Measurements of the fine structure constant at high redshift

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MG15 *PT4 - Variation of the fundamental constants, violation of the fundamental symmetries and dark matter 3 July 2018*

Abstract:
High redshift measurements of the fine structure constant have been time consuming and prone to systematic uncertainties that require considerable effort to quantify.
New methods, based on a genetic algorithm, fully automate the analysis and produce more robust results.
A new large survey, using these new techniques, is currently in progress, to make the first 1000 measurements of alpha at high redshift.
The genetic procedure has been applied to a new XSHOOTER/VLT IR spectrum of a very high redshift quasar. The z(em)=7.048 quasar J1120+0641 reveals 11 absorption systems intersecting the line of sight, three of which produce varying alpha measurements: z(abs)= 5.51, 5.95, and 6.17. These are the highest redshift direct quasar constraints to date.

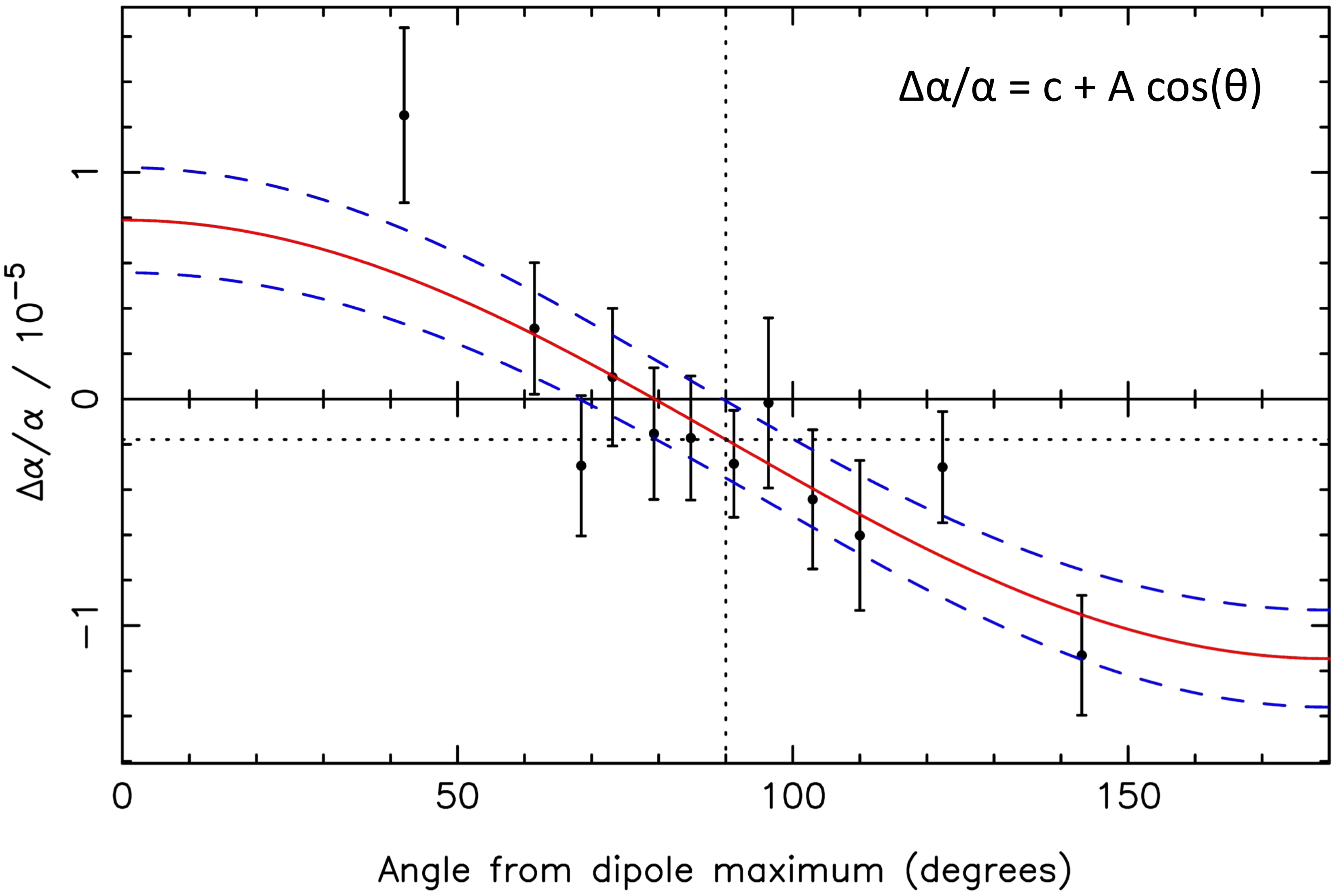
Summary

1. Spatially varying alpha – status unchanged. Result does not "go away". Long-range echelle spectrograph wavelength distortions do not account for it (arXiv:1701.03176).

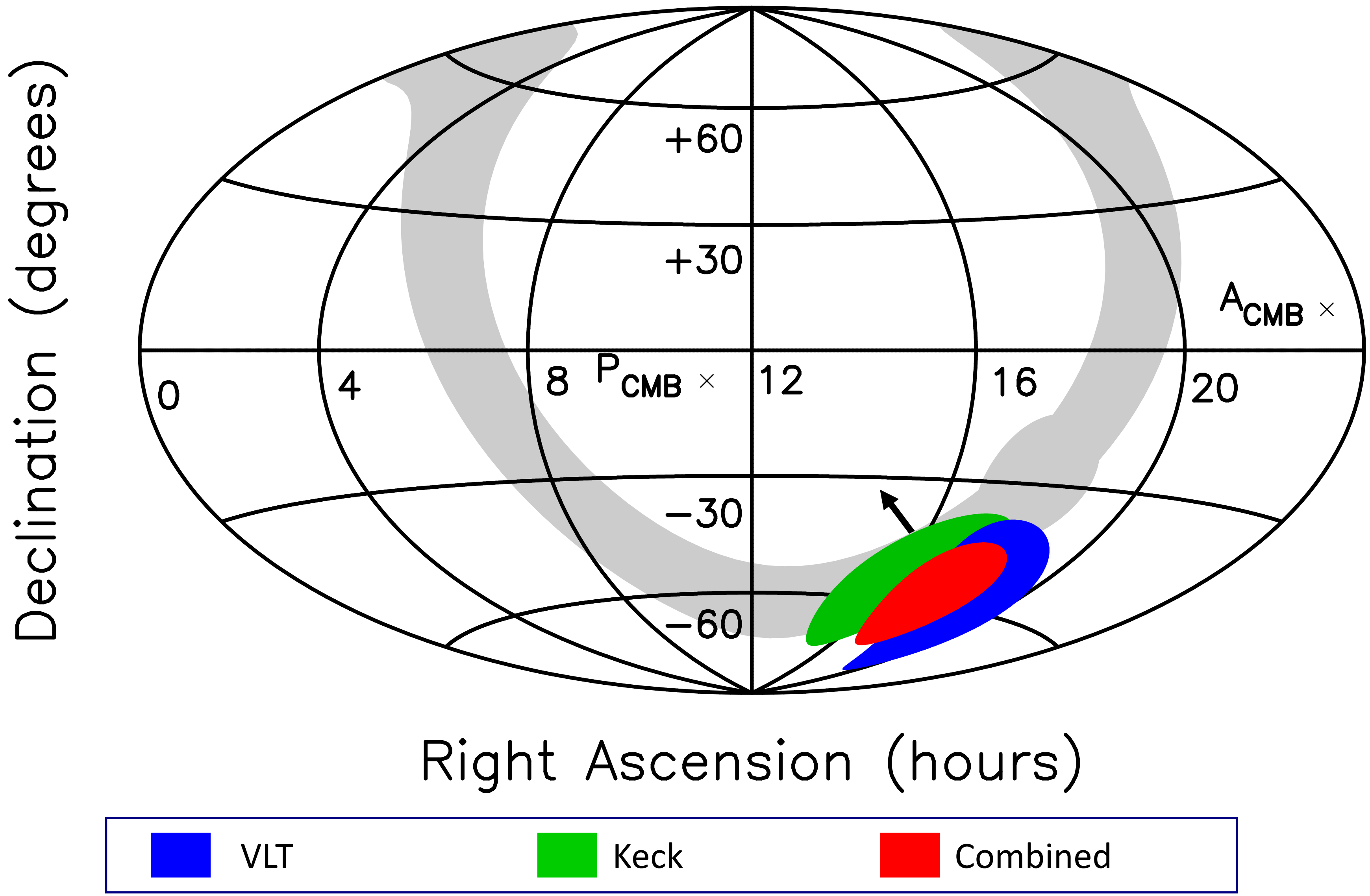
2. New AI method full automates analysis and gives more robust and faster measurements (but requires supercomputers). Target is the first 1000 measurements of varying alpha. Timescale 18 months (arXiv:1704.08710, arXiv:1606.07393).

3. Three new measurements at z~6 give the highest redshift direct quasar constraint so far: $\Delta\alpha/\alpha = -22 \pm 10 \times 10^{-5}$

