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Dynamically modelling the MW

Outline

- The challenge
- Equilibrium dynamical models
- Axisymmetric models
- Including the bar
  - M2M models
  - Torus models
- Why orbit-based models of the solar nhd are problematic
- Conclusions

The challenge

- Spectacular data sets are flooding in
  - Gaia + spectroscopic surveys
    - APOGEE, RAVE, GES, LAMOST, Galah, WEAVE,....
- We want to learn how our Galaxy formed
  - First we must establish how it is structured now
- Each survey has non-trivial selection function
  - It images the MW through a distorting lens
- Also most interesting parts of the MW obscured by dust
- So non-trivial to infer MW's structure from catalogues
- We must build a model that's consistent with catalogues
  - This model will *embody all we know about the MW*

Models

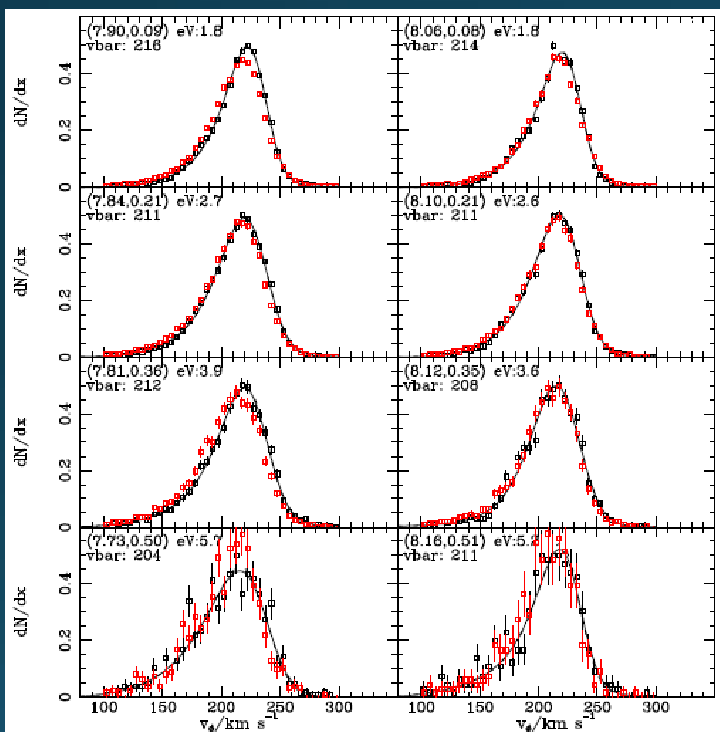
- We have to model stars & gas in parallel
  - Don't forget: since 1950s radio observations of HI, CO, etc have provided crucial constraints on MW's gravitational field g(x)
- >90% of MW's mass is dark
  - We must model DM too!
- We have to track DM from its contribution to g(x)
  - Can only infer g(x) from kinematics to the extent that the MW is in equilibrium
- So we must start from *equilibrium dynamical* models
  - Later we will add non-equilibrium features (spirals, warp, streams,..) as perturbations

Jeans theorem

- Given equilibrium, Jeans' theorem collapses 6d phase space to 3d orbit space
- In principle infinite freedom in choice of constants of motion to use as coordinates of orbit space
  - But in practice only one rational choice:
    - action integrals J
- We now have axisymmetric models specified by analytic
  - Extended Distribution Functions (EDFs) $f_*(J,age,[Fe/H])$
  - $f_{DM}(J)$
  - (B & McMillan 2011; Bovy & Rix 2013; Sanders & B 2015; Penoyre+ 2015)

