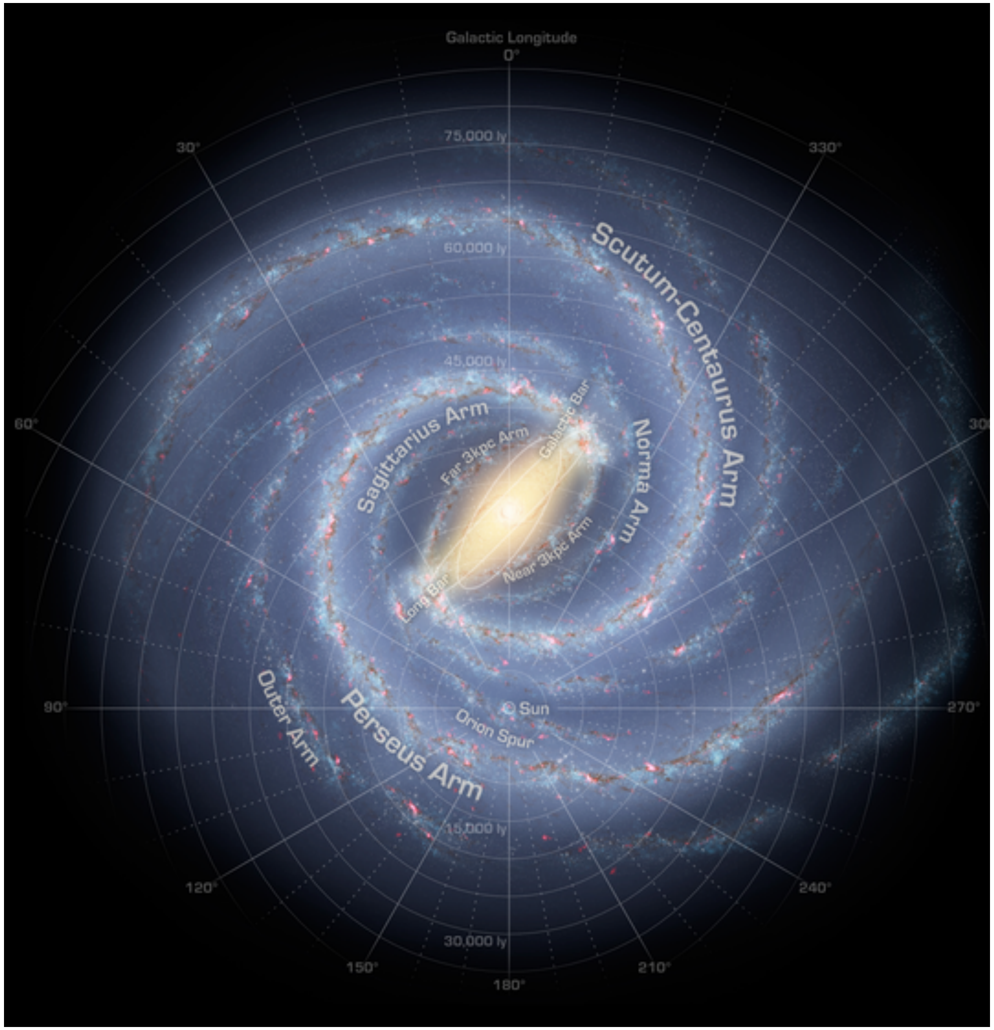
The Gaia-ESO survey

M. Schultheis
Observatoire de la Côte d'Azur, Nice
& the Gaia-ESO consortium

Galactic archaeology
The Gaia era



Galactic archaeology
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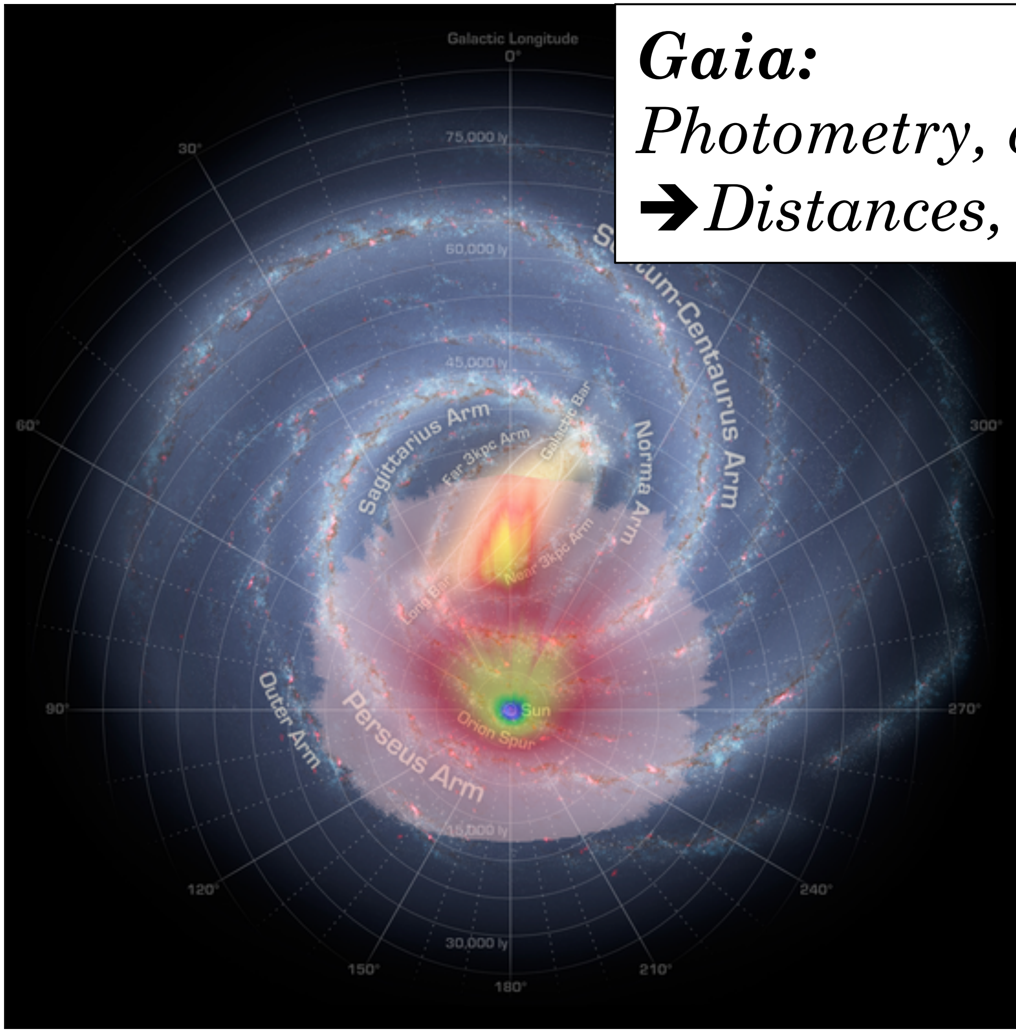
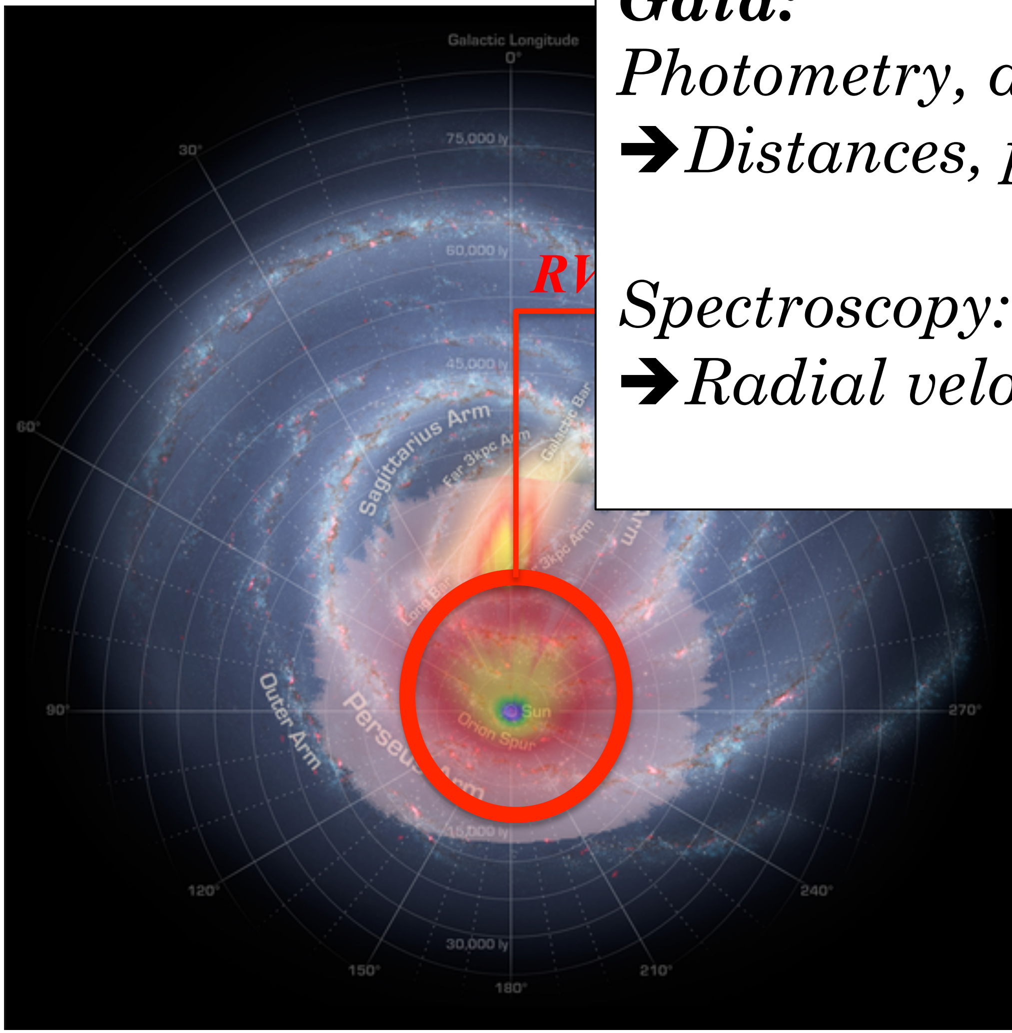


Gaia:
Photometry, astrometry: V<19
➔*Distances, proper motions*

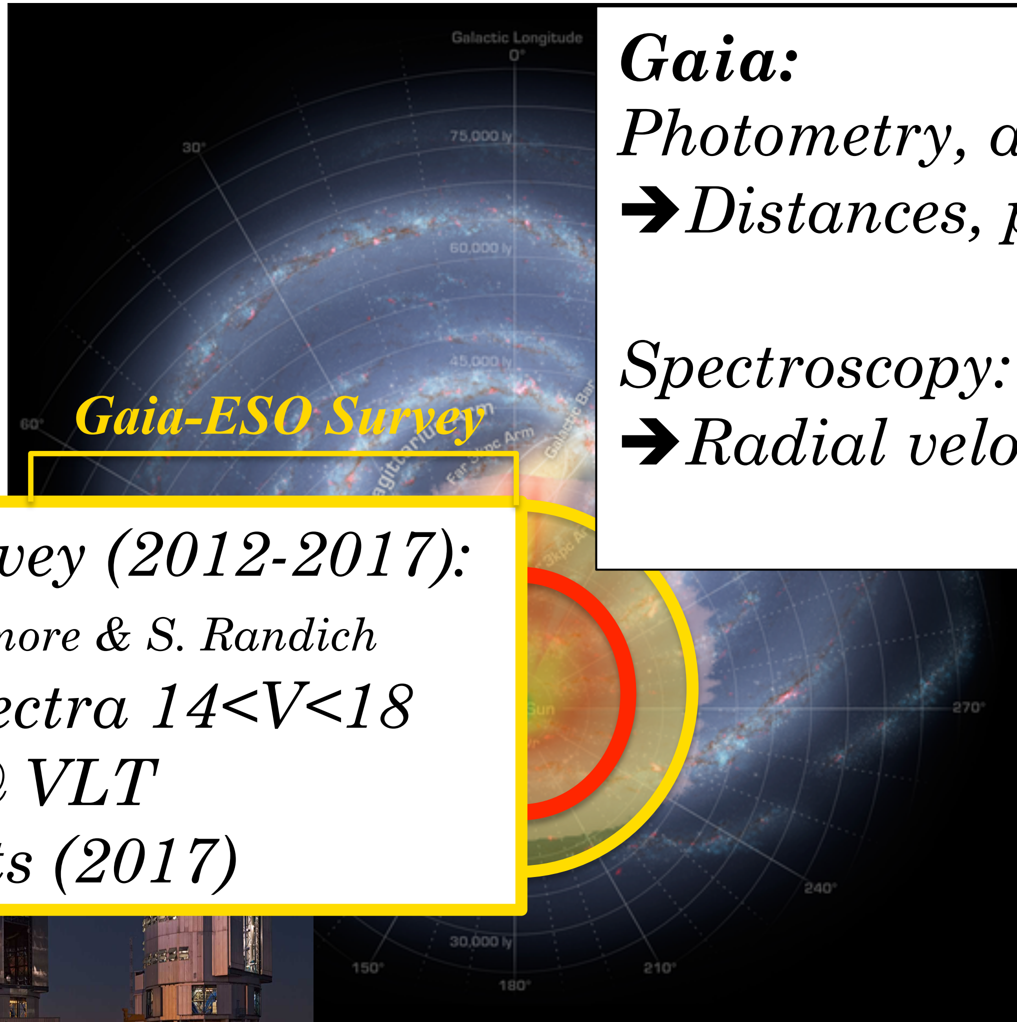
Galactic archaeology
The Gaia era



Gaia:
Photometry, astrometry: V<19
➔*Distances, proper motions*

Spectroscopy: V<16
➔*Radial velocity, abundances*

Galactic archaeology
The Gaia & Gaia-ESO era



Gaia:

Photometry, astrometry: V<19

➔ *Distances, proper motions*

Spectroscopy: V<16

➔ *Radial velocity, abundances*

Gaia-ESO Survey (2012-2017):

P.I.: G. Gilmore & S. Randich

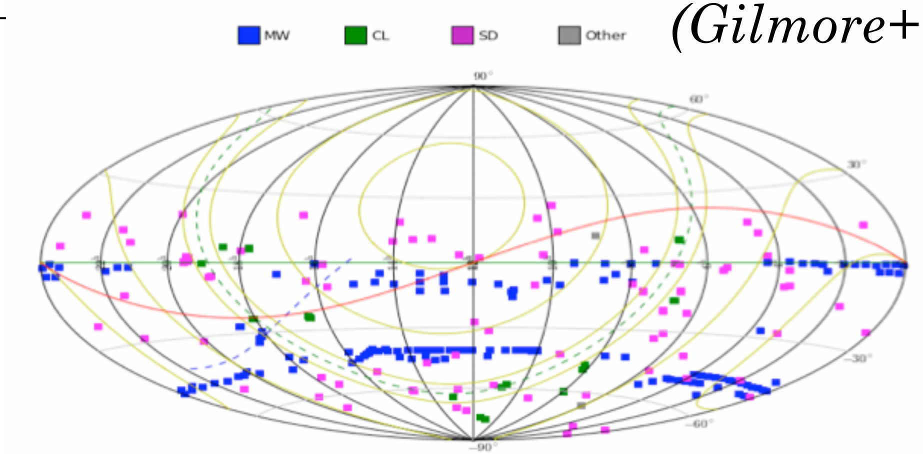
➔ *High-res spectra 14<V<18*

➔ *300 nights @ VLT*

➔ *N=10^5 targets (2017)*

Gaia-ESO Survey
PIs: G. Gilmore & S. Randich

(Gilmore+12)



- 14<V<18
- R~20 000 (& 40 000)
- 300 nights @VLT (2012-2017)
- $N=10^5$

➔ ***Homogeneous overview of kinematics and abundances of young, mature and old stellar populations***

- Consortium: 400+ members (FR: ~50 members)
- T_{eff}, log(g), [M/H], [α/Fe], [X/Fe]
  - GIRAFFE WP: A. Recio-Blanco (Nice) (80% of the targets)
  - UVES WP: R. Smiljanic (Torun, Poland)

- 2 internal Data-Releases : 25 000 targets

- Around 300 CoIs from 90 Institutes.
- Astrophysical data products to be released
- Huge collaboration with a huge task!

1 The Gaia-ESO Survey

Co-PIs: Gerry Gilmore[1370], Sofia Randich[1336]

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], C. Abia[abc], 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[7a30], J. Alves[1893], 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[1088], C. Battistini[1473], I. Bellas-Velidis[1550], 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[1680], C. Boeche[2112], S. Bonito[1344], S. Boudreault[1393], J. 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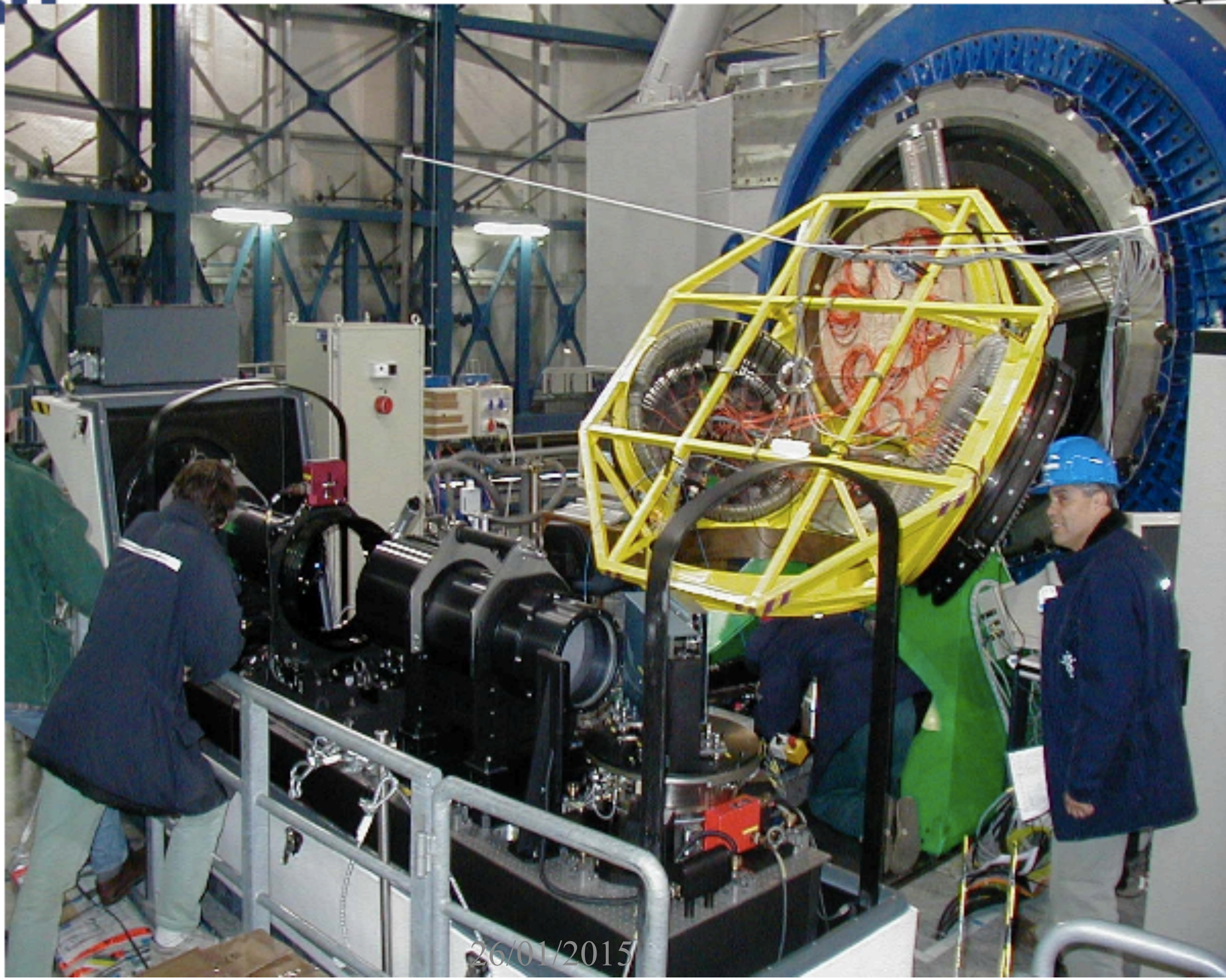
The FLAMES Instrument



The FLAMES Instrument

- A Fiber positioner with two plates (FoV of 25' diameter).
- 132 fibers of 1.2 arcsec connected to Giraffe.
- 8 fibers of 1.0 arcsec connected to UVES.

- Giraffe: medium-high resolution spectrograph
  R ~ 20000
  HR10, 15N, 21: λλ 533-562, 647-679, 848-900 nm

- UVES: high-resolution echelle spectrograph
  R ~ 47000
  #580 nm set up (λλ 476-684 nm)

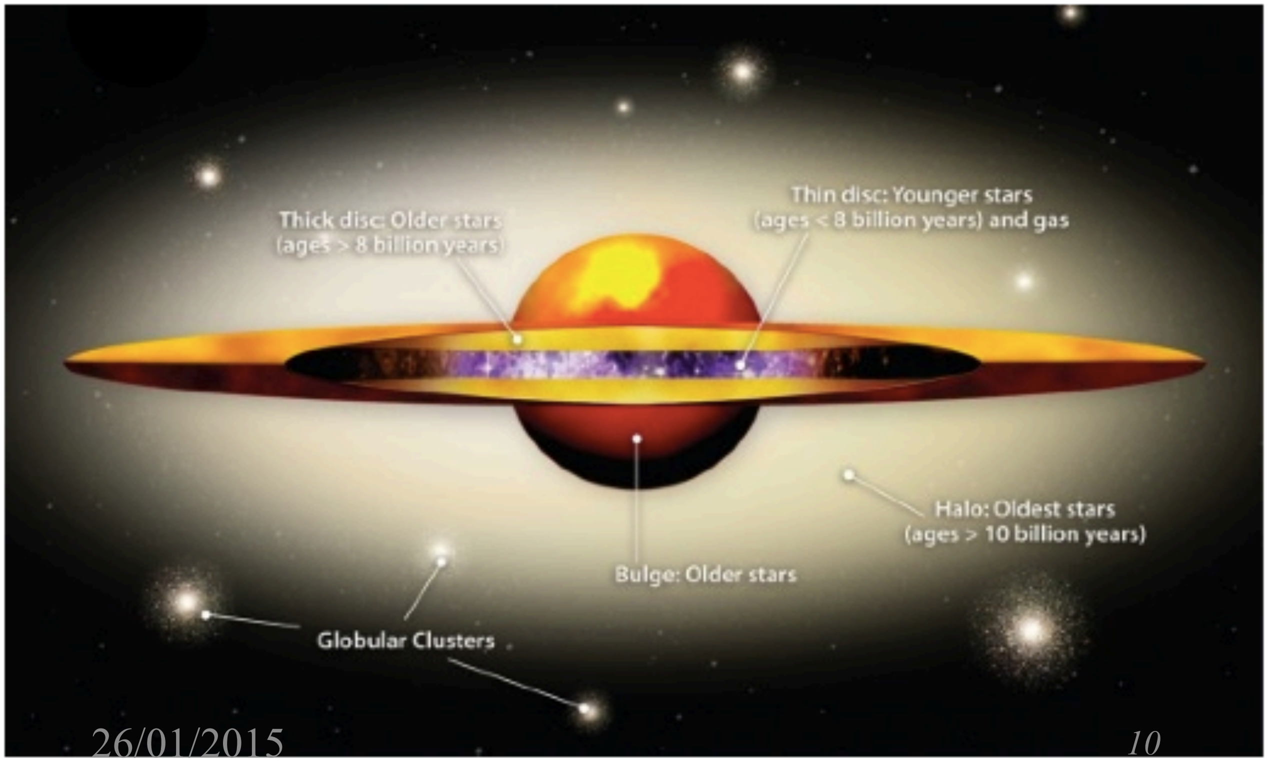
Gaia-ESO

http://www.gaia-eso.eu/

- All Galactic components (halo, bulge, thick and thin disks)
- Sample of ~100 open clusters
- Selected calibration samples

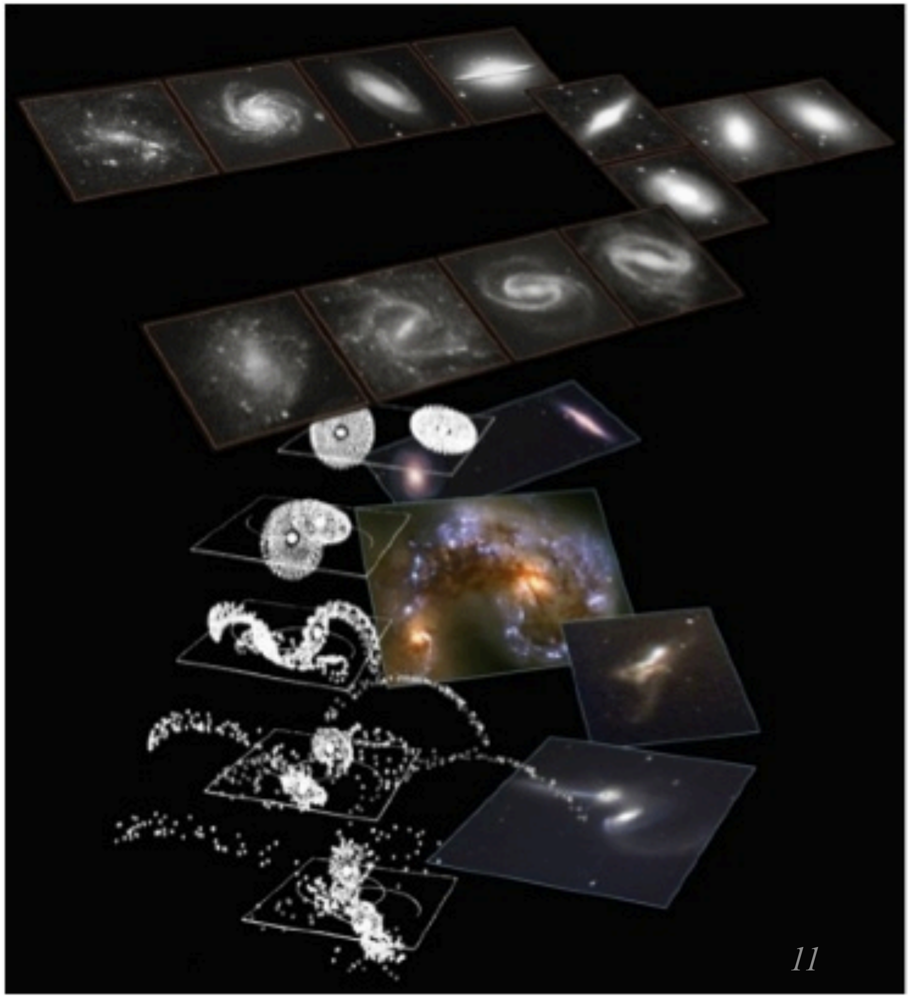
- PMS, MS and Giants
- OBAFGKM-types

- Multiple goals!



