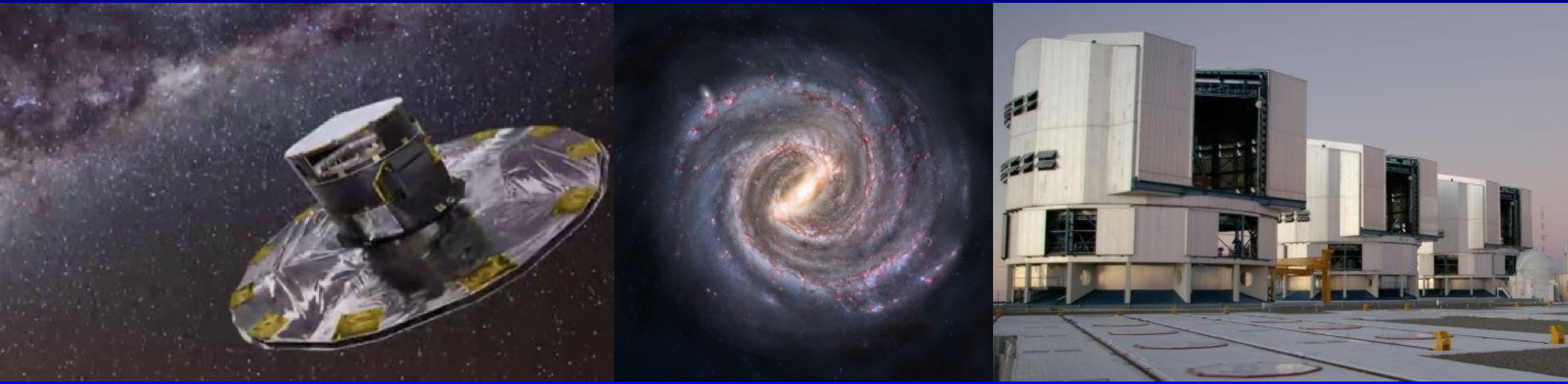
Atomic Data Requirements for Large Spectroscopic Surveys:

ESA Gaia and ESO GES



Alex Lobel

Royal Observatory of Belgium

Outline

- ESA Gaia mission & science objectives. Astrometric & spectroscopic census of all stars in Galaxy to *G*=20 mag.

- Preparations for photometry and spectroscopy data processing in Gaia-DPAC CU8: Astrophysical Parameters. APSIS development for stellar modeling and classification.

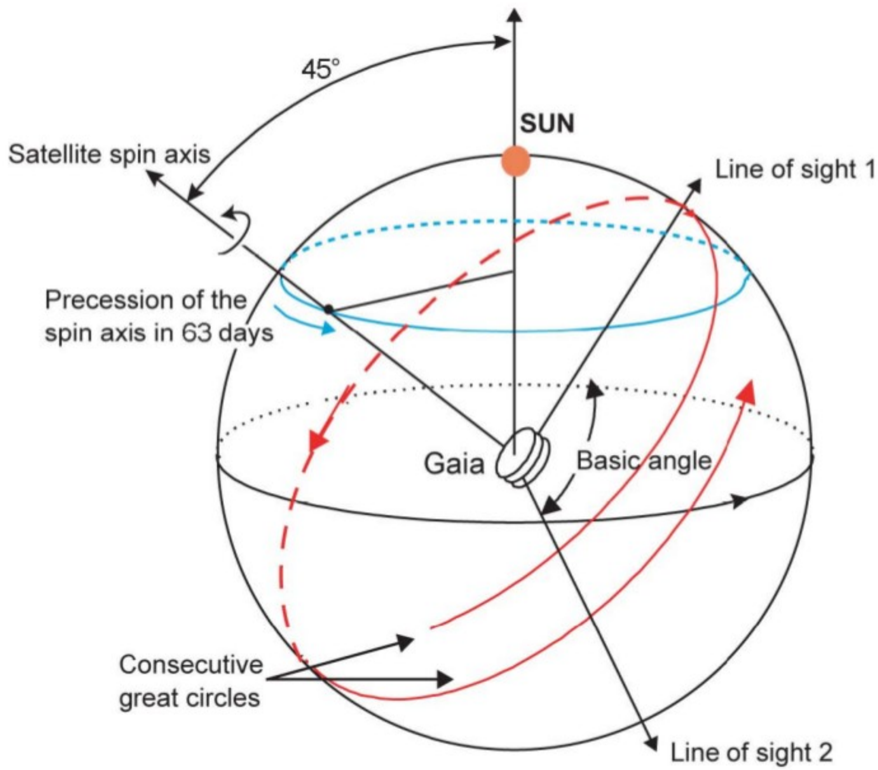
- GES Public Survey science objectives. Large ESO-VLT spectroscopic chemo-dynamical census of various components of the Galaxy. Complementary to Gaia.

- Atomic data needs in Gaia-DPAC and in GES WGs. Quality testing of atomic line data with ground-based benchmark stellar spectra.

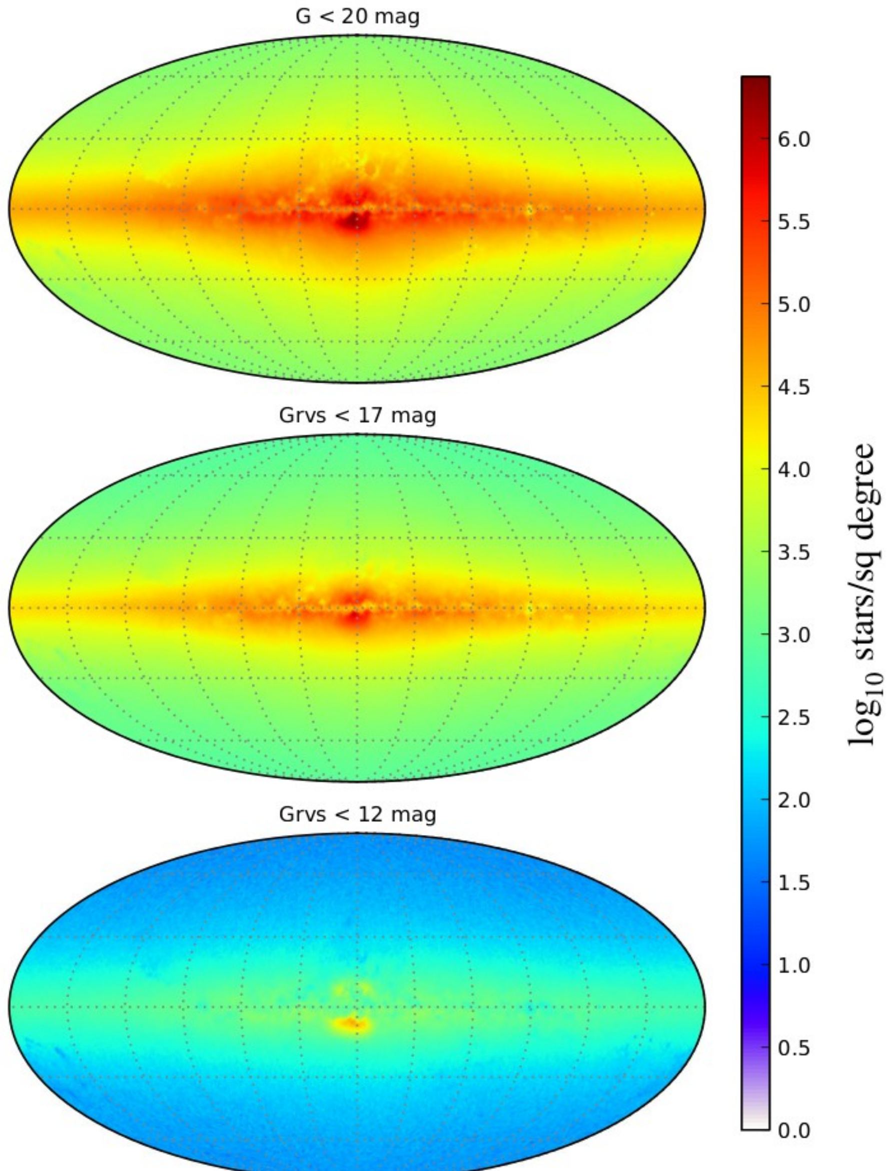
Launch 17 Nov – 5 Dec

Packed and shipped next month to Kourou

Gaia sky-scanning



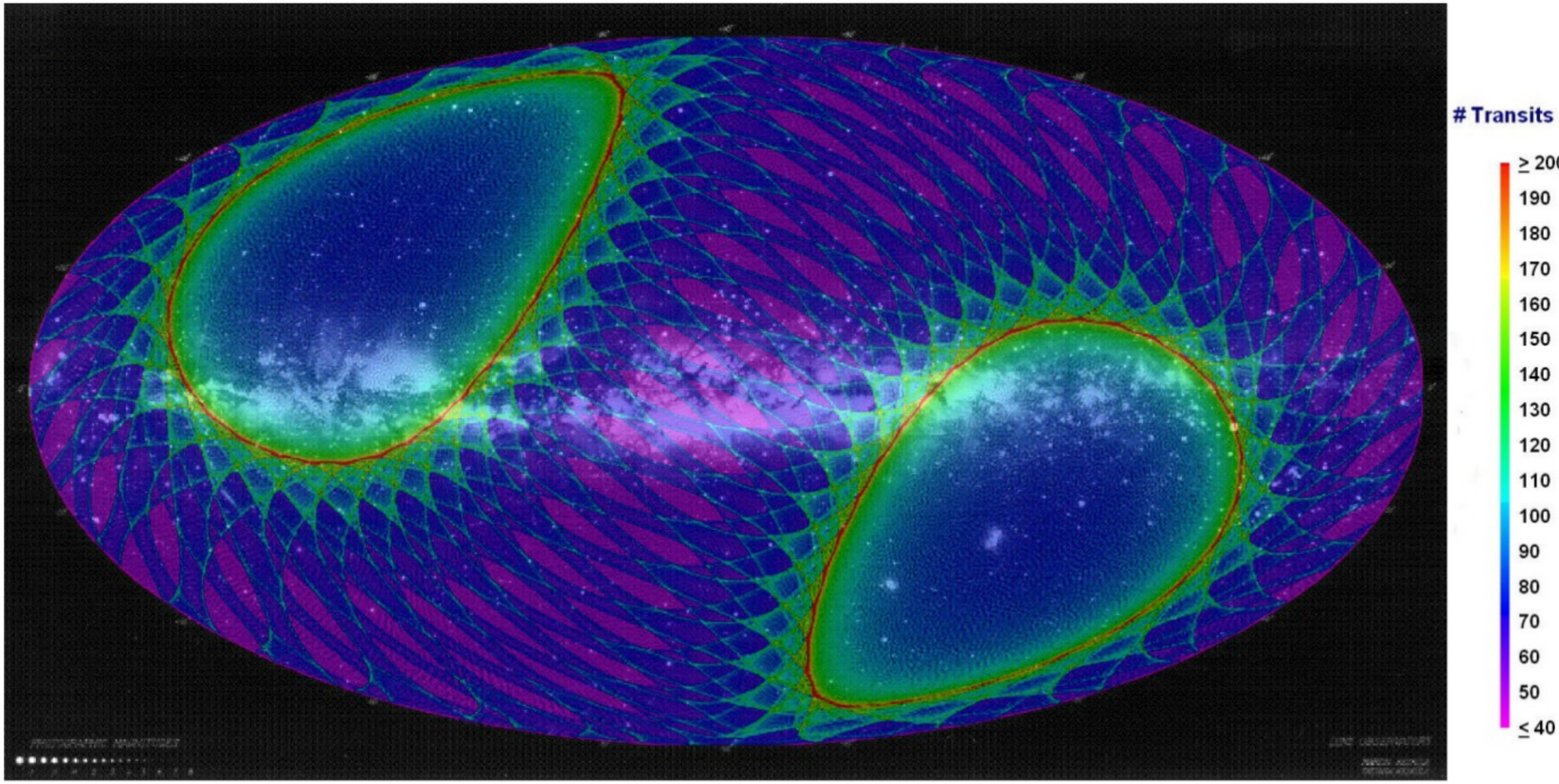
Simulated Gaia sky — Robin et al., arXiv:1202.0132



- **Spin axis: 45 deg. to Sun**
- **Spin period: 6 hours**
- **Observes all sources $6^m < G < 20^m$**
- **No input catalog, unbiased**

