Photometric and dynamical modelling of the Milky Way bar

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Outline

❶ Observed properties of barred galaxies

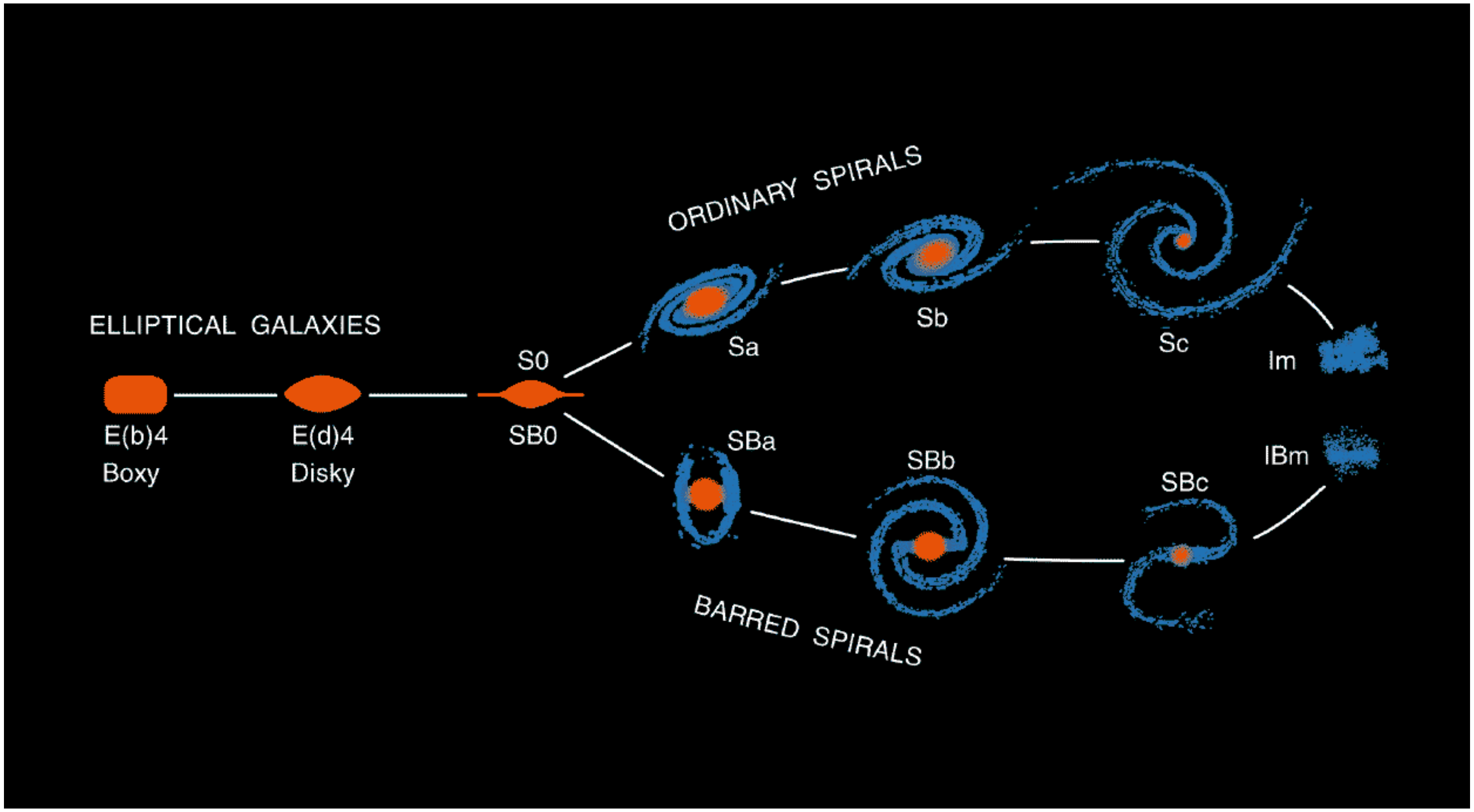
❷ The Milky Way bar

❸ Photometric modelling

❹ Dynamical modelling

❺ Summary and Future Outlook

❶ Overview: Hubble sequence of galaxies

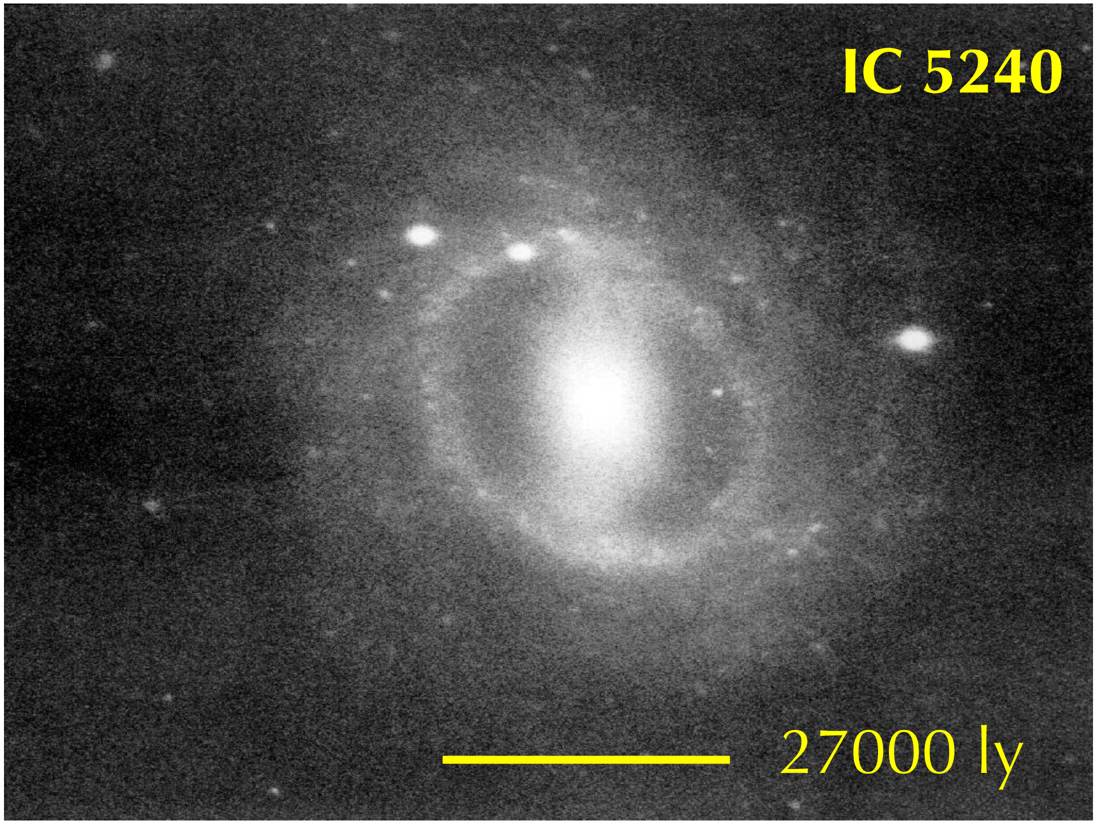


- 2/3 of spiral galaxies host bars, especially in infrared
- Understanding of the Milky Way bar is key to understanding other barred galaxies in the Universe

Barred galaxies in the Universe

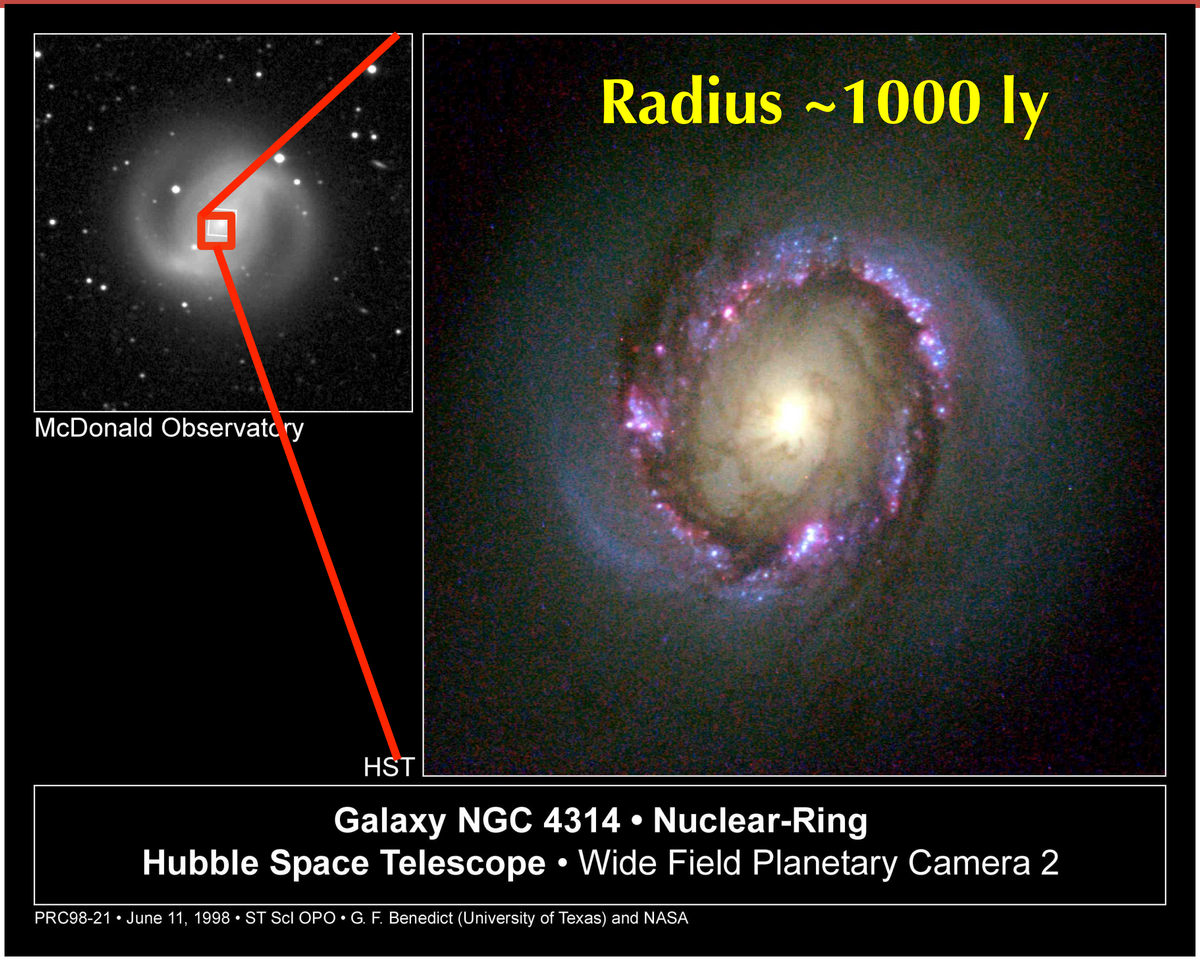
- Bars are straight – rigid angular pattern speed
  - ✓ no winding up due to differential rotation!
- Bars often host dust lanes & vigorous star formation at the end of bars

Rings in Barred galaxies



- Barred galaxies often show rings of star formations
- IC 5240 has an outer ring (~4 kpc) at the end of bar

Rings in Barred galaxies

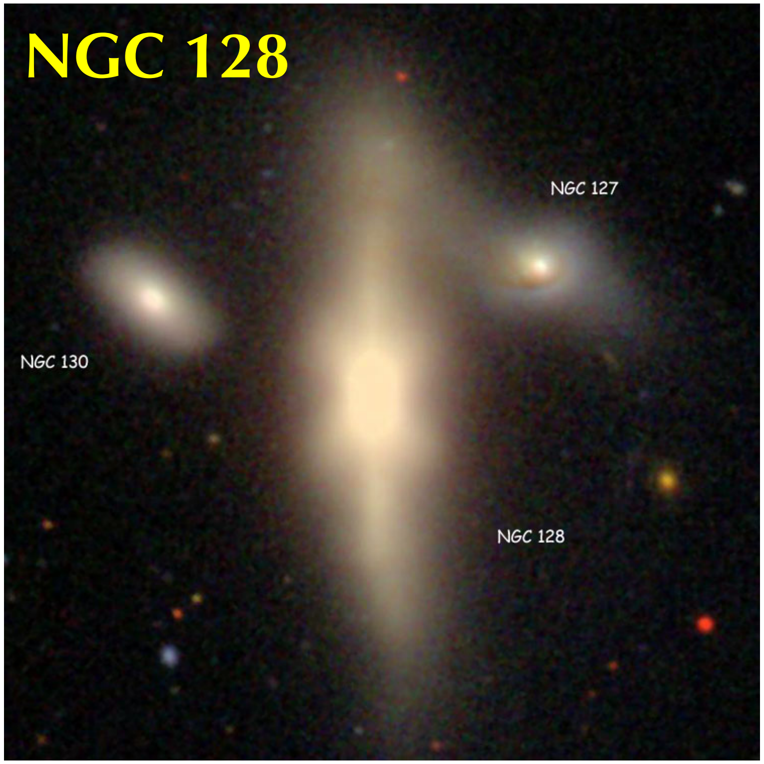


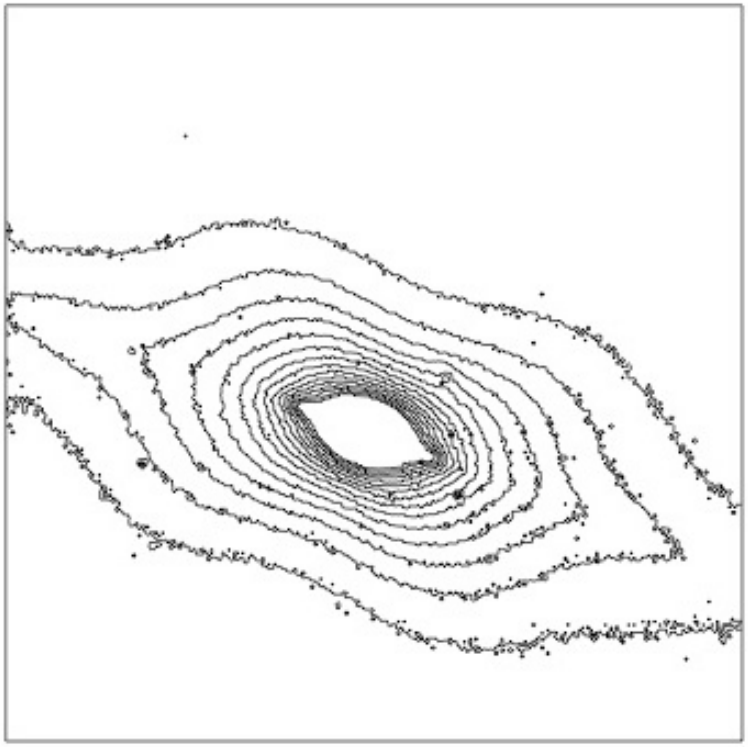
Rings are thought to be associated with resonances in barred galaxies.

