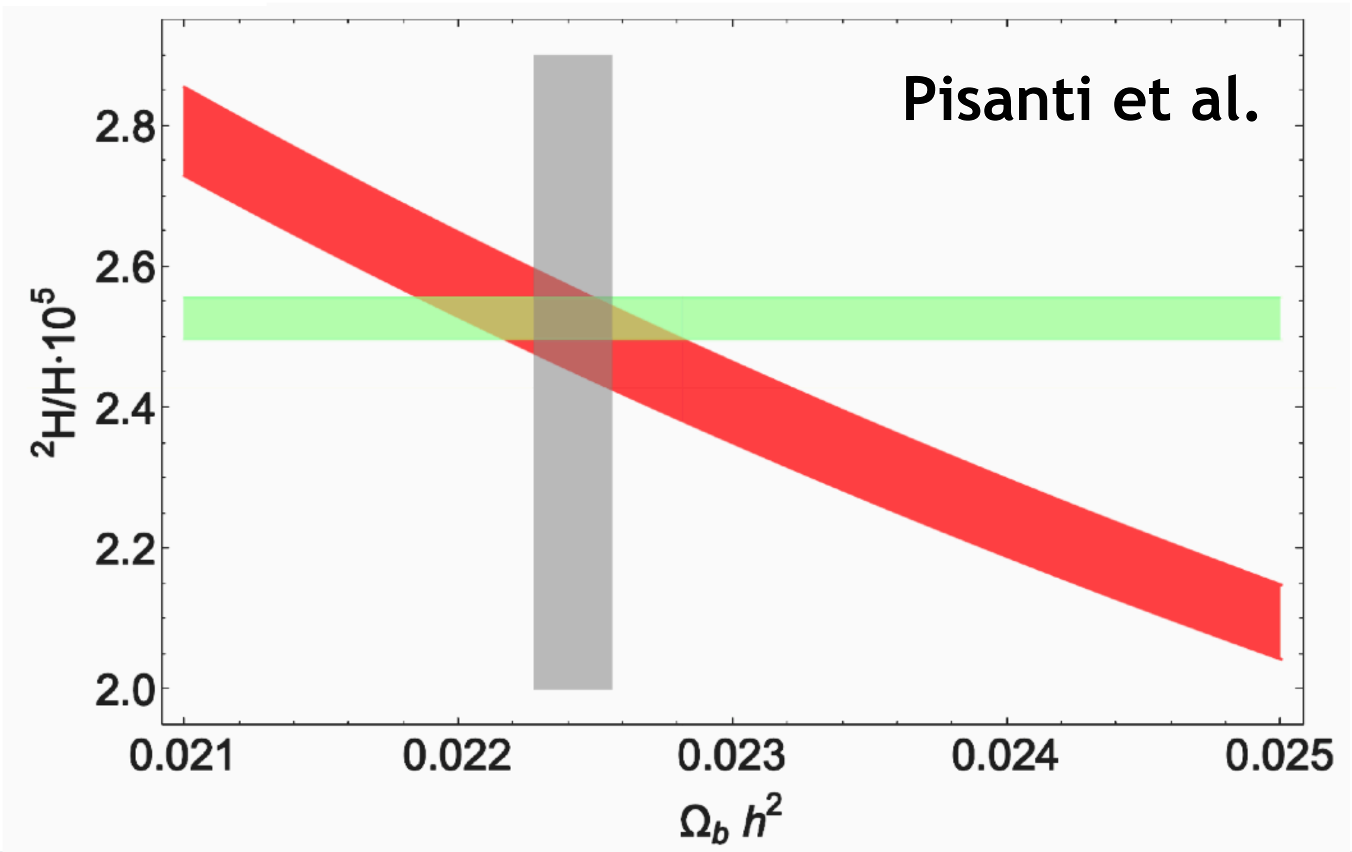
~1% precision

The primordial deuterium abundance





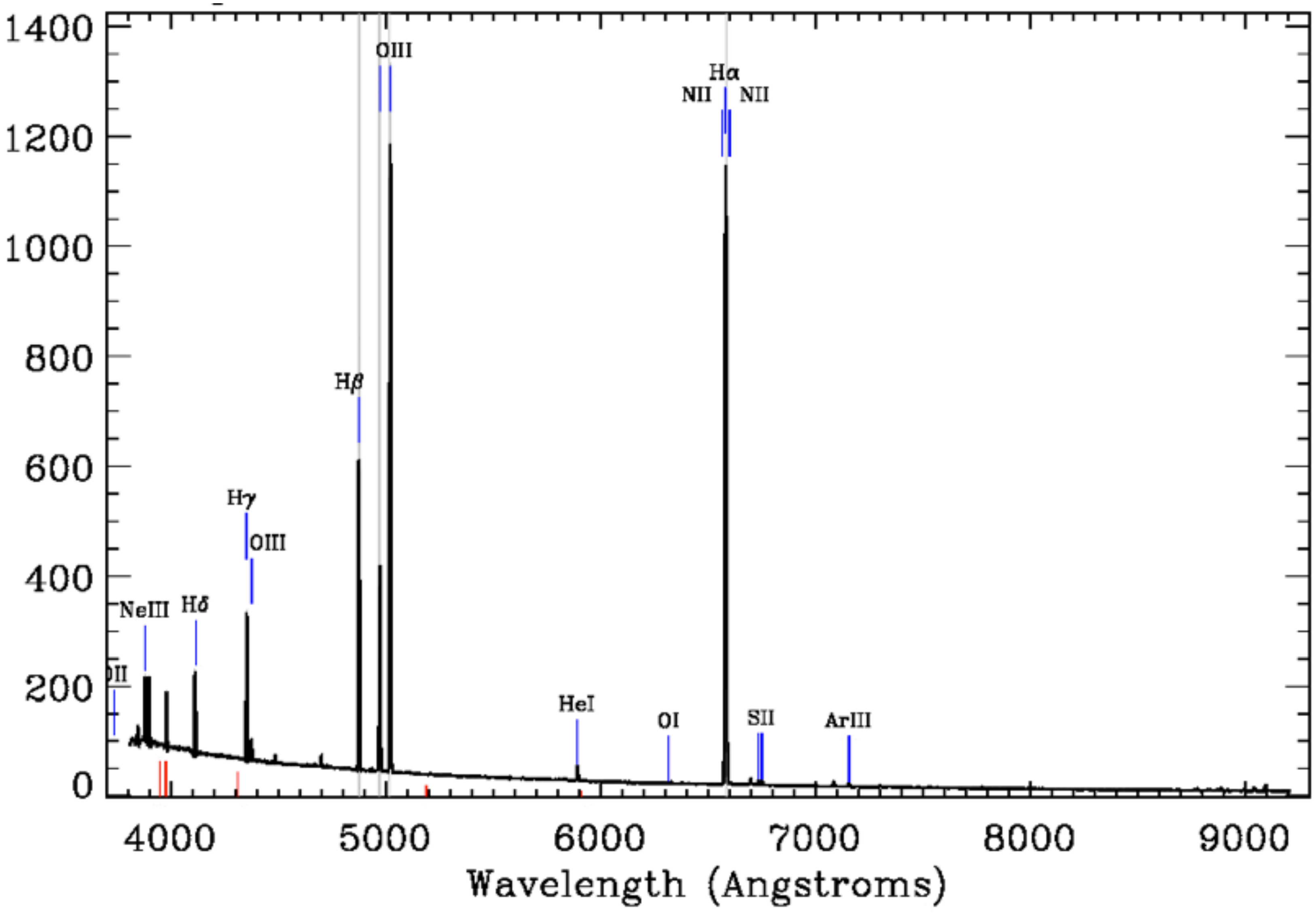




The primordial helium mass fraction

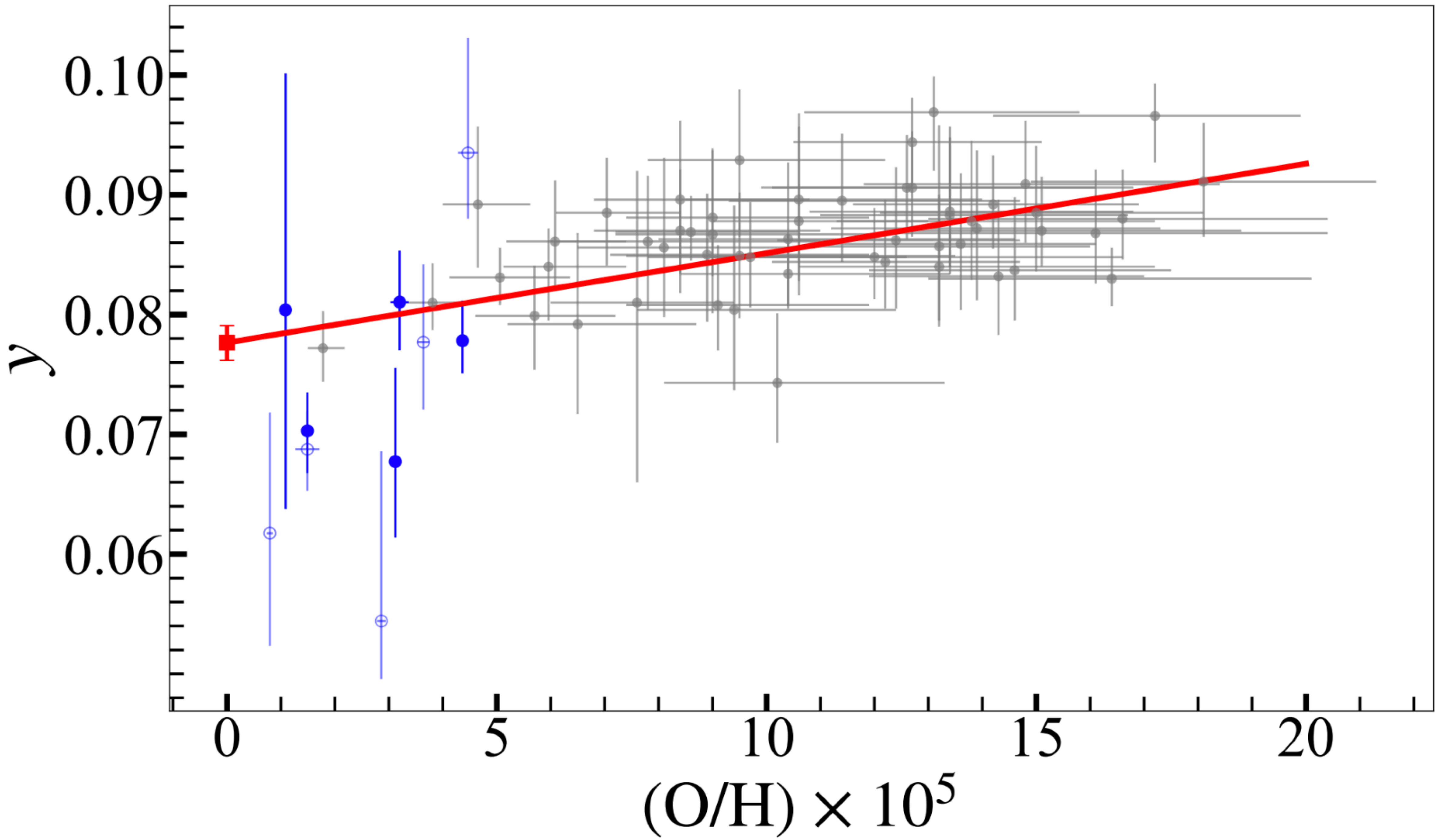
$$Y_{\mathrm{P}} = 4n_{\mathrm{He}}/n_{\mathrm{b}}$$

$$y_{\mathrm{P}} \equiv \frac{n(^4\mathrm{He})}{n(^1\mathrm{H})} = \frac{Y_{\mathrm{P}}}{4(1 - Y_{\mathrm{P}})}$$



