Detailed near-IR stellar abundances of red giants in the Bulge

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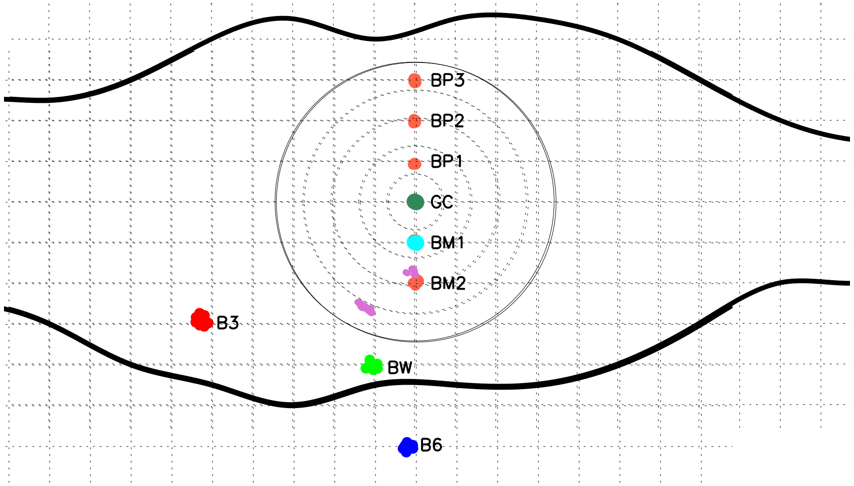
Outline

1. Project observations: high-resolution spectroscopy of K and M giants in the inner bulge

2. Abundance trends and
   Fe gradients in the inner bulge
   (b < 500pc)



3. Galactic Centre trends:
   observations and modelling

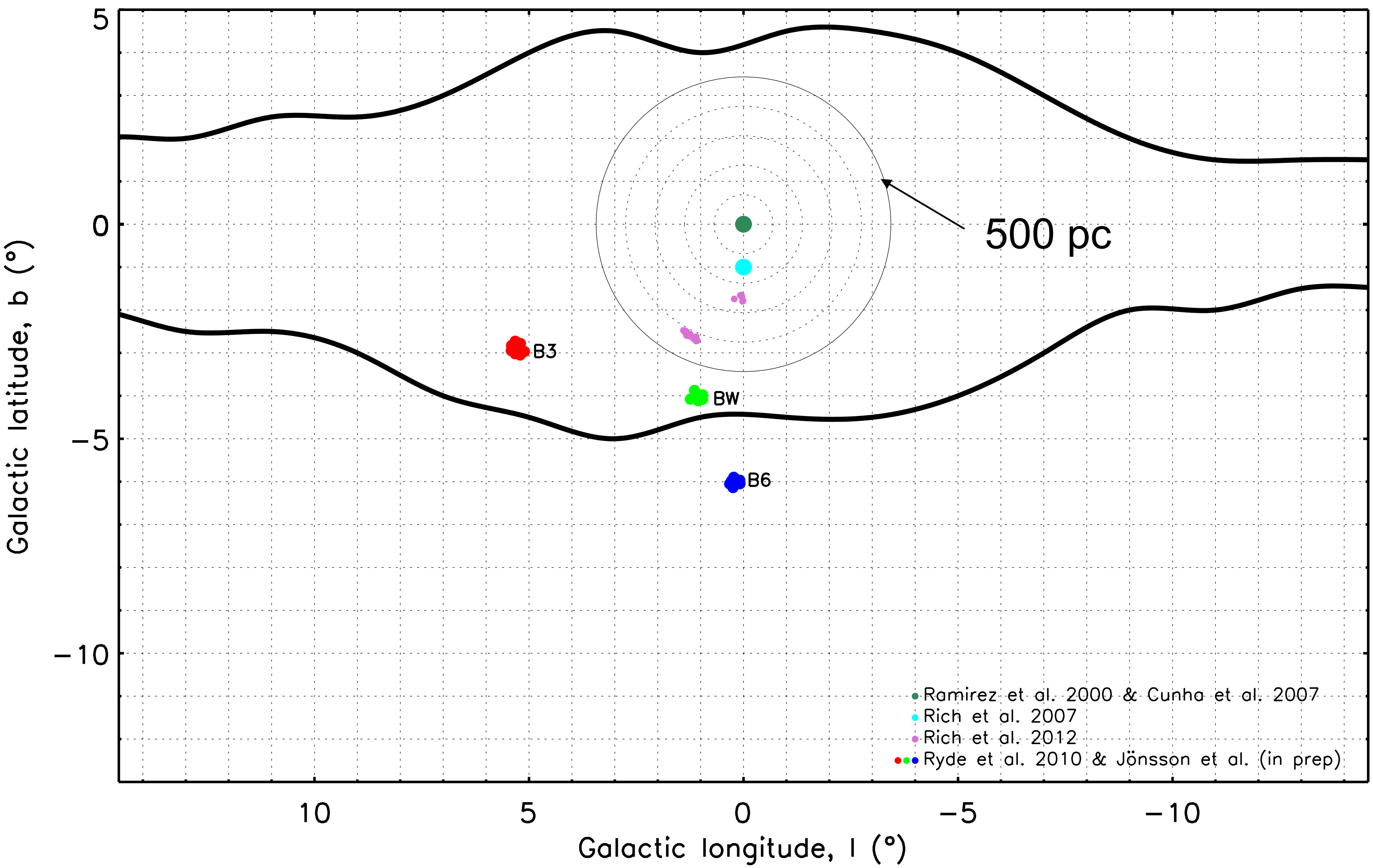
4. The role of massive stars in the Bulge

5. Conclusions

1. Project - NIR spectra of inner Bulge giants

- Goal to probe the very inner bulge, looking for a [Fe/H] gradient as homogeneously as possible
- Overcoming extinction by infrared light
- H and K bands, high-res spectra observed with VLT/CRIRES. Also VLT/ISAAC, NTT/SOFI, and if possible VLT/UVES
- K and M giants ($0.5 < \log g < 2.5$)
- Determine metallicities [Fe/H], CNO, F, and the alpha elements Mg, Si, S, Ca, and Ti
- 3 `outer Bulge’ fields ($3 < b < 6$ degrees) with ~50 stars
- 6 `inner Bulge’ fields $|b| < 3$ degrees ~ 50 stars

The Bulge - IR observations of Red giants



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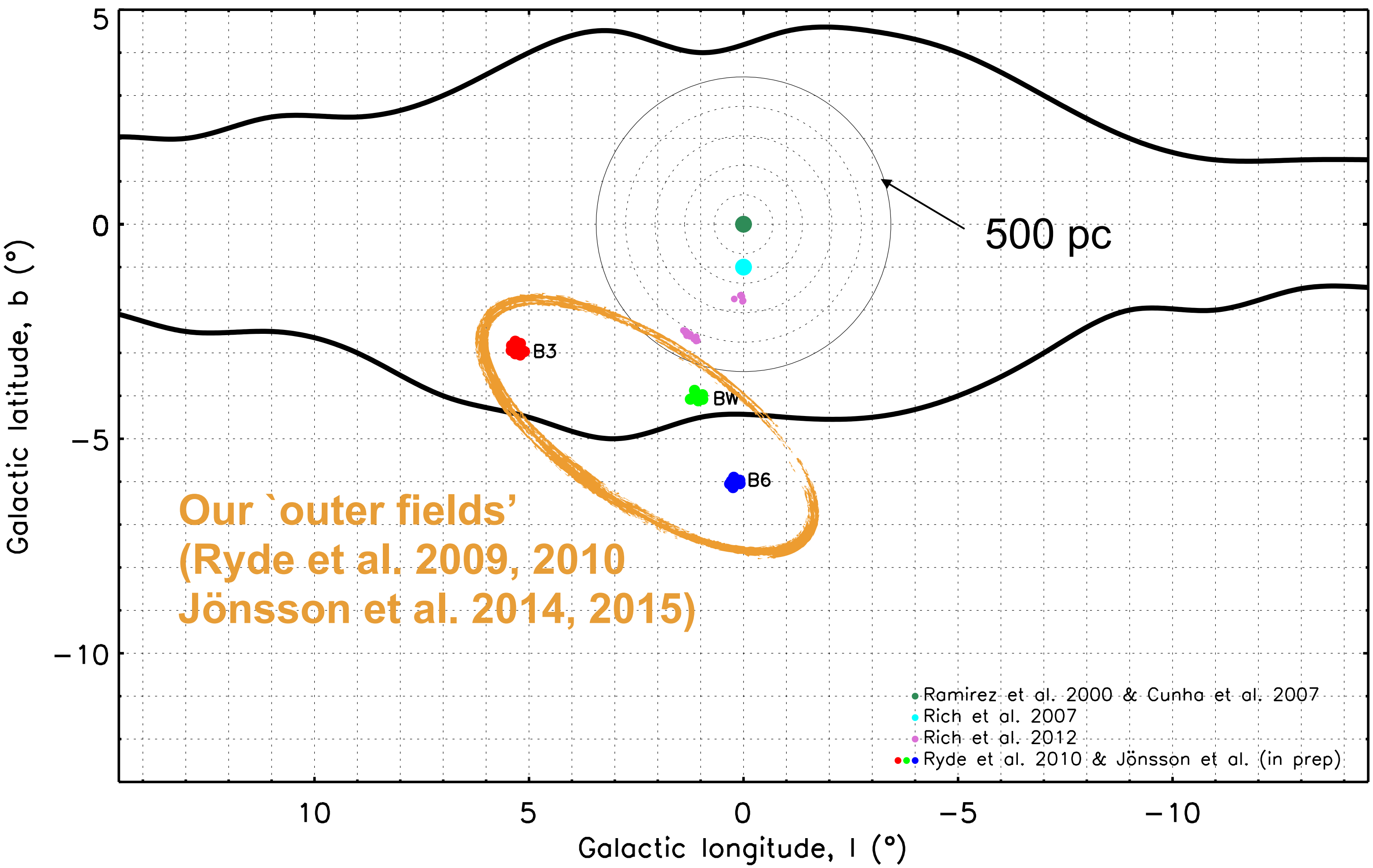
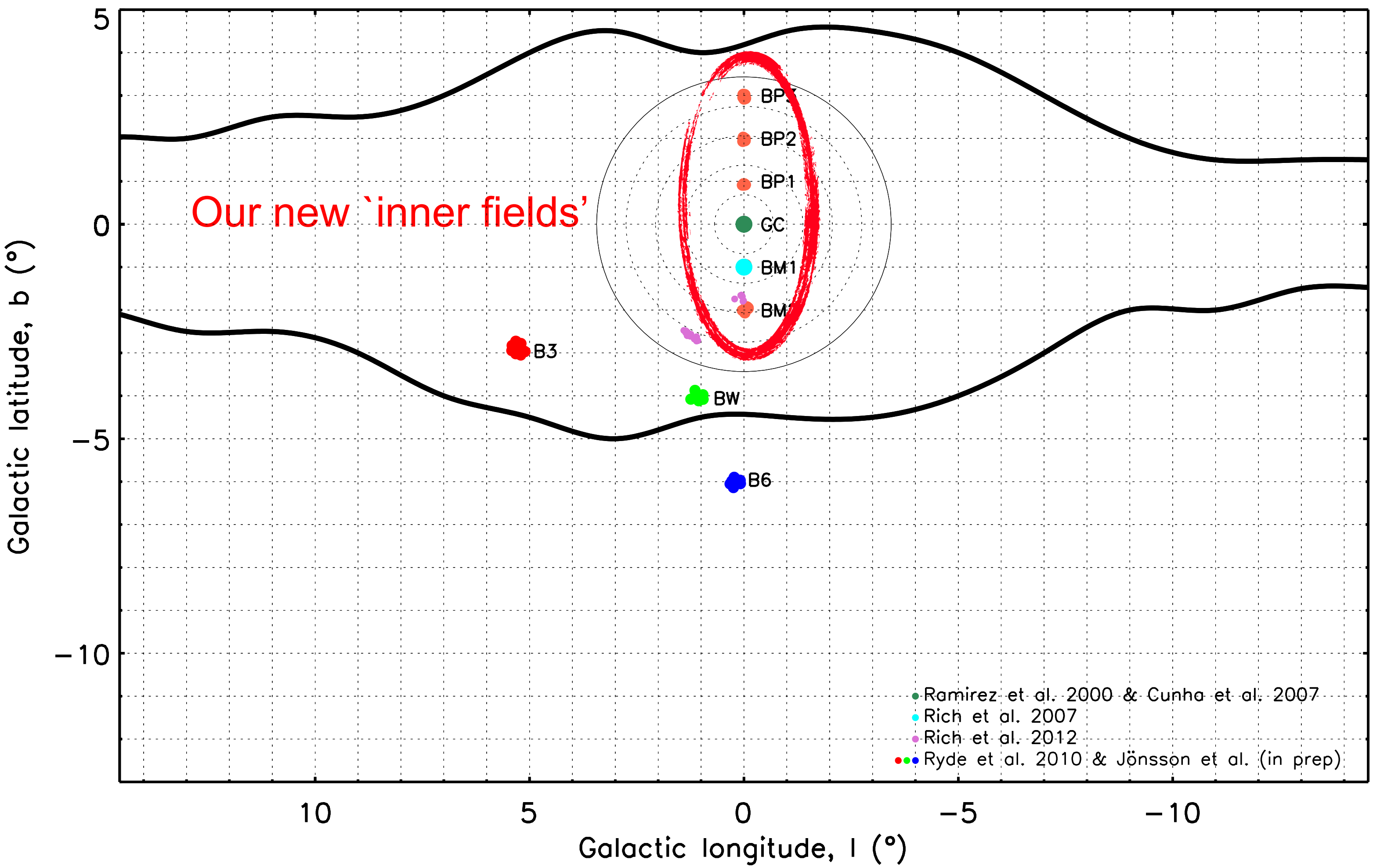


2. The Milky Way bulge - inner gradient



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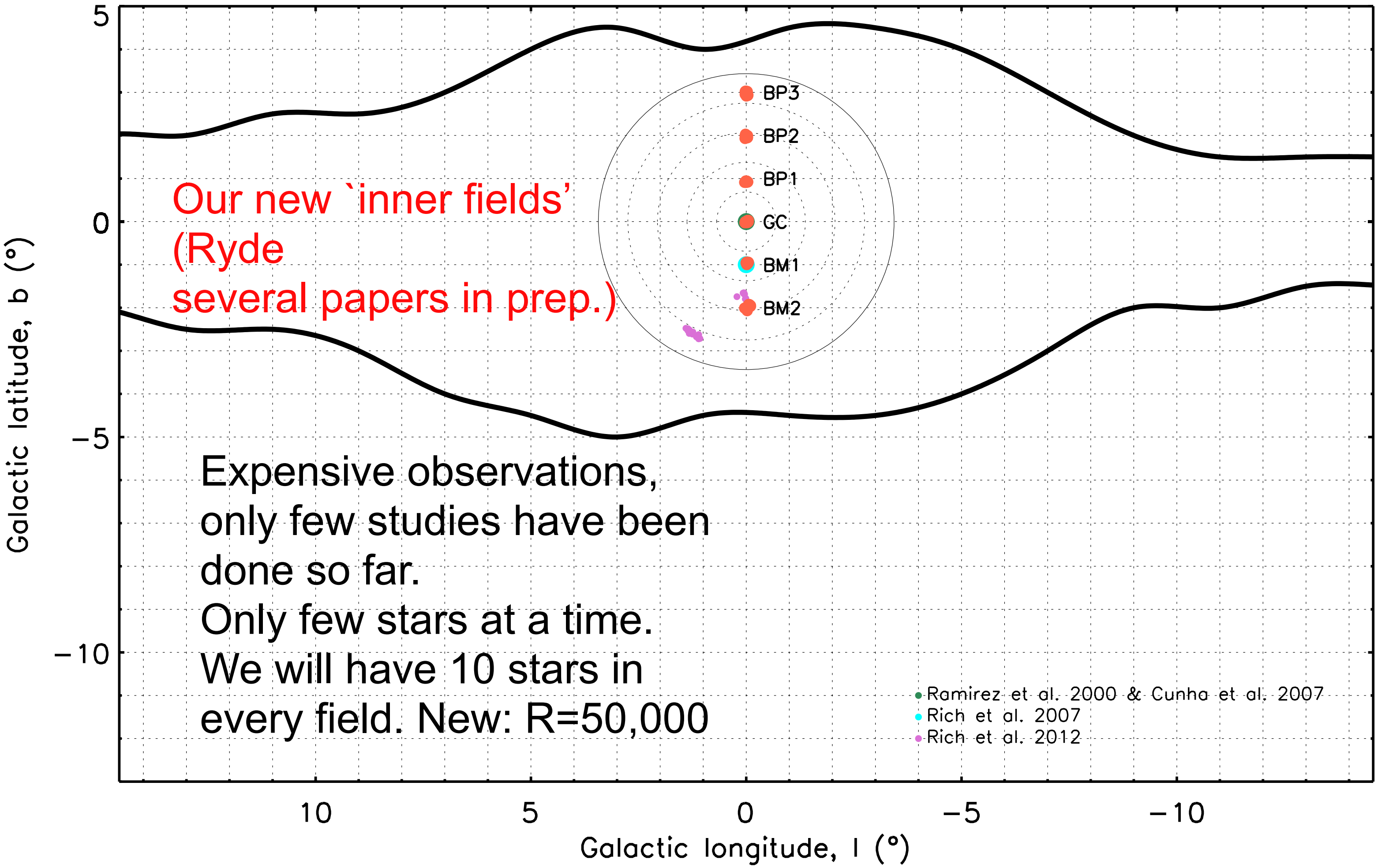

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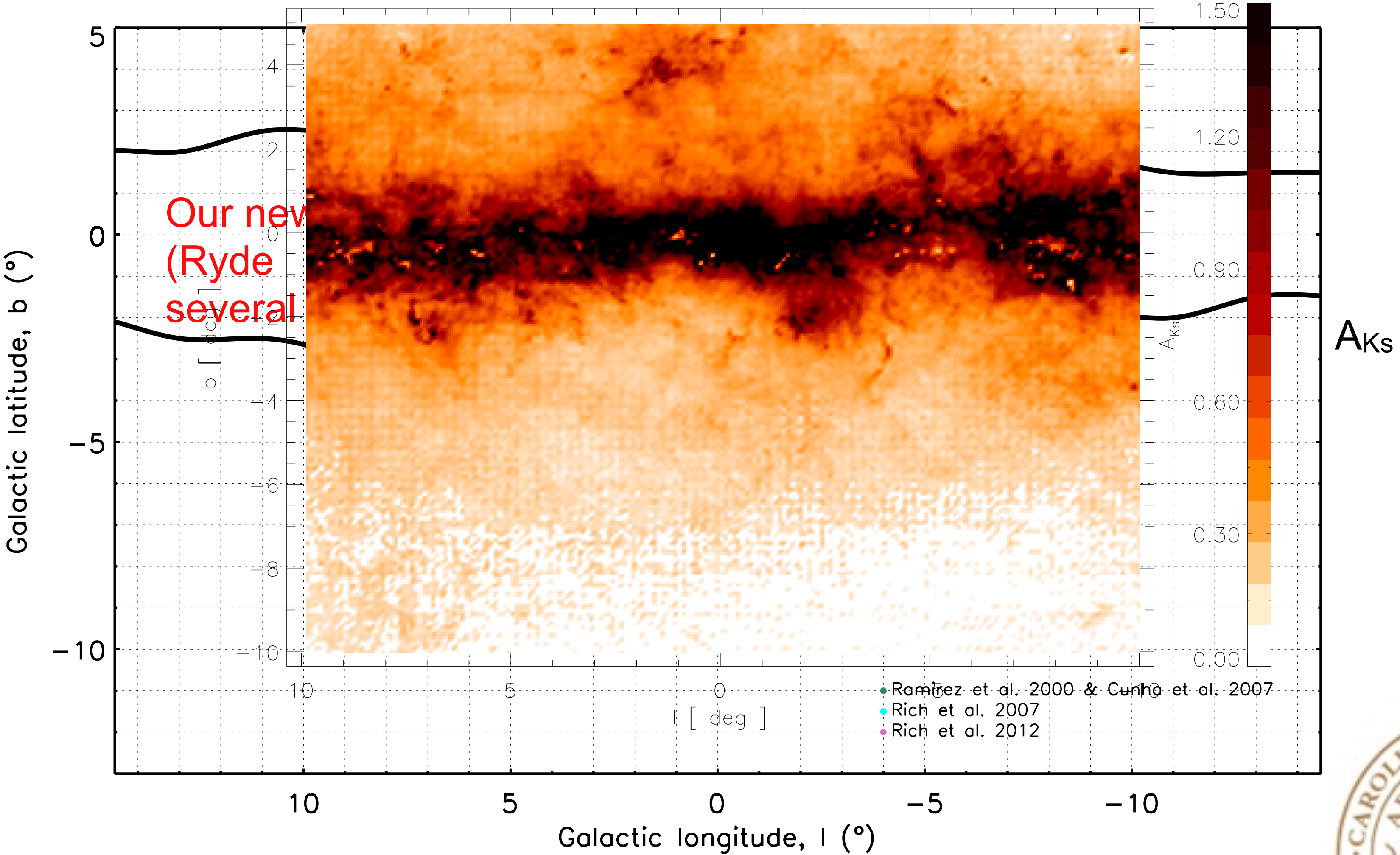

