The Gaia-ESO Survey

some reflections

Gerry Gilmore & Sofia Randich

Cambridge & INAF/Arcetri

- Brief update on Gaia GDR2
- Overview of the Gaia-ESO Public Spectroscopic Survey
- How and why we use many different reduction systems
- Why are there such big systematics in abundances?
- Are we doing things the right way?

Gaia DR2: April 2018

- Five-parameter astrometric solutions for all sources with acceptable formal standard errors ($> 10^9$ anticipated), and positions (α, δ) for sources for which parallaxes and proper motions cannot be derived
- G and integrated G_{BP} and G_{RP} photometric fluxes and magnitudes for all sources
- Median radial velocities for sources brighter than $G_{RVS} = 12$
- For stars brighter than $G = 17$, estimates of T_{eff} and, where possible, A_V, based on integrated photometry
- Photometric data for a sample of variable stars
- Epoch astrometry for a pre-selected list of $> 10\,000$ asteroids

Typical parallax precision

G=15	30 muas,
G=18	150muas
G=20	700muas

Photometry limits <2mmag

Radial velocity 400m/s 5<G<8 <2km/s to G=12
3-5 million stars

Teff accuracy to 400K

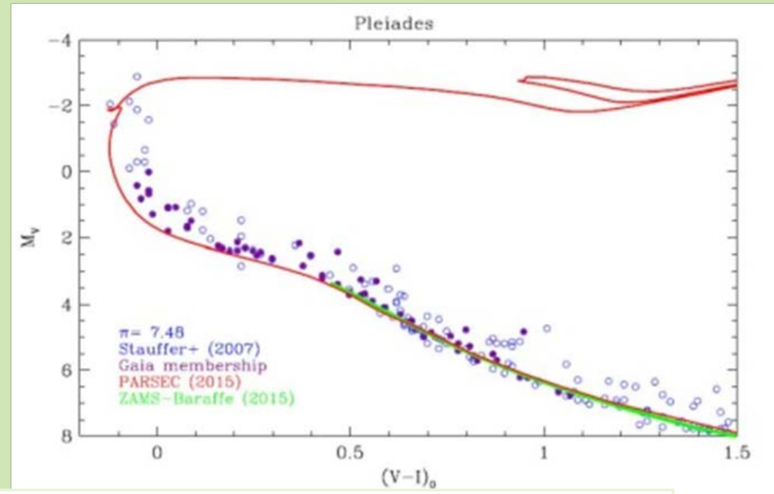
Luminosity to 15%

Radius to <5%

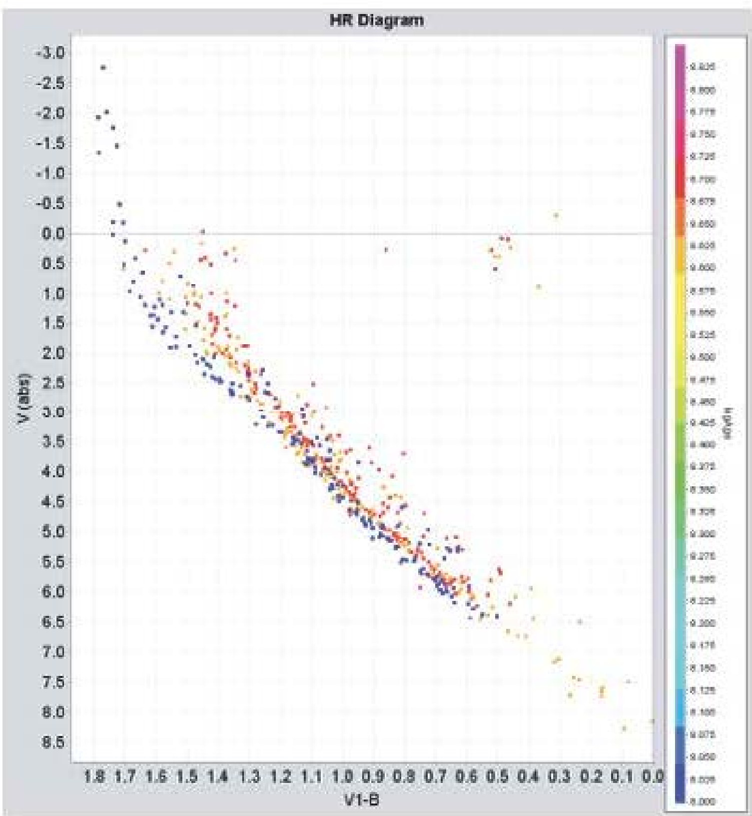
Gaia: GDR2 in April 2018

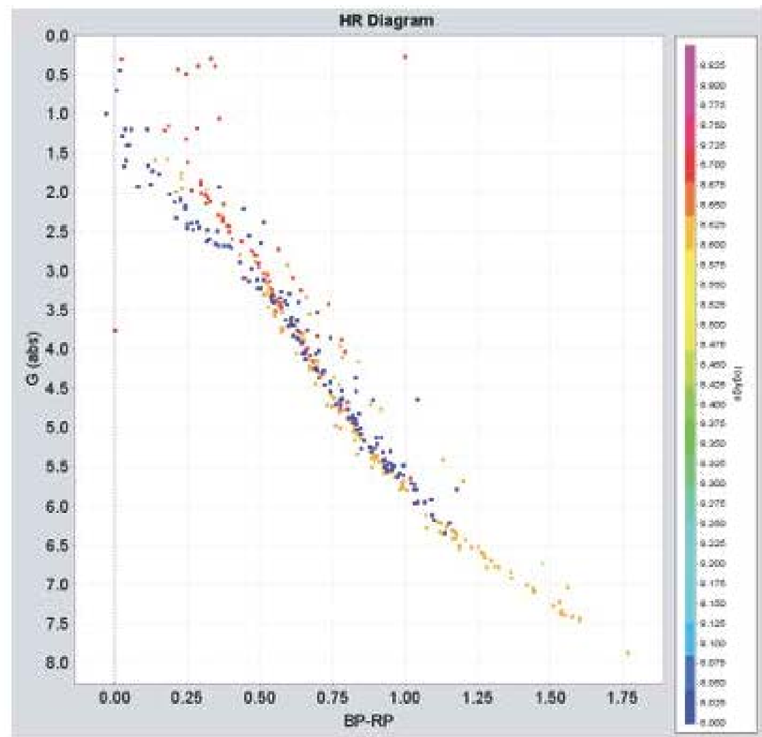
GDR1

Fig. 25. M_V, $(B-V)_0$ HR diagram of the Pleiades, with several sets of commonly used isochrones (top). Bottom panel is the analogous in the M_V, $(V-I)_0$. We assume an age of 130 Myr, solar metallicity, A_V=0.1



- Cluster HR diagrams will improve with use of DR2 colours





Co-PIs:
Gerry Gilmore
& Sofia Randich

Steering group:
12 members + CoPIs

450++ Co-Is
95+ institutes

20 WGs

http://gaia-eso.eu (public survey pages)
http://casu.ast.cam.ac.uk/gaiaeso/

http://great.ast.cam.ac.uk/GESwiki/GGESHome
http://ges.roe.ac.uk (public archive)