Gaia sky-scanning

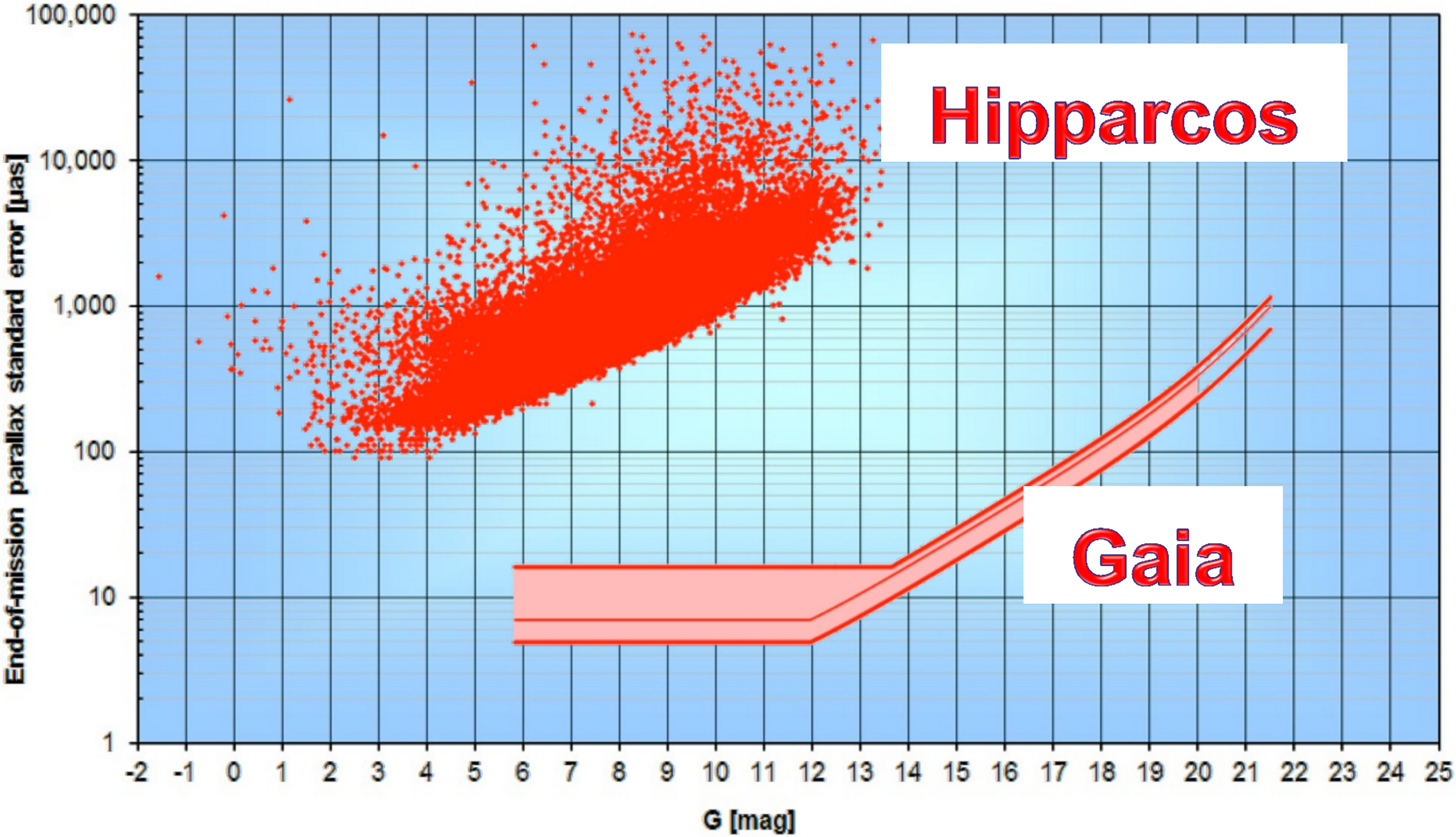
Number of field of view transits



- Observe 1 billion stars ~70 times each to *G*=20 mag.
- Astrometry and spectro-photometry for every source.
- Astrometric accuracies in final catalog of ~20 μ arcsecs (*G*=15 mag.)

Parallax errors

Distance errors: <0.1% for 700 000 stars   <1% for 21 million to 2.5 Kpc   <10% for 220 million to 25 Kpc



Gaia effective distance limit: 1 Mpc compared to 1 Kpc with Hipparcos

The Promise of Gaia

What will one billion stars in 3-D provide?

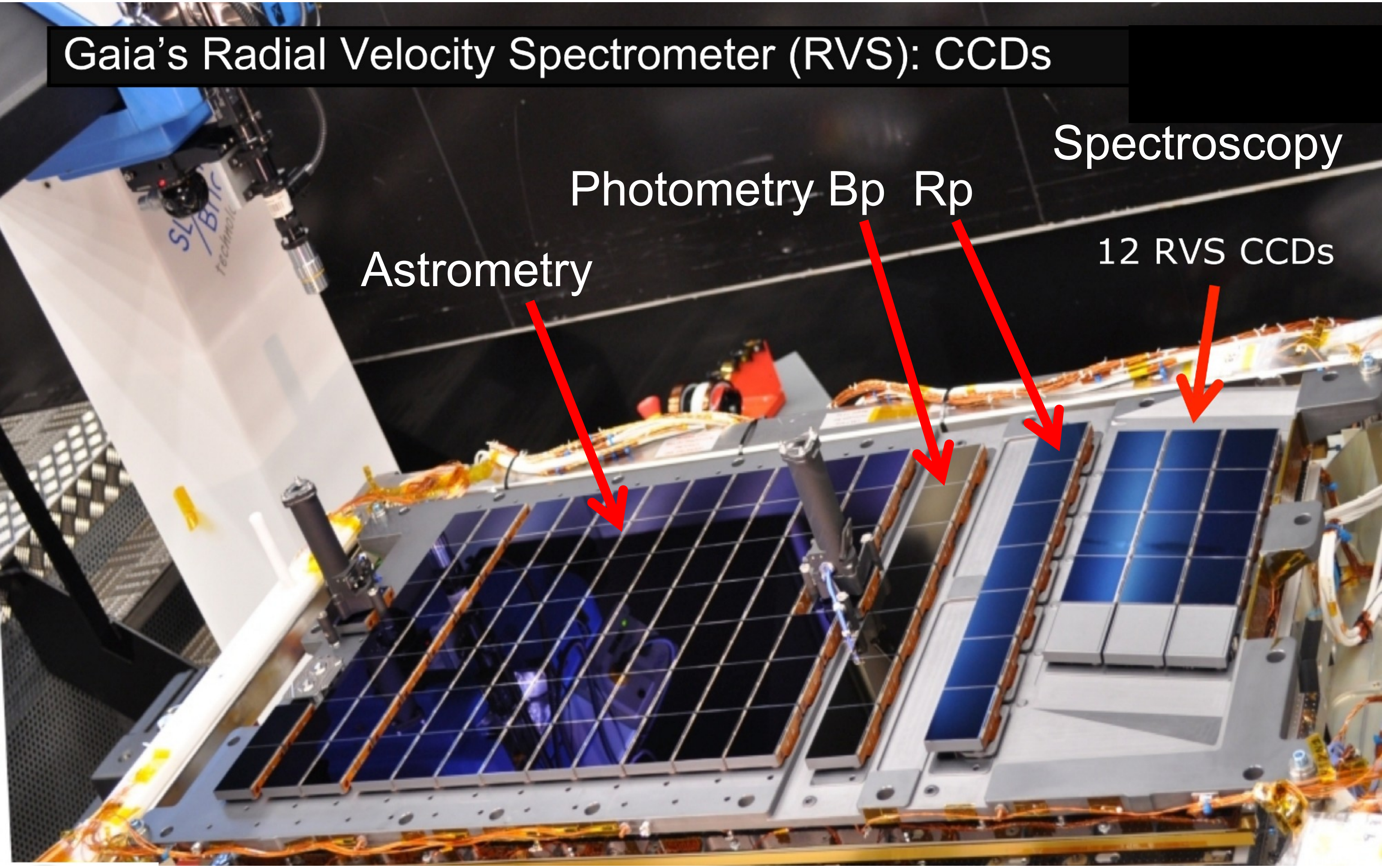
In our Galaxy...

- the distance and velocity distributions of all stellar populations
- the spatial and dynamical structure of the Galactic disk and halo
- its formation history
- a rigorous framework for stellar-structure and evolution theories
- a detailed mapping of the Galactic dark-matter distribution
- a large-scale survey of extra-solar planets (~7000)
- a large-scale survey of Solar-system bodies (~250,000)

... and beyond

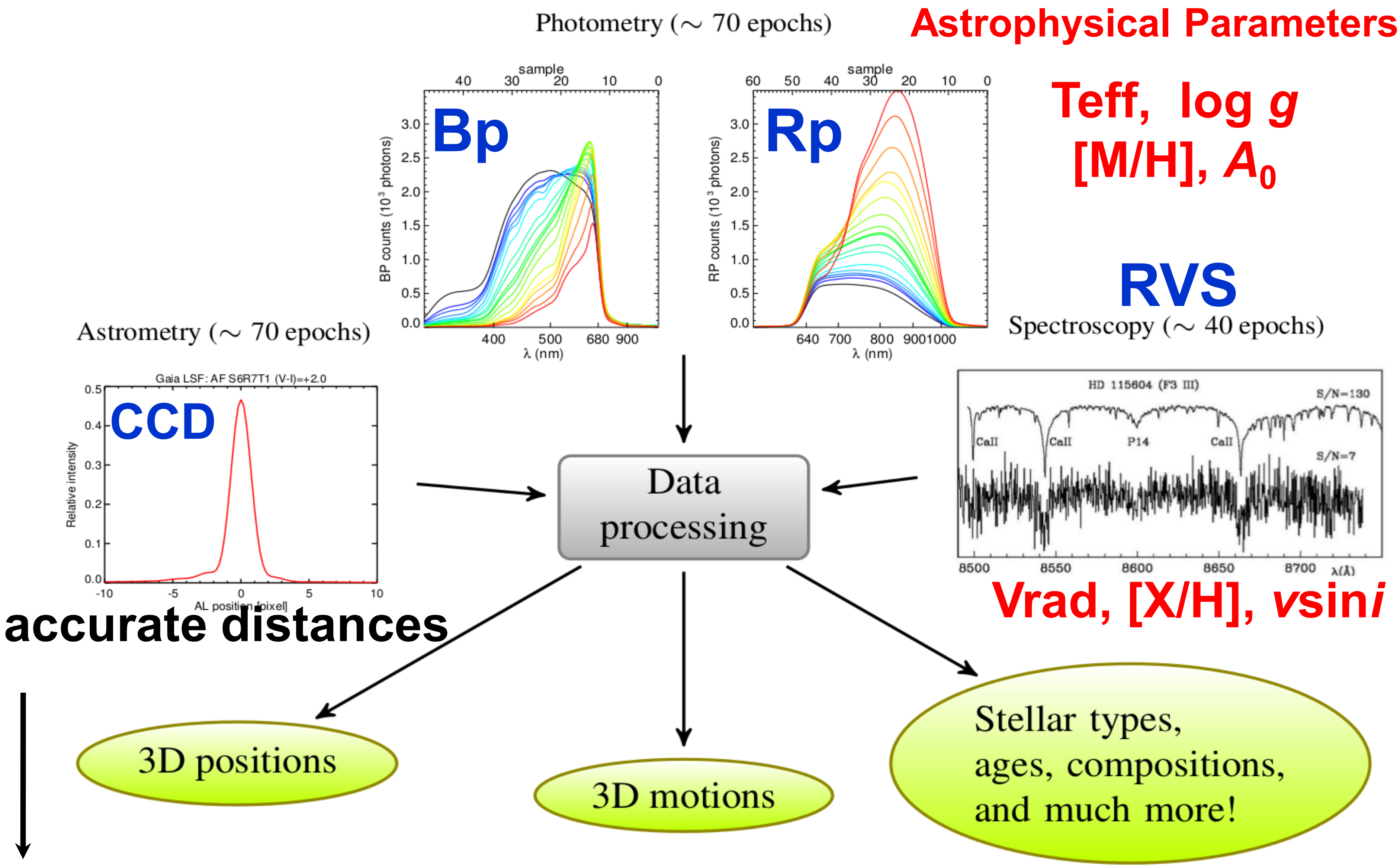
- definitive distance standards out to the LMC/SMC
- rapid reaction alerts for supernovae and burst sources (~20,000)
- quasar detection, redshifts, microlensing structure (~500,000)
- fundamental quantities to unprecedented accuracy: e.g. relativistic light bending due to gravity: PPN $\sigma_\gamma \sim 10^{-6}$ ($\sim 2\times10^{-5}$ present)

Gaia Focal Plane



106 CCDs ≅ 938 million pixels

Data processing in Gaia-DPAC



Stellar parameters: L*, R*, M*, evol. age

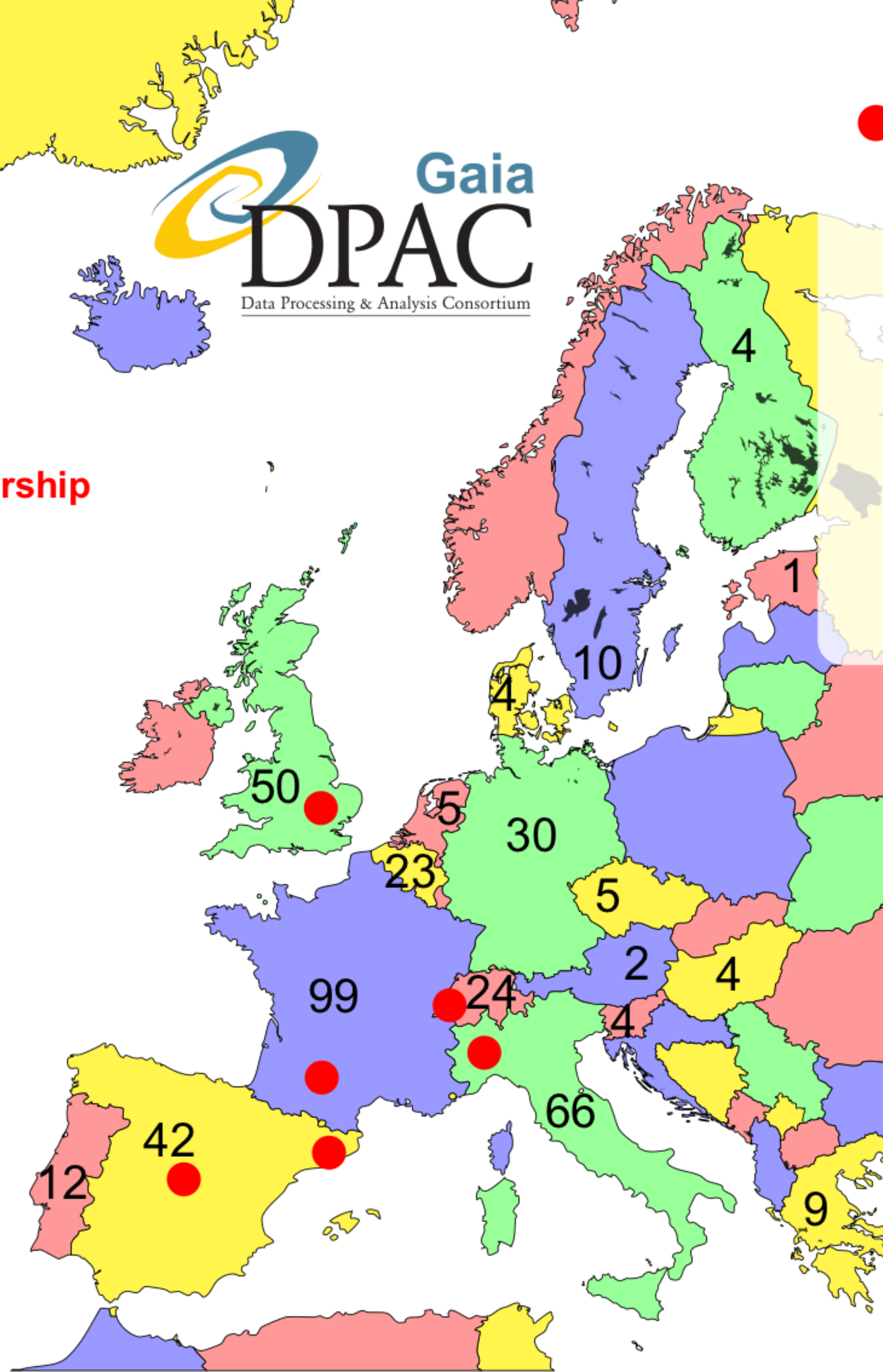
Gaia DPAC

Data Processing & Analysis Consortium

- Gaia data processing is a Pan-European cooperation
  - Over 1000 staff years effort since 2006
  - Processing power spread over 6 centres
  - Supported through national funding
  - Additional support from EC Marie Curie and ESF