Scientific Goals

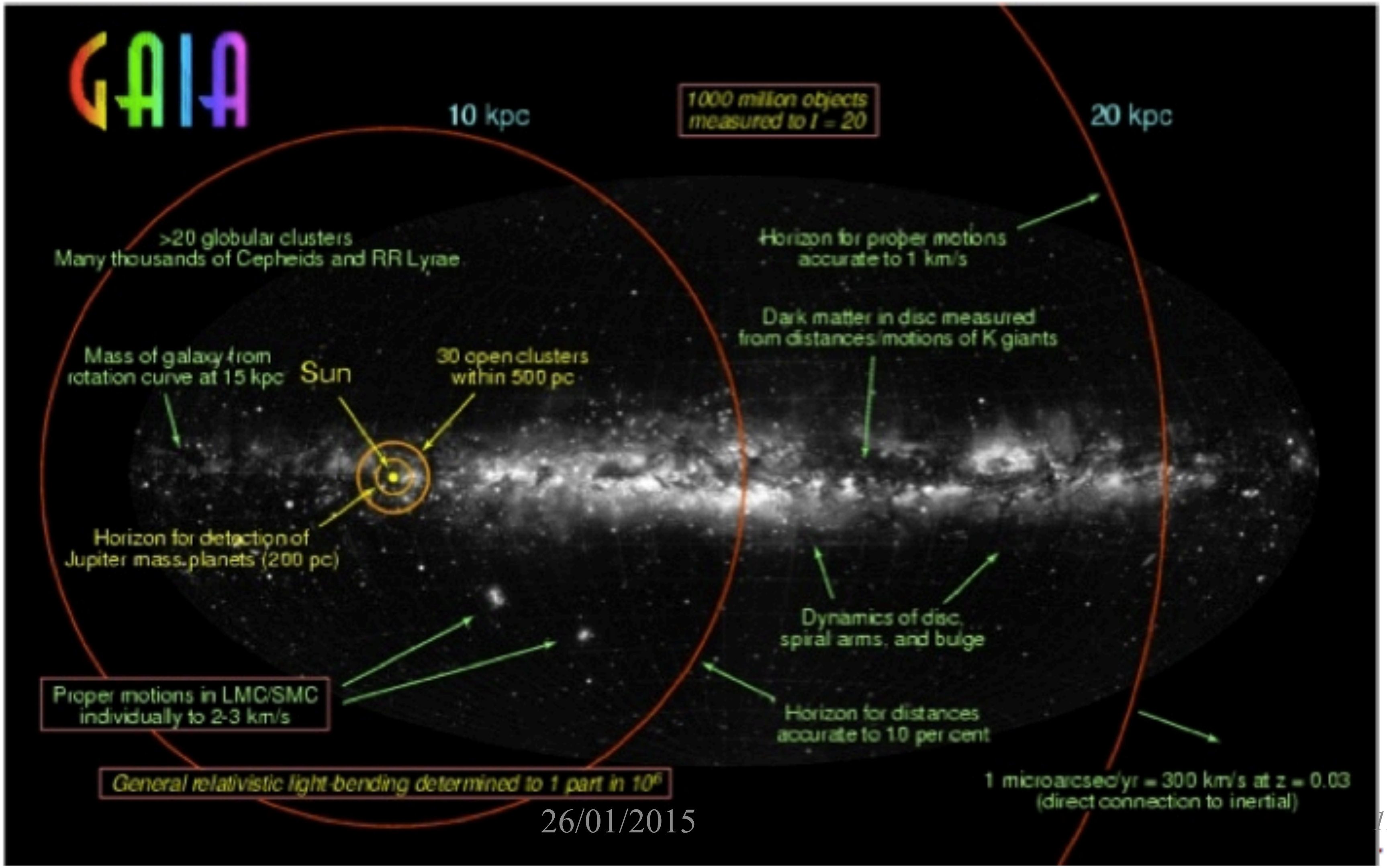
- **Formation and evolution of the Milky Way, its stars and stellar populations.**
- Kinematics and abundances



- Dynamical evolution of open clusters (birth to disruption).
- Stellar evolution.
- Halo substructures.
- Nature of the bulge.
- Formation of the thin and thick disks.

Gaia is coming!

It will observe 10^9 stars!!! (down to I ~ 20)



What can Gaia do?

- 10^9 objects (26×10^6 with V < 15, 250×10^6 with V < 18)

- Positions and proper motions better than 25µas at V=15
- Parallax error of 25µas at V=15
- RV error of 15 km/s at V=17
- Thousands of OCs (mean distances to 1%)
- Observations of clusters in the LMC (~ 200 µas)
- 80 GCs (+1000 stars) within 10kpc (mean distances to 1%)
- Discovery of 10^5-10^6 asteroids
- For stars within 200 pc, discover every Jupiter size planet with period between 1.5 - 9 years

- Spectra with R ~ 11500 of 1.5×10^8 stars with V < 17, around 870nm

What can we do for Gaia?

Gaia has limited spectroscopic capabilities

- Final σ_{RV} ~ 1 km/s for a G5V star with V=14, σ_{RV} ~ 5 km/s at V = 18; for hot stars σ_{RV} ~ 10 km/s at V = 16.
- Estimates of [Fe/H] and [alpha/Fe] for stars brighter than V~12.

Gaia-ESO: adds the spectroscopic information.

- Better RV precision.
- Detailed abundances down to V ~ 16 (UVES).
- At least [Fe/H] and [alpha/Fe] down to V~19 (Giraffe) – possibly more elements.

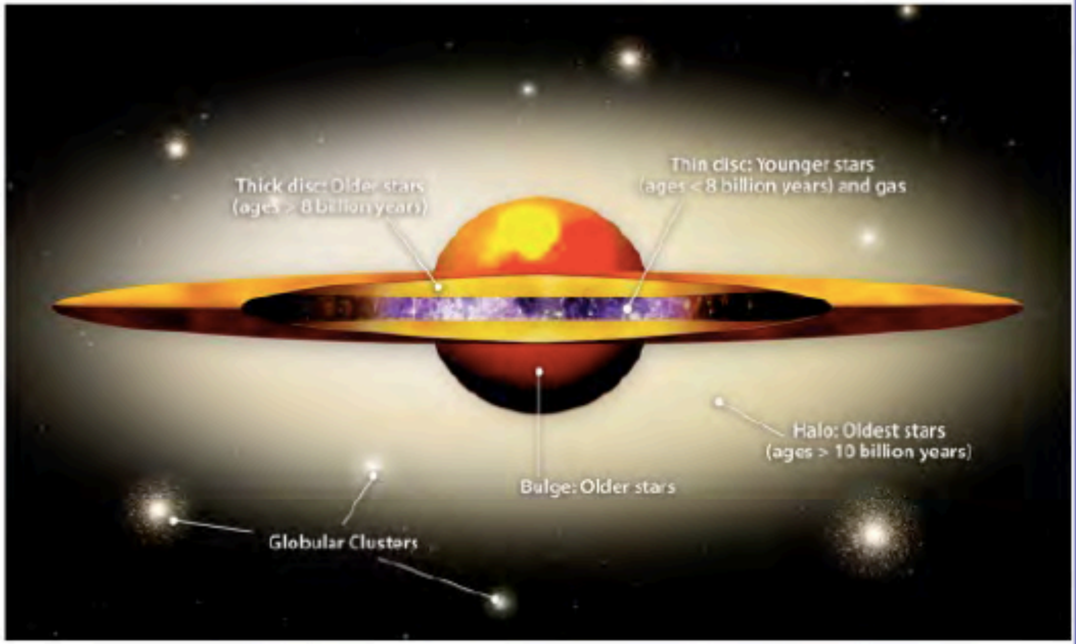
What can we do for Gaia?

Gaia			Gaia-ESO	
2-D →	3-D →	5-D →	6-D →	12+ D
position	parallax	proper motions	spectrum	Astrophysical parameters
Ultra-precision, over years	distance	Transverse velocities	Radial velocity + chemistry	Ages, histories, astrophysics

Stellar orbits, star formation history, origin of the elements, Galaxy assembly,....
Dark Matter, Cosmological initial conditions, fundamental physics, solar system(s)

(Gilmore et al. 2012)

Summary of survey aims (1/2)



10^5 stars -all populations of the MW:

- Halo
- Bulge
- Thick & Thin discs
- Open clusters

Well defined and rigorously implemented target selection criteria

Giraffe+UVES parallels

↓

RVs, vsini, APs, [Fe/H], chemistry

↓

Homogeneous overview of kinematics and abundances

Summary of survey aims (2/2)

- linking stellar populations from birth to the old field
- age, mass, and environment dependances of abundances, kinematics, stellar properties
- radial, vertical and azimuthal abundance gradients and their age dependance: from the inner Galaxy to the outer parts

Gaia-ESO + Gaia

Formation history and evolution of young, mature, and ancient Galactic populations

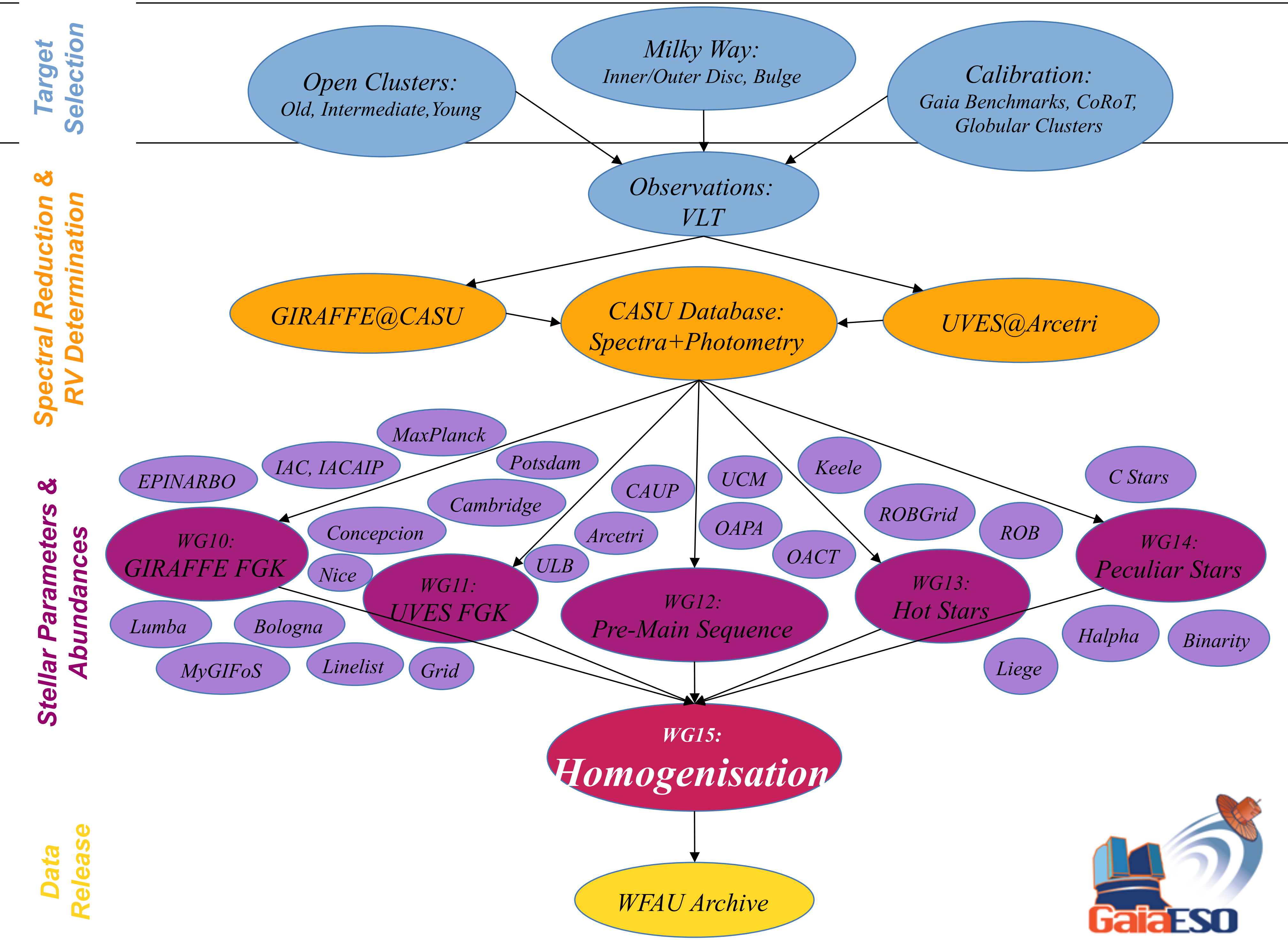
Summary of achievements (1/2)

- **Excellent** early **science**, with clear potential for a substantial **legacy impact**
- **An operational Survey**, from target selection to ESO releases of calibrated results
- **ESO-wide community** of researchers now working in co-operation (using FITS!)
  - -- Build ESO community for future **MOONS, 4MOST, …**
- Include **all major spectroscopic analysis methods**, from O- to M-stars, from PMS to old giants, from metal-poor to metal-rich
  - -- **resolve the major systematics** underlying spectrum analyses
  - -- Atomic and molecular linelists: Major effort in creating and publishing **cleaned, calibrated line lists** for general use
  - -- **Model Atmosphere & Synthetic Spectra Grid** covering a large parameter range

Summary of achievements (2/2)

- **Gaia Calibration**
  - -- **Benchmark stars:** Definition of accepted parameters & abundances (Jofre et al. 2014)
  - -- **COROT:** Fundamental parameters by astero-seismology iterated on Gaia-ESO parameters
- **Calibration of Gaia-ESO** using Gaia Benchmarks, standard clusters, and COROT targets ➔ ensures **Gaia stellar parameters are consistent** with and benefit from Gaia-ESO
  - -- The 3 major surveys, **Gaia-ESO, GALAH (& APOGEE)** now working in synergy towards the Gaia Standard

Plus: **successful synergies with public photometric surveys** (VHS, VVV; VPHAS+)


Target Selection
Open Clusters:
Old, Intermediate, Young
Milky Way:
Inner/Outer Disc, Bulge
Calibration:
Gaia Benchmarks, CoRoT, Globular Clusters
Spectral Reduction & RV Determination
Observations: VLT
GIRAFFE@CASU
CASU Database: Spectra+Photometry
UVES@Arcetri
Stellar Parameters & Abundances
MaxPlanck
IAC, IACAIP
Potsdam
EPINARBO
Cambridge
CAUP
UCM
Keele
C Stars
Concepcion
Arcetri
OAPA
ROBGrid
ROB
WG10: GIRAFFE FGK
Nice
ULB
OACT
WG14: Peculiar Stars
WG11: UVES FGK
WG12: Pre-Main Sequence
WG13: Hot Stars
Lumba
Bologna
Halpha
Binarity
MyGIFoS
Linelist
Grid
Liege
WG15: Homogenisation
Data Release
WFAU Archive
GaiaESO

Current Status

- *3.5 of 5 years observations completed*
- *4 data analysis cycles over the first 2.5 years of data*
- *Data Release 1 available through ESO, DR2/3 on the way*
- *iDR4 parameter & abundance analysis almost complete*
- *Over 150 projects listed on the Gaia-ESO wiki*

Publications thus far...

	Accepted	Submitted	Gaia-ESO Internal Review
Milky Way Programme	10	3	1
Open Cluster Programme	15	-	2
Technical	6	-	2

Interstellar extinction

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Observatoire de la Côte d'Azur, Nice

MOTIVATION

Interstellar extinction was and is still the major obstacle in studying detailed stellar populations in the Milky Way

Often people neglect the importance of interstellar extinction in their work or even worse they just ignore it

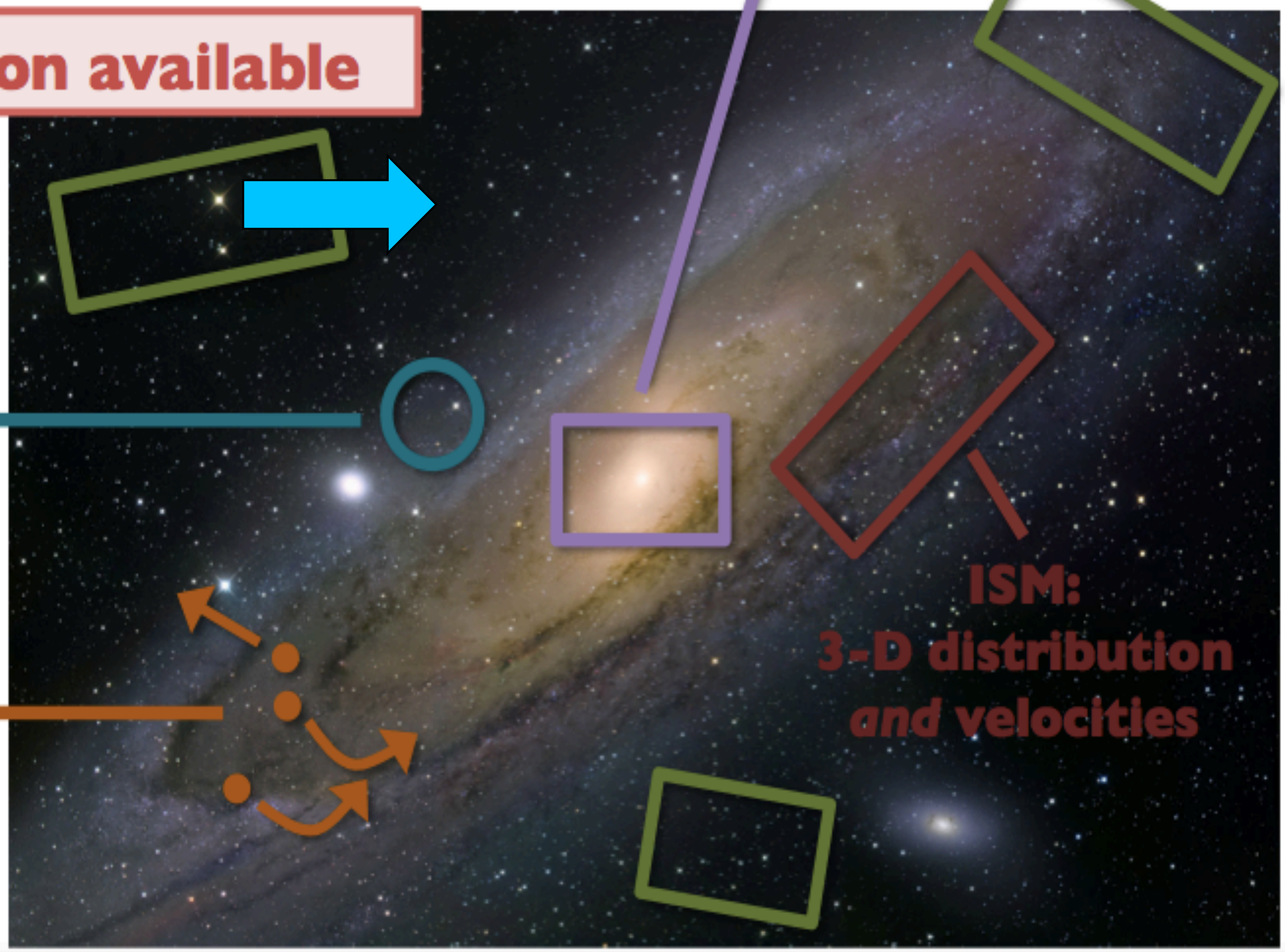
Galactic Archaeology Tools

Simulations

Extragalactic samples

Milky Way/Local Group

Unique information available



The Schlegel dust map

- Use of COBE/DIRBE maps and IRAS 100 μm maps
- Constructing dust temperature map based on DIRBE maps
- Dust temperature map varies between 17-21 K but affects the dust column density (factor 5)
- Schlegel map has IRAS resolution but is calibrated on COBE/DIRBE data

Schlegel maps are calibrated using standard reddening law and use colours of elliptical galaxies to measure reddening per unit flux density of the 100 μm emission

The Schlegel dust map

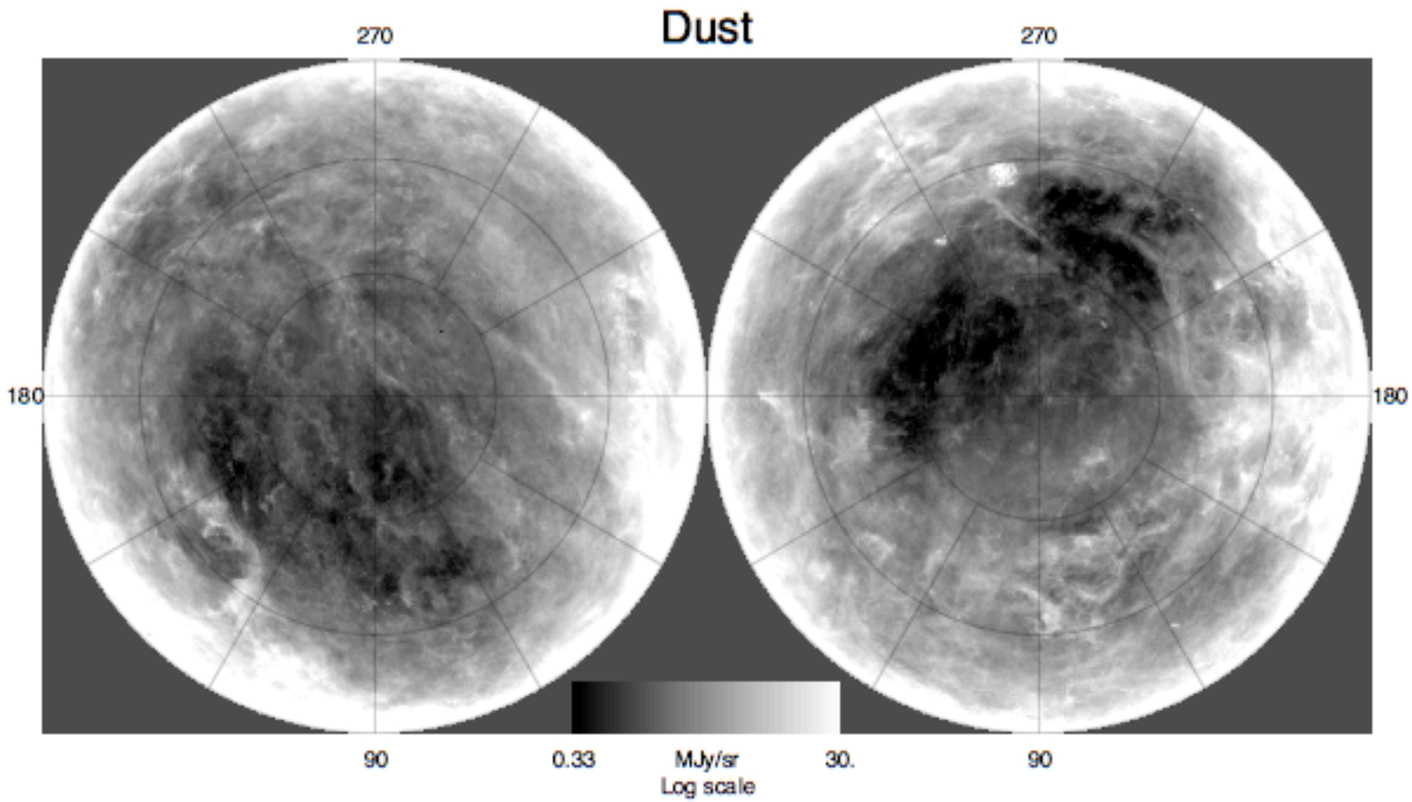


FIG. 8.—Full-sky dust map for the NGP (*top*) and SGP (*bottom*)

The Schlegel dust map

Schlegel map is the commonly used map

Easy to access : specify ra,dec → E(B-V)

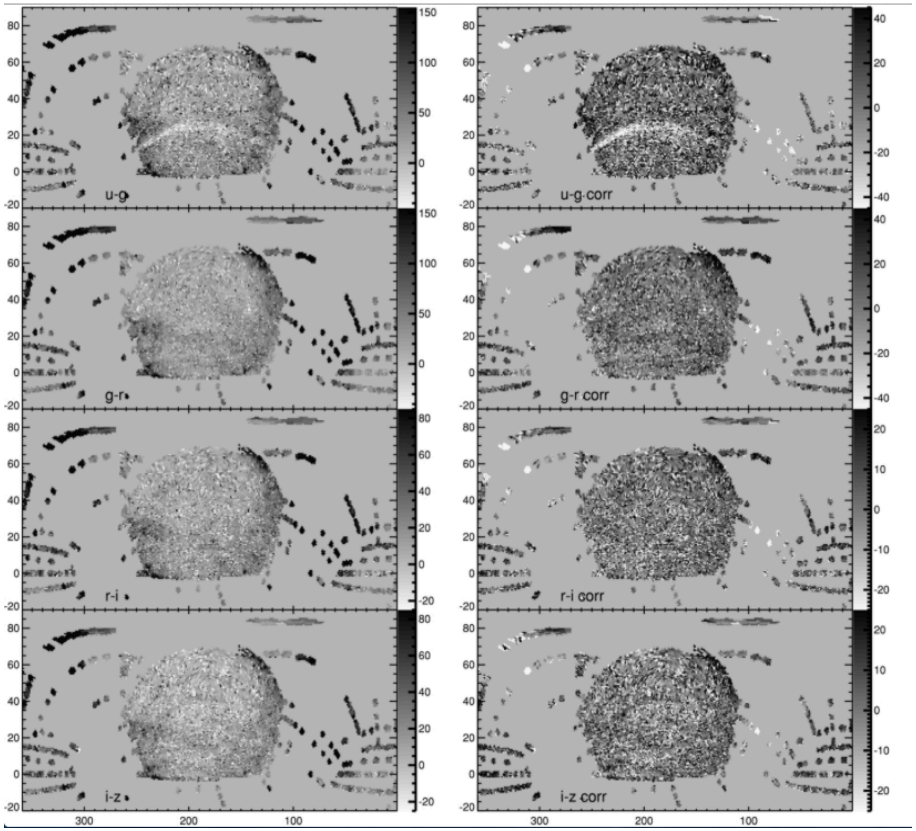
Works pretty well in high galactic latitudes

Only 2D map

BUT is not appropriate for $|b| < 10$!

