

Abundances of bulge giants from high-resolution spectra

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The structure of spiral galaxies



NGC 1232



NGC 4564

Pictures from http://www.eso.org/public/images/archive/category/galaxies/

The structure of bulges: spheroid



Messier 104

Picture from http://www.eso.org/public/images/archive/category/galaxies/

The structure of bulges: bar



NGC 7424

Picture from http://www.eso.org/public/images/archive/category/galaxies/

The structure of bulges: box/peanut



NGC 4564

Picture from http://www.eso.org/public/images/archive/category/galaxies/

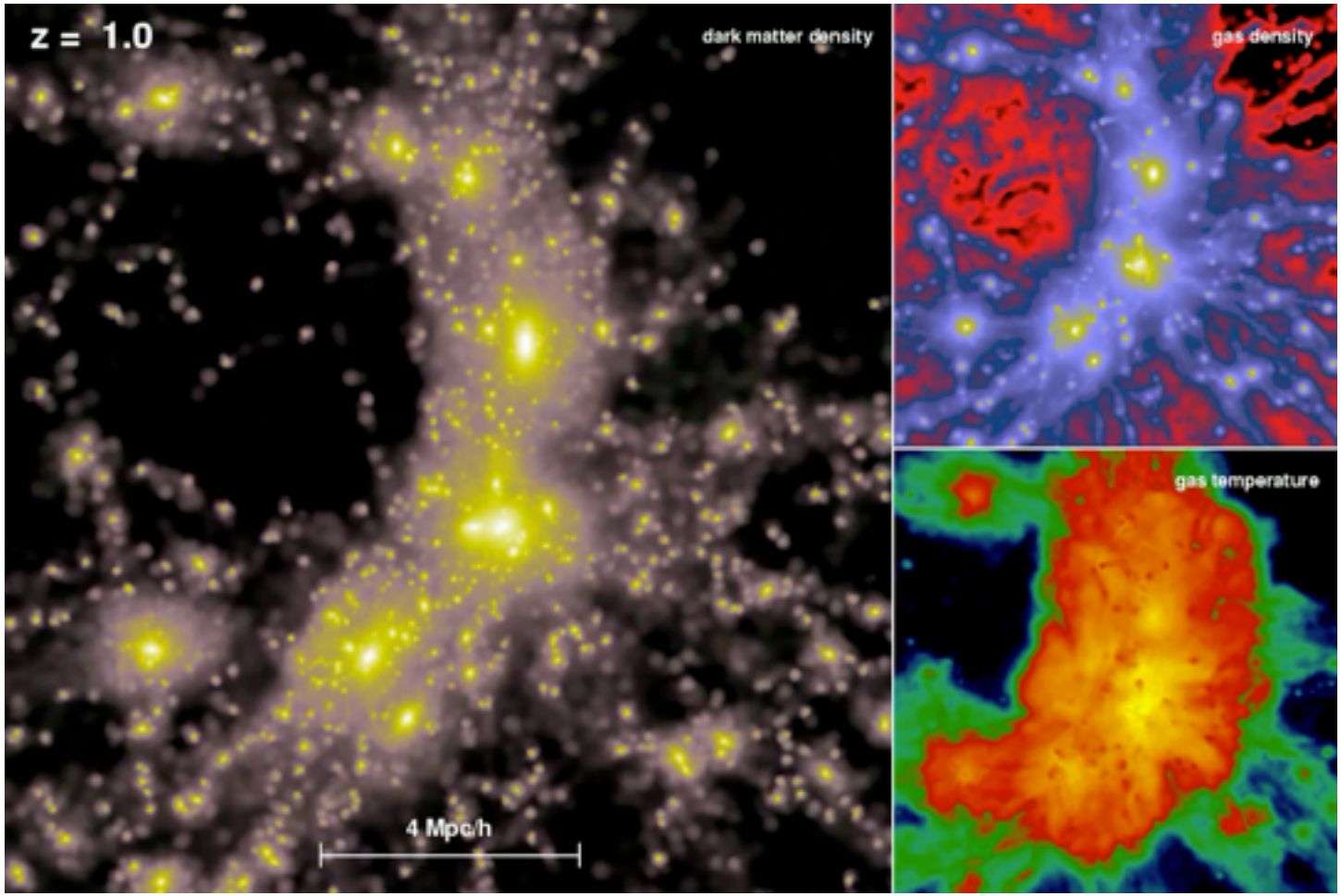
The structure of bulges: x-shape



NGC 4710

Picture from http://hubblesite.org/gallery/album/galaxy/npp/all/

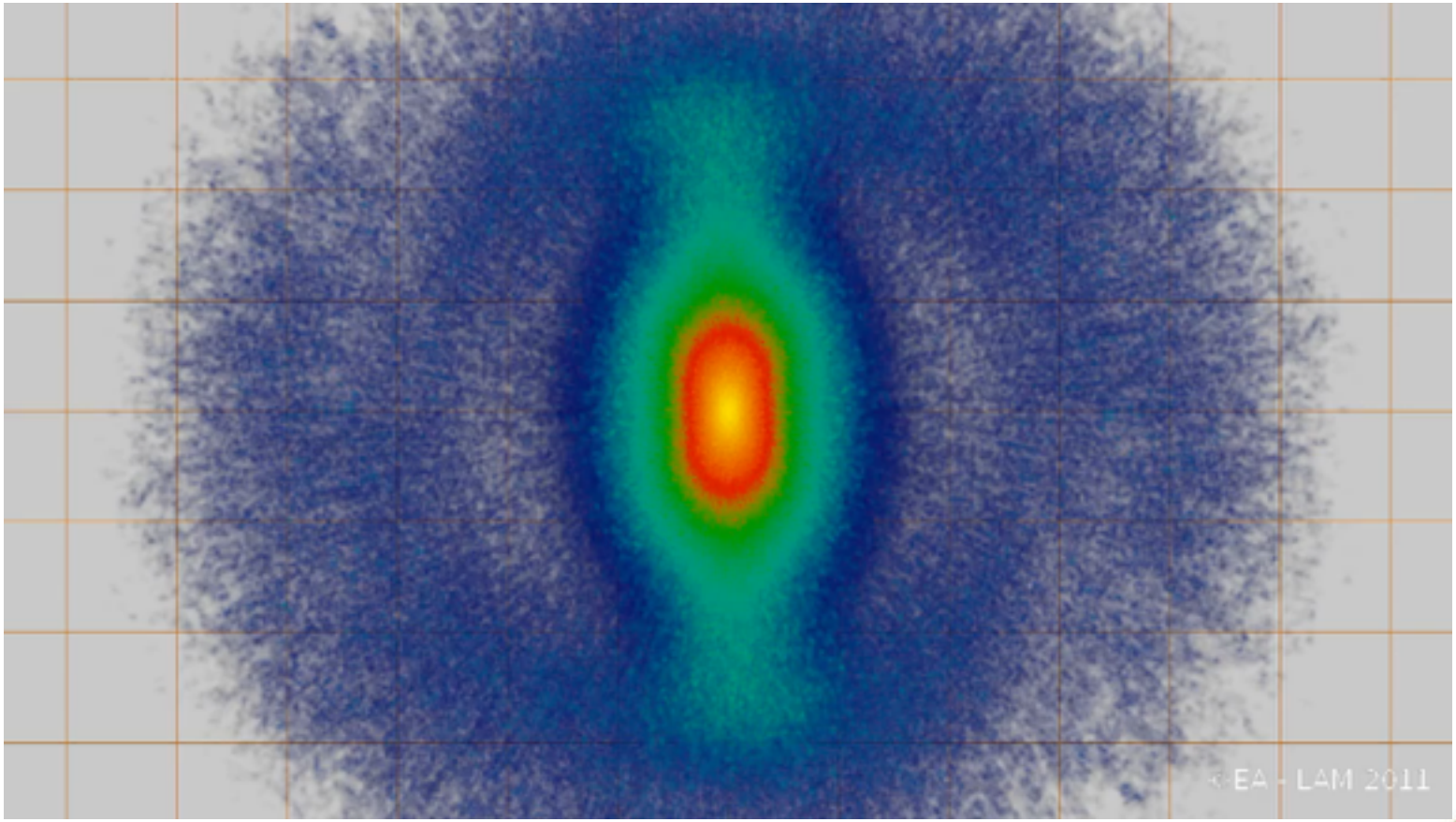
The formation of bulges: merger origin



ΛCDM-simulation by Volker Springel

Movie from http://www.mpa-garching.mpg.de/gadget/

The formation of bulges: secular evolution



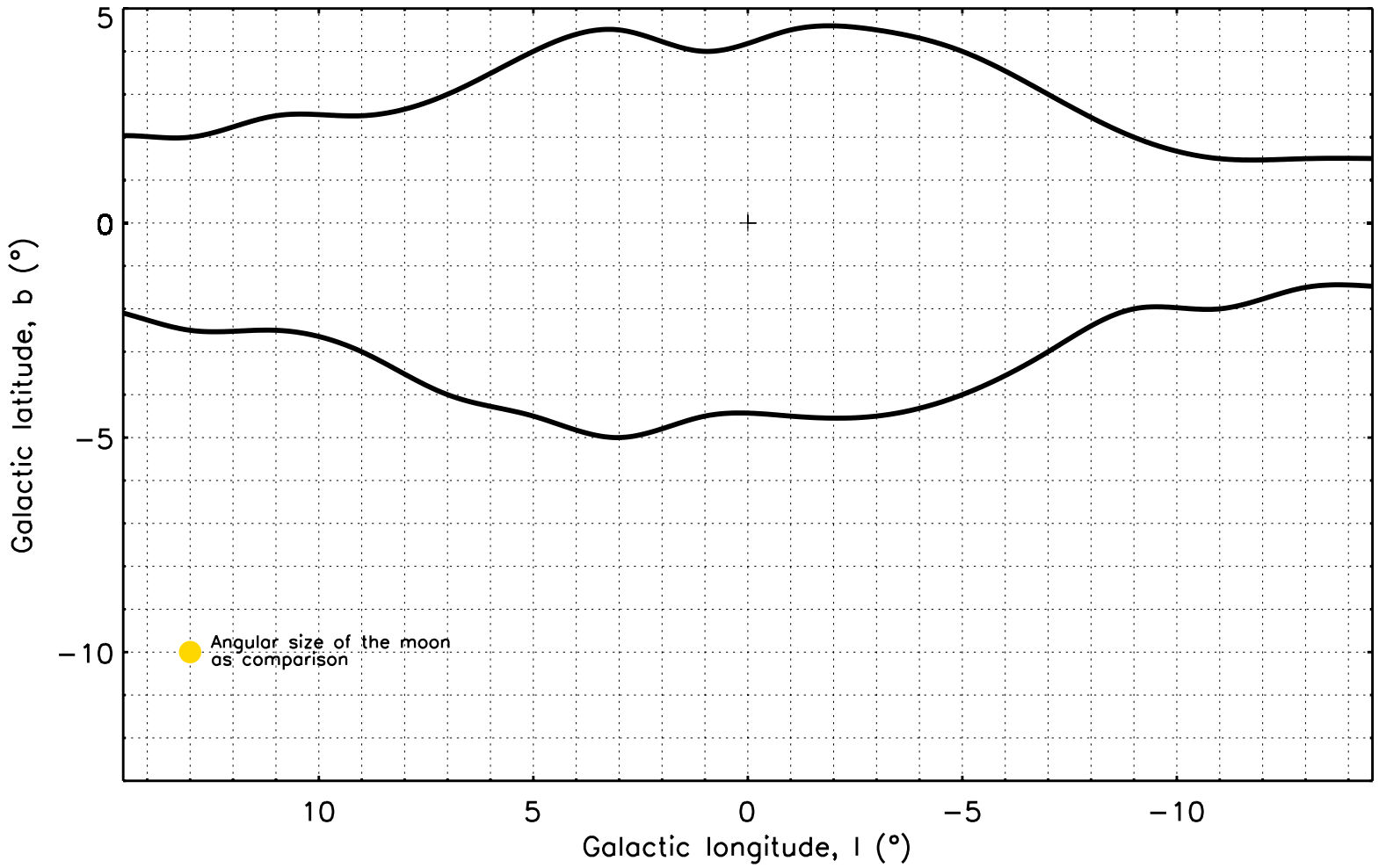
N-body simulation by Lia Athanassoula

Movie from http://www.lam.fr/recherche-14/dynamique-des-galaxies/scientific-results/

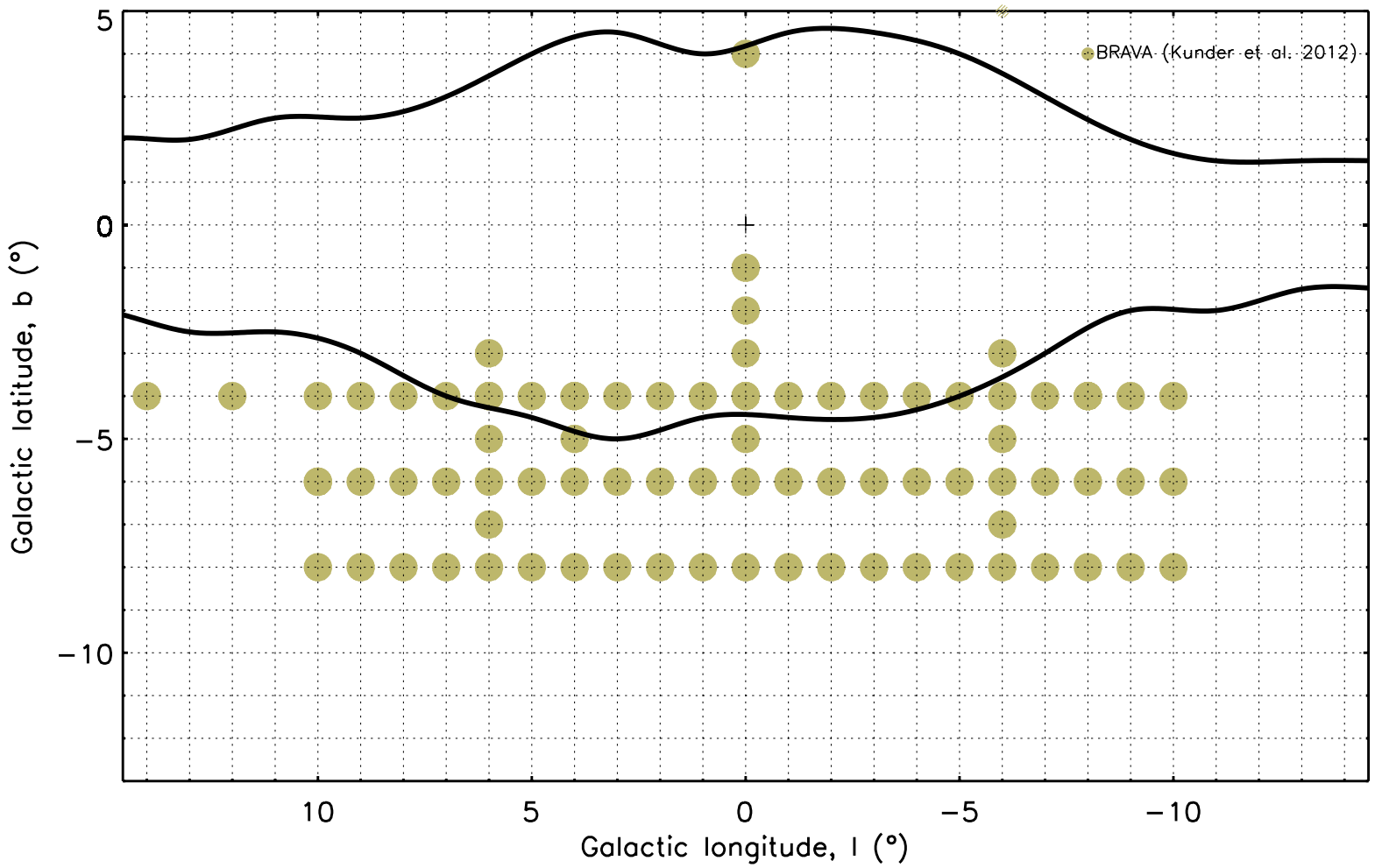
The Milky Way bulge: COBE/DIRBE



The Milky Way bulge: COBE/DIRBE



The Milky Way bulge: BRAVA



10000 giants
R=4200

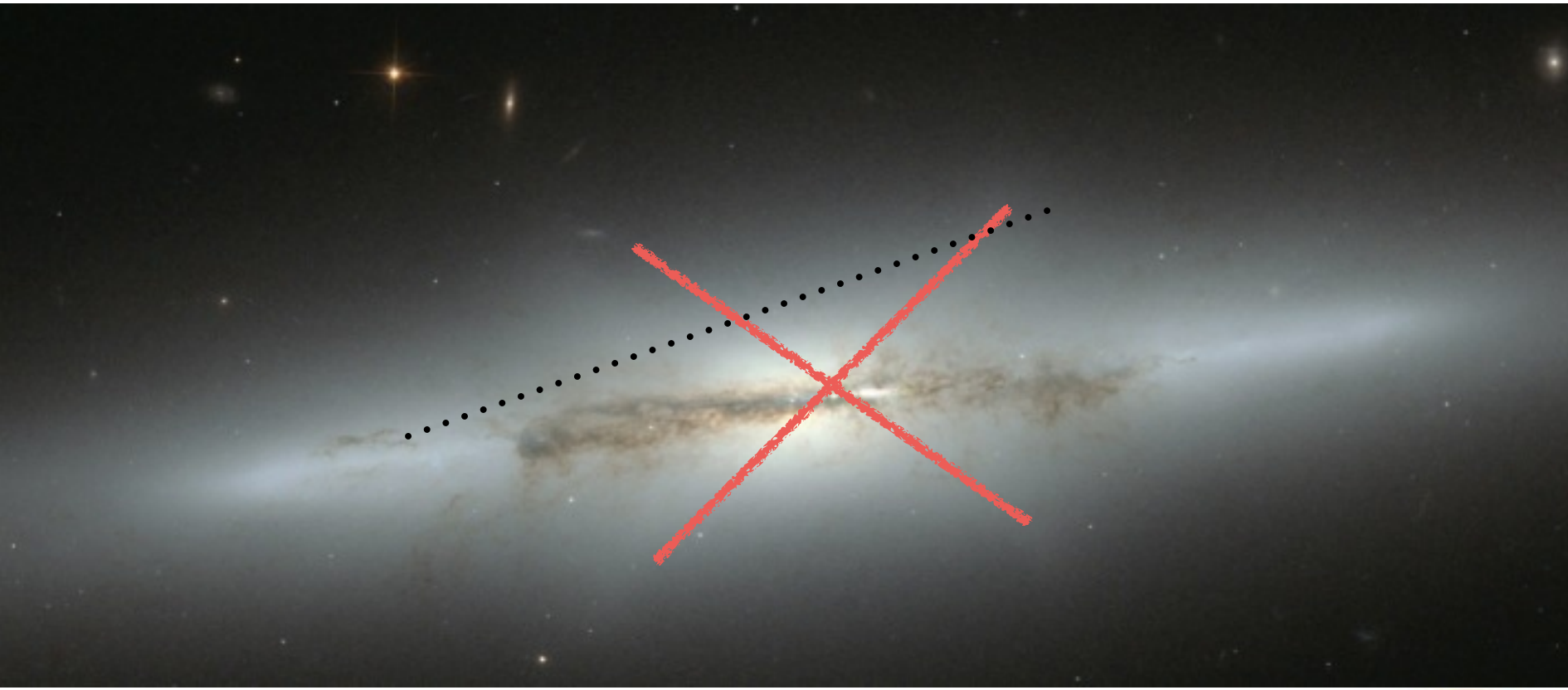
The Milky Way bulge: x-shape



McWilliam & Zoccali 2010

Picture from http://hubblesite.org/gallery/album/galaxy/npp/all/

The Milky Way bulge: x-shape



McWilliam & Zoccali 2010

Picture from http://hubblesite.org/gallery/album/galaxy/npp/all/

Kinematics/morphology: bar

A bar-bulge component

- Weiland et al. 1994 (COBE/DIRBE):
  - Bulge looks peanuty => there is a bar-bulge
- Rich et al. 2007 & Kunder et al. 2012 (BRAVA):
  - Bulge show cylindrical rotation => there is a bar-bulge
- McWilliam & Zoccali 2010:
  - Bulge has two red clumps => there is a x-shaped bar-bulge



Kinematics/morphology: bar and spheroid?

