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Self-consistent modelling of the Galaxy with Gaia data

Outline

- The Standard Galaxy
- Equilibrium models, Jeans' theorem & AA variables
- Achieving self-consistency
- Recent work on equilibrium models, self-consistent & otherwise
- Flies in the ointment: non-axisymmetry and non-stationarity
- Orbit models: Schwarzschild, M2M and Torus Mapping
- Selection functions: the need for a model history

Where we are headed

- In 2027 a Standard Galaxy (SG) will encapsulate our knowledge of the MW
- Like a Wiki page it will be a work in progress
- When a survey is planned, the SG will predict the survey's contents given its Selection Function (SF)
- When the survey is complete the SG will be updated by maximising the likelihood of the new data with respect to the SG's parameters and priors from earlier surveys
- The SG will describe what's out there, surveys will see just part of it

What's in the SG?

- The distribution in (x,v) of many types of stars
  - K giants, BHB stars, RC stars, A stars, FG stars, K & M dwarfs, white dwarfs
  - Most types subdivided by age, [Fe/H] and [α/Fe] and possibly other abundance ratios
- The distribution in (x,v) of dark matter
- Density of H1, H_2, perhaps density of H^+

What lies behind the SG?

- We can't avoid DM but we can't (yet?) directly see it
- We have to infer its distribution from the impact its contribution to Φ(x,t) has on the distribution in (x,v) of stars & gas
- The distribution of tracers constrains Φ only to the extent that the MW is in statistical equilibrium
- So we have to start from equilibrium models
- We can add non-equilibrium features (spiral arms, warp,..) later
- The natural way to specify an equilibrium is to use Jeans' thm to argue that *each component* has f(integrals of motion)
  - This result reduces each component to a distribution of stars in a 3d orbit space – easier to imagine that 6d phase space!

AA variables

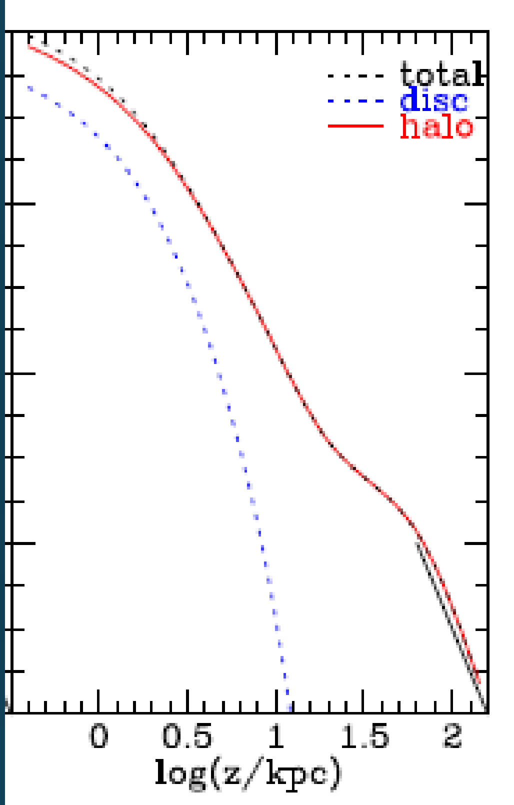
- Since any function g(integrals of motion) is an integral of motion, there are infinitely many possible choices for the arguments of f
  - But there's only one sensible choice
  - To use actions J as our integrals
- Action are special
  - The are the only integrals that can be complemented by canonically conjugate coordinates (angle variables) to make up a complete set of coordinates
  - They are adiabatically invariant, so slow changes in Φ don't cause any change in f
    - makes it easy to compute response to secular change
  - They range from (0,oo) or (-oo ,oo) and $(2\pi)^3 d^3J = d^3x d^3v$
    - This fact makes it possible to specify the mass of a component before solving for Φ
  - Their values have immediate physical meaning: In the simplest case:
    - J_r quantifies radial oscillations, Jz quantifies oscillations perp to plane, $J_\phi = L_z$ is angular momentum around symmetry axis
  - They are designed for use with *perturbation theory*

Basic procedure (Binney 2014, Piffl+ 2015)

