”Interdisciplinary Physics of the Sun”, Bad Honnef, July 2025

Solar elemental abundances

Maria Bergemann

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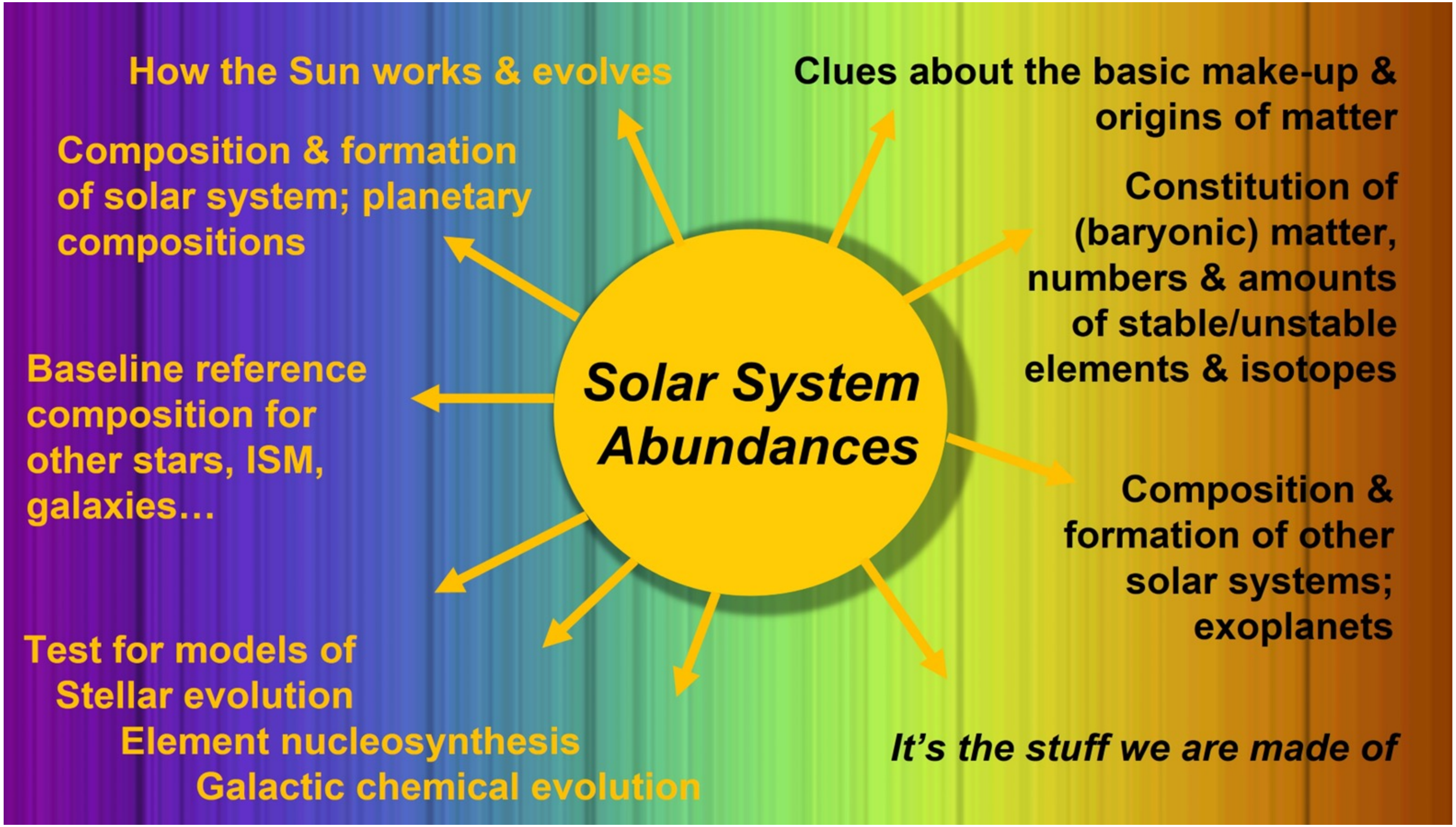
in collaboration with Katharina Lodders and Herbert Palme

We thank the organizers for the invitation to this meeting and our institutions and funding agencies and many collaborators for supporting our research.

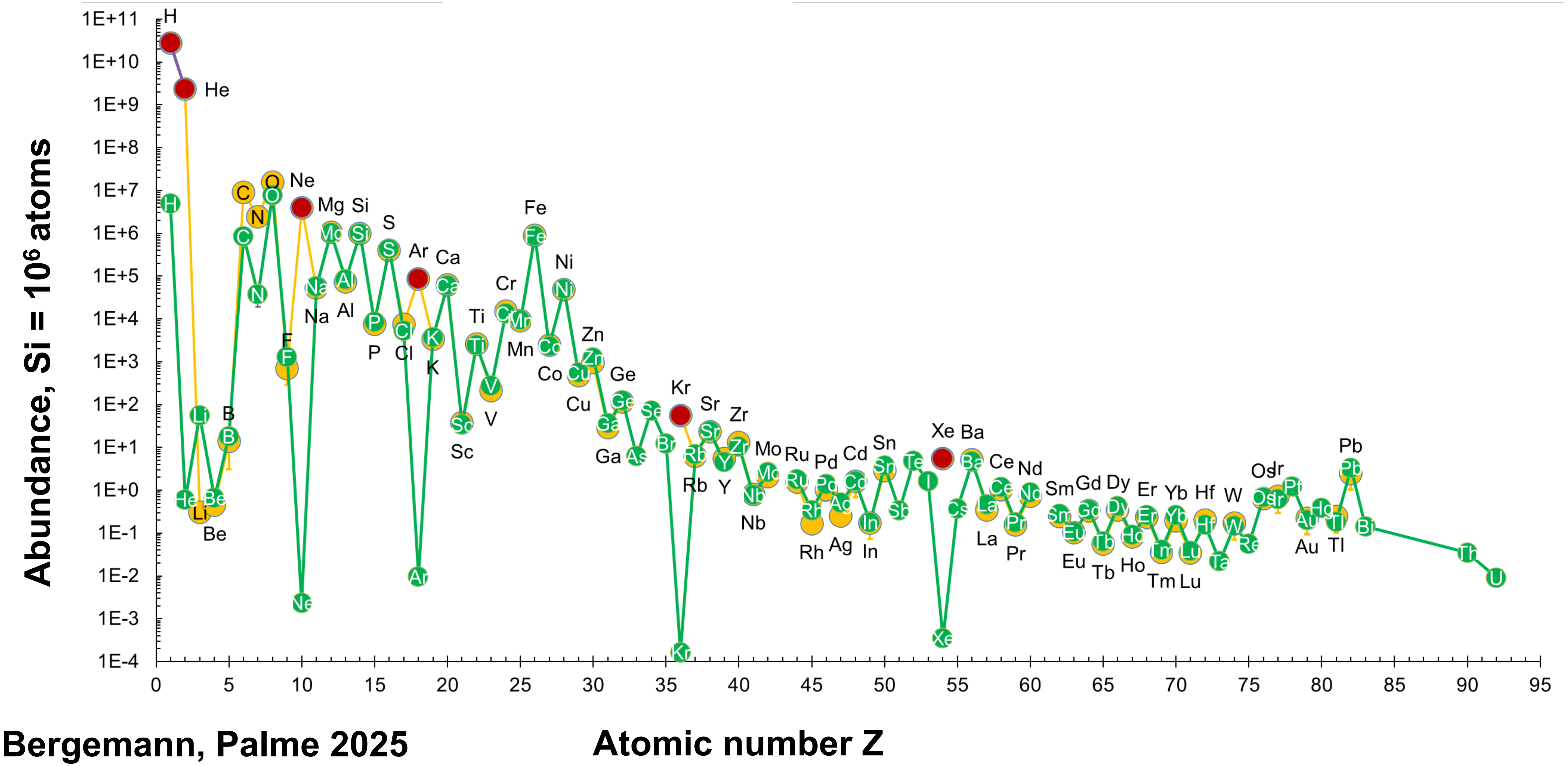
Outline

- Abundances from C I meteorties + asteroids
- Abundances from the solar spectra
- Implications: SSM, solar *Z*, chondrites
- Conclusions



Lodders, Bergemann and Palme 2025

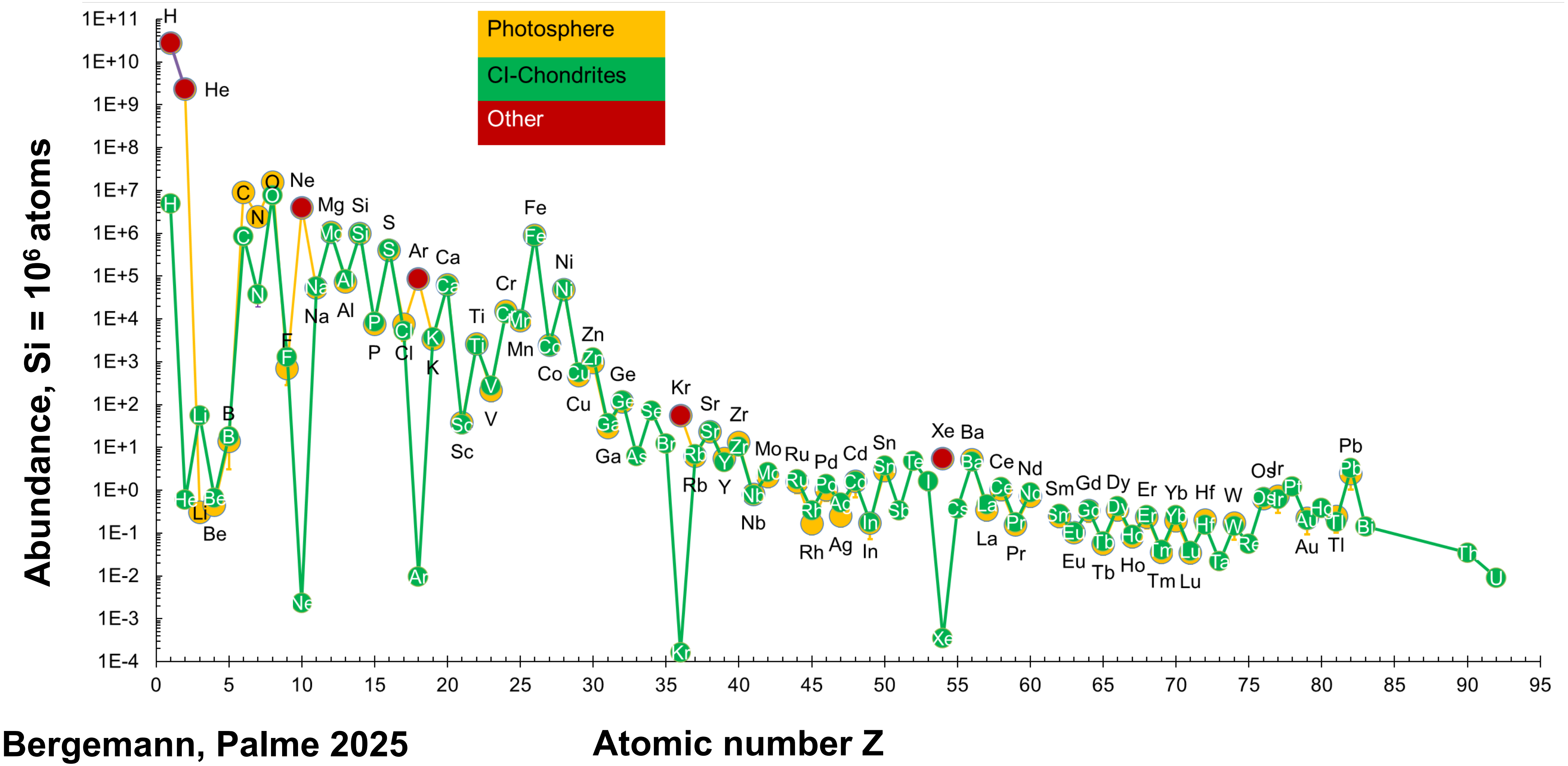
Solar elemental abundances



Lodders, Bergemann, Palme 2025

Solar elemental abundances

need different sources: the Sun (surface, interior), meteorites, indirect (GCE)



Lodders, Bergemann, Palme 2025

Solar elemental abundances

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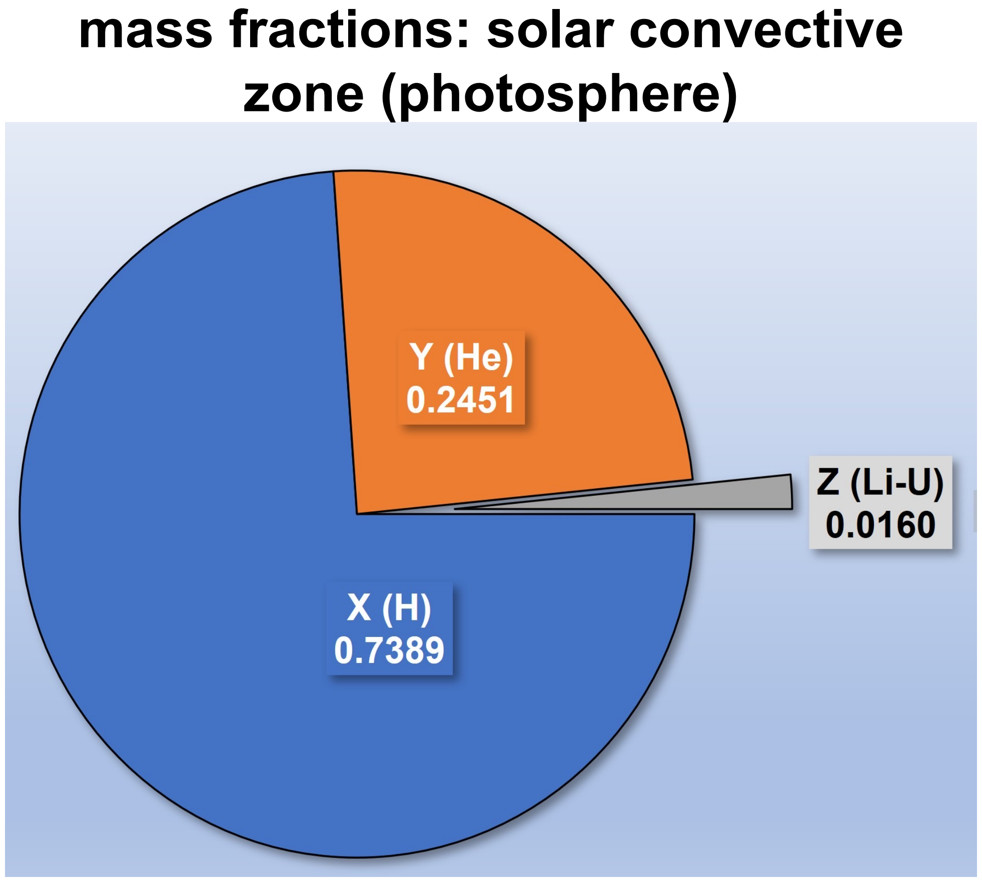


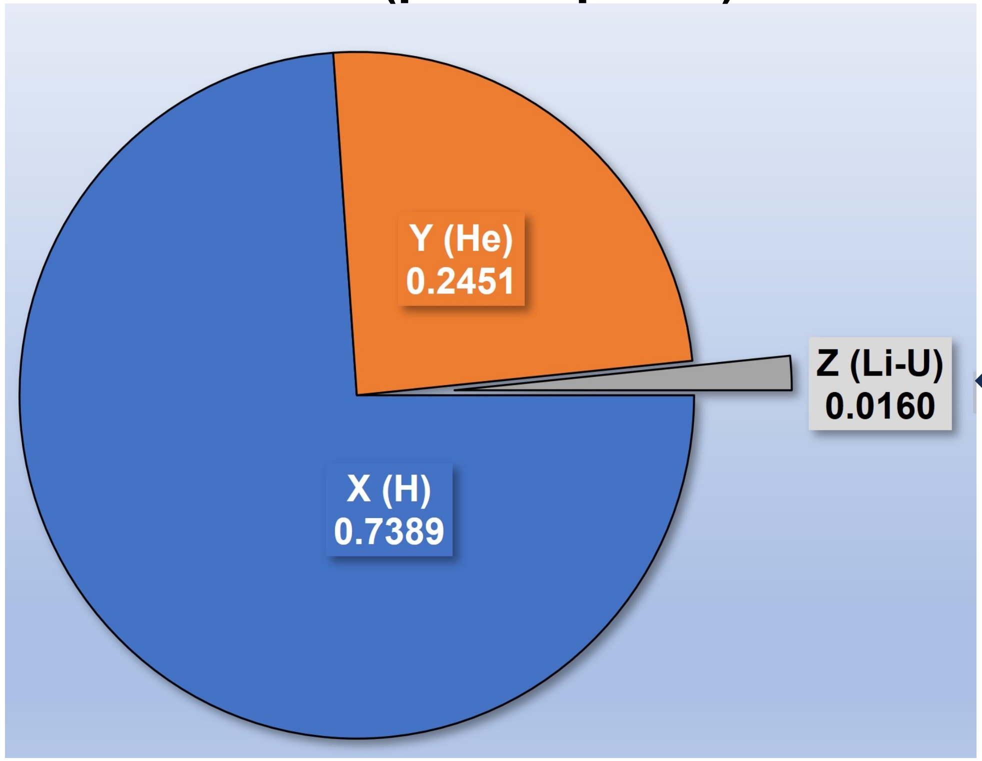
H and He are not measurable from observed solar spectra

1.6% in metals (Li – U)

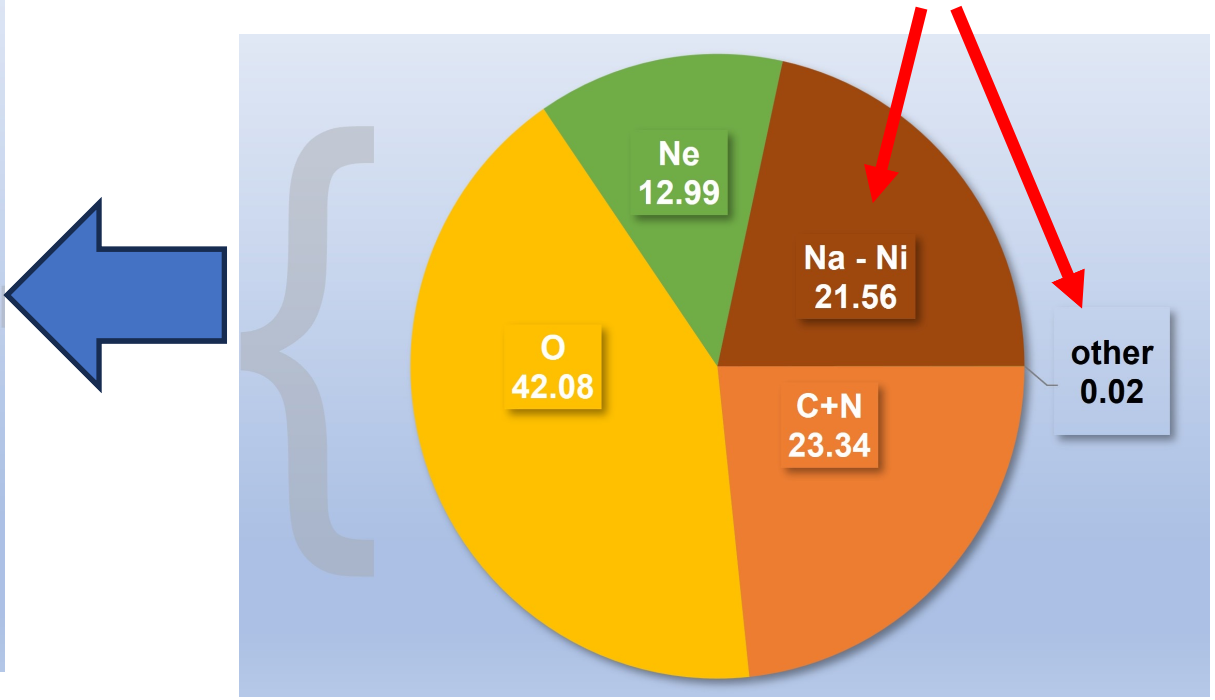
Solar elemental abundances

need different sources: the Sun (surface, interior), meteorites, indirect

mass fractions: solar convective zone (photosphere)



these elements are derived from solar spectra + meteorites

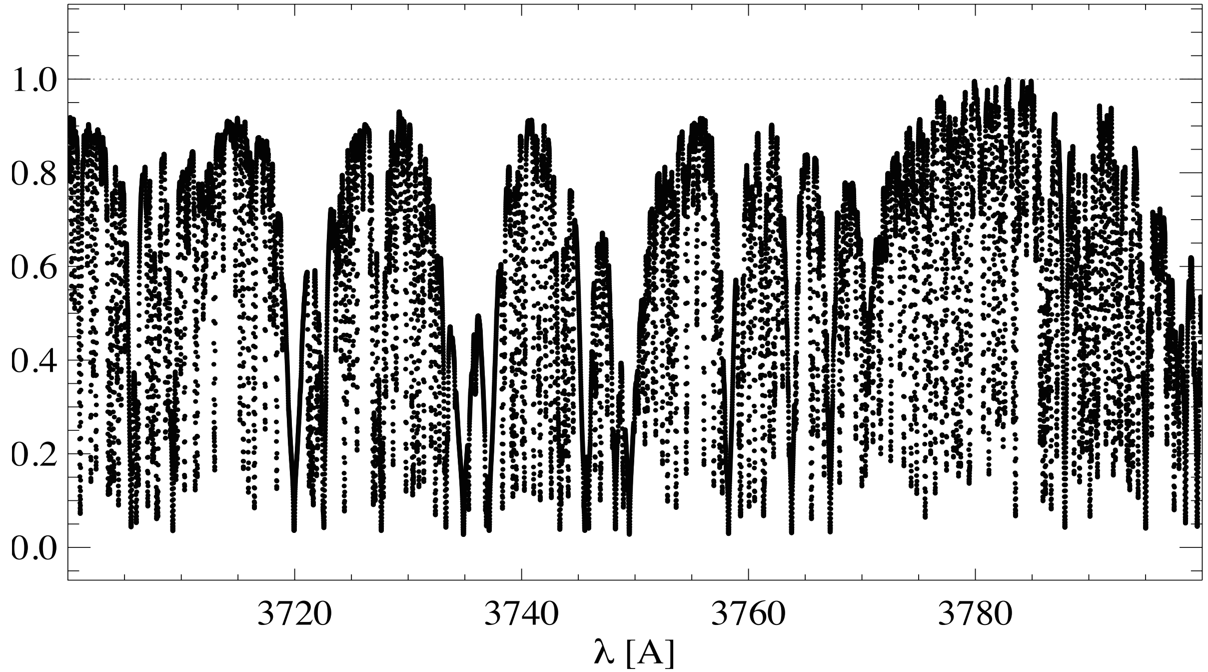


Sun (surface + interior)