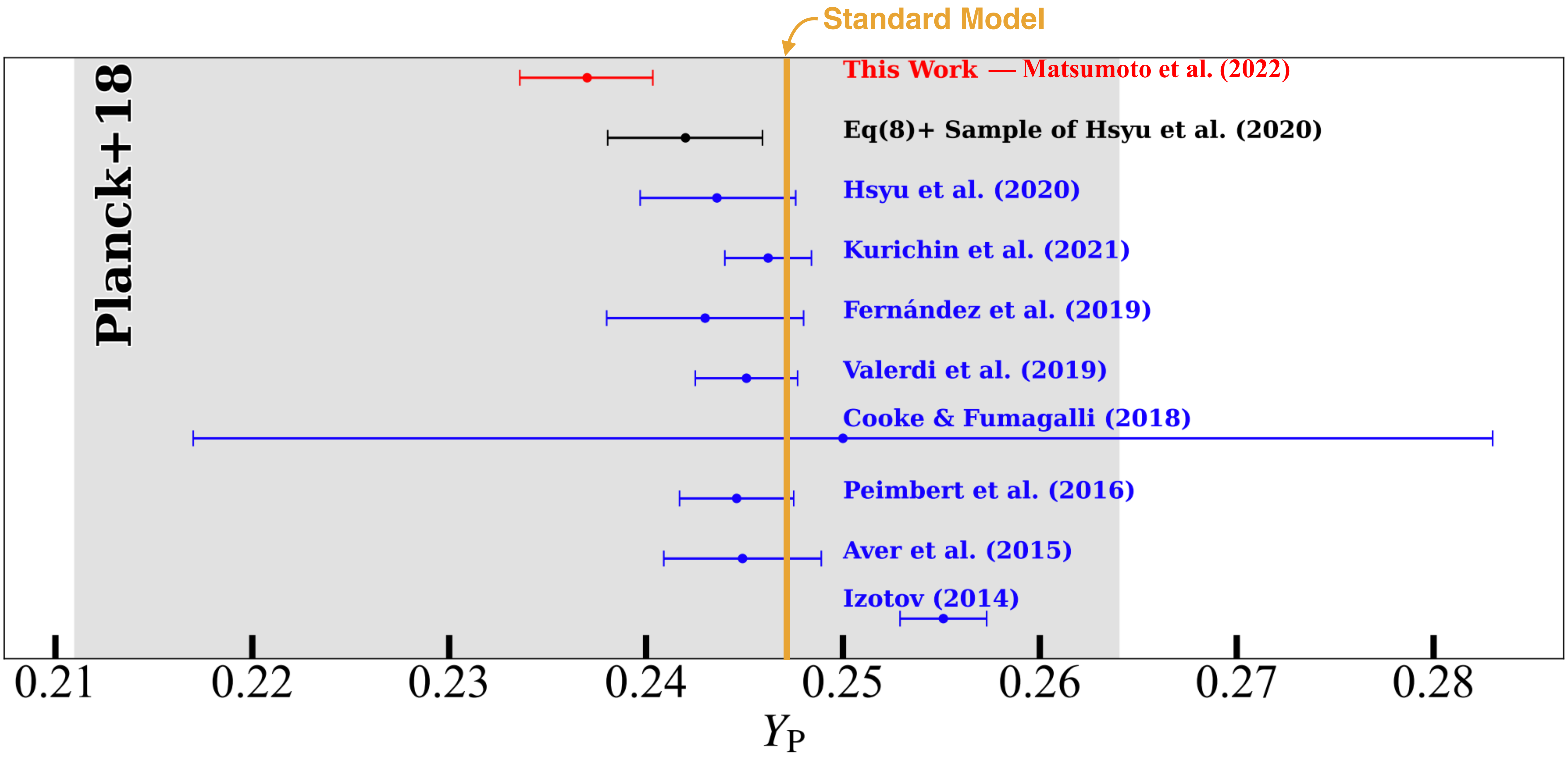
I Zwicky 18

The primordial helium mass fraction



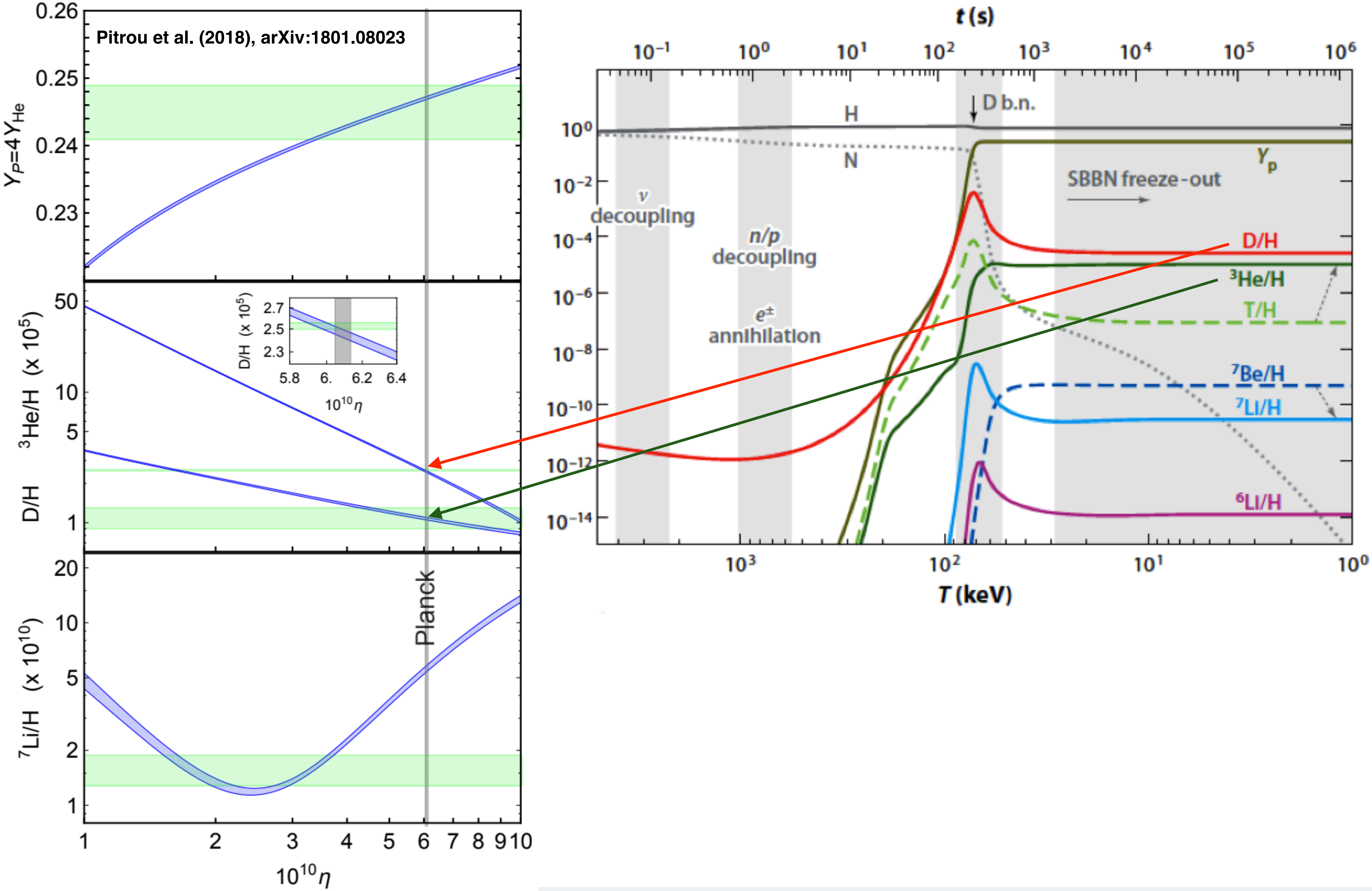
Matsumoto et al. (2022), arXiv:2203.09617

