Numerical Simulations of the ISM: What Good are They?

Alyssa A. Goodman

Harvard-Smithsonian Center for Astrophysics

Principal Collaborators

Héctor Arce, CfA

Javier Ballesteros-Paredes, AMNH

Sungeun Kim, CfA

Paolo Padoan, CfA

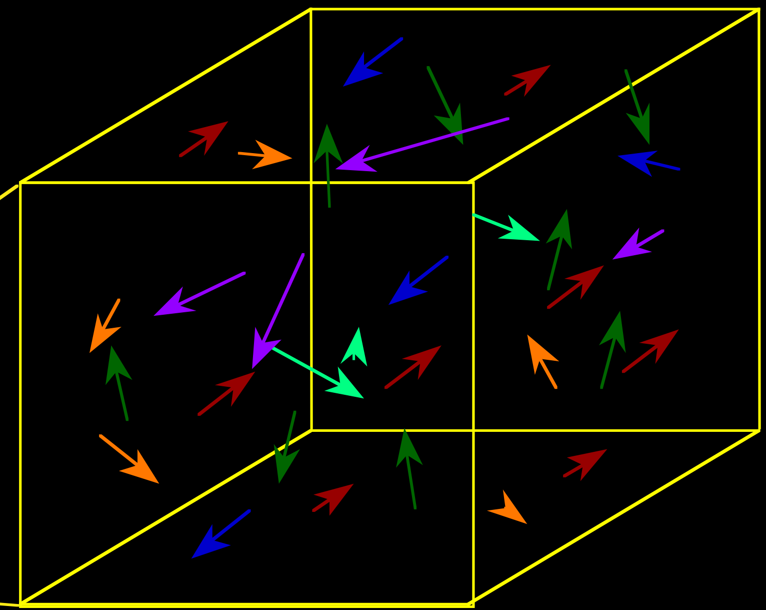
Erik Rosolowsky, UC Berkeley

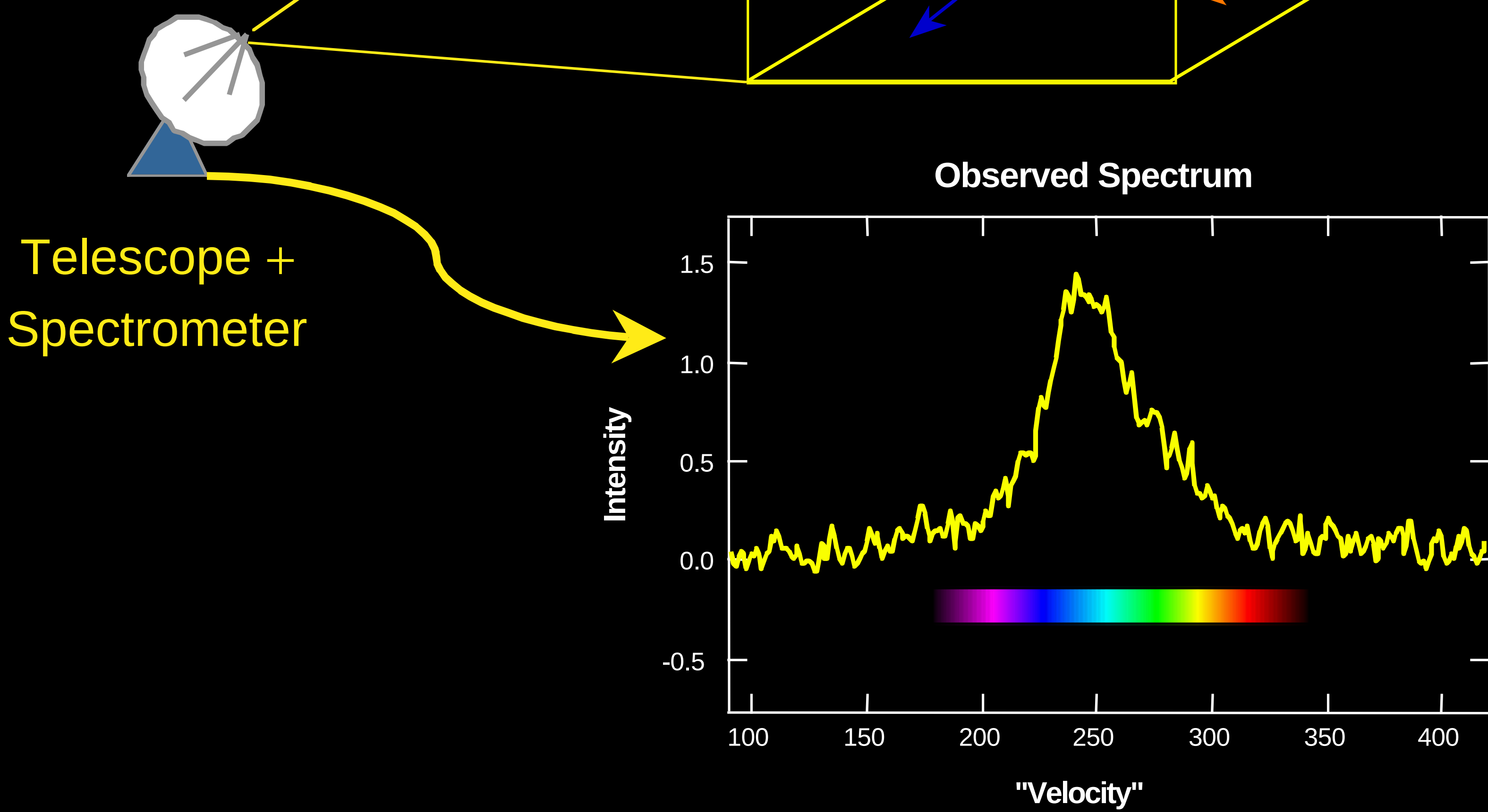
Enrique Vazquez-Semadeni, UNAM

Jonathan Williams, U. Florida

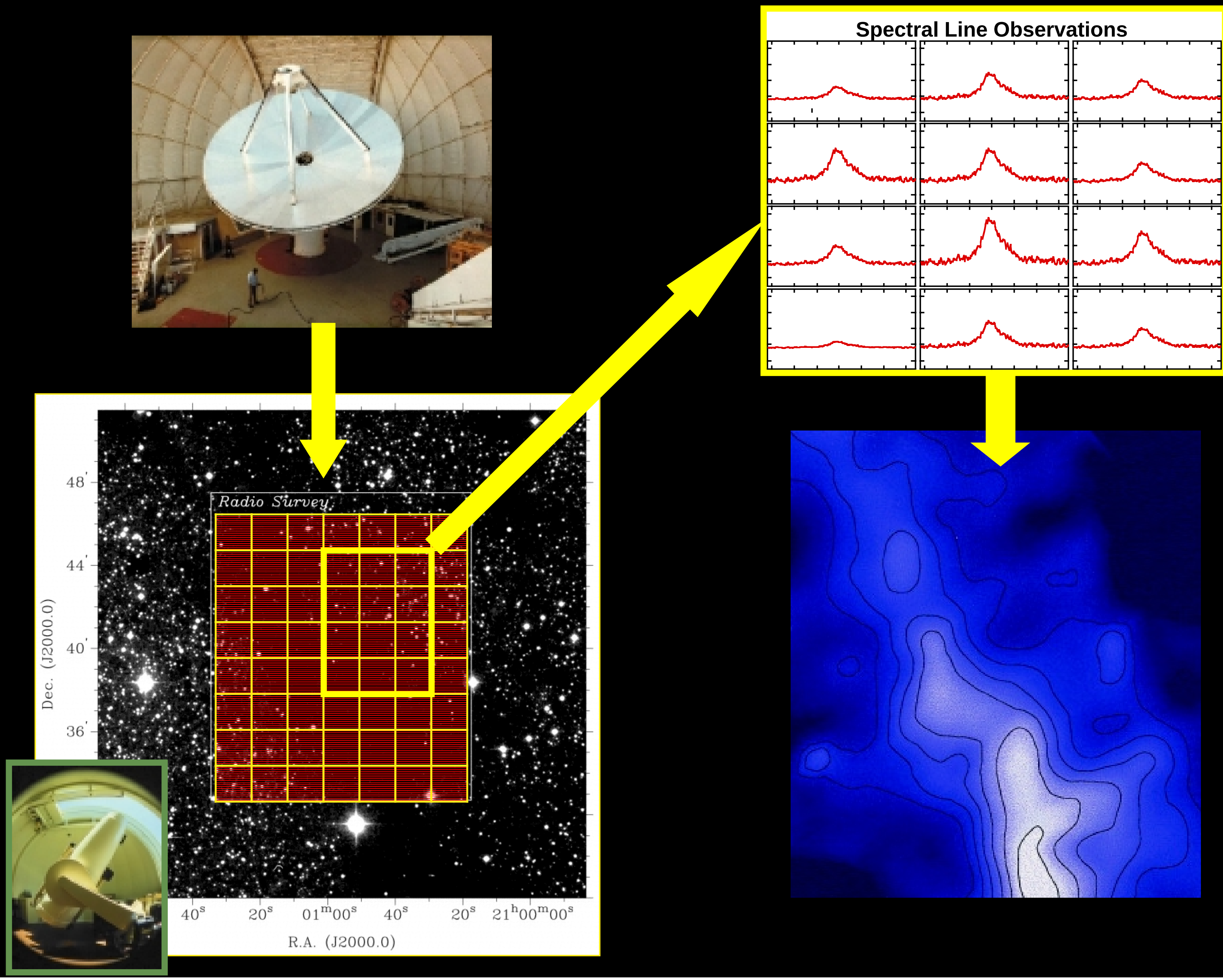
David Wilner, CfA

Spectroscopy →Velocity Information



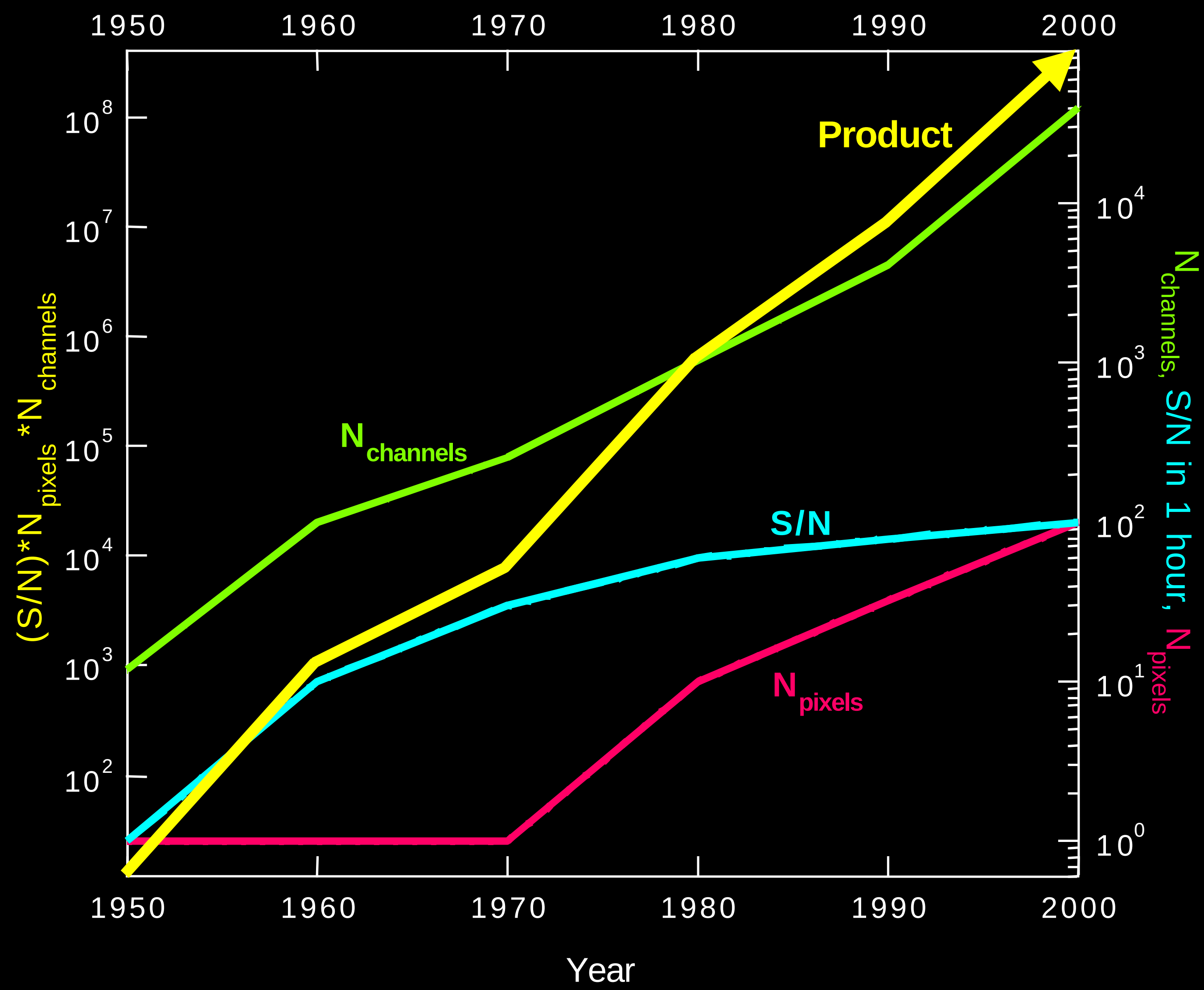


Radio Spectral-line Observations of Interstellar Clouds

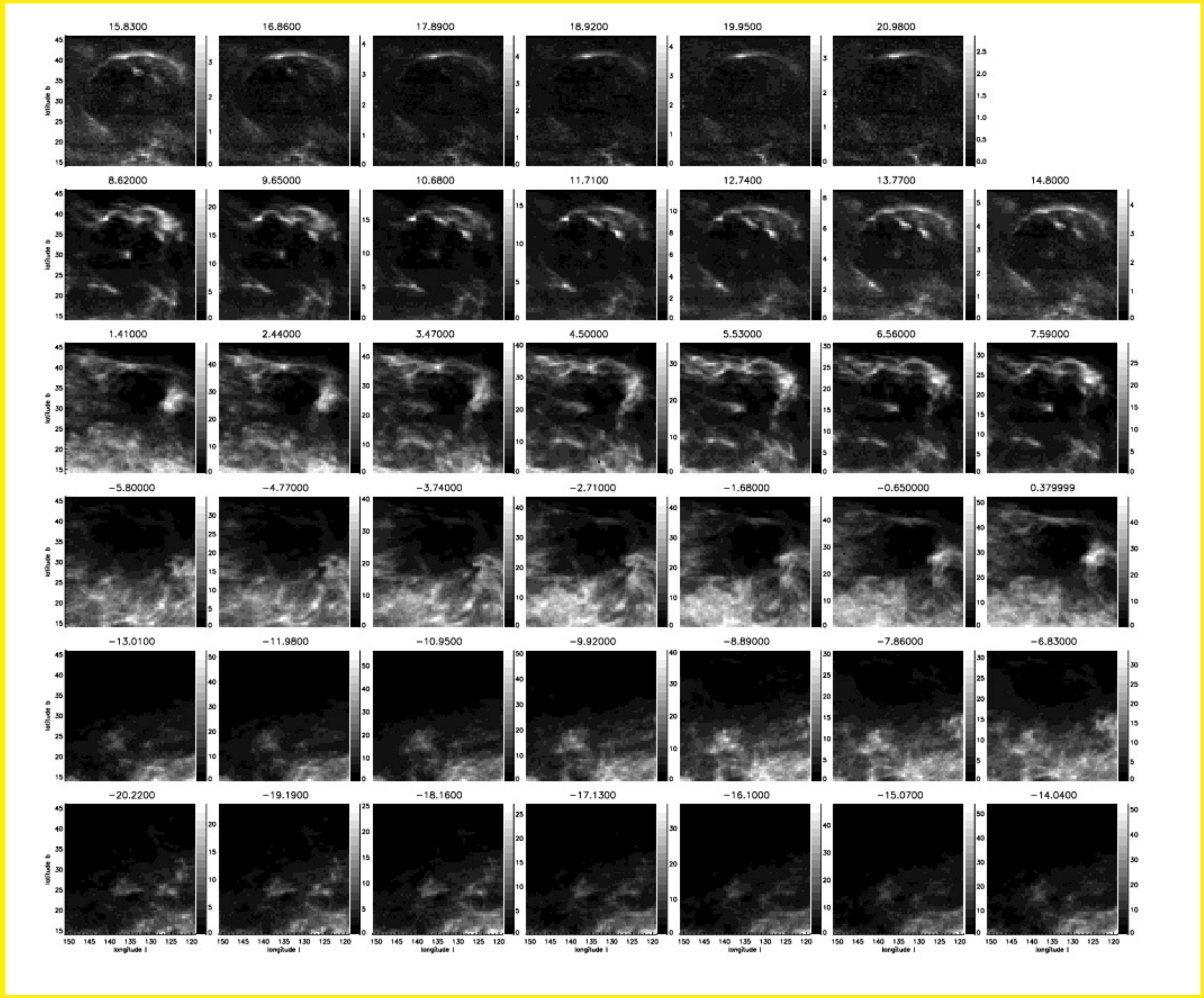


The Superstore:

Learning More from "Too Much Data"



A Free Sample



Data: Hartmann & Burton 1999; Figure: Ballesteros-Paredes, Vazquez-Semadeni & Goodman 2001