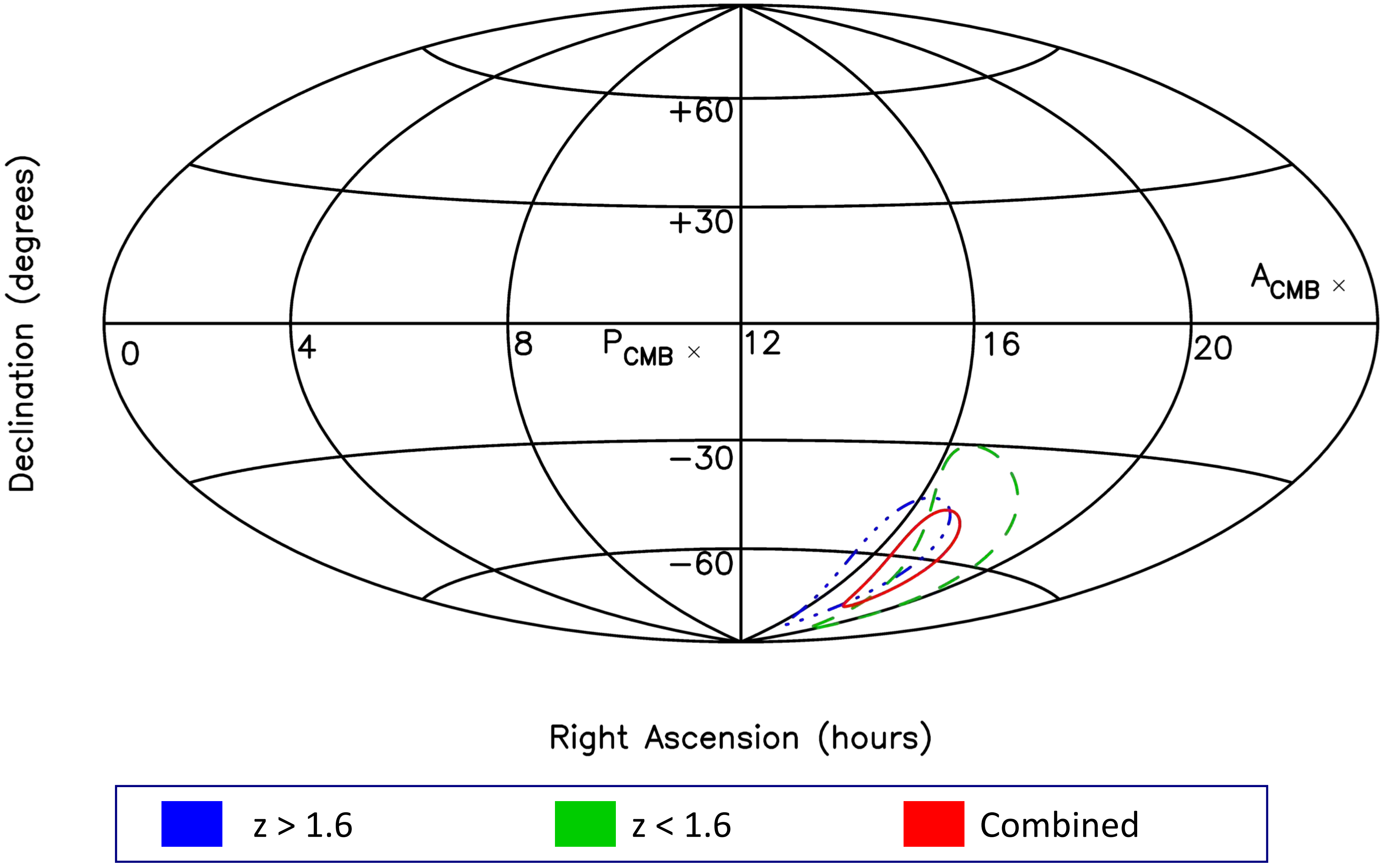
4.2σ evidence for a Δα/α dipole from VLT + Keck



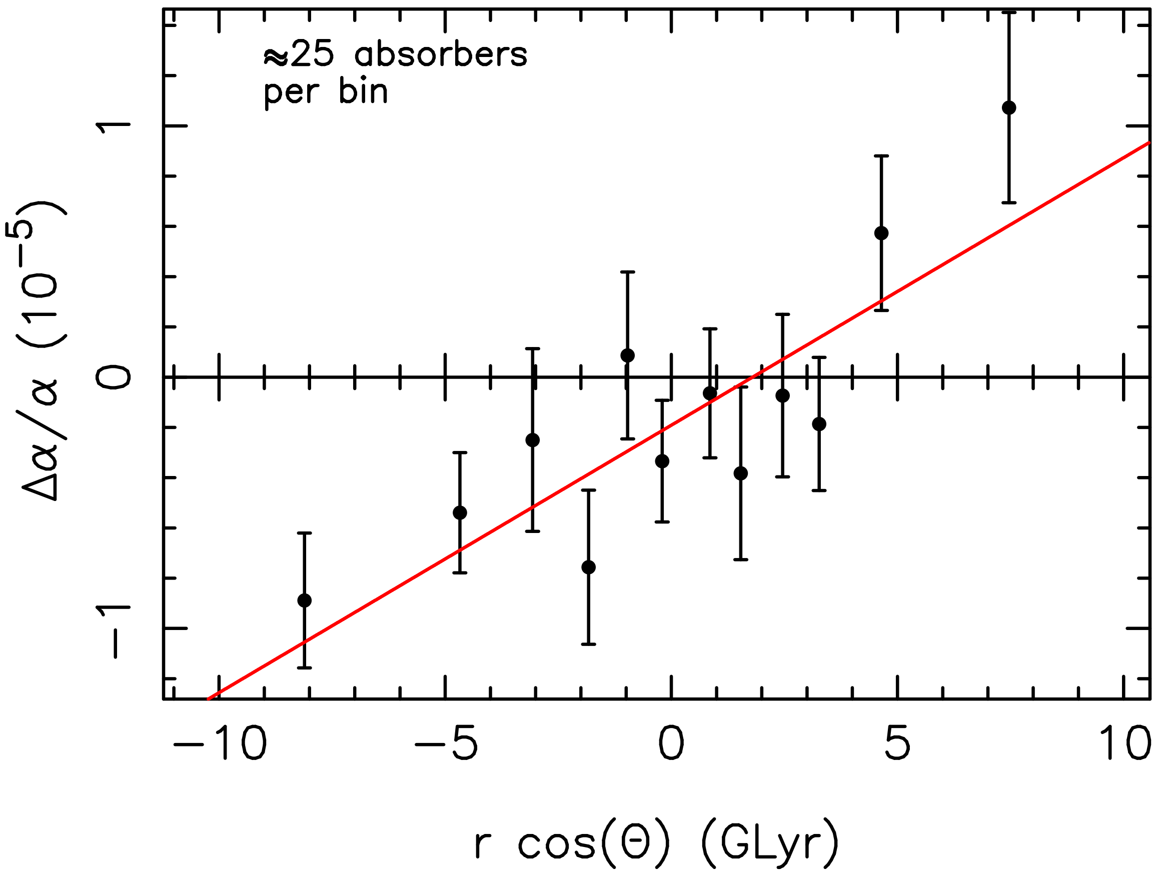
Keck & VLT dipoles independently agree, p=6%



Low and high redshift cuts are consistent in direction. Effect is larger at high redshift.

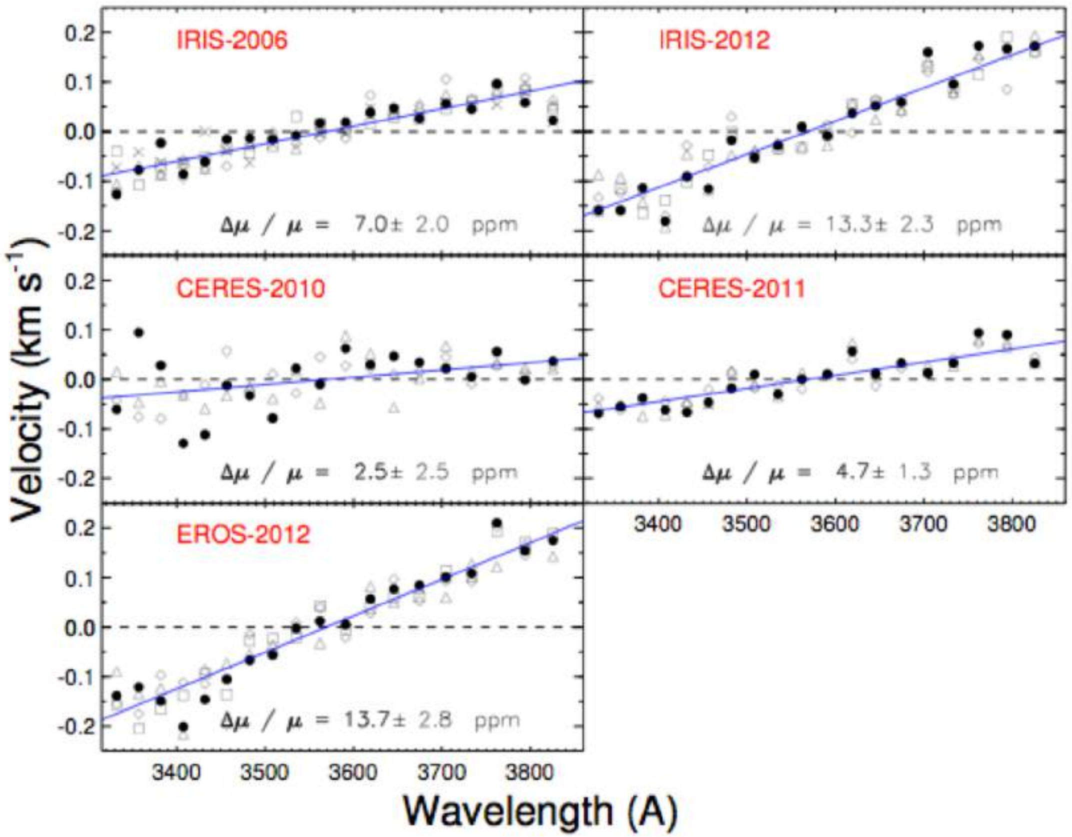


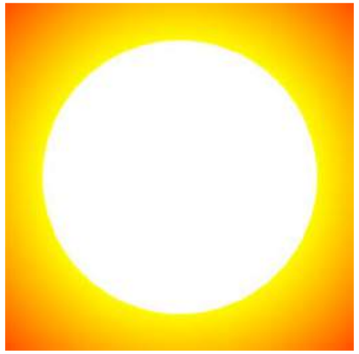
Distance dependence

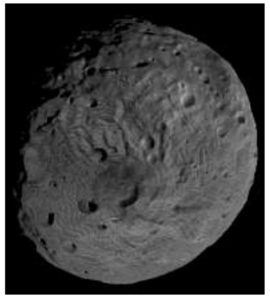


Δα/α vs BrcosΘ for the model Δα/α=BrcosΘ+m showing the gradient in α along the best-fit dipole. The best- fit direction is at right ascension 17.4 ± 0.6 hours, declination −62 ± 6 degrees, for which B = (1.1 ± 0.2) × 10^{-6} $GLyr^{-1}$ and m = (−1.9 ± 0.8) × 10−6. This dipole+monopole model is statistically preferred over a monopole-only model also at the 4.2σ level. A cosmology with parameters (H_0 , Ω_M , Ω_Λ) = (70.5, 0.2736, 0.726).