The primordial helium mass fraction

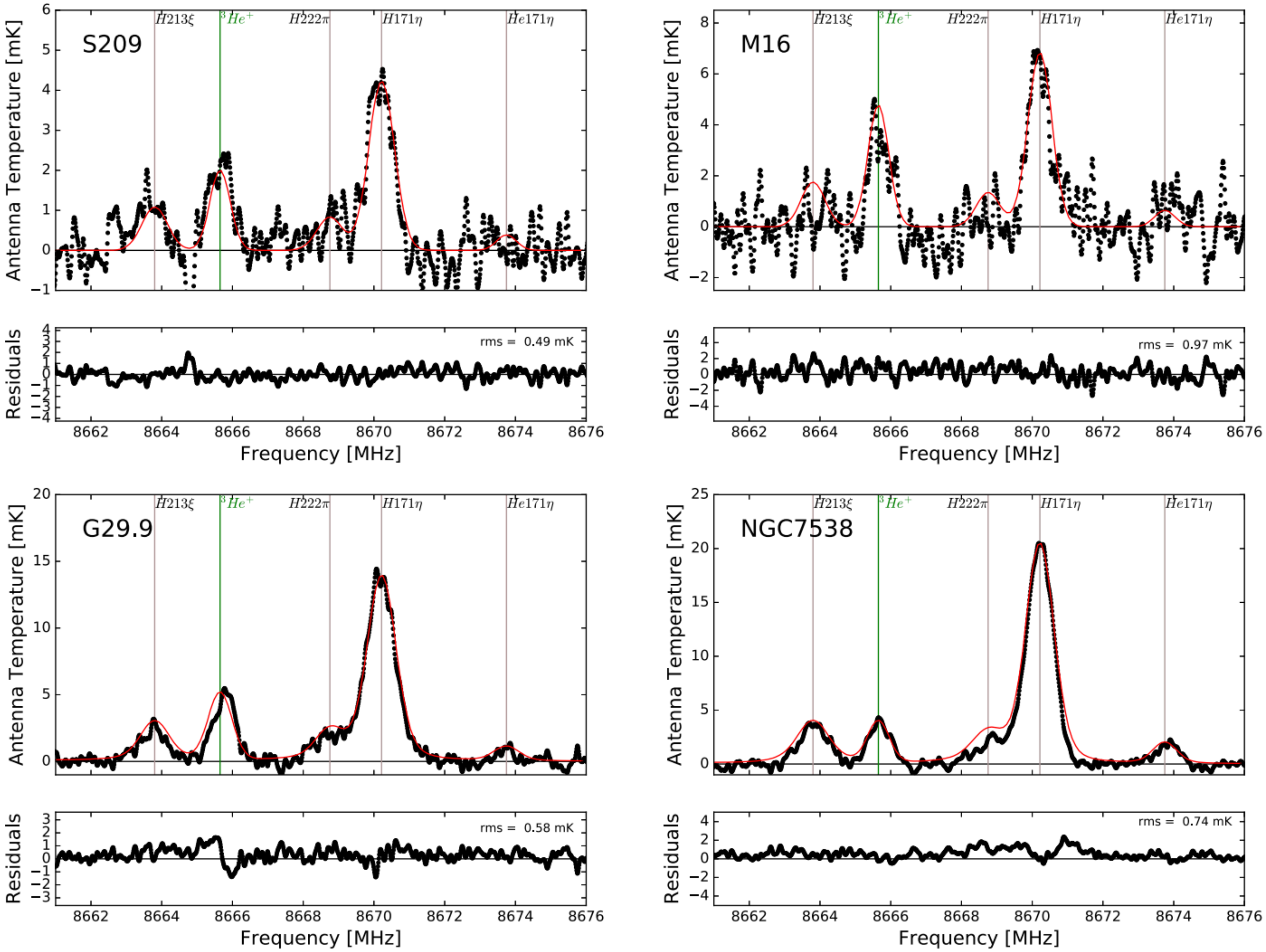


Matsumoto et al. (2022), arXiv:2203.09617

Timeline of Big Bang Nucleosynthesis

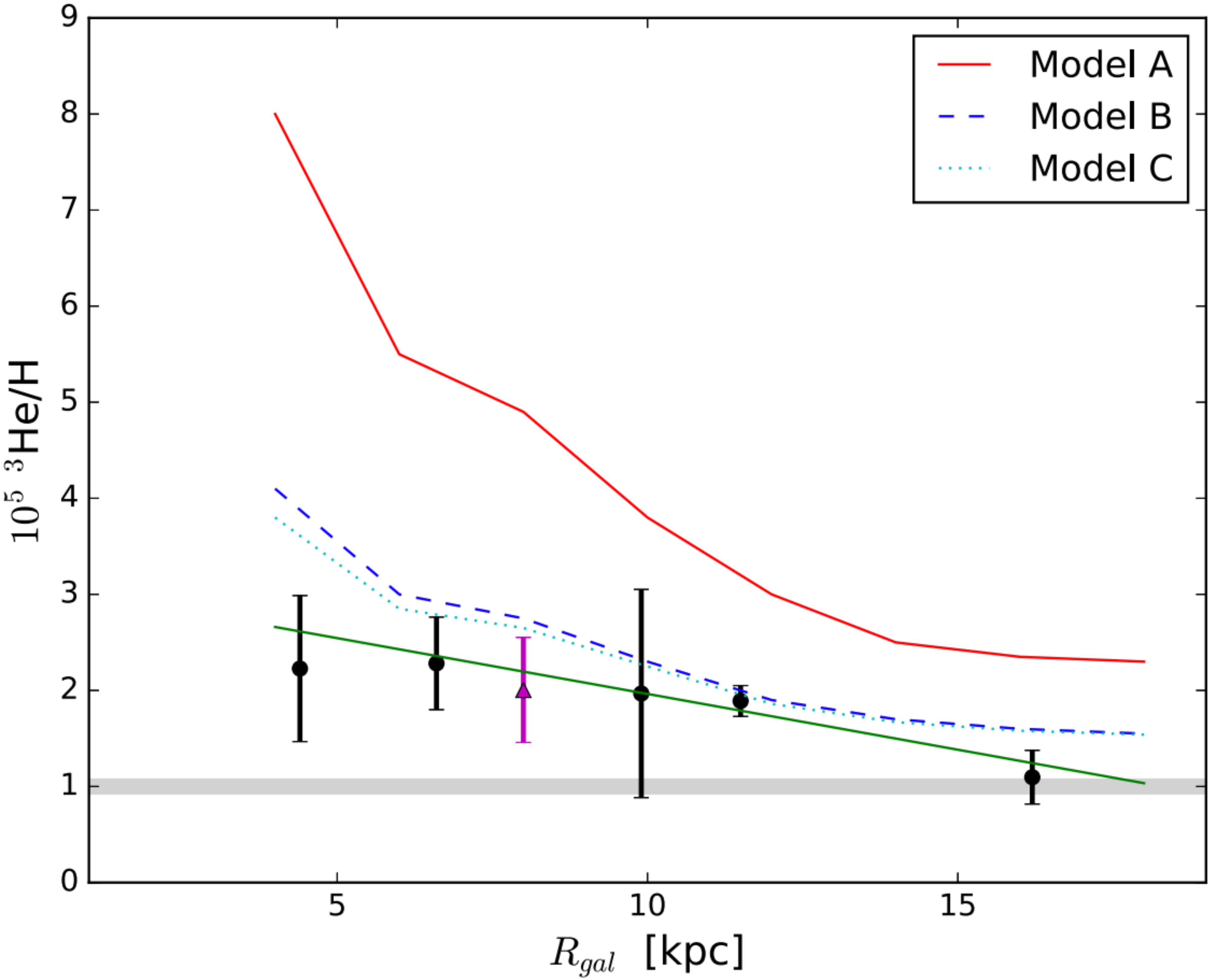


^{3}He abundance (^{3}He/H)



Balser & Bania (2018), AJ, 156, 280

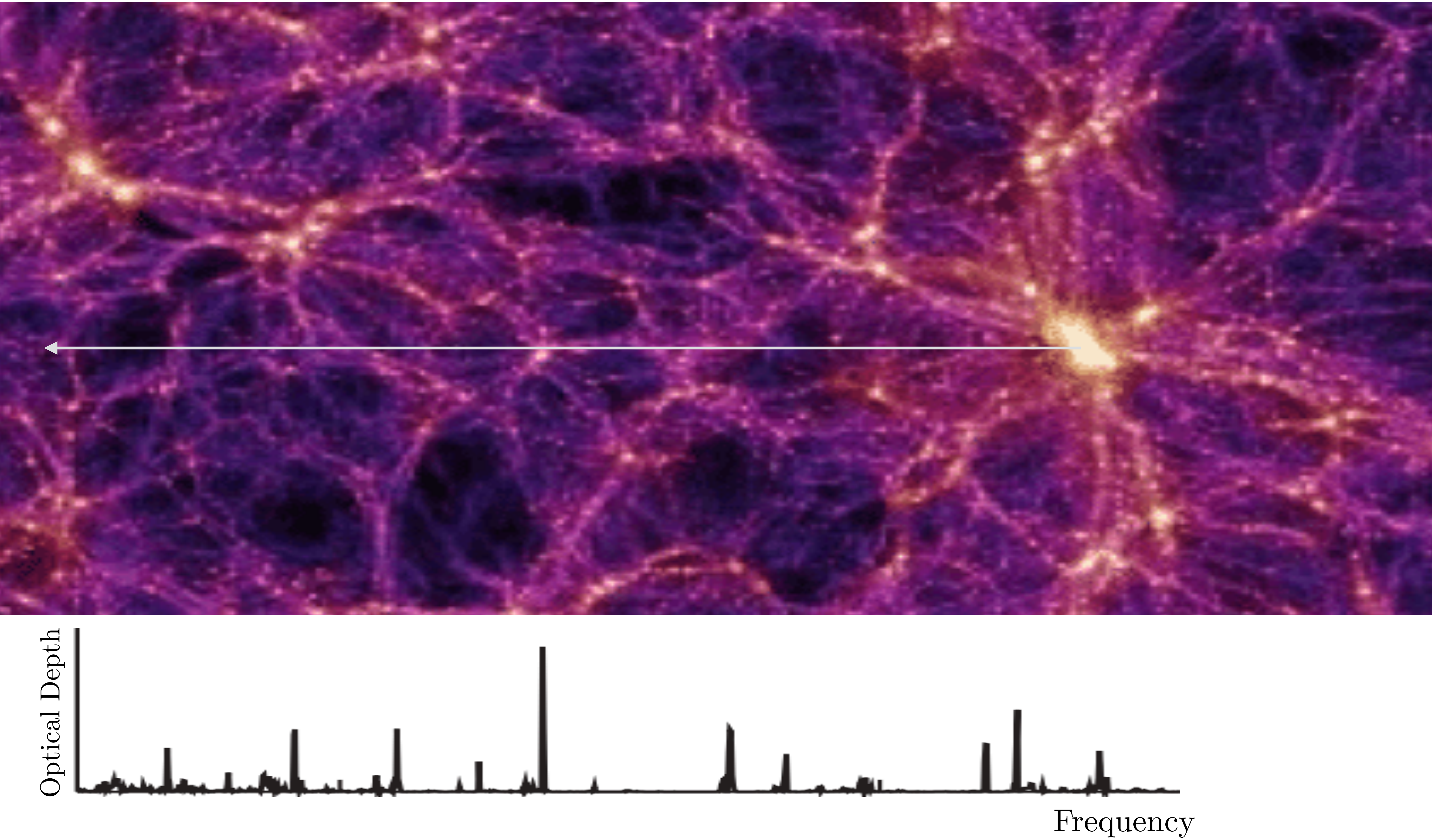
^{3}He abundance (^{3}He/H)



Balser & Bania (2018), AJ, 156, 280

^{3}He abundance (^{3}He/H)

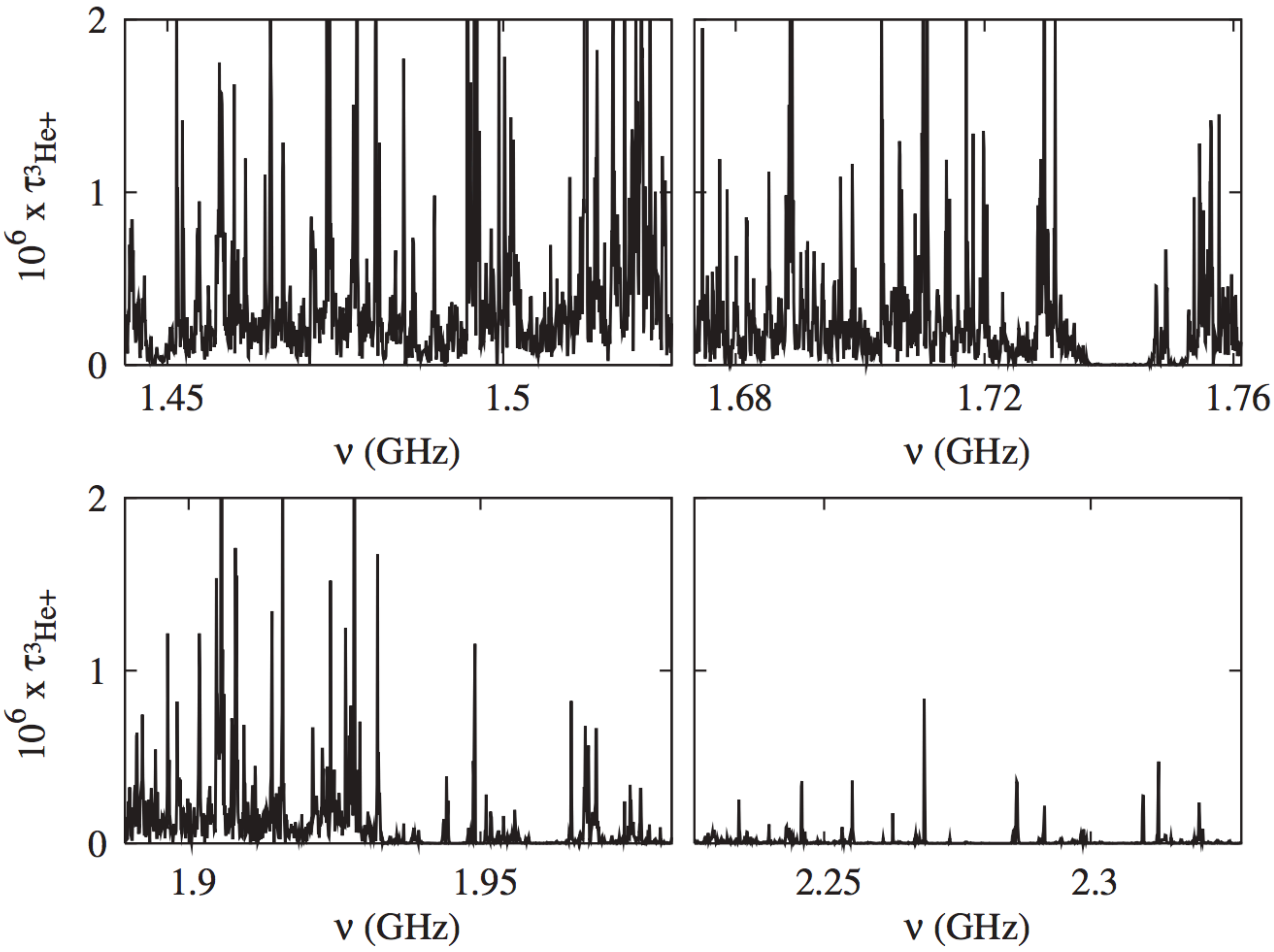
Millenium simulation



^{3}He abundance (^{3}He/H)

