Improved line formation models
//
accurate stellar abundances

Anish Amarsi (MPIA)

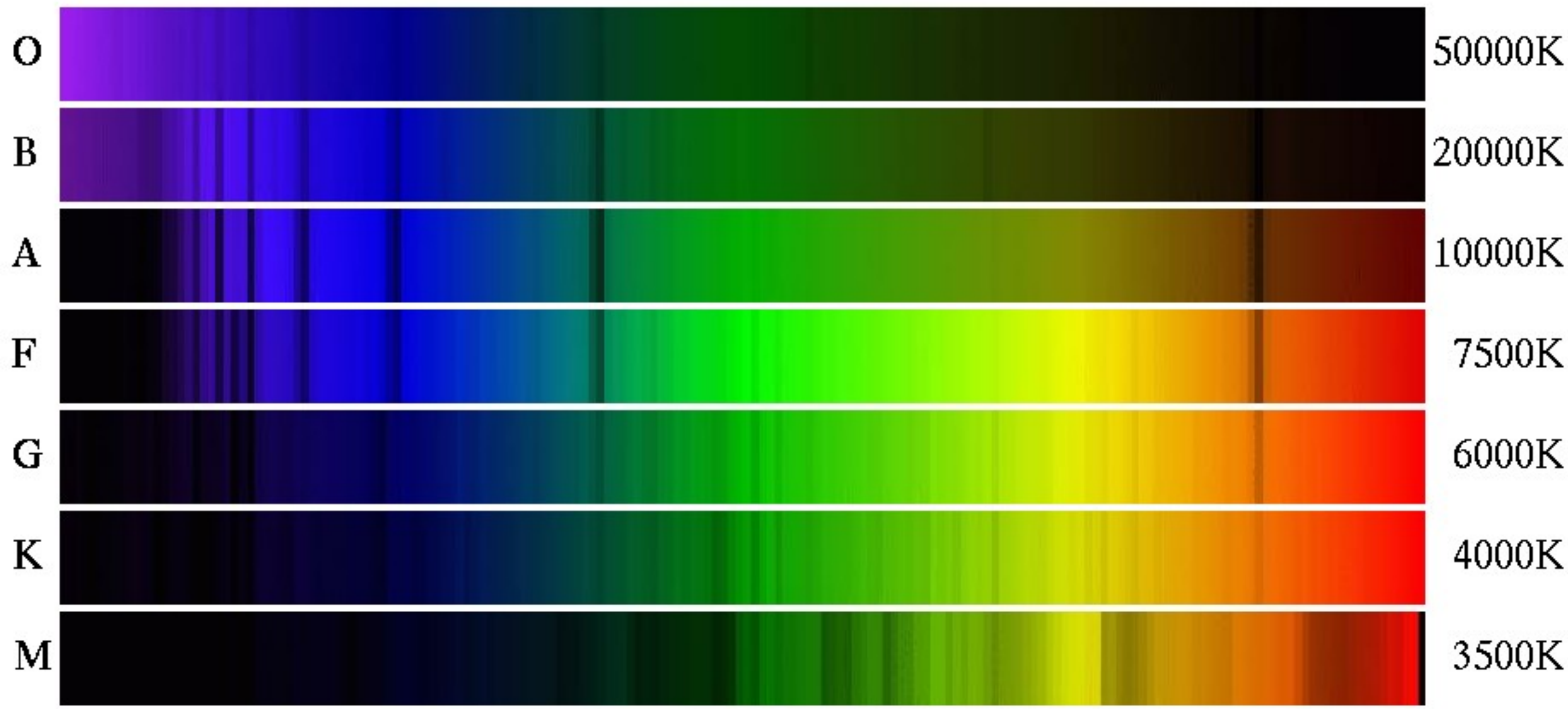
Lagrange 5 Feb 2019

Intro

Why abundances?

- Long-lived information in abundances A(X), ratios [X/Y]
- Learn about
  - **Stellar** structure, evolution & nucleosynthesis
  - **Supernova** mechanisms & nucleosynthesis
  - **Exoplanet** formation & characterisation
  - **Galaxy** formation & evolution

Reliable abundances?

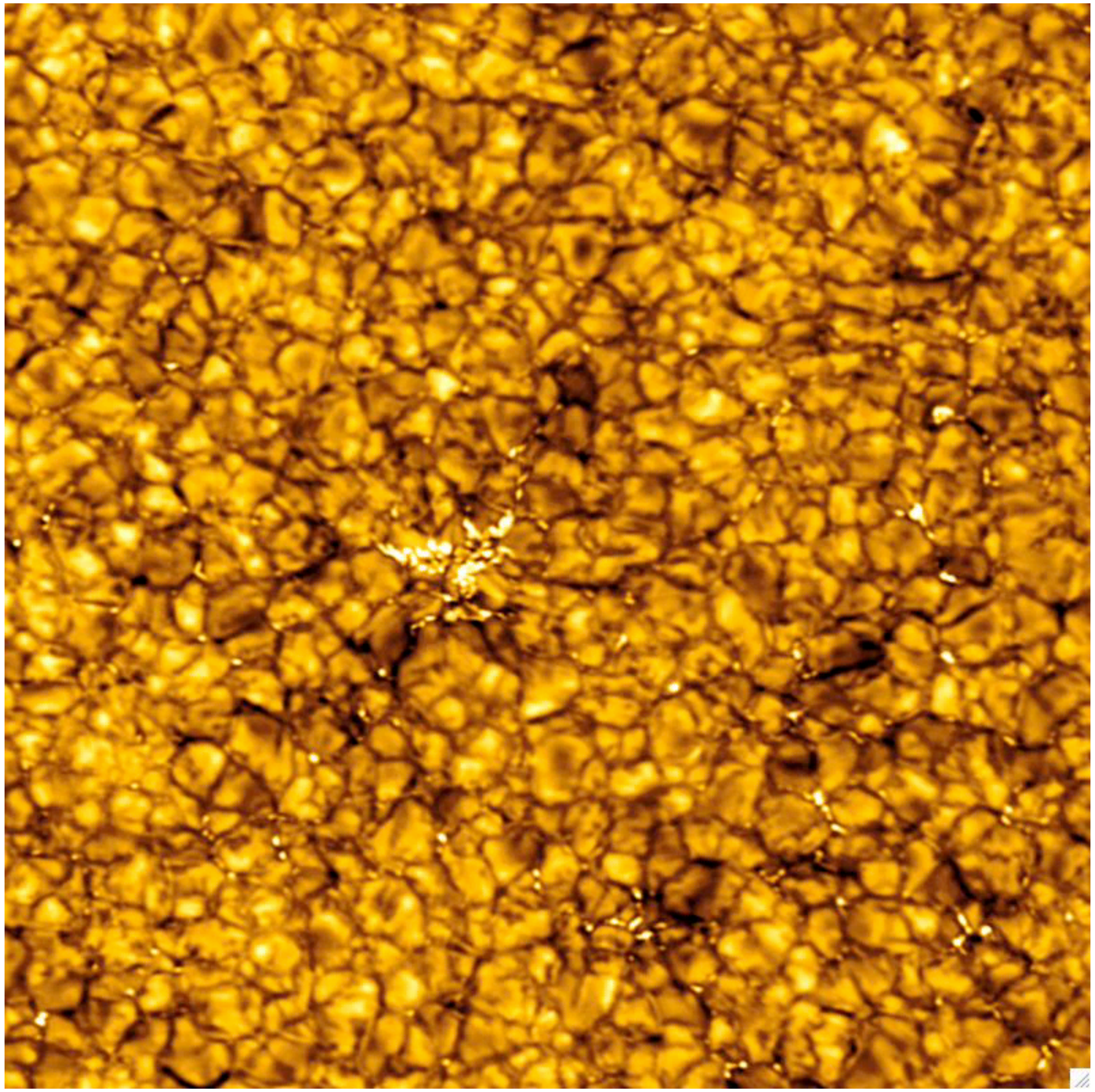


- Information in absorption & emission lines
- Infer stellar parameters; **abundances**

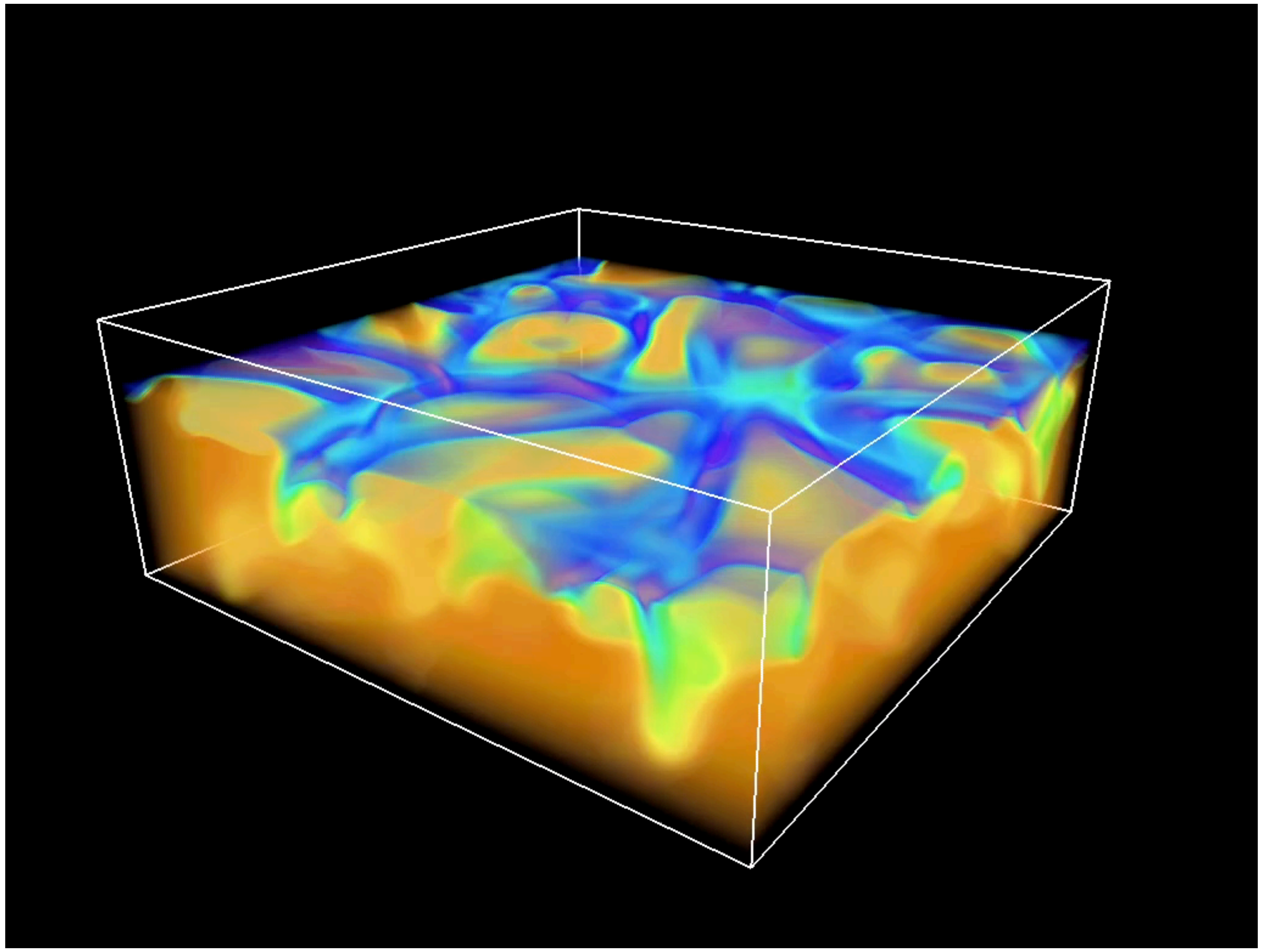
Reliable abundances?

- Prone to systematic modelling errors
- 1D vs **3D**; LTE vs **non-LTE**

1D vs 3D

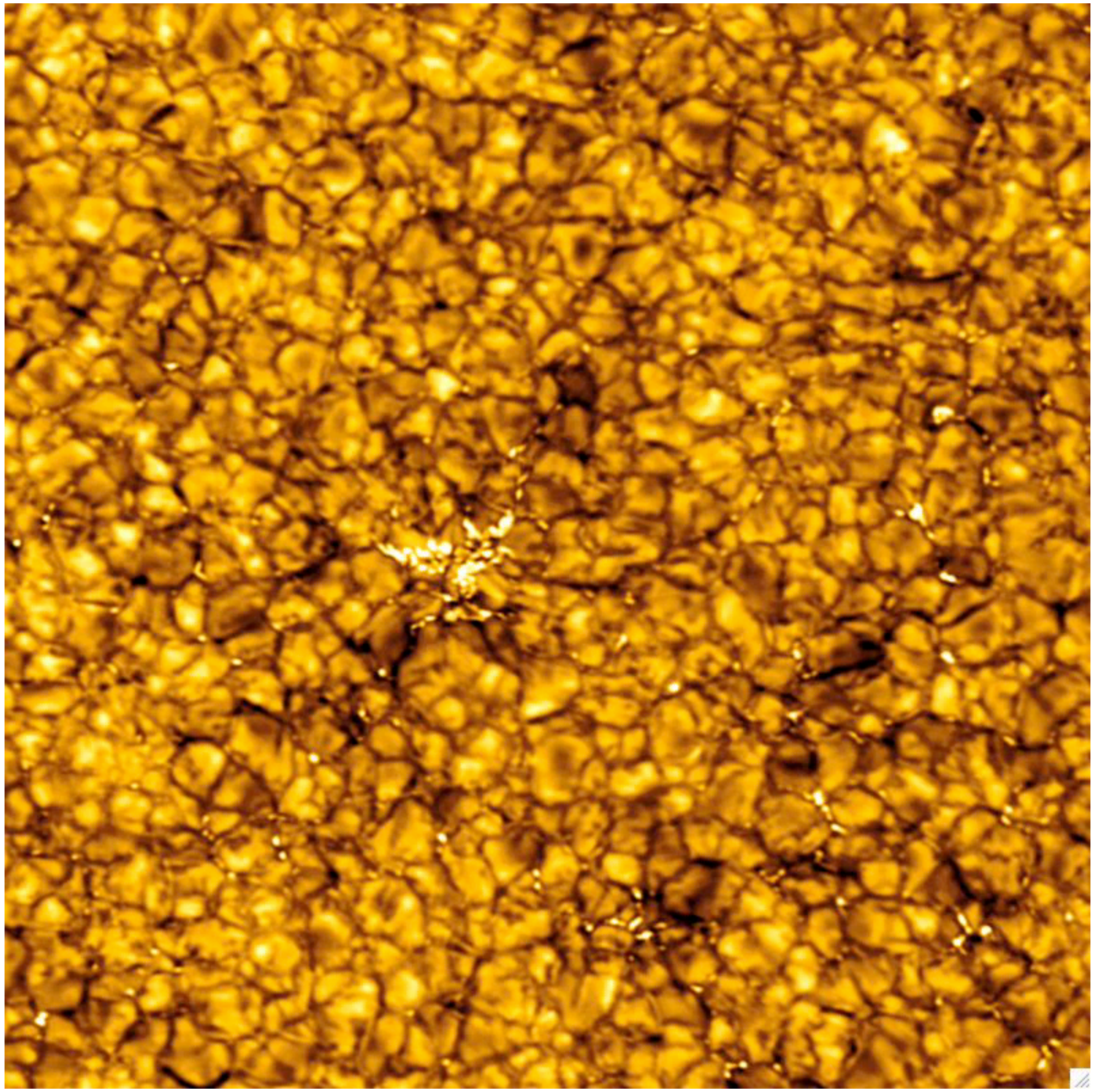


SST observations
van der Voort 2006



3D hydro. simulation
Collet+ 2018

1D vs 3D



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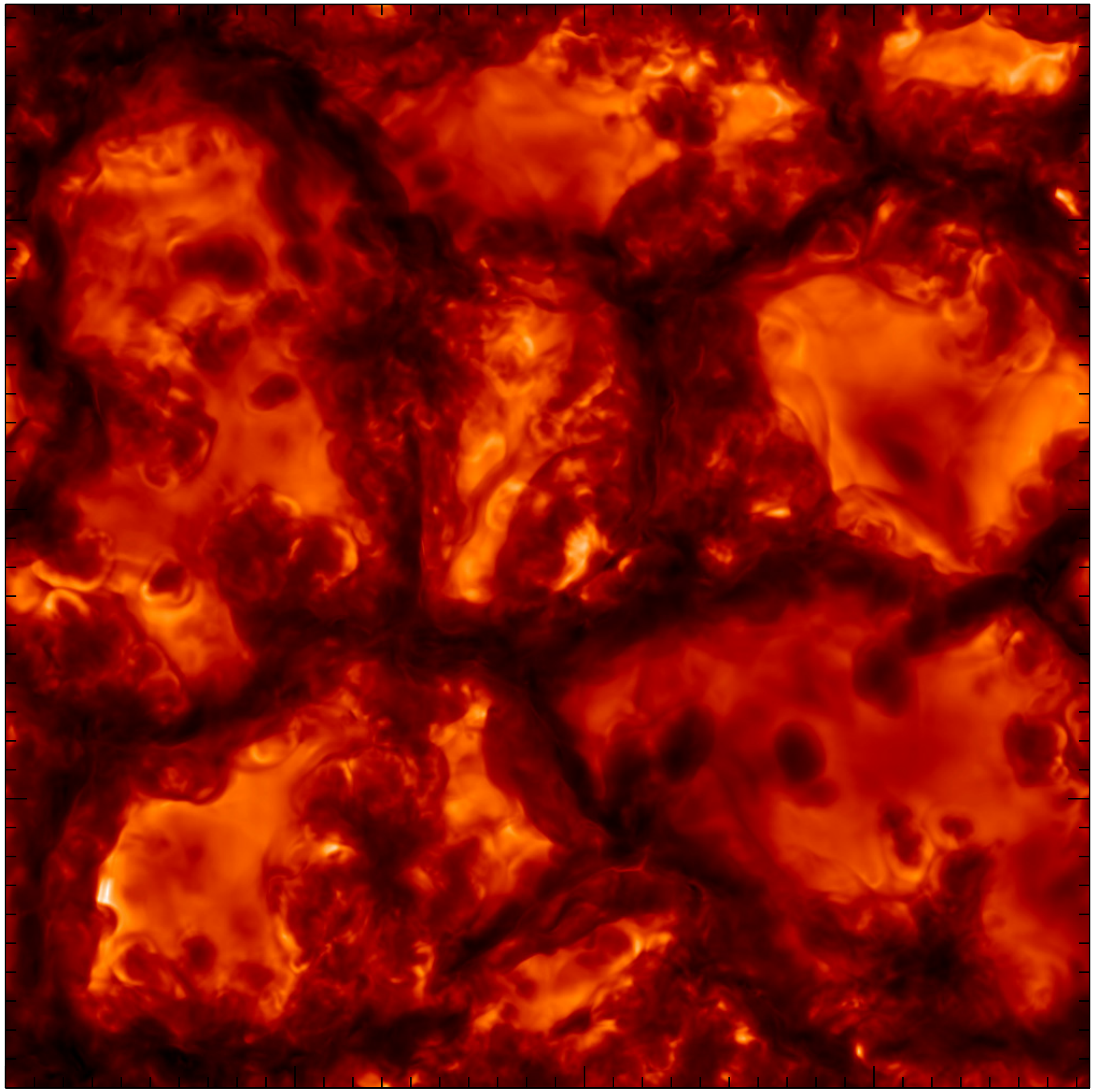

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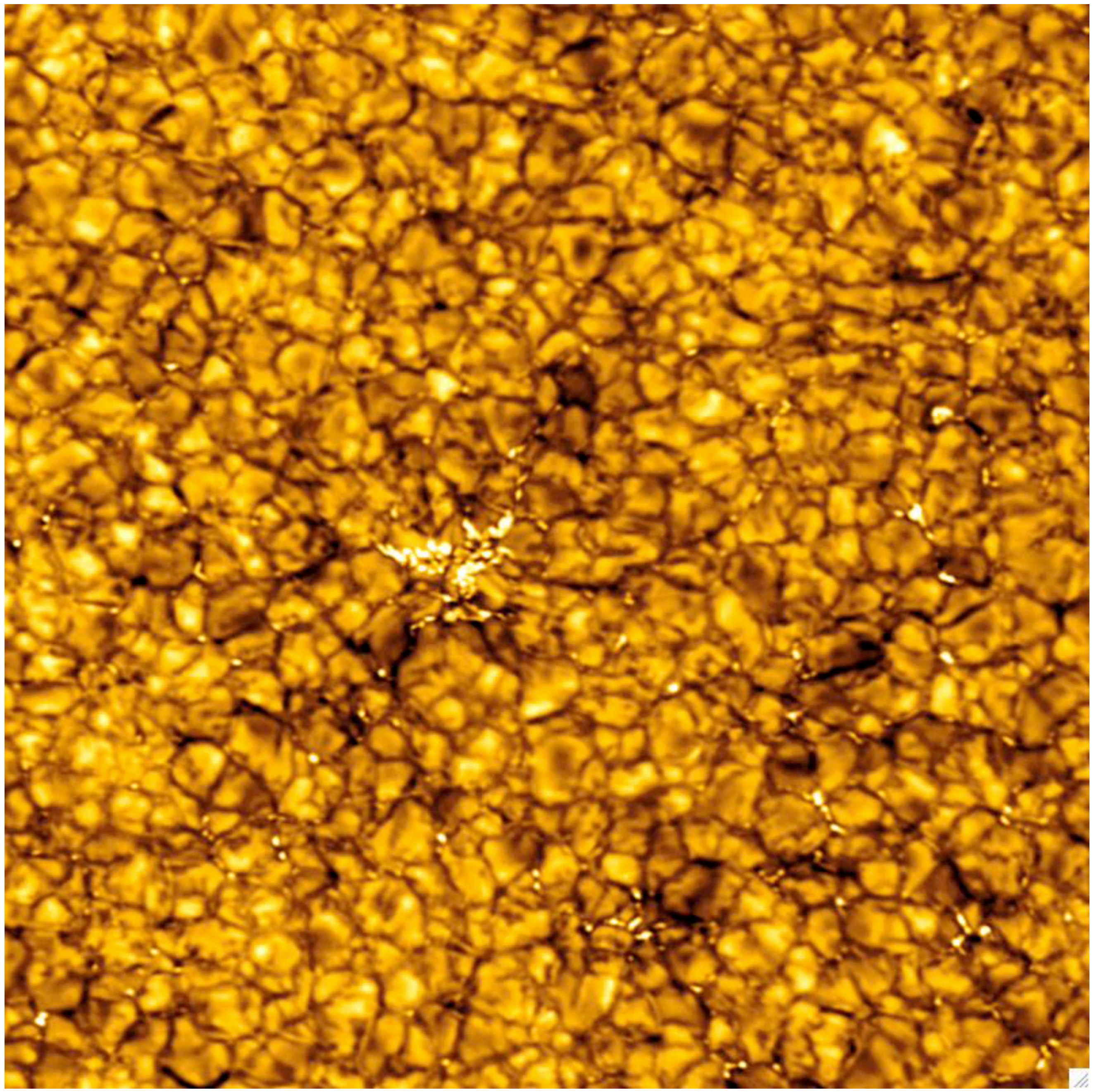
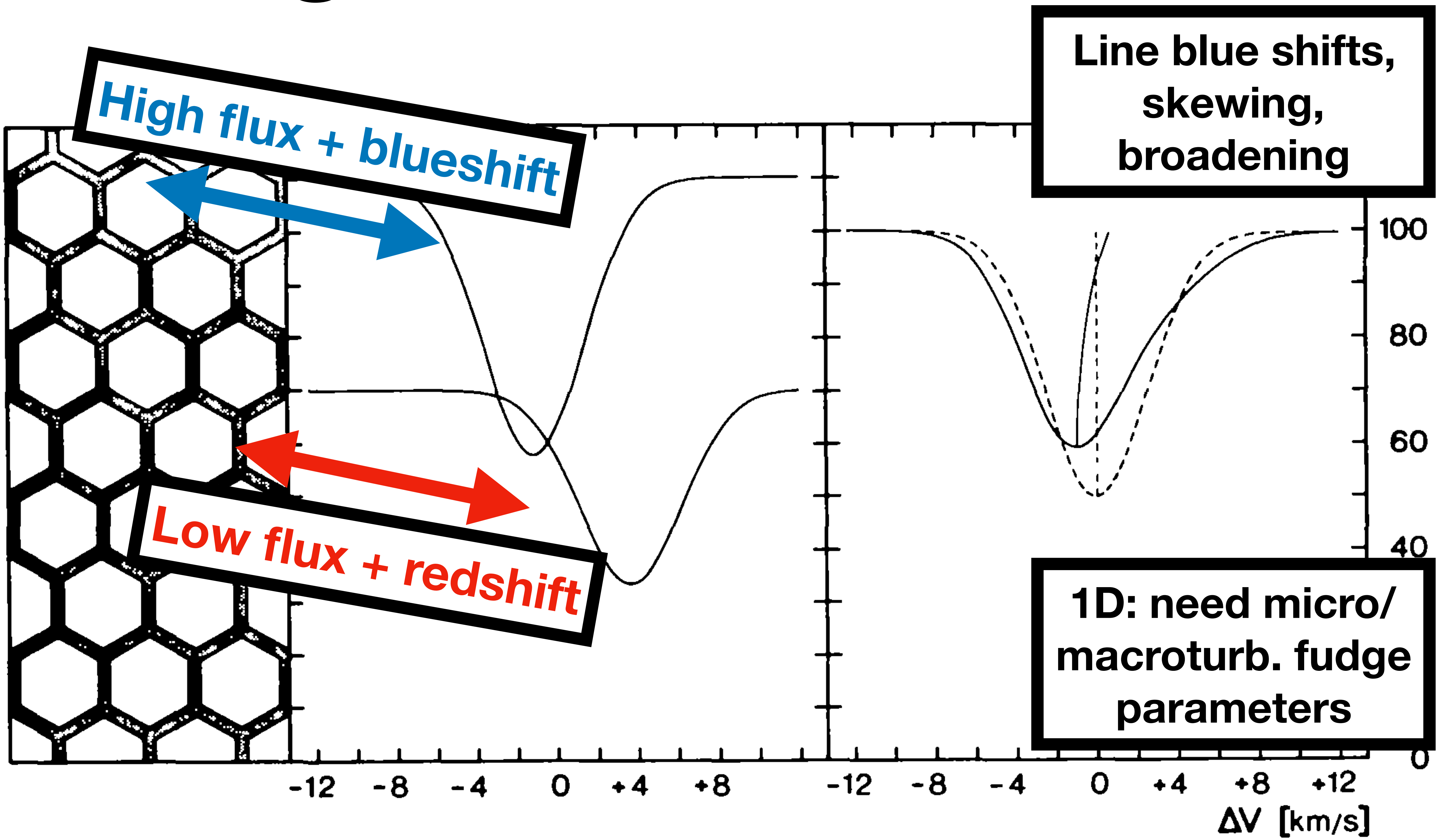


