Modelling Microlensing events and the structure of the Milky Way

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Outline

1. Reminiscence
2. Modelling microlensing events
3. Modelling the Galactic structure
4. Summary

1. Reminiscence: My connection with OGLE

- My only contribution to microlensing is to add the buzzword "dark matter" in Paczynski (1986)

- My main contribution to OGLE is to find people who can do everything: hardware, software and observing …

My papers with Bohdan

#	Bibcode	Score	Date	Links		Title
1	2006ApJ...644L..37G	1.000	06/2006	A E F X D R C U	Gould, A.; Udalski, A.; An, D.; Bennett, D. P.; Zhou, A.-Y.; Dong, S.; Rattenbury, N. J.; Gaudi, B. S.; Yock, P. C. M.; Bond, I. A.; and 26 coauthors	Microlens OGLE-2005-BLG-169 Implies That Cool Neptune-like Planets Are Common
2	2003MNRAS.339..925S	1.000	03/2003	A E F G X R C U H	Smith, Martin C.; Mao, Shude; Paczyński, Bohdan	Acceleration and parallax effects in gravitational microlensing
3	2002MNRAS.337..895M	1.000	12/2002	A E F G X R C U H	Mao, Shude; Paczyński, Bohdan	Constraining the Galactic bar parameters with red clump giants
4	1996ApJ...473...57M	1.000	12/1996	A F G X R C U	Mao, Shude; Paczynski, Bohdan	Mass Determination with Gravitational Microlensing
5	1992ApJ...386...30R	1.000	02/1992	A F G R C	Rauch, Kevin P.; Mao, Shude; Wambsganss, Joachim; Paczynski, Bohdan	Caustic-induced features in microlensing magnification probability distributions
6	1991ApJ...374L..37M	1.000	06/1991	A F G R C U	Mao, Shude; Paczynski, Bohdan	Gravitational microlensing by double stars and planetary systems

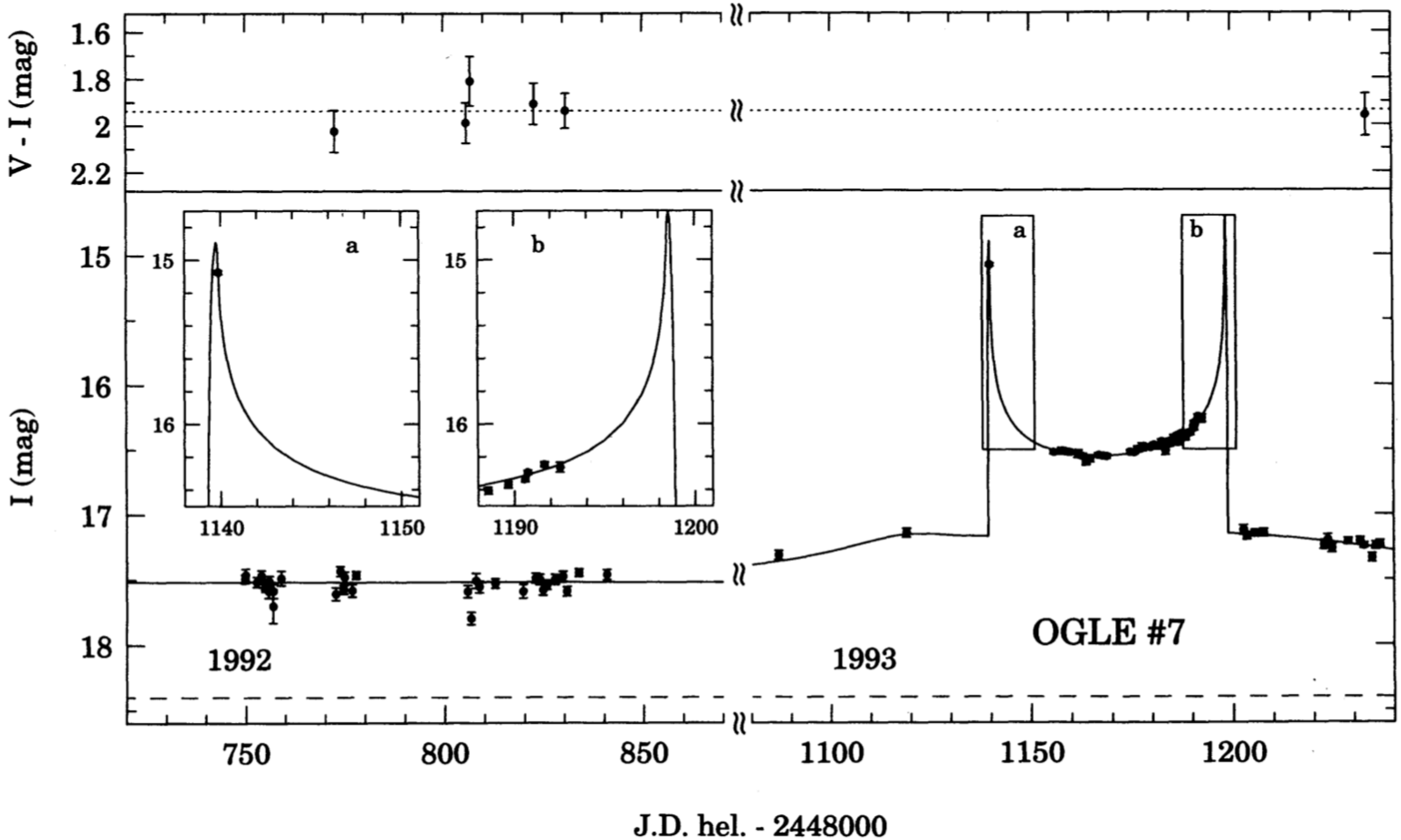
- **Out of 8 papers I wrote with him from 1991-2006, 6 are on microlensing, including one on galactic structure.**

Community's scepticism and Bohdan's optimism

- **Referee (1991):** "it is incumbent upon theorists to provide the best guidance (***even if this theorist is extremely skeptical that any convincing examples of gravitational lensing will be found in this way***). "
- **A Harvard professor (fall of 1992):** I doubt microlensing will be discovered - the contamination from variable stars is just too high.
- **Bohdan in Mao & Paczynski (1991):** "A massive search for microlensing of the Galactic bulge stars may lead to a discovery of the first extrasolar planetary systems."

2. Modelling microlensing events: the first binary?

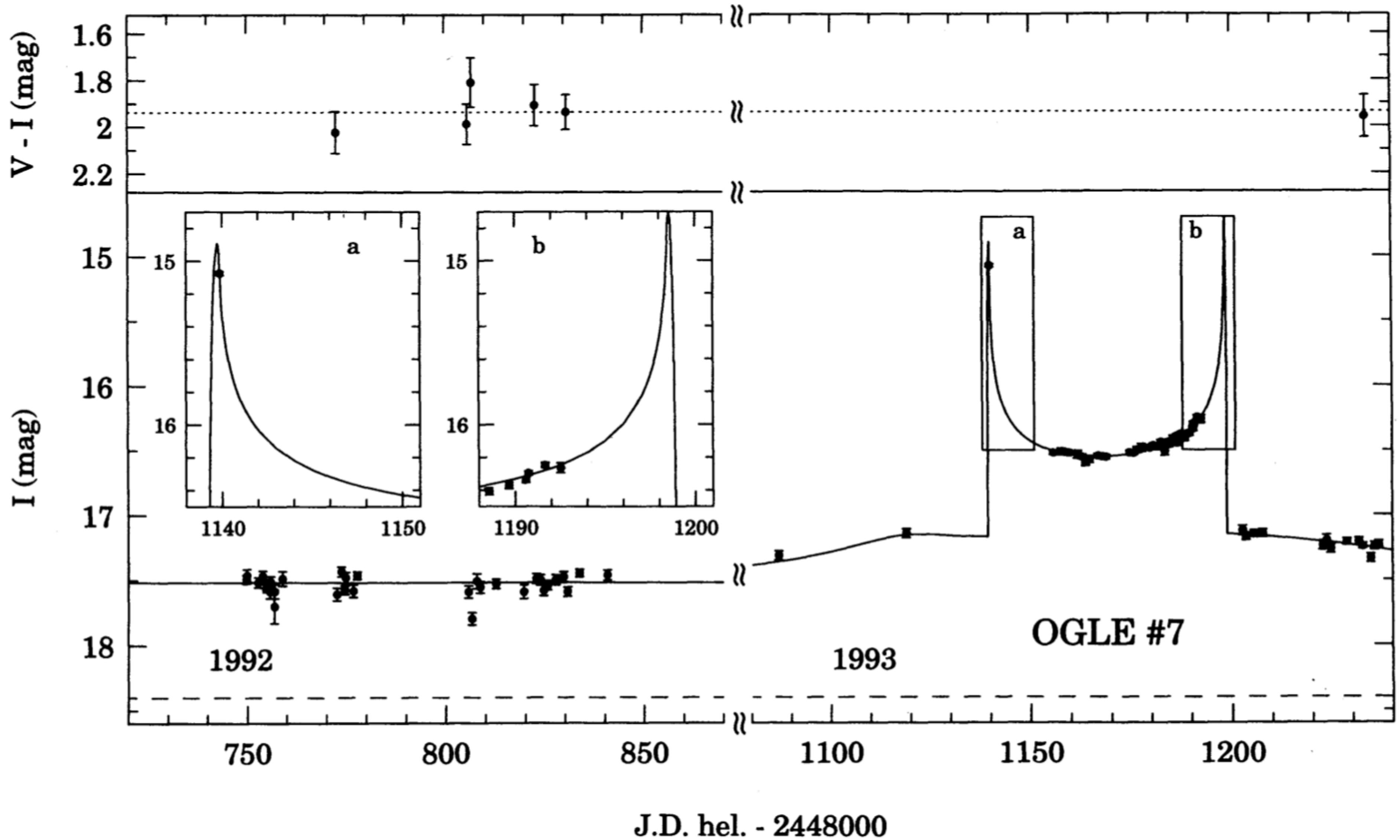
OGLE NO. 7: Binary microlens or a new unusual variable?



(Udalski et al. 1994)

Abstract: the binary microlens model seems to be the most likely explanation

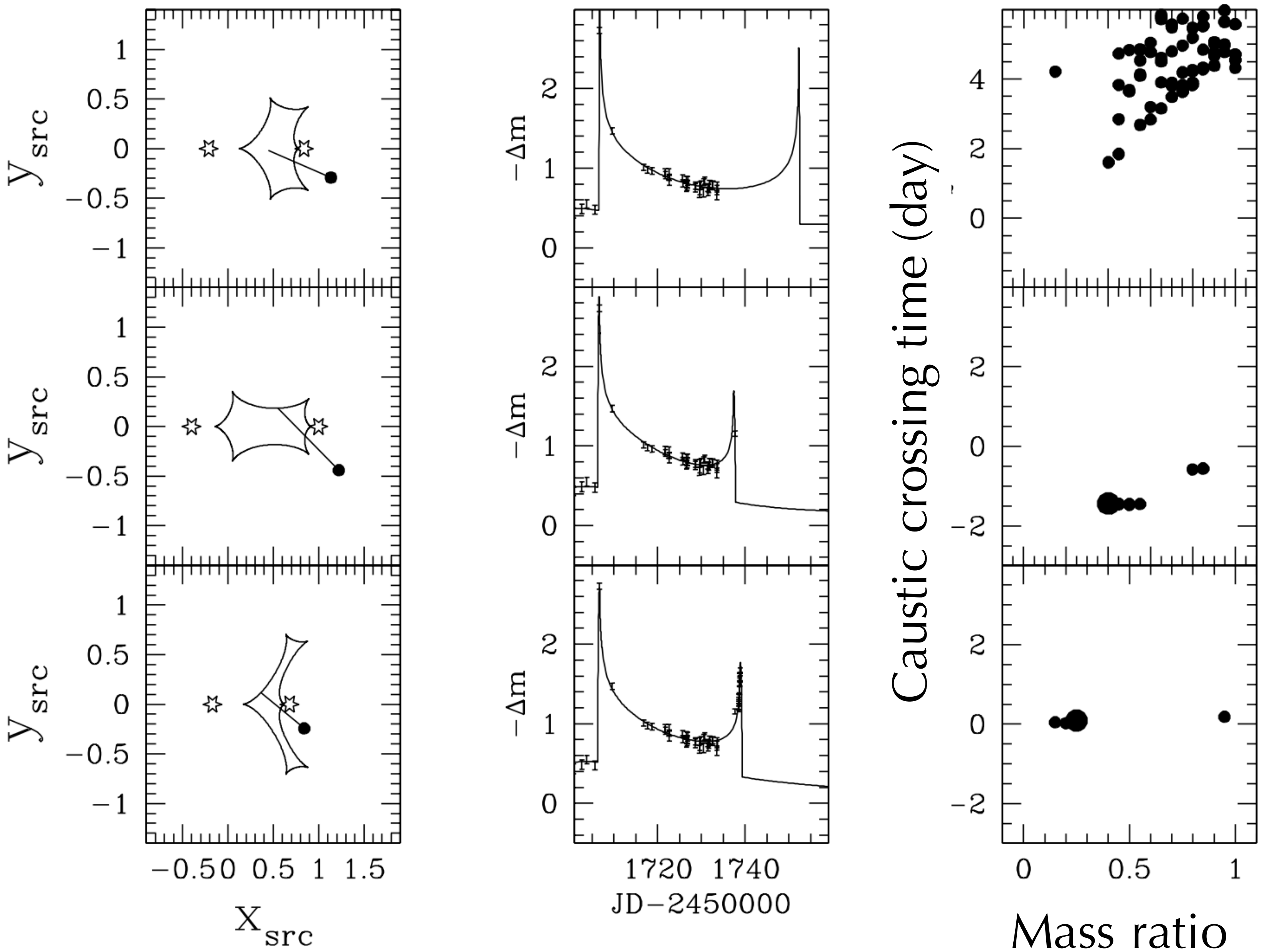
Minimum magnification between caustics & degeneracy



- **dm ~ 1.2 mag**
- **Observed: 1 mag**

- Minimum magnification between caustic crossing is 3; Violated by OGLE #7 → blending in crowded fields (f_{lens}=56%)
- Binary lens equation is no longer analytical (Witt & Mao 1994; Rhie 1997)
- Beautiful symmetry revealed by Dominik (1999), An (2005), Bozza (2009)
- Further MACHO data reveal heavy degeneracy (unpublished, Bennett's talk)

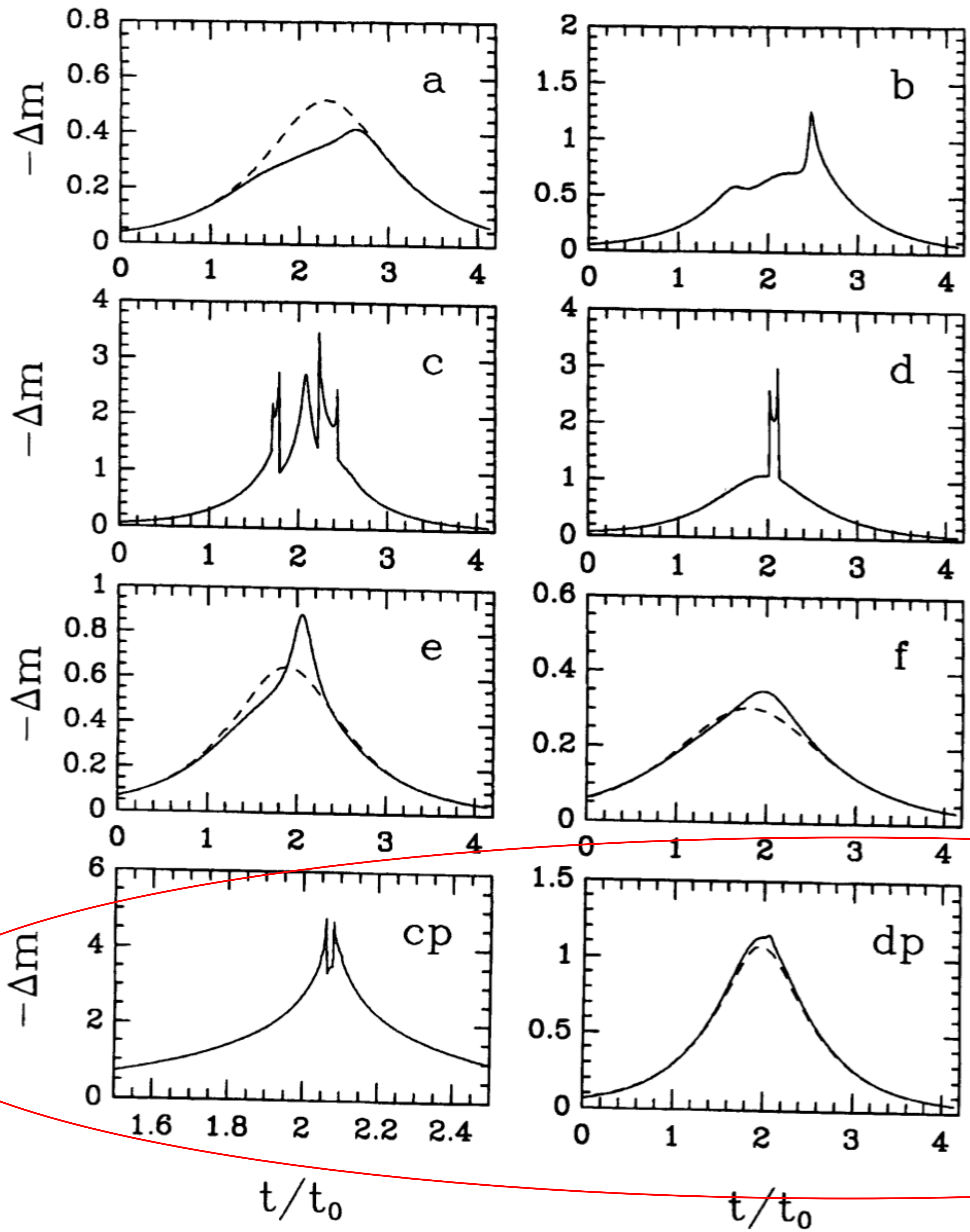
Predicting binary caustic crossings



Jaroszynski and Mao (2001)

Our calculations show that the reliable prediction of the second crossing can only be made very late, when the light curve has risen appreciably after the minimum between the two caustic crossings.