z = 5.0

z = 4.2



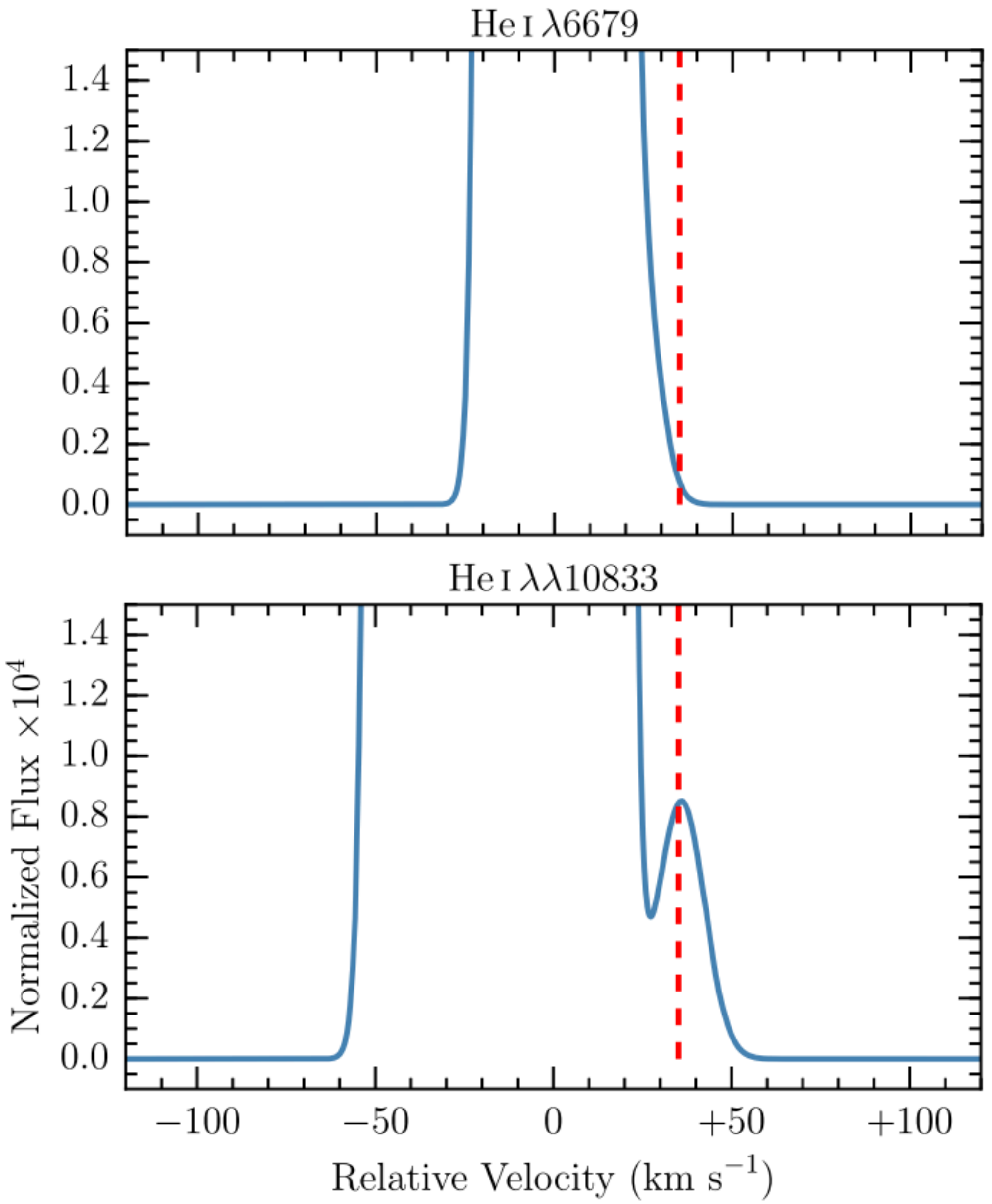
z = 3.6

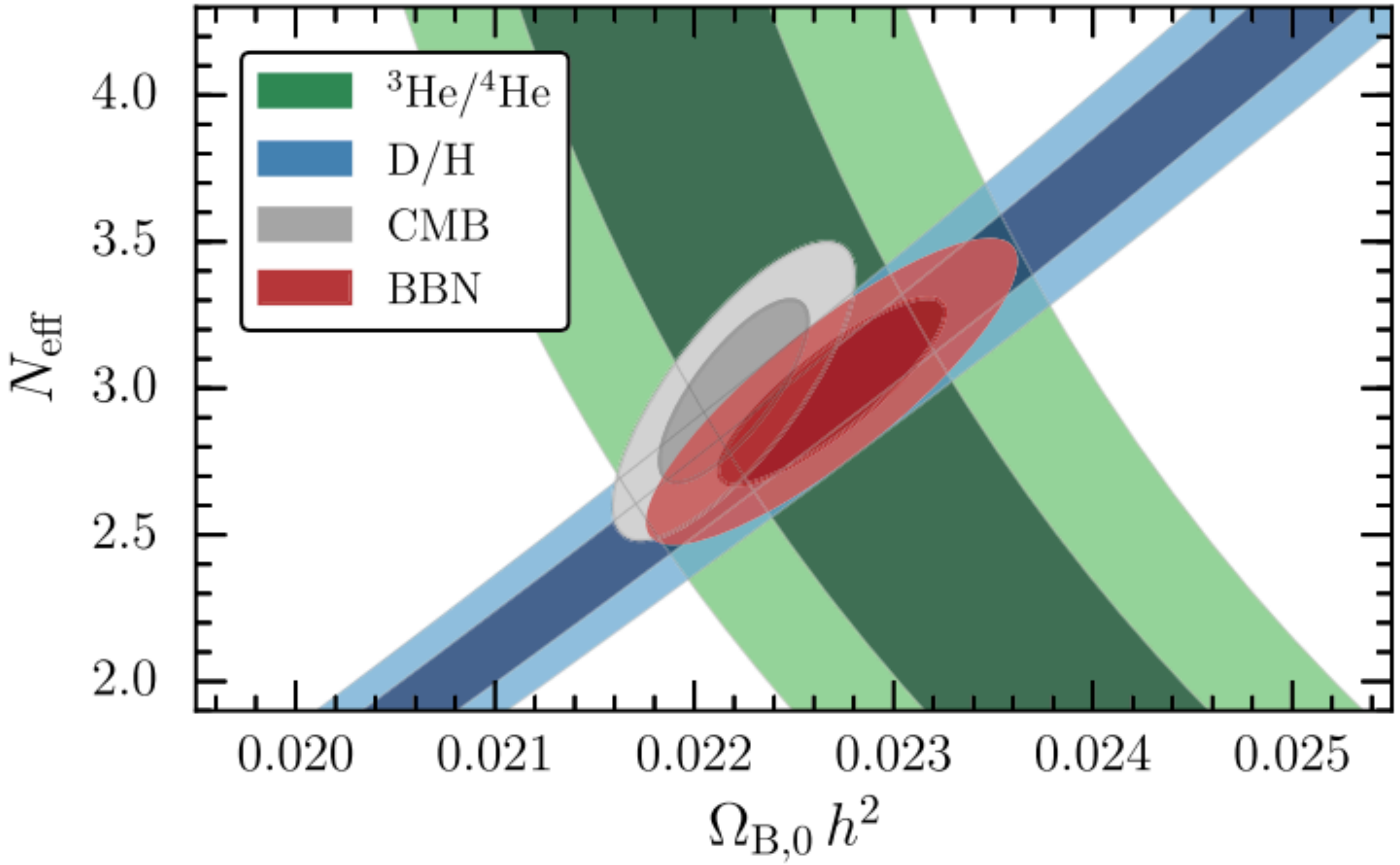
z = 2.9

McQuinn & Switzer (2009), Phys. Rev. D, 80, 063010

Benefits of the helium isotope ratio

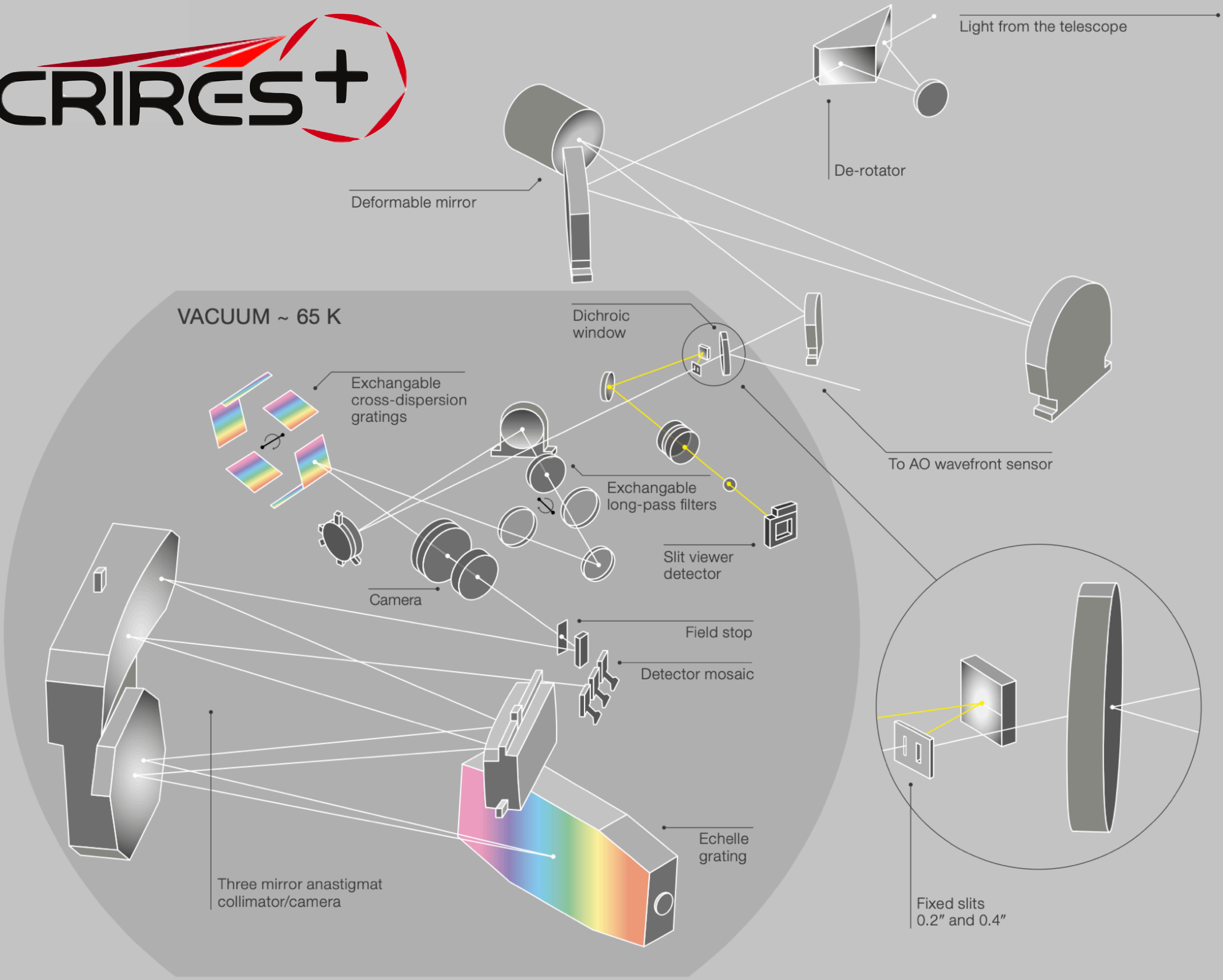
- ^{3}He and ^{4}He have very similar ionisation potentials
- The isotope shift is different for different transitions
- Primordial helium and hydrogen isotope ratios offer orthogonal bounds on Neff and the baryon density



