Statistical methods and HI in the Magellanic Bridge

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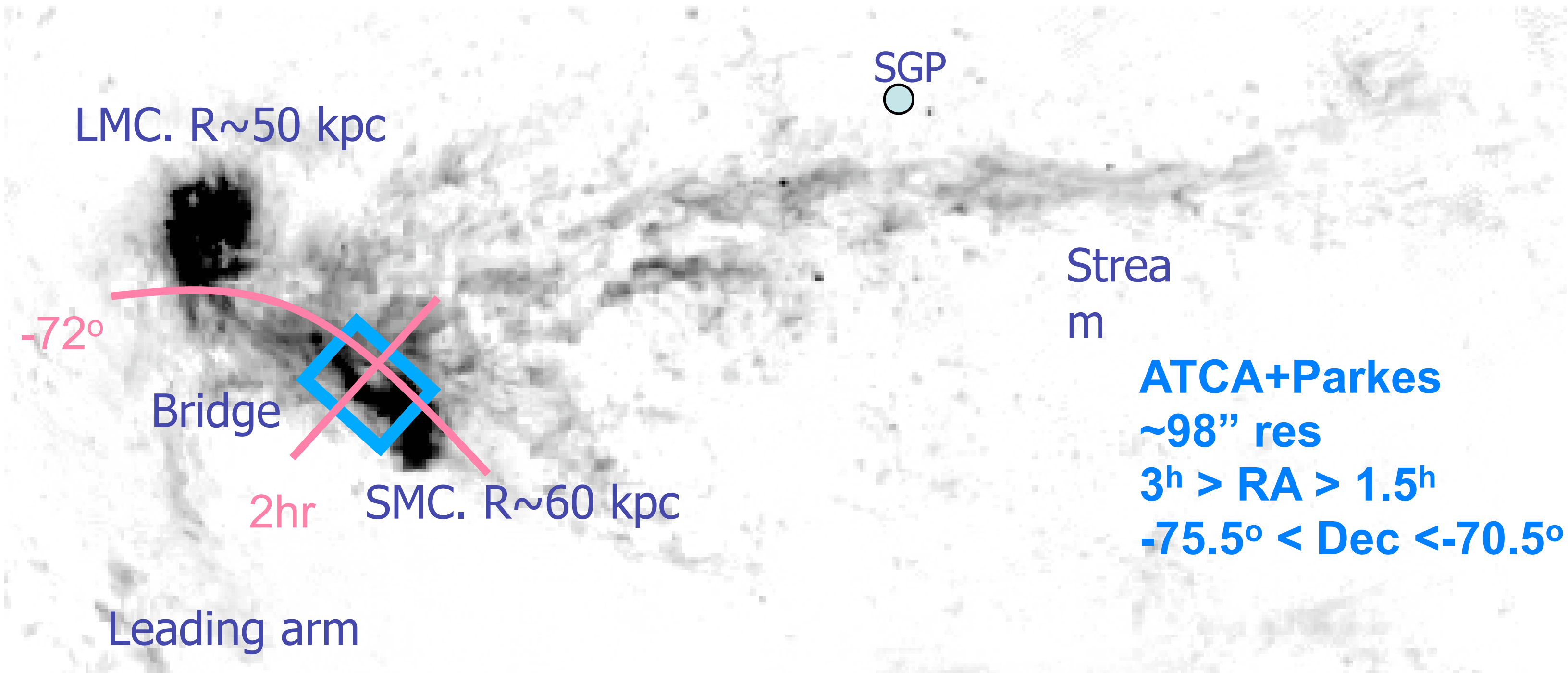
Preamble

Using numerical simulations to assist in the interpretation of observational data.

- Intro to the Mag. System and Bridge HI dataset
- Numerical simulations; using simulations to understand real data.
- Numerical simulations of the Mag. System
- Simulations and interpreting the statistical analyses.
  - Some statistical methods for HI
    - Spatial Power spectrum (SPS)
    - Spectral Correlation Function (SCF)

The Magellanic System. HI:

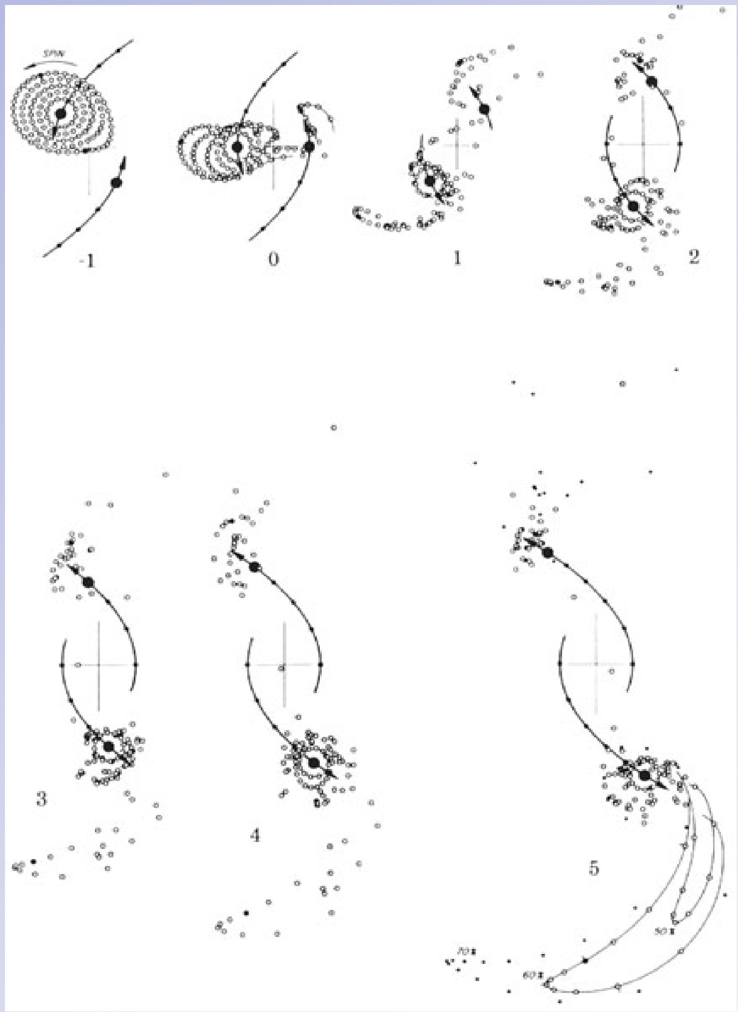


Magellanic System in HI (Putman, 2000)

Why simulate interactions?

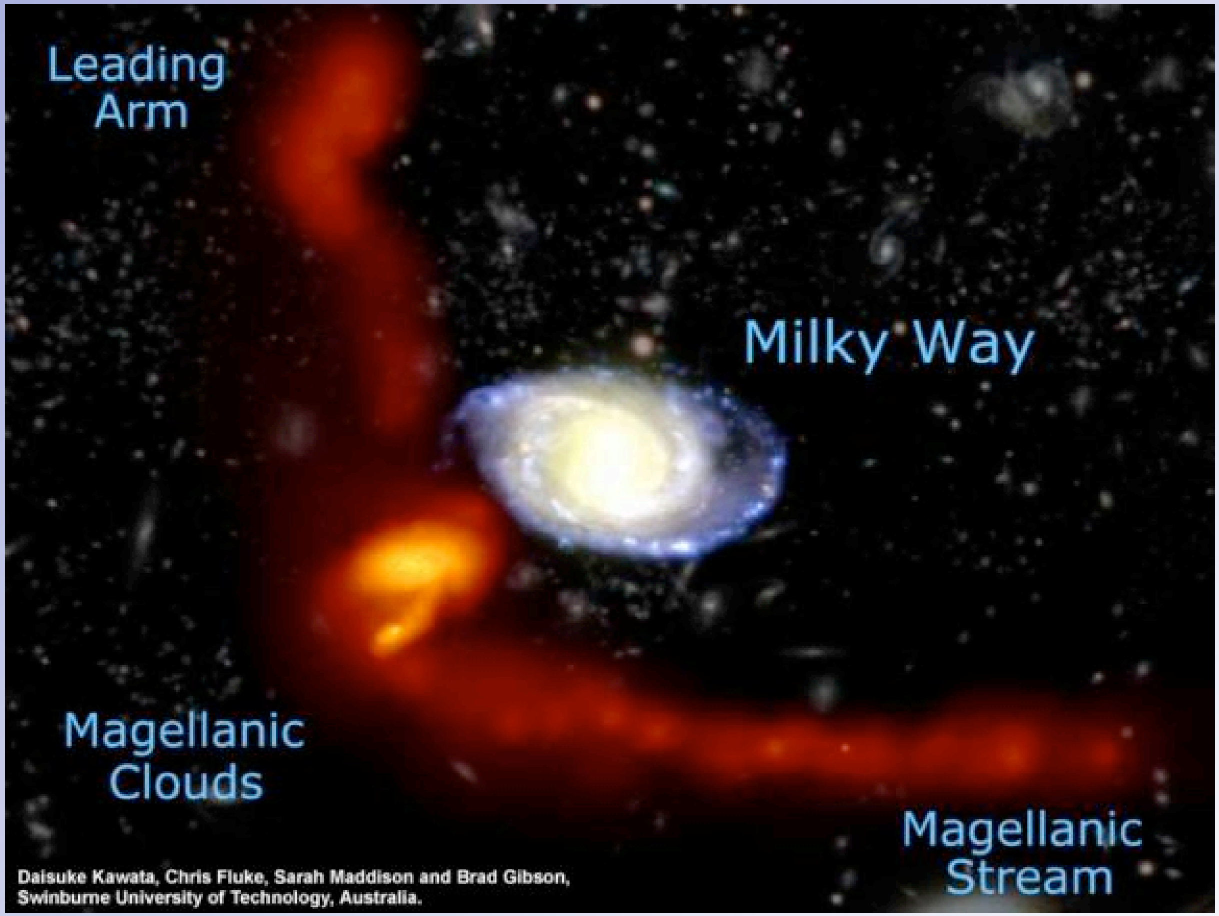
1. We can better understand the processes and conditions in and around the systems if we can understand their evolutionary histories

2. We can project forward to estimate the future conditions of the systems, or backward to understand the origins of the components.



