



# Watching Stars Form

*(or “The Importance of  $p$ - $p$ - $v$  Data and Linked Views in Understanding Star Formation”)*

Alyssa A. Goodman

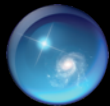
*Harvard-Smithsonian Center for Astrophysics*

*Modern Hydrodynamic AMR Simulation, ( $B=0$ ), courtesy Stella Offner*

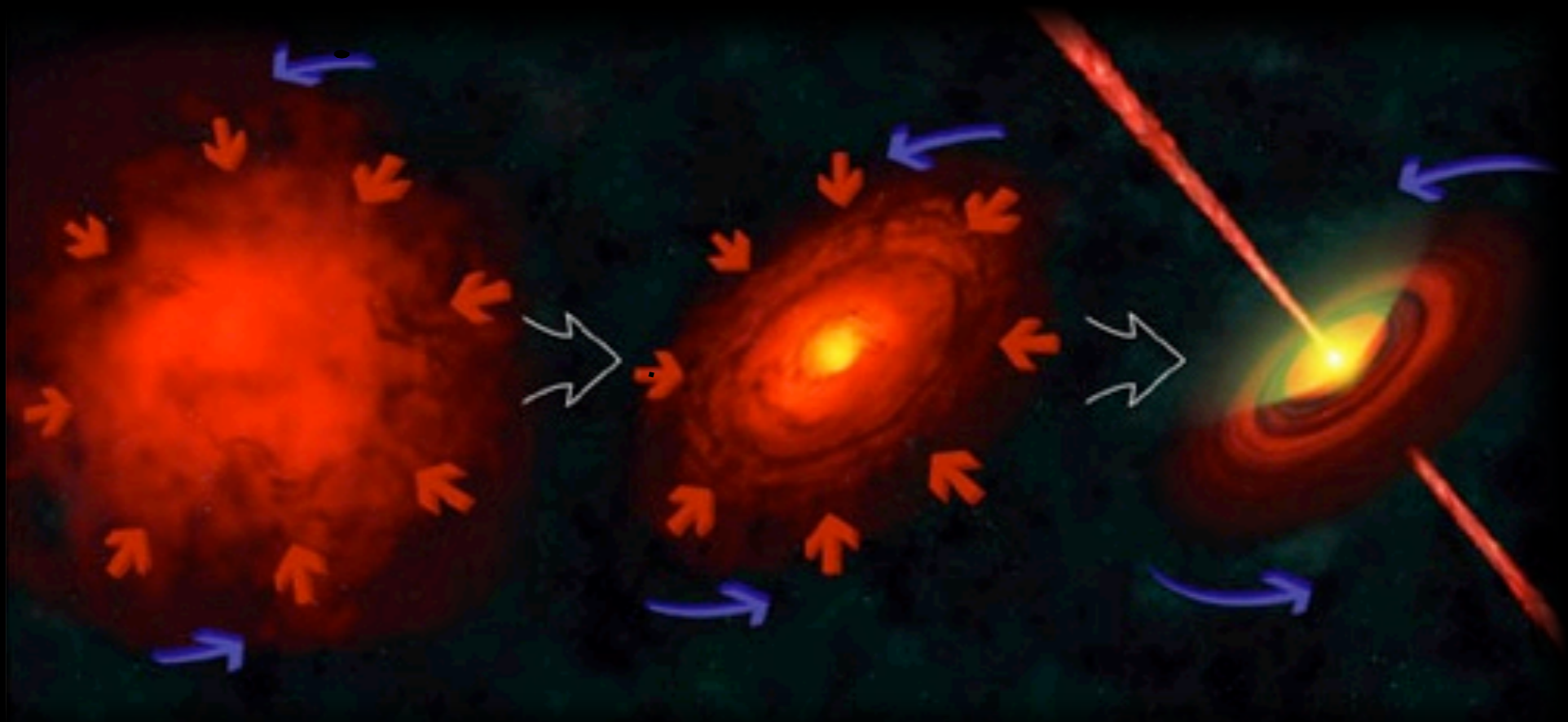


Perseus

[www.flickr.com/photos/66496709@N00/6791649829/in/photostream](http://www.flickr.com/photos/66496709@N00/6791649829/in/photostream)  
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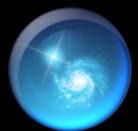
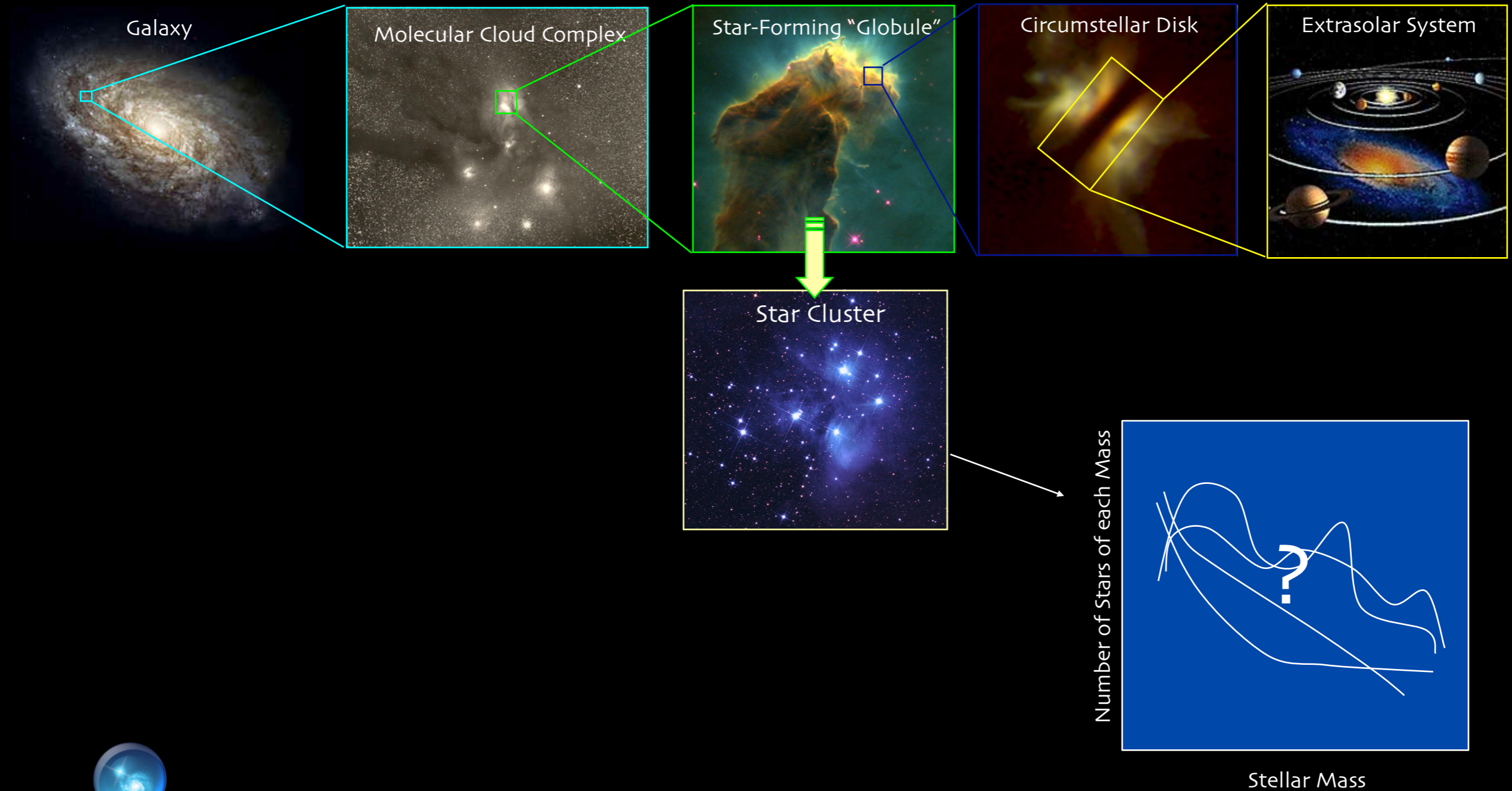


# Star Formation 101



©Adison-Wesley 2004

# Star Formation 201



*Magnetic  
Fields*

*Gravity*

*Chemical & Phase  
Transformations*

*~ 1 pc*

*Star (& Planet) Formation  
Radiation*

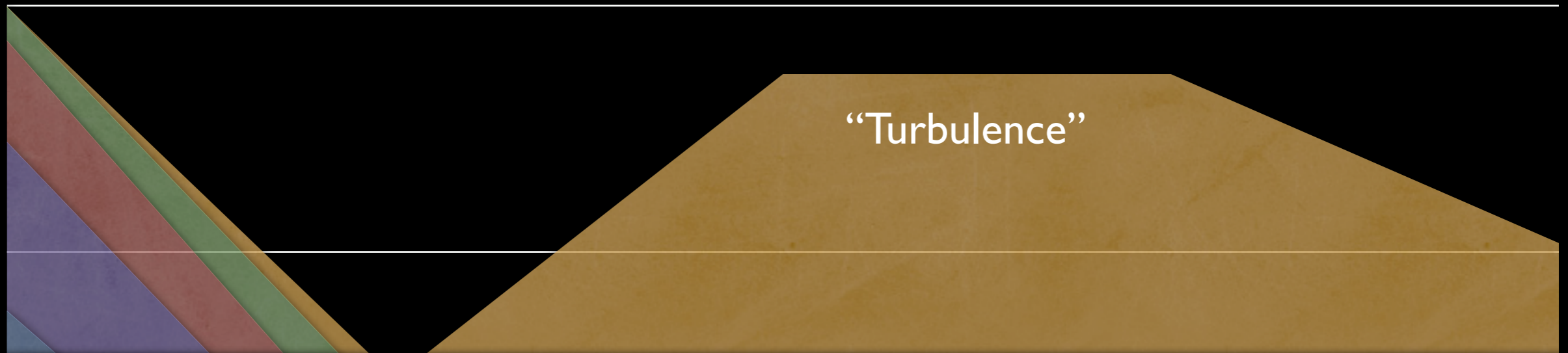
*Thermal  
Pressure*

*“Turbulence”  
(Random Kinetic Energy)*

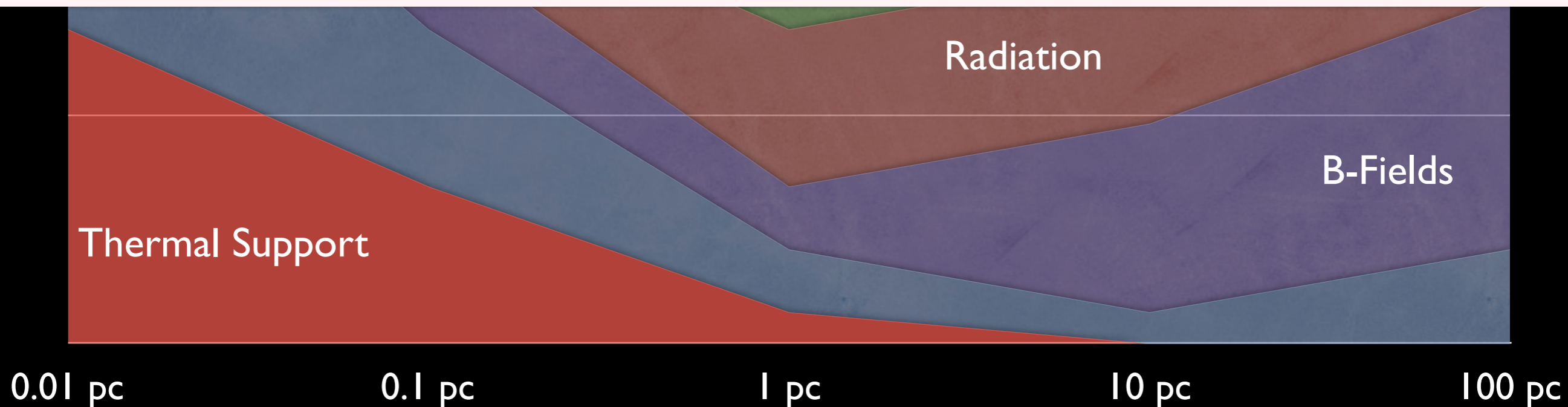
*Outflows  
& Winds*

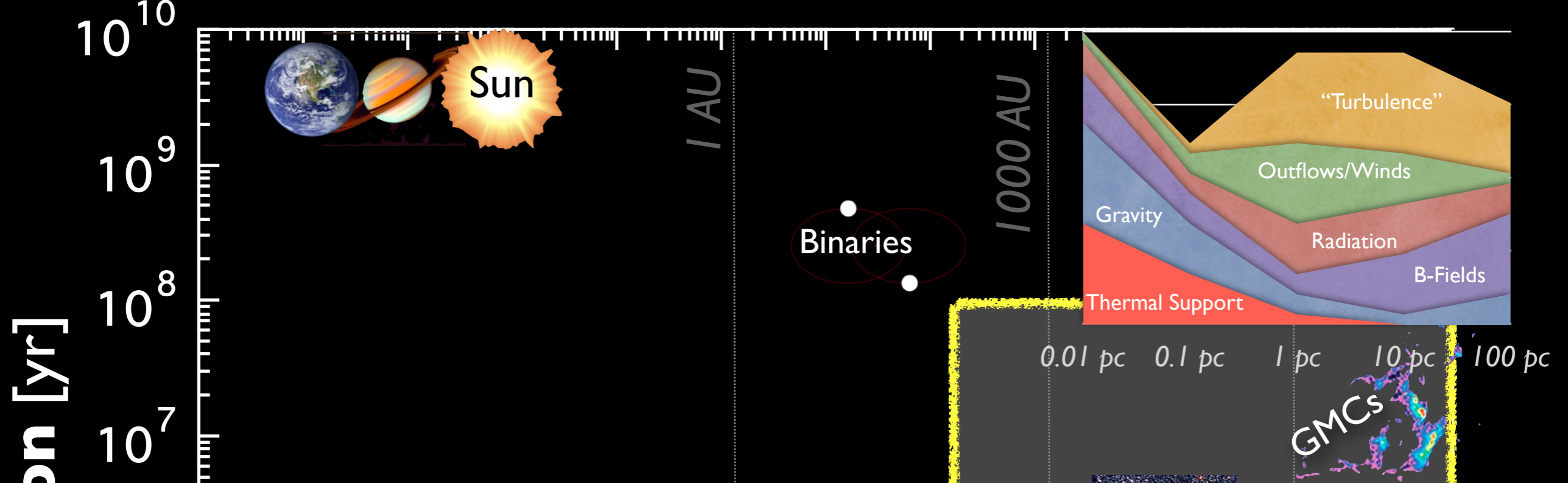
*Image Credit: Jonathan Foster, CfA/COMPLETE Deep Megacam Image of West End of Perseus*

# What forces matter most on what scales?

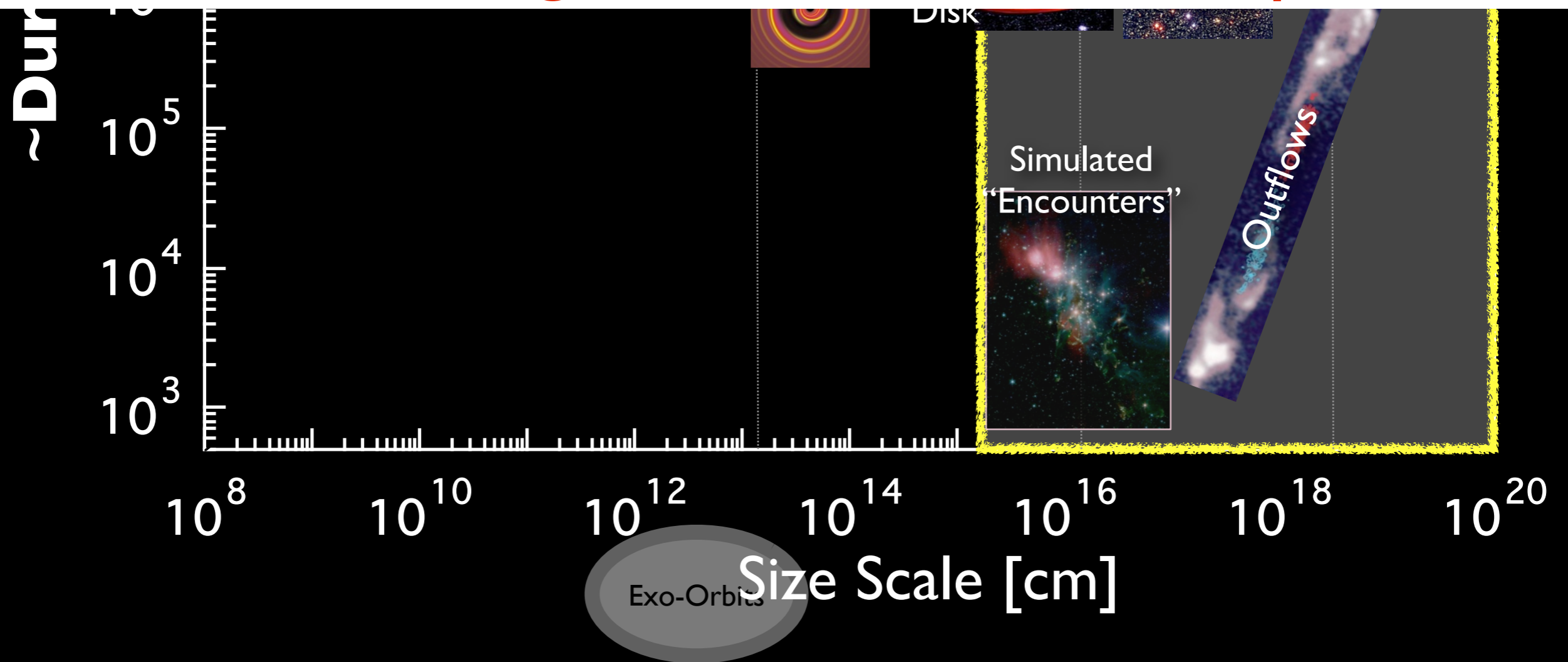


**Warning to Theorists:**  
This is a schematic, philosophical diagram,  
not data...or even necessarily true, yet.

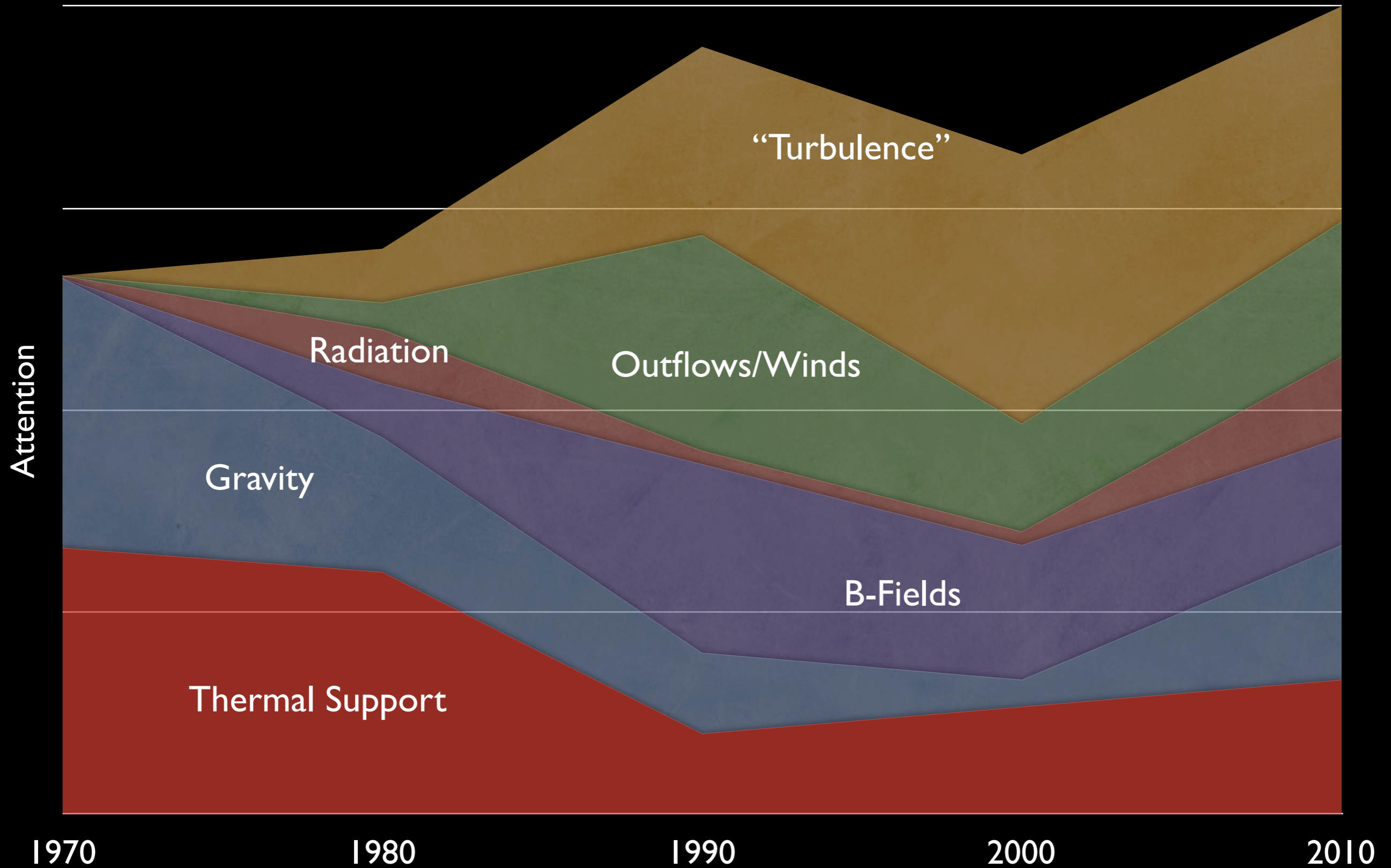




## Second Warning: Answer is Time-Dependent



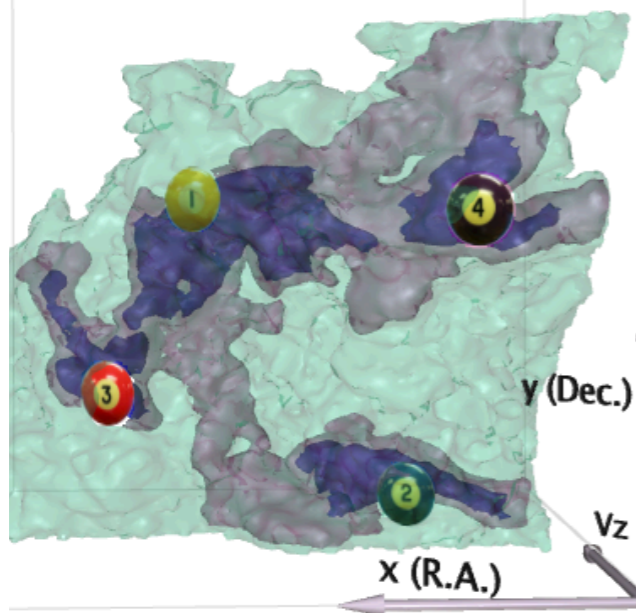
# Changes of Heart, rather than in Physics...



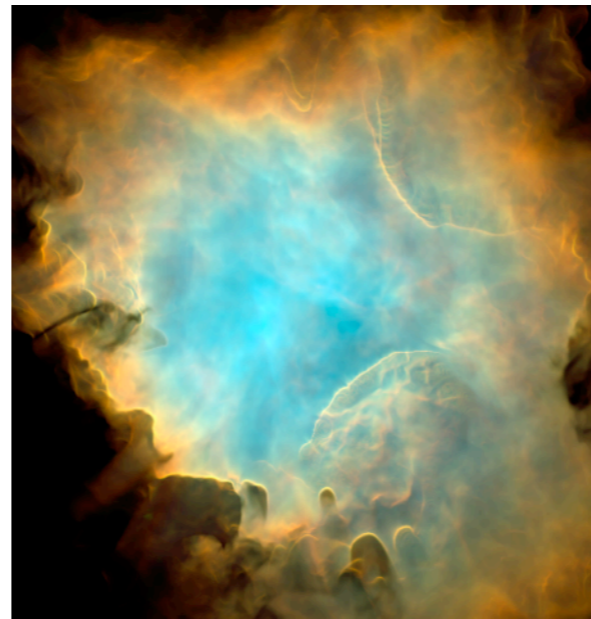


# 3 Questions

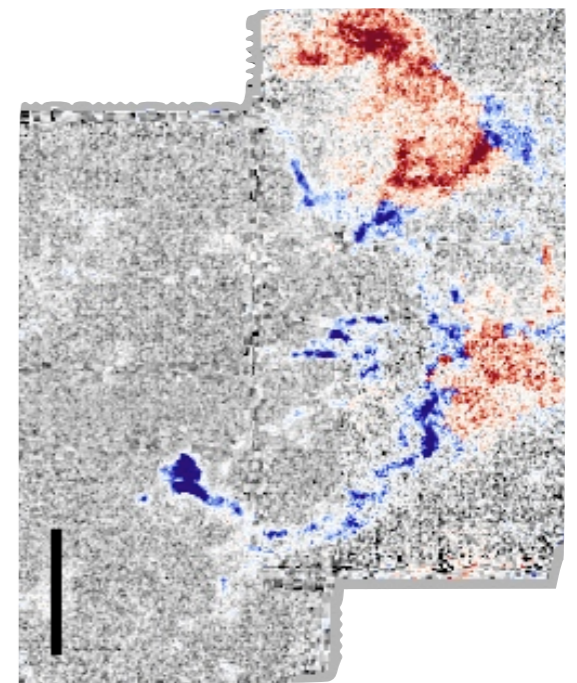
1. At what scales does **gravity** matter?



