Modelling the Milky Way bar

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Outline

❶ Observed properties of barred galaxies

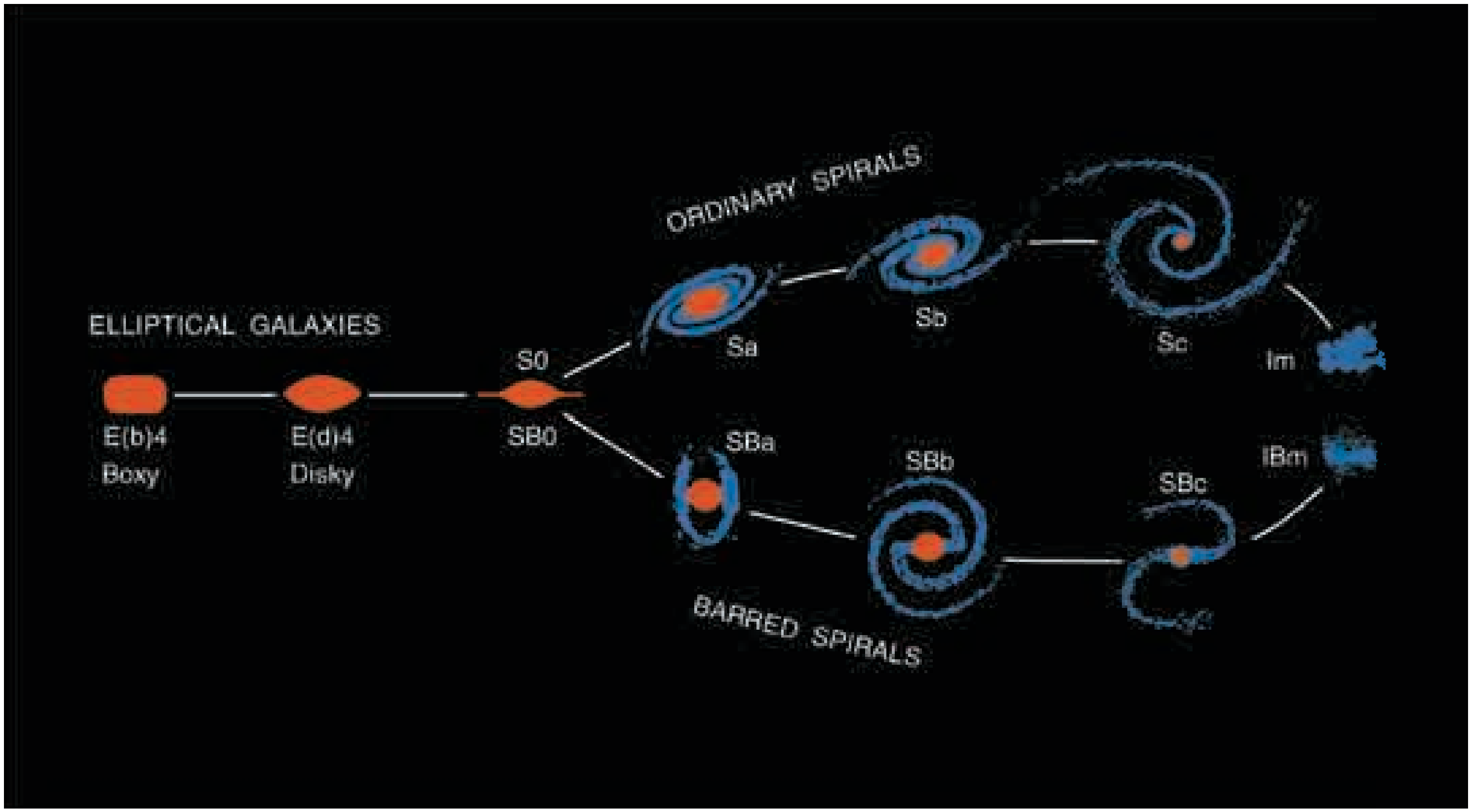
❷ The Milky Way bar

❸ Photometric modelling

❹ Dynamical modelling

❺ Summary and future outlook

➊ Overview: Hubble sequence of galaxies

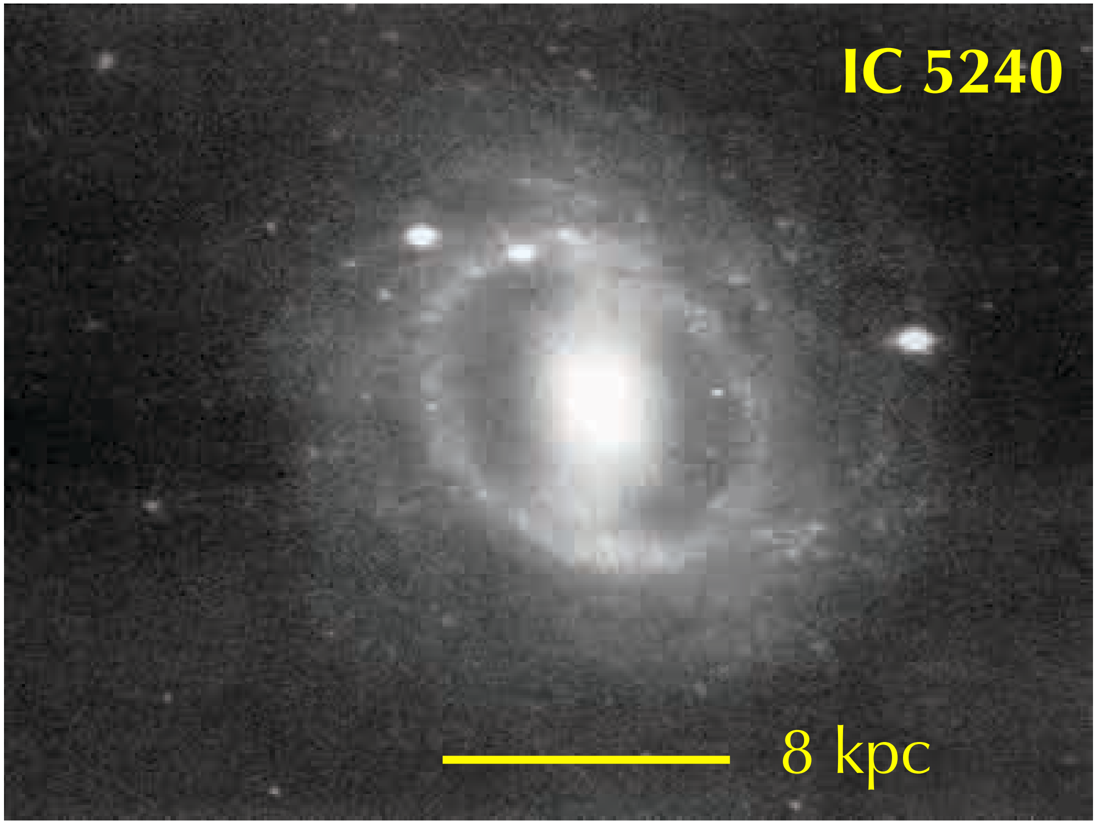


- **2/3 of spiral galaxies host bars, especially in the infrared**
- **Understanding of the Milky Way bar is key to understanding other barred galaxies in the Universe**

Barred galaxies in the Universe

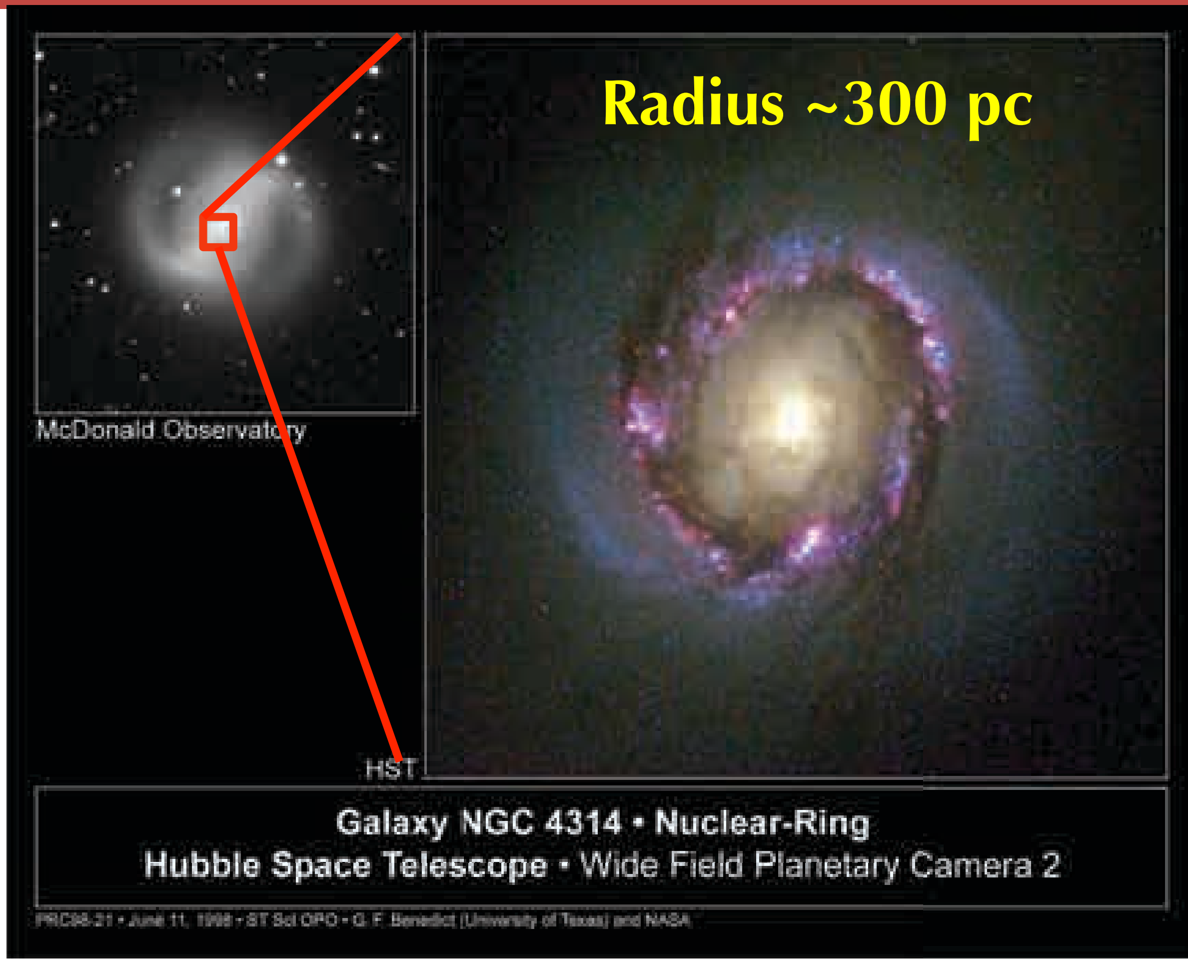
- Bars are straight – rigid angular pattern speed
  - ✓ no winding up due to differential rotation!
- Bars often host dust lanes & vigorous star formation at the end of bars

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

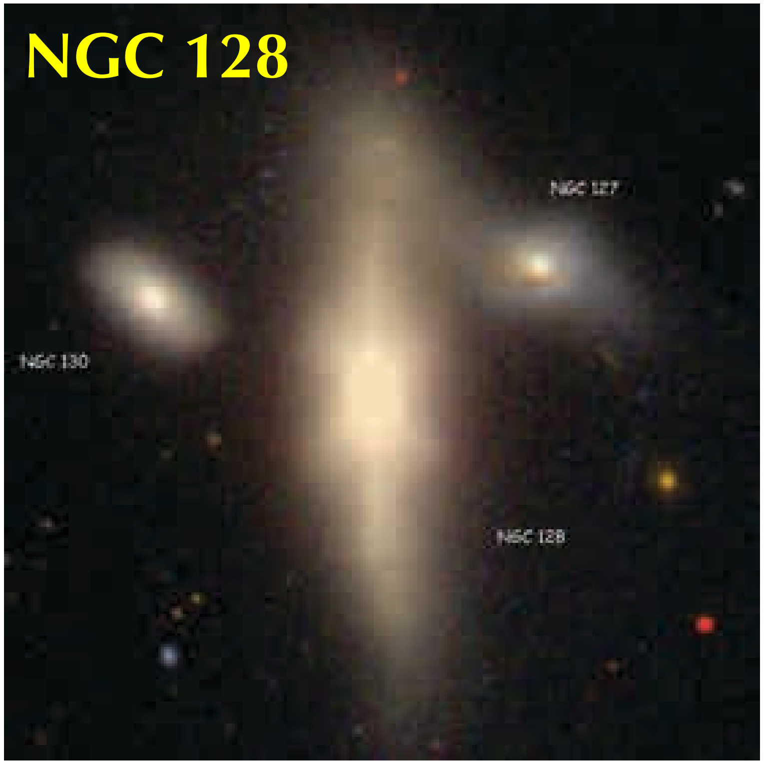


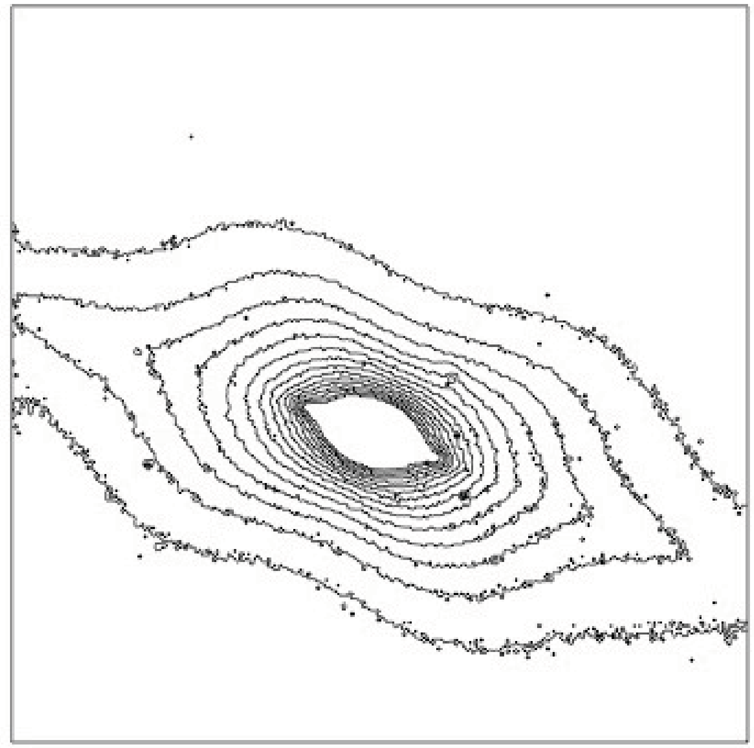
Rings are thought to be associated with resonances in barred galaxies.

