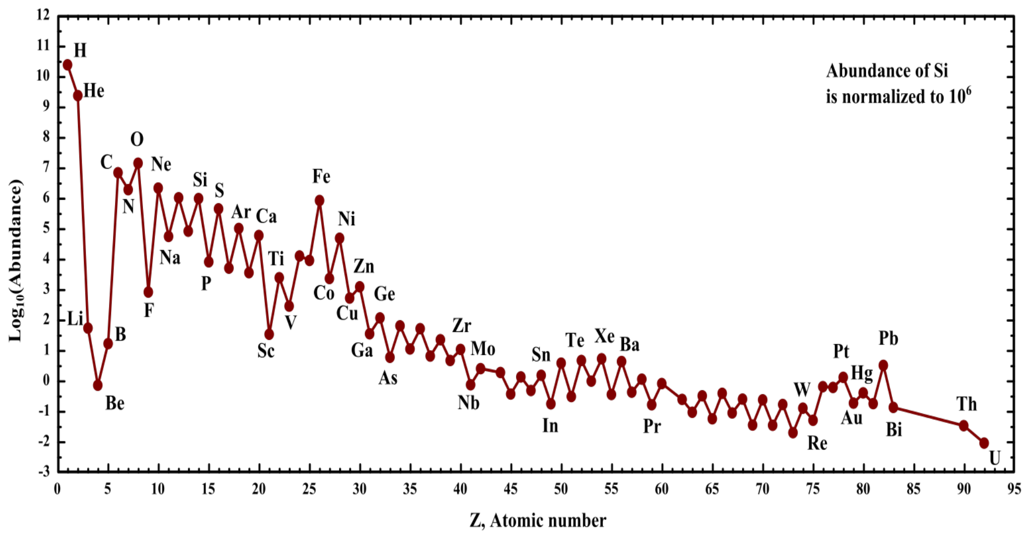
Exemplary talk: THCA student seminar 2017/09/14

Solar Abundances: Measurements from Solar Spectroscopy and Meteorites

Xuening Bai (白雪宁)



Institute for Advanced Study (Tsinghua)

& Tsinghua Center for Astrophysics

清華大學

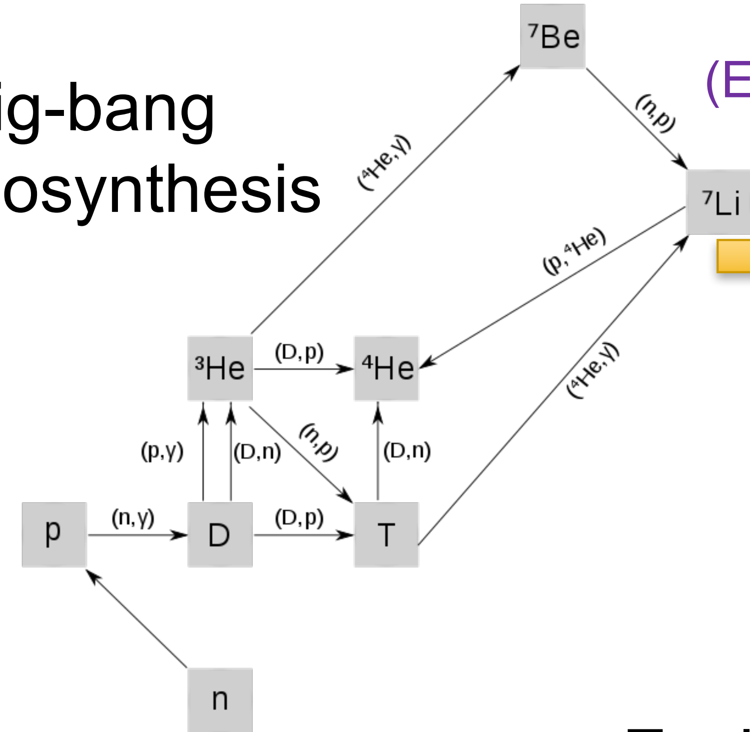
Tsinghua University

Outline

- Introduction
- Spectroscopy of the Sun
- Measurement from primitive meteorites
- Other methods
- Results
- Summary and discussion

Origin of solar abundance

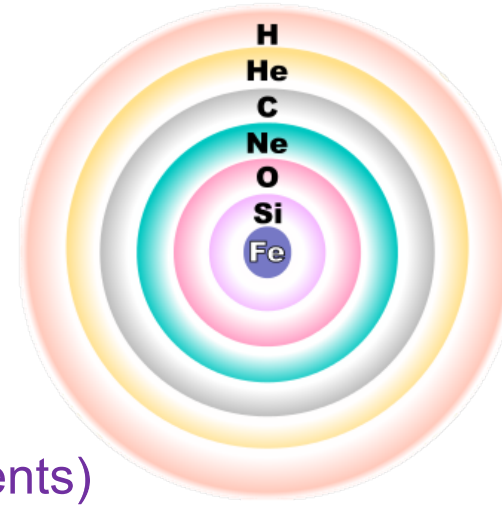
Big-bang nucleosynthesis



(Elements up to Li^7)

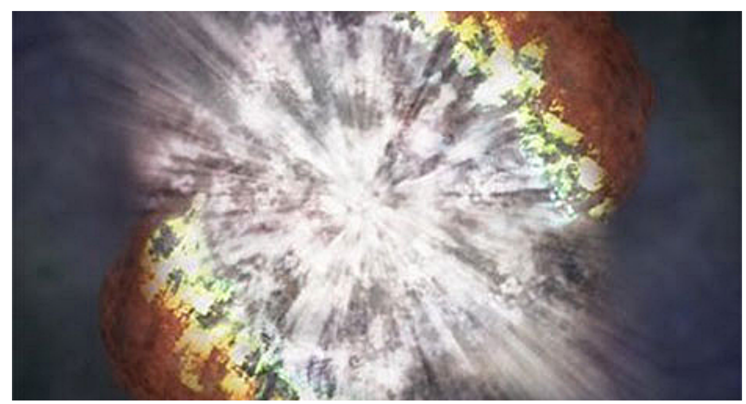
Stellar nucleosynthesis

(Elements up to Fe + some s-process elements)



Explosive (supernova) nucleosynthesis

(Elements heavier than Fe + r process elements)



Cosmic-ray spallation

(Light elements such as He^3, Li^7, Be, B, etc.)