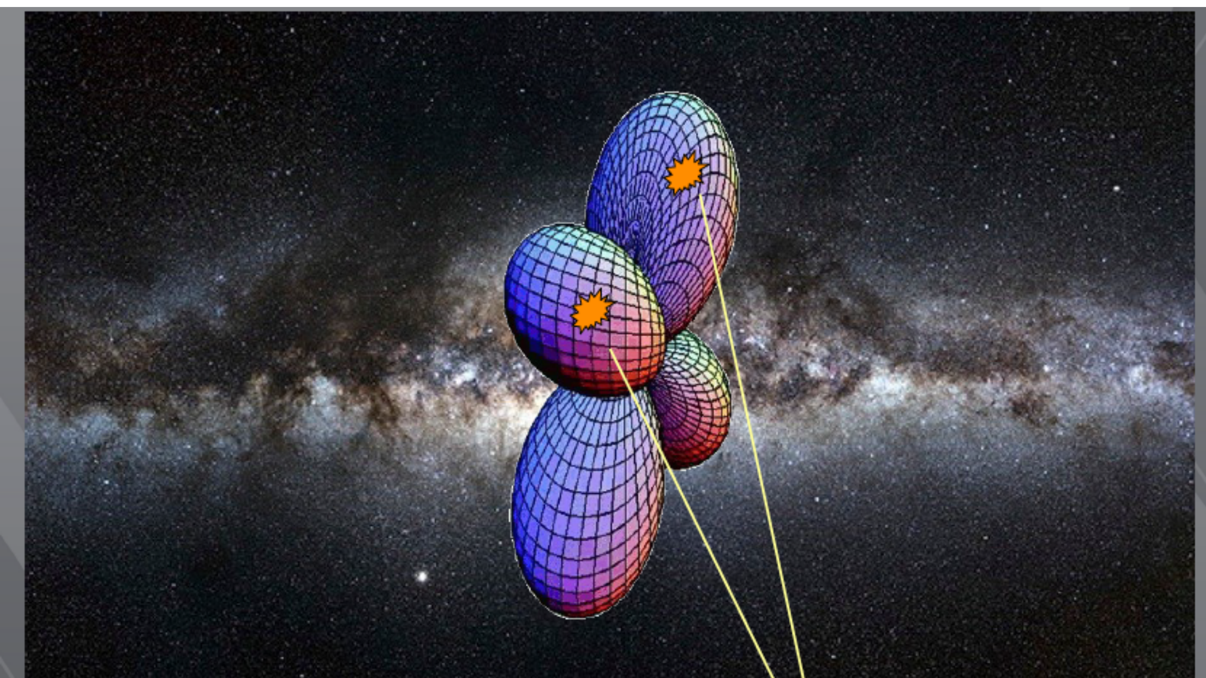
Improving the Schlegel map (Schlafly&Finkenbeiner 2011)

Use of SDSS data photometric and stellar parameters of SDSS (Teff,logg,Z)
Comparison with intrinsic colours of MARCS model
Much more precise map using individual stars



The Galactic Bulge

- Closest spheroide
- The only galactic environment with a large dispersion of metallicity: $-1 < [Fe/H] < 1$
- Old component: 8-12 Gyr
- Galactic Bar
- X-shaped Bulge with two densities



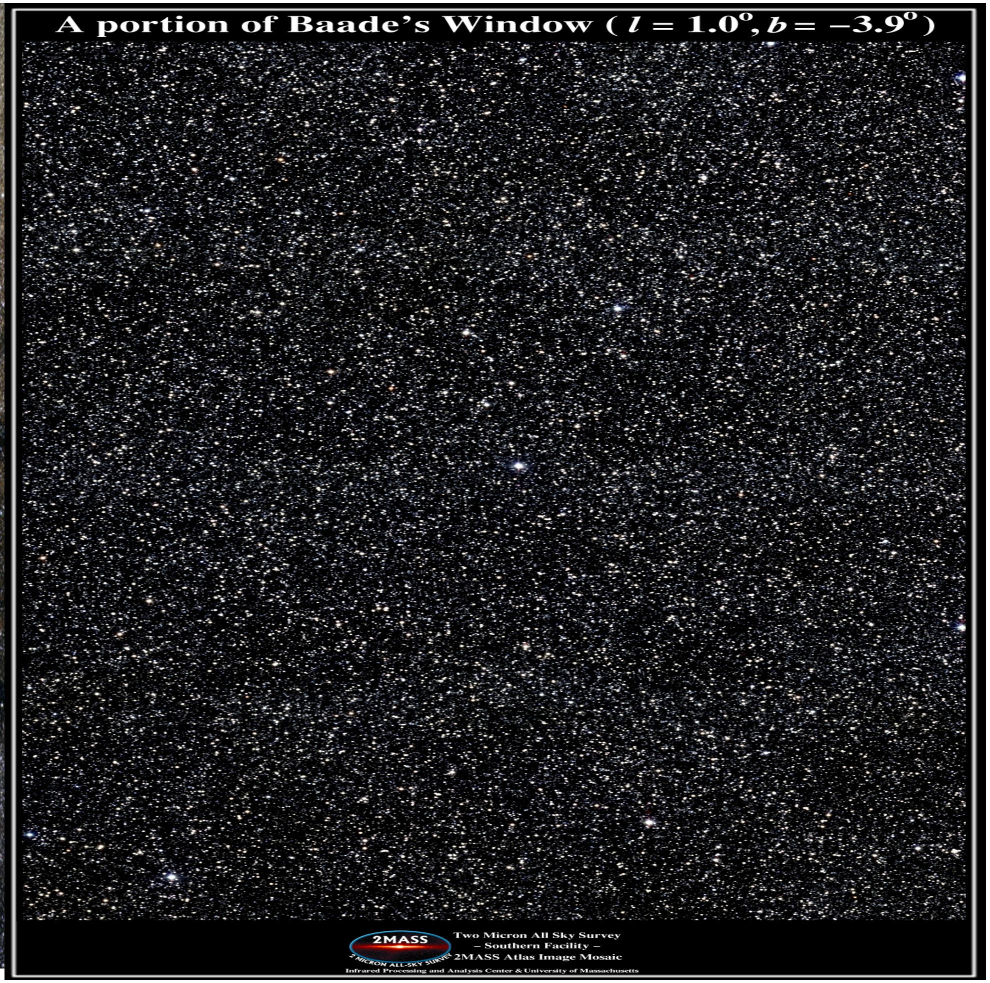
… and Interstellar Extinction!

Most of the interstellar extinction is concentrated towards the Bulge and especially towards the Galactic Center

Spitzer composite image 3.6, 4.5,5.8 and 8 micron

200 pc

Low extinction windows: Baade's window

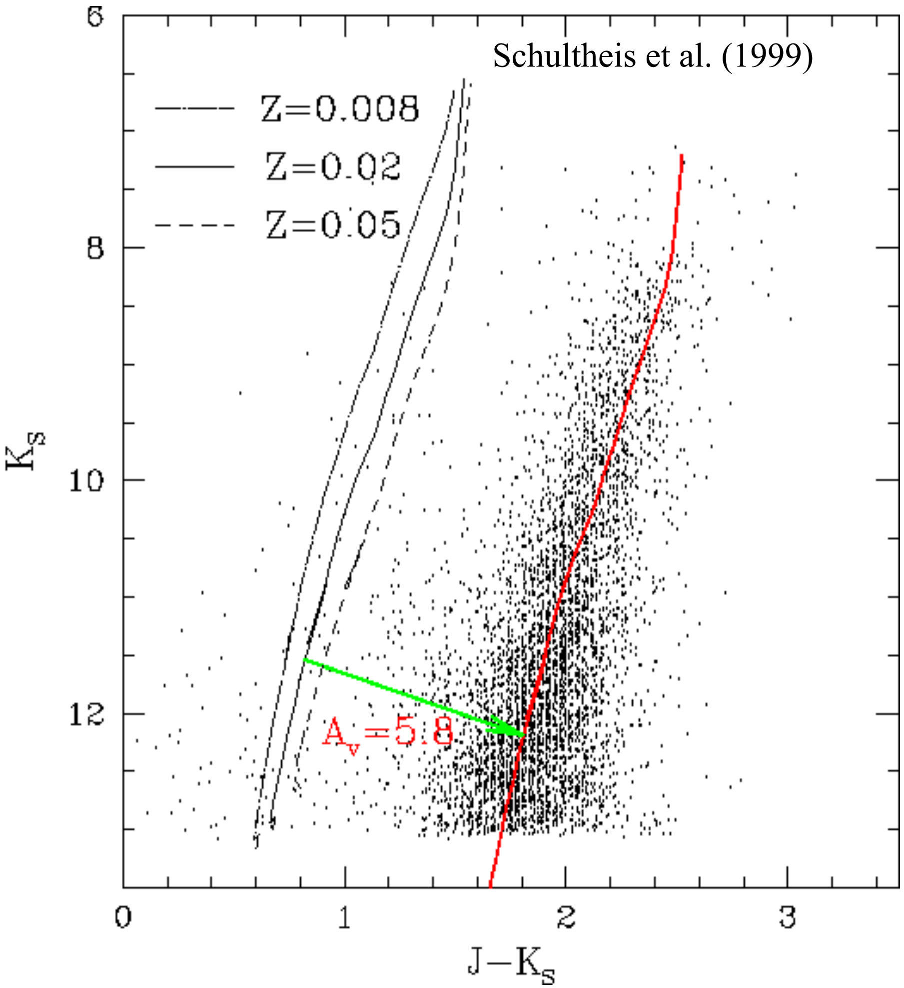


Visible light

Infrared

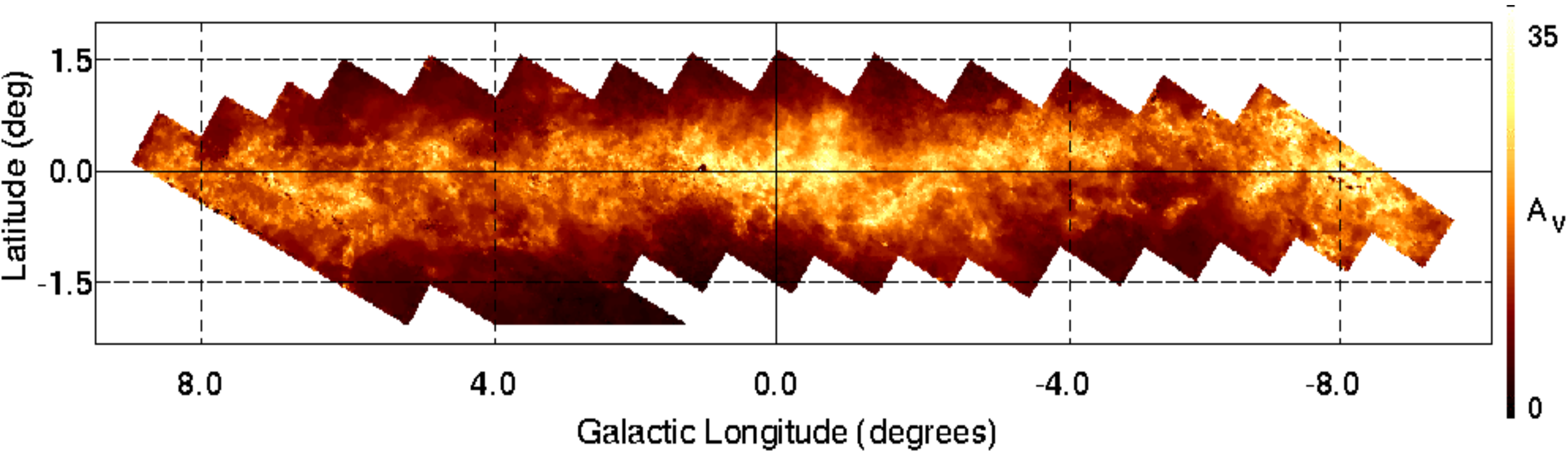
2D maps

Use of M giants as tracer of extinction



- **2MASS observations in J et K_S**
- **Comparison with theoretical isochrones of the stellar populations of RGB et AGB (Bertelli et al. 1994)**
- **First detailed extinction map with a spatial resolution of 2'**
- **~ 2 million sources, typical error A_V~2^m**
- **Resolution of high extincted regions with A_V< 35^{mag}**

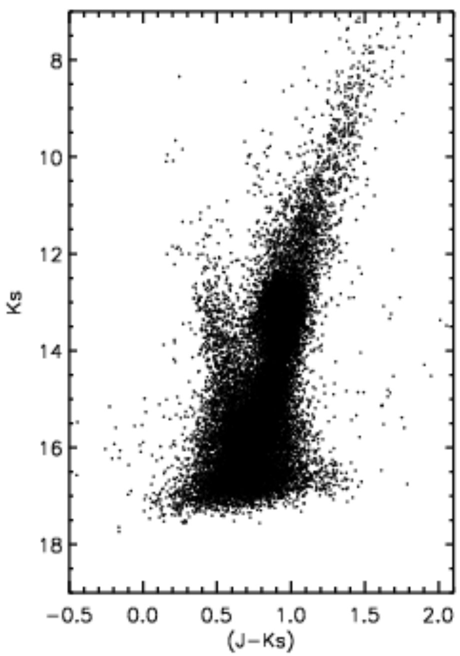
First high-spatial resolution 2D extinction map



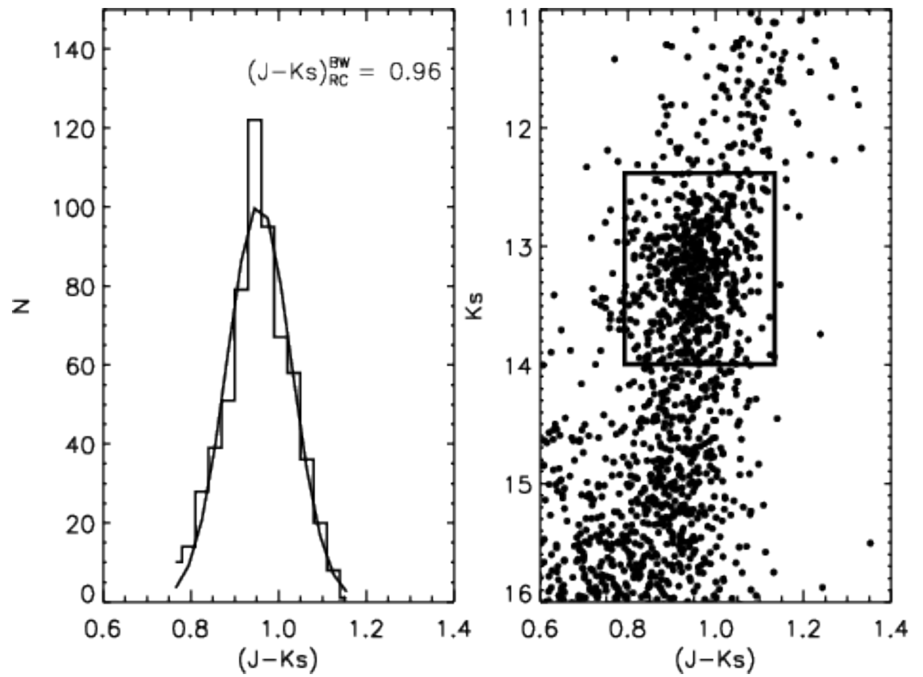
Schultheis et al. (1999)

Red clump stars

Gonzalez et al. (2012) : red clump stars

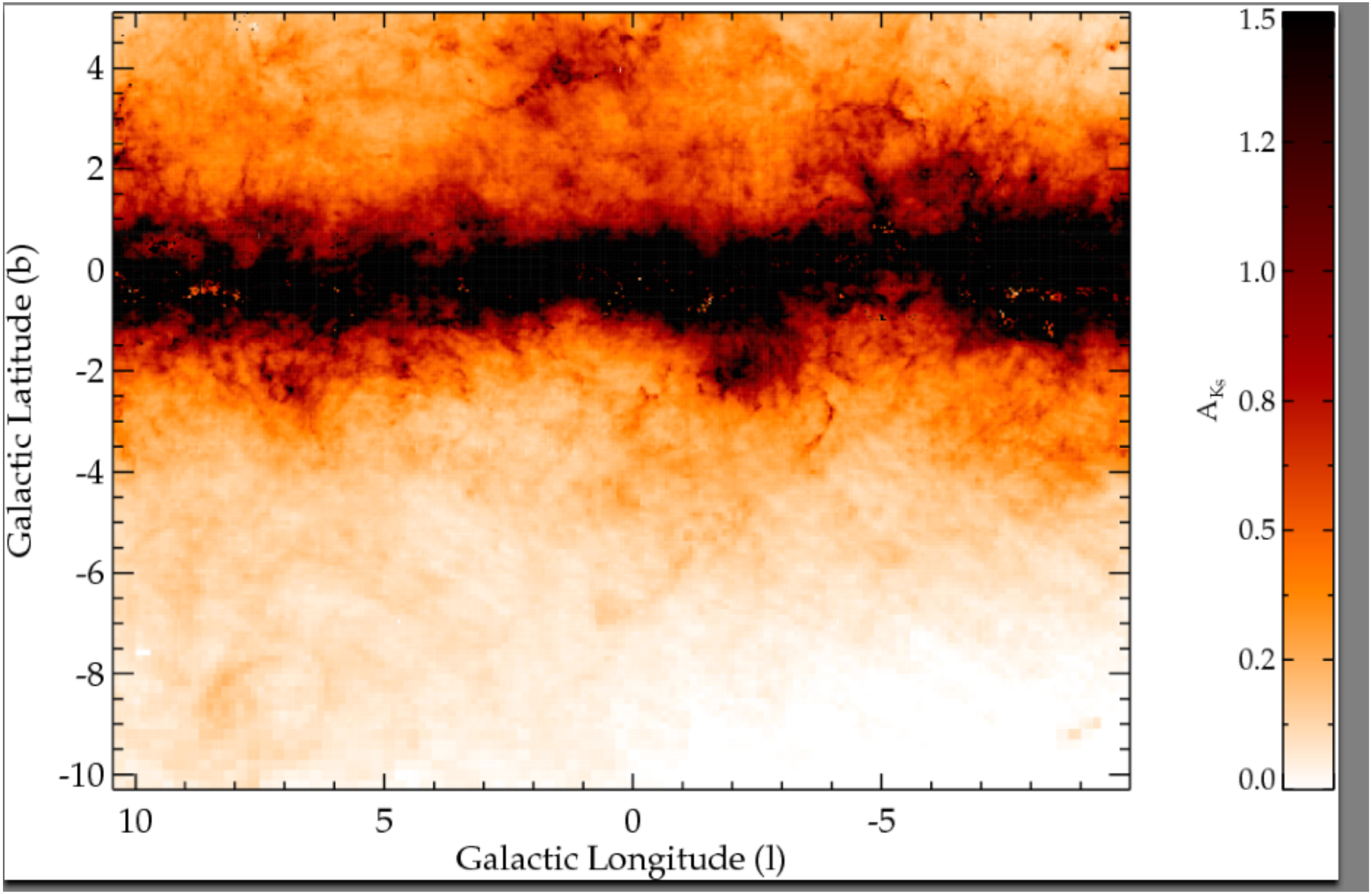


Red clump of Baade 's window



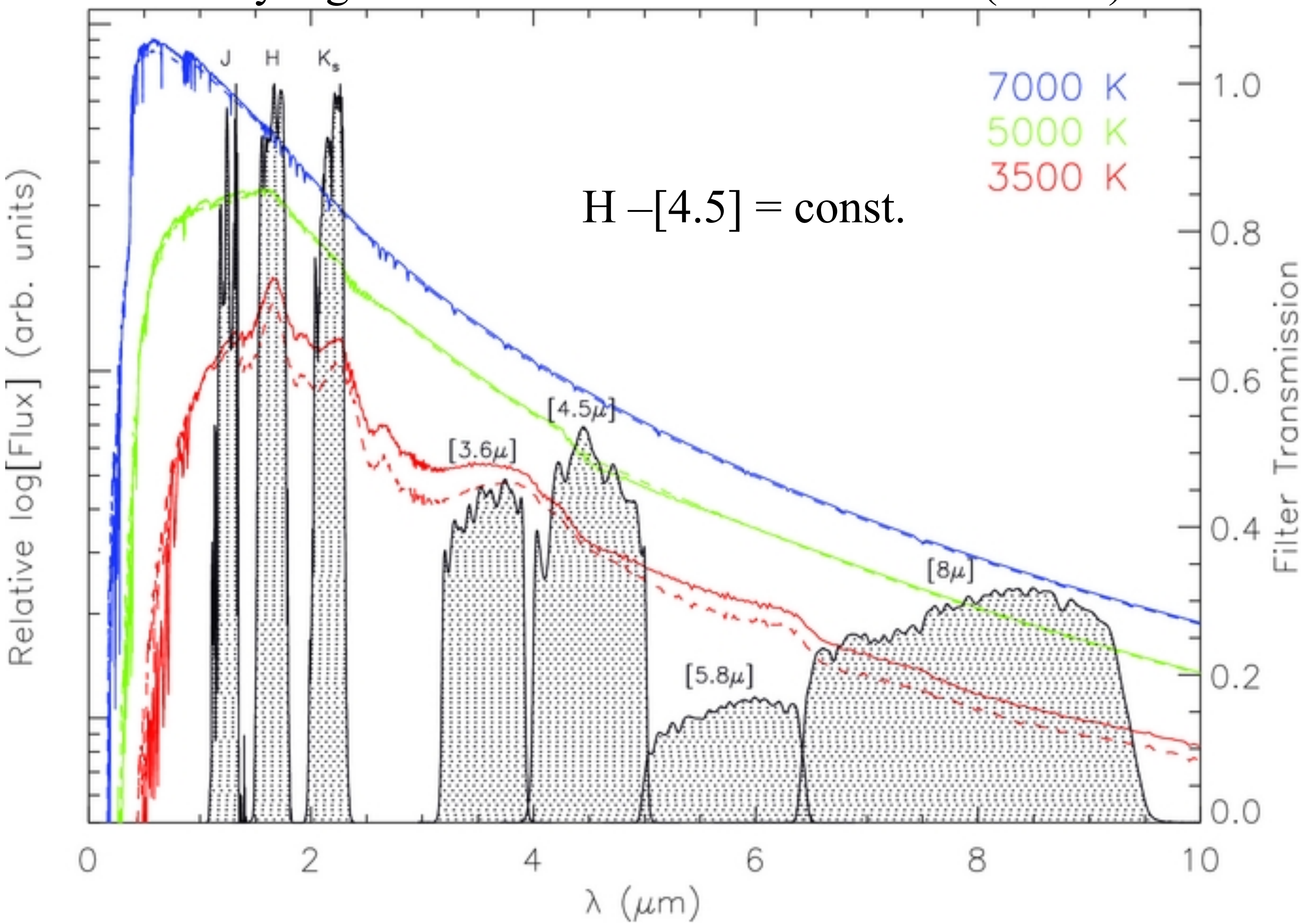
Advantage: homogeneous population, less affected by metallicity

