Measuring Turbulent Motions: from Galaxies to GMCs to Star-Forming Cores

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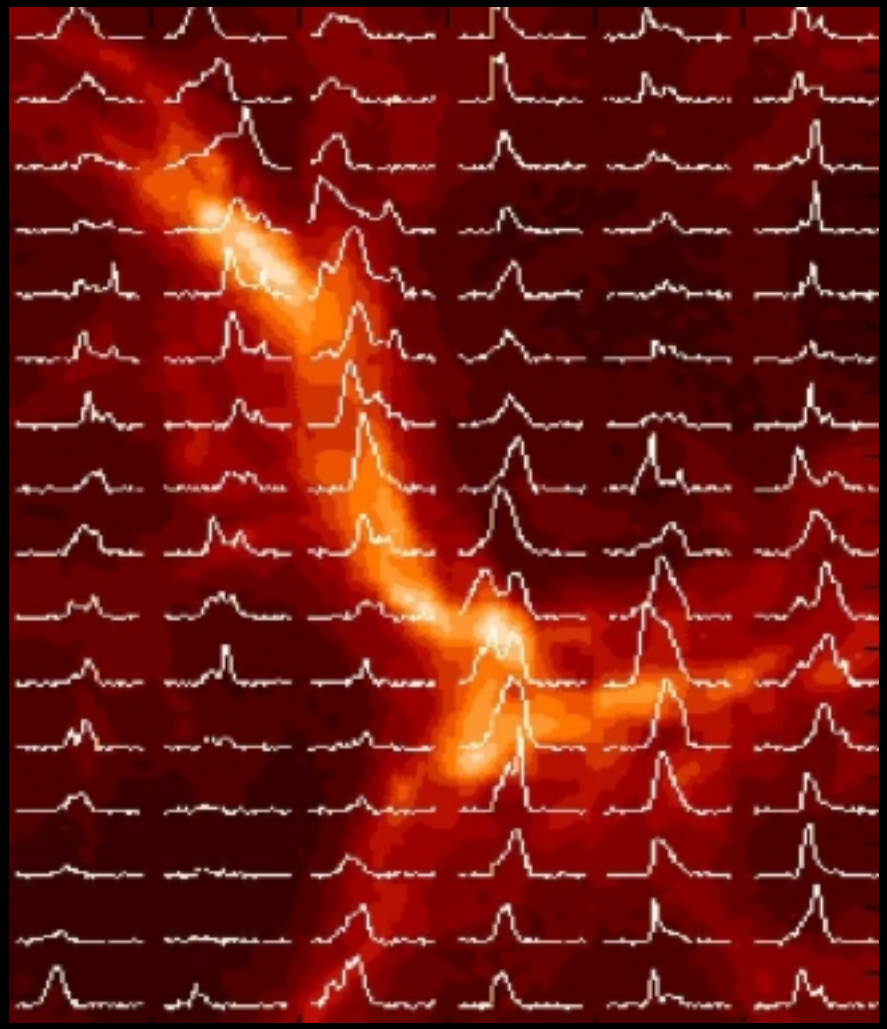


What did Alyssa Goodman say about "Measuring Turbulent Motions" in Santa Cruz?

The Spectral Correlation Function (SCF)

- Can **discriminate amongst** observed and simulated spectral-line **maps** other statistical measures find identical (Rosolowsky, Goodman, Wilner & Williams 1999, ApJ, 524, 887).
- Exhibits power-law behavior as a function of scale, the index of which seems to be excellent **diagnostic of the nature of turbulence** (Padoan, Rosolowsly & Goodman 2001, ApJ, 547, 862).
- Can **map the scale height** of a mostly **face-on galaxy** (the LMC; Padoan, Kim, Goodman & Stavely-Smith 2001, ApJ, 555, 33).
- Should have its greatest use in the **fine-tuning of simulations** (e.g. Ballesteros-Paredes, Vazquez-Semadeni & Goodman 2001, preprint).
- Should be able to **find "coherent cores"** (see Goodman, Barranco, Wilner & Heyer 1998, ApJ, 504, 223). MHD simulations already show a **"turbulent shock origin of cores"** (Padoan, Juvela, Goodman & Nordlund 2001, ApJ, 553, 227), as well as **"accidental" infall profiles** (Padoan et al. 2001, in prep).

Outflows

- Are *definitely* highly **episodic**, and their episodic nature can explain steep observed mass-velocity relations (Arce & Goodman 2001, ApJL, 551, L171; Arce & Goodman 2001, ApJ, 554, 132). Influence of episodicity on "driving" turbulence still needs to be understood.

Provacative Suggestion

- The central source of the outflow in **PVCeph** might be **moving at ~10 km s^{-1}** (Arce & Goodman 2001, in prep.).

What is the Spectral Correlation Function?

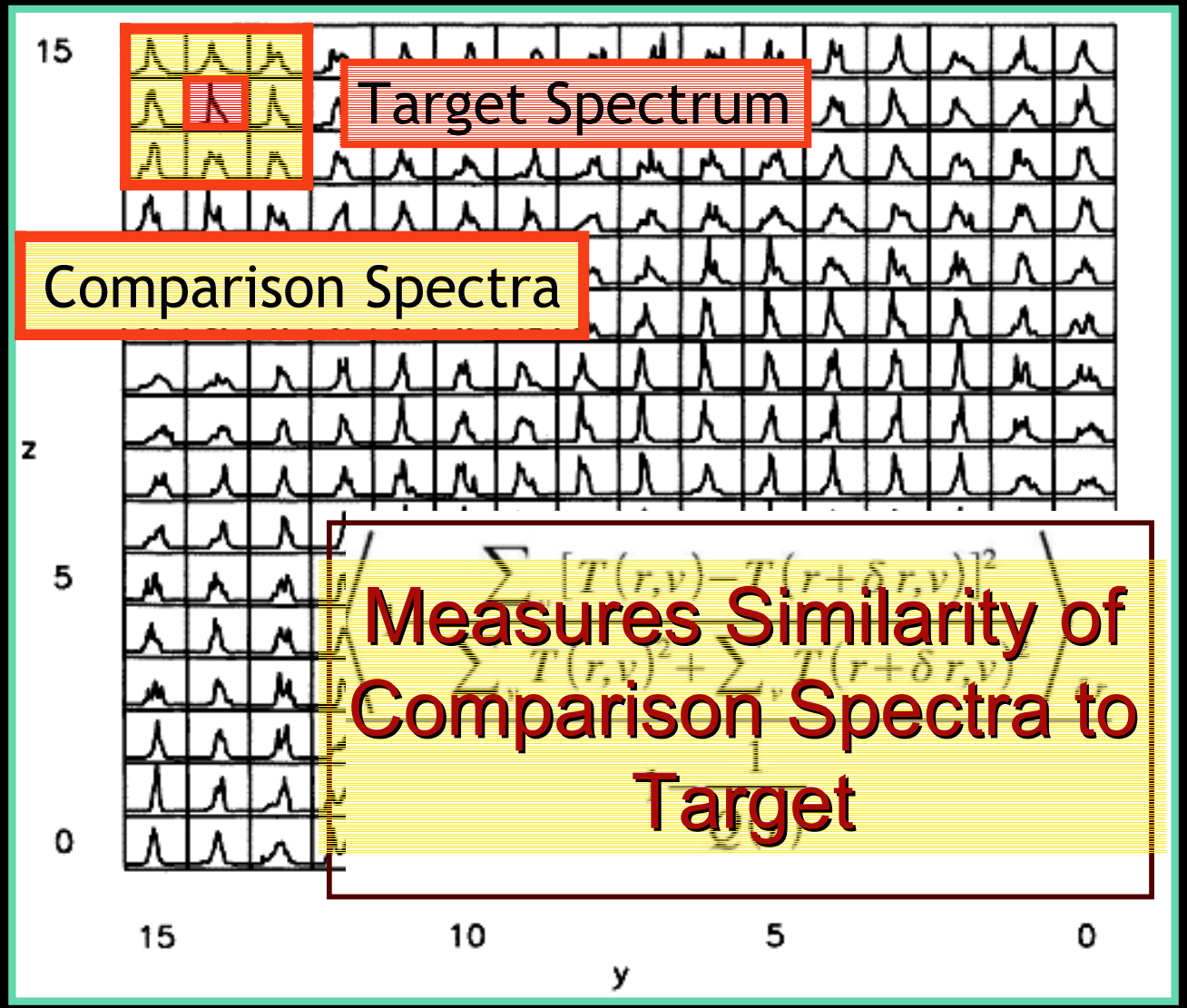


Figure from Falgarone et al. 1994

SCF, v.1.0

(Rosolowsky et al. 1999)

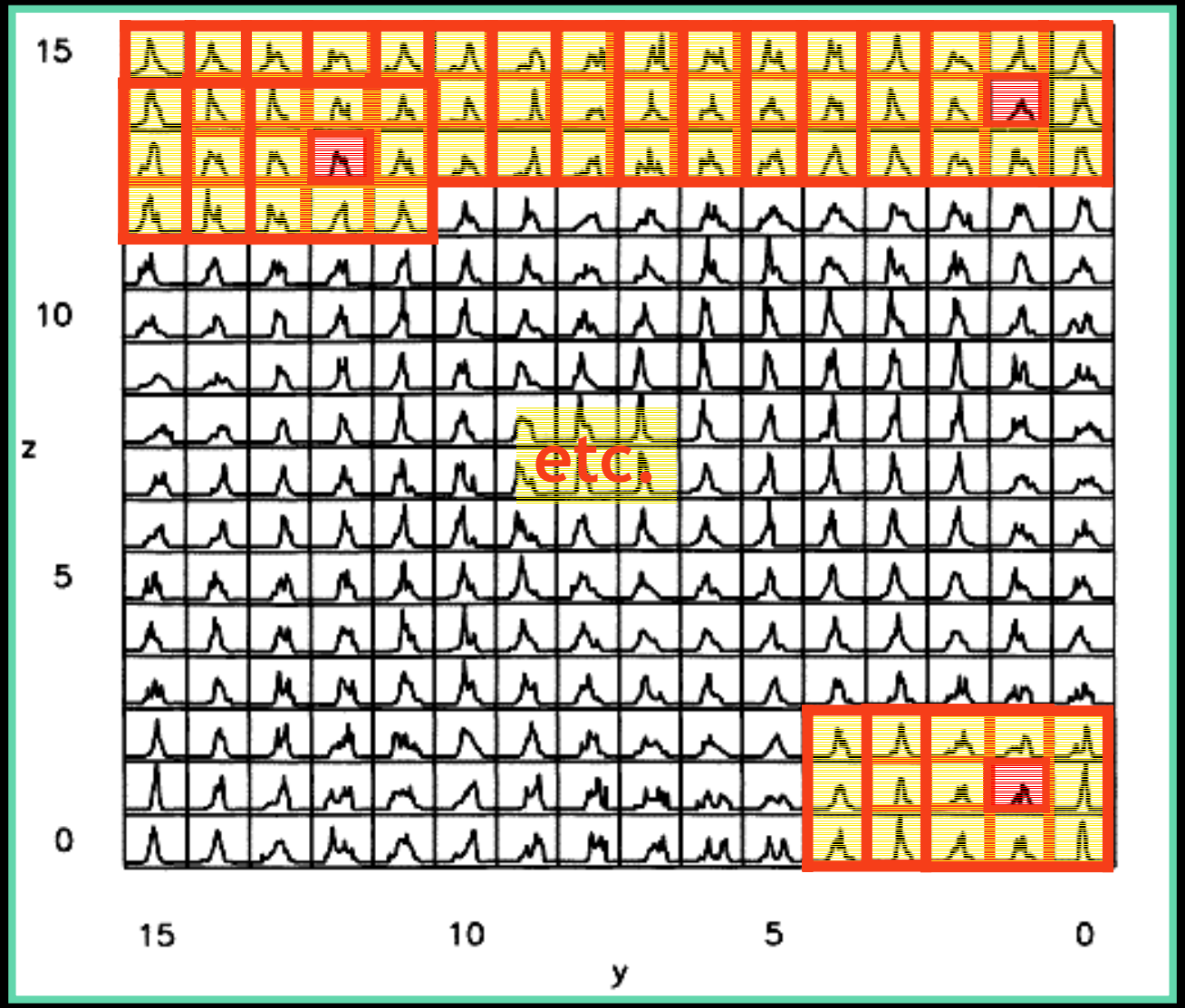
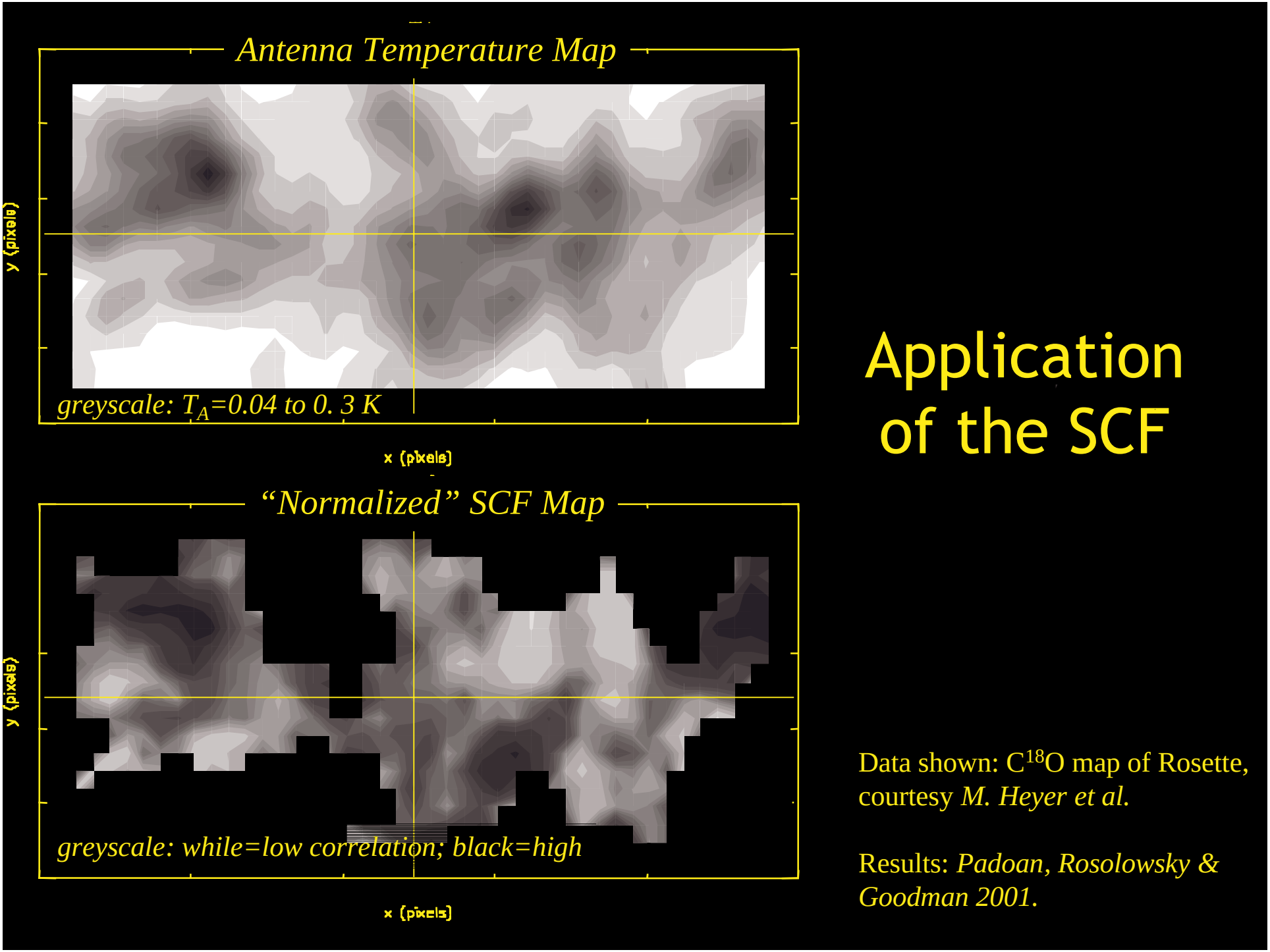


