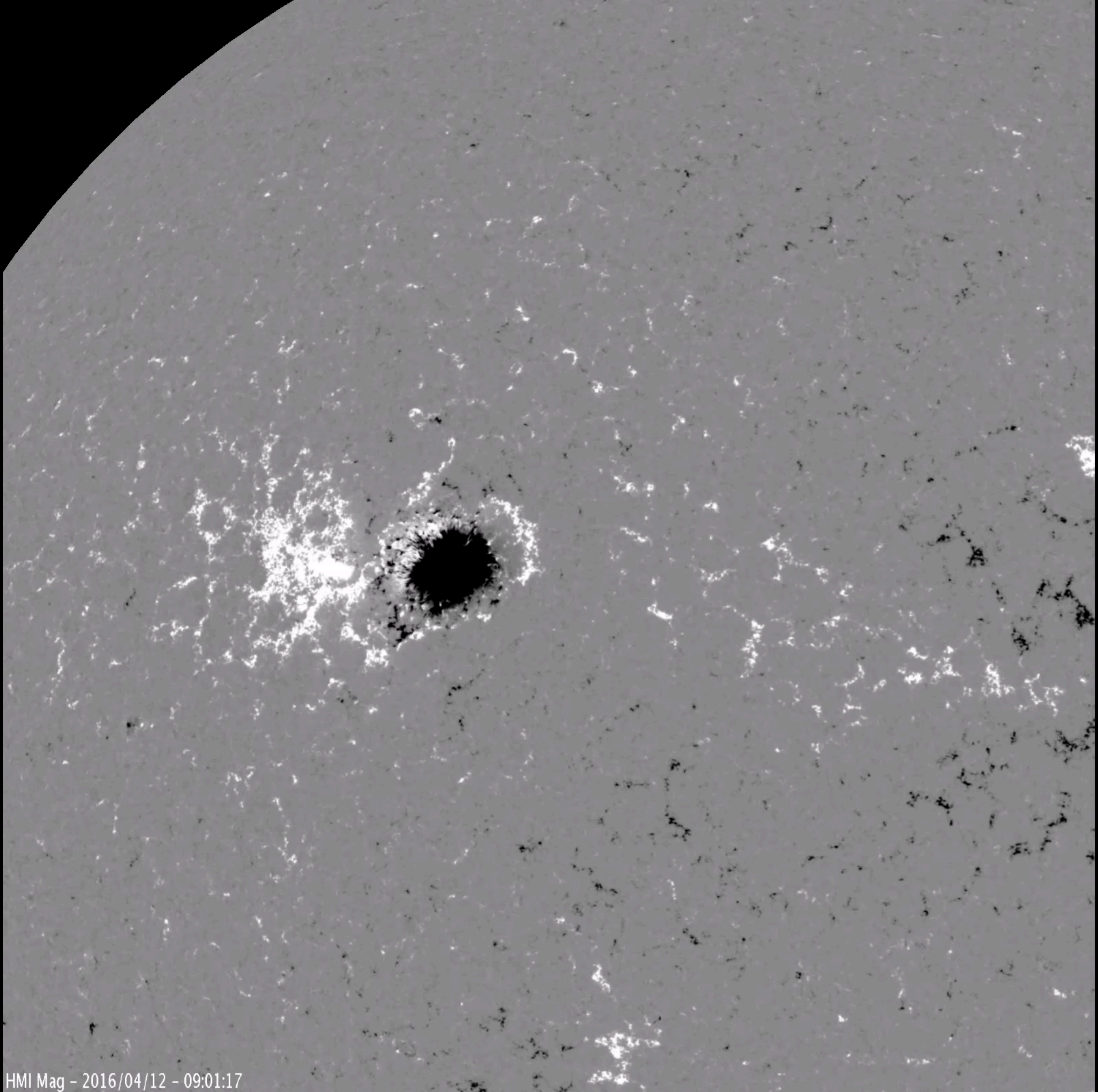
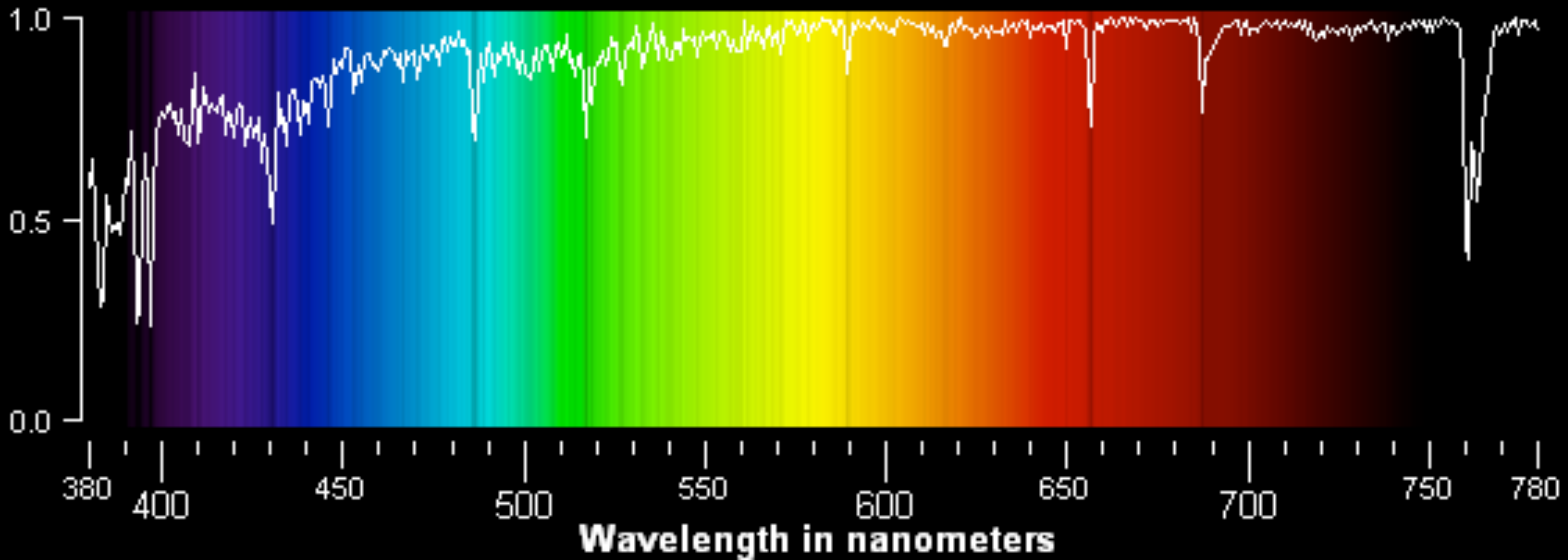
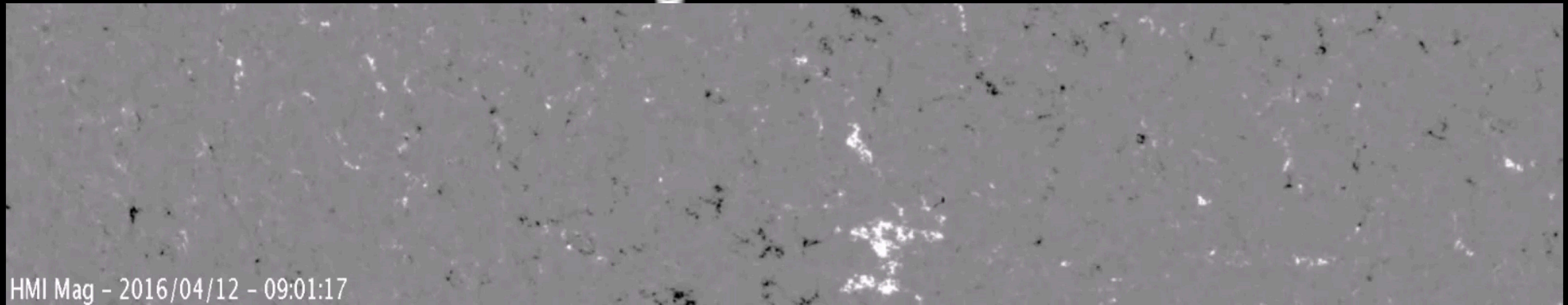
Atomic astrophysics with 3D non-LTE stellar spectroscopy

Anish Amarsi (Uppsala University)

ASOS14, Paris, 11 July 2023


HMI Mag – 2016/04/12 – 09:01:17


1.0
0.5
0.0
380
400
450
500
550
600
650
700
750
780
Wavelength in nanometers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The solar chemical composition

- Thanks to **improved atomic data**, composition of the Sun was apparently well-constrained at the end of the 20th century
  - Grevesse & Noels 1993: Z=1.72%
  - Grevesse & Sauval 1998: Z=1.69%

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Physica Scripta. Vol. T47, 133–138, 1993

Atomic Data and the Spectrum of the Solar Photosphere

N. Grevesse and A. Noels

Institut d'Astrophysique, Université de Liège, 5, avenue de Cointe, B-4000 Liege, Belgium

Received October 14, 1992; accepted in revised form February 12, 1993

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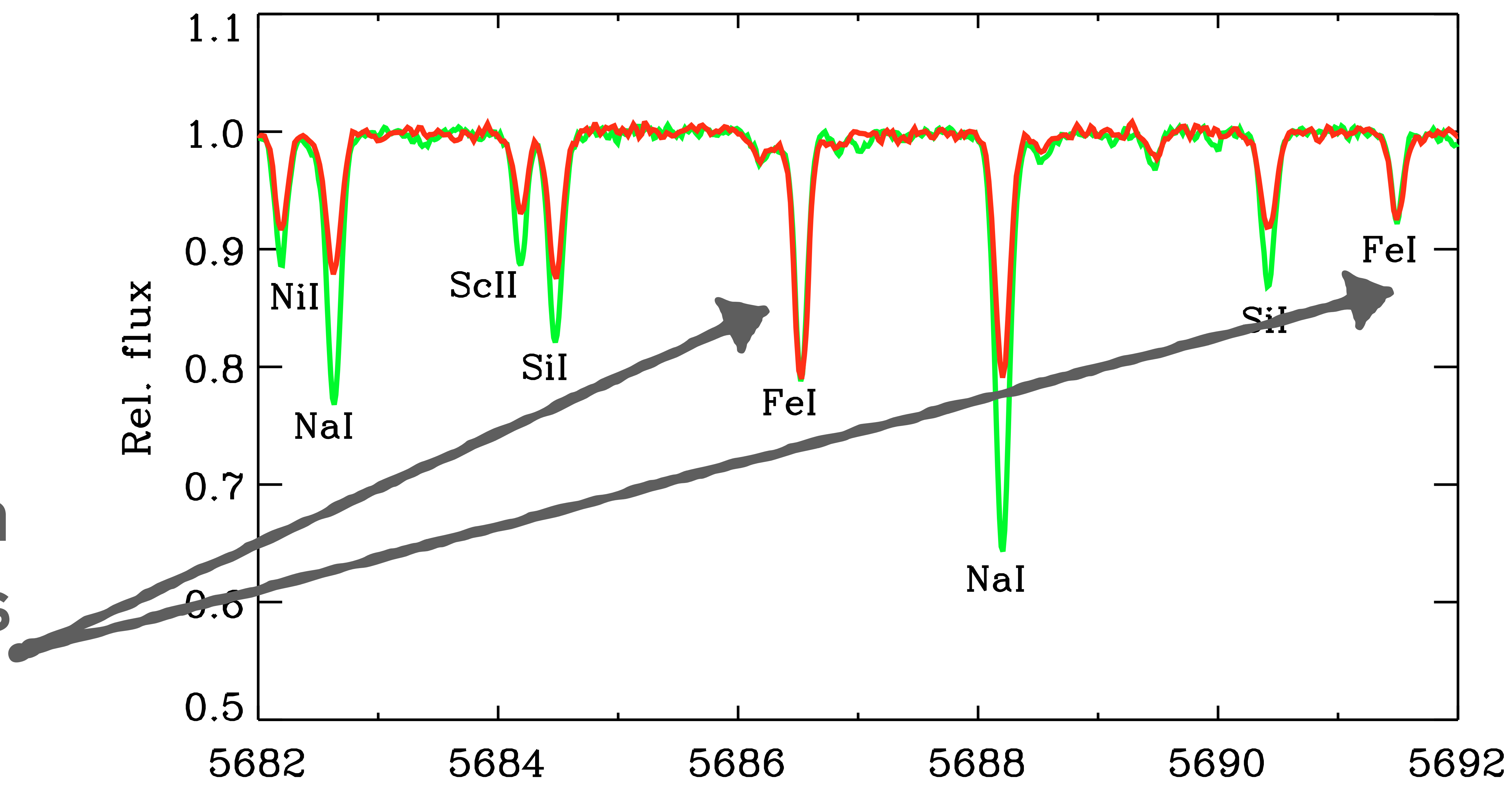
Much smaller line-by-line scatter when they used improved oscillator strengths



Example stellar spectra [Nissen & Schuster 2010]

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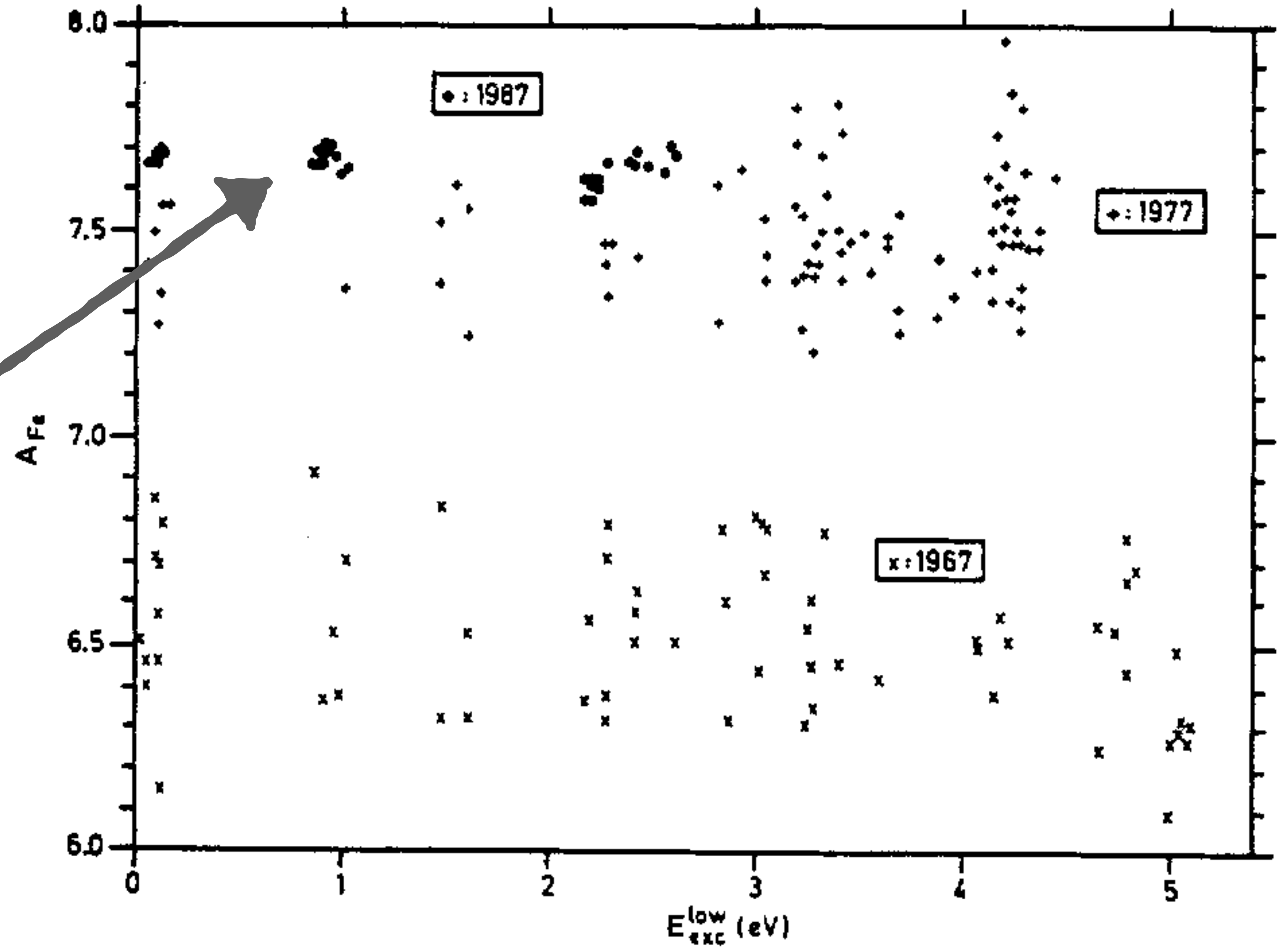

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(In this plot: Blackwell et al. 1987)

Evolution of solar iron abundance with improving log gf data [Grevesse & Noels 1993]

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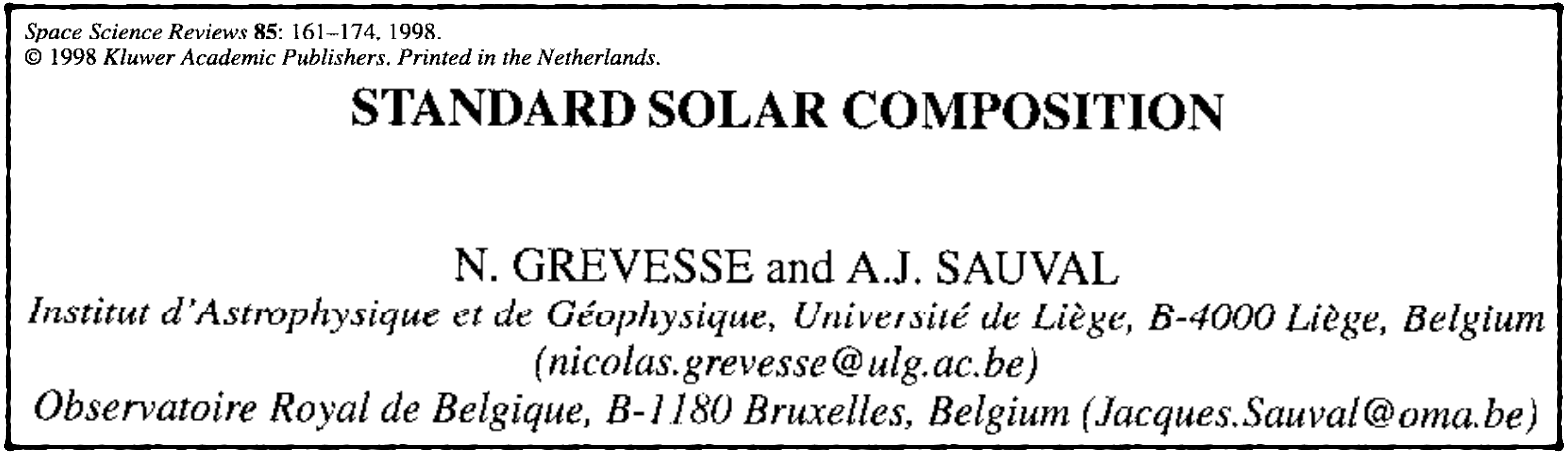
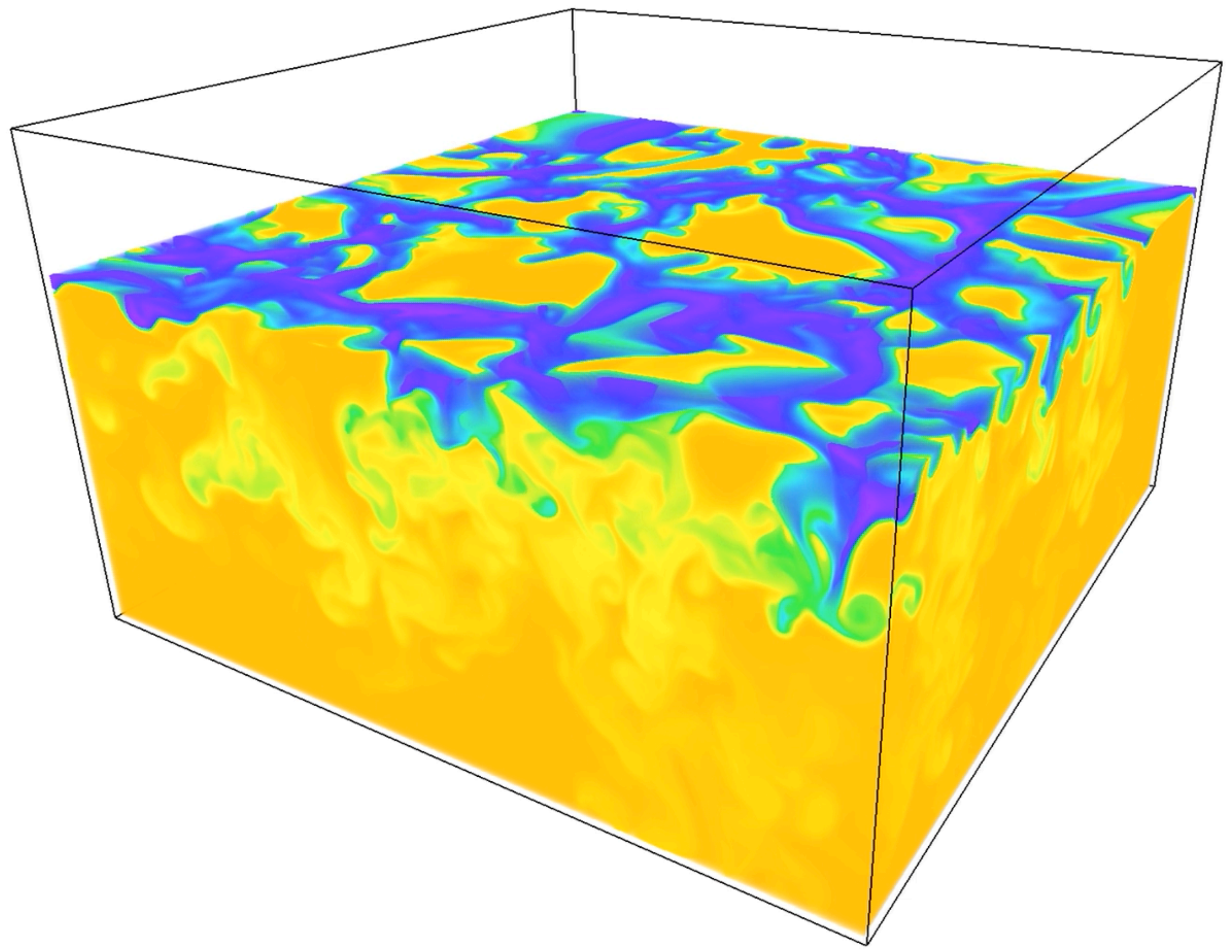

Space Science Reviews **85**: 161–174, 1998.

STANDARD SOLAR COMPOSITION

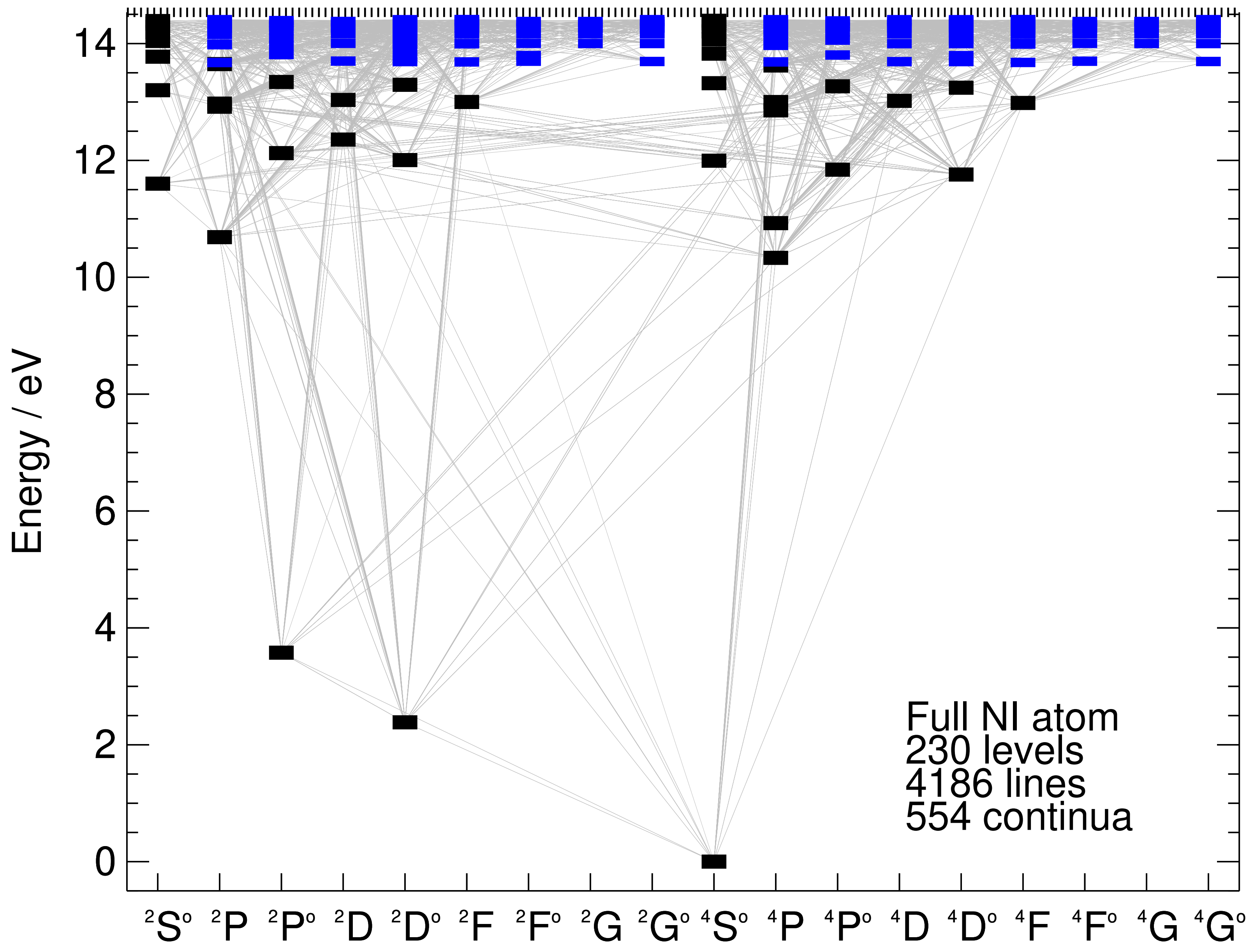
N. GREVESSE and A.J. SAUVAL
Institut d'Astrophysique et de Géophysique, Université de Liège, B-4000 Liège, Belgium
(nicolas.grevesse@ulg.ac.be)
Observatoire Royal de Belgique, B-1180 Bruxelles, Belgium (Jacques.Sauval@oma.be)

The revised solar chemical composition

- However, 1990's analyses were based on simple 1D LTE models:
  - Grevesse & Sauval 1998, Z=1.69%



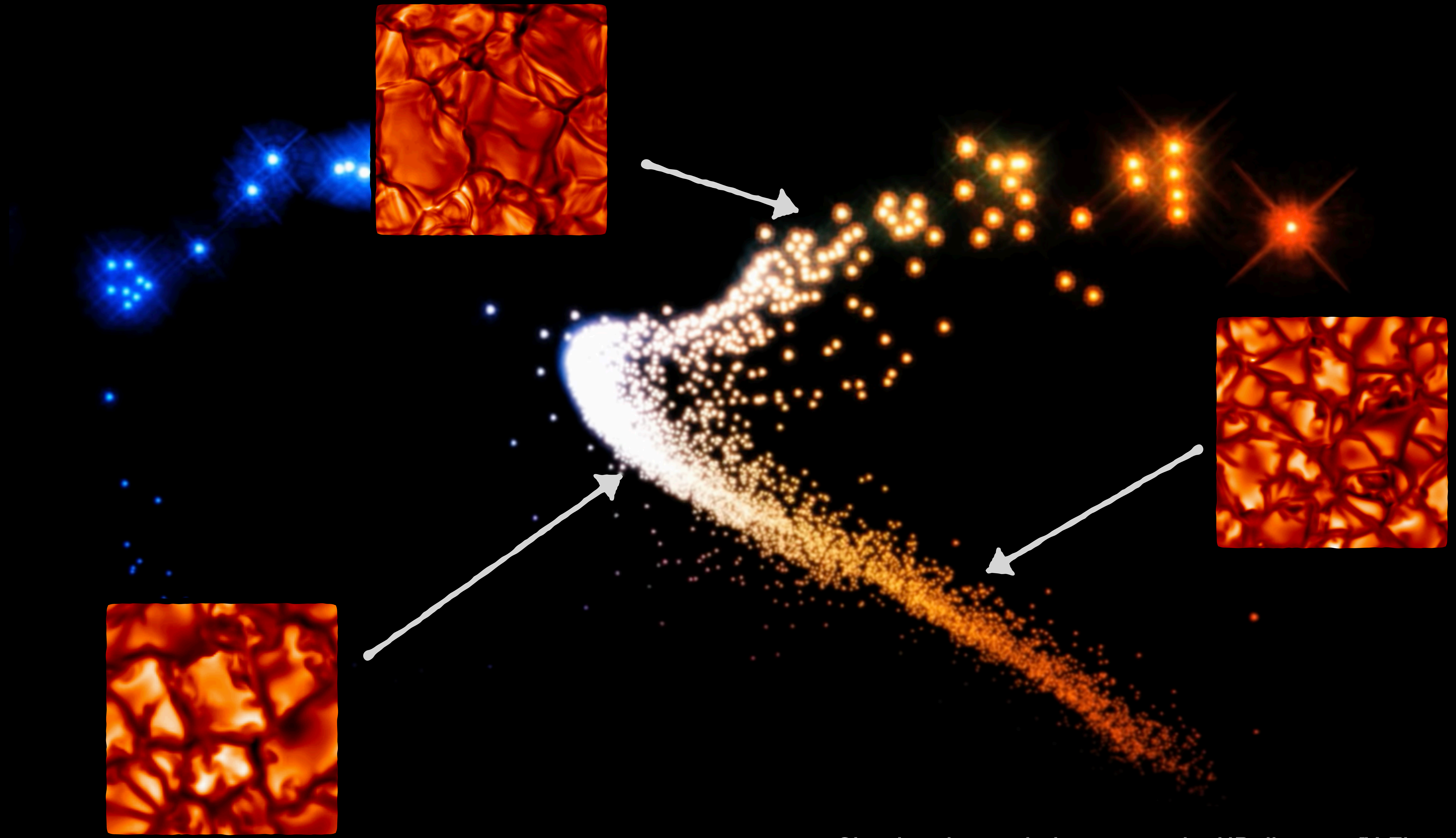
- Reality: stellar atmospheres are 3D non-LTE



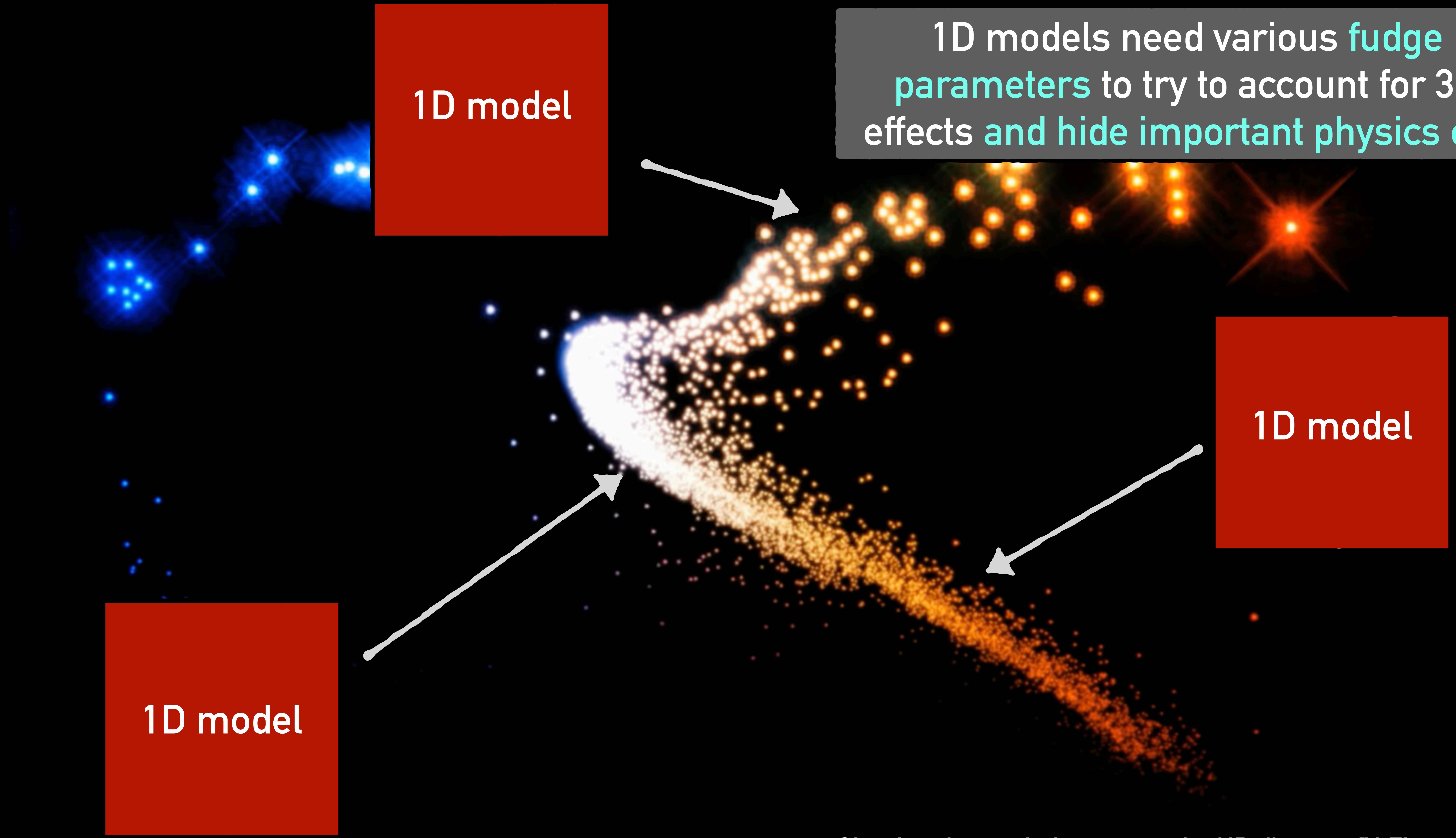

2016 Sep 19 09:01:00.000 (TAI)
SDO/HMI + SST view of the Sun [J. Leenaarts & J. de la Cruz Rodriguez, Stockholm; NASA Scientific Visualisation Studio]

y [Mm]
0
2
4
6
x [Mm]
0
2
4
6
x [Mm]
0
2
4
6

y [Mm]
6
4
2
0
0
0
Observations
(Swedish solar telescope)
Simulations
(Stagger code)



Simulated granulation across the HR diagram [Y. Zhou, Aarhus]



1D models need various fudge parameters to try to account for 3D effects and hide important physics e.g.