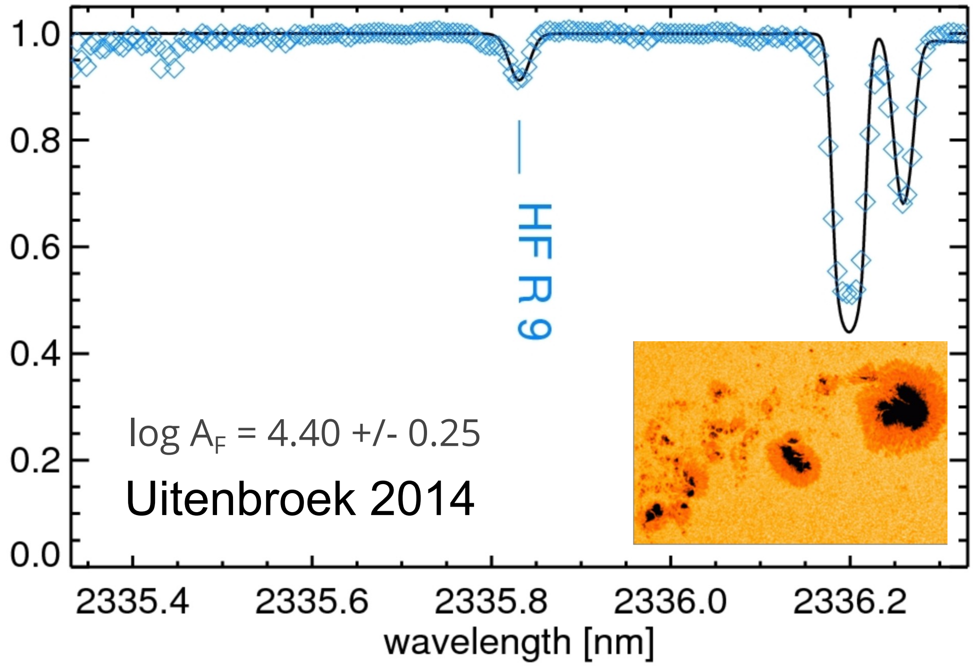
60 elements from the photospheric spectra
4 sunspots: F, Cl, In, Ti
4 solar wind: Ne, Ar, (Kr, Xe)
2 helioseismology + SSM: H, He

see talks by
Gaël Buldgen
Aldo Serenelli
Francesco Villante

solar photosphere



spectroscopy of sunspots



Meteorites and asteriods

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Abundant ammonia and nitrogen-rich soluble organic matter in samples from asteroid (101955) Bennu

Daniel P. Glavin ✉, Jason P. Dworkin, Conel M. O'D. Alexander, José C. Aponte, Allison A. Baczynski, Jessica J. Barnes, Hans A. Bechtel, Eve L. Berger, Aaron S. Burton, Paola Caselli, Angela H. Chung, Simon J. Clemett, George D. Cody, Gerardo Dominguez, Jamie E. Elsila, Kendra K. Farnsworth, Dionysis I. Foustoukos, Katherine H. Freeman, Yoshihiro Furukawa, Zack Gainsforth, Heather V. Graham, Tommaso Grassi, Barbara Michela Giuliano, Victoria E. Hamilton, ... Dante S. Lauretta

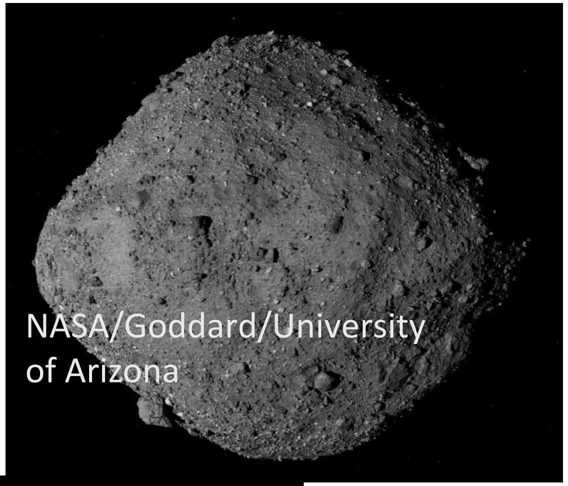
+ Show authors

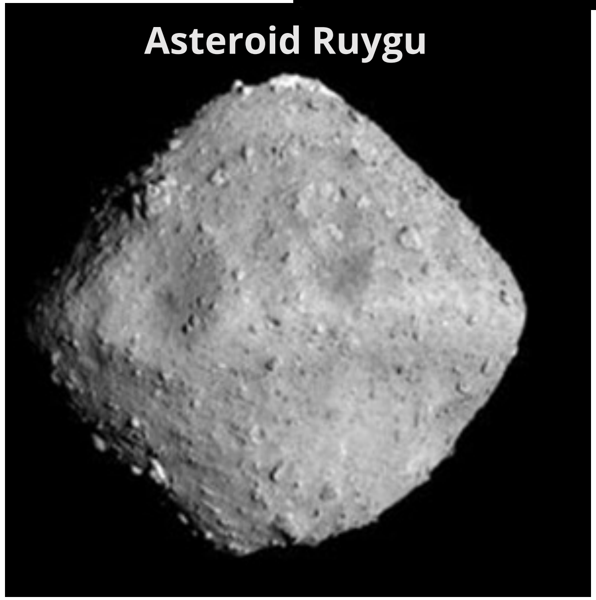
Nature Astronomy **9**, 199–210 (2025) | Cite this article

Abstract

Organic matter in meteorites reveals clues about early Solar System chemistry and the origin of molecules important to life, but terrestrial exposure complicates interpretation. Samples returned from the B-type asteroid Bennu by the Origins, Spectral Interpretation, Resource Identification, and Security–Regolith Explorer mission enabled us to study pristine

Asteroid Bennu





Tokyo, Kochi University, Rikkyo University, Nagoya University,
echnology, Meiji University, University of Aizu, AIST

Meteorites and asteriods

83 elements can be measured + (most) isotopes

good consistency, but terrestrial environment (oxidation), mass effects, solar system formation

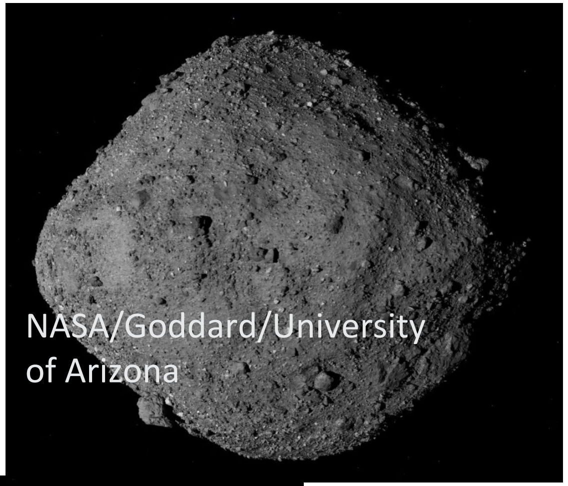
H, C, N, O + noble gases not quantitatively retained ➔ requires another element to connect to the Sun

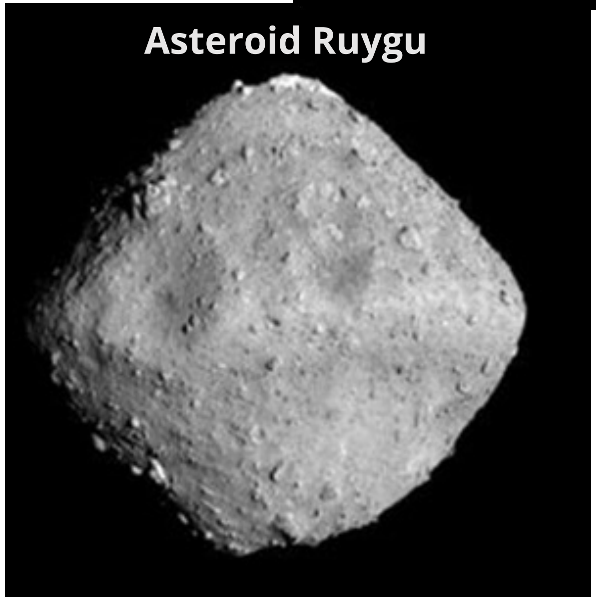
Asteroid sample return missions

Bennu 2023 (e.g., Lauretta et al. 2024)

Ryugu 2020 (e.g., Yokoyama et al. 2025)

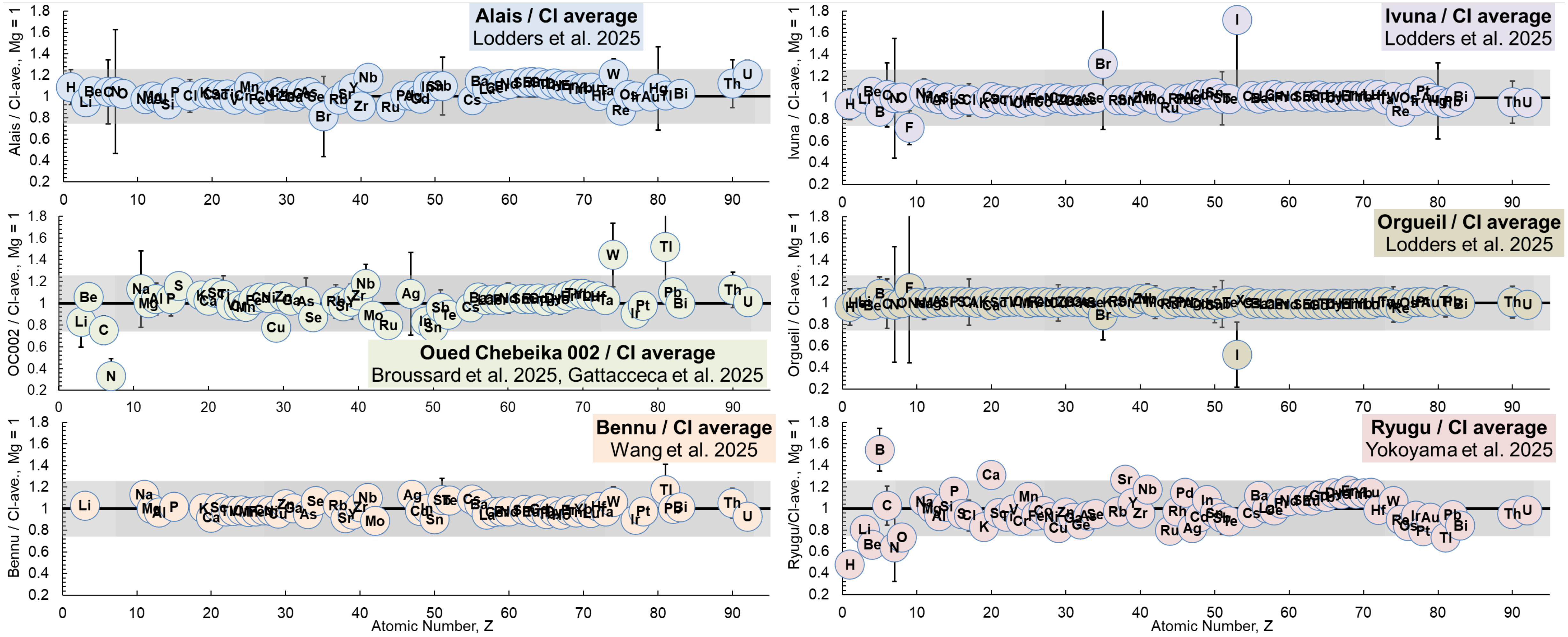
Asteroid Bennu



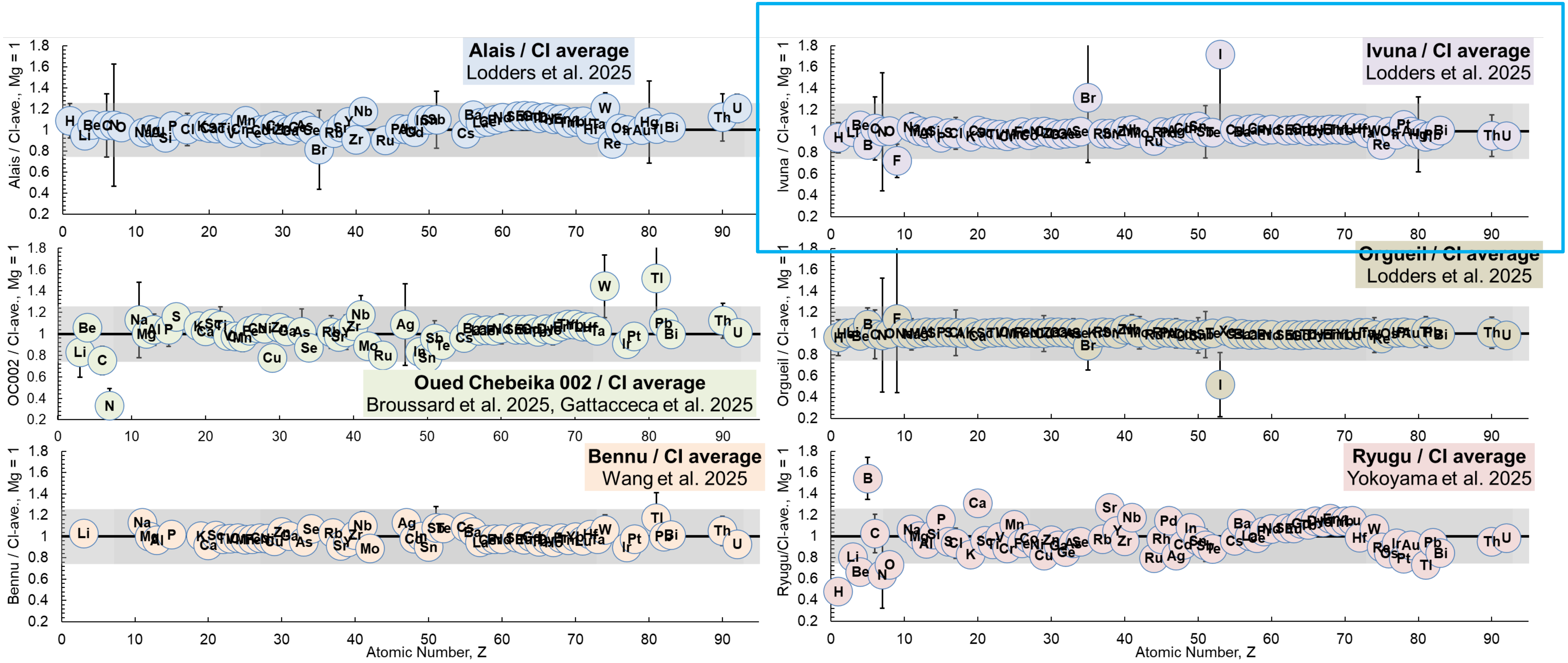


JAXA, University of Tokyo, Kochi University, Rikkyo University, Nagoya University, Chiba Institute of Technology, Meiji University, University of Aizu, AIST

Compositions of Individual **CI-Chondrites** and Asteroids **Bennu and Ryugu relative to CI-chondrite average** composition



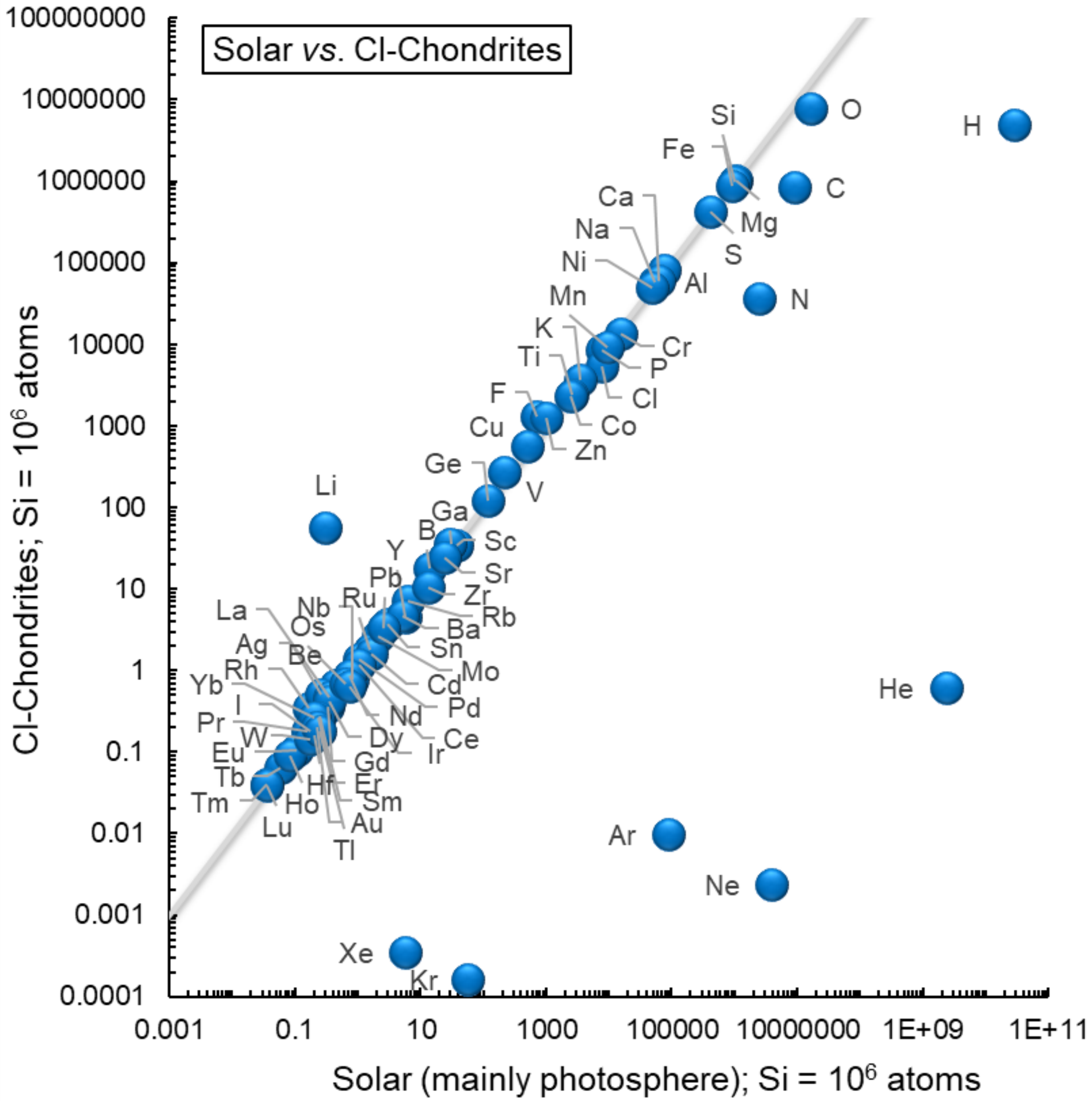
Compositions of Individual **CI-Chondrites** and Asteroids **Bennu and Ryugu relative to CI-chondrite average** composition



Why are C I type chondrite meteorites the best proxies?

