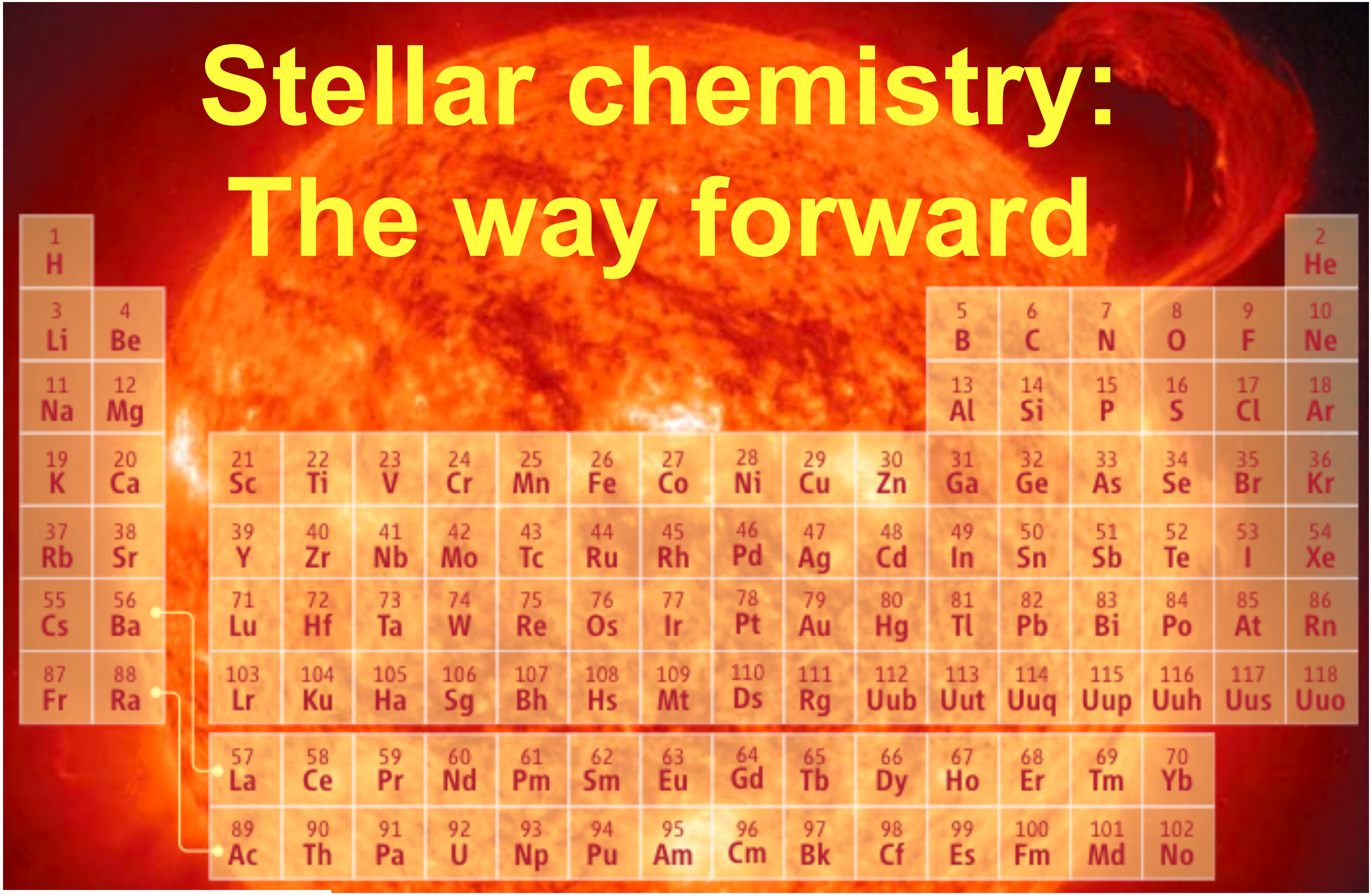
Stellar chemistry: The way forward



1 H																	2 He
3 Li	4 Be											5 B	6 C	7 N	8 O	9 F	10 Ne
11 Na	12 Mg											13 Al	14 Si	15 P	16 S	17 Cl	18 Ar
19 K	20 Ca	21 Sc	22 Ti	23 V	24 Cr	25 Mn	26 Fe	27 Co	28 Ni	29 Cu	30 Zn	31 Ga	32 Ge	33 As	34 Se	35 Br	36 Kr
37 Rb	38 Sr	39 Y	40 Zr	41 Nb	42 Mo	43 Tc	44 Ru	45 Rh	46 Pd	47 Ag	48 Cd	49 In	50 Sn	51 Sb	52 Te	53 I	54 Xe
55 Cs	56 Ba	71 Lu	72 Hf	73 Ta	74 W	75 Re	76 Os	77 Ir	78 Pt	79 Au	80 Hg	81 Tl	82 Pb	83 Bi	84 Po	85 At	86 Rn
87 Fr	88 Ra	103 Lr	104 Ku	105 Ha	106 Sg	107 Bh	108 Hs	109 Mt	110 Ds	111 Rg	112 Uub	113 Uut	114 Uuq	115 Uup	116 Uuh	117 Uus	118 Uuo
		57 La	58 Ce	59 Pr	60 Nd	61 Pm	62 Sm	63 Eu	64 Gd	65 Tb	66 Dy	67 Ho	68 Er	69 Tm	70 Yb		
		89 Ac	90 Th	91 Pa	92 U	93 Np	94 Pu	95 Am	96 Cm	97 Bk	98 Cf	99 Es	100 Fm	101 Md	102 No		

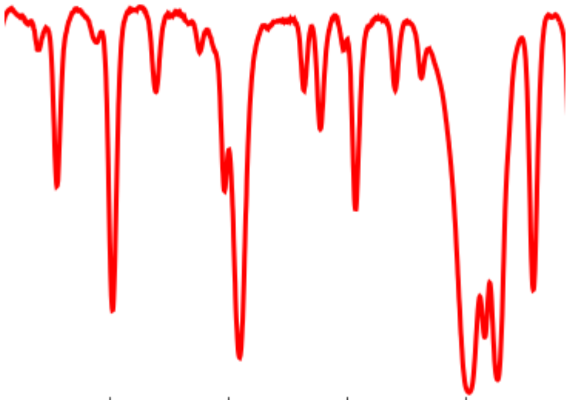
THE AUSTRALIAN NATIONAL UNIVERSITY

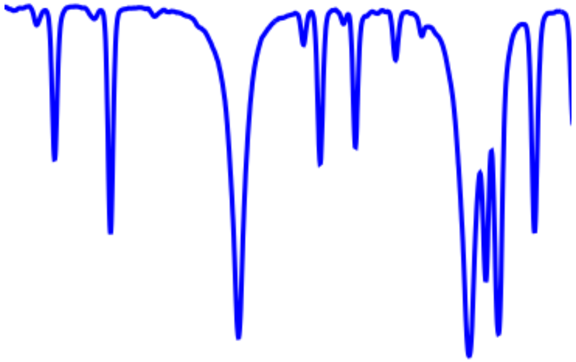
Martin Asplund

ASTRO 3D

Happy [redacted] birthday Joss!

Stellar spectroscopy



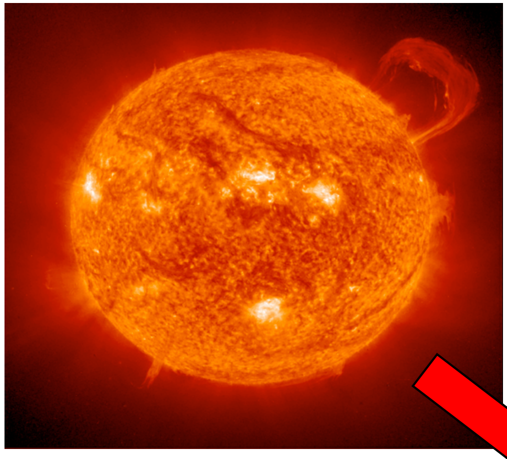


Temperature
Radius
Mass
Chemistry
Age
Rotation
Magnetic fields
etc

Stellar Atmosphere
Magnetohydrodynamics
Radiative transfer
Atomic physics

Optimal solution
Robustness
Speed

Stellar analysis



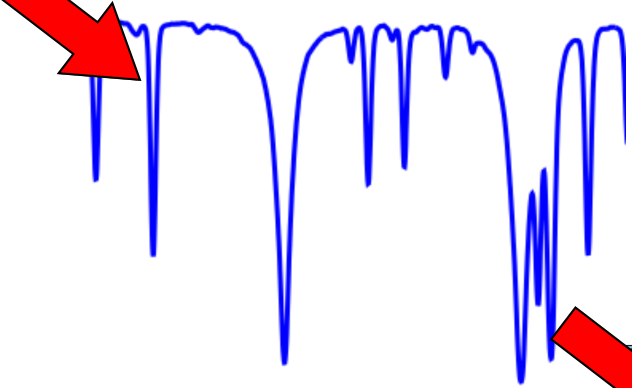
Stellar atmospheres & parameters

Effective temperature T_{eff}

Surface gravity logg

Metallicity [Fe/H]

Microturbulence (1D)



Radiative transfer:

LTE vs non-LTE

1D vs 3D

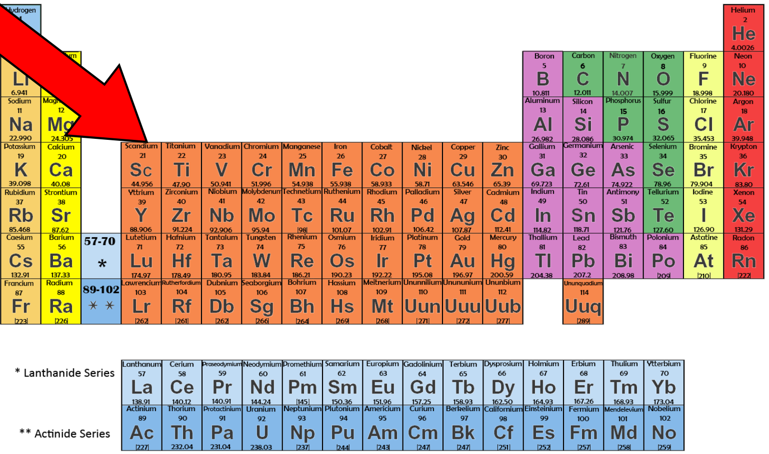
Stellar abundances:

logε(X), [X/H]

