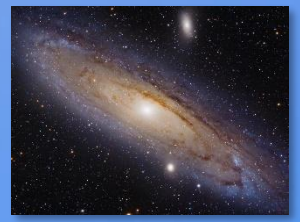


Сектор теоретической астрофизики

Физико-технический институт им. А.Ф. Иоффе

Первичные распространенности химических элементов: универсальный тест теорий Новой физики

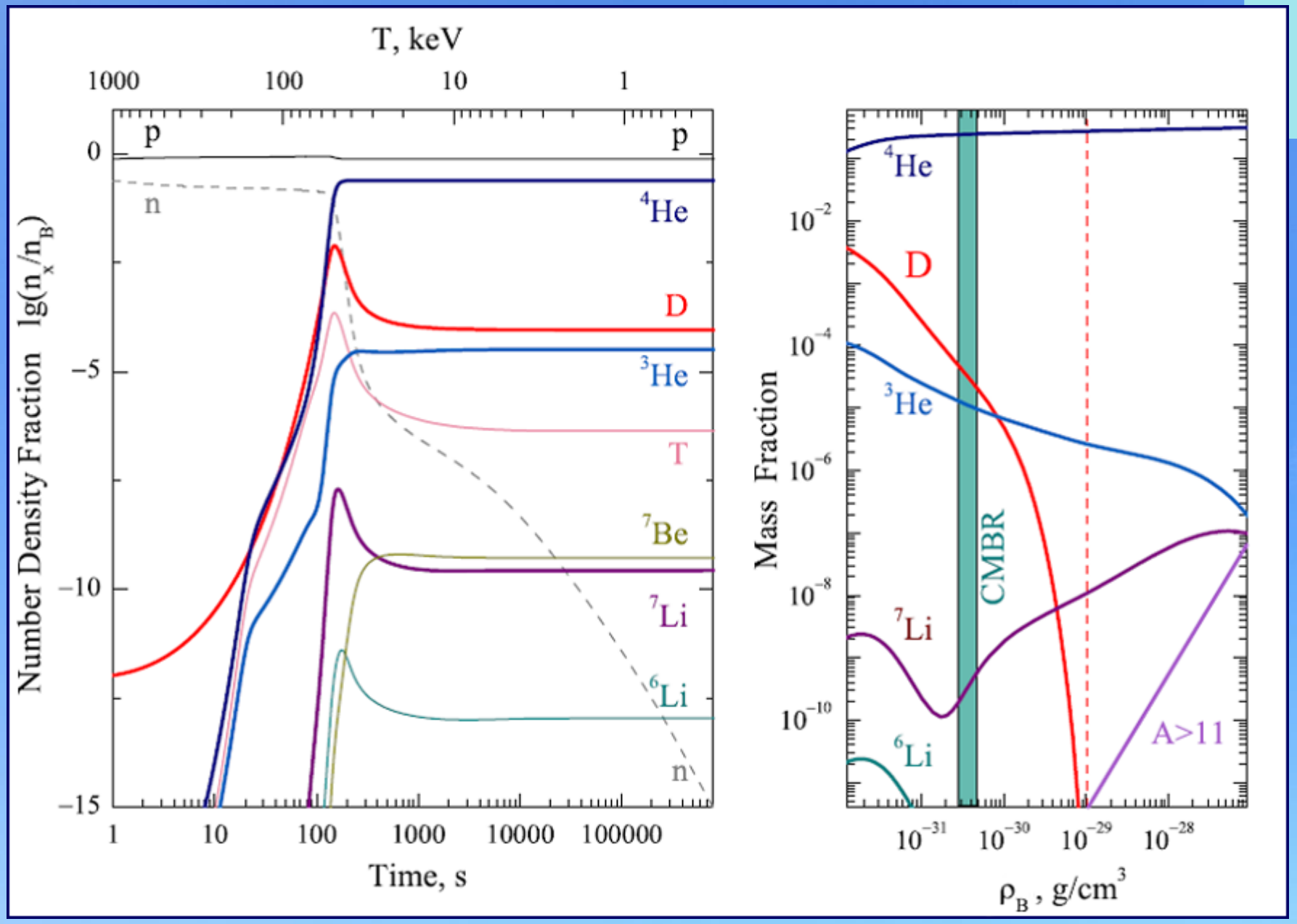
П.А. Кислицын*, С.А. Балашев, А.В. Иванчик

*pavel.kislitsyn@gmail.com

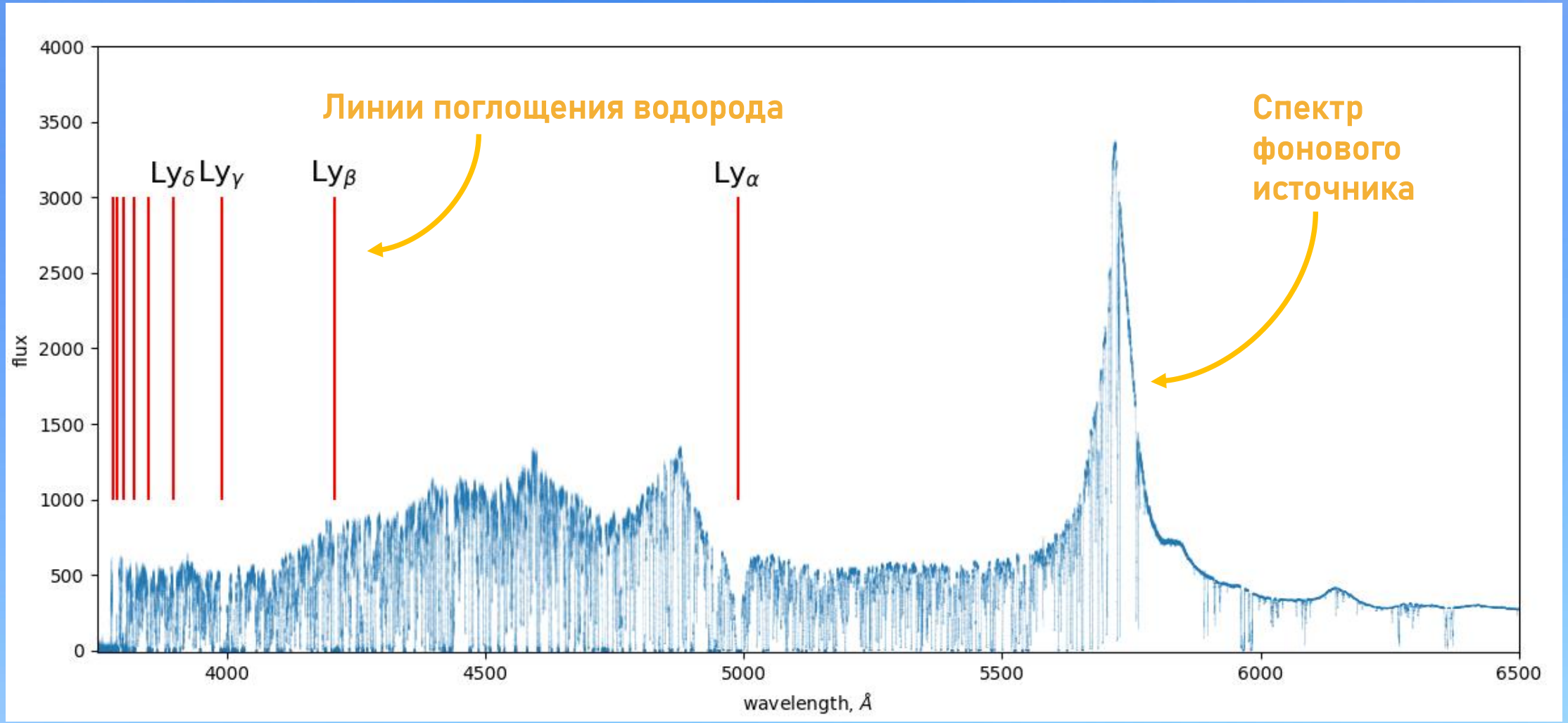
Летняя школа Фонда «Базис»

11.08.2026

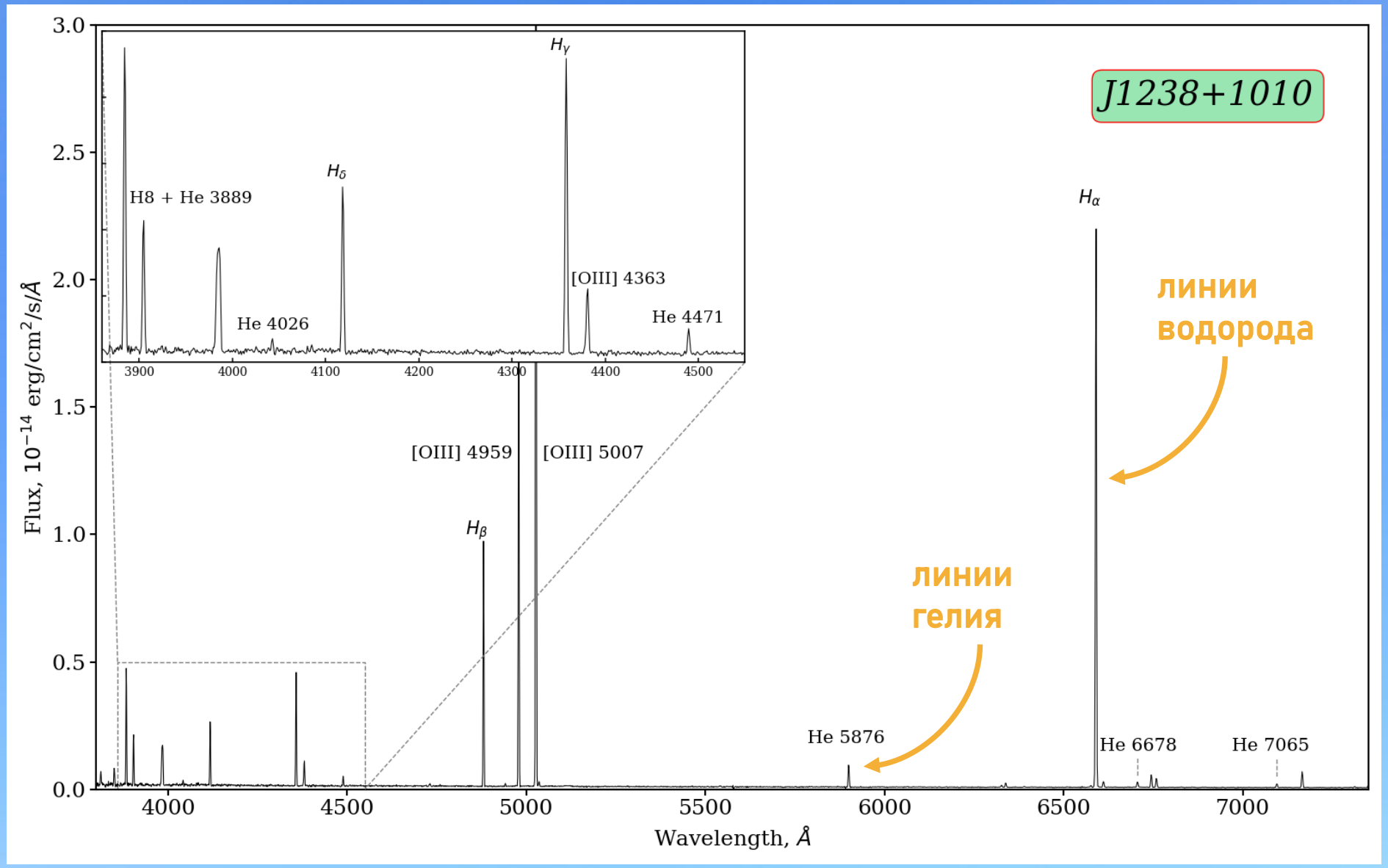
Первичный нуклеосинтез



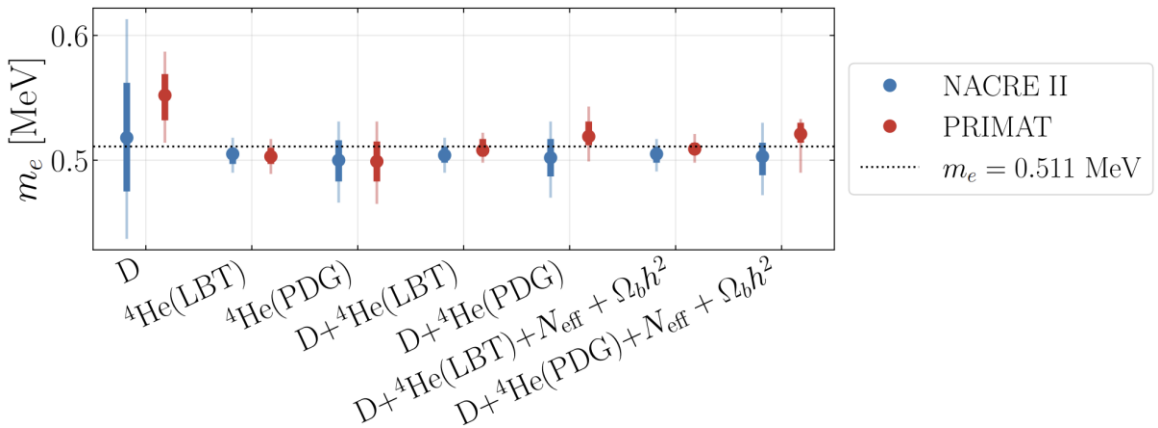
Измерения D/H



Оценки распространенности первичного ^{4}He

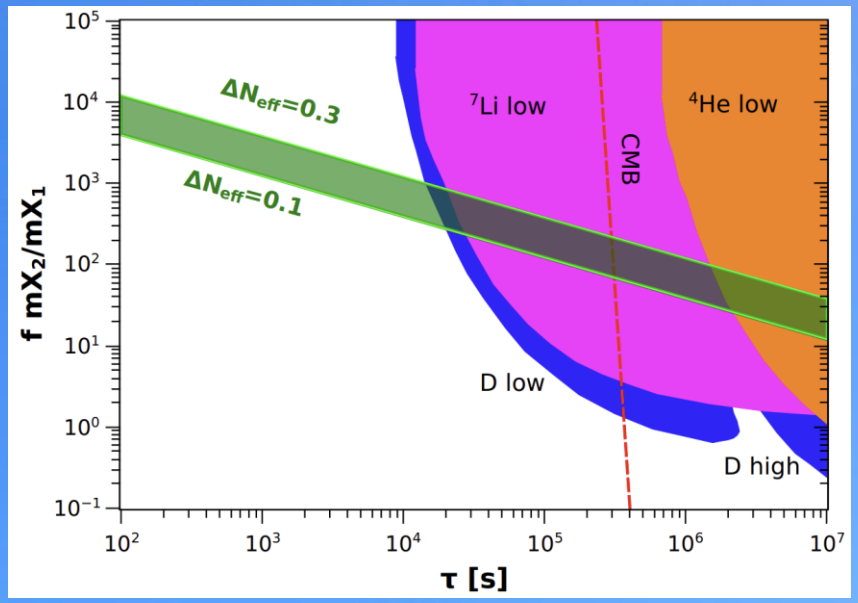


Теории Новой физики

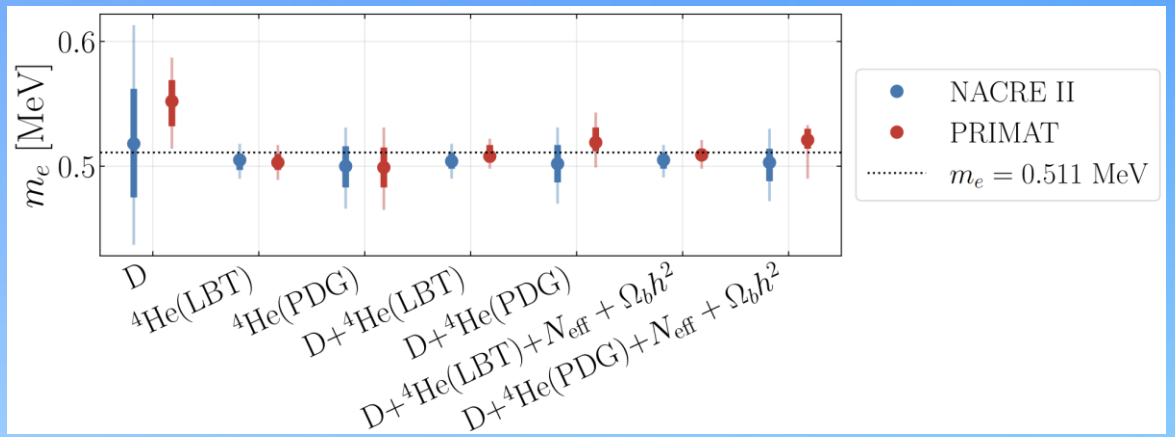


variyng m_e, https://arxiv.org/pdf/2602.05720

Теории Новой физики

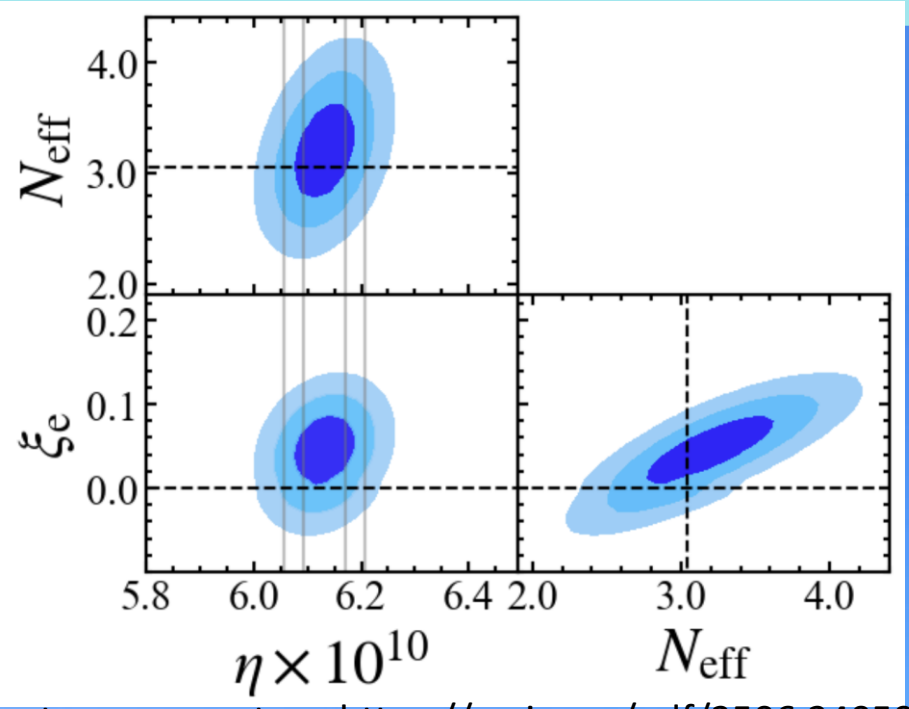


Long-lived particles, https://arxiv.org/pdf/2602.18580

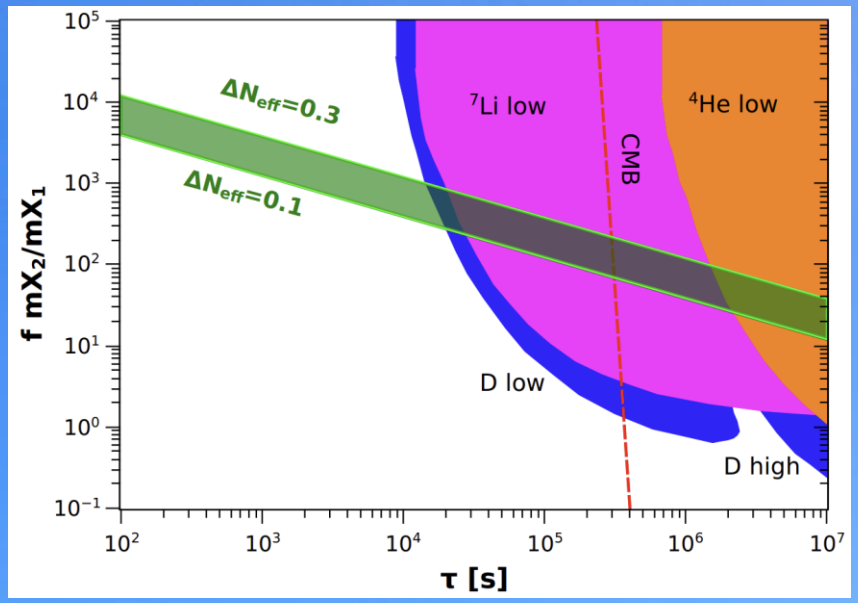


variyng m_e, https://arxiv.org/pdf/2602.05720

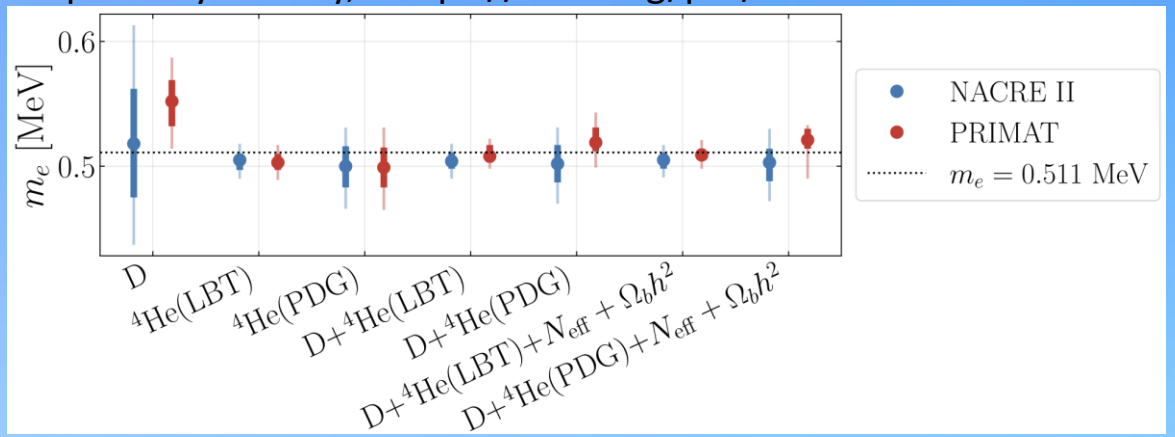
Теории Новой физики



Lepton asymmetry, https://arxiv.org/pdf/2506.24050



Long-lived particles, https://arxiv.org/pdf/2602.18580



variyng m_e, https://arxiv.org/pdf/2602.05720

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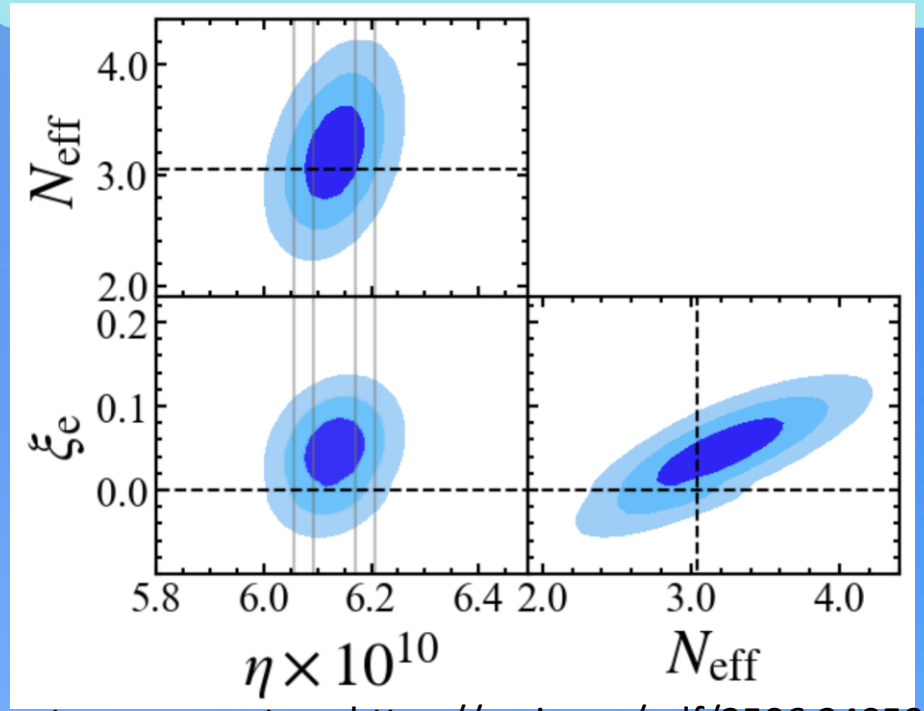
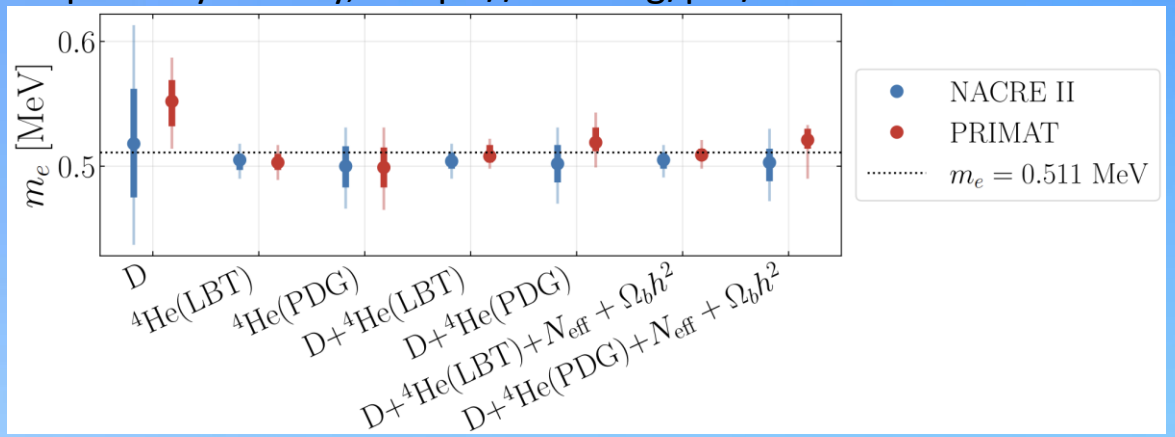
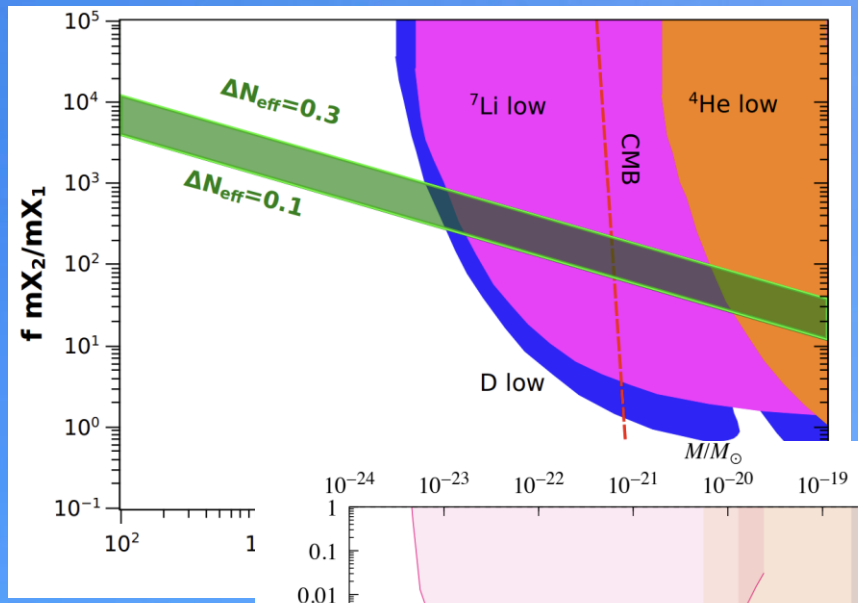