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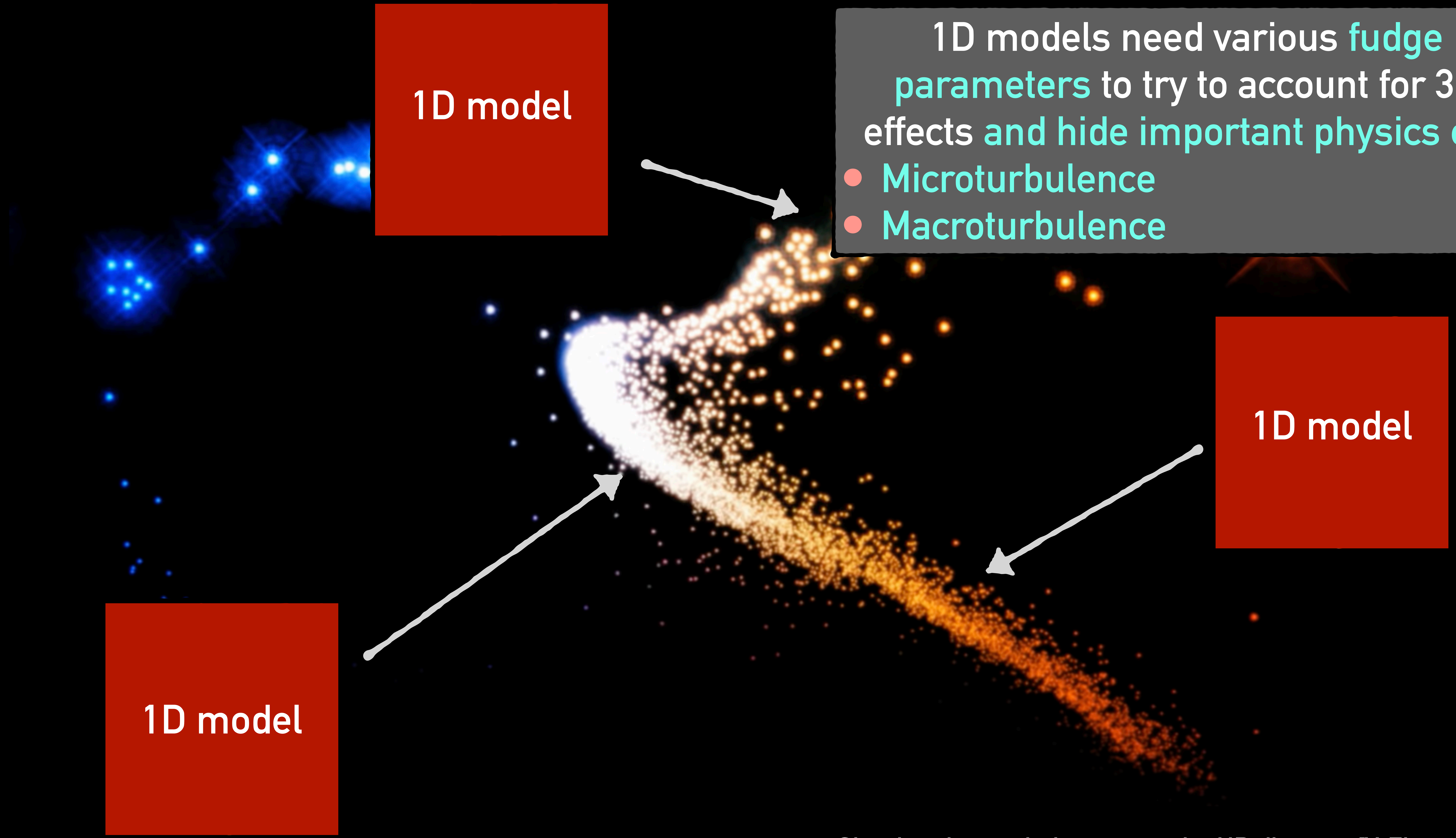

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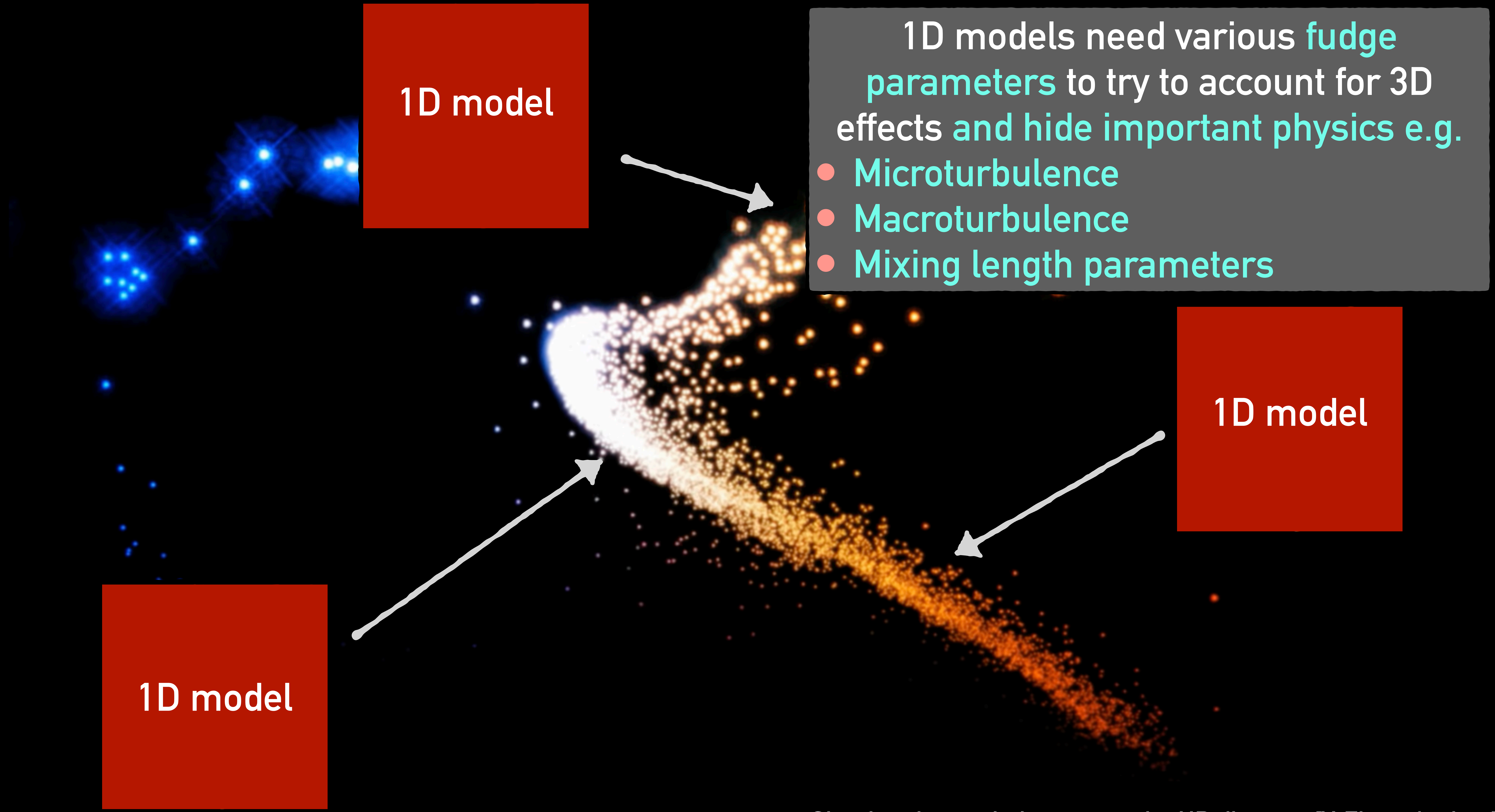

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1D models need various fudge parameters to try to account for 3D effects and hide important physics e.g.

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- Mixing length parameters
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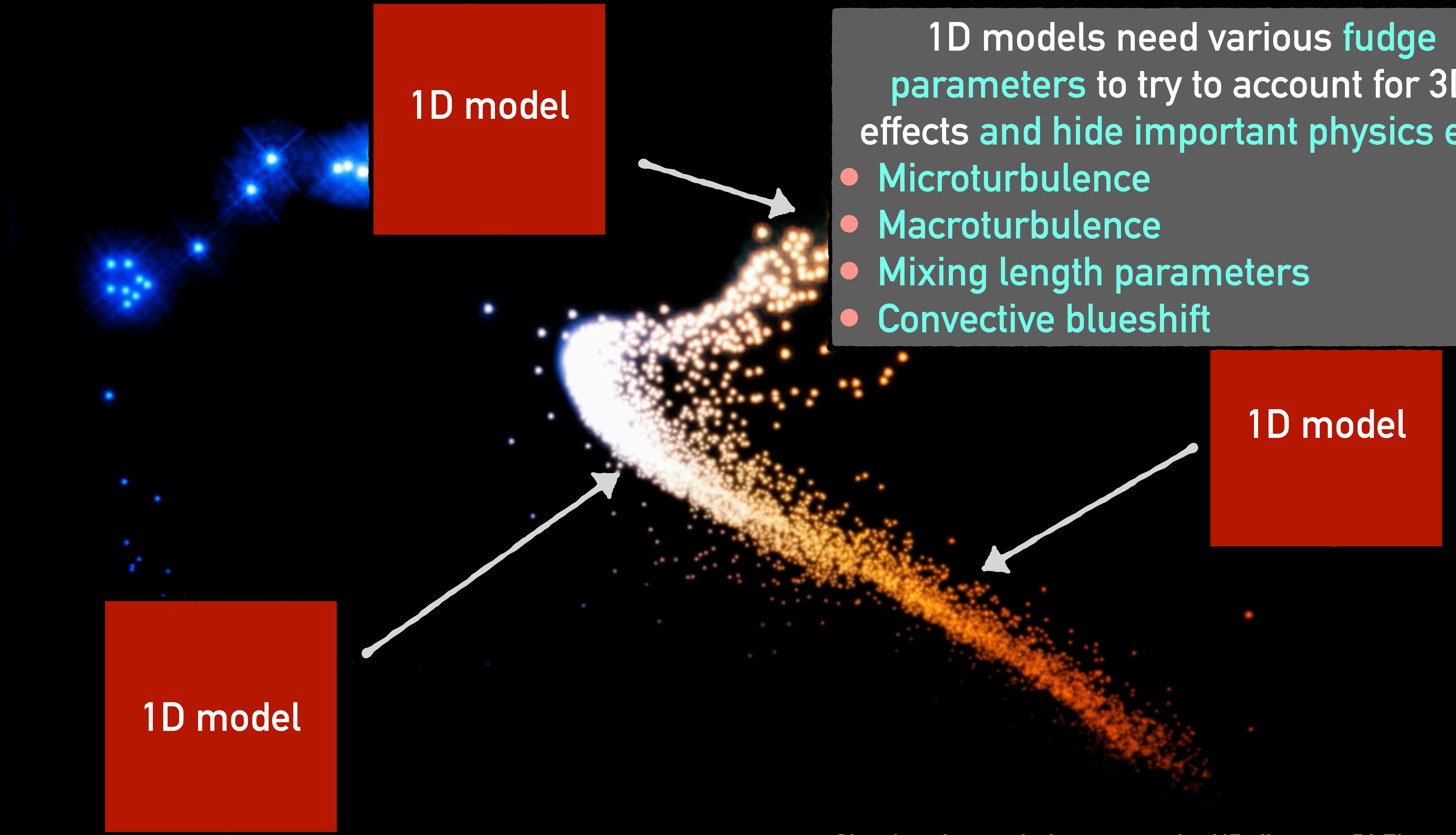

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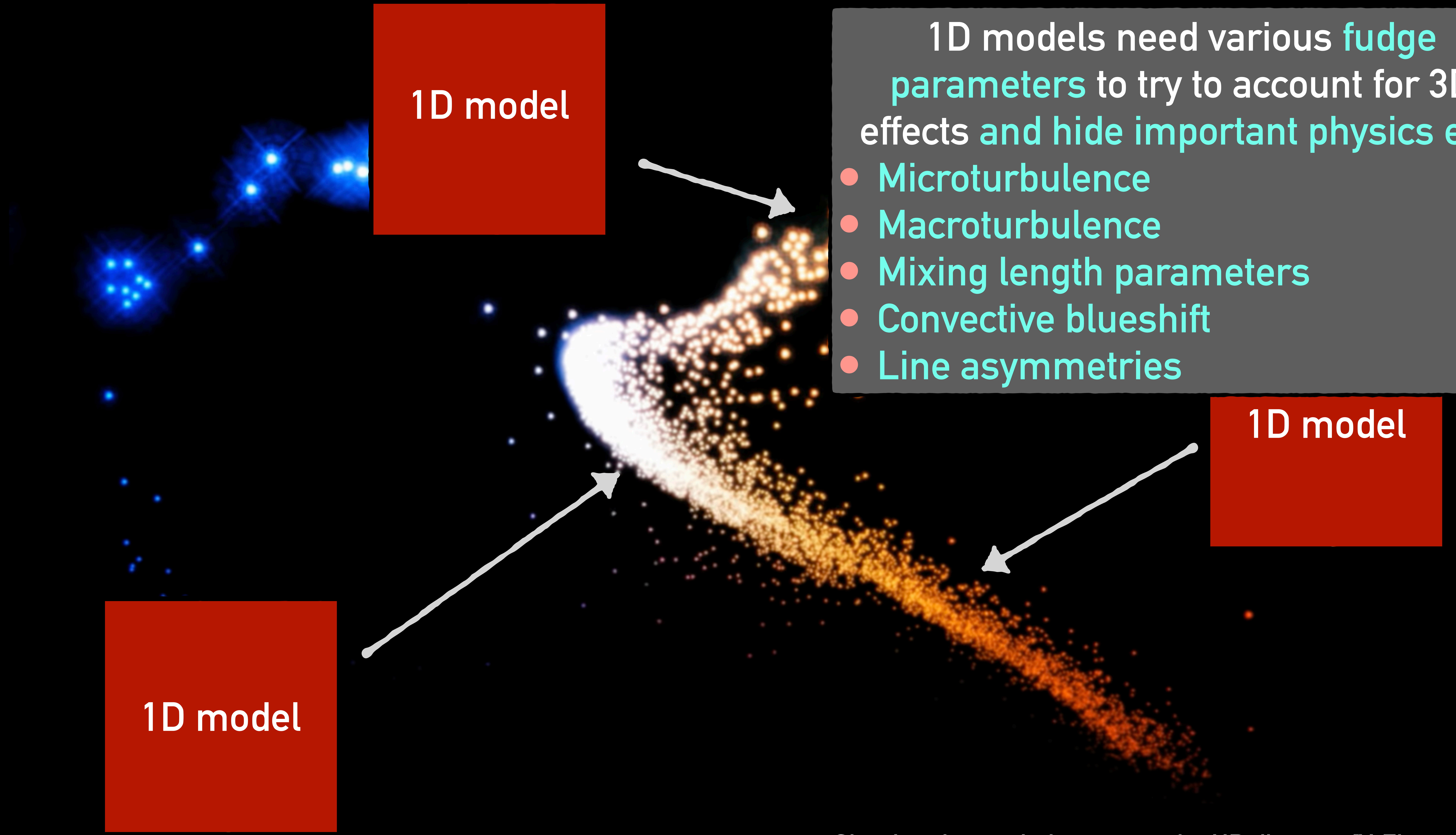

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- Microturbulence
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- Line asymmetries

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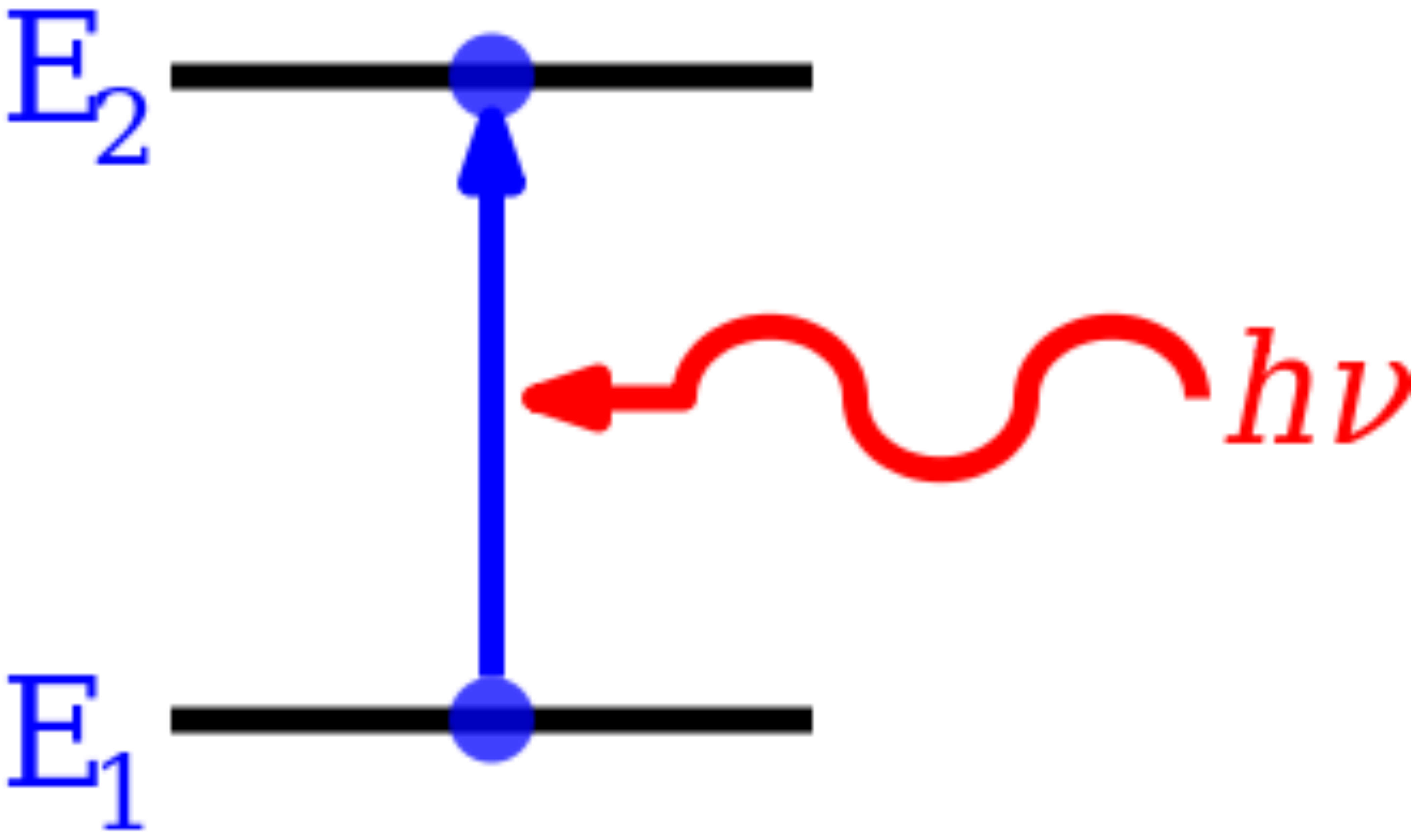
1D model
1D model
1D models need various fudge parameters to try to account for 3D effects and hide important physics e.g.
Microturbulence
Macroturbulence
Mixing length parameters
Convective blueshift
Line asymmetries
Line strengthening/weakening
Simulated granulation across the HR diagram [Y. Zhou, Aarhus]

LTE versus non-LTE

$$n_1 \propto \exp(-\frac{E_1}{k_b T})$$



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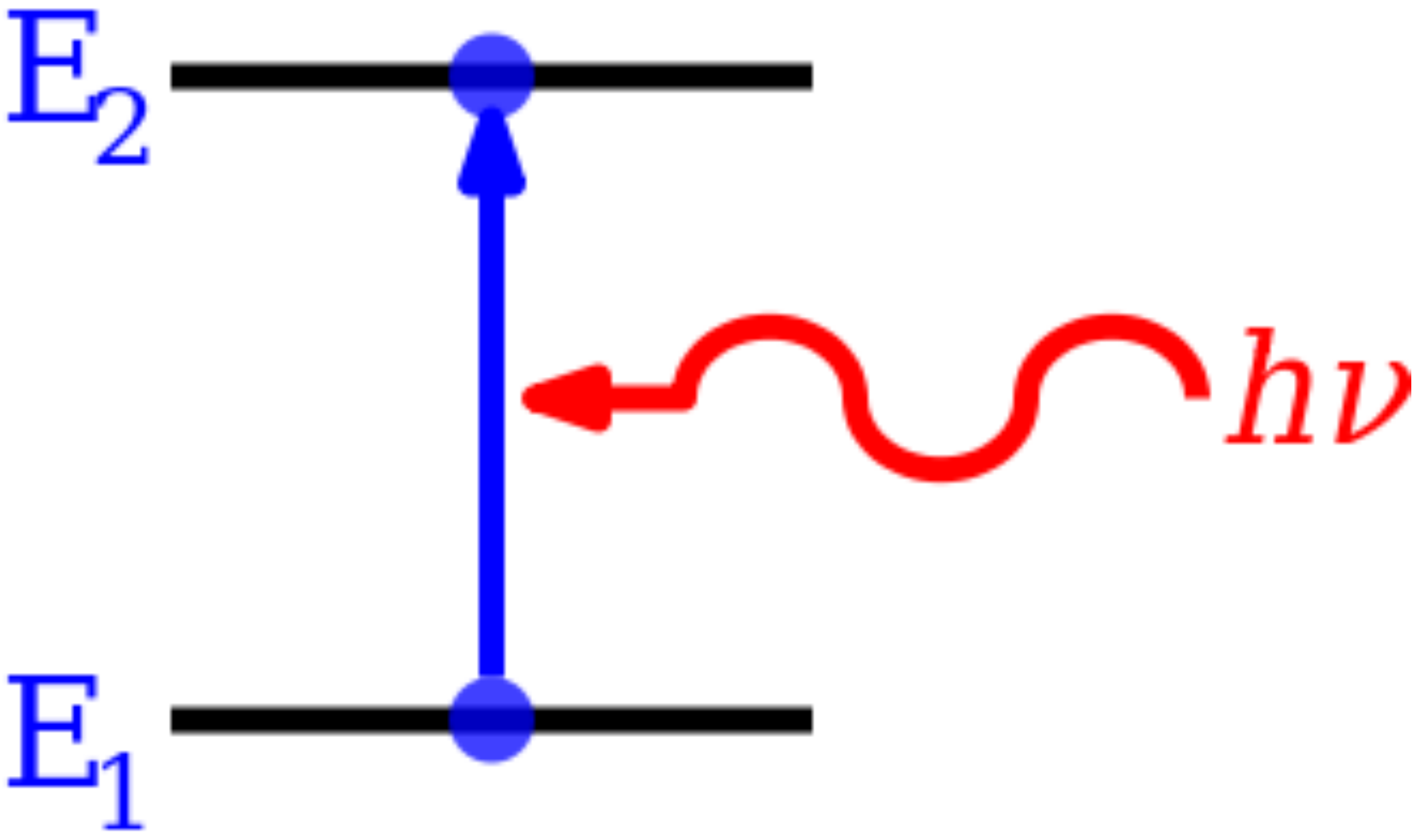
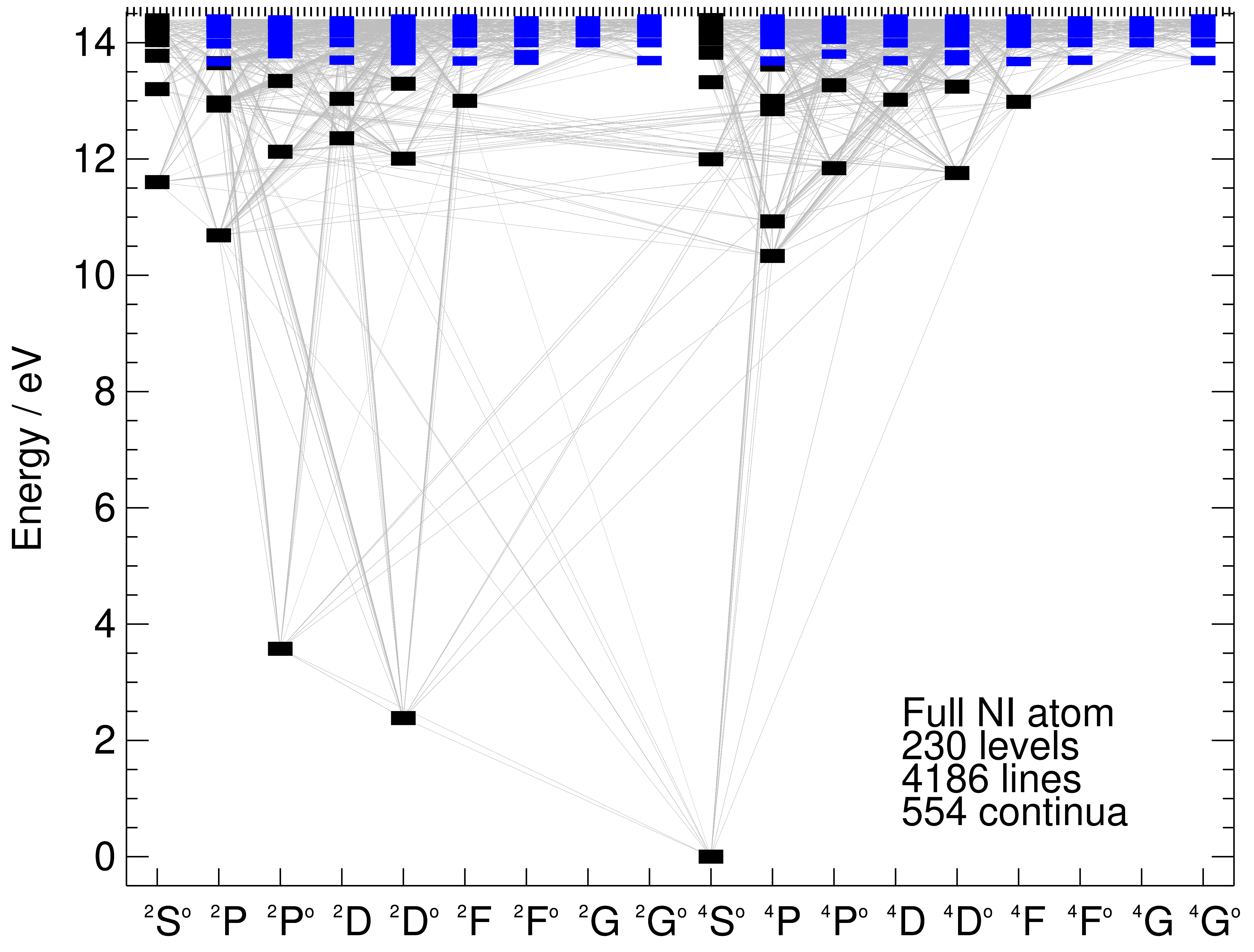


$$n_i \sum_j P_{i\to j} = \sum_j n_j P_{j\to i}$$

$$\frac{\mathrm{d}I_\nu}{\mathrm{d}\tau_\nu} = S_\nu - I_\nu$$



Grotrian diagram for neutral nitrogen [Amarsi+ 2020]

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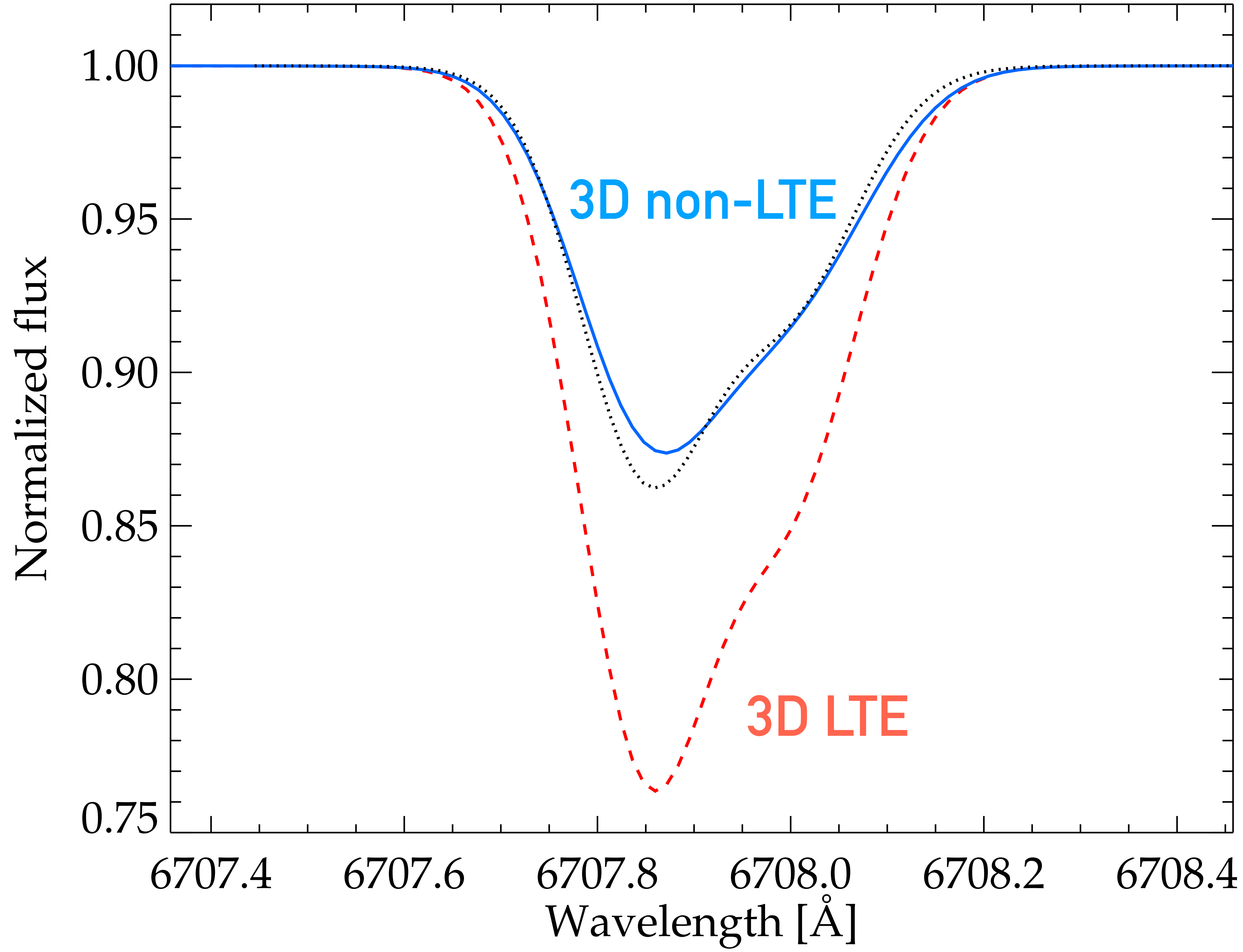
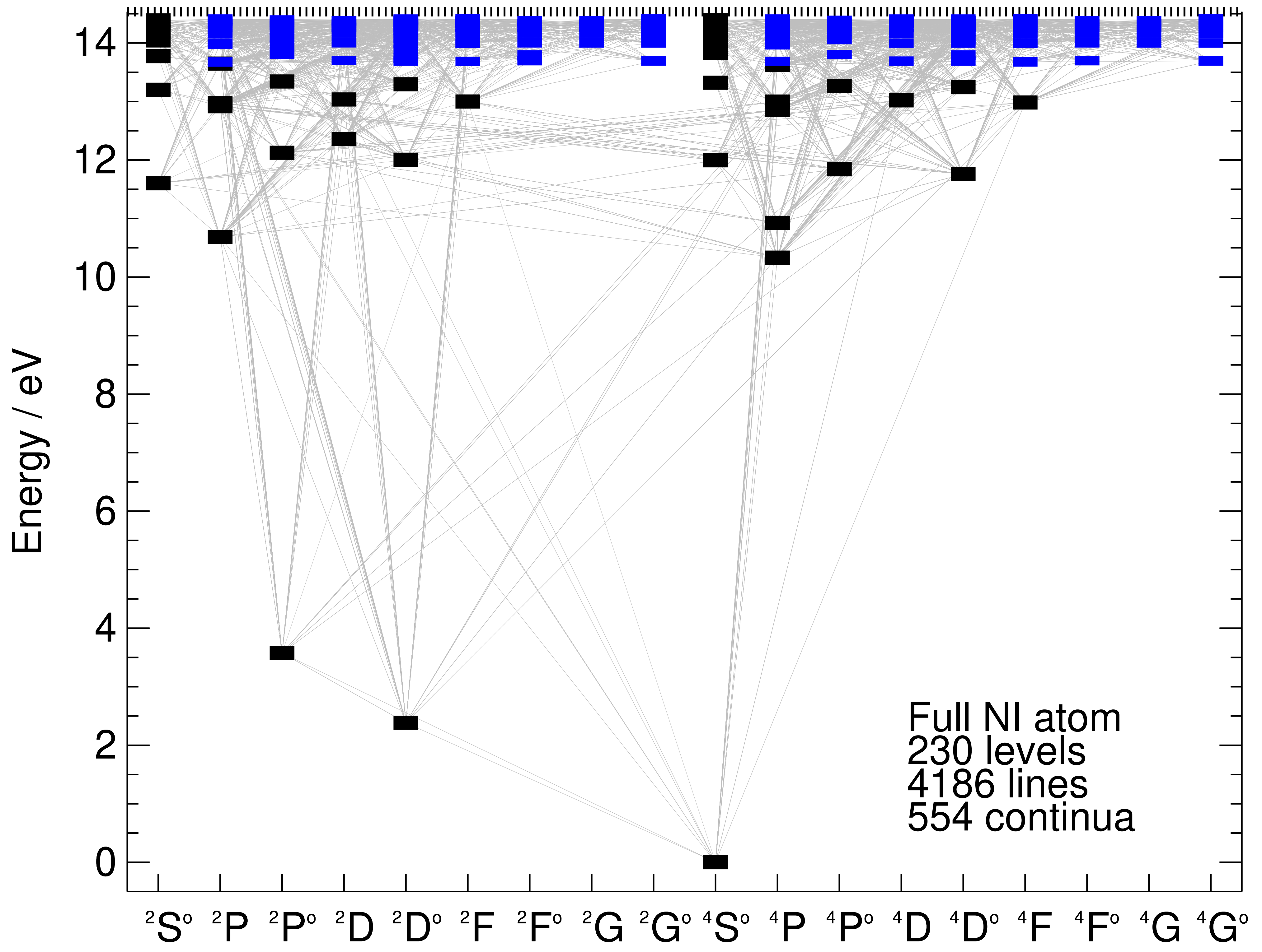


Lithium 671nm line in a metal-poor subgiant [Lind+ 2013]



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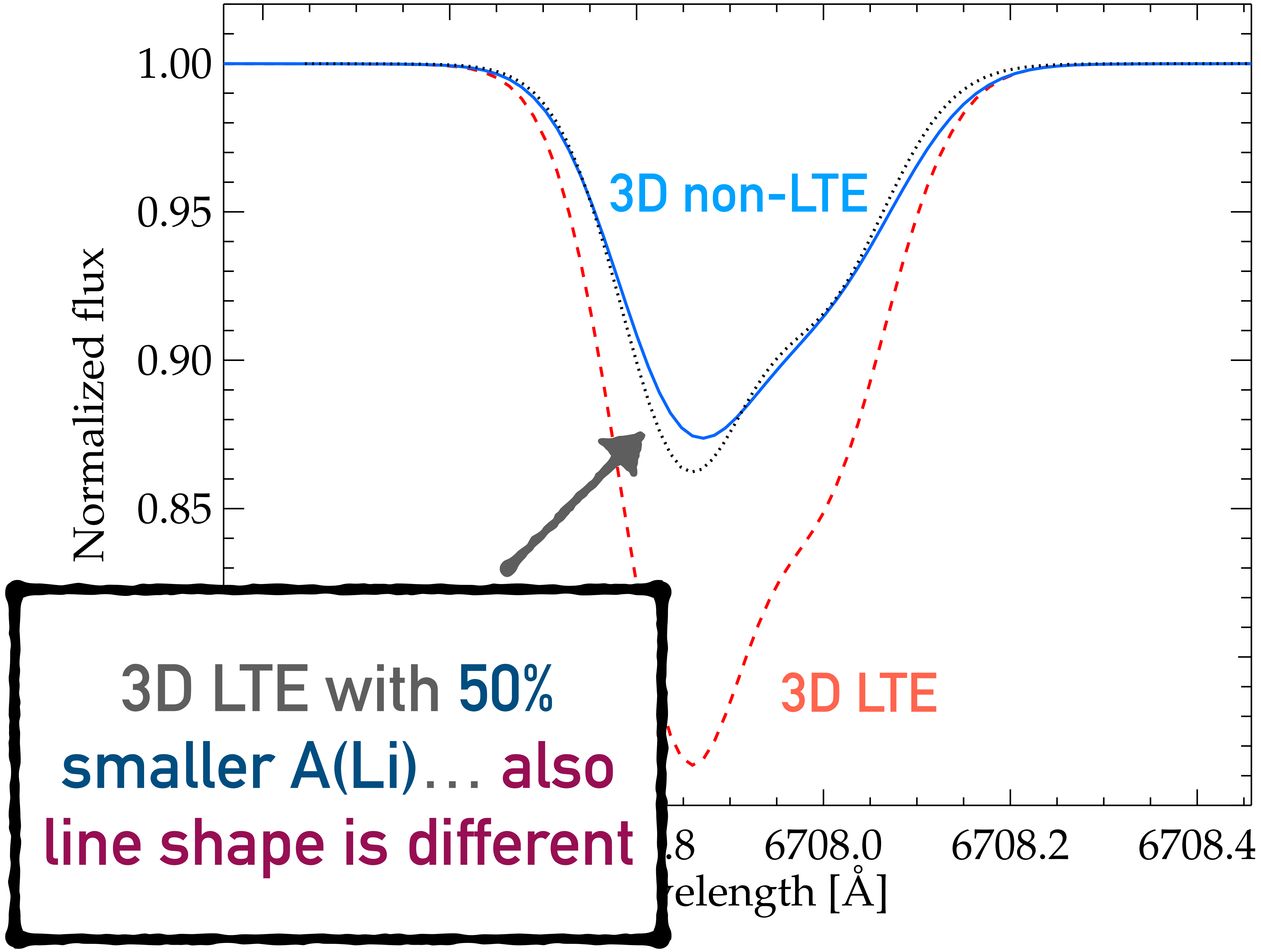

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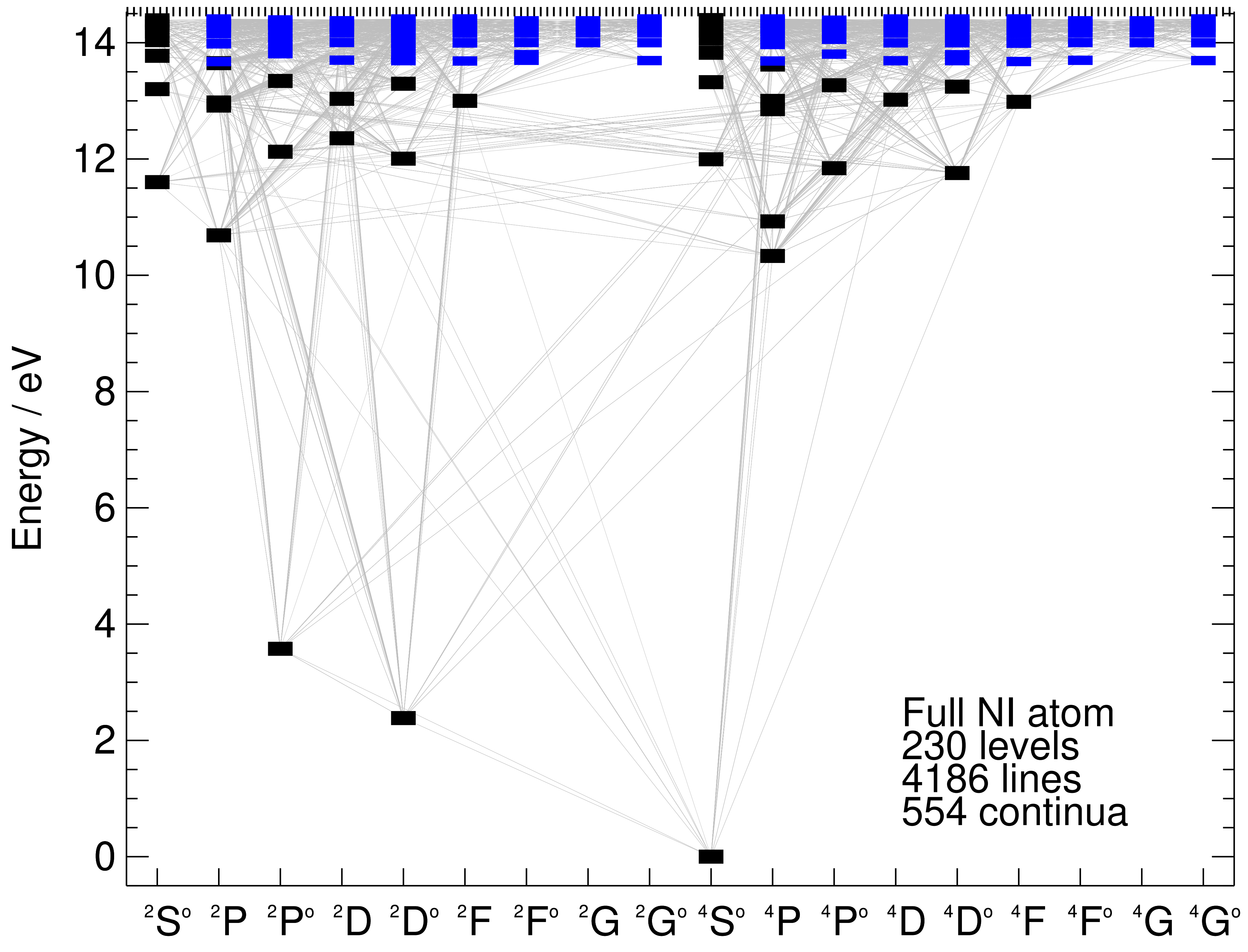