Boxy/peanut-shaped barred galaxies

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

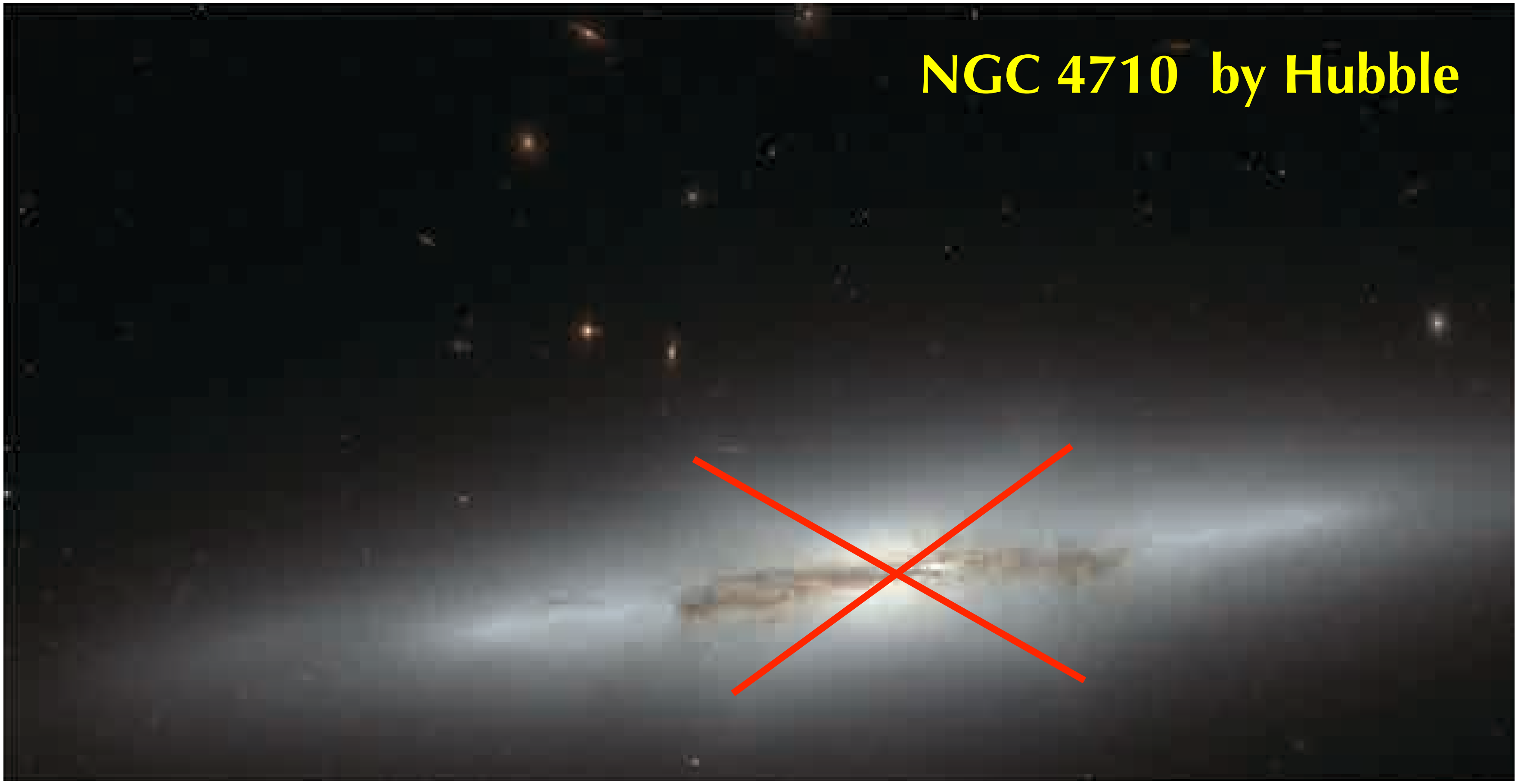
Peanut-shaped galaxy NGC 128



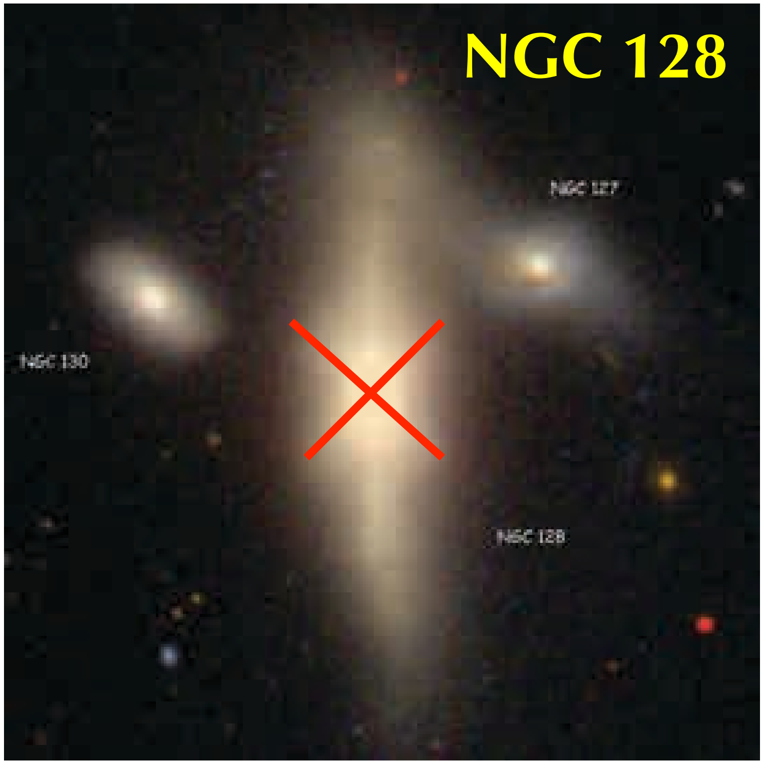


- Located in a group of five galaxies.
- External tidal origin (Li, Gadotti, Mao et al. 2009) or internal secular evolution?

X-shaped Structure



X-shaped structure

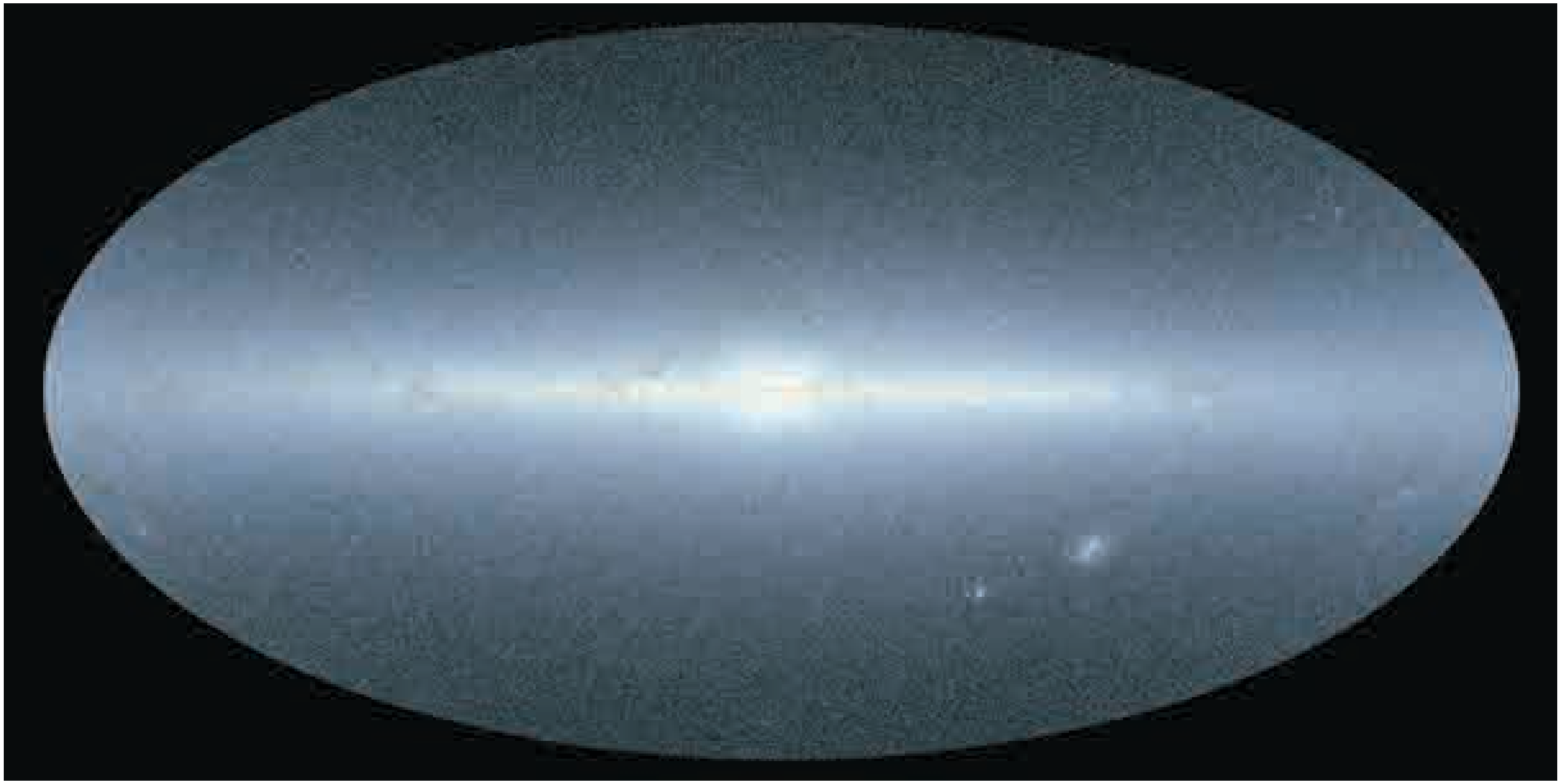


- X-shaped structure may be related to resonant orbits

Summary: barred galaxies

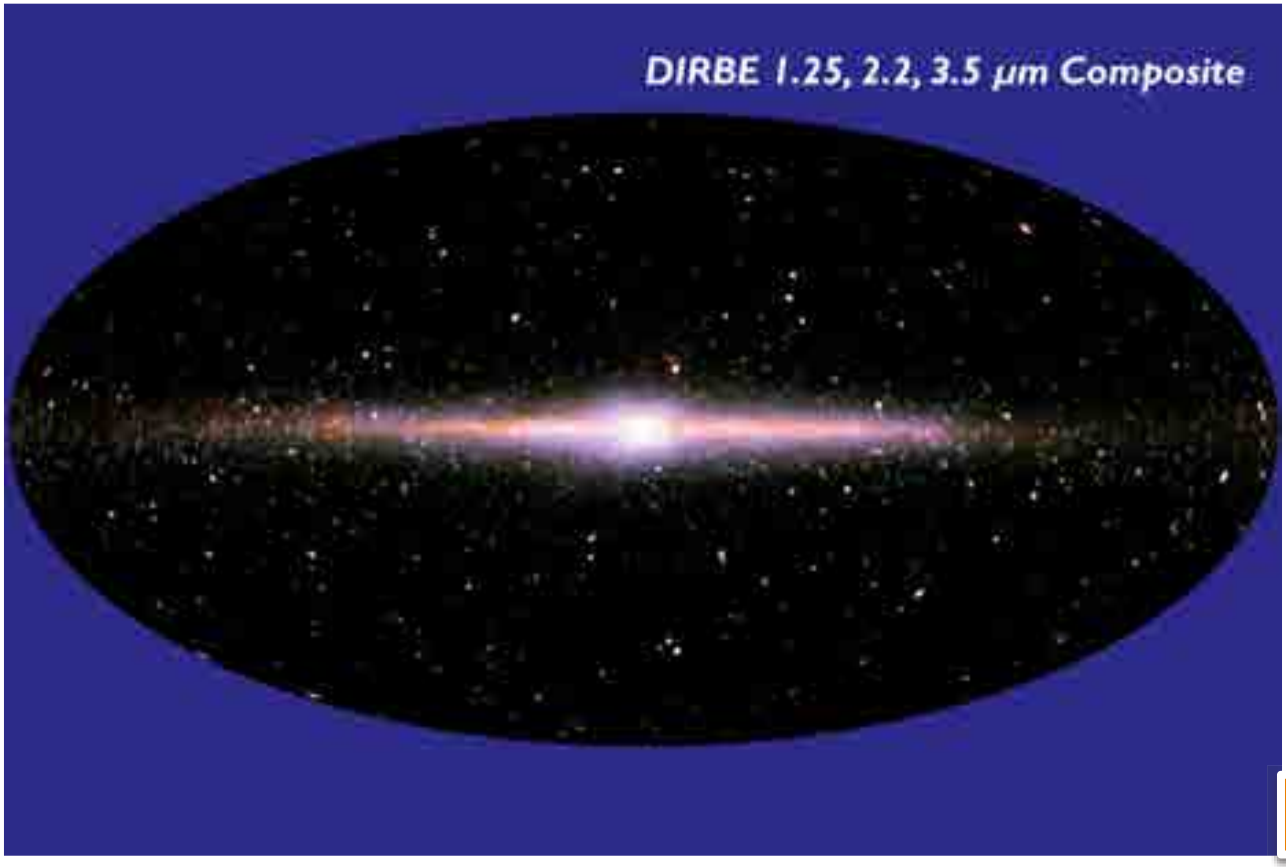
- Barred galaxies are very common
  - ➢ Straight → rigid rotation
  - ➢ Dust lanes (gas streaming motions)
  - ➢ Rings of star formation (resonances)
- Edge-on bars
  - ➢ exhibit as boxy, peanut-shaped or X-shaped galaxies
  - ➢ Kinematics are more complex
- They likely form via internal secular (long-term)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