- Choose f(J) for each component (stars of given age & chemistry; DM)
- Guess Φ(x) use J(x,v) (e.g. from Staeckel Fudge) to determine ρ(x) by integrating over v on grid in x
- Solve Poisson eq for corresponding Φ(x) and return to previous step
- Converges in 4-5 iterations
- If you allow E to enter f it's hard to achieve convergence, & if you succeed, convergence will be slow

What’s been done so far

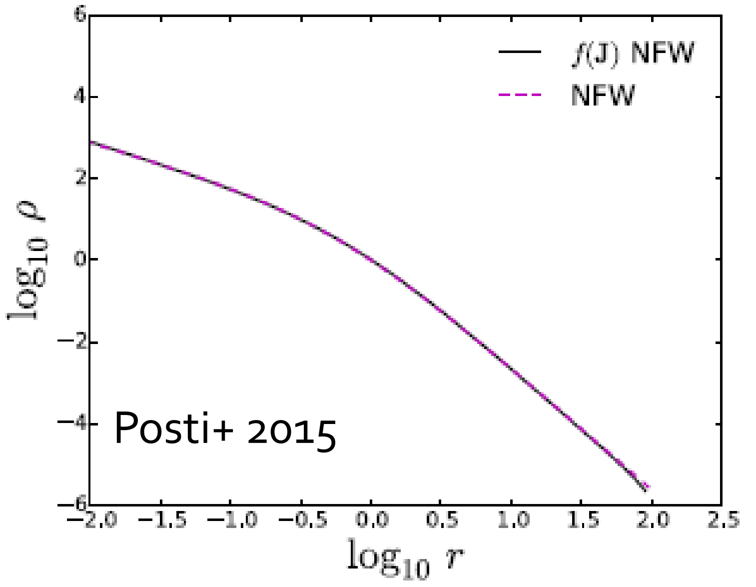
- Much work with f(J) for stars but ρ(x) given for DM
  - Binney 2010, 2012, Bovy & Rix 2013, Piffl+ 2014, Trick+ 2016
- Then it’s ok to assume parametrised Φ(x) rather than getting Φ(x) from Poisson’s eq because reasonable to assume that
  - $\Phi_{DM}(x) = \Phi(x) - \Phi_*(x)$
- Less challenging computationally because you don’t have to do 3d integral at points of (R,z) grid
- Downsides:
  - Can’t predict kinematics of DM (direct detection experiments)
  - We expect f(J) of DM to be smooth but ρ(x) to have complex shape due to squeezing by disc (Binney & Wong 2017)
- Cole (last talk) will update on state of the art:
  - Axisymmetric disc & dark halo in self-consistent Φ
  - Strong constraints on ρ_{DM}(x) at $R<R_o$

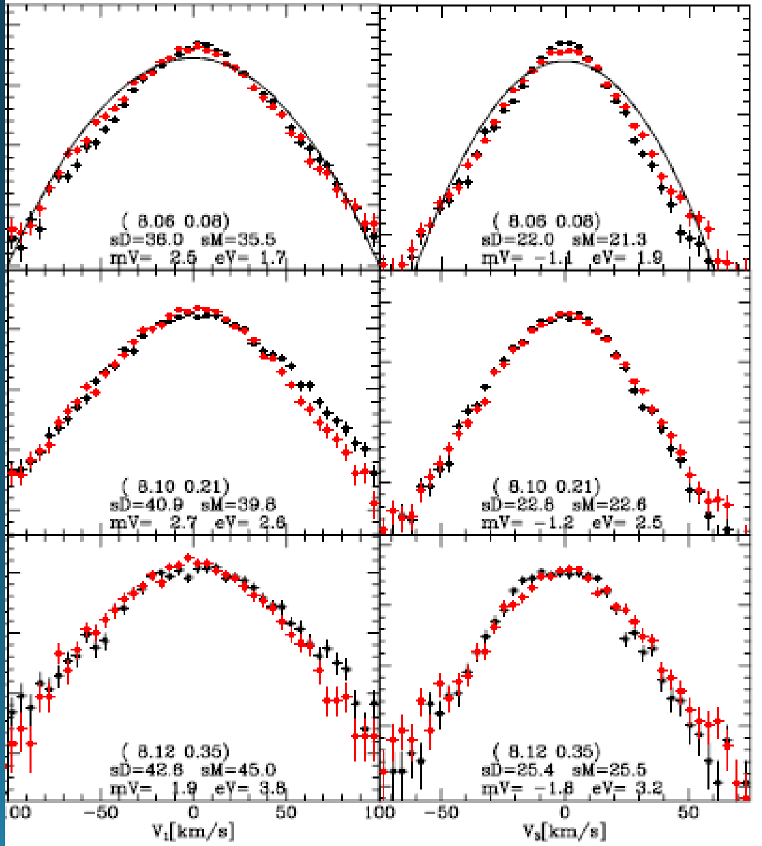


Binney & Wong 2017

On choice of f(J)