The Consortium

Co-PIs: Gerry Gilmore[1370], Sofia Randich[1335]
CoIs: M. Asplund[1490], J. Binney[1611], P. Bonifacio[1588], J. Drew[1668], S. Feltzing[1473], A. Ferguson[1649], R. Jeffries[1132], G. Micela[1344], I. Negueruela[7609], T. Prusti[1278], H-W. Rix[1489], A. Vallenari[1343], U. Abbas[1346], D. Aden[1473], V. Adibekyan[1200], C. Aerts[1399], L. Affer[1344], J-M. Alcala[1340], E. Alfaro[1392], C. Allende Prieto[1393], G. Altavilla[7530], J. Alves[1895], T. Antoja[1422], A. Aparicio[1393], F. Arenou[1588], C. Argiroffi[1883], A. Asensio Ramos[1393], C. Babusiaux[1588], C. Bailer-Jones[1489], L. Balaguer-Nunez[1821], G. Barentsen[1668], A. Bayo[1261], B. Barbuy[1828], G. Barisevicius[1376], D. Barrado y Navascues[1068], C. Battistini[1473], I. Bellas-Velidis[1555], M. Bellazzini[1329], V. Belokurov[1370], T. Bensby[1473], M. Bergemann[1490], G. Bertelli[1343], K. Biazzo[1340], O. Bienayme[1582], S. Blanco Cuaresma[1592], J. Bland-Hawthorn[2044], R. Blomme[1650], C. Boeche[2112], S. Bonito[1344], S. Boudreault[1393], J. Bouvier[1449], A. Bragaglia[1327], I. Brandao[1200], A. Brown[1716], E. Brugaletta[1874], J. de Bruijne[1278], M. Burleigh[1244], J. Caballero[8545], E. Caffau[2112], F. Calura[1337], T. Cantat[1343], R. Capuzzo-Dolcetta[1657], M. Caramazza[1344], G. Carraro[1261], L. Casagrande[1490], S. Casewell[1244], S. Chapman[1370], C. Chiappini[1135], Y. Chorniy[1376], N. Christlieb[1982], M. Cignoni[7530], G. Cocozza[7530], M. Colless[1017], R. Collet[1490], M. Collins[1489], M. Correnti[1329], M. Cottaar[1371], E. Covino[1340], D. Crnojevic[1649], M. Cropper[1242], P. Cruz Gamba[1068], M. Cunha[1200], F. Damiani[1344], M. David[1233], A. Delgado[1392], E. Delgado-Mena[1200], R. Dorda Laforet[7609], S. Duffau[2112], S. Van Eck[1358], B. Edvardsson[6181], J. Eldridge[1370], H. Enke[1135], K. Eriksson[6181], N.W. Evans[1370], L. Eyer[1277], B. Famaey[1582], M. Fellhauer[1824], I. Ferreras[1242], F. Figueras[1821], G. Fiorentino[1422], E. Flaccomio[1344], C. Flynn[2044], D. Folha[1200], E. Franciosini[1335], P. Francois[1588], A. Frasca[1341], K. Freeman[1139], Y. Fremat[1650], E. Friel[1355]; B. Gaensicke[1241], P. Galindo[1068], J. Gameiro[1200], F. Garzon[1393], M. Gebran [5741], S. Geier[5677], D. Geisler[1824], O. Gerhard[1496], B. Gibson[1197], M. Gieles[1370], A. Gomboc[1995], A. Gomez[1588], C. Gonzalez-Fernandez[7609], J.I. Gonzalez Hernandez[1393], E. Gosset[1359], E. Grebel[2112], R. Greimel[1423], M. Groenewegen[1650], J Groh[1494], F. Grundahl[1368], P. Gruyters[6181], M. Guarcello[1312], B. Gustafsson[6181], P. Hadrava[1116], T. Hansen[1982], D. Hatzidimitriou[1559], N. Hambly[1649], P. Hammersley[1258], C. Hansen[2112], M. Haywood[1588], U. Heber[5677], U. Heiter[6181], E. Held[1343], A. Helmi[1422], G. Hensler[1893], A. Herrero[1393], V. Hill[1591], S. Hodgkin[1370], N. Huelamo[8545], A. Huxor[2112], R. Ibata[1582], M. Irwin[1370], H. Jacobson[1461], R. Jackson[1132], P. Jofre[1592], R. de Jong[1135], P. Jonker[1660], S. Jordan[2112], C. Jordi[1821], A. Jorissen[1358], N. Kacharov[1244] D. Katz[1588], D. Kawata[1242], S. Keller[1139], N. Kharchenko[1135], R. Klement[1489], A. Klutsch[1803], J. Knude[1966], A. Koch[1244], O. Kochukhov[6181], M. Kontizas[1560], S. Koposov[1370], G. Kordopatis[1370], A. Korn[6181], A. deKoter[1614], P. Koubsky[1116], A. Lanzafame[1874], R. Lallement[1588], C. Lardo[1337], P. de Laverny[1591], F. van Leeuwen[1370], B. Lemasle[1422], G. Lewis[2044], K. Lind[1490], H.P.E. Lindstrom[1966], A. Lobel[1359], J. Lopez Santiago[1803], P. Lucas[1668], H. Ludwig[2112], T. Lueftinger[1895], L. Magrini[1335], L. Mahy[1359], J. Maiz Apellaniz[1392], J. Maldonado[1803], M. Mapelli[1343], G. Marconi[1261], A. Marino[1490], S. Marinoni[1337], C. Martayan[1261], S. Martell[1017], I. Martinez-Valpuesta[1496], T. Masseron[1358], G. Matijevic[1995], R. McMahon[1370], S. Messina[1341], M. Meyer[1377], A. Miglio[1359], S. Mikolaitis[1376], I. Minchev[1135], D. Minniti[1801], A. Moitinho[8848], Y. Momany[1261], L. Monaco[1261], M. Montalto[1200], M.J. Monteiro[1200], R. Monier[5695], D. Montes[1803], A. Mora[1350], E. Moraux[1449], T. Morel[1359], J. Muijos[5688], N. Mowlavi[1583], A. Mucciarelli[7530], U. Munari[1343], R. Napiwotzki[1698], N. Nardetto[1591], T. Naylor[1130], Y. Naze[1359], G. Nelemans[1638], S. Okamoto[1616], S. Ortolani[6311], G. Pace[1200], F. Palla[1335], J. Palous[1116], E. Pancino[1337], R. Parker[1377], E. Paunzen[1893], J. Penarrubia[1828], I. Pillitteri[1312], G. Piotto[1343], H. Posbic[1588], L. Prisinzano[1344], N. Przybilla[1251],

Gaia-ESO Survey in a nutshell - Targets

MW field Giraffe: Bulge: mostly giant stars; **halo /thick disc** FG TO stars (17 < r < 18);
Large sample of calibration stars – for all surveys
UVES parallels: Solar neighborhood: 5000- star sample. Look at Mv~5.5 → unbiased survey to 1kpc at V=15.

60-70 Open Clusters in all phases of evolution
(~1 Myr → several Gyr), sampling the age-distance-R_{GC}-density-mass-[Fe/H]) parameter space.
UVES: Mostly known members (PMS, MS, evolved – V<16.5) – from 10 to 50 stars per cluster
Giraffe: unbiased samples, photometric candidates (V < 19) – several x 100 stars/cluster

Gaia-ESO Survey in a Nutshell - products

Giraffe, 132 fibers
R=16000-25000, H3…H21
403-476…848-900

Parallel UVES, 6/8 fibers
R=42,000, 520/580 nm
416-617/475-678

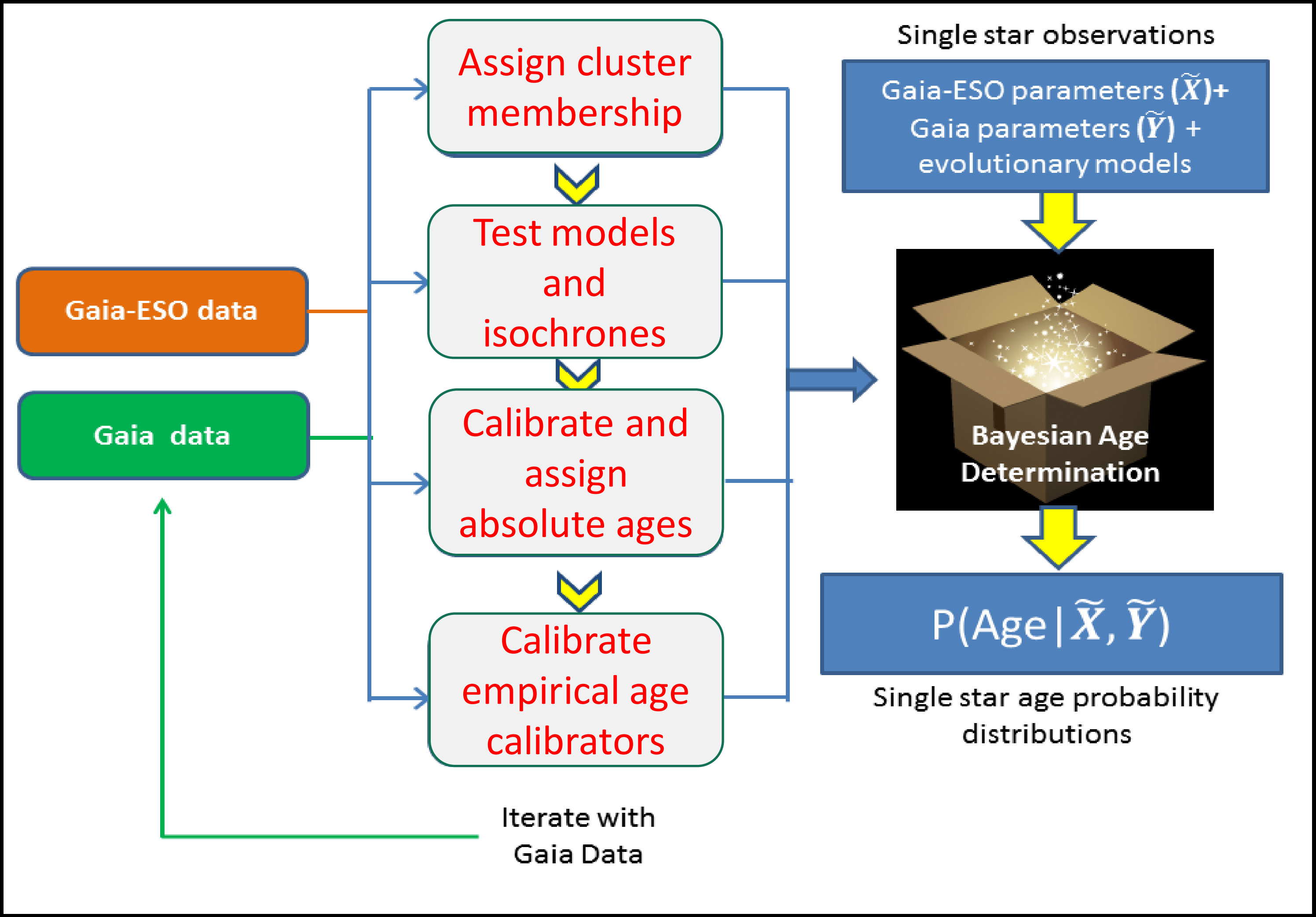
Plus ESO archive re-analysis

→ ADVANCED **PRODUCTS**

- RVs (+variability), vsini
- T_{eff}, log g, [Fe/H], [X/Fe] (Li, α, Fe-, s-,..)
- stellar properties: (activity, M_{acc}, $\dot{M}$, etc.)