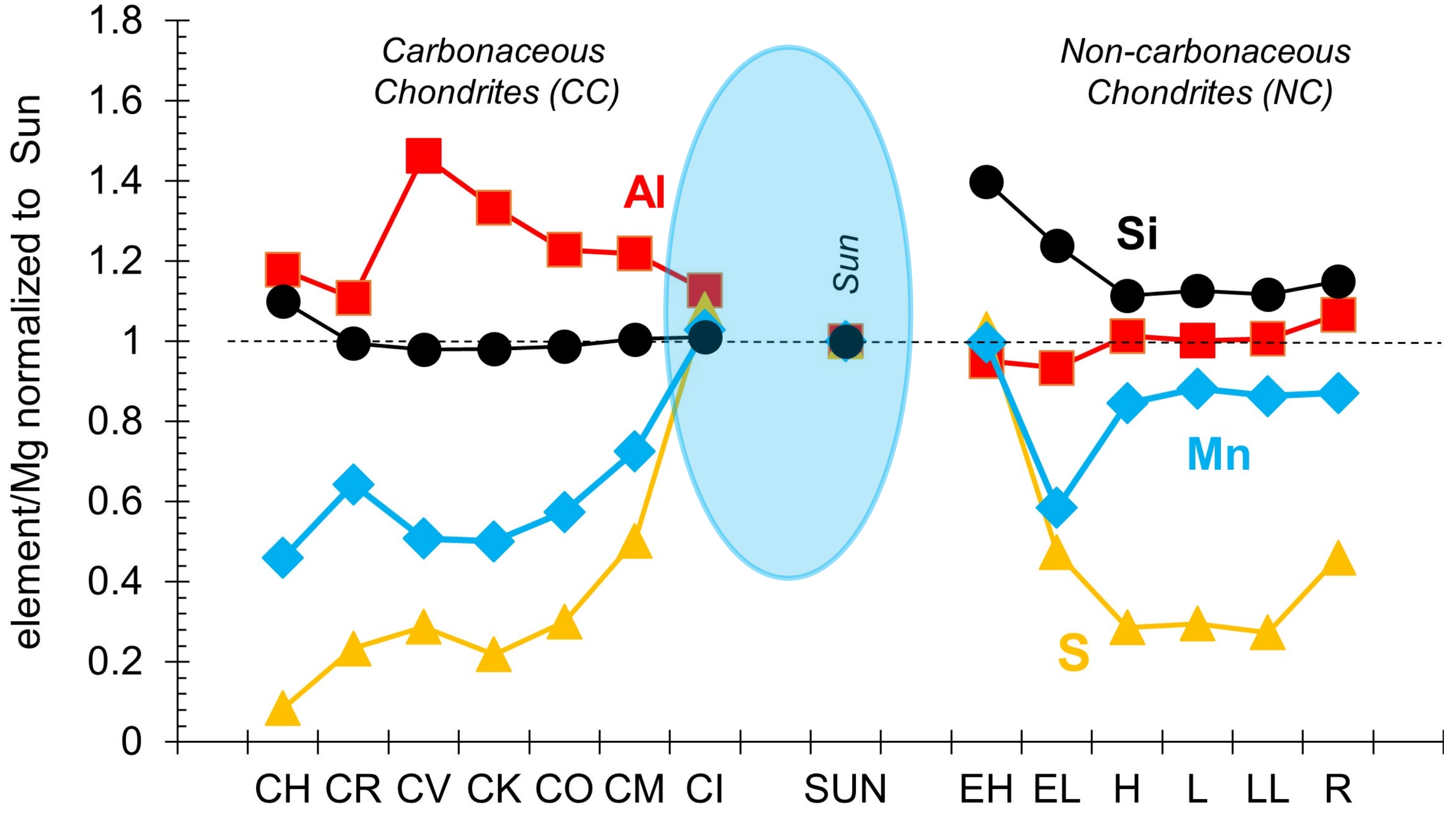
- closest in abundances (of non-volatiles) to solar photosphere

agreement over 8 orders of magnitude



Why are C I type chondrite meteorites the best proxies?

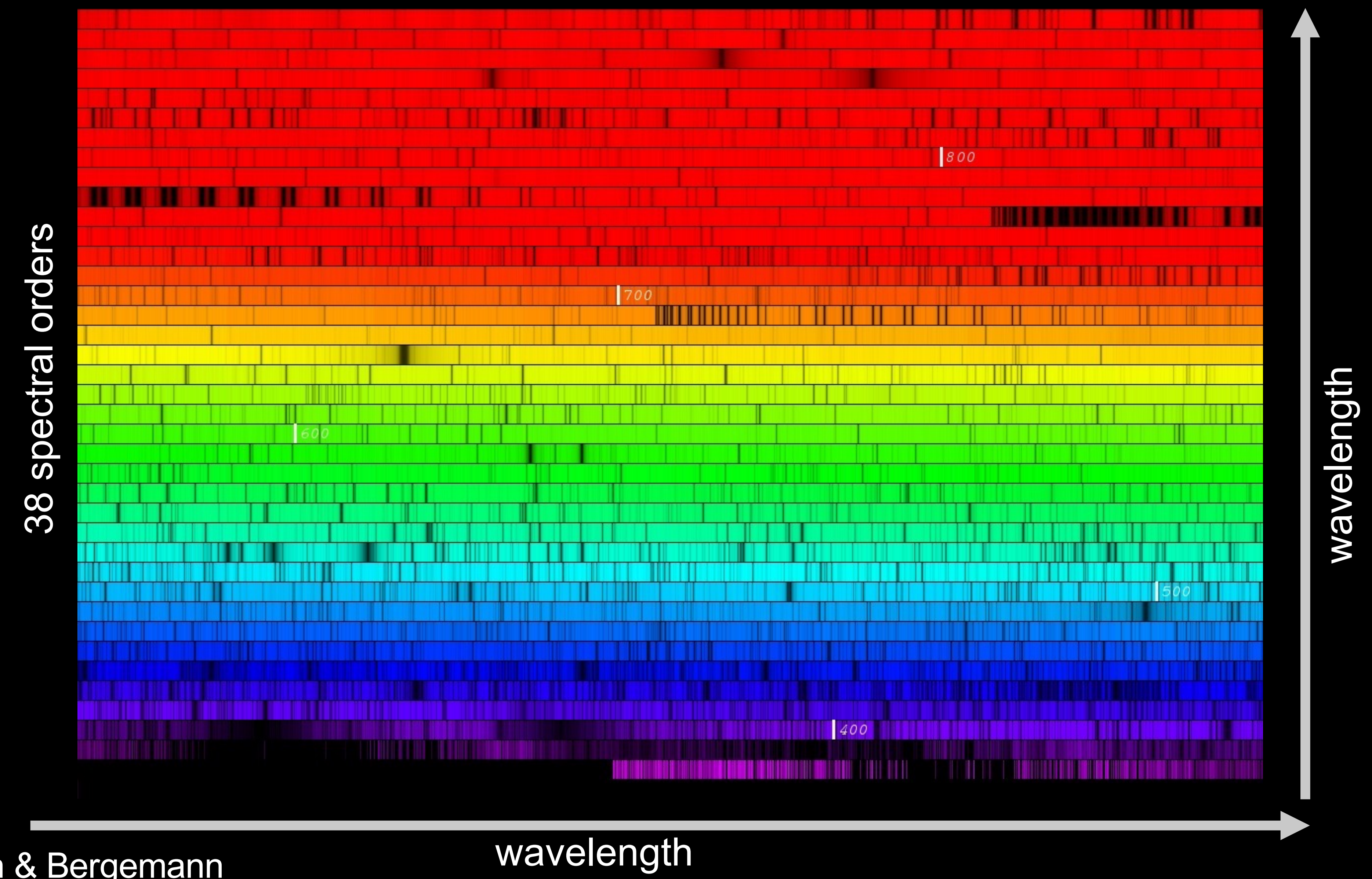
- agreements in **major element** abundance **ratios**, e.g., Si/Mg, Fe/Mg, Ca/Al
- **highest relative content of volatile elements** among most other chondrite groups; e.g., S/Mg
- likely formed in the 3-7 AU region (i.e., outer solar system) *Scott & Krot 2013*



Al for refractory. Si, (Mg) for major. Mn,S for volatile

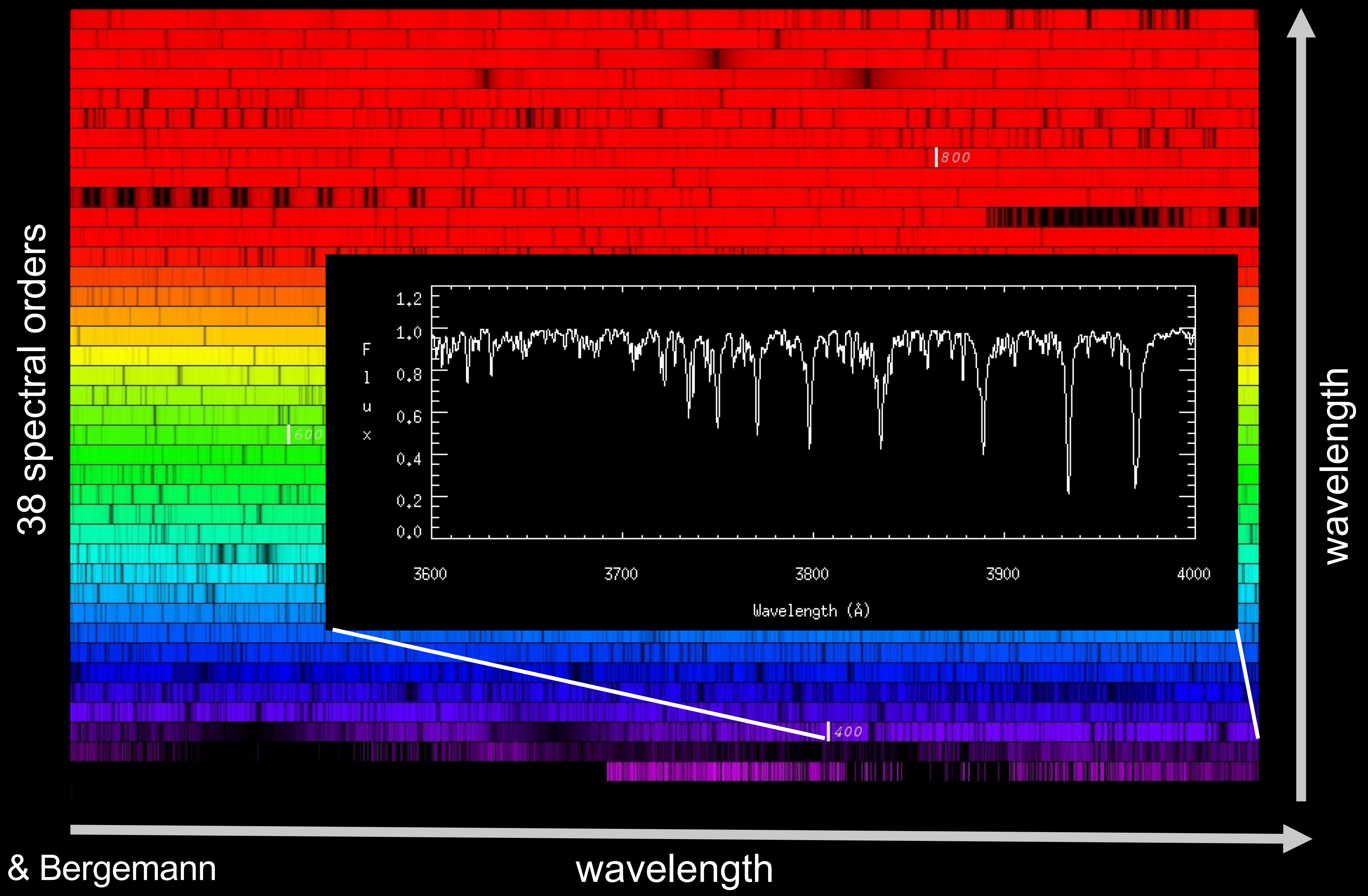
Abundances from the Solar spectra

UV to infra-red spectra of the Sun, R ~ 80000



(c) Brinkmann & Bergemann

UV to infra-red spectra of the Sun, R ~ 80000



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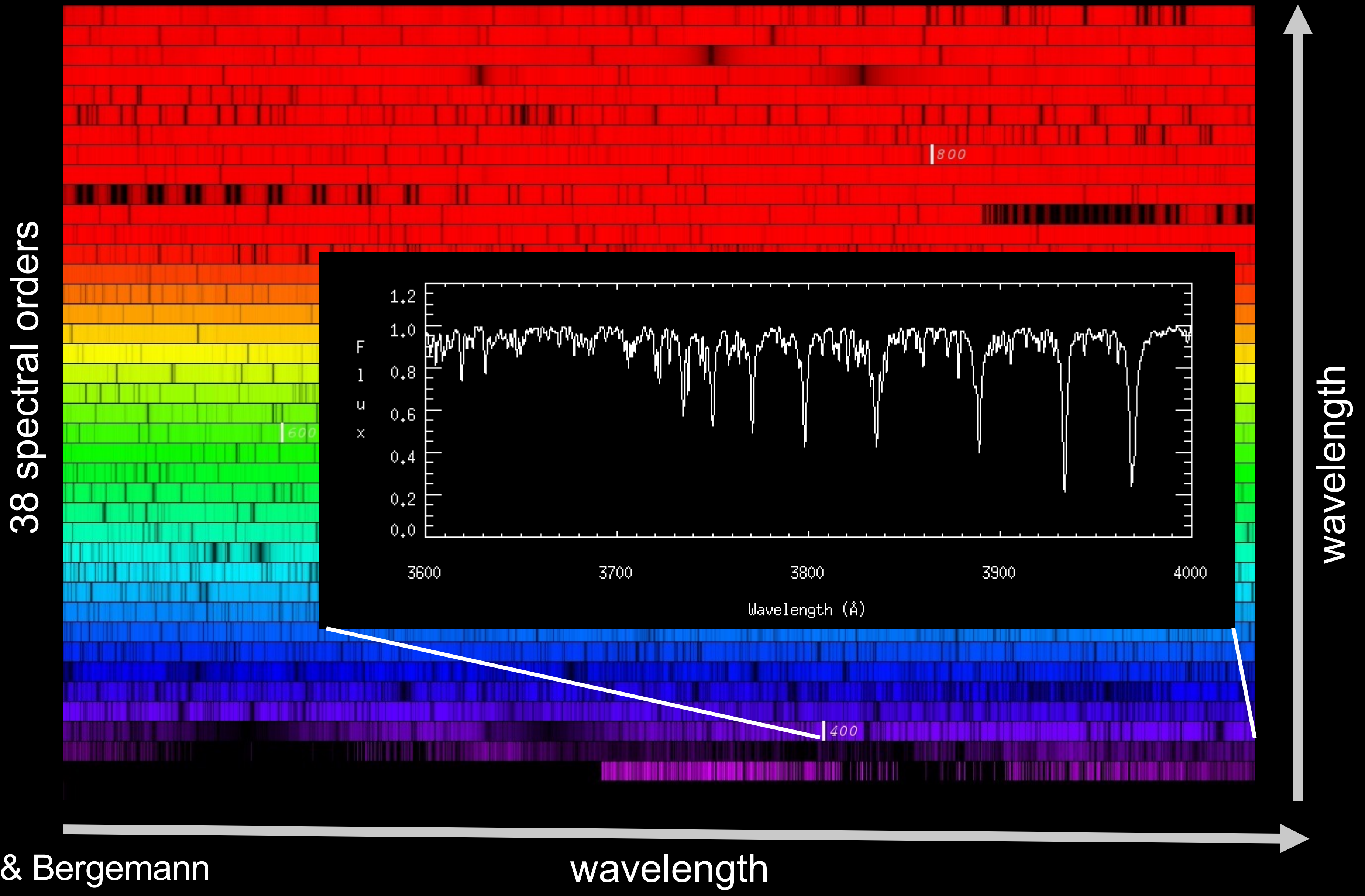

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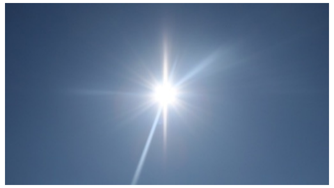
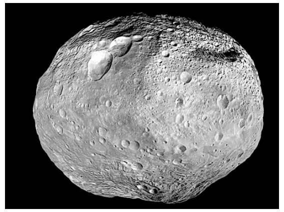
Abundances from the Solar Photosphere

Sun

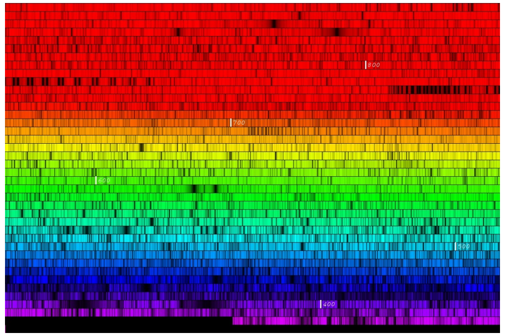




Vesta

Ceres

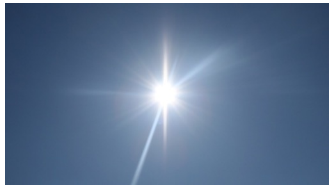
Observed spectra

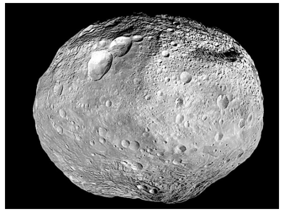


Solar chemical abundances

Abundances from the Solar Photosphere

Sun





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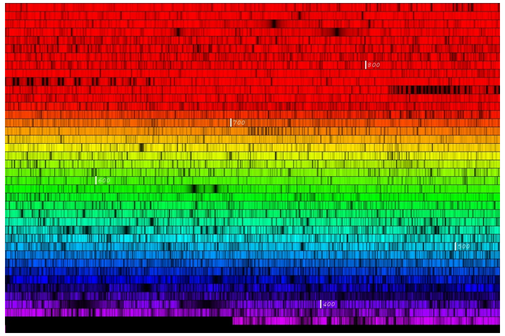

~~Solar chemical abundances~~

Abundances from the Solar Photosphere

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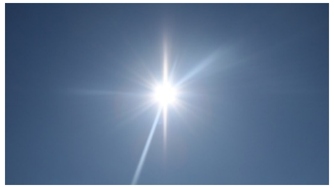

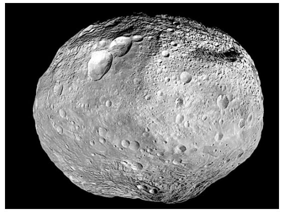

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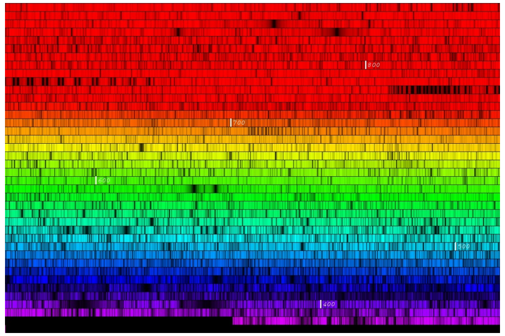
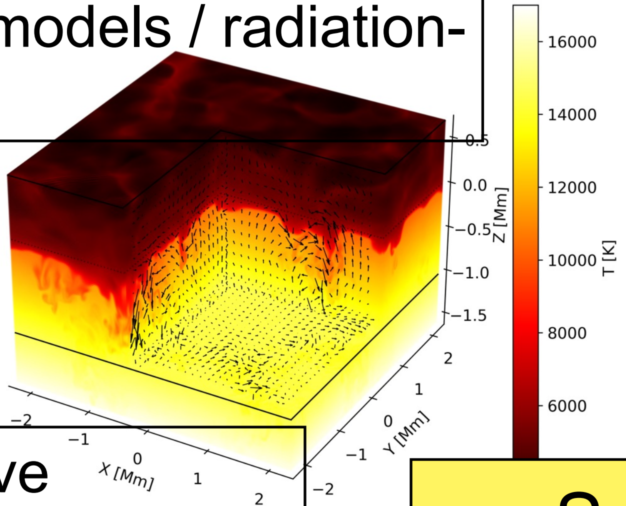
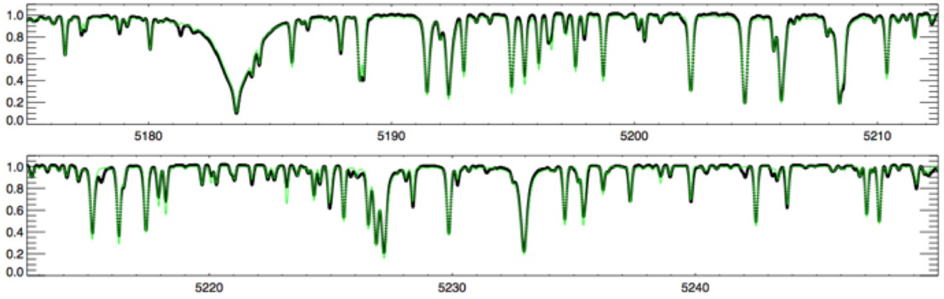