A bar-bulge component

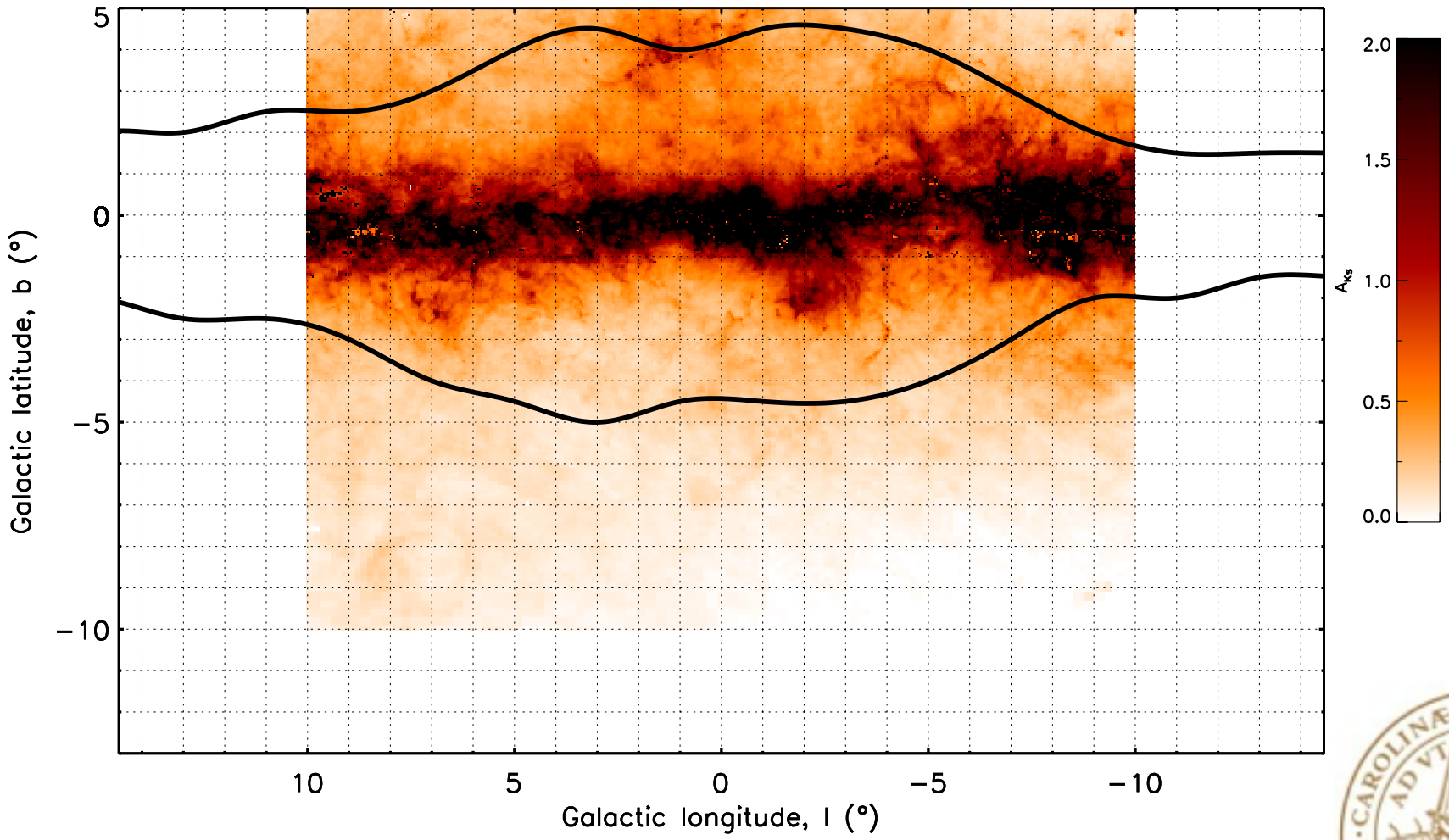
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  - Bulge has two red clumps => there is a x-shaped bar-bulge

A merger-bulge component

- Ness et al. 2012/2013:
  - The x-shape is not visible for low [Fe/H] => there is an old spheroid-bulge?
- Dékány et al. 2013:
  - The old RR Lyrae stars in the bulge do not have bar-kinematics => there is an old spheroid-bulge?

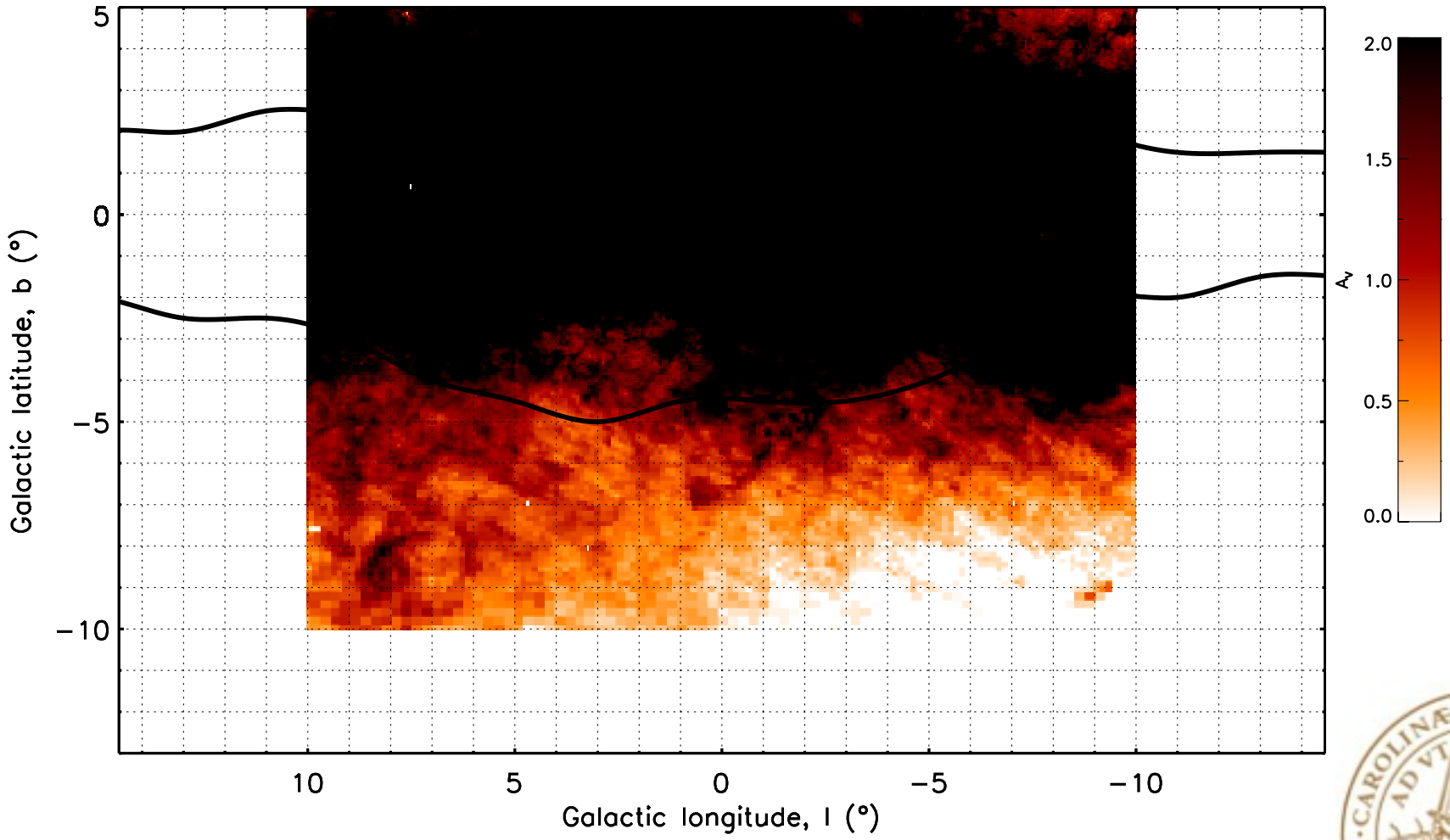


The Milky Way bulge: K-band extinction



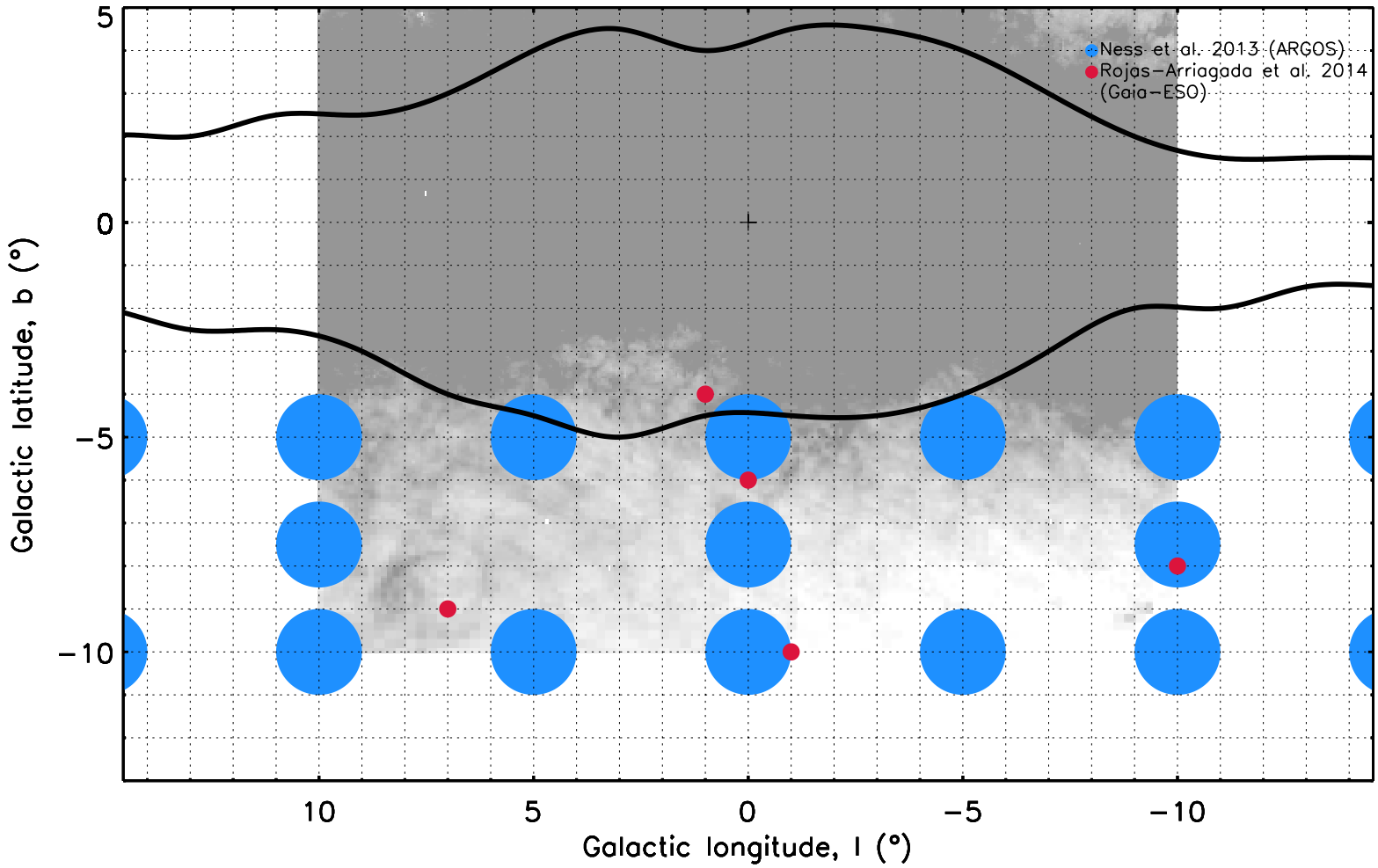
Data from http://mill.astro.puc.cl/BEAM/calculator.php

The Milky Way bulge: V-band extinction



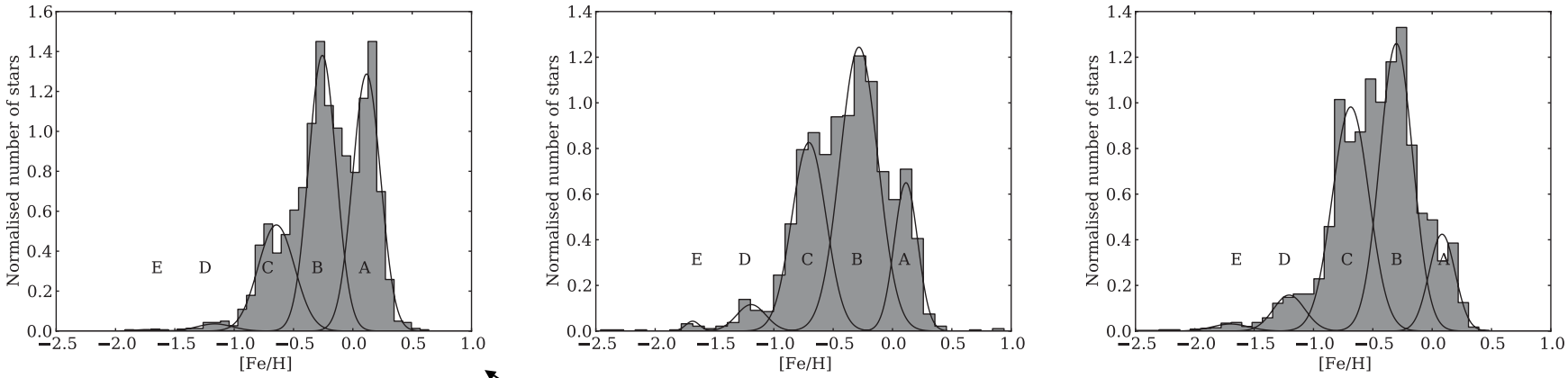
Data from http://mill.astro.puc.cl/BEAM/calculator.php