SST observations
van der Voort 2006

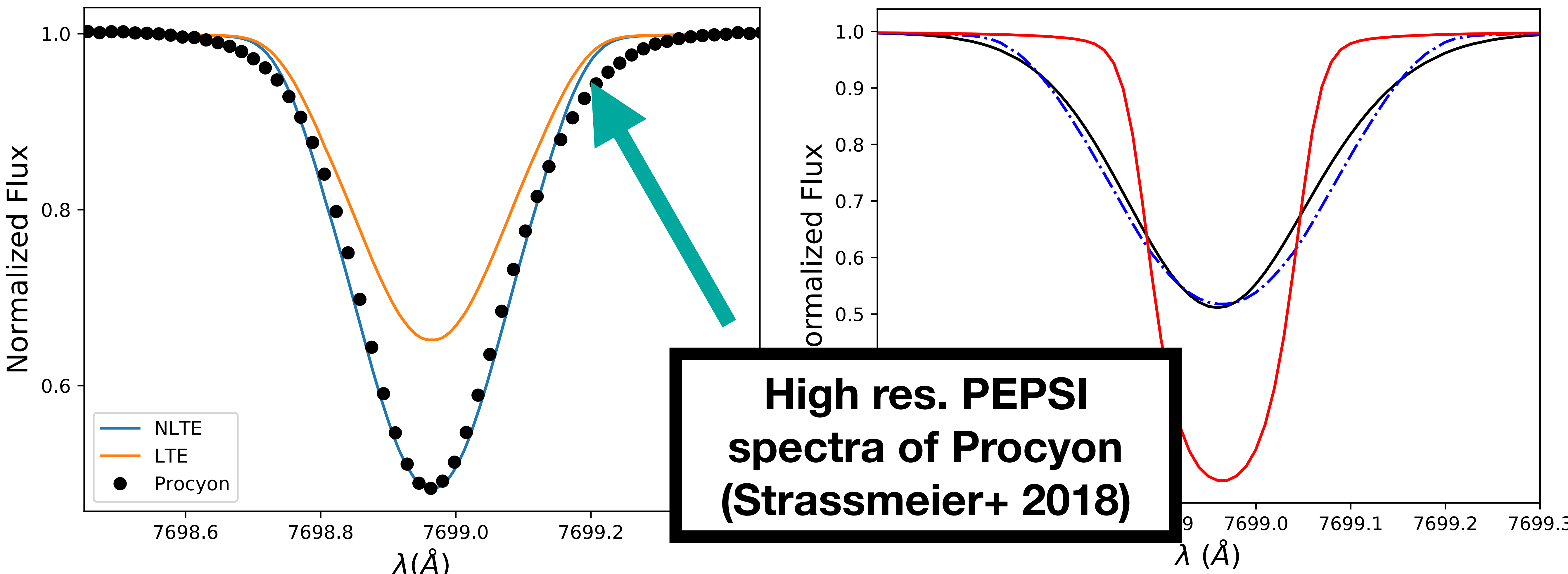
1D simulation
//

3D granulation effects



Dravins+ 1981

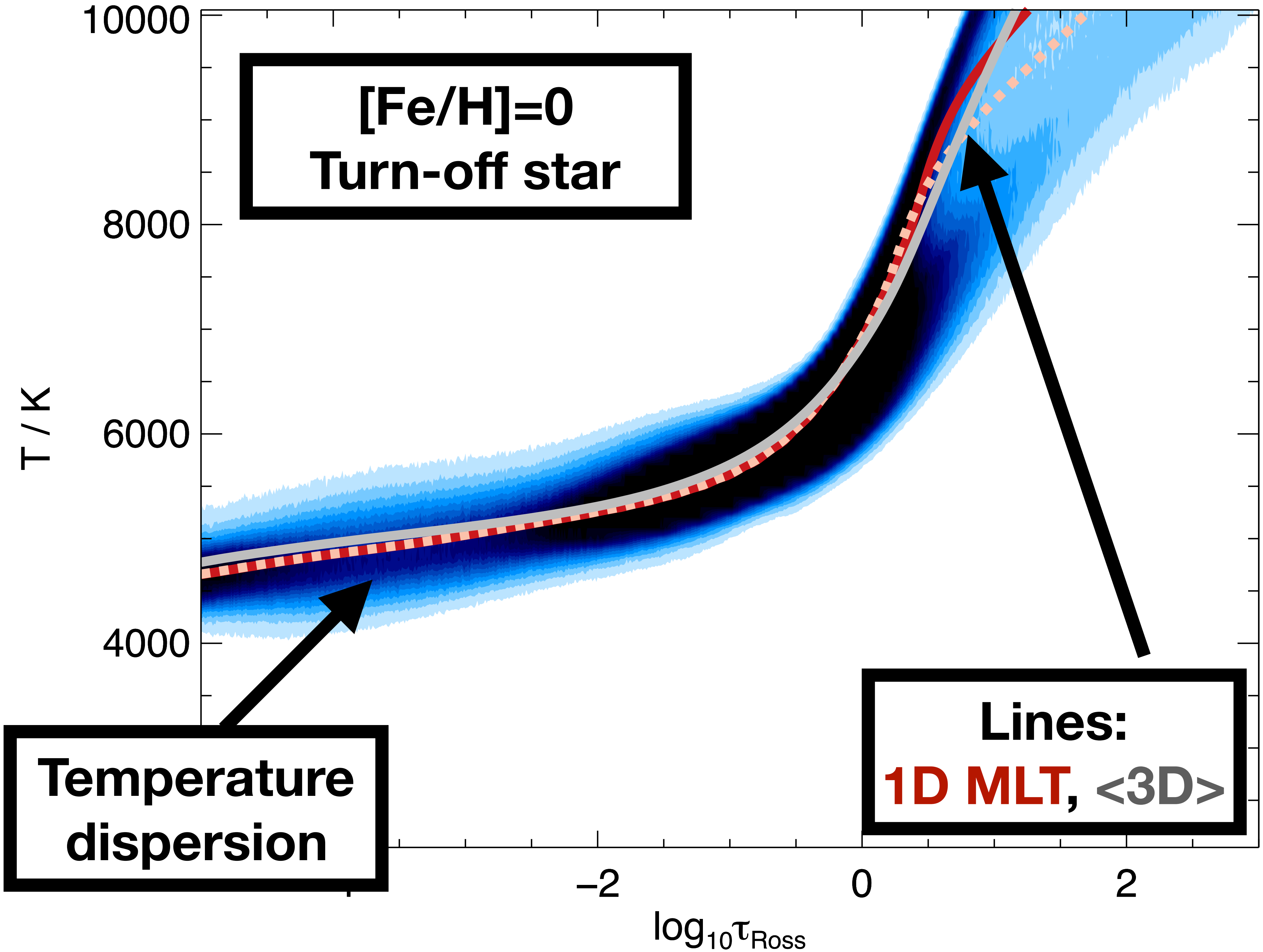
3D granulation effects



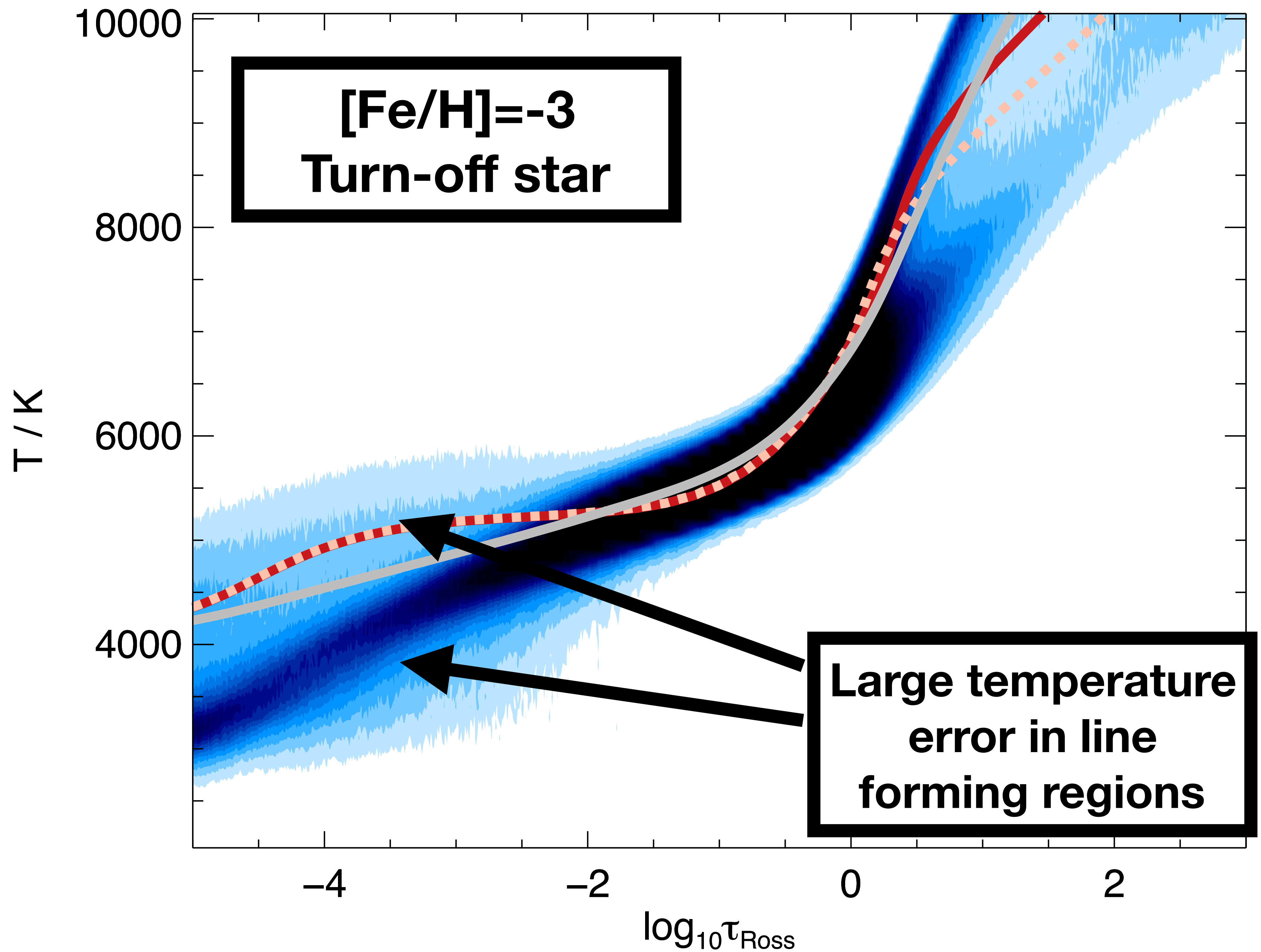
*Reggiani, **Amarsi**+ sub.*

- Effects are apparent in high-resolution observations
- Even of stars ≠ Sun

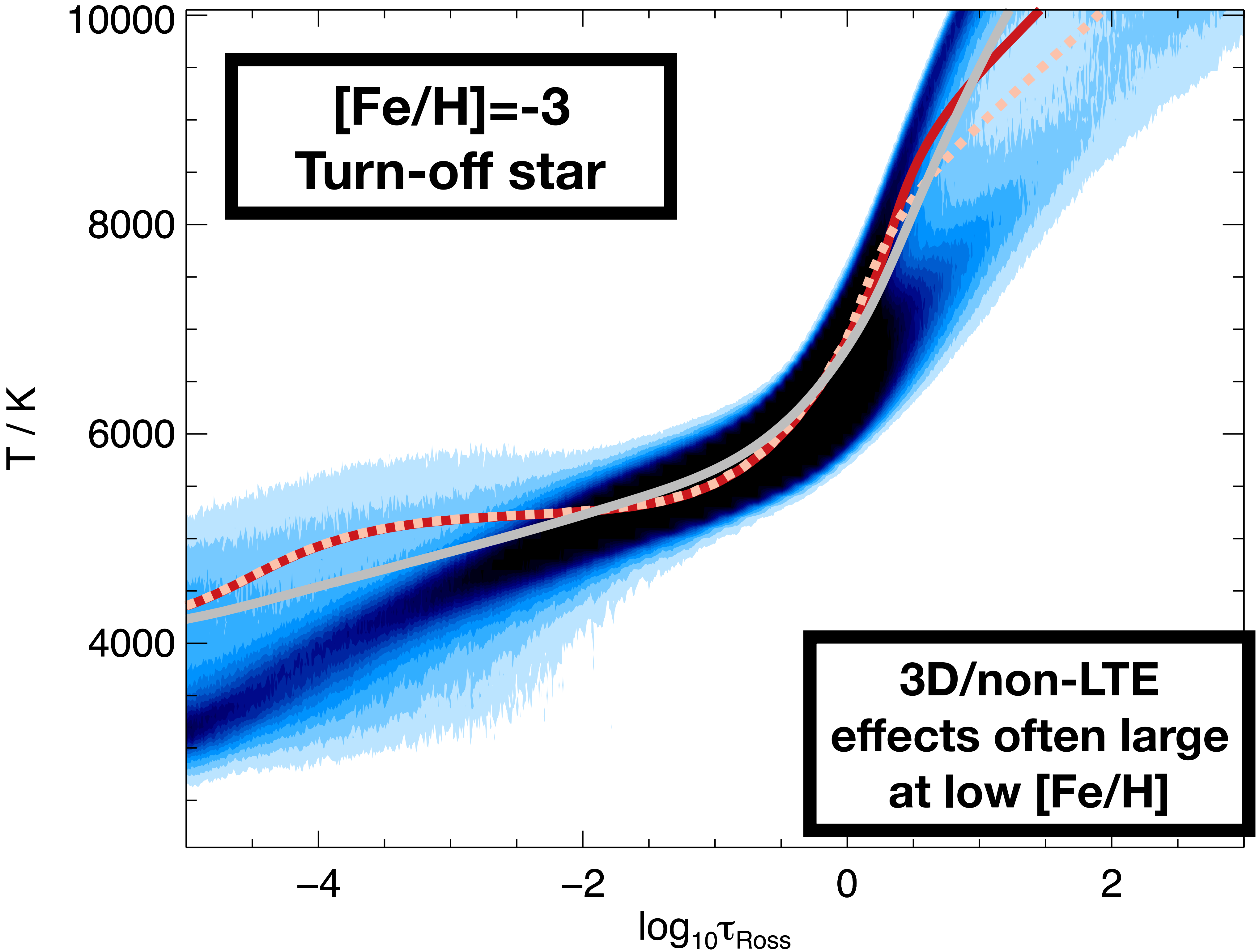
3D structure effects



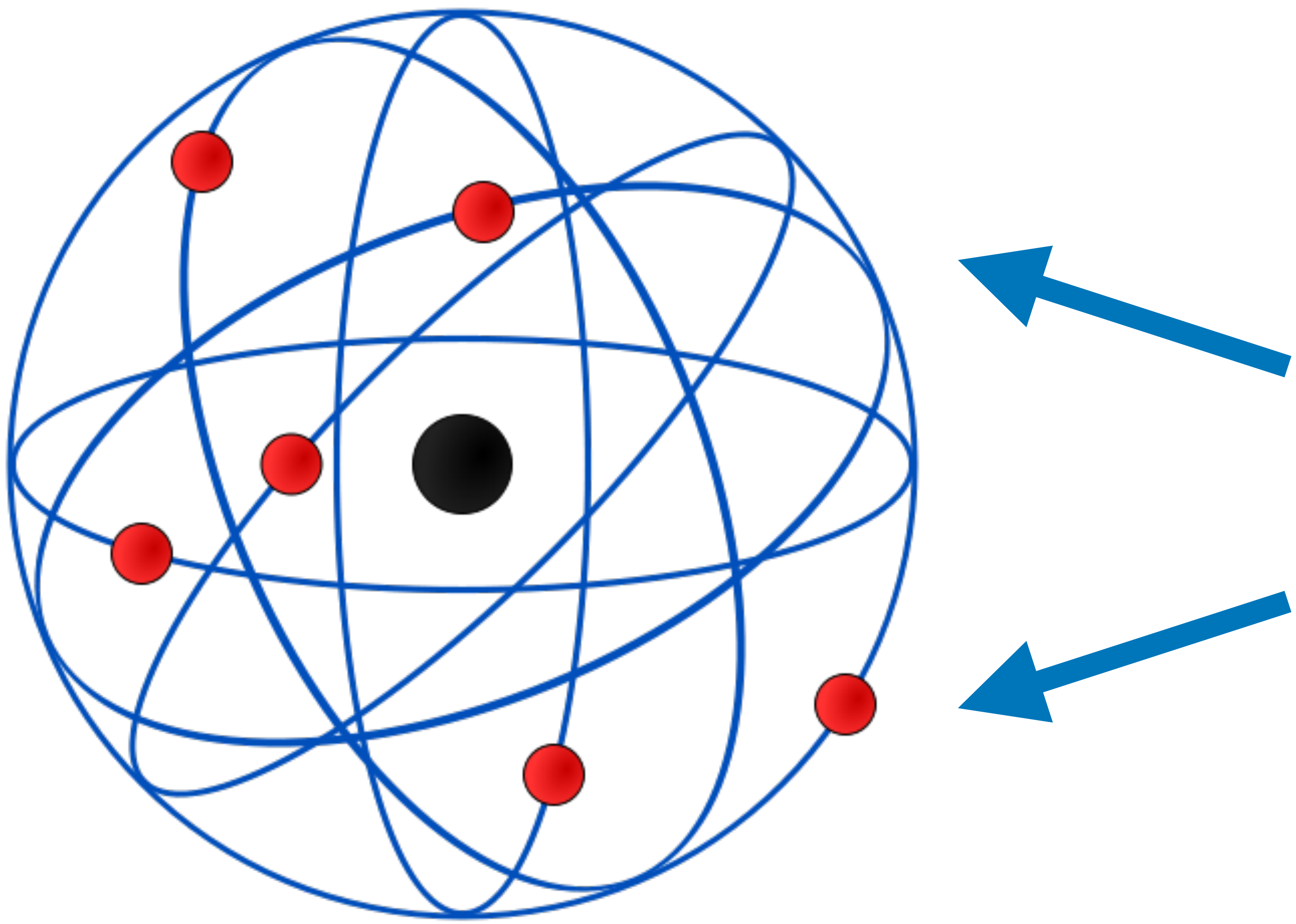
3D structure effects



3D structure effects



LTE vs non-LTE

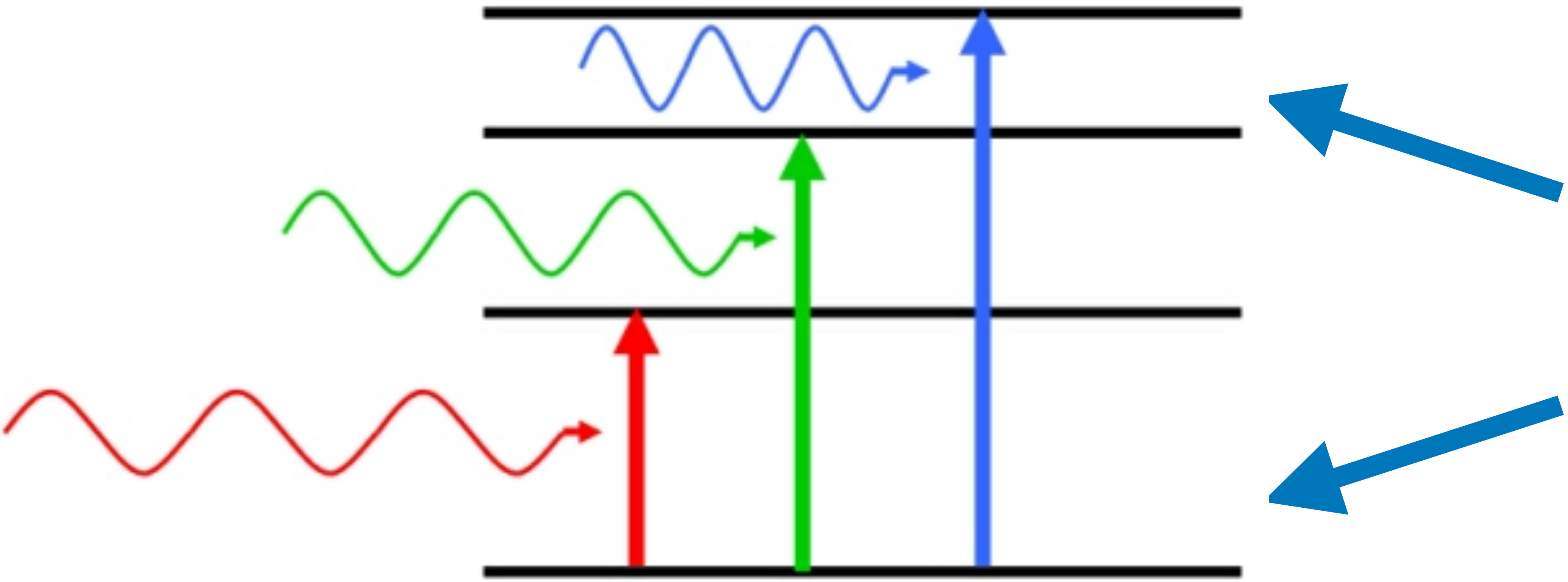


$$e^{-\frac{E}{kT}} \ ?$$

- Need some model for energy partitioning

- Local thermodynamic equilibrium (LTE): **neglect radiation**

LTE vs non-LTE



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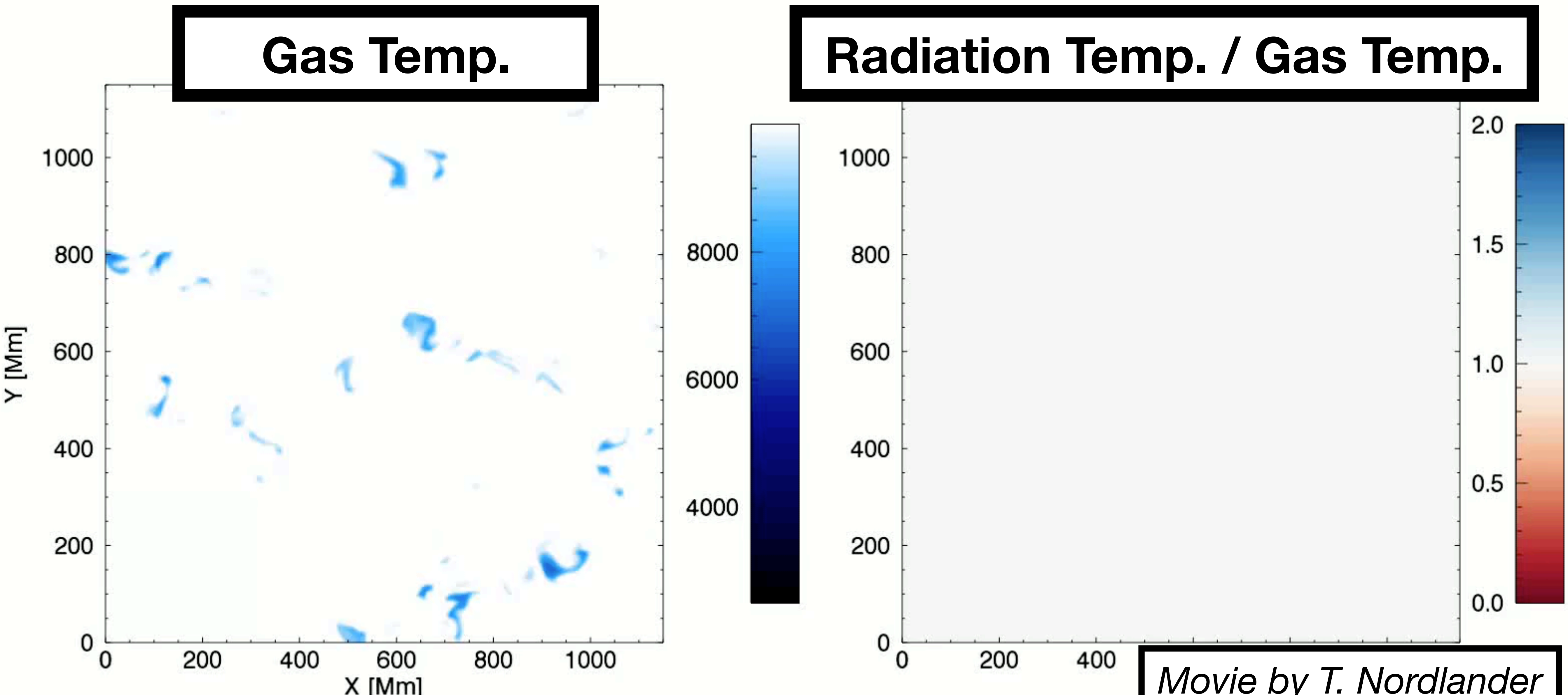
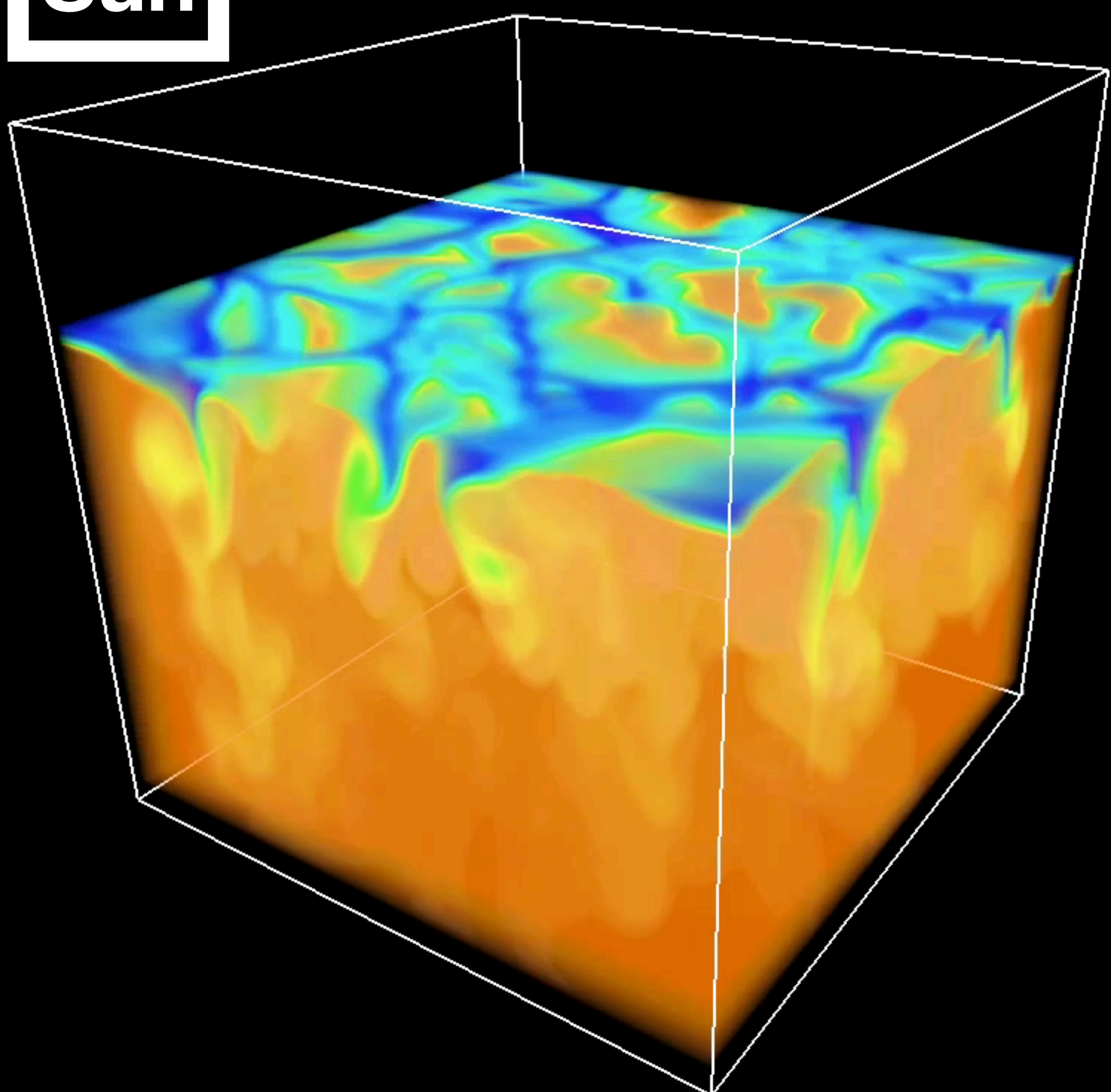


- Non-thermal radiation field
- Variation with granulation features ➡ **3D non-LTE**

