Galactic Archaeology

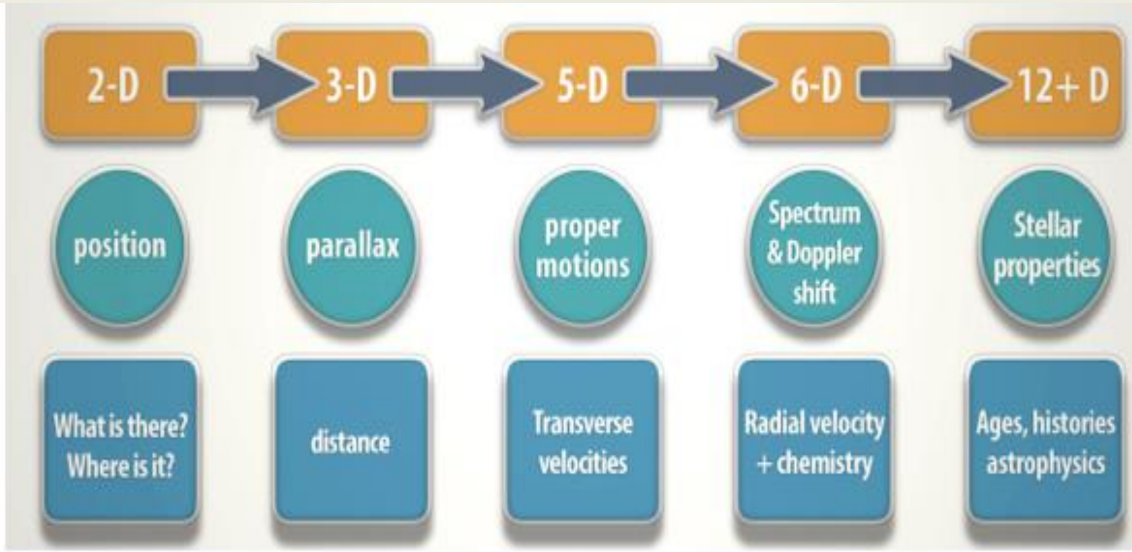
increasing the dimensionality

Challenge: detailed local group mapping to quantify a galaxy's history – and see if we can learn both dark matter and baryon physics

Gerry Gilmore

IoA Cambridge

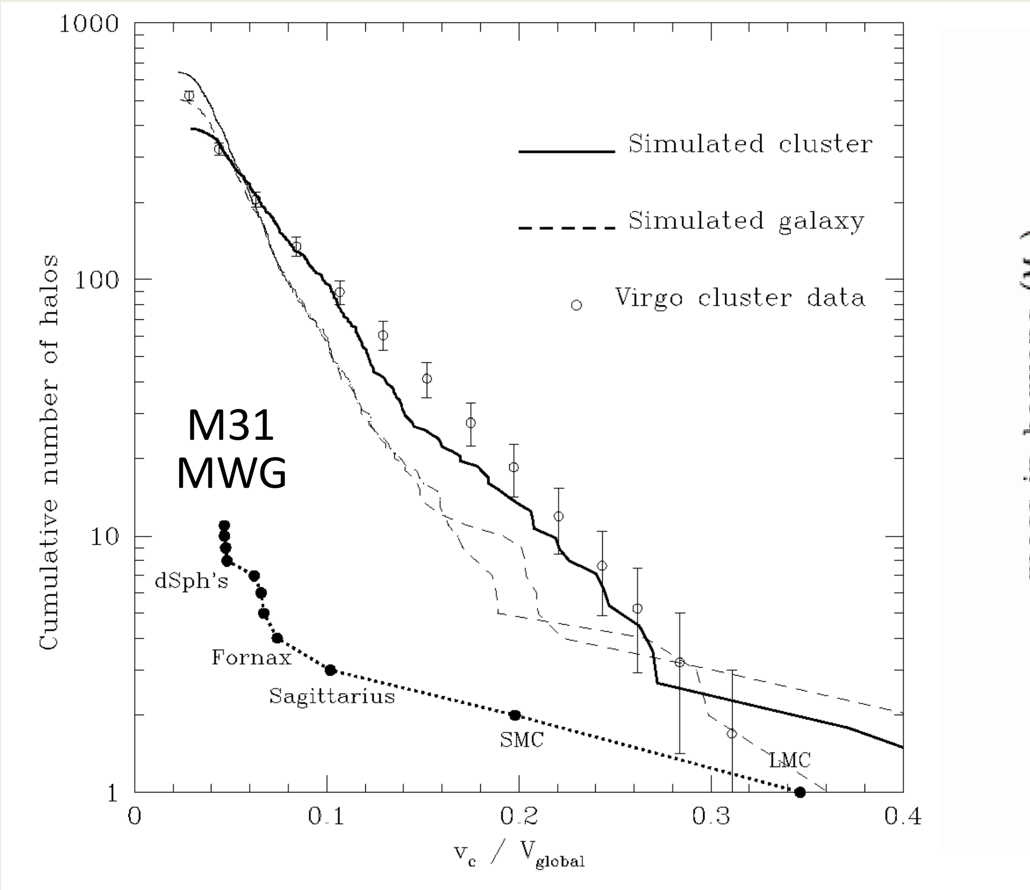
Science challenge – brief reminder
Then two examples of how we need to expand our approaches to use both the statistical and astrophysical information content

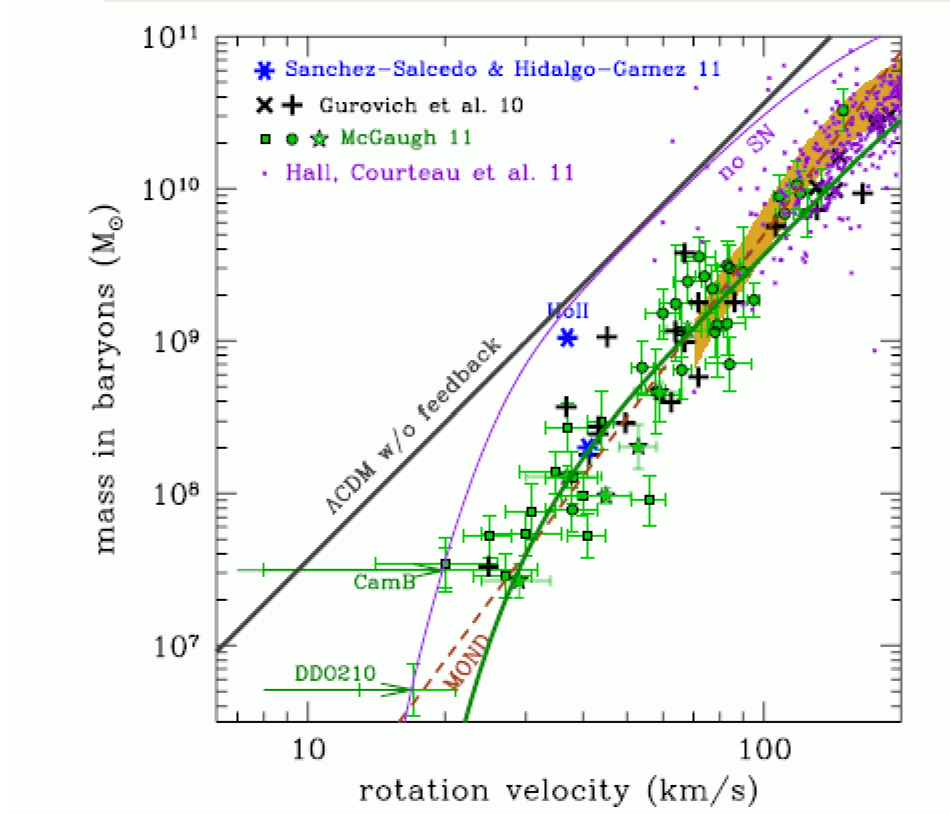


Stellar orbits, star formation history, origin of the elements, Galaxy assembly, dark matter, cosmological initial conditions, fundamental physics, solar system(s), ...

- We are/will soon be VERY data-rich. What must we do to deliver the science?
- Combining technical and astrophysical information -- what can we believe: calibration, calibration…
- How do we progress combining both stellar evolution and stellar populations, to raise the dimensionality?

Little evidence to support LCDM on sub-galaxy scales
Very soon, with both LHC and Gaia we can go beyond vanilla LCDM will become science, with DM thermodynamics. We hope!!





Suppression of star formation due to reionization and SN feedback is a semi-analytic fit to the galaxy luminosity function: it is a hypothesis and not a proof

Supernova++ feedback

something we must understand better

- to explain lack of small galaxies (Rees & Ostriker 1977);
- Why so few baryons are in stars (overcooling)
- Why the Inter-Galactic Medium is metal-rich
- To make galaxy-like galaxies (McCarthy etal MN 2012)
- SNe release a lot of energy, which must drive gas winds (Creasey etal 1211.1395)
- Details are complex (Recchi & Hensler 1301.0812)
- May perturb CDM halo inner structure (Read & GG 2005; Ruiz etal MN 2013; Teyssier etal MN 2013, Penarrubia etal ApJ 2012)
- Major uncertainty is efficiency coupling star formation to mass loss , and SFR(t)

GAIA: Key Science Objectives

$\Rightarrow$ Origin, Formation and Evolution of the Galaxy

Structure and kinematics of our Galaxy:

- shape and rotation of bulge, disk and halo
- internal motions of star forming regions, clusters, etc
- nature of spiral arms and the stellar warp
- space motions of all Galactic satellite systems

Stellar populations:

- physical characteristics of all Galactic components
- initial mass function, binaries, chemical evolution
- star formation histories

Tests of galaxy formation:

- dynamical determination of dark matter distribution
- reconstruction of merger and accretion history

Revolutionary science from solar system to cosmology

planets, cosmology, fundamental physics, NEOs, …..

LHC/core dynamics- we can hope for real progress in knowing realistic initial conditions

What’s the (Gaia) science?

- Proper motions of 20 muas/a: (V=15)
  - 20 muas/a = 10 m/s at 100 pc, i.e. planets can be found at half a million stars (Jupiter moves the sun by 15m/s) (M_V=+10)
  - 20 muas/a = 1 km/s at 10 kpc, i.e. even the lowest-velociy stellar populations can be kinematically studied throughout the entire galaxy (M_V=0)
  - 20 muas/a = 5 km/s at 50 kpc, i.e. the internal kinematics of the Magellanic clouds can be studied in as much detail as the solar neighbourhood can be now (5 km/s = 2.5 mas/a at 400 pc!) (M_V=-3.5)
  - 20 muas/a = 100 km/s at 1 Mpc, i.e. a handful of very luminous stars in M31 will show the galaxy’s rotation (M_V=-10)
- Parallaxes of 20 muas: (V=15)
  - 20 muas = 1 percent at 0.5 kpc, i.e. 6-dimensional structure of the Orion complex at 2pc depth resolution
  - 20 muas = 10 percent at 5 kpc, i.e. direct high-precision distance determination of even very small stellar groups throughout much of the Galaxy

Stellar evolution, young stars, rare objects, Galactic structure, SFR(t)

Luminosity calibrations with Hipparcos and Gaia

	Hipparcos	Hipparcos 2	Gaia
$\sigma_\pi/\pi < 0.1$ %	-	3	100 000 ★
$\sigma_\pi/\pi < 1$ %	442 ★	719 ★	~ 11 x 10^6 ★ up to 5-10 kpc (Mv<-5) up to 1-2 kpc (Mv<5)
$\sigma_\pi/\pi < 10$ %	22 396 ★	30 579 ★	~ 150 x 10^6 ★ up to 30-50 kpc (Mv<-5) up to 2-5 kpc (Mv<5)
Error on Mv	0.3 mag at 100 pc		0.1 mag at 10 kpc
Stellar pop.	mainly disk		all populations, even the rarest
HR diagram < 10 %	-4 to 13, -0.2 to 1.7		all mag and colours

Gaia will produce 60 million spectra
and astrophysical parameters for 1+ billion stars.
End of history?