Why simulate interactions?

1. We can obtain an estimate of the 3-D shapes of large-scale features in the larger context.



Kawata, Fluke, Maddison & Gibson, 2003
(Swinburne University of Technology)

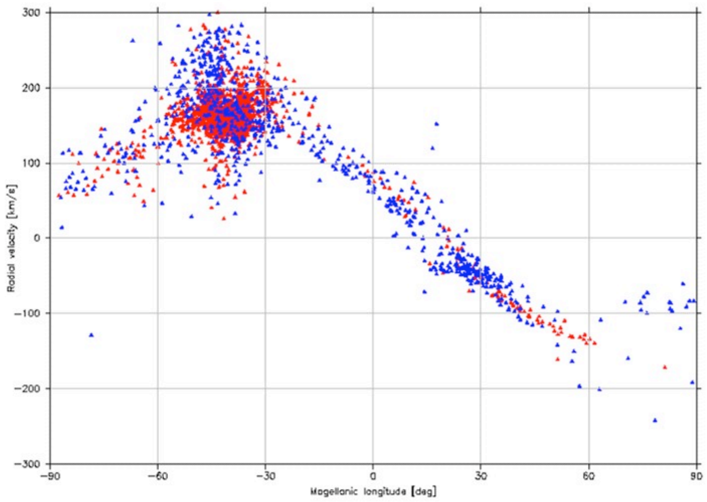
A few constraints:

- Physical parameters of current epoch are usually quite poorly understood
  - a number of plausible histories usually result (i.e. redundant histories).
  - Additional information is required to discriminate between alternative histories.
- Fine-resolution simulations are very cpu and time-intensive, and need detailed and well-understood initial conditions.
  - As a consequence, numerical systems of interacting systems tend to be of very coarse resolution – detailed comparisons with real data are not always practical.
- Simulations and Observations (should be) constantly referring to one another:
  - Simulations can be refined by accurate measurements
  - Interpretation can be more complete, by study of simulations

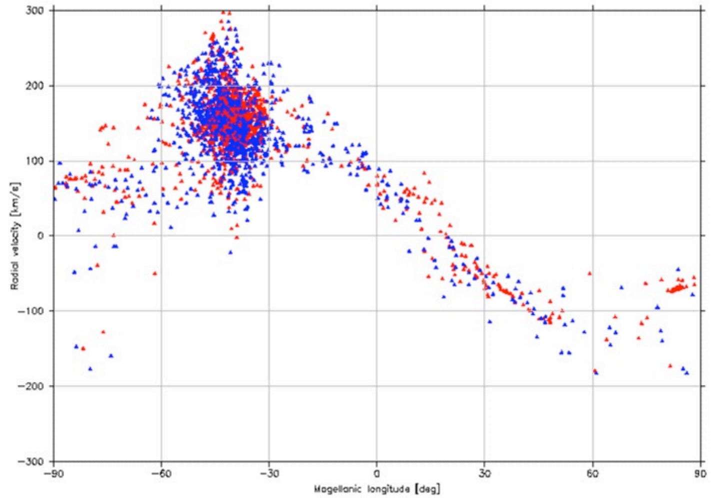
A few more constraints

- Simulations of interactions are usually fine-tuned by a direct comparison with real data
  - Many estimates and assumptions of the physical parameters for the current epoch.
  - Potentially VERY time consuming since many assumptions are made and initial conditions are not unique. Genetic algorithms?

Target



Simulation via GA



Rusicka, Palous, Theis & Bruns (2005)

Using statistical methods to understand the Magellanic Bridge.

- Used in this context to understand the gross morphology of the HI in the Magellanic Bridge
- Statistical properties of Bridge are readily interpreted in conjunction with numerical simulations.

About the analyses:

– Spatial power spectrum (SPS)
  - Operates in the Fourier domain to obtain a measure of power as a function of scale
  - Incompressible fluid will normally show a structure-power cascade, having a *"Kolmogorov"* organisation of $P(\lambda^{\gamma})$.
    – 3-D power distribution is characterised by a γ = -11/3 power index.
  - SPS on datacubes leads naturally to the velocity component analysis.

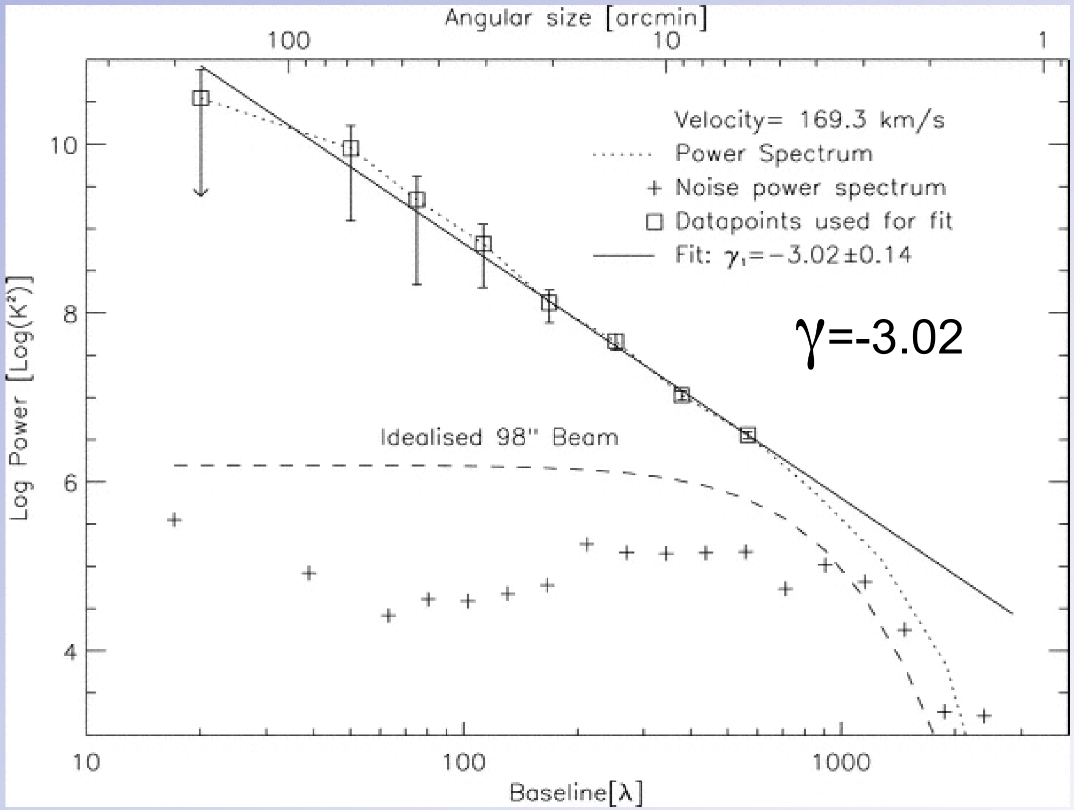
– Spectral Correlation Function (SCF)
  - Measure spectral similarity as a function of angular separation
  - Still largely untested on real data.

Spatial Power spectrum

- Power normally cascades down through available scales.
- SPS is a measure of the distribution of power as a function of scale.
  - *Fourier transform of the Auto-correlation of the HI brightness distribution:*

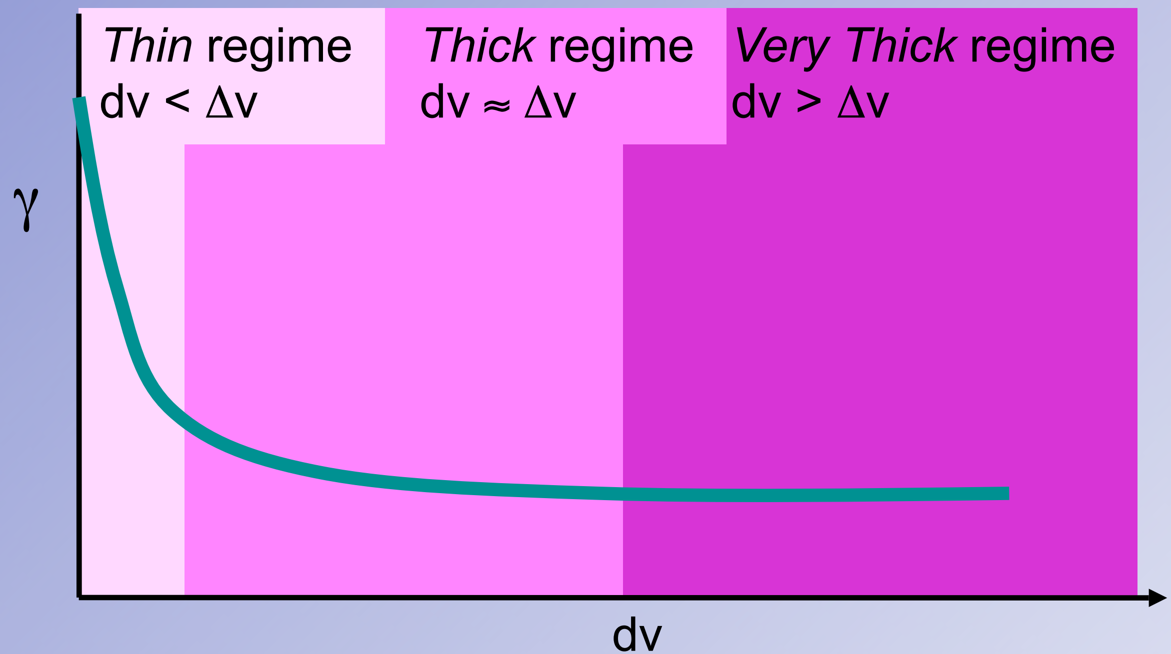
$$P(k)=\iint\langle I(x)I(x')\rangle e^{-iL\cdot k}\, dL$$