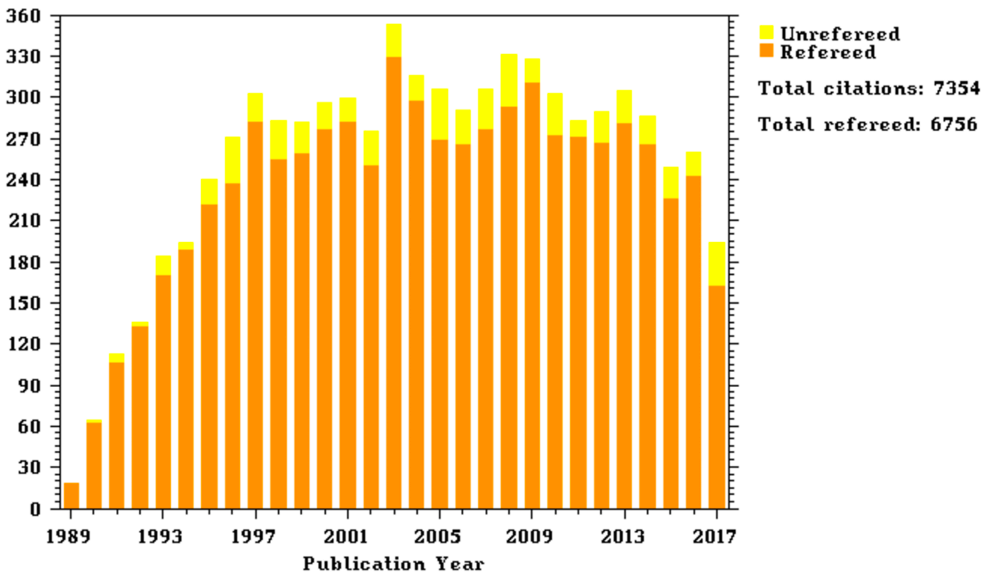
Why solar abundance

- **A fundamental benchmark to normalize elemental abundance of almost all astronomical objects.**
- ***Planets:*** abundance of heavy elements is a crucial parameter to determine the outcome of planet formation
- ***Stars:*** stellar evolution depends on "metallicity"; important information for galactic archeology
- ***Nebular gas:*** opacity and thermodynamics of gas is very sensitive to elemental composition
- ***Galaxies:*** contain gas and stars, whose evolution affect the overall appearance and evolution of galaxies.

Overall, stellar abundances shed light on the cosmos history.

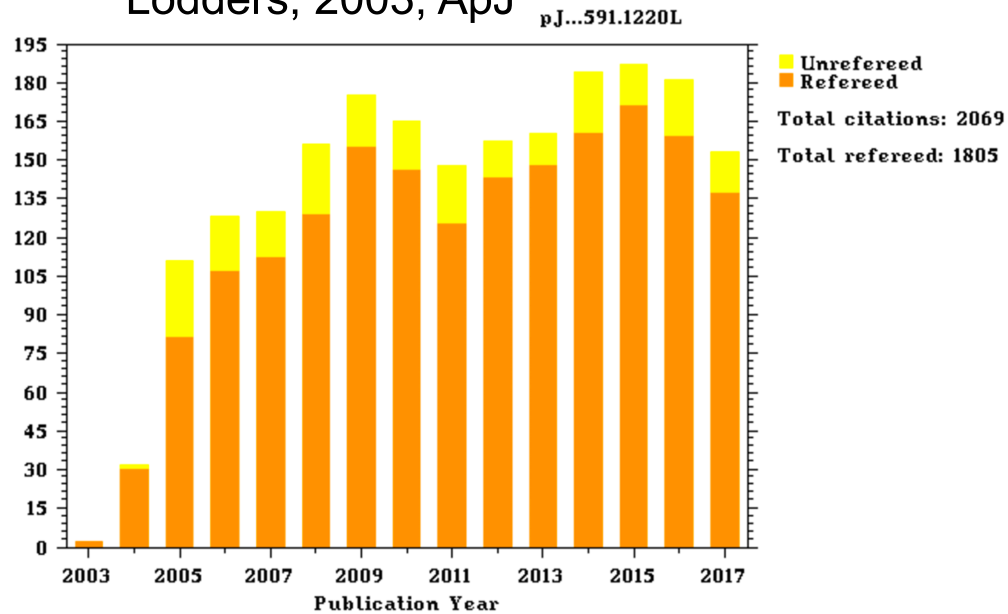
Main references and citation metrics

Anders & Grevesse, 1989, Geochimica et Cosmochimica Acta



Most widely adopted solar abundance.

