



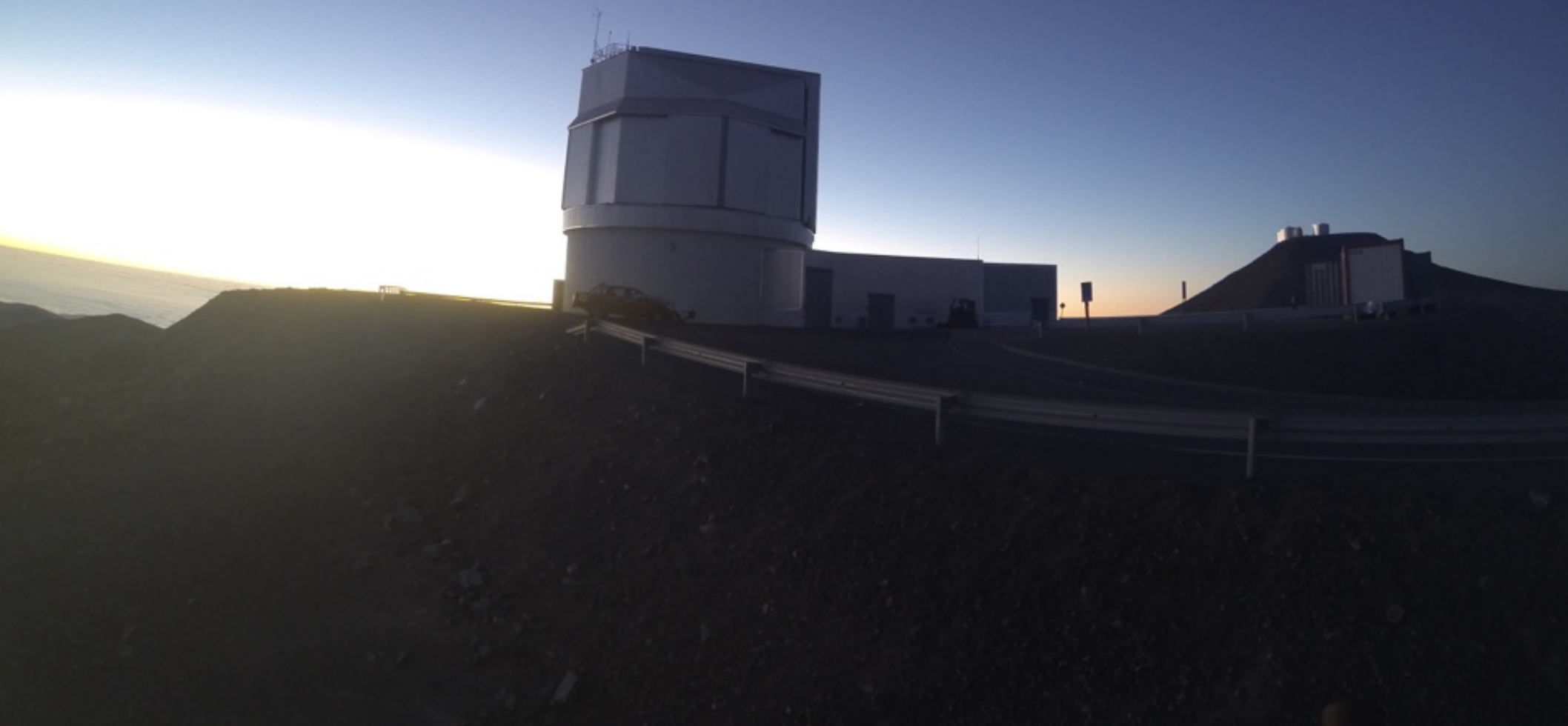
ESO Workshop on Deconstructing Galaxies:
Structure and Morphology in the Era of Large Surveys

MW Structure from the VVV Survey

Dante Minniti

22 Nov 2013

VVV Survey of the Milky Way Bulge



The VVV Science Team

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The VVV Science Team

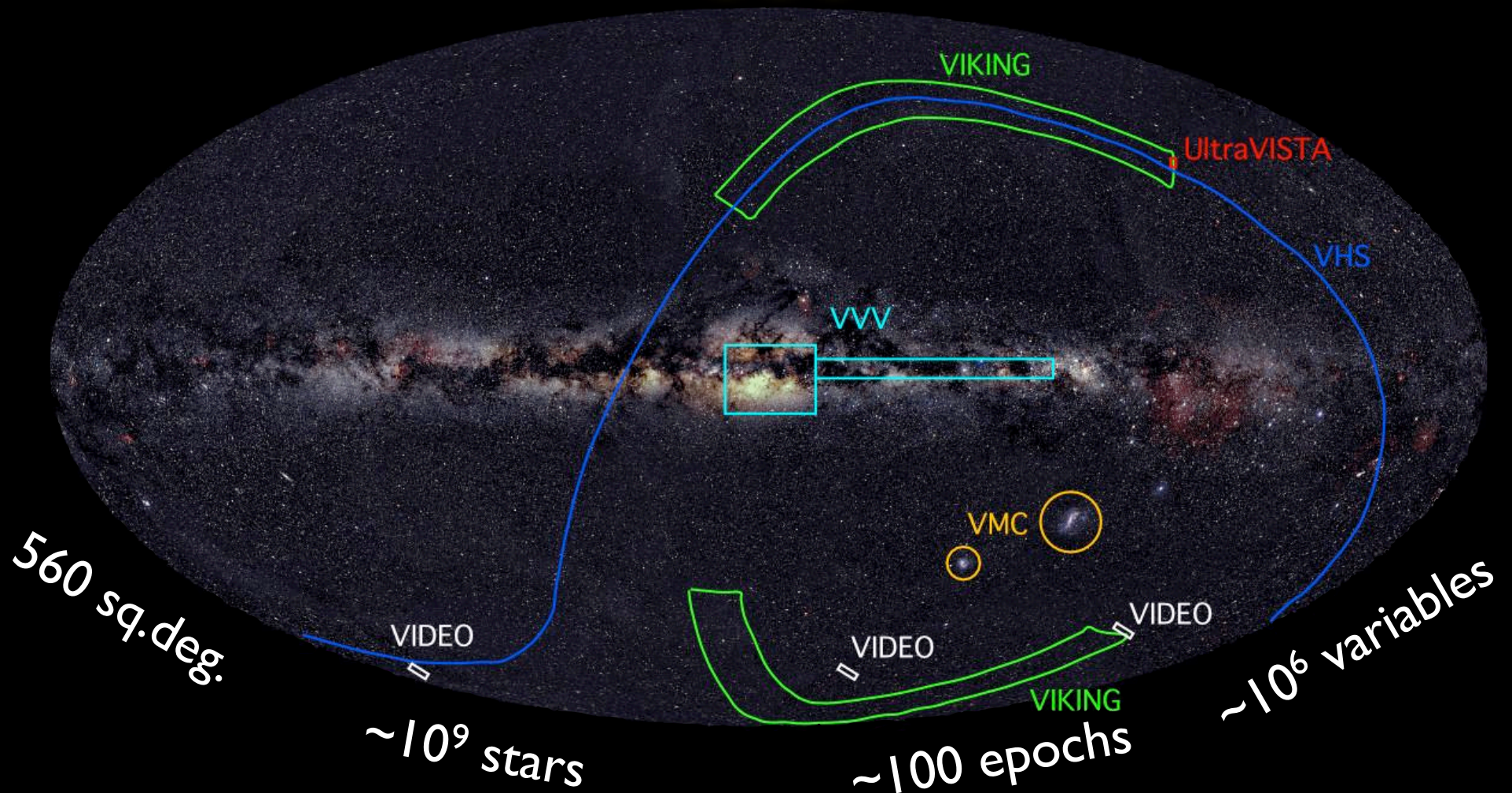


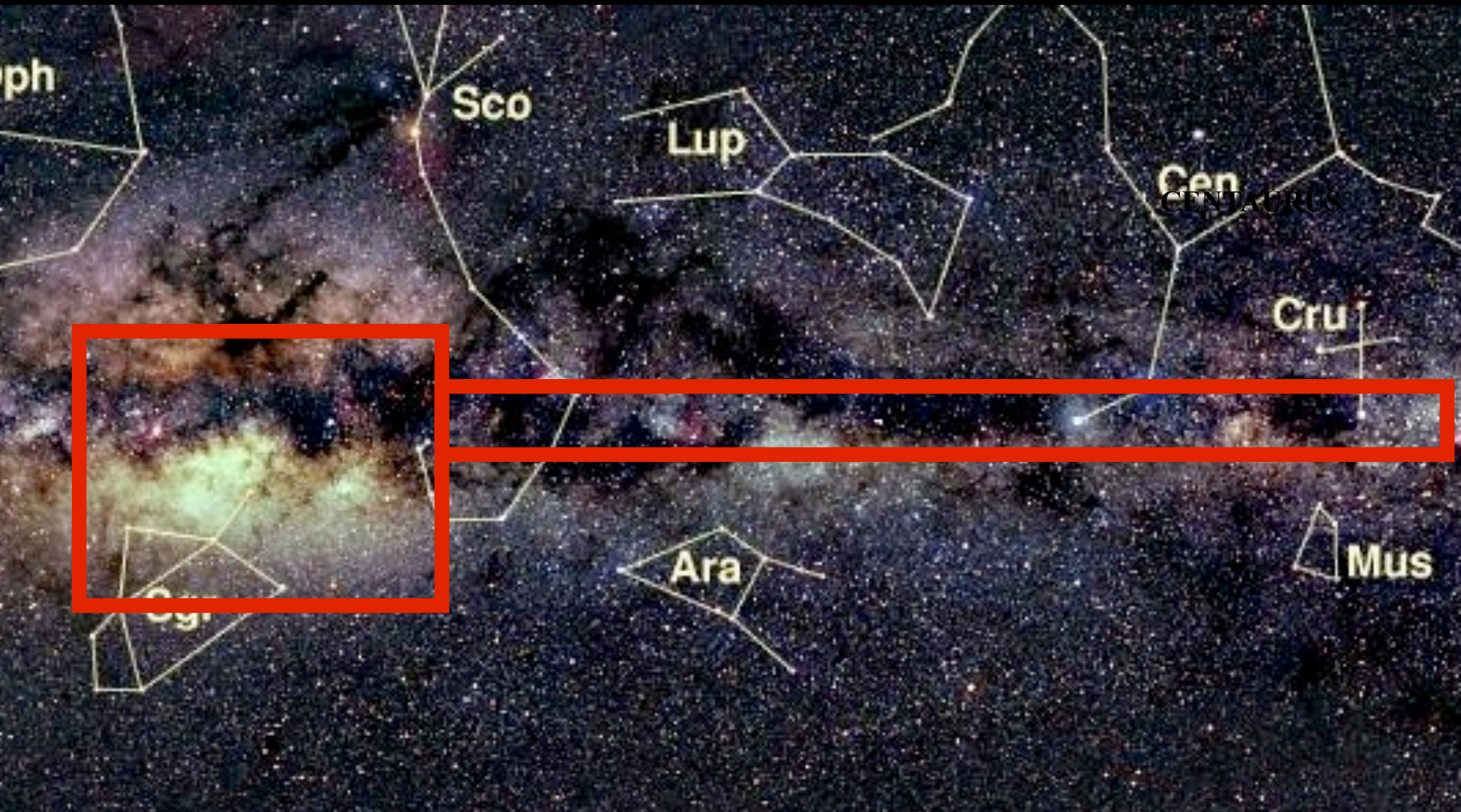


VISTA PUBLIC SURVEYS

VISTA VARIABLES IN THE VIA LACTEA

VVV



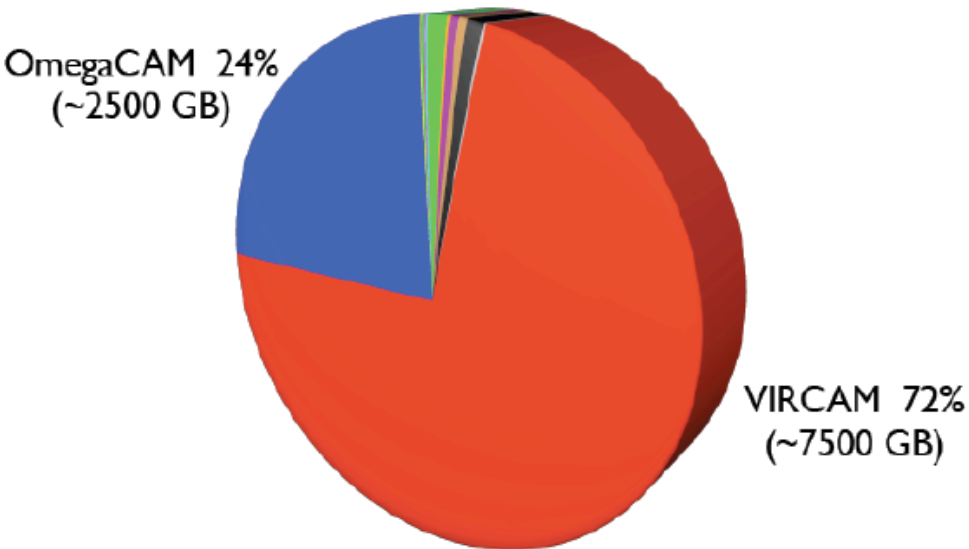


VVV maps 560 sqdeg in the central region of our galaxy

Expected monthly dataflow: raw calibrations and science frames



All Current Paranal Instruments 4% (433.2 GB)



from Magda Arnaboldi (EDT)

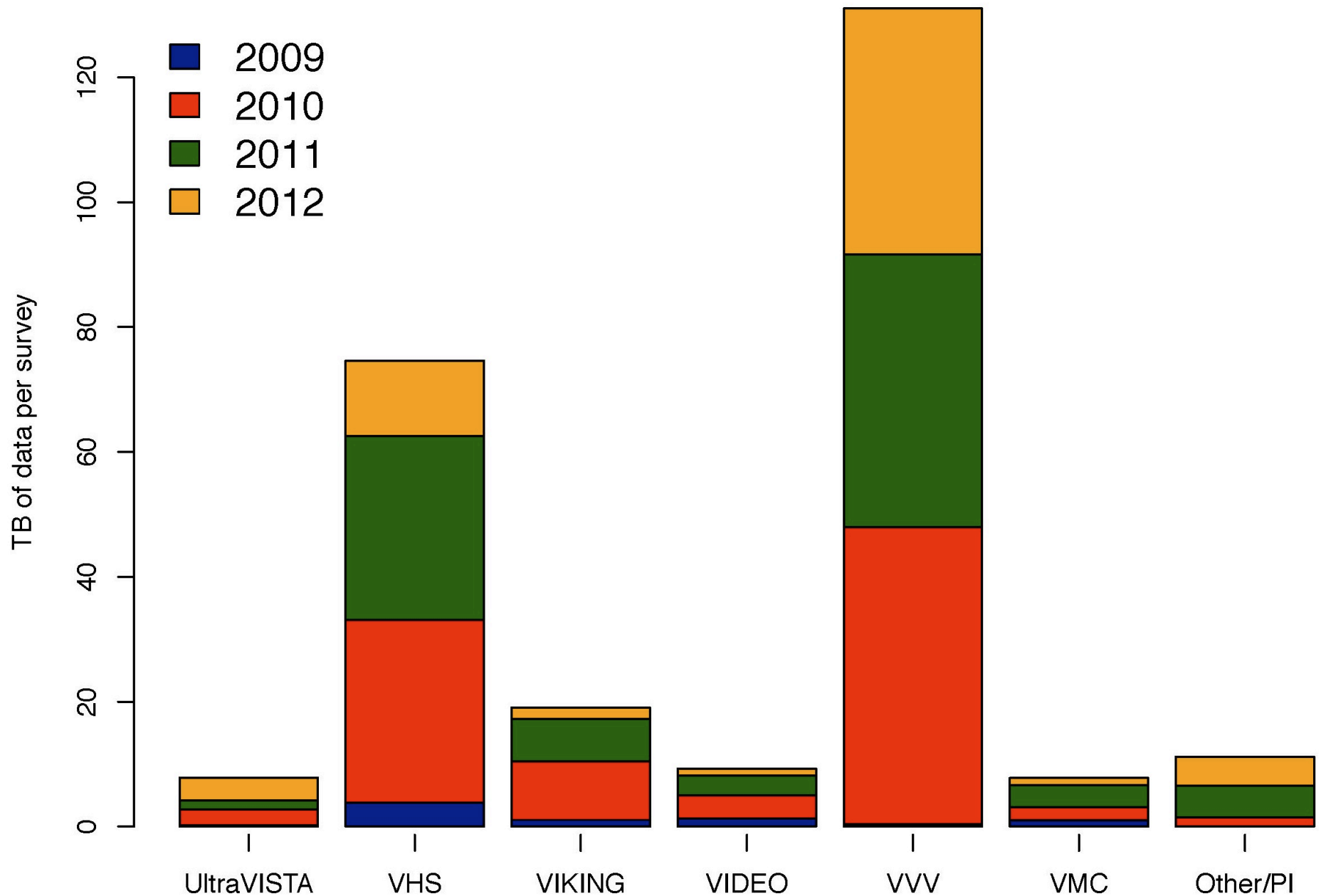


VISTA

- ➔ 4m diameter
- ➔ IR optimized
- ➔ large field

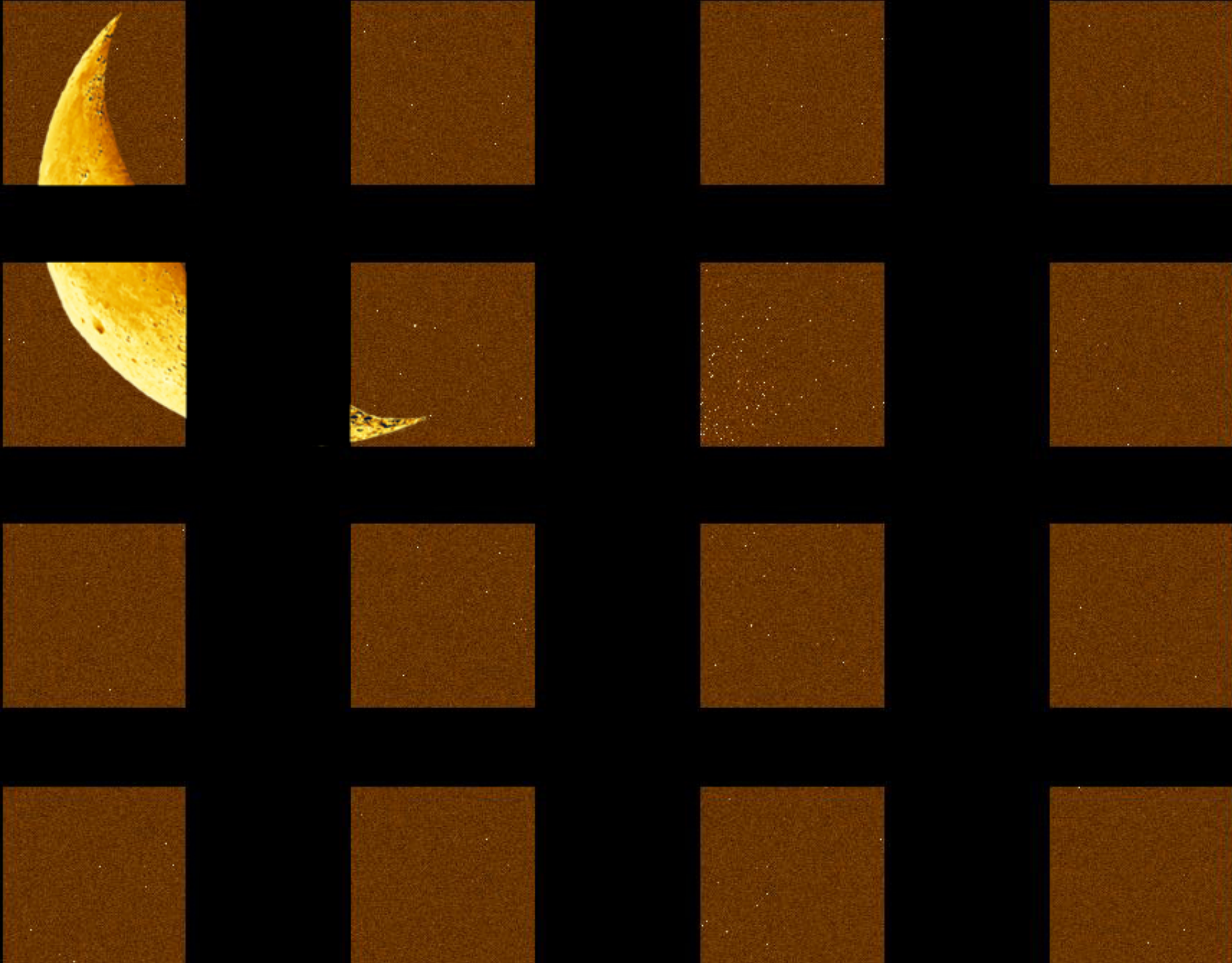
Data Volumes produced by CASU

Jim Emerson



VISTA Near-IR Wide Field Camera

vvvsurvey.org



VISTA Near-IR Wide Field Camera

vvvsurvey.org



16x 2048x 2048 VIRGO IR detectors



large numbers of hot pixels, dead zones in detector 1

sensitivity: 0.84 to 2.5 microns

filters: Z, Y, J, H, Ks

pixel scale: 0.34"

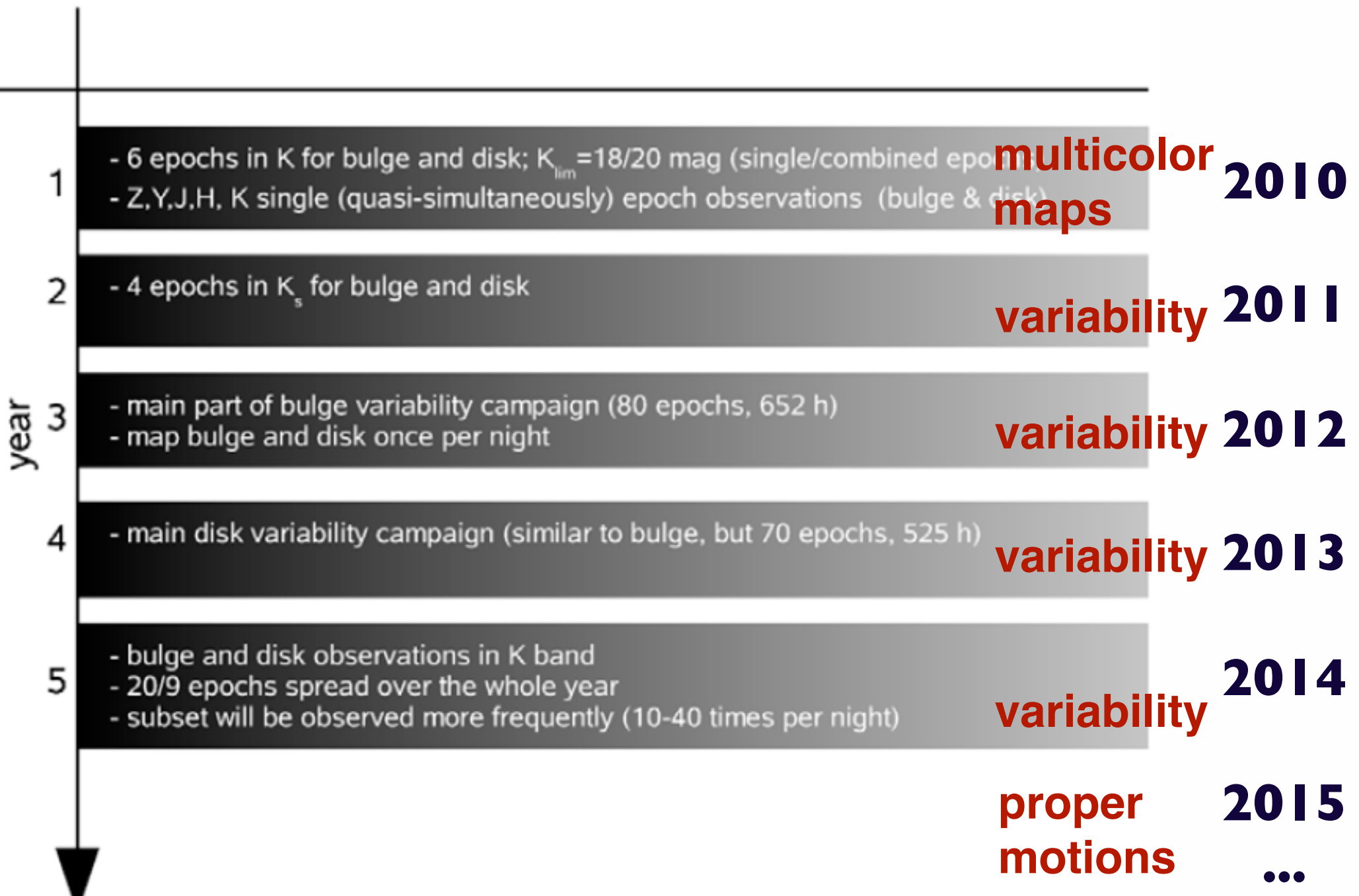
active optics

“tile” field of view: 1.0x1.5 deg (6 pointings)

best image quality: 0.6" (incl. seeing, optics, sampling)

image distortion: <15% of PSF at field corners

The VVV Survey: Timeline



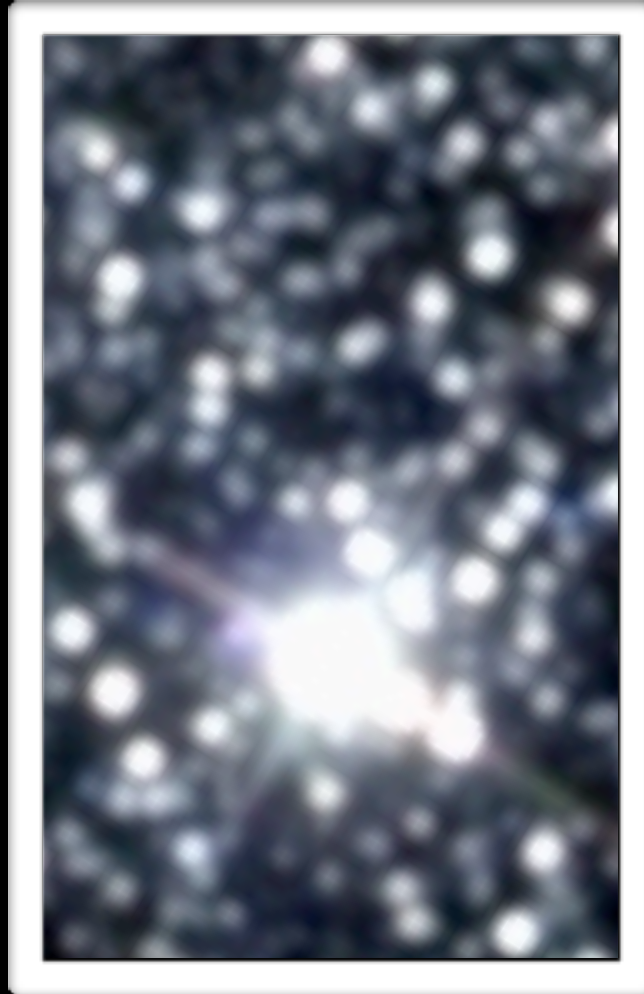
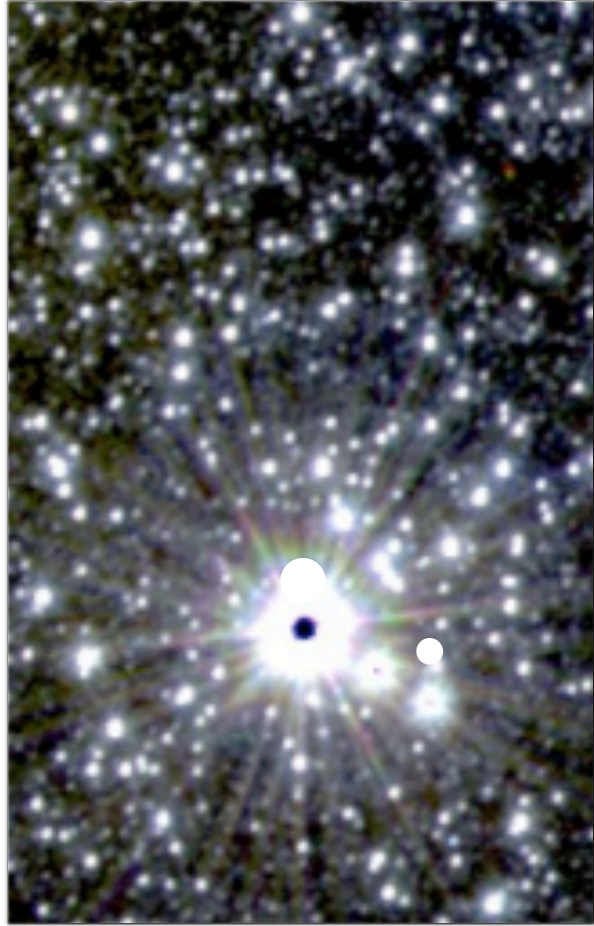
The VVV Survey: Timeline

Multicolor Photometry: ZYJHKs

Variability: Ks

Proper Motions: Ks

DEEPER AND HIGHER RESOLUTION



Main differences with 2MASS

2MASS covers the whole sky, VVV only 1.3%

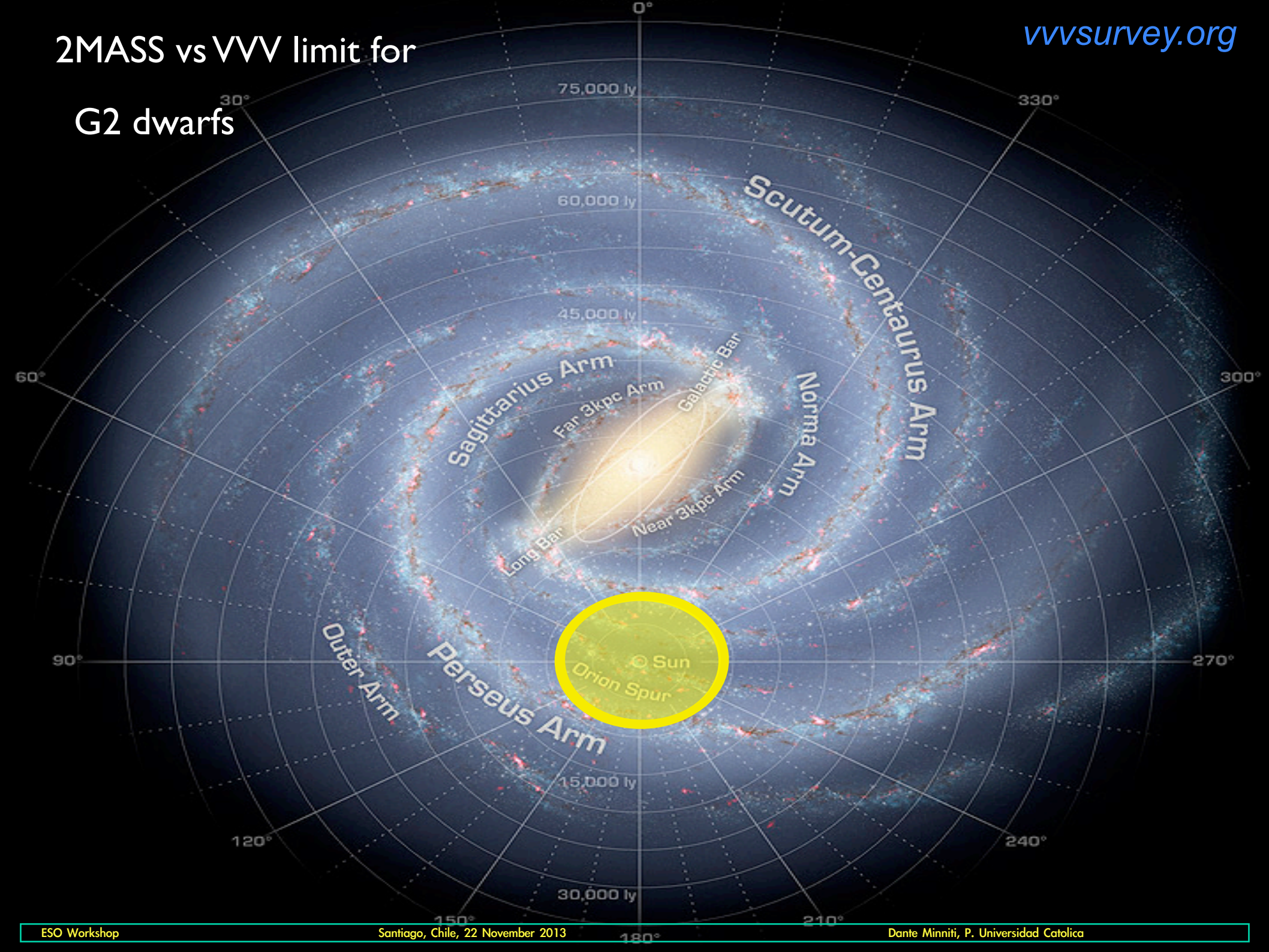
VVV has higher resolution ($0.34''/\text{pix}$)