Boxy/peanut-shaped barred galaxies

- edge-on barred galaxies often exhibit boxy or peanut shapes
- They follow more complex kinematics

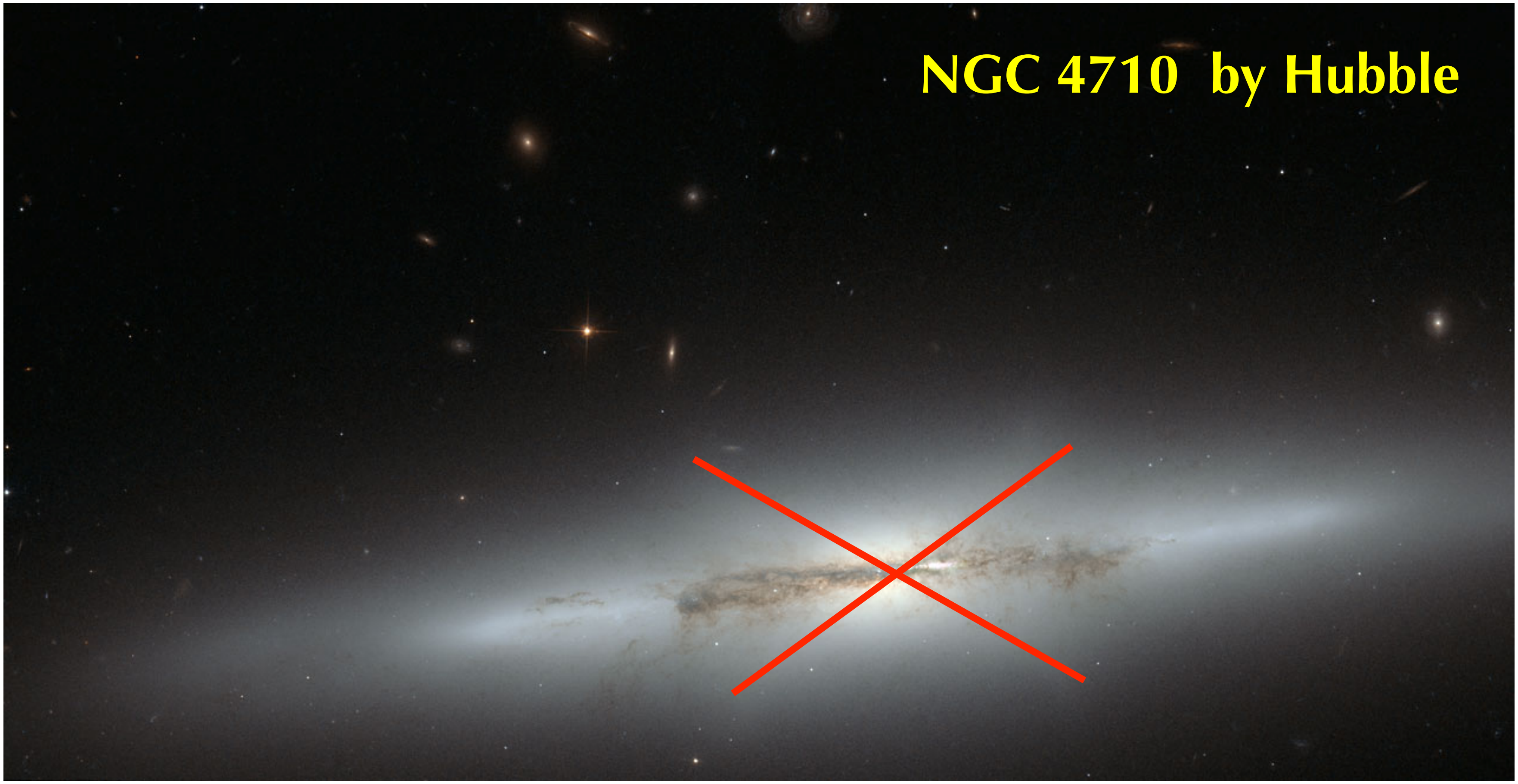
Peanut-shaped galaxy NGC 128



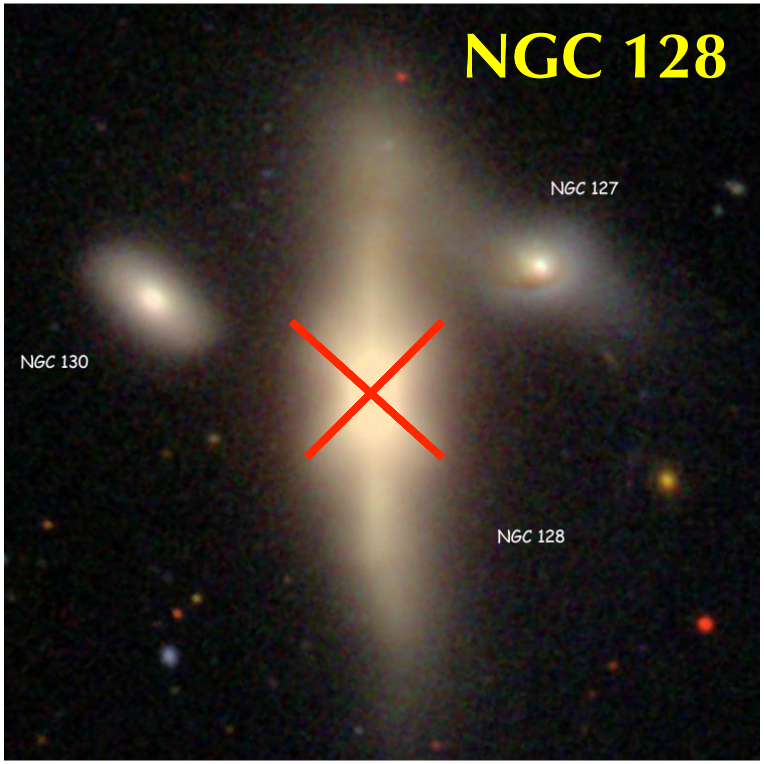


- Located in a group of five galaxies.
- External tidal origin (Li, Mao et al. 2009) or internal secular evolution?

X-shaped Structure



X-shaped structure

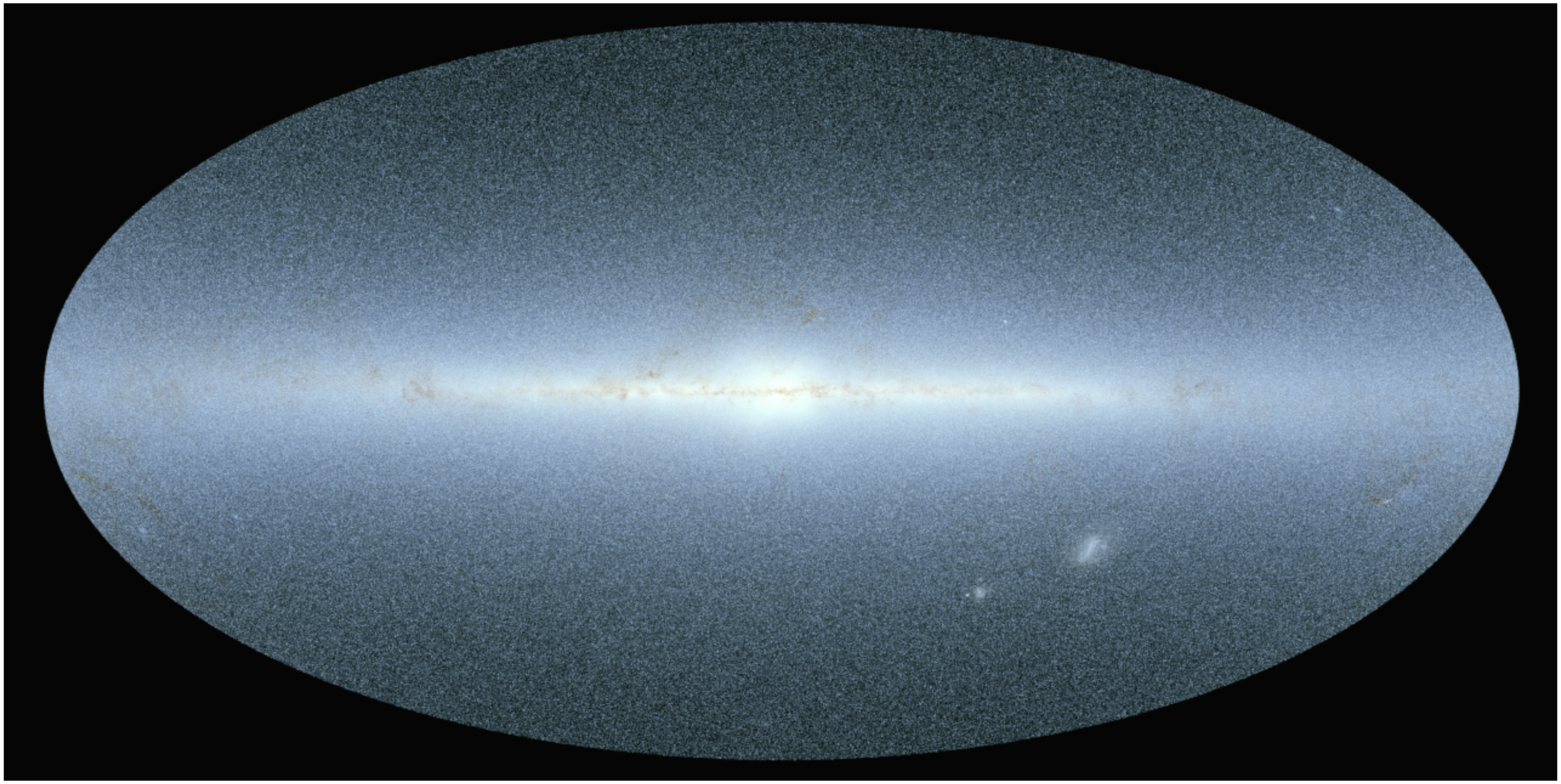


- X-shaped structure may be related to resonant orbits

Summary: barred galaxies

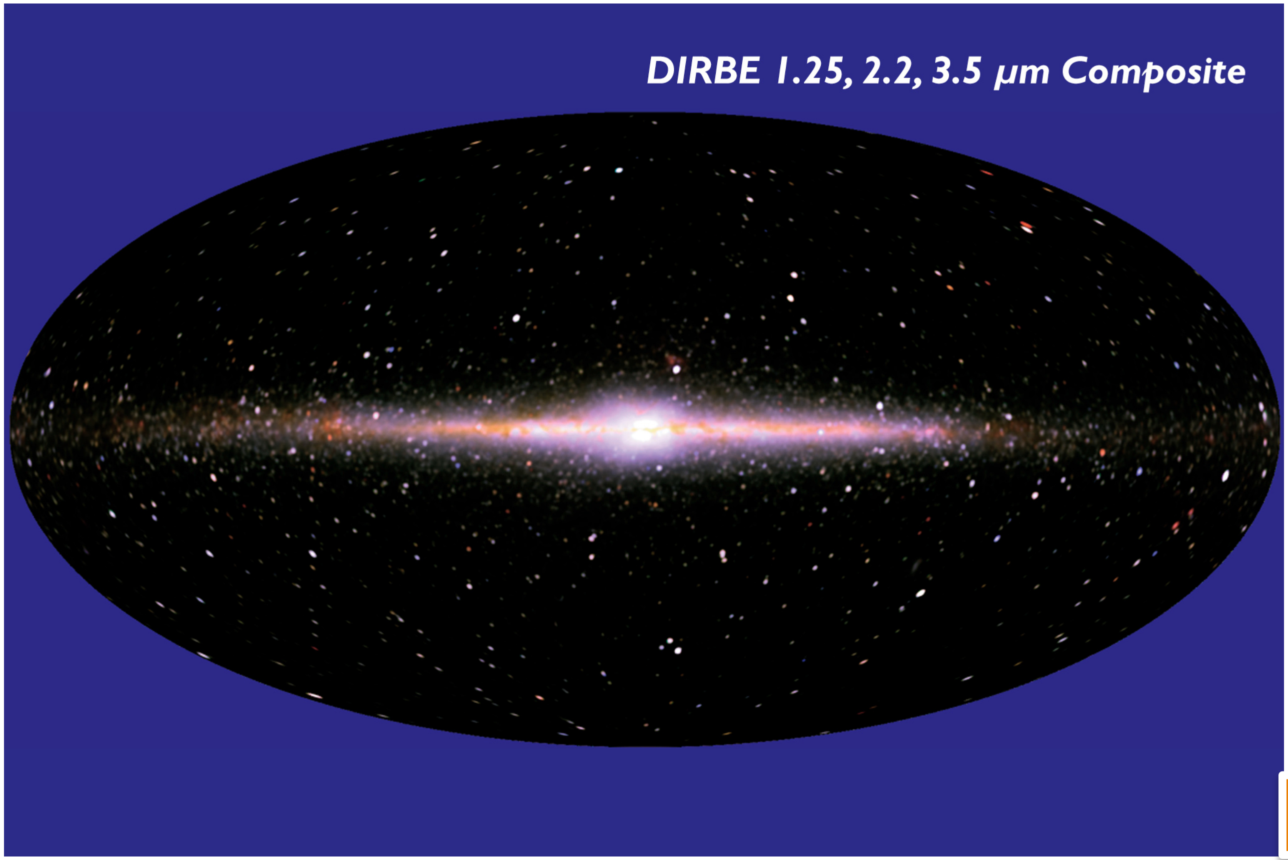
- Barred galaxies are very common
  - ➢ Straight → rigid rotation.
  - ➢ Dust lanes (gas streaming motions).
  - ➢ Rings of star formation (resonances).
- Edge-on bars
  - ➢ exhibit as boxy, peanut-shaped or X-shaped galaxies.
  - ➢ Kinematics are more complex.
- They likely form via internal secular (long-term) evolution.

❷ The Milky Way bar



2MASS NIR images of the MW: disk + bulge

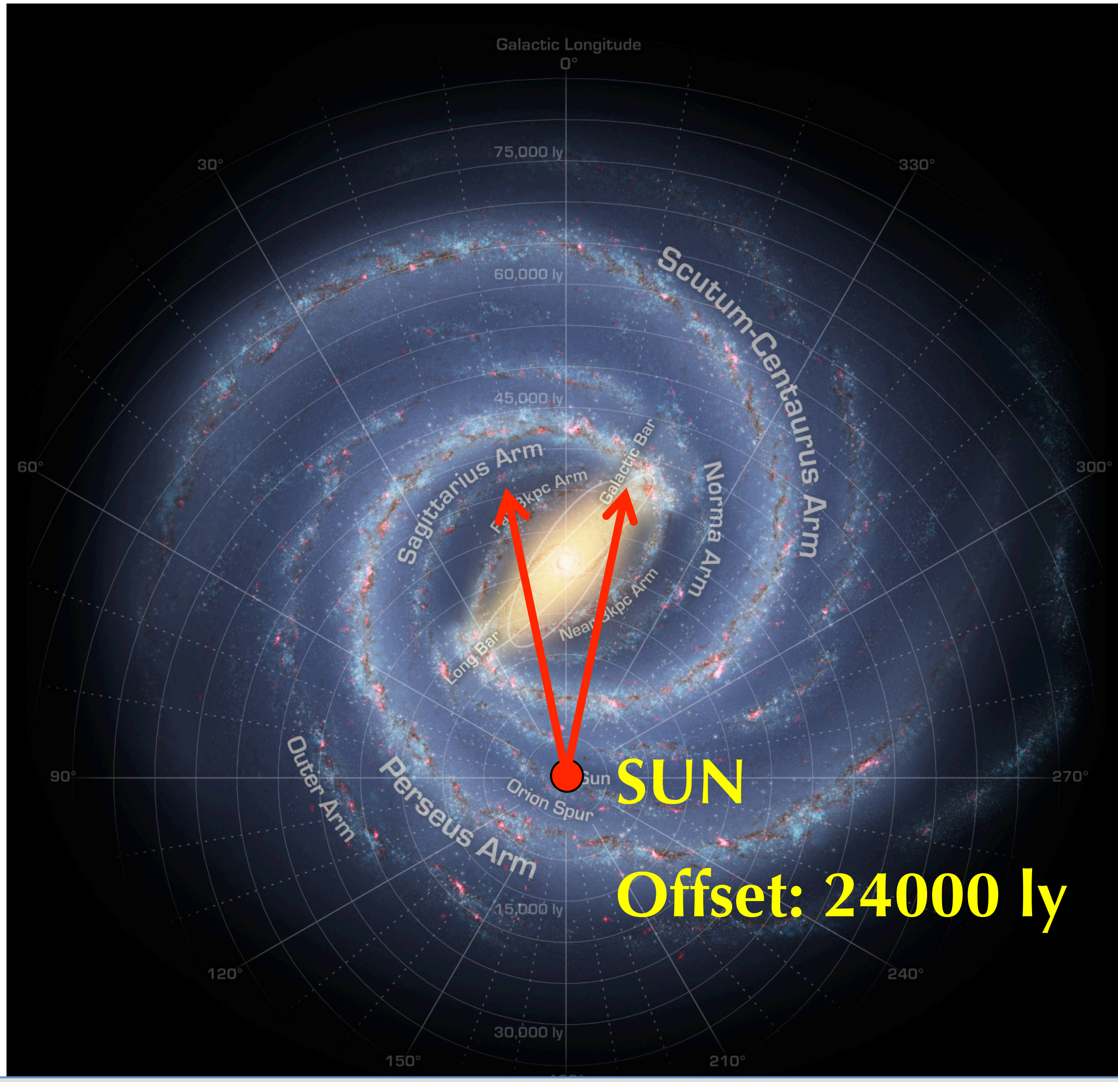
COBE map of the Milky Way bar



Dwek et al. (1995)

- Milky Way from the space satellite COBE.
- The asymmetric shapes implies the presence of a bar.