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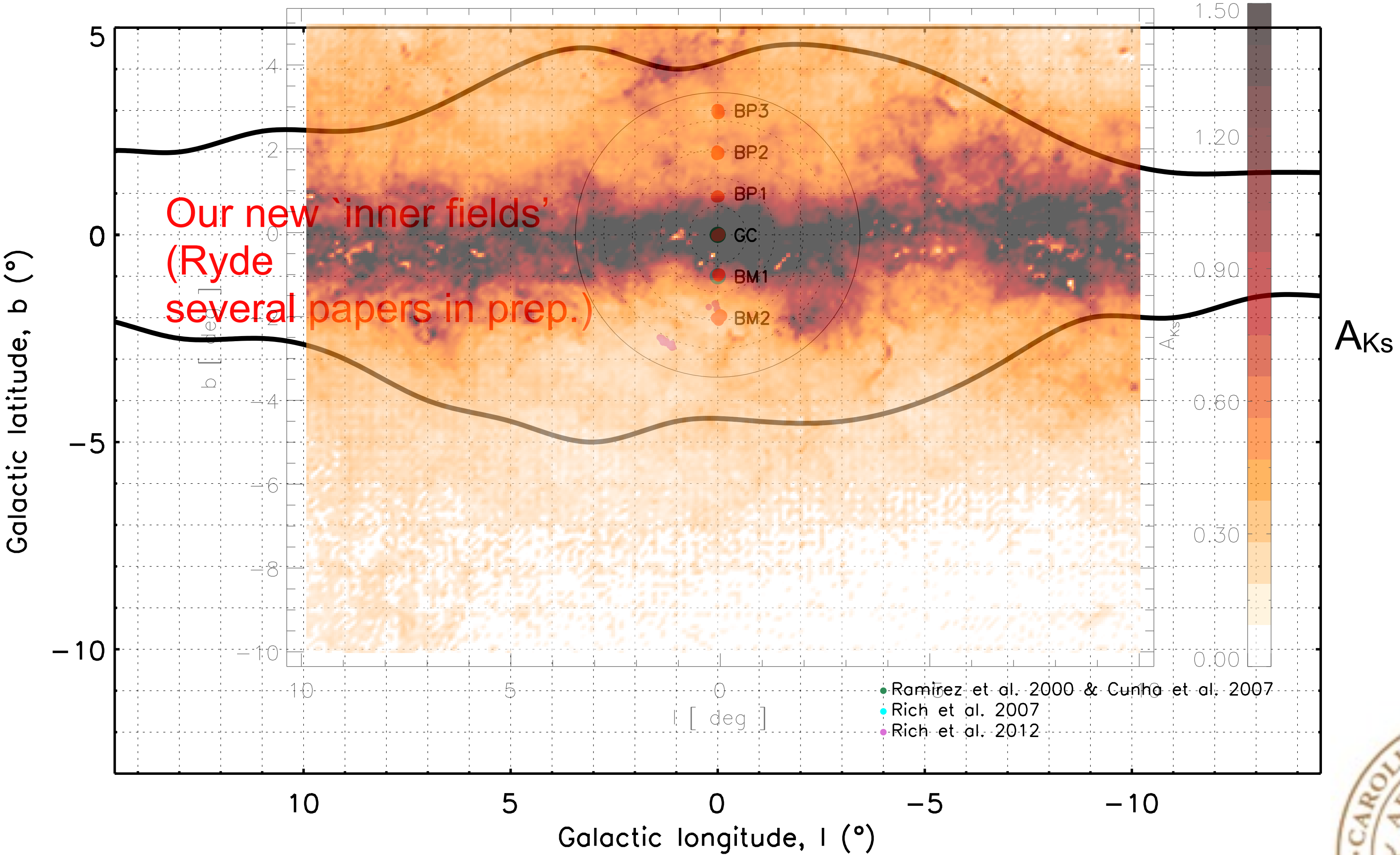
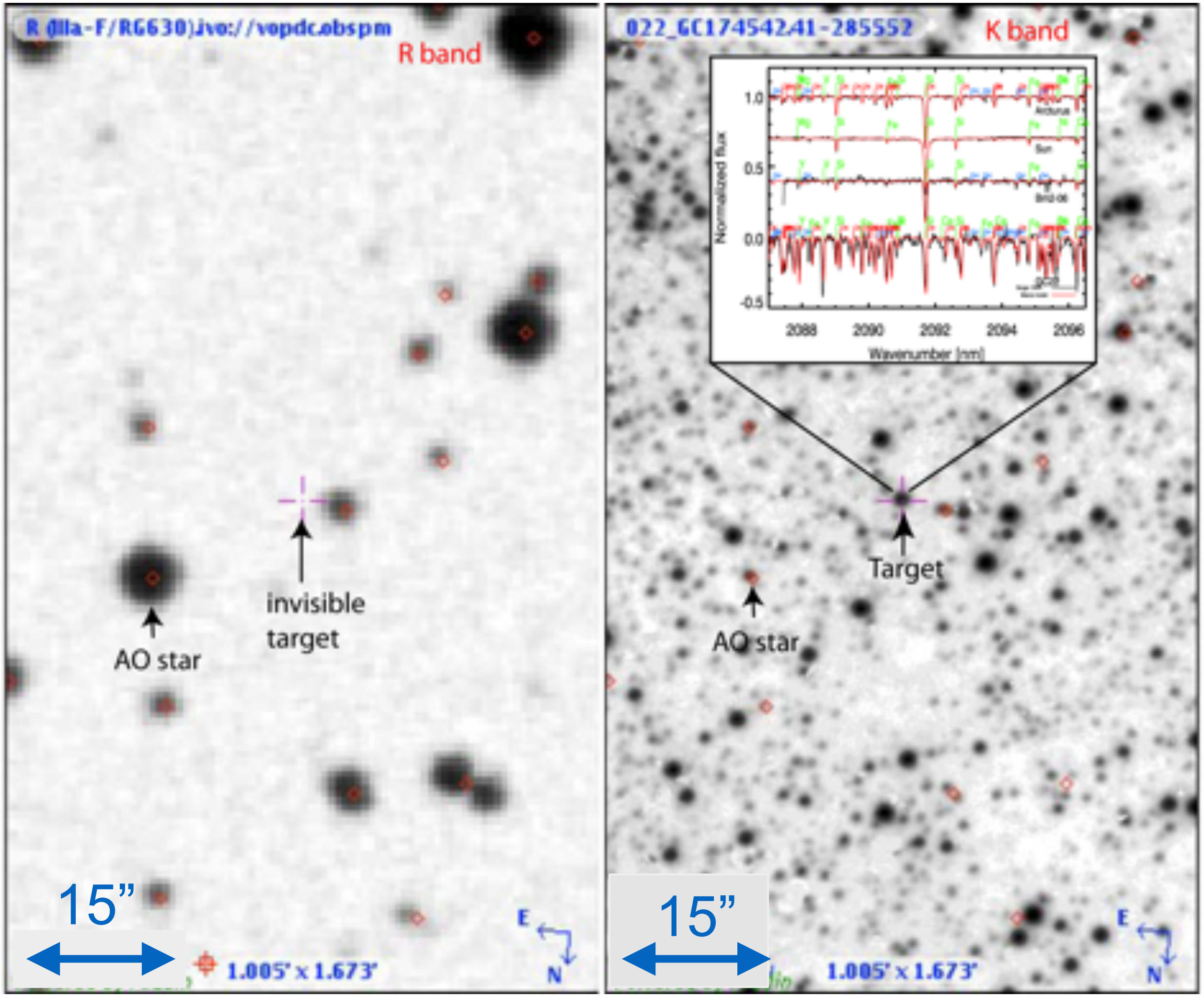


The Bulge — near-IR high-res spectra

Finding charts for VLT/CRIRES GC observations



R band UKIDSS K band

The extinction in the K band is a factor of 10 lower that in the V band (Cardelli et al 1989).

The Bulge — near-IR high-res spectra

Table 2. Summary of the observations with VLT/UVES and VLT/CRIRES.

Star	Total integration time			S/N[a]			Magnitude	
	Visual	H	K	Visual	H	K	H	K
B3-b1	6h 10m	40m	52m	20	55	44	*11.5*	*11.3*
B3-b7	6h 10m	1h 10m	20m	38	31	37	*11.6*	*11.3*
B3-b8	6h 10m	1h 04m	1h 20m	65	80	79	*11.4*	*11.1*
B3-f3	11h 50m	–	56m	31	–	35	*11.7*	*11.5*
BW-b6	6h 25m	1h 04m	–	24	34	–	*11.9*	*11.7*
BW-f6	6h 25m	1h 20m	1h 20m	34	46	38	*12.0*	*11.8*
B6-b8	8h 30m	1h 04m	1h 20m	55	35	44	*11.9*	*11.6*
B6-f1	5h 15m	32m	40m	75	33	28	*11.9*	*11.7*
B6-f7	5h 15m	32m	1h 20m	30	42	36	*11.9*	*11.7*

Jönsson, Ryde. et al. A&A 564, A122 (2014)

This is for b = -3 and beyond. At GC H band very difficult at R = 50000

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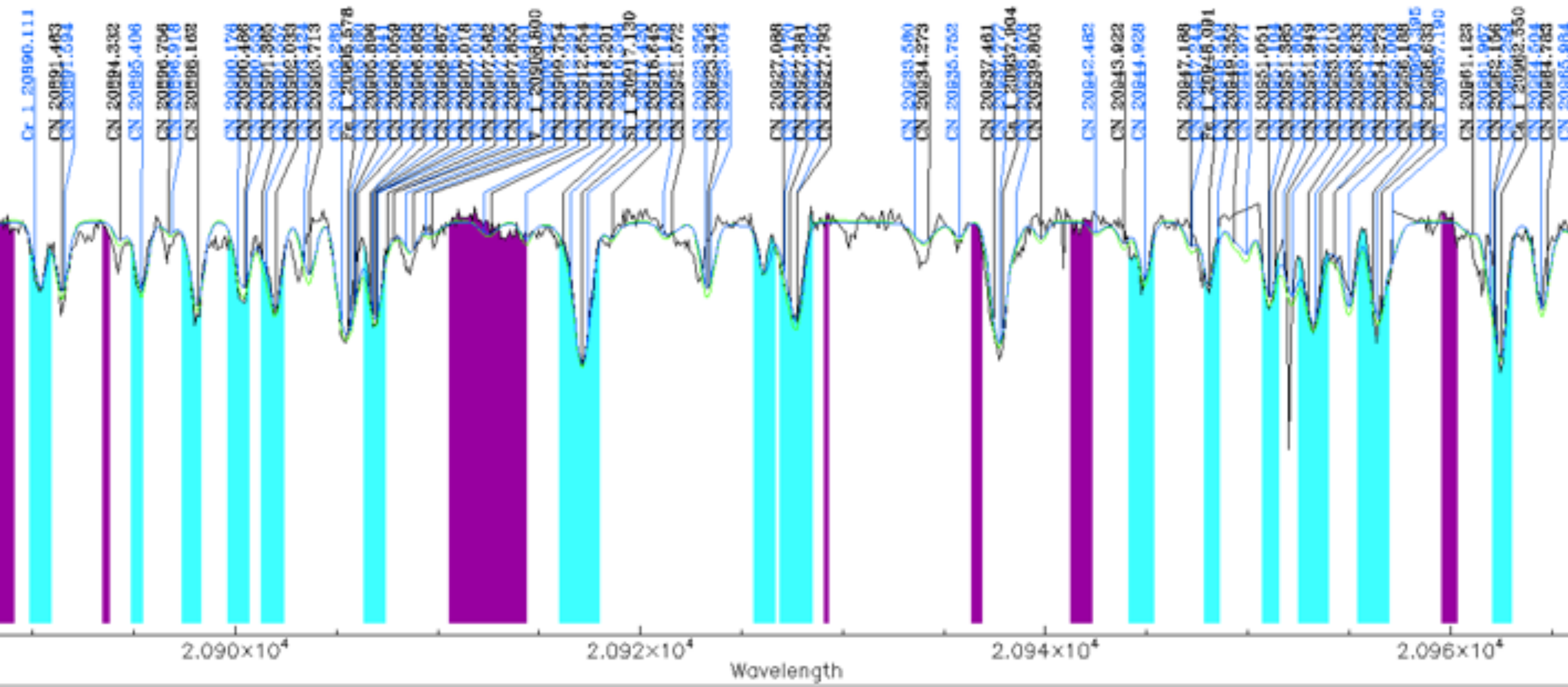
Challenging observations in GC

Example: M giant GC22:

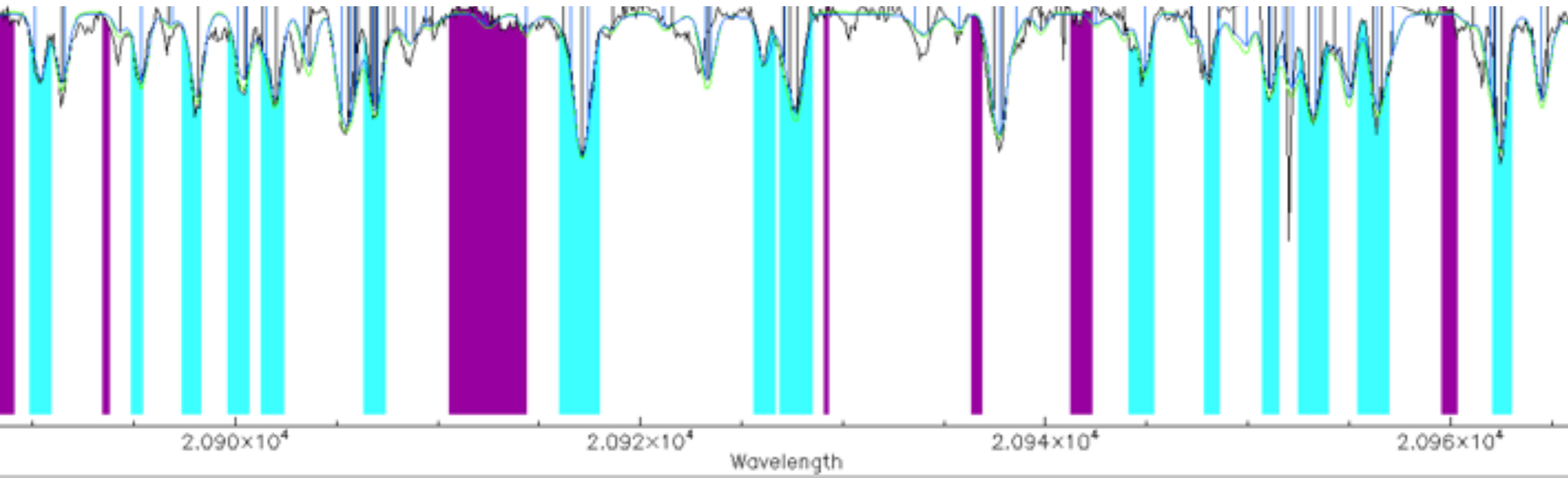
3600 K, logg = 0.7, [Fe/H] = 0;

1 hour for K = 11.5, R = 50000; SNR = 90



Challenging observations: Specific issues

- High-metallicities: increased blending, unknown blends. Spectral resolution.
- Cool stars: molecular blending, how good are the line lists?
- NIR lines saturate earlier (dB/dT smaller). Need higher SNR for same abund.
- NIR, high-met: saturation: insensitive to abundance. Large sensitivity to ξmicro
- Uncertainties & systematics depend on [Fe/H]. Different lines for different [Fe/H]-regimes. Careful line selection, cf. Fulbright et al. 2007.



