Observational Magnetohydrodynamics of the Interstellar Medium

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Observational MHD of the ISM

The Good Old Days

- *Low Resolution*, Observationally & Computationally

⇒Spherical, Smooth, Long-lasting "Cloud" Structures

And "*structure*" came from fragmentation

Observational MHD of the ISM

The "New Age"

- *High(er) Resolution*, Observationally & Computationally

⇒Highly irregular structures, many of which are "transient" on long time scales

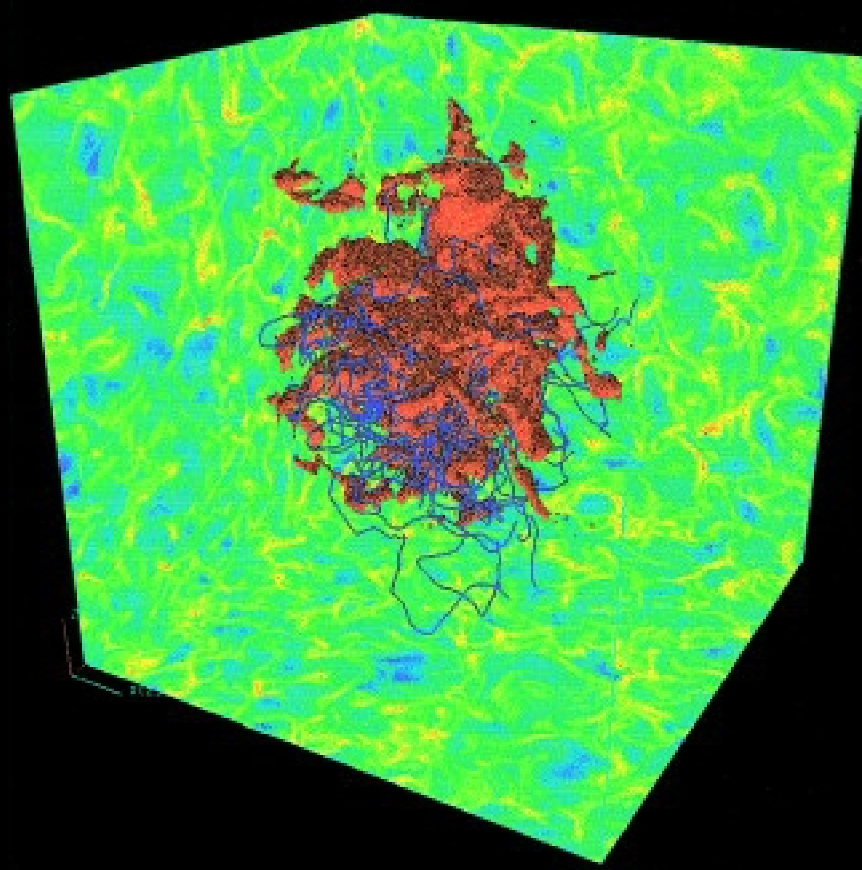
NGC 3603 **HST • WFPC2**
PRC99-20 • STScI OPO • June 1, 1999
Wolfgang Brandner (JPL/IPAC), Eva K. Grebel (Univ. Washington), You-Hua Chu (Univ. Illinois, Urbana-Champaign) and NASA

"Observational" MHD of the ISM

The "New Age"

- *High(er) Resolution*, Observationally & Computationally

⇒Highly irregular structures, many of which are "transient" on long time scales

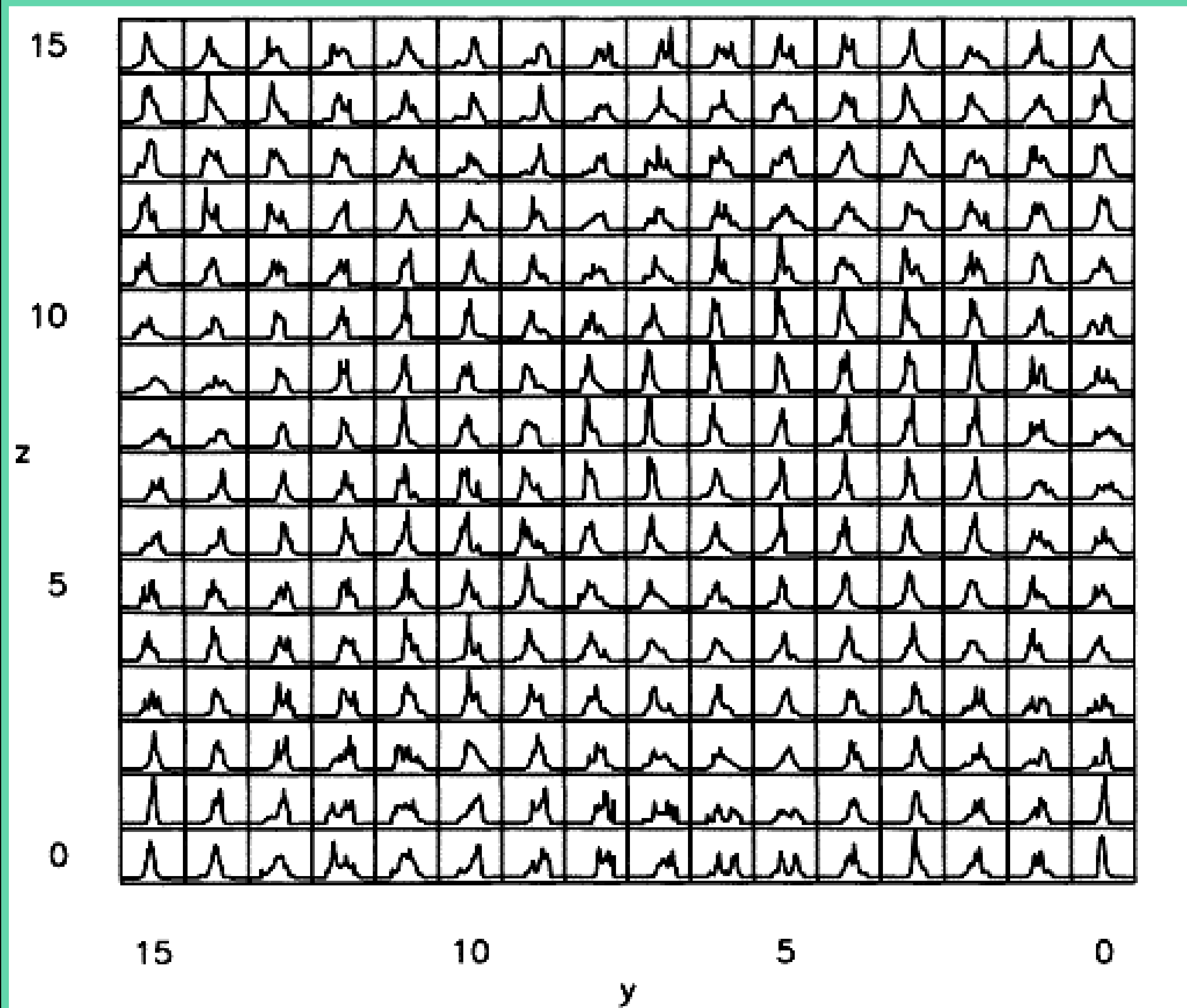


Stone, Gammie & Ostriker 1999

And "*structure*" comes from turbulence on all but smallest scales

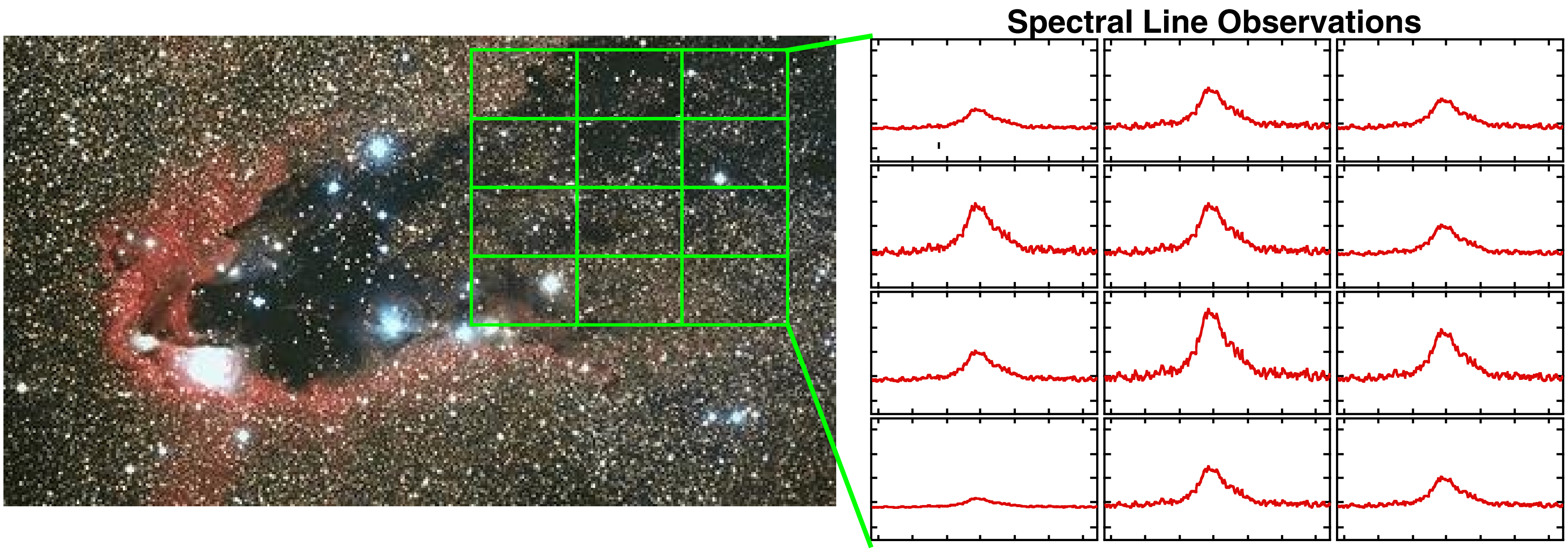
What can we actually observe?