DPAC membership
January 2013
432 total

BR: 5
CA: 1
CL: 1
ESA: 28
IL: 1
US: 2



Importance for Stellar Astrophysics

Accurate stellar luminosity calibrations

- distances to 1 % for 21 million stars to 2.5 kpc.
- distances to 10 % for 220 million stars to 25 kpc.
- parallax calibration of all distance indicators
  e.g., Cepheids and RR Lyrae to LMC/SMC.

Accurate stellar physical properties

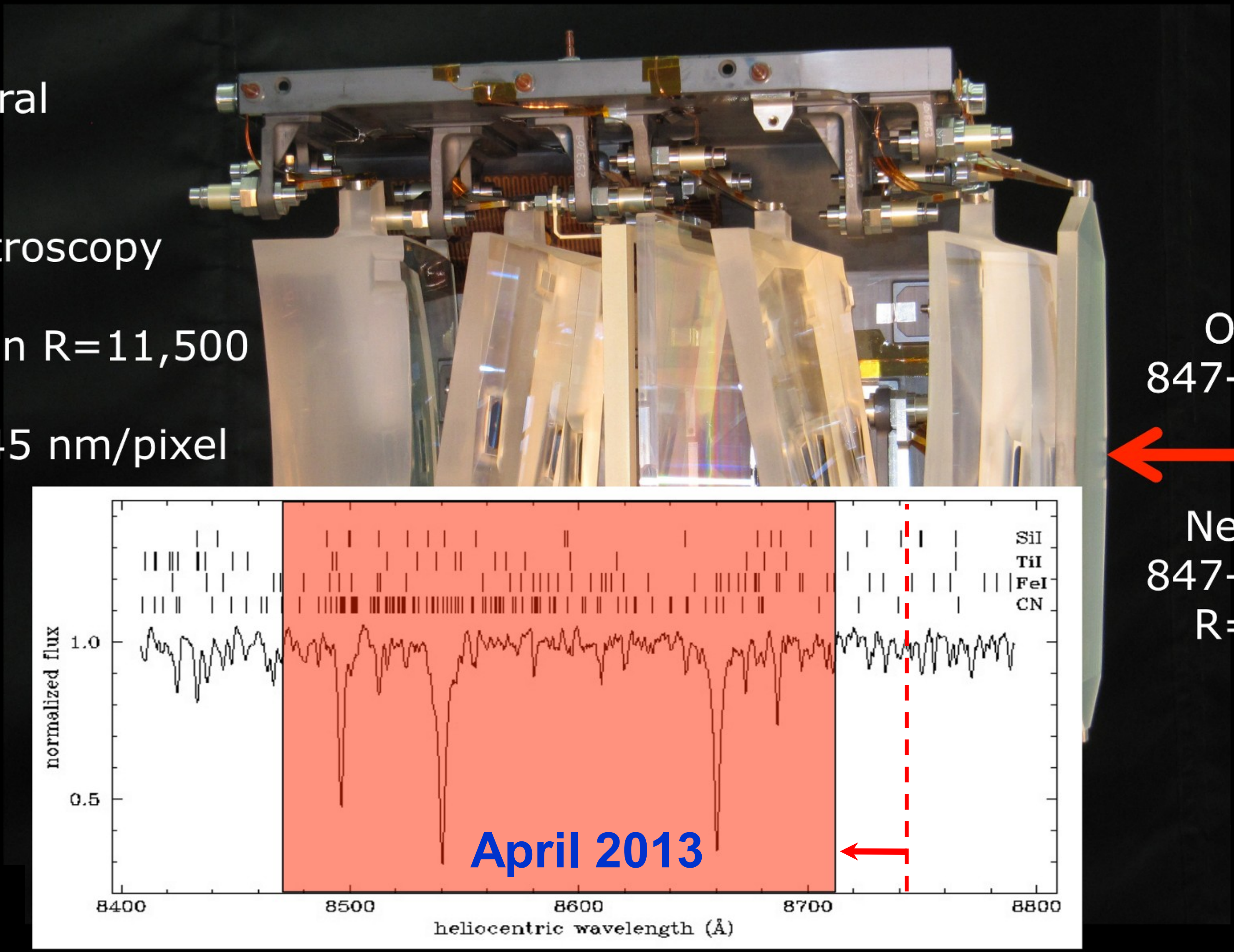
- clean Hertzsprung-Russell sequences throughout the Galaxy.
- detailed characterization of stellar populations.
- initial mass and luminosity functions in star forming regions.
- Galactic star formation history and chemical evolution.
- solar neighbourhood mass function and luminosity function
  e.g., white dwarfs (~200,000) and brown dwarfs (~50,000).
- 10,000 stellar masses with sigma less than 1 % therefore accurate constraints on evolutionary models.

Gaia Radial Velocity Spectrometer

Integral
Field
Unit
Spectroscopy

Design R=11,500

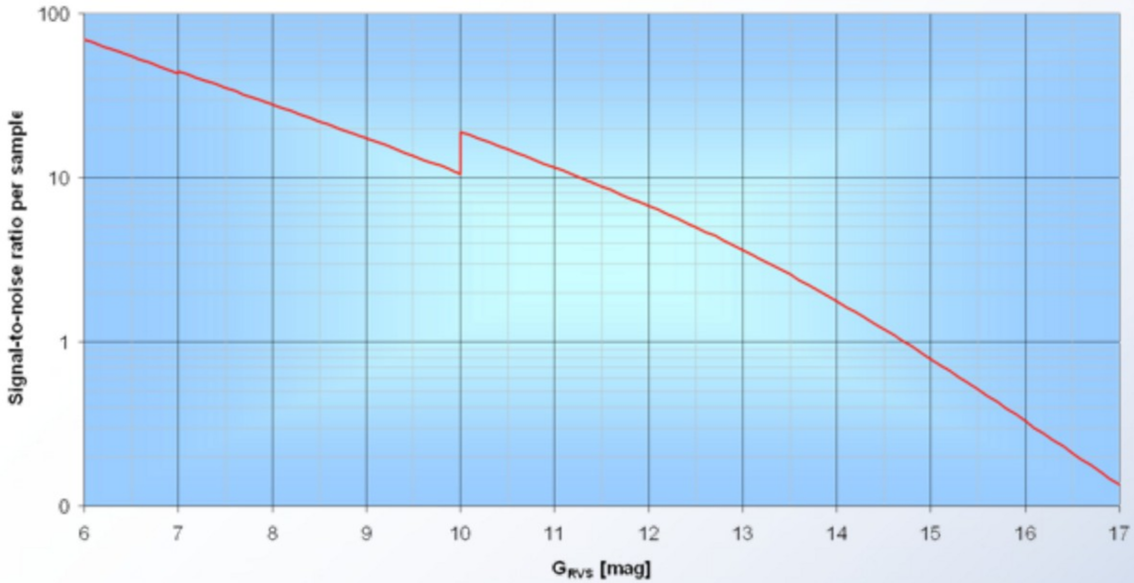
0.0245 nm/pixel



Old filter:
847-874 nm

New filter:
847-871 nm
R=11,236

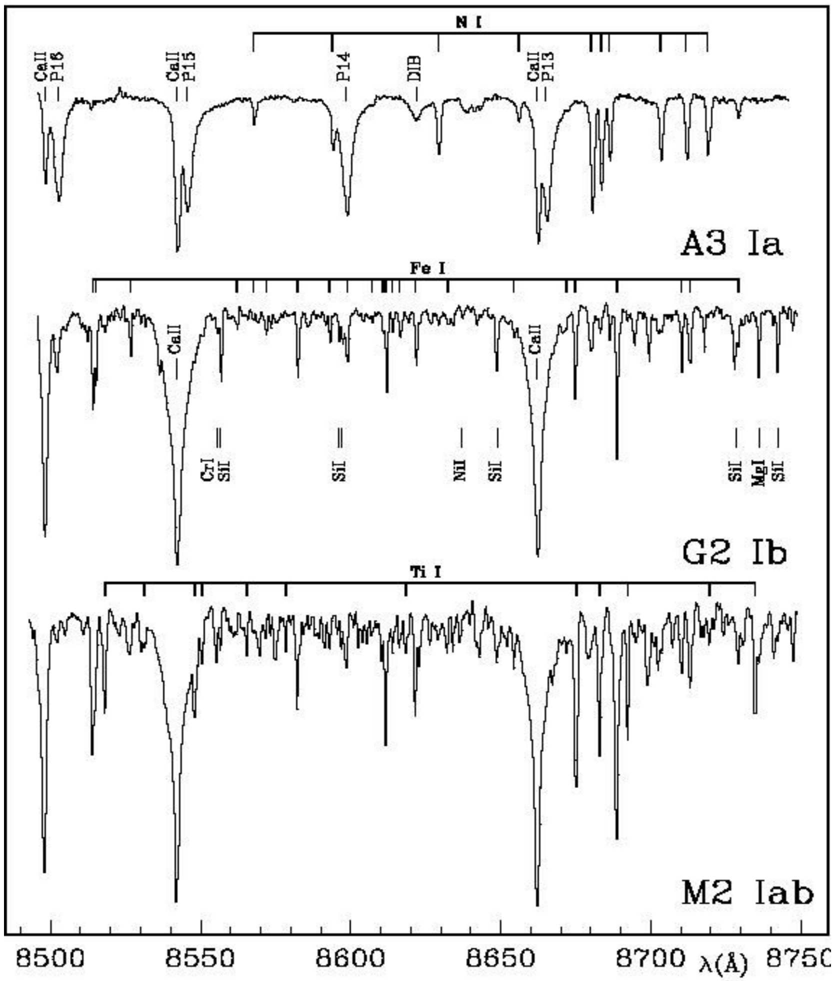
RVS Spectroscopy

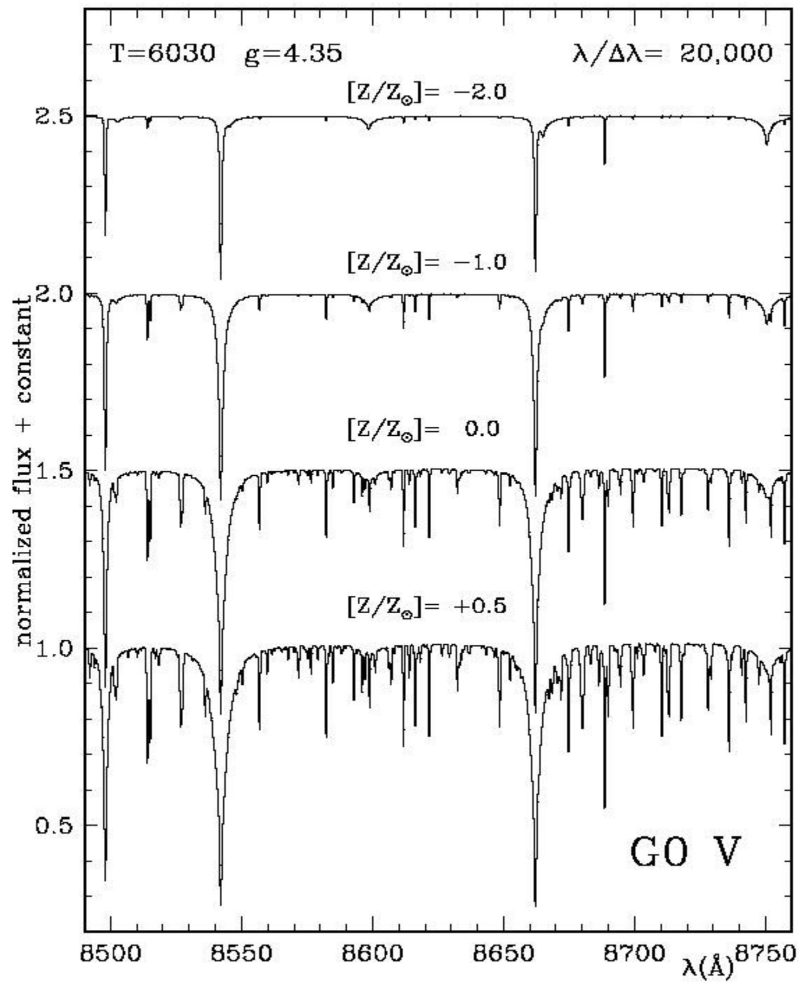


Single CCD S/N estimate

- Interstellar reddening, atmospheric parameters, and rotational velocities, for stars brighter than G_{RVS} ≈ 12 mag (~5 million stars)
- provide element abundances for stars brighter than G_{RVS} ≈ 11 mag (~2 million stars)