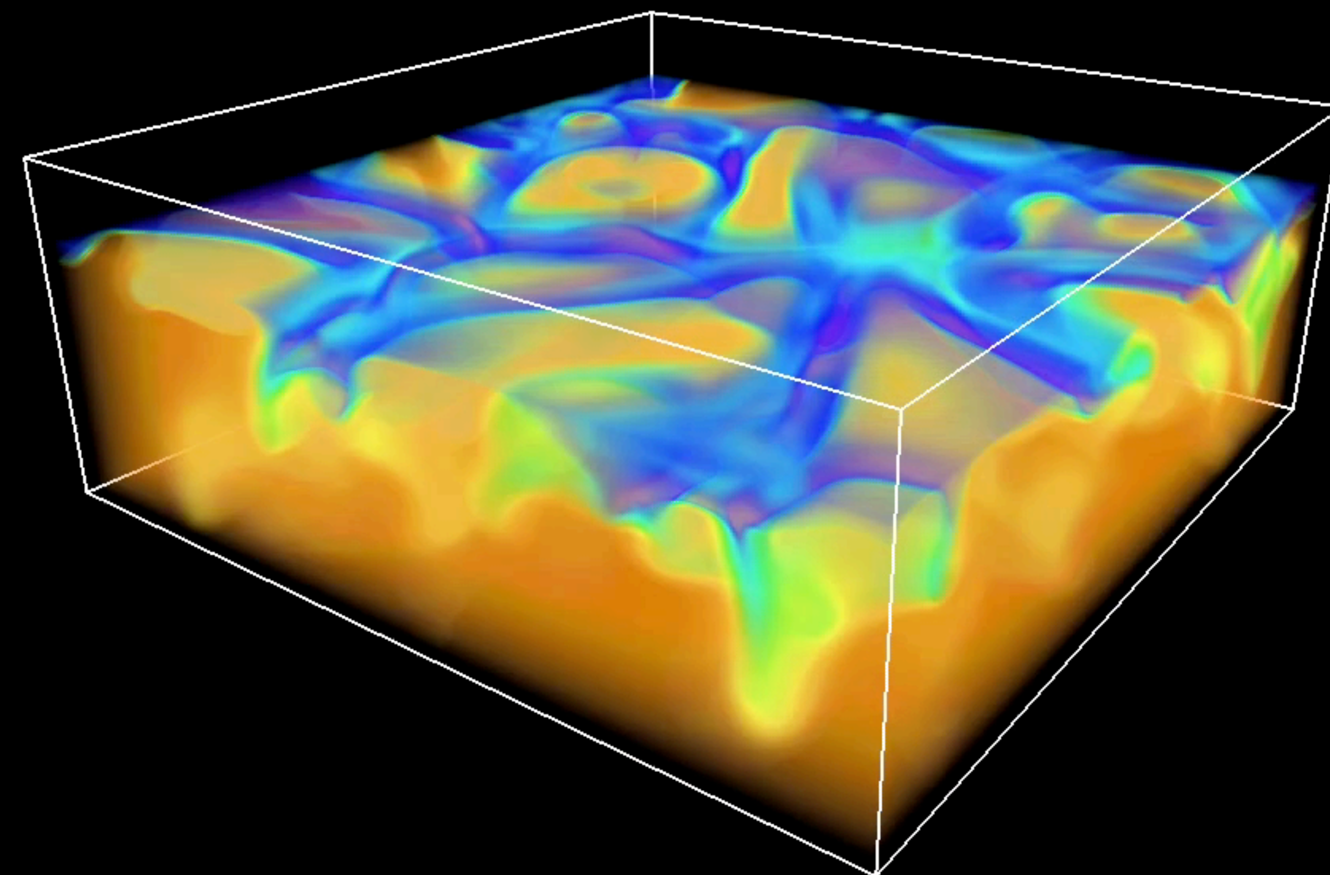
Codes

STAGGER

Sun



Sub-giant

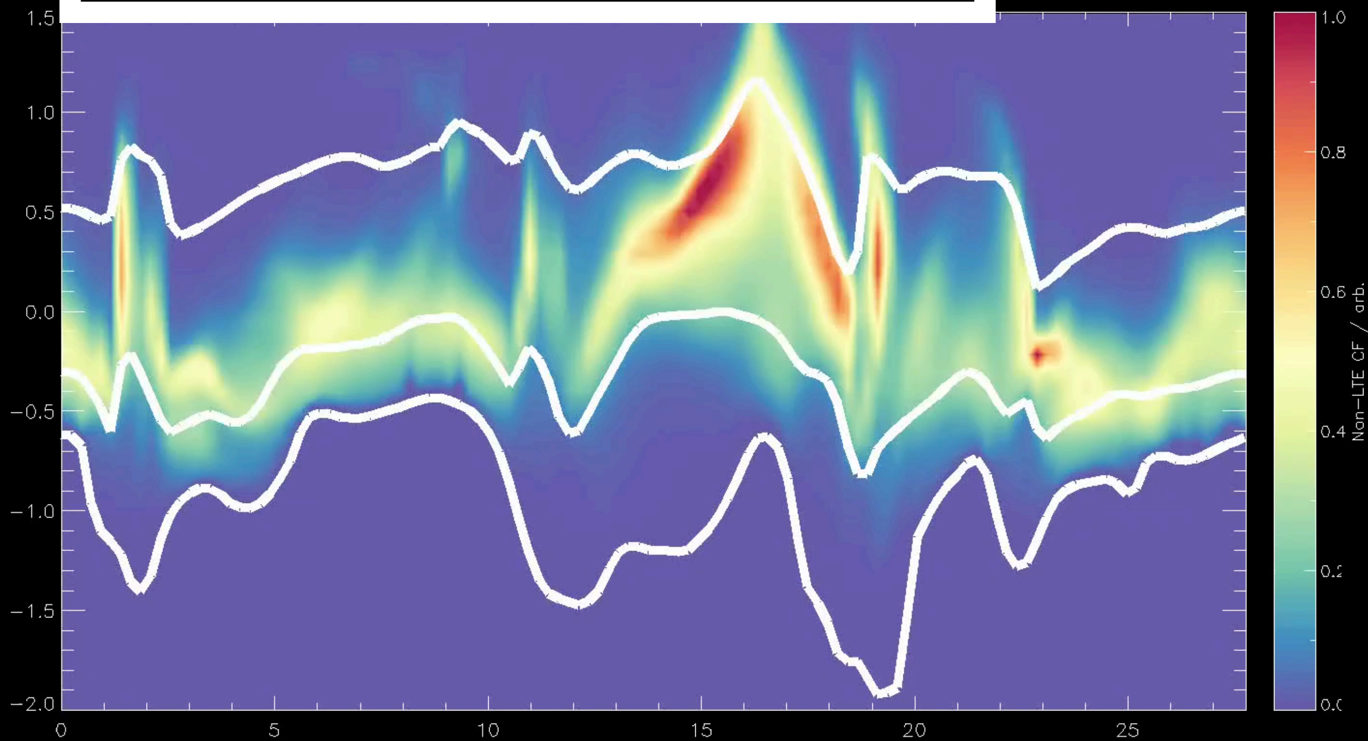


Movies by R. Collet

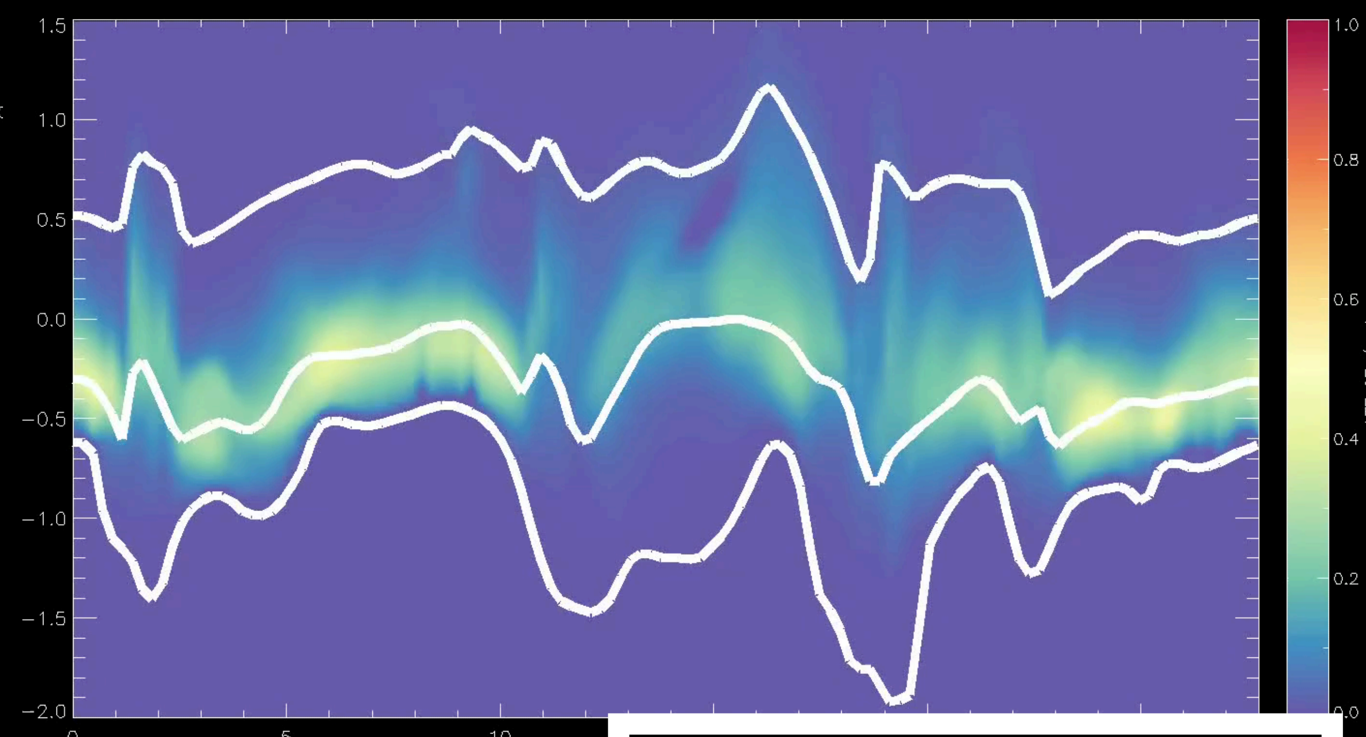
- 3D (magneto-)hydrodynamics
- 3D LTE radiative transfer with opacity binning

BALDER

Non-LTE contribution



- 3D multi-level non-LTE radiative transfer
- MALI preconditioning (R&H 1992)



LTE contribution

- Updated background opacities
- Efficient MPI parallelisation

Results: solar abundances

Why care about the Sun?

- Only understand **other stars** as well as one understands **the Sun**
- **Solar abundances**
  - Key ingredient in solar/stellar/galactic models
  - **Yardstick** for understanding the cosmos
- Benchmark for spectroscopic models

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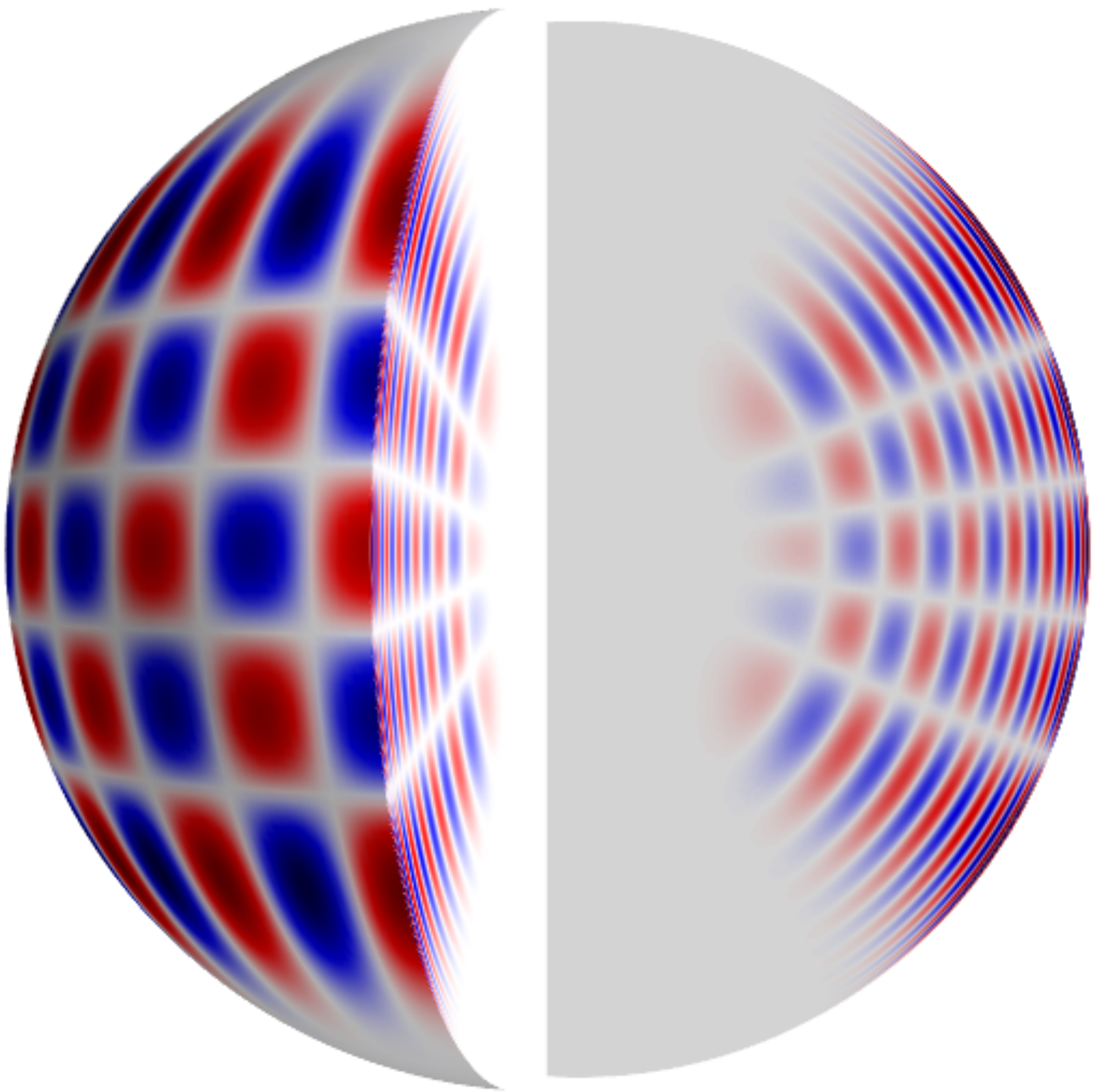
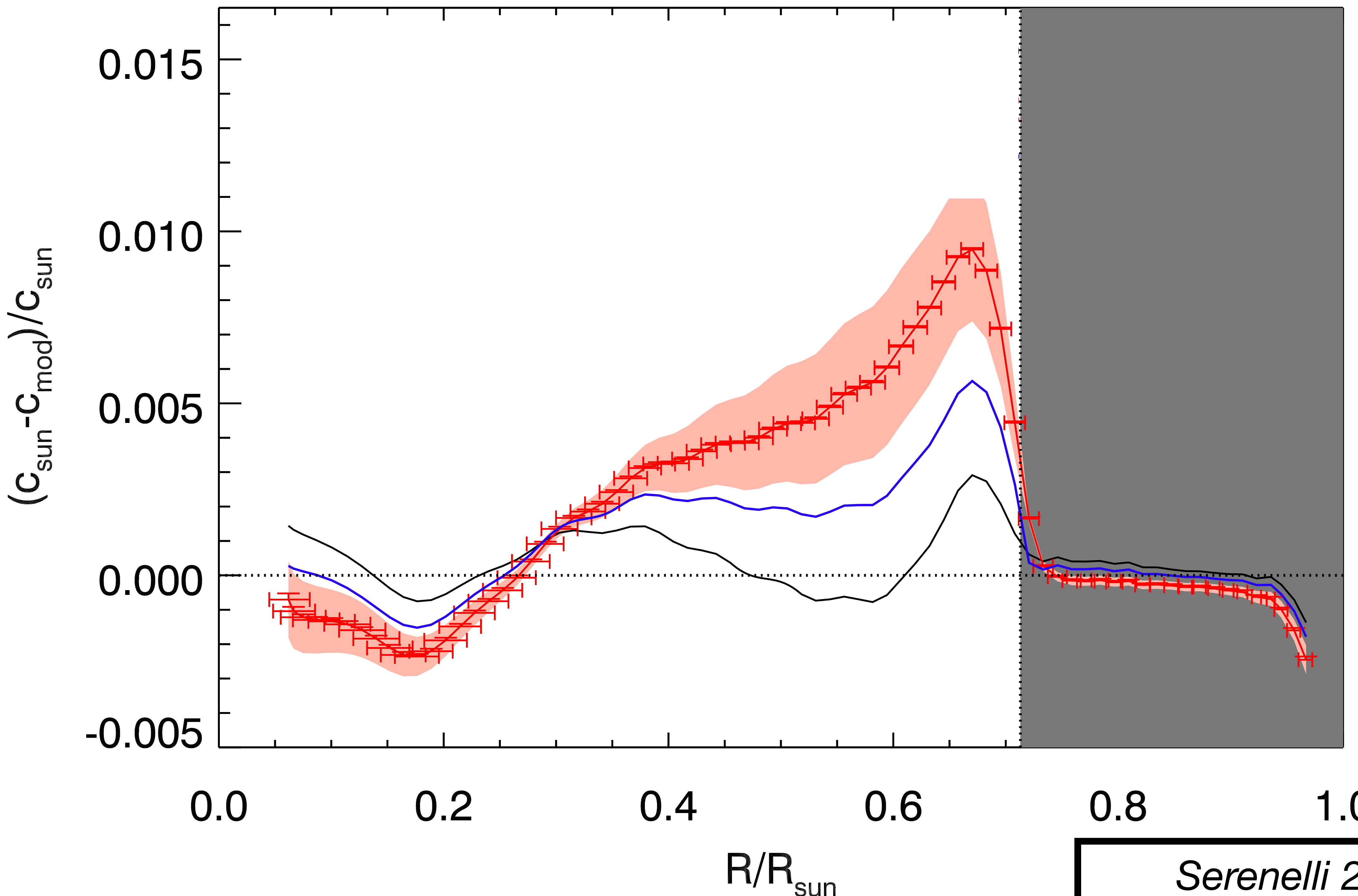
New physics via solar analyses
//
Improved abundances of all stars

Solar modelling problem



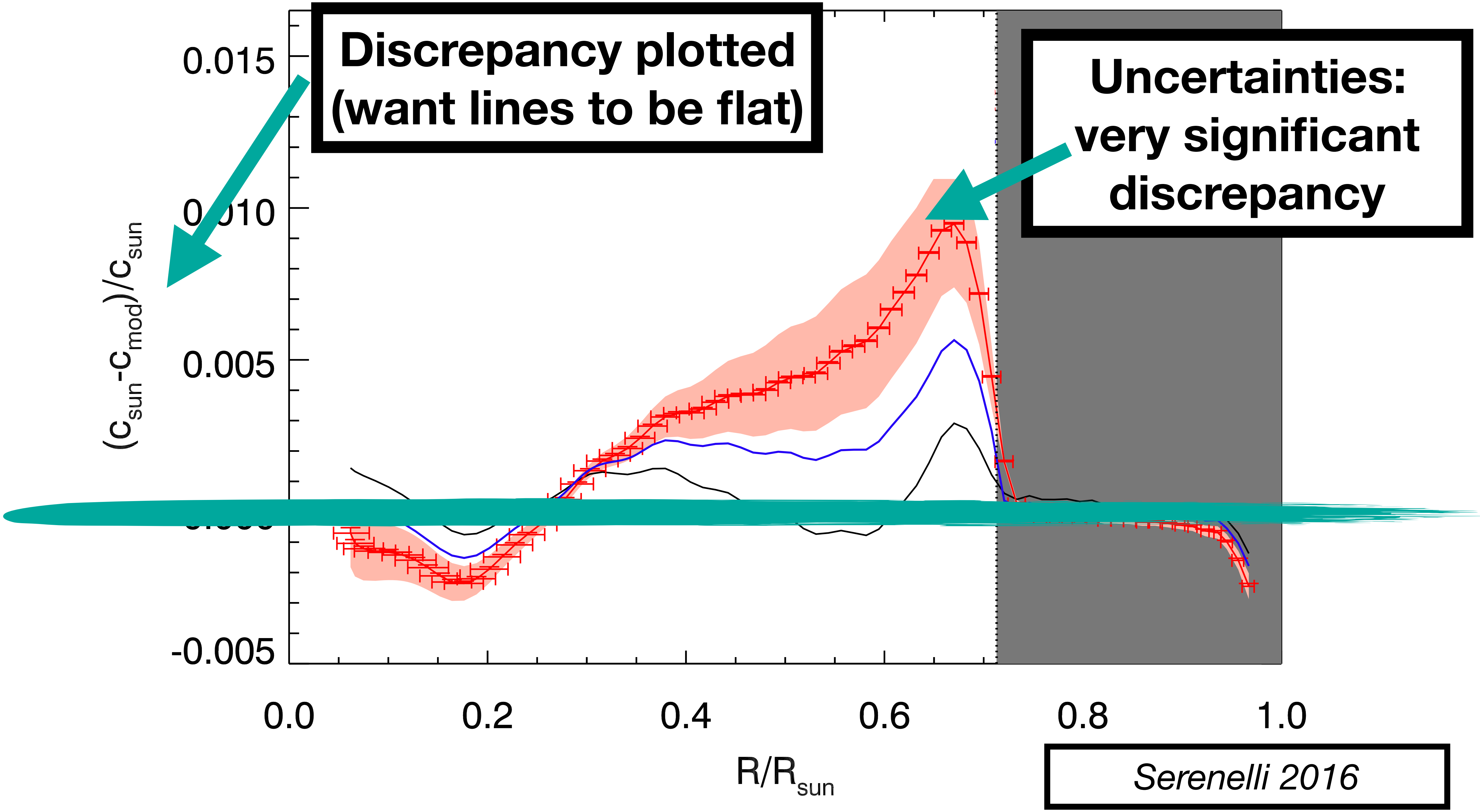
- Take a **standard solar interior model** based on spectroscopic abundances
- Compare against **helioseismic** measurements
- Disagree on structure of the solar interior (**sound speed**)

Interior sound speed

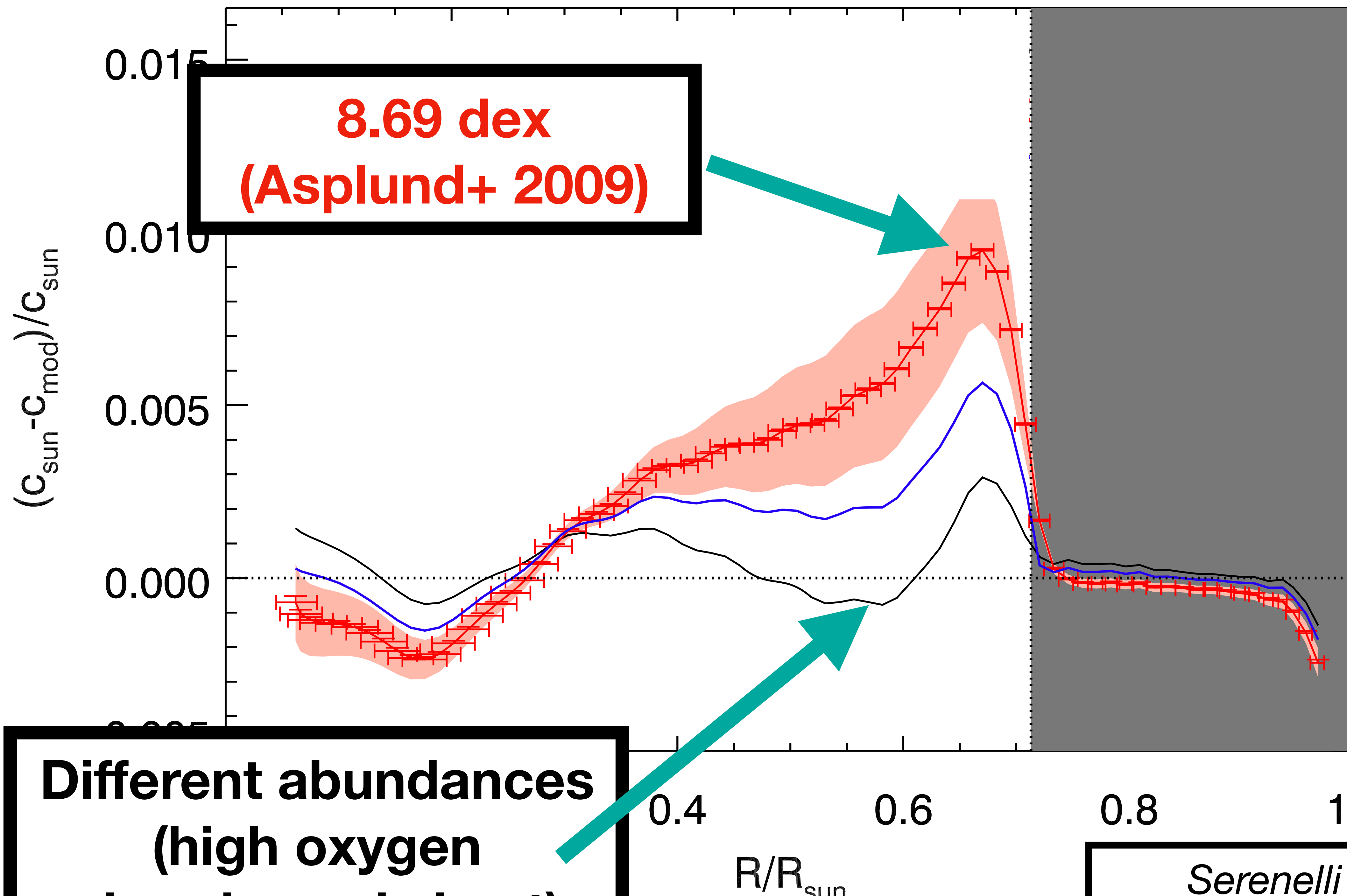


Serenelli 2016

Interior sound speed



Interior sound speed



8.69 dex (Asplund+ 2009)

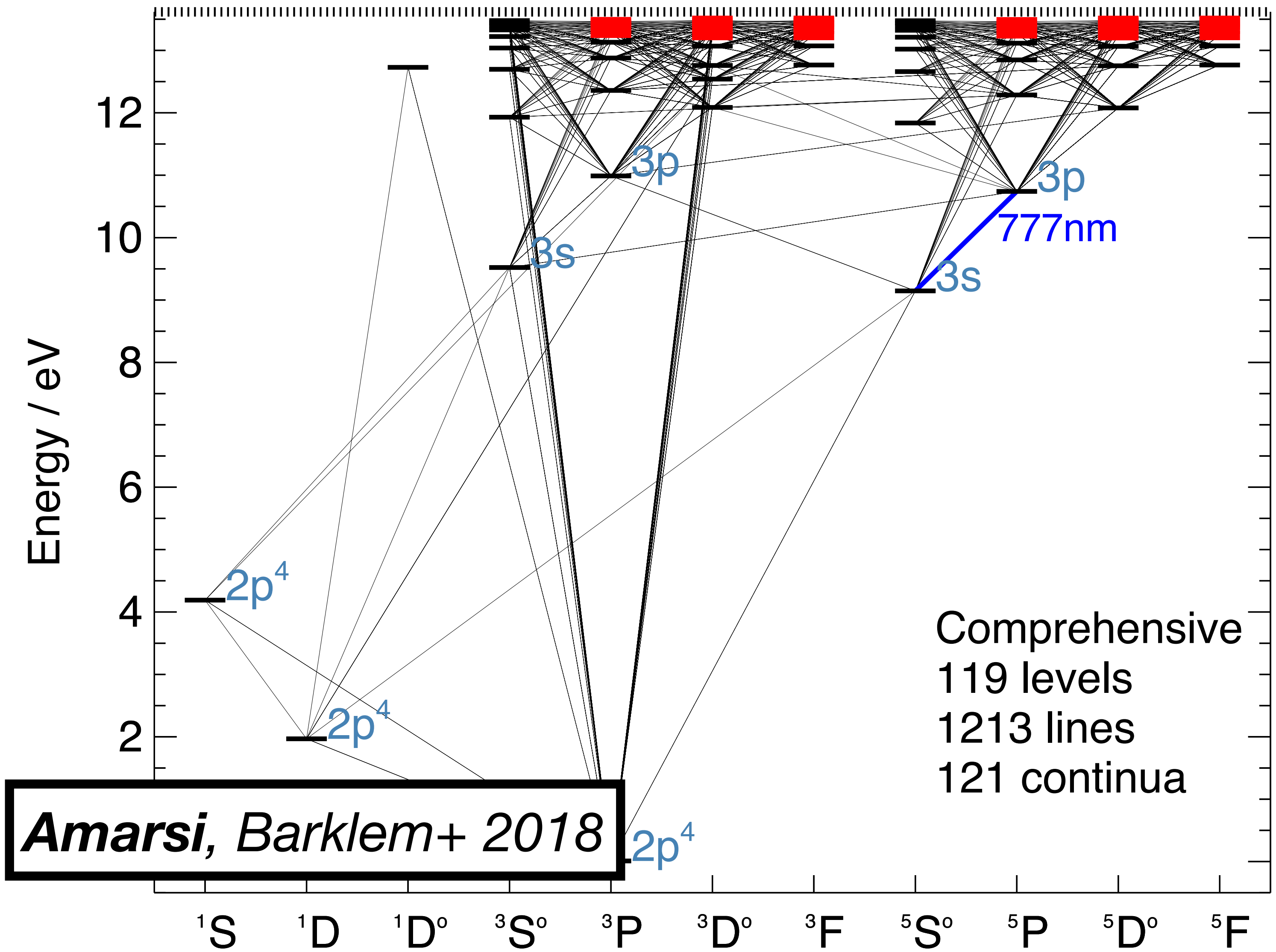
Different abundances (high oxygen abundance is best)

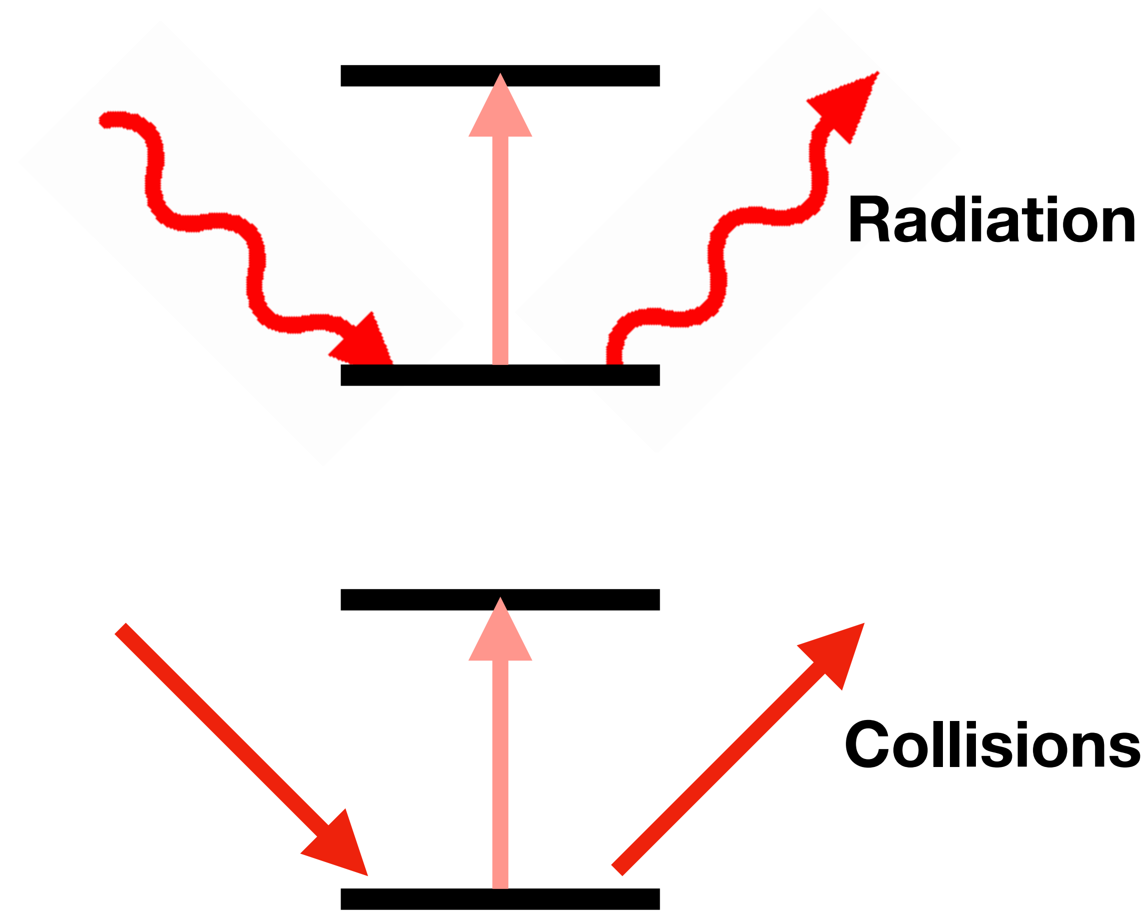
Serenelli 2016

Solar modelling problem

- Problem is largest at base of convection zone
- Missing solar interior physics (extra mixing)?
- Missing **interior opacities** (Opacity Project / OPAL)?
- Too low **oxygen** (neon, iron, carbon, …) **abundances**?
  - O, Ne, C are depleted in meteorites
  - Scrutinise **non-LTE models** of carbon and oxygen