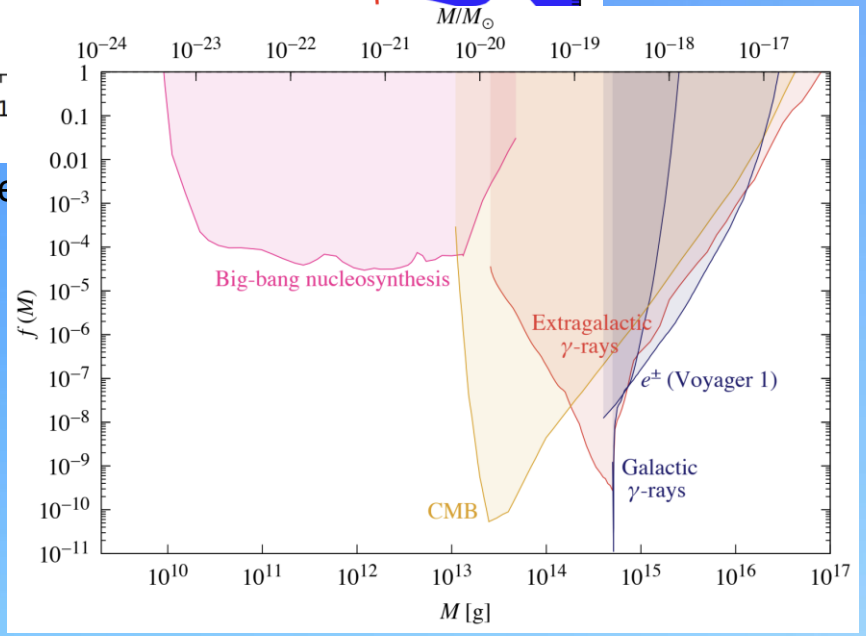
Lepton asymmetry, https://arxiv.org/pdf/2506.24050



variyng m_e, https://arxiv.org/pdf/2602.05720

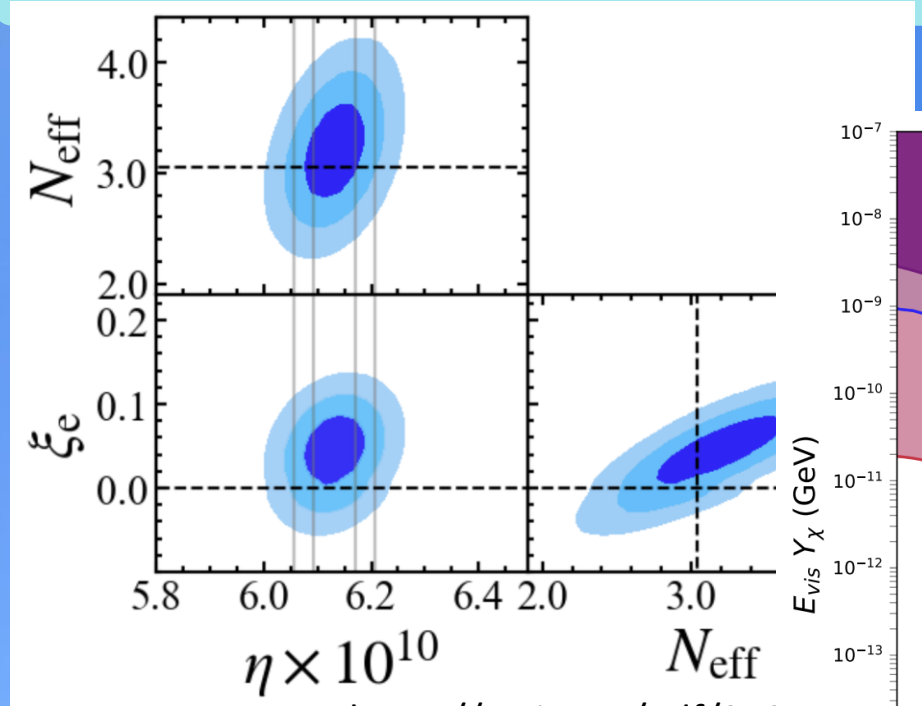


Long-lived particle

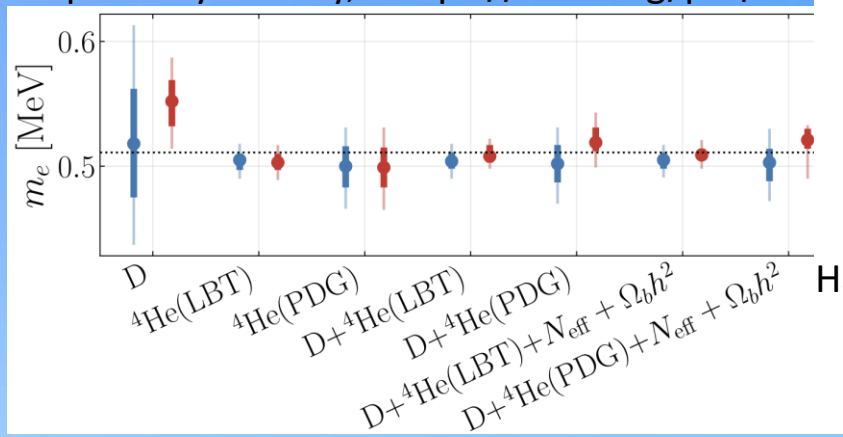


Primordial black holes, https://arxiv.org/pdf/2002.12778

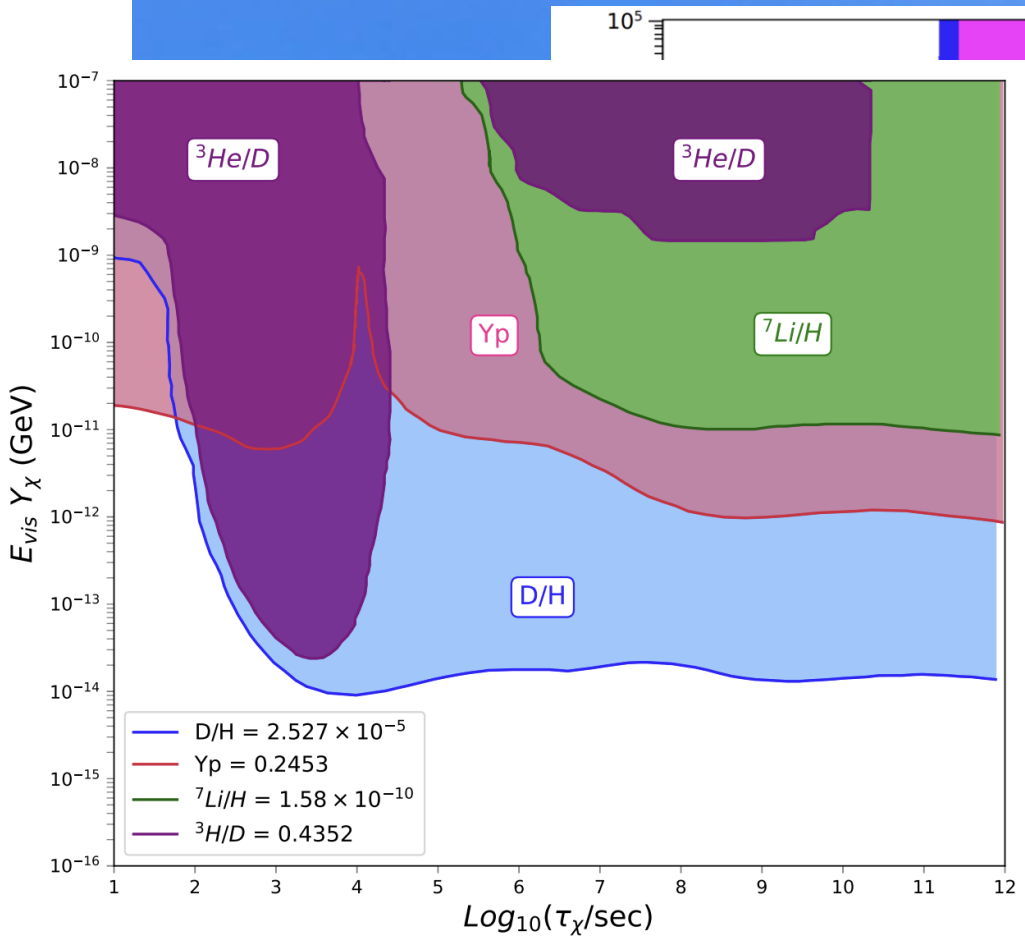
Теории Новой физики



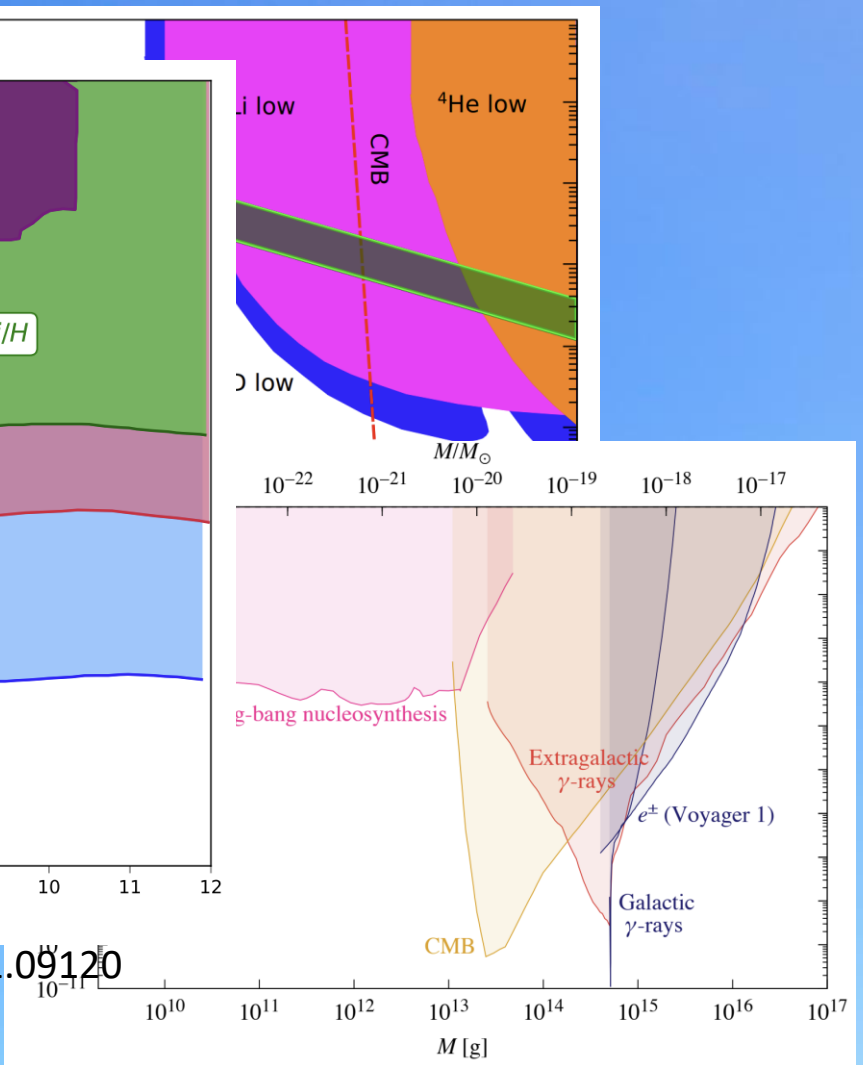
Lepton asymmetry, https://arxiv.org/pdf/250



variyng m_e, https://arxiv.org/pdf/2602.05720

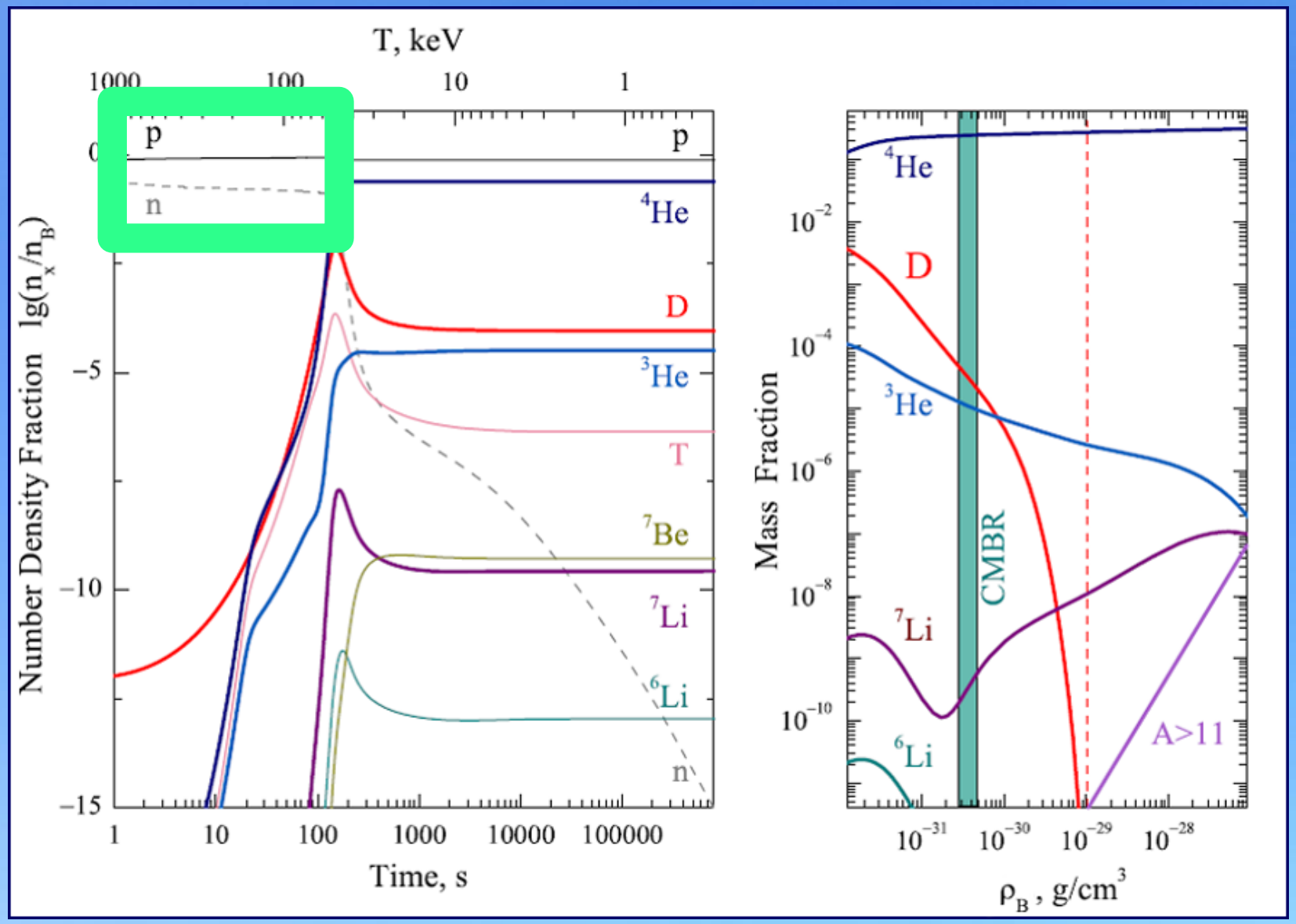


Hadronic injection, https://arxiv.org/pdf/2501.09120



Primordial black holes, https://arxiv.org/pdf/2002.12778

Фиксация отношения n/p

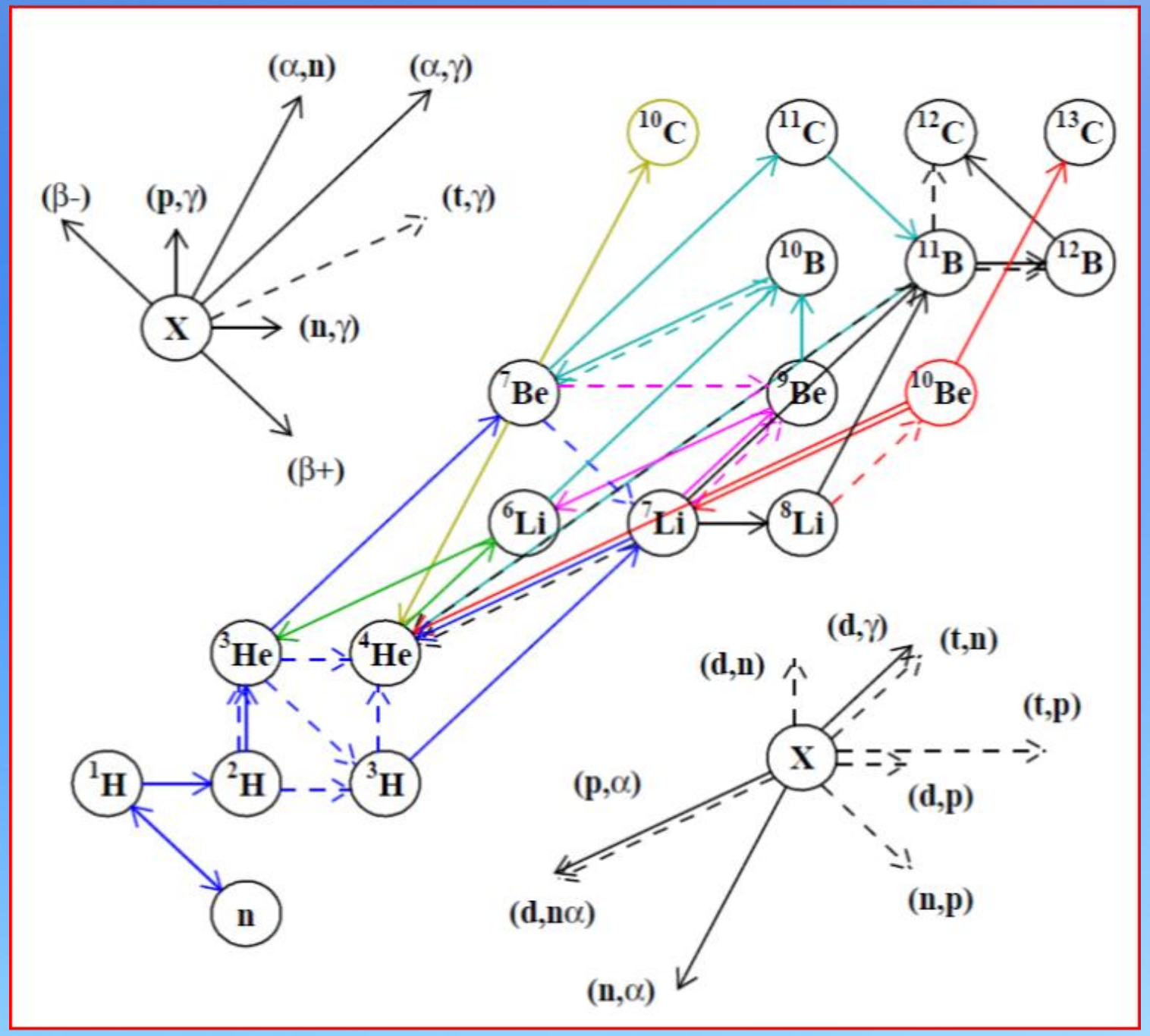


$$p + e^- \longleftrightarrow n + \nu_e$$

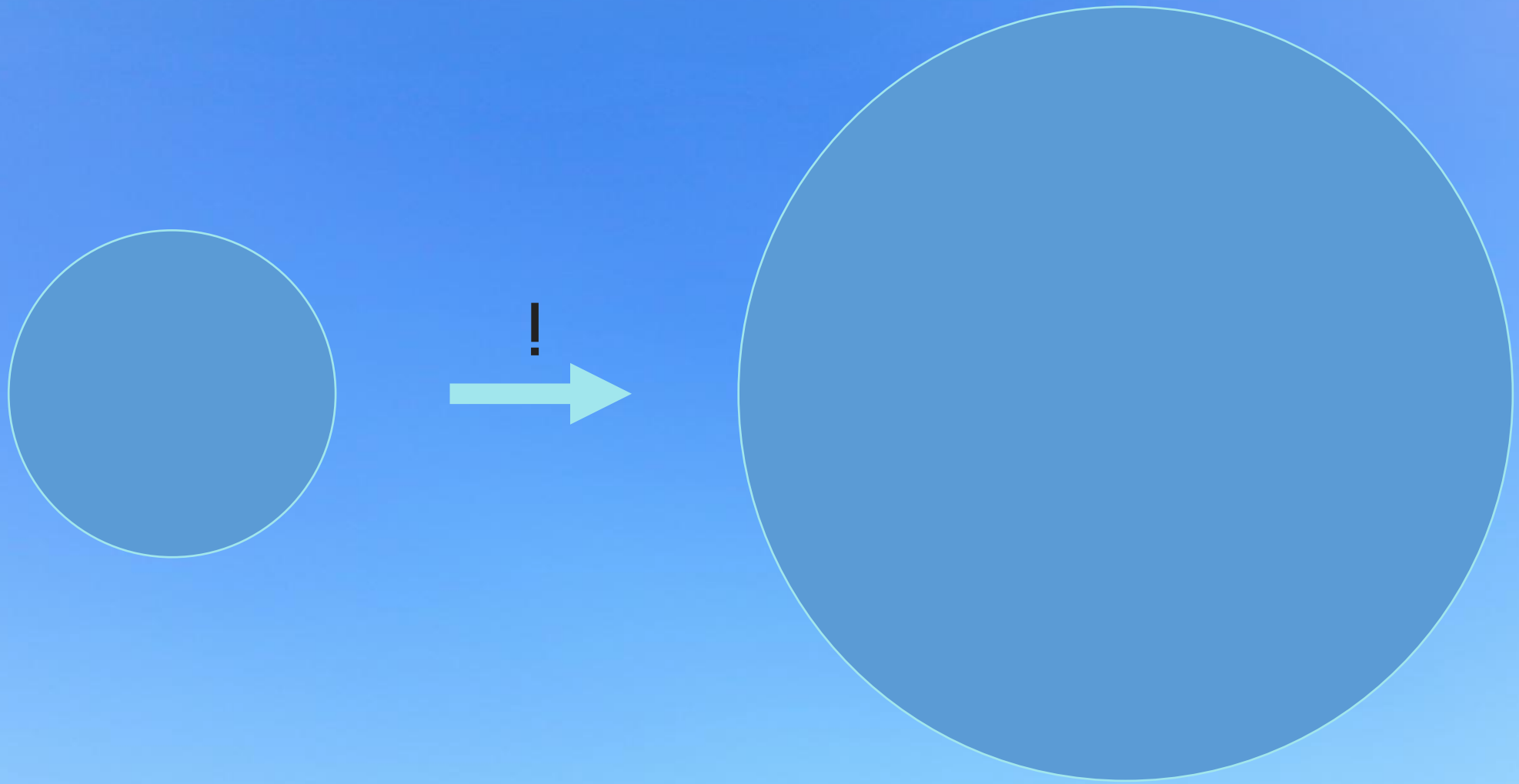
$$n \longrightarrow p + e^- + \bar{\nu}_e$$

$$n/p \approx e^{-\Delta m/kT}$$

Цепочка ядерных реакций первичного нуклеосинтеза



Расширение Вселенной

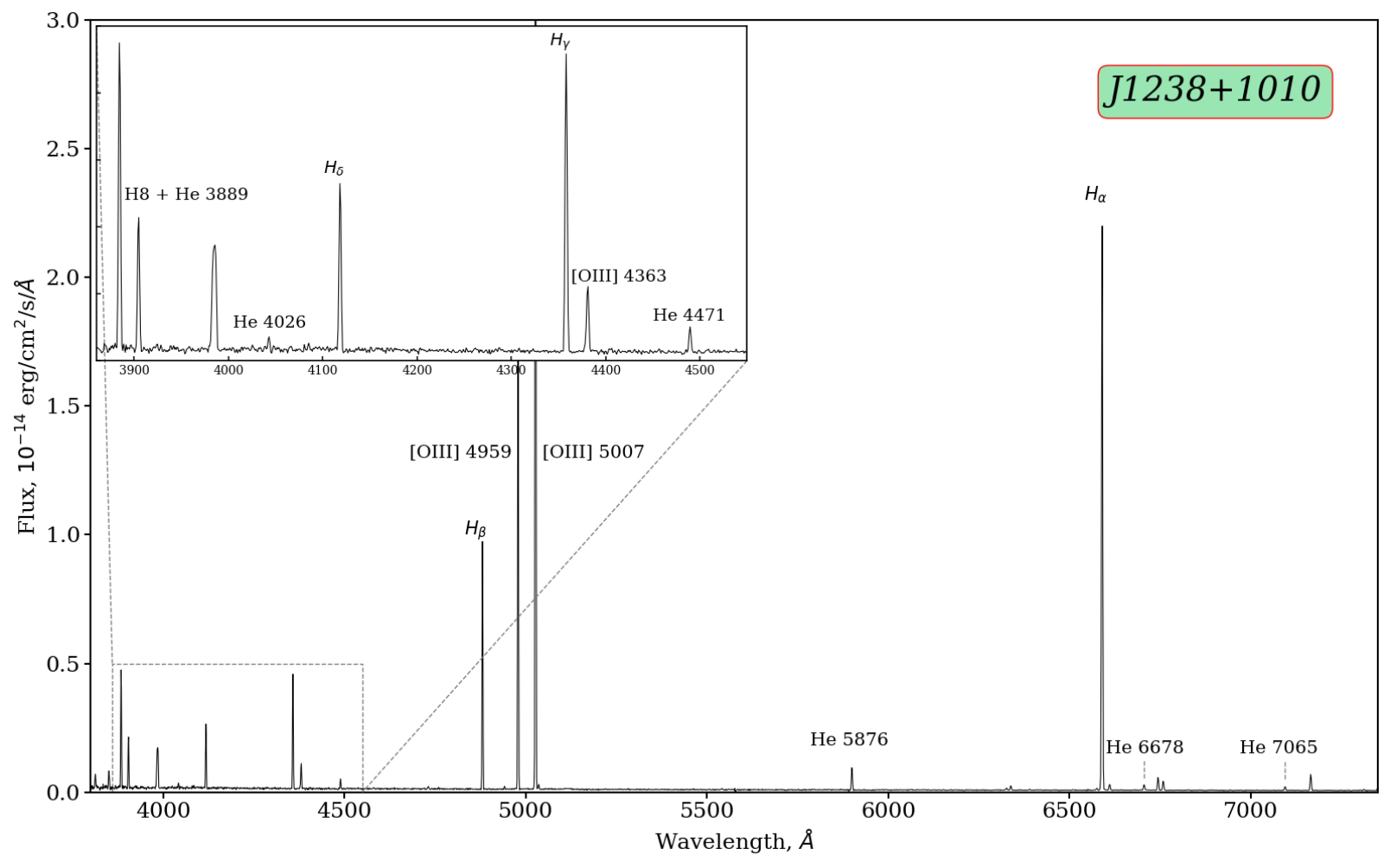


Выводы

Если вы придумали новую теорию,
то первым делом проверьте, как она сломает первичный нуклеосинтез