The Gaia Data Release (GDR) Scenario

http://www.cosmos.esa.int/web/gaia/release

- GDR1 ~7/16: positions, G-magnitudes (all sky, single stars)
  proper motions for Hipparcos stars (~50 μarcsec/yr) – the Hundred Thousand Proper Motions (HTPM) catalogue
- GDR2 ~2/17: + radial velocities for bright stars, two band photometry and full astrometry (α, δ, ϖ, μ_α, μ_δ) where available for intermediate brightness stars
- GDR3 ~1/18: + first all sky 5 parameter astrometric results (α, δ, ϖ, μ_α, μ_δ) BP/RP data, RVS radial velocities and spectra, astrophysical parameters, orbital solutions short period binaries
- GDR4 ~1/19: + variability, solar system objects, updates on previous releases, source classifications, astrophysical parameters, variable star solutions, epoch photometry
- GDR-Final: final data release (thus in 2022/23 or 2025)

There is an interesting tension between early data release, quality control, and over-ambition

Big spectroscopic surveys

- mega-star, low-res: SDSS, LAMOST
- Multi-mega star, v-lo-res: – Gaia (1000x)
- mega-star, int-res: RAVE
- Multi-mega-star, int-res: **Gaia (100x)**
- Many-star, high-res: Gaia-ESO, Apogee, Galah
- Future capabilities (moons, weave, 4most, apogee-S)
-
- there is a planning gap: current optical spectroscopy surveys end at ESO when Gaia astrometric data start.
- Gaia first astrometric data release – 2017

- Suggestions that LSST – with only photometry – can deliver metallicities to 0.05dex…

Is Gaia-ESO the right approach?

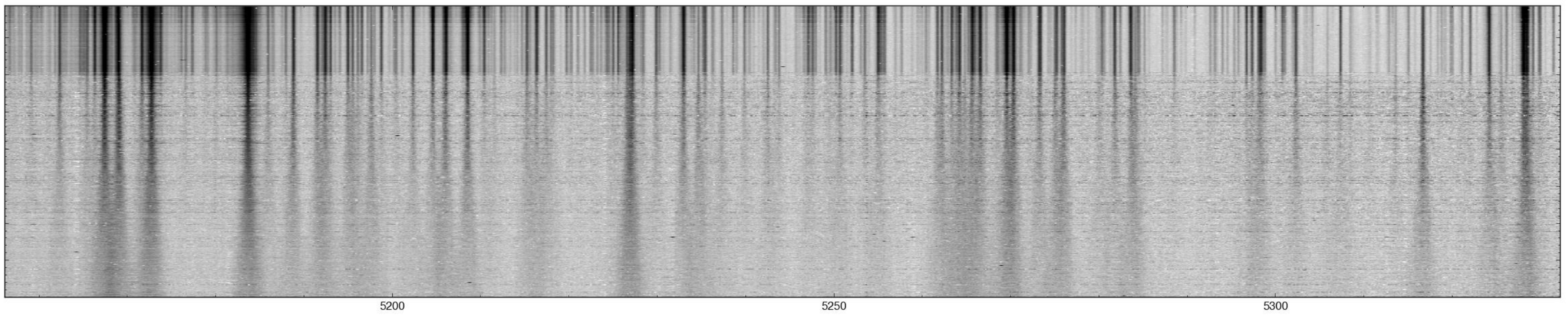
no-one else is putting in this methods effort

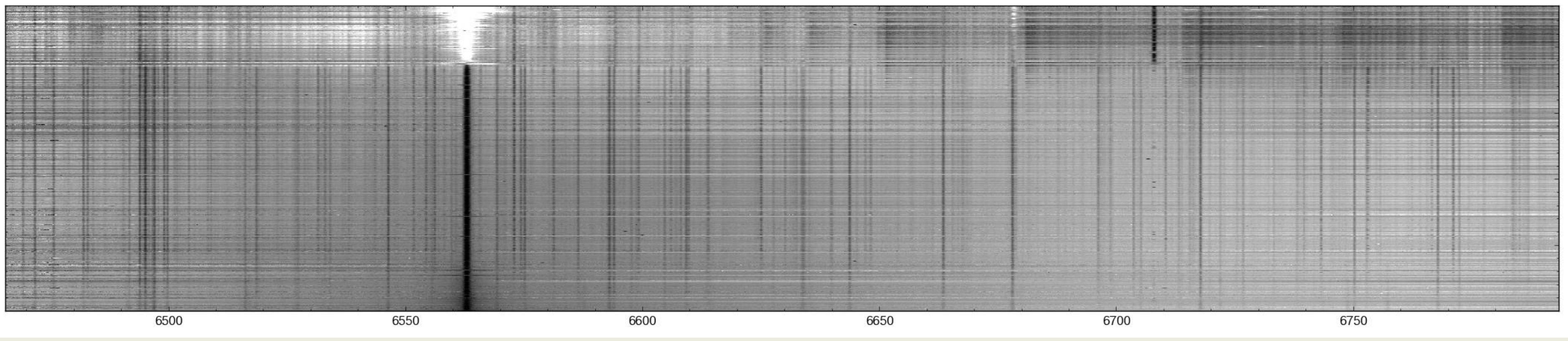
- Involve all spectroscopic analysis methods
- Identify the dominant systematic variables, and fix them – version control
- Analyse spectra through all interested groups
- In principle, this allows us to identify both systematic method errors and random errors
- ➔ parameter +/- random +/- systematic
- More methods means more information

Gaia-ESO Giraffe spectra

even with narrow target selection, a very wide range of parameters is evident

➔ there is no single analysis aproach

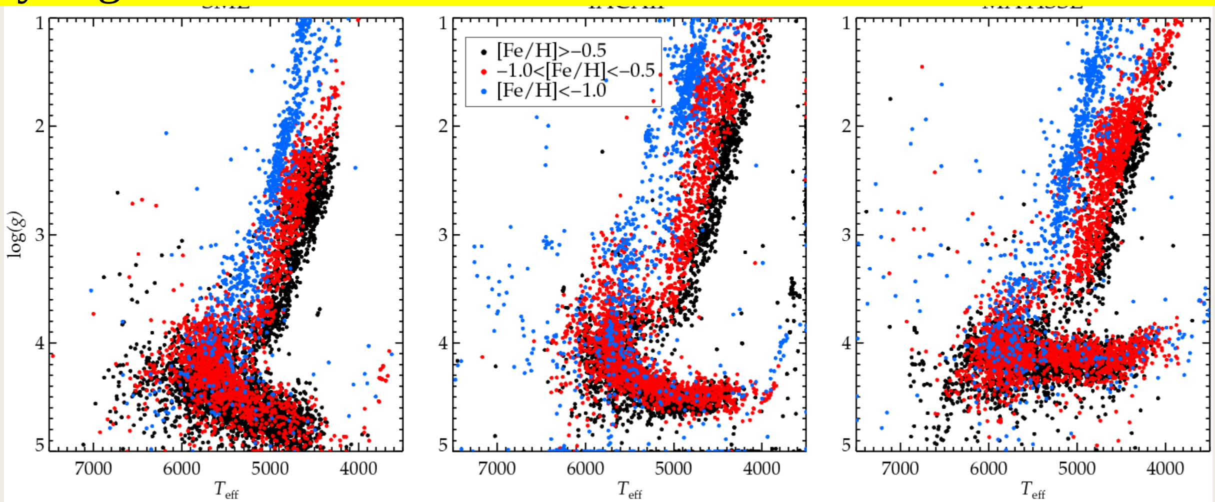




Big surveys are essential: going from data to science remains a challenge

What can we believe from the famous public proven 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.

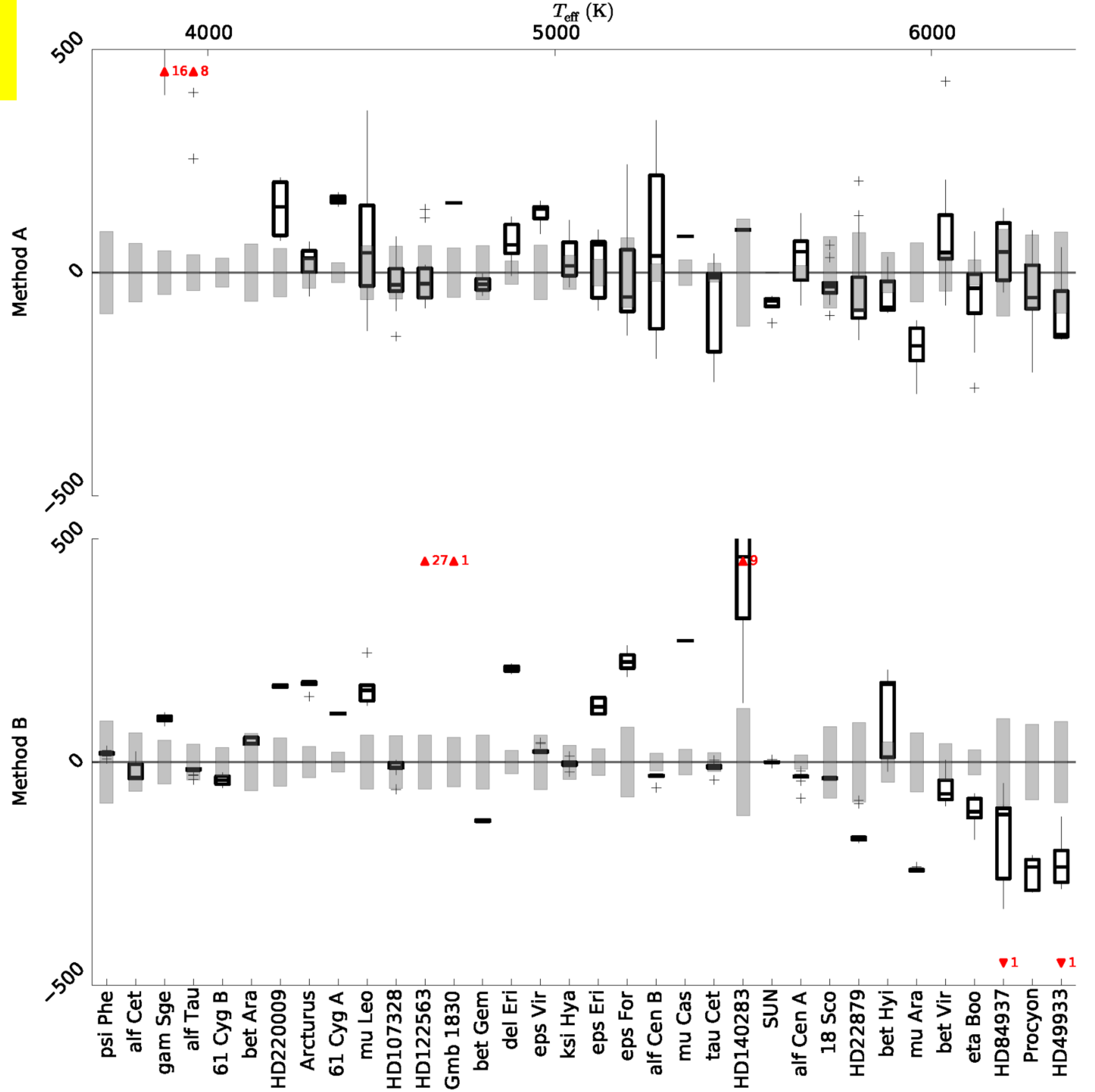


Indeed, stellar photospheres are neither one-dimensional, nor plane-parallel, nor in local thermodynamic equilibrium, assumptions that underlie the vast majority of all published stellar parameters and abundances. It turns out that these restrictive assumptions significantly distort the derived results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

Gaia-ESO node example
Teff: node vs standard

Fails at low Teff

Fails at low [Fe/H]



Calibrating surveys
Gaia-ESO vs APOGEE

In this context, claims of 0.05dex photometric metallicity may seem optimistic?