Lodders, 2003, ApJ

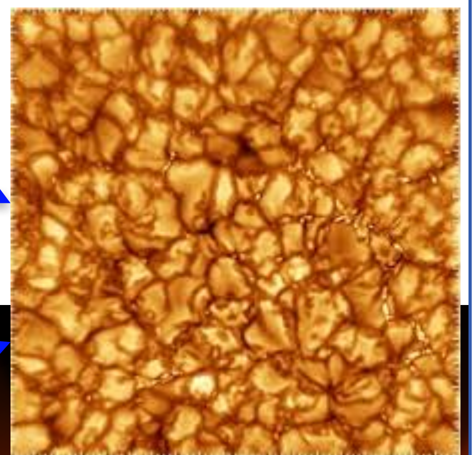


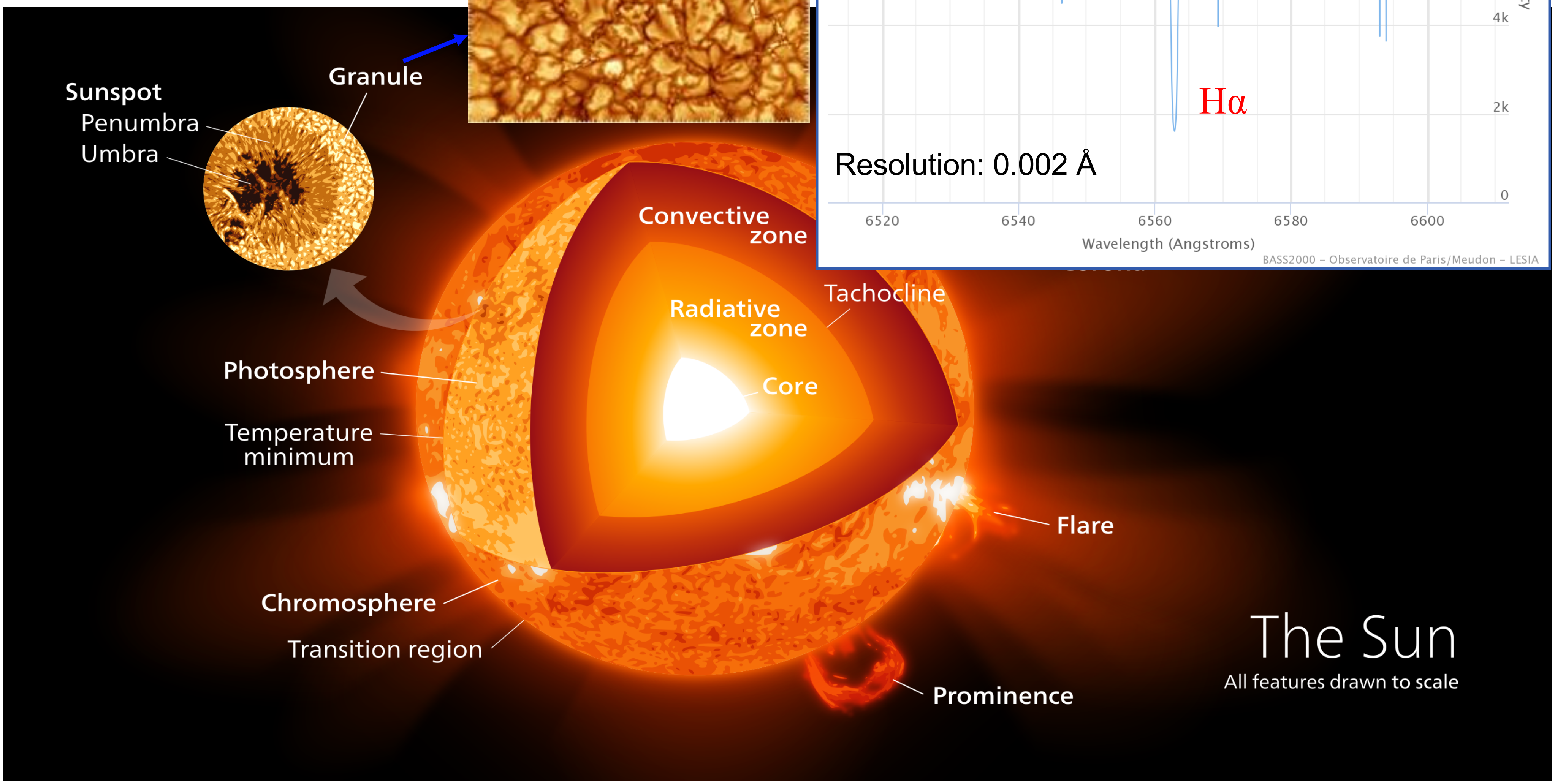
Current standard of solar abundance.

Most recent review with updates: Asplund, Grevesse, Sauval & Scott, 2009, ARA&A

Solar spectroscopy

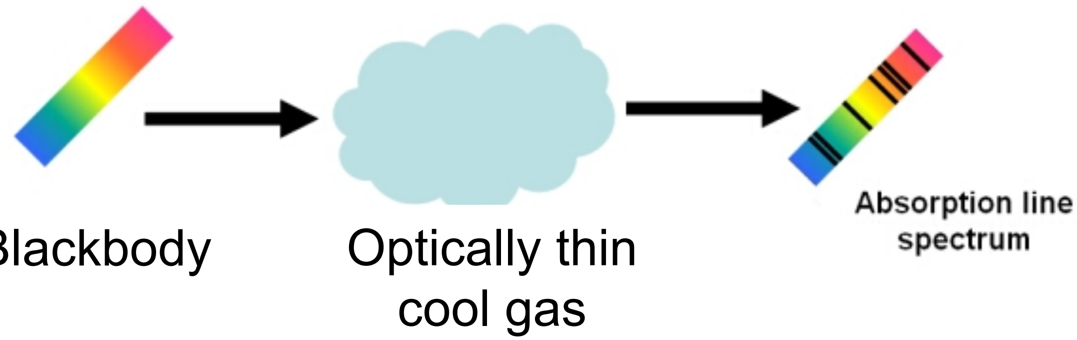
Most (absorption) lines form around here





Conversion from spectroscopy to abundances

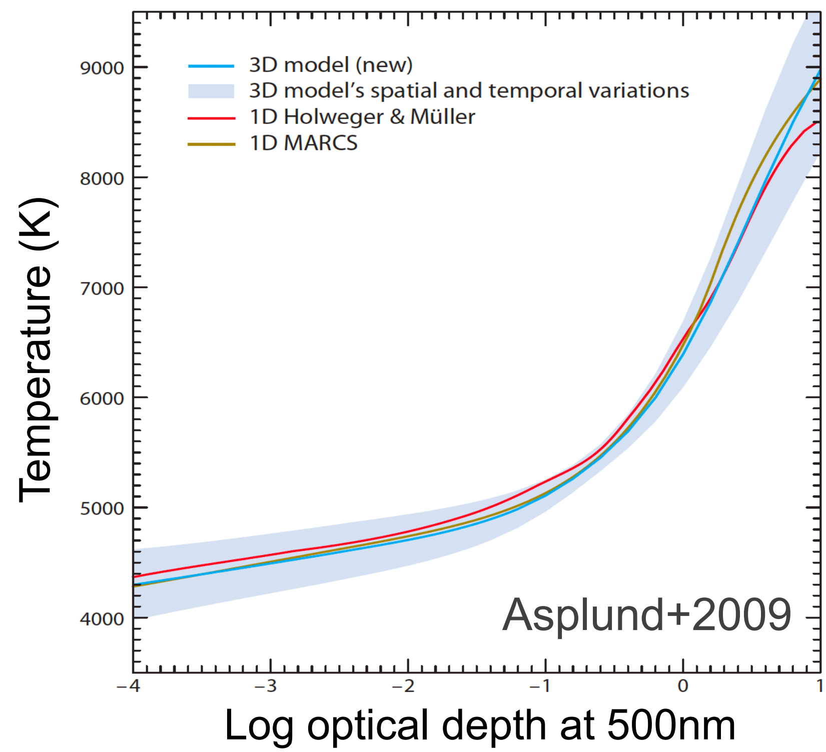
The simple case:



Then, there is a linear relationship between absorption line properties and elemental abundances in the cool gas.