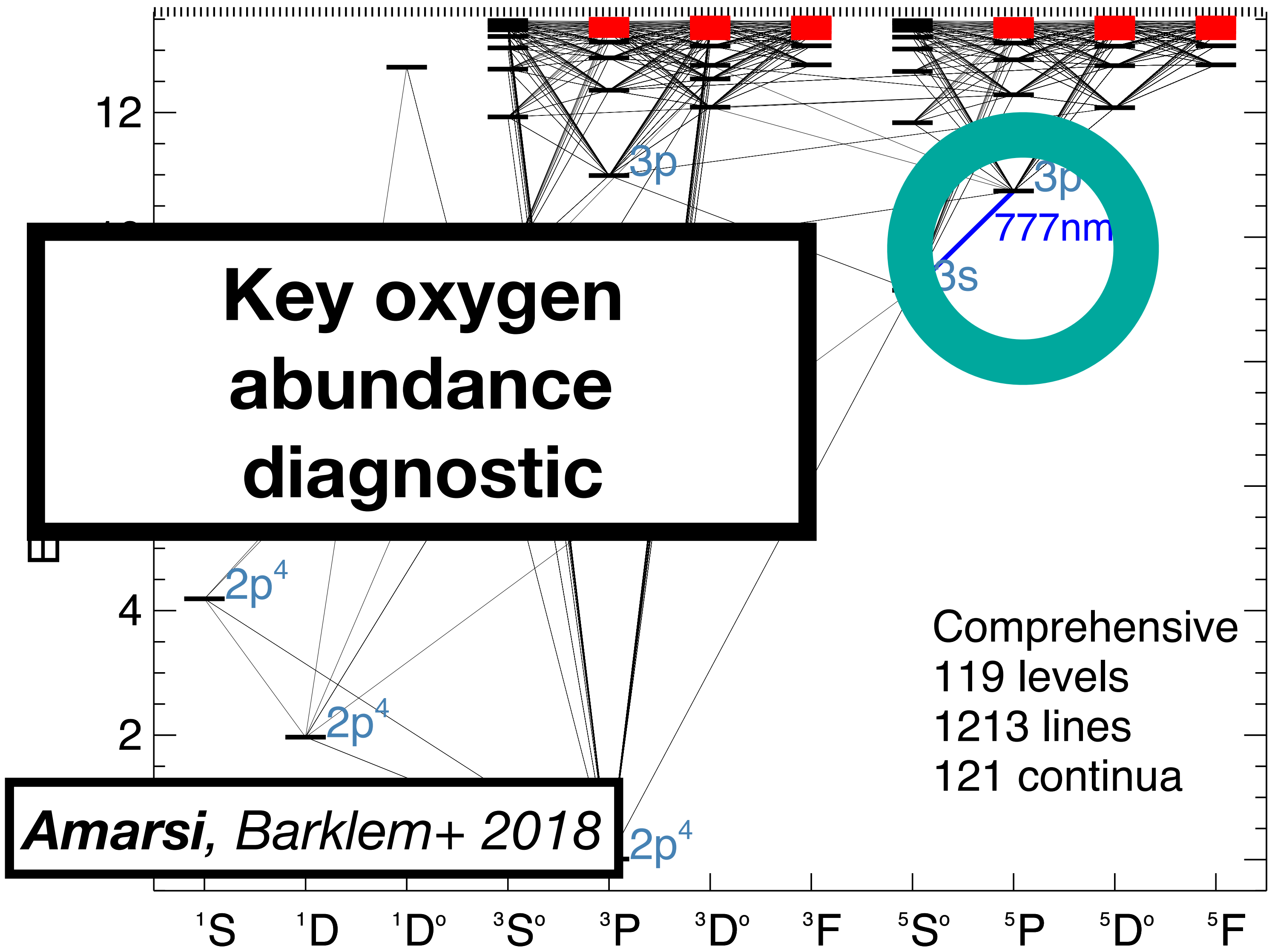
Non-LTE model atoms

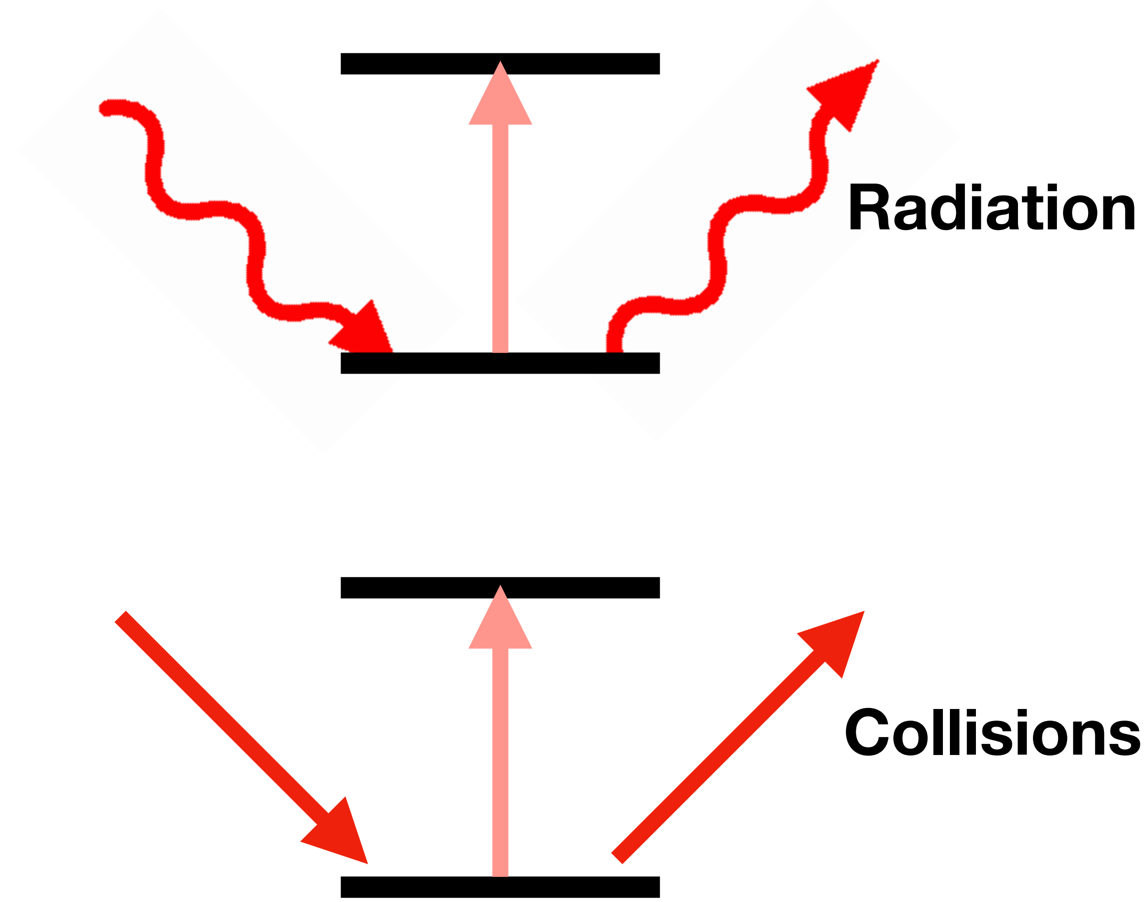




- Improved **atomic data** and **realistic model atoms**
- New: **first principles** inelastic X+H collisions

Non-LTE model atoms





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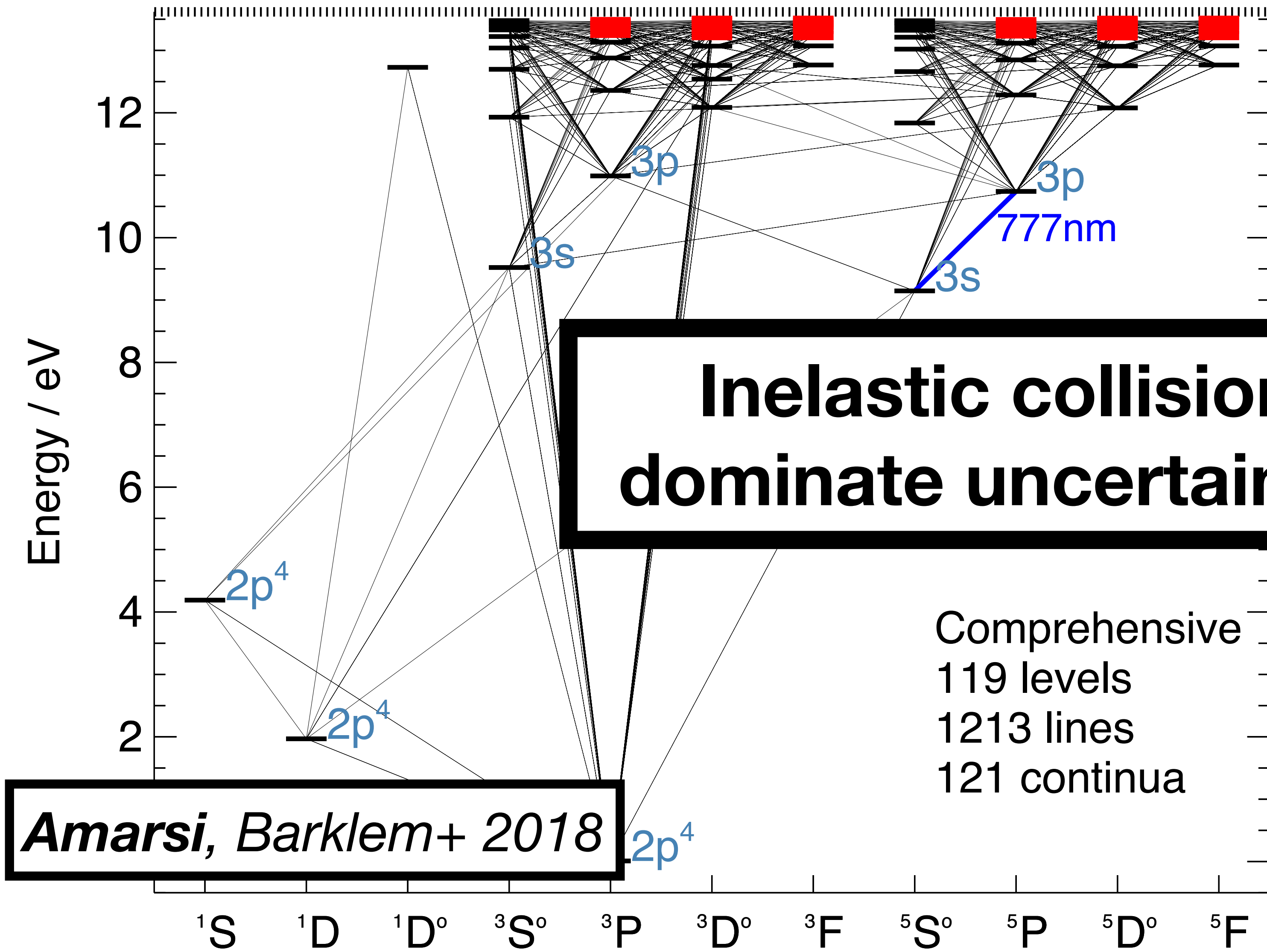
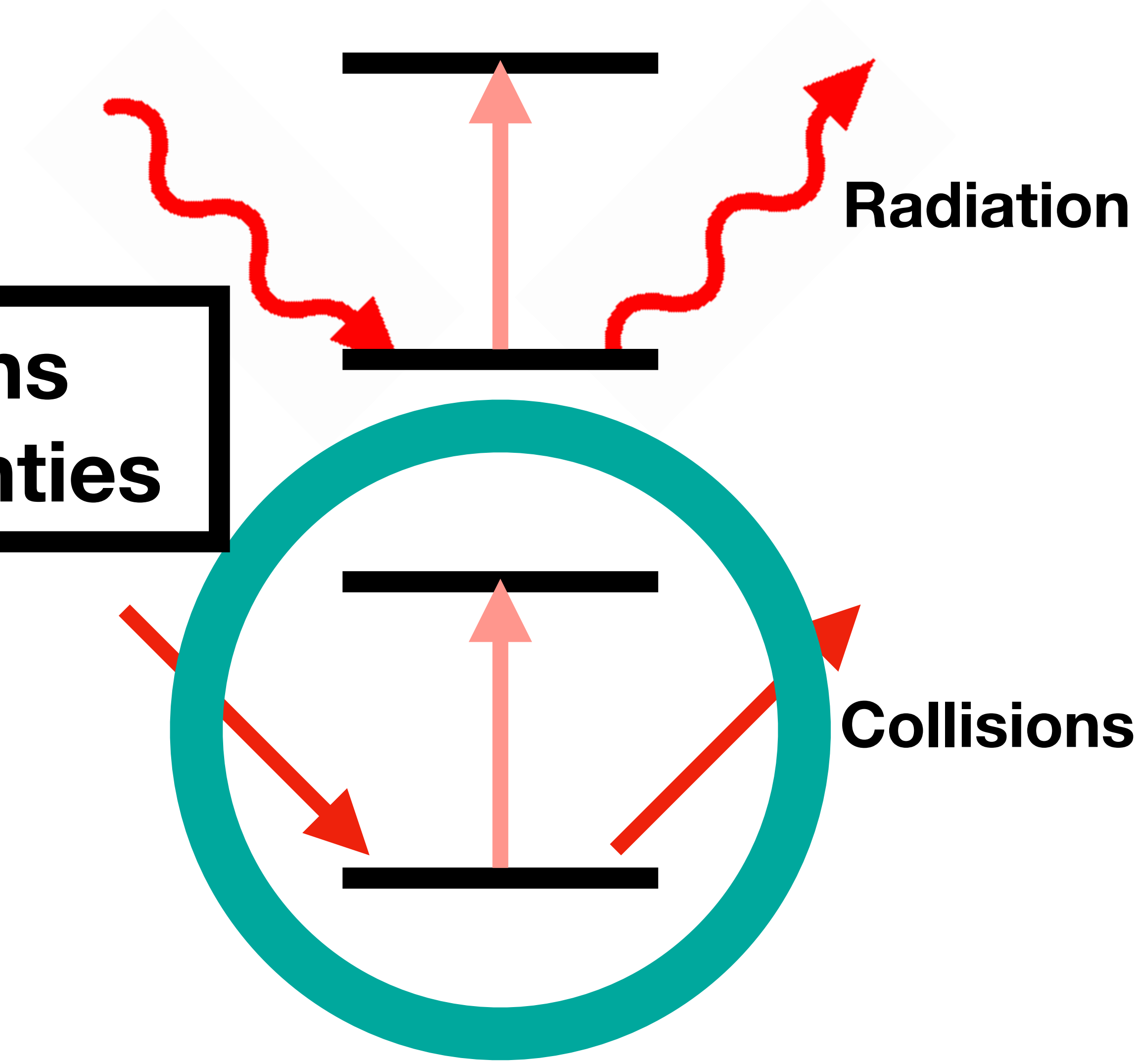


***Amarsi**, Barklem+ 2018*

Inelastic collisions dominate uncertainties



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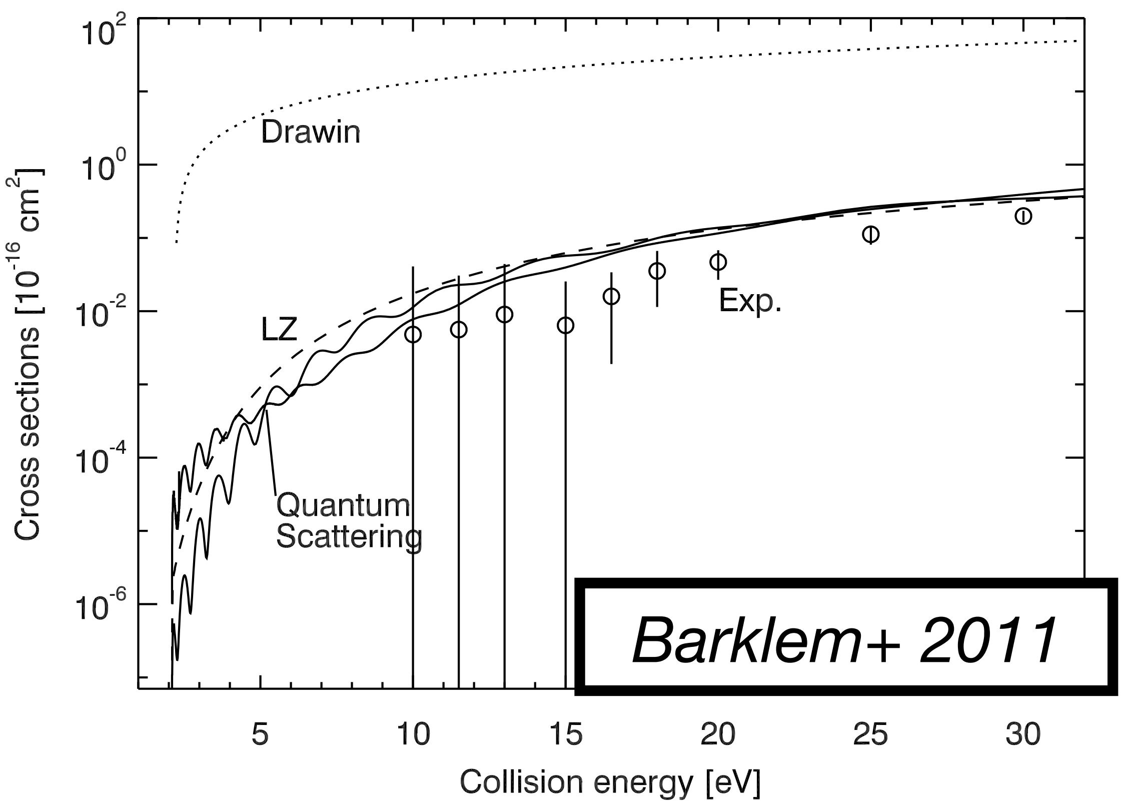
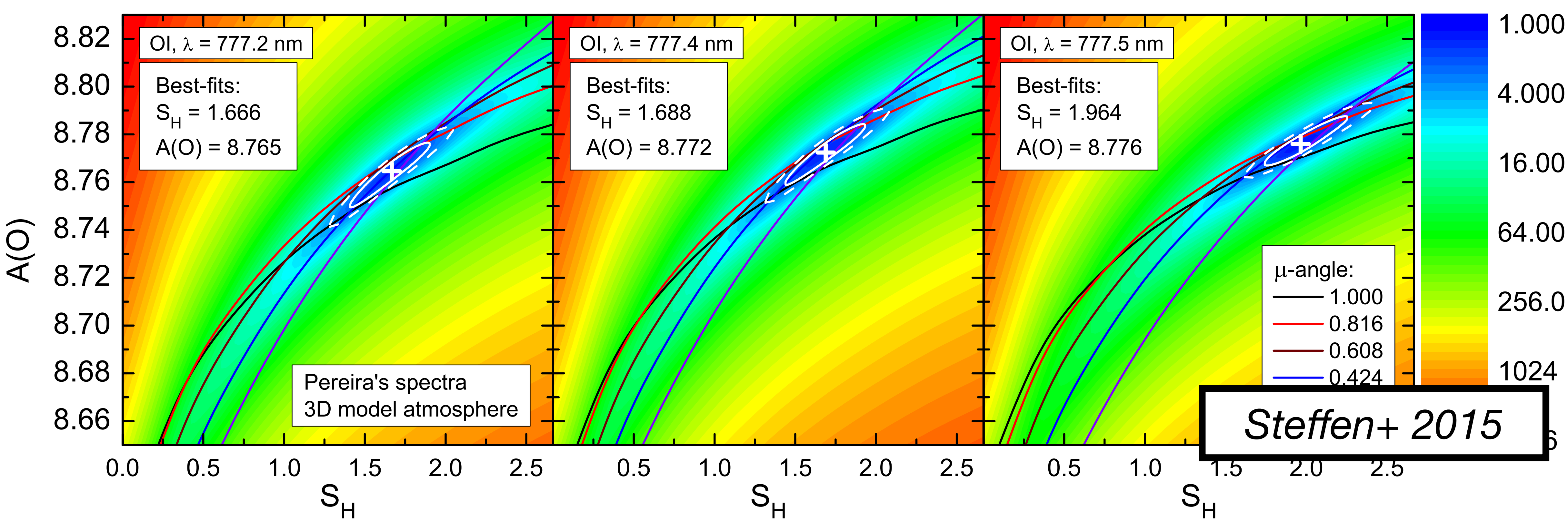
Inelastic O+H collisions



- Previous work: **calibrated** Drawin collisions (unreliable)
- This work: calculate collisions from **first principles** (see papers by Paul Barklem, Andrey Belyaev)



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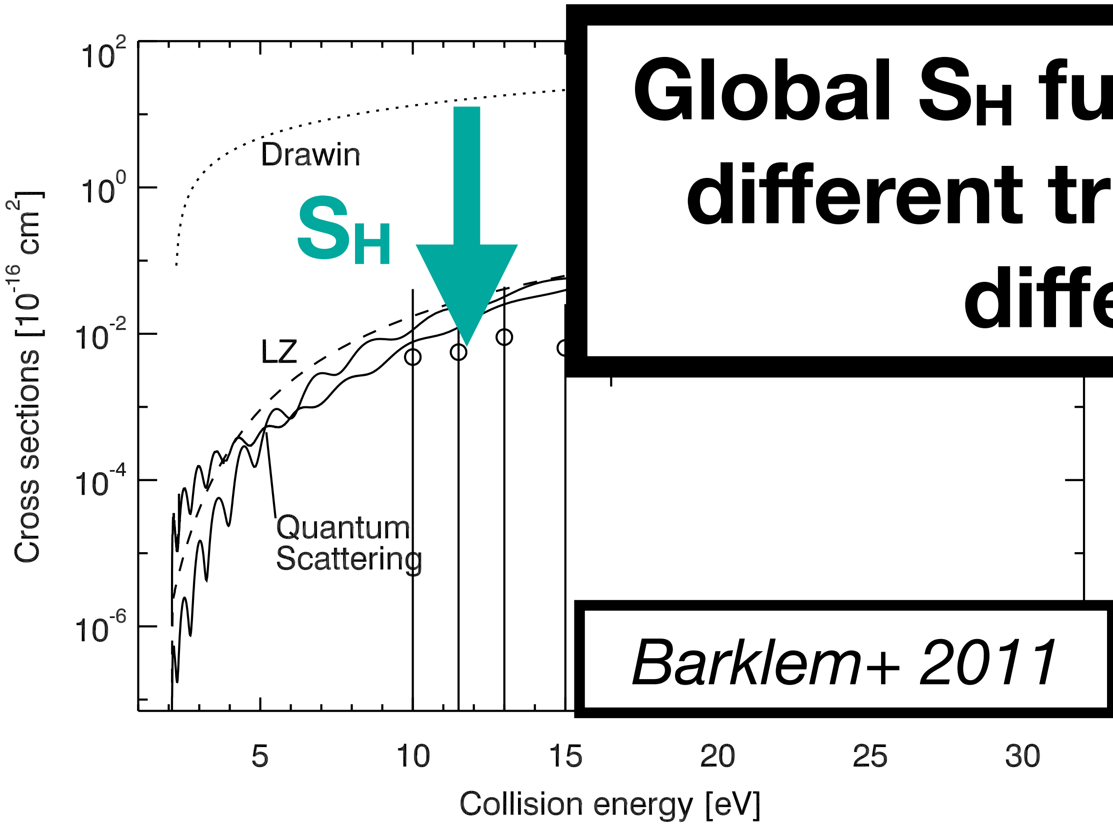

Global S_H fudge factor…but different transitions need different S_H

… **calibrated** Drawin … eliable)

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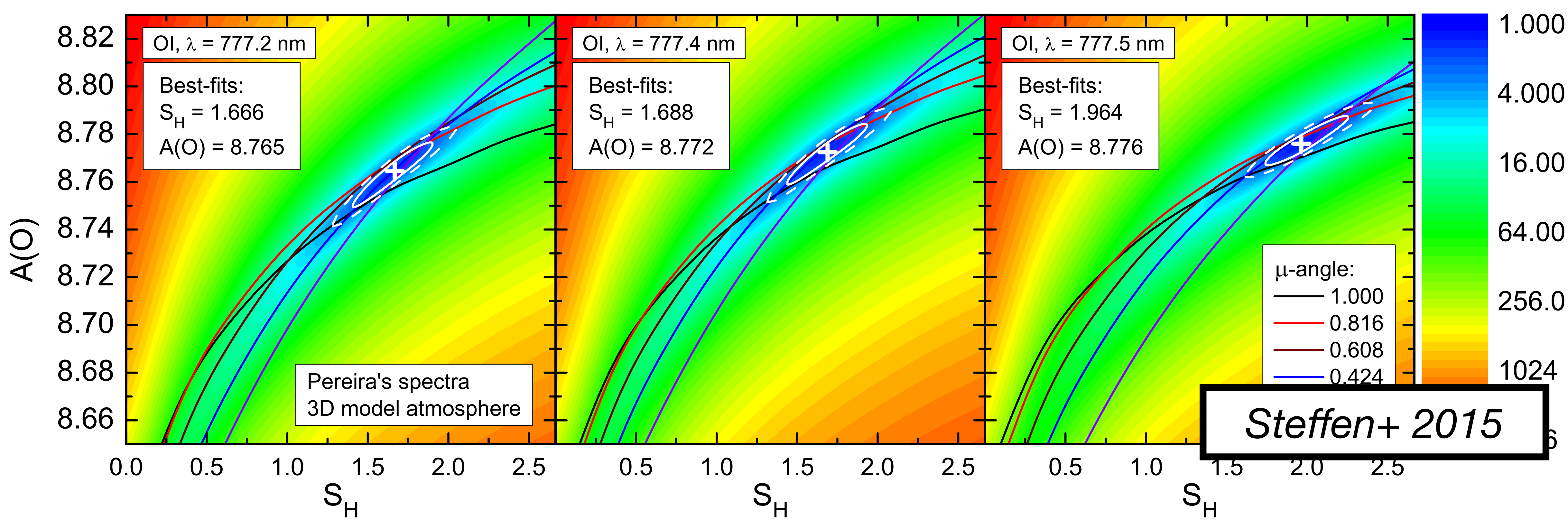