- Simple analytic functions generate excellent approximations to familiar models (Hernquist, NFW,..)
  - Posti+ 2015, Williams+ 2015
  - Models can be flattened, set rotating, whatever you want
- Models of the Galactic disc have been assembled from *quasi-isothermal* DF (Binney & McMillan 2011)
  - Fit data to extraordinary precision
  - Have demonstrated predictive power (Binney+ 2014)
- Quasi-isothermal DF was used by Bovy & Rix 2013 to model mono-abundance populations, but it cannot fit many such populations
  - We need to generalise
  - Sander & Binney (2015) suggest a direction of travel, but we should explore further





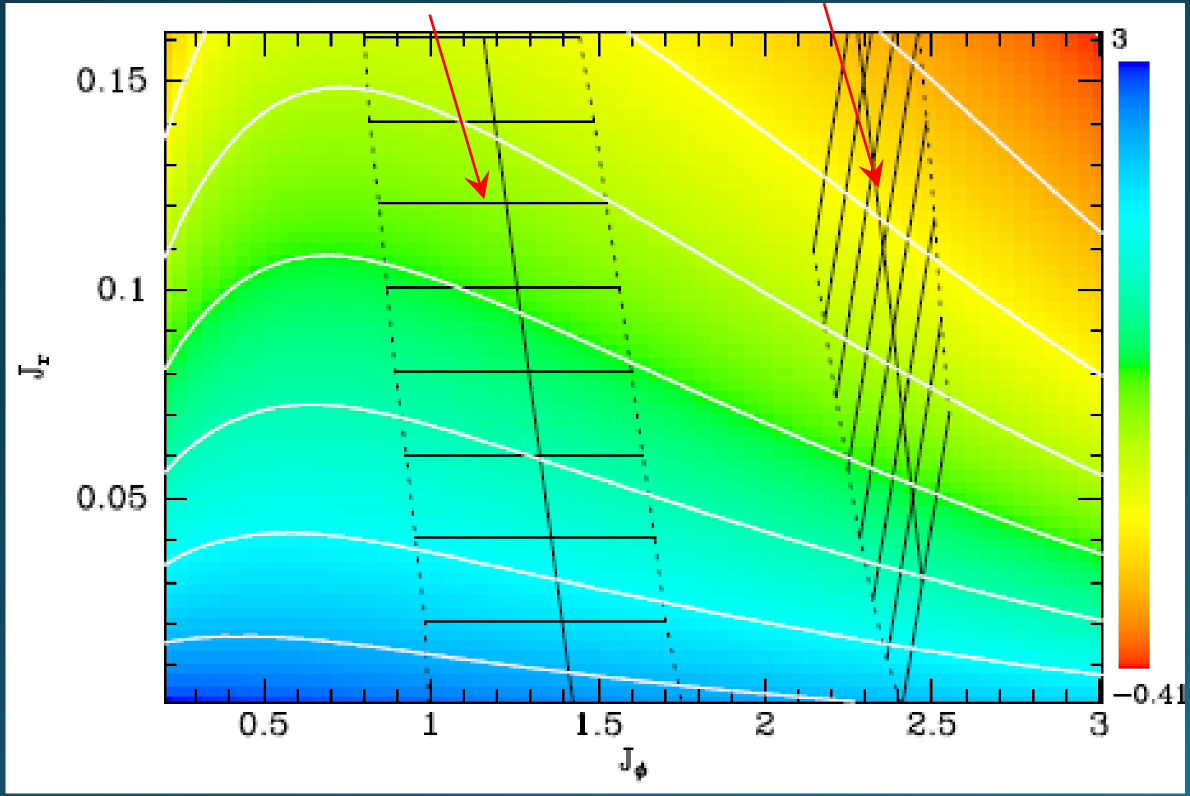
Moving on

- Non-axisymmetry is of fundamental importance for MW
  - Aumer+ 2016a,b, 2017a,b
- The bar seems to extend to R~6 kpc & strongly affects Snhd
  - Perez-Villegas+ 2017, Portail+ 2017
- Spiral structure is δf(x,v,t) and should be modelled dynamically
  - Traditionally traced through ρ(x) but it has v-signature too
- Φ(x,t) can affect DFs in 2 ways
  - Non-resonant perturbation: J -> J + δJ, θ -> θ + $\delta\theta$
  - Resonant trapping: in restricted region of (x,v) old AA variables must be traded in for new ones
- Big problem: in trapped regions Staeckel Fudge doesn't work
- We are driven back to an orbit model: given (J,θ) we can find (x,v) but not vice versa