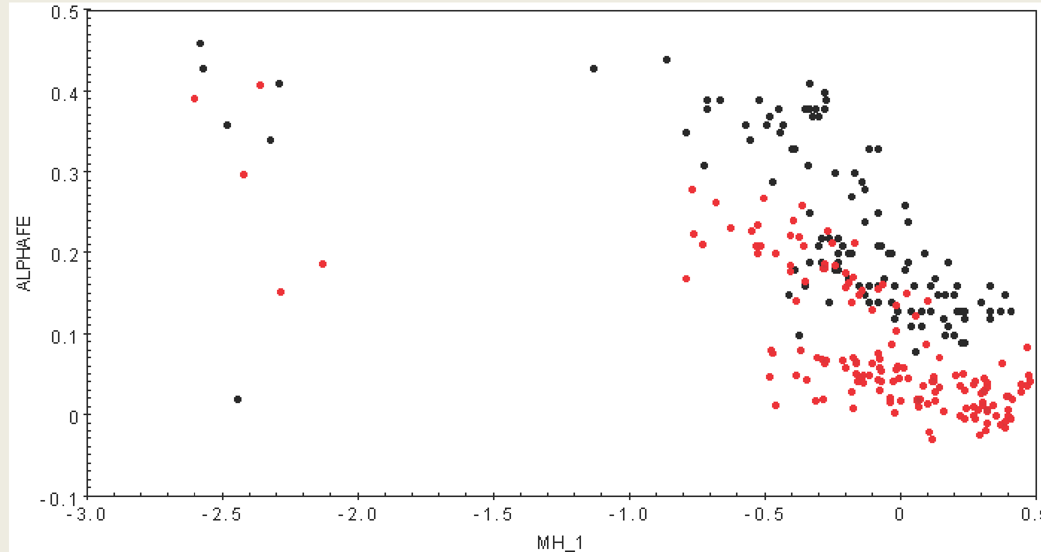
Table 3. Comparisons of stars in common with Reddy et al. (2003, 2006), Adibekyan et al. (2012), and Valenti & Fischer (2005).

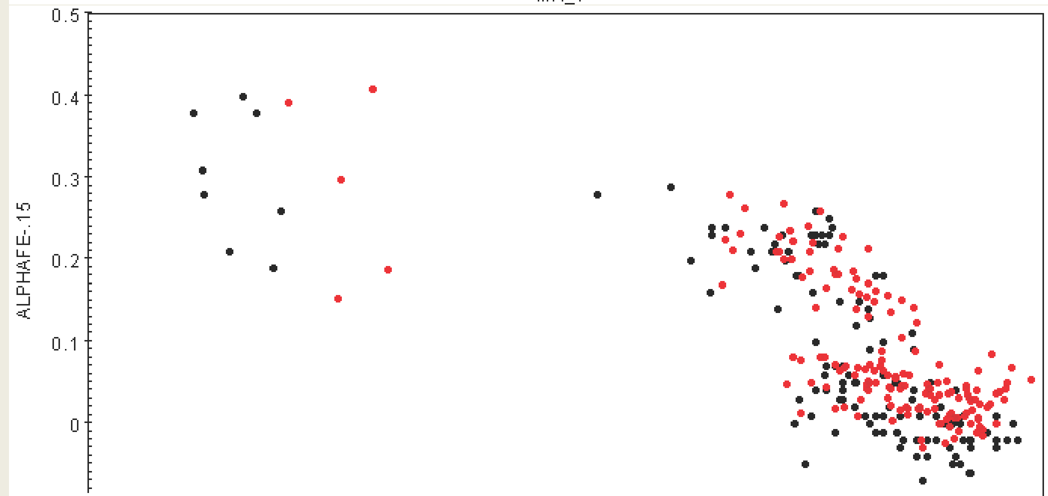
	R03/06	A12	VF05
# of stars	355	1111	1040
overlap	64	168	140
$\Delta T_{\rm eff}$	$+124 \pm 57$	-10 ± 42	-2 ± 67
$\Delta \log g$	-0.05 ± 0.10	-0.06 ± 0.10	-0.07 ± 0.12
Δ[Fe/H]	$+0.03 \pm 0.05$	-0.02 ± 0.04	-0.01 ± 0.03
Δ[O/H]	-0.09 ± 0.08		
Δ[Na/H]	0.00 ± 0.04	-0.05 ± 0.03	$+0.05 \pm 0.21$
Δ[Mg/H]	$+0.04 \pm 0.04$	$+0.01 \pm 0.03$	
Δ[Al/H]	$+0.01 \pm 0.05$	-0.01 ± 0.04	
Δ[Si/H]	$+0.01 \pm 0.03$	-0.01 ± 0.04	$+0.06 \pm 0.18$
Δ[Ca/H]	$+0.07 \pm 0.04$	-0.02 ± 0.03	
Δ[Ti/H]	$+0.10 \pm 0.06$	-0.03 ± 0.04	$+0.05 \pm 0.20$
Δ[Cr/H]	$+0.05 \pm 0.04$	-0.02 ± 0.04	
Δ[Ni/H]	$+0.03 \pm 0.04$	-0.02 ± 0.04	$+0.04 \pm 0.20$
Δ[Zn/H]	$+0.06 \pm 0.07$		
Δ[Y/H]	-0.02 ± 0.09		
Δ[Ba/H]	$+0.06 \pm 0.07$		

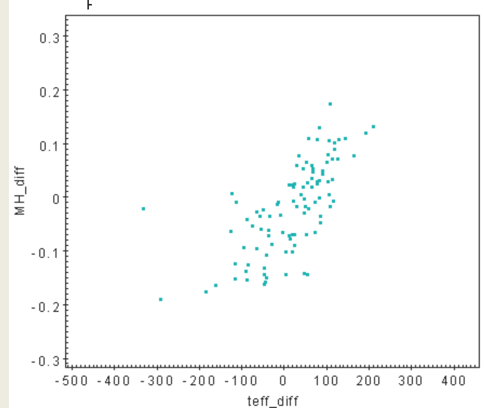
Exploring the Milky Way stellar disk★,★★,★★★

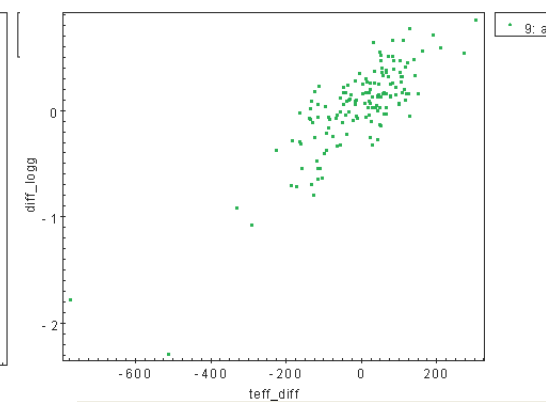
A detailed elemental abundance study of 714 F and G dwarf stars in the solar neighbourhood