❷ The Milky Way bar



2MASS NIR images of the MW: disk + bulge

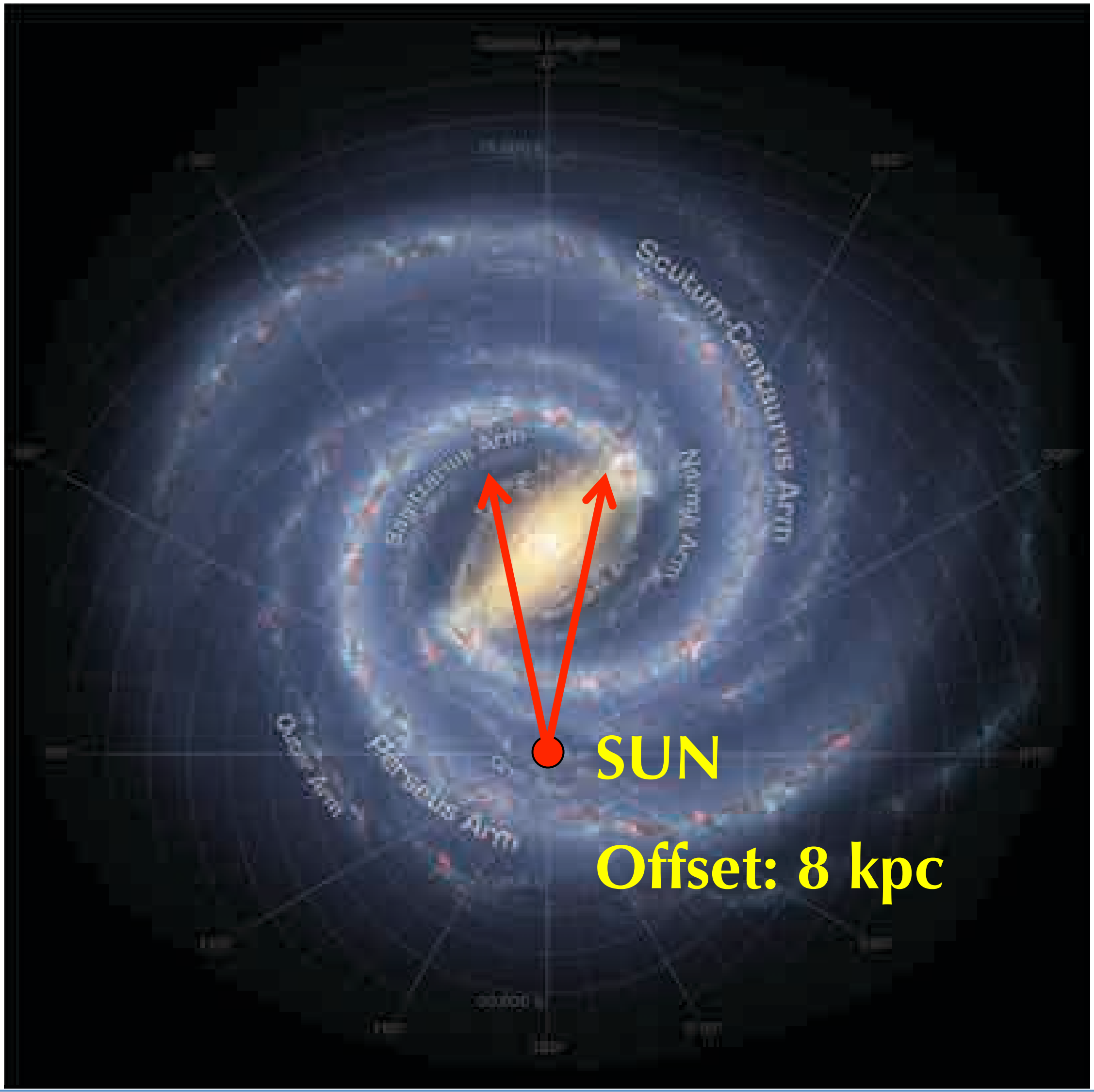
COBE map of the Milky Way bar



Dwek et al. (1995)

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

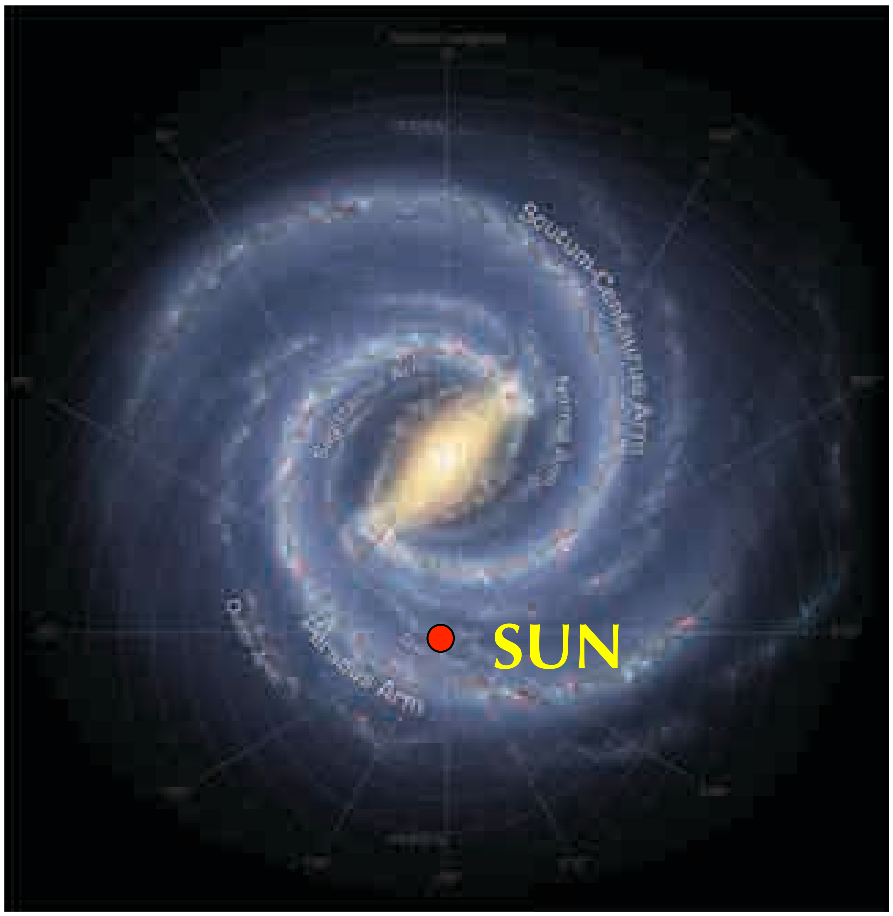
Top-down view of the Galaxy



Credit: Robert Hurt (SSC/JPL/ Caltech)

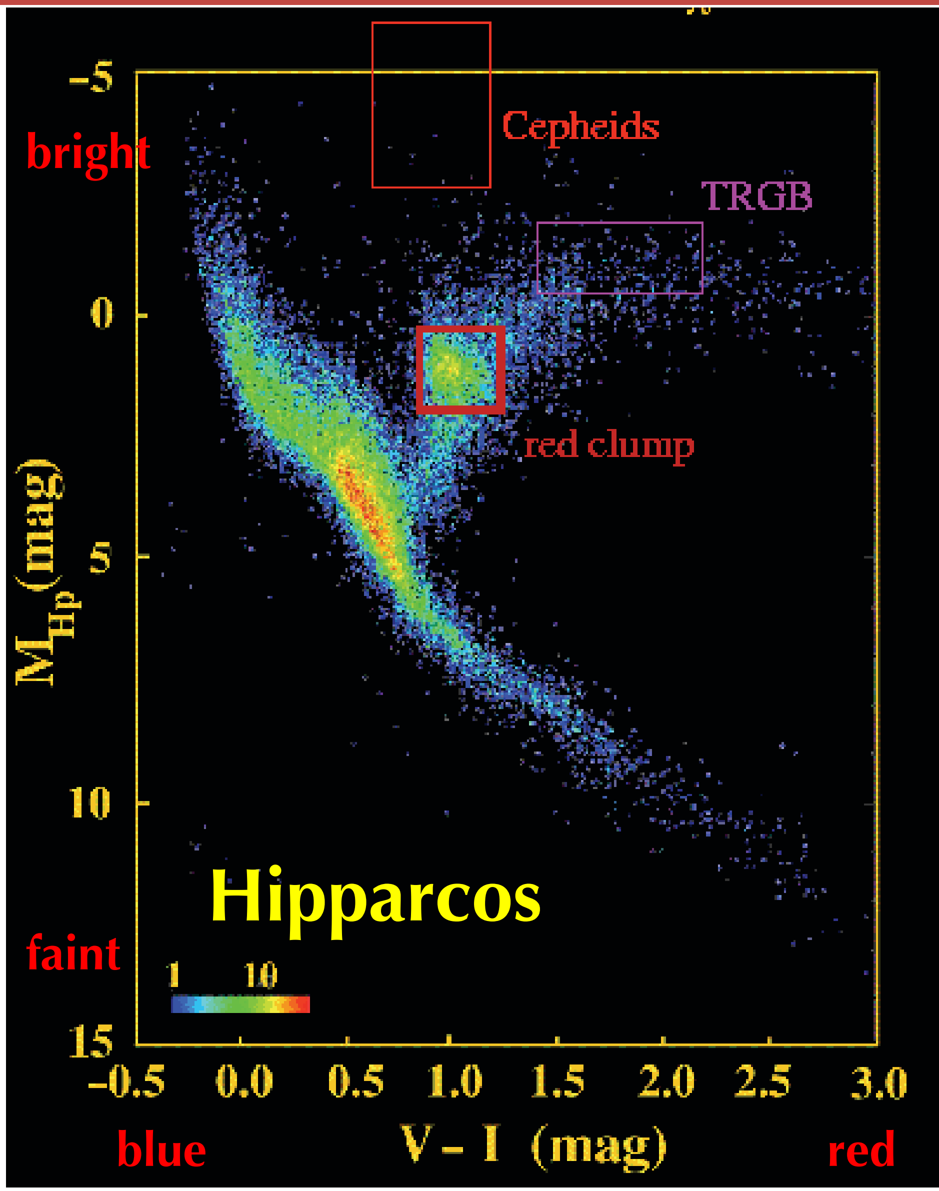
The Milky Way is a beautiful SBc type galaxy

❸ Photometric modelling of the Milky Way bar



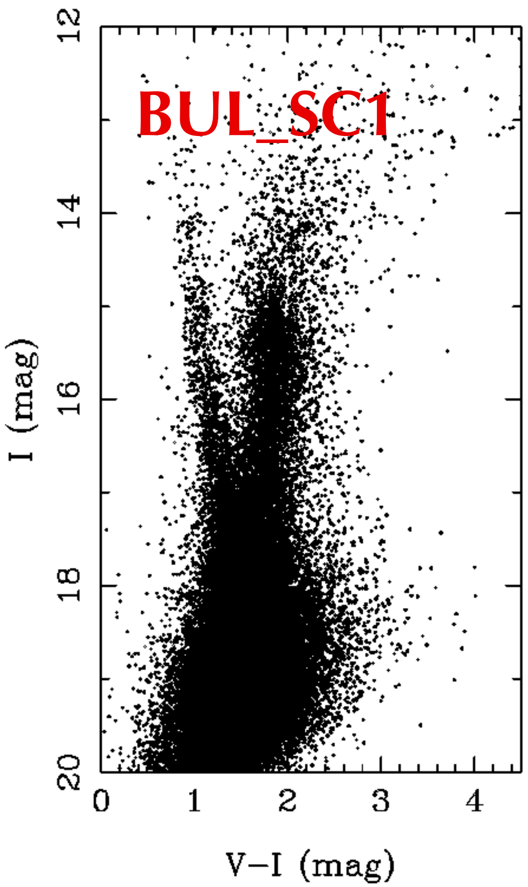
- **Bar basic parameters:**
  - ✓ Bar angle
  - ✓ Bar tri-axial lengths
- **How many bars?**
  - ✓ boxy/peanut bar
  - ✓ Long, thin bar
  - ✓ Super-thin bar
- **Needs tracer populations: RR Lyrae stars, red clump giants**

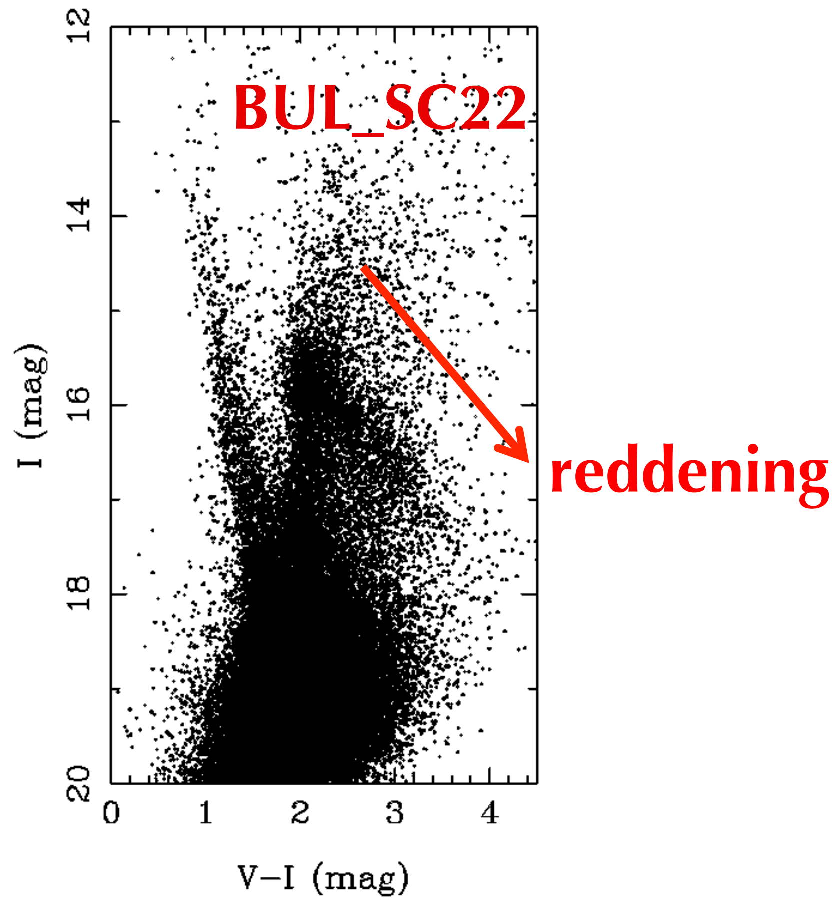
Color-magnitude diagram close to the Sun