Gonzalez et al. (2012) : red clump stars

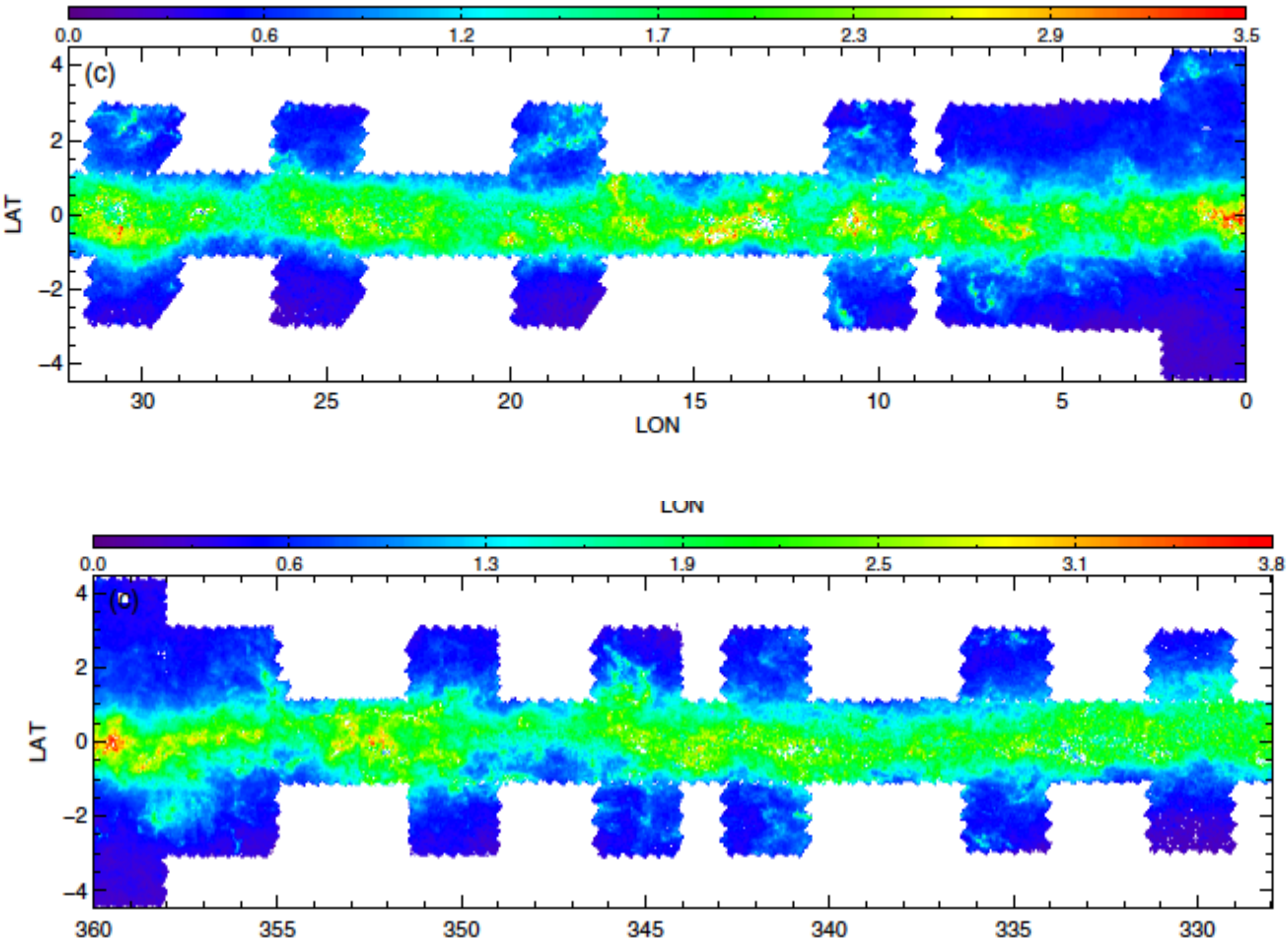


Nidever et al. (2012)

Rayleigh Jeans Colour Excess Methode (RJCE)



Nidever et al. (2012) RJCE



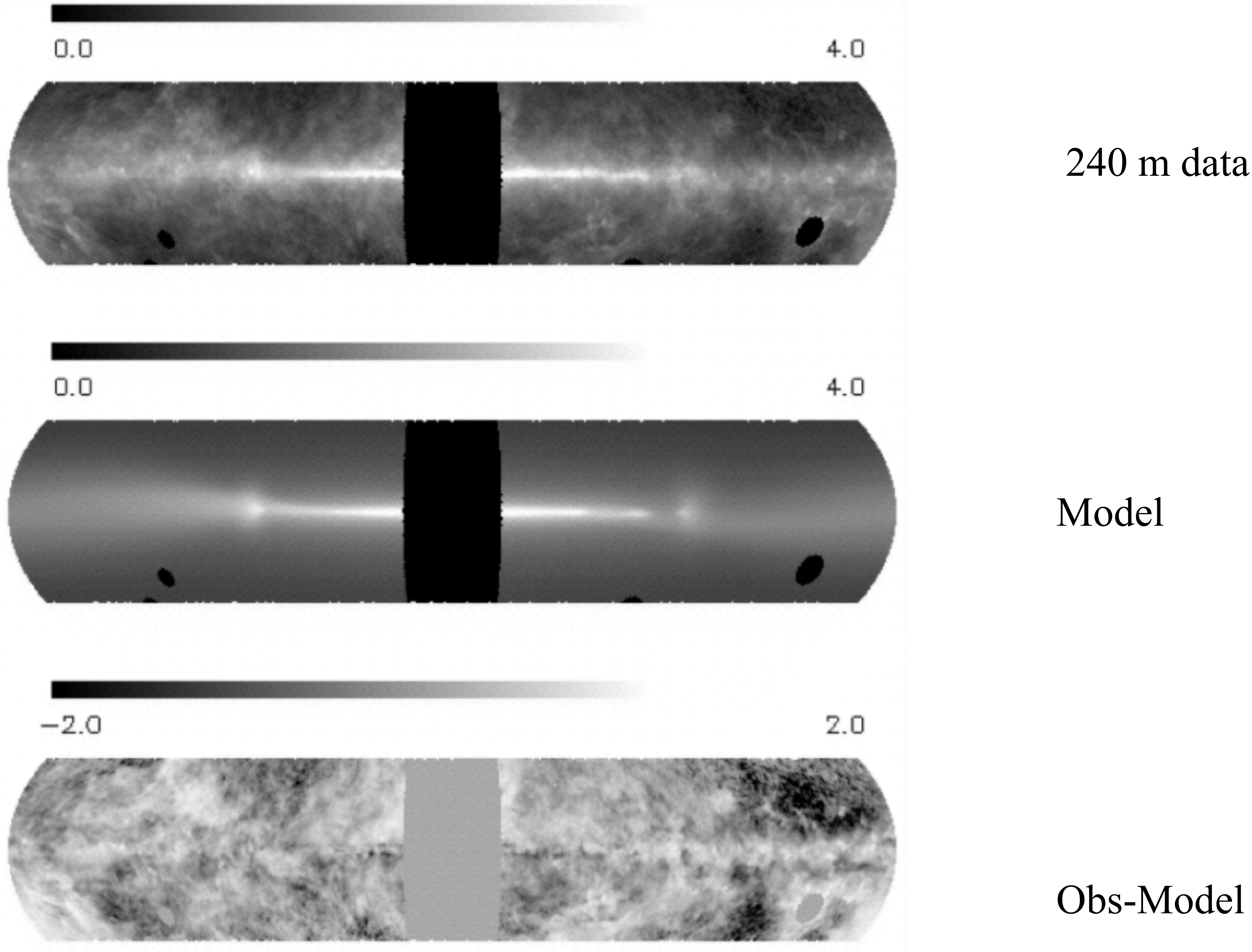
3D interstellar extinction

Drimmel & Spergel 3D dust map

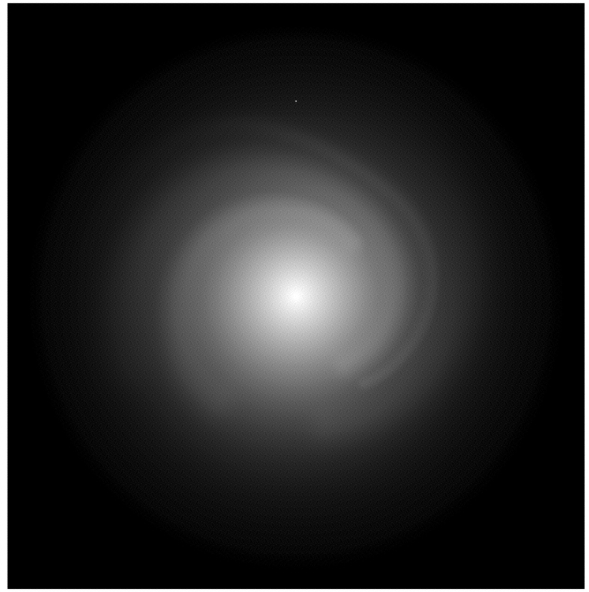
Based on modeling the 240 micron emission of DIRBE data

A complete 3D sky dust model

Spatial resolution of 21’ x 21’

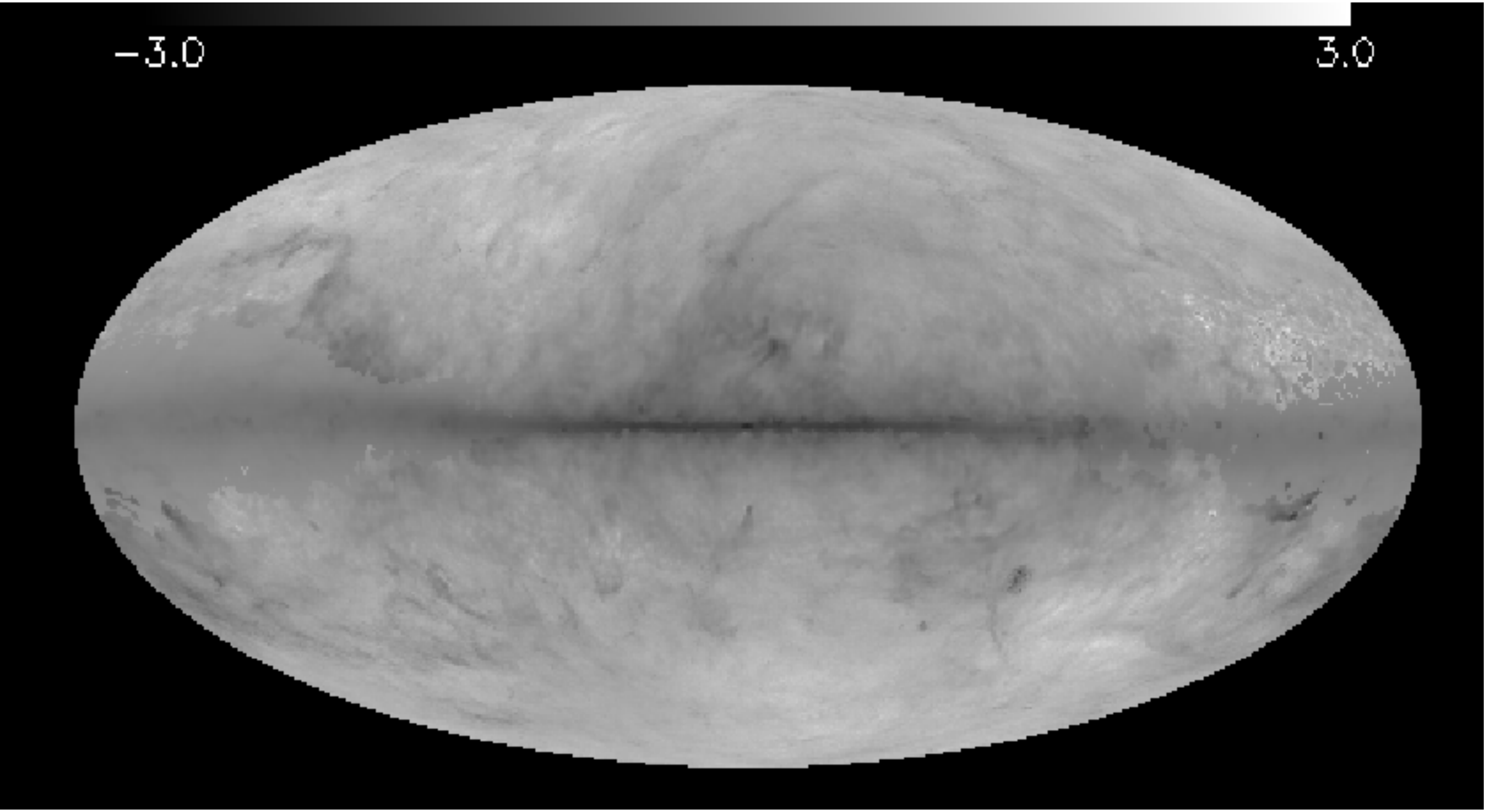

0.0
4.0
240 m data
0.0
4.0
Model
−2.0
2.0
Obs-Model

Drimmel & Spergel 3D dust map



Simple 3D dust model. Does not include features related to the galactic bar nor nuclear disk but works on average not too bad

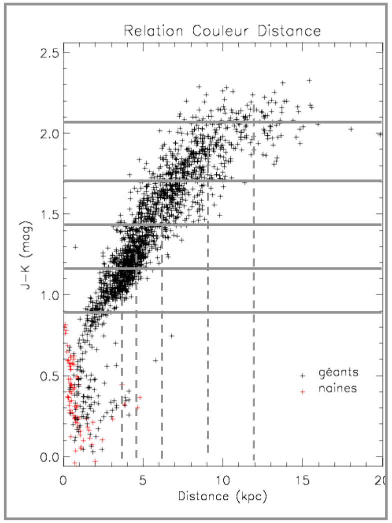
Drimmel et al. (2003)



3D maps in the galactic Bulge

The Marshall et al. (2006) model

Method

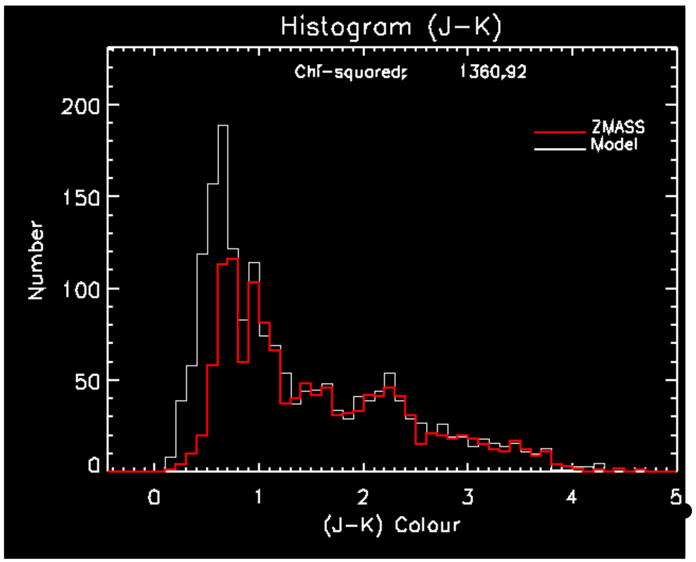


We compare 2MASS & Besançon model of the Galaxy - see Robin et al. (2003)

K & M Giants

Similar J-K colour - modified by extinction

- Both catalogues are sorted by increasing J-K colour and binned
  - Distance of model bins → observations



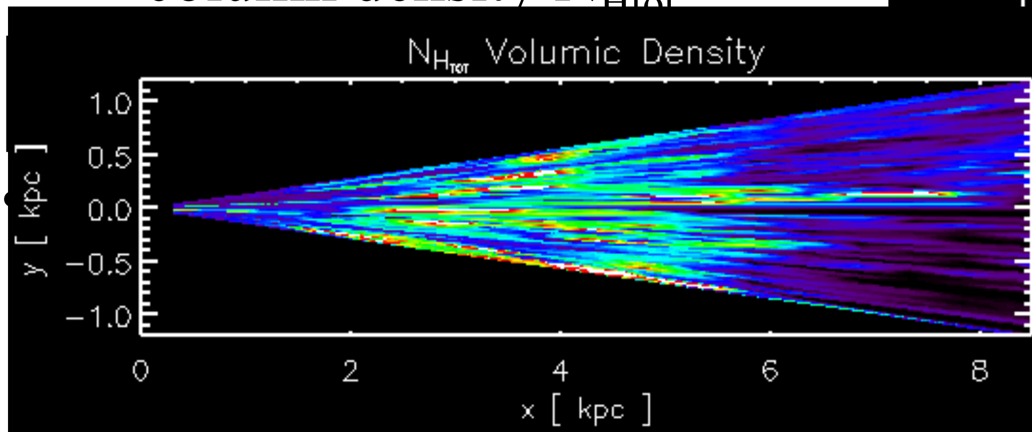
Compare median J-K colour and adjust :

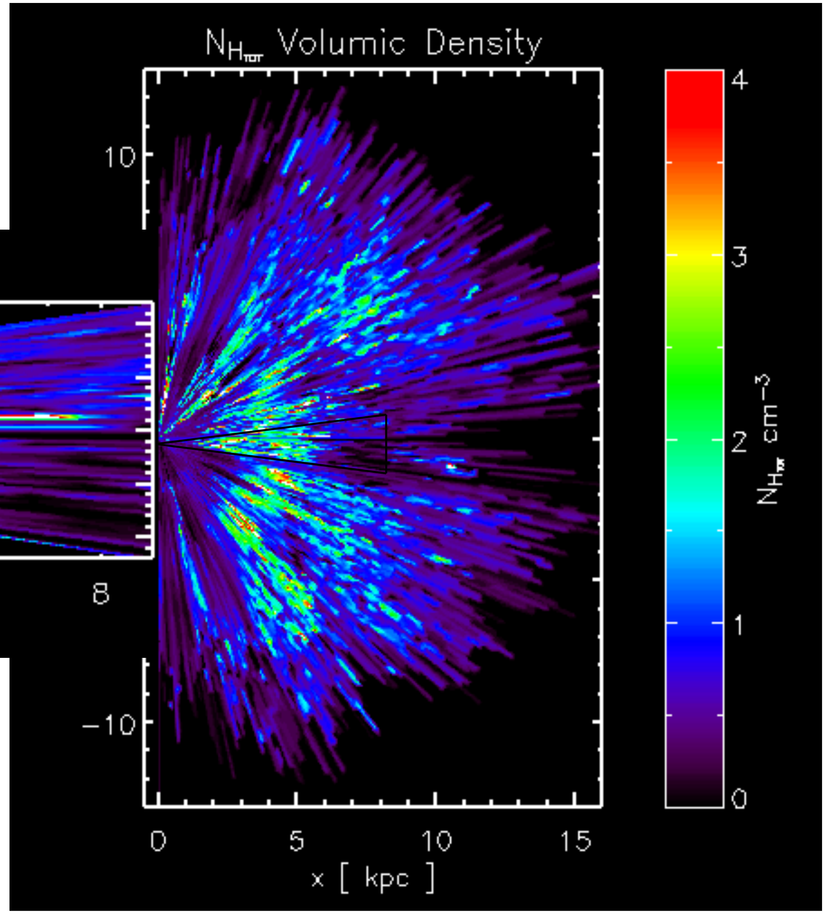
$$\delta(J-K) = A_J - A_K = 0.174 \times A_V$$
$$A_V = \delta(J-K)/0.174$$

- J-K Histogram provides a check

A Galactic Bird's Eye View

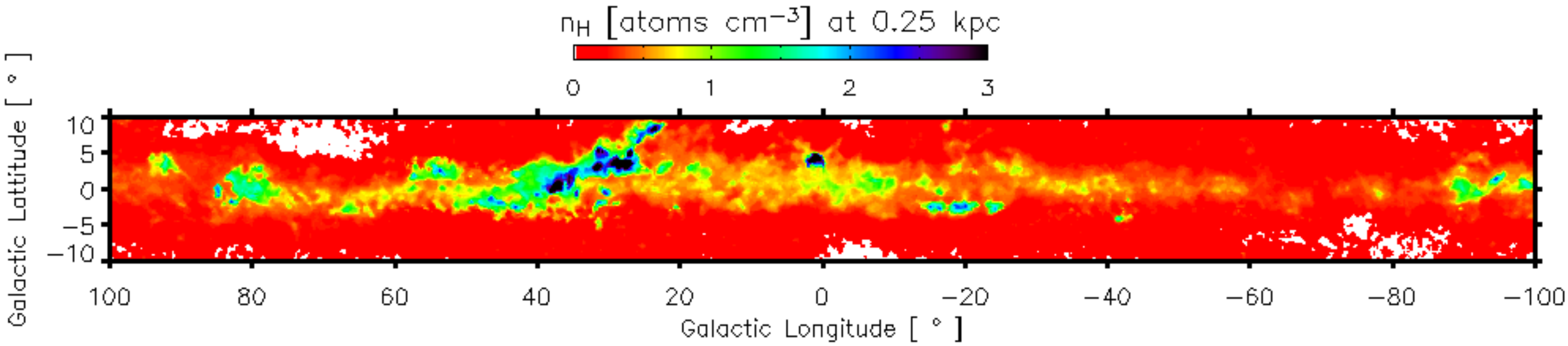
- Inner Galaxy, b=0, -90 < l < 90
- Extinction difference
  → column density N_{Htot}





- Molecular Ring RGAL~ 4 kpc
- Resolution :
  - Spatial : 7,5'^{2} → 15'^{2}
  - Radial : ~ 1 kpc

Marshall et al. (2006)

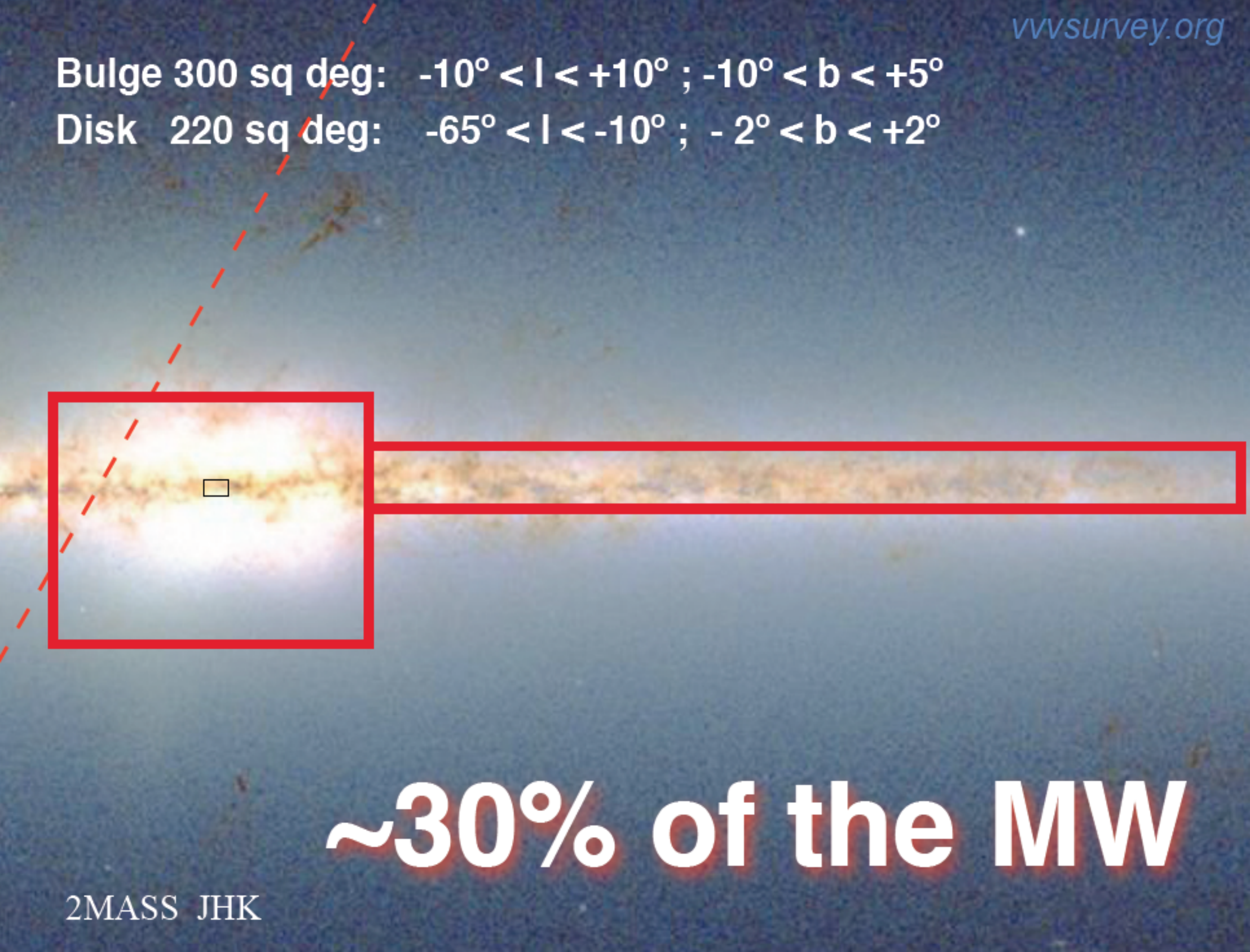


BUT: depend on input parameters of galactic model !
Use of 2MASS data problematic for Bulge analysis (confusion!)

