# **Solar System Elemental Abundances**

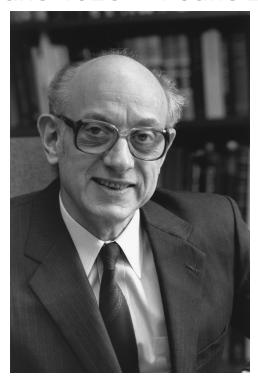
from the Solar Photosphere & Cl-chondrites

Katharina Lodders<sup>1</sup> & Maria Bergemann<sup>2</sup>

We thank the organizers for the invitation to this meeting, Herbert Palme for input and discussions, and our institutions and funding agencies for supporting our research.

Nuclei in the Cosmos 2025, Girona Spain 
<sup>1</sup>Washington University, St. Louis, <sup>2</sup>Max-Planck-Institut für Astronomie, Heidelberg

In Memoriam
Edward Anders
21 June 1926 – 1 June 2025



A Pioneer in Elemental Abundances and Cosmochemistry

### **Topics for this presentation**

#### Introduction

- (1) Abundances from CI-chondrites and Related Asteroids
- (2) Solar Photospheric Abundances

#### **Conclusions**

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

updates: **Bergemann, Lodders & Palme 2025** Elsevier online encyclopedia – arXiv:2503.05402 **Lodders, Bergemann, & Palme 2025**, Space Science Reviews 221, 23

How the Sun works & evolves

Composition & formation of solar system; planetary compositions

Baseline reference composition for other stars, ISM, galaxies...

Test for models of
Stellar evolution
Element nucleosynthesis
Galactic chemical evolution

Clues about the basic make-up & origins of matter

Solar System

**Abundances** 

Constitution of (baryonic) matter, numbers & amounts of stable/unstable elements & isotopes

Composition & formation of other solar systems; exoplanets

It's the stuff we are made of

#### Solar System Abundances: Need both sources - the Sun and meteorites - for all elements



1E+8

1E+7

1E+6

1E+5

1E+4

Sun:

60 Photosphere, heavy elements

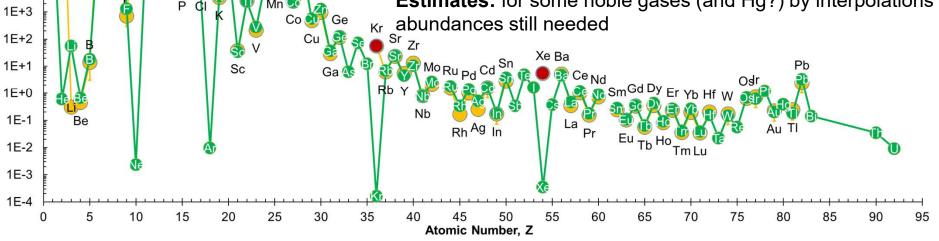
- 4 Sunspots: F, Cl, In, Tl
- 4 Solar wind: noble gases: Ne, Ar, (Kr, Xe)
- 2 Helioseismology, standard solar models: H, He

Sun only reliable source for highly volatiles HCNO, noble gases Overall uncertainties typically larger than for meteorites

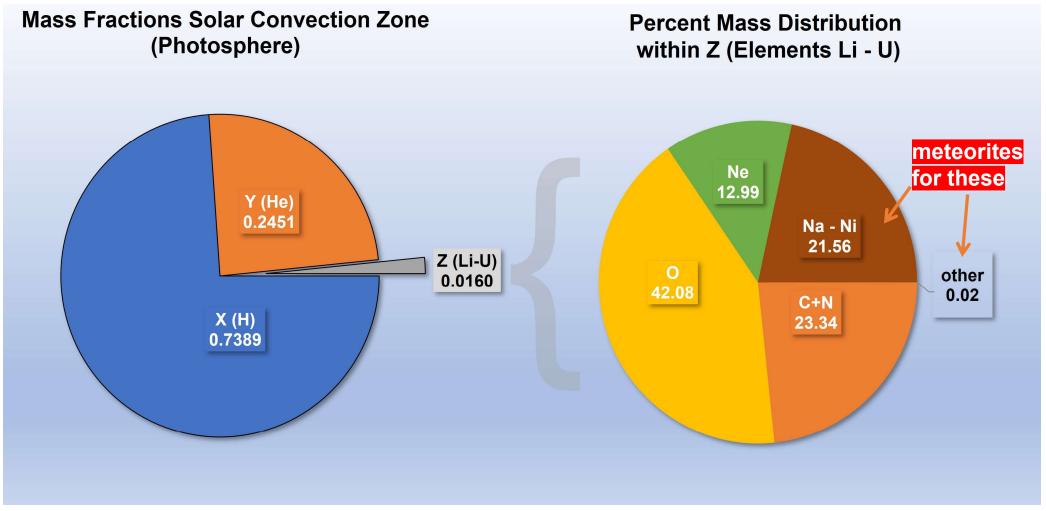
#### **Meteorites**:

