Determining the compositions of stars using 3D non-LTE models

Anish Amarsi

SNAQs 11 May 2022

Outline

I. Abundances… what/why/which/how?

II. Some of the physics of spectral line formation

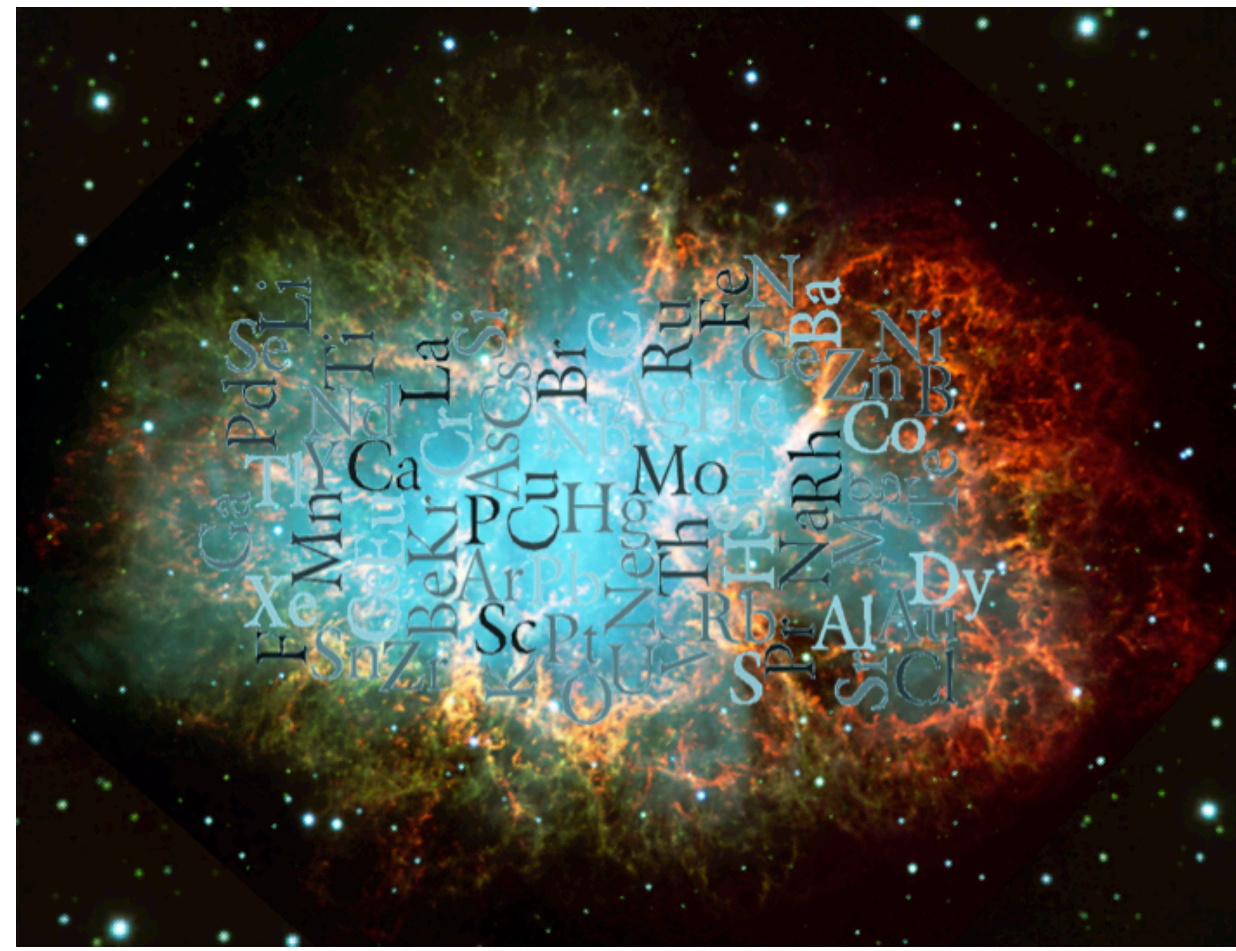
- **3D** atmospheres
- **Non-LTE** absorber populations

III. Impact of models on the interpretation of abundances

I. Abundances

Abundances… what/why?

- Ratios of different **nuclei** in the **atmospheres** of stars
- **Fossil record**: reflects abundances in molecular gas cloud from which the star formed
- Trace **cosmic origins of the elements** (supernovae, kilonovae, stellar winds, …) through space and time

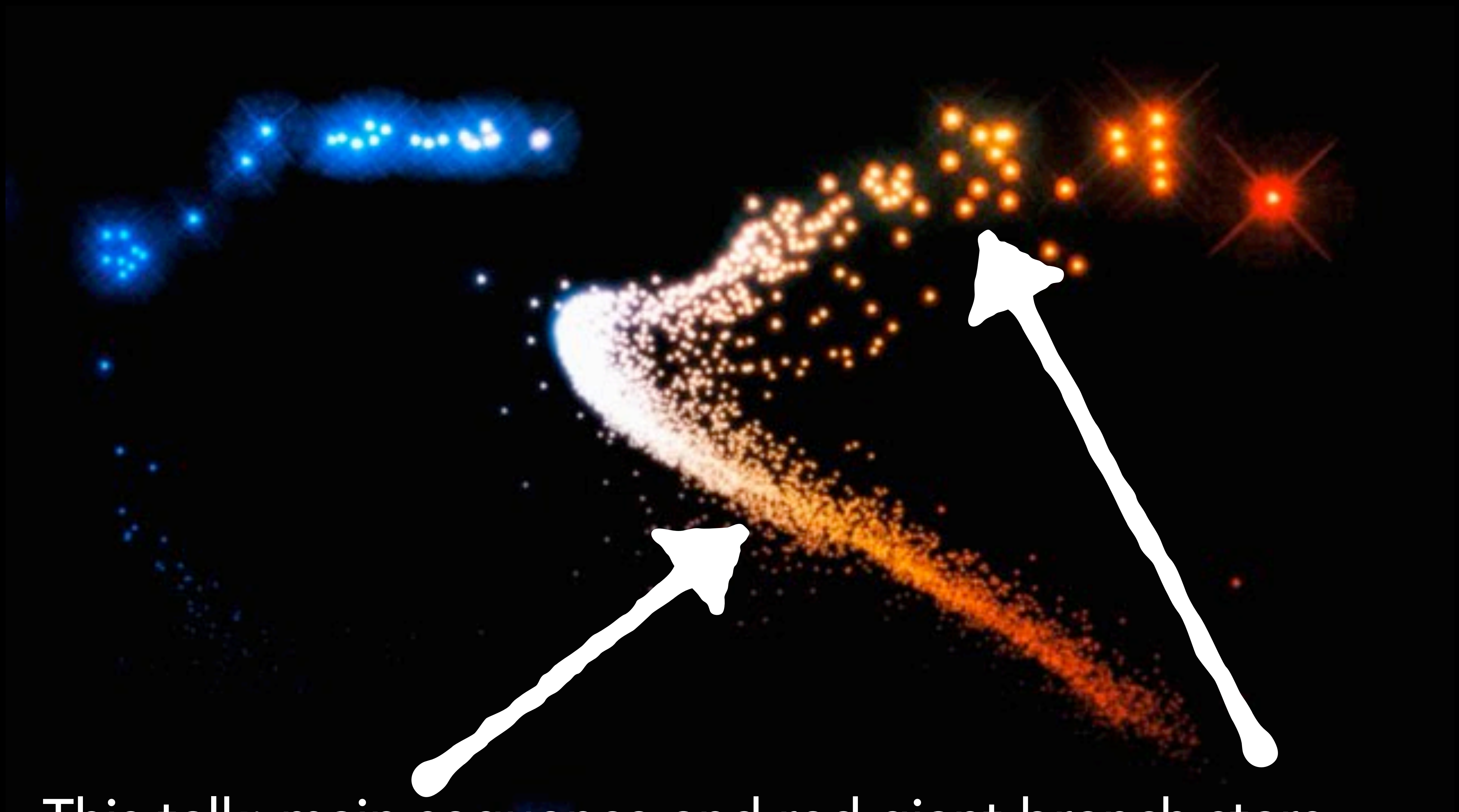


Elemental (nuclear) abundances:

$$A(\mathrm{Fe}) = \log_{10}\frac{N_{\mathrm{Fe}}}{N_{\mathrm{H}}} + 12$$

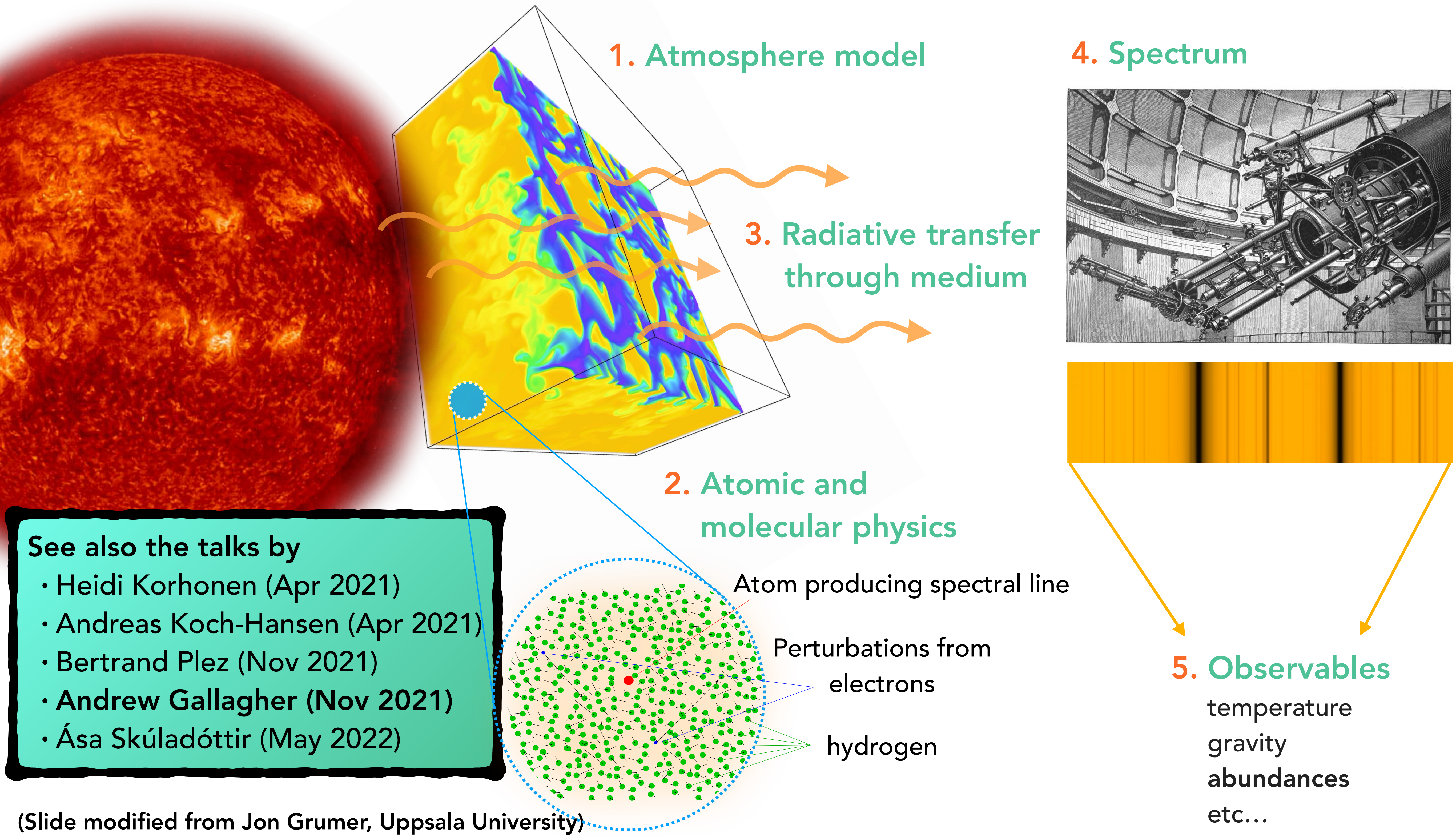
$$[\mathrm{Fe/H}] = A(\mathrm{Fe})_{\mathbf{Star}} - A(\mathrm{Fe})_{\mathbf{Sun}}$$

Abundances… which (stars)?



- This talk: main sequence and red giant branch stars
- Surface temperatures between ~4000K and 6500K

Abundances... how?



See also the talks by

- Heidi Korhonen (Apr 2021)
- Andreas Koch-Hansen (Apr 2021)
- Bertrand Plez (Nov 2021)
- **Andrew Gallagher (Nov 2021)**
- Ása Skúladóttir (May 2022)

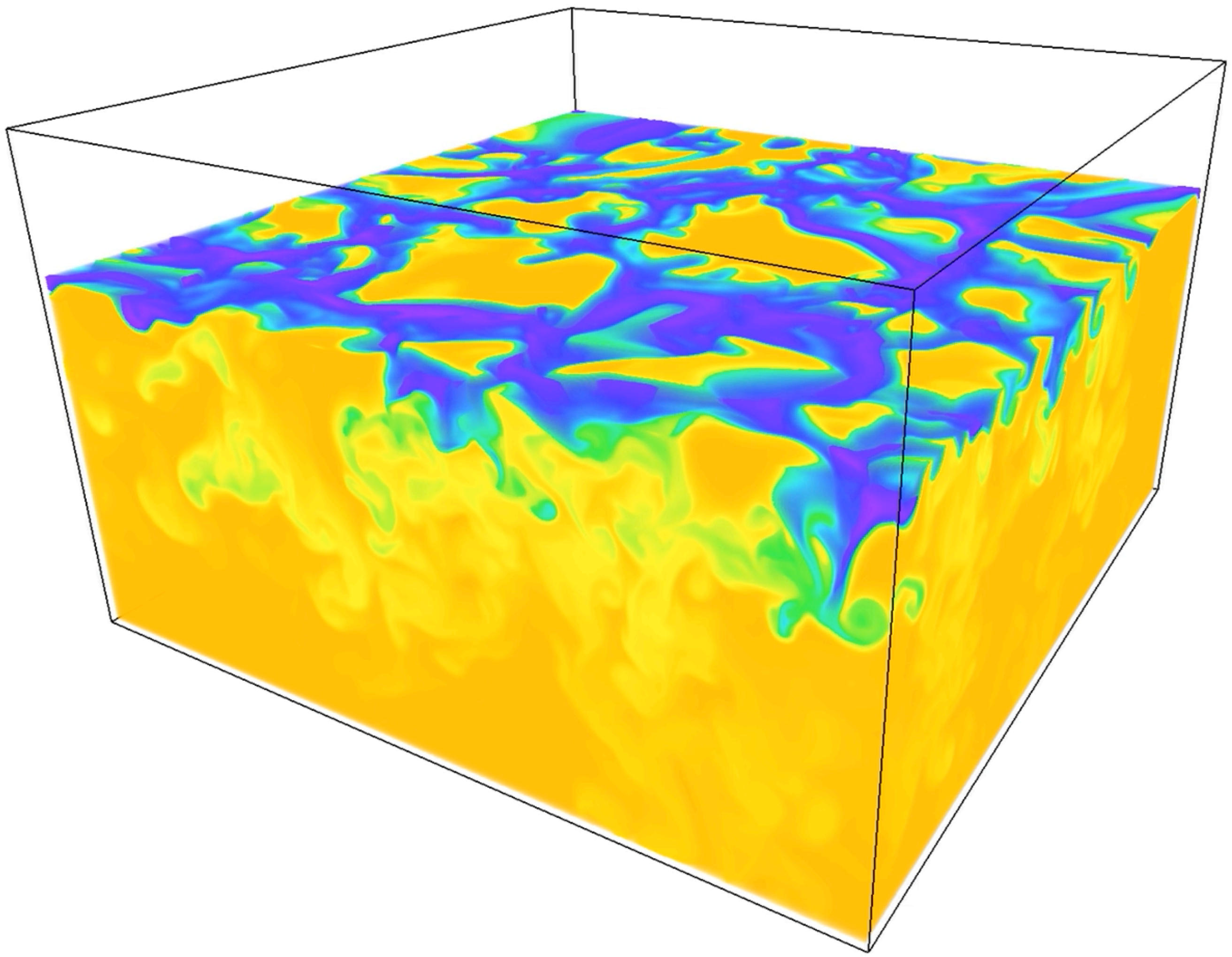
(Slide modified from Jon Grumer, Uppsala University)