vvvsurvey.org

PI: D. Minniti

VISTA Variables in the Vía Láctea: The Big Picture

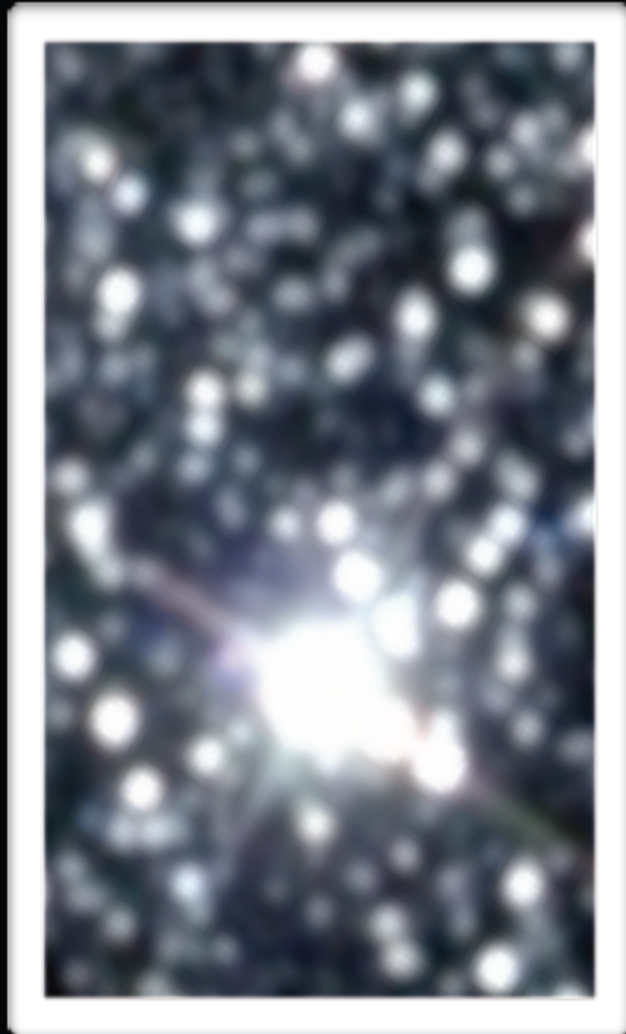


vvvsurvey.org
Bulge 300 sq deg: -10° < l < +10° ; -10° < b < +5°
Disk 220 sq deg: -65° < l < -10° ; - 2° < b < +2°
~30% of the MW
2MASS JHK

VISTA TELESCOPE AT ESO PARANAL

4.1 m telescope
f3.25 focus
near-IR camera
1.5 sqdeg fov
193 nights

DEEPER AND HIGHER RESOLUTION



new

Main differences with 2MASS

2MASS covers the whole sky, VVV only 1.3%

VVV has higher resolution (0.34"/pix)

VVV is deeper (Ks<18)

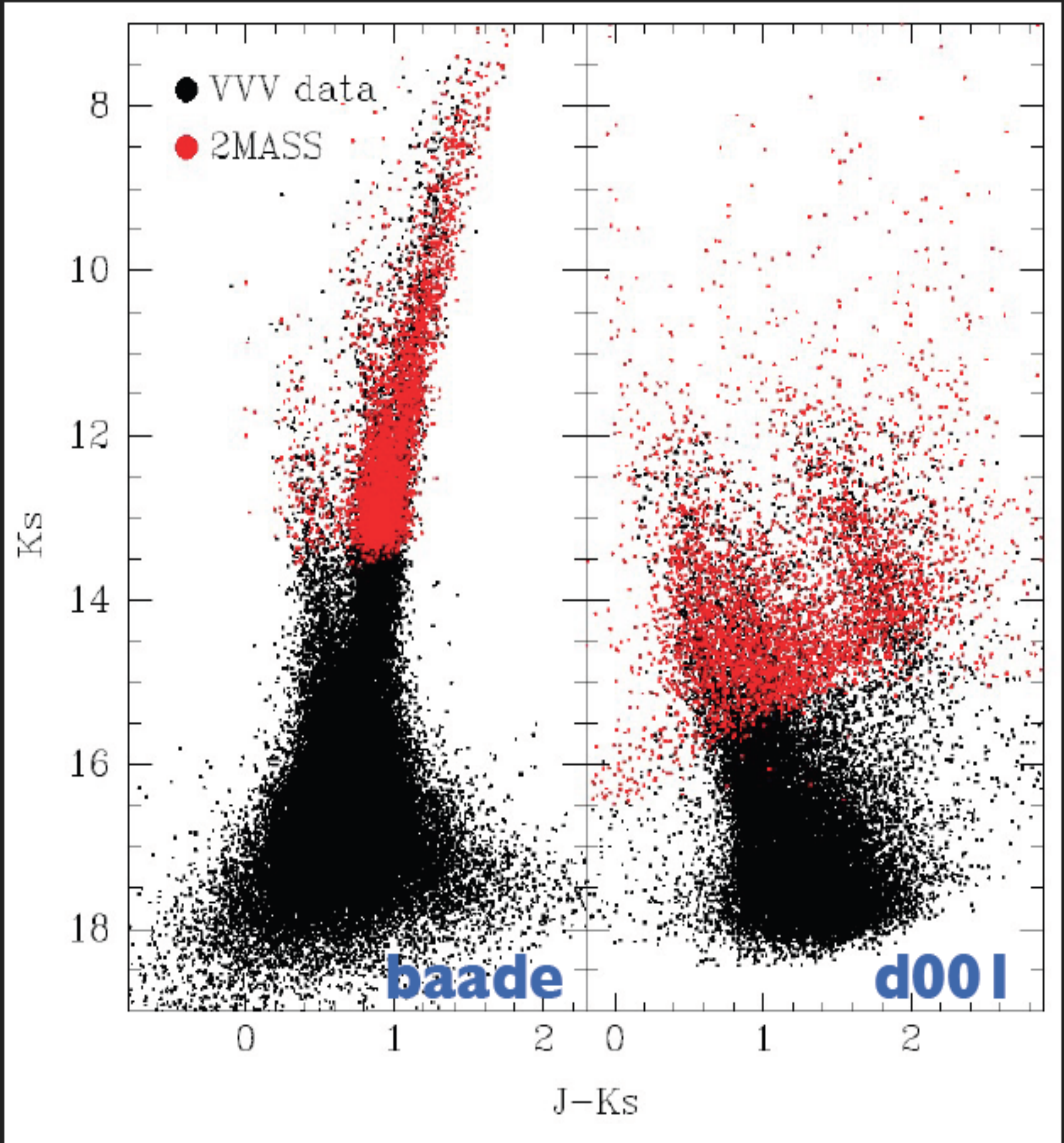
VVV has 5 filters (ZYJHKs)

VVV is a multiepoch survey (~100 epochs)

All in all the VVV survey is 2x bigger than 2MASS

VVV CMDs

Color-magnitude diagrams of bulge and disk fields compared with 2MASS.



A high resolution 3D interstellar extinction map

DATA SET

GLIMPSE-II: [3.6],[4.5],[5.8],[8.0]
VVV Data :ESO VISTA Variables in Via Lactea

Near-IR ESO public survey (Minniti et al . 2010)

VVV covers 300 sq. deg of the Galactic Bulge covering
$-10^\circ < l < +10^\circ$ and
$-10^\circ < b < 5^\circ$

Carried out with VIRCAM on ESO 4.1m VISTA telescope (Paranal Observatory)
Pixel size 0.3 arcsec
196 tiles each 1.48 x 1.18 sq degree

Repeated Ks observations for variable stars (RR Lyrae, Cepheids, LPVs, etc.)
Single epoch catalog already available (Gonzalez et al. 2011)

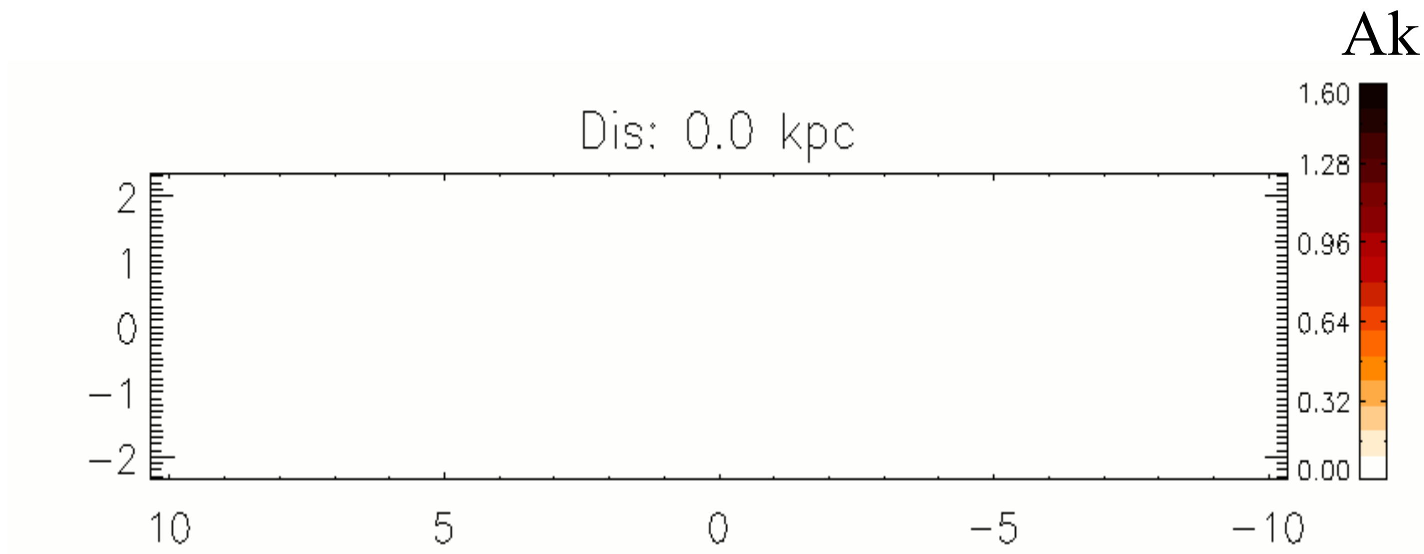
Construction of 3D map with GLIMPSE-II data and VVV data together with the Besancon model

- Similar methode as Marshall et al. (2006) BUT

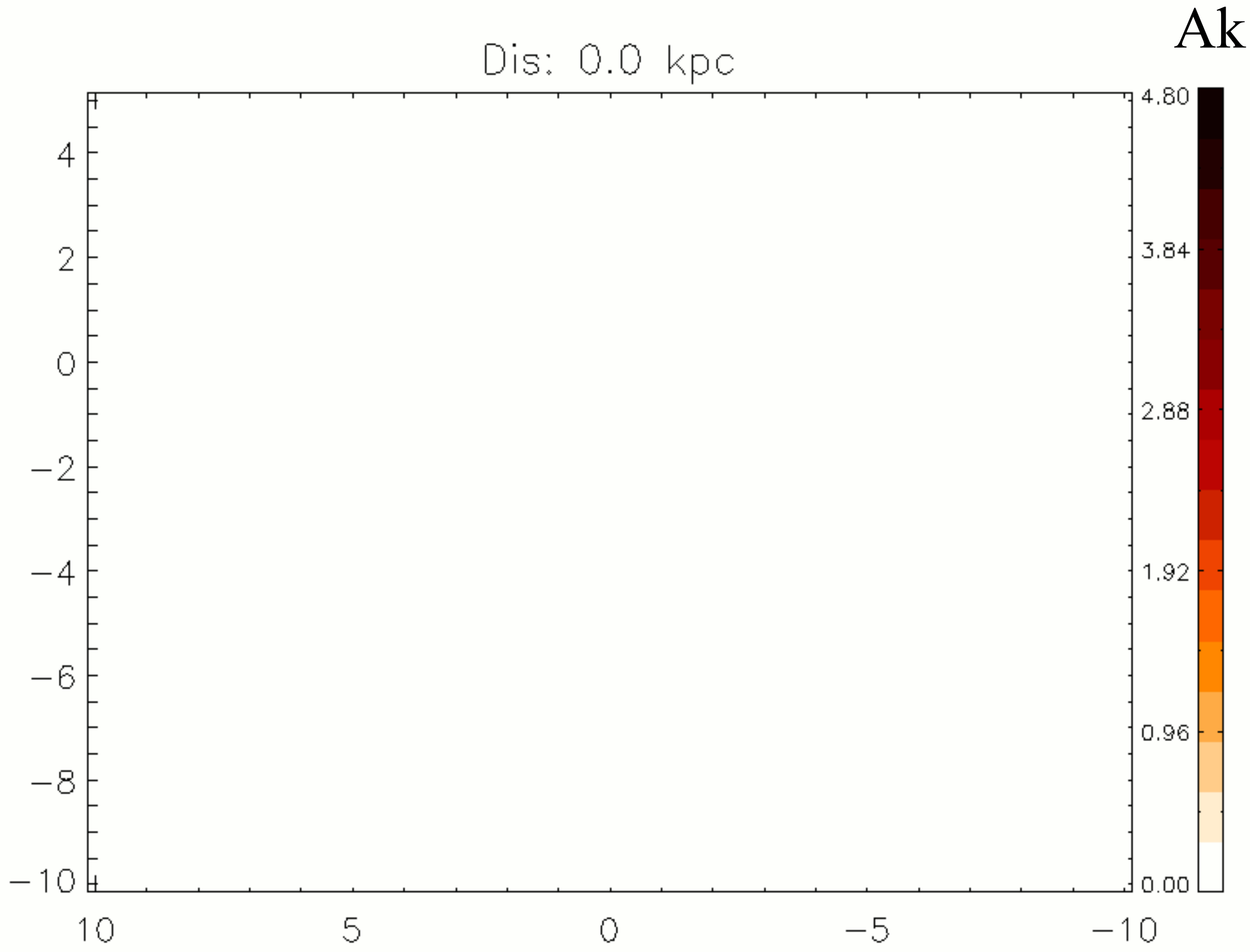
- Use of new Bulge model (Robin et al. 2012) with two populations:bar/bulge
- New Teff-colour relation for K/M giants extending to cooler temperatures until 2500 K including mass-loss (TP-AGB) → better agreement with colour-Teff relations from angular diameter measurements of red giants and with Padua isochrones (Girardi et al.)
- Implementation of GLIMPSE colours in the Besancon model [3.6],[4.5],[5.8],[8.0].
- Mapping extinction simultaneously in J-K,H-K,K-[3.6],K-[4.5],K-[5.8],K-[8.0]
- Check the complete CMD to validate our extinction method!
- Advantage: Mapping extinction at different depths and deriving in parallel extinction coefficients

GLIMPSE-II Chen et al. (2013)

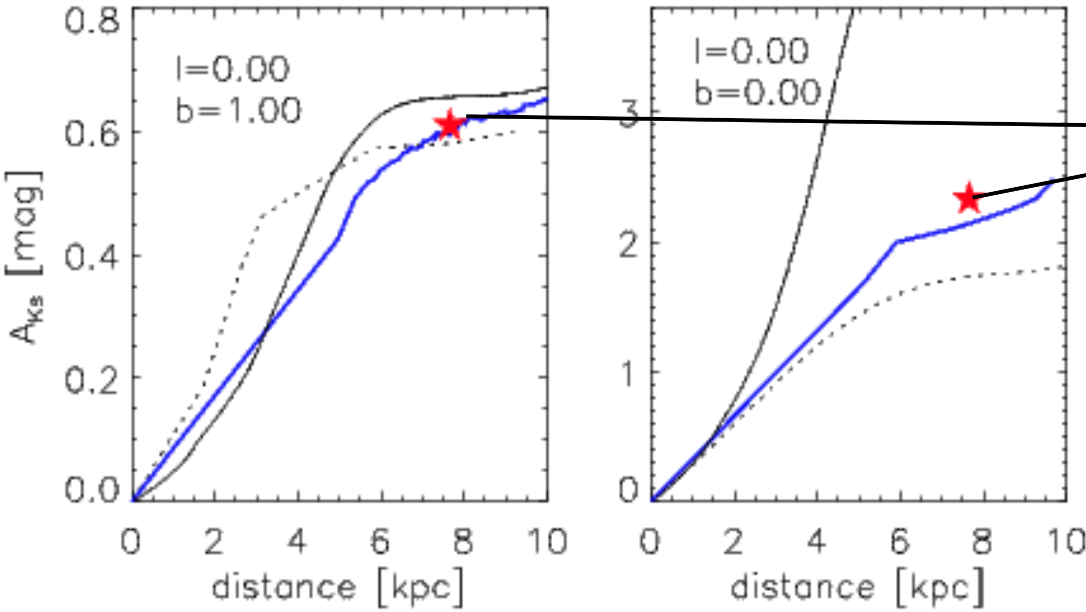
K-[3.6], K-[4.5],K-[5.8],K-[8.0]



VVV data: Schultheis et al. (2014): 330 sq degree
Resolution: 6', distance bins of 500 pc



Chen et al. (2012)



Red clump position
Gonzalez et al. (2012)

Resolution 6' x 6'

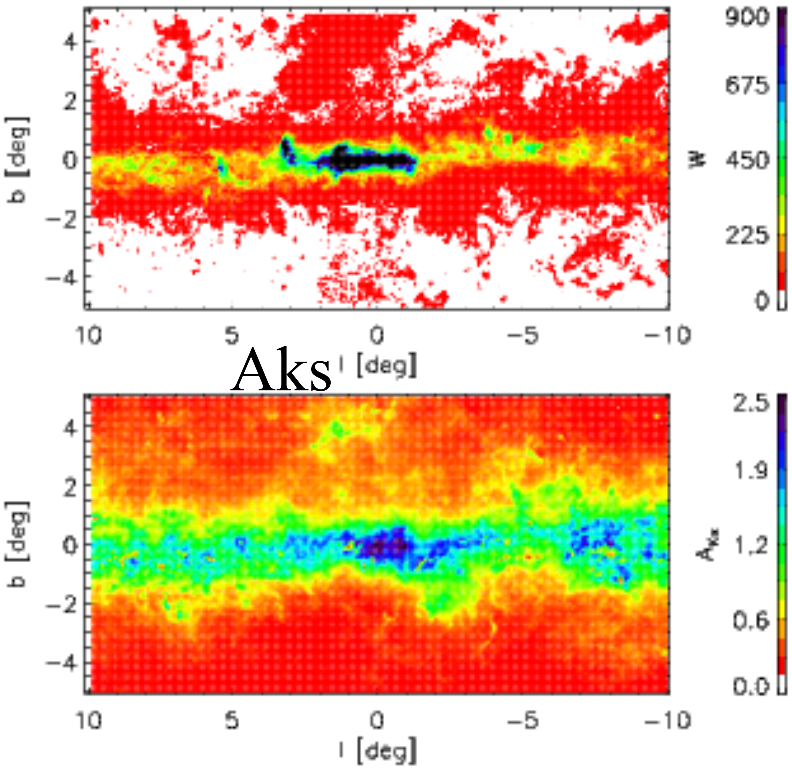
3D maps available in electronic form and beamer webpage

→ Global use for stellar population synthesis models

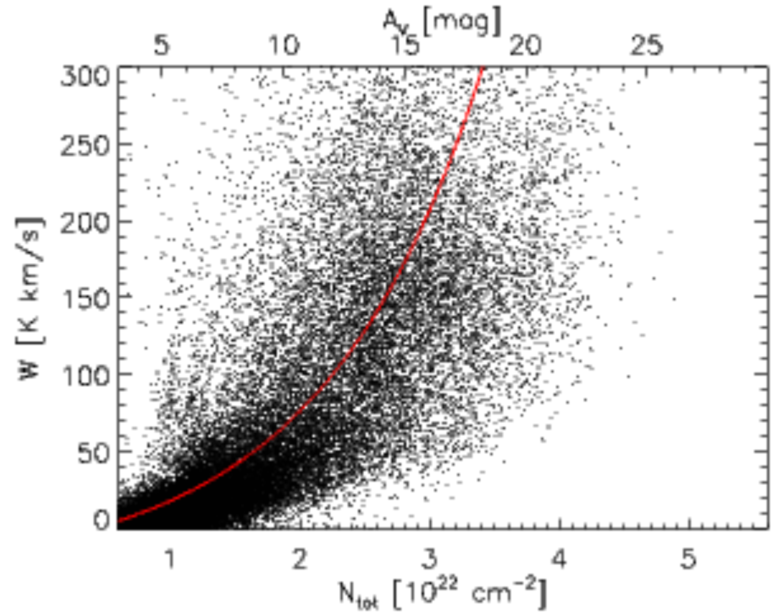
Correlation dust to gas

Schultheis et al. (2014)

^{12}CO



Aks



BUT: how can we verify the 3D extinction maps?

Until now: just based on stellar population synthesis models which have a lot of assumptions !!

Can we get 3D extinction directly from observations?

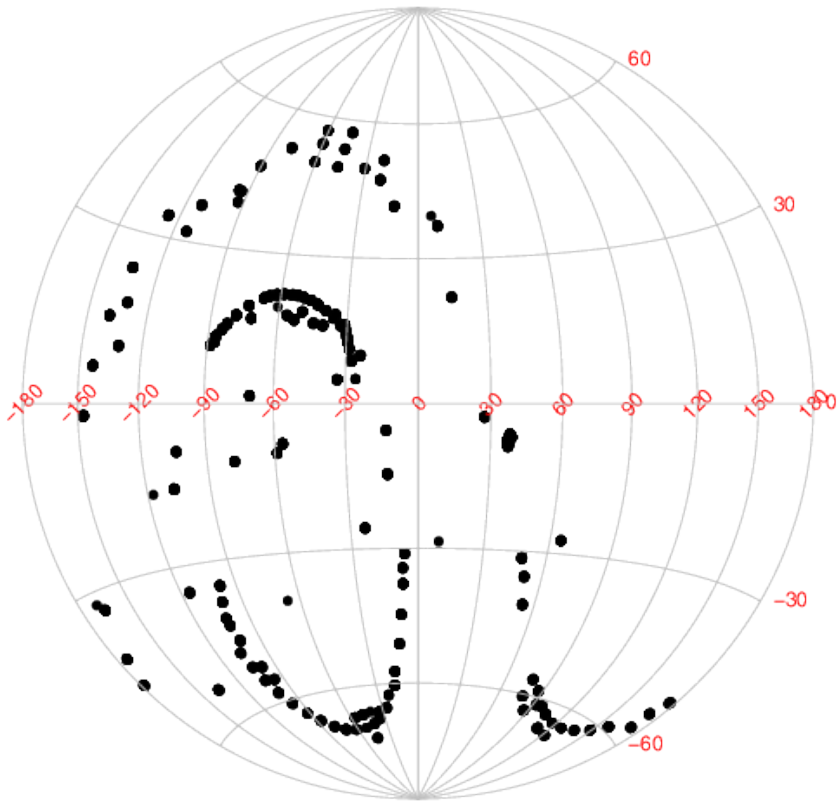
→ Large spectroscopic survey can reveal 3D extinction!

Interstellar Extinction with the Gaia-ESO survey

Use of DR2 release of GES

S/N > 10, sigma(RV) < 1.5 km/s and reliable
Stellar parameters (Teff, logg, Fe/H) -----> 5600 reliable stars

Photometry of SDSS and VISTA (ugrizJHK)



Interstellar Extinction with the Gaia-ESO survey

Take advantage of high precison stellar parameters to derive extinction

- ❖ Direct measure of interstellar reddening
- ❖ Tracing extinction in 3D as we get distances
- ❖ No galactic model!