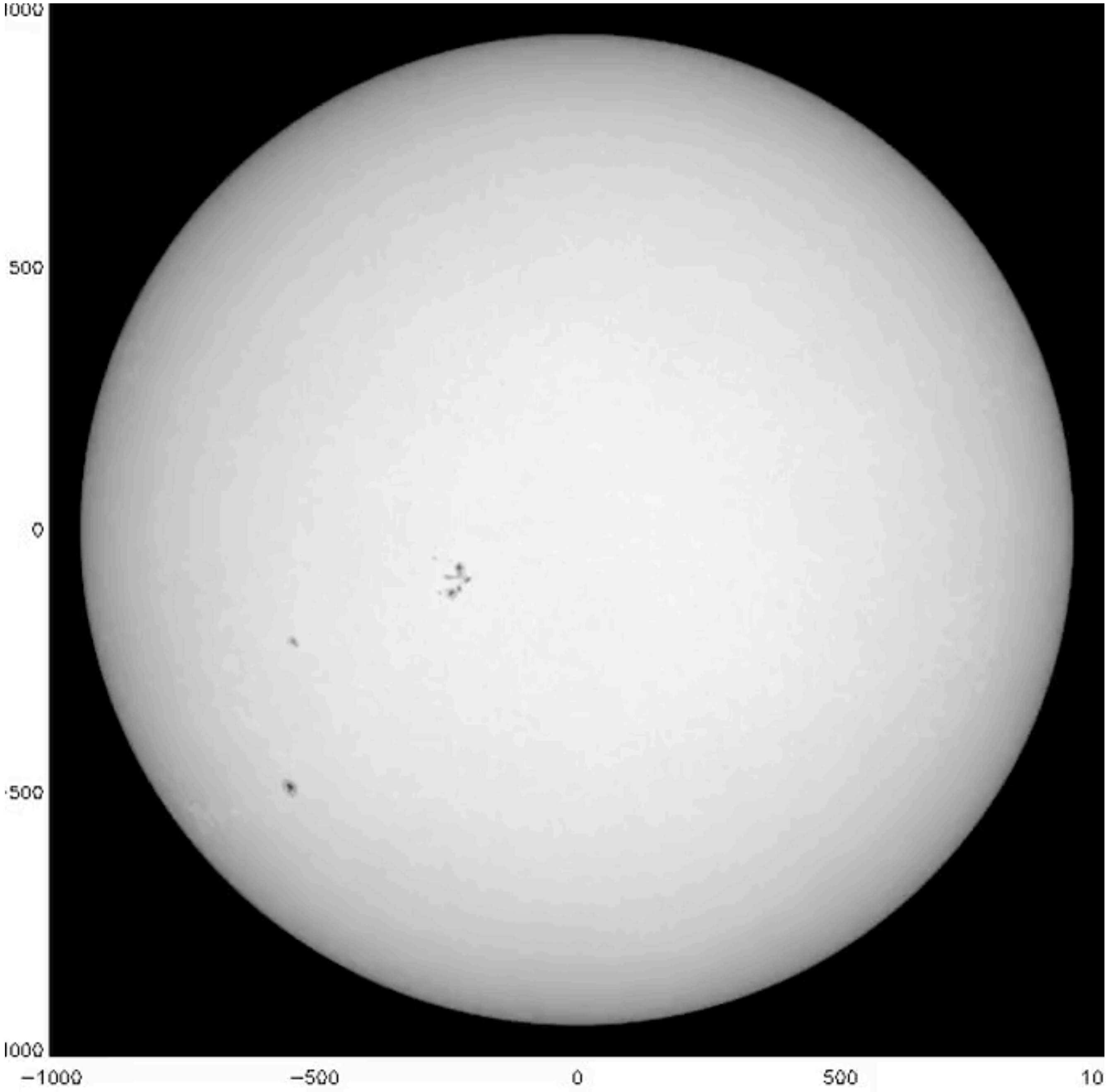
Uncertainties

Large stellar surveys

Auxiliary information



Stellar surface convection



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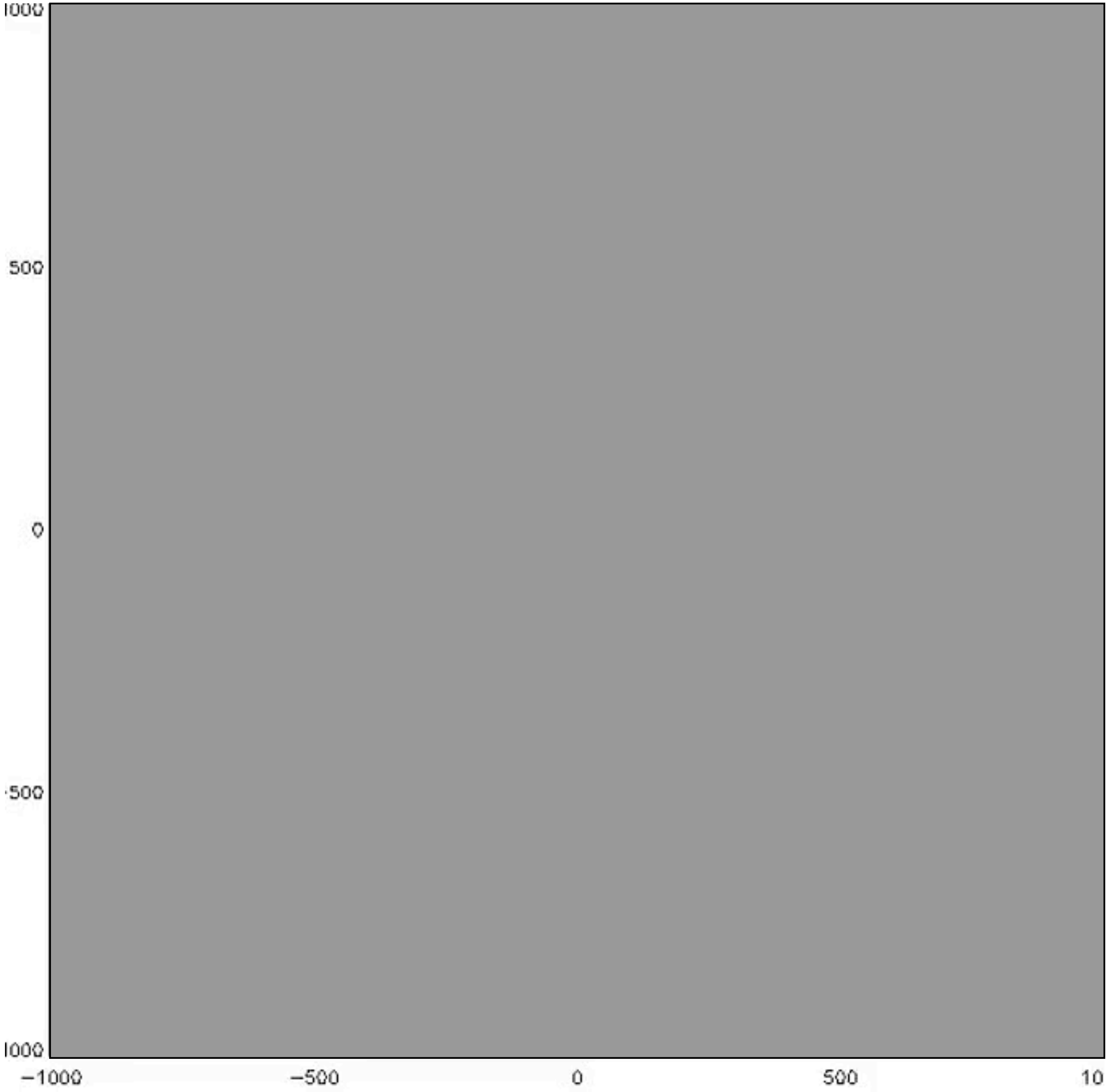
Stellar surface convection



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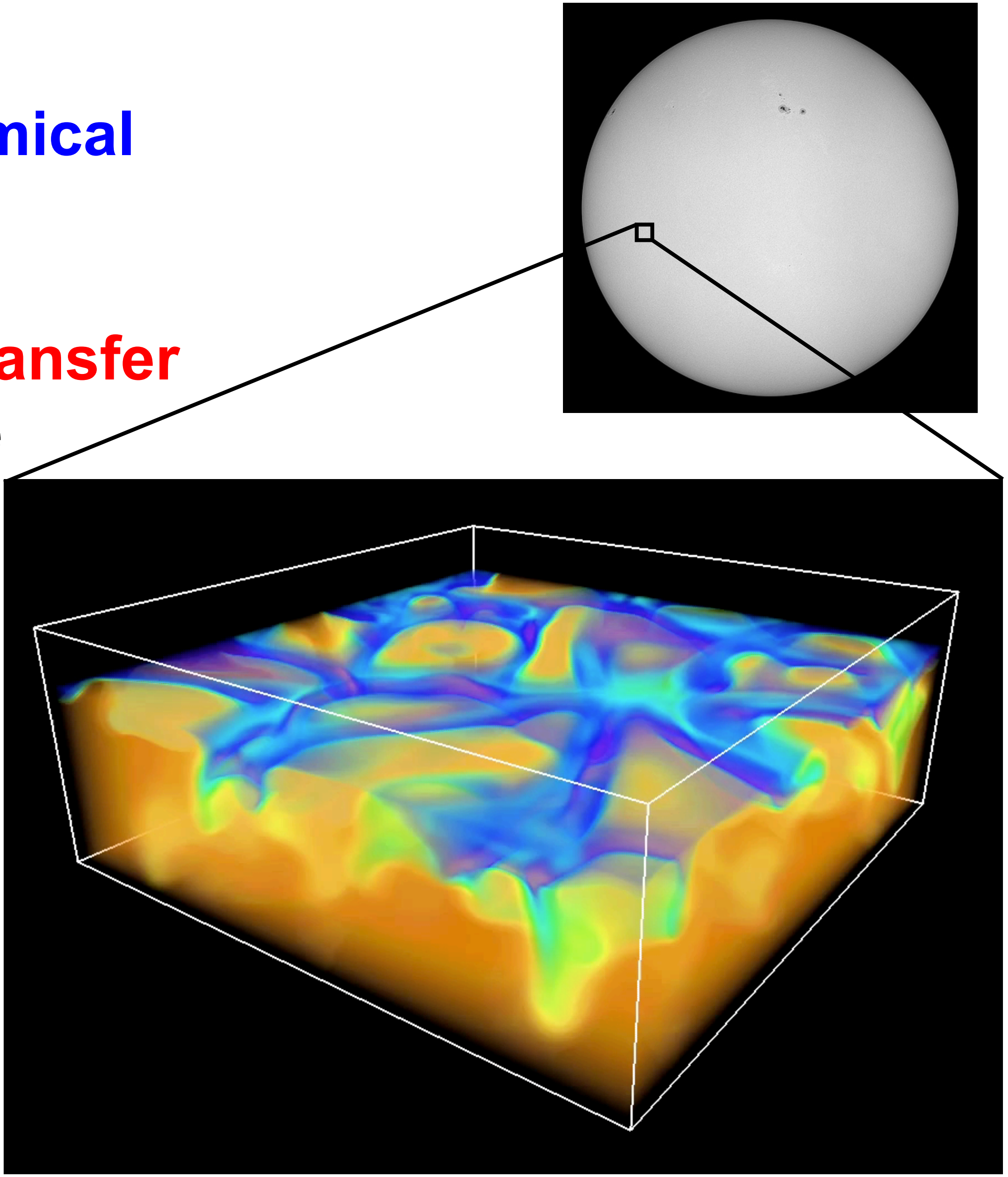
3D stellar atmosphere models

Ingredients:

- Radiative-hydrodynamical
- Time-dependent
- 3-dimensional
- Simplified radiative transfer

Essentially parameter free



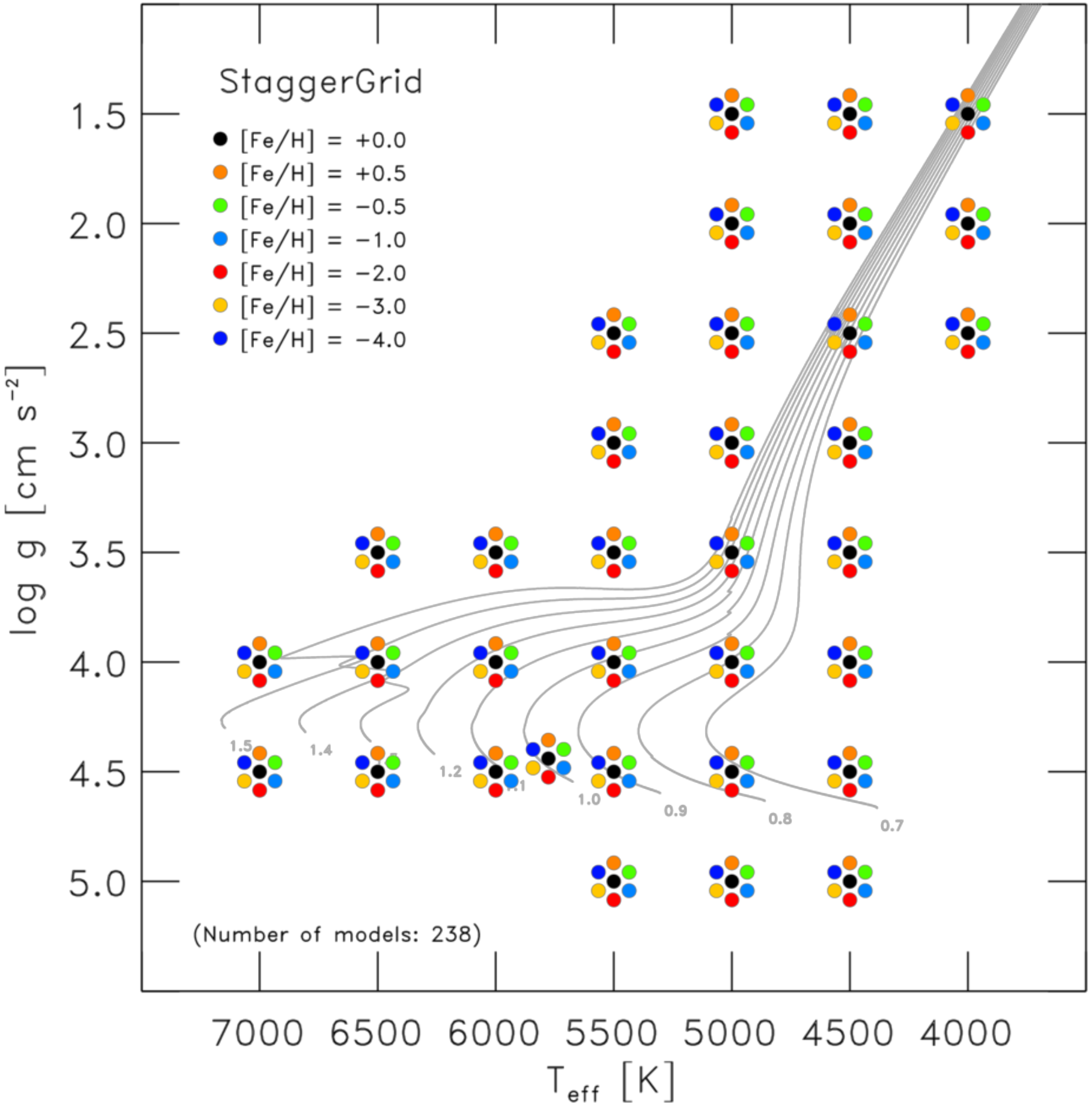
For the aficionados:

Stagger-code (Nordlund et al.)
MHD EoS (Mihalas et al.)
Opacities (Gustafsson et al.)
Opacity binning