Дополнительные слайды

Первичный гелий

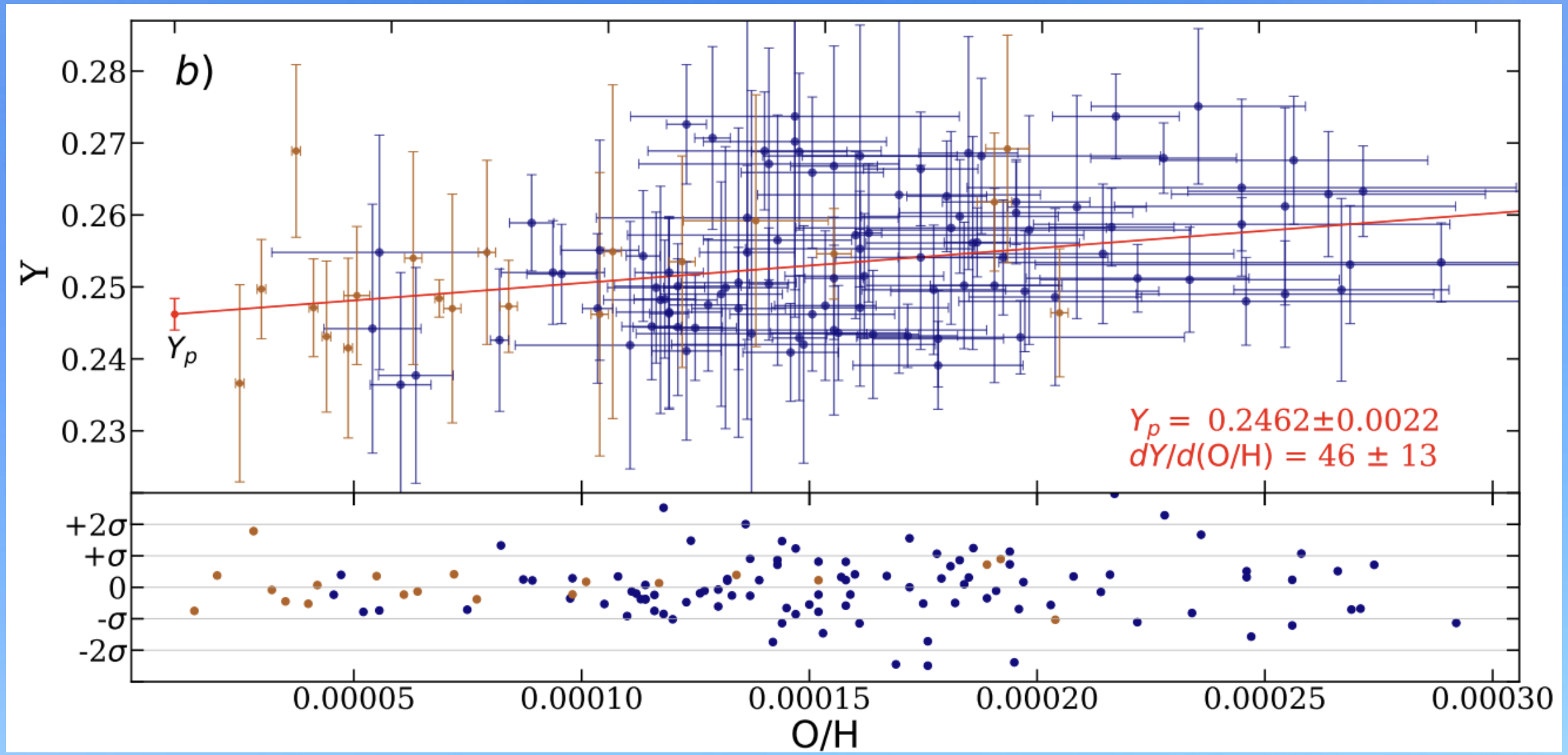


Низкометалличные карликовые галактики

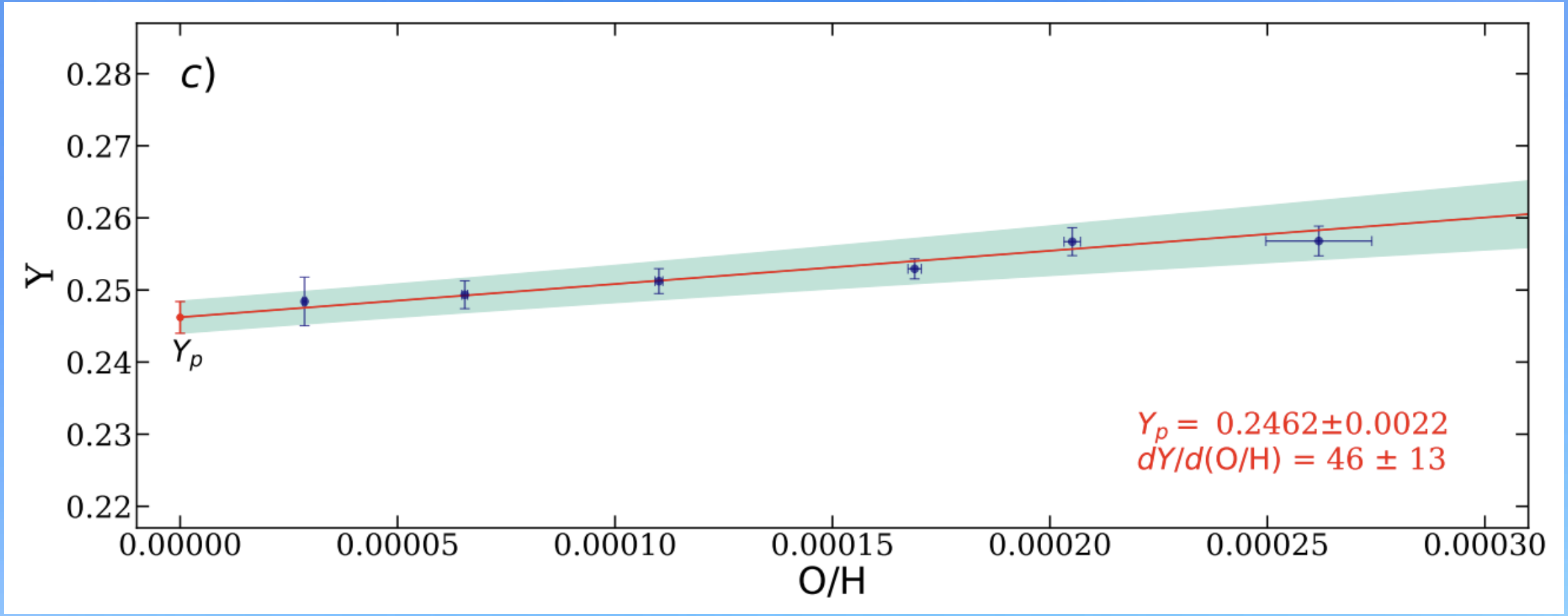
$z \lesssim 0.2$

https://arxiv.org/pdf/2101.09127
https://arxiv.org/pdf/2201.06431

Оценки He/H



Оценки He/H

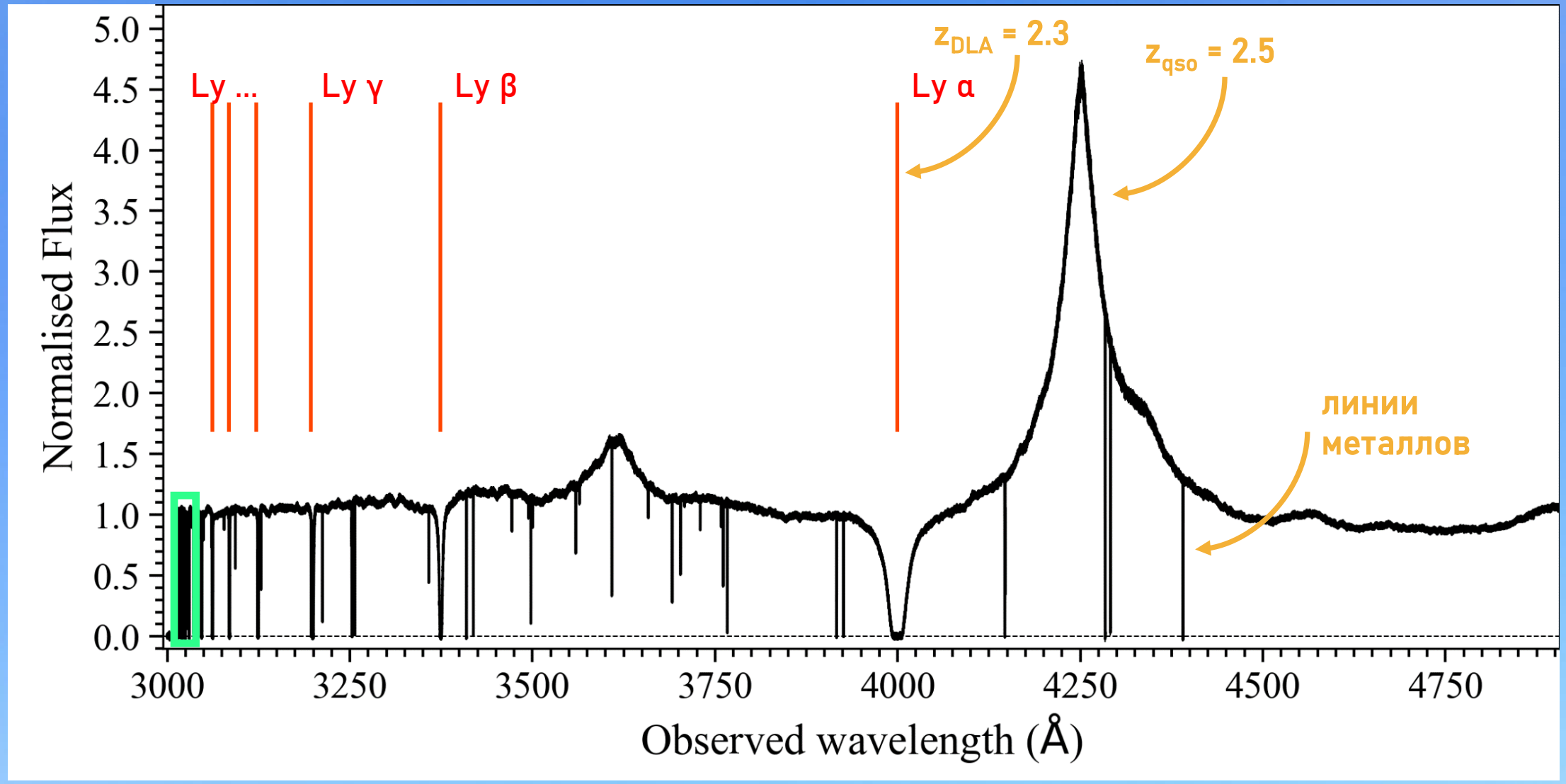

c)
0.28
0.27
0.26
0.25
0.24
0.23
0.22
Y
Y_p
Y_p = 0.2462±0.0022
dY/d(O/H) = 46 ± 13
0.00000
0.00005
0.00010
0.00015
0.00020
0.00025
0.00030
O/H

Оценки He/H

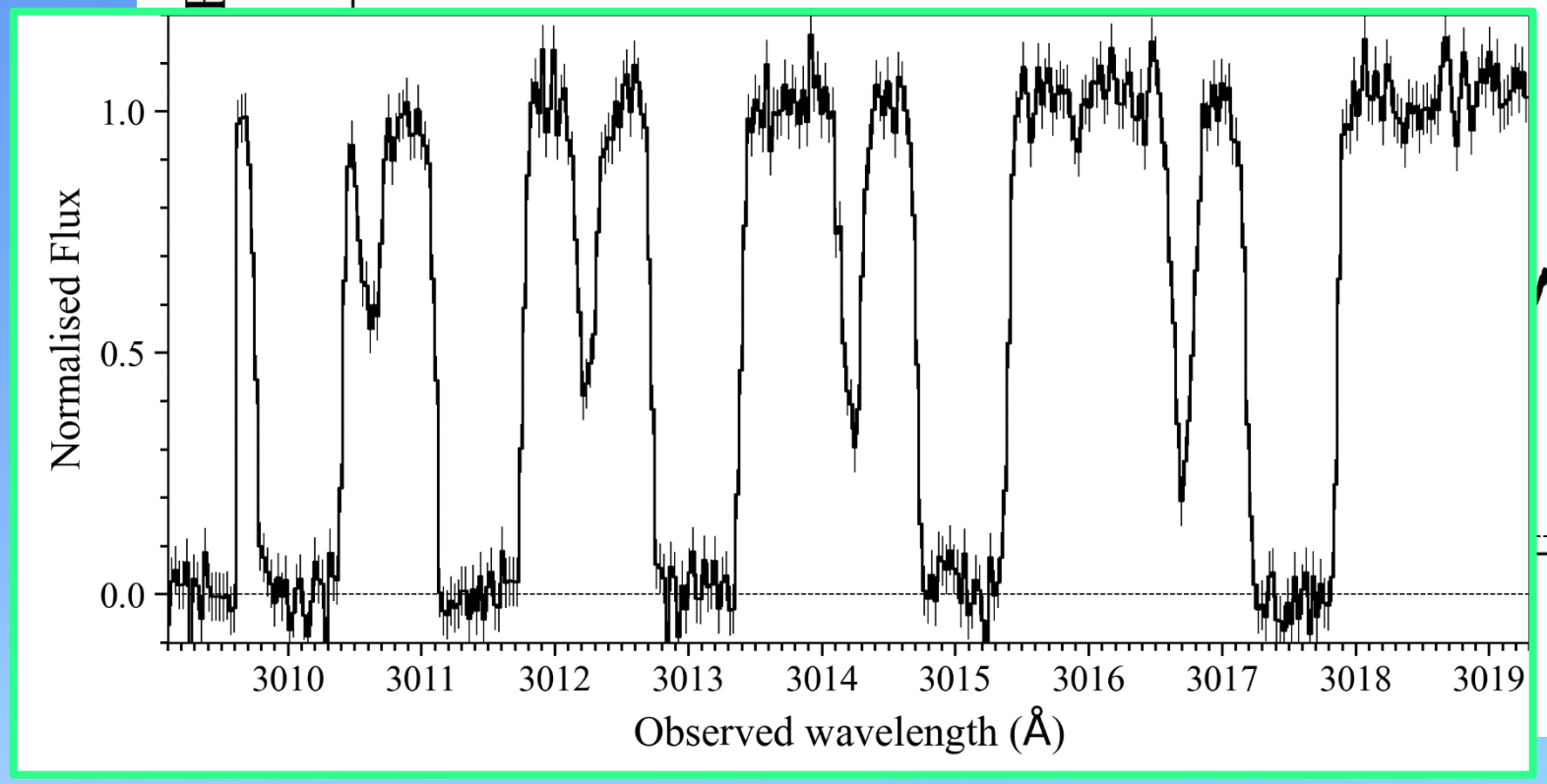
$$\frac{F(\lambda)}{F(H\beta)} = y^{+} \frac{E(\lambda)}{E(H\beta)} \frac{\frac{W(H\beta)+a_H(H\beta)}{W(H\beta)}}{\frac{W(\lambda)+a_{He}(\lambda)}{W(\lambda)}} f_\tau(\lambda) \frac{1}{1+\frac{C}{R}(H\beta)} 10^{-f(\lambda)C(H\beta)}$$

$$\frac{F(\lambda)}{F(H\beta)} = \frac{E(\lambda)}{E(H\beta)} \frac{\frac{W(H\beta)+a_H(H\beta)}{W(H\beta)}}{\frac{W(\lambda)+a_H(\lambda)}{W(\lambda)}} \frac{1+\frac{C}{R}(\lambda)}{1+\frac{C}{R}(H\beta)} 10^{-f(\lambda)C(H\beta)}$$