Evidence for large-scale wavelength distortions





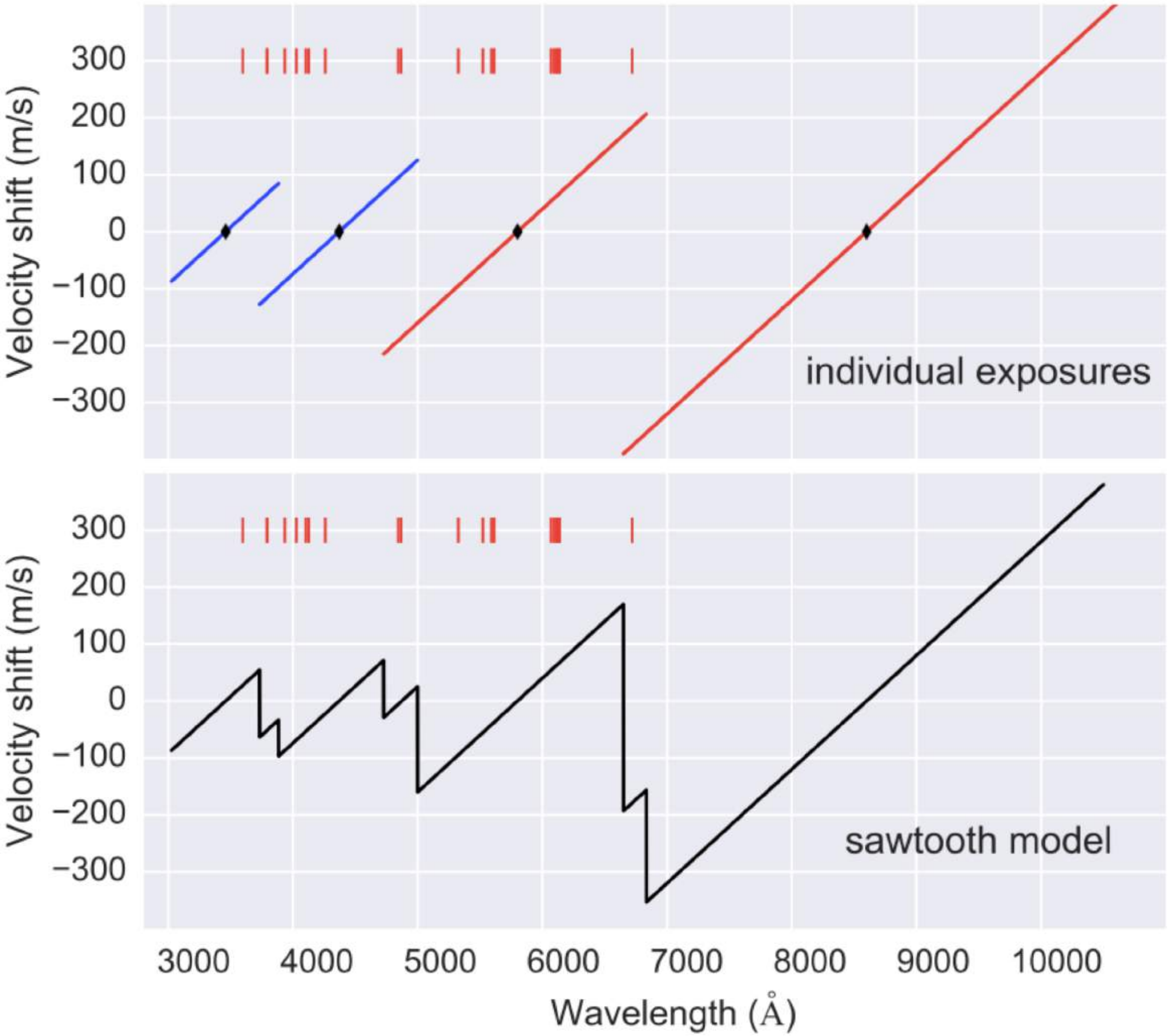


Note the zero point is at the central wavelength

In practice quasars are generally observed at multiple central wavelength settings so actual distortion model is complicated and specific to every quasar observation.

Each spectrum must be individually modelled.

Bottom line:
One can solve simultaneously (with alpha) for the distortion model.
The distortion is significant but does not dominate the overall uncertainty.



Distortion does not explain the VLT results

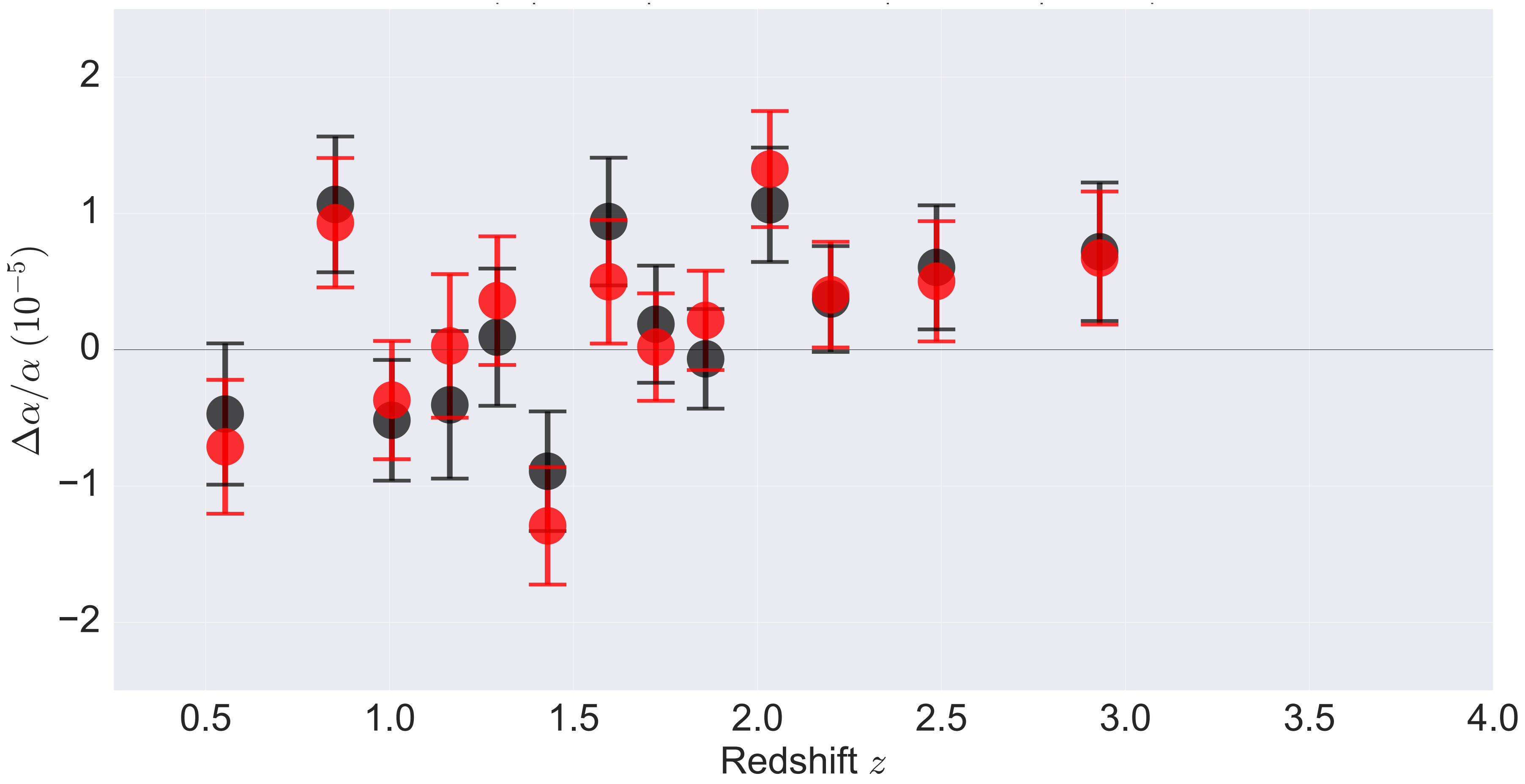
1. arXiv:1701.03176 [pdf, other]

Modeling long-range wavelength distortions in quasar absorption echelle spectra

Vincent Dumont, John K. Webb

Comments: 8 pages, 7 figures, 3 tables

Subjects: **Cosmology and Nongalactic Astrophysics (astro-ph.CO)**



BLACK: Original results – no distortion correction

RED: Distortion corrected results

Removing the human element – applying AI to varying constants

New method, combining three procedures into one AI process:

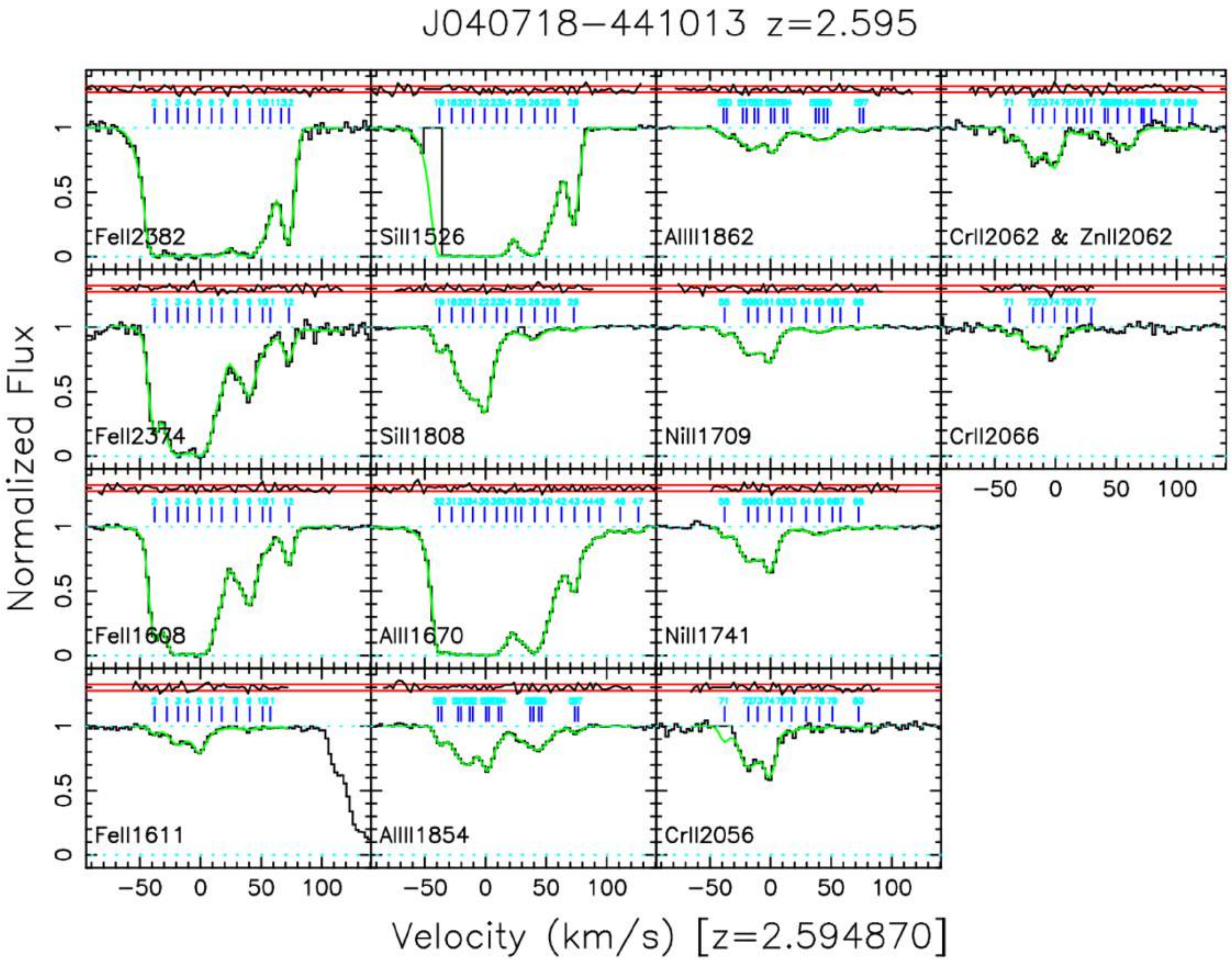
- Genetic algorithm
- Local non-linear least-squares
- Bayesian model averaging

