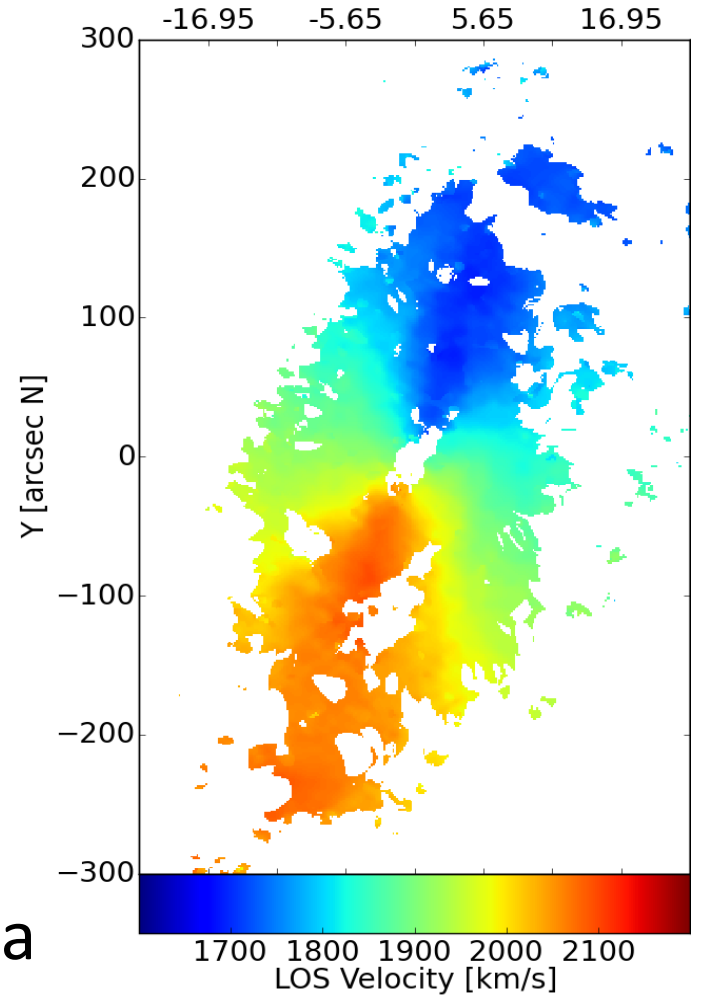
Uncertainties in rotation curve estimation



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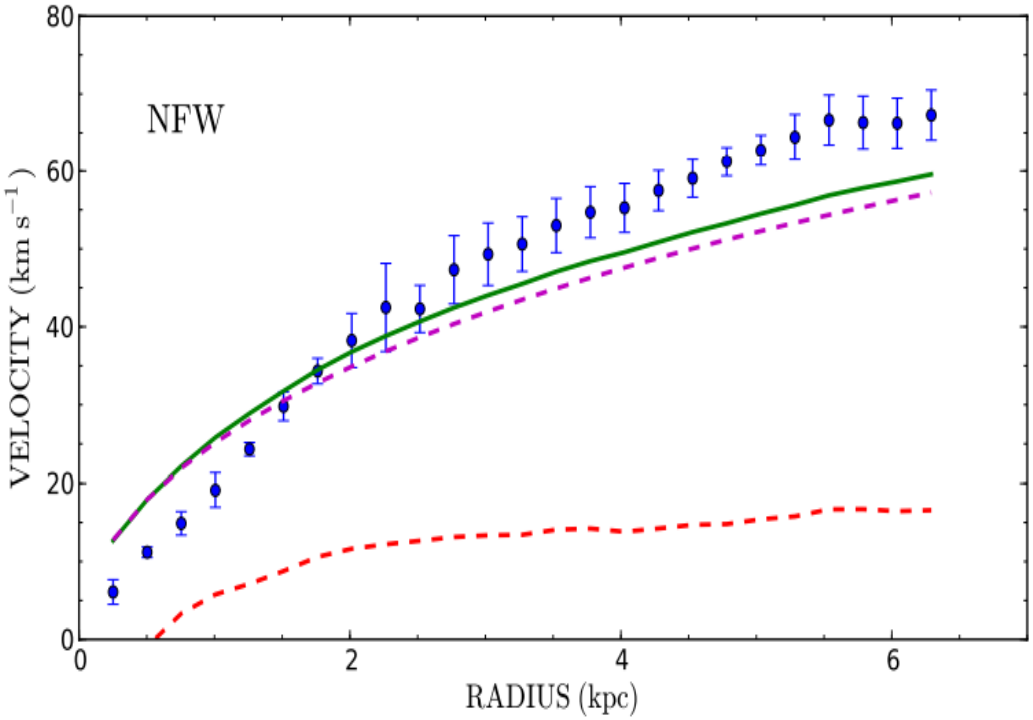
acknowledging significant advice from Tad Pryor and Carl Mitchell

Mar 16, 2015 – PHISCC workshop, Rutgers University

NGC 3109

Carignan et al. (2013)