Stellar spectral sequences around Ca II triplet





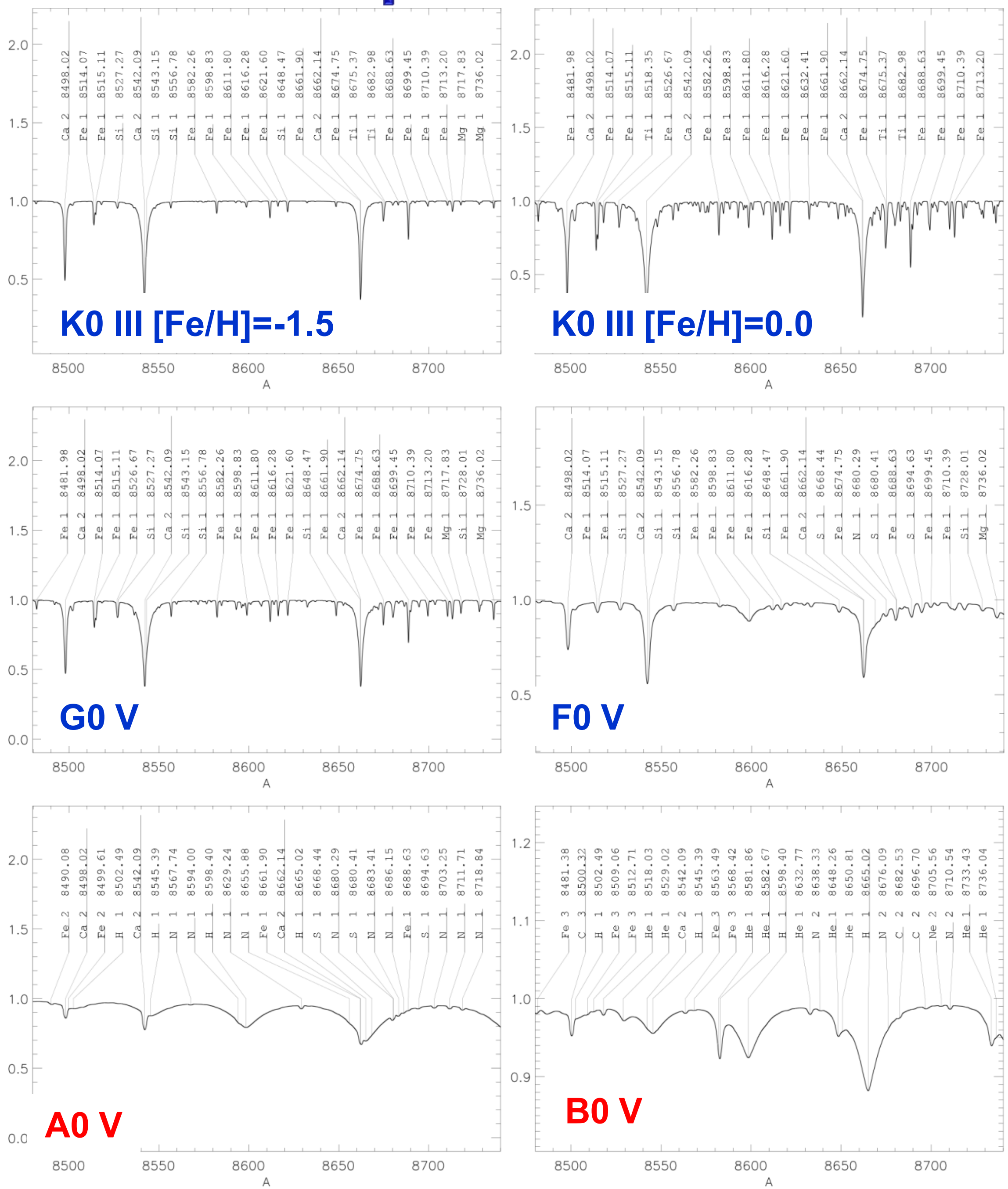
Effect of temperature: A to M stars

Effect of metal abundance in G stars

Atomic absorption lines in Gaia-RVS

Teff < 7500 K
'Cool stars'

3 Ca II lines
Fe I, Ti I, Si I
~~**Mg I 873.6**~~

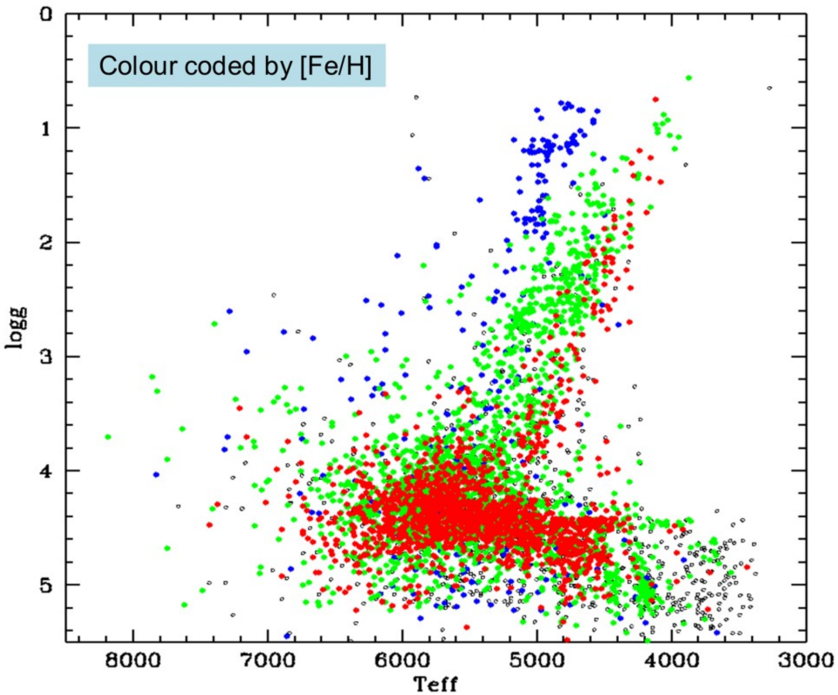


Teff > 7500 K
'Hot stars'

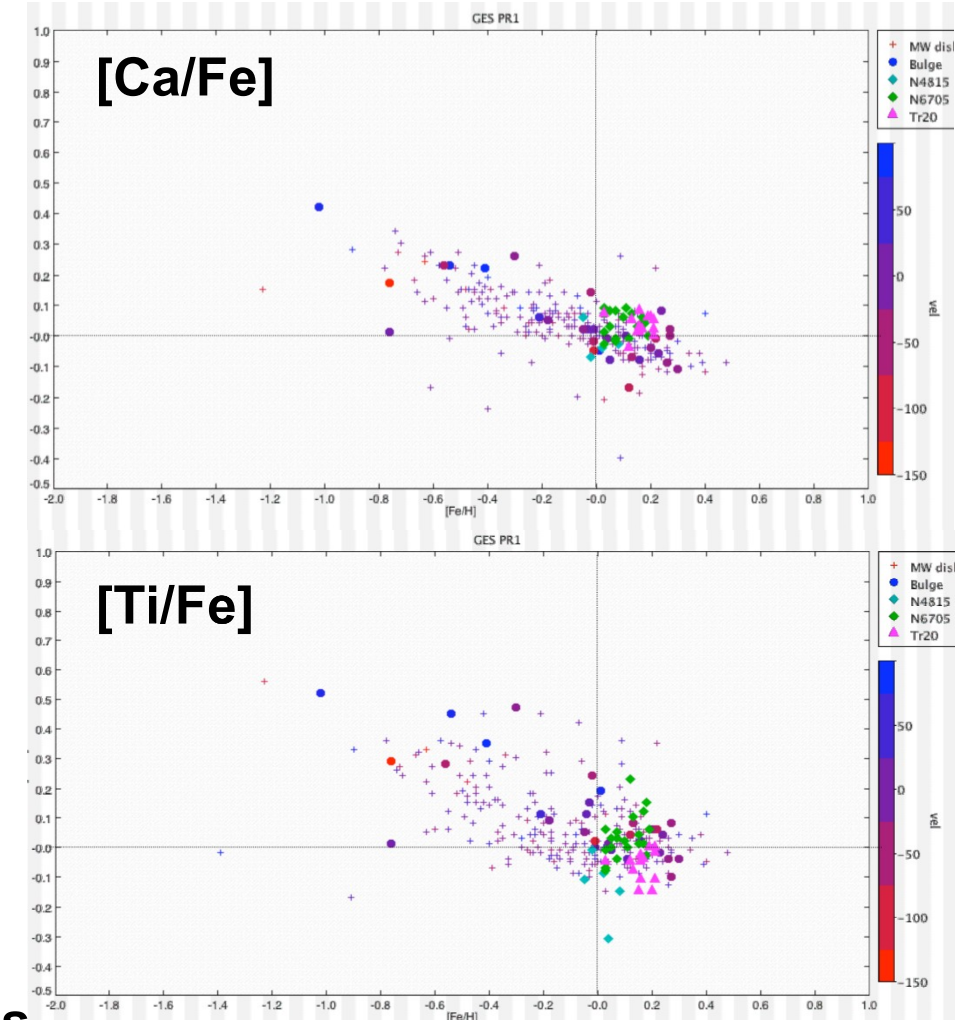
4 H Pa13-Pa16
N I, He I

Astrophysical parameters & chemical abundances

Giraffe early-release iDR1 HRD for this meeting
stars with both HR21 and HR10 parameters shown here

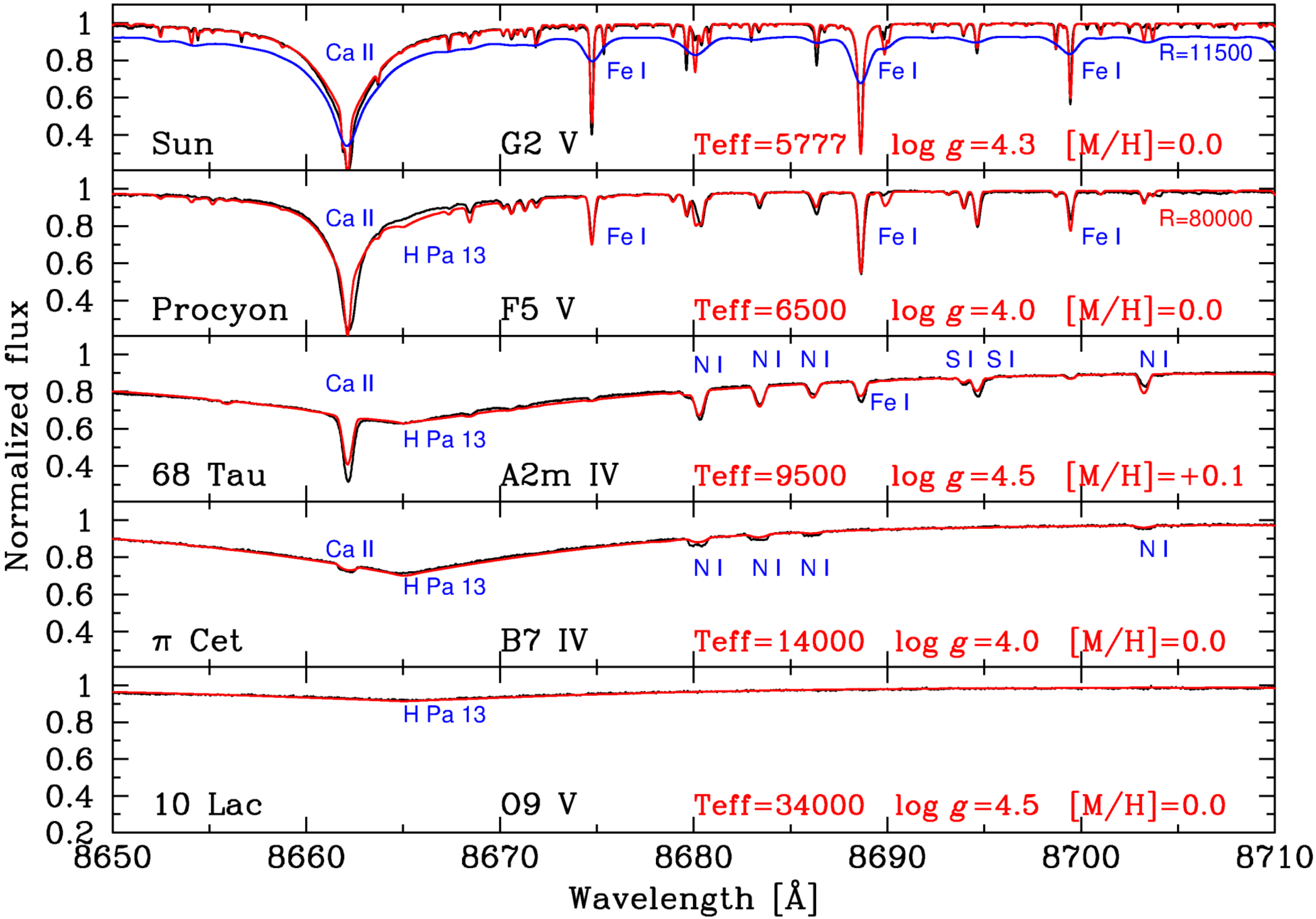


Teff vs. Log*g* ⇒ evolutionary stages



[Fe/H] vs. [α/Fe] ⇒ stellar ages

Atomic data testing with benchmark spectra of S/N~1000



Gaia RVS Stellar Spectroscopy

- RVS end-of-mission sum spectra S/N>80 of ~2 million stars for *G* < 11^m. DPAC determines APs, Vrad, *v*sin*i*, including abundances of various key elements:

  FGKM types : Ca, Ti, Si & Fe (3 Ca II, 10 Ti I, 3 Si I, & 14 Fe I)
  A type : 4 H Pa, 3 Ca II (weak), 5 N I, 2 Fe I , 2 Fe II, 2 S I
  OB types : 4 H Pa, He I, N I (weak), 1 C III, 1 DIB

- RVS 847 – 871 nm contains 30 - 40 important lines per stellar spectral type. Atomic line data testing (λ_0, log(*gf*), damping const.) using benchmark stars observed with Mercator-HERMES for S/N~800-1000.