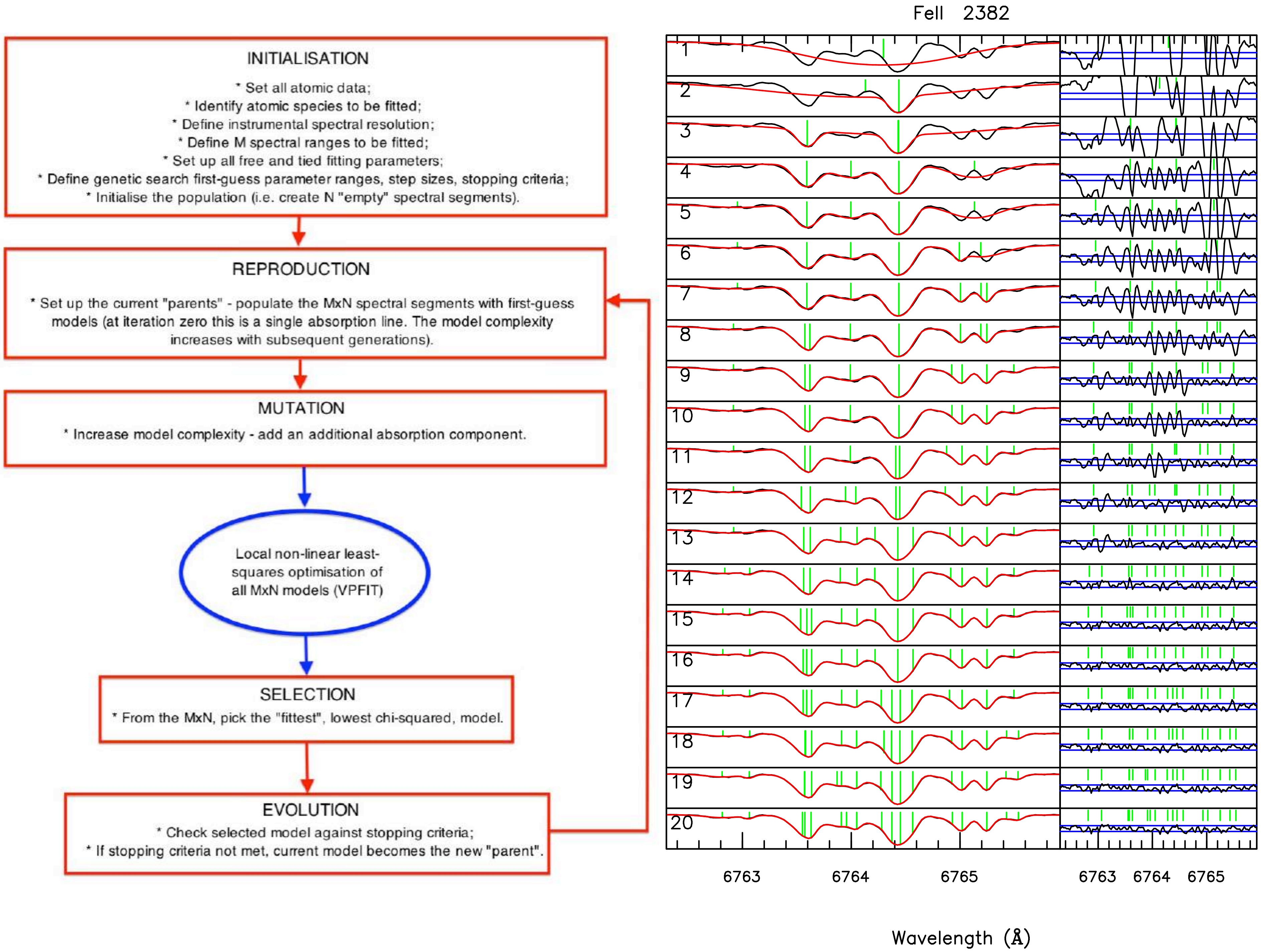
Artificial intelligence applied to the automatic analysis of absorption spectra. Objective measurement of the fine structure constant

Matthew B. Bainbridge ✉, John K. Webb ✉

Monthly Notices of the Royal Astronomical Society, Volume 468, Issue 2, 21 June 2017, Pages 1639–1670, https://doi.org/10.1093/mnras/stx179

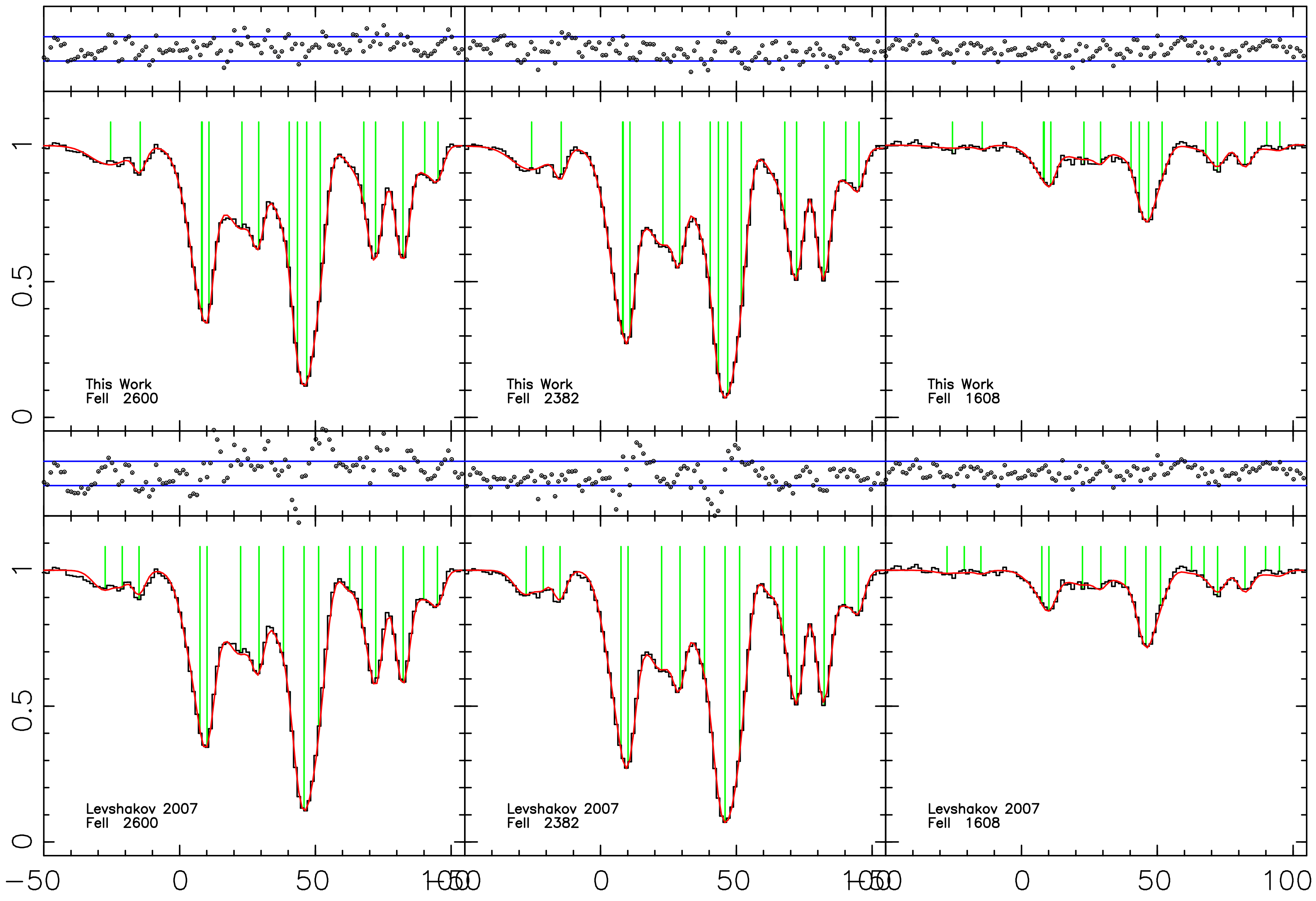
The challenge: complicated data – need models with many free (and tied) parameters