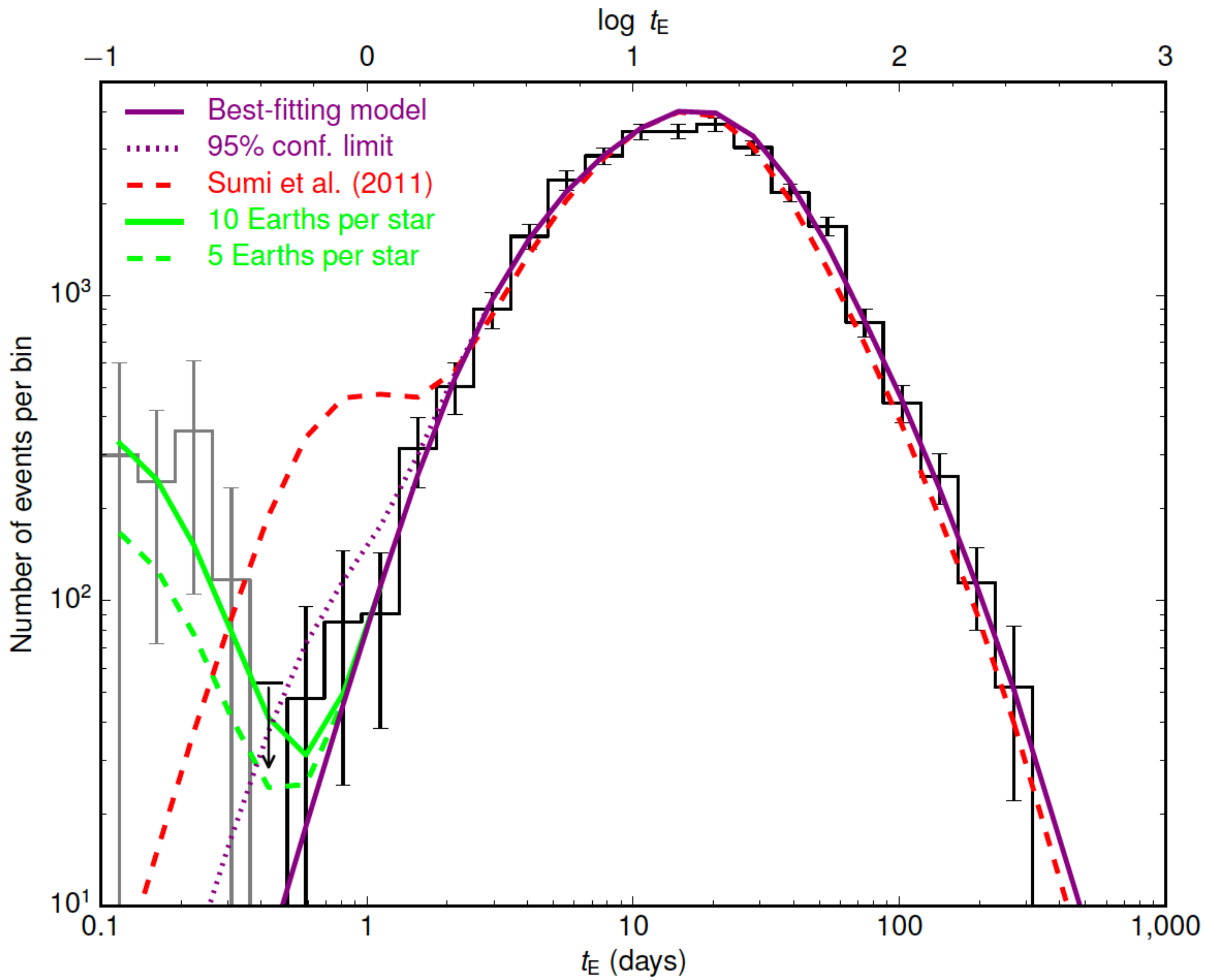
Binary/planet predictions



- **5-10% should exhibit binary/planetary signatures**
- **Binary events**
- **planetary events**
- **70 by OGLE + transits**

Gaudi's & Cassan's talk

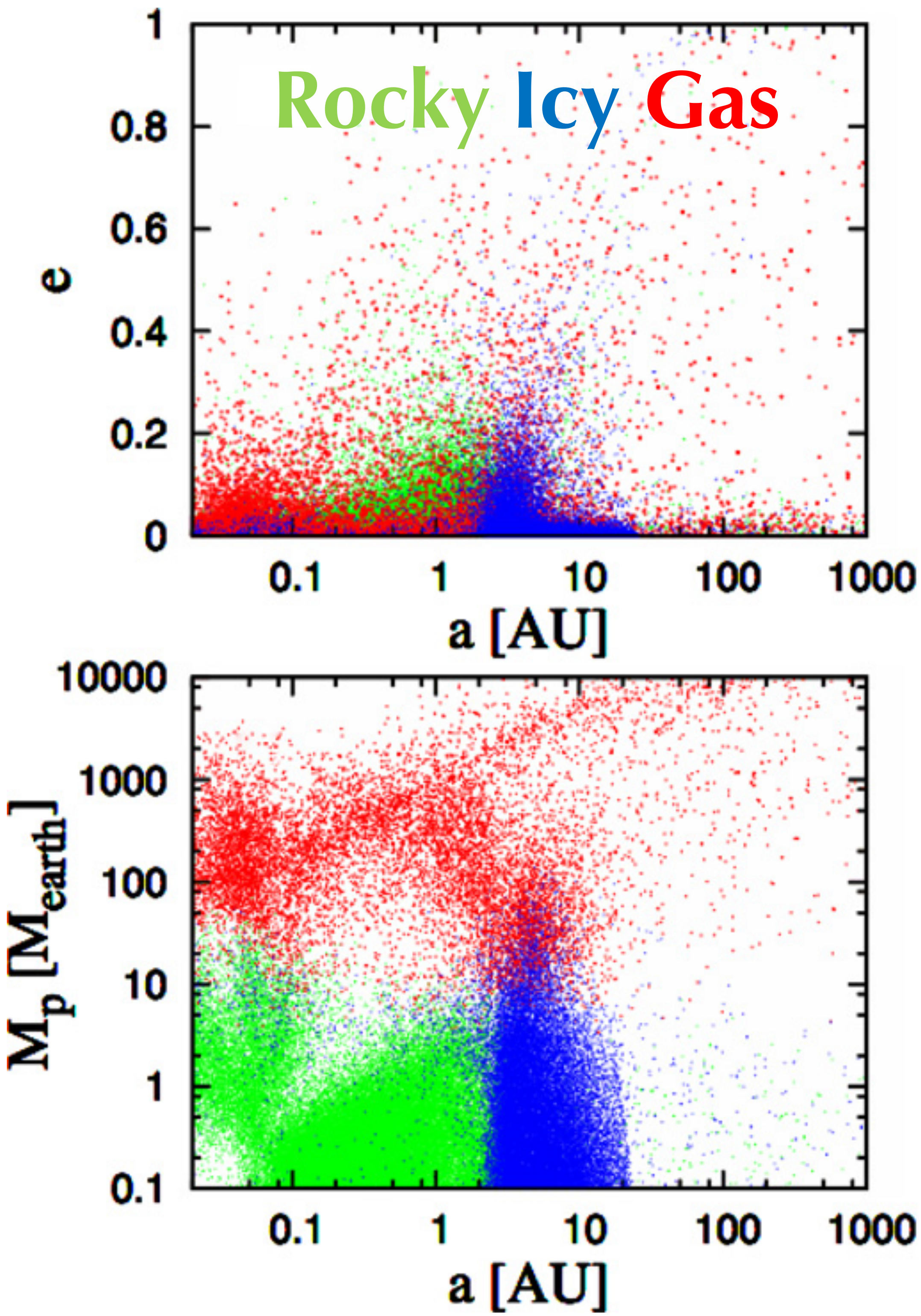
Free floating planets by Mroz et al. (2017)



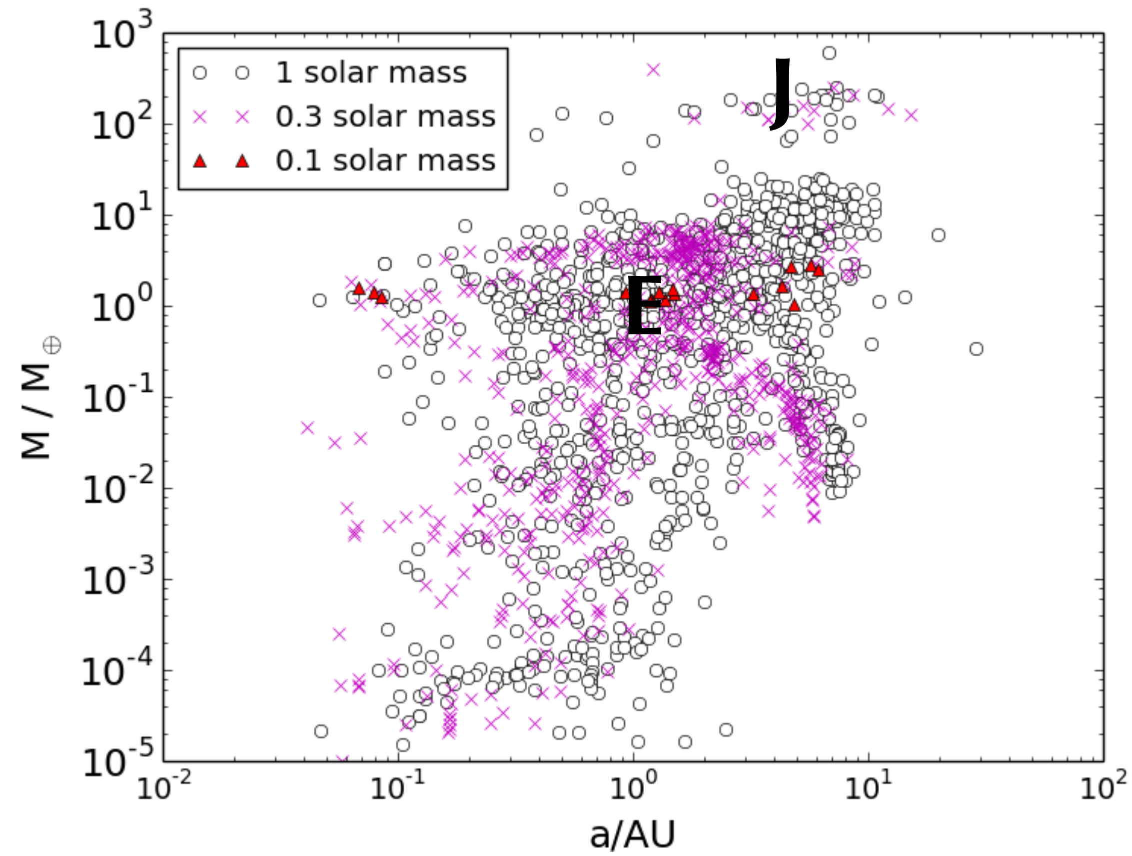
- **Mroz et al. (2017), Nature**
- **Efficiency corrected**

Population synthesis with core accretion: bound planets

Ida, Lin, & Nagasawa (2013)
[see also Mordasini+ 2009]



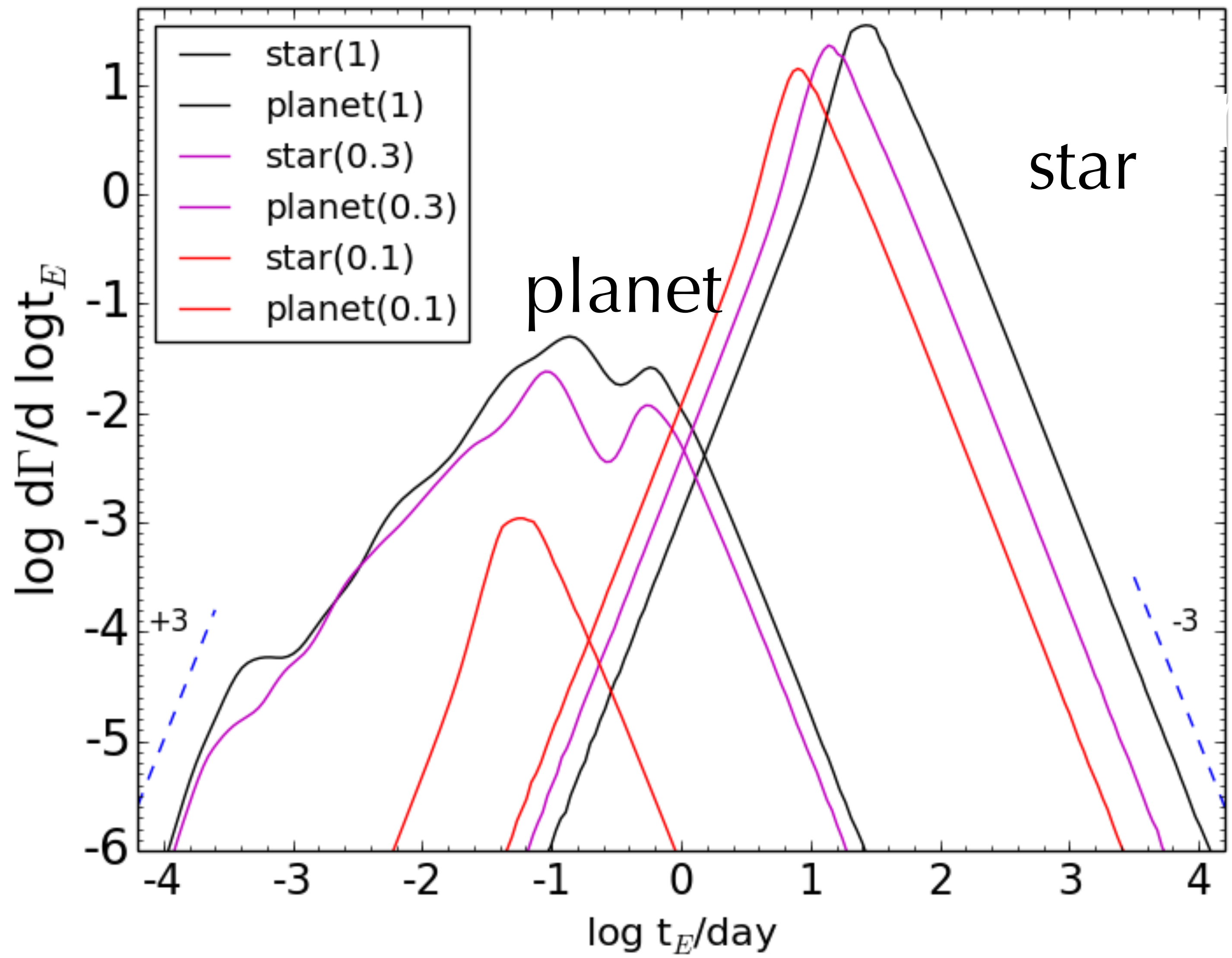
Free Floating Planets



For a typical 0.3 M□□ lens

- 10% eject ~ 4 planets
- M_{total}=5M□
- $M_{1/2}$=0.3 M□

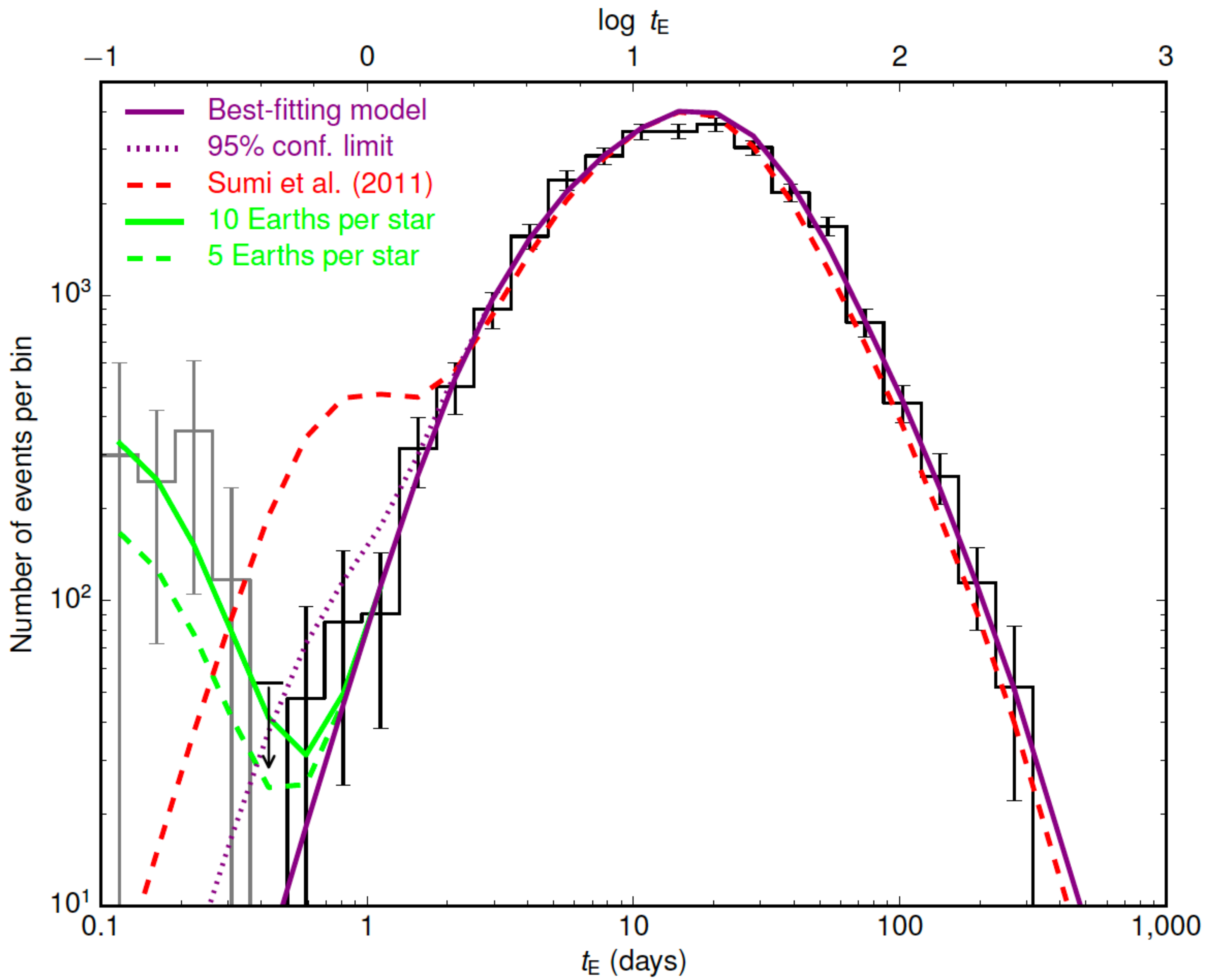
Predictions from core accretion theory



Ma, Mao, Zhu, et al. (2016)

- **Event rate: for 0.3 solar mass lenses**
  - we expect ~10^{-3} free-floating events per stellar event
  - median timescale median timescale: ~0.1 days

Comparison with Mroz et al. (2017)

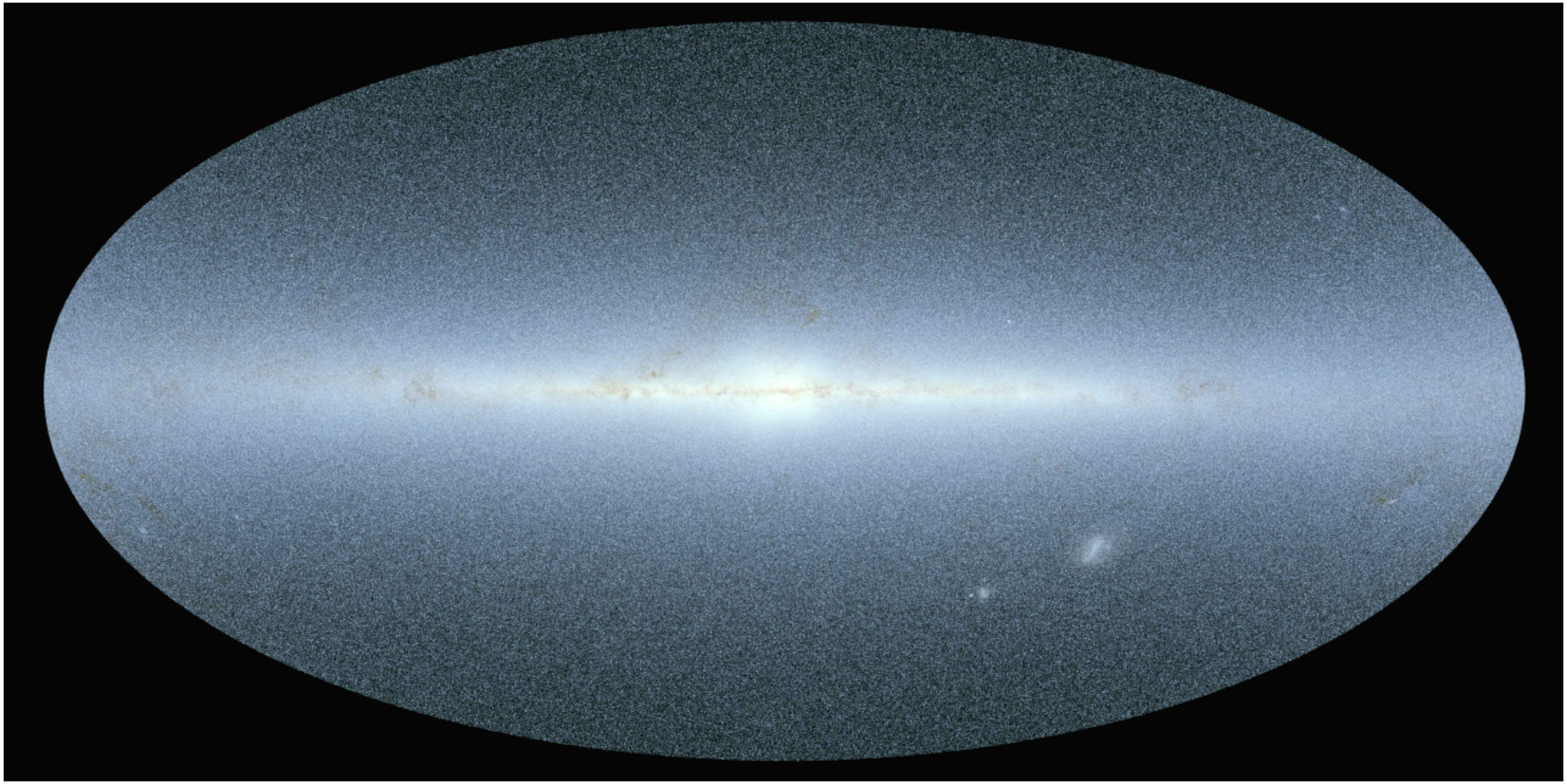


Mroz et al. (2017), Nature

Efficiency corrected

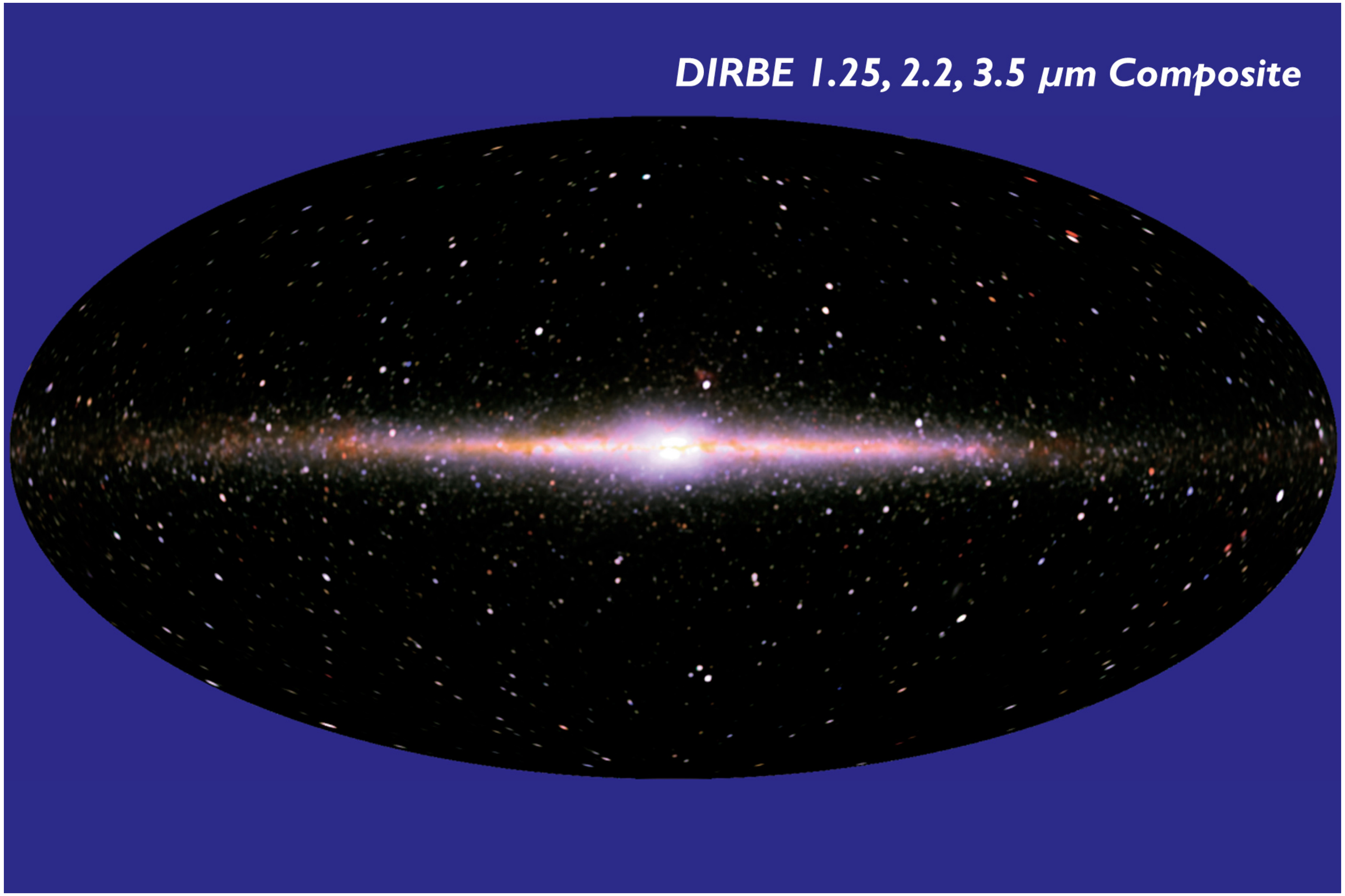
- **Predictions too low to be consistent with Mroz et al. (2017, Nature),** ***if all are due to microlensing***
- **Direction gravitational collapse and/or ejections in binary stars?**