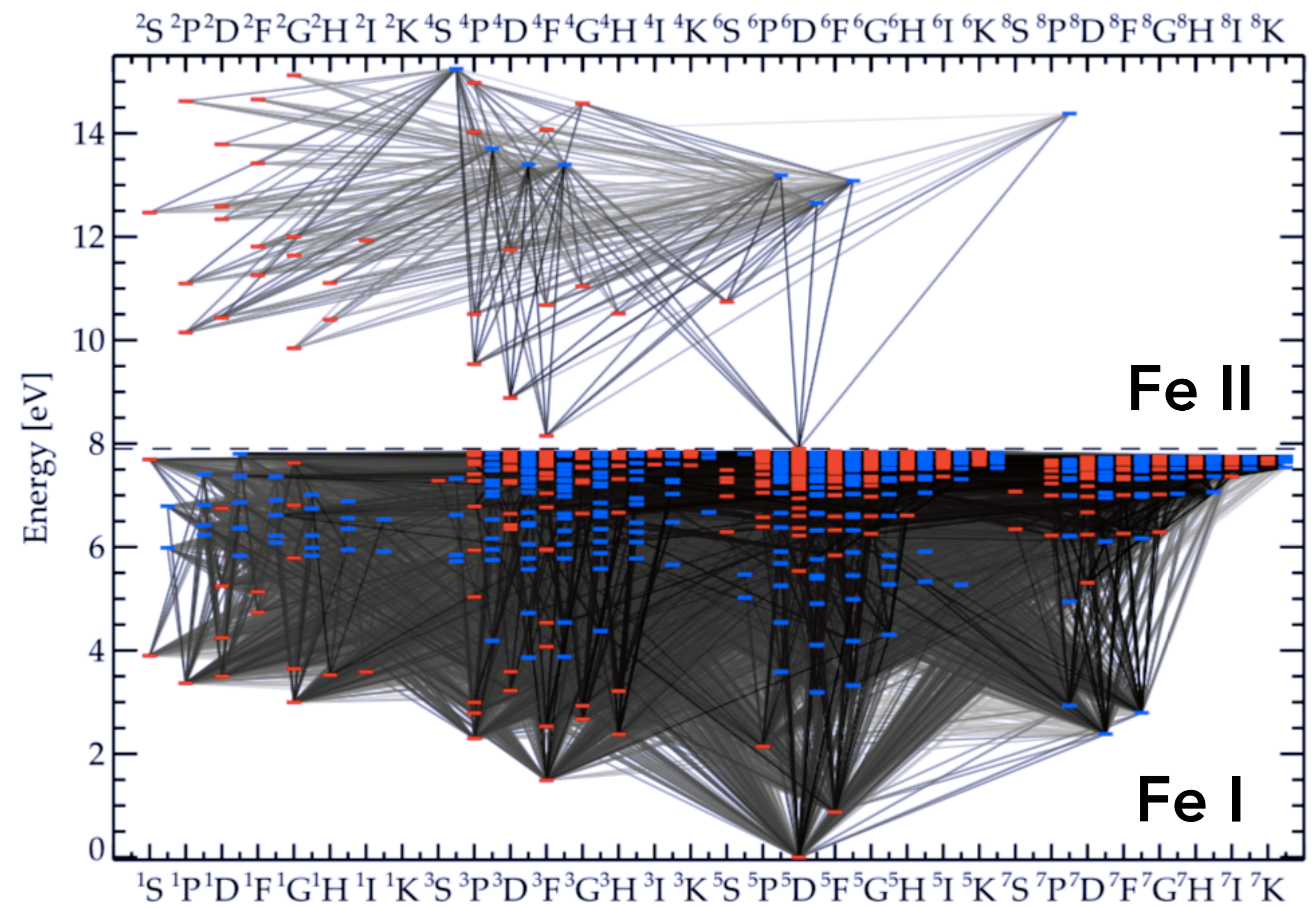
Abundances…

- …are **inferred** from observed spectral lines via **models**
- …are thus prone to **systematic modelling inaccuracies**

II. Spectral line formation

The models

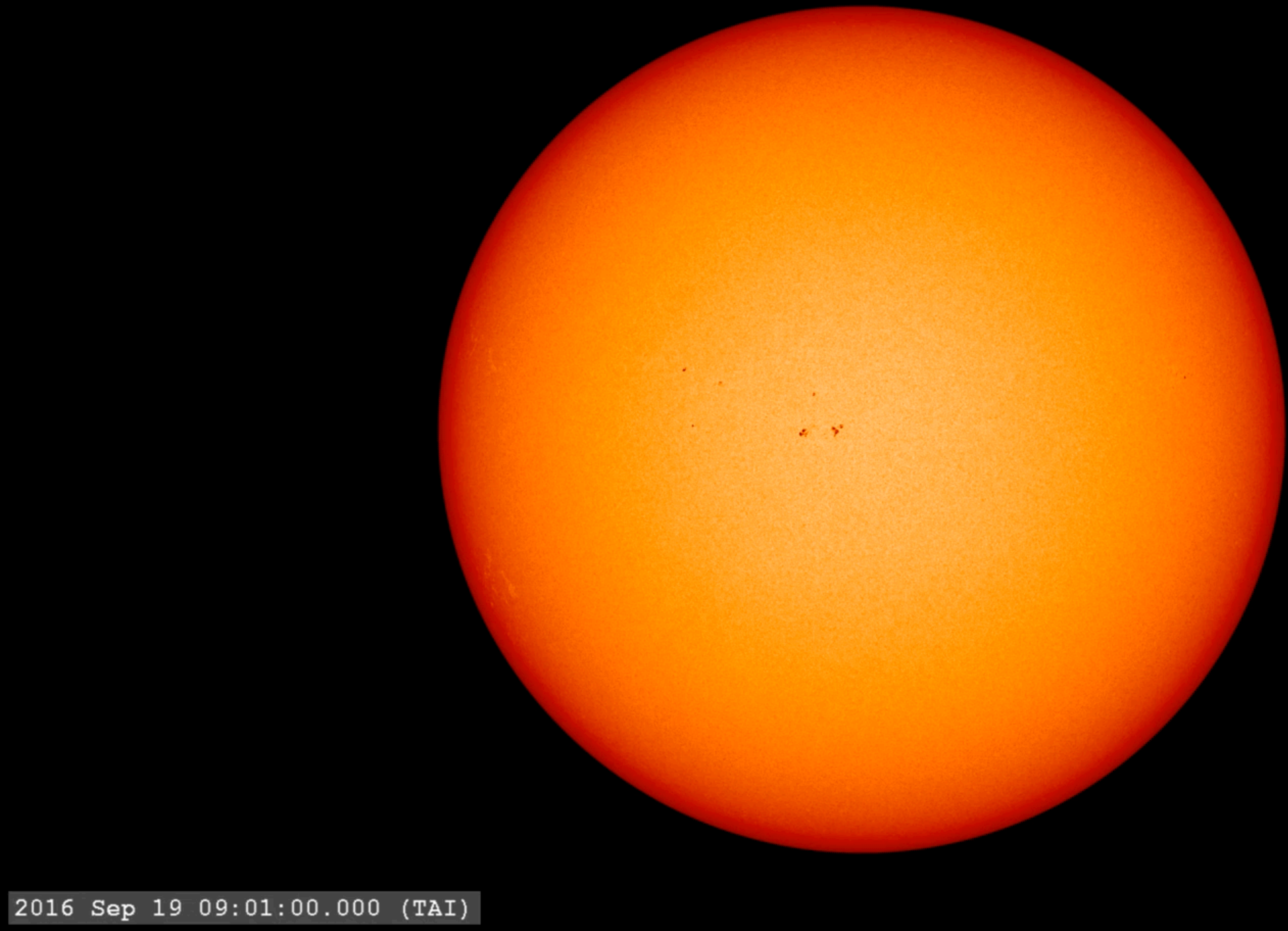




1. Atmosphere
(1D versus 3D)

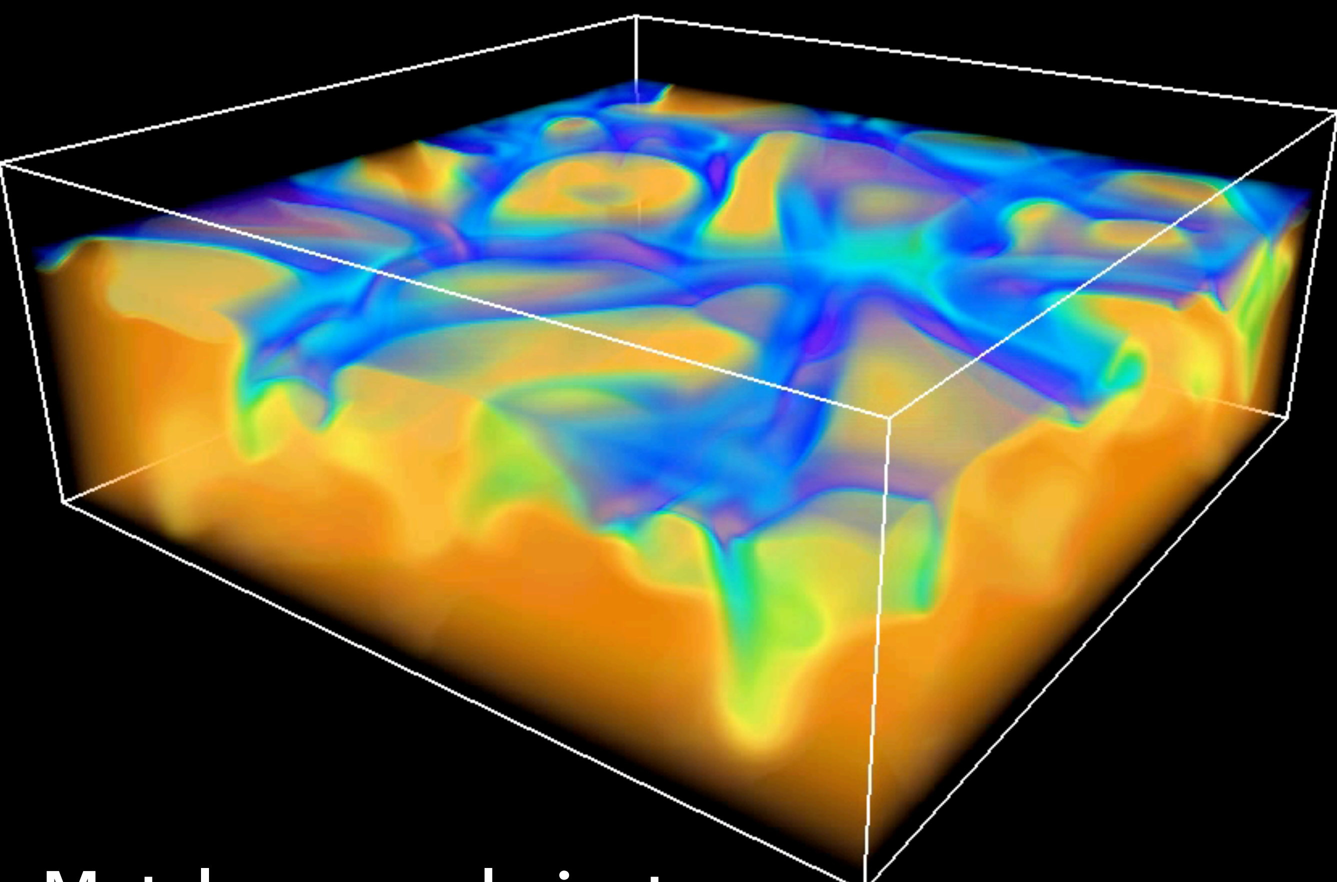
2. Absorber populations
(LTE versus non-LTE)

Atmosphere: observations

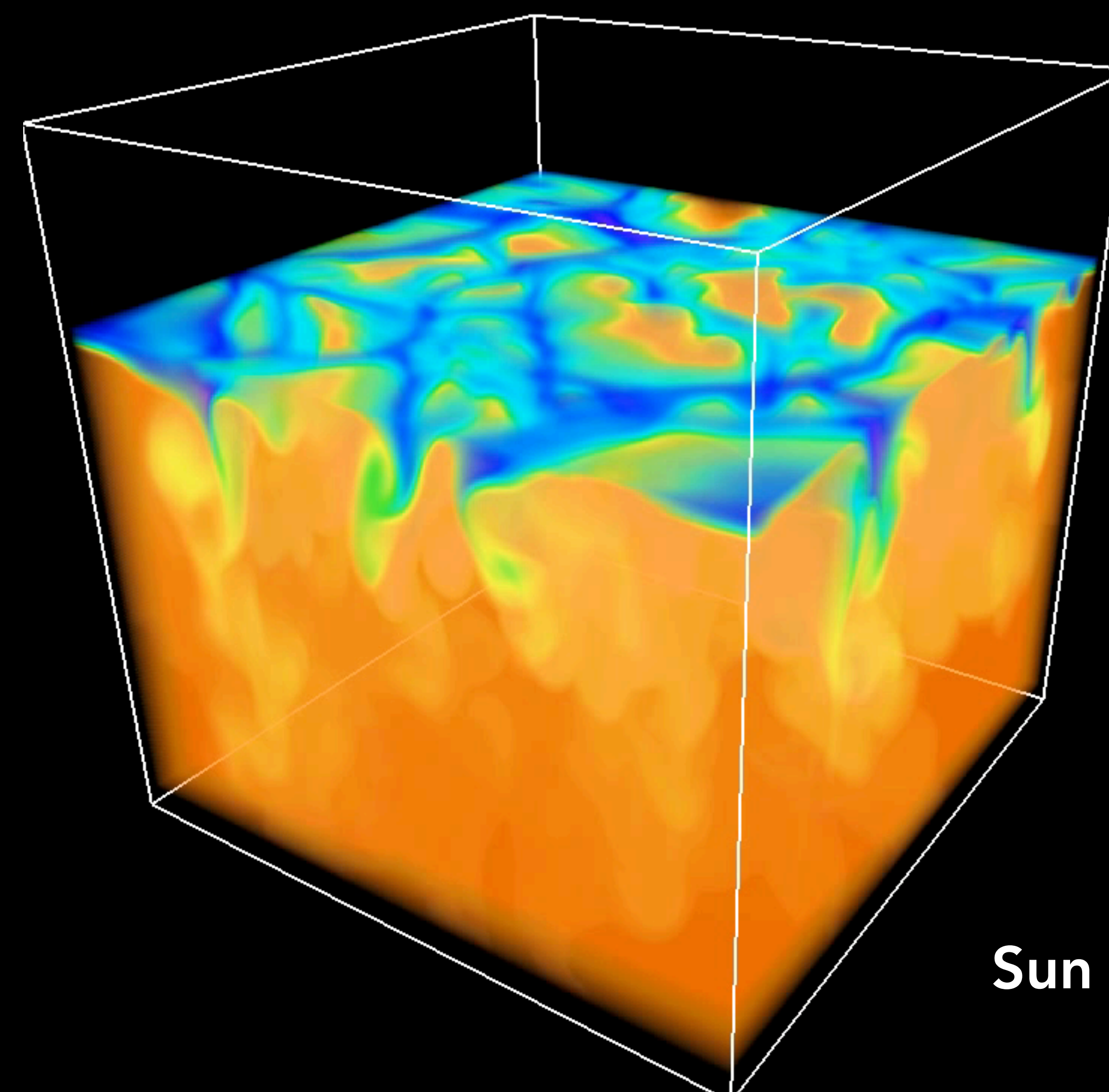


(SDO/HMI + SST (Leenaarts & de la Cruz Rodriguez); NASA Scientific Visualisation Studio)

Atmosphere: simulations



Metal-poor red giant



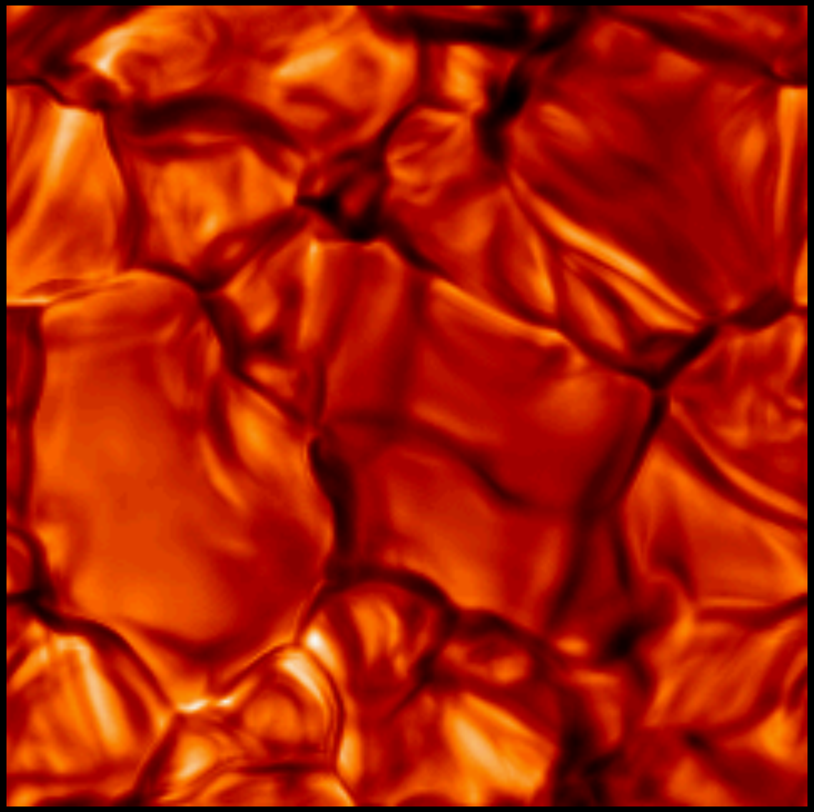
Sun

- 3D radiation-hydrodynamics with the stagger code

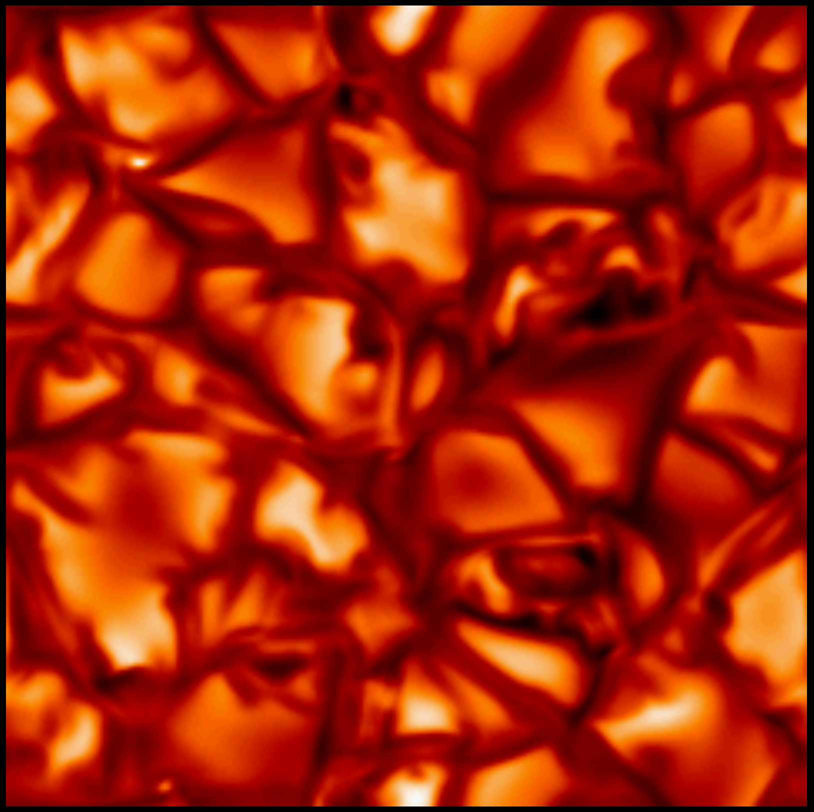
(Remo Collet, Aarhus University)