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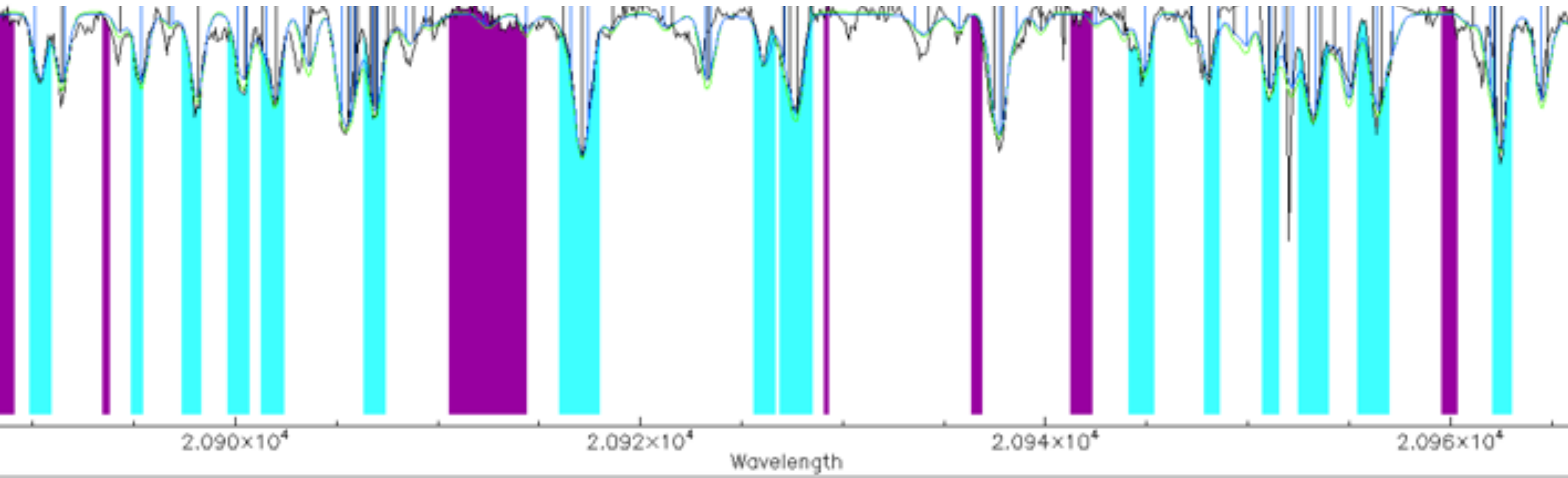
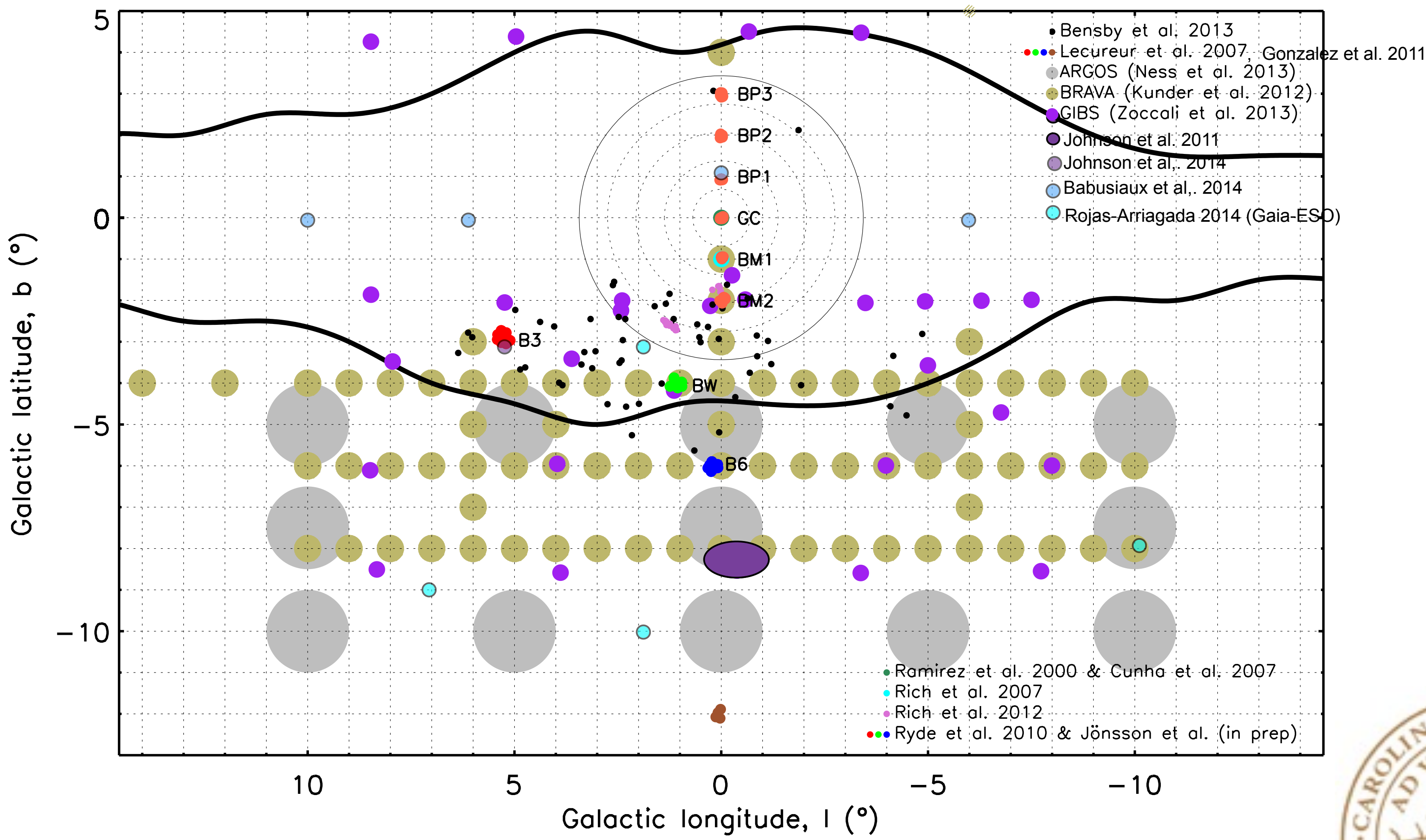
Important with benchmarking, comparison between methods and groups. Solve issues.



The Bulge - fields in the recent literature



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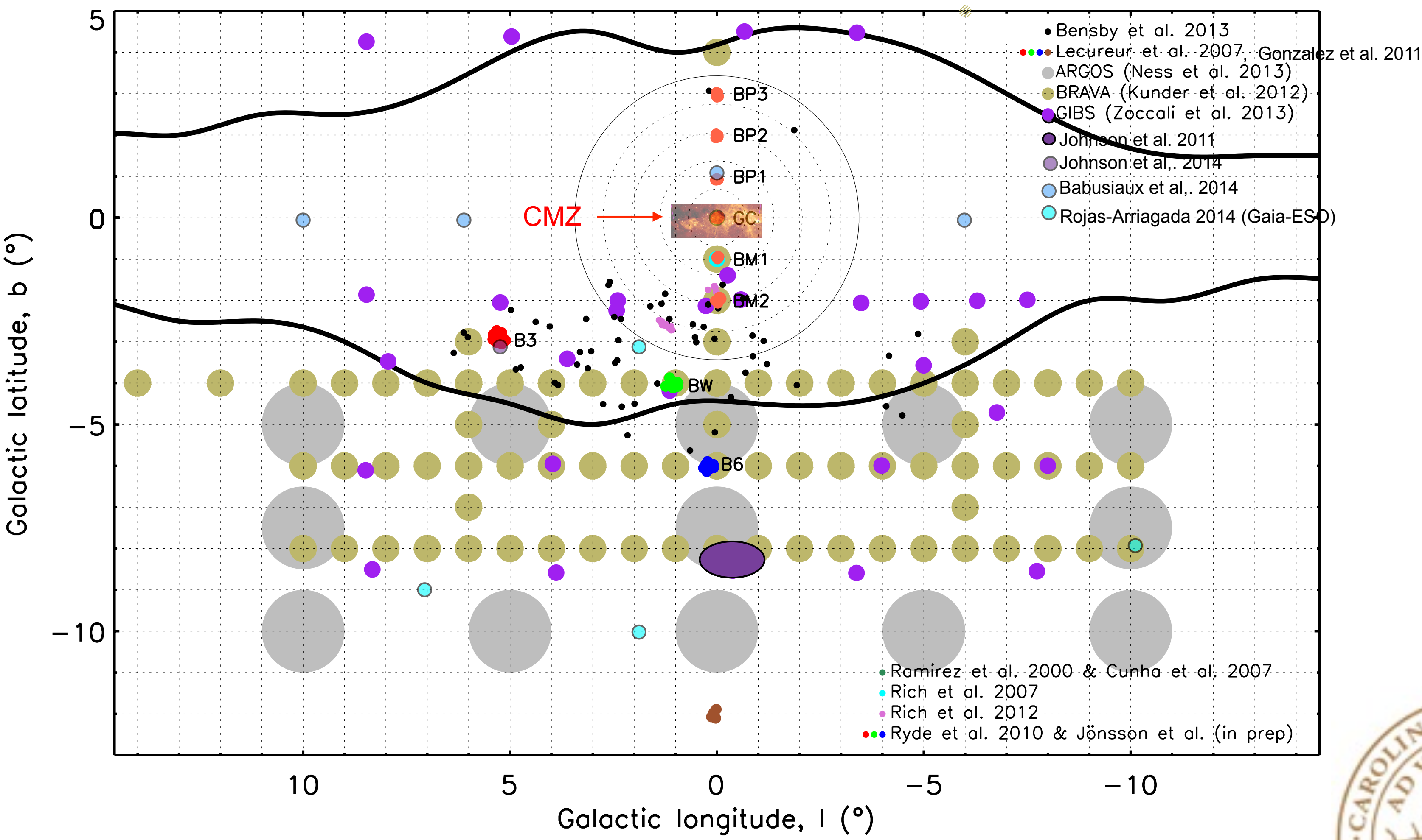

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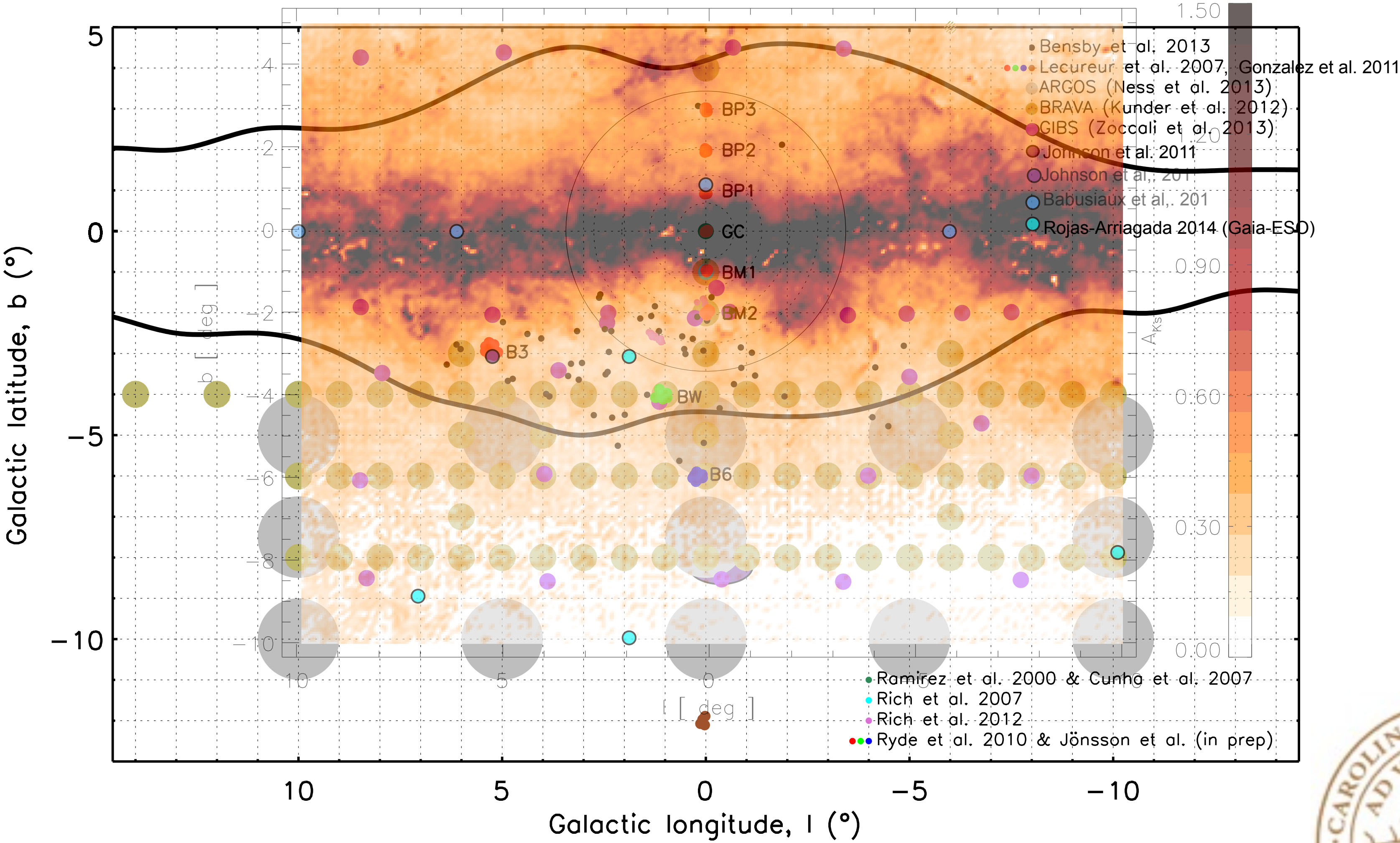
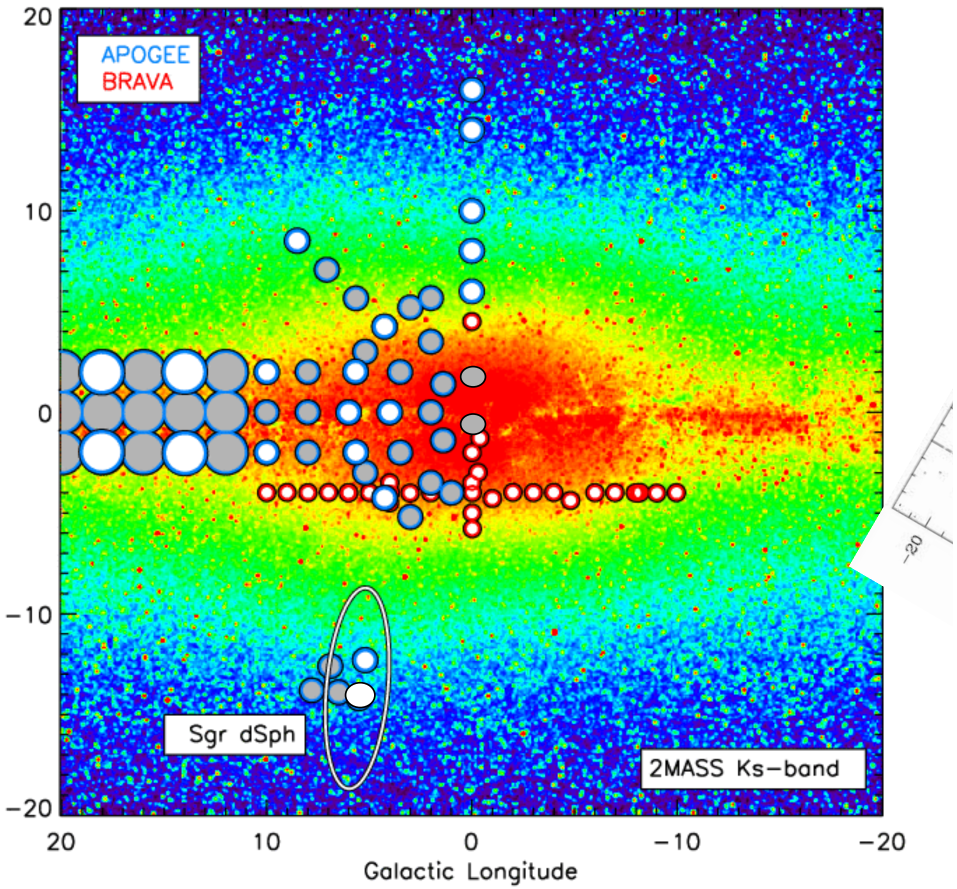


The Milky Way bulge - APOGEE



H band (1.5-1.7 microns)
R = 23,000
300 fibers
8000 stars in the Bulge

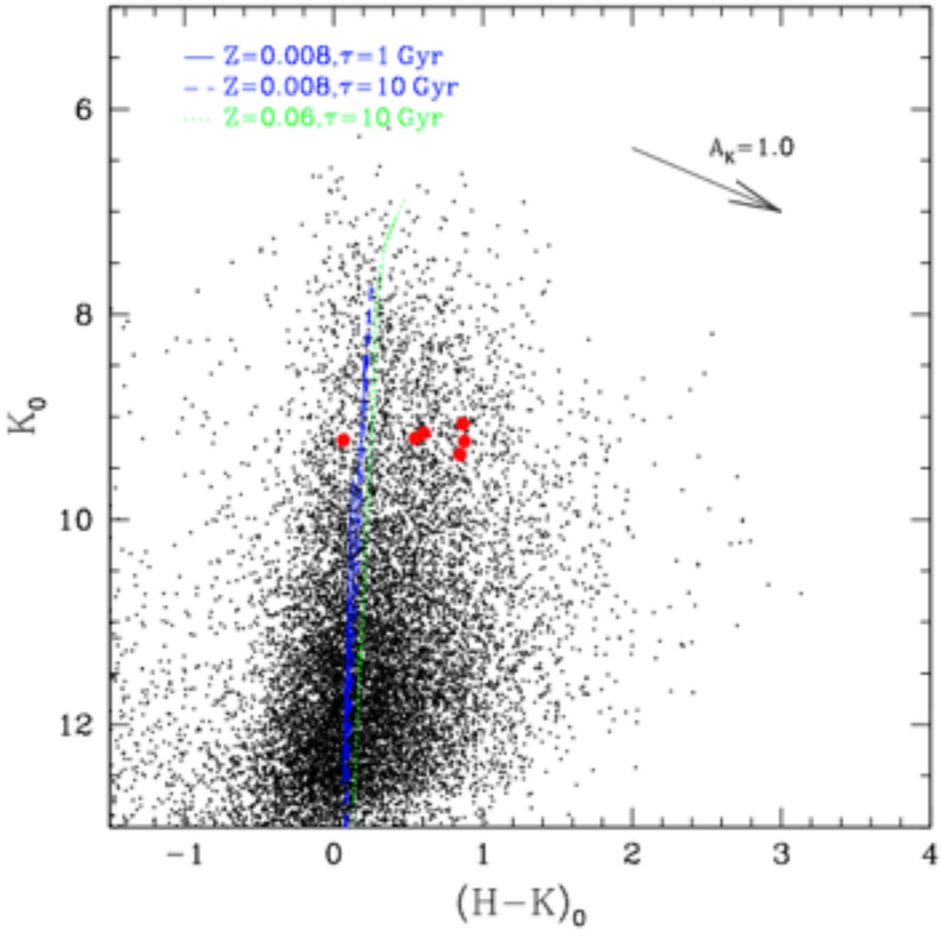
Stellar parameters

1. Low-obscured fields (outer fields): from high-res optical spectra

- Optimised Fe line list for red giants
- Unblended lines and with spread in excitation energy $\longrightarrow$ Teff, [Fe/H], and ξ_{micro}
- FeII & some Ca lines, both weak and strong ones $\rightarrow$ log(g)
- 40 lines from VLT/UVES optical spectra with SNR= 25 — 40 retrieves stellar parameters surprisingly well. Tested against benchmark stars
- Implemented in the LUMBA node analysis for the Gaia-ESO survey