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

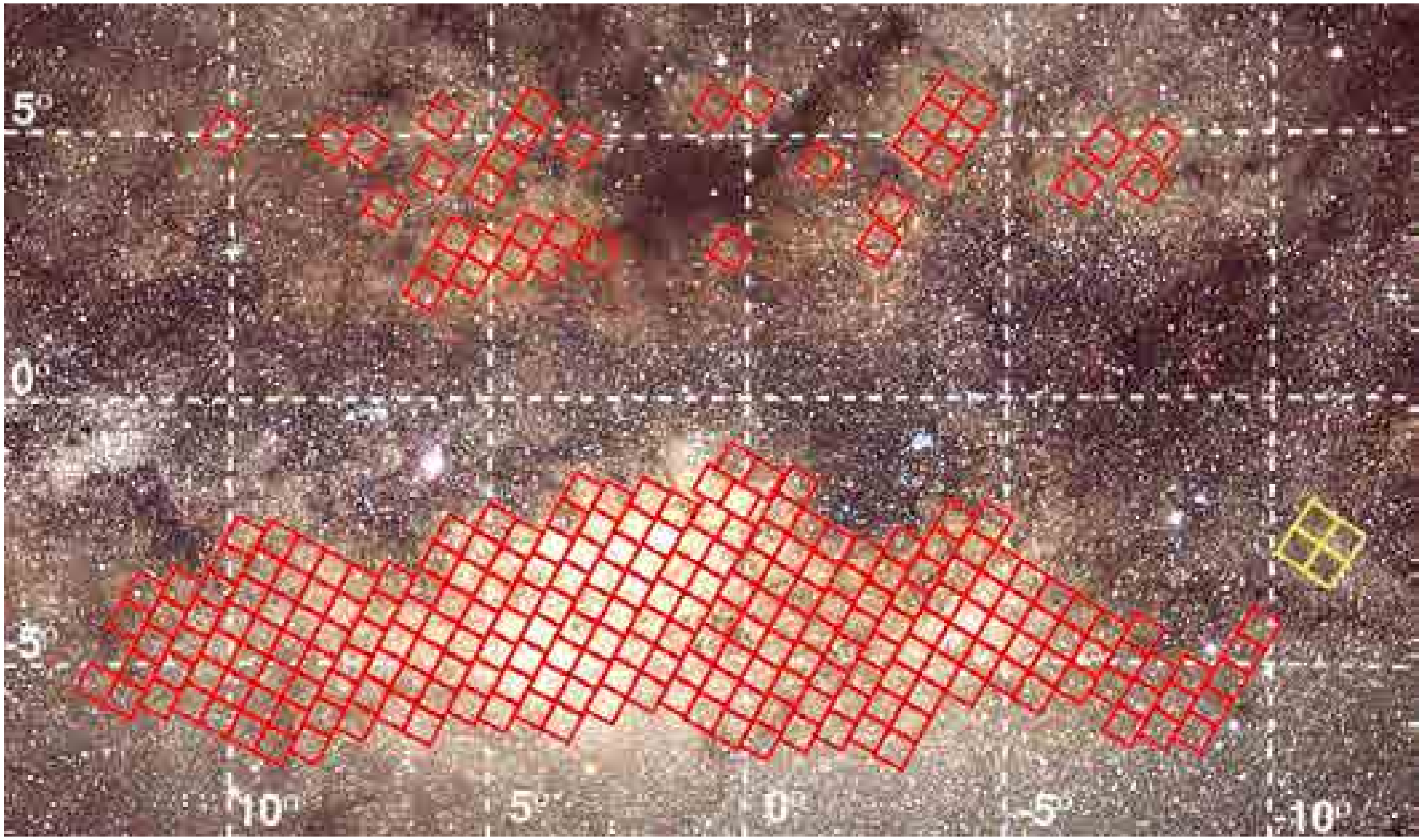
Bulge Color-magnitude diagrams





- 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

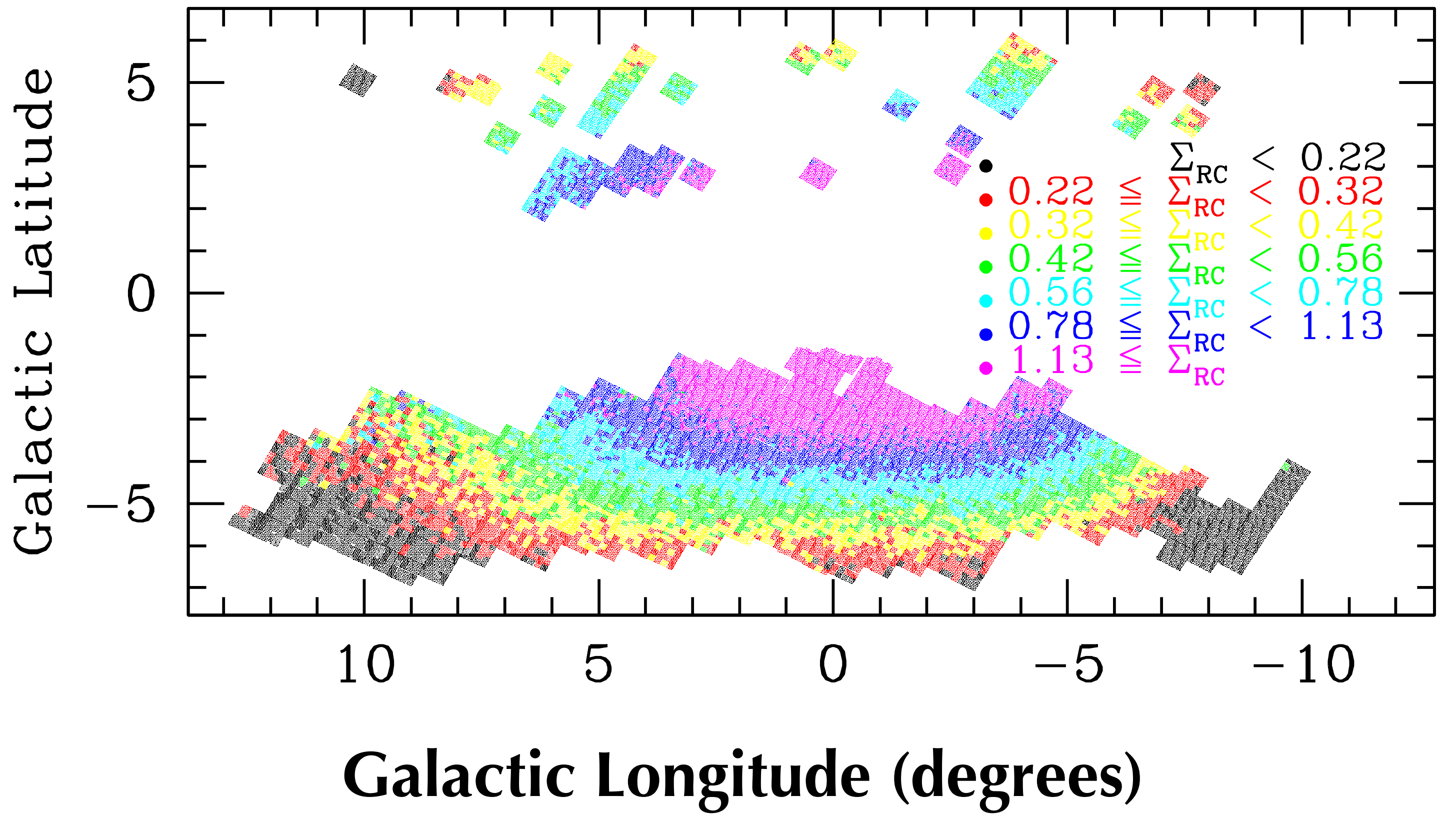


Latitude (degrees)

Longitude (degrees)

- OGLE-III fields Cover ~ 100 square degrees
- For each field, we can obtain the LF & total #of RCGs

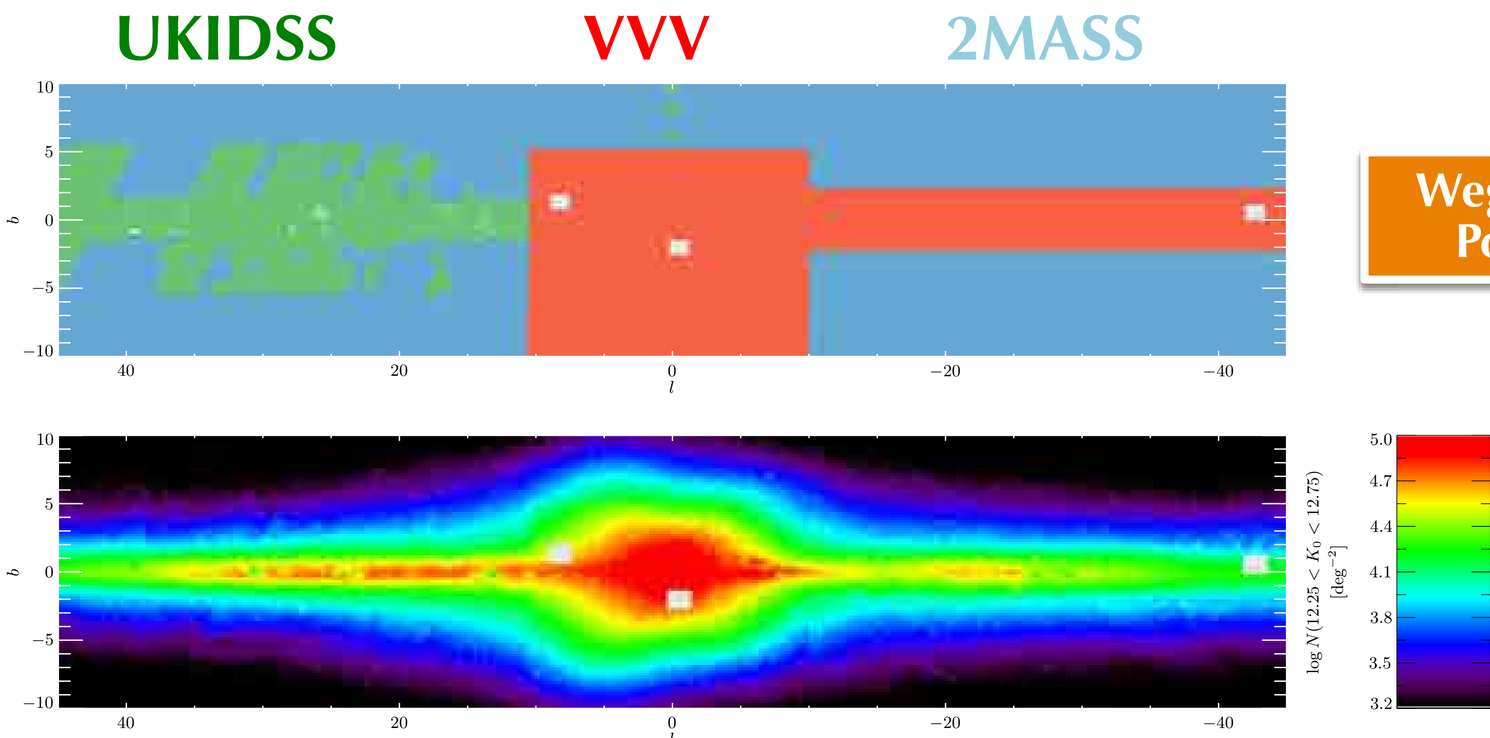
Number counts of red clump giants



Nataf et al. (2012)

- **Contours at fixed surface density are approximate ellipses.**

Other surveys

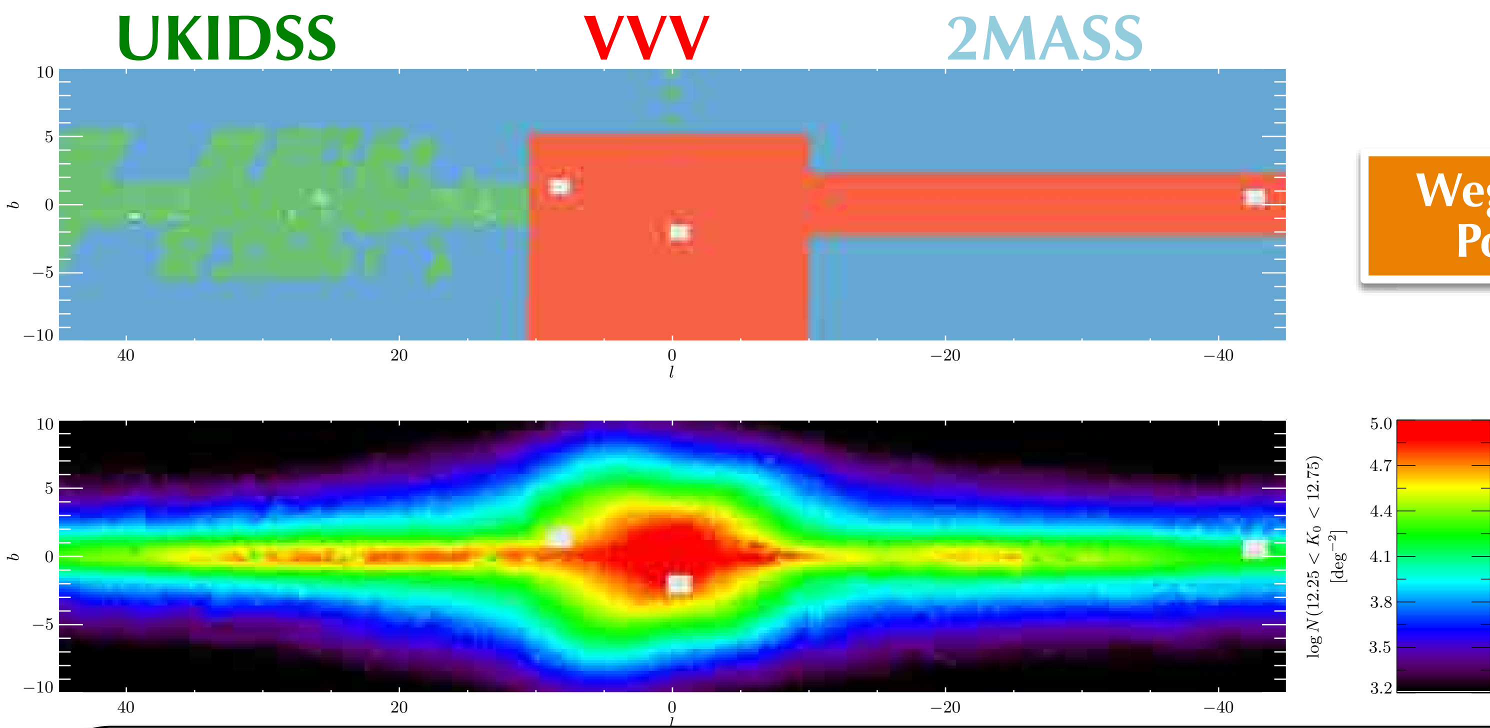


Wegg, Gerhard & Portail (2015)