Calibration of ages

One of the legacies of the cluster dataset



Calibration Concept

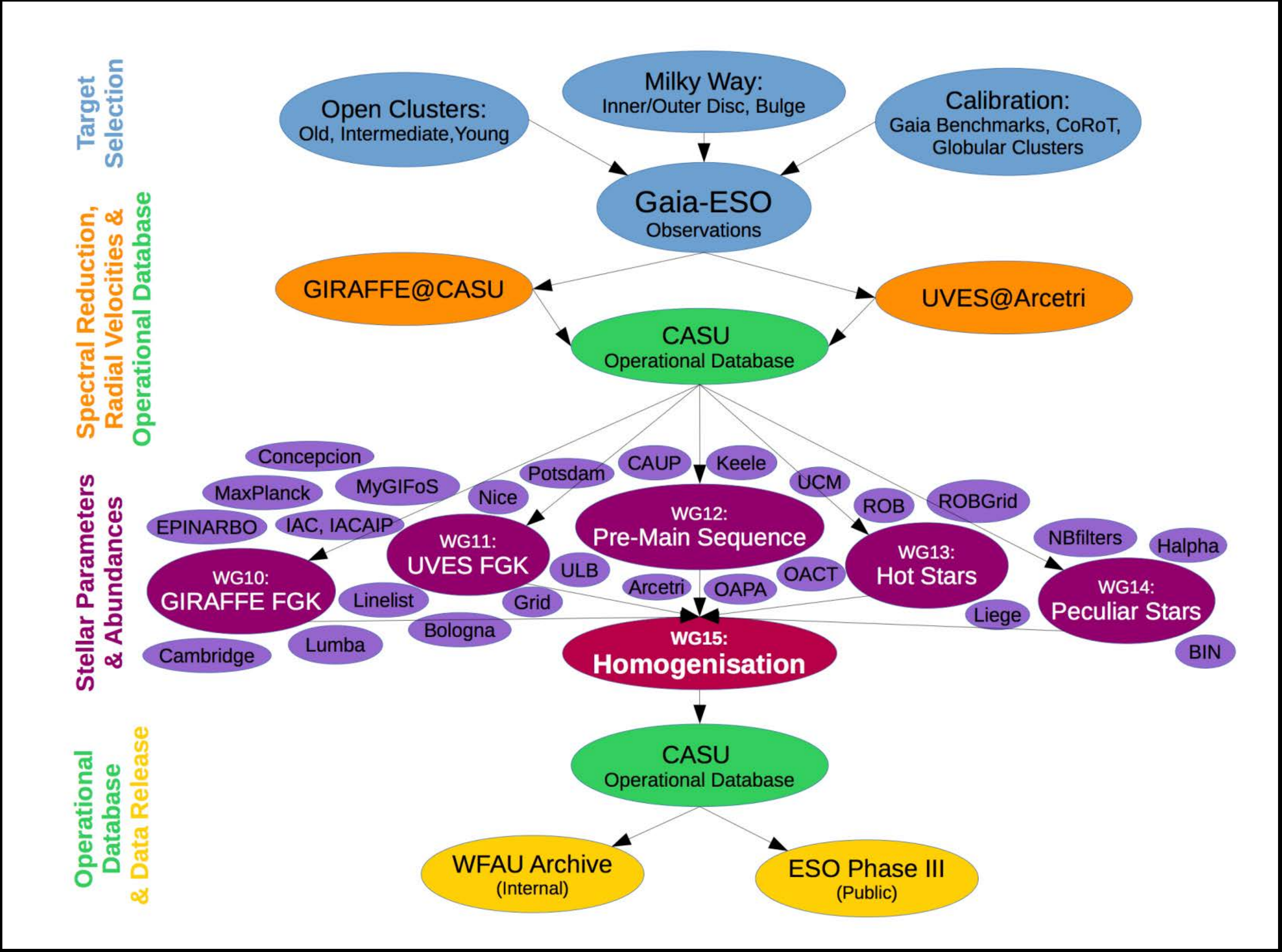
internal calibrations: different stellar types and settings, several nodes analyzing the same stars

external calibrations: w.r.t other surveys and Gaia

maximize legacy value and provide a rich dataset for future inter-survey calibration

- RV standards
- Gaia benchmark stars: method/node performances, internal homogeneization
- Clusters: hot vs. cool; PMS vs. MS vs. evolved; test metallicity
- CoRoT Red Giants and Kepler II targets: asteroseismic gravities and ages

Gaia-ESO Survey - dataflow



Is Gaia-ESO the right approach?

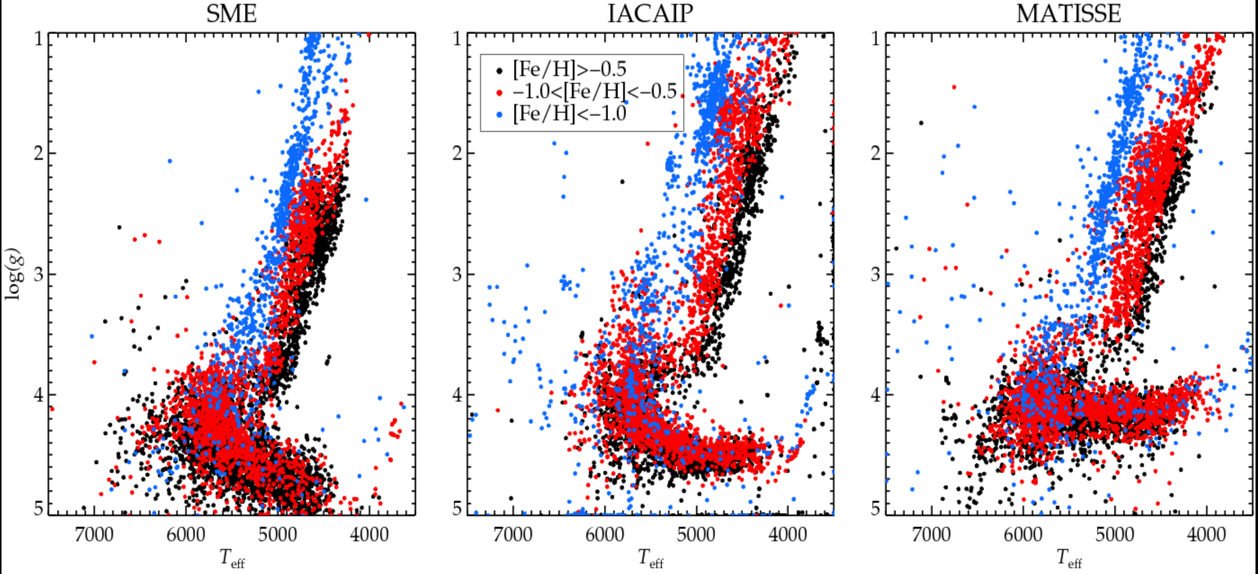
no-one else is putting in this methods effort

- Involve all spectroscopic analysis methods
- Identify the dominant systematic variables, and fix them – version control
- Analyse spectra through all interested groups
- In principle, this allows us to identify both systematic method errors and random errors
- ➔ parameter +/- random +/- systematic
- More methods means more information
- Add seismic data for precision and systematics
- Share calibration across all the Surveys
- Bootstrap everything onto Gaia benchmark stars

Big surveys are essential: going from data to science remains a challenge

What can we believe from the famous public, proven, analysis pipelines?

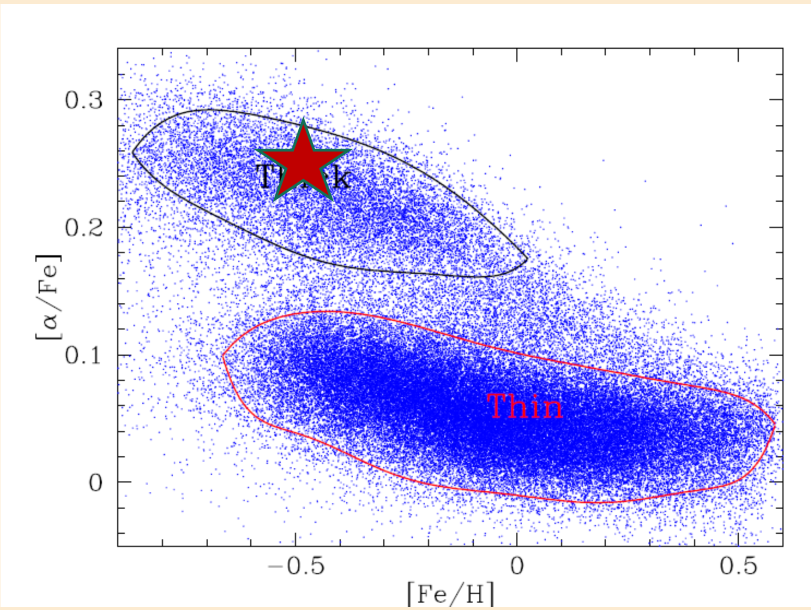
The figure shows the stellar parameters determined from 7 500 medium-resolution spectra with S/N>15 collected so far in the Gaia-ESO survey. The performance of three state-of-the-art pipelines analysing the same data set is contrasted.