Figure from Falgarone et al. 1994

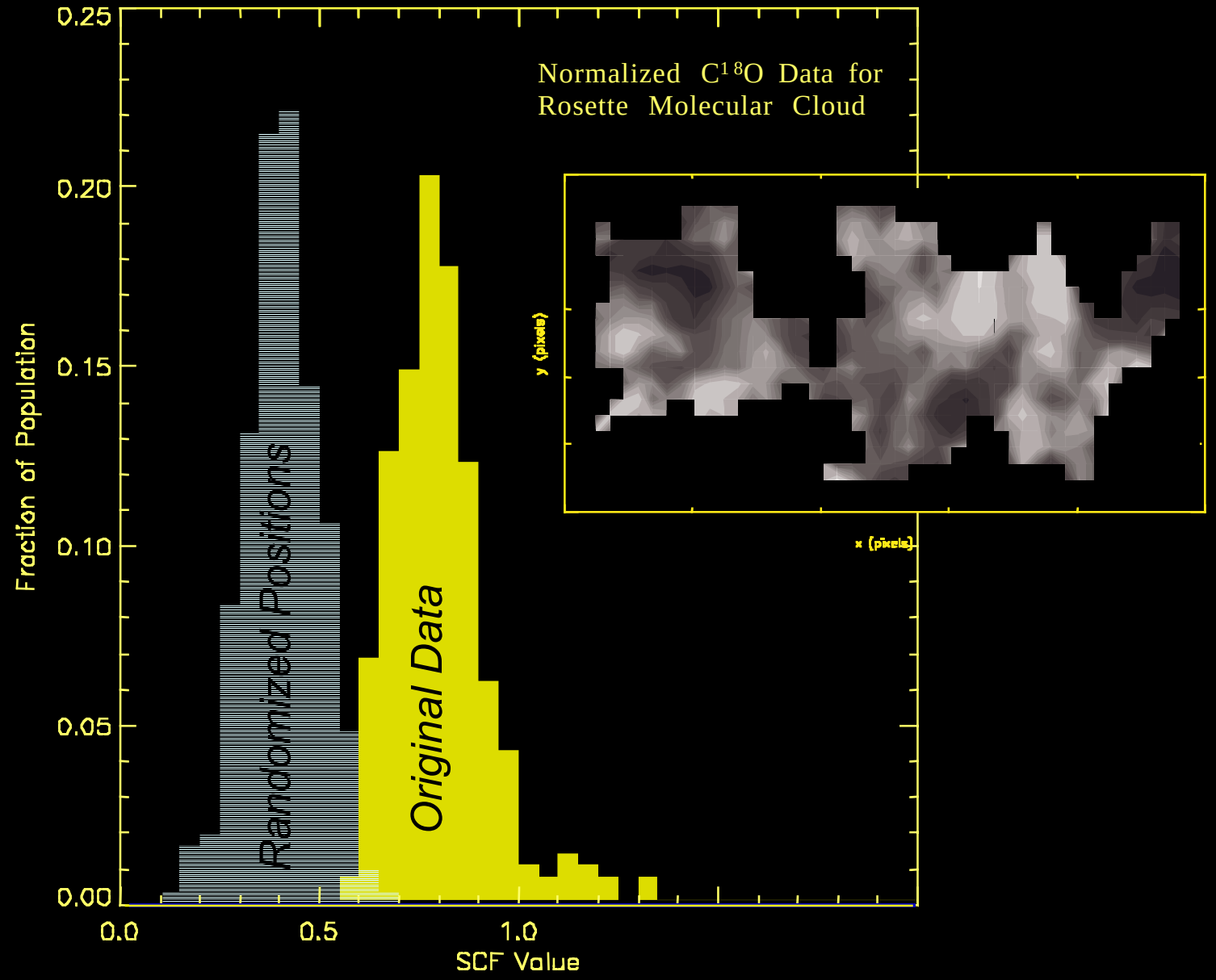


Application of the SCF

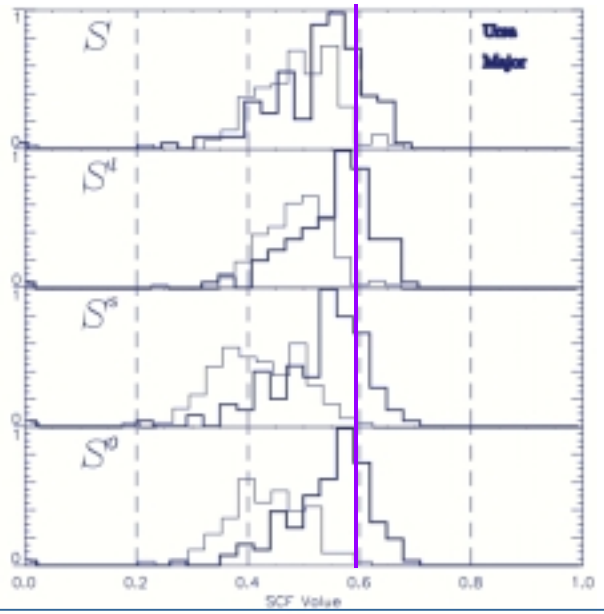
Data shown: $C^{18}O$ map of Rosette, courtesy *M. Heyer et al.*