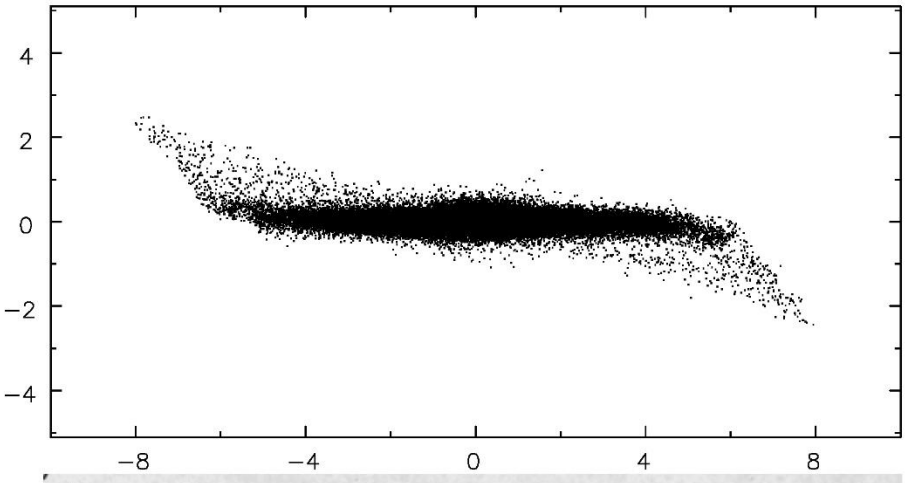
- It is clear that NFW is a poor fit
- But we want to be able to quantify the likelihood that any given model is consistent with the data
  - can we make error estimates more statistically robust?

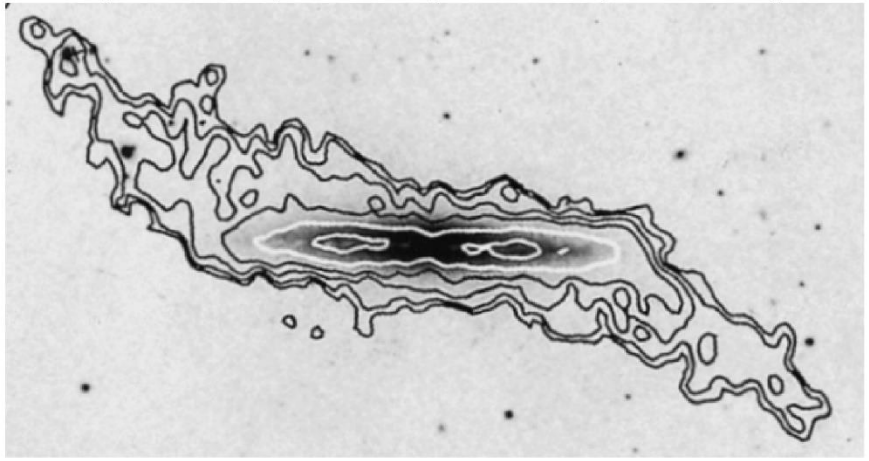
Sources of systematic error

- A circular flow pattern in a flat disk may not fit a velocity map because of:
  1. bars and ovals (perhaps in the halo)
  2. warps
  3. spiral arm streaming
  4. asymmetries (lop-sidedness)
  5. turbulence
  6. out-of-plane motion – *e.g*. Sancisi's "beard"
  7. …
- 1 & 2 can be modeled with *DiskFit* and tilted rings
- rest are best treated as sources of uncertainty
  - asymmetric drift corrections can be made once $\langle V \rangle(R)$ is known

Warps

(Model from Shen & JS 06 and NGC 4013 from Bottema 96)





- Theoretical prejudice:
  - real warps are possible only in the low-density outer disk
  - the massive part of a disk is quite stiff, and should be flat – unless the galaxy is disturbed

- Two conclusions
  - Undesirable to use tilted ring fits that allow PA and *i* to vary in the inner disk
  - also radial changes to the PA and *i* in a warp should perhaps be constrained to vary smoothly

THINGS data for NGC 3621

(de Blok et al. 2008)