All 83 elements can be precisely measured Highly volatile elements HCNO & noble gases are not quantitatively retained

Estimates: for some noble gases (and Hg?) by interpolations of nuclide abundances still needed



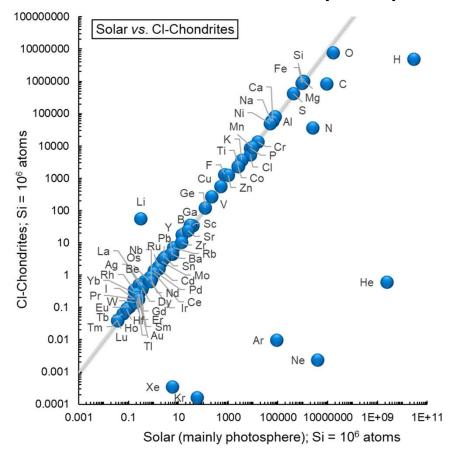
Elemental Abundances from CI – Chondrites & Asteroids



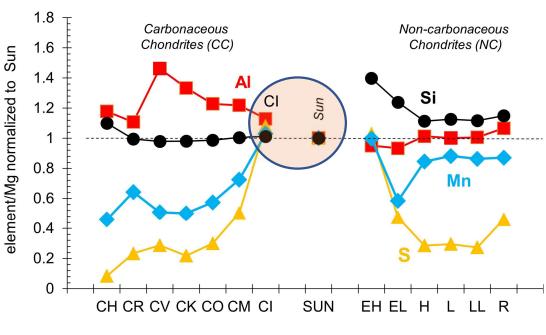
Meteorites constrain rocky element abundances, these are 21.8% of the "heavy element fraction" Z, or a mass fraction of 0.0035 in the photosphere CNO are heavy highly volatile elements, or "icy elements" making about 2/3 (65%) of Z, or a mass fraction of 0.0105 in the photosphere

# Meteorites are needed for complete solar and solar system abundances: Why are CI-Chondrites the Best Proxies?

#### Closest in abundances to solar photosphere



- Agreements in major element abundance ratios, e.g., Si/Mg, S/Mg; also Fe/Mg, Ca/Al (not shown)
- Highest relative content of volatile elements among most other chondrite groups; e.g., Sufur/Mg



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

Smooth curve of nuclide abundances with mass numbers

#### New developments

CI-like(!) samples from asteroid sample return missions

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

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

Controlled storage/handling:

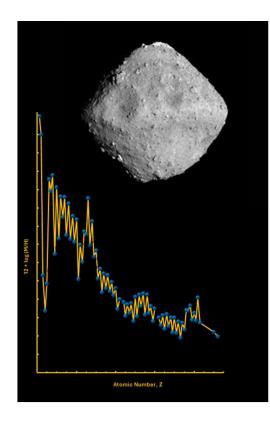
not contaminated

samples not exposed to the oxidizing and humid terrestrial environment terrestrial mobilization & redistribution of elements is excluded/minimized

New CI-chondrite Oued Chebeika 002 found in Morocco 2024 must be recent fall, does not (yet) show "classic" terrestrial alteration (oxidation) products as the older five CI-chondrite falls