Stellar parameters

2. Highly obscured fields (inner fields): from low-res near-IR spectra

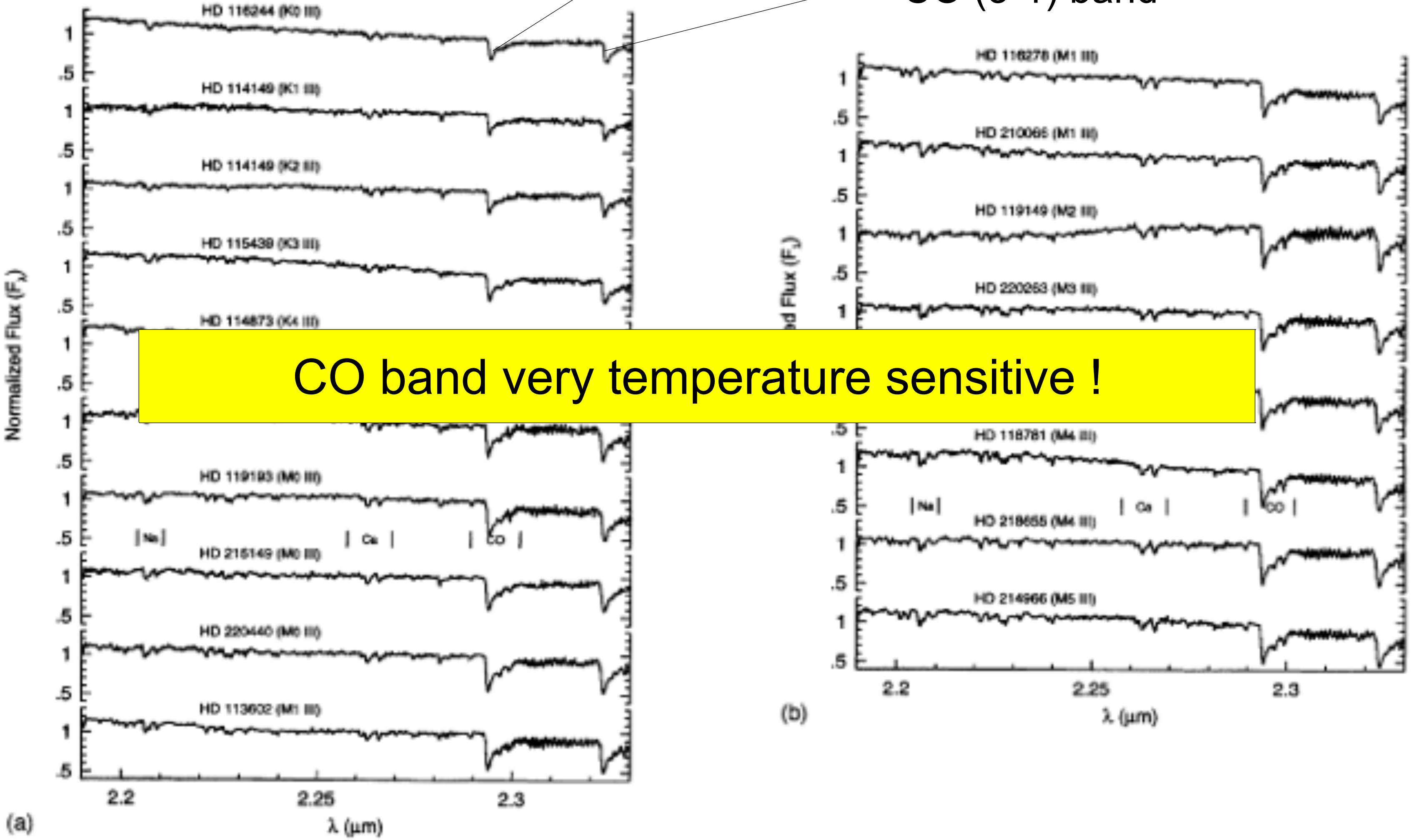


Stellar parameters from low-resolution K-band spectra in the Galactic Bulge

Ramirez et al. (1997)

^{12}CO (2-0) band

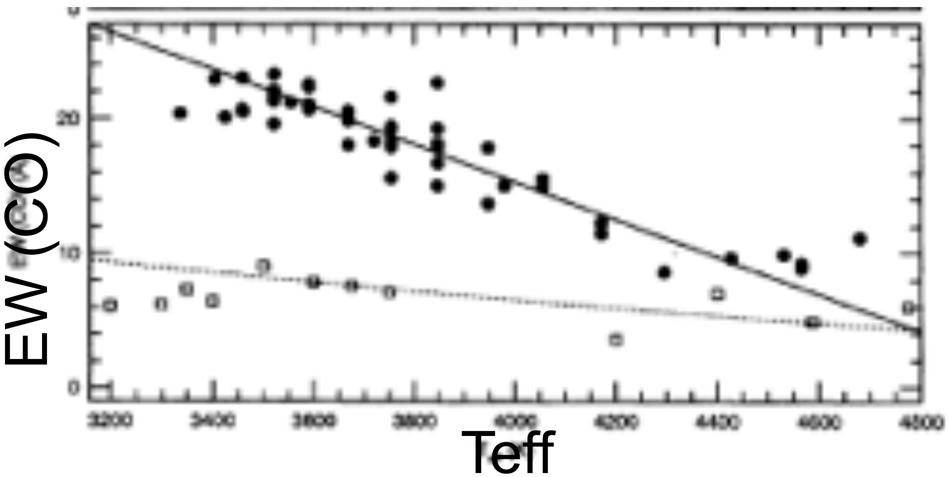
^{12}CO (3-1) band



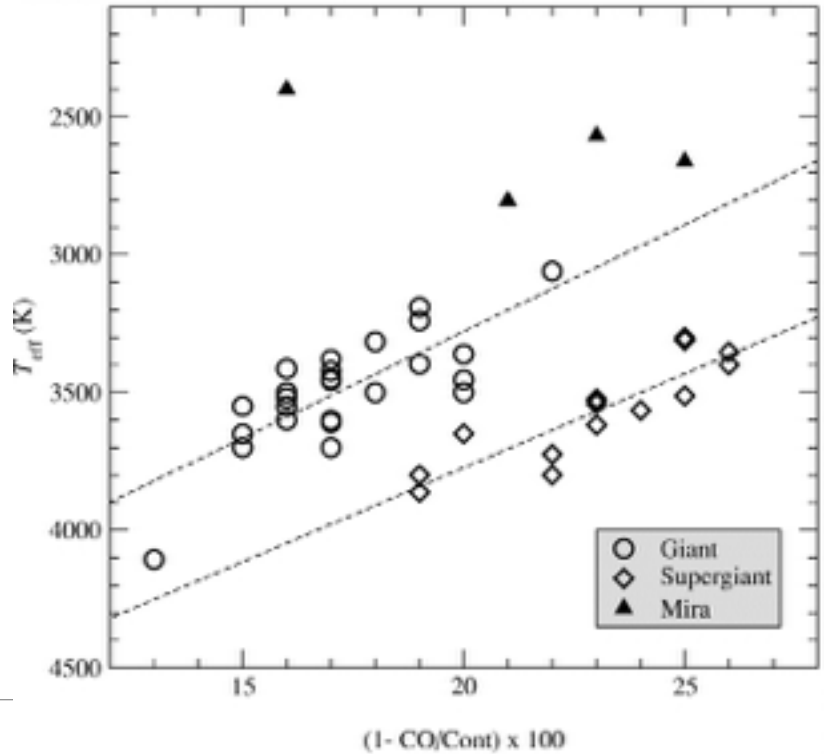
CO band very temperature sensitive !

Stellar parameters from low-resolution K-band spectra in the Galactic Bulge

Ramirez et al. (1997)

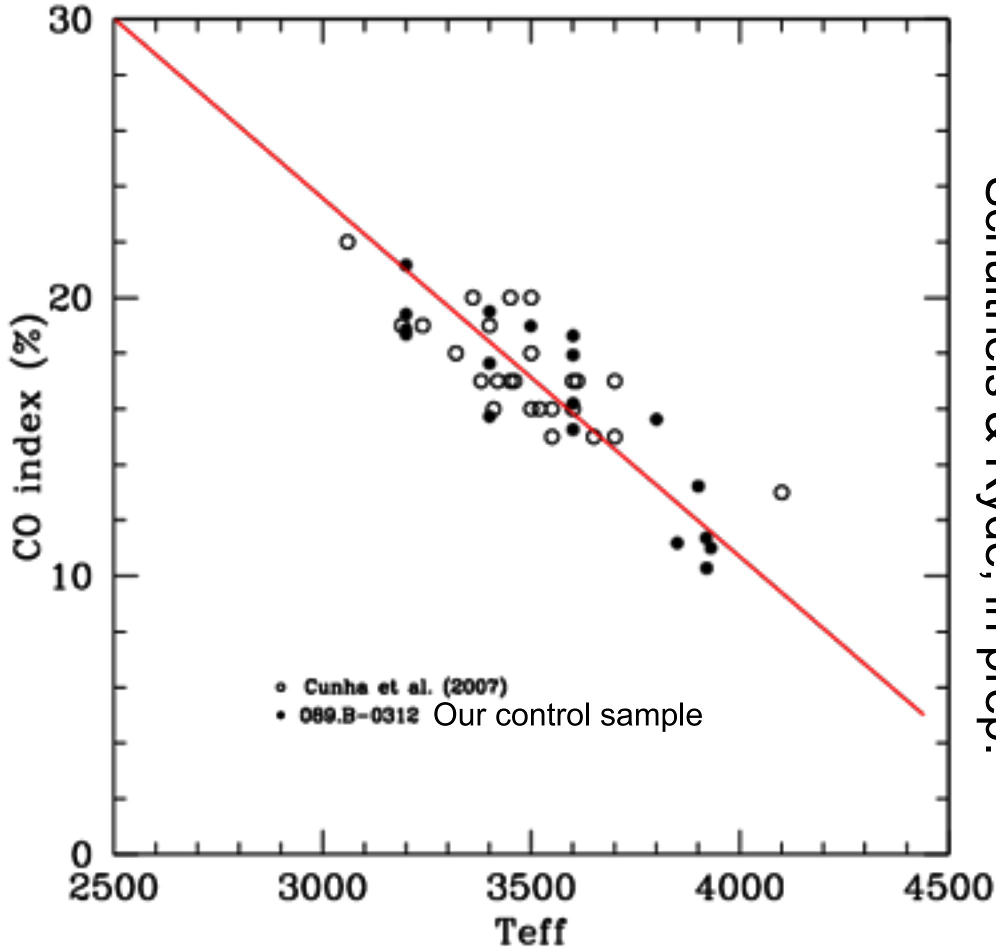


Blum et al. (2003)



Semi-empirically

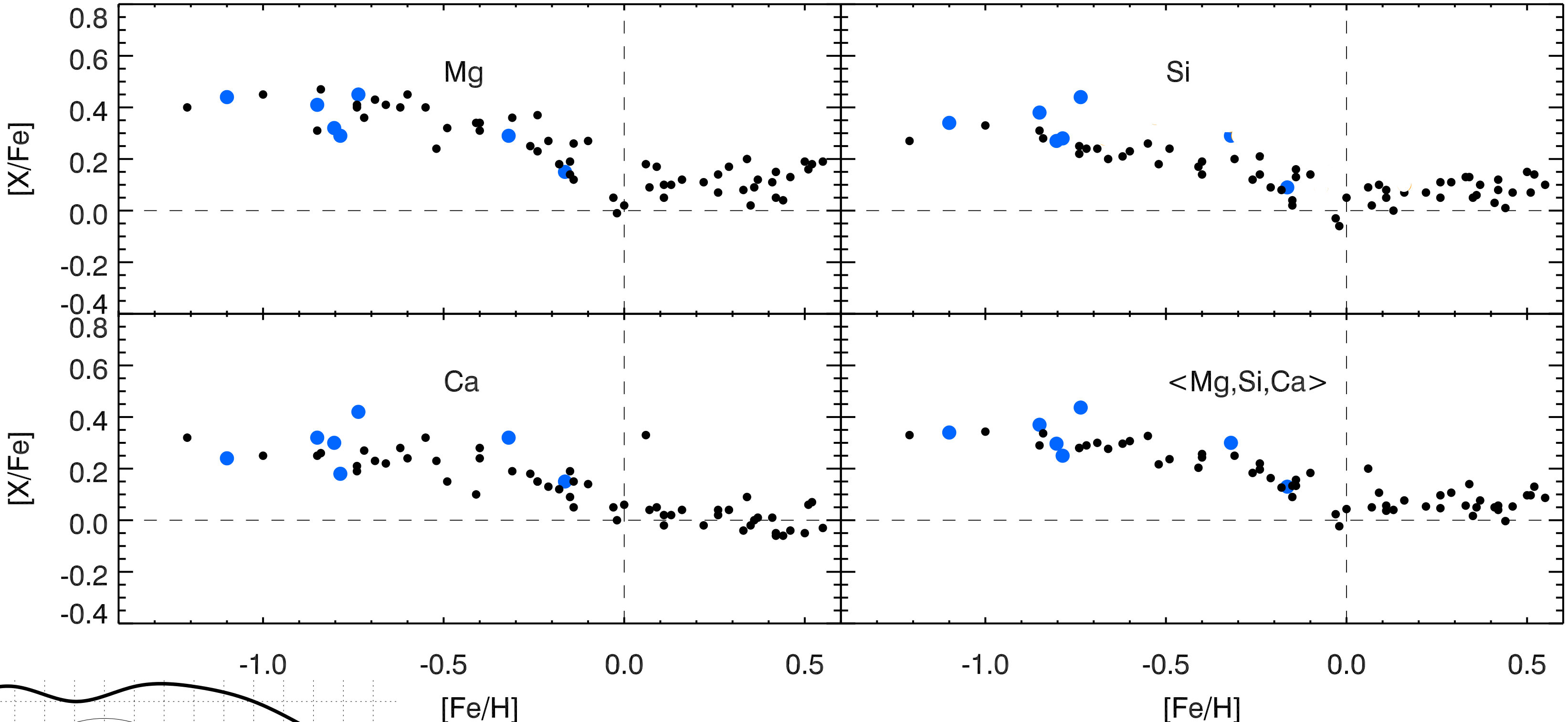
r.m.s ~90 K



Schultheis & Ryde, in prep.

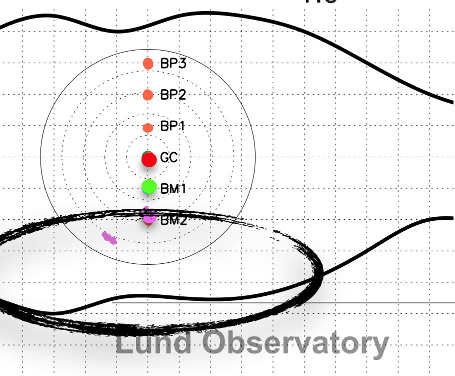
Mixture of field stars and Bulge stars.
Mixture of Teff from optical/IR spectroscopy.
Synthetic spectra notoriously bad in CO bands.

2. Results:
α-abundance trends in the Bulge



Thick disk stars
Ryde & Schultheis 2015

Microlensed bulge dwarfs
(Bensby et al. 2013)



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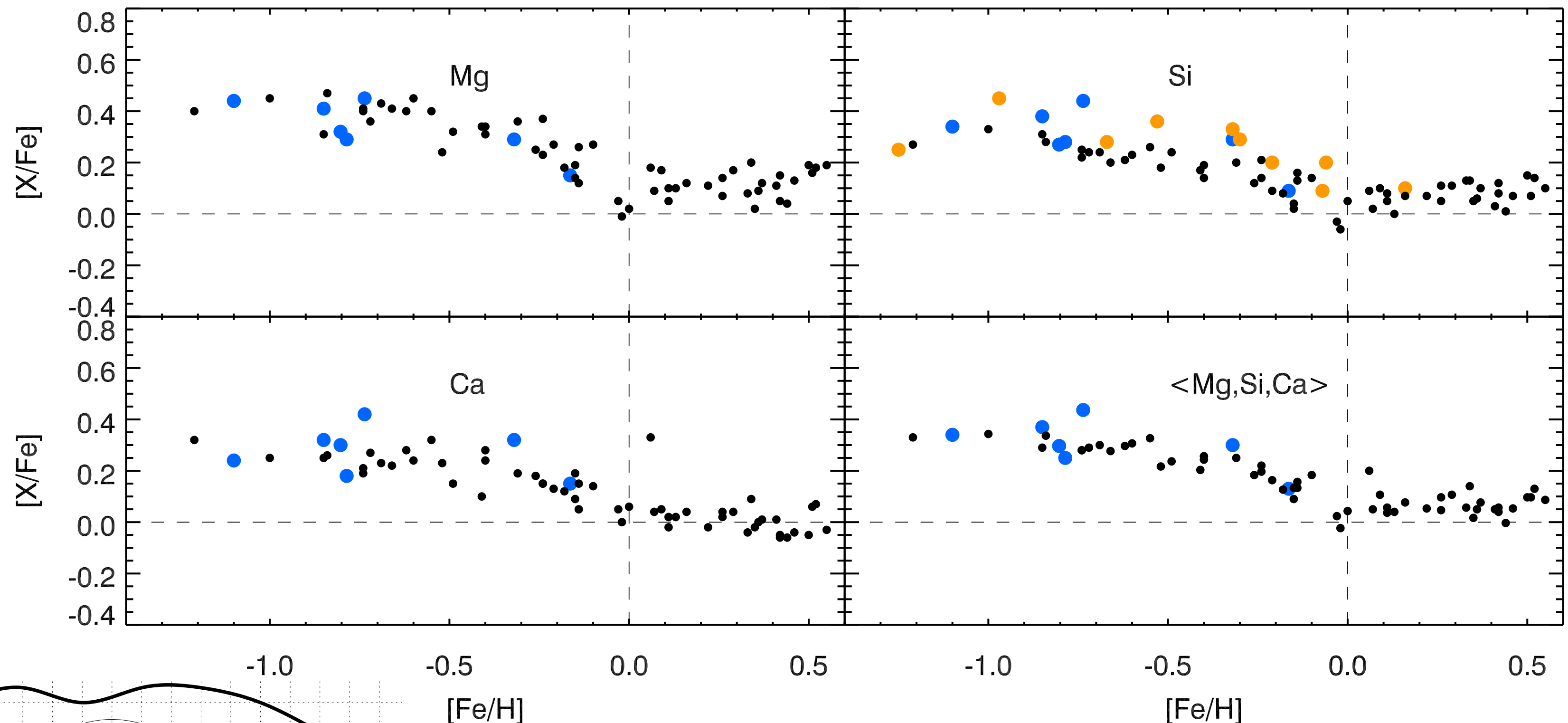

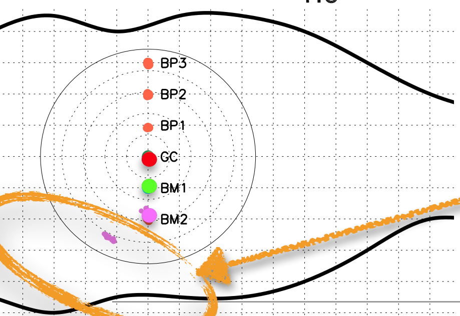

b = -3, -4, -6 deg (11 stars; Ryde et al. 2009, 2010)