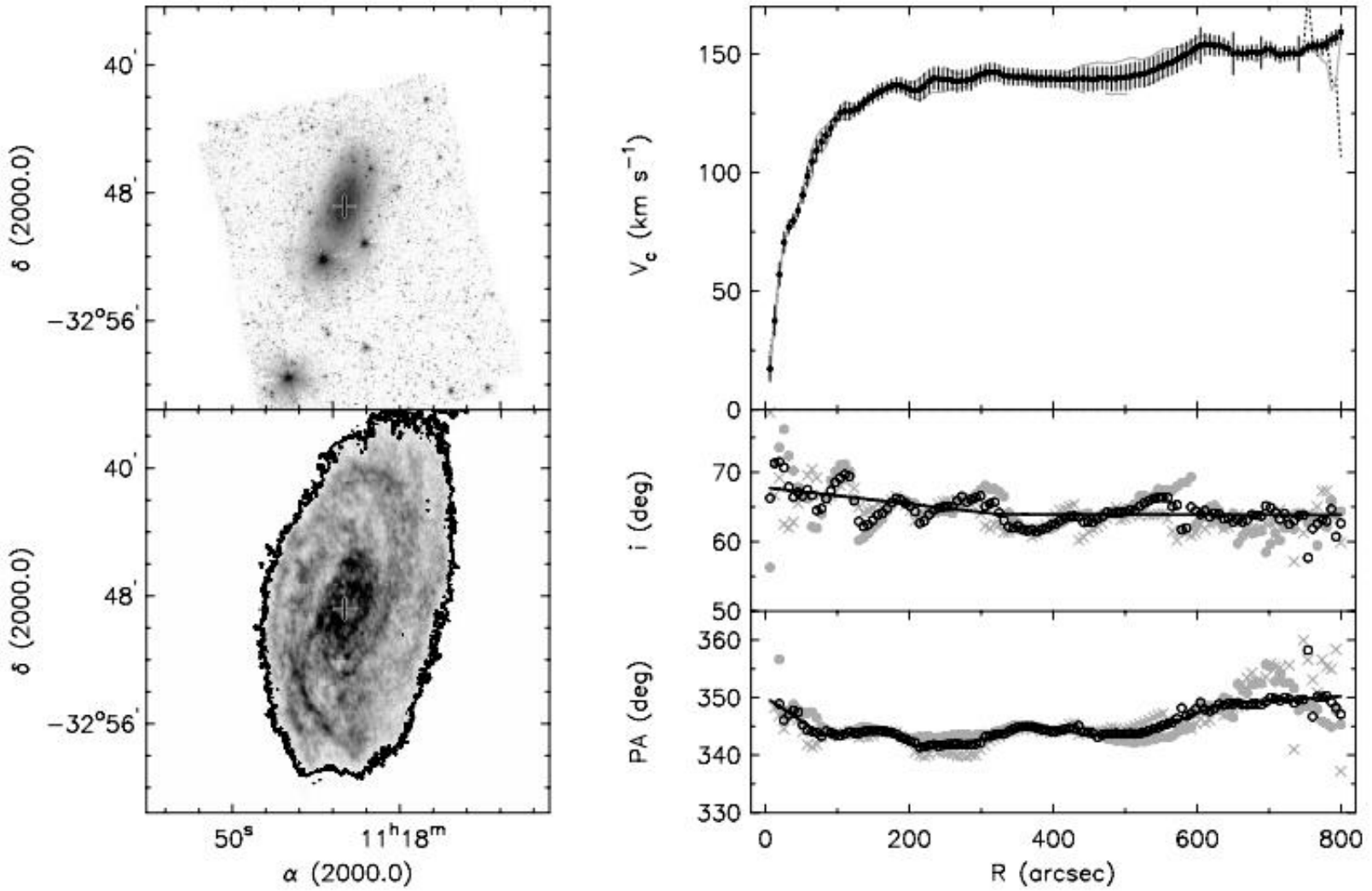
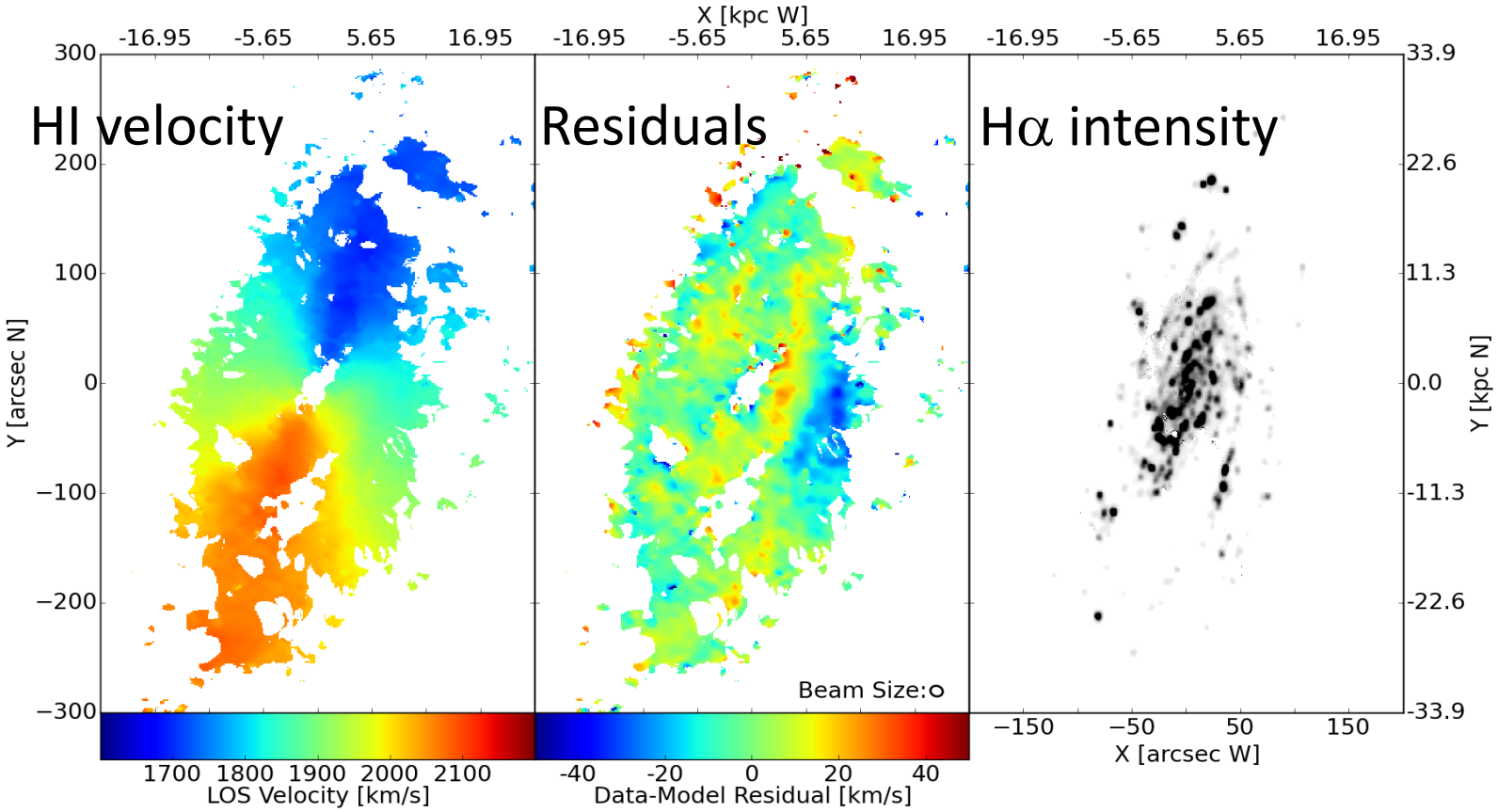


Figure 78. Summary panel for NGC 3621. See the Appendix for more information.