The Milky Way bulge: MDF

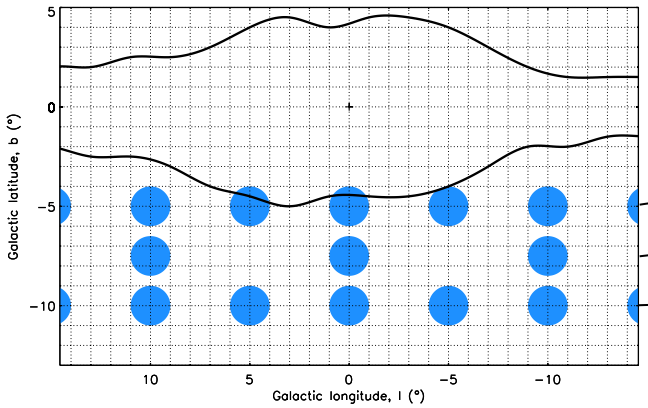


ARGOS:
R=11000
8400-8850 Å
Gaia-ESO:
R=16200
8484-9001 Å

The Milky Way bulge: MDF

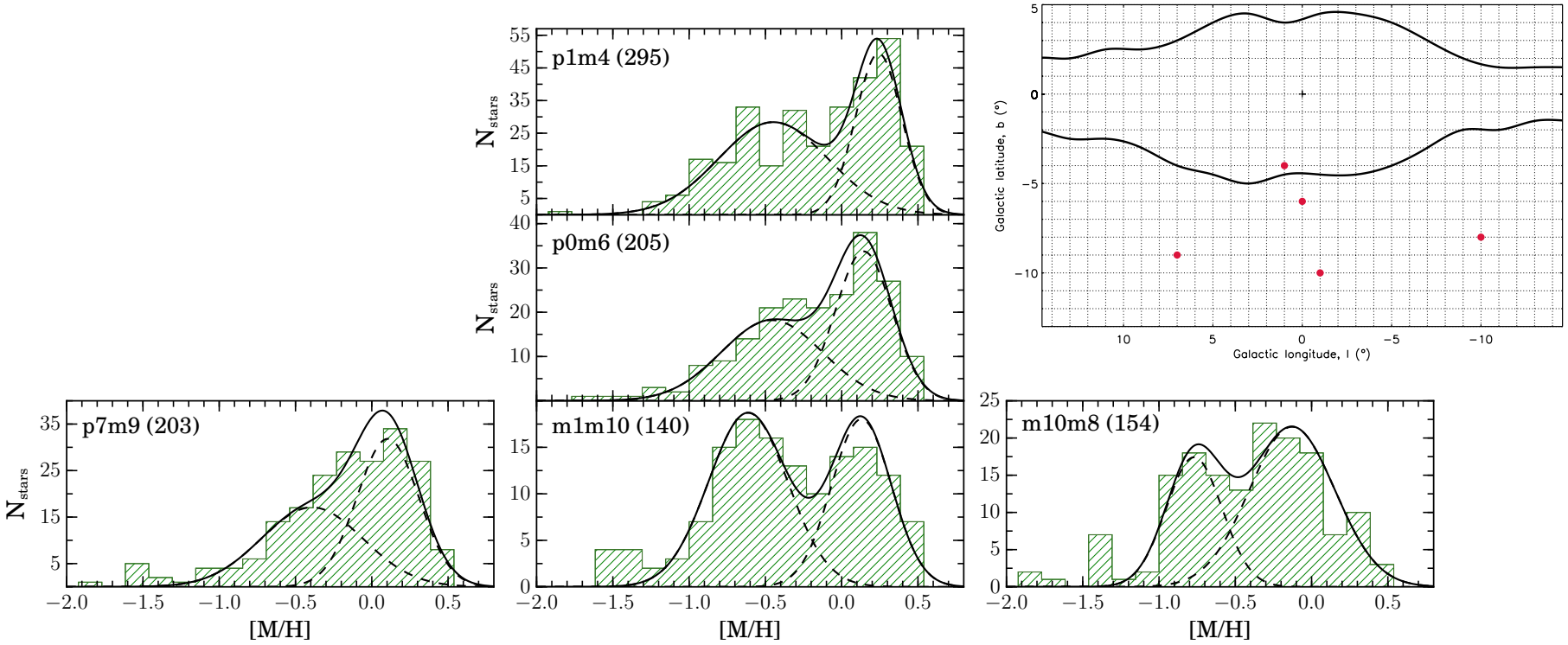


(a) $l \pm 15°, b = -5°$ (b) $l \pm 15°, b = -7.5°$ (c) $l \pm 15°, b = -10°$



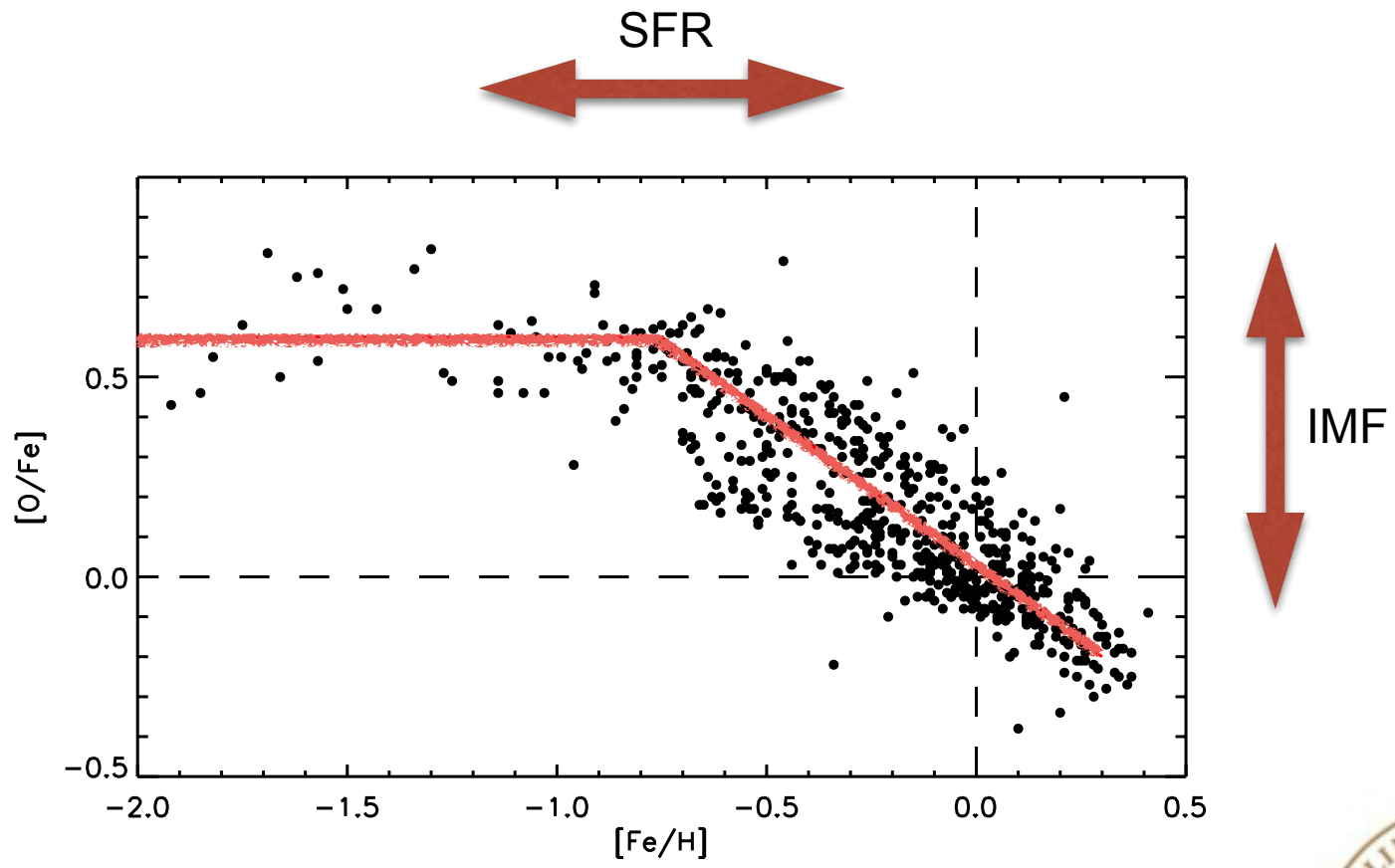
Ness at al. 2013 (ARGOS)

The Milky Way bulge: MDF

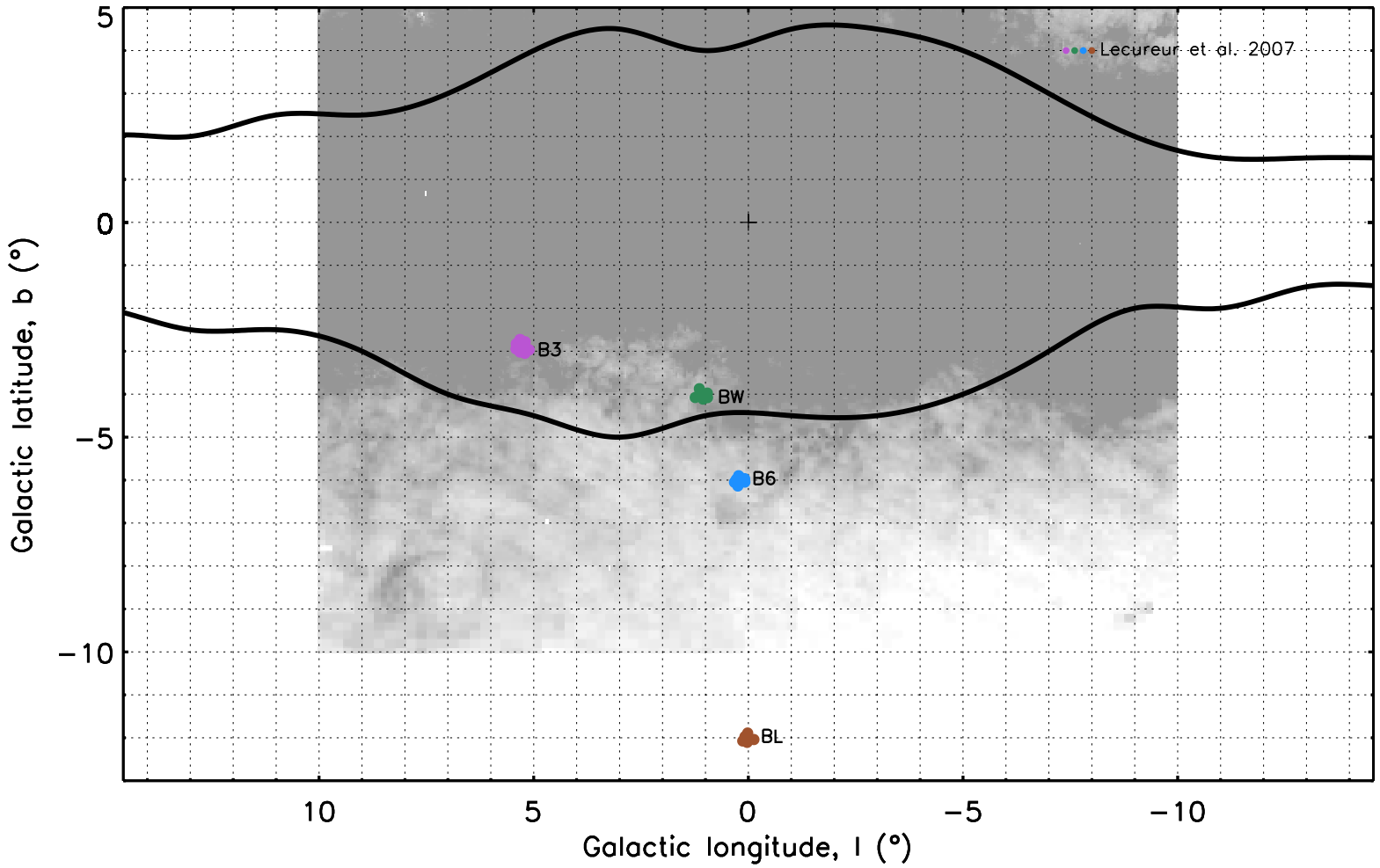


Rojas-Arriagada et al. 2014 (Gaia-ESO)

Alpha elements

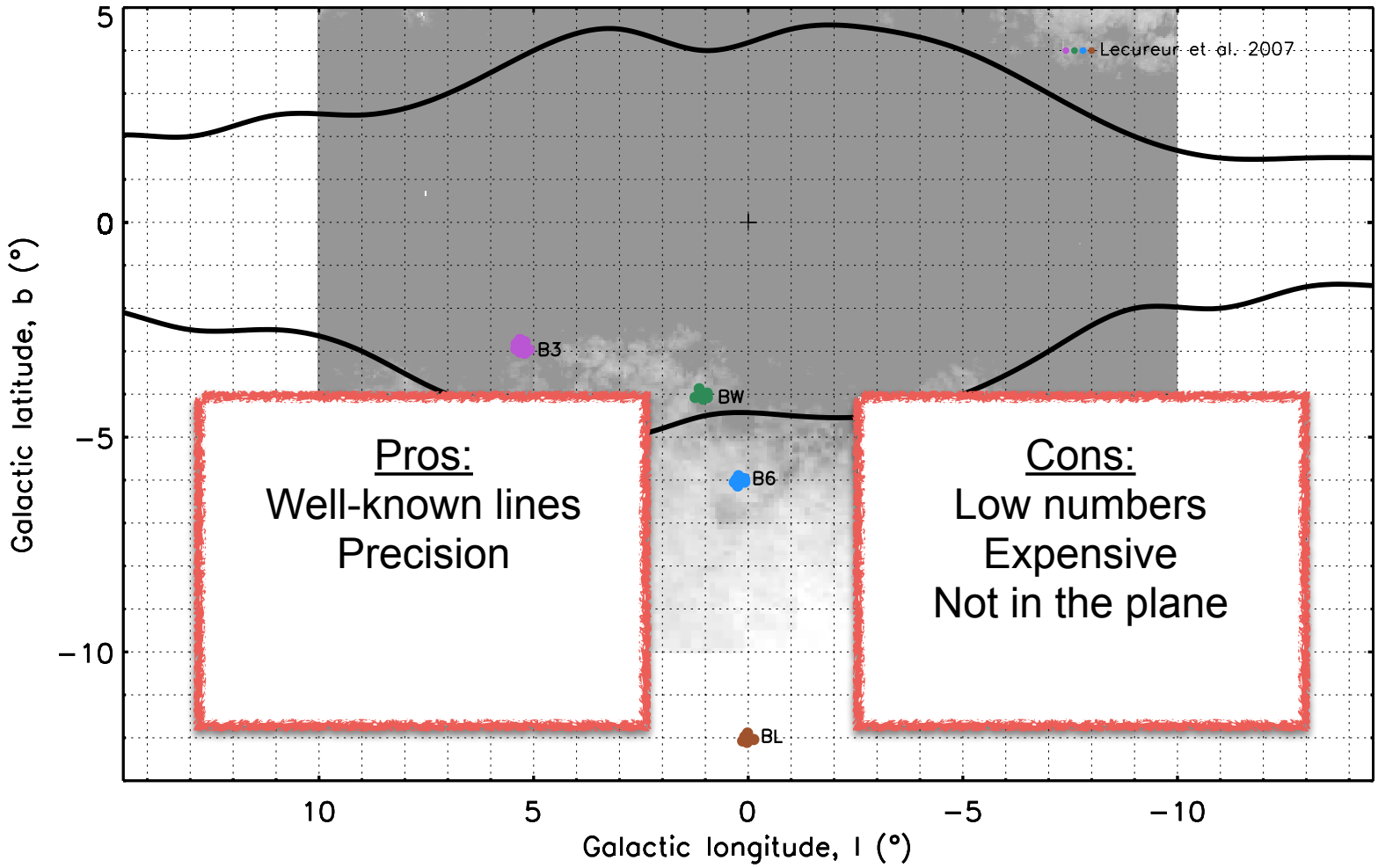


The Milky Way bulge: low extinction fields



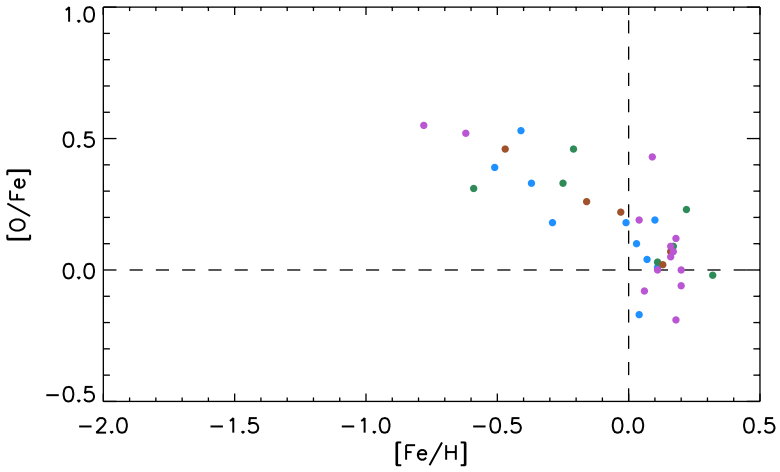
53 giants
FLAMES
R=47000
T=1-2 h/star

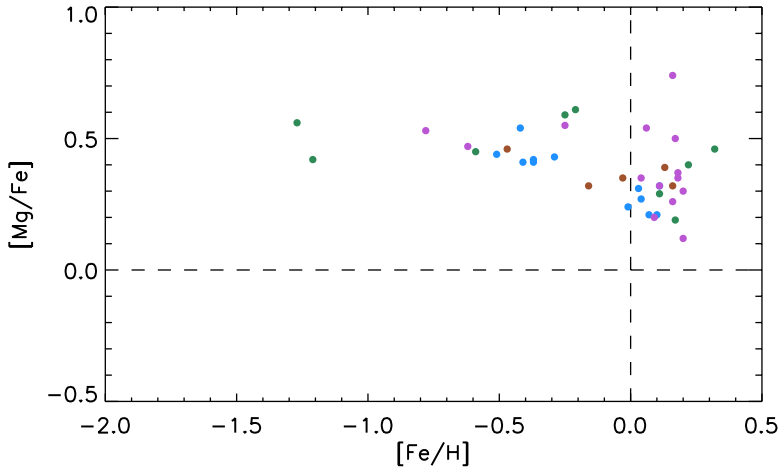
The Milky Way bulge: low extinction fields



53 giants
FLAMES
R=47000
T=1-2 h/star

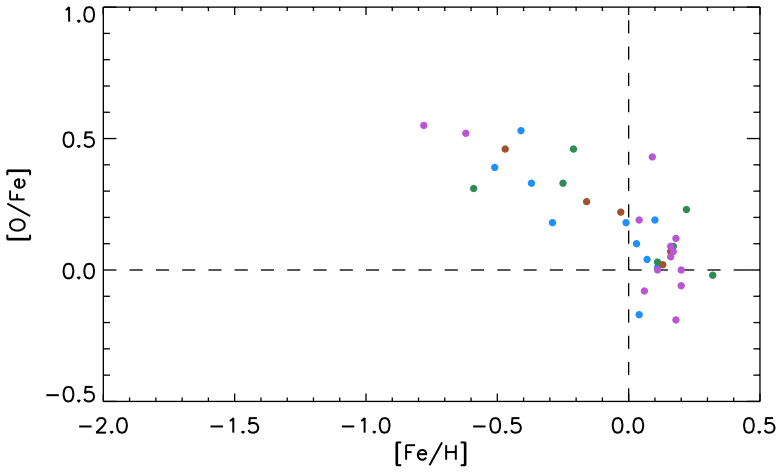
The Milky Way bulge: low extinction fields

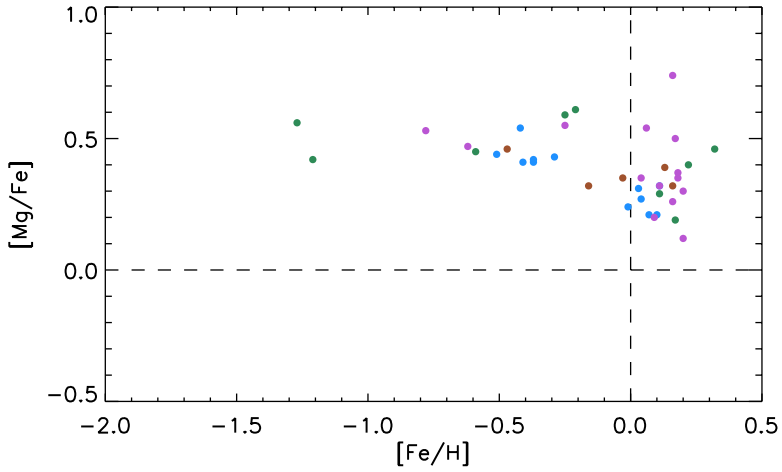




53 giants
FLAMES
R=47000
T=1-2 h/star

The Milky Way bulge: low extinction fields





53 giants
FLAMES
R=47000
T=1-2 h/star

Different trends of O and Mg might be explained if there are relatively more massive bulge stars, making WR-stars important in the chemical evolution of the bulge.