(See A. Gallagher's talk, Nov 2021)

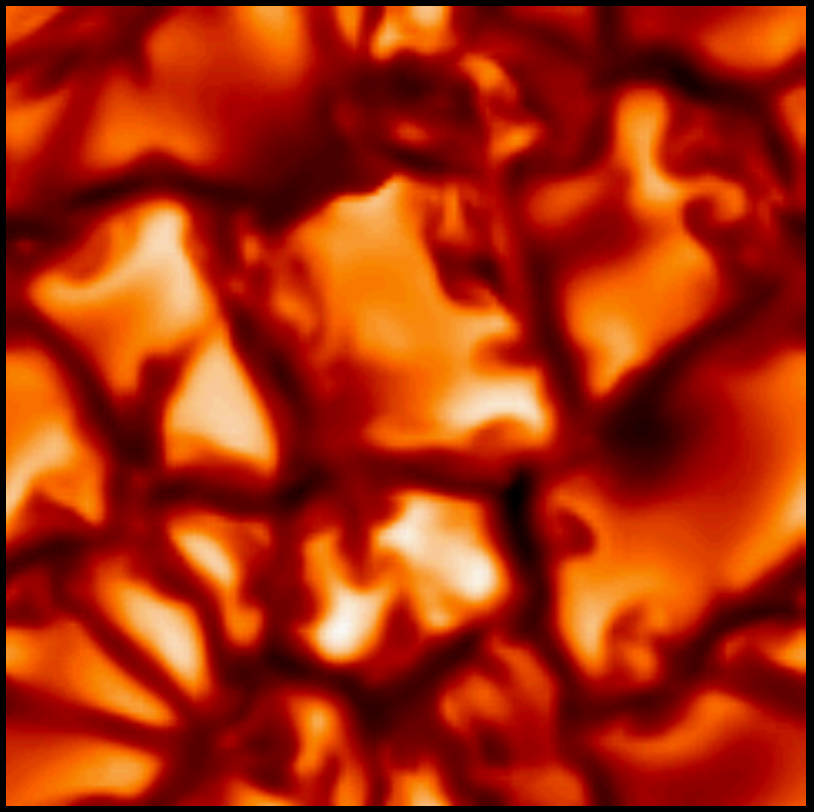
Atmosphere: simulations



Red giant



K-dwarf

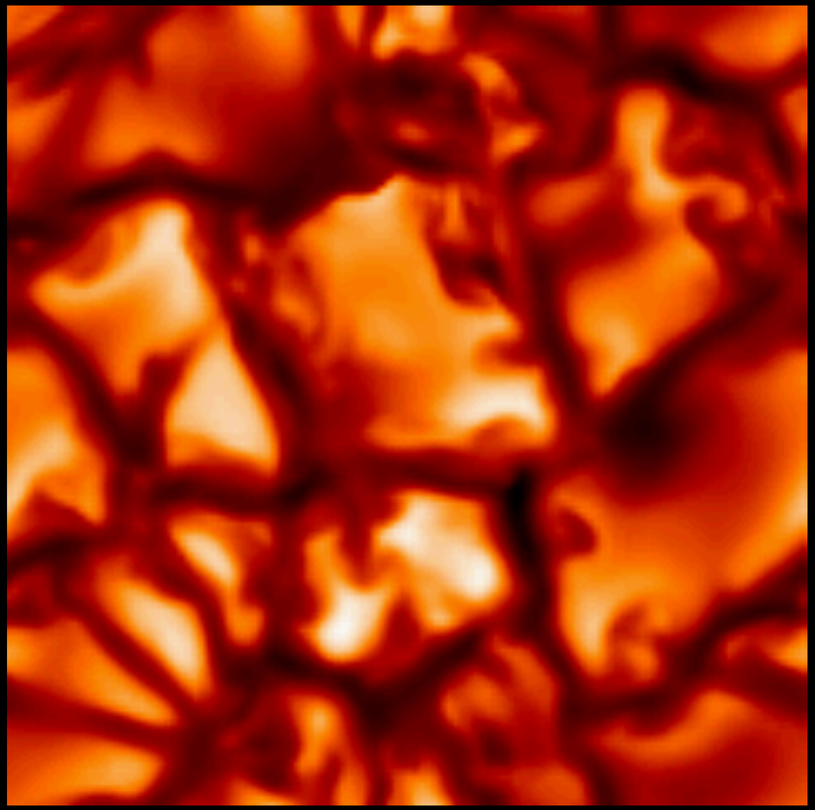


Sun

(Yixiao Zhou, Aarhus University)

Atmosphere: simulations

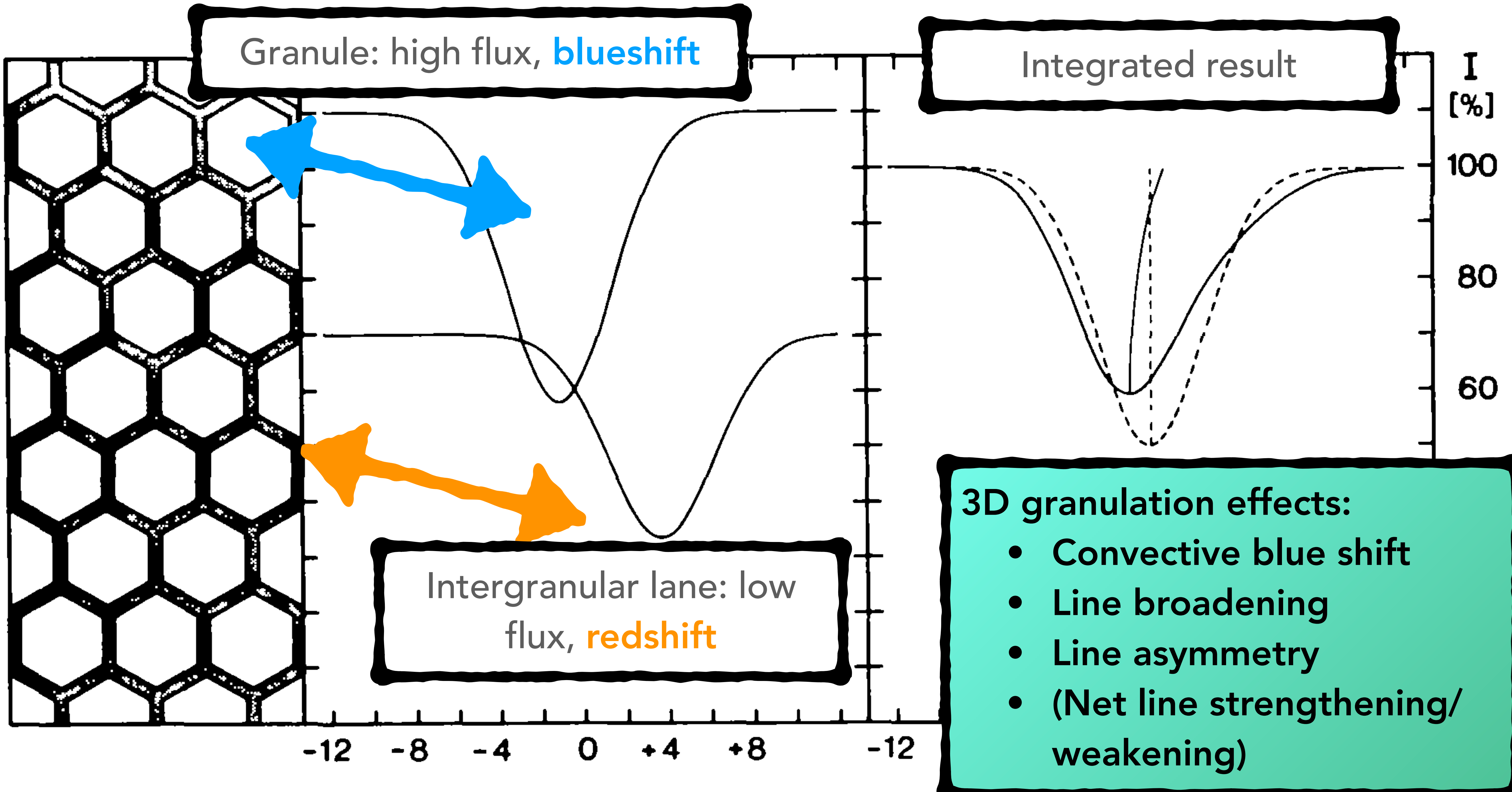
- Ab initio treatment of stellar convection
  - Avoids mixing length, micro turbulence, macro turbulence fudge parameters needed by 1D models
- What are the effects on spectral line formation (and abundances)?



Sun

(Yixiao Zhou, Aarhus University)

Granulation effects

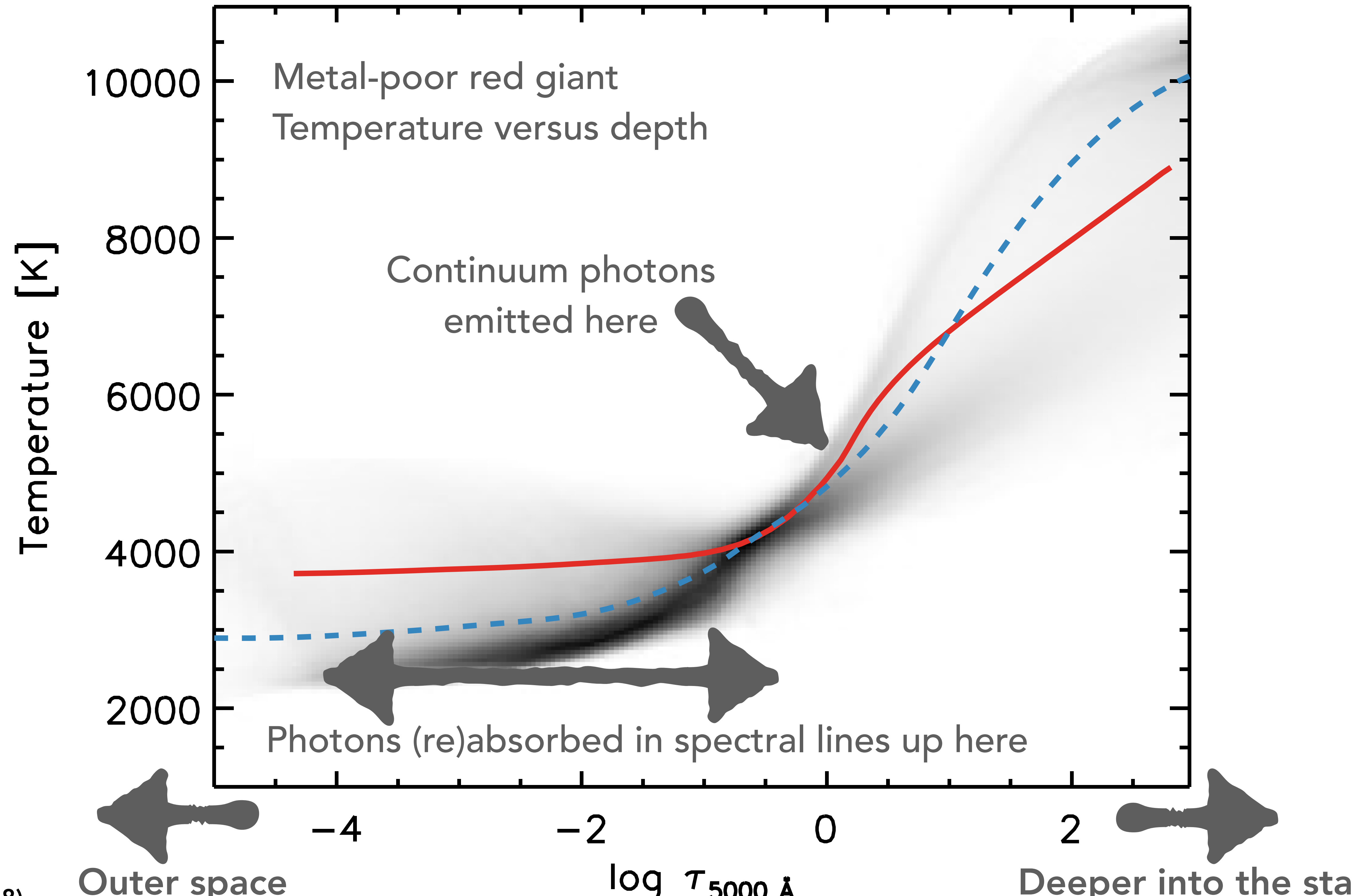


3D granulation effects:

- **Convective blue shift**
- **Line broadening**
- **Line asymmetry**
- **(Net line strengthening/ weakening)**

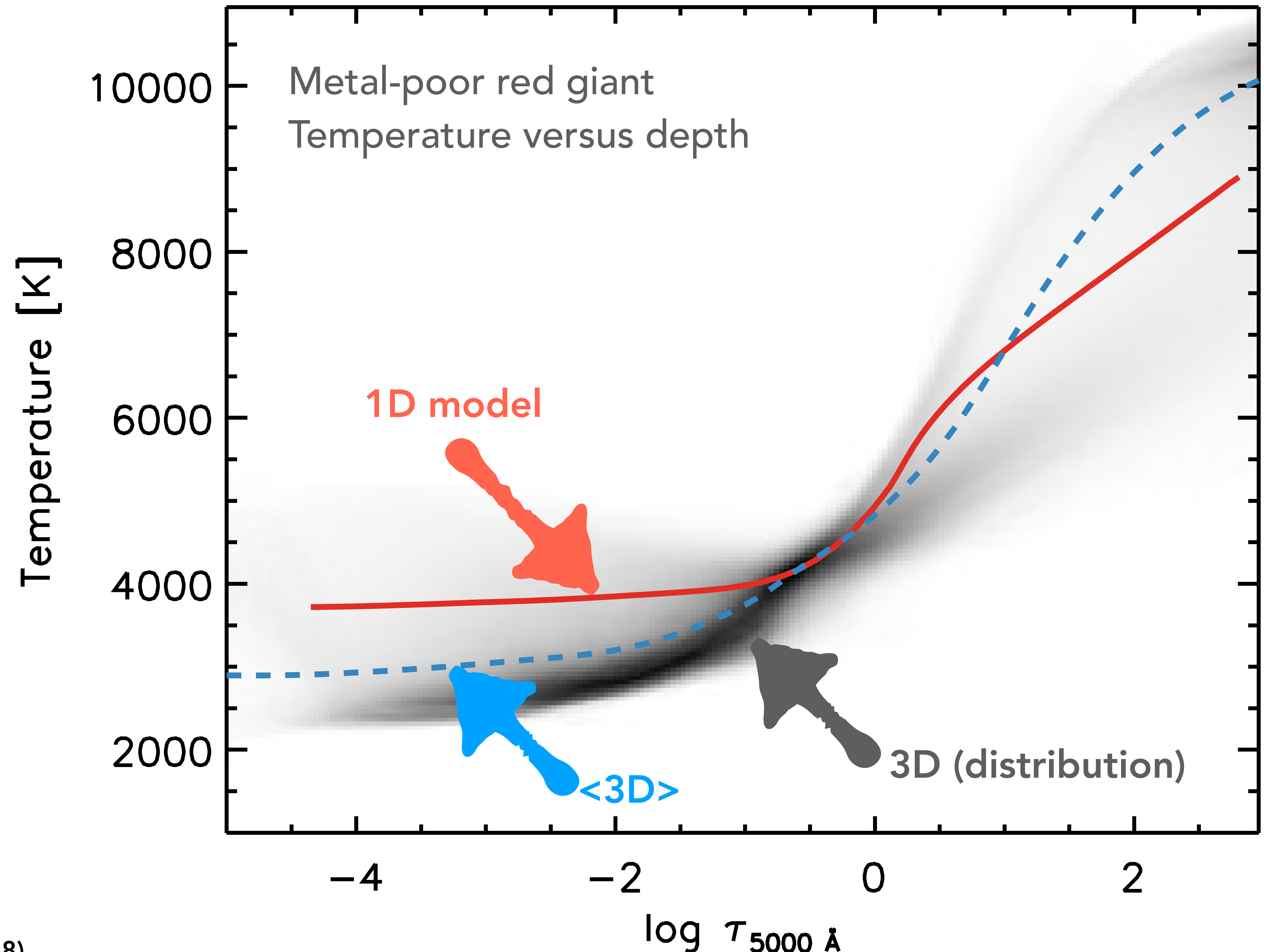
(Dravins+ 1981)

Energy transport effects



(Collet+ 2018)