3. Modelling the bar of the Milky Way



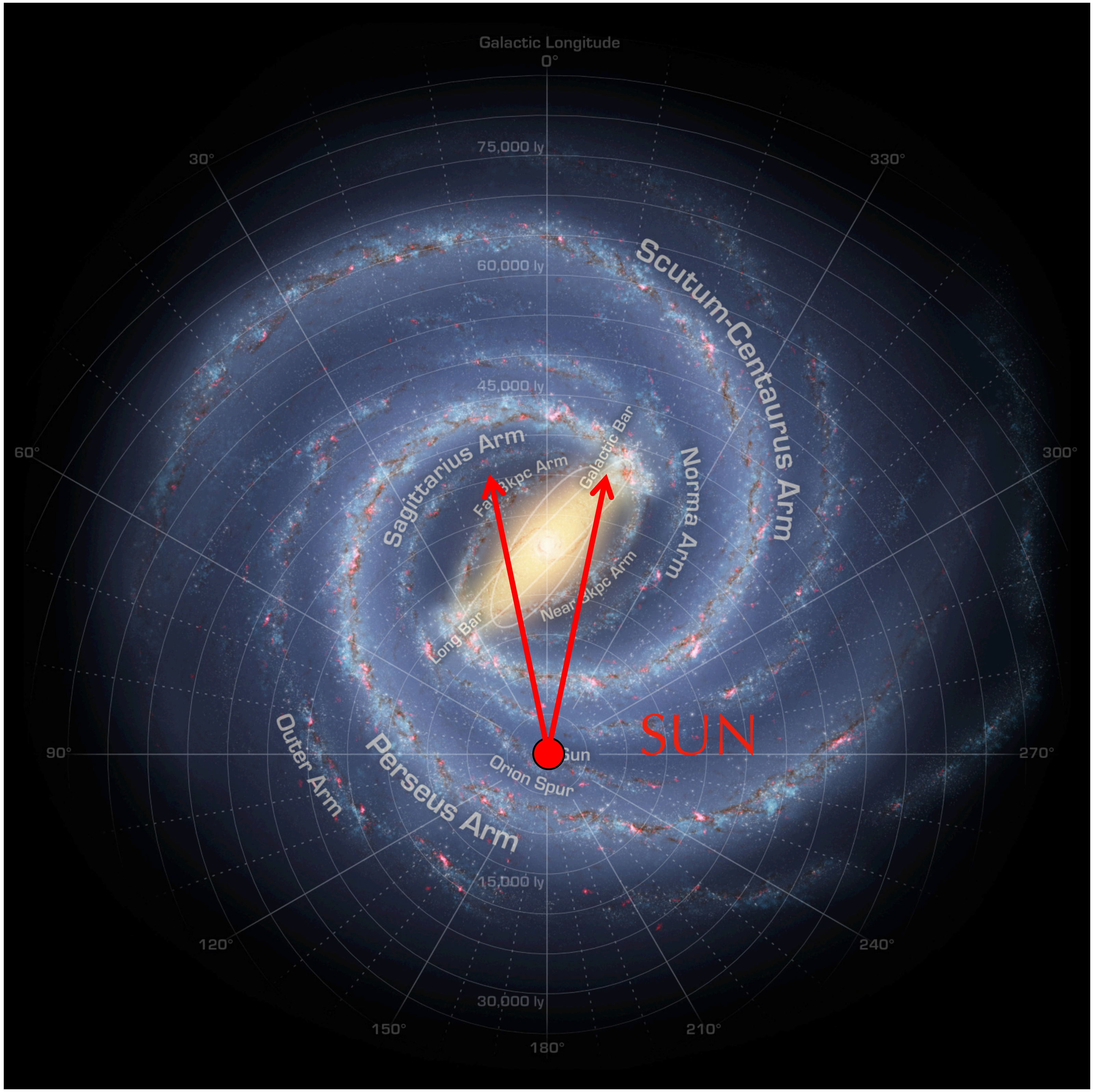
2MASS view of the Milky Way

The Milky Way: COBE view



- Light is asymmetric! MW is a barred galaxy
- Kiraga & Paczynski (1994) & Udalski et al. (1994) rediscovered the Galaxy is barred

Top-down view of the Galaxy



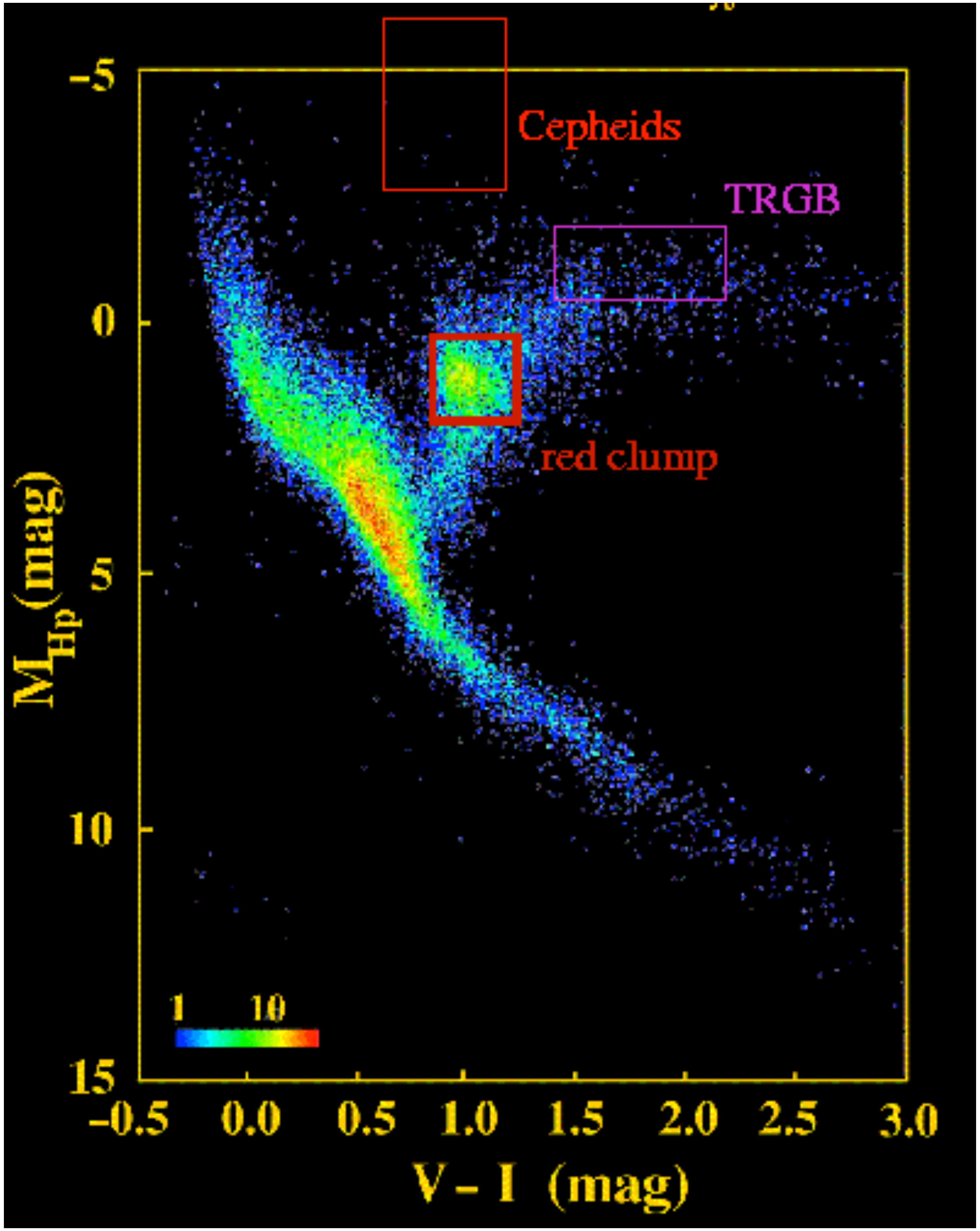
The Milky Way is an SBc type galaxy

Bar angle:
15-45 degrees

Pattern speed:
30-60 km/s/kpc

Impact on WFIRST

Color Magnitude Diagram close to the Sun

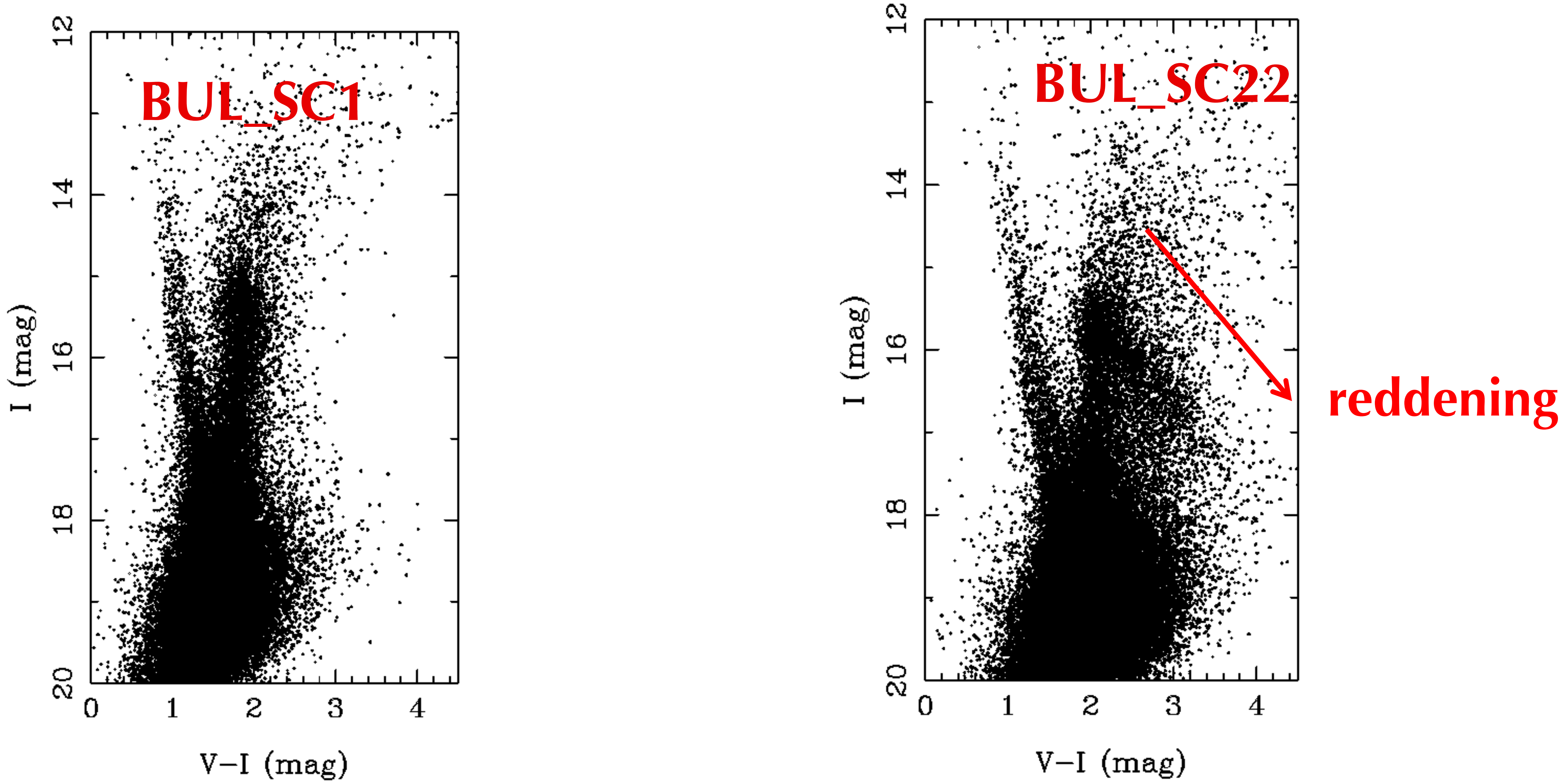


CMDs for the solar neighborhood from Hipparcos

- Red clumps are metal-rich horizontal branch stars
- Small intrinsic width in luminosity (~0.09mag)
- Good standard candles! (Paczynski & Stanek 1998)

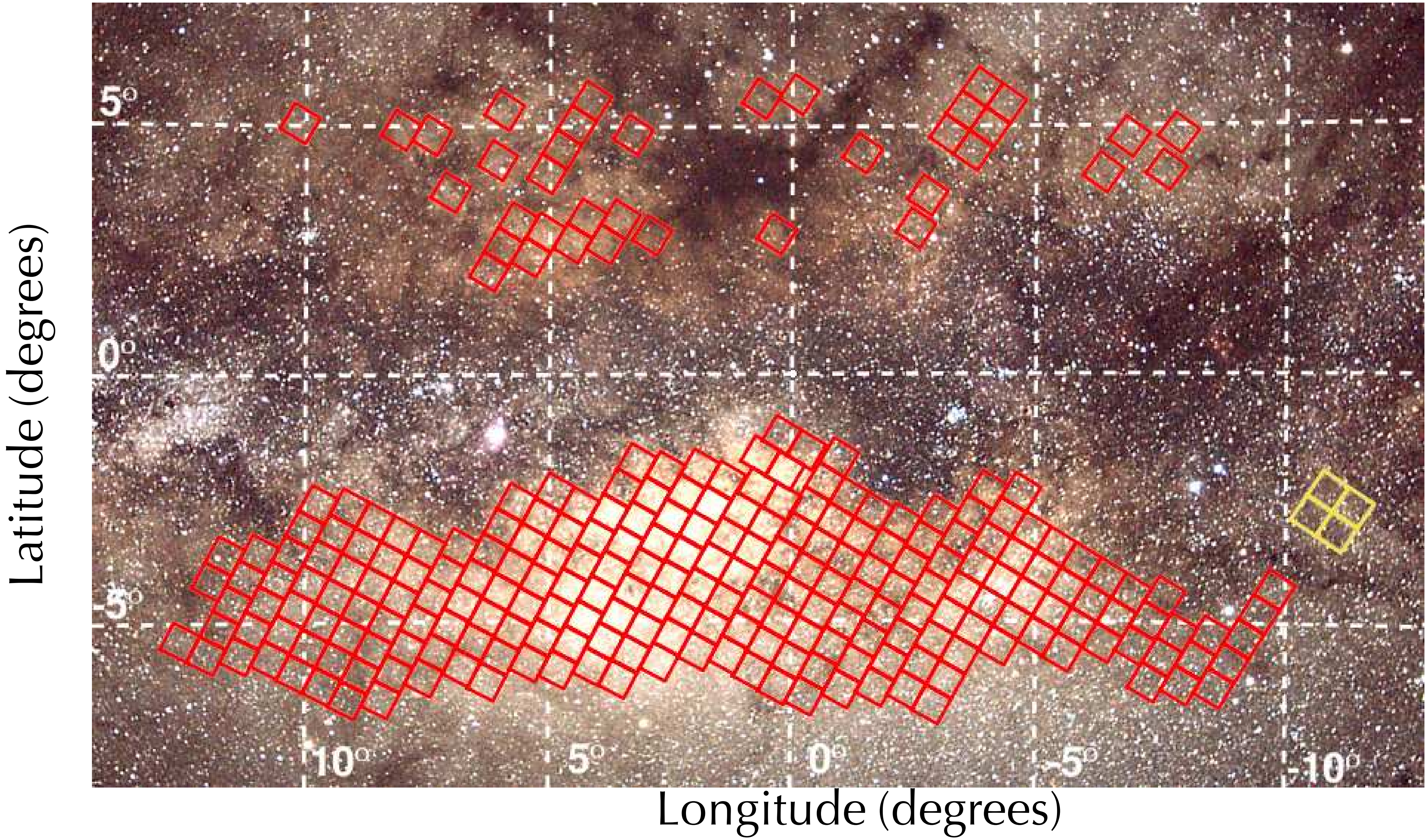
e.g. Udalski 2000; Nataf & Udalski 2011

Bulge Color-magnitude diagrams



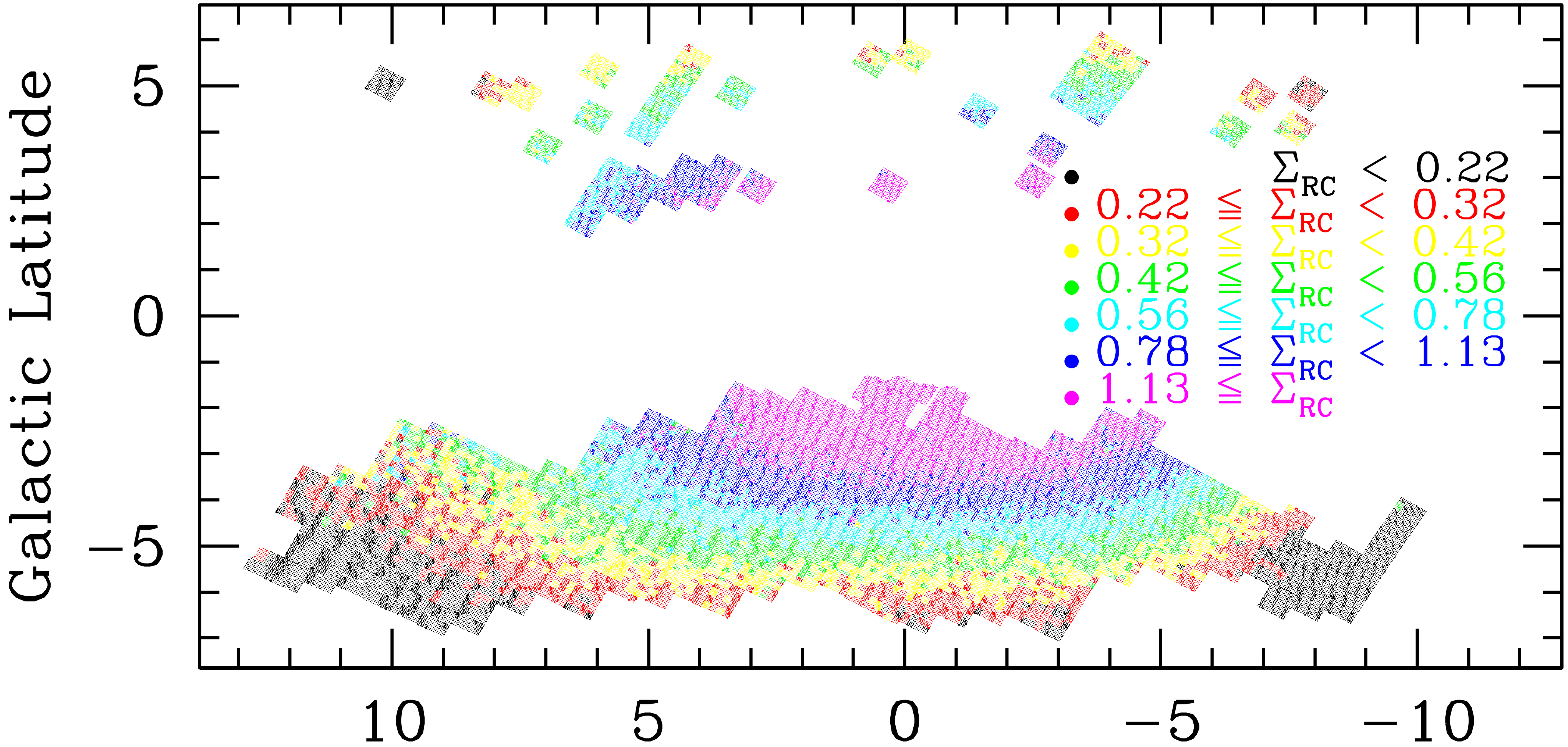
- Observed RCG width larger in the bulge is larger due to extension of the bulge.
- Careful studies of RCGs provide a 3D map of the bar