The "Good" Old Days

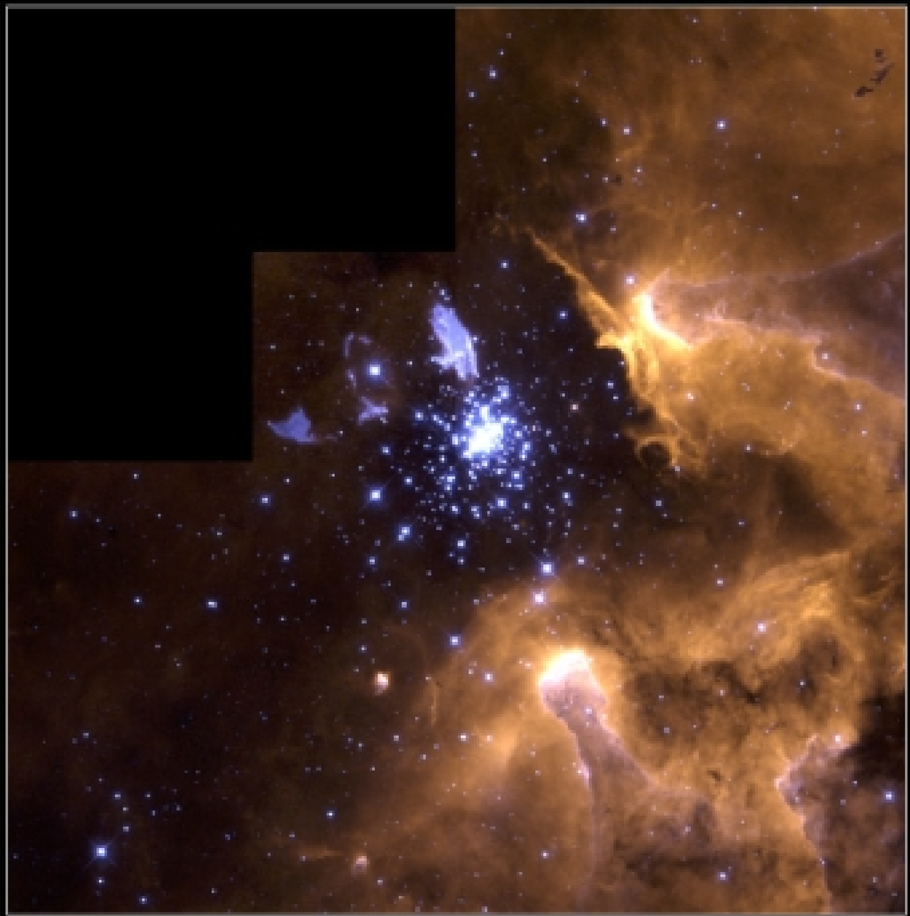
- *Low Observational Resolution*
- ⇒Models of spherical, Smooth, Long-lasting "Cloud" Structures

And more "*structure*" came from fragmentation

The New Age

High(er) Observational Resolution (at many λ's)

⇒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

So, are numerical simulations physically illuminating in this New Age?

If so, in what way(s)?

How might simulations be improved (i.e. to better match observations)?

Numerical MHD: The State of the Art 25 Years Ago

- Two-dimensional "CEL" code
- 10's of hours of CPU time
- Only possible to run 1 case
- Grid size ~96 x 188 (~128^2)

- No magnetic fields
- No gravity
- Heating & cooling treated
- R-T and K-H Instabilities traced well

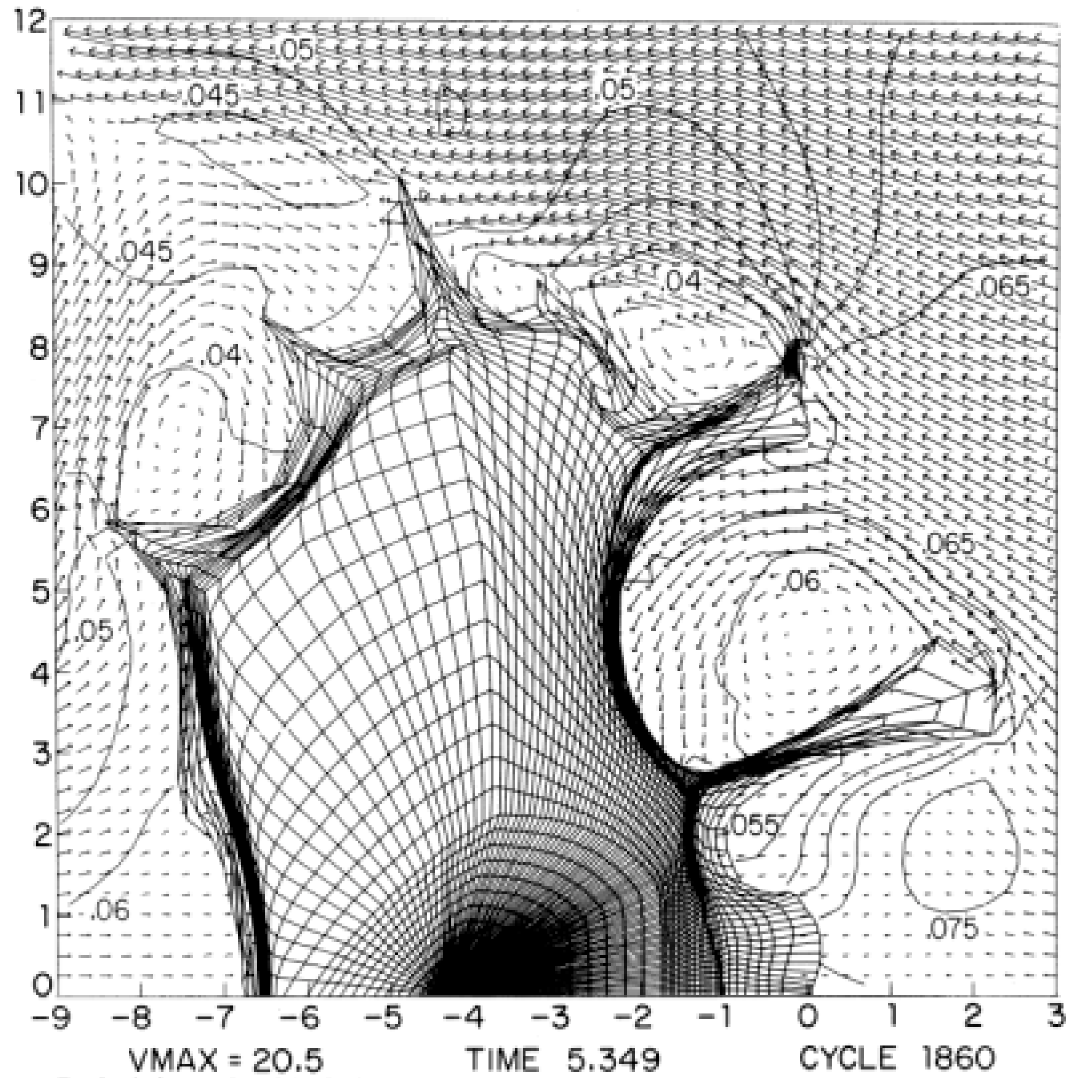


FIG. 5.—A close-up view of the cloud at $t = 5.35$. Velocity vectors are plotted at every Eulerian mesh point. The Rayleigh-Taylor instability of the front surface has caused previous Kelvin-Helmholtz modes to grow into long, dense tongues of compressed material. These contain a substantial fraction of the gas swept up by the cloud shock. Near the symmetry axis the instability has become nonlinear. It consists principally of two modes, one half the wavelength of the other. The clump of compressed gas centered on the axis contains 25 $M_{\odot}$ of material. Shell densities and their locations are as follows: 280 (0, −0.5), 110 (0.75, −0.2), 60 (2, −1.2), 70 (3.75, 1.75), 50 (4.5, −2.35), 70 (7, −0.25), 50 (7.75, −0.25), 45 (7.5, −2), 20 (6.25, −6.25), 30 (2.5, −7.25), 55 (0, −6.6).

Star-formation "triggered" by a spiral-density wave shock. (Woodward 1976)

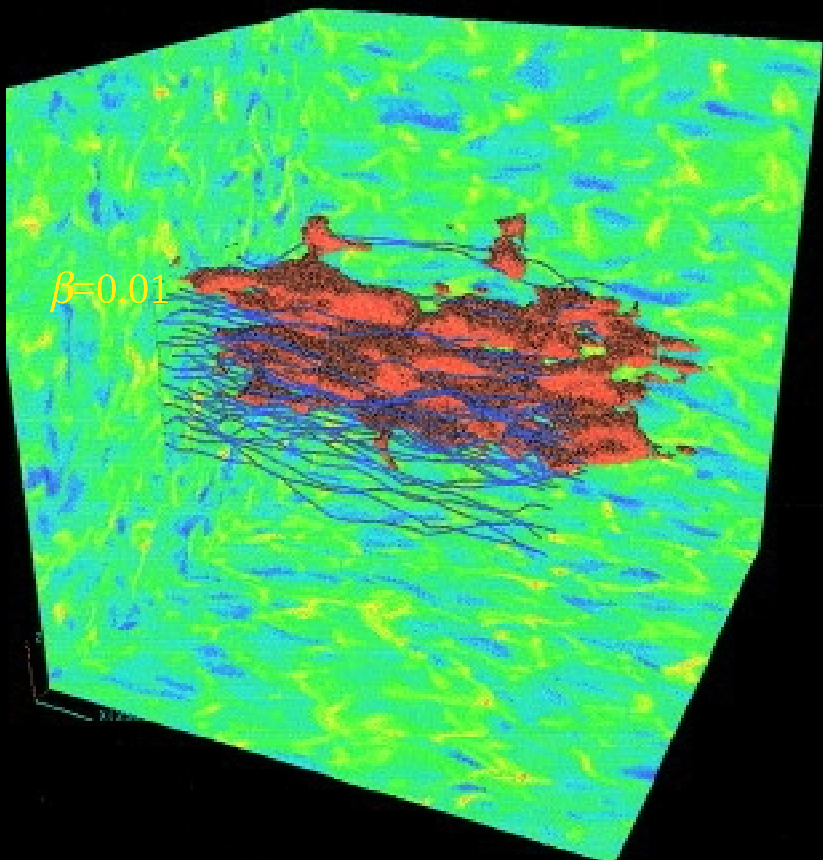
Woodward's Conclusions (1976)

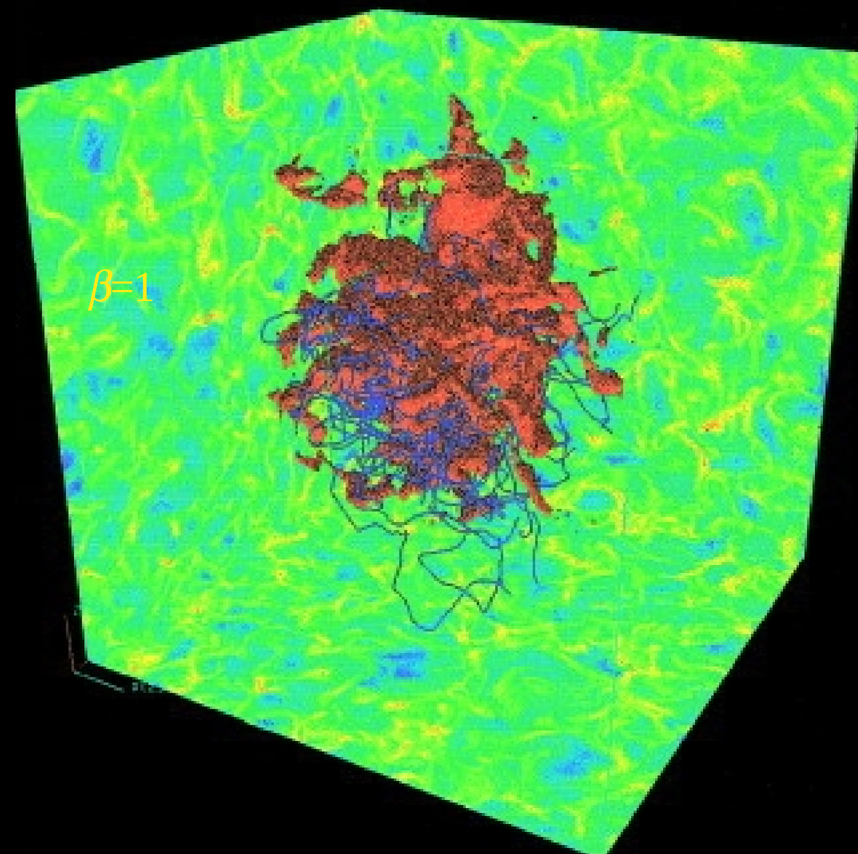
V. OBSERVATIONAL IMPLICATIONS

Although detailed comparisons of the computed example with specific objects will be reserved for a later paper, we will give a brief summary here of the general features of the cloud implosion mechanism which bear on observations of dense interstellar clouds. Those observations quite naturally tend to favor the more massive and more exotic objects, which would require the case computed here to be scaled up considerably in mass, by perhaps a factor 10 or 20. The features of the model most important for observations are as follows:

1. Stars are formed in small high-density regions within much more massive and extended clouds.
2. The extended region of dense cloud gas produced, which is visible in CO emission, has a general slab geometry, so that a straightforward mass estimate can easily yield far too large a number.
3. Young stars and H II regions appear to be located on the outsides of dense gas clouds.
4. The newly formed stars and the associated dense gas have systematic noncircular velocities which depend upon their location in the Galaxy.
5. Dense gas which originally surrounds the newly formed stars but which cannot collapse gravitationally is eventually swept away by external forces.
6. Ordered motions not associated with gravitational collapse are set up in the dense cloud material which result in supersonic broadening of CO lines.