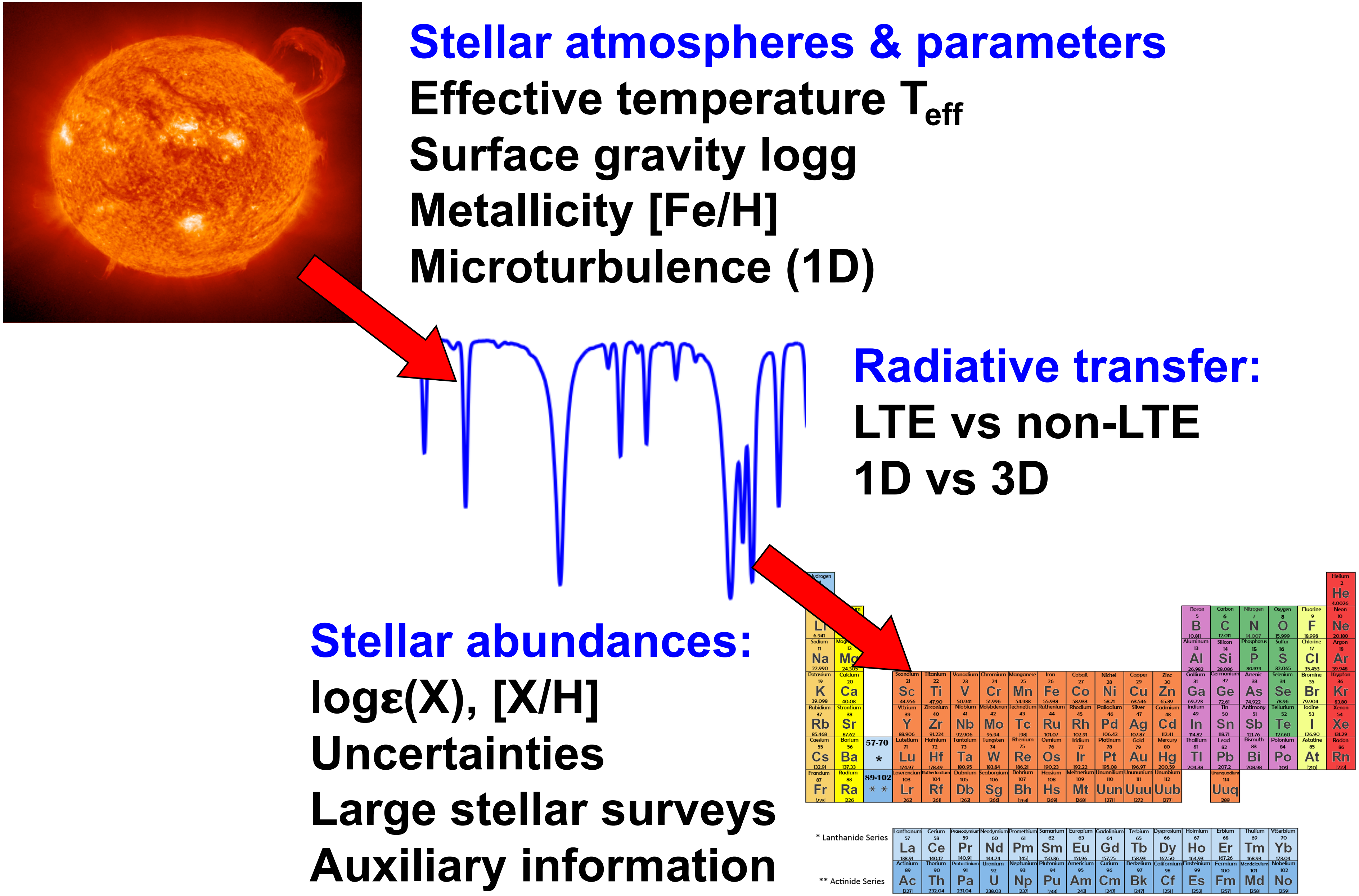
Stagger-grid of 3D stellar models

Magic et al. 2013;
Collet et al. 2018:
3D and <3D> models and fluxes public:

- **Stellar spectroscopy**
- **Stellar evolution**
- **Asteroseismology**
- **Exoplanet searches**
- **Etc, etc**



Stellar analysis



Stellar atmospheres & parameters

Effective temperature T_{eff}
Surface gravity logg
Metallicity [Fe/H]
Microturbulence (1D)

Radiative transfer:

LTE vs non-LTE
1D vs 3D

Stellar abundances:

logε(X), [X/H]
Uncertainties
Large stellar surveys
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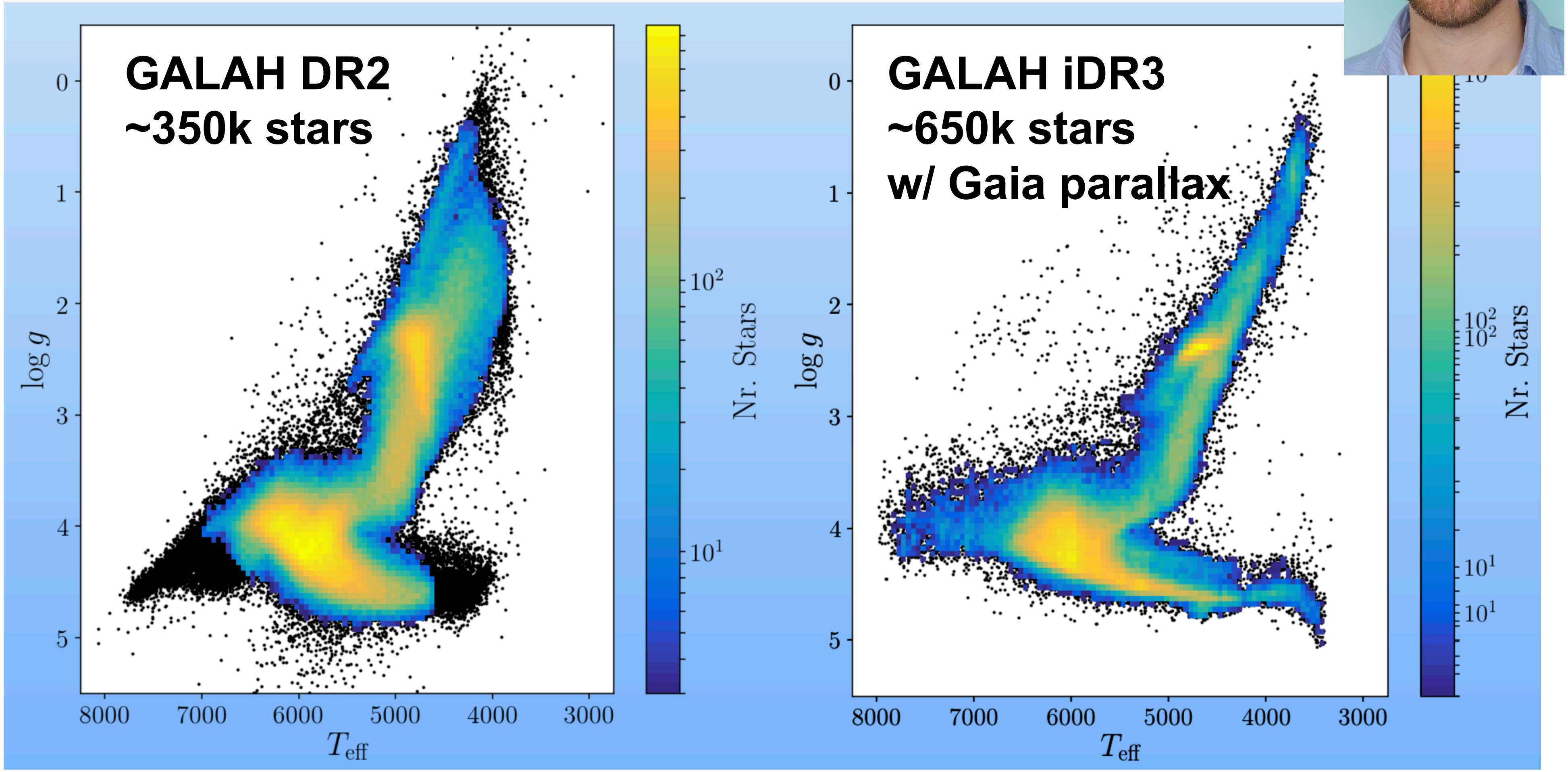
Surface gravity: Gaia revolution

$$\log\frac{g}{g_\odot} = 4\log\frac{T_{eff}}{T_{eff,\odot}} + \log\frac{M}{M_\odot} + 2\log\pi + 0.4\left(m_V + BC_V - A_V\right) + 0.10$$

Parallax

Buder et al. 2019:



Effective temperature: Gaia

Gaia BP/RP spectrophotometry

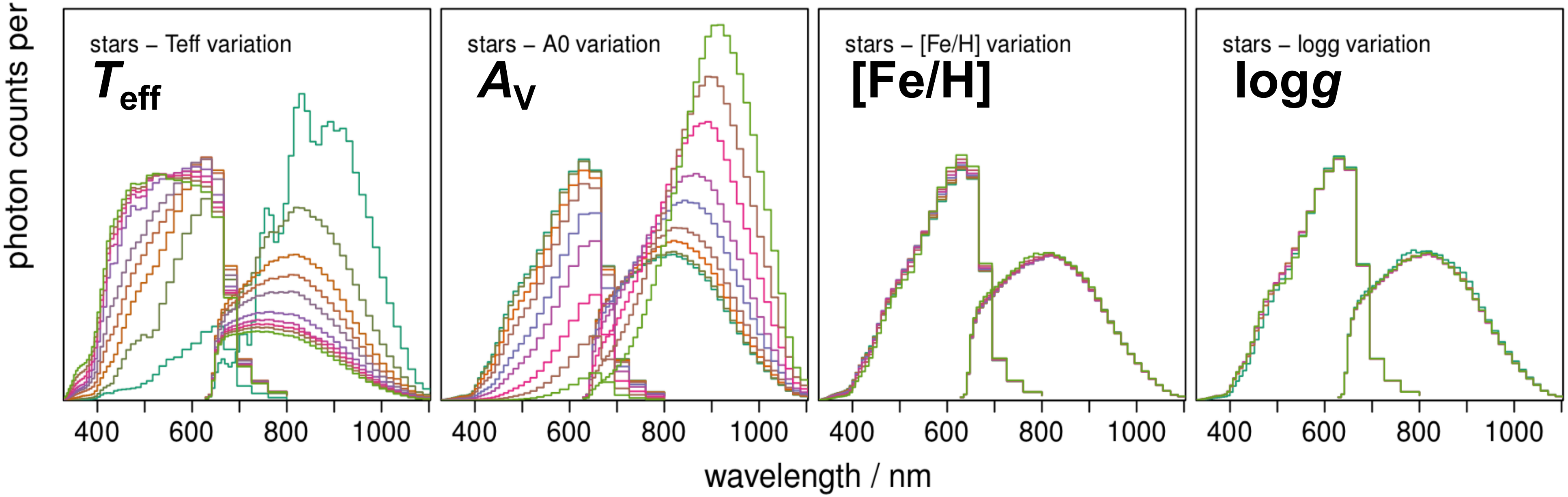
R~50, 330-1050nm

~10^9 stars with G<20

δT_{eff}~100K, $\delta \log g$~0.2, δ[Fe/H]~0.2, δA_V~0.1mag

Gaia DR3: end of 2021 (incl. BP/RP & RVS spectra)