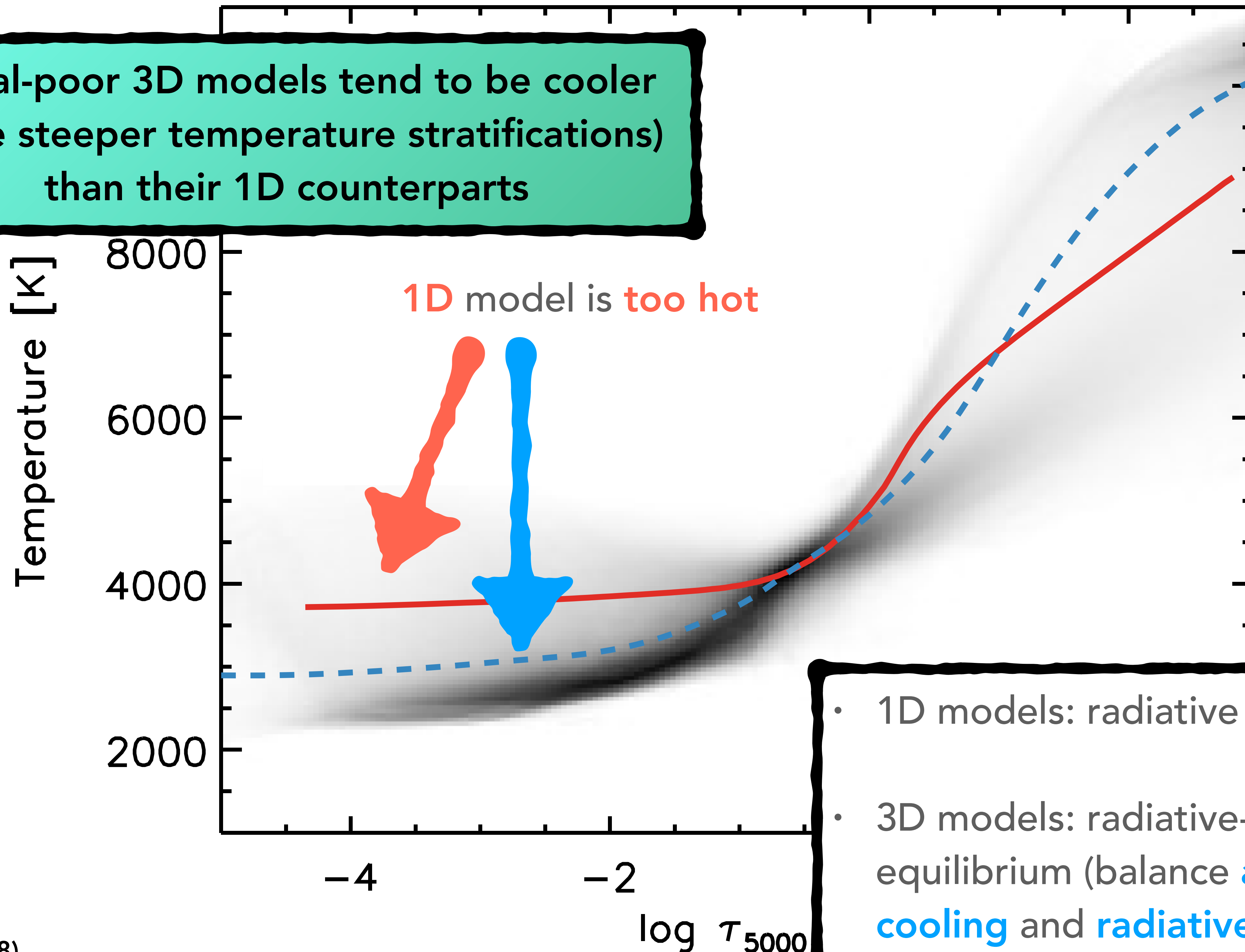
Energy transport effects



(Collet+ 2018)

Energy transport effects

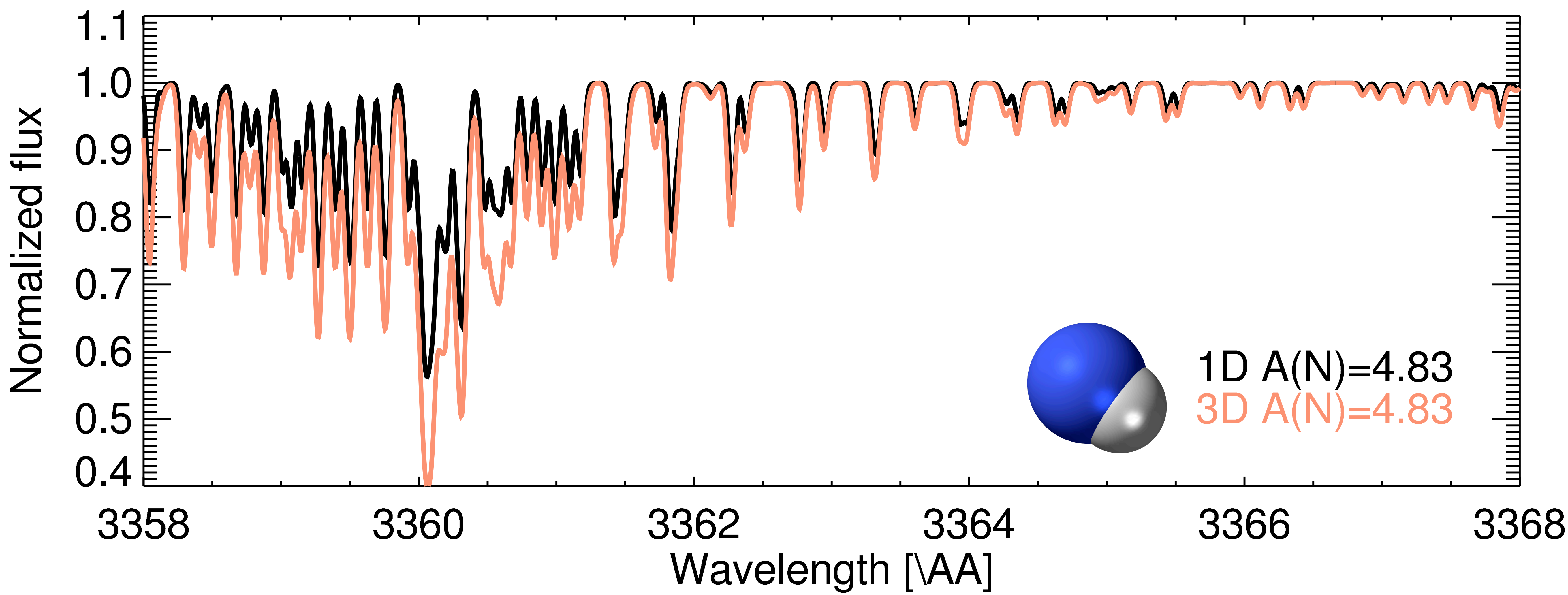
Metal-poor 3D models tend to be cooler (have steeper temperature stratifications) than their 1D counterparts



- 1D models: radiative equilibrium
- 3D models: radiative-convective equilibrium (balance **adiabatic cooling** and **radiative heating**)

(Collet+ 2018)

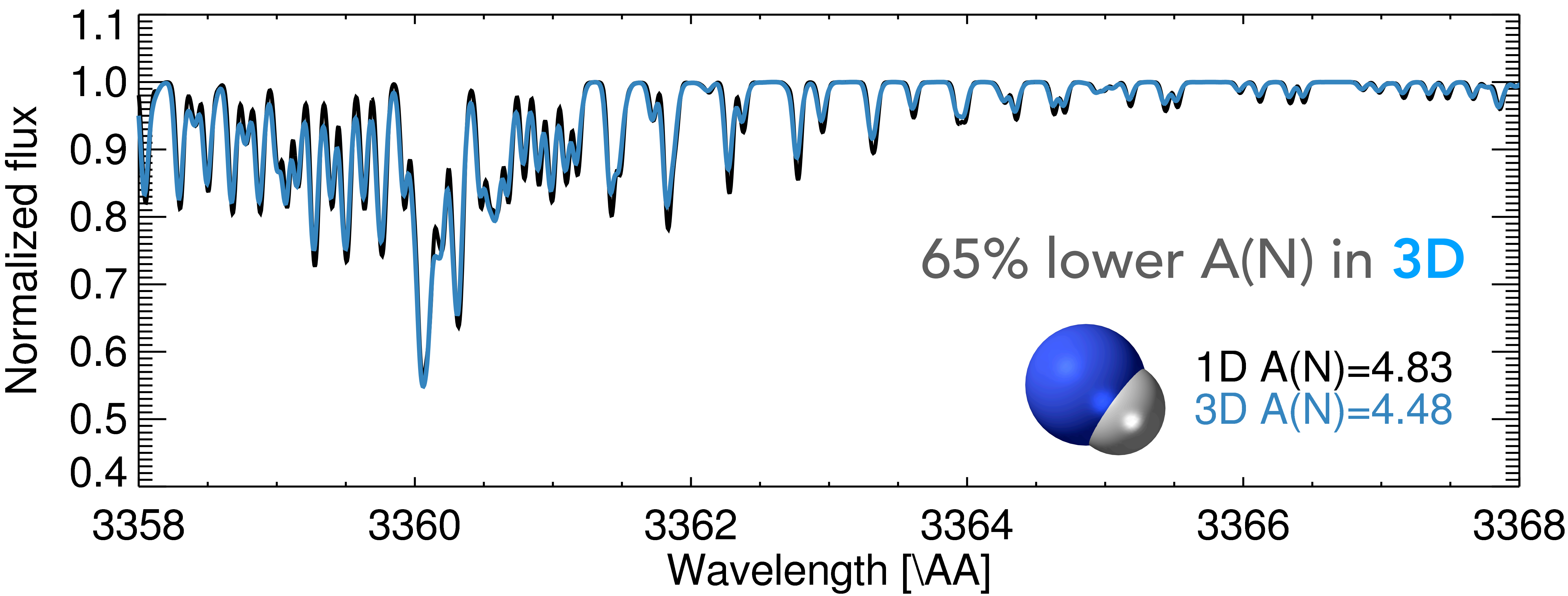
Energy transport effects



- Molecular NH lines in a metal-poor red giant
- Cooler 3D atmosphere → more molecules; stronger lines

(Adapted from Collet+ 2018)

Energy transport effects



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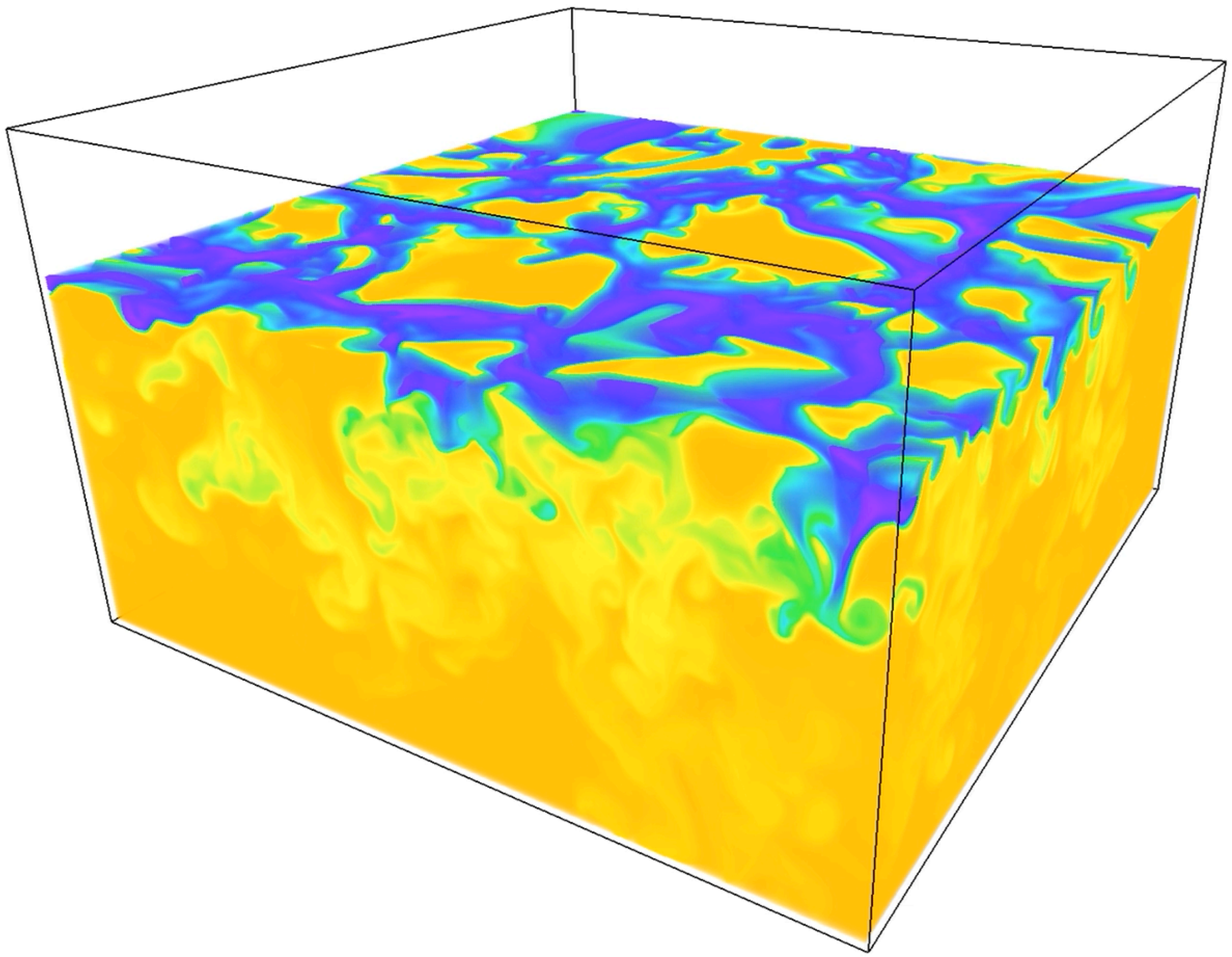
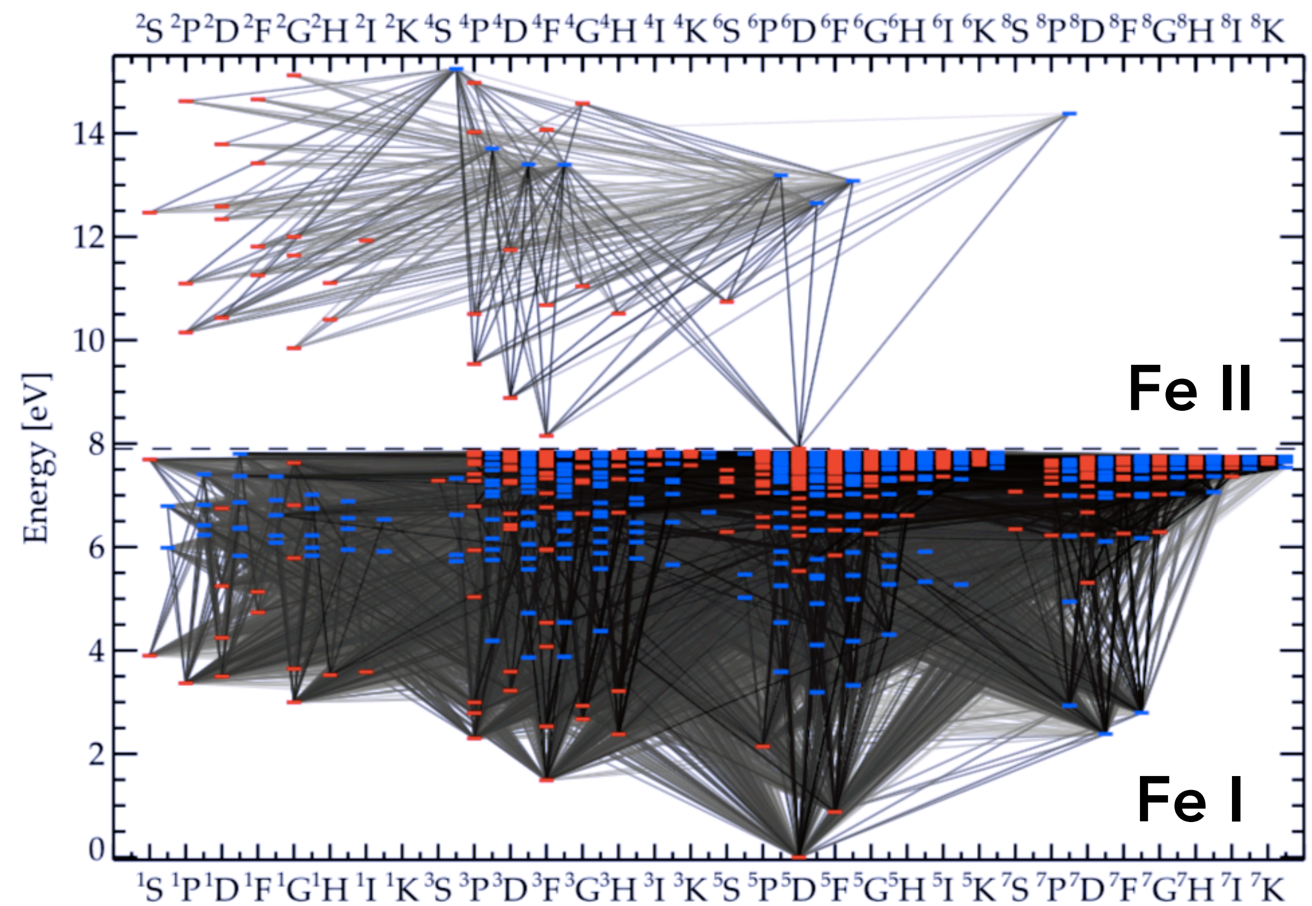
The models