T. Bensby[1], S. Feltzing[1], and M. S. Oey[2]



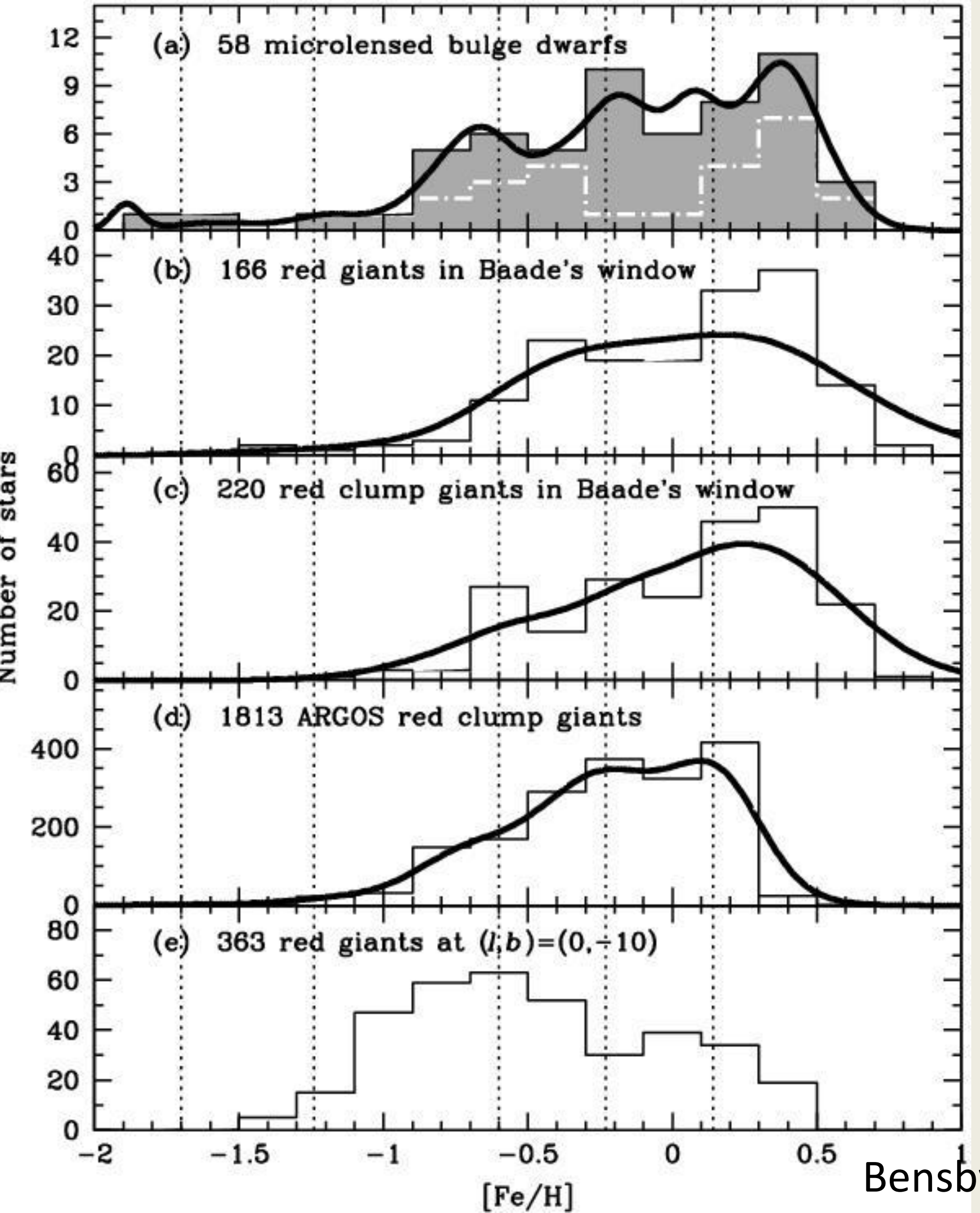


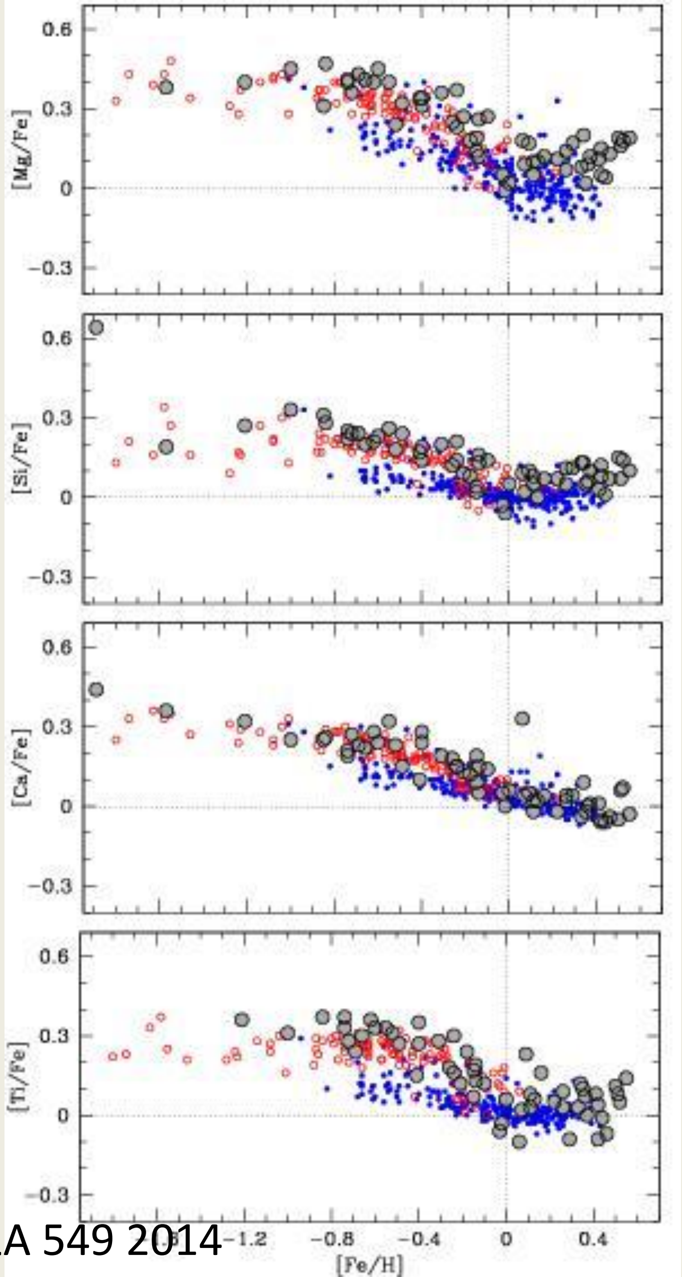




Calibration issues dominate astrophysical conclusions

Where do the local super-metal rich stars come from?



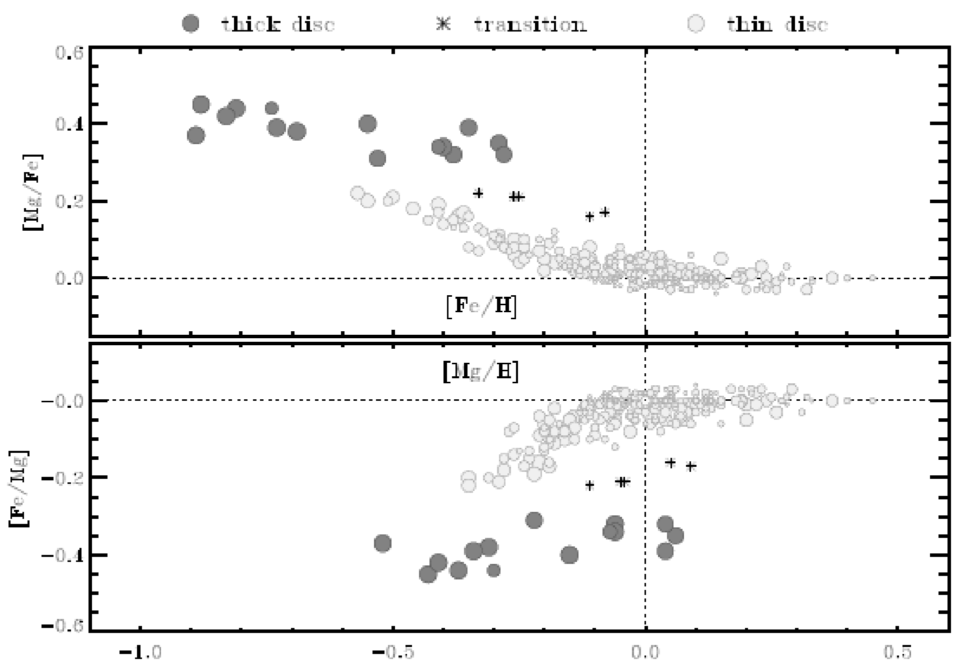


Bensby etal A&A 549 2014

calibration can be solved

- Lets move on to large-survey statistical analyses, and how to include minimal priors from stellar evolution and previous small, high-quality, biased samples when analysing large data sets

Is there a thin-thick difference in alpha/Fe DF?
Furhmann was there first – careful, single method approach



Fuhrmann MNRAS 414 2893 (2011)

THE ASTROPHYSICAL JOURNAL, 738:187 (17pp), 2011 September 10

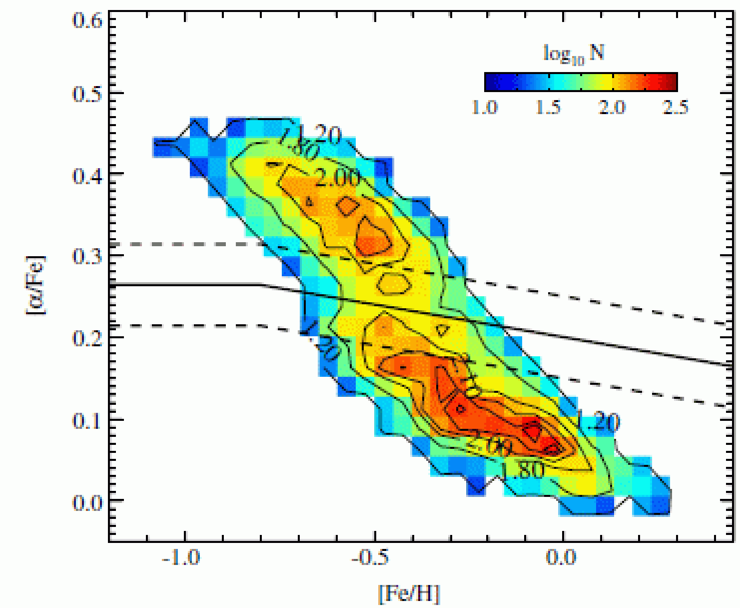


Figure 2. Distribution of logarithmic number densities, in the [α/Fe] vs. [Fe/H] plane, overplotted with equidensity contours. Each bin is 0.025 dex in [α/Fe] by 0.05 dex in [Fe/H] and is occupied by a minimum of 20 stars. The median occupancy is 70 stars. The solid line is the fiducial for division into likely thin- and thick-disk populations; the dashed lines located ±0.05 dex in [α/Fe] on either side of the solid line indicate the adopted dividing points for the high-[α/Fe] (upper-dashed) and low-[α/Fe] (lower-dashed) stars in our sample.

Recent fuss from SDSS about (lack of) complexity in disk chemistry-kinematics
Disagreed with available high-resolution studies: issue was biases, priors

The alpha-element break in the thick disk is a clear diagnostic, and clearly distinguishes thick and thin disks

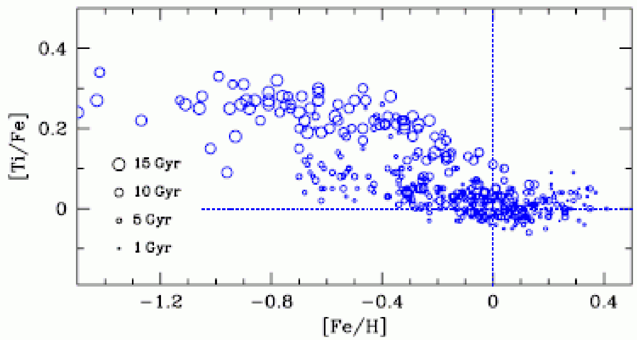


Fig. 22. [Ti/Fe] versus [Fe/H] for stars that have low age uncertainties (the differences between upper and lower age estimates are less than 4 Gyr). The sizes of the circles are scaled with the ages of the stars as indicated in the figure.

and 156 stars have [M/H] < −0.7. Our sample originally

Bensby, Feltzing & Oey 2014
A&A 562 A71

[Fe/H] < −0.7 after the spectroscopic analysis. Therefore, we believe that [Fe/H] ≈ −0.7 could be interpreted as a lower metallicity limit for the Galactic thin disk.

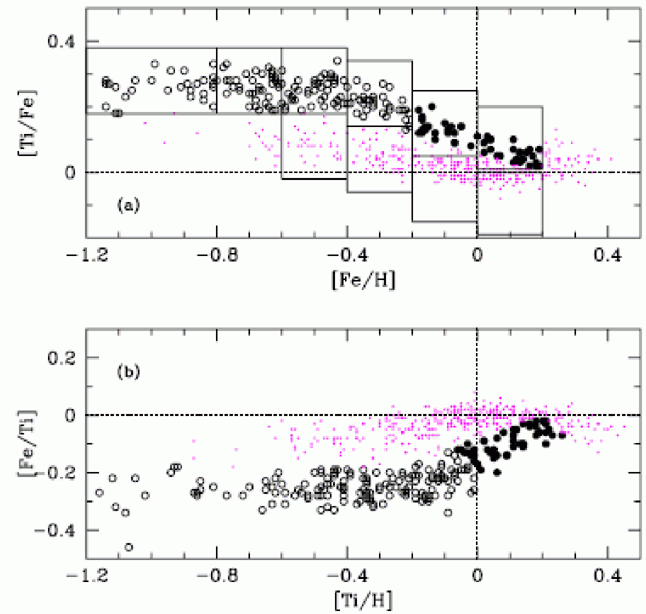
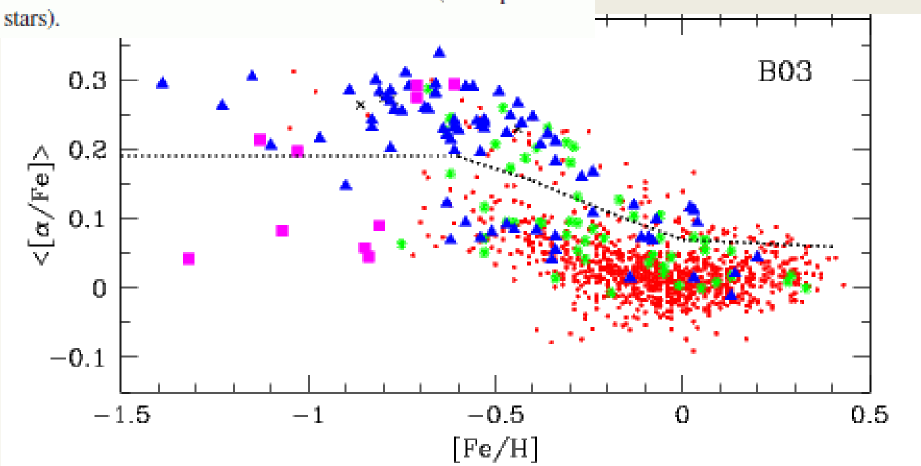
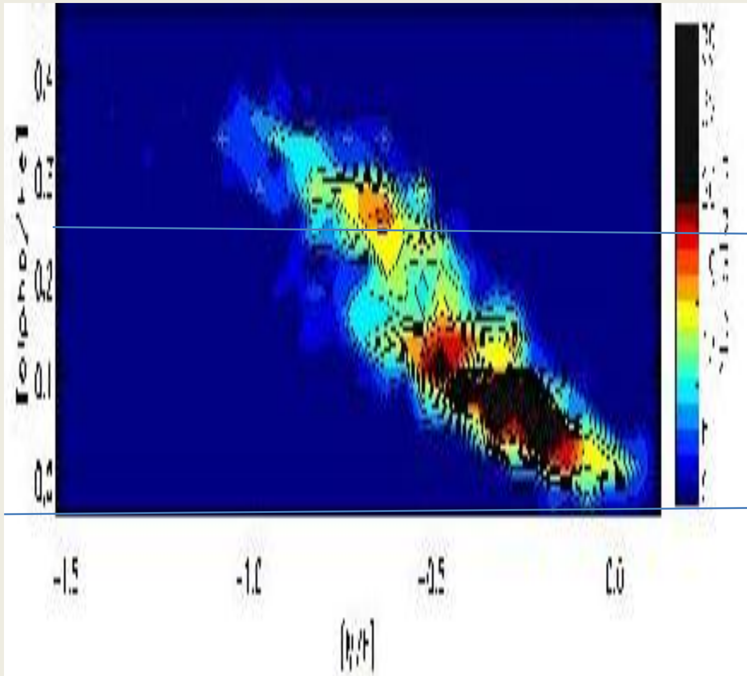