Results: *Padoan, Rosolowsky & Goodman 2001.*

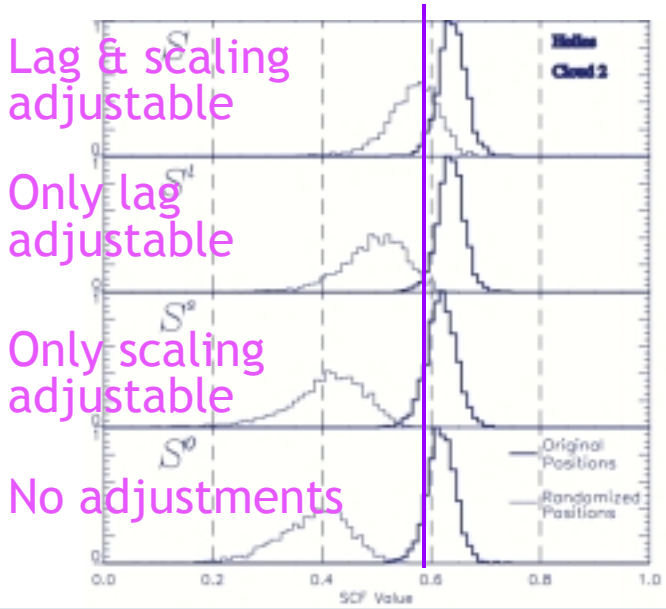
SCF Distributions



Unbound High-Latitude Cloud



Self-Gravitating, Star-Forming Region



Insights from SCF v.1.0

Rosolowsky, Goodman, Williams & Wilner 1999

Lag & scaling adjustable

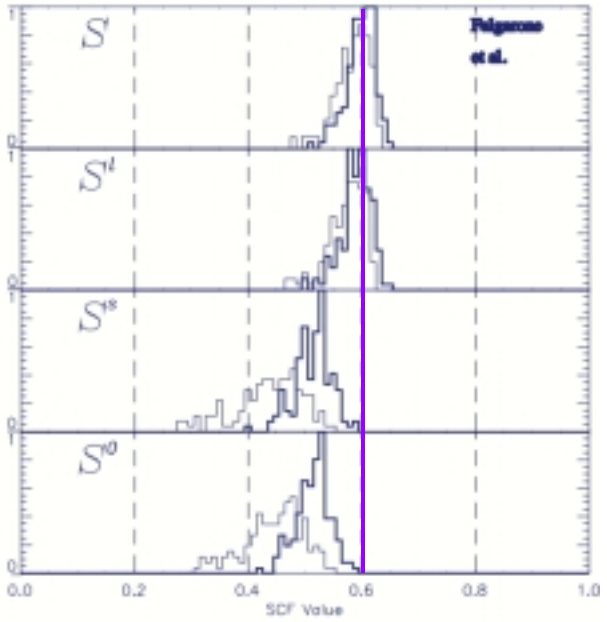
Only lag adjustable

Only scaling adjustable

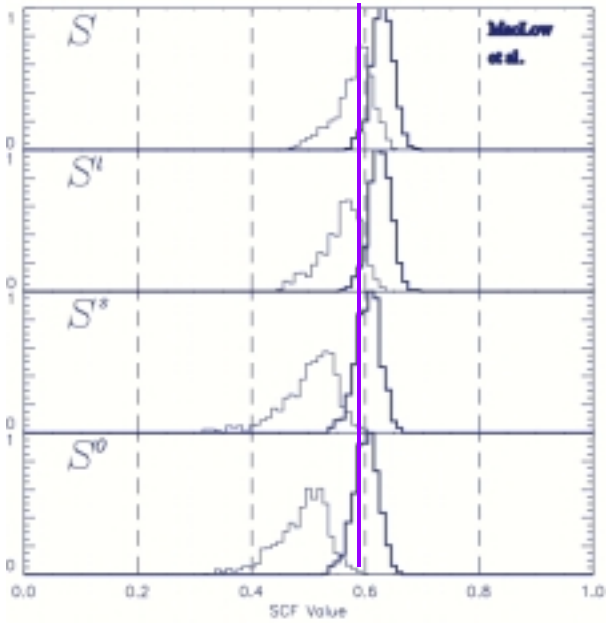
No adjustments

Observations

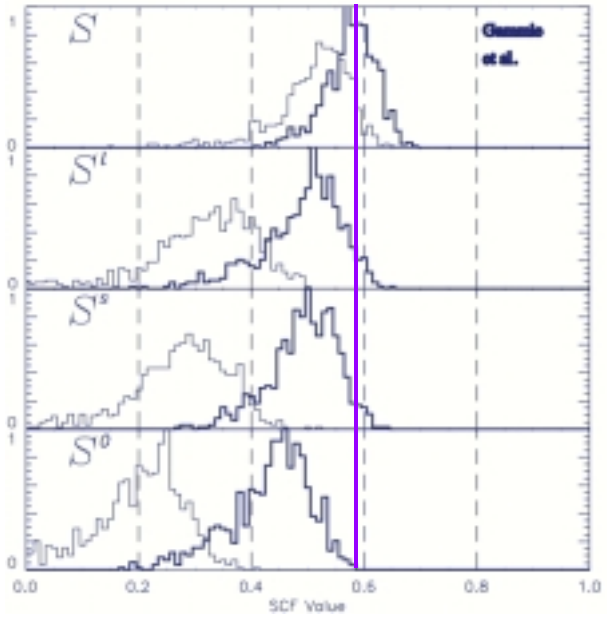
Simulations



No gravity, No B field

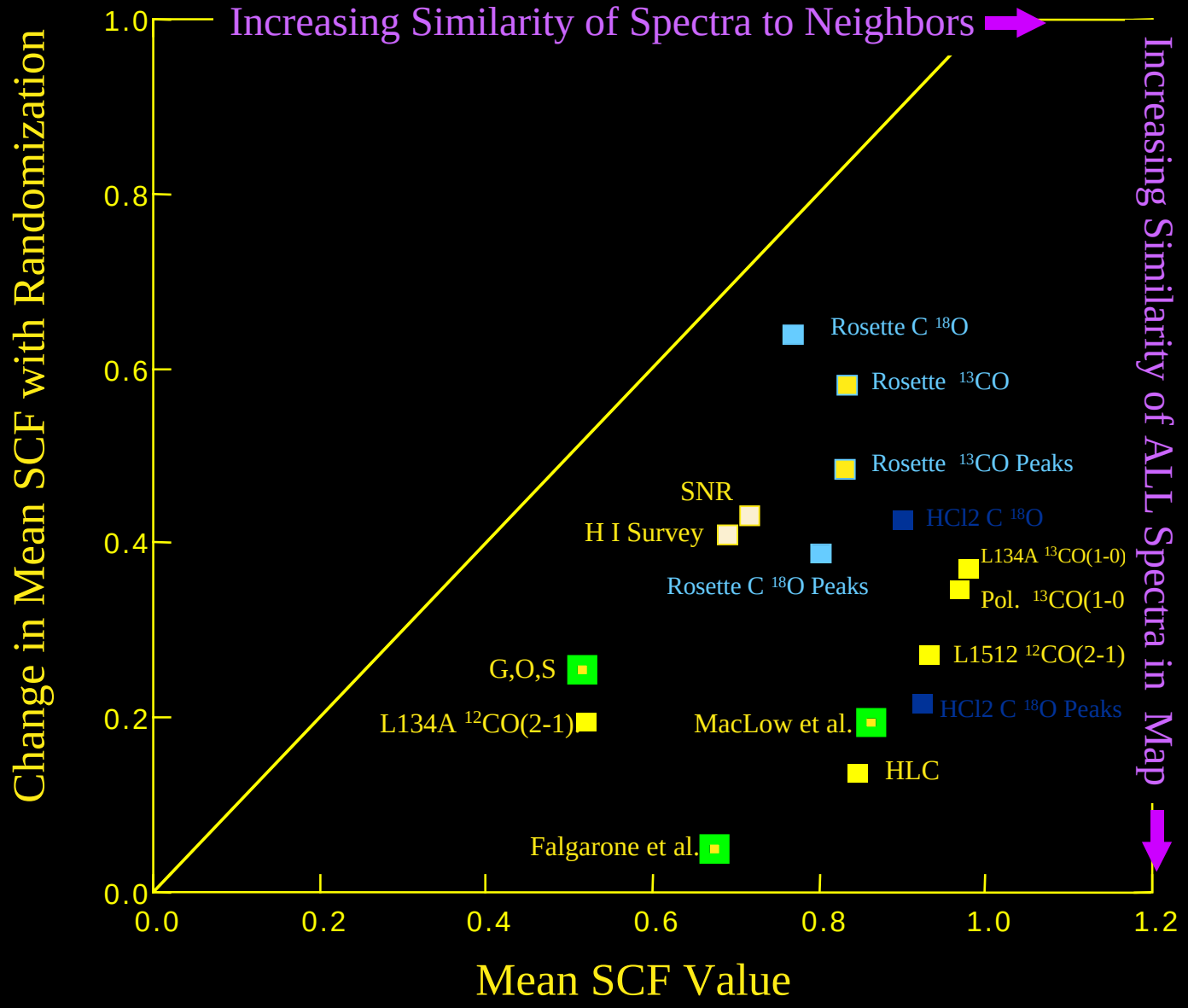


No gravity, Yes B field



Yes gravity, Yes B field

Which of these is not like the others?



The Spectral Correlation Function as a Function of Spatial Scale

(v.2.0; Padoan et al. 2001)

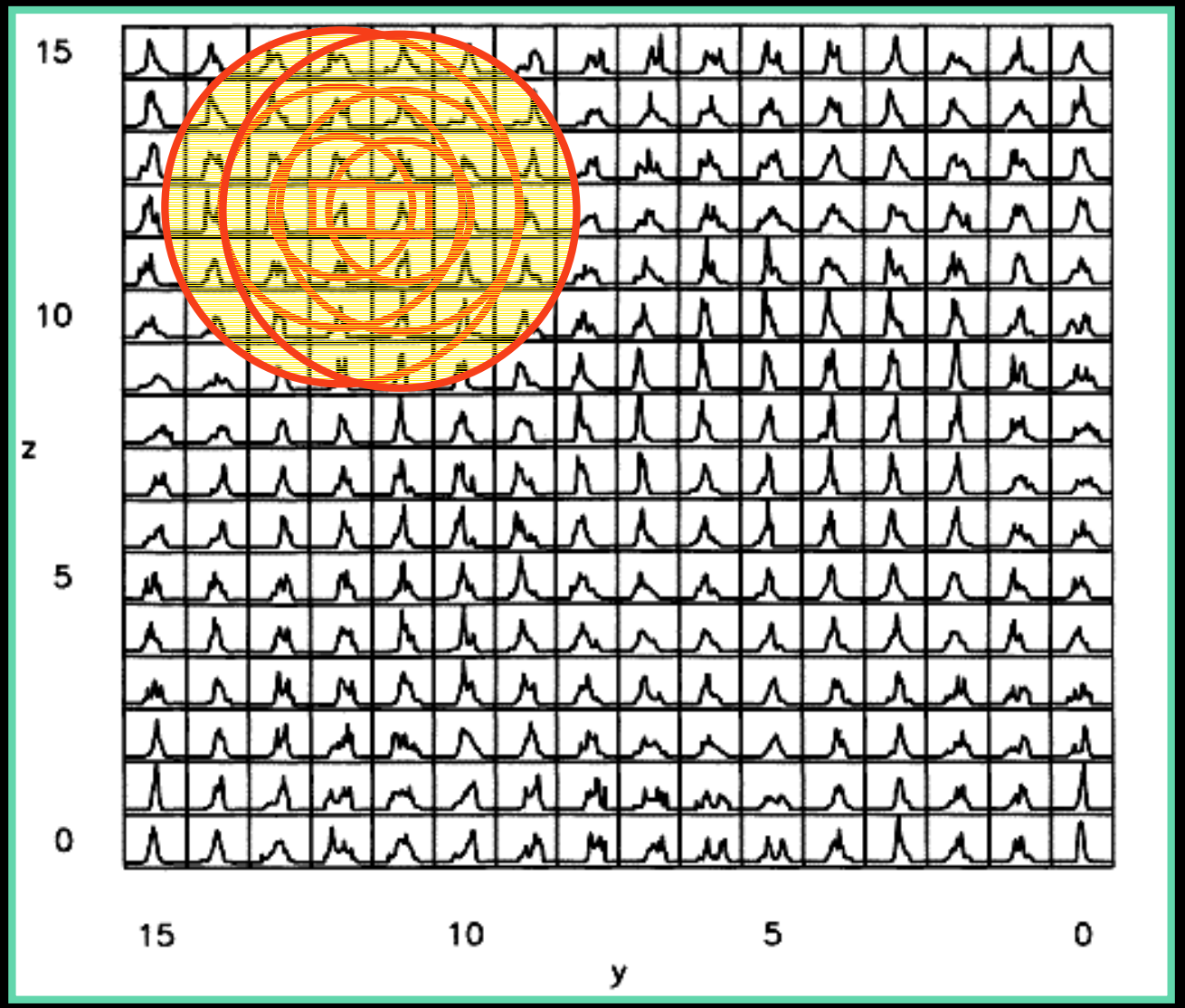
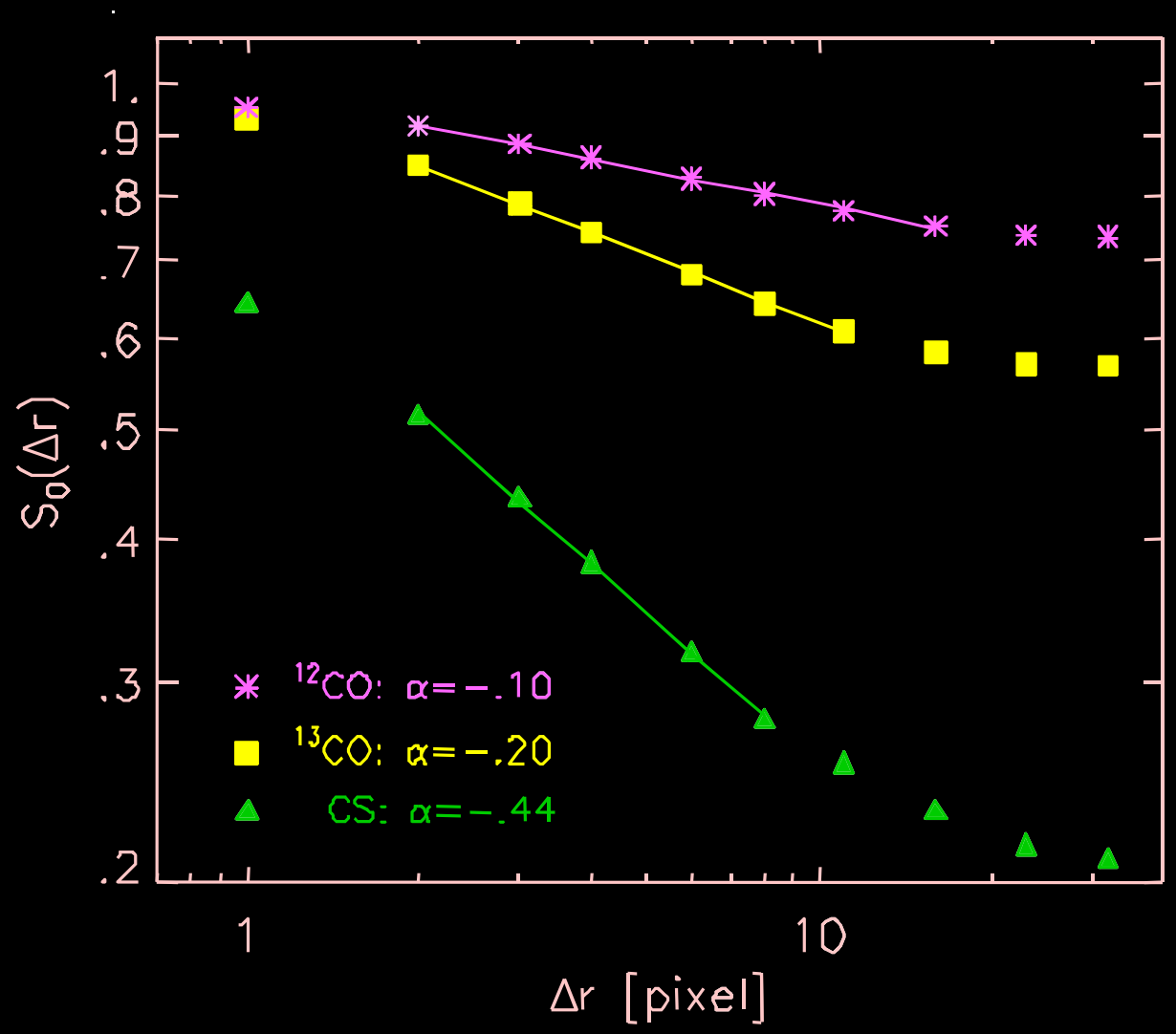