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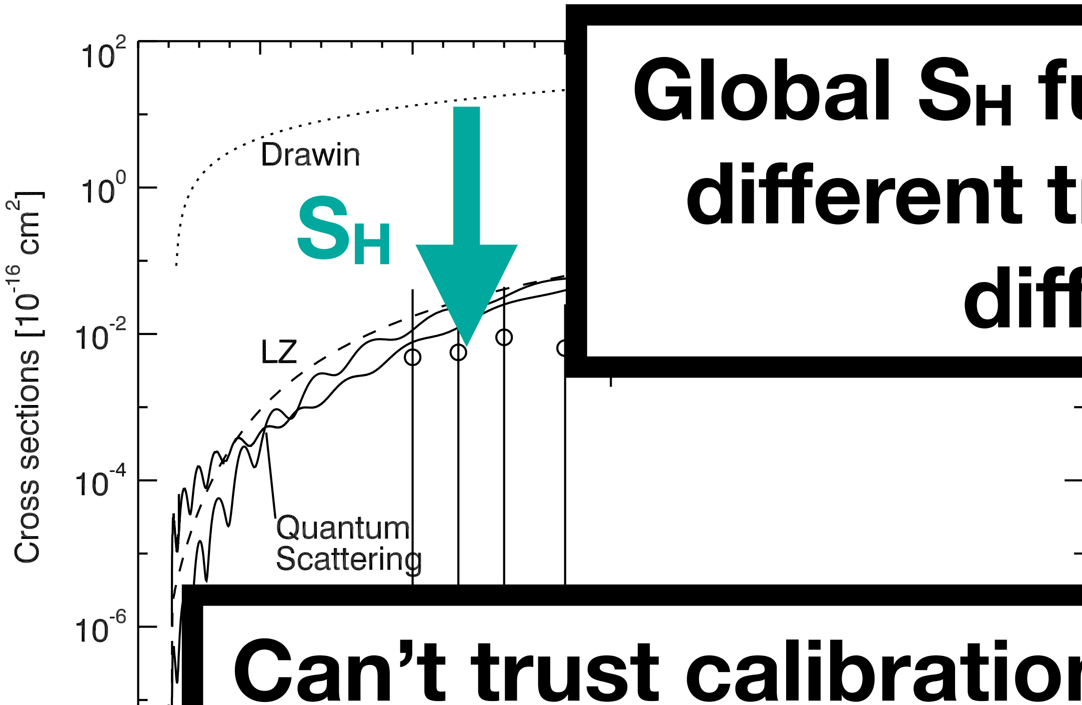

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calibrated Drawin
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Can't trust calibration for stars ≠ Sun

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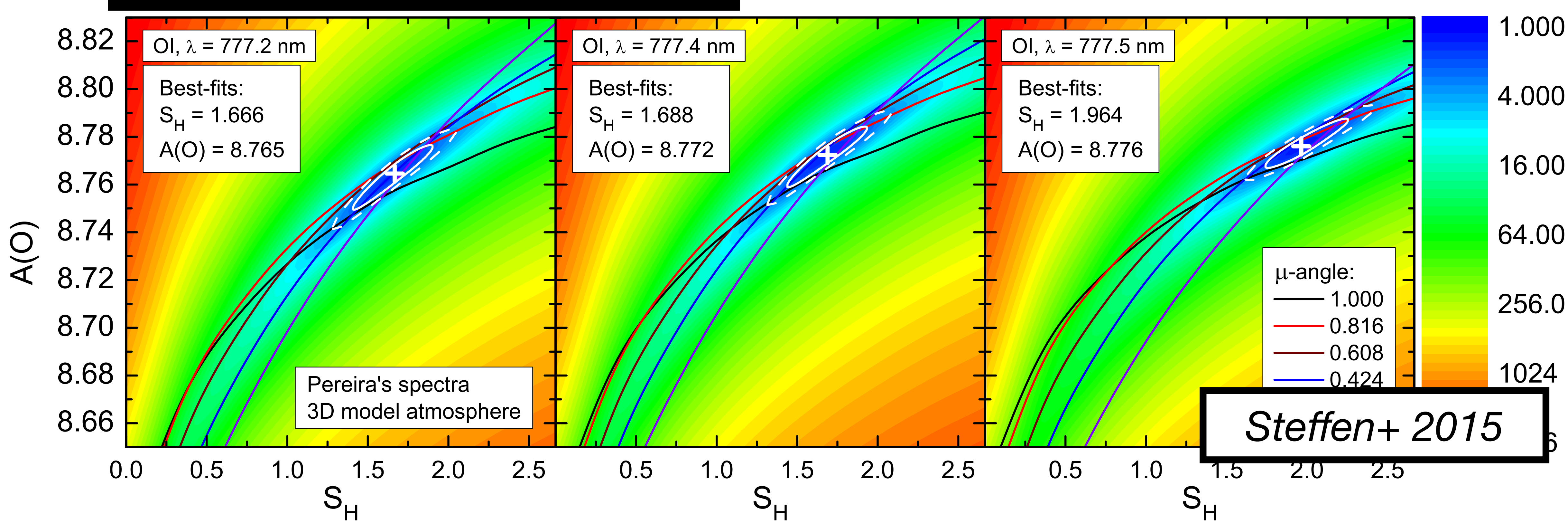
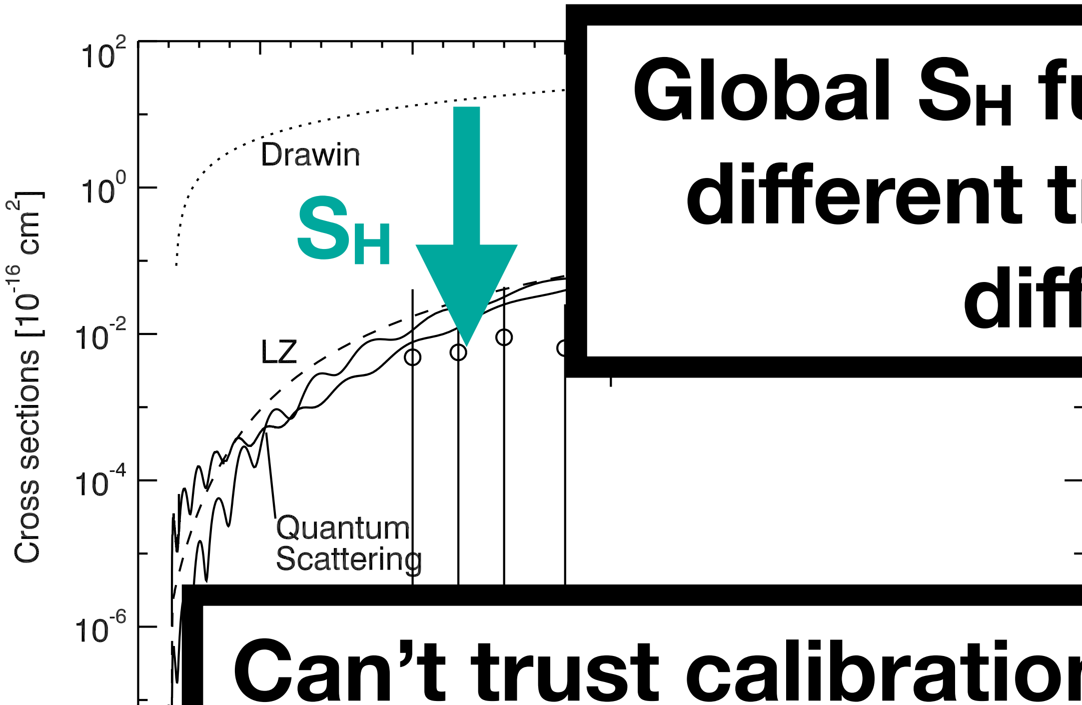


Steffen+ 2015

Inelastic O+H collisions



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S_H

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…eliable)

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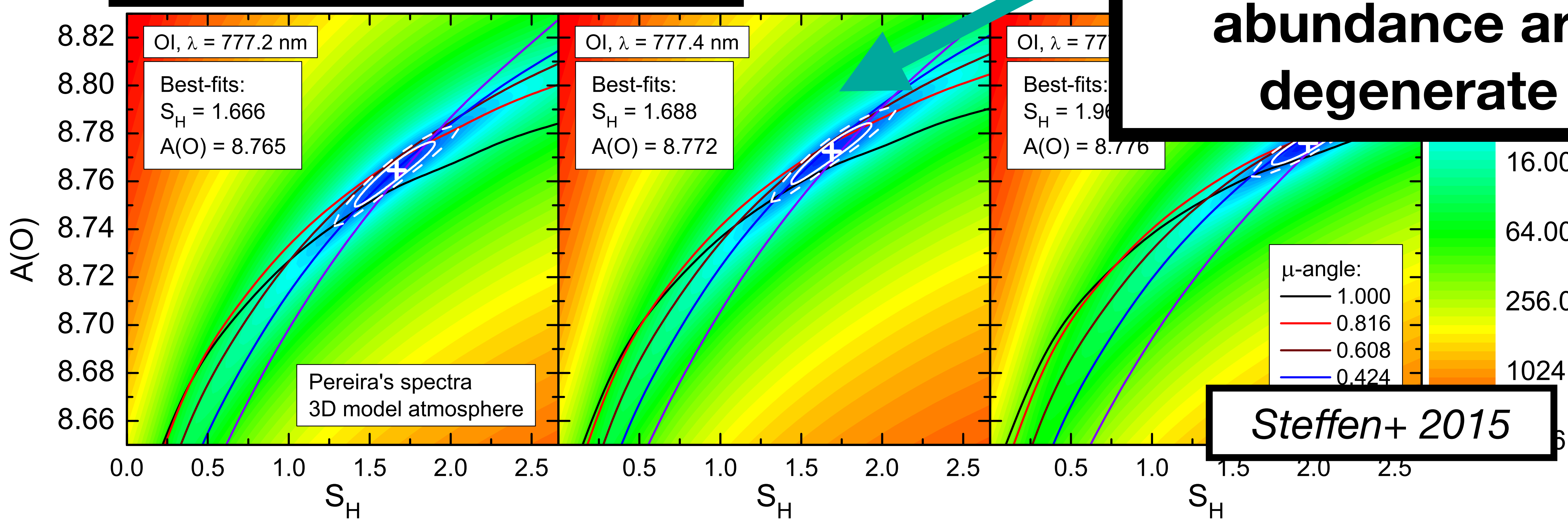
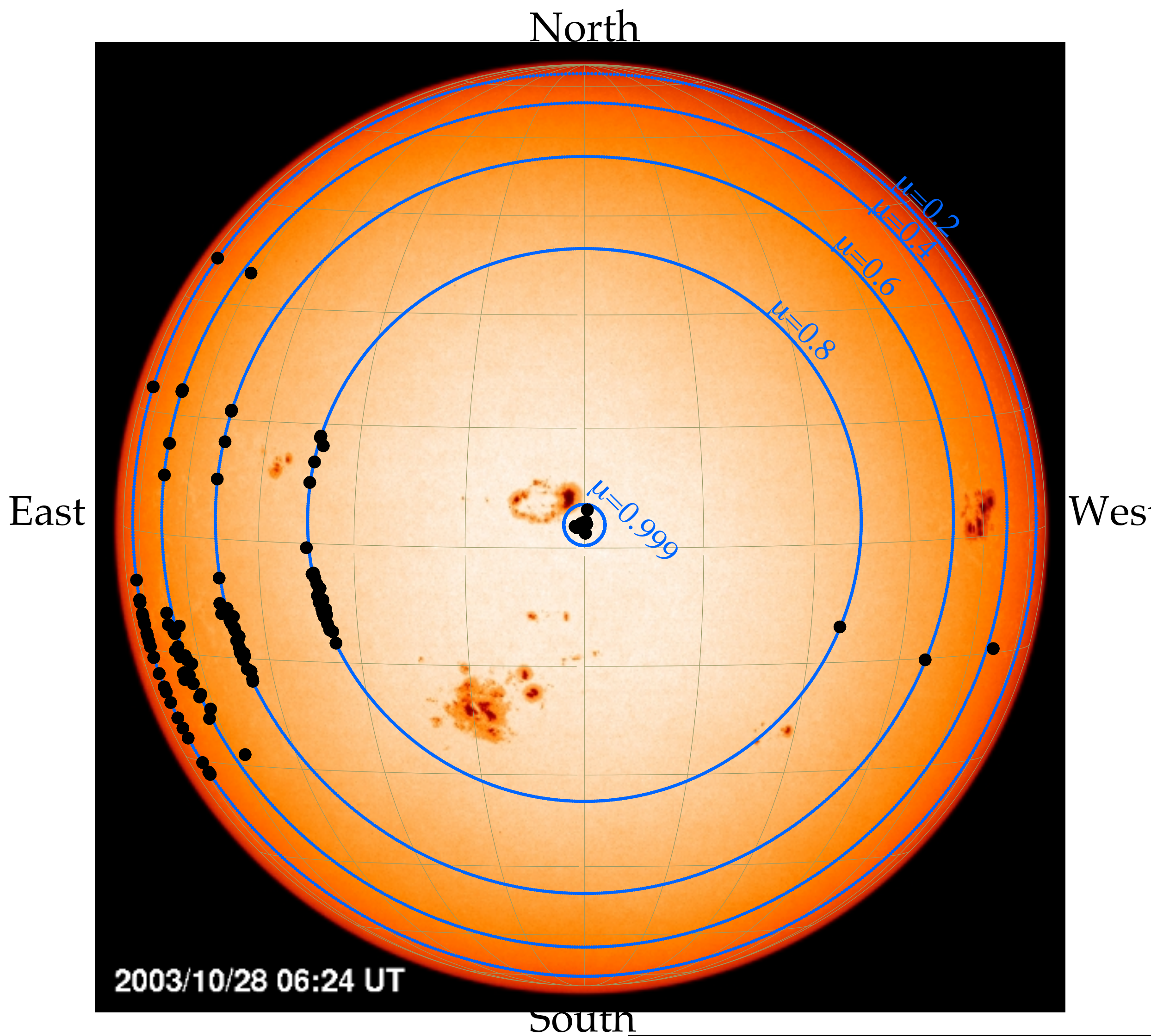
Even for Sun: S_H and abundance are degenerate



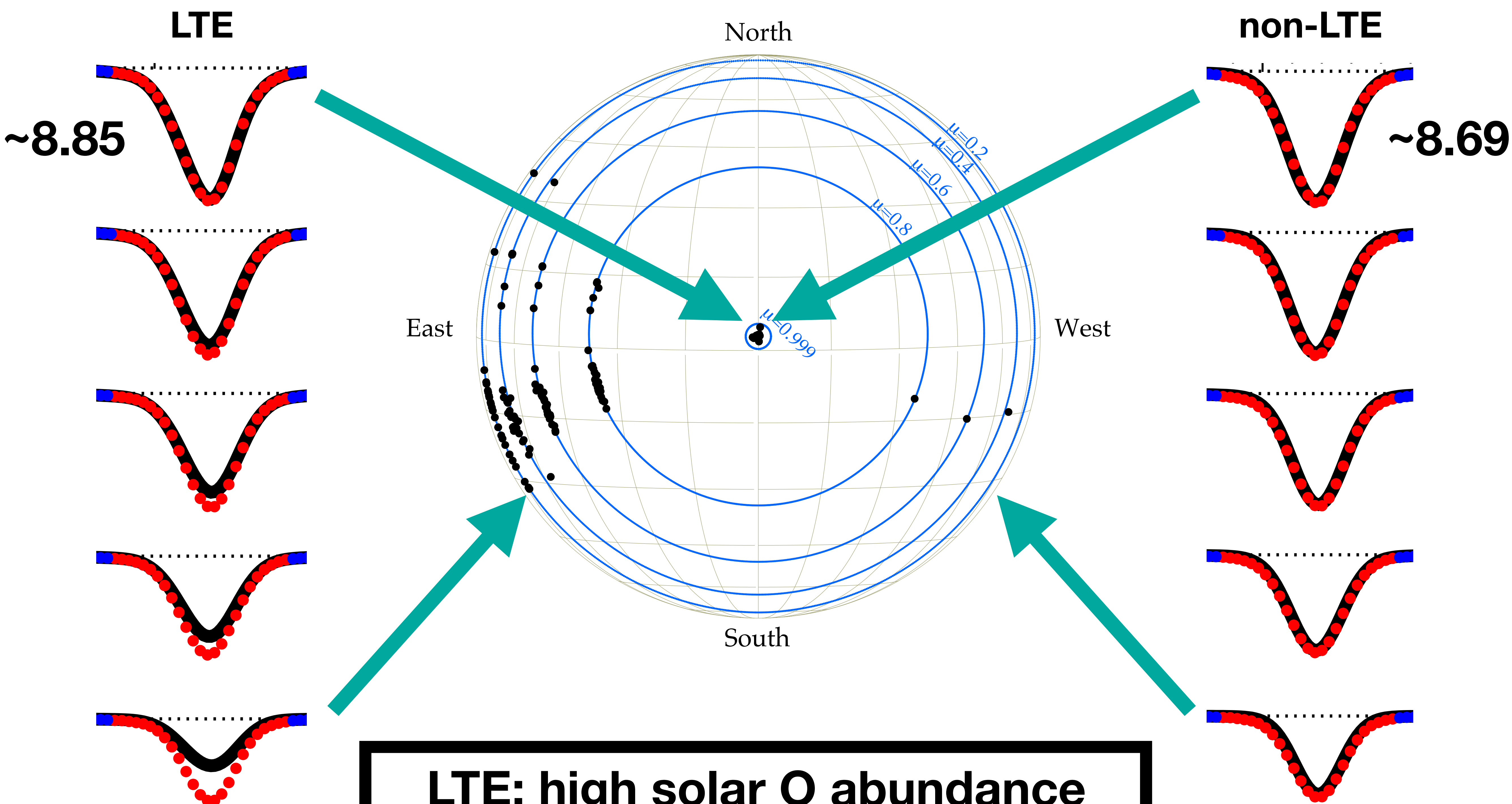
Steffen+ 2015

Centre-to-limb variation



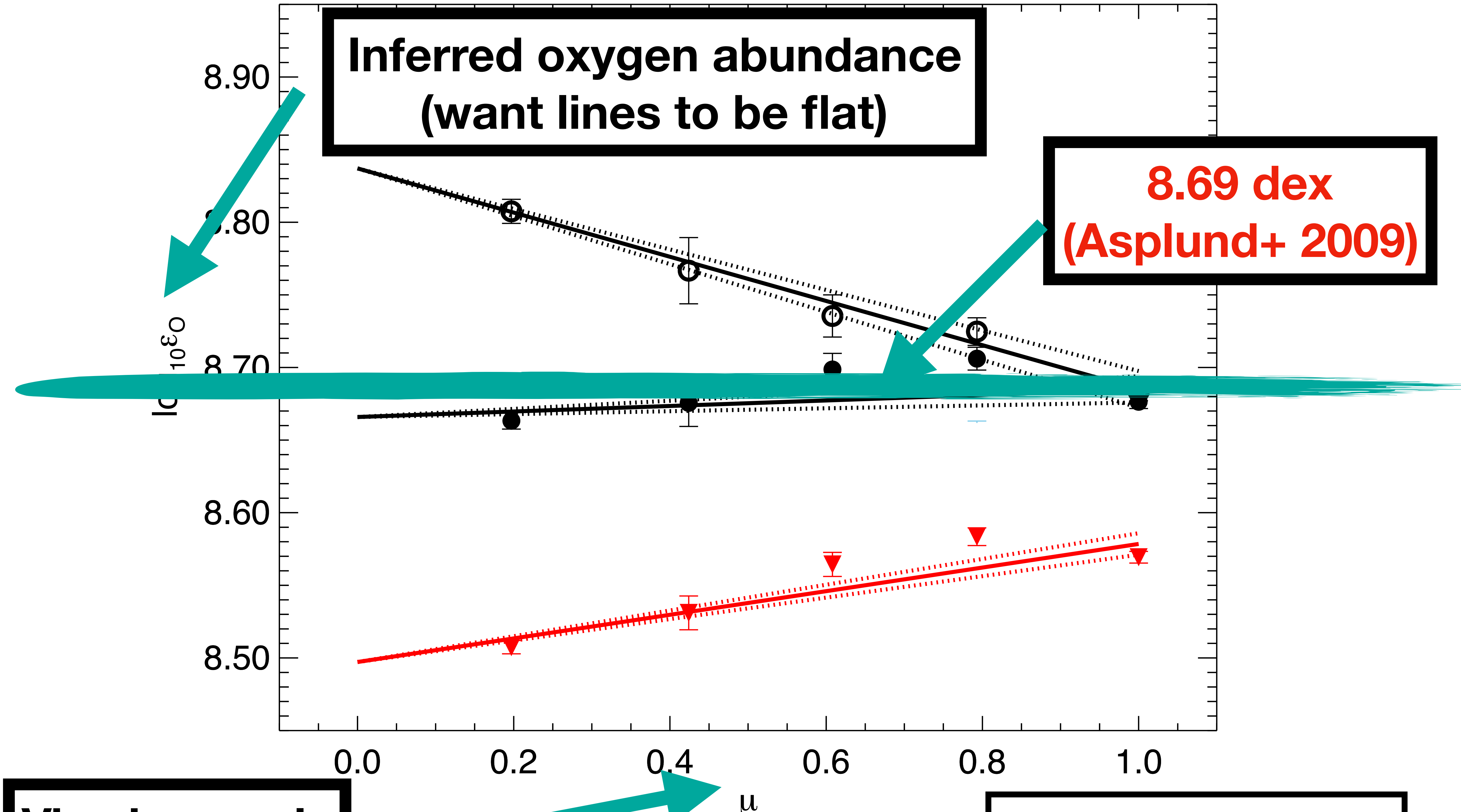
*Contours: Lind, **Amarsi**+ 2017*

Centre-to-limb variation



LTE: high solar O abundance
Non-LTE: low solar O abundance

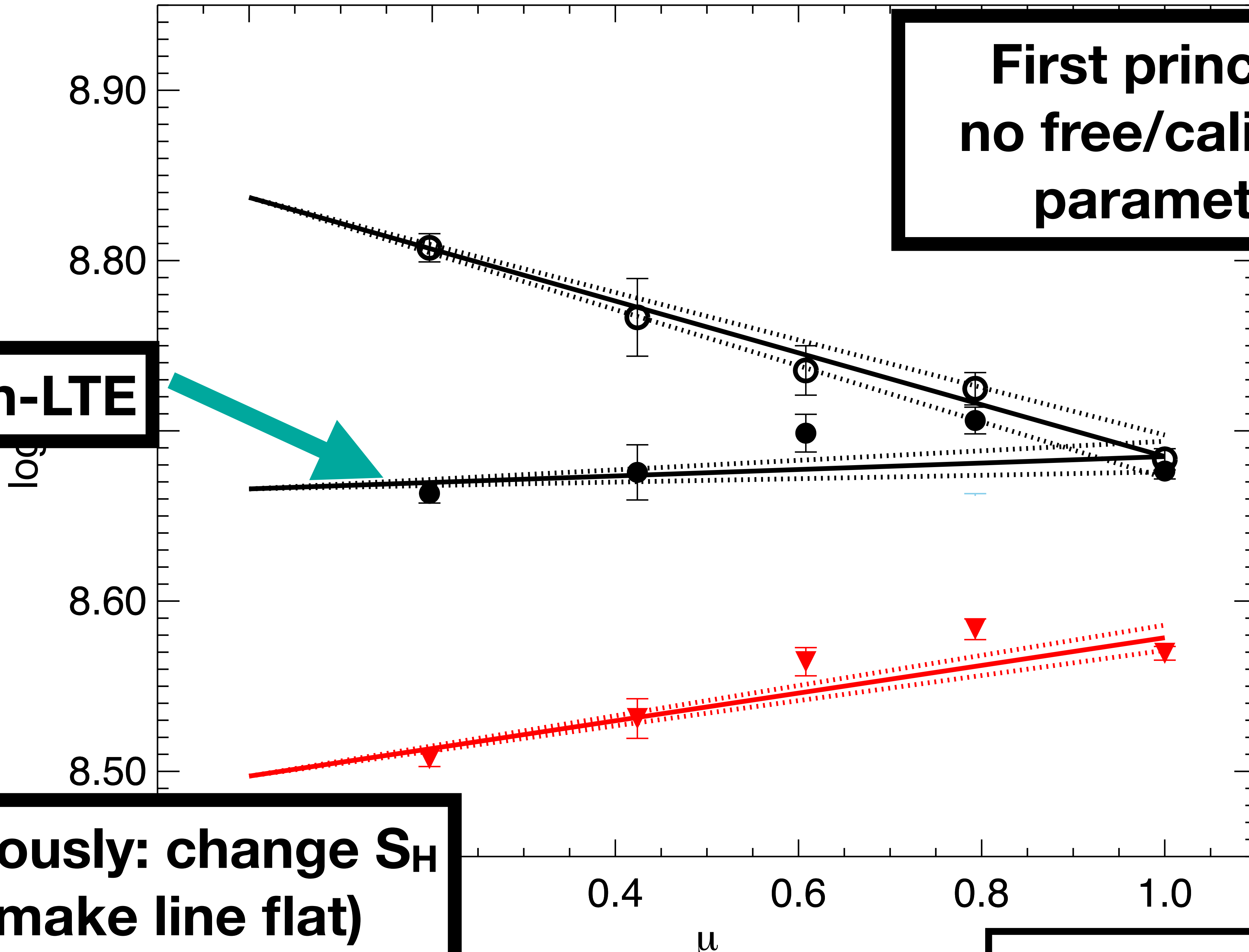
Centre-to-limb variation



Viewing angle

***Amarsi**, Barklem+ 2018*

Centre-to-limb variation



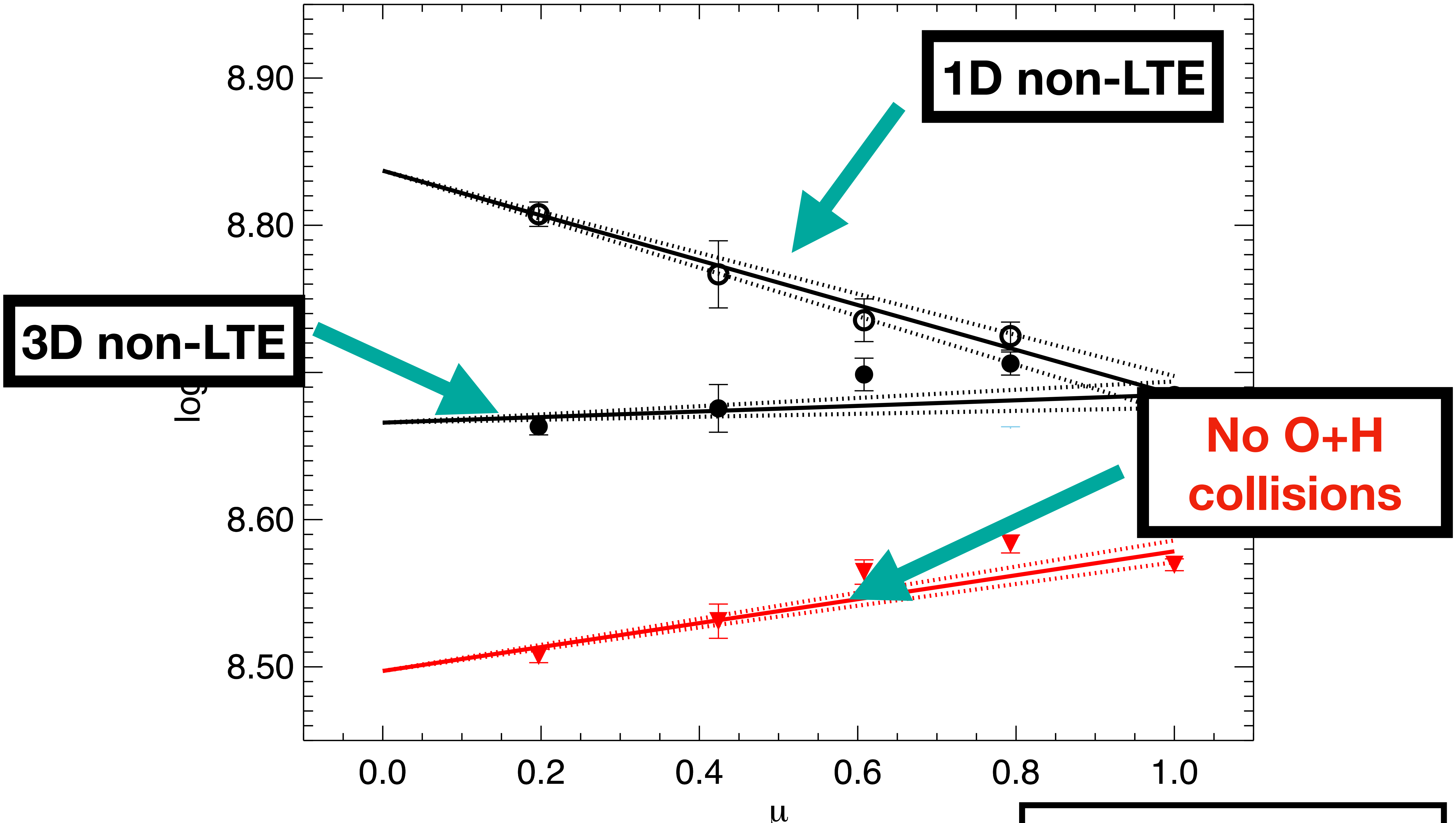
First principles; no free/calibrated parameters!