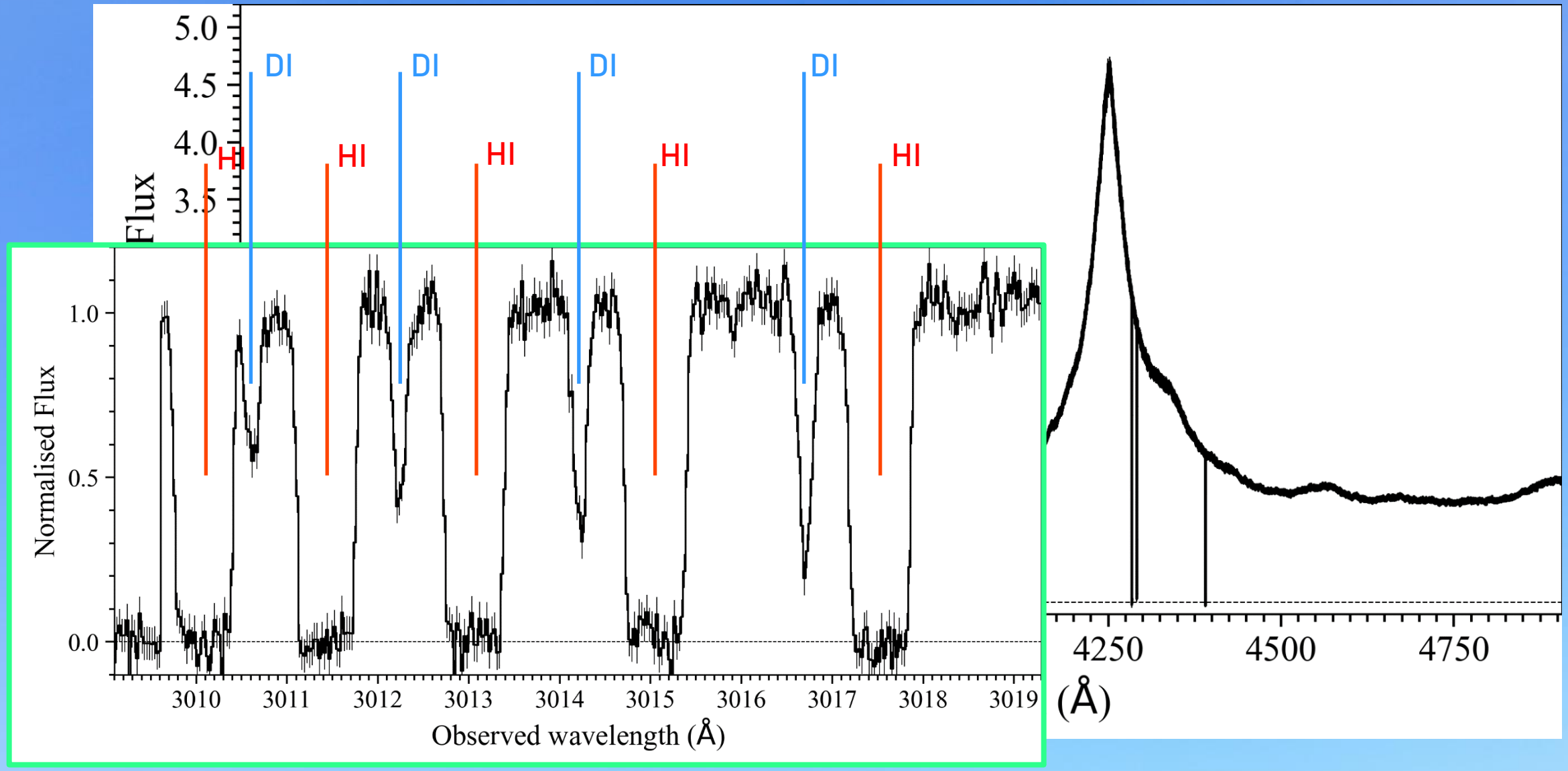
Измерения D/H



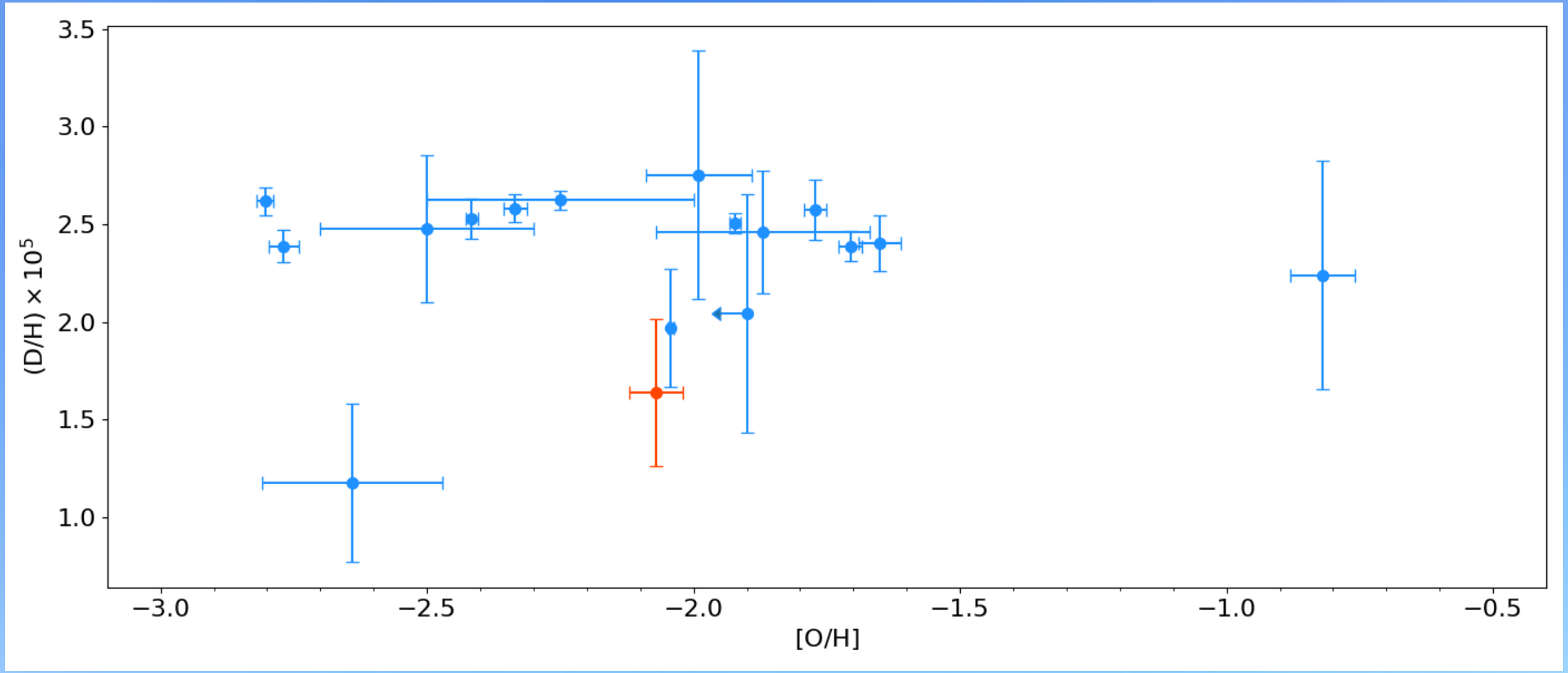
Измерения D/H



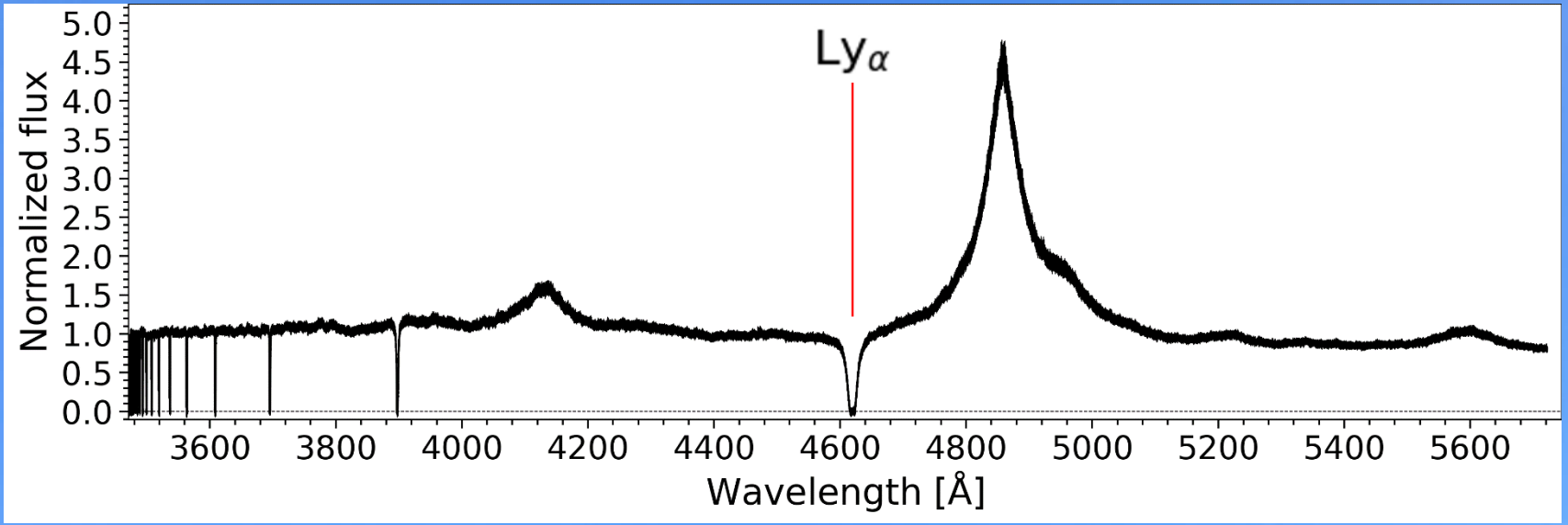
Измерения D/H

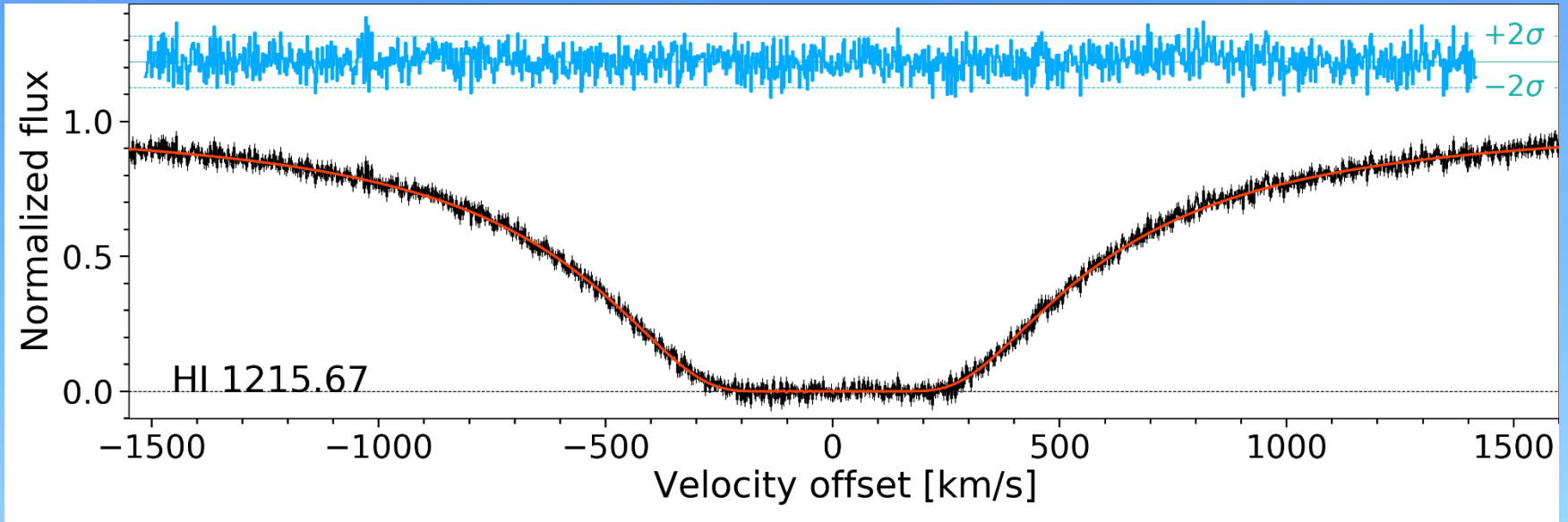


Измерения D/H

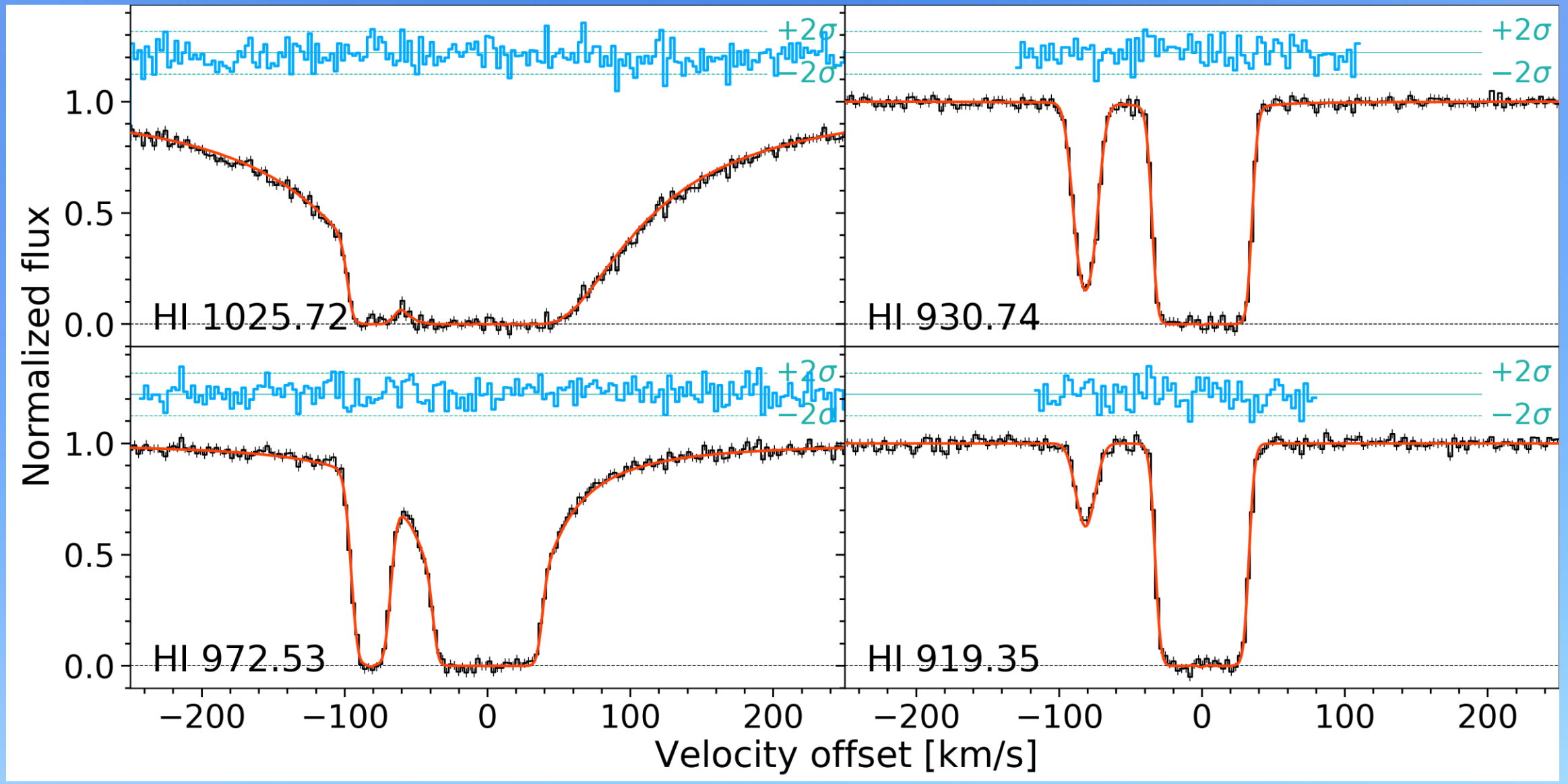


Идеальный случай

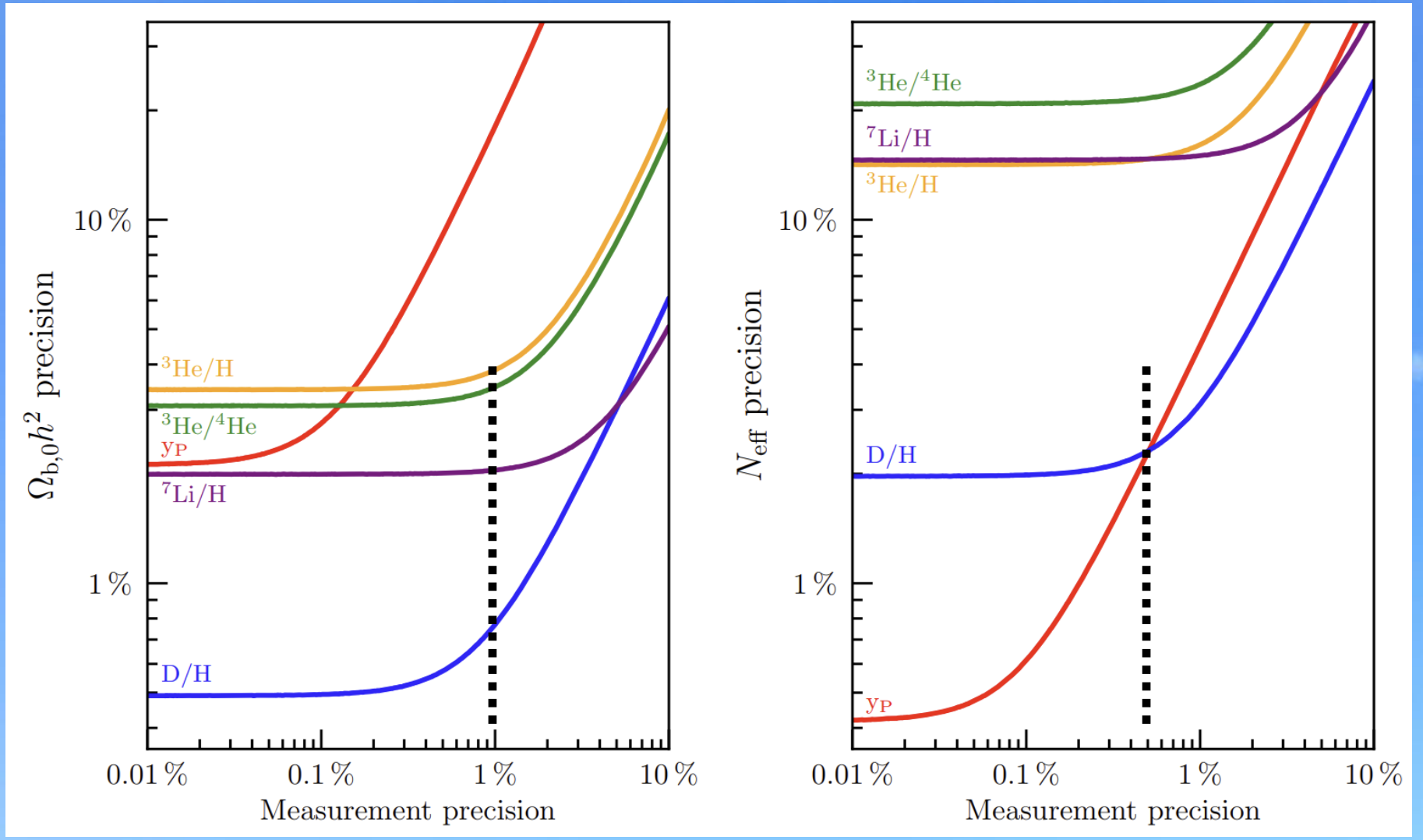




Идеальный случай



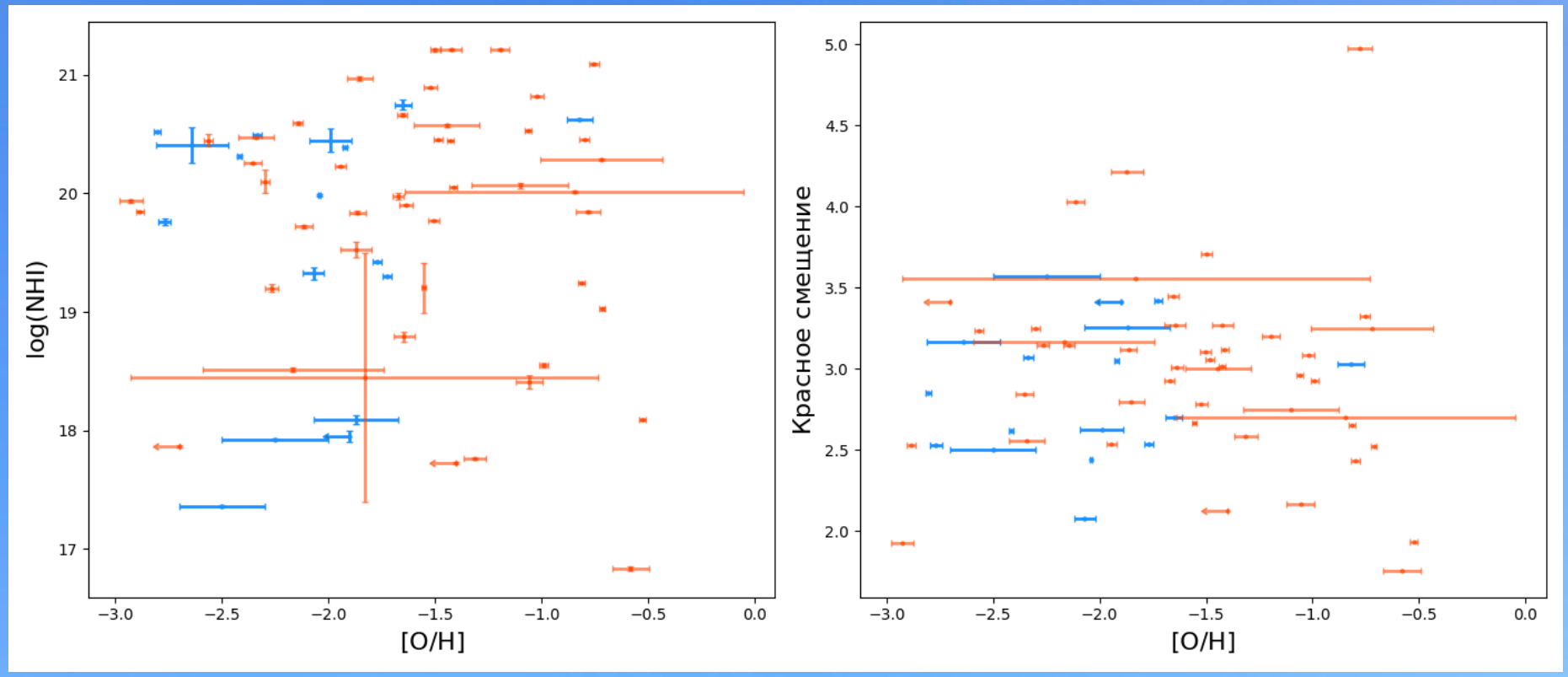
Современные наблюдения



R. Cooke, https://arxiv.org/pdf/2409.06015

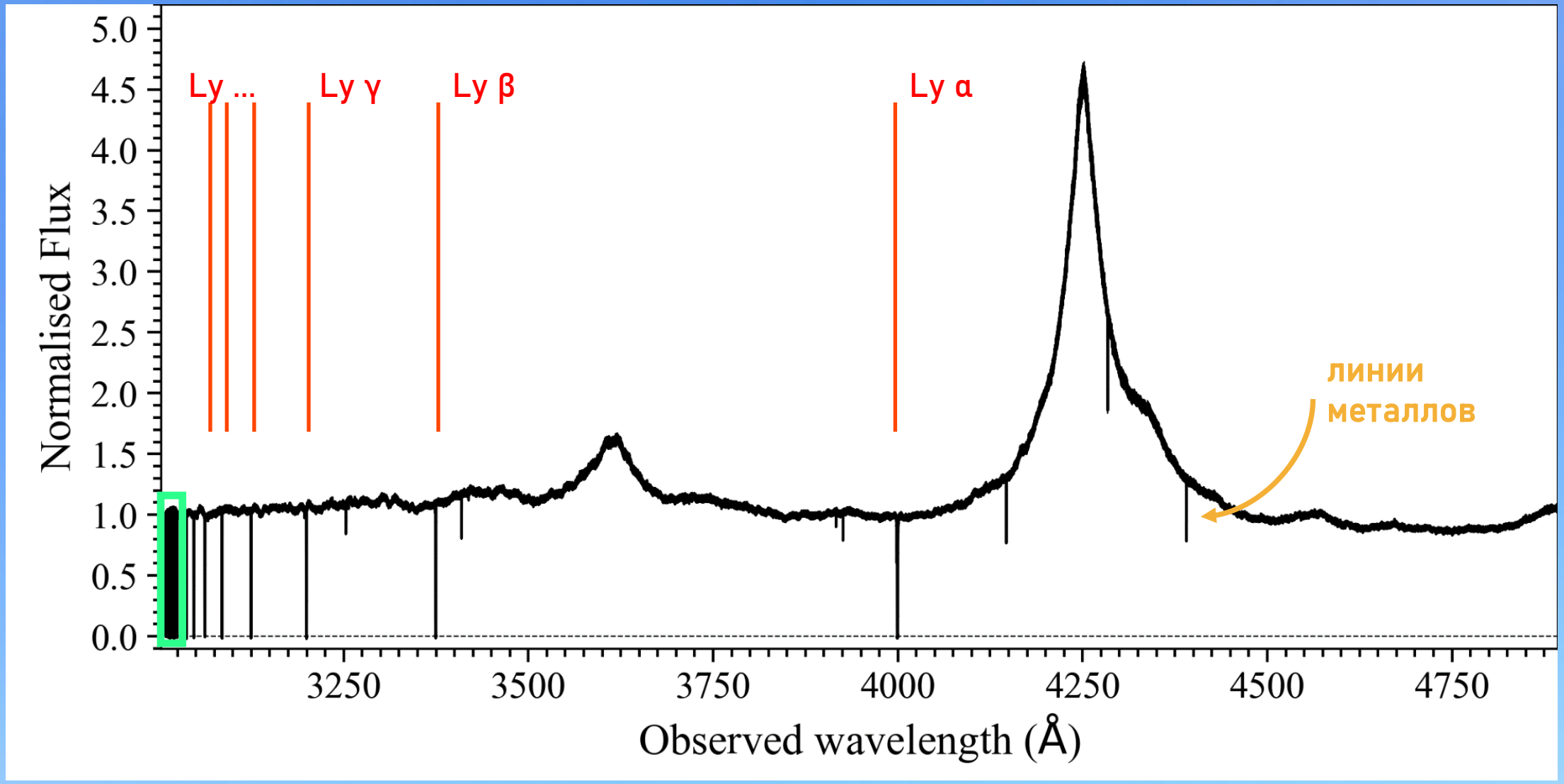
Новые оценки D/H

767 спектров SQUAD +KODIAQ

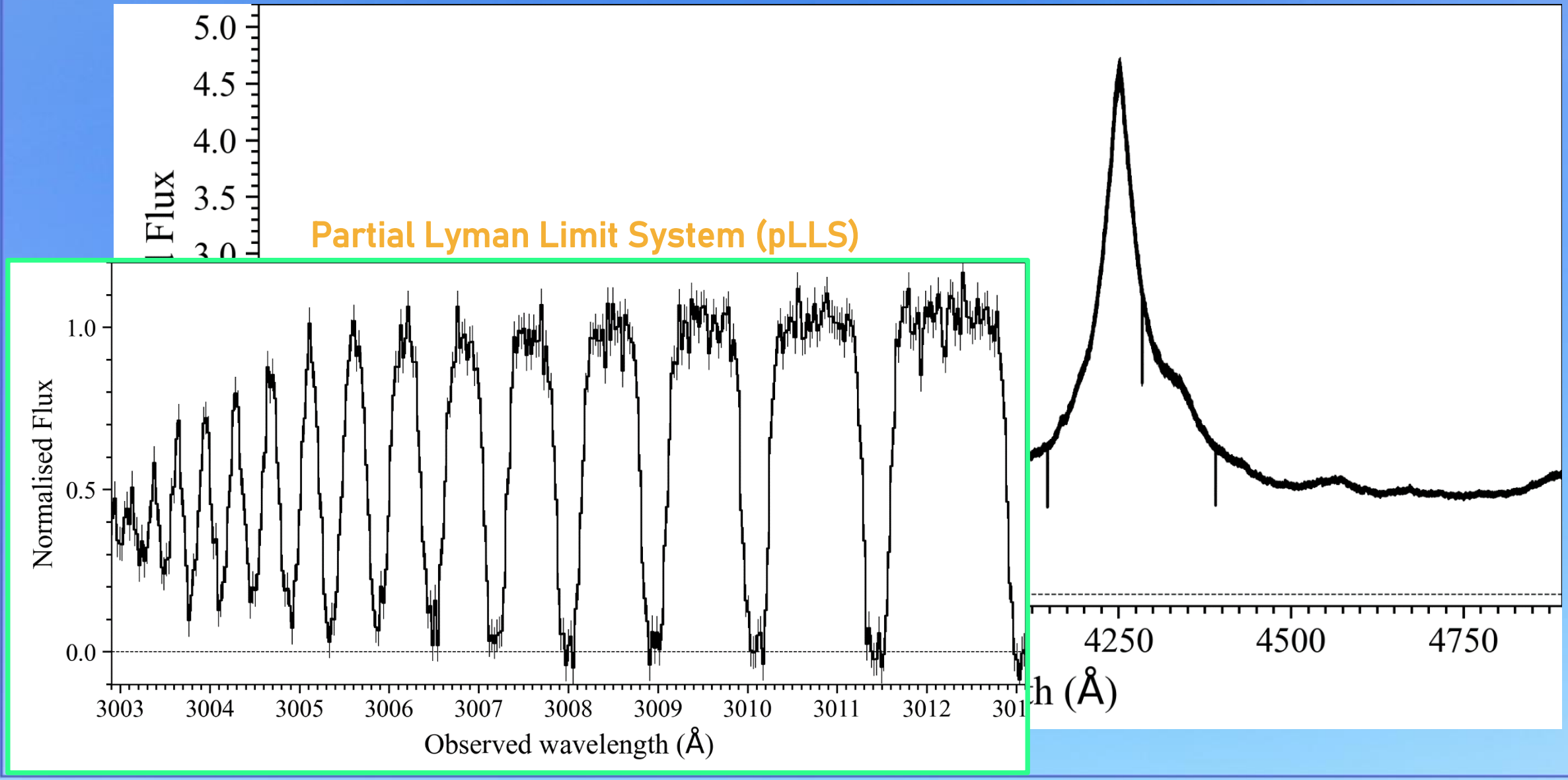



```
...
J004216-333754 wavelengths > 3300 DLA NHI=20.729+-0.013 z=2.2238271
J010311+131617 wavelengths > 3300 high s/n DLA NHI=21.362+-0.005 z=2.3090804418 metSi=-1.368+-0.008 very clear structure
J094202+042244 z=2.3067138 possible D/H if wavelengths down to 3000
J143500+535953 wavelengths > 3500 DLA NHI=21.074+-0.003 z=2.3426859407
...
```

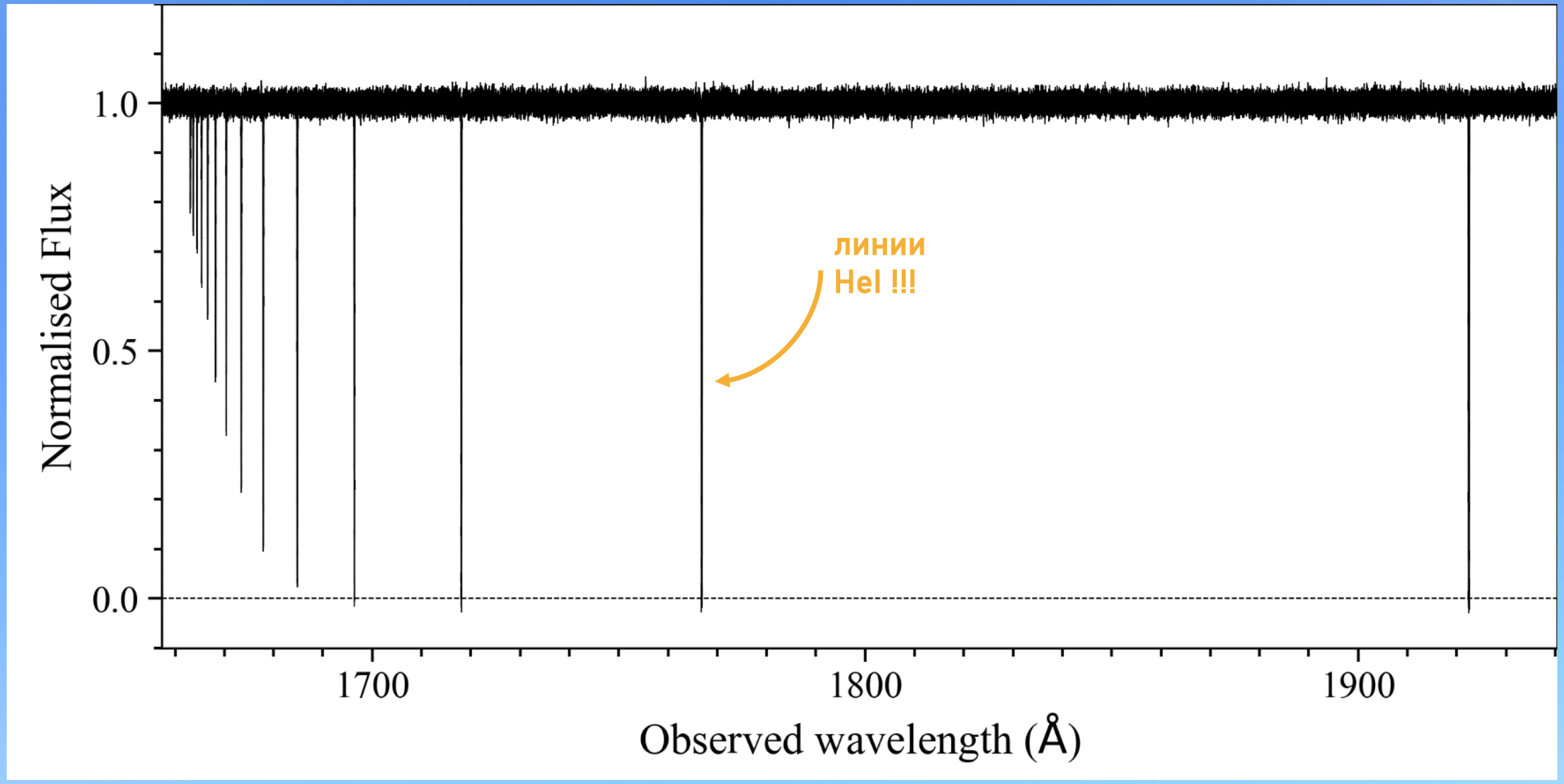
Или...