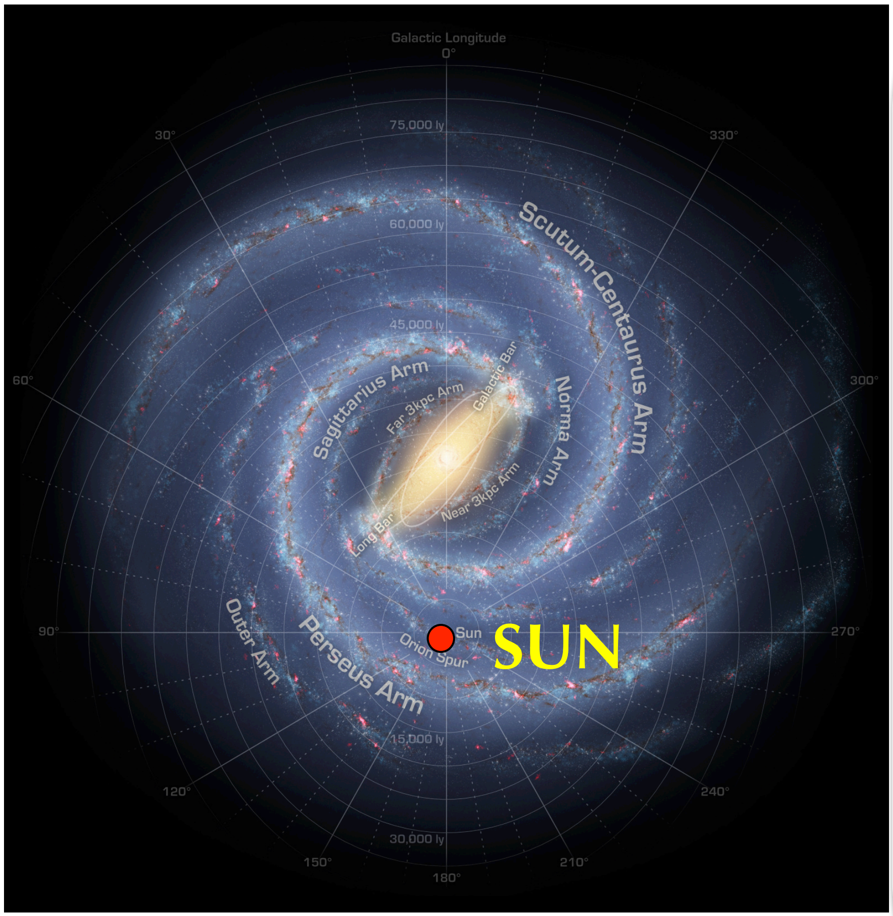
Top-down view of the Galaxy



Credit:
Robert Hurt
(SSC/JPL/
Caltech)

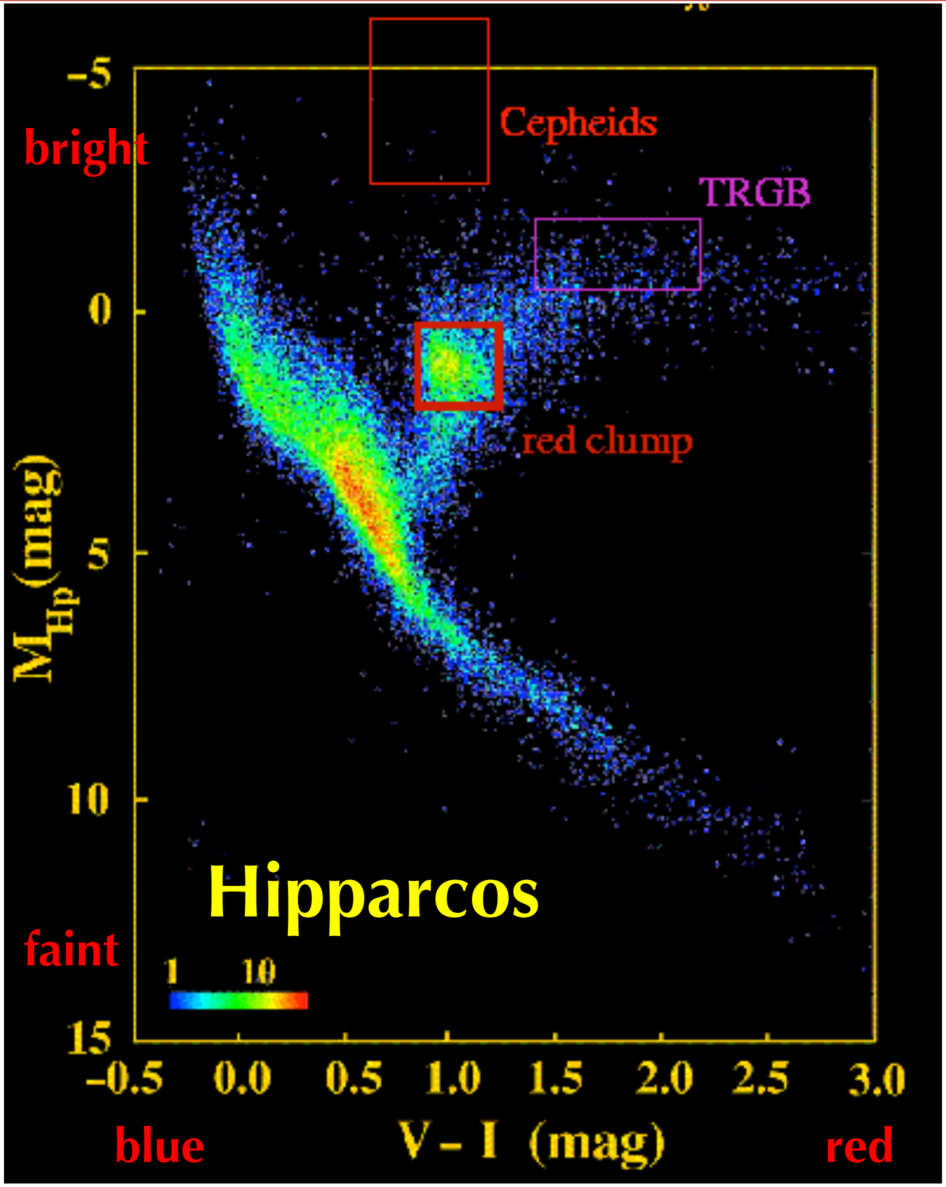
The Milky Way is a beautiful SBc type galaxy

❸ Photometric modelling of the Milky Way bar



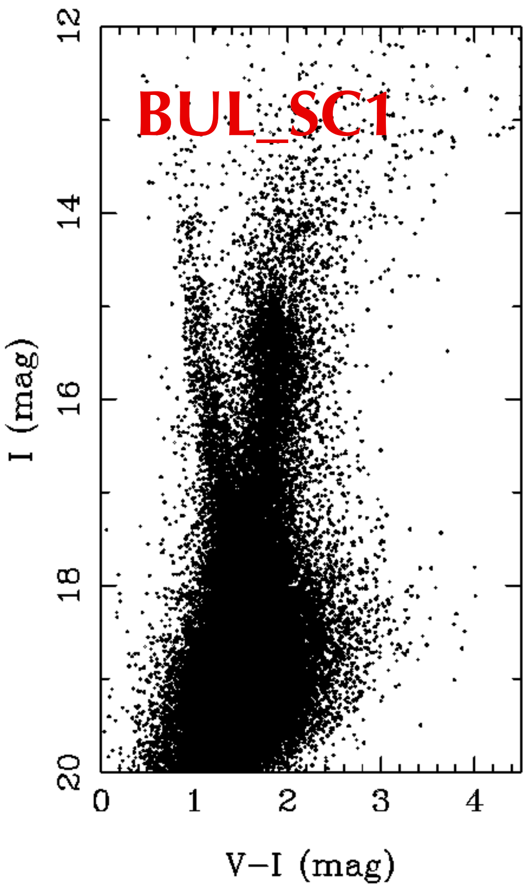
- **Bar basic parameters:**
  - ✓ Bar angle
  - ✓ Bar tri-axial lengths
- **How many bars?**
  - ✓ boxy/peanut bar
  - ✓ Long, thin bar
  - ✓ Super-thin bar
- **Needs tracer populations: RR Lyrae stars, red clump giants**

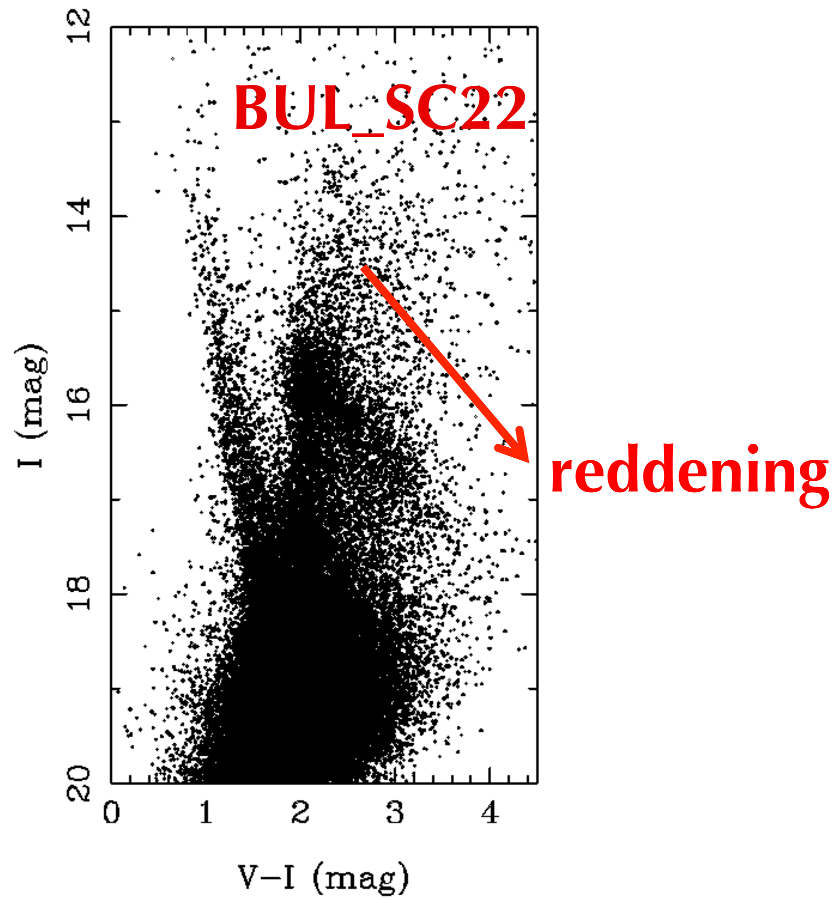
Color Magnitude Diagram close to the Sun



- Red clump giants are metal-rich horizontal branch stars
- Small intrinsic scatter in luminosity (~0.09mag)
- Good standard candles!

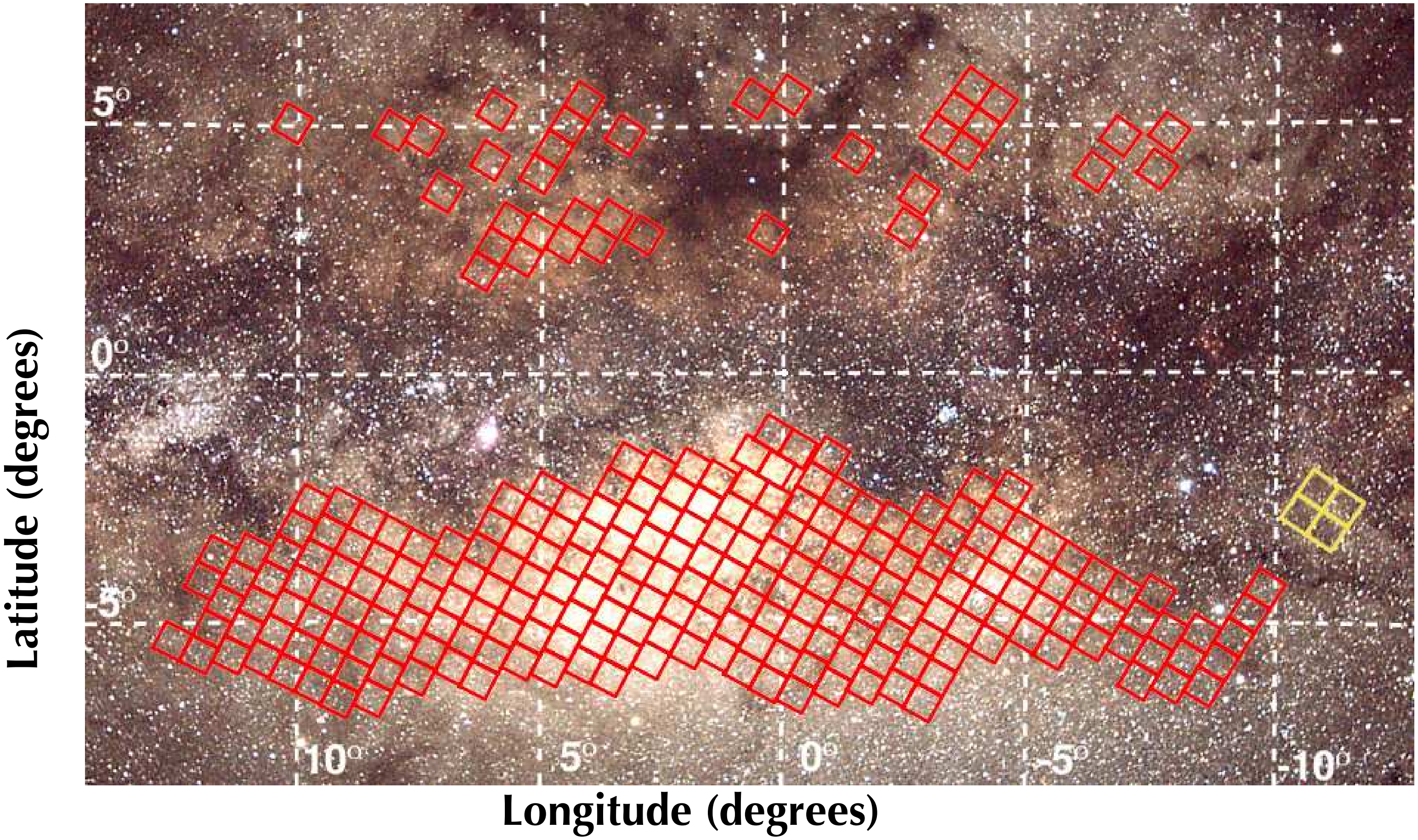
Bulge Color-magnitude diagrams





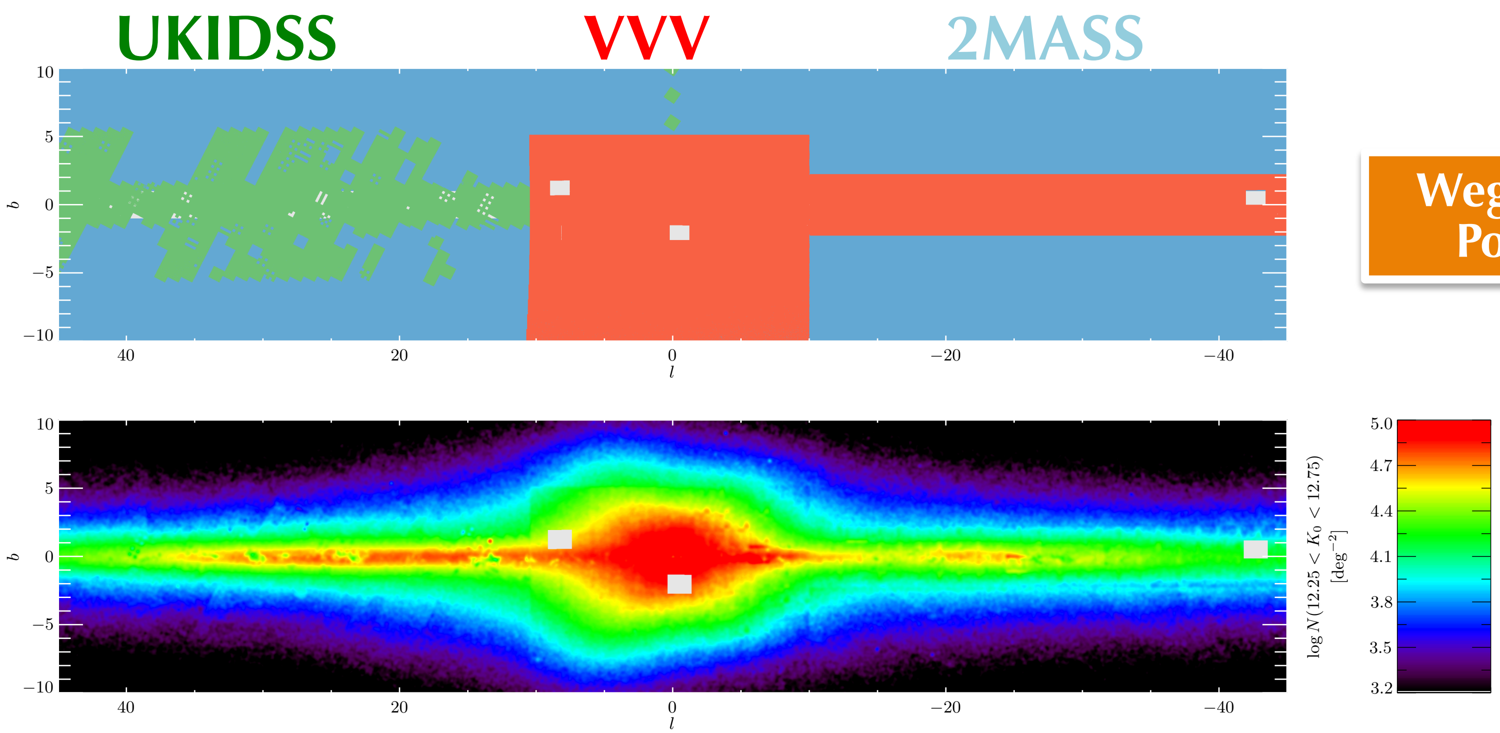
- Observed RCG width is larger in the bulge due to the extension of the bulge.
- Careful studies of RCGs provide a 3D map of the bar.