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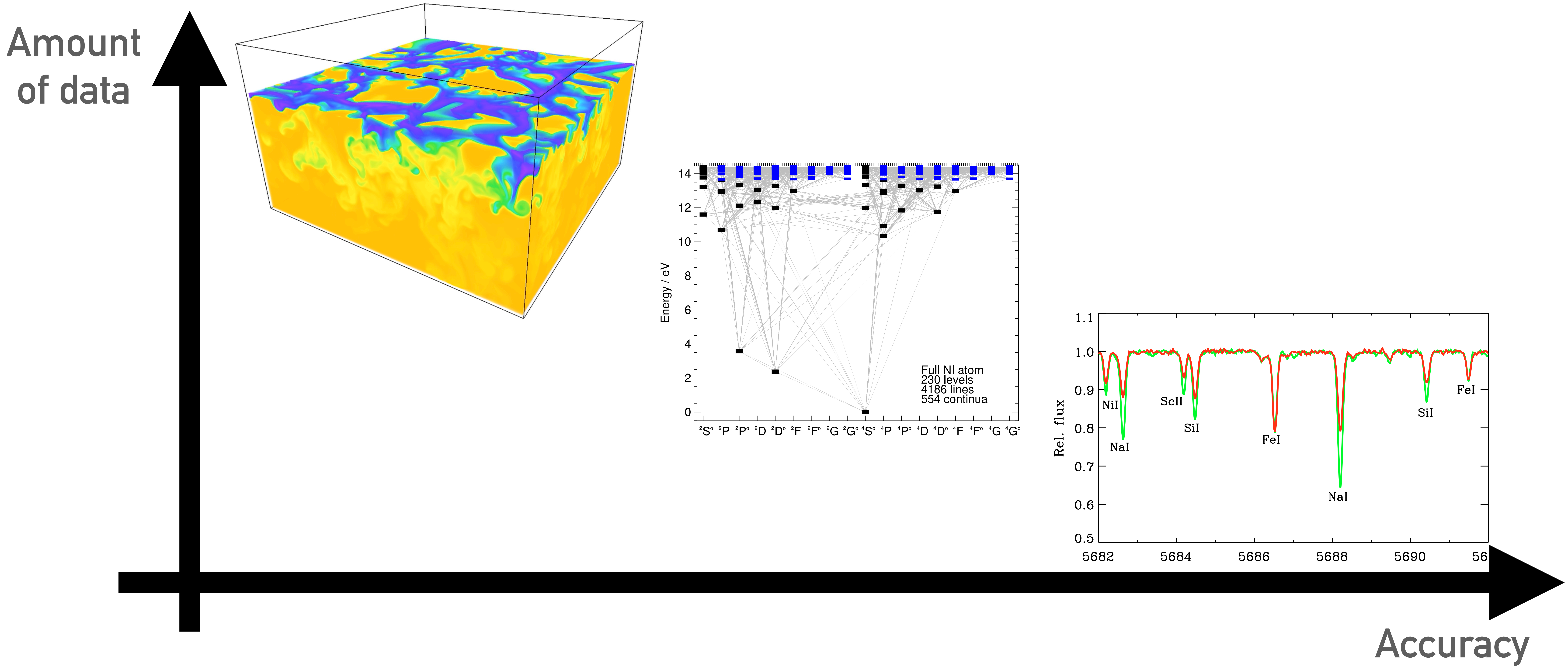
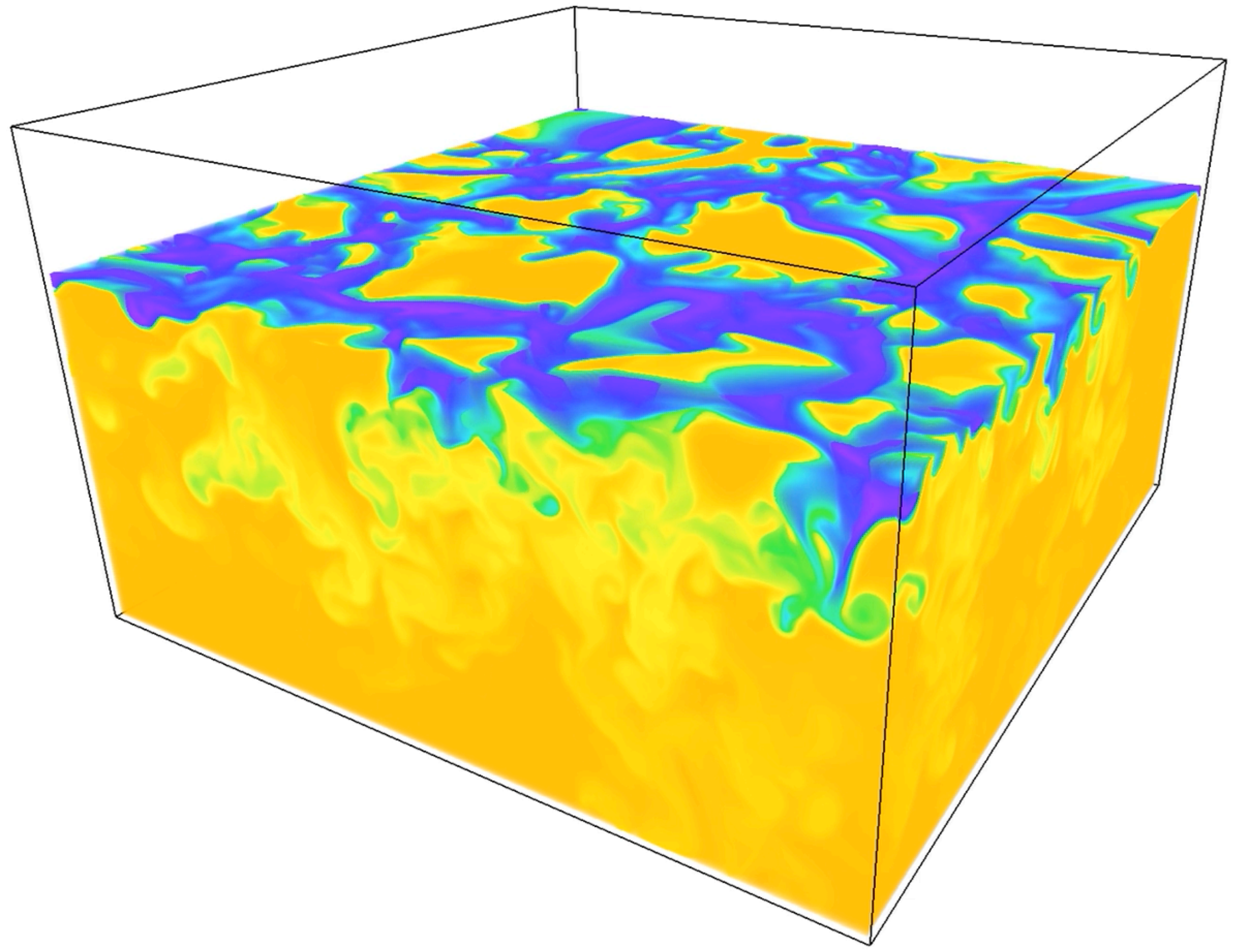
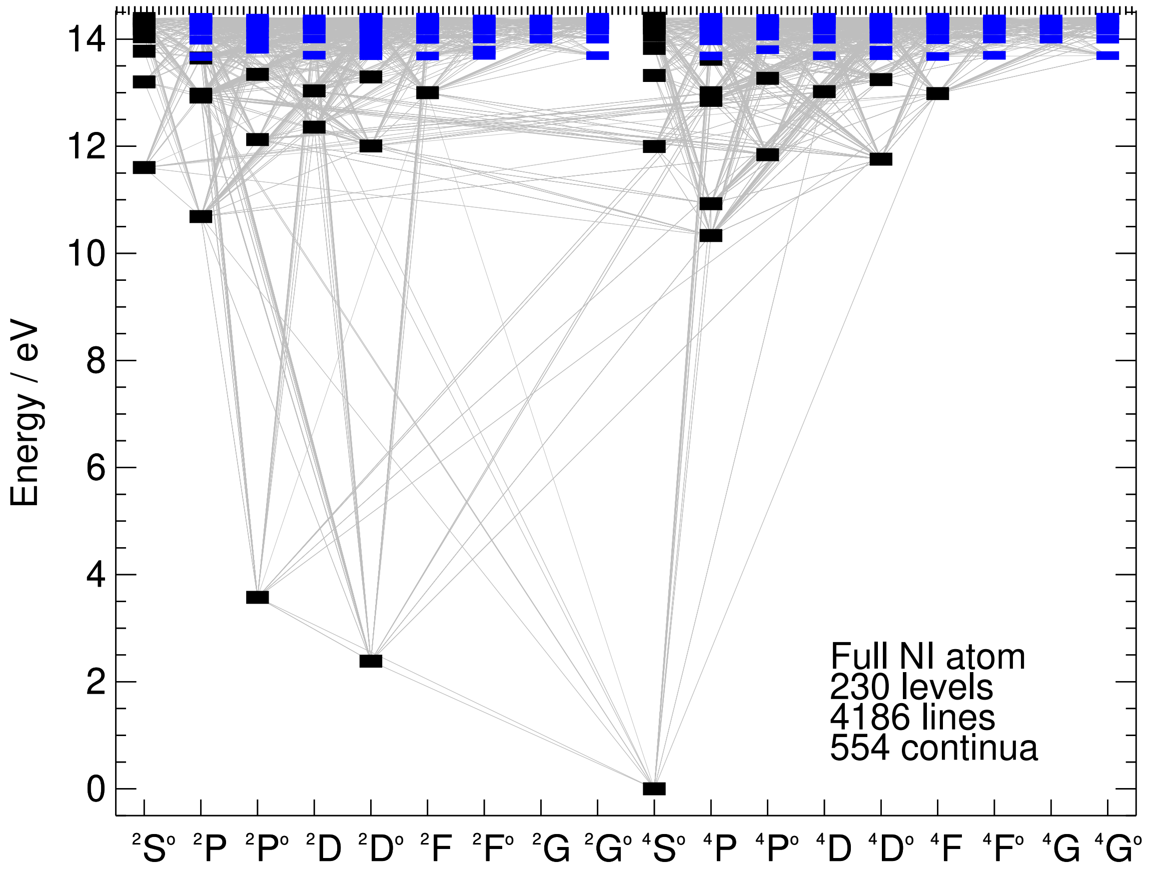


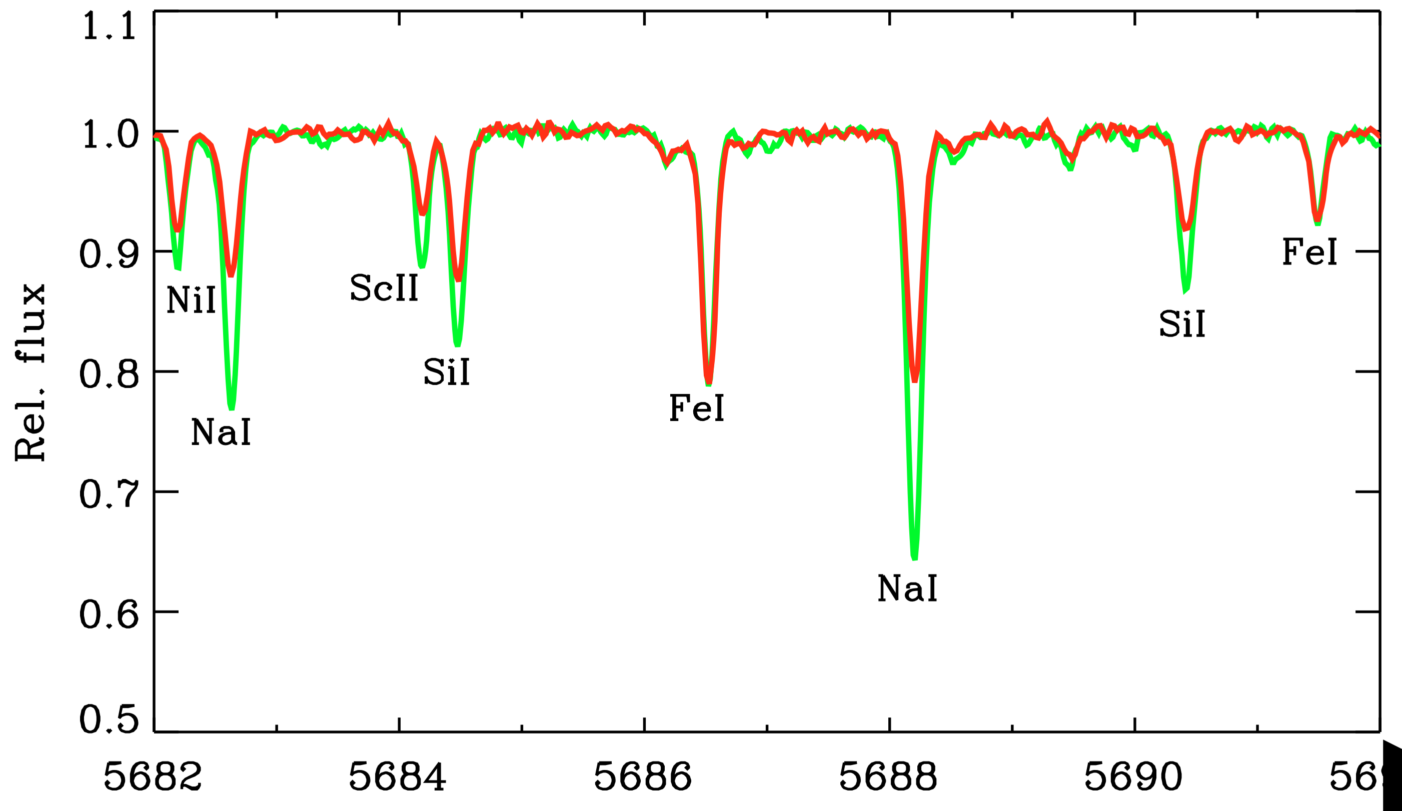
Atomic data needs

3D RHD simulations:
opacities, partition functions (EOS)

Amount of data







Accuracy

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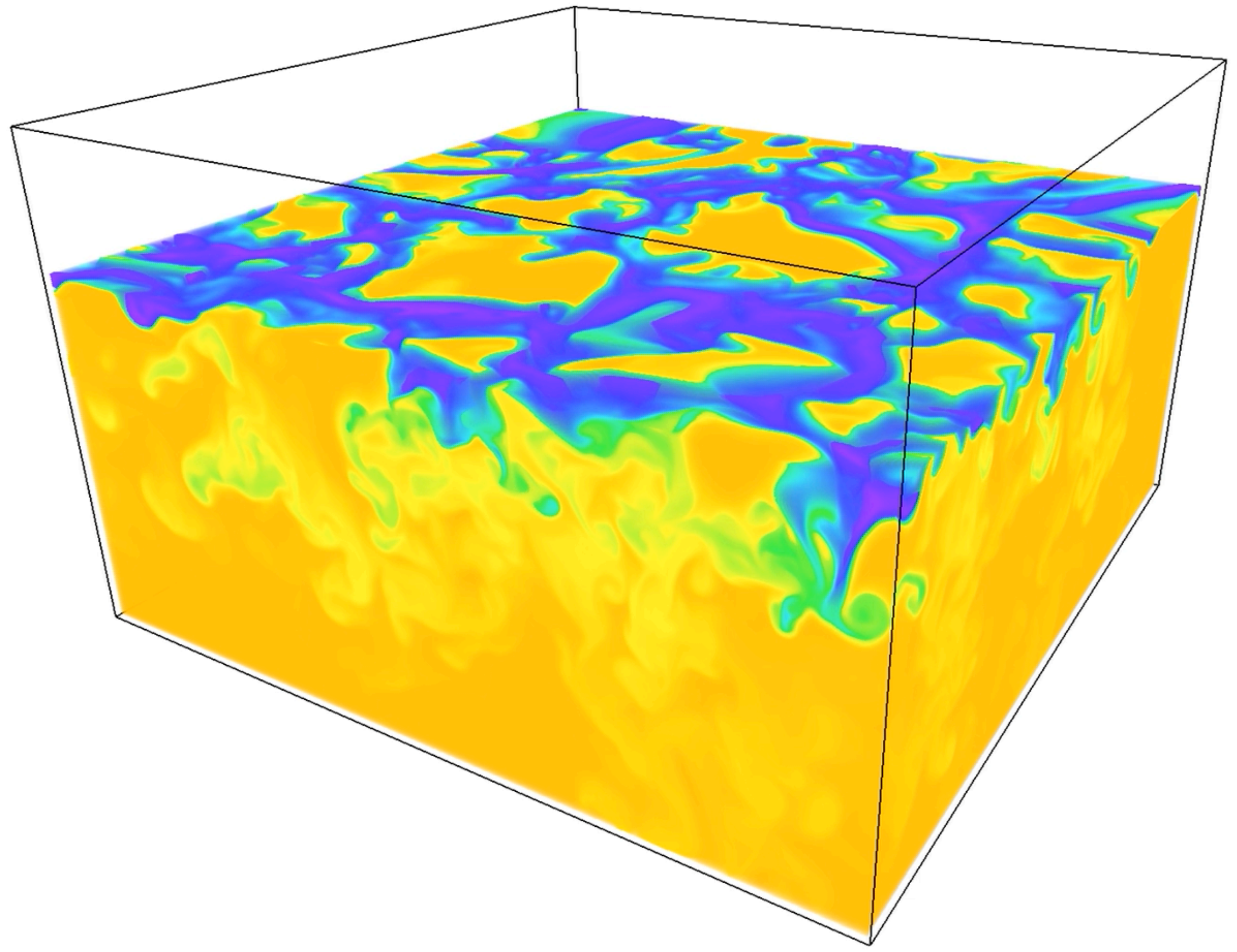

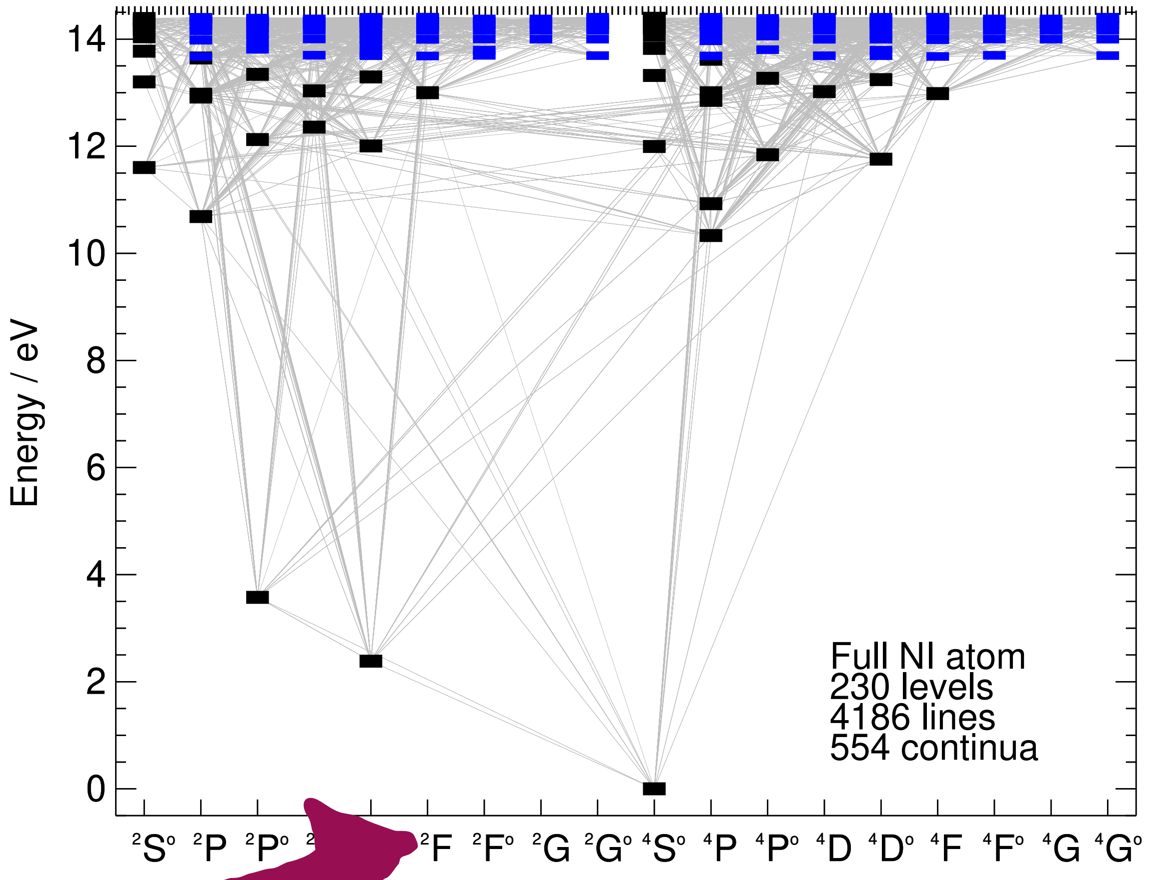

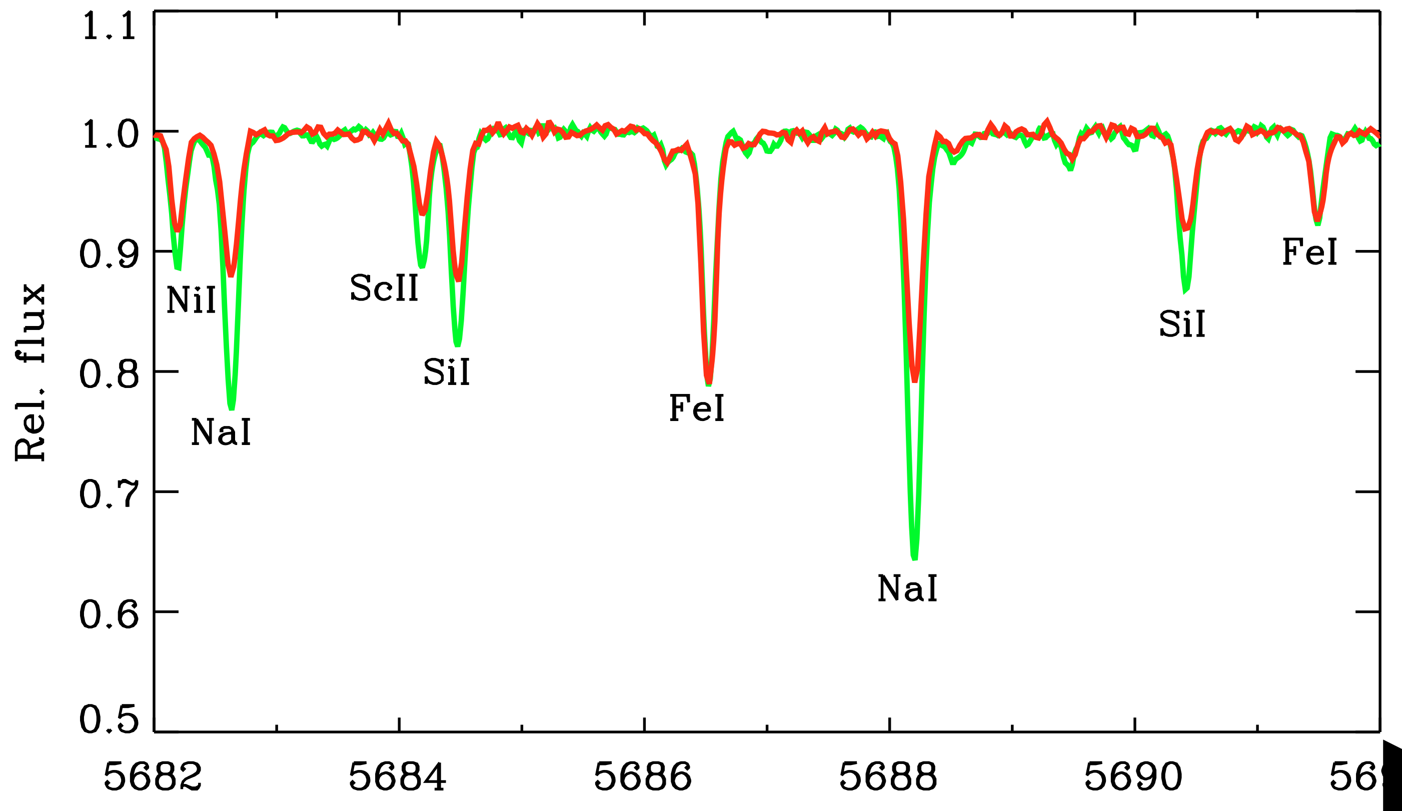

Non-LTE models:
Radiative/collisional BB and BF transition rates

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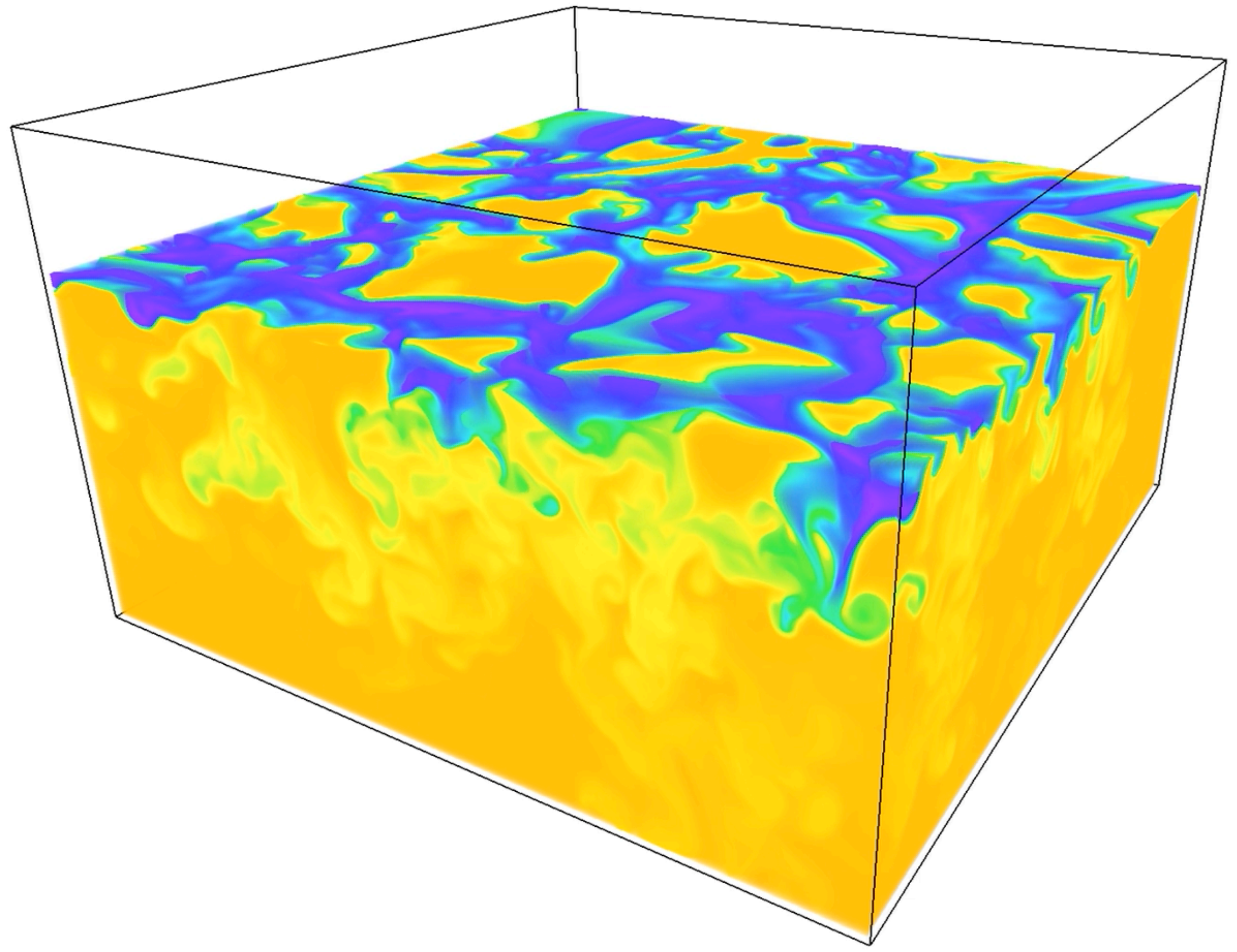

High precision spectroscopy:
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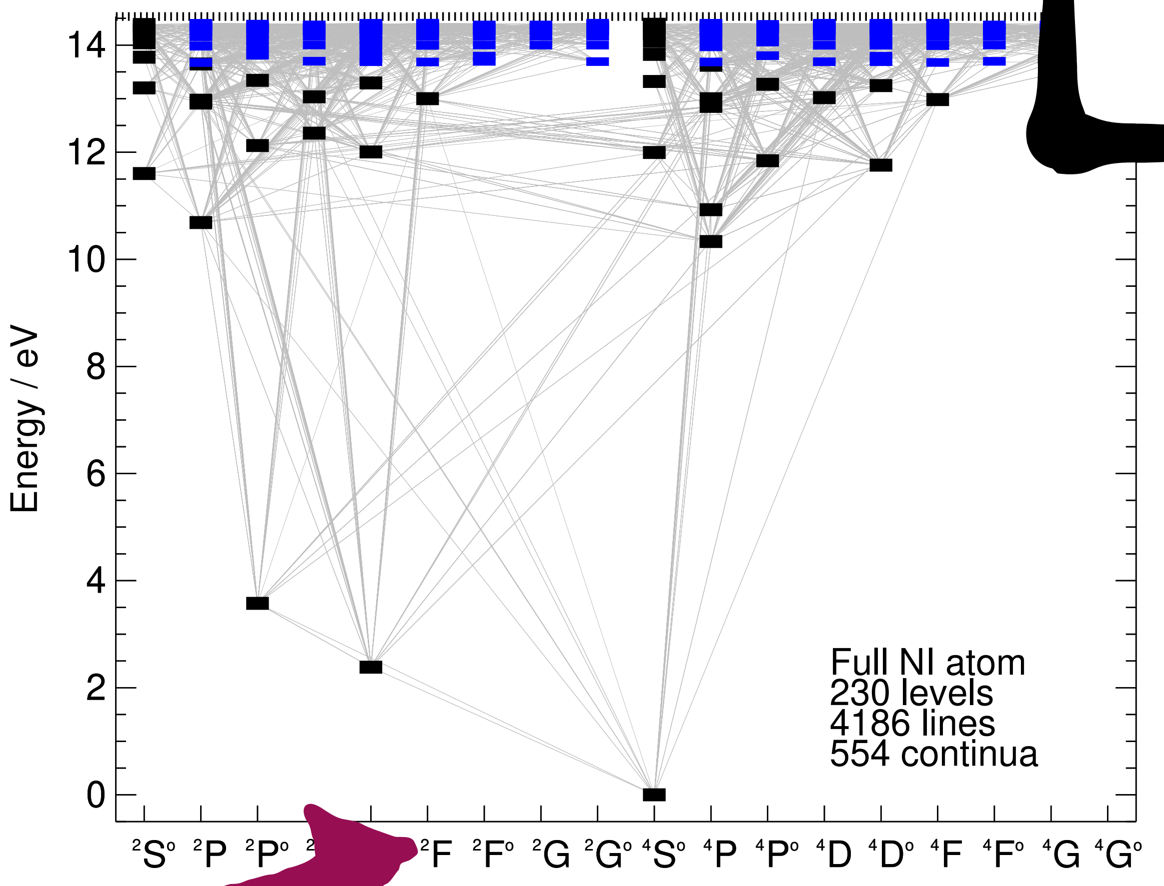
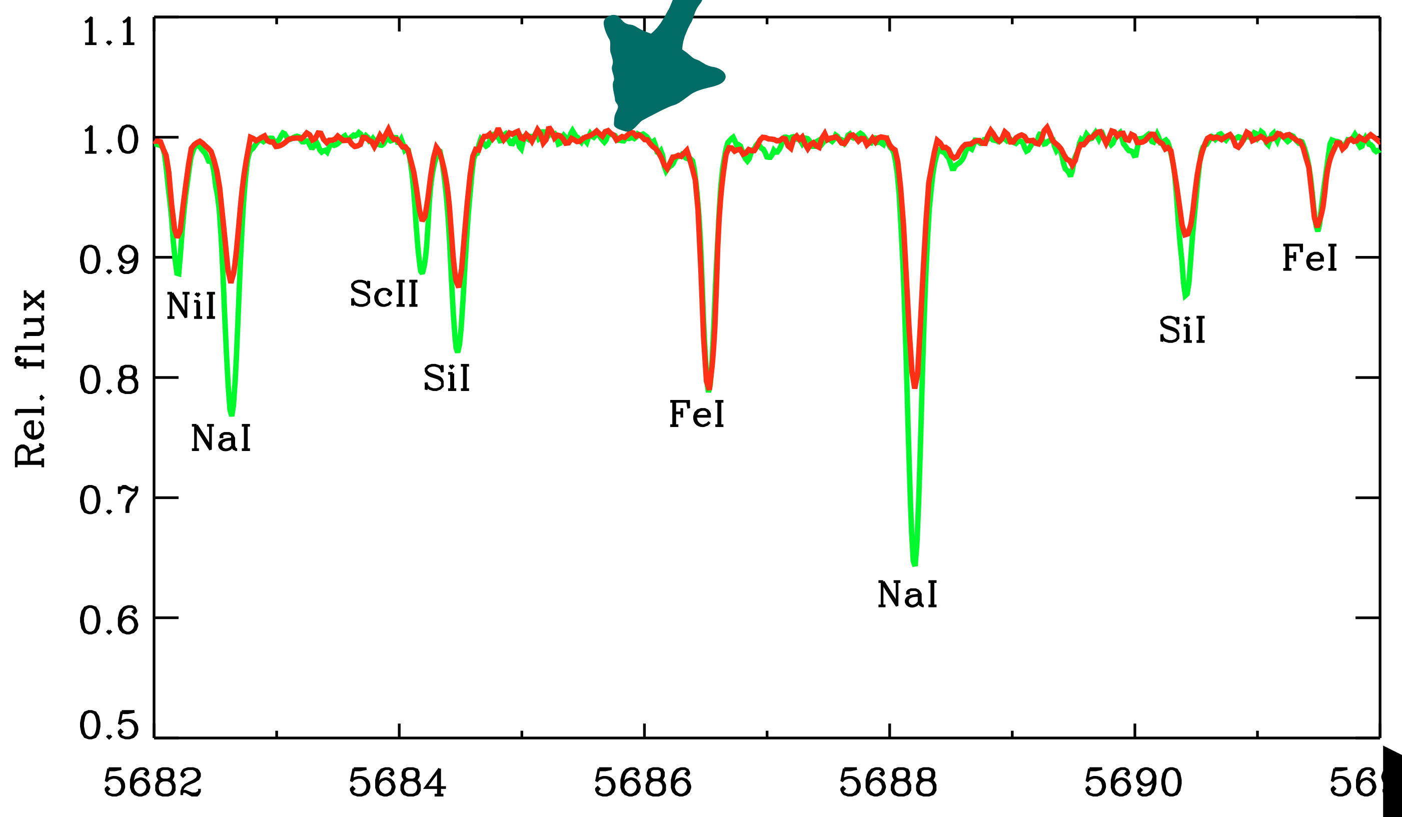
Amount of data





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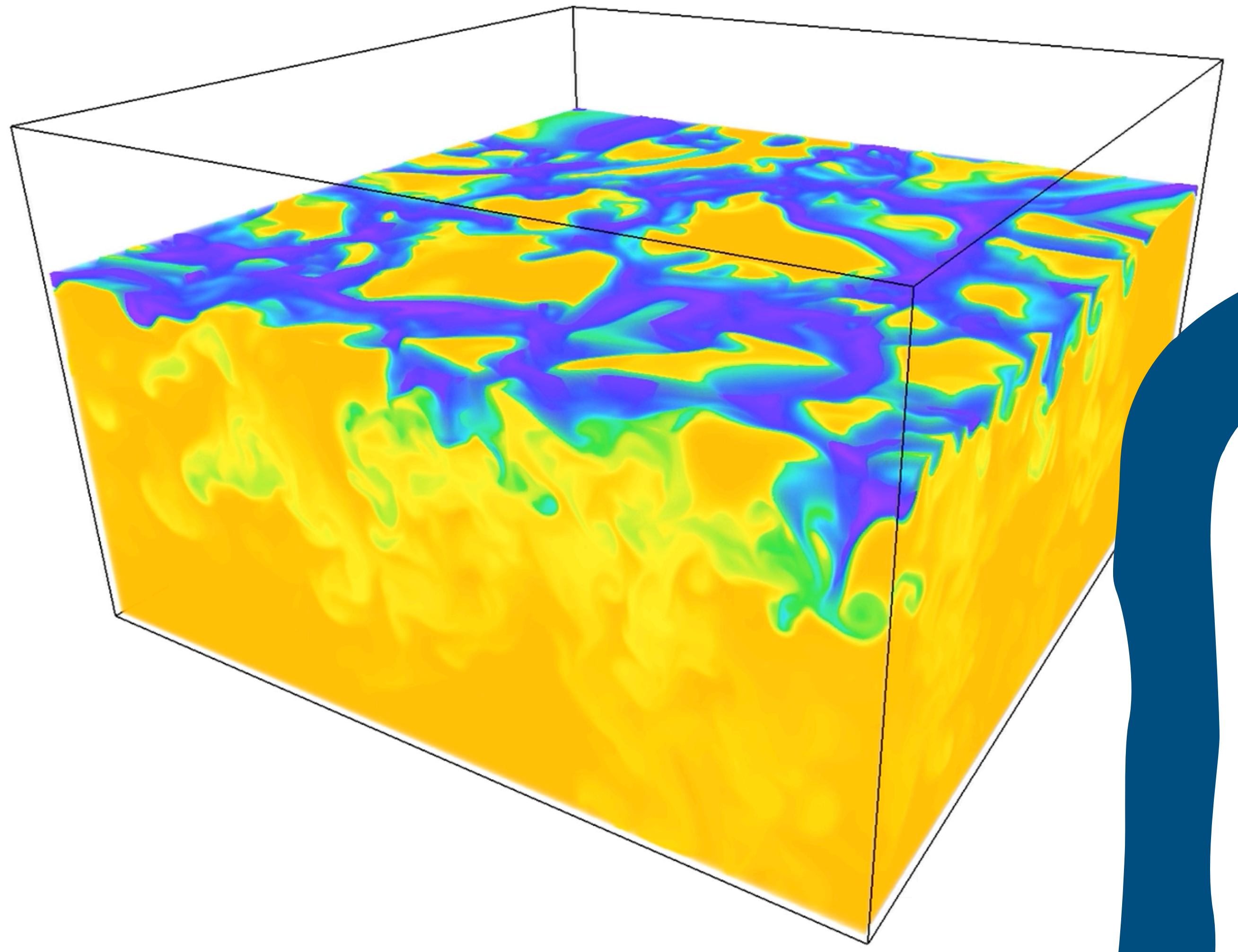