Intensity(position, position,velocity)

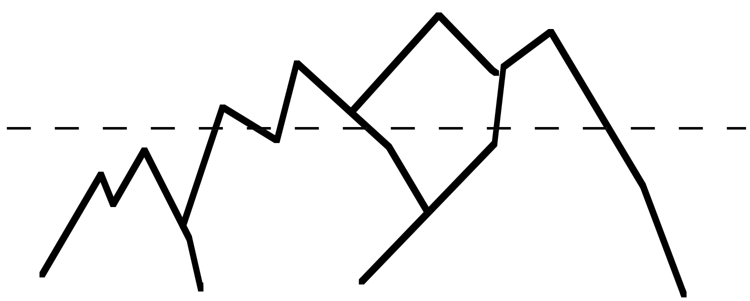


Falgarone et al. 1994

Velocity is the Observer's "Fourth" Dimension

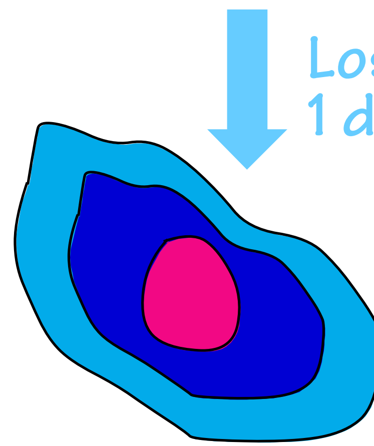


Loss of
1 dimension

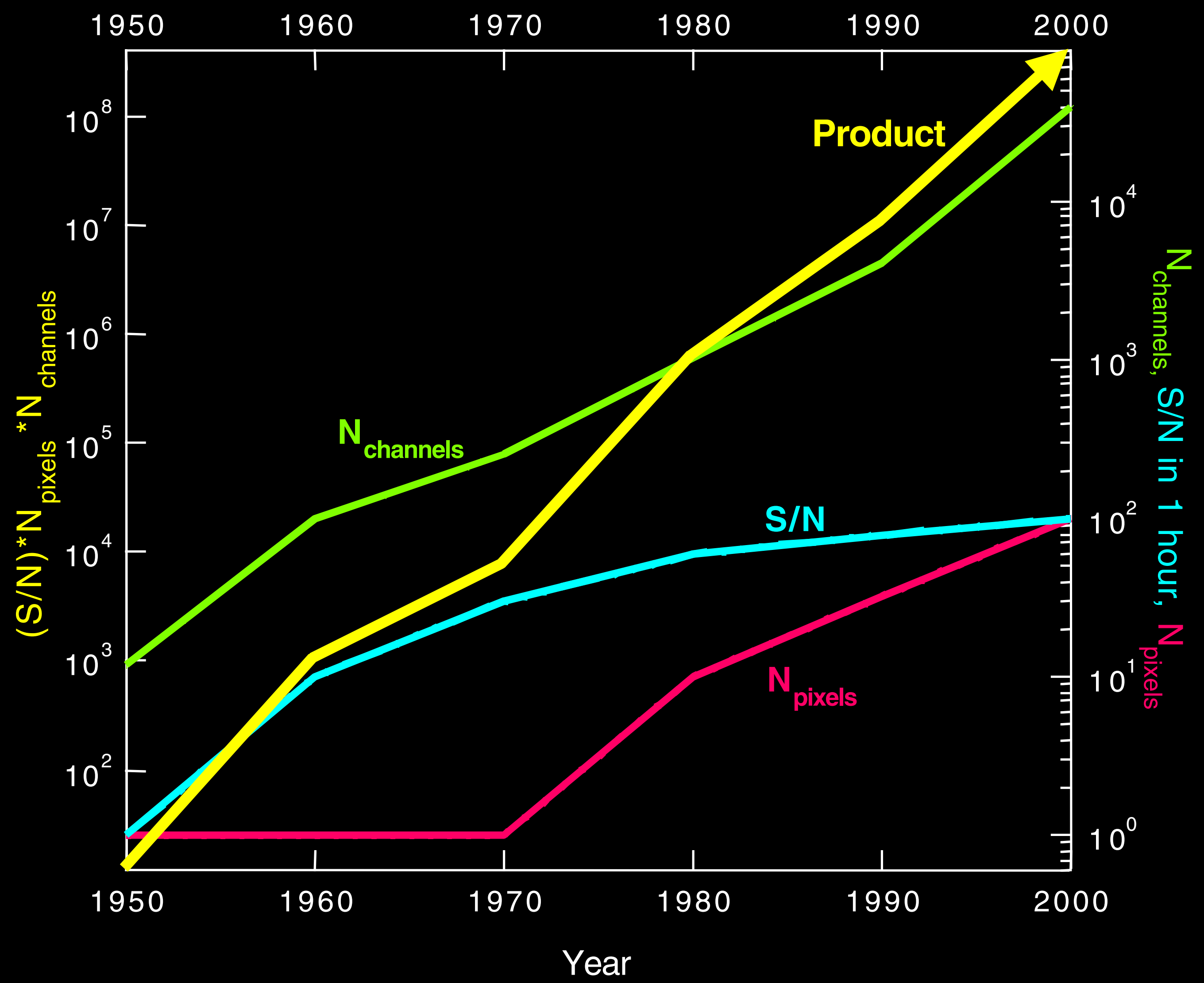


Mountain Range

No loss of
information



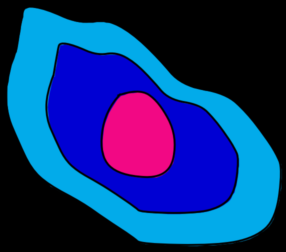
How Many Bits?



Statistical Tools

- Can no longer examine "large" spectral-line maps or simulations "by-eye"
- Need powerful, discriminatory tools to quantify and intercompare data sets
- Previous attempts are numerous: ACF, Structure Functions, Structure Trees, Clumpfinding, Wavelets, PCA, Δ-variance, Line parameter histograms

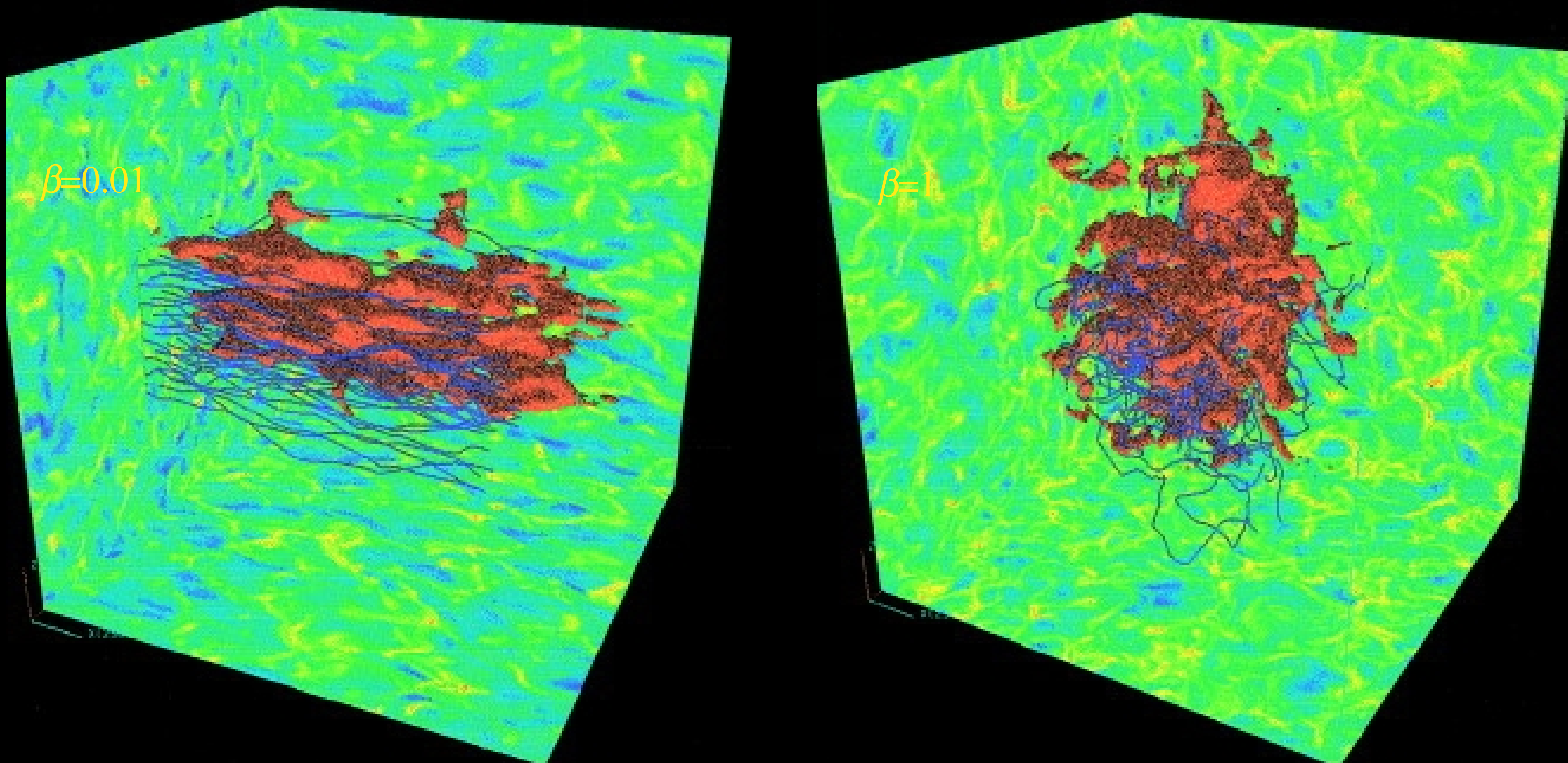
Most previous attempts discard or compress either position or velocity information