Y2K MHD





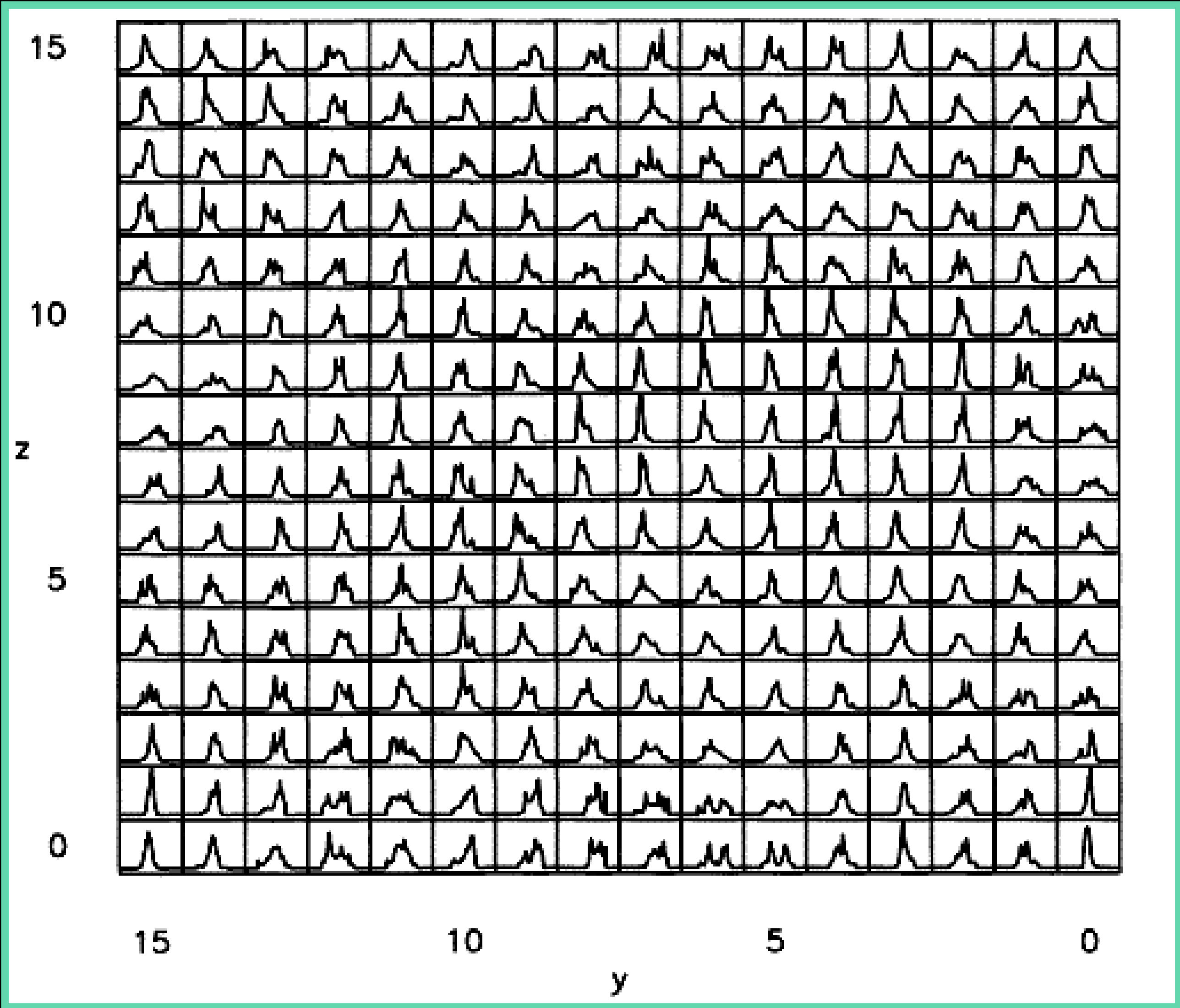
Stone, Gammie & Ostriker 1999

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

- ***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*

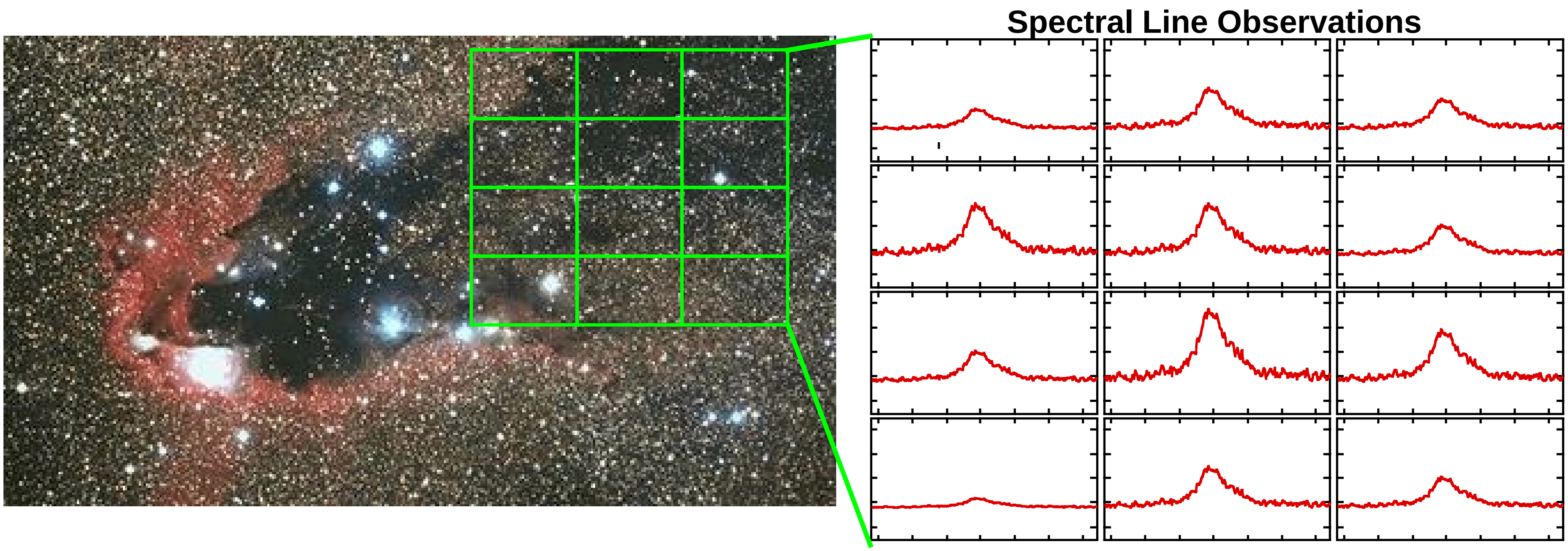
But, recall what we actually observe

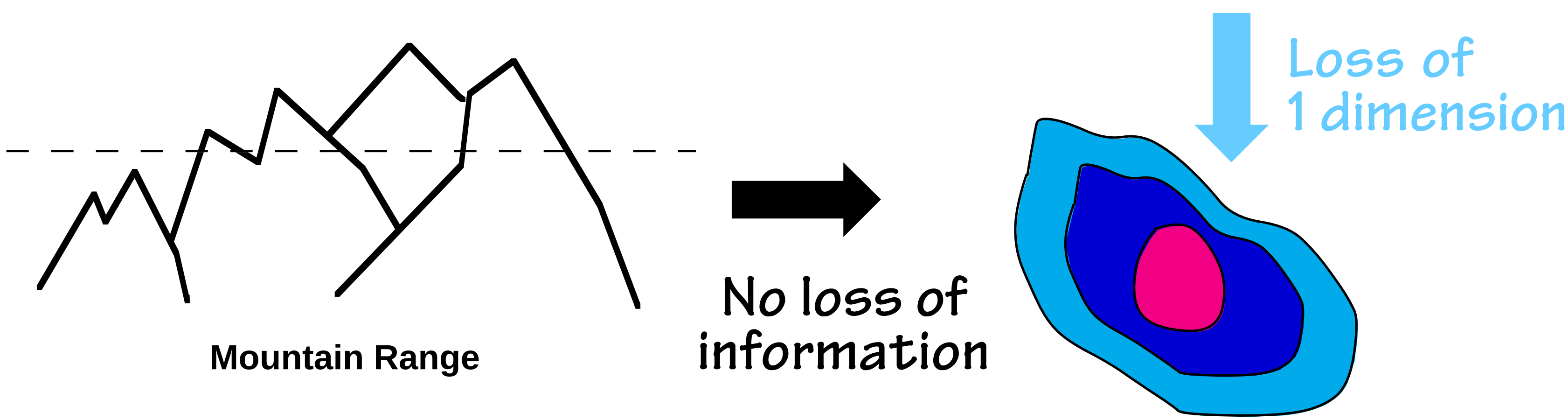
Intensity(position, position,velocity)



Falgarone et al. 1994

Velocity is the Observer’s "Fourth" Dimension

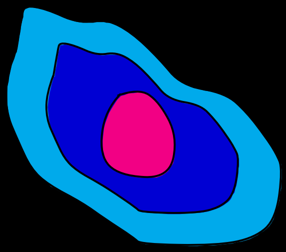




Statistical Tools

- 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*

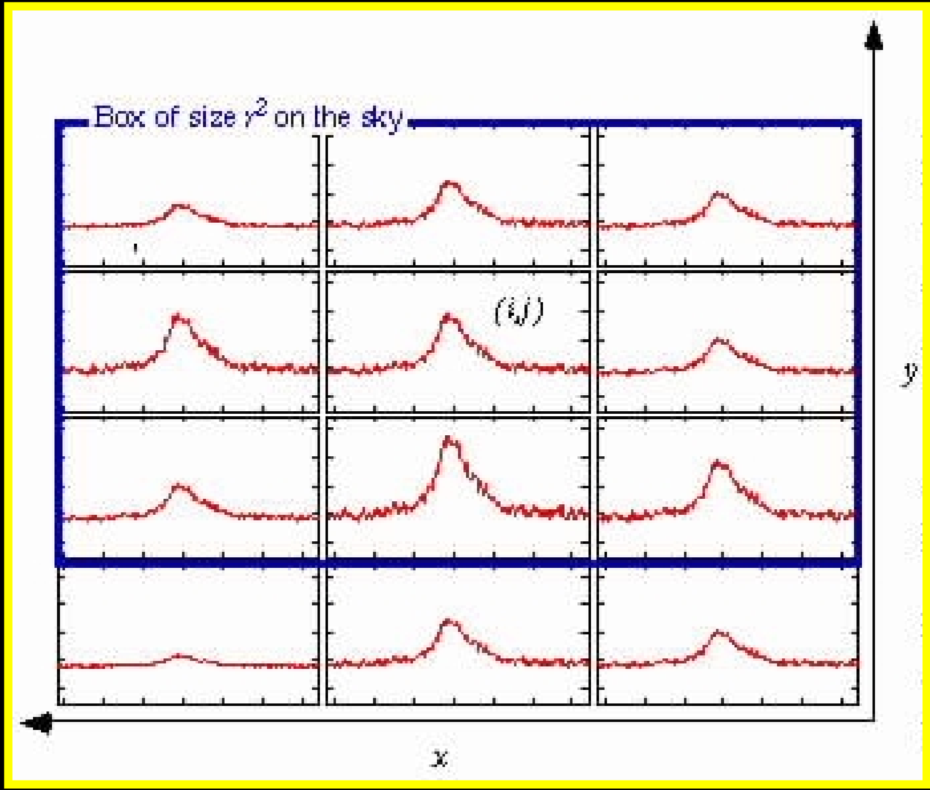
The Spectral Correlation Function

- v.1.0 Simply measures similarity of neighboring spectra *(Rosolowsky, Goodman, Wilner & Williams 1999)*
  - S/N equalized, observational/theoretical comparisons show discriminatory power

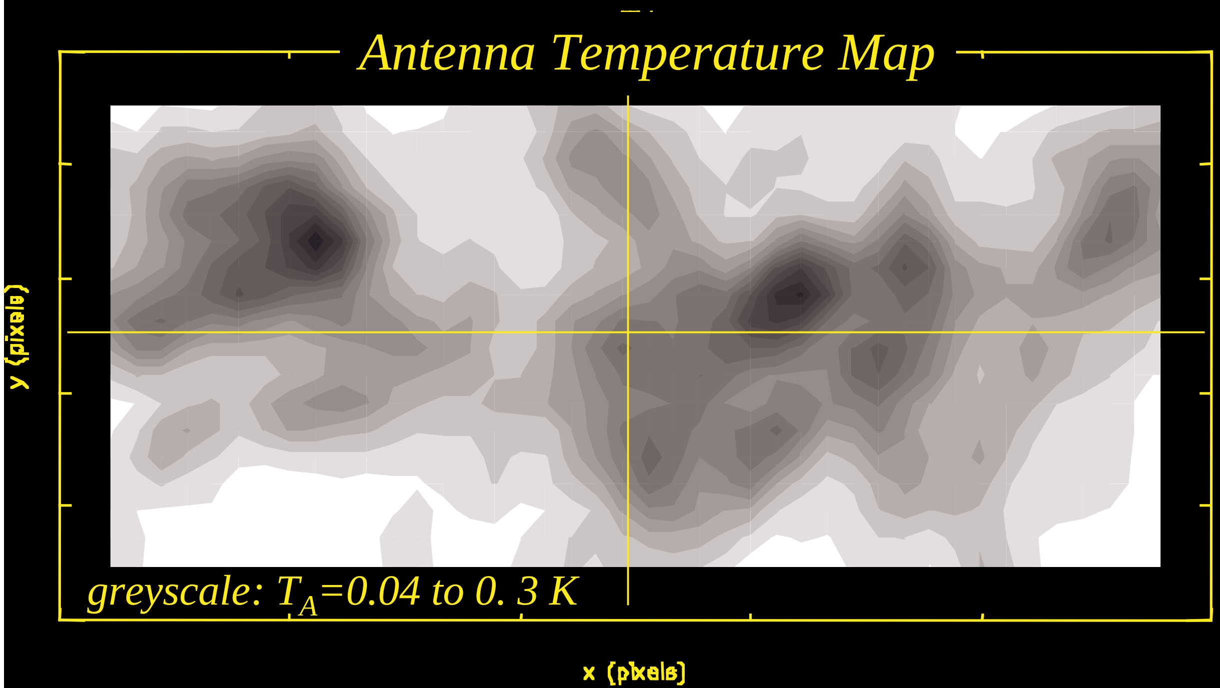
- After explaining v.1.0, I'll show:
  - v.2.0 Measures spectral similarity as a function of spatial scale
  - Applications