Figure from Falgarone et al. 1994

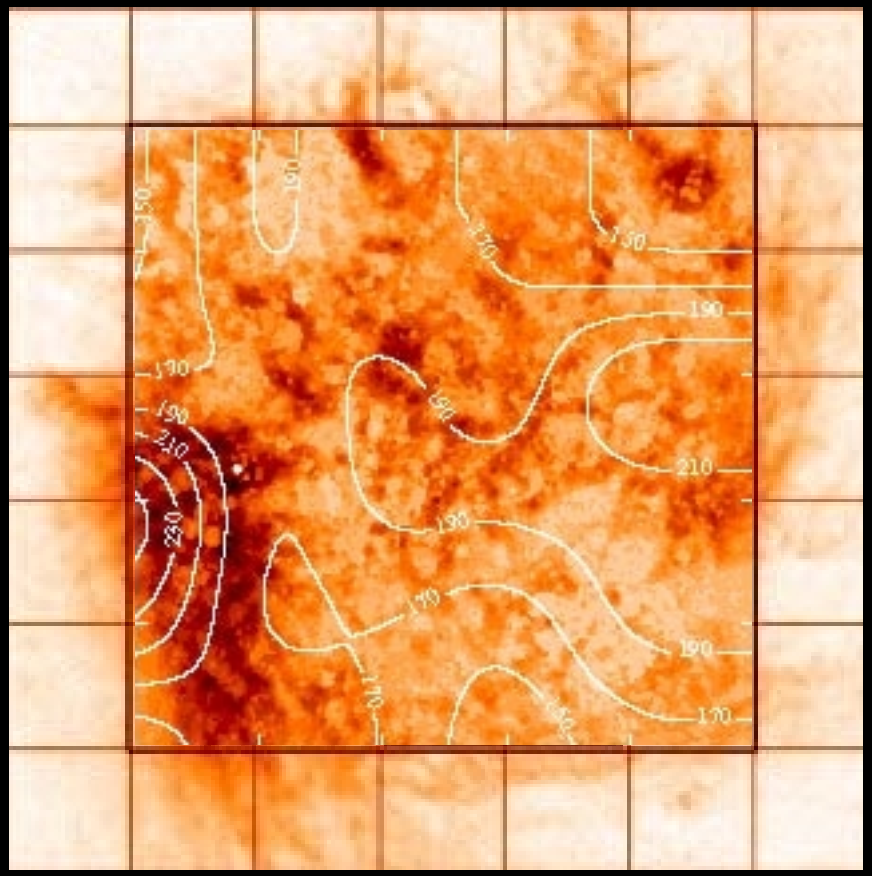
v.2.0: Scale-Dependence of the SCF



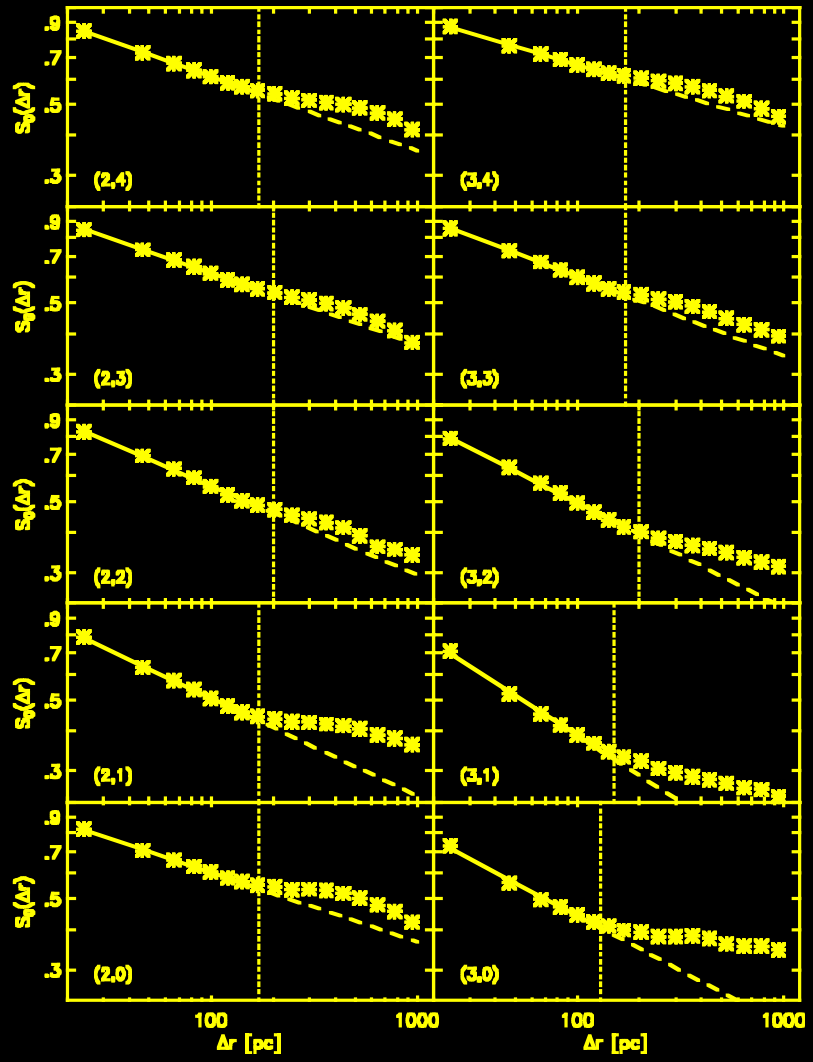
Example for "Simulated Data"

Padoan, Rosolowsky & Goodman 2001

Galactic Scale Heights from the SCF (v.2.0)

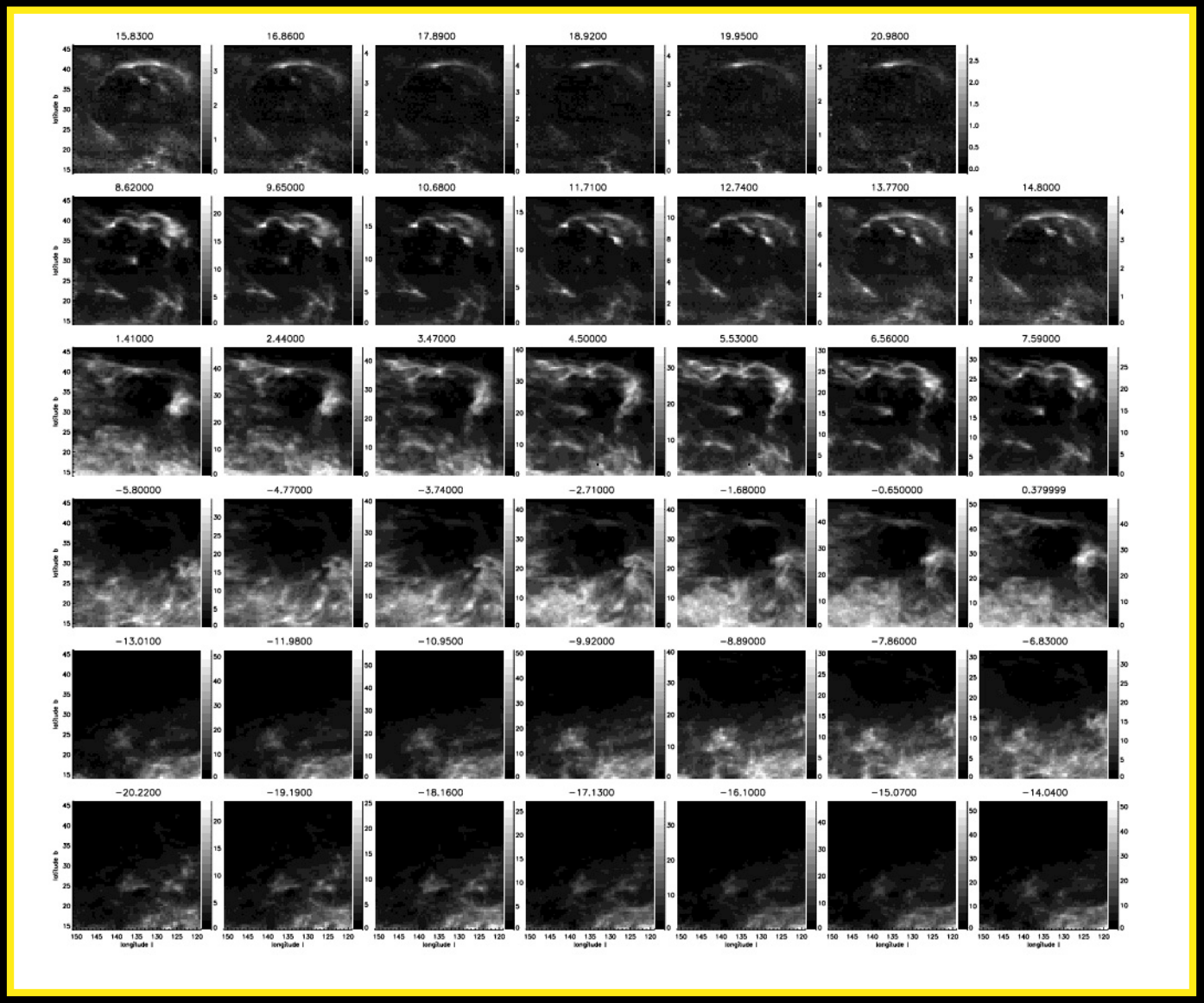


HI map of the LMC from ATCA & Parkes Multi-Beam, courtesy Stavely-Smith, Kim, et al.



Padoan, Kim, Goodman & Stavely-Smith 2001

“Fine-tuning Simulations with the SCF”



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

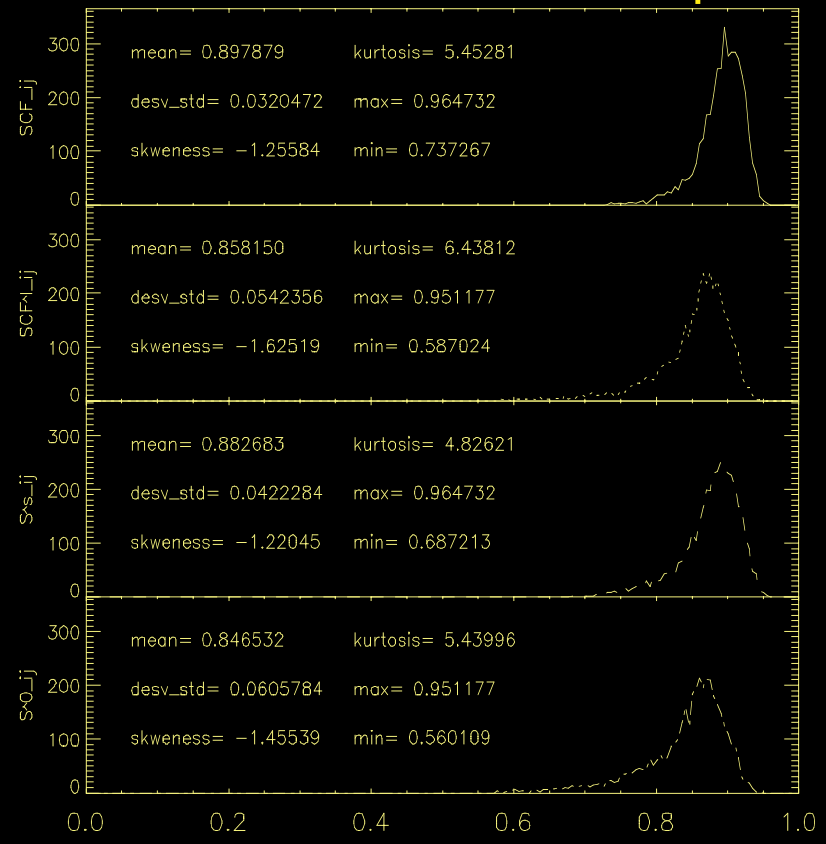
An Example of Fine-tuning

Comparison with simulations of Vazquez-Semadeni, Ballesteros-Paredes & collaborators shows:

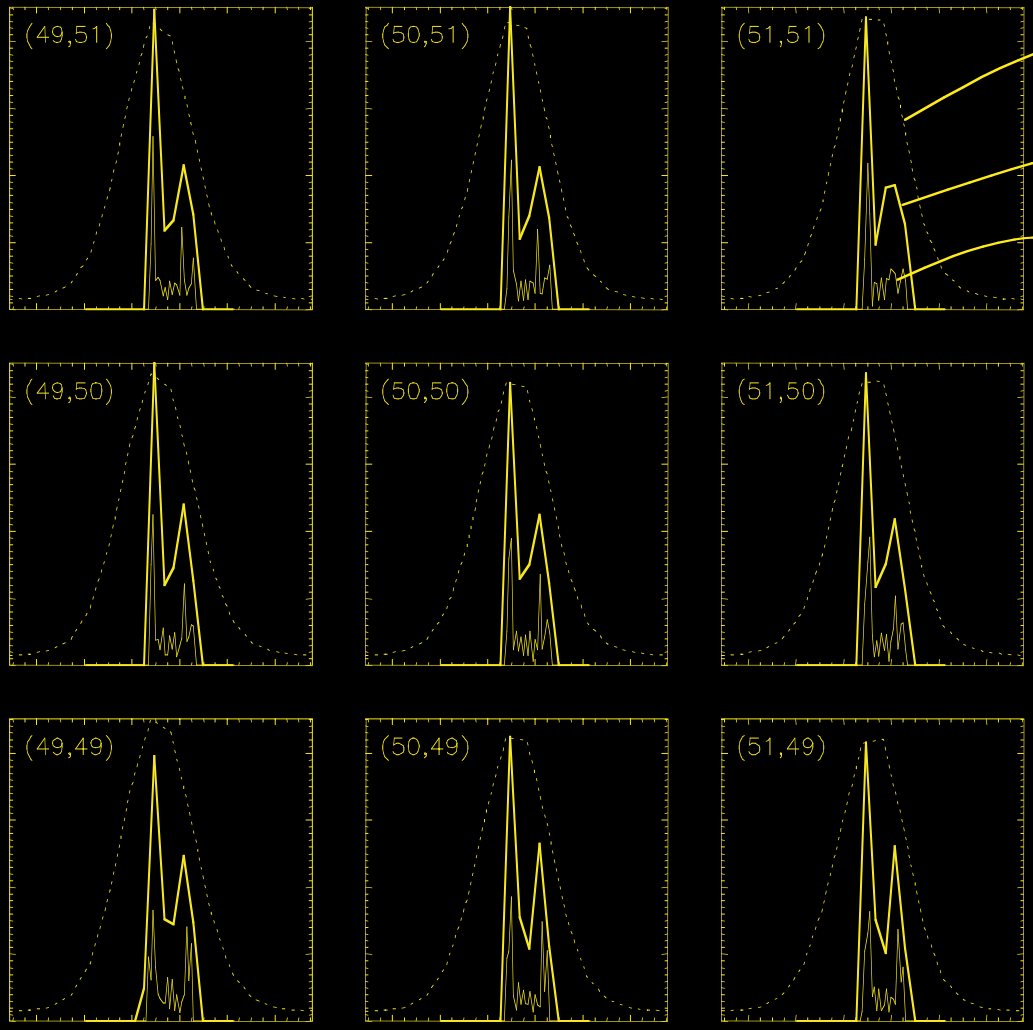
- *"Thermal Broadening"* of H I Line Profiles *can hide* much of the true(?) *velocity structure*
- SCF v.1.0 good at picking out shock-like structure in H I maps (also gives low correlation tail)