1997 Goals of the "Spectral Correlation Function" Project

- ✓ Develop "sharp tool" for statistical analysis of ISM, using as much data of a data cube as possible
- ✓ Compare information from this tool with other statistical tools applied to same cubes
- ❒ Incorporate continuum information
- ✓ Use best suite of tools to compare "real" & "simulated" ISM
- ✓ Adjust simulations to match, understanding physical inputs
- ✓ *Develop a (better) prescription for finding star-forming gas*

Strong vs. Weak B-Field



Stone, Gammie & Ostriker 1999

$$\beta = \frac{[T / 10\ \mathrm{K}]}{[n_{H_2} / 100\ \mathrm{cm}^{-3}][B / 1.4\ \mu\mathrm{G}]^2}$$

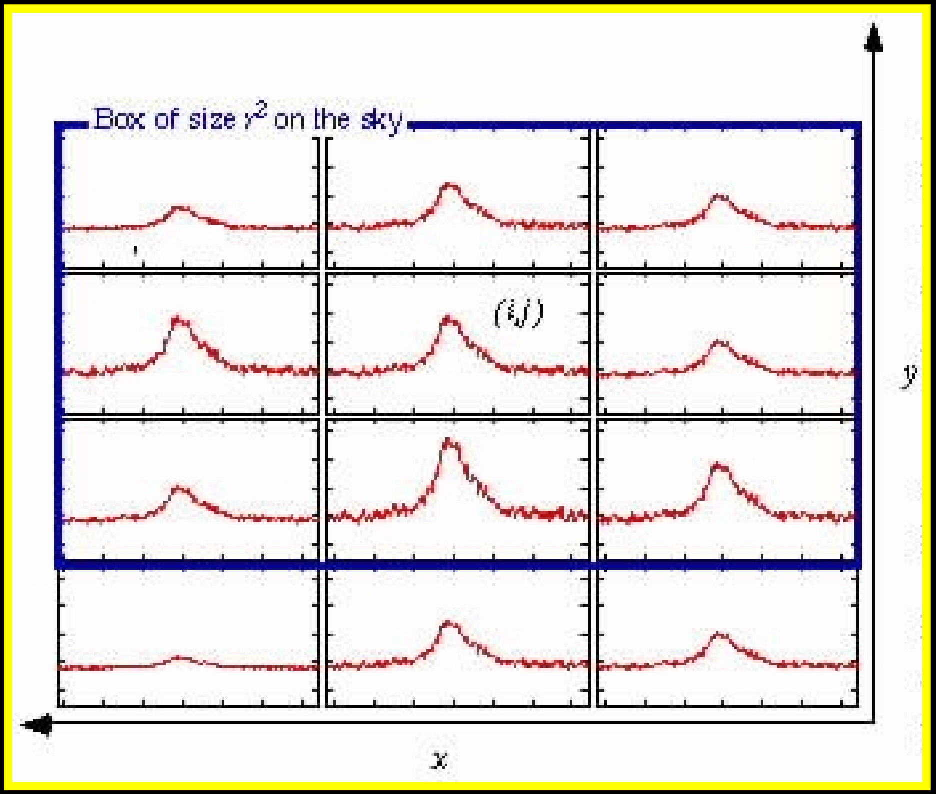
- ***Driven*** *Turbulence;* M→ K; no gravity
- *Colors: log density*
- *Computational volume:* 256^3
- *Dark blue lines: B-field*
- *Red : isosurface of passive contaminant after saturation*

The Spectral Correlation Function

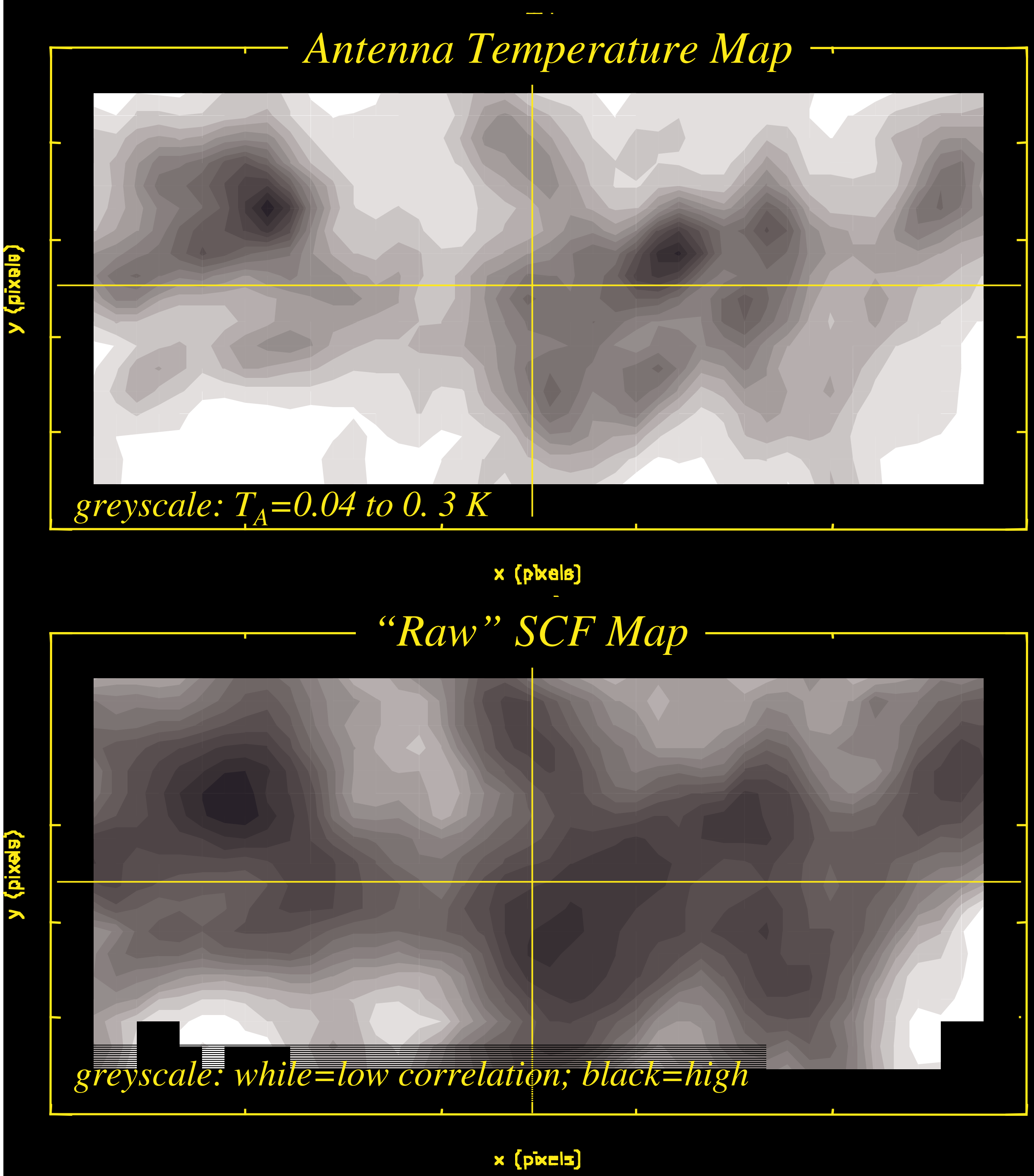
- v.1.0 Simply measures similarity of neighboring spectra *(Rosolowsky, Goodman, Wilner & Williams 1999)*
  - S/N equalized, observational/theoretical comparisons show discriminatory power
- v.2.0 Measures spectral similarity as a function of spatial scale *(Padoan, Rosolowsky & Goodman 2001)*
  - Noise normalization technique found
  - SCF(lag) even more powerful discriminant
- Applications
  - Finding the scale-height of face-on galaxies! *(Padoan, Kim & Goodman 2001)*
  - Understanding behavior of atomic ISM *(e.g. Ballesteros-Paredes, Vazquez-Semadeni & Goodman 2001)*

How SCF v.1.0 Works

- Measures similarity of neighboring spectra within a specified "beam" size
  - lag & scaling adjustable
  - signal-to-noise accounted for