Views of the Milky Way combining three surveys

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

Parametric modelling



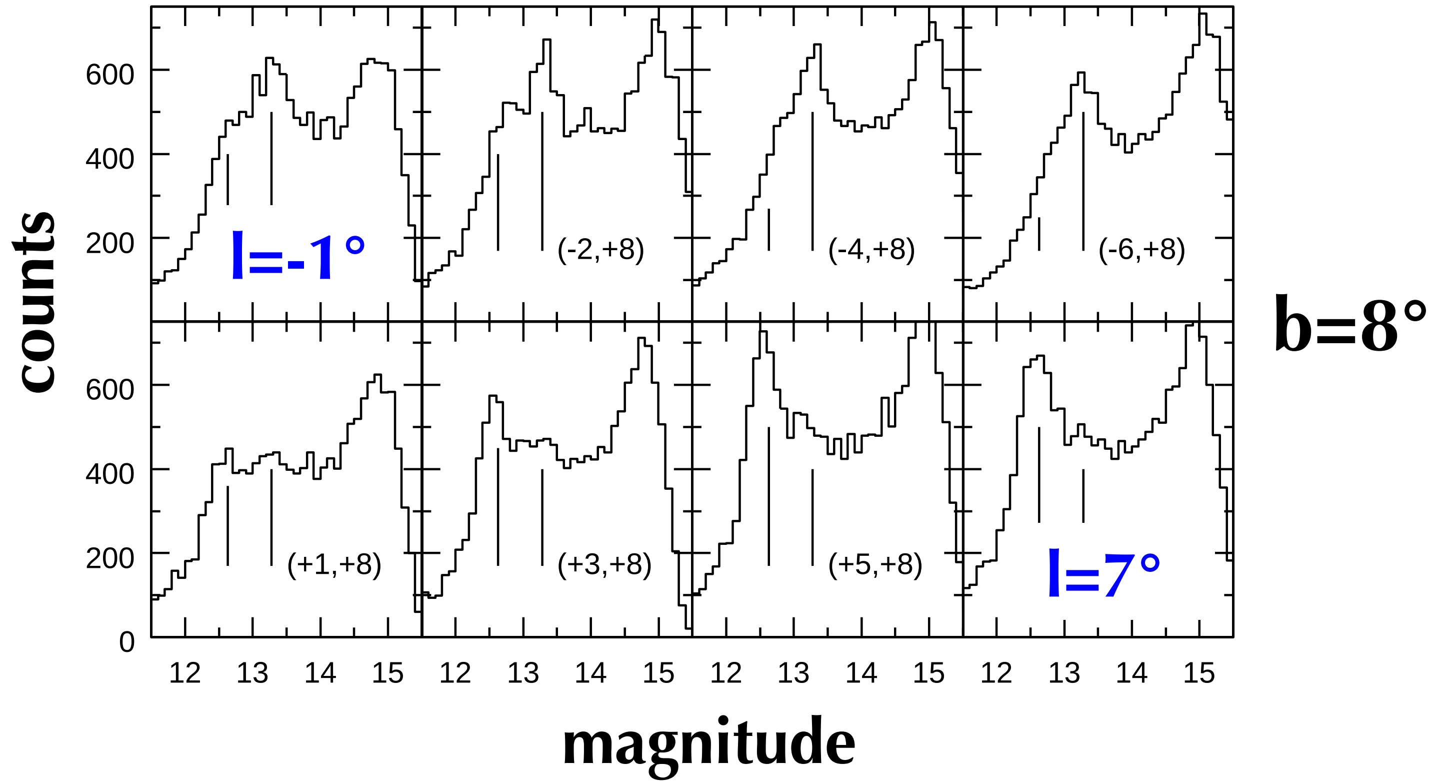
Wegg, Gerhard & Portail (2015)

- 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. 2013):
  - ✓ 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).

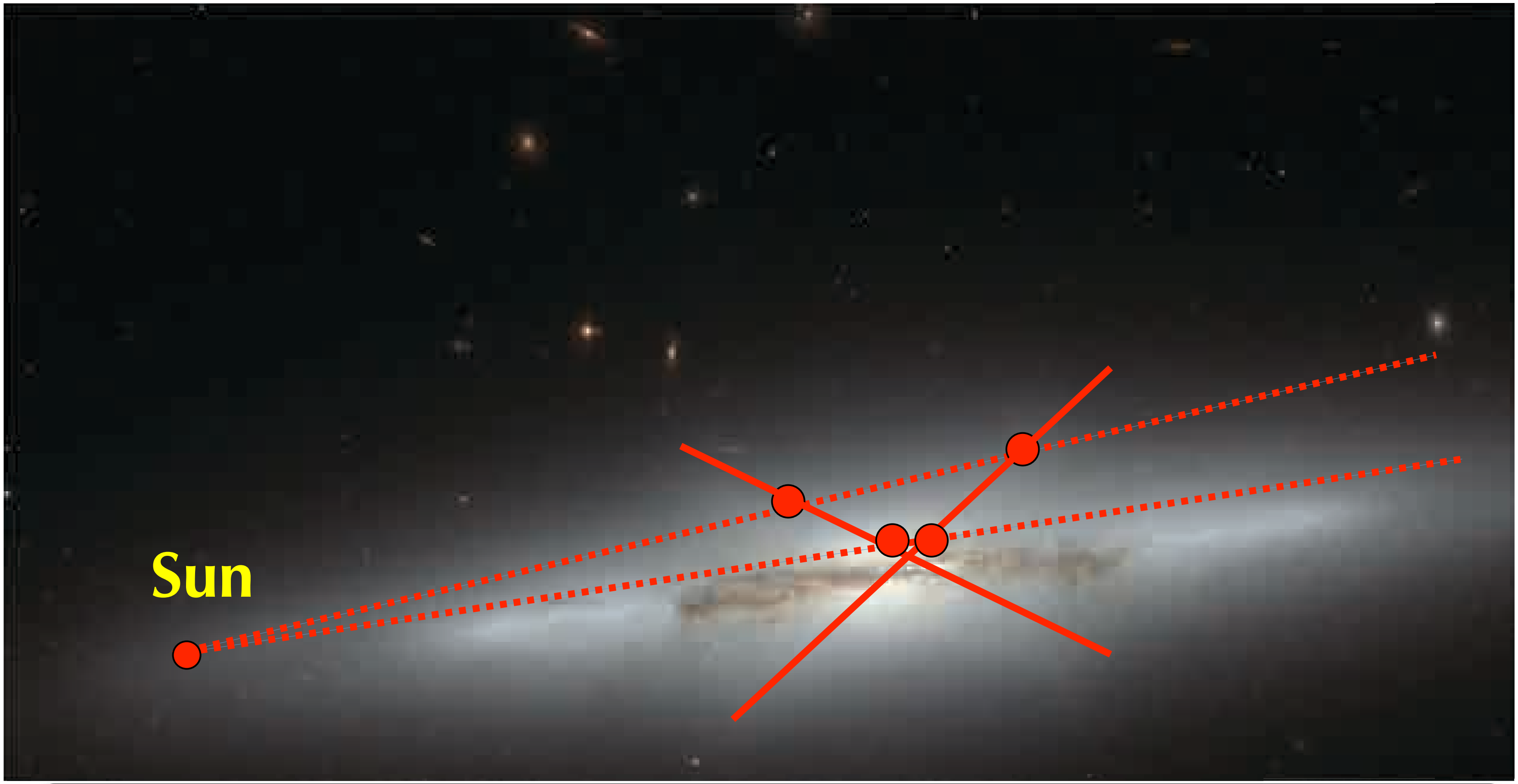
Double peaks in RCG counts



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

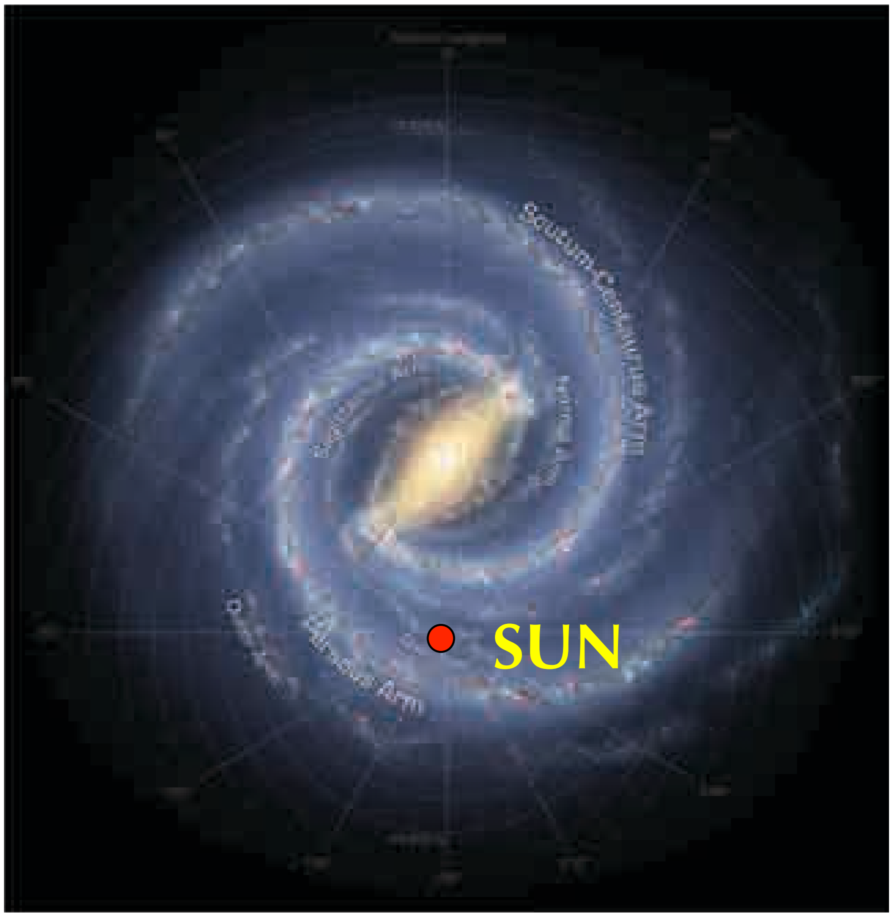
- Most fields exhibit a single peak.
- Double peaks are only prominent at large b.

X-shaped structure in the Milky Way



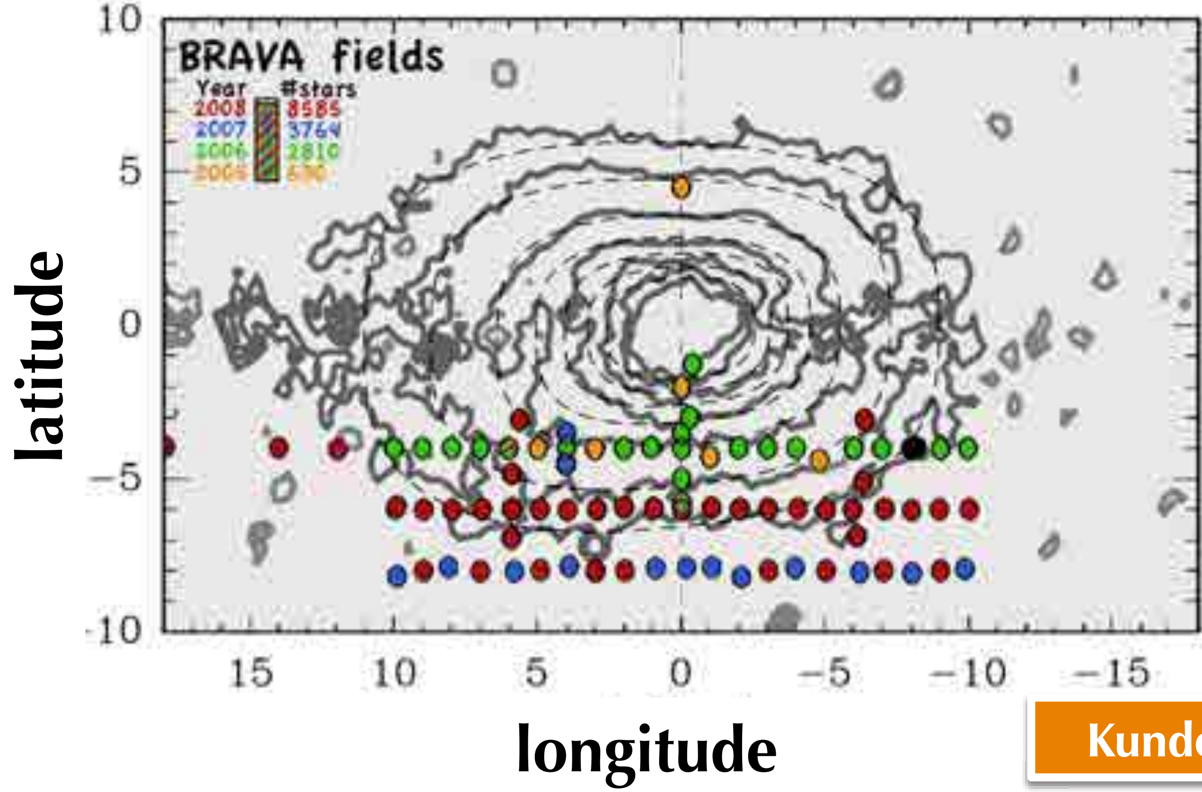
- At high latitude fields, double peaks
- Low latitude fields exhibit a single peak
- Kinematics (Qin, Shen, Mao et al. 2015)