Stellar photospheres are much more complex:

- Lines formed around the photosphere with a temperature gradient.
- The temperature gradient is by itself the outcome of radiative balance, which depends on opacity (including the lines).

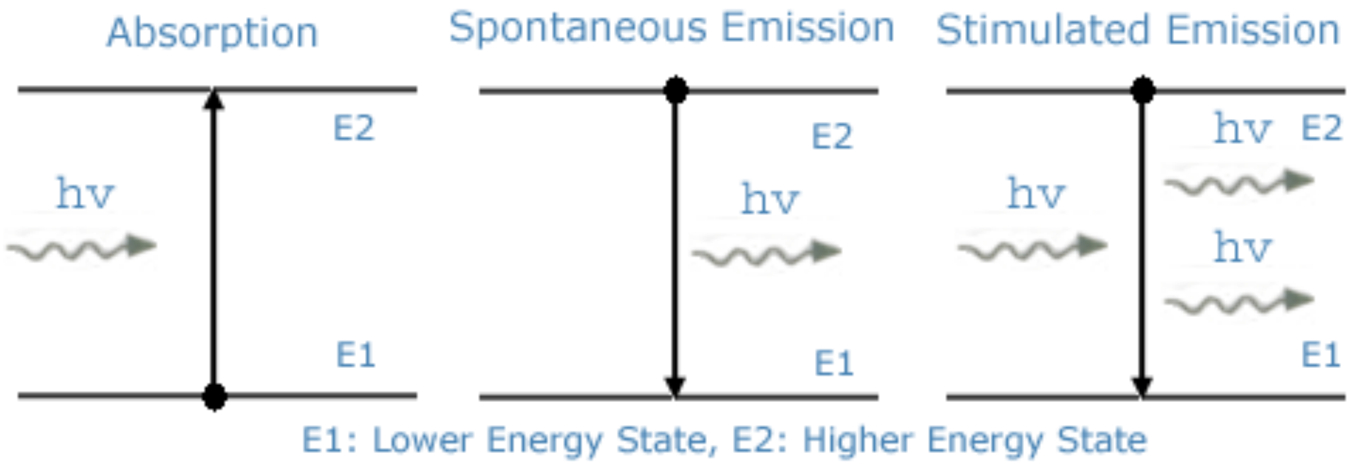


What are needed?

We are talking about precision measurement of elemental abundance to better than a few % level => Need very accurate models!

- Atomic physics
  - Huge number of lines from different ionization states and energy levels.
  - Lifetimes, branching fraction and transition probabilities of each lines.
  - Rates for collisional excitation/deexcitation of lines (for non-LTE)
- Line and continuum radiative transfer
  - Need to compute level populations and know radiation field
  - Lines are broadened by fluid motion (Doppler broadening) and collisions (pressure broadening) => some lines are blended.
- Radiation hydrodynamics/magnetohydrodynamics
  - Conventionally, simple 1D hydrostatic models + artificially prescribed microturbulence (mimicking convection) based on mixing length theory
  - More recently, full 3D models that self-consistently capture convective motion + temperature structure of the photosphere.

Line formation



degeneracy: g_2

degeneracy: g_1

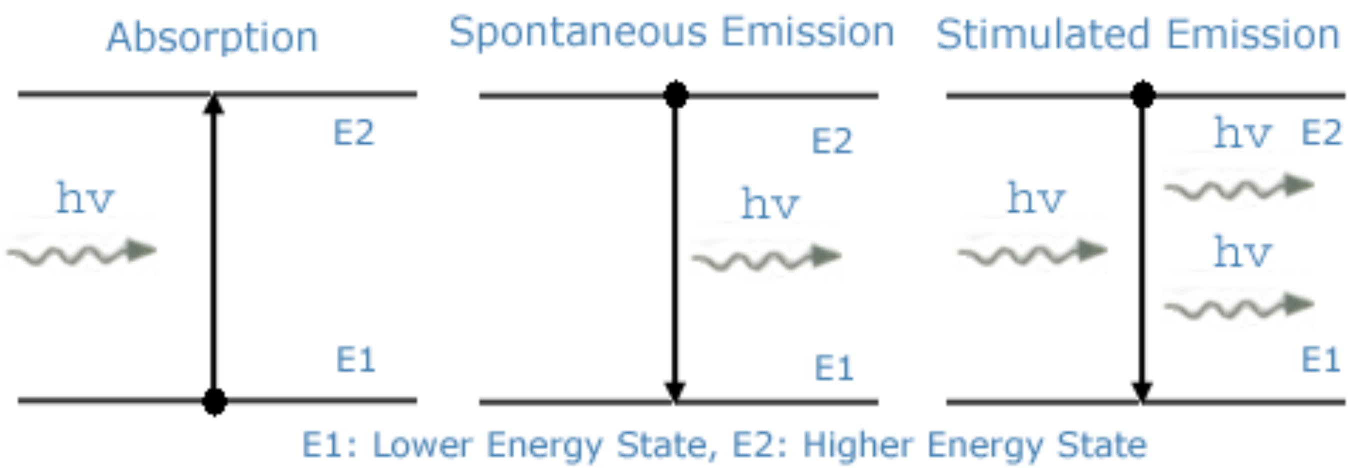
Absorption: $$\left(\frac{dn_2}{dt}\right)_{1\to 2} = -\left(\frac{dn_1}{dt}\right)_{1\to 2} = n_1 B_{12} u_\nu$$