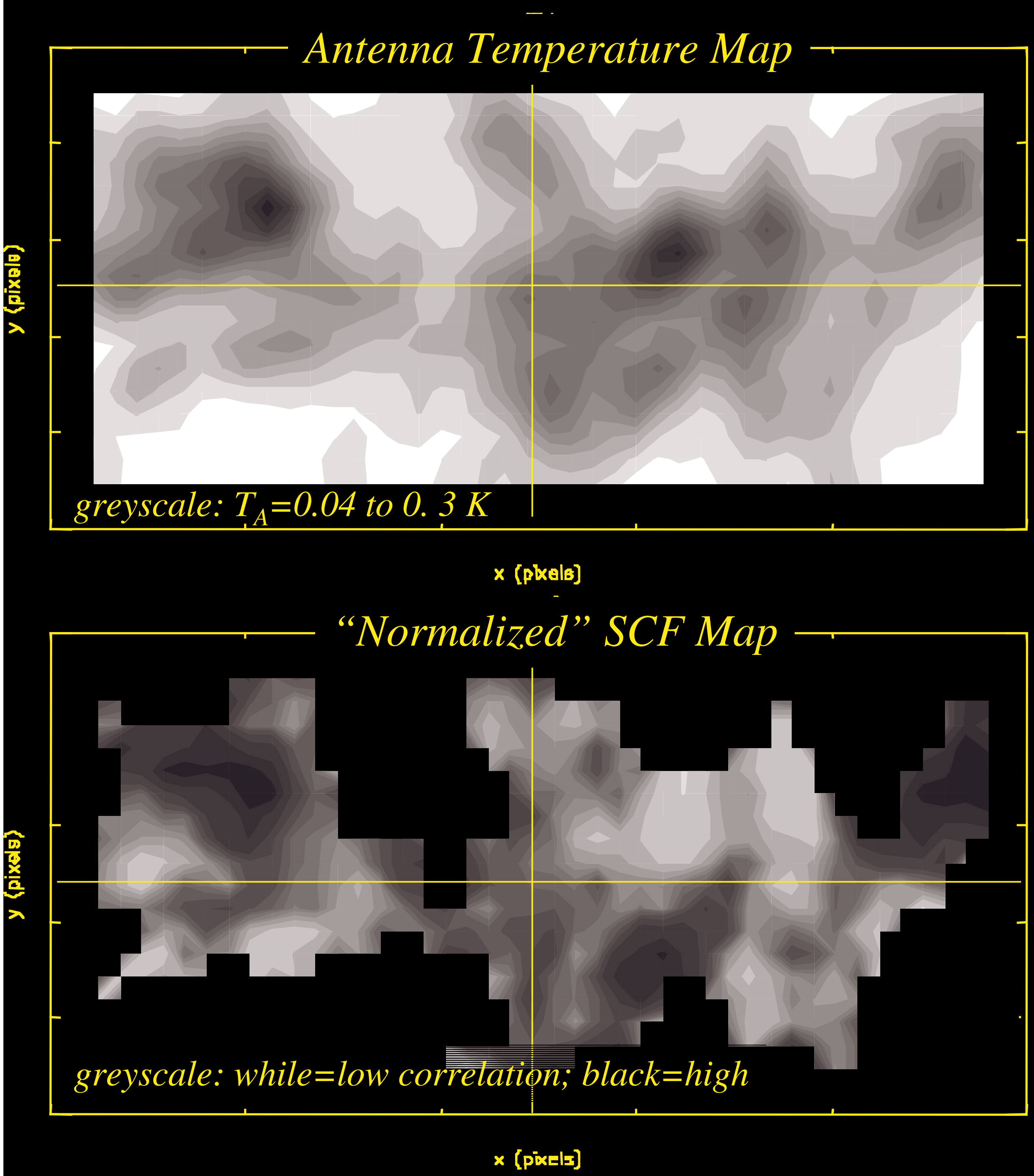
See: Rosolowsky, Goodman, Wilner & Williams 1999; Ballesteros-Paredes, Vazquez-Semadeni & Goodman 2001



Application of the "Raw" SCF

Data shown: $C^{18}O$ map of Rosette, courtesy *M. Heyer et al.*

Results: *Padoan, Rosolowsky & Goodman 2001*

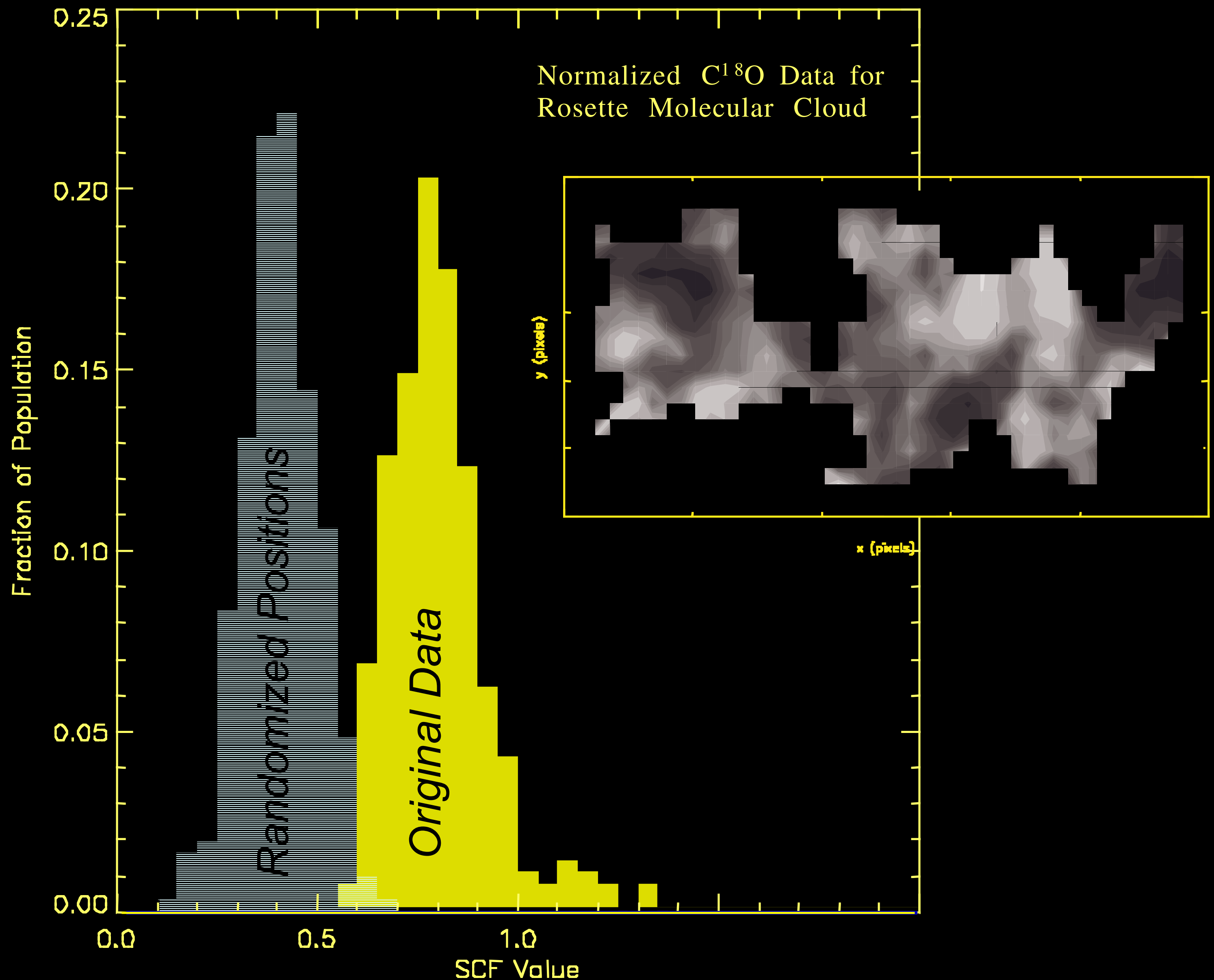


Application of the SCF

Data shown: $C^{18}O$ map of Rosette, courtesy *M. Heyer et al.*

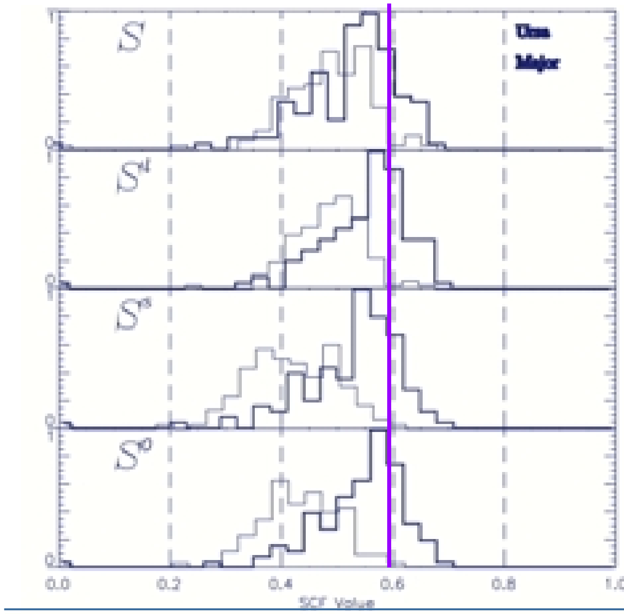
Results: *Padoan, Rosolowsky & Goodman 2001.*