Thick disk stars
Ryde & Schultheis 2015

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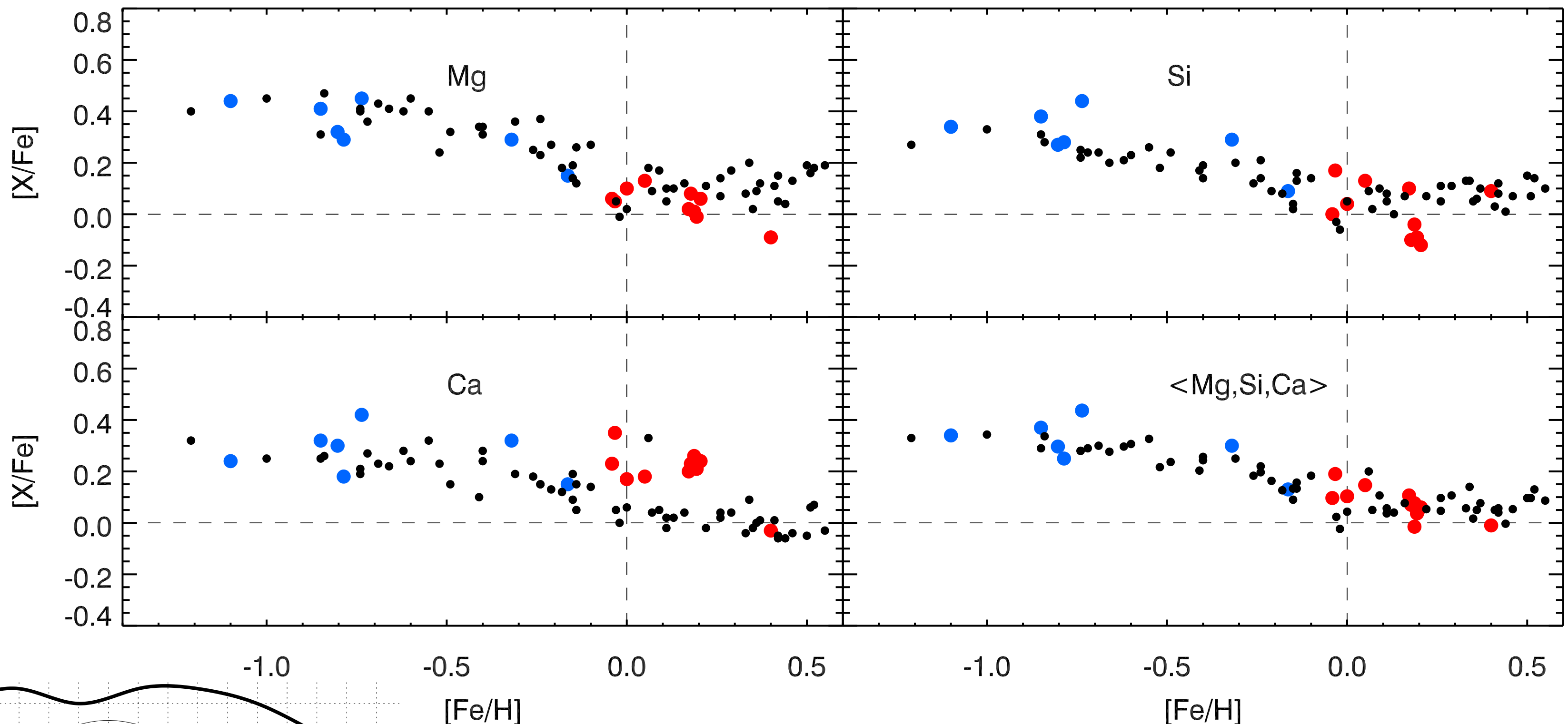
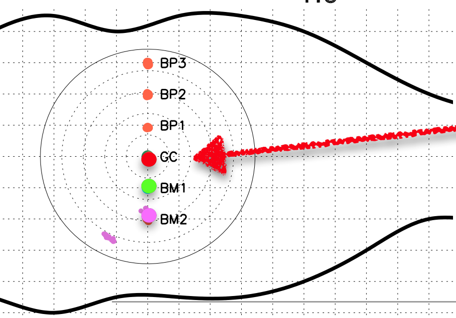
α-abundance trends in the Bulge



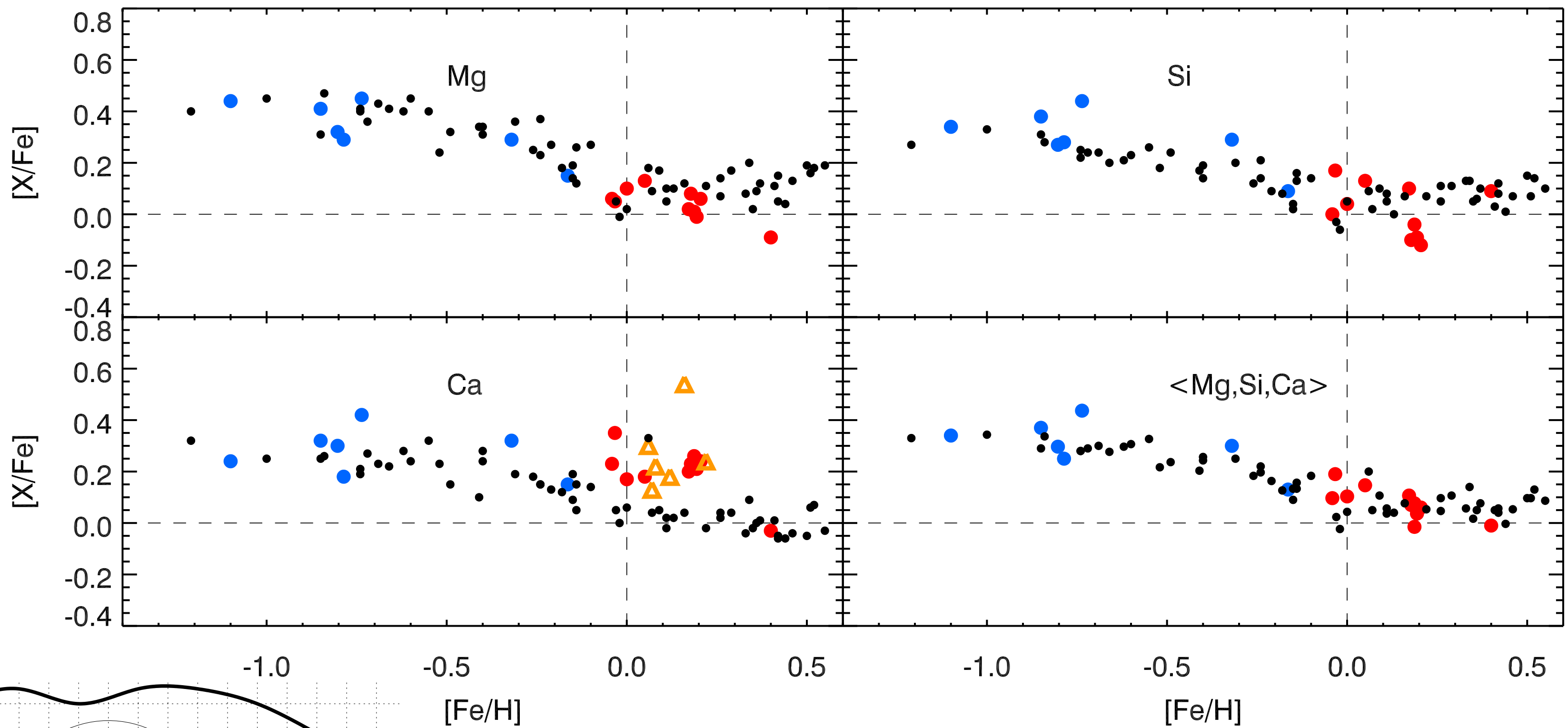


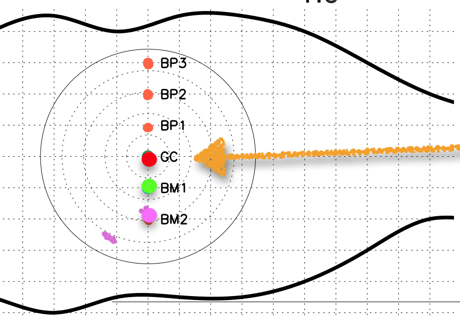
Galactic centre within 10 pc

Thick disk stars

Microlensed bulge dwarfs
(Bensby et al. 2013)

α-abundance trends in the Bulge





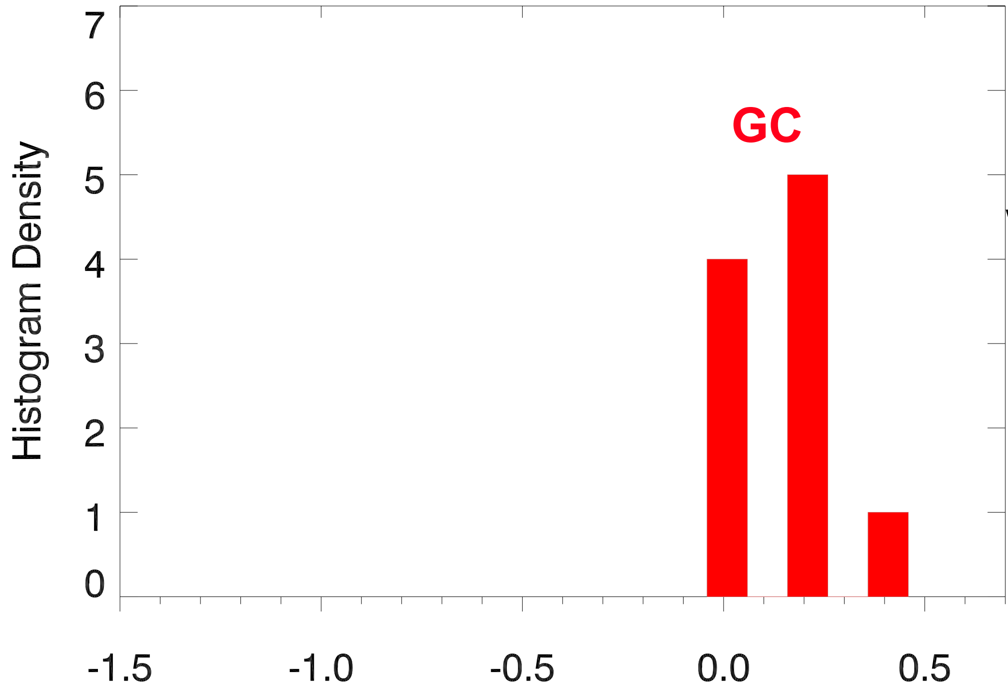
Galactic centre within 10 pc

Galactic centre (Cunha et al. 2007)

Thick disk stars

Microlensed bulge dwarfs (Bensby et al. 2013)

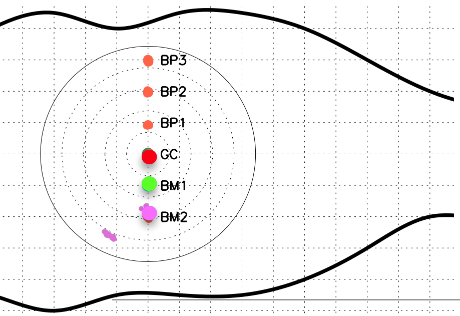
[Fe/H] gradient in the Bulge



Note:

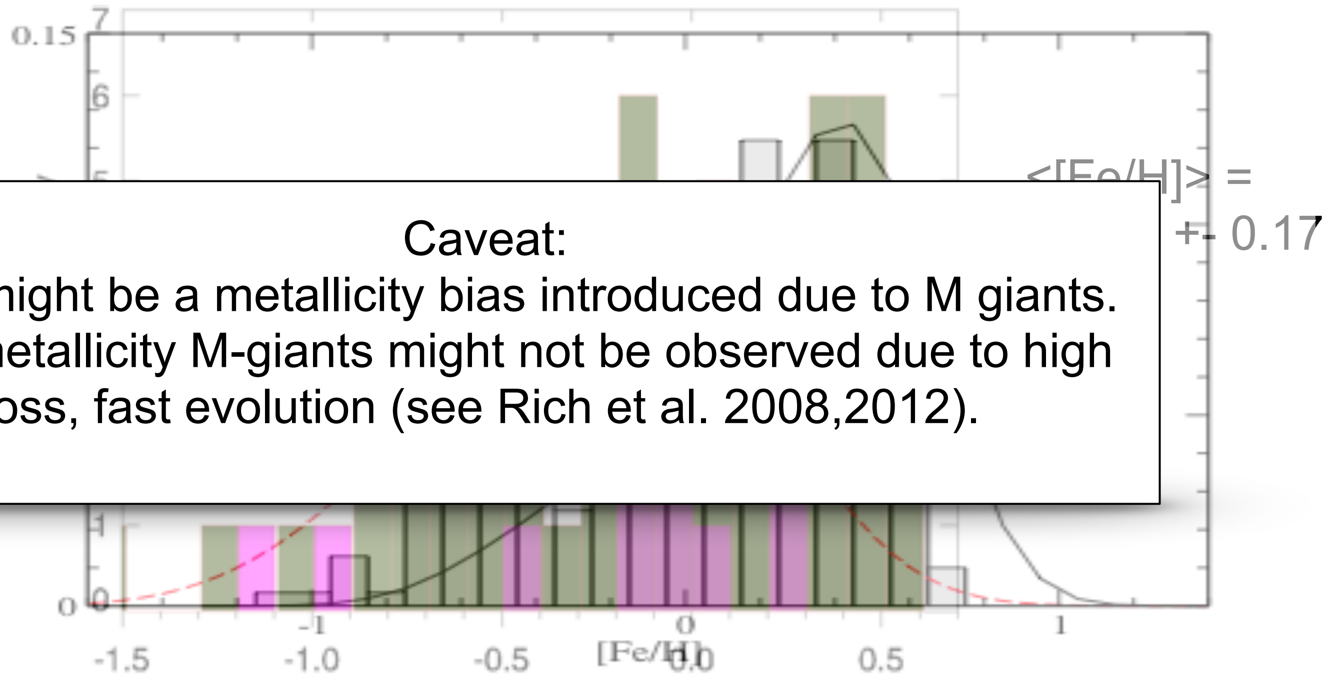
- small statistic with few stars
- selection bias
- more stars needed Keck/nirspec April (PI: Rich).

Galactic centre within 10 pc
Bulge field b = -1 deg
Bulge field b = -2 deg

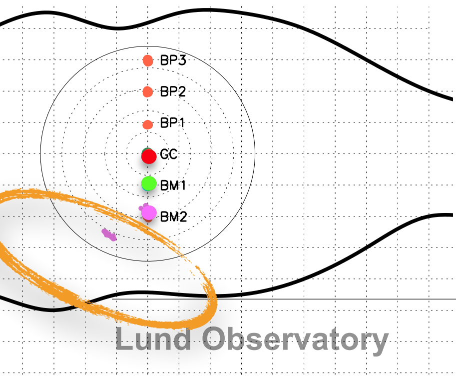


[Fe/H] gradient in the Bulge

Grieco et al. (2012) plotting the Hill et al. 2011 MDF

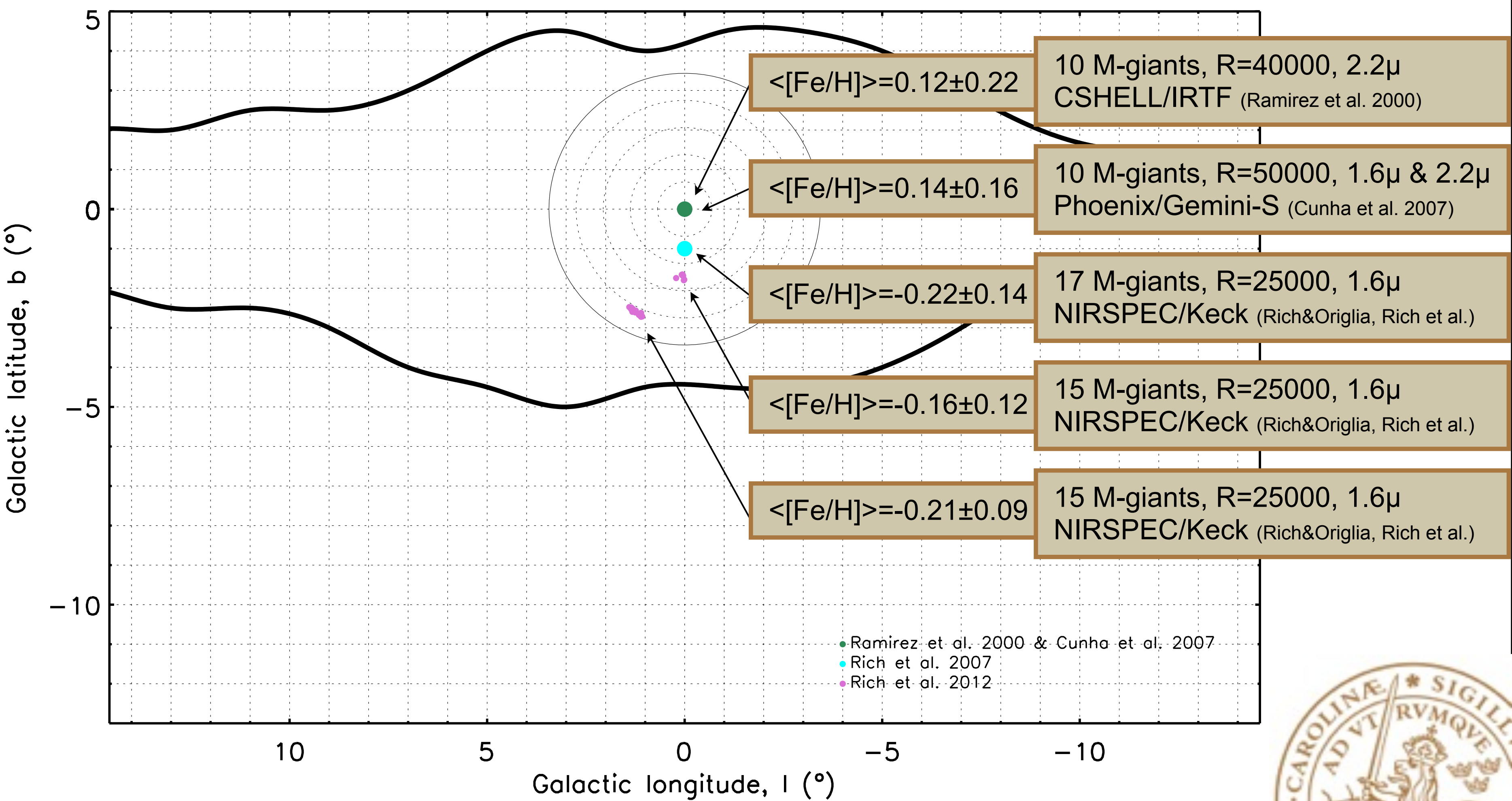


Caveat:
there might be a metallicity bias introduced due to M giants. High metallicity M-giants might not be observed due to high mass loss, fast evolution (see Rich et al. 2008,2012).