OGLE-III sky coverage



OGLE-III fields Cover ~ 100 square degrees

Other surveys

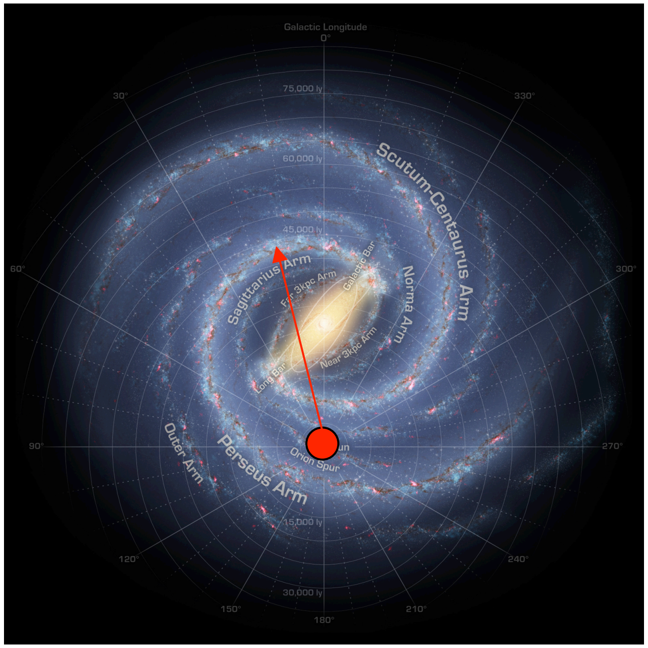


Wegg, Gerhard & Portail (2015)

Views of the Milky Way combining three surveys

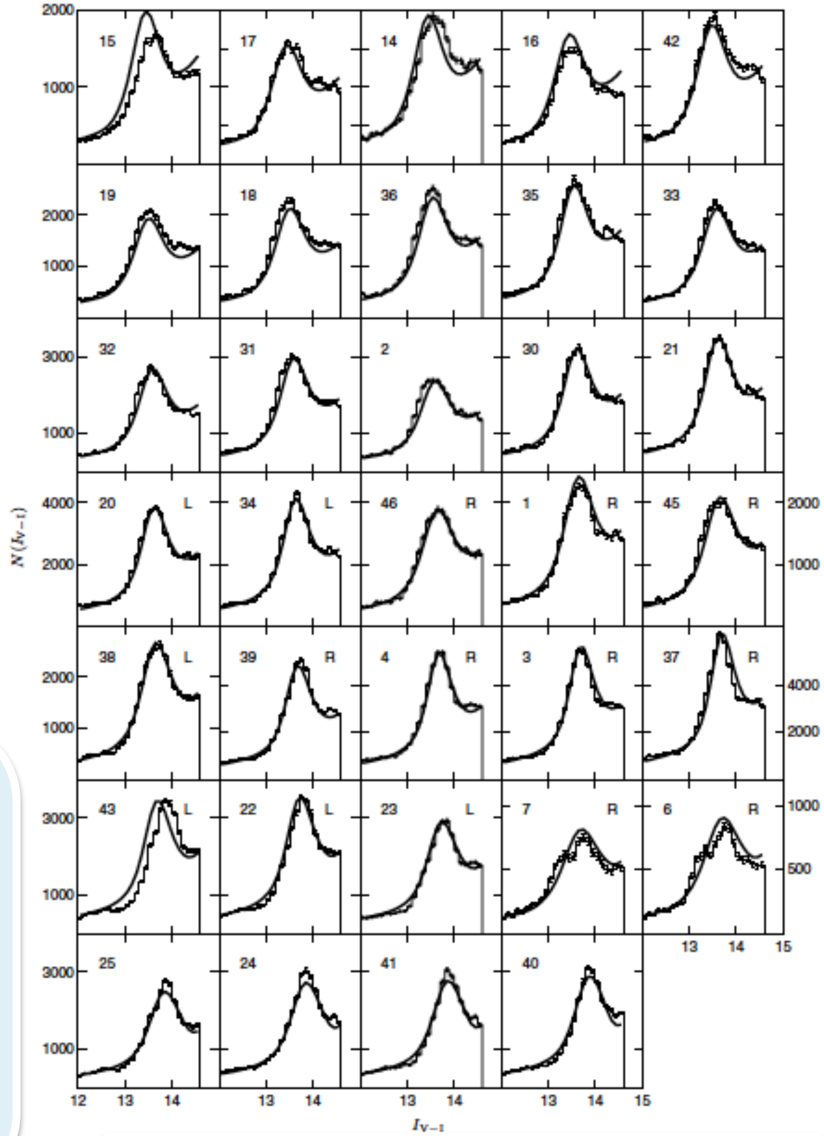
- Vista Variables in the Via Lactea (VVV)
- United Kingdom Infrared Deep Sky Survey (UKIDSS)
- 2MASS

Red clump giants luminosity function



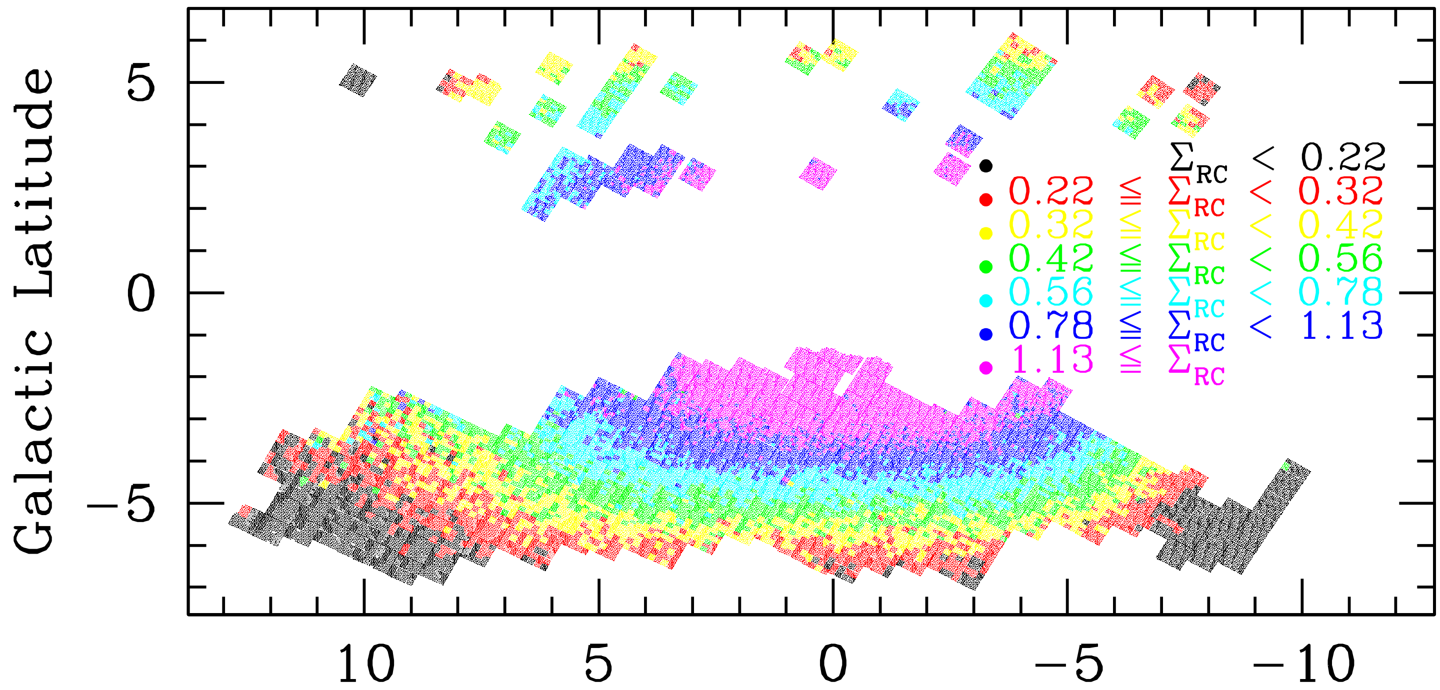
For each field, we can obtain

- **luminosity function (number as a function of brightness)**
- **integrated number counts**



Rattenbury, Mao et al. (2007)

Number counts of red clump giants



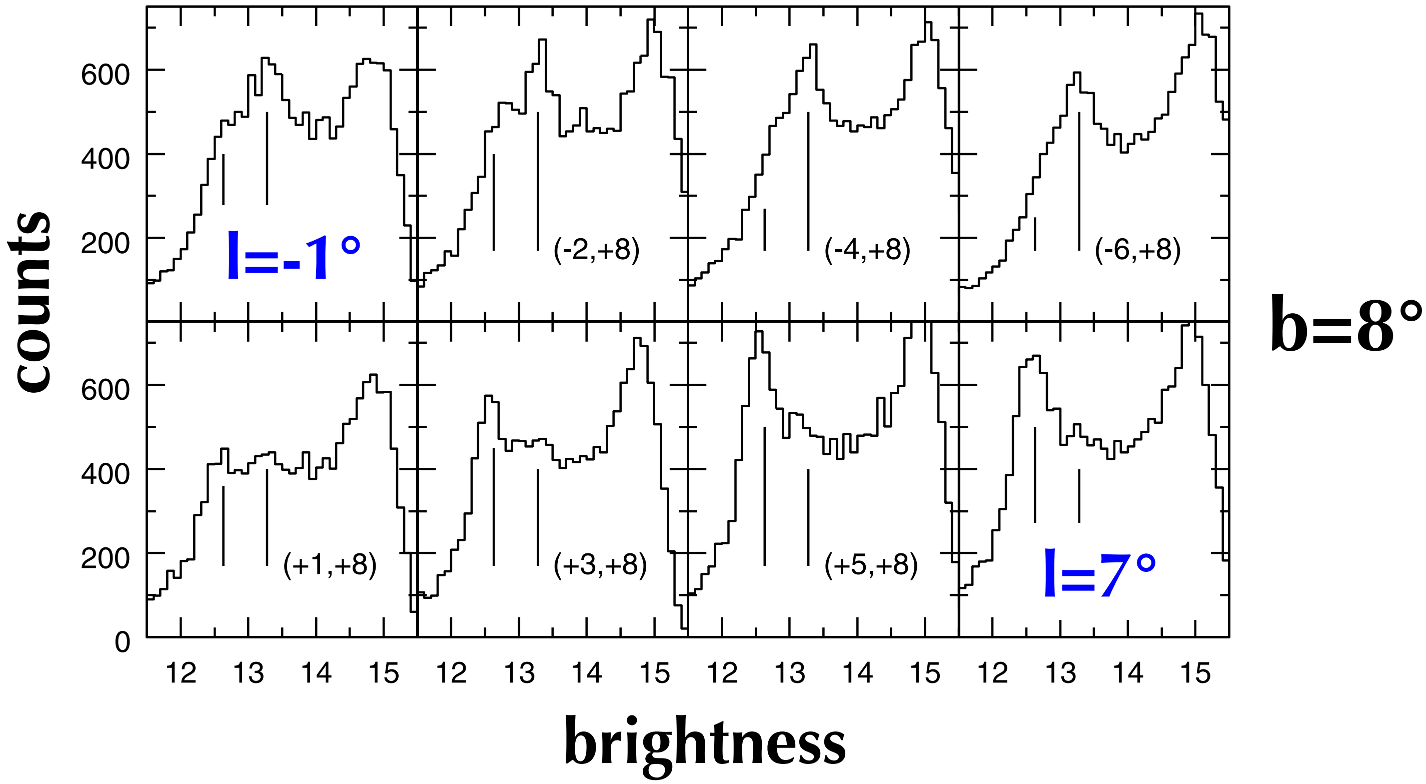
Nataf et al. (2012)

- **Regular elliptical contours 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 MW

- **Tri-axial "exponential" density model preferred over Gaussian (Cao, Mao 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 (statistically very well constrained).**

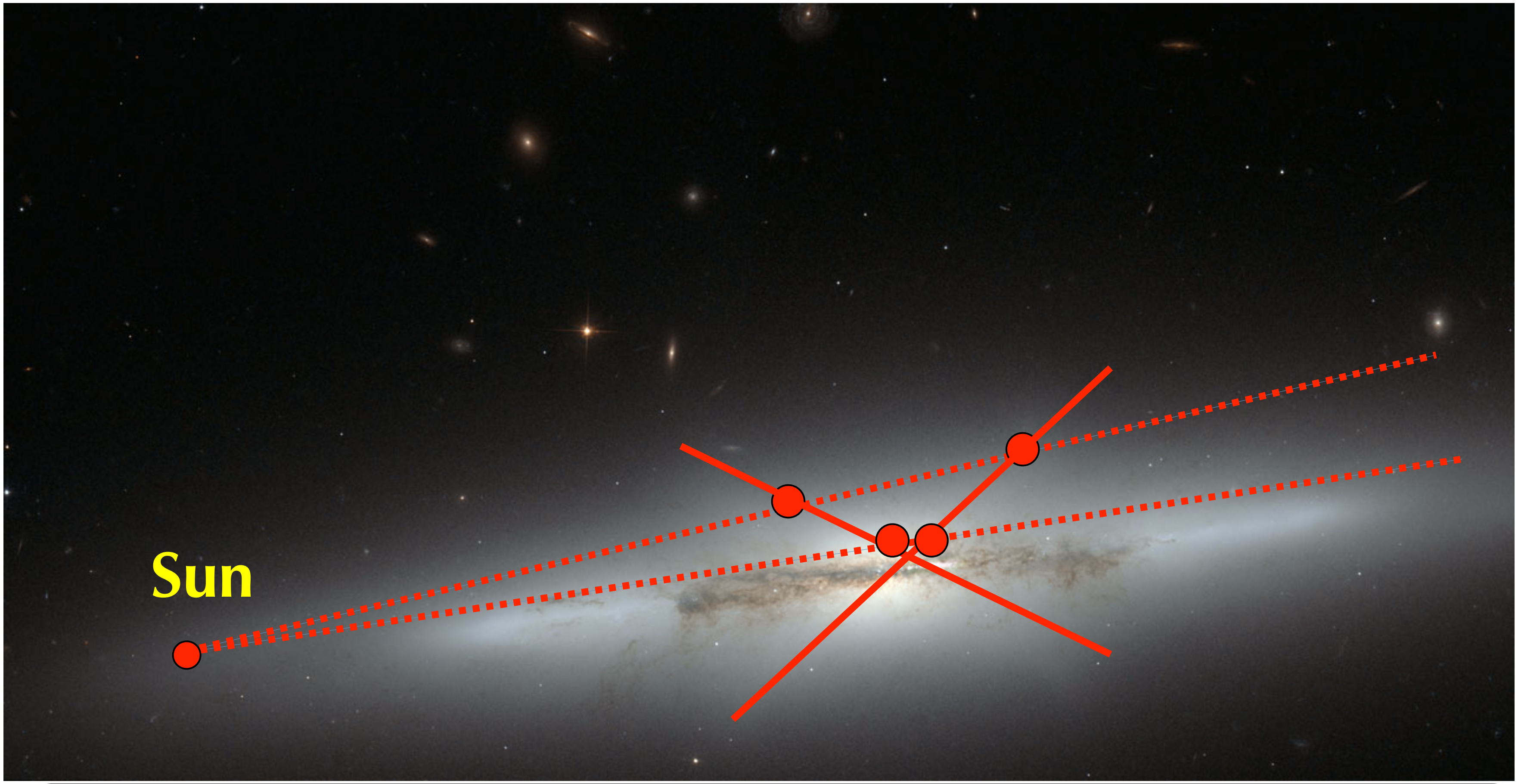
Double peaks in RCG counts



Mcwilliam & Zoccali (2010); Nataf et al. (2010)

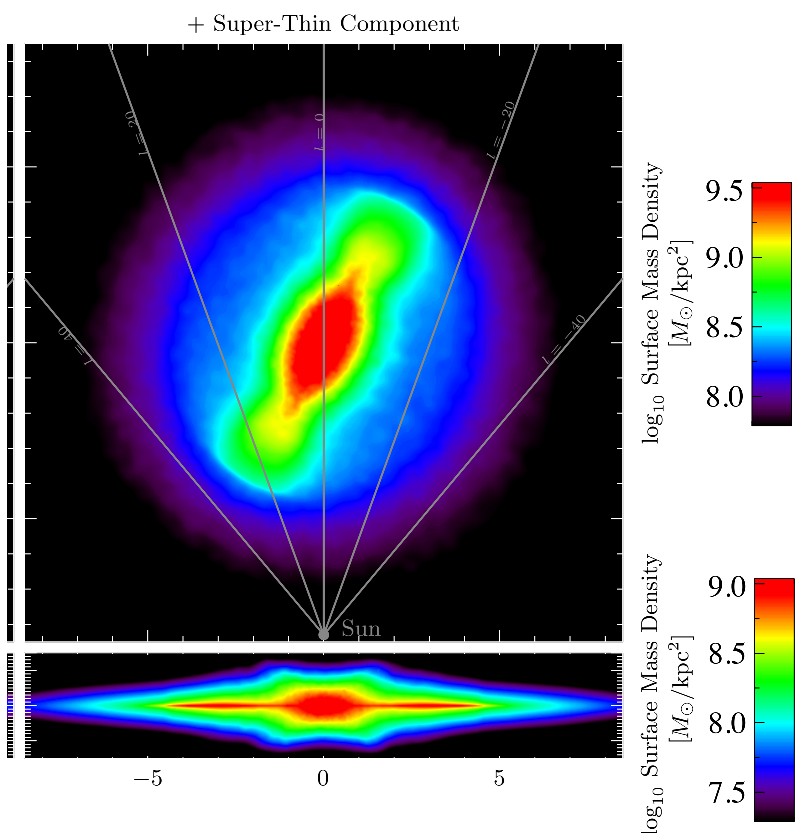
- Most fields exhibit a single peak.
- Double peaks are only prominent at large b.