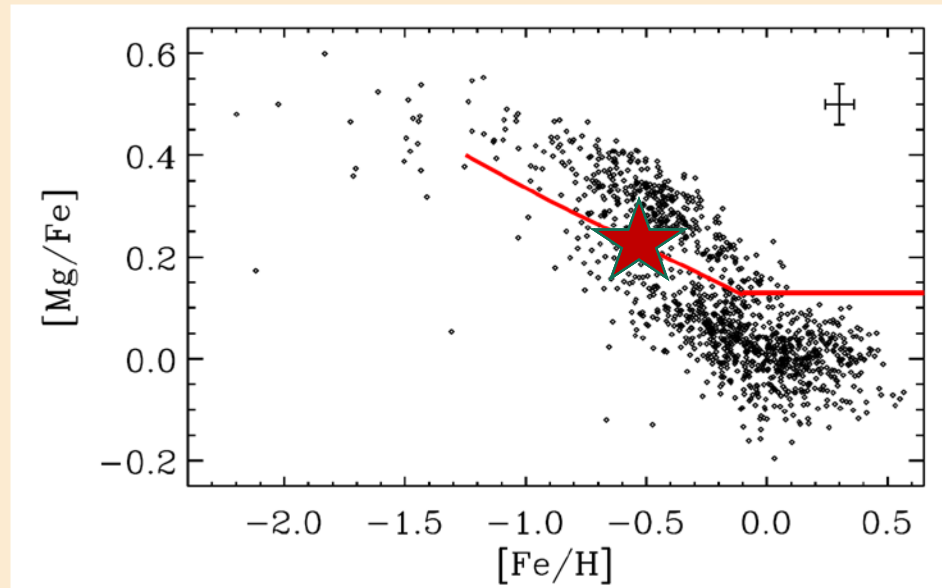
Indeed, stellar photospheres are neither one-dimensional, nor plane-parallel, nor in local thermodynamic equilibrium, assumptions that underlie the vast majority of all published stellar parameters and abundances. It turns out that these restrictive assumptions significantly distort the derived results in many important circumstances.

Systematic scale differences between surveys the chemical compositions of the disks

APOGEE data (Holtzman et al. 2015)



Gaia-ESO data (Guiglion et al. 2015)



Note the different vertical scales

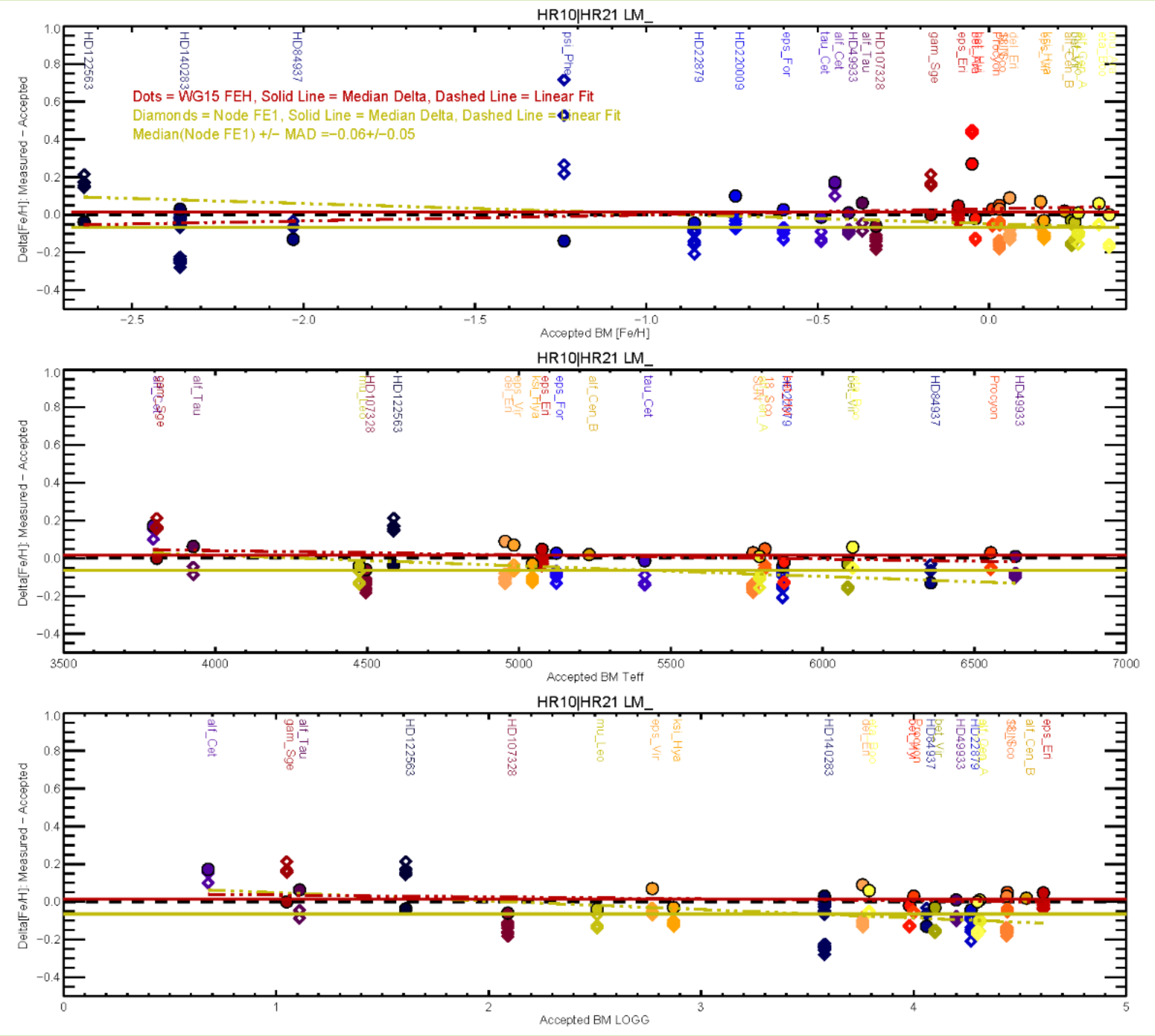
The red star, at (-0.5, 0.25) shows the peak of the APOGEE thick disk star distribution is in the gap between thick and thin disks in the Gaia-ESO scale (and for most literature).

What chemical evolution model can one deduce?

Gaia-ESO homogenization(s)

1) we map node results to the benchmark stars and to many clusters to remove systematics in the Giraffe spectra

2) we use a data model approach for UVES (very many line measures)

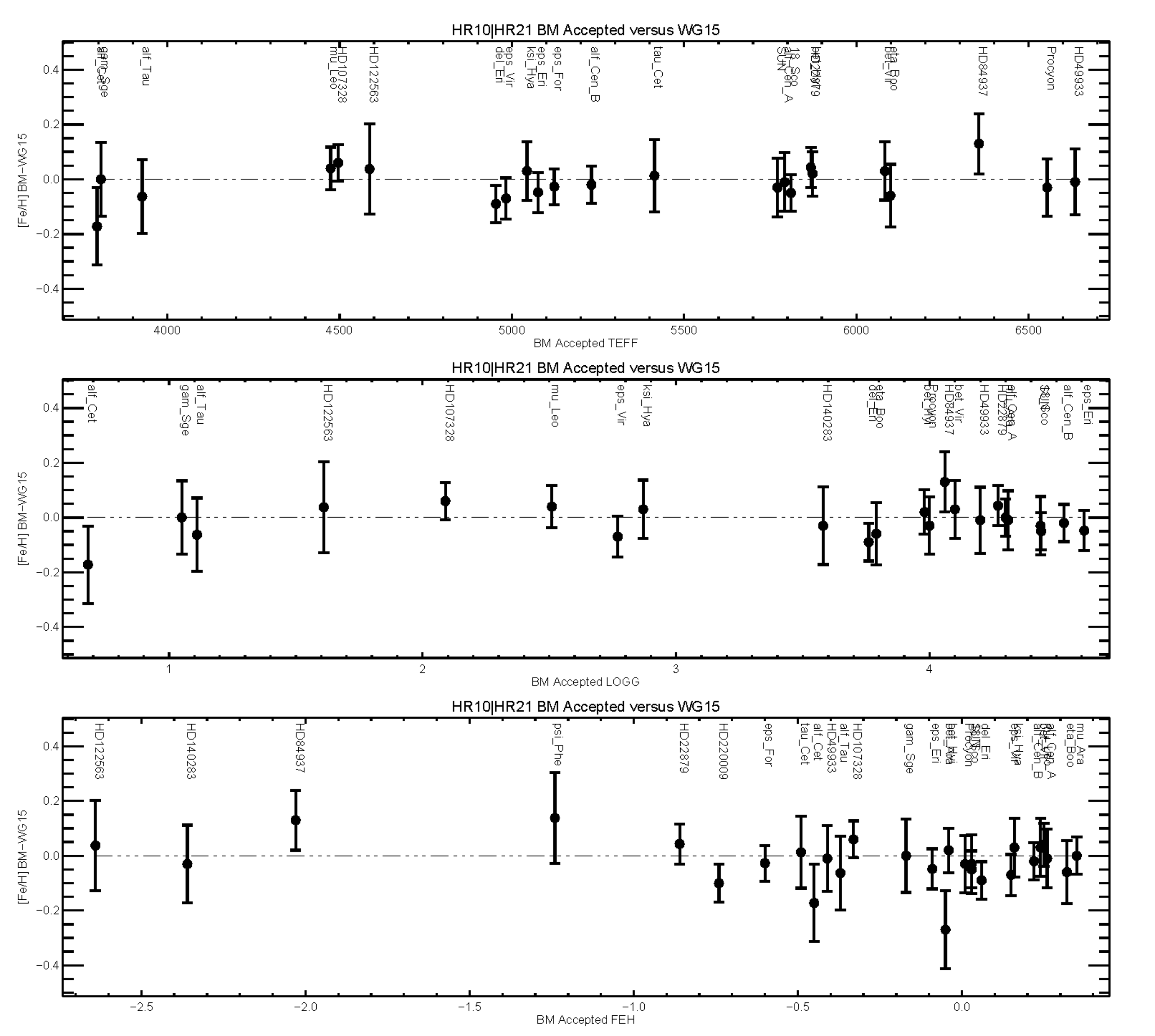


GIRAFFE example: results from one node for its analysis of many different SNR spectra of the Benchmark stars.