2. What do **stars** really do to clouds?

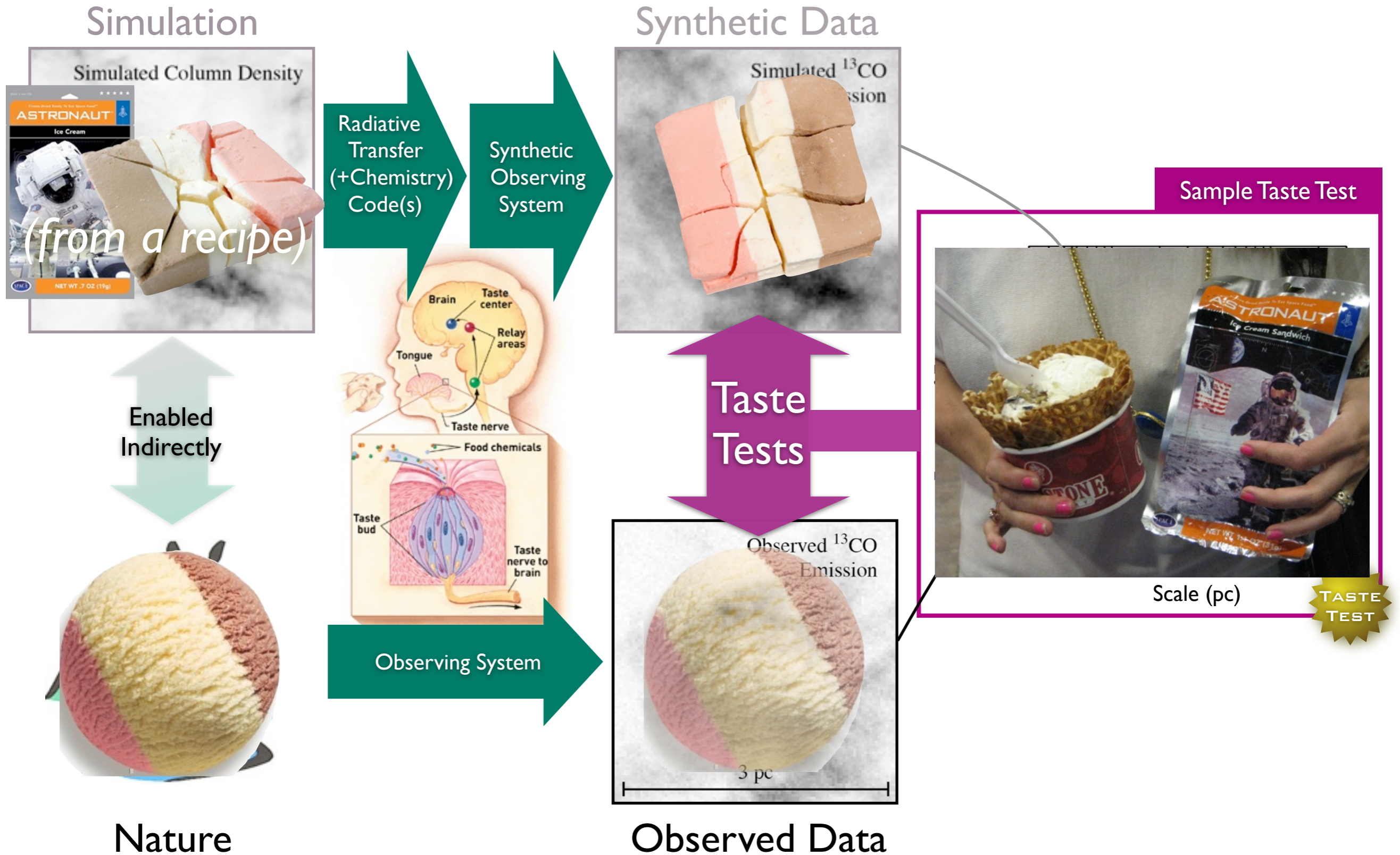


3. How can “new” statistical **visualization** tools help?

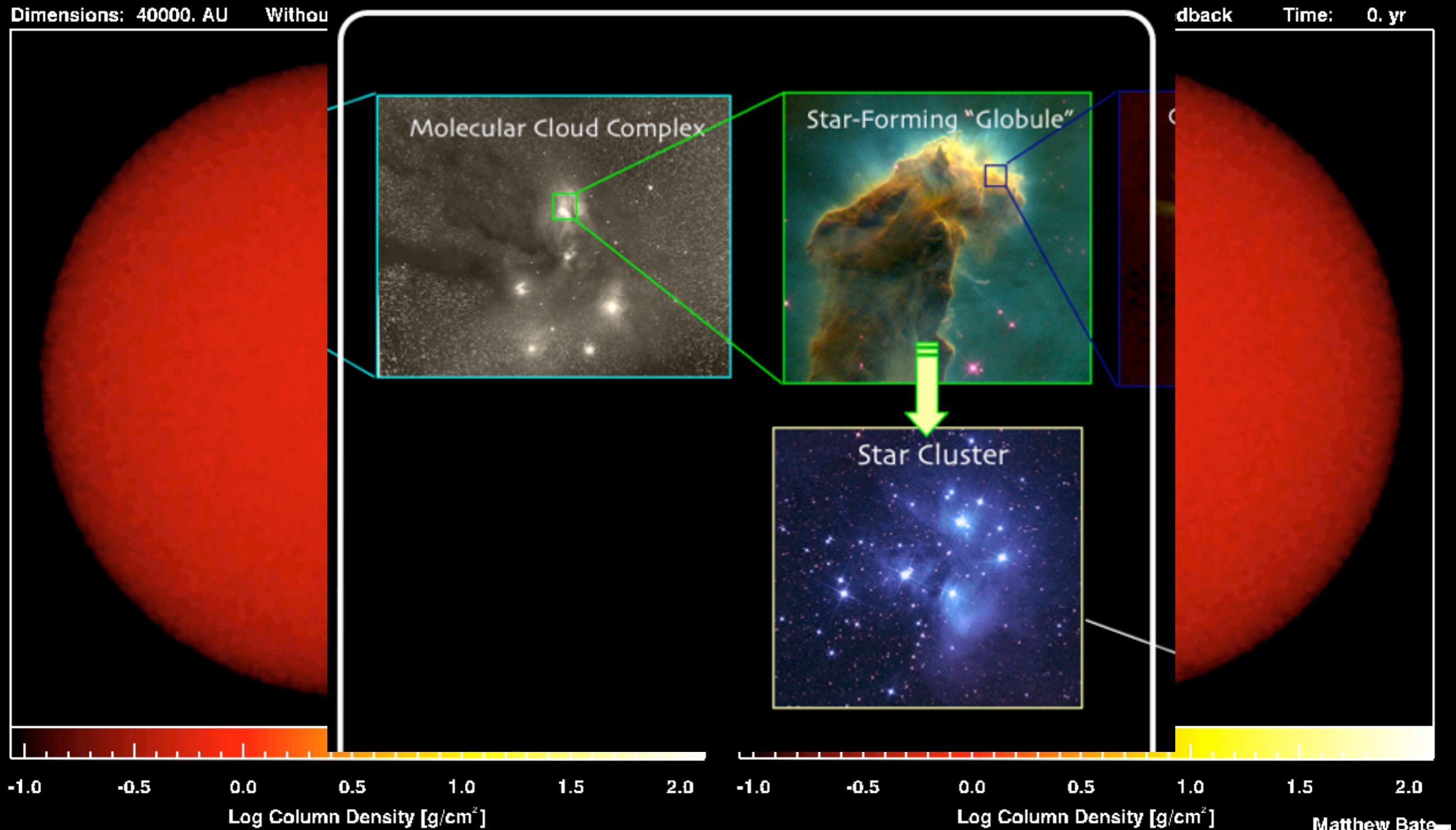


+ “tasty” approaches to answers

# The Taste-Testing Process



# Our Goal is to “Taste” Star Formation



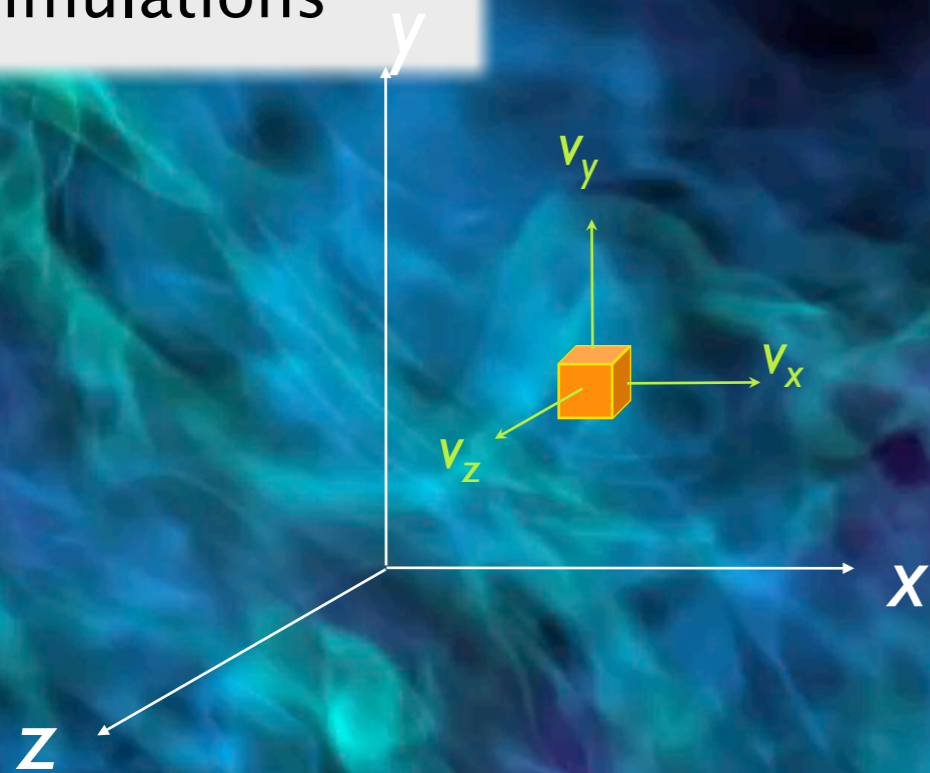
*Simulations of Bate 2009*

# “Three” Dimensions: Spectral-Line Mapping

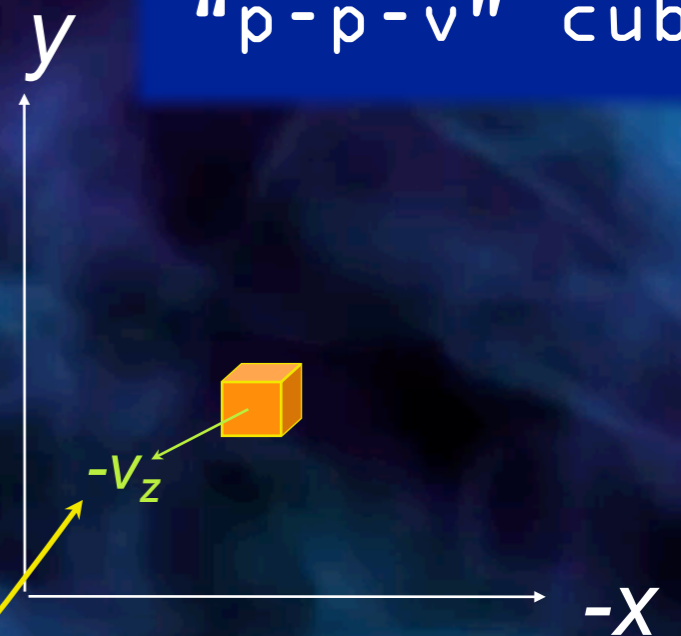
We wish we could measure...

*But* we can measure...

Simulations



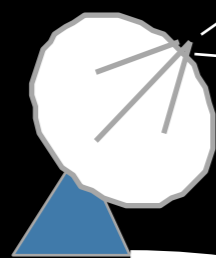
“p-p-v” cubes



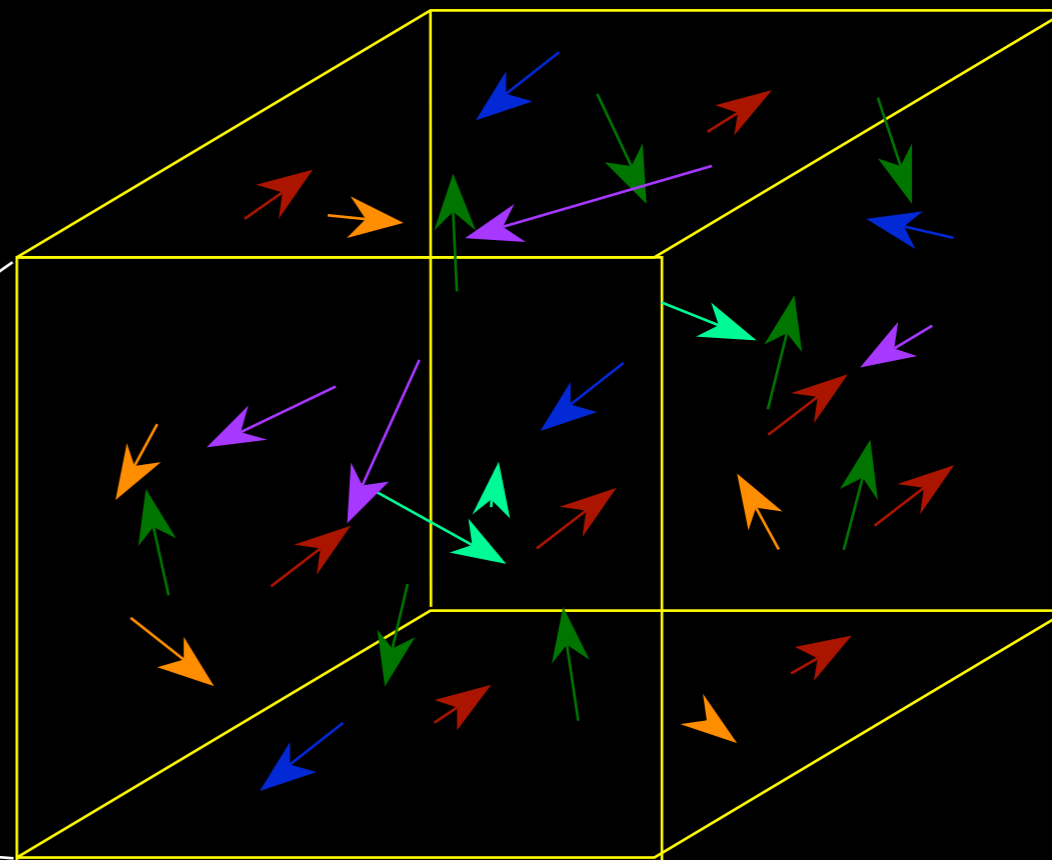
$v_z$  *only* from  
“spectral-line  
maps”

*Hydrodynamic AMR Simulation, courtesy Stella Offner*

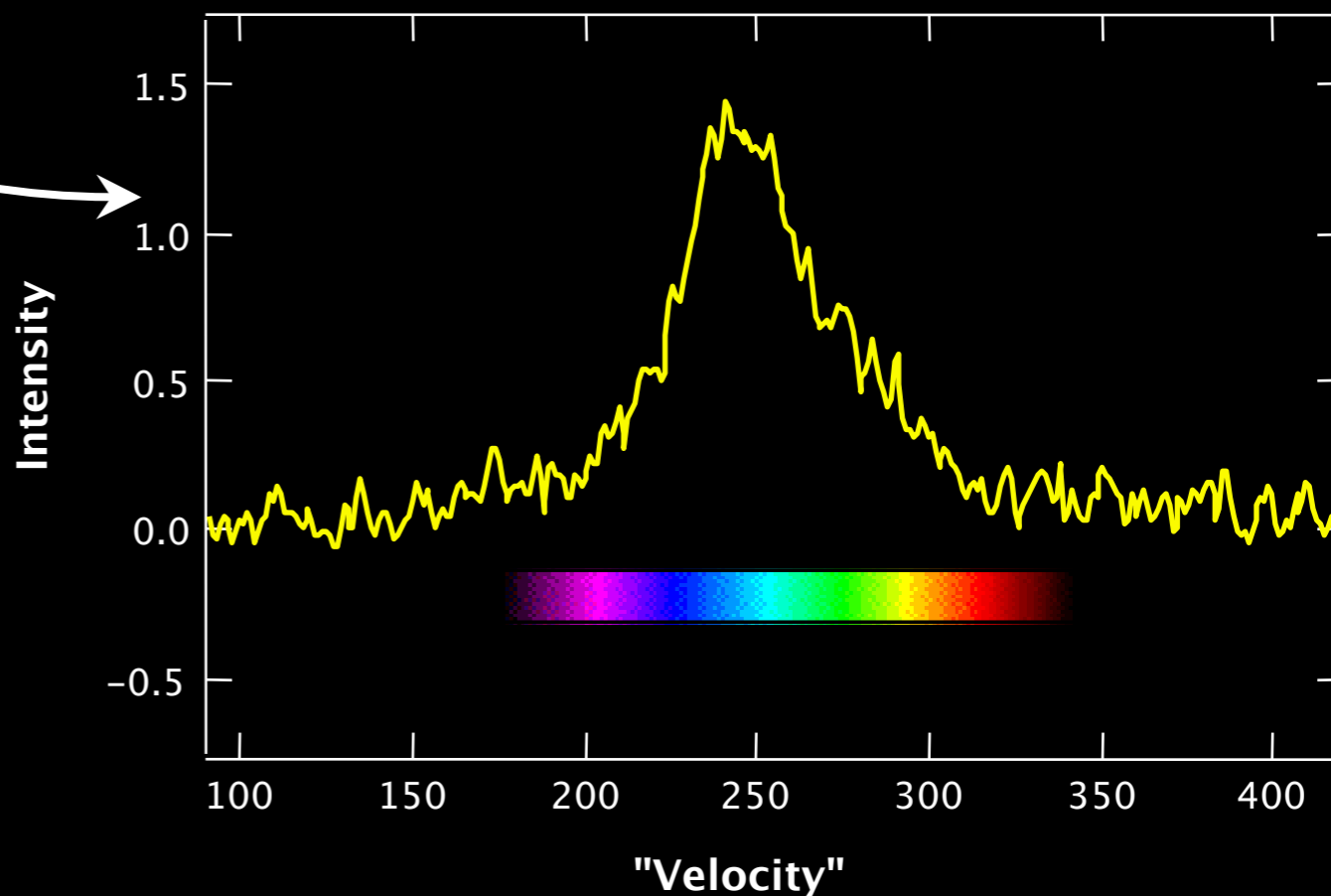
# Velocity from Spectroscopy



Telescope +  
Spectrometer

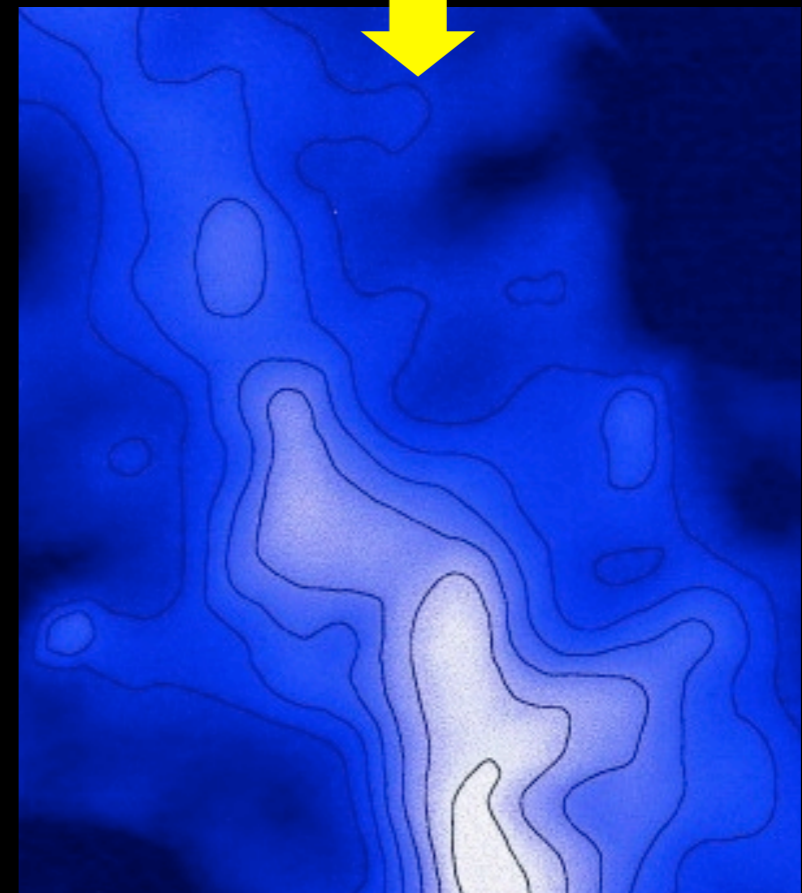
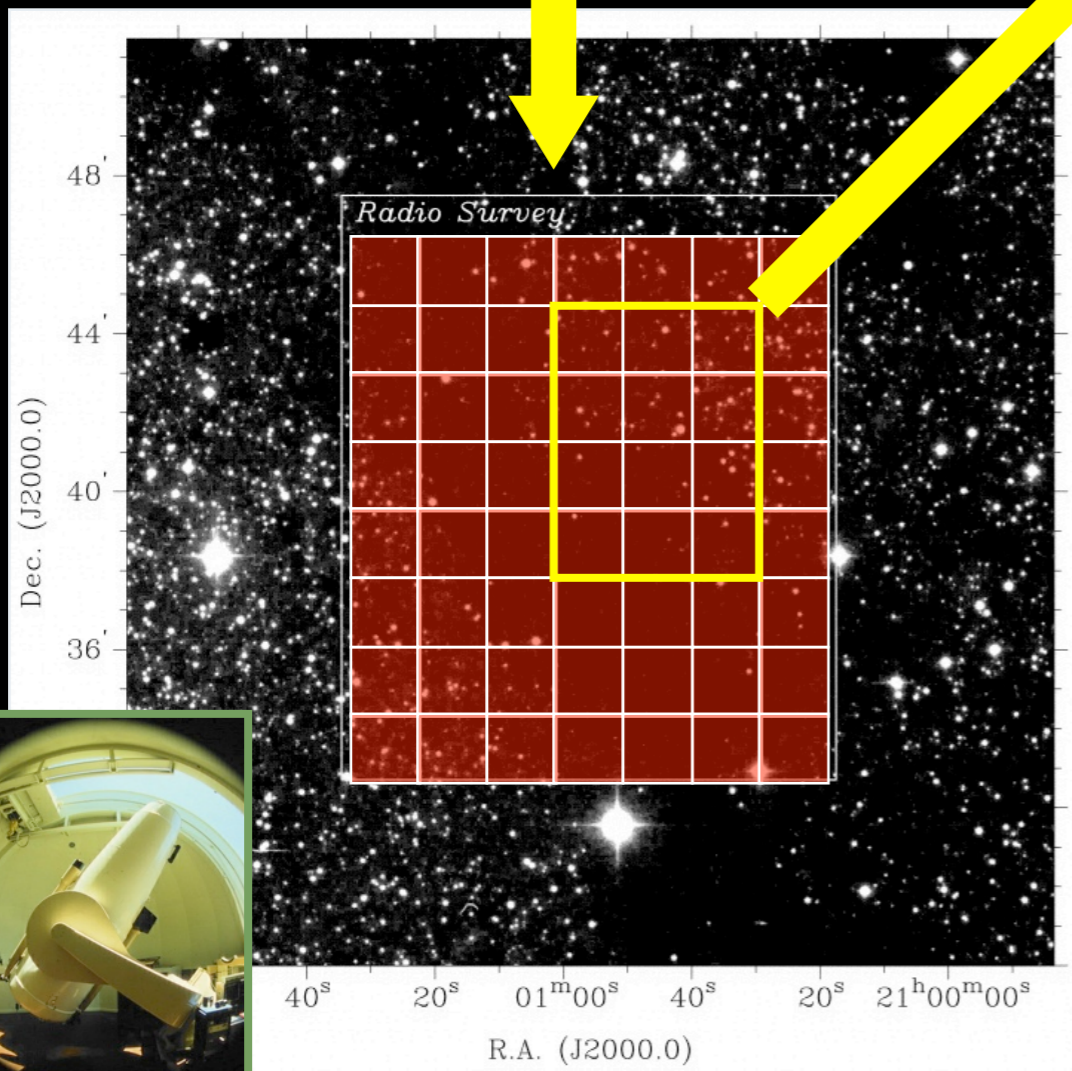
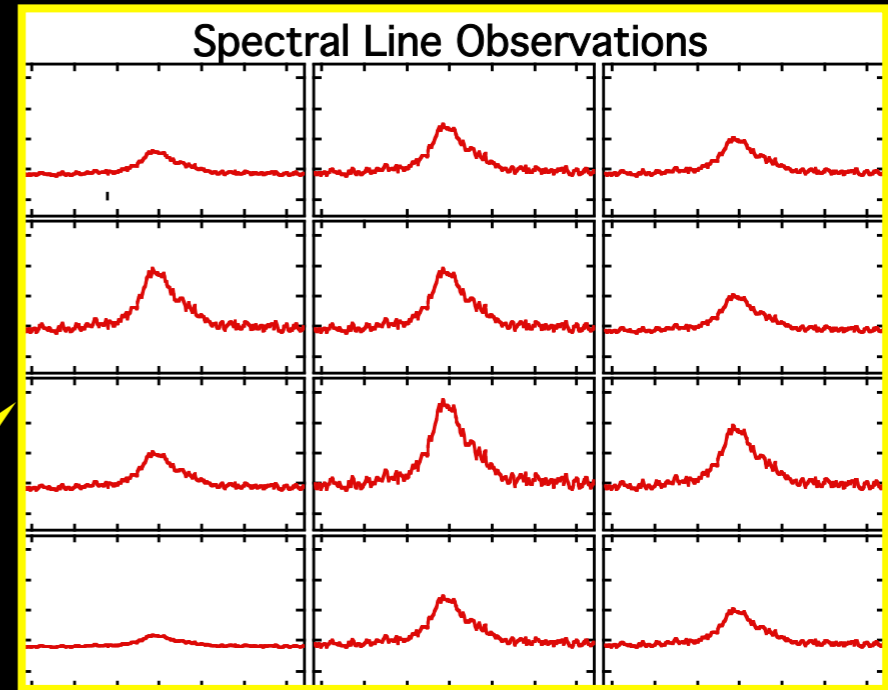


Observed Spectrum

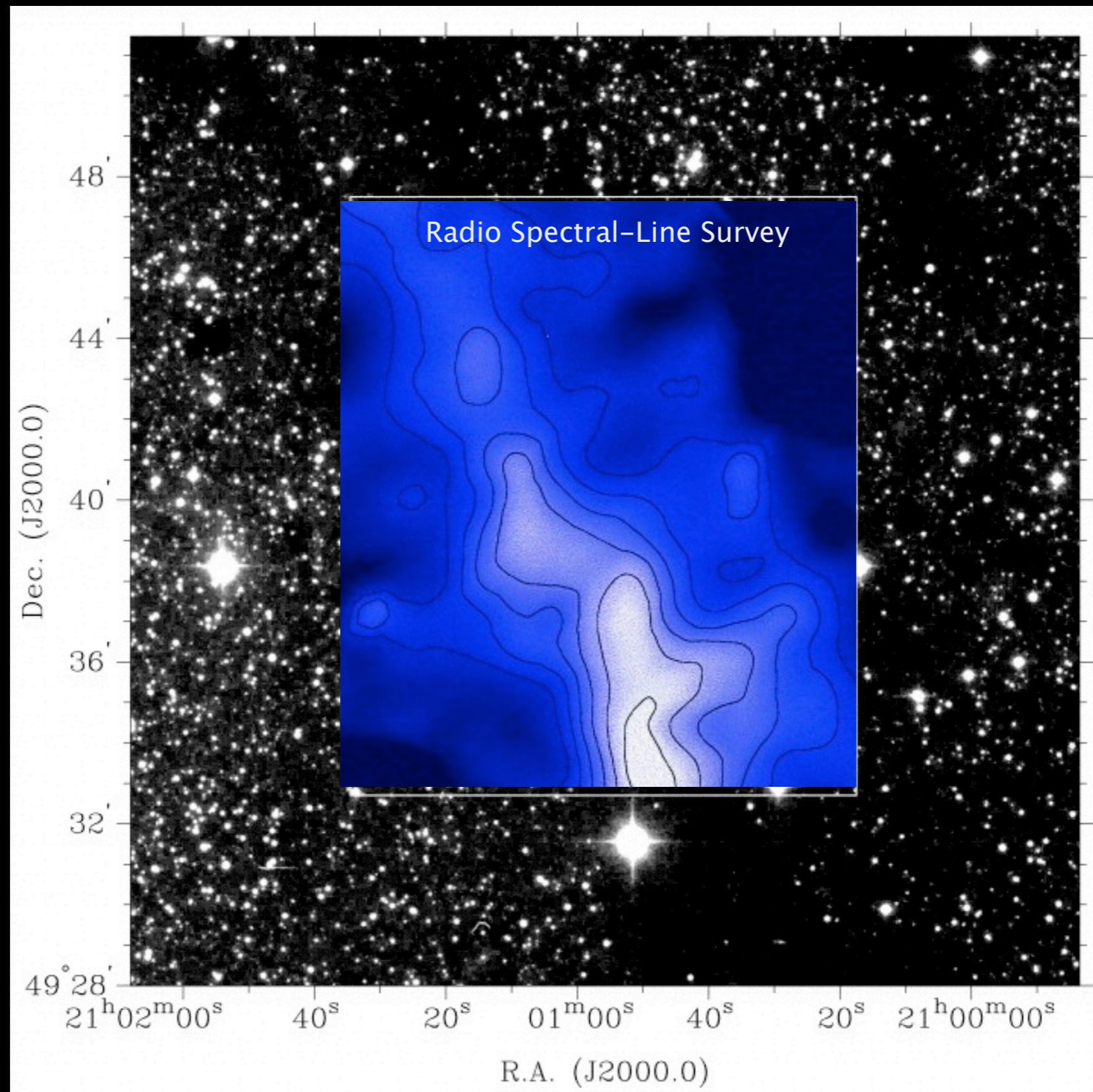


All thanks to **Doppler**

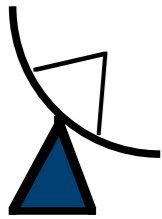
# Radio Spectral-line Observations of Interstellar Clouds



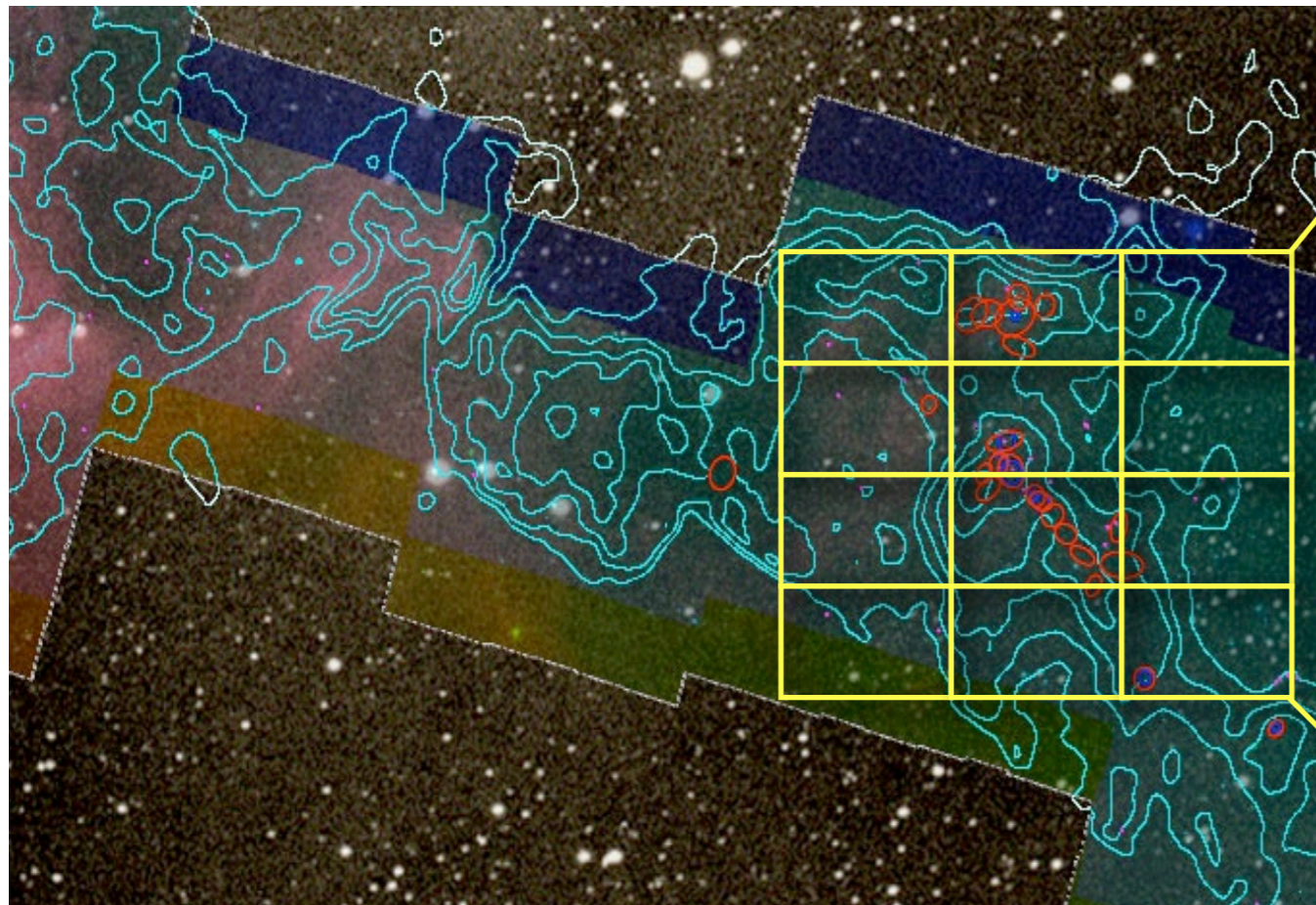
# Radio Spectral-line Observations of Interstellar Clouds



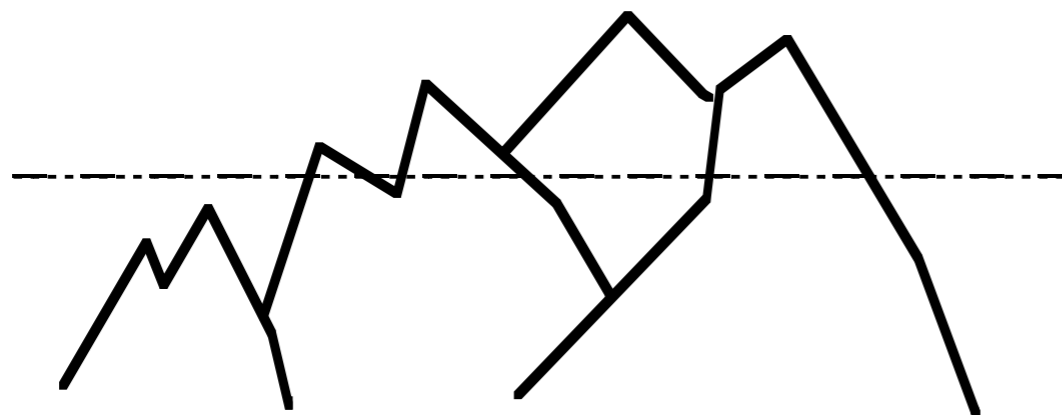
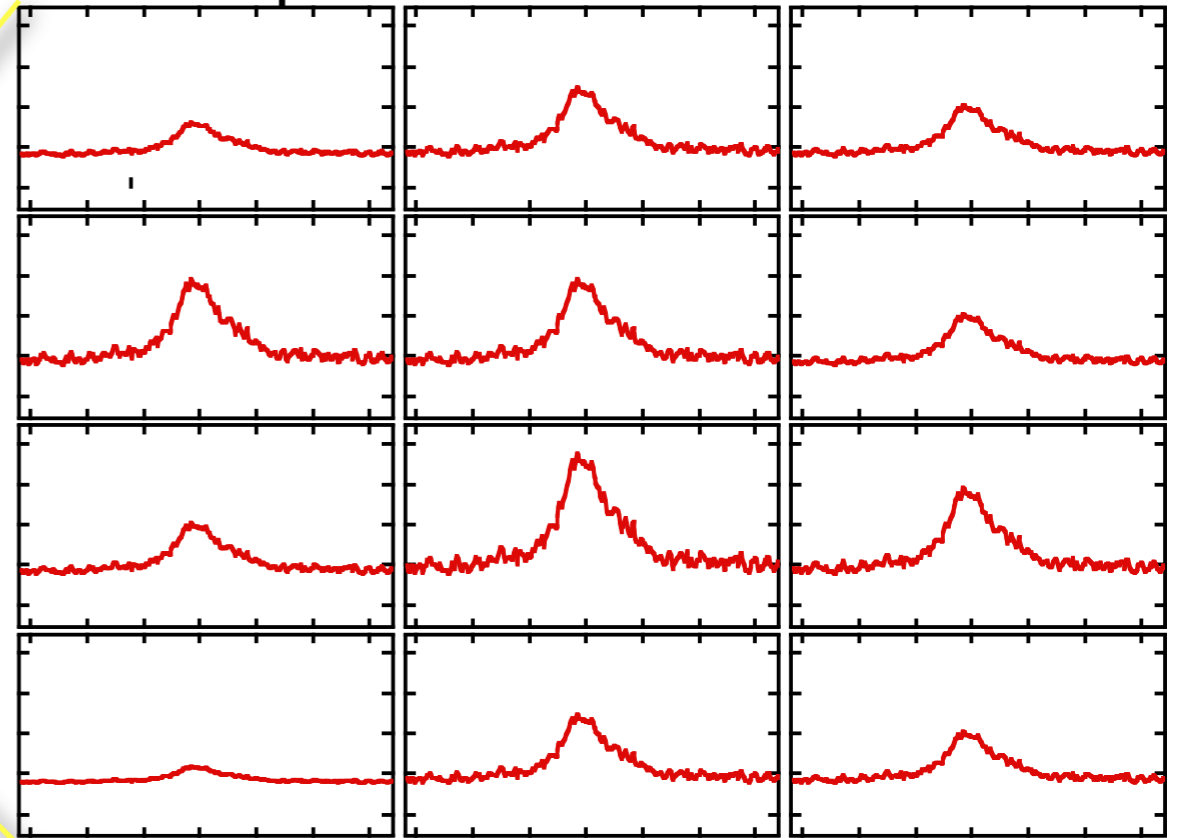
Alves, Lada & Lada 1999



# Velocity as a "Fourth" Dimension



Spectral Line Observations



Mountain Range



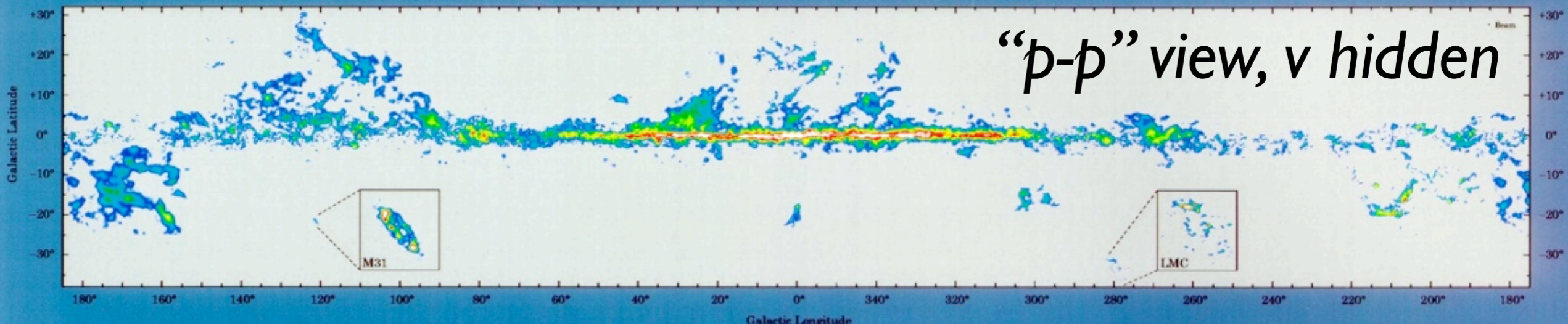
No loss of information



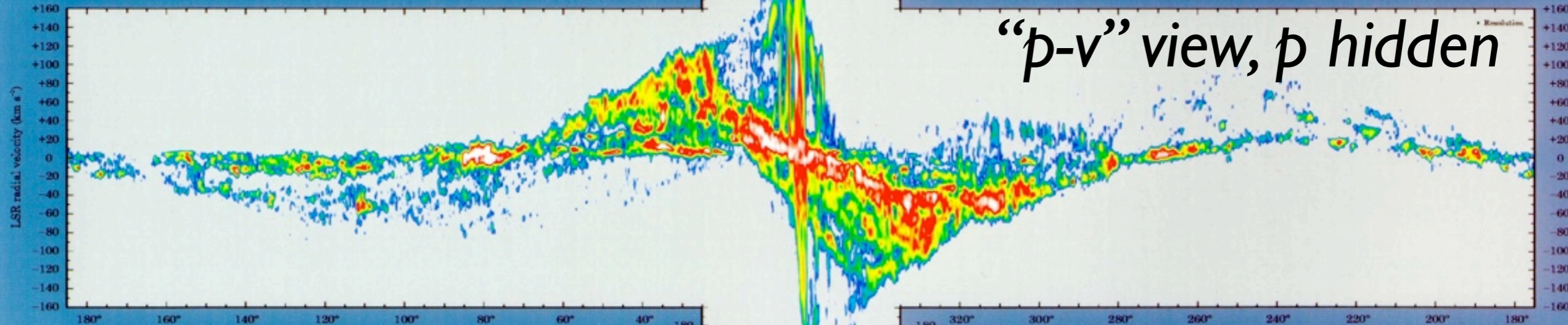
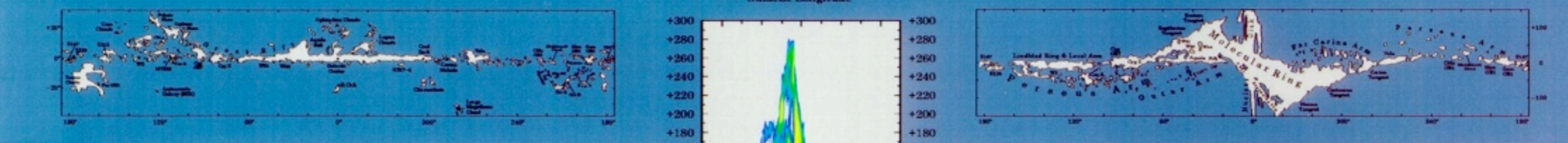
Loss of 1 dimension



# The Milky Way in Molecular Clouds



“p-p” view, v hidden



“p-v” view, p hidden

The Milky Way and its nearest neighbors, the Andromeda galaxy (M31) and the Large Magellanic Cloud (LMC), as observed in the 115 GHz line of carbon monoxide (CO), the best tracer of interstellar molecular clouds. These clouds, the factories of essentially all star formation, are composed almost entirely of molecular hydrogen and atomic helium, both nearly impossible to detect.