The Milky Way bulge: role of massive stars

Several indications that there are relatively more massive stars in the bulge

- Morris (1993):
  - Star formation conditions differ from Solar neighborhood
- McWilliam & Rich (2004), Fulbright et al. (2007), McWilliam et al. (2008):
  - Low O, high Mg indicating need for WR stars
- Cunha et al. (2008):
  - F-trend in the bulge indicate need for WR stars
- Johnson et al. (2014):
  - Galactic chemical evolution models require hypernovae
- Grieco et al. (2012, 2015):
  - Modeling of the Galactic center



The Milky Way bulge: role of massive stars

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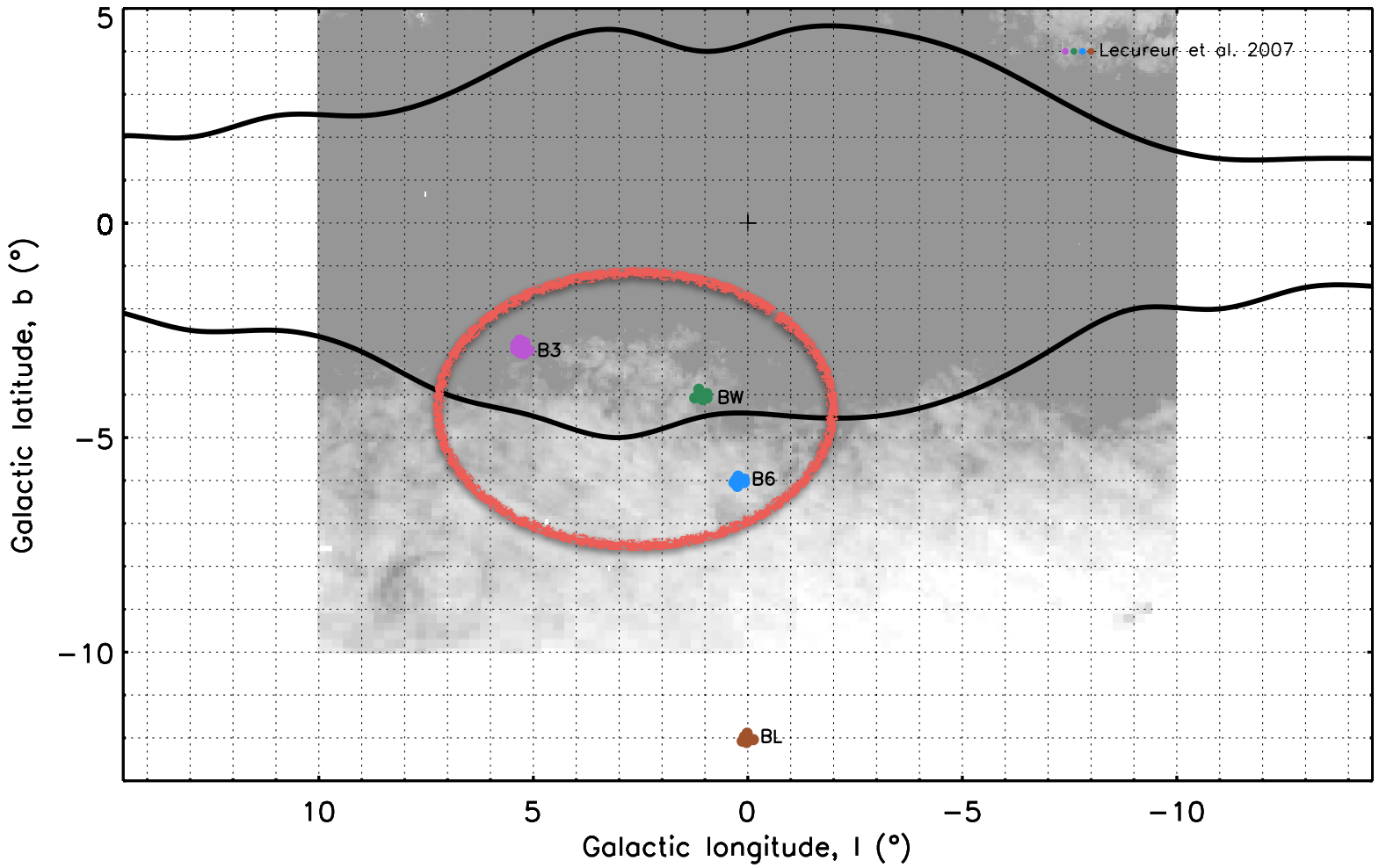
A short detour: fluorine in the bulge

- **Low-mass, thermal-pulsing AGB-stars (2-4 $M_{\odot}$)**
  - direct measurements of F in AGB-stars (Jorissen et al. 1992, Abia et al. 2009, 2010)
  - measurements of F in post AGB-stars and PNe (Werner et al. 2005, Zhang & Liu 2005, Otsuka et al. 2008)
  - measurements of F in CEMP stars (Schuler et al. 2007, Lucatello et al. 2011)
  - measurements of F in Ba-stars (Alves-Brito et al. 2011)
- **v-process in SNIIe**
  - no evidence in interstellar medium (Federman et al. 2005)
- **W-R stars**
  - theoretically questioned (Palacios et al. 2005)



Jönsson et al. A&A 564 (2014)

A short detour: fluorine in the bulge



8 giants
CRIRES
R=40000
5 giants
Phoenix
R=50000

Jönsson et al. A&A 564 (2014)

A short detour: fluorine in the bulge

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INCONCLUSIVE

Jönsson et al. A&A 564 (2014)

A short detour: fluorine in the SN

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Jönsson et al. ApJL 789 (2014)



A short detour: fluorine in the SN

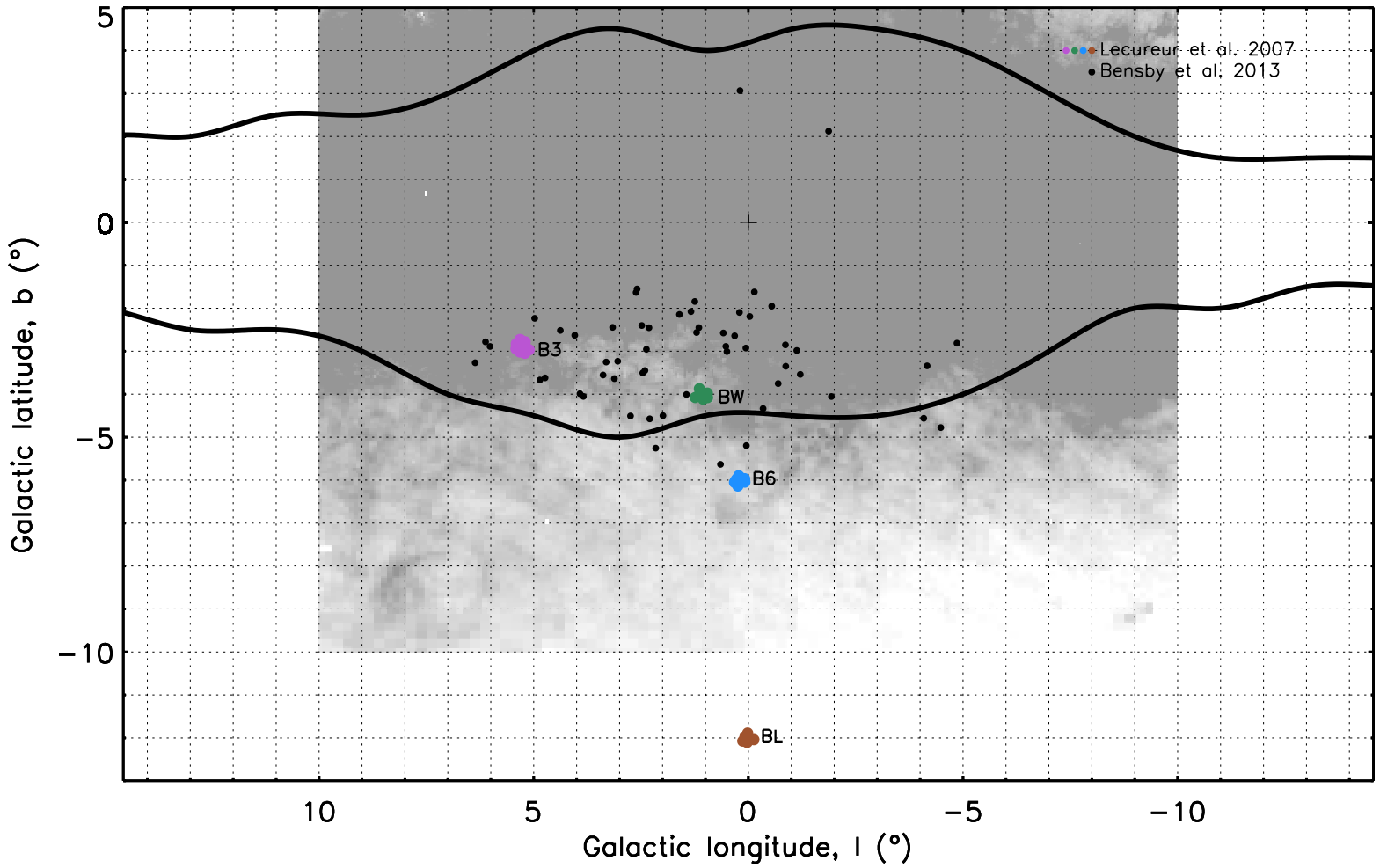
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More results coming this autumn,
both in the Solar neighborhood and in the bulge
including Galactic chemical evolution modeling (Matteucci, Grieco)

Jönsson et al. ApJL 789 (2014)

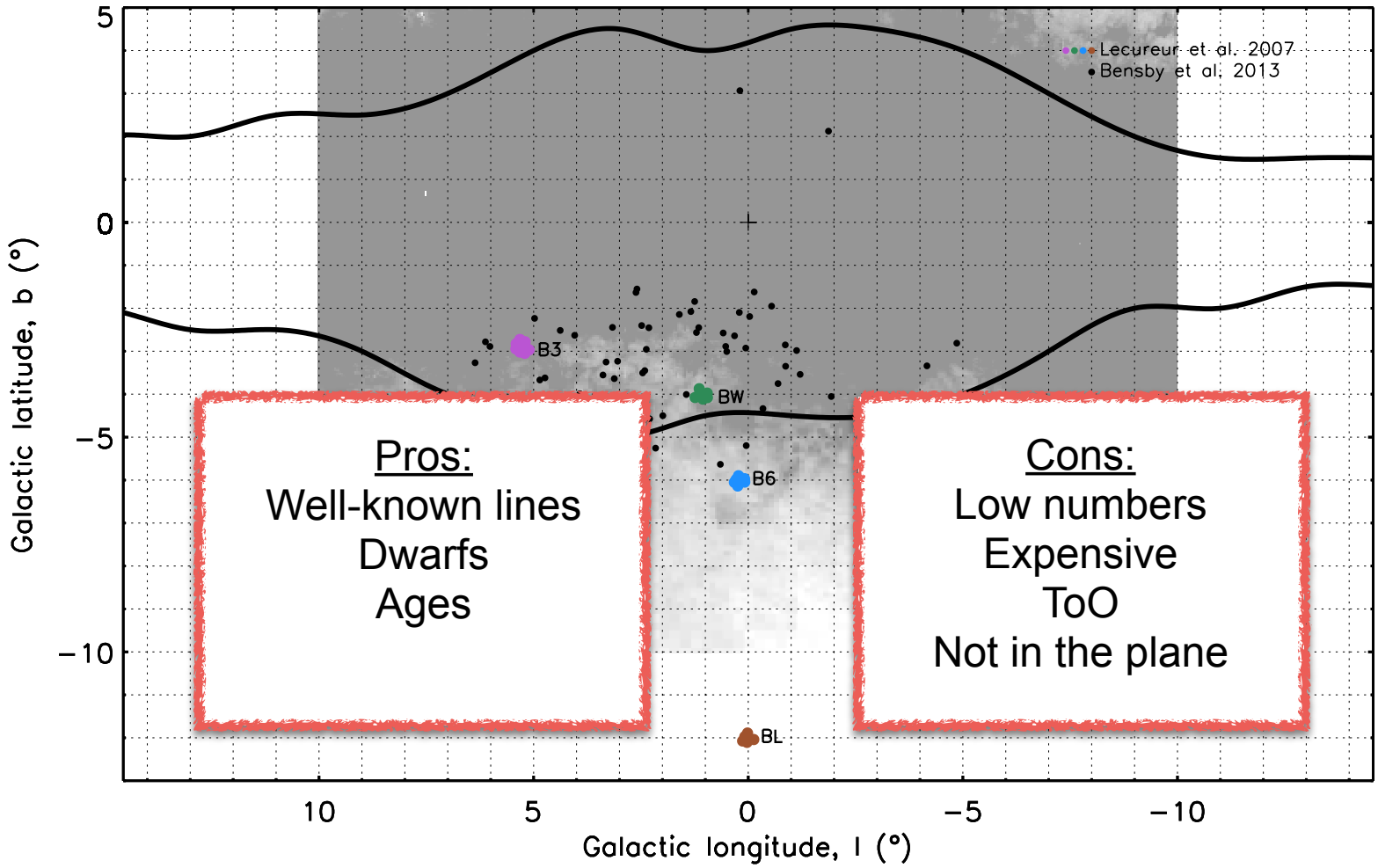


The Milky Way bulge: micro lensing



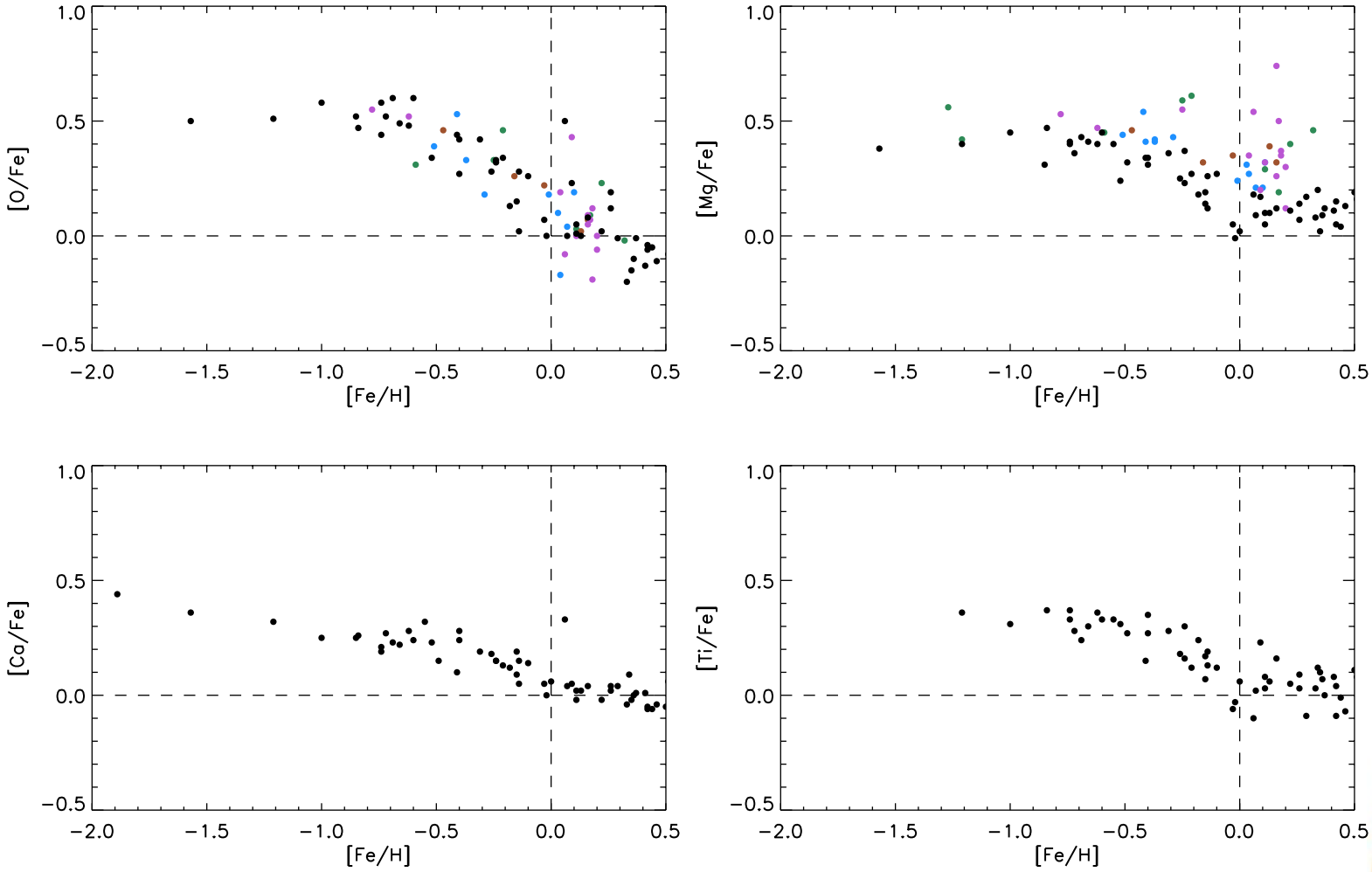
58 dwarfs
UVES
HIRES
MIKE
R=42-90000
T=1-2 h/star