SCF Distributions



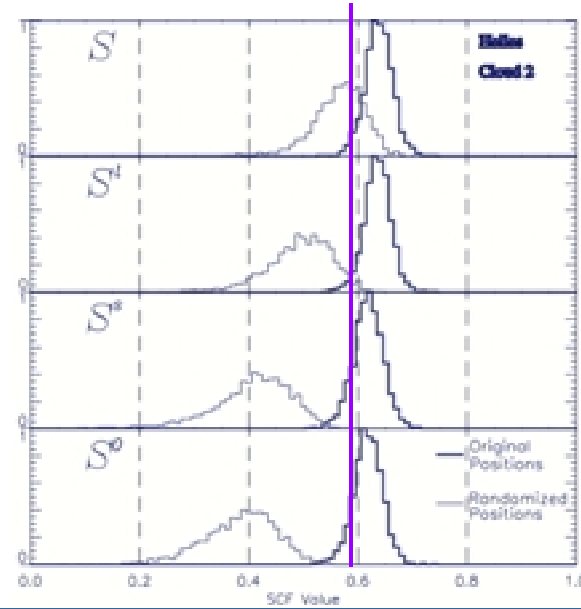
Unbound High-Latitude Cloud

Self-Gravitating, Star-Forming Region



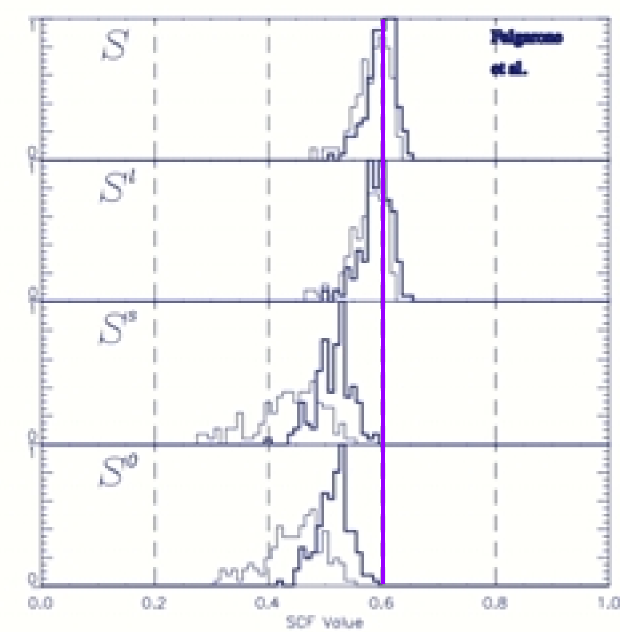
Insights from SCF v.1.0

Rosolowsky, Goodman, Williams & Wilner 1999

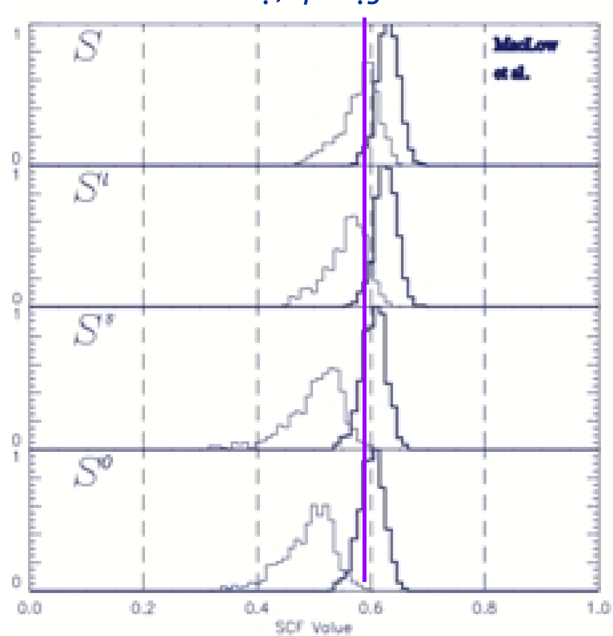


Observations

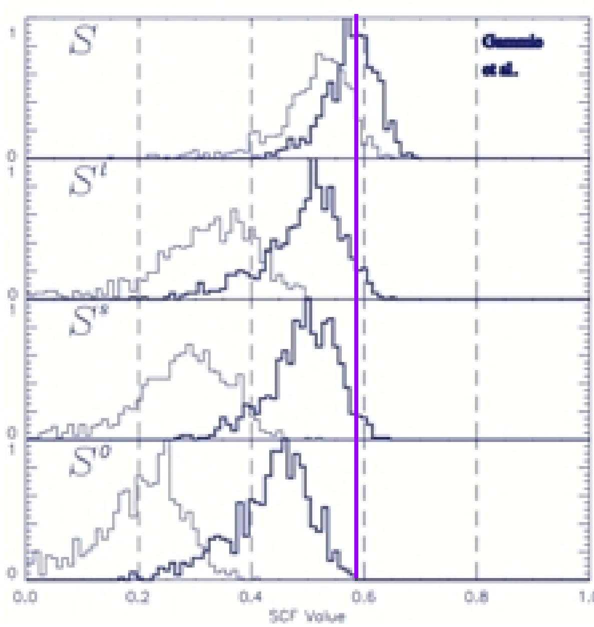
Simulations



No gravity, No B field