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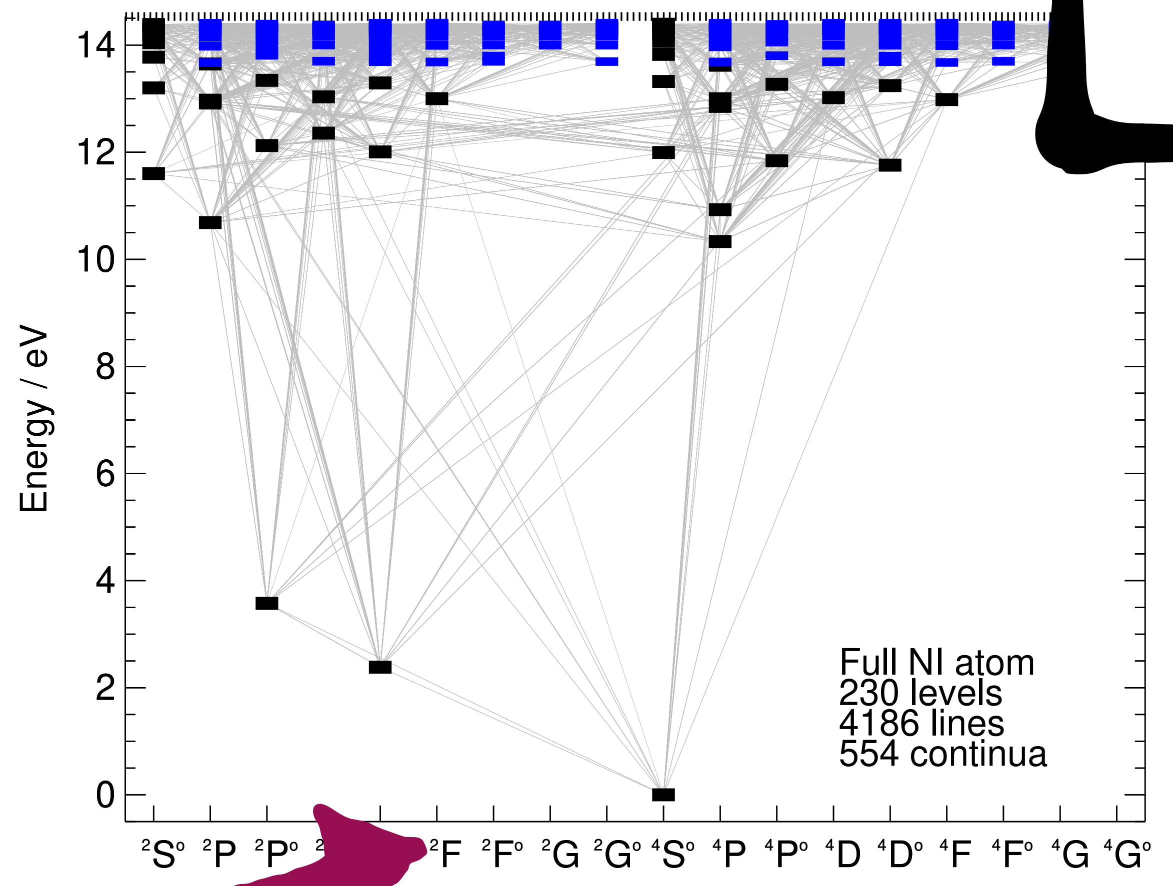

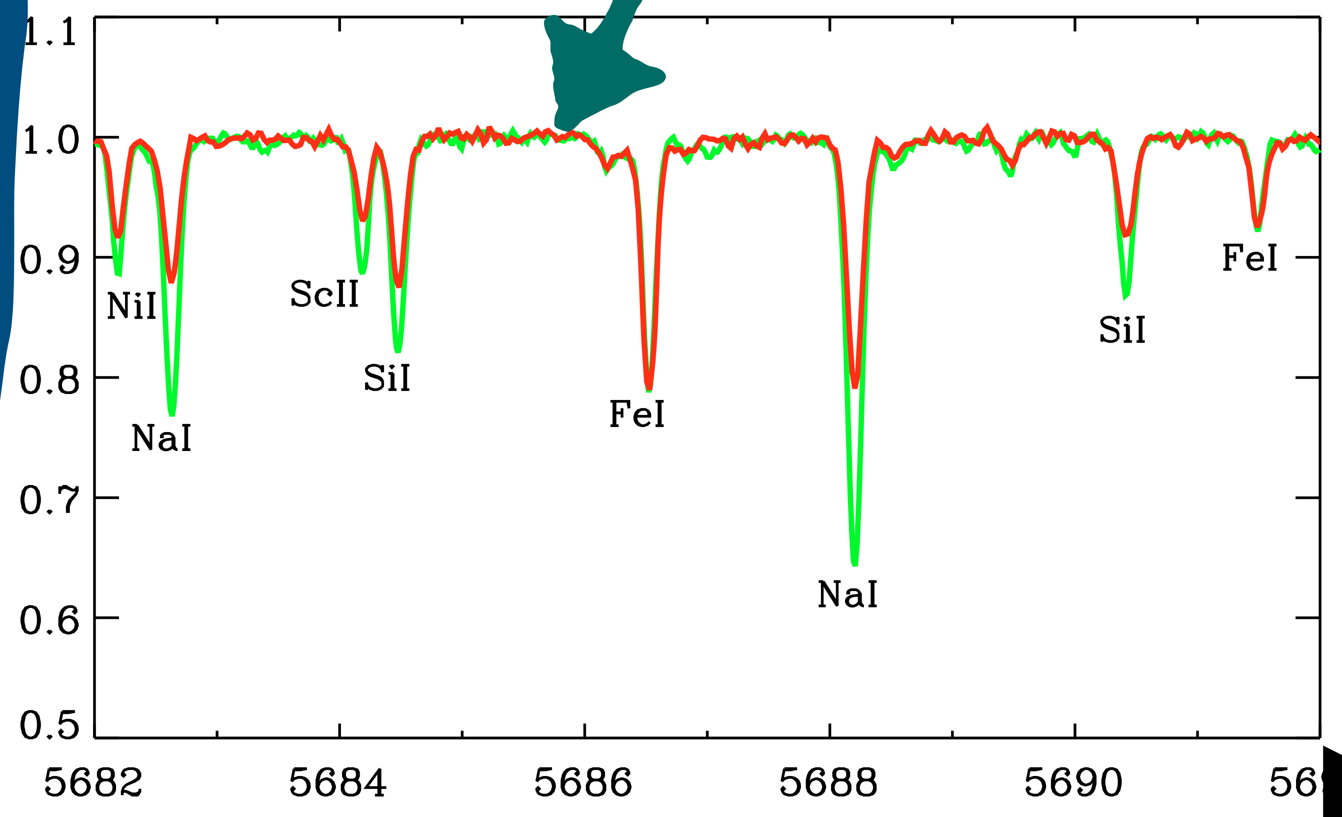

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Databases (not exhaustive):

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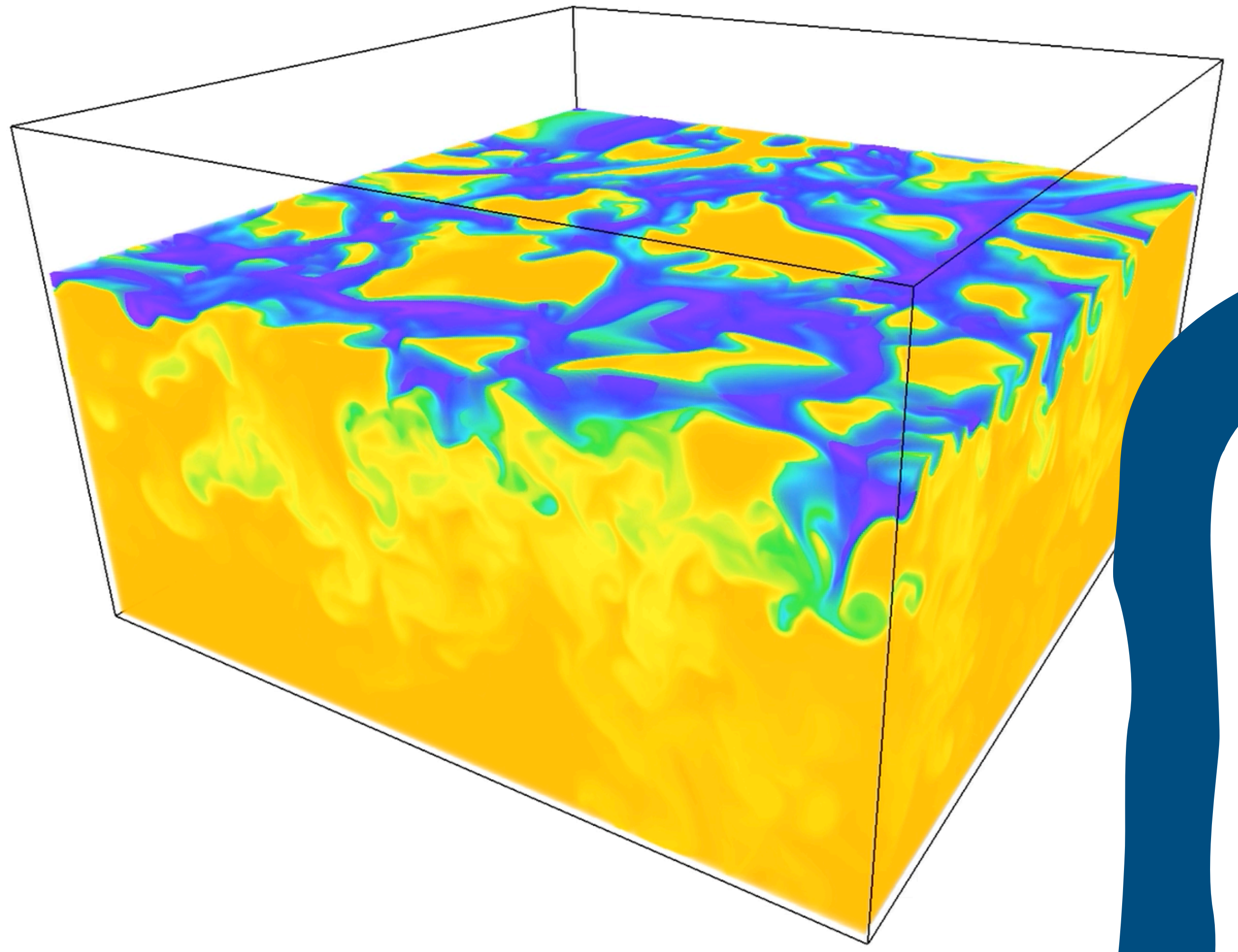
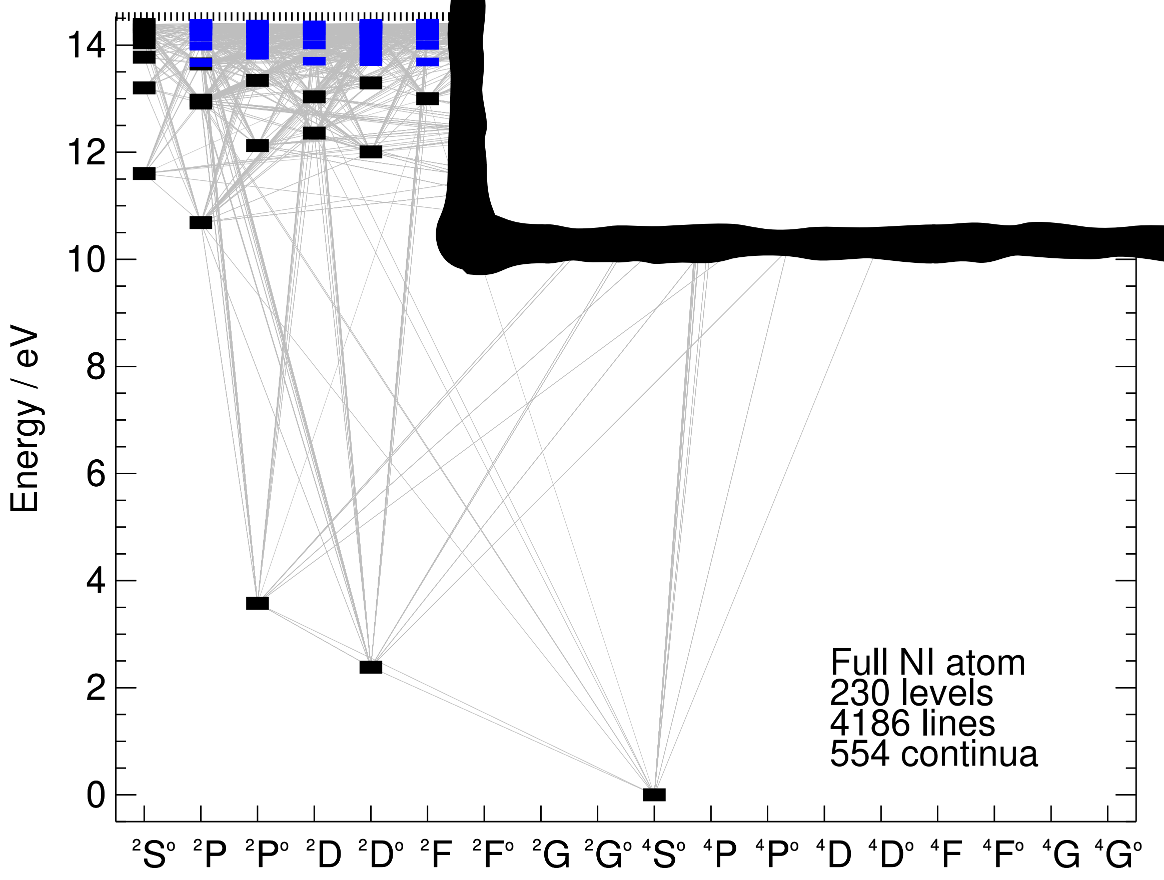
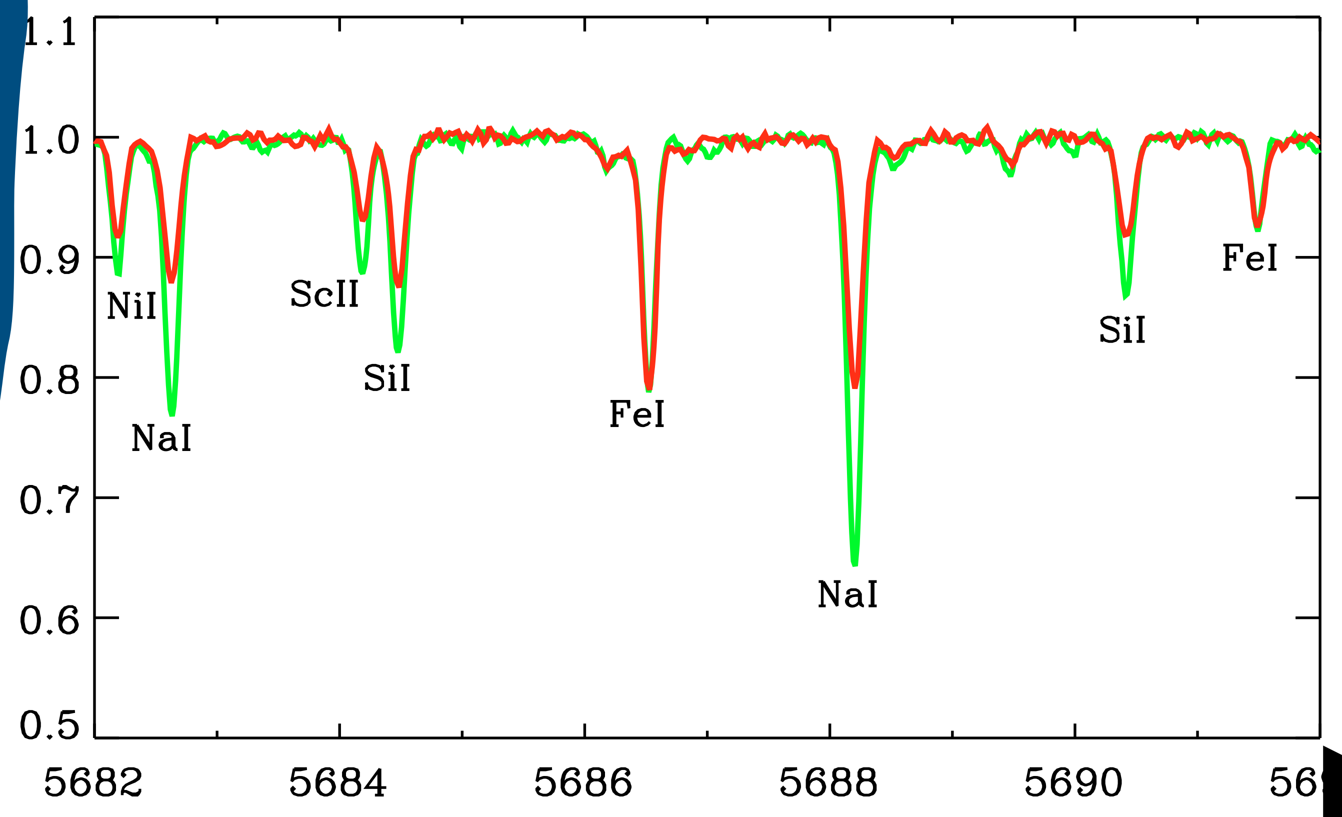
Amount of data







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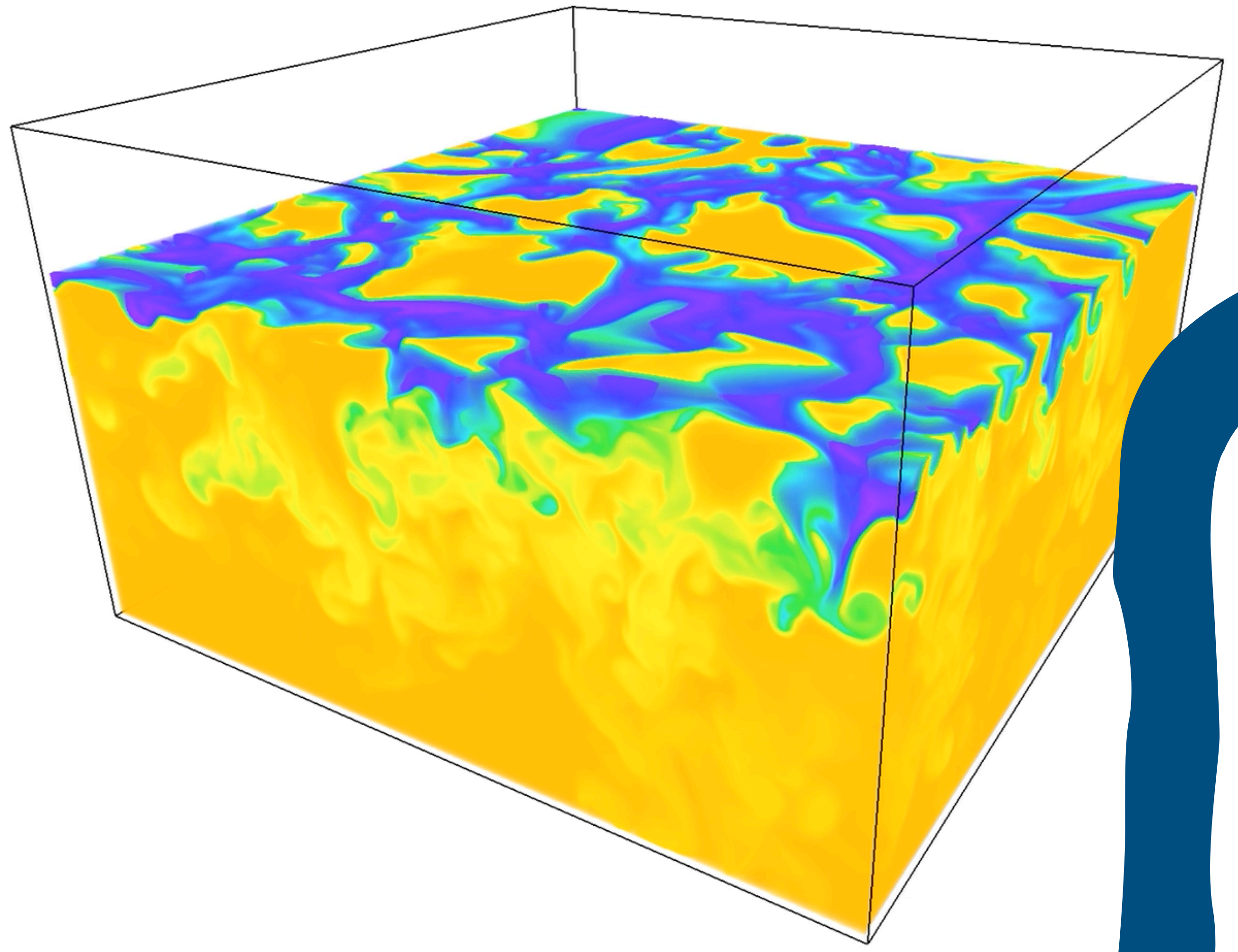

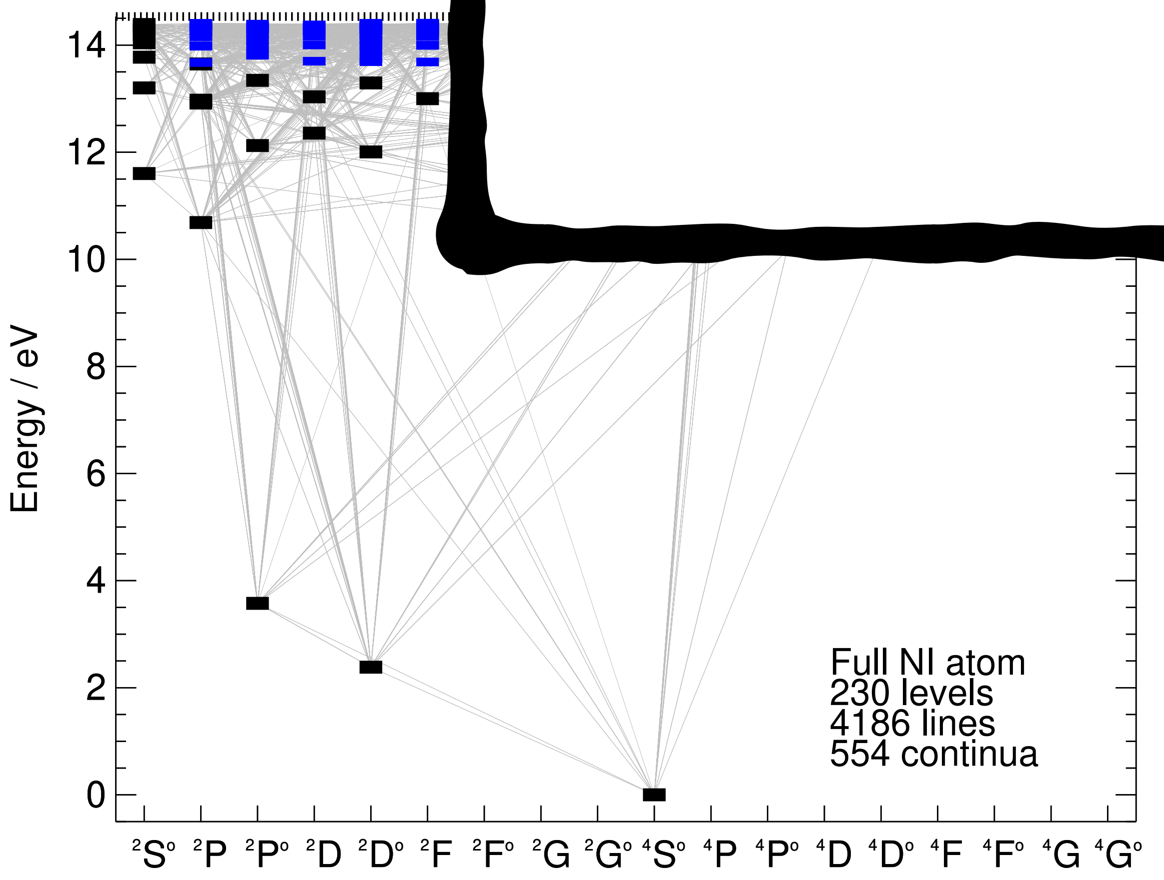

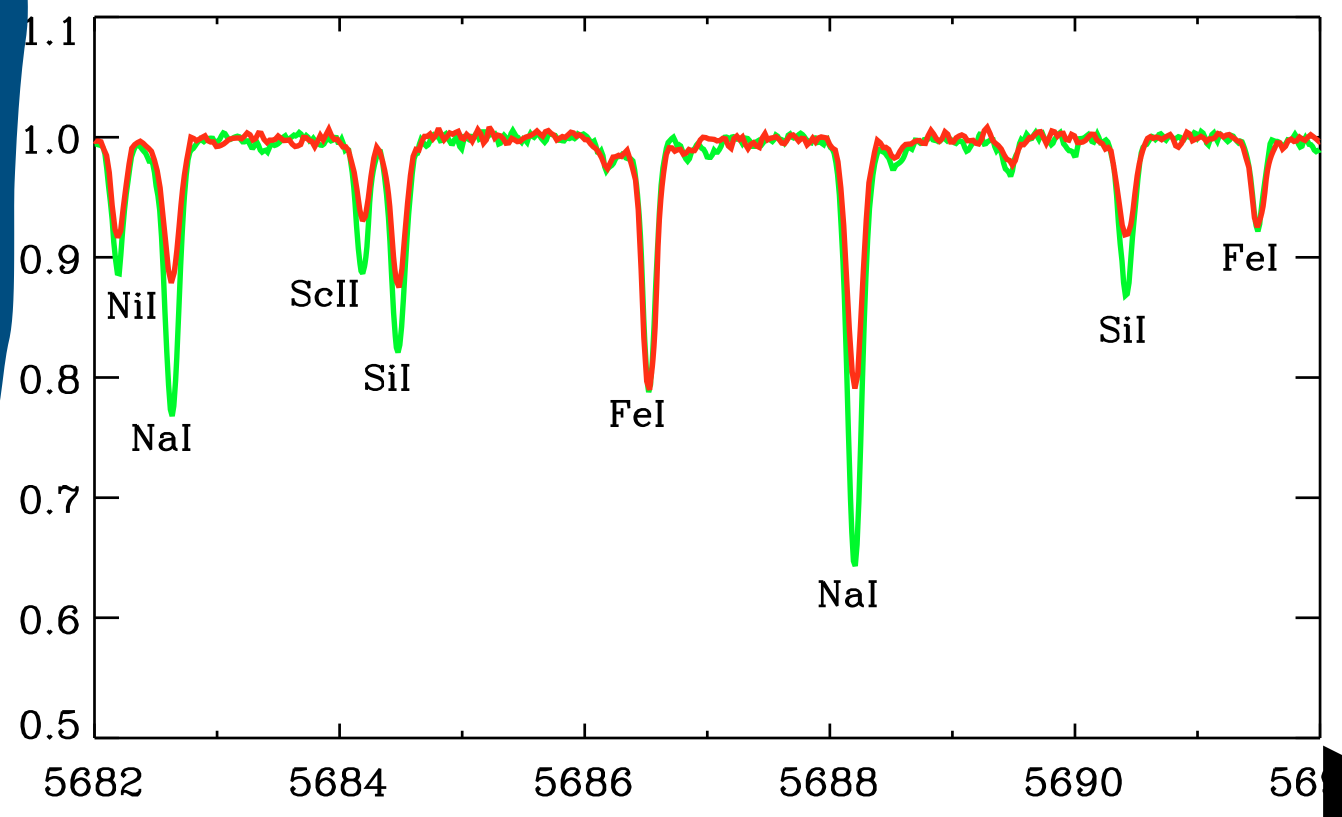

Accuracy

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Databases (not exhaustive):

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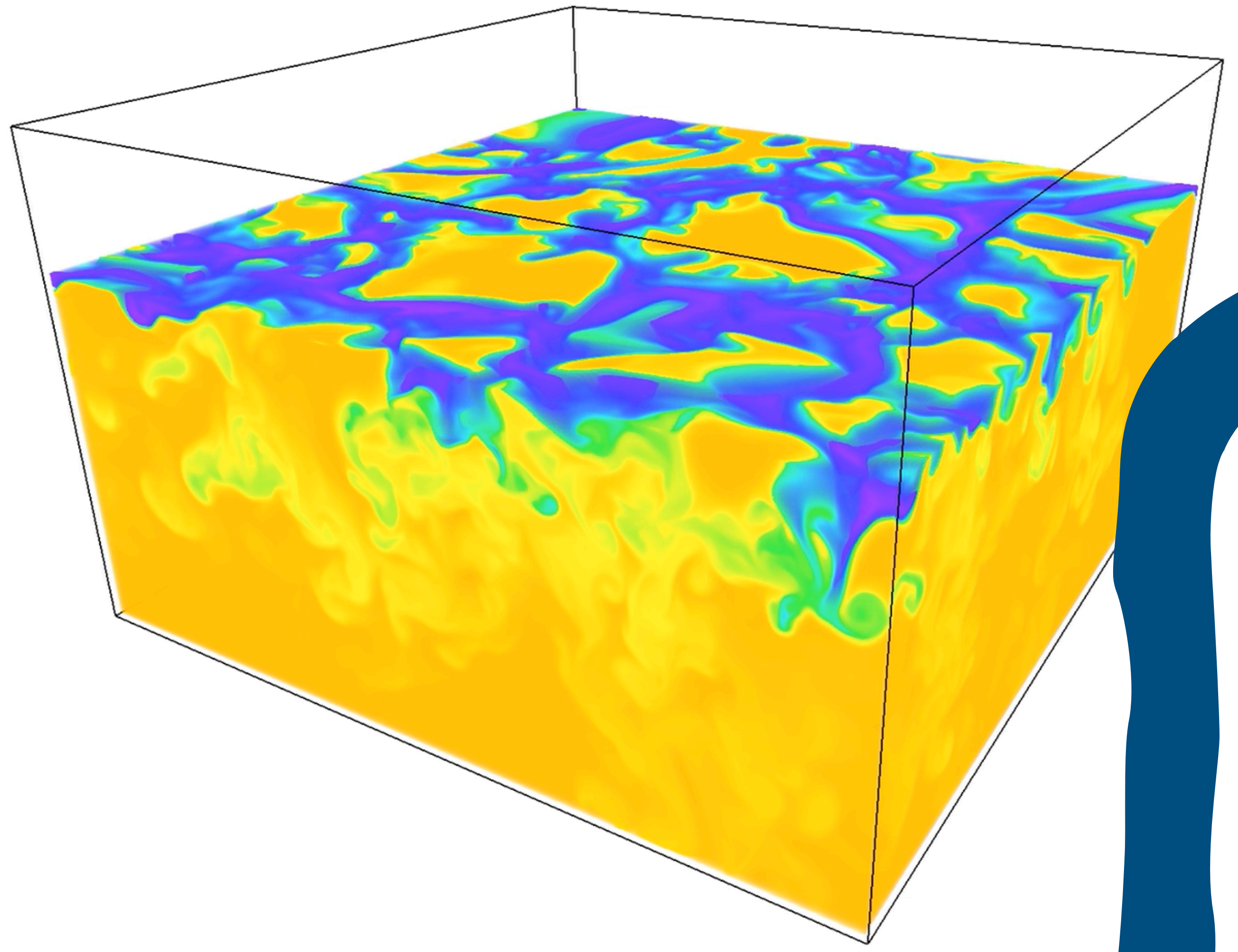
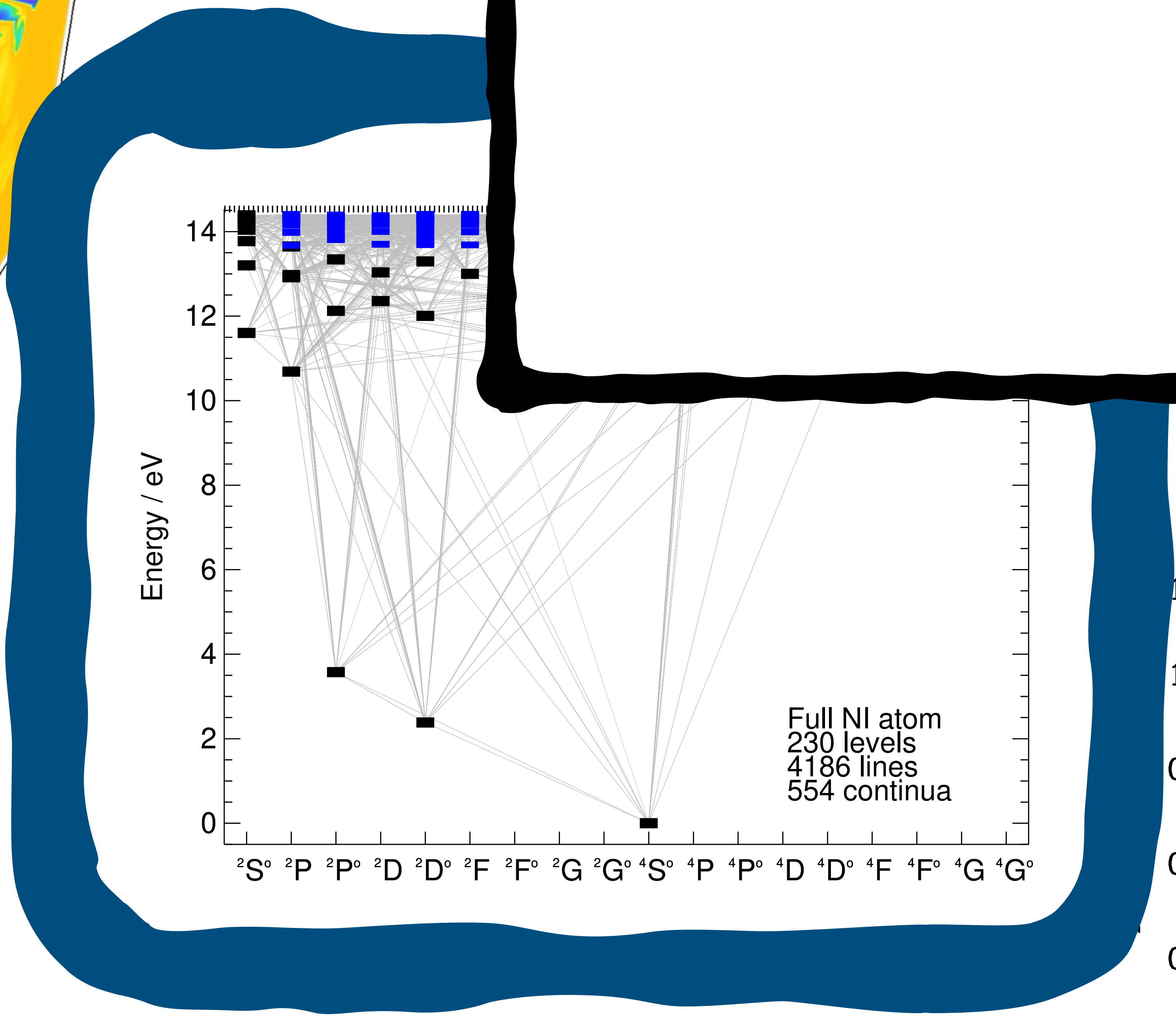
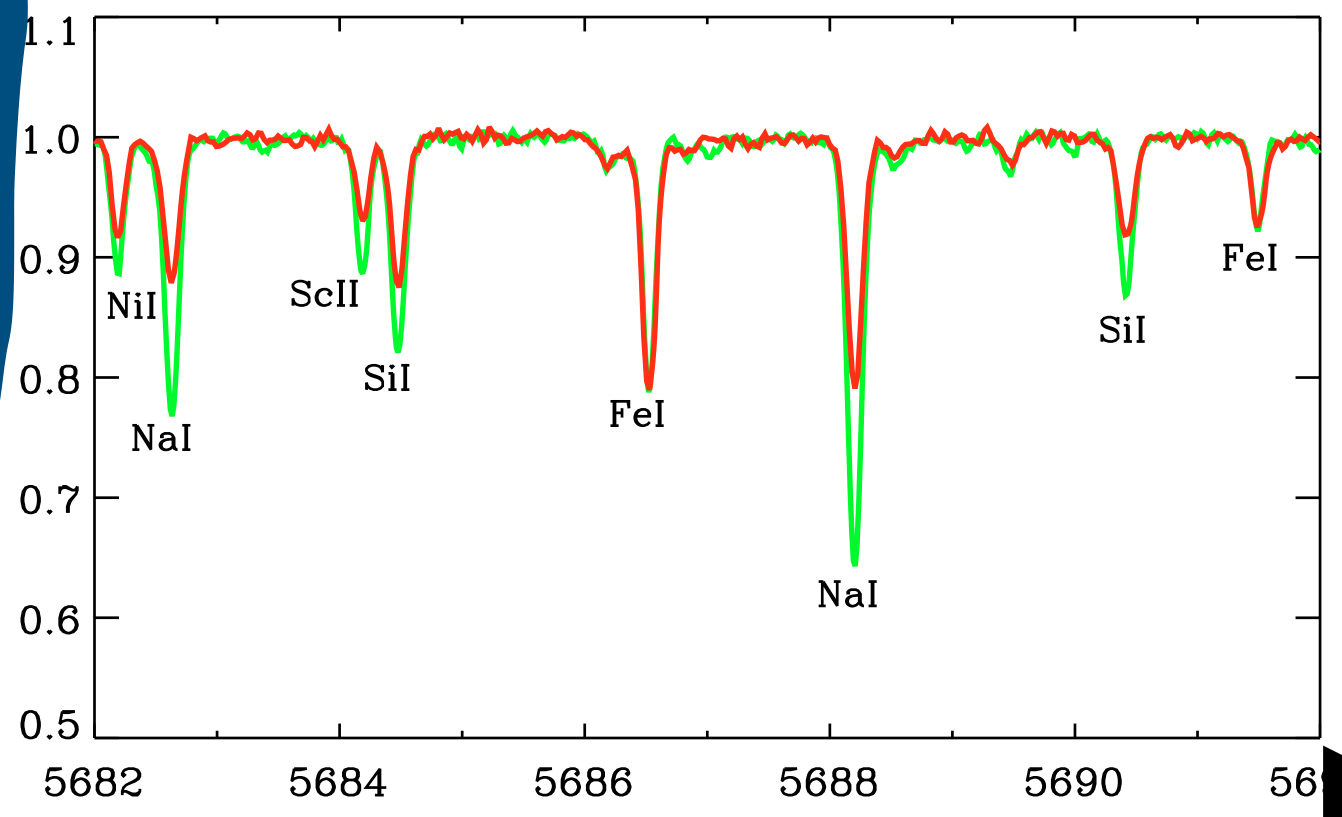
- Kurucz