❹ Dynamical modelling of MW bar



- Kinematic data
- Dynamical modelling techniques

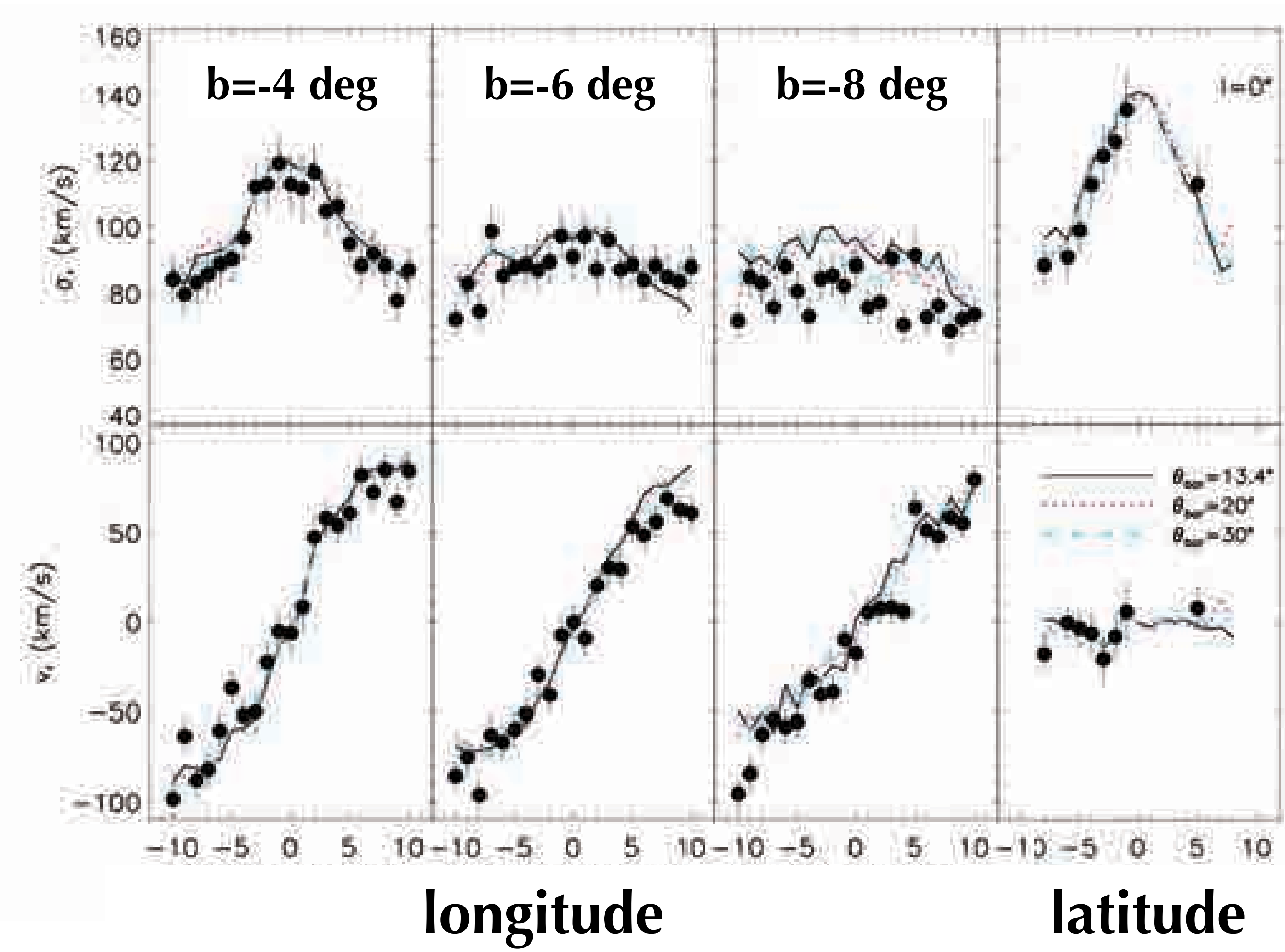
Radial velocity fields of BRAVA



Kunder et al. (2012)

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

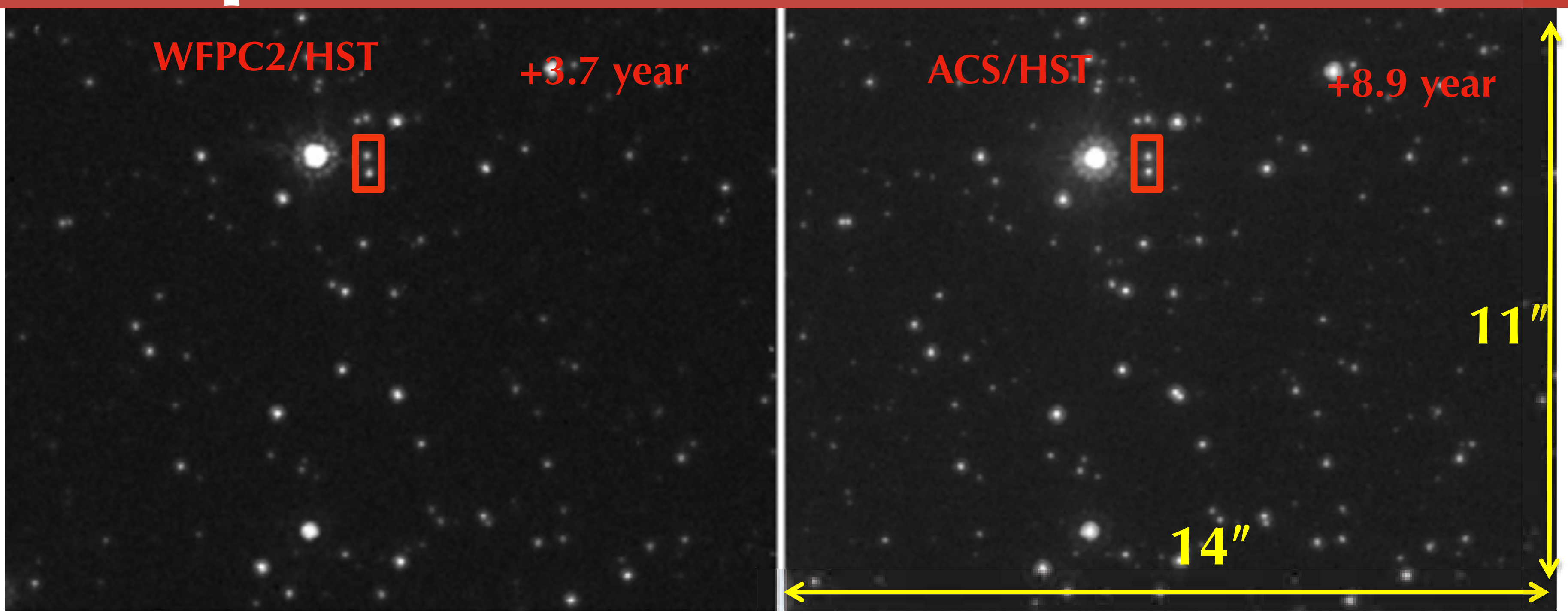
BRAVA Radial velocity data



Velocity dispersion

Mean velocity: rotation

Proper motions of stars with HST



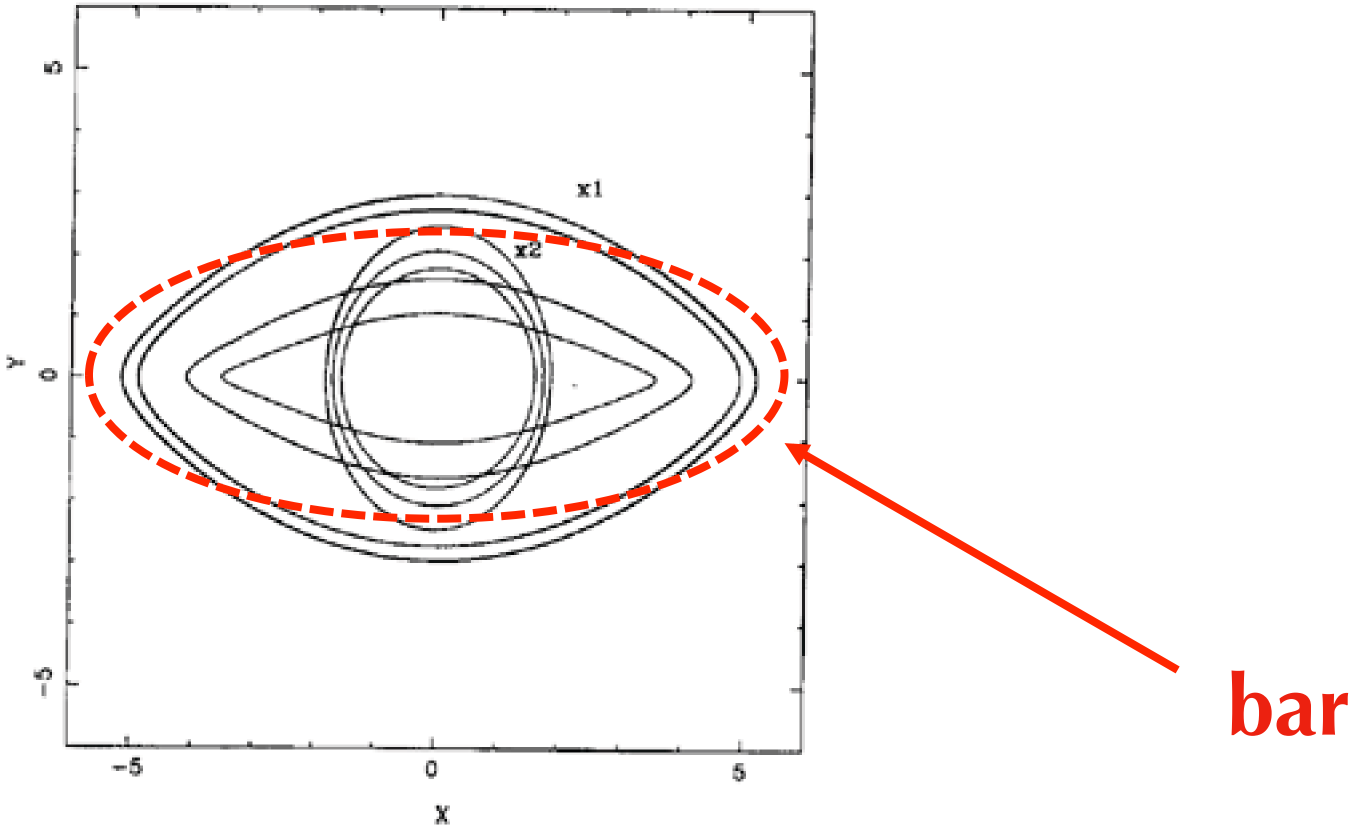
Kozlowski, Wozniak, Mao et al. (2006)

- 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.

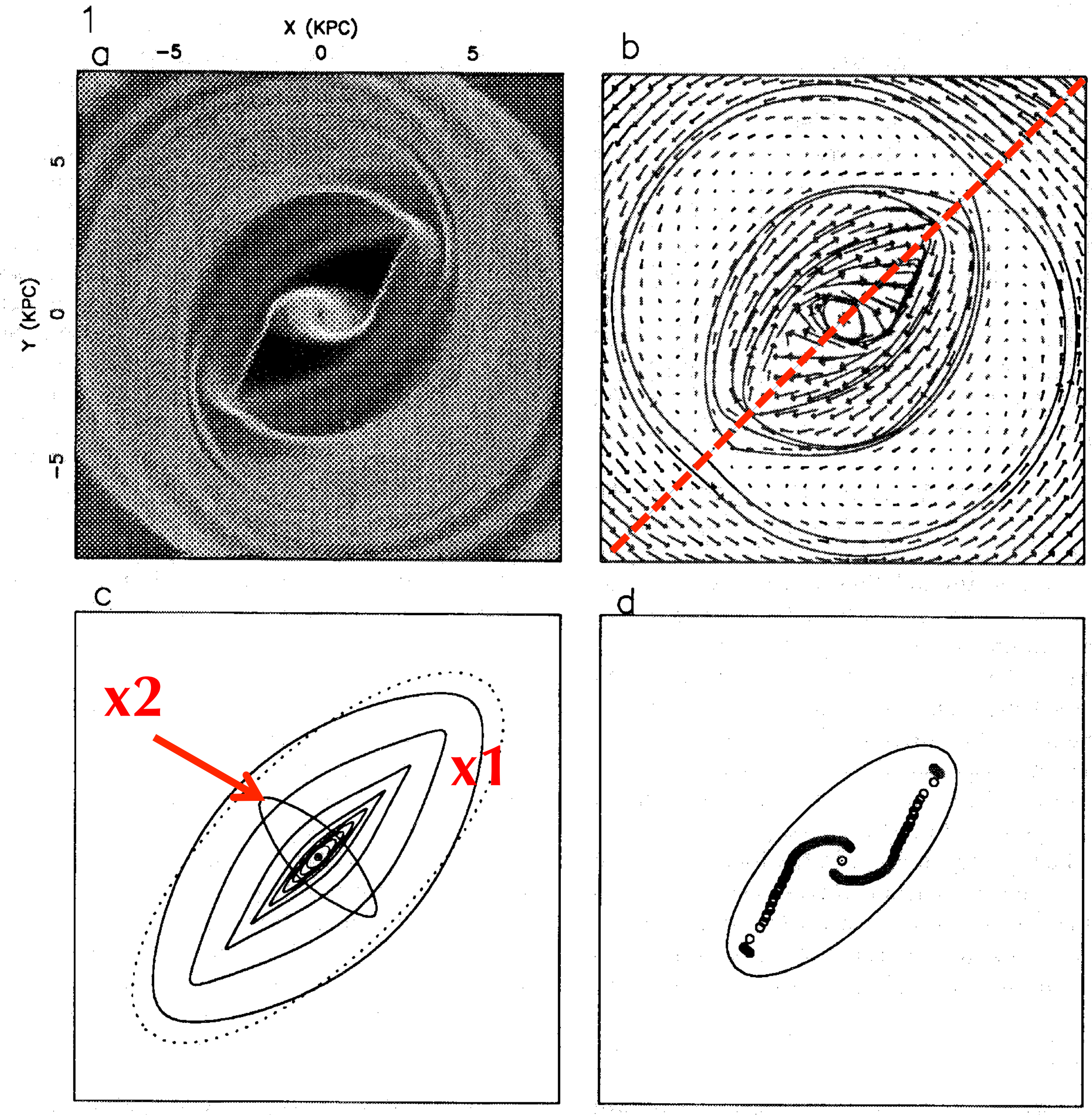
Orbital families in rotating bars: x1 and x2 families of closed orbits



As viewed in the co-rotating frame

Contopoulos & Grosbol (1989)

Gas motions in a rotating bar

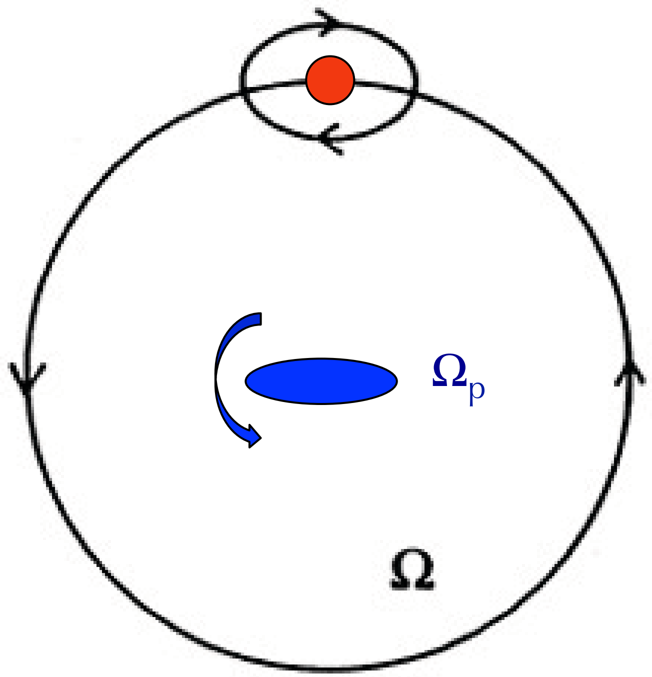


Bar major axis

Athanassoula (1992)