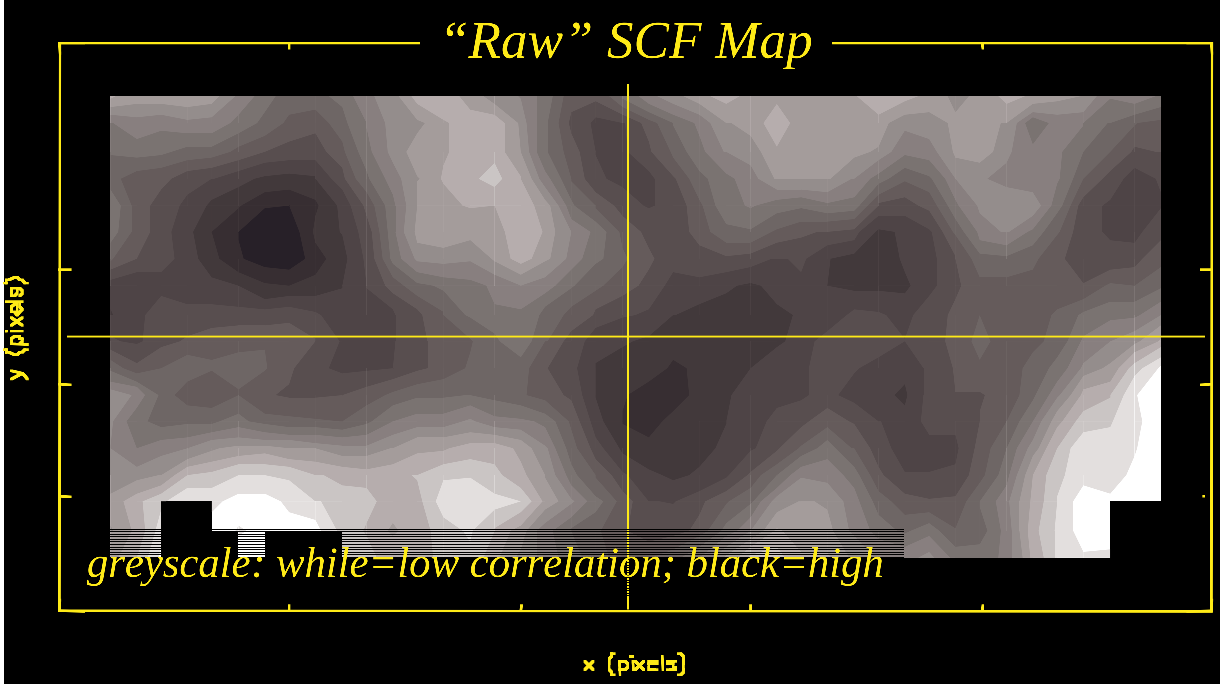
How SCF v.1.0 Works

- 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

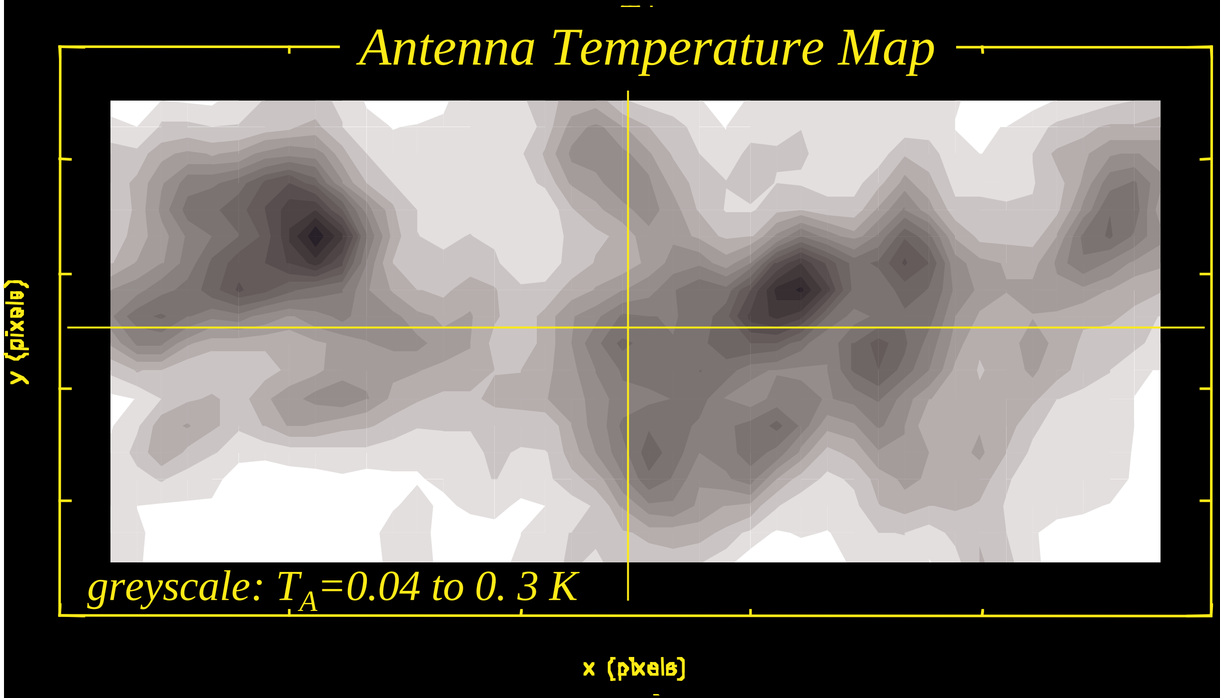


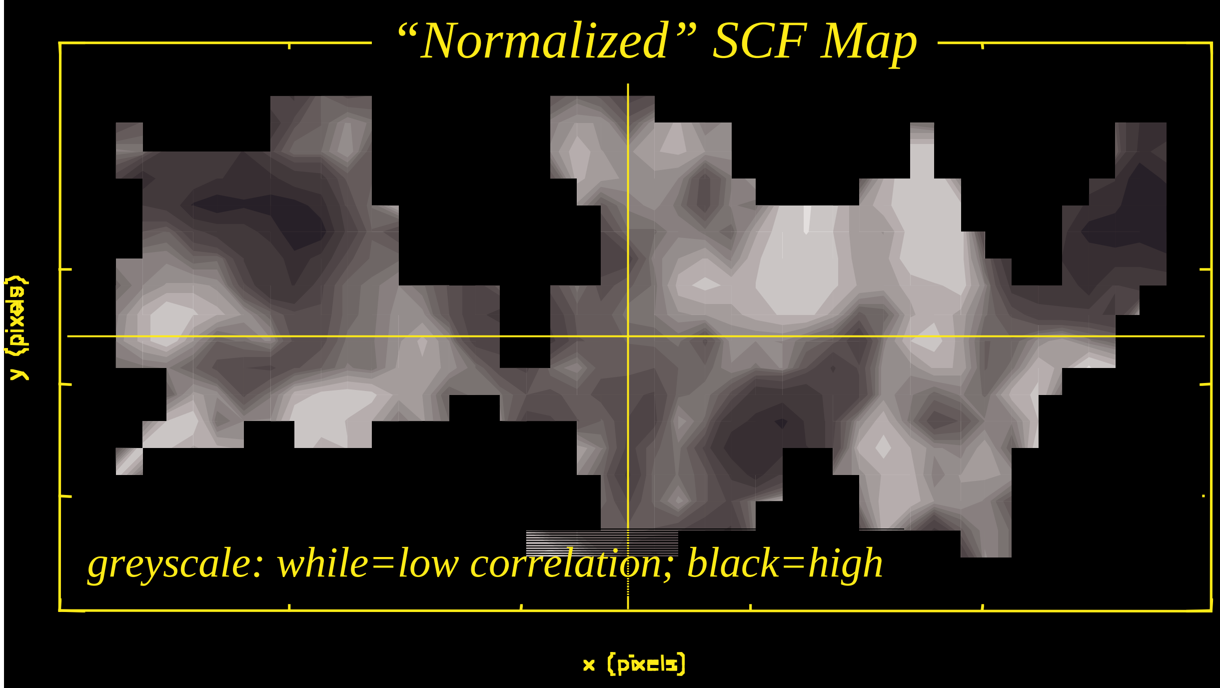


Application of the "Raw" SCF

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

Results: *Padoan, Rosolowsky & Goodman 2001*



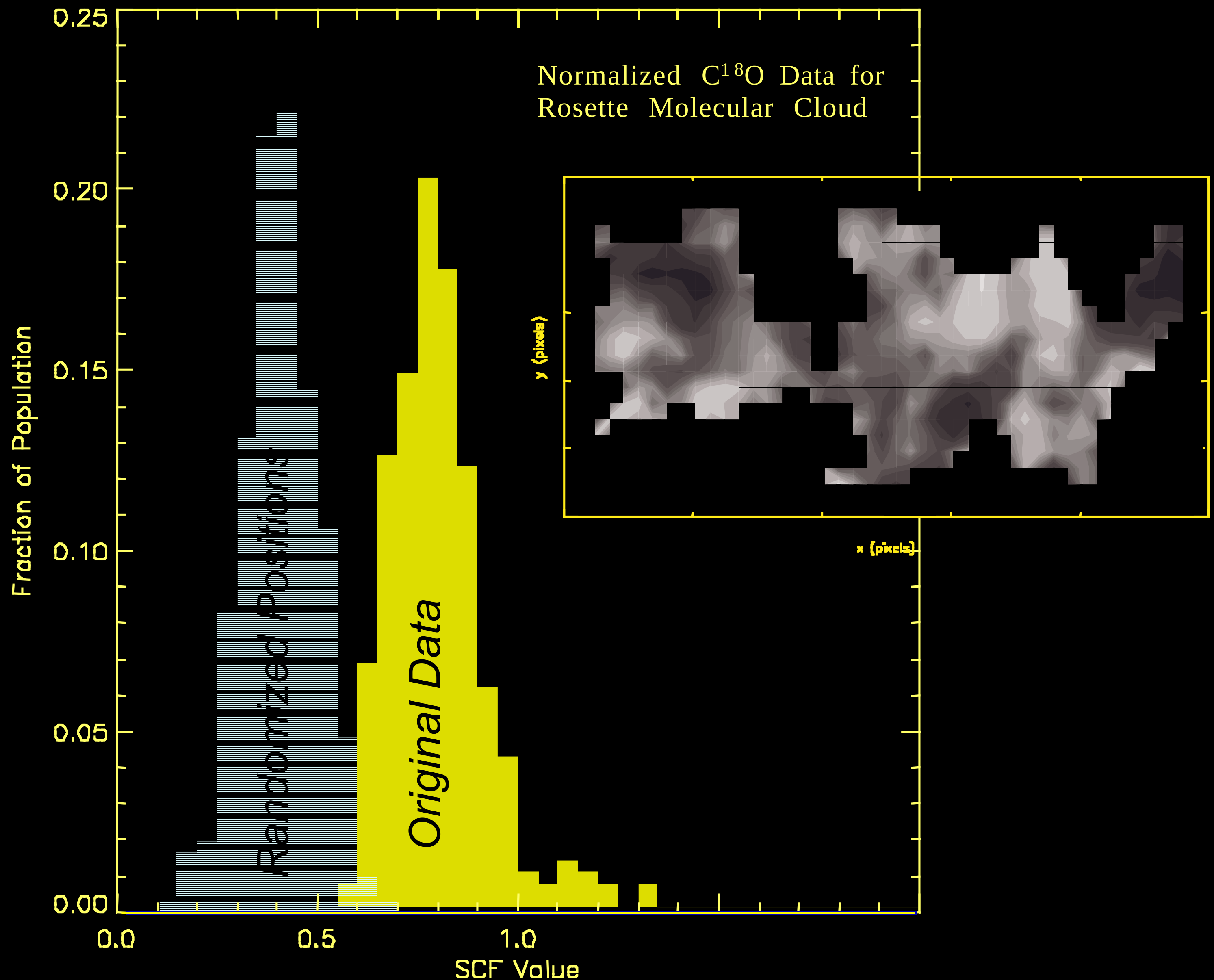


Application of the SCF

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

Results: *Padoan, Rosolowsky & Goodman 2001*.

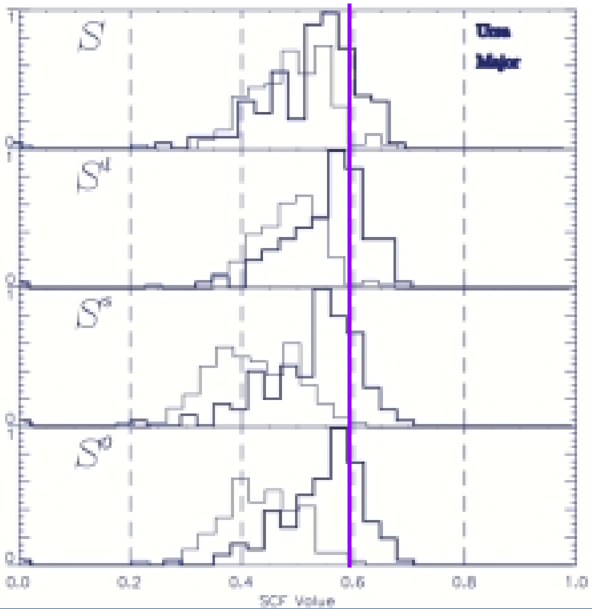
SCF Distributions



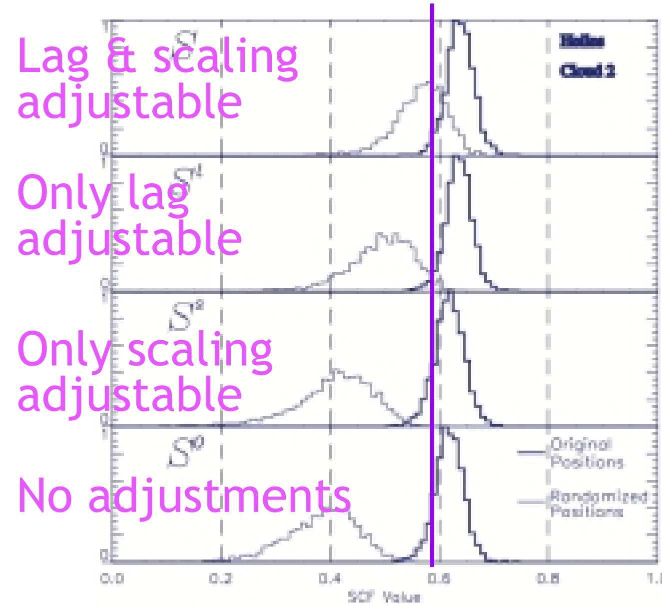
Insights from SCF v.1.0

Rosolowsky, Goodman, Williams & Wilner 1999

Unbound High-Latitude Cloud

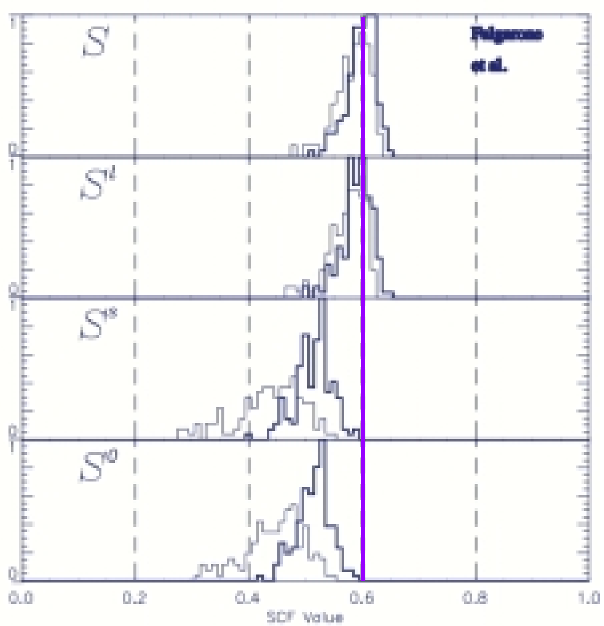


Self-Gravitating, Star-Forming Region

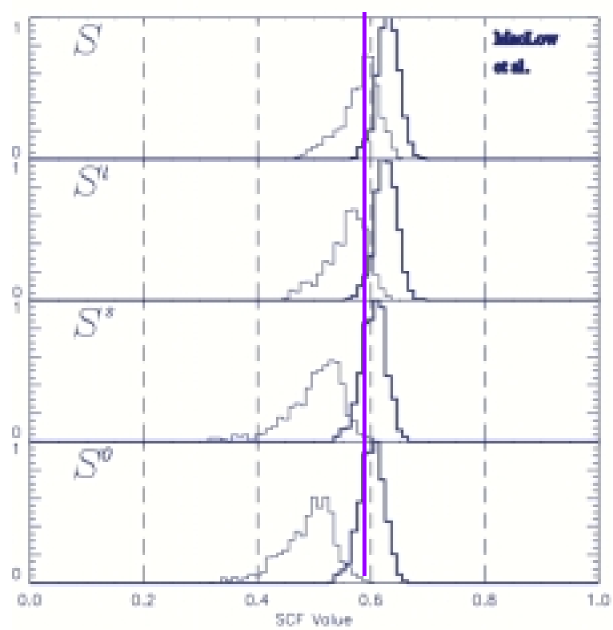


Observations

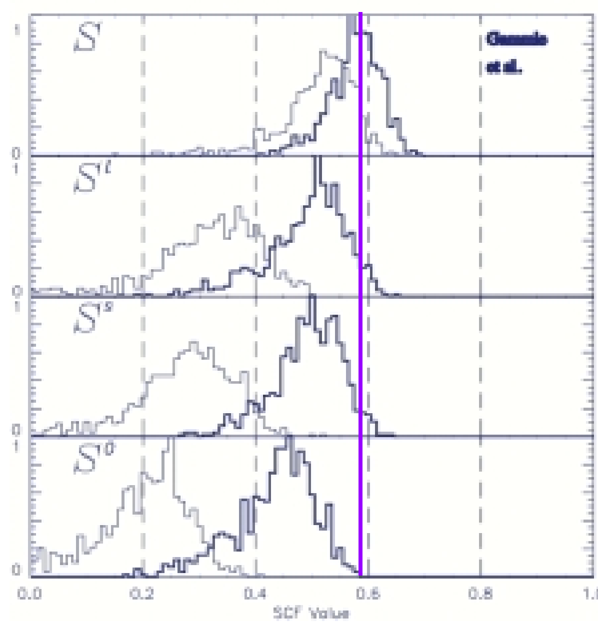
Simulations



No gravity, No B field

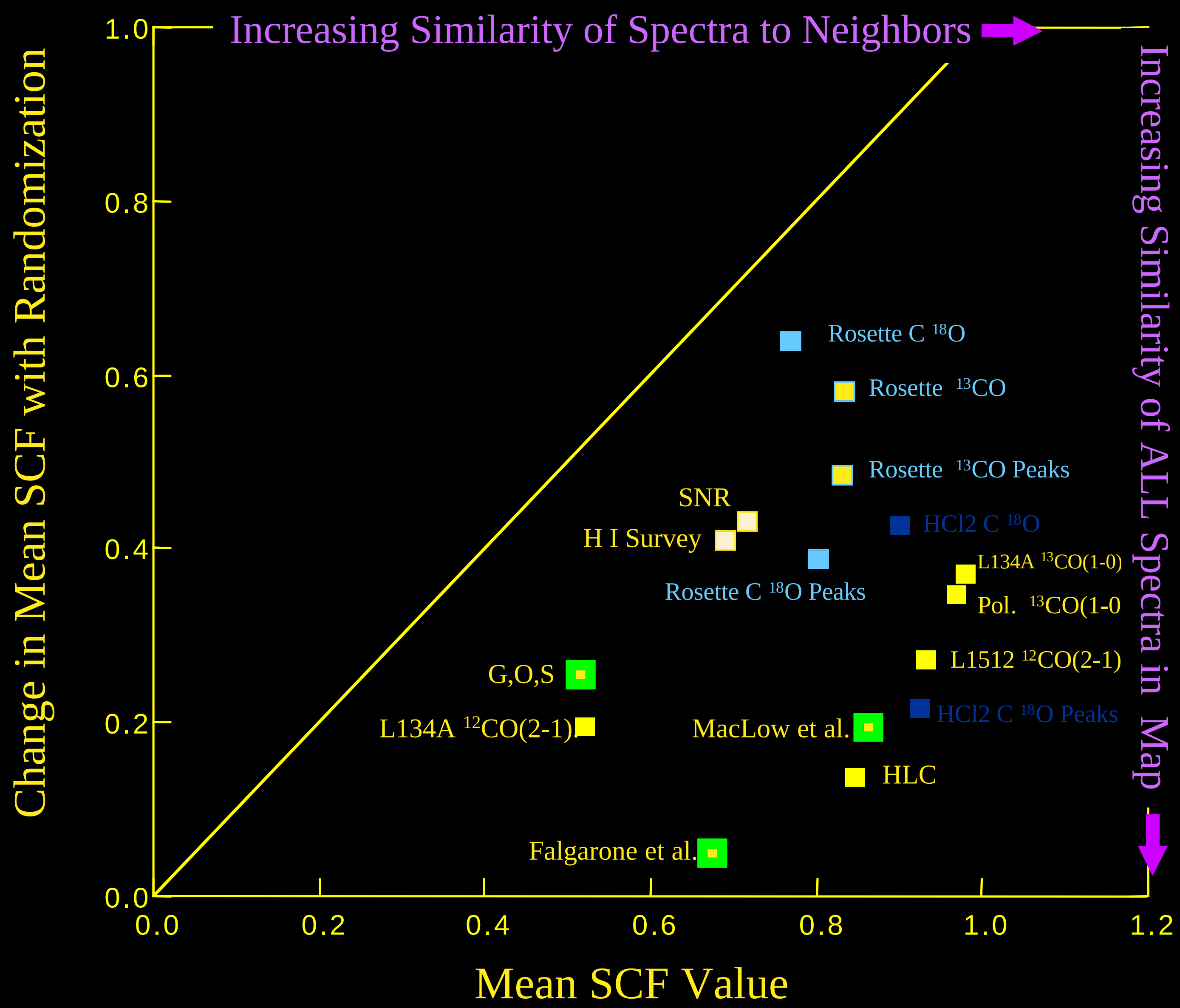


No gravity, Yes B field



Yes gravity, Yes B field

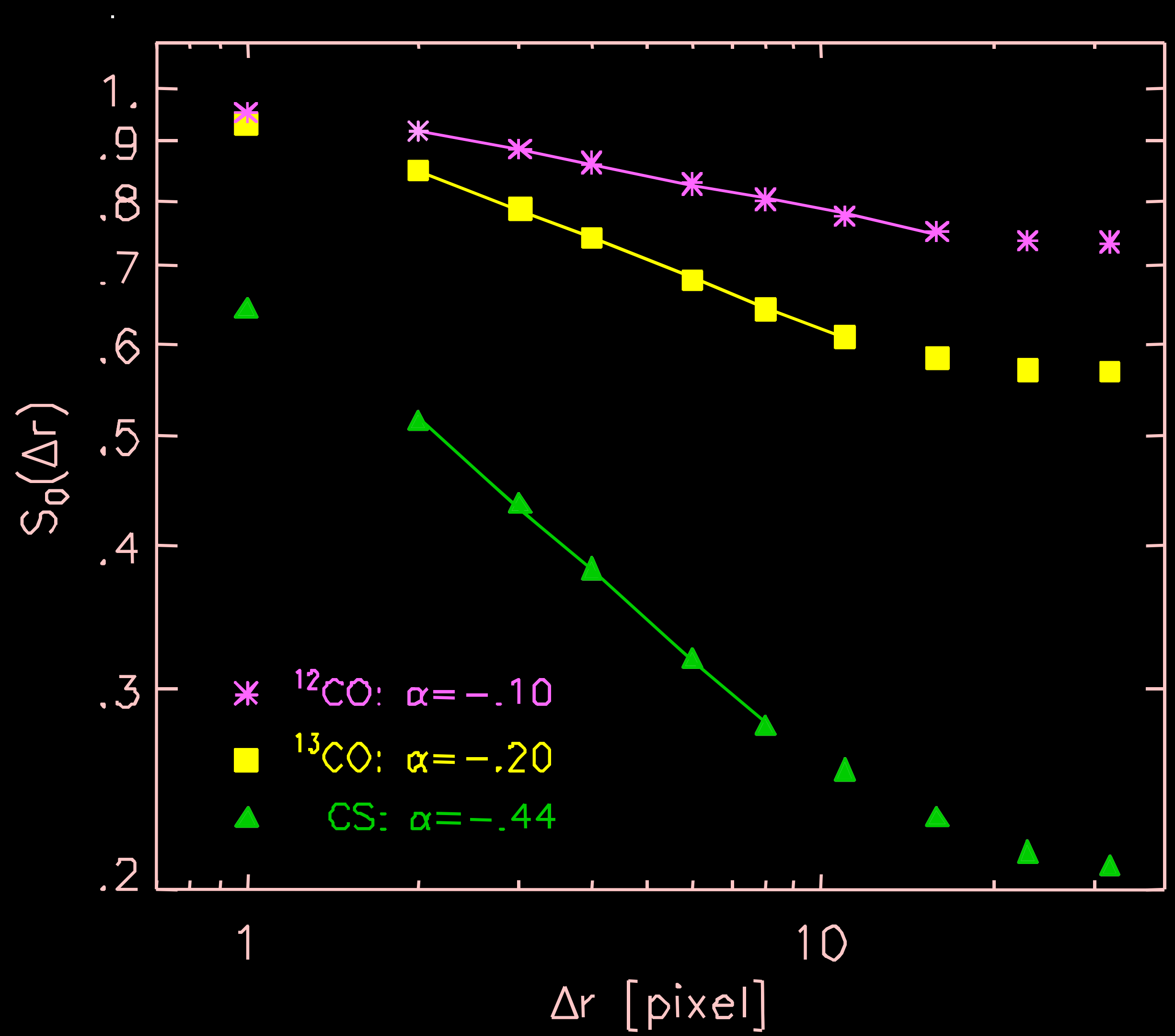
Which of these is not like the others?