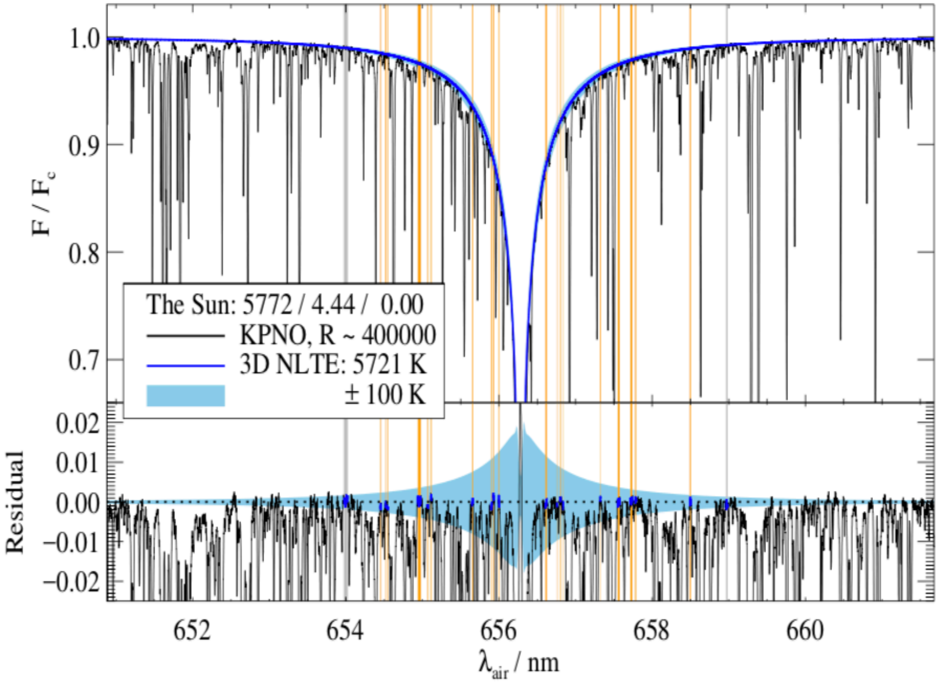
Bailer-Jones et al. 2013

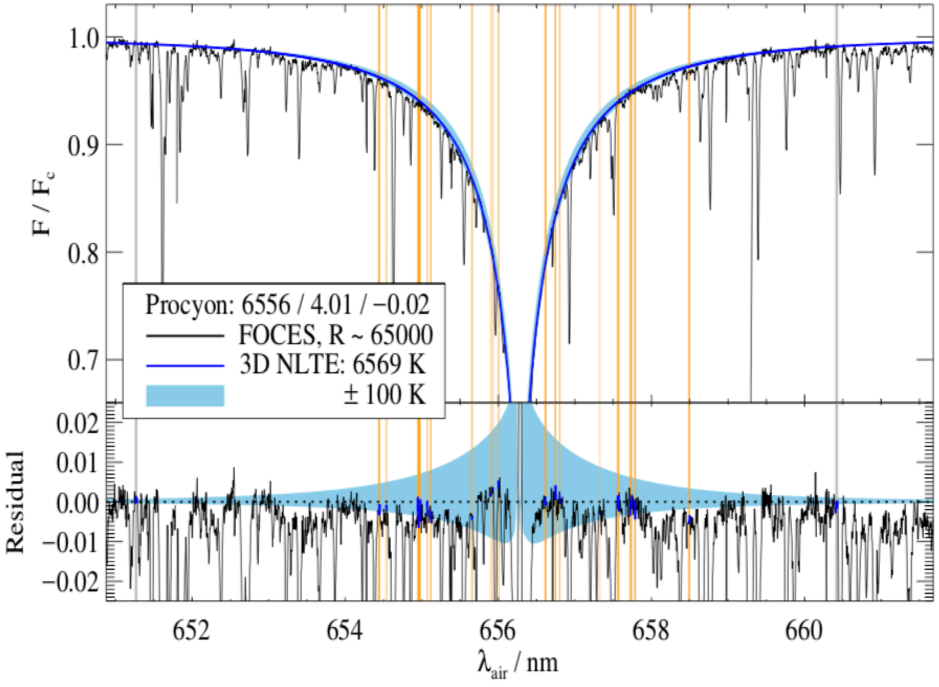


Effective temperature: H lines

Very T_{eff} sensitive but sophisticated modelling needed:
3D: Realistic atmospheric temperature structure
Non-LTE: Small effects flux variations ⇒ large T_{eff} effect

Amarsi et al. 2017: grid of 3D non-LTE H line profiles





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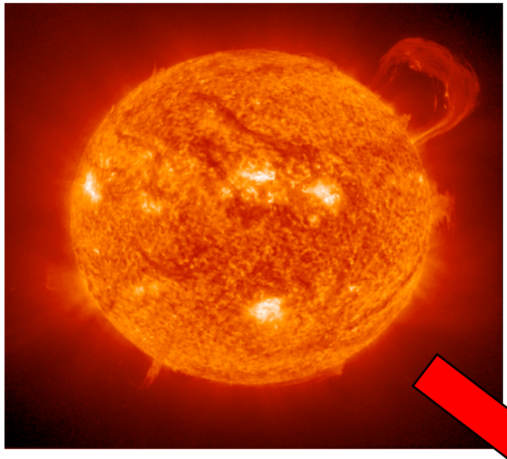

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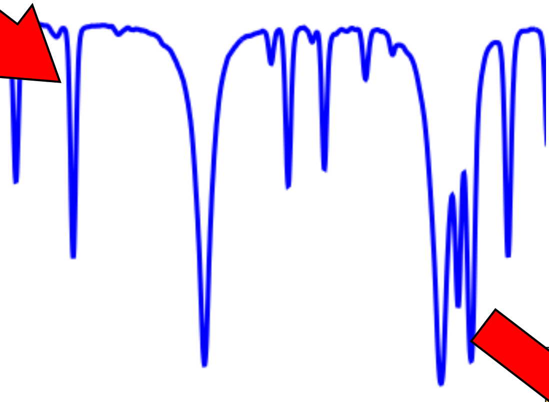


Radiative transfer:

LTE vs non-LTE

1D vs 3D

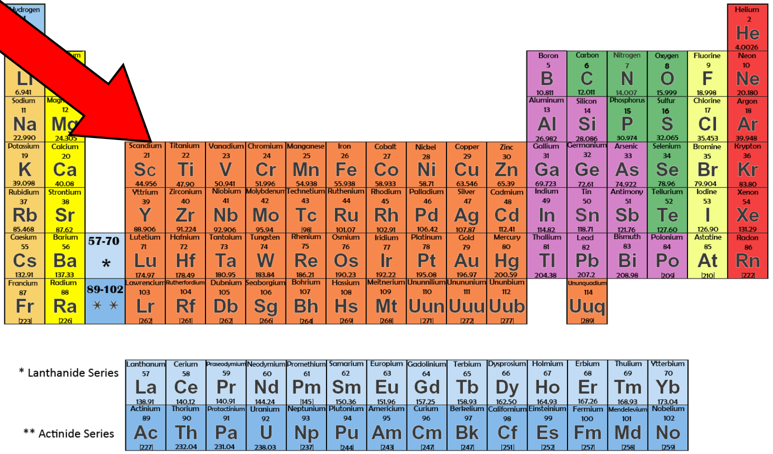
Stellar abundances:

logε(X), [X/H]

Uncertainties

Large stellar surveys

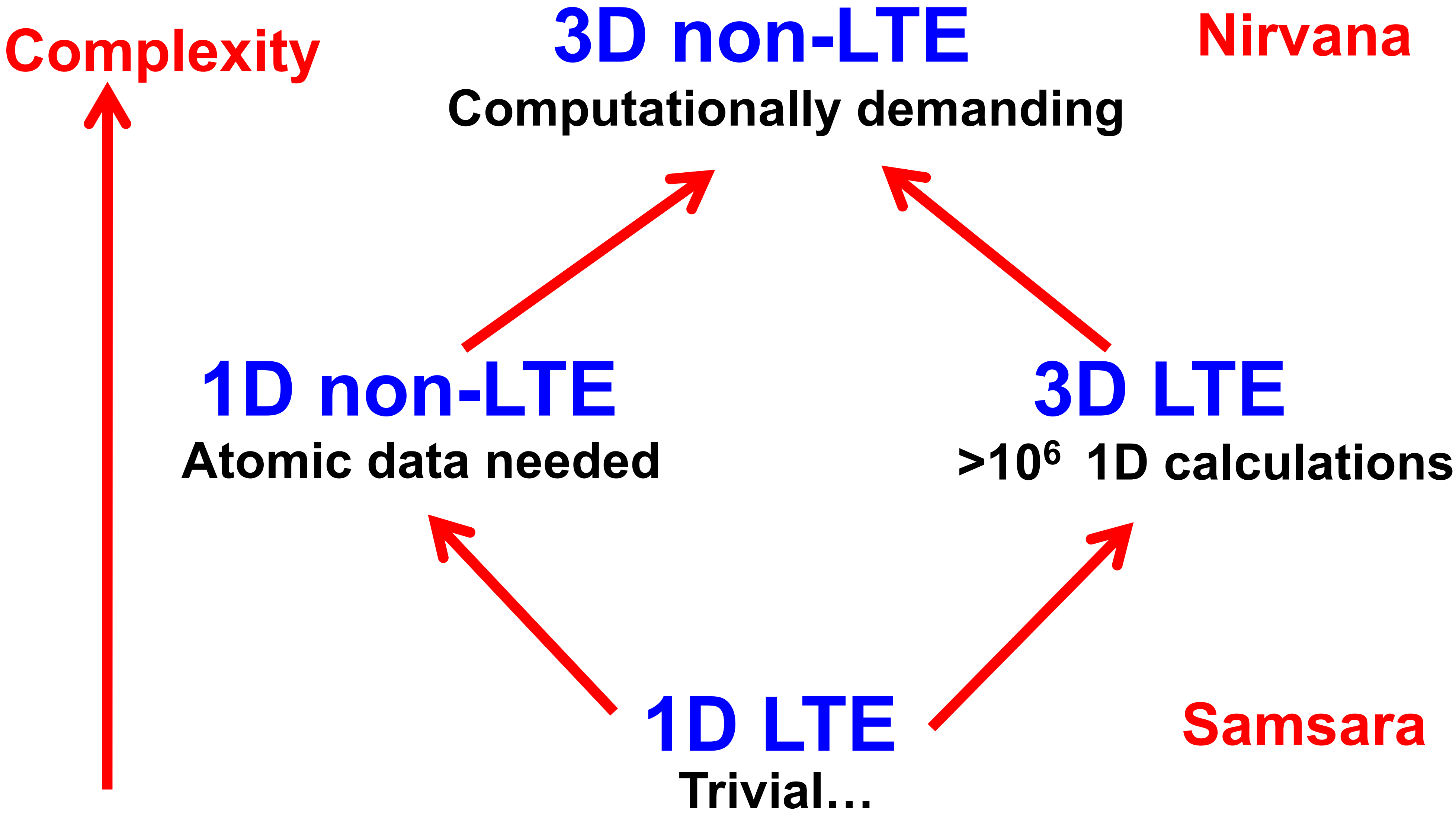
Auxiliary information



																		He
Li														B	C	N	O	F	Ne
Na	Mg													Al	Si	P	S	Cl	Ar
K	Ca		Sc	Ti	V	Cr	Mn	Fe	Co	Ni	Cu	Zn	Ga	Ge	As	Se	Br	Kr
Rb	Sr		Y	Zr	Nb	Mo	Tc	Ru	Rh	Pd	Ag	Cd	In	Sn	Sb	Te	I	Xe
Cs	Ba	57-70 *	Lu	Hf	Ta	W	Re	Os	Ir	Pt	Au	Hg	Tl	Pb	Bi	Po	At	Rn
Fr	Ra	89-102 * *	Lr	Rf	Db	Sg	Bh	Hs	Mt	Uun	Uuu	Uub		Uuq				

* Lanthanide Series	La	Ce	Pr	Nd	Pm	Sm	Eu	Gd	Tb	Dy	Ho	Er	Tm	Yb
** Actinide Series	Ac	Th	Pa	U	Np	Pu	Am	Cm	Bk	Cf	Es	Fm	Md	No

Radiative transfer



Complexity

3D non-LTE

Computationally demanding

Nirvana

1D non-LTE

Atomic data needed

3D LTE

$>10^6$ 1D calculations

1D LTE

Trivial…

Samsara

LTE: Maxwell + Boltzmann + Saha + Planck

Non-LTE radiative transfer

Level populations <u>not</u> determined by Saha & Boltzmann

Radiative transfer eq.

$$\frac{\mathrm{d}I_\nu}{\mathrm{d}\tau_\nu} = S_\nu - I_\nu$$

Source function:

$$S^l_\nu = (1-\varepsilon_\nu)\, J_\nu + \varepsilon_\nu B_\nu.$$

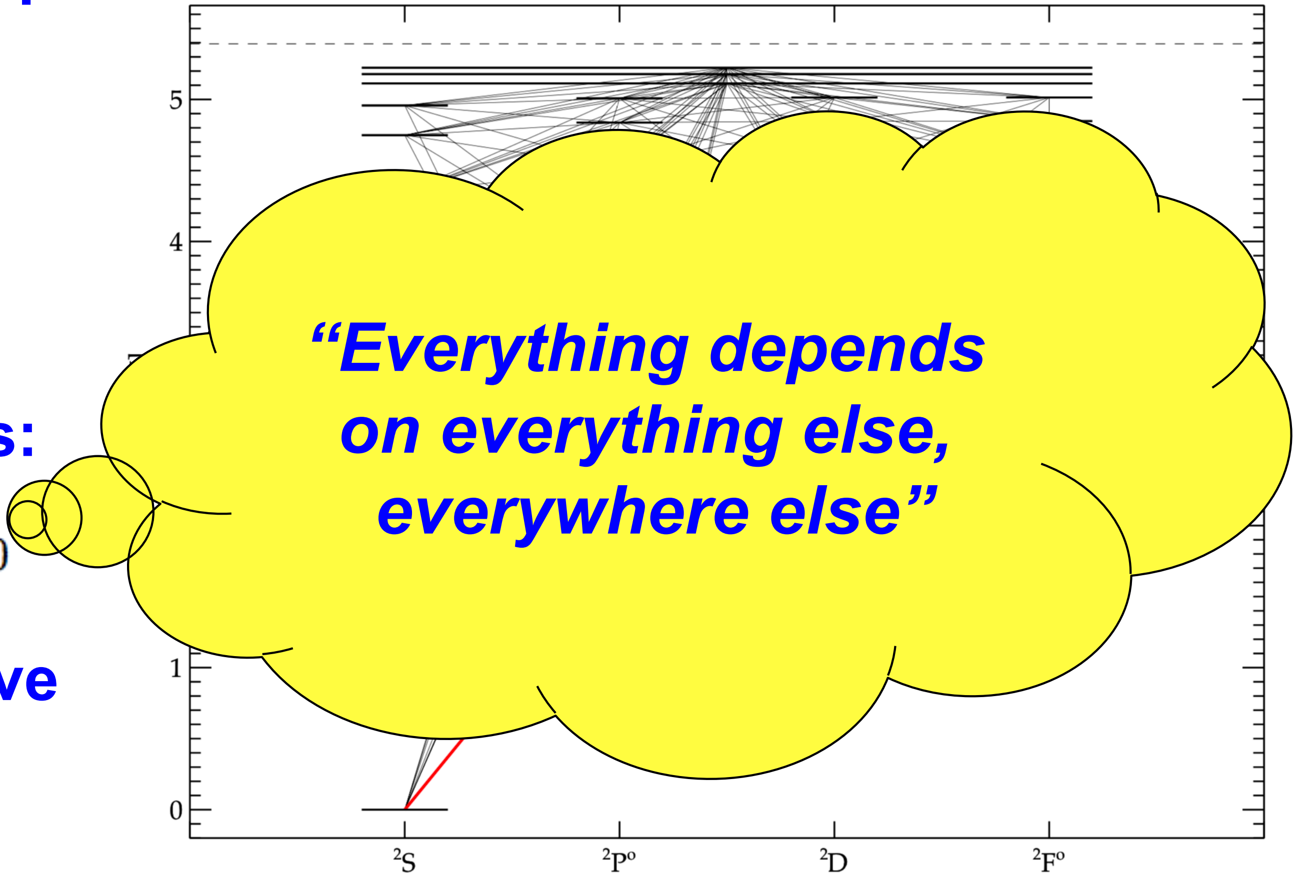
Level rate equations:

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

Collisional & radiative rates:

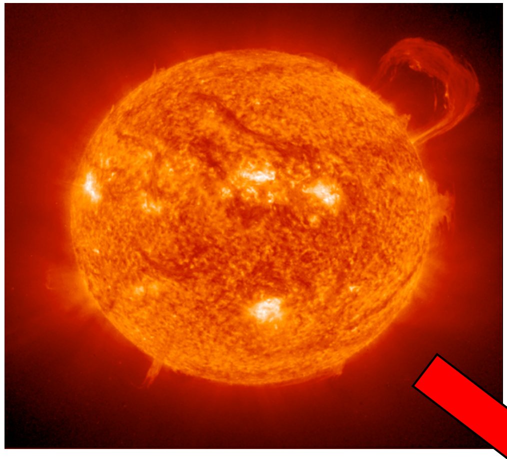
$$P_{ij} = A_{ij} + B_{ij}\bar{J}_{\nu_0} + C_{ij}.$$

Lithium term diagram



"Everything depends on everything else, everywhere else"

Stellar analysis



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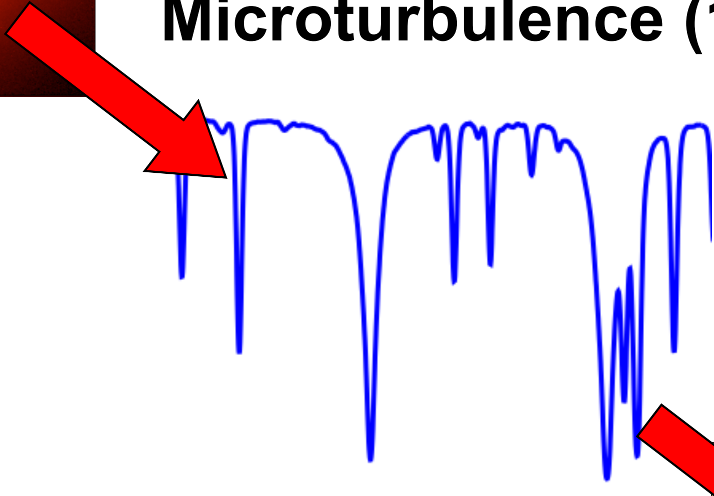

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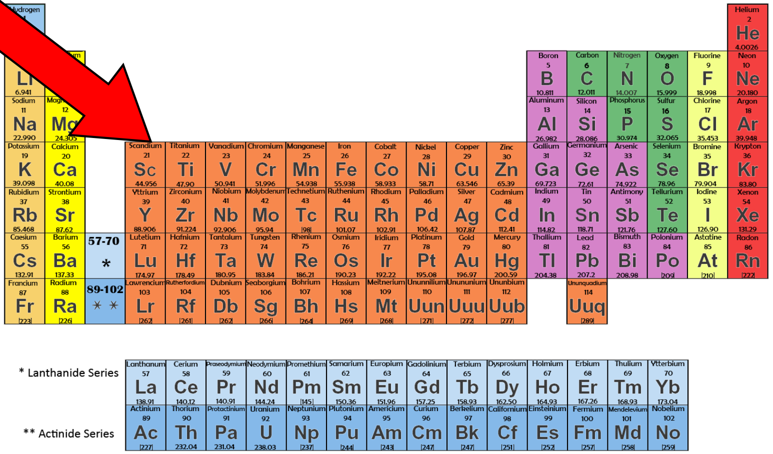
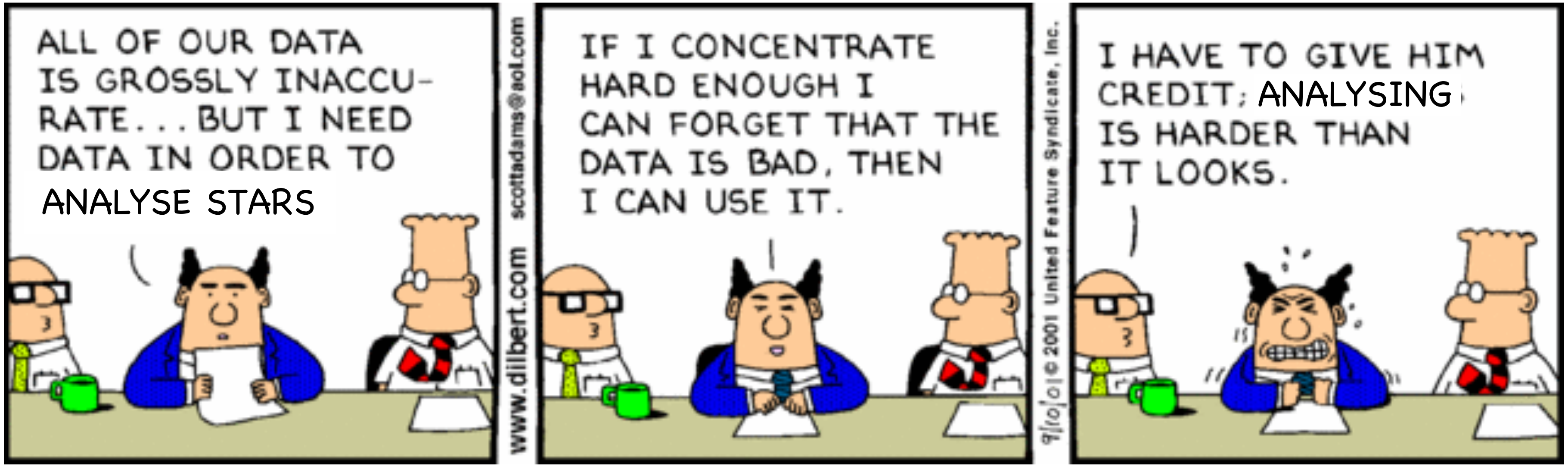


Atomic data

Huge amount of (uncertain) data needed in non-LTE:
Transition probabilities, photo-ionisation cross-sections, collisional excitation/ionisation with H and e$^-$, charge transfer, pressure broadening, hyperfine splitting etc

⇒ Support your local atomic physicist!



Differential stellar analysis

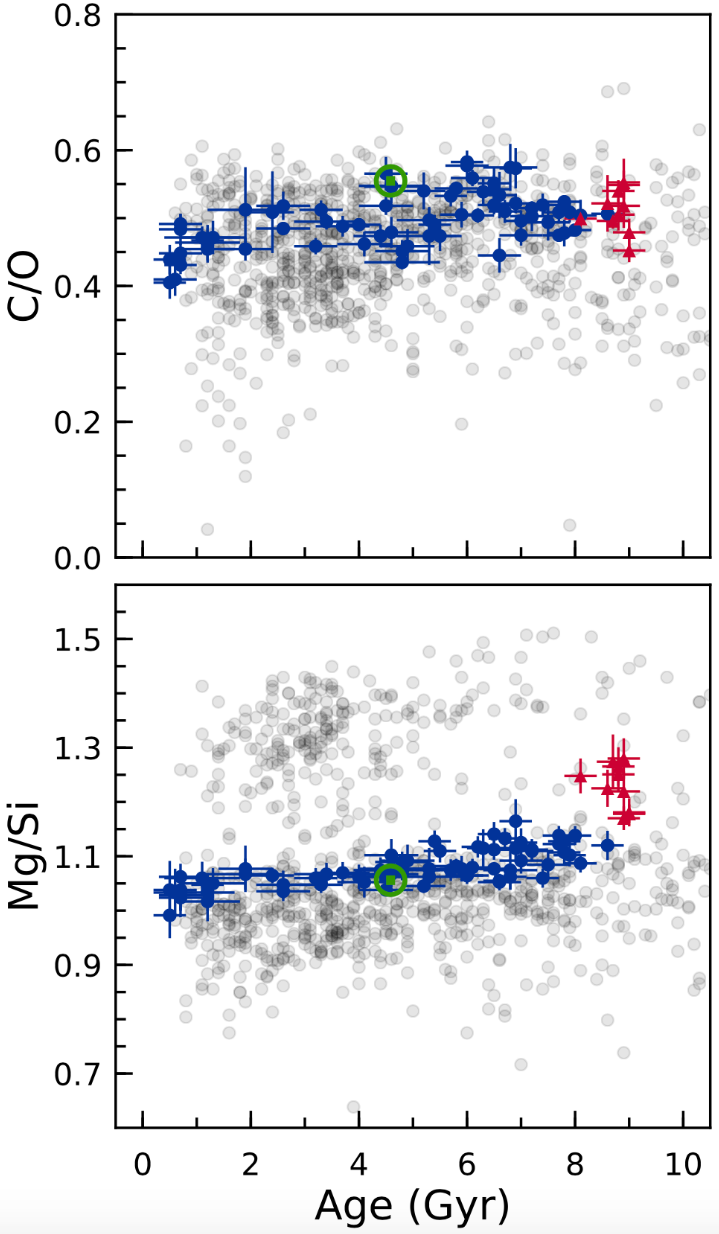
Extremely high precision (0.01 dex) for stars with similar parameters:

Melendez et al. 2009:
⇒ Signature of planet formation

Bedell et al. 2018:
⇒ Chemical enrichment vs time

Reggiani et al. 2017:
⇒ Tiny abundance scatter in halo

Bedell et al. 2018



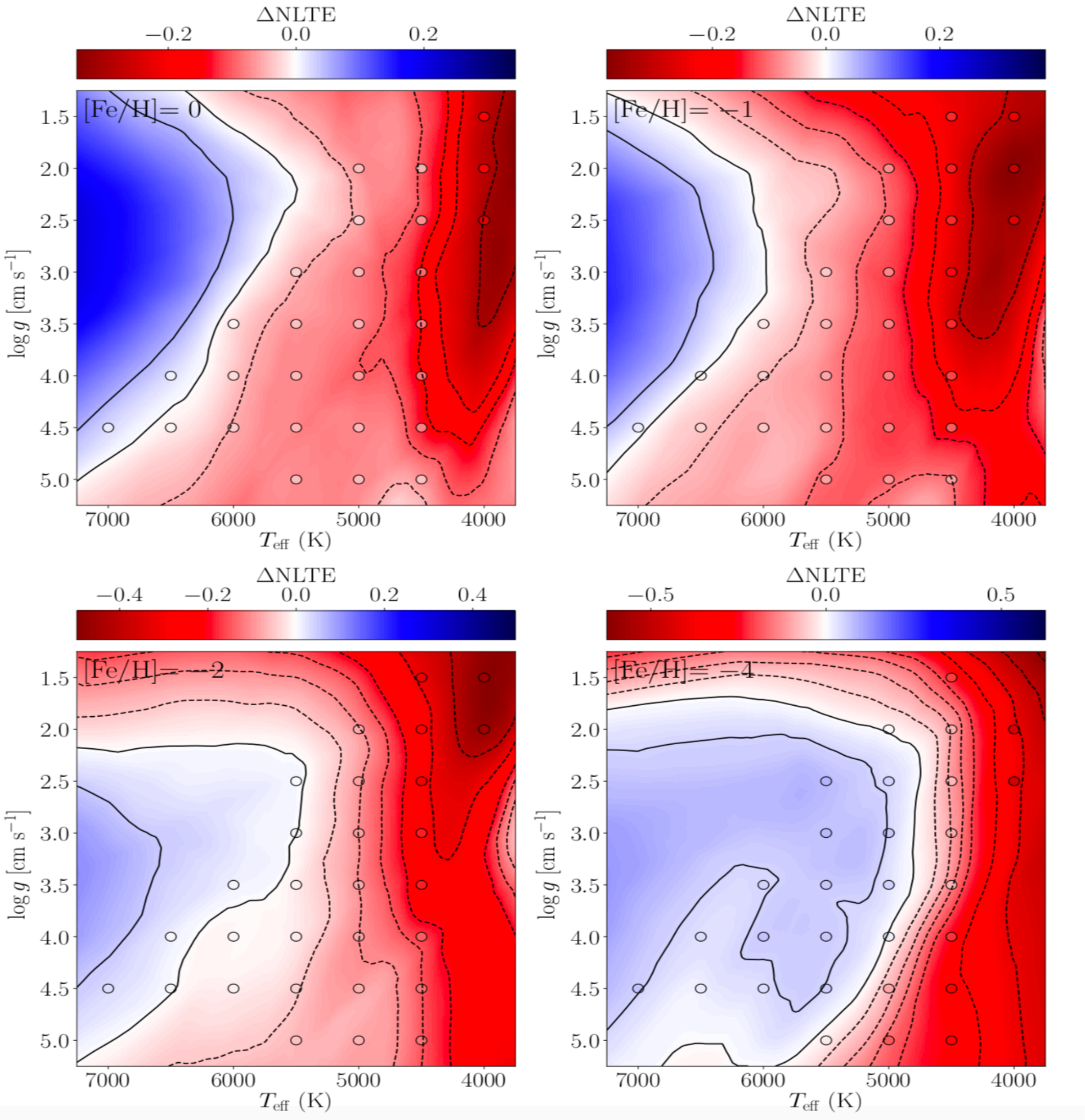
3D non-LTE line formation

Wang et al. 2019:

3D non-LTE for Li for FGK dwarfs/giants and Li abundances

Interpolation in parameters and abundances using neural networks (MLP) publicly available

3D non-LTE – 1D LTE abundances

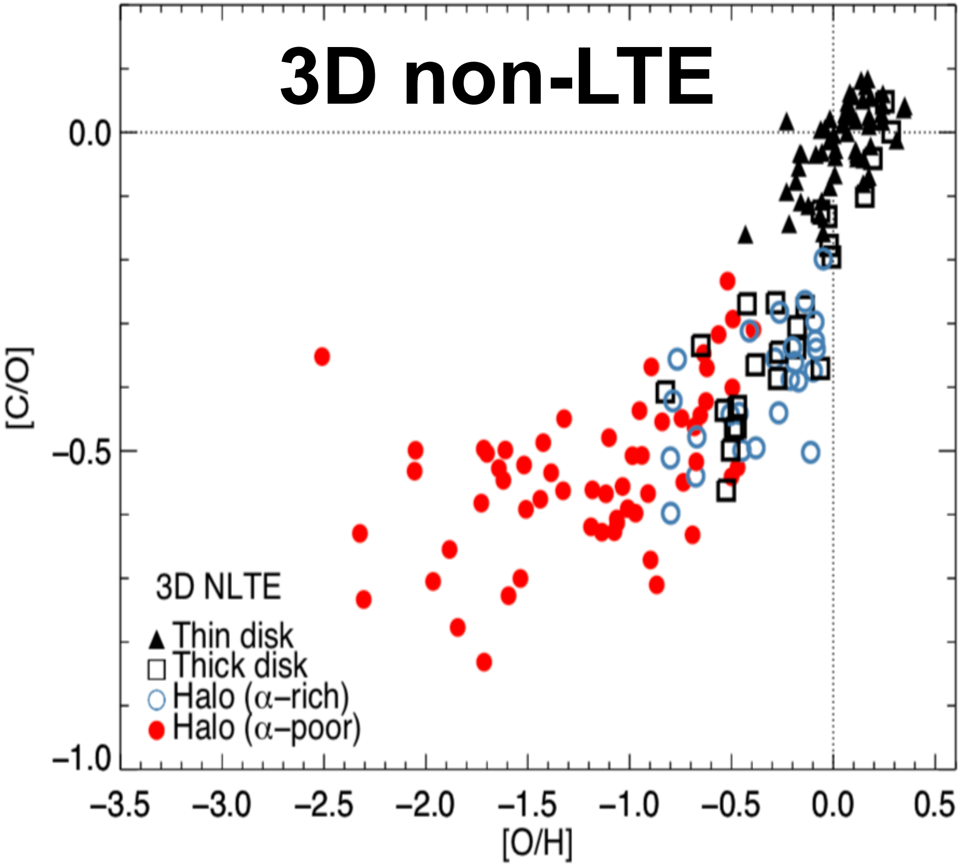


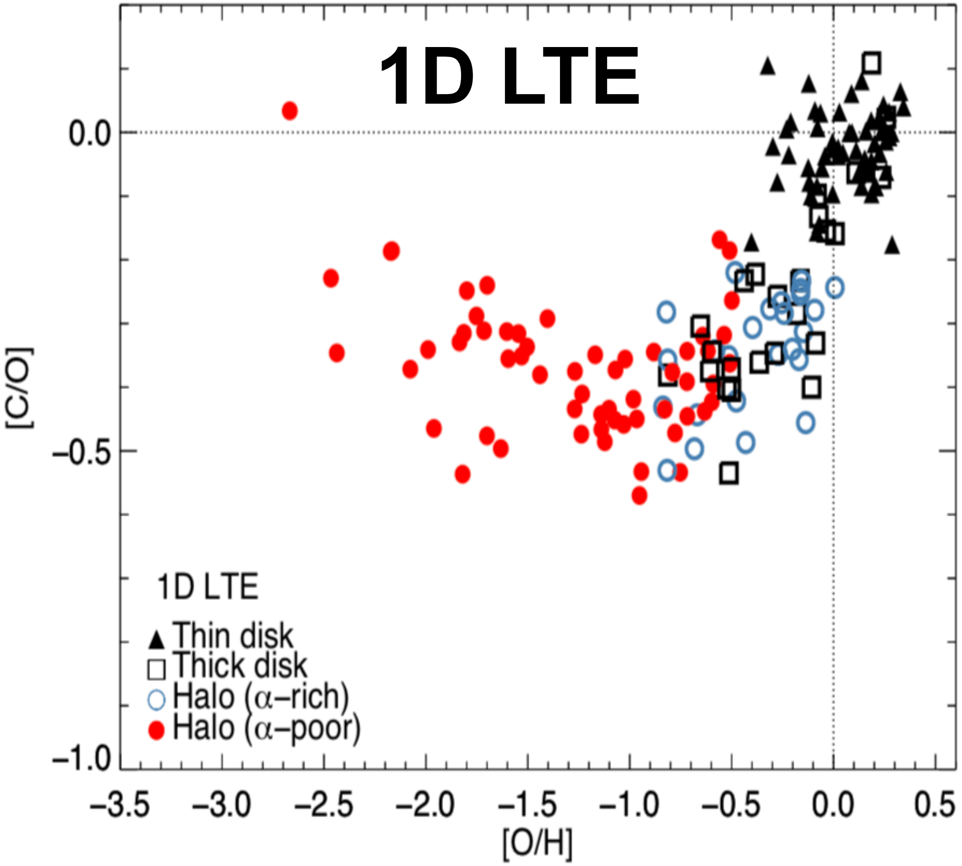
Evolution of C and O

Amarsi et al. 2019a,b:

3D non-LTE line formation of C, O and Fe

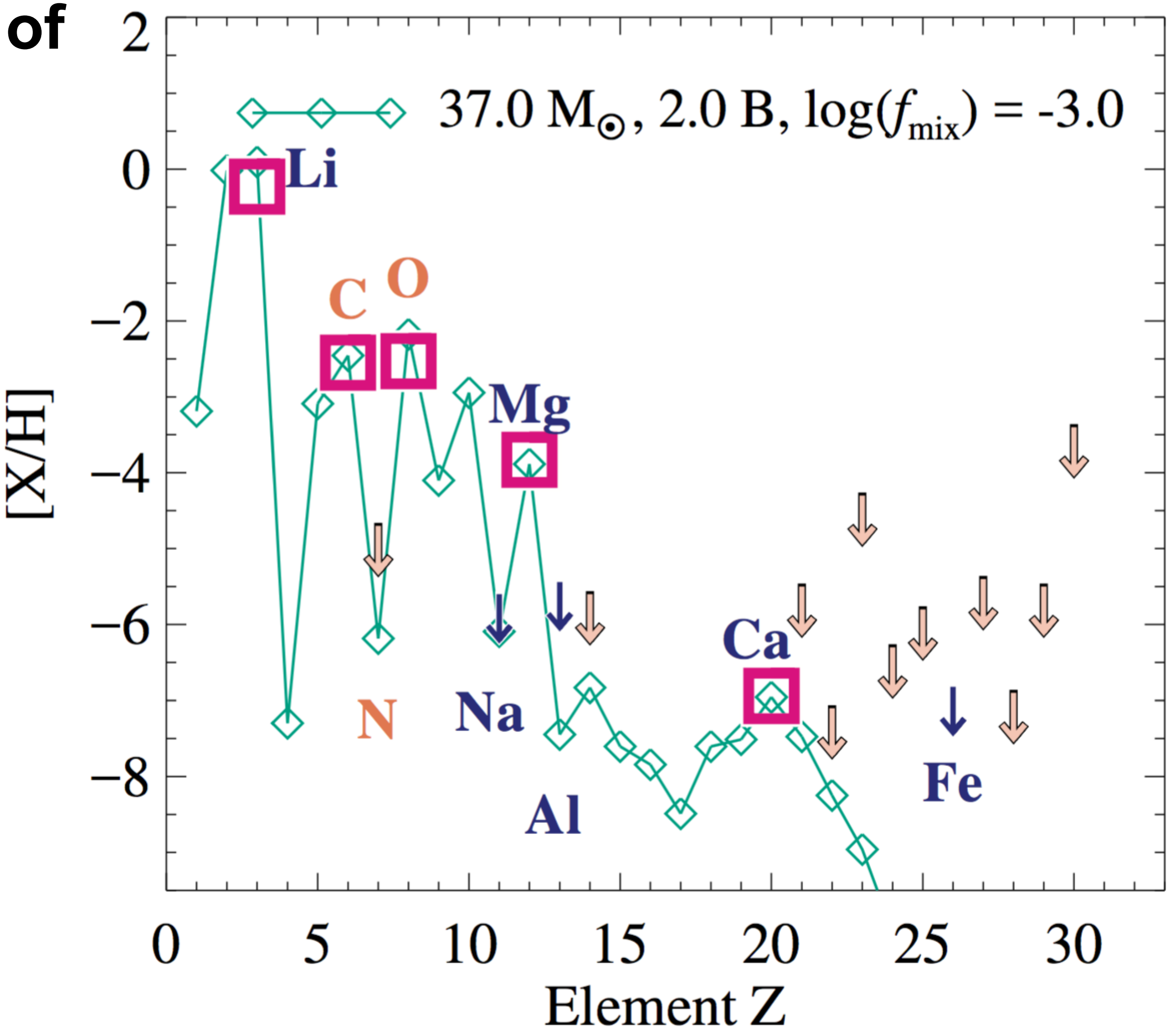
⇒ No signature of Pop III nucleosynthesis





First stars

Nordlander et al. 2017:
3D non-LTE analysis of SMSS0313-6708 with [Fe/H]<-6.5
Non-LTE abundance corrections >0.5 dex for Mg, Al, Ca, Fe

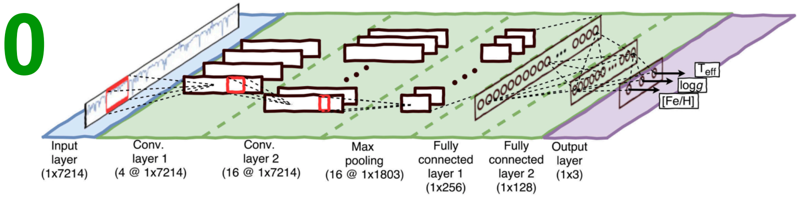


How to analyse a million stars?