X-shaped structure in the Milky Way



- At high latitude fields, double peaks
- Low latitude fields exhibit a single peak

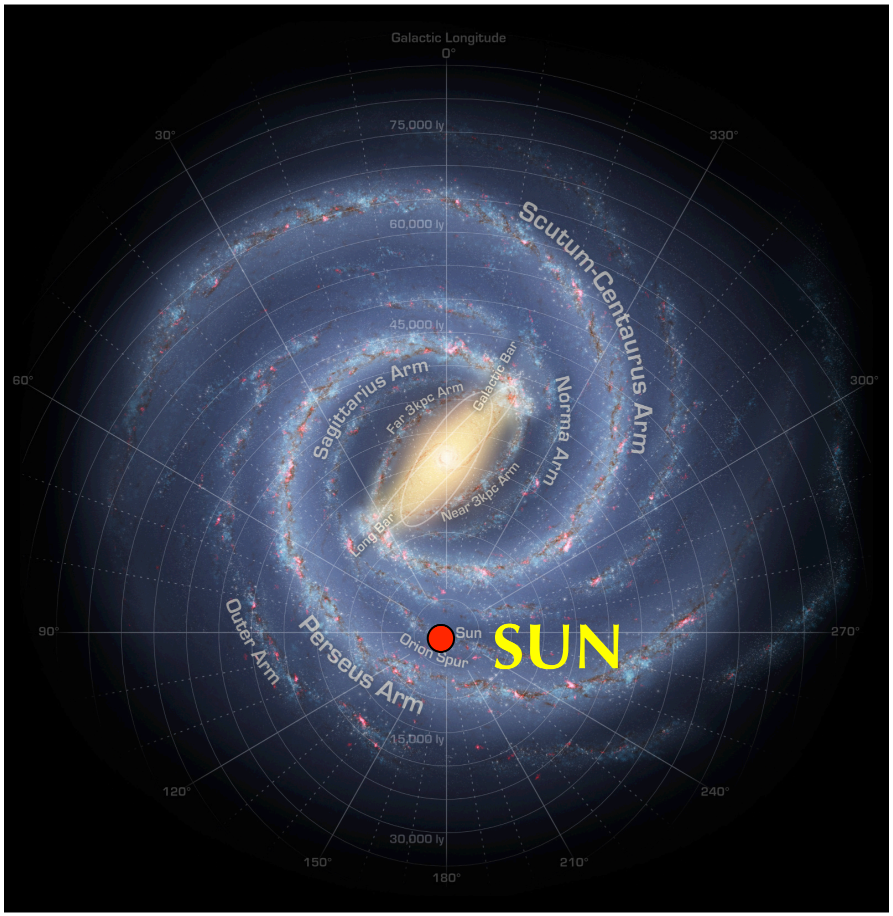
More complexities in the outer part



Wegg, Gerhard & Portail (2015)

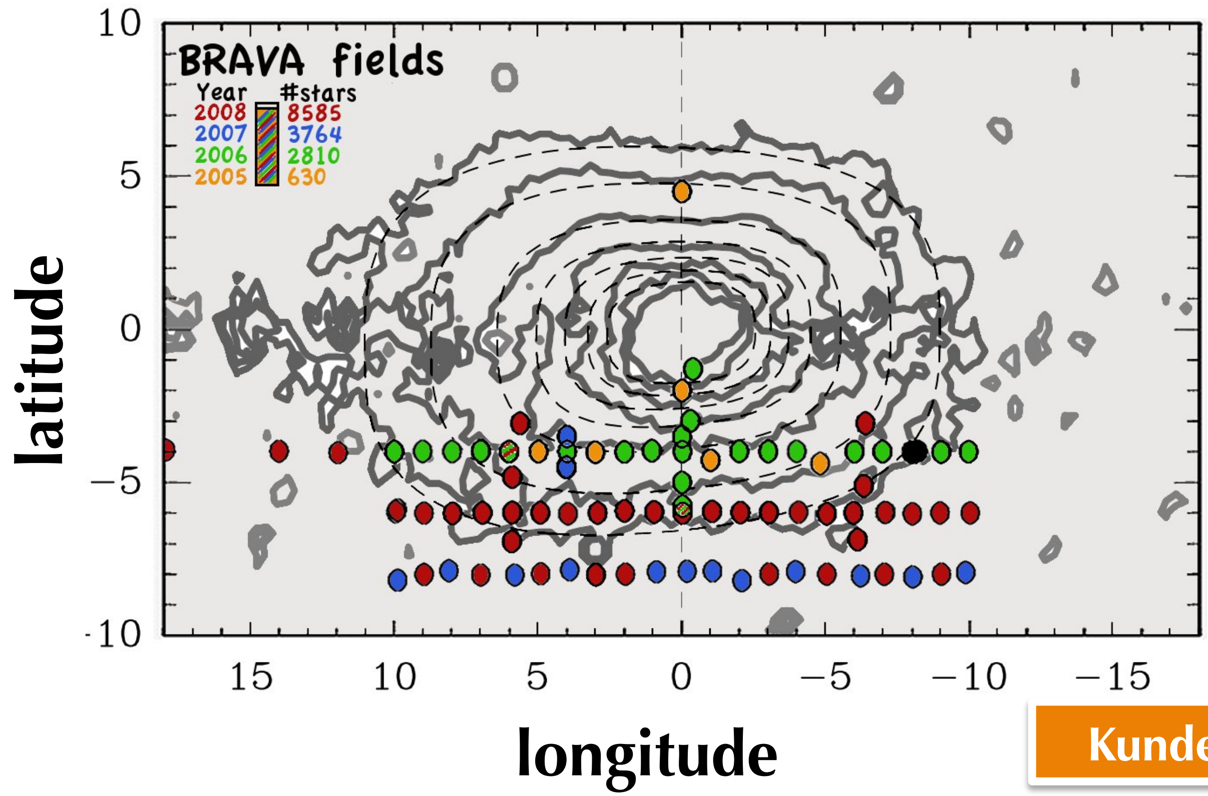
- **The Galaxy may not only contain a central boxy/peanut tri-axial bar.**
- **The outer part may contain a long, thinner bar with similar bar angle.**
- **Are they dynamically distinct?**

❹ Dynamical modelling of MW bar



- Kinematic data
- Dynamical modelling techniques

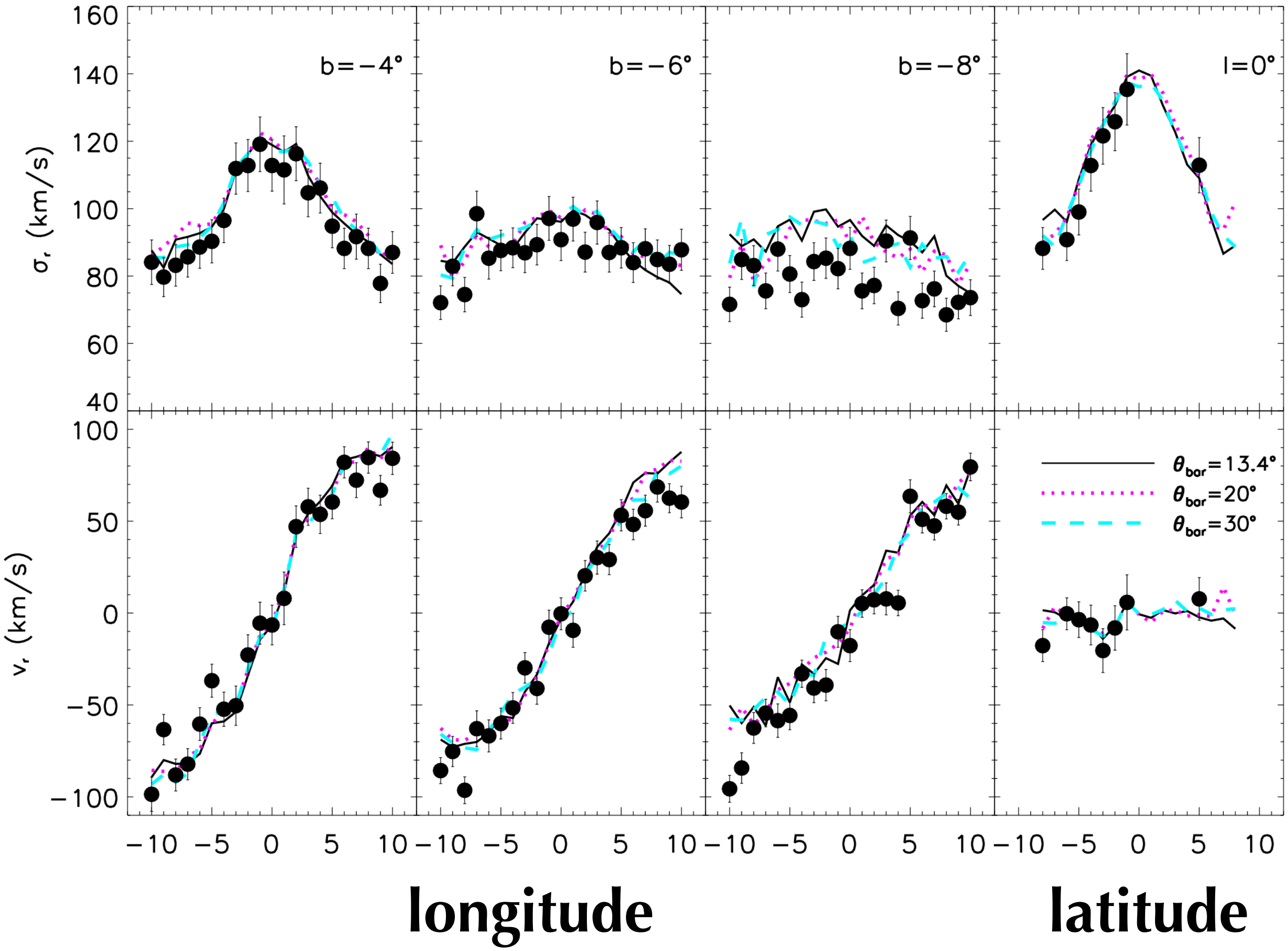
Radial velocity fields of BRAVA



Kunder et al. (2012)

- Radial velocities of 8500 red giants.
- Radial velocity accuracy ~ 5 km/s.
- More data available from other surveys (ARGOS).

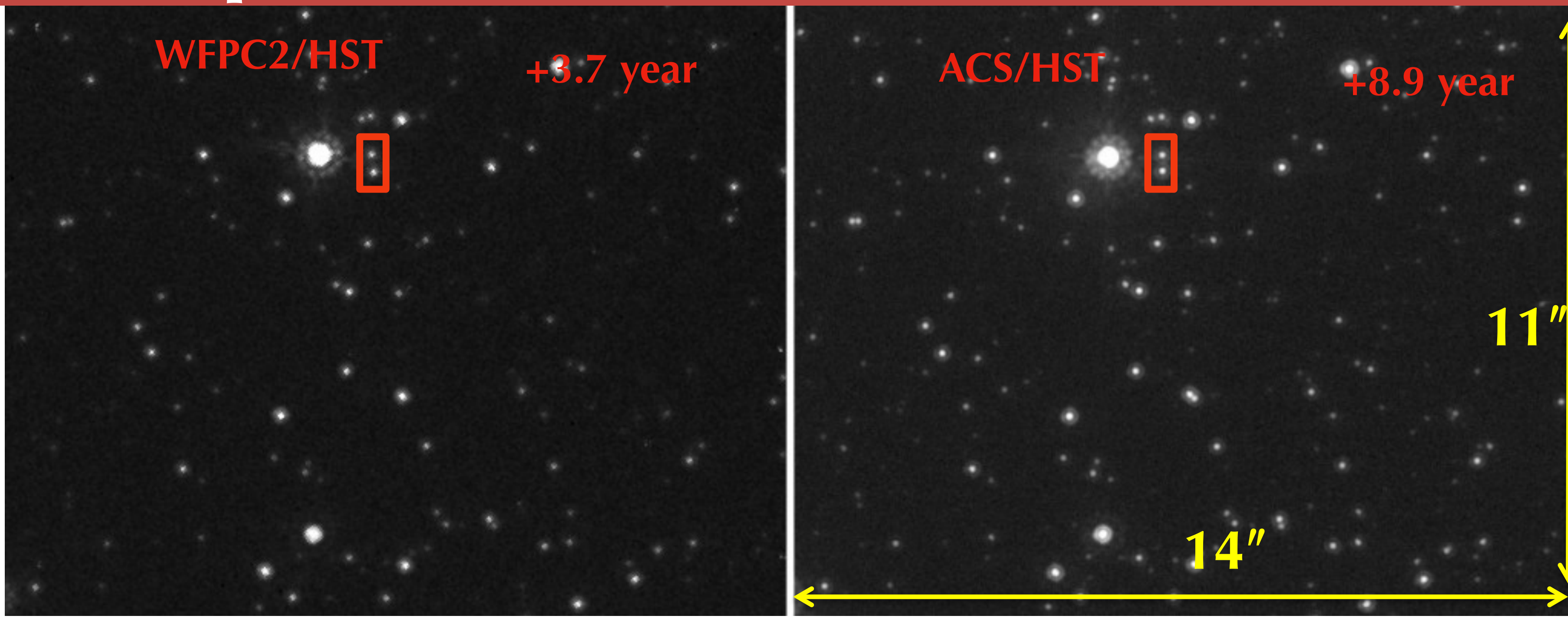
BRAVA Radial velocity data



Velocity dispersion

Mean velocity: **rotation**

Proper motions of stars with HST



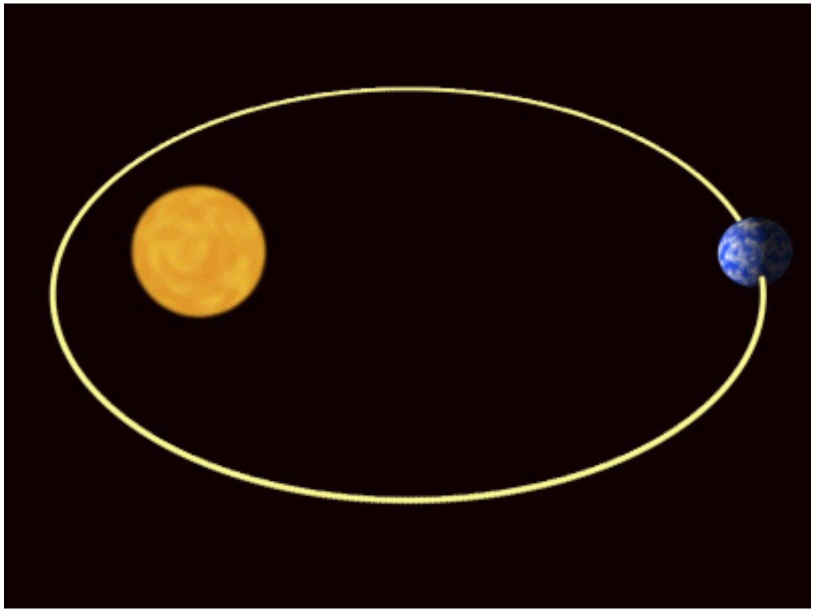
Kozlowski, Wozniak, Mao et al. (2006)

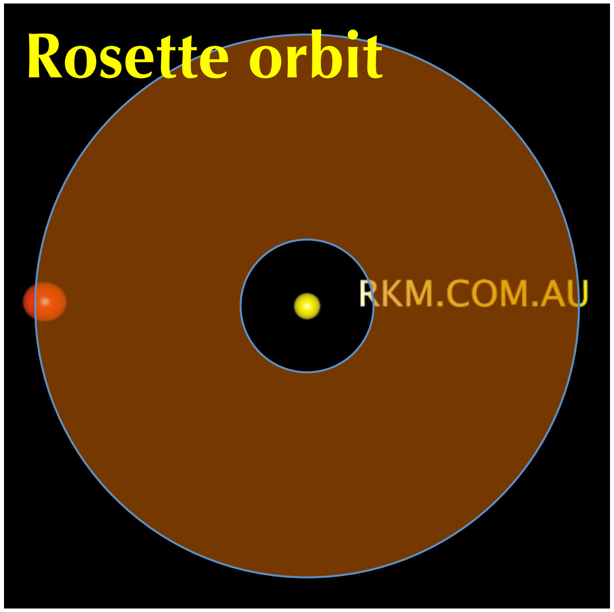
- Two decades of microlensing surveys enabled proper motions to be measured for millions of stars (~few mas/yr).
- HST observations enable proper motions to even higher accuracy (~ 0.2-0.6 mas/yr)

Galactic dynamics

- Stars in galaxies are collisionless.
- stars move in collective gravitational field with effects of star-star scattering negligible over the Hubble time.
- Galaxies are a sum of stars on different orbits.