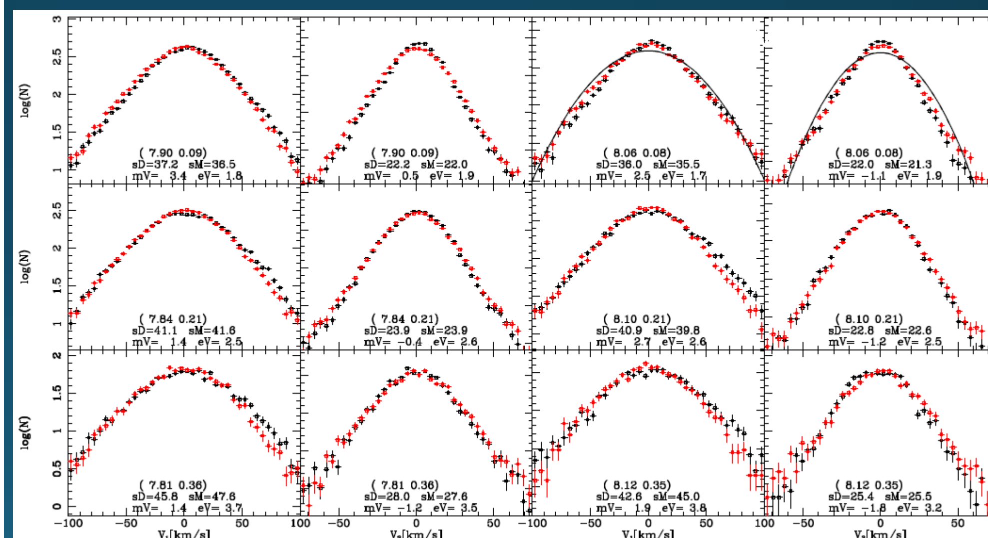
Rave kinematics Binney, Burnett + RAVE 2014

- Binney (2012) fitted disc f(J) to GCS data (s <~ 0.1 kpc)
- Binney + (2014) tested its *predictions* for kinematics of RAVE stars in 8 volumes with s <~ 2 kpc



Cool dwarfs

$R < R_0$ $R > R_0$



Self-consistent multi-component models

- First models used fixed parametrised Φ but current models have self-consistent Φ
- Major advantages of using actions:
  - Ease of constructing models that contain many populations (stars of each [mass, age & chemistry], DM, white dwarfs, n-stars,…)
  - Ease of finding self-consistent gravitational potential $\Phi(x)$
    - Penoyre+ 2015; B & Piffl 2015; Cole & B 2016

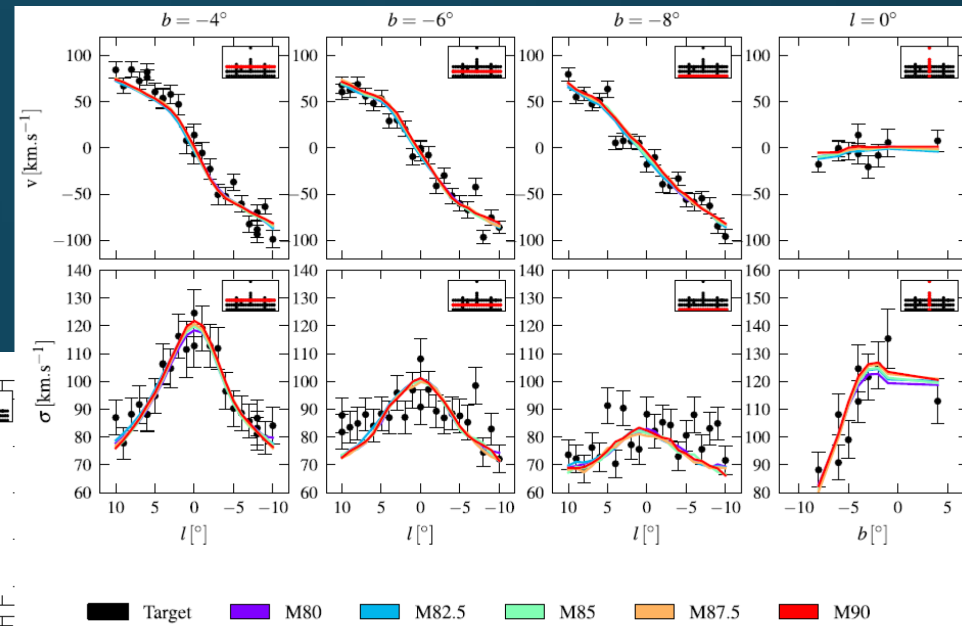
Non-axisymmetry

- MW is a *barred spiral*
  - Simplest ansatz is that Φ steady in rotating frame
- Models to date exploit Staeckel Fudge, which gives J(x,v)
  - Converts f(J) to f(x,v) so can get v-distribution & ρ by integrating over v
- Unfortunately SF not available for Φ with figure rotation
- Without SF can only build orbit-based models
  - N-body, M2M, Schwarzschild, Torus
- We treat a galaxy as a sum of orbits