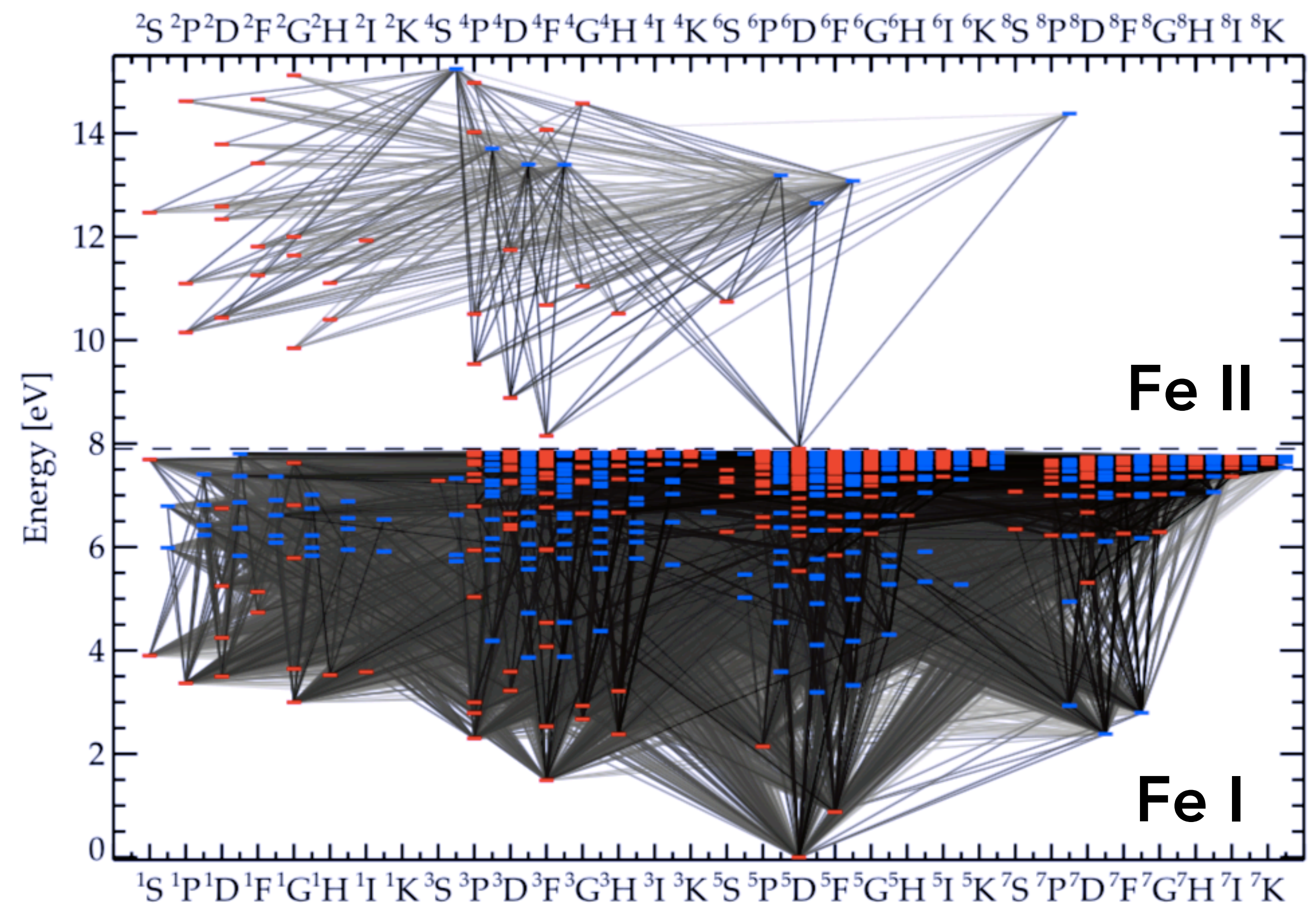


1. Atmosphere
(1D versus 3D)

2. Absorber populations
(LTE versus non-LTE)

Absorber populations

- Given A(Fe), at every point in the model atmosphere, one needs to know how many Fe nuclei exist as e.g.
  - Fe I atoms in the a $^5D_4$ ground state?
  - Fe II ions in the d $^2F_{2.5}$ excited state?
  - Fe III ions? FeH molecules? Other species? etcetera.



"LTE" allows you to trivially calculate the excitation/ionisation/molecular equilibria throughout the atmosphere… but it is often wrong

(Lind+ 2017)

Absorber populations

- Classical approach: adopt Saha-Boltzmann statistics

$$n_{i;\mathrm{LTE}} \propto g_i e^{-\frac{E_i}{kT}}$$

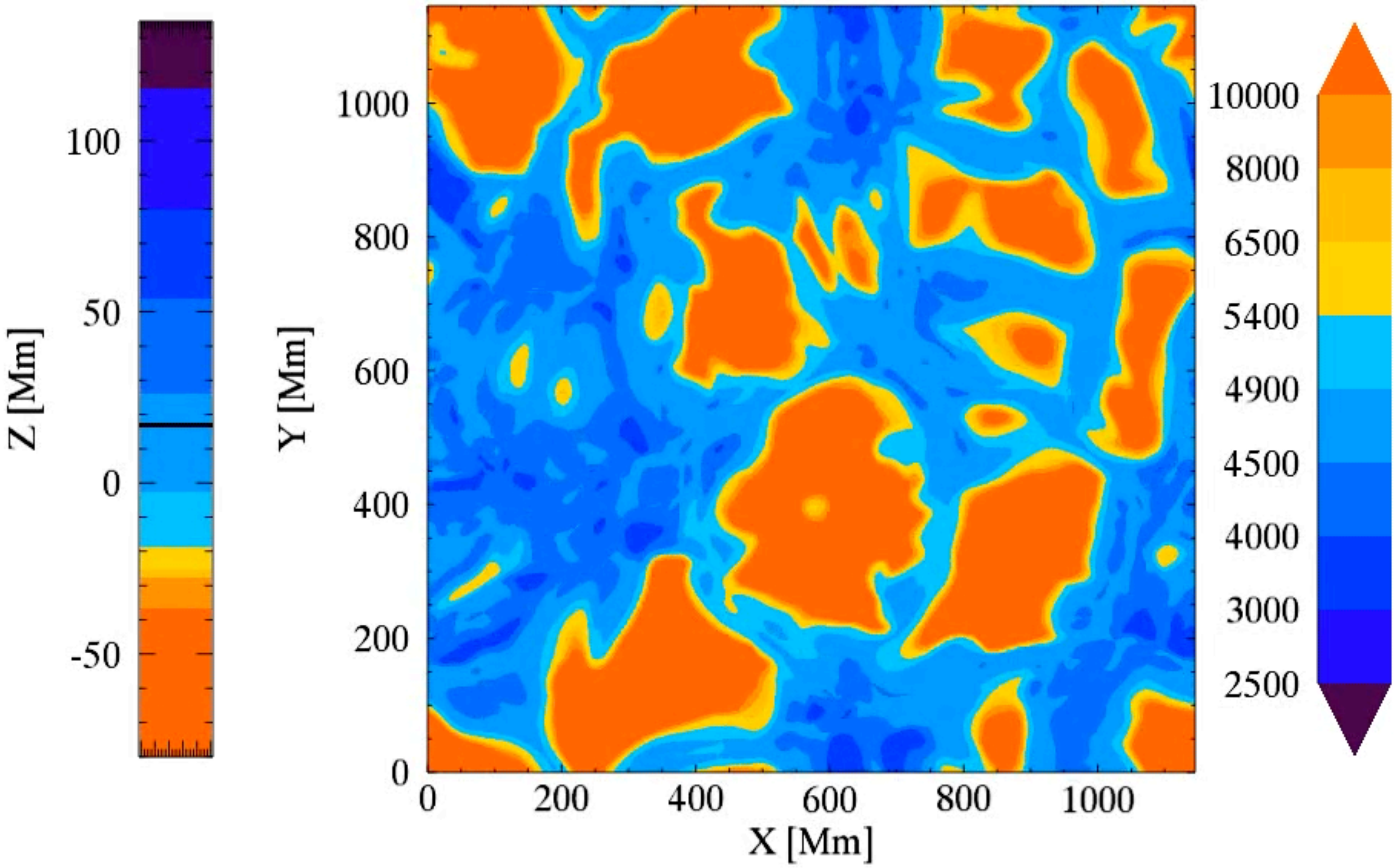
- “The **matter** is in **local thermodynamic equilibrium** (**LTE**)”

- Note: the radiation field in the atmosphere is obviously far from LTE (it does not follow Planck’s law)

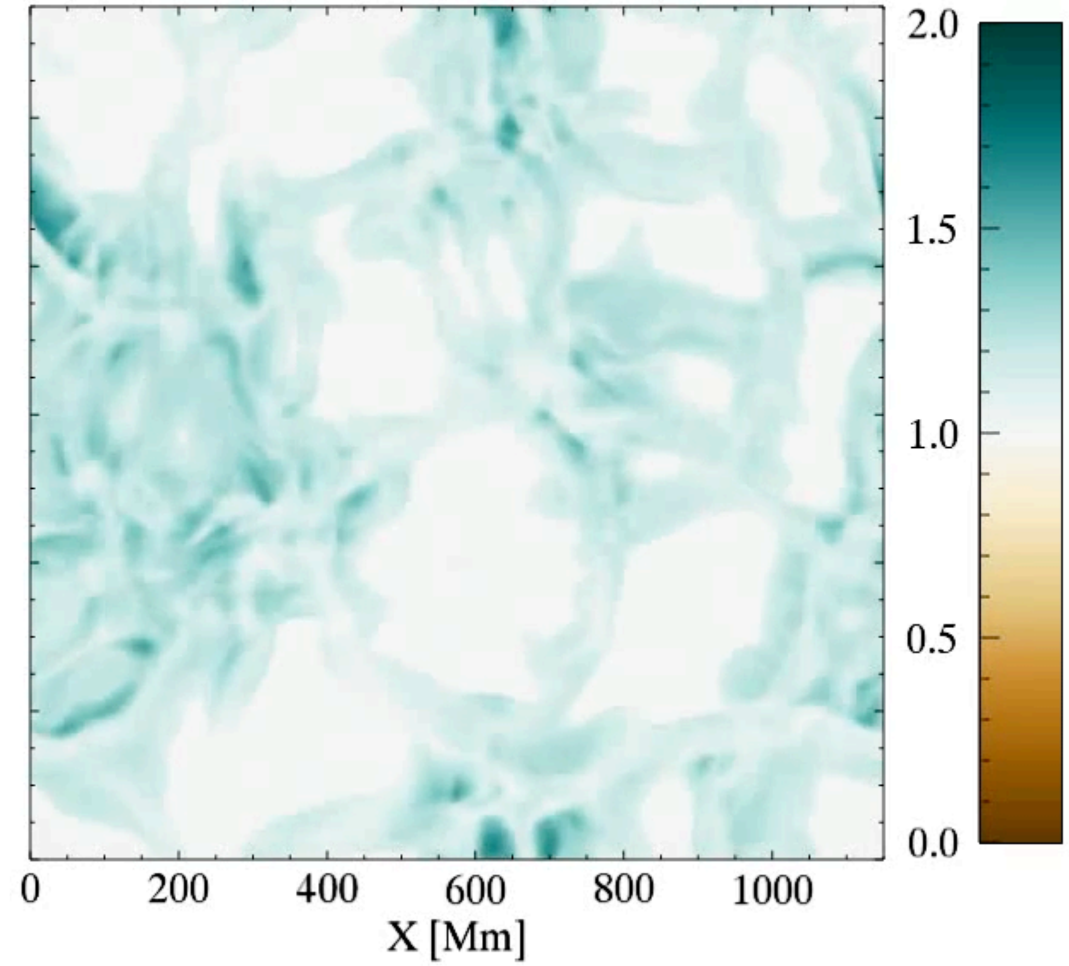
- Thus: here LTE implicitly assumes that matter-matter interactions (**collisions**) are **more efficient** than matter-photon interactions

Non-local photons

Gas temperature



UV radiation temp. / gas temp.



(Thomas Nordlander, Australian National University)

Non-local photons

- Instead of adopting Saha-Boltzman, solve the equations of **statistical equilibrium**

$$n_i \, \Sigma_j [R_{ij} + C_{ij}] = \Sigma_j n_j [R_{ji} + C_{ji}]$$

- Interplay between all radiative/collision rates ***R*** and ***C***

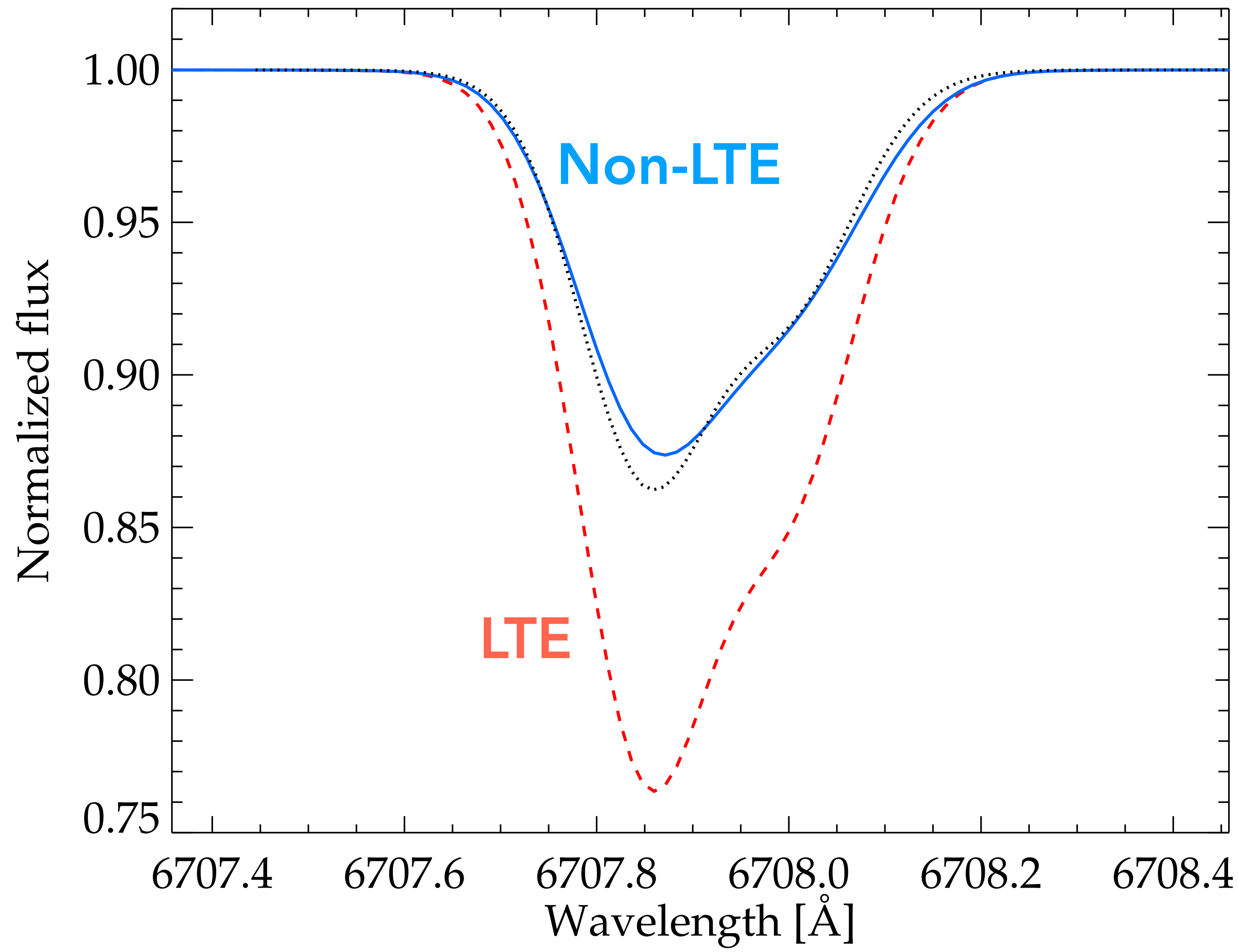
- Rates ***R*** take into account non-local photons

- What are the effects on **spectral line formation** (and **abundances**)?