3D non-LTE

(Previously: change S_H to make line flat)

***Amarsi**, Barklem+ 2018*

Centre-to-limb variation



Amarsi, Barklem+ 2018

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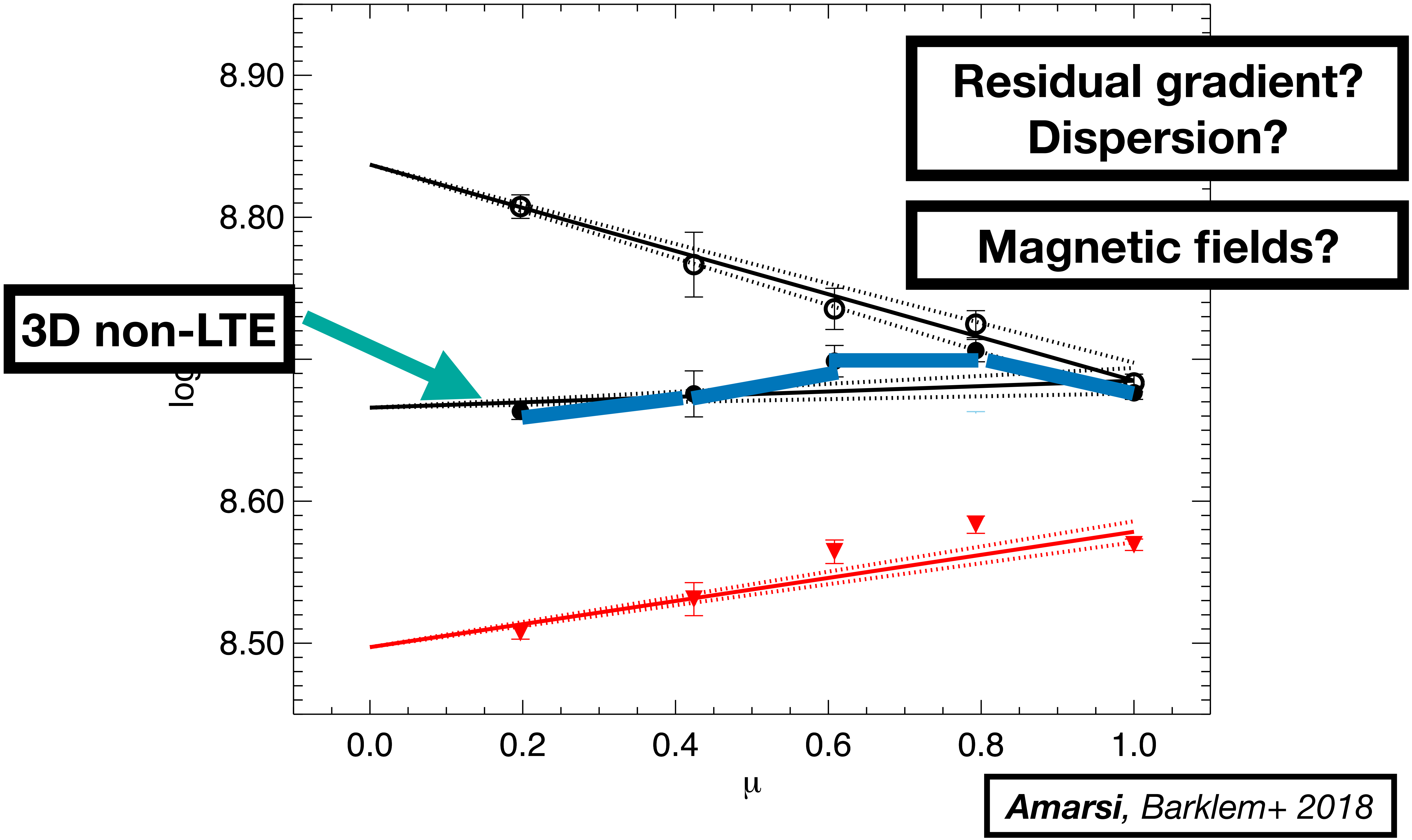
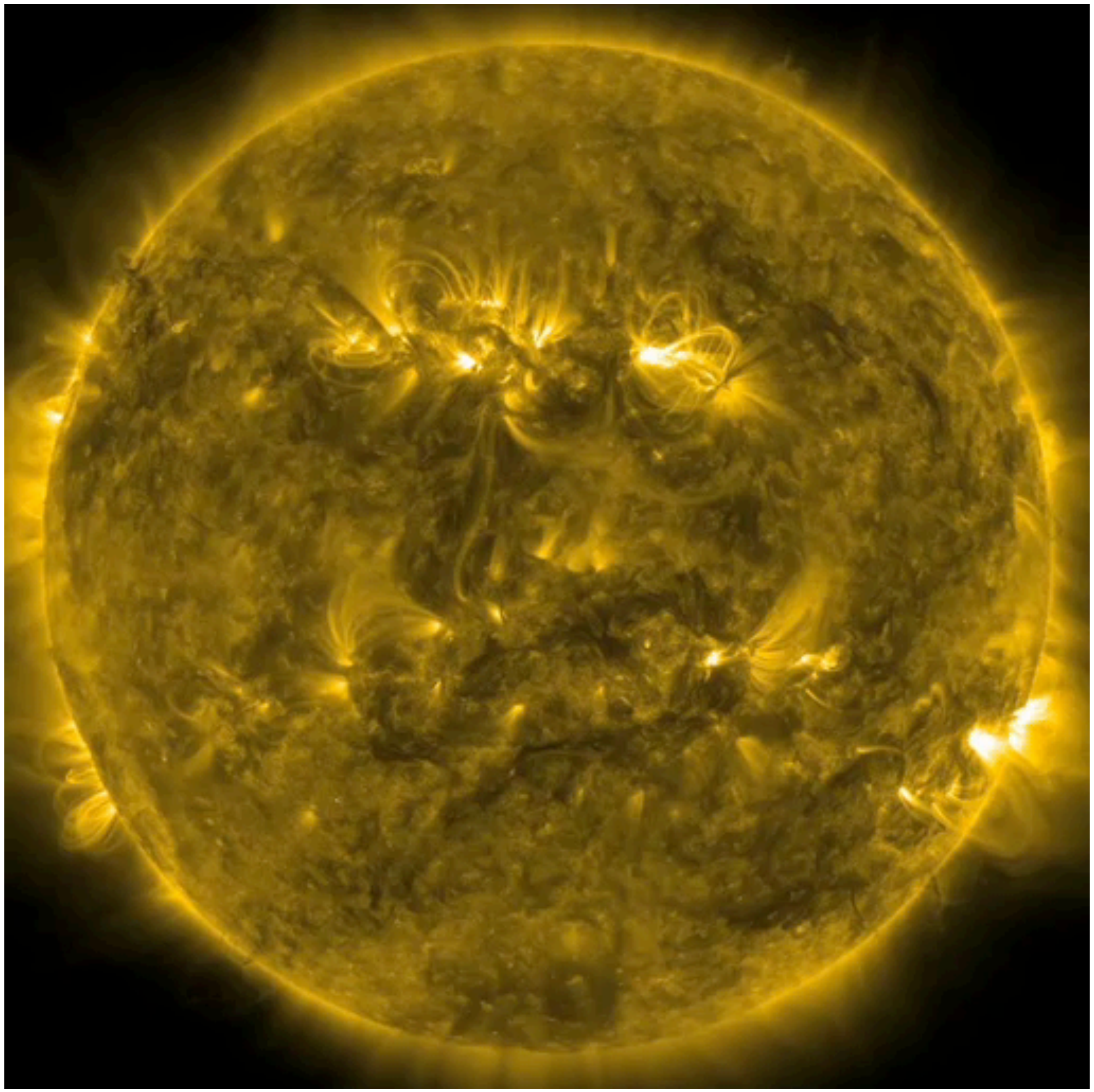


Magnetic fields?

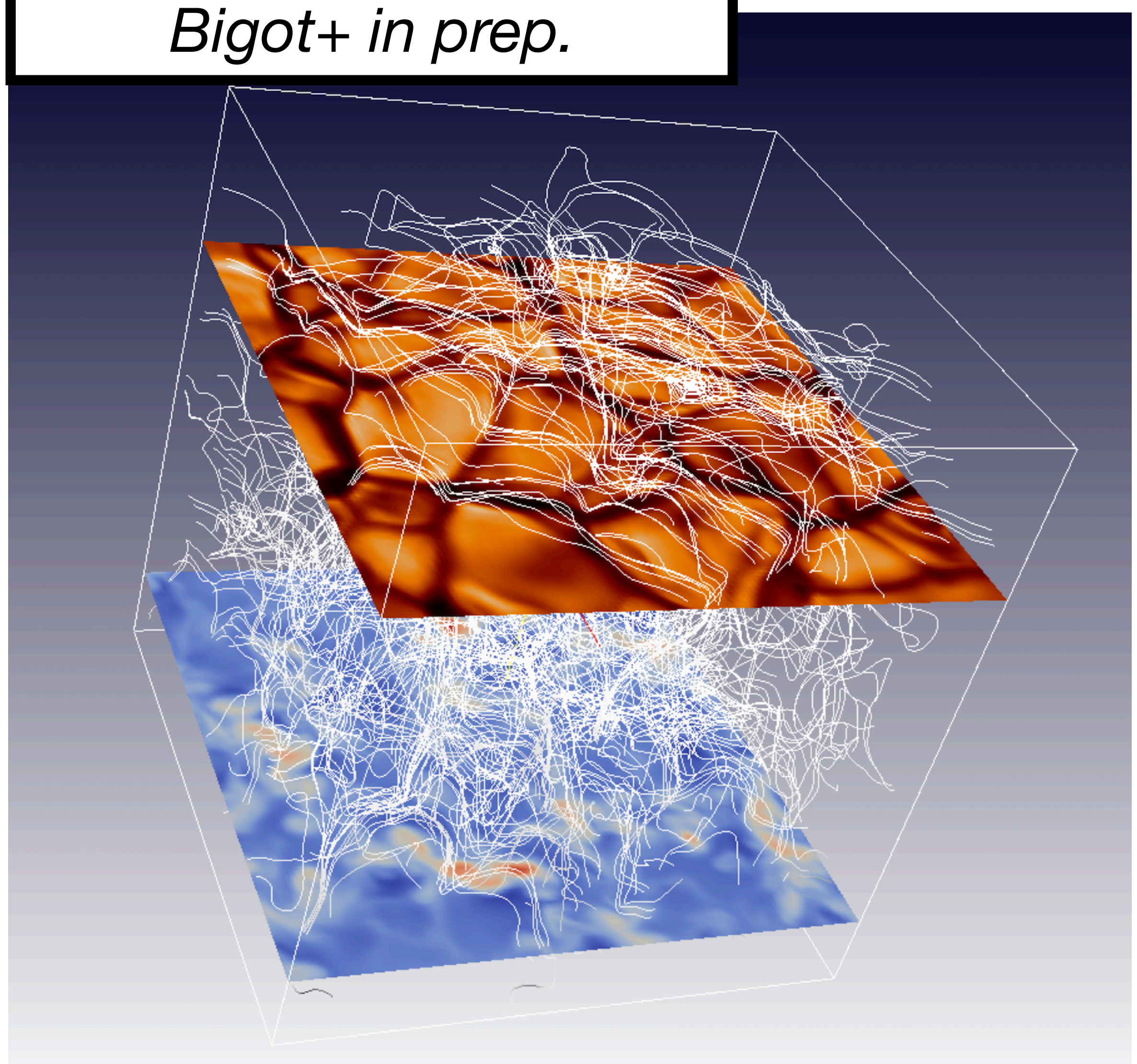


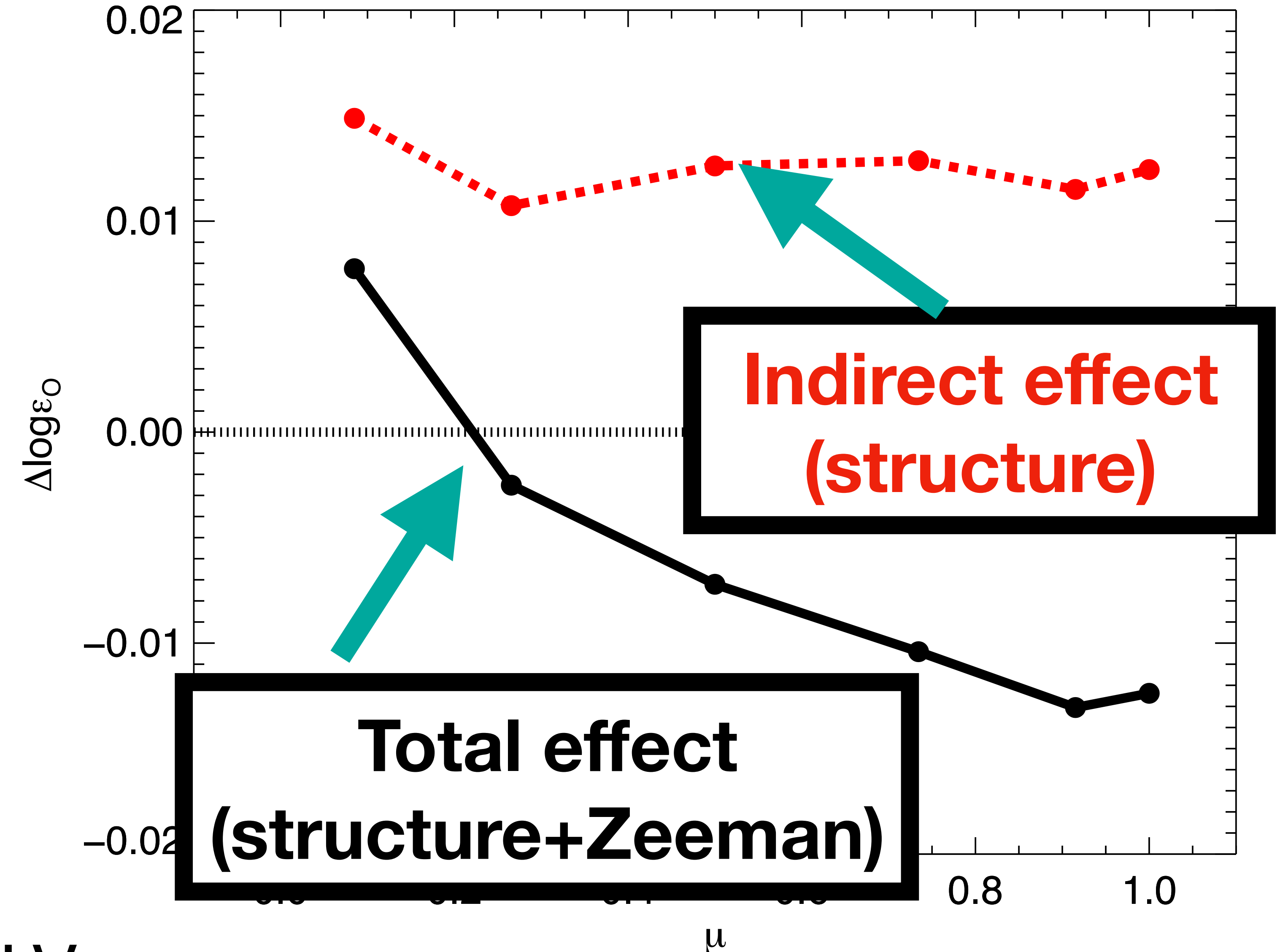
Movie credit: SDO, NASA

- Sun displays evidence of magnetic fields
- "Quiet Sun" also has magnetic fields: 50-200G
- Need **3D MHD** simulations…

Magnetic fields?

Bigot+ in prep.





Amarsi *& Bigot in prep.*

- MHD effects could fix CLV
- Lowers oxygen abundance (slightly)

Solar abundances summary

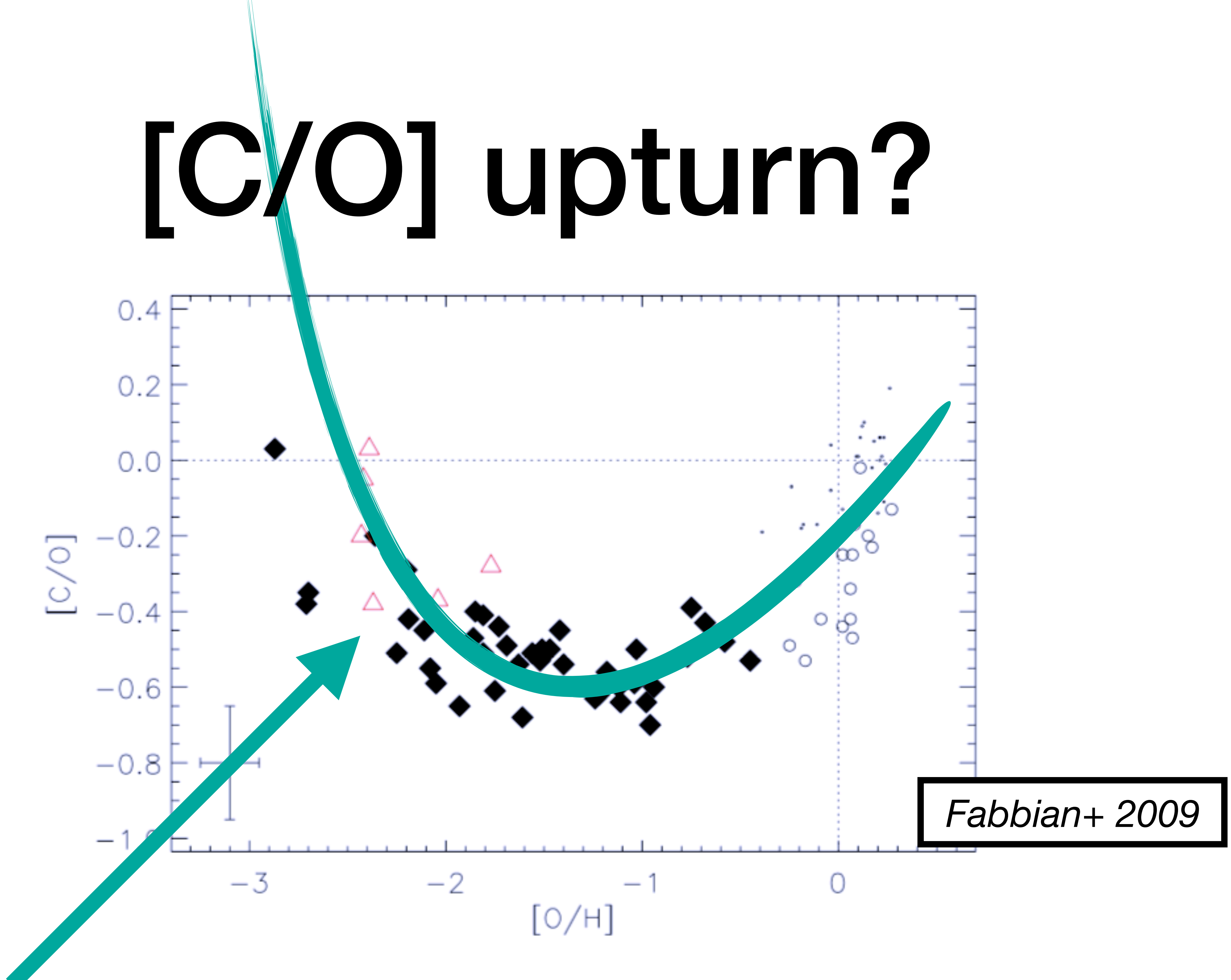
- New 3D non-LTE results ~ **consistent** with **old ones**
  - Oxygen 777nm (Amarsi, Barklem+ 2018) — **8.69** (8.69)
  - Also carbon lines (Amarsi, Barklem+ sub.) — **8.44** (8.43)
- Full CNO analysis in prep.
- Validated models (collisions); **apply to other stars**…

Results: carbon/oxygen/iron GCE

Why COFe?

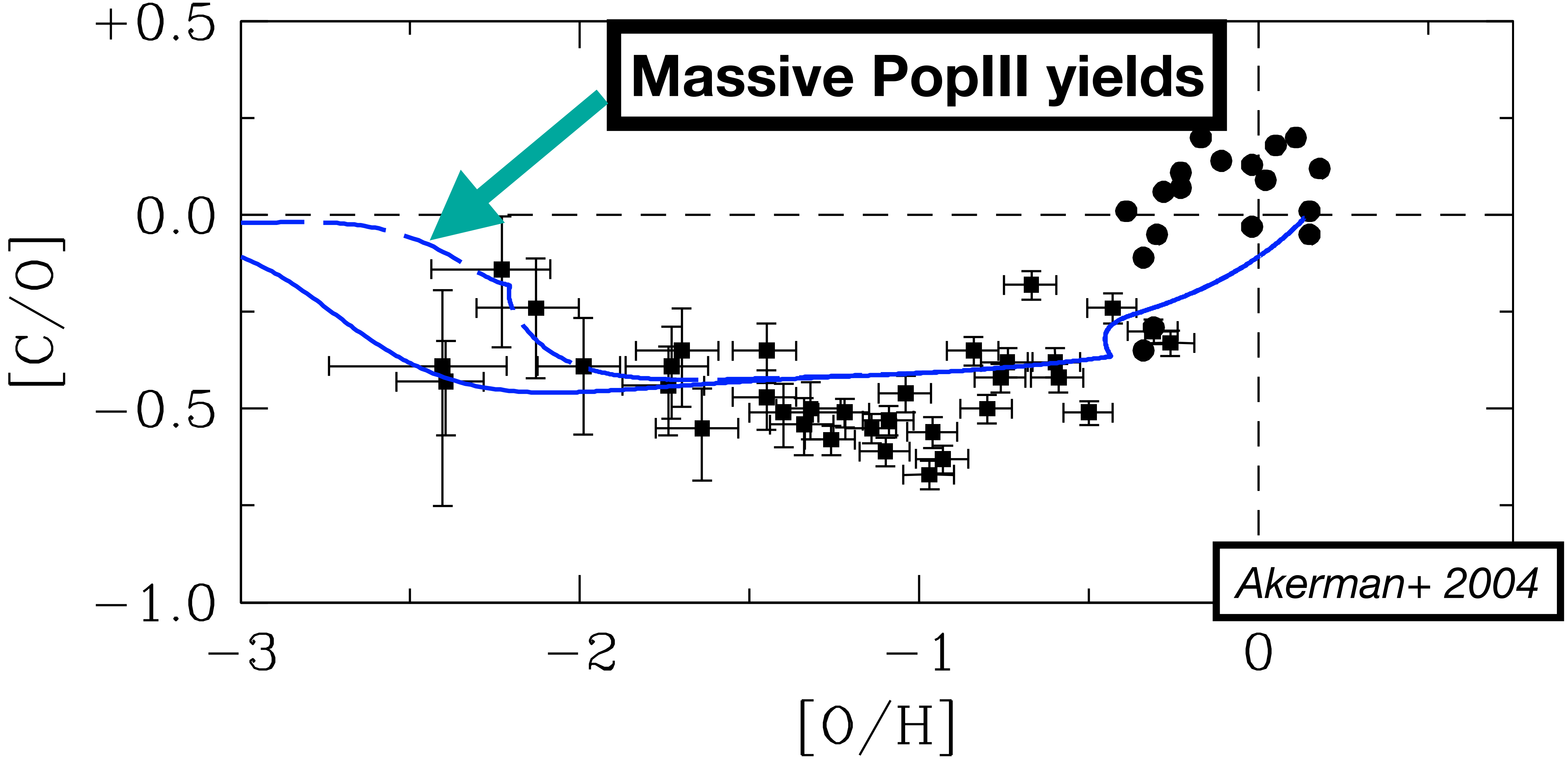
- Three of the most abundant metals
- C/O important in exoplanet studies (in prep.)
- C, O, Fe are key **GCE tracers** (e.g. Tinsley 1979)
  - C & O from hydrostatic burning in **massive stars**
  - C also from **low/intermediate mass stars**
  - Fe from **core-collapse** and **TypeIa supernovae**

[C/O] upturn?



- **Upturn** in [C/O] at low [O/H]
- Signature of **first stars**? Or **rotation**?

[C/O] upturn?



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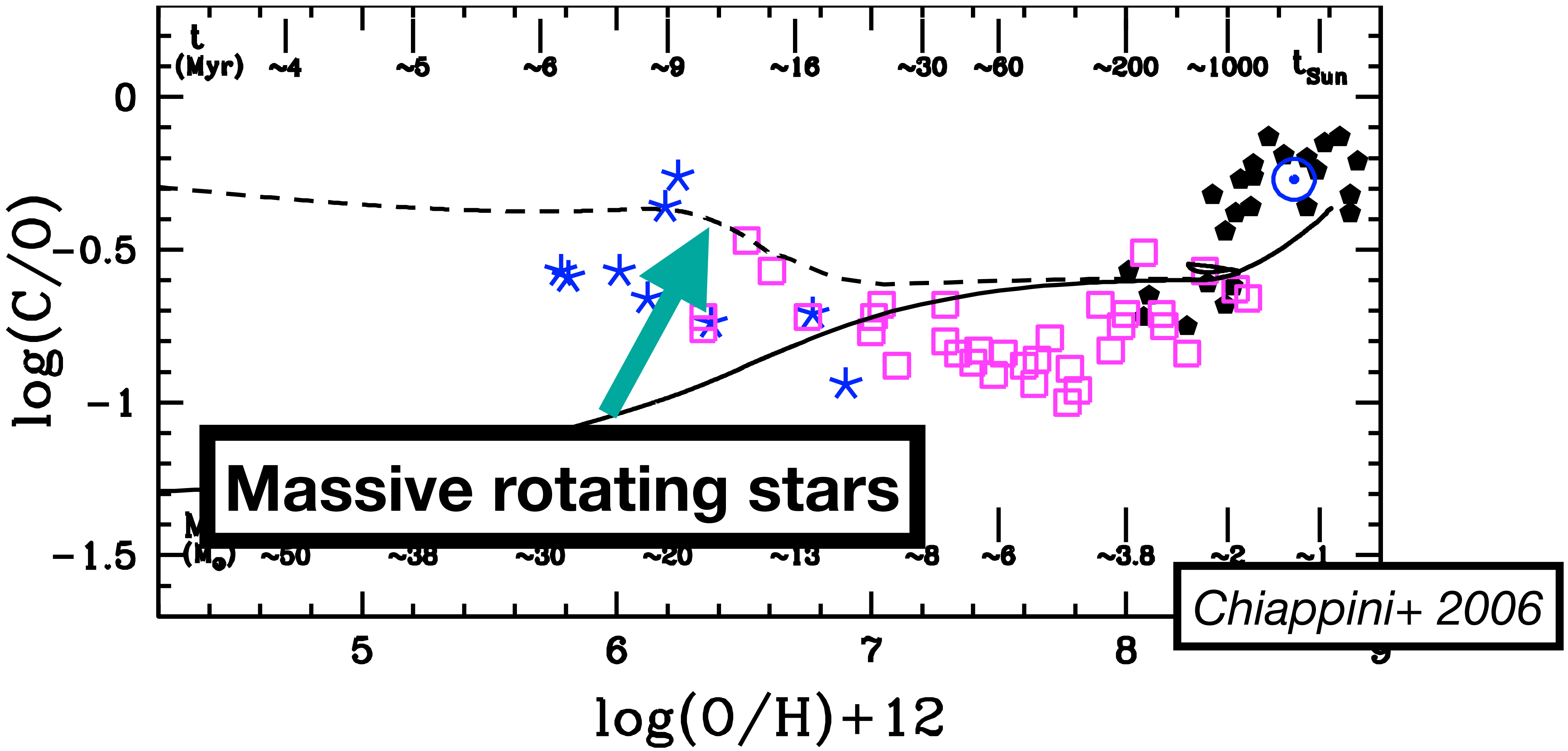
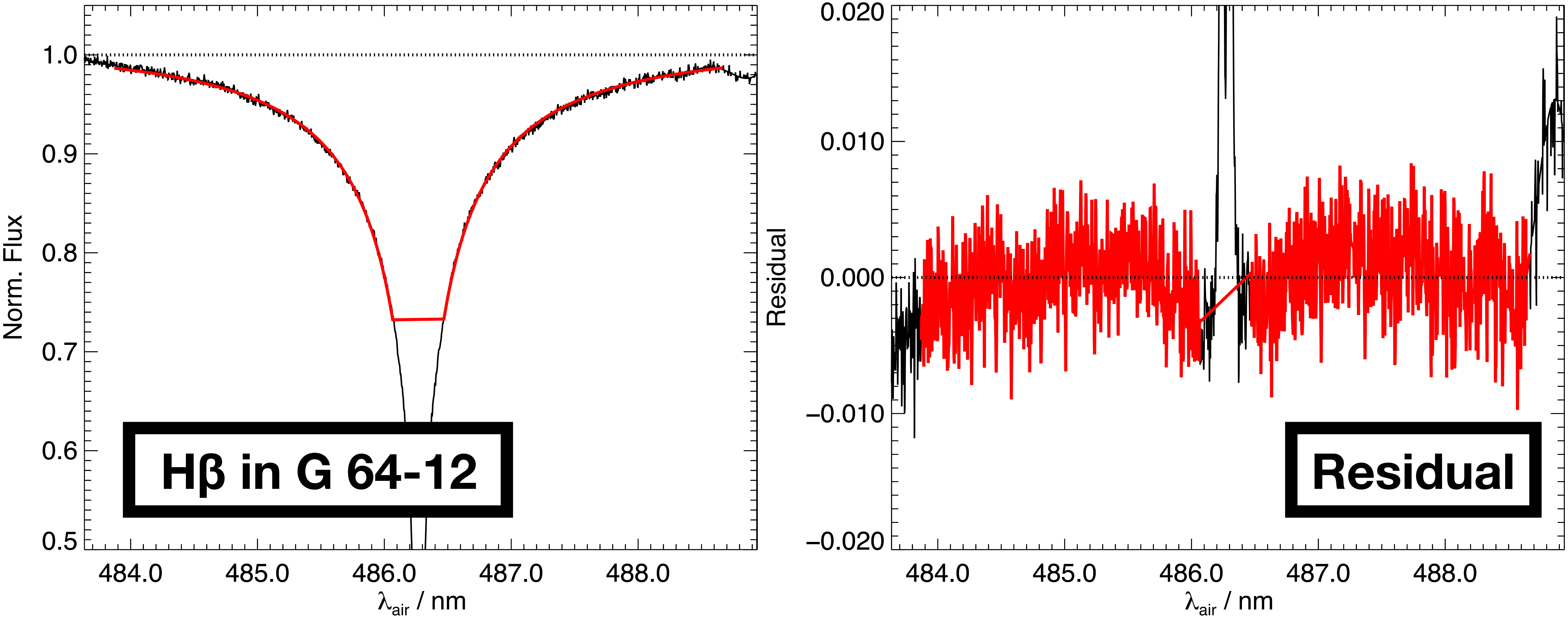


- **Upturn** in [C/O] at low [O/H]
- Signature of **first stars**? Or **rotation**?