VVV is deeper ($K_s < 18$)

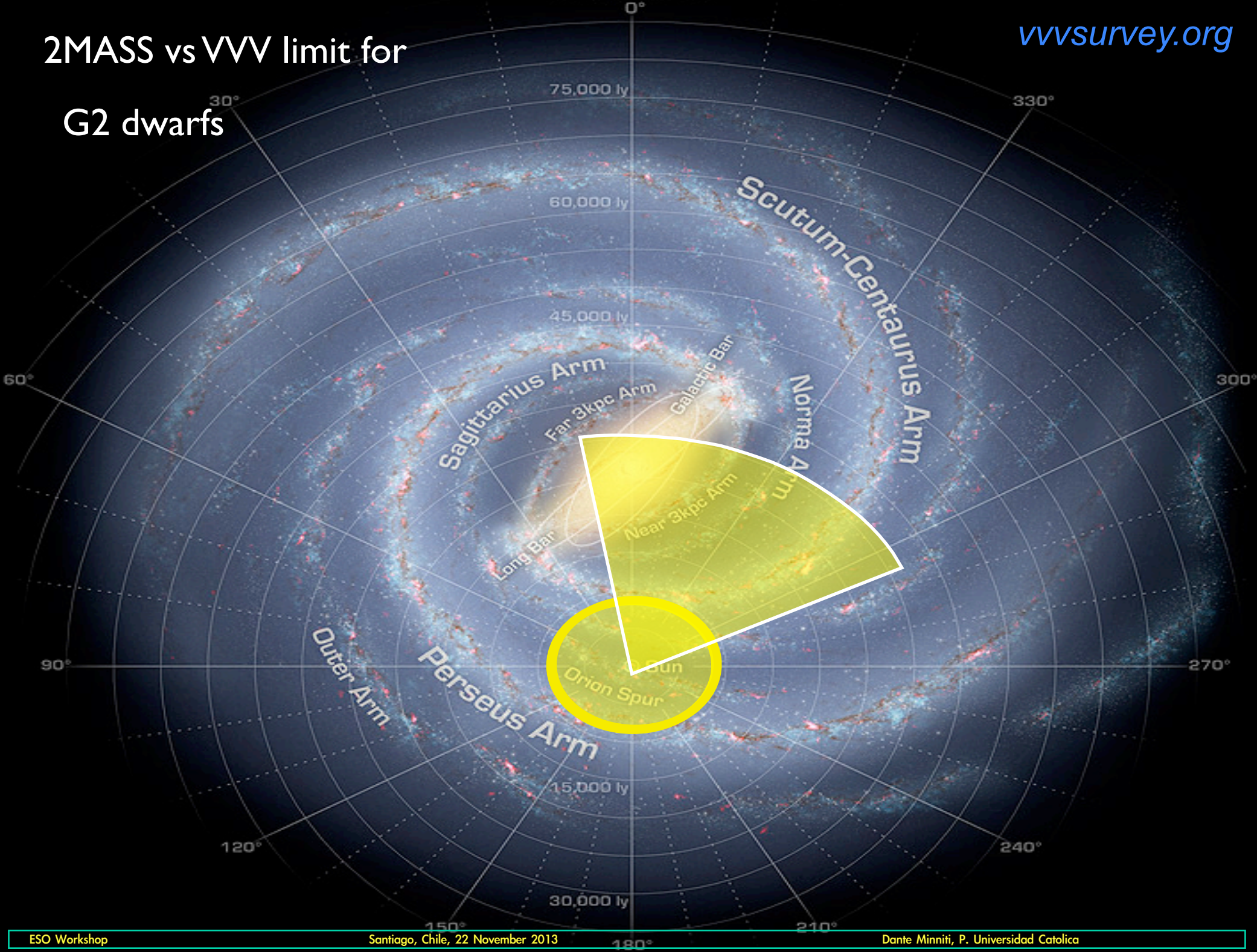
VVV has 5 filters (ZYJHKs)

VVV is a multiepoch survey (~ 100 epochs)

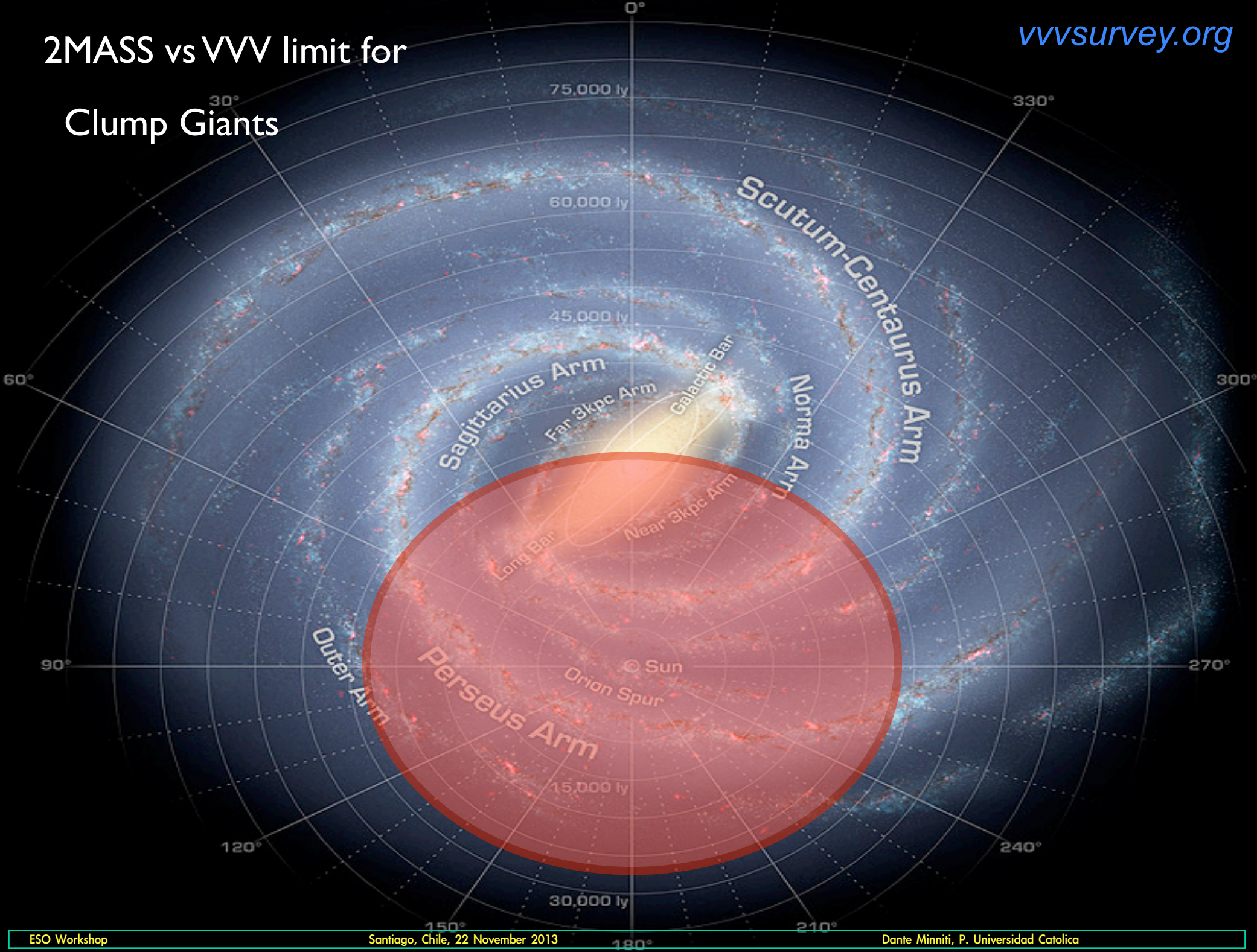
2MASS vs VVV limit for G2 dwarfs



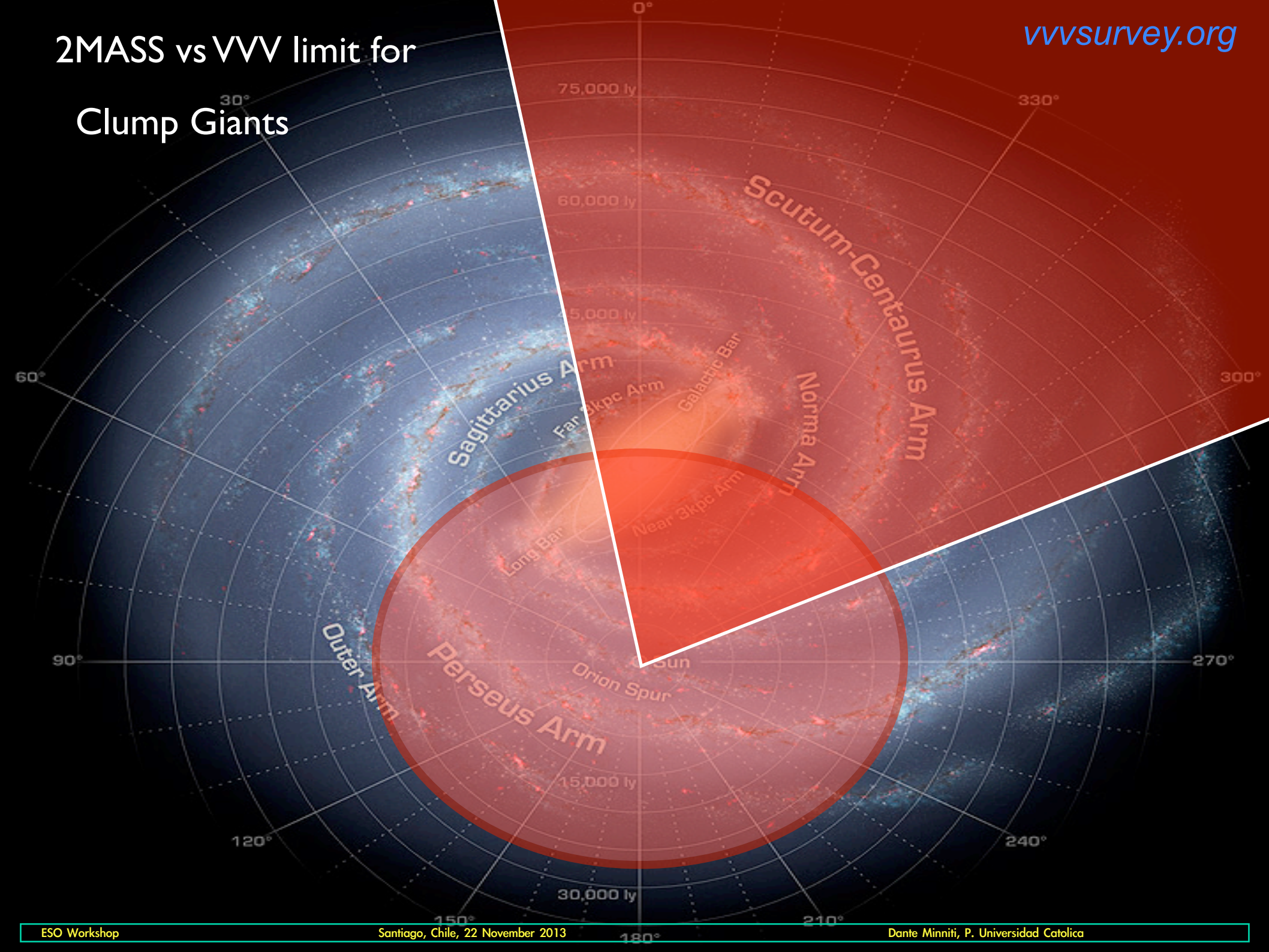
2MASS vs VVV limit for G2 dwarfs



2MASS vs VVV limit for Clump Giants

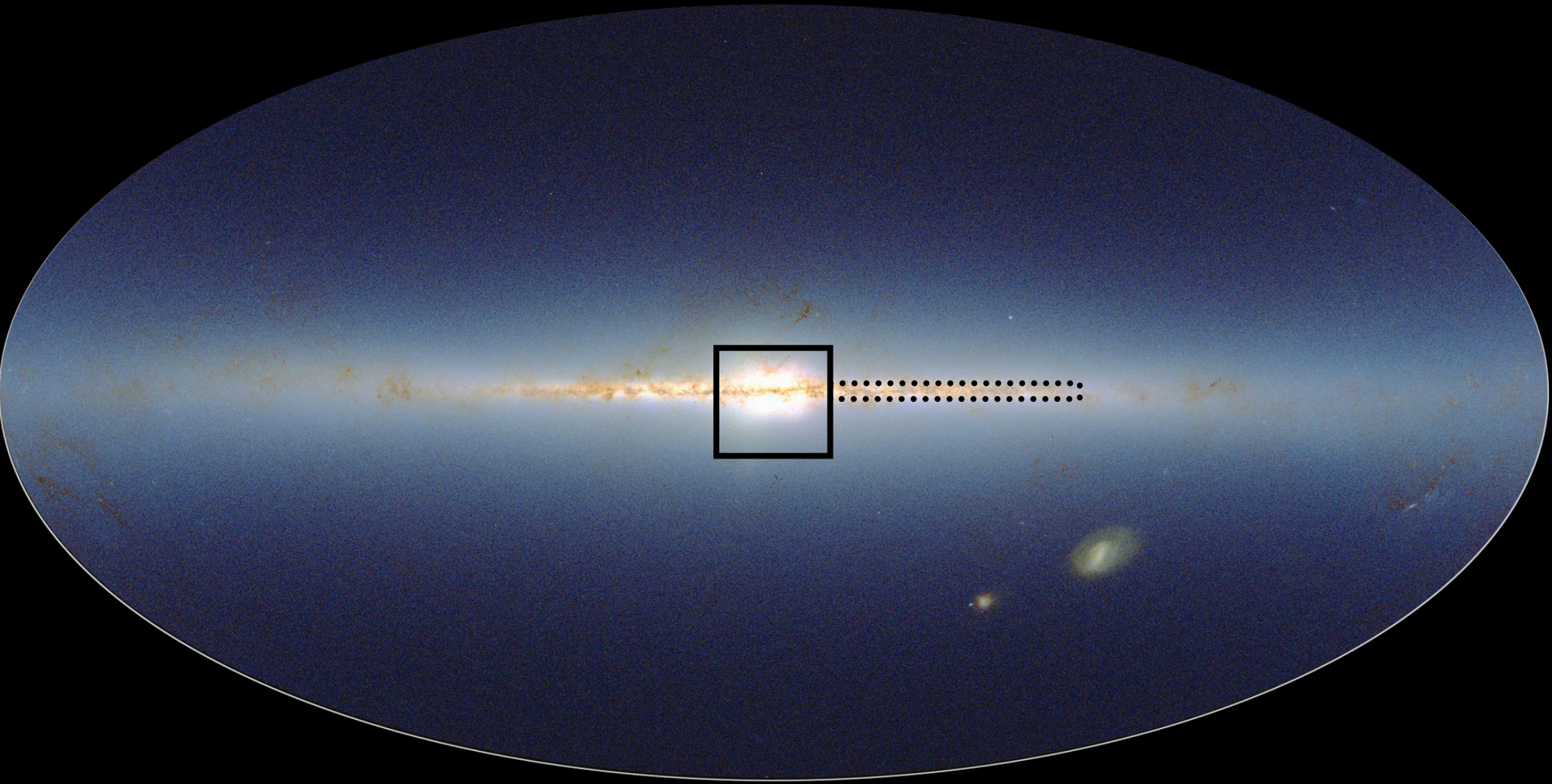


2MASS vs VVV limit for Clump Giants



The photo album of the
MW is not complete yet!!!

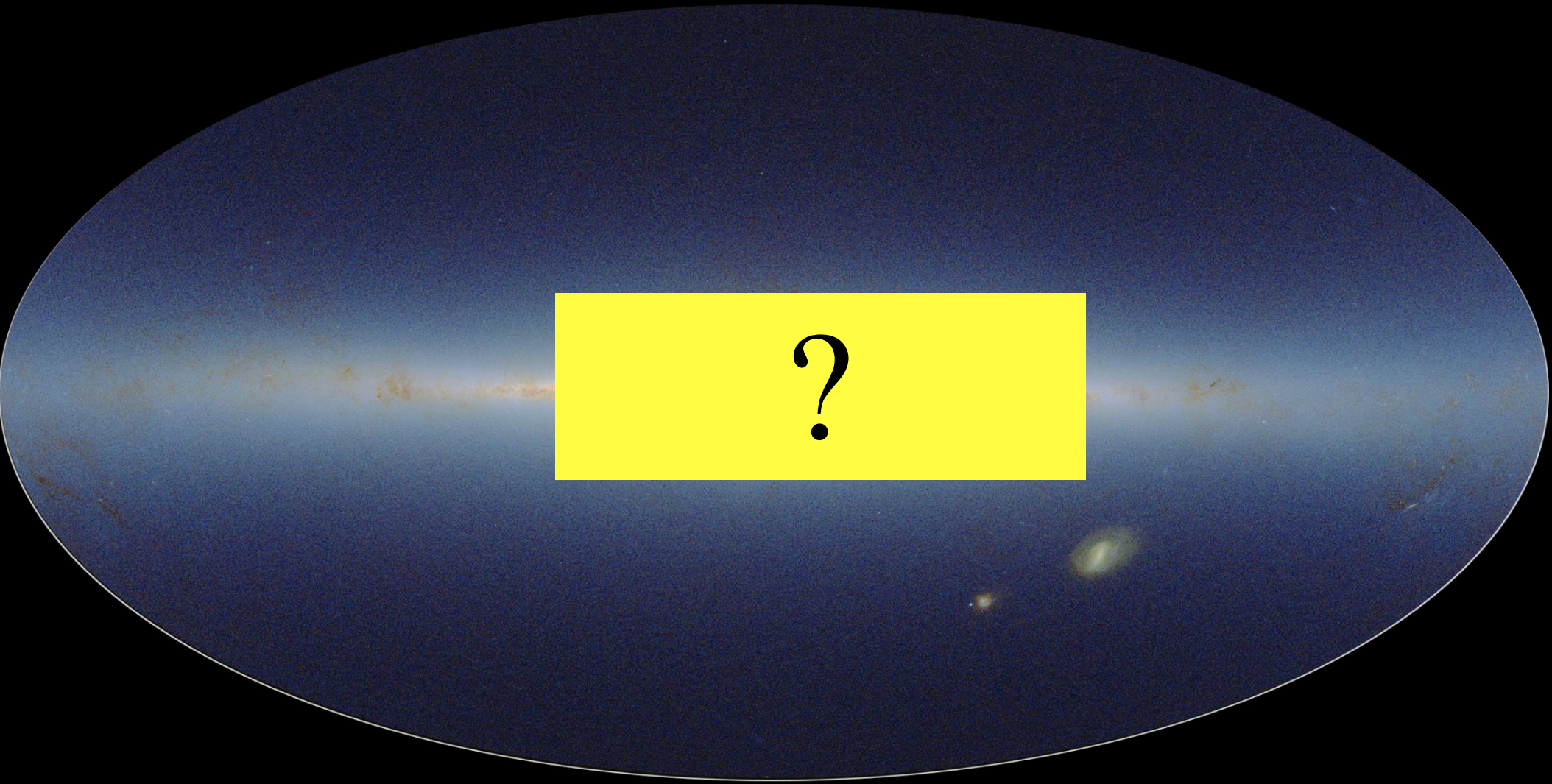
vvvsurvey.org



2MASS IMAGE OF THE MILKY WAY

The photo album of the
MW is not complete yet!!!

vvvsurvey.org



2MASS IMAGE OF THE MILKY WAY

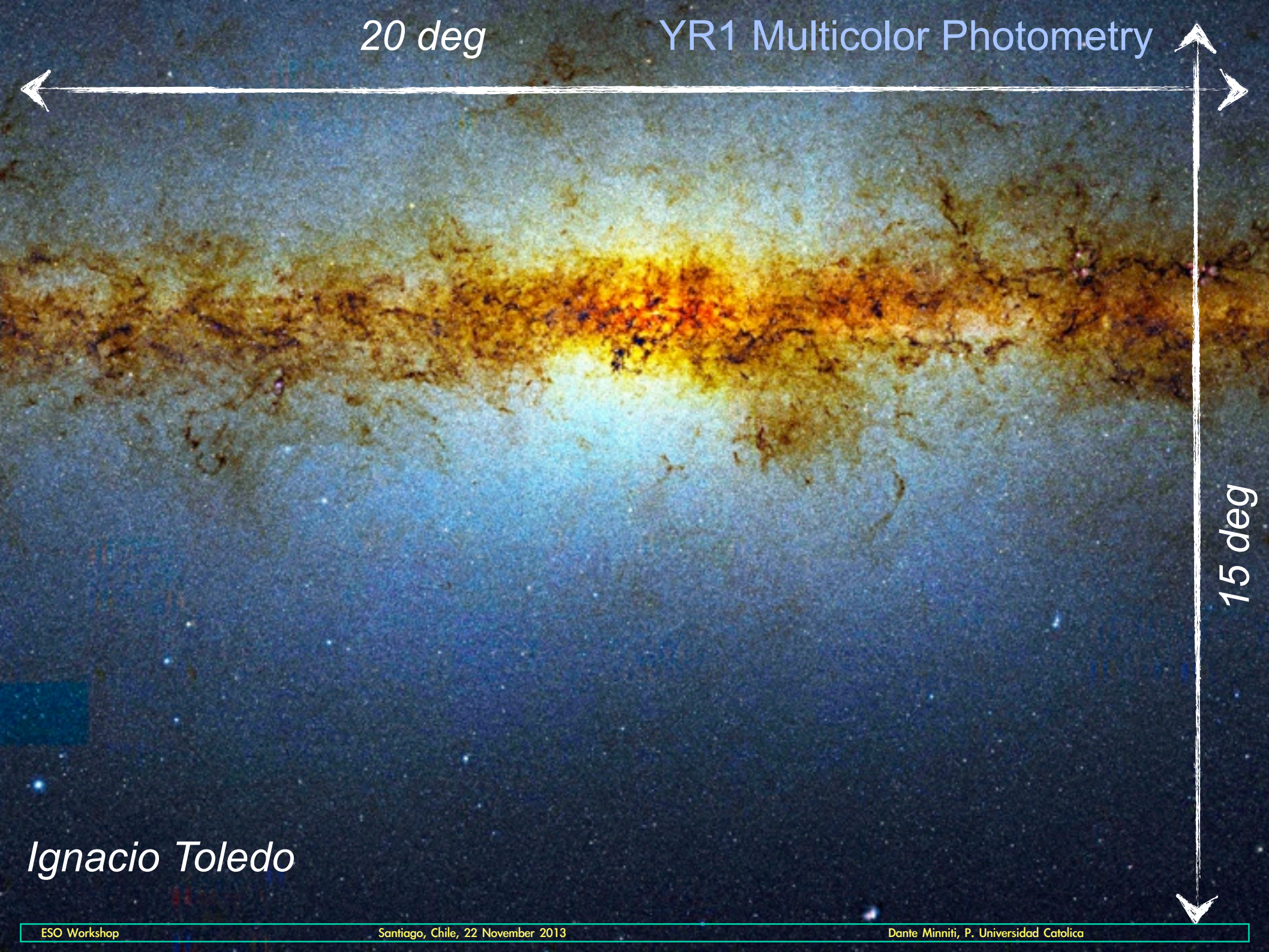
VVV Goal

What is the 3-D
structure of the
Milky Way



20 deg

YR1 Multicolor Photometry

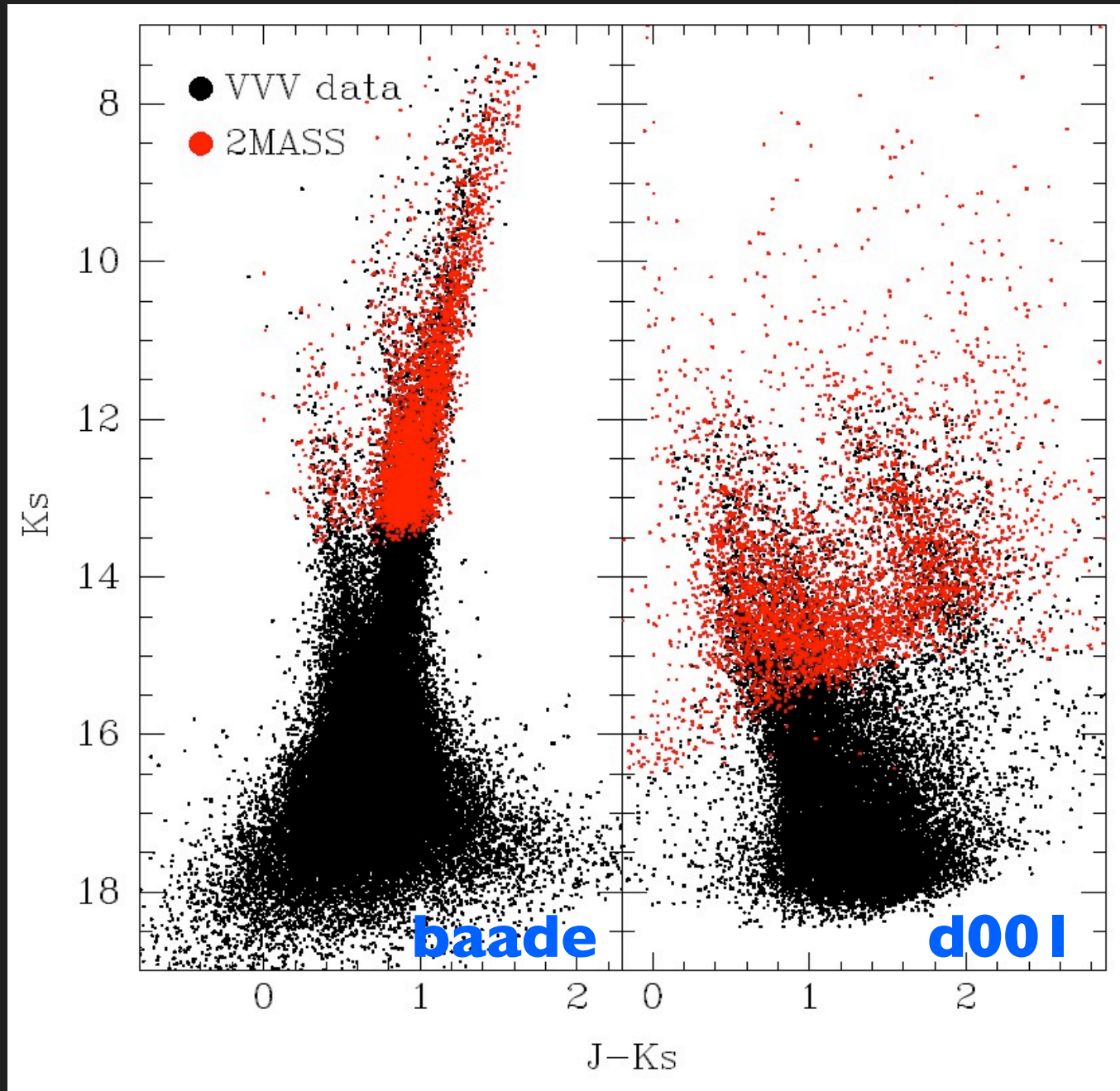


15 deg

Ignacio Toledo

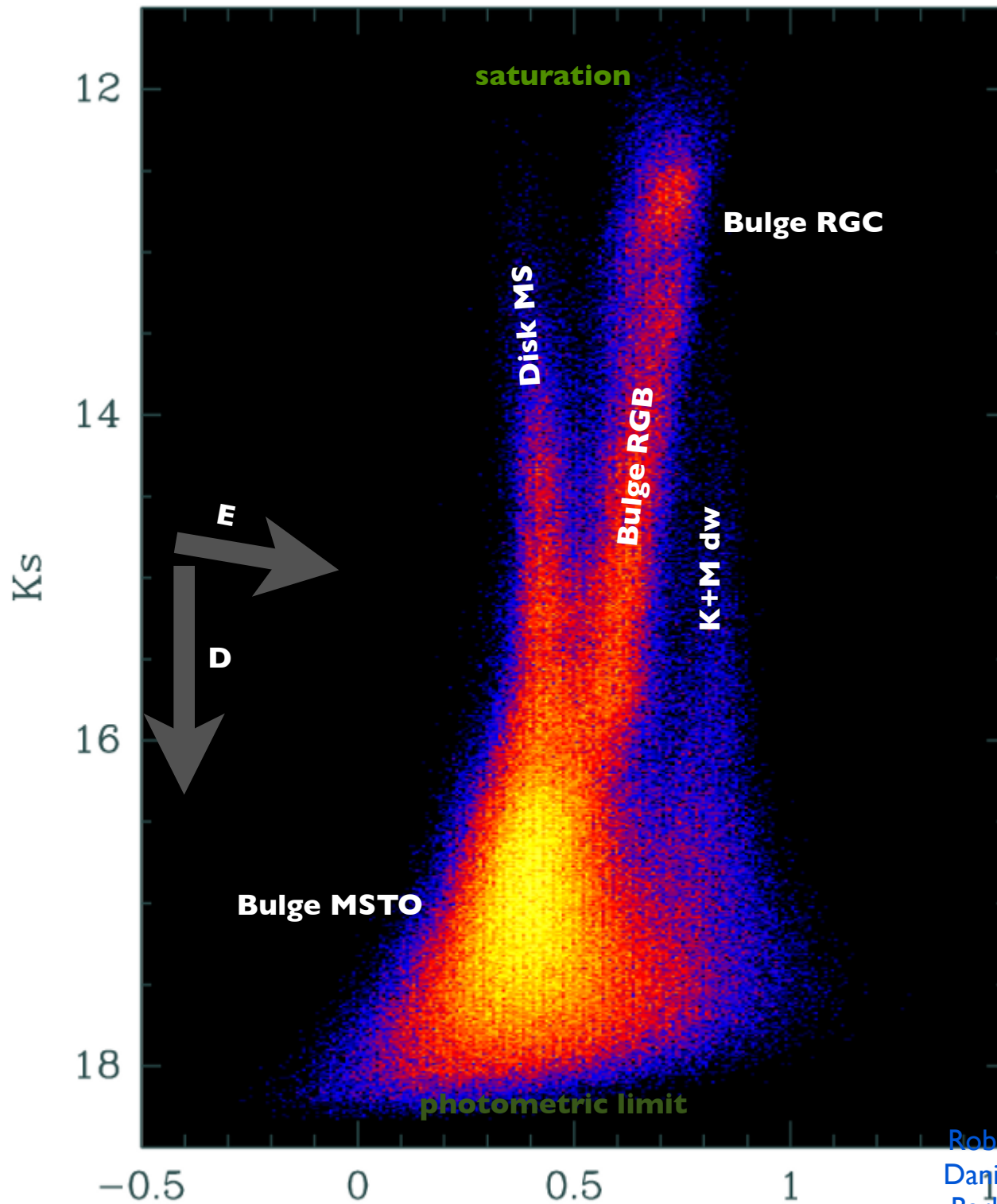
VVV CMDs

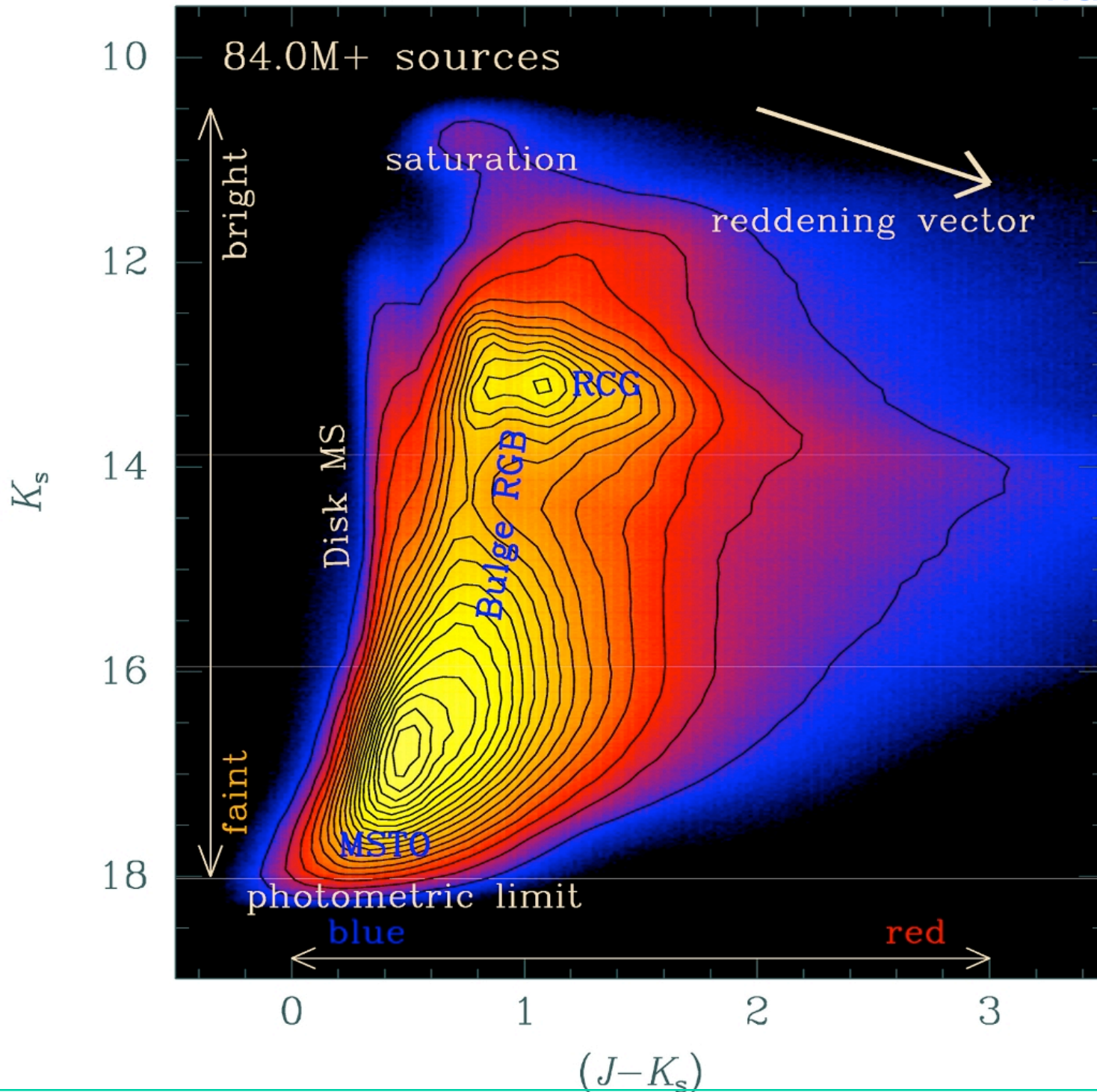
Color-magnitude diagrams of bulge and disk fields compared with 2MASS.