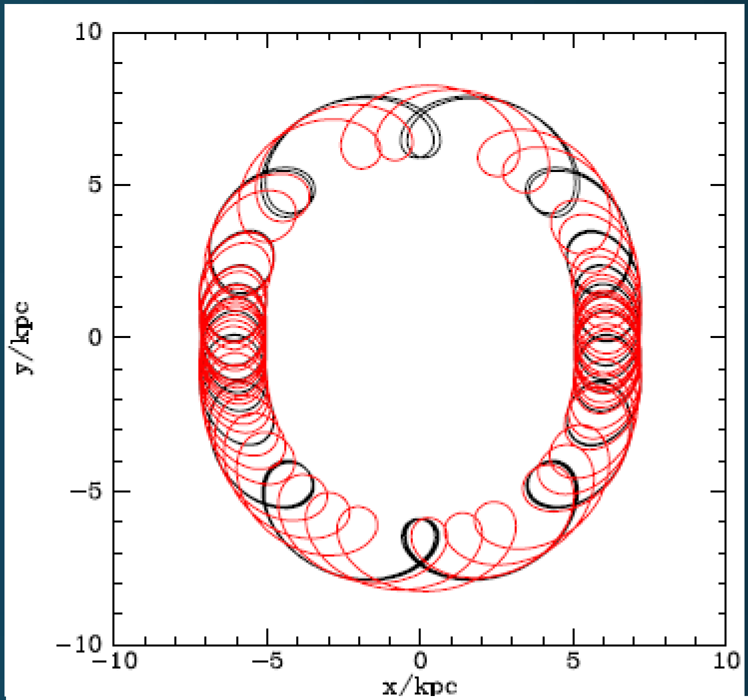
Impact of the bar

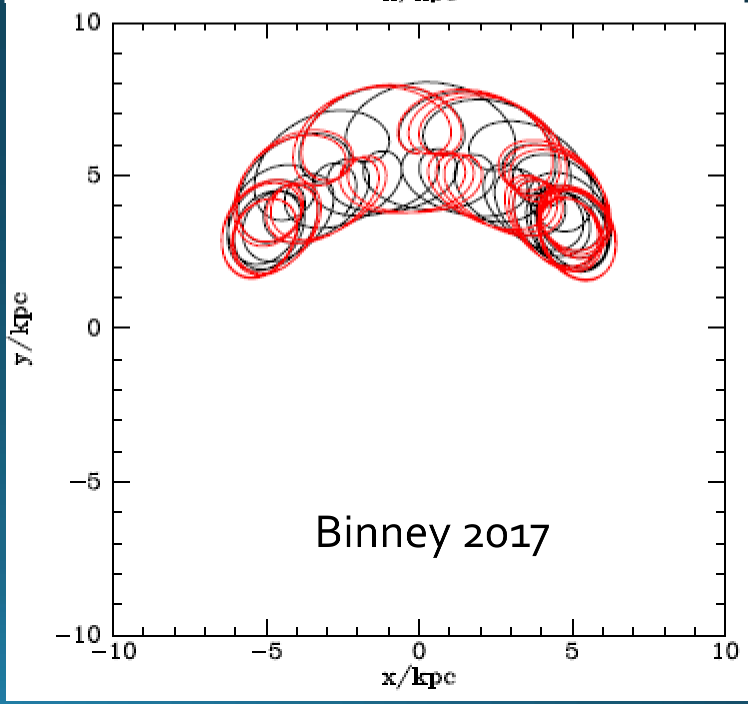
corotation

OLR



Colour give value of DF

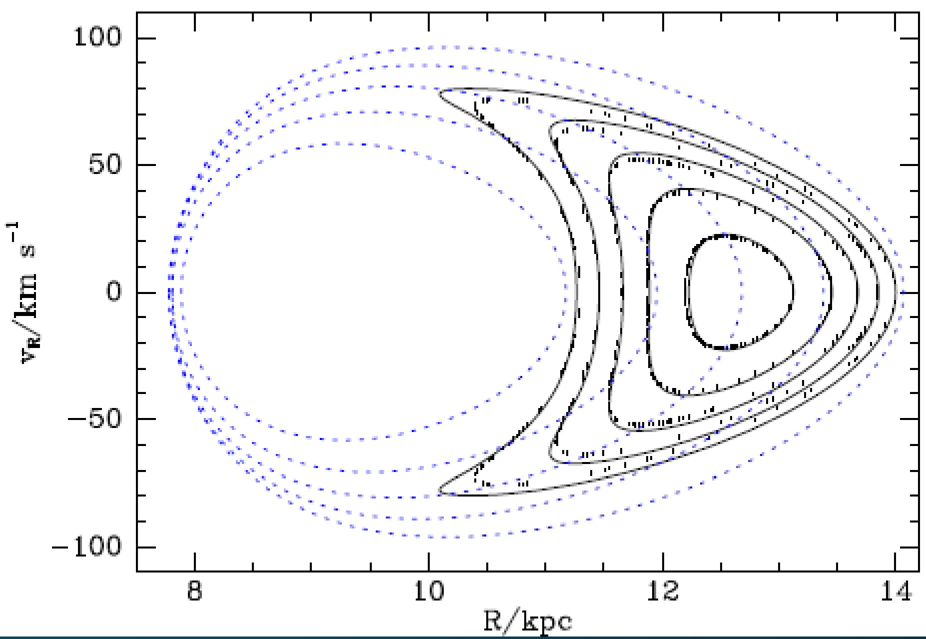




Traditional orbit models

- Schwarzschild models (Schwarzschild 1979, Cappellari+ 200, van der Ven 200)
  - Currently provides best models of external ETGs
- M2M models (Syer & Tremaine 1996, De Lorenzi+2007)
  - Currently provides the best models of the bulge/bar (Portail+ 2016)
- In these models
  - Initial conditions for orbit integration play role of integrals of motion
  - Weights of the orbits play role of f(orbit)
- It's relatively straightforward to fit models to data
- Non-axisymmetry & resonant trapping not problematic
- Major differences with f(J) modelling
  - Very many more parameters in DF and parameters lack evident physical meaning
  - Labels of orbits are complex and lack physical meaning