Gaia-ESO homogenization(s)

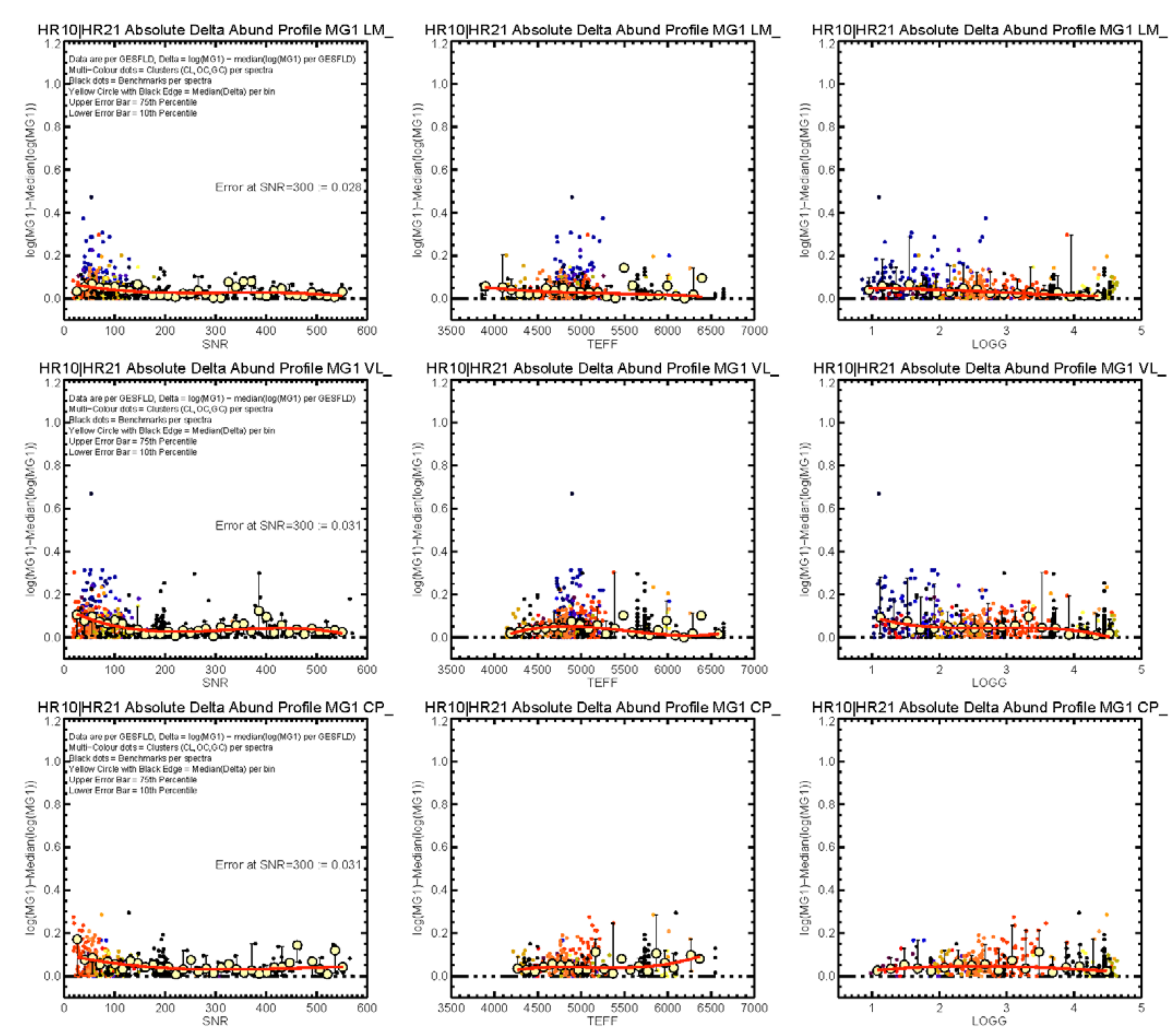
1) we map node results to the benchmark stars to remove systematics in the Giraffe spectra

2) we use a data model approach for UVES (very many line measures)



Results for the Giraffe spectra scaled onto the standards

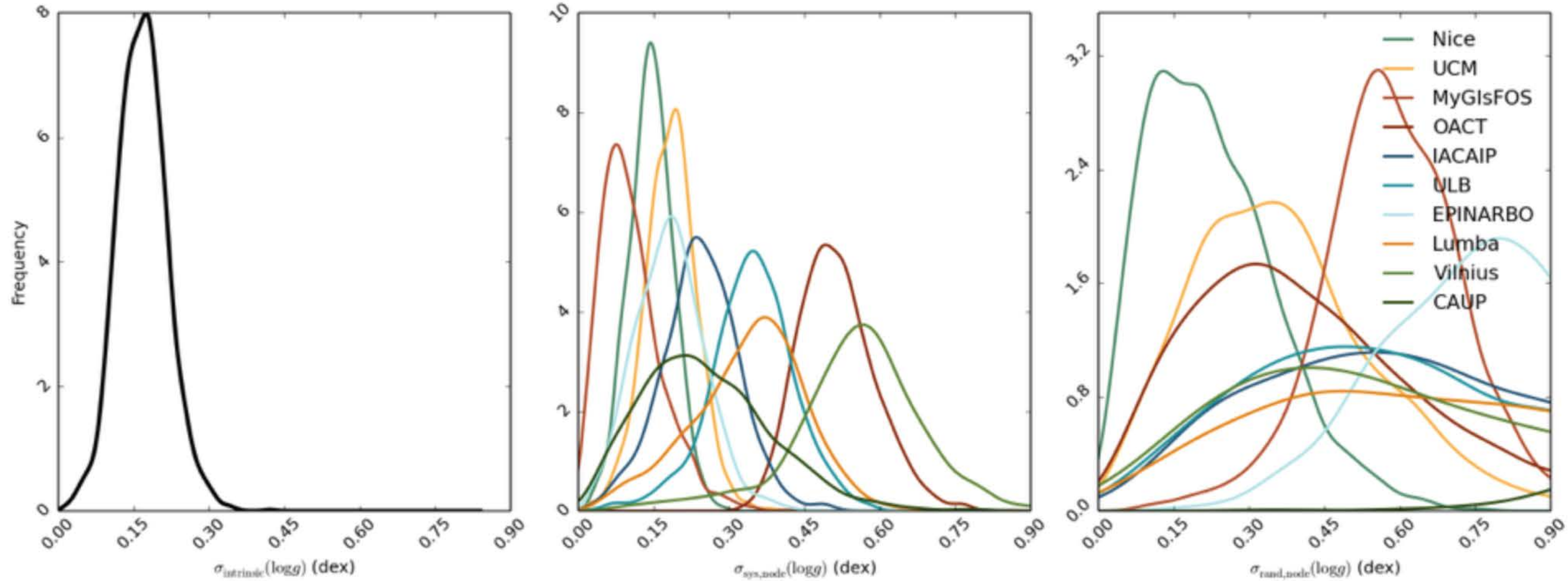
Gaia-ESO homogenization(s)
1) we map node results to the benchmark stars to remove systematics in the Giraffe spectra



We measure the accuracy for each node and each element from Giraffe Spectra.

UVES: Build a statistical model and use MCMC to span the (HUGE) parameter space
6.2 million abundance measurements, 6 nodes, 36 species, 28 elements