Oscar Gonzalez

VVV 0.3M SINGLE TILE BULGE CMD

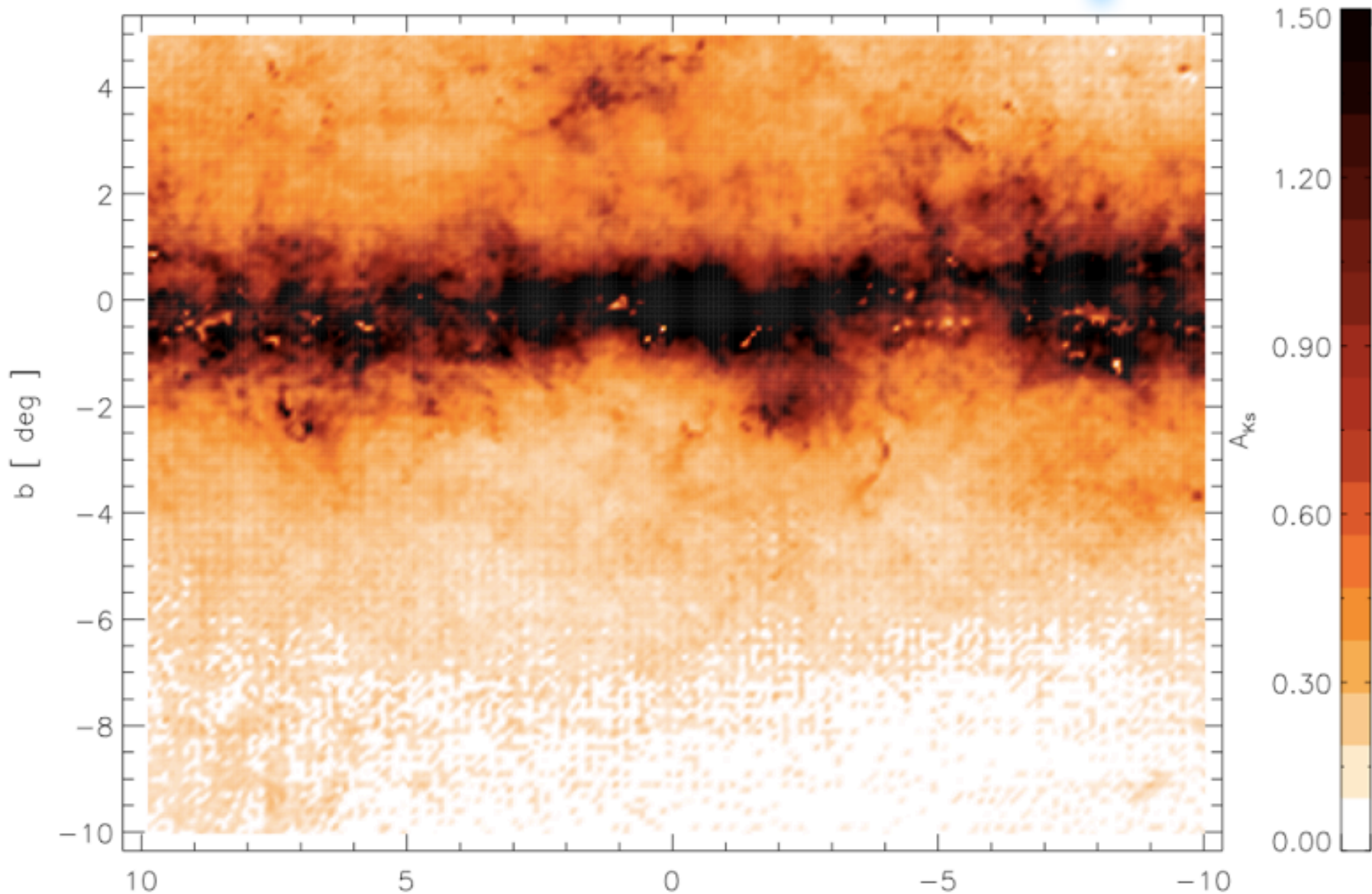




VVV
84M
STARS
BULGE
CMD

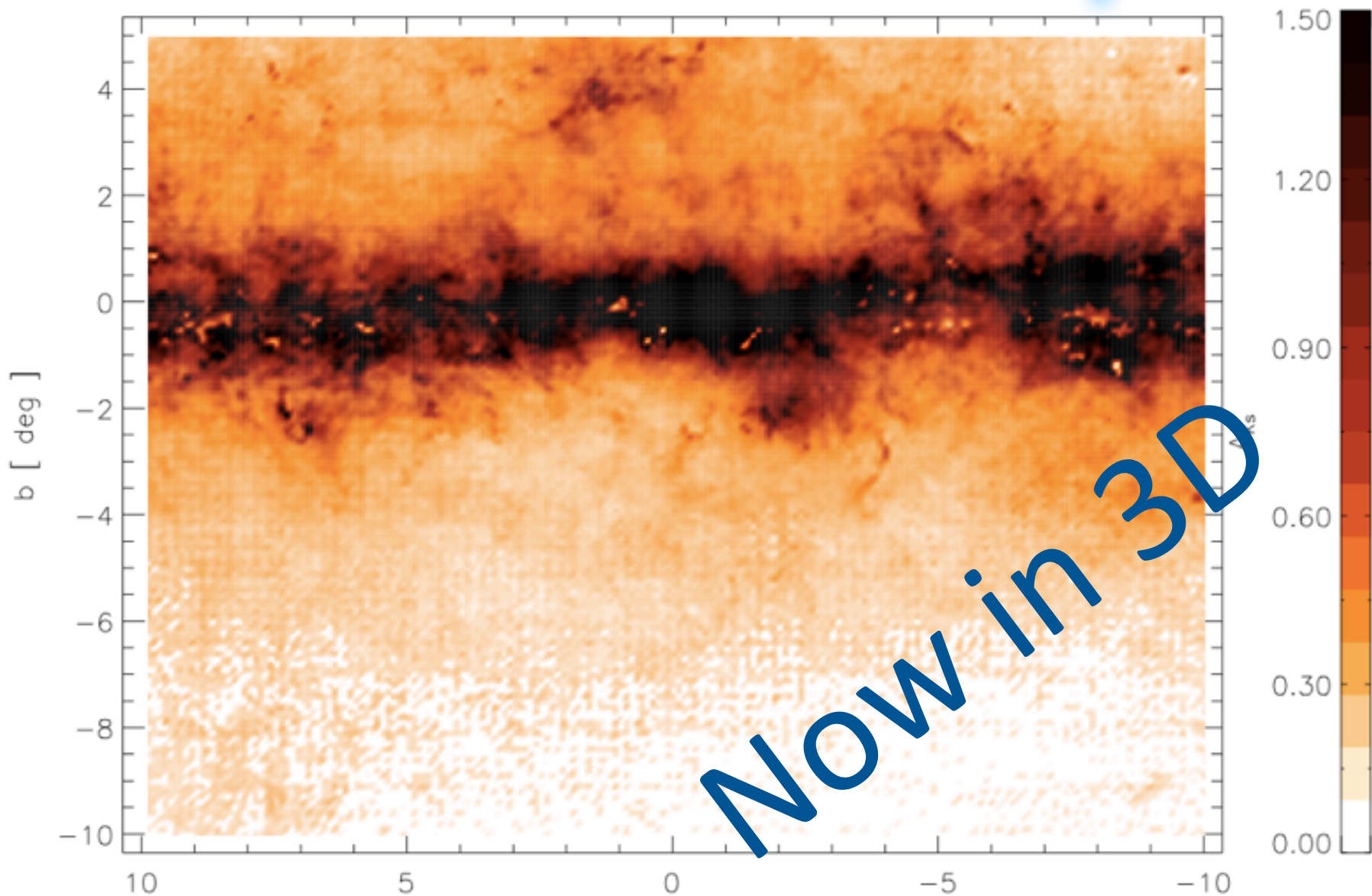
R. Saito et al. 2012

Extinction Maps



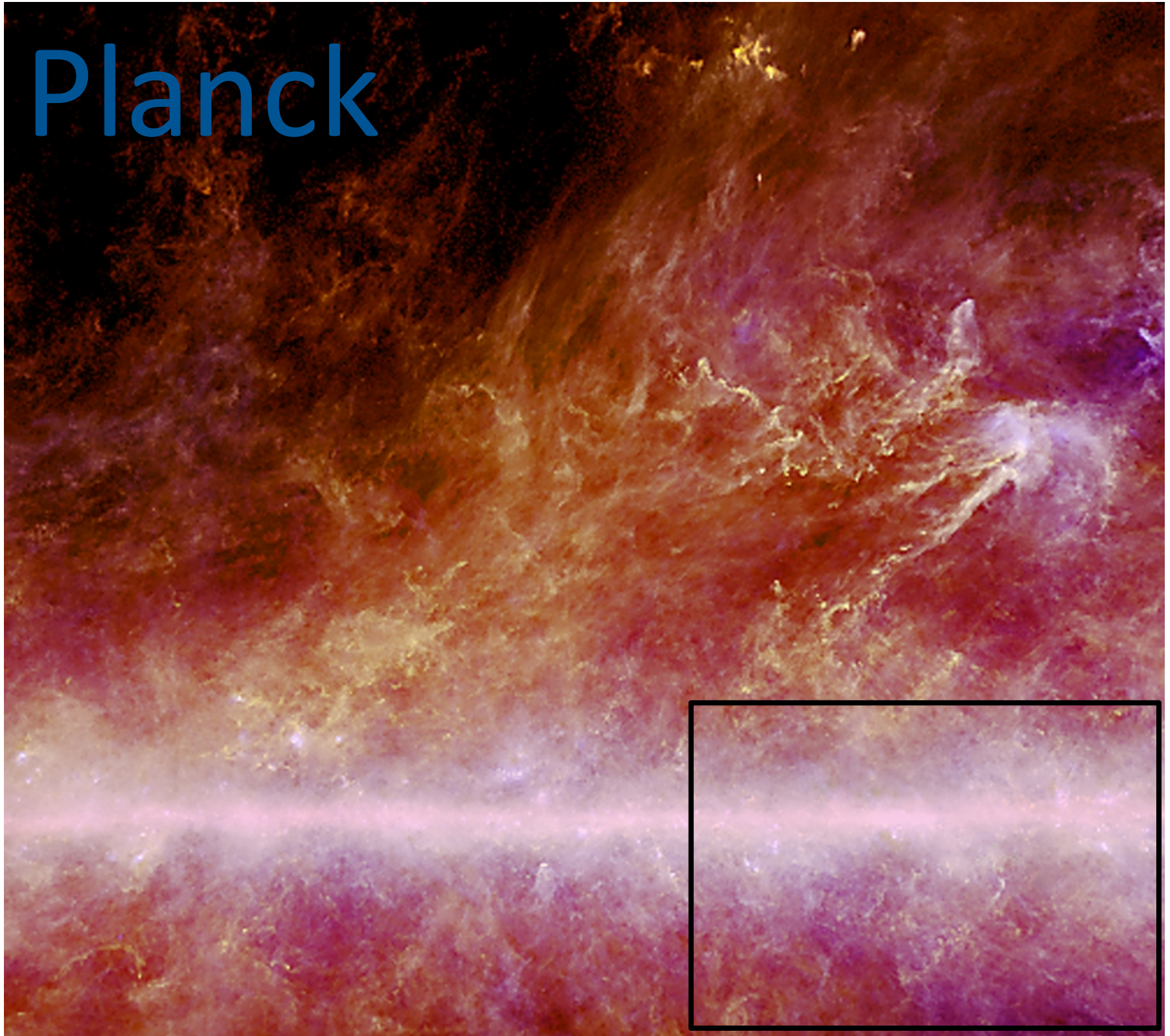
O. Gonzalez, et al. A&A 2012, B. Chen et al. A&A 2013

Extinction Maps

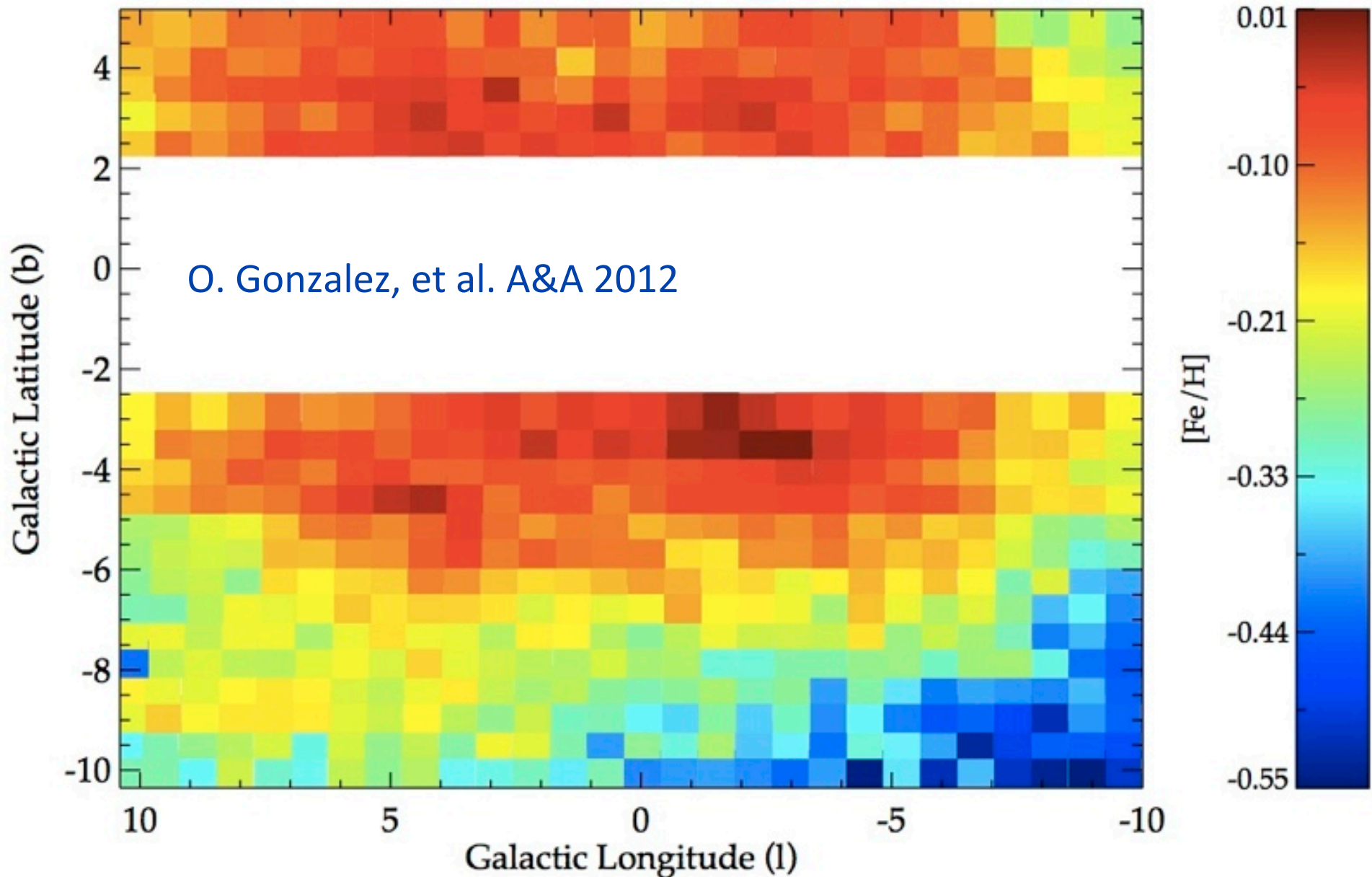


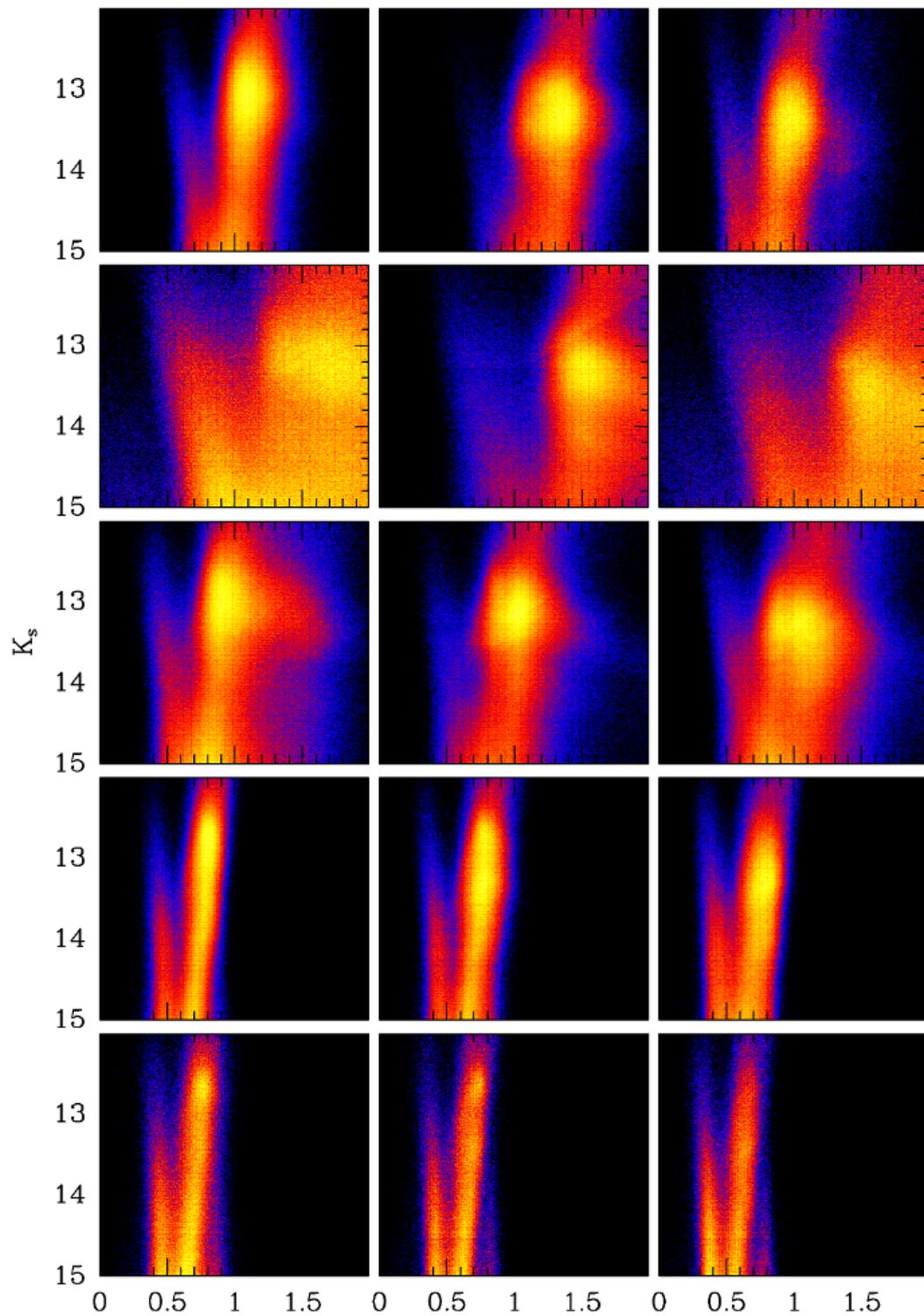
O. Gonzalez, et al. A&A 2012, B. Chen et al. A&A 2013

Planck

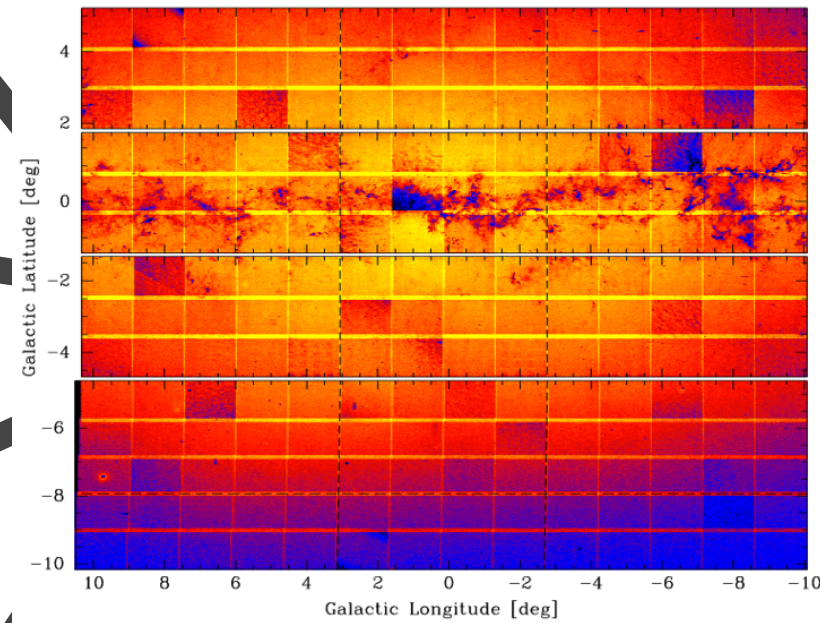


Metallicity Maps





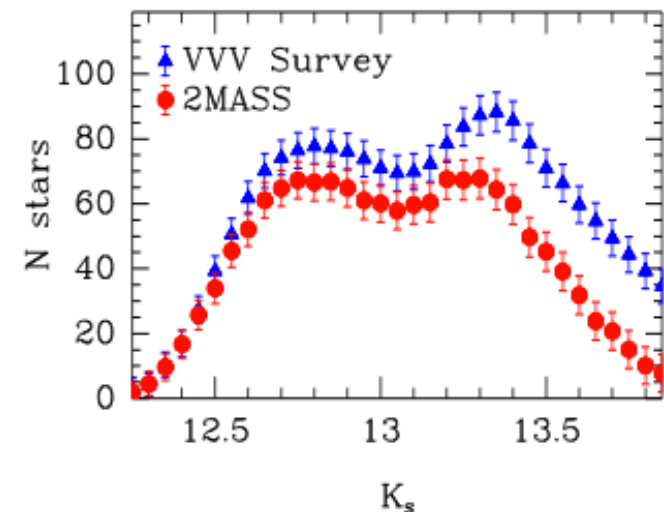
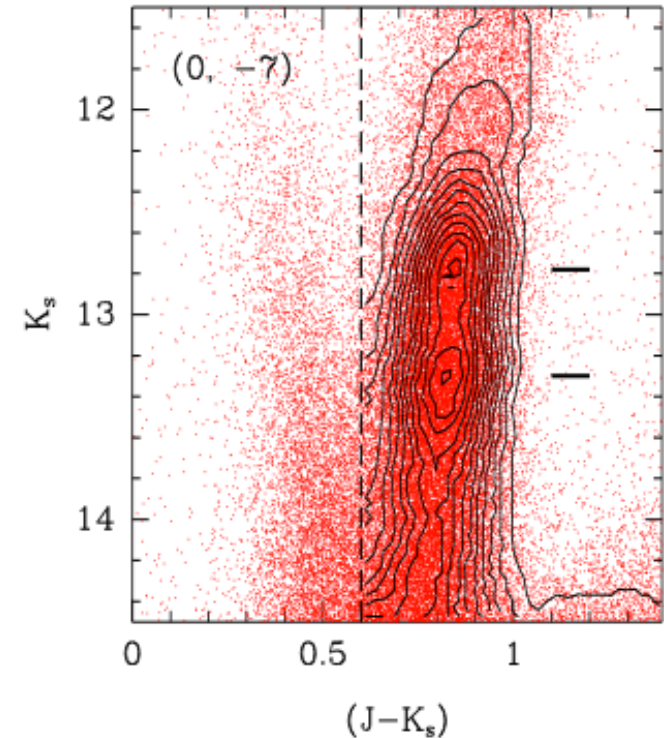
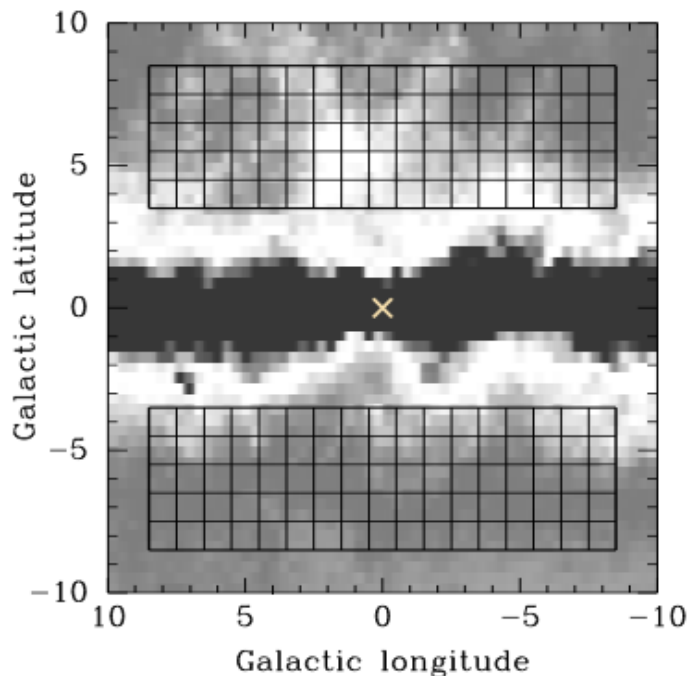
Interpretation of the
Galactic bulge CMDs:
RGB clump region



Roberto Saito

The X-shaped structure of the galactic bulge

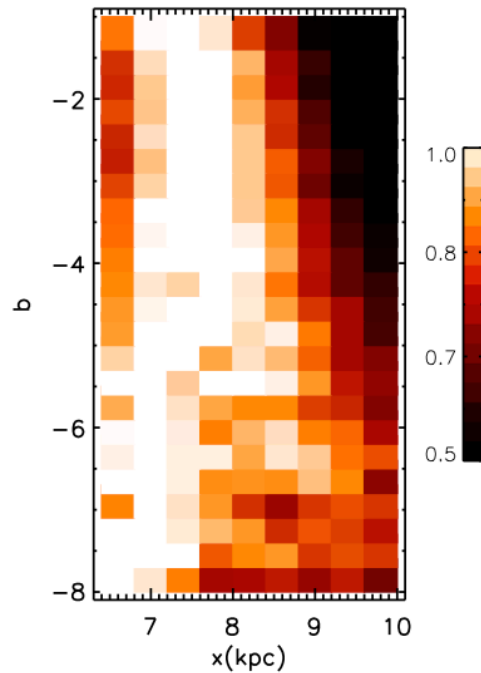
A double clump structure is seen along different directions towards the bulge. This is present in 2MASS and VVV data.