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

SCF v.1.0 for NCP Loop



Revealing Shortcomings of a Simulation



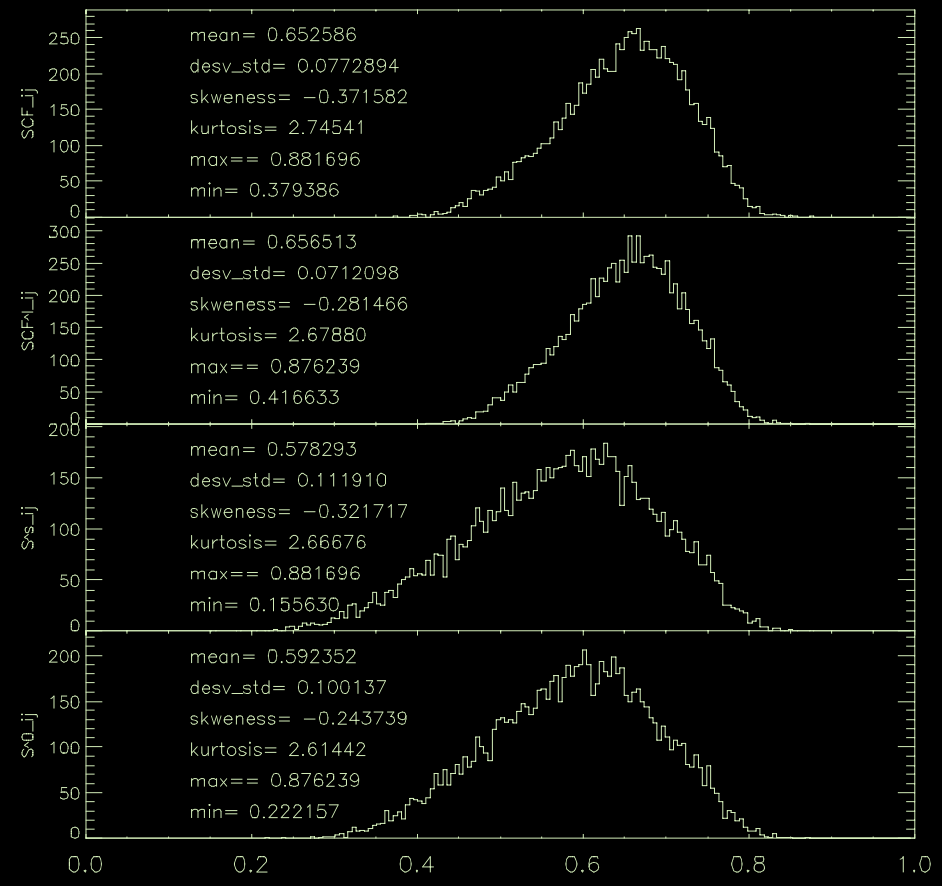
"Thermally Broadened," very high therm/turb Velocity histogram, 16 bins

Velocity histogram, 64 bins

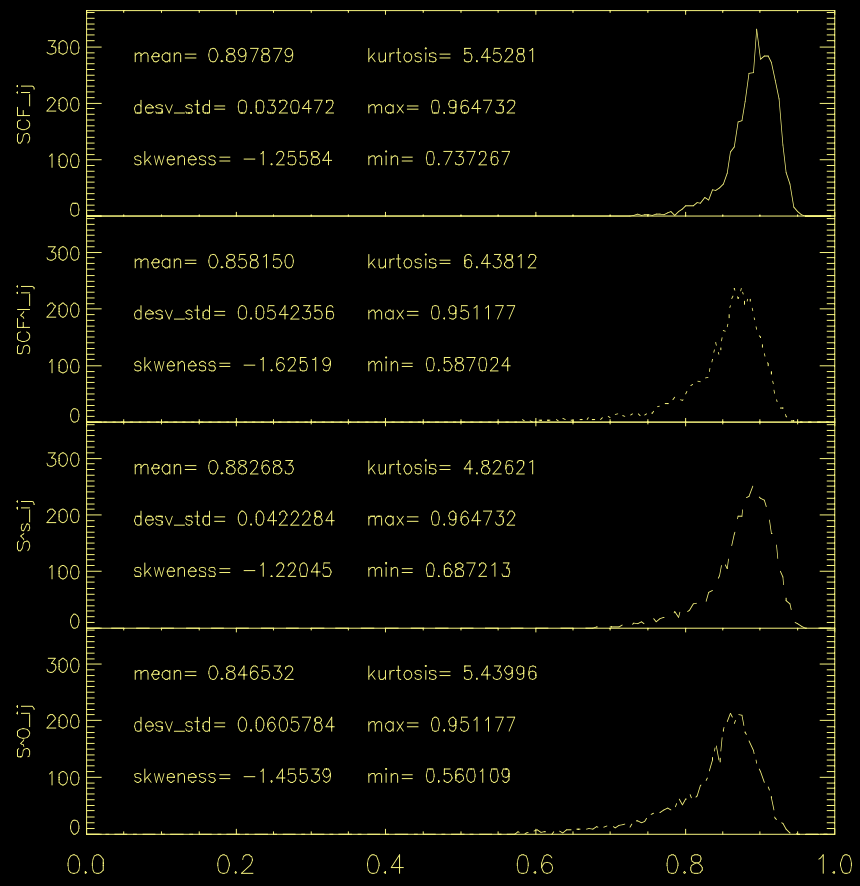
Ballesteros-Paredes, Vazquez-Semadeni & Goodman 2001

An Example of Fine-tuning

From v-histograms, 64 bins

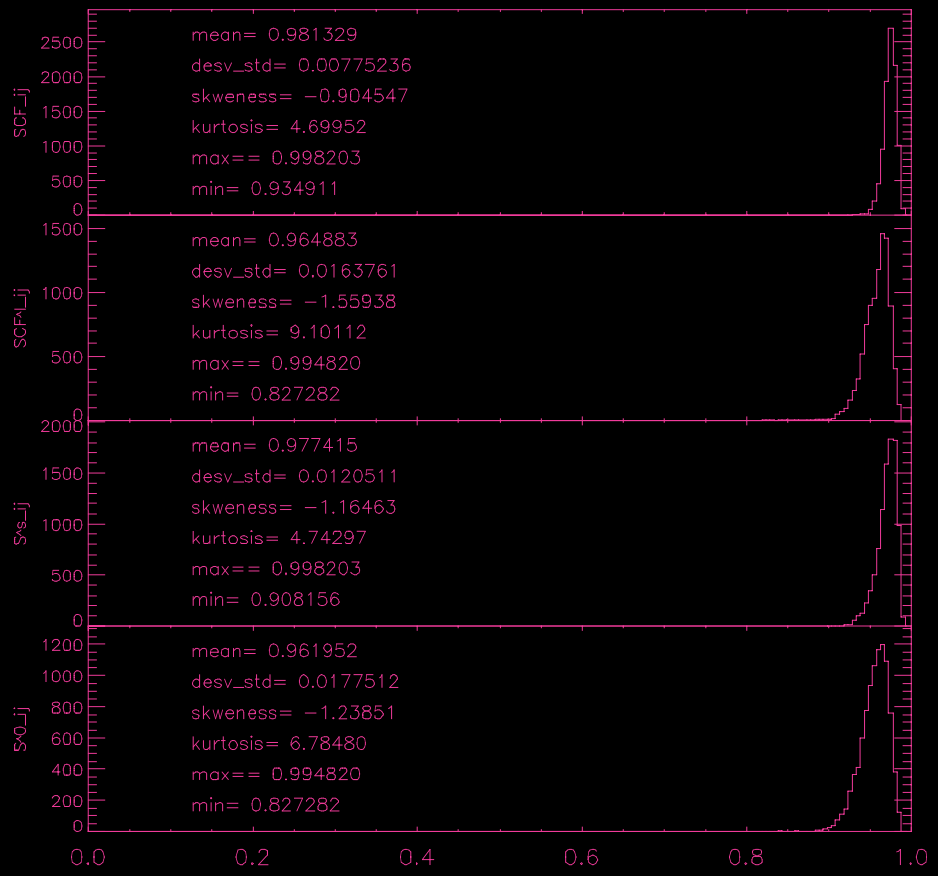


H I Observations

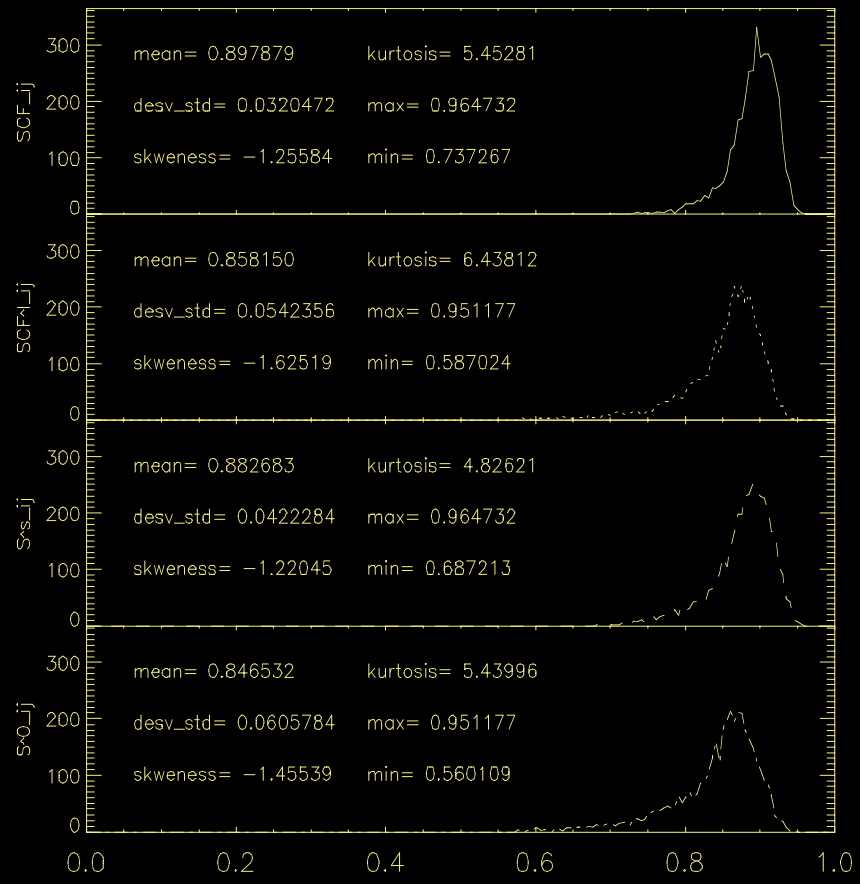


An Example of Fine-tuning

Thermally Broadened, high therm/turb

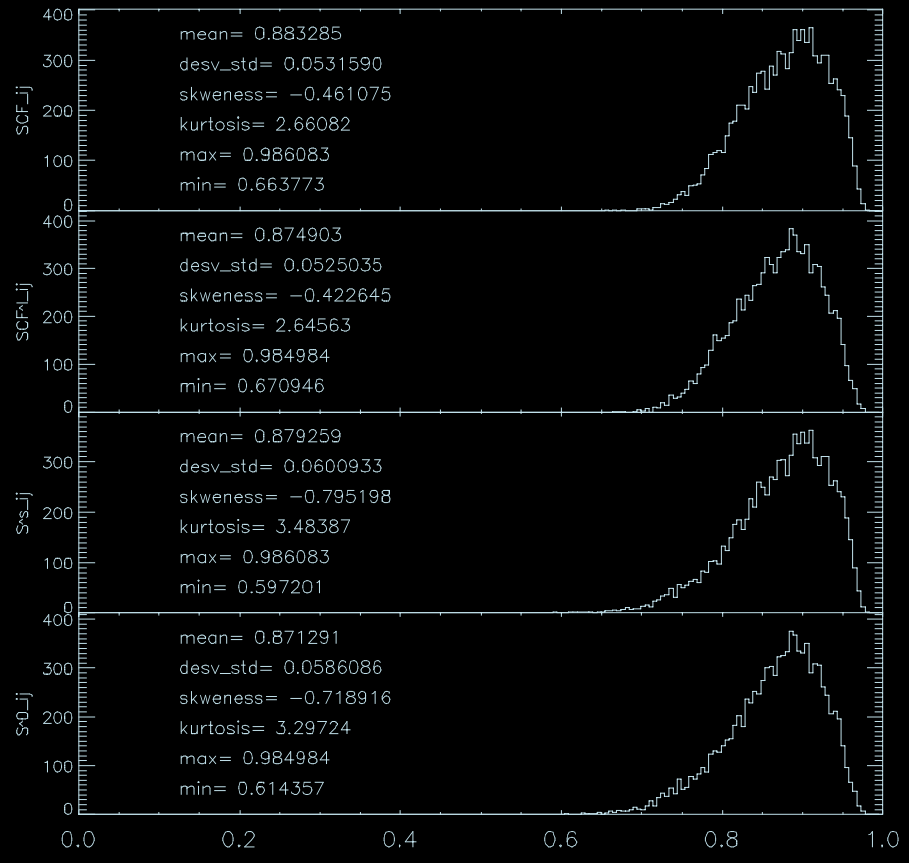


H I Observations

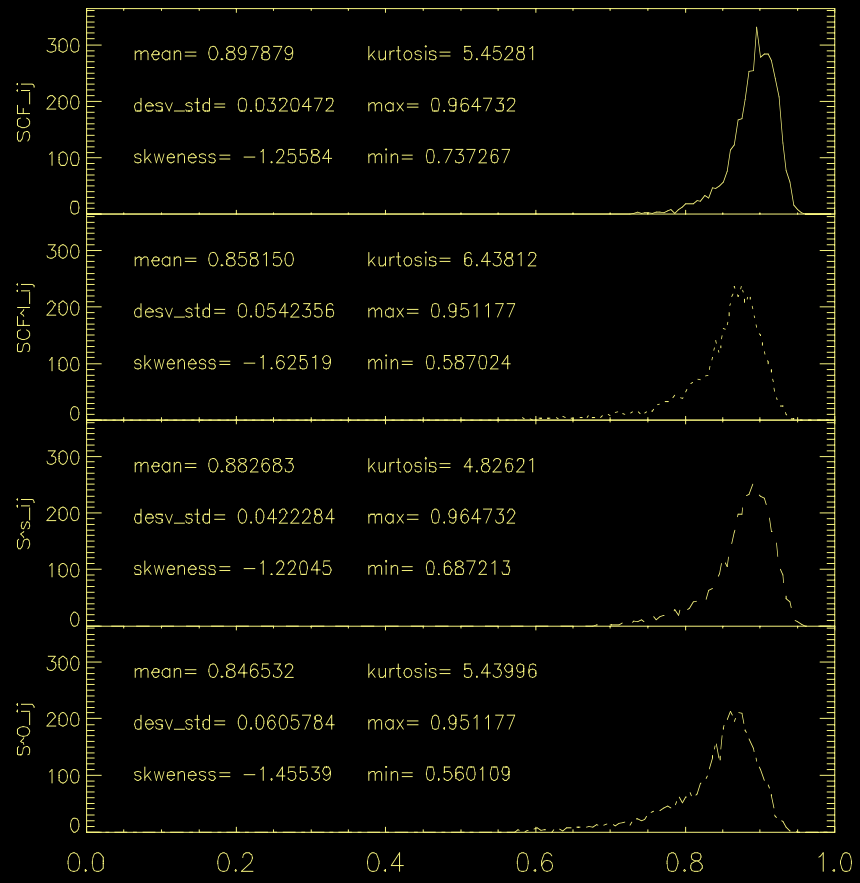


An Example of Fine-tuning

Reduce therm/turb x 6 --best match!