[C/O] upturn revisited

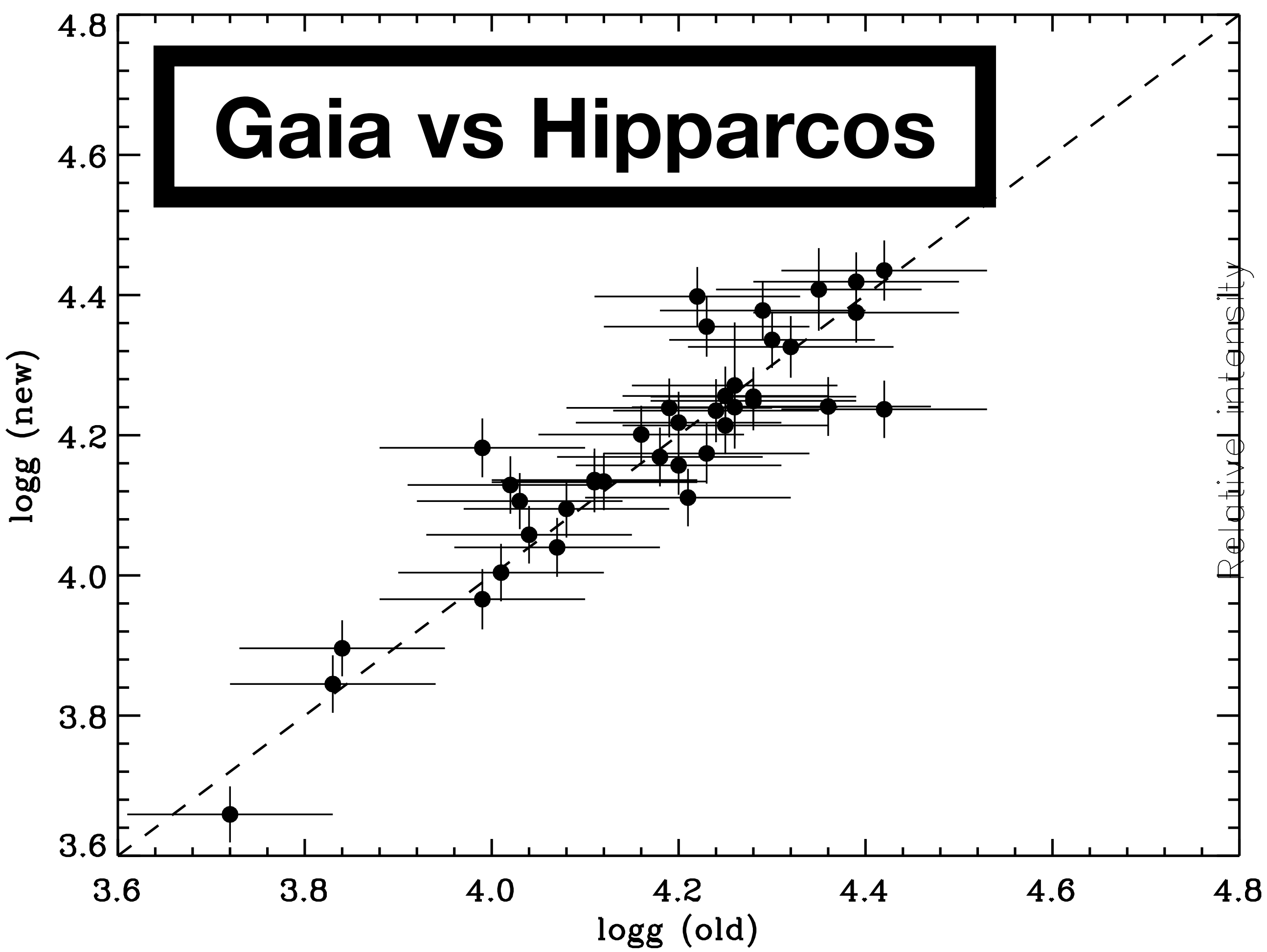
- **First time**: a "**full**" 3D non-LTE analysis
  - **Both** stellar parameters **and** abundances based on 3D non-LTE
  - 40 metal-poor turn-off halo stars (Nissen+ 2007)
- Easy to replicate method to **large samples**

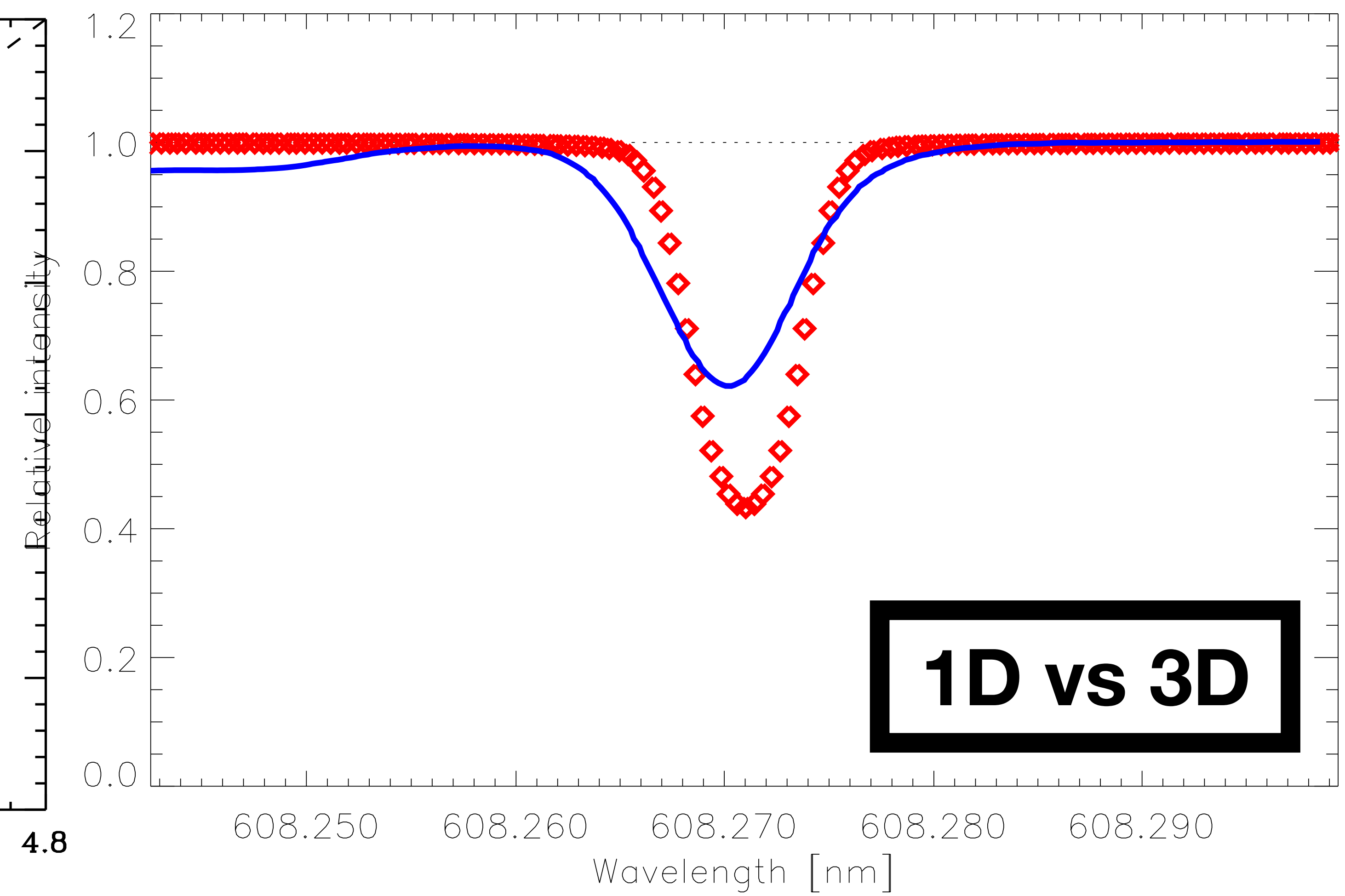
A “full” 3D non-LTE analysis



- Effective temperatures from **3D non-LTE Hβ** lines
- Grid available: Amarsi, Nordlander+ 2018

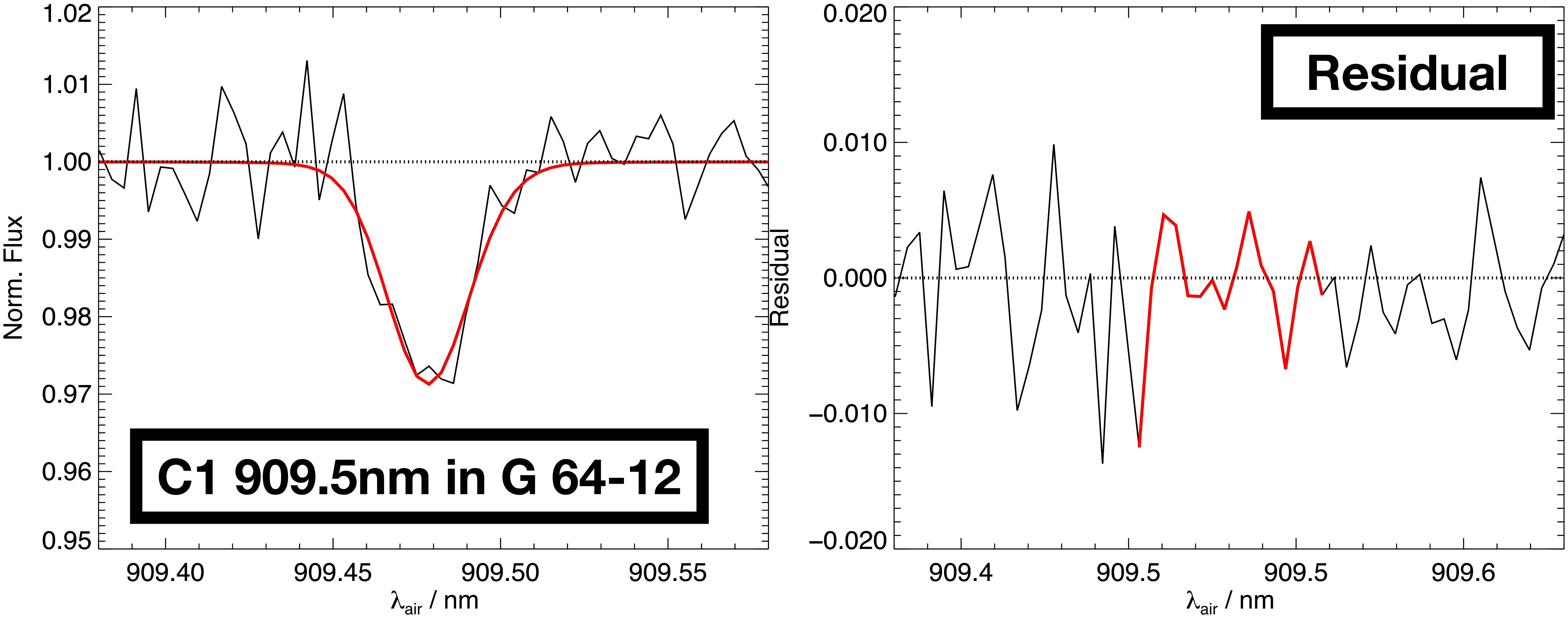
A “full” 3D non-LTE analysis





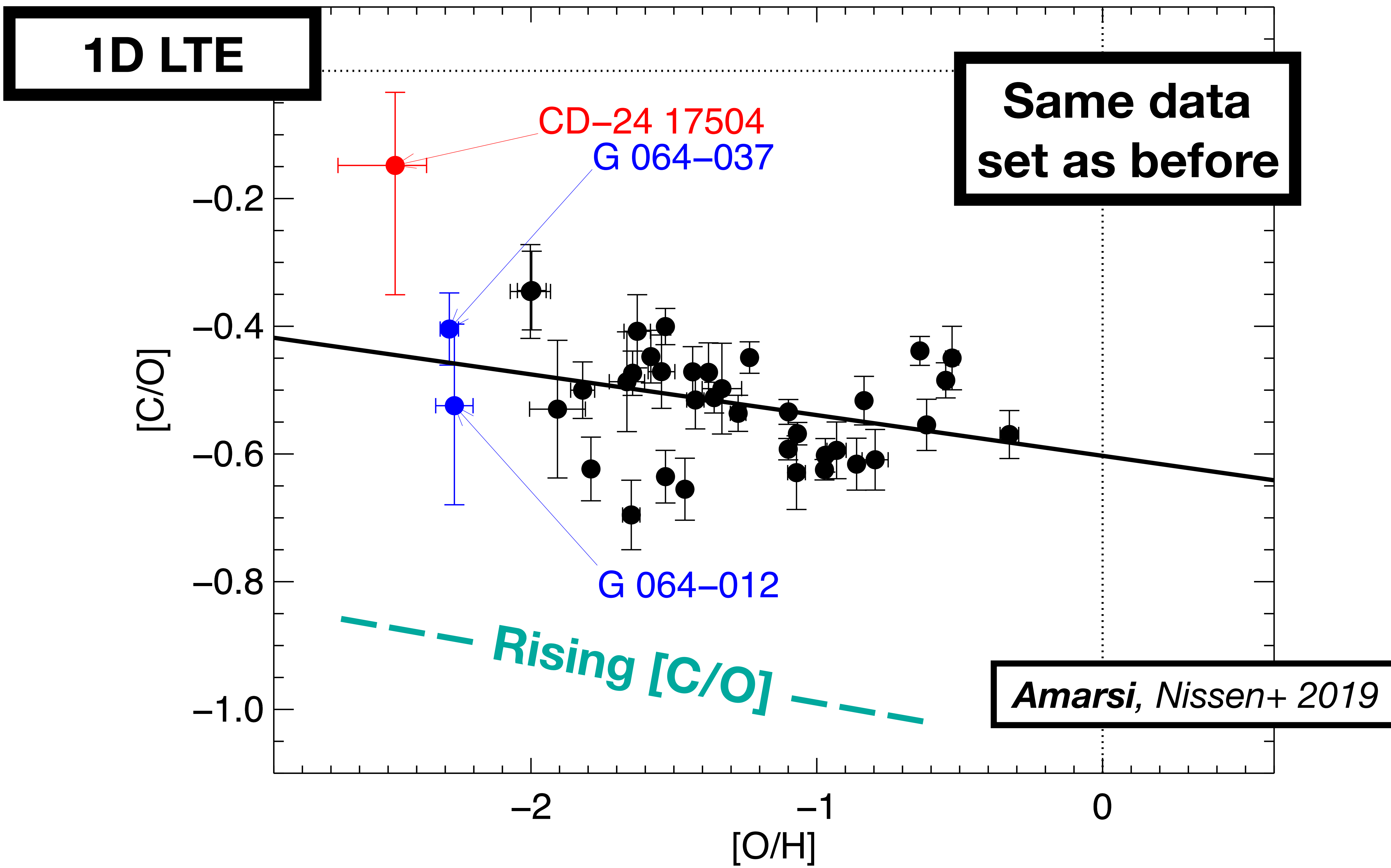
- Surface gravities from Gaia DR2
- [Fe/H] from 3D LTE Fe2 lines (non-LTE effects are small)

A “full” 3D non-LTE analysis



- Carbon and oxygen from 3D non-LTE **atomic lines**
- **High-excitation, near-IR:** similar sensitivities

[C/O] in halo stars



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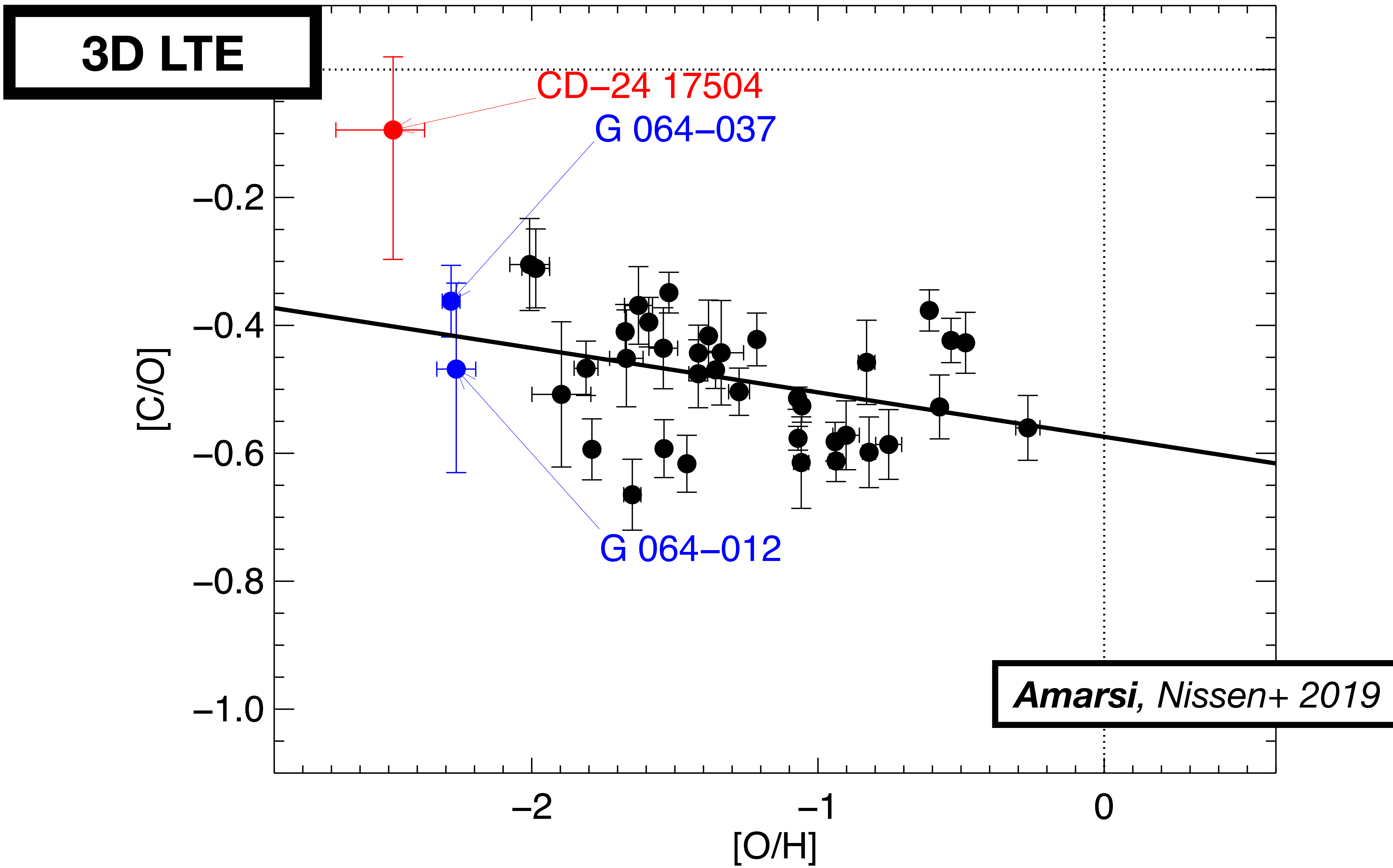

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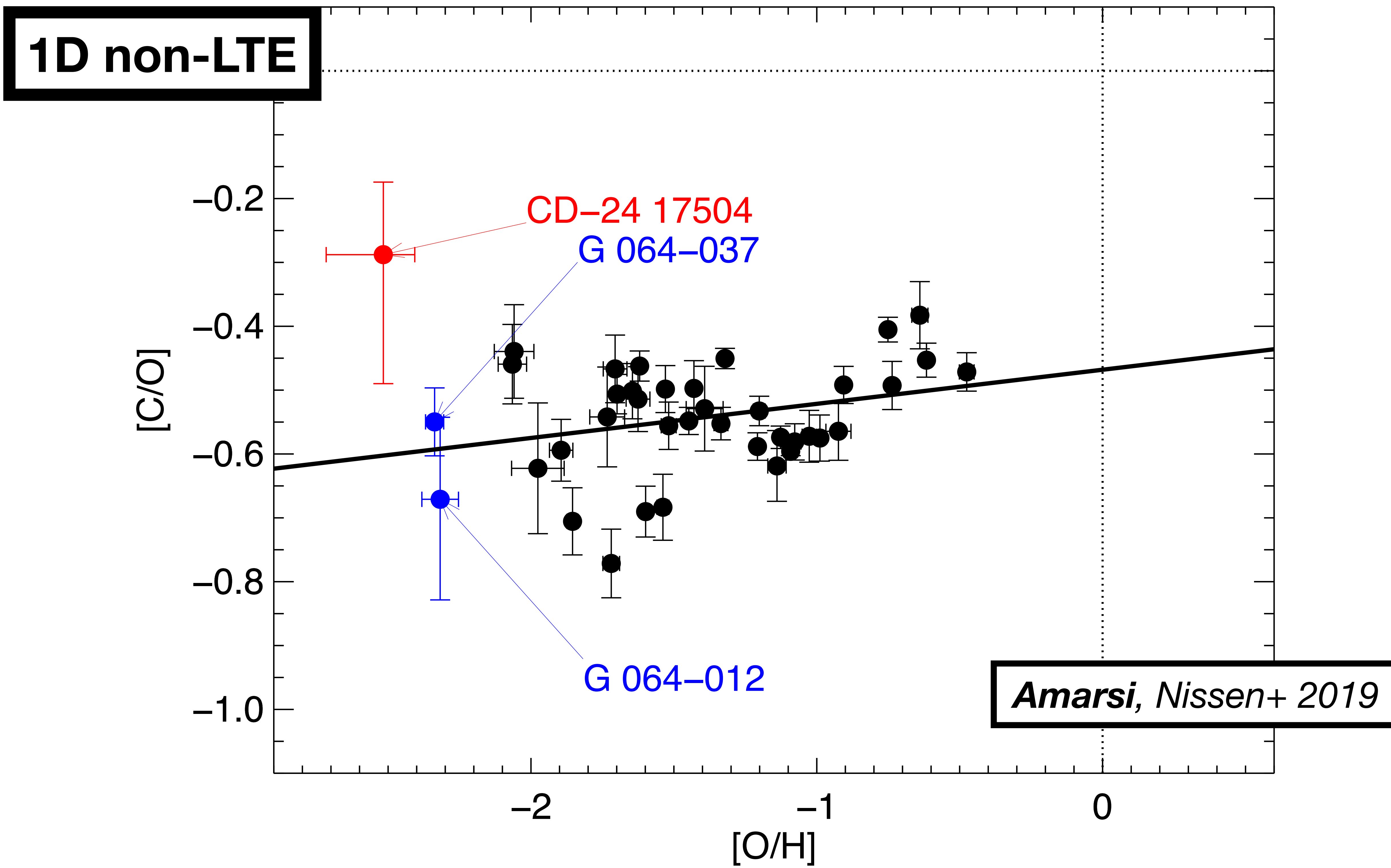