Fig. 23. Solid black circles mark stars that are α-enhanced and metal-rich (HAMR stars); the empty black circles mark stars that are α-enhanced at lower [Fe/H] (a.k.a. potential thick disk); and the small blue circles mark stars with low or moderate α-enhancement (a.k.a. potential thin disk stars).

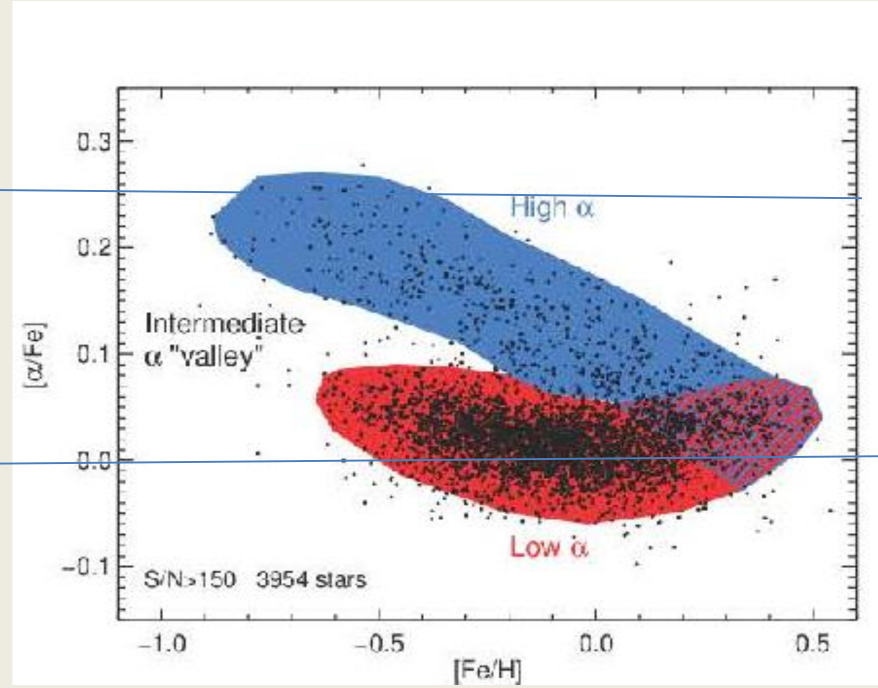


Adibekyan etal A&A 545 A32 2012

Note the different alpha calibrations..



Gaia-ESO



Peace and light prevail

point of the two α sequences is at a significantly higher metallicity than the peak of the low-α MDF, by ~0.2–0.3 dex. This offset makes it difficult (perhaps impossible) to explain the high-α and low-α stars as the outcome of a single chemical enrichment history, indicating the presence of at least two distinct populations. While this discrepancy has been seen before in the solar neighborhood (e.g., Bensby et al. 2011a; Adibekyan et al. 2013) the APOGEE RC sample presents the best-populated, most-accurate distributions yet and the first time this has been plainly seen in the outer Galaxy.

TRACING CHEMICAL EVOLUTION OVER TI
THE MILKY WAY'S DISK WITH APOGEE REI

David L. Nidever[1], Jo Bovy[2,3], Jonathan C. Bird[4], Brett H. Andrew
teven R. Majewski[7], Verne Smith[8], Annie C. Robin[9], Ana E. García P
Prieto[12,13], Gail Zasowski[14], Ricardo P. Schiavon[15], Jennifer A. Jo
Feuillet[6], Donald P. Schneider[16,17], Matthew Shetrone[18], Jennifer So
Zamora[12,13], Hans-Walter Rix[19], Timothy C. Beers[20,21], John C. Wi
Minchev[22], Cristina Chiappini[22,23], Friedrich Anders[22], Dmitry Bizya
Ebelke[24], Peter M. Frinchaboy[25], Jian Ge[26], Karen Kinemuchi[24],
Malanushenko[24], Moses Marchante[24], Szabolcs Mészáros[27,28], Daniel Oravetz[24], Kaike Pan[24], Audrey
Simmons[24], Michael F. Skrutskie[7]

Turning selection bias to advantage

We explored a new method to measure the global structure of the thick disc of the Milky Way from a Solar-neighbour sample of thick-disc stars. By applying this method to a chemically-selected local sample of 127 stars, we found that the vertical velocity dispersion as a function of Galactocentric radius R declines approximately as $\sigma_z \propto \exp(-R/R_s)$ at 4.5 kpc $\lesssim R \lesssim$ 10 kpc, where the scale length R_s is around 8-9 kpc. We also found that the thickness H of the thick disc increases with increasing R, from 0.5 ± 0.1 kpc at $R = 4.5$ kpc to 0.8 ± 0.1 kpc at $R = 10$ kpc, when realistic potential models were adopted. The flaring thick disc that we have found favours scenarios that the thick disc of the Milky Way formed through external heating due to minor mergers or through radial migration due to non-axisymmetric structure, and disfavours the scenario that the Galactic thick disc formed from a clumpy disc.

5.2 Reconstructed vertical velocity dispersion

Figure 4 shows the reconstructed profile of $\sigma_{z,\odot}$ for the three potential models. Here we use an approximation of

$$\sigma^2_{z,\odot}(R_\mathrm{m}, 0) \simeq \frac{\sum_i s_i w_i \int_{R_\mathrm{m}-\Delta R}^{R_\mathrm{m}+\Delta R} dR\, 2\pi R \int d^3v\, v_z^2 f_i^\mathrm{single}}{\sum_i s_i w_i \int_{R_\mathrm{m}-\Delta R}^{R_\mathrm{m}+\Delta R} dR\, 2\pi R \int d^3v\, f_i^\mathrm{single}} \quad (24)$$

for the Stäckel potential, and another approximation of

$$\sigma^2_{z,\odot}(R_\mathrm{m}, 0) \simeq \frac{\sum_i s_i w_i \int_{-\Delta z}^{\Delta z} dz \int_{R_\mathrm{m}-\Delta R}^{R_\mathrm{m}+\Delta R} dR\, 2\pi R \int d^3v\, v_z^2 f_i^\mathrm{single}}{\sum_i s_i w_i \int_{-\Delta z}^{\Delta z} dz \int_{R_\mathrm{m}-\Delta R}^{R_\mathrm{m}+\Delta R} dR\, 2\pi R \int d^3v\, f_i^\mathrm{single}} \quad (25)$$

Thick disk flare in outer Galaxy:
Hattori & GG in prep

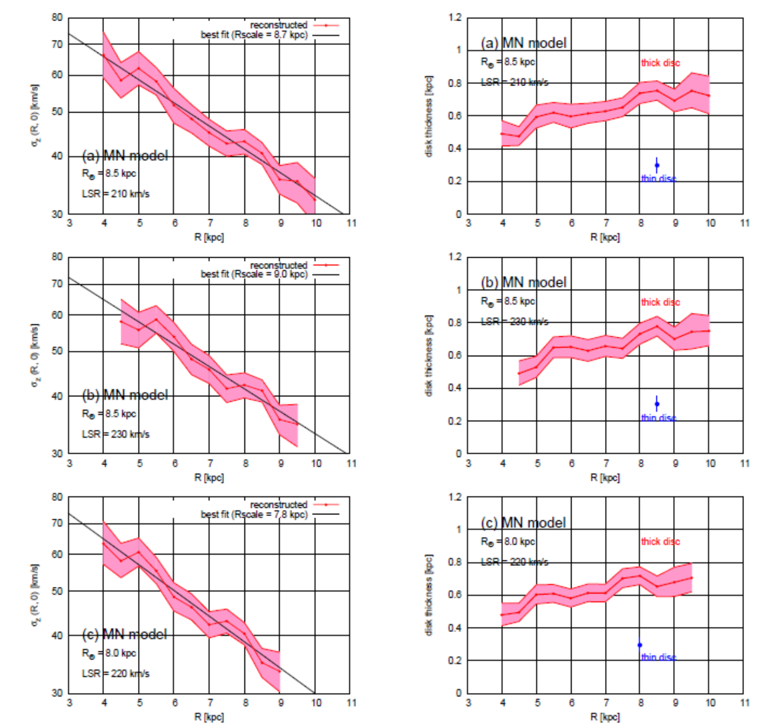
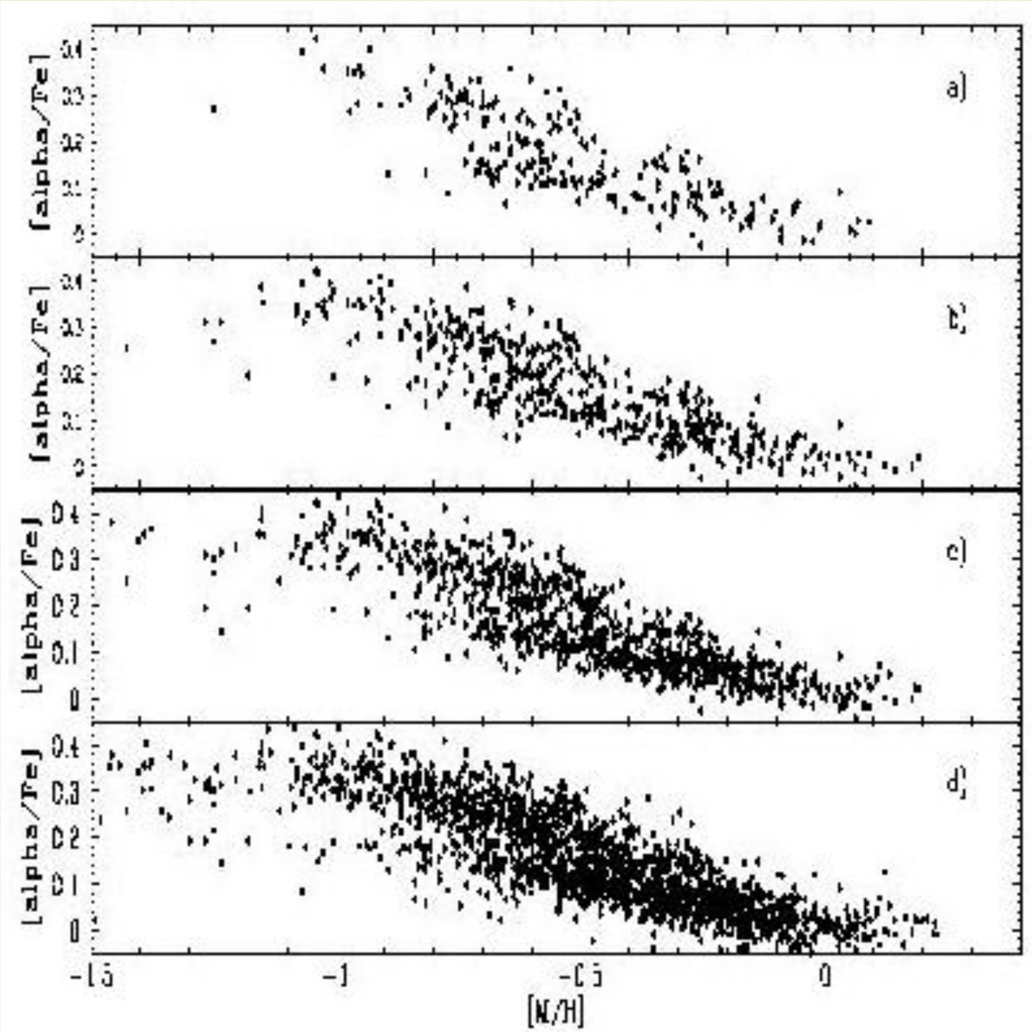