Orbits in spherical potentials



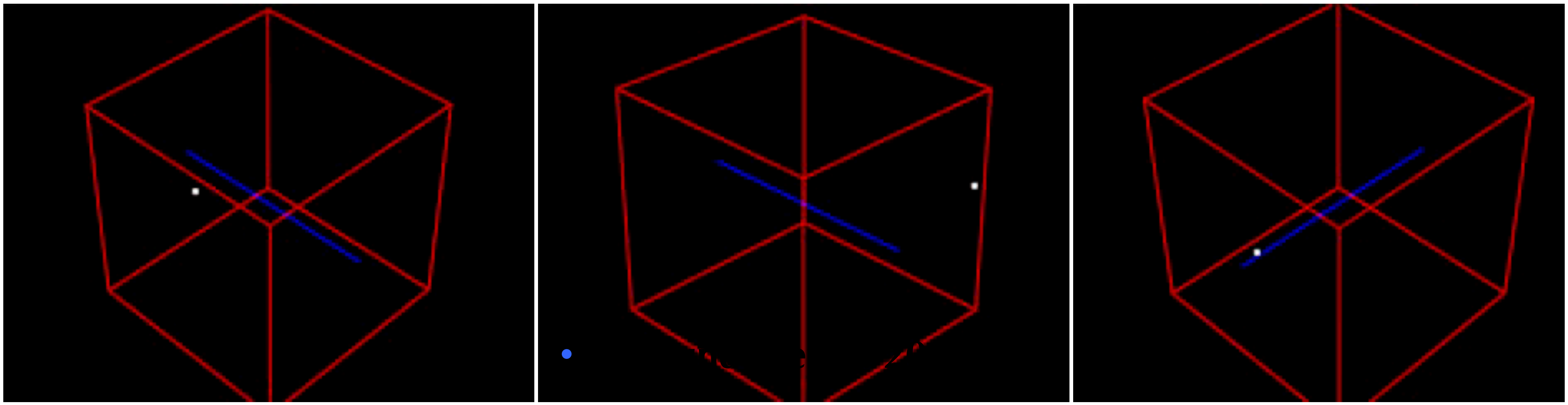


Loop orbit

- In a Keplerian potential, Force ~ $1/r^2$
- all orbits are closed ellipses

- Rosette orbits for a potential, Force ~ $1/r$
- eventually fills an annulus.

Orbits in 3D Stackel tri-axial potentials



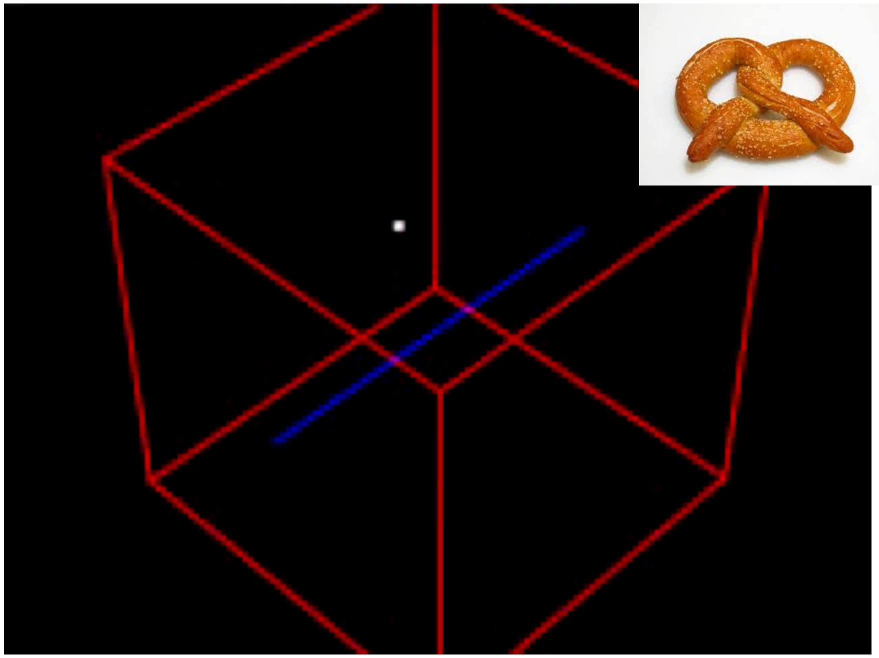
short-axis (z-) tube orbits

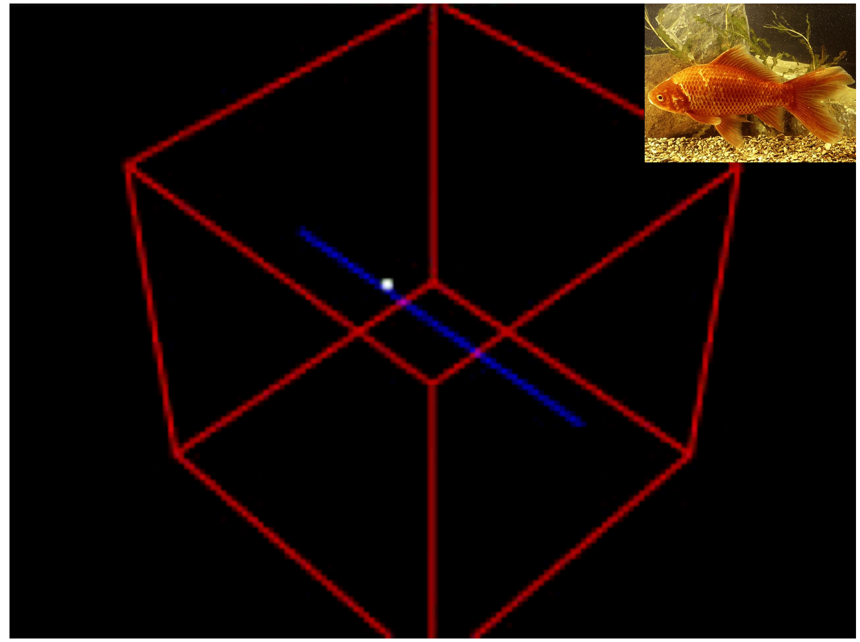
major-axis (x-) tube orbits

box orbits

From Barnes

Resonant Orbits in 3D triaxial potentials



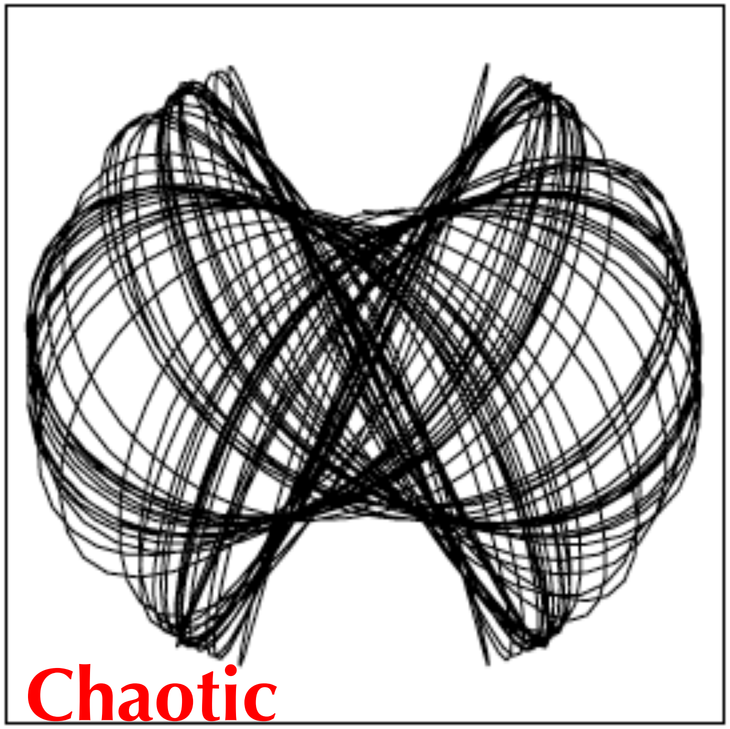


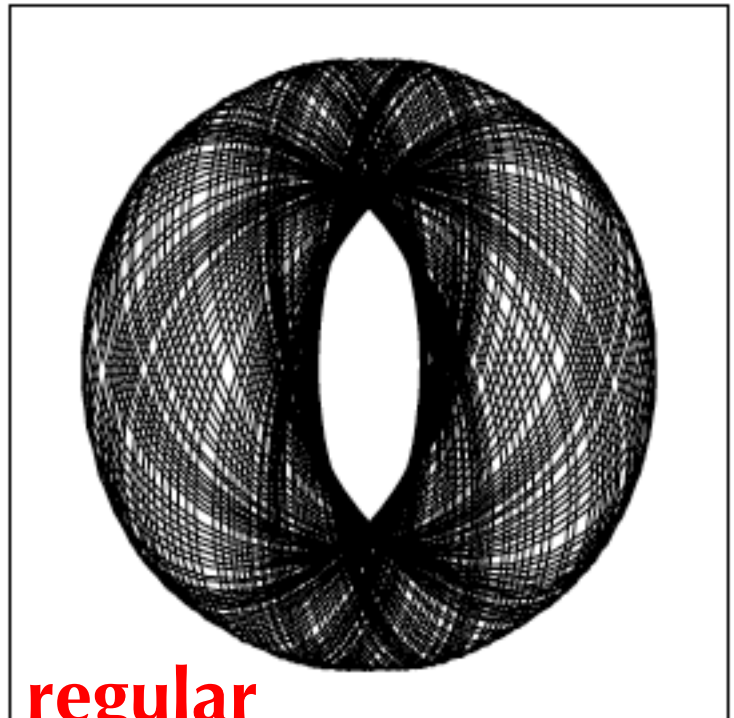
Pretzel orbits
4:3 resonance

Fish orbits
3:2 resonance

From Barnes

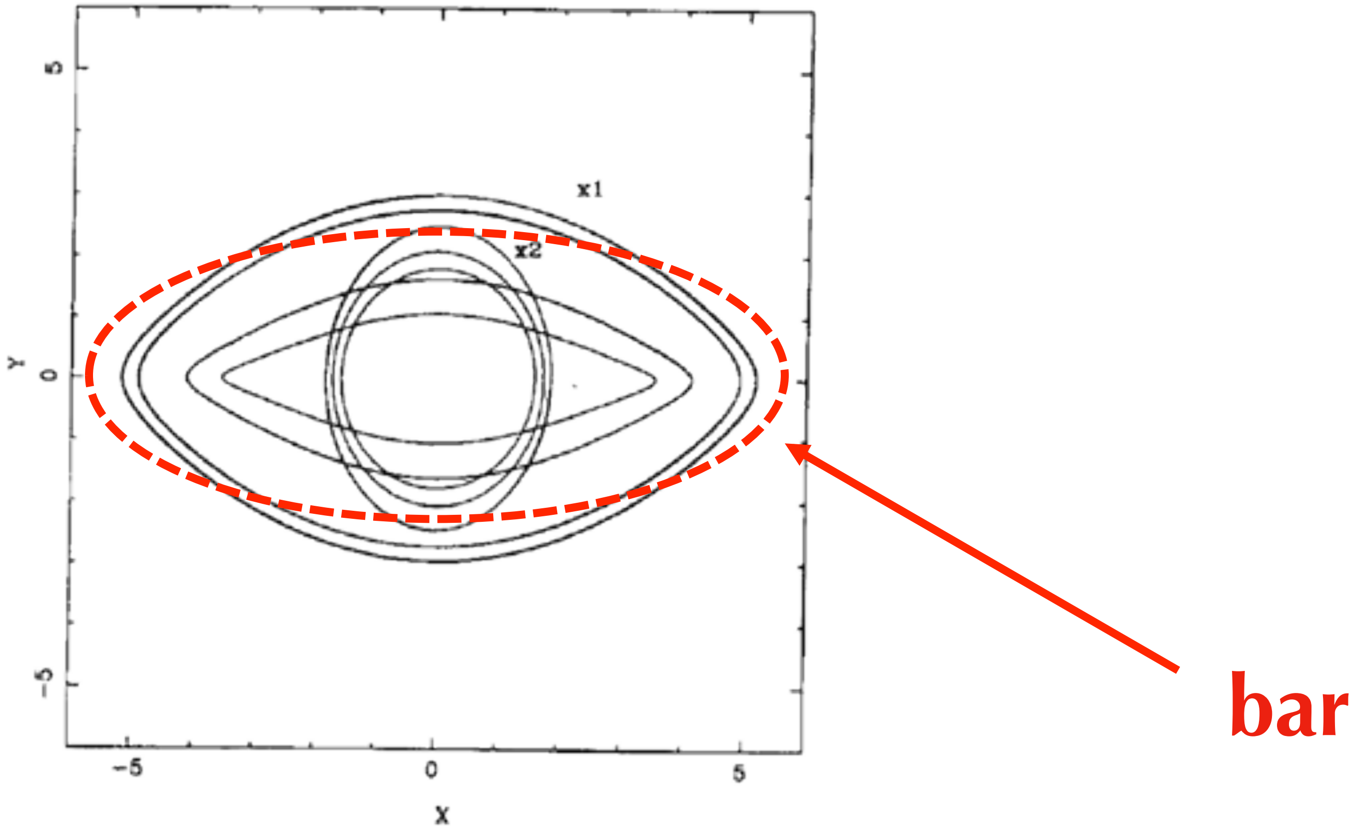
Chaotic orbits





- **Chaotic orbits diverges in the phase space.**
- **How do we find chaotic orbits is not an easy issue!**
  (Wang, Athanassoula & Mao 2015, in preparation).

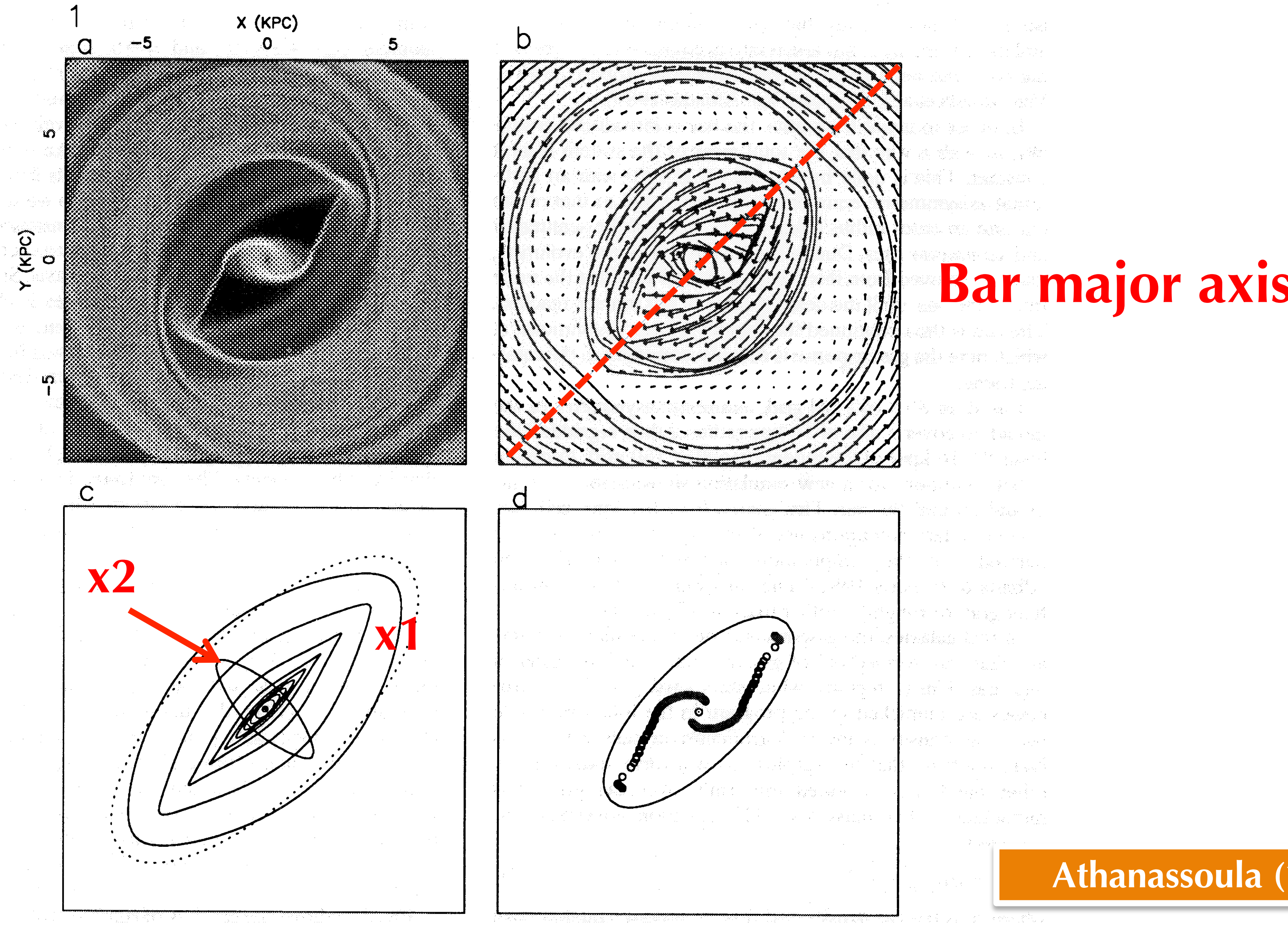
Orbital families in rotating bars: x1 and x2 families of closed orbits