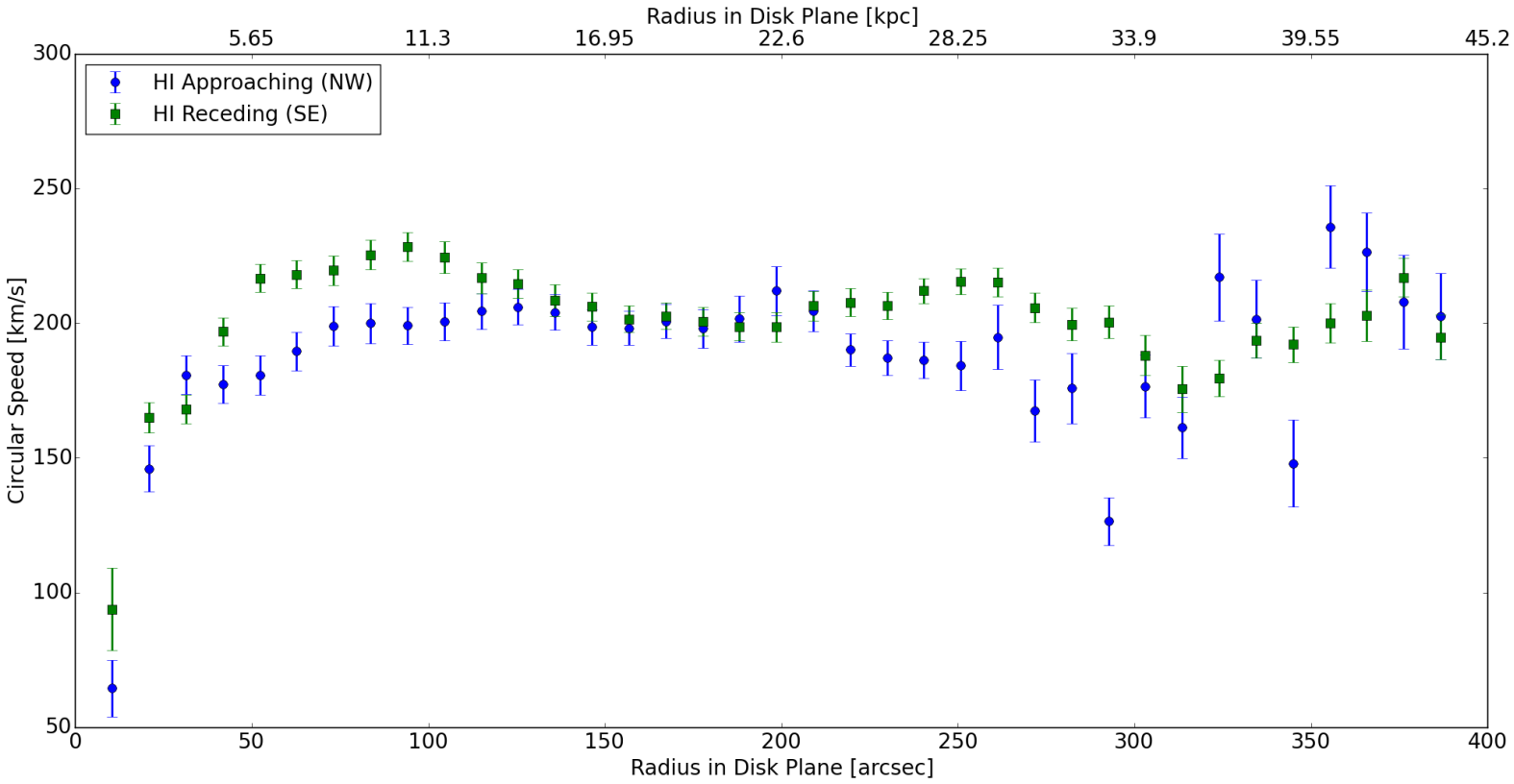
Coherent residuals and asymmetries

- NGC 2280 data – Mitchell *et al*. (2015)
- Coherent residuals after fitting a flat disk with circular motion only – some correlation with spirals



Fitted rotation curve

- Approaching and receding halves fitted separately
- Asymmetries not due to the clearest spirals, which are bi-symmetric



Approaching/receding

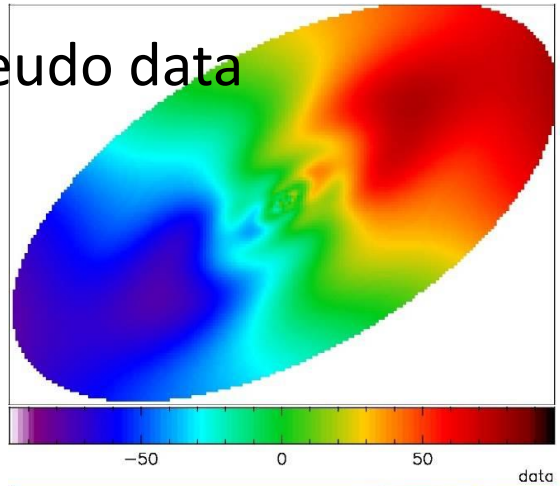
- Traditional error in tilted ring studies is to add to the statistical error $(V_{app} - V_{rec})/2$ in quadrature
  - no statistical basis for doing this, but
  - years of experience suggest it yields "realistic" errors

- *DiskFit*, on the other hand, uses bootstrap iterations
- Illustrate the idea with pseudo-data:
  - artificial map with no noise plus velocity distortions due to an *m*-armed spiral pattern
  - coherent residuals after fitting a flat, circular flow pattern