- Automated
- Accurate
- Precise
- Fast
- Reliable
- Reproducible

Large spectroscopic surveys

- Spectrum synthesis
  - Automated, brute force
- Grids of spectra
  - Recio-Blanco et al. 2006
  - Garcia Perez et al. 2016
- Data-driven analysis
  - Ness et al. 2015
  - Casey et al. 2017
- Neural networks
  - Bailer-Jones et al. 2000
  - Fabbro et al. 2017



Smart & sparse grids

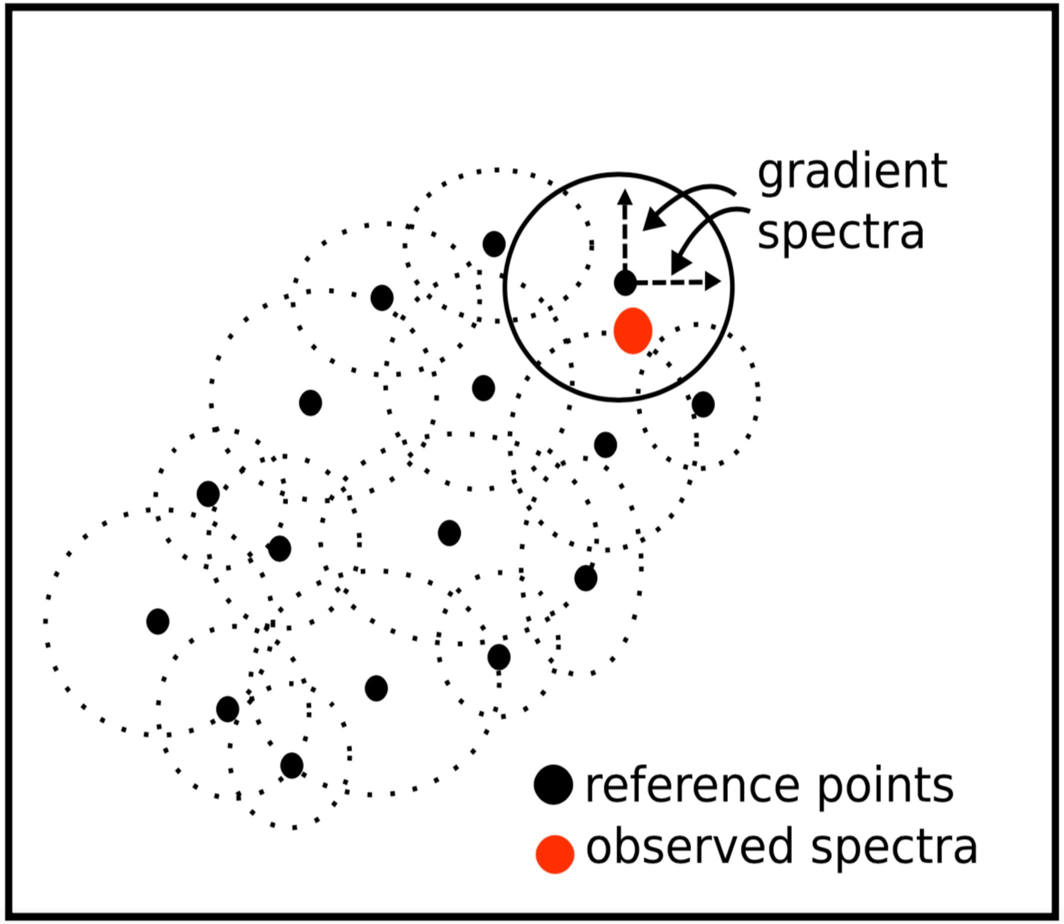
Rectilinear grids very expensive for high dimensions:

$N_{models} \propto (N_{bin})^{dimensions}$

Ting et al. 2016;
Rix et al. 2016:
Grid models only were needed combined with linear expansion of gradient spectra

$N_{models} \propto$ **dimensions!**
$N_{models} \sim 1000?$

3D non-LTE grids with ~30 dimensions!

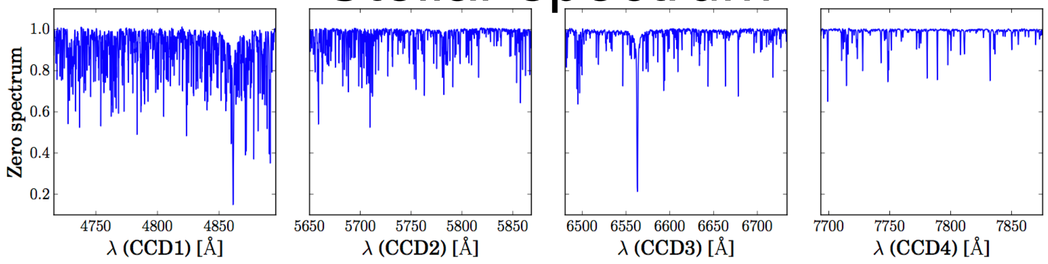


Cannon: data-driven analysis

Ness et al. 2015:

Use linear algebra to construct flux spectra in terms of stellar labels

Stellar spectrum



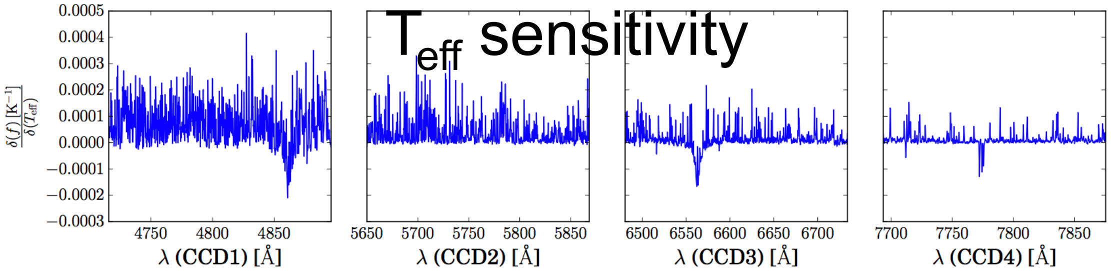
Flux at a pixel

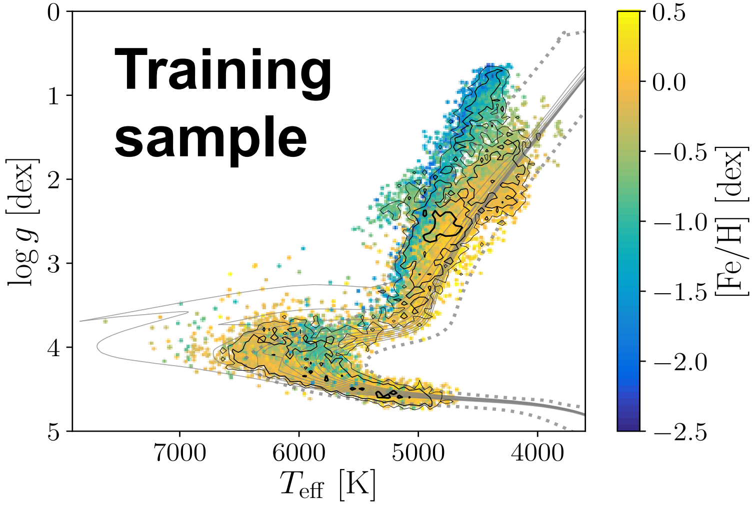
Label coefficients

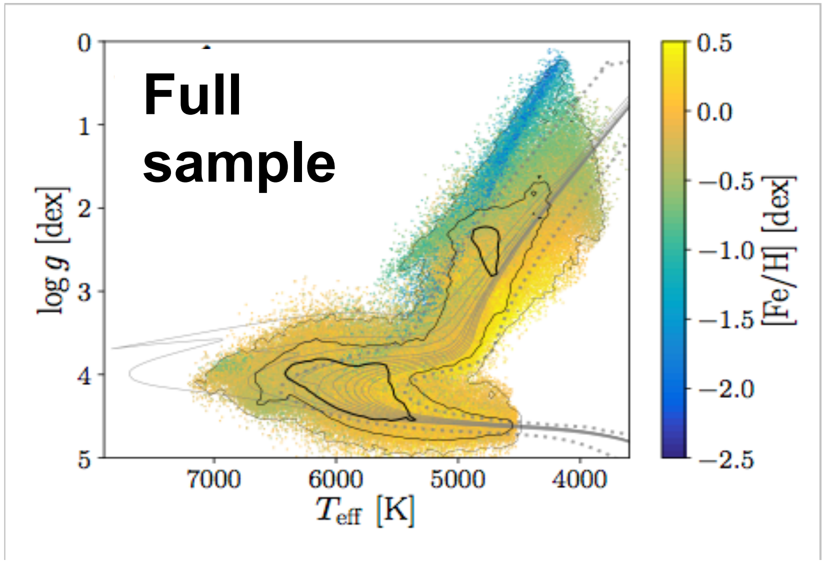
Labels

$$f_{n\lambda} = \theta_\lambda^T \cdot \ell_n + noise$$

T_{eff} sensitivity



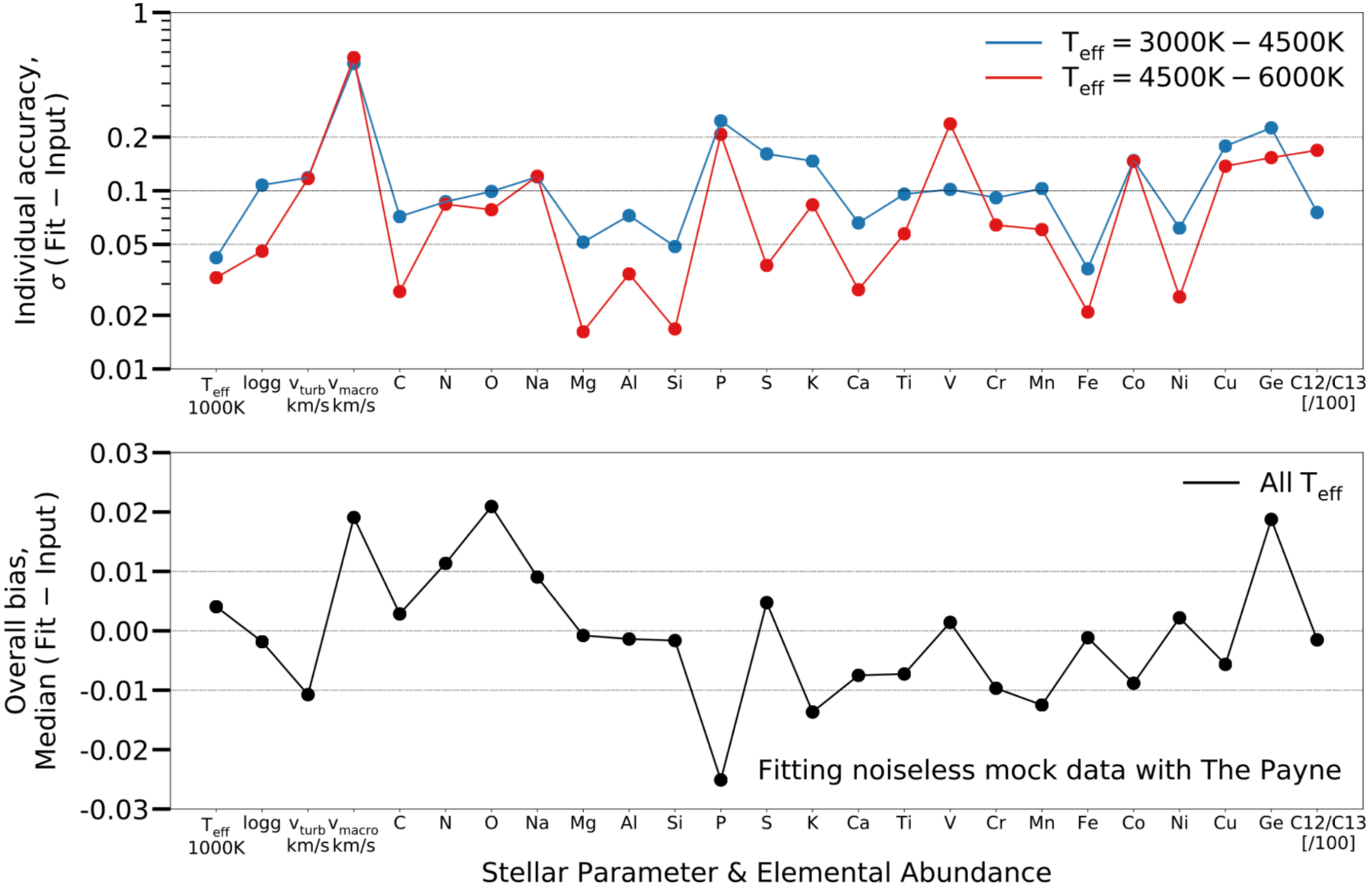




Payne

Ting et al. 2019:

Physics-informed ab-initio theoretical spectra for sparse and randomly selected grid models with ANN interpolation