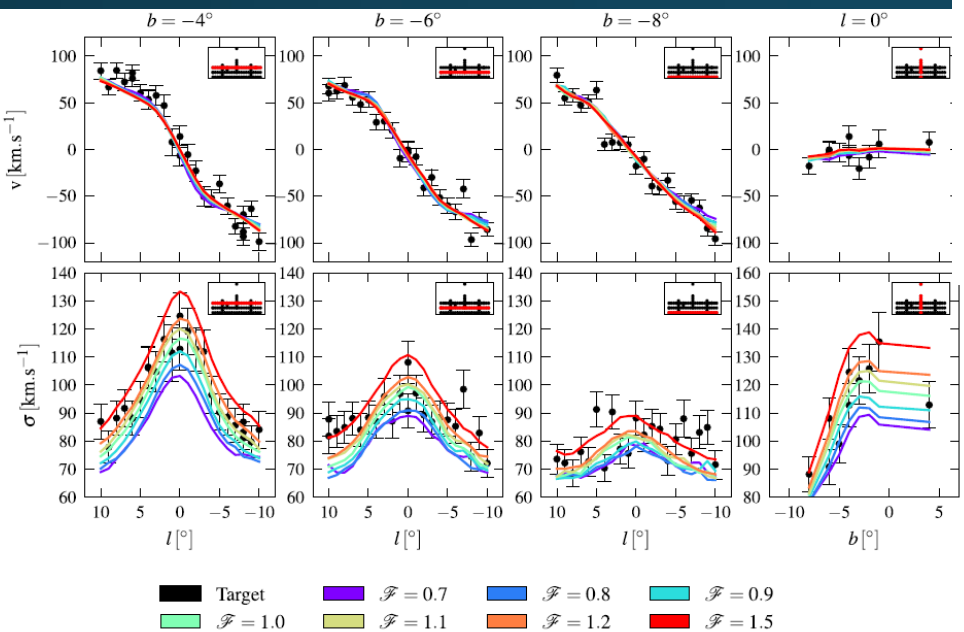
M2M models

- (Syer & Tremaine 1996; De Lorenzi+ 2007; Long+ 2013; Martinez-Valpuesta 2012; Portail+ 2015)
- Let N-body model develop a bar
- Vary particle weights while integrating eqs of motion to optimize fits to observables
- Occasionally update Φ
- Has produced very convincing models of bar/bulge

Pattern speed: 27 km/s/kpc



Decreasing halo mass in bulge



Increasing stellar mass

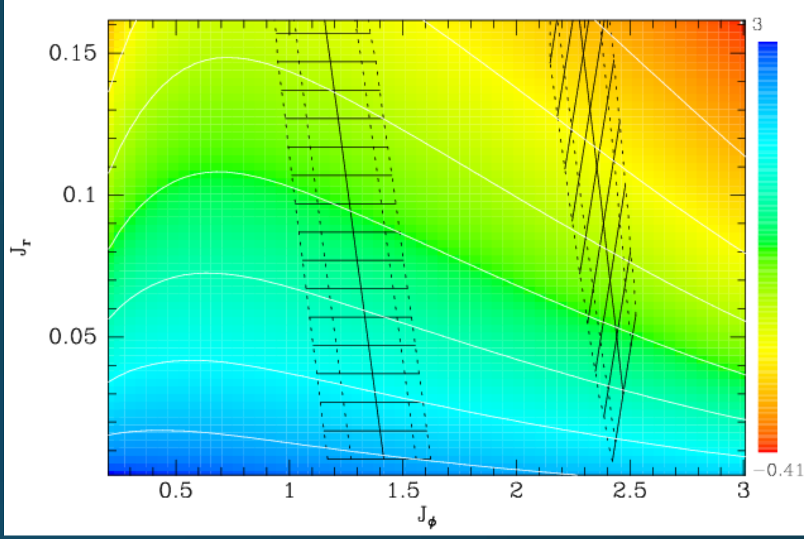
Portail+ 2015

Schwarzschild & Torus modelling

- Schwarzschild (1979) is industry standard for models of early-type galaxies
- Choose Φ and integrate an orbit library
  - then choose weights to fit data
- For many reasons it's best to represent orbits with tori
  - Structures with known actions J equipped with angle variables
  - A torus encodes every orbit J to all eternity in ~100 numbers
  - Torus Mapper (B & McMillan 2016) generates torus more quickly than a long orbit integration
  - TM's methods return anything you might compute ([ρ(x), v(x), ..]
  - Can now relax Φ to self-consistency
- Traditional representation of orbits as time series not competitive