Amount of data







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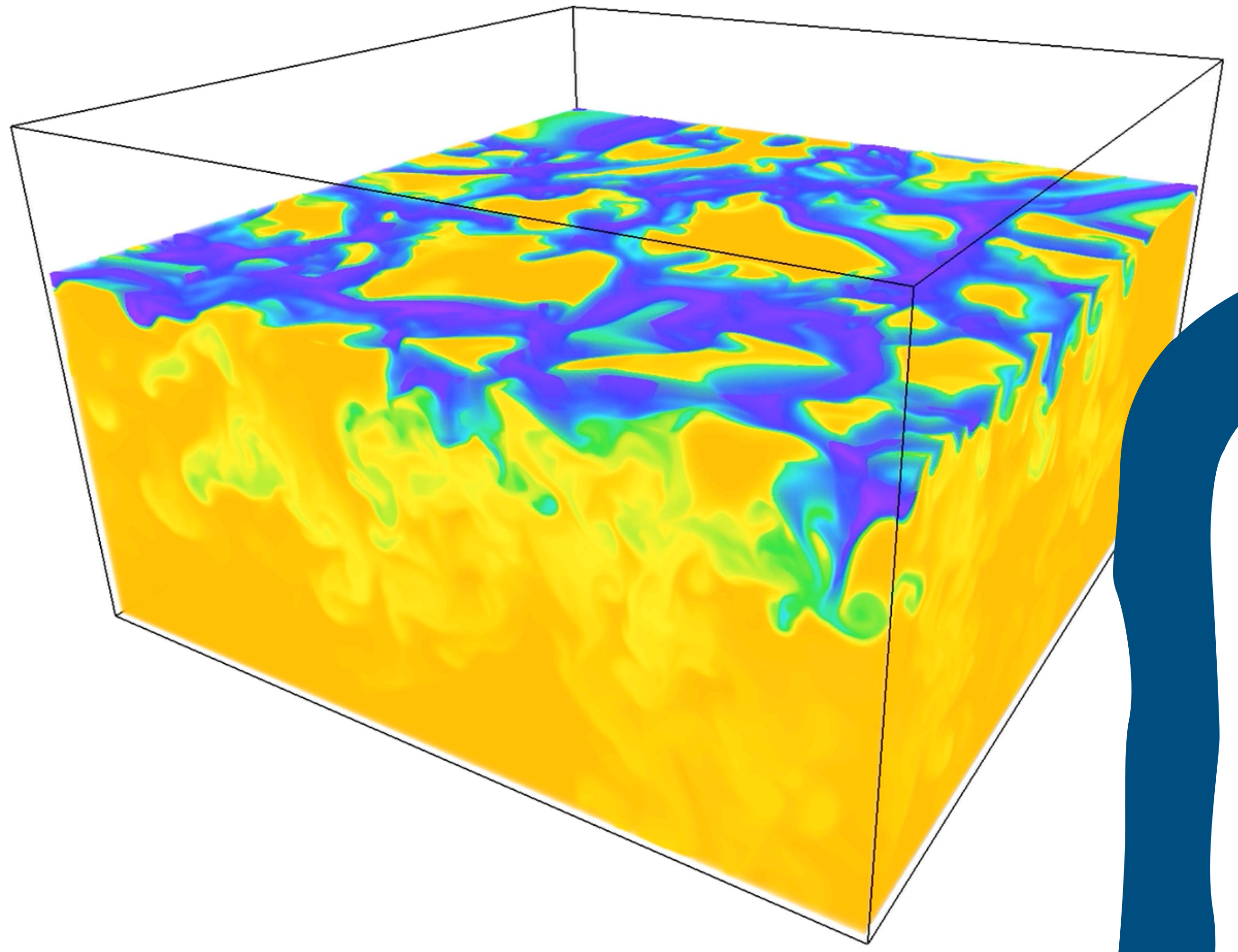
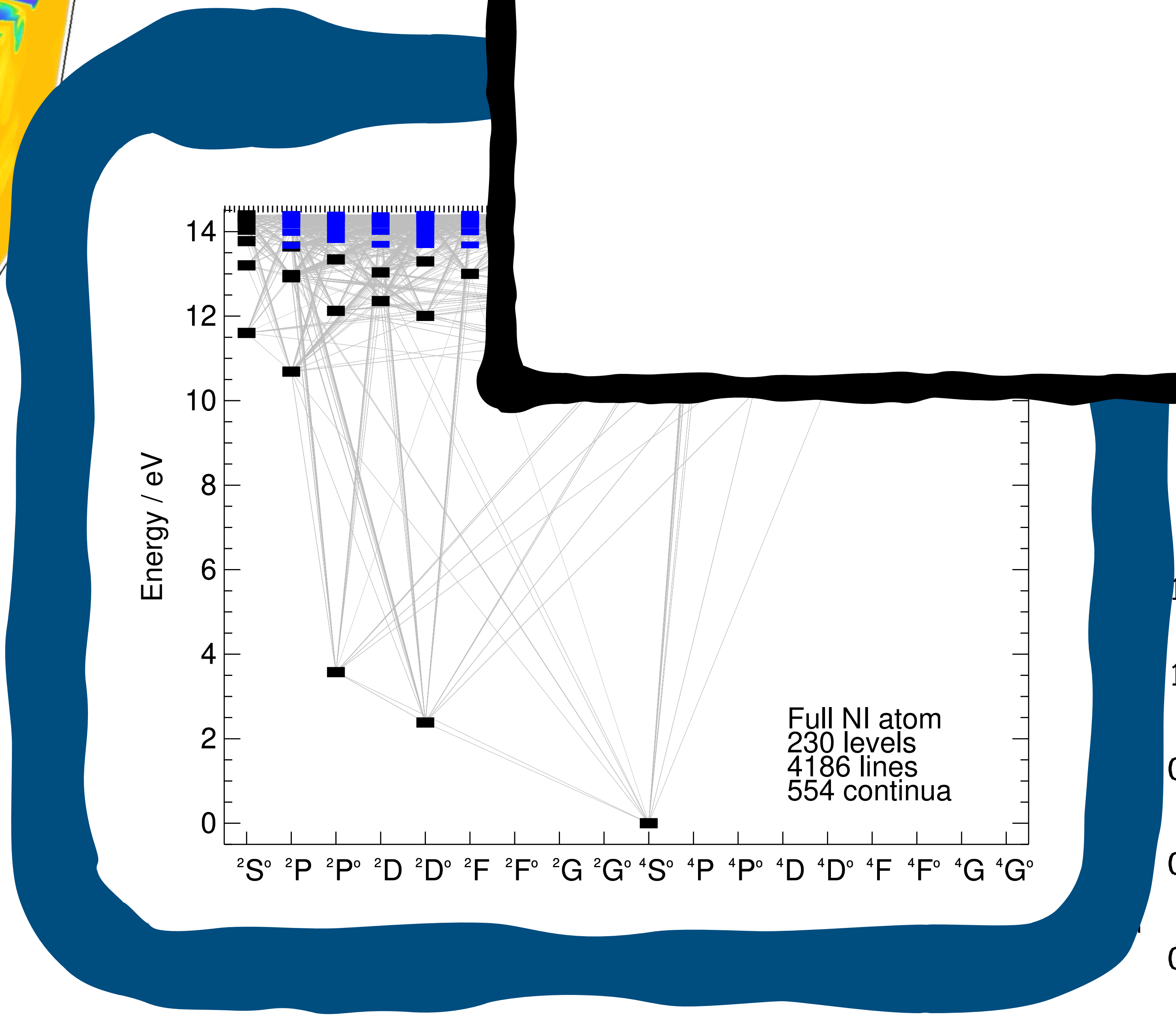
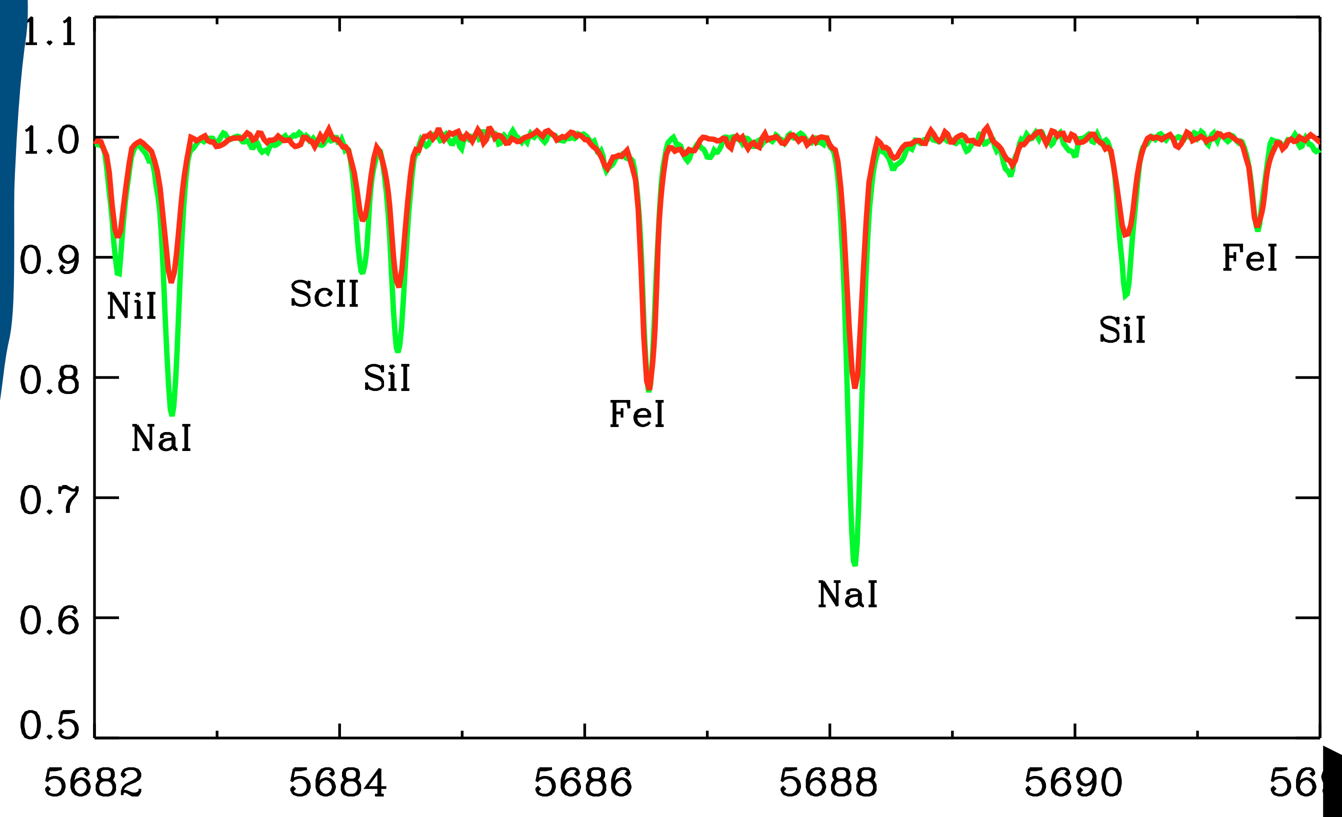
- VALD

Amount of data







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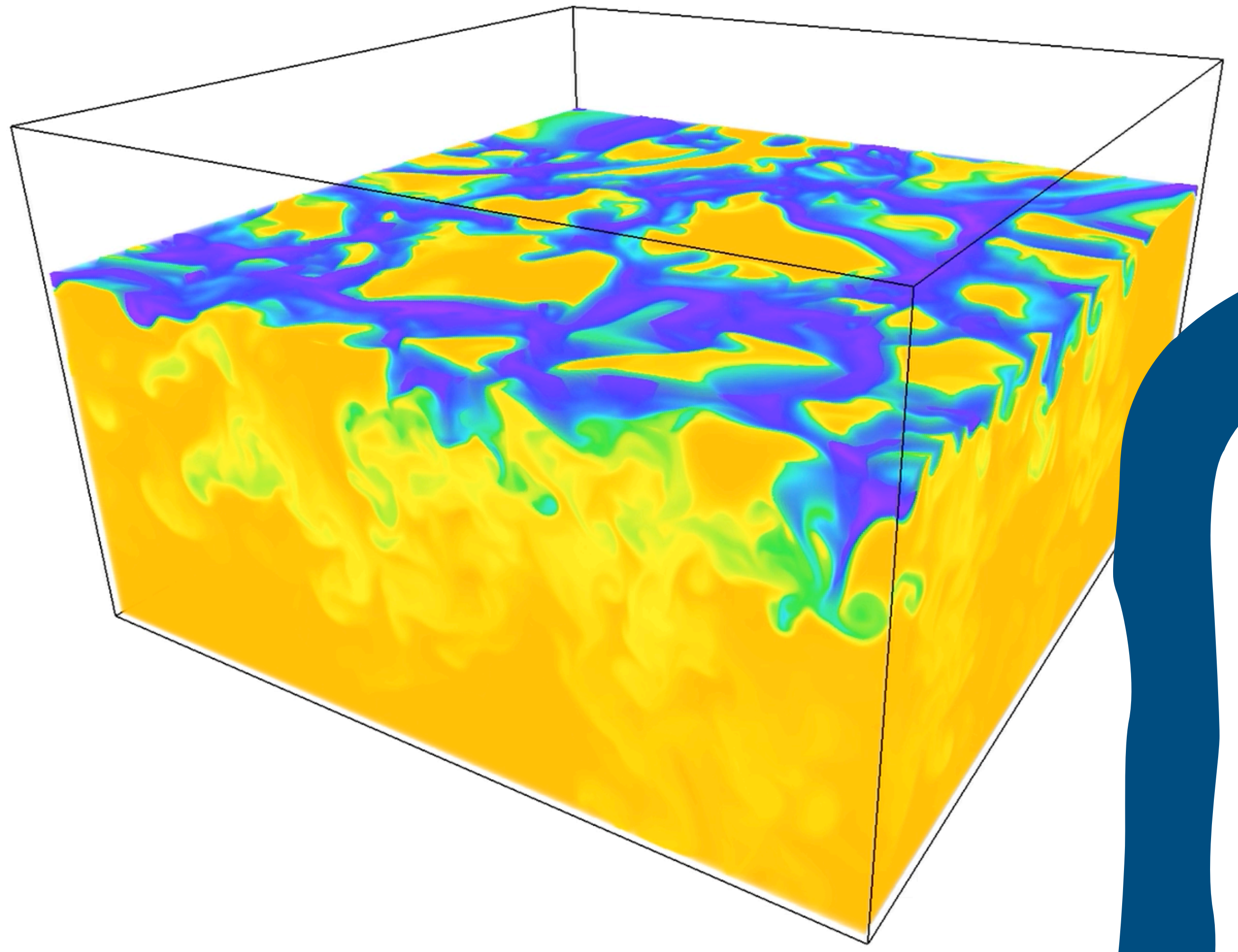

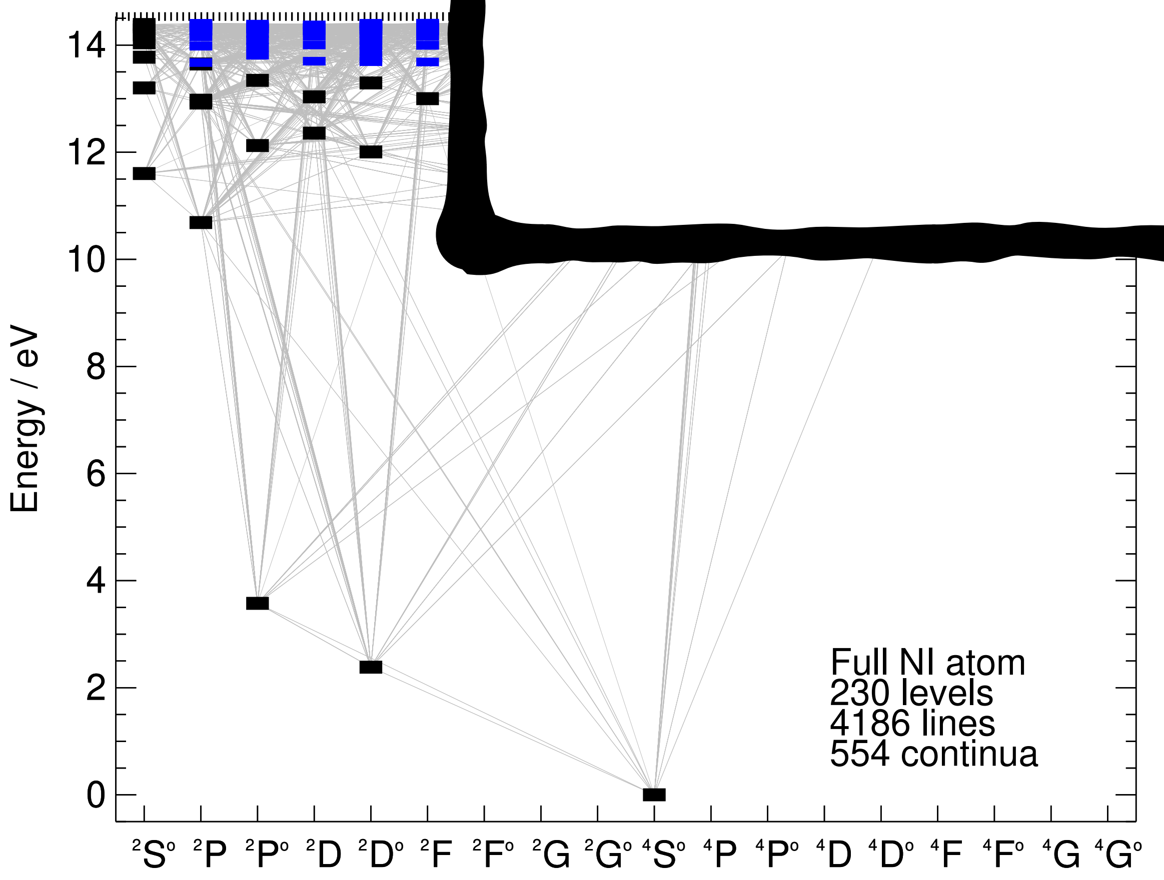

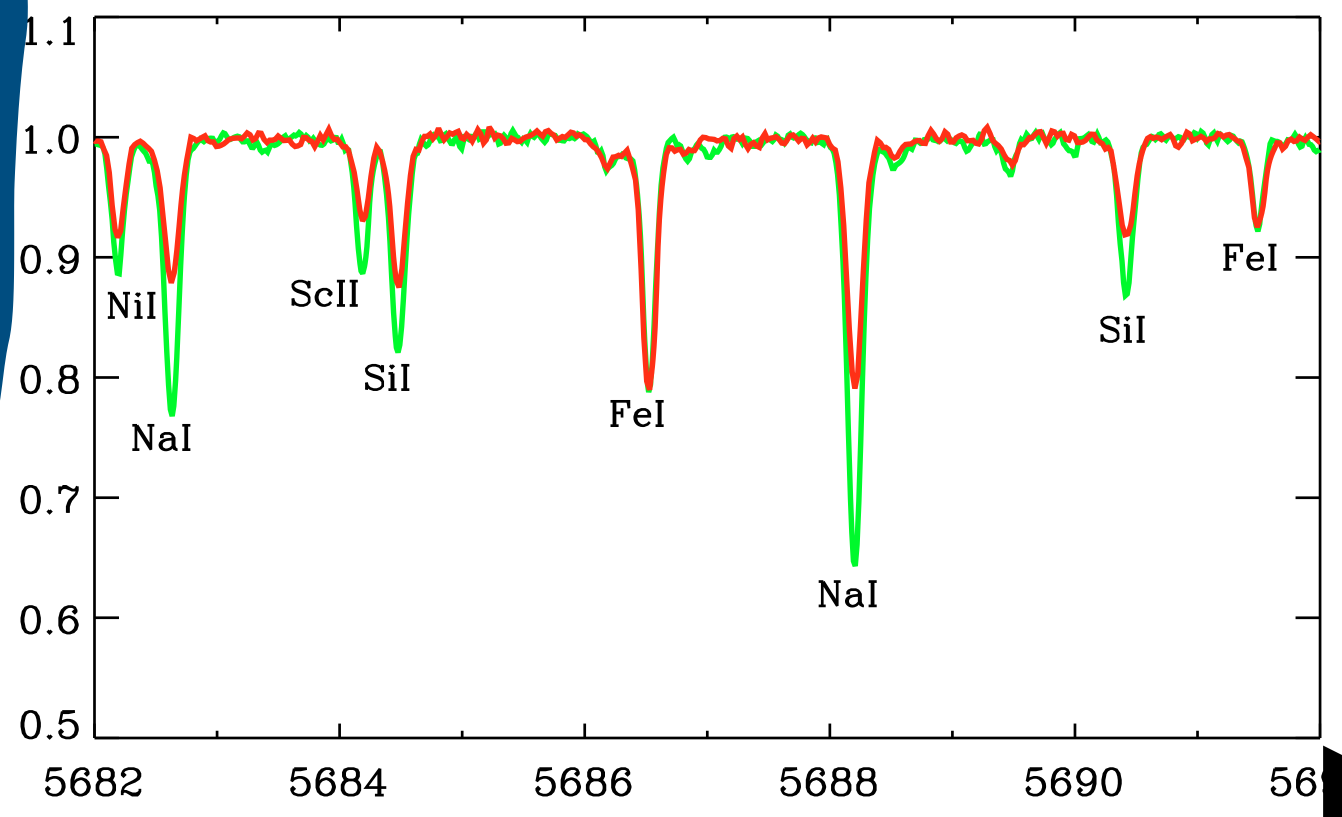

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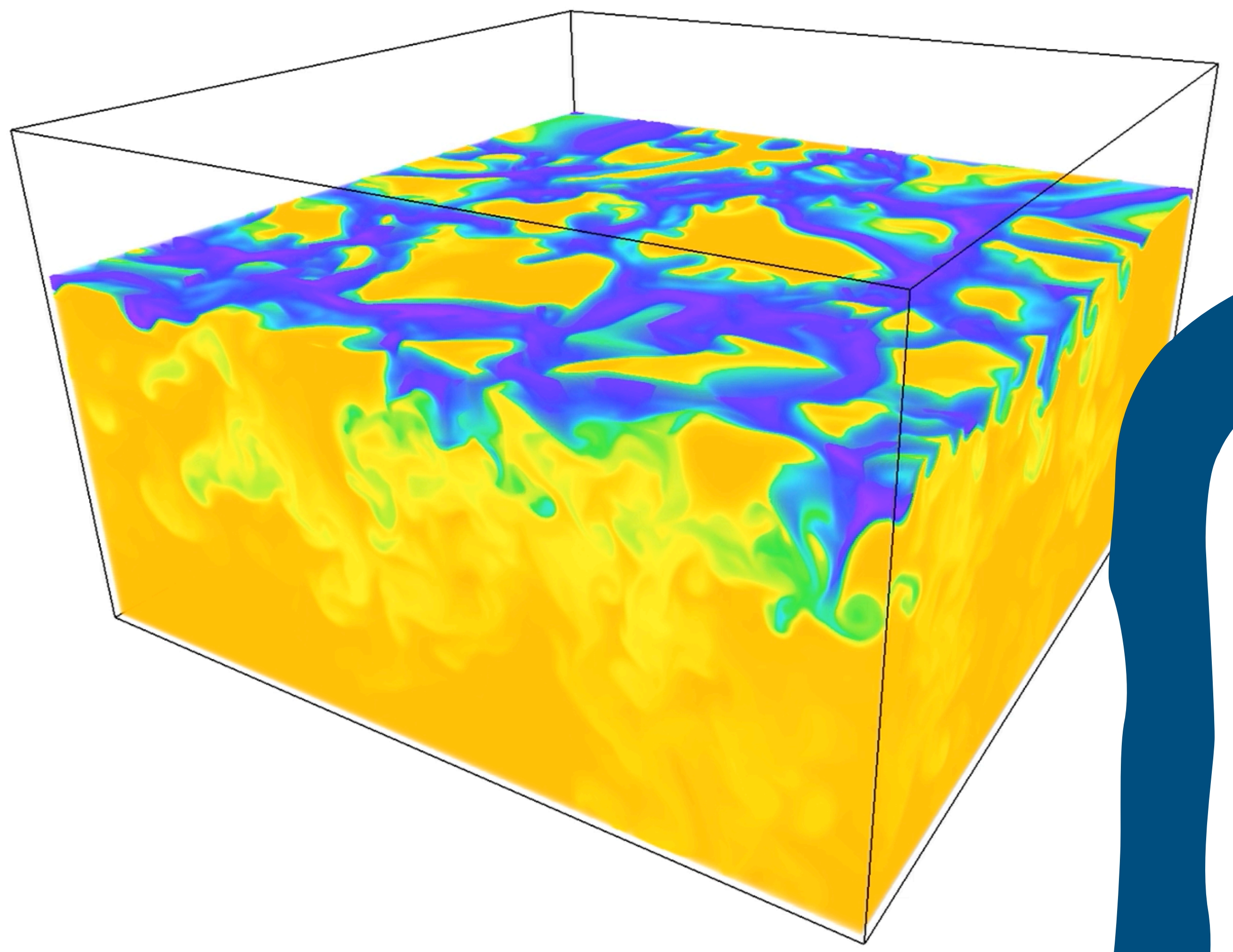
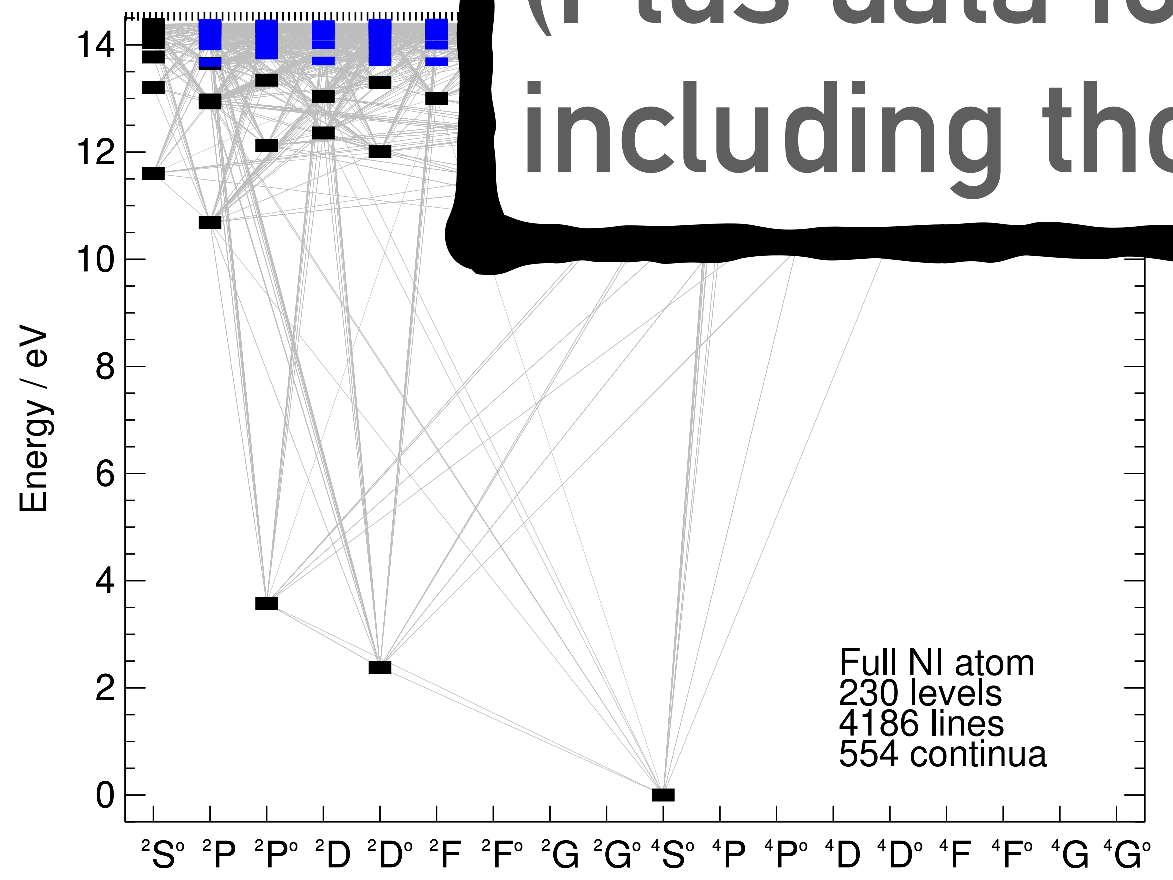
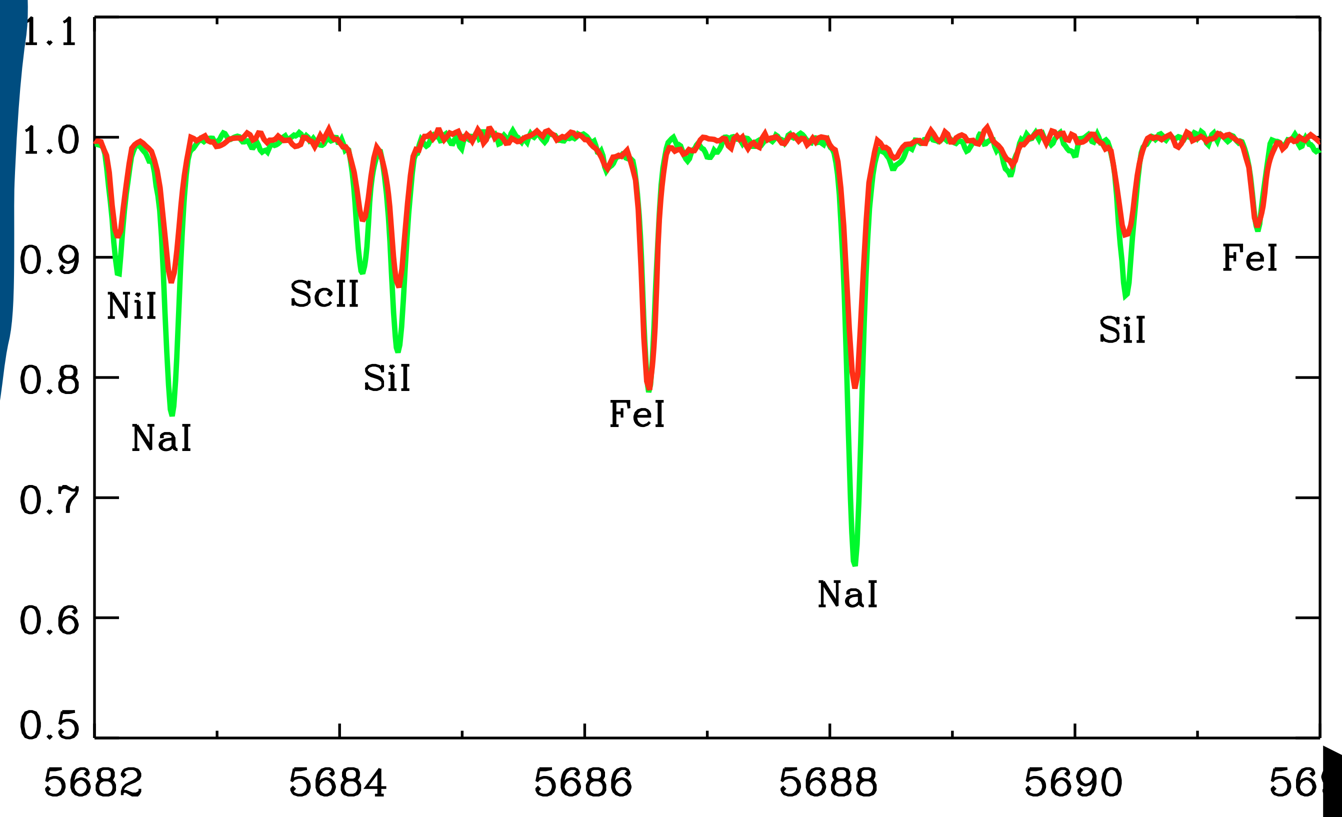
(Plus data found scattered in the literature, including those produced by people here)

Amount of data







Accuracy

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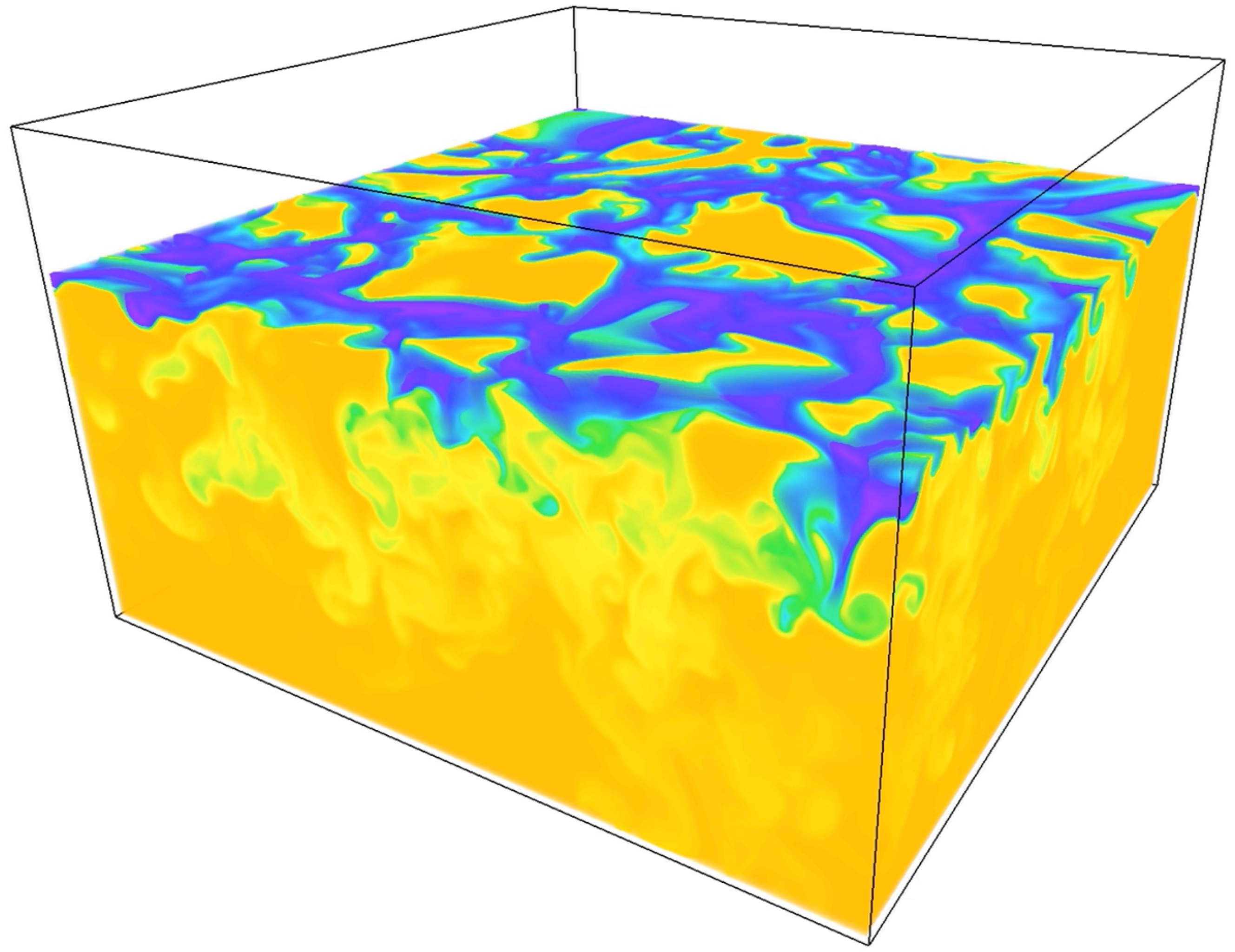