- RVS OB spectra dominated by broad wings of 4 H Pa lines. Metal lines are absent (only weak N I and He I).

- Ongoing developement of algos for APs determination in CU8 (APSIS). Spectral libraries collected from various spectrum synthesis codes.

Stellar Libraries for Gaia-DPAC Apsis

- Synthetic spectrum grids computed for cool and hot stars.
- Used to develop the DPAC-CU8 star classification and APs codes.
- From various spectrum synthesis codes: MARCS, PHOENIX, TLUSTY, ...

(C. Bailer-Jones & DPAC-CU8, 2013 A&A, submitted)

Table 2. Stellar libraries used to simulate BP/RP and RVS spectra. N is the number of spectra in the library. Ap/Bp are peculiar stars; UCD are ultracool dwarfs; WR are Wolf Rayet stars; WD are white dwarfs.

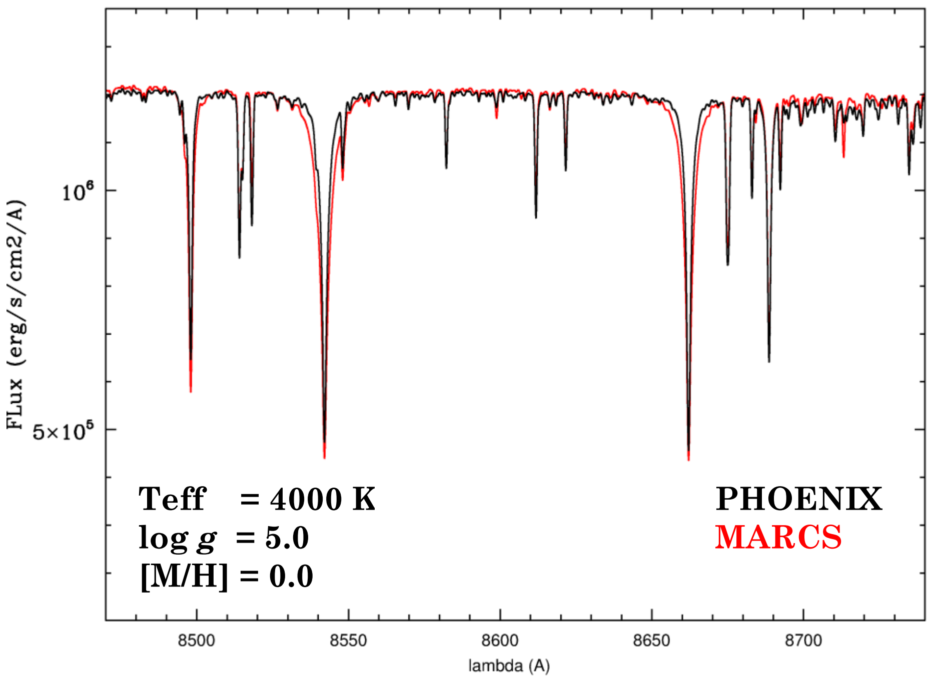
Name	N	T_{eff} / K	$\log g$ / dex	[Fe/H] / dex	Ref.†	Notes
OB stars	1296	15 000–50 000	1.0–5.0	−5.0–1.0	1	TLUSTY code; NLTE, mass loss, v_{micro}
Ap/Bp stars	36	7000– 16000	4.0	0.0	2	LLmodels code, chemical peculiarities
A stars	1450	6000–16 000	2.5–4.5	0.0	3	LLmodels code, $[\alpha/\mathrm{Fe}] = 0.0, +0.4$
MARCS	1792	2800– 8000	−0.5–5.5	−5.0–1.0	4	Galactic enrichment law for $[\alpha/\mathrm{Fe}]$
Phoenix	4575	3000–10 000	−0.5–5.5	−2.5–0.5	5	ΔT_{eff}=100 K
UCD	2560	400– 4000	−0.5–5.5	−2.5–0.5	6	various dust models
C stars	428	4000– 8000	0.0–5.0	−5.0–0.0	7	[C/Fe] depends on [Fe/H]
Be	174	15 000–25 000	4.0	0.0	8	range of envelope to stellar radius ratios
WR	43	25 000–51 000	2.8–4.0	0.0	9	range of mass loss rates
WD	187	6000–90 000	7.0–9.0	0.0	10	WDA & WDB
MARCS NLTE	33	4000– 6000	4.5–5.5	0.0	11	NLTE line profiles
MARCS RVS	146 394	2800– 8000	−0.5–5.5	−5.0–1.0	12	variations in individual elements abundances
3D models	13	4500– 6500	2.0–50	−2.0–0.0	13	StaggerCode models and Optim3D code
SDSS stars	50 000	3750–10 000	0.0–5.5	−2.5–0.5	14	semi-empirical library
Emission line stars	1620	–	–	–	15	semi-empirical library (see section 5.4)

†References: 1 Bouret et al. (2008); 2 Kochukhov & Shulyak (2008); 3 Shulyak et al. (2004); 4 Gustafsson et al. (2008); 5 Brott & Hauschildt (2005); 6 Allard et al. (2001); 7 Alvarez & Plez (1998); 8 Martayan et al. (2008); 9 Martayan et al. (2008); 10 Castanheira et al. (2006); 11 Korn et al. 2009, priv. comm.; 12 Recio-Blanco et al. 2011, priv. comm.; 13 Chiavassa et al. (2011); 14 Tsalmantza & Bailer-Jones (2010b); 15 Lobel et al. (2010)

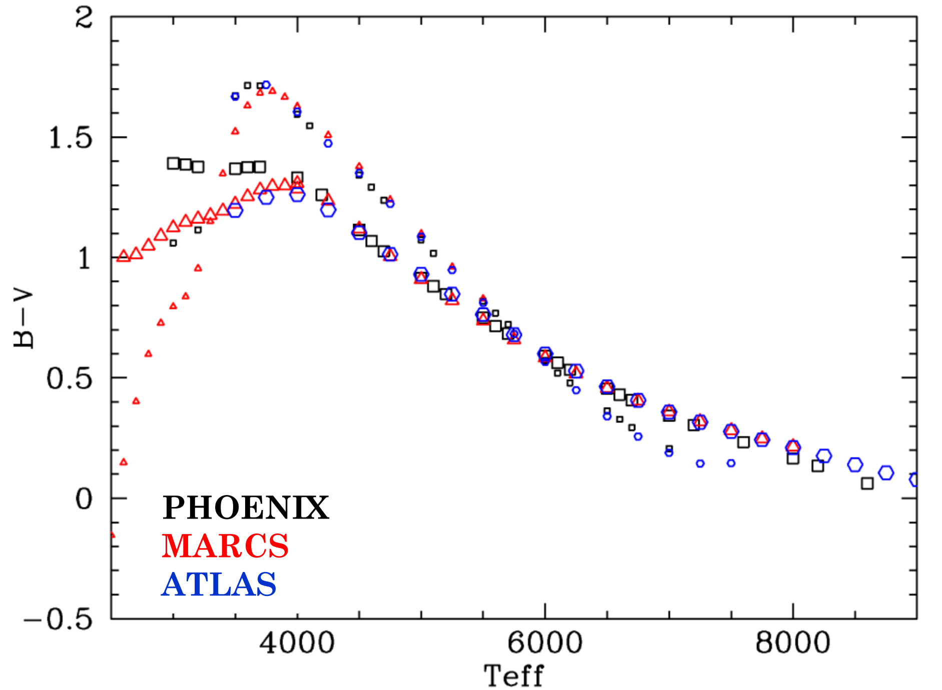
- AFGKM model spectra computed in 1-D LTE.
- OB model spectra in 1-D NLTE.
- Comparison of atmosphere models and testing of atomic & molec. data.

Detailed Comparison of Synthetic Spectral Libraries

K dwarf in Gaia-RVS

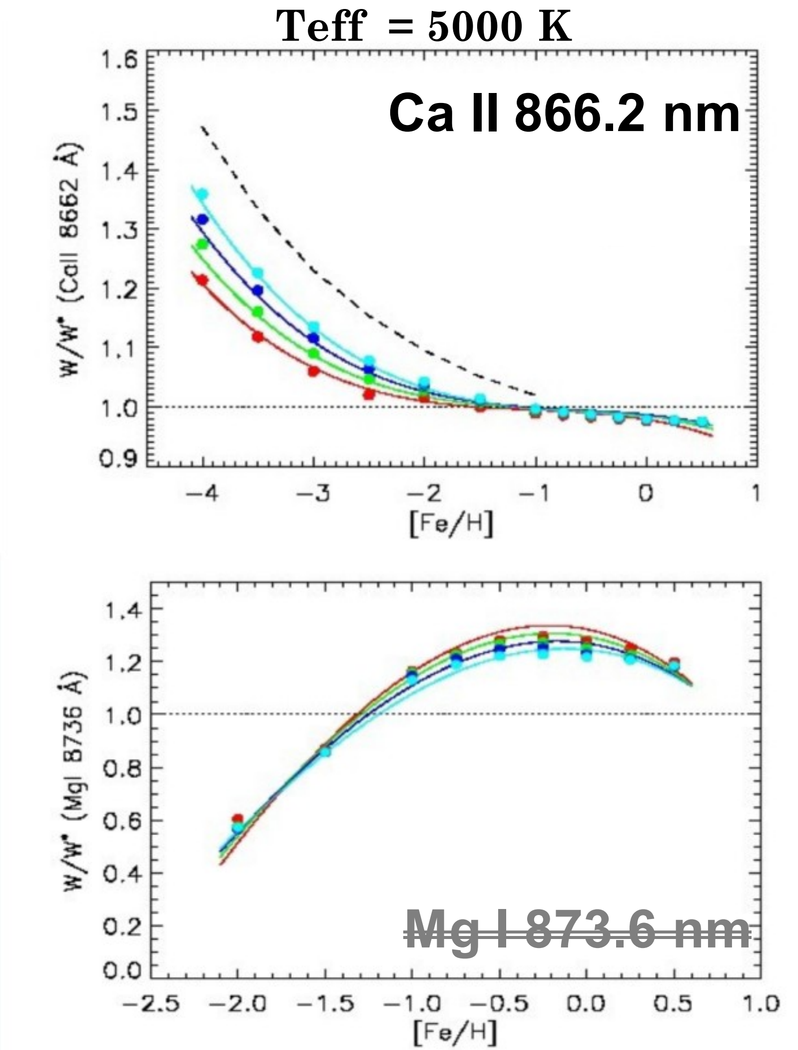


B -V in AFGKM dwarfs



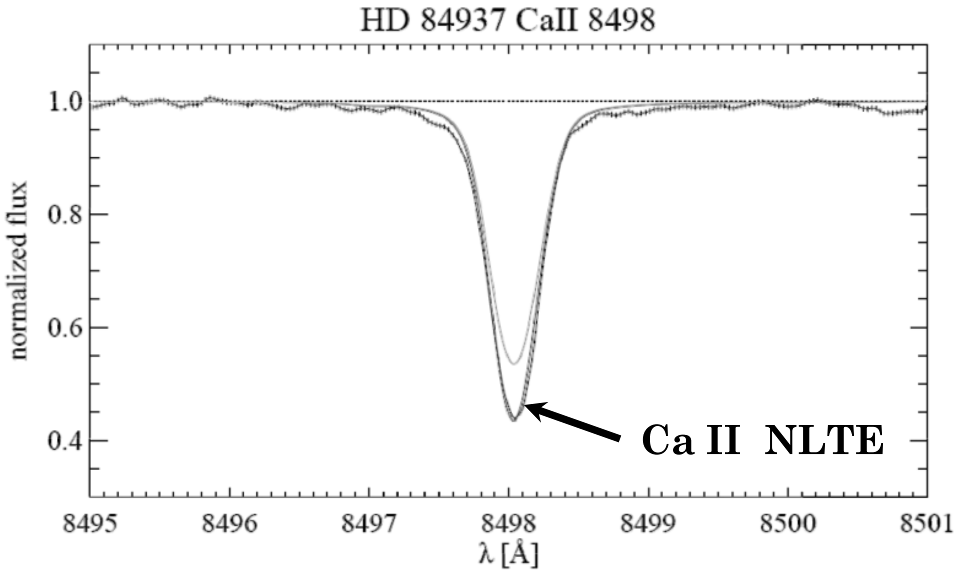
- **Differences in Ca II TR line widths due to collisional broadening data.**
- **Differences in *B-V* color for Teff < 4000 K due to EOS and continua (H^- opacity, strong molecular bands, ...)**