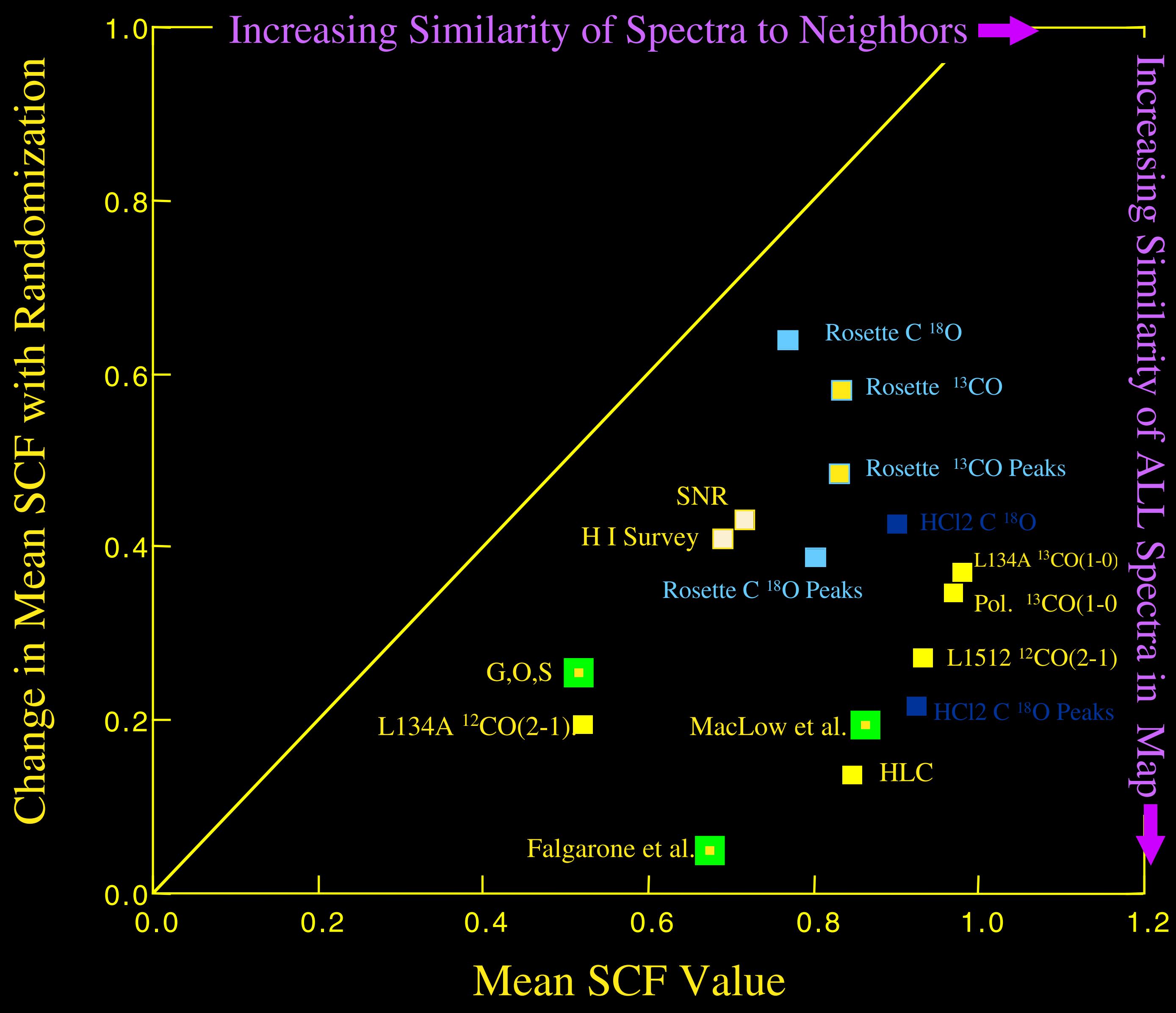


No gravity, Yes B field

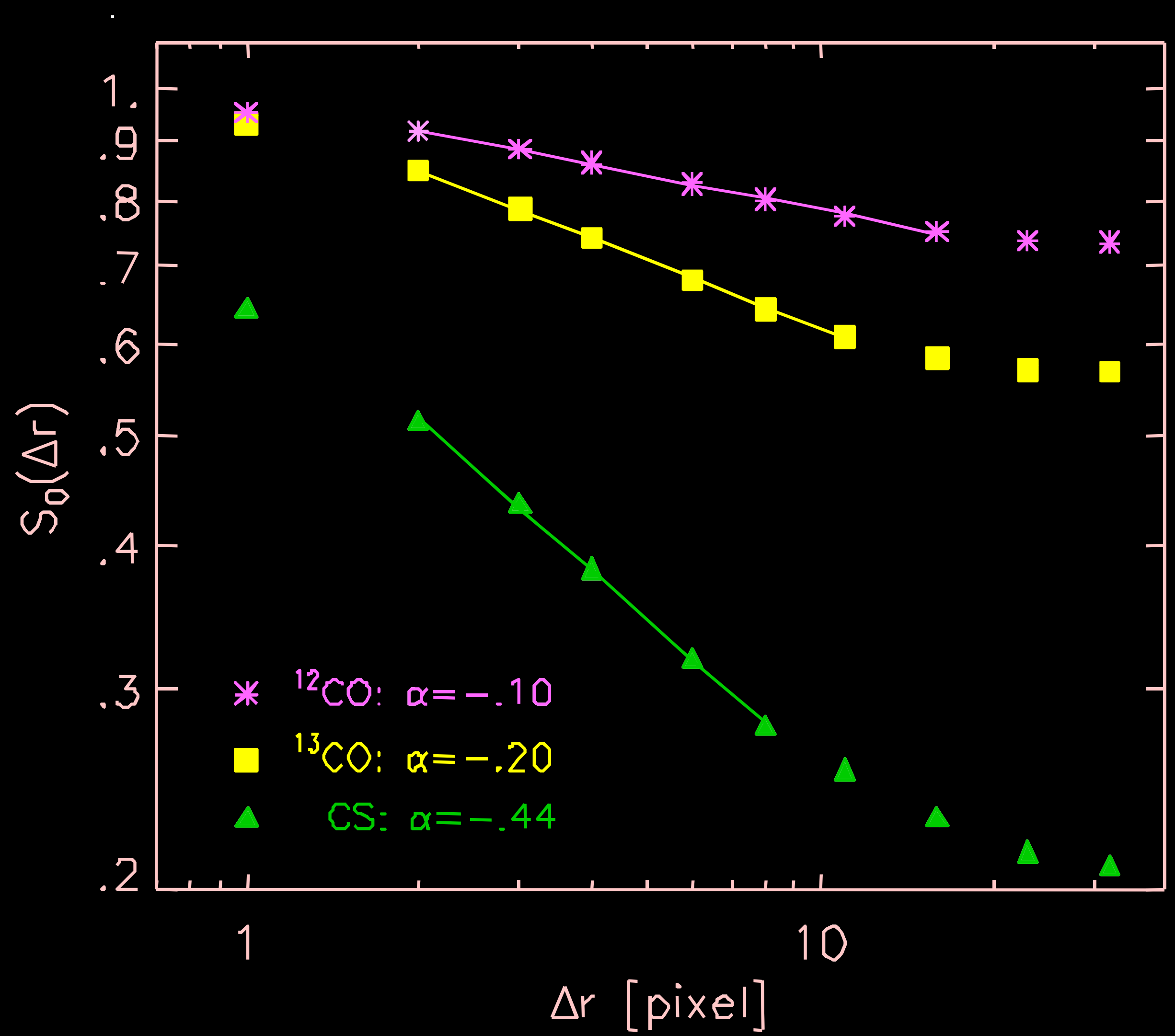


Yes gravity, Yes B field

Which of these is not like the others?



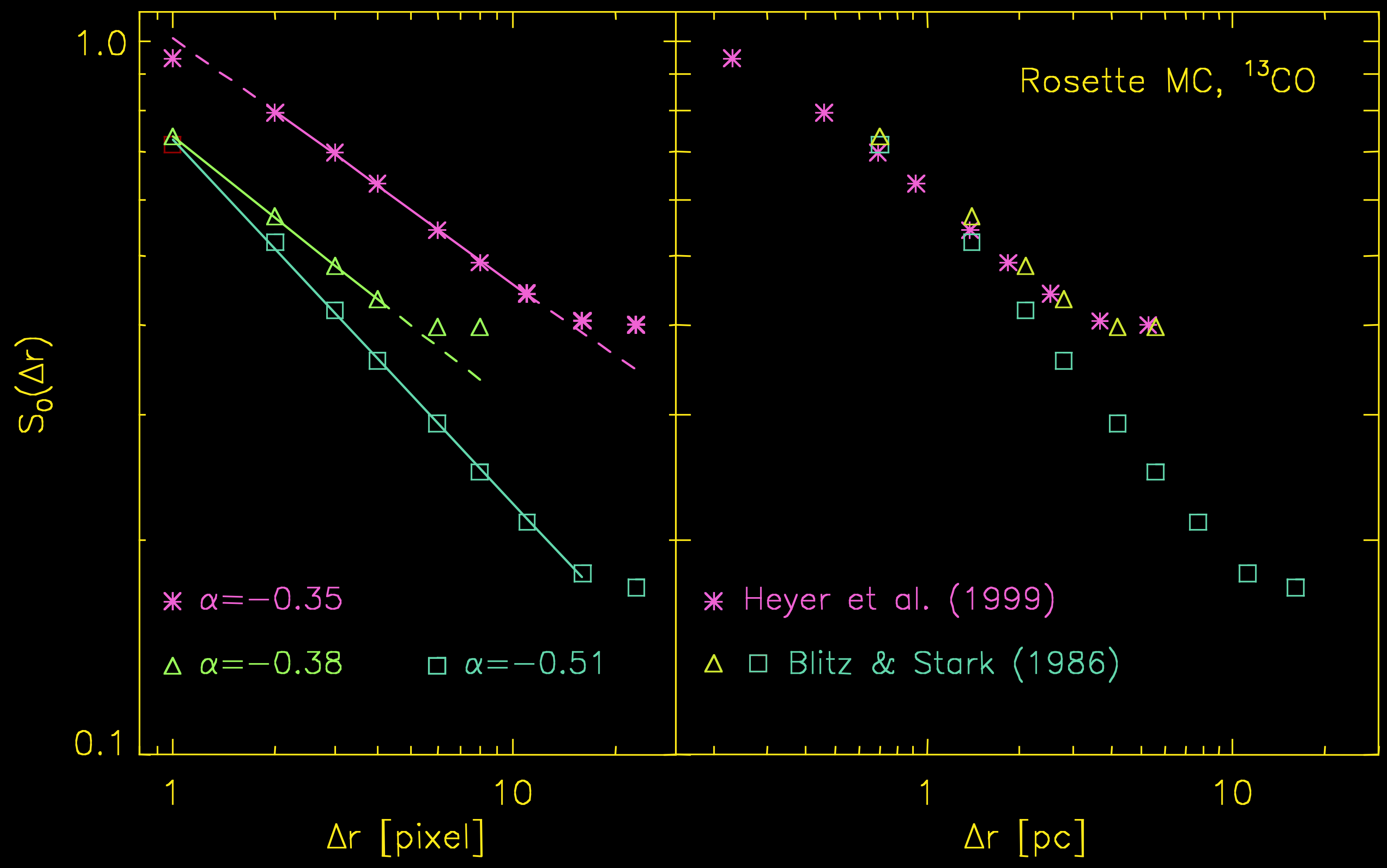
v.2.0: Scale-Dependence of the SCF



Example for "Simulated Data"

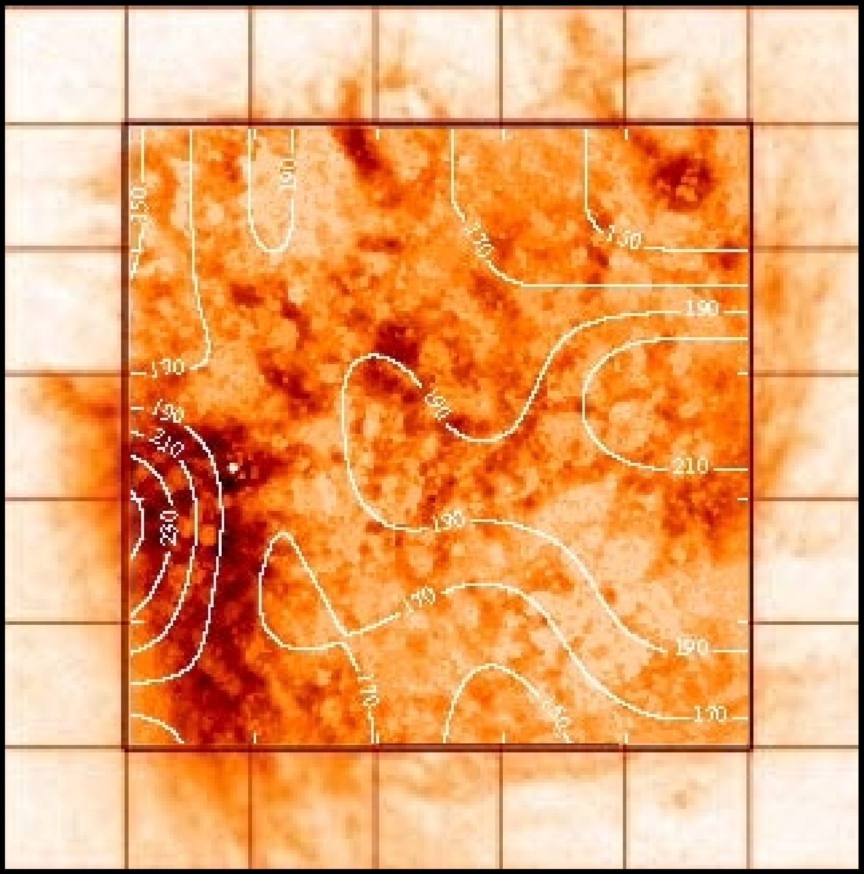
Padoan, Rosolowsky & Goodman 2001

"A Robust Statistic"