Solar physical models / radiation-hydrodynamics



Line formation + nuclear dynamics + atomic /molecular physics (lab + theory)

Grid calculations for different values of [X/H]



Comprehensive (probabilistic + e.g. machine learning) statistical analysis of the data: model vs observed

Solar chemical abundances

Abundances from the Solar Photosphere

- Currently 16 elements with full 3D NLTE analysis
- Many recent improvements, more revisions forthcoming
- Overall abundances trending to higher values

Li, Be, C, N, O,
Na, Mg, Al, Si, K, Ca,
Mn, Fe, [Ni]
Y, Ba, Eu

Asplund et al. (2021), Amarsi et al. (2020, 2024), Bergemann (2019, 2021), Caffau et al. (2011, 2015), Deshmukh et al. (2022)*, Gallagher et al. (2020), Magg et al. (2022), Lind et al. (2017), Steffen et al. (2016), Storm et al. (2024) and other studies by these groups

Different reasons to re-visit

systematic analysis and new calculations in *Magg et al. 2022*
Bergemann, Lodders, & Palme 2025
Lodders, Bergemann & Palme 2025

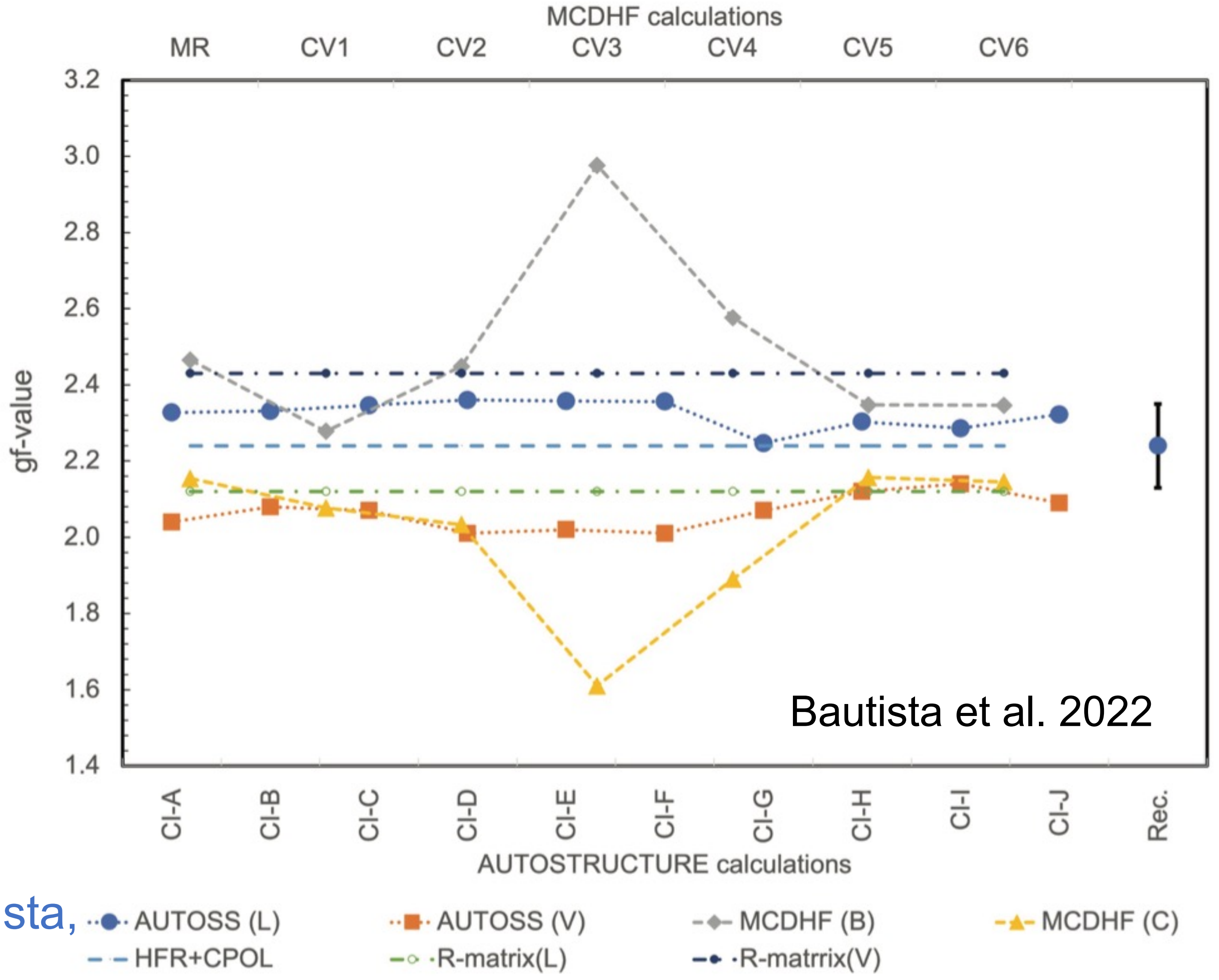
many elements higher compared to Asplund et al. 2009, 2021

- New atomic and molecular data, NLTE models
- New solar model atmospheres
- New observational data (solar spectra)

Recent improvements

Uncertainty of f-values for the key solar oxygen transitions constrained to ~10%

C Li et al. 2021
O Bautista et al. 2022
N Bautista et al. 2022
Si Pehlivan Rhodin et al. 2021, Den Hartog et al. 2023
Ca Den Hartog et al. 2021



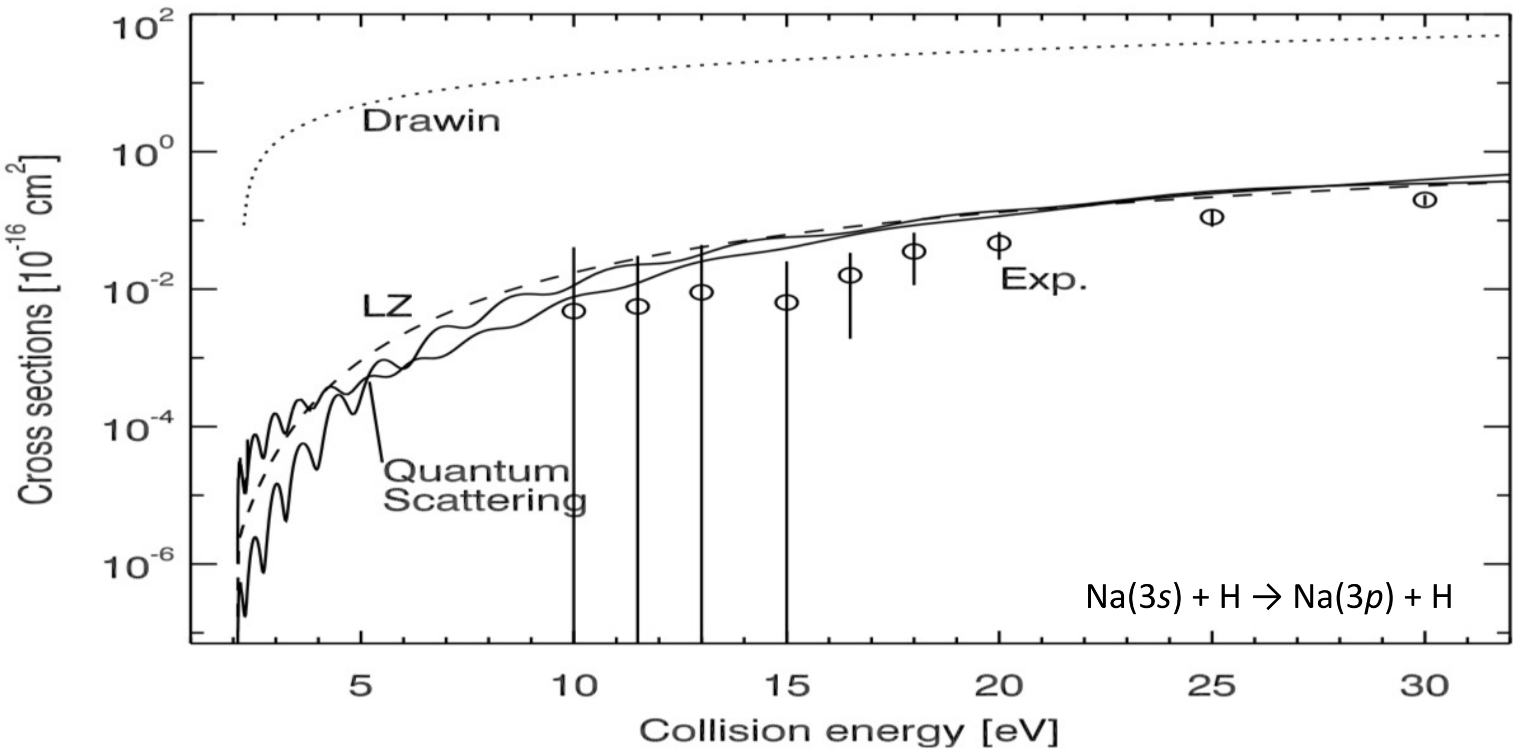
work in collaboration with Manuel Bautista, Patrick Palmeri, Pascal Quinet, Chris Sneden et al.

Recent improvements

Uncertainty of charge transfer, ion-pair, neutralization reactions to better than a factor of 2-5

B	Belyaev & Voronov 2022
S	Belyaev & Voronov 2020
Mn	Bergemann et al. 2019
Co	Yakovleva et al 2020
Ni	Voronov et al 2022
Cu	Belyaev et al 2021
Sr	Yakovleva et al 2022
Y	Storm et al. 2024
Eu	Storm et al. 2024

reactions that describe processes in elastic and inelastic collisions



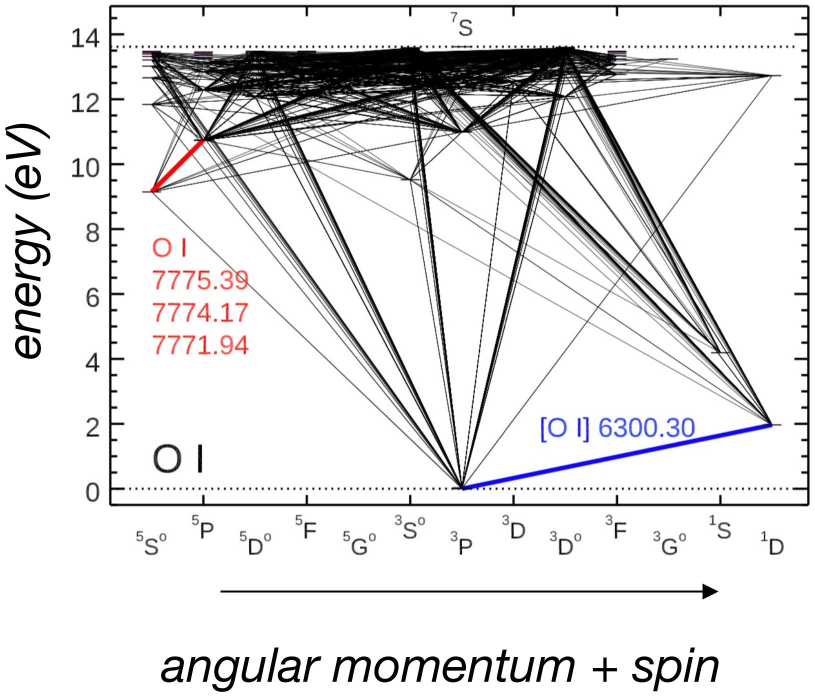
work in collaboration with Paul Barklem, Svetlana Yakovleva, Andrey Belyaev & colleagues