$L=x-x'$



Muller et al, 2004

Spatial Power spectrum; Velocity component Analysis (VCA)



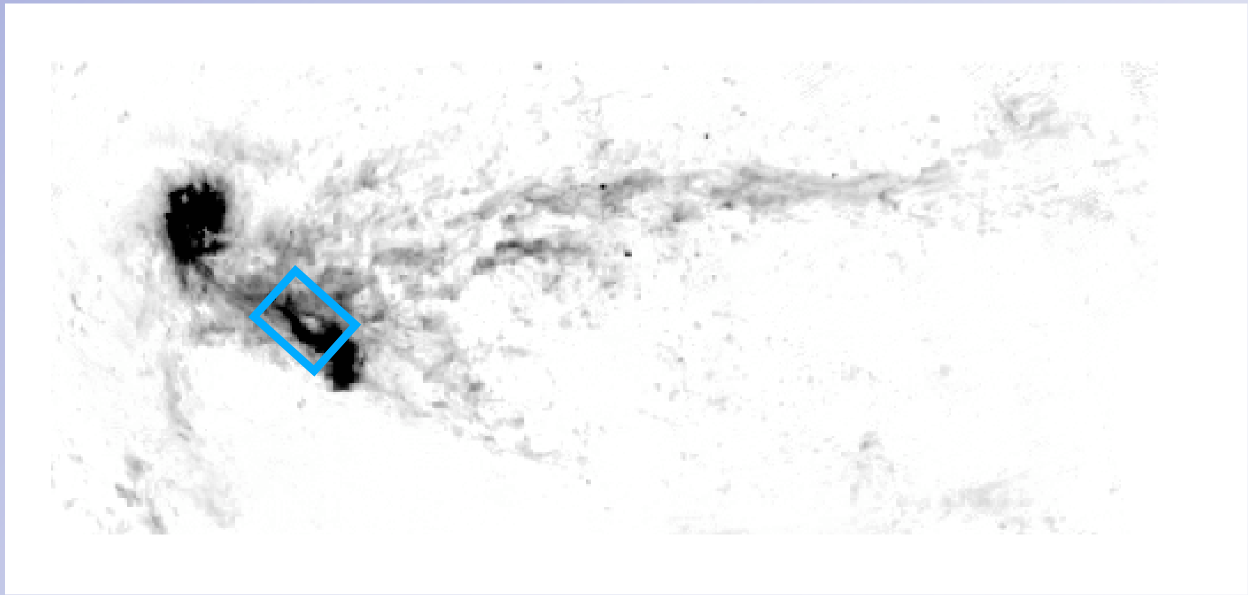
- Velocity fluctuations contaminate the *I(x,v)* data, and P(k)
- Integrations across successive velocity intervals (dv) can incrementally remove contributions to *I(x,v)* from the random velocity component.

Averaging adjacent velocity windows can average out random fluctuations. To yield the static density distribution.

VCA uses the SPS to probe the contribution to brightness distribution by velocity fluctuations.

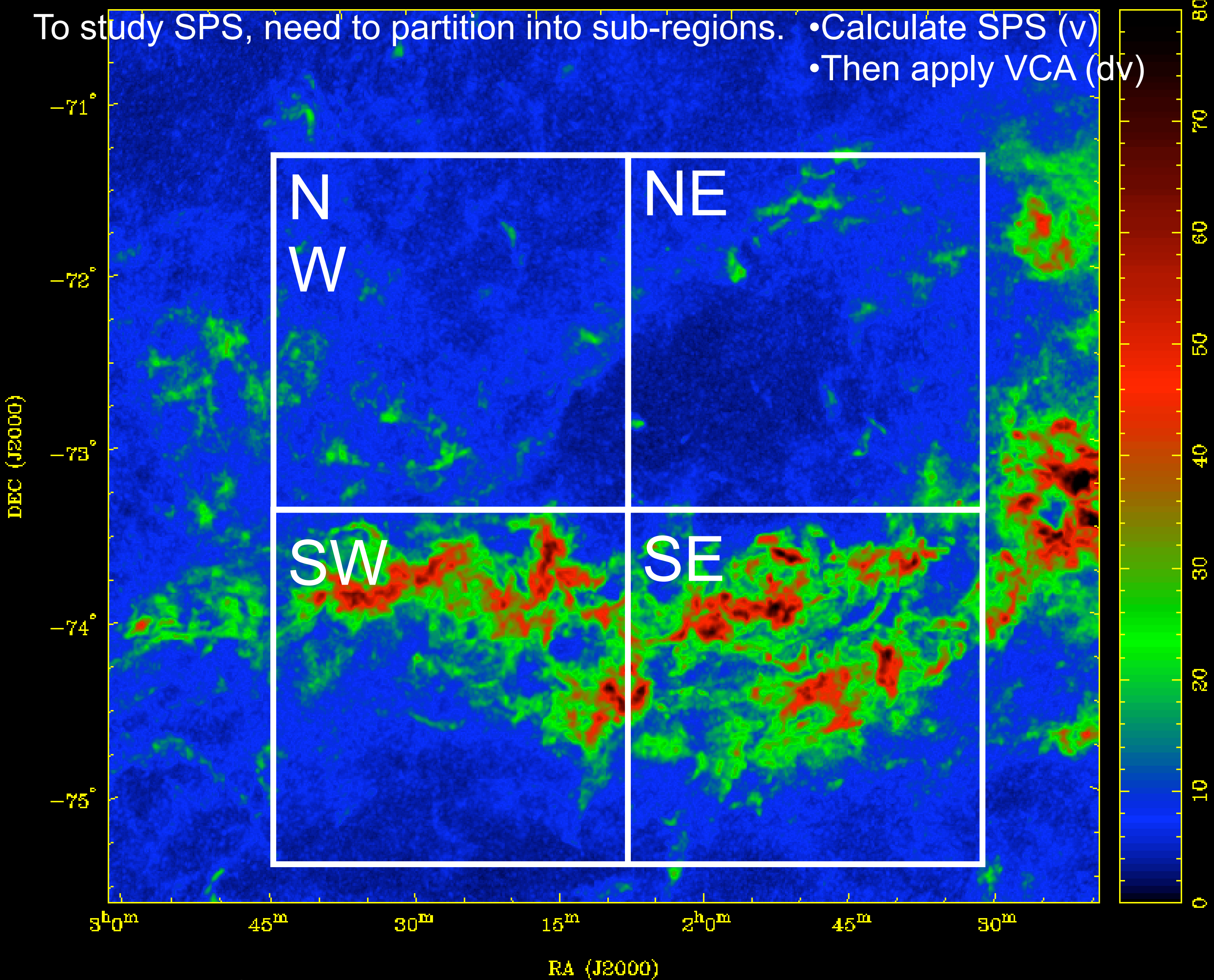
SPS, VCA, MB and Nsims

- Magellanic Bridge:
  - Nearby, out-of-plane, complete system, perfect for studying interacting systems.
  - New, high resolution dataset, resolution of 98”



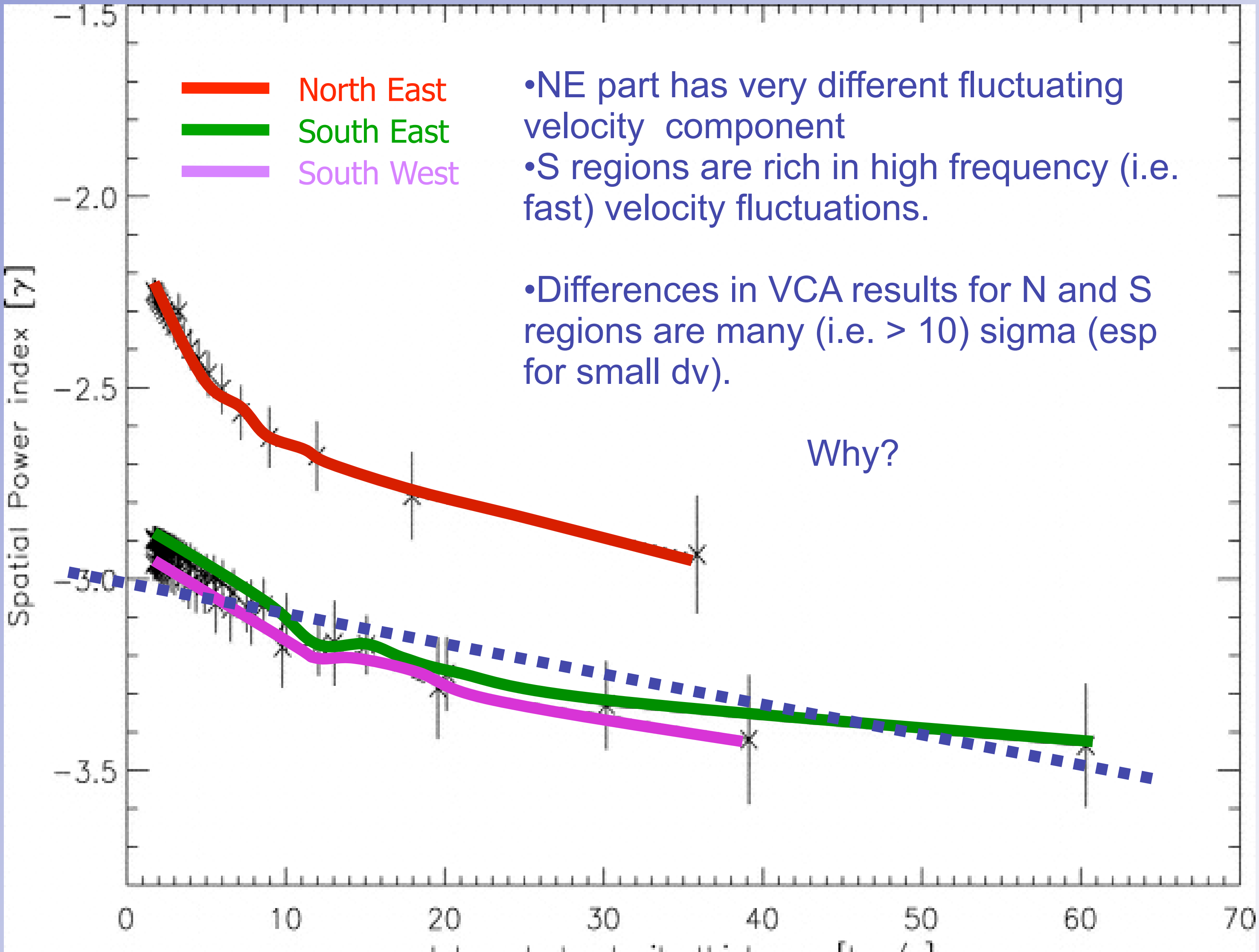
To study SPS, need to partition into sub-regions.