Ly ...
Ly γ
Ly β
Ly α
линии металлов
Normalised Flux
5.0
4.5
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
3250
3500
3750
4000
4250
4500
4750
Observed wavelength (Å)

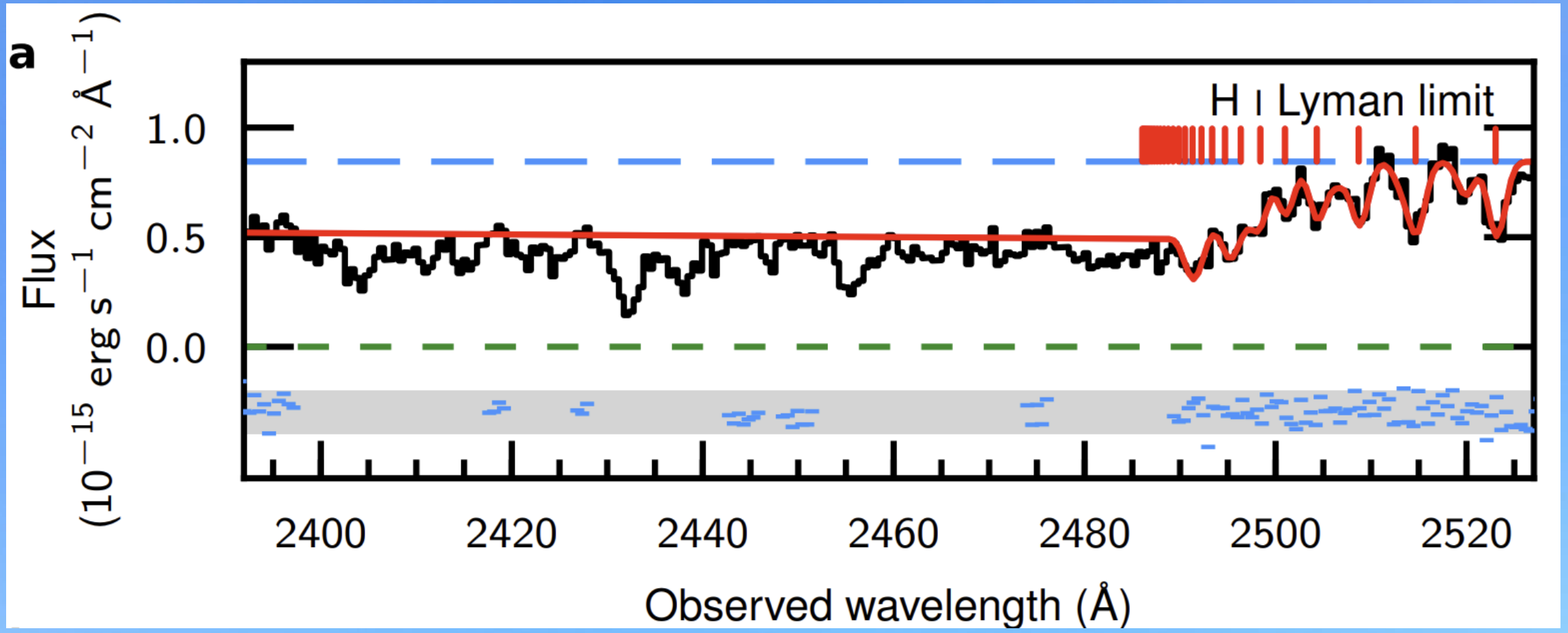
...


Partial Lyman Limit System (pLLS)
Normalised Flux
1.0
0.5
0.0
3003
3004
3005
3006
3007
3008
3009
3010
3011
3012
Observed wavelength (Å)
5.0
4.5
4.0
3.5
4250
4500
4750
h (Å)

Линии HeI

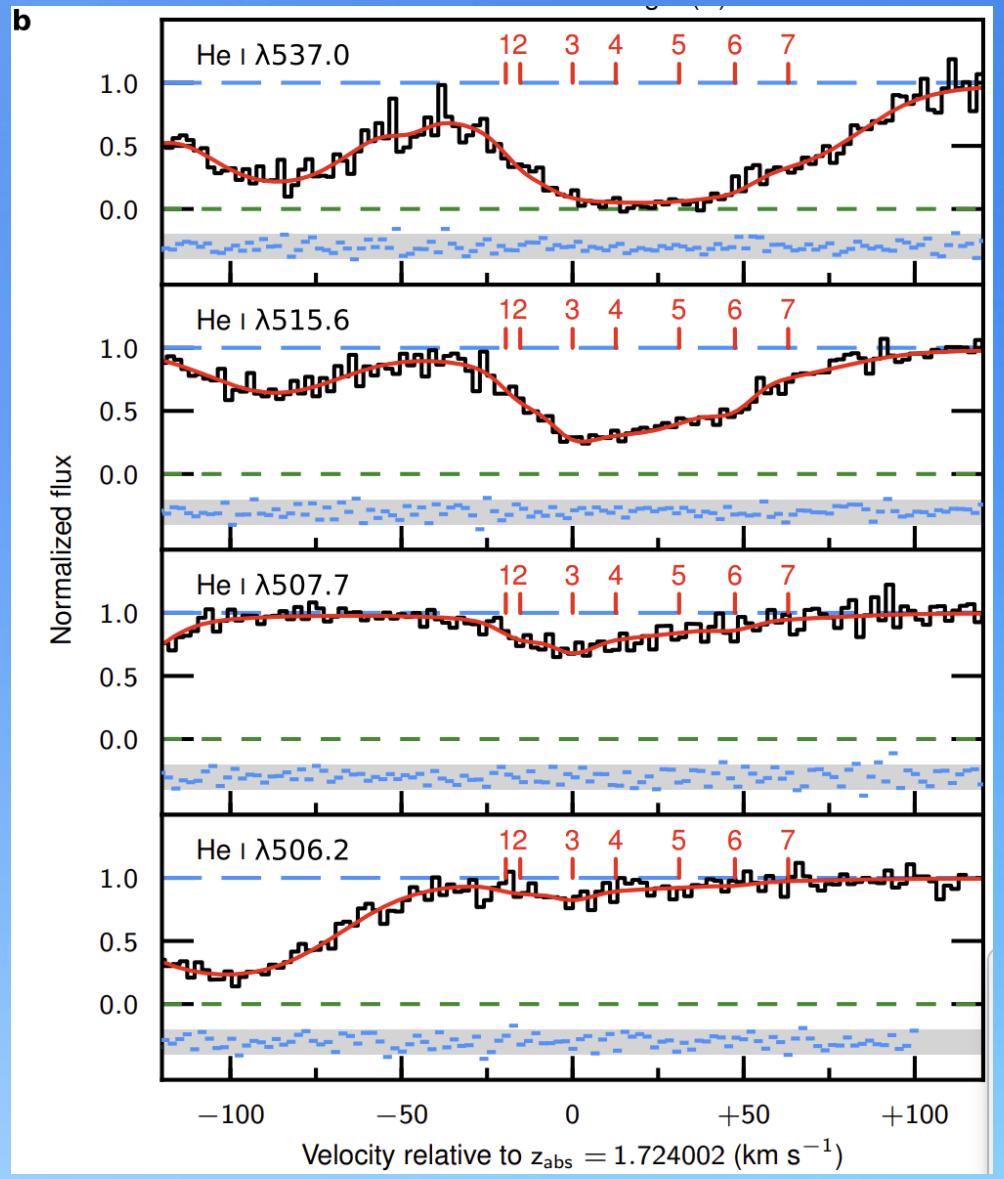

1.0
0.5
0.0
Normalised Flux
1700
1800
1900
Observed wavelength (Å)
линии
HeI !!!

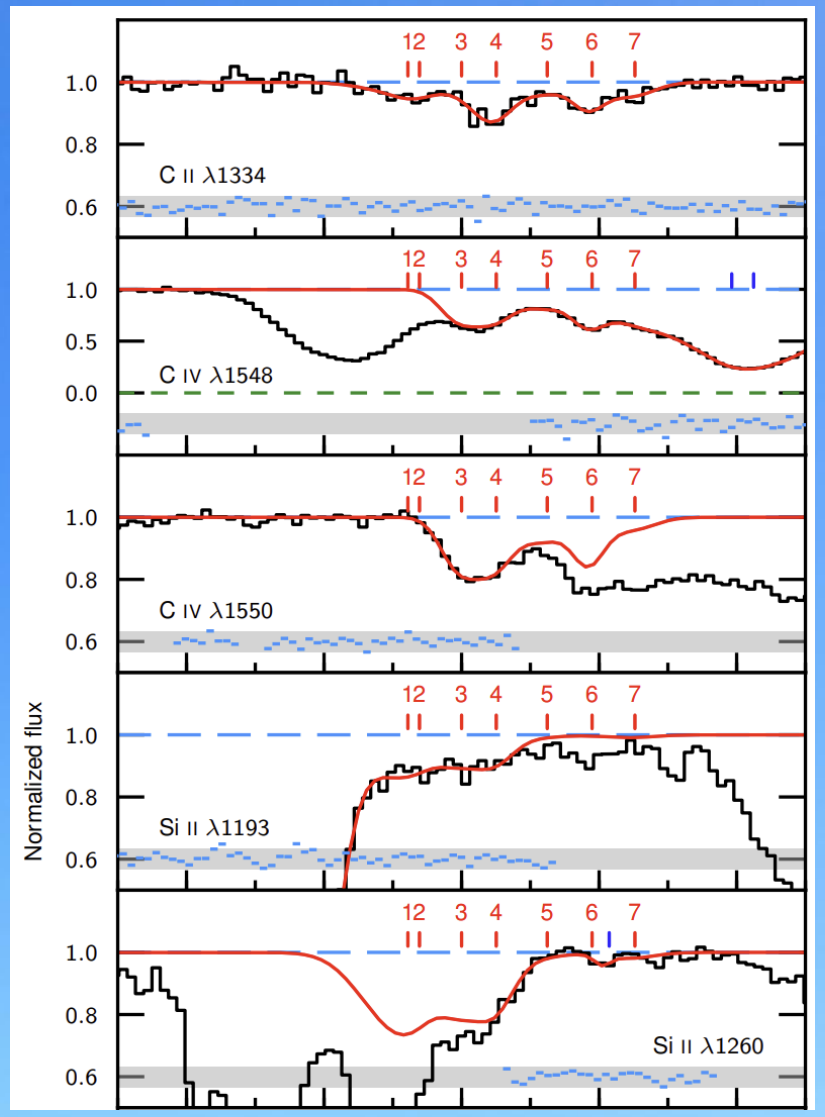
Оценки распространенности He/H



Cooke et al. 2018,https://arxiv.org/pdf/1810.06561

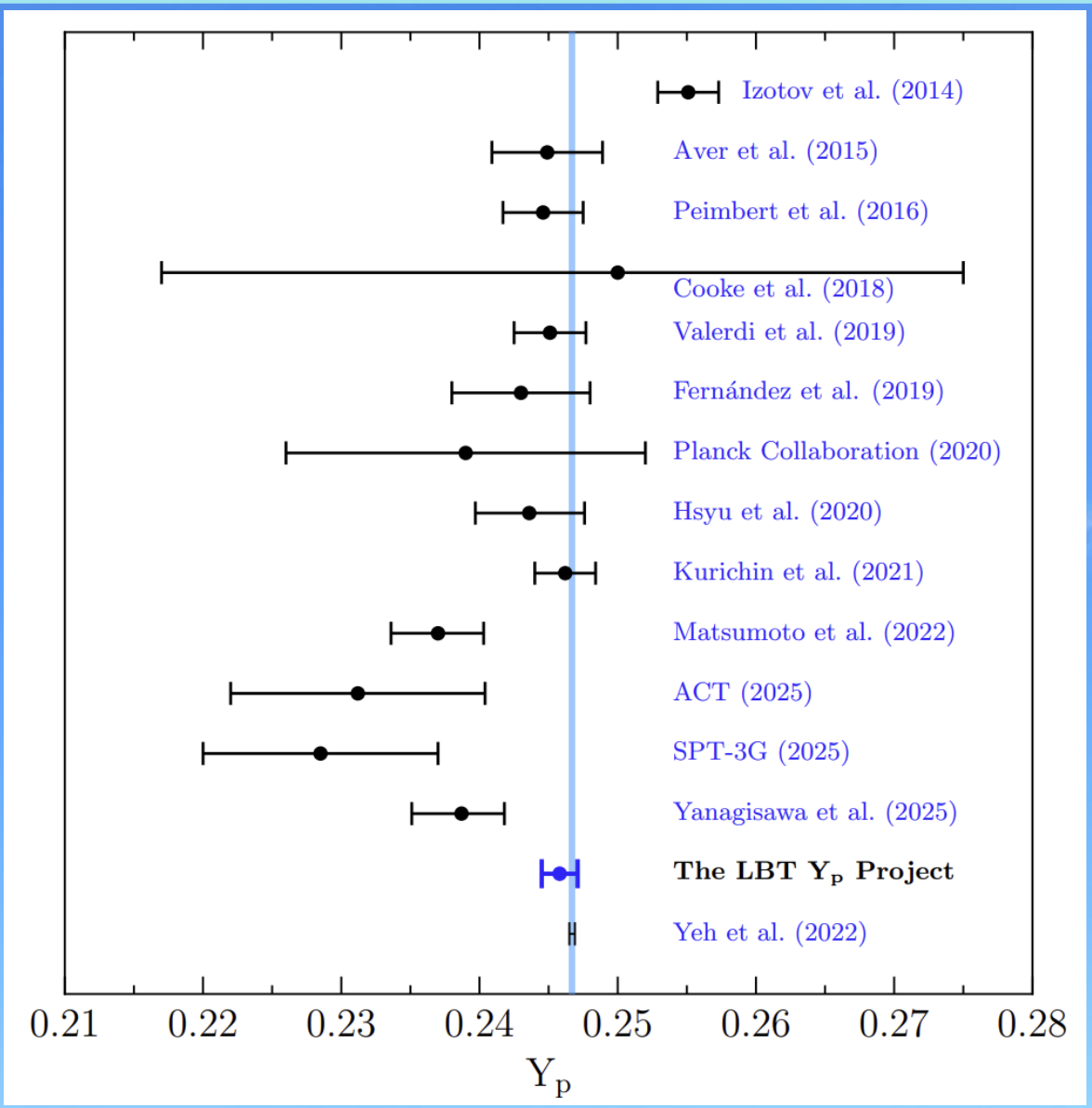
Оценки распространенности He/H





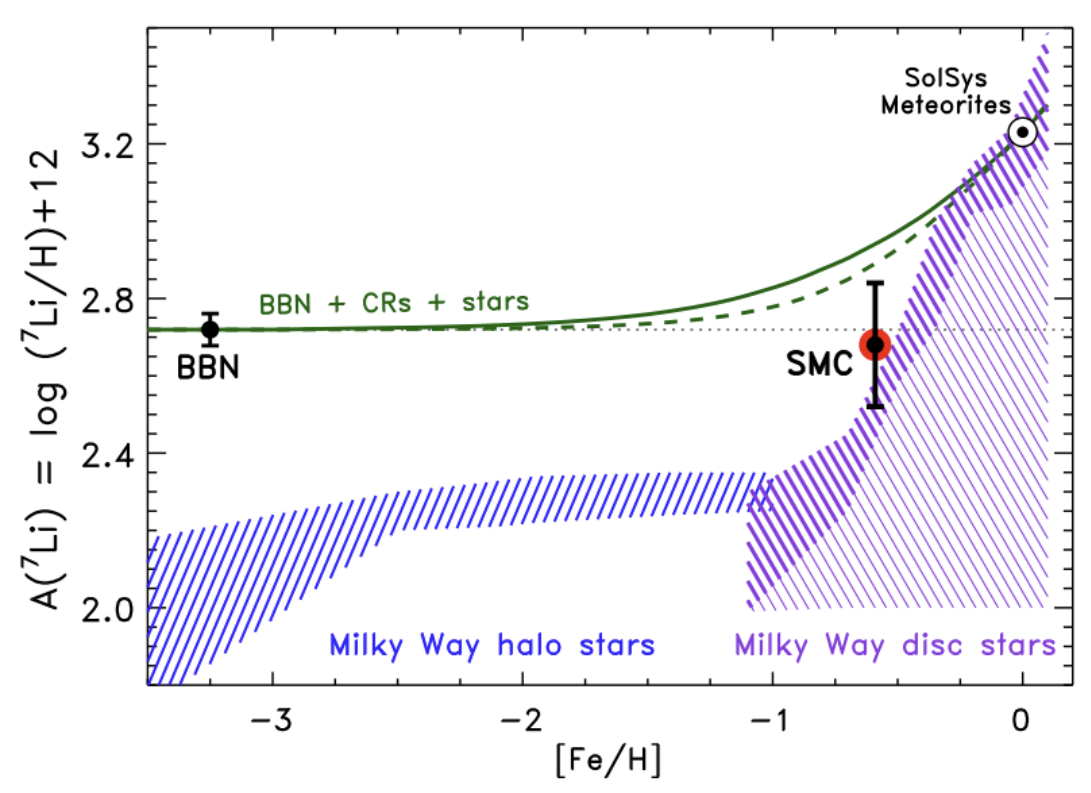
Cooke et al. 2018, https://arxiv.org/pdf/1810.06561

Оценки распространенности He/H

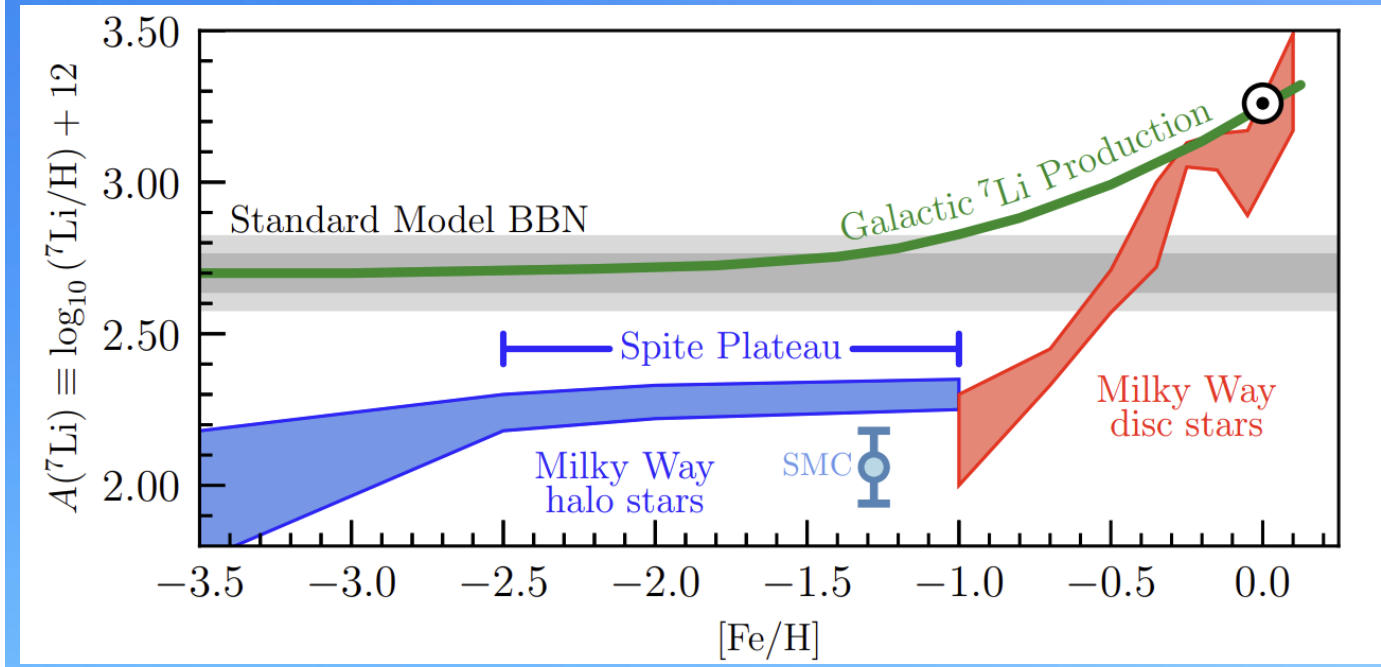


Aver et al. 2026
https://arxiv.org/pdf/2601.22238

Оценки распространенности первичного Li



Howk et al. 2012, https://arxiv.org/pdf/1207.3081



Cooke 2024, https://arxiv.org/pdf/2409.06015
based on Molaro et al. 2024 https://arxiv.org/pdf/2407.10818

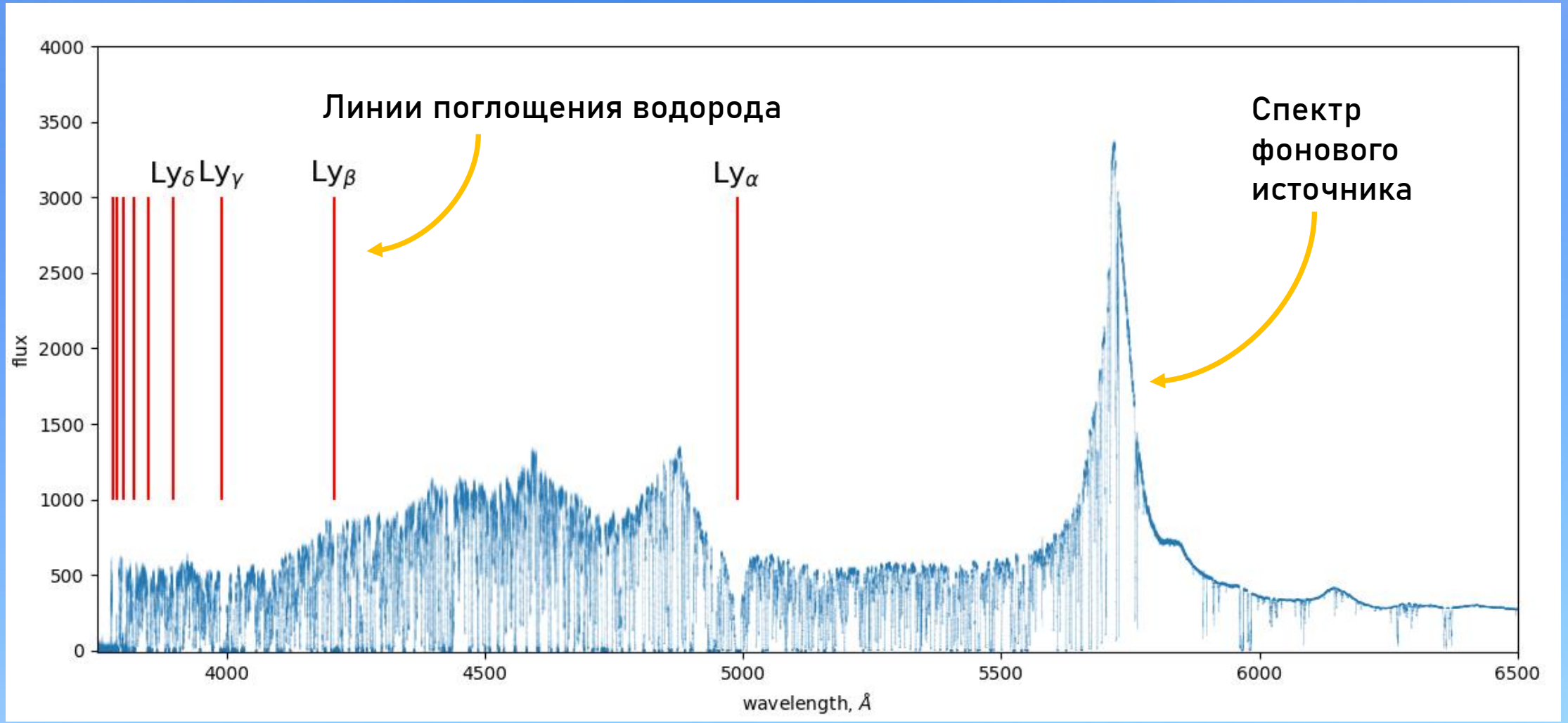
Новые оценки распространенности первичного Li