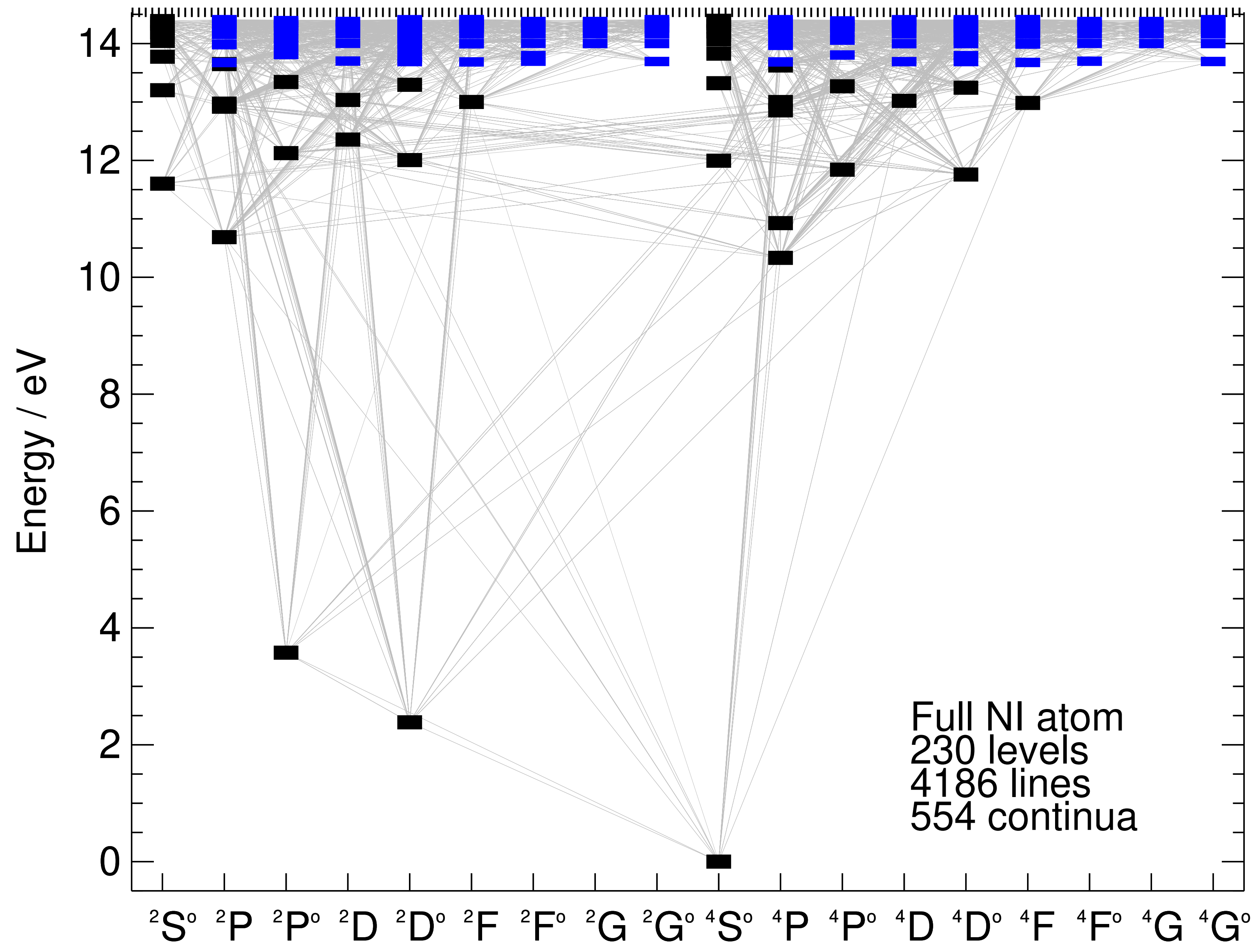

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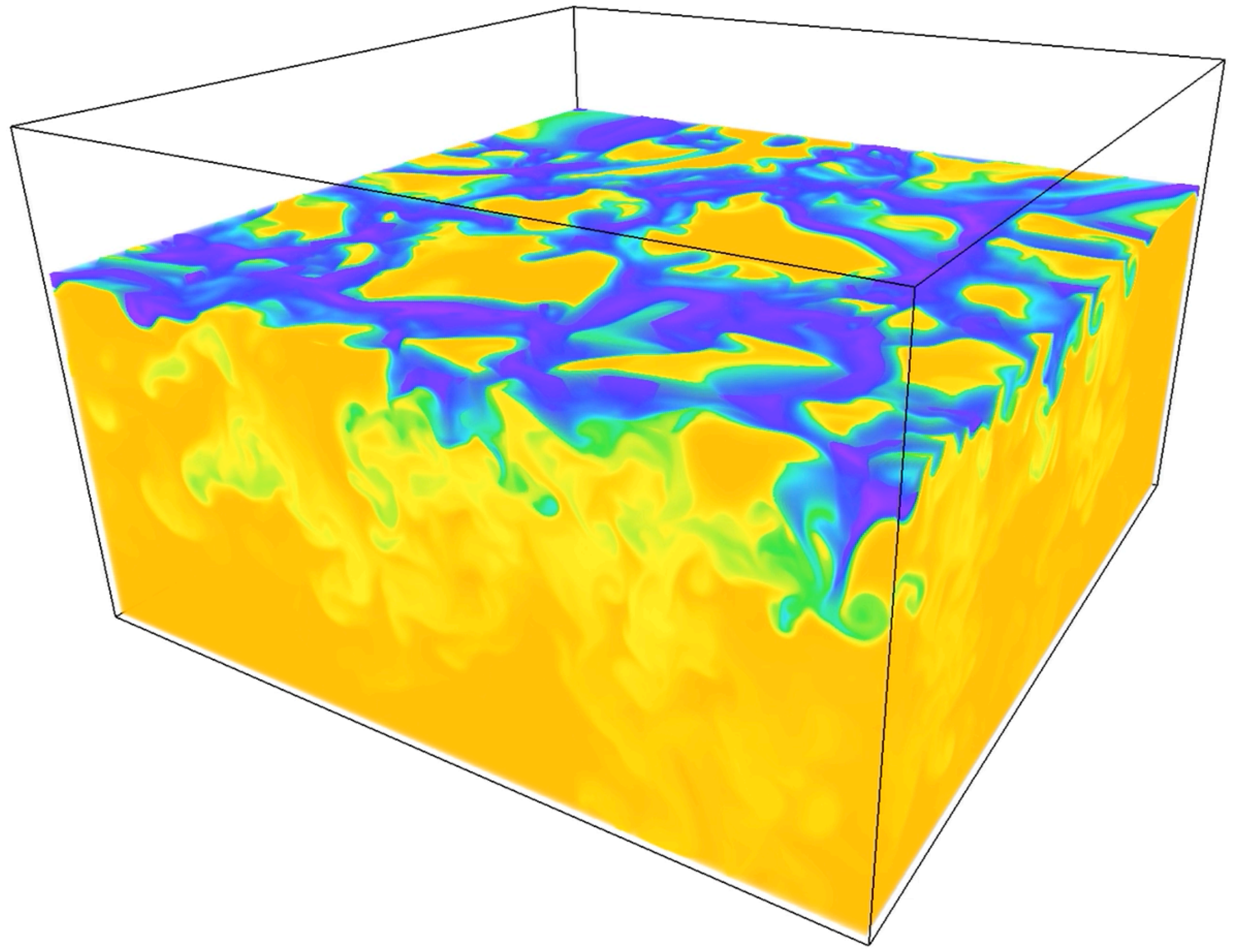
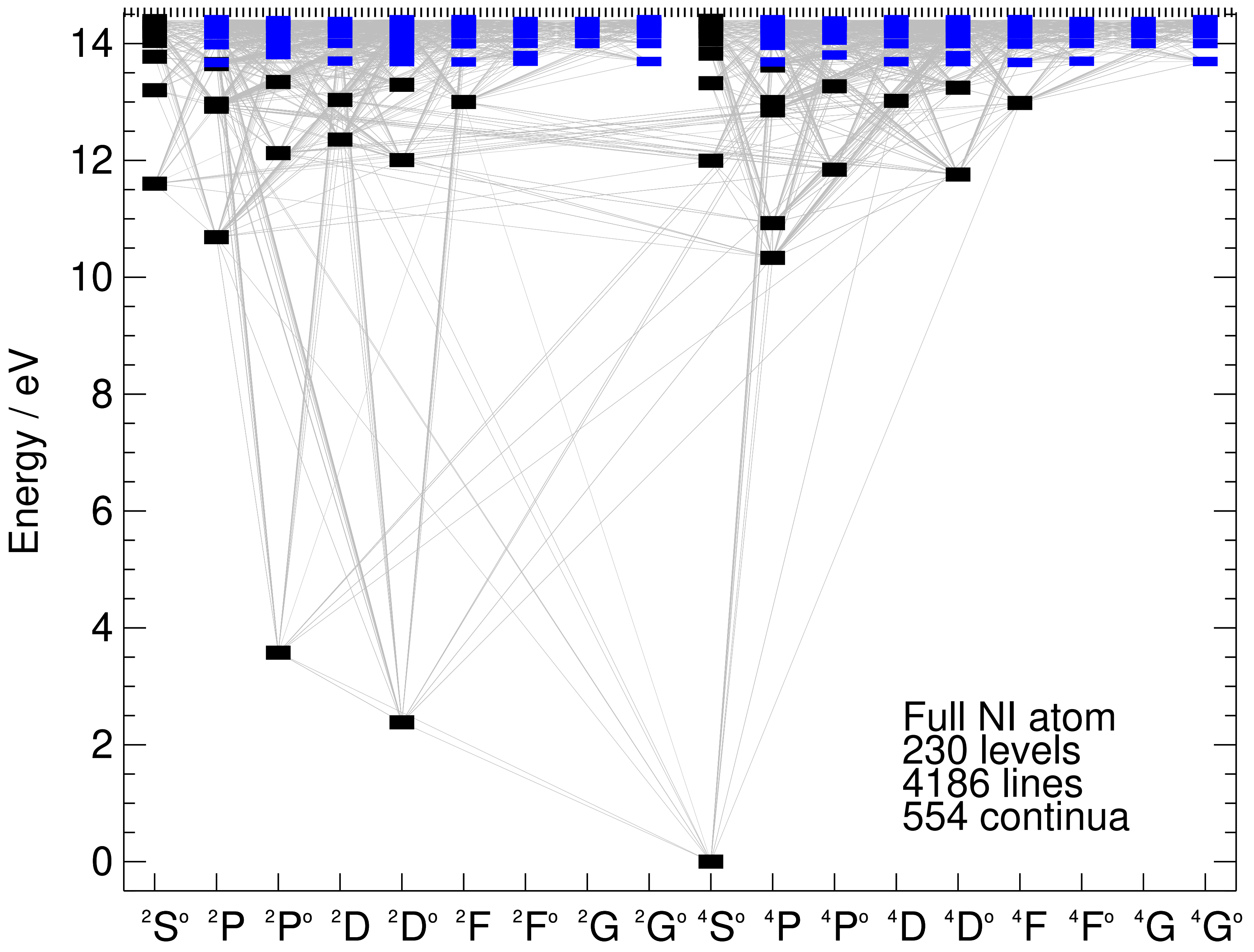
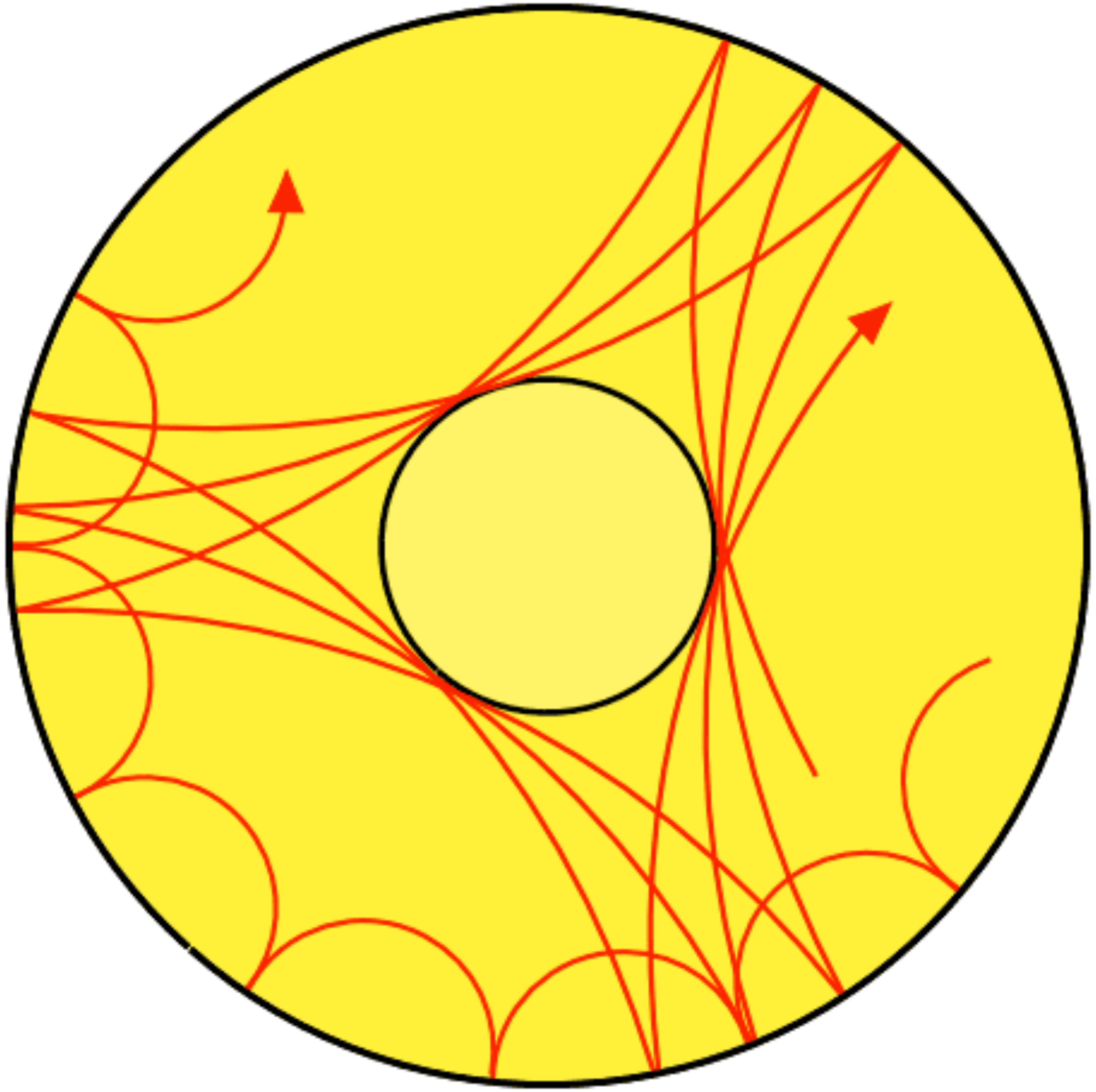
- Reality: stellar atmospheres are **3D non-LTE**
- **More realistic 3D/non-LTE** modelling presented in 2005, refined in 2009, 2015, and most recently in 2021:
  - **Asplund, Amarsi, Grevesse 2021, Z=1.39%**





The solar modelling problem

- 3D/non-LTE modelling: downwards revision of solar metallicity
  - Grevesse & Sauval 1998: Z=1.7%
  - Asplund, Amarsi, Grevesse 2021: Z=1.4%
- Revealed a severe discrepancy between solar interior structure models and helioseismic inferences
- Worrying broader implications for (stellar) astrophysics



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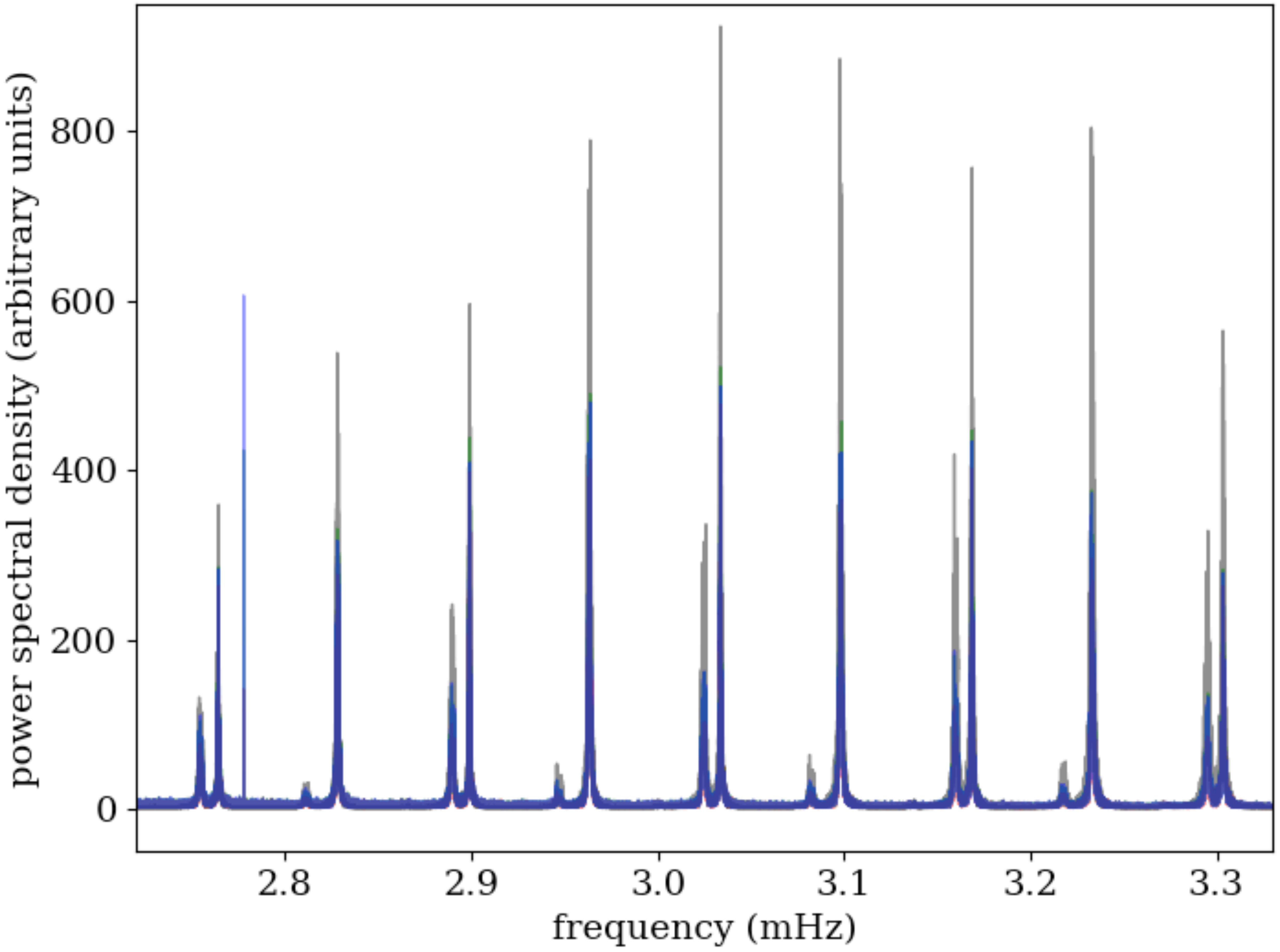

Power spectrum of the Sun [W. Ball, Birmingham]

The solar modelling problem

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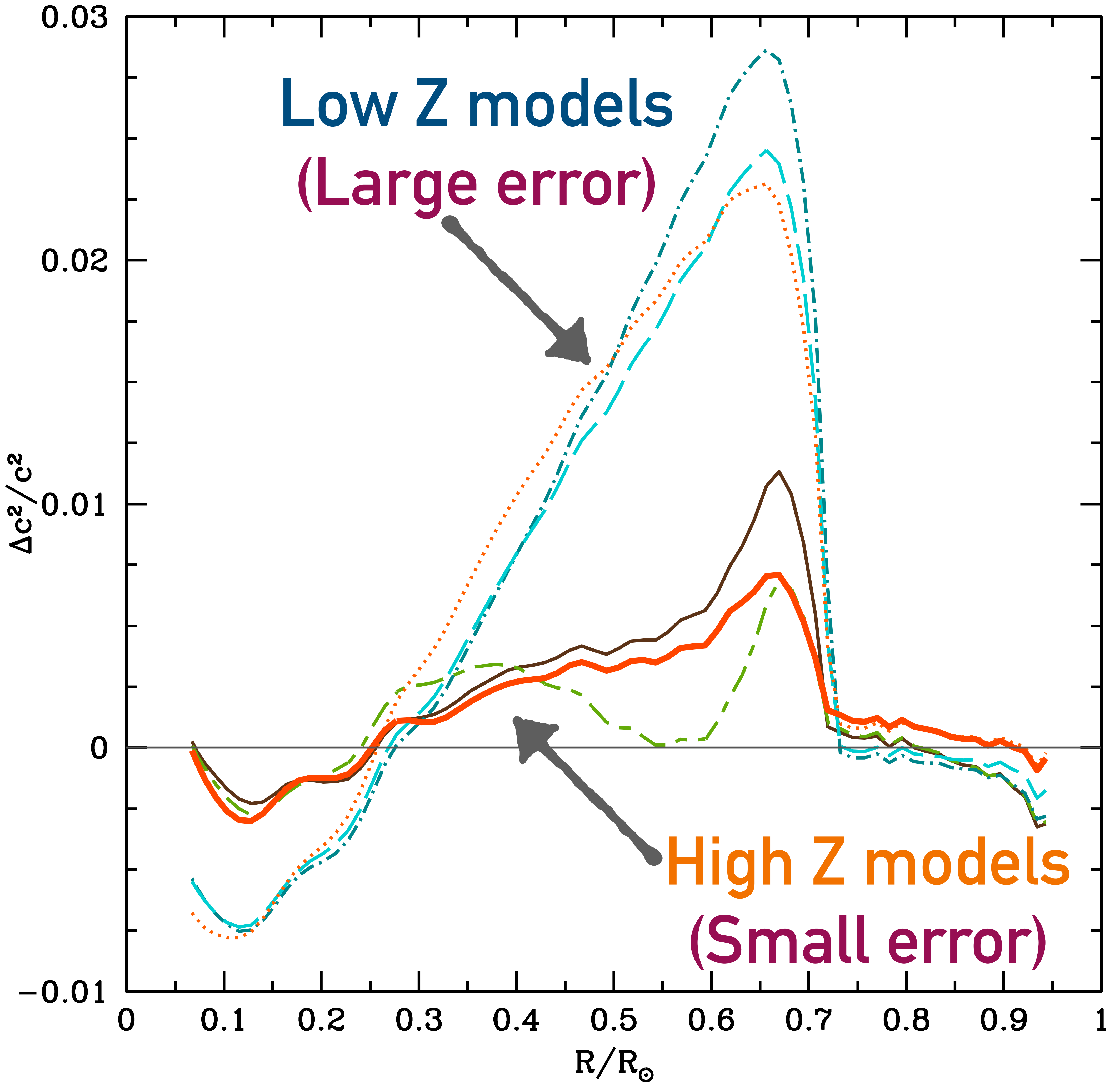
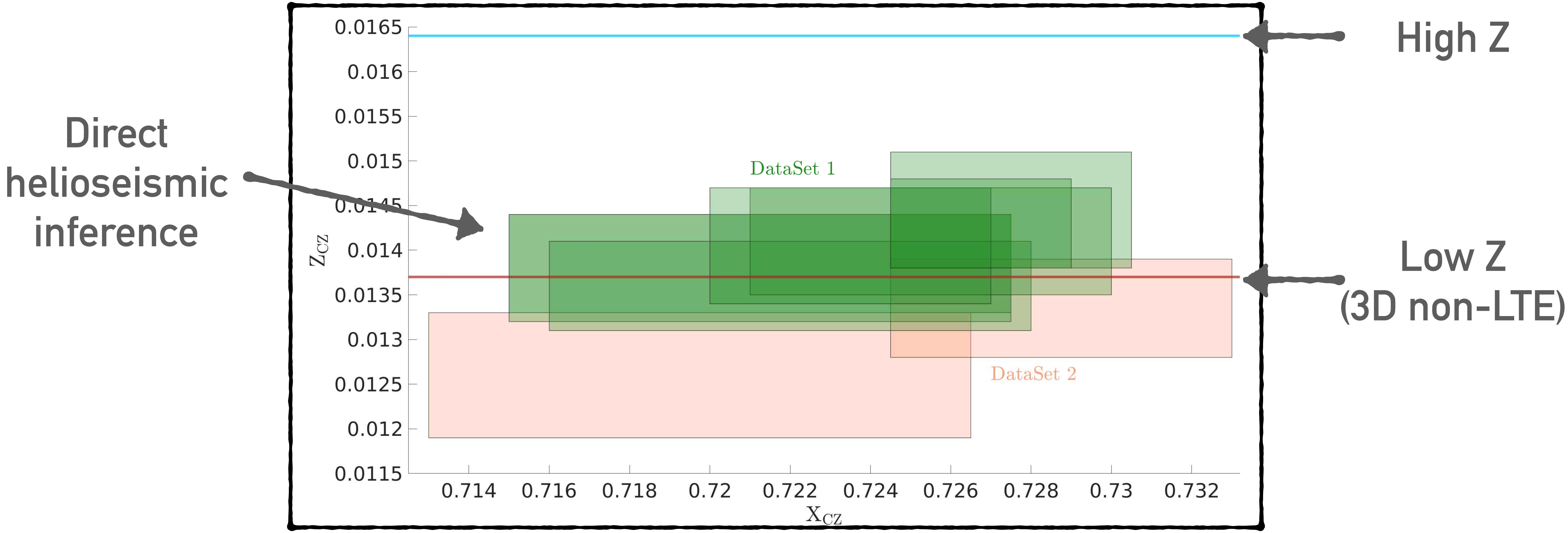


Error in the predicted interior sound speed [Stasińka+ 2012]

A problem with 3D non-LTE models?

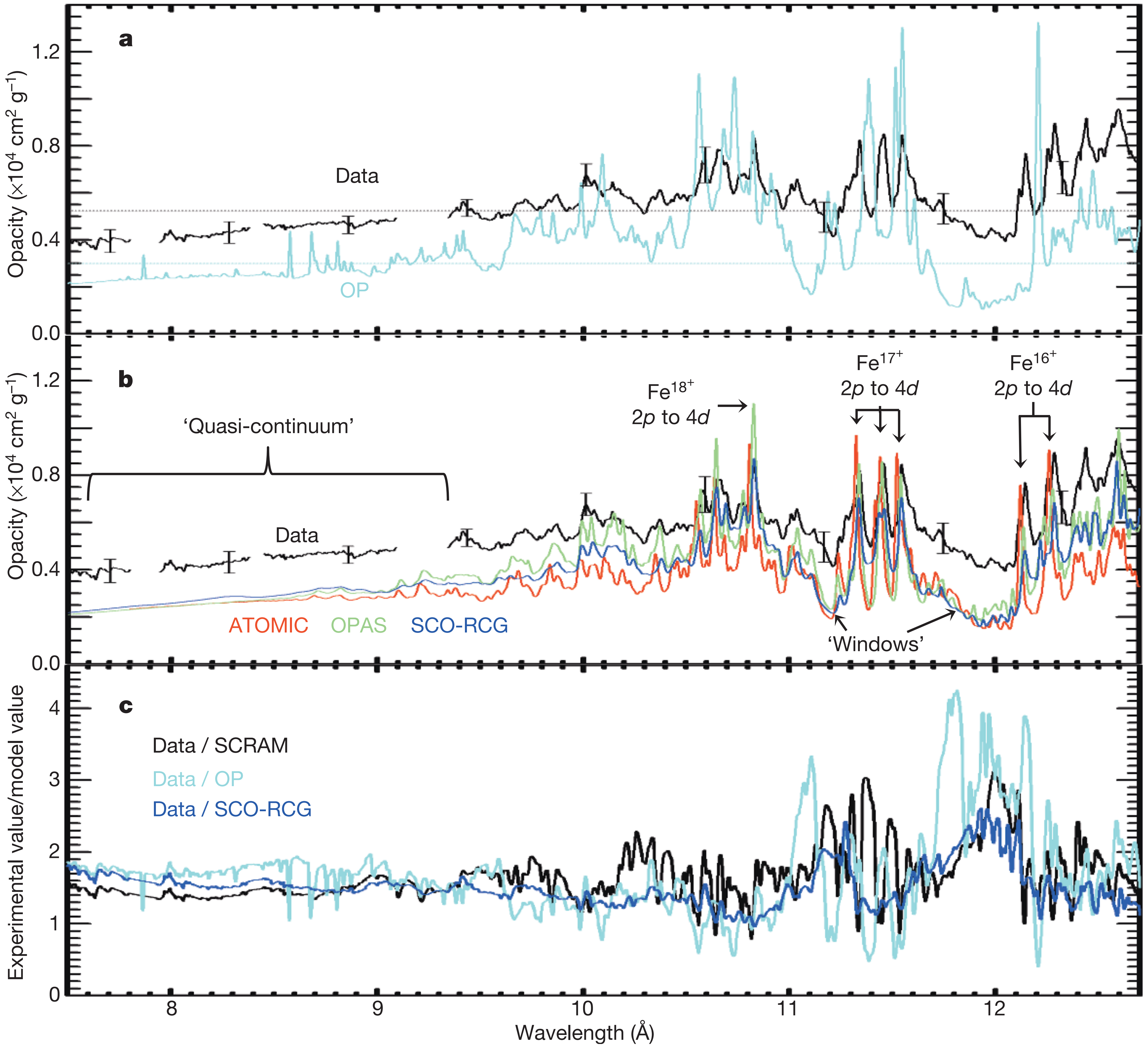


- Unlikely, because **direct inversions** of helioseismic data also suggest **Z~1.4% consistent with 3D non-LTE models** (Buldgen et al. submitted)

Best estimate of Z directly from helioseismic data [Buldgen+ submitted]

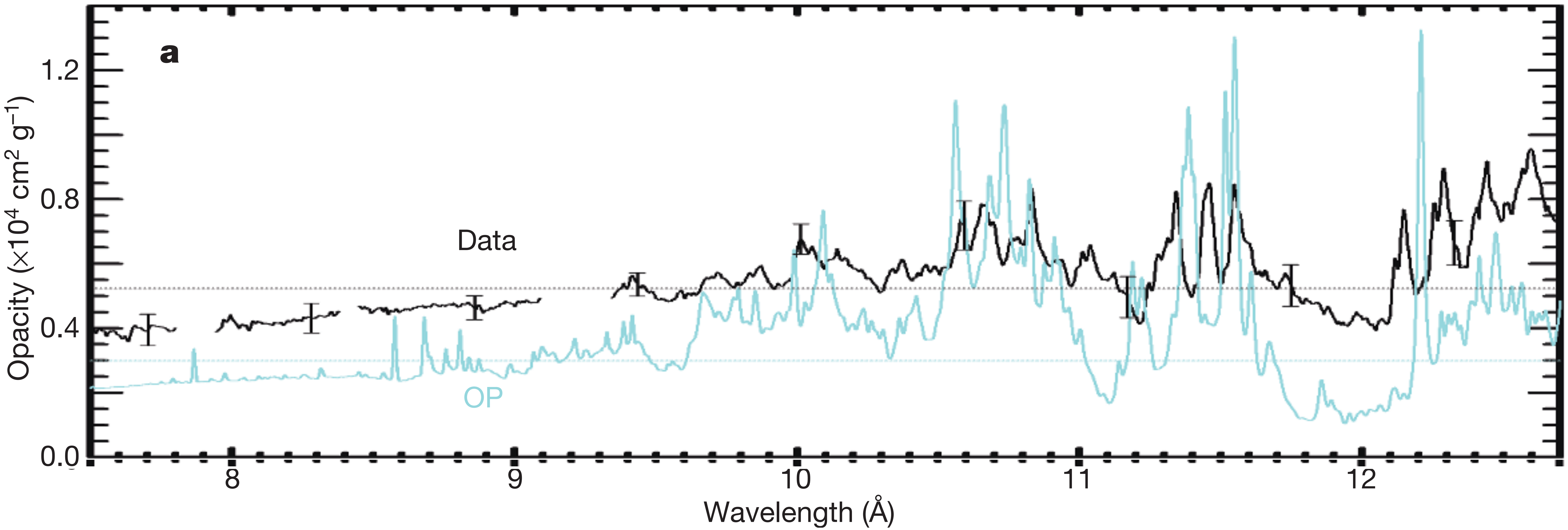
A problem of missing opacity?

- A possible contributing factor to the solar problem is the treatment of **interior opacities**
  - Temperatures of around 2 million kelvin
  - Larger abundances or larger opacities = similar impact on solar models
- (Also see talk #4 on Monday; poster #26)



Higher-than-predicted measured opacities [Bailey+ 2015]

A problem of missing opacity?

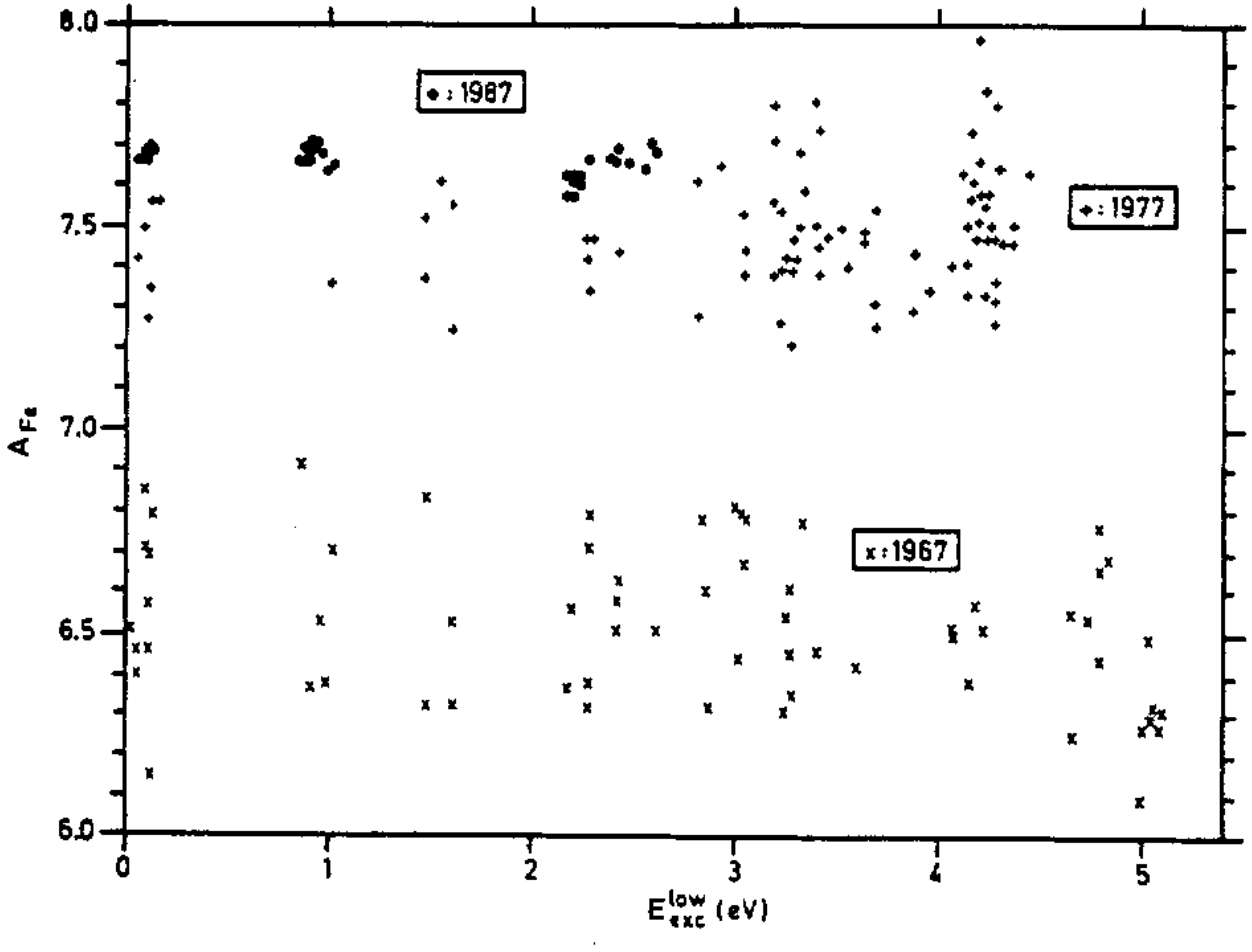


- "The measured wavelength-dependent opacity is 30–400 per cent higher than predicted. This represents roughly **half the change** in the mean opacity needed to **resolve the solar discrepancy**, even though **iron is only one of many elements** that contribute to opacity" [Bailey+ 2015]

Higher-than-predicted measured opacities [Bailey+ 2015]

Atomic-astrophysics connections

- The solar problem is a good illustration of the **connections** between atomic physics and astrophysics
- Atomic → Astro
  - **Improved log gf's** = well-constrained **1D LTE** composition (e.g. 1990's)



Evolution of solar iron abundance with improving log gf data [Grevesse & Noels 1993]

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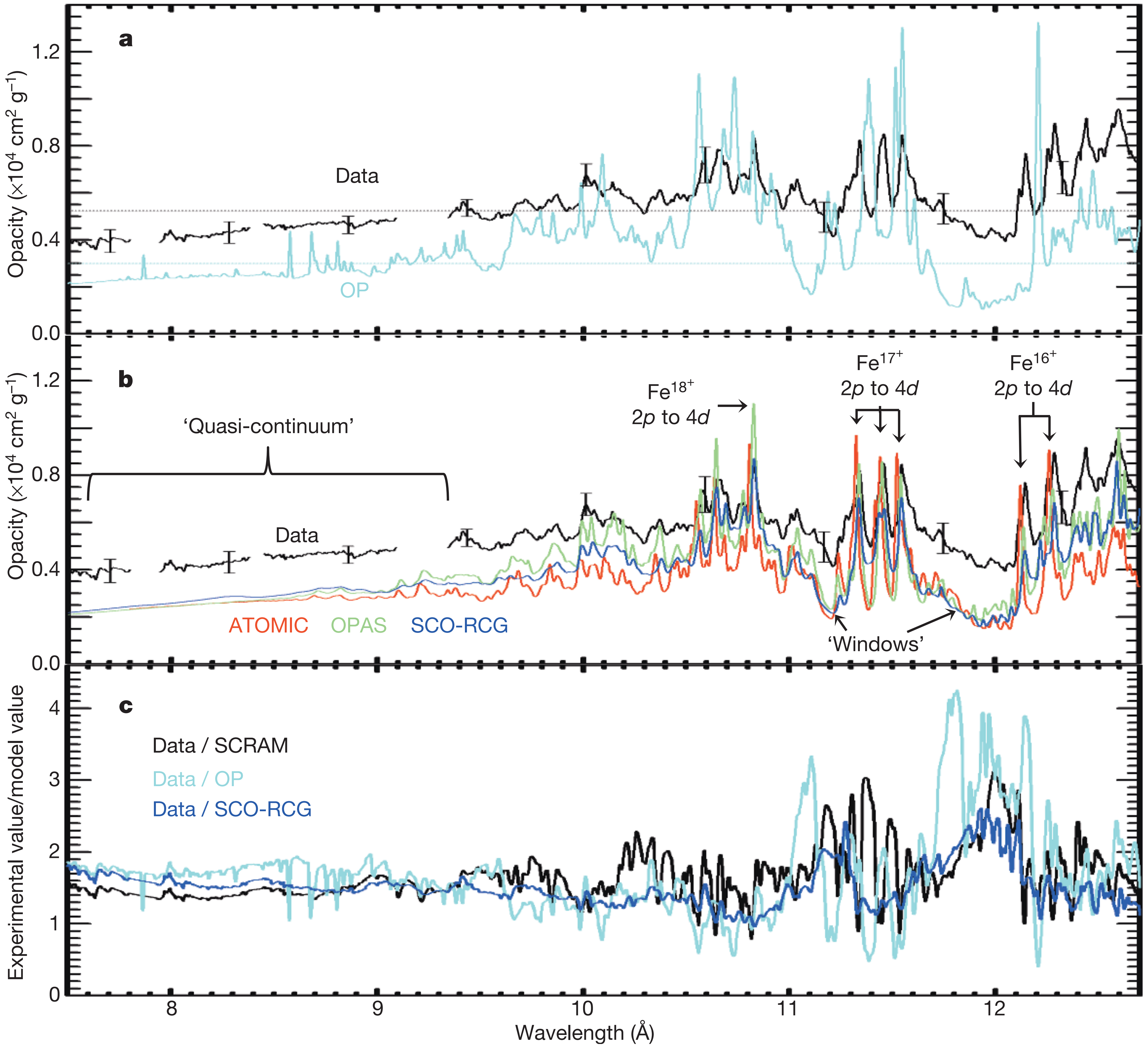
- Astro → Atomic
  - **More realistic 3D/non-LTE models** in the 2000's helped motivate a deeper look into theoretical opacities