Ca II NTLE line formation effects at low [Fe/H]



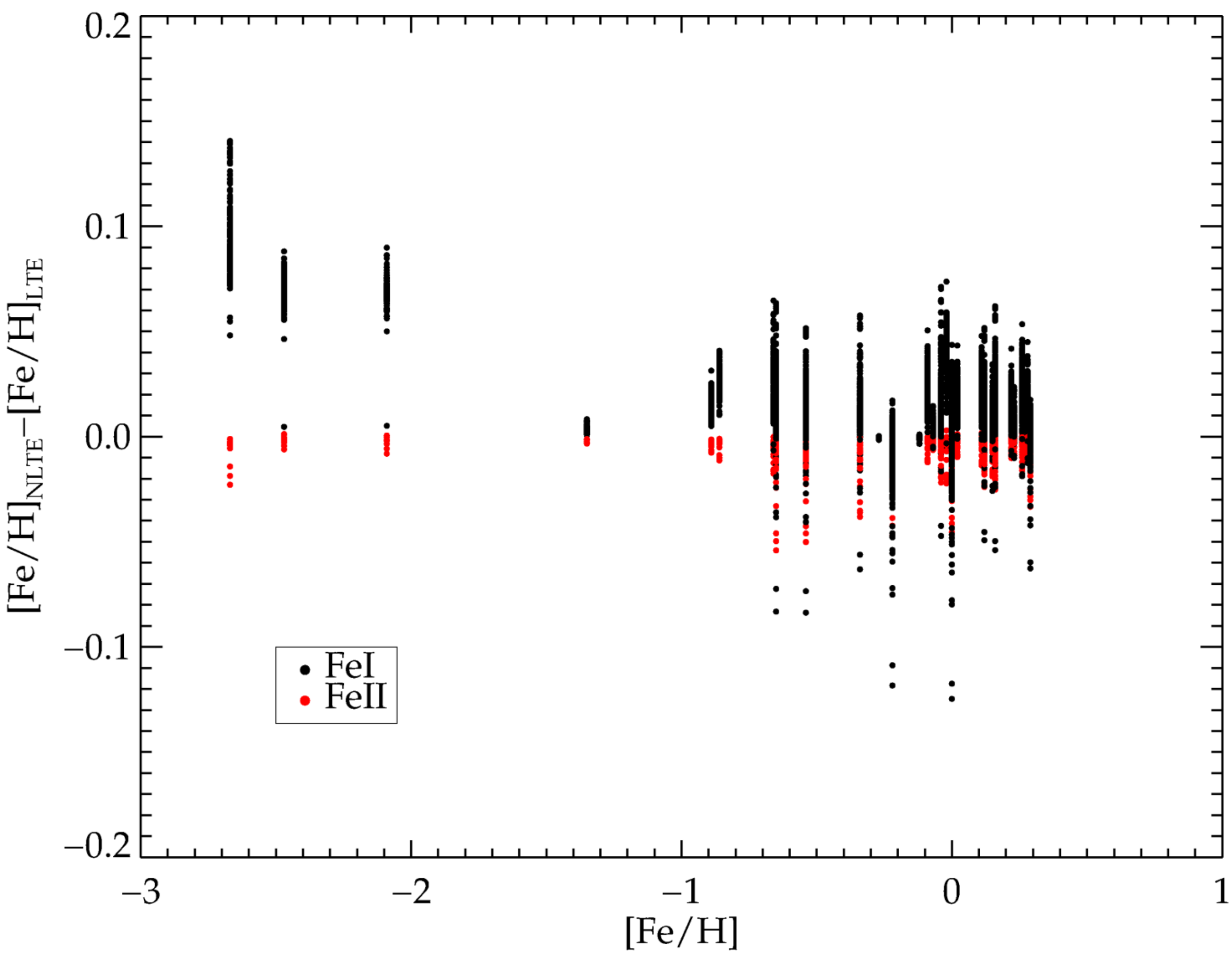
NLTE/LTE ratio for the CaII 866.2 nm as a function of the metallicity for T_{eff} = 5000 K and for four values of the surface gravity (log g = 0.5, 1, 1.5 and 2 in red, green, blue and cyan respectively). Same for MgI 873.6 nm.

- Ca II TR lines show strong NLTE effects in metal-poor stars.
- NLTE effects on line EW increase towards smaller log *g*.

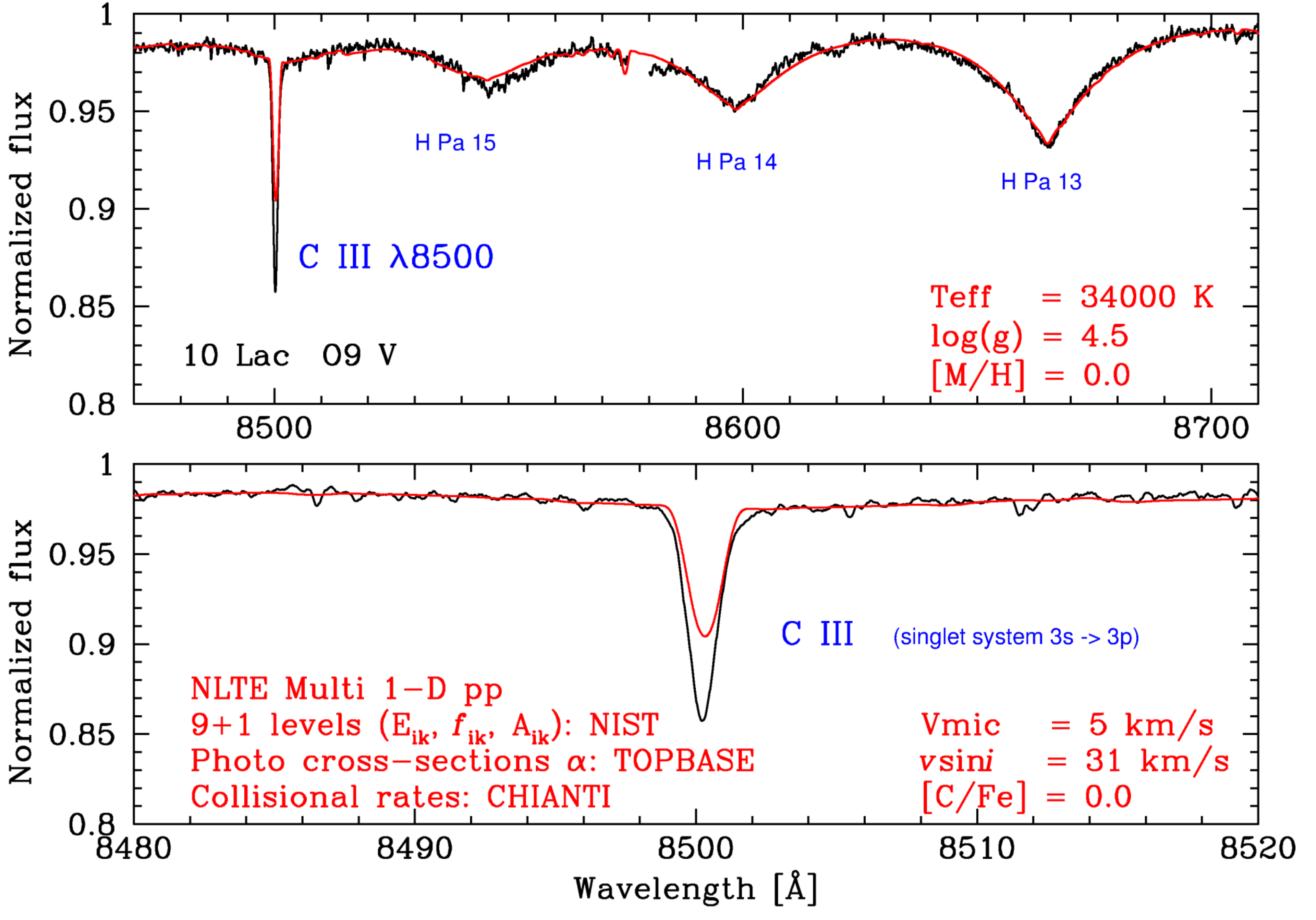


- LTE assumption yields [Ca/H]-errors to ~0.3 dex compared to detailed NLTE line profiles.

Non-LTE effects in Fe I at low [Fe/H]



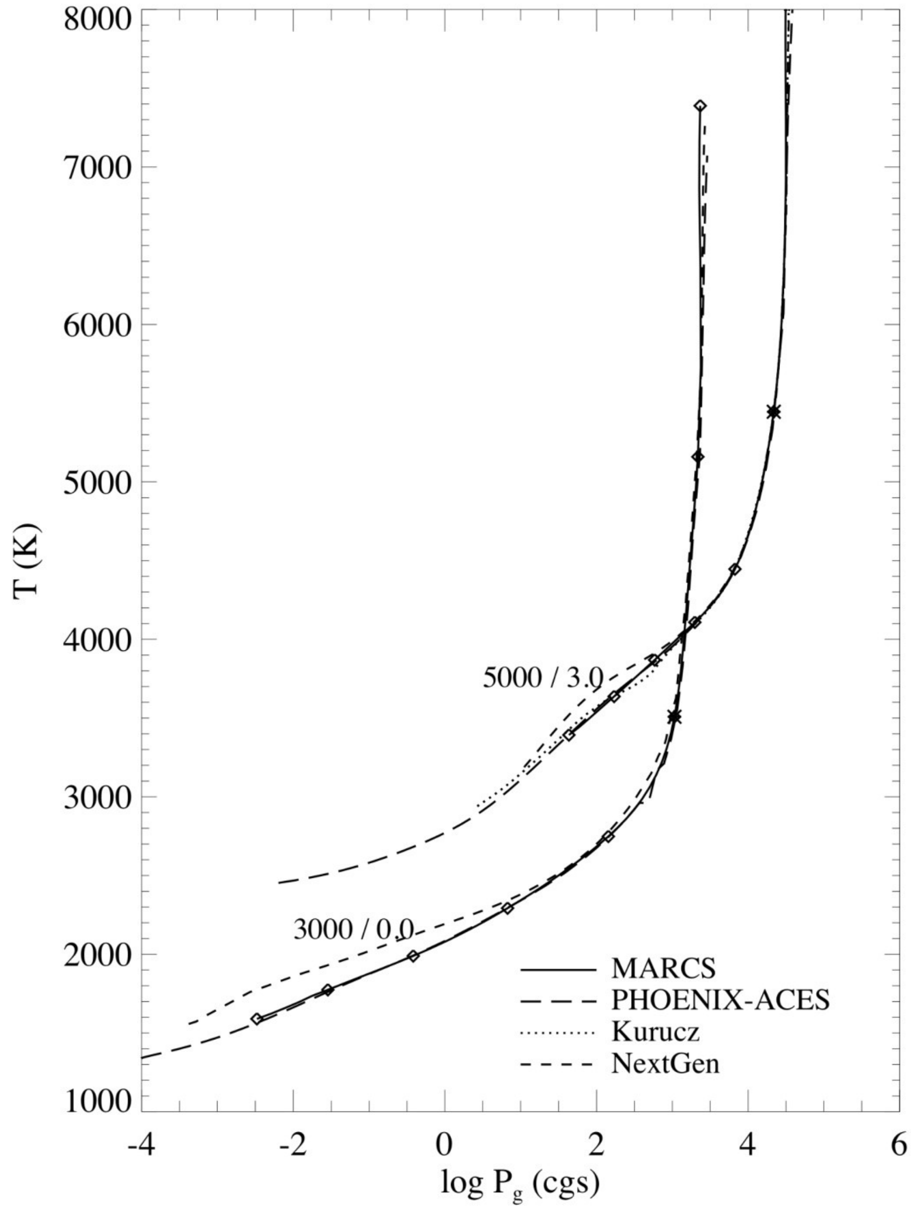
NLTE modeling of benchmark O dwarf in Gaia-RVS



- **Photospheric model structures Tgas, Pgas are almost identical.**

MARCS + Phoenix (Sph)

ATLAS (PP)