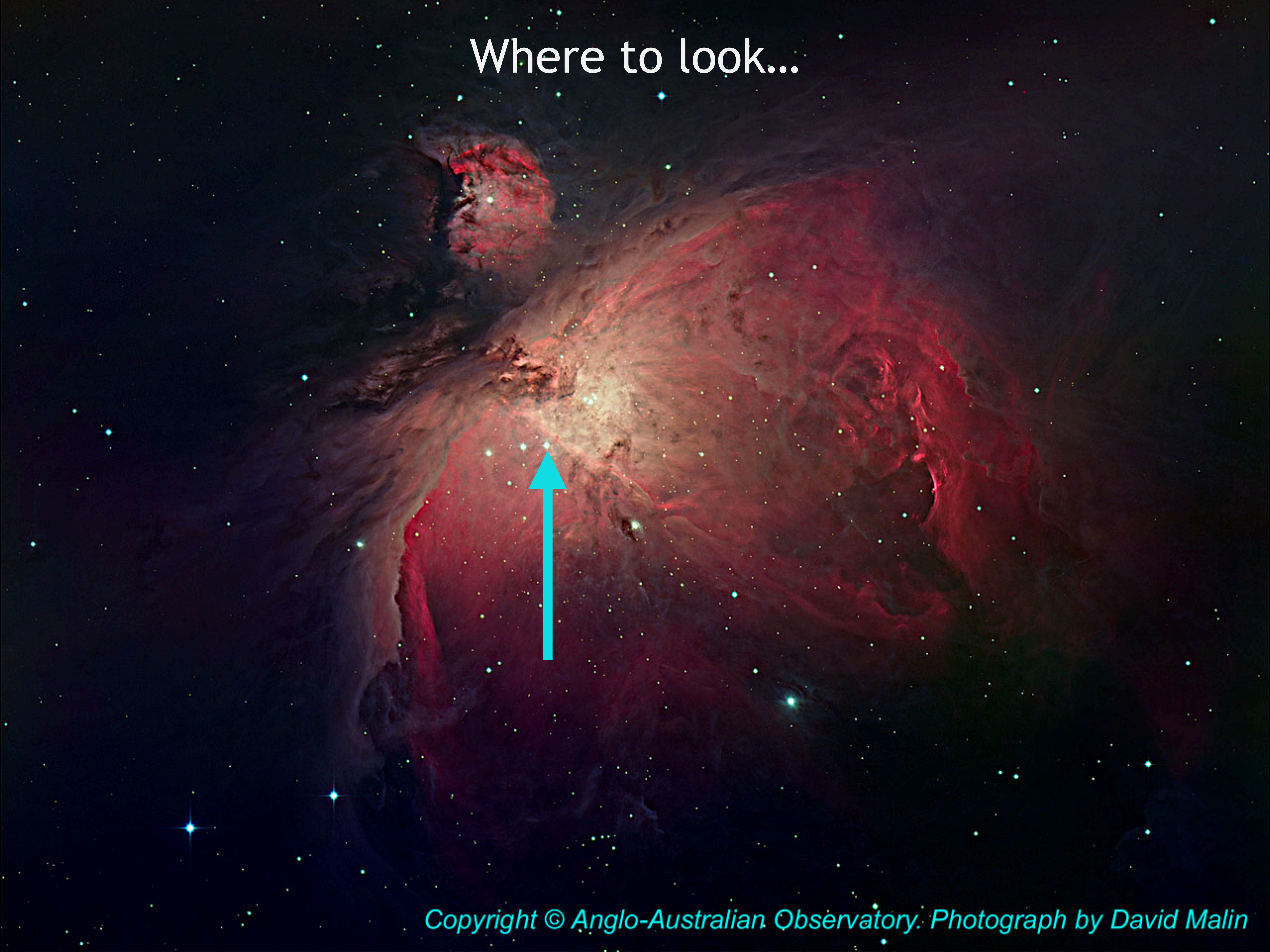


Cooke (2015), ApJL, 812, 12

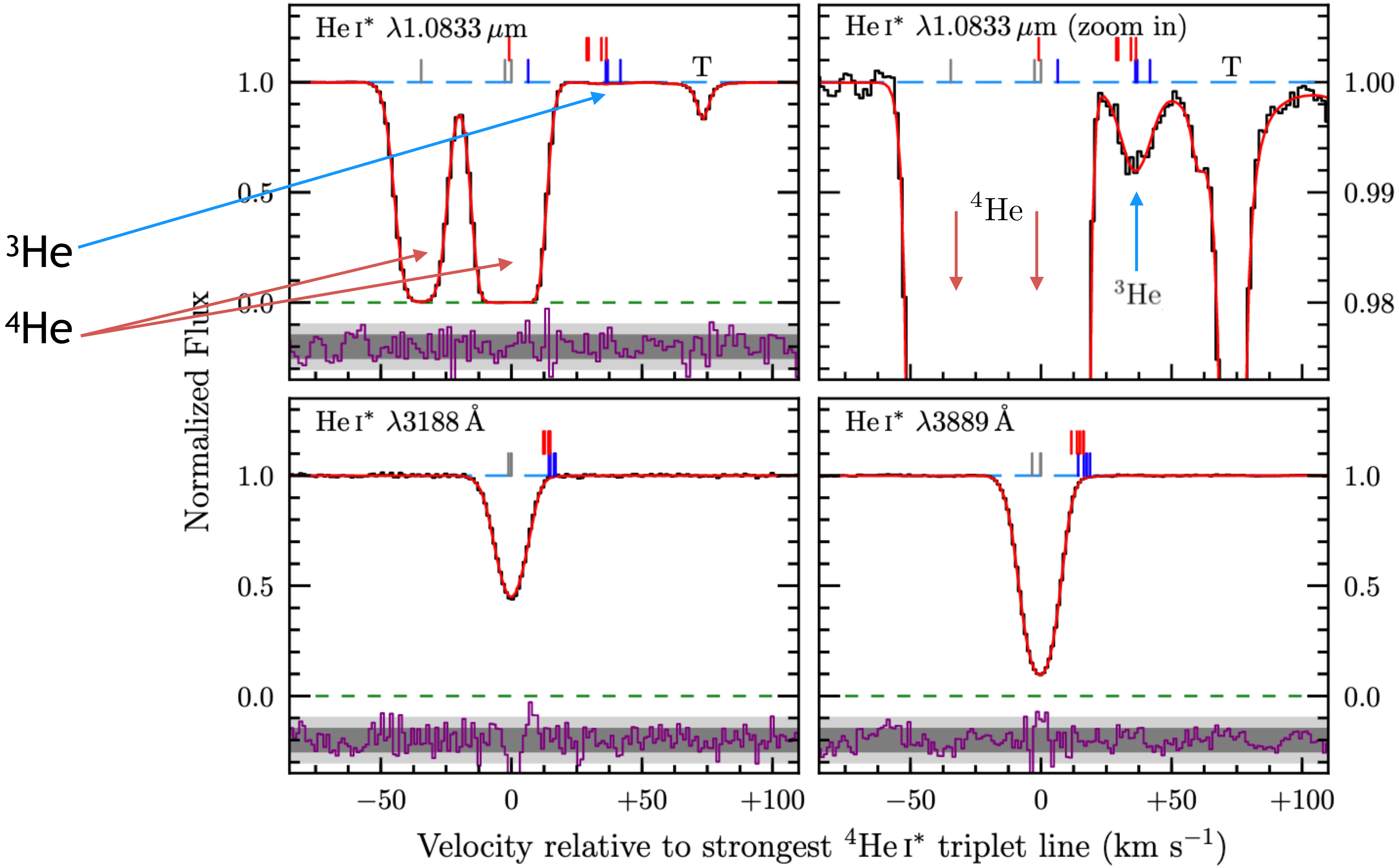
CRIRES+


Light from the telescope
De-rotator
Deformable mirror
VACUUM ~ 65 K
Dichroic window
To AO wavefront sensor
Exchangable cross-dispersion gratings
Exchangable long-pass filters
Slit viewer detector
Camera
Field stop
Detector mosaic
Echelle grating
Three mirror anastigmat collimator/camera
Fixed slits 0.2″ and 0.4″