- ✓ How does the extinction values compare with extinction maps ?
- ✓ How does extinction increase with distance ?
- ✓ Is there any bias in the extinction using a certain population (e.g. RGB stars, red clump stars, main sequence stars) ?
- ✓ How reliable are the 2D and 3D dust extinction models?

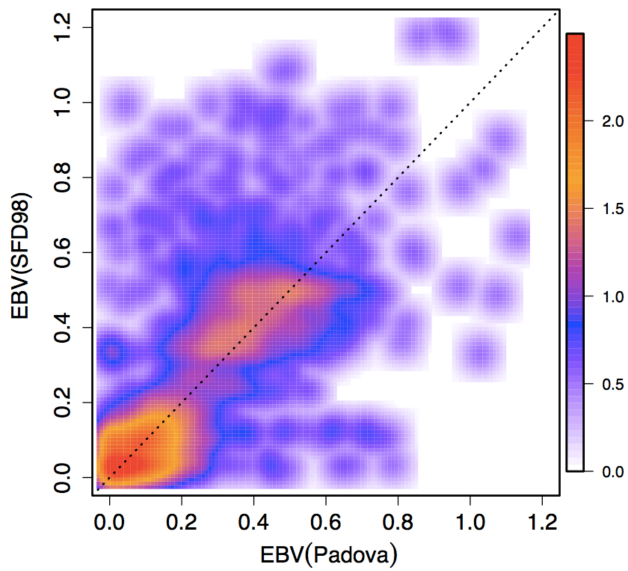
The "Isochrone matching" methode:

- For each star we take the closest point to the corresponding isochrone with its corresponding metallicity (0.2 dex bins)
- Add errors in Teff, logg and Fe/H
- Stars which are too far off the grid are skipped
- Distance between each star in the Teff and log g grid together with the individual errors give realistic errors in E(J-K) and d
- Extinktion: $E(J\text{-}K) = (J\text{-}K)_{2MASS} - (Mj\text{-}Mk)_{Padova}$
- $d = 10^{0.2(Ks - Mk)+5-Ak}$

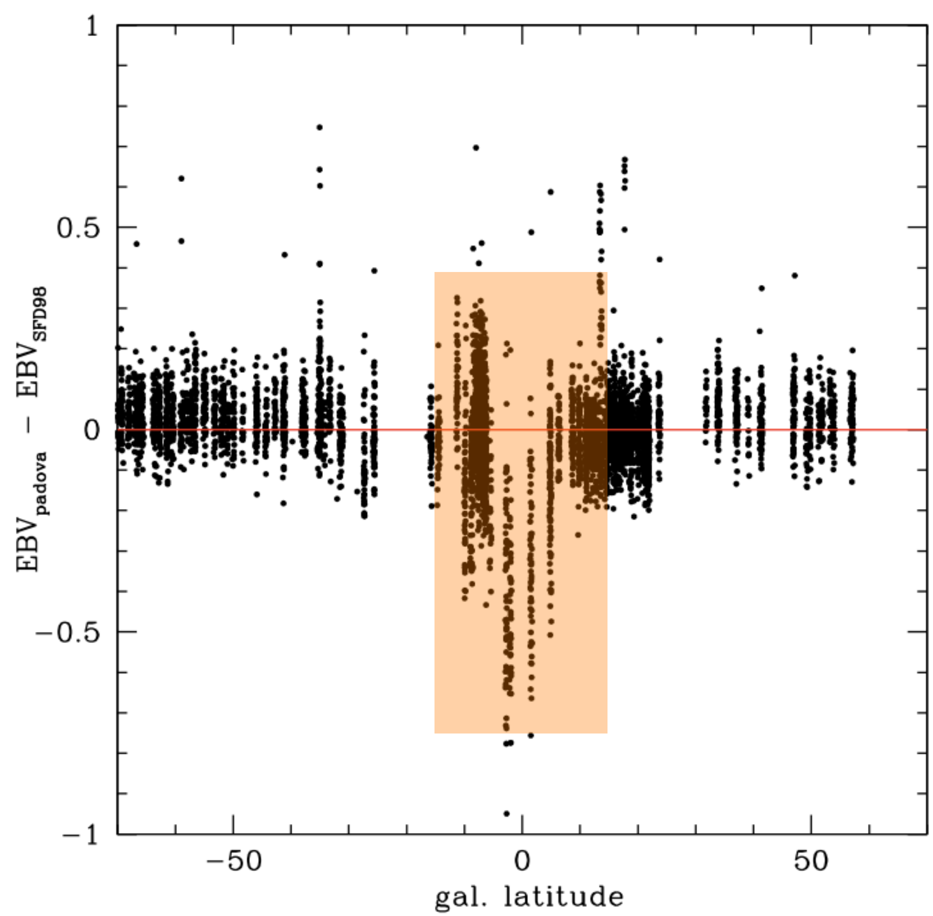
→ Powerful method to get out of large spectroscopi survey directly extinction and distance

→ Succesfully applied for APOGEE (SDSS-III): Schultheis et al. (2014)

2D-Extinction: Comparison with Schlegel

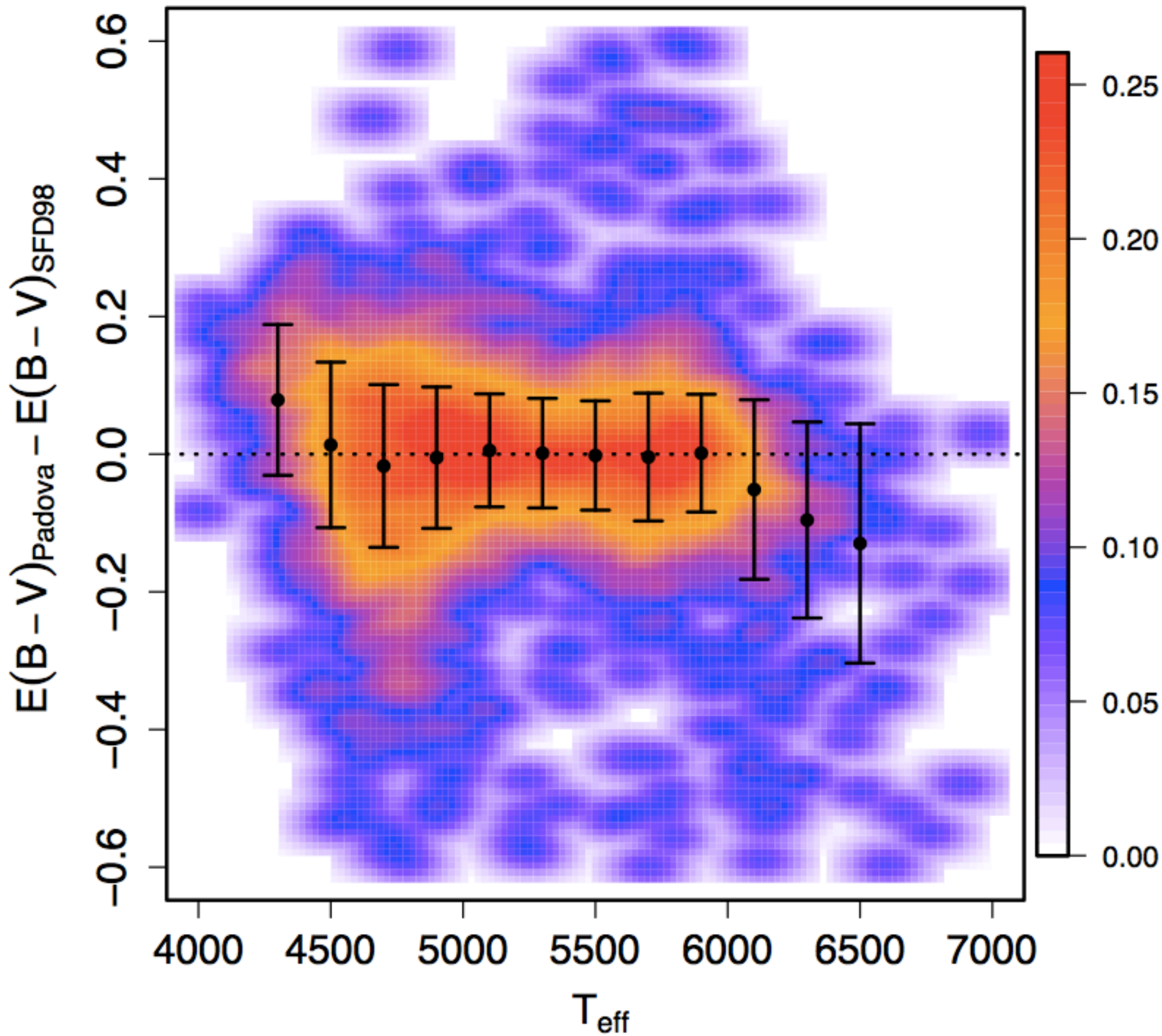


80 mmag of dispersion.. BUT



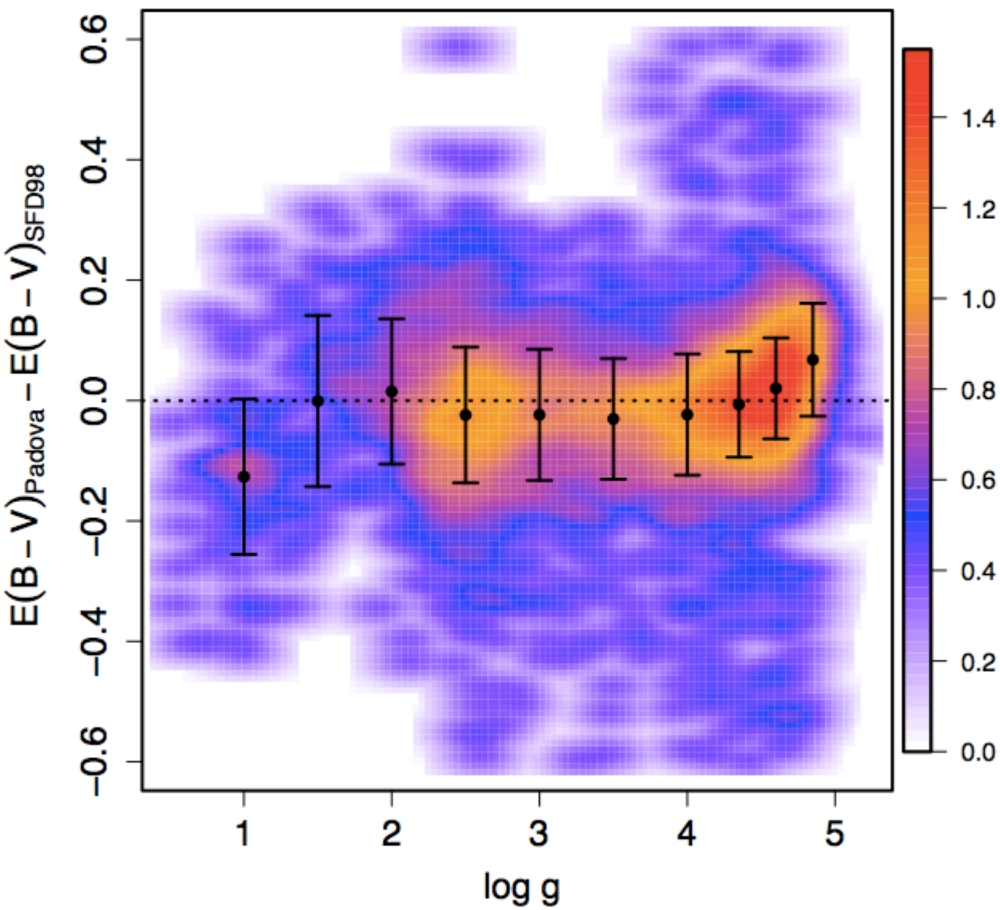
2D-Extinction: Comparison with Schlegel

As a function of Teff



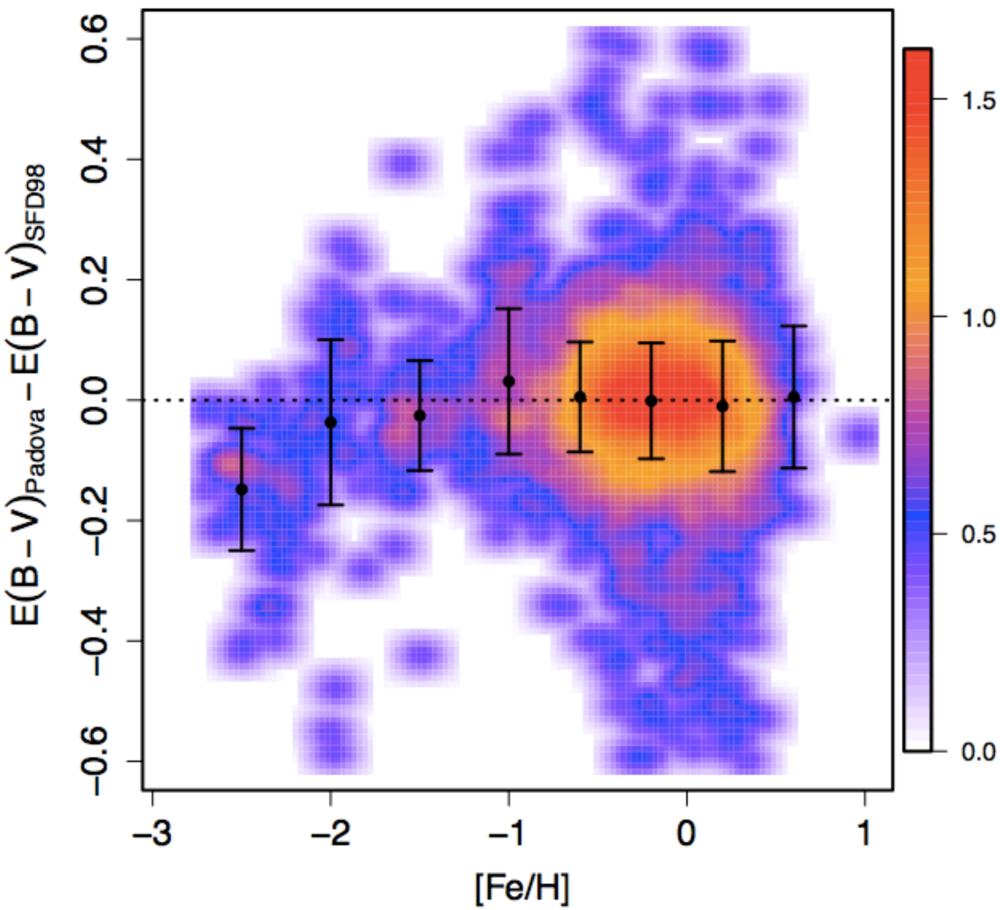
2D-Extinction: Comparison with Schlegel

As a function of logg

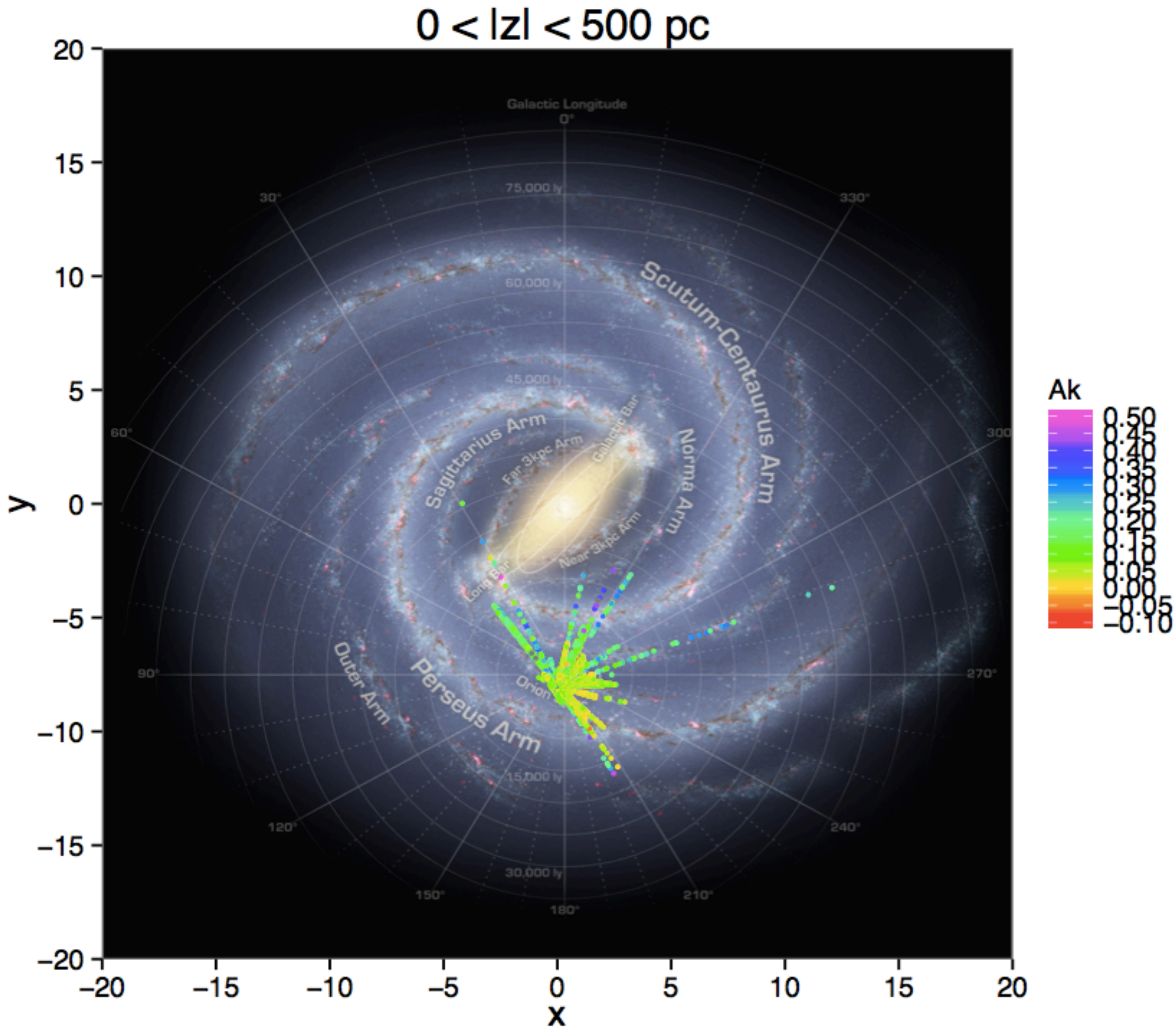


2D-Extinction: Comparison with Schlegel

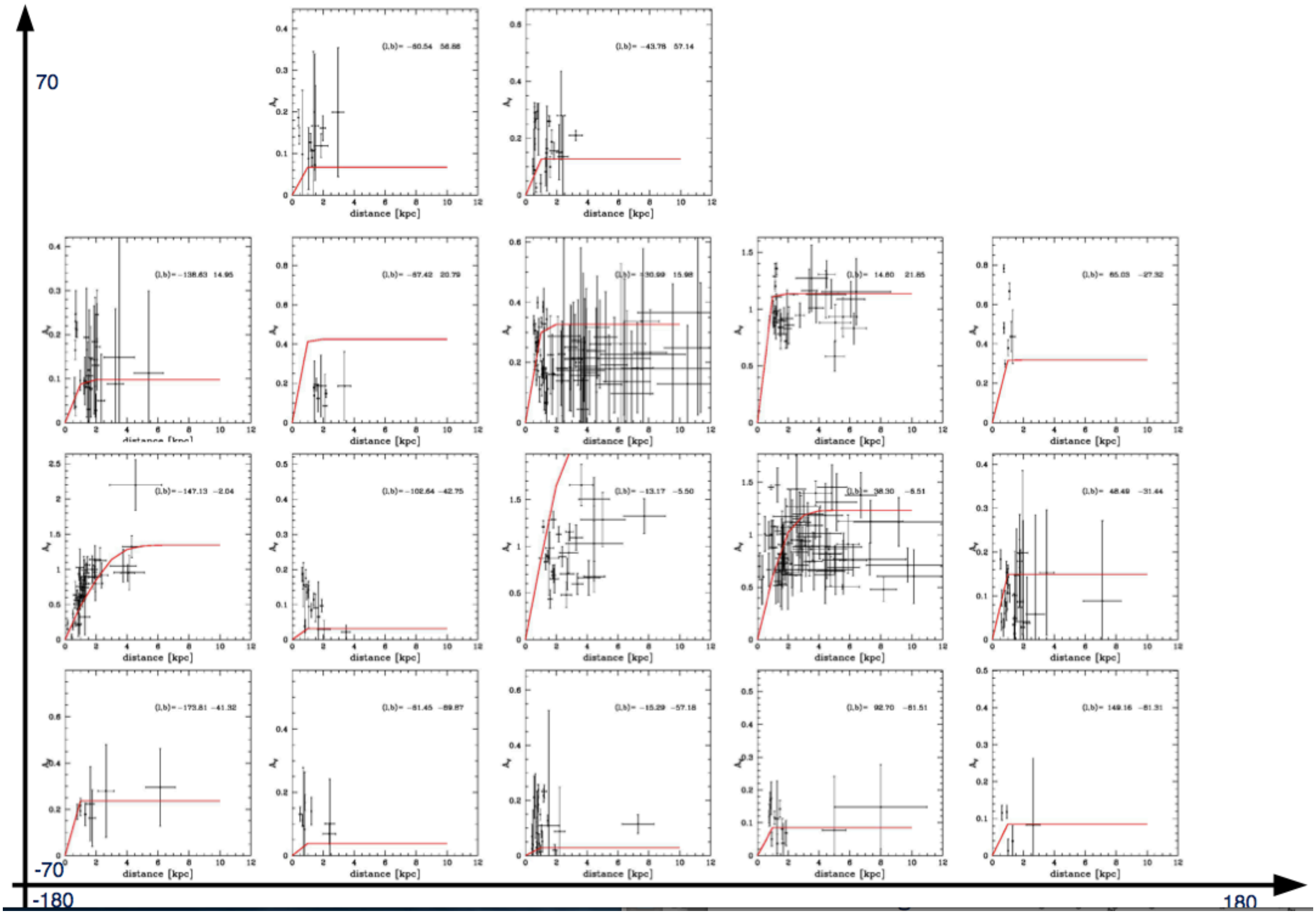
As a function of [Fe/H]

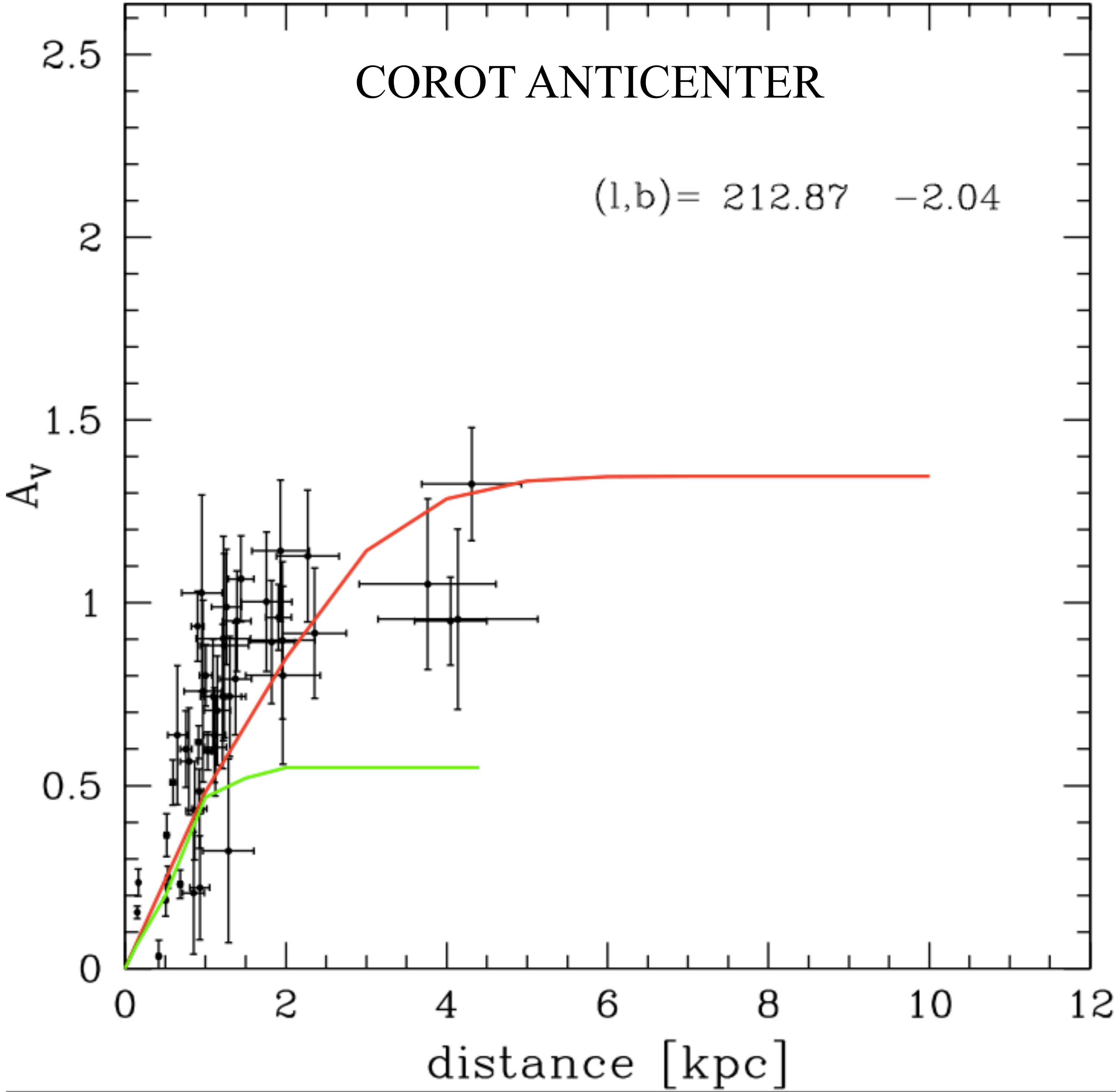


3D-Extinction: Comparison with Drimmel



3D extinction with APOGEE





COROT ANTICENTER
(l,b)= 212.87 −2.04
A_V
0
0.5
1
1.5
2
2.5
0
2
4
6
8
10
12
distance [kpc]