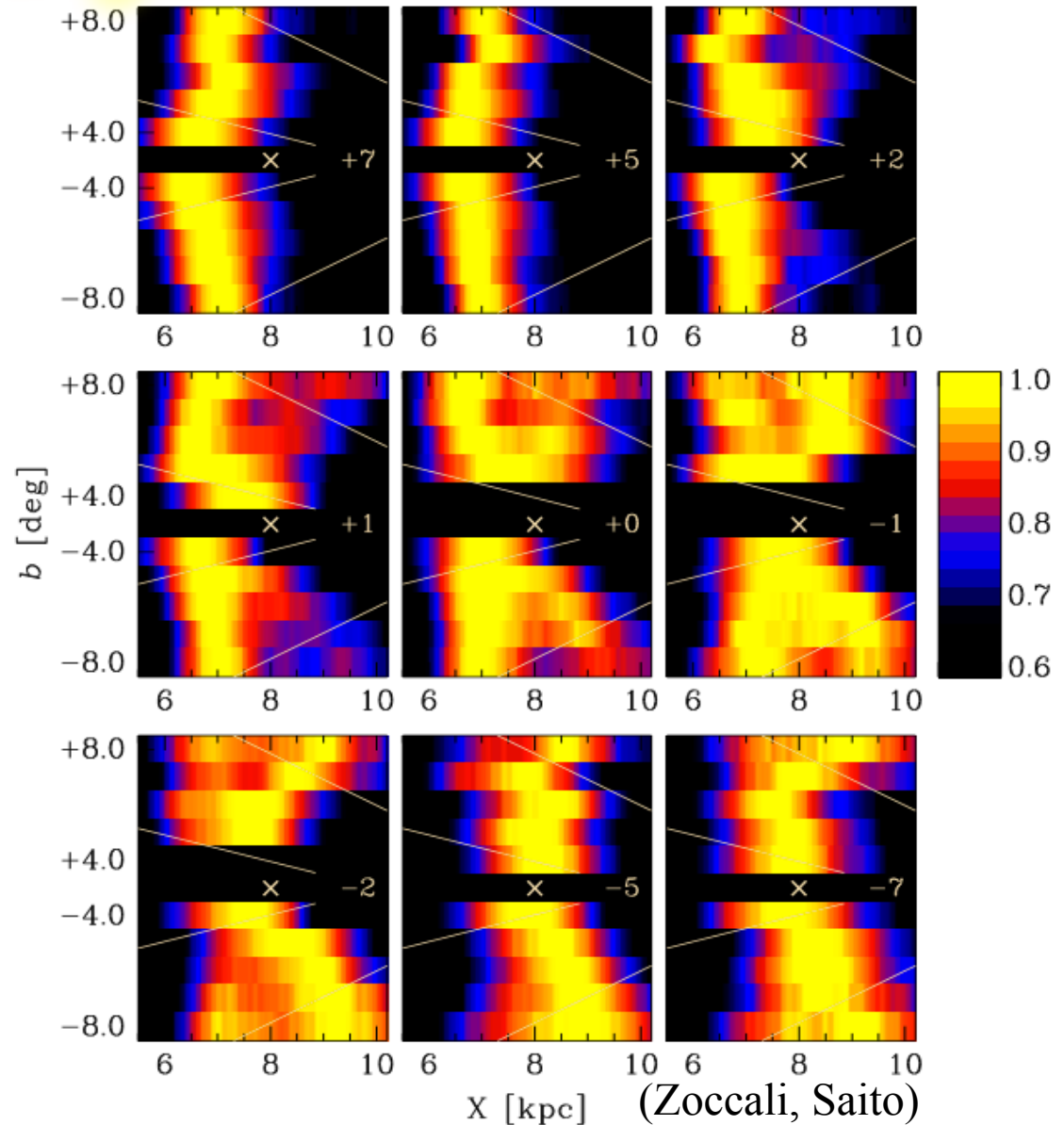
Zoccali et al. 2011

The X-shaped structure of the galactic bulge

The Milky Way bulge is X-shaped.
Two independent datasets and analysis.



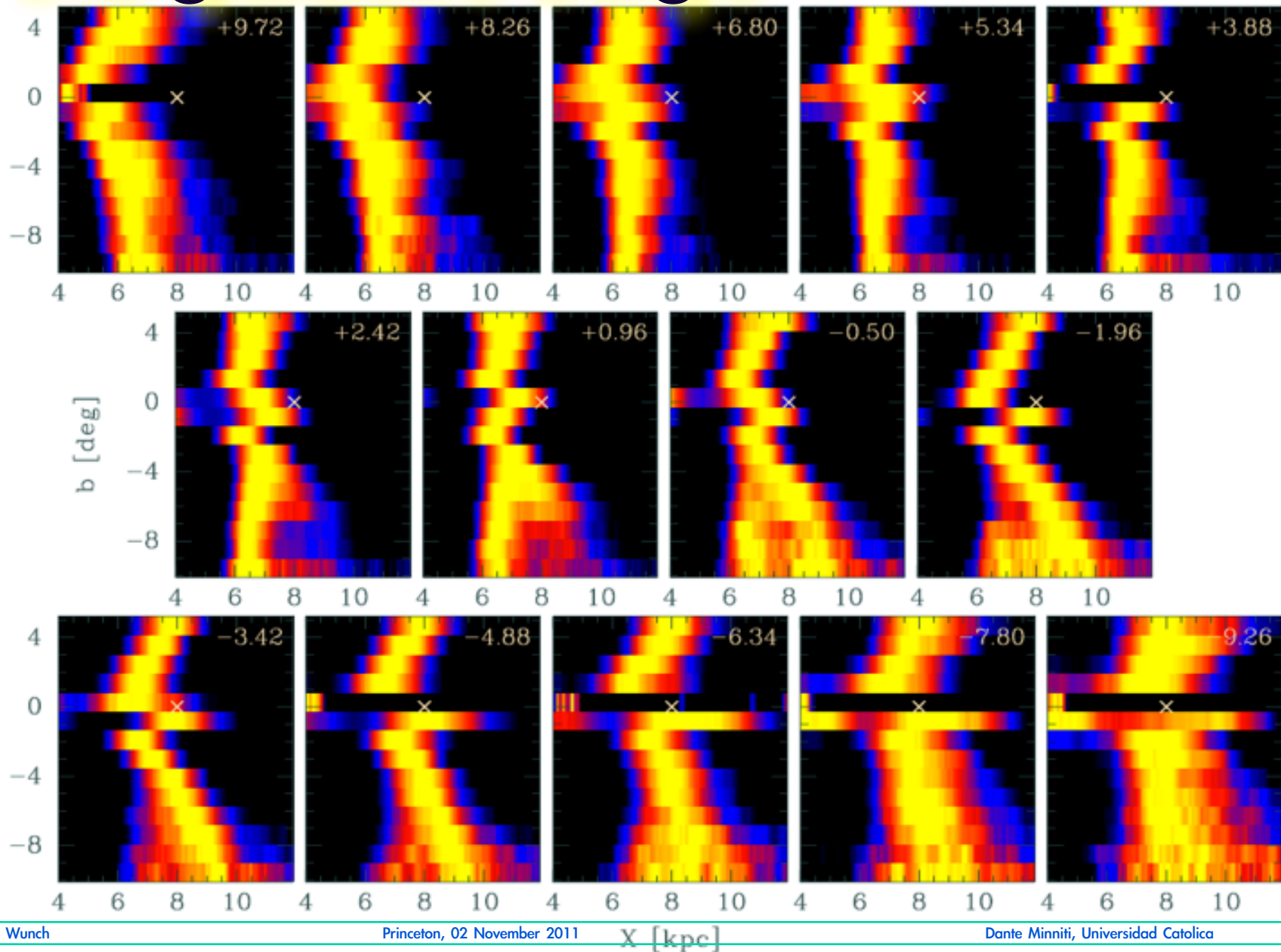
(Gonzalez, Rejkuba)



(Zoccali, Saito)

The X-shaped structure of the galactic bulge

Saito, Zoccali et al. 2012



The X-shaped structure of the galactic bulge

Proper motions:
Vasquez et al. 2013



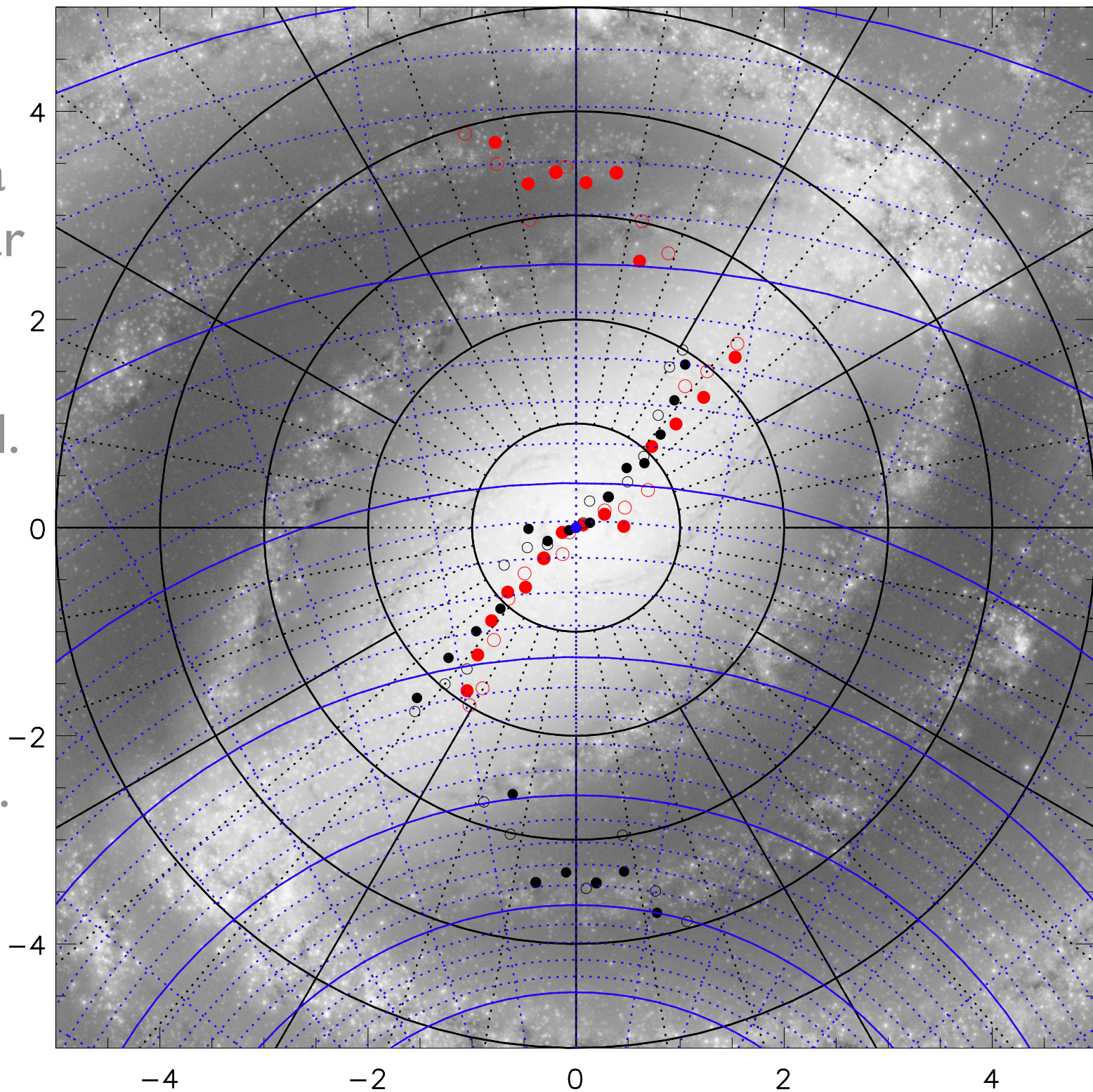
NGC 1365: two nested bars with two arms

VLT INFRARED

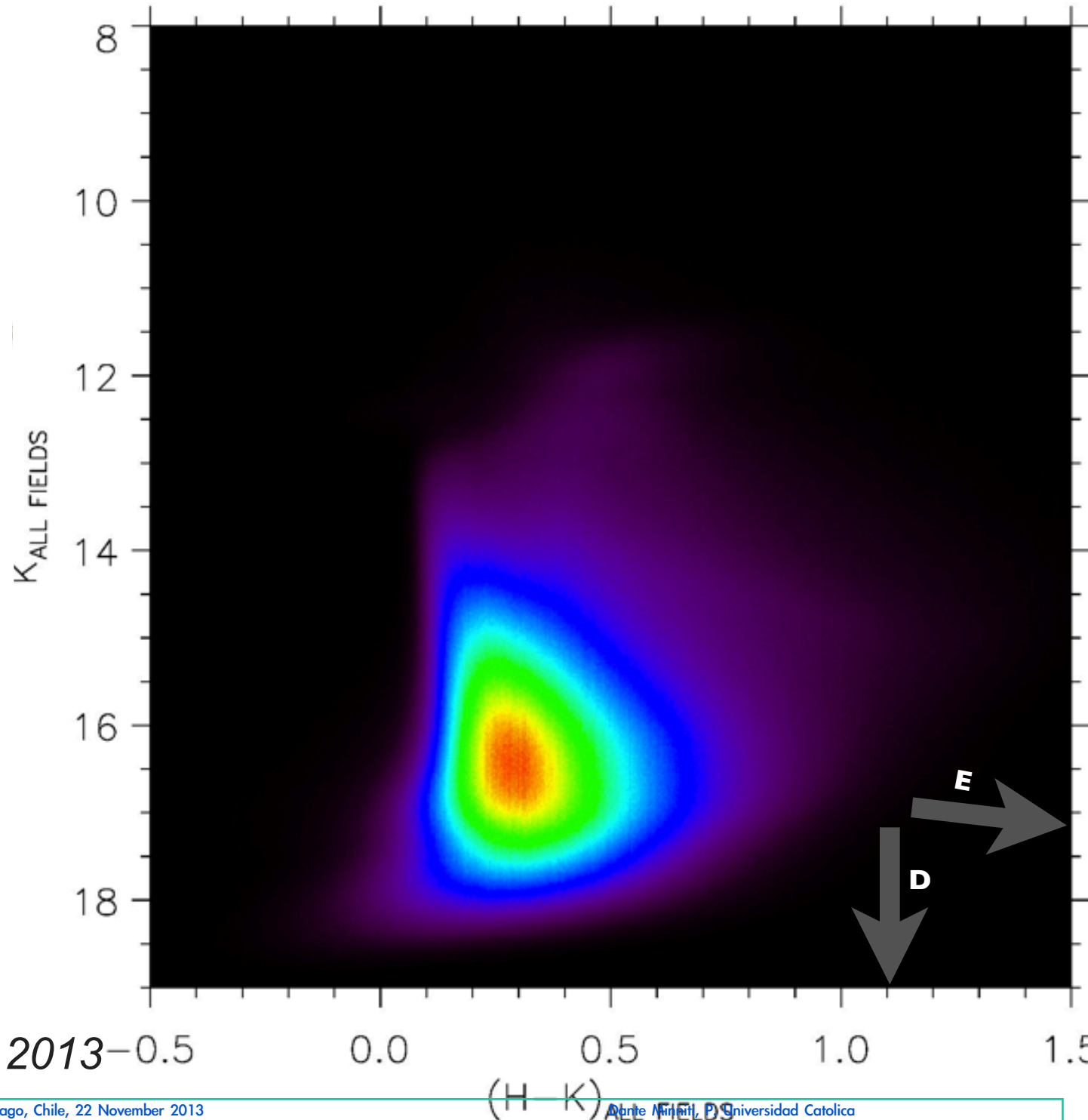


Evidence for a tilted inner bar from bulge clump giants
Gonzalez et al.
A&A 2012

Or projection effects
Valpuesta et al.
2012

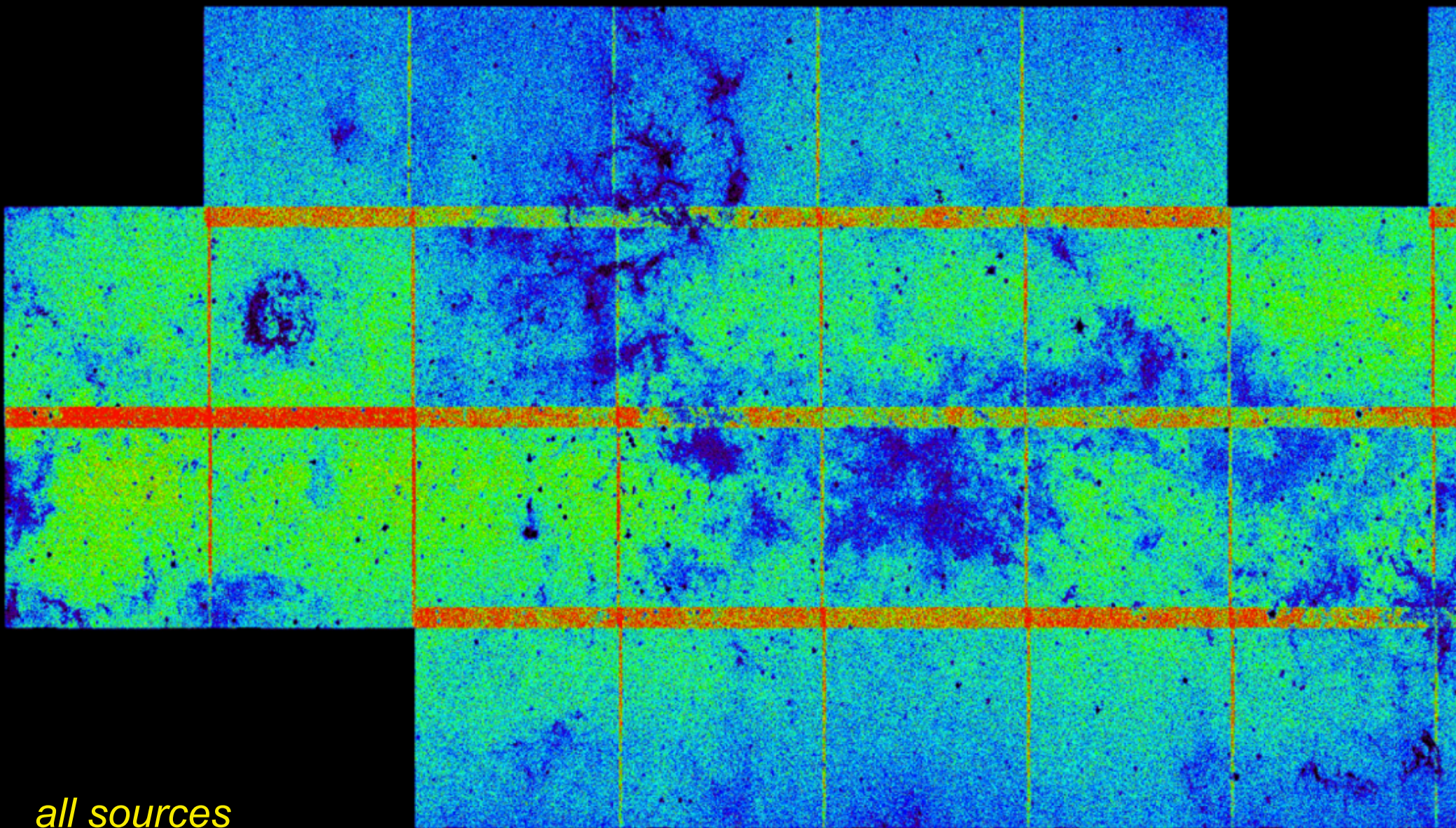


VVV DISK I40M STARS



M. Soto, R. Barba, et al. 2013

VVV DISK DENSITY MAPS

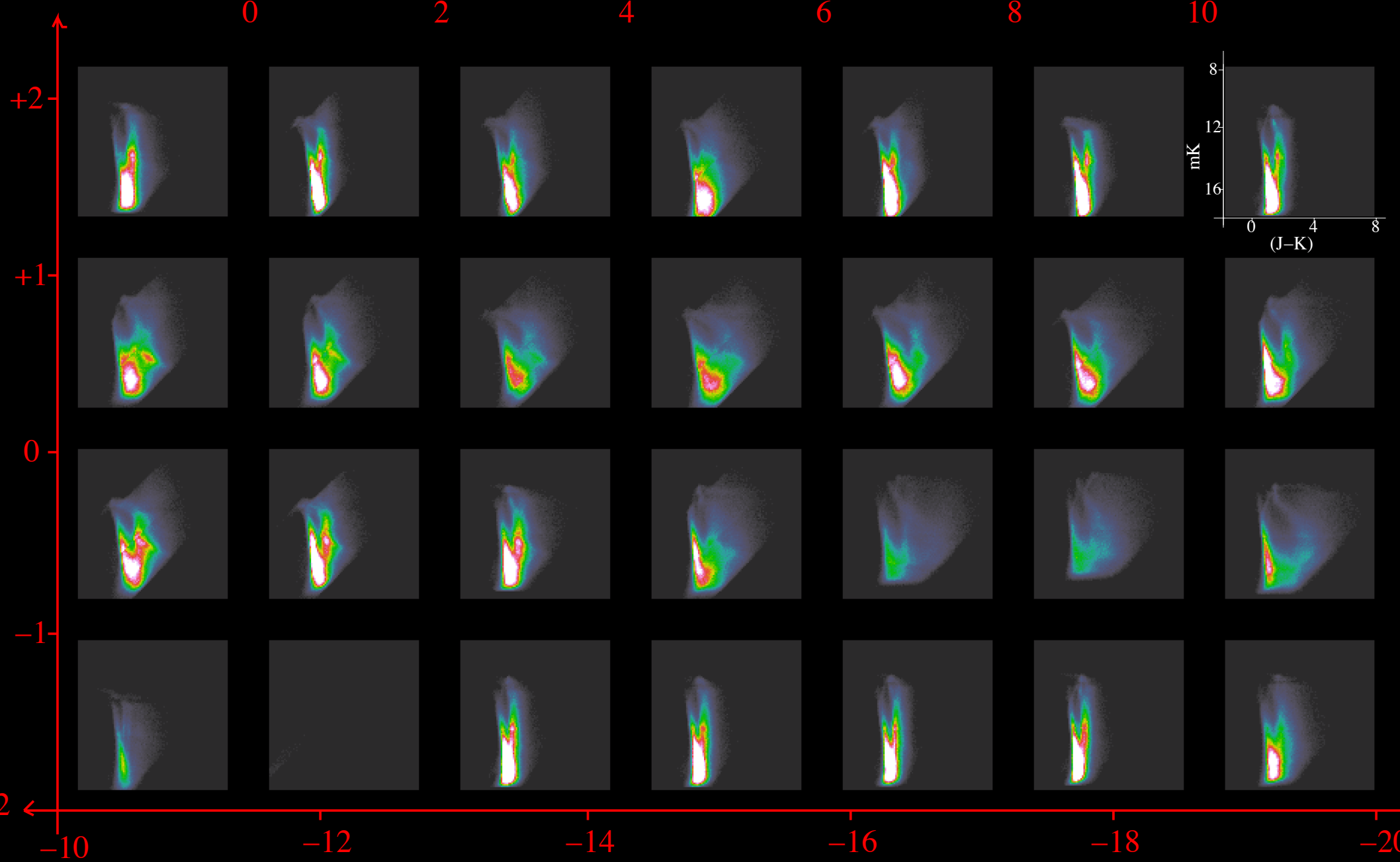


all sources

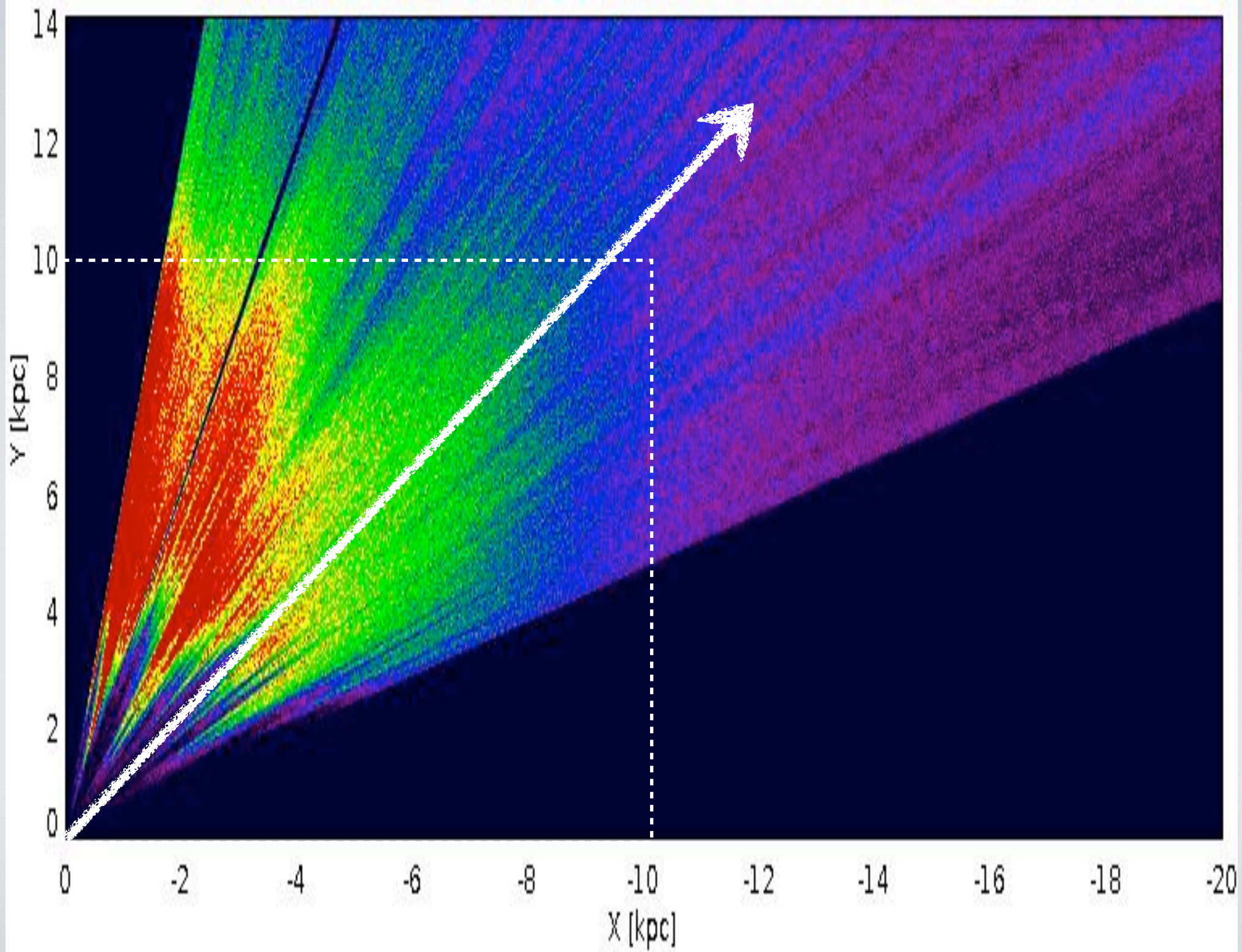
M. Soto, R. Barba

$dN/dm_K/d(J-K) [10^4 \text{ mag}^{-2}]$

VVV DISK CMDS

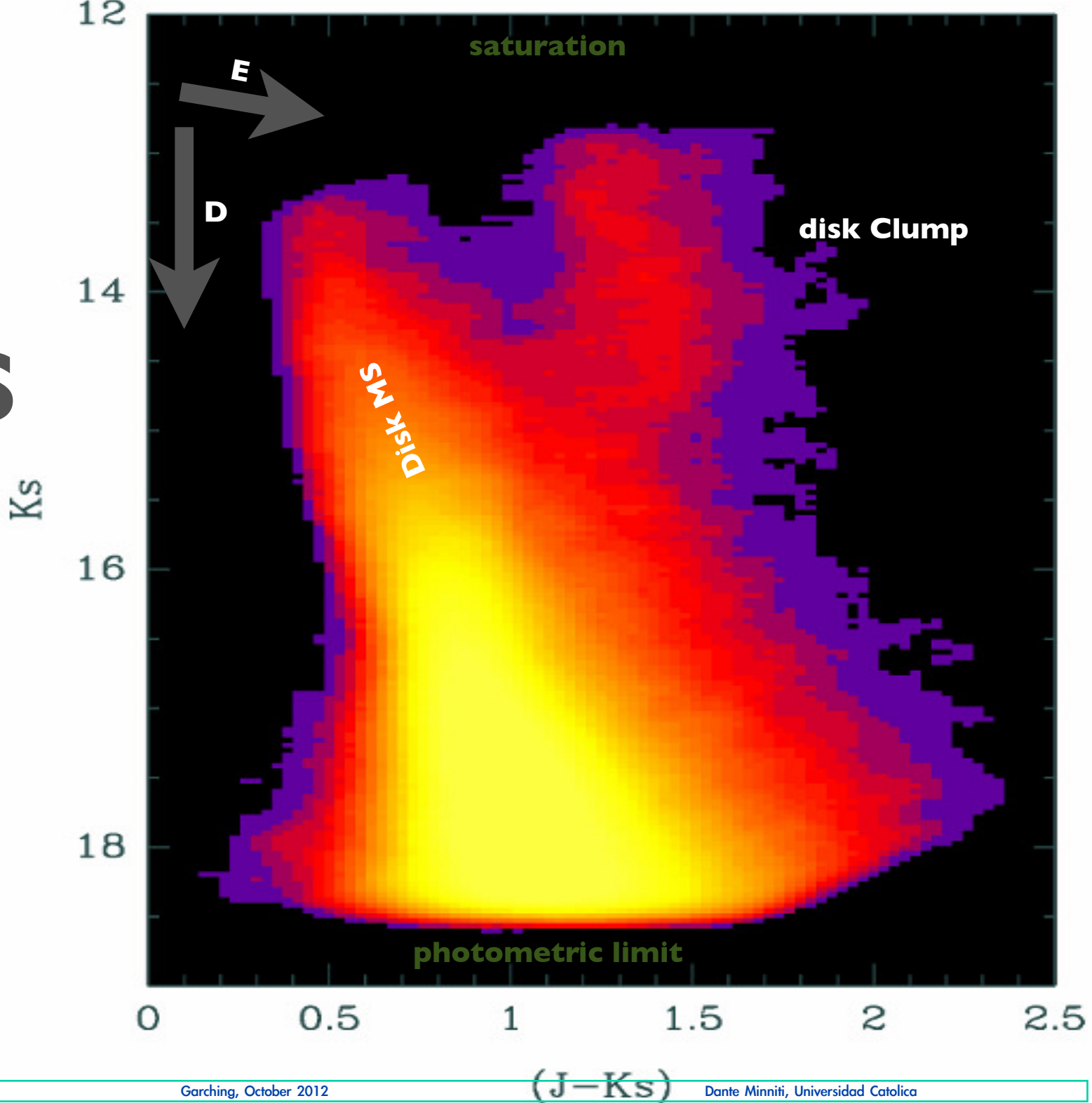


Galactic longitude (deg.) *C. Gonzalez Fernandez et al. 2012*



VVV 0.5M+ STARS DISK CMD

d003 field

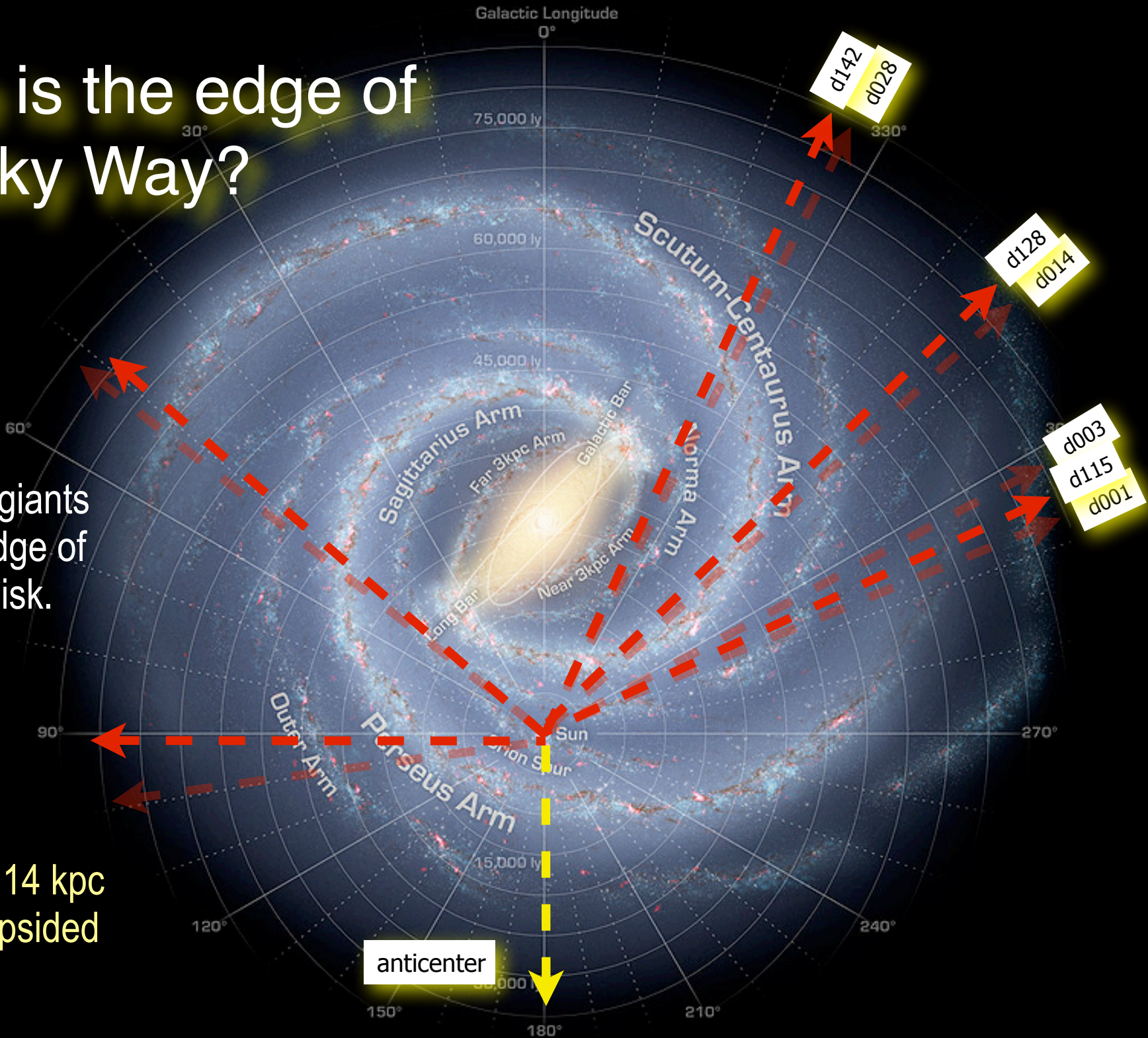


Where is the edge of the Milky Way?