OGLE-III sky coverage



- **OGLE-III fields cover ~ 100 square degrees**
- **OGLE-IV fields cover 3500 square degrees**

Number counts of red clump giants



Nataf, Gould + OGLE (2013)

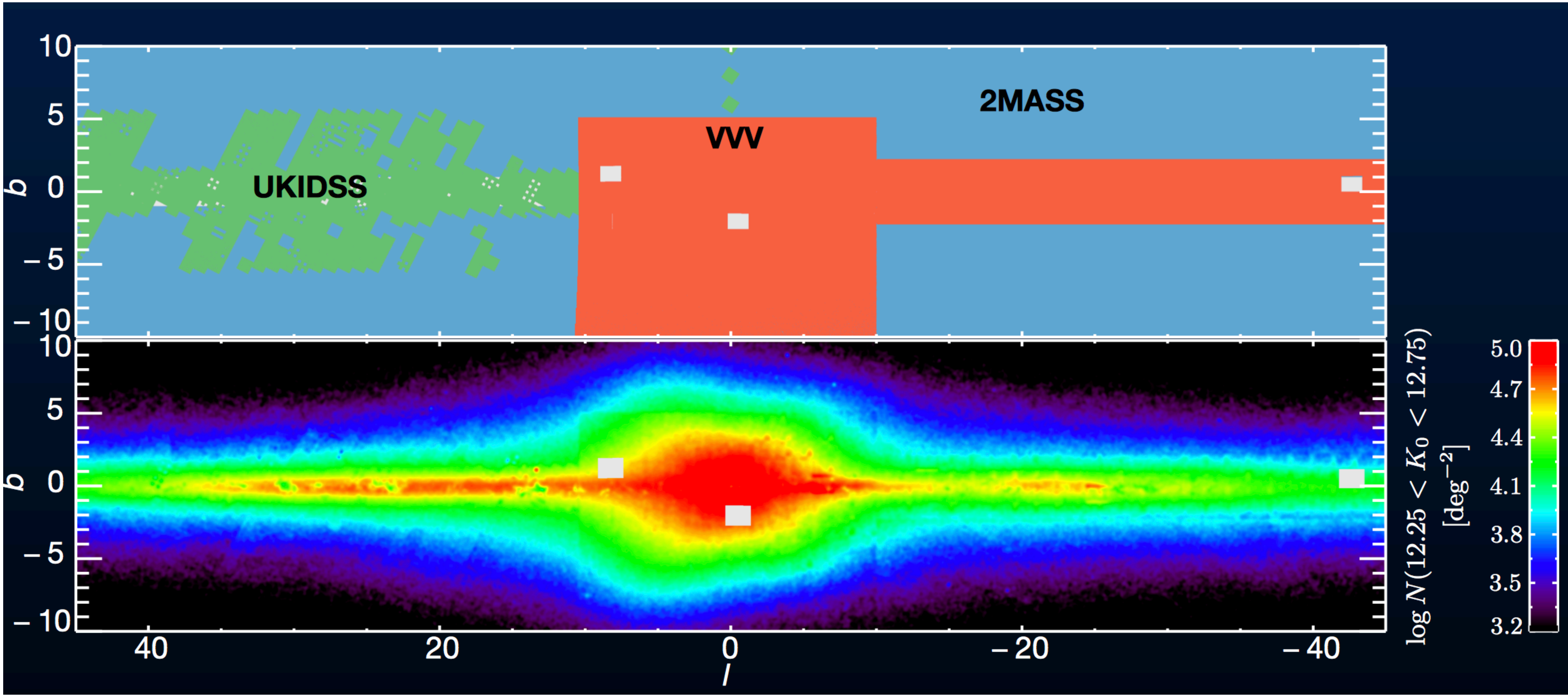
- **Regular elliptical counts close to the plane**
- **Fit smooth tri-axial ellipsoidal models, such as**
  - **$\rho = \rho_0 \exp(-r^2/2)$, Gaussian model**
  - **$\rho = \rho_0 \exp(-r)$, exponential model,**

  where $r^2=(x/x_0)^2+(y/y_0)^2+(z/z_0)^2$

Photometric model of the Milky Way

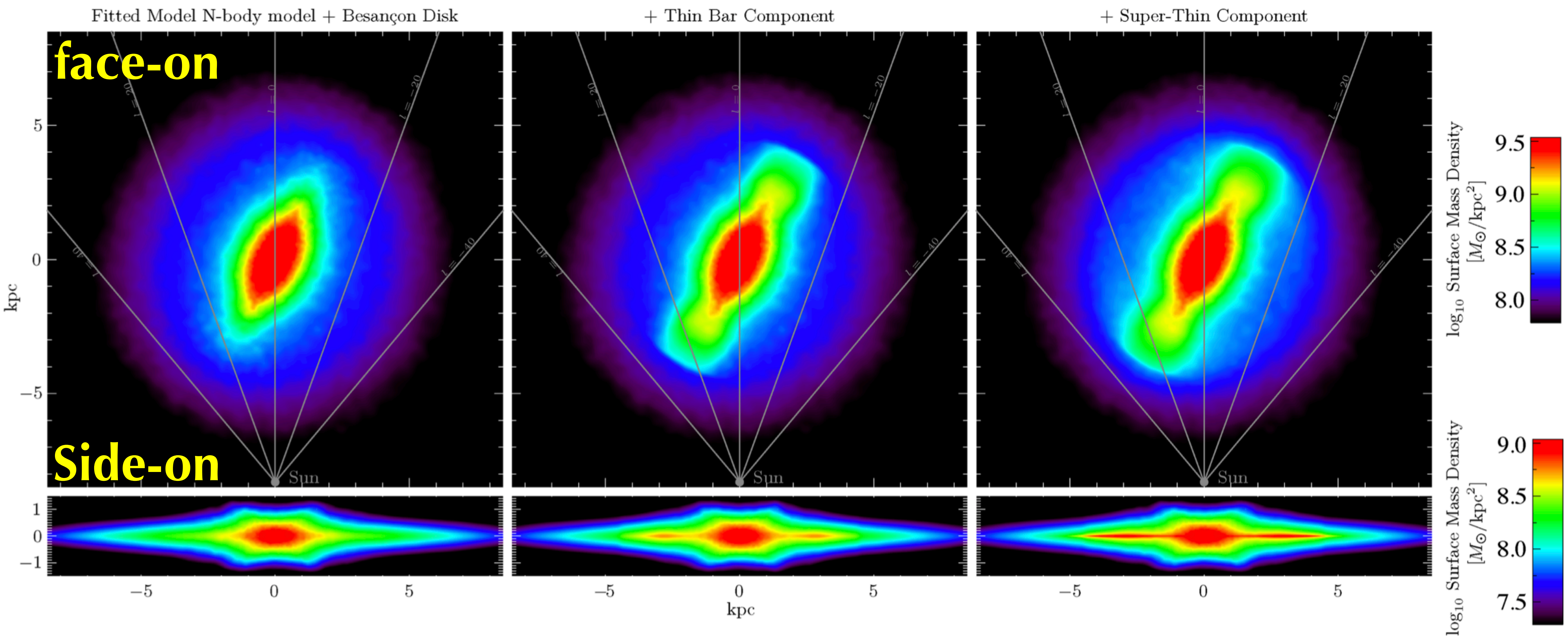
- **First parametric modelling was made by Stanek + OGLE team (1997)**
- **Tri-axial "exponential" density model preferred over Gaussian (Cao, Mao, Gould et al. 2012):**
  - $x_0:y_0:z_0$=0.68kpc: 0.28kpc: 0.25kpc
  - Close to being prolate (cigar-shaped)
  - Bar angle ~ 30 degrees
- **Much better studies by Gerhard and his associates using the non-parametric method (Wegg et al. 2015; Portail et al. 2017)**

Non-parametric reconstruction



- **Wegg, Gerhard & Portail et al. (2015)**

The bar structure



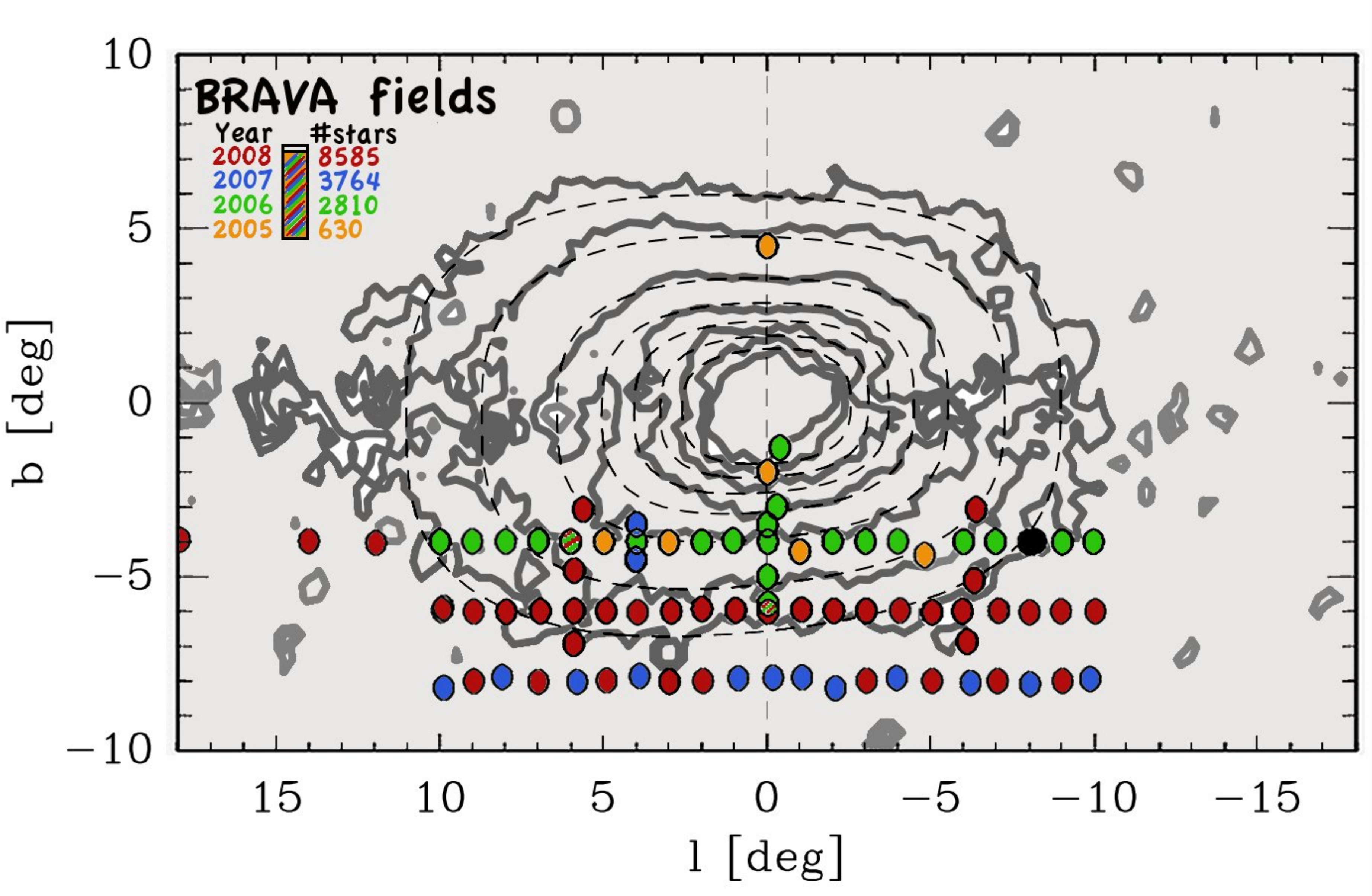
- **The bar is oriented at 28 degrees with respect to the line of sight**
- **Has a single bar which becomes thinner in the outer region**

Dynamical modelling of the bar: data

- **Radial velocities of red giants from BRAVA/ARGOS/APOGEE**

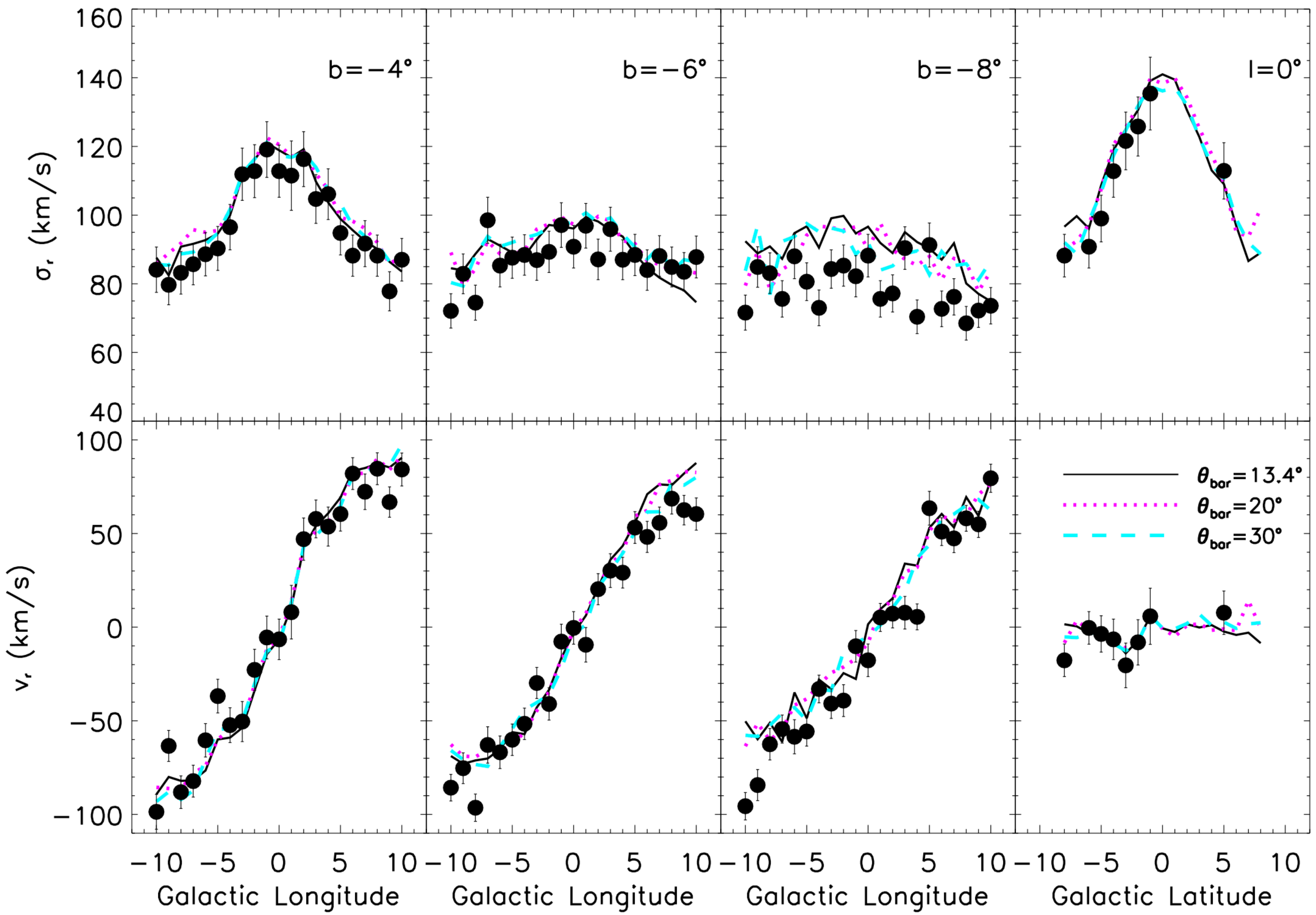
- **Proper motions (from 25 years of microlensing surveys)**

Radial velocity fields of BRAVA



- Radial velocities of 8500 red giants (Kunder et al. 2012)
- Velocity accuracy ~ 5 km/s
- Much better dataset from the ARGOS survey by Ness & Freeman

BRAVA Radial velocity data

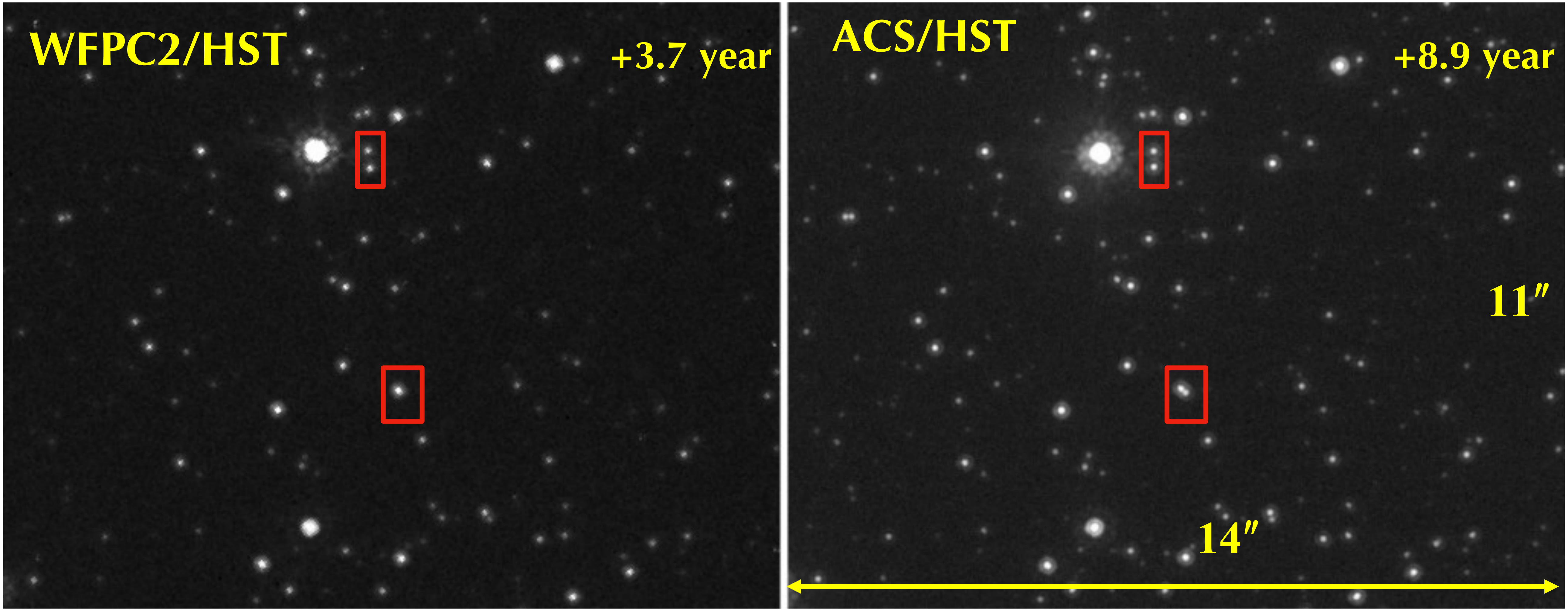


Velocity dispersion

Mean velocity: rotation

-1.5->1.5 kpc

Proper motions of stars with HST



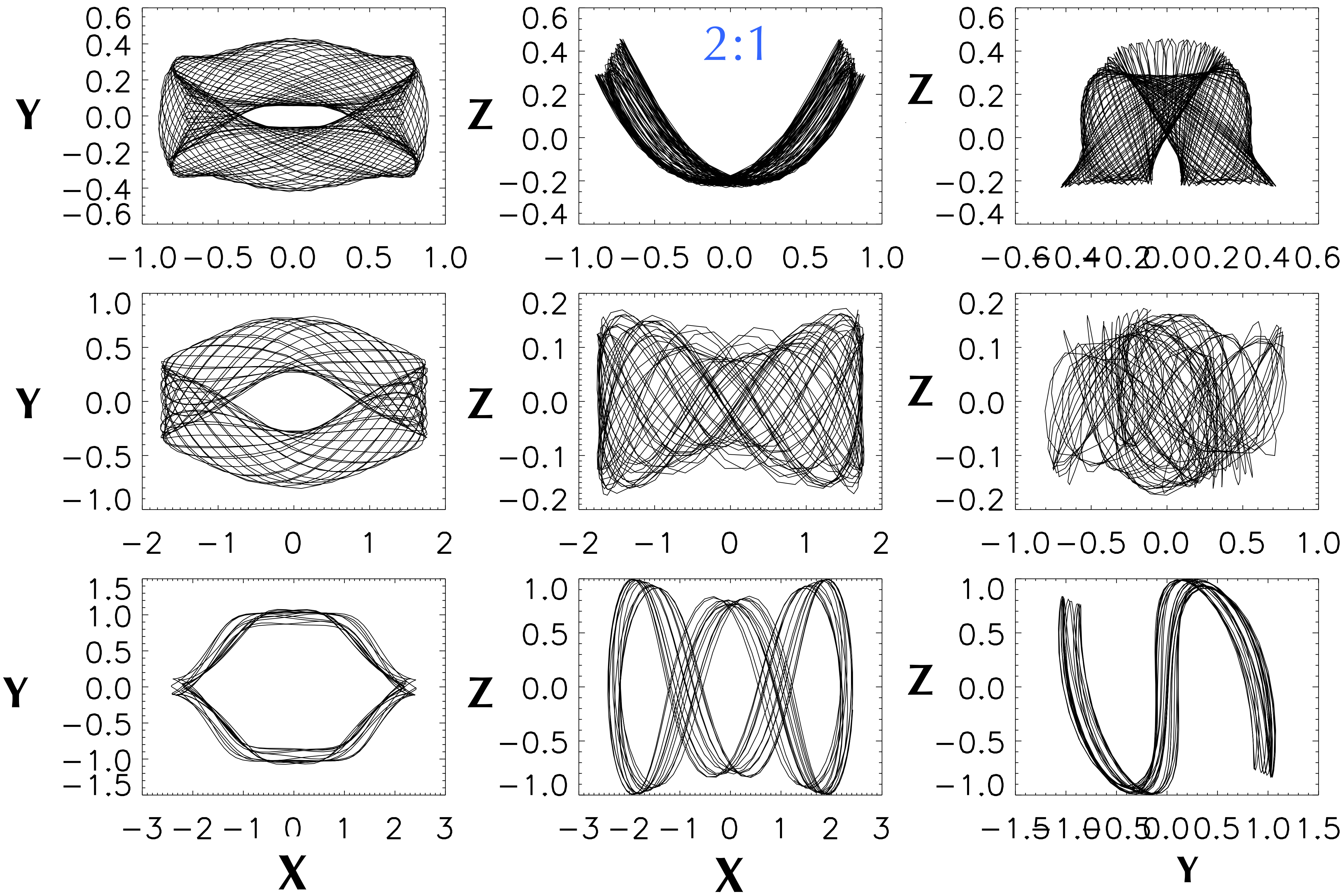
Kozlowski, Wozniak, Mao et al. (2006)