(See A. Gallagher's talk, Nov 2021)

Li I 670.8nm line

- Important for testing e.g. Big Bang models; mixing in stars
- Metal-poor F-dwarfs: LTE line **too strong**
- Sun: LTE line **too weak**
- Competition between different non-LTE effects

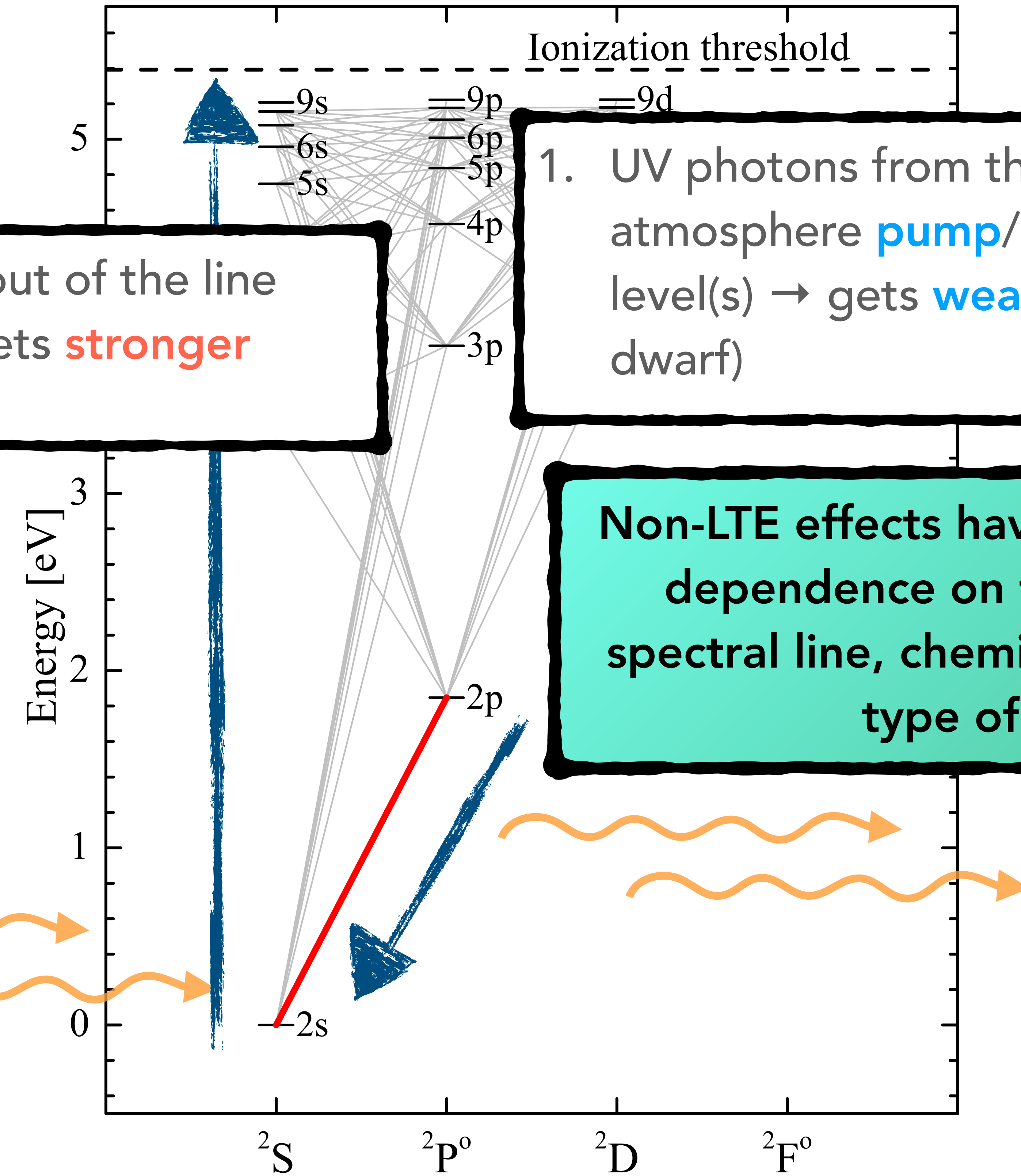


Metal-poor F-dwarf

50% lower A(Li) in **non-LTE**

(Lind+ 2013)

Li I 670.8nm line



2. Photons scatter out of the line and are **lost** → gets **stronger** (Sun)

1. UV photons from the warmer deeper atmosphere **pump**/**overionise** lower level(s) → gets **weaker** (metal-poor F dwarf)

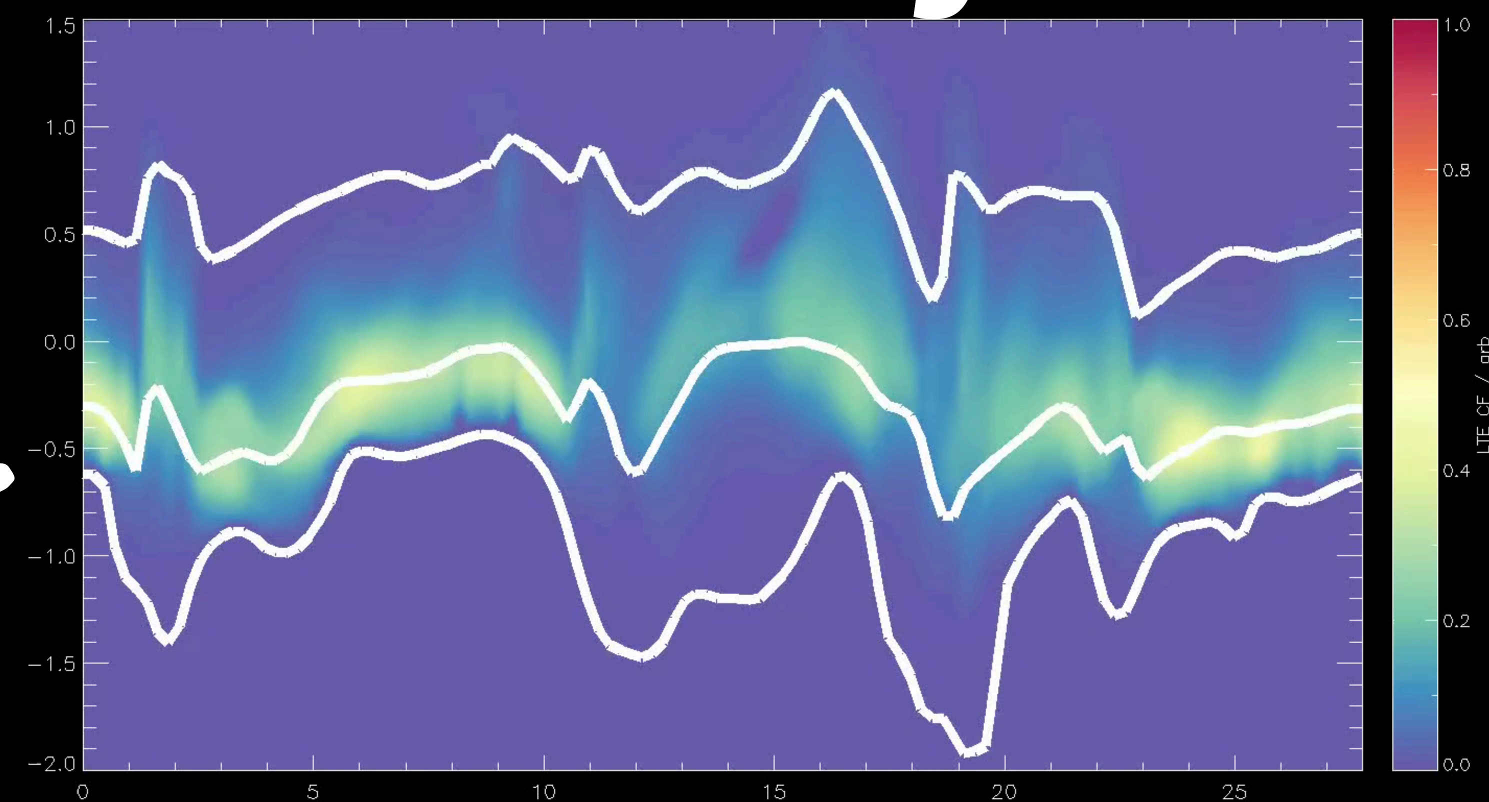
Non-LTE effects have a complicated dependence on the particular spectral line, chemical species, and type of star

(Klevas+ 2016)

(See also Wang+ 2021)

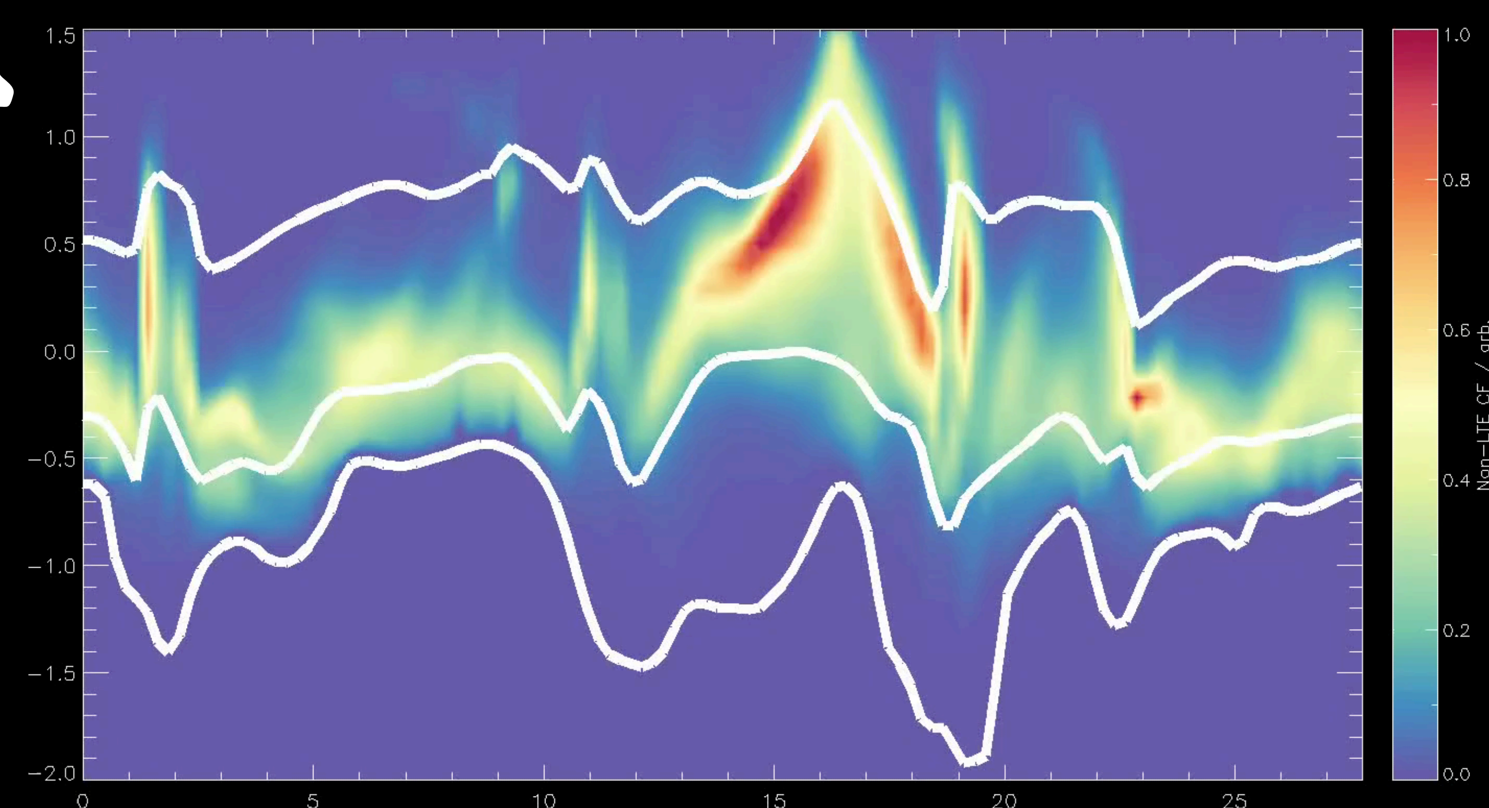
3D non-LTE… why?

Contribution function
(O1 777nm)



3D LTE

3D non-LTE



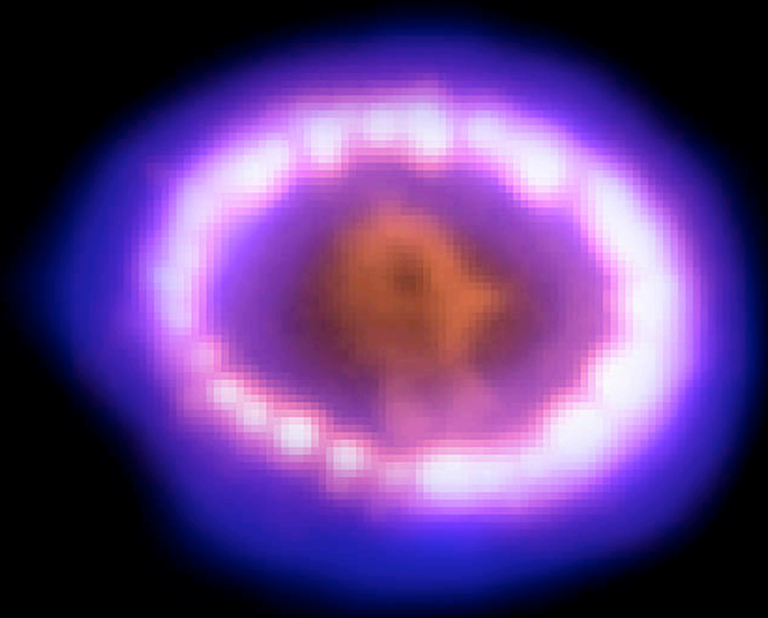
3D non-LTE line formation is **qualitatively different** to 1D LTE

(Amarsi 2015)

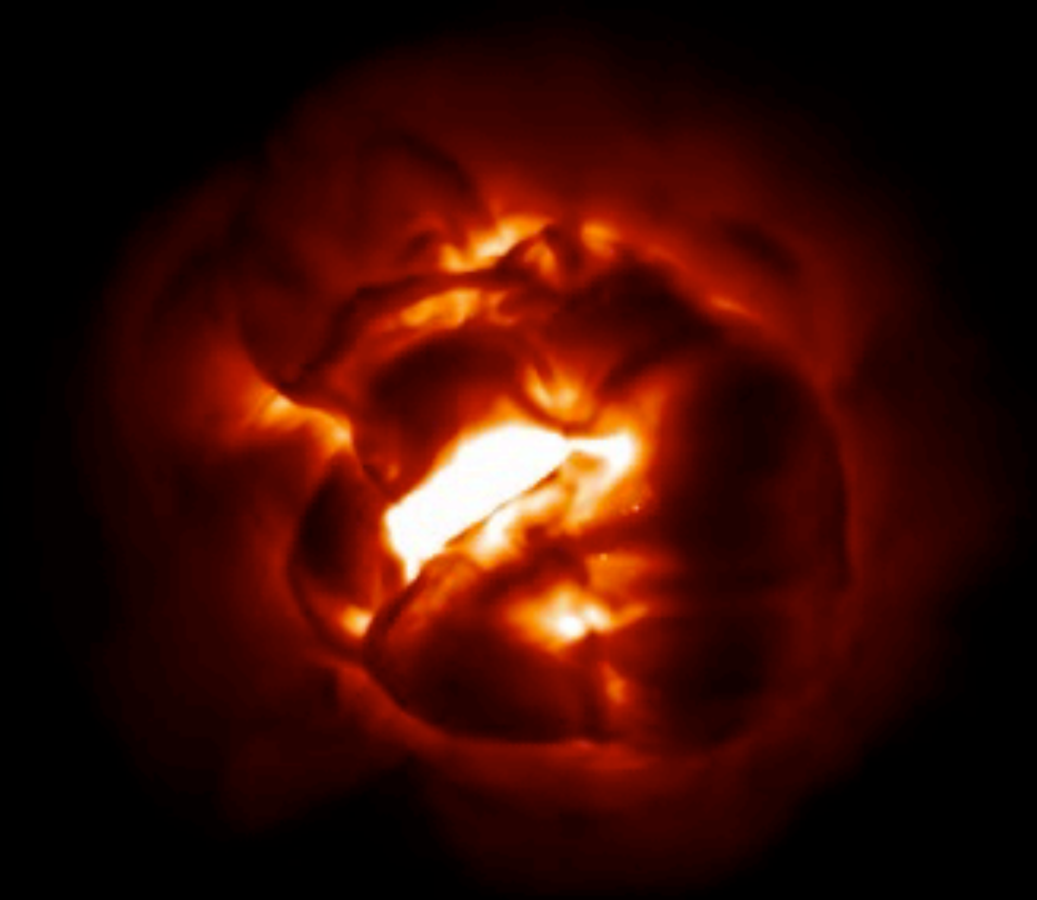
III. Impact on abundances

Illustrative example: carbon and oxygen

C and O: origins



- C & O: hydrostatic burning in **massive stars**, released via core-collapse supernova

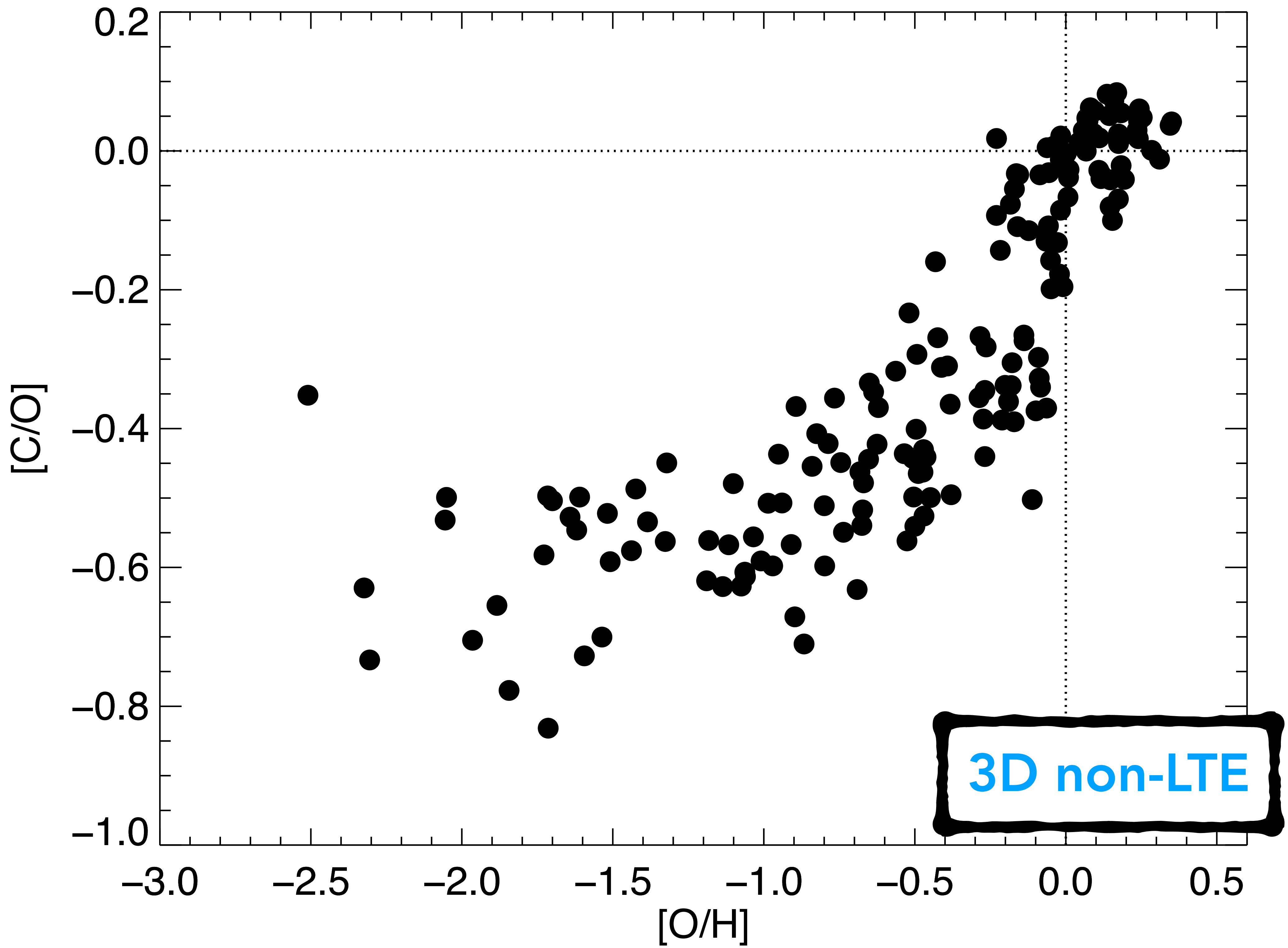


- C: **stellar winds**… "secondary" production from massive, rapidly-rotating stars? And/or delayed production from AGB stars?