Barklem 2011, 2016

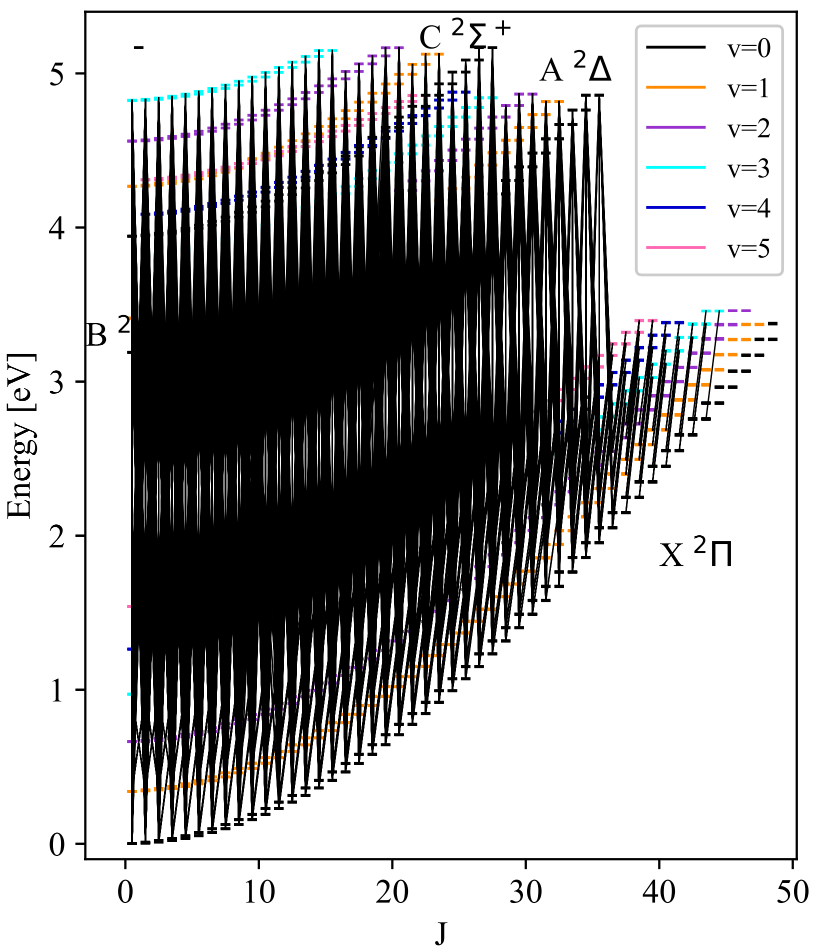
Recent improvements

NLTE models

atoms



molecules

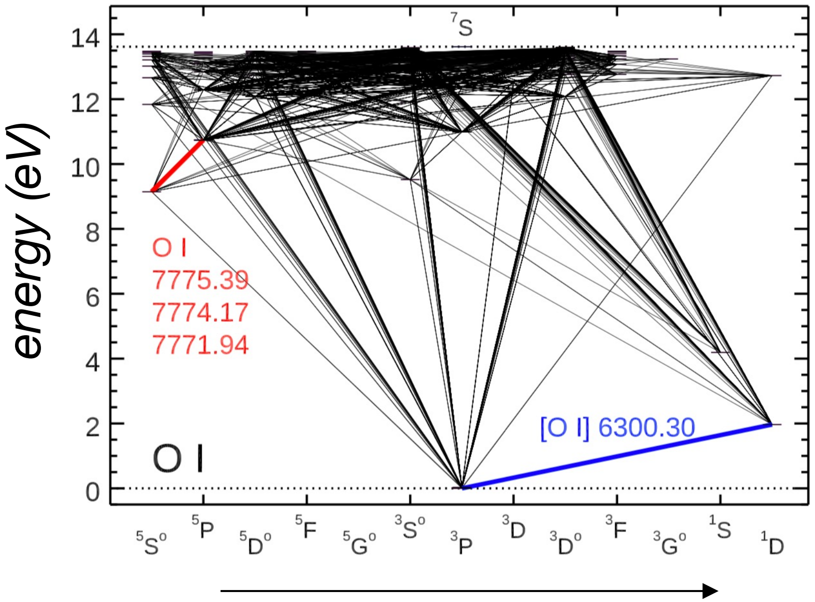


Bergemann & Hoppe subm. LRCA

Recent improvements

NLTE models

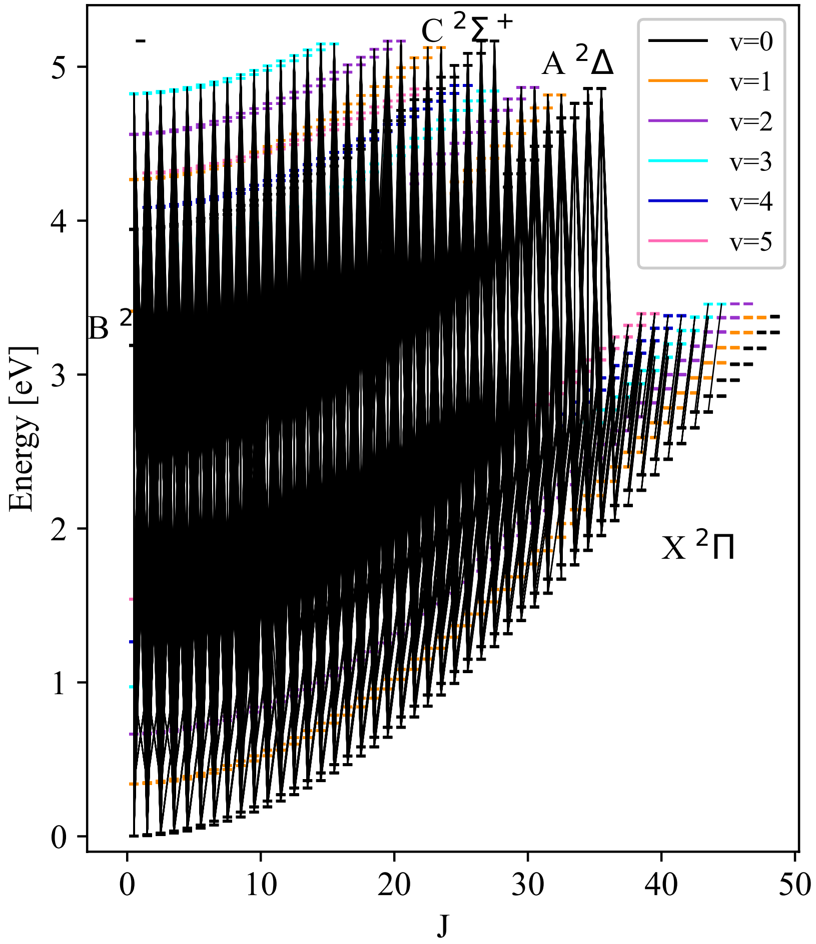
atoms



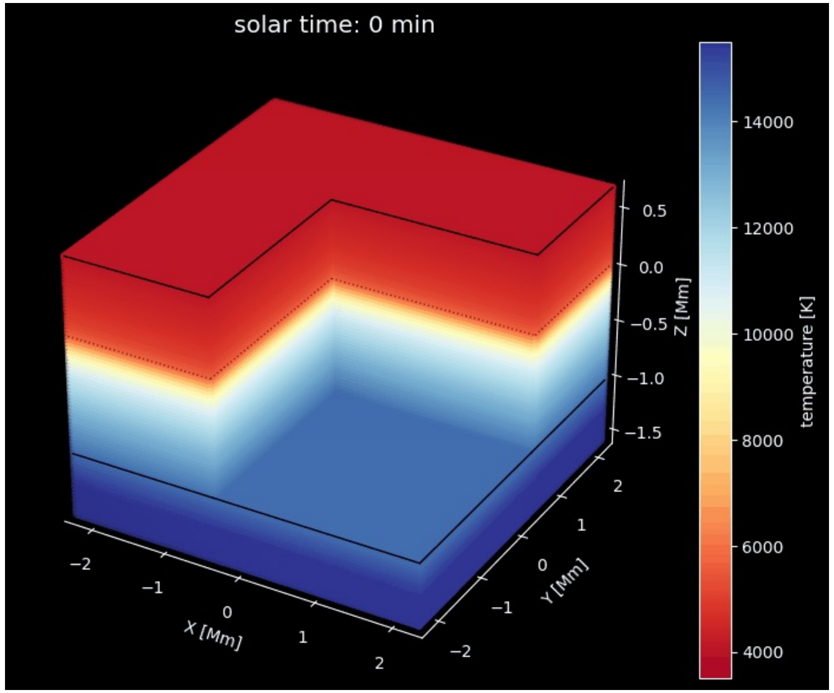
angular momentum + spin

Bergemann & Hoppe subm. LRCA

molecules



solar model atmospheres



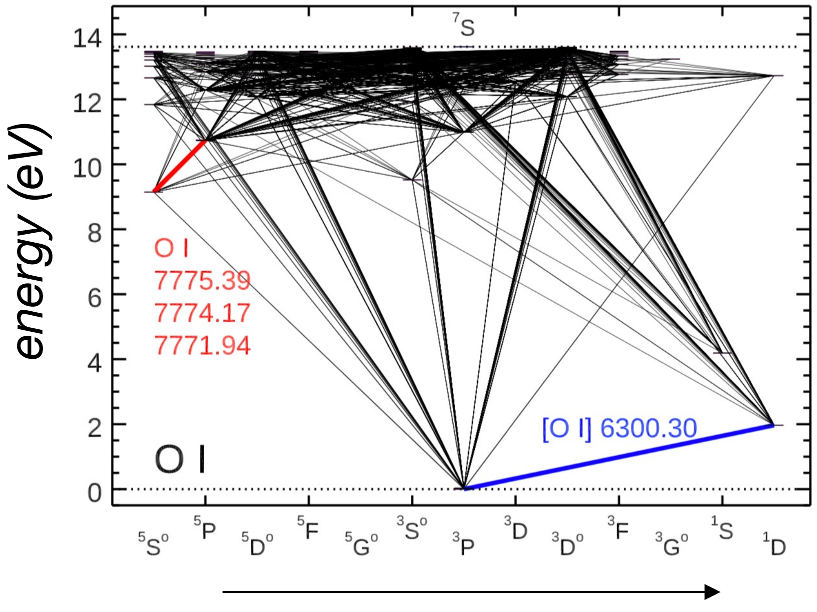
Eitner et al. 2024

Norldund et al. 2009,
Freytag et al. 2012, Vögler et al. 2004

T- ρ - v structures computed using Co^{5}BOLD, Stagger, Dispatch, Bifrost, Muram

Recent improvements

atoms



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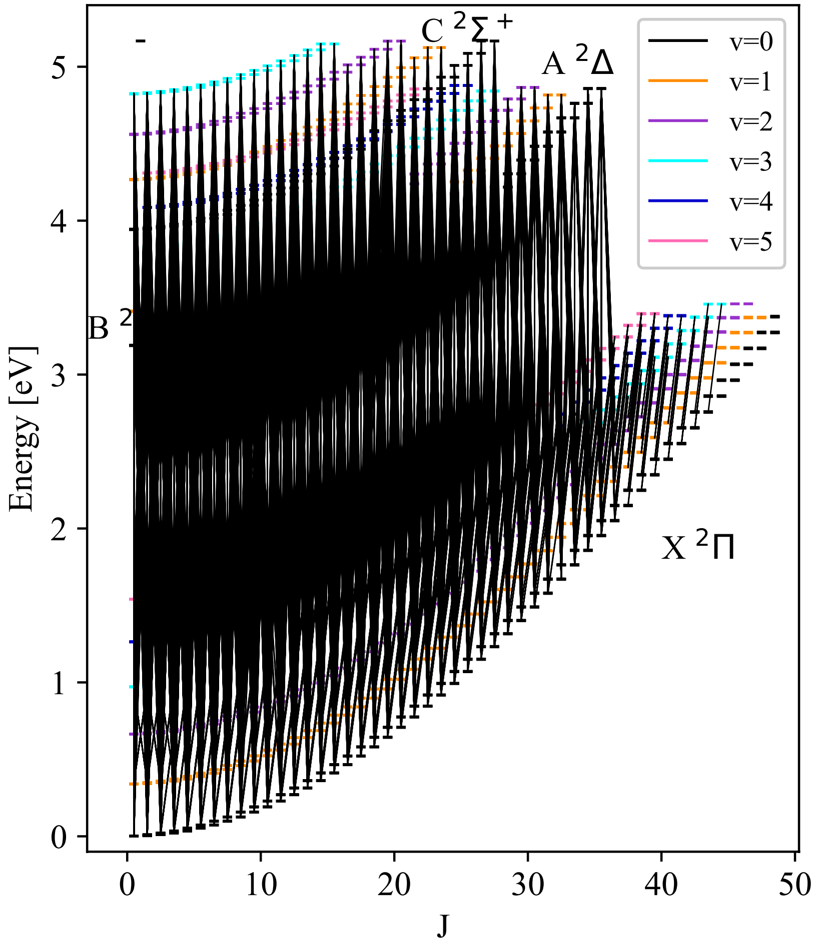

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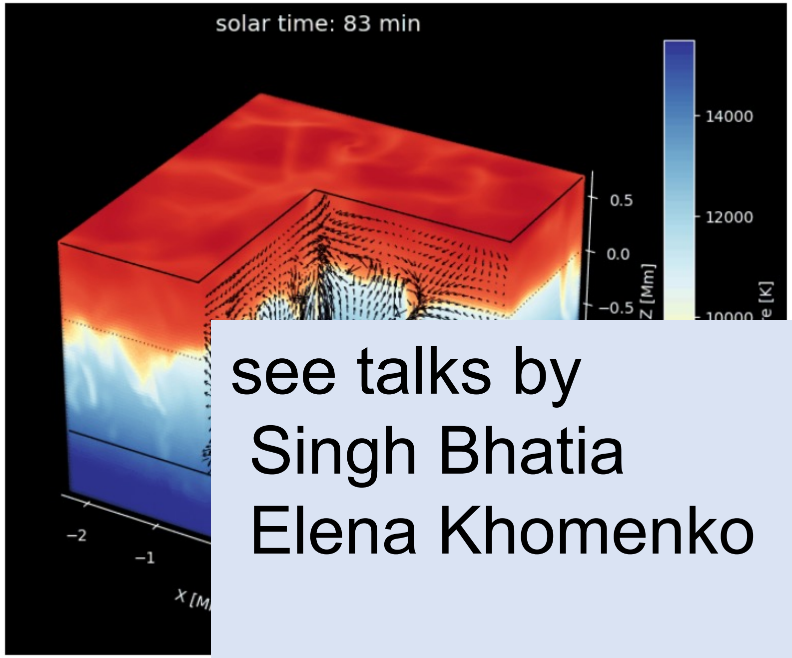


see talks by
Singh Bhatia
Elena Khomenko

effects of 3D MHD

T- ρ - v structures computed using Co^{5}BOLD, Stagger, Dispatch, Bifrost, Muram

Bergemann & Hoppe subm. LRCA

Differences between Solar Abundance Sets

systematic analysis in Magg et al. 2022, Lodders et al. 2025, Bergemann et al. 2025

atomic data: lower f-values lead to higher abundances

C (atomic), Si, Mg, O (perm.), Cu, Si

realistic quantum-mechanical data (NLTE): over-estimated collision rates

Mg, Mn, Co, Ni, Zn, Ba, Y, Eu

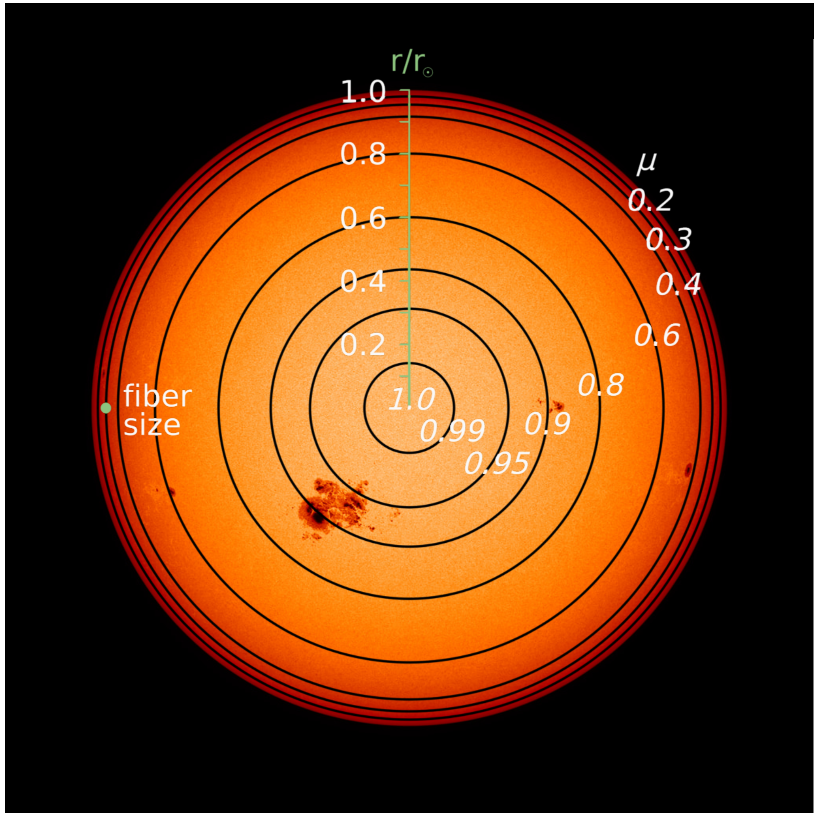
systematic uncertainties of 3D models: more recent estimates use different 3D RHD solar structures to account for incomplete physics

observed solar spectra: higher R and spatial resolution (IAG and SST data), line selection (e.g. misclassified blends, continuum)

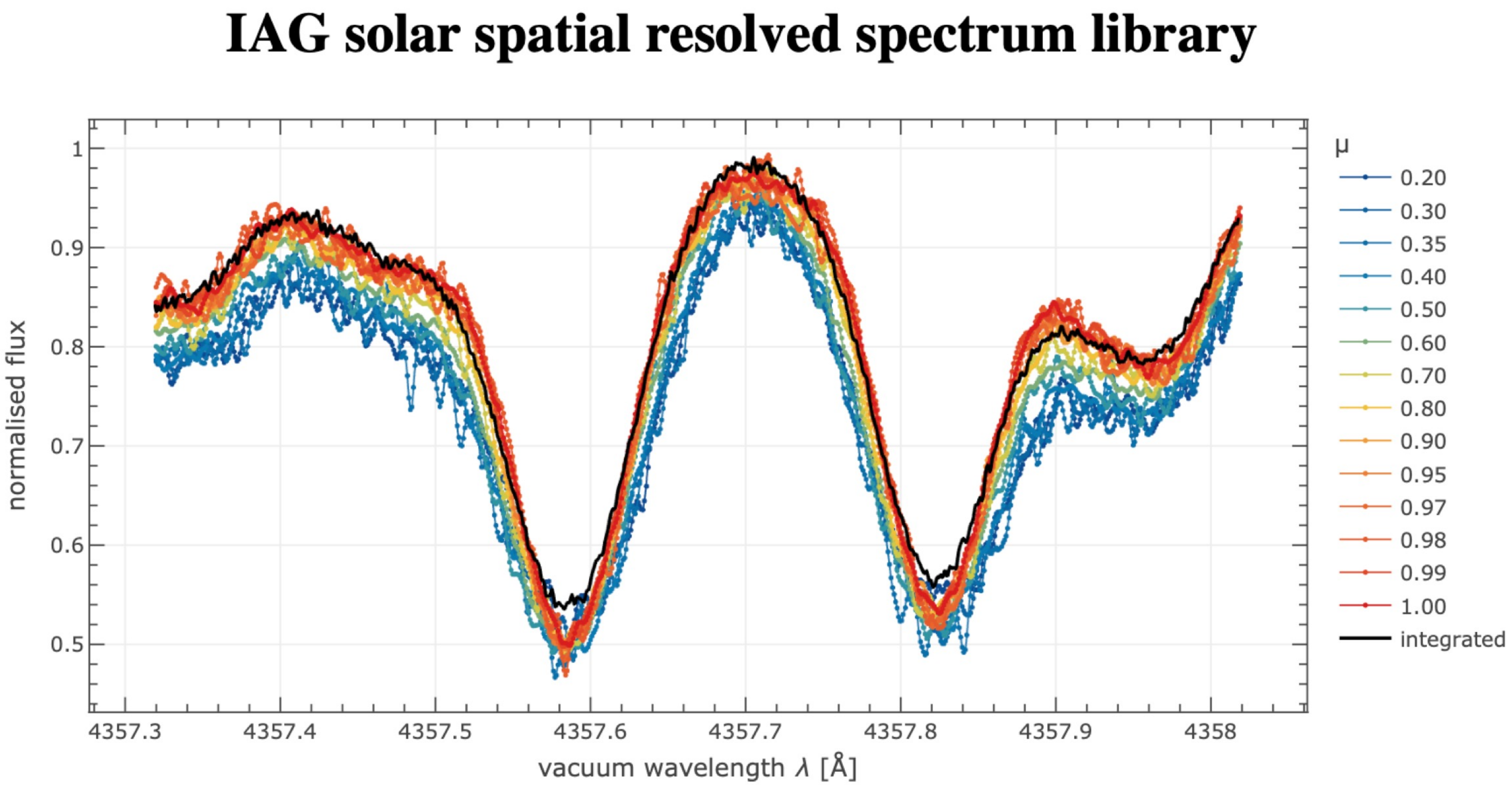
C (molecular), N, O (forb.), Fe, Ca

Solar center-to-limb variation

Different angles probe different layers of the solar atmosphere



(c) Richard Hoppe



Ellwarth et al 2023 (intensity)

https://www.astro.physik.uni-goettingen.de/research/solar-lib/

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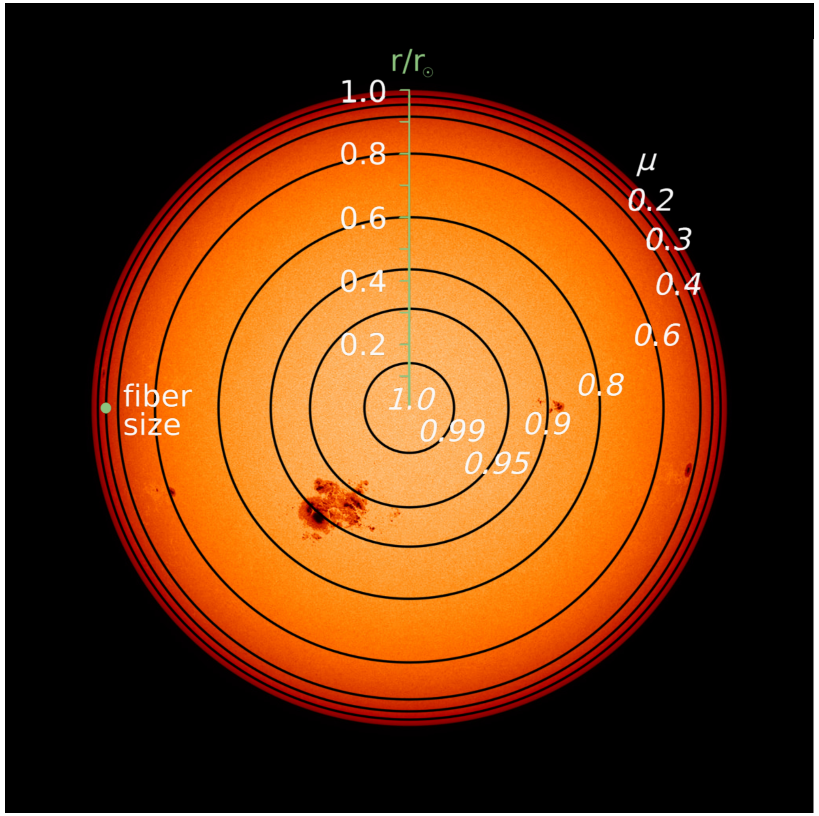

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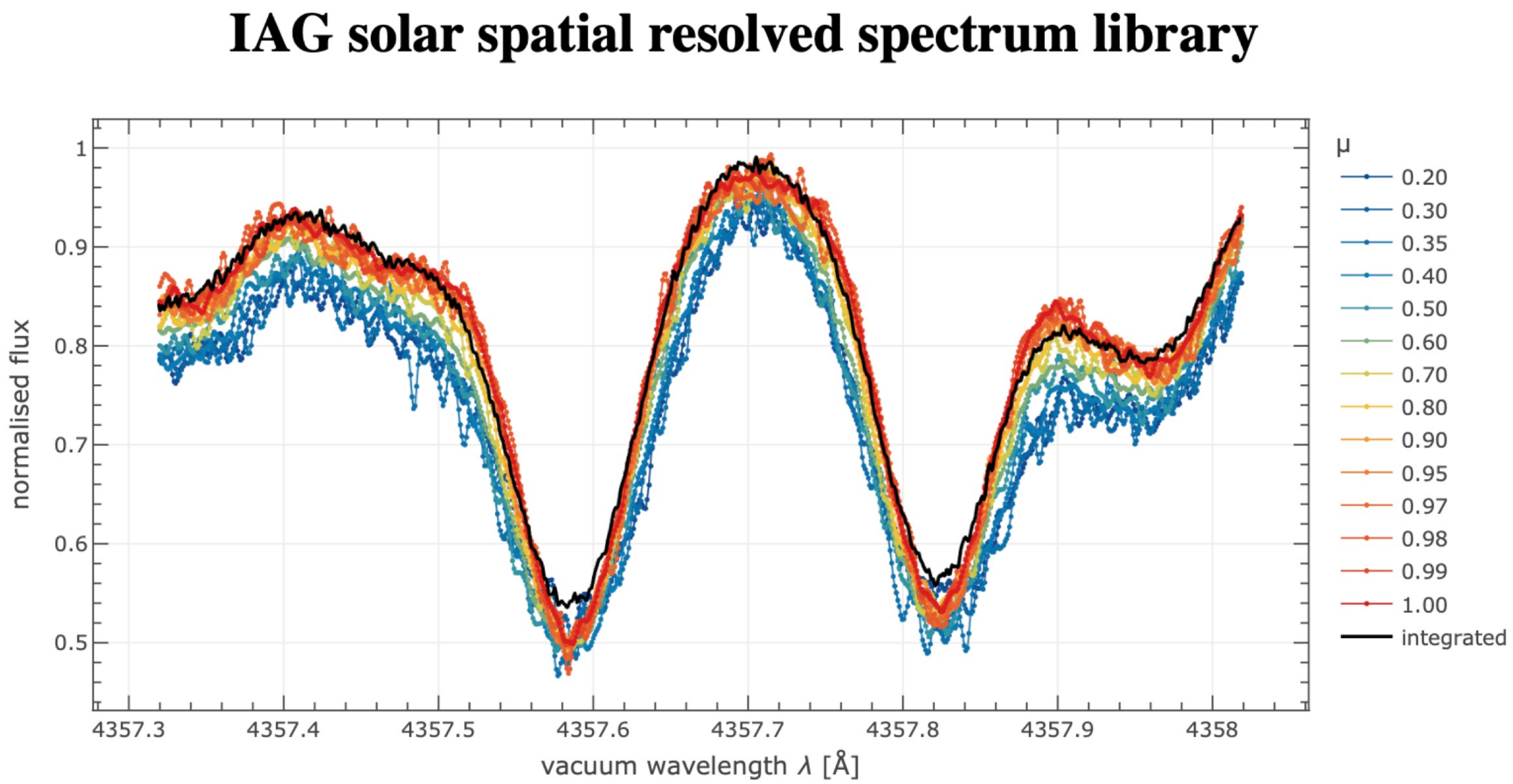