In the top map the colors, from dark blue (weakest) to white (strongest), represent the CO line intensity summed over all radial velocities, a measure of the total amount of molecular gas along the line of sight. The intense red-to-white horizontal strip at the center of the map is produced by the large number of molecular clouds in the inner spiral arms of the Galaxy, while elsewhere in the map individual nearby molecular clouds are prominent. Both the LMC and M31 are so weak in CO that their intensities have been scaled up by factors of 3 and 10, respectively. A further detail is on the left.

This paper is an update of one produced six years ago which presented the first complete survey of the Milky Way in CO (first reference is right, also Dame 1986, Sly & Shappee, '96, '00). Since well before completion of that survey, data at an effective angular resolution of 95", the same six 12 meter telescopes in Cambridge, Mass., and in Ohio, Texas, Ohio, have been mapping the Galaxy and its nearest

neighbors at several times higher angular resolution—many beamwidths (3.7 arcmin) or half beamwidths—and at 7 to 10 times higher accuracy per solid angle. These improvements have now mapped in the very near to the entire Galactic plane over a 4°×4° strip of latitude, as well as many local clouds at higher latitude. The maps above include these 273,000 new spectra, the original 273 maps (used in some high-latitude regions, e.g., Shappee) where administrative considerations do not permit.

Eighty half of the new data have already been published as separate surveys of particular clouds or regions (see list at right), and since 1993 have formed the basis for 13 Ph.D. dissertations. The balance was obtained in the past few years in new large-scale surveys of the first and second Galactic quadrants.

This paper was supported by a generous grant from the Albertus Seidel Endowment of the Smithsonian Institution.

180° 160° 140° 120° 100° 80° 60° 40° 20° 0° 340° 320° 300° 280° 260° 240° 220° 200° 180°

LSR radial velocity (km s<sup>-1</sup>)

Galactic Longitude

Walter-Oelgem (9)	Dame et al. 1997, ApJ, 472, 106
Walter-Oelgem (10)	Dame et al. 1998, ApJ, 50, 692
Walter-Oelgem (11)	Dame et al. 1998, ApJ, 50, 1174
Walter-Oelgem (12)	Long et al. 1998, ApJ, 50, 107
Walter-Oelgem (13)	Chapman et al. 1997, ApJ, 467, 101
Walter-Oelgem (14)	Chapman et al. 1997, ApJ, 467, 101
Walter-Oelgem (15)	Walter-Oelgem et al. 1993, AJ, 105, 150
Walter-Oelgem (16)	Shappee et al. 1995, AJ, 110, 107
Walter-Oelgem (17)	Shappee et al. 1995, AJ, 110, 107
Walter-Oelgem (18)	Shappee et al. 1995, AJ, 110, 107
Walter-Oelgem (19)	Shappee et al. 1995, AJ, 110, 107
Walter-Oelgem (20)	Shappee et al. 1995, AJ, 110, 107
Walter-Oelgem (21)	Shappee et al. 1995, AJ, 110, 107
Walter-Oelgem (22)	Shappee et al. 1995, AJ, 110, 107
Walter-Oelgem (23)	Shappee et al. 1995, AJ, 110, 107
Walter-Oelgem (24)	Shappee et al. 1995, AJ, 110, 107
Walter-Oelgem (25)	Shappee et al. 1995, AJ, 110, 107
Walter-Oelgem (26)	Shappee et al. 1995, AJ, 110, 107
Walter-Oelgem (27)	Shappee et al. 1995, AJ, 110, 107
Walter-Oelgem (28)	Shappee et al. 1995, AJ, 110, 107
Walter-Oelgem (29)	Shappee et al. 1995, AJ, 110, 107
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Walter-Oelgem (35)	Shappee et al. 1995, AJ, 110, 107
Walter-Oelgem (36)	Shappee et al. 1995, AJ, 110, 107
Walter-Oelgem (37)	Shappee et al. 1995, AJ, 110, 107
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Walter-Oelgem (40)	Shappee et al. 1995, AJ, 110, 107
Walter-Oelgem (41)	Shappee et al. 1995, AJ, 110, 107
Walter-Oelgem (42)	Shappee et al. 1995, AJ, 110, 107
Walter-Oelgem (43)	Shappee et al. 1995, AJ, 110, 107
Walter-Oelgem (44)	Shappee et al. 1995, AJ, 110, 107
Walter-Oelgem (45)	Shappee et al. 1995, AJ, 110, 107
Walter-Oelgem (46)	Shappee et al. 1995, AJ, 110, 107
Walter-Oelgem (47)	Shappee et al. 1995, AJ, 110, 107
Walter-Oelgem (48)	Shappee et al. 1995, AJ, 110, 107
Walter-Oelgem (49)	Shappee et al. 1995, AJ, 110, 107
Walter-Oelgem (50)	Shappee et al. 1995, AJ, 110, 107

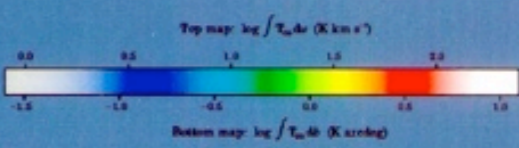







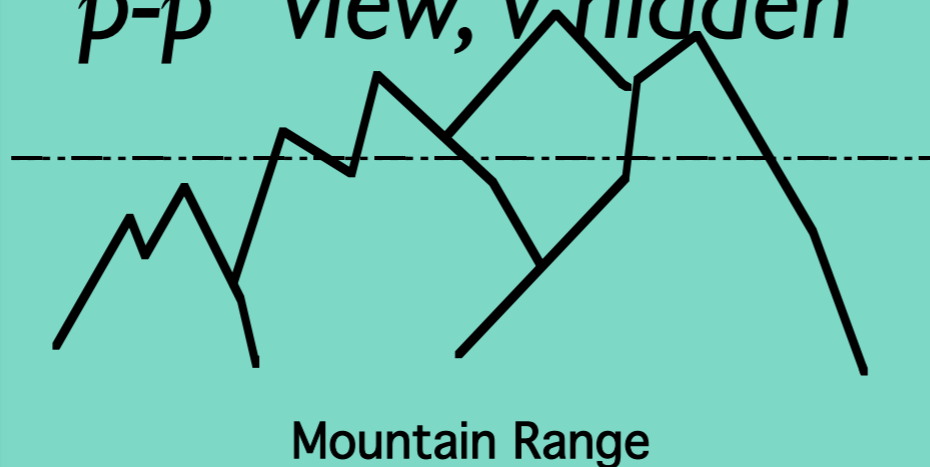
image size: 520 x 274  
view size: 1305 x 733  
WL: 63 WW: 127

# COMPLETE Perseus

"p-p-v" data

-  mm peak (Enoch et al. 2006)
-  sub-mm peak (Hatchell et al. 2005, Kirk et al. 2006)
-   $^{13}\text{CO}$  (Ridge et al. 2006)
-  mid-IR IRAC composite from c2d data (Foster, Laakso, Ridge, et al.)
-  Optical image (Barnard 1927)

"p-p" view, *v* hidden



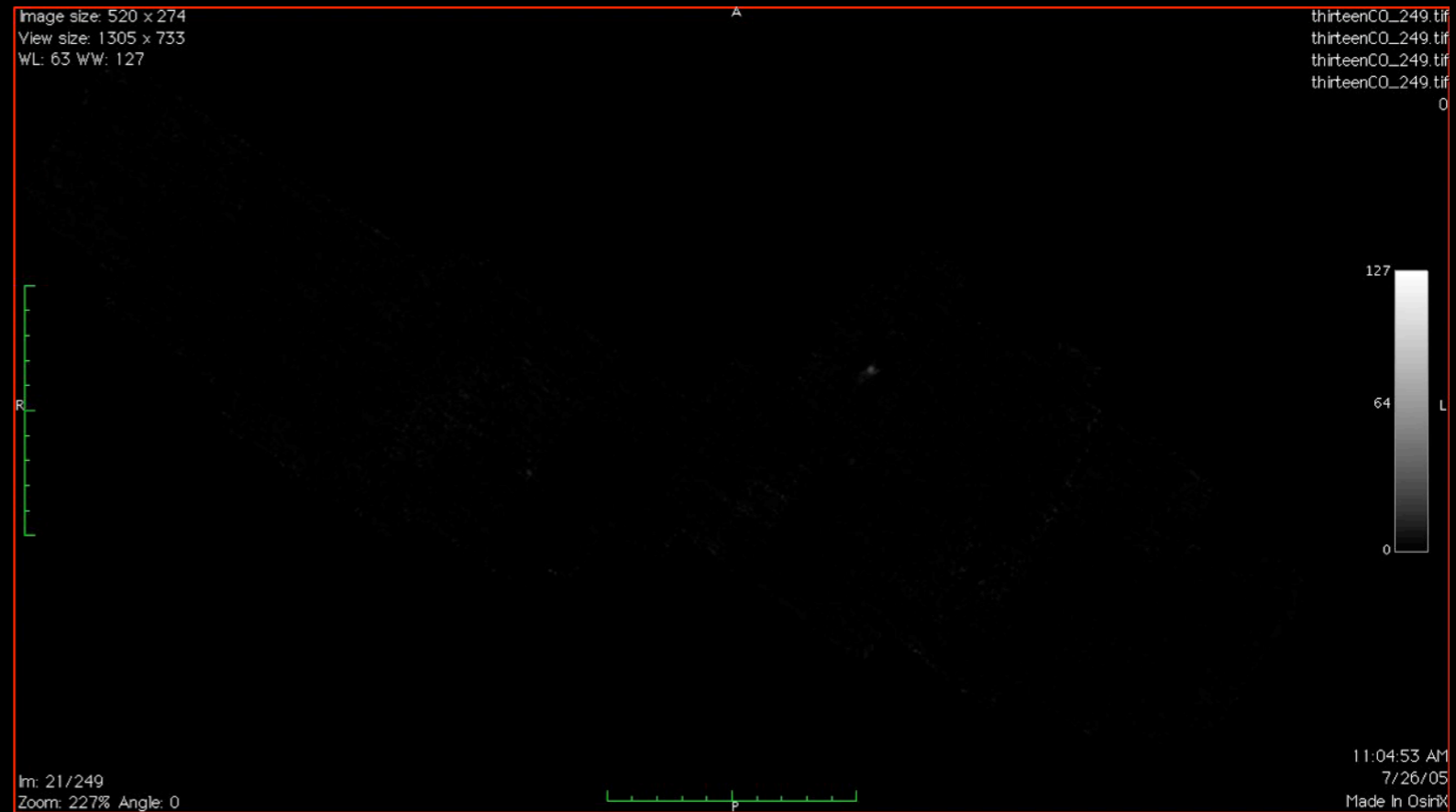
# “Astronomical Medicine”

“KEITH”



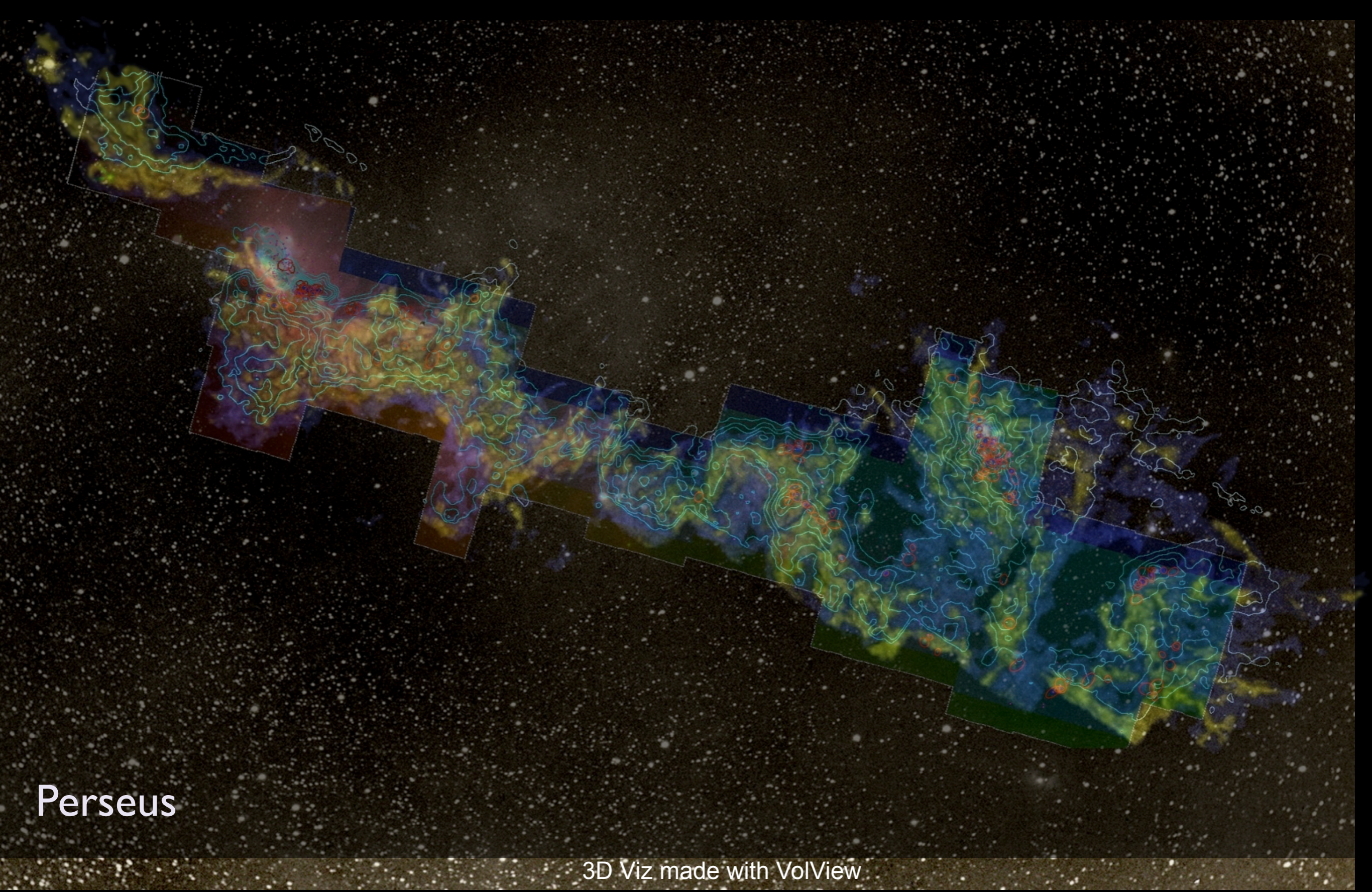
“z” is depth into head

“PERSEUS”



“z” is line-of-sight velocity

<http://am.iic.harvard.edu/>



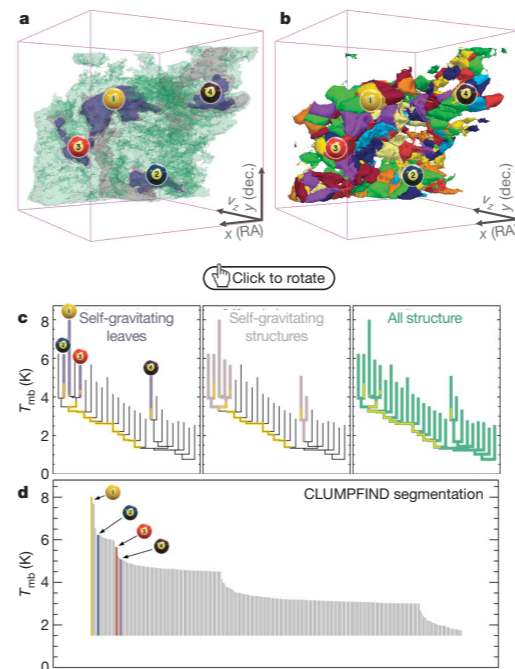
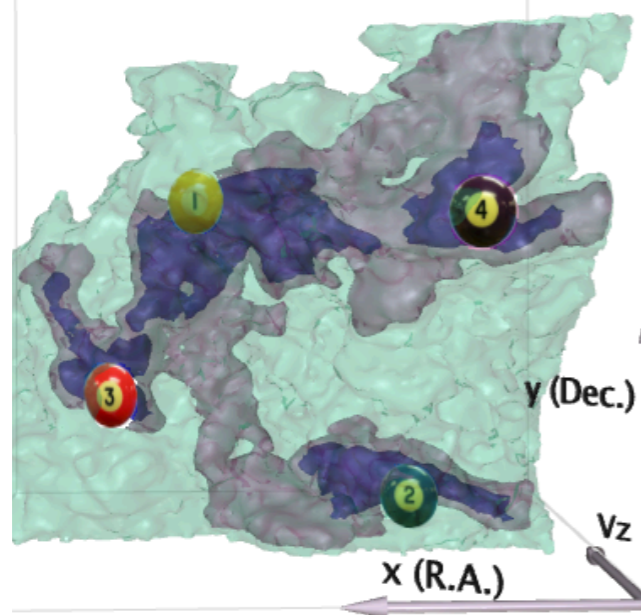
Perseus

3D Viz made with VolView

AstronomicalMedicine@iig

COMPLETE

# I. At what scales does gravity matter?



**Figure 2** | Comparison of the 'dendrogram' and 'CLUMPFIND' feature-identification algorithms as applied to  $^{13}\text{CO}$  emission from the L1448 region of Perseus. **a**, 3D visualization of the surfaces indicated by colours in the dendrogram shown in **c**. Purple illustrates the smallest scale self-gravitating structures in the region corresponding to the leaves of the dendrogram; pink shows the smallest surfaces that contain distinct self-gravitating leaves within them; and green corresponds to the surface in the data cube containing all the significant emission. Dendrogram branches corresponding to self-gravitating objects have been highlighted in yellow over the range of  $T_{\text{mb}}$  (main-beam temperature) test-level values for which the virial parameter is less than 2. The  $x$ - $y$  locations of the four 'self-gravitating' leaves labelled with billiard balls are the same as those shown in Fig. 1. The 3D visualizations show position-position-velocity ( $p$ - $p$ - $v$ ) space. RA, right ascension; dec., declination. For comparison with the ability of dendrograms (**c**) to track hierarchical structure, **d** shows a pseudo-dendrogram of the CLUMPFIND segmentation (**b**), with the same four labels used in Fig. 1 and in **a**. As 'clumps' are not allowed to belong to larger structures, each pseudo-branch in **d** is simply a series of lines connecting the maximum emission value in each clump to the threshold value. A very large number of clumps appears in **b** because of the sensitivity of CLUMPFIND to noise and small-scale structure in the data. In the online PDF version, the 3D cubes (**a** and **b**) can be rotated to any orientation, and surfaces can be turned on and off (interaction requires Adobe Acrobat version 7.0.8 or higher). In the printed version, the front face of each 3D cube (the 'home' view in the interactive online version) corresponds exactly to the patch of sky shown in Fig. 1, and velocity with respect to the Local Standard of Rest increases from front ( $-0.5 \text{ km s}^{-1}$ ) to back ( $8 \text{ km s}^{-1}$ ).

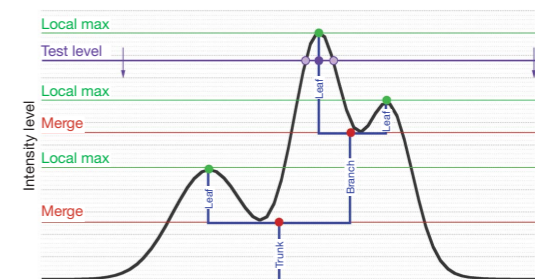
data, CLUMPFIND typically finds features on a limited range of scales, above but close to the physical resolution of the data, and its results can be overly dependent on input parameters. By tuning CLUMPFIND's two free parameters, the same molecular-line data set<sup>8</sup> can be used to show either that the frequency distribution of clump mass is the same as the initial mass function of stars or that it follows the much shallower mass function associated with large-scale molecular clouds (Supplementary Fig. 1).

Four years before the advent of CLUMPFIND, 'structure trees'<sup>9</sup> were proposed as a way to characterize clouds' hierarchical structure

using 2D maps of column density. With this early 2D work as inspiration, we have developed a structure-identification algorithm that abstracts the hierarchical structure of a 3D ( $p$ - $p$ - $v$ ) data cube into an easily visualized representation called a 'dendrogram'<sup>10</sup>. Although well developed in other data-intensive fields<sup>11,12</sup>, it is curious that the application of tree methodologies so far in astrophysics has been rare, and almost exclusively within the area of galaxy evolution, where 'merger trees' are being used with increasing frequency<sup>13</sup>.

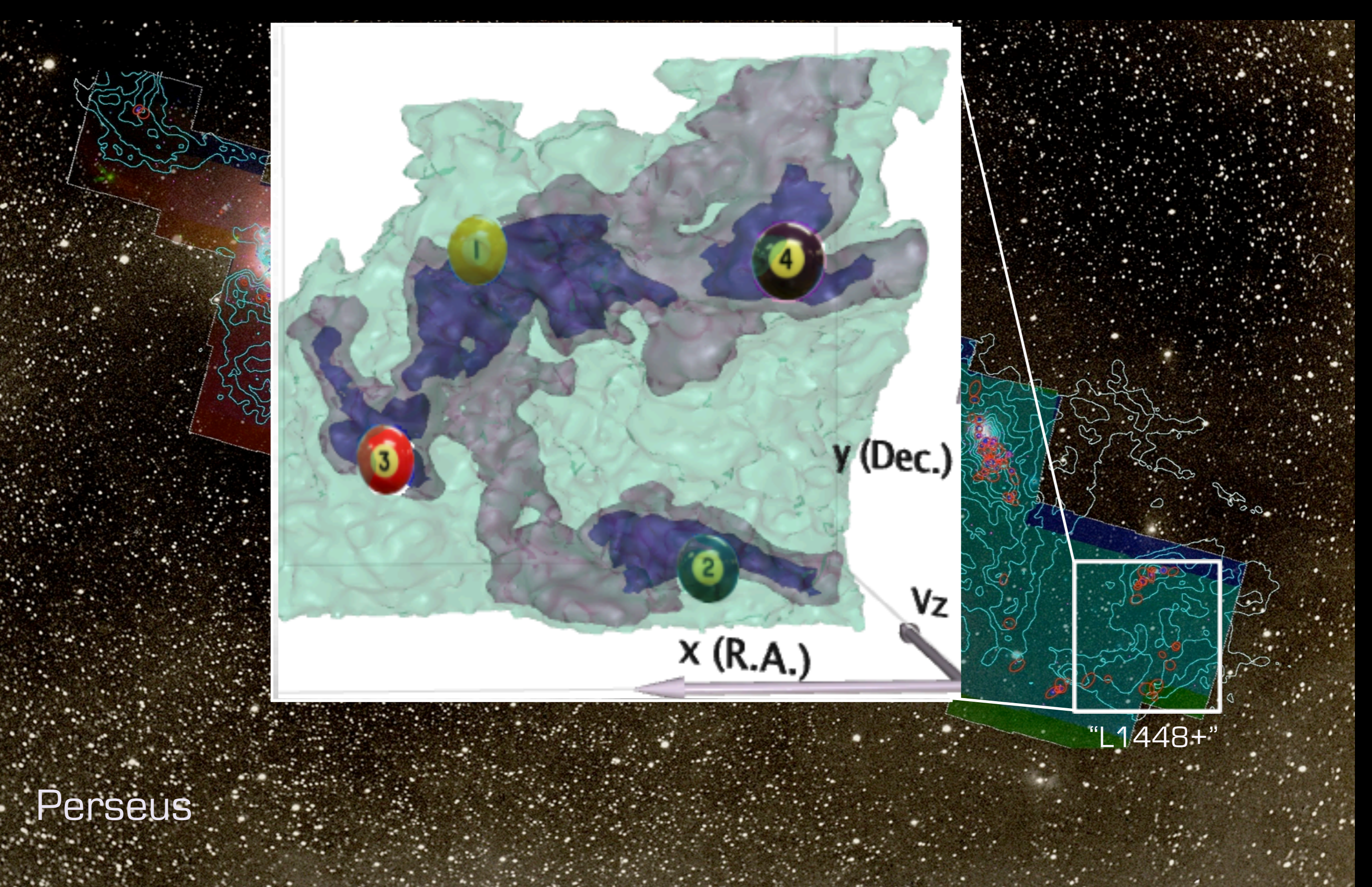
Figure 3 and its legend explain the construction of dendrograms schematically. The dendrogram quantifies how and where local maxima of emission merge with each other, and its implementation is explained in Supplementary Methods. Critically, the dendrogram is determined almost entirely by the data itself, and it has negligible sensitivity to algorithm parameters. To make graphical presentation possible on paper and 2D screens, we 'flatten' the dendrograms of 3D data (see Fig. 3 and its legend), by sorting their 'branches' to not cross, which eliminates dimensional information on the  $x$  axis while preserving all information about connectivity and hierarchy. Numbered 'billiard ball' labels in the figures let the reader match features between a 2D map (Fig. 1), an interactive 3D map (Fig. 2a online) and a sorted dendrogram (Fig. 2c).

A dendrogram of a spectral-line data cube allows for the estimation of key physical properties associated with volumes bounded by iso-surfaces, such as radius ( $R$ ), velocity dispersion ( $\sigma_v$ ) and luminosity ( $L$ ). The volumes can have any shape, and in other work<sup>14</sup> we focus on the significance of the especially elongated features seen in L1448 (Fig. 2a). The luminosity is an approximate proxy for mass, such that  $M_{\text{lum}} = X_{^{13}\text{CO}} L_{^{13}\text{CO}}$ , where  $X_{^{13}\text{CO}} = 8.0 \times 10^{20} \text{ cm}^{-2} \text{ K}^{-1} \text{ km}^{-1} \text{ s}$  (ref. 15; see Supplementary Methods and Supplementary Fig. 2). The derived values for size, mass and velocity dispersion can then be used to estimate the role of self-gravity at each point in the hierarchy, via calculation of an 'observed' virial parameter,  $\alpha_{\text{obs}} = 5\sigma_v^2 R / GM_{\text{lum}}$ . In principle, extended portions of the tree (Fig. 2, yellow highlighting) where  $\alpha_{\text{obs}} < 2$  (where gravitational energy is comparable to or larger than kinetic energy) correspond to regions of  $p$ - $p$ - $v$  space where self-gravity is significant. As  $\alpha_{\text{obs}}$  only represents the ratio of kinetic energy to gravitational energy at one point in time, and does not explicitly capture external over-pressure and/or magnetic fields<sup>16</sup>, its measured value should only be used as a guide to the longevity (boundedness) of any particular feature.



**Figure 3** | Schematic illustration of the dendrogram process. Shown is the construction of a dendrogram from a hypothetical one-dimensional emission profile (black). The dendrogram (blue) can be constructed by 'dropping' a test constant emission level (purple) from above in tiny steps (exaggerated in size here, light lines) until all the local maxima and mergers are found, and connected as shown. The intersection of a test level with the emission is a set of points (for example the light purple dots) in one dimension, a planar curve in two dimensions, and an isosurface in three dimensions. The dendrogram of 3D data shown in Fig. 2c is the direct analogue of the tree shown here, only constructed from 'isosurface' rather than 'point' intersections. It has been sorted and flattened for representation on a flat page, as fully representing dendrograms for 3D data cubes would require four dimensions.