H I Observations



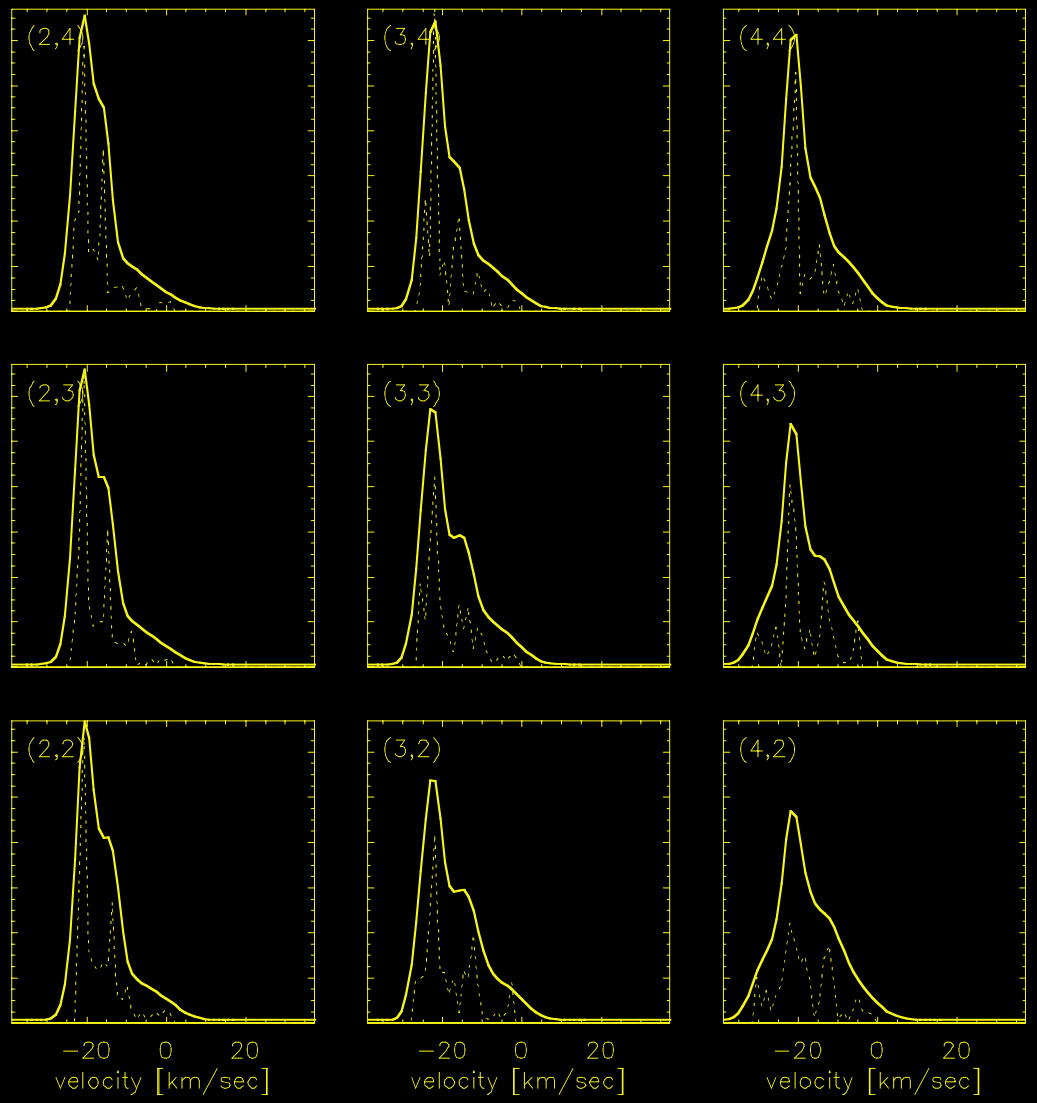
The Fine-Tuned Simulation

Sample spectra after velocity scale expanded x6 (to mimic lower ratio of thermal to turbulent pressure)

Mean temperature should really be <<8000 K

and/or

Much more energy input to turbulence (e.g. real SNe) needed



Ballesteros-Paredes, Vazquez-Semadeni & Goodman 2001

Recent SCF Comparisons

What have we learned, lately, from well-matched simulations?

- Realistic core properties, and the IMF can be reproduced from "turbulent fragmentation." (Padoan & Nordlund 2000; Padoan, Juvela, Goodman & Nordlund 2001)
- Reduction in polarization near peaks of SCUBA maps caused by reduced polarization efficiency, not geometry. (Padoan, Goodman, Draine, Juvela, Nordlund & Rögnvaldsson 2001)
- "Infall" can be faked, but not w/o non-LTE radiative transfer. (Padoan et al., in prep.)

Simulations by Padoan et al.

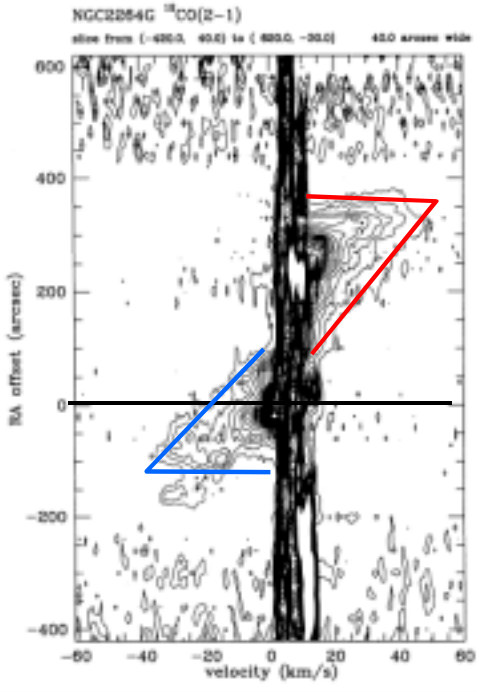
Pattern is similar to observations of extended infall by e.g. Lee, Myers & Tafalla 2001.

What *about* outflows, Mordecai??

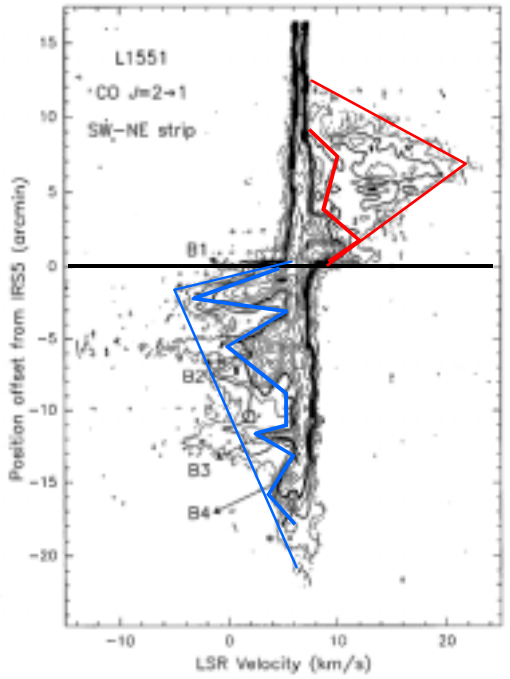
- They're highly episodic.
- Much momentum and energy *is* deposited in the cloud (~10^{44} to 10^{45} erg, comparable or greater than cloud K.E.).
- Some cloud features are *all* outflow. That's how much gas is shoved around!

See collected thesis papers of H. Arce.
(Arce & Goodman 2001a,b,c,d).

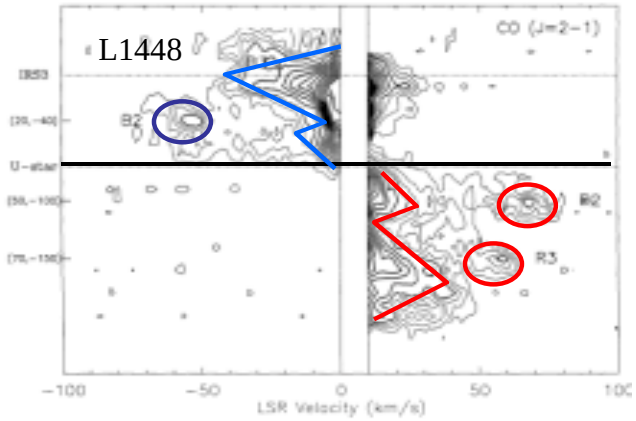
Sample outflow position-velocity diagrams