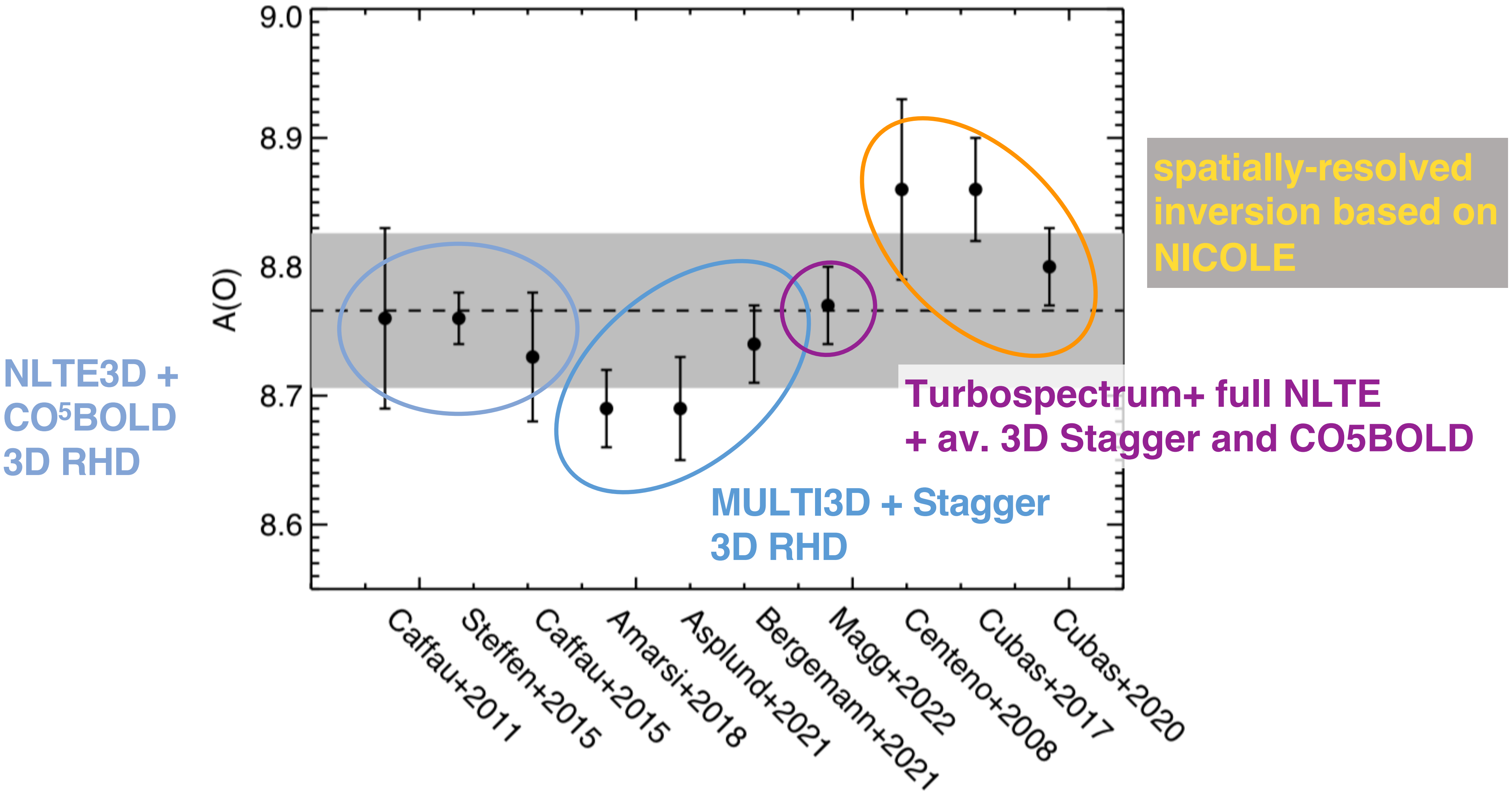
Ellwarth et al 2023 (intensity)

https://www.astro.physik.uni-goettingen.de/research/solar-lib/

applied to O (Bergemann & Hoppe et al. 2021),
C (Hoppe et al. 2025, subm.), Eu,Y (Storm et al. 2024)

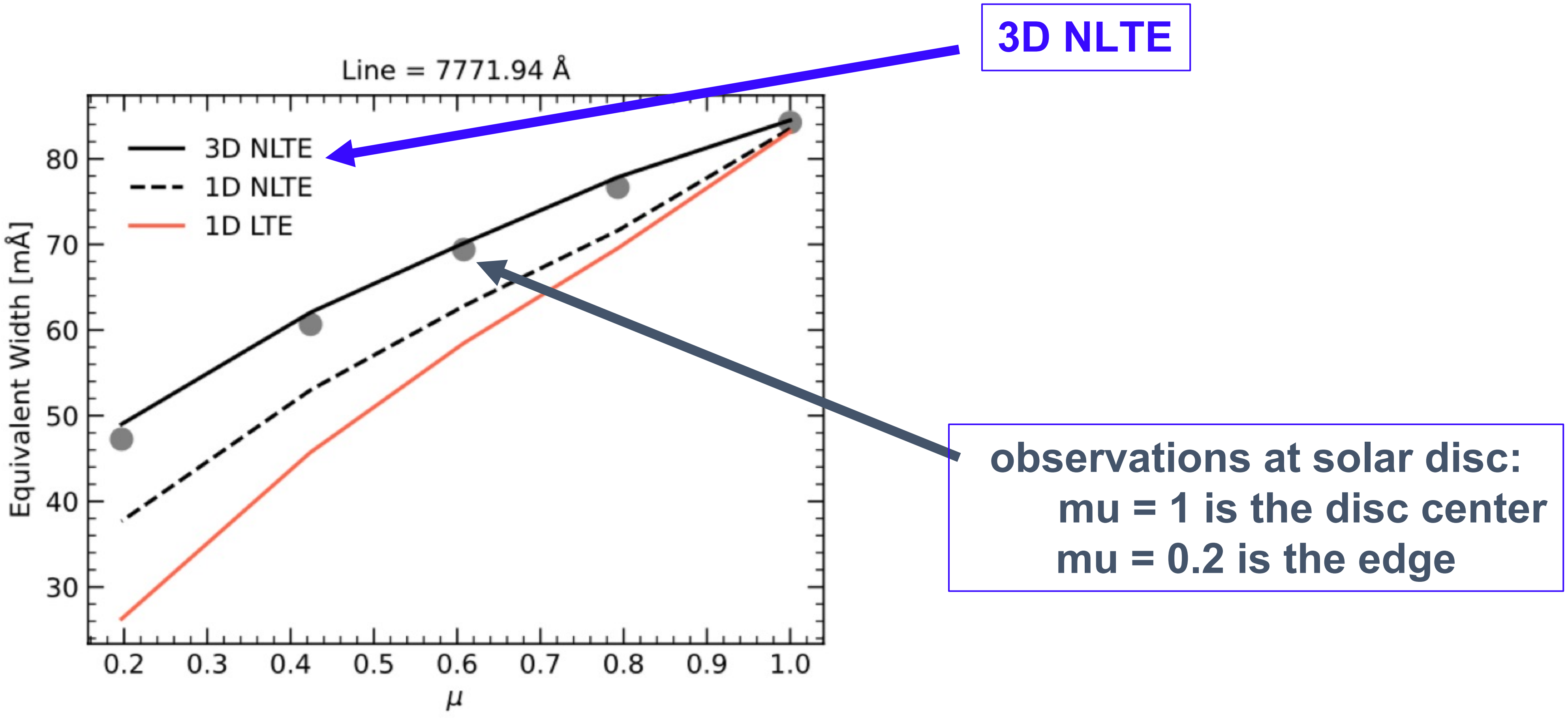
Solar Oxygen Abundance

3d most abundant element by number (after H, He)
highly relevant for solar interior
influences water ice:rock ratios in protoplanetary disks, planetary oxidation state



Solar center-to-limb variation

3D NLTE: consistent oxygen EWs (O I, [O I]) and abundances at all positions across the solar disc



Bergemann & Hoppe et al. 2021

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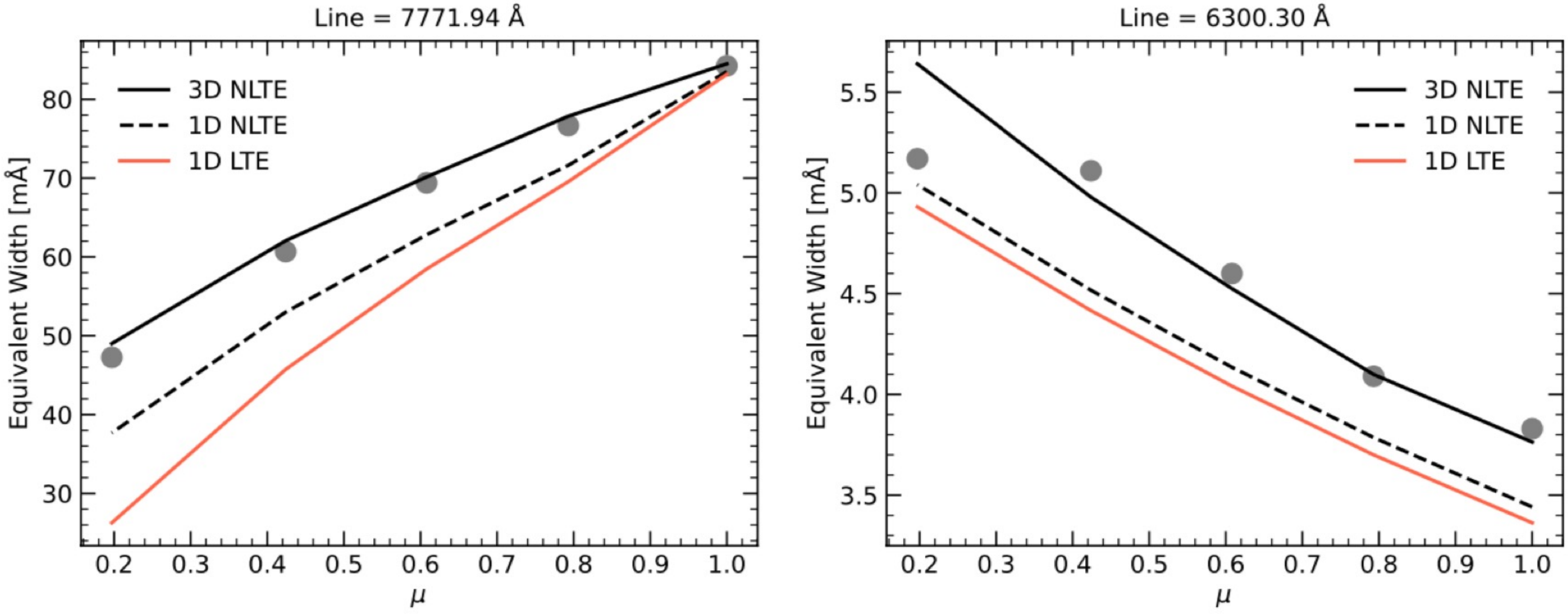

Bergemann & Hoppe et al. 2021

Solar Oxygen Abundance

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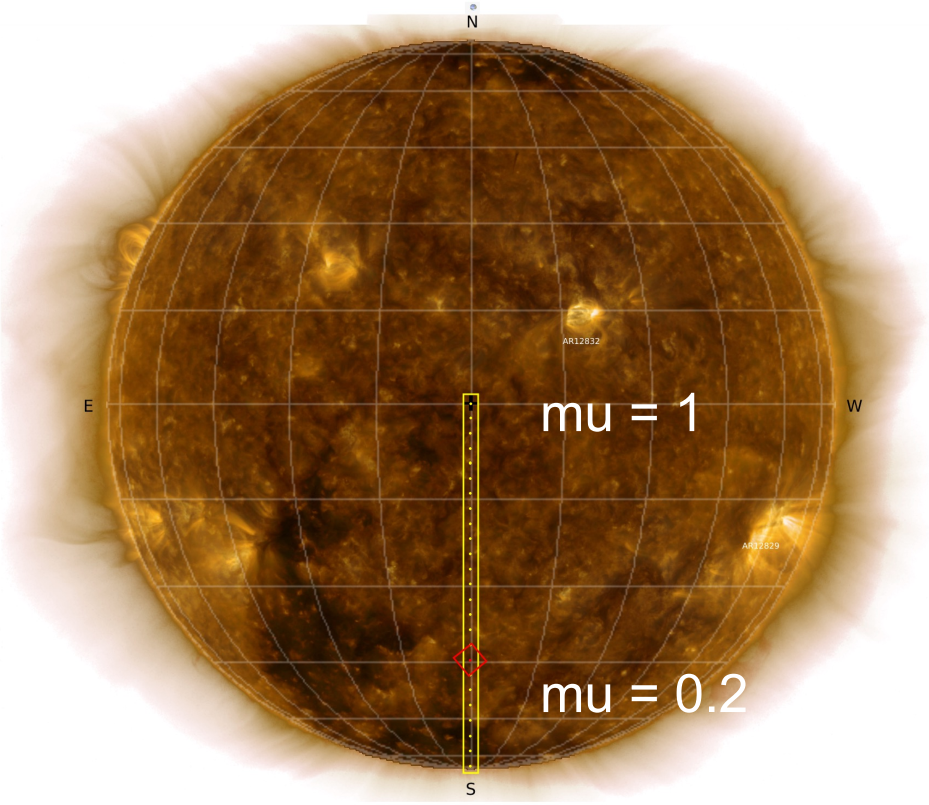

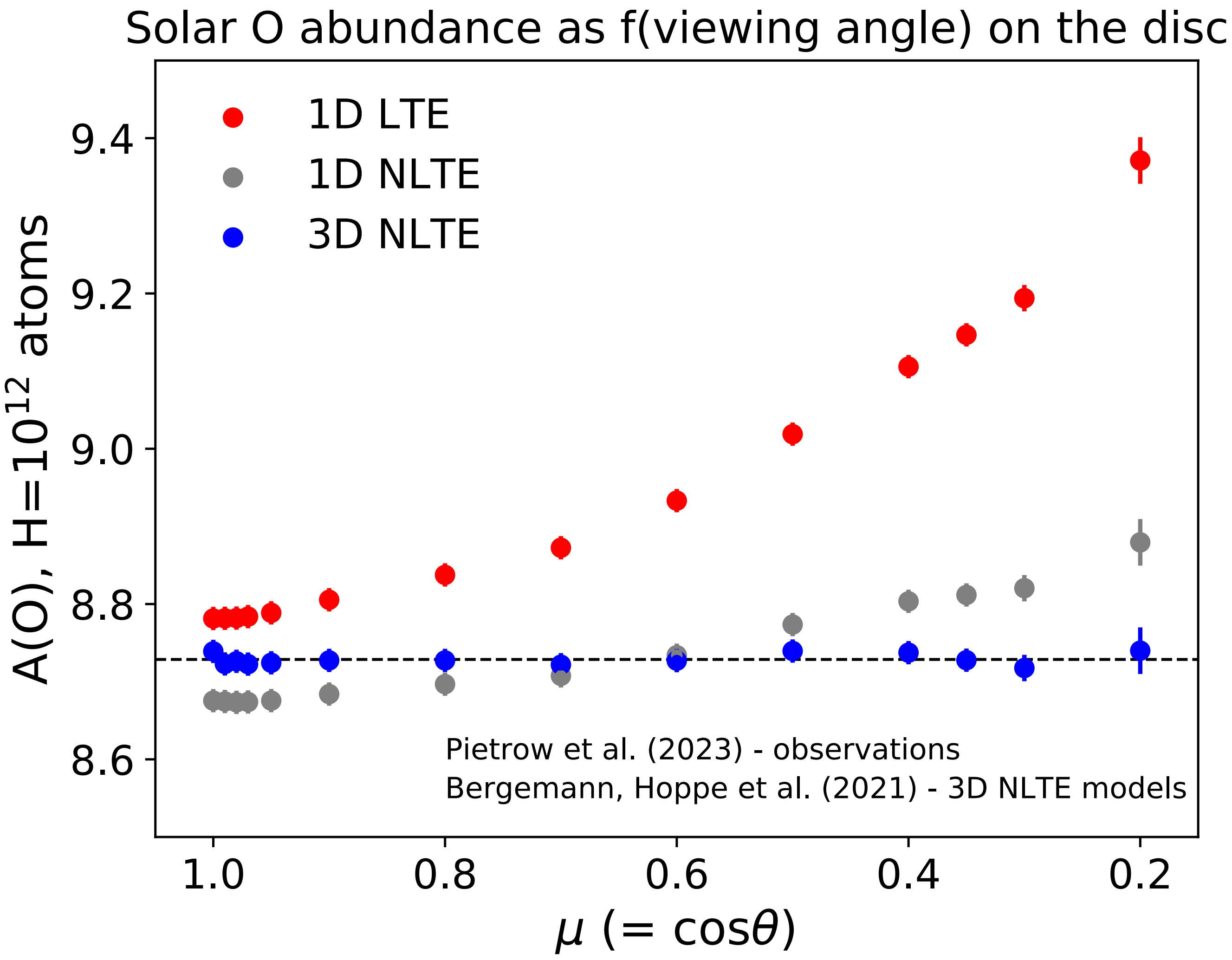

Bergemann & Hoppe et al. 2021
Pietrow et al. 2023

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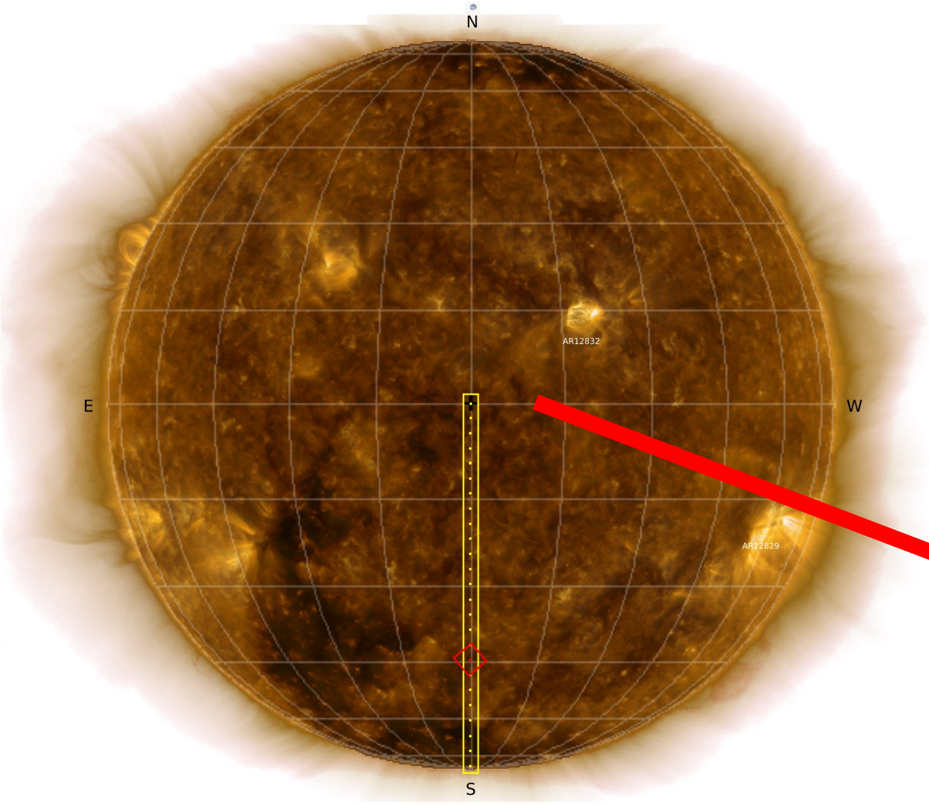
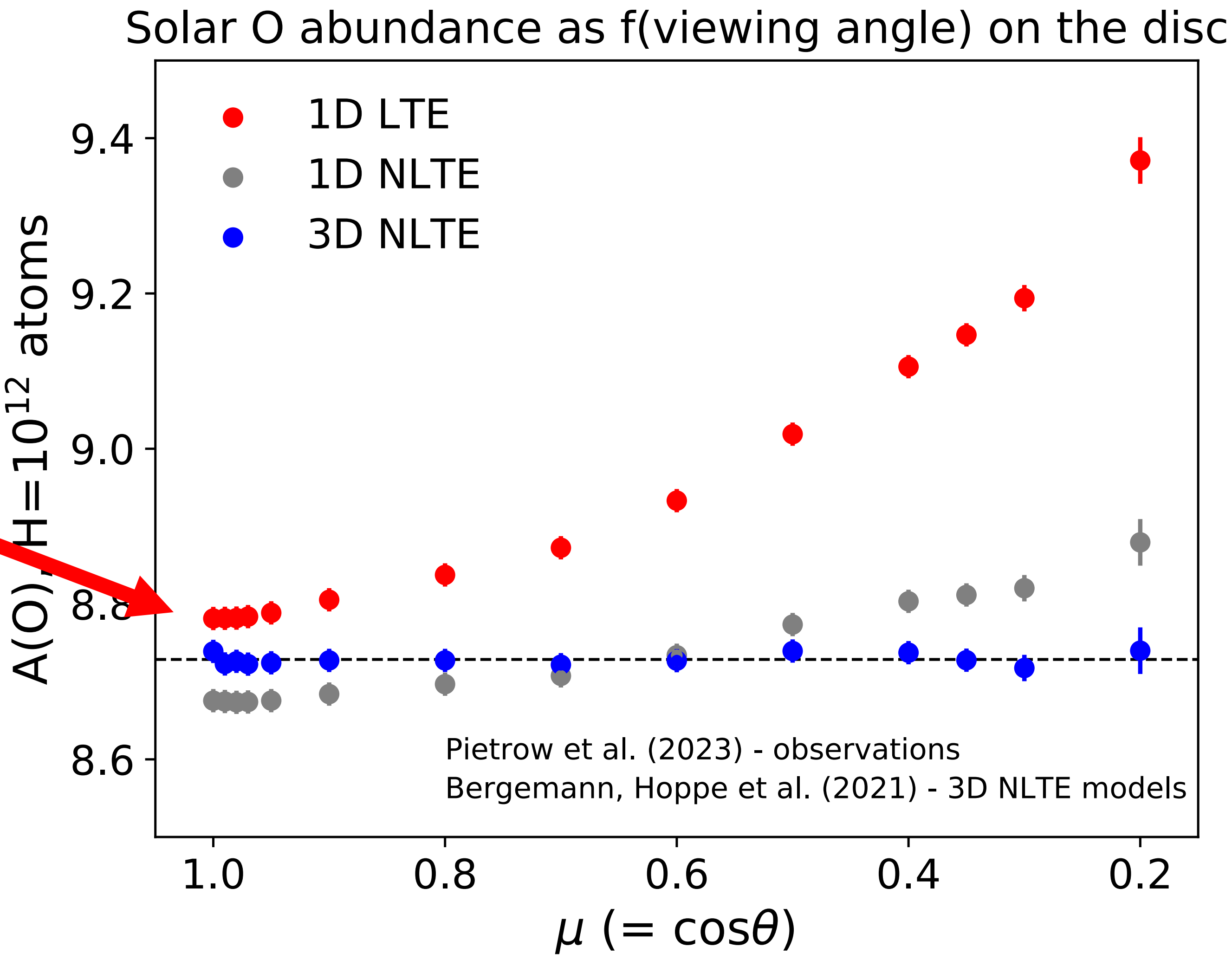
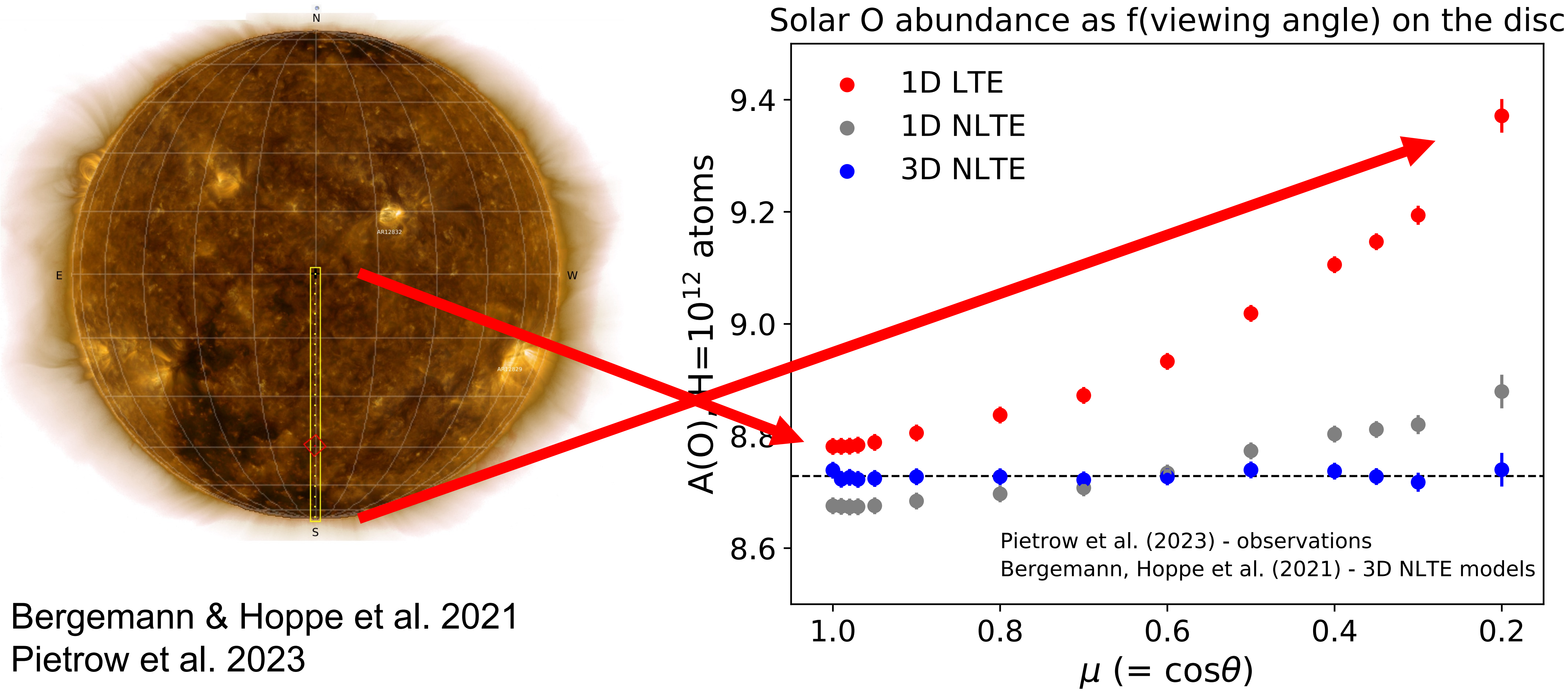