Figure 11. The reconstructed vertical velocity dispersion profile of the thick disc as a function of R for MN models with different pairs of $(R_\odot, v_\mathrm{LSR})$. Panels (a)-(c) show the results for models (a)-(c) in Table 2.

Figure 12. The kinematically-estimated thickness of the thick disc as a function of R for MN models with different pairs of $(R_\odot, v_\mathrm{LSR})$. Panels (a)-(c) show the results for models (a)-(c) in Table 2.

The Gaia-ESO Survey: the Galactic Thick to Thin Disc transition*

A. Recio-Blanco[1], P. de Laverny[1], G. Kordopatis[2], A. Helmi[3], V. Hill[1], G. Gilmore[2], R. Wyse[4], S. Randich[5],



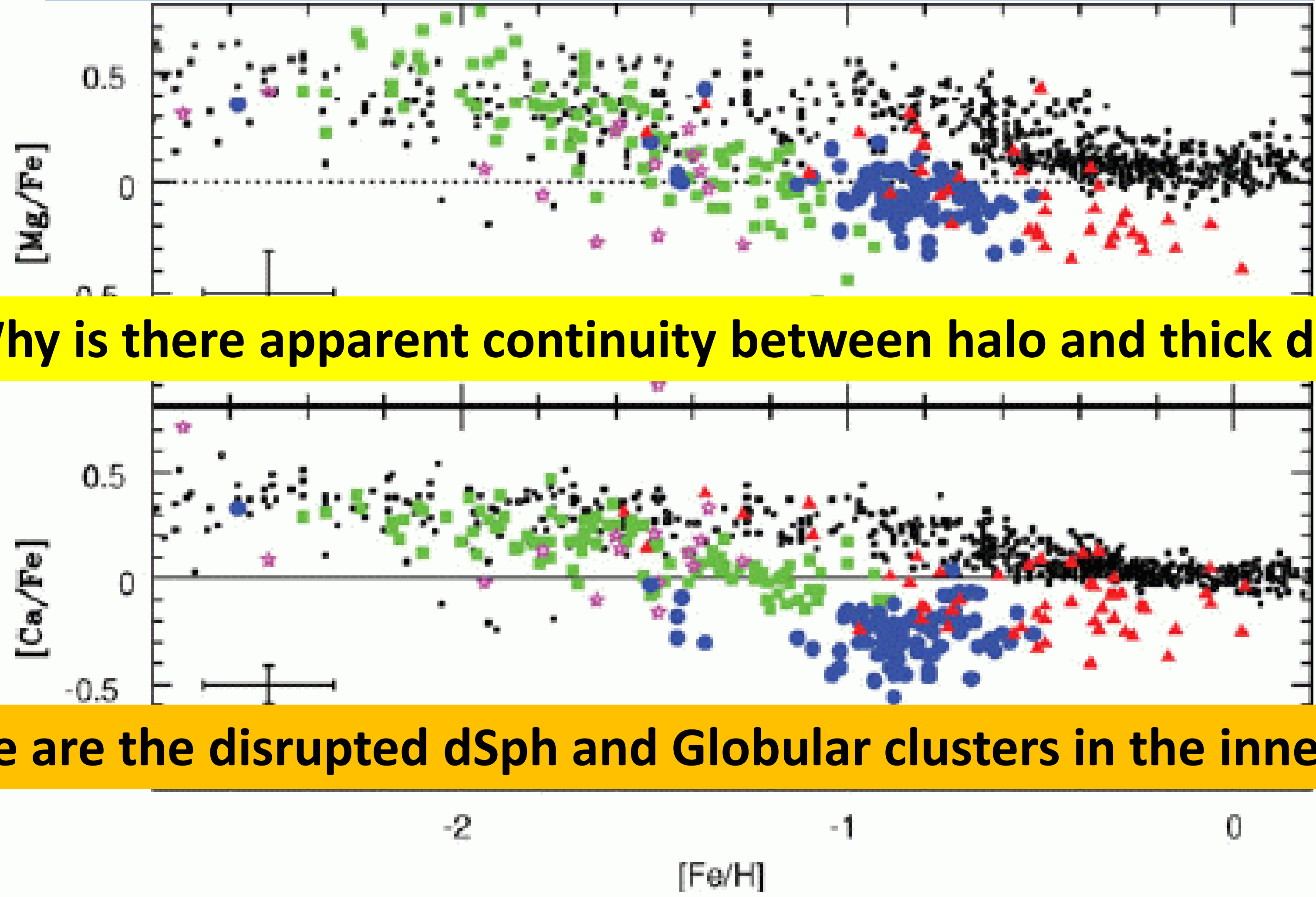
Time to move on?

Note the halo-thick disk apparent continuity is still apparent. WHY?

The Gaia-ESO Survey: the chemical structure of the Galactic discs from the first internal data release *

Š. Mikolaitis[1,2], V. Hill[1], A. Recio–Blanco[1], P. de Laverny[1] C. Allende Prieto[9], G. Kordopatis[3], G. Tautvaišiene[2] D. Romano[10], G. Gilmore[3], S. Randich[4], S. Feltzing[5], G. Micela[6], A. Vallenari[7], E. J. Alfaro[8], T. Bensby[5], A. Bragaglia[10], E. Flaccomio[6], A. C. Lanzafame[11], E. Pancino[10,12], R. Smiljanic[13,14], M. Bergemann[3], G. Carraro[15], M. T. Costado[8], F. Damiani[6], A. Hourihane[3], P. Jofré[3], C. Lardo[10], L. Magrini[4], E. Maiorca[4], L. Morbidelli[4], L. Sbordone[16], S. G. Sousa[17,18], C. C. Worley[3], and S. Zaggia[7]

Element ratios in MWG field stars (black) and dSph stars (colours)

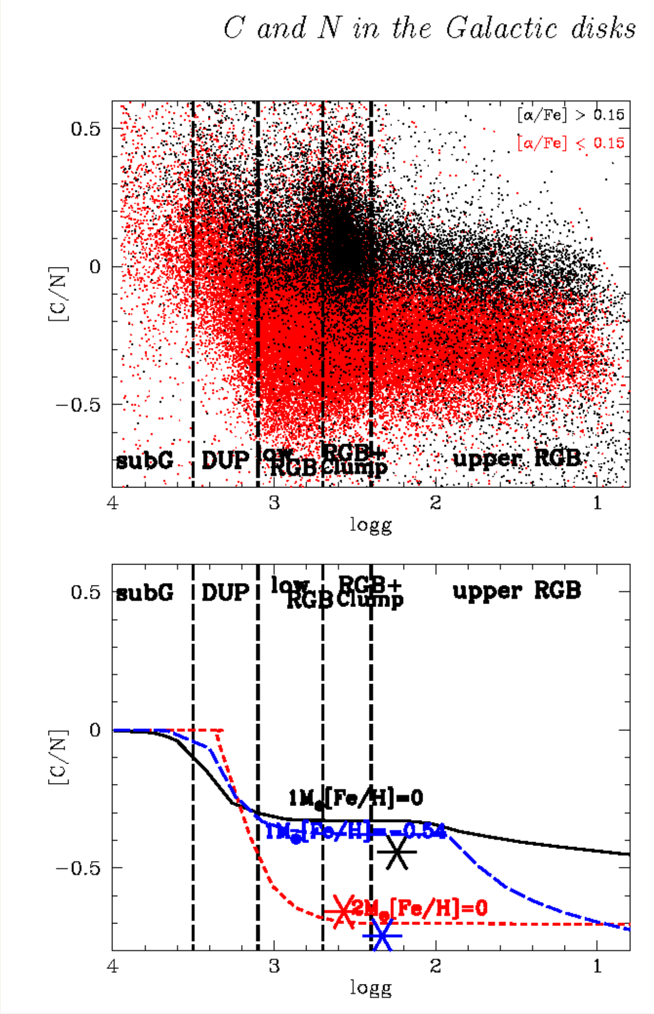


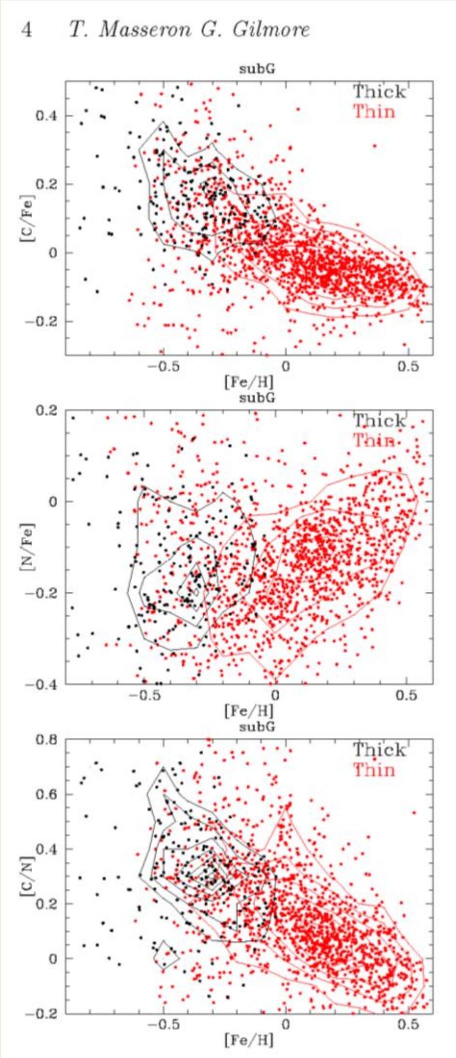
Why is there apparent continuity between halo and thick disk?