Emission: $$\left(\frac{dn_1}{dt}\right)_{2\to 1} = -\left(\frac{dn_2}{dt}\right)_{2\to 1} = n_2 (A_{21} + B_{21} u_\nu)$$

The Einstein coefficients are related (from conditions at radiative thermodynamic equilibrium):

$$g_1 B_{12} = g_2 B_{21} \ , \ B_{12} = \frac{c^3}{8\pi h \nu^3} A_{12}$$

Line formation



degeneracy: g_2

degeneracy: g_1

Absorption is related to a cross section: $$\left(\frac{dn_2}{dt}\right)_{1\to 2} \approx n_1 u_\nu \frac{c}{h\nu} \int d\nu \sigma_{12}(\nu)$$

Equivalently, one can define "oscillator strength" (which is dimensionless): $$f_{12} \equiv \frac{m_e c}{\pi e^2} \int d\nu \sigma_{12}(\nu) \propto A_{12}\ , B_{12}$$

The key quantity from atomic physics is the product $g_1 * f_{12}$ (called gf-value) associated with each transition.

This requires substantial laboratory work/ab initio calculations!

Atomic databases

The Iron Project - The Opacity Project

IPOPv2

Home | The Opacity Project | The Iron Project | TOPbase | TIPbase | OPserver | OP tables | Contact

The Opacity Project - The Iron Project

The names Opacity Project (OP) and Iron Project (OP) refer to an international collaboration that was formed in 1984 to calculate the extensive atomic data required to estimate stellar envelope opacities and to compute Rosseland mean opacities and other related quantities. It involved research groups from France, Germany, the United Kingdom, the United States and Venezuela. The approach adopted by the OP to calculate opacities is based on a new formalism of the equation of state and on the computation by ab initio methods of accurate atomic properties such as energy levels, f-values and photoionization cross sections. The OP final results are discussed by Seaton et al.

About us - List of members

Badnell Nigel, Ballance Connor, Bautista Manuel, Burke Phil, Butler Keith, Chen Guoxin Delahaye Franck, Del Zanna Giulio, Eissner Werner, Fivet Vanessa, Hudson Claire, Liang Guiyun, Mason Helen, McLaughlin Brendan, Mendoza Claudio, Montenegro Max, Nahar Sultana, Oelgoetz Justin, Palmeri Patrick, Pradhan Anil, Quinet Pascal, Ramsbottom Cathy, Saraph Hannelore, Scott Penny, Storey Peter, Wasson Ian, Withoeft Mike, Zeippen Claude,

http://cdsweb.u-strasbg.fr/topbase/home.html

LTE vs. non-LTE

Local thermodynamic equilibrium (LTE):

There are sufficiently frequent collisions so that level populations follow a well-defined Boltzmann distribution.

Non-LTE: (expected to be applicable to solar photosphere)

Collisions are insufficient (e.g., low density). Need to follow level populations:

$$\frac{\mathrm{d}n_i(\vec{r})}{\mathrm{d}t} = \sum_{j \neq i}^{N} n_j(\vec{r}) P_{ji}(\vec{r}) - n_i(\vec{r}) \sum_{j \neq i}^{N} P_{ij}(\vec{r}) = 0$$

In general, statistical equilibrium is assumed

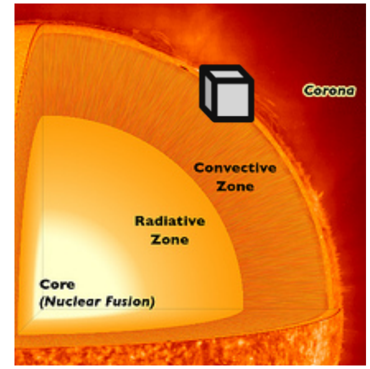
where $P_{ij} = A_{ij} + B_{ij}\bar{J}_\nu + C_{ij}$

Rate coefficients for collisional excitation/deexcitation

Requires collisional data for all transitions, but this is far from complete and available data can be very inaccurate.

Following all level populations is also extremely computationally intensive.