- **Two decades of microlensing enabled proper motions to be measured for millions of stars (~few mas/yr, Sumi et al. 2004 for OGLE-II).**
- **HST observations enable proper motions to even higher accuracy (~ 0.2-0.6 mas/yr)**

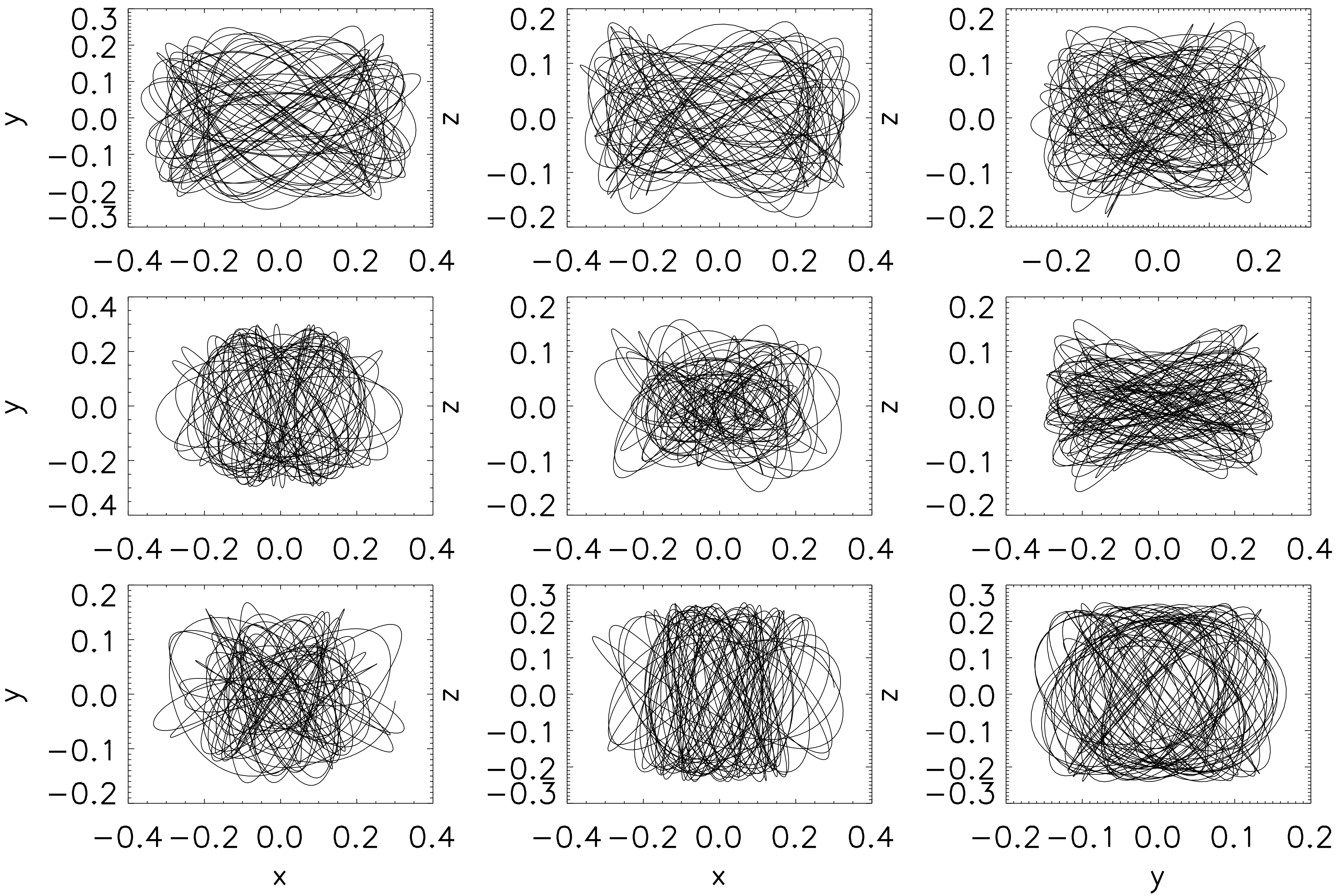
Methods of dynamical modelling

- Schwarzschild method (Orbit based)
- Made-to-Measure (Particle based)
- Binney's action-angle method (may not work well for bar)

Some typical regular orbits

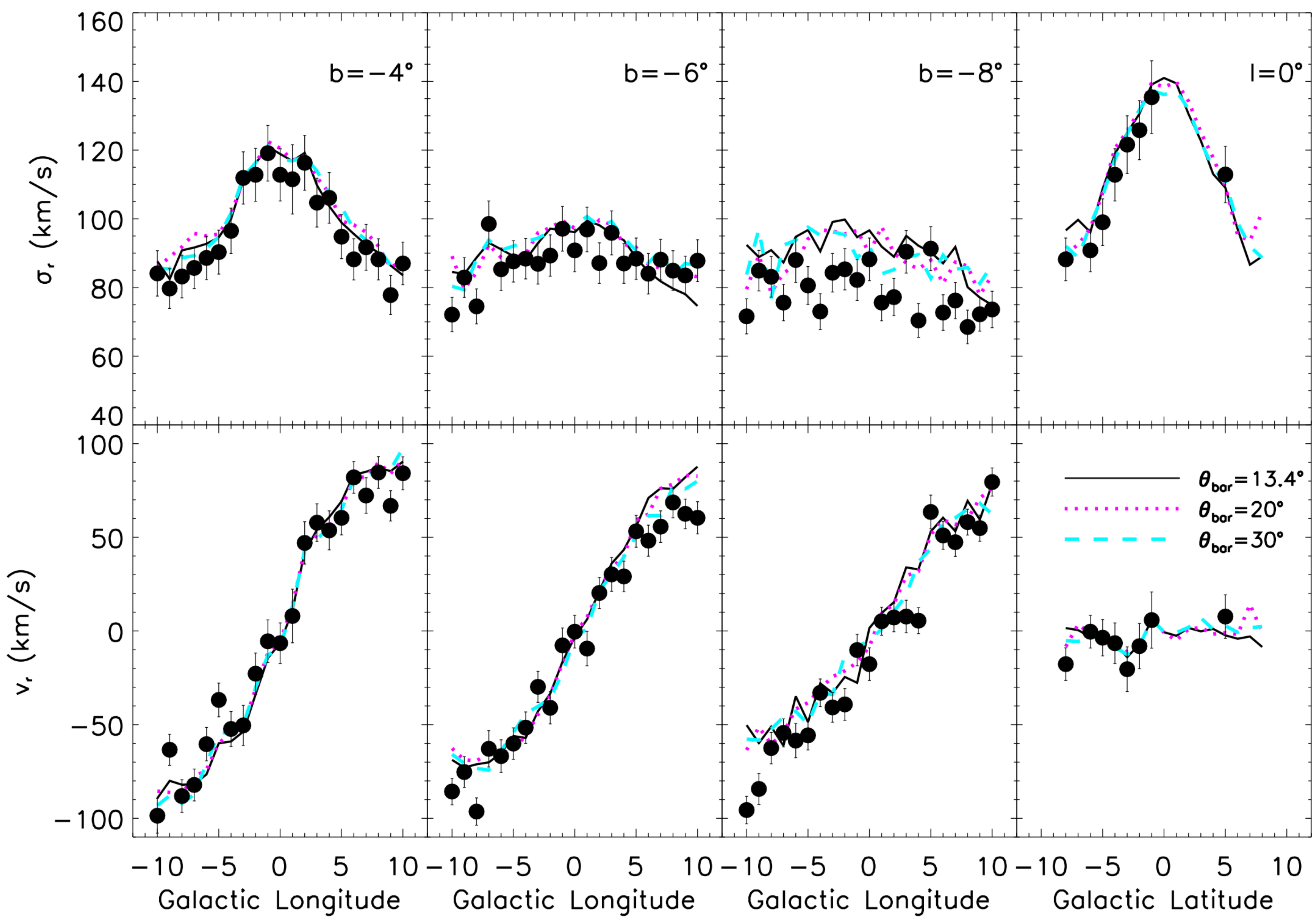


Chaotic orbits



Many orbits are in fact chaotic!

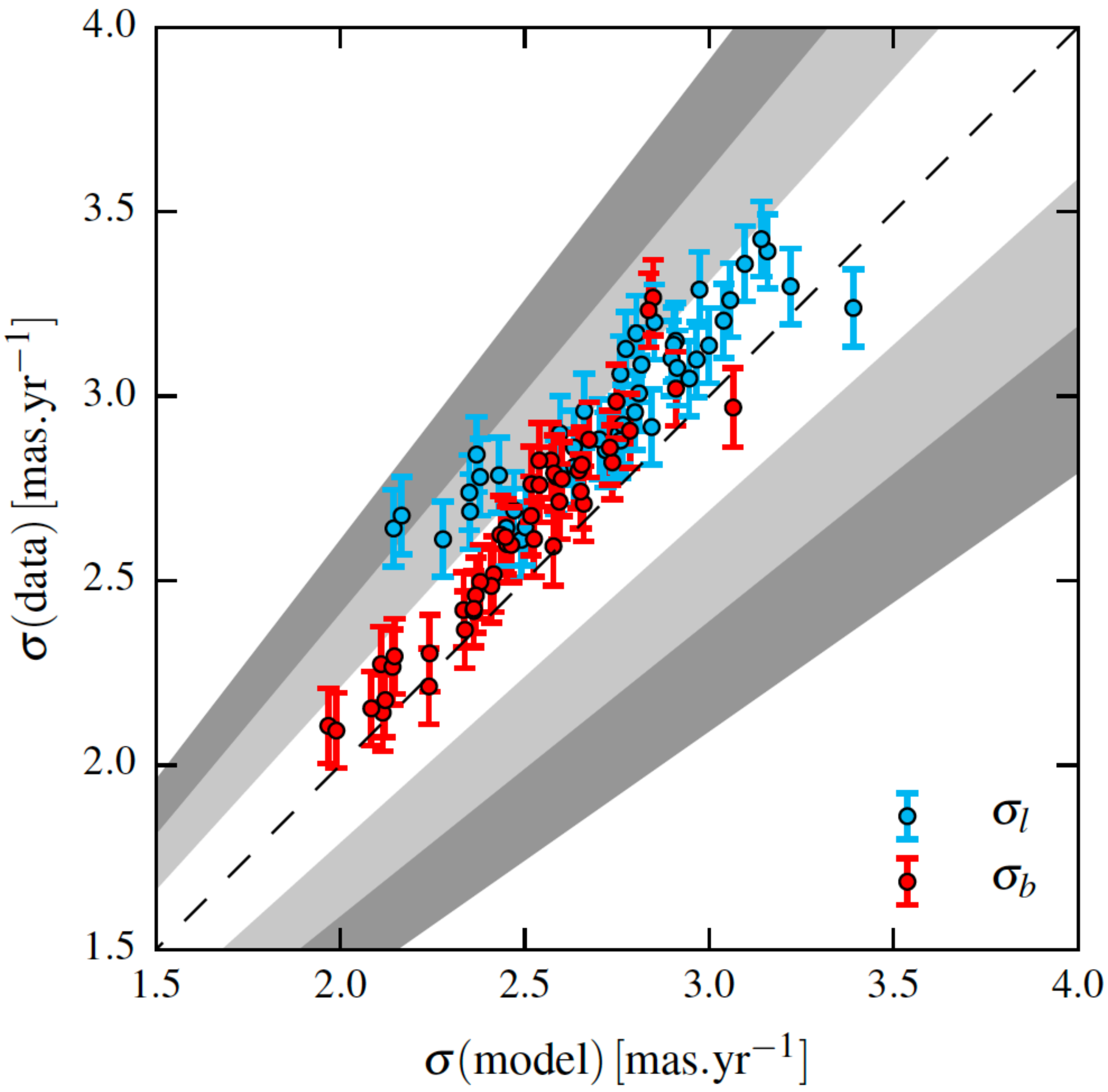
Fitting Brava data



Wang, Zhao, Mao et al. (2012)

Bar angle is not so well constrained

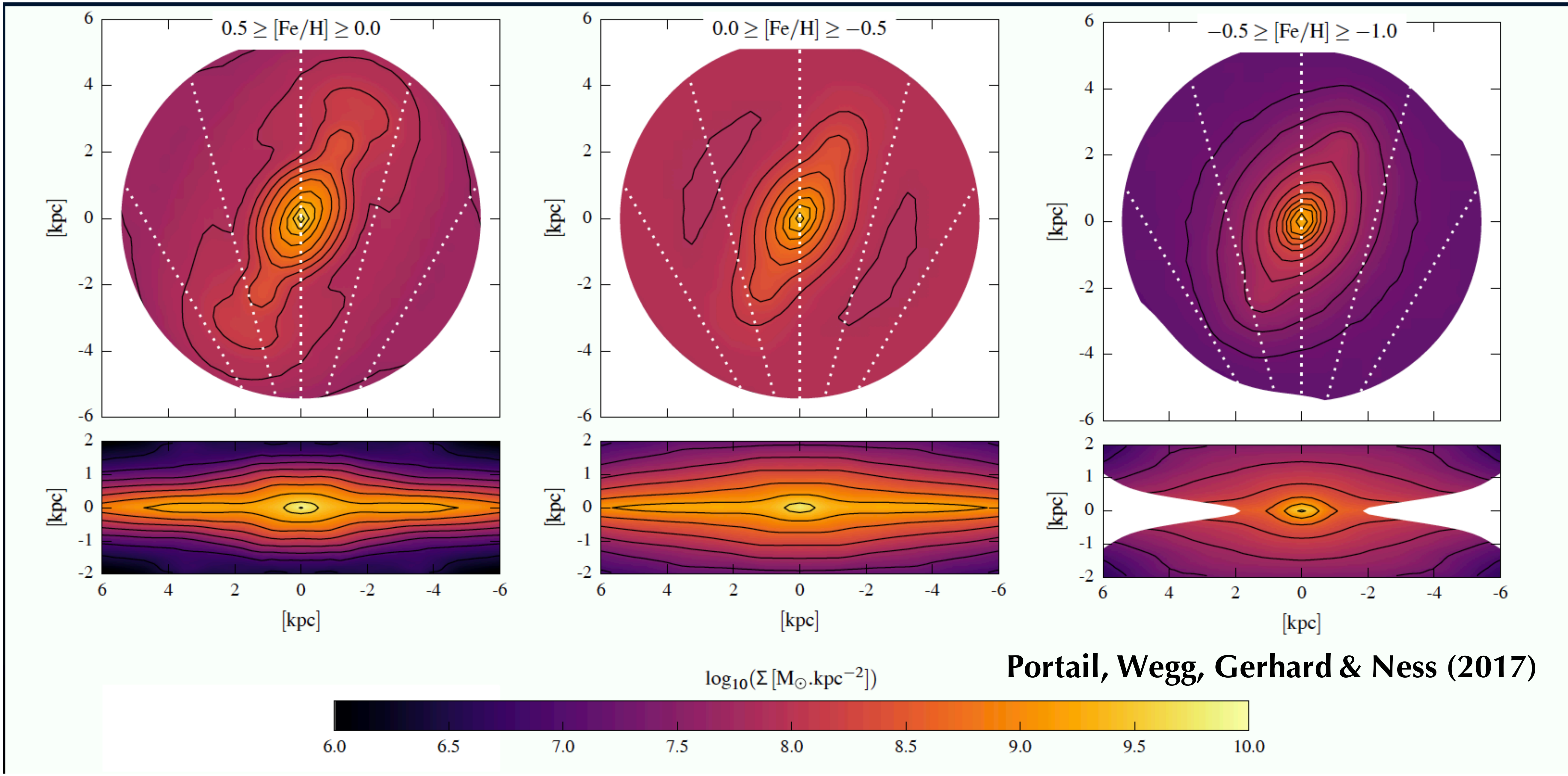
Predictions of proper motions



Portail, Gerhard, Wegg & Ness (2016)

- Consistent with OGLE data within 10%
- But both are systematically larger than observations.

Chemo-dynamical modelling of the Milky Way

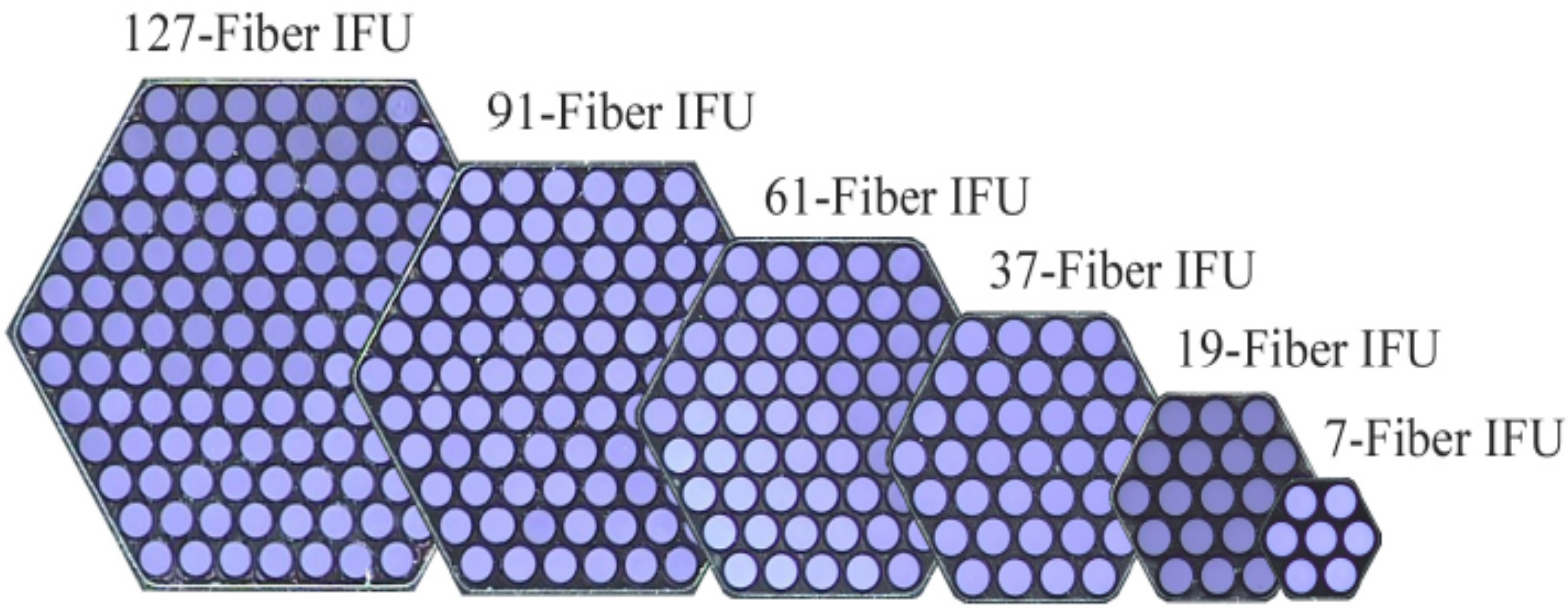


- **The bar rotates at W = 40 km/s/kpc**
- **Bar length: 5.3±0.36 kpc**
- **radial velocity field in the bar region, and bar angle 28 degrees**