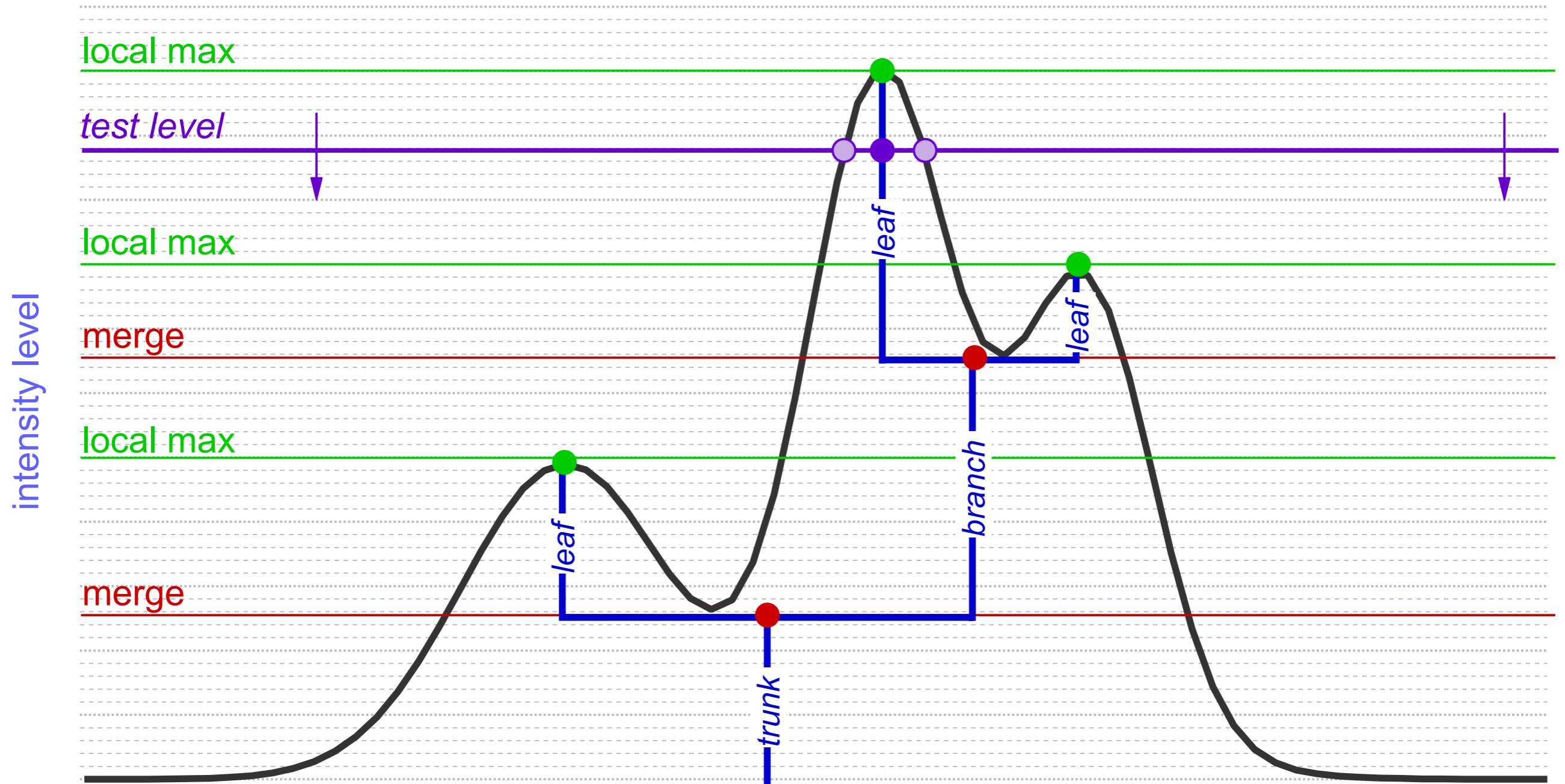
+ "tasty" approaches to answers



Perseus

COMPLETE

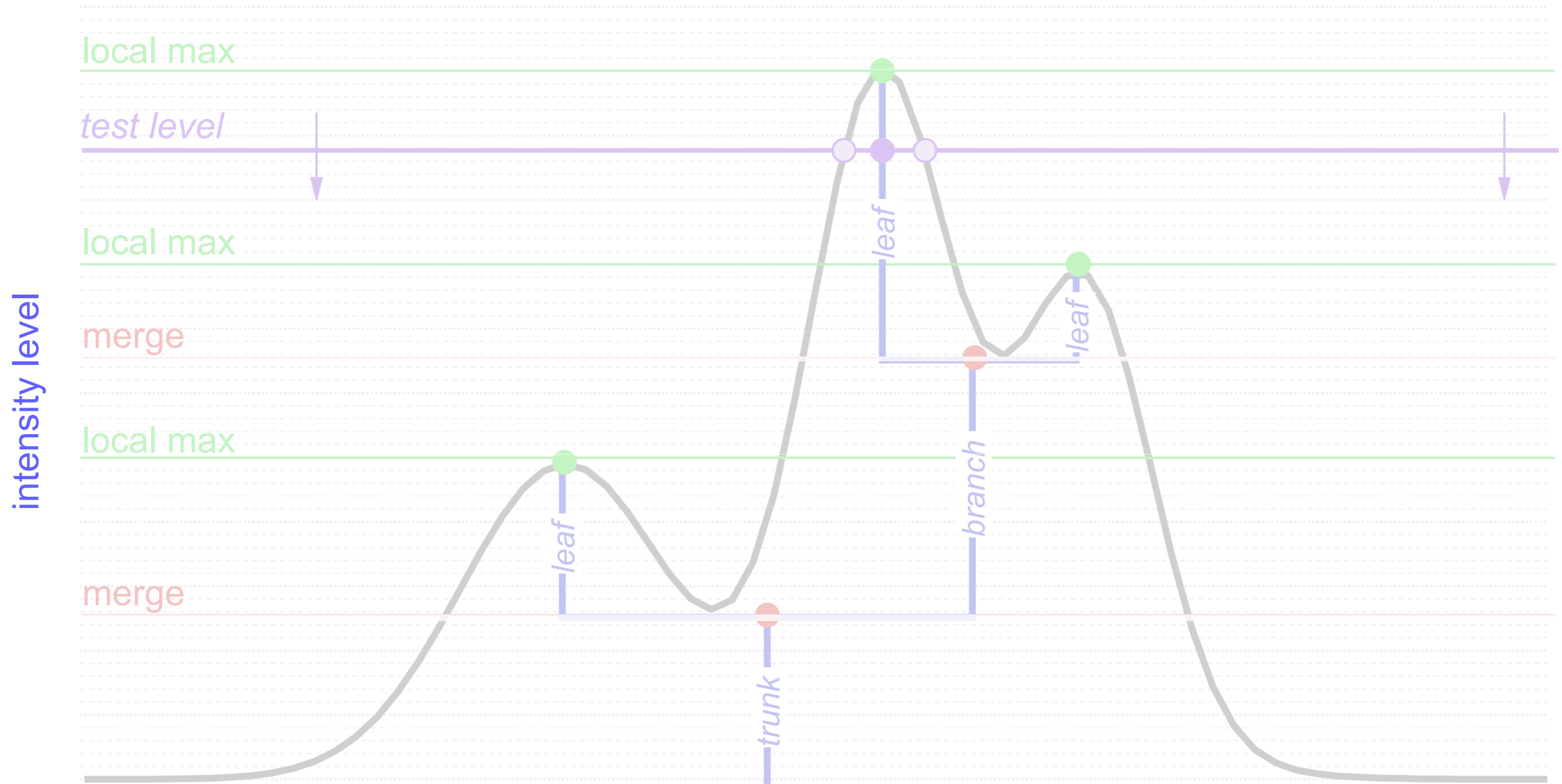
# Dendrograms



## Hierarchical "Segmentation"

*Rosolowsky, Pineda, Kauffmann & Goodman 2008*

# Dendrograms



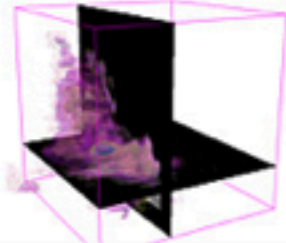

1-D: points; 2-D closed curves (contours); 3-D surfaces enclosing volumes  
see 2D demo at <http://am.iic.harvard.edu/index.cgi/DendroStar/applet>



DendroStar/applet - IIC/AstroMed

http://am.iic.harvard.edu/index.cgi/DendroStar/applet

astronomical medicine

The Astronomical Medicine Project

Initiative In Innovative Computing at Harvard

### The DendroStar Applet for L1448: Try me!

**Harvard IIC Home**

**AM Project**  
 overview  
 what's new?  
 press  
 about us  
 contact us

**Research**  
 background  
 projects  
 papers  
 images  
 movies

**Software**  
 overview  
 Slicer: getting started  
 Slicer 3  
 fits2itk  
 OsiriX  
 DendroStar

**Links**  
 Center for Astrophysics  
 COMPLETE Survey  
 Surgical Planning Lab  
 3D Slicer  
 related projects

**User**  
 Login

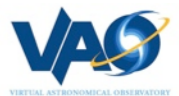
**Search**

Tint:

Suppress tint:

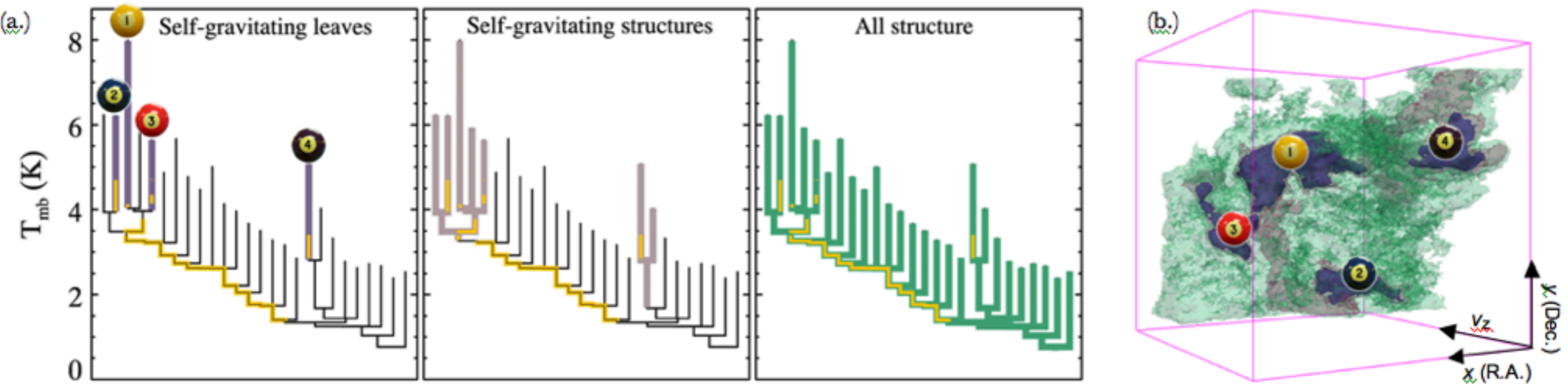
Reset:

Applet DendroStar started



<http://am.iic.harvard.edu/index.cgi/DendroStar/applet>  
 Dendrogram Algorithm by Erik Rosolwosky; Applet by Douglas Alan

# I. At what scales does gravity matter?



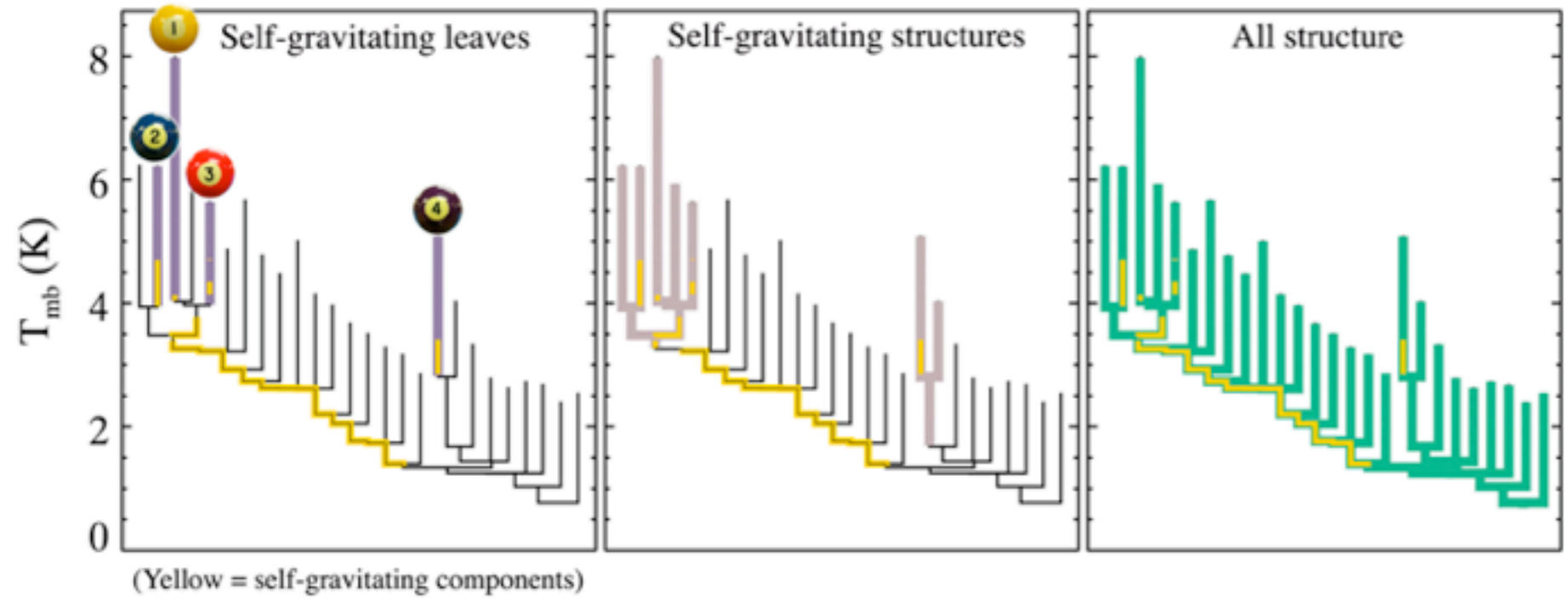
**Yellow** highlighting= “self-gravitating”  
(according to virial theorem!?!)

“Self-gravitating” here just means  $\alpha_{vir}$  ( $=5s_v^2R/GM_{lum}$ )  $< 2$   
(à la Bertoldi & McKee 1992–*BUT*–see Shetty et al. 2010)

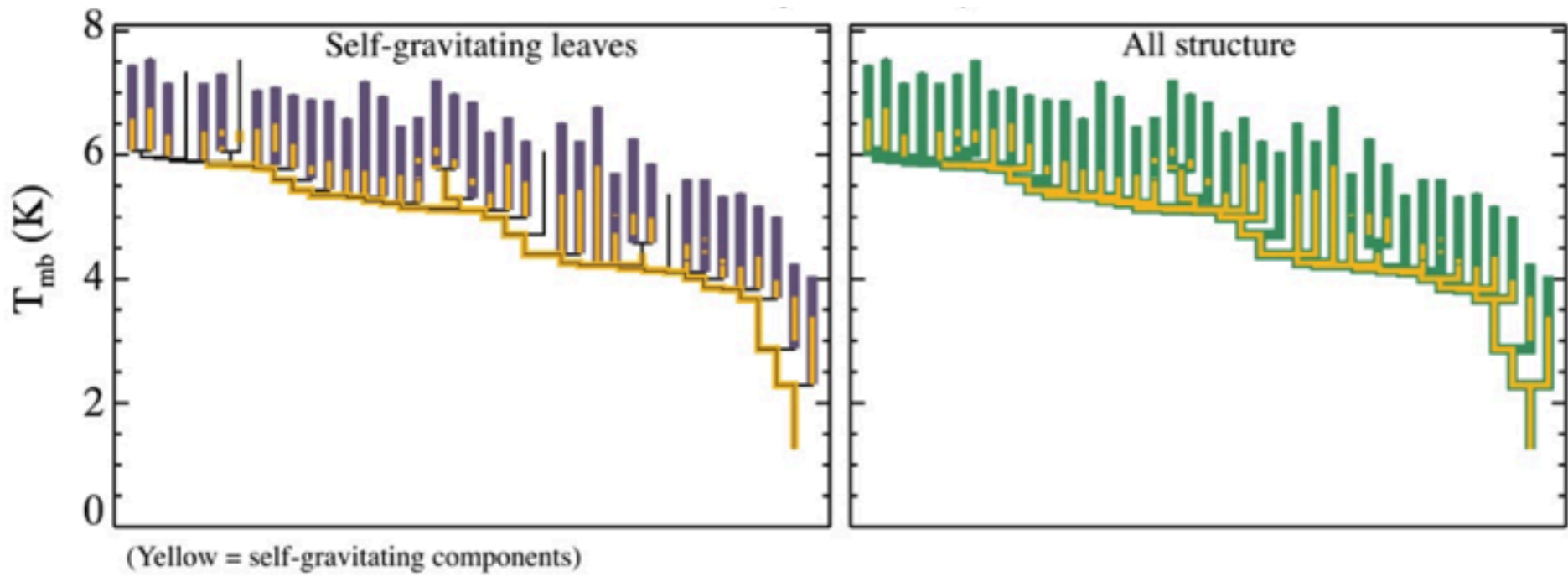
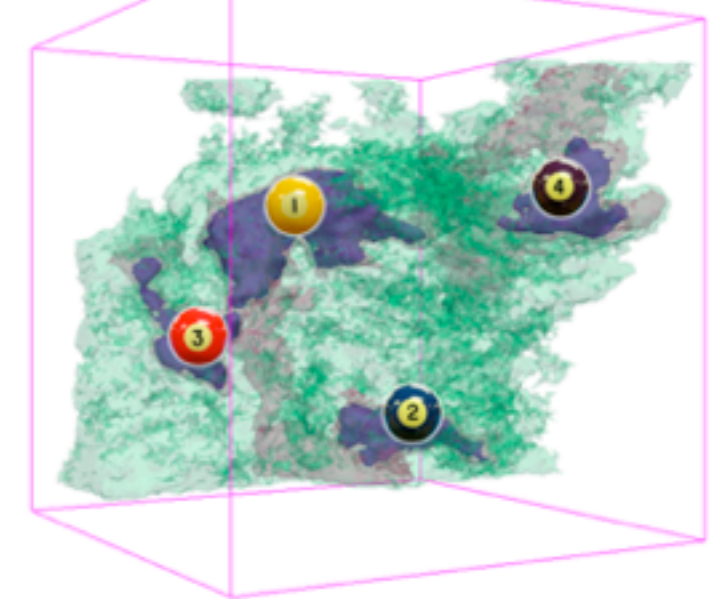
Rosolowsky et al. 2008 (ApJ) &  
Goodman et al. 2009 (Nature)

see PDF...

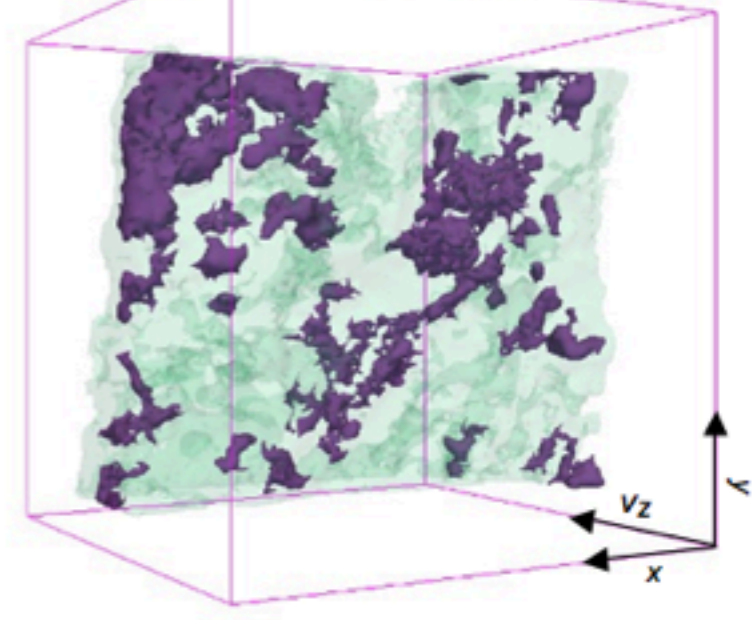
# Real and Simulated $^{13}\text{CO}$



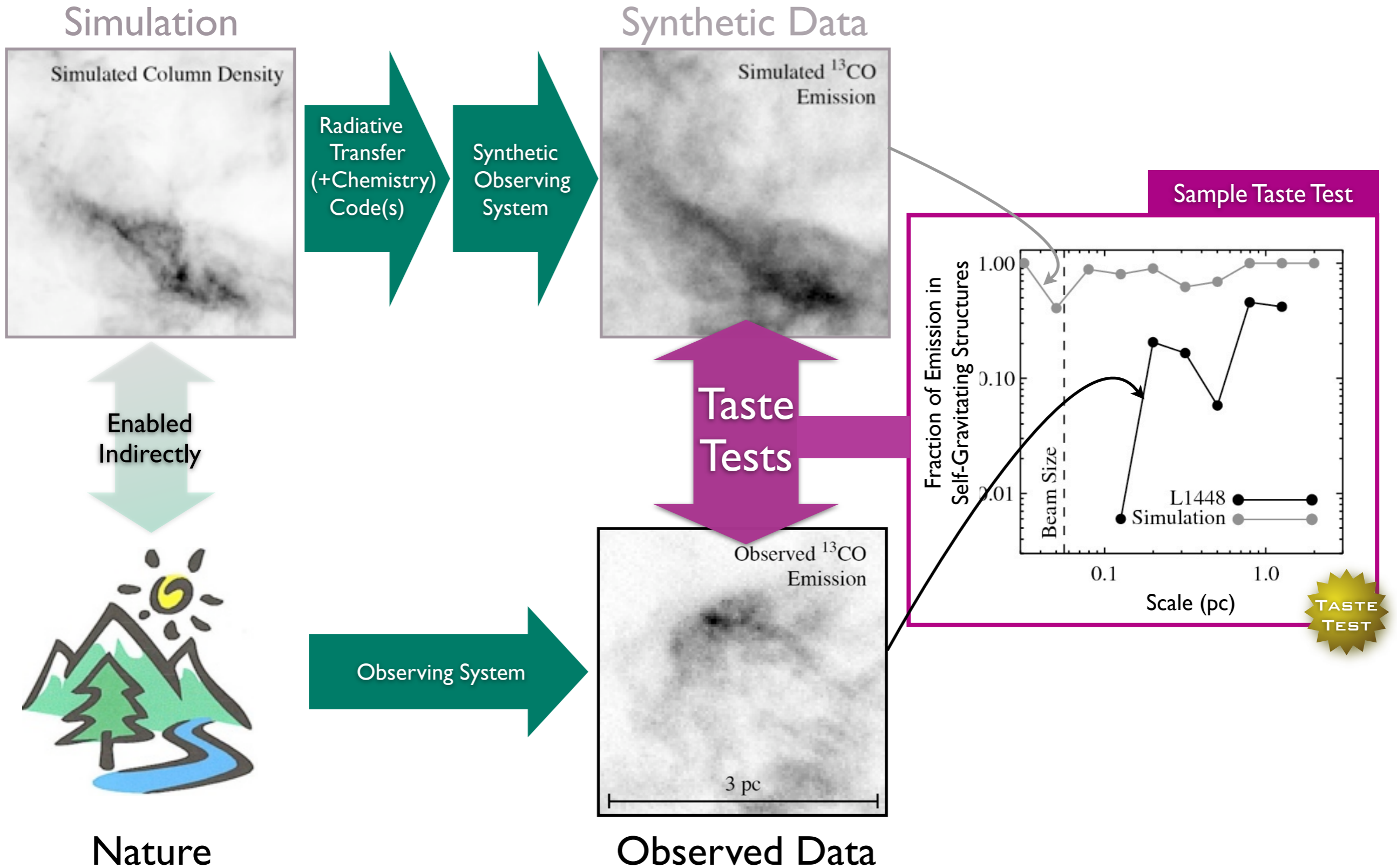
## Real



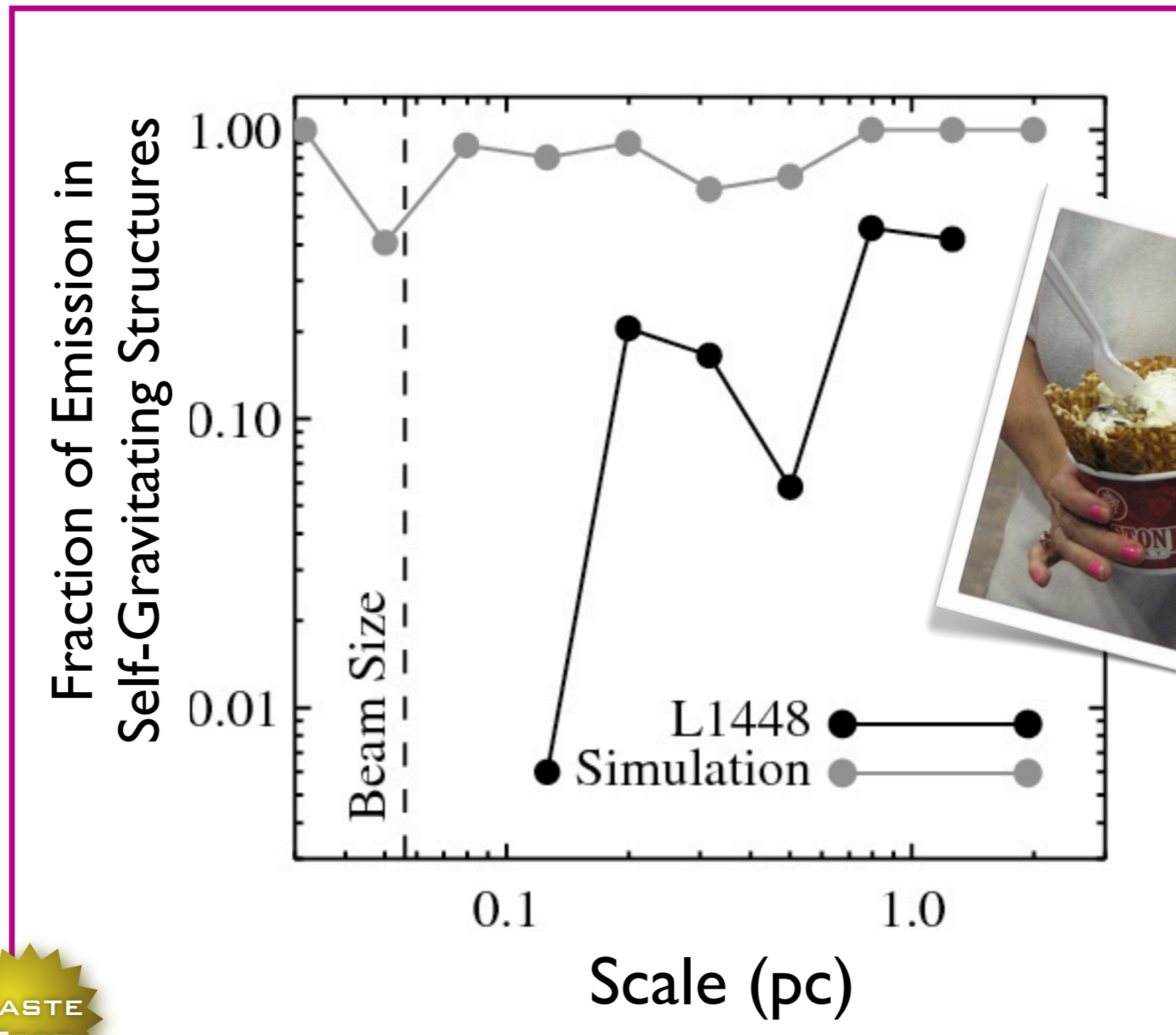
## Simulated



# The Taste-Testing Process



# Taste-Testing “Gravity”

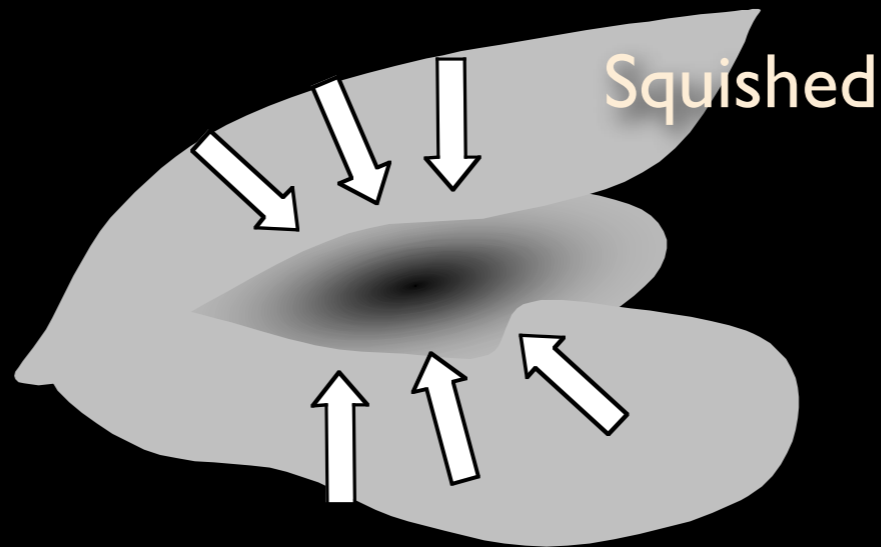
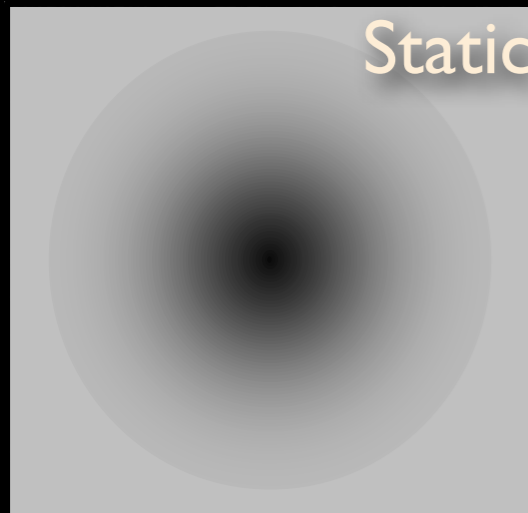


*Gravity-free HD Simulations from Padoan et al. 2006;  
L1448 analysis from Rosolowsky et al. 2008  
both lines derived from  $^{13}\text{CO}$  “observations”*

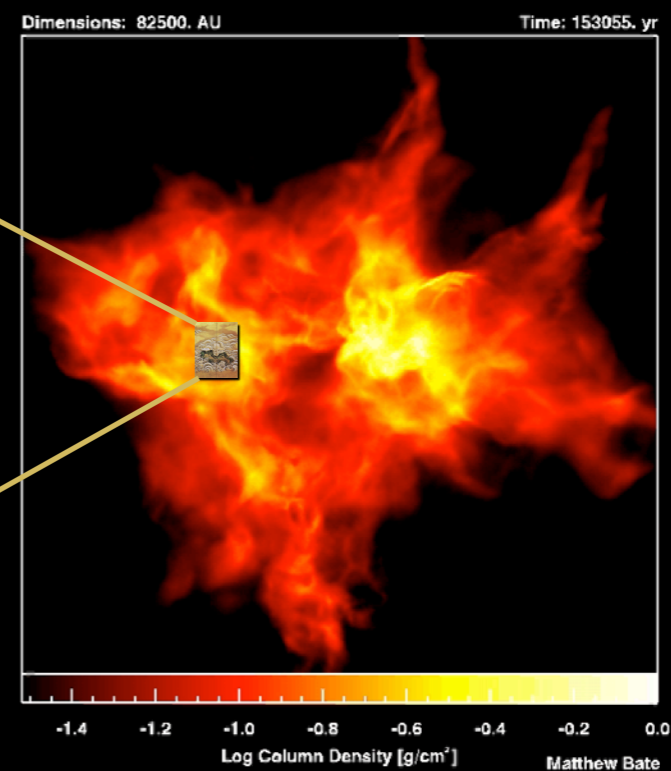
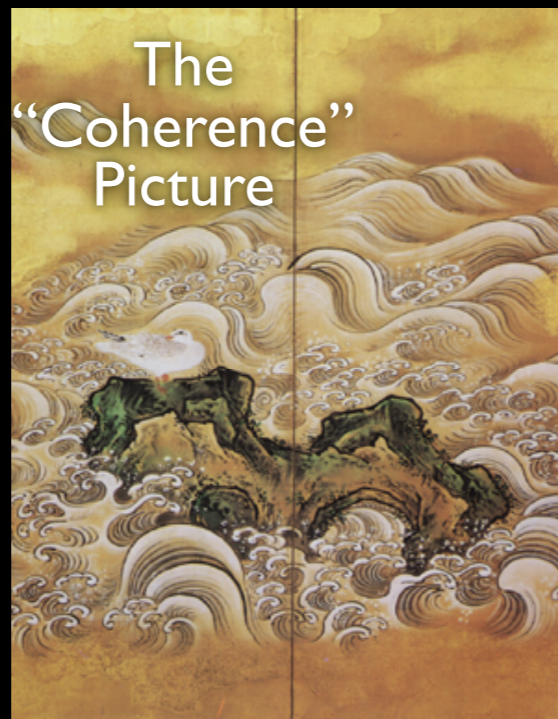
# Philosophical Interlude