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The message of this talk

- Rapid progress in developing **3D non-LTE model stellar spectra,** with **increasing sophistication and accuracy**
- Cause/caused by stronger connections between **atomic/astrophysics**
- **Atomic → Astro**
  - Improved atomic data *improve the models*
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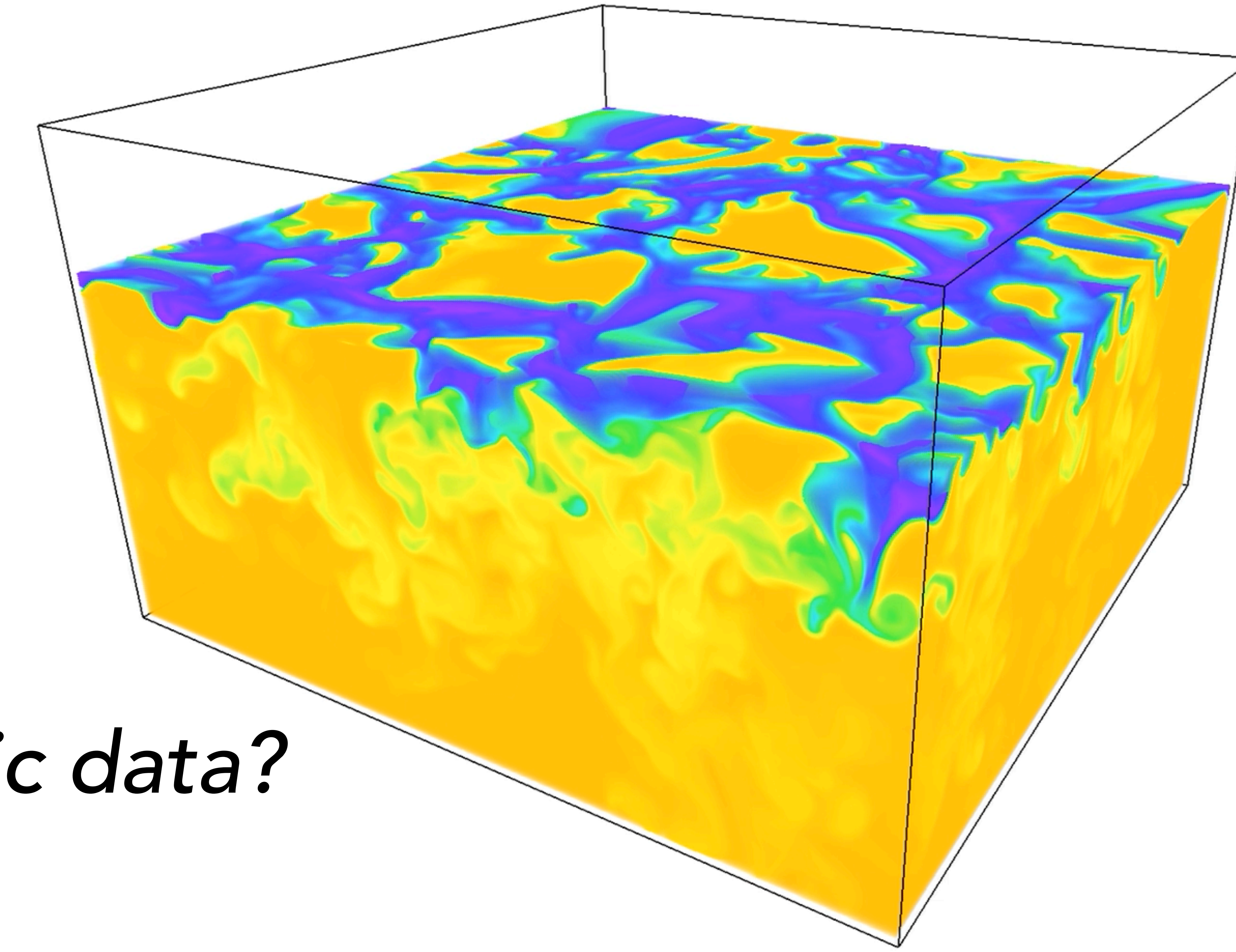

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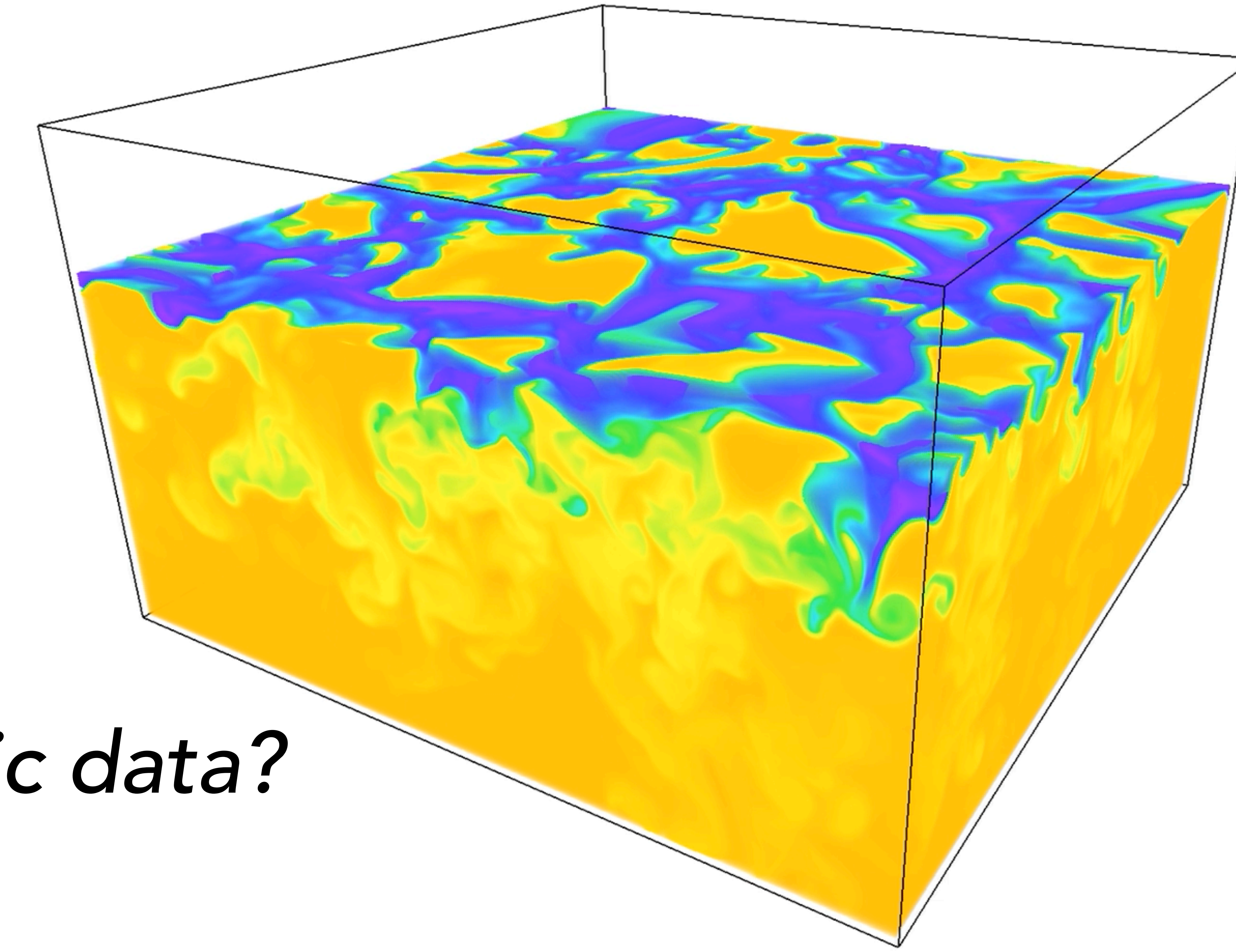
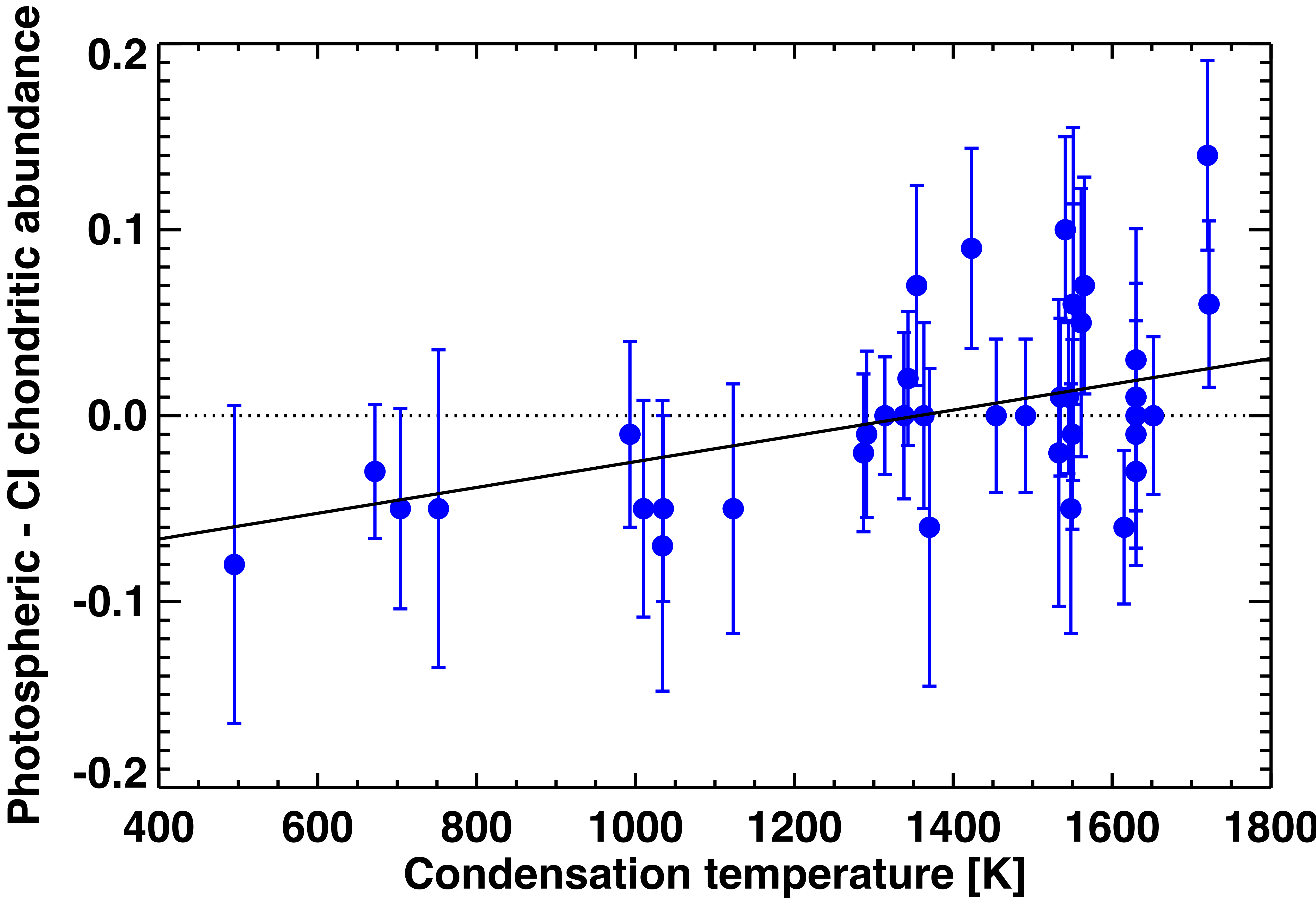


Imprints of solar system formation

- The solar abundances are reaching precision/accuracy to resolve possibly **intrinsic differences with pristine meteorites**
- Trend with condensation temperature at ~2 sigma



Sun - meteoritic abundances versus condensation temperature [Asplund+ 2021]

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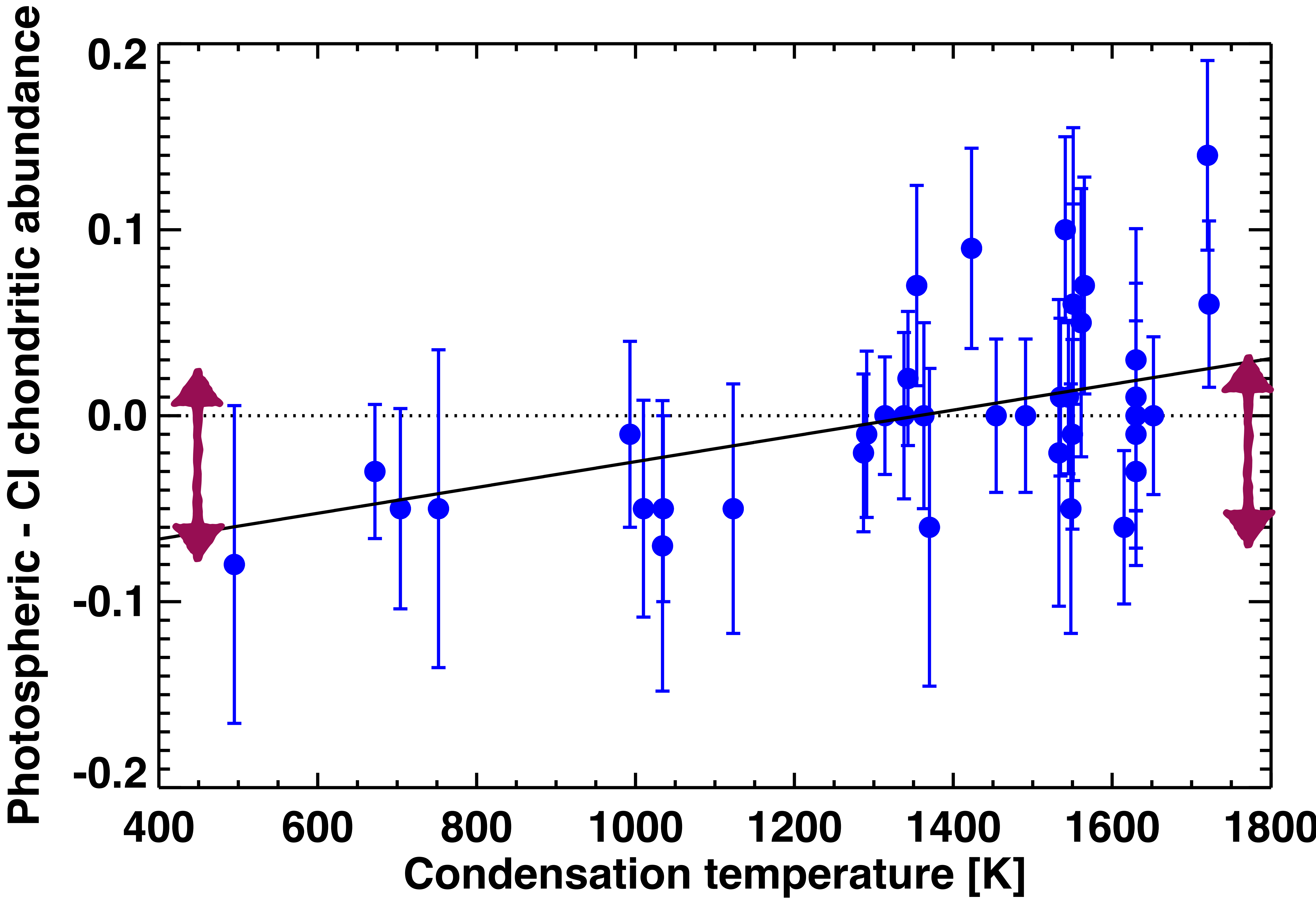
- The solar abundances are reaching precision/accuracy to resolve possibly **intrinsic differences with pristine meteorites**
- Trend with condensation temperature at ~2 sigma
- Amplitude of signature ~ **25%**
- Precision (for one element) ~**10-25%**



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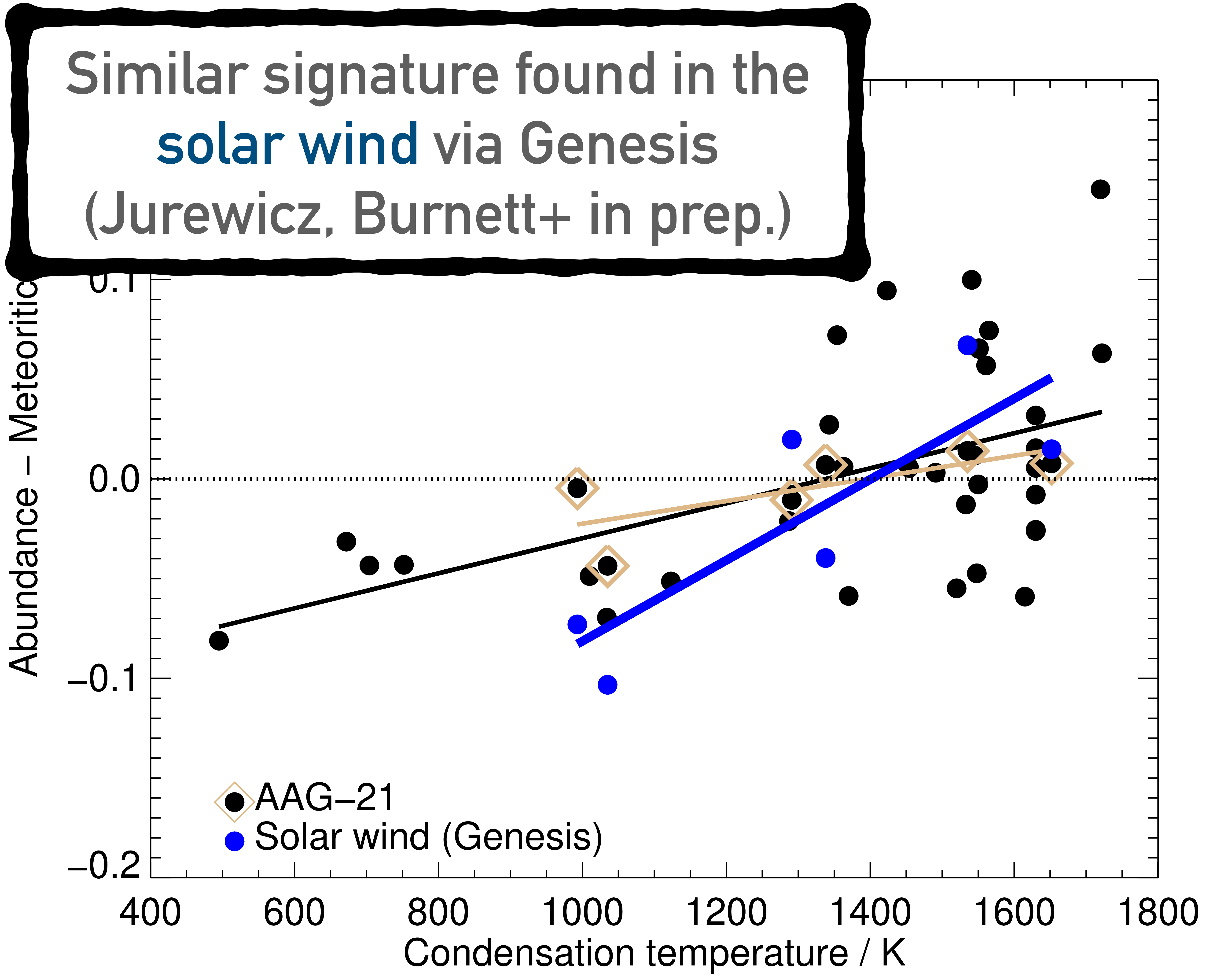
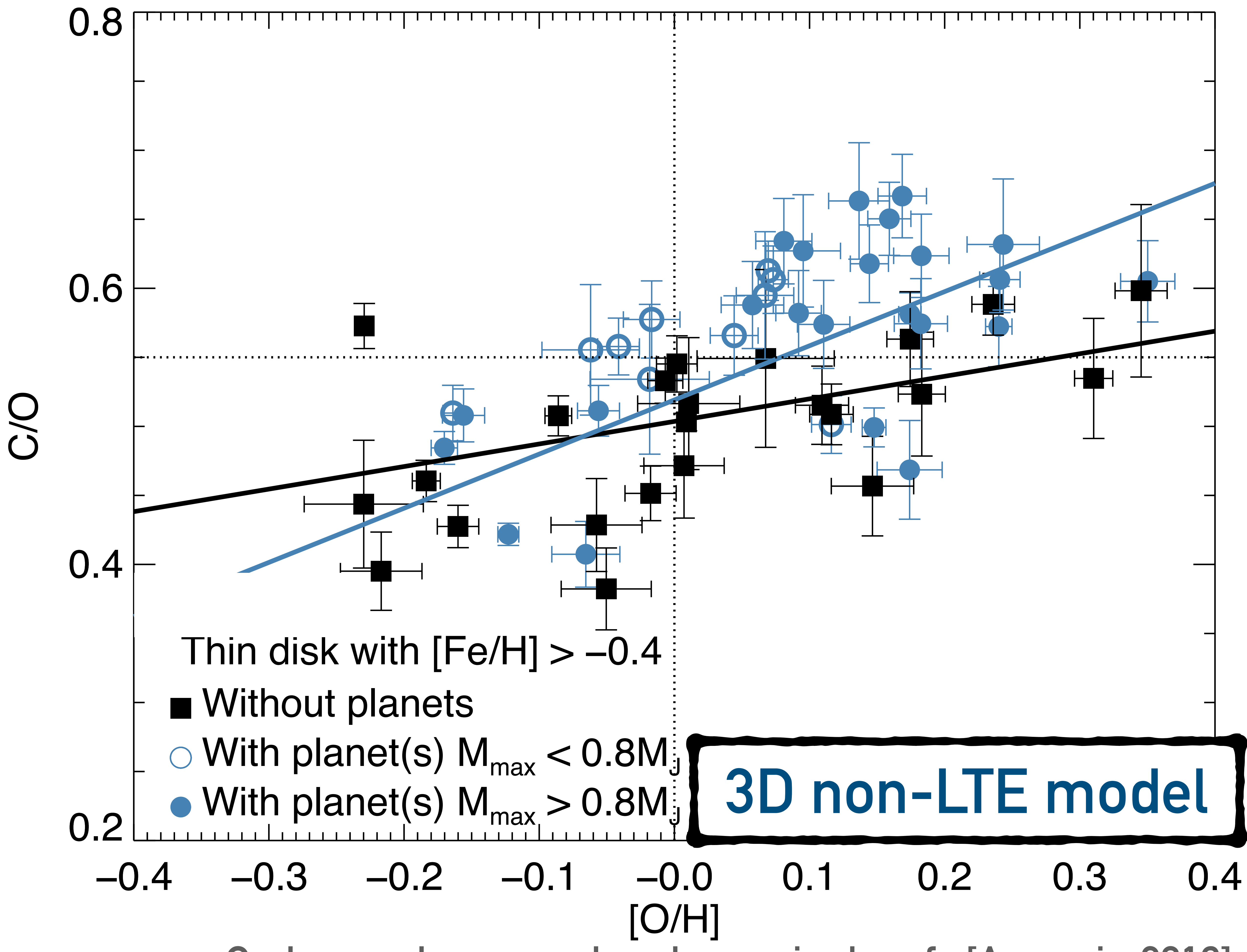


Stars with and without planets

- Look at **carbon to oxygen abundance ratios** in different stars
  - X-axis is a proxy for cosmic time



Carbon and oxygen abundances in dwarfs [Amarsi+ 2019]

Stars with and without planets

- Look at **carbon to oxygen abundance ratios** in different stars
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- Separation between stars **with** and **without planets**
- Amplitude of signature ~ **10-20%**
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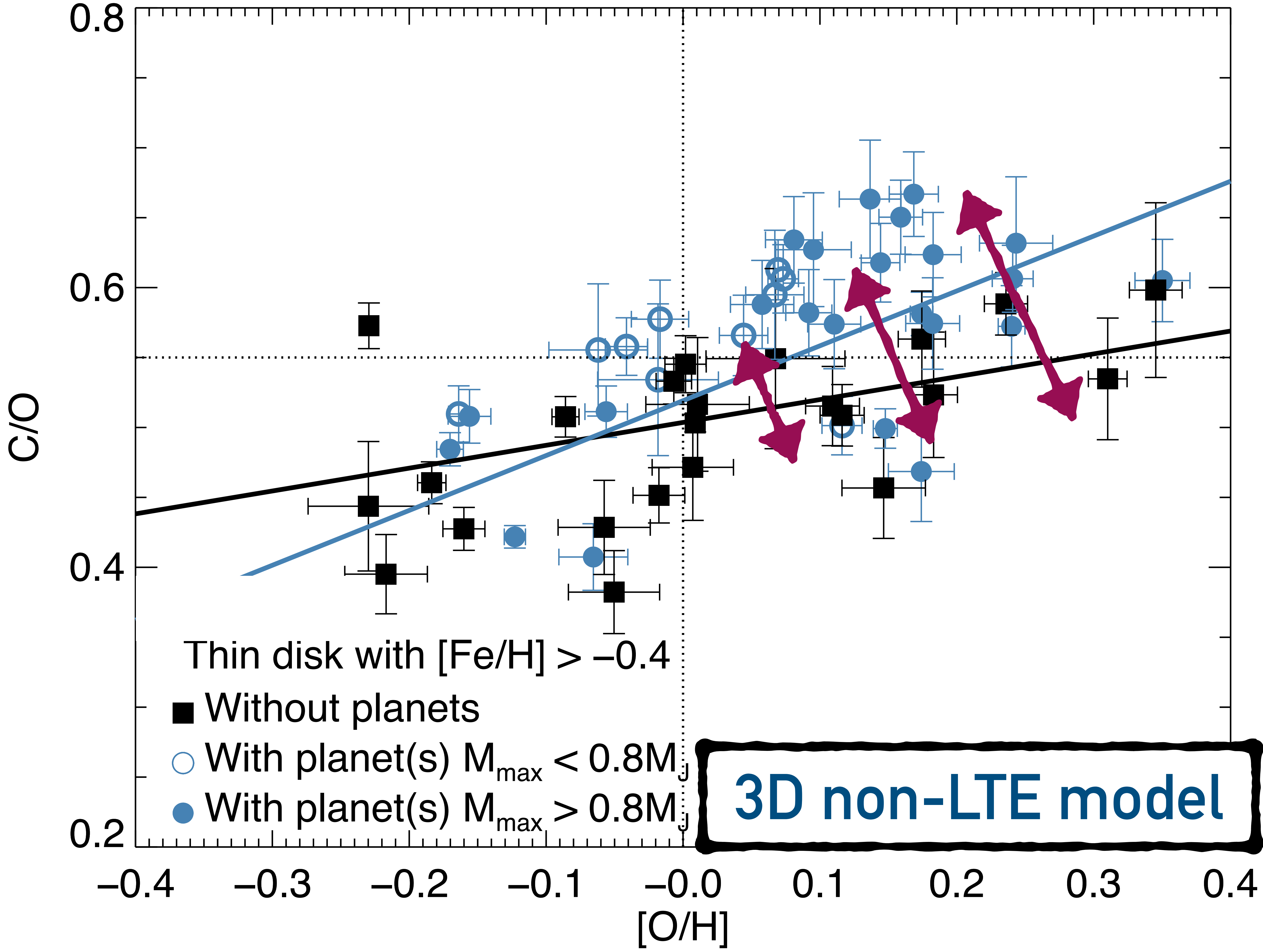

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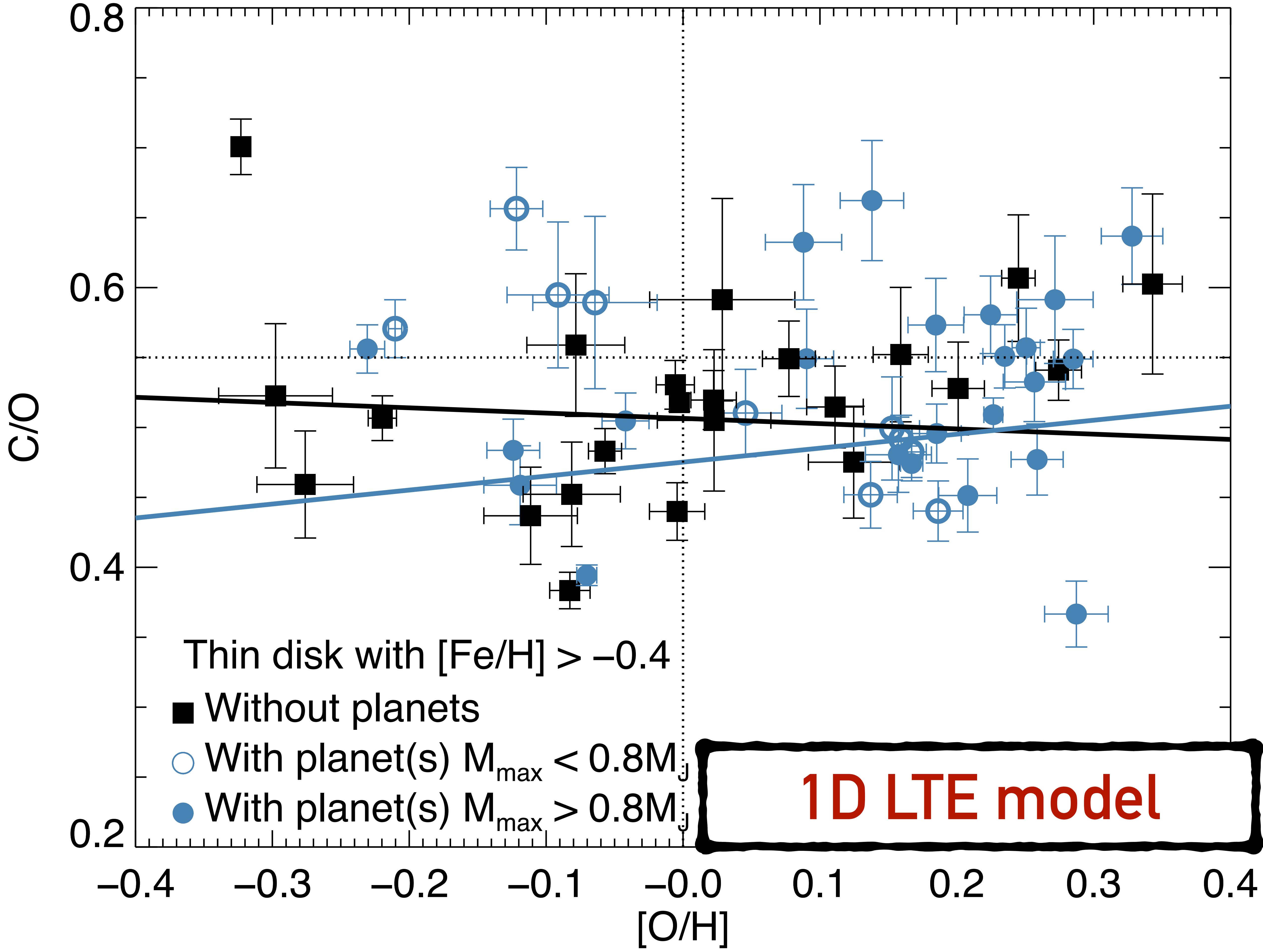

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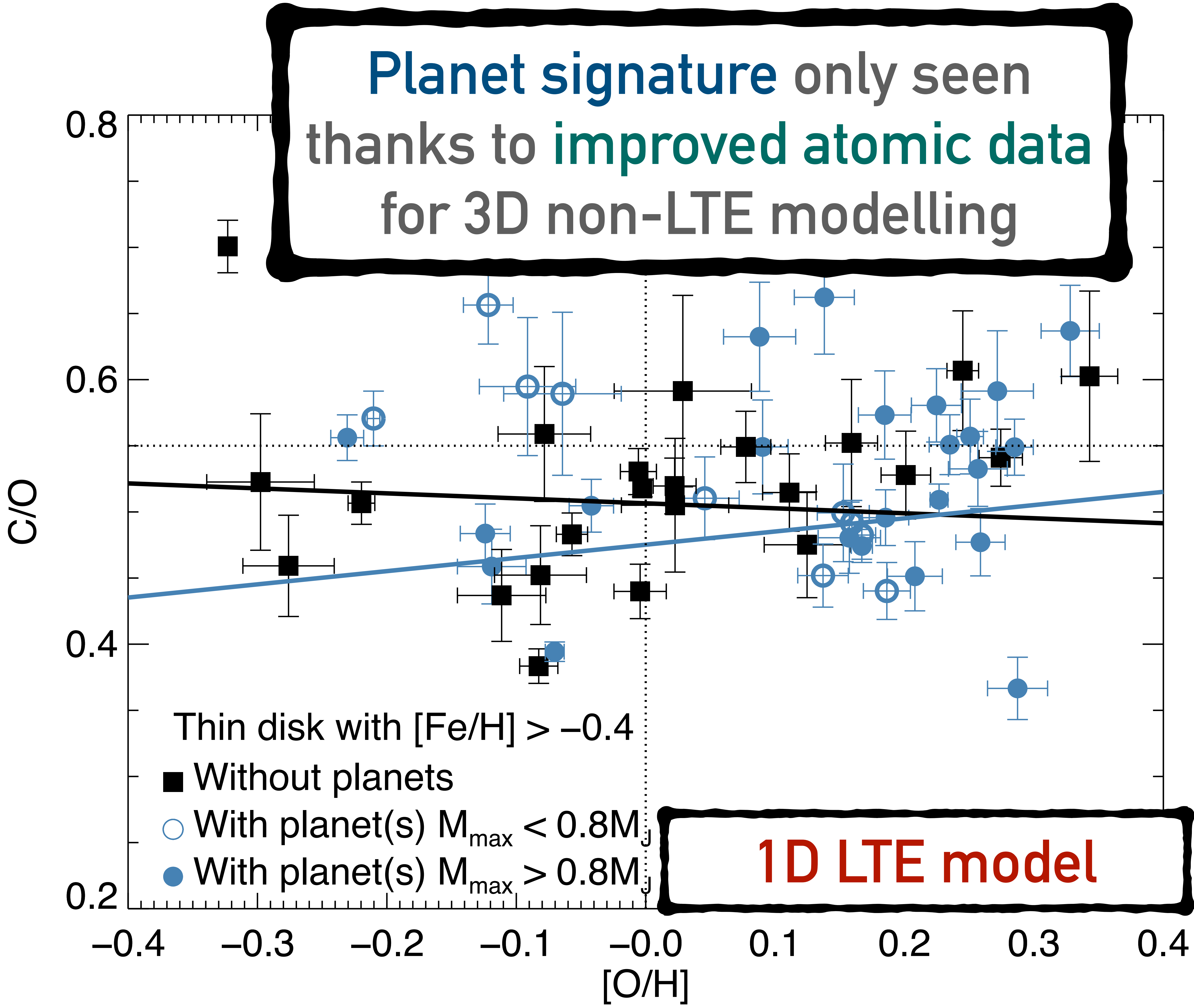