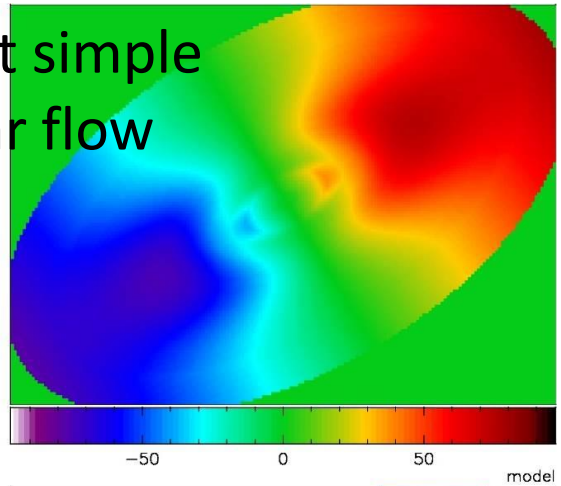
Bootstrap estimation of uncertainties

- Modified bootstrap to take account of the coherent residuals
- Noise-free map with a spiral flow pattern added

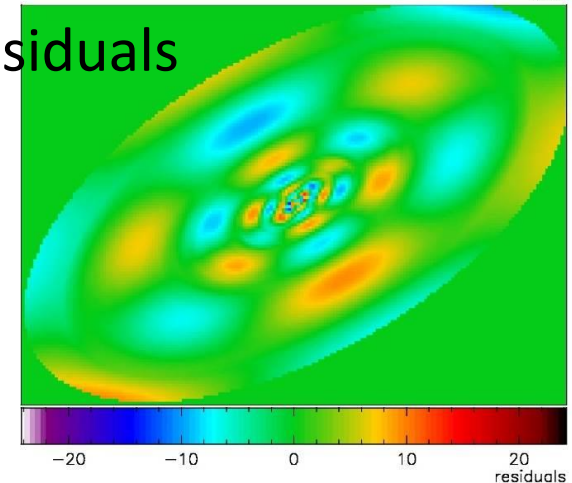
Pseudo data



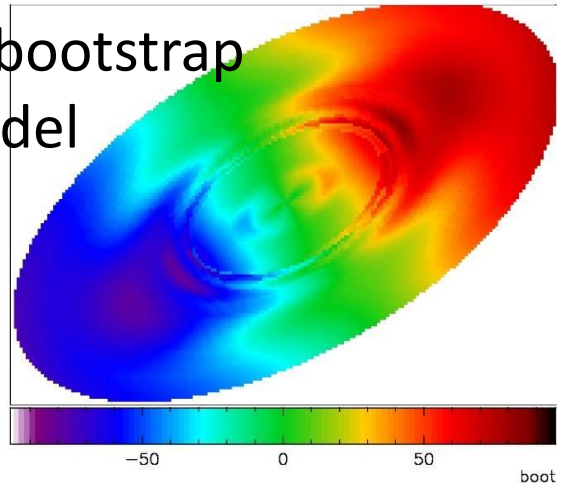
Best fit simple circular flow



Residuals

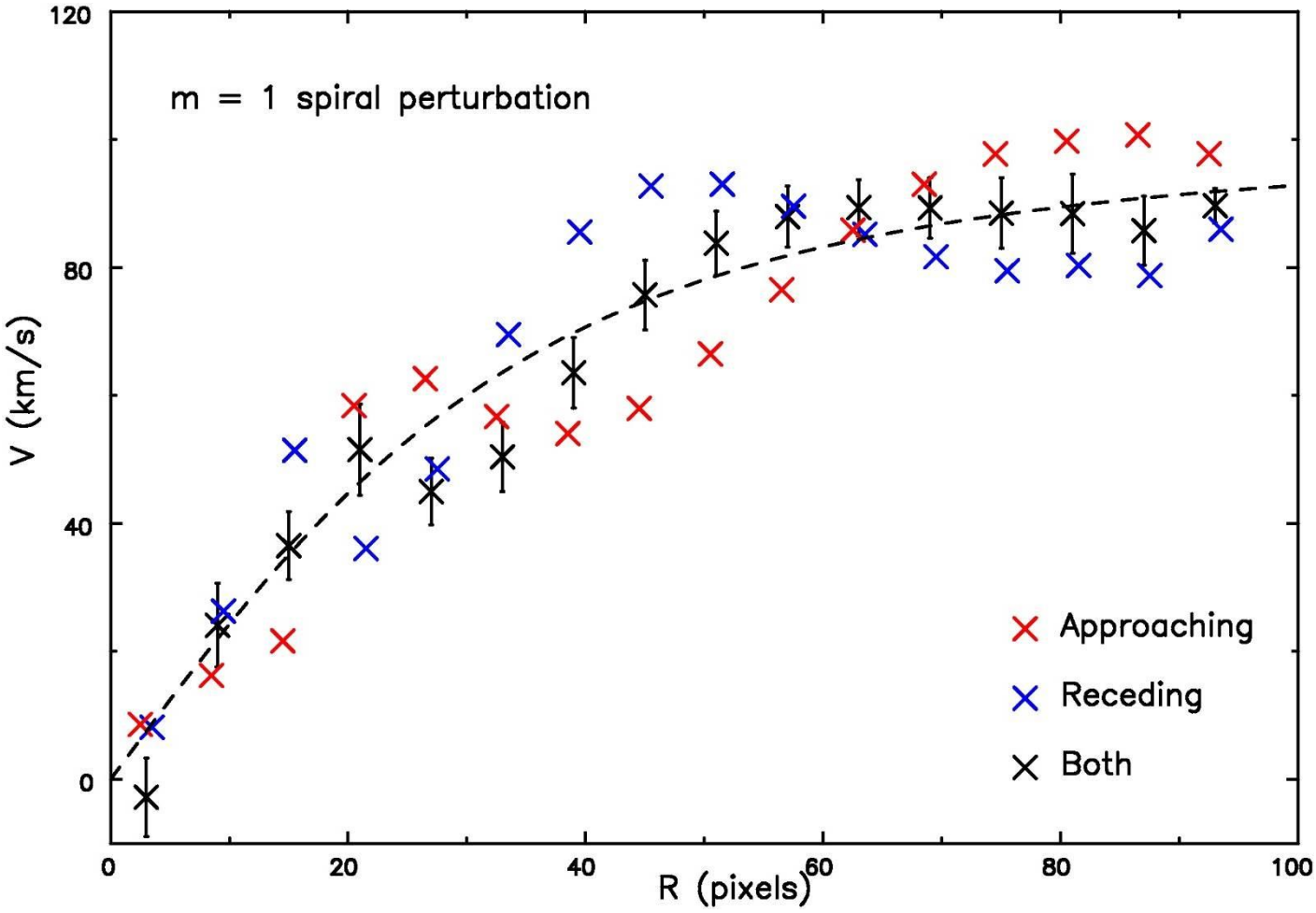


1st bootstrap model