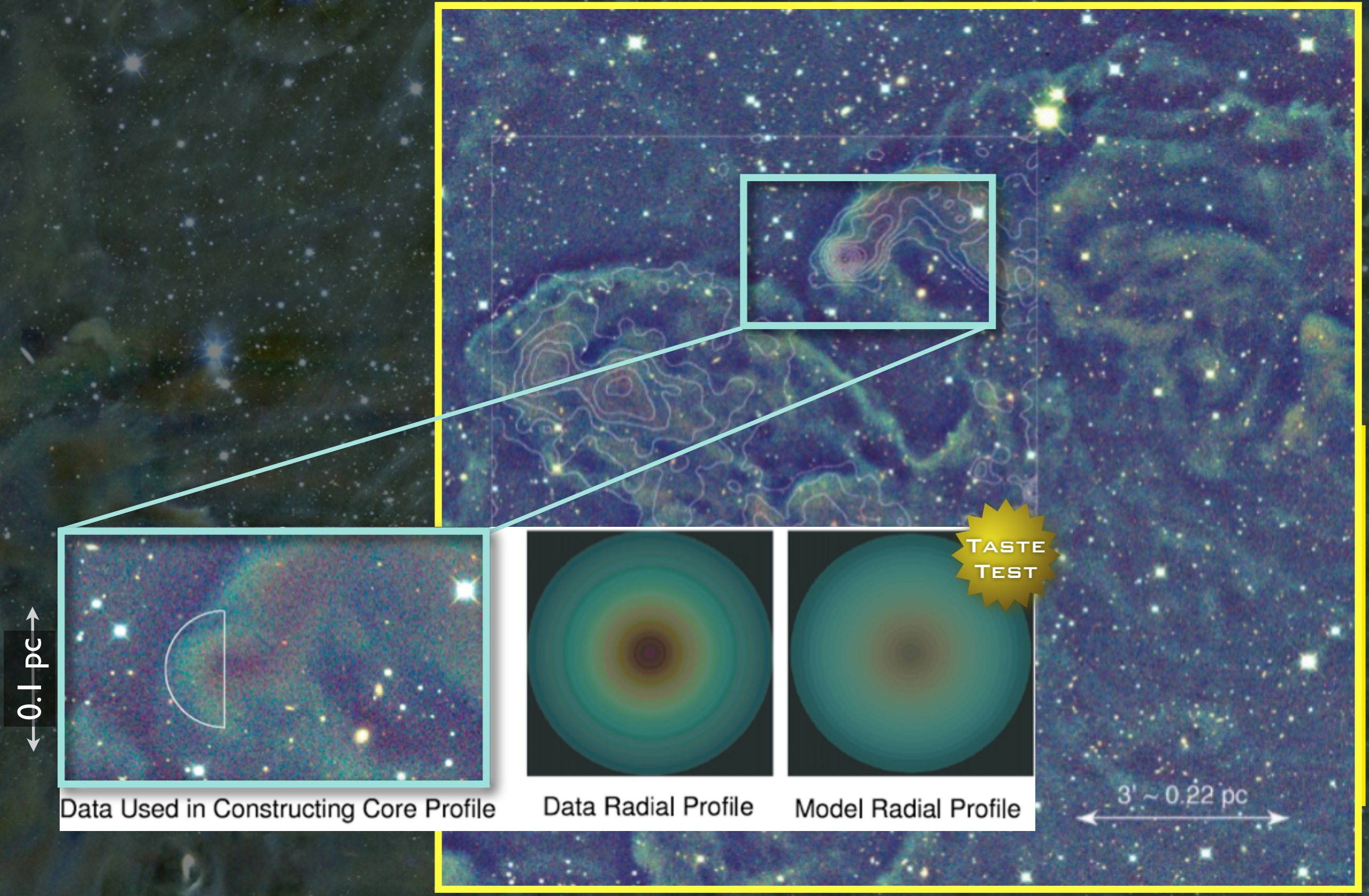
# for non-Experts



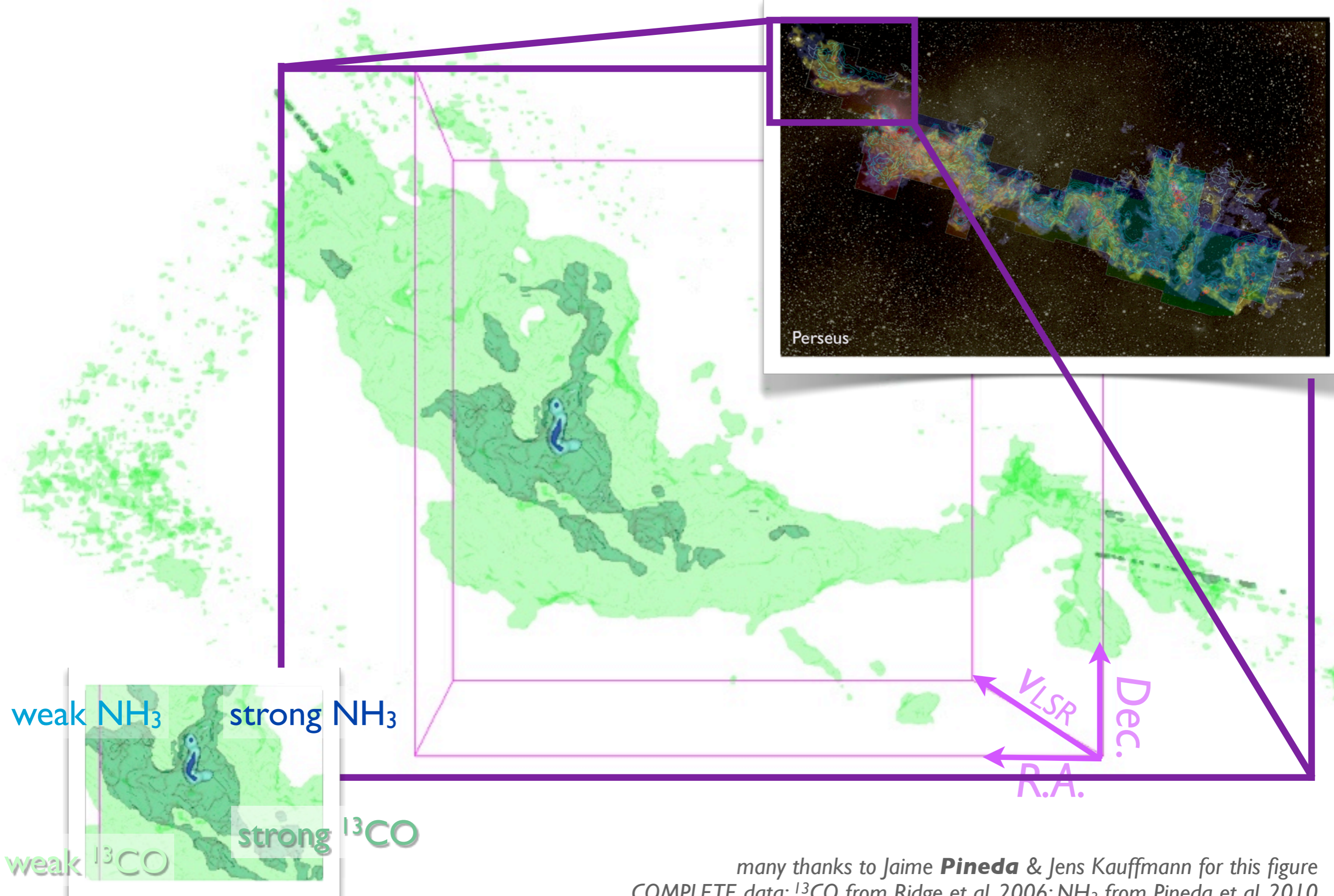
Ask me later...



# “Islands of Calm in a Turbulent Sea”



# $p$ - $p$ - $v$ structure of the B5 region in Perseus

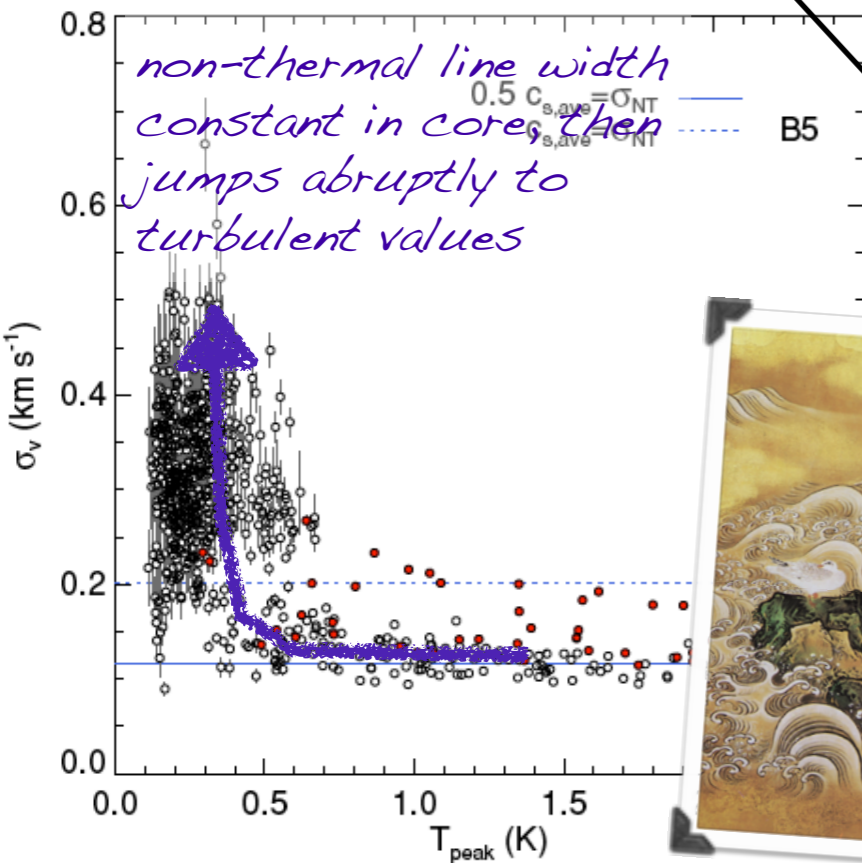
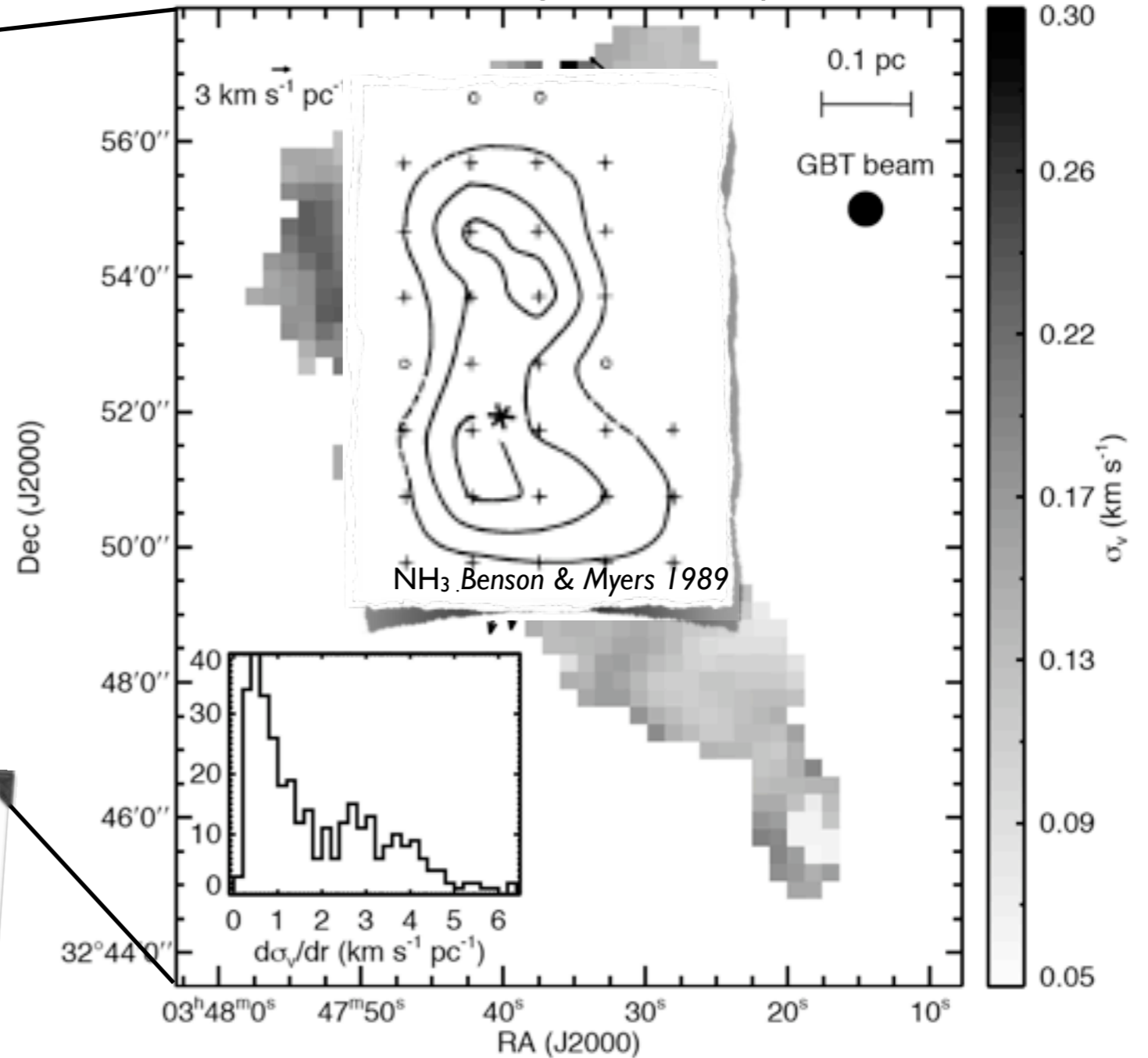
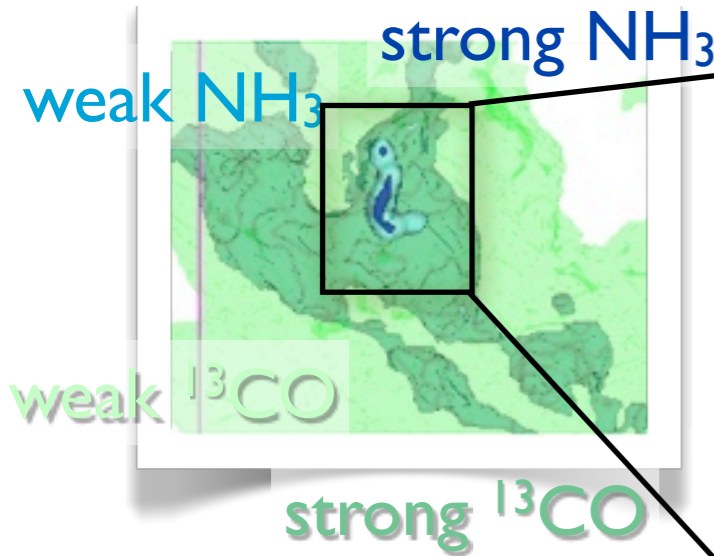


many thanks to Jaime **Pineda** & Jens Kauffmann for this figure  
COMPLETE data:  $^{13}\text{CO}$  from Ridge et al. 2006;  $\text{NH}_3$  from Pineda et al. 2010



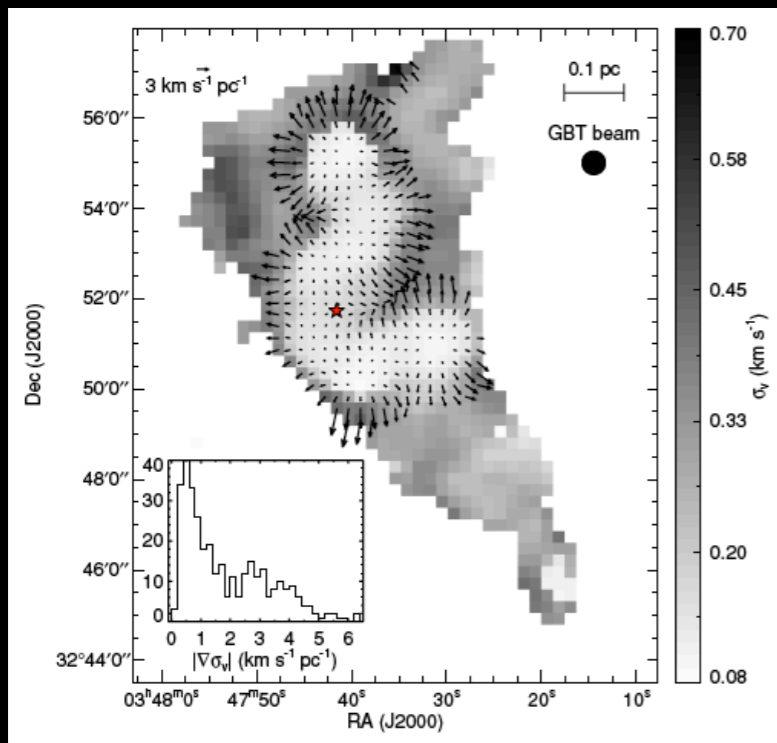
# STRONG Evidence for Coherence in Dense Cores

greyscale shows  $\text{NH}_3$  velocity dispersion, arrows show gradient in dispersion



*GBT  $\text{NH}_3$  observations of the B5 core (Pineda et al. 2010)*

# I. At what scales does gravity matter?



“Transition” so sharp  
the GBT cannot  
resolve it.  
We need EVLA...

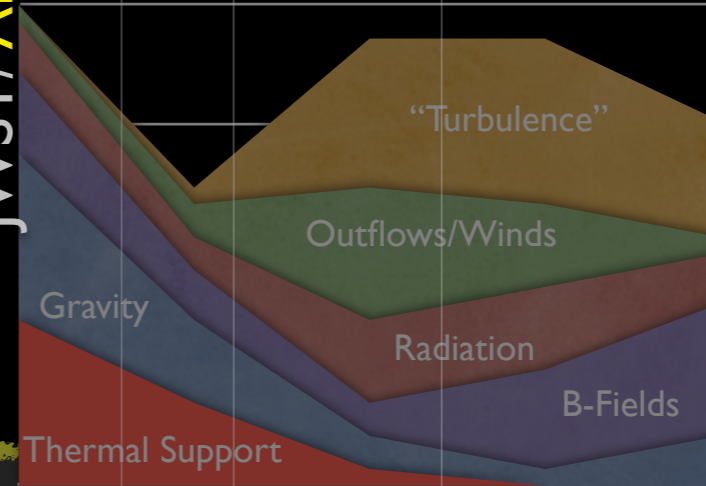
GAIA

JWST/ALMA/ EVLA

GBT

FCRAO

“CfA” mini

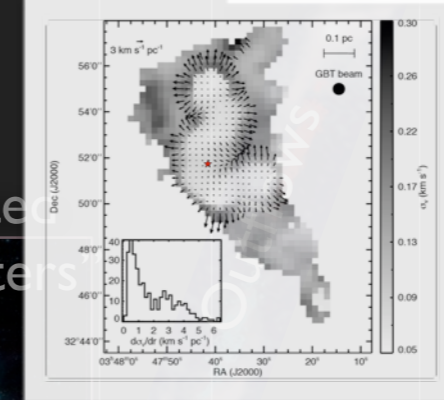
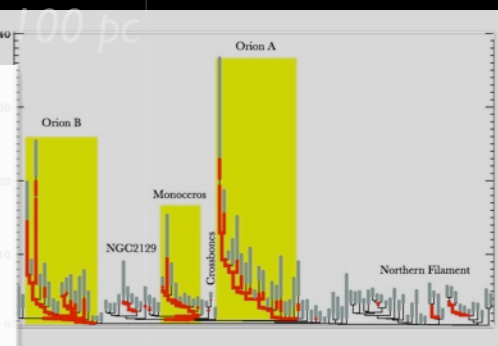
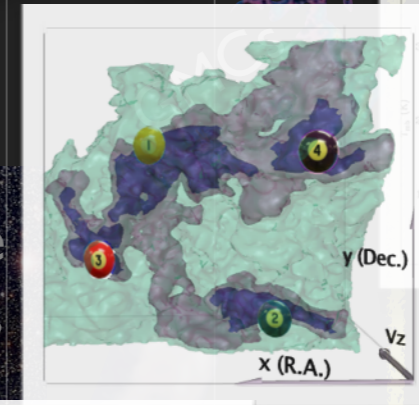


Years

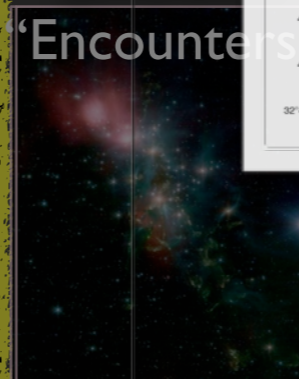
$10^7$   
 $10^6$   
 $10^5$   
 $10^4$   
 $10^3$

0.01 pc 0.1 pc 1 pc 10 pc 100 pc

Dense  
Cores



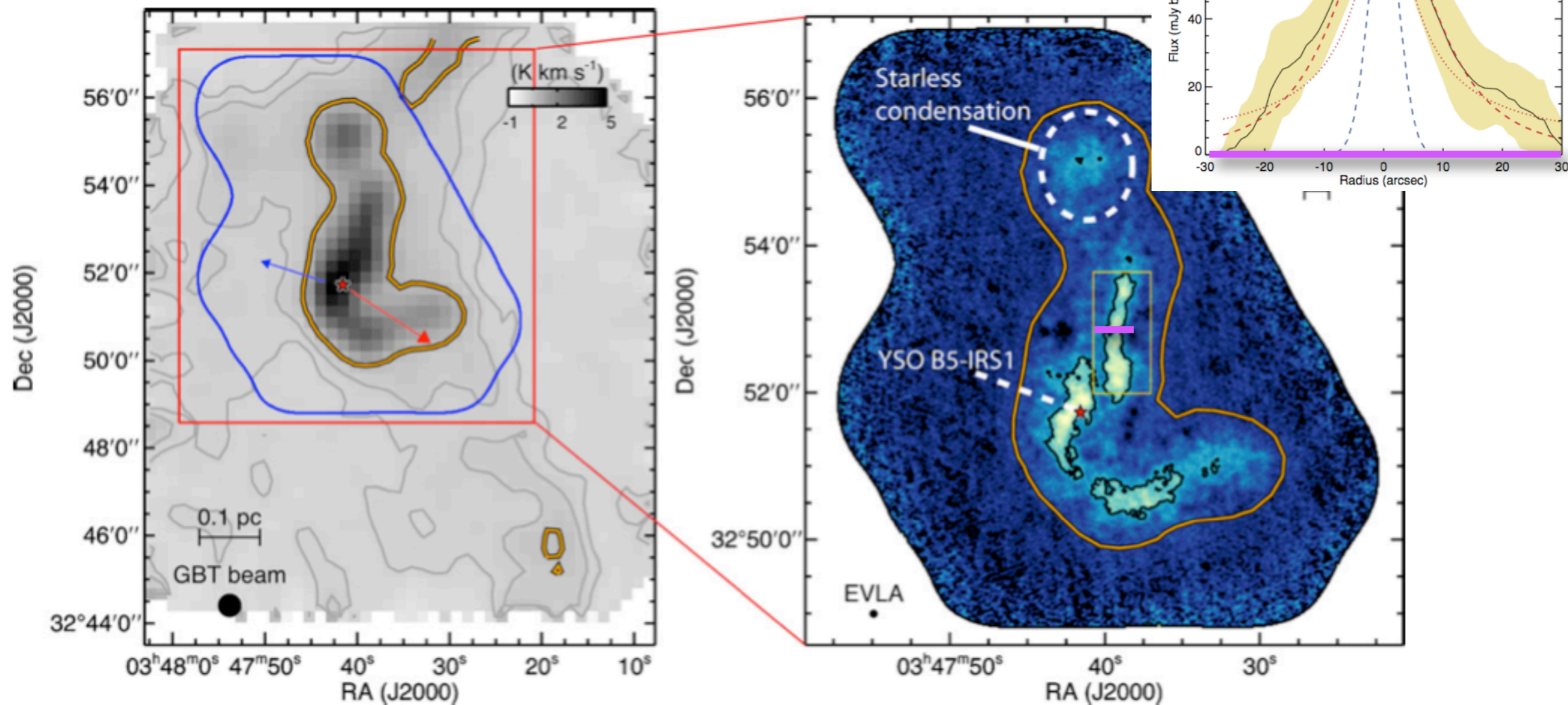
Simulated  
“Encounters”



# Thermal Fragmentation *in* Bound Coherent Cores?!

## Thank you EVLA!

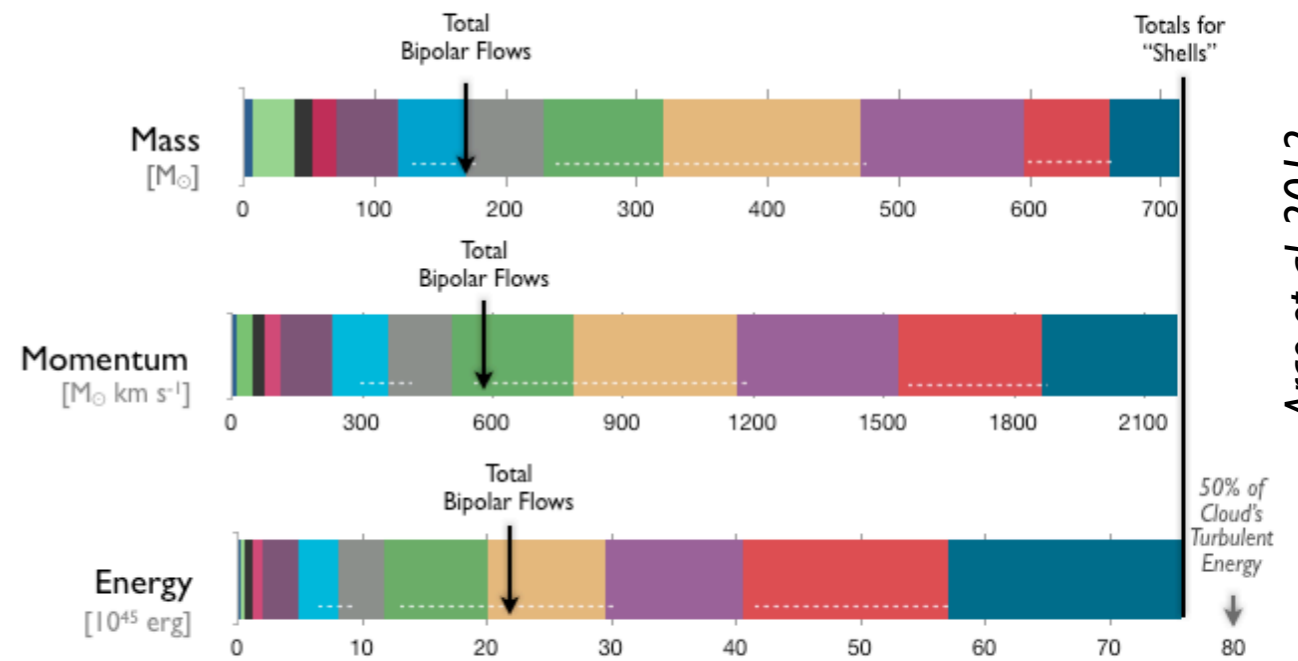
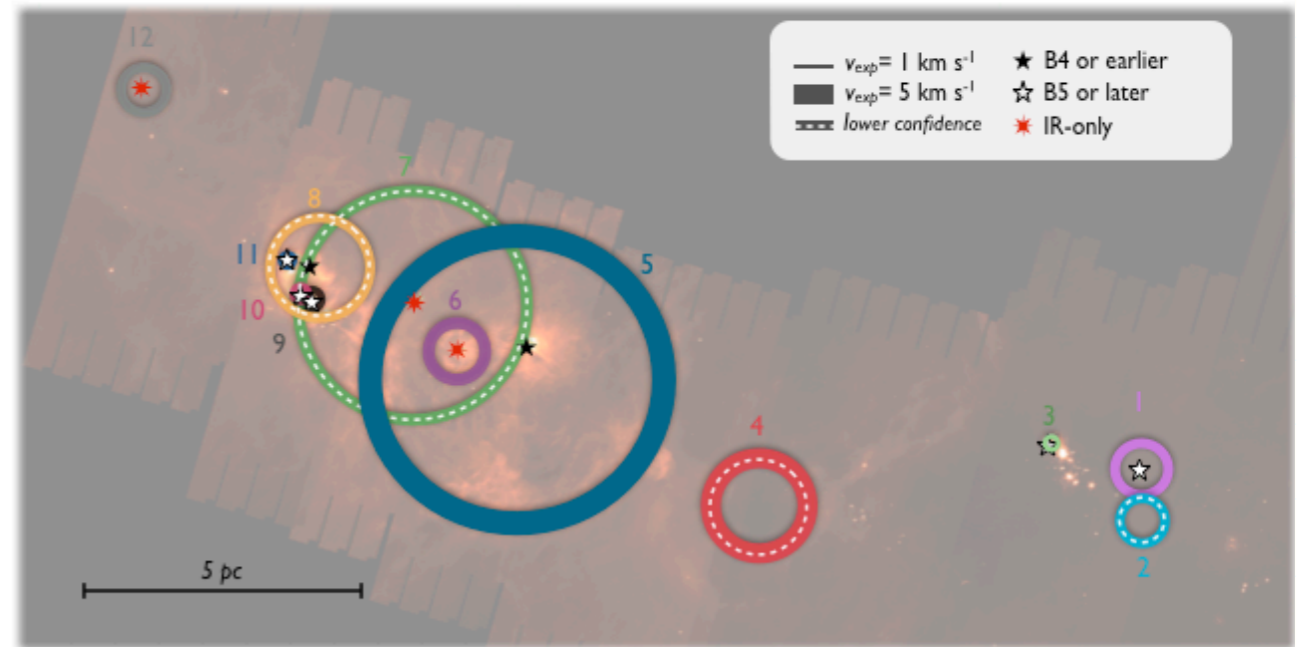
THE ASTROPHYSICAL JOURNAL LETTERS, 739:L2 (5pp), 2011 September 20



**Figure 1.** Left panel: integrated intensity map of B5 in NH<sub>3</sub> (1,1) obtained with GBT. Gray contours show the 0.15 and 0.3 K km s<sup>-1</sup> level in NH<sub>3</sub> (1,1) integrated intensity. The orange contours show the region in the GBT data where the non-thermal velocity dispersion is subsonic. The young star, B5-IRS1, is shown by the star in both panels. The outflow direction is shown by the arrows. The blue contour shows the area observed with the EVLA and the red box shows the area shown in the right panel. Right panel: integrated intensity map of B5 in NH<sub>3</sub> (1,1) obtained combining the EVLA and GBT data. Black contour shows the 50 mJy beam<sup>-1</sup> km s<sup>-1</sup> level in NH<sub>3</sub> (1,1) integrated intensity. The yellow box shows the region used in Figure 4. The northern starless condensation is shown by the dashed circle.