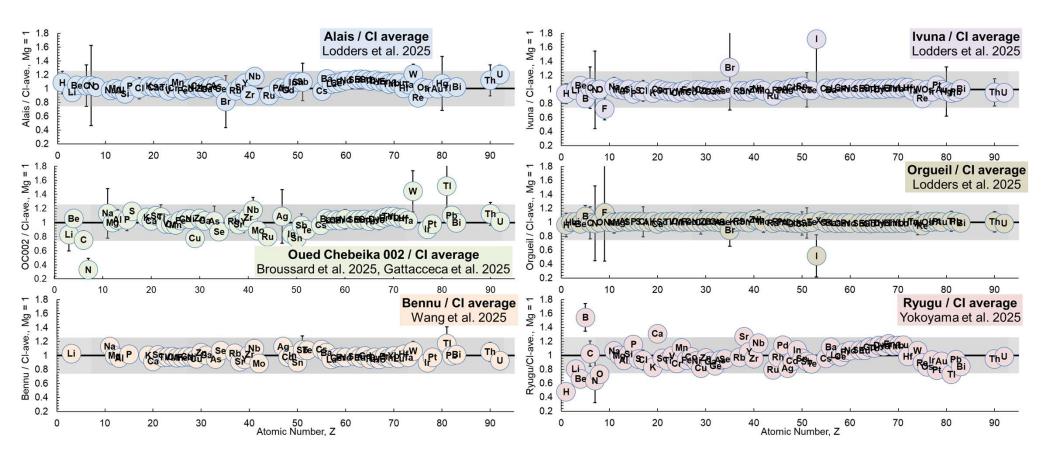
First analyses do not indicate any major changes for the "meteoritic" solar system abundances from CI-chondrites.

Samples very promising to improve on abundances that have been problematic (e.g., Halogens!)



**Ryugu**, as seen by Japan's Hayabusa2 spacecraft on June 26, 2018. (Image credit: JAXA, University of Tokyo, Kochi University, Rikkyo University, Nagoya University, Chiba Institute of Technology, Meiji University, University of Aizu, AIST

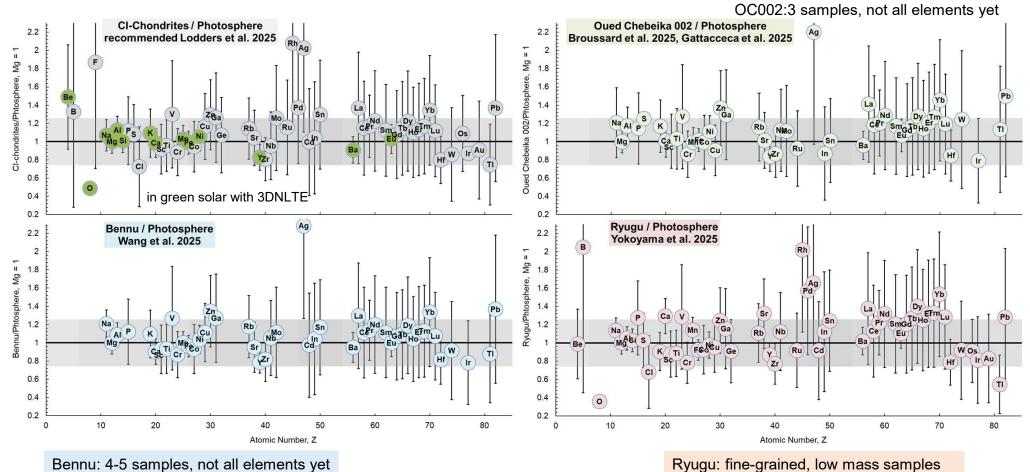
# Compositions of Individual CI-Chondrites and Asteroids Bennu and Ryugu relative to CI-chondrite average composition



Grey band indicates agreement within 26% (0.1 dex). Variability often for aqueously mobile elements. Only few samples analyzed for Bennu & OC002; not all elements covered. Only small samples (heterogeneity!) for Ryugu.

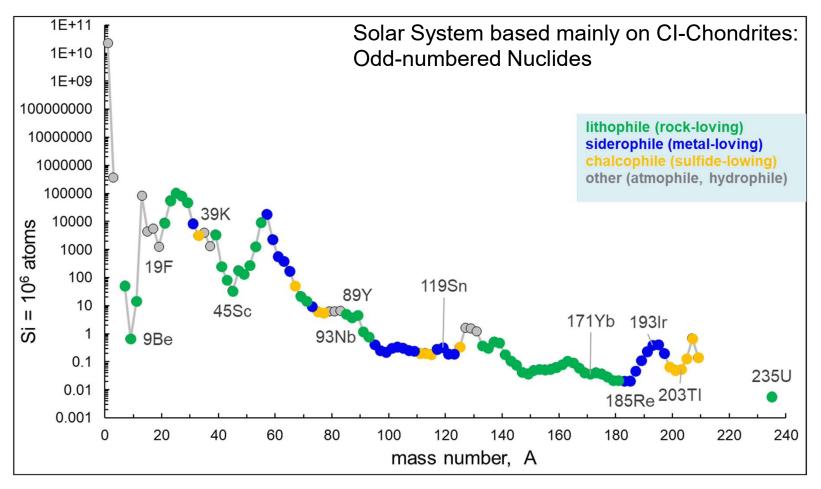
#### Comparison to Solar (photosphere and sunspots) where possible