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 & Stavely-Smith 2001)*
  - Understanding behavior of atomic ISM *(e.g. Ballesteros-Paredes, Vazquez-Semadeni & Goodman 2001)*

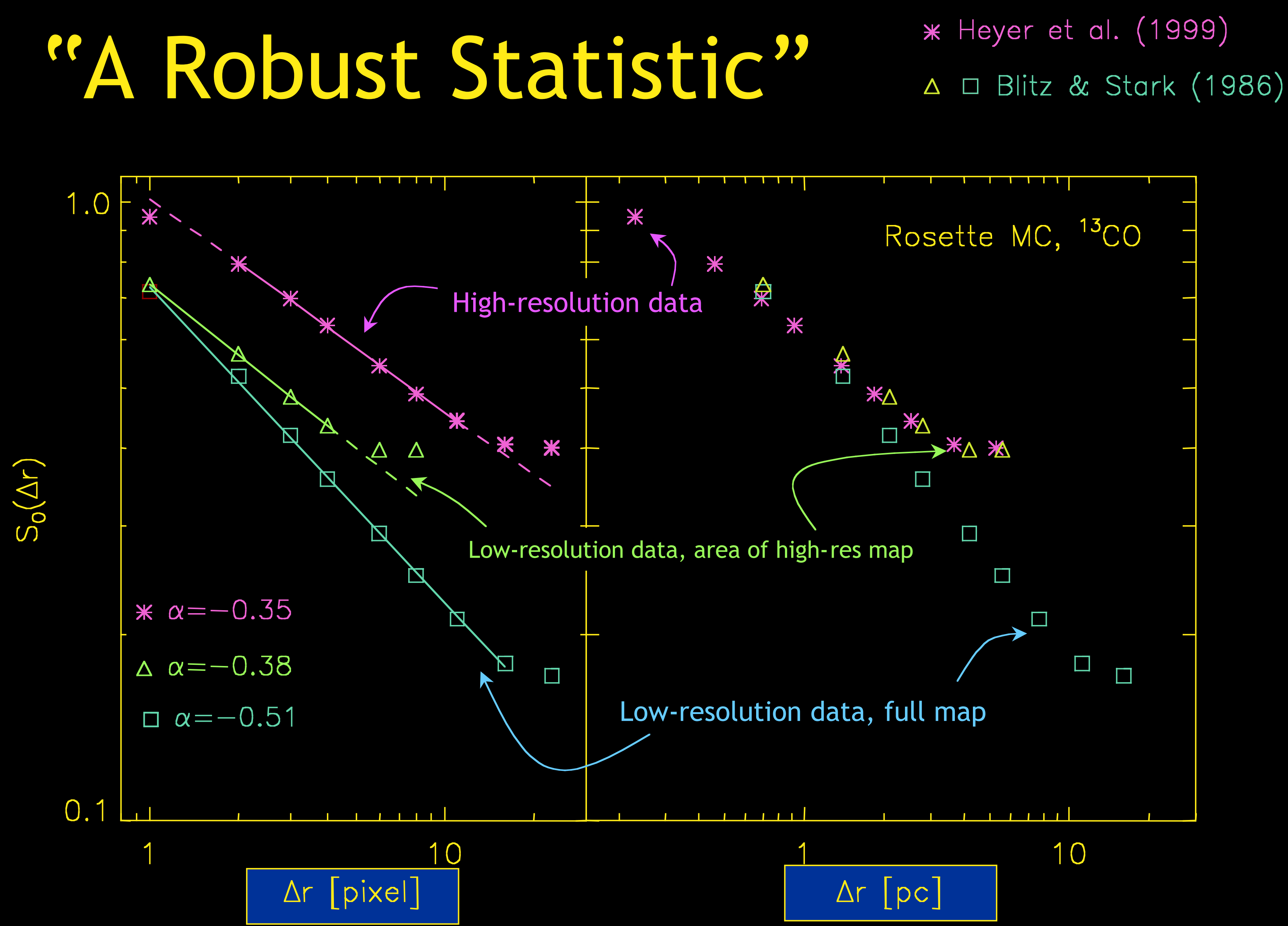
v.2.0: Scale-Dependence of the SCF



Example for "Simulated Data"

Padoan, Rosolowsky & Goodman 2001

"A Robust Statistic"

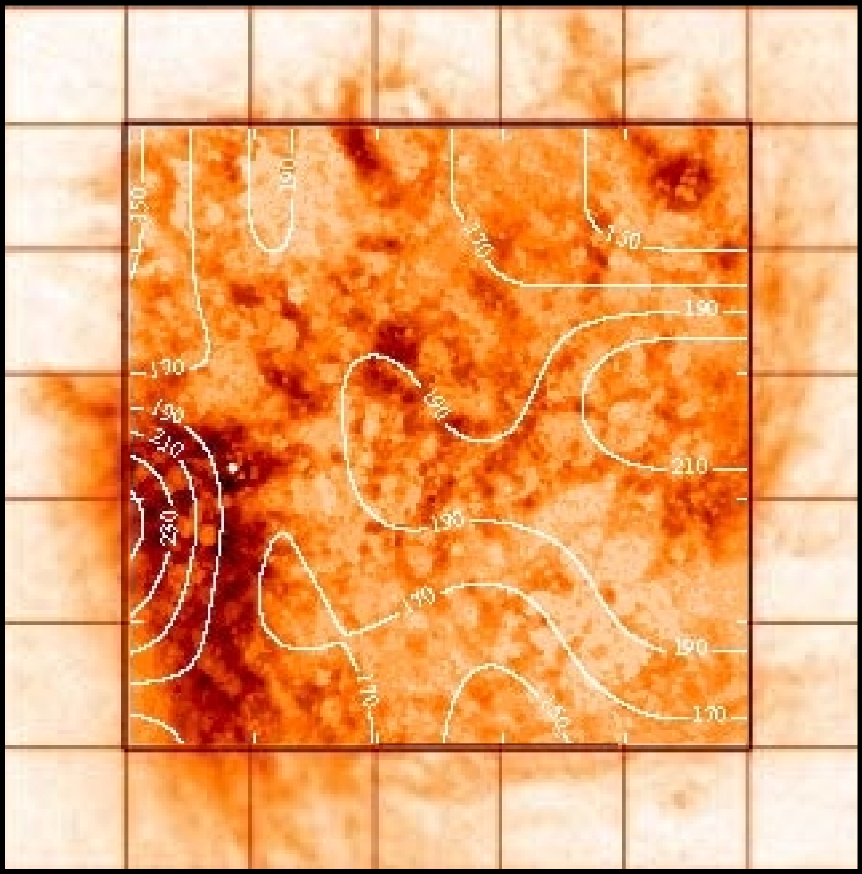


Padoan, Rosolowsky & Goodman 2001

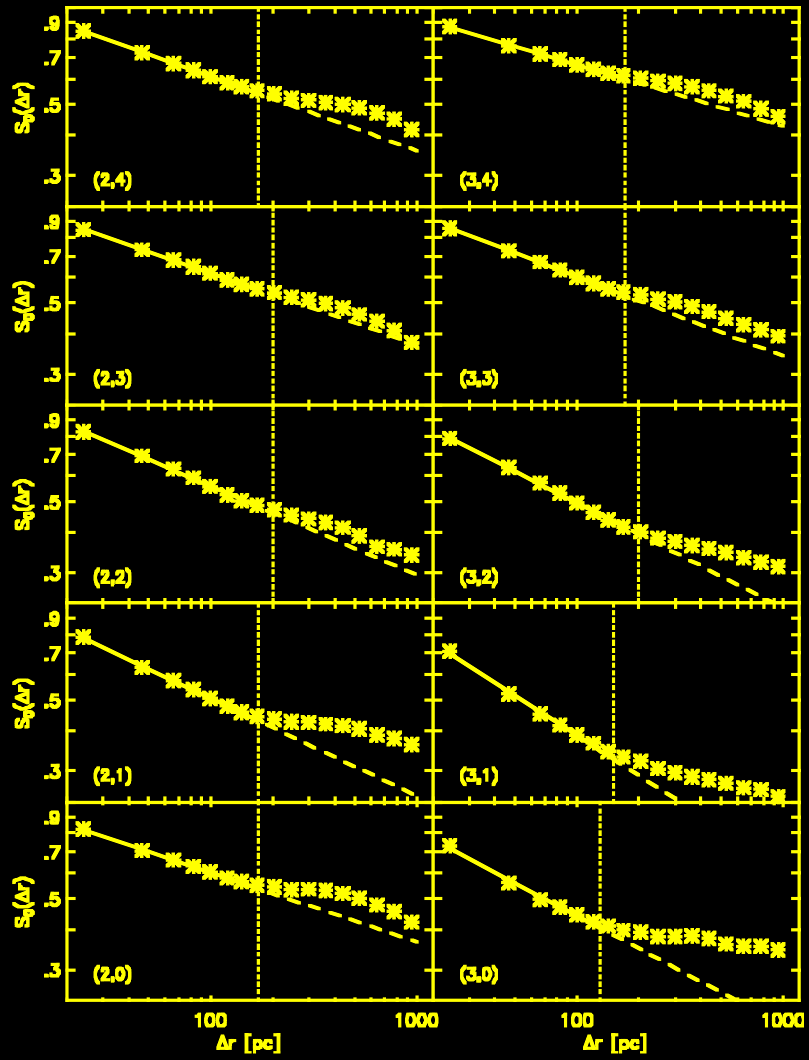
The Spectral Correlation Function

- 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 & Stavely-Smith 2001)*
  - Understanding behavior of atomic ISM *(e.g. Ballesteros-Paredes, Vazquez-Semadeni & Goodman 2001)*

Galactic Scale Heights from the SCF (v.2.0)

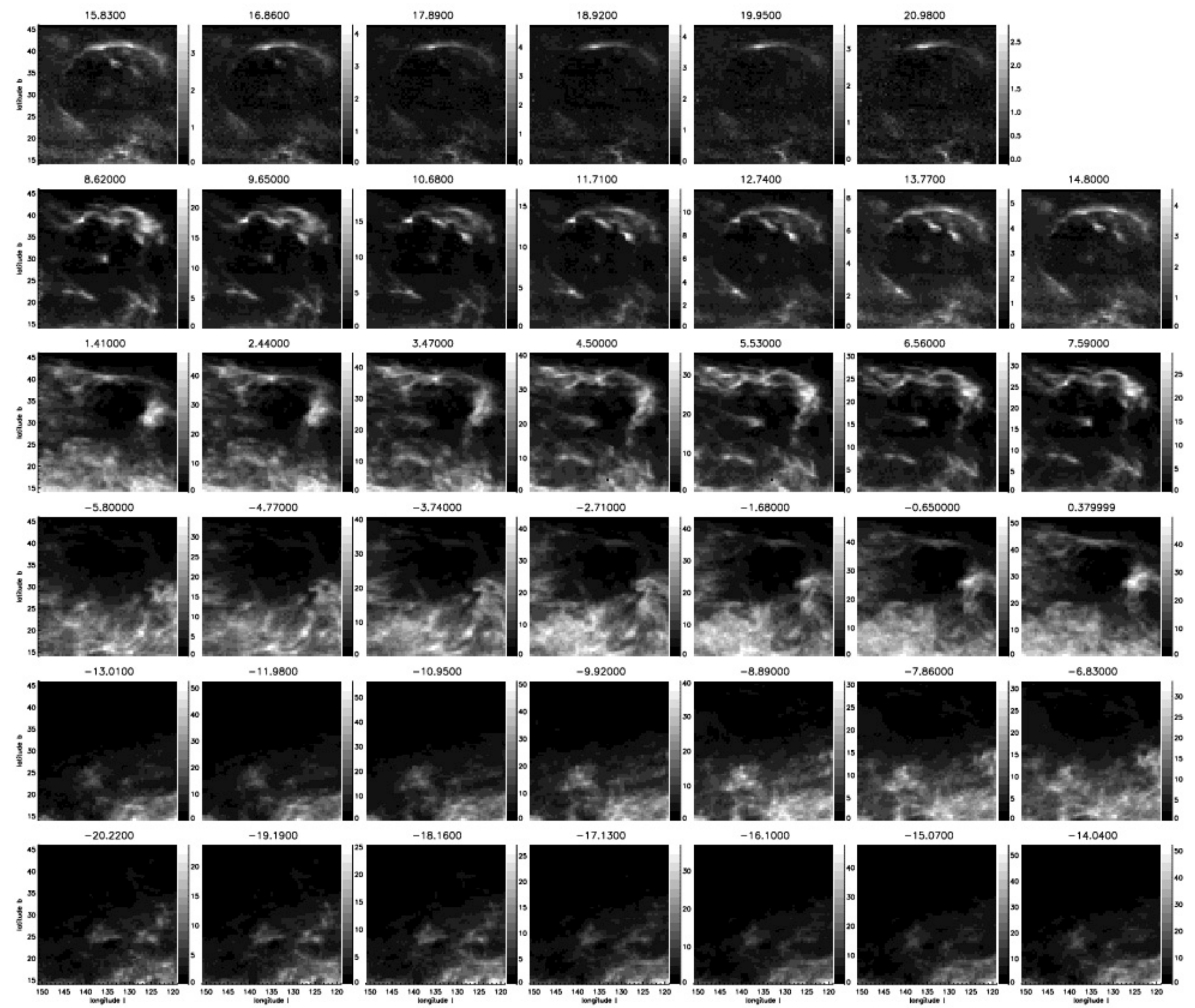


HI map of the LMC from ATCA & Parkes Multi-Beam, courtesy Stavely-Smith, Kim, et al.