Bergemann & Hoppe et al. 2021
Pietrow et al. 2023

Solar Oxygen Abundance

consistent oxygen EWs (O I, [O I]) and abundances across the solar disc

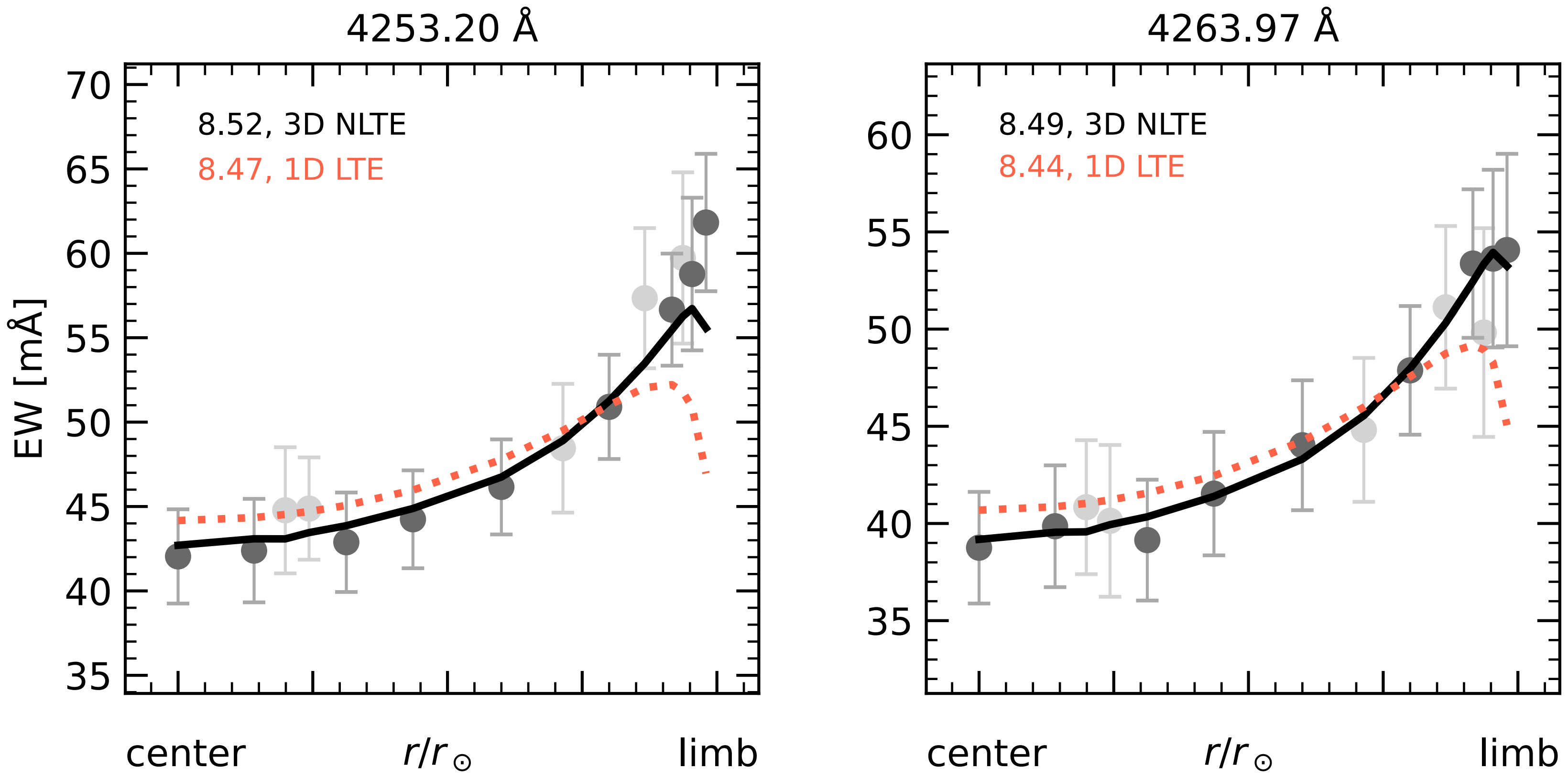


Bergemann & Hoppe et al. 2021
Pietrow et al. 2023

Solar Carbon Abundance

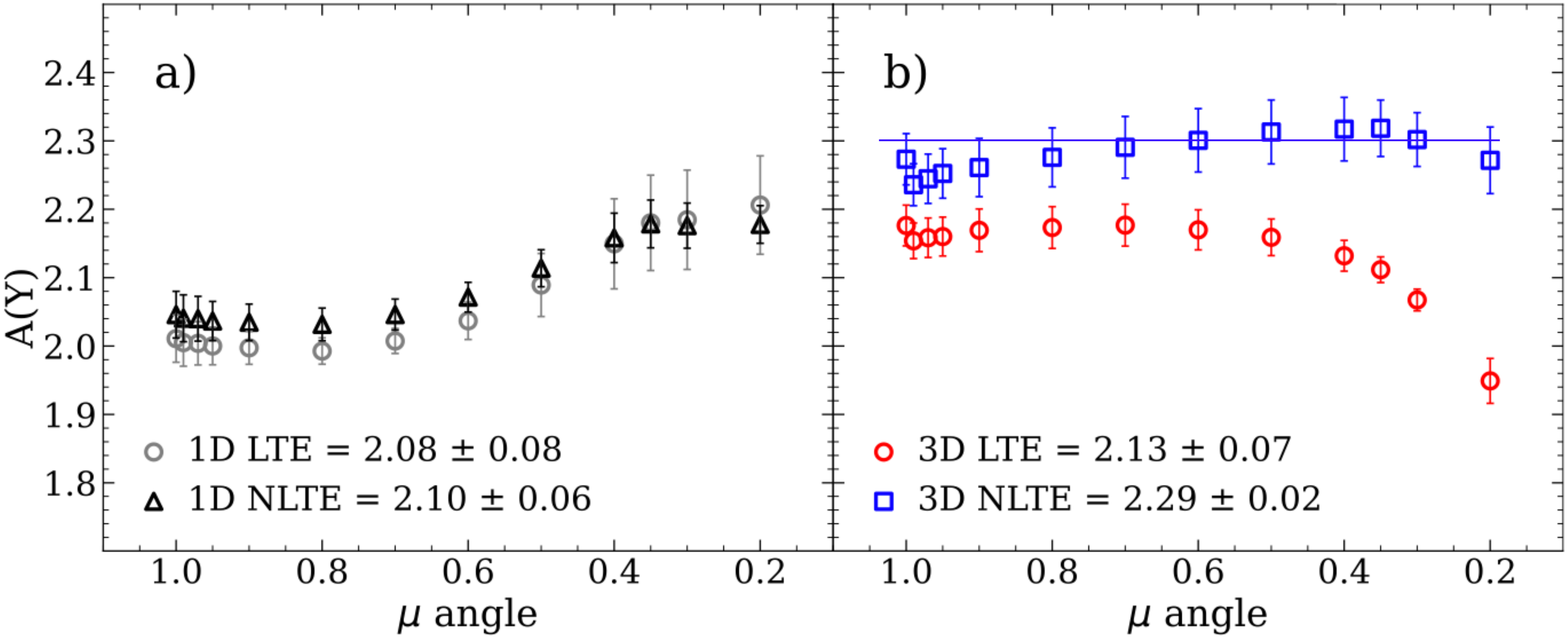
center-to-limb variation of CH lines and carbon abundance

Lines	N_μ	N_{lines}	NLTE
A-X (optical)	9	9	8.52
vib-rot (infra-red)	1	50	8.51



Hoppe, B+ et al. subm.

Solar Yttrium Abundance



Storm, B+ et al. 2024

Higher abundances for many elements

Bergemann, Lodders, & Palme 2025
Lodders, Bergemann & Palme 2025

- complete revision of the chemical composition: elemental abundances and isotopes for all elements

- 3D NLTE analysis, where possible

- new atomic and molecular data

- quality flags (A....E)

Solar System Elemental Abundances from the Solar Photosphere… Page 5 of 66 23

Table 2 Solar photospheric abundances

Element	This work					Asplund et al. (2021)		
	12+log N(E/H)dex	$\pm 1\sigma$ dex	1σ %	Quality index	Notes*	12+log N(E/H)dex	$\pm 1\sigma$ dex	Difference (1) - (6)
E	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
H	12	0.004	0.9	NA	…	12.00	0.00	0.00
He	10.922	0.012	2.8	NA	see text	10.91	0.013	0.01
Li	1.04	0.09	23	B	see text	0.96	0.06	0.08
Be	1.21	0.14	38	C	A24, U	1.38	0.09	0.00
B	2.7	0.25	78	E	CS99, U	2.70	0.20	0.00
C	8.51	0.09	23	B	see text	8.46	0.04	0.05
N	7.98	0.11	29	B-	see text	7.83	0.07	0.15
O	8.76	0.05	12	A	see text	8.69	0.04	0.07
F	4.4	0.2	58	D	sunspot; see text	4.40	0.25	0.00
Ne	8.15	0.12	32	D	see text	8.06	0.05	0.09
Na	6.29	0.05	12	A	see text	6.22	0.03	0.07
Mg	7.58	0.05	12	A	see text	7.55	0.03	0.03
Al	6.43	0.05	12	A	see text	6.43	0.03	0.00
Si	7.56	0.05	12	A	see text	7.51	0.03	0.05

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Solar System Elemental Abundances from the Solar Photosphere… Page 5 of 66 23

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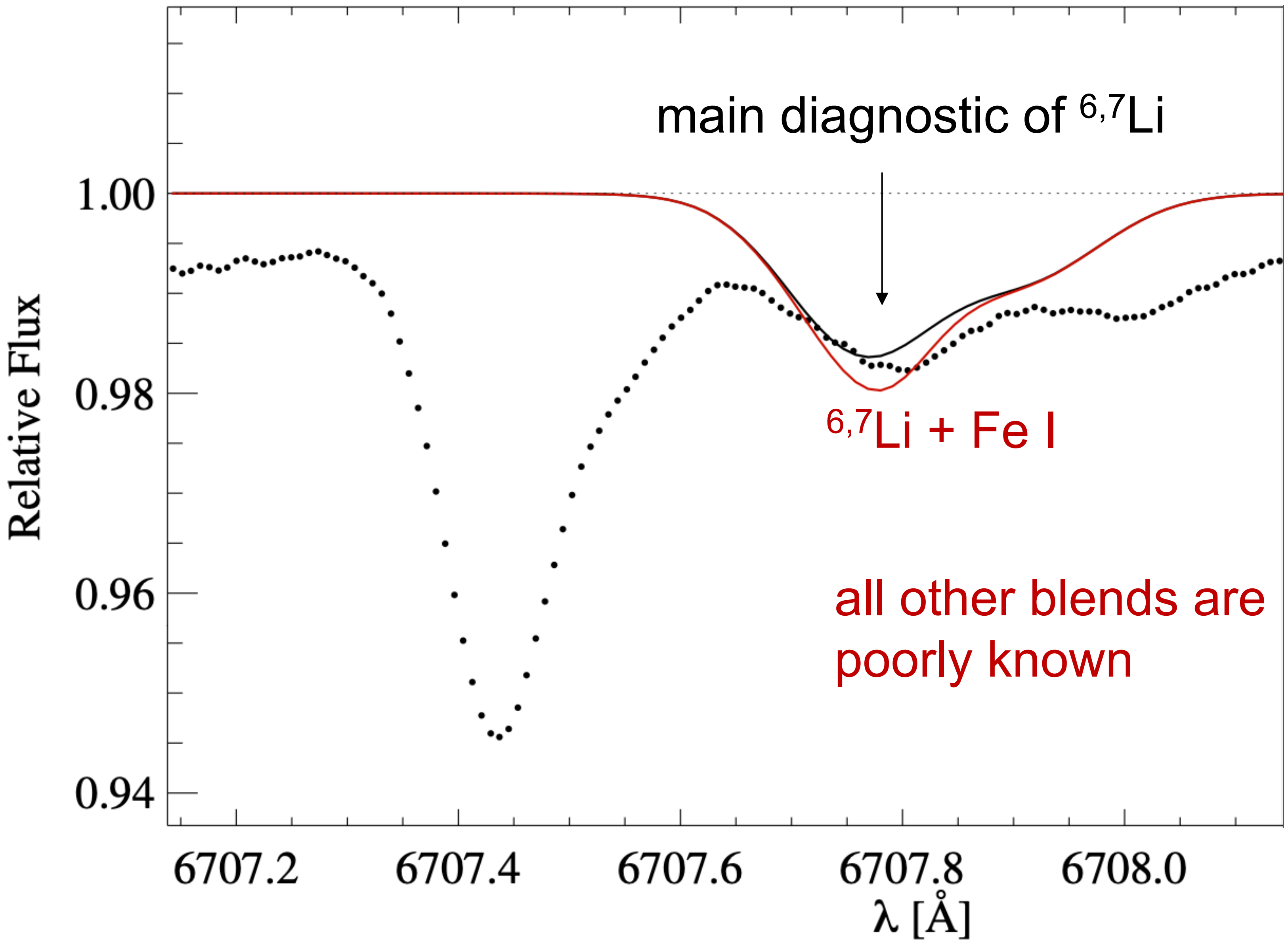
Solar Lithium Controversy