Is our Milky Way special? IFU surveys

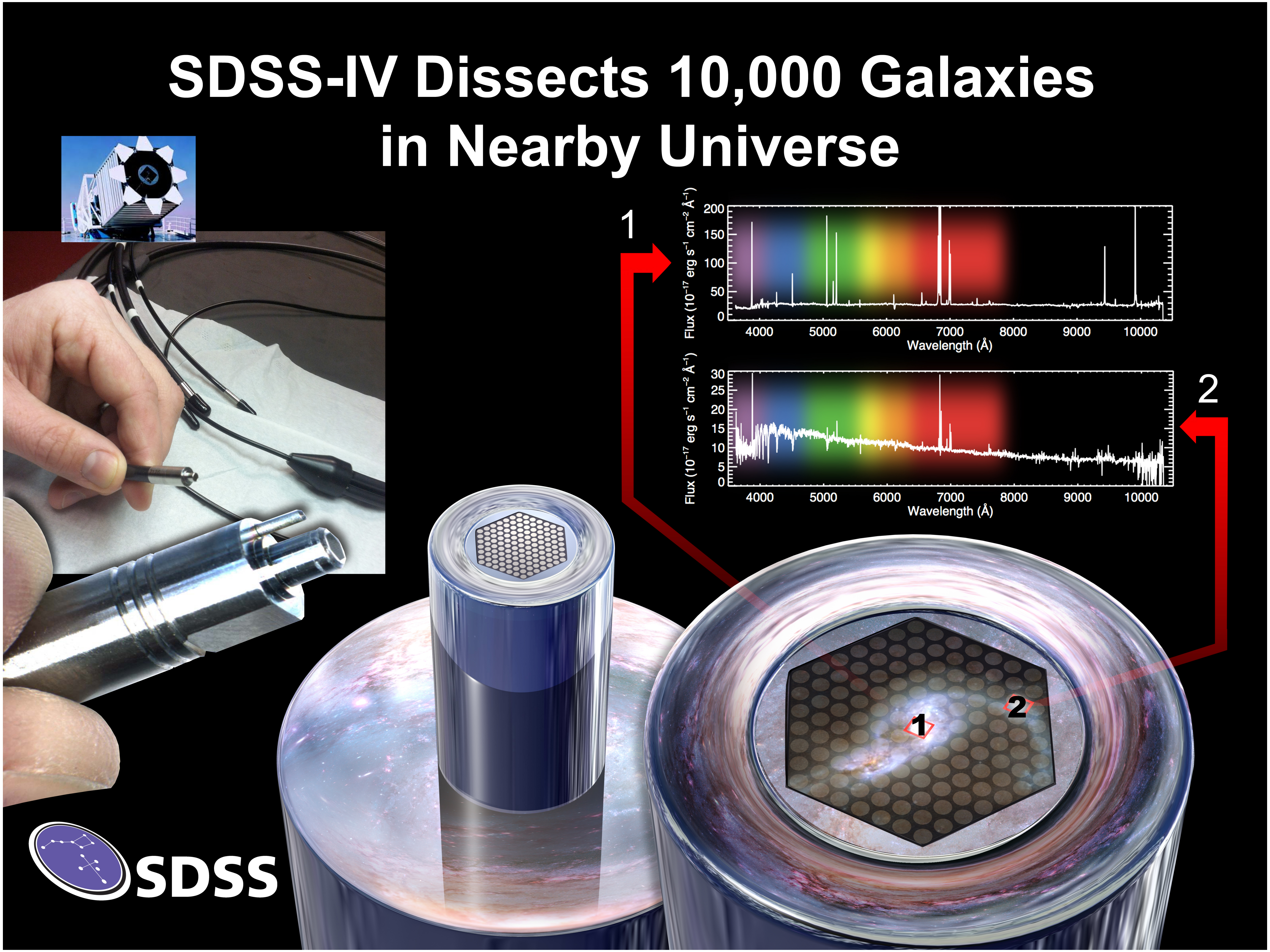
Many IFU surveys have been conducted or are ongoing

- SAURON, atlas3D, diskMass, CALIFA, SAMI
- **SDSS-IV/MaNGA**



- **10,000 SDSS galaxies at 0.01<z<0.15**
- **Mass-limited sample: log(M*)>9.0**
- **Spatial resolution = 2″ (1-2 kpc)**
- **Spectral resolution = 50-70 km/s, Spectral coverage: 3600 - 10000 AA, S/N = 4-8@1.5 Re**

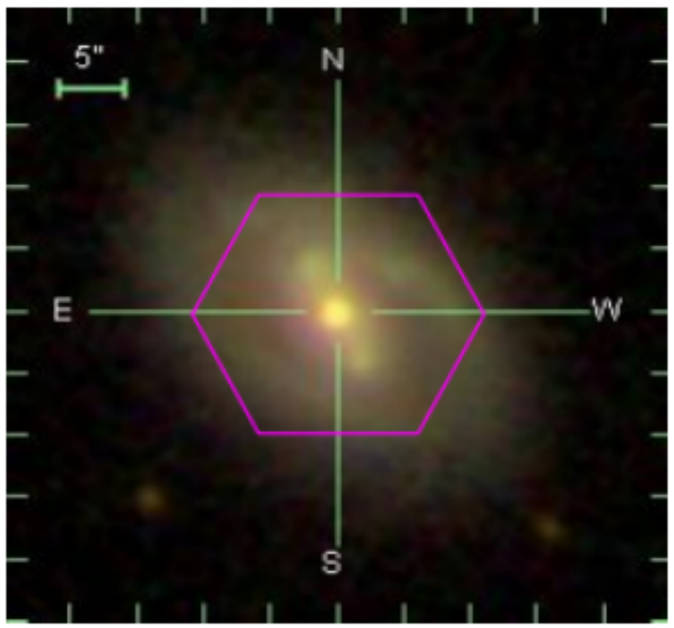
MaNGA in a single picture

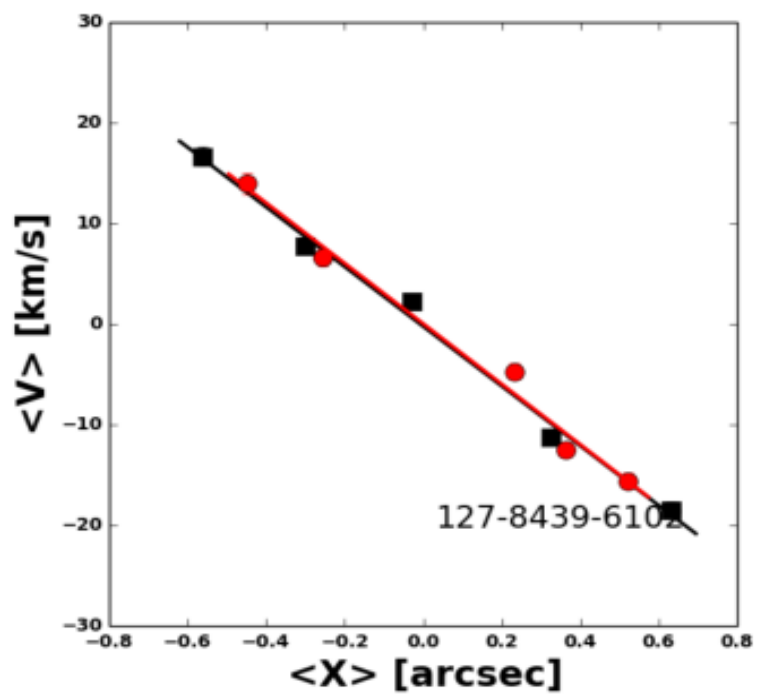


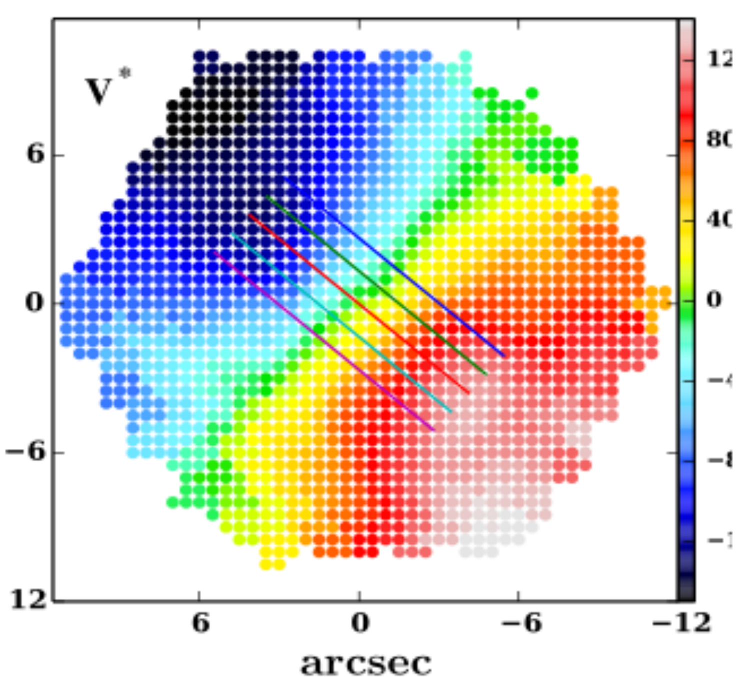
Tremaine-Weinberg method

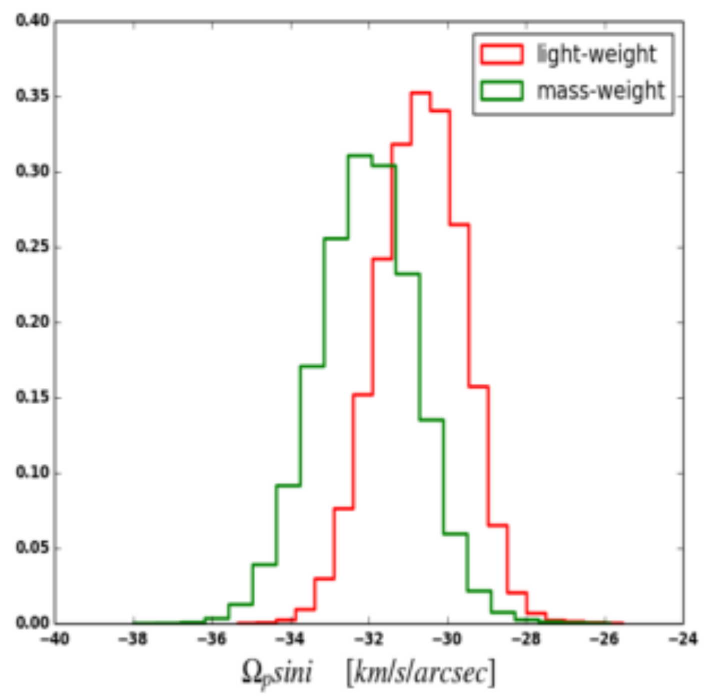
- Assumes continuity equation, and the bar is rotating steadily

$$\Omega_b \sin i = \frac{\int_{-\infty}^{+\infty} h(Y) \int_{-\infty}^{+\infty} \Sigma(X, Y)\, V_{LOS}(X, Y)\, dX\, dY}{\int_{-\infty}^{+\infty} h(Y) \int_{-\infty}^{+\infty} X\, \Sigma(X, Y)\, dX\, dY} \equiv \frac{\langle V \rangle}{\langle X \rangle},$$





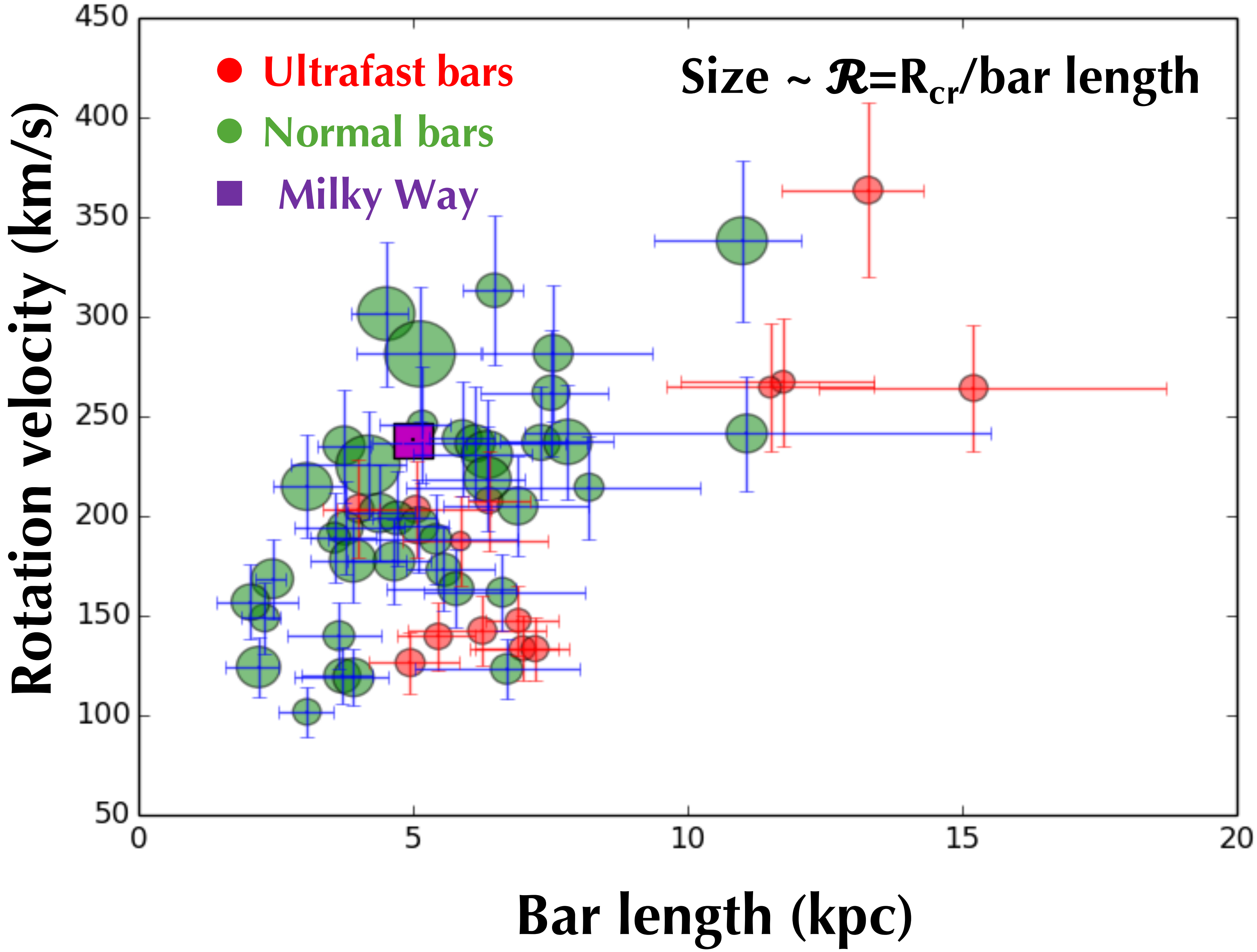




MaNGA bar Sample

- 235 bar candidates
- 53 final bar sample with good quality and 0.3<b/a < 0.8.

Is our milky Way bar special?



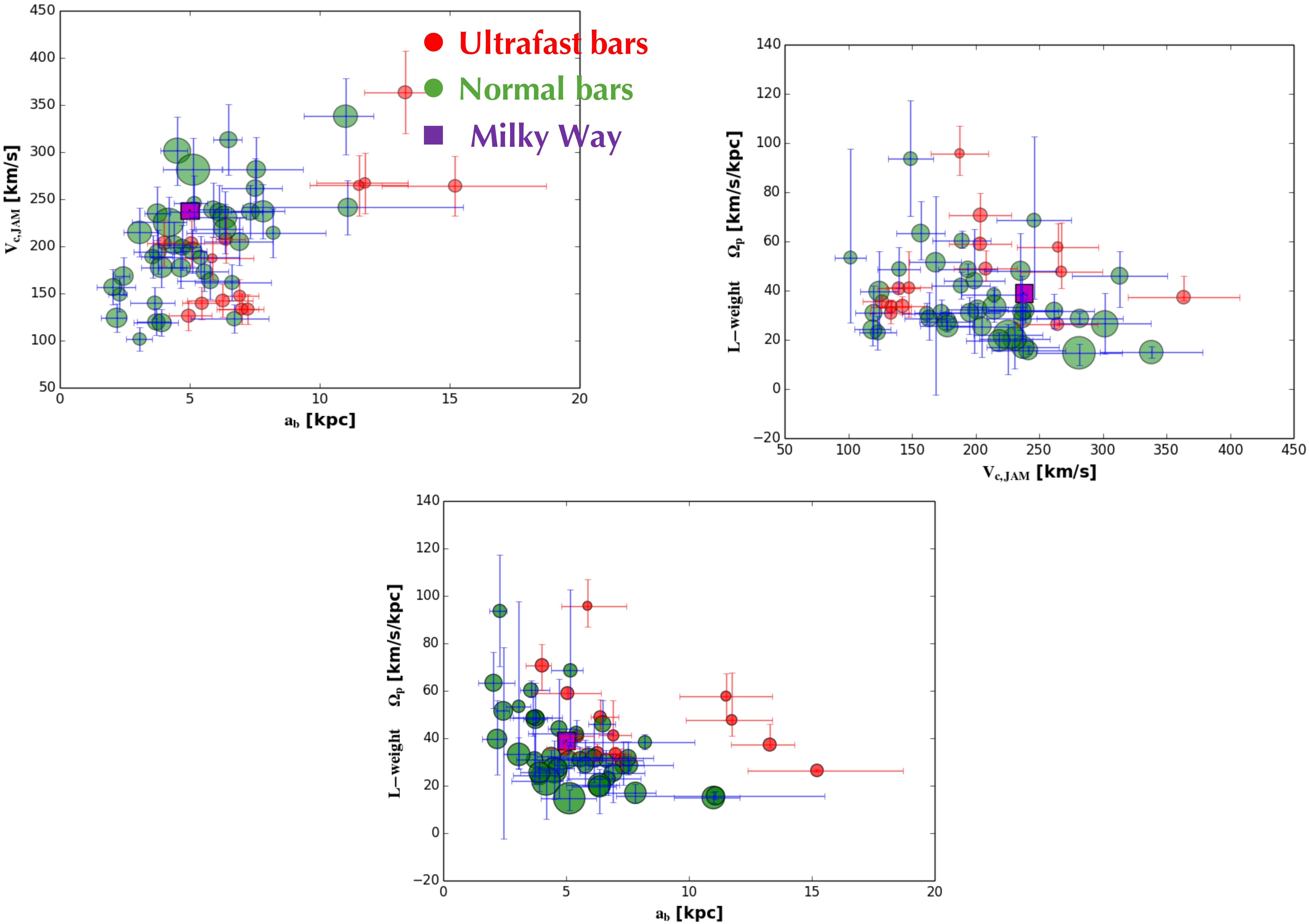
Guo, Mao et al. (2017)

- Ultrafast bars ($\mathcal{R}$<1) should not exist!!!