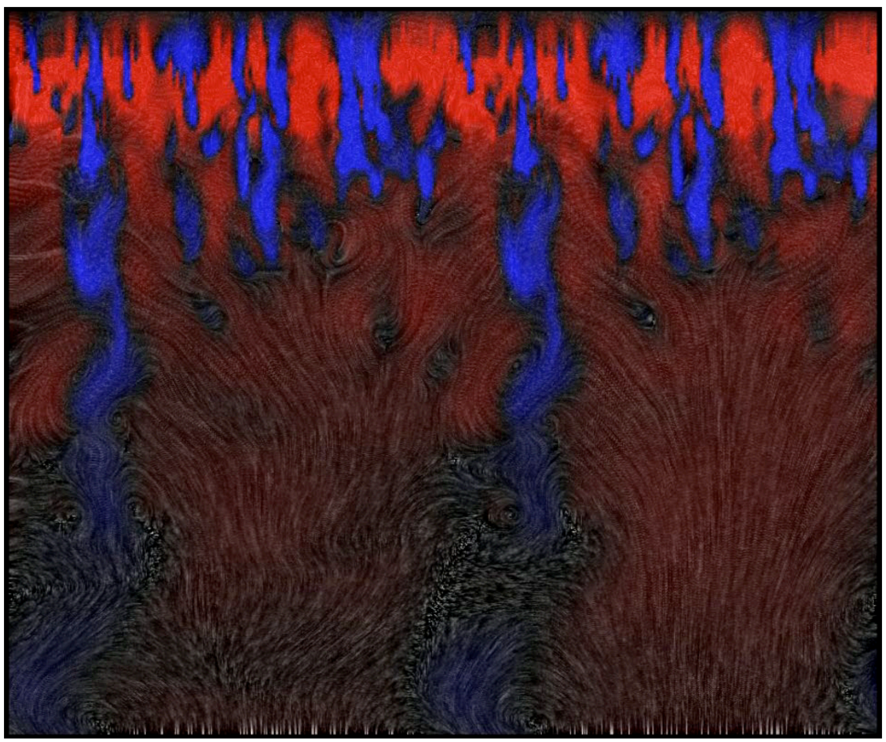
Hydrodynamics: solar surface convection

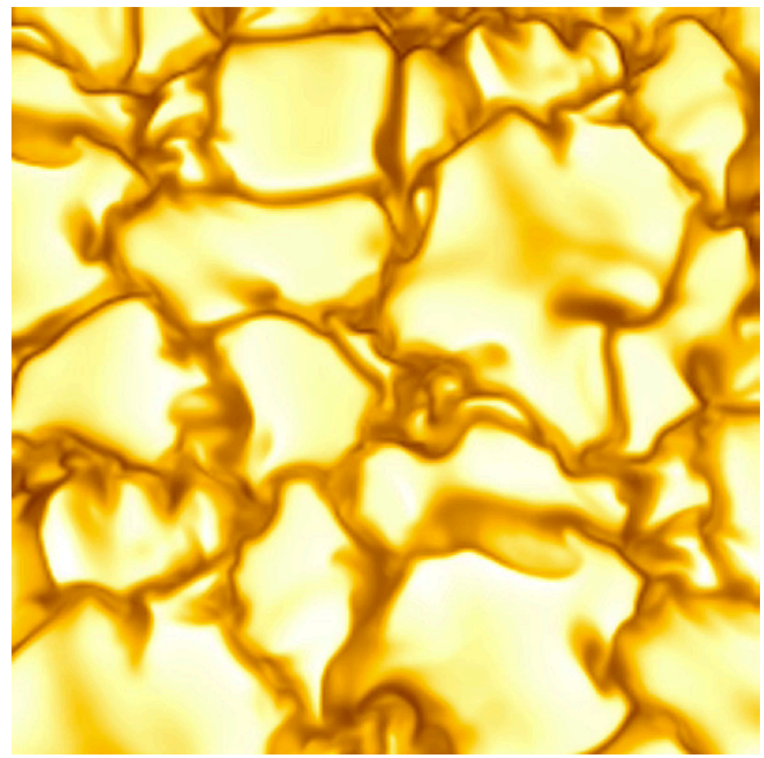


Focus on a local patch of the solar surface.

Solve (magneto-)hydrodynamic equations together with (multi-group) radiative transfer accounting for line opacities, convection driven from the bottom.

Typical simulation box size: $\sim 100^3$.

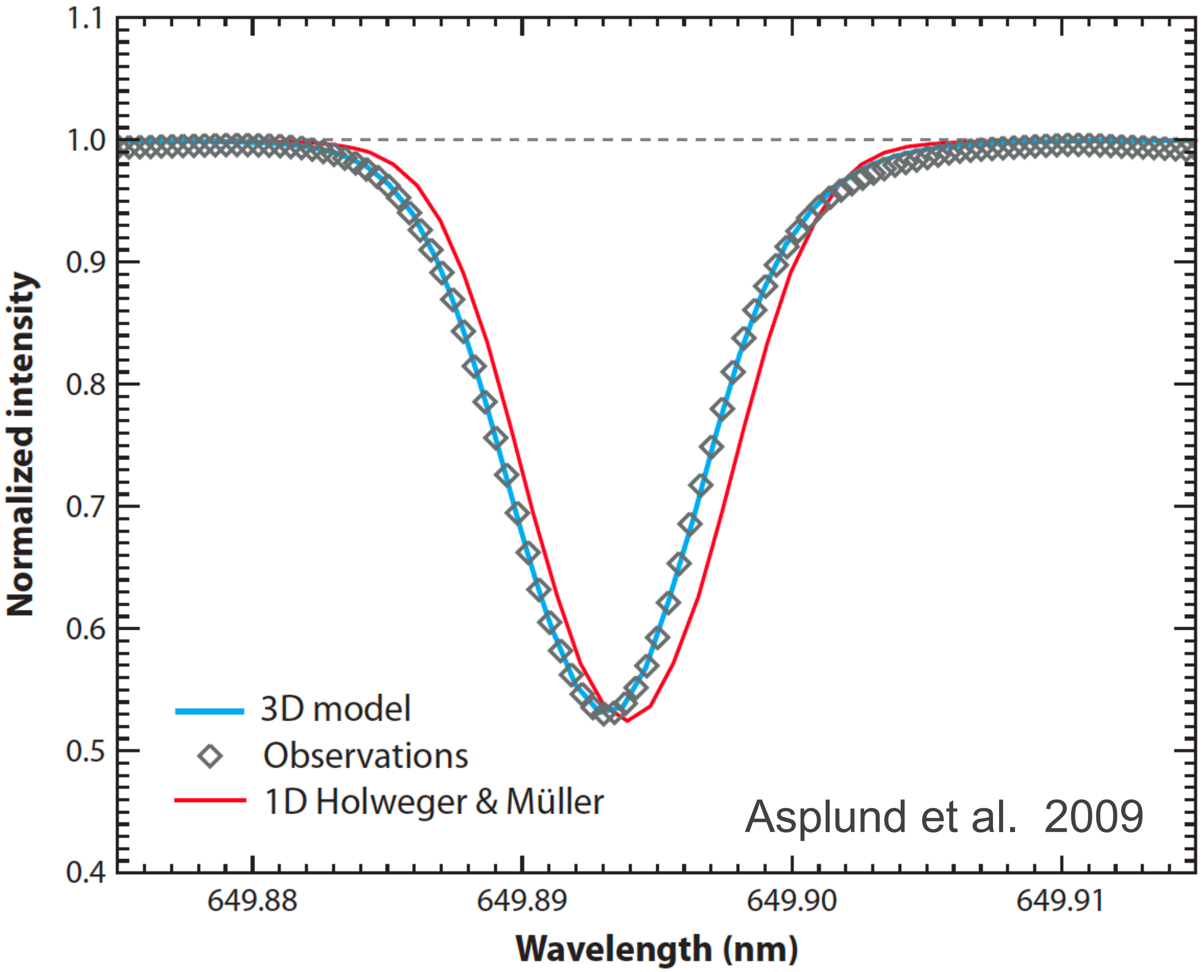




Nordlund et al. 2009

1D model v.s. 3D model: an example

A typical predicted FeI line



Upward convective cells are hotter, move faster, with stronger T gradient => line is stronger @ blue side

1D calculations with artificial microturbulence generally fail to produce the asymmetry

Main updates from recent solar spectroscopy

- Li is depleted by a factor of ~150 compared to meteoritic value.