As viewed in the co-rotating frame

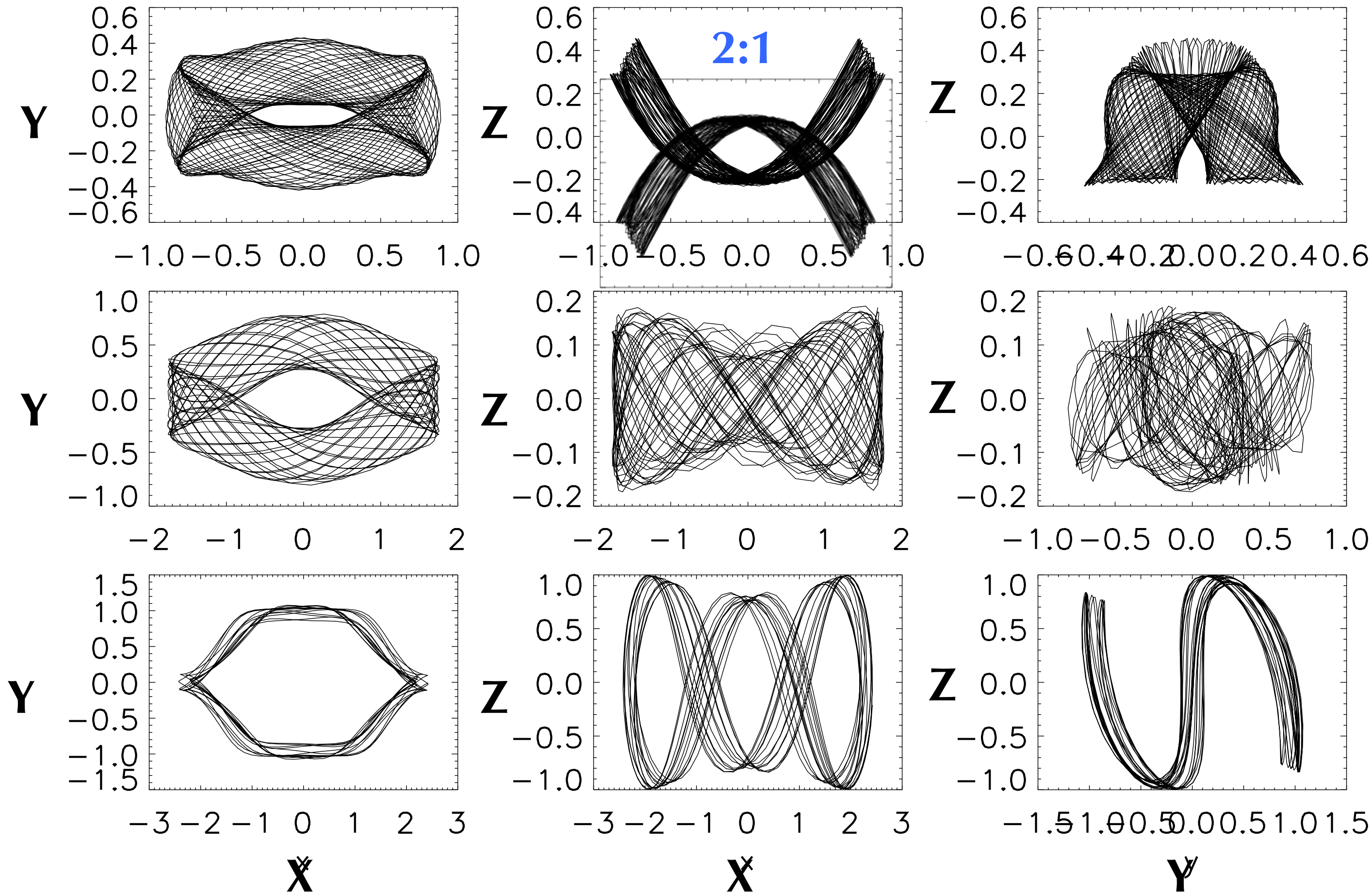
Contopoulos & Grosbol (1989)

Gas motions in a rotating bar



Athanassoula (1992)

Typical regular orbits



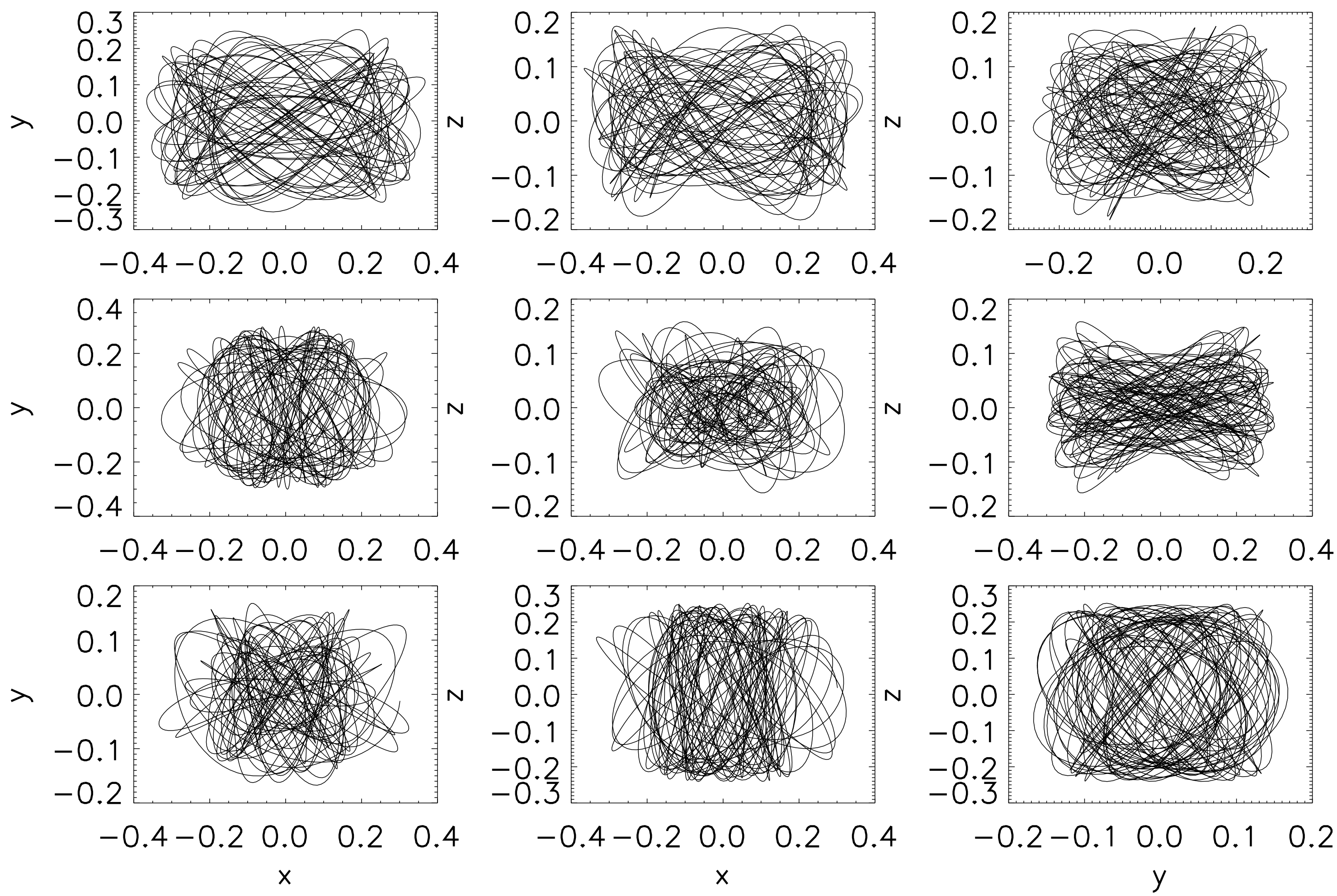
Banana or Pretzel

↓

X-shaped structure ???

Provided by Yougang Wang

Chaotic orbits

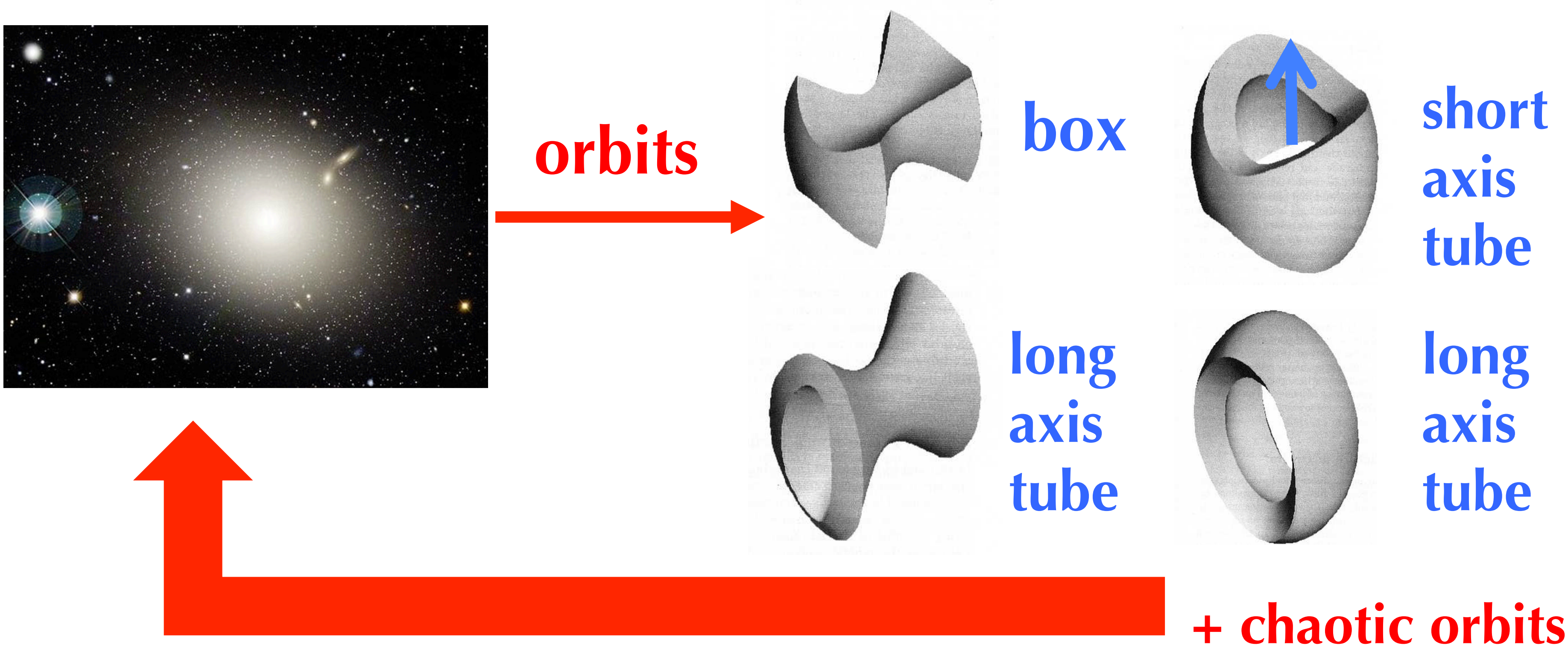


Many orbits are in fact chaotic!

Methods of orbit superposition

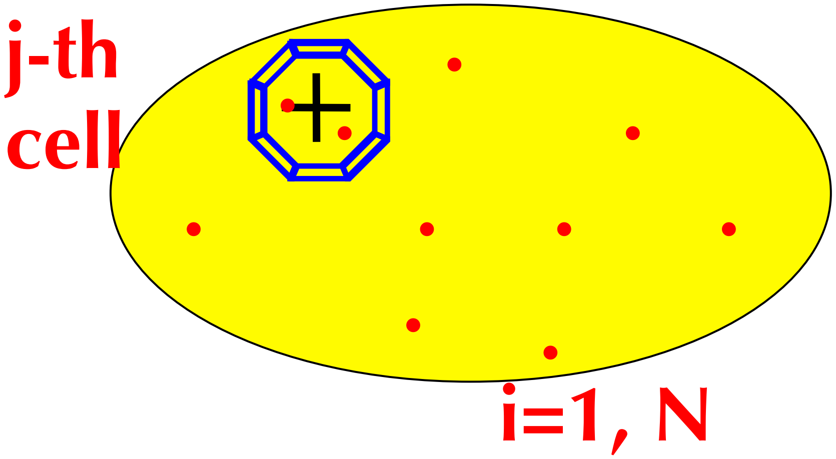
- **Schwarzschild method: orbit-based**
  - ✓ Choose $\Phi(x)$, integrate orbits, fit data by weighting orbits.
- **Made-to-Measure method: particle-based**
  - ✓ Choose $\Phi(x)$, integrate orbits, fit data by changing particle weights.

Schwarzschild method



- Find the right mix of orbits to fit density and kinematics.
- May suffer from degeneracy & stability issues.

Made-to-Measure Method
(Syer & Tremaine 1996)



$$\bar{v}_{los,j} = \frac{\sum_{i}^{N} w_i v_{los,i} \delta_{ij}}{\sum_{i}^{N} w_i \delta_{ij}}$$

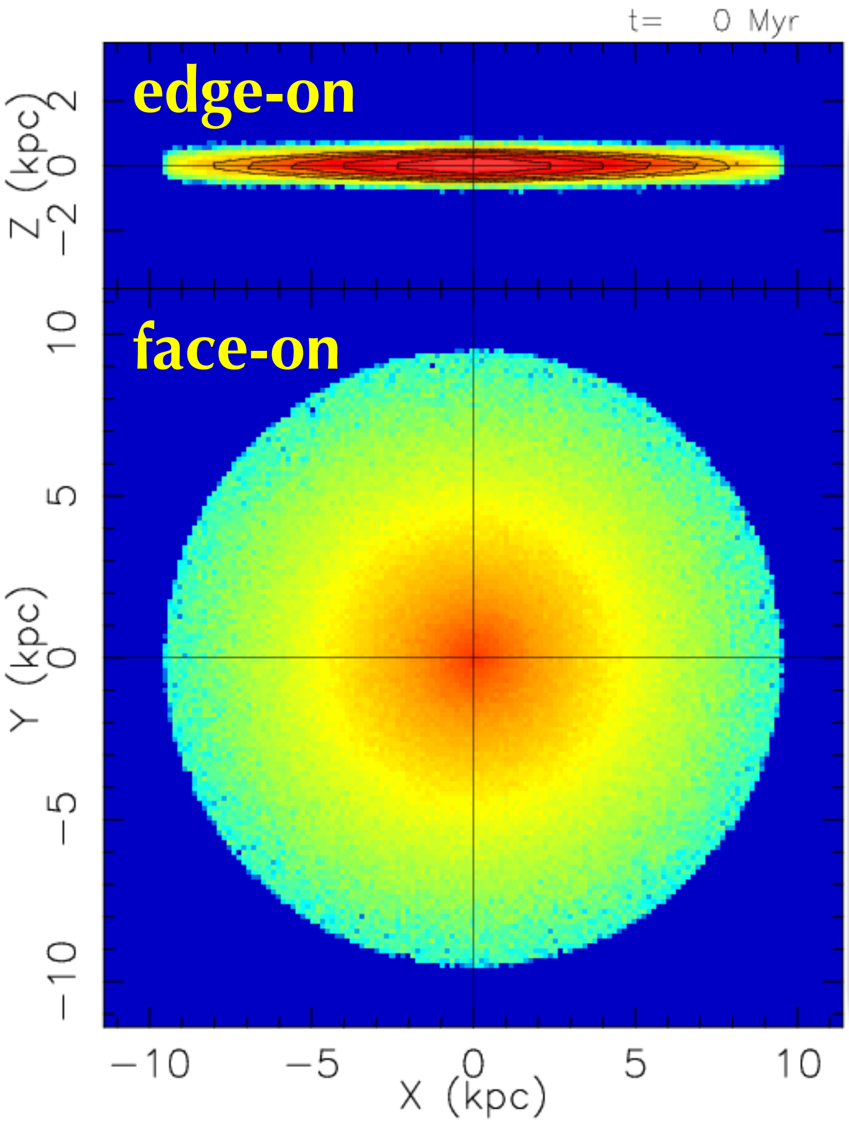
- De Lorenzo 07, 08; Morganti & Gerhard 12;
- Dehnen 09;
- Long & Mao 10, 12; Zhu et al. 14
- Hunt et al. 12