The Milky Way bulge: micro lensing



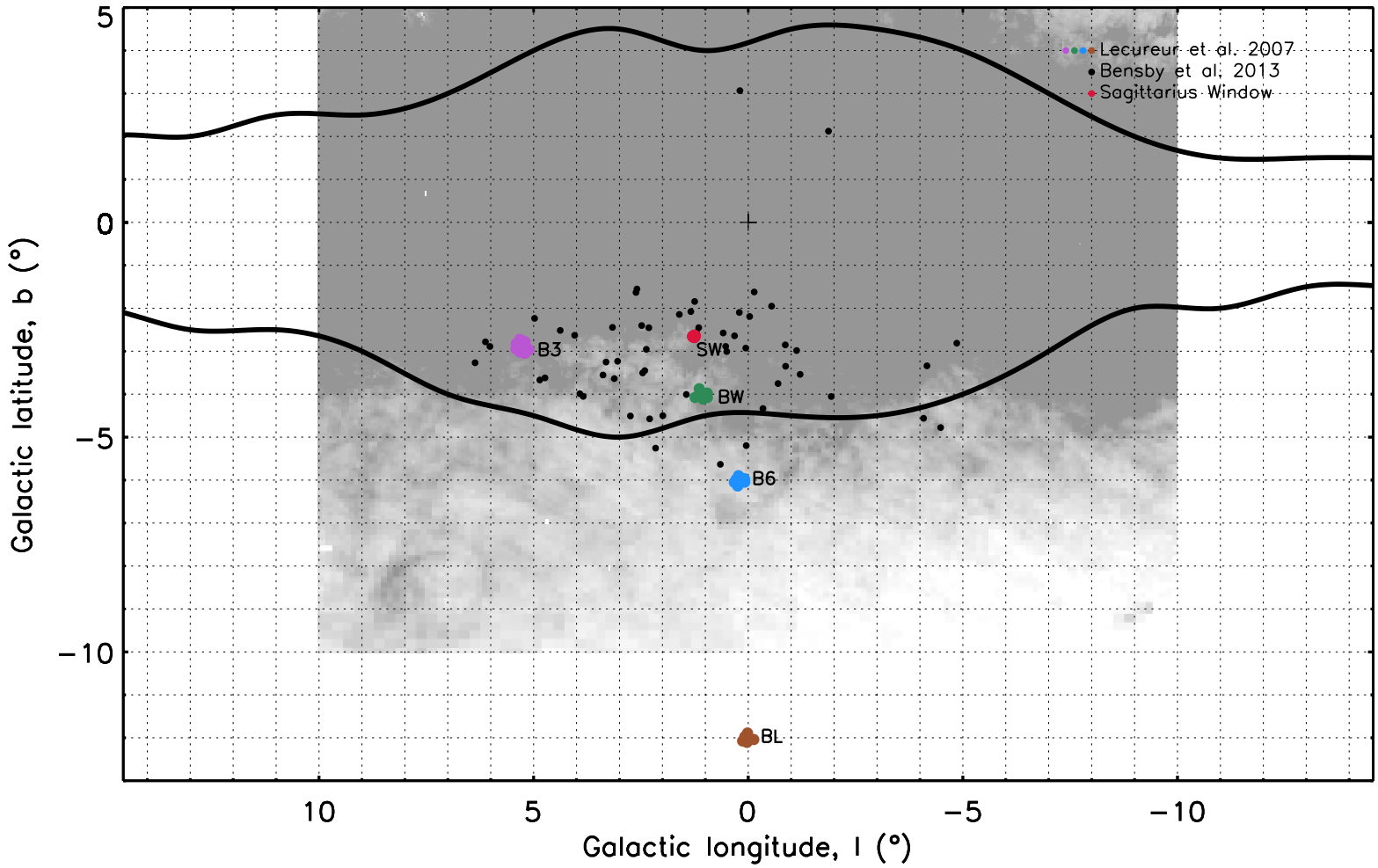
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The Milky Way bulge: micro lensing



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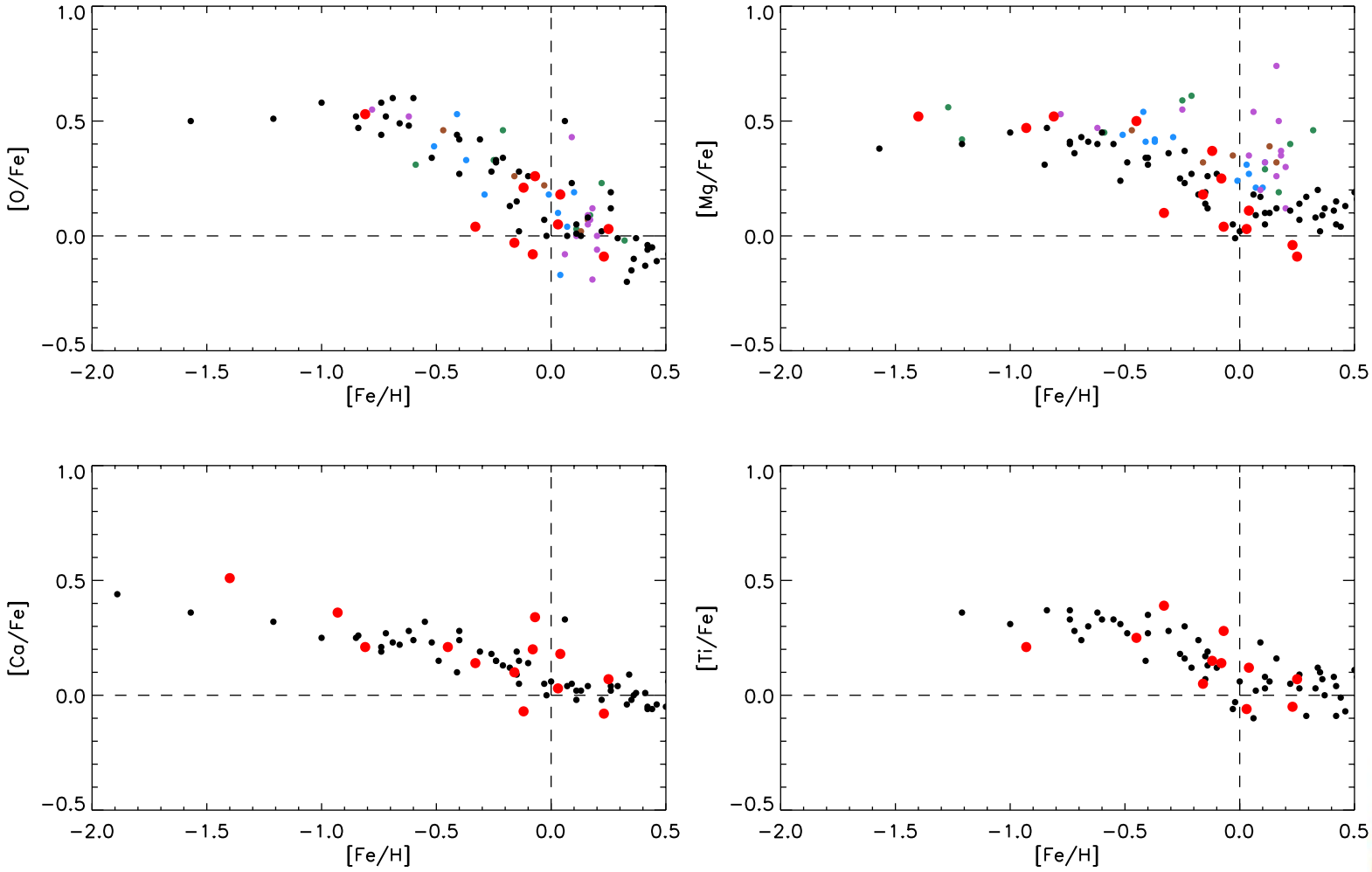
The Milky Way bulge: Sagittarius Window



13 giants
FLAMES
R=47000
T=1-2 h/star

Jönsson et al. (in progress)

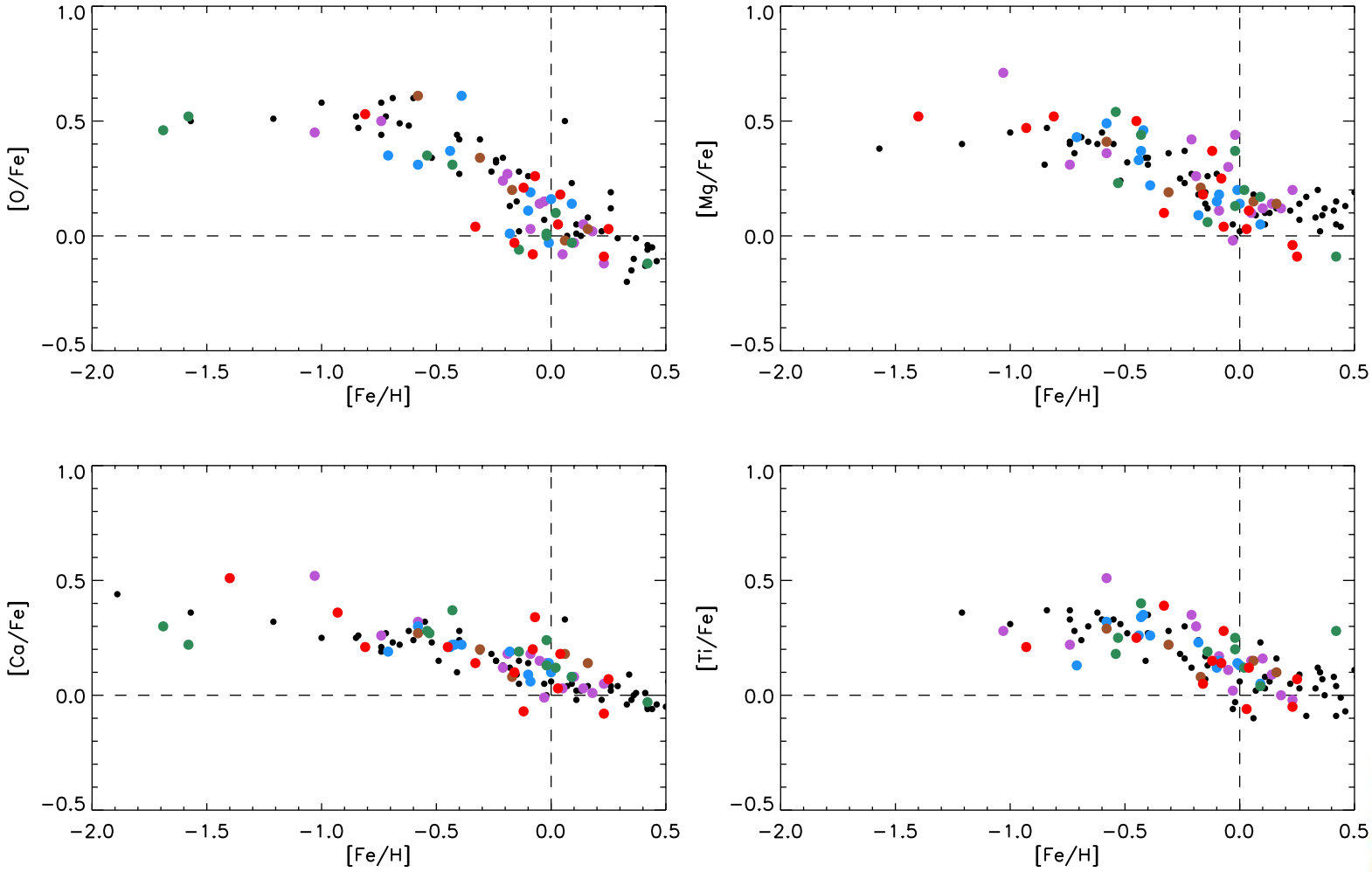
Sagittarius Window compared to others



13 giants
FLAMES
R=47000
T=1-2 h/star

Jönsson et al. (in progress)

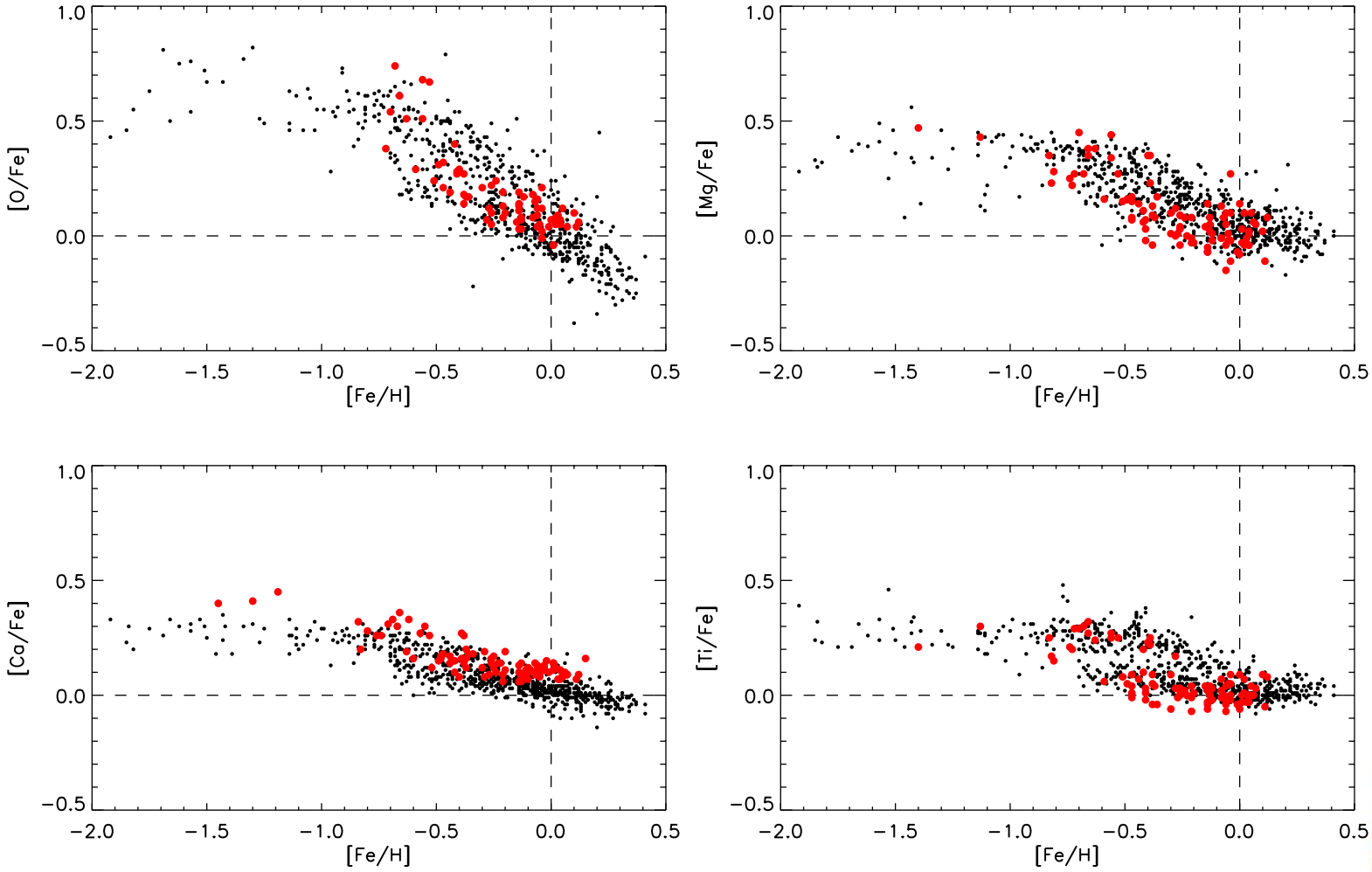
Re-analysis compared to micro lensed



55 giants
FLAMES
R=47000
T=1-2 h/star

Jönsson et al. (in progress)