z_{DLA} = 0.3 – 0.5 => HI, H2, HD? В спектр УФ

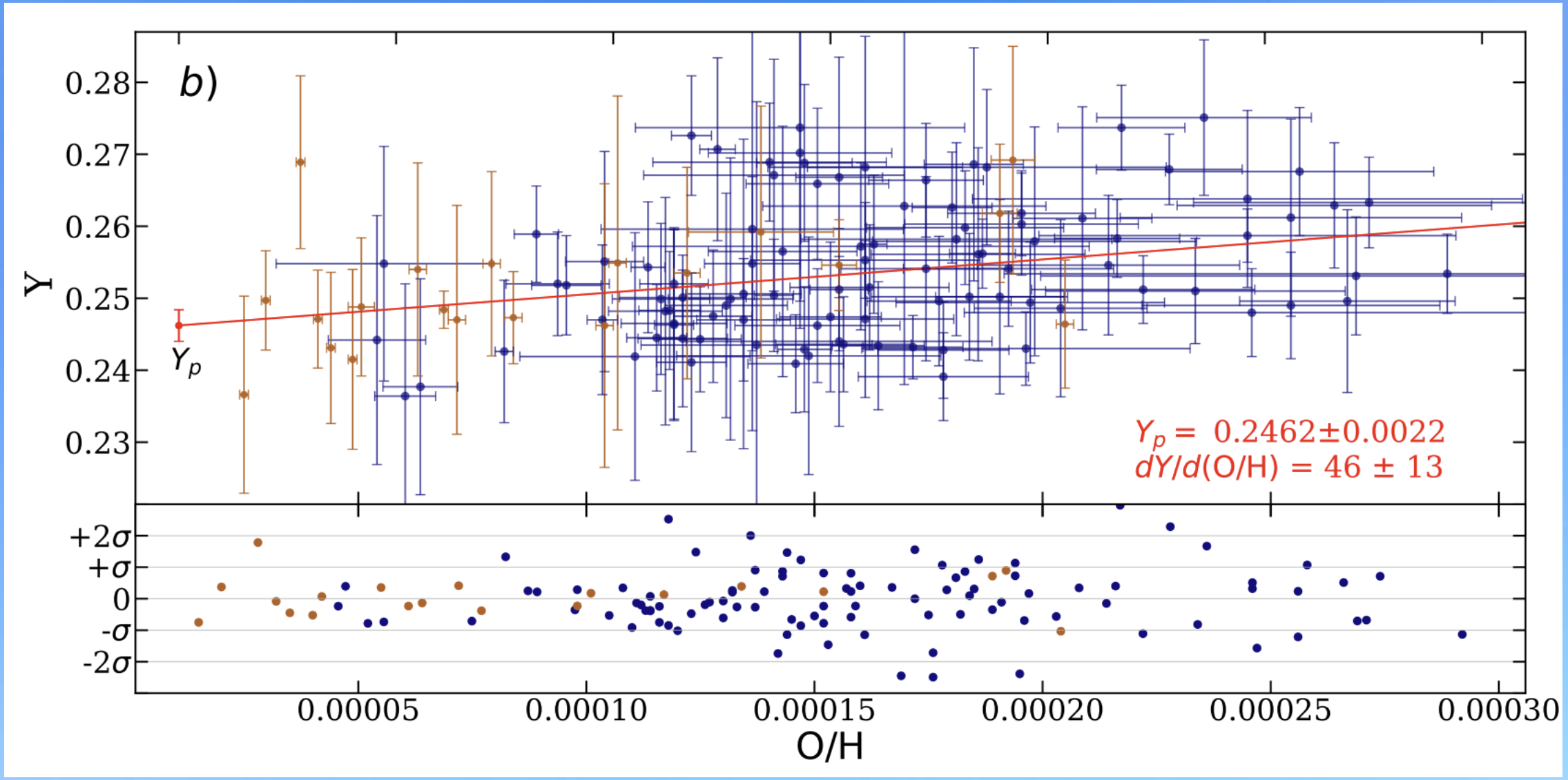
LiI В спектре UVES/ESPRESSO

[Fe/H] < -1 => Li/H = Li/H_{Pr}

Источники информации



Оценки распространенности первичного ^{4}He



Непростая систематика ^{4}He

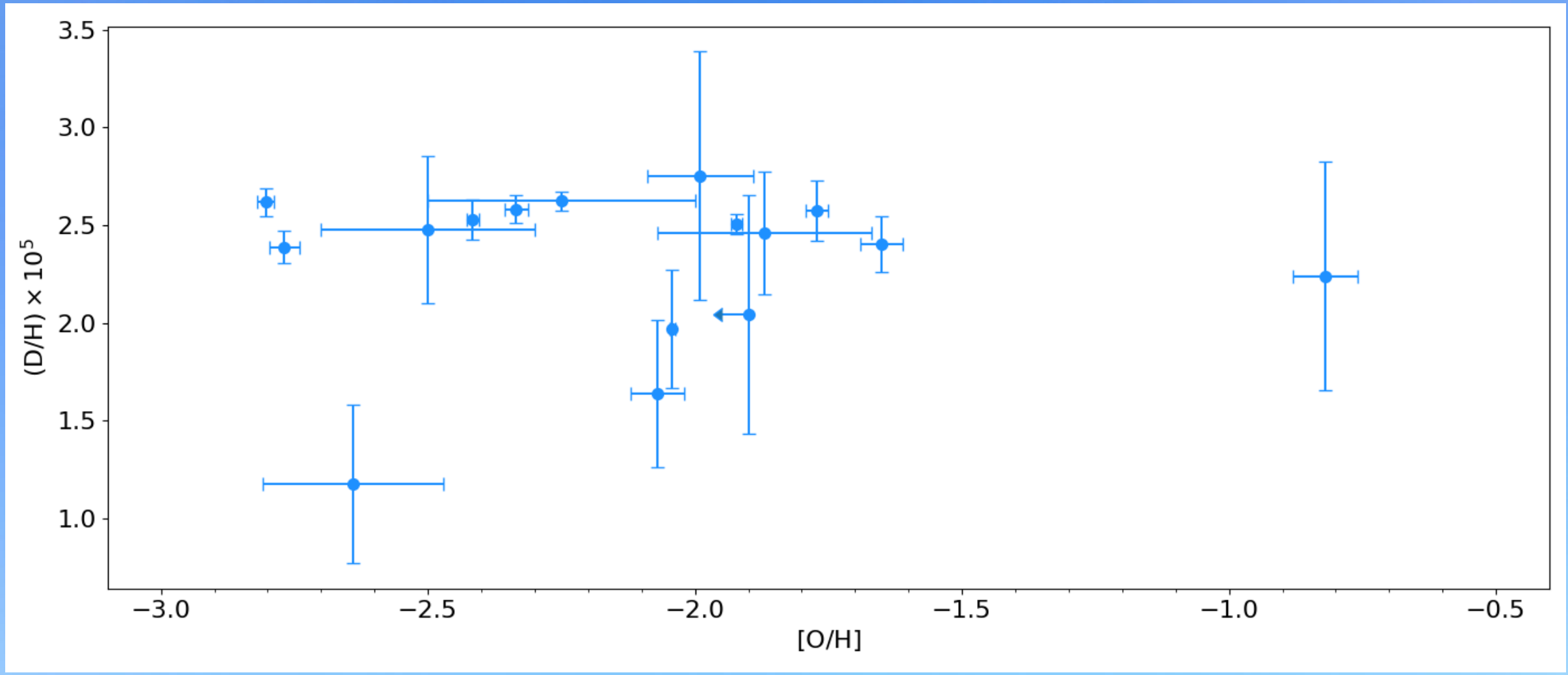
Helium emission lines:

$$\underbrace{\frac{F(\lambda)}{F(\mathrm{H}\beta)}}_{\text{flux ratio}} = \underbrace{\frac{n(\mathrm{He}^+)}{n(\mathrm{H}^+)}}_{\mathrm{He}^+\text{ abundance}} \times \underbrace{\frac{E(\lambda)}{E(\mathrm{H}\beta)}}_{\text{emissivity}} \times \underbrace{\frac{1 + a_{\mathrm{H}}(\mathrm{H}\beta)/EW(\mathrm{H}\beta)}{1 + a_{\mathrm{He}}(\lambda)/EW(\lambda)}}_{\text{stellar absorption}} \times \underbrace{\frac{1 + CR(\lambda)}{1 + CR(\mathrm{H}\beta)}}_{\text{collisional correction}} \times \underbrace{10^{-f(\lambda)\,c(\mathrm{H}\beta)}}_{\text{reddening}} \times \underbrace{f_\tau(\lambda)}_{\text{optical depth}} \quad (30)$$

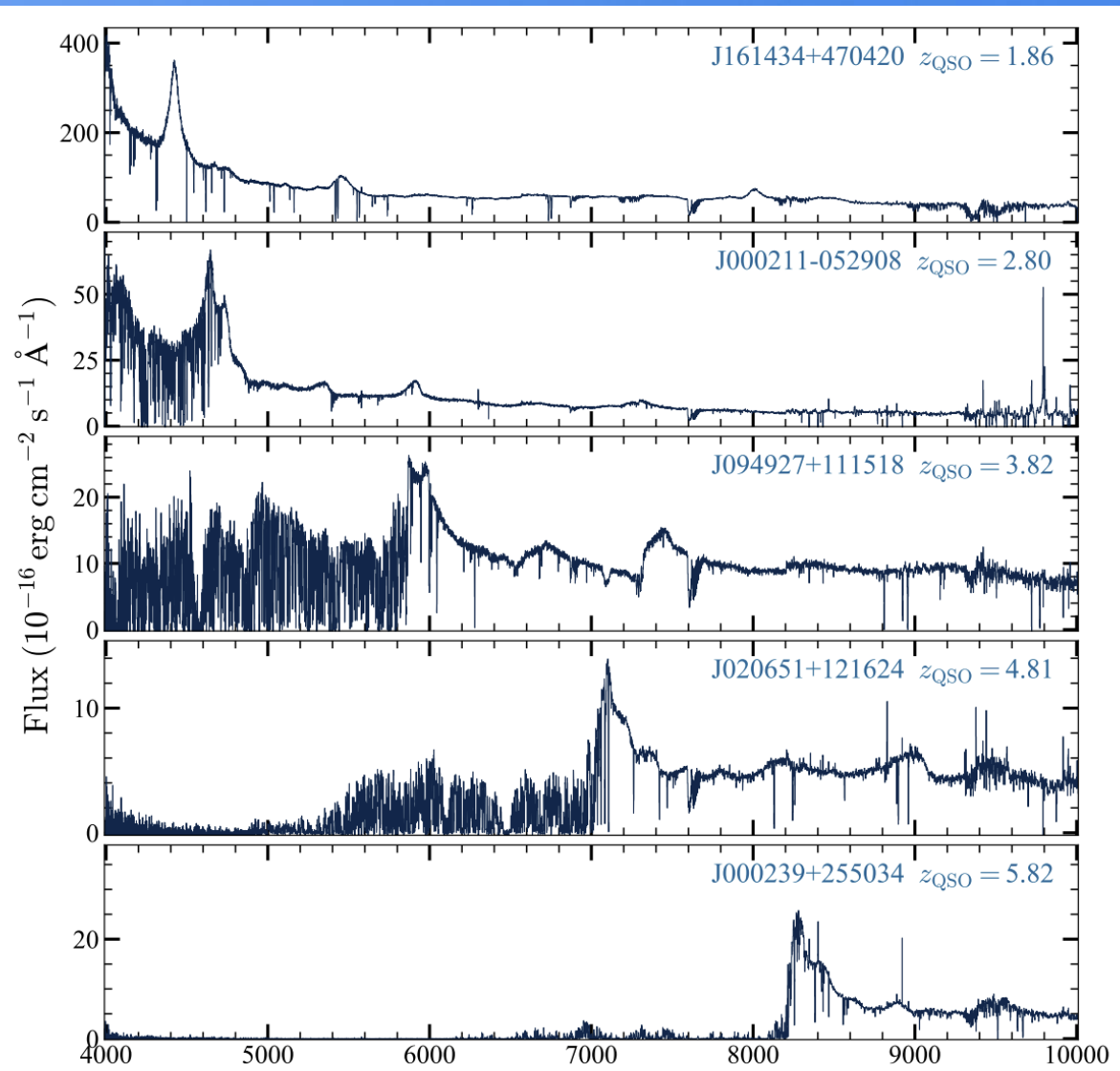
Hydrogen emission lines:

$$\frac{F(\lambda)}{F(\mathrm{H}\beta)} = \frac{E(\lambda)}{E(\mathrm{H}\beta)} \times \frac{1 + a_{\mathrm{H}}(\mathrm{H}\beta)/EW(\mathrm{H}\beta)}{1 + a_{\mathrm{H}}(\lambda)/EW(\lambda)} \times \frac{1 + CR(\lambda)}{1 + CR(\mathrm{H}\beta)} \times 10^{-f(\lambda)\,c(\mathrm{H}\beta)} \quad (31)$$