Padoan, Kim, Goodman & Stavely-Smith 2001

The Behavior of the Atomic ISM

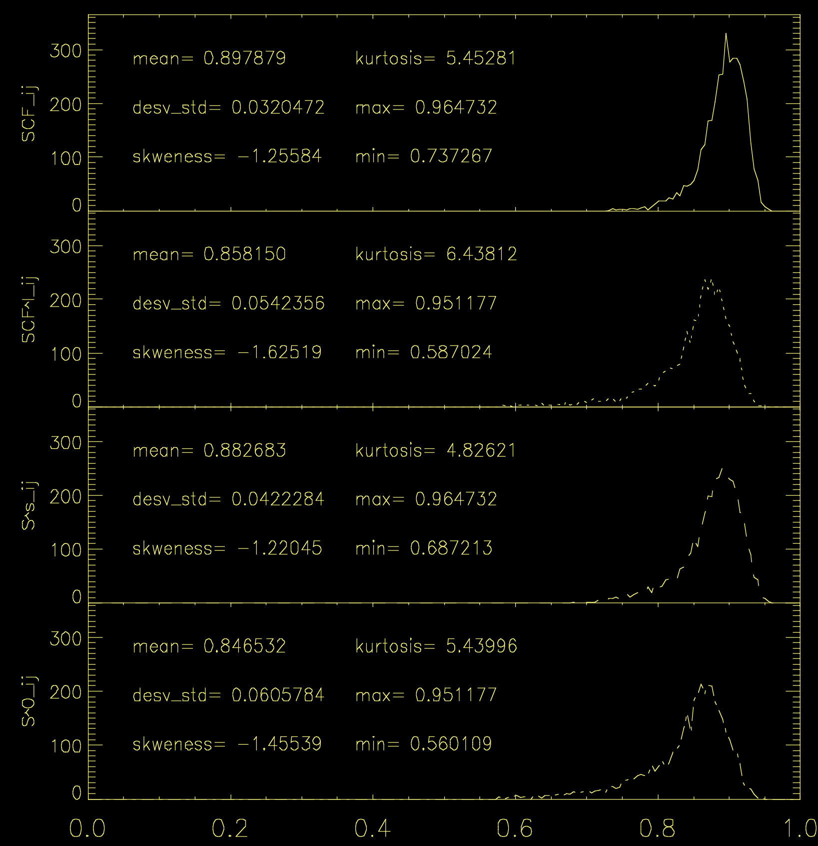


Data: Hartmann & Burton 1999;   Figure: Ballesteros-Paredes, Vazquez-Semadeni & Goodman 2001

Insights into Atomic ISM from SCF (v.1.0)

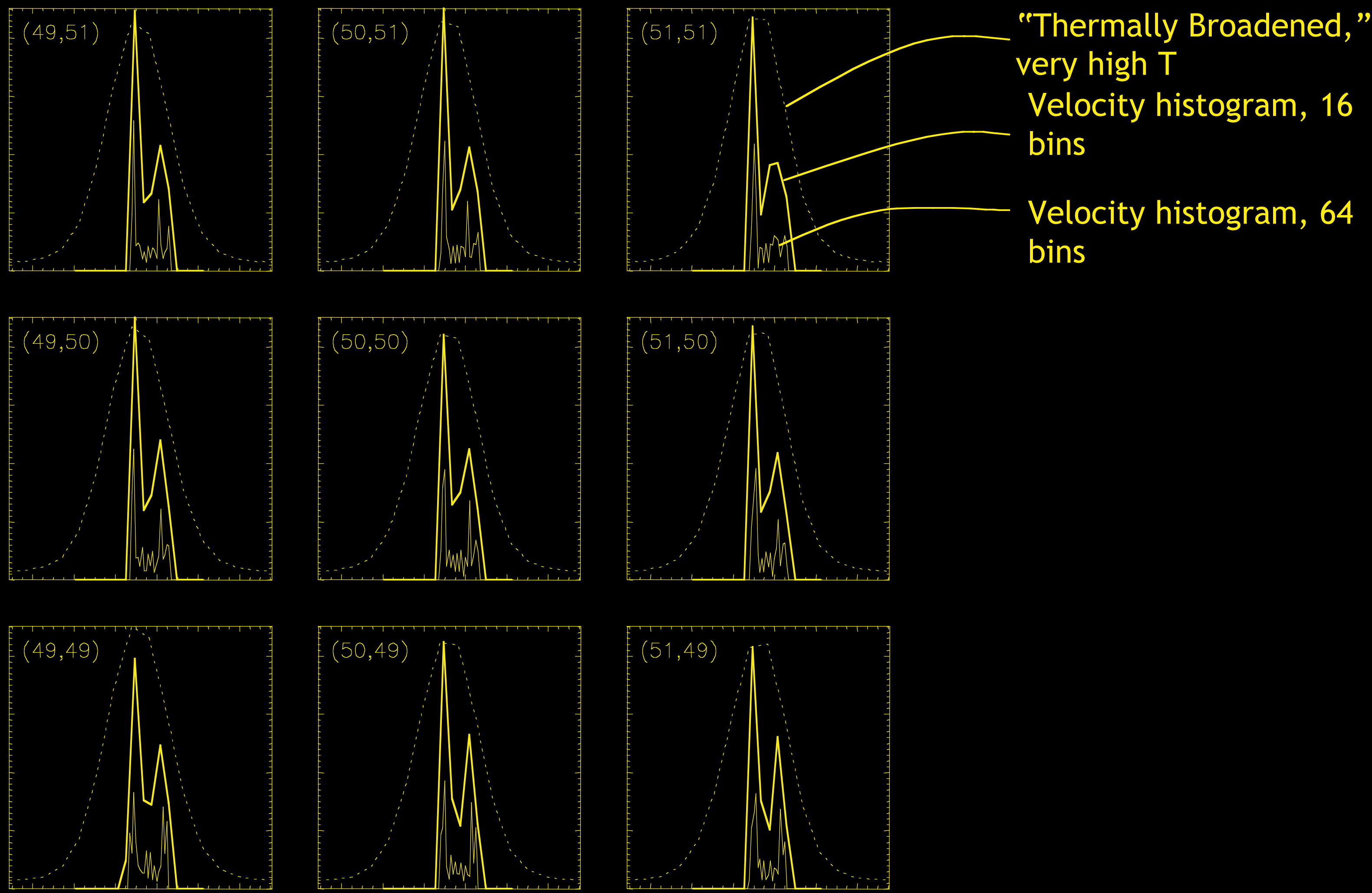
Comparison with simulations of Vazquez-Semadeni & collaborators shows:

- *"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.

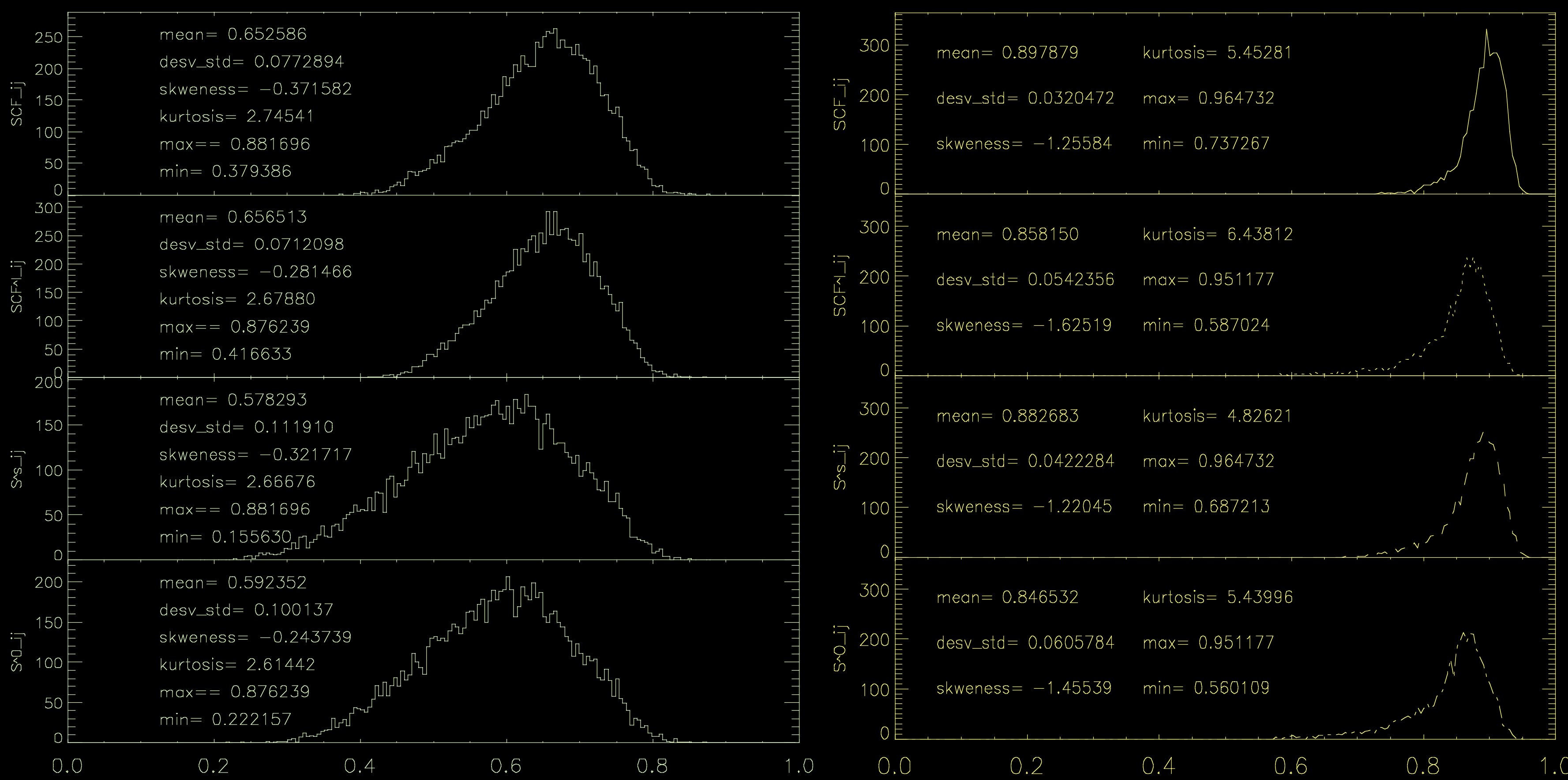
Revealing Shortcomings of a Simulation



Ballesteros-Paredes, Vazquez-Semadeni & Goodman 2001

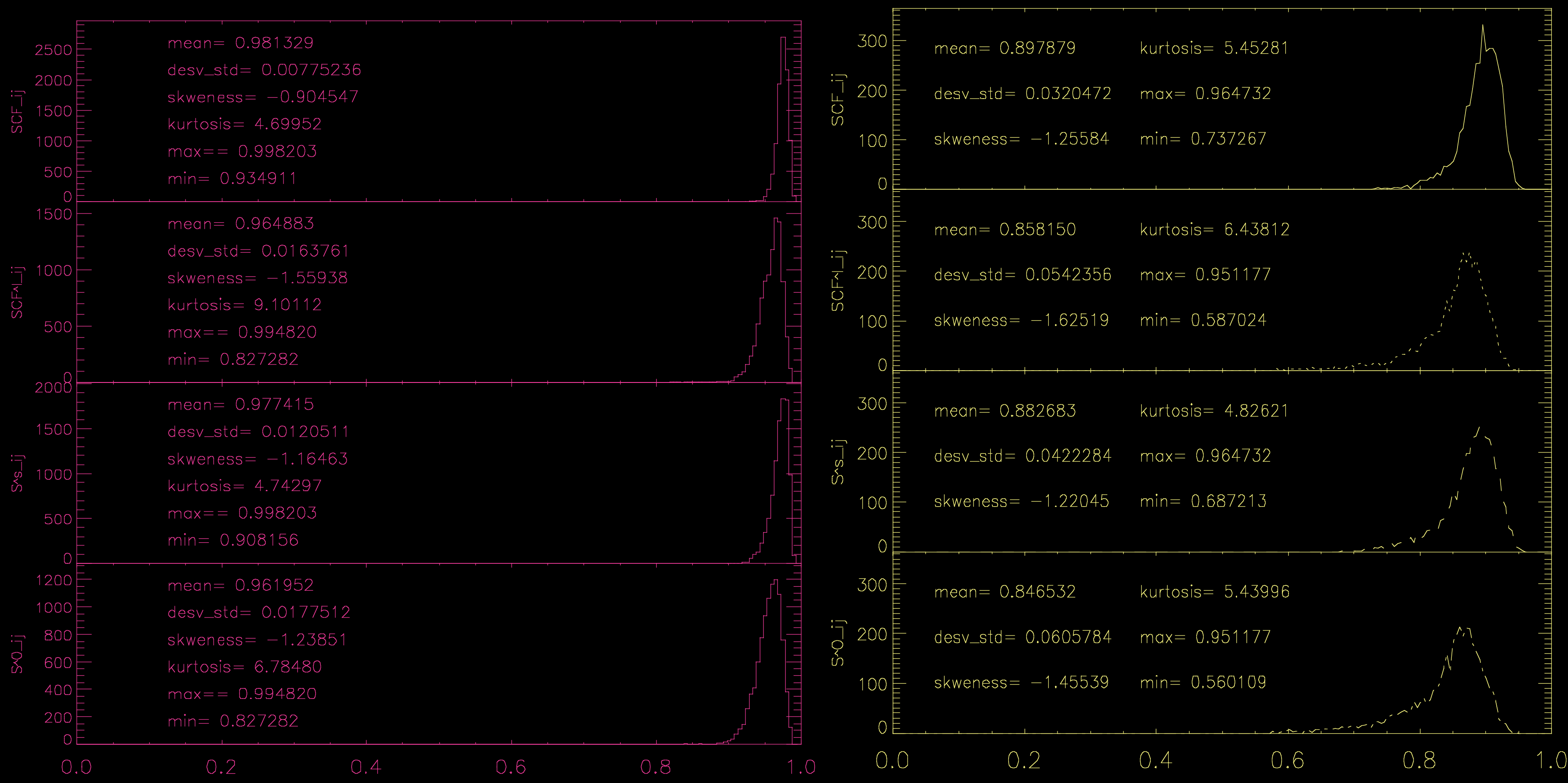
Insights into Atomic ISM from SCF (v.1.0)

From v-histograms, 64 bins



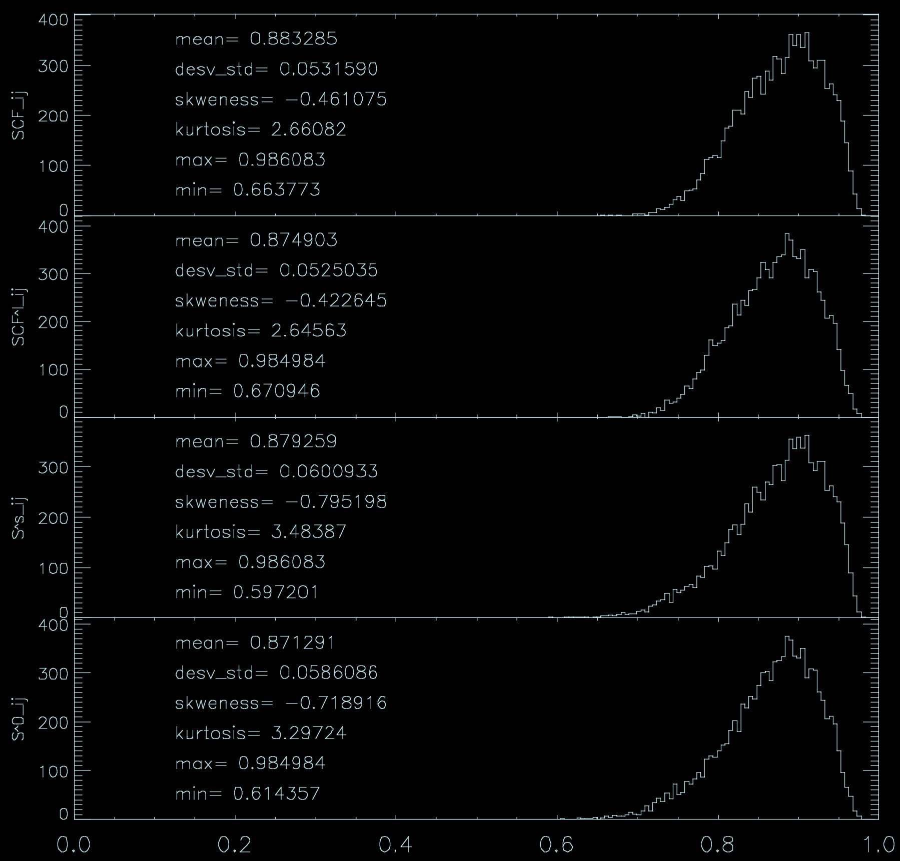
Insights into Atomic ISM from SCF (v.1.0)

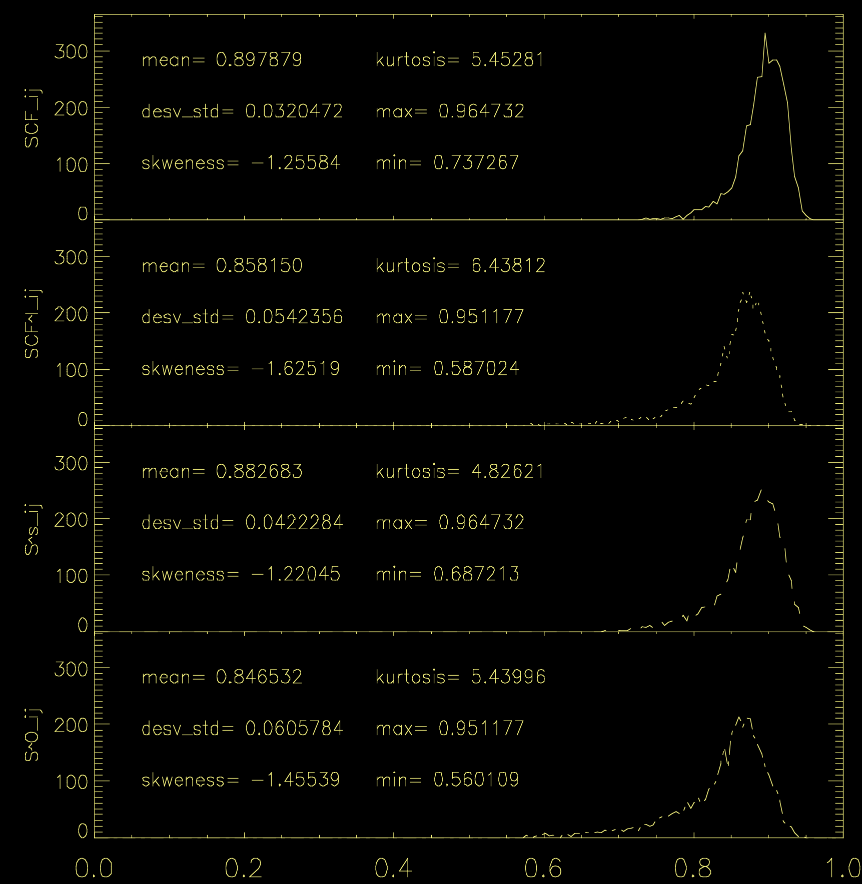
Thermally Broadened, very high T



Insights into Atomic ISM from SCF (v.1.0)