Using clump giants to map the edge of the galactic disk.

Results:

- $R_{\text{edge}} = 14 \text{ kpc}$
- disk not lopsided



The VVV Stages

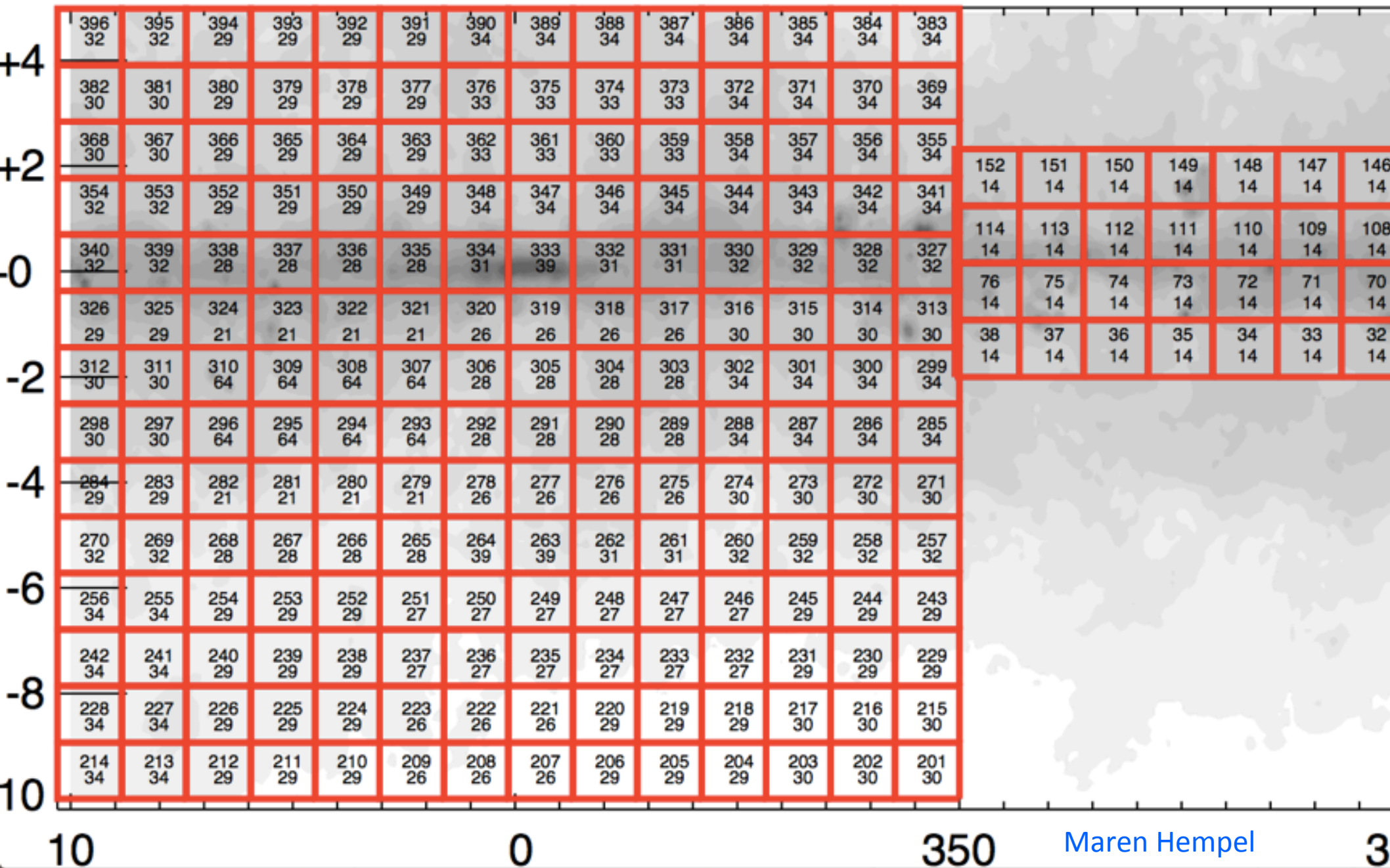
Multicolor Photometry: ZYJKs

Variability: Ks

LPVs, Cepheids, RR Lyrae, Binaries, Novae, Microlensing...

Proper Motions: Ks

Number of Epochs: Bulge



Number of Epochs: Bulge

366 29	365 29	364 29	363 29	362 33	361 33	360 33	359 33	358 34	357 34	356 34
352 29	351 29	350 29	349 29	348 34	347 34	346 34	345 34	344 34	343 34	342 34
338 28	337 28	336 28	335 28	334 31	333 39	332 31	331 31	330 32	329 32	328 32
324 21	323 21	322 21	321 21	320 26	319 26	318 26	317 26	316 30	315 30	314 30
310 64	309 64	308 64	307 64	306 28	305 28	304 28	303 28	302 34	301 34	300 34
296 64	295 64	294 64	293 64	292 28	291 28	290 28	289 28	288 34	287 34	286 34
282 21	281 21	280 21	279 21	278 26	277 26	276 26	275 26	274 30	273 30	272 30
268 28	267 28	266 28	265 28	264 39	263 39	262 31	261 31	260 32	259 32	258 32
254 29	253 29	252 29	251 27	250 27	249 27	248 27	247 27	246 27	245 29	244 29
240 29	239 29	238 29	237 27	236 27	235 27	234 27	233 27	232 29	231 29	230 29

Number of Epochs: Bulge

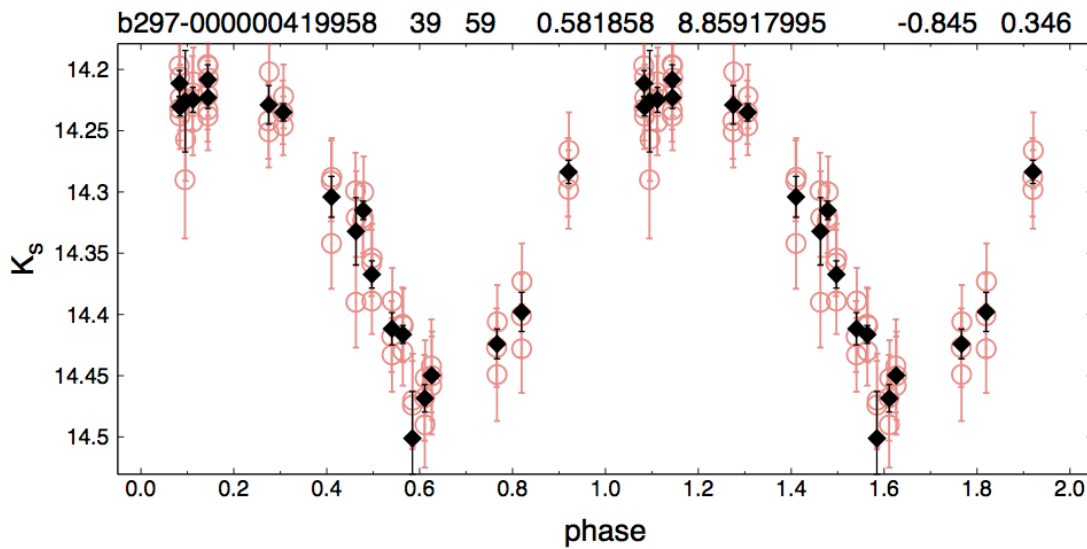
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352 29	351 29	350 29	349 29	348 34	347 34	346 34	345 34	344 34	343 34	342 34
338 28	337 28	336 28	335 28	334 31	333 39	332 31	331 31	330 32	329 32	328 32
324 21	323 21	322 21	321 21	320 26	319 26	318 26	317 26	316 30	315 30	314 30
310 64	309 64	308 64	307 64	306 28	305 28	304 28	303 28	302 34	301 34	300 34
296 64	295 64	294 64	293 64	292 28	291 28	290 28	289 28	288 34	287 34	286 34
282 21	281 21	280 21	279 21	278 26	277 26	276 26	275 26	274 30	273 30	272 30
268 28	267 28	266 28	265 28	264 39	263 39	262 31	261 31	260 32	259 32	258 32
254 29	253 29	252 29	251 27	250 27	249 27	248 27	247 27	246 27	245 29	244 29
240 29	239 29	238 29	237 27	236 27	235 27	234 27	233 27	232 29	231 29	230 29

Number of Epochs: Bulge

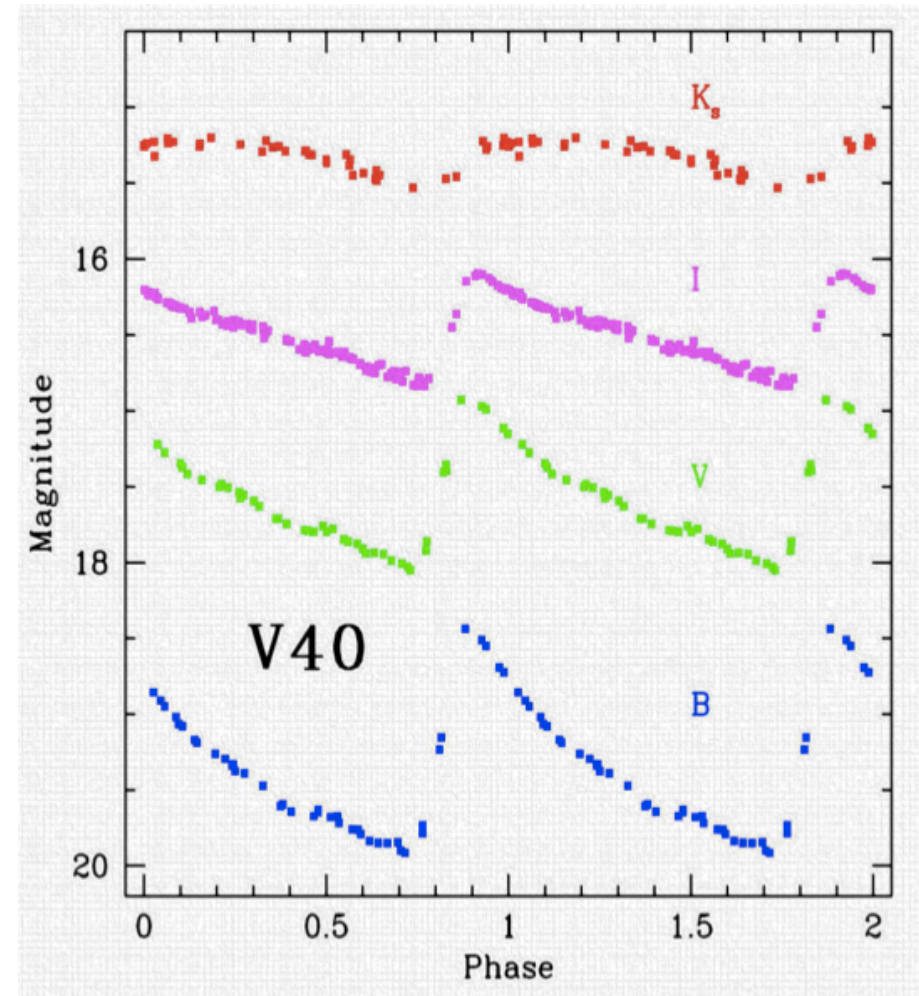
366 29	365 29	364 29	363 29	362 33	361 33	360 33	359 33	358 34	357 34	356 34
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338 28	337 28	336 28	335 28	334 31	333 39	332 31	331 31	330 32	329 32	328 32
324 21	323 21	322 21	321 21	320 26	319 26	318 26	317 26	316 30	315 30	314 30
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296 64	295 64	294 64	293 64	292 28	291 28	290 28	289 28	288 34	287 34	286 34
282 21	281 21	280 21	279 21	278 26	277 26	276 26	275 26	274 30	273 30	272 30
268 28	267 28	266 28	265 28	264 39	263 39	262 31	261 31	260 32	259 32	258 32
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240 29	239 29	238 29	237 27	236 27	235 27	234 27	233 27	232 29	231 29	230 29

Bulge RR Lyrae:

$P = 0.58 \text{ d}$

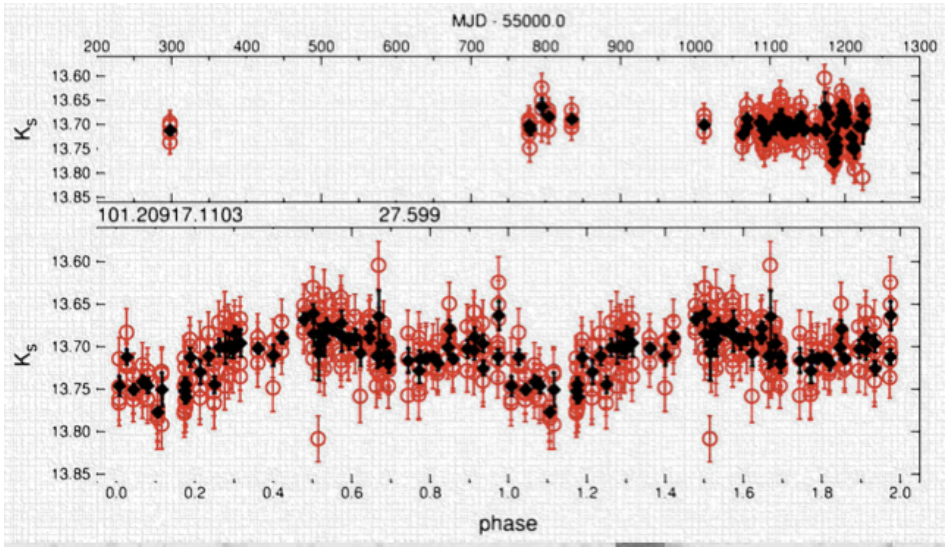


Comparison of optical and IR light curves

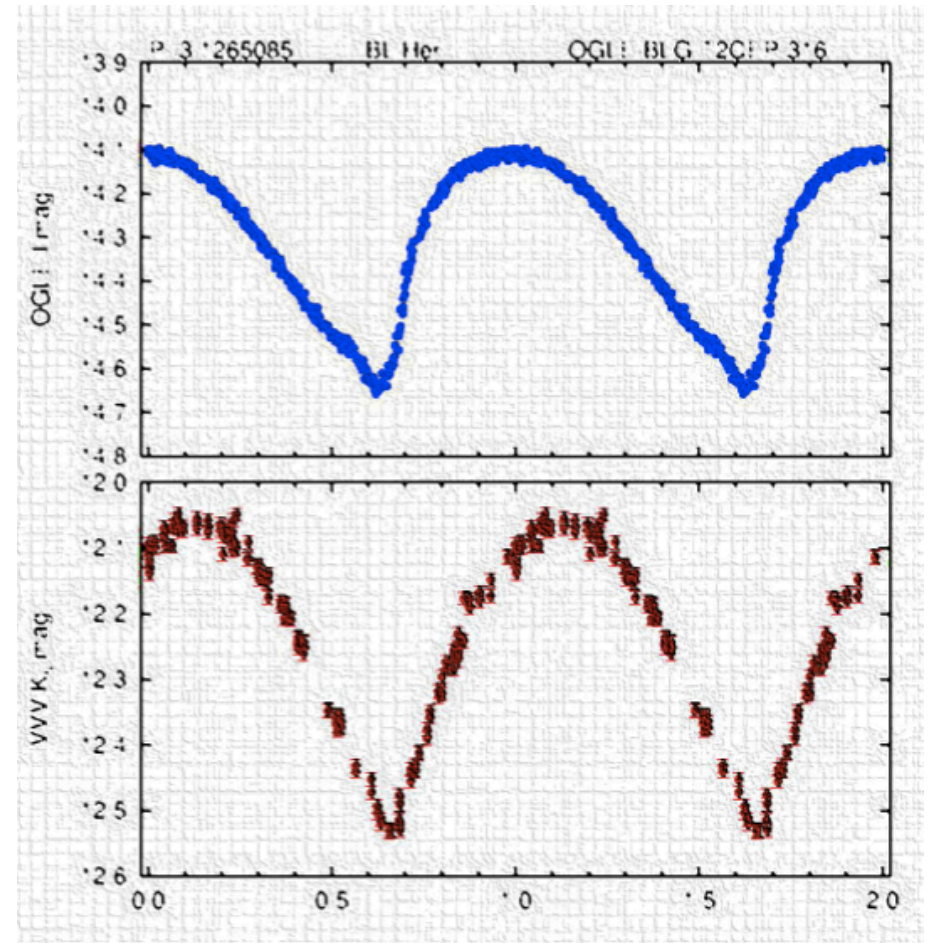


Istvan Dekany

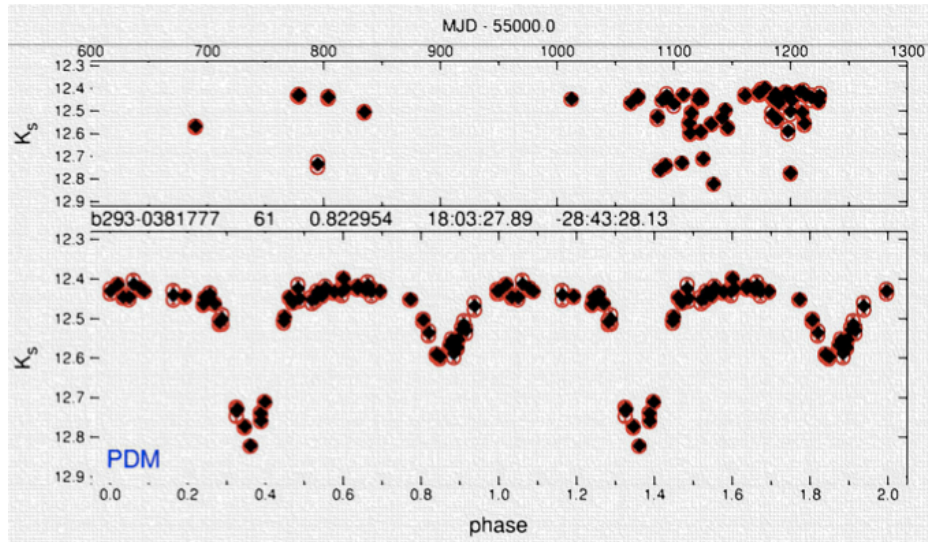
RSCVn type variable



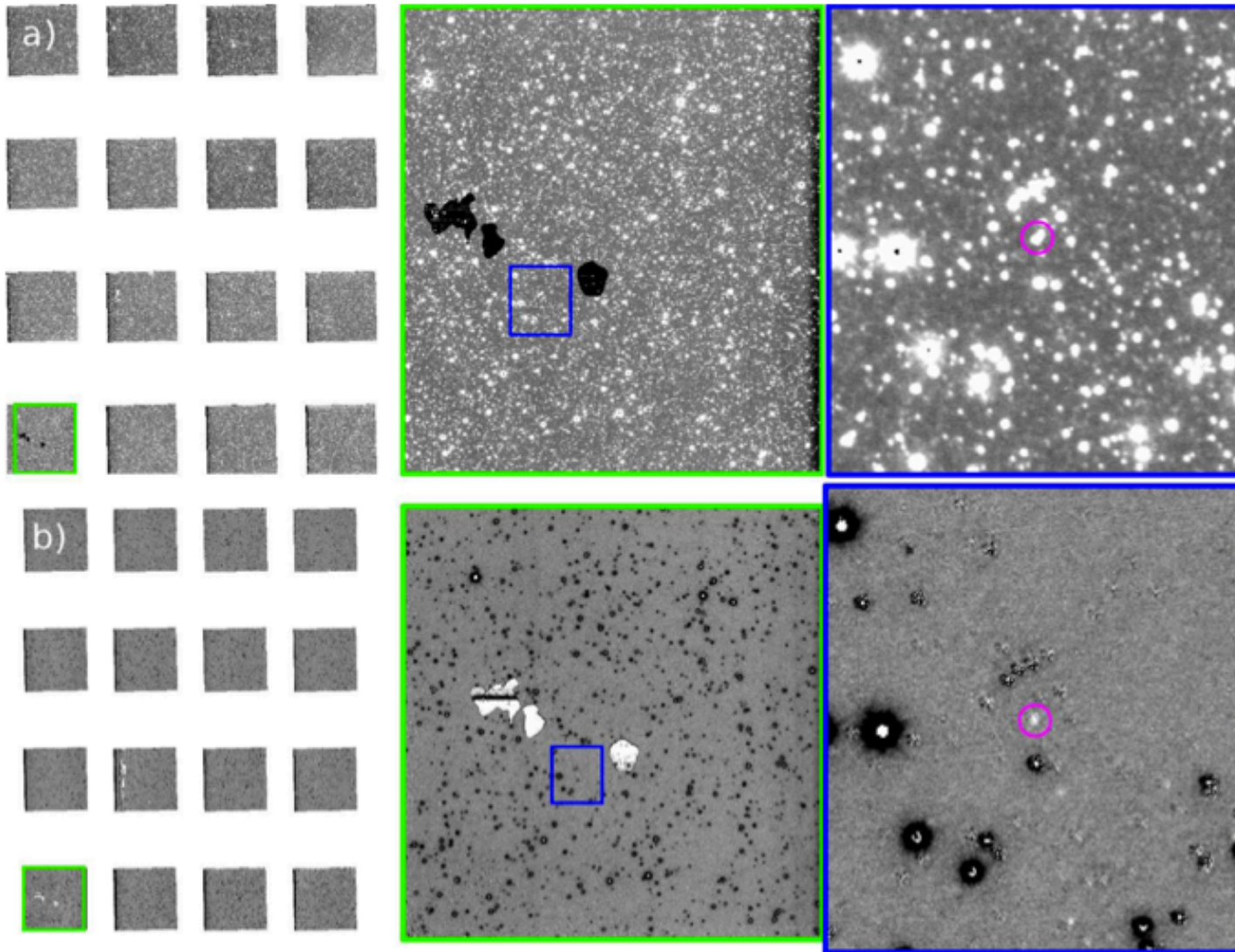
Bulge Type II Cepheid



Eclipsing Binary



DIA photometry



Main DIA problem:
undersampling

Total in VVV Survey
~few millions of
variables

Method based on
Alard & Lupton
1998 ApJ

Fig. 17. (a) A K_s band pawprint from one VVV SV bulge field epoch showing views of: the full pawprint (left); a zoom into Array 1 (middle); and a further zoom centred on a circled variable object (right). (b) The bottom row shows the respective difference image views.

(Eamonn Kerins, Leo Huckvale)

DIA photometry

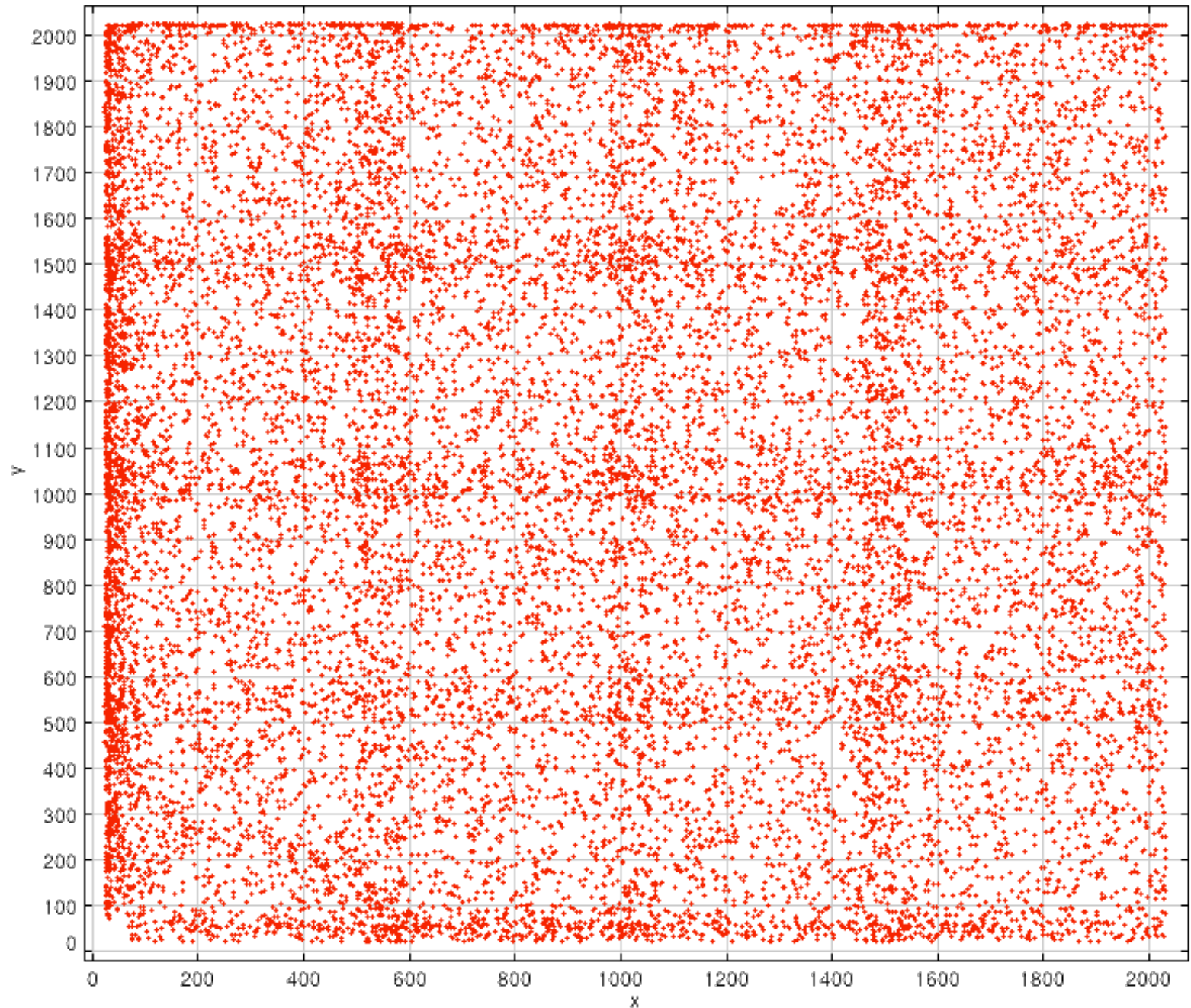
Ks-band Variability

Sep 2012:

DIA pipeline
working

Example:

DIA Variables
in tile d068

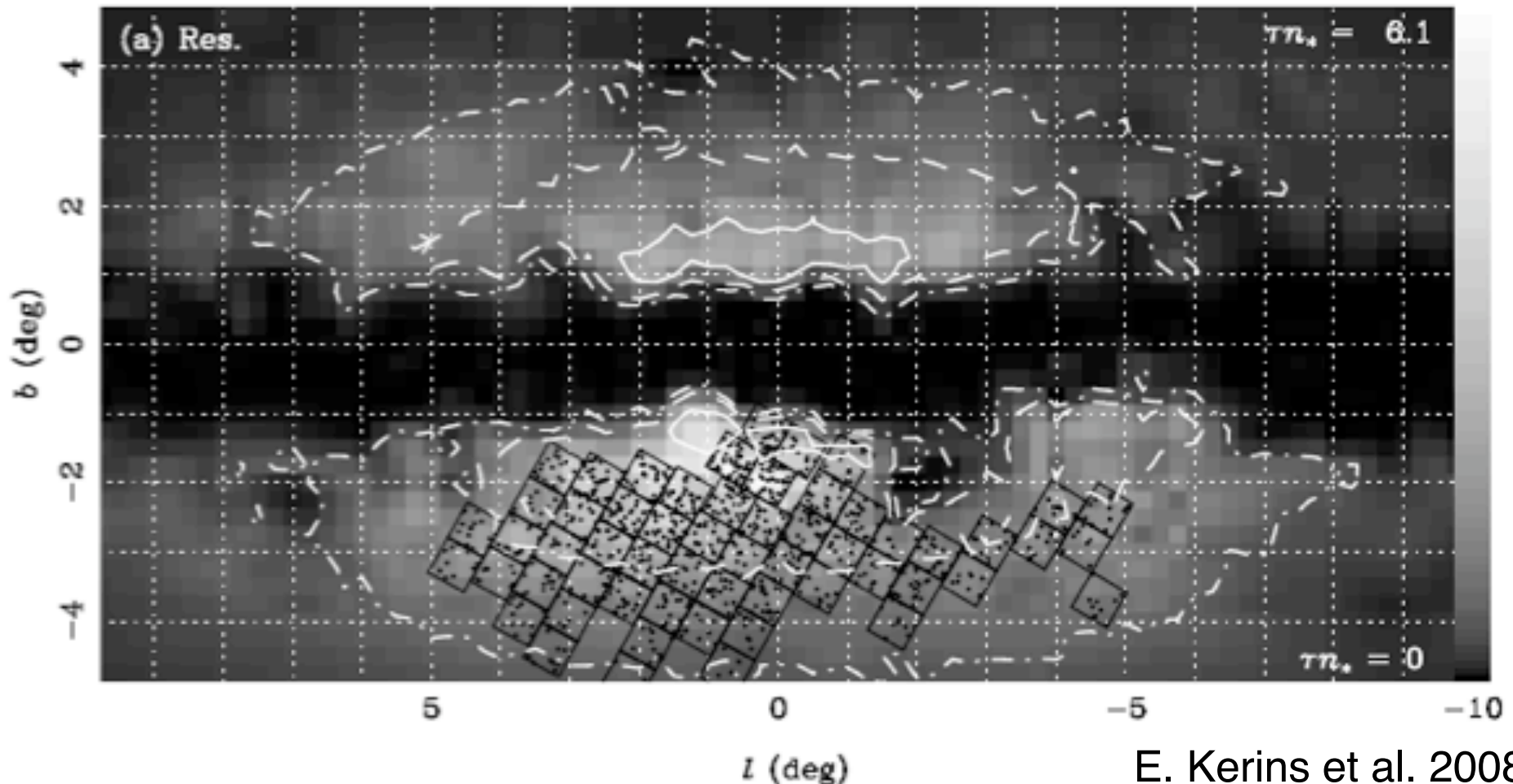


Eamonn Kerins, Leo Huckvale, Phil Lucas

Bulge Microlensing

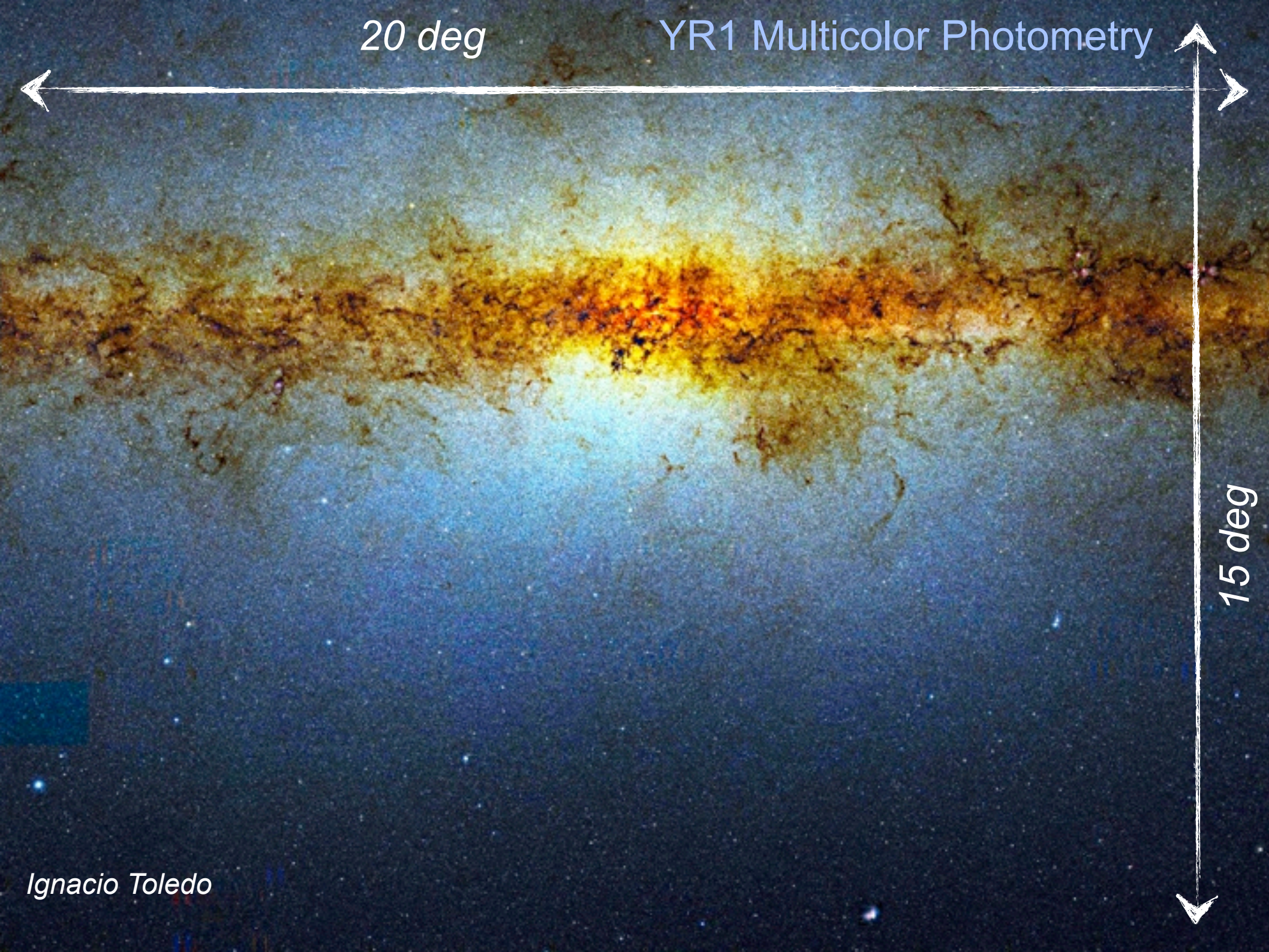
Microlensing is a useful tracer of the total bulge mass.

Previous bulge microlensing experiments do not cover the regions with largest optical depths.



20 deg

YR1 Multicolor Photometry

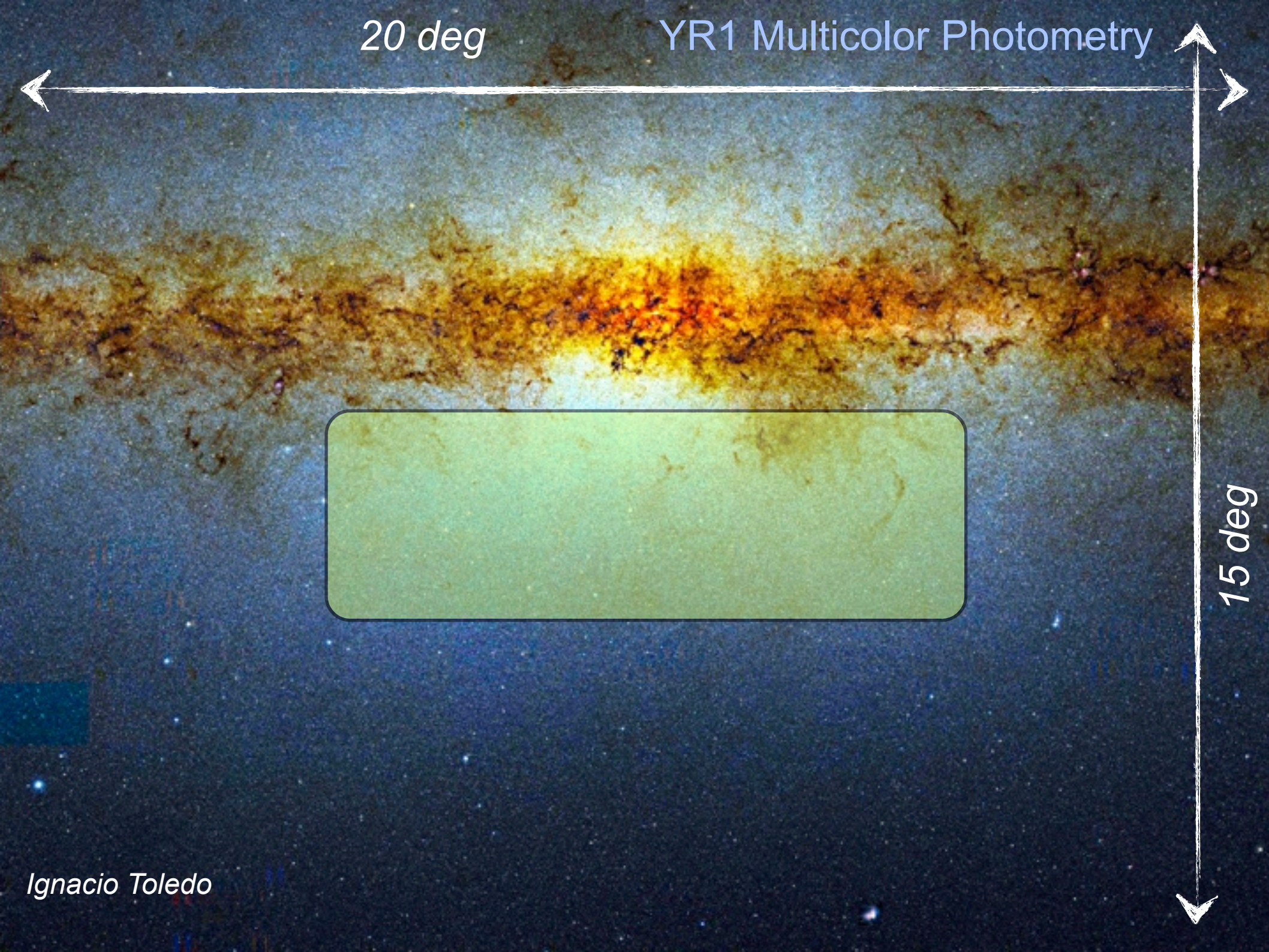


15 deg

Ignacio Toledo

20 deg

YR1 Multicolor Photometry



15 deg

Optical depth

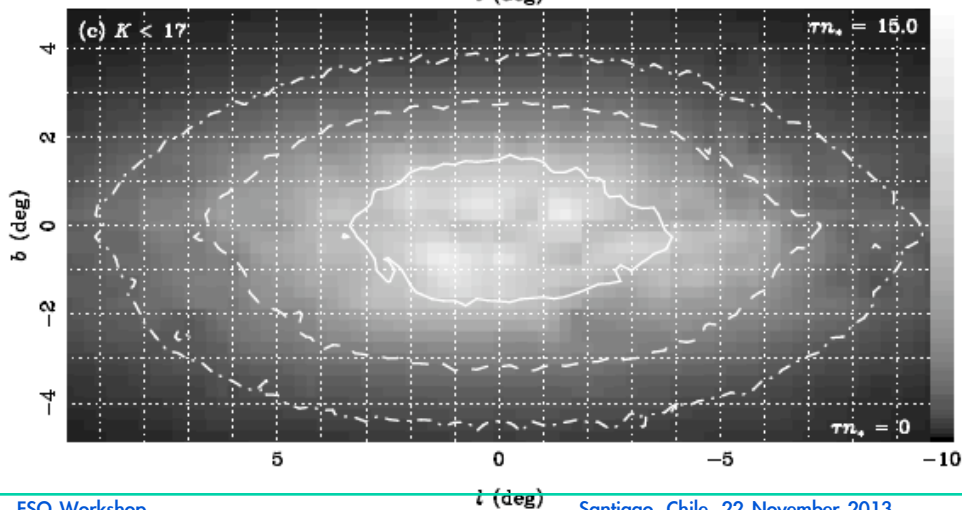
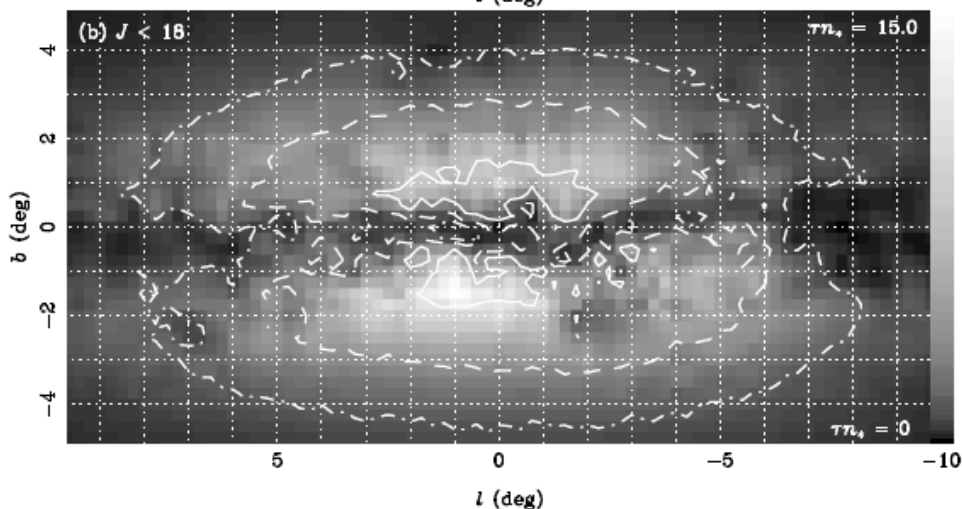
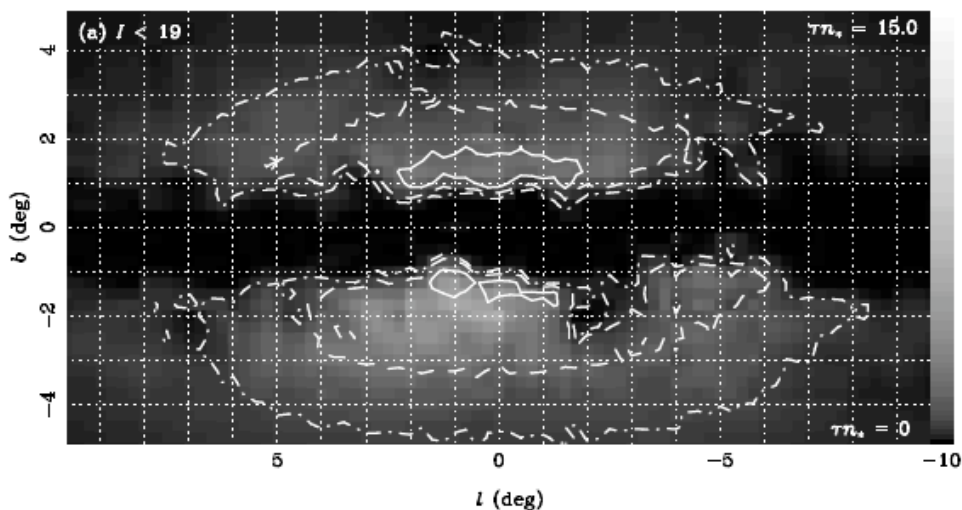
VVV will search for reddened bulge microlensing events, and produce a map of the optical depth τ , tracing the 3D bulge mass distribution.

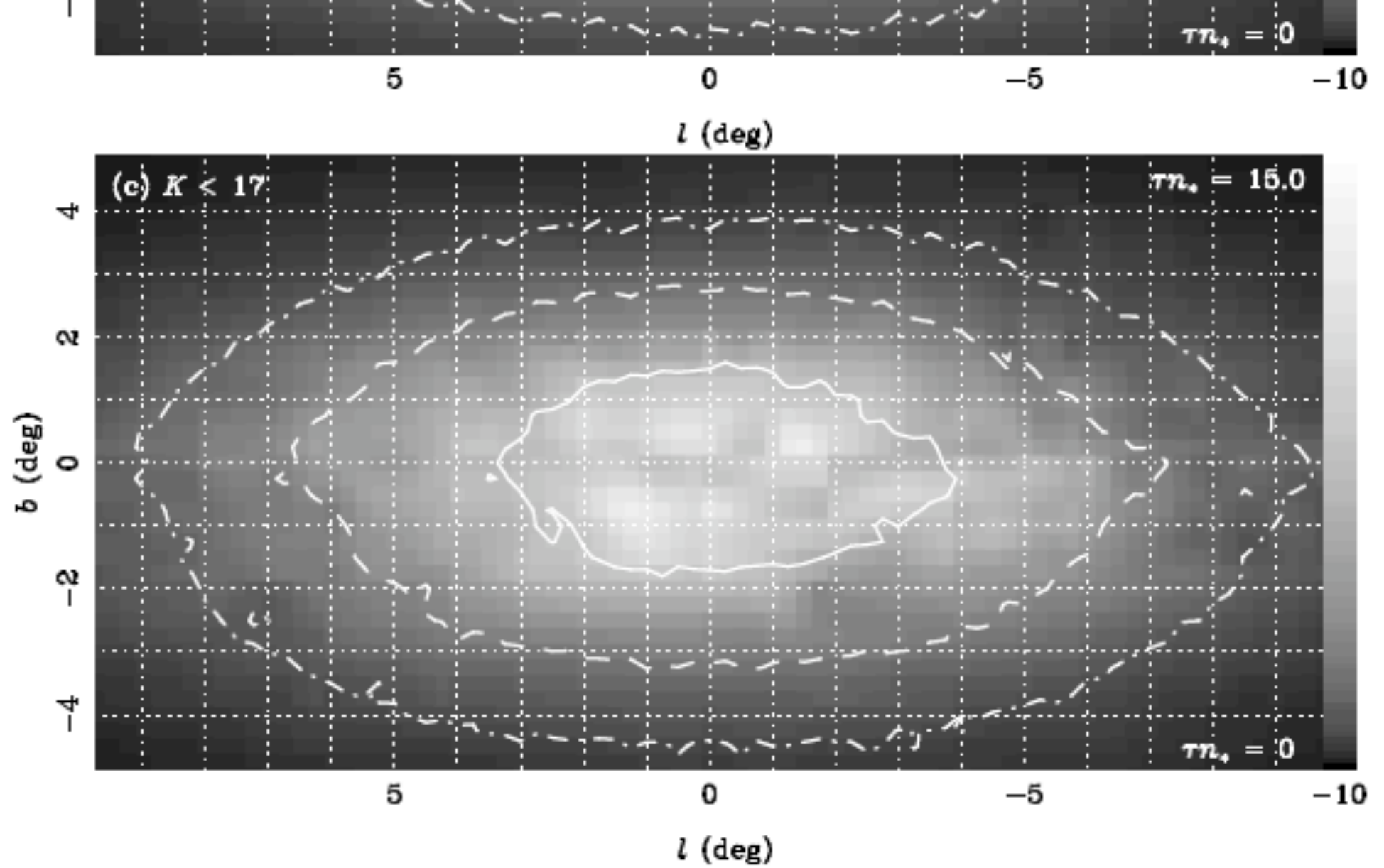
The near-IR advantage:

I, J and Ks-map event rates for sources with $K < 17$.

Contours = 17.5, 35, 52.4 per sqdeg per year.

E. Kerins et al. 2008





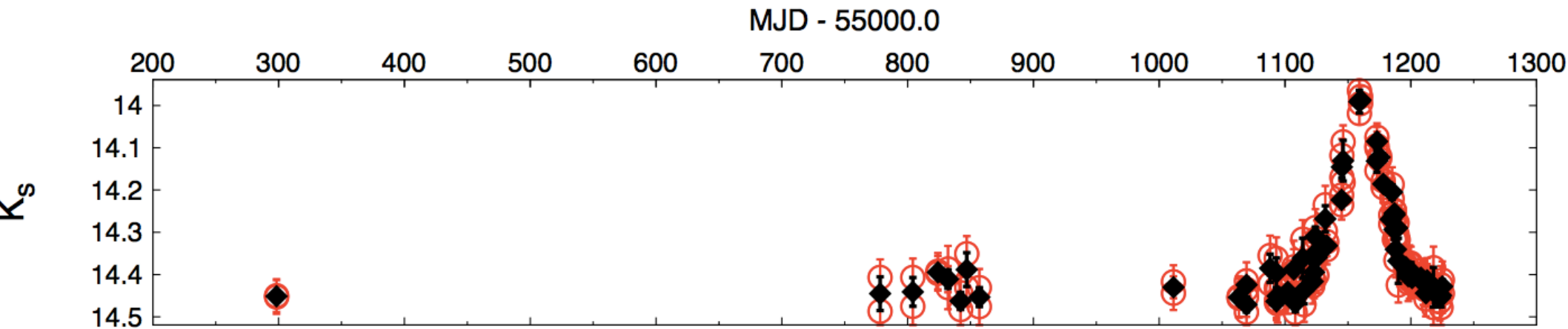
E. Kerins et al. 2008

VVV Microlensing

Candidate Microlensing events from the VVV Survey

- **serendipitous discoveries**
- **new approach**
- **proof of concept that allows us to explore the parameter space covered and plan future strategies**
- **complementary to optical surveys**

Eamonn Kerins, Roberto Saito, Istvan Dekany, Veronica Motta, Gabriela Muro, Felipe Gran, Mario Soto, Oscar Gonzalez, Leo Huckvale ...



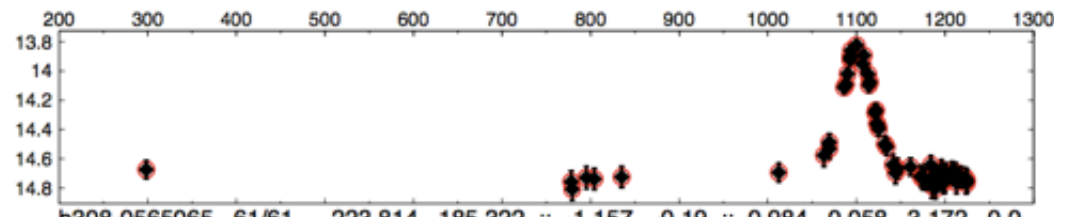
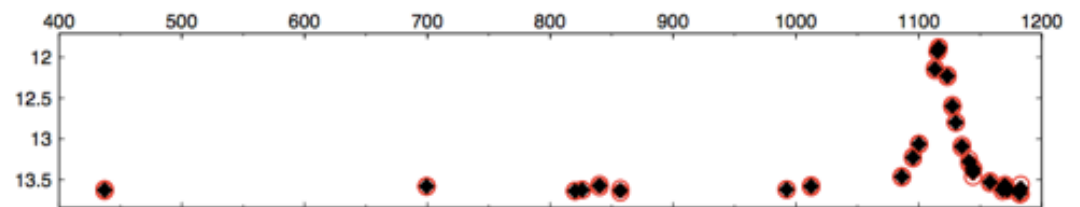
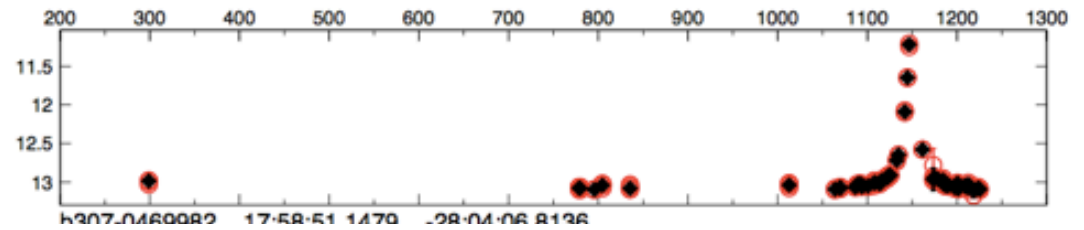
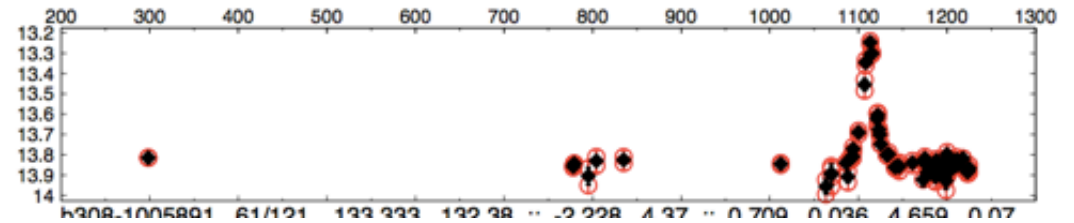
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Microlensing Events

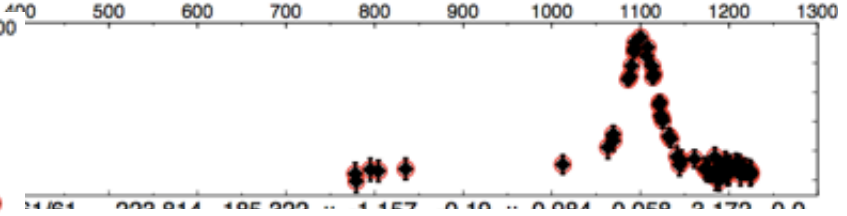
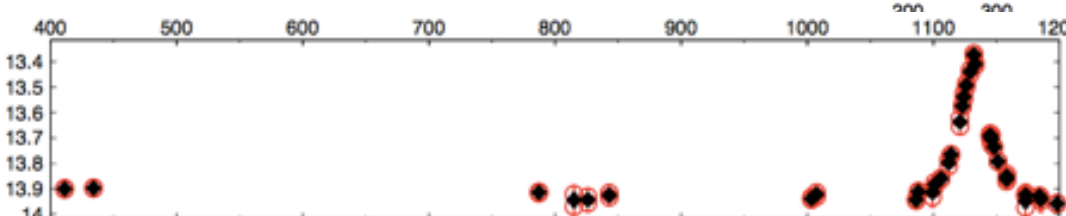
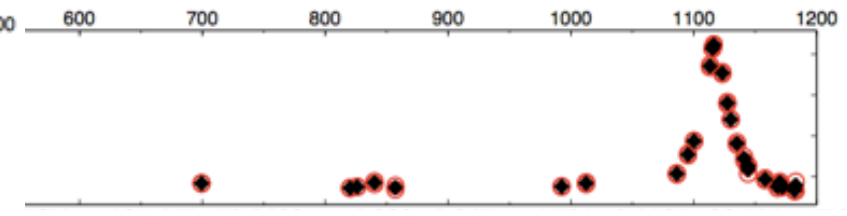
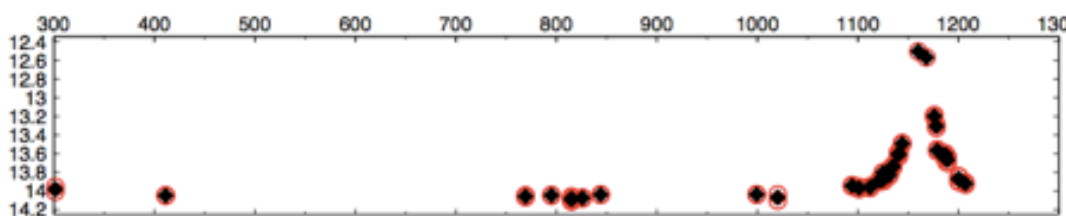
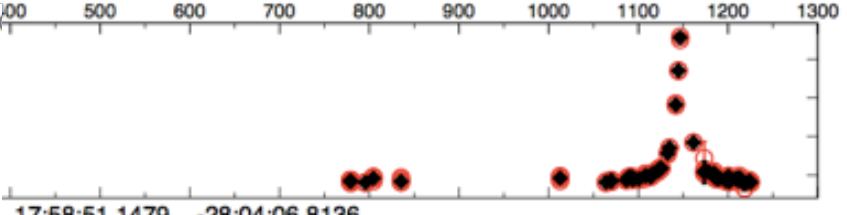
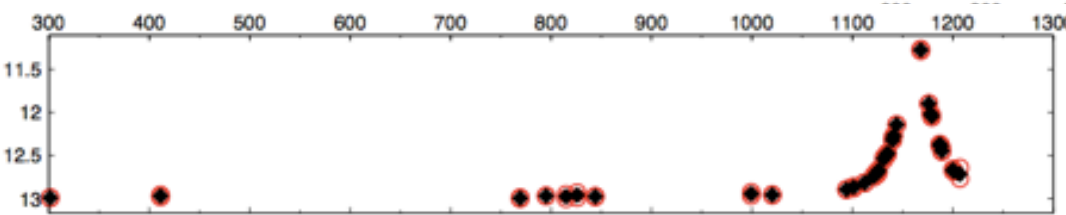
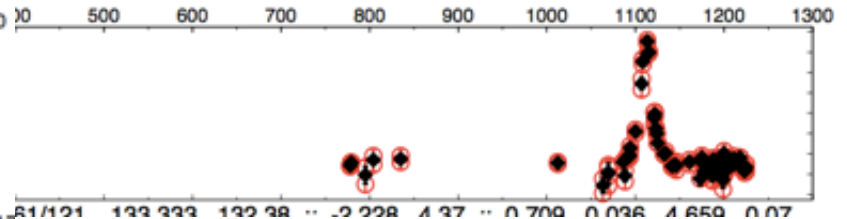
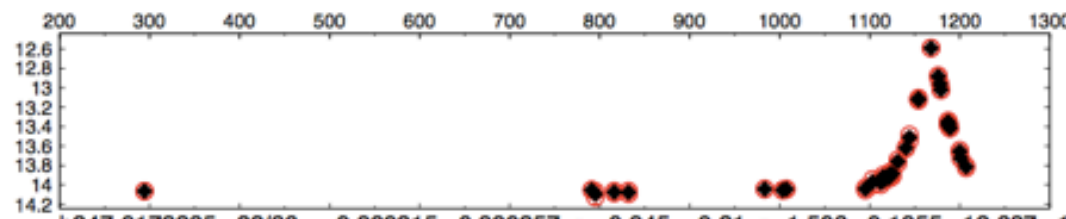
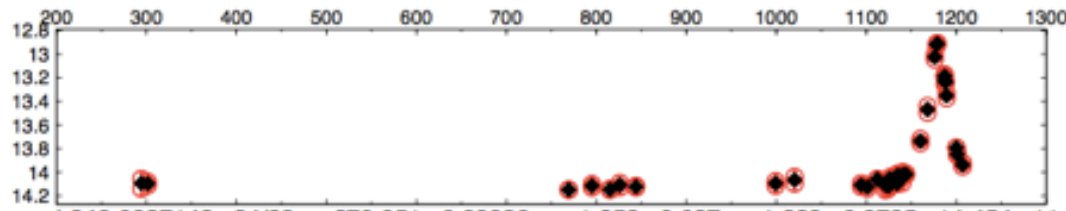
N=200!



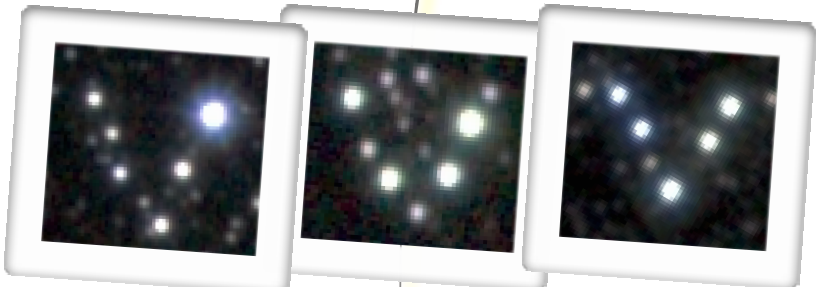
Istvan Dekany

Microlensing Events

N=200!