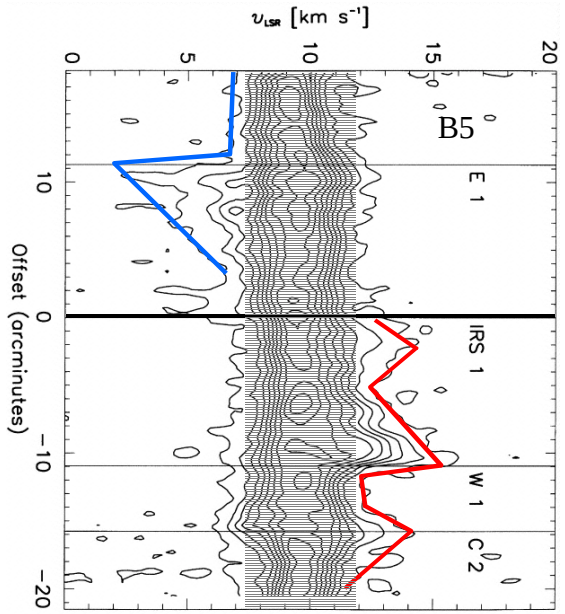
Lada & Fich 1996



Bachiller, Tafalla & Cernicharo 1994

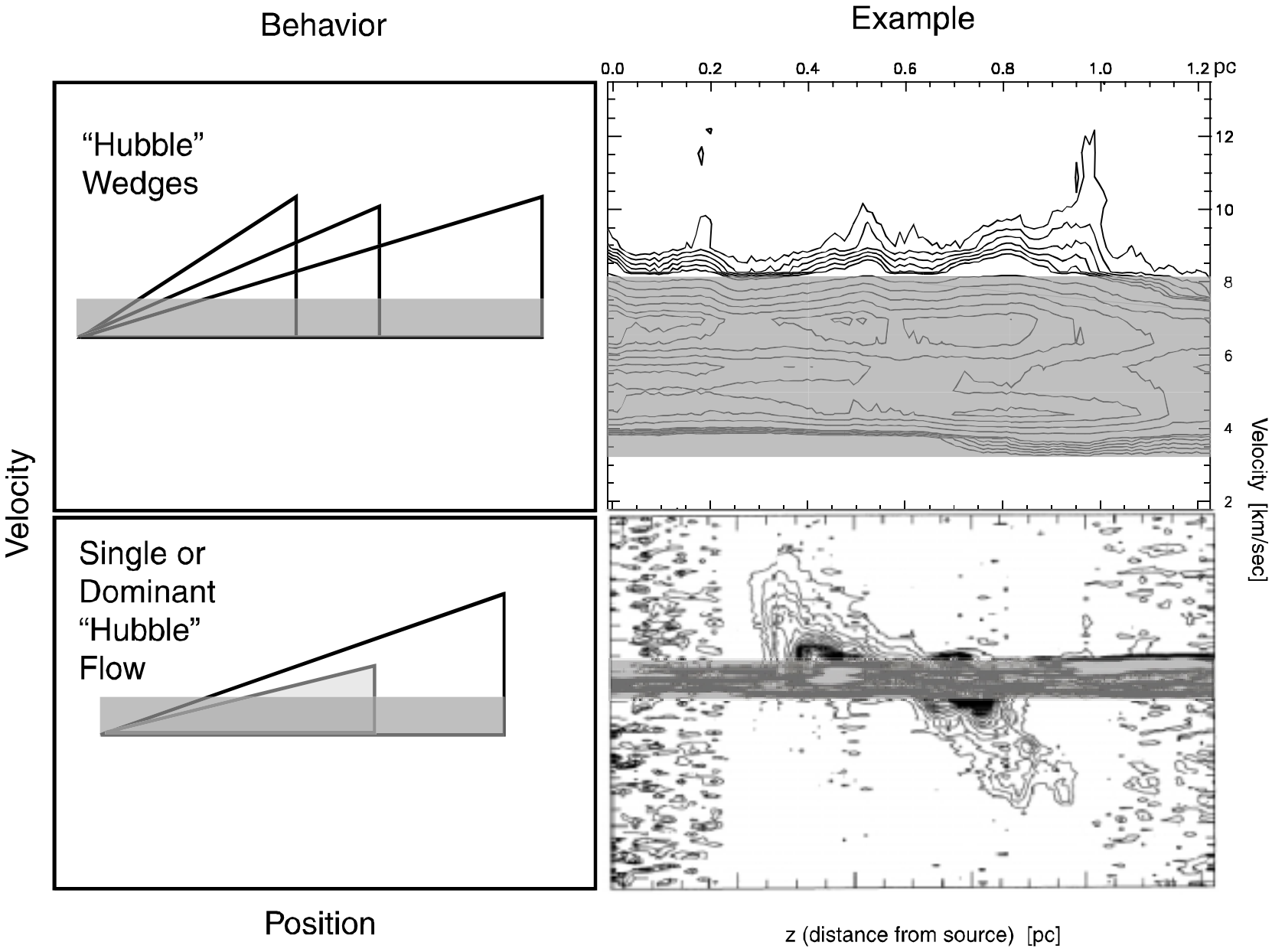


Bachiller et al. 1990

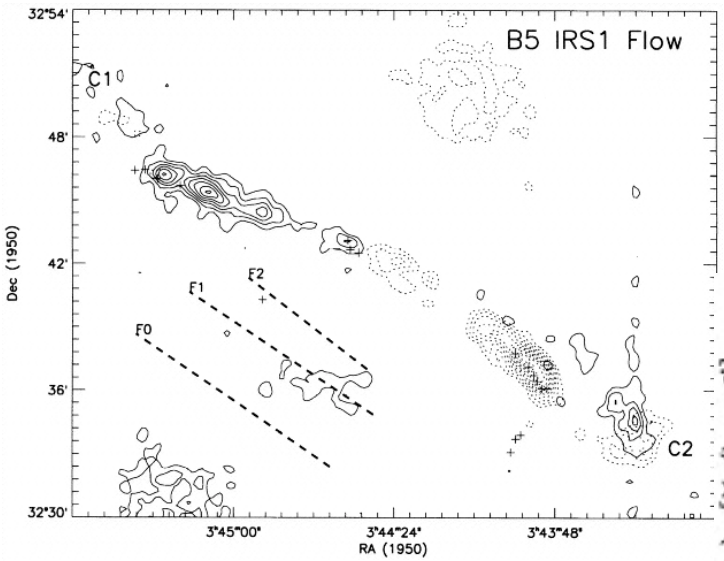


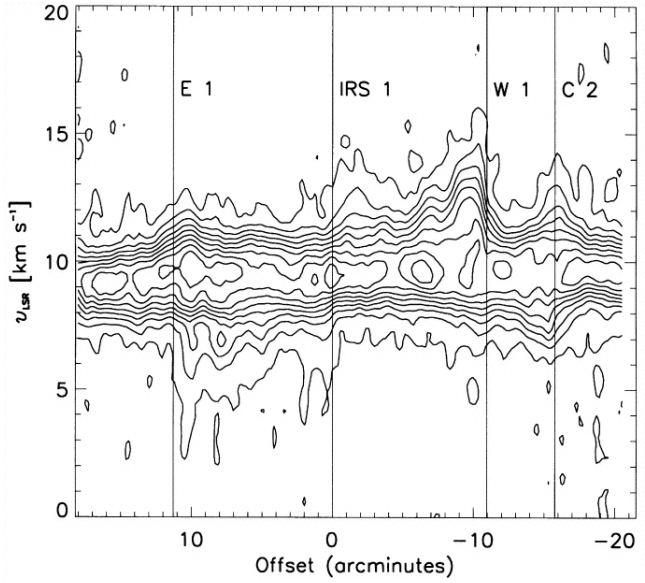
Yu Billawala & Bally 1999

Outflow position-velocity diagrams

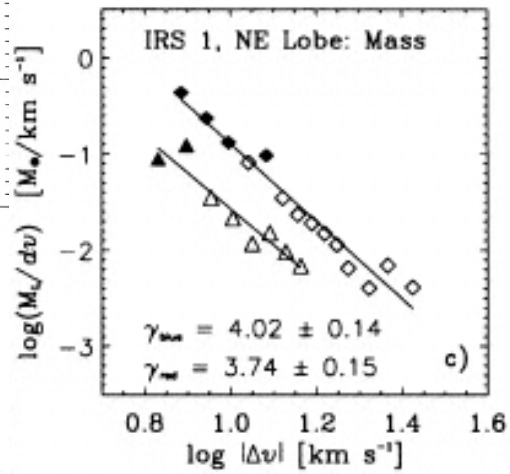


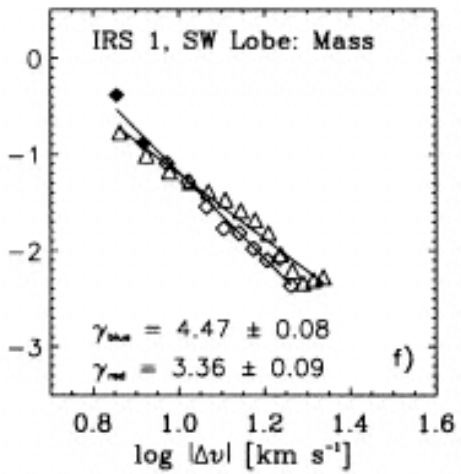
Arce & Goodman 2001

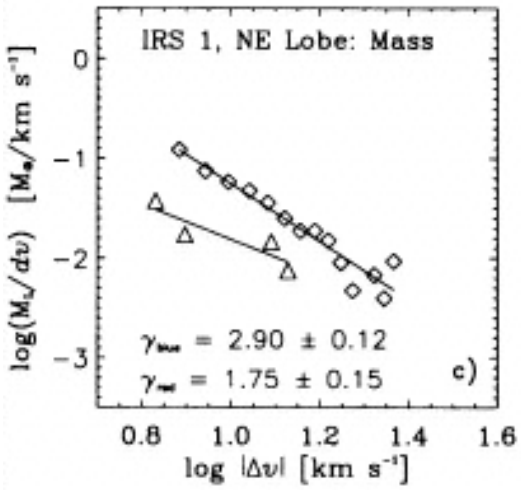


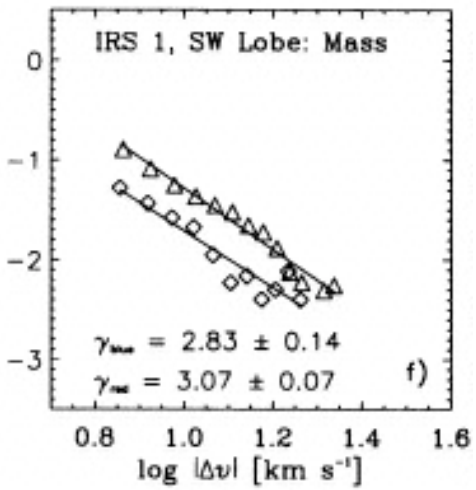


Mass-Velocity Relations can be very steep, especially in "bursty-looking" sources…





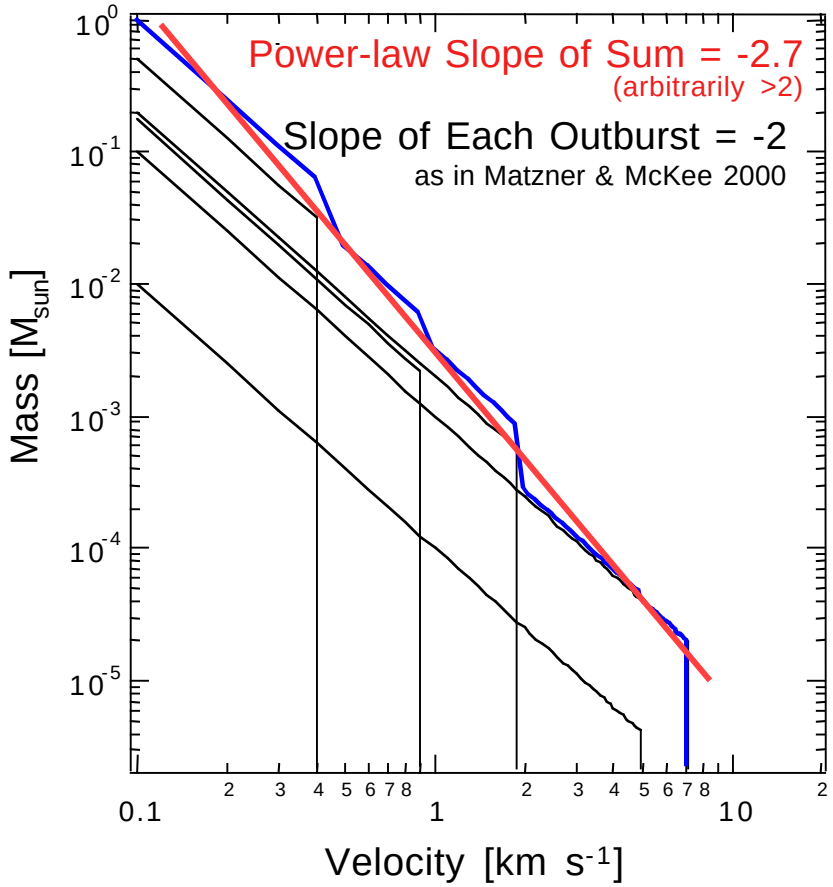


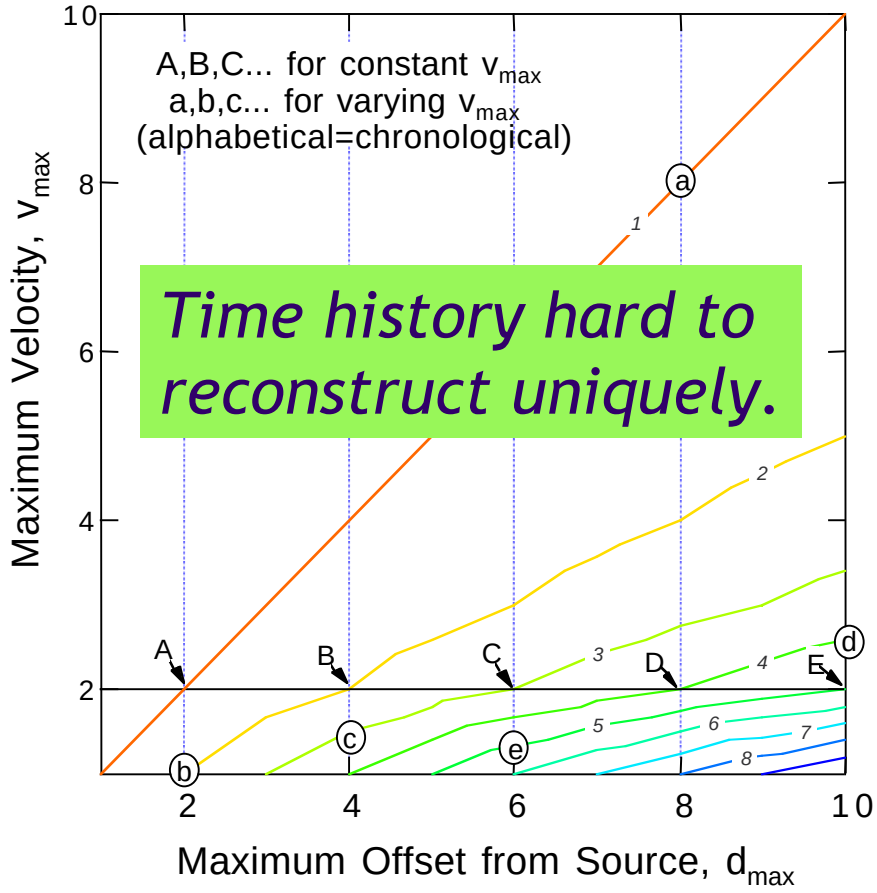


B5

Yu, Billawala, Bally, 1999

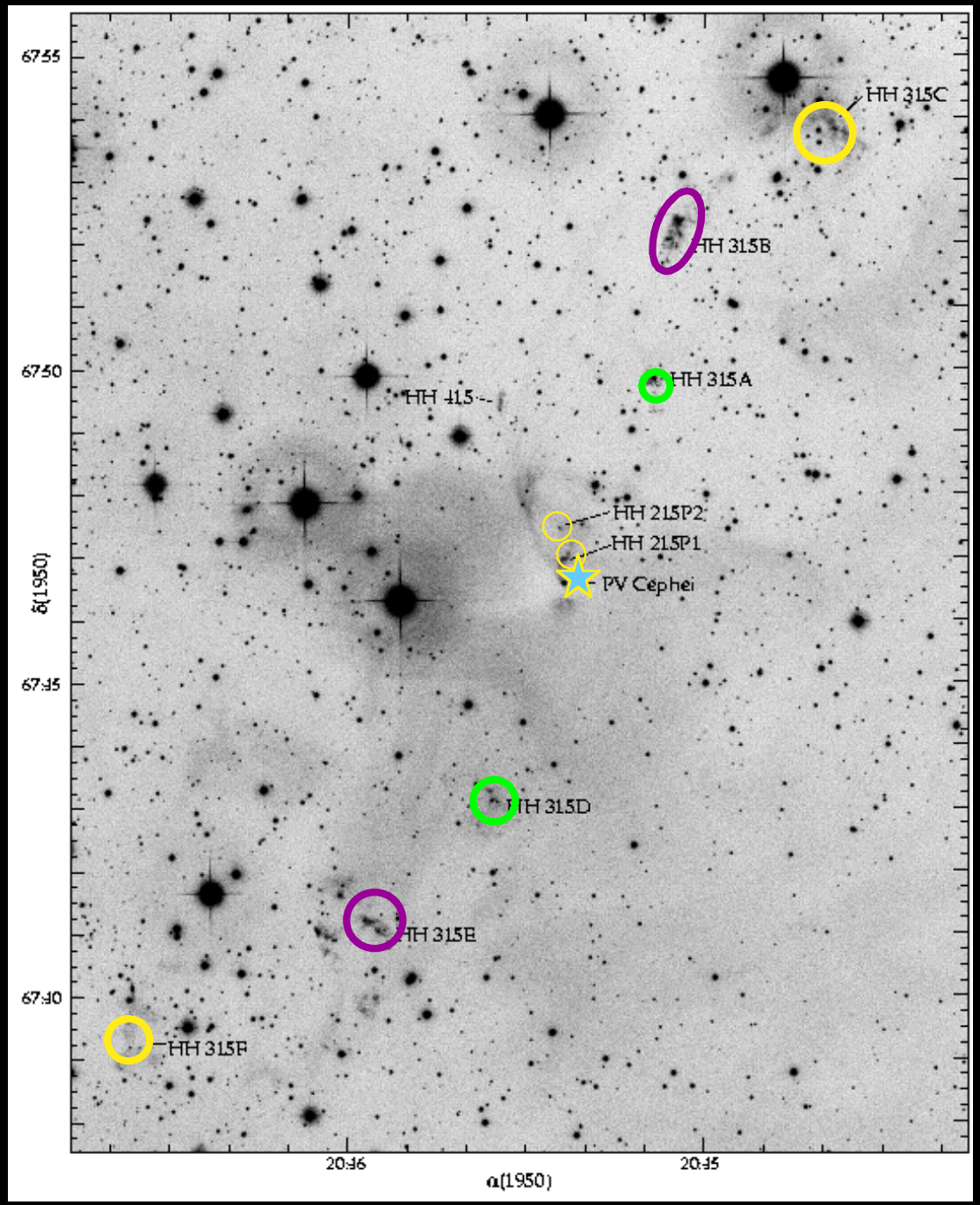
Mass-Velocity Relations in Episodic Outflows: *Steep Slopes result from Summed Bursts*