Resonances in bars

Epicycle frequency κ



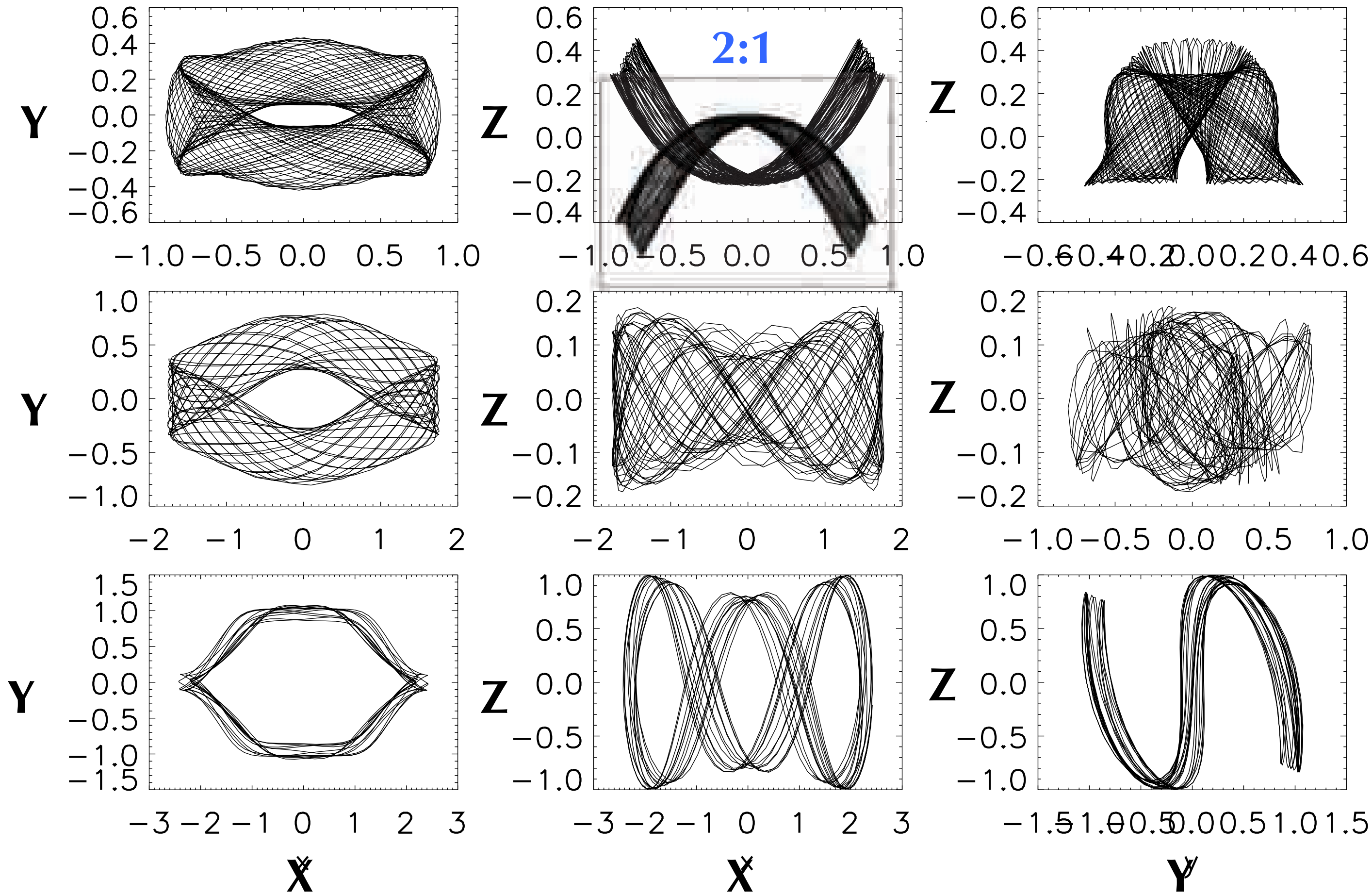
For perturbations with **m-fold symmetry,** resonances occur when

$$m(\Omega-\Omega_p)= \begin{cases} 0, & \text{Corotation} \\ +\kappa, & \text{Inner LR} \\ -\kappa, & \text{Outer LR} \end{cases}$$

Rings in bars are related to resonances (Corotation, inner & outer Lindblad resonances)!

Outer ring = CR, nuclear ring = ILR?

Regular orbits in realistic potentials



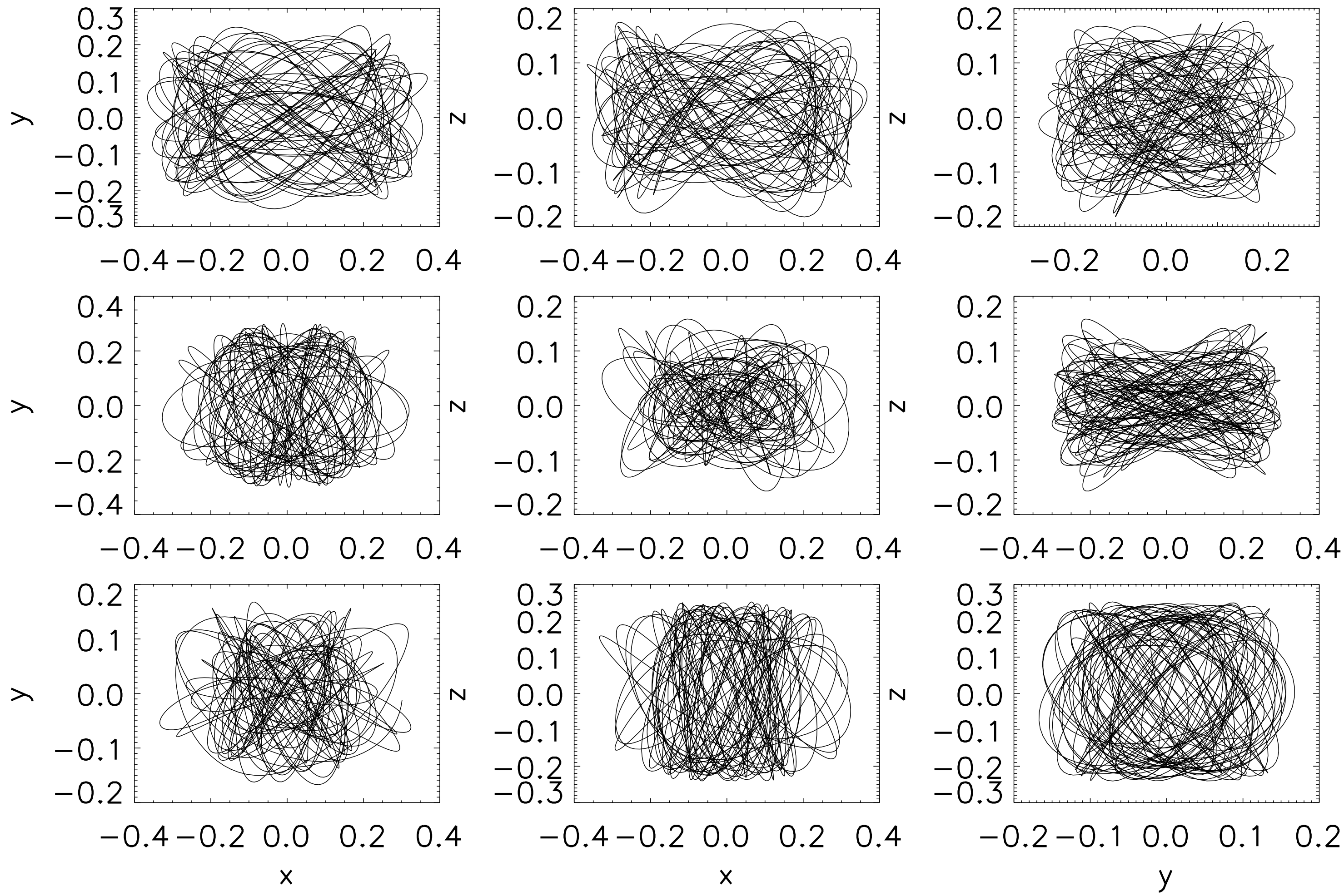
Banana or Pretzel

⬇

X-shaped structure ???

Provided by Yougang Wang

Chaotic orbits



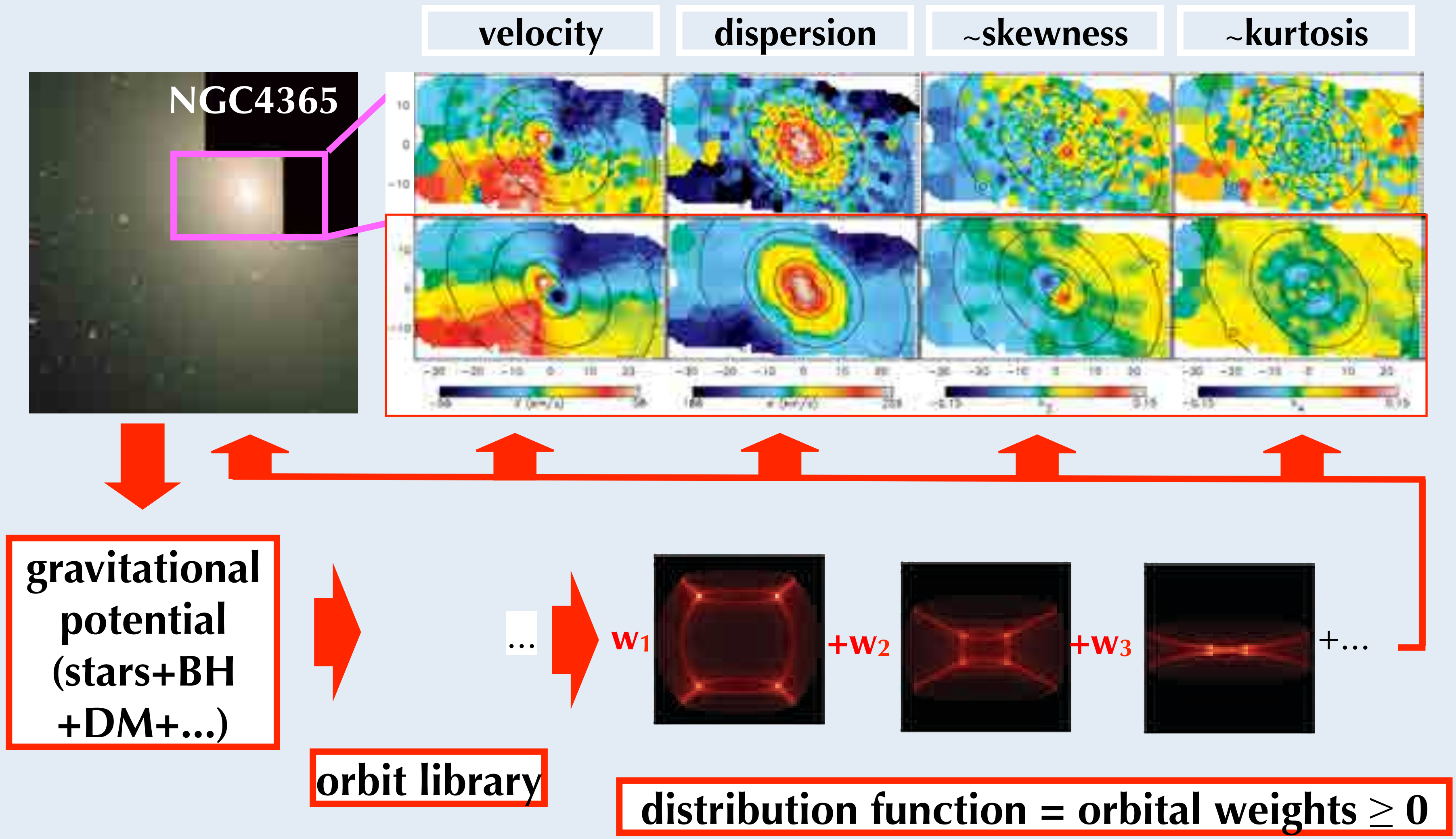
Many orbits are in fact chaotic!

Methods of orbit superposition

- **Schwarzschild method:** orbit-based
  - ✓ Choose $\Phi(x)$, identify families of orbits, fit data by weighting orbits.

- **Made-to-Measure method:** particle-based
  - ✓ Choose $\Phi(x)$, sample the system with particles. Integrate orbits, fit data by changing particle weights.