# 3 Questions

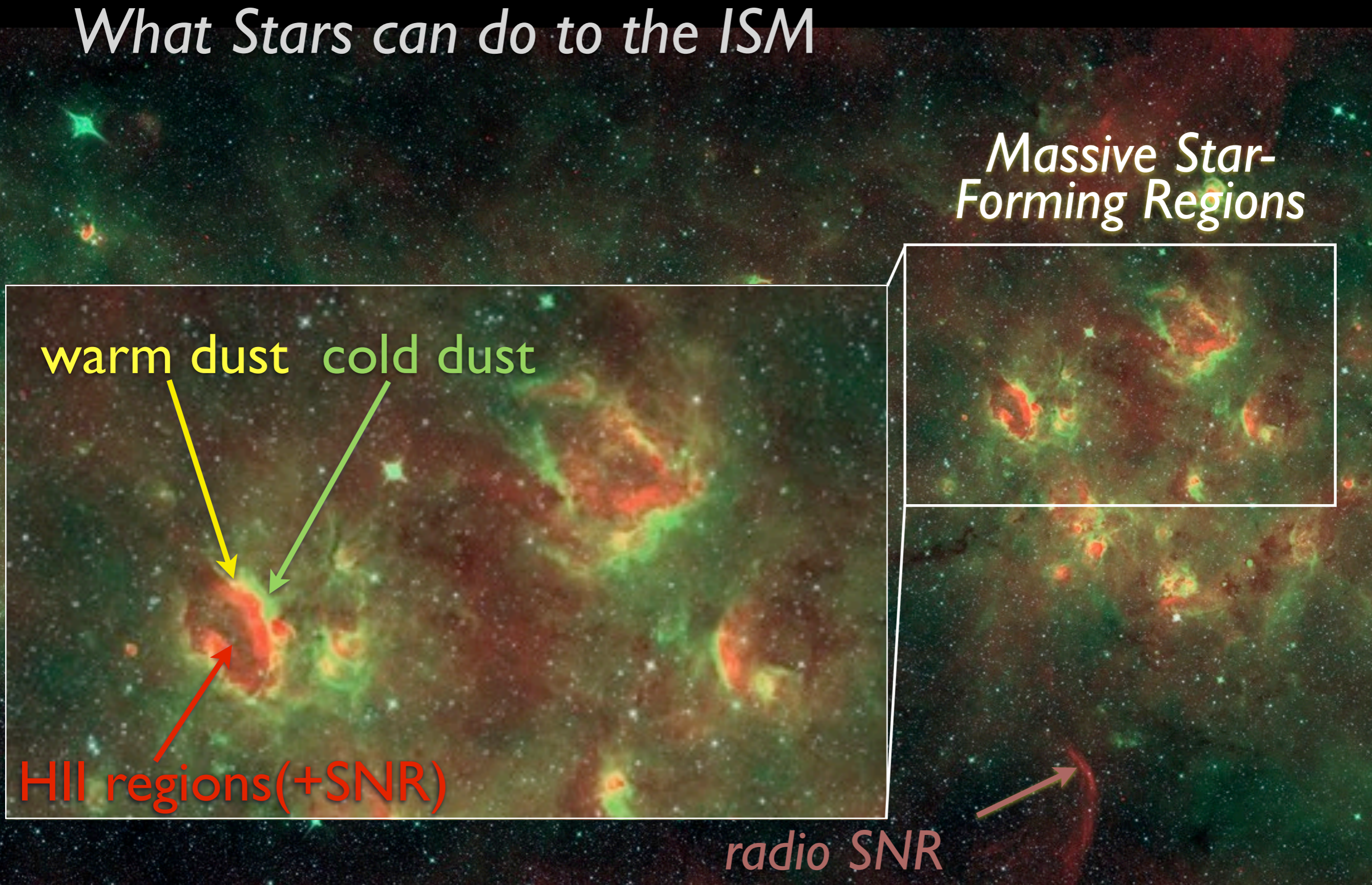
2. What  
stars  
do to



Arce et al. 2012

+ "tasty" approaches to answers

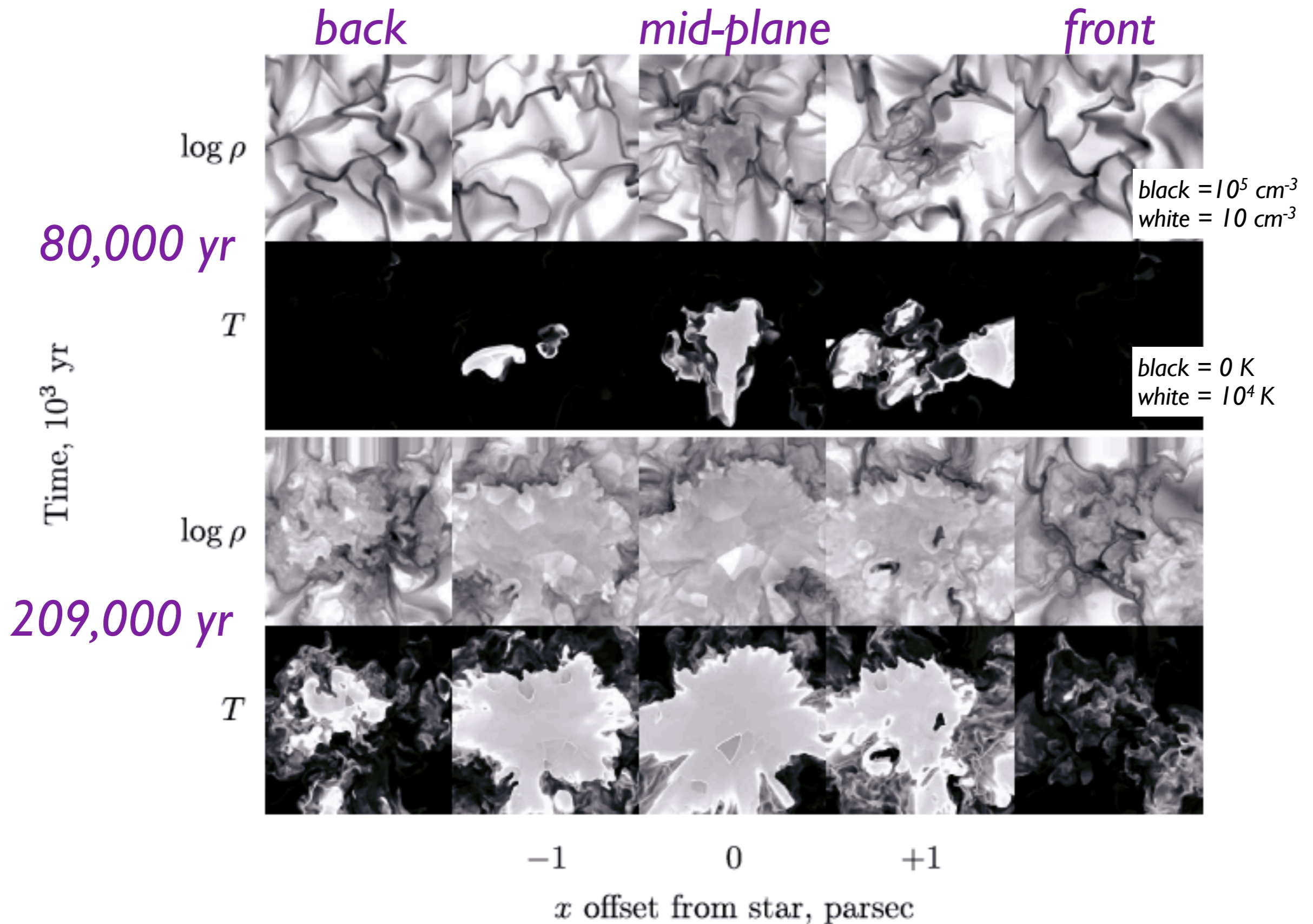
# What Stars can do to the ISM



20 cm VLA from MAGPIS (Helfand et al. 2006) & MIR from Spitzer GLIMPSE (see Churchwell et al.)  
3.6, 4.5, 8.0, 20cm (Luptonized, see Lupton et al. 2004)  
image "height" is 1.6 degrees (e.g. 140 pc at 5 kpc)

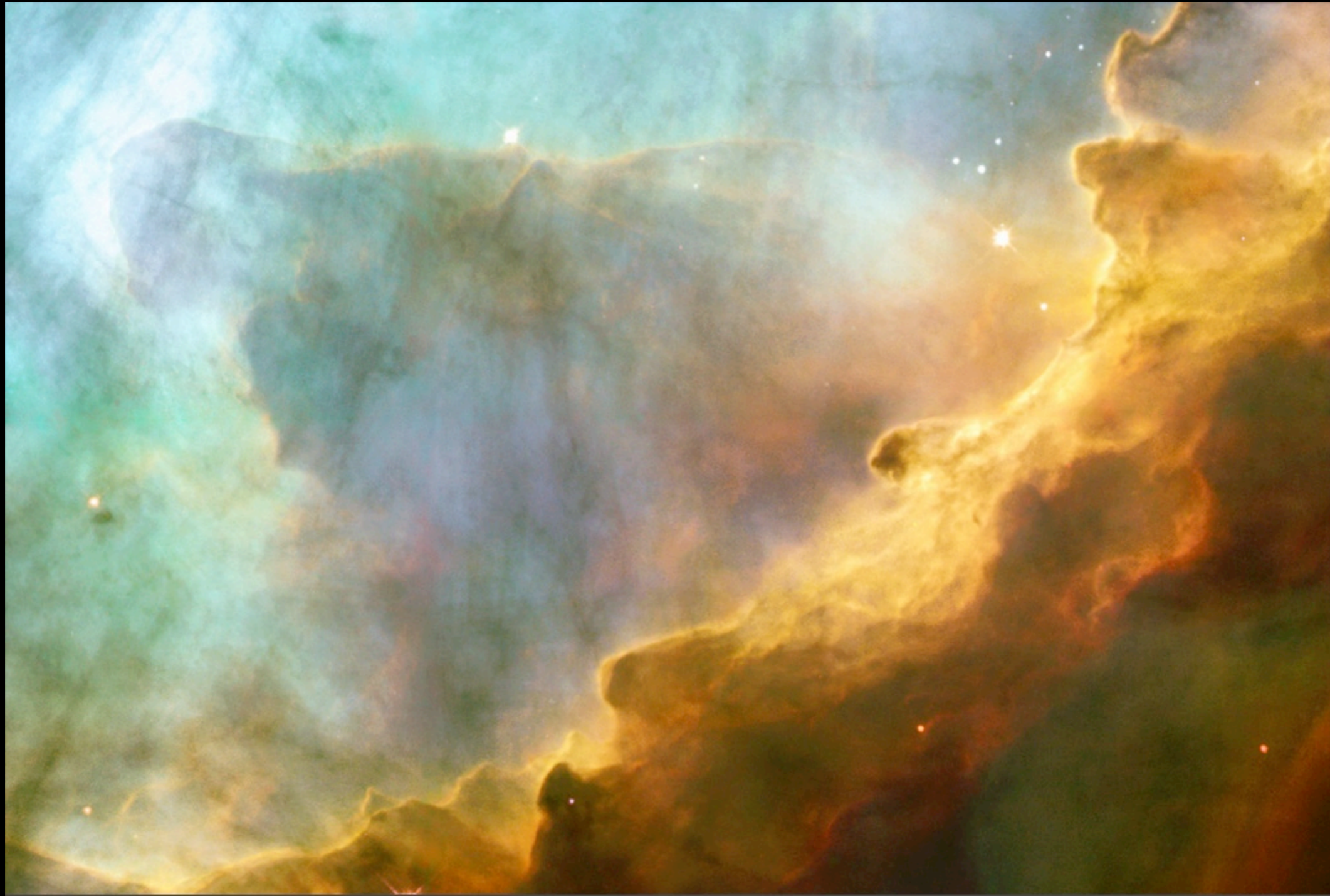


# Evolution of an HII Region in a Turbulent Medium



from S.J.Arthur 2007

# M17

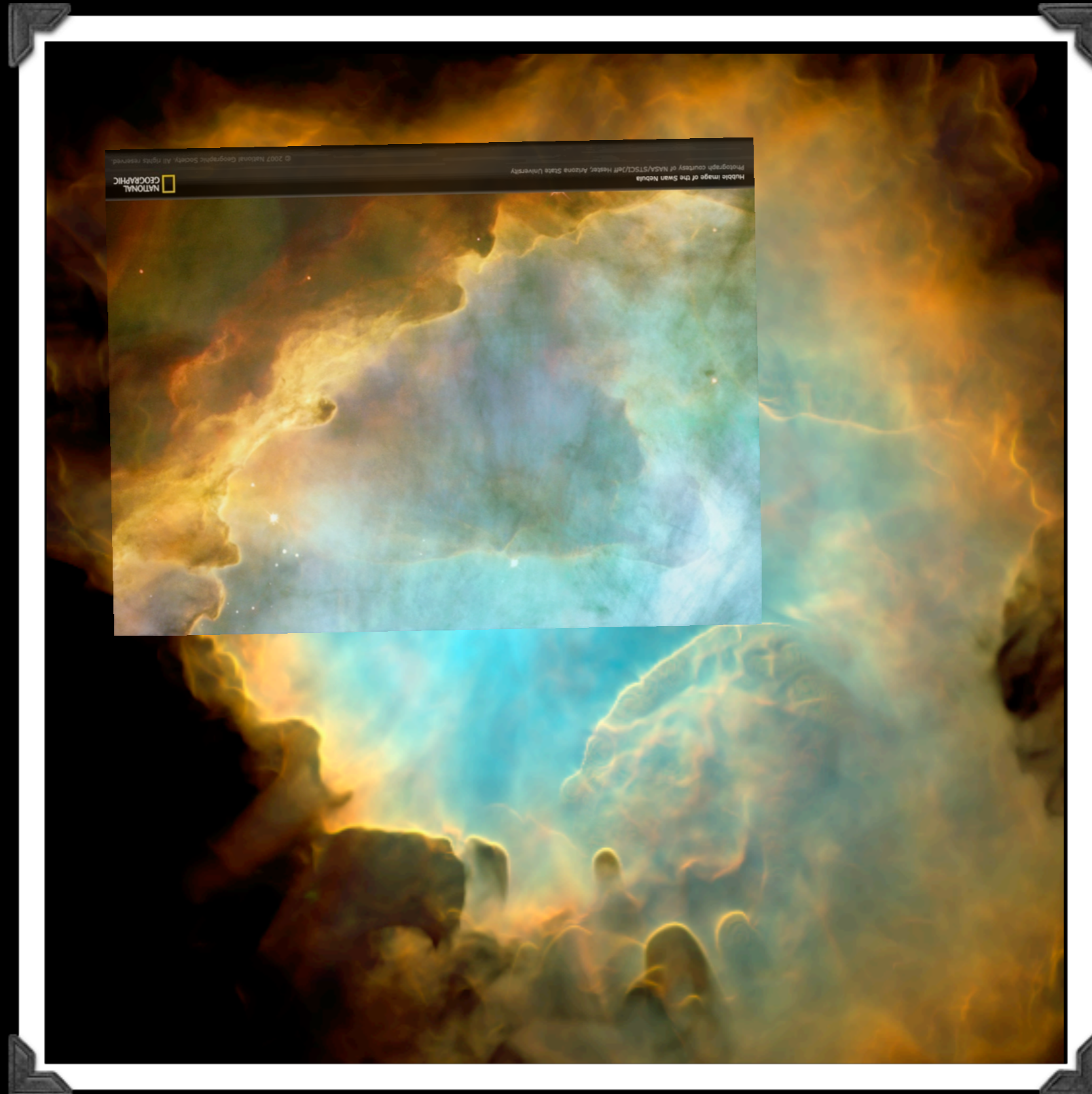


Hubble Image of the Swan Nebula  
Photograph courtesy of NASA/STSCI/Jeff Hester, Arizona State University



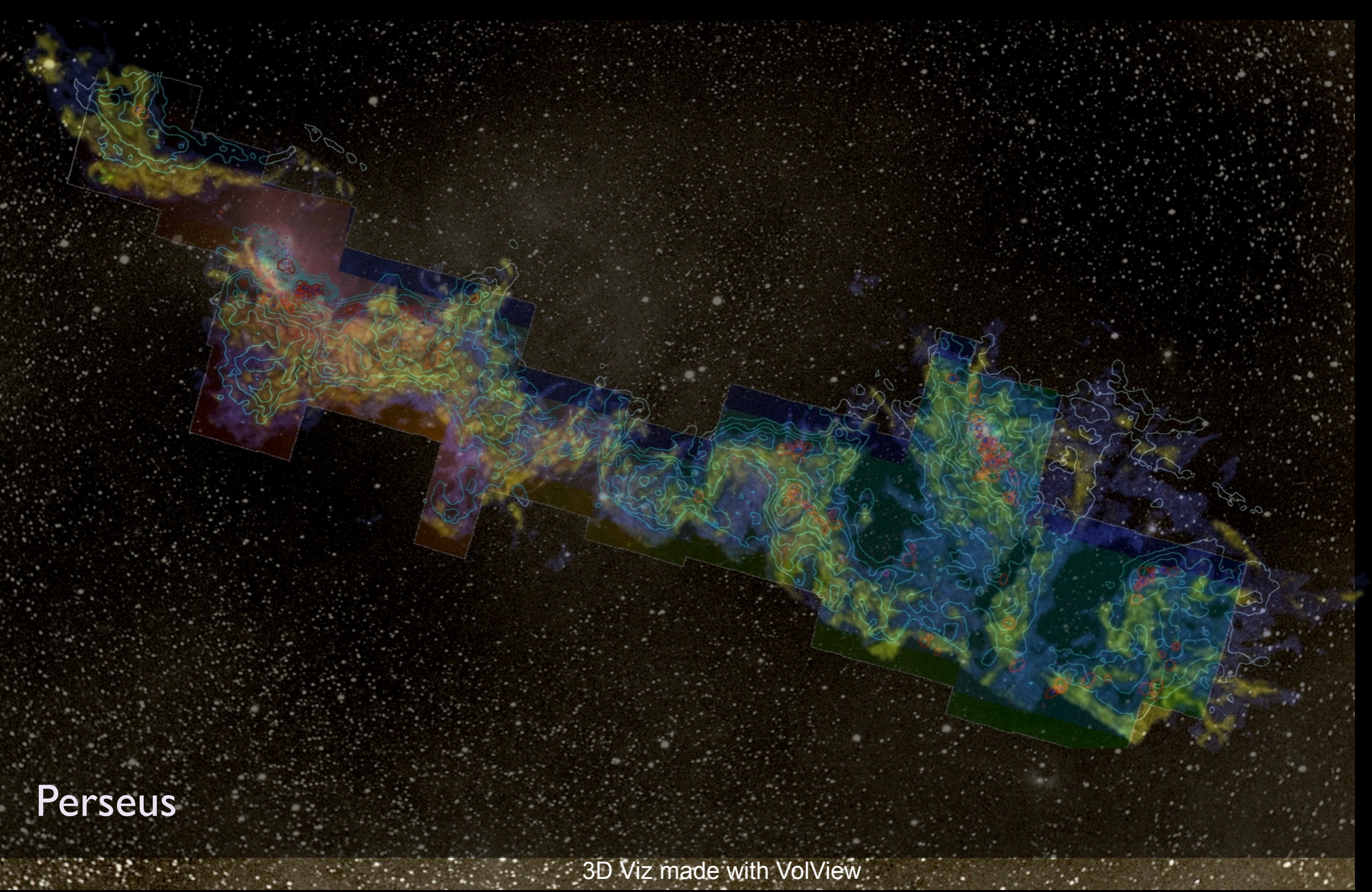
© 2007 National Geographic Society. All rights reserved.

# Tasting “M17”...



*Synthetic [OIII], Ha and [NII] emission-line image from a  $512^3$  numerical simulation: Mellema, Henney, Arthur & Vázquez-Semadeni 2009*





Perseus

3D Viz made with VolView

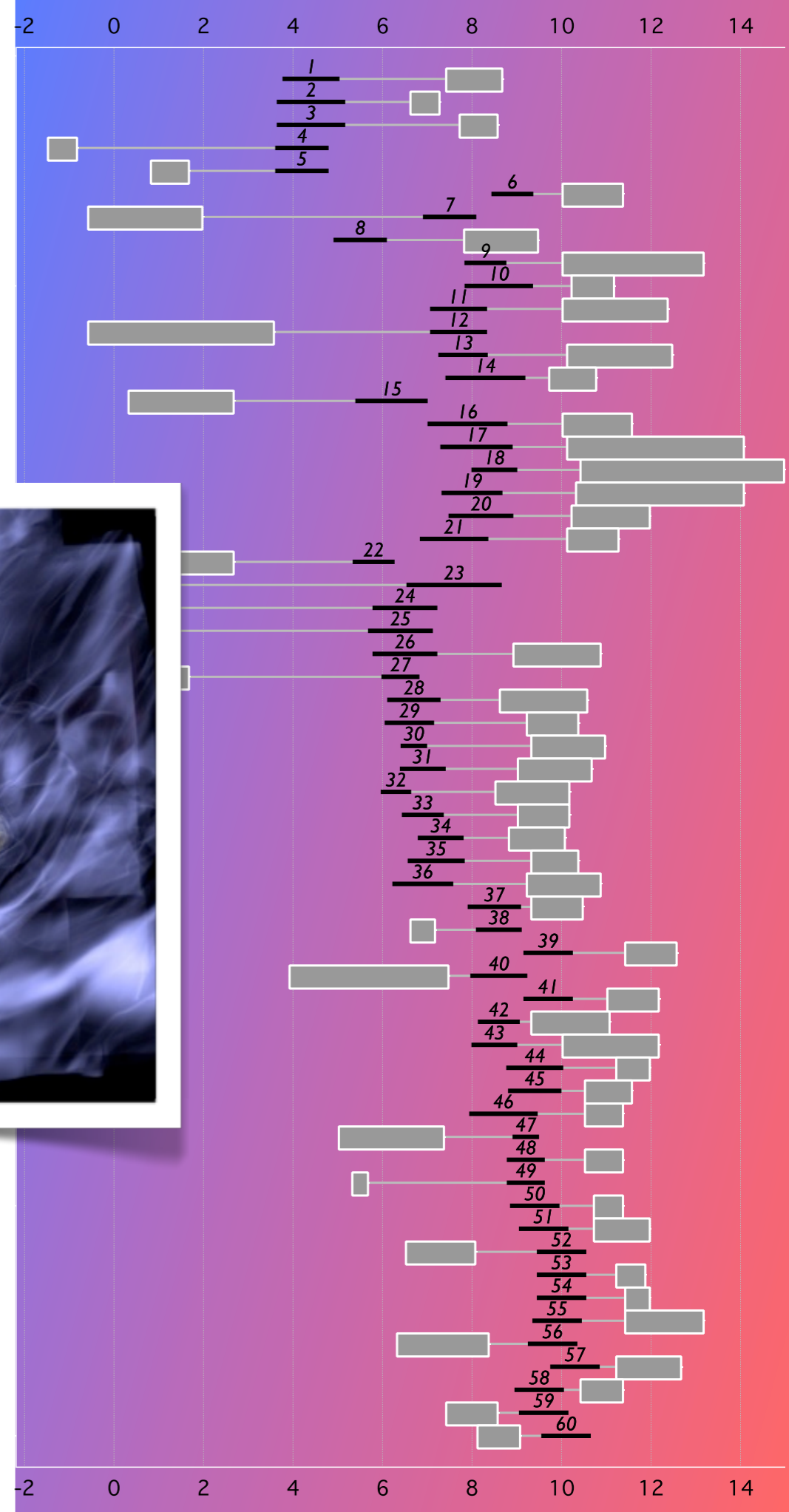
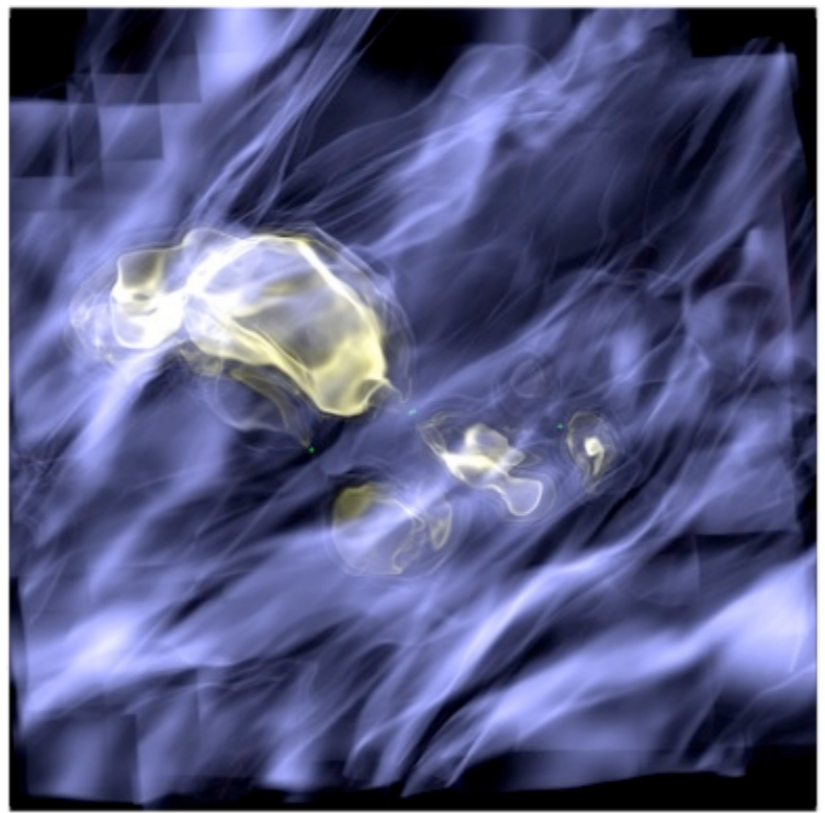
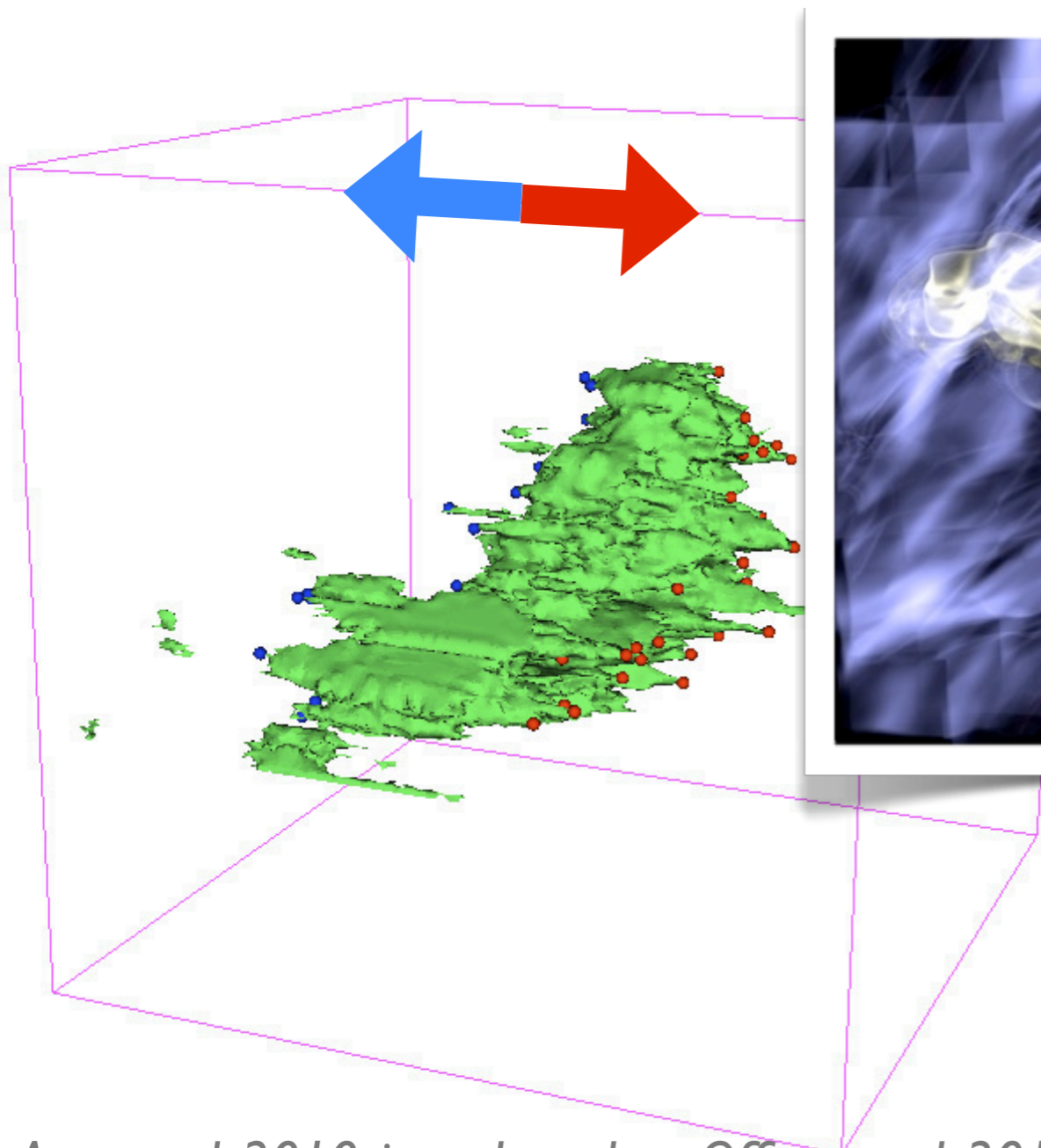
AstronomicalMedicine@iig

COMPLETE

# “CPOCs”

## COMPLETE Perseus Outflow Candidates

Note: I did not make up that name!



Arce et al. 2010; inset based on Offner et al. 2011

# Perseus Bipolar Outflows

Arce et al. 2010a

**Table 5**  
Physical Parameters of Active Star-forming Regions in Perseus

Name	$M_{\text{reg}}^a$ ( $M_{\odot}$ )	$R_{\text{reg}}^b$ (pc)	$\Delta v^c$ ( $\text{km s}^{-1}$ )	$T_{\text{ex}}^d$ (K)	$v_{\text{esc}}^e$ ( $\text{km s}^{-1}$ )	$E_{\text{grav}}^f$ ( $10^{46}$ erg)	$E_{\text{turb}}^g$ ( $10^{45}$ erg)	$t_{\text{diss}}^h$ ( $10^5$ yr)	$L_{\text{turb}}^i$ ( $10^{32}$ erg $\text{s}^{-1}$ )
L1448	150	0.6	1.9	10	1.5	0.3	2.9	2.6	3.6
NGC 1333	1100	2.0	2.2	13	2.2	5.2	28.8	5.7	15.9
B1-Ridge	210	0.7	1.9	13	1.6	0.5	4.1	3.1	4.1
B1	430	0.9	2.1	13	2.0	1.8	10.2	2.9	11.2
B5	420	1.4	1.5	12	1.6	1.1	5.1	7.6	2.1
IC 348	620	0.9	1.8	15	2.4	3.7	10.9	3.0	11.4

**Notes.**

- <sup>a</sup> Mass of star-forming region, obtained using the procedure described in Section 5.1.
- <sup>b</sup> Radius estimate of the region obtained from the geometric mean of minor and major axes of the extent of the  $^{13}\text{CO}$  integrated intensity emission.
- <sup>c</sup> Average velocity width (FWHM) of the  $^{13}\text{CO}(1-0)$  line in the region.
- <sup>d</sup> Average excitation temperature of region.
- <sup>e</sup> Escape velocity, given by  $\sqrt{2GM_{\text{reg}}/R_{\text{reg}}}$ .
- <sup>f</sup> Gravitational binding energy given by  $GM_{\text{reg}}^2/R_{\text{reg}}$ .
- <sup>g</sup> Turbulence energy given by  $\frac{3}{16ln2}M_{\text{reg}}\Delta v^2$ .
- <sup>h</sup> Turbulence dissipation time, see Section 5.2.1.
- <sup>i</sup> Turbulence energy dissipation rate given by  $E_{\text{turb}}/\tau_{\text{diss}}$ .

**Table 6**  
Total Outflow Mass, Momentum, Energy, and Luminosity in Star-forming Regions

Name	$M_{\text{flow}}^a$ ( $M_{\odot}$ )	$P_{\text{flow}}^a$ ( $M_{\odot} \text{ km s}^{-1}$ )	$E_{\text{flow}}^a$ ( $10^{44}$ erg)	$L_{\text{flow}}^b$ ( $10^{32}$ erg $\text{s}^{-1}$ )
L1448	1.0/5	3.1/21.7	1.2/12	8
NGC 1333	5.0/25	17.4/121.8	6.9/69	44
B1-Ridge	1.1/5.5	3.2/22.4	1.0/10	6
B1	1.5/7.5	6.2/43.4	3.1/31	20
IC 348	4.2/21	7.7/53.9	1.5/15	10
B5	12.8/64	22.3/156.1	4.1/41	26

**Notes.**

- <sup>a</sup> Values before and after the slash are the original estimates and the estimates adjusted by the correction factor, respectively (see Section 5.1).
- <sup>b</sup> Outflow luminosity,  $L_{\text{flow}} = E_{\text{flow}}/\tau_{\text{flow}}$ , obtained using the value of the total outflow kinetic energy adjusted by the correction factor and using an average outflow timescale of  $5 \times 10^4$  yr.