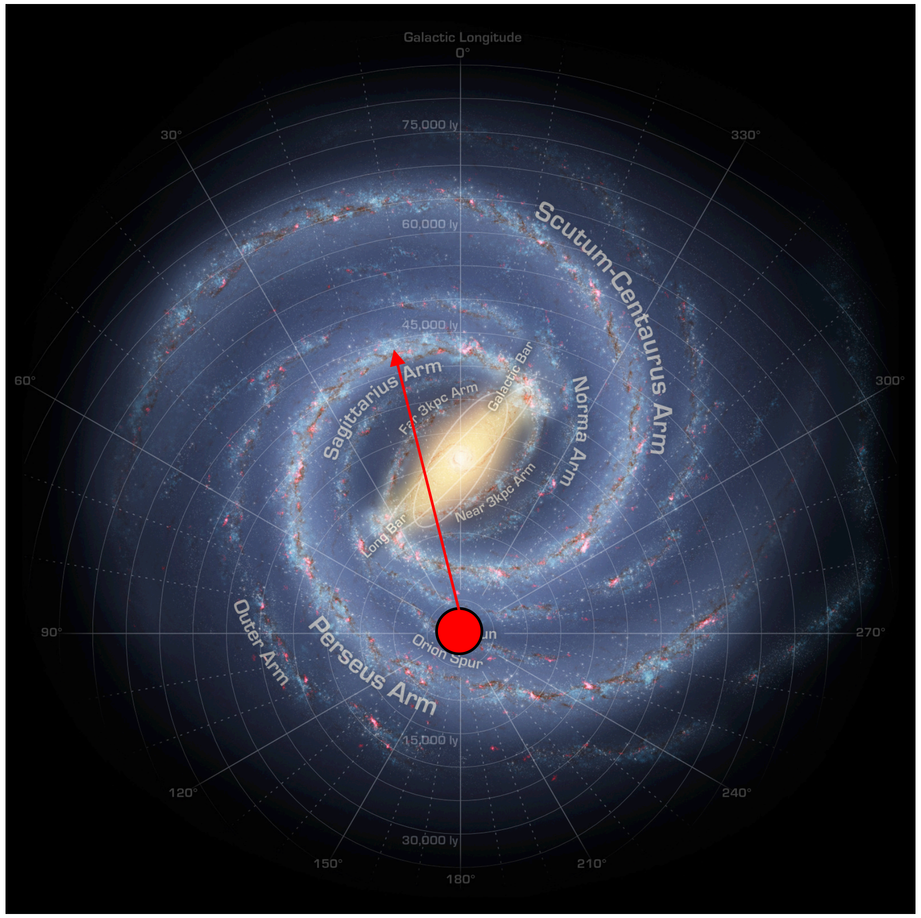
Summary

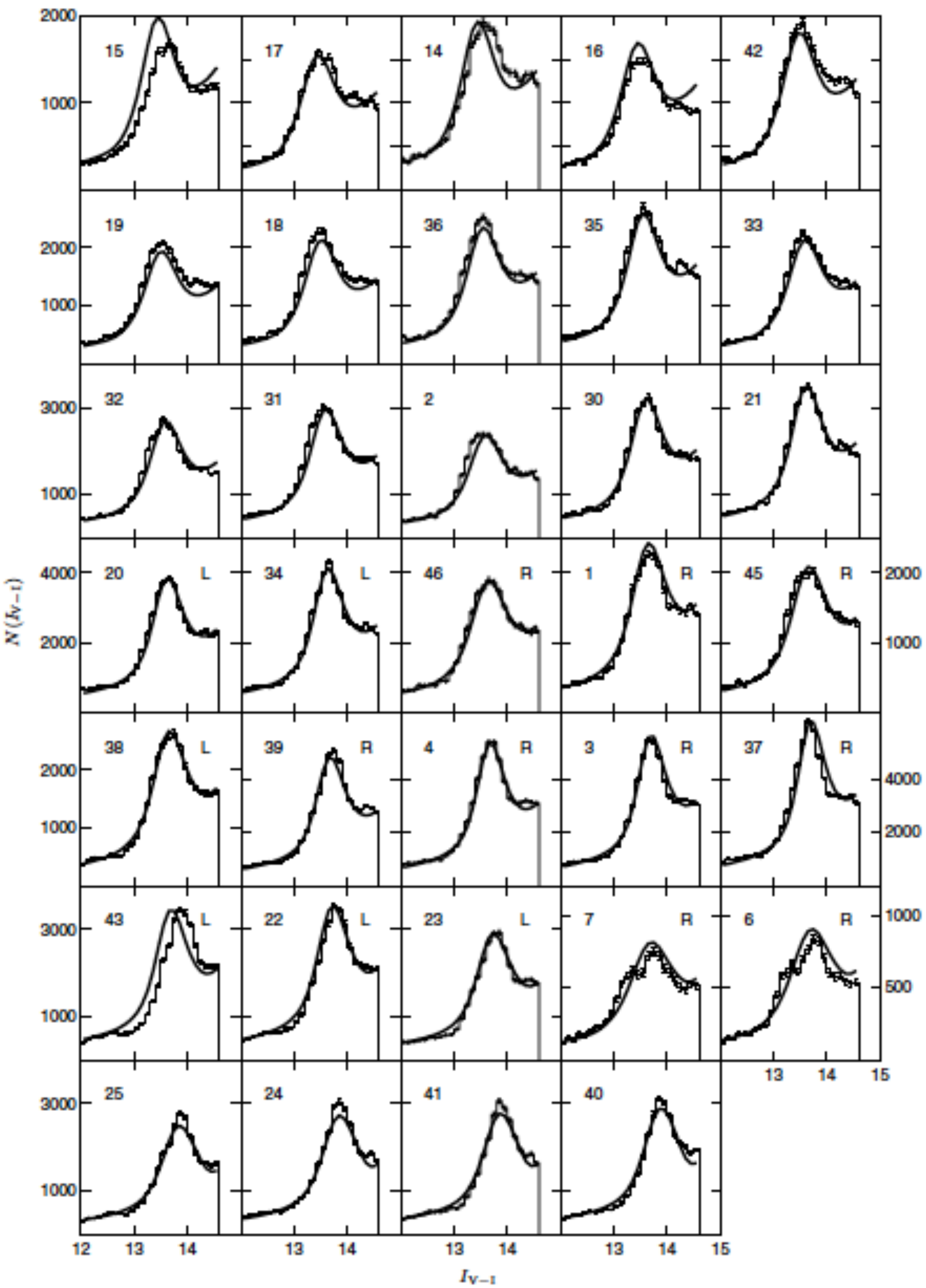
- **Despite initial scepticisms, the field is now very healthy**
- **More work remains to be done**
  - More general triple/quadruple lensing modelling?
  - Determination of the binary mass function (Trimble 1990) and separation distribution (Abt 1983) with a mass-selected sample
  - Are there differences in the IMFs between bulge/disk? (Li, Mao et al. 2016)
  - New proper motion catalogues from OGLE-III, IV?
  - complementary with GAIA, and useful for dynamical modelling

Is our milky Way bar special?



Red clump giants luminosity function

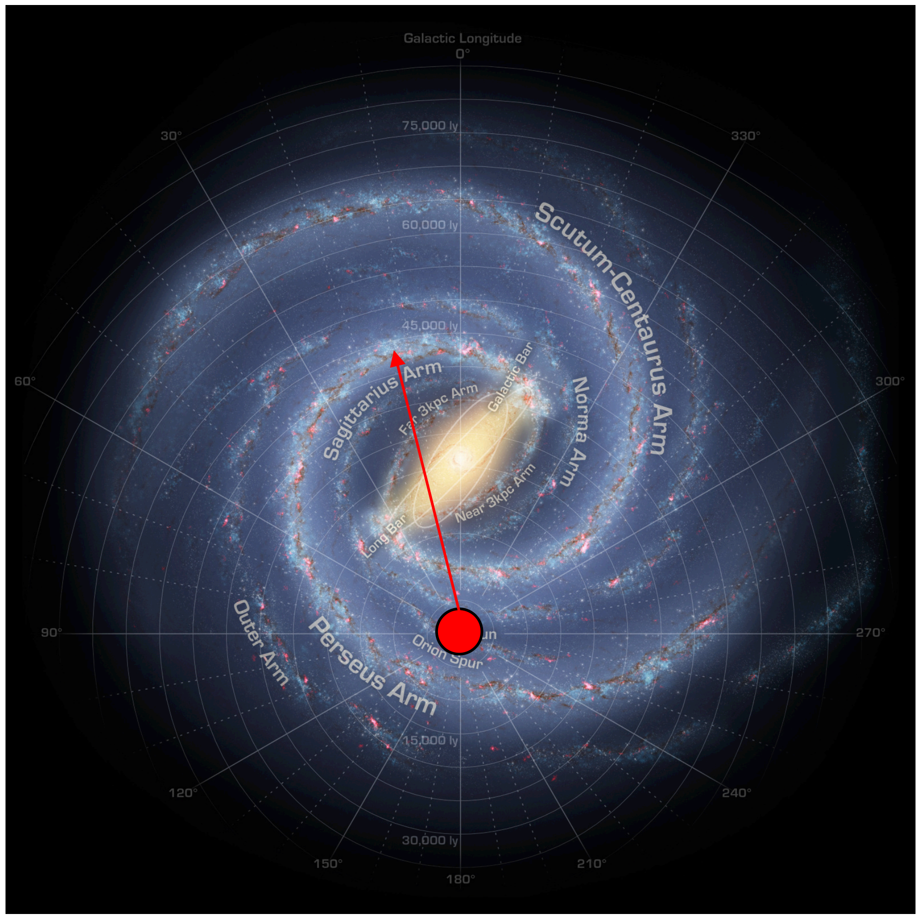


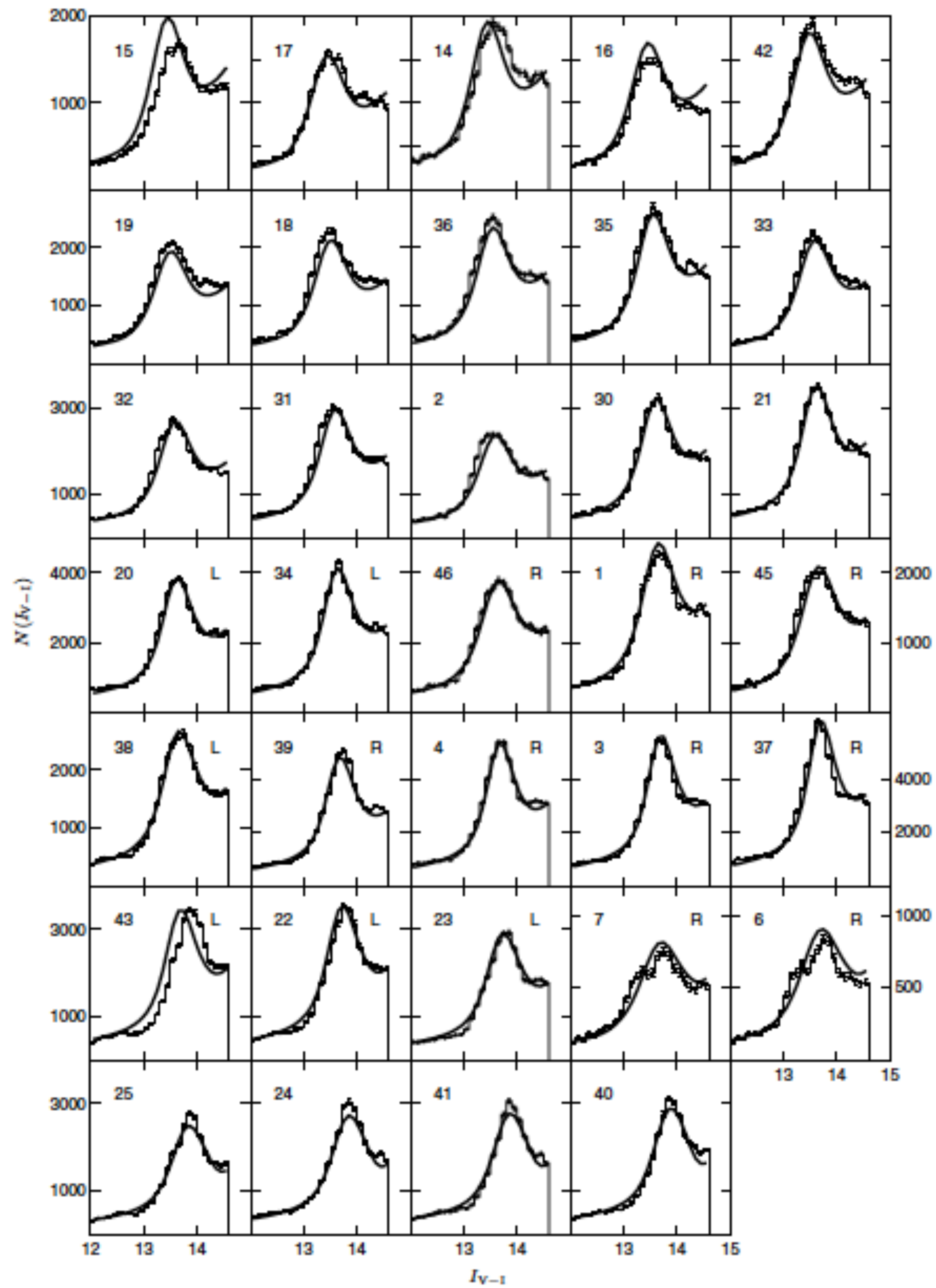


For each field, we can obtain

- luminosity function
- integrated number counts

Red clump giants luminosity function





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- luminosity function
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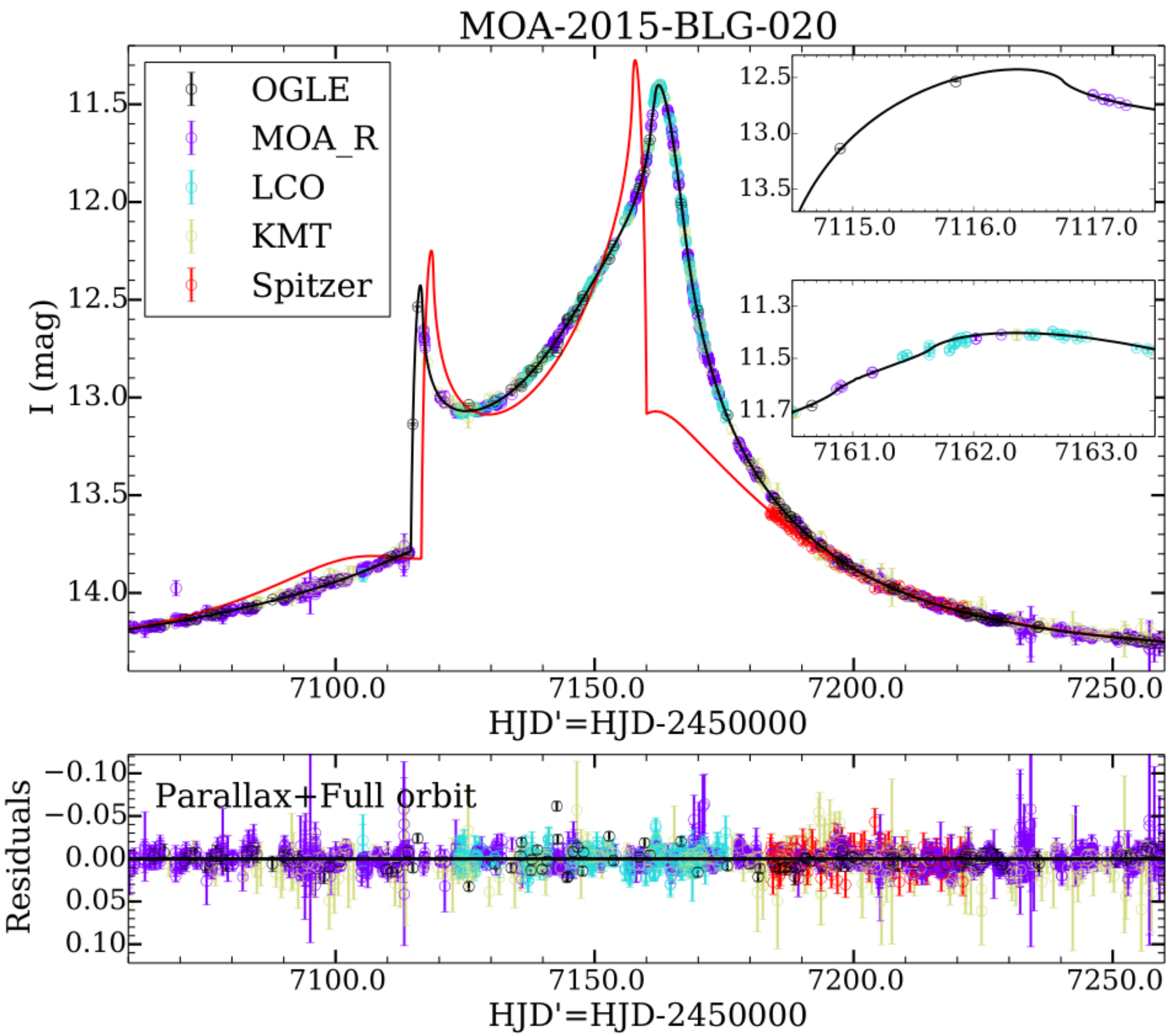
Satellite parallax: MOA-2015-BLG-020



θ_E (mas)	1.329±0.049
π_{rel} (mas)	0.296±0.017
M_1 ($M_\odot$)	0.606±0.028
M_2 ($M_\odot$)	0.125±0.006
Distance to lens (kpc)	2.44±0.10
Projected separation (AU)	4.04±0.23
Geocentric proper motion (mas yr^{-1})	7.64±0.28

- The parallax fitted from ground based data is confirmed by Spitzer data

- Two M dwarf stars located in Galactic disk

Wang, Zhu, Mao et al. (2017), ApJ, in press

Future microlensing in China

- **two 1m telescopes to be built in Tibet: $2.5m + $1.5m**

- **to reap science benefits, building up time-domain expertise**
  - Joined RoboNET through LCO
  - TESS followup – long period planets and TTV

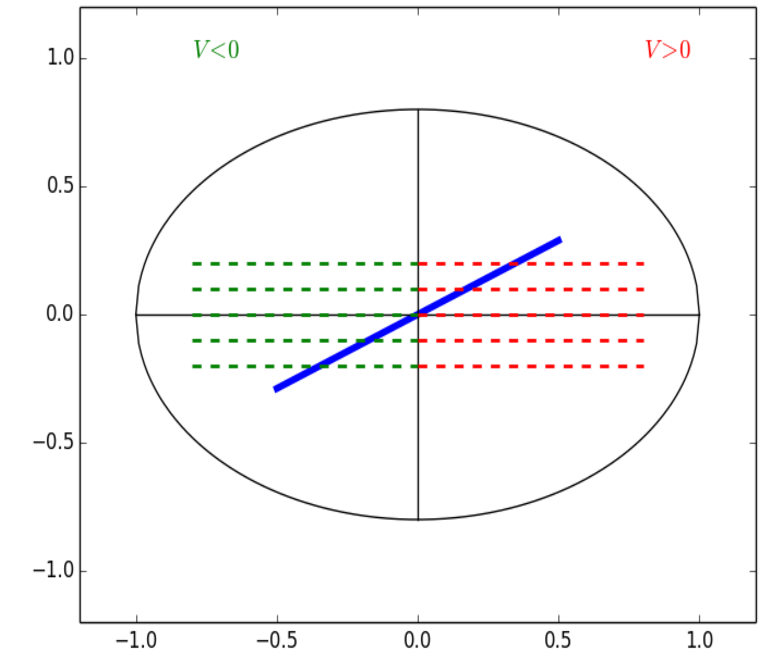
- LAMOST spectroscopic followup of Kepler/TESS targets

After 2019: ~2500 hours

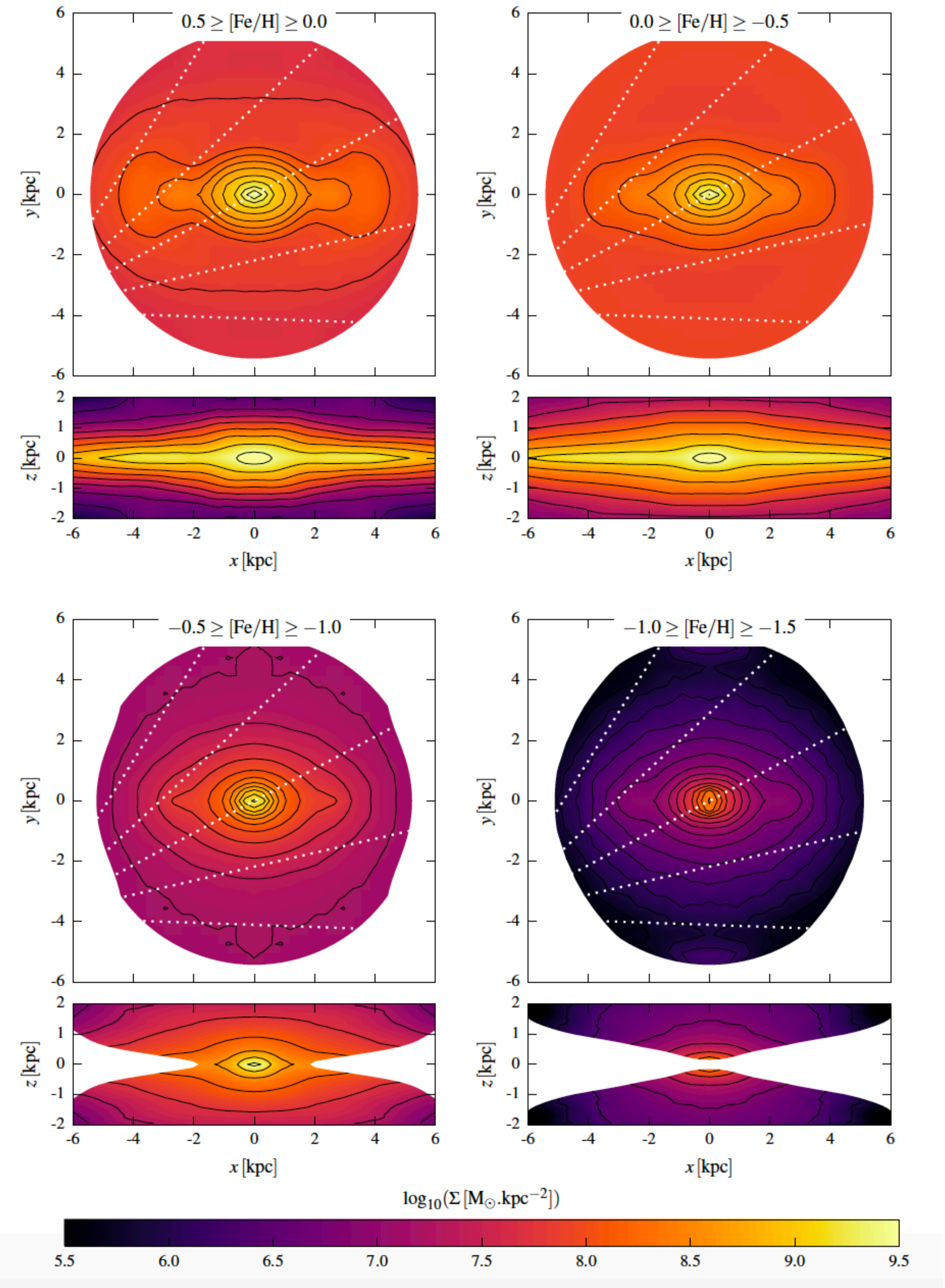
1.1 Pattern Speed: TW method

- Tremaine & Weinberg method (1984):

$$\Omega_b \sin i = \frac{\int_{-\infty}^{+\infty} h(Y) \int_{-\infty}^{+\infty} \Sigma(X,Y)\, V_{LOS}(X,Y)\, dX\, dY}{\int_{-\infty}^{+\infty} h(Y) \int_{-\infty}^{+\infty} X\, \Sigma(X,Y)\, dX\, dY} \equiv \frac{\langle V \rangle}{\langle X \rangle},$$