- Calculate SPS (v)
- Then apply VCA (dv)



Peak intensity map of Bridge, Muller et al, 2003

Spatial Power spectrum - VCA



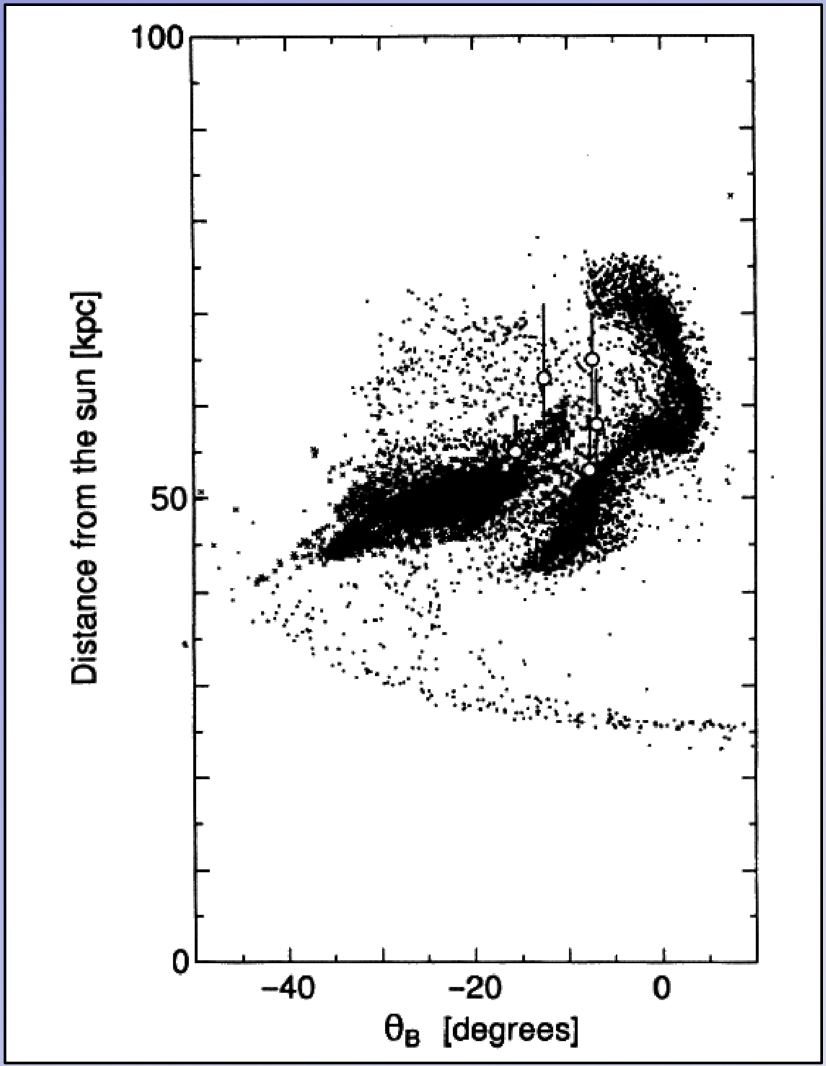
Muller et al. 2004

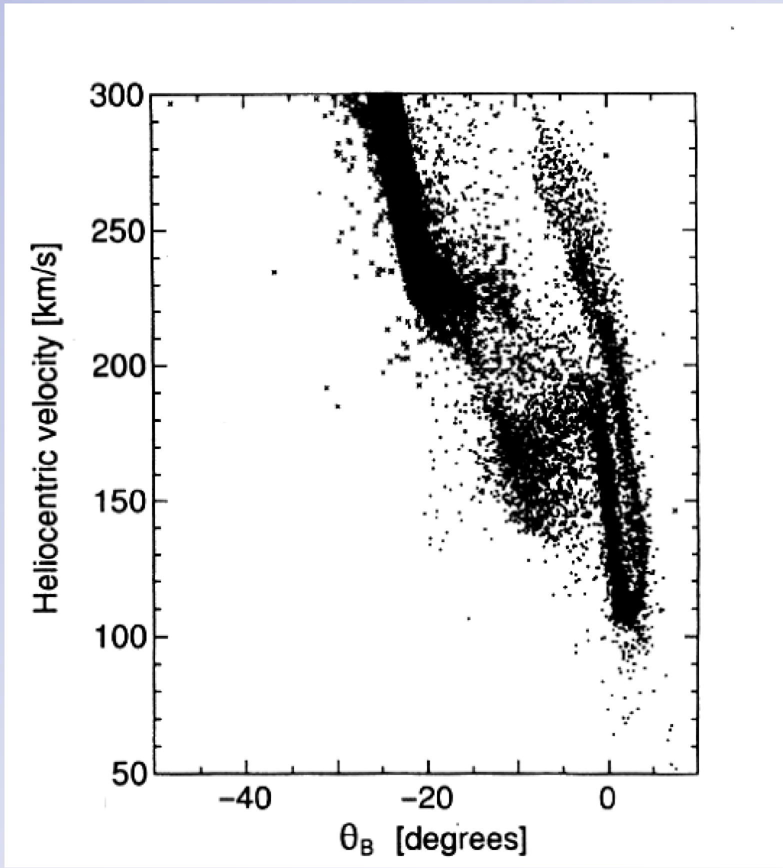
How can the SPS result be interpreted?

- Problem:
  - The Magellanic Bridge harbours two apparently adjacent regions which have an utterly inconsistent turbulent component.
- A solution:
  - The two regions are offset from each other in velocity.
  - Numerical simulations show that the Bridge may be a superposition of two ‘arms’ of the SMC: a transverse and a radial arm. These have an offset in velocity.

Velocity structure – simulations.

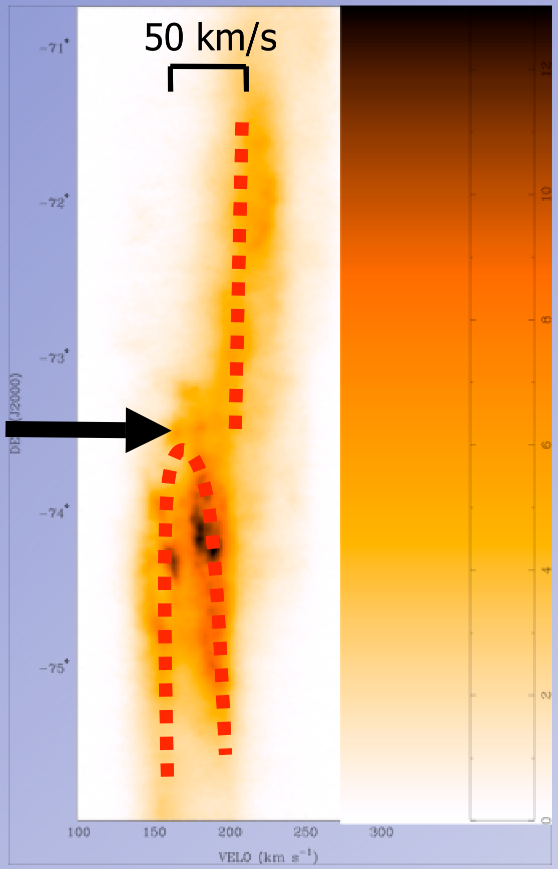
- N-Body Numerical simulations
- non-interacting particles.
- SMC, LMC, Galaxy
- M_{LMC}/M_{SMC} ~10
- (Gardiner, Sawa & Fujimoto, 1994)