**Table 7**  
Quantitative Assessment of Outflow Impact on Star-forming Regions

Name	$E_{\text{flow}}/E_{\text{turb}}$	$r_L = L_{\text{flow}}/L_{\text{turb}}$	$E_{\text{flow}}/E_{\text{grav}}$	$M_{\text{esc}}^a$ ( $M_{\odot}$ )	$M_{\text{esc}}/M_{\text{reg}}$
L1448	0.41	2.1	0.40	15	0.10
NGC 1333	0.30	3.4	0.17	76	0.07
B1-Ridge	0.24	1.5	0.20	14	0.07
B1	0.30	1.7	0.17	21	0.05
IC 348	0.14	0.8	0.04	23	0.04
B5	0.80	12.4	0.37	98	0.23

**Note.** <sup>a</sup> Escape mass, given by  $M_{\text{esc}} = P_{\text{out}}/v_{\text{esc}}$  (see Section 5.2.3).

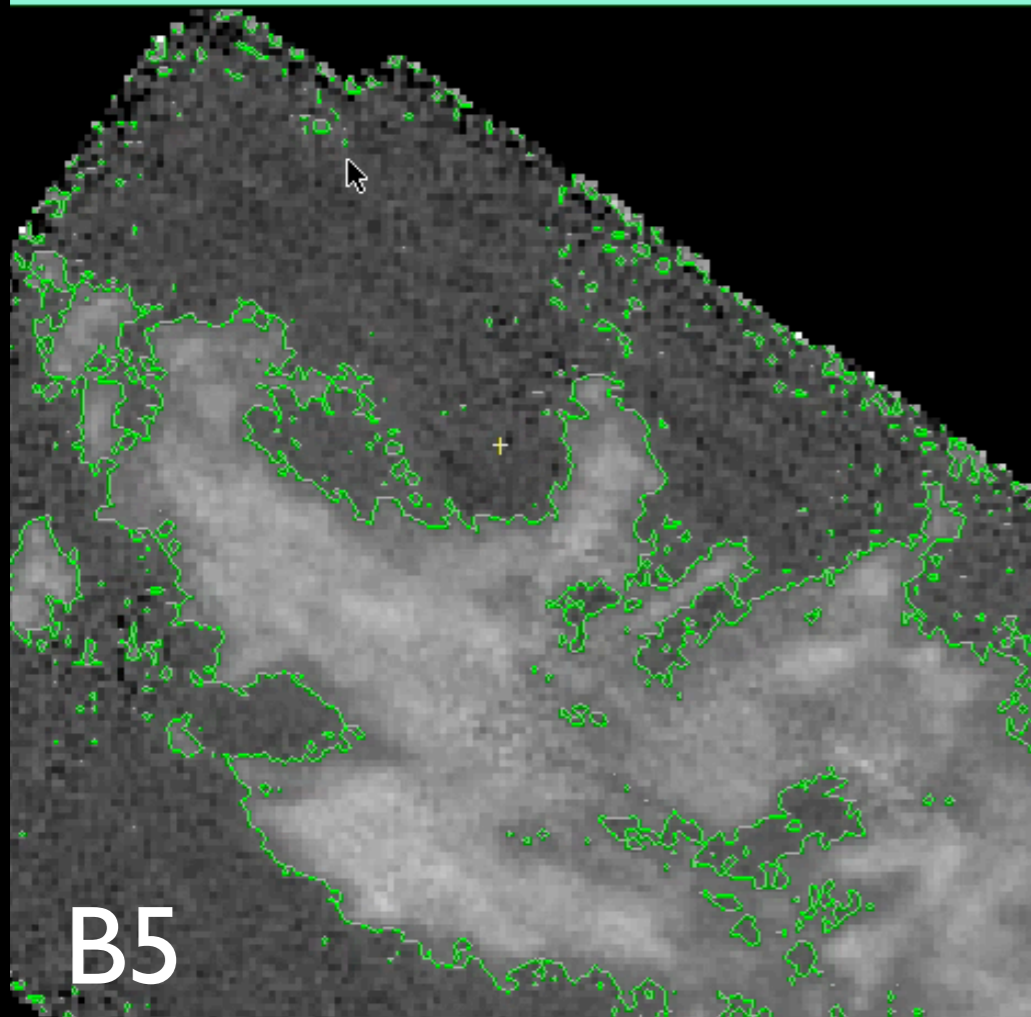
Typically 20% binding energy in flows.

Bottom line  
local influence significant,  
HOMEWRECKERS *not.*

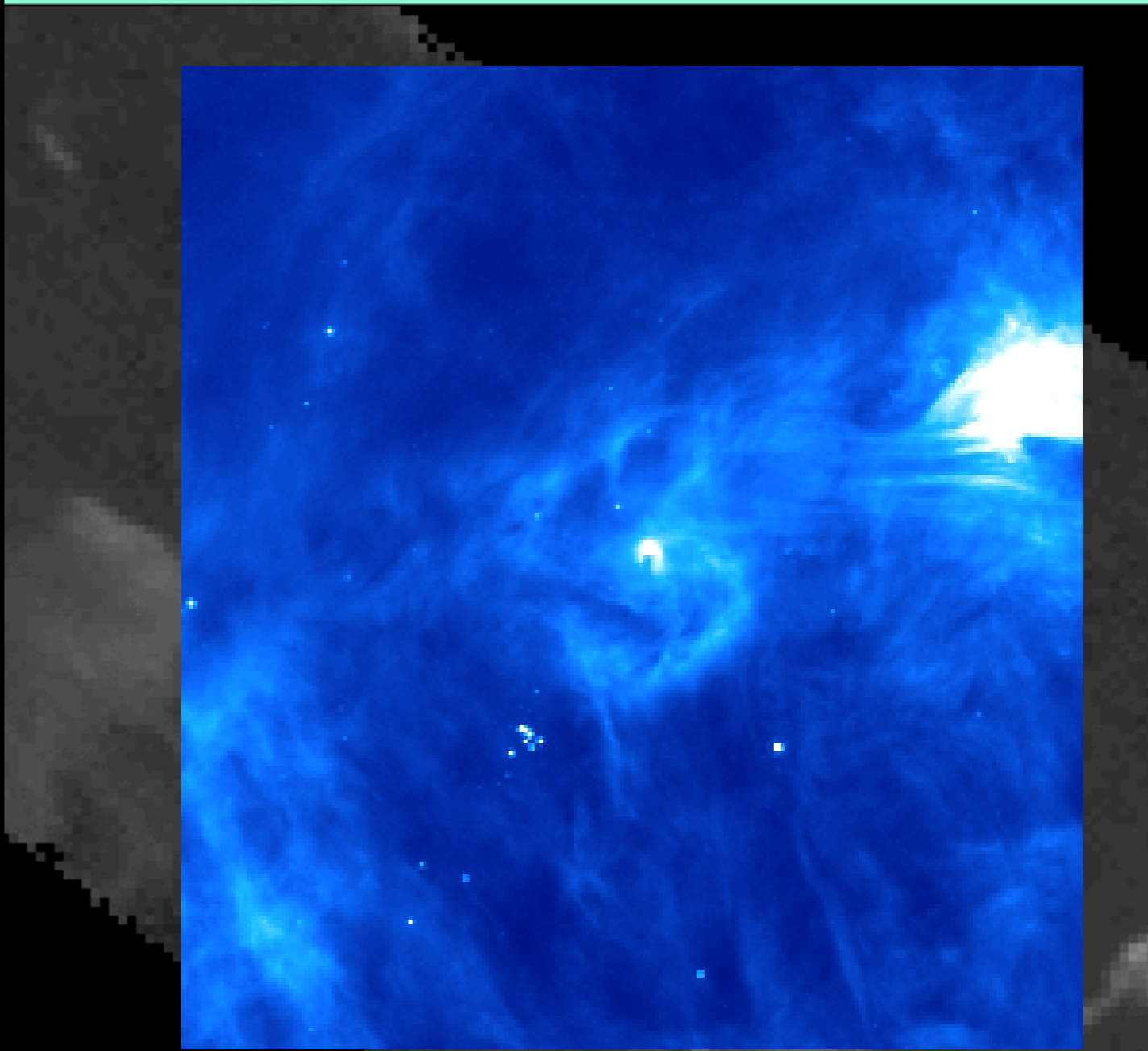
But, we have other options.  
Turns out bipolar outflows are nothing  
compared to spherical shells...

# “Cinema Arce”

x: 100 y: 523 z: 296 value: 0.312653 K
Ra 03h 48m 28.082s Dec 33d 20m 34.95s Vel: 8.83 km/s



x: 168 y: 150 z: 257 value: -0.554963
Ra 03h 41m 19.851s Dec 31d 55m 51.95s Vel: 6.35 km/s



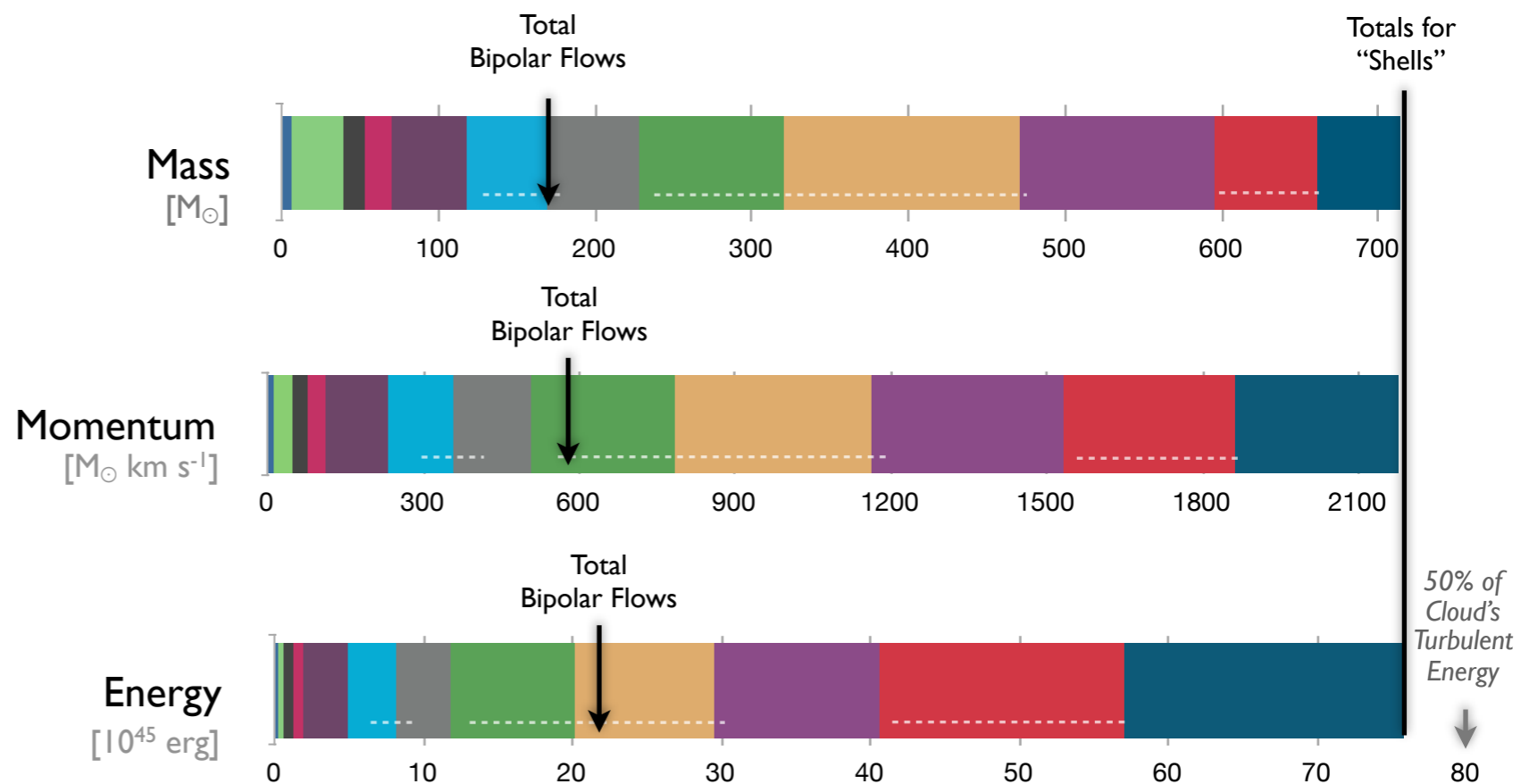
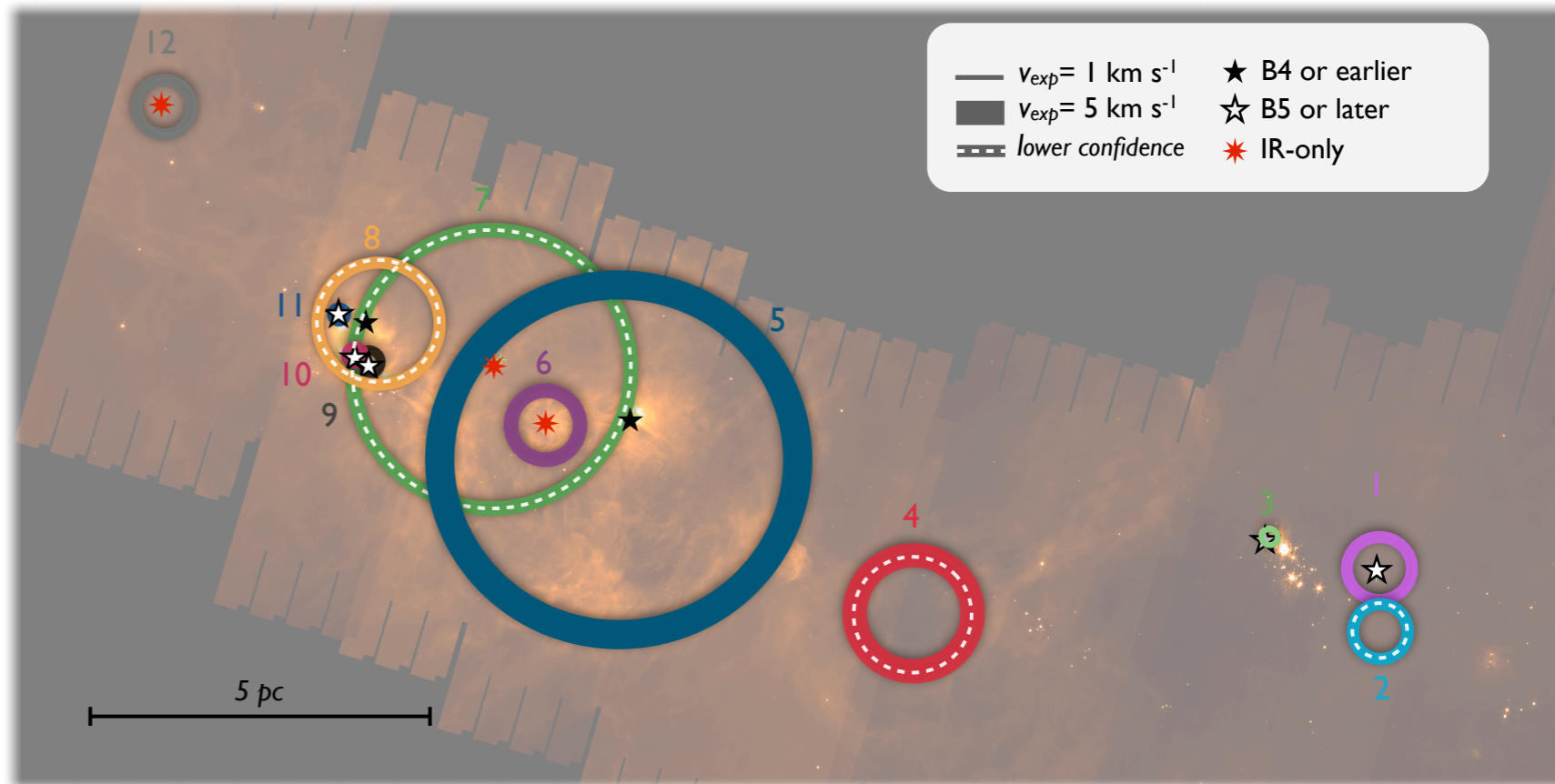
IRAS 03382+3145

# “Spherical” Outflows

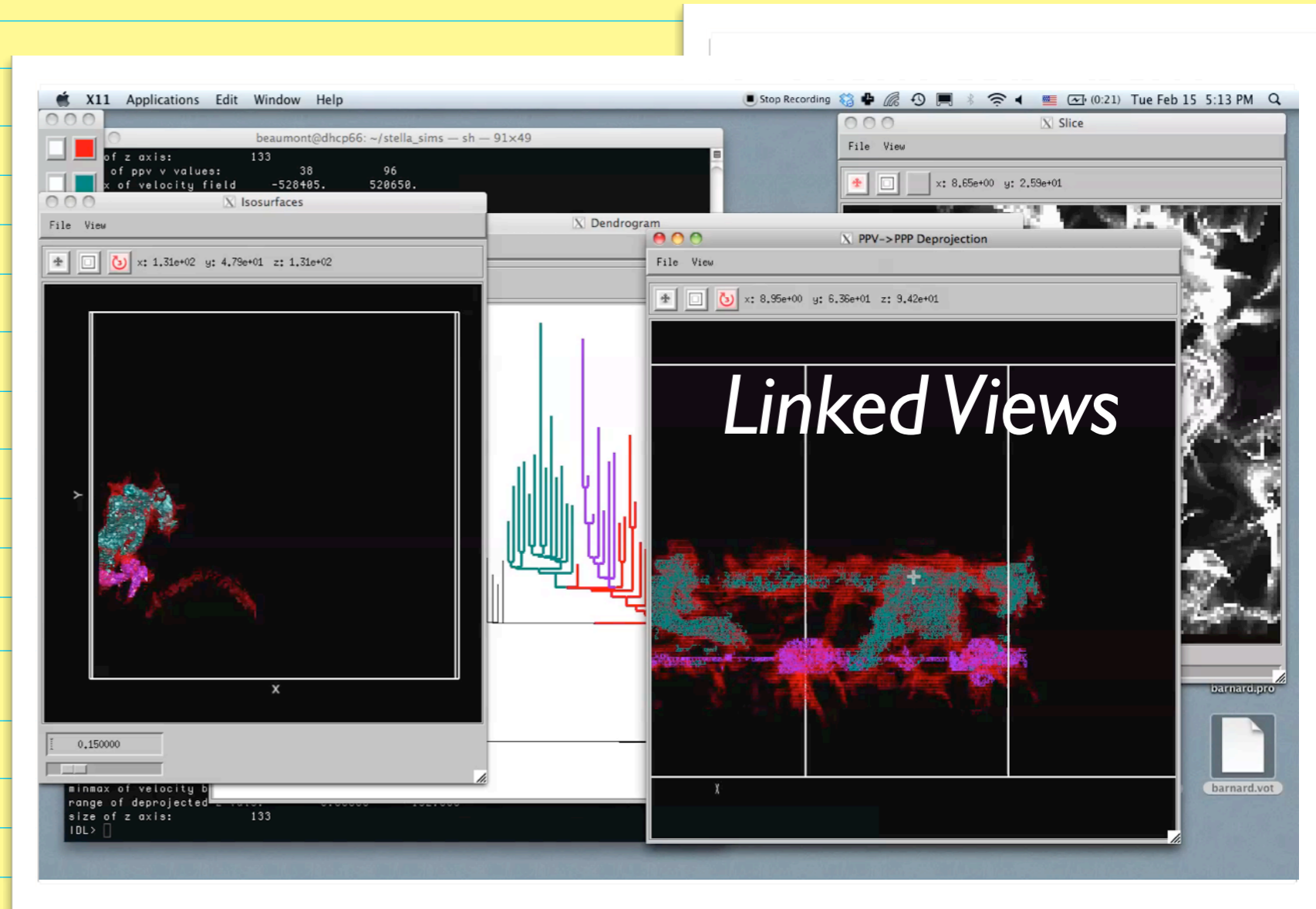
## News Flash

Spherical shells from young-ish stars may stir molecular clouds (much) MORE than bipolar flows, and B-stars may matter much.

*Arce et al. 2011*



# 3 Questions

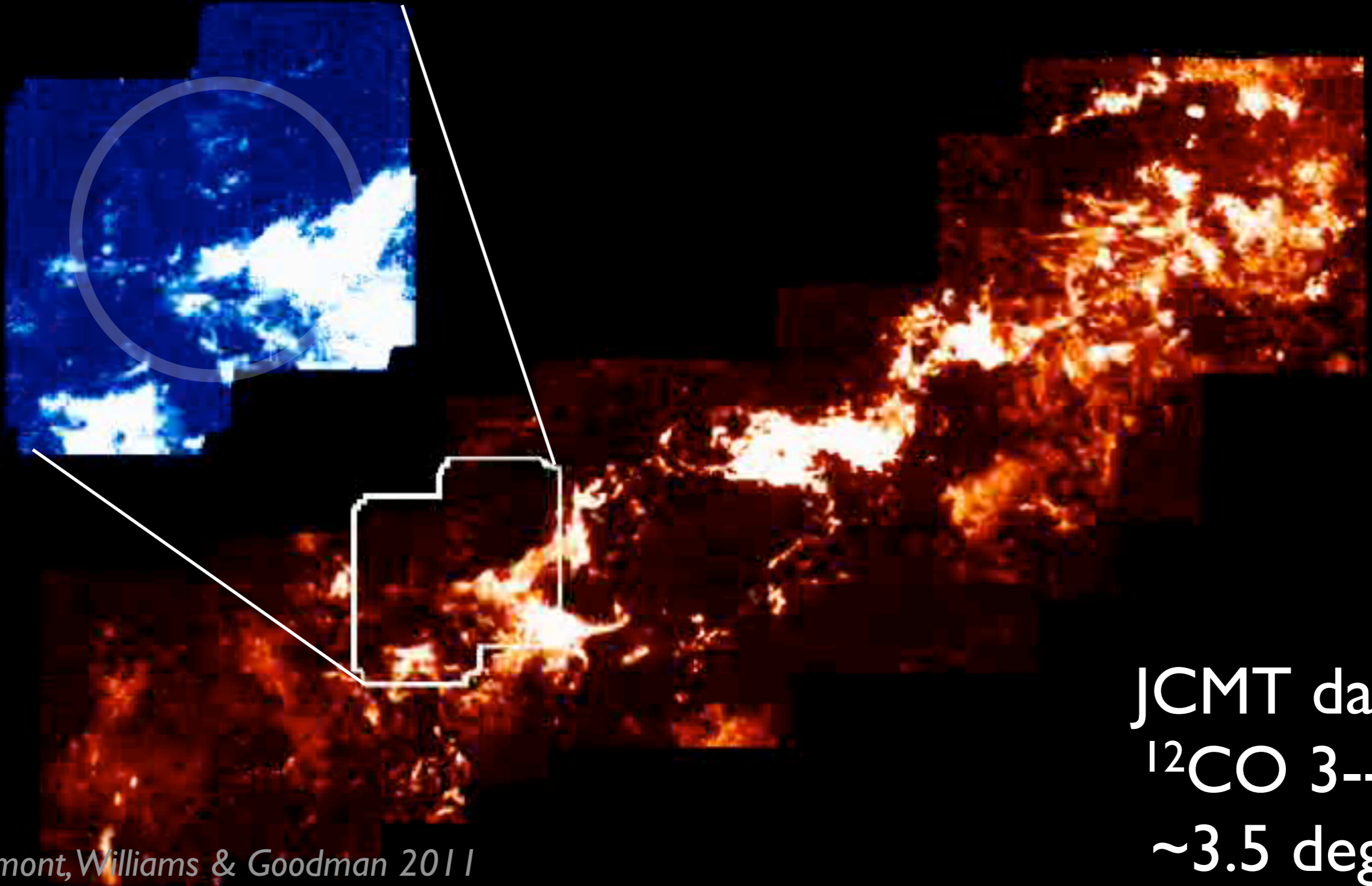


+ "tasty" approaches to answers

# $(p-p-v)$ Case Study

“Buried” SNR GI 6.05-0.57

All of **MI7**



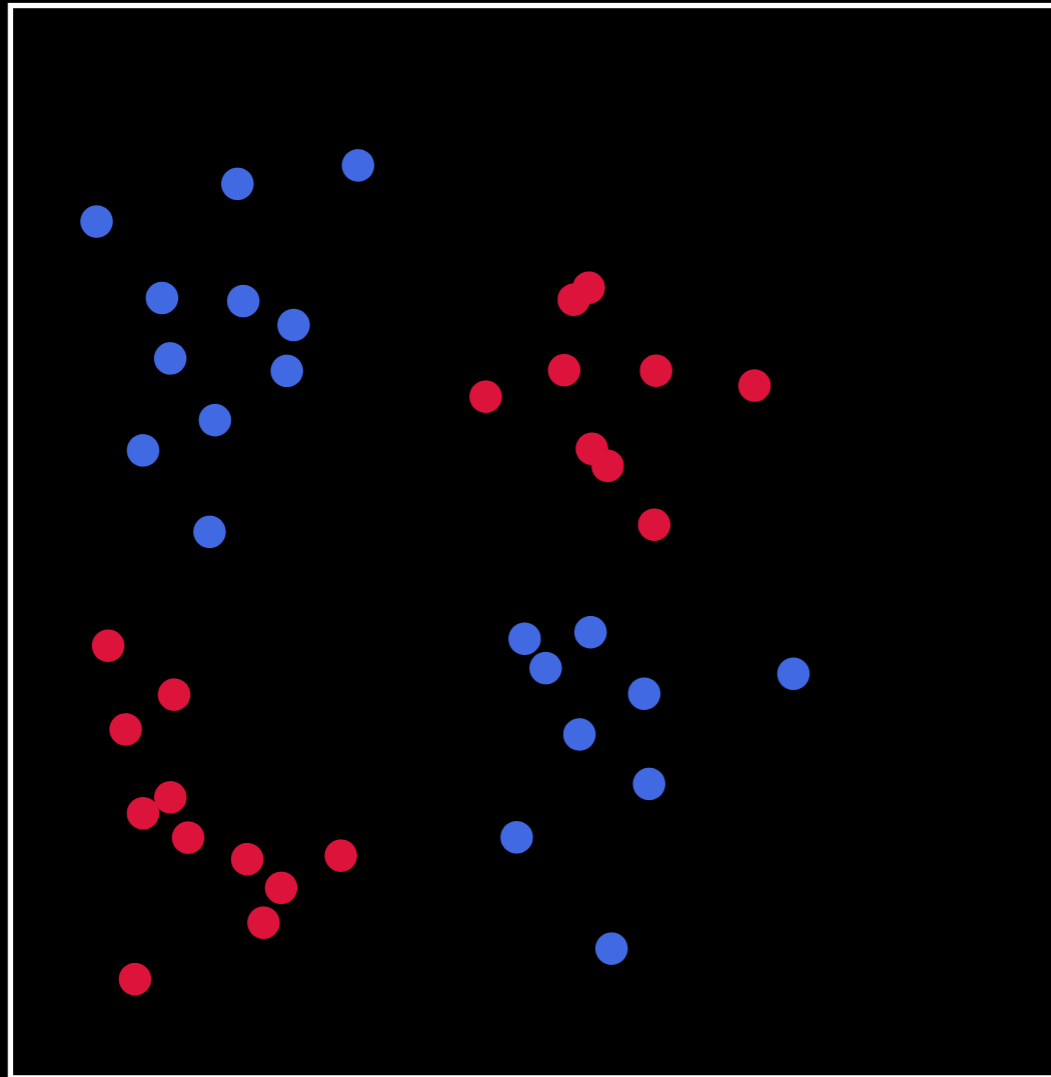
JCMT data  
 $^{12}\text{CO } 3\text{--}2$   
 $\sim 3.5 \text{ deg}^2$

*Beaumont, Williams & Goodman 2011*



# Support Vector Machines in One Minute (SVM is a kind of “Machine Learning”)

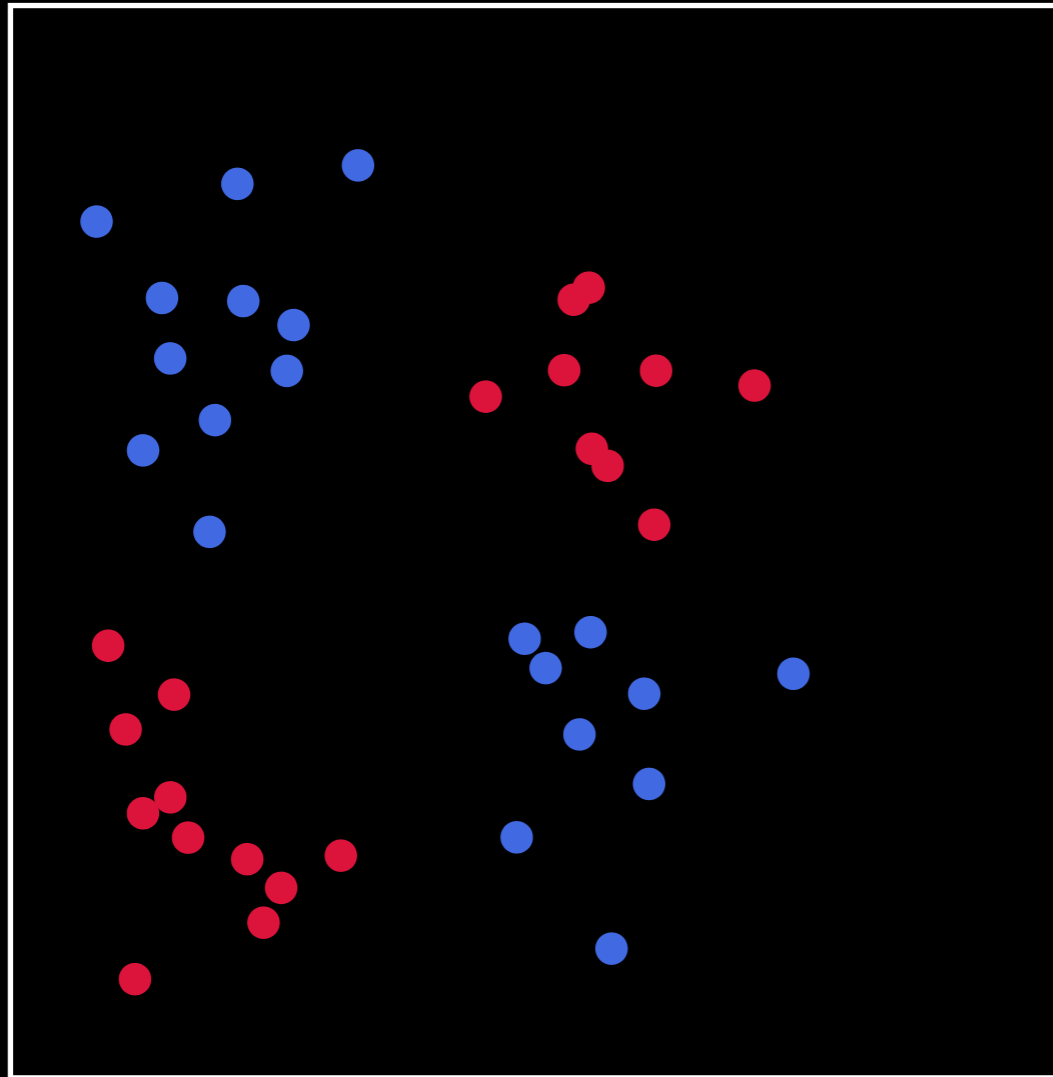
Feature 2 (“Linewidth”)