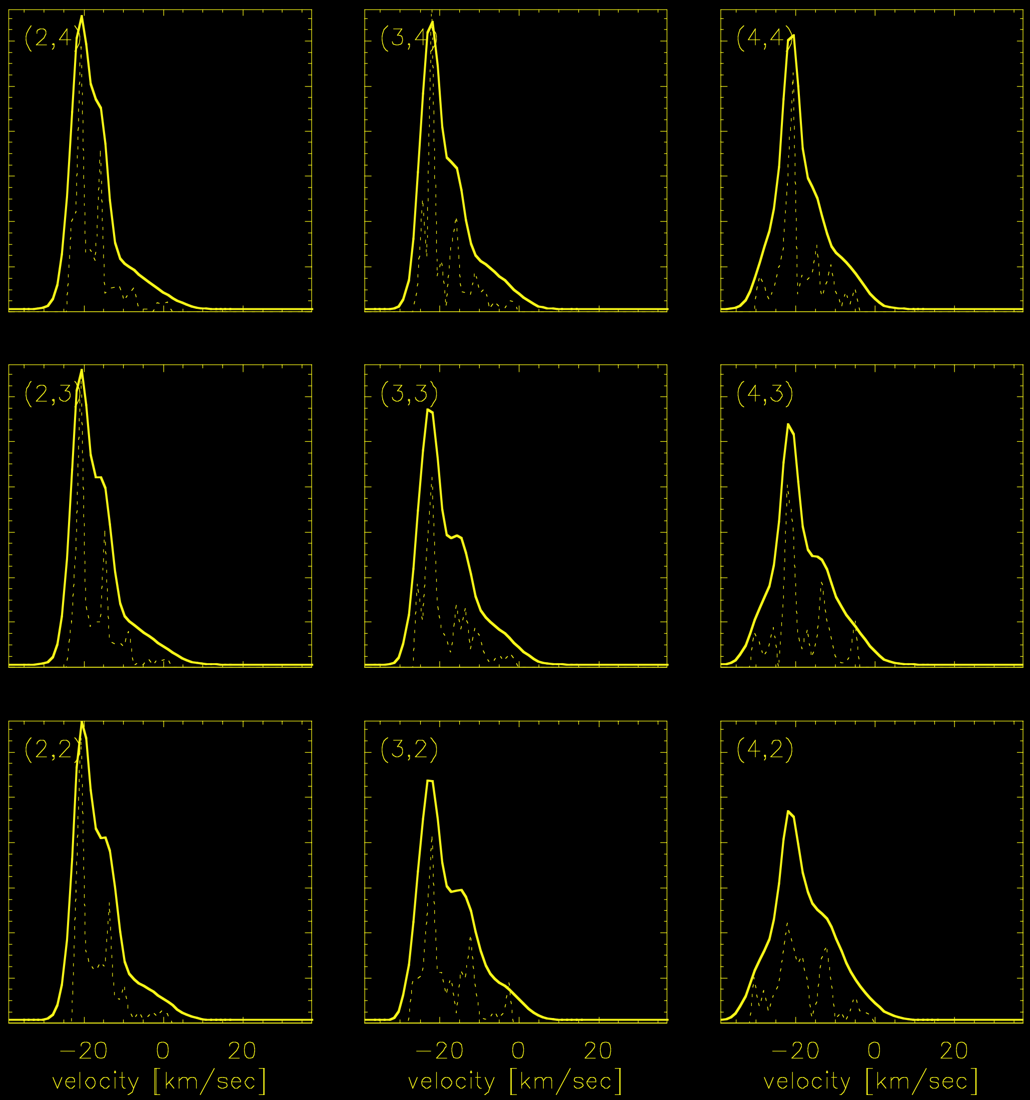
Thermally Broadened, equivalent of much lower T--best match!





A Success of the SCF

Sample spectra after velocity scale expanded x6 (to mimic lower temperature, and give more importance to "turbulence" in determining line shape)

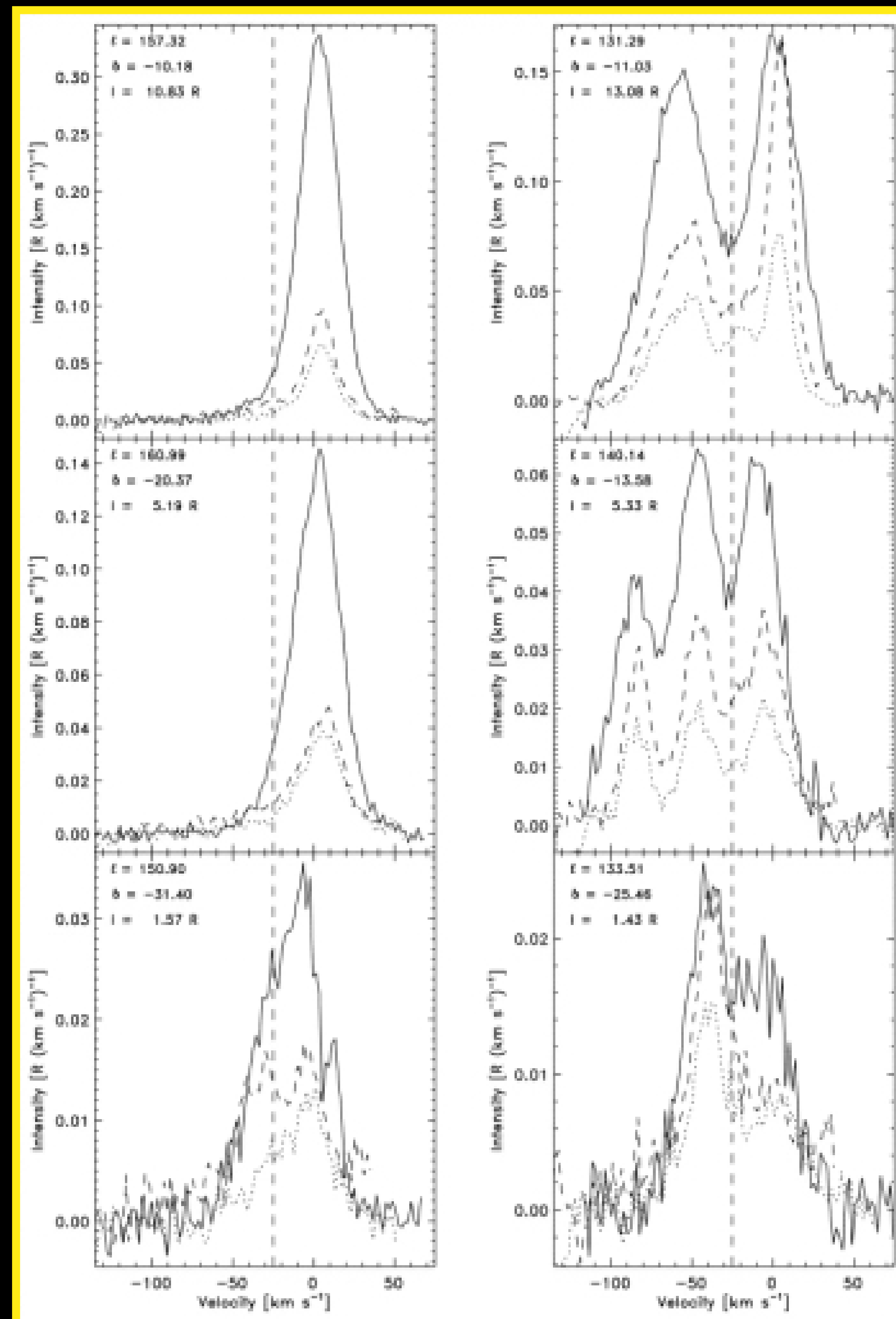


Ballesteros-Paredes, Vazquez-Semadeni & Goodman 2001

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 & Stavely-Smith 2001)*
  - Understanding behavior of atomic ISM *(e.g. Ballesteros-Paredes, Vazquez-Semadeni & Goodman 2001)*

How about applying the SCF to the ionized ISM?



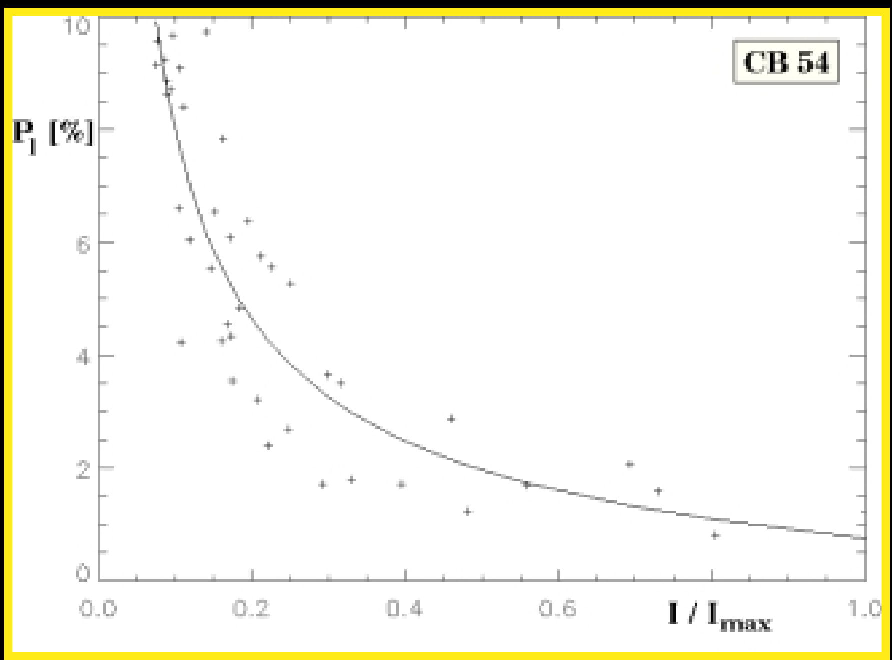
WHAM Results from Haffner, Reynolds & Tufte 1999

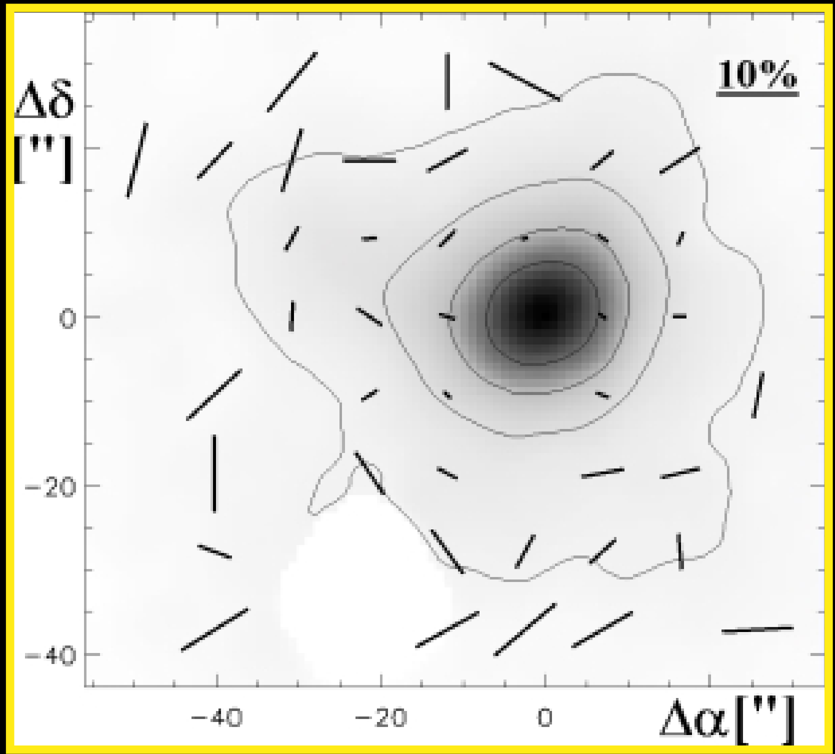
What good are they anyway?? (In case you're still not convinced:)

- MHD Simulations' illumination of observed emission polarization maps
- MHD Simulations & the IMF (ask me later)

SCUBA Polarimetry of Dense Cores & Globules

Polarization drops with sub-mm flux (similar to p decreasing with A_V)





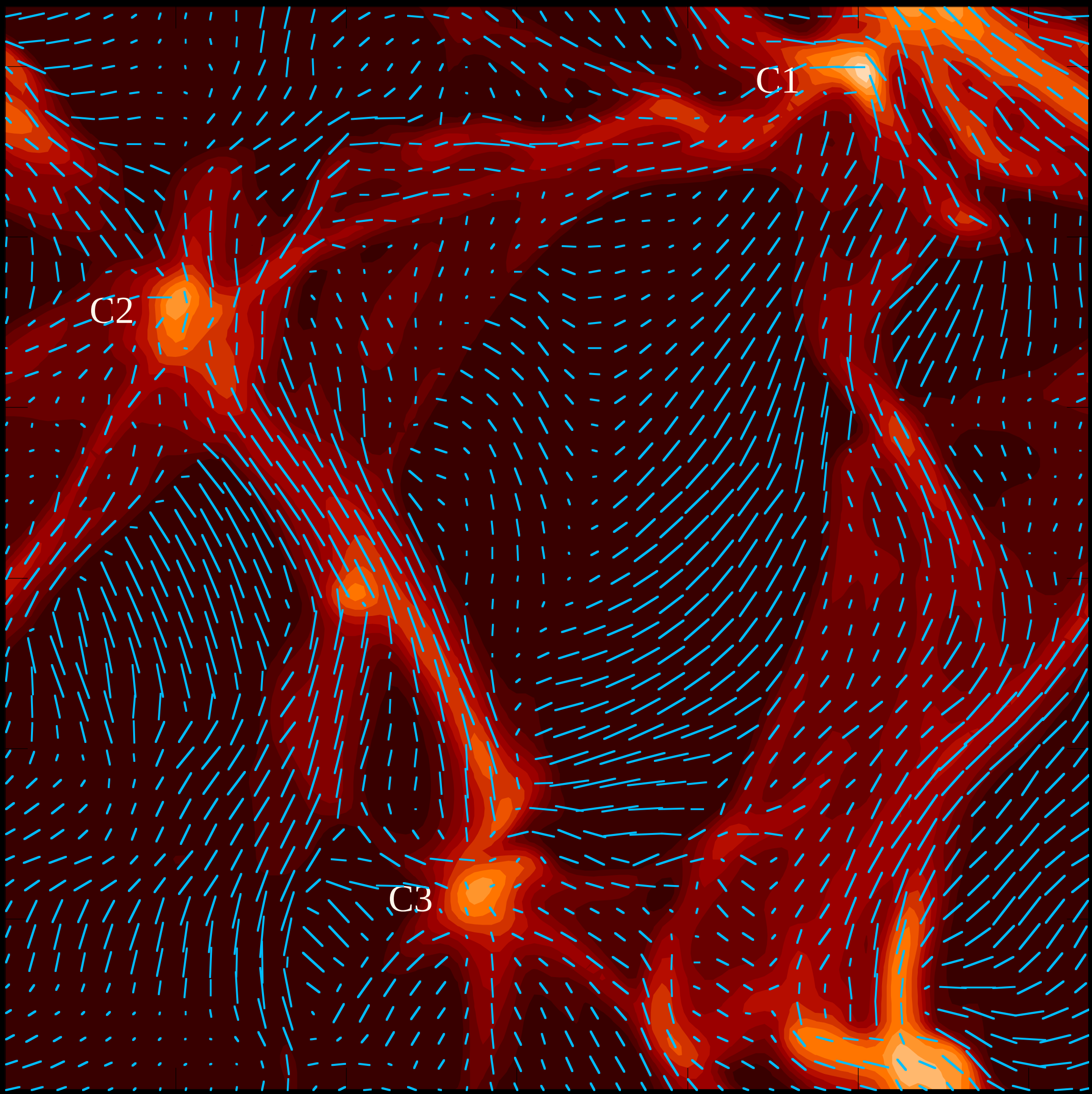
Does polarization map give true field structure?