Arce & Goodman 2001

"Giant" Herbig-Haro Flows: PV Ceph



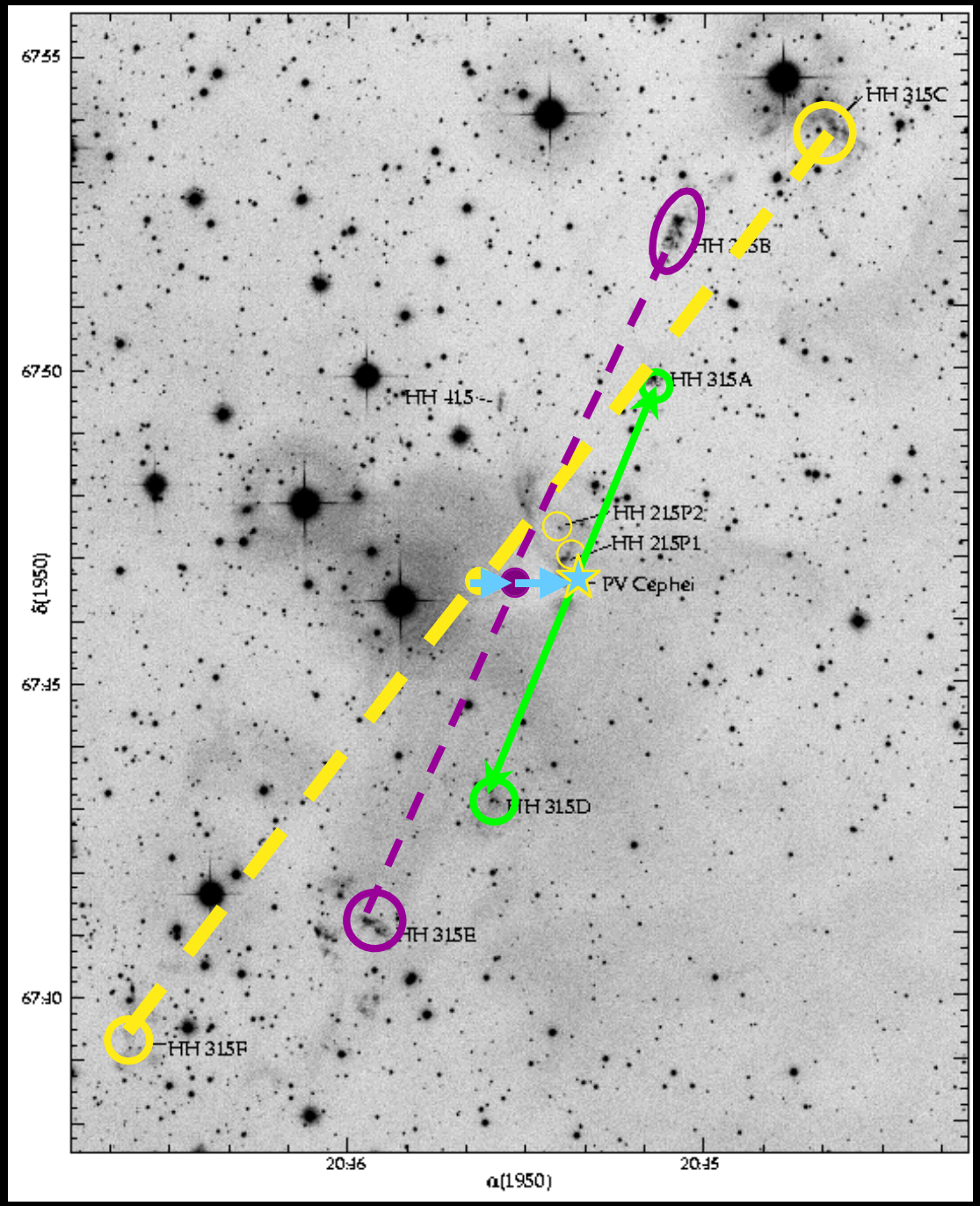
Reipurth, Bally & Devine 1997

A New Proposal:

Episodic ejections from precessing or wobbling moving source

Required motion of 0.25 pc (e.g. 2 km s^{-1} for 125,000 yr or 20 km s^{-1} for 12,500 yr)

Arce & Goodman 2001

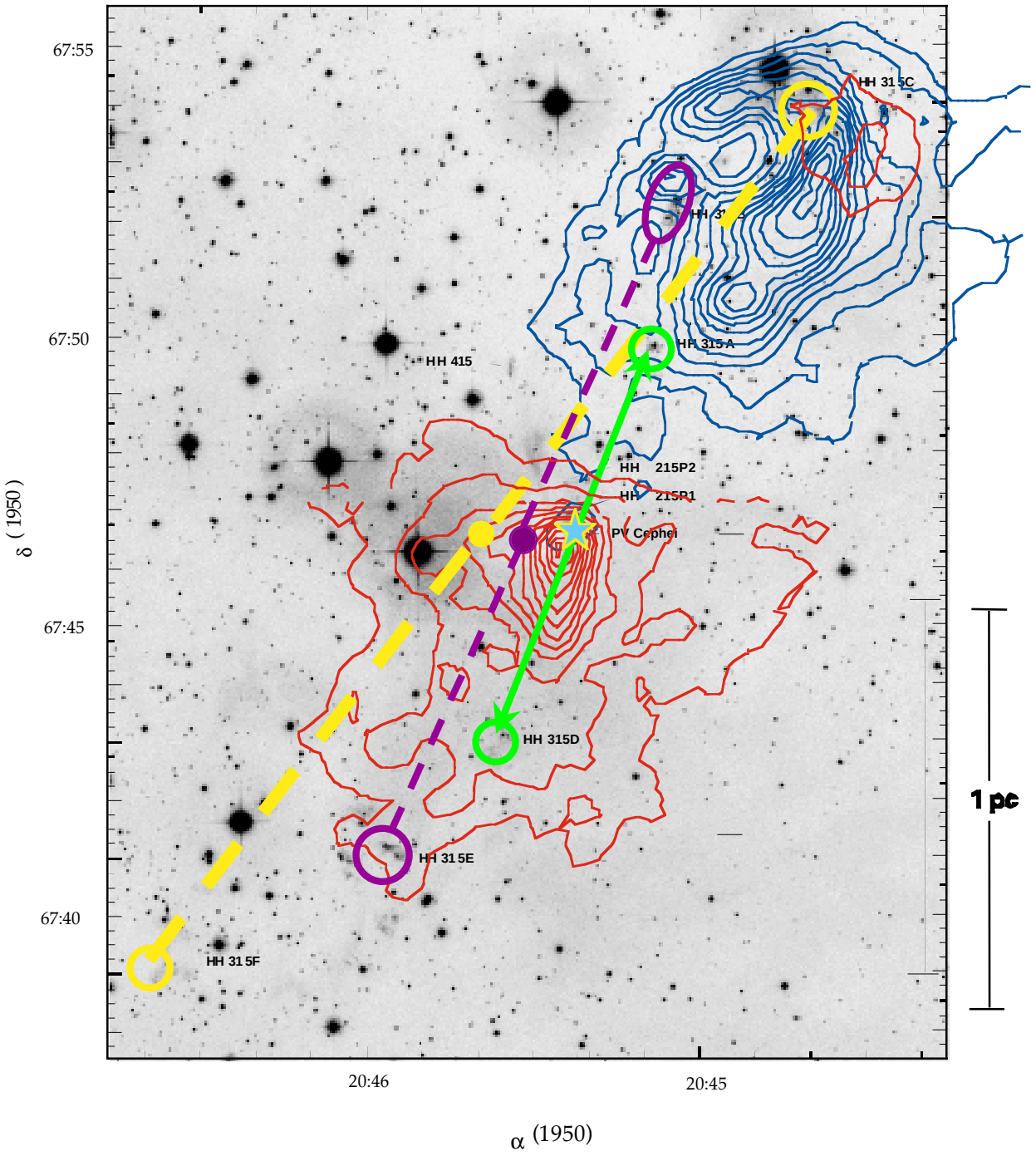


PV Ceph

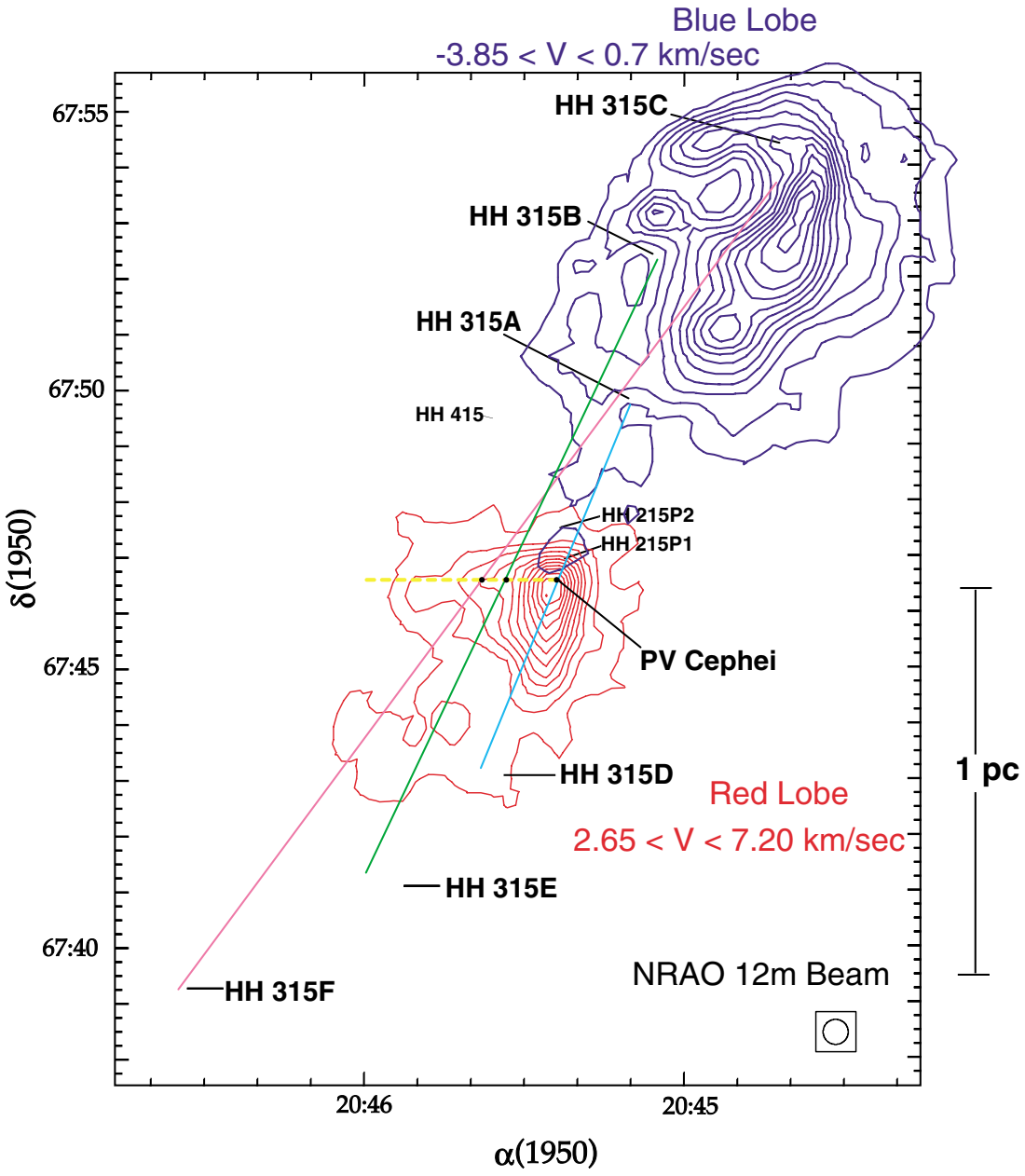
^{12}CO (2-1) OTF
*Map from **NRAO 12-m***

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

Arce & Goodman 2001



Even leaves a trail?



Arce & Goodman 2001

Cloud V_{LSR}= 1.68 km/sec

starting contour= 1.5 K km/sec
contour steps= 1 K km/sec