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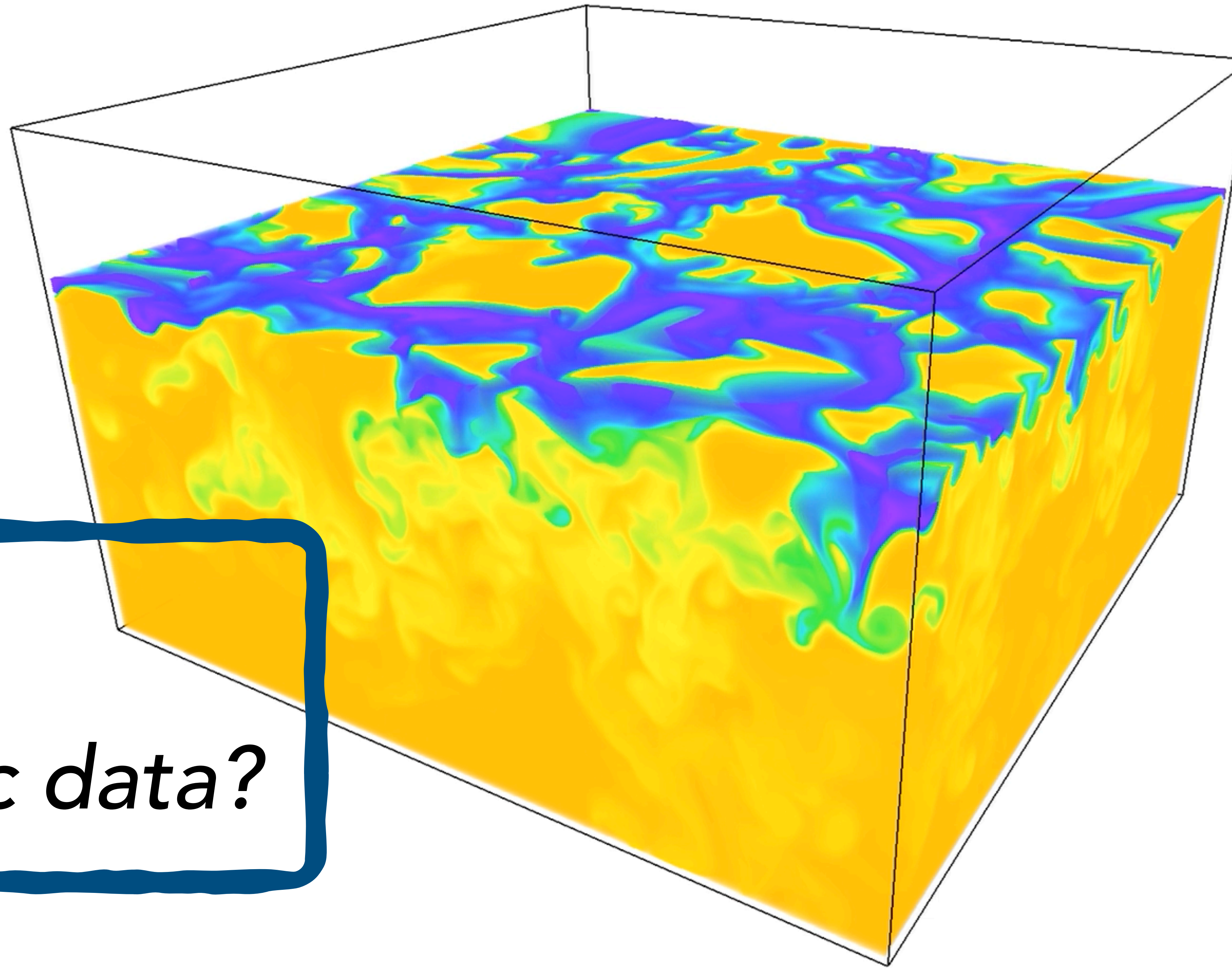
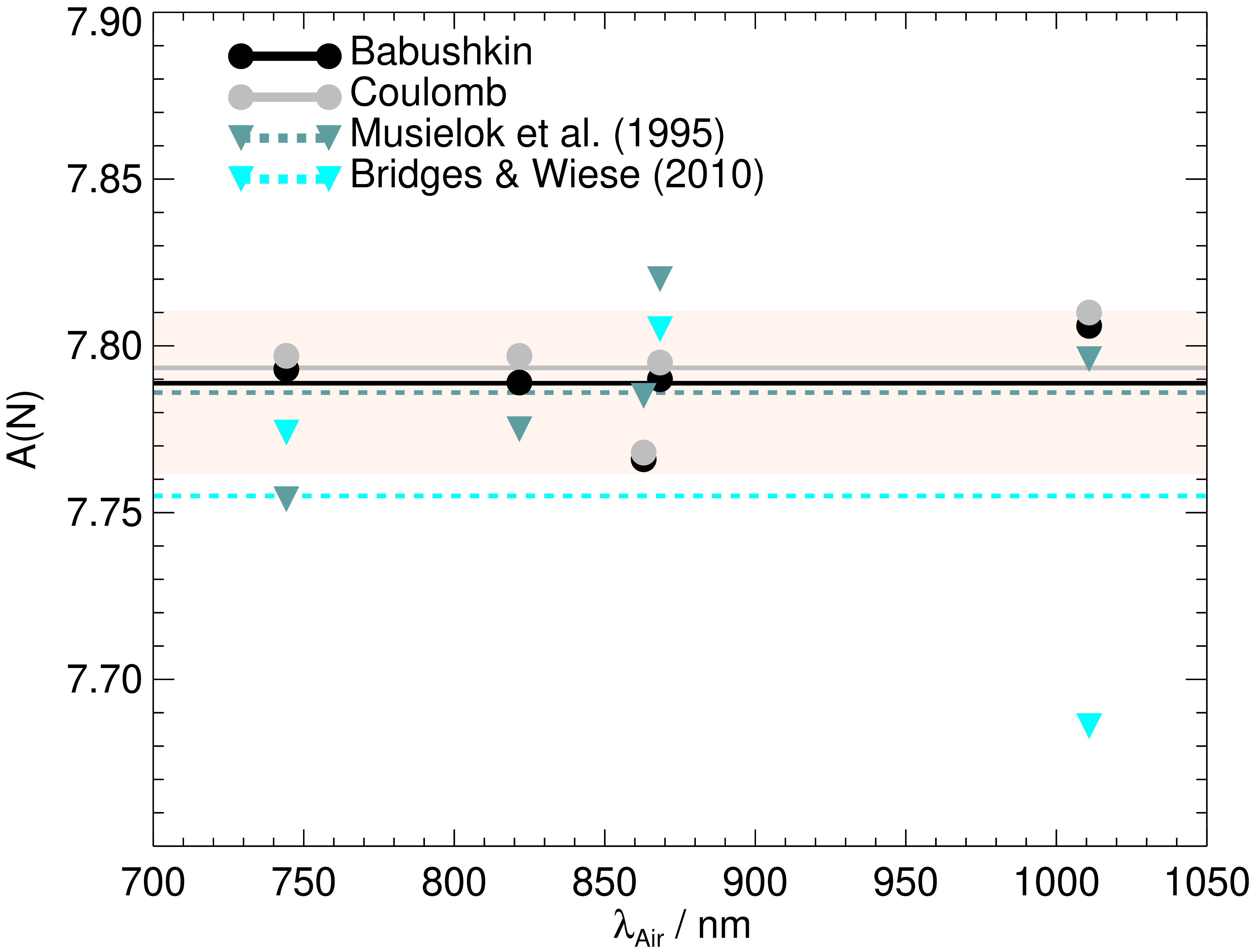


Astrophysical tests of atomic data

- Oscillator strengths
  - Examine scatter and trends in line-by-line analyses of standard stars using different data sets



Astrophysical tests of N I oscillator strengths [Li et al. 2023]

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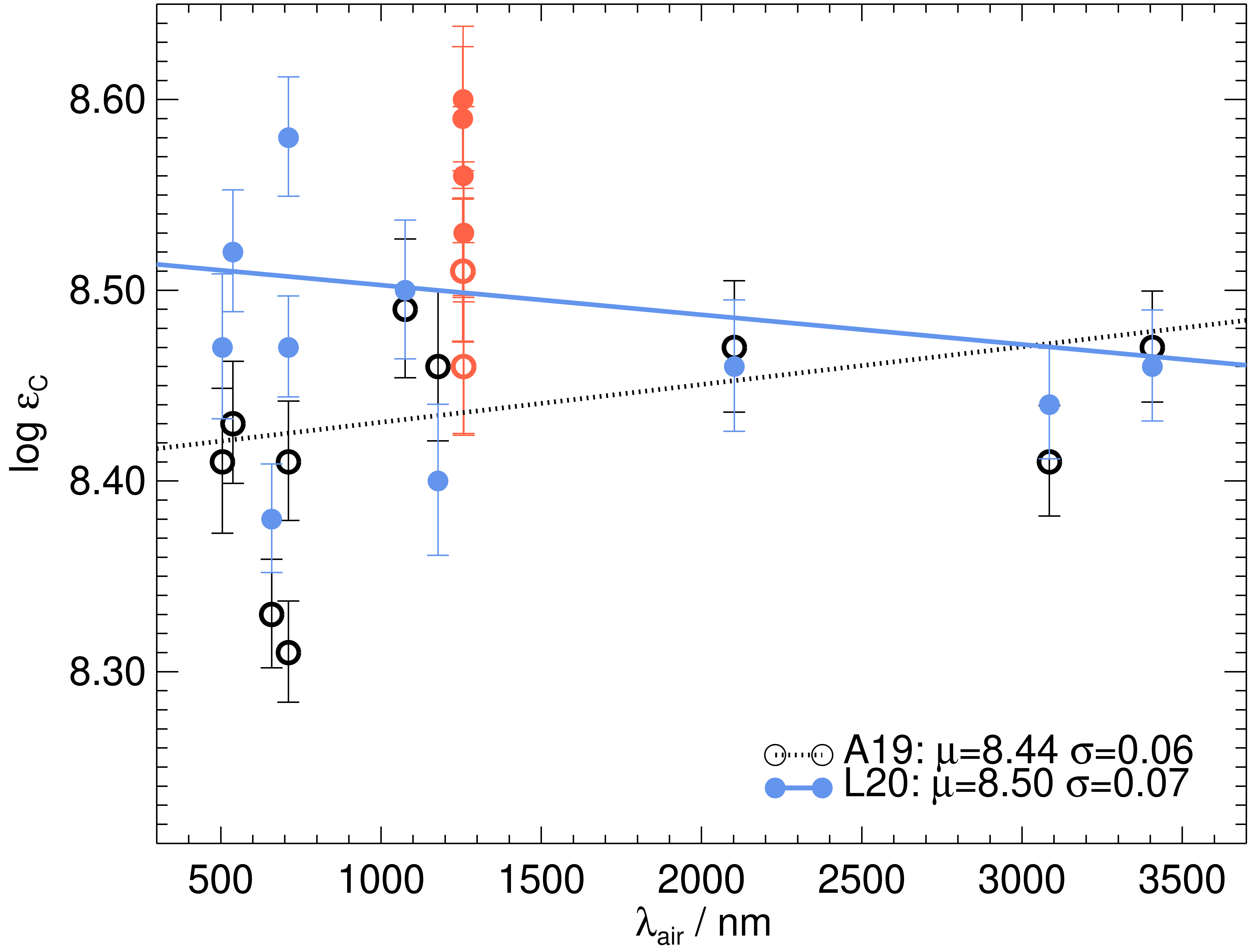

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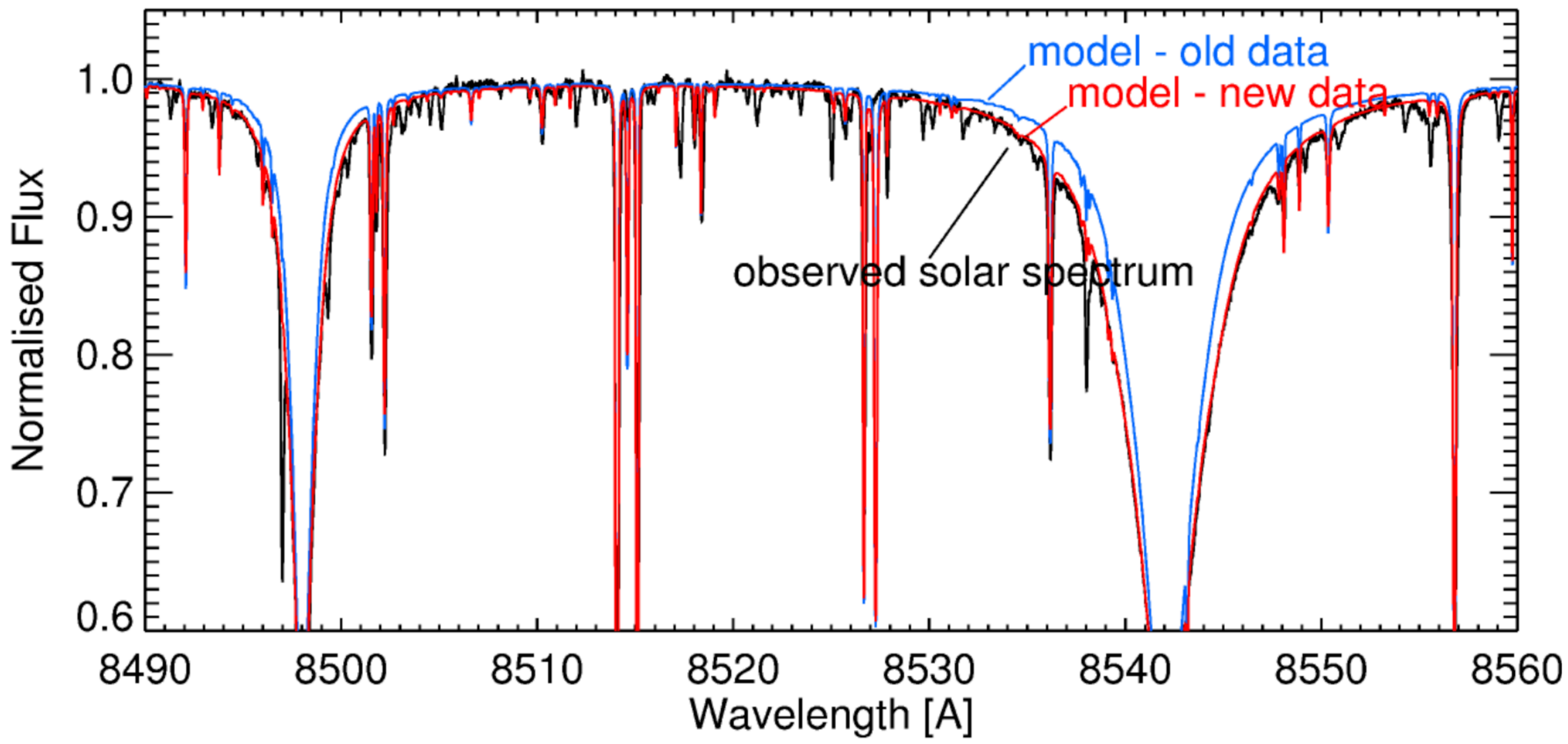

Validation of hydrogen collisional broadening data [Barklem 2016]

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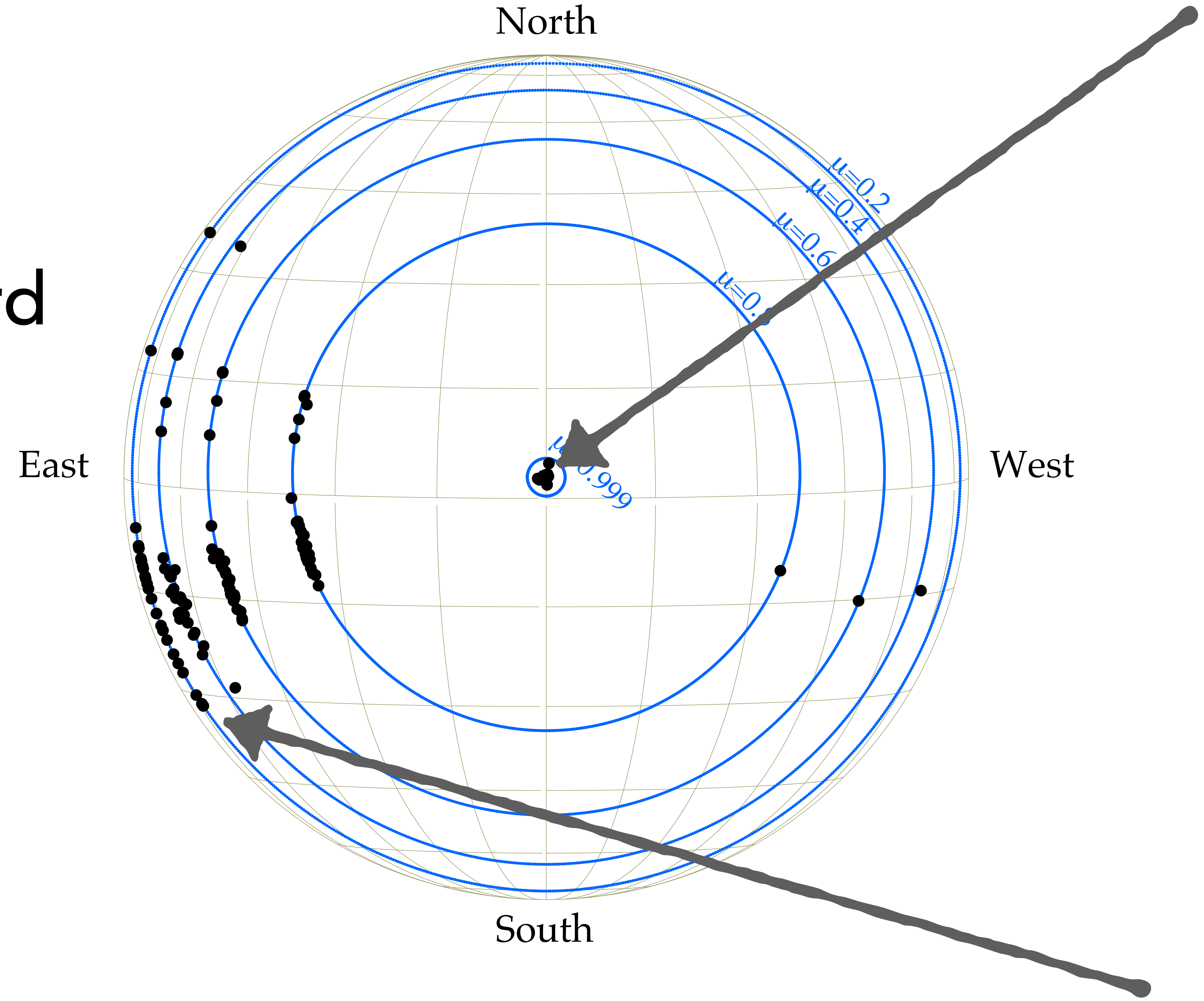
- Inelastic collisions
  - Examine centre-to-limb variations



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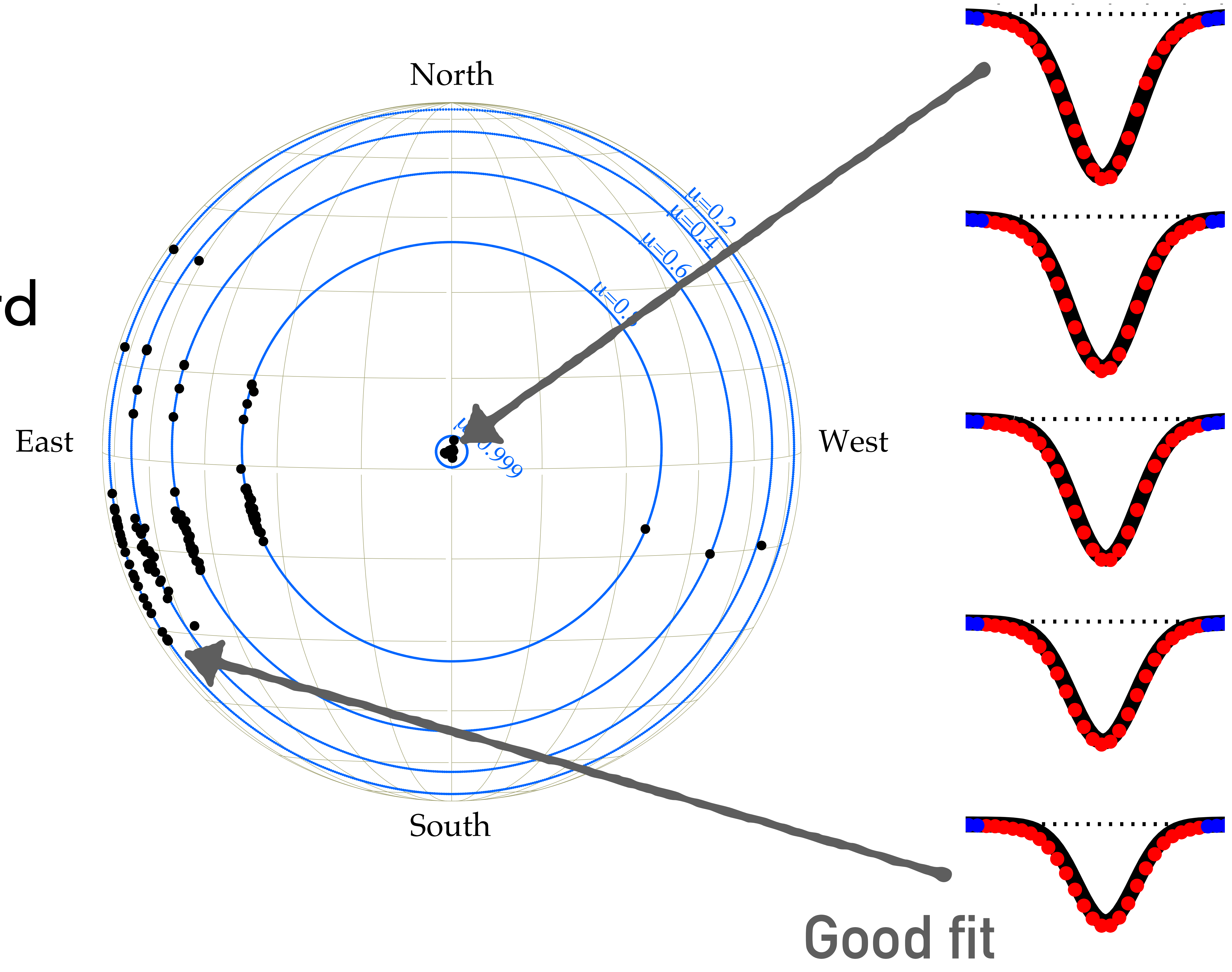

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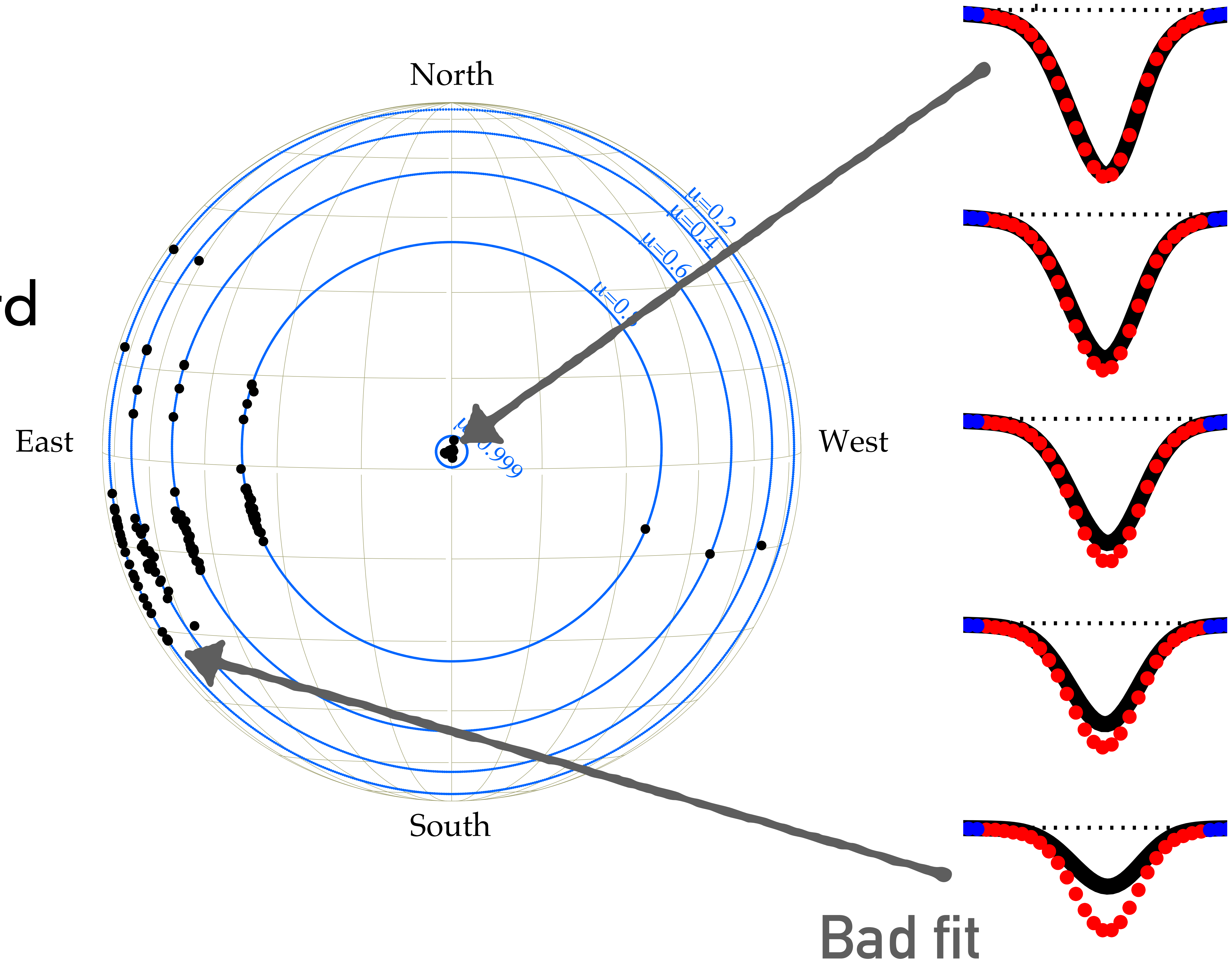

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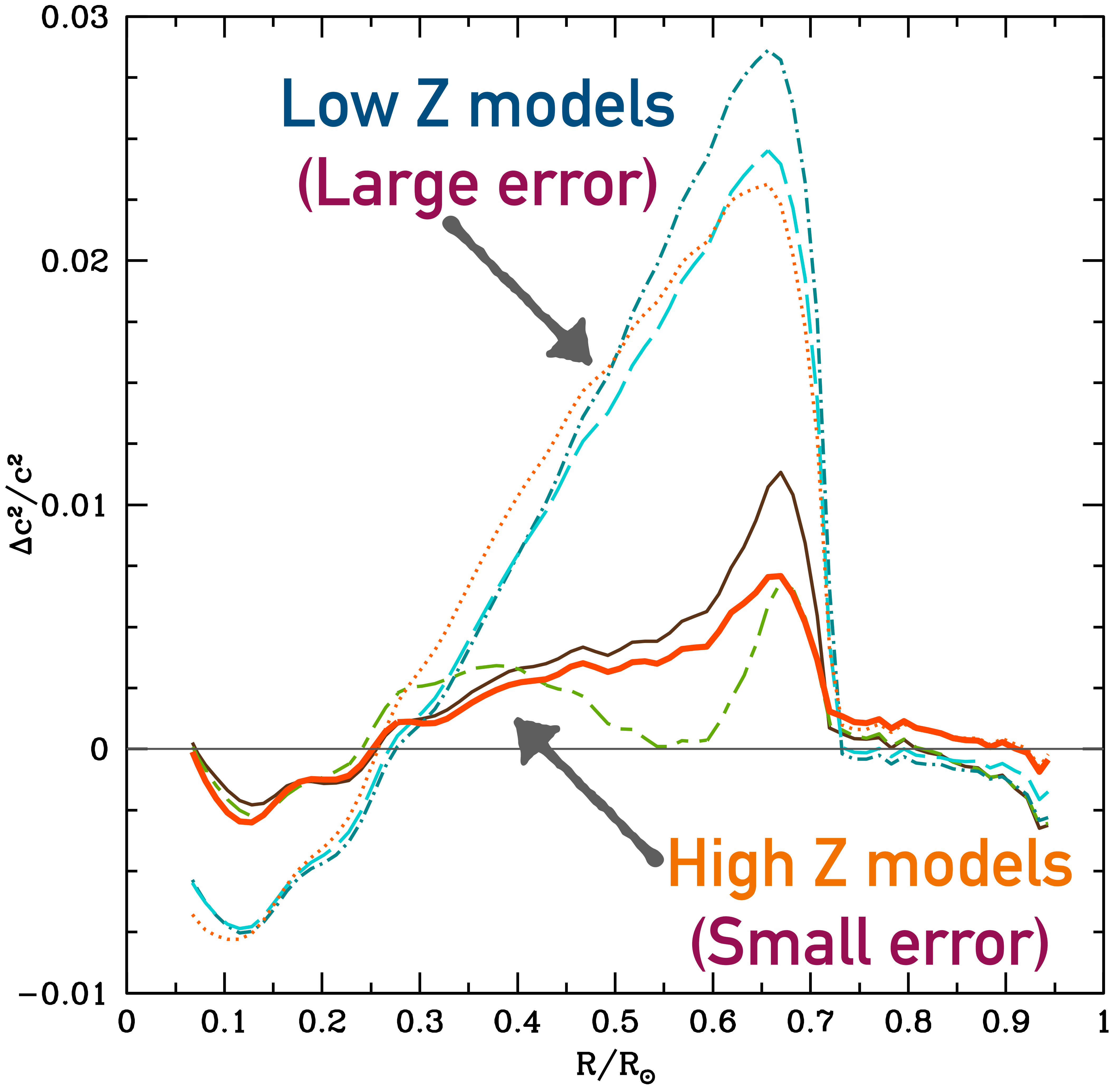
Astrophysical tests of atomic data

- Oscillator strengths
- Broadening parameters
- Inelastic collisions
- More ideas are welcome
  - Increasing potential to use stars as lab benches as 3D non-LTE models continue to improve in sophistication



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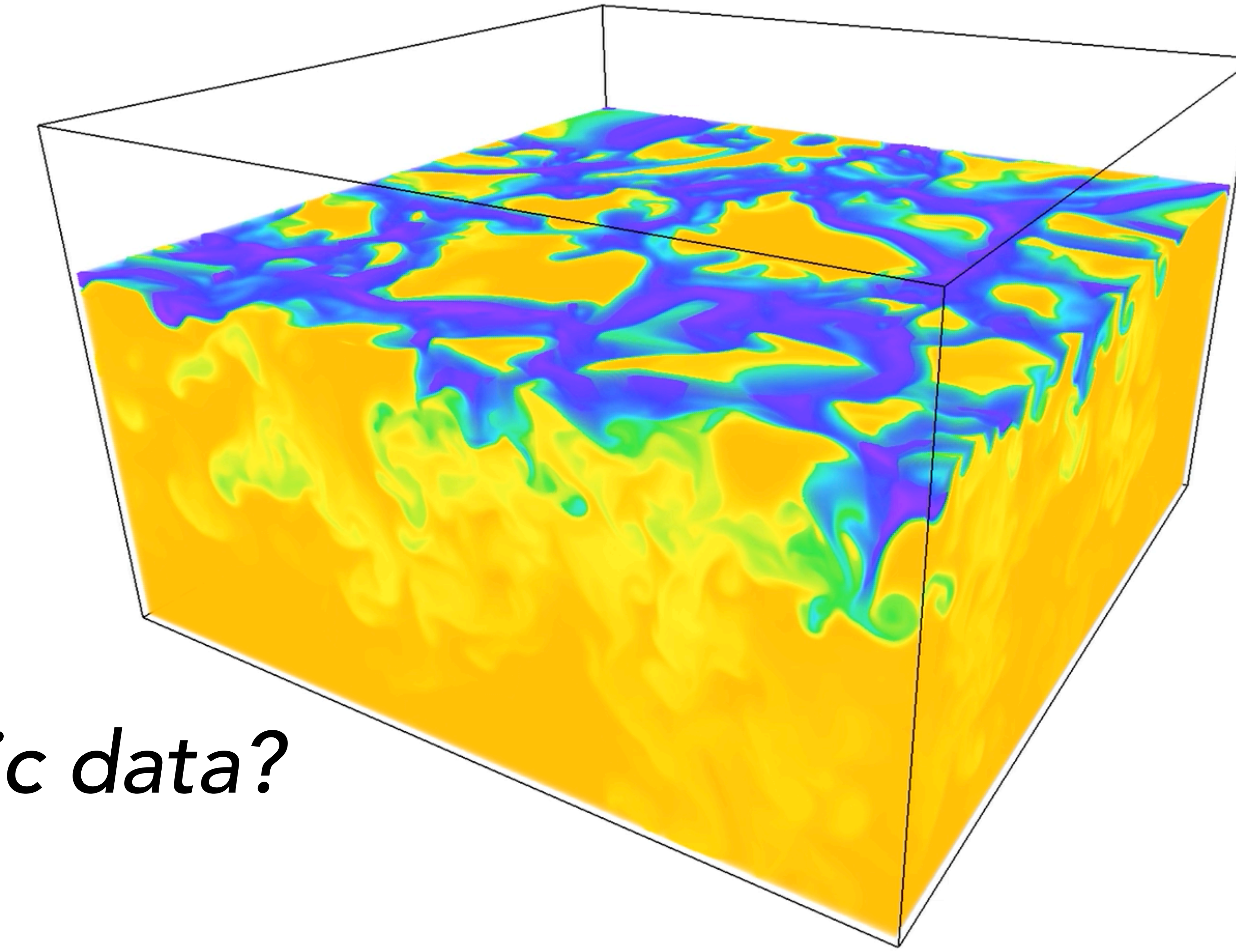
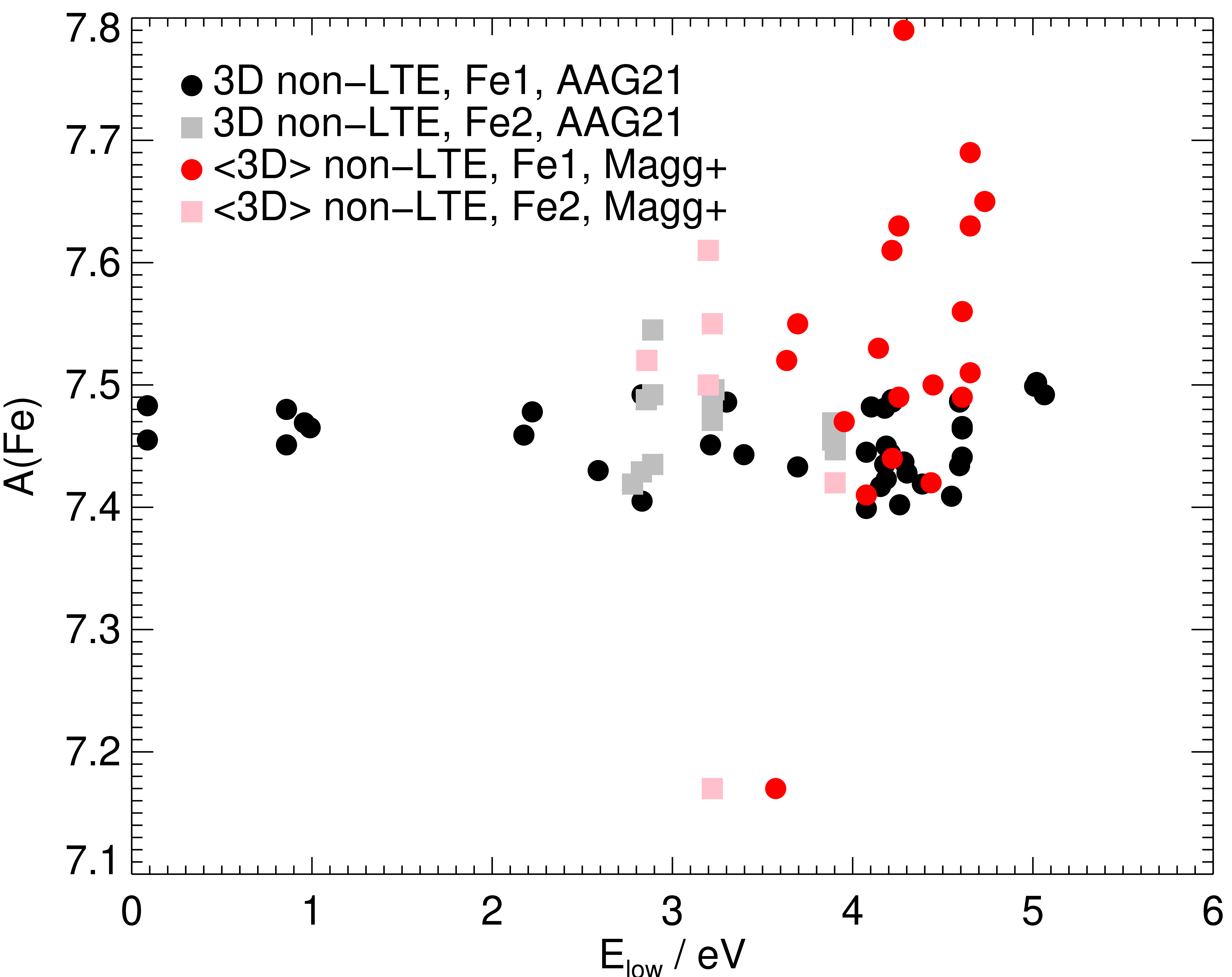
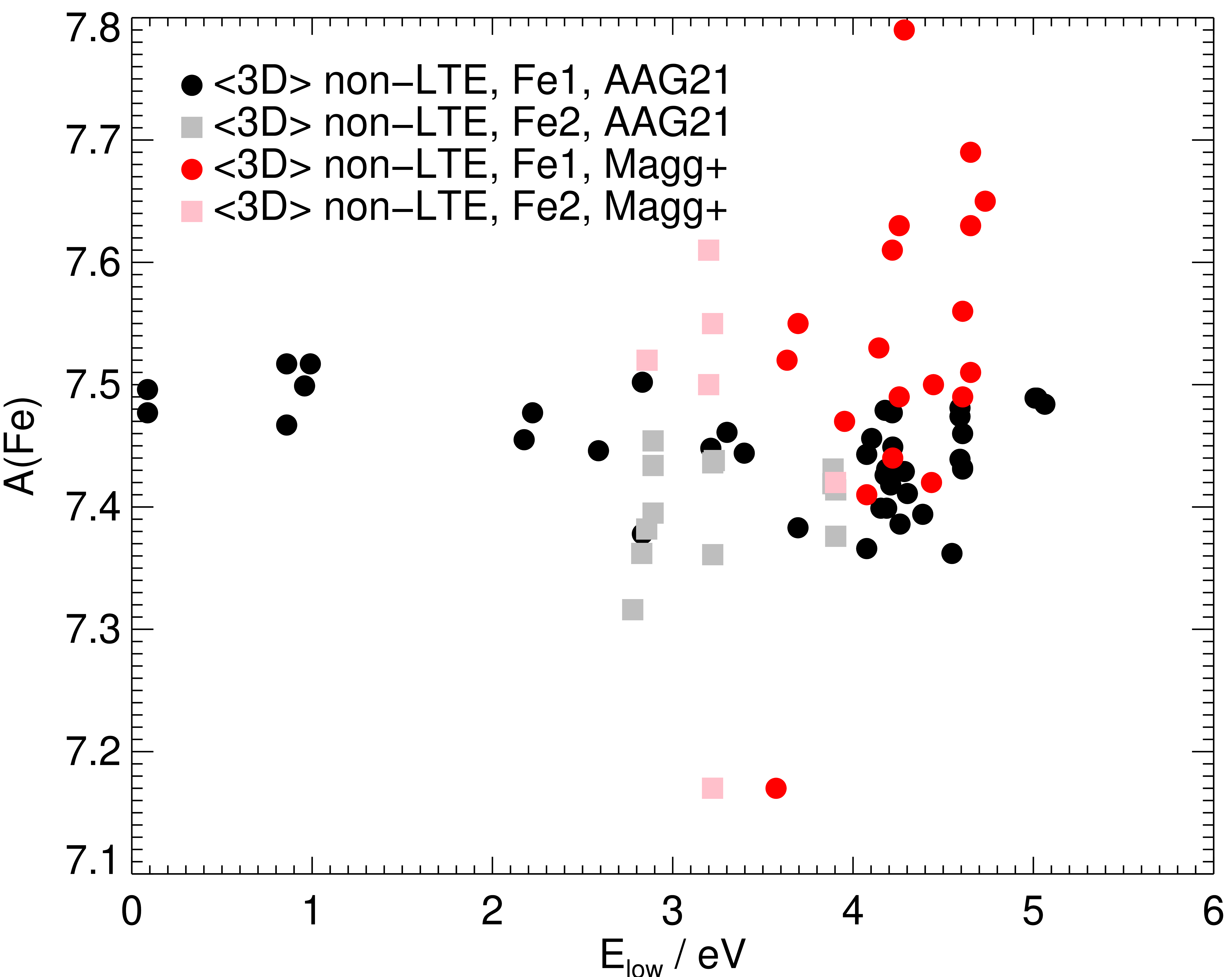




3D non−LTE, Fe1, AAG21
3D non−LTE, Fe2, AAG21
<3D> non−LTE, Fe1, Magg+
<3D> non−LTE, Fe2, Magg+
A(Fe)
E_{low} / eV
7.1
7.2
7.3
7.4
7.5
7.6
7.7
7.8
0
1
2
3
4
5
6



<3D> non−LTE, Fe1, AAG21
<3D> non−LTE, Fe2, AAG21
<3D> non−LTE, Fe1, Magg+
<3D> non−LTE, Fe2, Magg+
A(Fe)
7.8
7.7
7.6
7.5
7.4
7.3
7.2
7.1
0
1
2
3
4
5
6
E_low / eV