- Galactic centre within 10 pc
- Bulge field b = -1 deg
- Bulge field b = -2 deg
- b = -3, -4, -6 deg (50 stars; Jönsson et al. in prep)
- Microlensed bulge dwarfs (Bensby et al. 2013)

The Milky Way bulge - inner gradient



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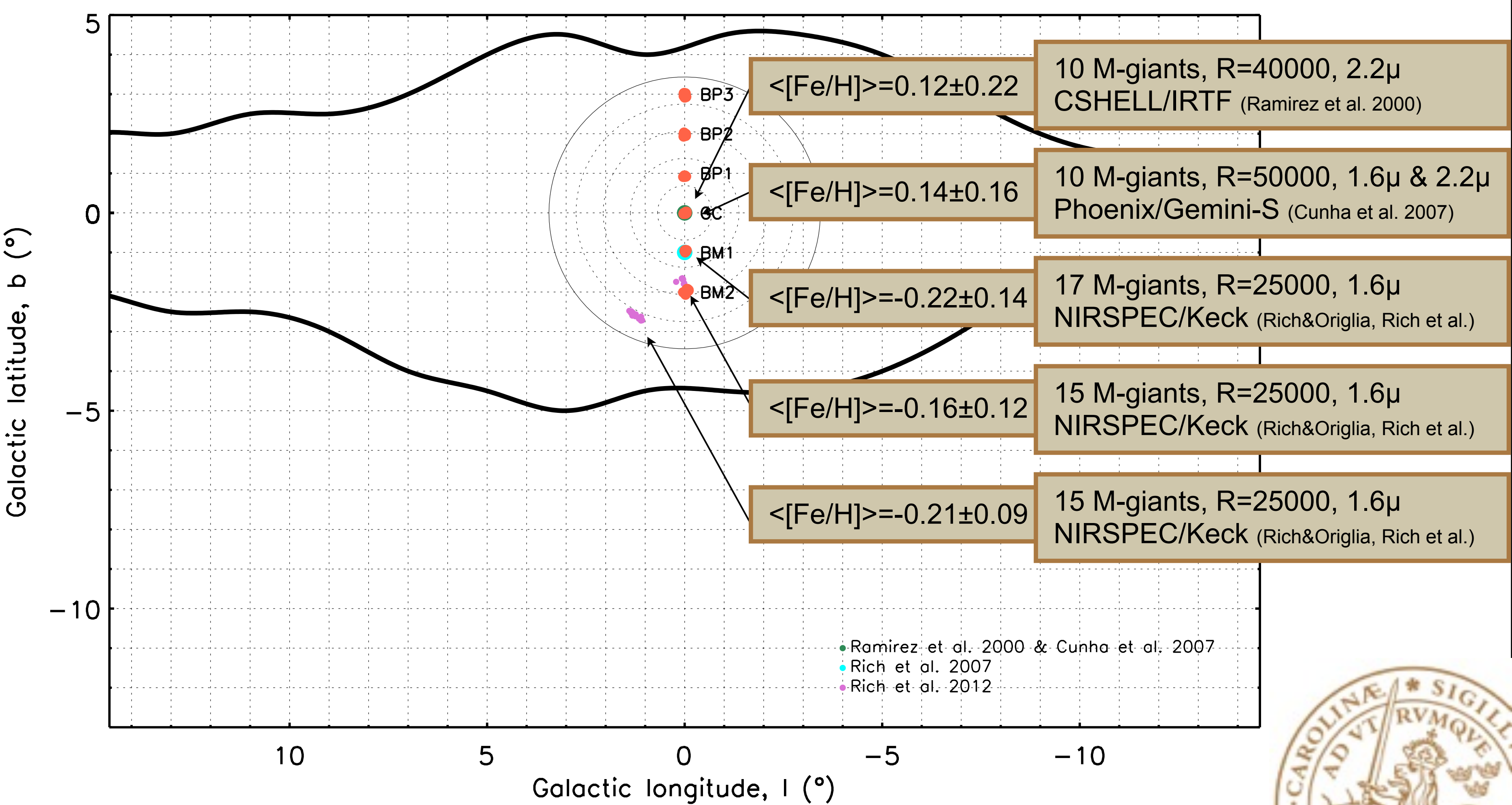

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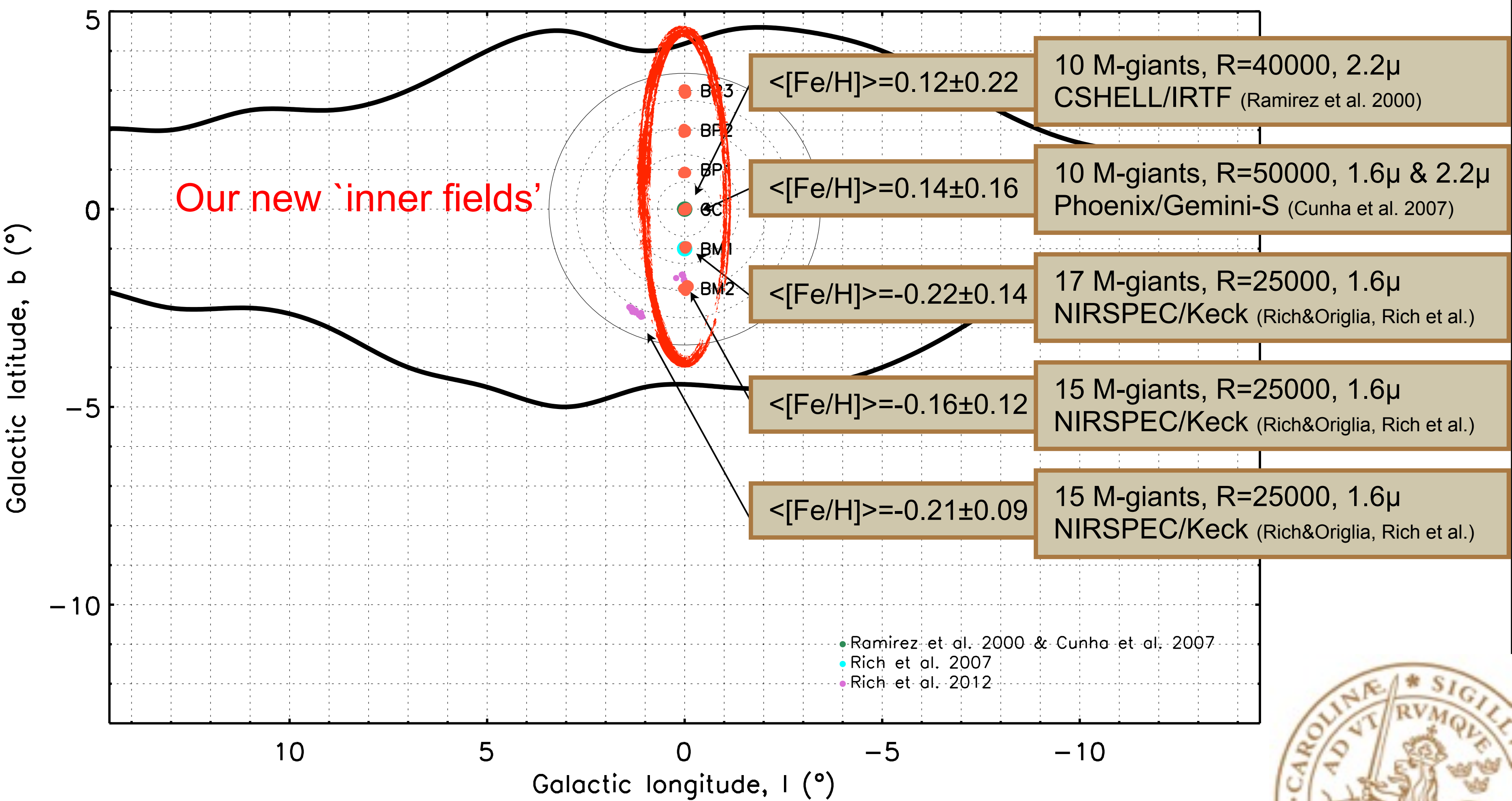

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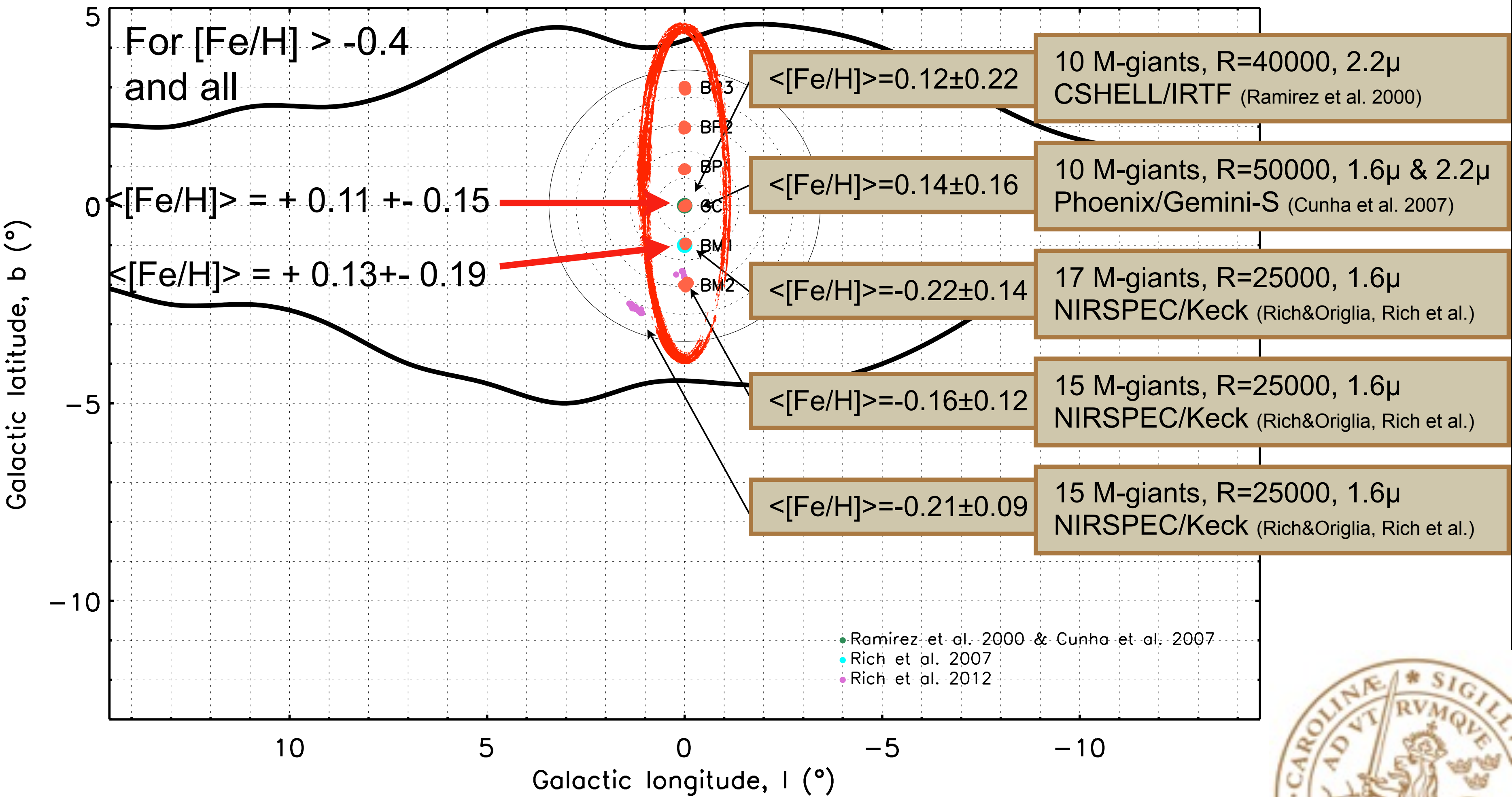


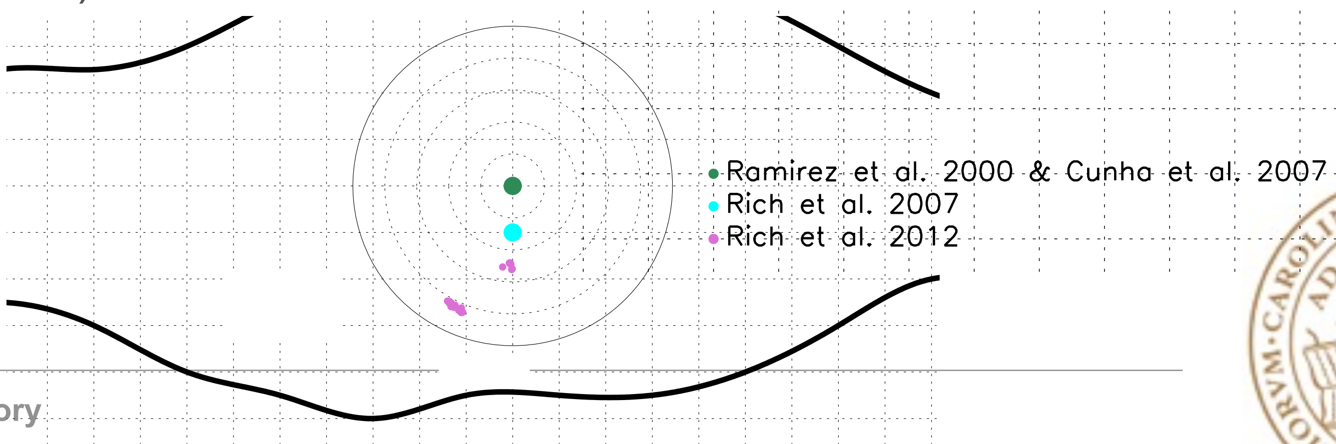
The inner 500 pc - [Fe/H] Gradients

The [Fe/H] in Galactic Center Red Giants

- Ramirez et al. ApJ (2000):
  [Fe/H] = +0.12 +- 0.22 from 7 supergiants and 3 giants (R=40000 IRTF/CSHELL spectra K band)

- Cuhna et al. ApJ (2007):
  [Fe/H] = +0.14 +- 0.16 from the same stars (R=50000 Gemini/Phoenix spectra at 1.6 and 2.3 microns)

- [Fe/H] from supergiants: Carr et al. (2000), Najarro et al. (2008), Davies et al. (2009): +0.00–0.15 dex



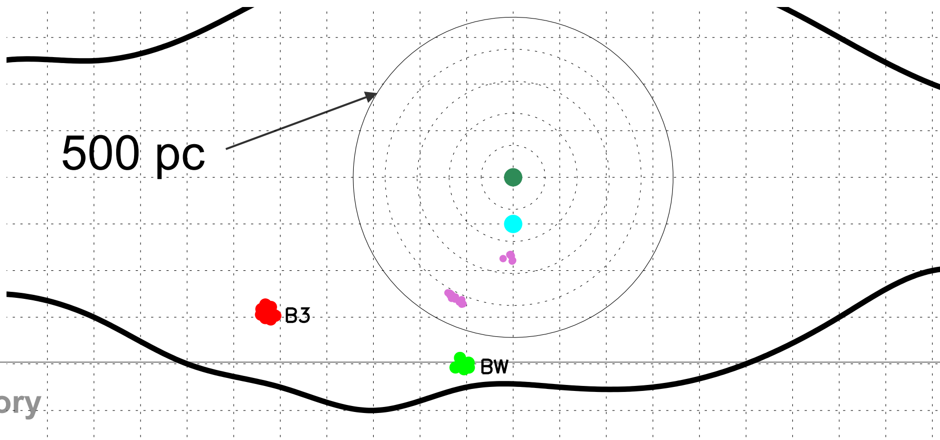
The inner 500 pc - [Fe/H] Gradients

A gradient might be a signature of a dissipative collapse (classical bulge).
No gradient from a bar-thickening hypothesis (Rich et al. 2007).

- Frogel et al. (1999): *no gradient* from JHK photometry
- Ramirez et al. (2000): *no gradient* at [Fe/H] = -0.2+-0.3 from NIR, R<5000. First spectroscopic study of metallicities in the inner bulge
- Rich & Origlia (2005) & Rich et al. ApJ (2007, 2012) from 1.5 micron, R=25000 spectra (Keck/NIRSPEC) of M giants:
  no gradient at [Fe/H]=-0.2 with a dispersion Δ of <0.15 dex
  - [Fe/H](b=-1) = -0.22+-0.14 (17 giants)
  - [Fe/H](b=-2) = -0.16+-0.12 (15 giants)
  - [Fe/H](b=-3) = -0.21+-0.09 (15 giants)
  - [Fe/H](b=-4) = -0.19+-0.08 (14 giants in BW). Hill et al. finds a broader Δ
- Vasquez et al. (2014), GIBS, *no gradient*
- Babusiaux et al. (2014), *no gradient, maybe a inversion*

The inner 500 pc - [Fe/H] Gradients

- Kunder et al. (2012) from BRAVA TiOε index: see signature of a gradient.
- A gradient of <[Fe/H]> = - 0.26 dex/kpc is predicted by Grieco et al. (2012), i.e. -0.13 dex/500 pc —> still within our uncertainties.



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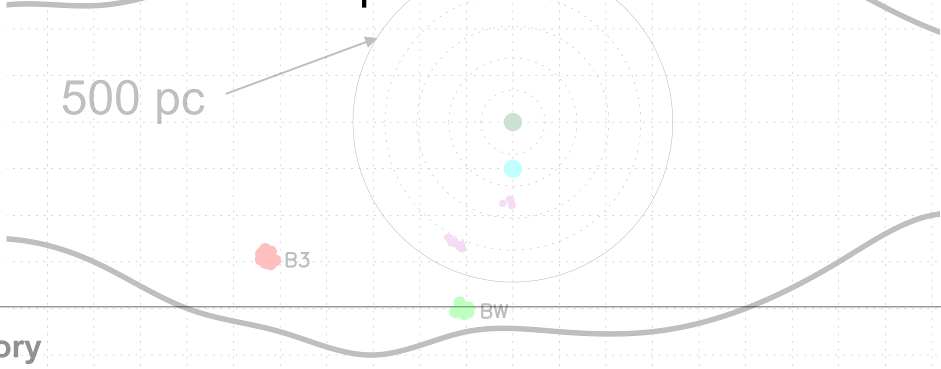
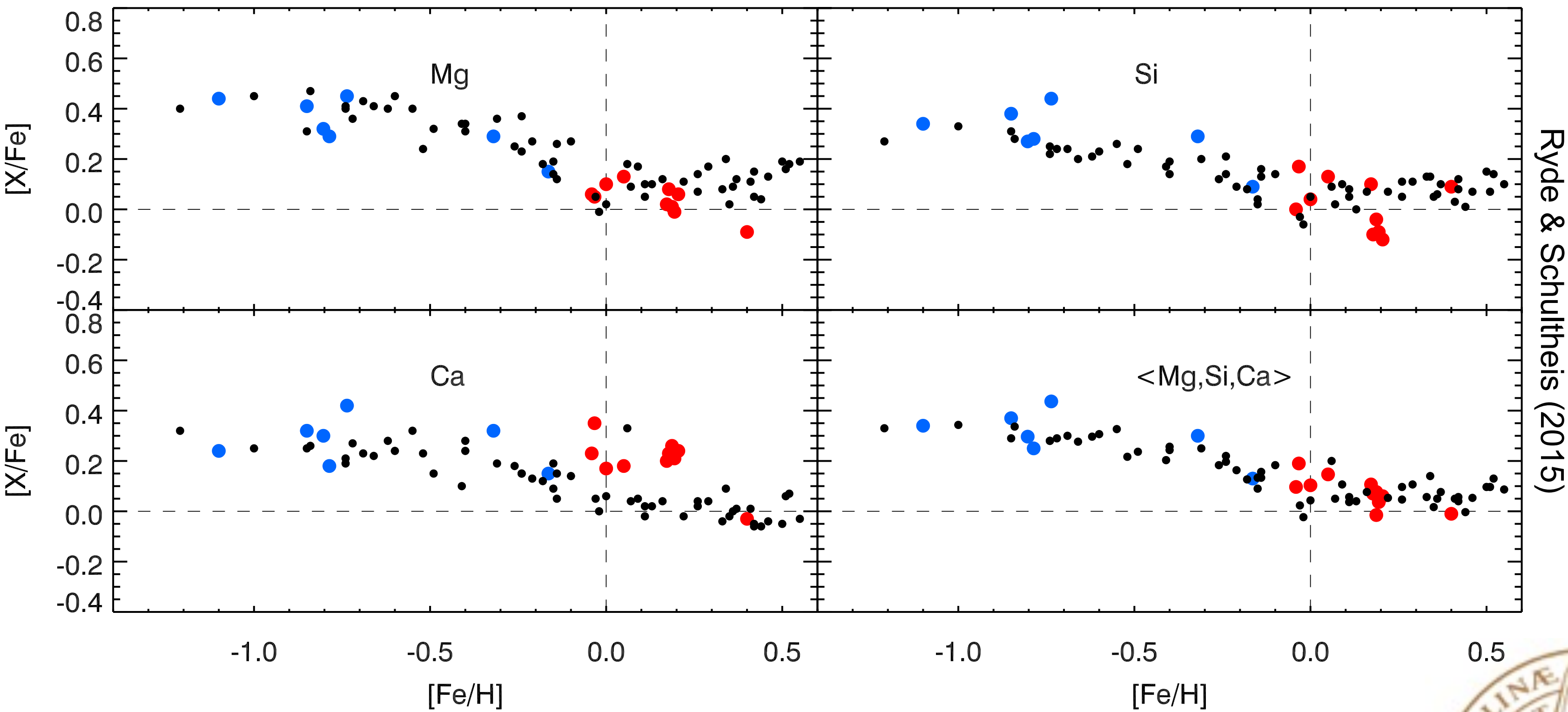
- Question of a metallicity gradient in the inner |b| < 3 degrees should be investigate more.