Where to look…



Helium isotope ratio

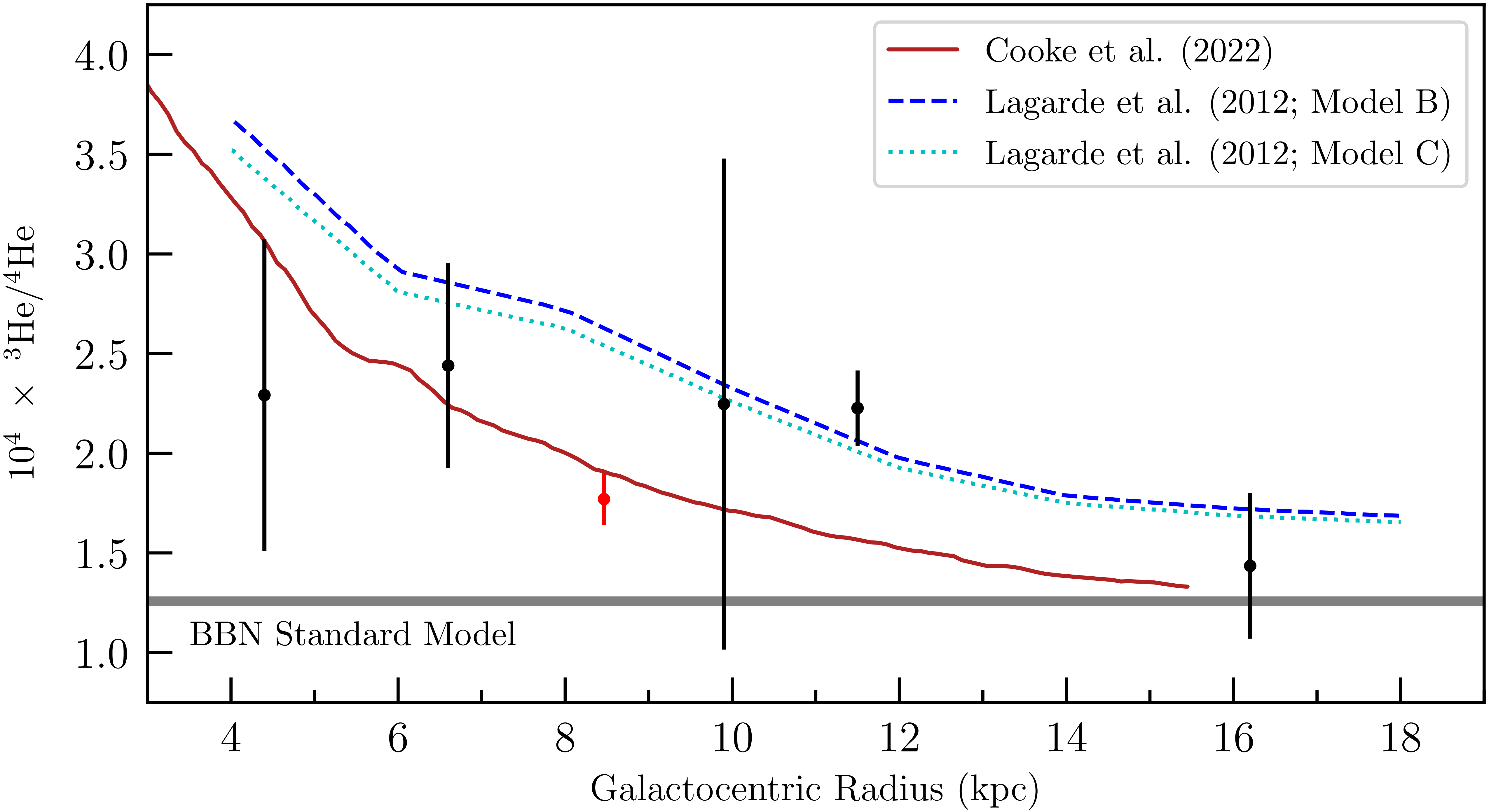


Cooke et al. (2022), ApJ, 932, 60

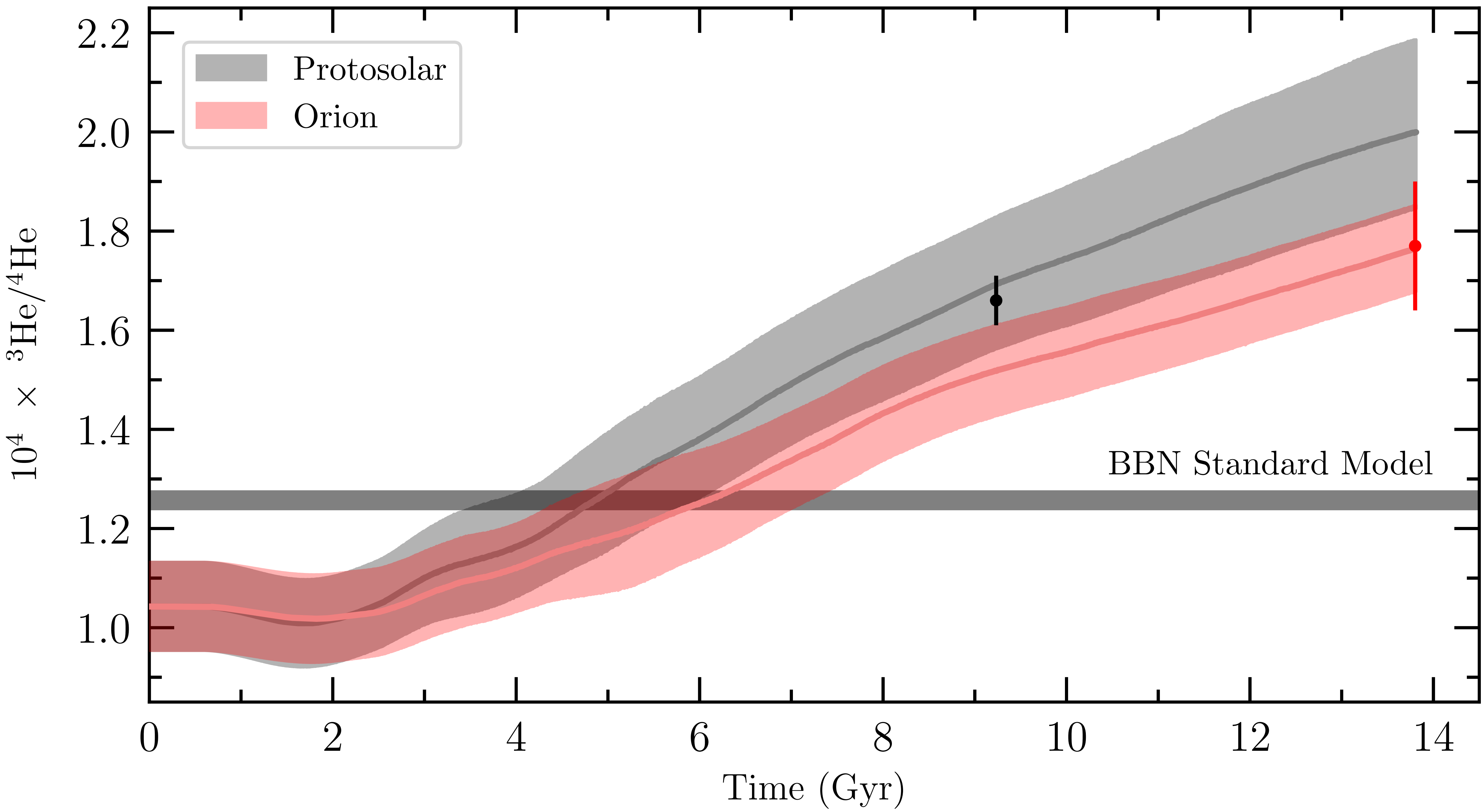
VICE: Versatile Integrator for Chemical Evolution

Johnson et al. (2021), MNRAS, 508, 4484

VICE



Next thing



Cooke et al. (2022), ApJ, 932, 60

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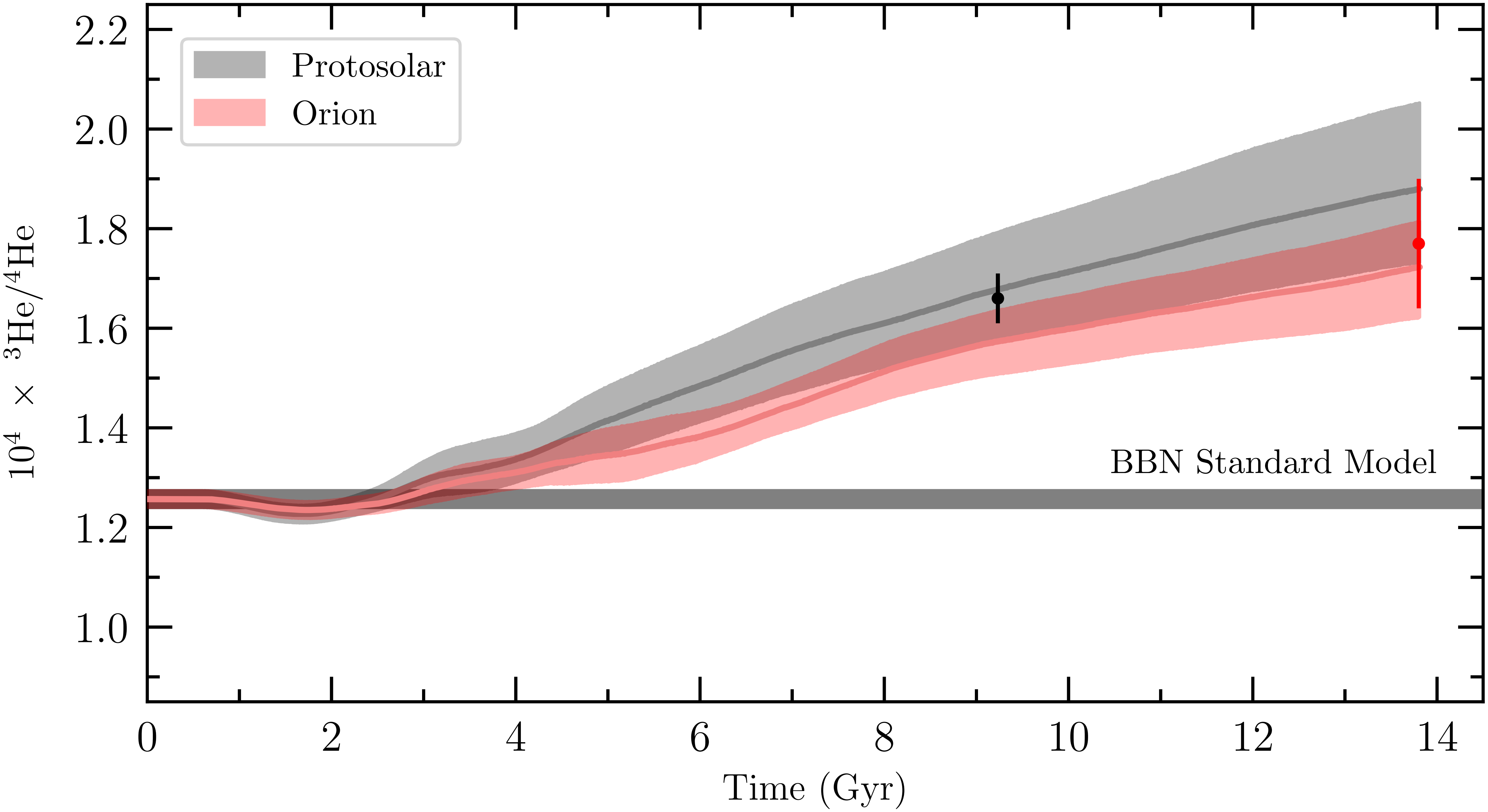
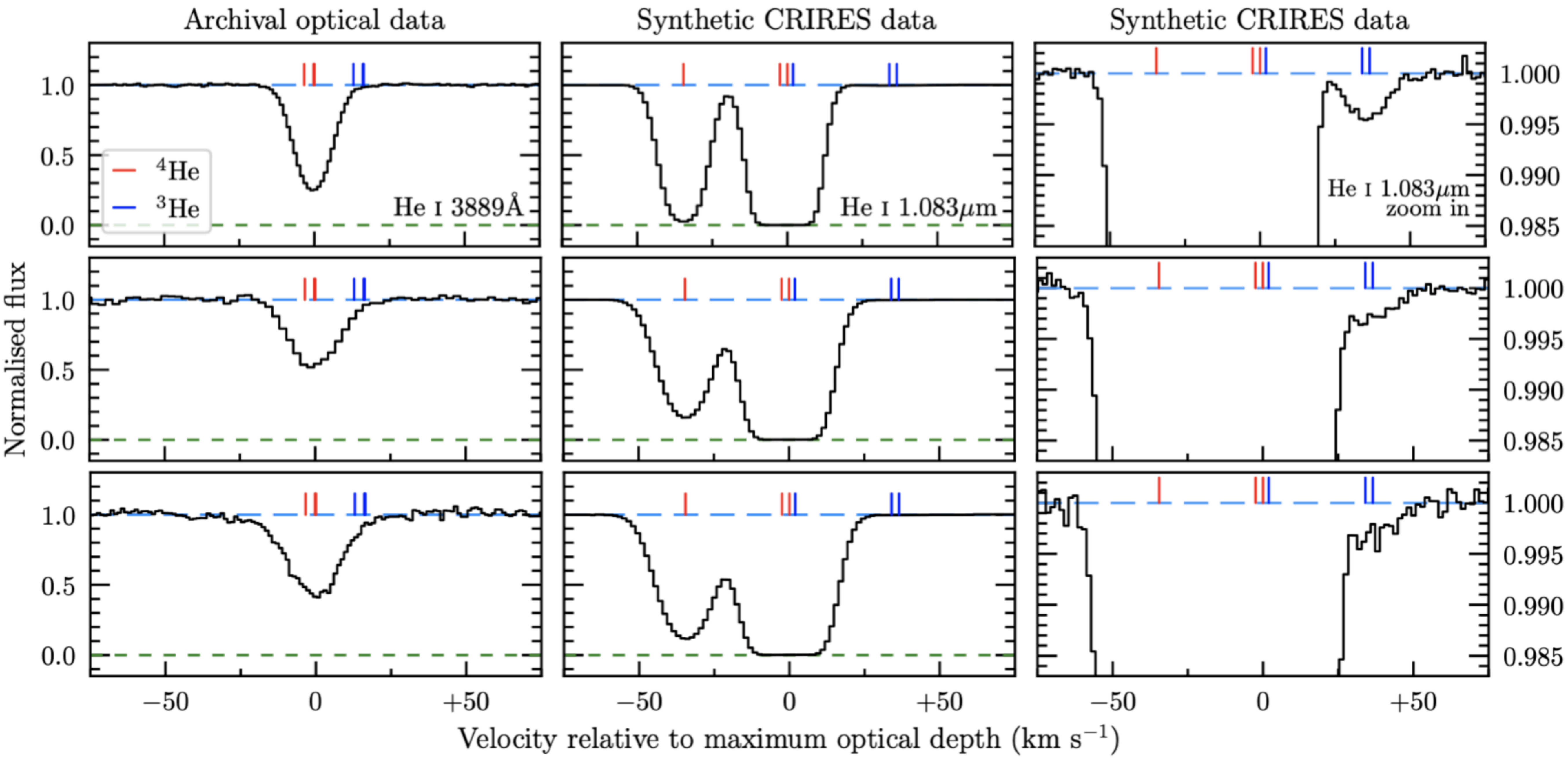