- I don't like these models because:
  - They are cumbersome: specified by millions of weights with low individual information content
    - Consequently
      - it's hard to compare models
      - It's hard to add components (DM, stars of various ages, chemistries,..)
  - DM is problematic because not directly constrained by data

So back to f(J)!



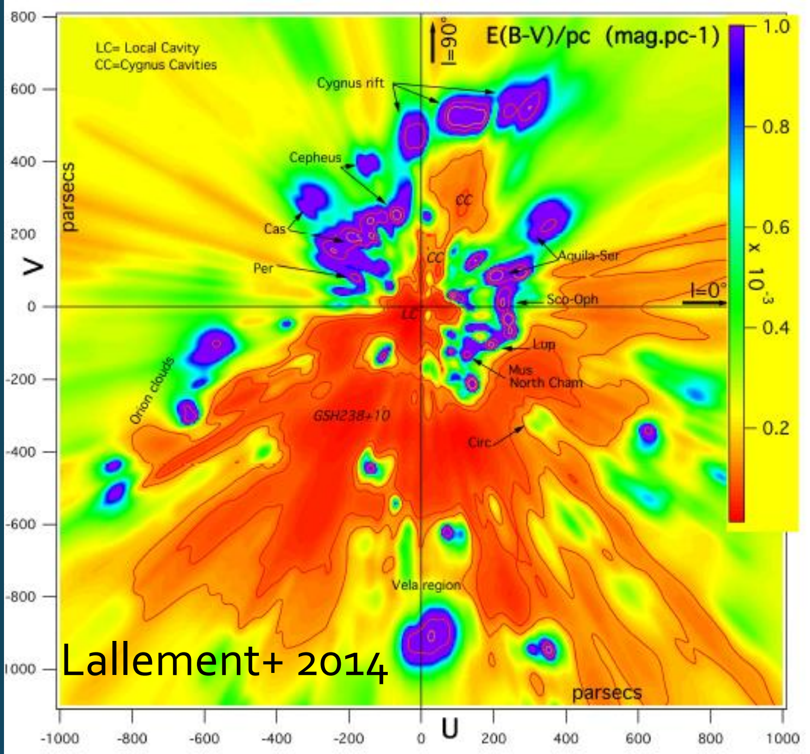
- For each component we need f(J) for non-trapped orbits
- For each major family of trapped orbits we need a new f(J)
- To evaluate observables we must currently use x(J,θ) v(J,θ) provided by Torus Mapper plus perturbation theory
- The good news is that perturbation theory works remarkably well
- It is, however, harder to fit (f,Φ) to data when using x(J,θ) than when using J(x,v) (McMillan & Binney 2013)
- Gaia data will help us determine f(J) for trapped orbits – no current knowledge of this