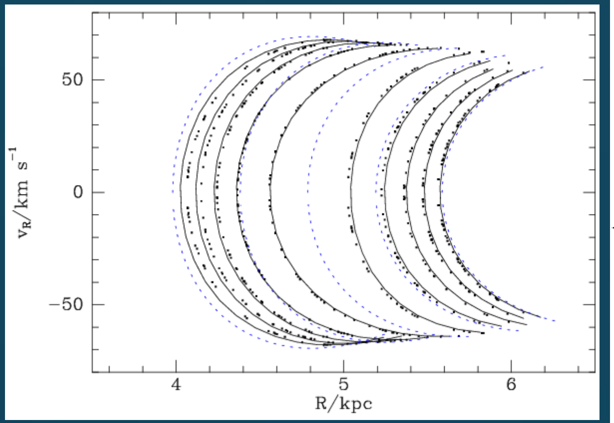
Orbit families

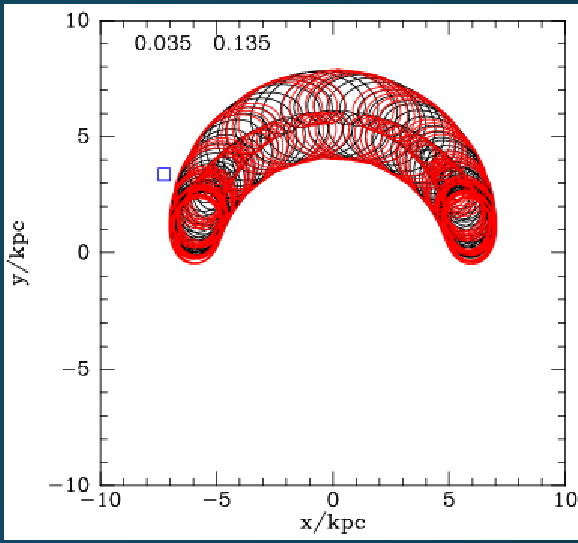
- Once Φ is non-axisymmetric, cannot ignore that there's >1 orbit family
- Each family has its own angle-action coordinates
- Orbits that belong to >1 family are "chaotic"
- Families normally considered to arise from "resonant trapping"
- In a realistic Galactic bar (Sormani+2016) corotation and Lindblad resonances have significant zones of entrapment
- Using perturbation theory we can construct tori for trapping zones