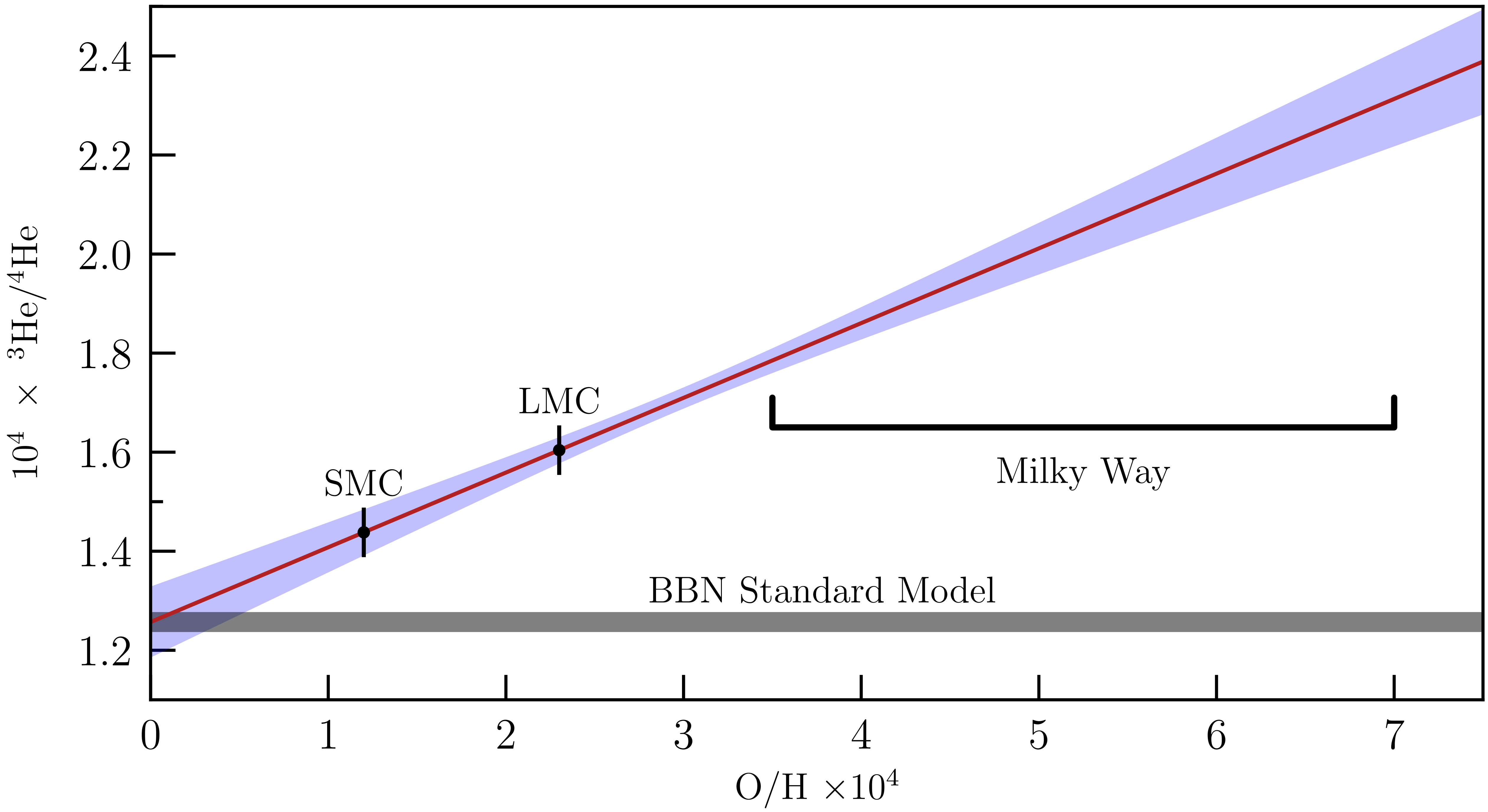
Cooke et al. (2022), ApJ, 932, 60

The near future…



There's potential for more helium-3 absorbers — stay tuned!

The near future...



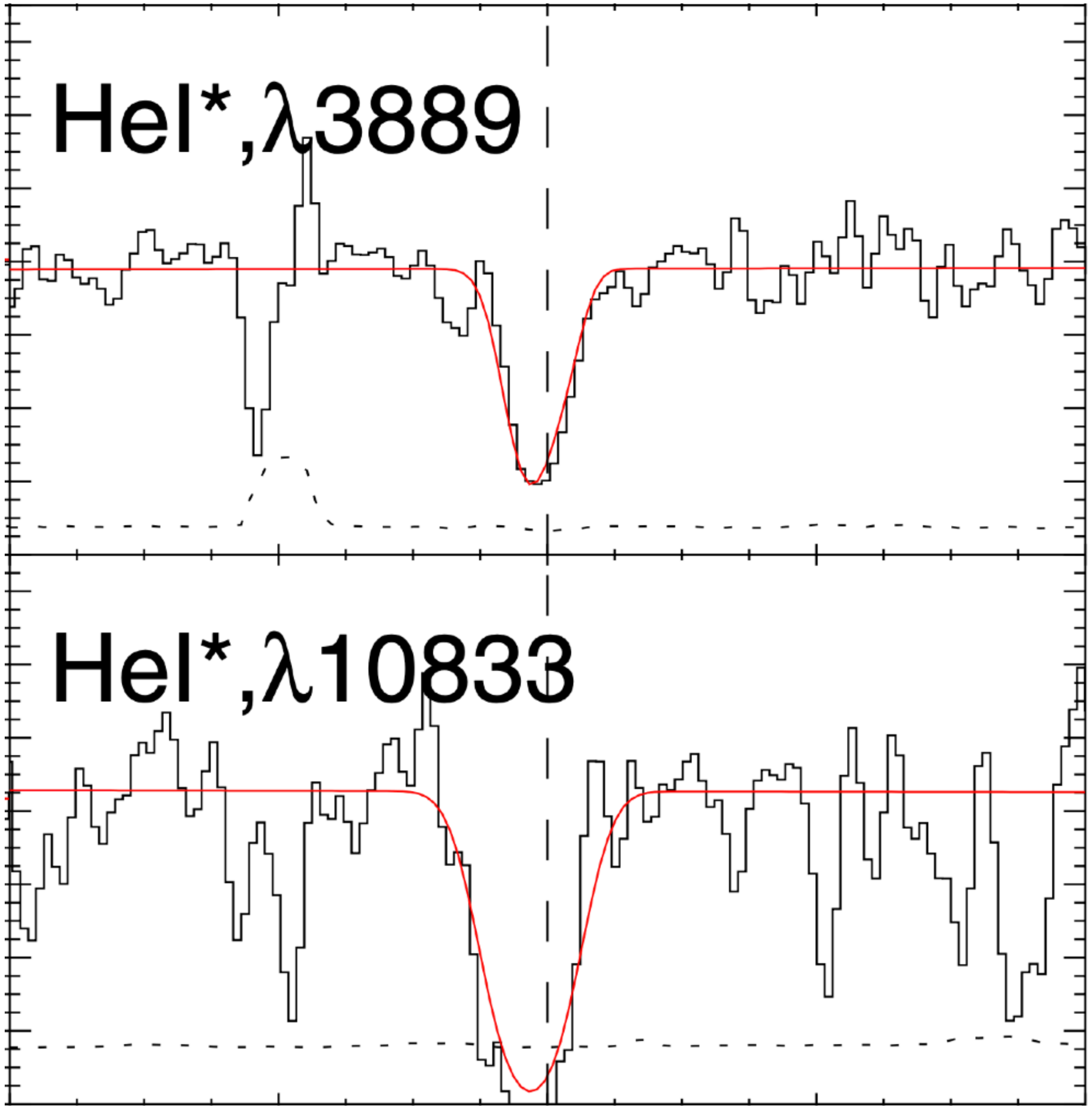
There's potential for more helium-3 absorbers — stay tuned!

The far future… extragalactic absorbers

Some low redshift, long-duration GRBs may be ideal environments to measure the helium isotope ratio, especially if their host is a metal-poor galaxy.