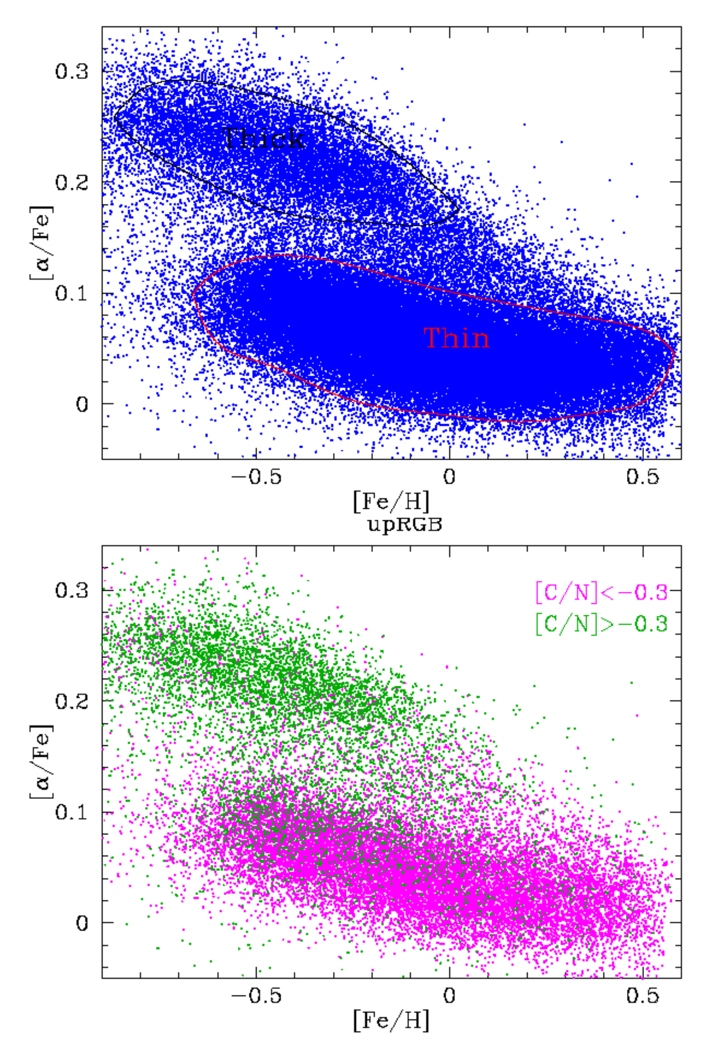
Where are the disrupted dSph and Globular clusters in the inner halo?

including thick disk (red) and thin disk (blue) stars: Chemically the local halo is much more similar to the thick disk (progenitor?) than anything else, but has very different orbital angular momentum.
Sgr and its clusters are shown from Sbordone etal A+A 465 815 2007

More information, more discrimination
stars with higher alpha are older at same [Fe/H]







Thomas Masseron & GG submitted

APOGEE data

Stellar evolution provides ages

is the oldest thin disk the same age as the thick disk?

8 *T. Masseron G. Gilmore*

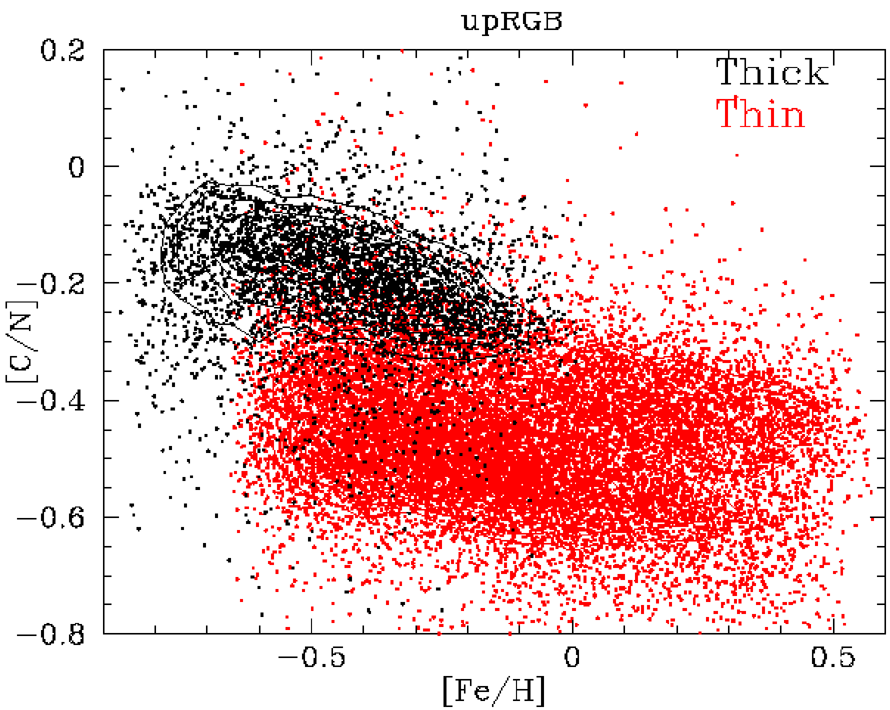
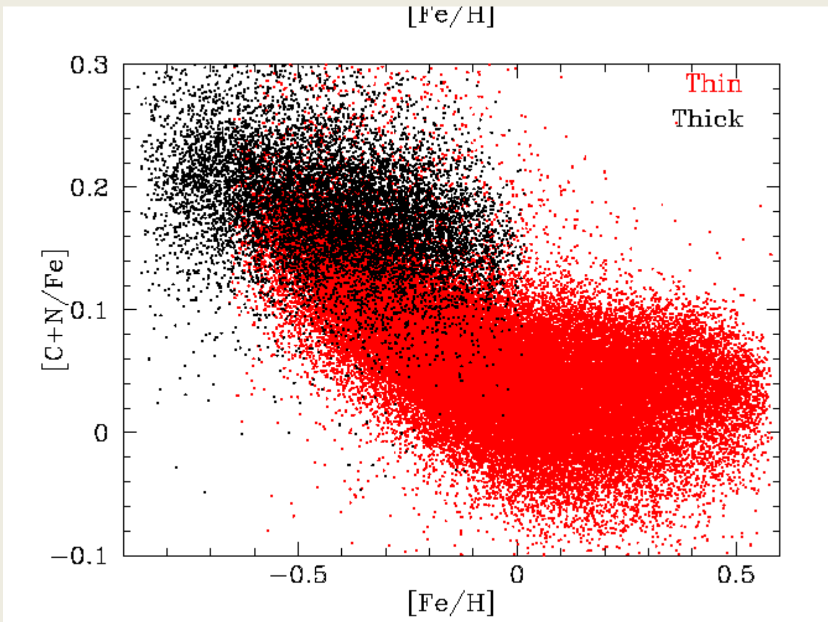


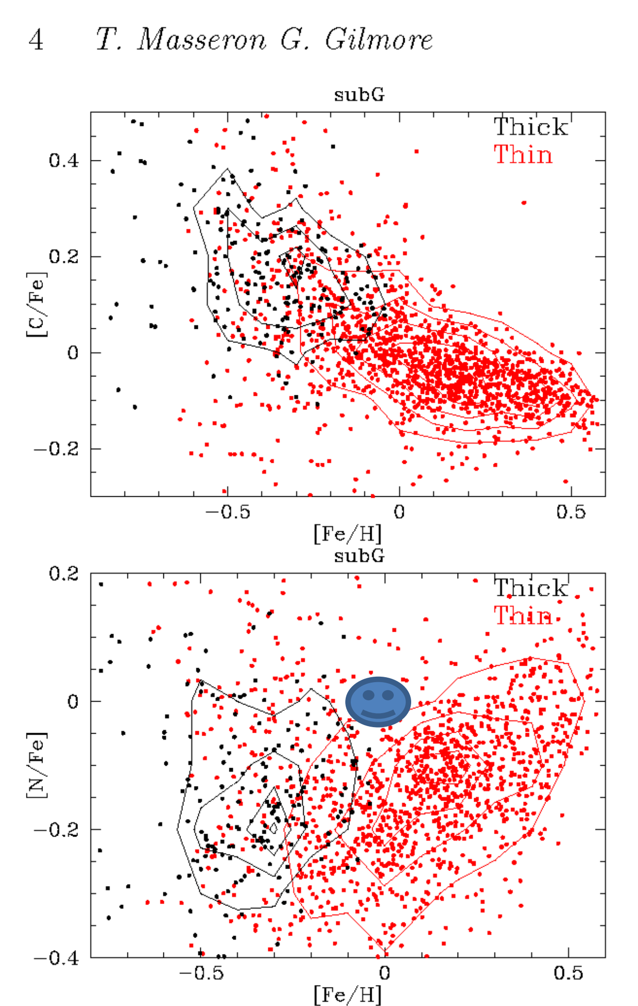
Figure 8. C/N ratio as a function of metallicity for upper RGB stars, with thick and thin disk stars classified from Fig. 3 and with N abundances corrected by +0.2. While thin disk stars show a low and almost flat level of [C/N], the thick disk stars have a high [C/N] ratio. Recall that we have applied a zero-point offset to the [C/N] values.

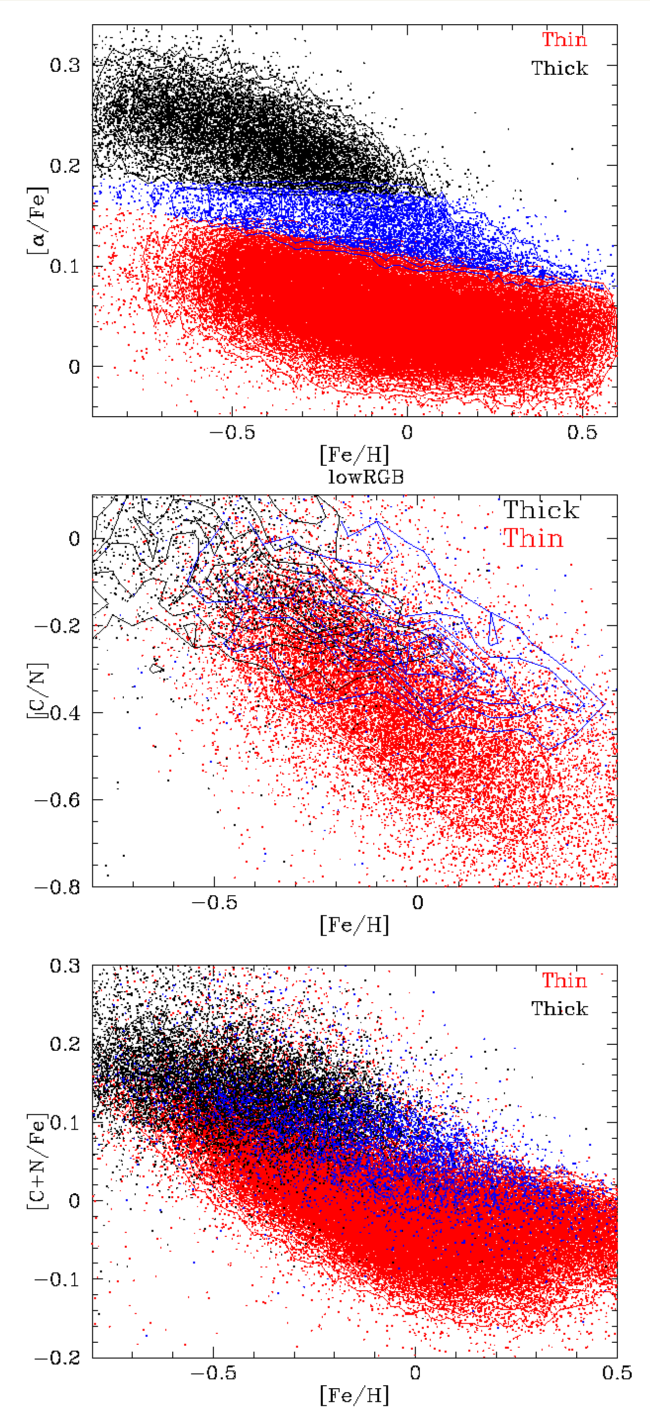


How discrete is discrete?