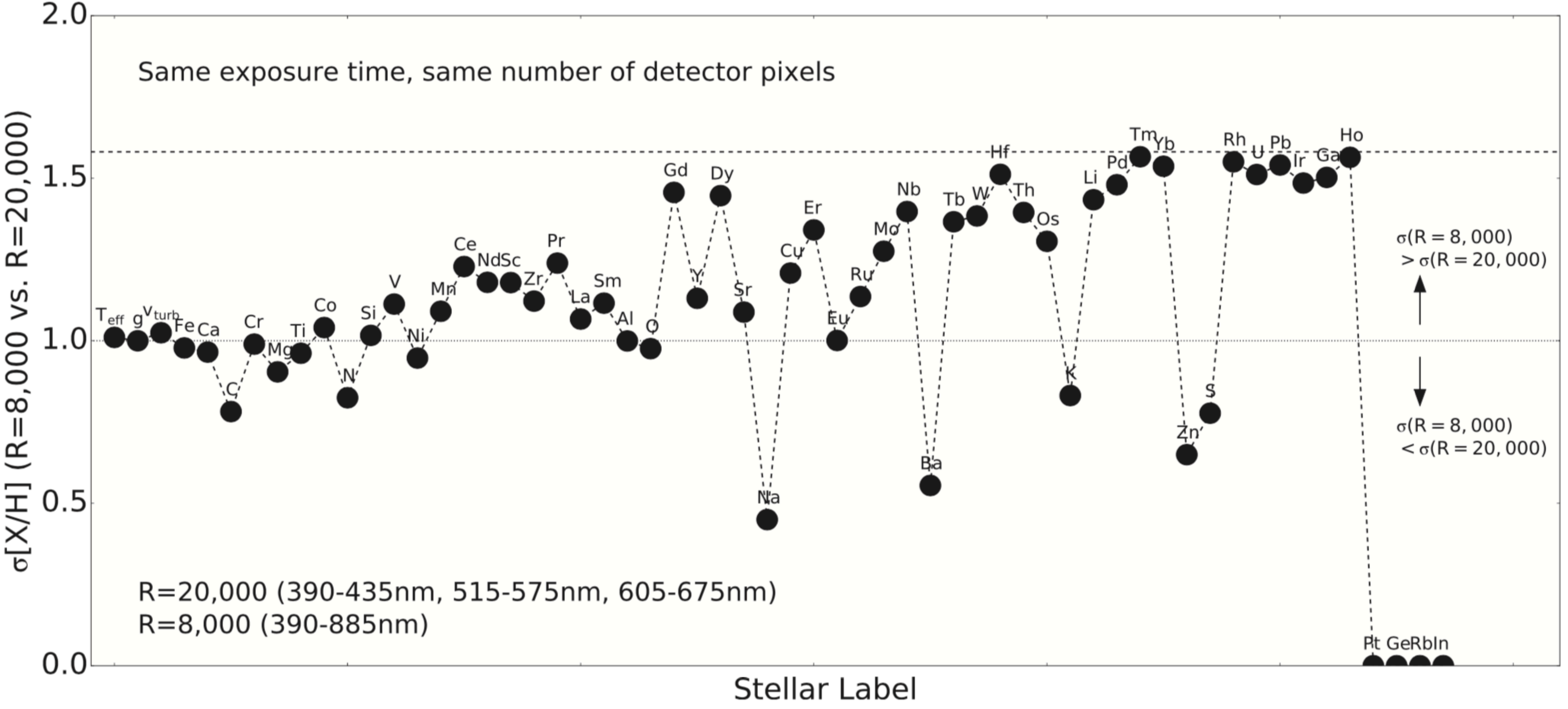
Low vs high resolution

High-res: analysis of selected “good” lines

Low-res: global fit to whole spectrum

Similar information content for equal τ_{exposure} and N_{pixels}

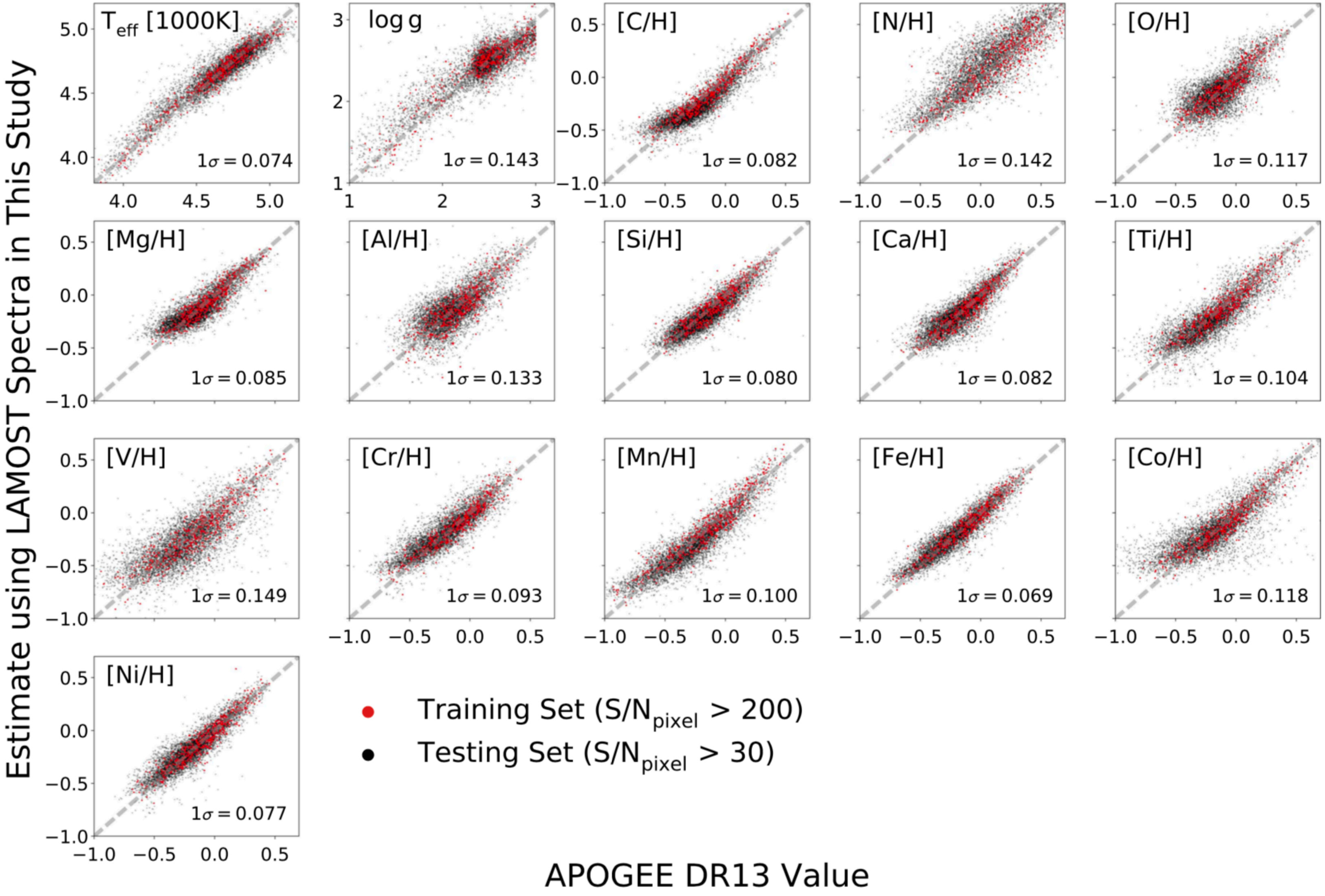
Ting et al. 2017:



Payne + LAMOST

Ting et al. 2017:

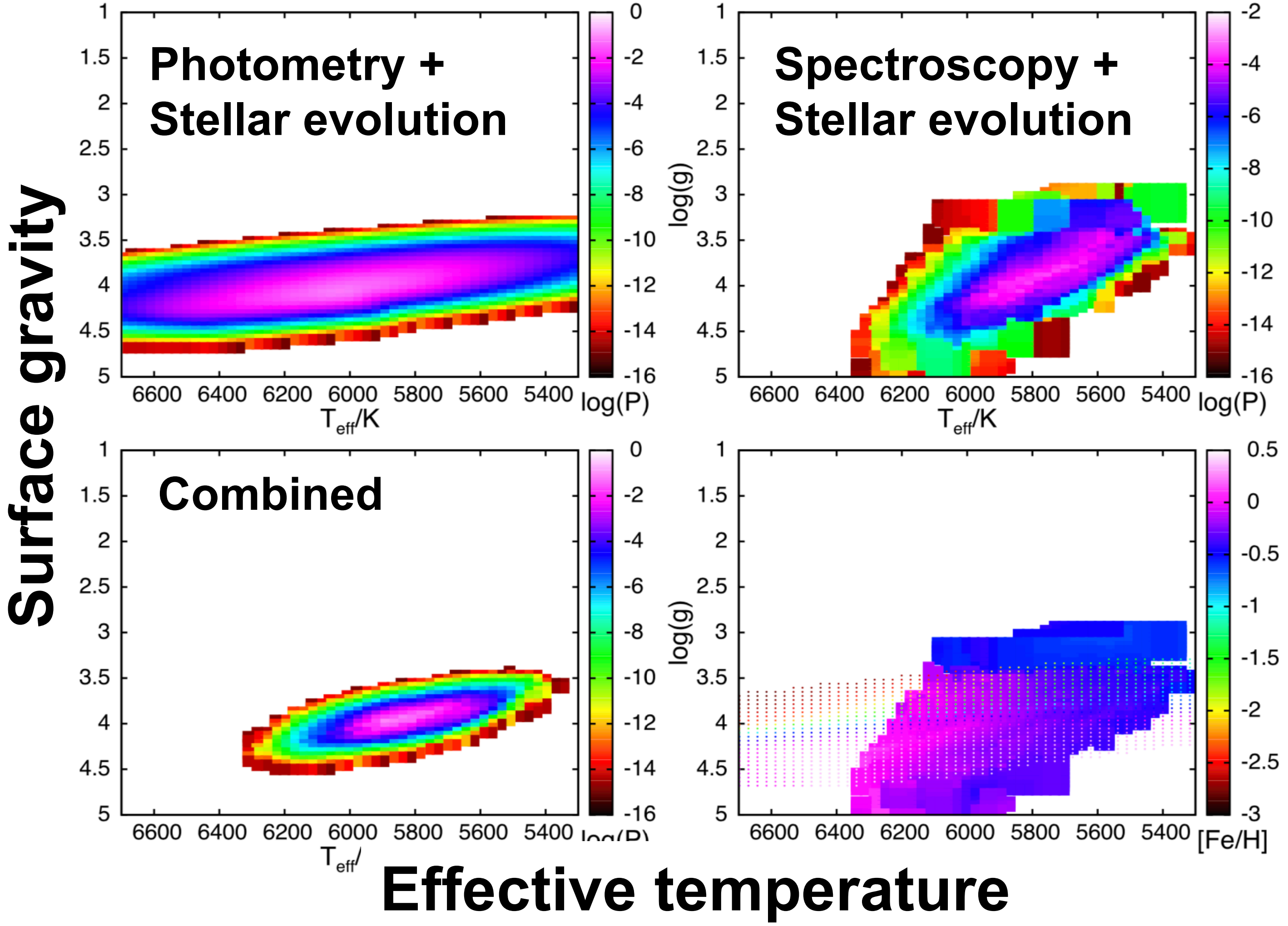
Measure 14 elements with R=1800 spectra with 0.1 dex precision



Bayesian spectroscopy

Schönrich & Bergemann 2014 (also Bailer-Jones et al. 2013)

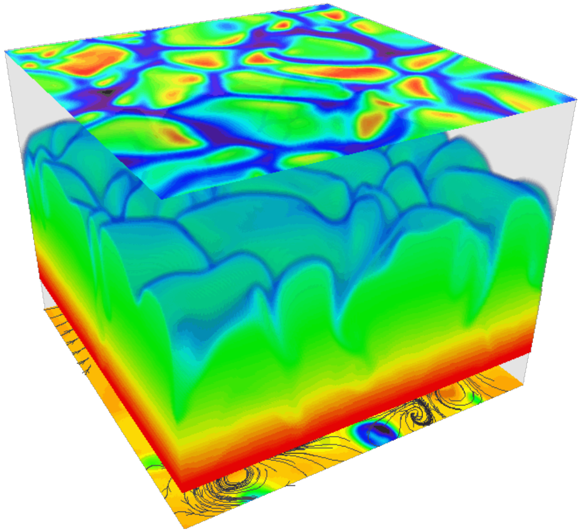
Combine all spectroscopic, photometric, astrometric, and asteroseismic information with stellar evolution priors

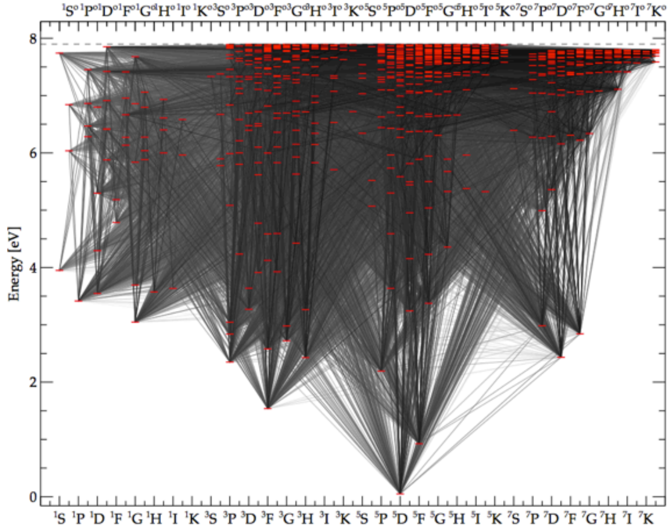


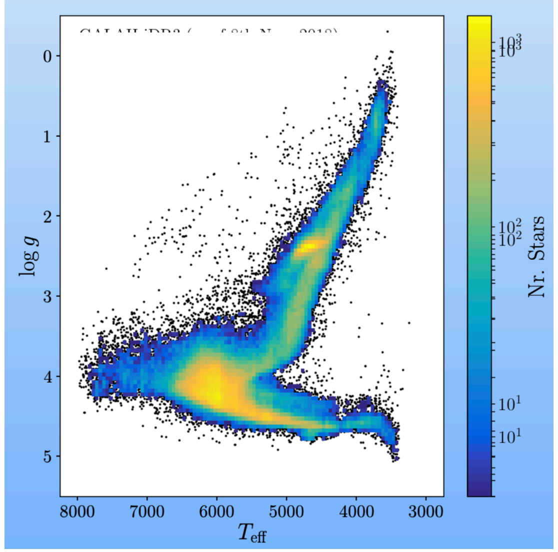
Schönrich & Bergemann 2014

Outlook

- 3D stellar atmosphere models
- 3D non-LTE spectrum formation
- Large spectroscopic surveys
- Physics-informed machine learning
- Bayesian spectroscopy







Great collaborators