(Type-II supernova 1987A; ALMA/NASA)

(AGB star model; Bernd Freytag, Uppsala University)

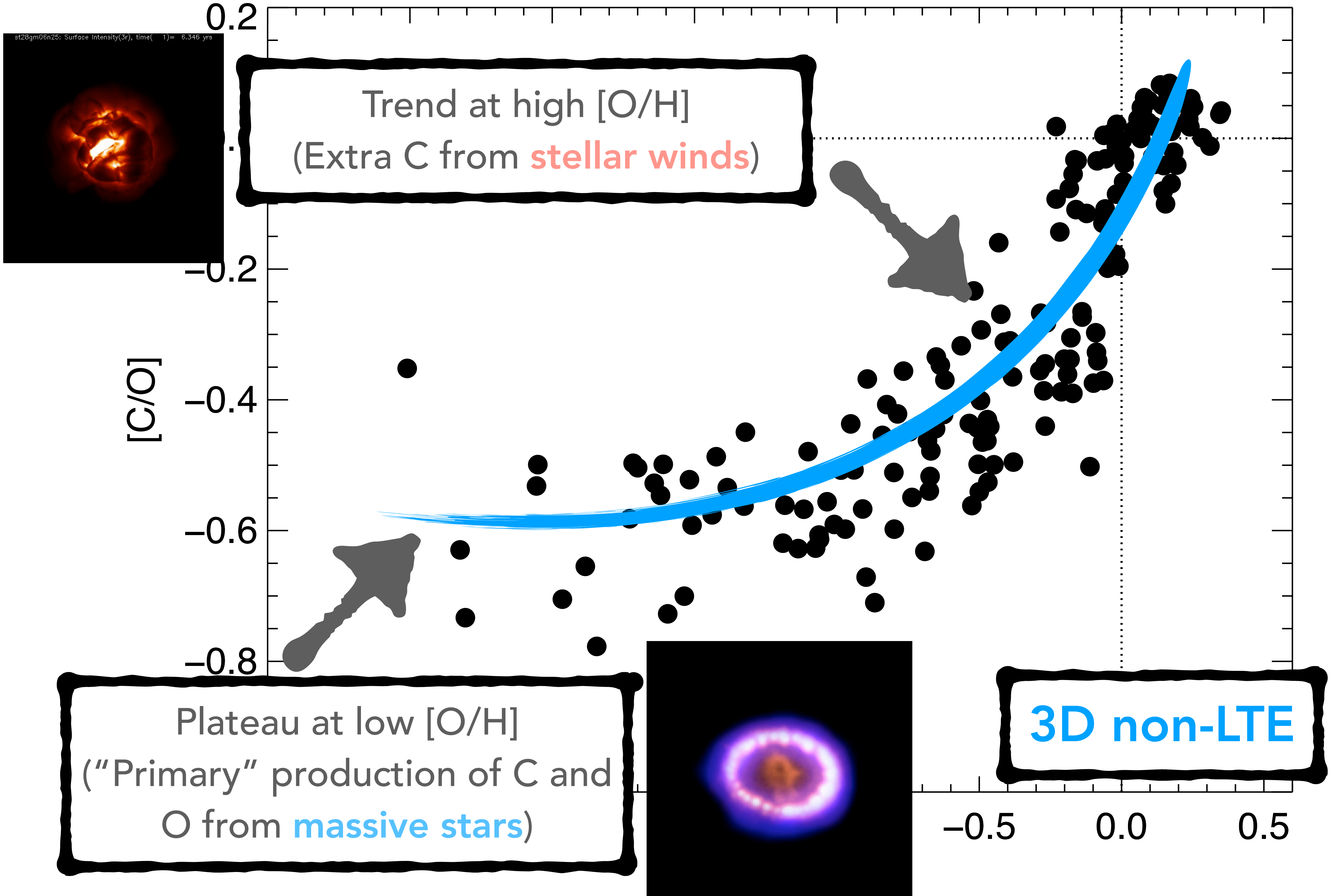
C and O: evolution



(Amarsi, Nissen, Skúladóttir 2019)

(See also Gustafsson+ 1999, Akerman+ 2004)

C and O: evolution



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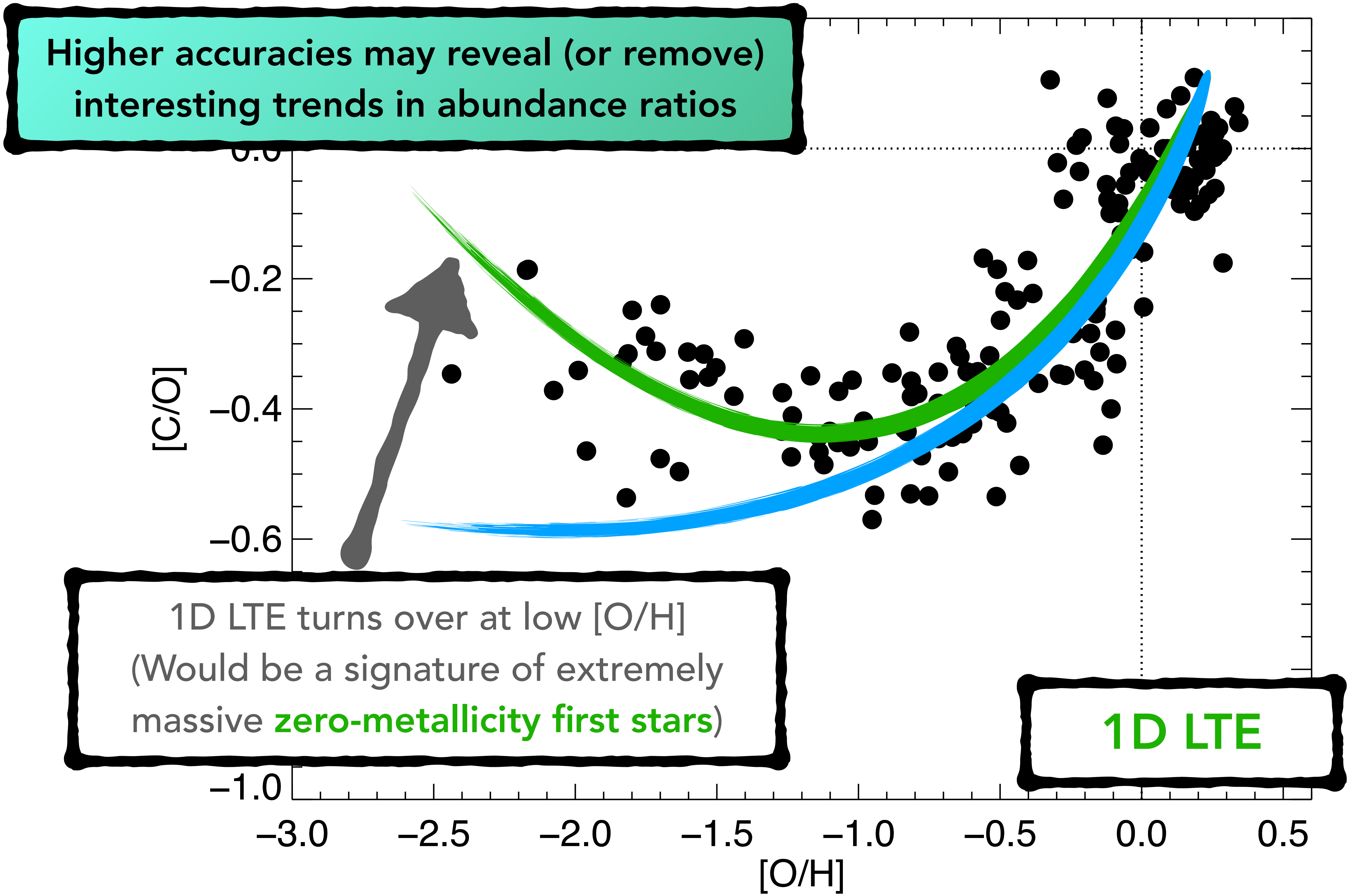

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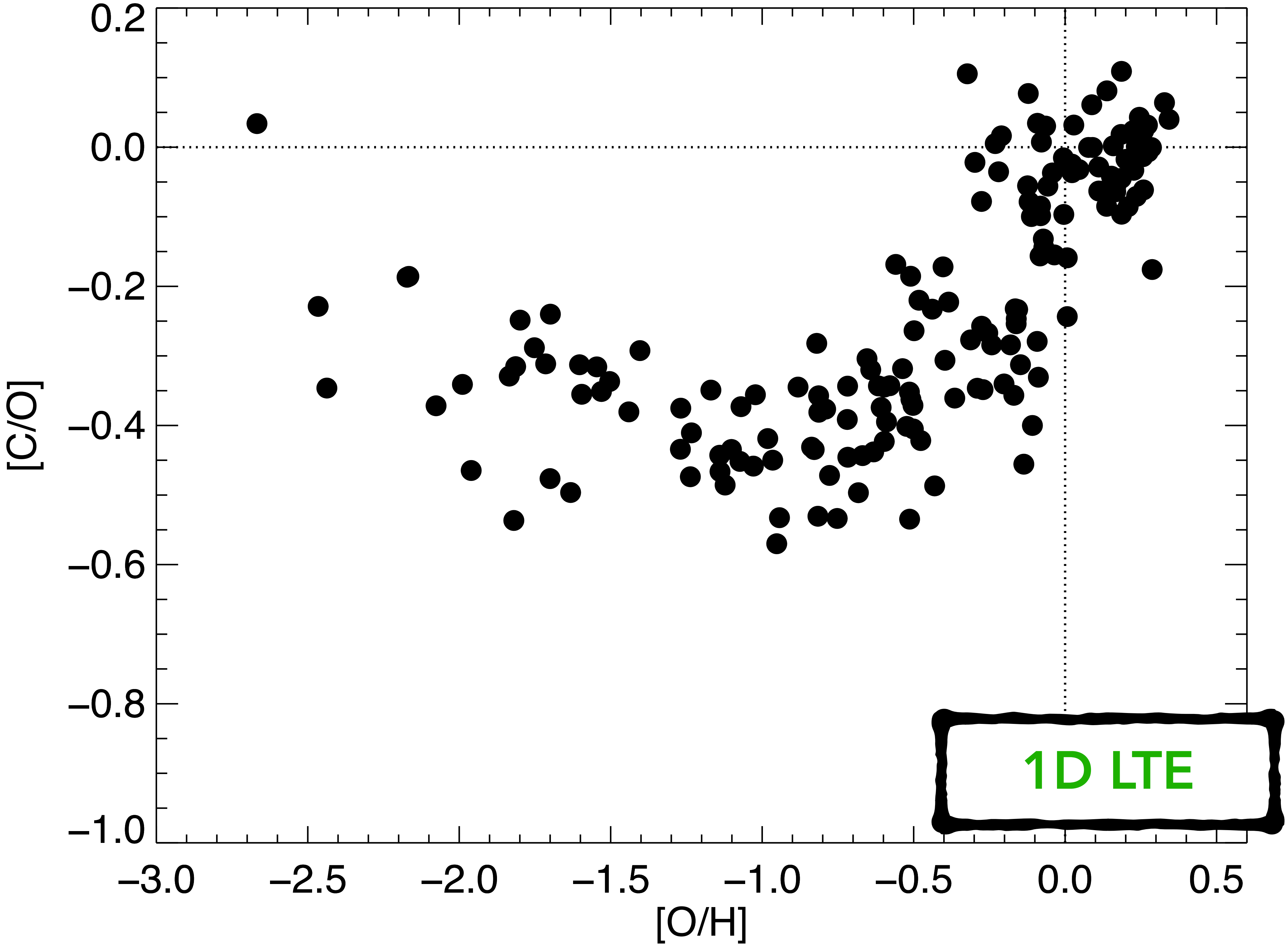

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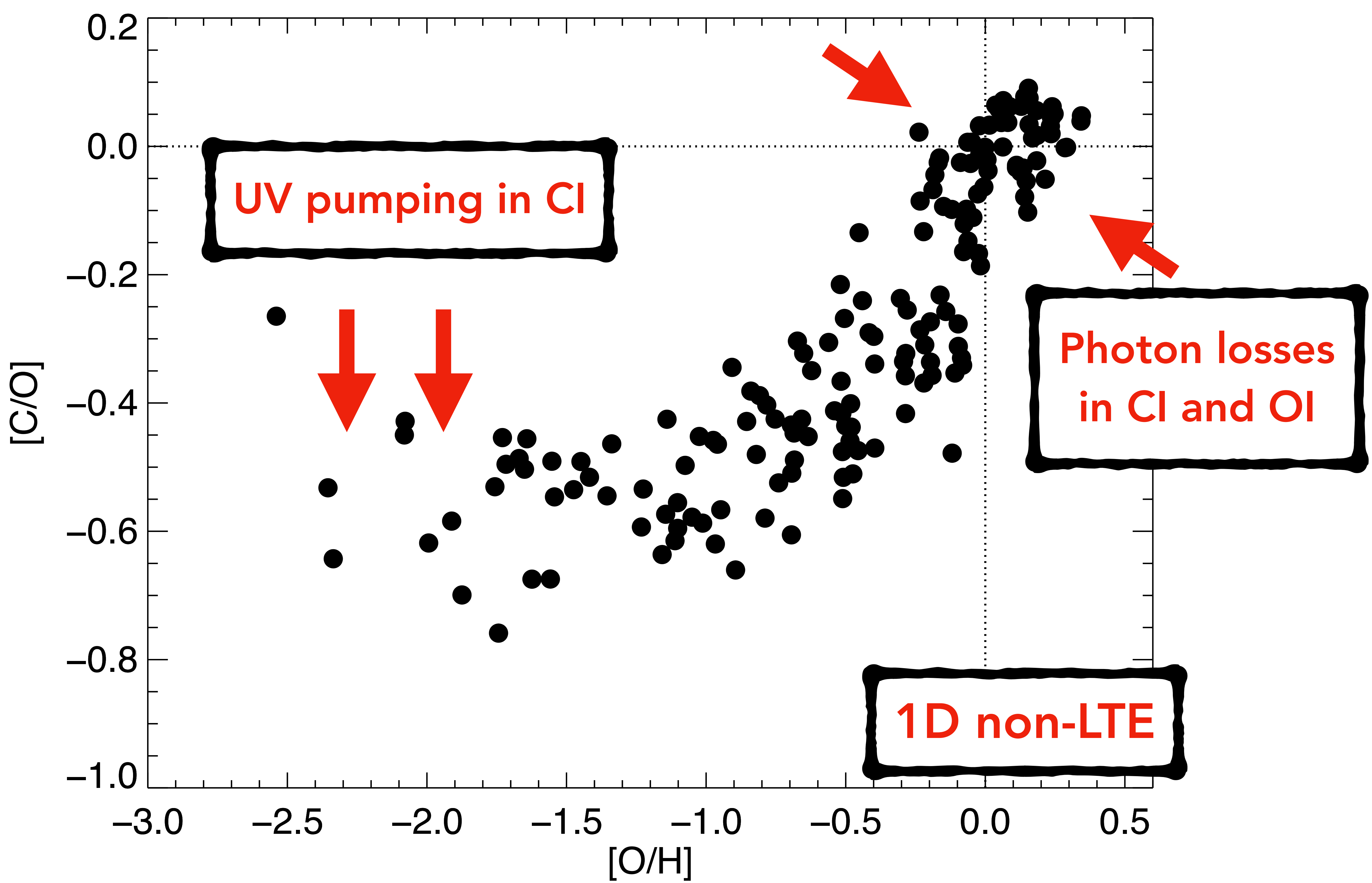