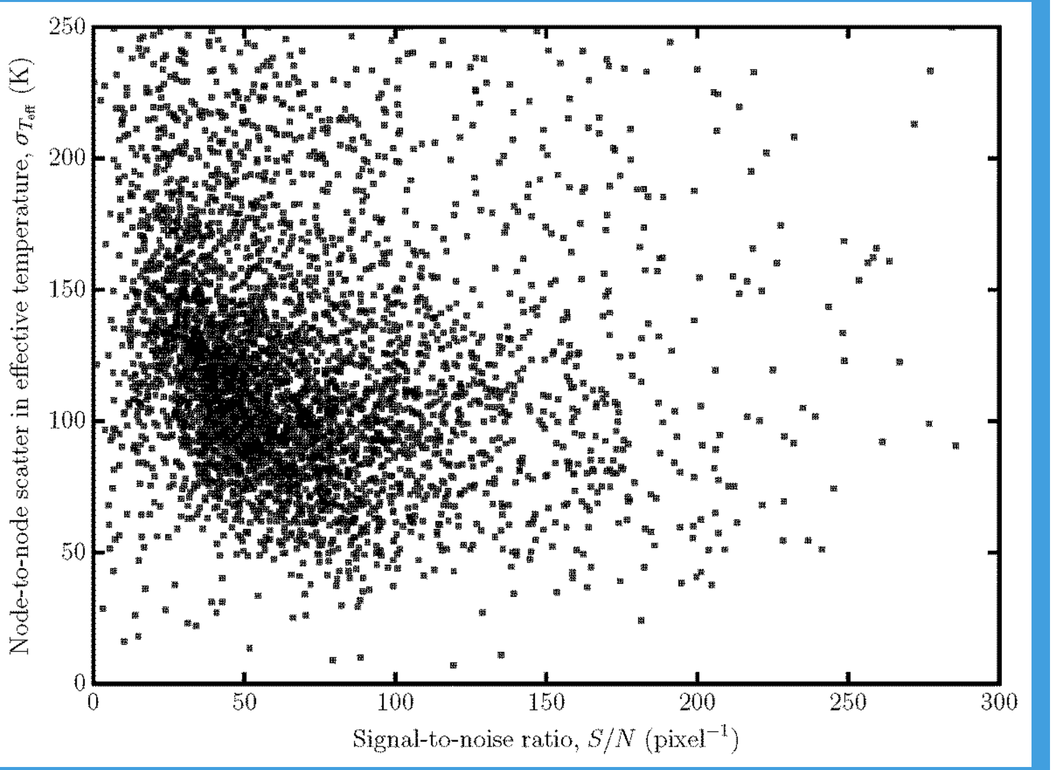
The Ensemble Model

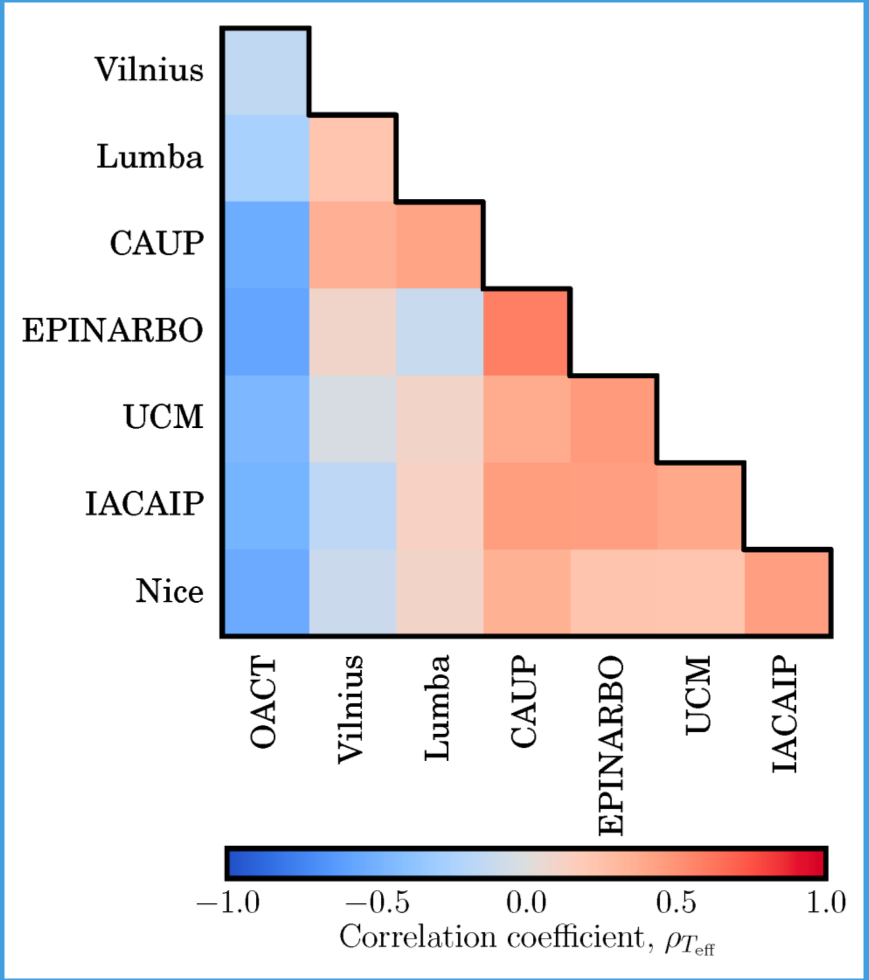


Inferred random and systematic log(g) uncertainties for each node

Similar systematic distributions may imply same method.

Gaia-ESO: how good are the parameters?
Large scatter between individual determinations of Te from many pipelines – happily, the noise is correlated

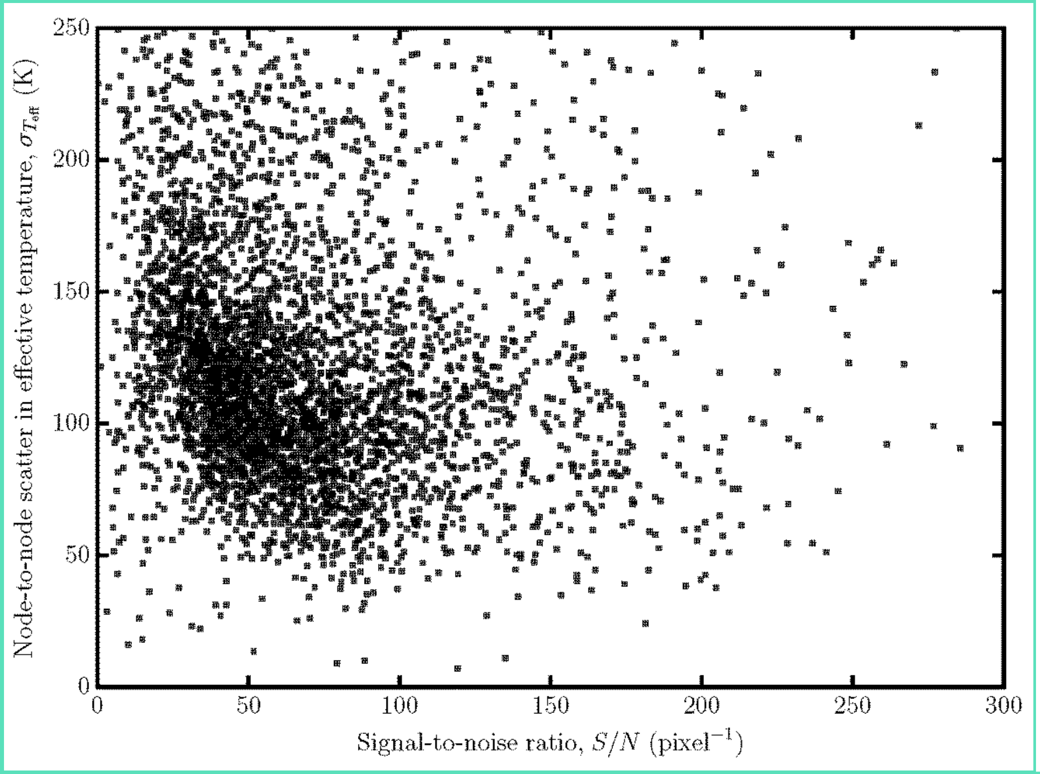


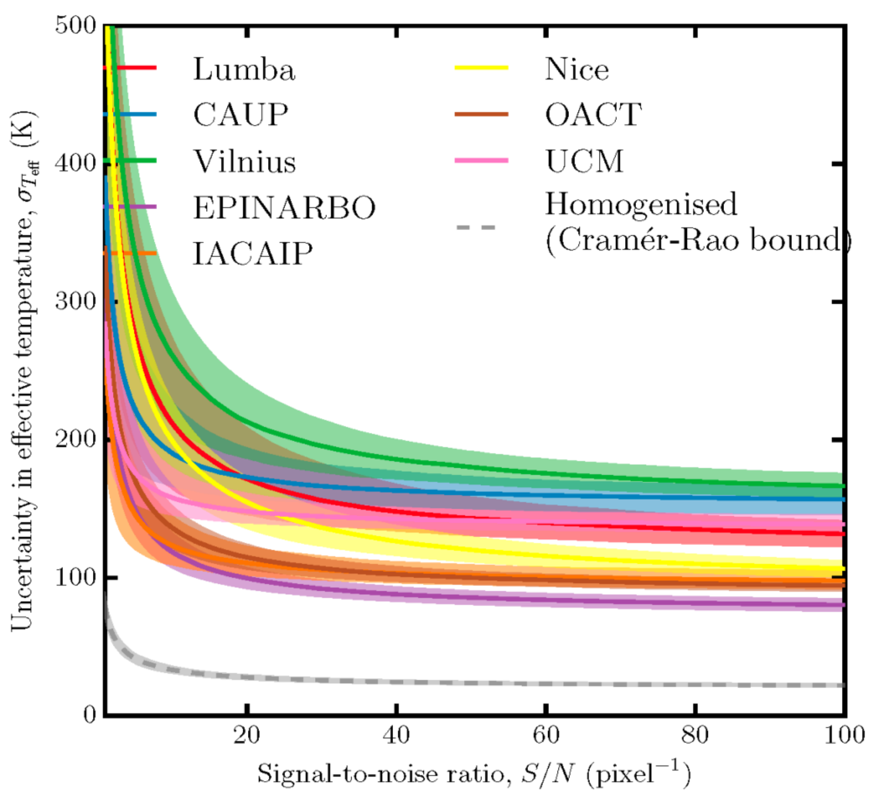


Great way to find screw-ups too….