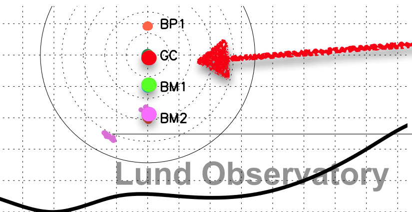
- Our project will differentially measure metallicities of ~50 red giants in the |b|<3 deg bulge (within 400 pc) at 6 locations along the minor axis with high resolution K band spectra. Also to the North. More to come!



3. The Galactic Centre and CMZ

We find metal-rich M giants only.
We find low alphas.





Galactic centre within 10 pc

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Microlensed bulge dwarfs
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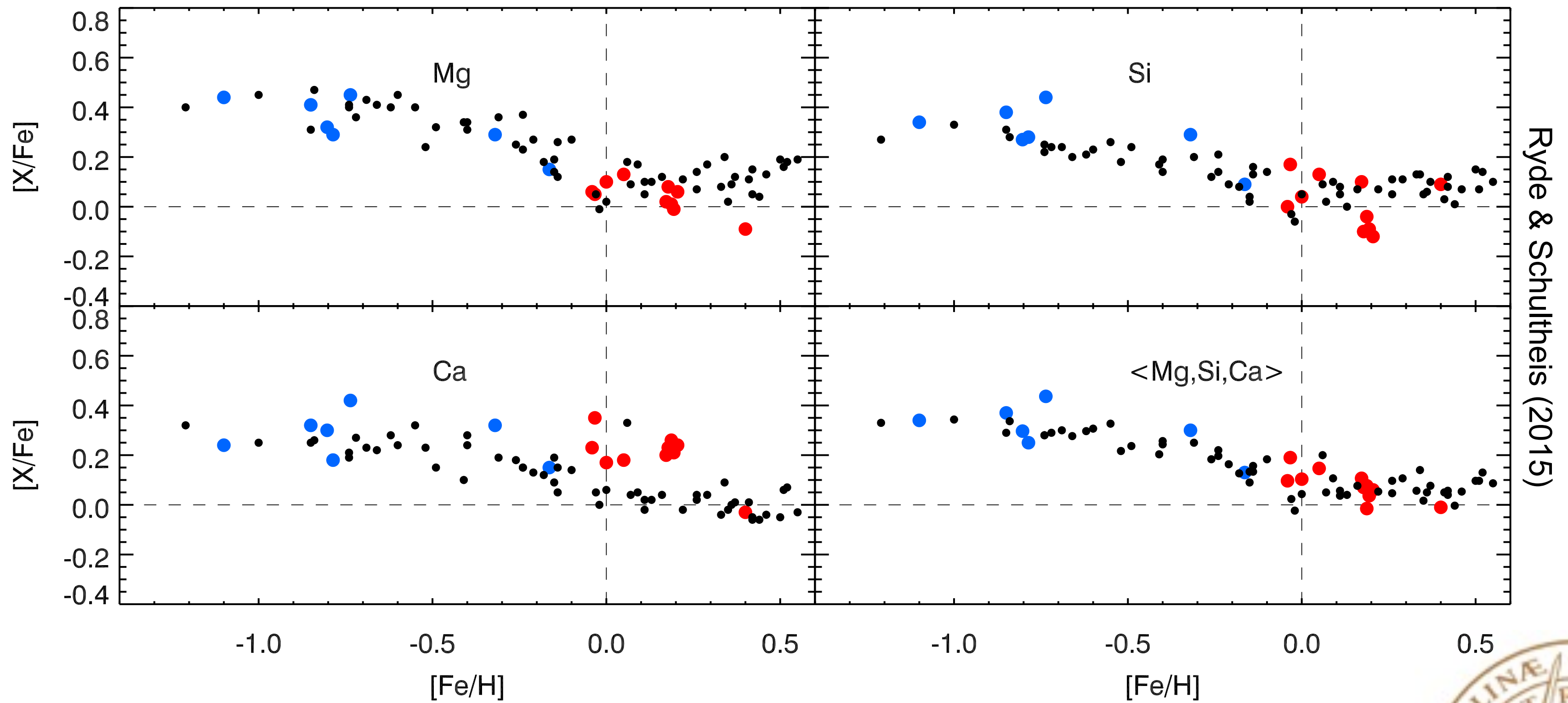

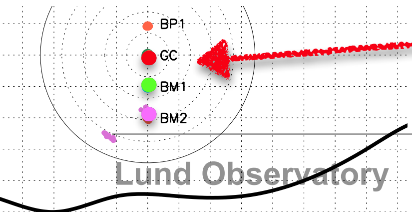

Galactic centre within 10 pc

Thick disk stars

Microlensed bulge dwarfs
(Bensby et al. 2013)

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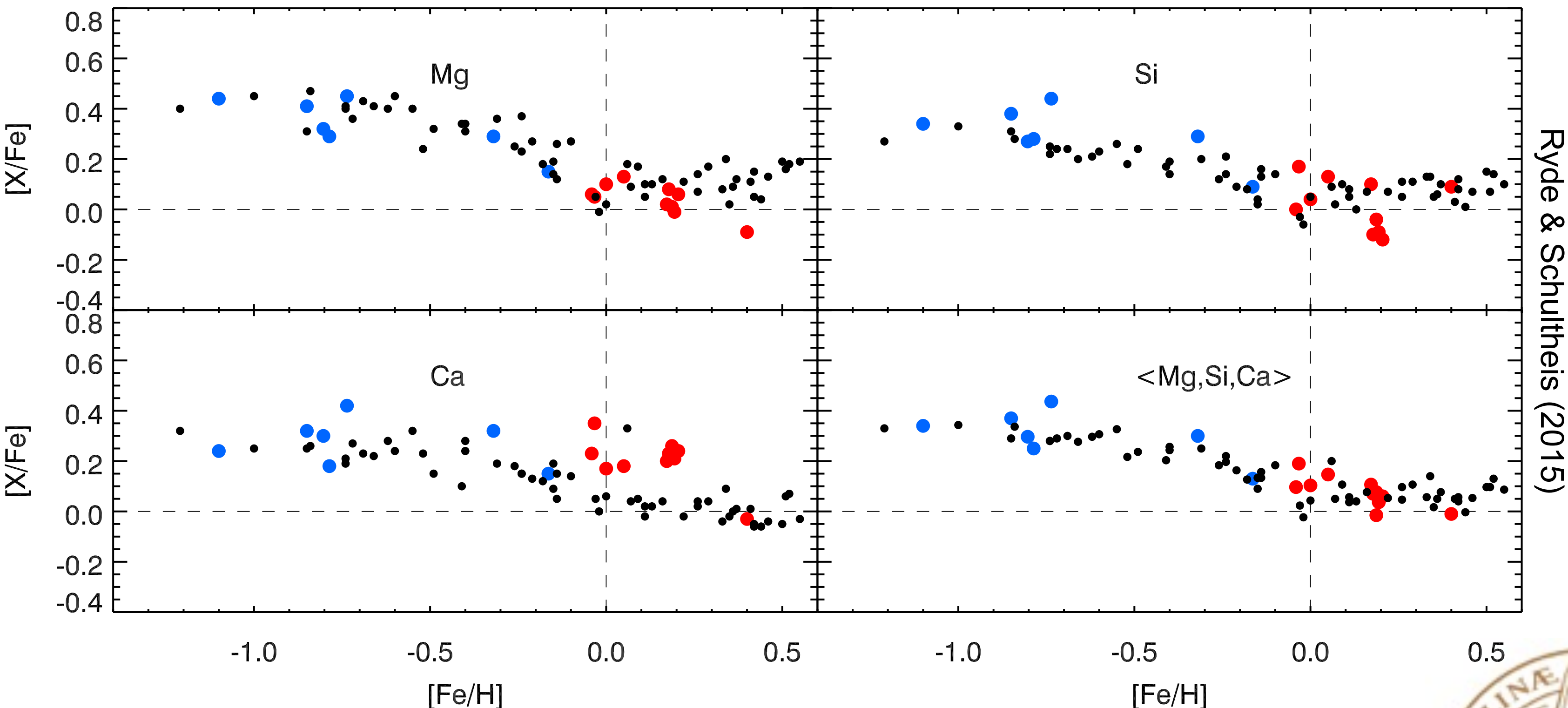

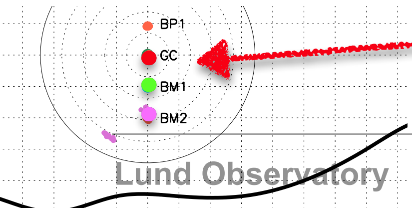

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Lund Observatory

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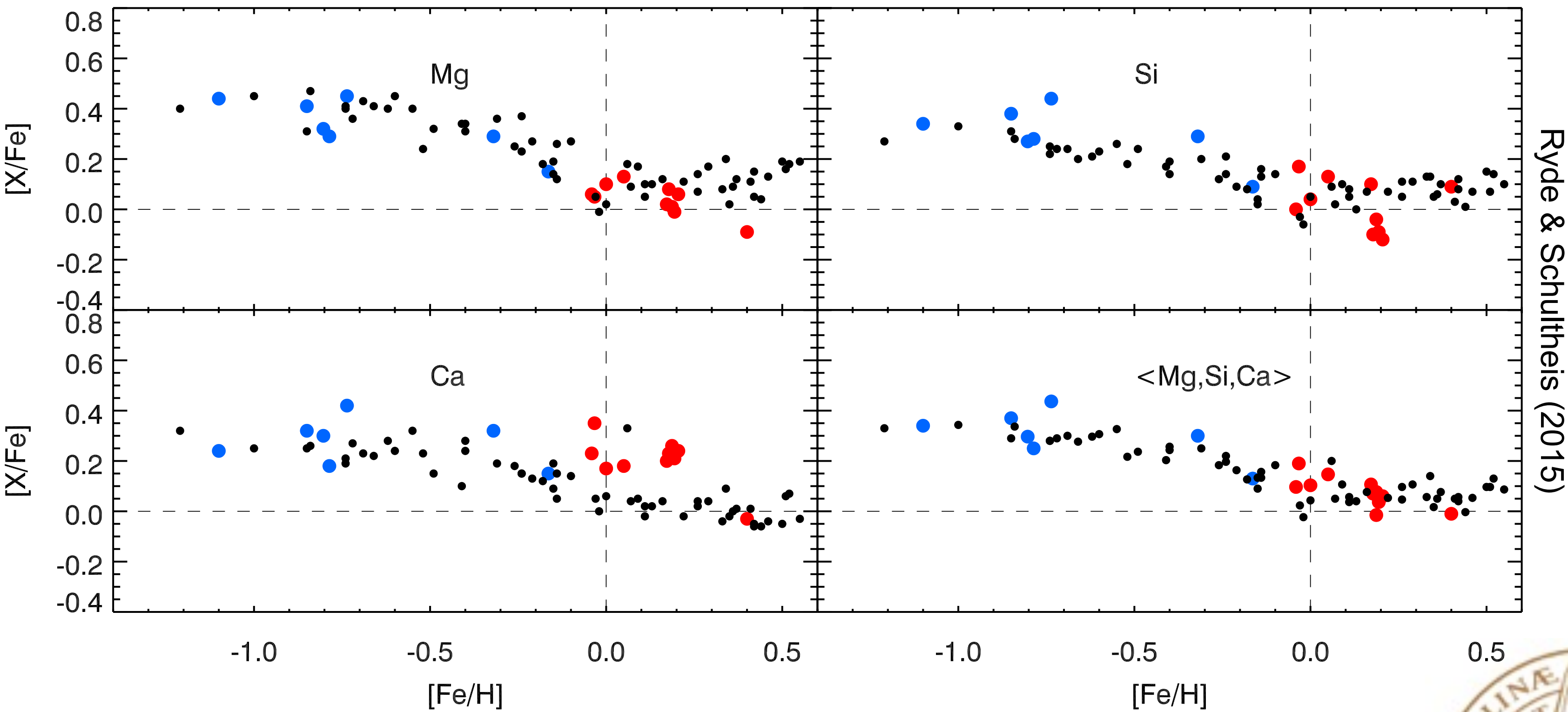

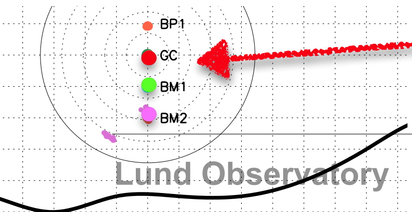

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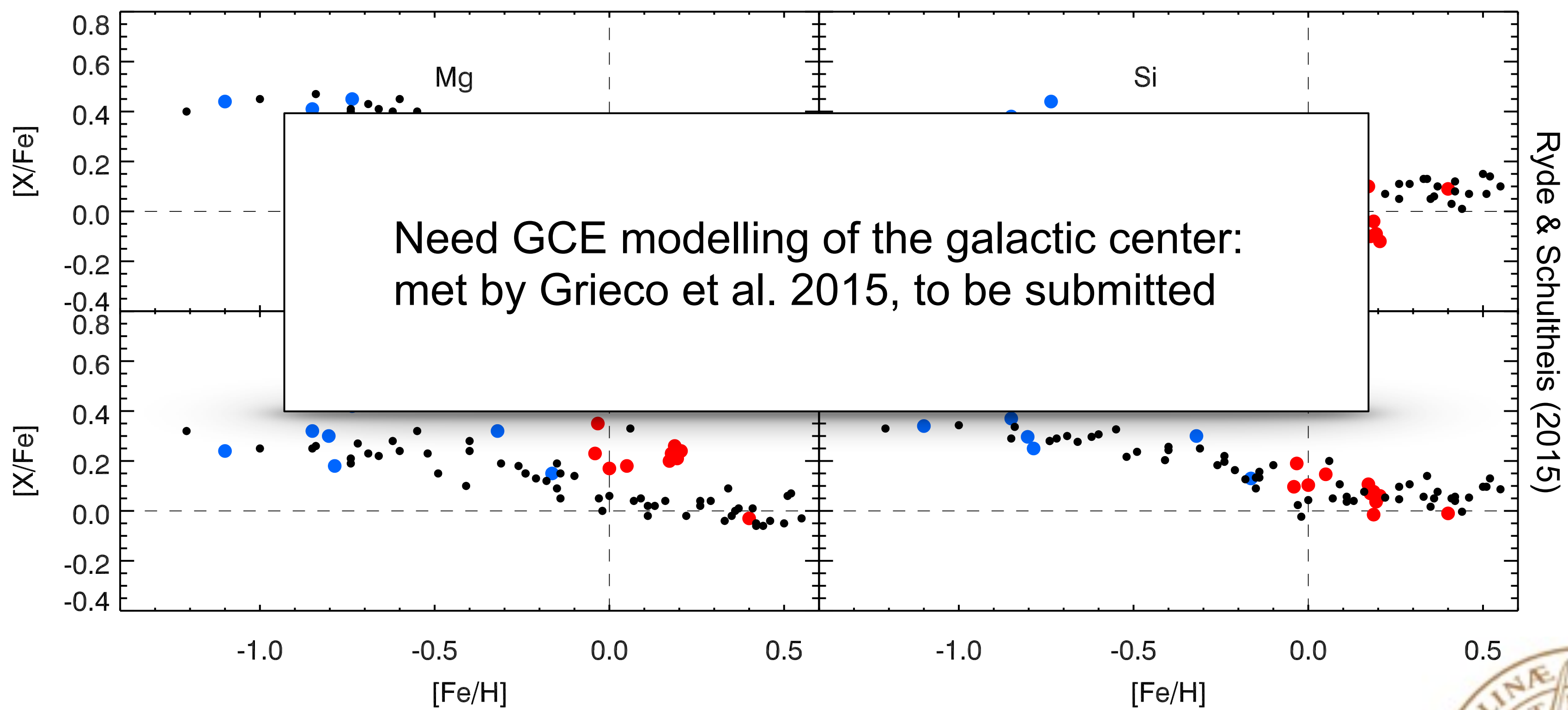
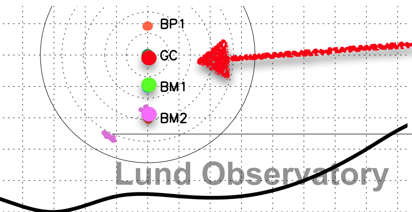


Need GCE modelling of the galactic center: met by Grieco et al. 2015, to be submitted



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Lund Observatory

3. The Galactic Centre and CMZ

Confrontation our spectroscopic observations with new chemical evolution model is presented in Grieco et al. 2015). MDF and abundance trends important diagnostics.

- Adopt model for the GC (<200 pc) as the metal-poor population of Grieco et al. (2012) assuming a intense initial burst of star formation (20 more efficient than thin disk) triggered by heavy gas infall from initial collapse (-> halo and bulge), on a very short timescale.

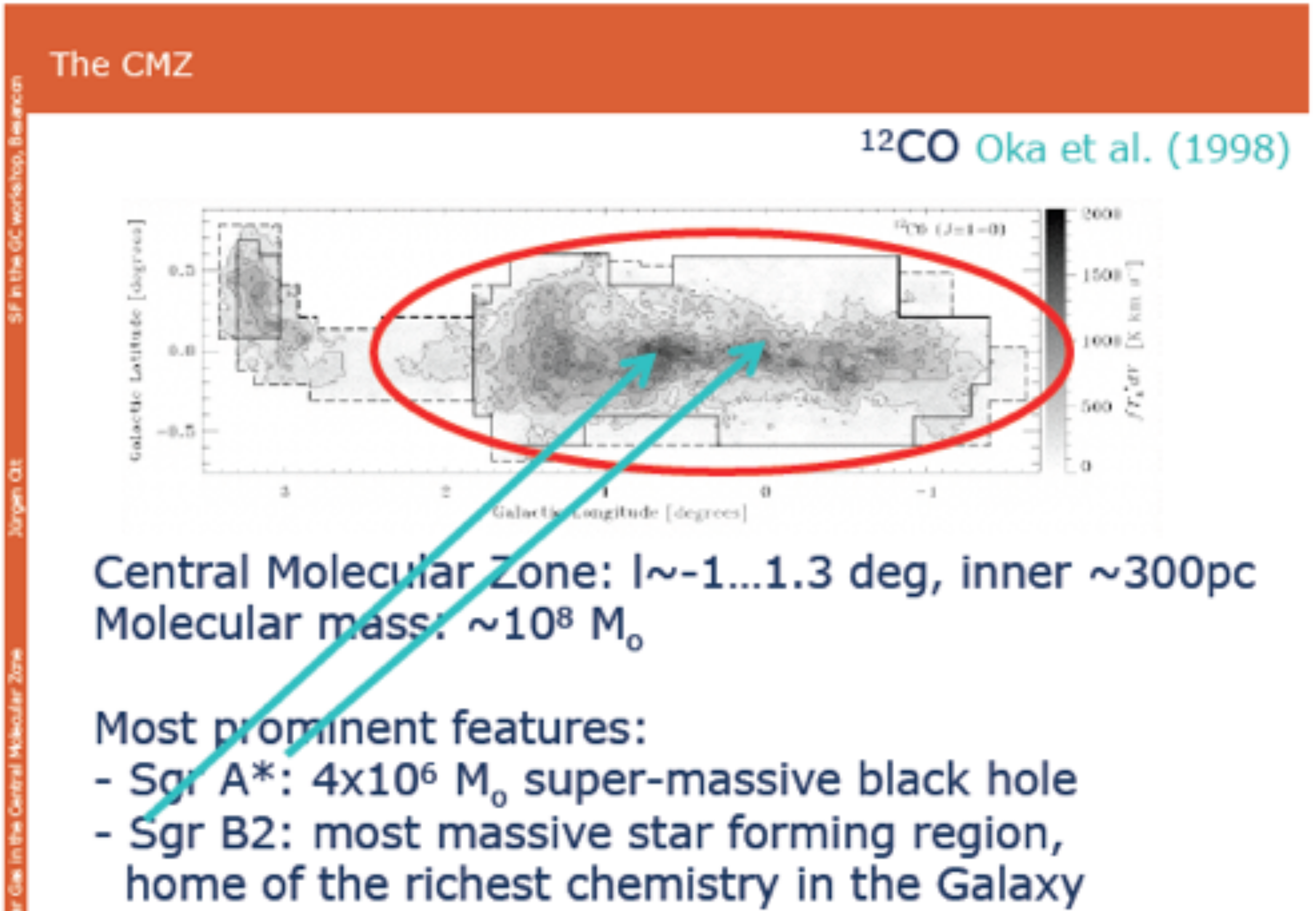
- To reproduce SFR at the present time, we over-impose a recent star burst fitting literature SFR

- Assuming different

  - IMF (Ballero et al. 2007, Salpeter, Kroupa et al. 1993, Chabrier et al. 2003)
  - star formation efficiencies (20 – 200 Gyr^{-1})
  - gas infall time-scales

3. The Galactic Centre and CMZ

Rich environment: intense star formation (past few Myr), massive stars, three of the most massive young clusters in MW. However, most stars old (Gensler et al. 2006).