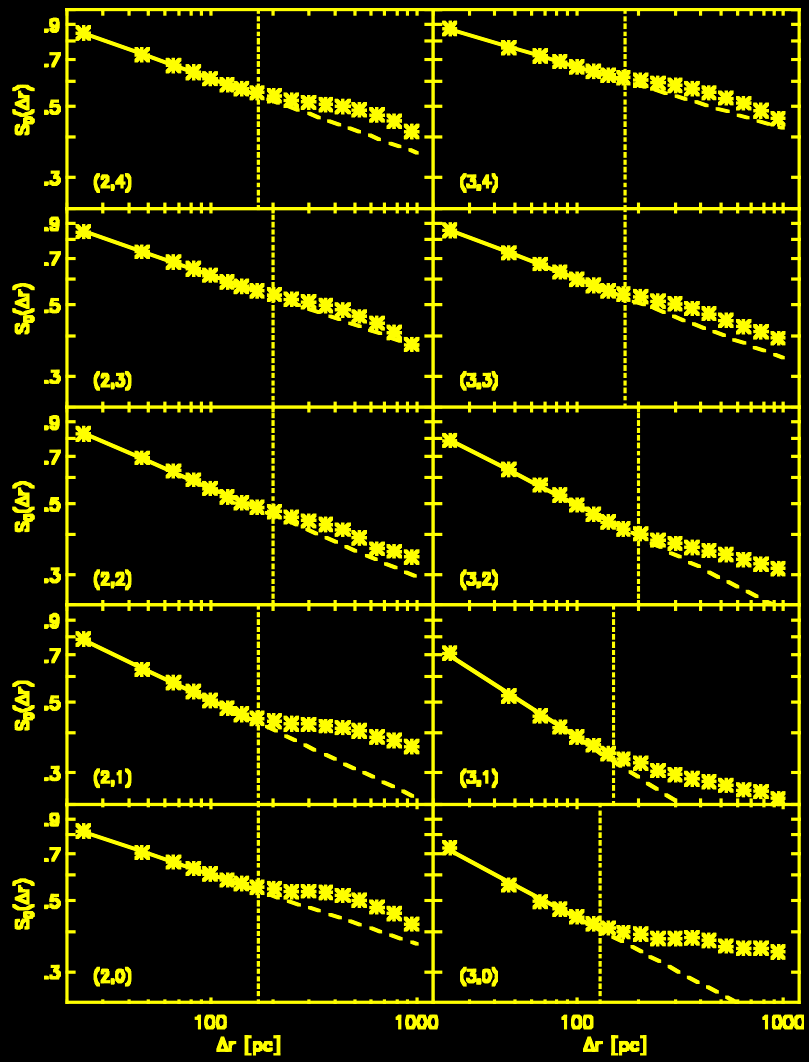


Padoan, Rosolowsky & Goodman 2001

Galactic Scale Heights from the SCF (v.2.0)



HI map of the LMC from ATCA & Parkes Multi-Beam, courtesy Stavely-Smith, Kim, et al.

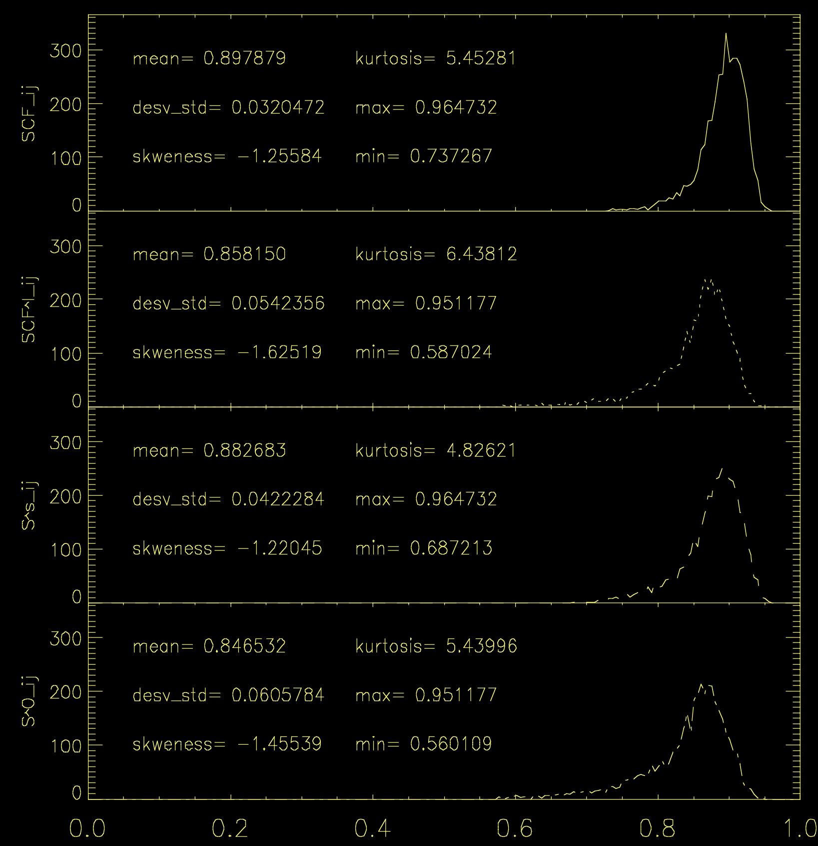


Padoan, Kim & Goodman 2001

Insights into Atomic ISM from SCF (v.1.0)

Comparison with simulations of Vazquez-Semadeni & collaborators shows:

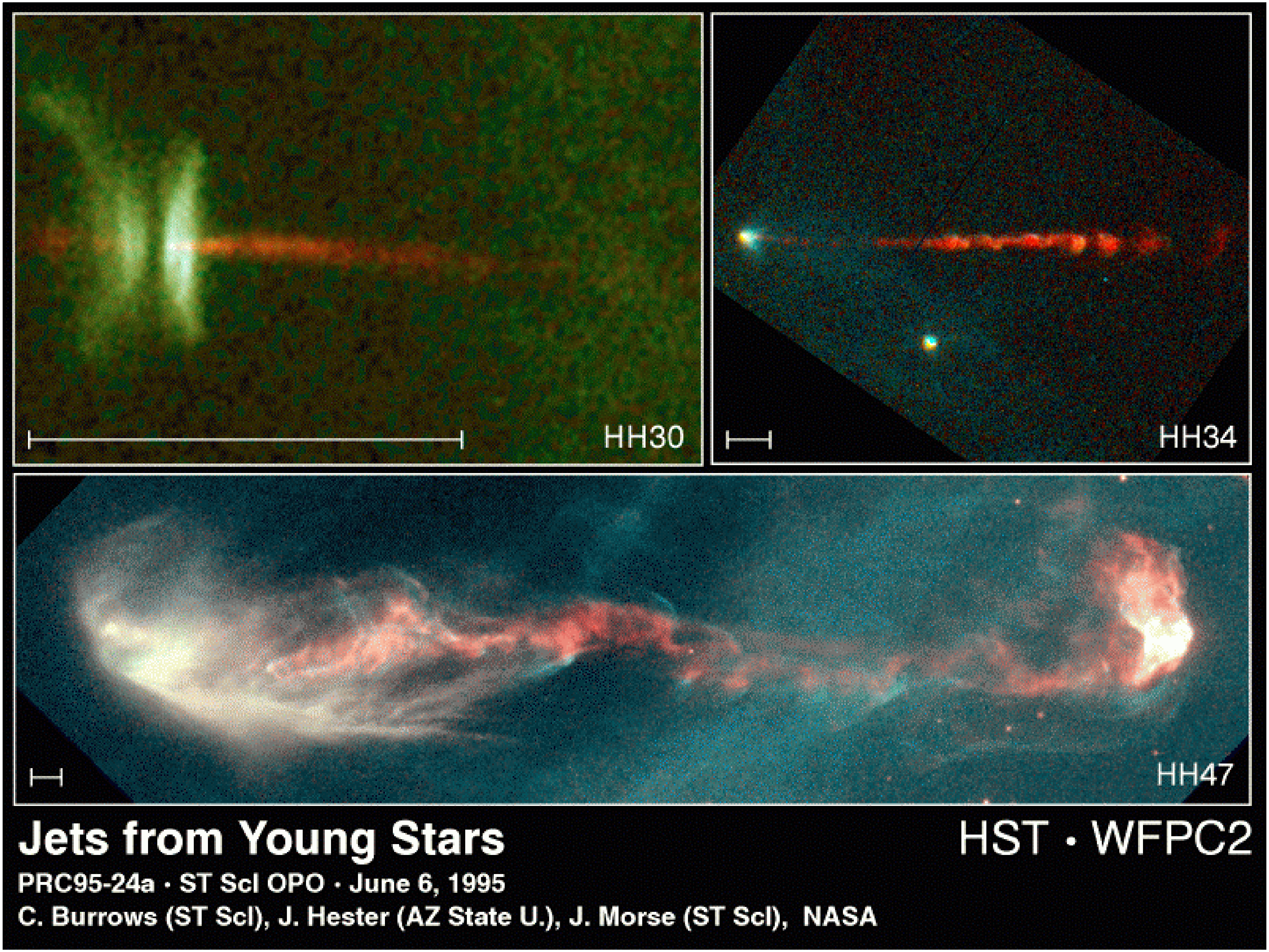
- *"Thermal Broadening"* of H I Line Profiles *can hide* much of the true *velocity structure*
- SCF v.1.0 good at picking out shock-like structure in H I maps (also gives low correlation tail)