(grey band = agreement within 26%, 0.1 dex)



(heterogeneity)

Combined uncertainties shown are largely driven by uncertainties in solar values. Solar F, Cl, Rh, Ag, Pd very uncertain.



- Smooth abundance curve for odd nuclides irrespective of geochemical properties of the elements
- Overall abundances not controlled by geochemical affinities or by cosmochemical behavior (volatility)
- Not expected if CI-chondrites were chemically fractionated

# **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

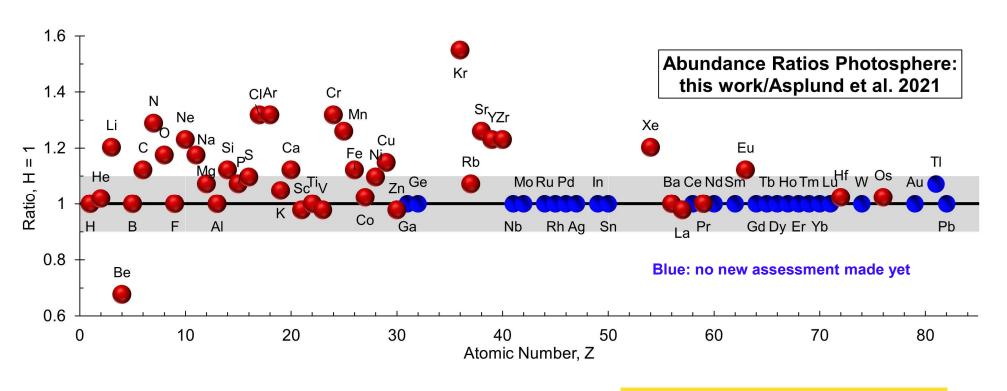
# Different reasons to re-visit

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

Lodders, Bergemann & Palme 2025

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

# Higher abundances for many elements



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

# Recent improvements in microphysics

Radiative data: b-b and b-f transitions transition probabilities and photo-ionization cross-sections

- 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, Pascal Palmeri, Pascal Quinet **Collisional data**: charge transfer with H and H-induced inelastic excitation

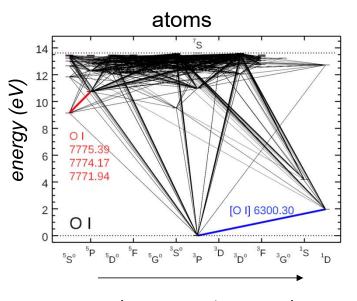
- B Belyaev & Voronov 2022
- S Belyaev & Voronov 2020
- Mn Bergemann et al. 2019
- Co Yakovleva et al 2020
- Ni Voronov et al 2022
- Cu Belyaev et al 2021
- Sr Yakovleva et al 2022
- Y Storm et al. 2024
- Eu Storm et al. 2024

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

<sup>\*</sup>comparison of **4 different QM** codes: AUTOSTRUCTURE (Badnell 2011), R-matrix (Berrington et al. 1995), GRASP2018 (MC Dirac-Hartree Fock, Froese Fischer+2019), HFR+CPOL (Quinet et al. 2002)

# Recent improvements in macrophysics

#### **NLTE** models

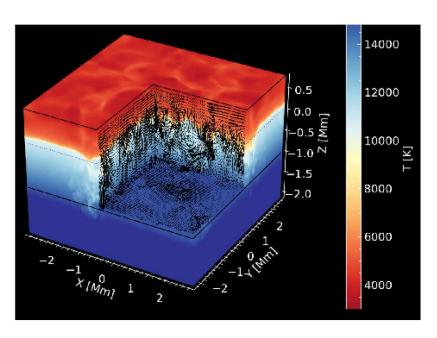


angular momentum + spin

\* detailed comparison of NLTE departures and abundance corrections from 4 different line formation codes: SIU+DETAIL, MULTI, Turbospectrum v20, MULTI3D@Dispatch