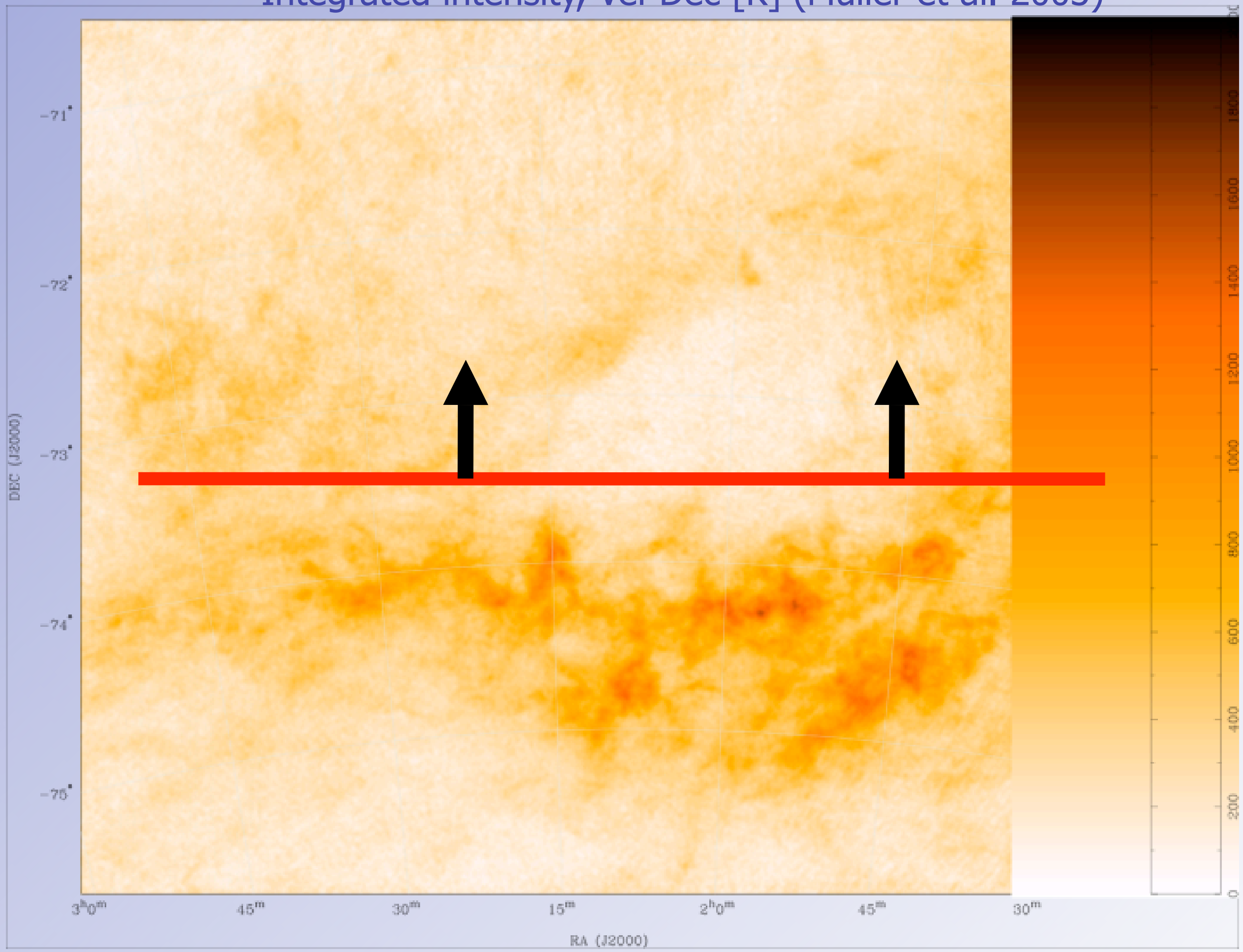




Velocity structure – Shift with Declination

Integrated intensity, Vel-Dec [K] (Muller et al. 2003)

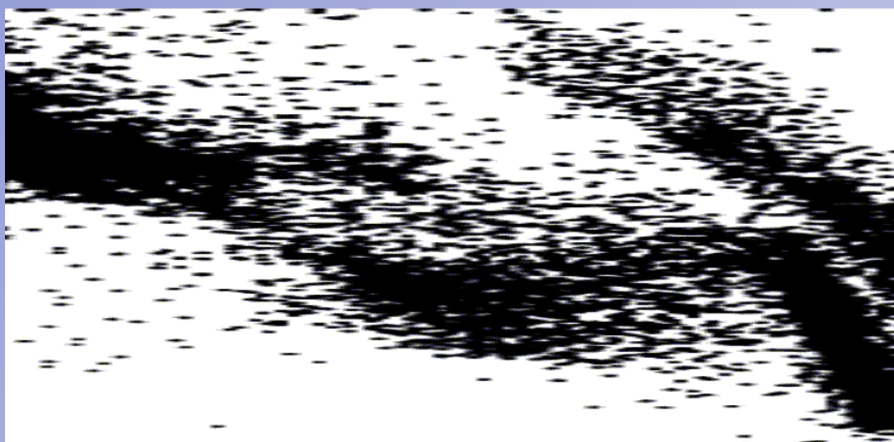


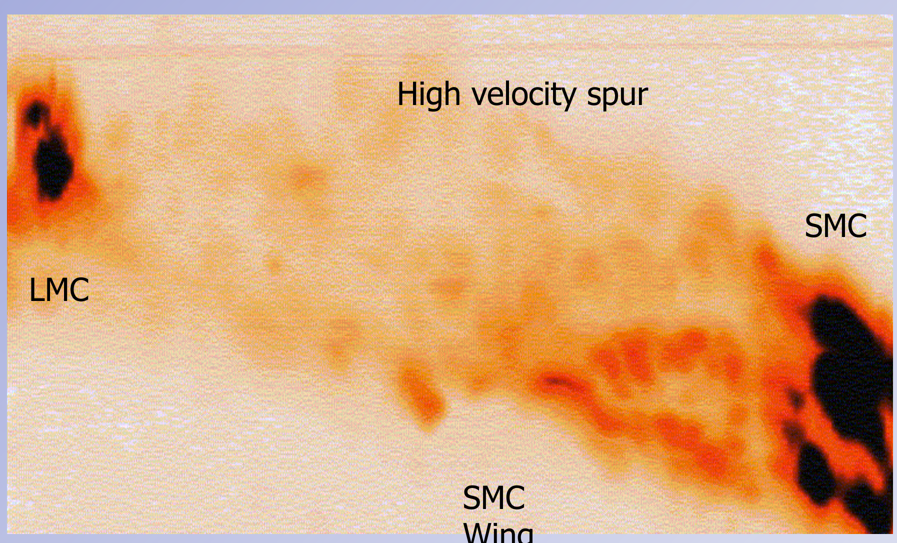


Peak intensity, Vel-Dec [K] (Muller et al. 2003)

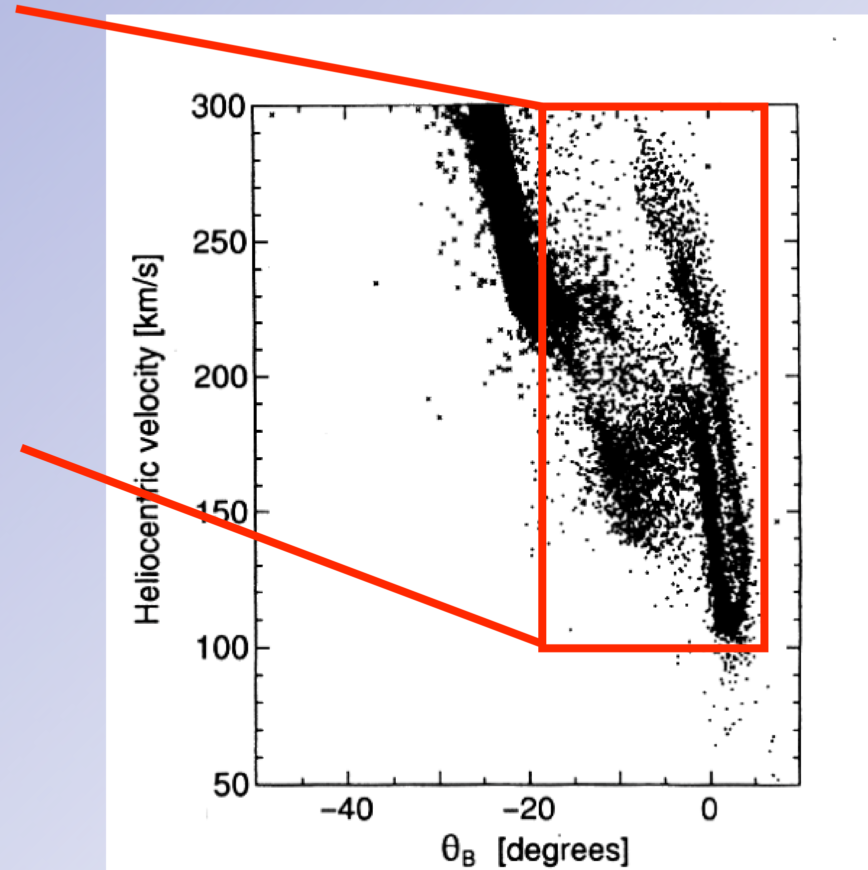
Velocity structure – N-Body Numerical simulations

The Hand-wavey bit.





Peak intensity, RA-Vel [K] (Bruns 2003 – Parkes data only)



Some conclusions from SPS

1. The SPS shows two apparently adjacent regions with very different morphological and velocity components.
2. Numerical simulations show that the Bridge may constitute two superimposed arms of the SMC.
3. The velocity structure of the Bridge reinforces the correlation with simulations.

Spectral Correlation Function

- A modified structure function.
- Probes 'degree of spectral similarity' as a function of spatial lag.
- Operates purely in the image domain.
  - Immune to difficulties and poor dynamic range and etc. which affect Fourier-based analyses
- Does not seem to function well with significant noise.
- Returns a value of 1 for perfect correlation, and a value of 0 for no correlation, or anti correlation.

$$S_o(\Delta\mathbf{r}) = \left\langle \frac{S_o(r,\Delta\rho)}{S_{\mathrm{o,N}}(\rho)} \right\rangle_r$$

$$S_o(\mathbf{r},\Delta r) = \left\langle 1 - \sqrt{\frac{\sum_r \left[T(\mathbf{r},v) - T(\mathbf{r}+\Delta r,v)\right]^2}{\sum_r T(\mathbf{r},v)^2 + \sum_r T(\mathbf{r}+\Delta r,v)^2}} \right\rangle_{\Delta r}$$