None of the available 3D maps reproduce the global Ak vs. Distance relation along all lines of sight

- Confirmation of steep rise in A(Ks) with a flattening at 4-6 kpc
- Drimmel et al. (2003) underestimates Av systematically for high galactic latitudes
- For high extincted regions we don't have enough data points

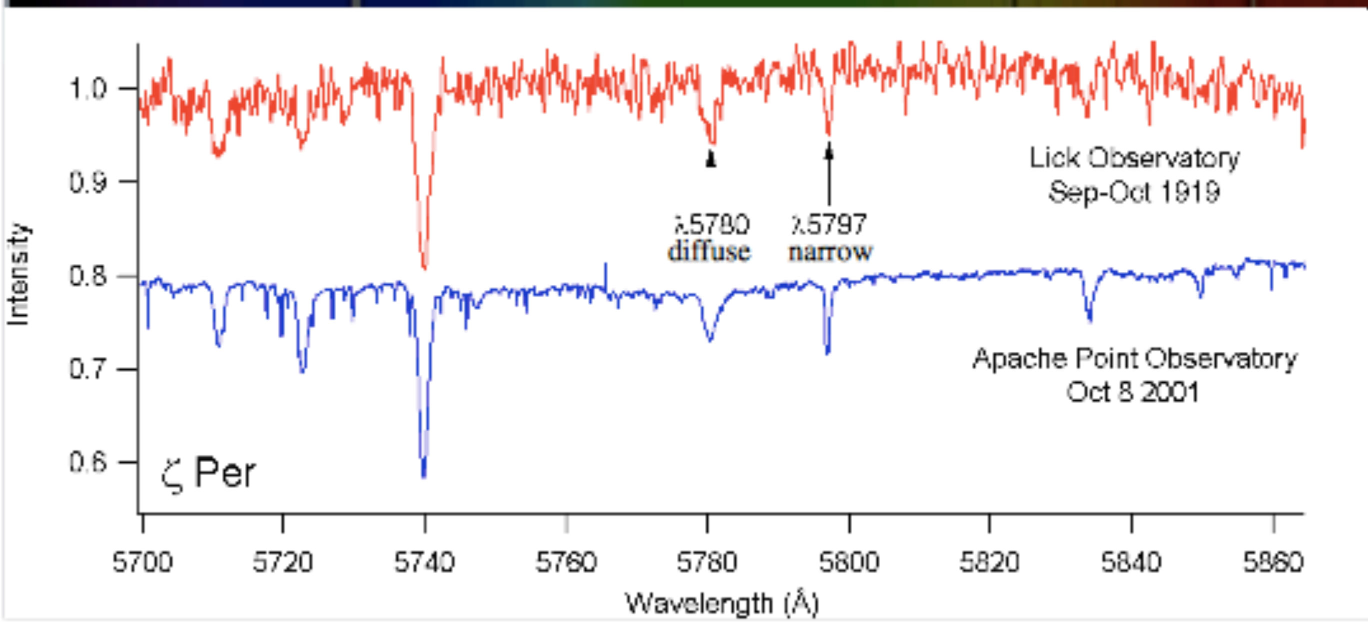
→ New GES data (DR4) available soon

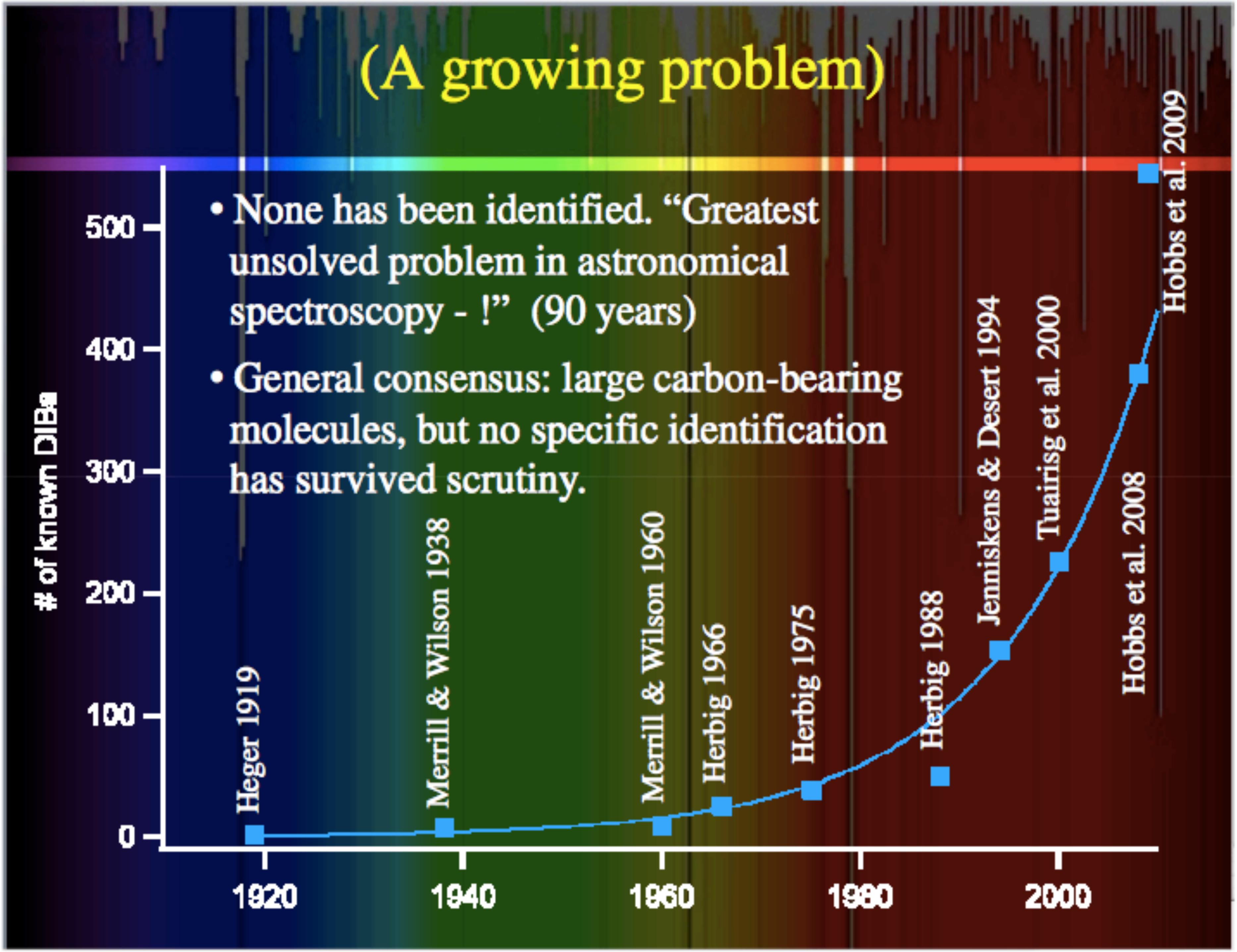
Diffuse interstellar bands (DIBs)

What are DIBs ?

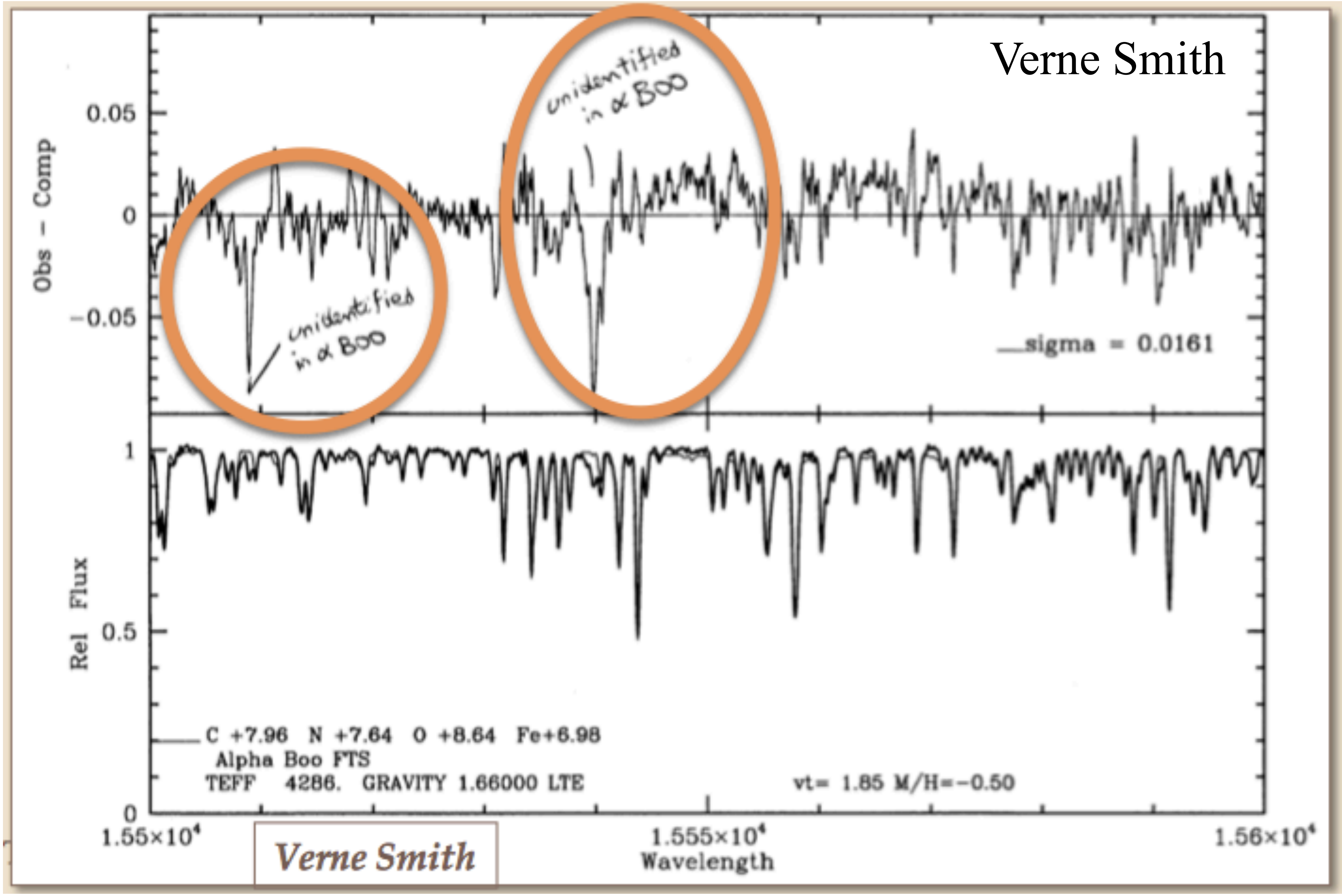
- First two bands discovered: λλ5780, 5797 in ζ Per, ρ Leo (Mary Lea Heger, Lick, 1919)
- some broad ("diffuse"), many narrow
- "Stationary" (interstellar)
- Strengths scale roughly with extinction, but different DIBs not tightly correlated from sightline to sightline

  ➔ family of carriers.

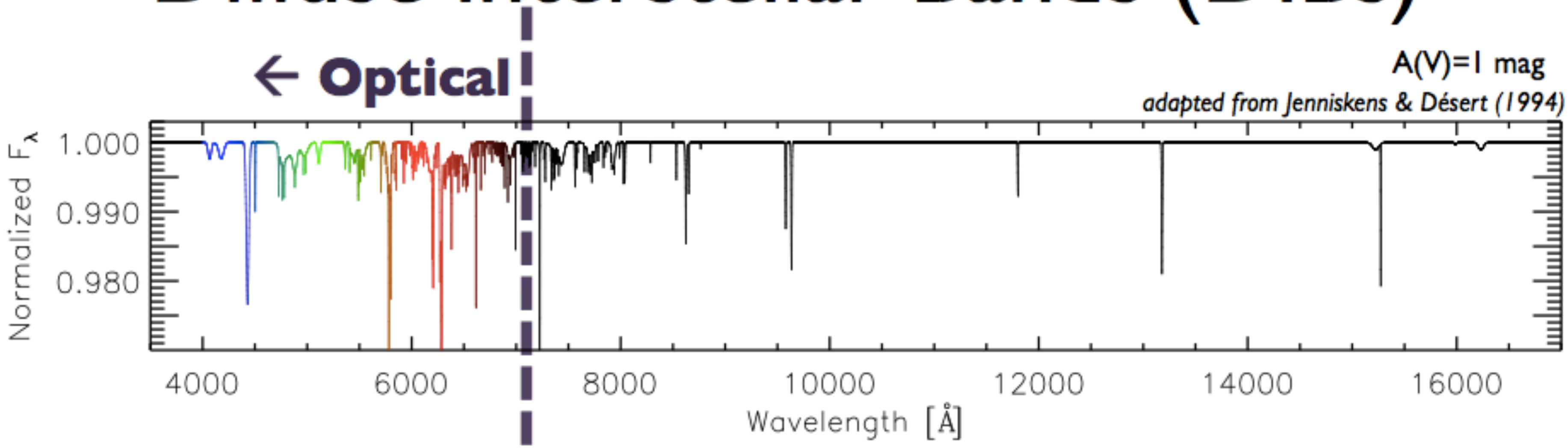



(A growing problem)
• None has been identified. "Greatest unsolved problem in astronomical spectroscopy - !" (90 years)
• General consensus: large carbon-bearing molecules, but no specific identification has survived scrutiny.
# of known DIBs
0
100
200
300
400
500
1920
1940
1960
1980
2000
Heger 1919
Merrill & Wilson 1938
Merrill & Wilson 1960
Herbig 1966
Herbig 1975
Herbig 1988
Jenniskens & Desert 1994
Tuairisg et al. 2000
Hobbs et al. 2008
Hobbs et al. 2009

DIBs in the Infrared……

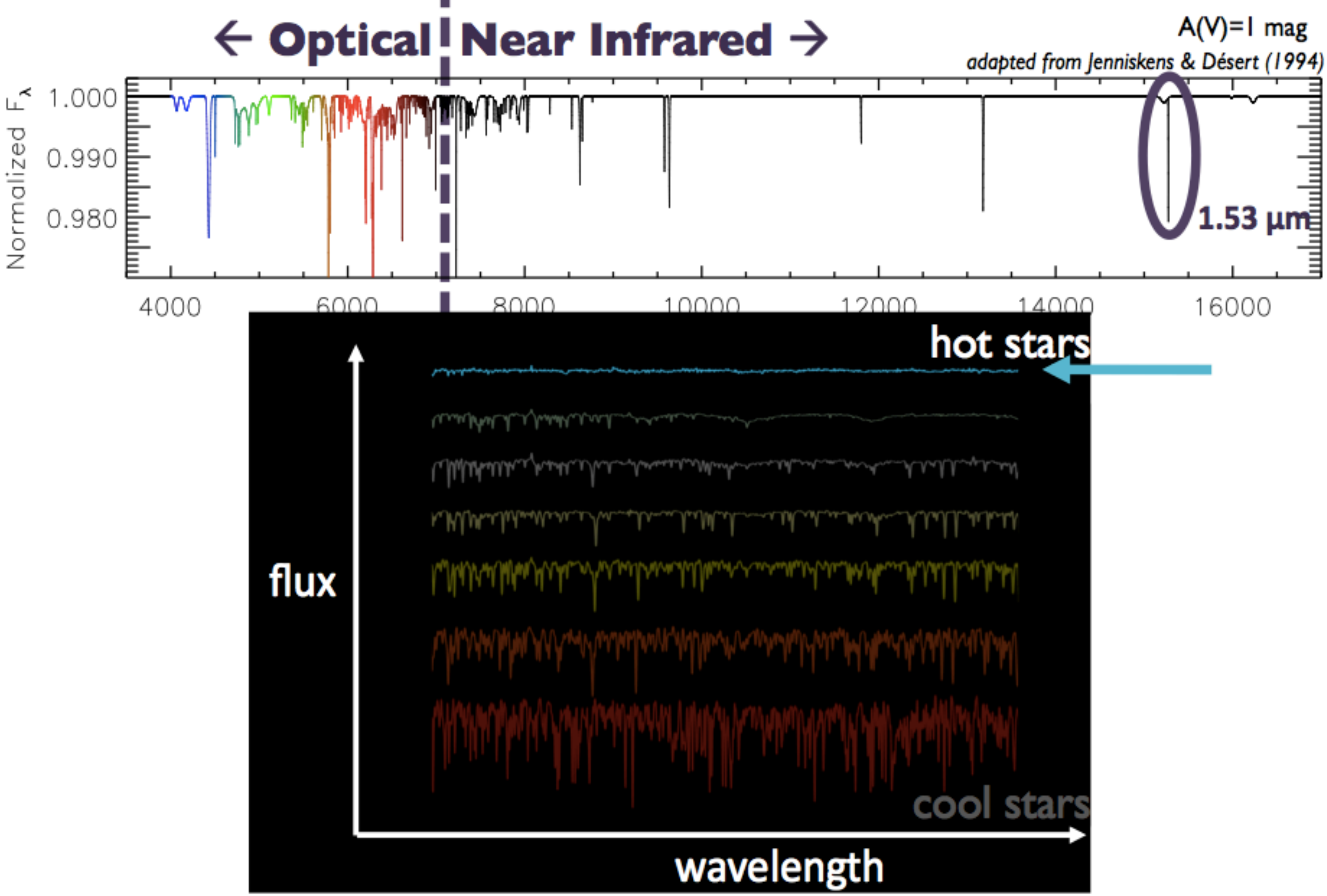


Diffuse Interstellar Bands (DIBs)

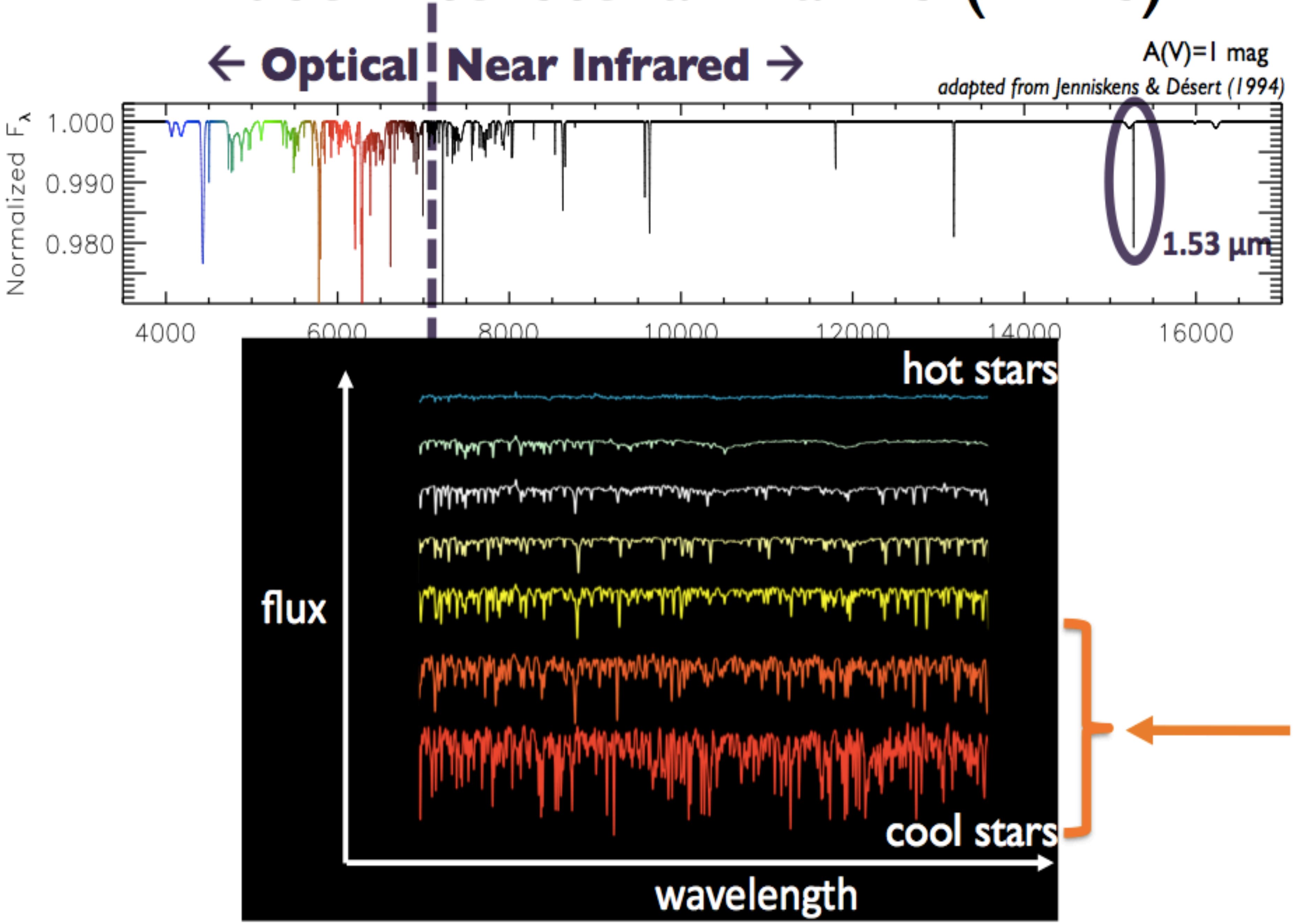


- ISM absorption lines in the optical to near-IR
- Carrier families still unknown! (Probably C-H heavy)
- Ubiquitous throughout galactic ISM
- Trace both atomic and molecular ISM

Diffuse Interstellar Bands (DIBs)

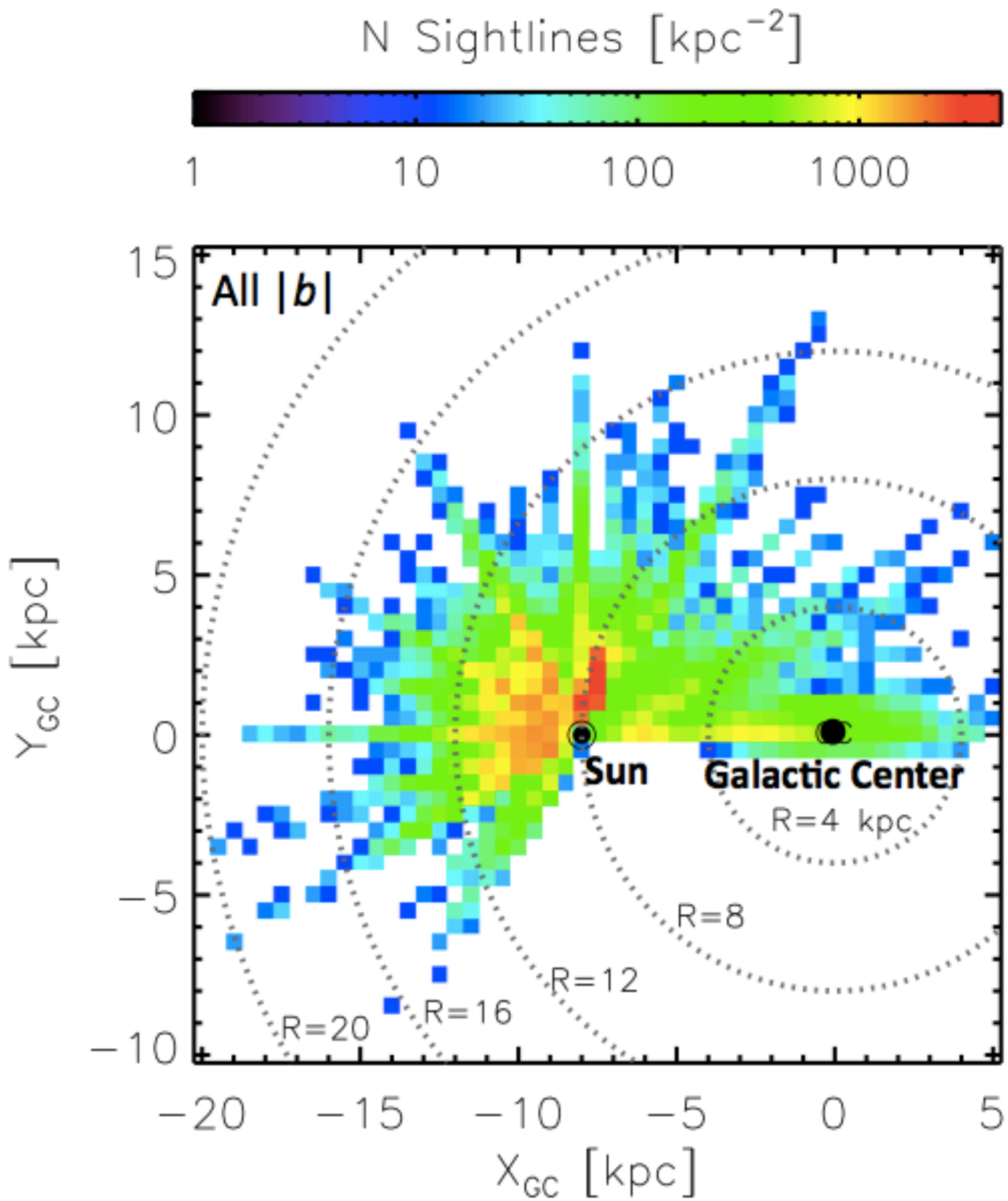


Diffuse Interstellar Bands (DIBs)