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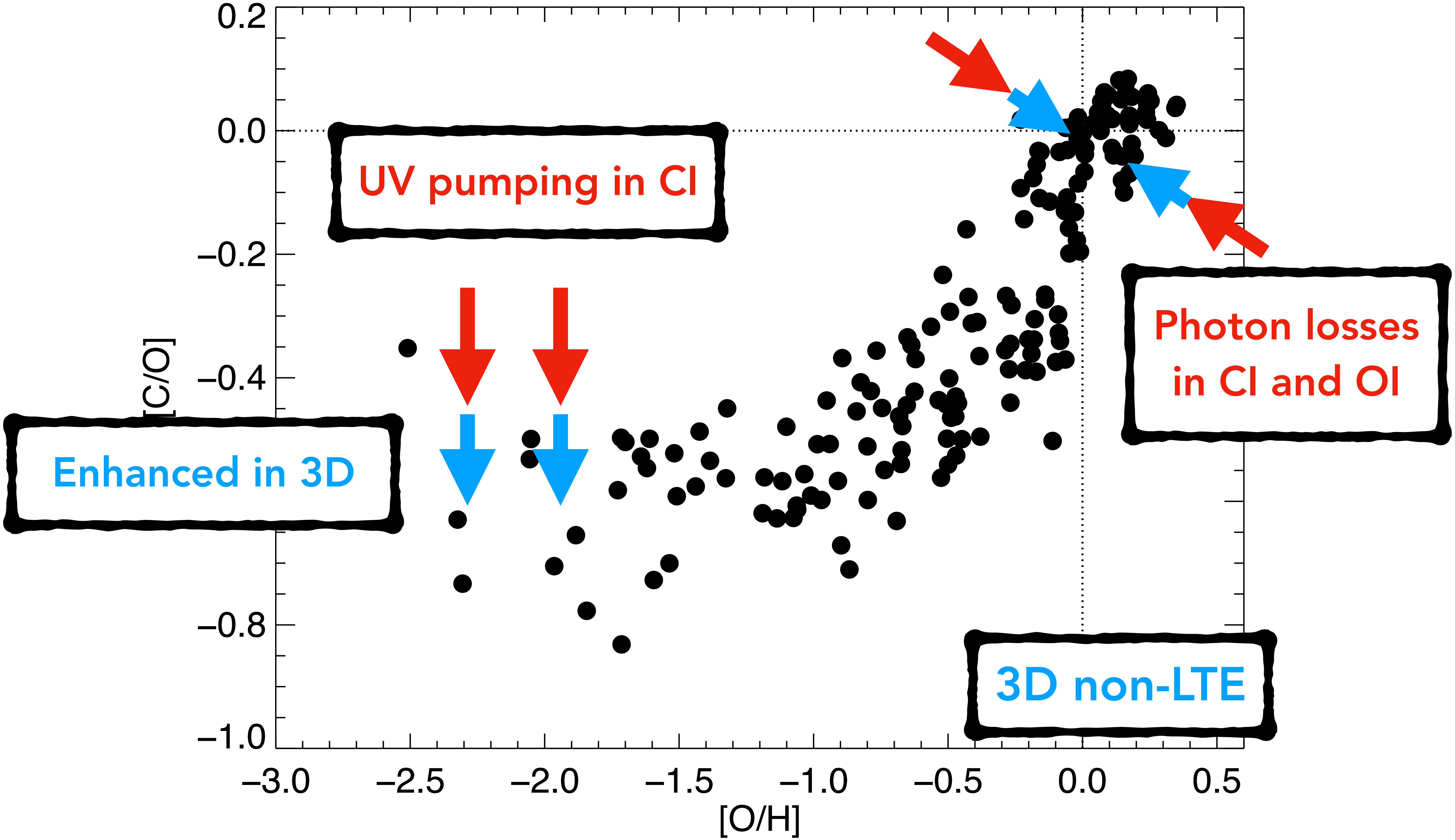

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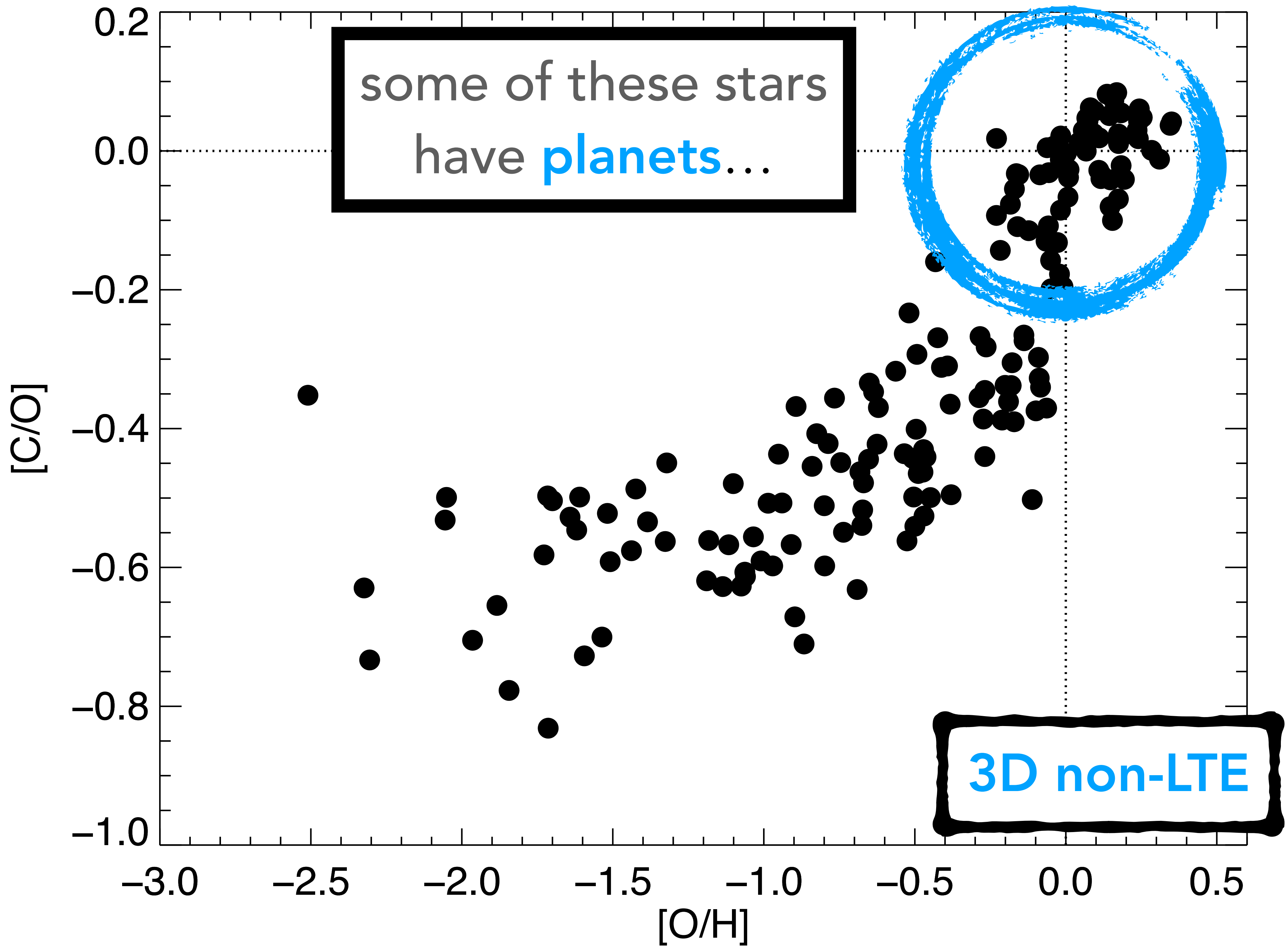

(Amarsi, Nissen, Skúladóttir 2019)

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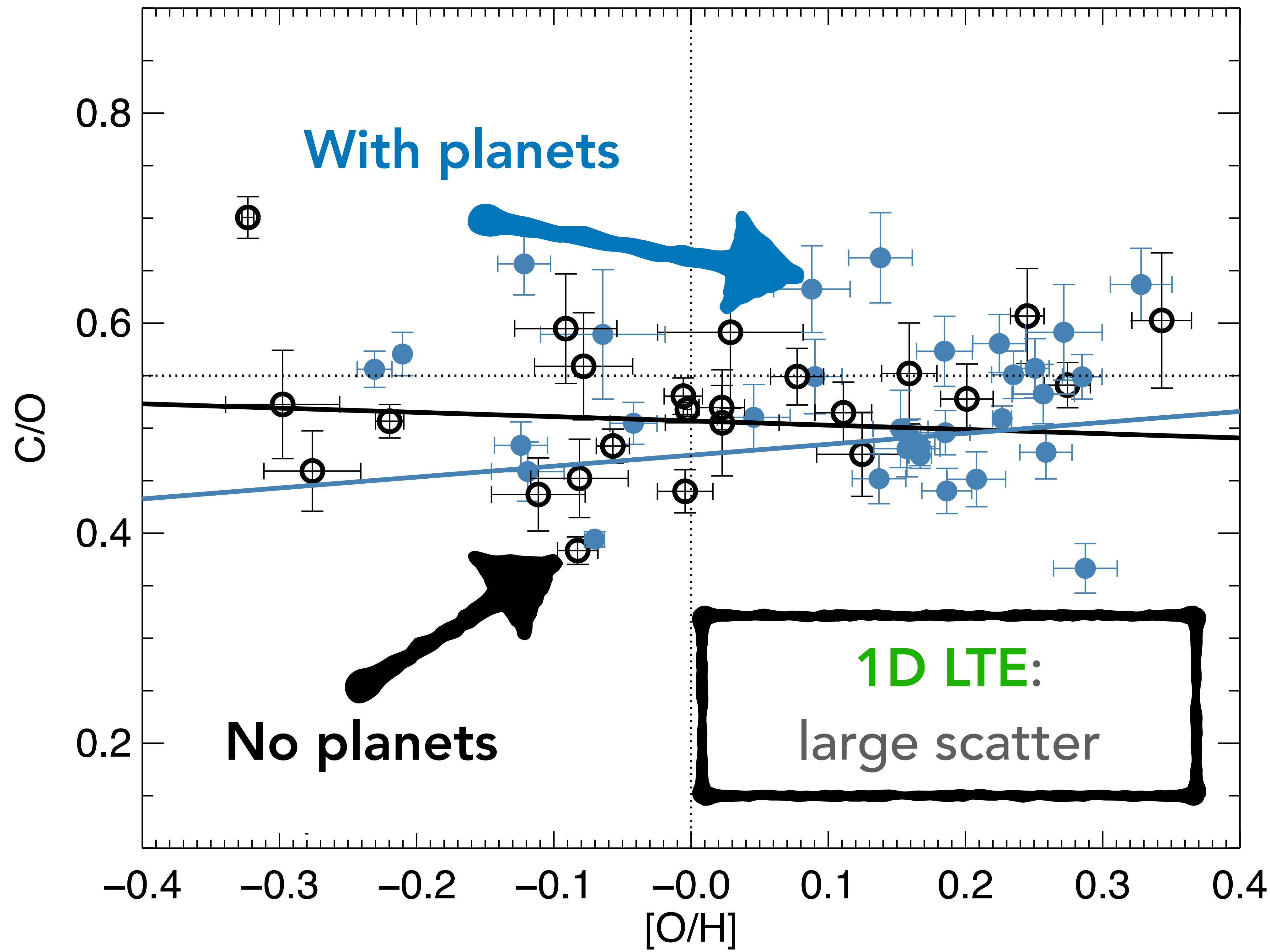
C and O: planet signature



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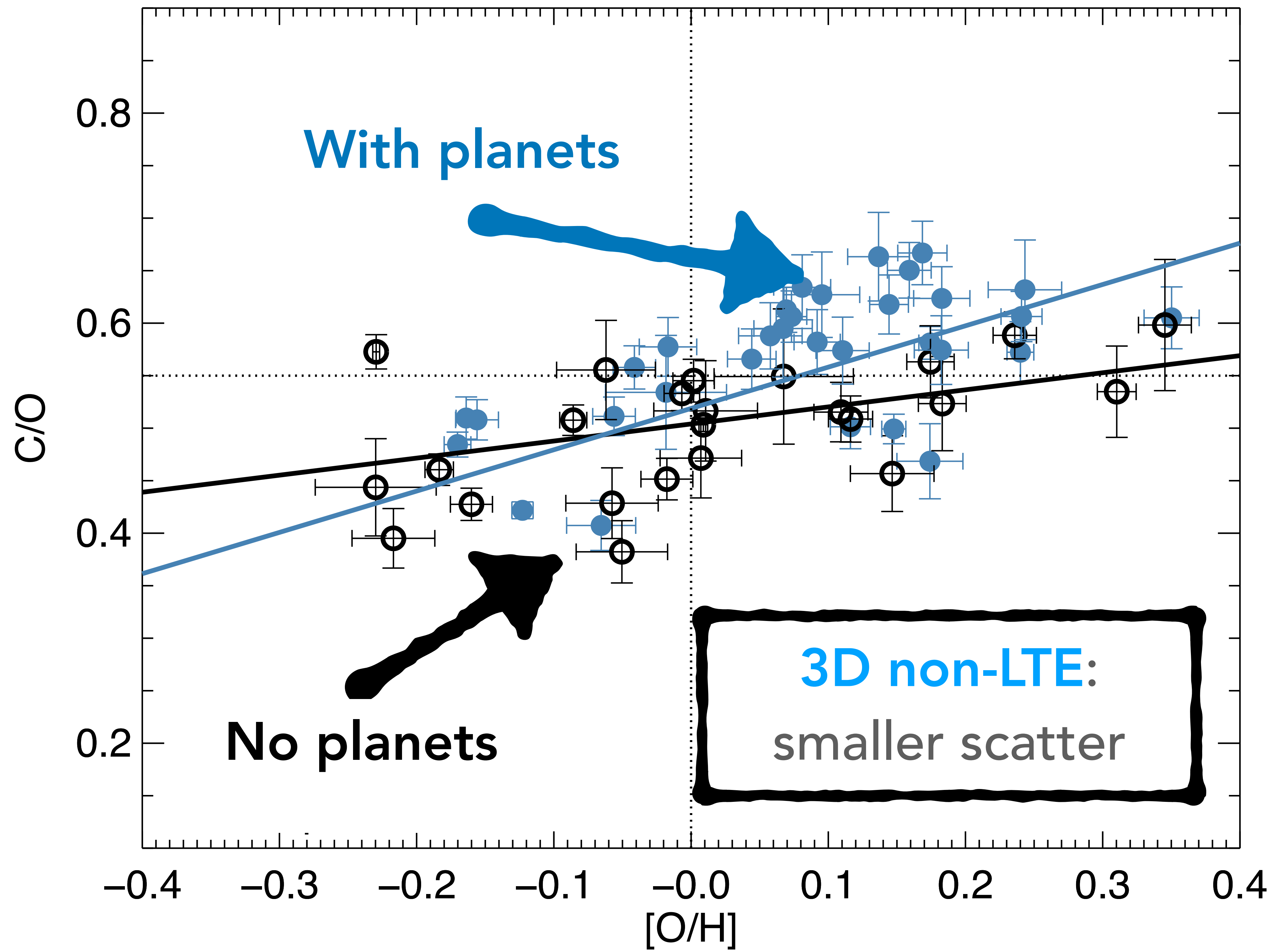
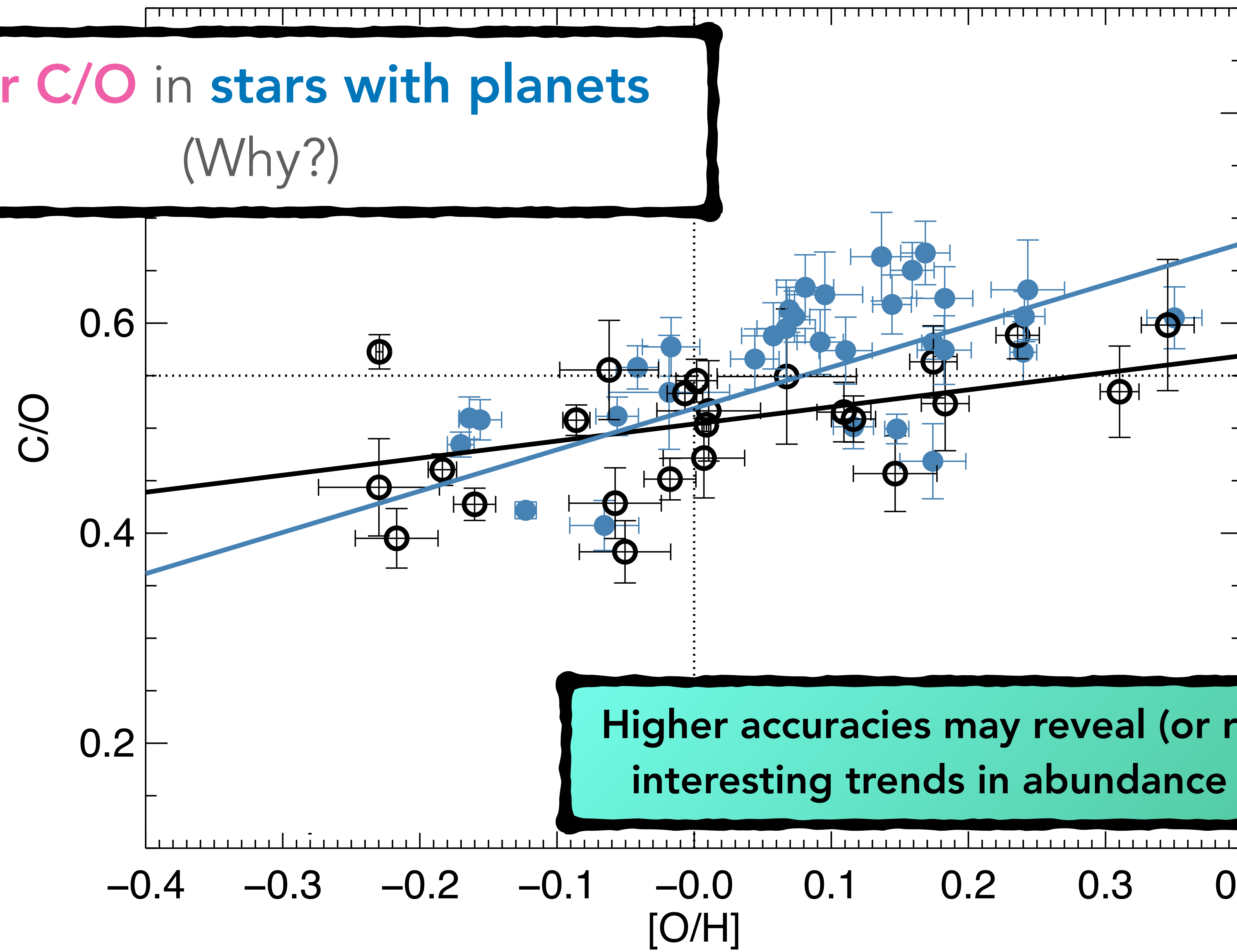


(Amarsi, Nissen, Skúladóttir 2019)

C and O: planet signature

larger C/O in stars with planets

(Why?)



Higher accuracies may reveal (or remove) interesting trends in abundance ratios

(Amarsi, Nissen, Skúladóttir 2019)