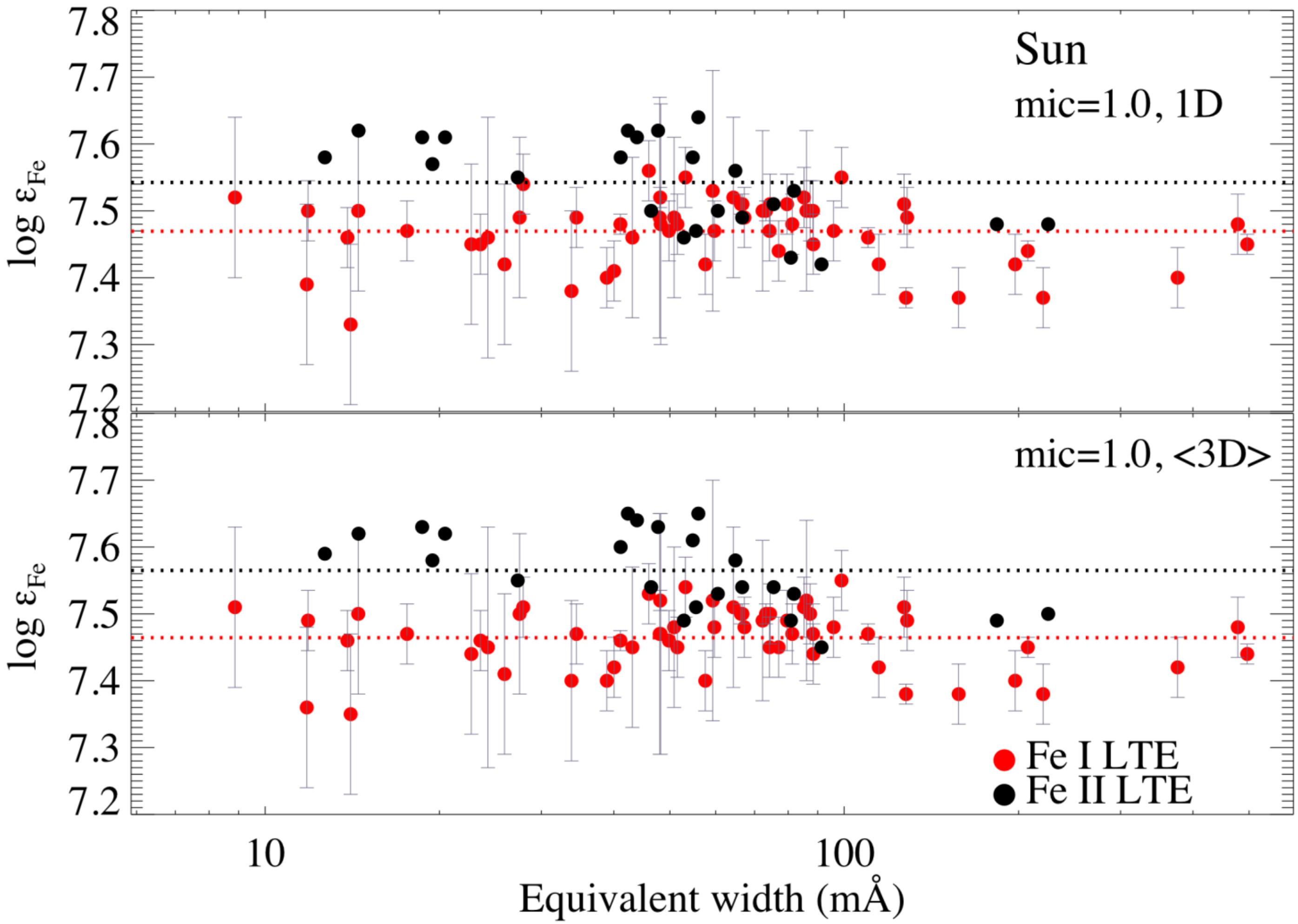


GREAT-ESF Workshop: Stellar Atmospheres in the Gaia Era

***J. Phys.: Conf. Ser. Vol. 328*.**

LTE Fe abundance in 1D vs. 3D models of Sun

Huge line-to-line scatter in 1D and <3D>: 7.35 … log A(Fe) … 7.65 dex
(meteorites: log A(Fe) = 7.48 dex)



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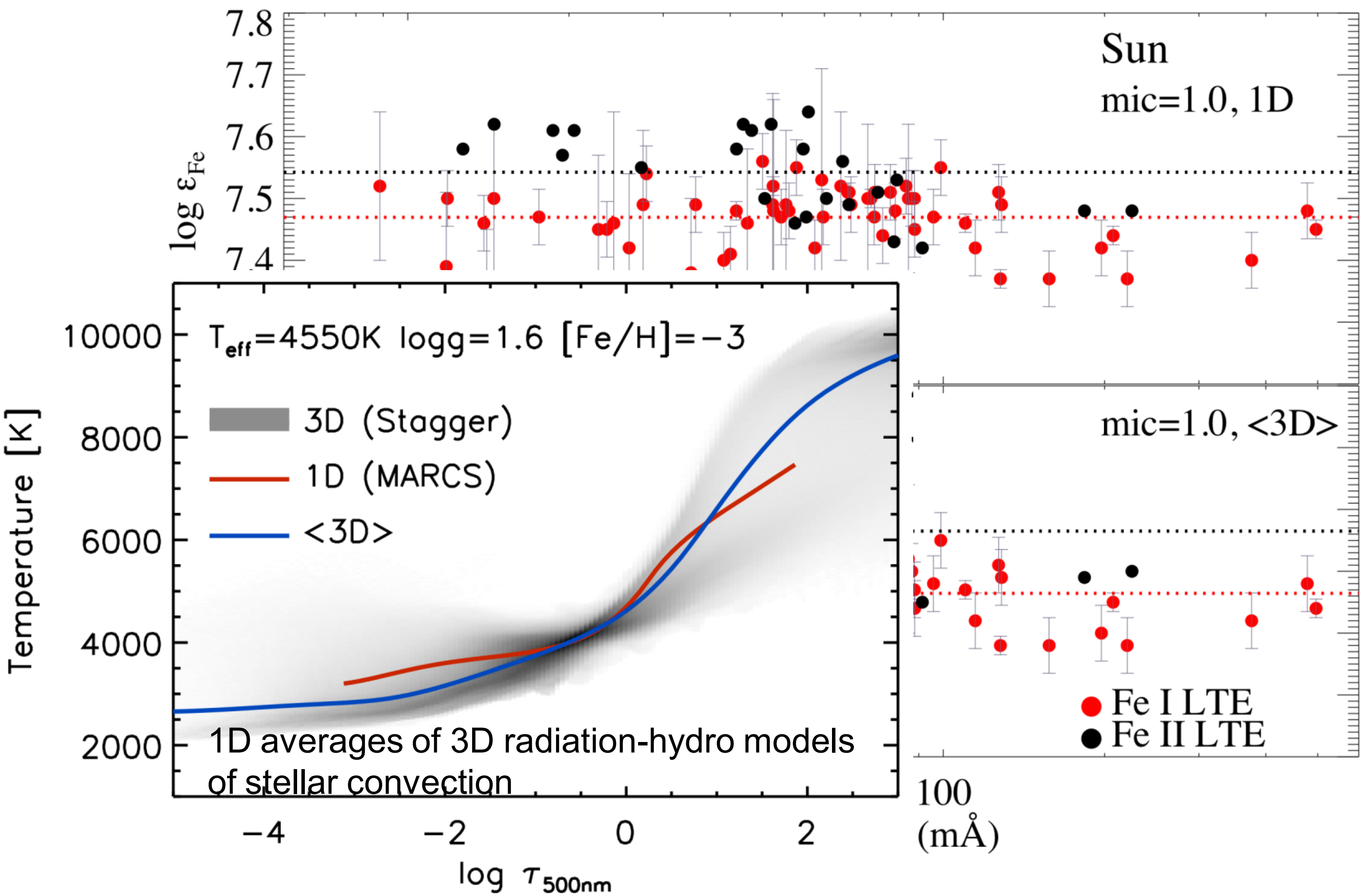
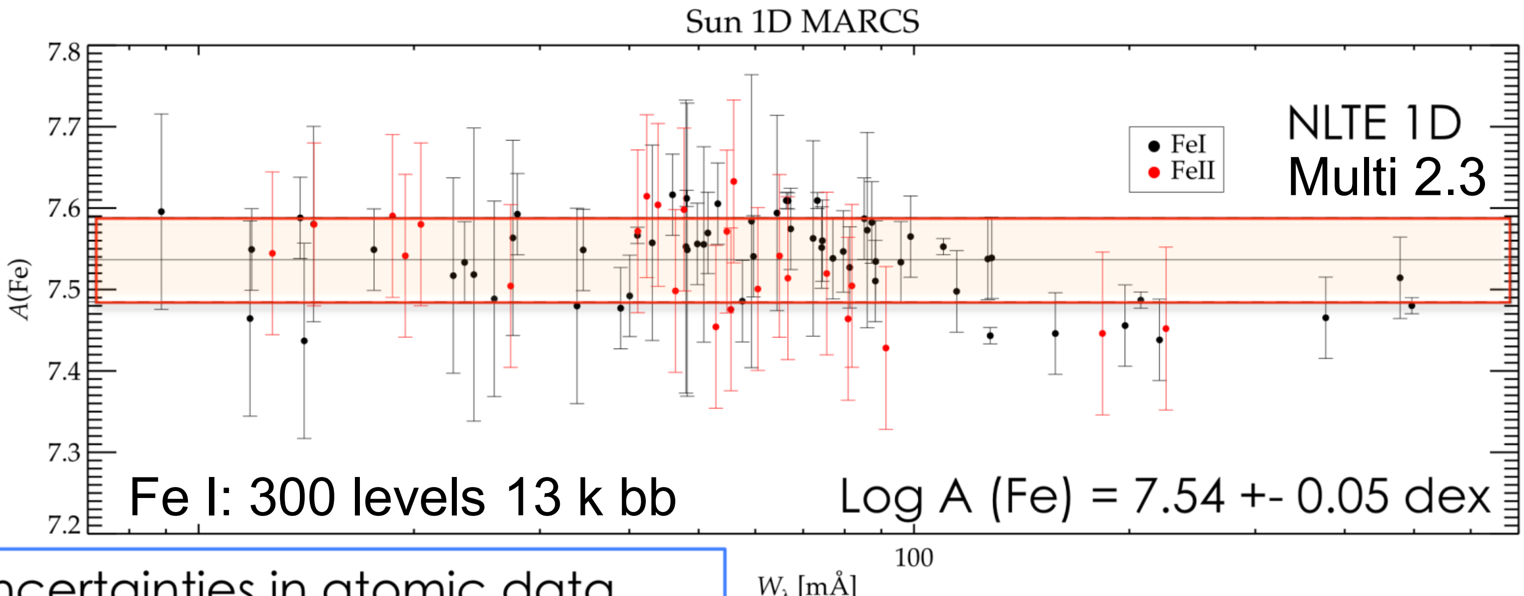


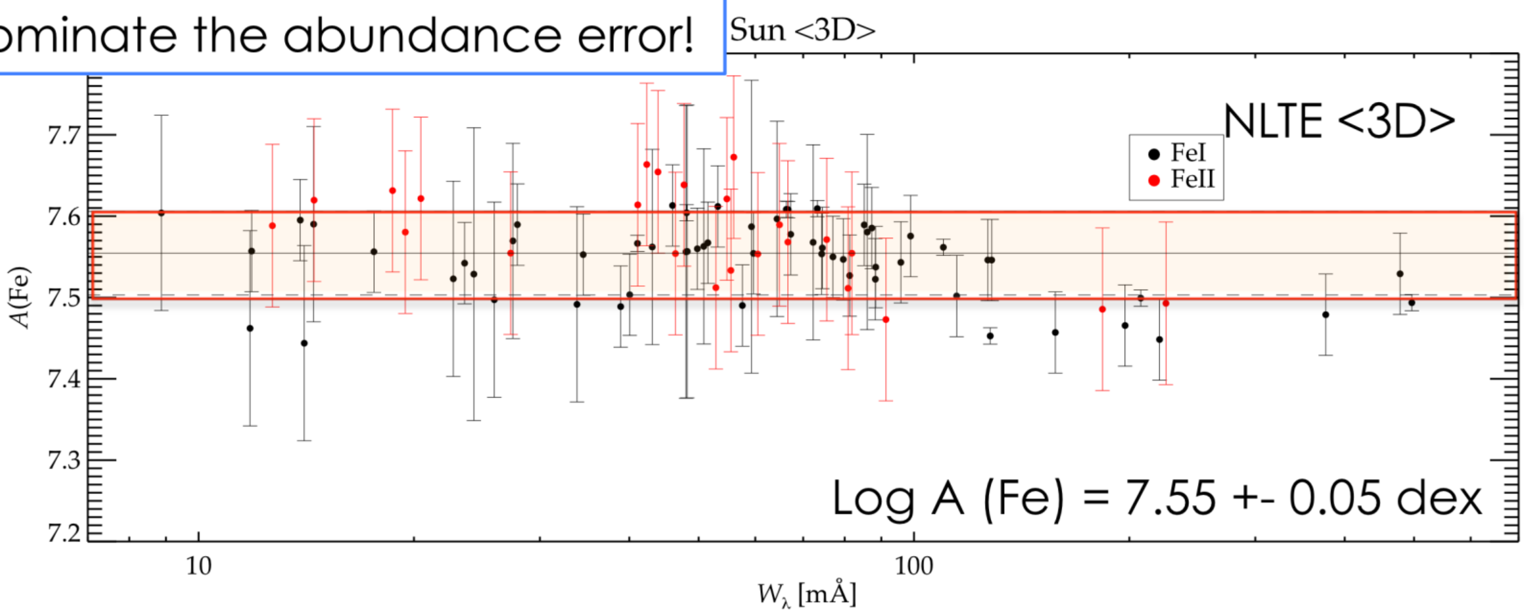
1D averages of 3D radiation-hydro models of stellar convection

NLTE Fe abundance in 1D vs. 3D models of Sun

Solar Fe abundance: <3D> - **7.55** dex, 1D - **7.54** dex



Sun: uncertainties in atomic data fully dominate the abundance error!