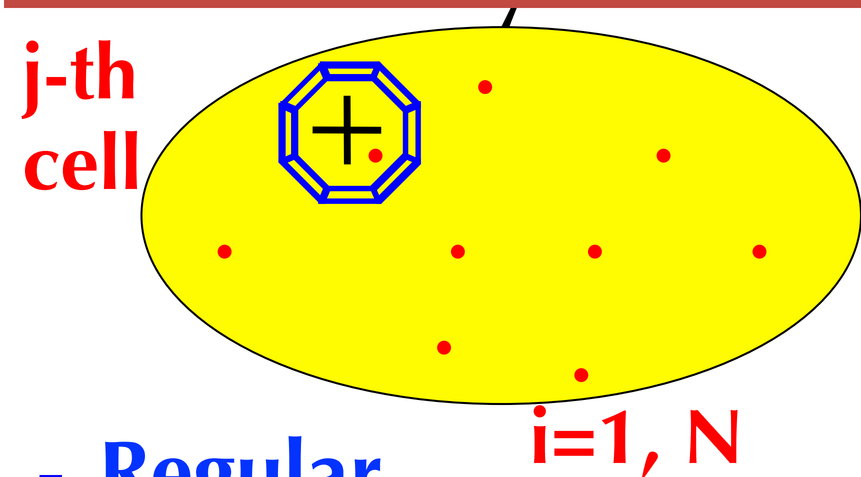
Schwarzschild orbit superposition method



From Ling Zhu

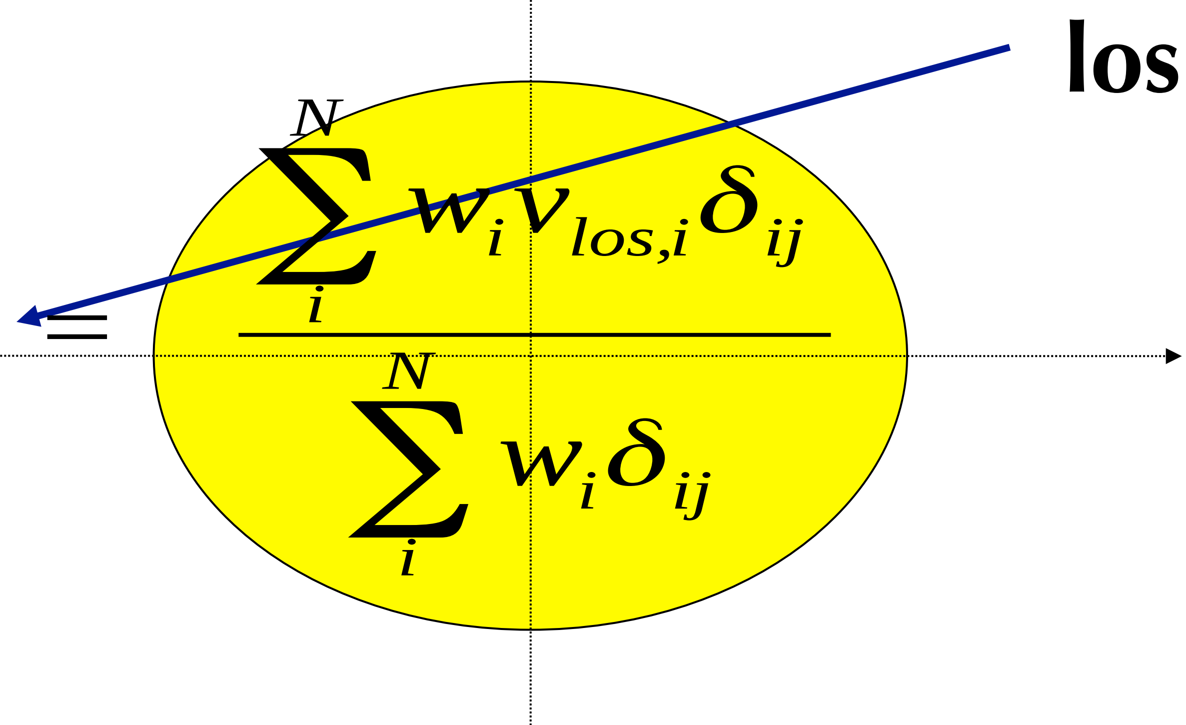
Schwarzschild (1979), Richstone & Tremaine (1988), Rix et al. (1997), Gebhardt et al. (2003), ...

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



- N (~10^6) particles are orbited
- Particle weights adjusted as a function of time

- **Regular**
  - Cartesian, polar,
- **Irregular**
  - e.g. from Voronoi binning of actual data



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

Model observables

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

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

Position = j

Number of particles = N

Individual particle = i

$$y_j = \sum_i^N w_i K_{ji}$$

Kernel:

- **Surface brightness**
- **Average velocity, dispersion, …**

Weight evolution equation

Weight evolution equation (Syer & Tremaine 96):

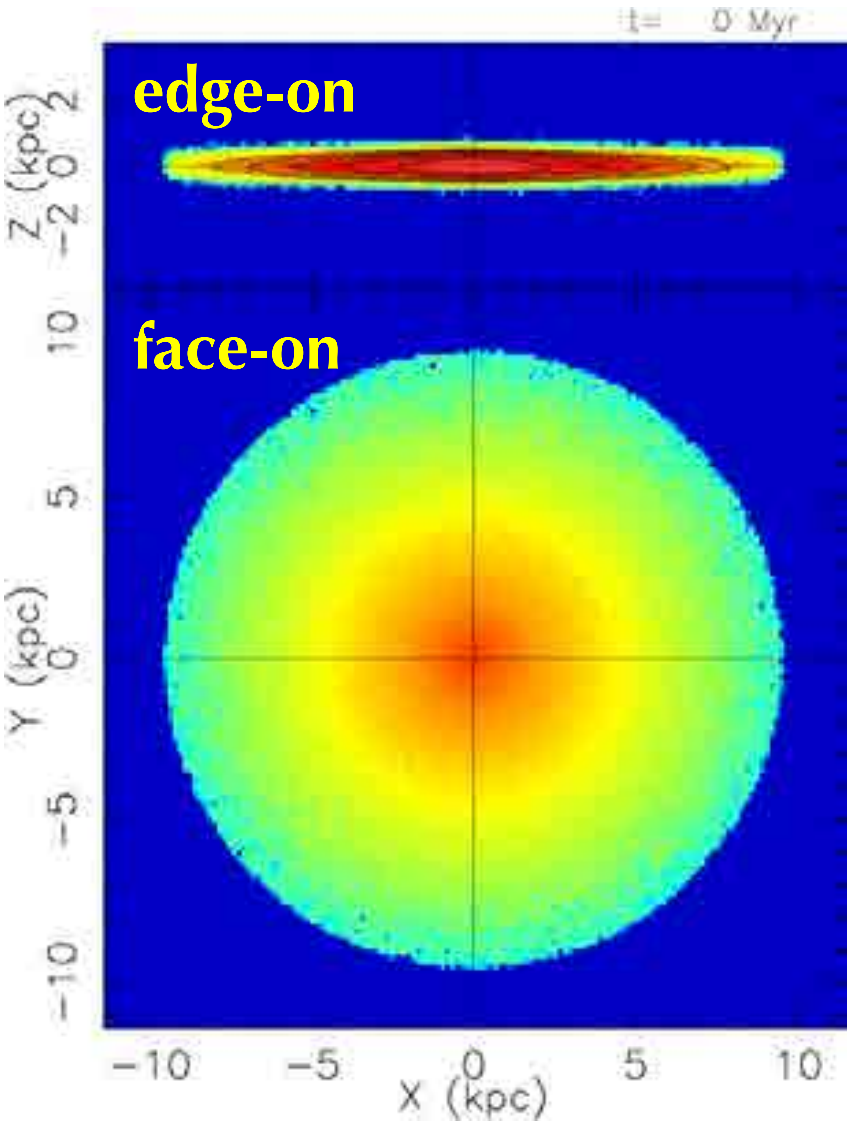
$$\frac{dw_i}{dt} \propto -\varepsilon w_i \left(\sum_j^J K_{ji} \Delta_j \right), \ \Delta_j = \frac{y_j - Y_j}{Y_j}, \ \varepsilon > 0$$

When the predicted y_j > observed Y_j, weight is reduced, and vice versa, until convergence is reached.

Advantages:

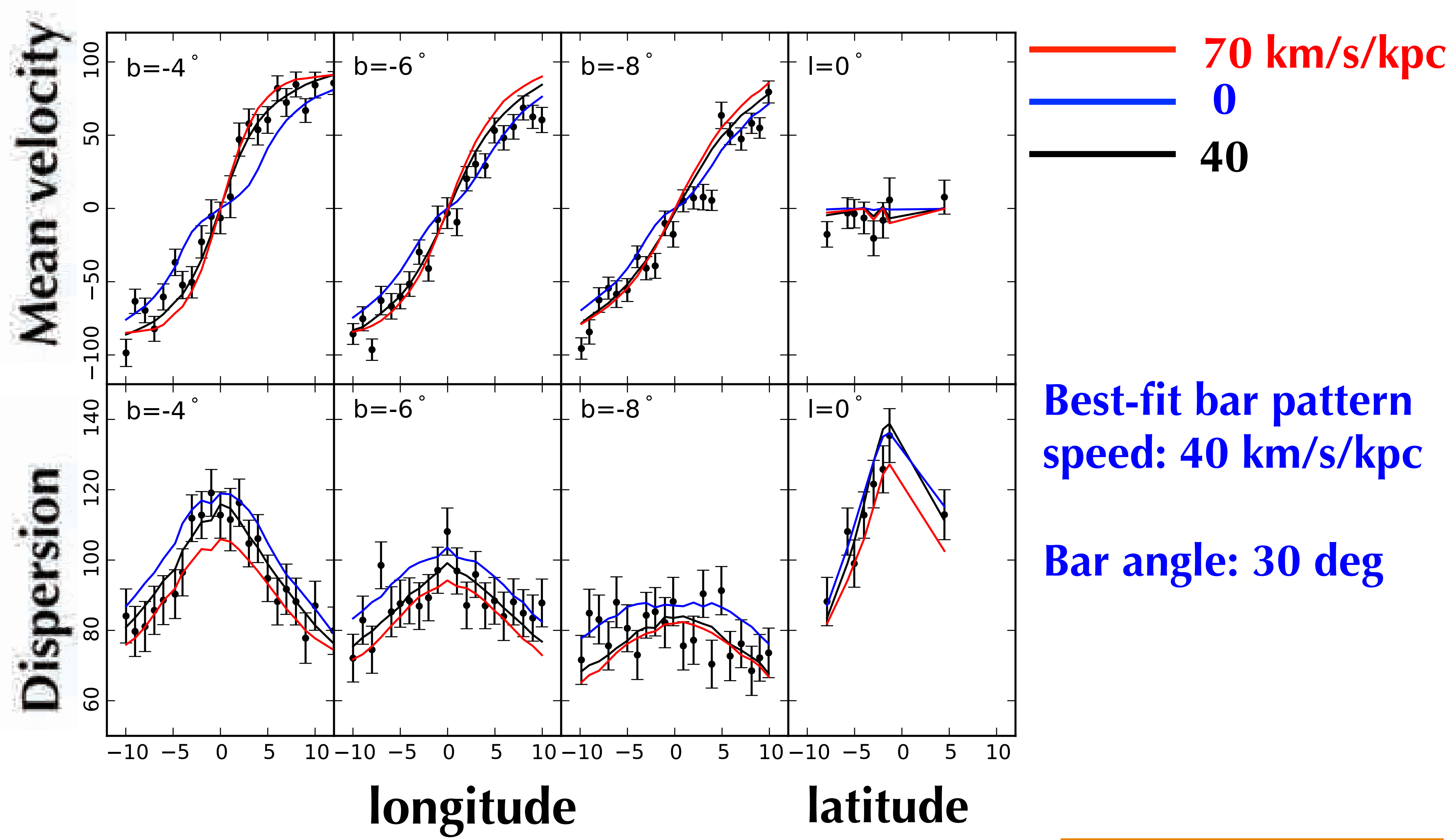
- **Adjusts the weights on-the-fly to fit obs. Data**
- **More flexible than the Schwarzschild method**
- **Cross-check on model degeneracy**

Numerical Model of the Milky Way Bulge



- Shen et al. (2010) starts with an exponential disk plus a fixed DM halo
- Bar and buckling instabilities induce boxy/ peanut-shaped bulges
- Taken as the initial condition

Reproducing BRAVA radial velocity



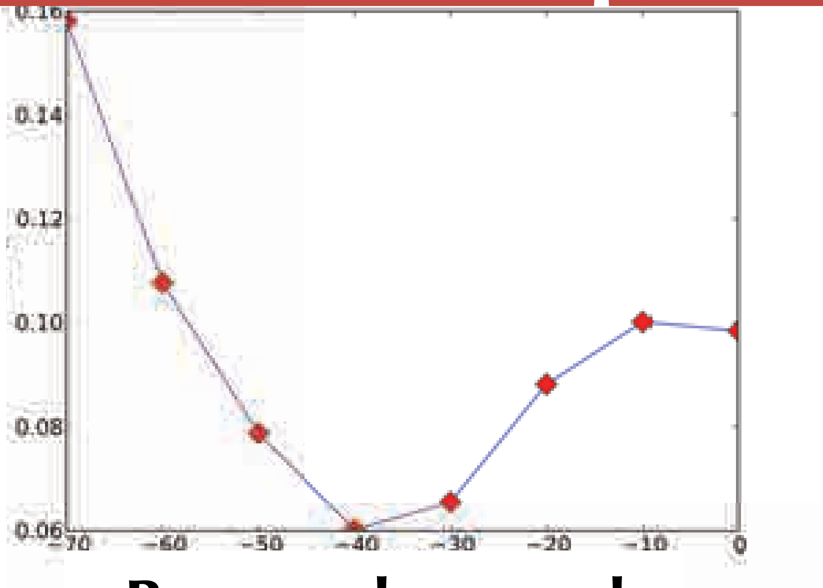
Best-fit bar pattern speed: 40 km/s/kpc

Bar angle: 30 deg

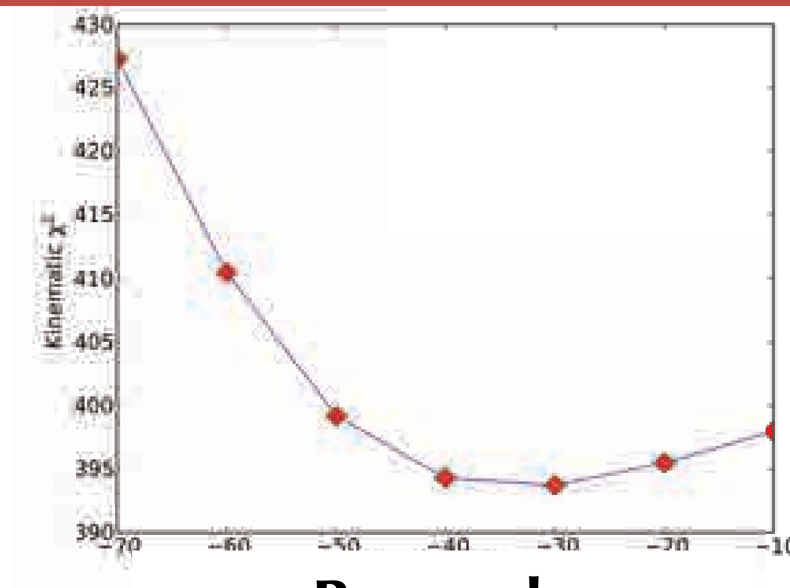
Long, Mao, Wang & Shen (2012)

Constraints on the Galactic bar parameters

Model chi^2



Bar angular speed



Bar angle

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!

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.
- MaNGA data!
- Much theoretical work yet to be done
  - ✓ Needs to explain new chemo-dynamical correlations in particular (Long, Mao, Merrifield 2015).
  - ✓ Stability and degeneracy issues need to be further explored.