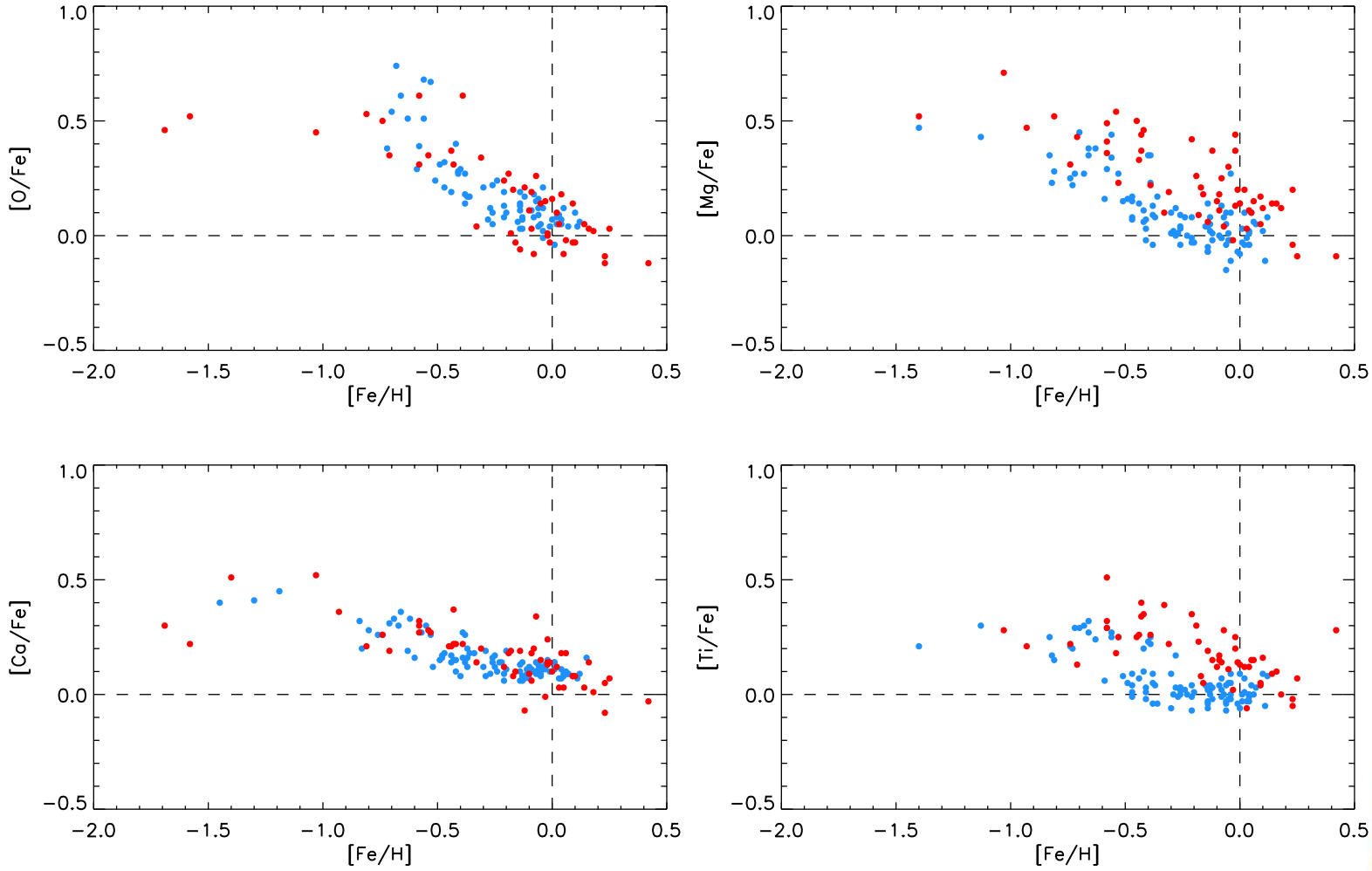
Solar neighborhood sample



108 giants
NOT
ELODIE
NARVAL
FEROS
R=42-115000

Jönsson et al. (in progress)

Bulge compared to Solar neighborhood

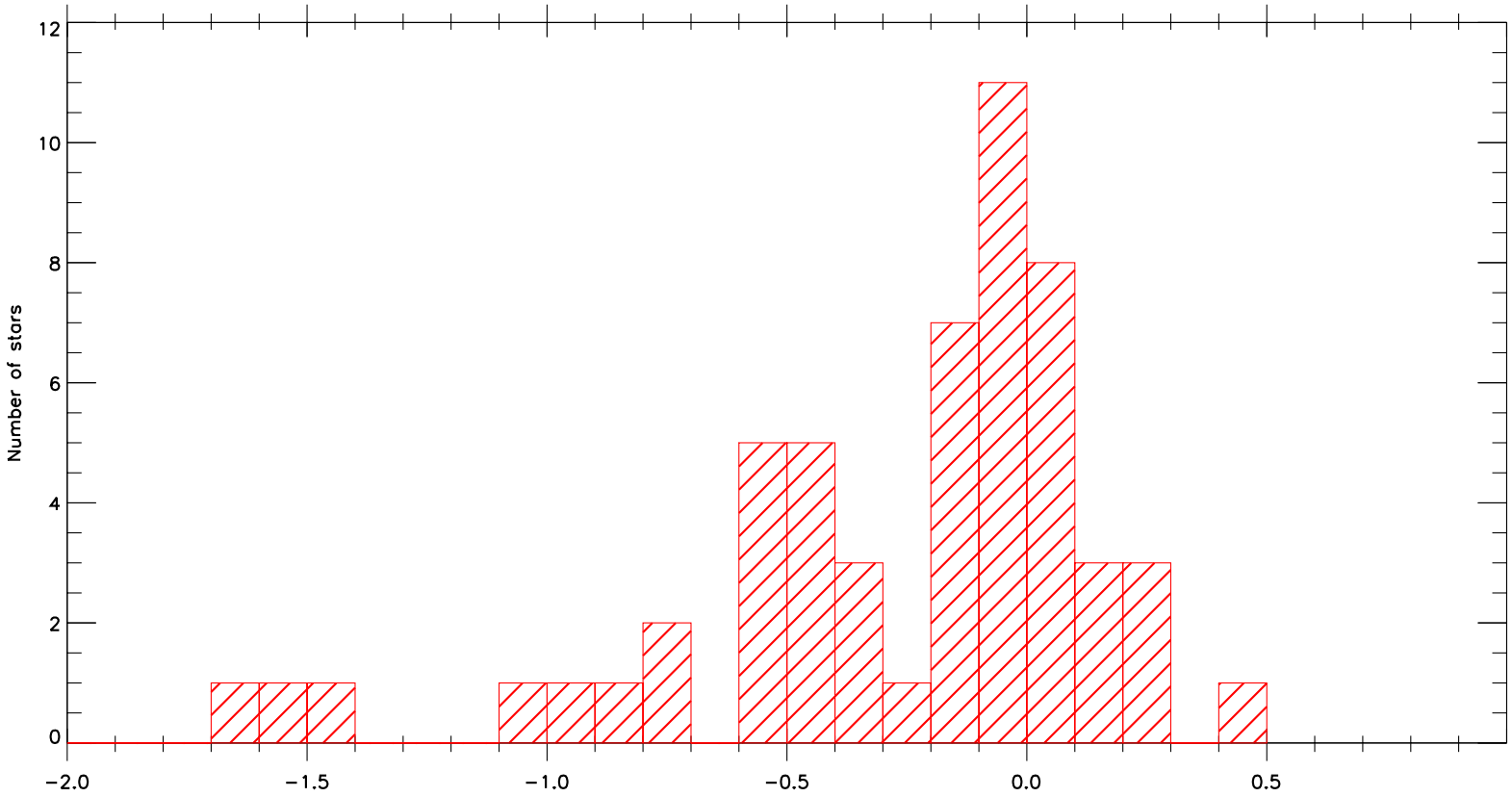


55 giants
FLAMES
R=47000
T=1-2 h/star

Bulge
Solar neigh.

Jönsson et al. (in progress)

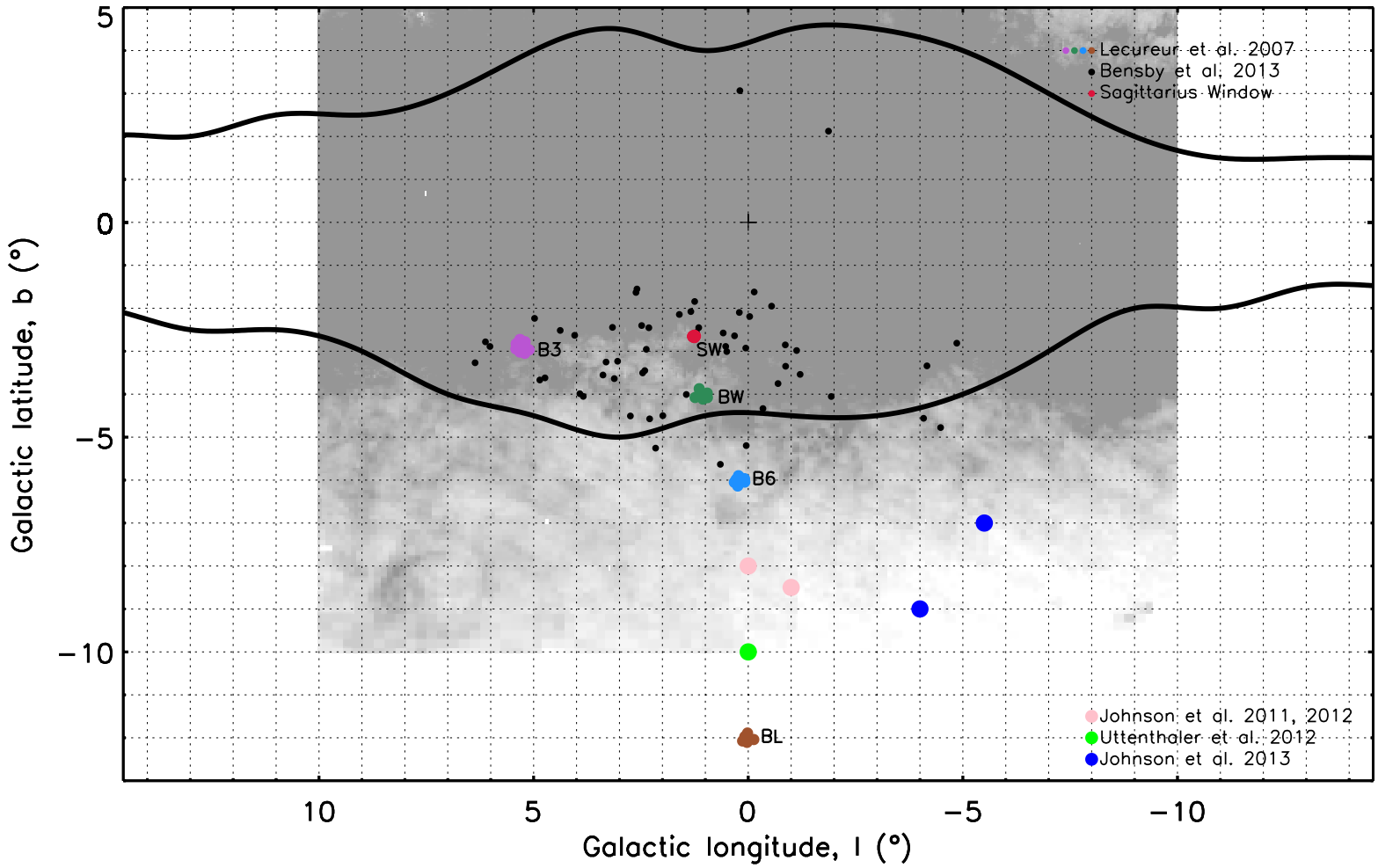
Low-number, probably biased MDF



55 giants
FLAMES
R=47000
T=1-2 h/star

Jönsson et al. (in progress)

Some other visual observations



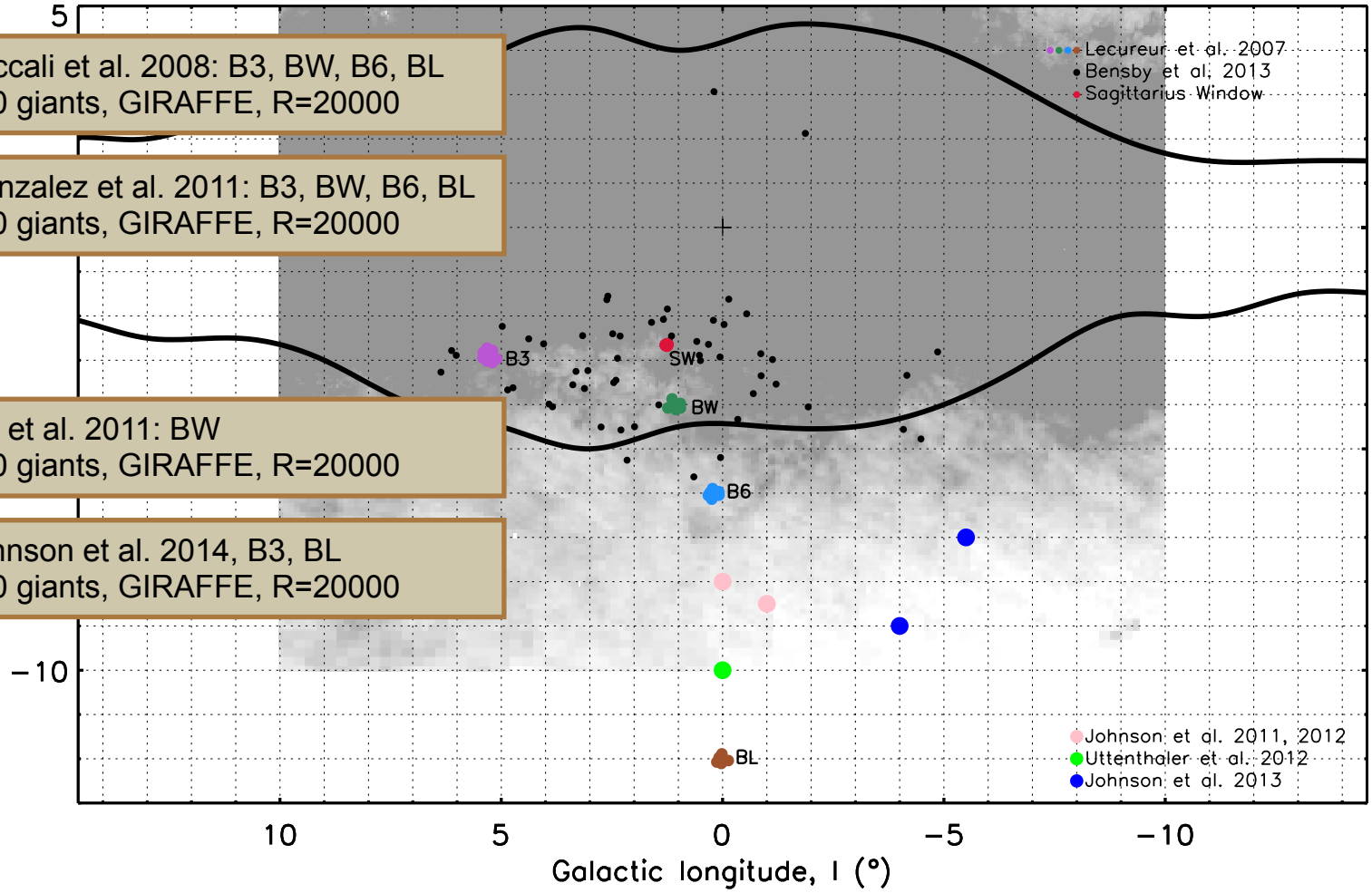
Some other visual observations

Zoccali et al. 2008: B3, BW, B6, BL
800 giants, GIRAFFE, R=20000

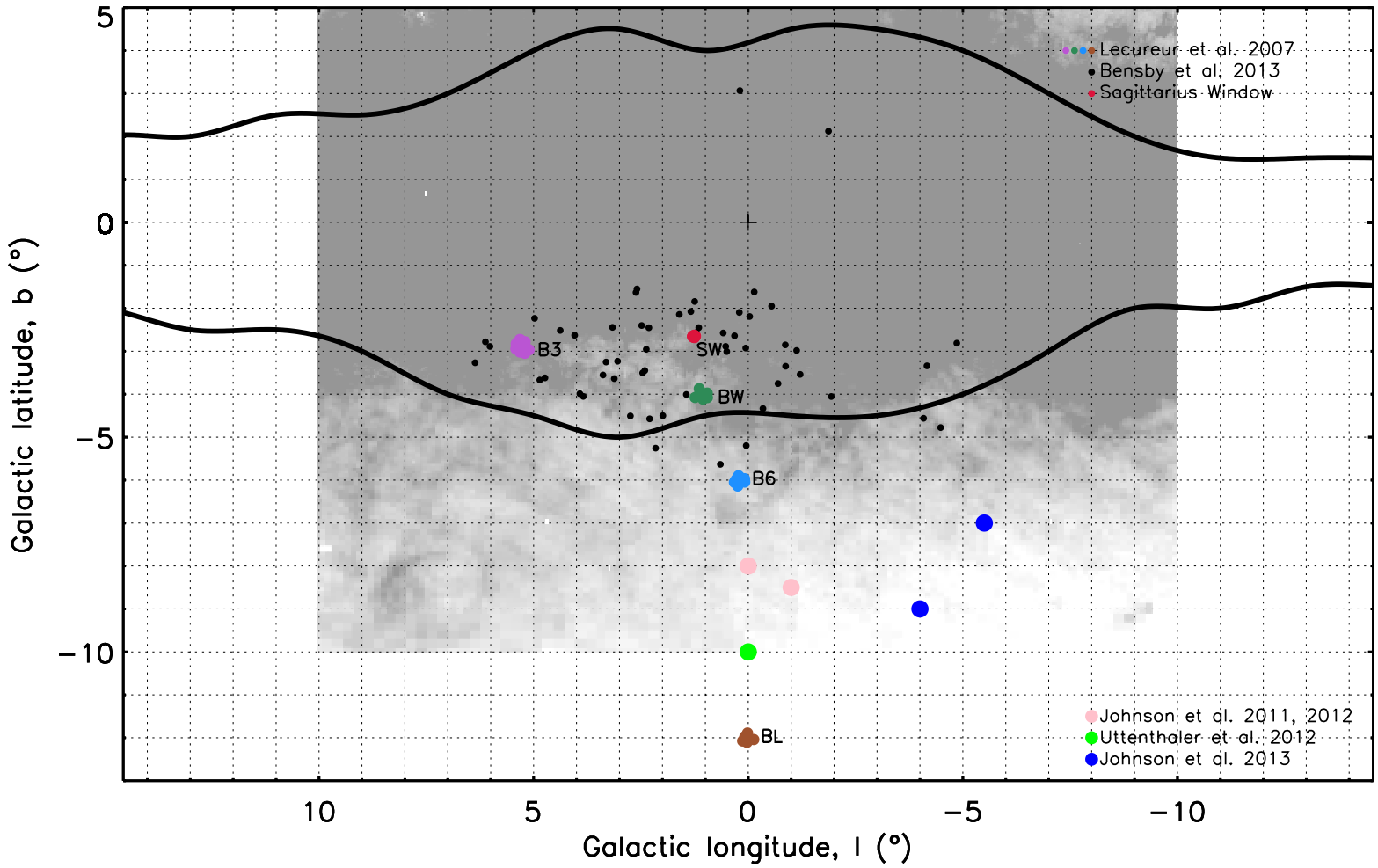
Gonzalez et al. 2011: B3, BW, B6, BL
700 giants, GIRAFFE, R=20000