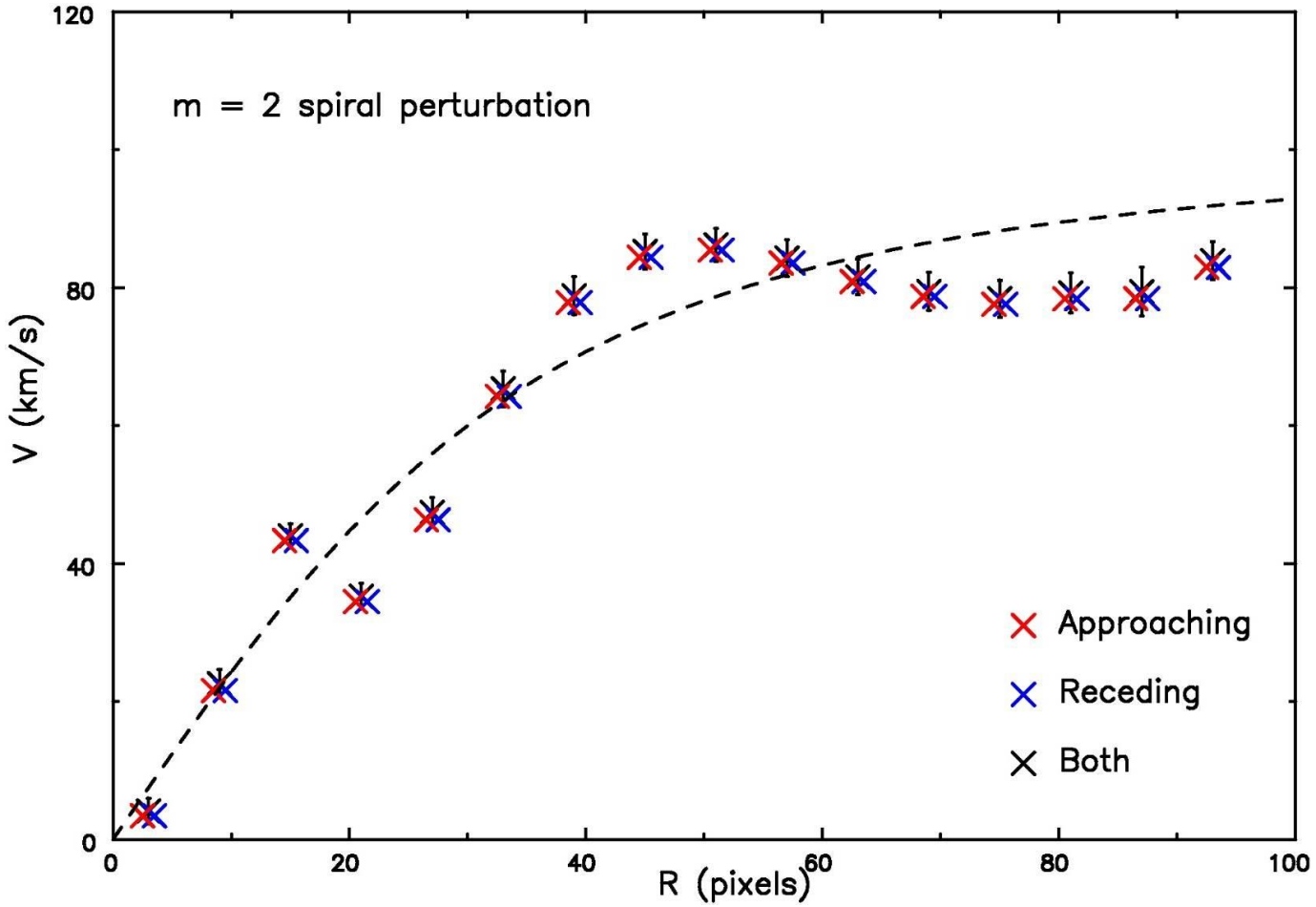
Results

- An *m*=1 spiral flow pattern added to the noise-free map
- Fitted with a flat, circular flow pattern with bootstrap errors



Bi-symmetric spiral flow

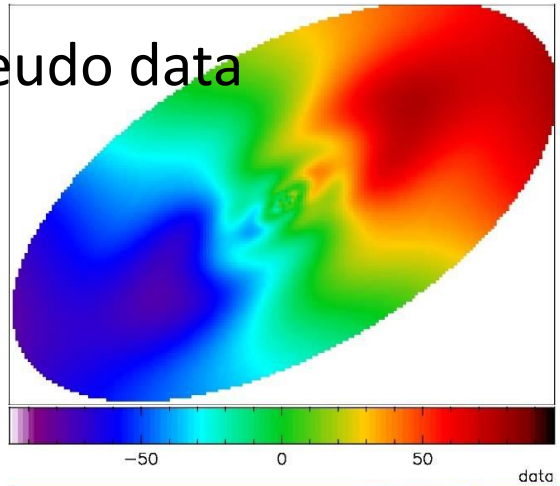
- The systematic error in the velocity from an *m*=2 spiral is the same on both sides
- Neither method for error estimation is adequate