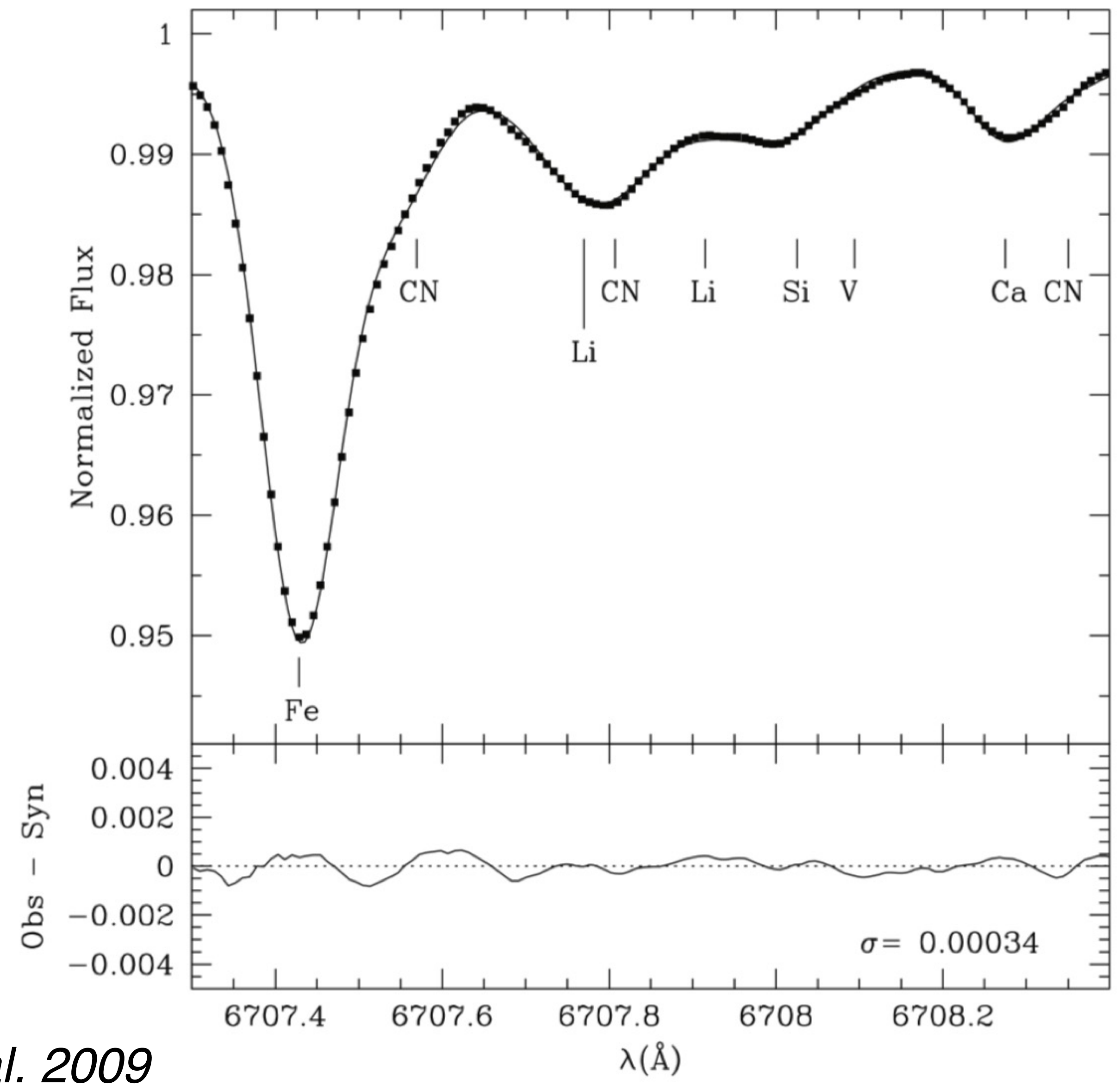
Solar Lithium Controversy

The main problem with ^7Li is <u>not</u> ^7Li

Li measurements in the solar spectrum rely on empirically-calibrated atomic data

λ,f-values for Si, Fe, V, CN lines needed

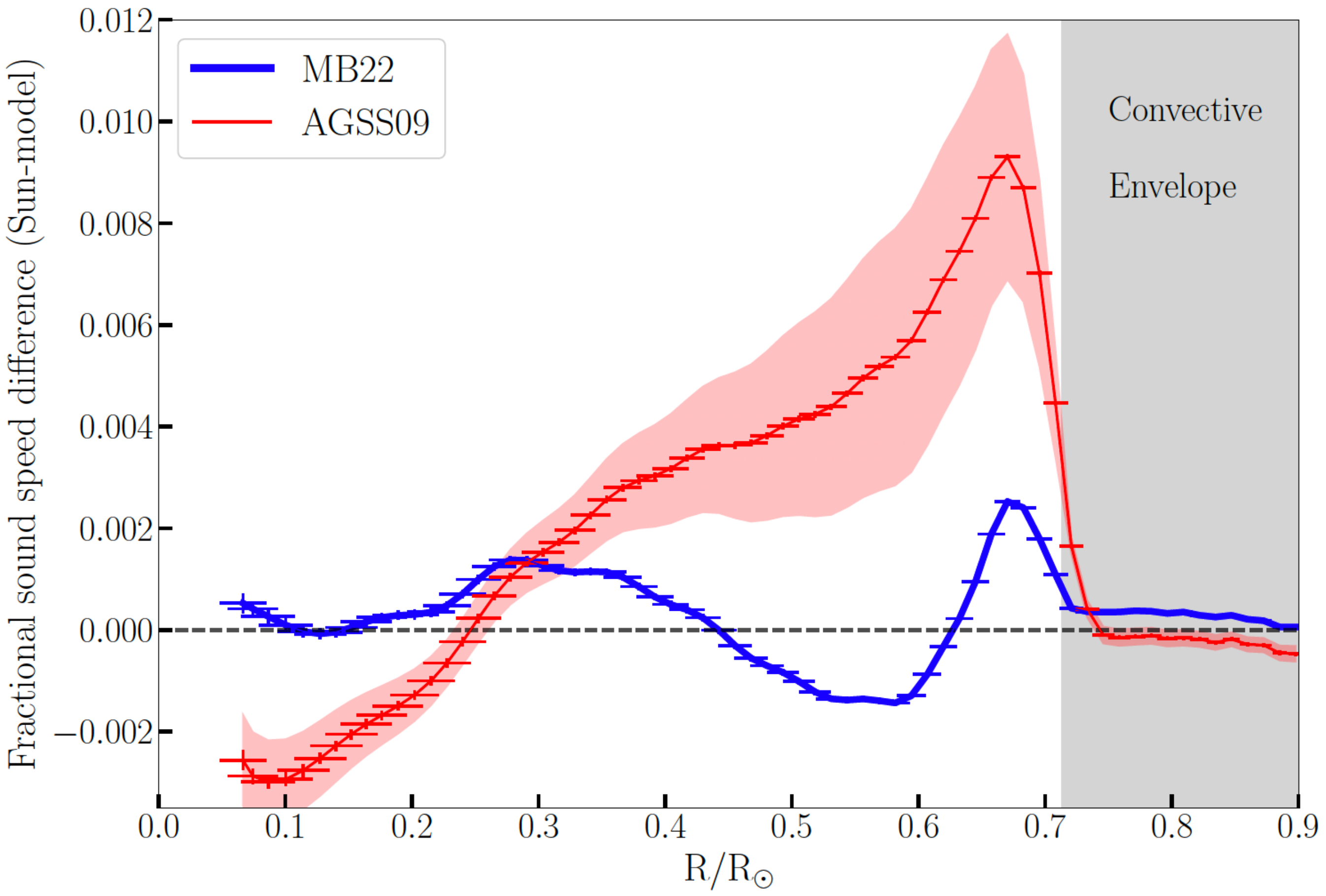
cf. Asplund et al. 1999, Steffen et al. 2010, 2012, Harutyunyan et al. 2018, Melendez et al 2012, Mandell et al 2004, Bensby & Lind 2018, Wang et al. 2021



Ghezzi et al. 2009

Implications

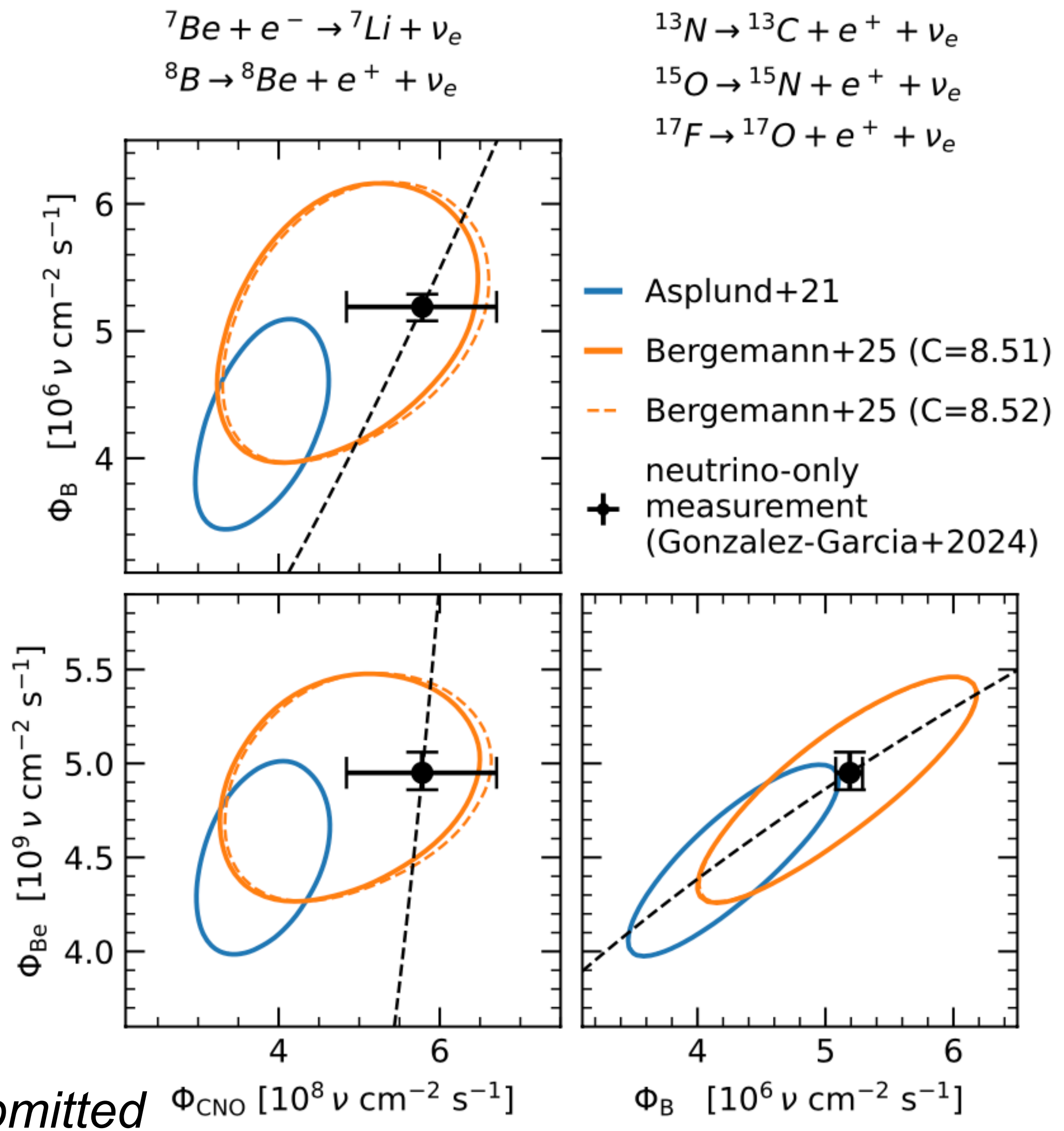
- **higher metallicity** in solar convection zone: X = 0.7389, Y = 0.2451, Z(Li-U) = 0.0160
- affects indirectly derived **abundances from ratios** (e.g., O/Ne) or **interpolations** (Kr,Xe)
- restores/improves **agreement** with standard solar models



Magg et al. 2022

Implications

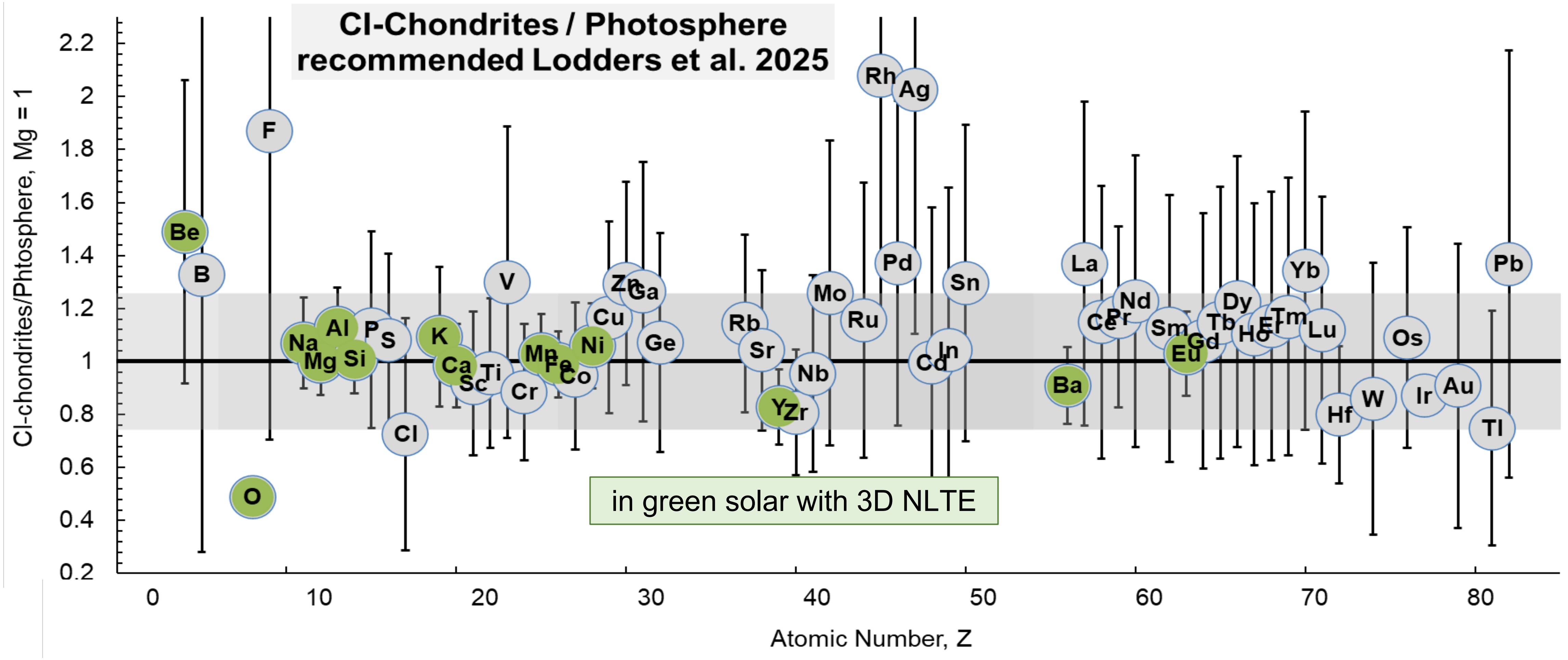
- **higher metallicity** in solar convection zone: X = 0.7389, Y = 0.2451, Z(Li-U) = 0.0160
- affects indirectly derived **abundances from ratios** (e.g., O/Ne) or **interpolations** (Kr,Xe)
- restores/improves **agreement** with standard solar models + neutrino fluxes



Hoppe, B+ submitted

Implications

- increases **factor for linking solar and meteoritic abundances** to get full abundance set
- excellent convergence with CI-chrondrite values



Conclusions I

– Recently revised solar and solar system abundances (Magg et al. 2022, Bergemann et al. 2025, Lodders et al. 2025)

Abundances from CI-Asteroid Samples (delivered as meteorites or collected by spacecrafts)

CI-Chondrites

- well defined & the best proxy for solar reference composition of non-highly volatile elements.
- Uncertainties in concentrations are around 5 to 15%
- Analytical challenges remain e.g., halogens (F, Cl, Br, I)
- Data for a new “fresh” CI chondrite, Oued Chebeika 002, forthcoming

Samples from asteroids Bennu and Ryugu

- CI-like compositions, abundances can refine CI-based values
- Clean samples, but need representative sample masses for abundance refinements

Abundances of non-highly volatile elements that are well-determined in the photosphere show excellent convergence with CI-chondrite values

Conclusions II

Solar Photospheric Abundances

– Only the Sun provides reliable abundances for highly volatile elements (HCNO, noble gases)

– **Generally higher abundances, thus higher solar & protosolar metallicity**

  protosolar X = 0.7060, Y = 0.2753, Z(Li-U) = 0.0187

– better agreements with independent constraints (SSM, Borexino + other experiments)

– Multiple reasons for higher abundances:

- more realistic solar 3D atmospheric models accounting for convection
- comprehensive Non-LTE models
- line selections, transition probabilities, photoionisation cross-sections

– only analyses of more cosmochemically distinct elements in the Sun can prove that CI-meteorite and asteroid samples represent the pristine protosolar composition of elements more refractory than water ice

→ Solar system formation & evolution, origin of organic matter and emergence of life, Sun as a laboratory for particle physics

Table 1 Sources for Solar System Abundances

Abundances from:	Limitations:
Sun: Photosphere & Sunspots representative of present-day solar convection envelope (CE)	68 of 83 natural occurring elements were analyzed, about 10-20 elements with nominal uncertainties <10%. Limitations are line accessibilities, atomic parameters and transition probabilities. Model atmosphere (1D vs 3D) and choices between local thermodynamic equilibrium (LTE) vs. non-LTE (NLTE) are required. The best solar system source for abundances of C, N, O are currently debated. No direct method for noble gases is available. To obtain proto-solar values from the present-day convective envelope (CE), corrections for atomic diffusion (gravitational settling and radiative acceleration) are needed.
Sun: Corona/solar wind (SW) from GENESIS representative of FIP/FIT biased photospheric values	Genesis provides direct measurements of all noble gases, but other data are limited to abundant elements. To derive photospheric values first ionization potential (FIP) & first ionization time (FIT) corrections from fast and slow SW, and solar energetic particles are required. Coronal sources corrected for FIP/FIT bias from photosphere need further settling and diffusion corrections to obtain proto-solar values (see Lodders 2020 for a review).
CI-Chondrites representative of proto-solar condensable fraction	All elements are measurable. Ultra volatile elements (H, C, N, O, noble gases) are strongly depleted in CI-chondrites. Elements are usually determined with 3-10% relative uncertainties. This requires representative sampling. Limited available material may be a problem.
Other Sources indirect and/or model-dependent	He abundance can be calculated from helioseismology, Ne from O/Ne of solar wind and B stars, Ar, Kr, Xe from nucleosynthesis systematics and abundance curve interpolations. Additional data are provided by B stars, the ISM (interstellar medium), and gas-giant planets in the solar system.

Issues with CI-Chondrites (also applies to Bennu & Ryugu)

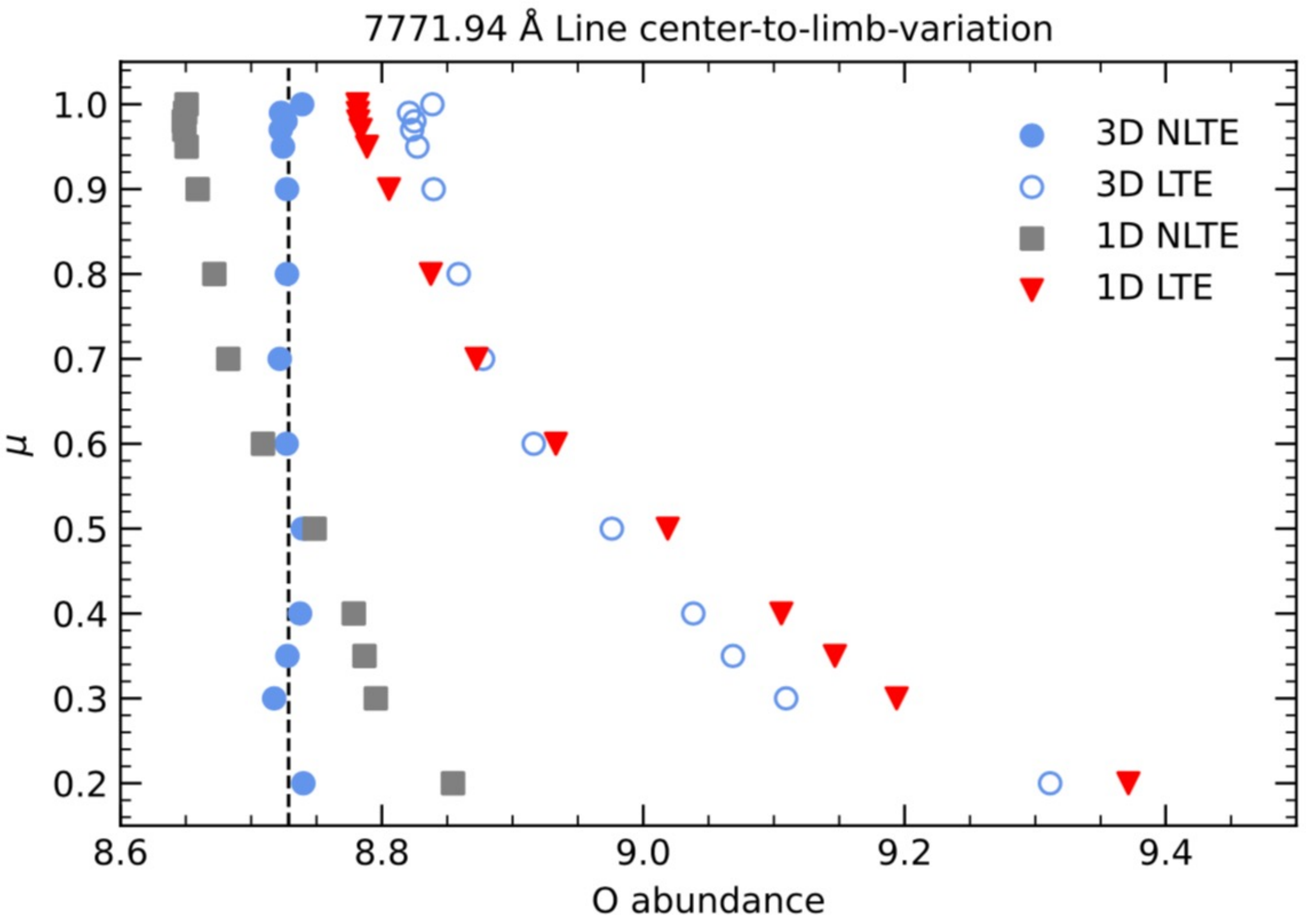
Aqueous alteration on parent body, water-bearing minerals, salt deposits, evaporites:
Sulfides, Carbonates, Phosphates, Halides, (Sulfates?)
small samples, varying homogeneity & contents of aqueously mobile elements

e.g., alkalis (Na, K, Rb, Cs), alkaline earth (Mg, Ca, Sr, Ba); halogens (F, Cl, Br, I),
B, C, P, As, Sb, S, Se, Te, Mn, Sc, Zr, Hf, Nb, Ta, U, Th, REE (+possibly other elements)

Issues unique to CI-Chondrites:

Terrestrial oxidation (air and humidity), **efflorescence** formation in the museum
sulfide oxidation to sulfates & ferrihydrite, mobilization & **redistribution** of elements within the rock

Contamination during storage and handling: Alais since 1806, Orgueil 1864, Ivuna 1938
but contamination mainly restricted to Hg



7771.94 Å Line center-to-limb-variation
3D NLTE
3D LTE
1D NLTE
1D LTE
μ
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
8.6
8.8
9.0
9.2
9.4
O abundance

Solar abundances = abundances in current Sun's outer convection zone with photopshere
Solar system abundances = representative proto-solar abundances 4.567 Ga ago.

recent updates: **Bergemann, Lodders & Palme 2025** Elsevier online encyclopedia – on arxiv
Lodders, Bergemann, & Palme 2025, Space Science Reviews