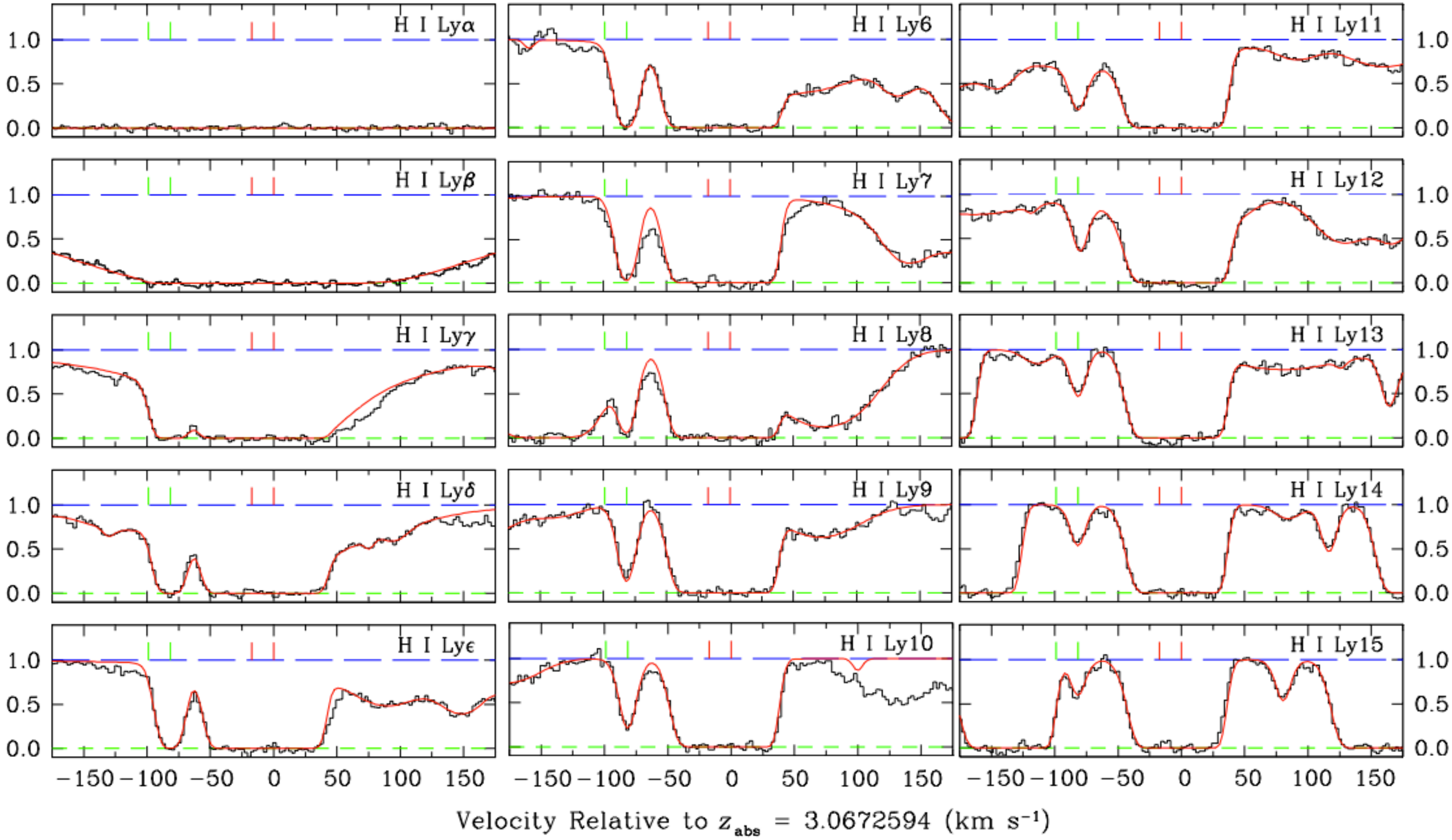
Credit: ***NASA, ESA, M. Kornmesser***

Fynbo et al. (2014), A&A, 572, A12
GRB140506A, z=0.88



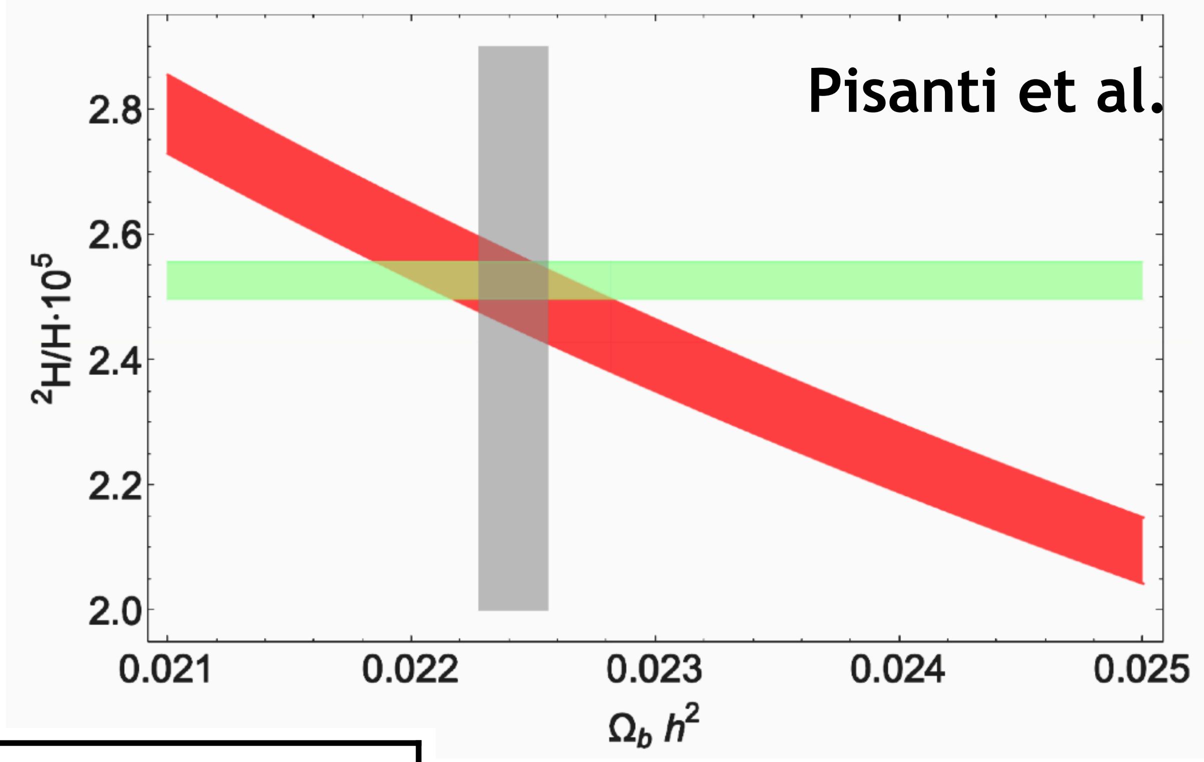
Summary and Conclusions

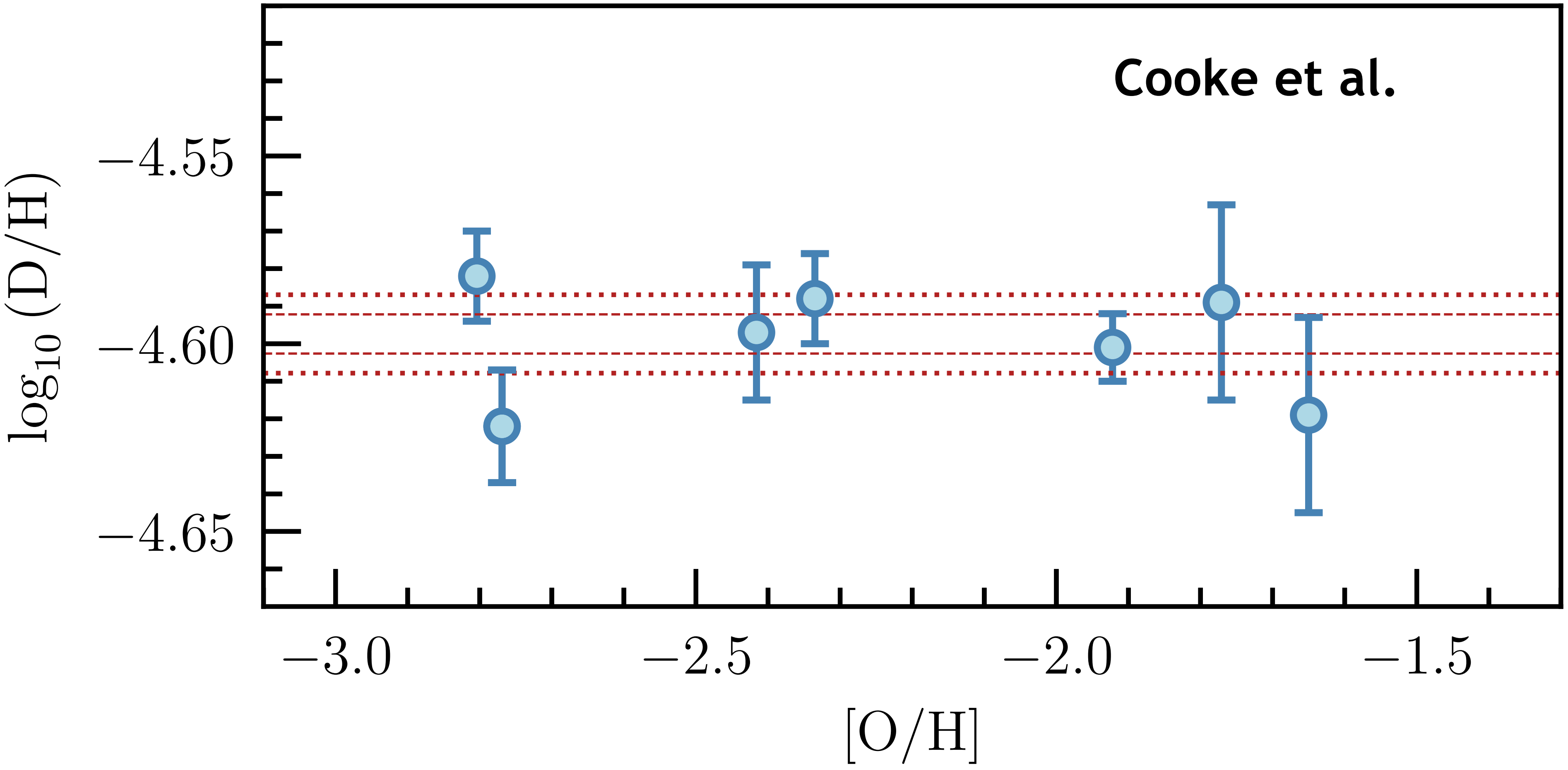
- The most metal-poor DLAs allow us to place tight limits on Big Bang Nucleosynthesis, and of physics beyond the Standard Model.



Summary and Conclusions

- The most metal-poor DLAs allow us to place tight limits on Big Bang Nucleosynthesis, and of physics beyond the Standard Model.
- The baryon density derived from BBN and the CMB agree with astonishing precision.





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- Recently reported a new determination of the ^{3}He/^{4}He.

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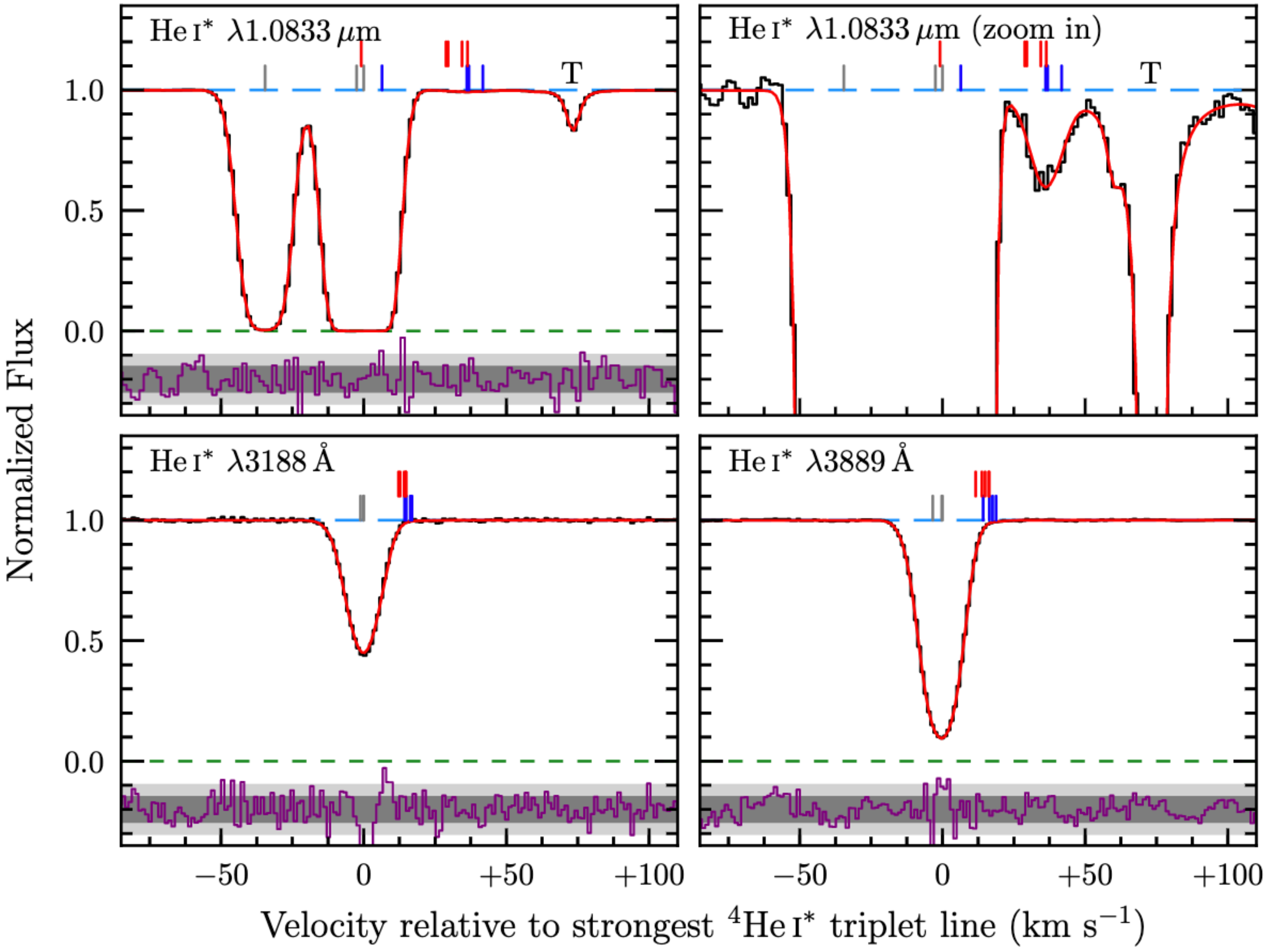

Summary and Conclusions

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- The baryon density derived from BBN and the CMB agree with astonishing precision.
- Recently reported a new determination of the ^{3}He/^{4}He.
- The helium isotope ratio offers a promising approach for a future determination of the primordial ^{3}He/^{4}He.