Scatter between individual determinations of Te from many pipelines – happily, the noise is correlated

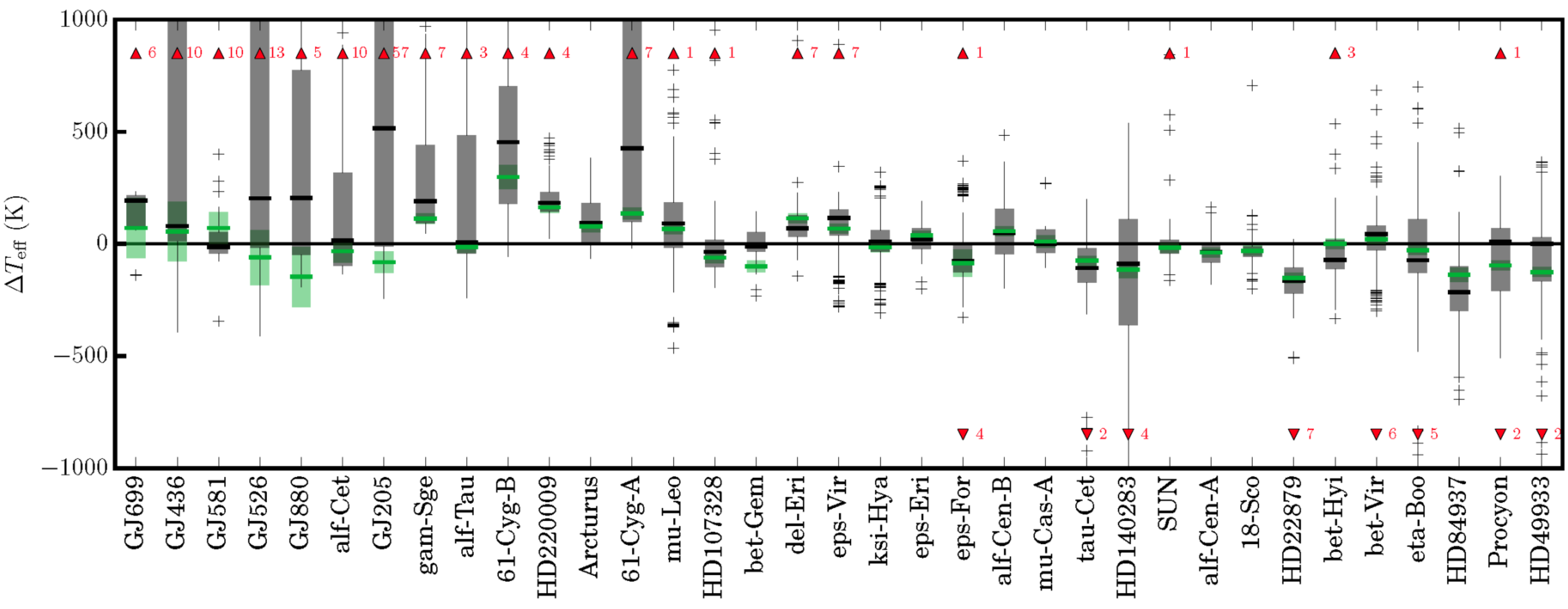
Use the information to reduce the measurement systematics from 120K to 30K





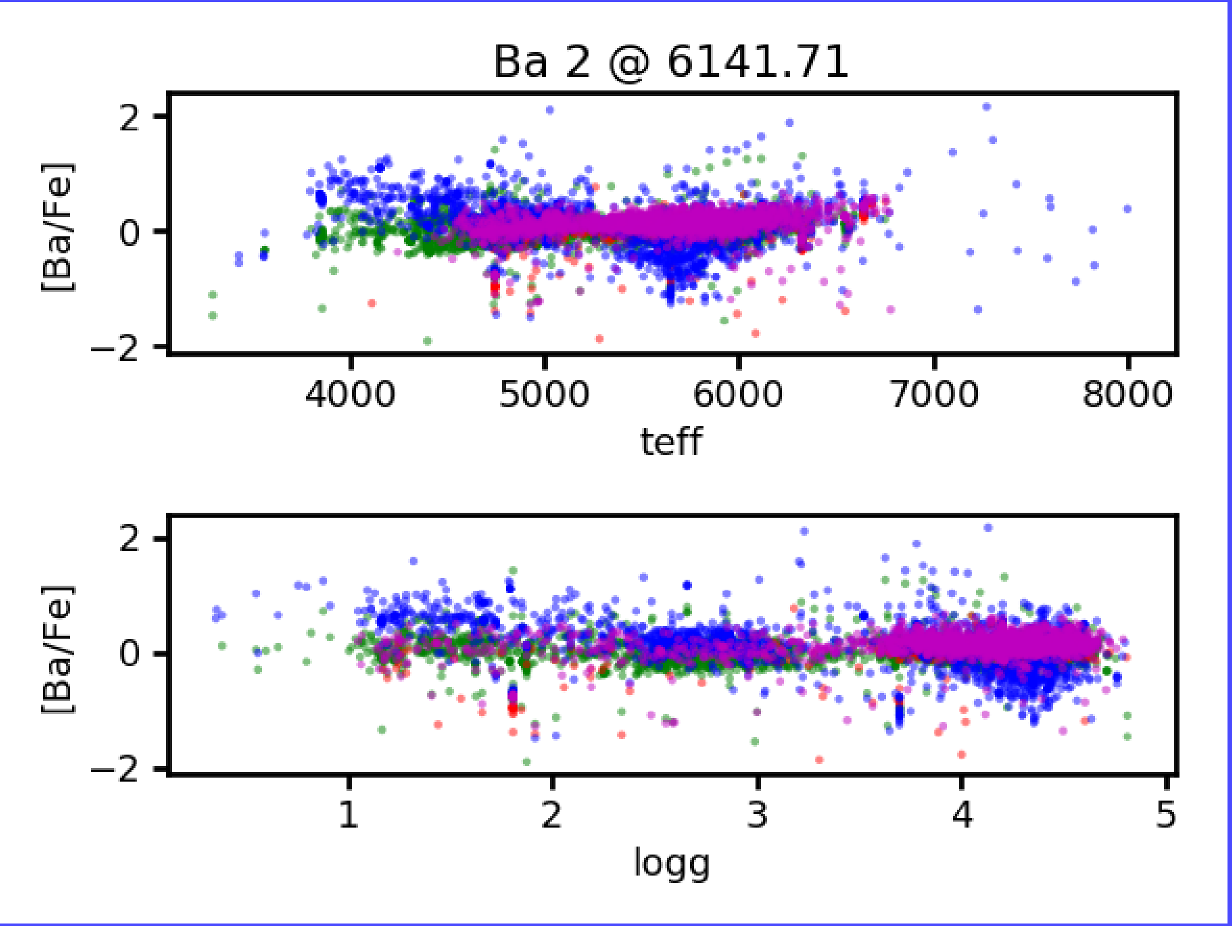
Correlated noise reduces systematics

homogenized results outperform the median



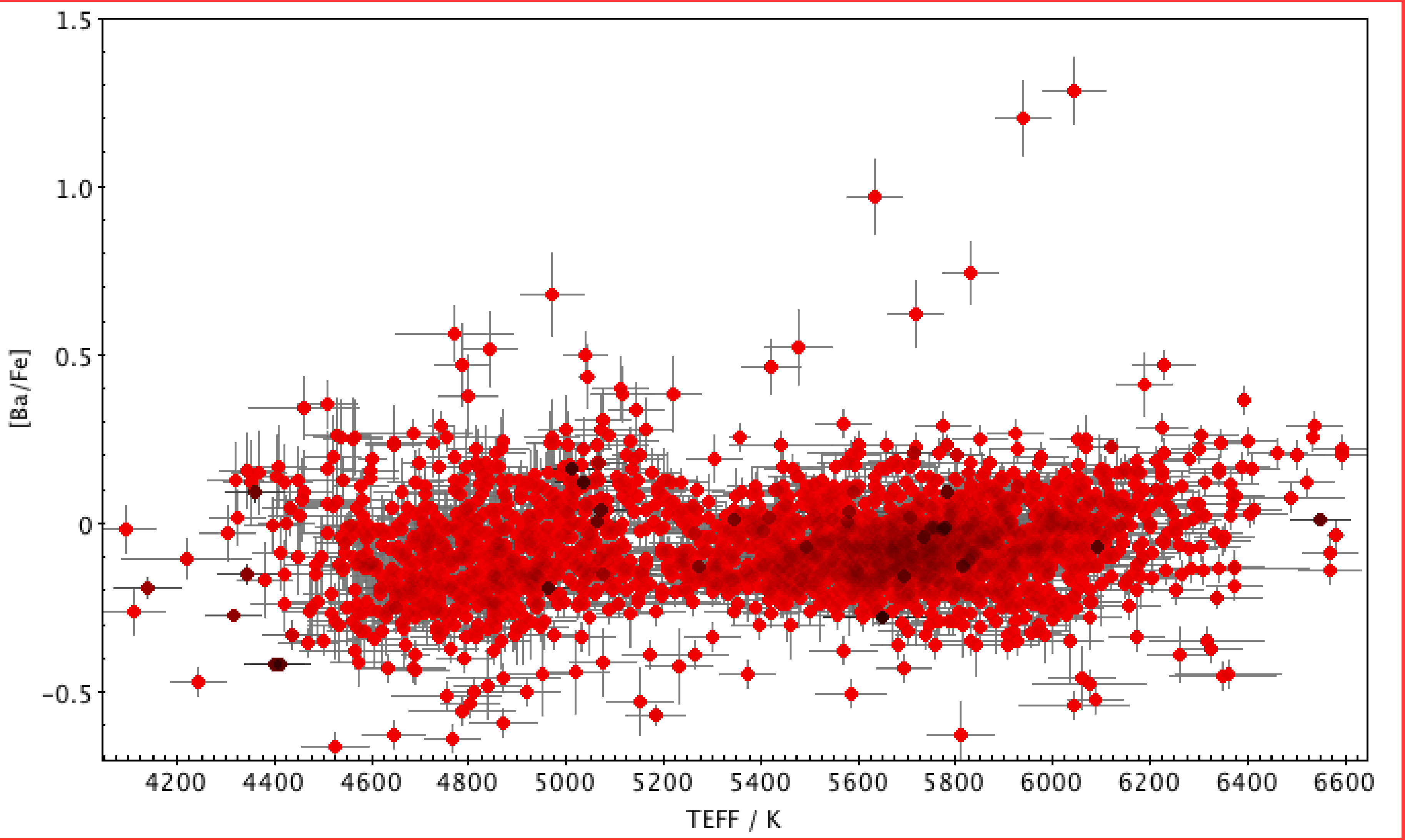
UVES calibrated benchmark stars: grey is raw median and range, green is corrected