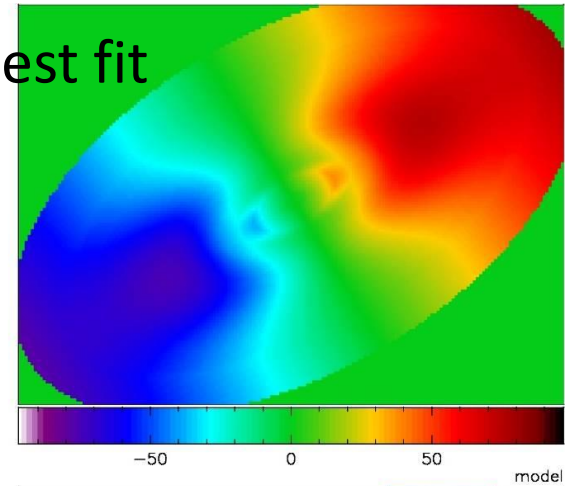
Root of the problem

- Best fit model is too strongly affected by spiral arm crossings on the major axis
- Residuals not large enough to compensate

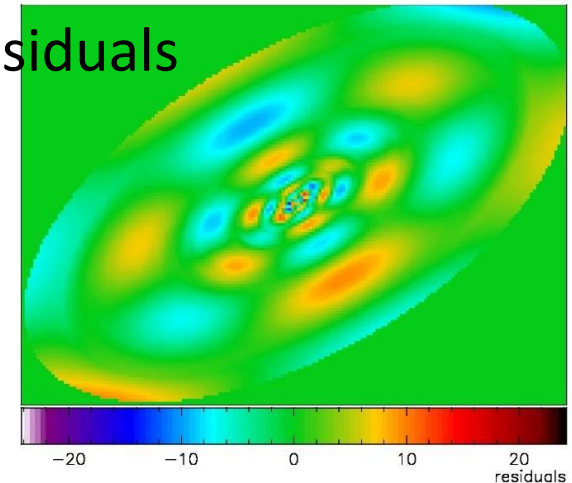
Pseudo data



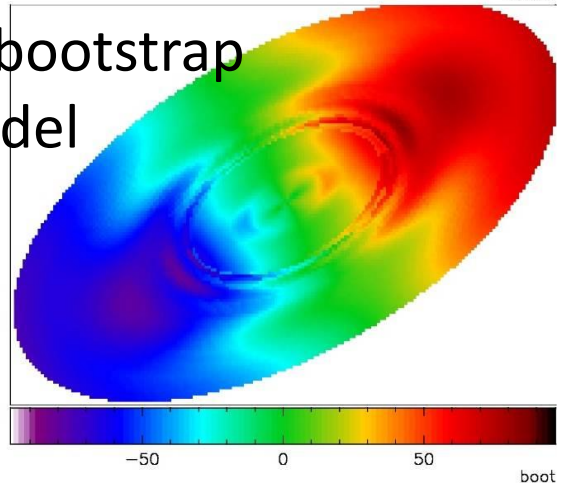
Best fit



Residuals

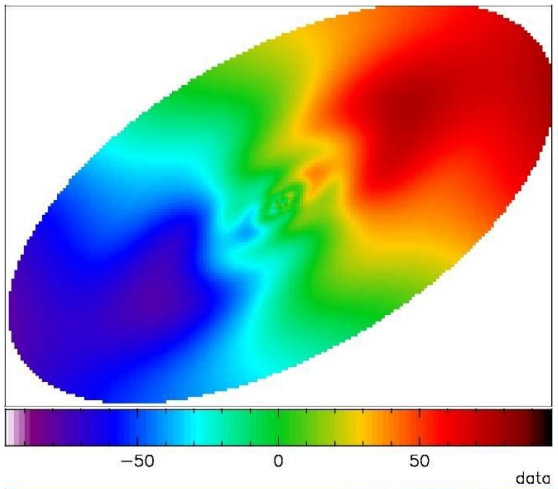


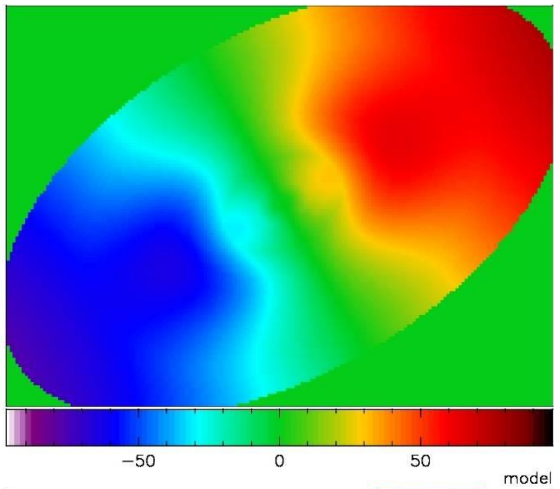
1st bootstrap model

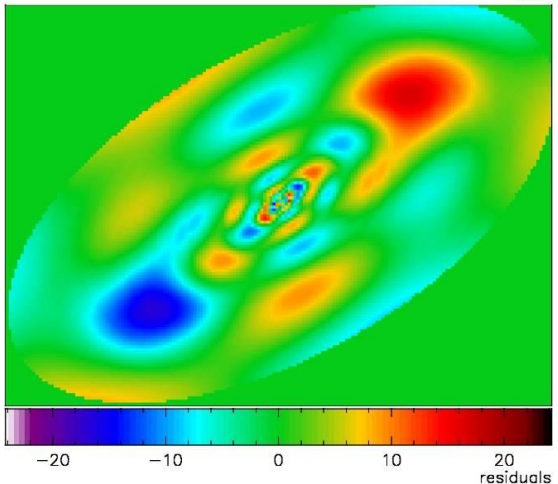


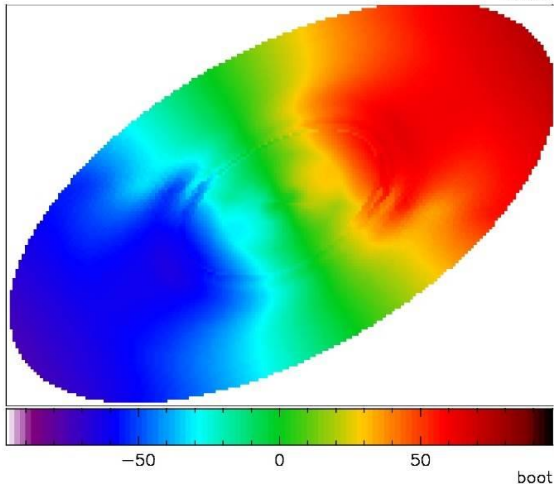
We can do better

- Arm crossings on the major axis are given too much weight – so
- reduce the weight of points on the major axis



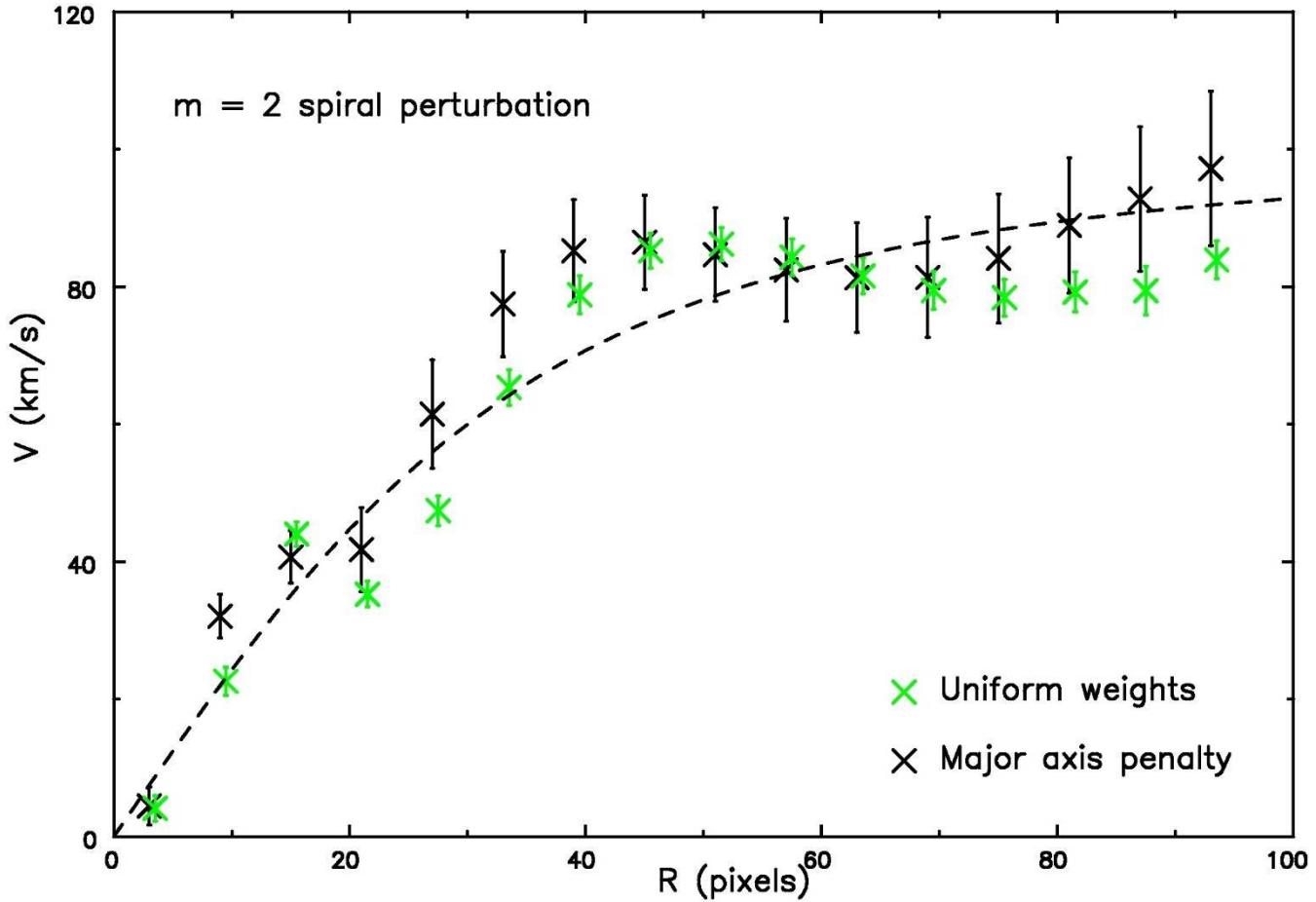






Off-axis data influence fit more

- Best fit averages more over spiral phase
- Residuals, and therefore, bootstrap errors are increased



Conclusions

- Massive inner disks should be flat
  - tilted ring fits there are undesirable
  - warps in the outer disk should be “smooth”
- Flat disk fits leave coherent patterns of residuals due to spirals, asymmetries, turbulence, *etc*.
- Need a statistically valid means to estimate these systematic uncertainties in $V_c(R)$
  - $(V_{app}-V_{rec})/2$ not statistically robust and does not take account of errors due to 2-arm spiral flows
  - modified bootstrap is one possible way to do it
  - ideas still “in progress”, and need extensive testing
- Errors must be estimated properly in order to mount a quantitative challenge to theoretical models