Предыдущие измерения D/H

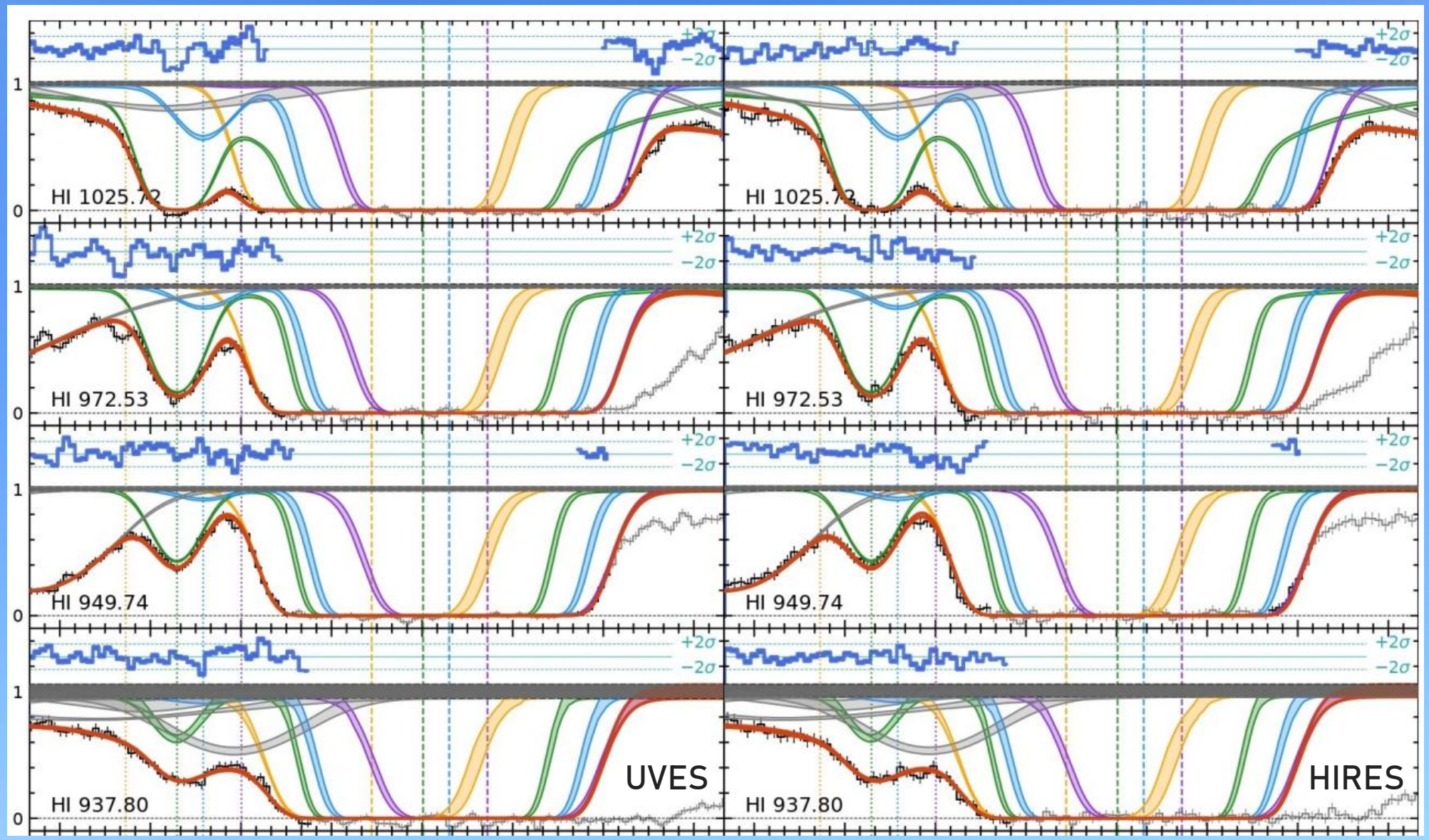


UVES / SQUAD + HIRES / KODIAQ

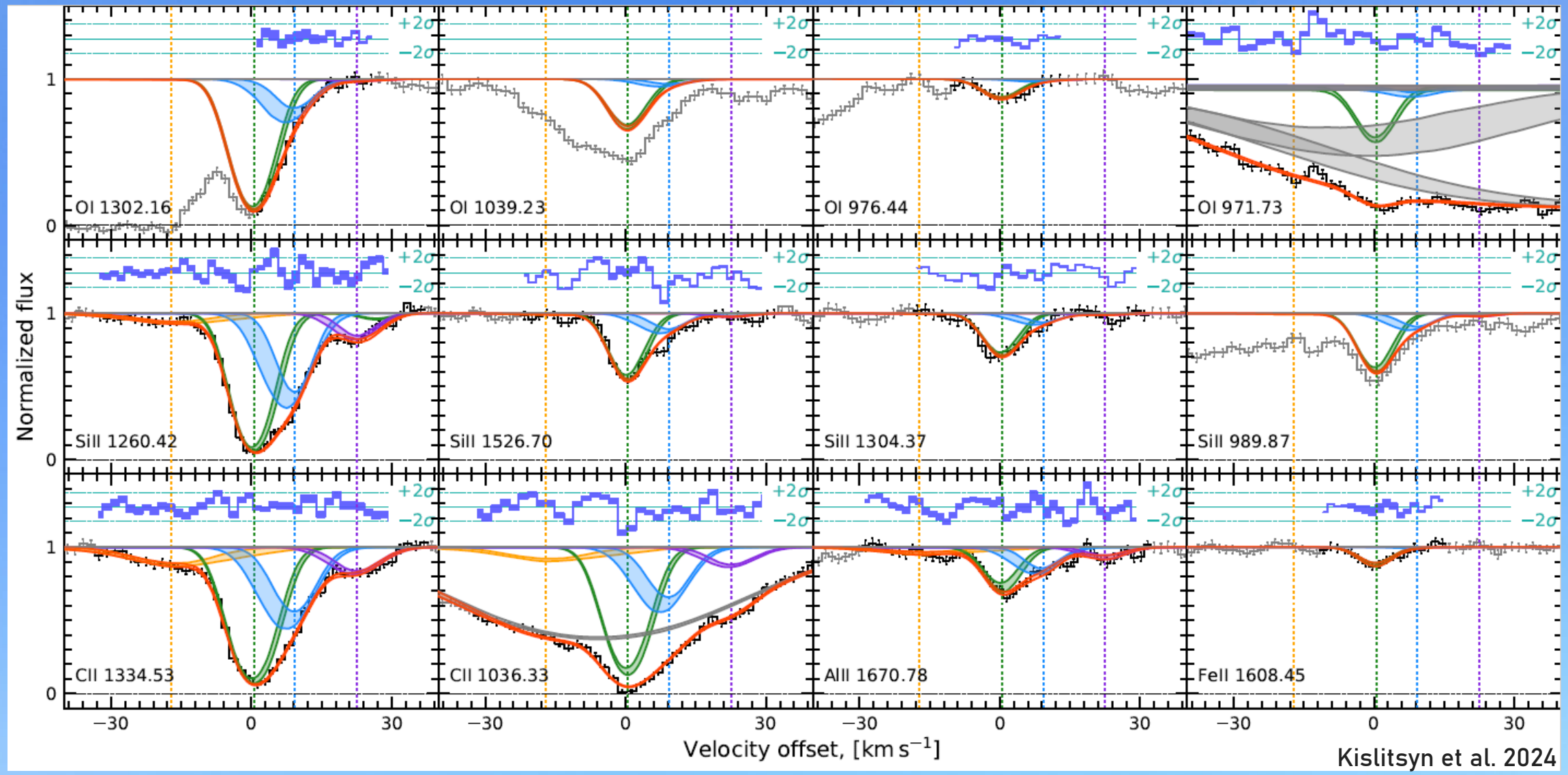


O'Meara et al. 2020
arxiv:2010.09061

Линии DI

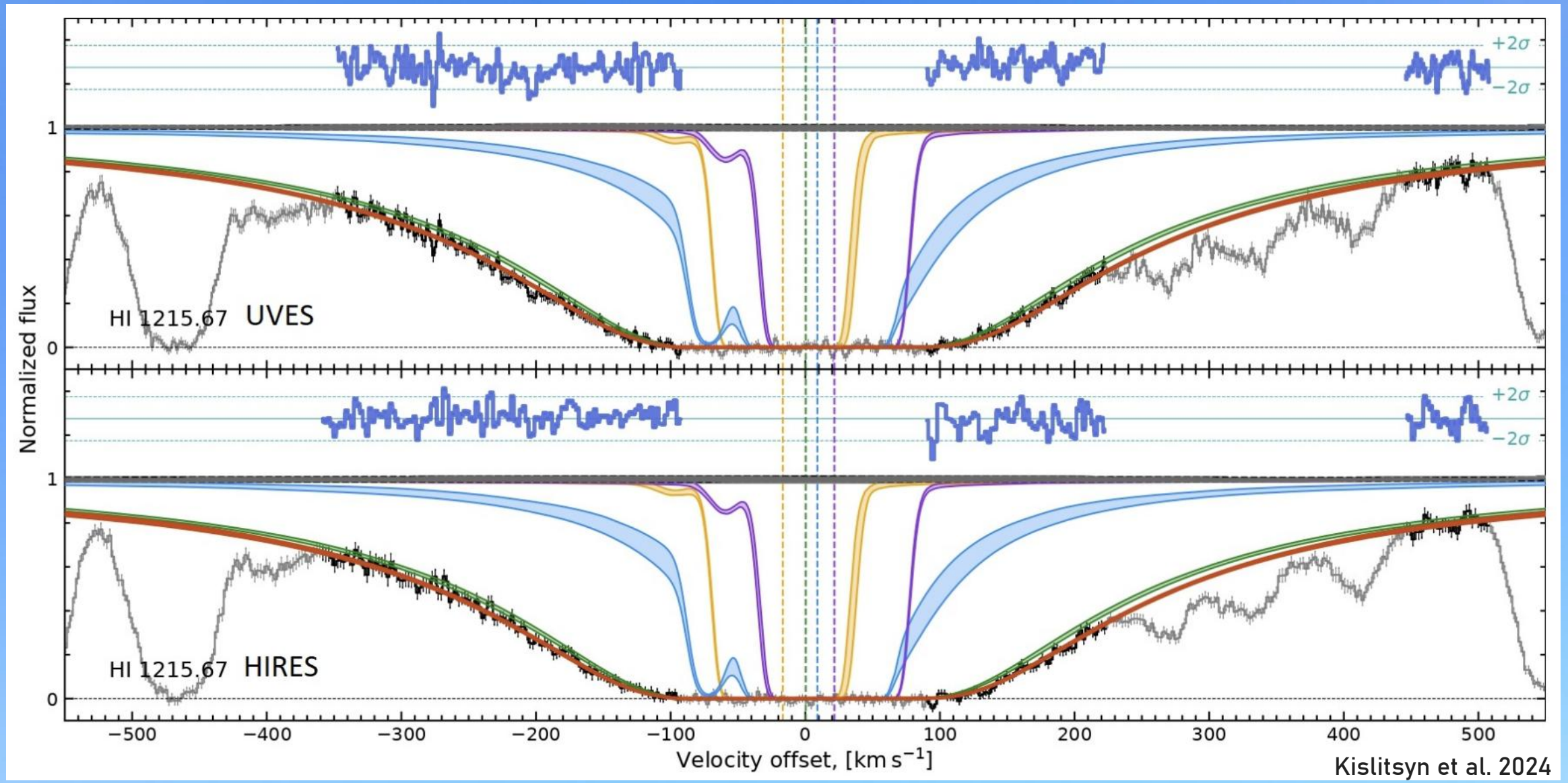

+2σ
−2σ
1
0
HI 1025.72
HI 1025.72
HI 972.53
HI 972.53
HI 949.74
HI 949.74
HI 937.80
HI 937.80
UVES
HIRES

Кинематическая структура облака



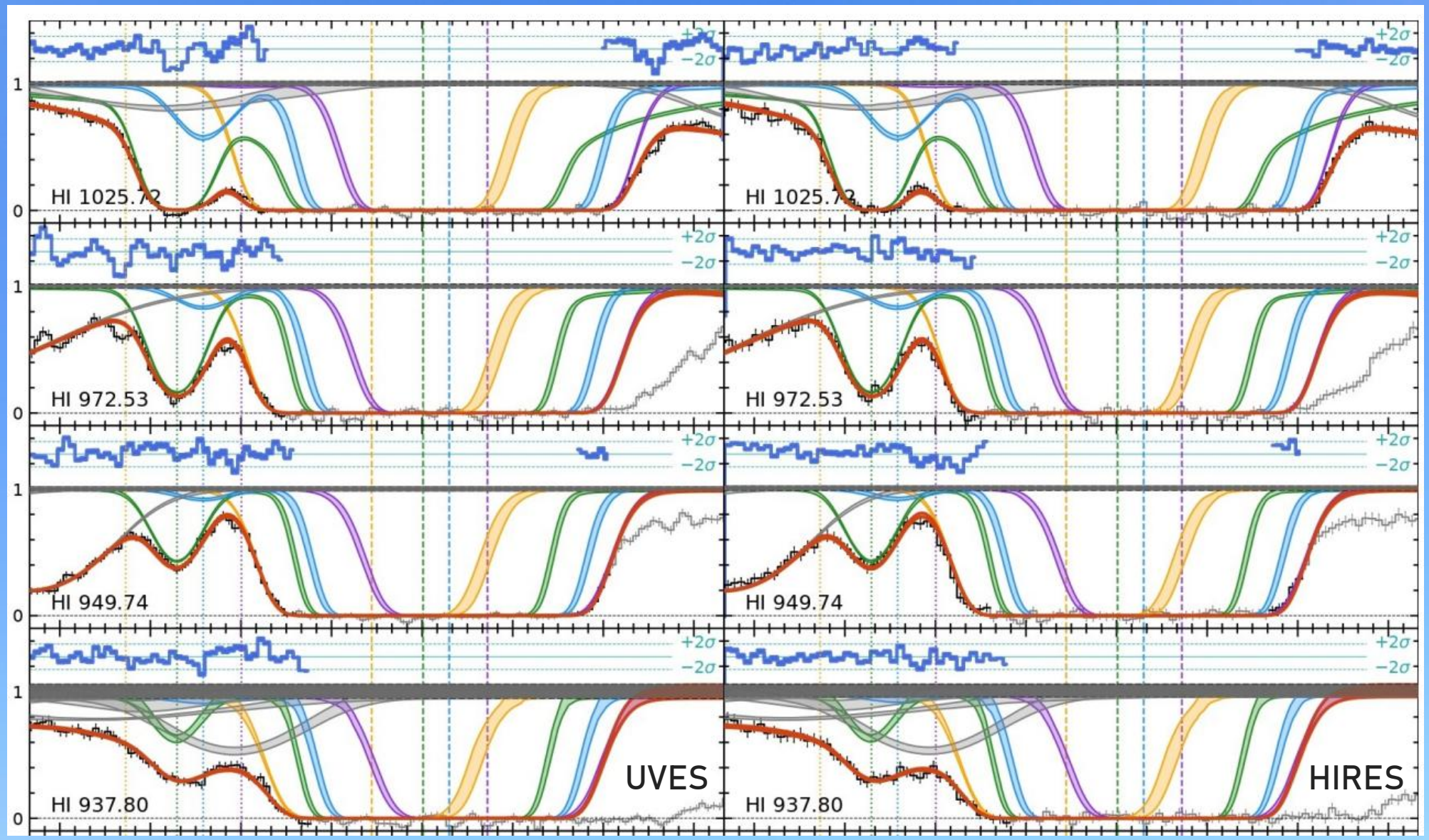
Kislitsyn et al. 2024
arxiv:2401.12797

Линия HI Lyα

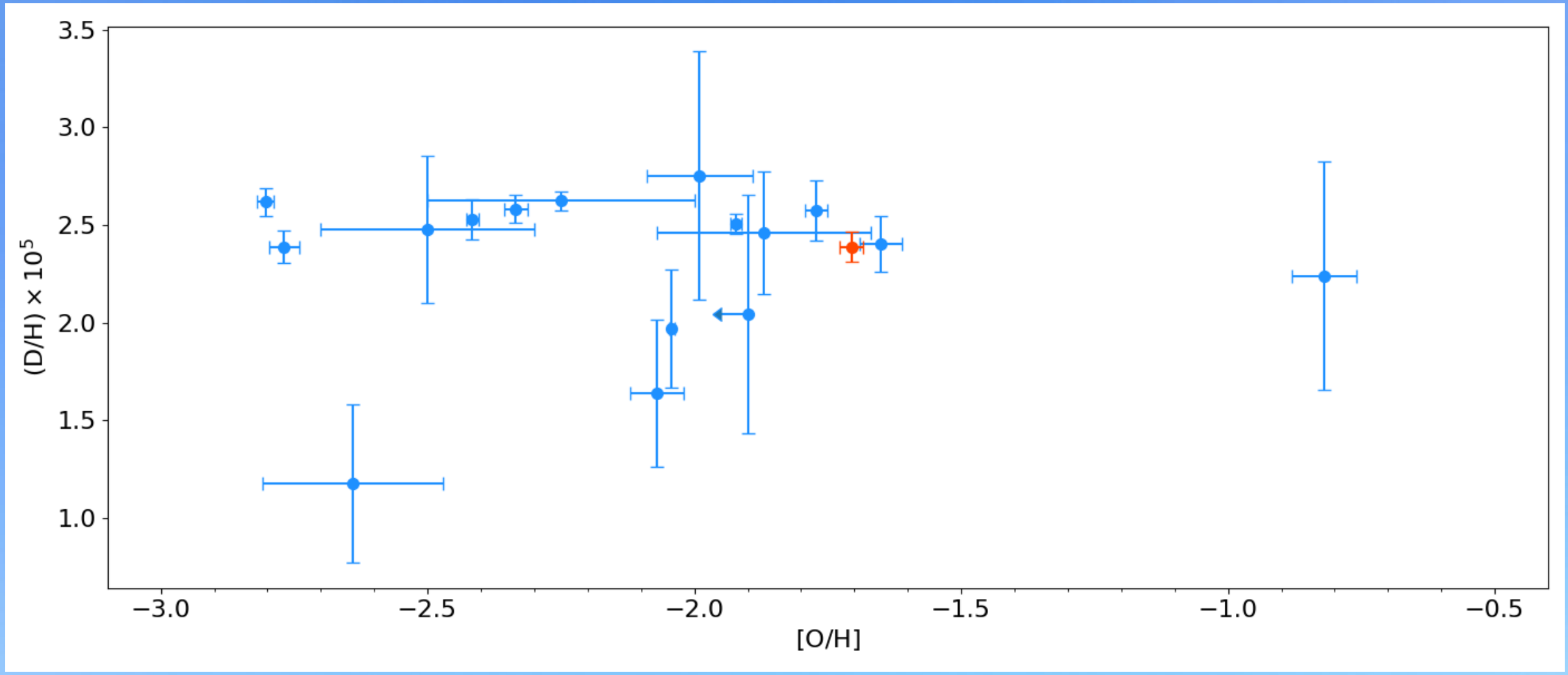


Kislitsyn et al. 2024
arxiv:2401.12797

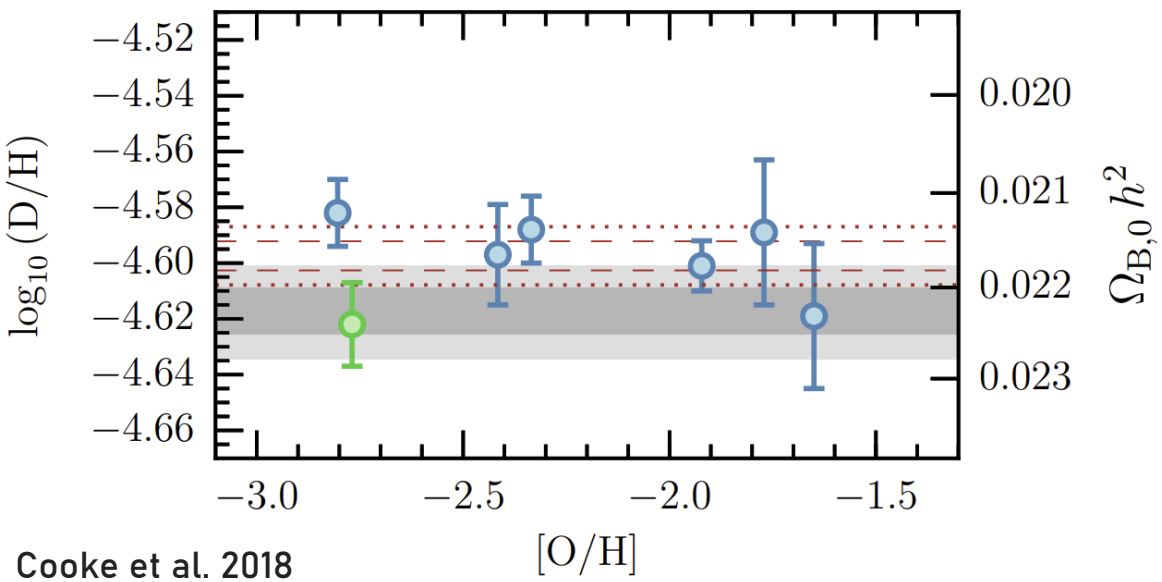
Линии DI


HI 1025.72
HI 1025.72
HI 972.53
HI 972.53
HI 949.74
HI 949.74
HI 937.80
HI 937.80
UVES
HIRES
+2σ
−2σ
1
0

Результаты анализа



Результаты анализа



Cooke et al. 2018
arxiv:1710.11129

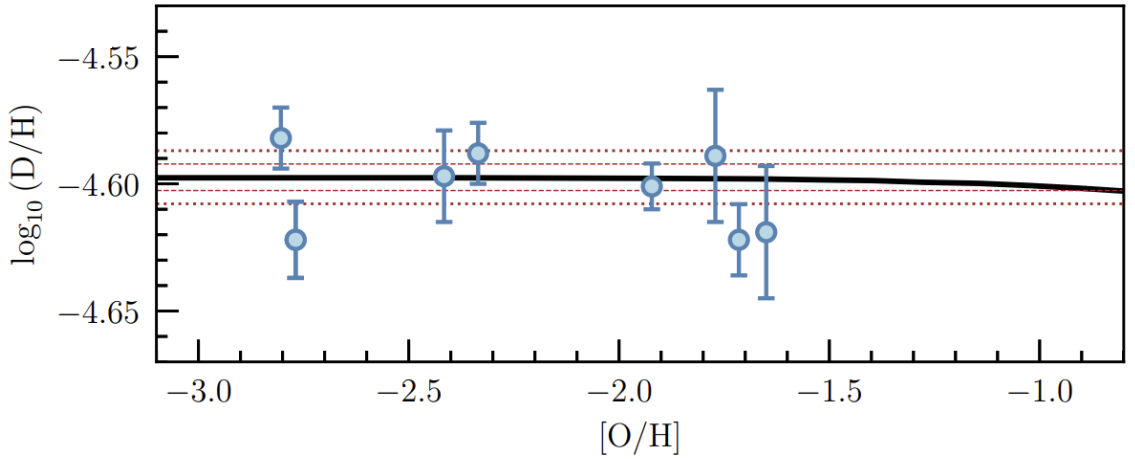
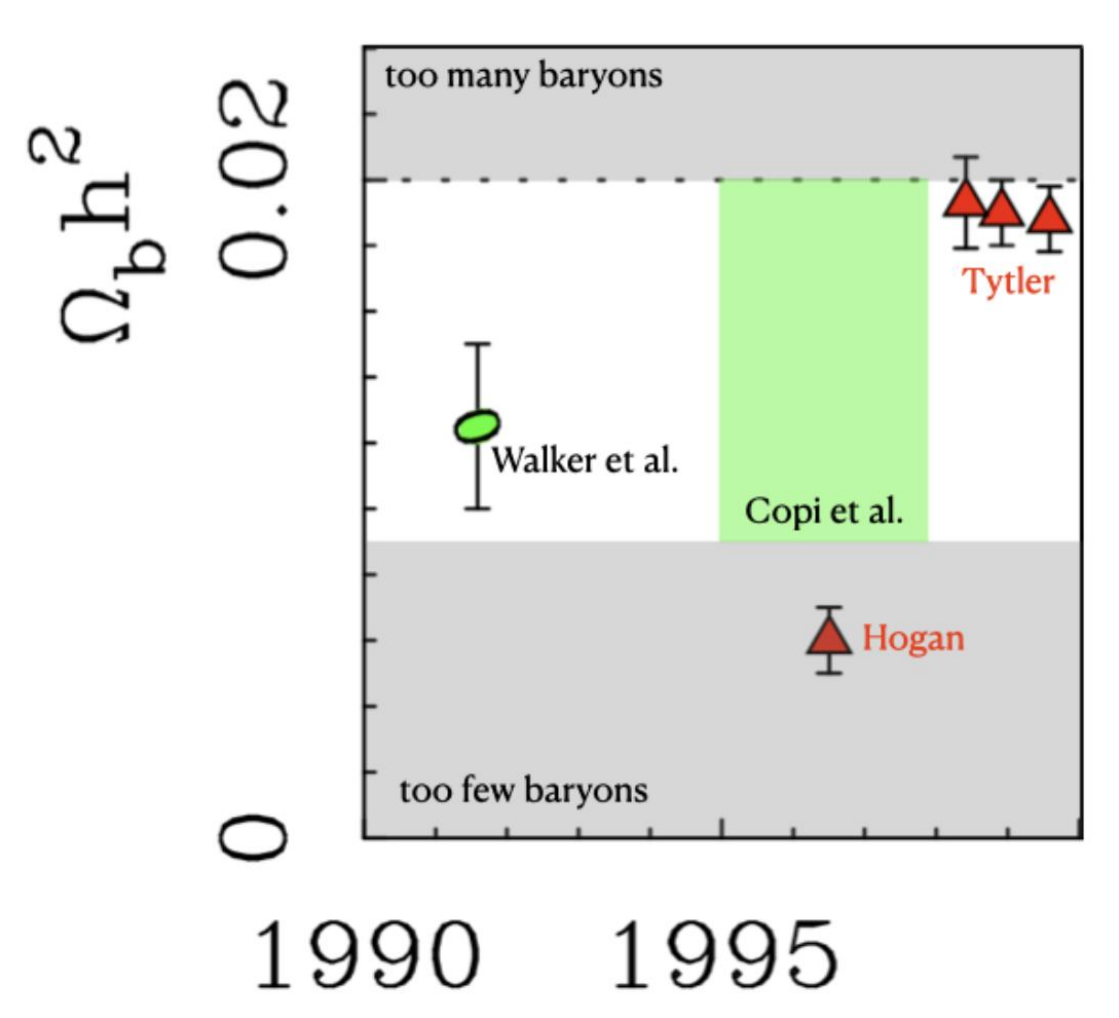
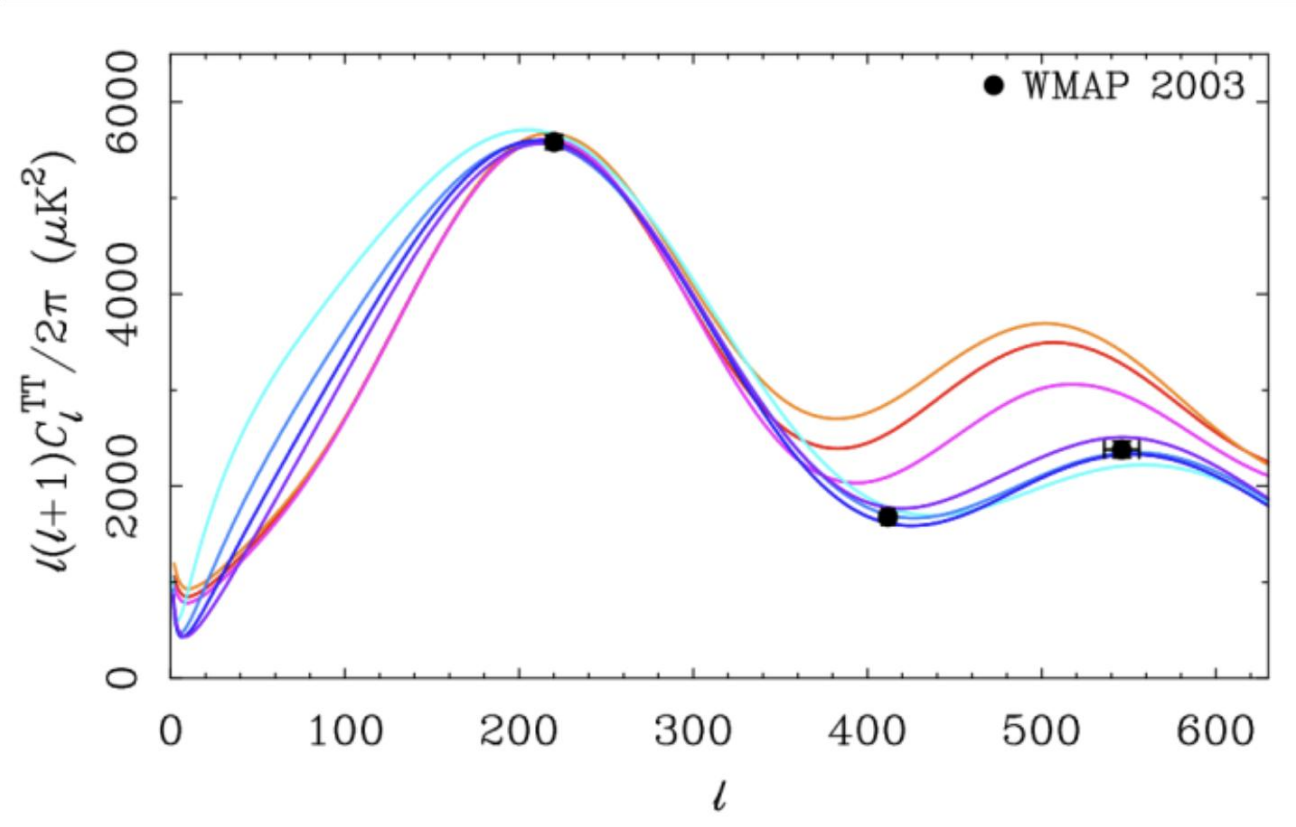


Fig. 5 The 'precision sample' of eight measures of the D/H in metal-poor DLAs, plotted against the oxygen abundance. 1 σ errors are shown. Seven of the values are from Cooke et al. (2018), while the eighth is from the recent work by Kislitsyn et al. (2024). The dotted lines indicate the 1 and 2 σ

Pettini & Cooke 2025 arxiv:2511.06275

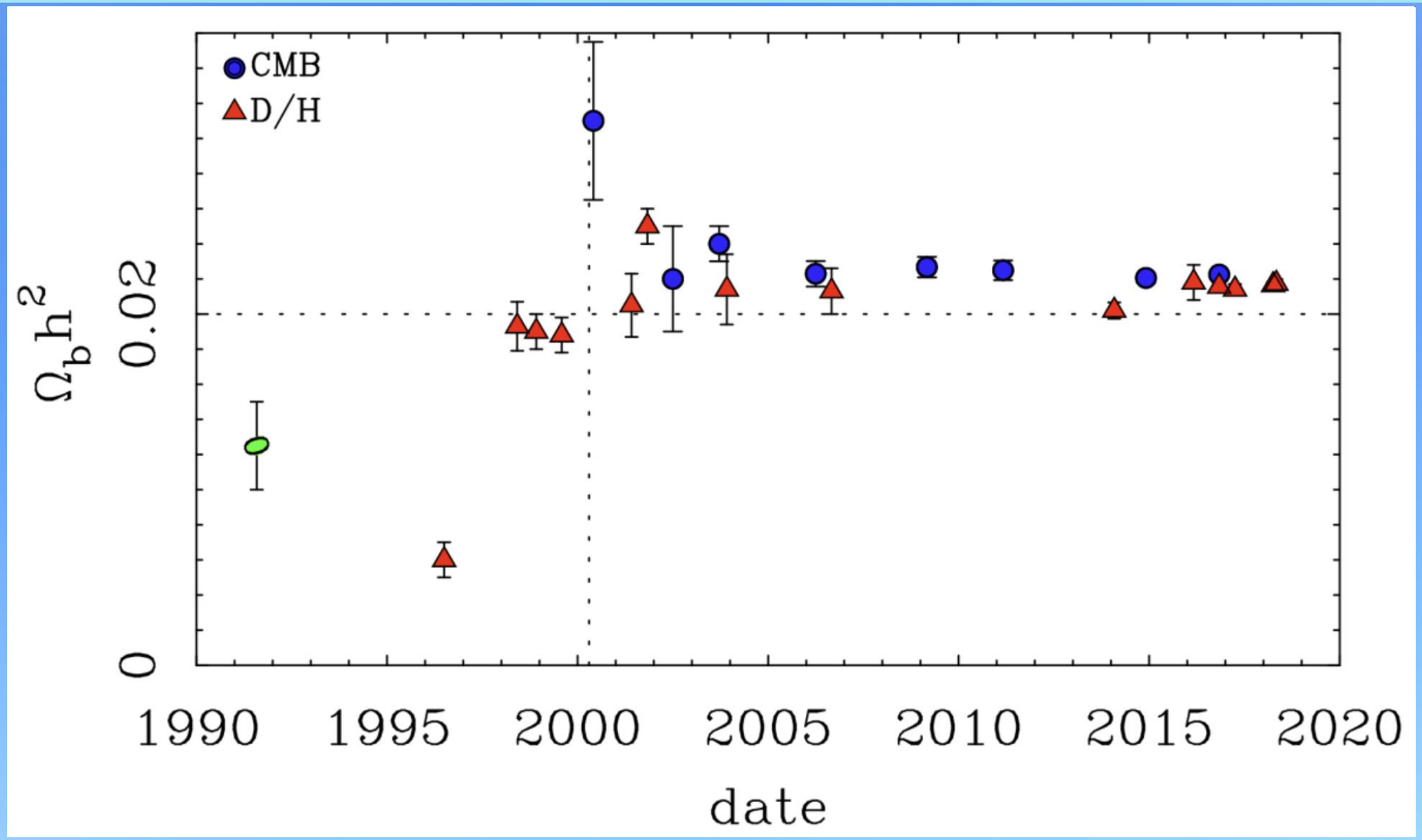
Confirmation bias

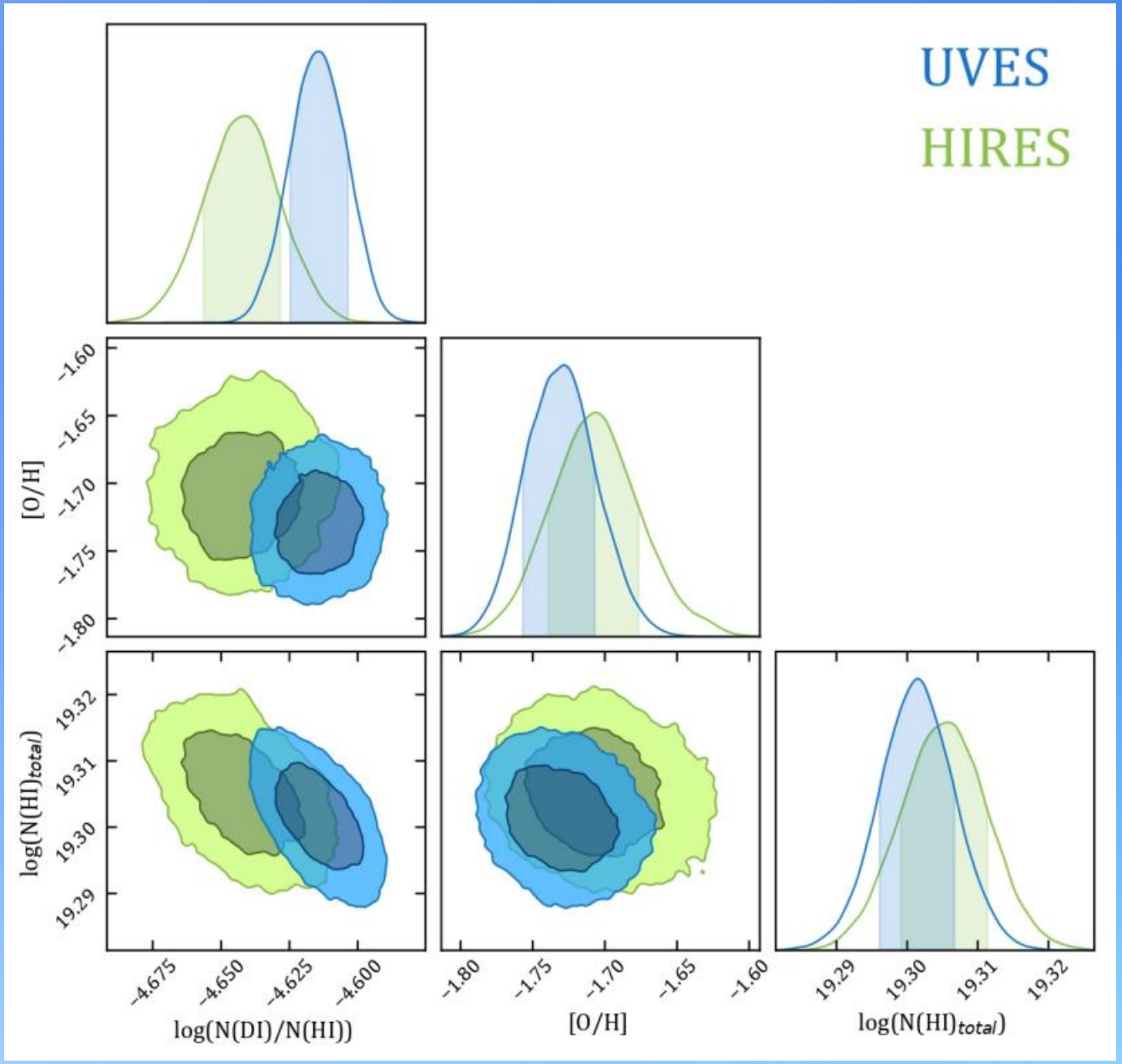


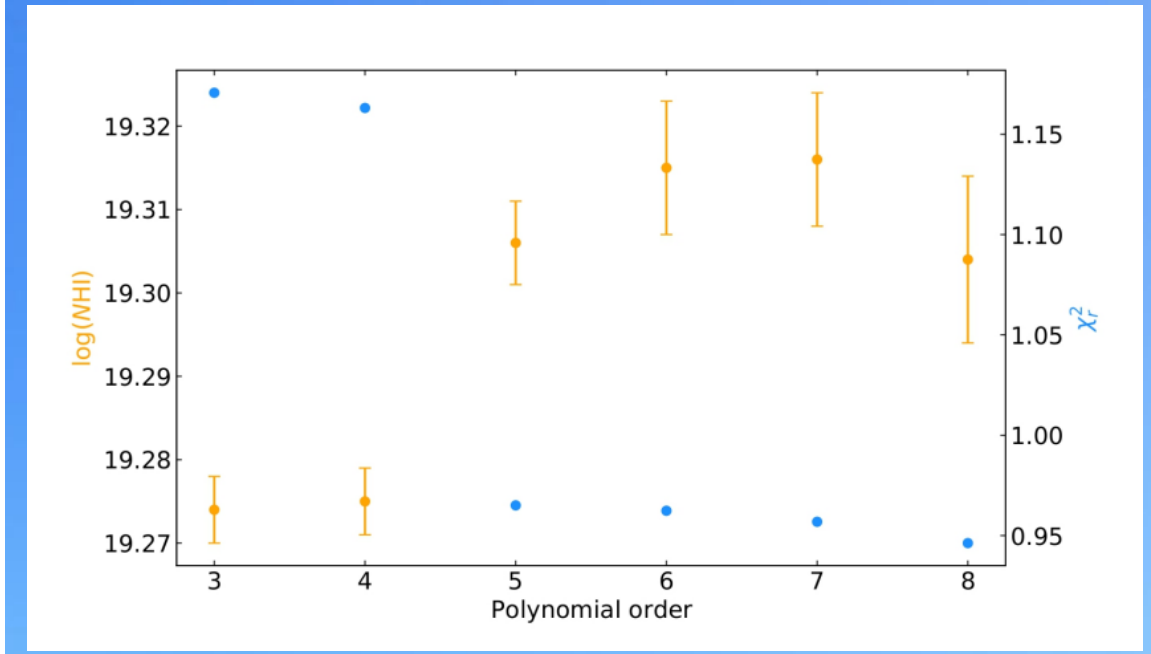


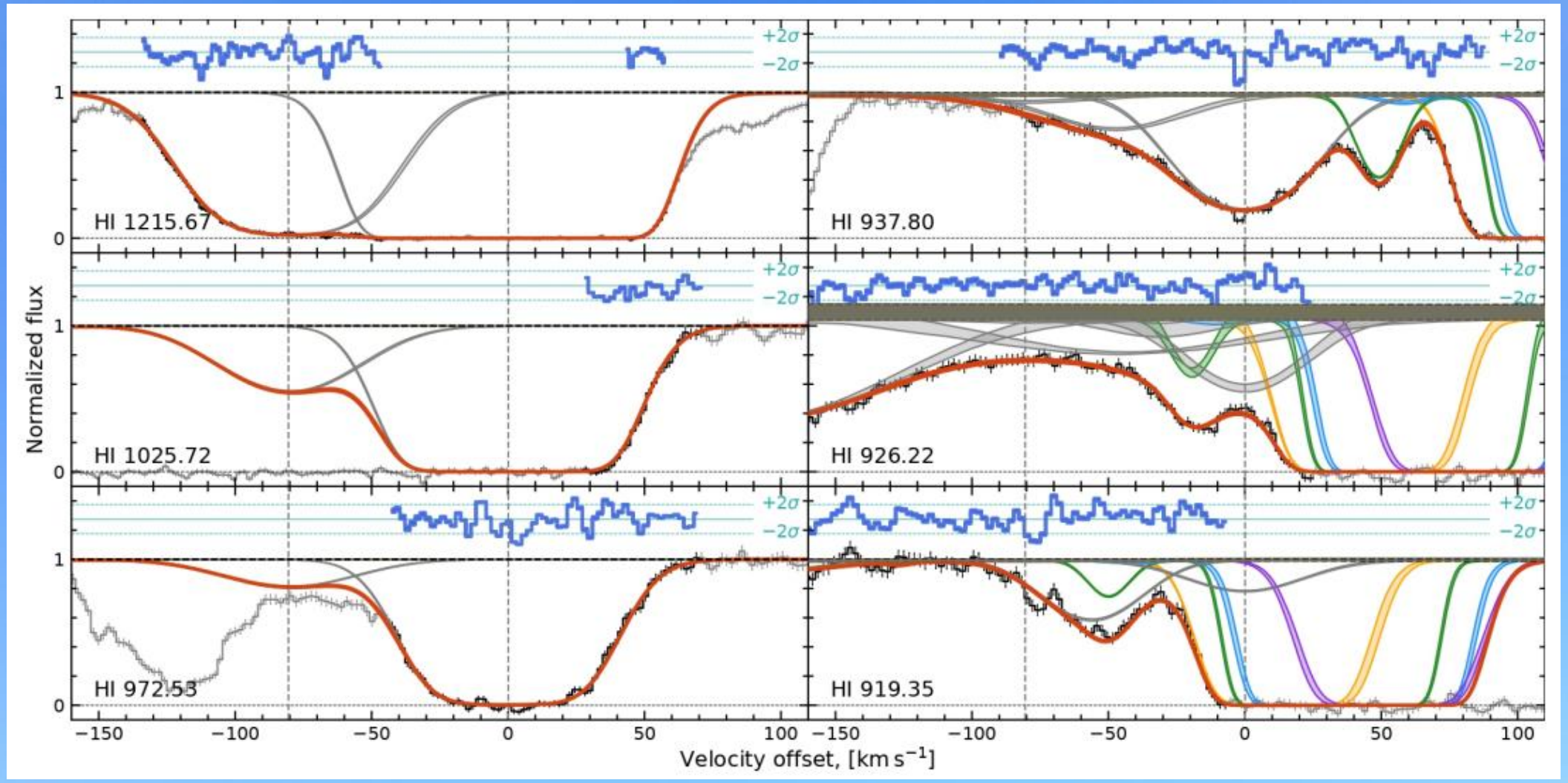
McGaugh, 2025
https://tritonstation.com/2025/05/16/