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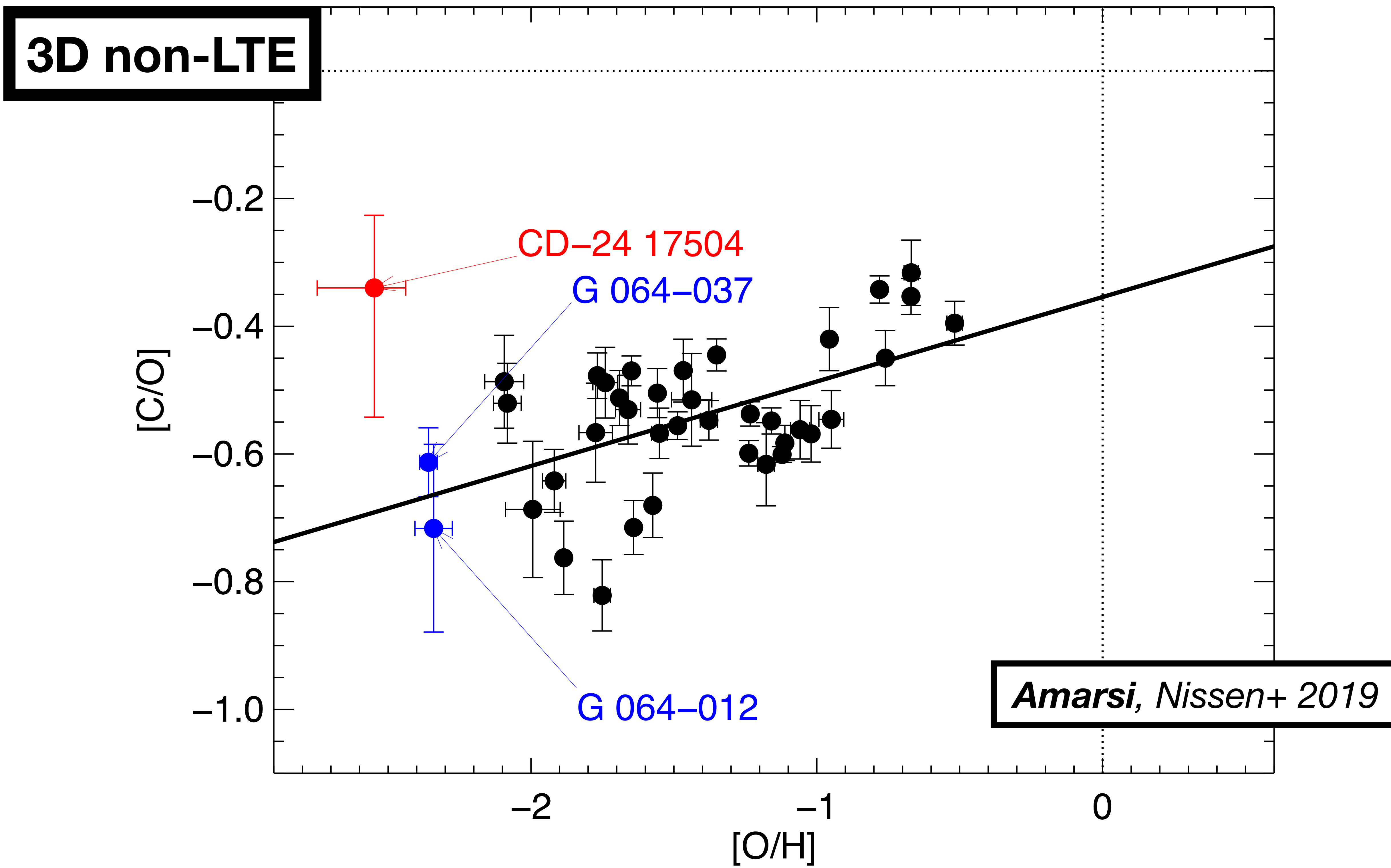
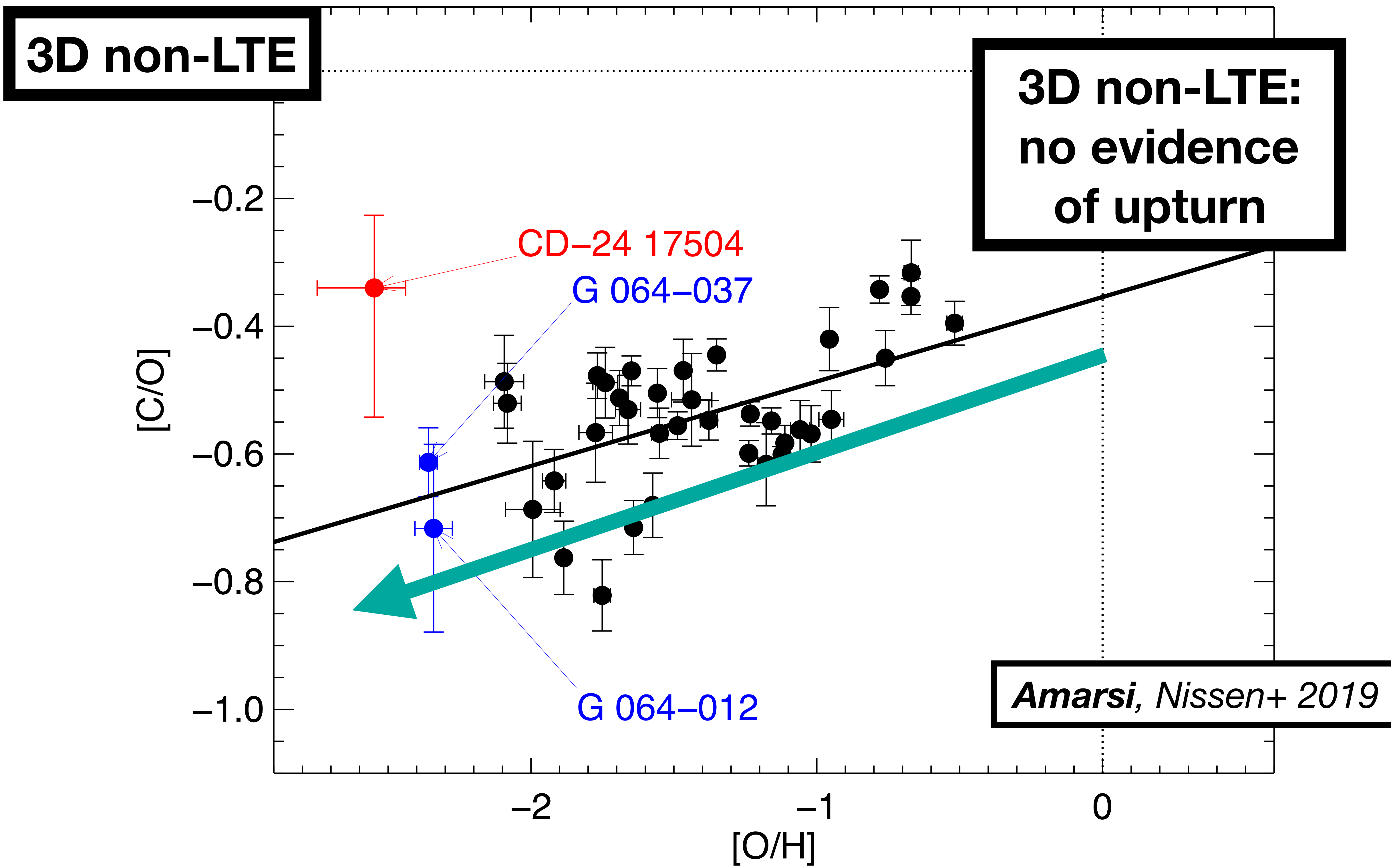
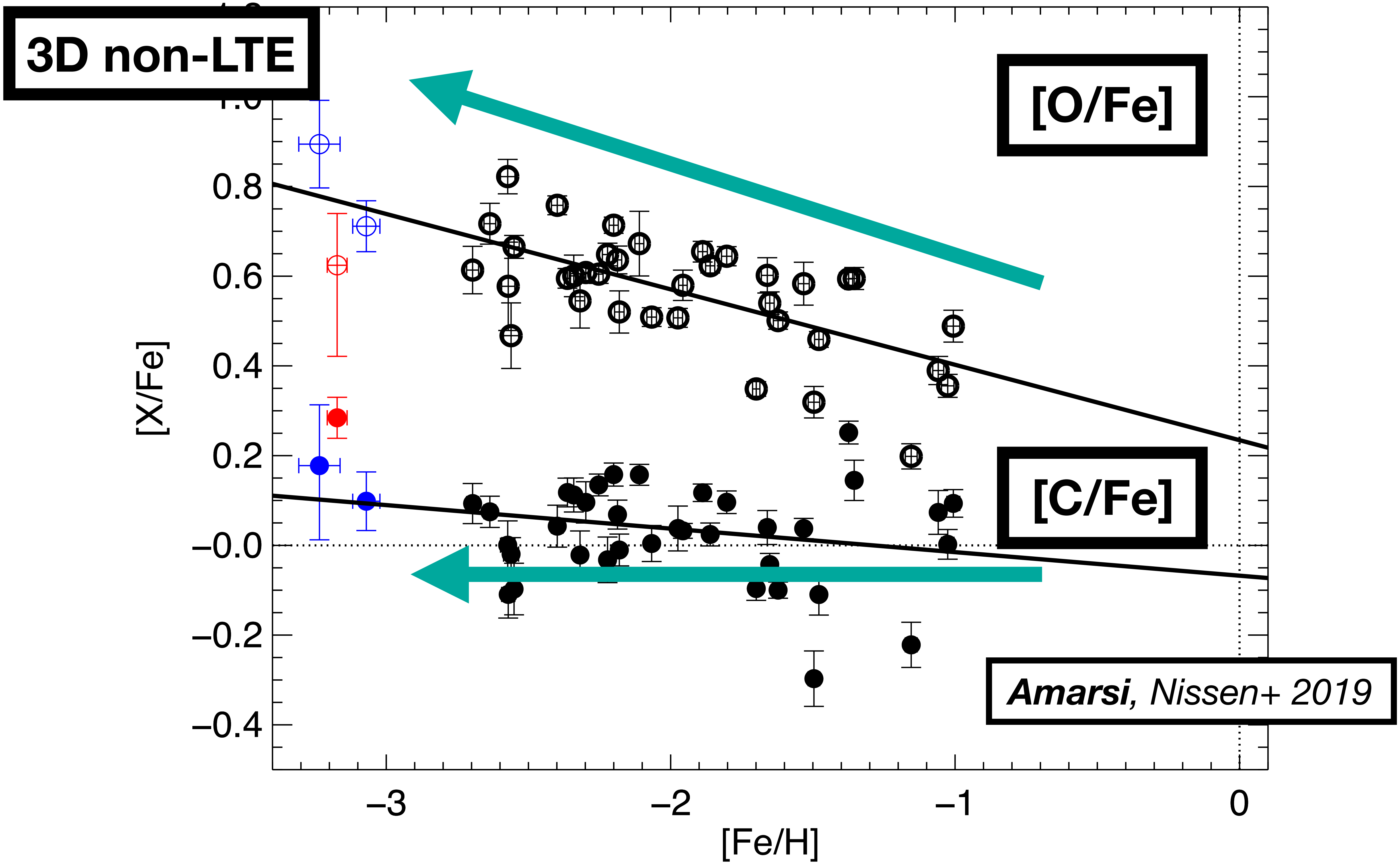


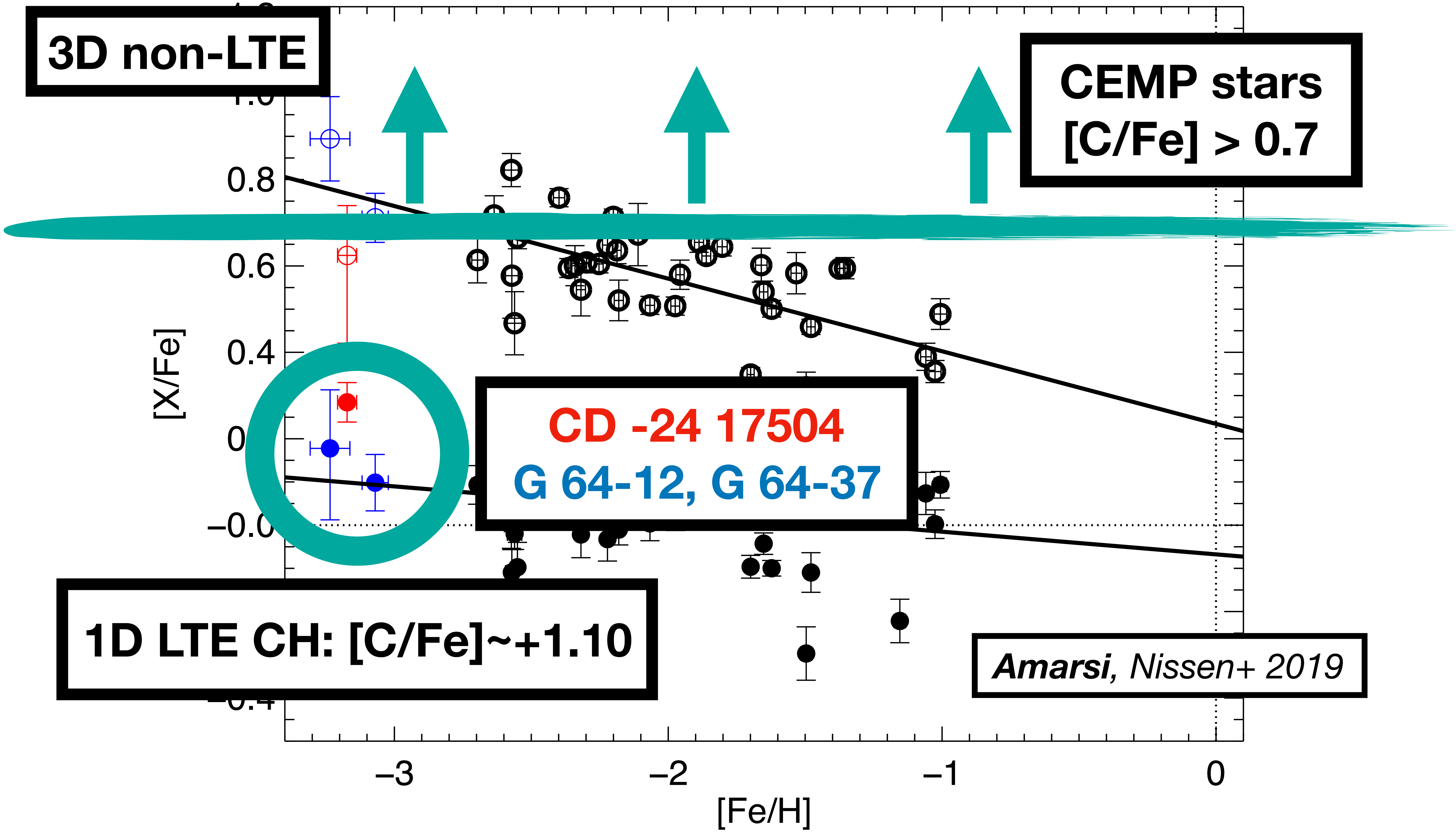
[C/O] in halo stars



[C/Fe] and [O/Fe]?


3D non-LTE
[O/Fe]
[C/Fe]
Amarsi, Nissen+ 2019
[X/Fe]
[Fe/H]
0.8
0.6
0.4
0.2
−0.0
−0.2
−0.4
−3
−2
−1
0

[C/Fe] and [O/Fe]?



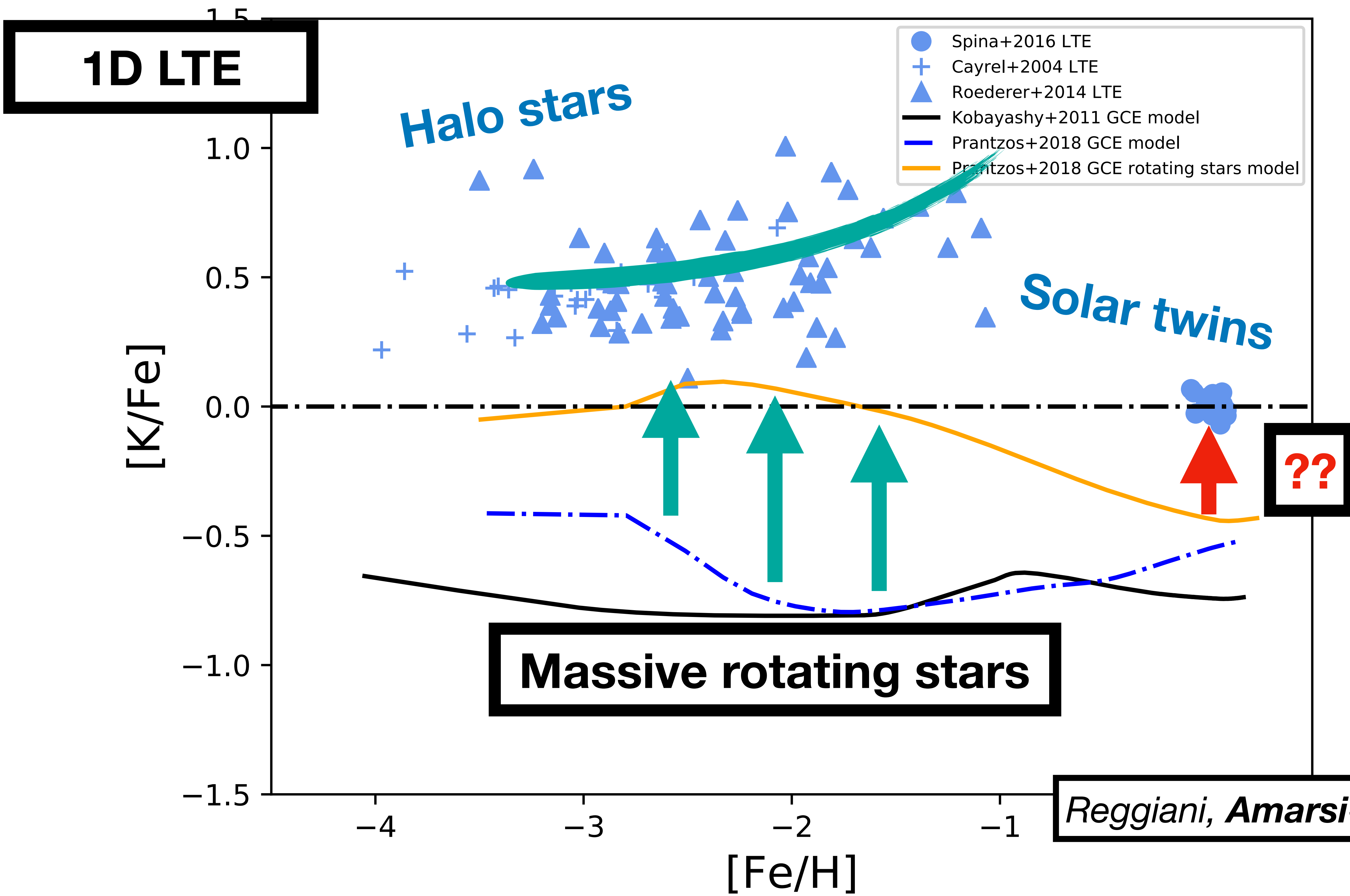
3D non-LTE
CEMP stars
[C/Fe] > 0.7
0.8
0.6
0.4
[X/Fe]
CD -24 17504
G 64-12, G 64-37
1D LTE CH: [C/Fe]~+1.10
Amarsi, Nissen+ 2019
−3
−2
−1
0
[Fe/H]

Extra results: potassium GCE

Potassium GCE

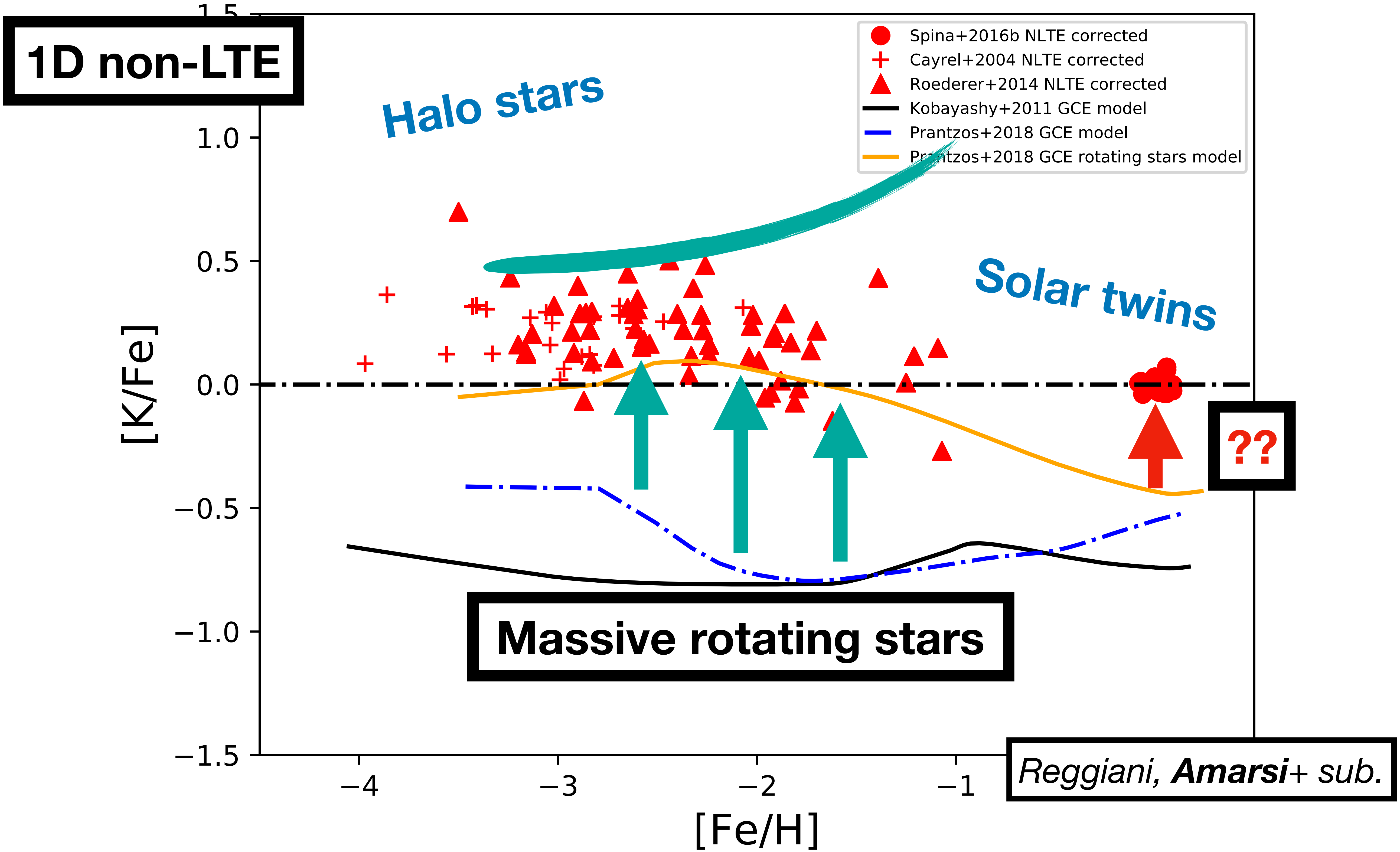
- Potassium production is not completely understood
- Massive stars
    - **Hydrostatic** oxygen shell burning
    - **Explosive** oxygen burning
- Extra nucleosynthesis channels? (Kobayashi+ 2011; Prantzos+ 2018)

Potassium GCE



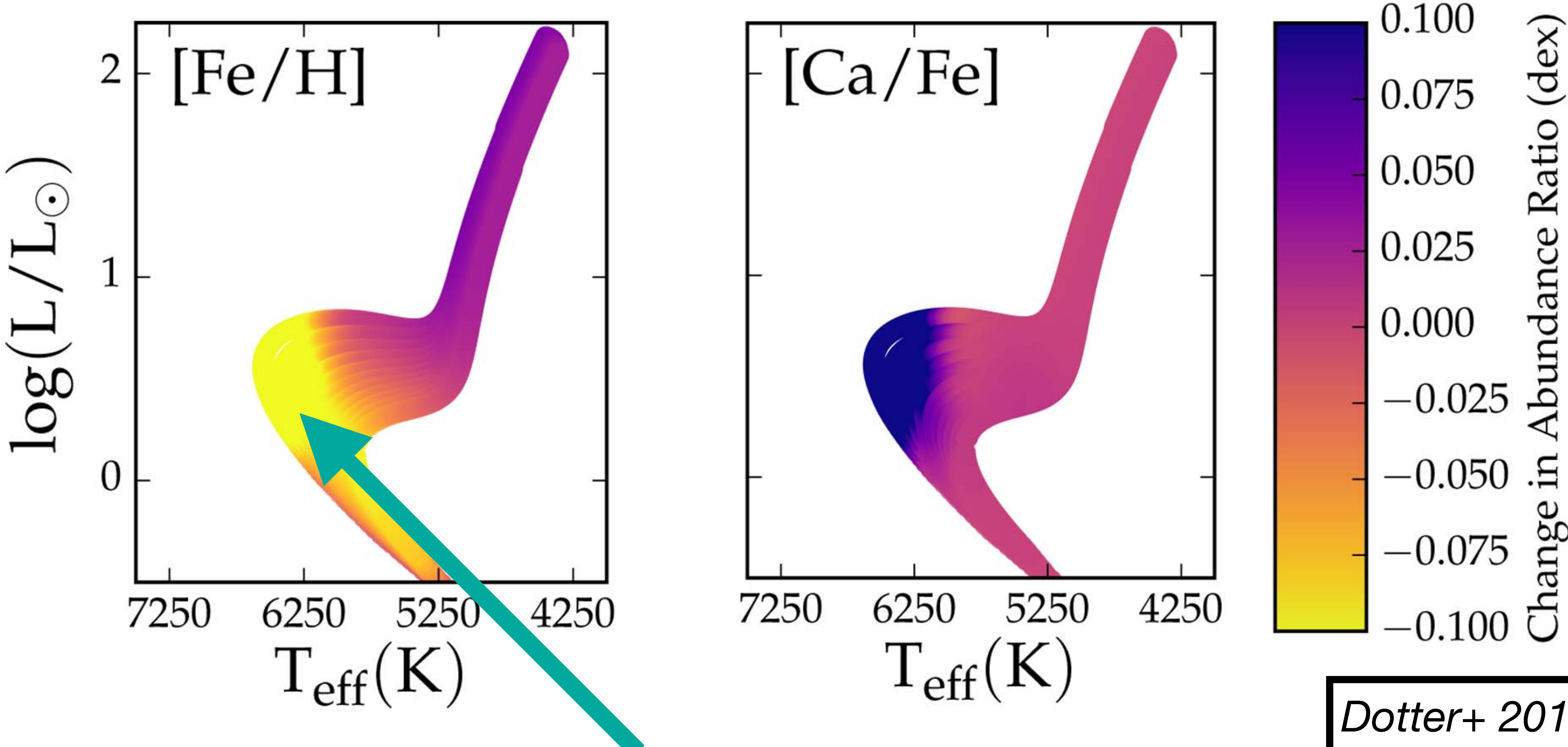
Reggiani, **Amarsi**+ sub.

Potassium GCE



Extra results: atomic diffusion

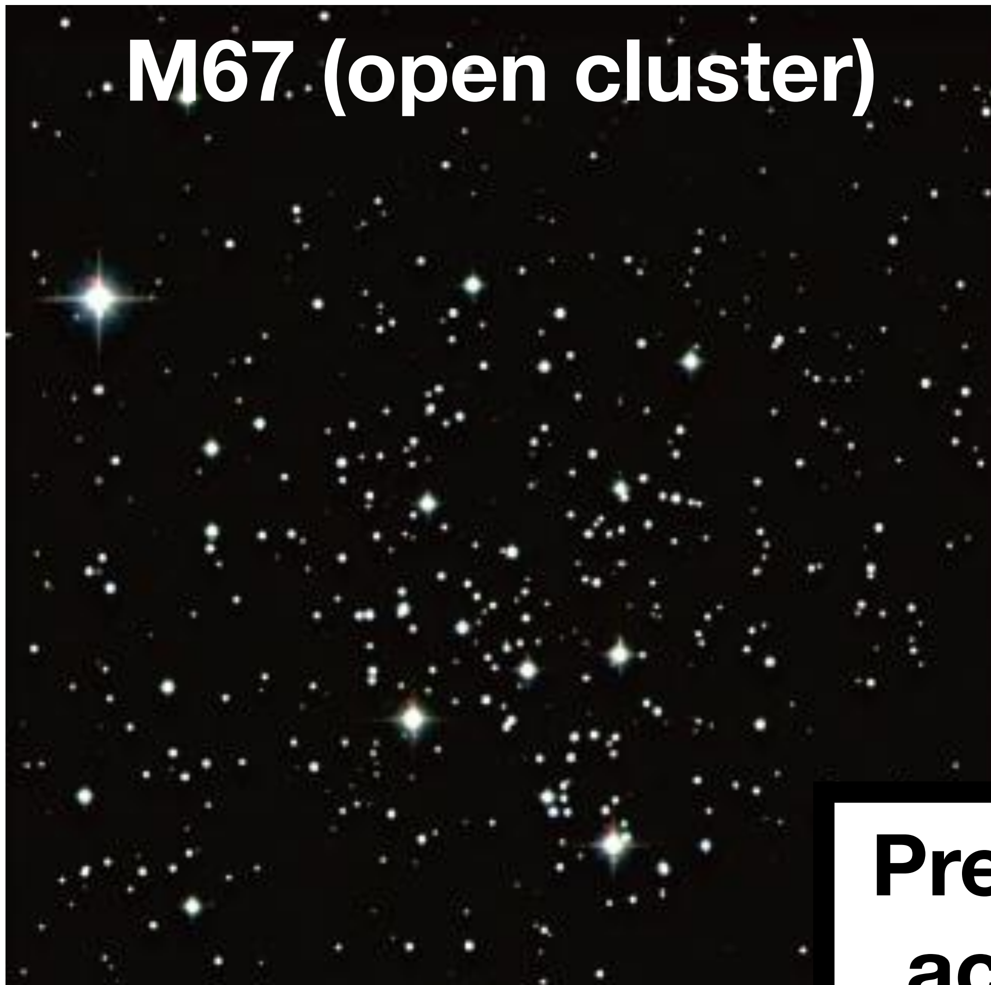
Atomic diffusion

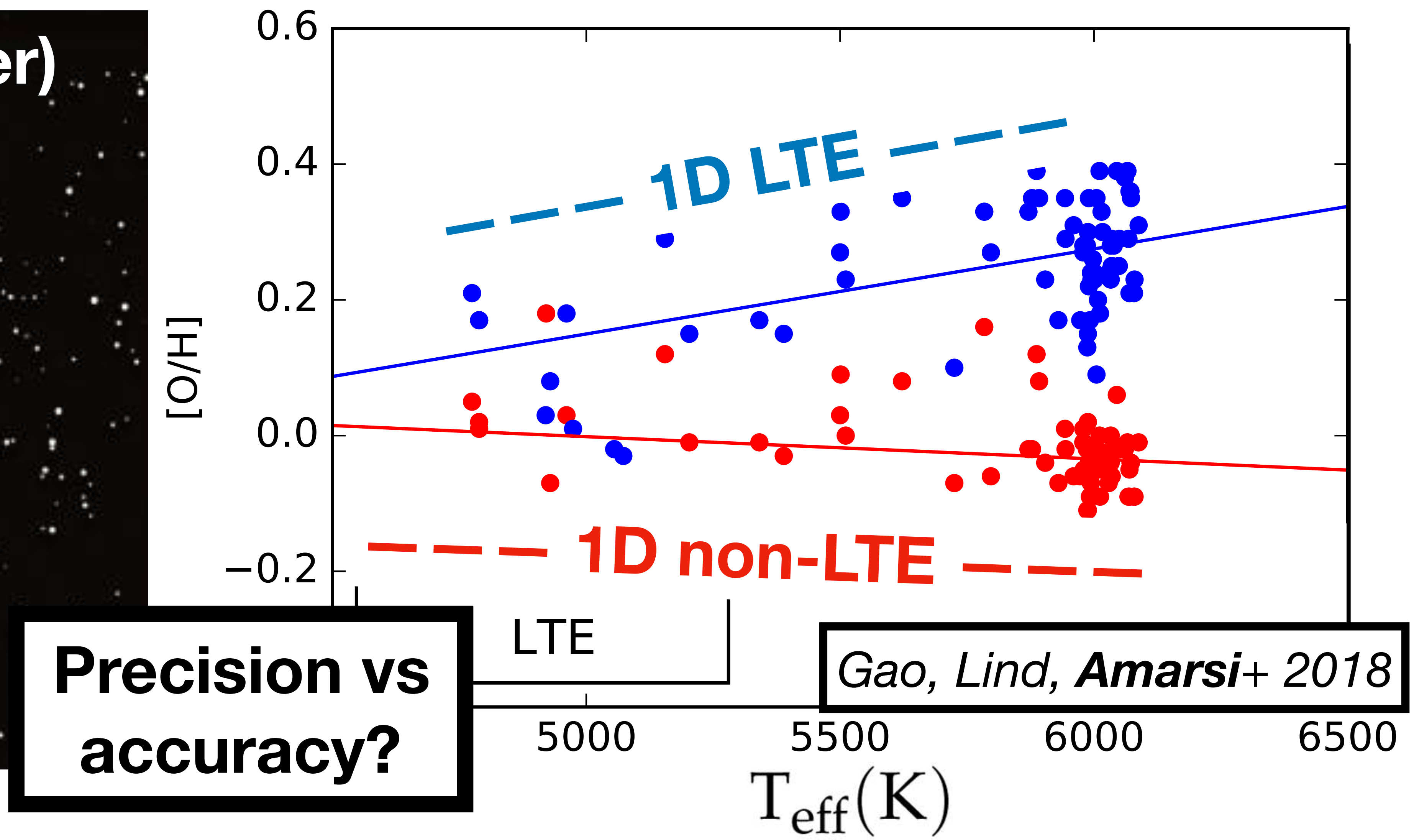


Dotter+ 2017

- Surface abundances **depleted** in turn-off stars
- Investigate in mono-populations: **open clusters**

Atomic diffusion





- LTE: positive gradient ➡ difficult to explain
- Non-LTE: negative gradient ➡ **atomic diffusion**(?)

Conclusion

Conclusion

- **First principles inelastic X+H collisions**, validated on solar CLV
- Solar C & O abundances largely unchanged
- **3D non-LTE effects** can strongly alter abundance trends and thus **our understanding of the Sun, stars, and our Galaxy**