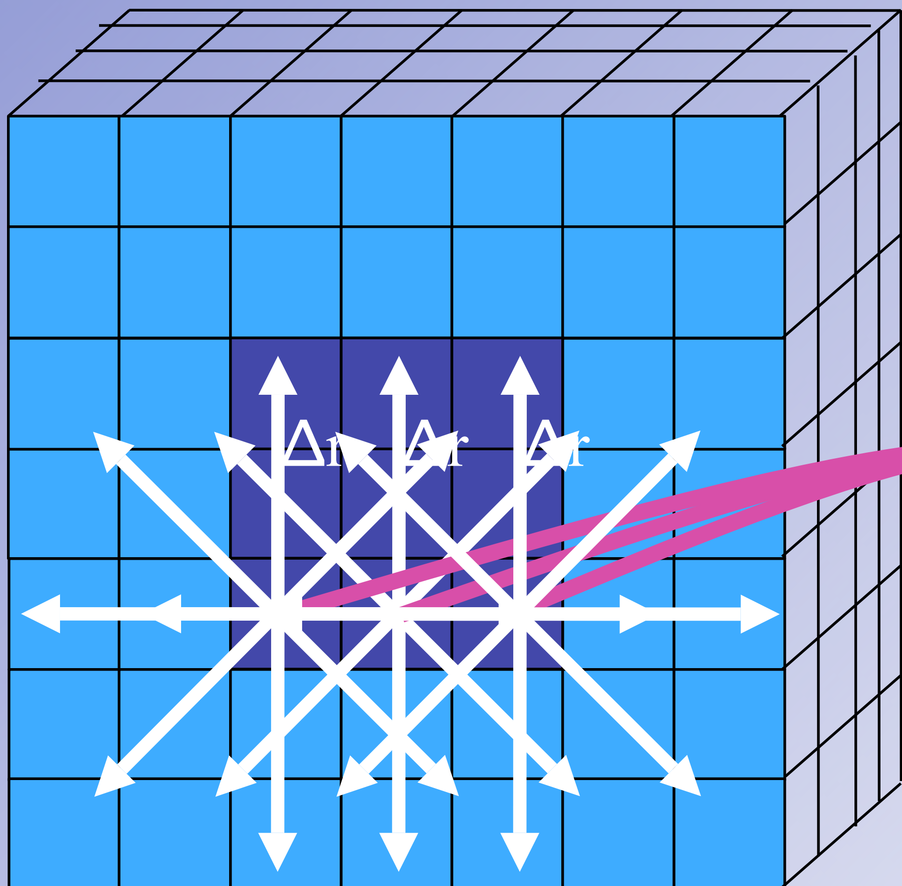
$$S_{0,N}(\Delta\mathbf{r}) = 1 - \frac{1}{Q(r)}$$

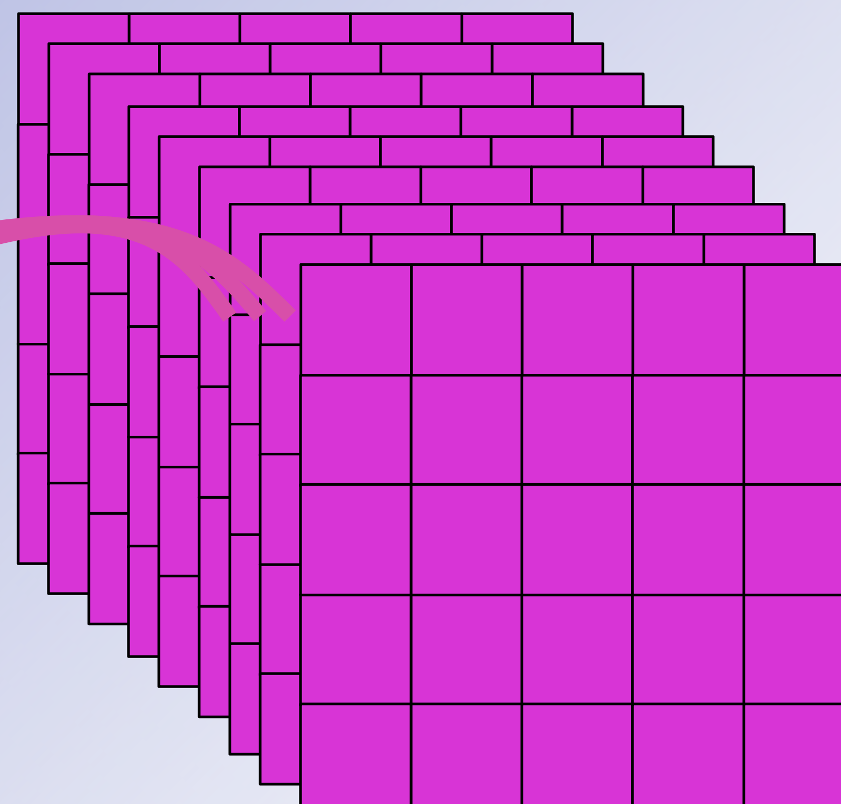
$$Q(\mathbf{r}) = \frac{1}{N}\sqrt{\frac{\sum_r T(\mathbf{r},v)^2\,dv}{W}}$$

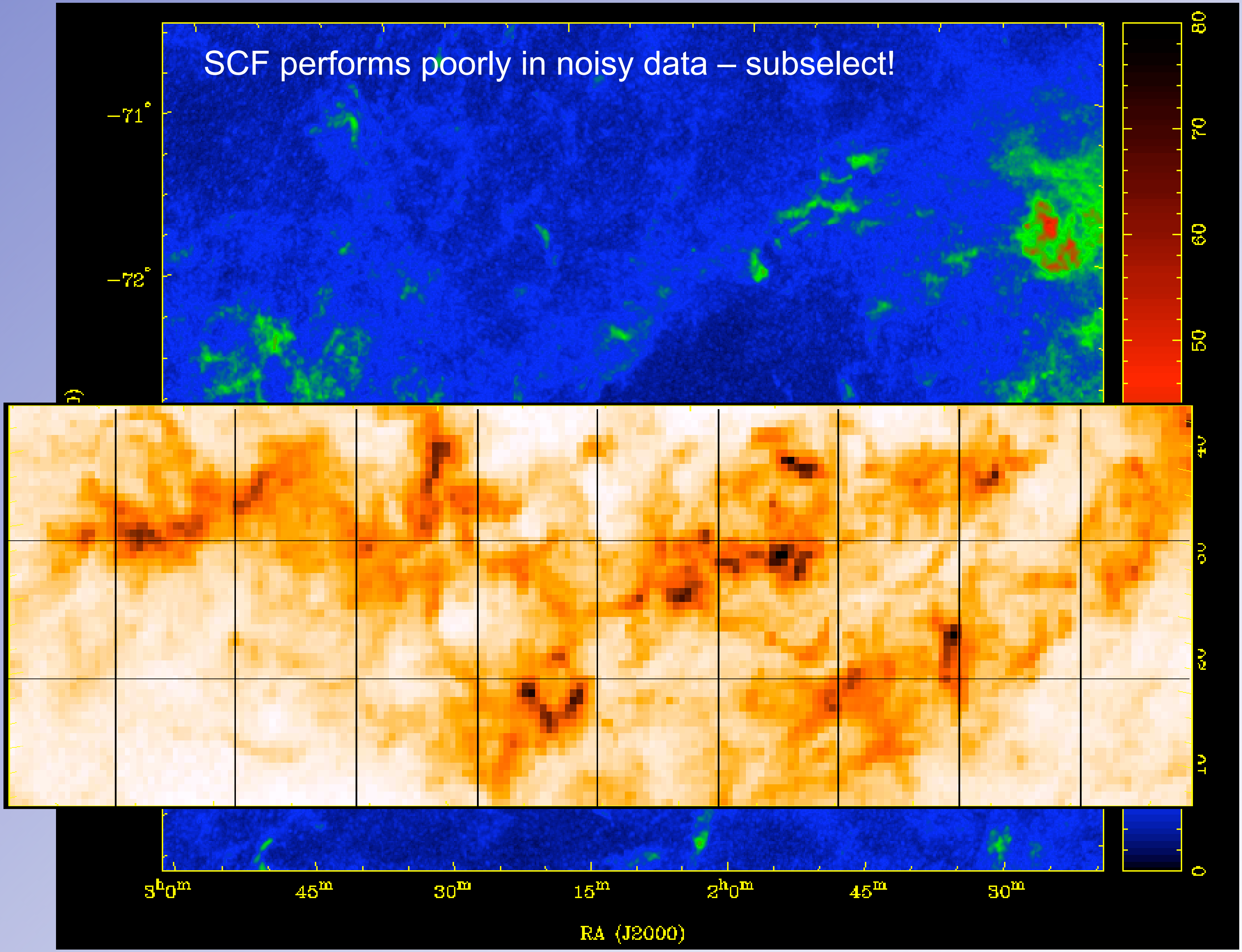
Spectral Correlation Function

How it works:

- Generate one S_o map for each pixel.
- Take average of all maps
- Optionally azimuthally average to create 1-D dataset.