DIBs: Old Puzzle → New Opportunity

Use DIBs as a *tool* to trace MW structure, the DIB carrier distribution, and ISM properties on very large scales



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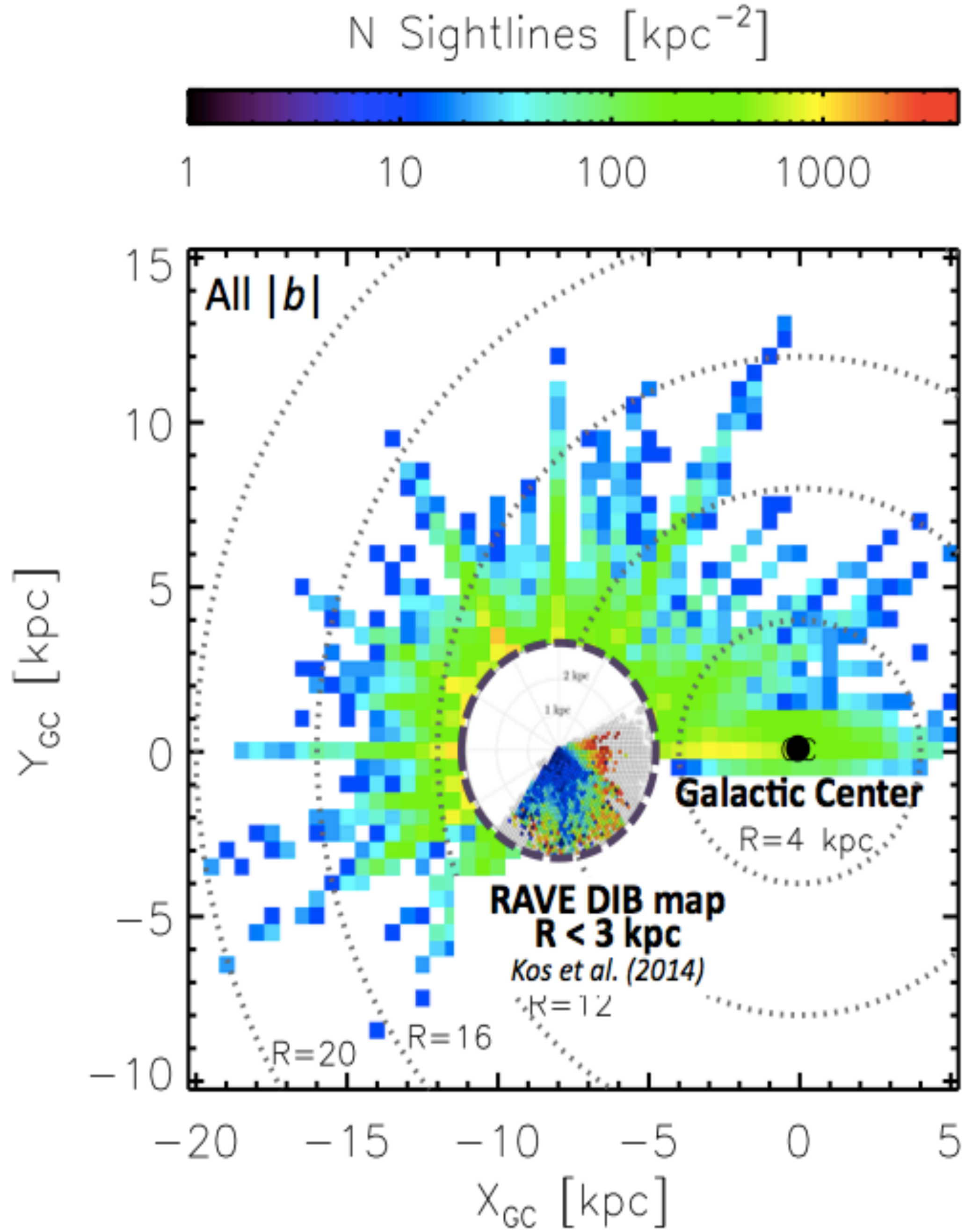
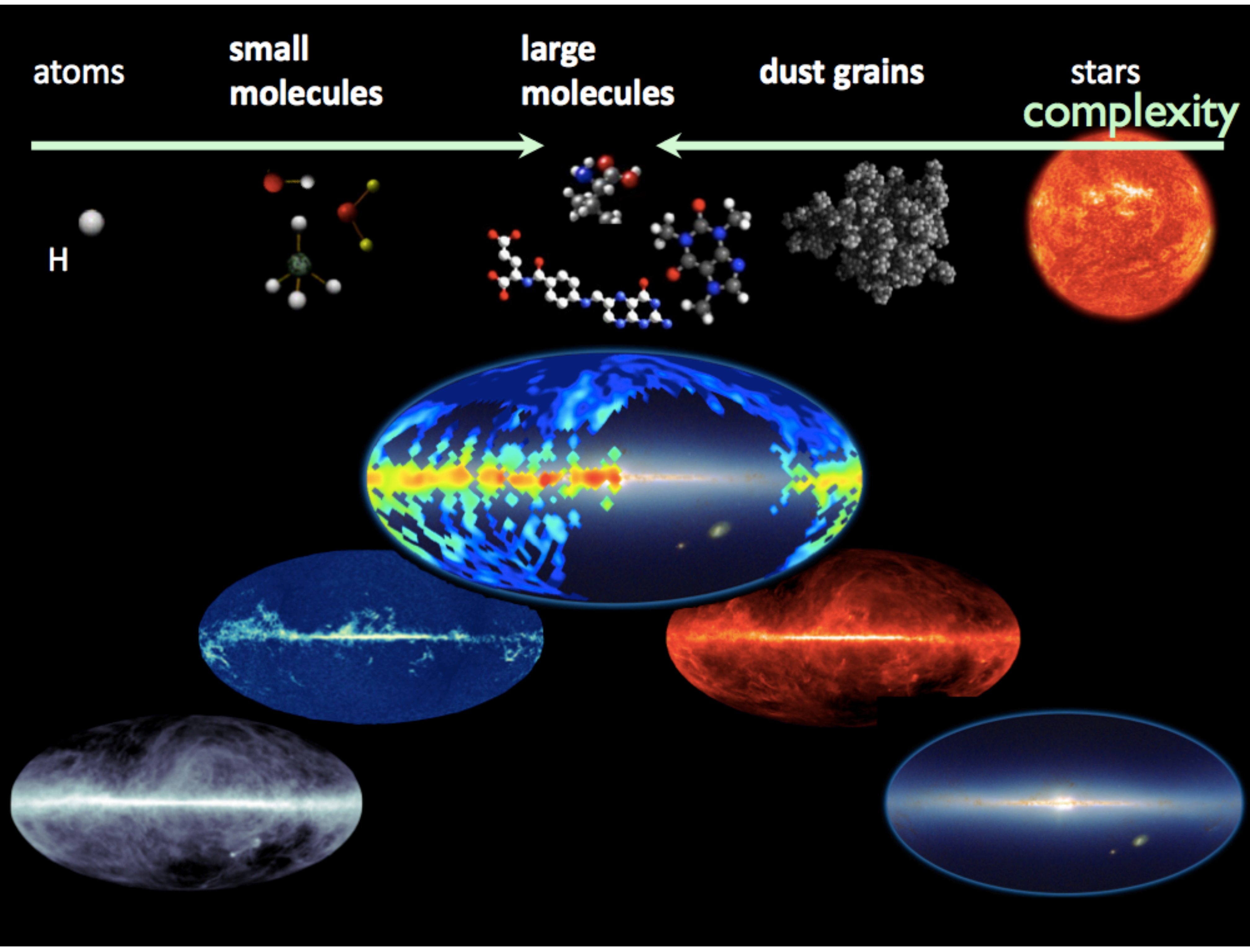
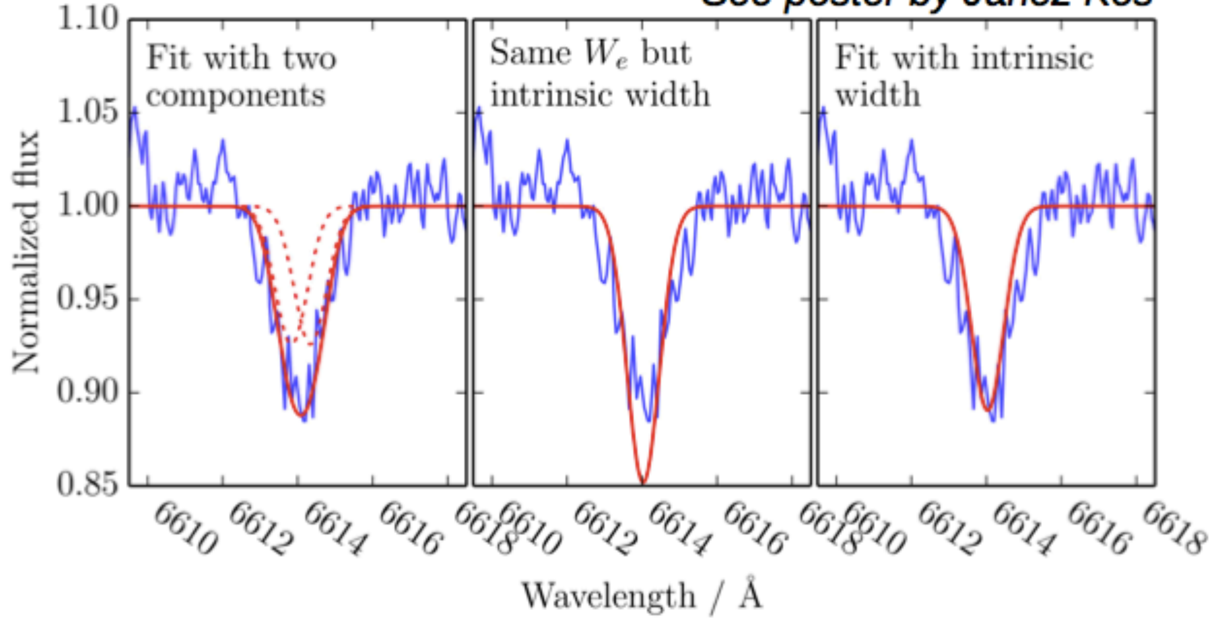



atoms
small molecules
large molecules
dust grains
stars
complexity
H

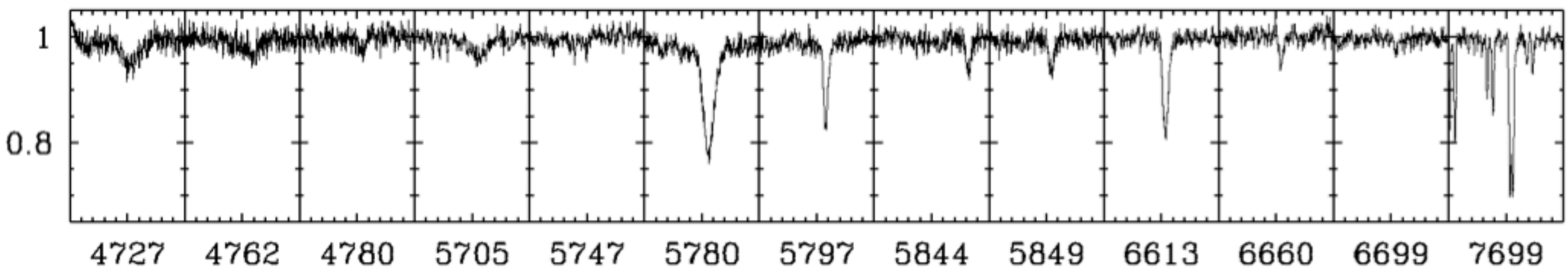
DIBs in: RAVE, Gaia-ESO, GALAH

- **RAVE**: ~500.000 spectra, one strong DIB at 8620 Å.
- **Gaia-ESO**:
  5 strong DIBs, some of them with multiple components. ►

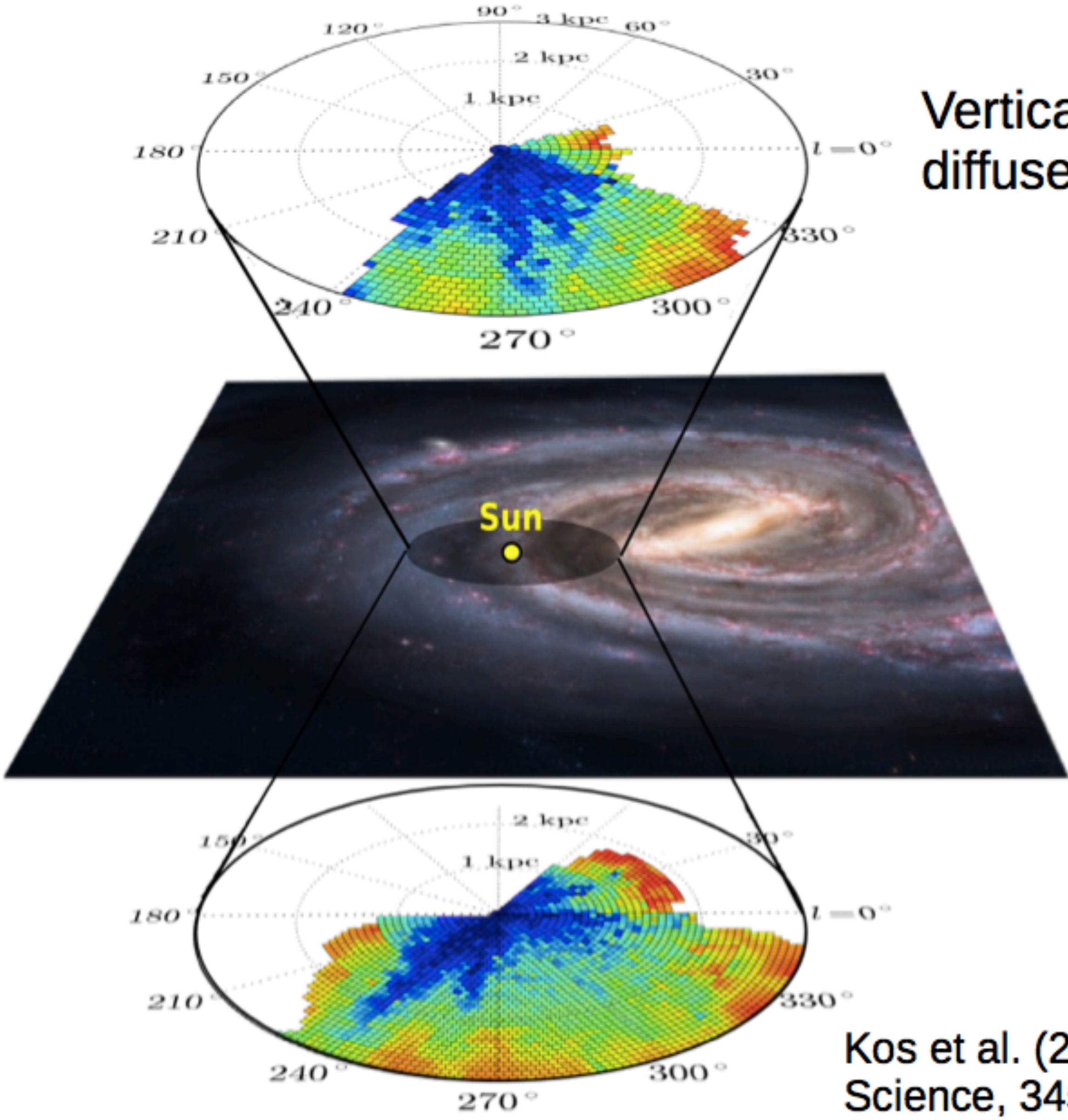
See poster by Janez Kos



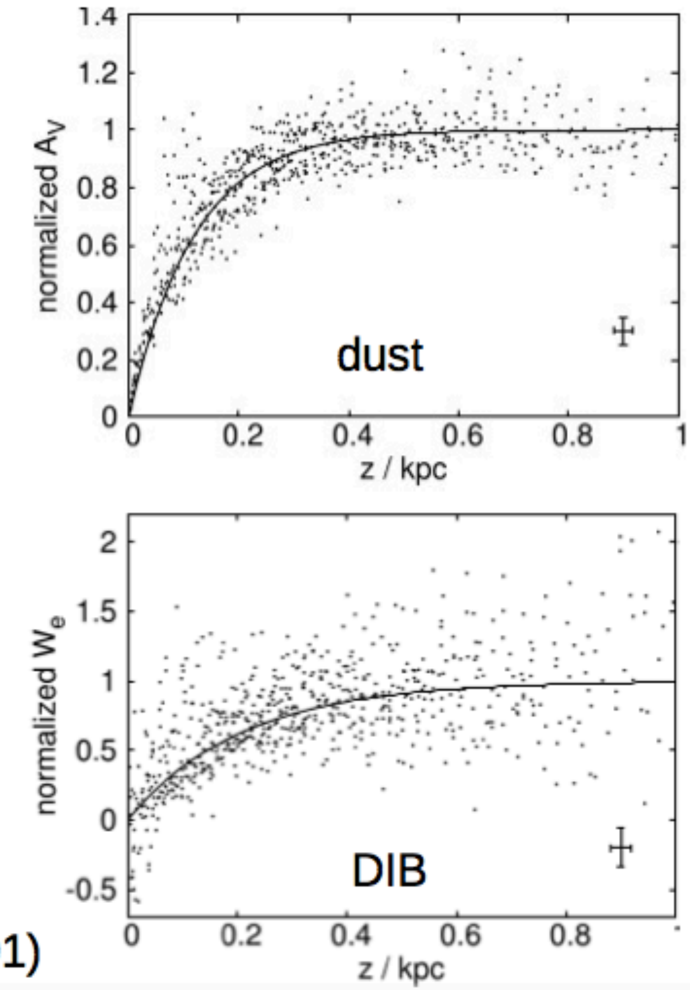
- **GALAH**: 12 strong DIBs plus the K I absorption at 7699 Å. ▼



RAVE – the first 3-D map of a DIB

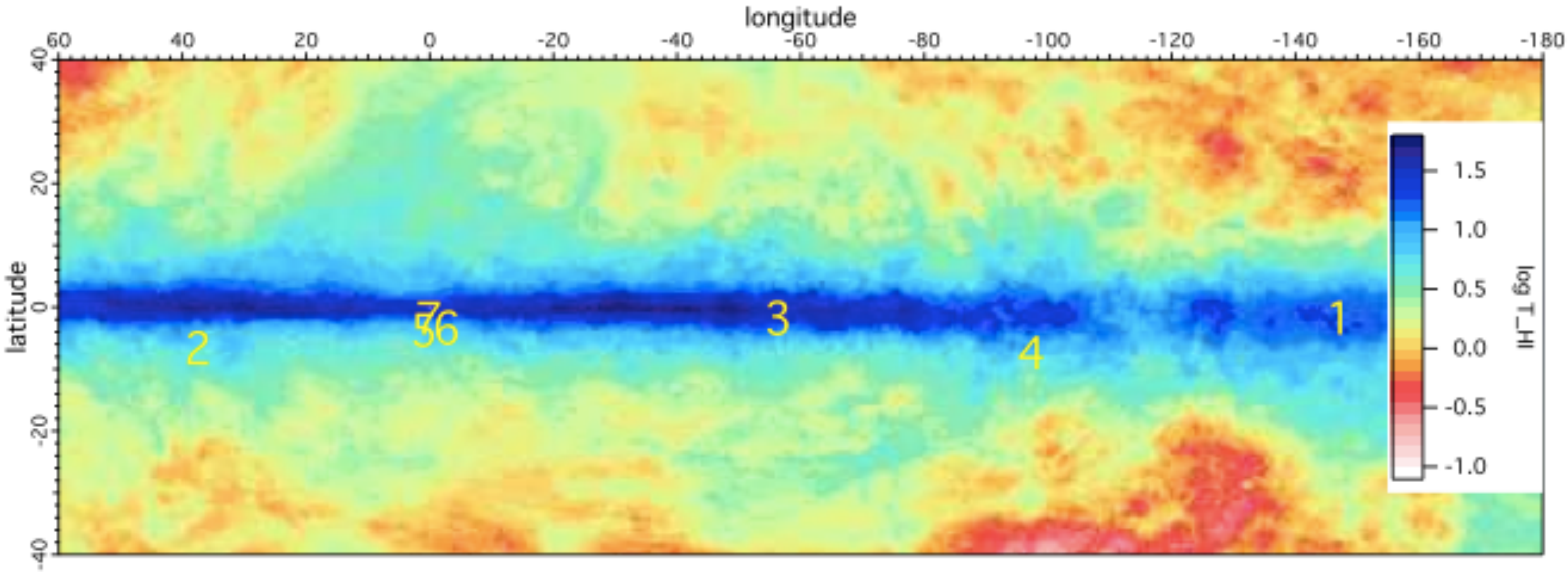


Vertical scale-height larger for the diffuse interstellar band than for dust.

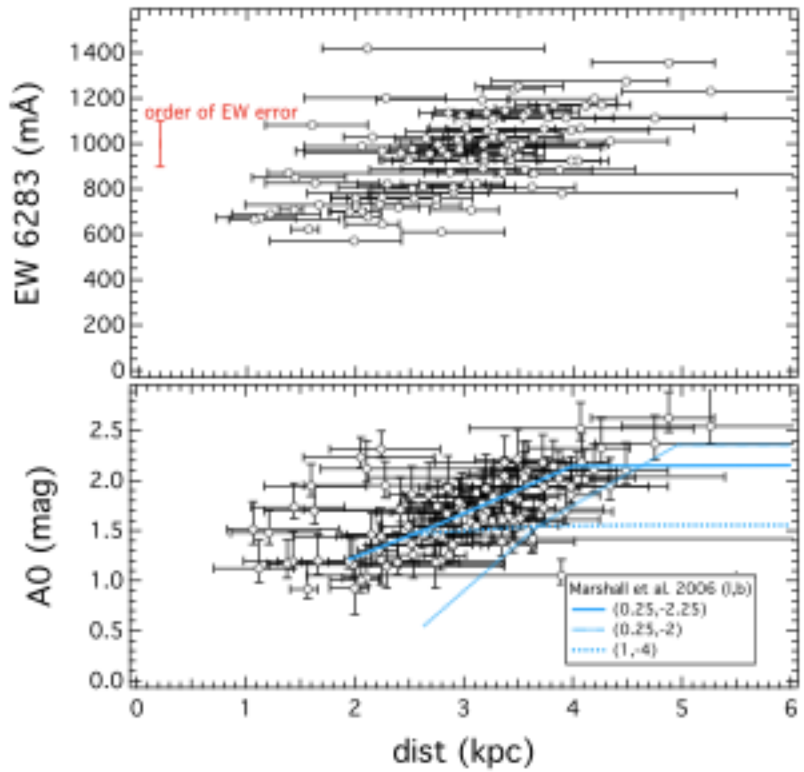


Kos et al. (2014, Science, 345, 791)

GES and DIBS (Puspiratani et al. 2014)



GES and DIBS (Puspiratani et al. 2014)



Issues: Need of high S/N

Very few stars to trace 3D extinction

Apropos GAIA:

5-9 December 2016: IAU symposium
« The first GAIA data » in Nice