Gaia-ESO Public Spectroscopic Survey

Science goals:

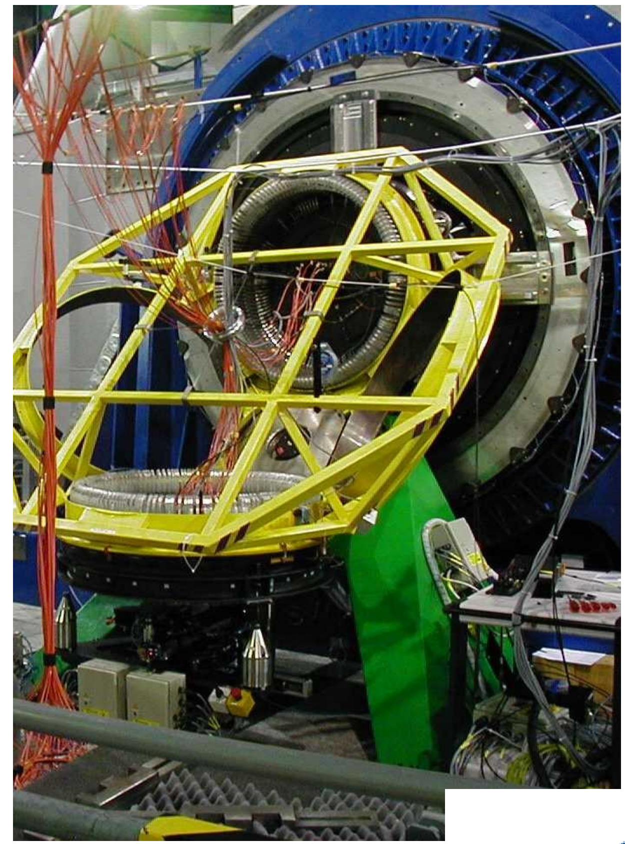
- **Observe 100,000 stars of all Galactic components; bulge, halo, thin & tick disc, star formation regions, open star clusters of all ages.**
- **Provide the first homogenuous overview of the distributions of stellar kinematics and elemental abundances = 'chemo-dynamical' survey.**
- **Complementary to Gaia mission. It will quantify the formation history and evolution of young, mature, and ancient Galactic star populations.**
- **Target stars of all spectral types, ages, & masses.**

Status:

- **PIs G. Gilmore & S. Randich, 350+ Co-Is, 95+ Institutes.**
- **300 nights in 5 years with VLT-Giraffe (R=20,000) and UVES (R=47,000).**
- **Started Jan. 2012, ends Sep 2016+.**
- **Currently ~20,000 Giraffe spectra & >1500 UVES spectra are observed.**
- **19 Working Groups for data reduction and analysis.**
- **First Science Conference, Nice, April 2013; 130 participants.**
- **Public website www.gaia-eso.eu**

Fibre Large Array Multi Element Spectrograph

Very Large Telescope at Cerro Paranal, Chile



- 132 fibres, Fov 20’, $+10^{o} \geq$ dec. $\geq -60^{o}$
- Field star catalog: VISTA images.

- 100 clusters with photometry and membership info.
- Giraffe $9^{m} > V \geq 19^{m}$; UVES $V \geq 16.5^{m}$

- Vrad for all stars of $V > 17^{m}$

GES Data Products

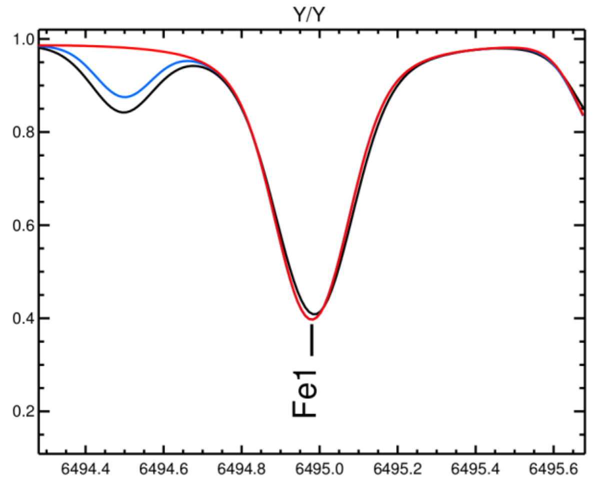
Delivery by WGs to ESO (semestrial & annual):

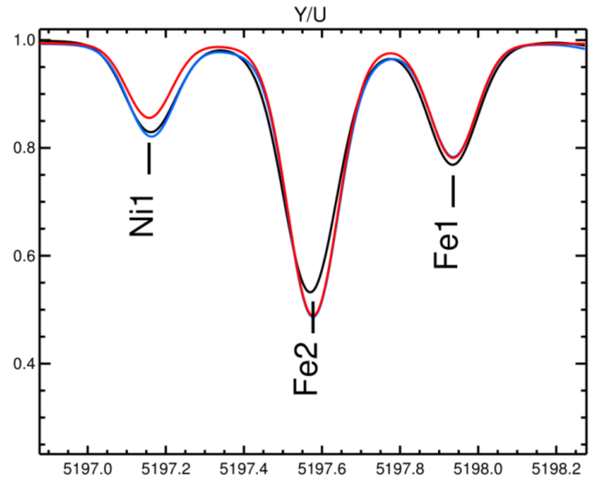
- **Calibrated 1D spectra, star IDs, photometry, ...**
- **Astrophysical parameters Teff, log*g*, [M/H],Vmic**
  ***v*sin*i*, Vrad+σ**
- **Giraffe: [Fe/H], [α/Fe], Li in cool stars, activity**
  Mg, Ca, Ti in FGK stars. Si, Cr, Mn, Co,
  Ni in Bulge K giants (B. Barbuy PO-01).
- **UVES: 5000 spectra (480-680 nm) within 2 Kpc**
  of the Sun. Elment abundances of C, O,
  Na, Mg, Si, Ca, Sc, Ti, Cr, Mn, Fe, Ni, Zn,
  Y, Zr, Ba, La, Ce, Eu.

GES spectral line lists & line data

- Special subgroup for FGK star analysis.
- 'CLEAN list' compiled for 478 - 685 nm & 845 - 895 nm.
- 1313 atomic lines (v3), 545 Fe I, 43 Fe II, 32 Ca I, 47 Si I, 105 Ti I, 12 Mg I,...
- log(*gf*) from published laboratory measurements (NIST) or QM calculations (OP Topbase), while the rest are predicted log(*gf*)-values.

- CLEAN lines tested with MARCS LTE synthesis of the Sun and Arcturus.

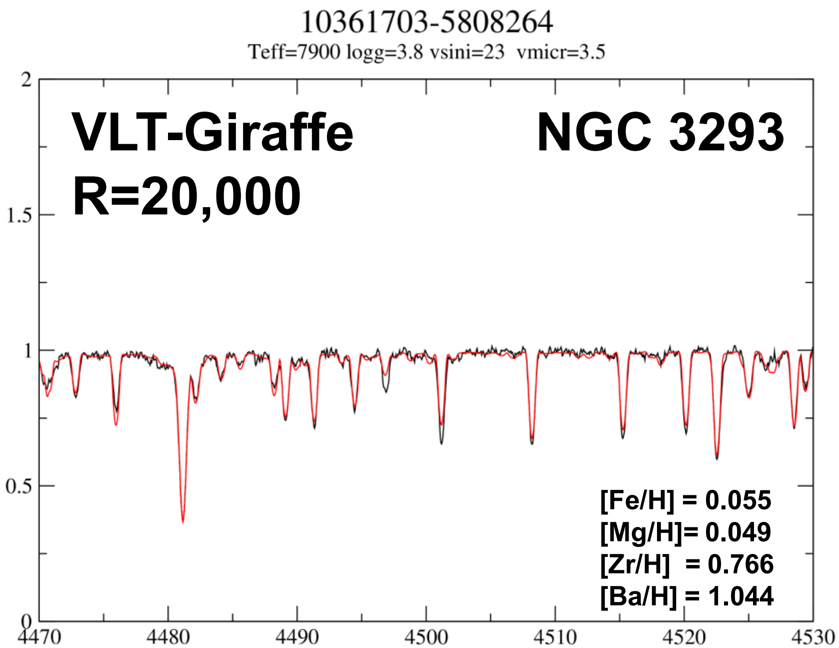


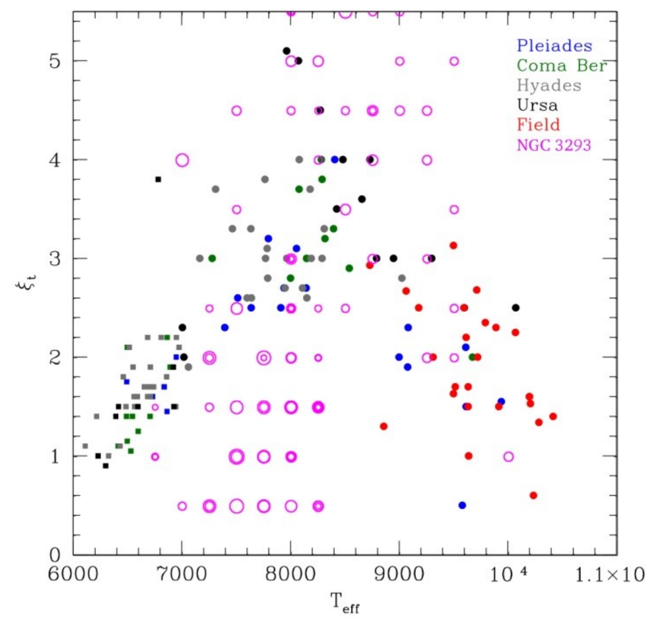


- 162 Fe I lines have accurate laboratory data and are unblended (M. Ruffoni CT-04, J. Pickering PO-43), while only 13 Fe II lines.
- Updates for collisional broadening by H (P. Barklem CT-05).

GES spectral line lists & line data

- Line lists for hot OBA stars compiled in WG13.
- Focus on element abundances of A-type stars in young open clusters.
- Blue Giraffe gratings used for OBA stars: 403 - 476 nm & 630 - 669 nm.
- Only 4 strong Fe II lines, (3 weak Fe I lines show NLTE effects).
- Atomic data from SpectroWeb database (includes hot benchmark stars).

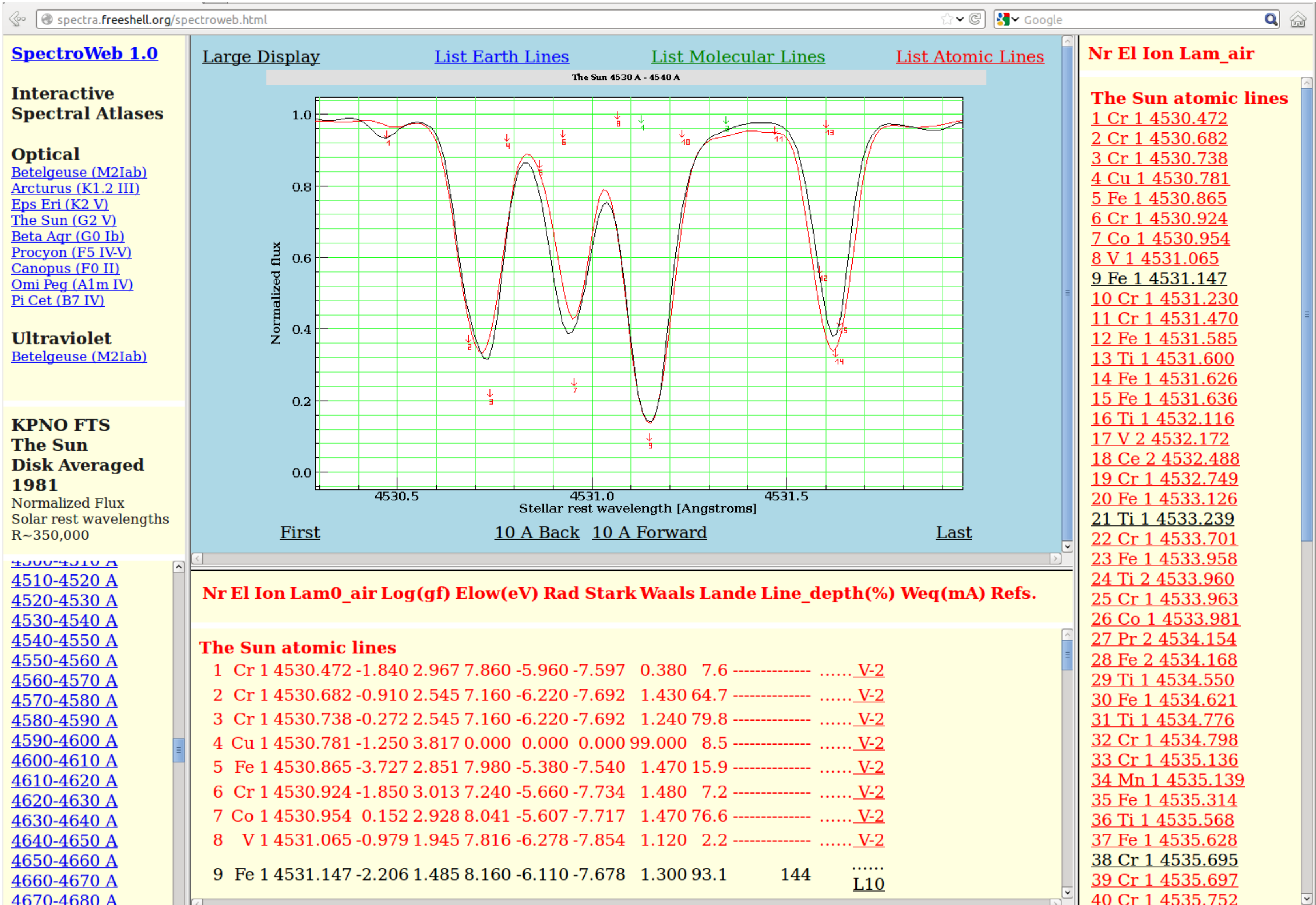




- Microturbulence velocity reveals maxium around mid A-types.
  Vmic parametrization 1-2 km/s for FGK stars is not valid for OBA stars.

SpectroWeb database

- AFGKM benchmark spectra 350 - 680 nm from Mercator-HERMES.
- Updates of tested atomic line data for astrophysical spectrum modeling.



Conclusions

- **Get ready for Gaia and GES, two tremendous boosts for stellar astrophysics & spectroscopy.**
- **Our needs for reliable and tested atomic data have never before been more urgent.**

- **Gaia: Improvement of synthetic model grids used in DPAC for stellar APs & classification.**

- **GES: More laboratory data of α-elements and iron-peak elements in 400 - 900 nm for detailed comparisons to benchmark stellar spectra.**