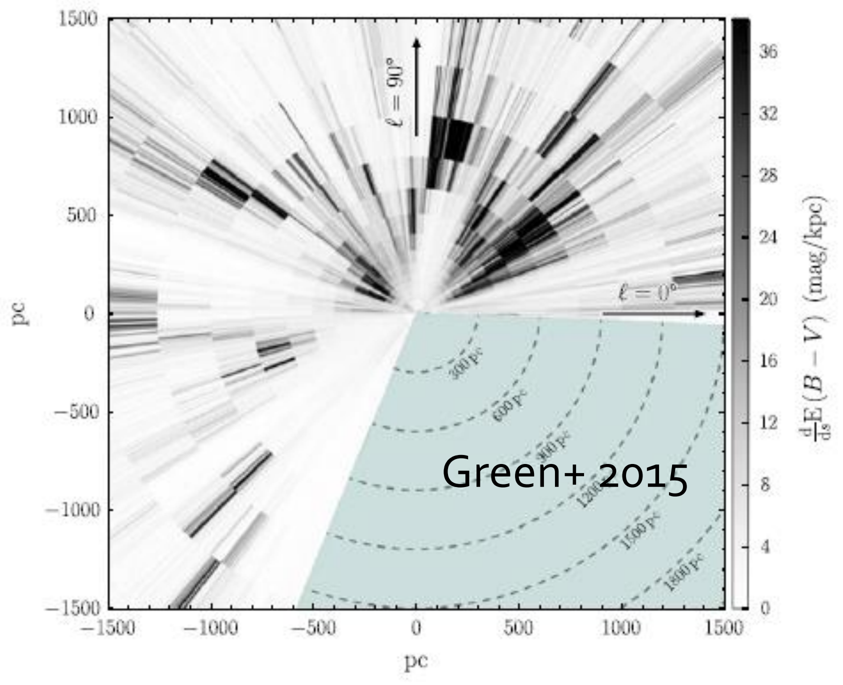
Selection functions

- We need SF to predict contents of survey from a model
  - and hence by evaluating likelihoods to update the model
- The observability of a star depends on L in various bands, so on (age,[Fe/H])
  - Hence DFs must depend on (age,[Fe/H])
  - That is *history* is required to specify *current state*
- Our job now is to pin down current state not guess how MW was assembled
  - but a model history is needed to determine even current state
  - Model history does not need to be true so long as it gives valid f(J,age,[Fe/H])
- Survey SF should be P(l,b,m in bands)
  - stellar models convert to P(s,age,[Fe/H]) which is handy when modelling
- Given importance of (age,[Fe/H]) spectroscopic surveys are essential
  - So we must work largely with intersection of Gaia and APOGEE/RAVE/LAMOST/...
  - Gaia-TGAS SF is complex and involves s,v,... so hard to work with