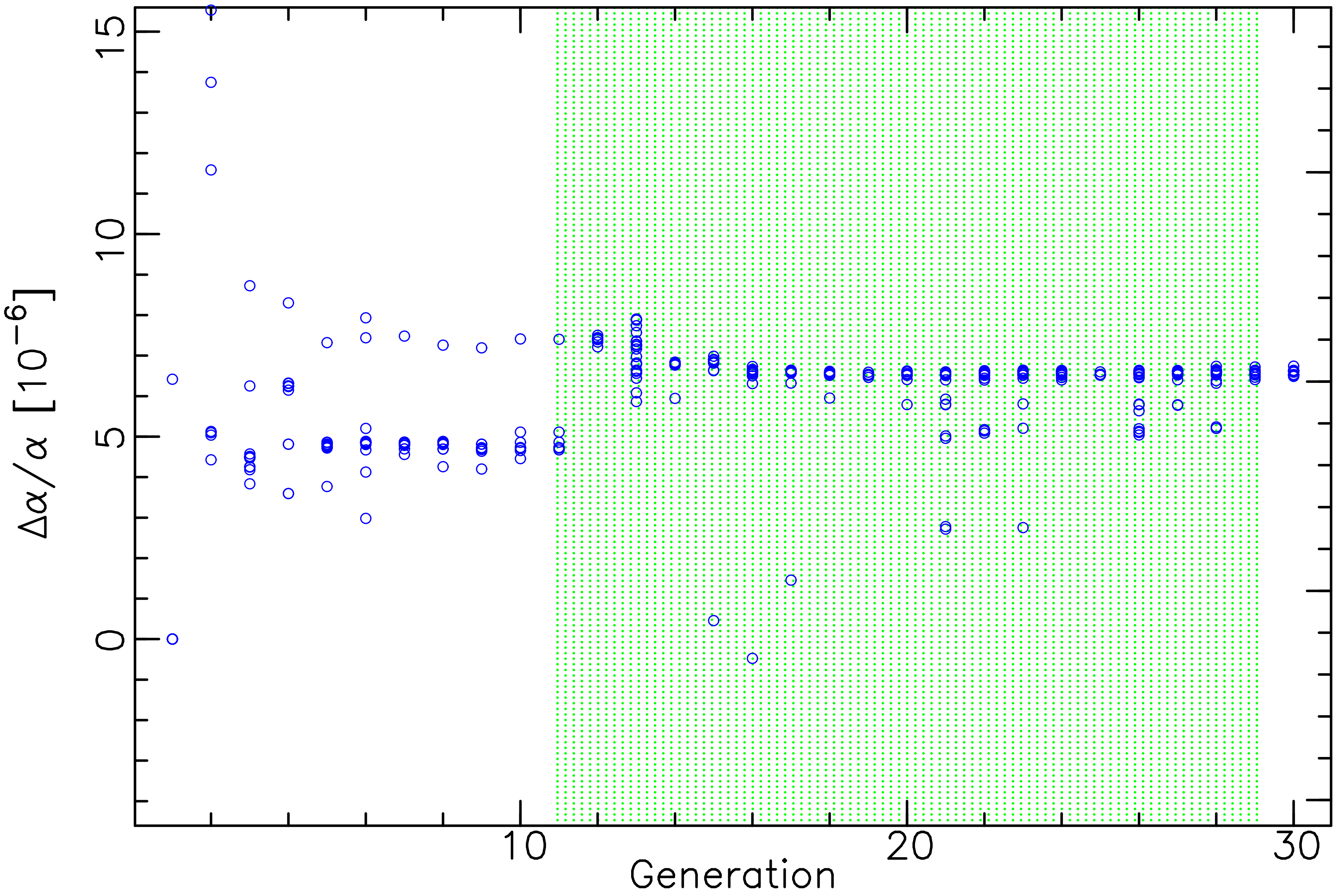


INITIALISATION
* Set all atomic data;
* Identify atomic species to be fitted;
* Define instrumental spectral resolution;
* Define M spectral ranges to be fitted;
* Set up all free and tied fitting parameters;
* Define genetic search first-guess parameter ranges, step sizes, stopping criteria;
* Initialise the population (i.e. create N "empty" spectral segments).
REPRODUCTION
* Set up the current "parents" - populate the MxN spectral segments with first-guess models (at iteration zero this is a single absorption line. The model complexity increases with subsequent generations).
MUTATION
* Increase model complexity - add an additional absorption component.
Local non-linear least-squares optimisation of all MxN models (VPFIT)
SELECTION
* From the MxN, pick the "fittest", lowest chi-squared, model.
EVOLUTION
* Check selected model against stopping criteria;
* If stopping criteria not met, current model becomes the new "parent".
FeII 2382
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
6763
6764
6765
6763
6764
6765
Wavelength (Å)

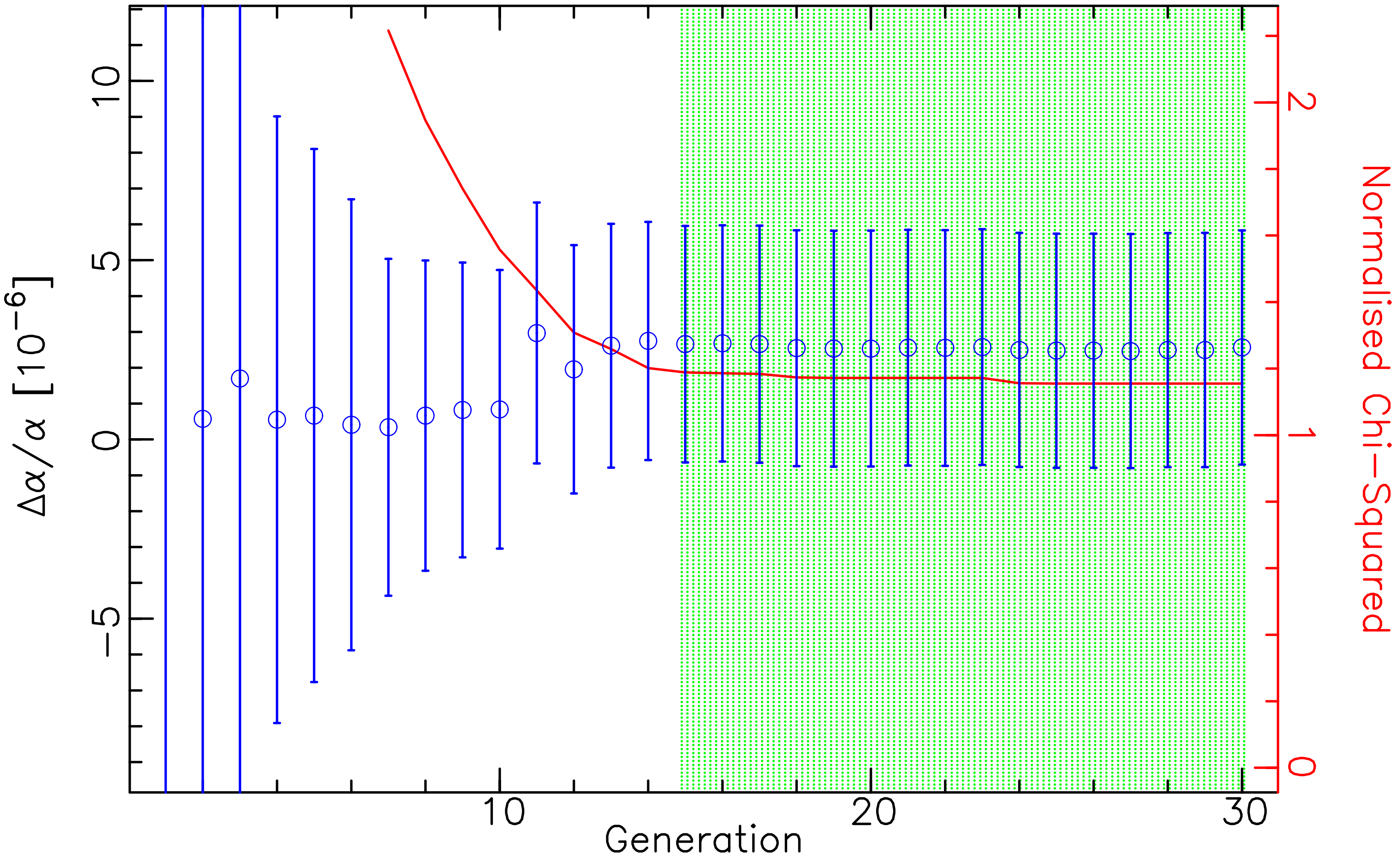
A genetic algorithm doesn't necessarily emulate what a human does – no unique model!



Every generation has a distribution of candidate Δα/α solutions



Δα/α solution is stable to first guesses and probably stable to small changes in the model



The first 1000 new measurements of the fine structure constant at high redshift using AI

Approximate many-multiplet sample sizes:
Already published: 300
Currently: ~500 completed measurements
Maximum possible using existing archives: ~1500

“Raijin” (named after the Shinto God of thunder, lightning and storms)
National Computational Infrastructure, ANU, Canberra, Australia

January-June 2017:

230,000 hours on “Raijin”, the world’s 24th most powerful computer

- 57,864 cores (Intel Xeon Sandy Bridge technology, 2.6 GHz) in 3602 compute nodes
- 56 NVIDIA Tesla K80 GPUs
- 162 TBytes of main memory
- Mellanox FDR 56 Gb/sec Infiniband full fat tree interconnect
- 12.5 PBytes of high-performance operational storage capacity
- This provides a peak performance of approximately 1.37 Pflops

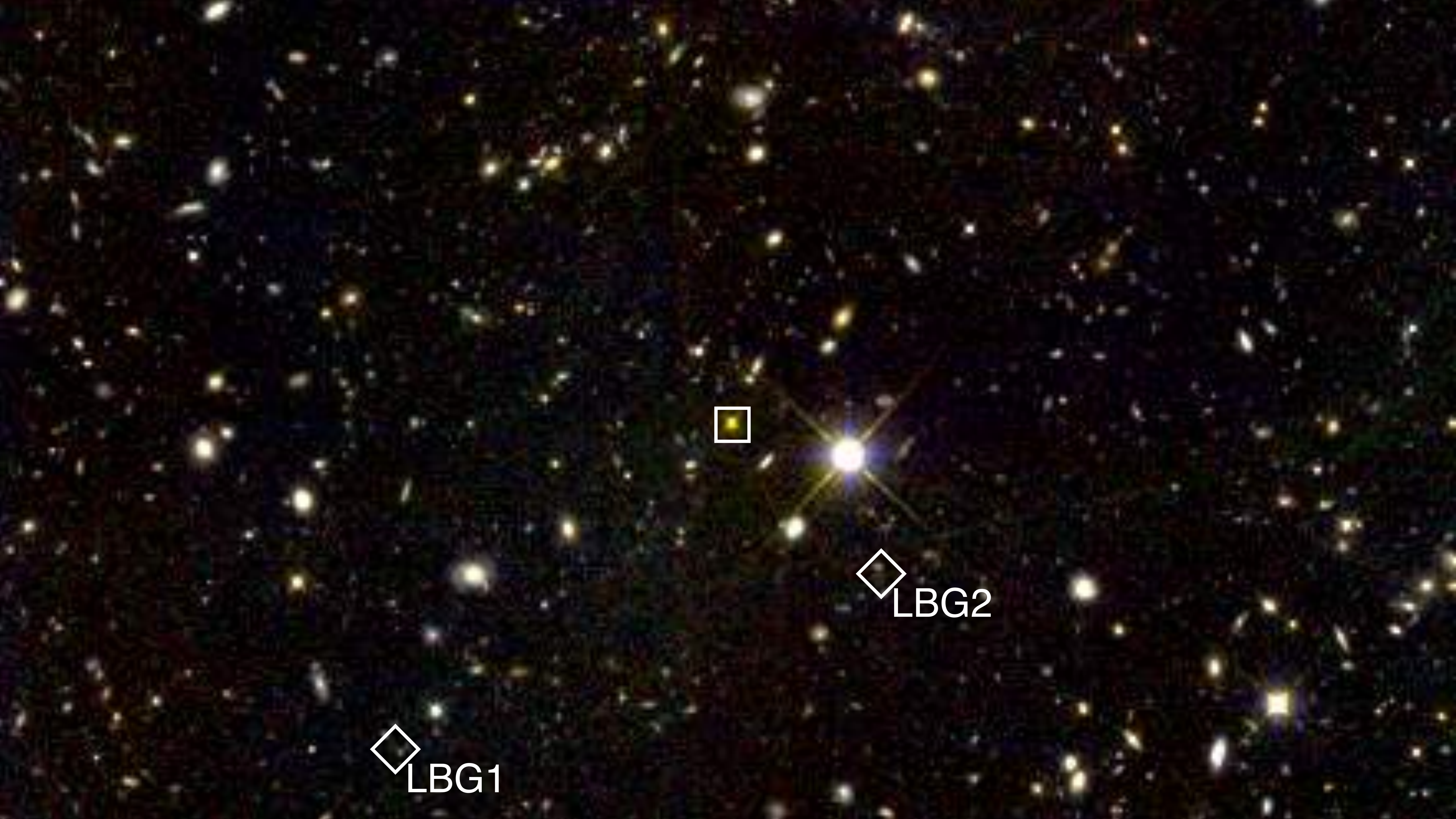
ULAS J1120+0641
2nd highest redshift quasar (as of Dec 2017)