3. The Galactic Centre and CMZ

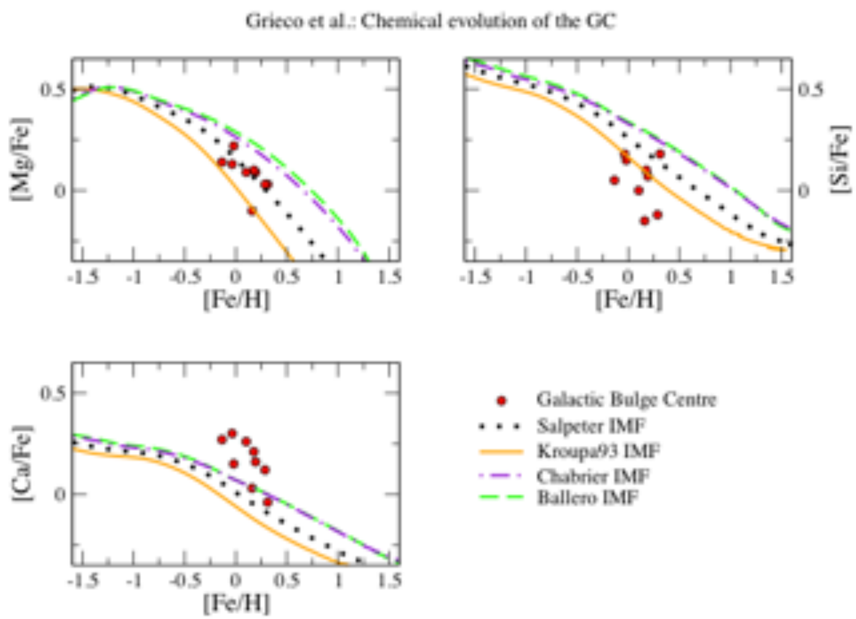
- CMZ is extremely rich in molecules. GMC complex. Most stars >9 Gyr
- CMZ has evidence of starburst activity in the last 100.000 years (Yusef Zadeh et al. 2009) → resemble low-luminous starburst Galaxies!
- Star formation rate can be obtained my counting young massive stars. By assuming an IMF and typical lifetime of massive stars one can get the SFR → typical SFR values of 0.04-0.1 Msun/year (e.g. Molinari et al. 2011, Immer et al. 2012)
- Gas pressure and temperature is higher → favour a larger Jeans mass for star formation and an initial mass biased towards massive stars.
- Due to the extreme conditions (magnetic fields, tidal shears, turbulence) Star formation is different than in the disk.
- CMZ is the best laboratory to study the interaction of energetic input on molecular gas and the subsequent star formation. One of the rare regions where we measures SFR!

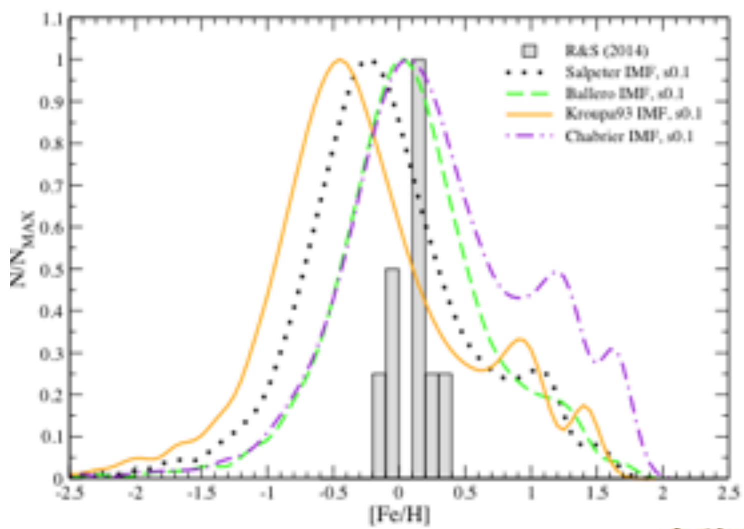
(Grieco et al. 2015)

3. The Galactic Centre and CMZ

Grieco et al. (2015): Effect of different IMF

- Salpeter and Kroupa fits better Mg and Si but not Ca
- Ca abundances are too low in the models → problem of analysis or yields?
- MDF very sensitive to IMF! Favours Ballero and Chabrier IMF, like the rest of the bulge



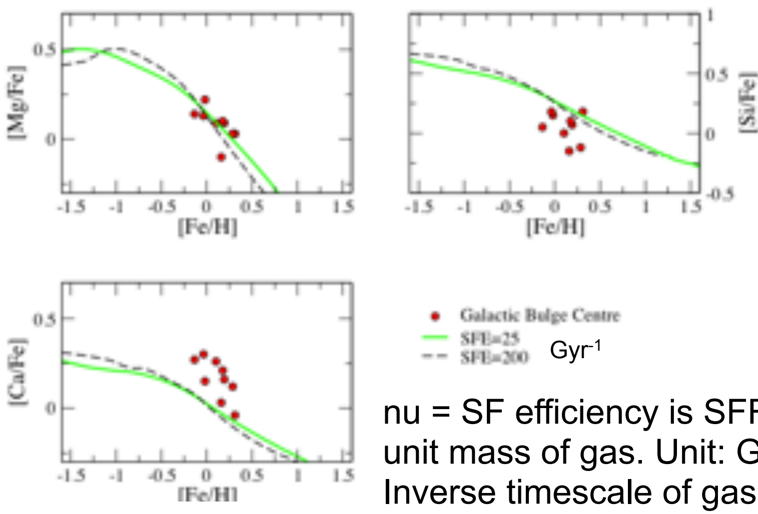


(Grieco et al. 2015)

3. The Galactic Centre and CMZ

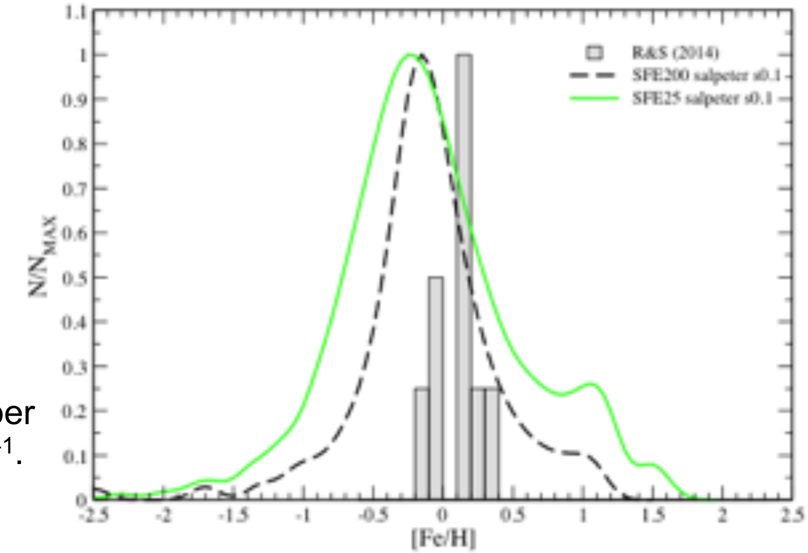
Grieco et al. (2015): Effect of different star-formation efficiency

Very small effect on changing star-formation efficiency in the abundances but also in the metallicity distribution. But need nu > 20 Gyr^{-1}. Similar to the rest of the bulge.



nu = SF efficiency is SFR per unit mass of gas. Unit: Gyr^{-1}. Inverse timescale of gas consumption.
Solar neighb.: 1Gyr^{-1}

Bulge: high, like star burst.

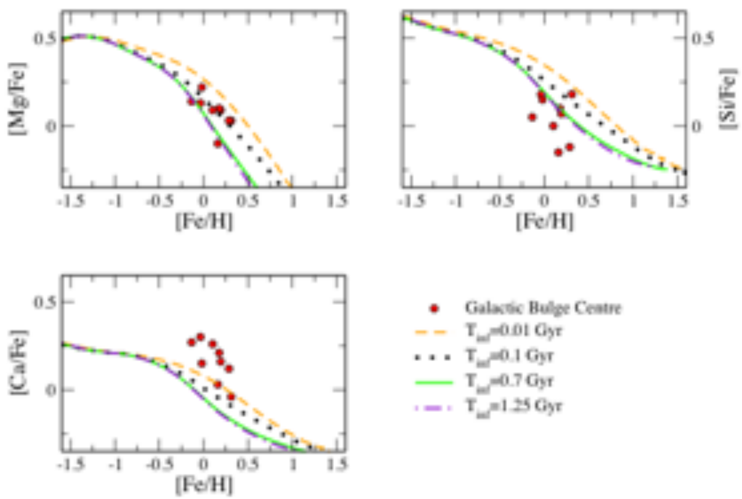


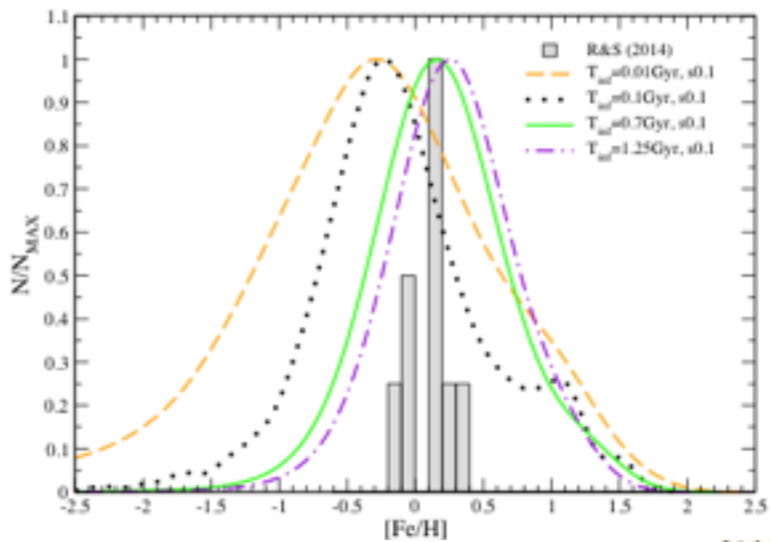
(Grieco et al. 2015)

3. The Galactic Centre and CMZ

Grieco et al. (2015): Effect of varying infall time-scale

Small effect in abundances.Timescale between 0.1 and 1.25 Gyr
MDF very sensitive: favoured time-scale: 0.7-1.25 Gyr





(Grieco et al. 2015)

3. The Galactic Centre and CMZ

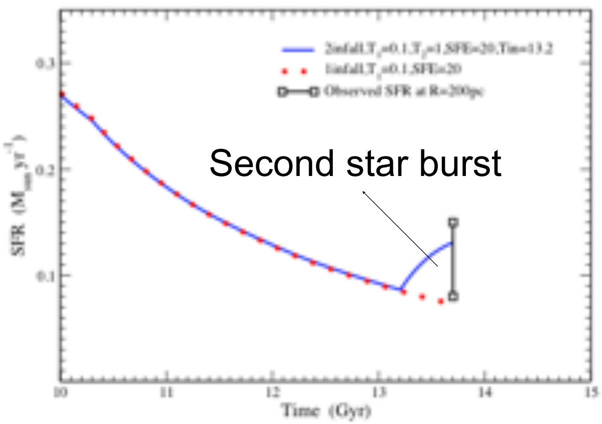
Grieco et al. (2015): Simulation of a recent starburst

To reproduce present time SFR: second burst 500 Myr ago. Origin of the gas can be either from merger processes or from gas in inner disk (galactic bar).

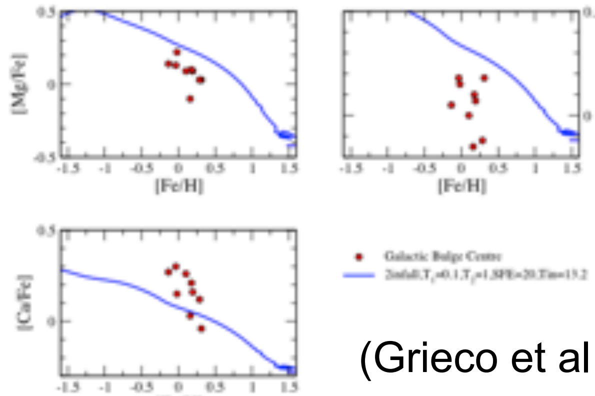
Testing several cases of second star burst : i) stong infall, ii) modest infall iii) starburst due to sudden increase of SFE

Best model is a second burst with modest infall with a SFR and SFE of 25 Gyr^{-1}. The SFR of 0.125 Msun/yr. Second star burst does not change MDF or abundances

We can exclude a huge second gas infall which would predict too low abundances and metallicities



No effect of second burst on abundances



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3. The Galactic Centre and CMZ

Grieco et al. (2015): Results

Confrontation our spectroscopic observations with new chemical evolution model is presented in Grieco et al. 2015):

- To reproduce [α/Fe] in GC: main strong burst of star formation and evolved very quickly (like rest of the bulge). Formation time 0.7-1.25 Gyr, high SF efficiency of 25 Gyr^{-1}.
- Best IMF needs more massive stars
- Late episode of SF (lasted several hundred years) trigged by modest (not large) gas infall/accretion in the GC, with high SF efficiency

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Low statistics: need of more stars

4. The Role of Massive Stars in the Bulge

Several indications that there are relatively more massive Bulge stars:

+ Morris (1993): SF conditions different from solar neighbourhood
+ McWilliam & Rich (2004): low oxygen; need for more WR stars
+ Fulbright et al. (2007): -“-
+ McWilliam et al. (2008): -“-
+ Cunha et al. (2008): Fluorine in the Bulge point to more WR stars
+ Jönsson, Ryde et al. (2014): -“-
+ Johnson et al. (2014): GCE models require hypernovae
+ Grieco et al. (2012, 2015) modelling of the Galactic Center

However, the Fluorine argument is uncertain depending on WR yields:

– Palacios et al. (2005). WR cannot produce much ^{19}F
– Uttenthaler et al. (2008) similarity F-production disk/bulge
– Ryde et al. (2010) no indication of large C abundances in the Bulge…

More observations at KPNO in May to test the WR contribution in the solar neighbourhood. New GCE modelling including F, aslo in the bulge with F. Matteucci and V. Grieco. Unsettled.

4. The Role of Massive Stars in the Bulge

Where can Fluorine be produced in the Universe?

- 3 main cosmic formation sites for Fluorine:
  - Low-mass, thermal-pulsing AGB stars (2-4 Msun)
  - nu-process in SNIIe
  - WR stars
- Solar neighbourhood no WR contribution? (Kobayashi et al. 2011, Jönsson et al. ApJL 2014). More observations at KPNO in May.
- Extra contribution needed in the Bulge (Cunha et al. 2008, Jönsson et al. A&A 2014)

4. The Role of Massive Stars in the Bulge

Observational difficulties:

- Quite few F-investigations at all due to few diagnostics
- Stellar Fluorine abundance difficult to measure
- The only Fluorine diagnostics is the HF molecule (hyrdofluoric acid)
- Only a single line at 23358 Å (K band)
- Confusion about zero-point energy of energy levels (Jönsson et al. 2014)

4. The Role of Massive Stars in the Bulge

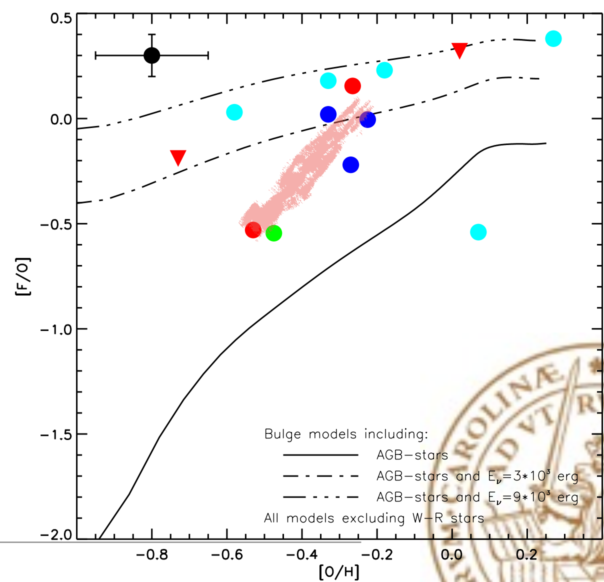
Jönsson et al. (2014):

- We see a steep increase in [F/O] vs [O/H]
- Larger increase than existing models
- These, however, do not include WR
- Together with decrease of [Zr/F] vs [Fe/H] we conclude that WR contribution might be important in the Bulge. See also Bulge Review by Rich (2013)

- We have demonstrated the importance of a consistent line list

Observations of Bulge K giants (VLT/CRIRES & UVES):

Star	$T_{\rm eff}$ [K]	$\log g$ (cgs)	[Fe/H][a]	[α/Fe][b]	$\xi_{\rm micro}$ [km s^{-1}]
Arcturus[c]	4262	1.62	−0.63	0.23	1.62
B3-b1	4372	1.11	−1.03	0.39	1.45
B3-b7	4261	1.86	−0.09	0.01	1.57
B3-b8	4282	1.67	−0.75	0.28	1.47
B3-f3	4573	2.55	0.19	0.00	1.76
BW-f6	4117	1.22	−0.54	0.20	1.70
B6-b8	3989	1.30	−0.17	0.05	1.46
B6-f1	4101	1.52	−0.10	0.02	1.65
B6-f7	4221	1.83	−0.41	0.14	1.63
BMB 78[d]	3600	0.8	−0.08	0.01	2.5
BMB 289[d]	3375	0.4	−0.10	0.02	3.0
I-322[d]	4250	1.5	−0.29	0.10	2.0
IV-072[d]	4400	2.4	0.19	0.00	2.2
IV-329[d]	4275	1.3	−0.57	0.21	1.8



Conclusions

- Inner <[Fe/H]> = +0.15 dex region extends out to 150 pc (1 degree). No gradient?
- alpha-enhancement trends very similar in the entire Bulge -> rapid formation scenario & homogeneity of enrichment process (Rich et al. 2012)
- In the galactic center we see

  - a high metallicity population
  - a lack of metal-poor stars
  - New GCE model of GC (Grieco et al. 2015): strong burst, very fast SF, efficiency of 25 Gyr^{-1}, more massive IMF, second burst for present SFR by *modest* infall

- WR star contribution may be needed in the bulge. New obs & models needed.
- Keep tuned for a discussion of a gradient in the inner Bulge