Bergemann & Hoppe subm., Popa et al. 2023

### 3D RHD model atmospheres

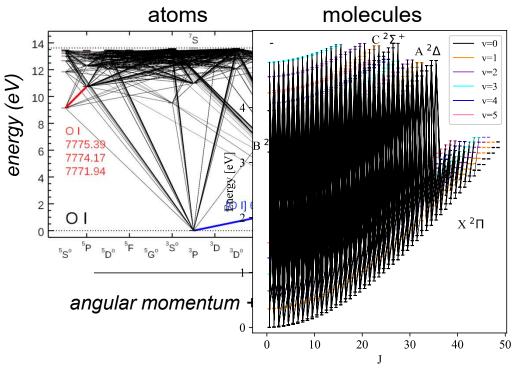


\* detailed comparison of structures from 4 different 3D RHD codes:

T- ρ - v structures computed using Co<sup>5</sup>BOLD, Stagger, Dispatch, Bifrost, Muram

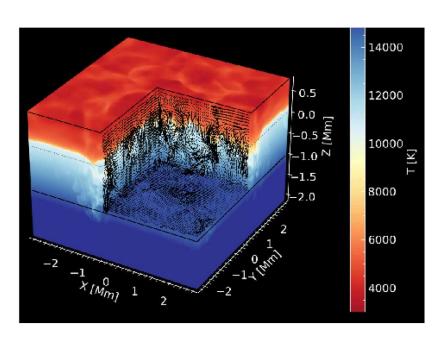
# Recent improvements in macrophysics

#### **NLTE** models



\* detailed comparison of NLTE departures and abundance corrections from 4 different line formation codes: SIU+DETAIL, MULTI, Turbospectrum v20, MULTI3D@Dispatch

### 3D RHD model atmospheres



\* detailed comparison of physical structures from 4 different 3D RHD codes:

T- ρ - v structures computed using Co<sup>5</sup>BOLD, Stagger, Dispatch, Bifrost, Muram

### Differences between Solar Abundance Sets

systematic analysis in Magg et al. 2022, and in Lodders, Bergemann & Palme 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

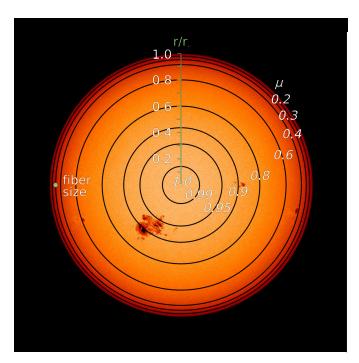
Mg, Mn, Co, Ni, Zn, Ba, Y, Eu

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. unidentified or misclassified blends, continuum)

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

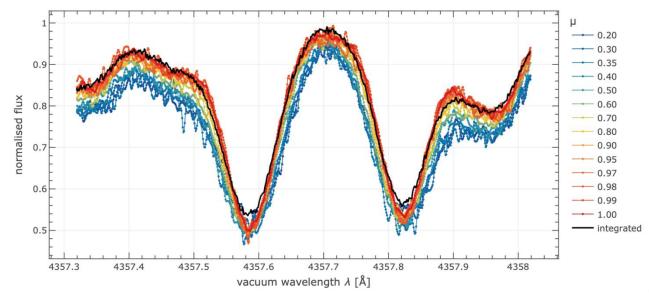
#### Different angles probe different layers of the solar atmosphere



(c) Richard Hoppe

Reiners et al. 2016 (flux), Ellwarth et al 2023 (intensity)

#### IAG solar spatial resolved spectrum library



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

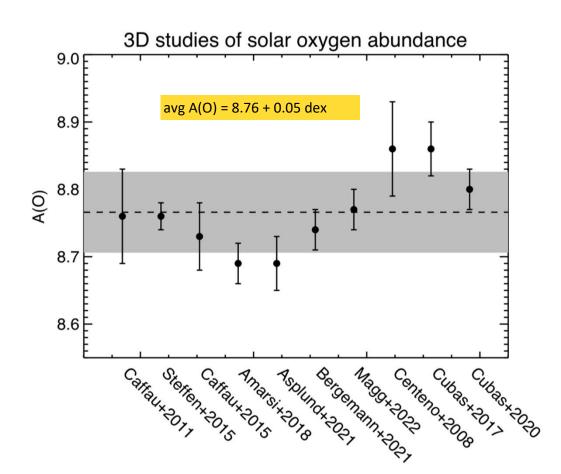
applied to O (Bergemann & Hoppe et al. 2021), C (Hoppe et al. 2025, subm.), Eu,Y (Storm et al. 2024),