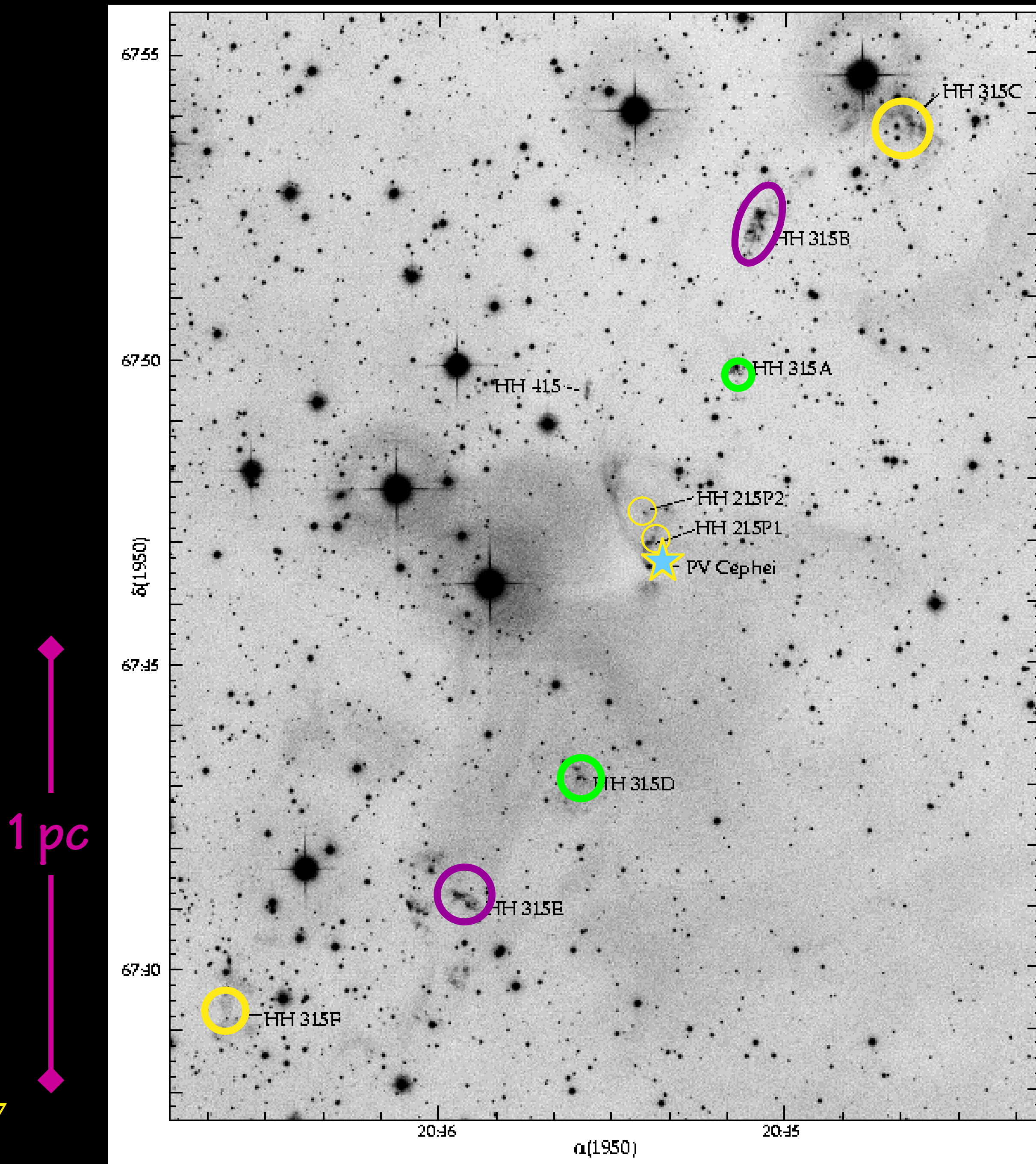
See Ballesteros-Paredes, Vazquez-Semadeni & Goodman 2001.

How is the MHD turbulence driven in the dense ISM?

pc-scale outflows?

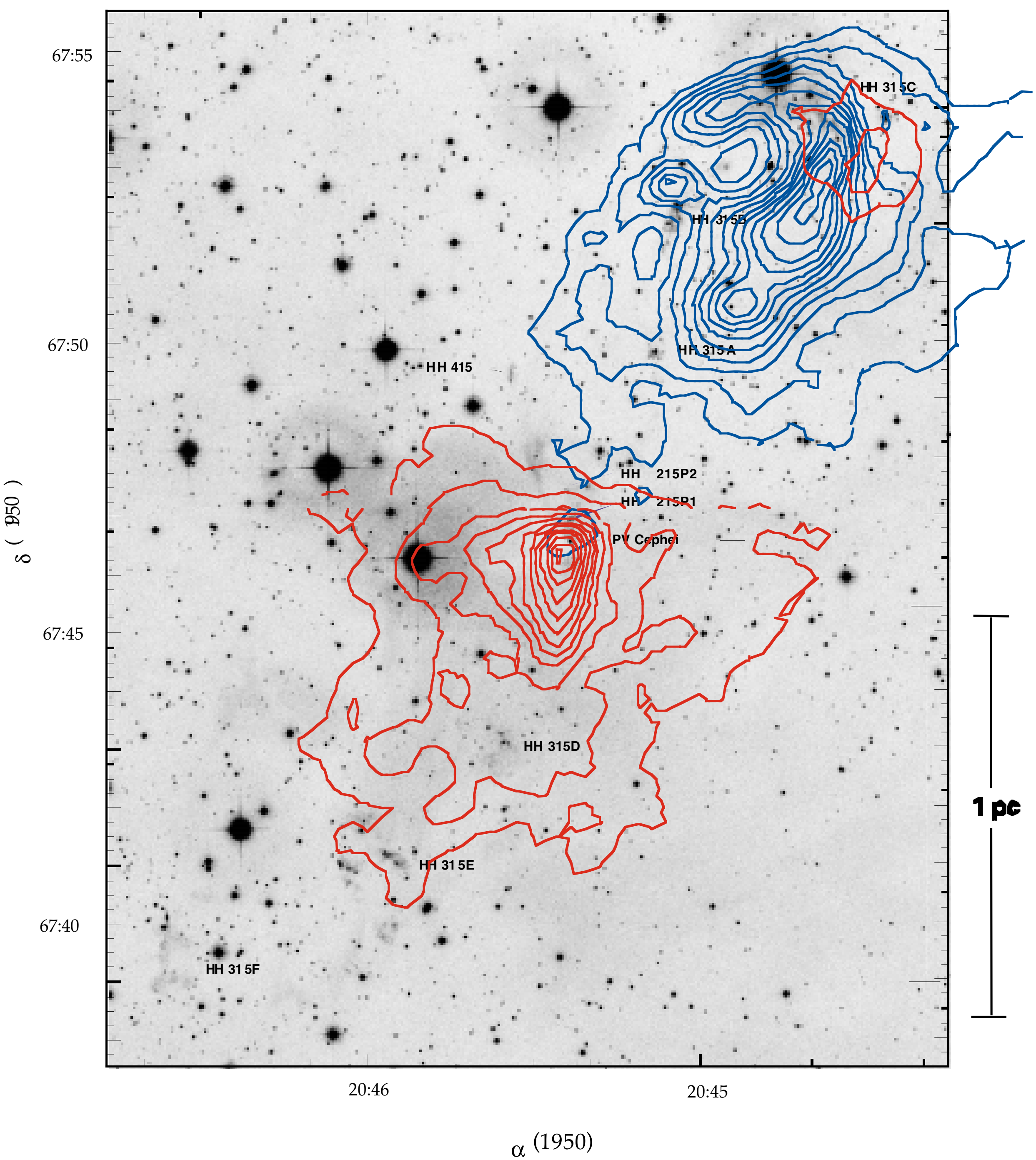

HH30
HH34
HH47
Jets from Young Stars
HST • WFPC2
PRC95-24a • ST ScI OPO • June 6, 1995
C. Burrows (ST ScI), J. Hester (AZ State U.), J. Morse (ST ScI), NASA

"Giant" Herbig-Haro Flows: PV Ceph



Reipurth, Bally & Devine 1997

Giant HH Flow in PV Ceph



^{12}CO (2-1) OTF
Map from ***NRAO 12-m***

Red: 3.0 to 6.9 km s^{-1}
Blue: -3.5 to 0.4 km s^{-1}

Arce & Goodman 2001

Driving Turbulence with Outflows

Studies in Héctor Arce's Ph.D. Thesis (Harvard, 2001; see Arce & Goodman 2001 a,b,c,d) show:

- HH 300 outflow has ~enough power (~0.5 L_{sun} at a 1-pc scale) to drive turbulence in its region of Taurus (using estimates based on *Gammie & Ostriker 1996*)
- Many outflows show clear evidence for "episodicity" and this may effect coupling of outflow energy to cloud
- Episodicity may also explain steep mass-velocity relations, and odd-looking p-v diagrams
- Outflow sources move through the ISM (e.g. PV-Ceph)