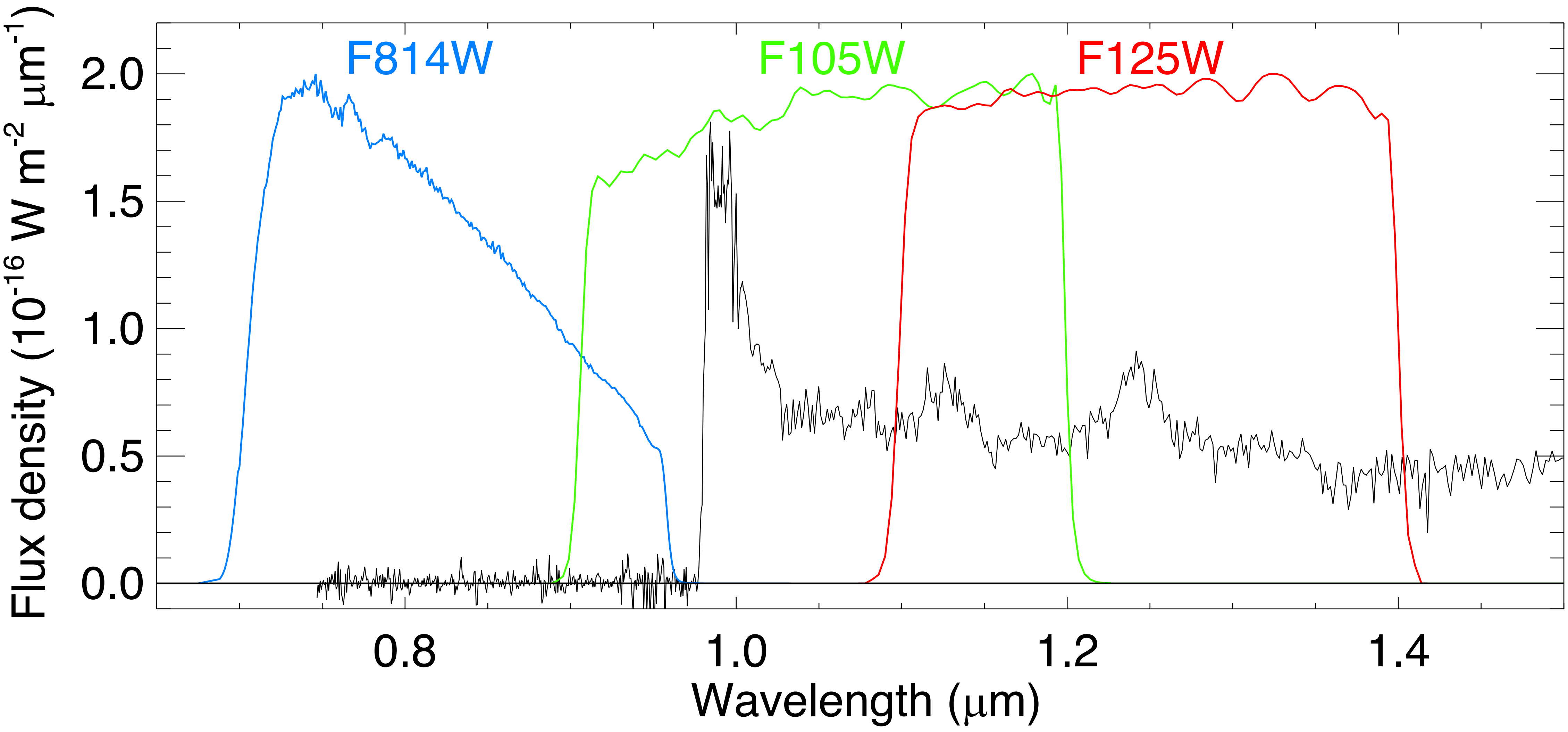
Discovered in 2011 by the UK Infrared telescope, Hawaii

Luminosity $6.3 \times 10^{13} L_{\odot}$

Black hole nucleus mass $2 \times 10^{9} M_{\odot}$

Mortlock et al
Nature, **474**, 616–619 (30 June 2011)