## Photospheric O abundance: Higher than previously thought, but still enigmatic(?)

Oxygen 3<sup>rd</sup> most abundant element by number after H, He

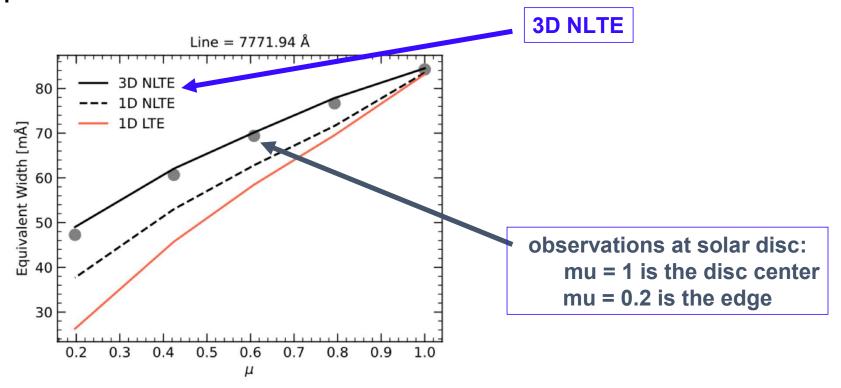
- significant contributor (42%) to heavy element mass fraction Z in Sun; opacity source
- abundances influences water ice:rock ratios in protoplanetary accretion disk, planetary oxidation state

Our recently recommended value  $A(O) = 8.76 \pm 0.05$  compares well to other 3D studies and less model-dependent techniques



8 15.999
Sauerstoff

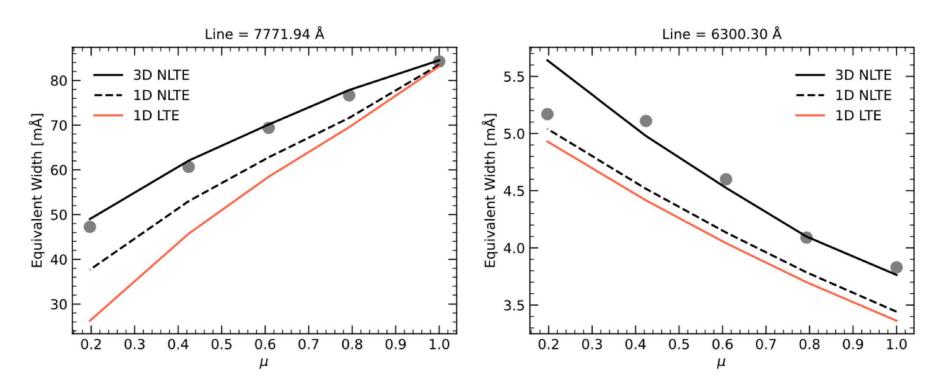
3D NLTE: consistent oxygen EWs (O I, [O I]) and abundances at all positions across the solar disc