Full interpretation in terms of stellar age distributions, SFR… testing dredge-up

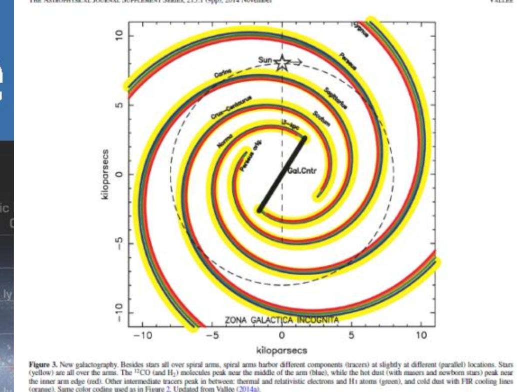
Needs robust calibrations

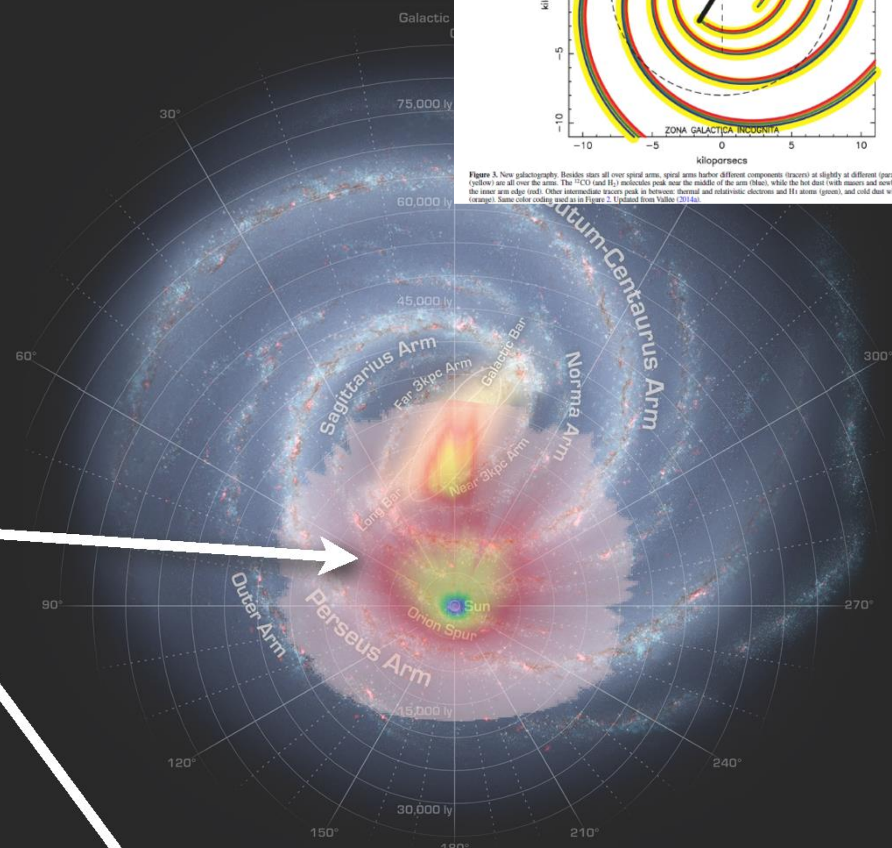




Scientific performance

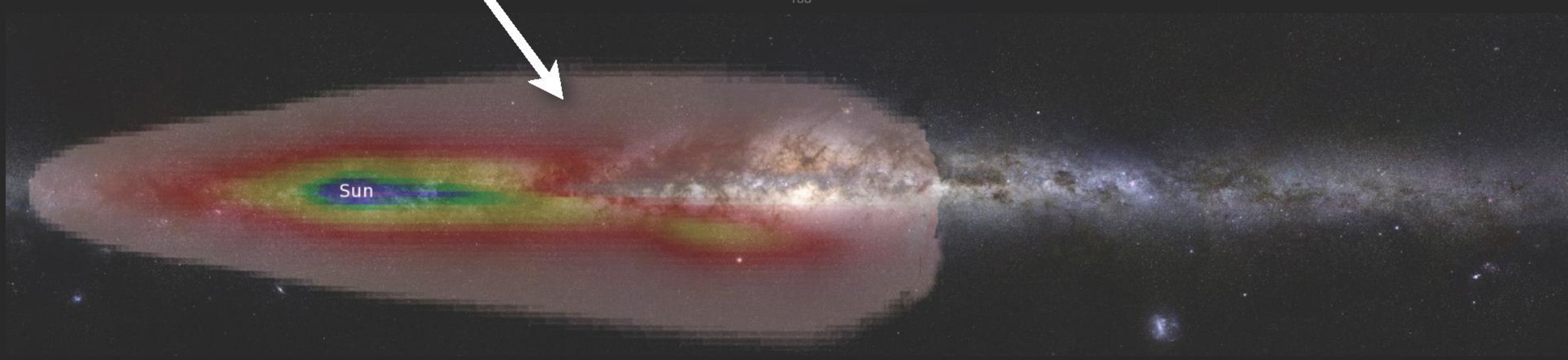
Vallee 2014
ApJS Nov





Gaia observed ~ **10⁹** stars in and around our Galaxy (~1%) up to ~150 kpc

As well as:
asteroids,
quasars,
supernovae,
etc.

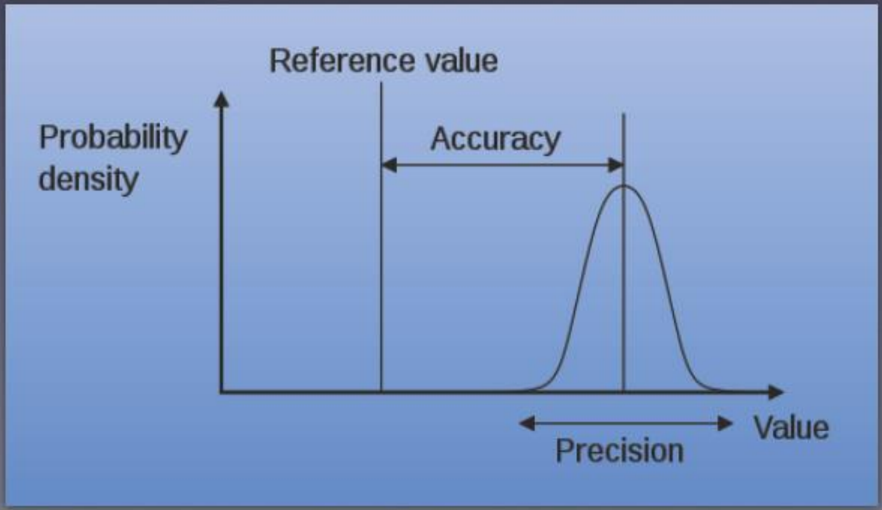


Two main lessons learned

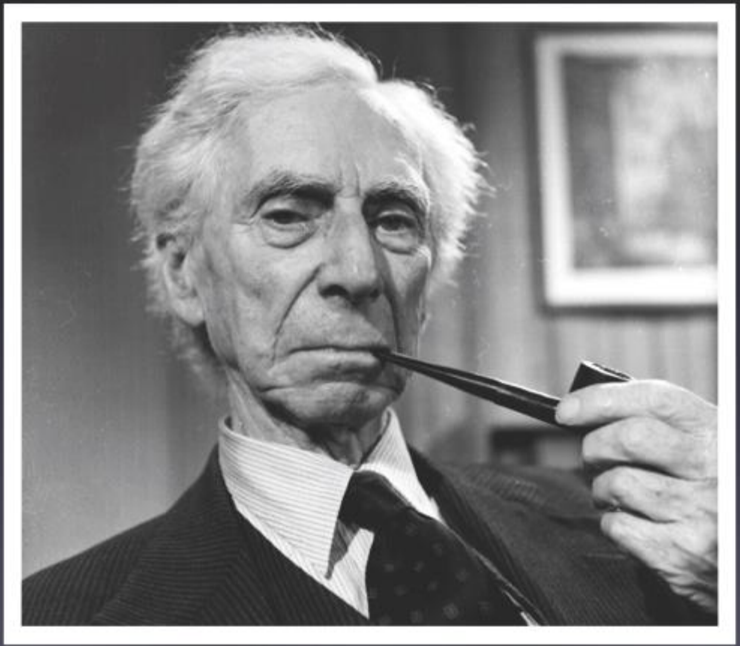
- One method definitely isn't enough because of unknown systematics.
- Methods with no strong observational/ theoretical basis for accuracy should not be used.

We need:

Precision
Accuracy

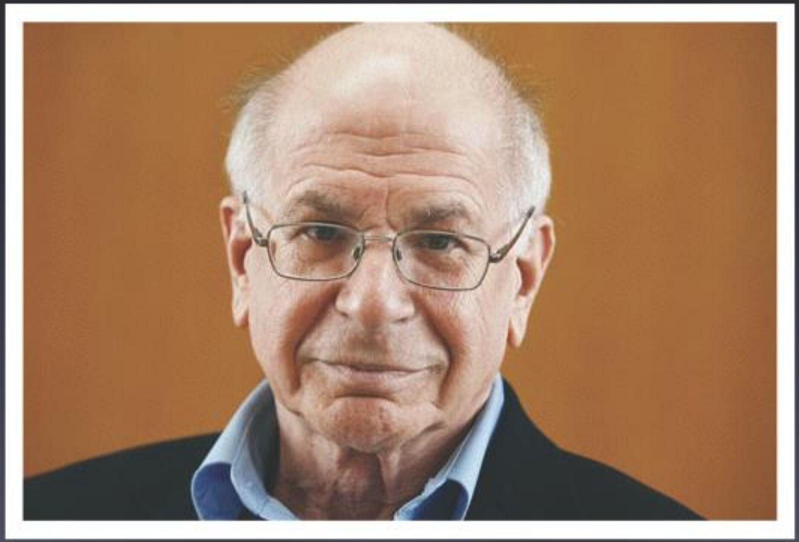


Good advice from Bertrand Russell



Hinge beliefs "upon observations and inferences as impersonal, and as much divested of local and temperamental bias, as is possible for human beings."

However since the orbitofrontal cortex always integrates emotions into the stream of rational thought, I hope we can rely on Nobel laureate Daniel Kahneman:



"I am not very optimistic about people's ability to change the way they think, but I am fairly optimistic about their ability to detect the mistakes of others."

Thanks to Mario Livio for the last 3 slides

summary

- Gaia is working. First science alerts are appearing now. Data will be good. And lots of it! And not faraway! LHC is gearing up!!
- Gaia-ESO, APOGEE, GALAH, LAMOST… are working. First science is good.
- The sociology in galactic astronomy is changing, towards large consortia.
- With Gaia + spectroscopic surveys the basic questions we ask today are evolving into more detailed issues – more sophisticated analyses needed
- Hopefully, this is progress towards "truth"

what do we do in Europe between Gaia-ESO and MOONS/WEAVE/4MOST to retain the community strength we have created, and get value from Gaia?