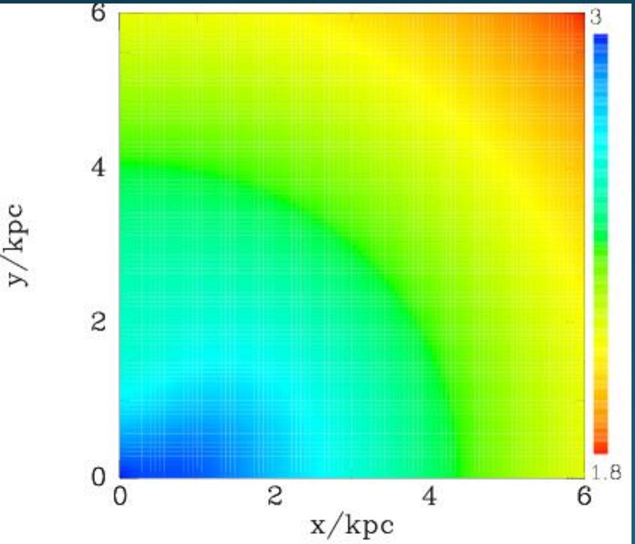


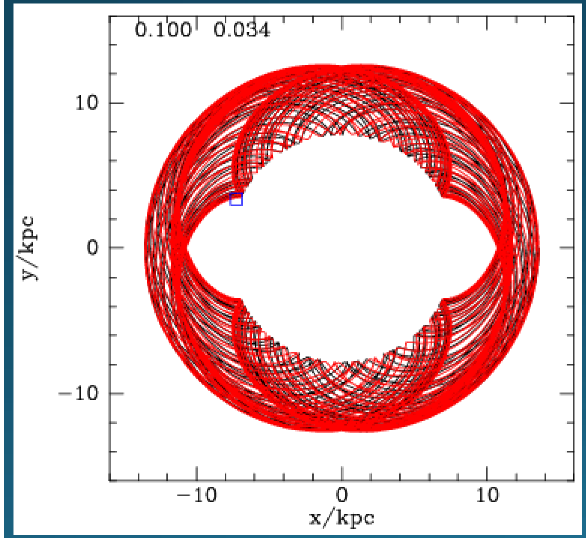
Binney 2017

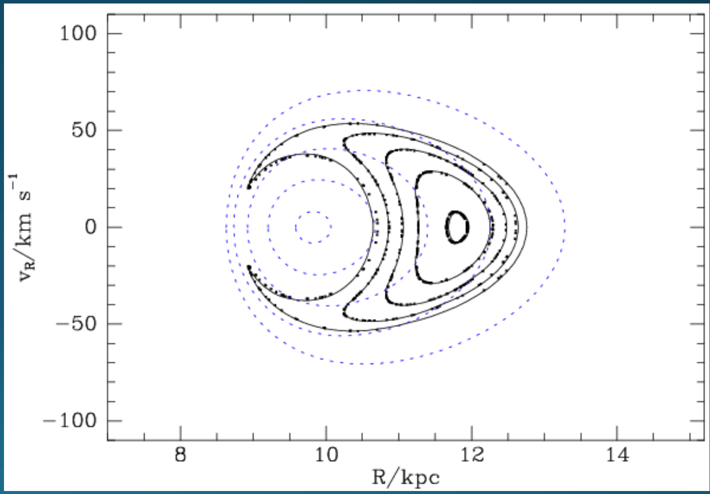
Non-axisymmetric tori
(Binney 2017)