Istvan Dekany



VVV CATALOGS

ASTROMETRY

- Asteroids $\sim 10^3$
- TNOs $\sim 10^2$
- high-PM $\sim 10^3$
- BDs $\sim 10^2$

- AGNs, QSOs $\sim 10^3$
- SN $\sim 10^3$
- CVs, Novae $\sim 10^3$
- LMXBs $\sim 10^3$
- dM flare $\sim 10^4$
- microlensing $\sim 10^3$

VARIABLES

$10^6 - 10^7$

Periodic

- Eclipsing $\sim 10^6$
- Ellipsoidal $\sim 10^4$
- Spotted $\sim 10^5$
- Pulsating $\sim 10^5$

- WUMas $\sim 5 \times 10^5$
- Semidetached $\sim 3 \times 10^5$
- Detached 10^5
- Planetary Transits 10^3
- RR Lyrae $\sim 10^5$
- Cepheids $\sim 10^3$
- Semiregulars $\sim 10^5$
- LPVs, Miras, R $\sim 10^3$
- dSct, SXPhe $\sim 10^4$
- RVTau $\sim 10^2$
- WVir $\sim 10^2$

PN

CLUSTERS

- stellar associations $\sim 10^2$
- open clusters $\sim 10^3$
- globular clusters ~ 10

RR LYRAE

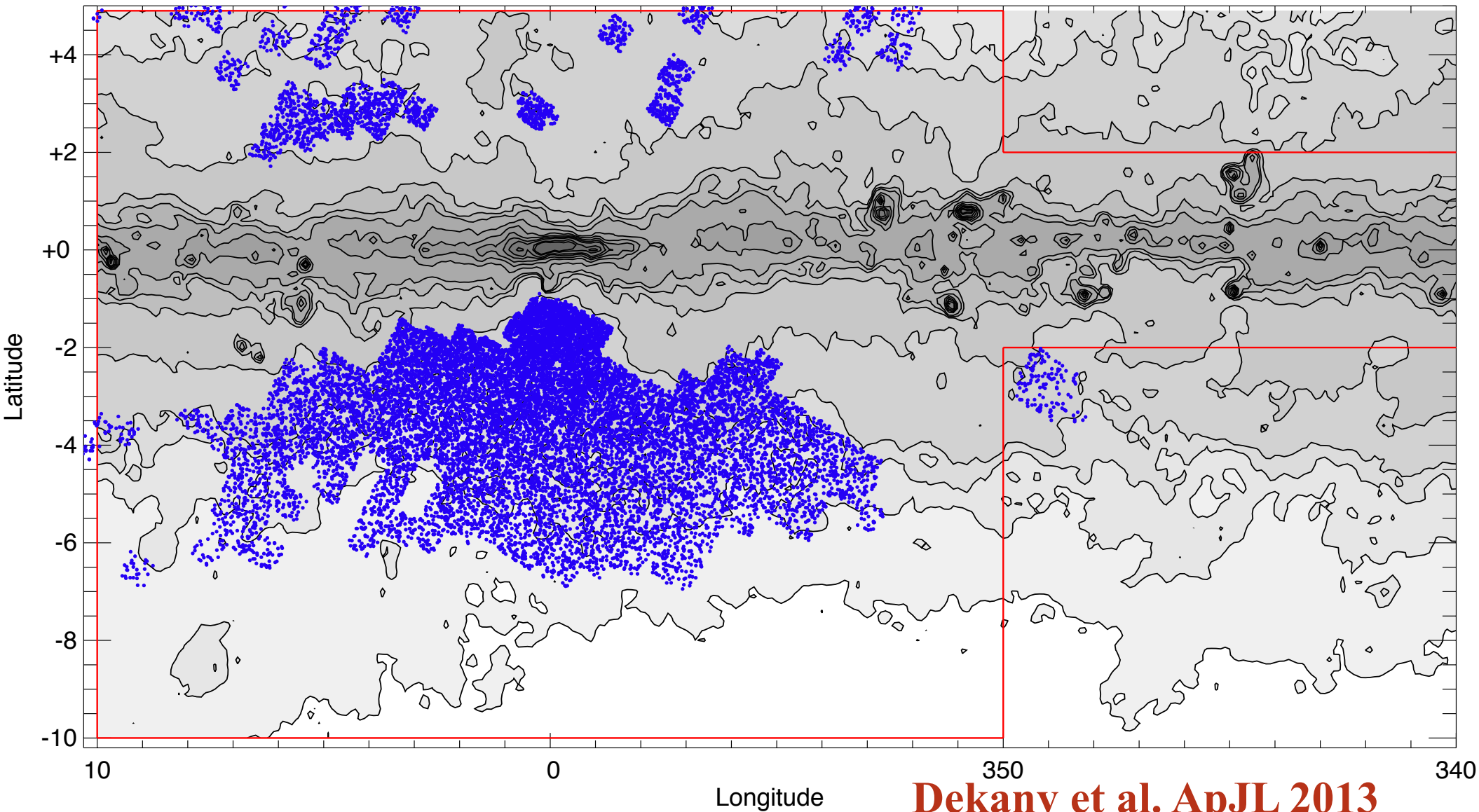
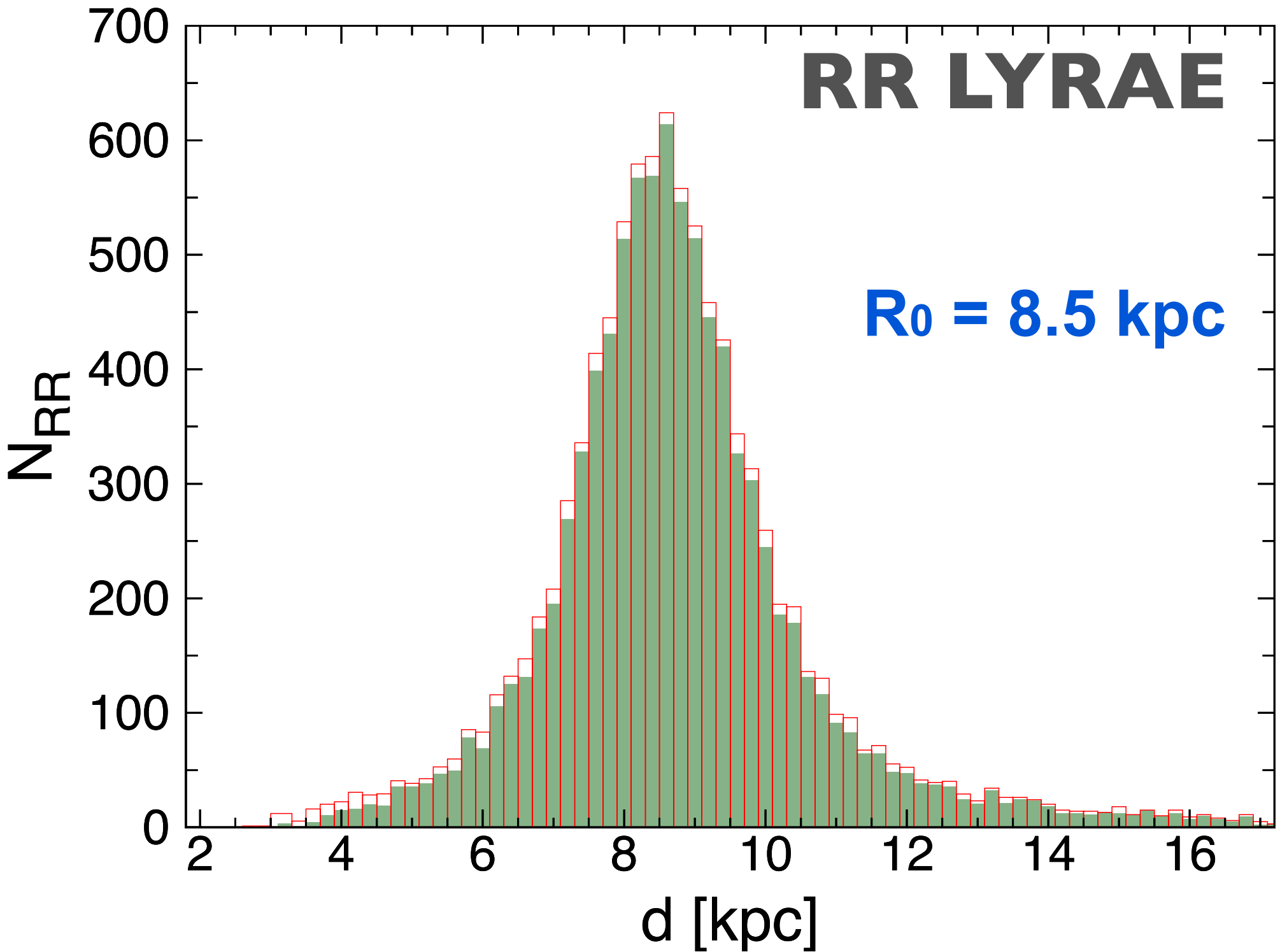
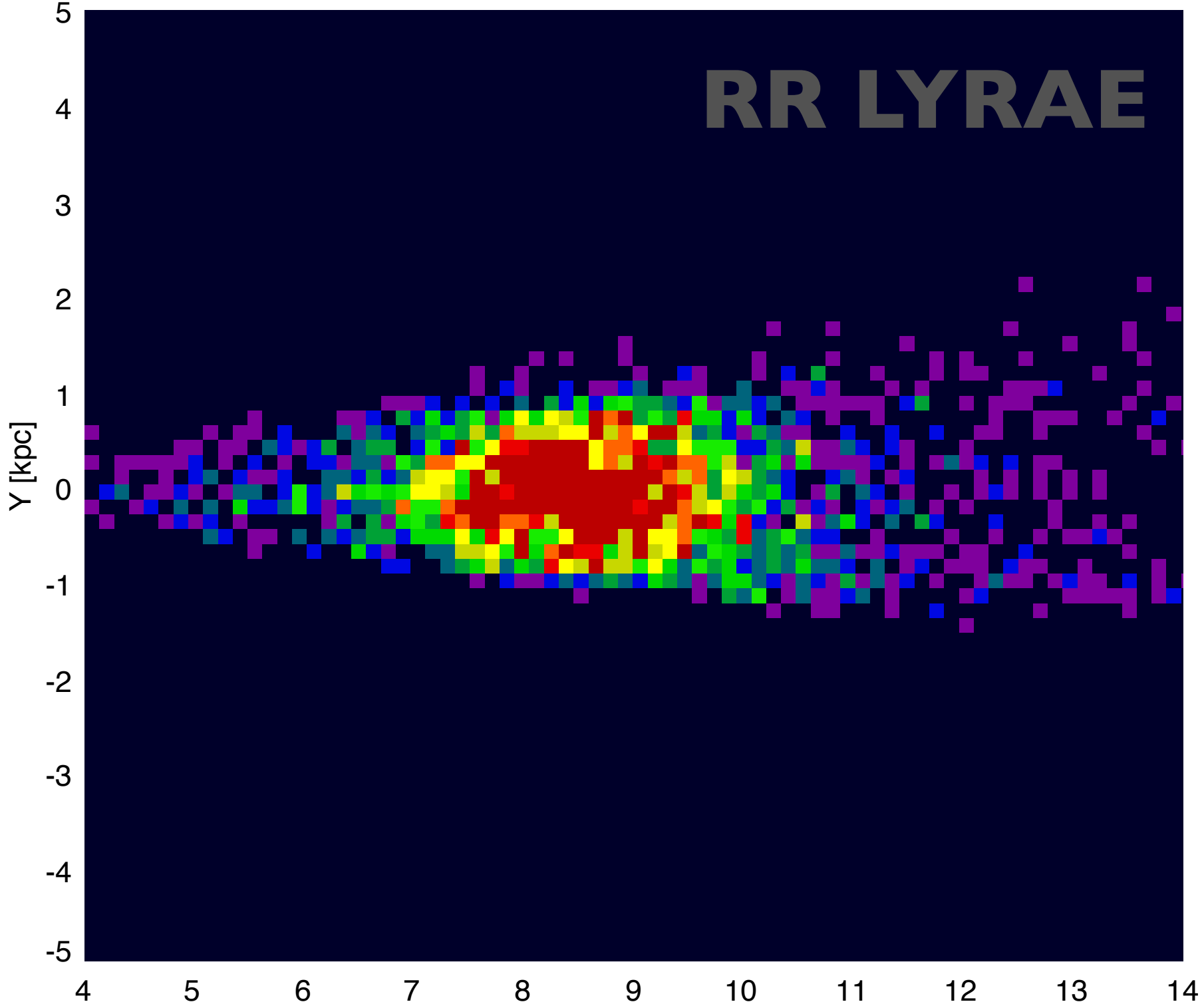
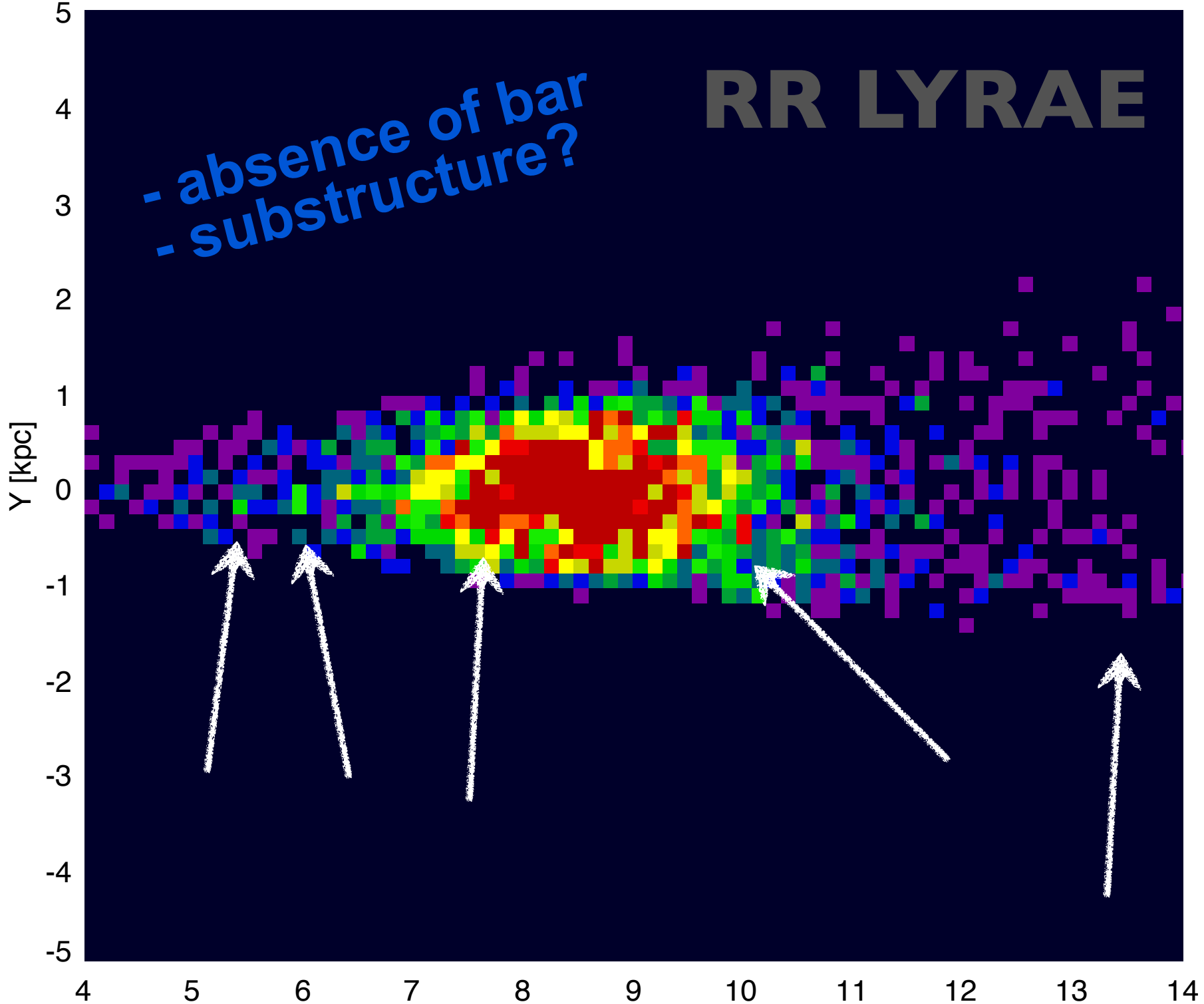