Gaia-ESO
why we homogenize

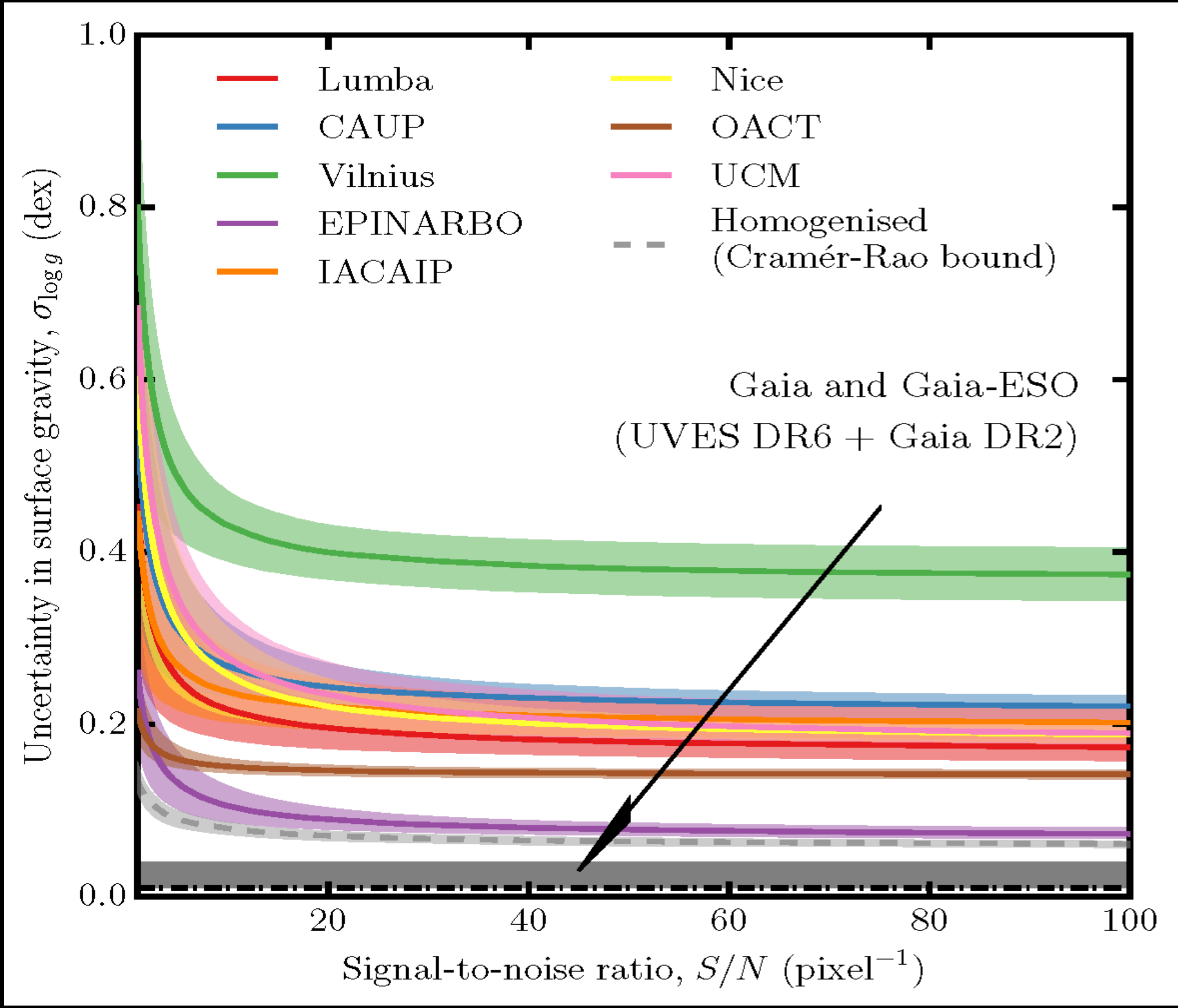


Ba/Fe data produced from several pipelines: note different scatter and systematics

Remove the systematics between pipelines➔ reduced scatter, trends



Next year GDR2: add Gaia to good spectra



Interpolation machines (Cannon)

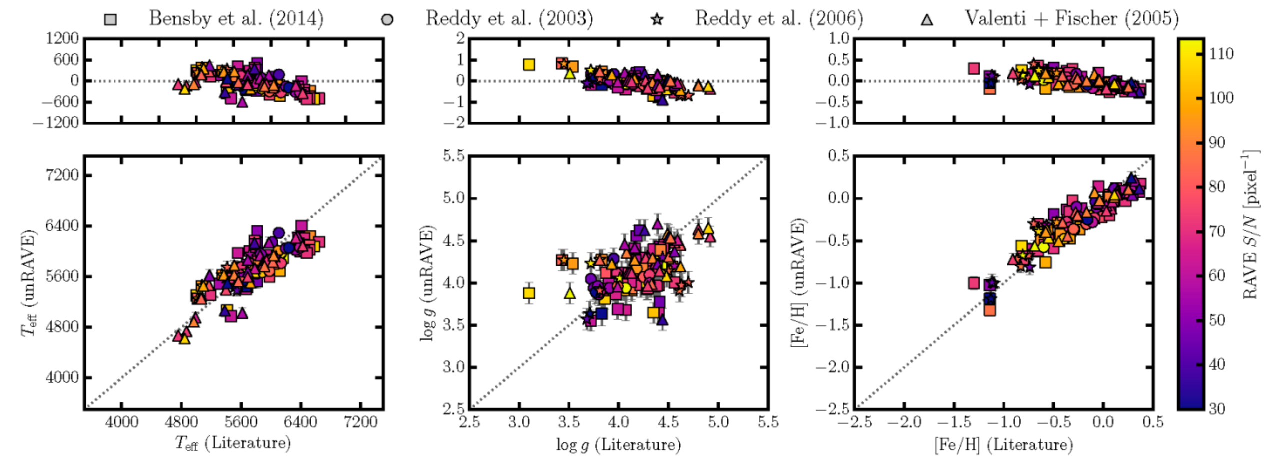


Fig. 11.— Stellar parameter ($T_{\rm eff}$, $\log g$, [Fe/H]) comparisons for stars in common between this work and 'gold standard' studies that use high-resolution, high S/N spectra and *Hipparcos* parallaxes where available: Bensby et al. (2014); Reddy et al. (2003, 2006); Valenti & Fischer (2005). Stars are colored by the S/N of the *RAVE* spectra.

Example from Casey etal using RAVE low res spectra

Many recent studies treat spectra via a simple data model.

No astrophysics. eg 1706.00009

WHY DOES THIS WORK?

<u>Spectrum analysis does not extract the full information content.</u>

Gaia-ESO Survey (GES)

The **IRON spectrum** is of vital importance to obtain **stellar metallicity**. A study of the Fe I spectrum within the GES spectral range revealed over 500 lines that are strong and unblended in stellar spectra.

449 lines were good candidates for study
167 had inaccurate atomic data
120 were absent from the literature

Existing oscillator strengths vs New Laboratory Measurements

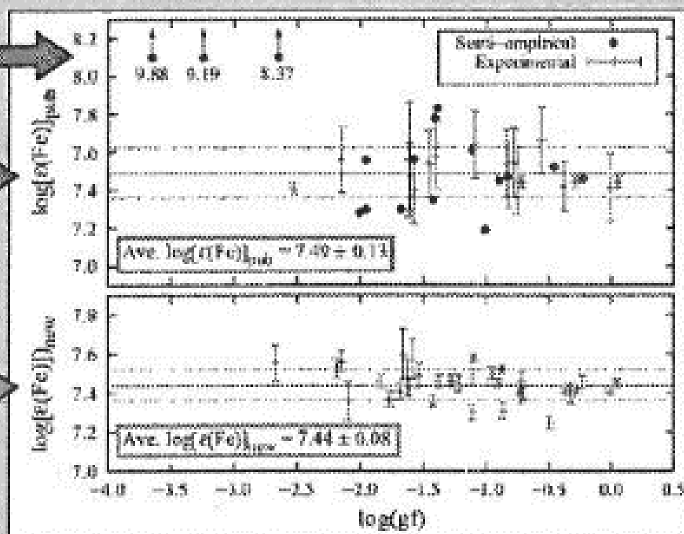
During the last years, our group has measured **new OSCILLATOR STRENGTHS** (f-values) for hundreds of transitions of **Fe I** in the laboratory [2-4]. Around 50 of them are urgently needed by GES.

To assess their impact on stellar spectral syntheses, we determined line-by-line solar Fe abundances for those that are unblended in the Sun and have good broadening parameters and continuum placement.

Older semi-empirical calculations show a large scatter. Weak lines have poor f-values.

Some older experimental data are accurate and precise, but many are accompanied by large uncertainties.

Our new lab measured log(gf)-values have smaller uncertainties and show less scatter. The mean abundance agrees well with recent values taken from the literature.



Lab data are essential

Work by
Belmonte & Pickering
IC London

www.sp.ph.ic.ac.uk/~julietp/FTS/

Apologies to them for the awful picture quality

Gaia-ESO summary

- More lab data are invaluable
- No single analysis system is robust – why?
- All analyses need calibration – why?
- Random and systematic uncertainties matter
- Robust science needs robust calibrations
- We use asteroseismic results as sanity check – with GDR2 we will include log g as a constrained input.
- Purely signal-processing approaches seem to do well. So what are we missing in detailed astrophysical studies?
- Gaia GDR2 in April 2018. GDR3 in 2020. GDR4, GDR5…