Confirmation bias




UVES
HIRES
[O/H]
log(N(HI)total)
log(N(DI)/N(HI))
[O/H]
log(N(HI)total)


log(NHI)
χ²r
Polynomial order


HI 1215.67
HI 937.80
HI 1025.72
HI 926.22
HI 972.53
HI 919.35
+2σ
−2σ
Normalized flux
Velocity offset, [km s^{-1}]

Confirmation bias

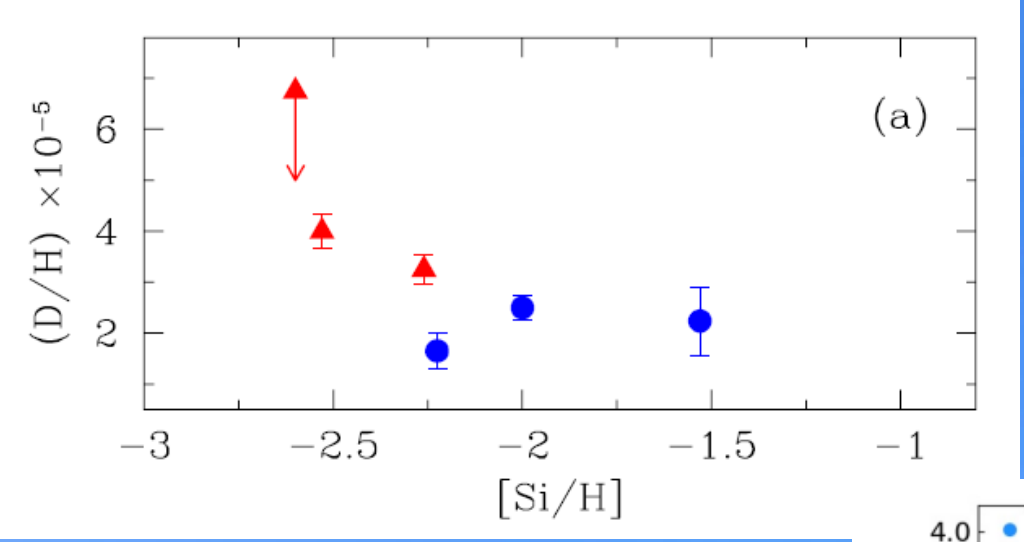
Понимание человека, когда он уже пришёл к какой-то мысли … притягивает все вещи для её поддержки и согласования с ней.

Ф. Бэкон

Способы решения:

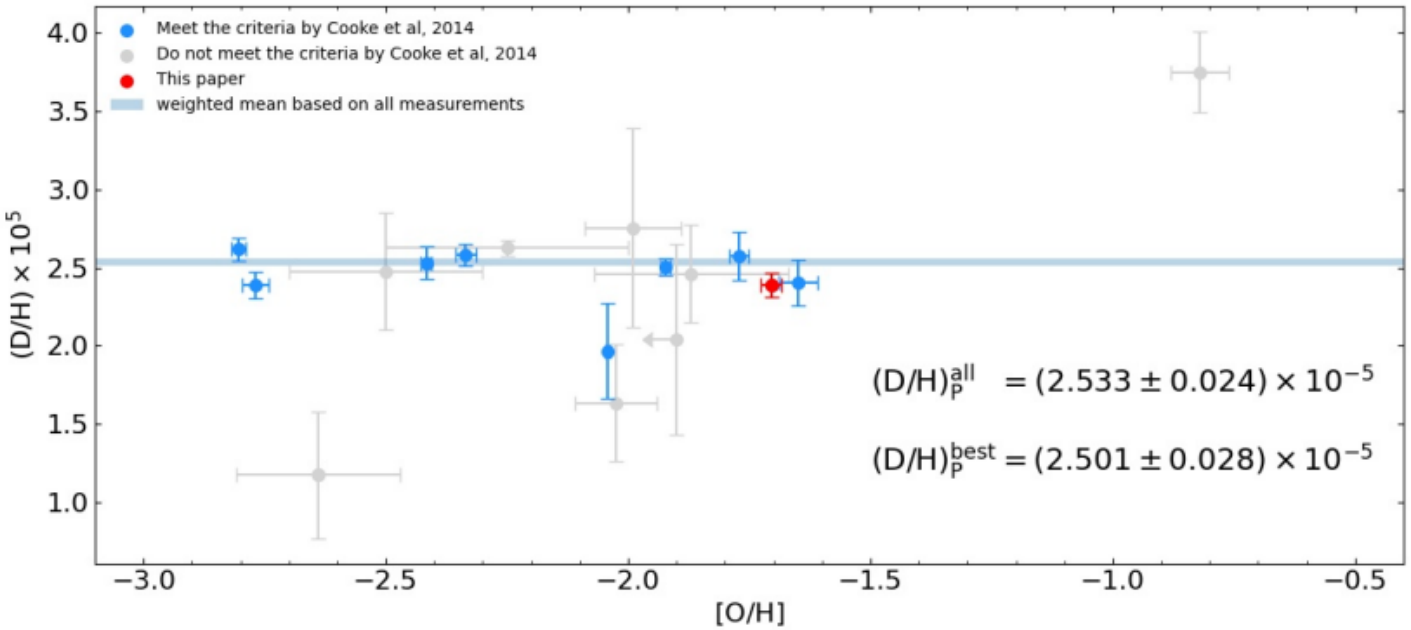
- Слепой метод (R. Cooke, https://arxiv.org/abs/1308.3240)
- Двойной слепой метод
- Участие многих независимых групп и большая статистика

Confirmation bias

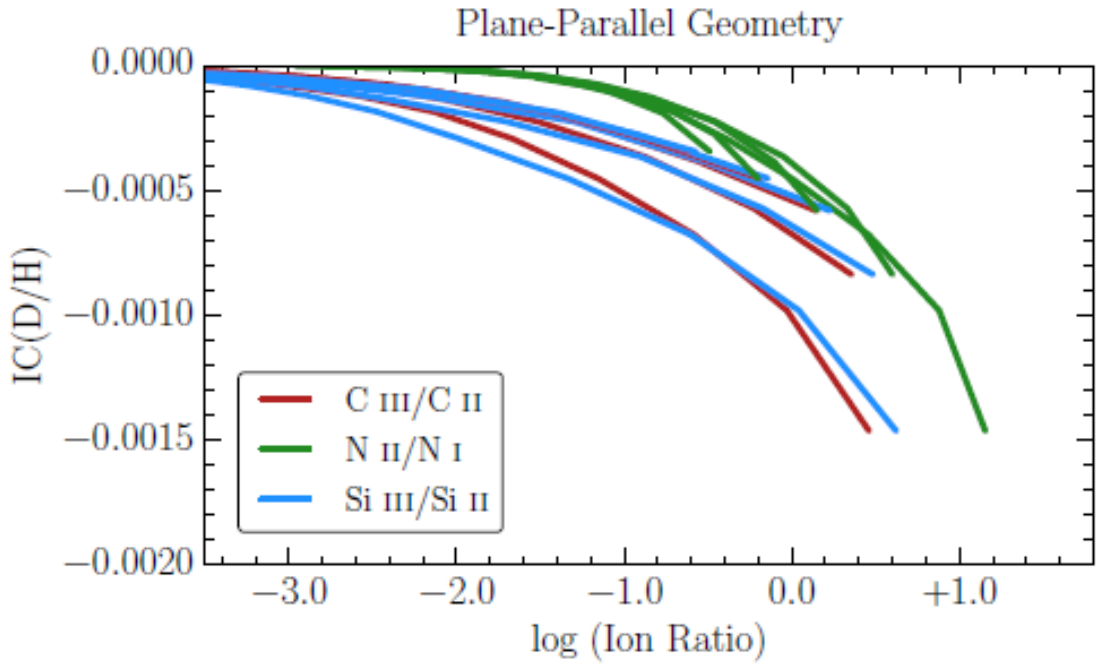


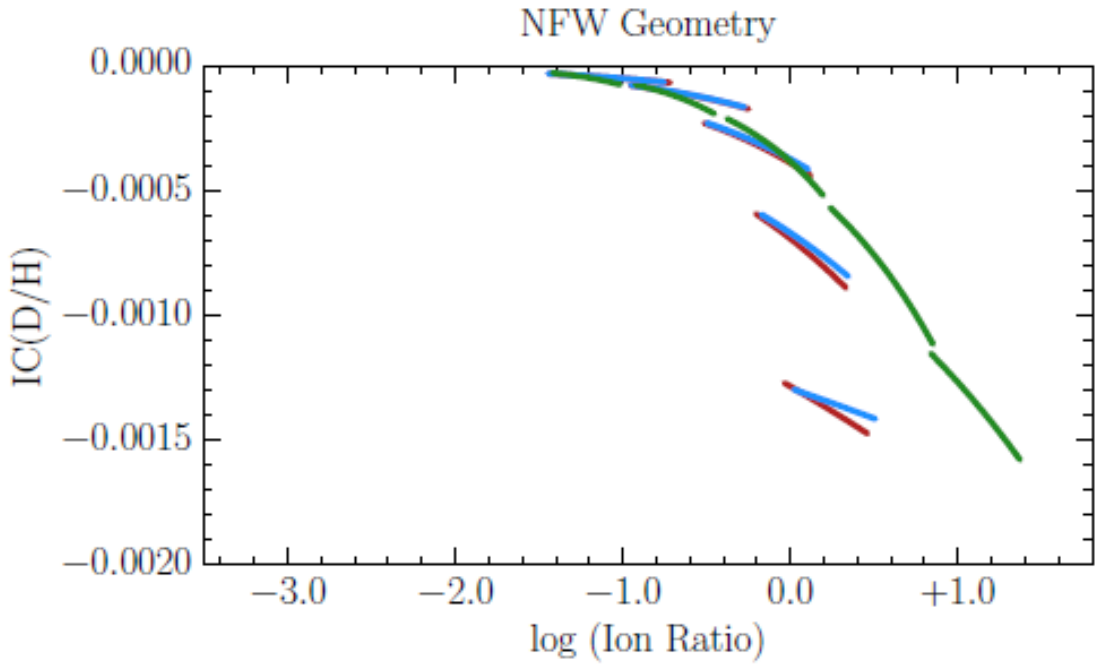
Pettini & Bowen 2001

Kislitsyn et al 2024

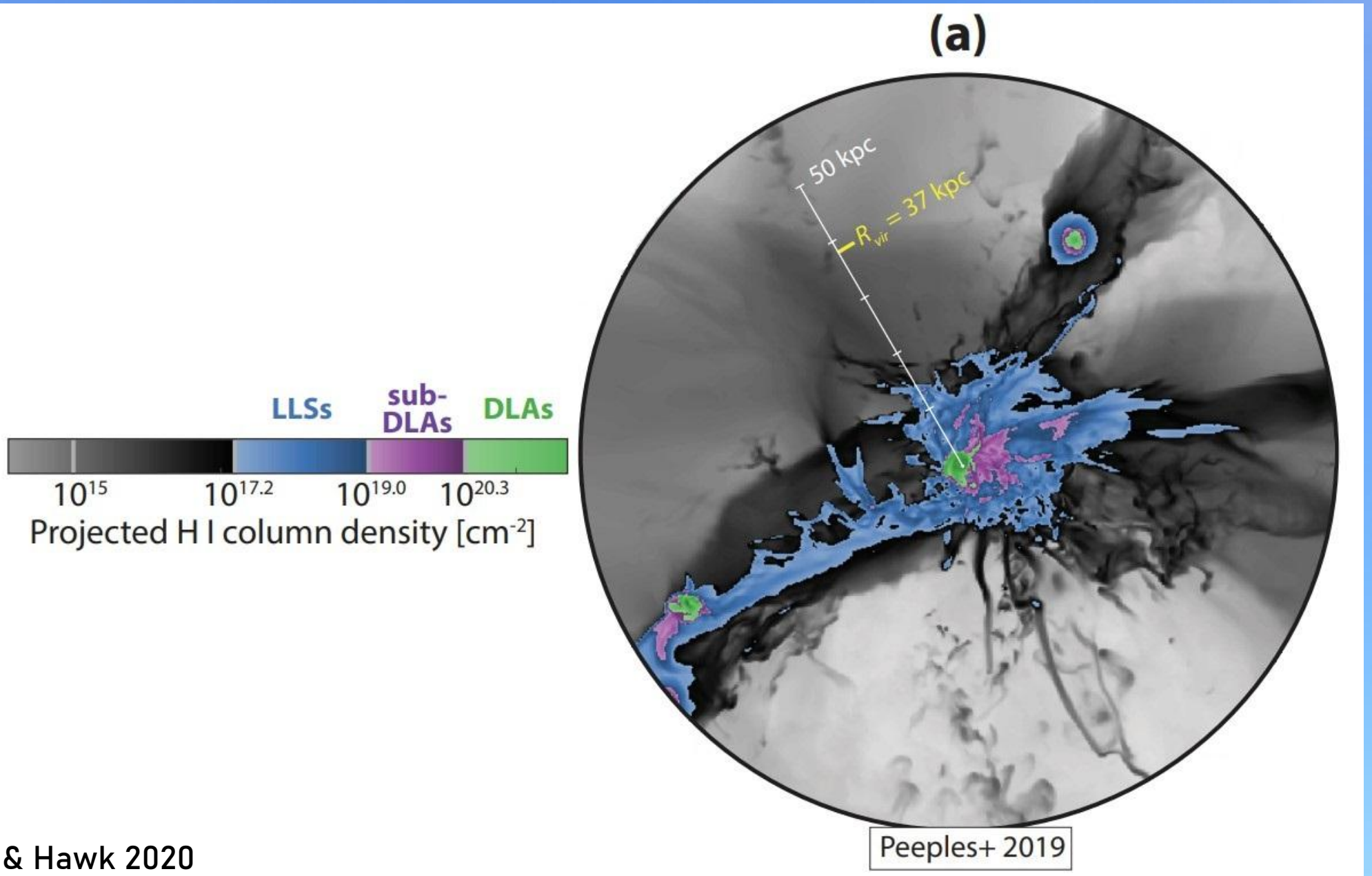


Ионизационные поправки

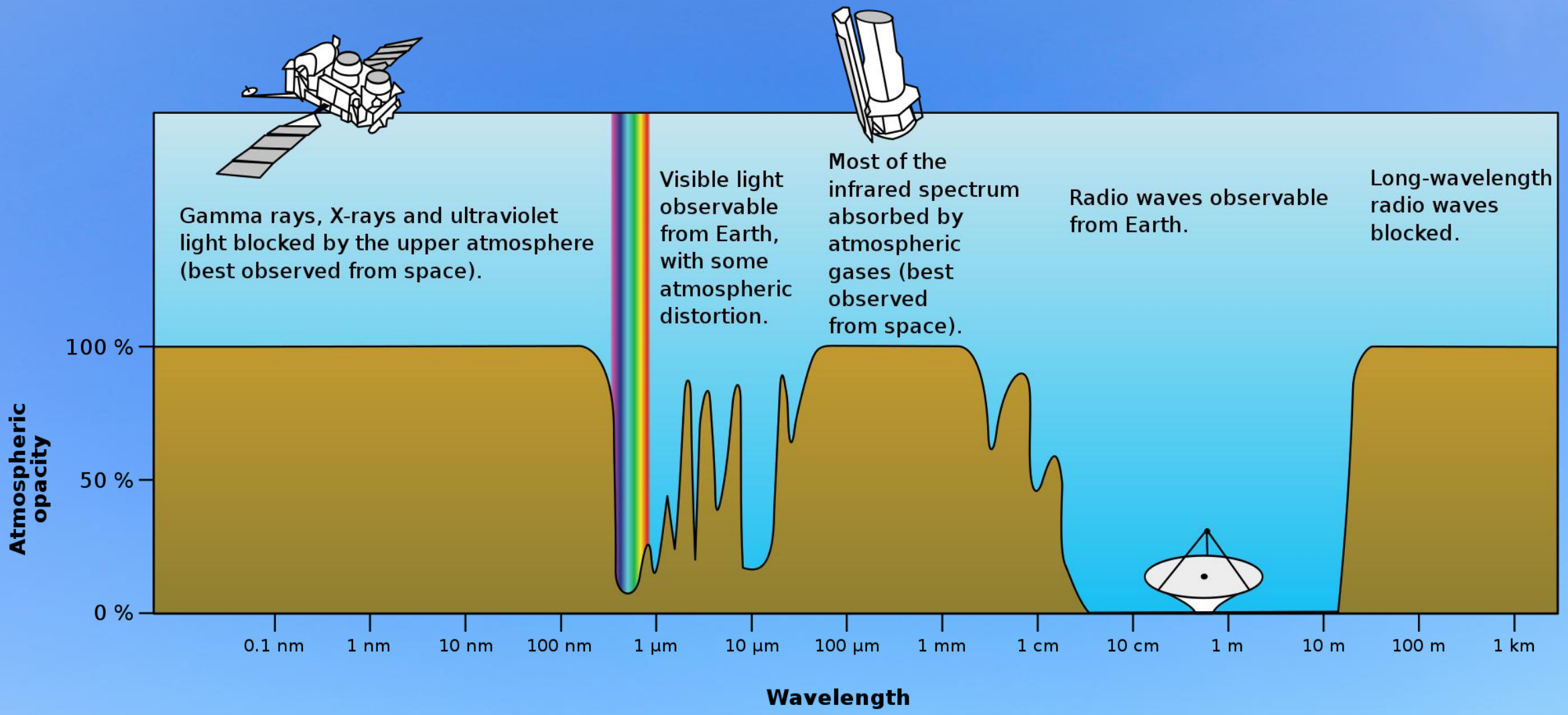




Cooke & Pettini 2015



Peroux & Hawk 2020


Gamma rays, X-rays and ultraviolet light blocked by the upper atmosphere (best observed from space).
Visible light observable from Earth, with some atmospheric distortion.
Most of the infrared spectrum absorbed by atmospheric gases (best observed from space).
Radio waves observable from Earth.
Long-wavelength radio waves blocked.
Atmospheric opacity
100 %
50 %
0 %
0.1 nm
1 nm
10 nm
100 nm
1 µm
10 µm
100 µm
1 mm
1 cm
10 cm
1 m
10 m
100 m
1 km
Wavelength

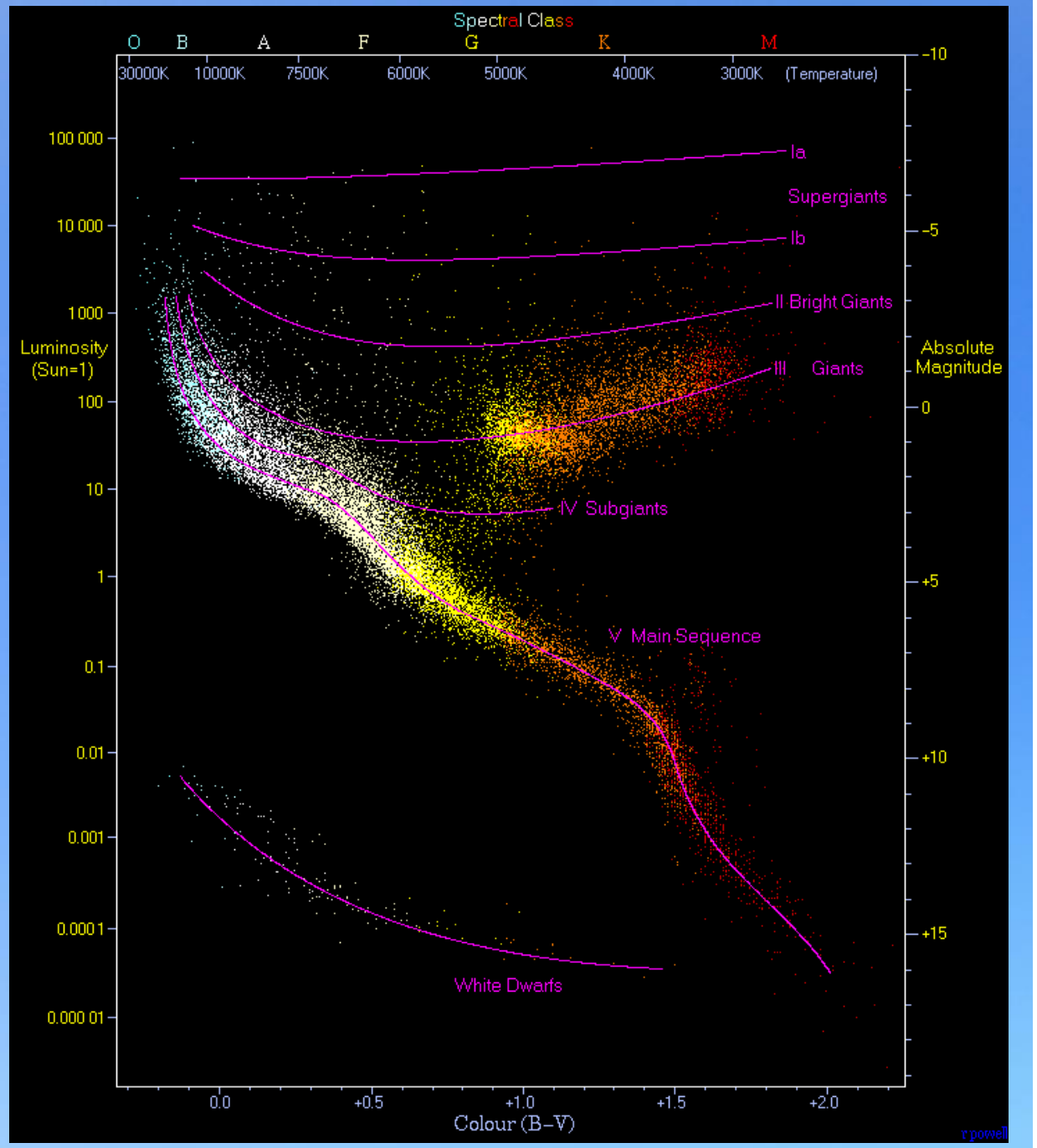


Table 1. Wavelengths and upper and lower levels of reported lines.

Wavelength (Å, Air)	Upper level	Lower level
2945	$5p\,^3P$	$2s\,^3S$
3188	$4p\,^3P$	$2s\,^3S$
3614	$5p\,^1P$	$2s\,^1S$
3889	$3p\,^3P$	$2s\,^3S$
3965	$4p\,^1P$	$2s\,^1S$
4026	$5d\,^3D$	$2p\,^3P$
4121	$5s\,^3S$	$2p\,^3P$
4388	$5d\,^1D$	$2p\,^1P$
4438	$5s\,^1S$	$2p\,^1P$
4471	$4d\,^3D$	$2p\,^3P$
4713	$4s\,^3S$	$2p\,^3P$
4922	$4d\,^1D$	$2p\,^1P$
5016	$3p\,^1P$	$2s\,^1S$
5048	$4s\,^1S$	$2p\,^1P$
5876	$3d\,^3D$	$2p\,^3P$
6678	$3d\,^1D$	$2p\,^1P$
7065	$3s\,^3S$	$2p\,^3P$
7281	$3s\,^1S$	$2p\,^1P$
9464	$5p\,^3P$	$3s\,^3S$
10830	$2p\,^3P$	$2s\,^3S$
11013	$5p\,^1P$	$3s\,^1S$
11969	$5d\,^3D$	$3p\,^3P$
12527	$4p\,^3P$	$3s\,^3S$
12756	$5p\,^1P$	$3d\,^1D$
12785	$5f\,^3F$	$3d\,^3D$
12790	$5f\,^1F$	$3d\,^1D$
12846	$5s\,^3S$	$3p\,^3P$
12968	$5d\,^1D$	$3p\,^1P$
12985	$5p\,^3P$	$3d\,^3D$