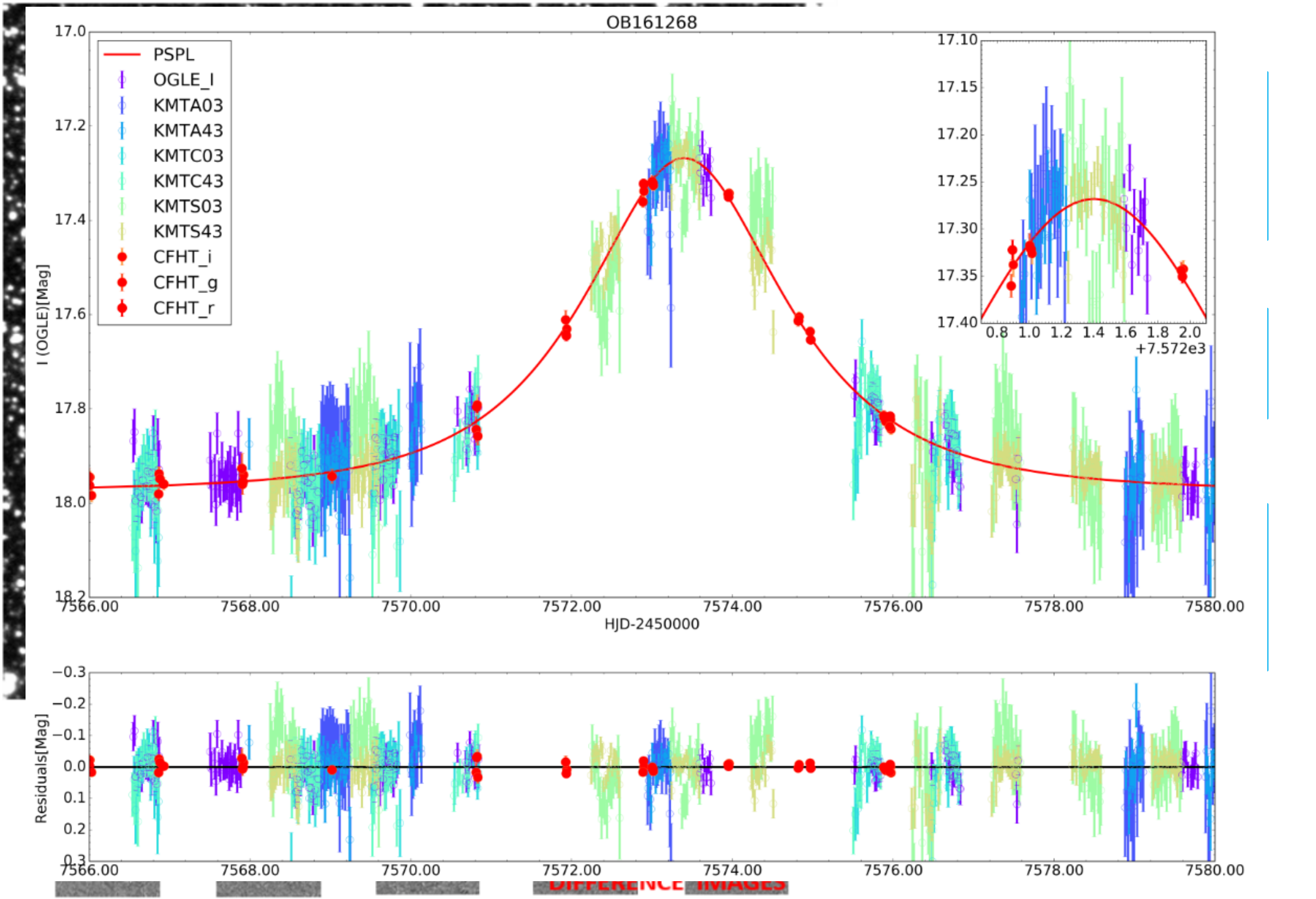


- Basic assumption
  - flat disc; a well--defined Ω_p ,
  - surface brightness of tracer obeys the continuity equation
- Error source: centering error; S/N; uncertainties of PA; dust obscuration and star formation; slits



Face-on and side-on surface densities of the fiducial model in the four metallicity bins obtained after fitting the ARGOS and APOGEE chemo-kinematic data.

Data reduction

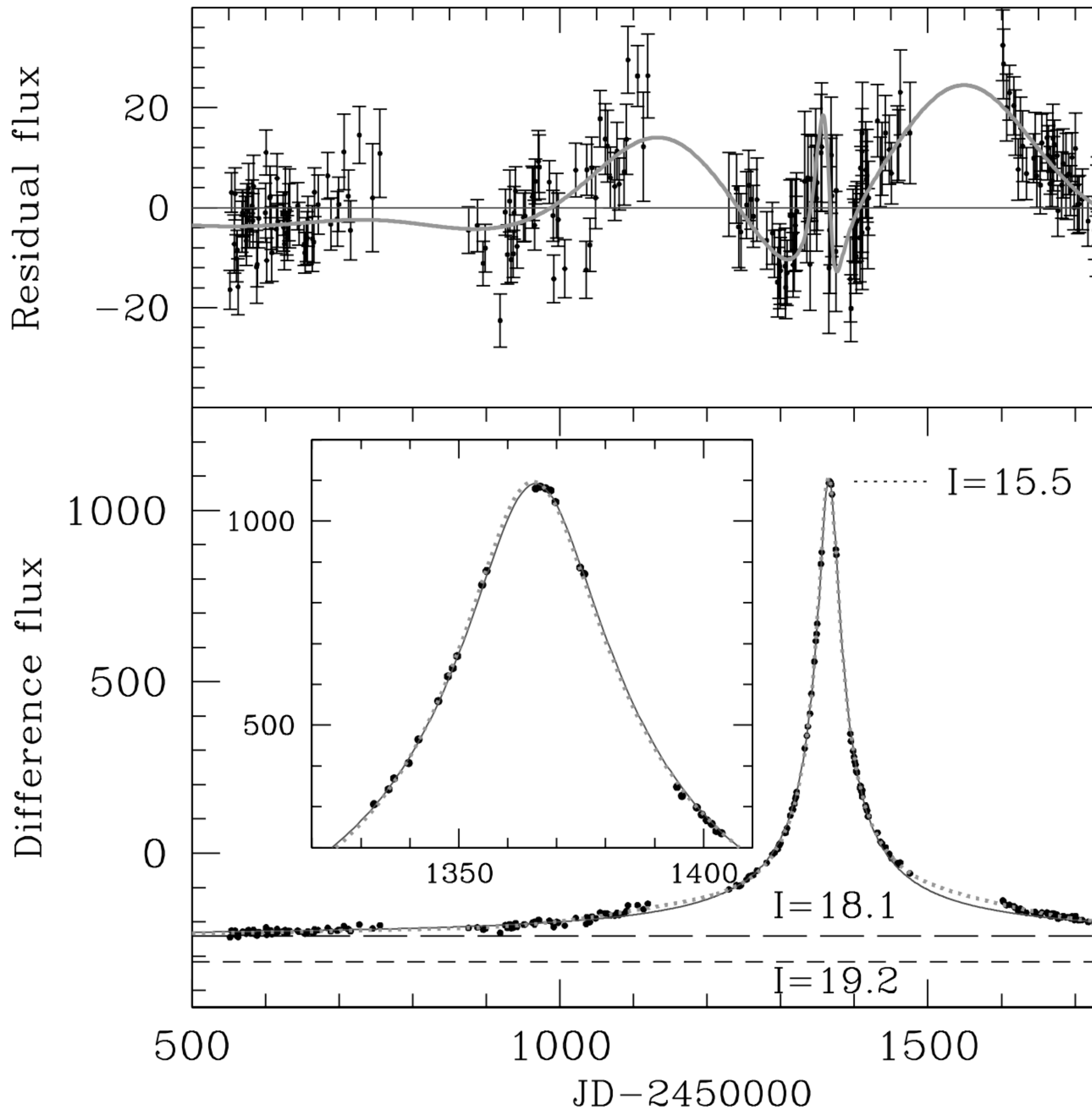


Modelling of parallax events

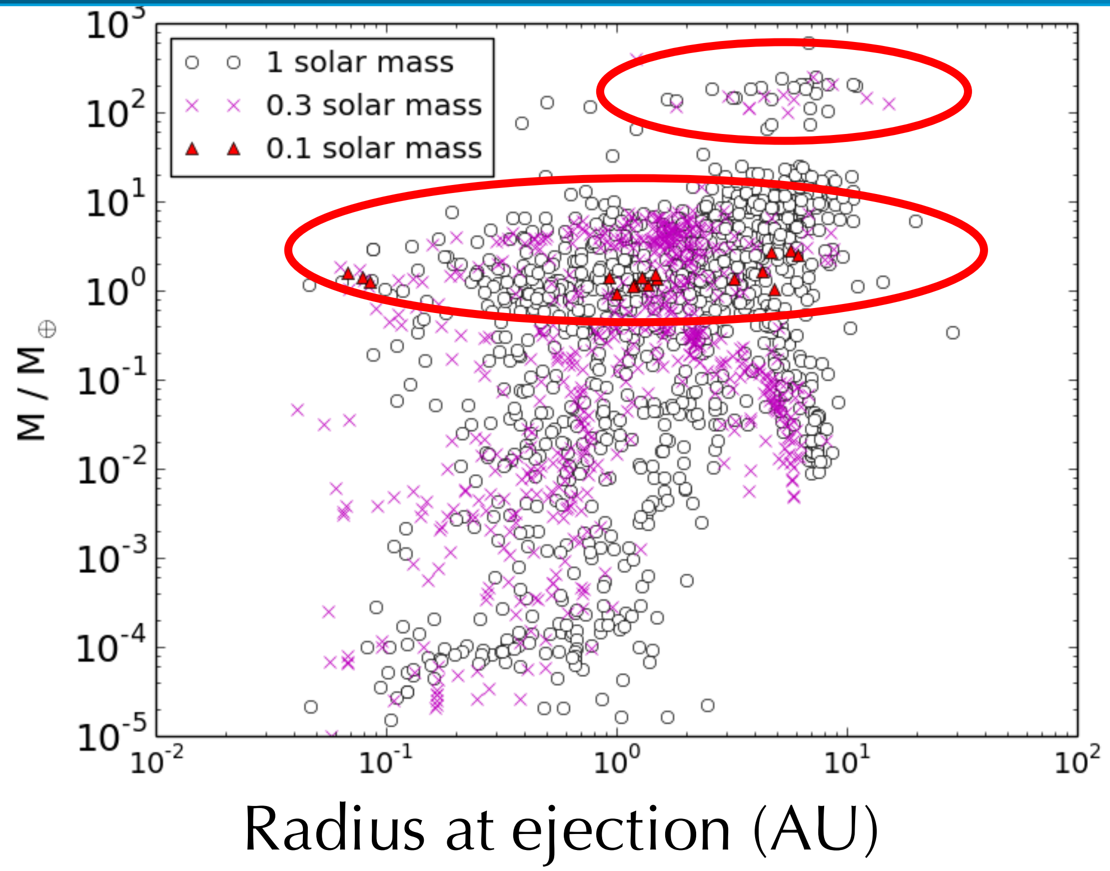
Smith, Mao & Wozniak (2003) has performed a detailed analysis of long events in the ogle database.

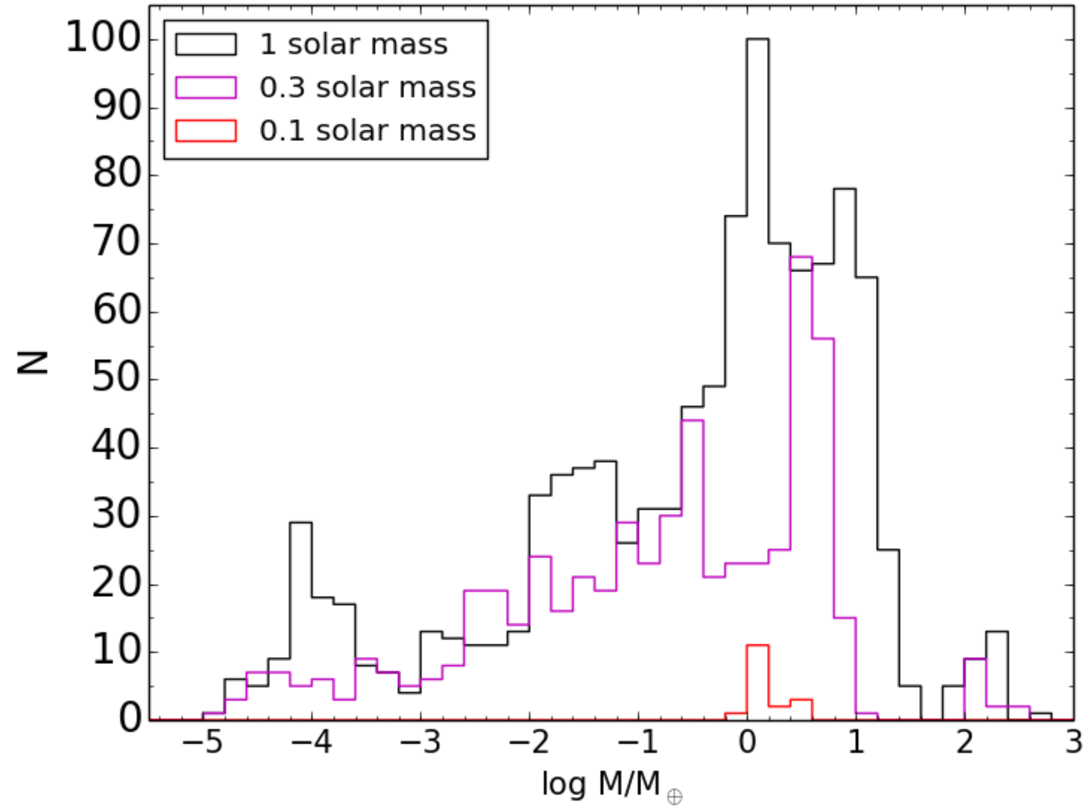
Optical Gravitational Lensing Experiment OGLE-1999-BUL-32: the longest ever microlensing event - evidence for a stellar mass black hole?
tE=1495 days, u0=0.01 (Mao et al. 2002)

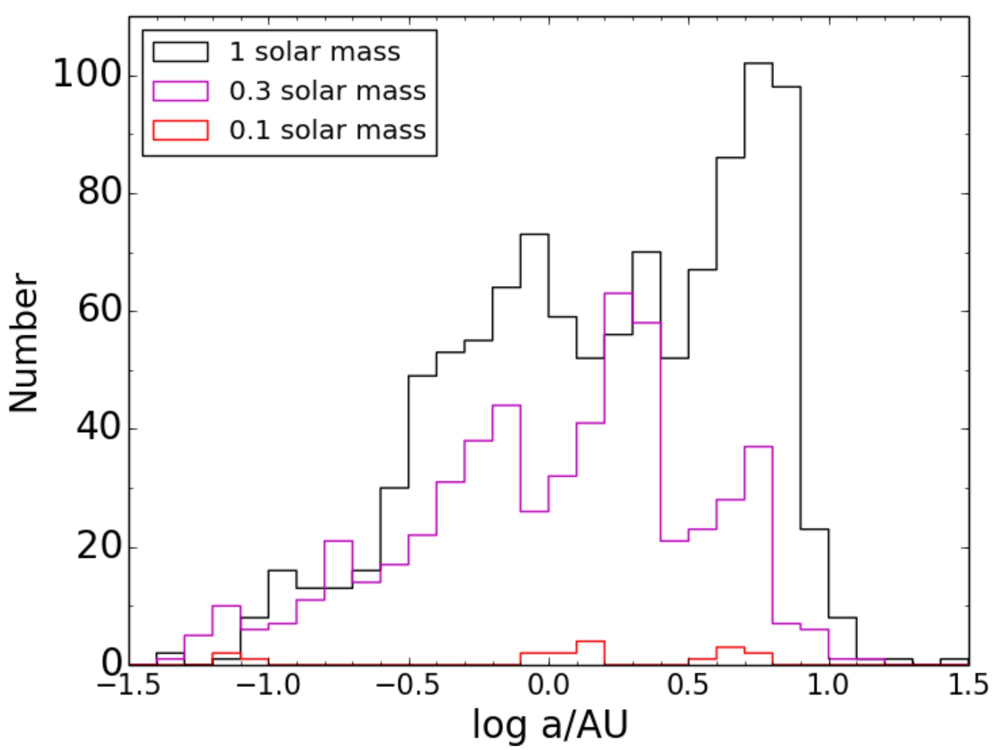
Much better works have been done
By ????



Properties of free-floating planets



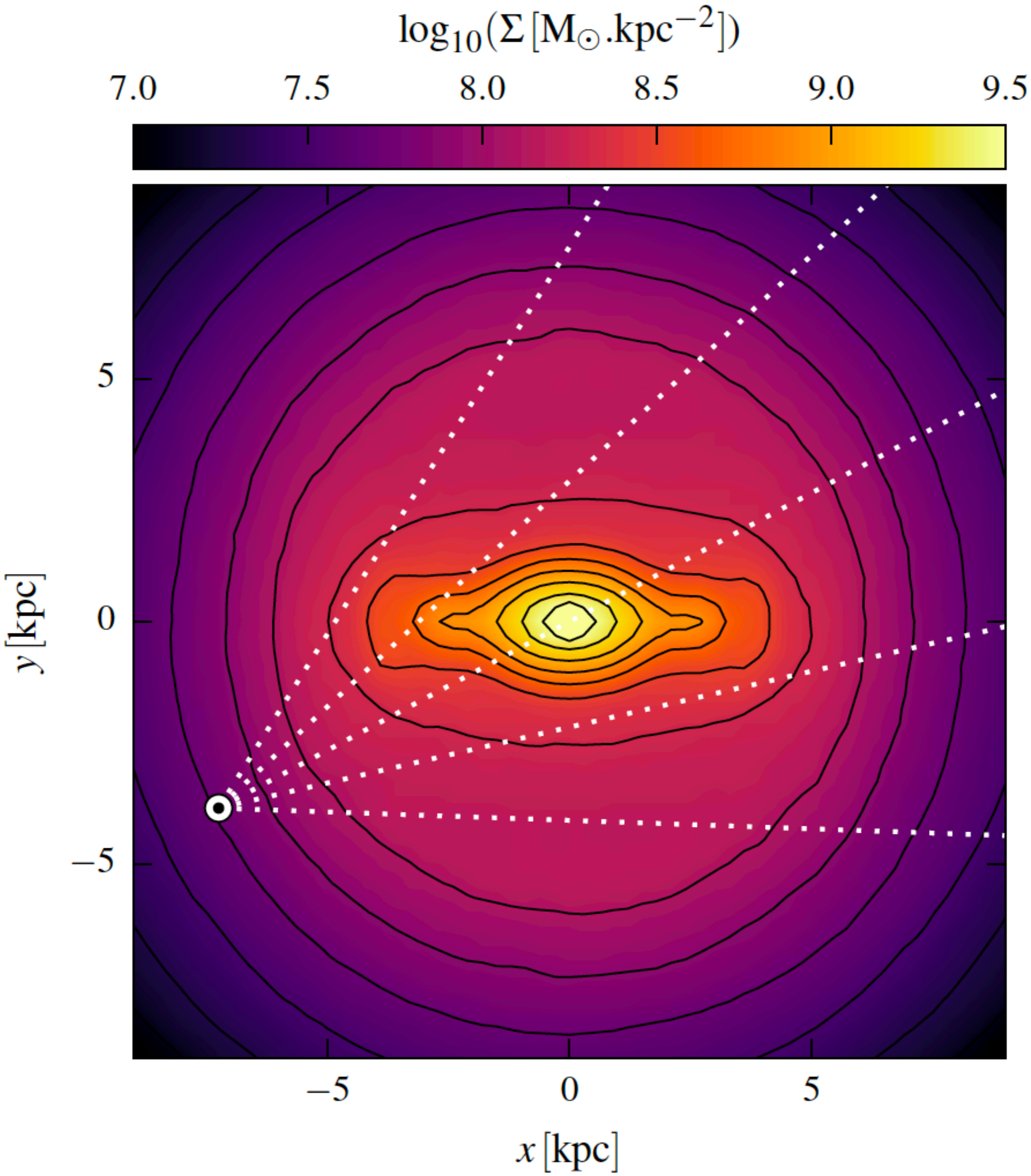




Simulated 1000 planetary systems for 1, 0.3 and 0.1 solar masses:

- 1 solar mass, 1069 ejected planets
- 0.3 solar mass, 571
- 0.1 solar mass, 17

Summary of Gerhard's group's work



- **28 degrees**
- **40km/s/kpc**

- **Portail, Gerhard, Wegg & Ness (2017)**

Summary & open questions

- Photometric modeling
  - prefers a short, exponential bar, angle=33 deg
- Dynamical models can fit the radial velocity data (too easily!)
- Open questions
  - Model appears to be stable only for 1Gyr
  - Predicted proper motions are too anisotropic compared with observations

Future outlook

- Lots of new data to come
  - Photometric data: OGLE-IV and VISTA surveys
  - Kinematic data: ARGOS, APOGEE, OGLE (proper motions), GAIA

- Much theoretical work yet to be done
  - Needs to incorporate post-COBE photometric density model
  - Stability issue needs to be further explored