Bergemann & Hoppe et al. 2021

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Sauerstoff

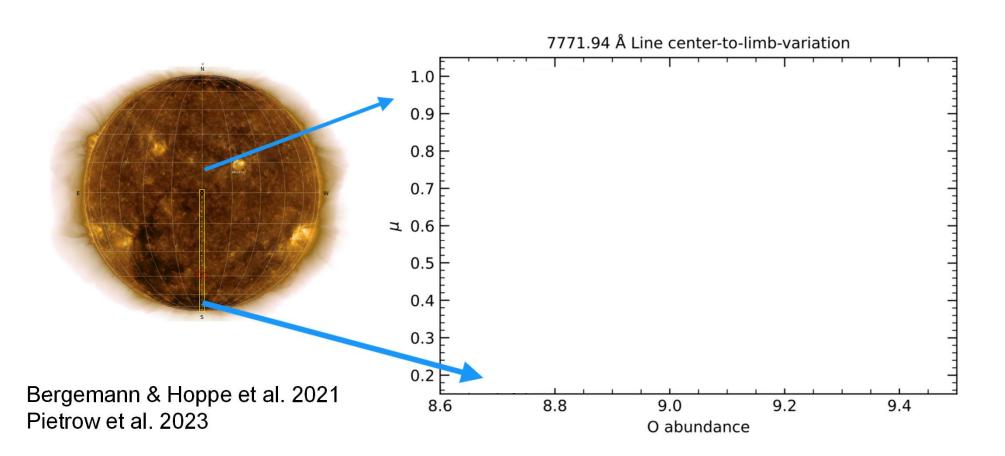
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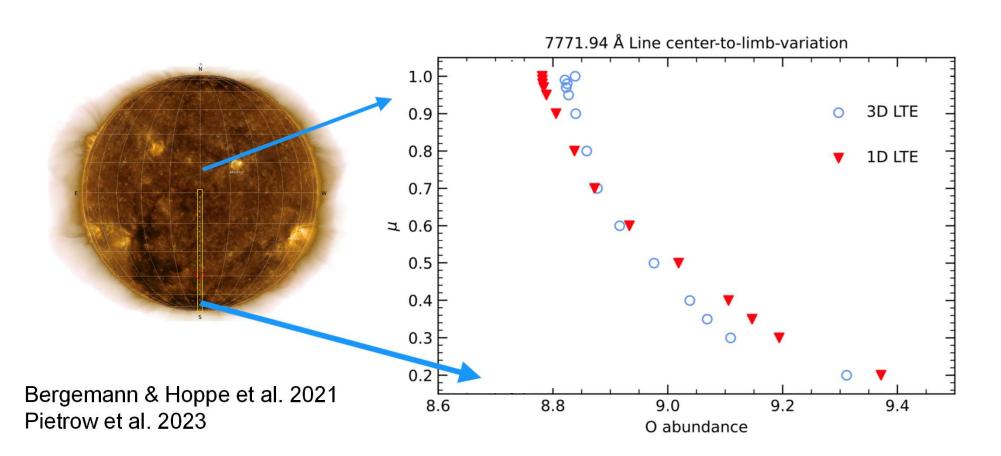
consistent oxygen EWs (O I, [O I]) and abundances across the solar disc



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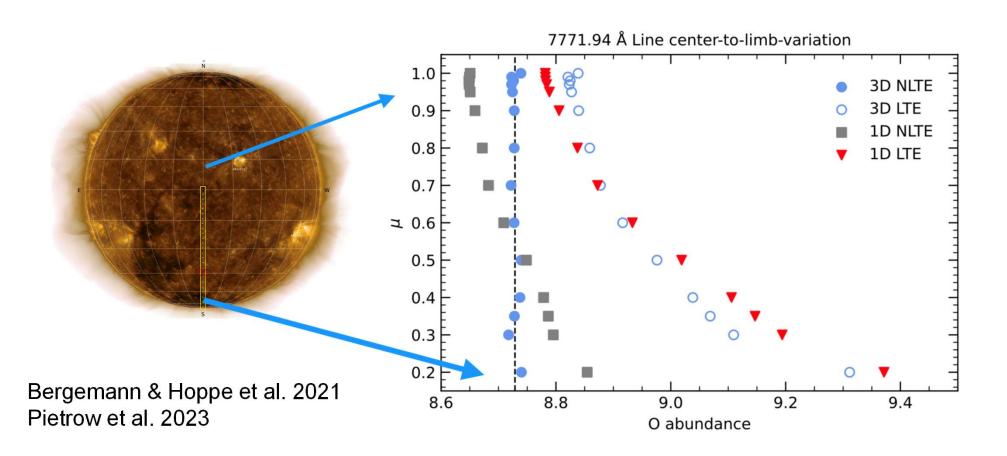
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Bergemann, Lodders, & Palme 2025 Lodders, Bergemann & Palme 2025

- 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...