The ISM

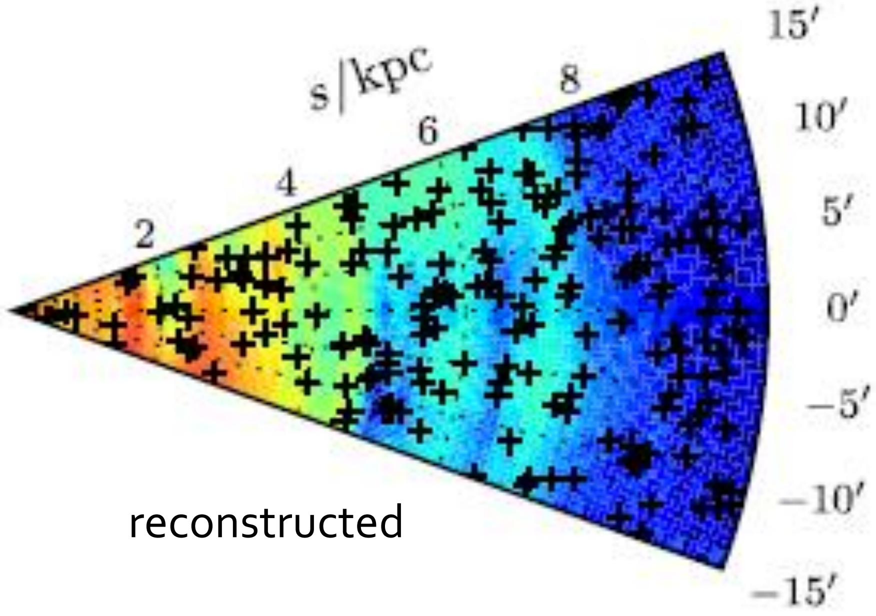
- At low b SF has significant dependence on ISM
- Hence we have to model ISM in parallel with stars
- Quality photometry for zillions of stars with trig parallaxes will be transformative
- Big issue is controlling Fingers of God

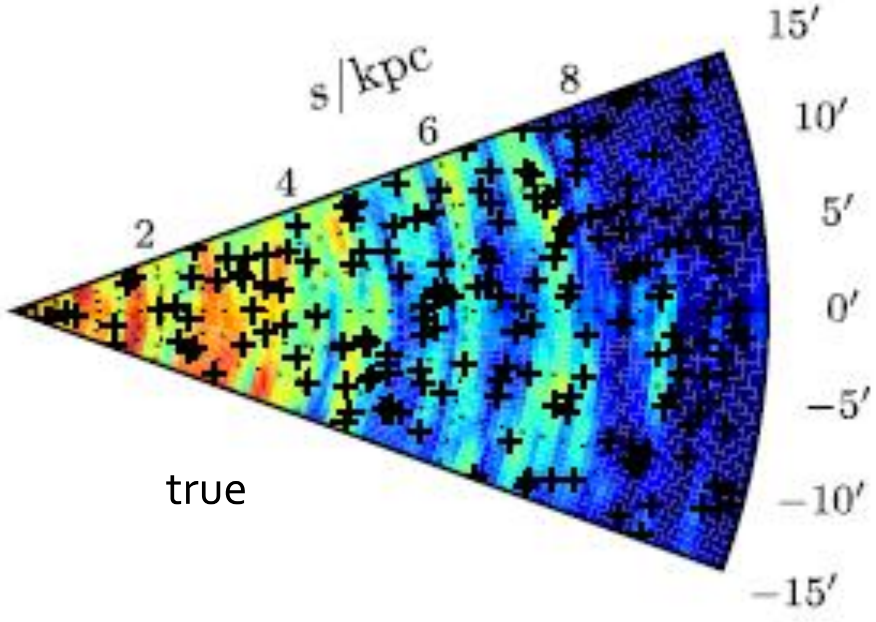




Gaussian random field

- Must avoid modelling each line of sight in isolation
- Need to impose continuity on ISM also transverse to los
- Simplest technique: represent ISM as Gaussian random field (Sale & Magorrian 2014)
- Computationally challenging





Conclusions

- The SG is the ultimate fruit of our efforts
- It must be elaborated from an equilibrium axisymmetric model
- f(J) modelling the most promising technology
- On account of SF we need f(J,age,[Fe/H]) & we probably want other chemical coordinates
- So a model history is required even to specify current state
- P-theory provides a promising way of including the bar & spirals
- Sadly, for each family of trapped orbits we need a new f(J)
- A model of the ISM has to be an integral part of the SG
- We have big computational challenges ahead