In a given potential

- N (~10^6) particles are orbited

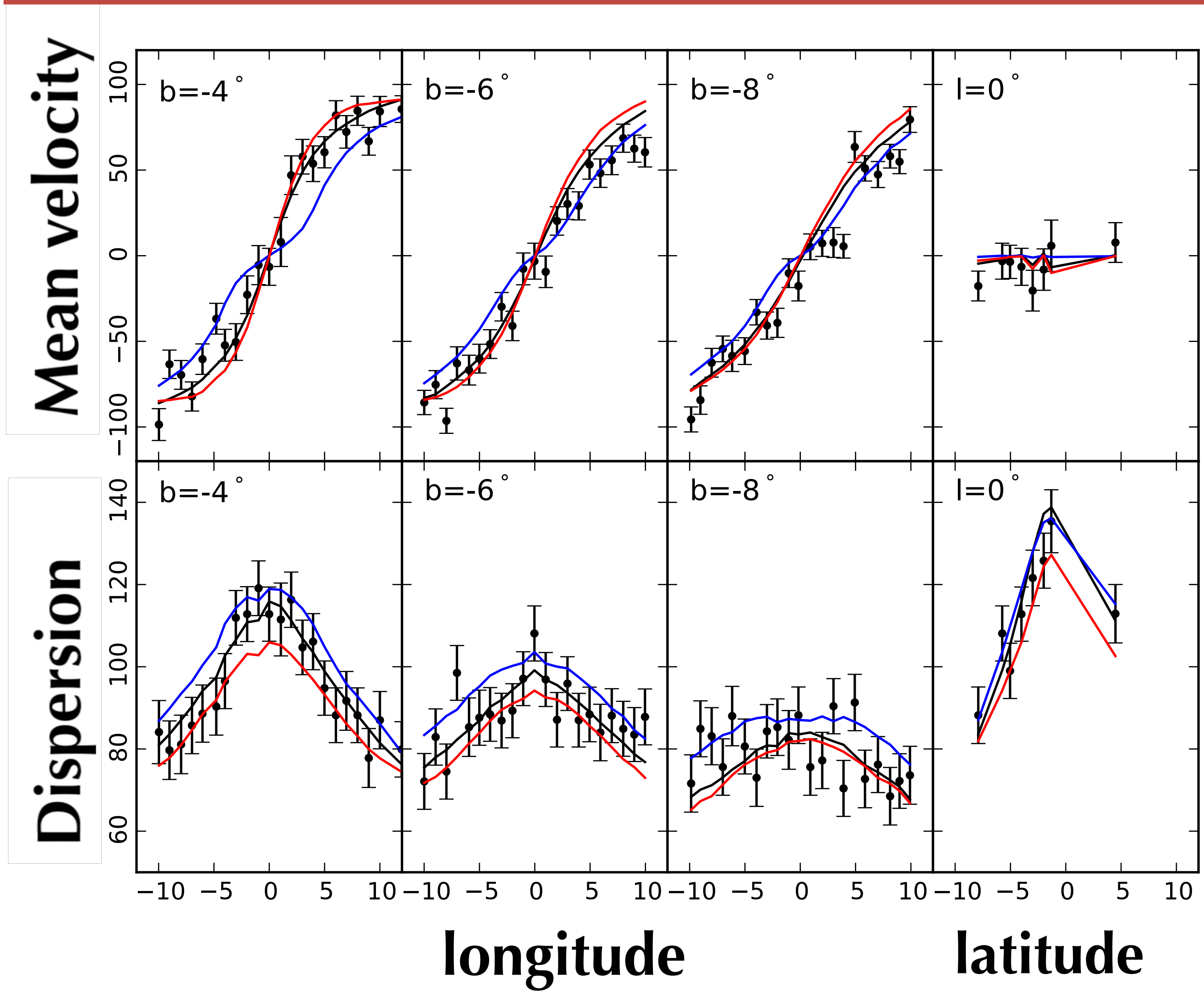
- Adjusts the weights on-the-fly to fit obs. Data
- More flexible than Schwarzschild method
- Cross-check on model degeneracy

Numerical Model of the Milky Way Bulge



- Shen et al. (2010) starts with an exponential disk plus a dark matter halo.
- Bar and buckling instabilities form boxy/peanut-shaped bulges.
- We use this as the initial condition and adjusts the particle weights to better match the kinematics.

Reproducing BRAVA radial velocity

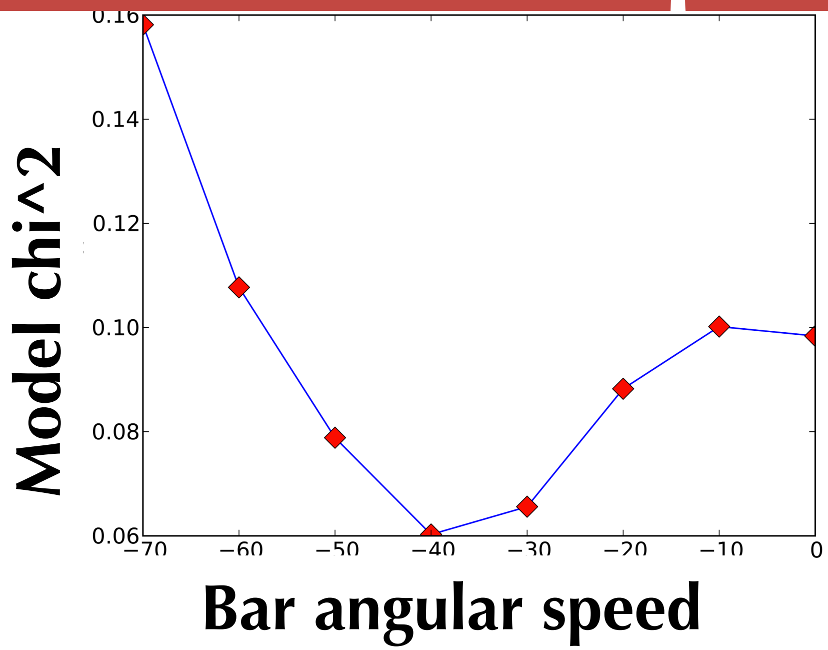


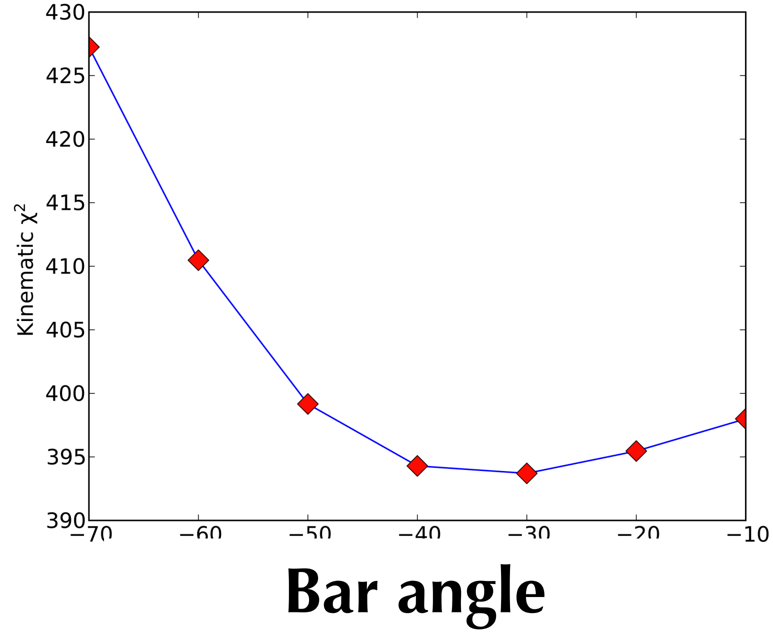
Best-fit bar pattern speed: 40 km/s/kpc

Bar angle: 30 deg

Long, Mao, Wang & Shen (2012)

Constraints on the Galactic bar parameters

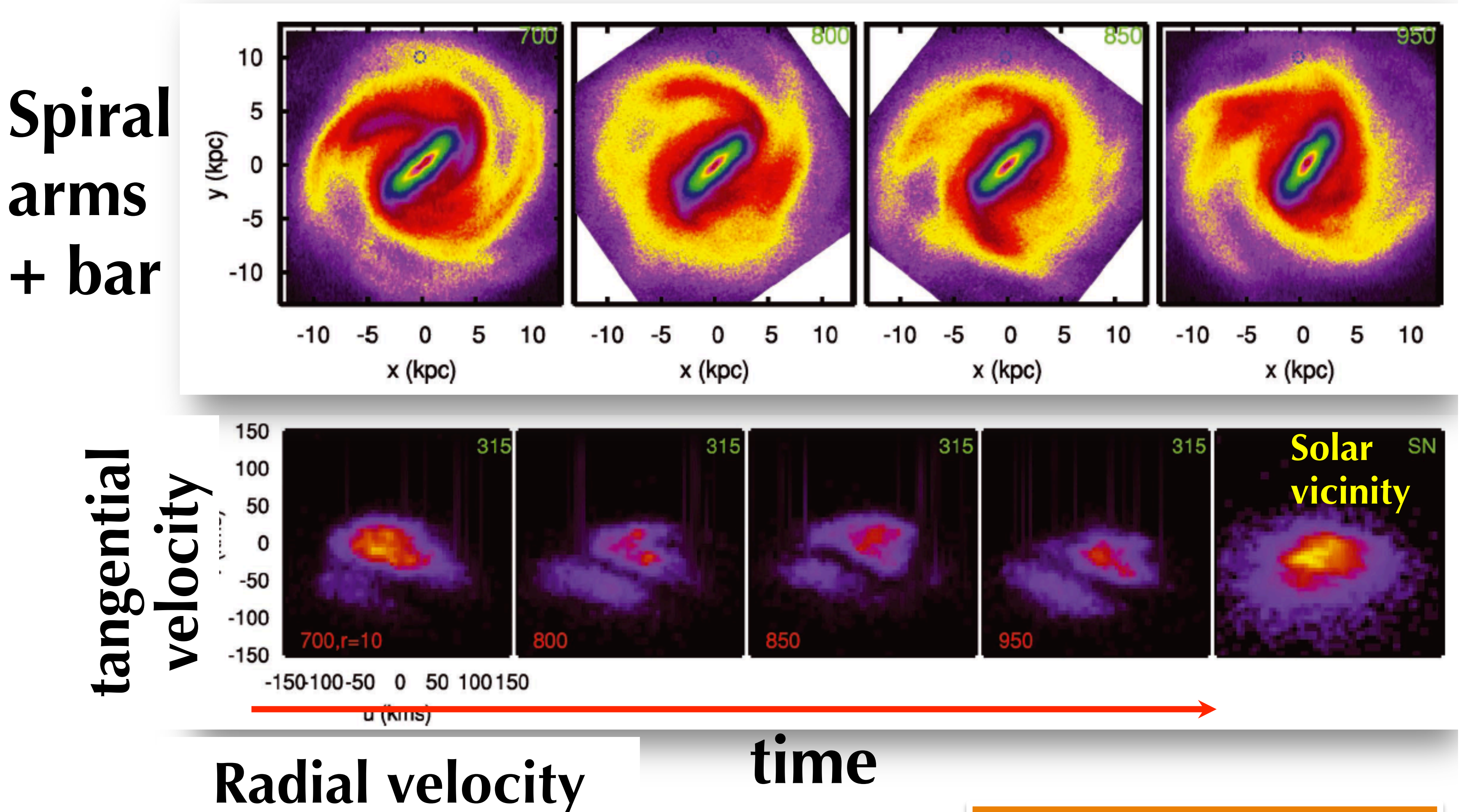




Long, Mao, Wang & Shen (2012)

- Fit both surface brightness and BRAVA radial velocities well.
- bar pattern speed: 40 km/s/kpc, angle: 30 degrees.
- not well constrained! Need more data!

Effects of the MW bar on the solar neighbourhood

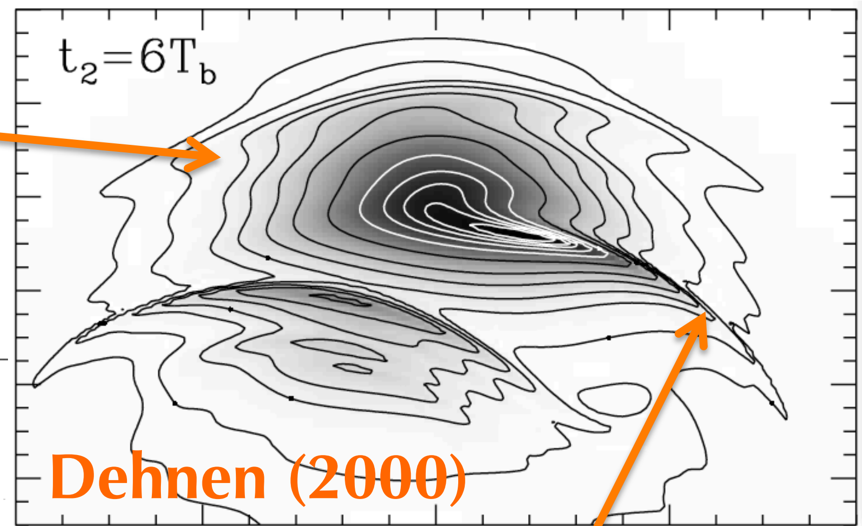


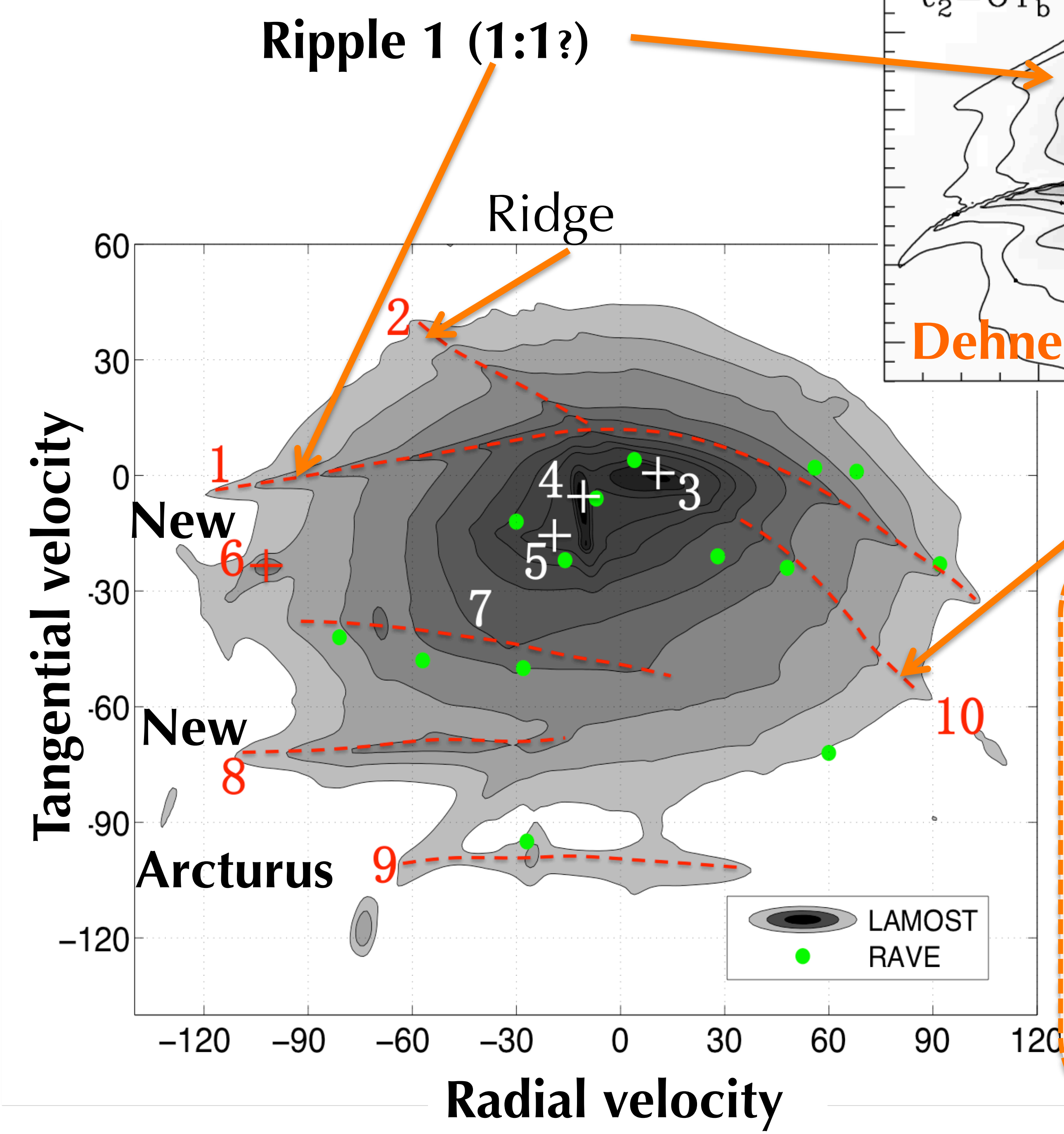
Quillen et al. (2011)

Velocity substructures from LAMOST

- We selected 13000 F&G dwarfs from LAMOST and 2MASS surveys
  - ✓ S/N>20, 100pc<z<500pc
- Biggest sample in similar volume
  - ✓ With fainter and more distant stars
- We use the extreme de-convolution method
  - ✓ Can better identify large-scale structures than the wavelet method used previously

Xia, Liu, Mao et al. (2014)





- Resonance due to bar or spiral arms?
- larger DR1 sample to study radial, metallicity dependence

Summary & open questions

- Photometric modelling indicates
  - ✓ a short, exponential boxy/peanut bar with a bar angle ~ 30 degrees.
  - ✓ There may be other thinner, longer bars in the outer part.
- Both the Schwarzschild and Made-to-Measure methods can be used to fit the data.

- Open questions
  - ✓ How long is the bar (5kpc)?
  - ✓ How fast does the bar rotate (30 km/s/kpc)?
  - ✓ Are different components distinct in kinematics and chemical abundances?

Future outlook

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

- **Much theoretical work yet to be done**
  - ✓ Needs to explain new chemo-dynamical correlations (Ness et al.) in particular.
  - ✓ Stability and degeneracy issues need to be further explored.