Hill et al. 2011: BW
400 giants, GIRAFFE, R=20000

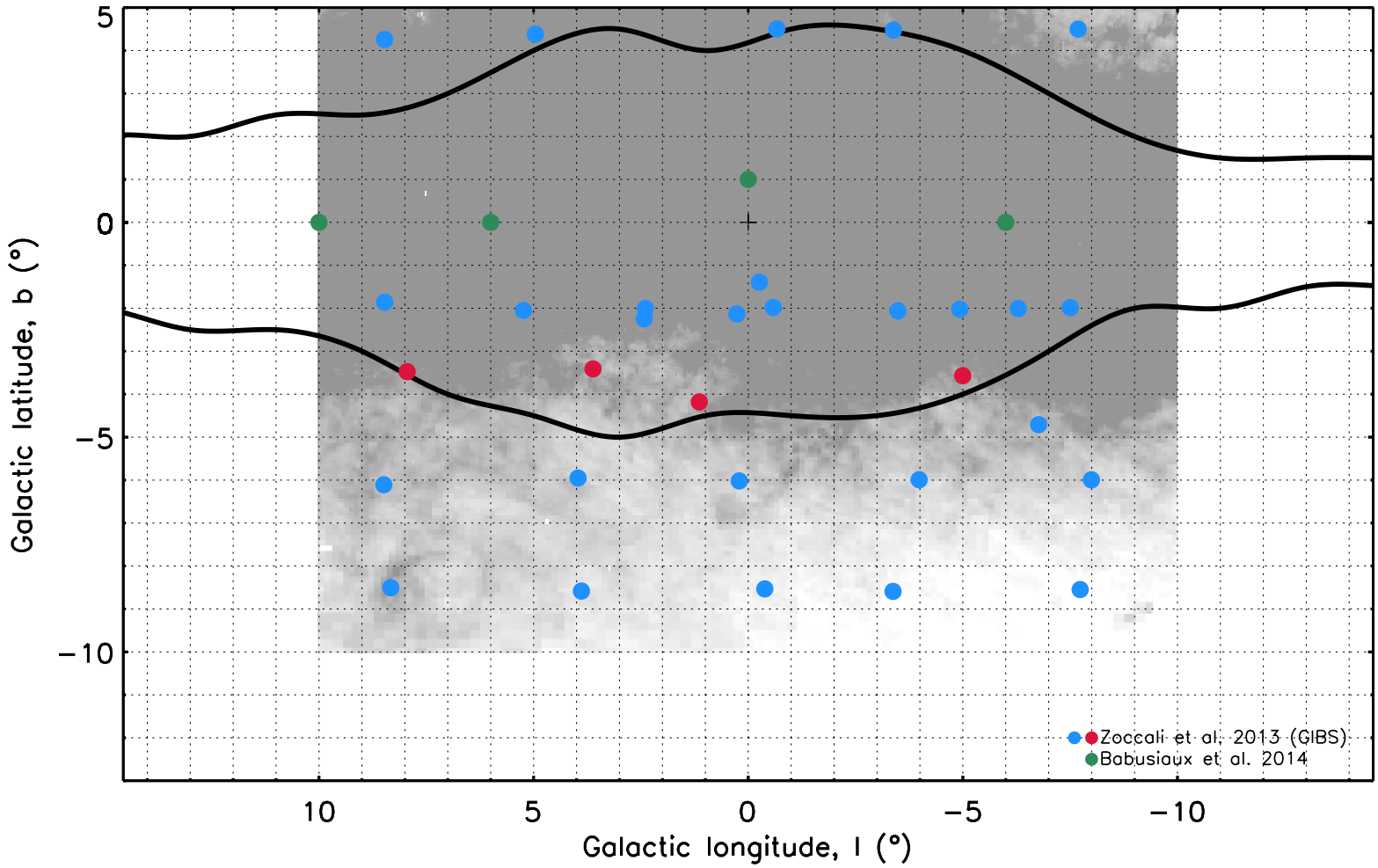
Johnson et al. 2014, B3, BL
150 giants, GIRAFFE, R=20000



The Milky Way bulge: What next?

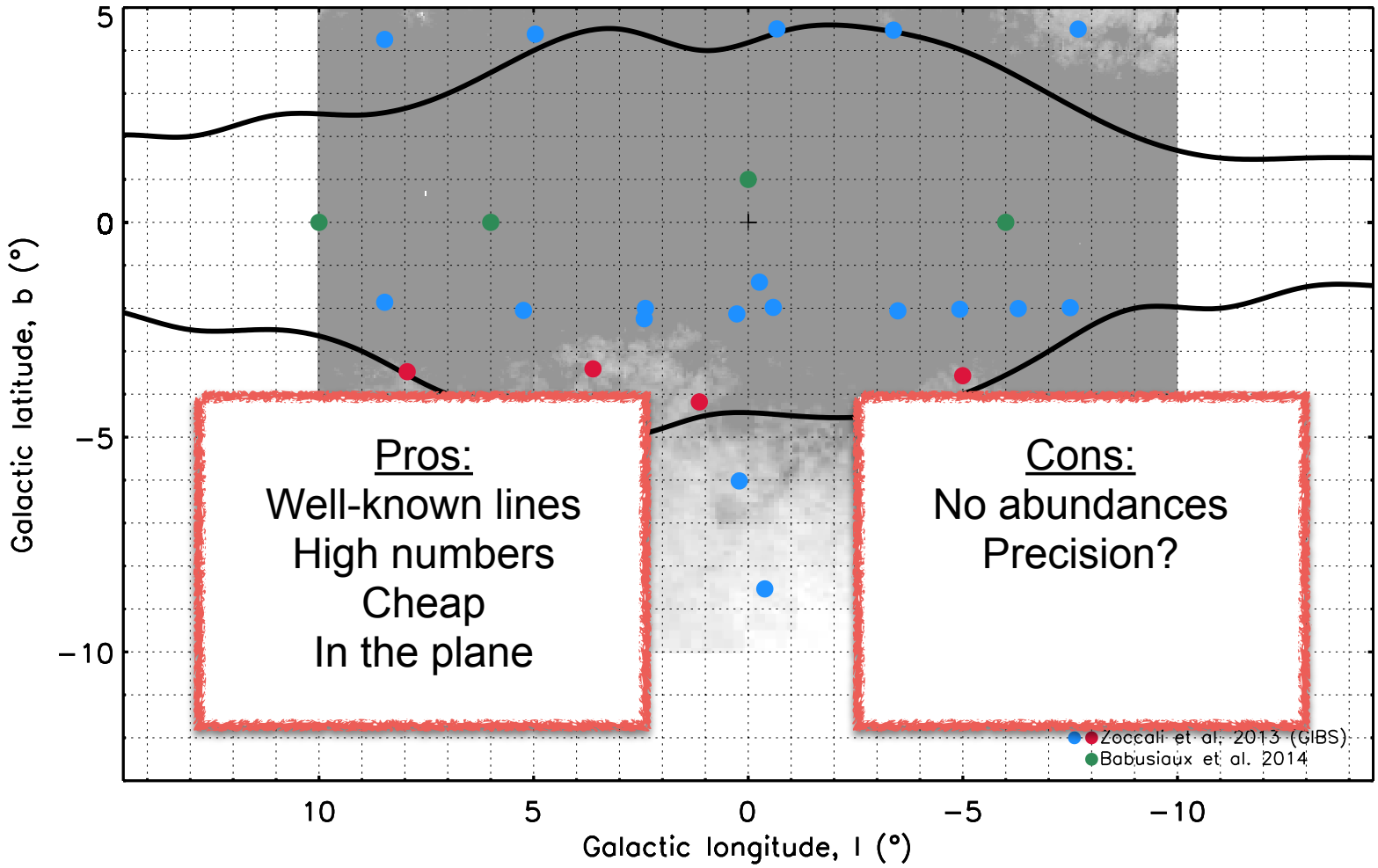


First way forward: medium-res (GIBS)



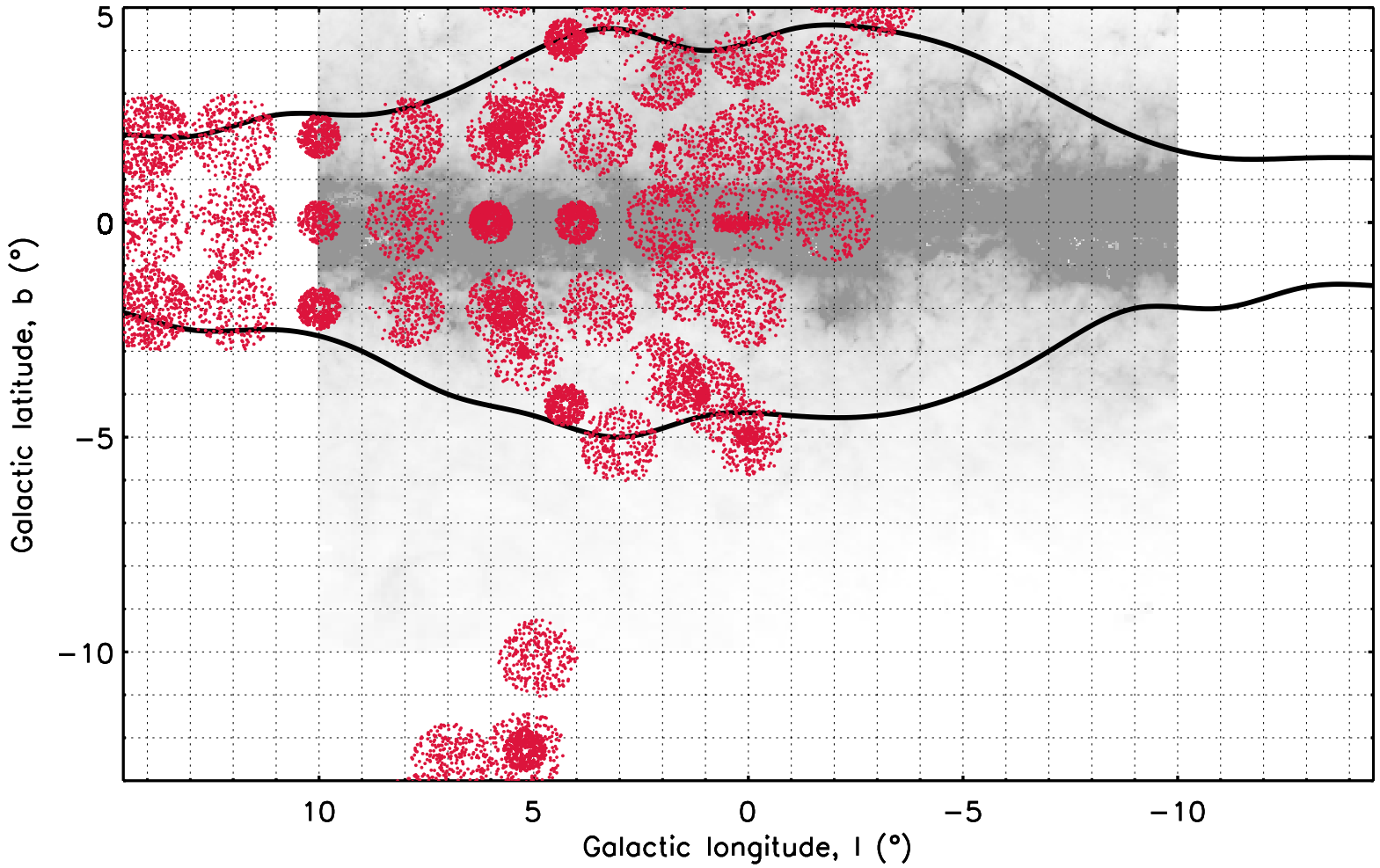
6200 giants
GIRAFFE
R=6500
T=1 min/star
450 giants
GIRAFFE
R=22500
T=5 min/star

First way forward: medium-res (GIBS)



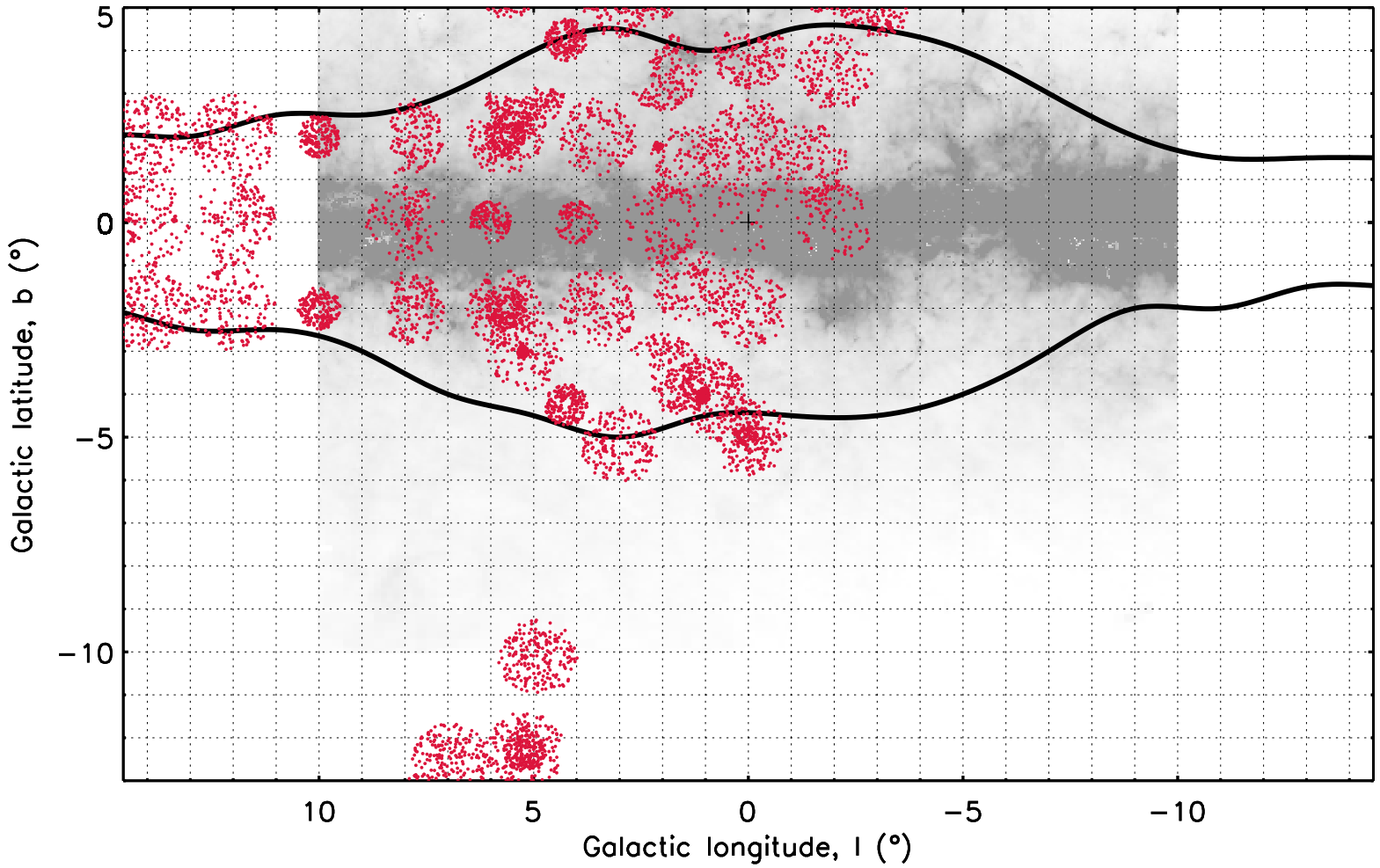
6200 giants
GIRAFFE
R=6500
T=1 min/star
450 giants
GIRAFFE
R=22500
T=5 min/star

Second way forward: H-band (APOGEE)



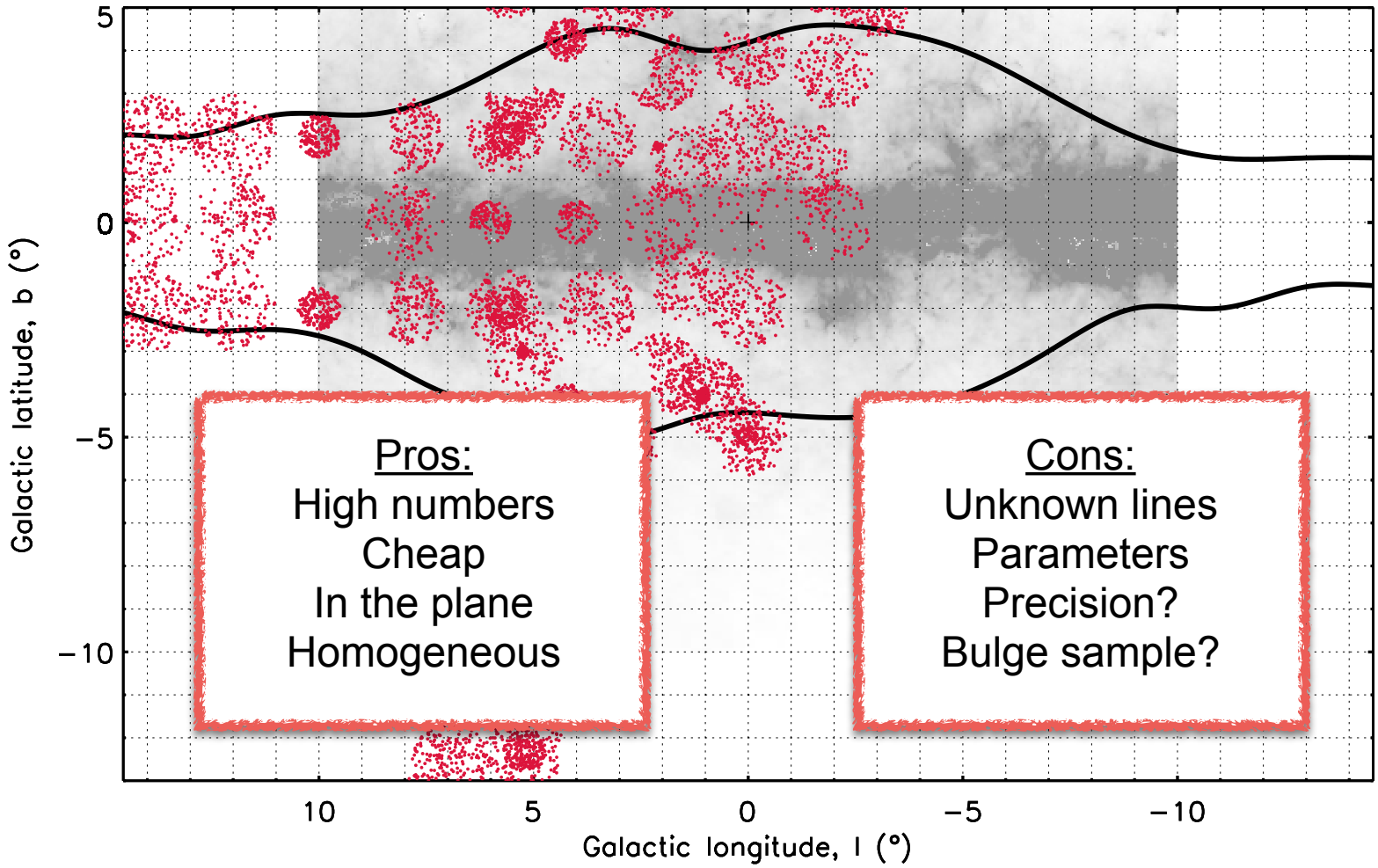
15000 giants
R=22500

Second way forward: H-band (APOGEE)