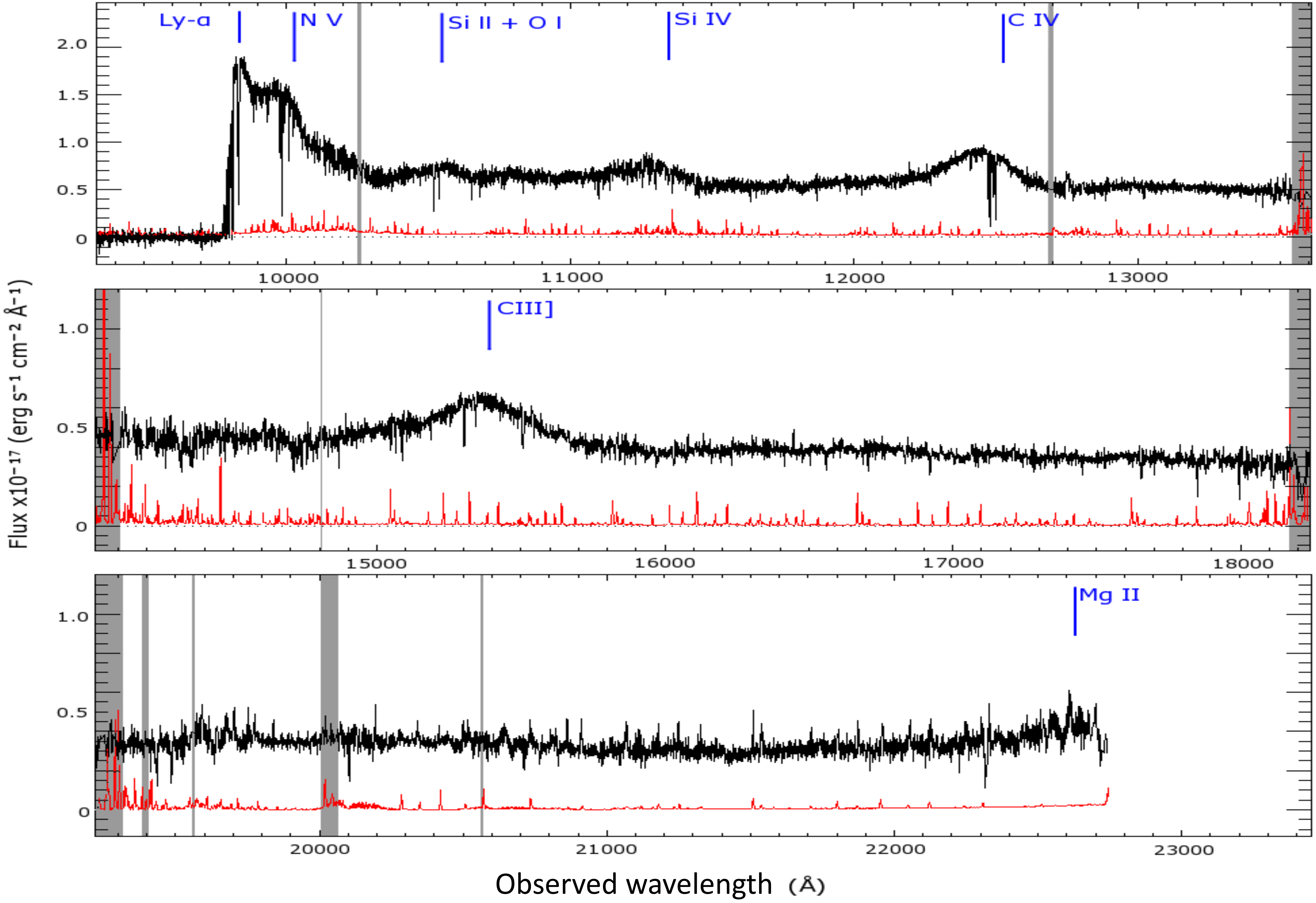

LBG2
LBG1

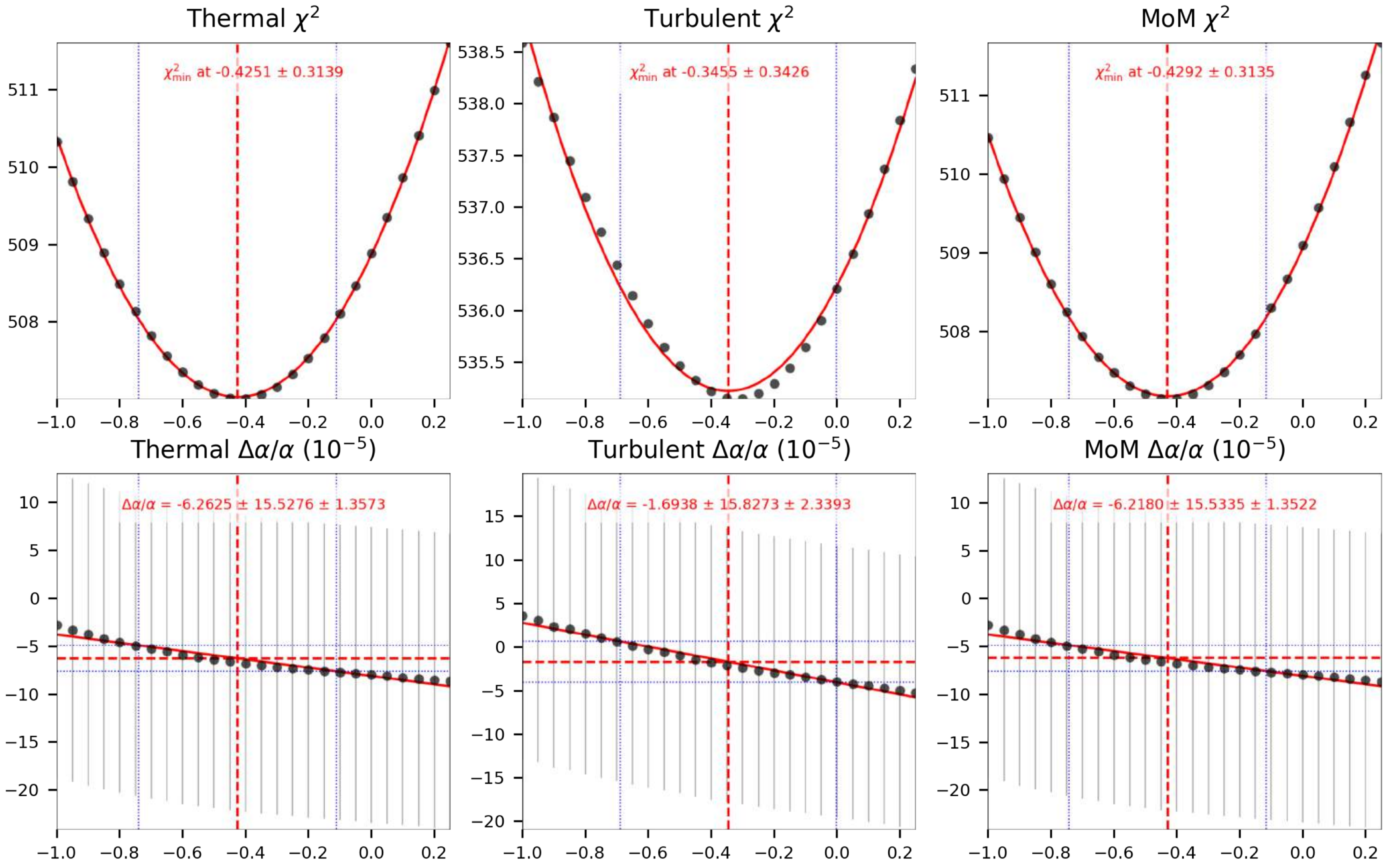


Mortlock et al 2011

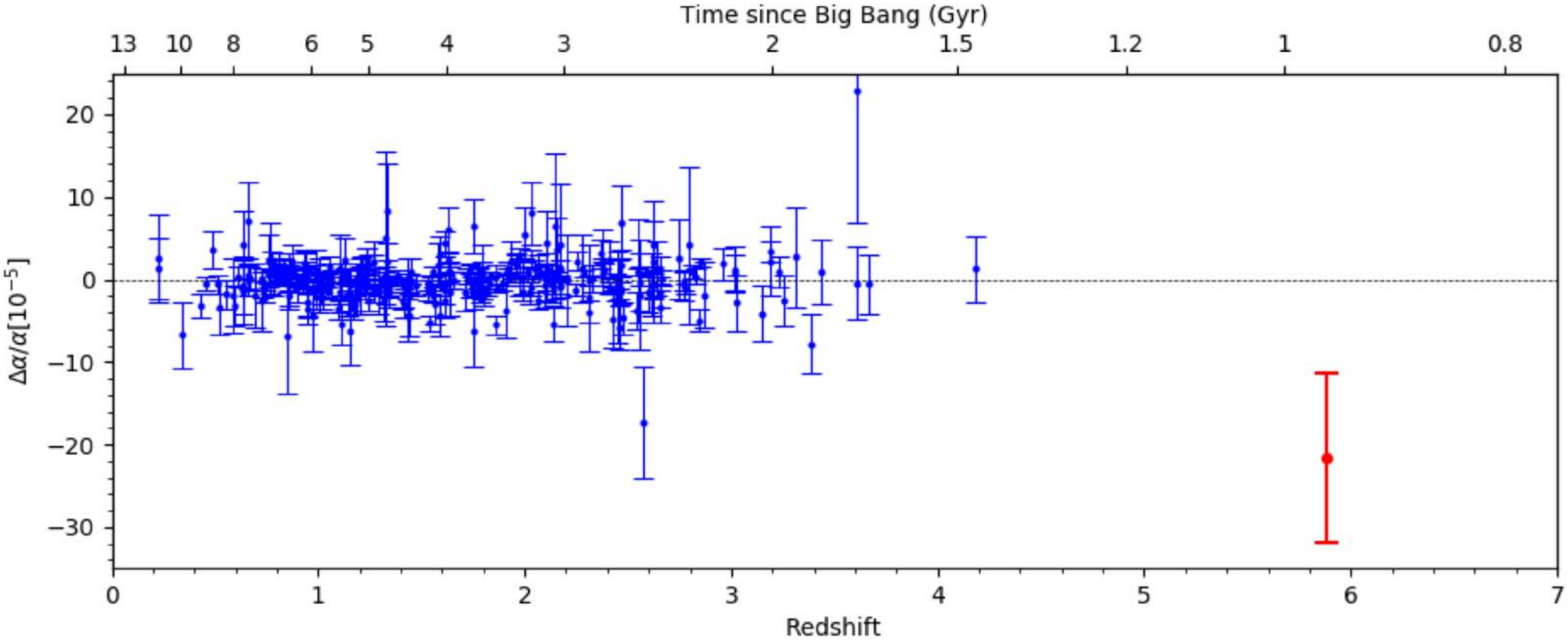
XSHOOTER/VLT spectrum

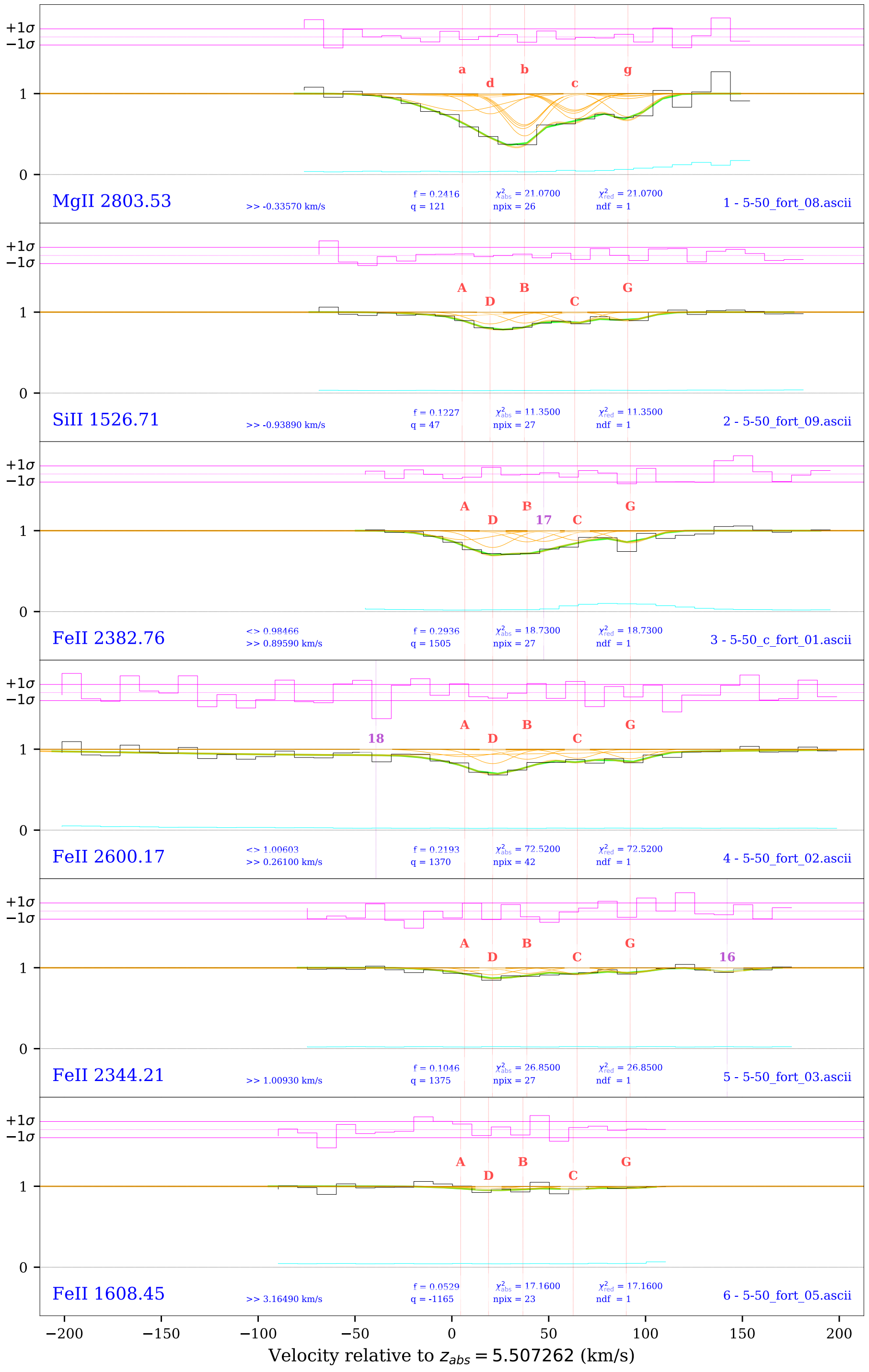
Bosman et al 2017
MNRAS 470 (2): 1919-1934 (2017)
arXiv:1705.08925v1