SCF performs poorly in noisy data – subselect!
−71°
−72°
3h0m
45m
30m
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2h0m
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RA (J2000)
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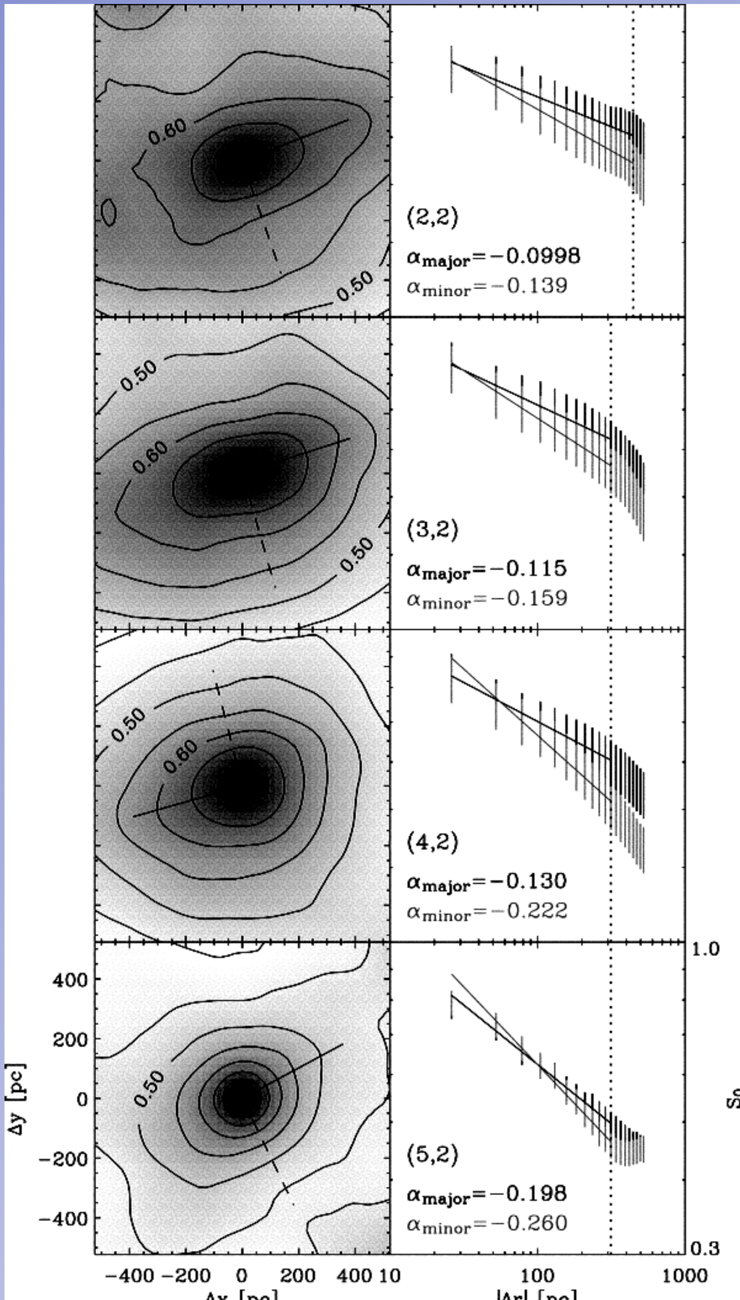
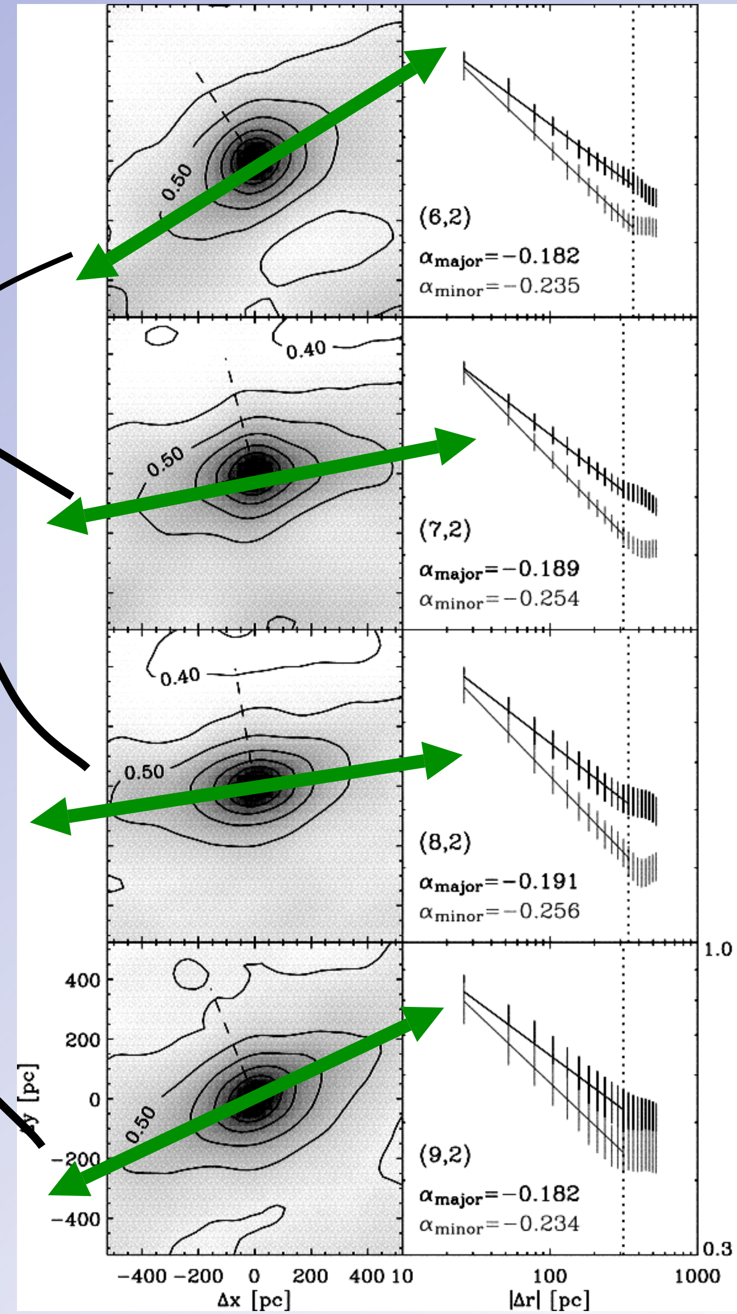


Signature of tidal evolution?

Noise Dominated?



Muller et al, 2004

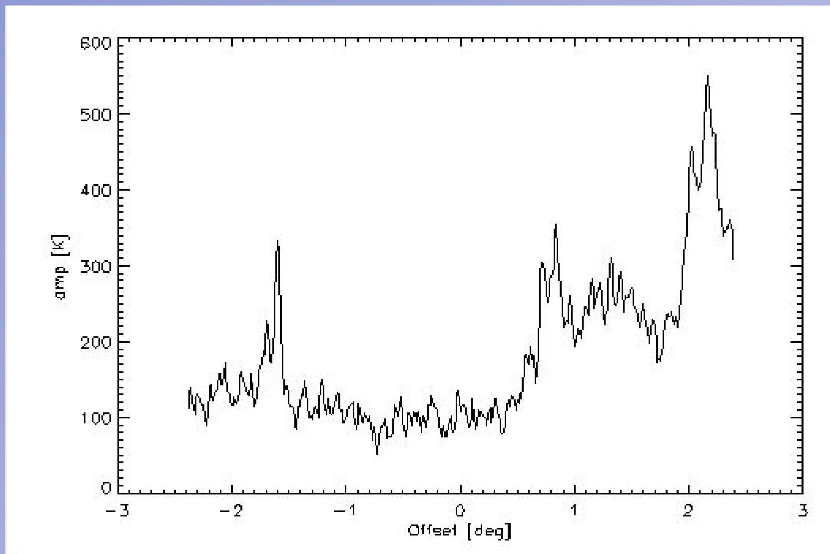
Some conclusions from SCF

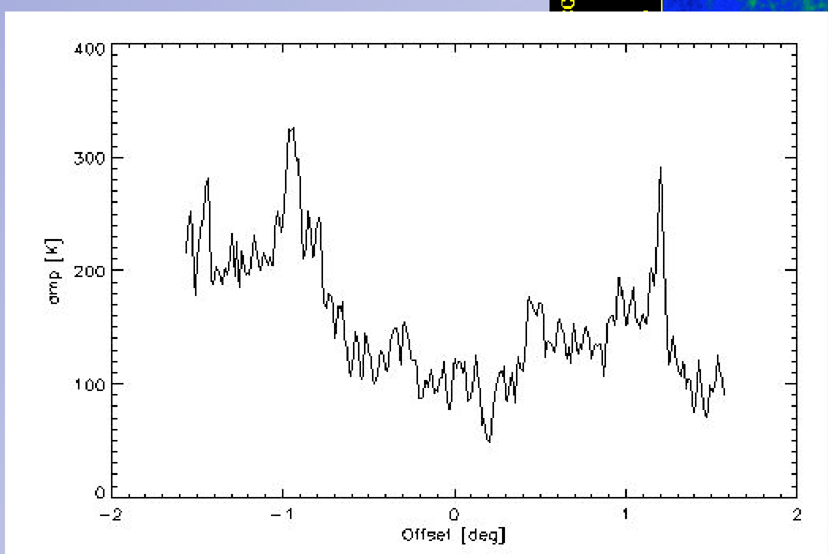
1. The SCF indicates a tendency for HI line profiles to be more similar in the ~E-W direction than in the ~N-S direction.
2. Numerical simulations have consistently reproduced the formation of the Magellanic Bridge as a tidal feature.