Plots and data from Henning, Wolf, Launhart & Waters 2001

Simulated Polarized Emission

3-D simulation
- super-sonic
- super-Alfvénic
- self-gravitating

Model A:
Uniform grain-alignment efficiency

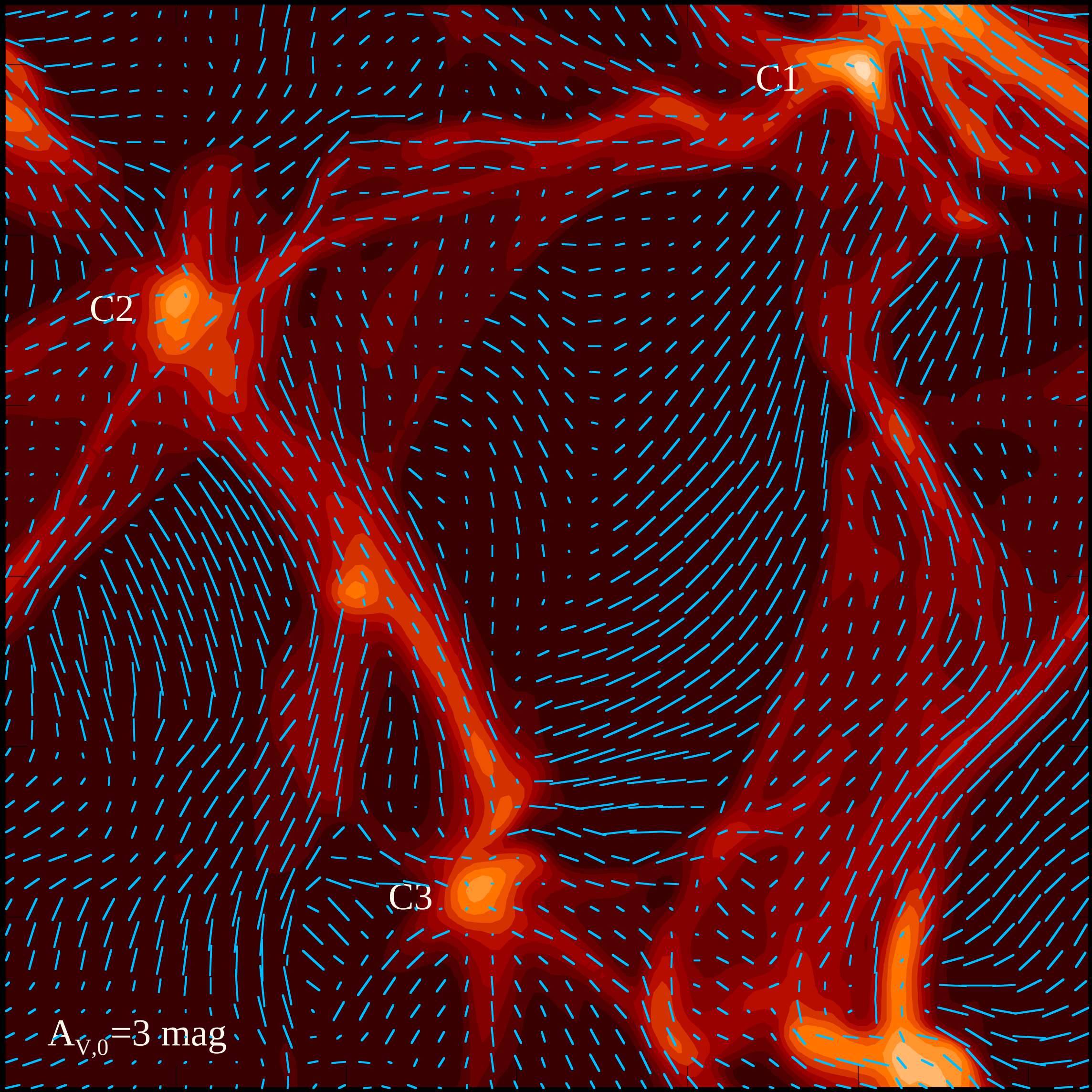


Padoan, Goodman, Draine, Juvela, Nordlund, Rögnvaldsson 2001

Simulated Polarized Emission

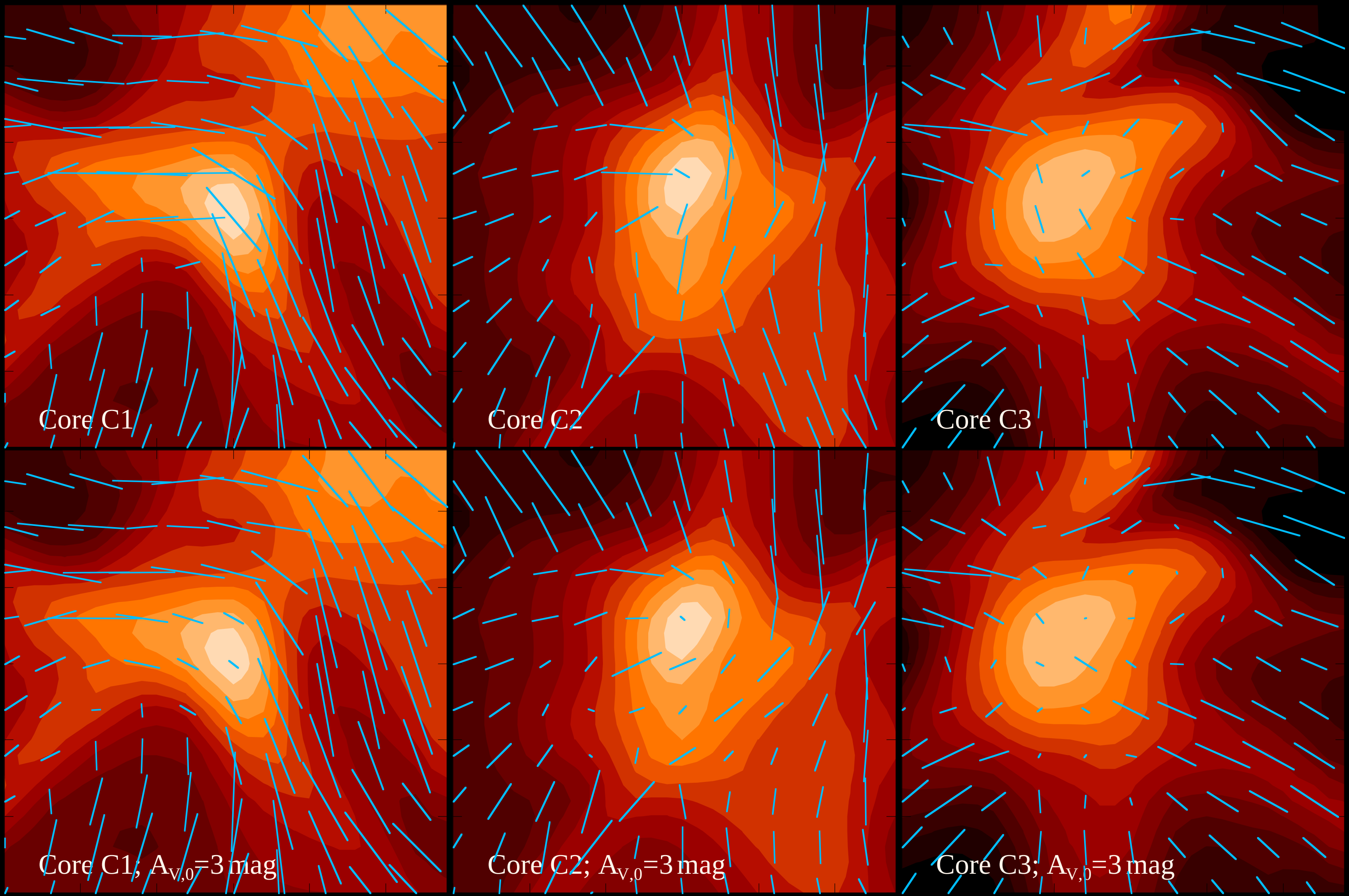
3-D simulation
- super-sonic
- super-Alfvénic
- self-gravitating

Model B:
Poor Alignment at
$A_V \geq 3$ mag



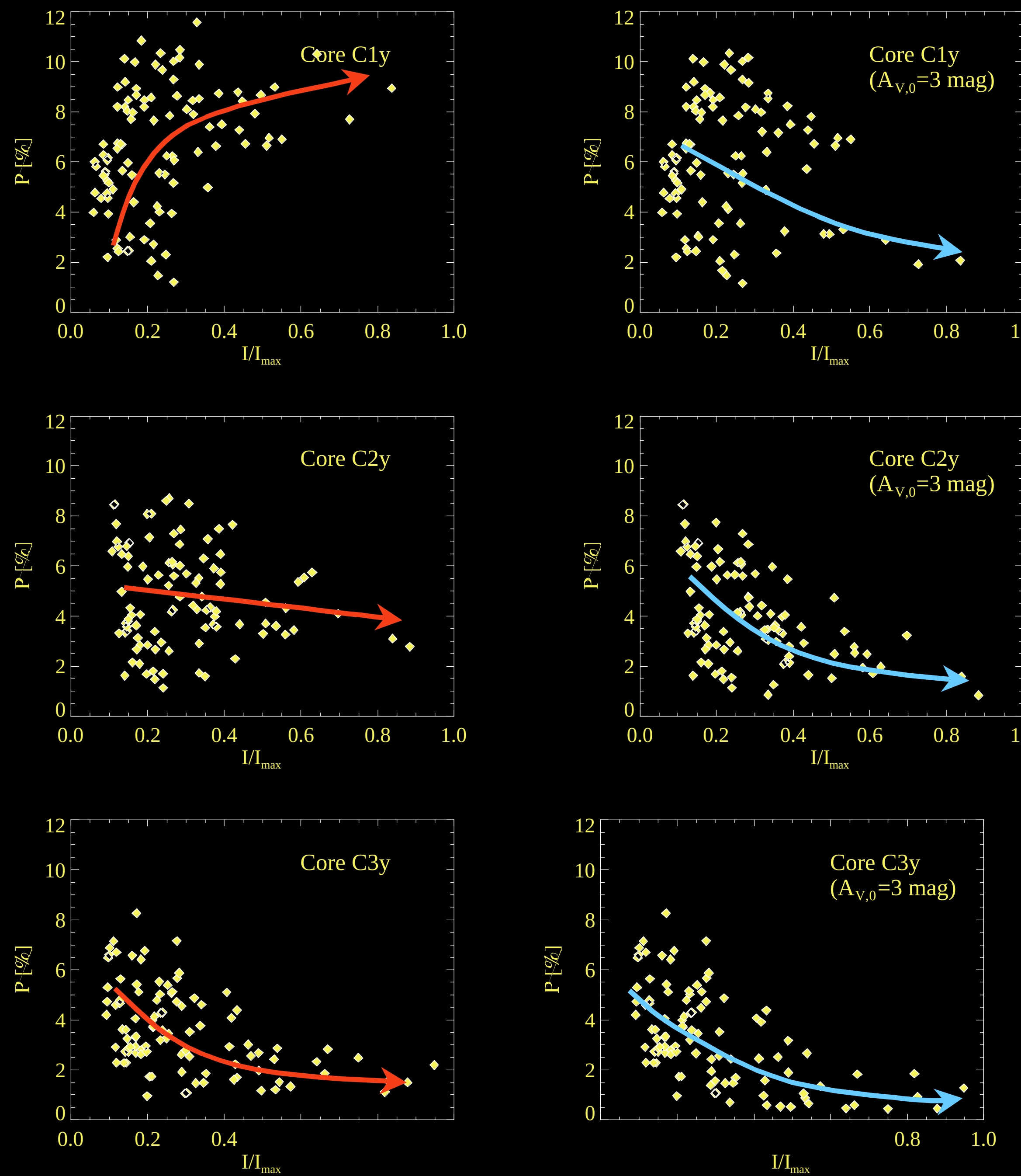
Padoan, Goodman, Draine, Juvela, Nordlund, Rögnvaldsson 2001

SCUBA-like Cores



Padoan, Goodman, Draine, Juvela, Nordlund, Rögnvaldsson 2001

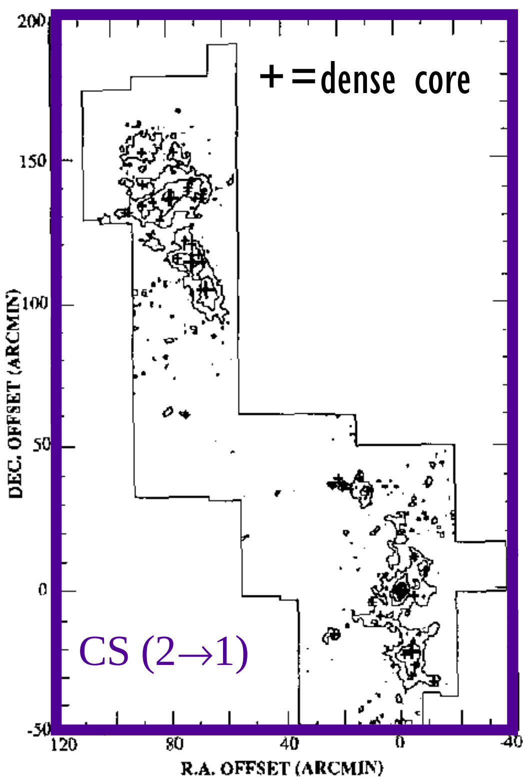
Polarization vs. Intensity



Padoan, Goodman, Draine, Juvela, Nordlund, Rögnvaldsson 2001

The Meaning of a "Clump IMF", c. 1996

What is a clump?



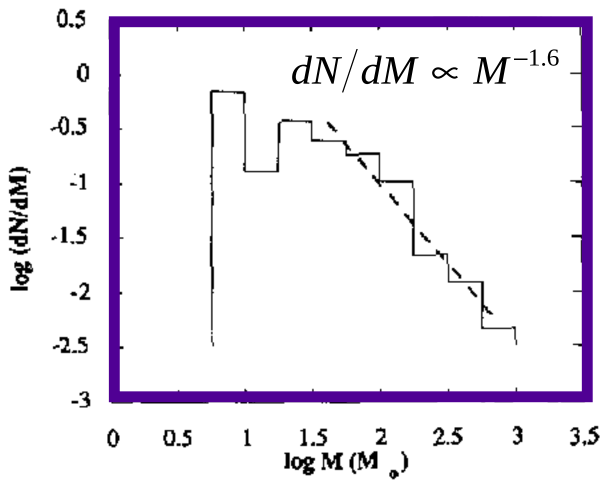
E. Lada 1992

Typical Stellar IMF

$$dN/dM \propto M^{-2.5\pm0.3}$$

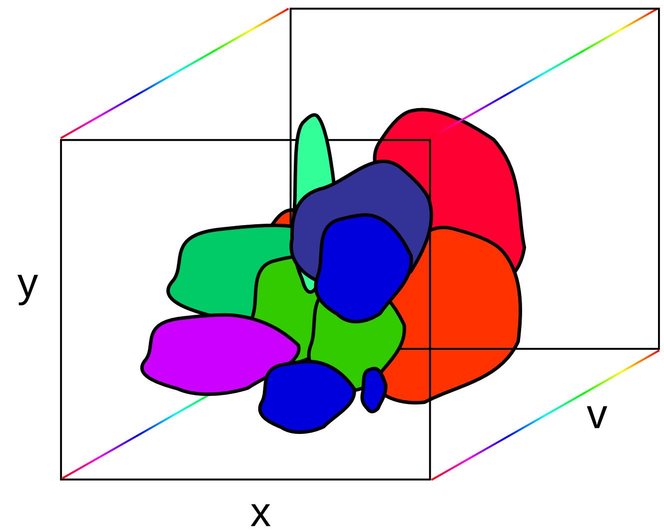
Salpeter 1955
Miller & Scalo 1979

What does the clump "IMF" look like?



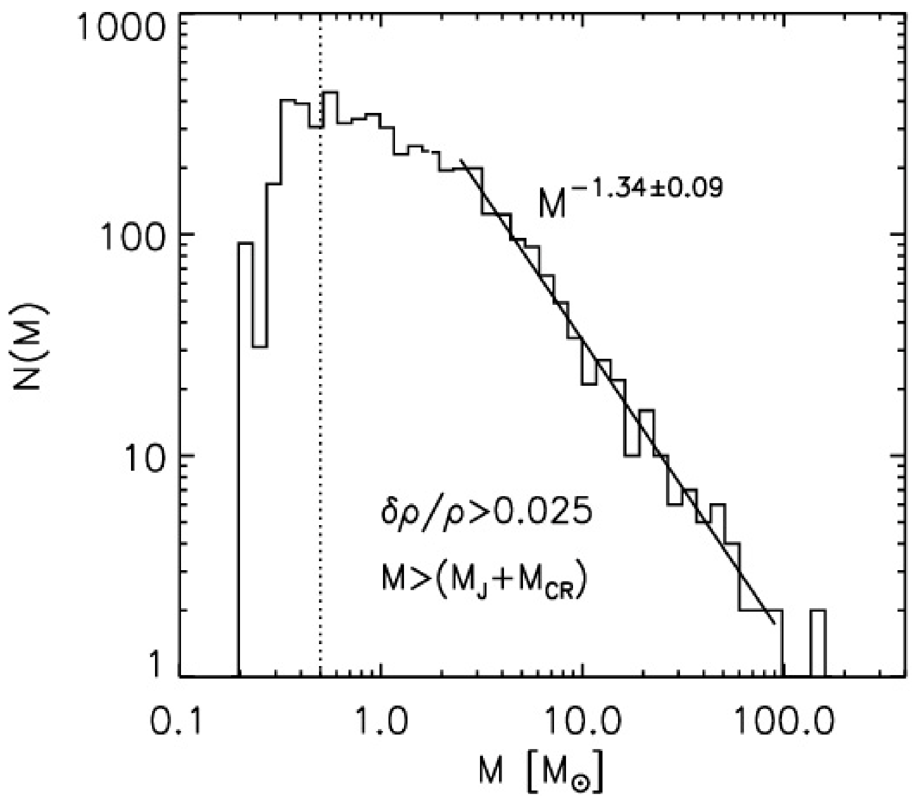
E. Lada et al. 1991

Structure-Finding Algorithms



- •CLUMPFIND (*Williams et al. 1994*)
- •Autocorrelations (e.g. *Miesch & Bally 1994*)
- •Structure Trees (*Houlahan & Scalo 1990,92*)
- •GAUSSCLUMPS (*Stutzki & Güesten 1990*)
- •Wavelets (e.g. *Langer et al. 1993*)
- •Complexity (*Wiseman & Adams 1994*)
- •IR Star-Counting (*C. Lada et al. 1994*)

Simulating the IMF--in the Gas: Success?



Includes ONLY:

- Simulated clumps massive enough to collapse and form a star

Padoan, Nordlund, Rognvaldsson & Goodman 2001; see also Klessen 2001

Acheivements & Plans

Acheievements

- SCF most discriminating descriptor of spectral-line data cubes
- SCF used to map "scale height" in the LMC
- SCF used to revise/improve MHD simulations

Plans

- Use the SCF to "find" star-forming gas observationally
- Try the SCF on the ionized ISM
- Study galaxy structure with SCF applied to extragalactic CO (BIMA SONG; ALMA) and H I (EVLA; SKA) maps