figure by M. Hempel



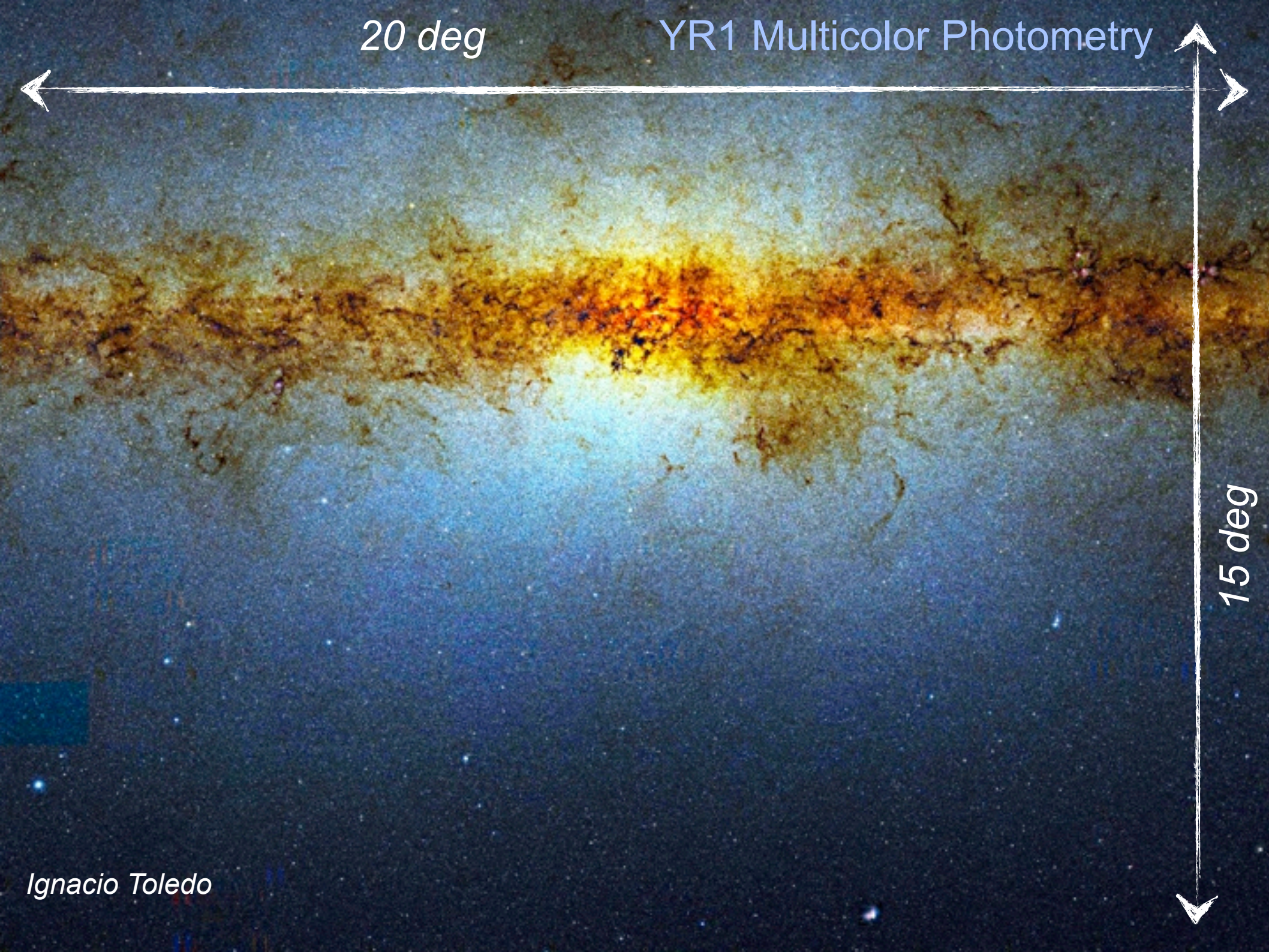
RR LYRAE





20 deg

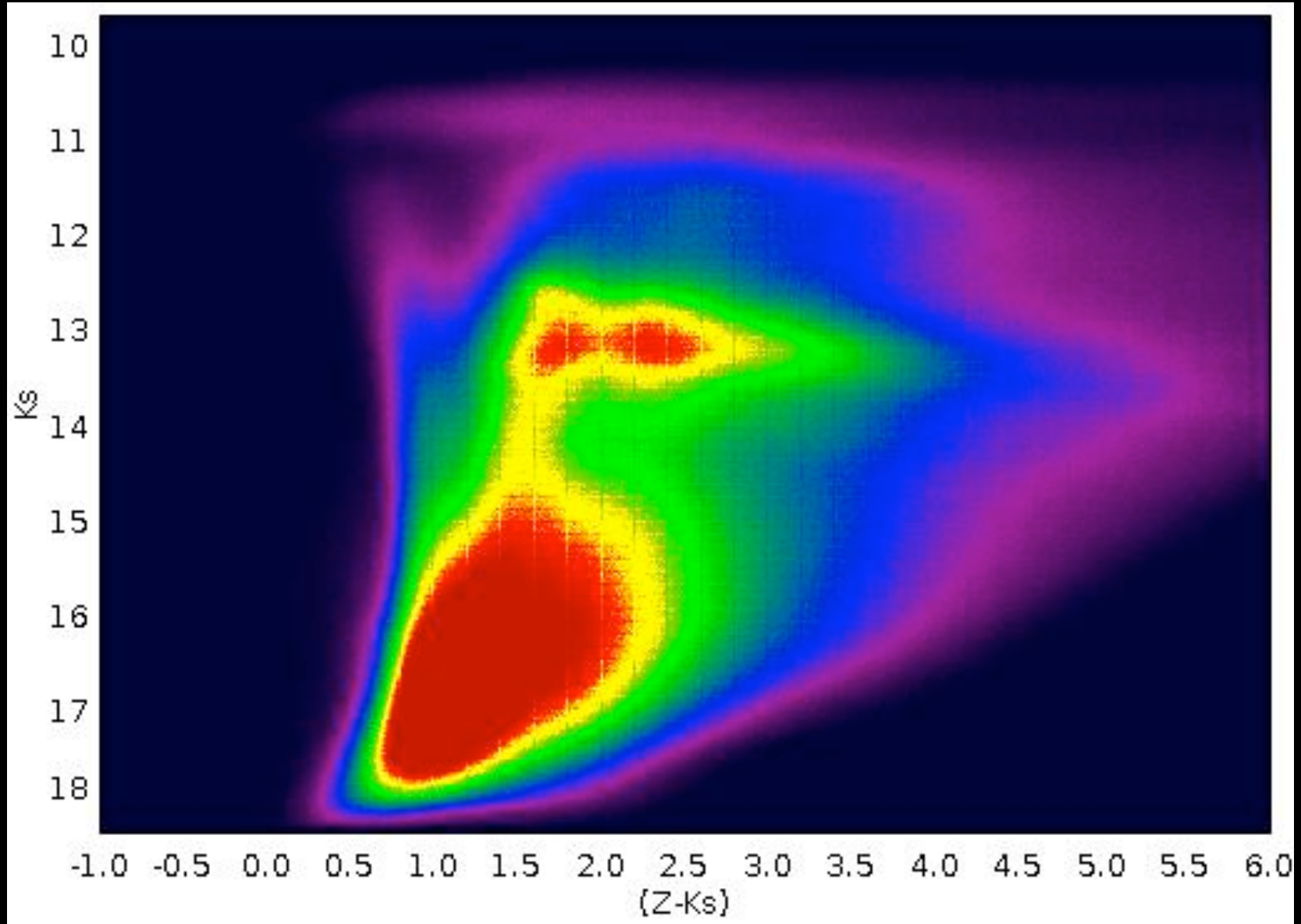
YR1 Multicolor Photometry



15 deg

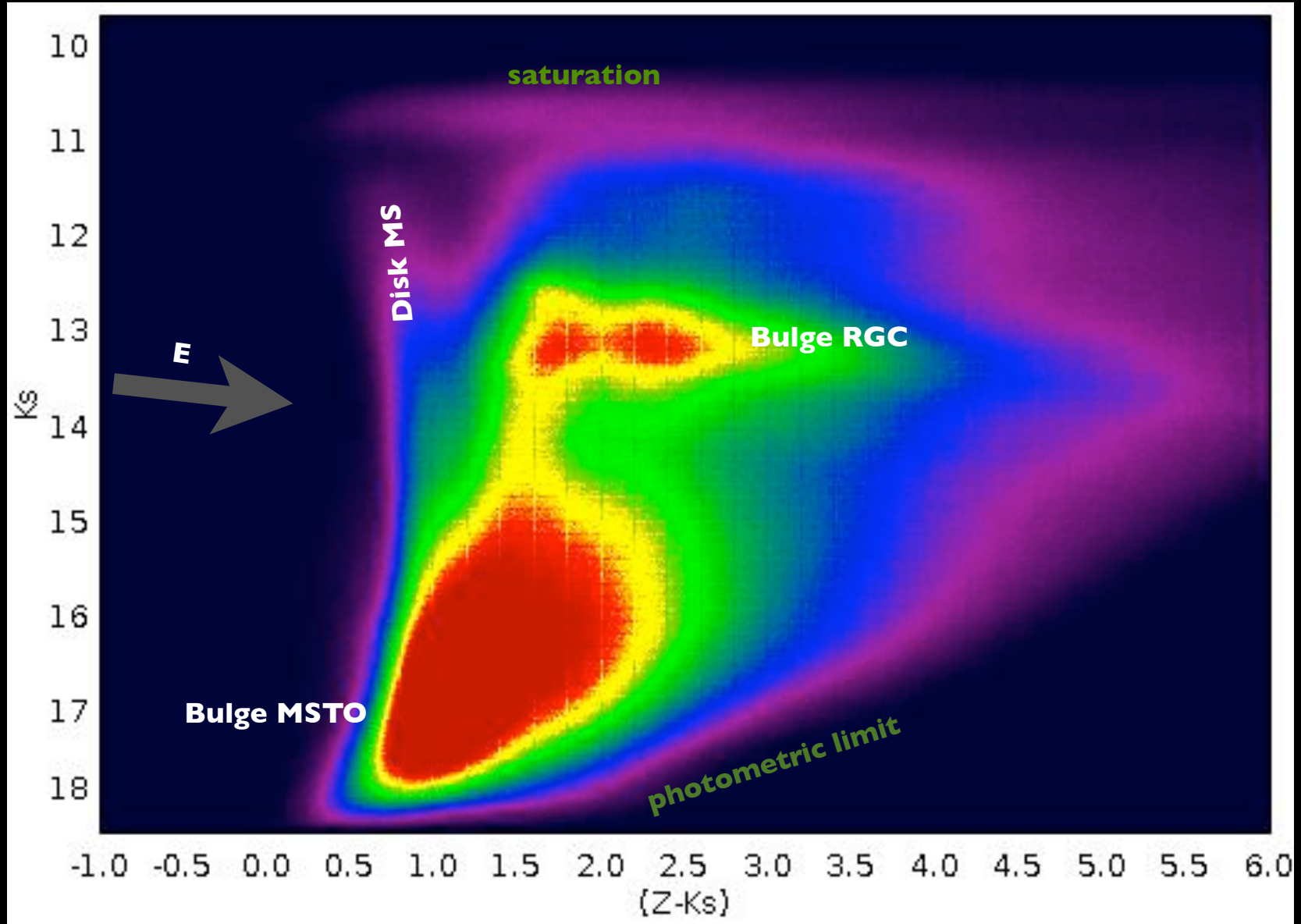
Ignacio Toledo

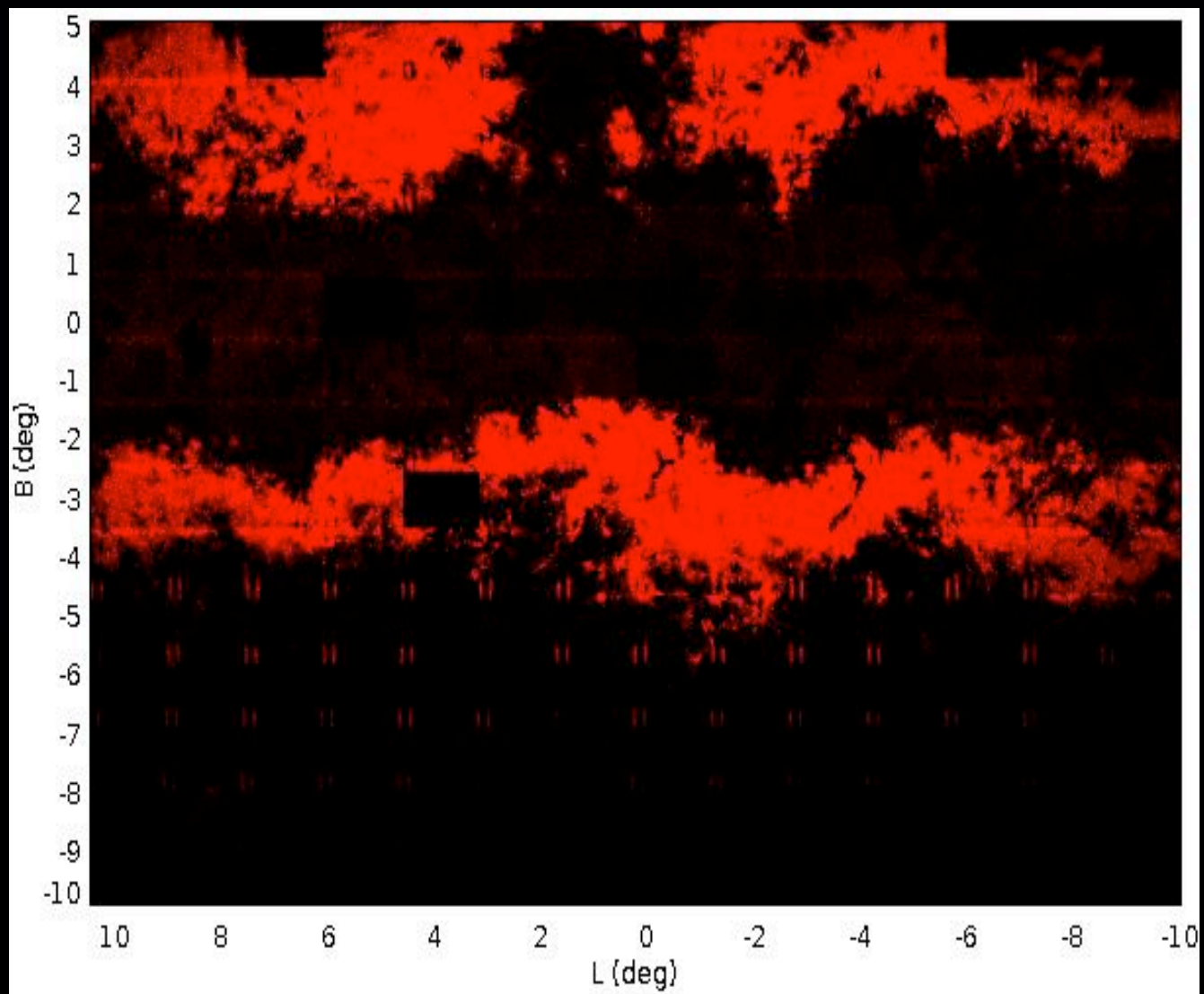
VVV I57M STARS BULGE CMD

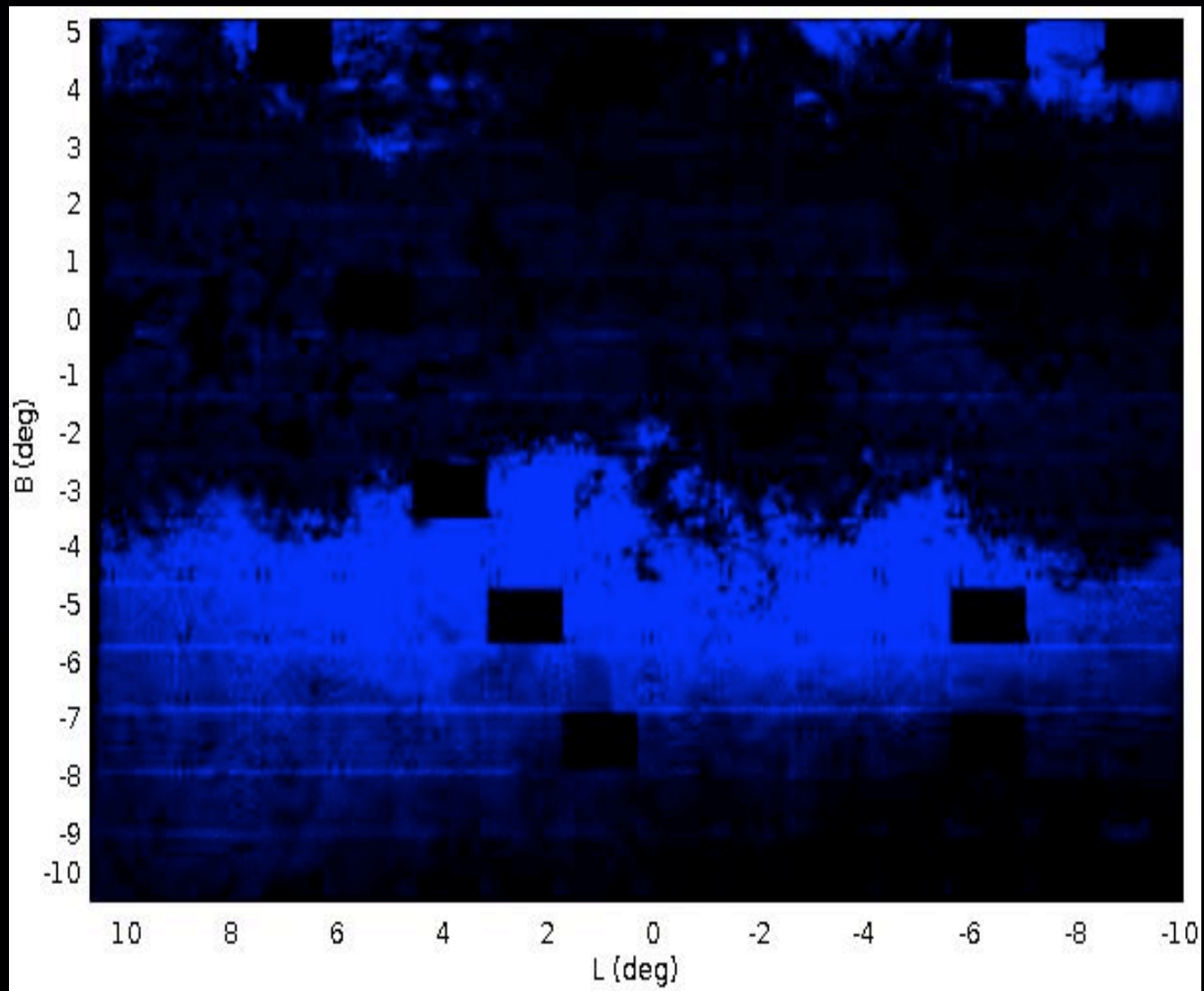


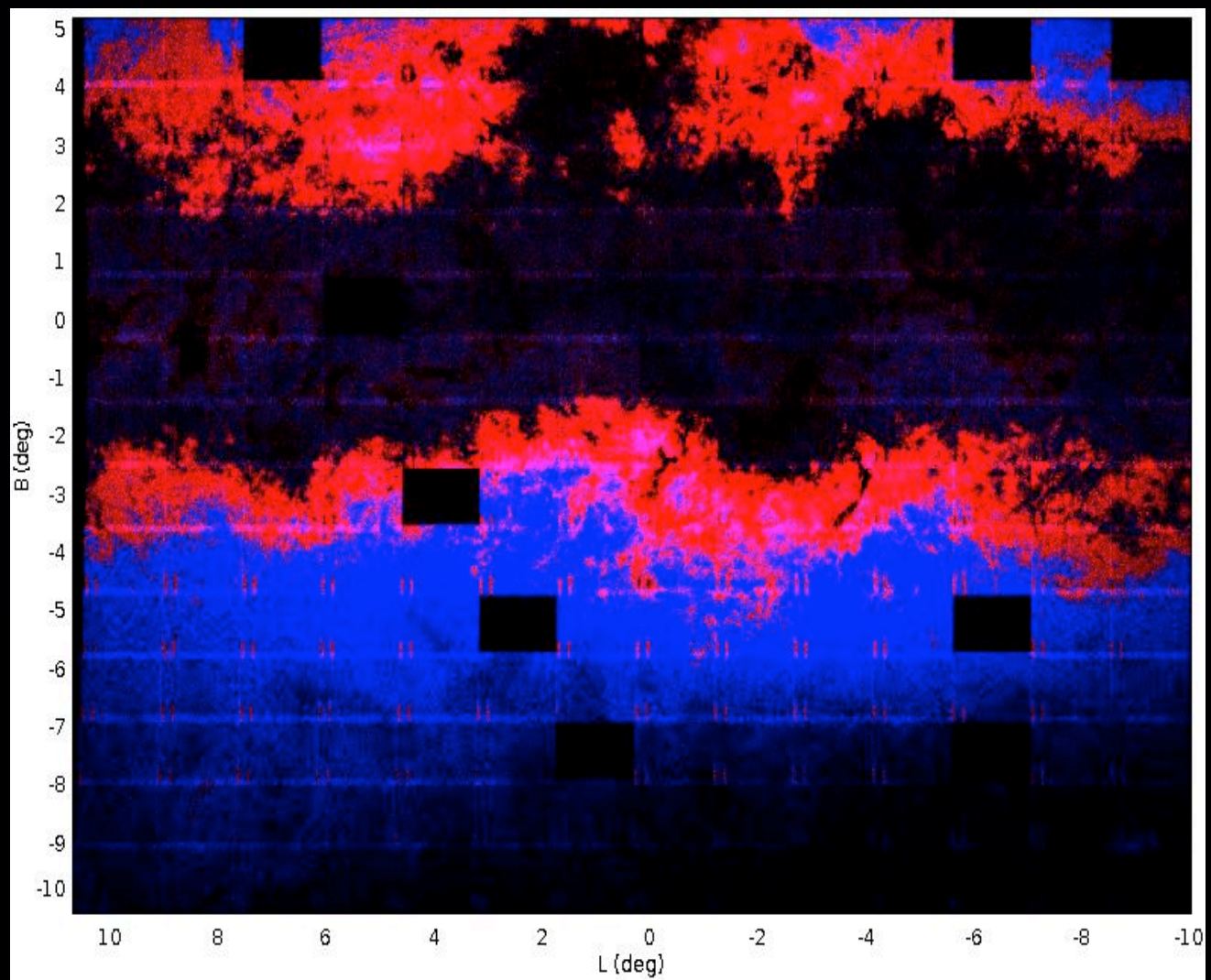
Mean color difference $(Z - K_s) = 0.55$ mag, equivalent to $A_V = 2.0$ mag

VVV I57M STARS BULGE CMD

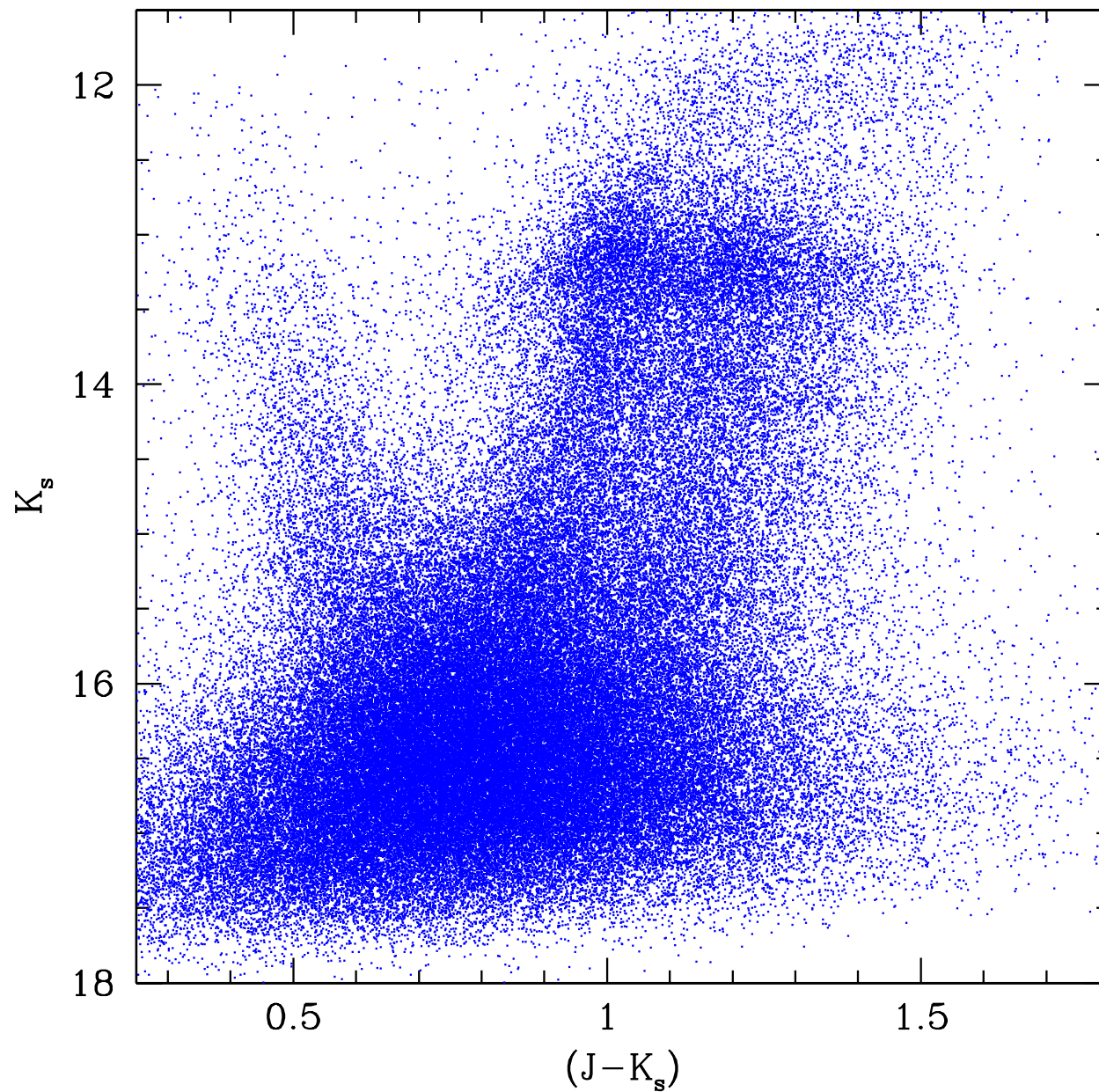




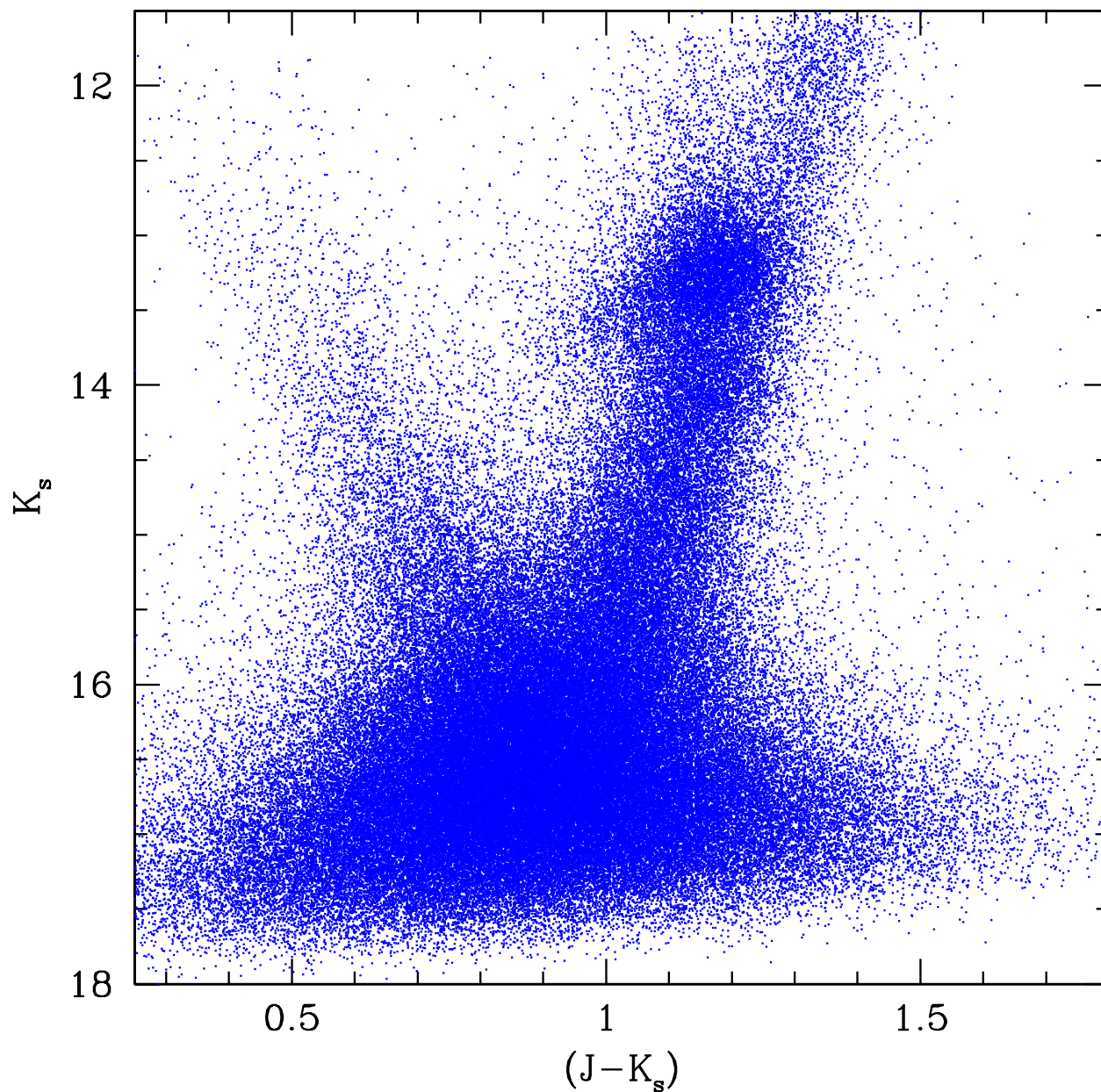




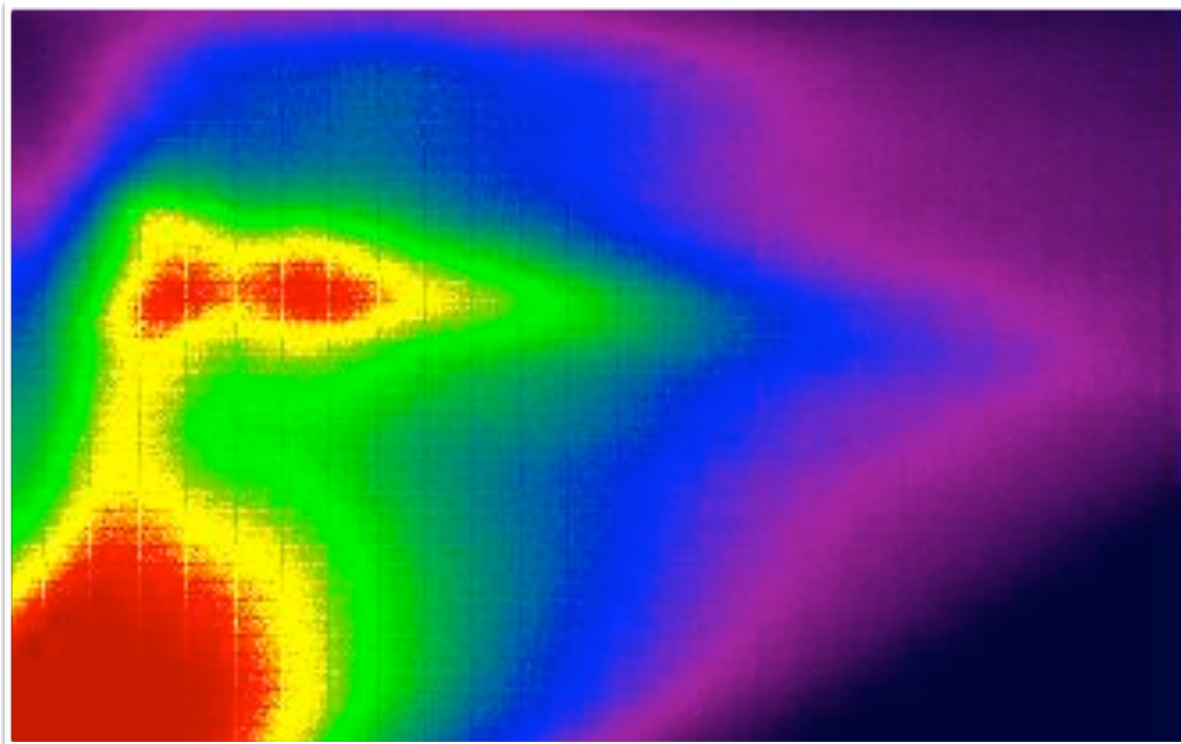
VVV TILE B304 BULGE CMD



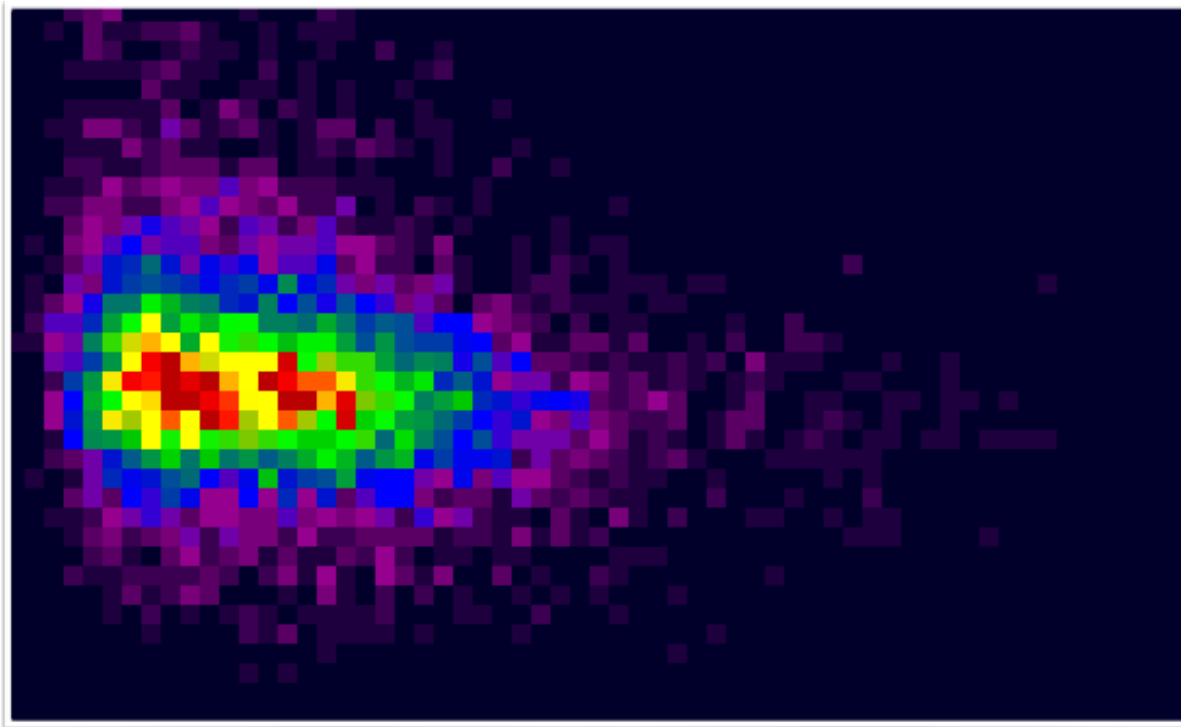
VVV TILE B248 BULGE CMD



Clump Giants

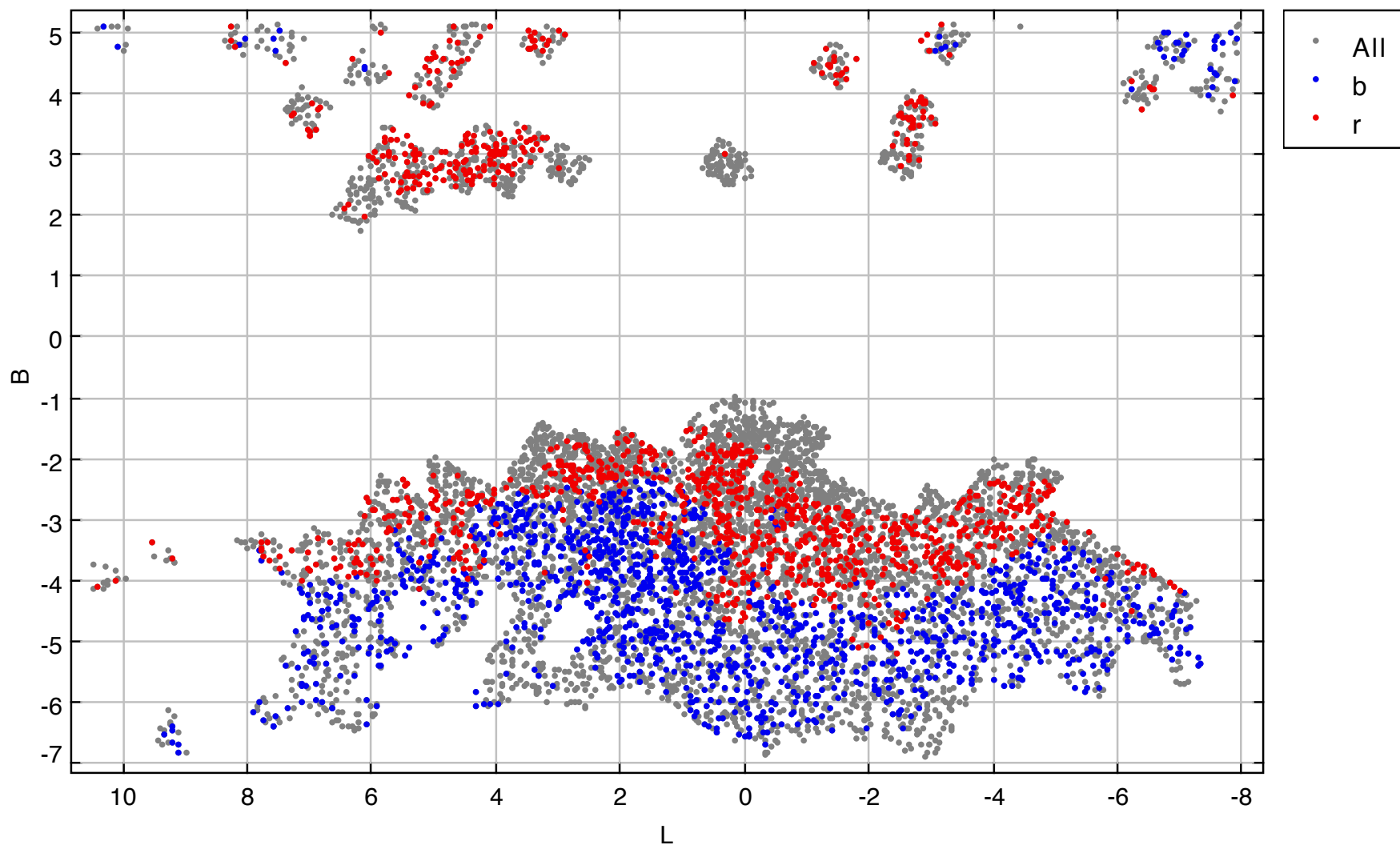


RR Lyrae



THIS IS REAL !

RR LYRAE



NGC 1365: two nested bars with two arms

HST OPTICAL



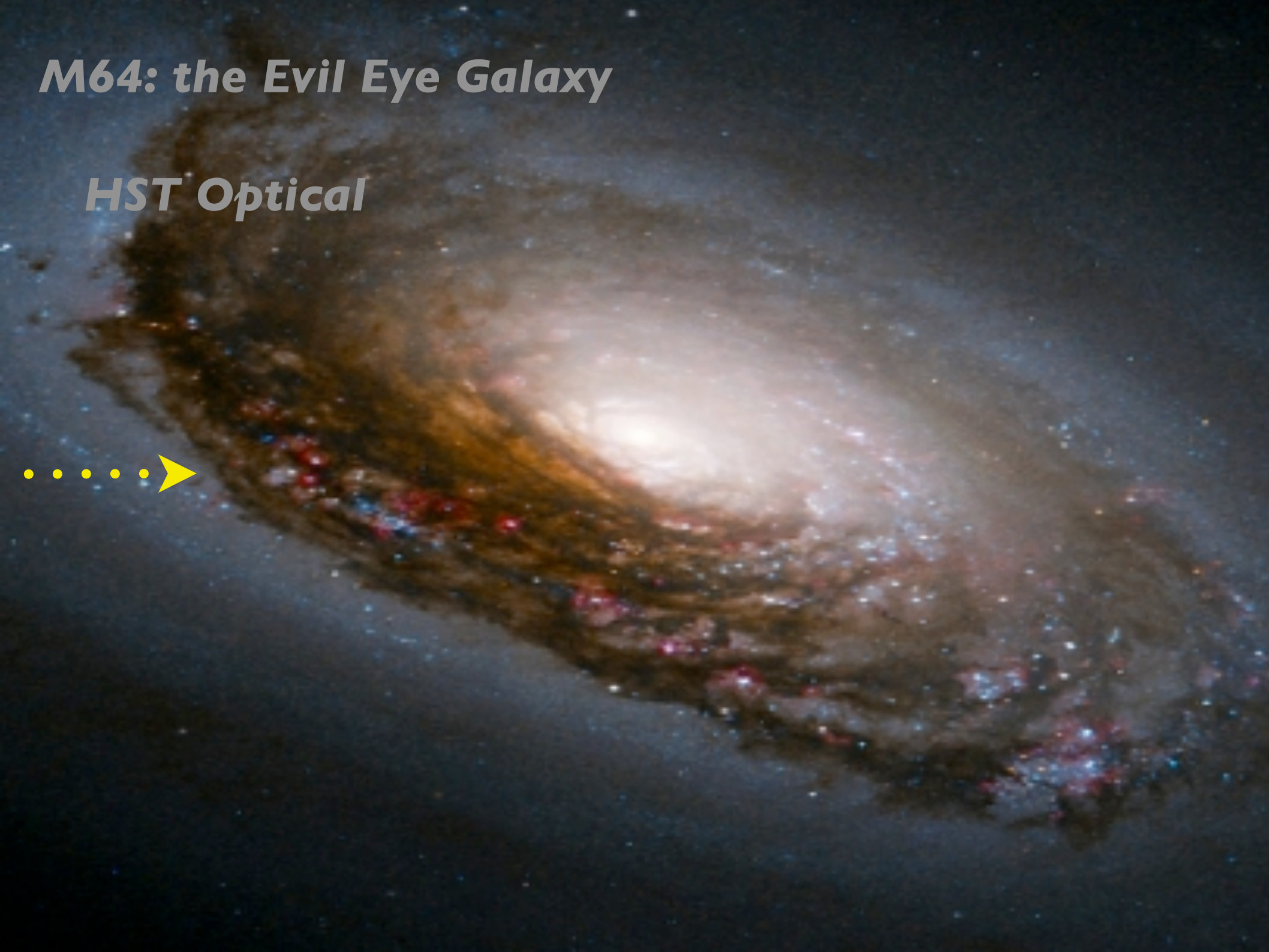
Sol

A 2MASS image of the Milky Way galaxy, showing a yellow star labeled 'Sol' on the left and a dark silhouette of Earth on the right, both connected to the galactic plane by lines. The image is a long, narrow strip of light with a dark blue background. The star 'Sol' is a small yellow dot on the left. The Earth is a dark, irregular shape on the right. Two black lines extend from the star and the Earth towards the center of the galaxy, forming a narrow cone that points towards the galactic core.

2MASS IMAGE OF THE MILKY WAY

M64: the Evil Eye Galaxy

HST Optical

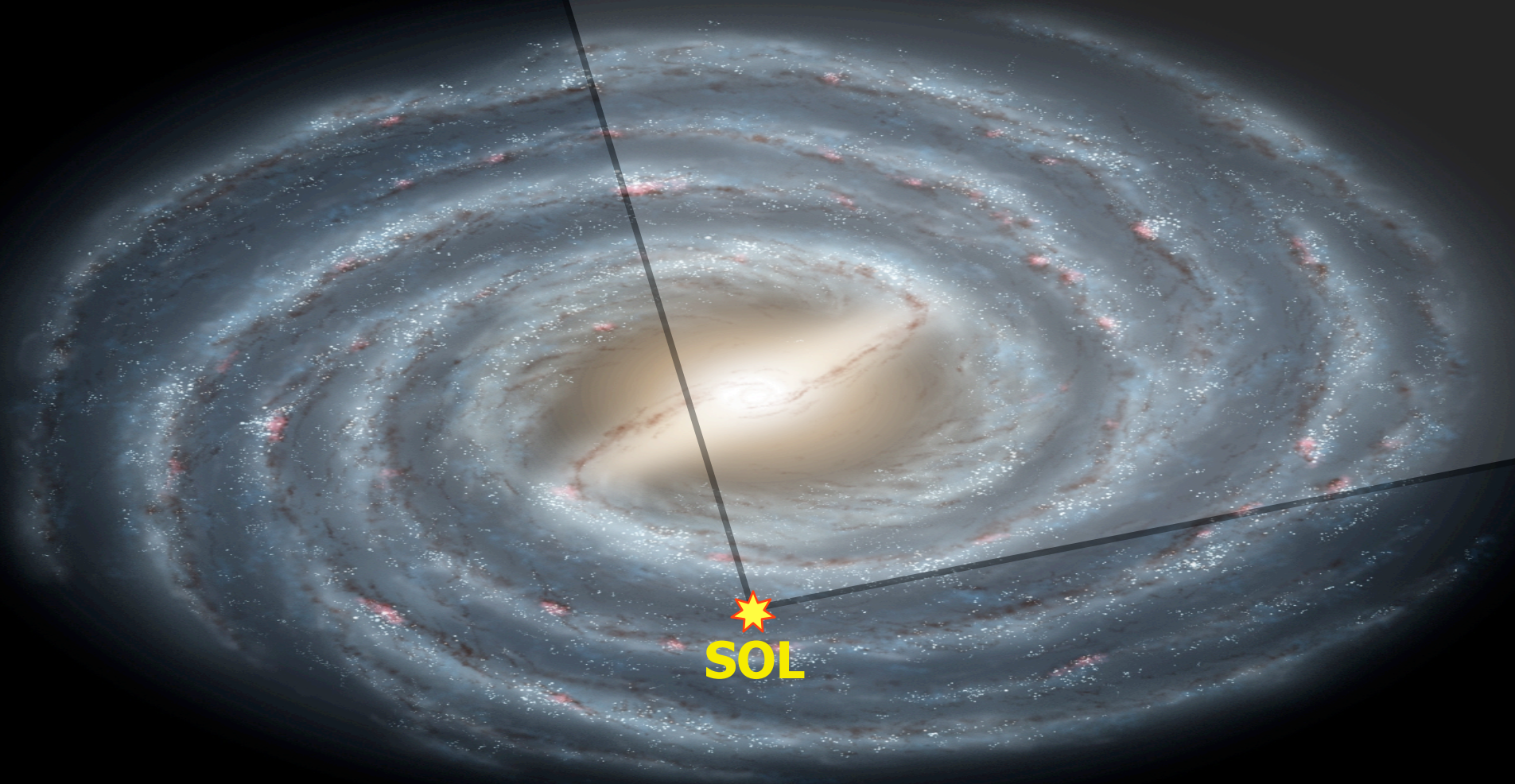


Sol



2MASS IMAGE OF THE MILKY WAY

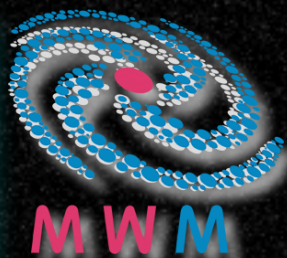
$\sim 1/2$ VVV



Conclusions

- We are about half way through the VVV Survey, with everything working well.
- Several discoveries have been made, with many more to come.
- We need help exploiting the VVV database and following up a wide variety of targets.

Acknowledgments



MW Structure from the VVV Survey