  It is mixed to the bottom of the convection zone, diffuse to the radiative zone, and get burned => meteoritic measurements are adopted.

  Be may also be affected, but no evidence so far.

- C, N, O, Fe abundances are substantially revised down by ~0.2 dex since the 1989 work owing to improved atomic physics, use of 3D atmosphere models, and consideration of non-LTE effects.
- Due to high excitation potentials, there are no photospheric lines for *noble gas*. Their abundances are derived by other means.
- Most other elements, including intermediate mass elements (up to Ca), ion-peak elements, neutron capture elements etc., show largely consistent results even with these improvements.

Asplund et al. 2009

Infer abundances from meteorites

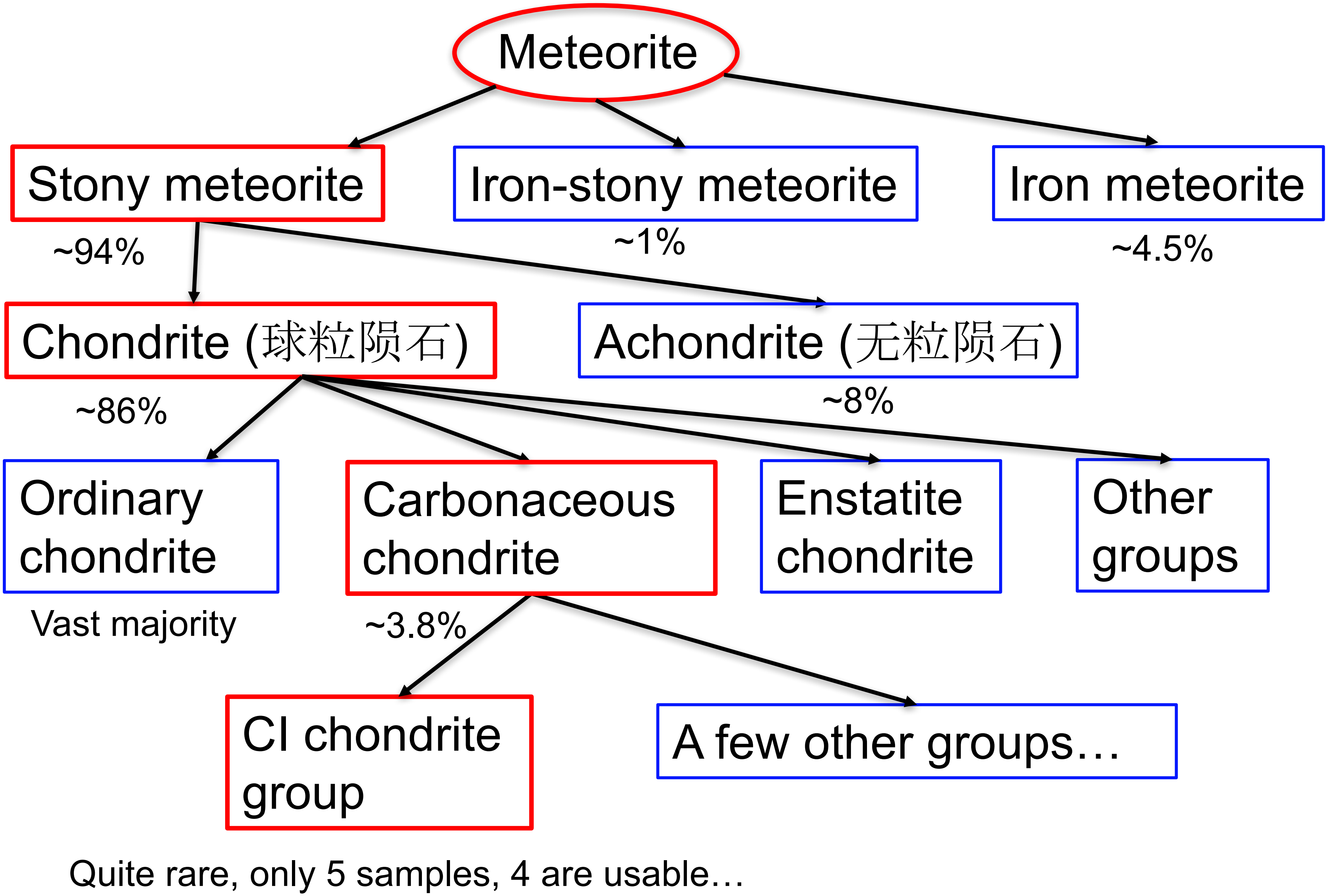
- Pros: abundance measurements can reach extraordinarily high precision.
- Cons: volatile elements, H, C, N, O and noble gases (which are also the most abundant) are heavily depleted.

The way to proceed:

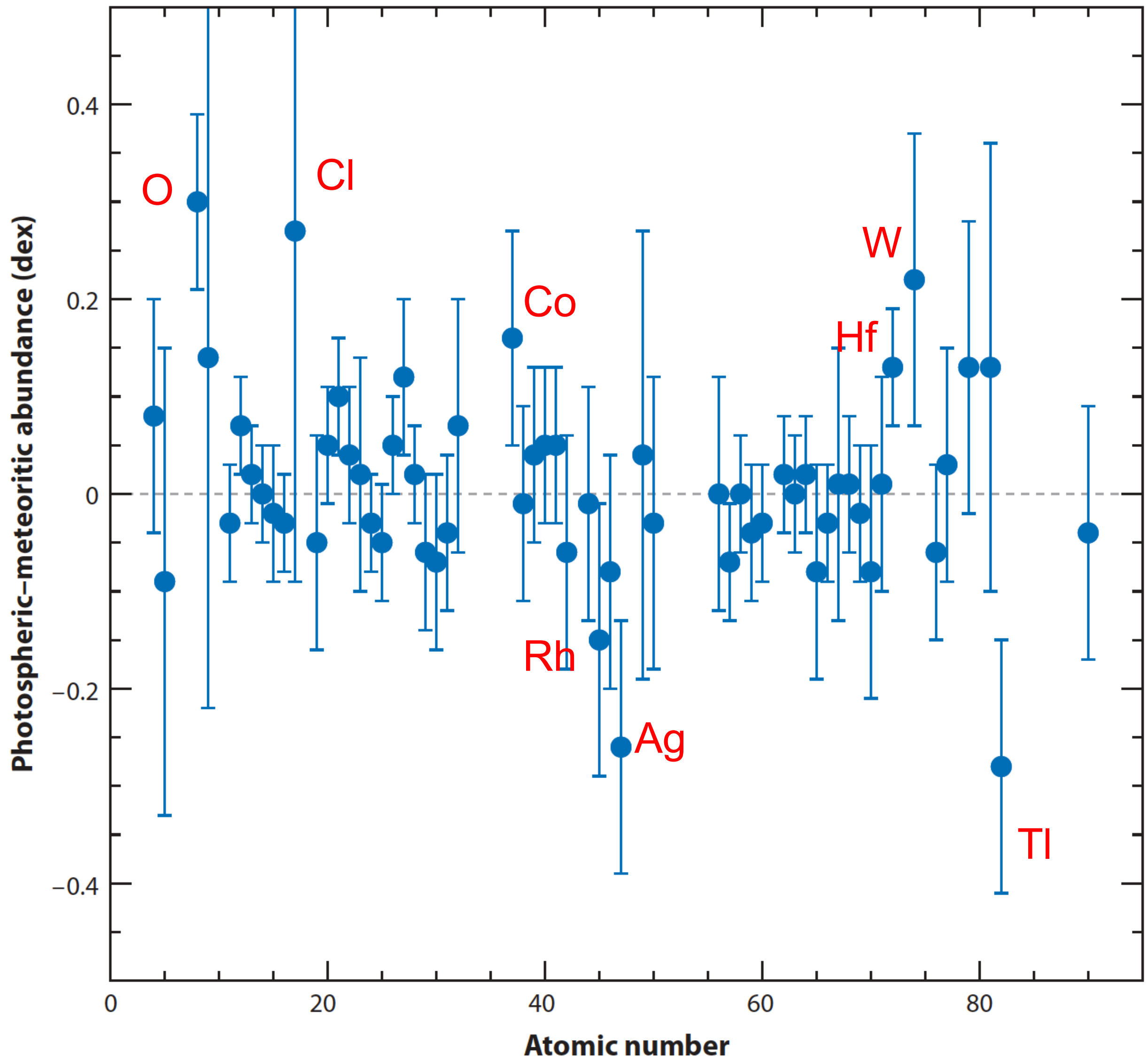
Abundances are normalized to Si (instead of H). The standard is $N(Si)=10^6$.

The result will be compared to photospheric results for calibration.

Abundances from meteorites: which ones are useful?



Differences between the two methods



Due to severe depletions in either sources, Li, C, N, O and noble gases fall outside the range of the figure.

With just a few exceptions, the agreement is excellent.

The main difference can be largely attributed to non-LTE effects.

Noble gas

- He: determination through helioseismology.

  Change of the adiabatic index (i.e., equation of state) in the HeII ionization zone (near the solar surface) can affect the the helioseismic spectrum.

- Ne & Ar: derived from the solar corona, solar wind and solar energetic particles.

  Complication by the *first-ionization-potential (FIP) effect*: elements with FIP<10 eV are enhanced in the upper solar atmosphere/solar wind.

  Solution: use a reference species (O) for normalization.

  (FIP for Ne is 21.6 eV, O is 13.6 eV)

- Ke & Xe: derived on theoretical basis (e.g., s-process production rates).

  Results can be cross-compared with measurements from the solar wind.

All in all: solar metallicity

Asplund et al. 2009

X, Y, Z: mass fractions of H, He and everything else (metals)

Source	*X*	*Y*	*Z*	*Z/X*
Present-day photosphere:				
Anders & Grevesse (1989)[a]	0.7314	0.2485	0.0201	0.0274
Grevesse & Noels (1993)[a]	0.7336	0.2485	0.0179	0.0244
Grevesse & Sauval (1998)	0.7345	0.2485	0.0169	0.0231
Lodders (2003)	0.7491	0.2377	0.0133	0.0177
Asplund, Grevesse & Sauval (2005)	0.7392	0.2485	0.0122	0.0165
Lodders, Palme & Gail (2009)	0.7390	0.2469	0.0141	0.0191
Present work	0.7381	0.2485	0.0134	0.0181
Protosolar:				
Anders & Grevesse (1989)	0.7096	0.2691	0.0213	0.0301
Grevesse & Noels (1993)	0.7112	0.2697	0.0190	0.0268
Grevesse & Sauval (1998)	0.7120	0.2701	0.0180	0.0253
Lodders (2003)	0.7111	0.2741	0.0149	0.0210
Asplund, Grevesse & Sauval (2005)	0.7166	0.2704	0.0130	0.0181
Lodders, Palme & Gail (2009)	0.7112	0.2735	0.0153	0.0215
Present work	0.7154	0.2703	0.0142	0.0199

Summary

- Two main ways to measure solar abundance: inference from solar spectroscopy and direct measurements from primitive meteorites
- Modeling solar spectroscopy is highly non-trivial. Requires substantial input from atomic physics, and radiative transfer and (magneto)-hydrodynamics.
- In the past few decades, abundances of major species C, N, O, Ne and Fe have been revised downwards thanks to the improvements in modeling solar spectroscopy.
- In general, results from solar spectroscopy and meteorites data show good agreement. A few species with larger discrepancies can be attributed to uncertain atomic physics/non-LTE effects.
- Future directions: largest uncertainties come from poor atomic and molecular data, and incomplete modeling for non-LTE effects