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 Table 2
 Solar photospheric abundances

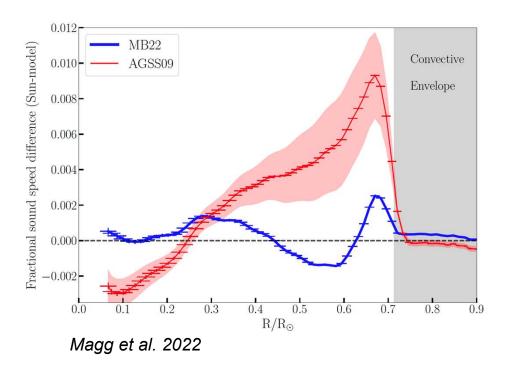
Ele- ment	This work					Asplund et al. (2021)		
	12+log N(E/H)dex	$\pm 1\sigma$ dex	1σ%	Quality index	Notes*	12+log N(E/H)dex	$\pm 1\sigma$ dex	Difference (1) - (6)
E	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
Н	12	0.004	0.9	NA		12.00	0.00	0.00
He	10.922	0.012	2.8	NA	see text	10.91	0.013	0.01
Li	1.04	0.09	23	В	see text	0.96	0.06	0.08
Be	1.21	0.14	38	C	A24, U	1.38	0.09	0.00
В	2.7	0.25	78	E	CS99, U	2.70	0.20	0.00
C	8.51	0.09	23	В	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	Α	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	Α	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

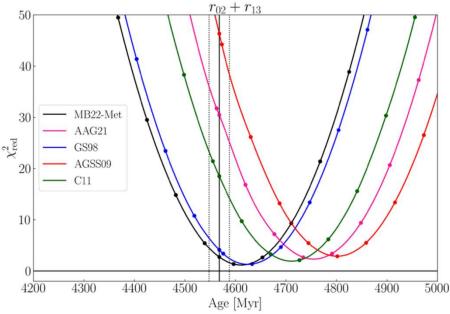
# **Implications**

- 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)

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- higher metallicity in solar convection zone: X = 0.7389, Y = 0.2451, Z(Li-U) = 0.0160
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- restores/improves agreement with standard solar models

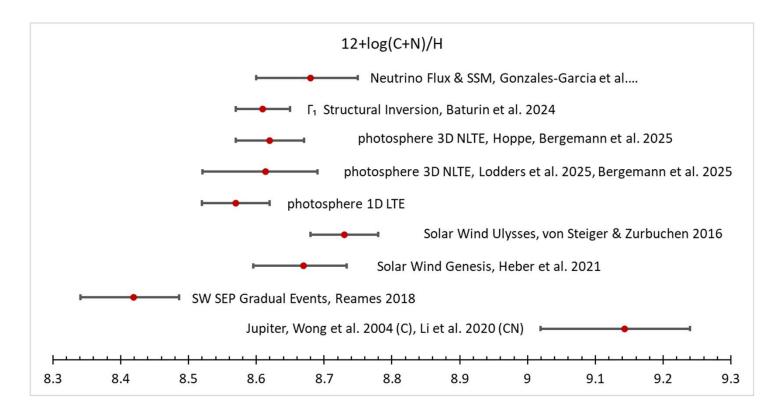




Bouvier & Wadhwa 2010 cf Amelin et al 2010, Nittler & Ciesla 2016

#### Solar models and other constraints

larger abundances → higher metallicity → Improved/restored agreement between the standard solar model and neutrino fluxes (pp and CNO chain)



Appel et al.,. Phys. Rev. Letters, 2022 The Borexino Collaboration, Nature, 587, 2020

# **Implications**

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- affects indirectly derived abundances from ratios (e.g., O/Ne) or interpolations (Kr,Xe)
- restores/improves agreement with standard solar models
- increases factor for linking solar and meteoritic abundances to get full abundance set:

here factor = 1.551 from Na, Mg, Al, Si, Ca, Mn, Fe, Ni (all analyzed by 3D NLTE )  $A(E) = 12 + \log_{10}(E/H)_{\text{photo}} = 1.551 + \log_{10}E/Si_{\text{Cl}}$ 

E/Si = atomic ratio x 1E6 in Cl-chondrites

#### **Conclusions I**

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

Abundances from CI-Asteroid Samples (delivered gratis 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% for most immobile elements and 10 to 15% for aqueously mobile elements.
- Analytical challenges remain e.g., halogens, siderophiles
- Data for a new "fresh" CI chondrite find, 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)
- Multiple reasons for higher abundances:
- more realistic 3D atmospheric models accounting for convection & turbulence
- comprehensive NLTE models
- line selections, transition probabilities, photoionisation cross-sections
- future analyses of the Sun and asteroidal/meteoritic CI samples remain necessary (i.e., mobile and siderophile elements in all sources)
- only analyses of more geochemically and cosmochemically distinct elements in the Sun can ultimately prove that CI-asteroid samples represent the pristine protosolar composition of elements more refractory than water ice