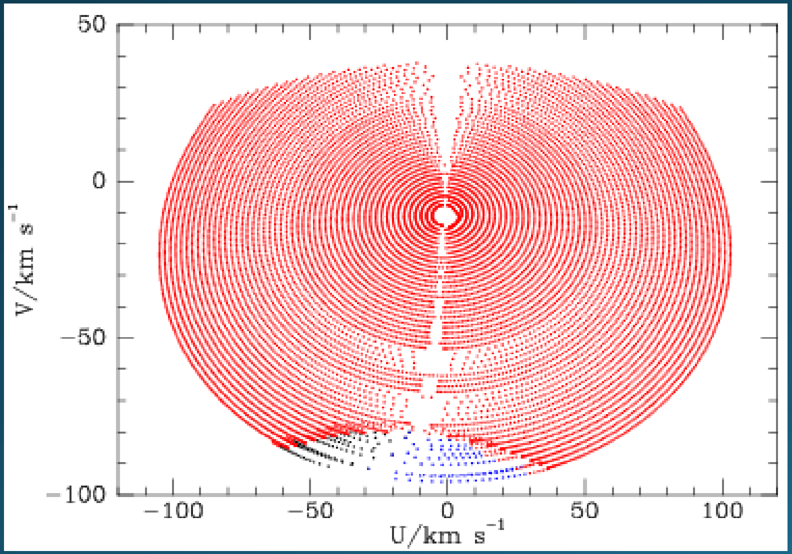


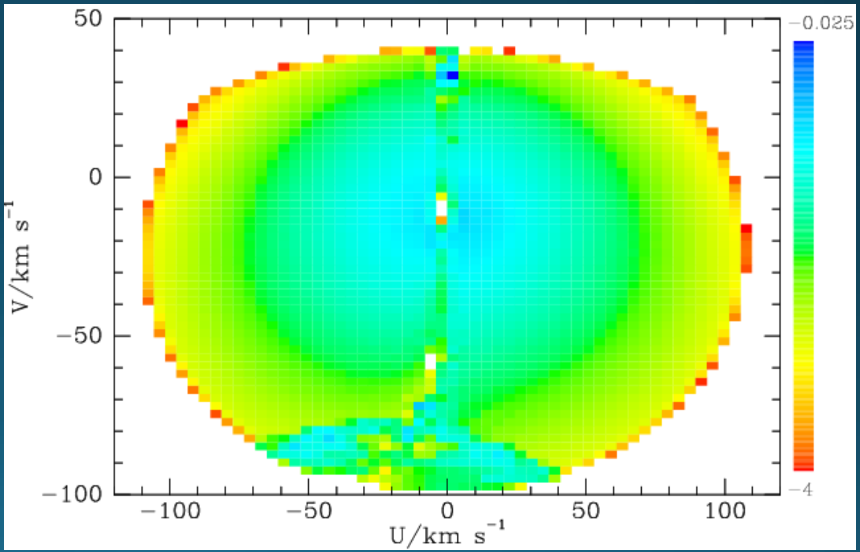




Local v-space from orbits

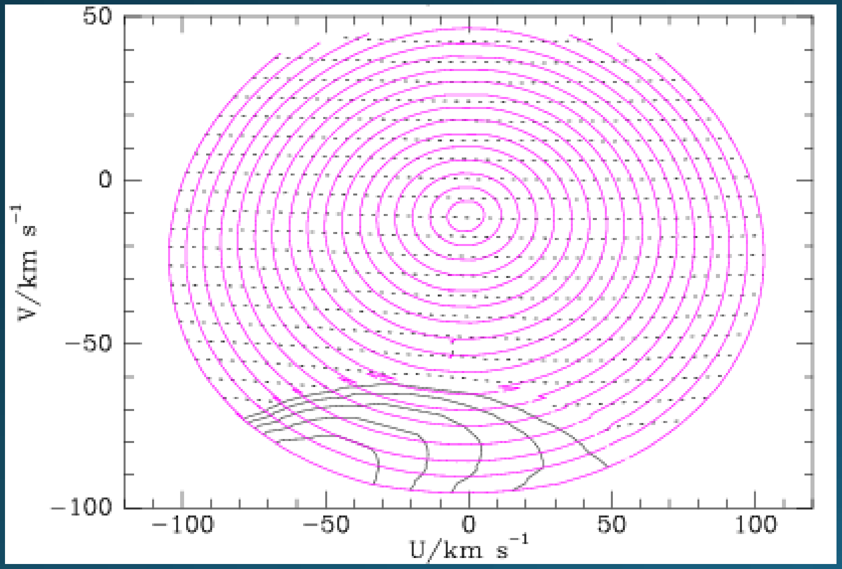
- Individual tori are beautiful
- But still hard to recover kinematics of solar nhd
  - Uniform grid in action space maps to an irregular grid in velocity space
  - Density of an orbit diverges at its edges
  - So small # of orbits contribute heavily to certain Vs -> enhanced Poisson noise

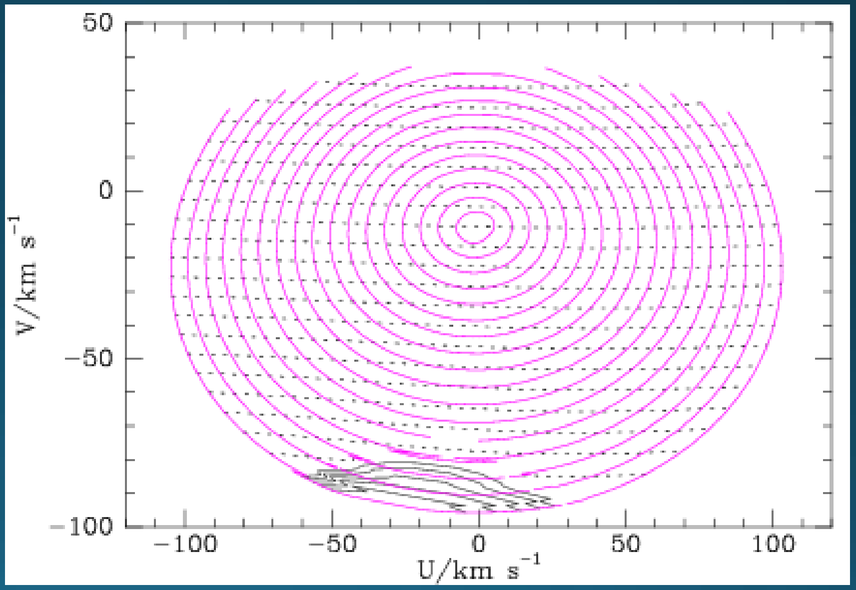




New constants of motion

- Determine map v -> J
- Can then evaluate f(v) (Schoenrich & McMillan 2016)





Conclusions

- Only by building models can we understand how the MW is structured
- We should start from equilibrium dynamical models
- Then Jeans theorem puts MW into 3d orbit space
- Actions are the preferred coordinates for orbit space
- DFs f(J) for DM and various stellar types readily combined to build multi-component, self-consistent axisymmetric models
- The bar forces recognition of several orbit families, each with its own AA variables
- Reluctantly accept that barred models cannot be based on J(x,v)
- Excellent models of bar/bulge constructed by M2M technique
- Torus modelling supersedes Schwarzschild modelling as an alternative
- But any orbit model liable to excessive Poisson noise
- Use tori to determine map v -> J at various x