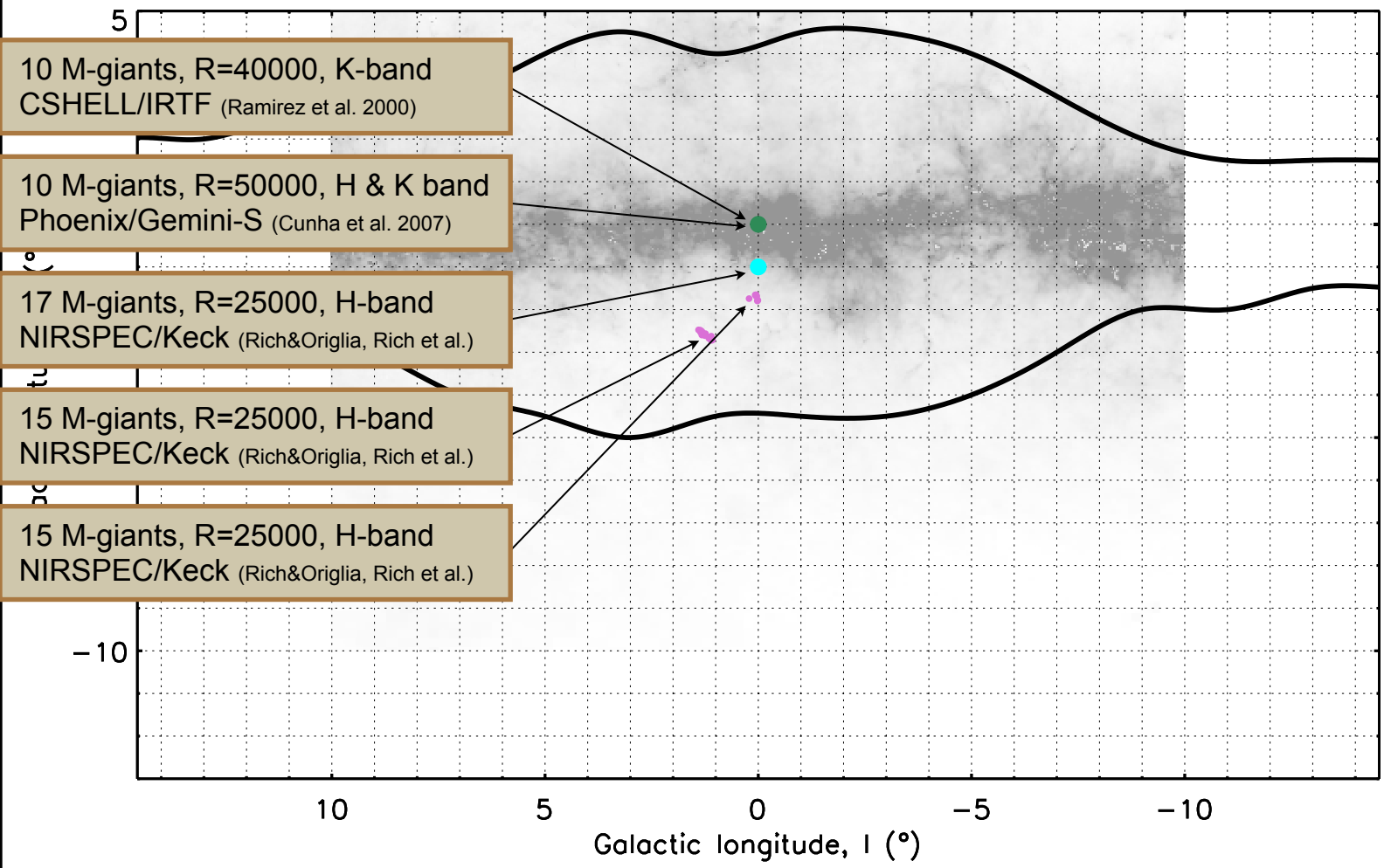
7000 giants
R=22500

Second way forward: H-band (APOGEE)

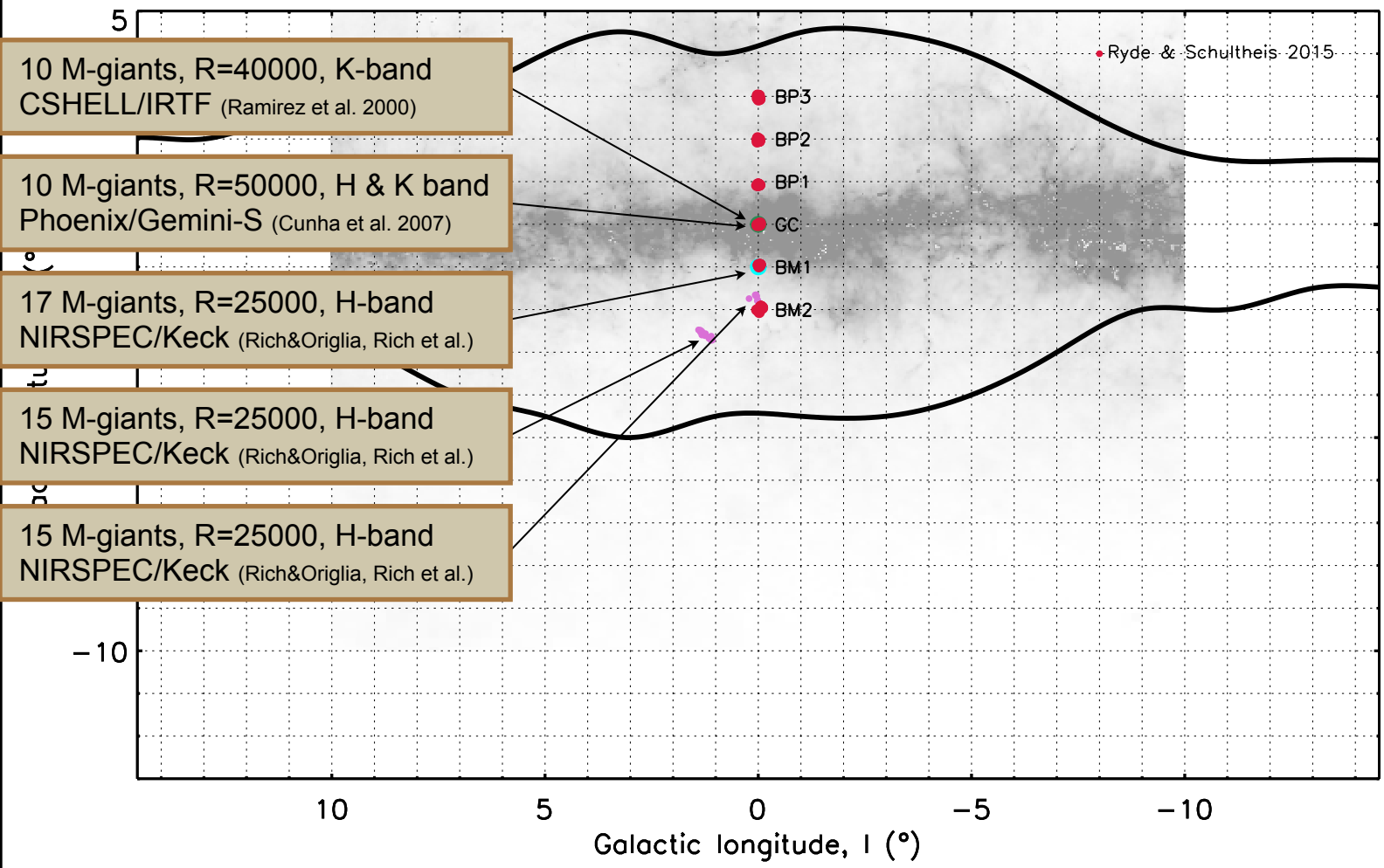


7000 giants
R=22500

Some previous H/K-band observations

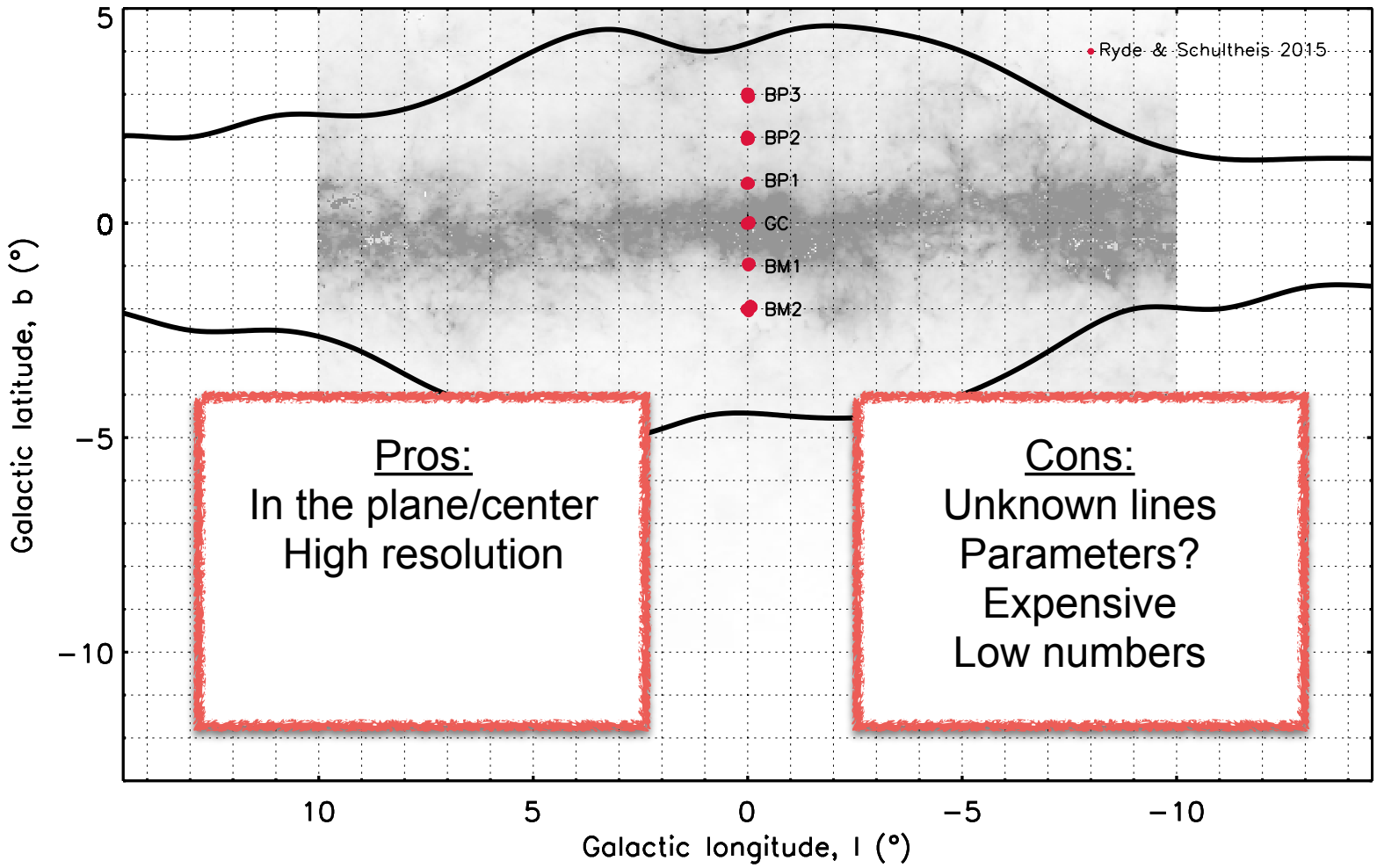


Third way forward: K-band



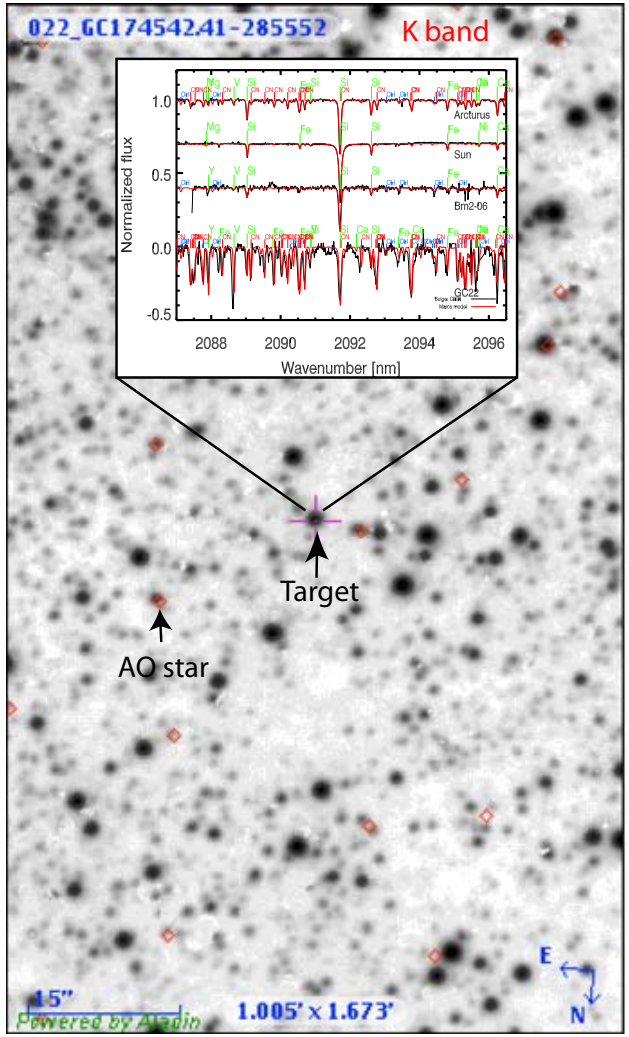
75 giants
ISAAC/SOFI
R=1000
T=5-20 min
CRIRES
R=50000
T=15-60 min

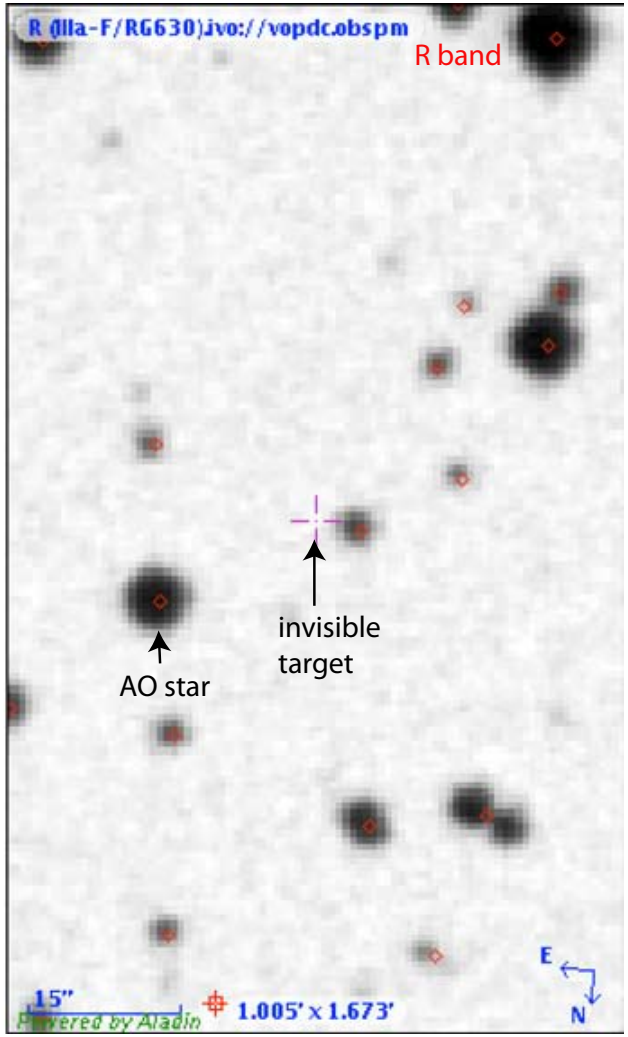
Third way forward: K-band



75 giants
ISAAC/SOFI
R=1000
T=5-20 min
CRIRES
R=50000
T=15-60 min

Third way forward: K-band





Third way forward: K-band

Instrument	R	Telescope	Diameter	Observatory	Bands	Availability
IGRINS	40000	Harlan Smith	2.7m	McDonald	H-K	now
GIANO	50000	TNG	3.6m	ORM	H-K	now
ISHELL	80000	IRTF	3.0m	Mauna Kea	H-K	2015
SPIRou	73500	CFHT	3.6m	Mauna Kea	H-K	2017
CRIRES+	100000	VLT	8.2m	Paranal	H or K	2017
HIRES	100000	E-ELT	39m	Armazones	V-K	2024



Punchlines

- The bulge is a significant part of the Galaxy and plays an important role in its evolution
- When studying the bulge one have to deal with large distances, disk star contamination, heavy crowding, and large extinction due to dust
- Possible ways to handle this are
  - long integration times (Lecureur et al., my work)
  - go down in spectral resolution (GIBS, APOGEE)
  - go to the infrared (APOGEE, Ryde & Schultheis)