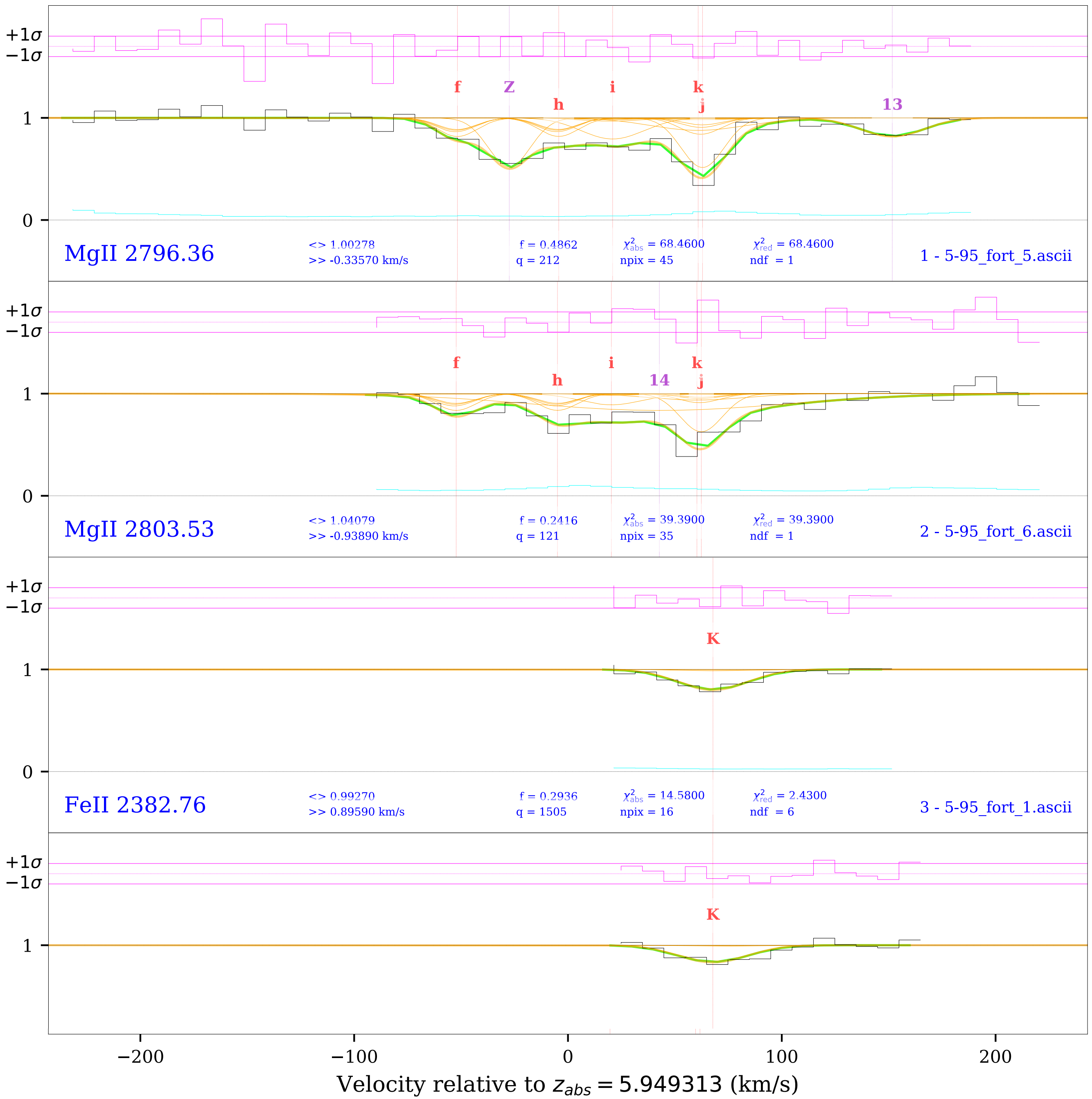


Thermal χ^2
Turbulent χ^2
MoM χ^2
χ^2_{min} at -0.4251 ± 0.3139
χ^2_{min} at -0.3455 ± 0.3426
χ^2_{min} at -0.4292 ± 0.3135
Thermal $\Delta\alpha/\alpha$ (10^{-5})
Turbulent $\Delta\alpha/\alpha$ (10^{-5})
MoM $\Delta\alpha/\alpha$ (10^{-5})
$\Delta\alpha/\alpha$ = -6.2625 ± 15.5276 ± 1.3573
$\Delta\alpha/\alpha$ = -1.6938 ± 15.8273 ± 2.3393
$\Delta\alpha/\alpha$ = -6.2180 ± 15.5335 ± 1.3522

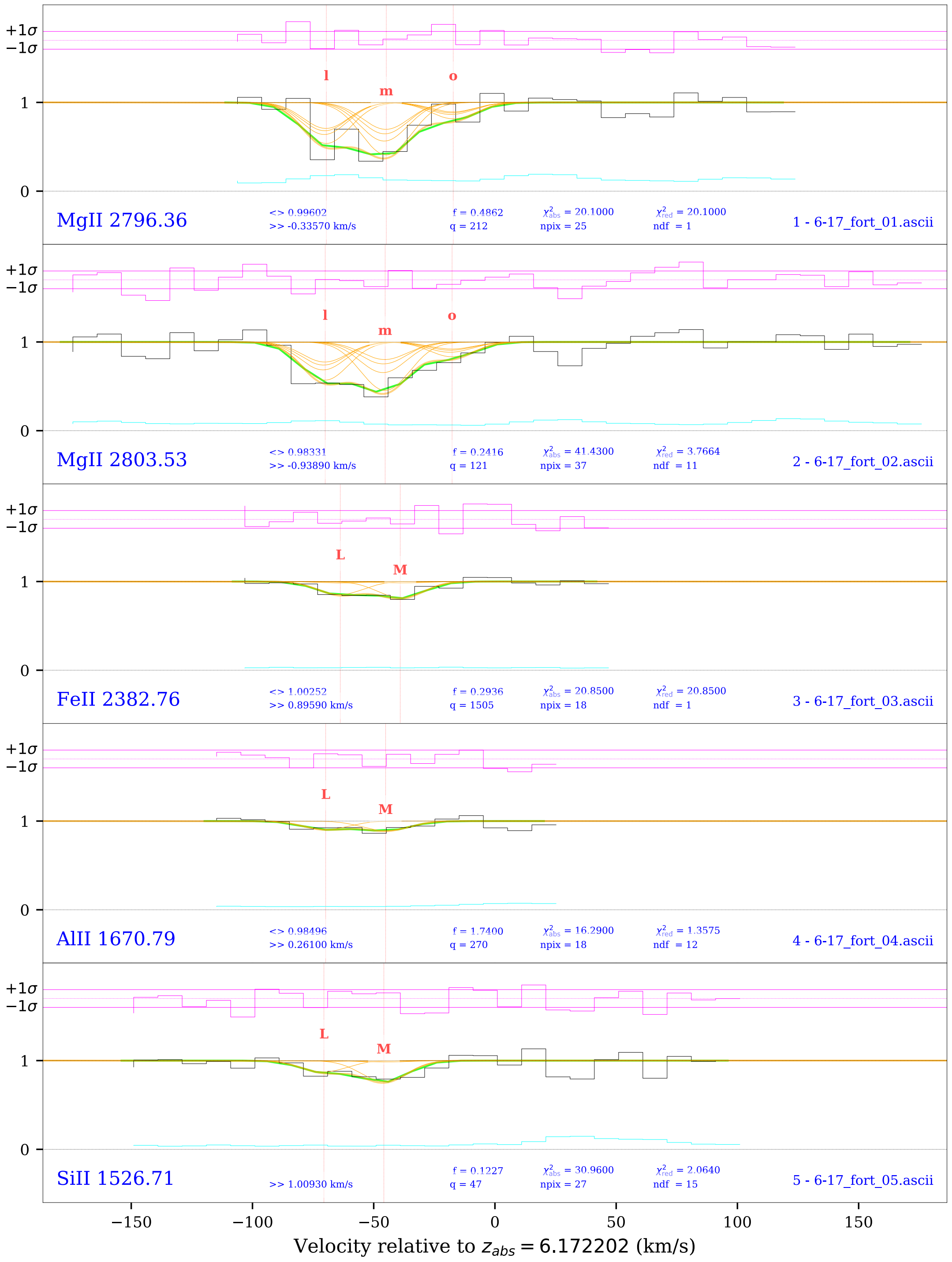

Time since Big Bang (Gyr)
13
10
8
6
5
4
3
2
1.5
1.2
1
0.8
$\Delta\alpha/\alpha[10^{-5}]$
20
10
0
−10
−20
−30
0
1
2
3
4
5
6
7
Redshift



MgII 2803.53
SiII 1526.71
FeII 2382.76
FeII 2600.17
FeII 2344.21
FeII 1608.45
1 - 5-50_fort_08.ascii
2 - 5-50_fort_09.ascii
3 - 5-50_c_fort_01.ascii
4 - 5-50_fort_02.ascii
5 - 5-50_fort_03.ascii
6 - 5-50_fort_05.ascii
Velocity relative to $z_{abs} = 5.507262$ (km/s)



+1σ
−1σ
f
Z
h
i
k
j
13
MgII 2796.36
<> 1.00278
>> -0.33570 km/s
f = 0.4862
q = 212
χ^2_{abs} = 68.4600
npix = 45
χ^2_{red} = 68.4600
ndf = 1
1 - 5-95_fort_5.ascii
14
MgII 2803.53
<> 1.04079
>> -0.93890 km/s
f = 0.2416
q = 121
χ^2_{abs} = 39.3900
npix = 35
χ^2_{red} = 39.3900
ndf = 1
2 - 5-95_fort_6.ascii
K
FeII 2382.76
<> 0.99270
>> 0.89590 km/s
f = 0.2936
q = 1505
χ^2_{abs} = 14.5800
npix = 16
χ^2_{red} = 2.4300
ndf = 6
3 - 5-95_fort_1.ascii
−200
−100
0
100
200
Velocity relative to z_{abs} = 5.949313 (km/s)



MgII 2796.36
<> 0.99602
>> -0.33570 km/s
f = 0.4862
q = 212
χ²abs = 20.1000
npix = 25
χ²red = 20.1000
ndf = 1
1 - 6-17_fort_01.ascii
MgII 2803.53
<> 0.98331
>> -0.93890 km/s
f = 0.2416
q = 121
χ²abs = 41.4300
npix = 37
χ²red = 3.7664
ndf = 11
2 - 6-17_fort_02.ascii
FeII 2382.76
<> 1.00252
>> 0.89590 km/s
f = 0.2936
q = 1505
χ²abs = 20.8500
npix = 18
χ²red = 20.8500
ndf = 1
3 - 6-17_fort_03.ascii
AlII 1670.79
<> 0.98496
>> 0.26100 km/s
f = 1.7400
q = 270
χ²abs = 16.2900
npix = 18
χ²red = 1.3575
ndf = 12
4 - 6-17_fort_04.ascii
SiII 1526.71
>> 1.00930 km/s
f = 0.1227
q = 47
χ²abs = 30.9600
npix = 27
χ²red = 2.0640
ndf = 15
5 - 6-17_fort_05.ascii
Velocity relative to $z_{abs} = 6.172202$ (km/s)

z_{abs}	Original $\Delta\alpha/\alpha\,[10^{-5}]$	Distortion Corrected $\Delta\alpha/\alpha\,[10^{-5}]$
6.17110	-25.34±14.69	-32.04±14.72
5.95070	-30.29±33.88	-38.51±33.88
5.50793	-7.95±15.41	-6.60±15.48
Weighted mean	-18.24±10.14	-21.64±10.17

Summary

1. Spatially varying alpha – status unchanged. Result does not "go away". Long-range echelle spectrograph wavelength distortions do not account for it (arXiv:1701.03176).

2. New AI method full automates analysis and gives more robust and faster measurements (but requires supercomputers). Target is the first 1000 measurements of varying alpha. Timescale 18 months (arXiv:1704.08710, arXiv:1606.07393).

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