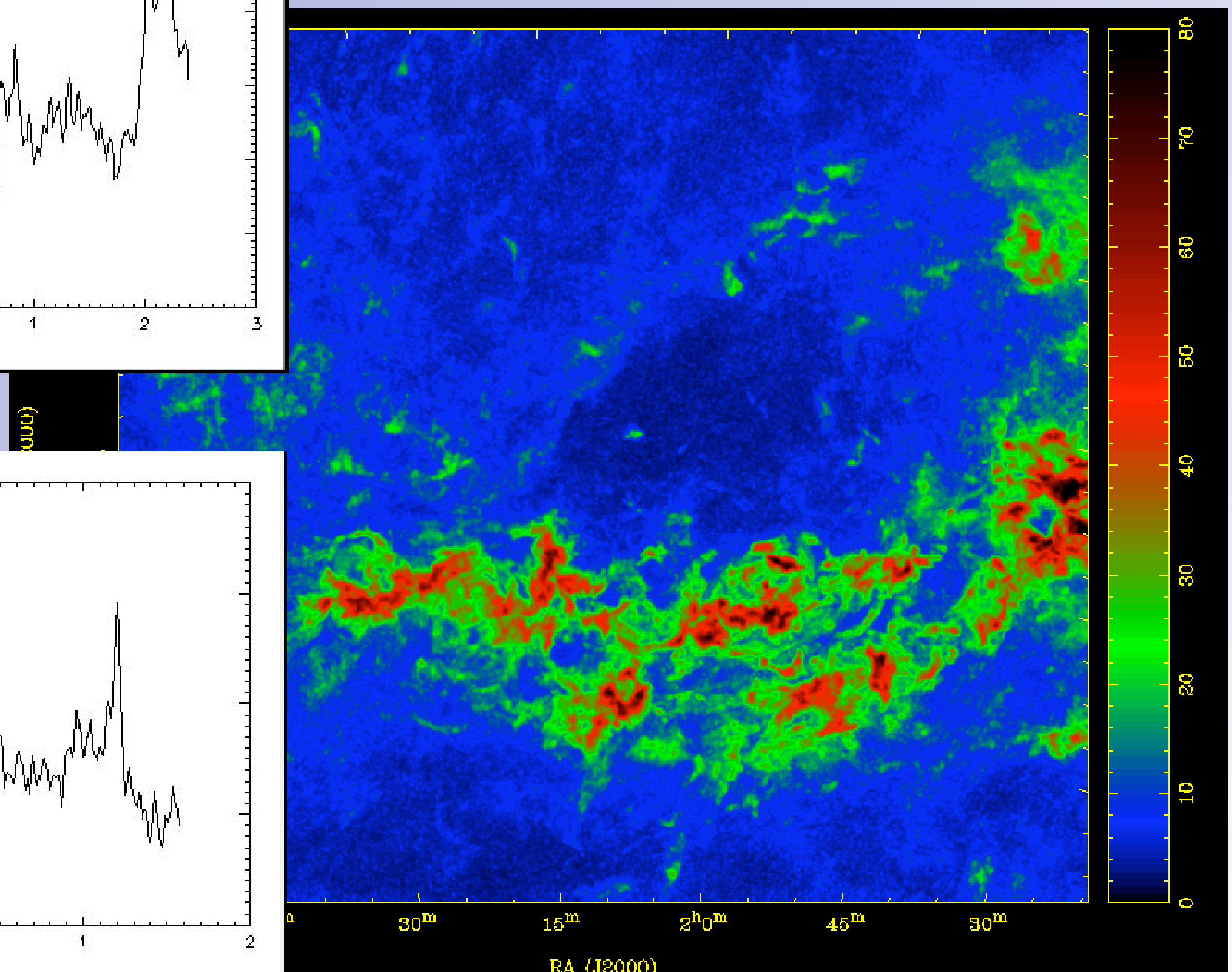
Assorted large-scale features

- A few large-scale (~kpc) features exist in the Bridge:
  - Can these be reproduced through numerical simulations?
  - What level of complexity is necessary?

Large-scale feature I: HI hole

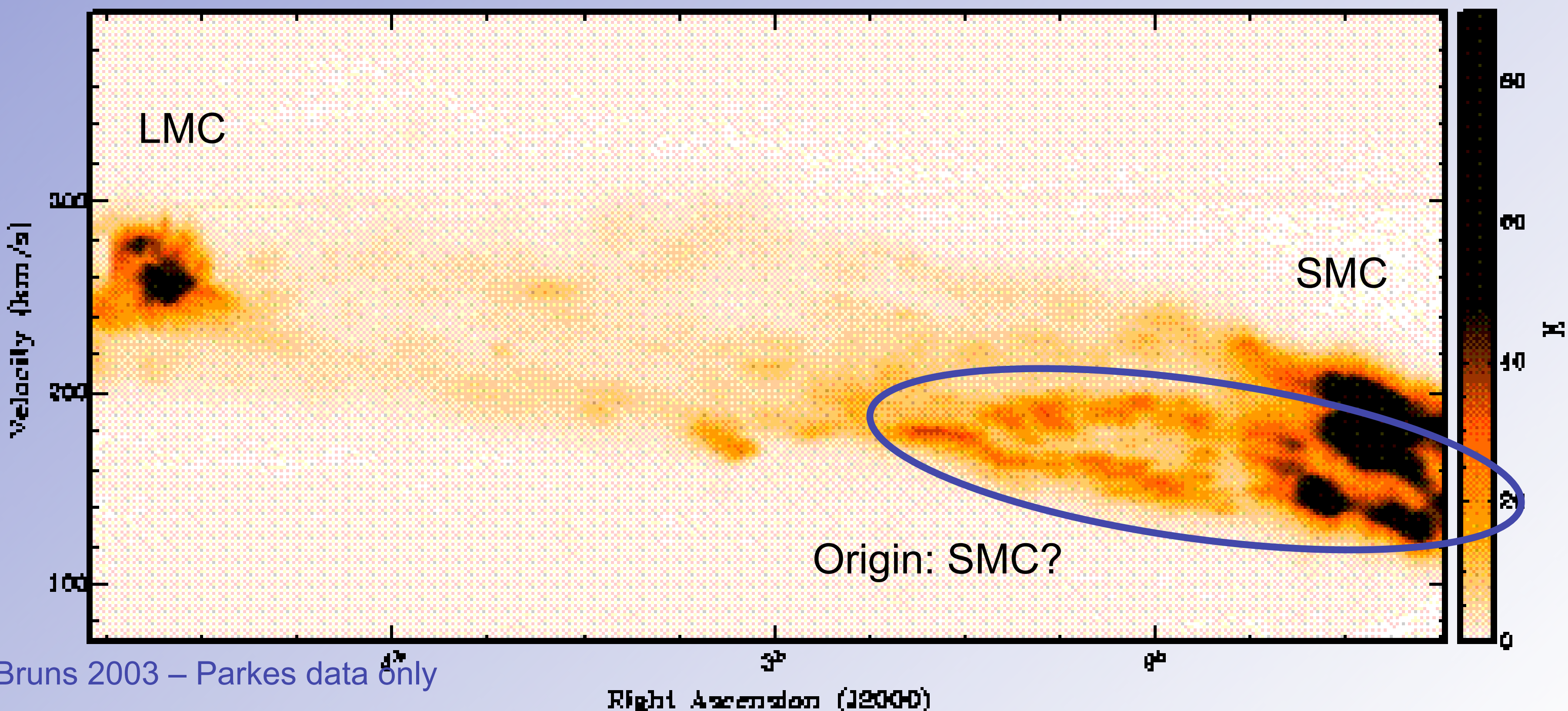






Large-scale feature II: Velocity Bifurcation

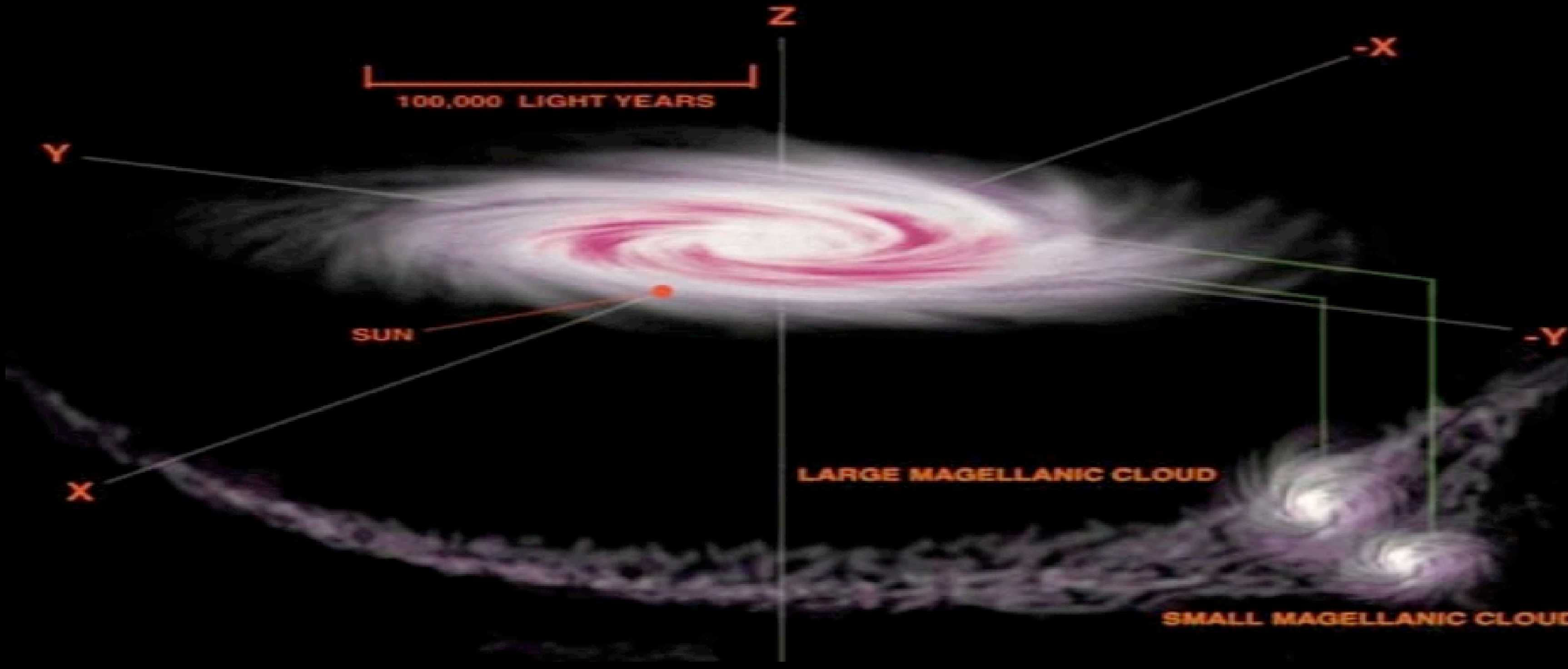
- Brightest part of Bridge shows a ~45 km/s velocity bifurcation.



Bruns 2003 – Parkes data only

Wrap-up and summary comments

- Numerical simulations were critical in understanding and interpreting the results from the SPS.
- The Bridge shows a tendency to vary more slowly in the E-W direction, as shown by the results of the SCF. This also makes sense under a scenario of tidal perturbation, such as that shown in numerical simulations of the system.
- Larger-scale structures exist in the Bridge, although the formation processes are unclear. Simulations will also help to rule out, or confirm candidate mechanisms.


Z
-X
100,000 LIGHT YEARS
Y
SUN
-Y
X
LARGE MAGELLANIC CLOUD
SMALL MAGELLANIC CLOUD