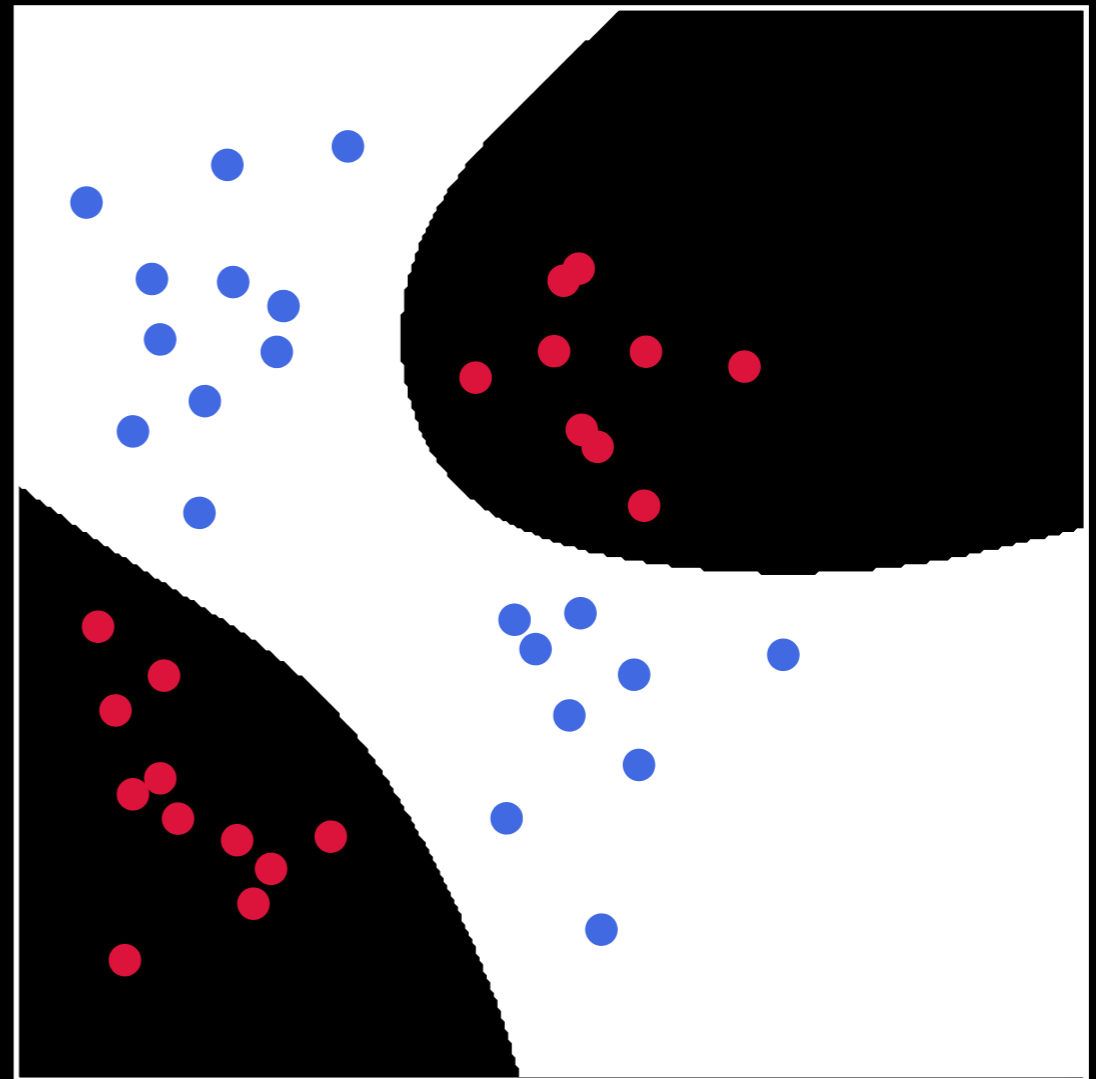
Feature 1 (“Intensity”)

# Support Vector Machines in One Minute

Feature 2 (“Linewidth”)



Feature 1 (“Intensity”)



# Training Set

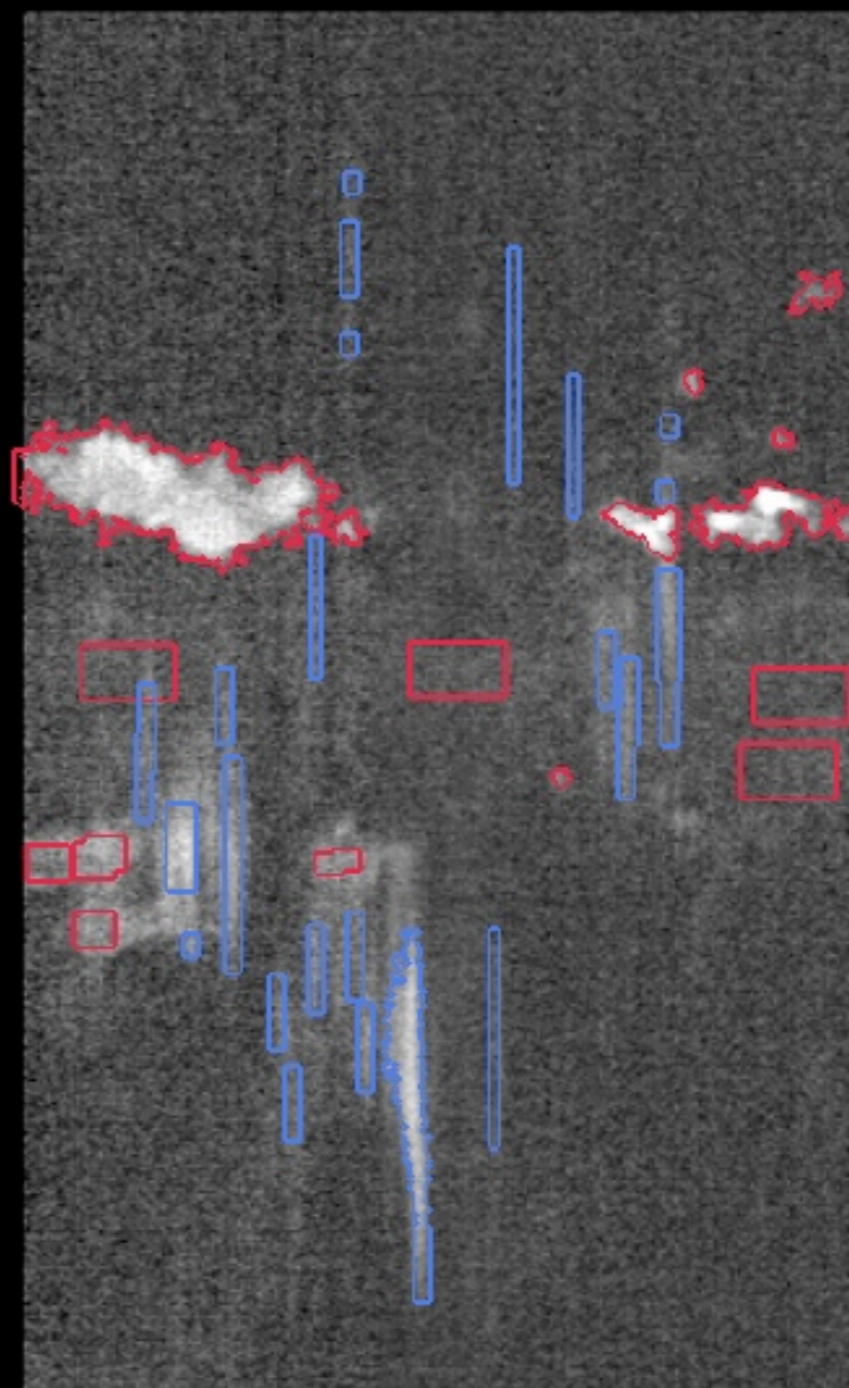
Slice

Classification

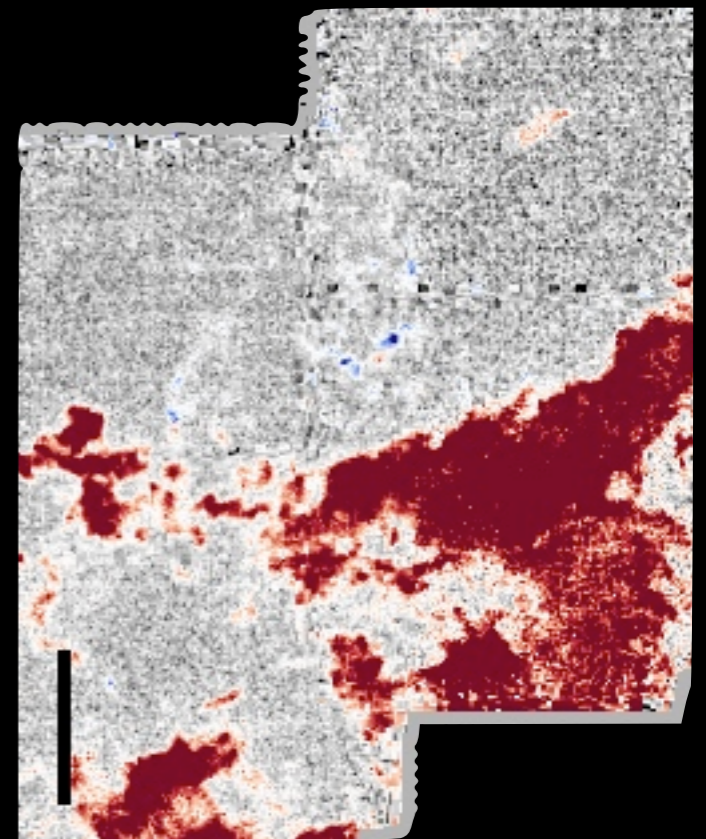
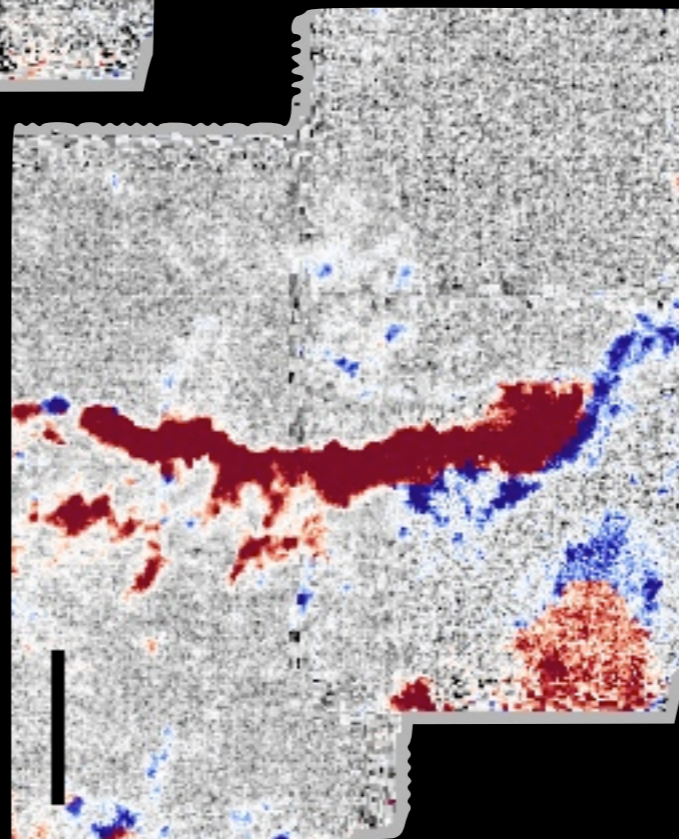
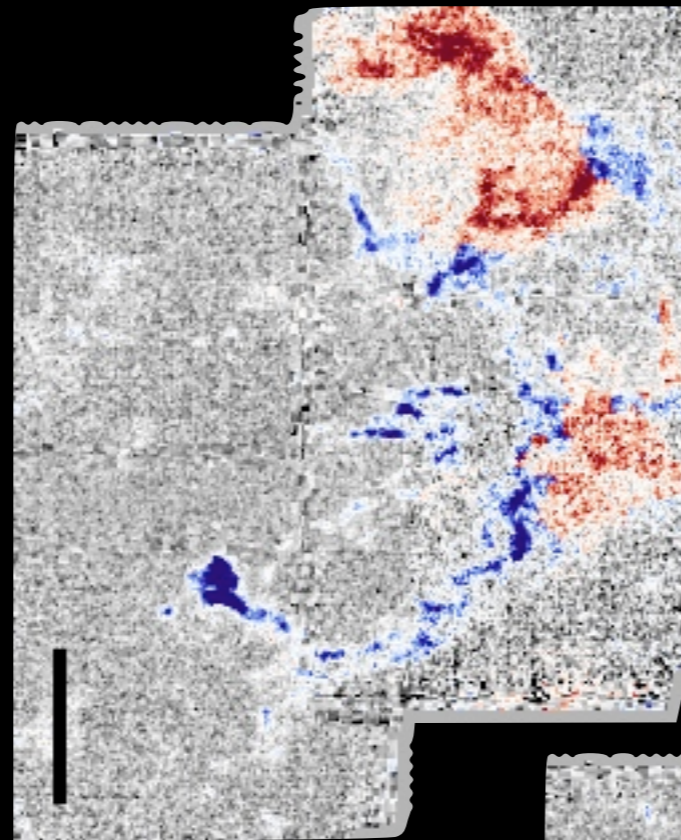
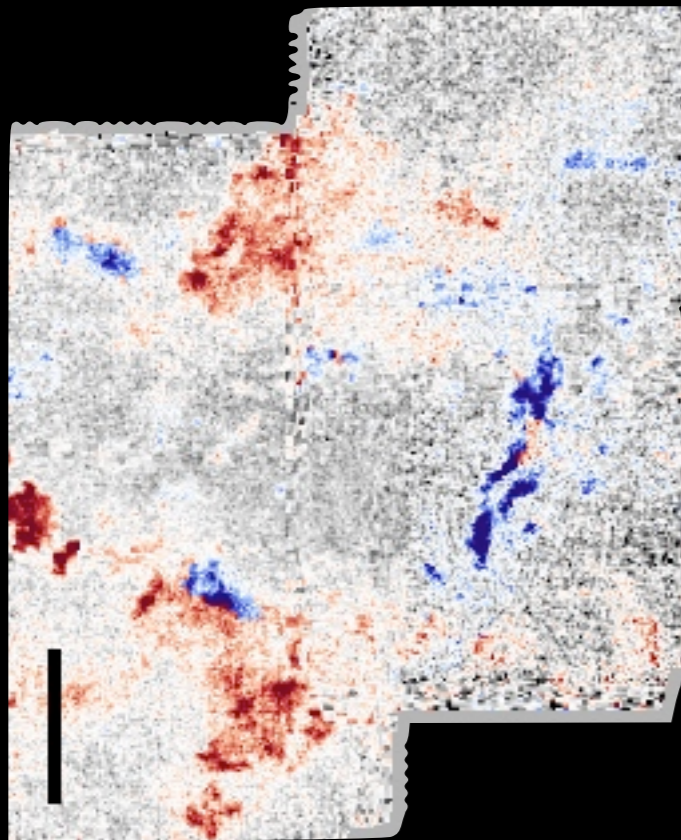


Cloud  
Supernova

(regions defined via  
rectangles and  
contours)



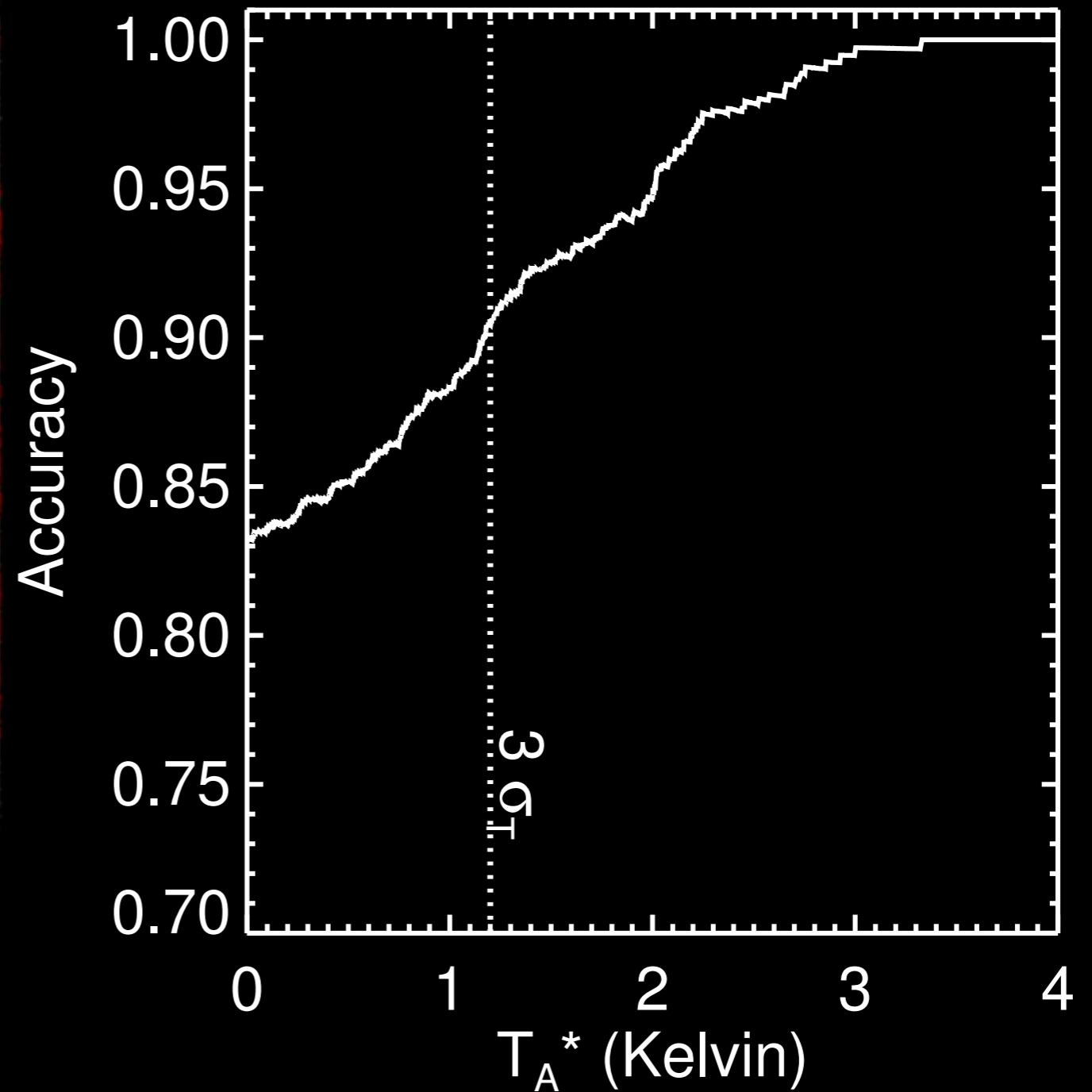
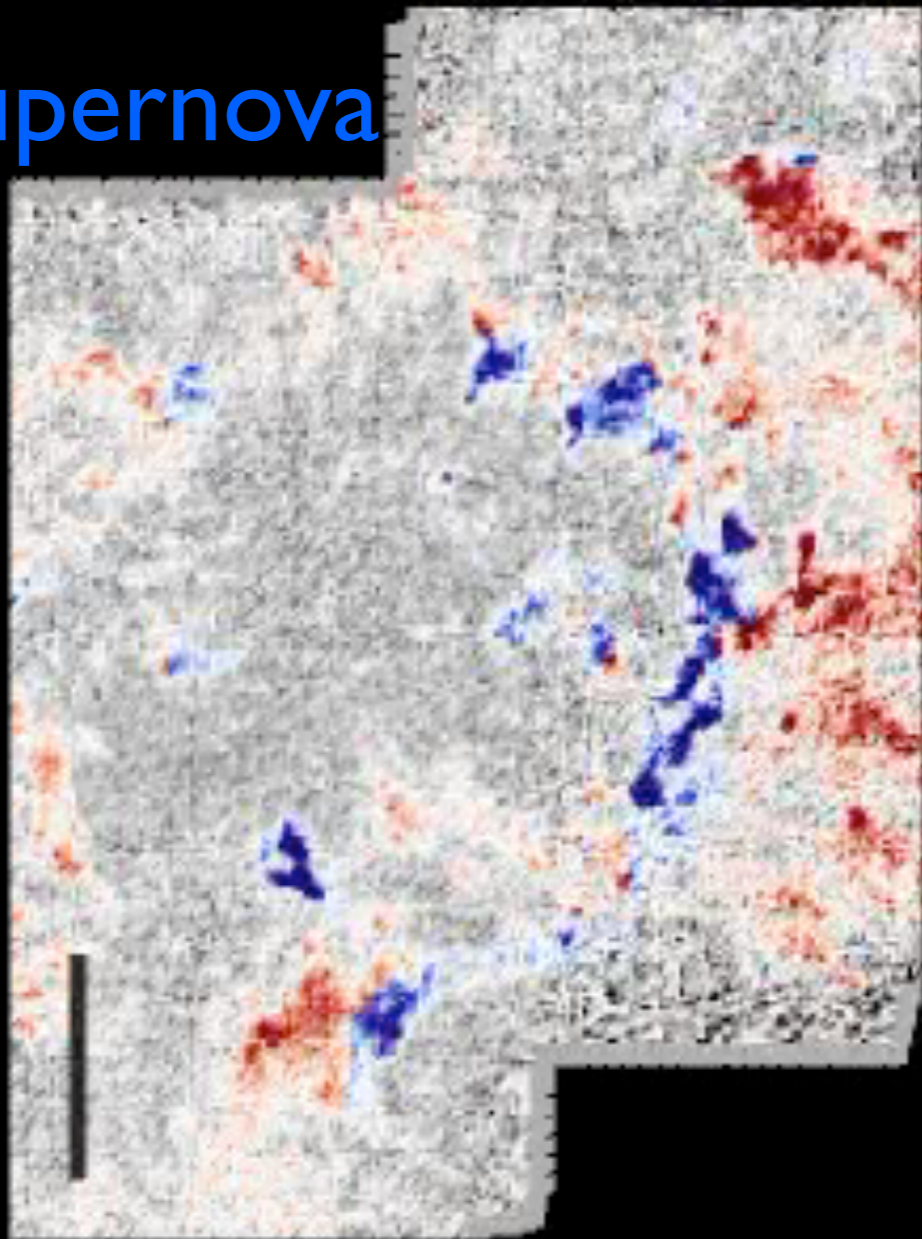
# Results



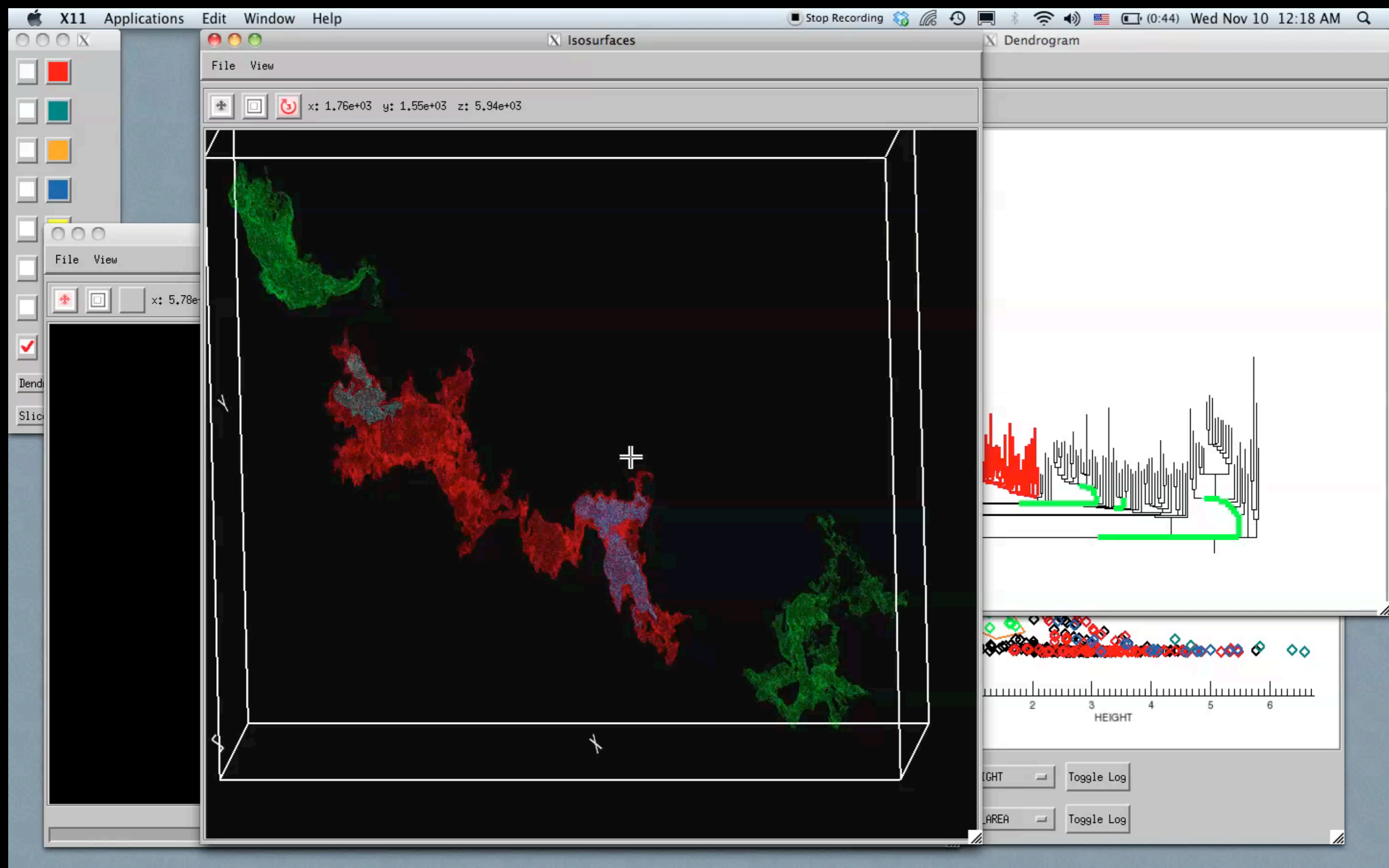
Cloud  
Supernova

# Results

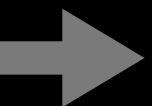
Cloud  
Supernova



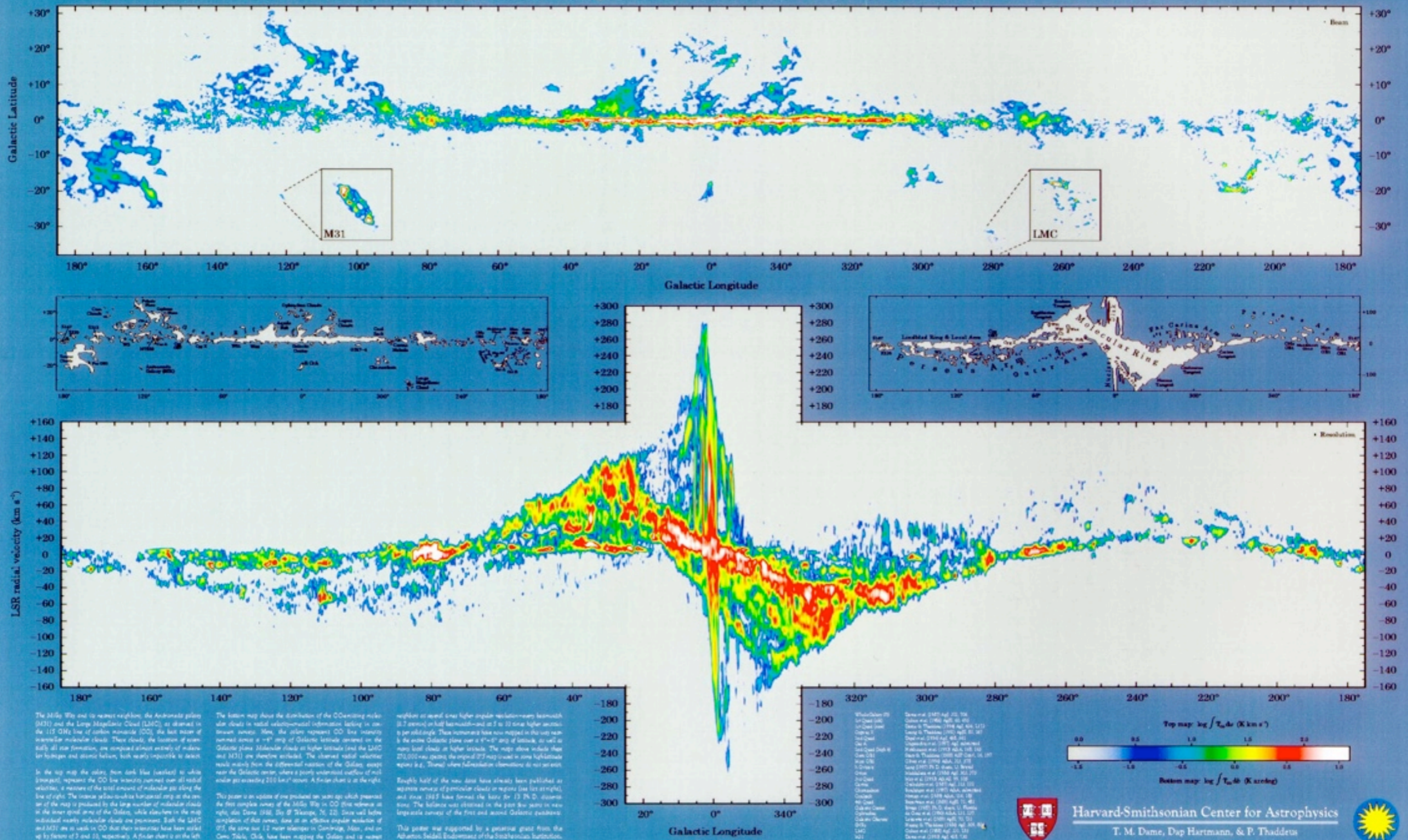
# Linked Dendrogram Views in IDL (I)



*Video & implementation: Christopher Beaumont, CfA/UHawaii;  
inspired by AstroMed work of Douglas Alan, Michelle Borkin, AG, Michael Halle, Erik Rosolowsky*



# The Milky Way in Molecular Clouds



The Milky Way and its nearest neighbors, the Andromeda galaxy (M31) and the Large Magellanic Cloud (LMC), as observed in the 115 GHz line of carbon monoxide (CO), the best tracer of interstellar molecular clouds. These clouds, the factories of essentially all star formation, are composed almost entirely of molecular hydrogen and atomic helium, both nearly impossible to detect.

In the top map the colors, from dark blue (weakest) to white (strongest), represent the CO line intensity summed over all radial velocities, a measure of the total amount of molecular gas along the line of sight. The intense blue-to-white horizontal strip at the center of the map is produced by the large number of molecular clouds in the inner spiral arms of the Galaxy, while elsewhere in the map individual nearby molecular clouds are prominent. Both the LMC and M31 are so weak in CO that their intensities have been scaled up by factors of 3 and 10, respectively. A further detail is on the left.

The bottom map shows the distribution of the CO-emitting nuclear star clouds in radial velocity-radial information lacking in conventional surveys. Here, the colors represent CO line intensity summed across a 10° strip of Galactic latitude centered on the Galactic plane. Molecular clouds at higher latitude (and the LMC and M31) are therefore excluded. The observed radial-velocity peaks mainly from the different positions of the Galaxy, except near the Galactic center, where a poorly understood outflow of multi-phase gas exceeding 200 km s<sup>-1</sup> occurs. A further detail is at the right.

This paper is an update of one produced six years ago which presented the first complete survey of the Milky Way in CO (first reference is right, also Dame 1986, Sly & Scoville, 76, 22). Since well before completion of that survey, data at an effective angular resolution of 95", the same size 12 meter telescope in Cambridge, Mass., and on Ohio State, Ohio, have been mapping the Galaxy and its nearest

neighbors at several times higher angular resolution—many beamwidth (3.7 arcmin) or half beamwidth—and at 7 to 10 times higher accuracy per solid angle. These improvements have now mapped in the very near-by the entire Galactic plane over a 4°-wide strip of latitude, as well as many local clouds at higher latitude. The maps above include these 273,000 new spectra, the original 273 maps used in some high-latitude regions (e.g., Throner) where administrative considerations do not permit.

Eighty half of the new data have already been published as separate surveys of particular clouds or regions (see list at right), and since 1987 have formed the basis for 13 Ph.D. dissertations. The balance was obtained in the past few years in new large-scale surveys of the first and second Galactic quadrants.

This paper was supported by a generous grant from the Albertus Seidel Endowment of the Smithsonian Institution.

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 Dame, T.M., 2012, *ApJ*, 66, 107

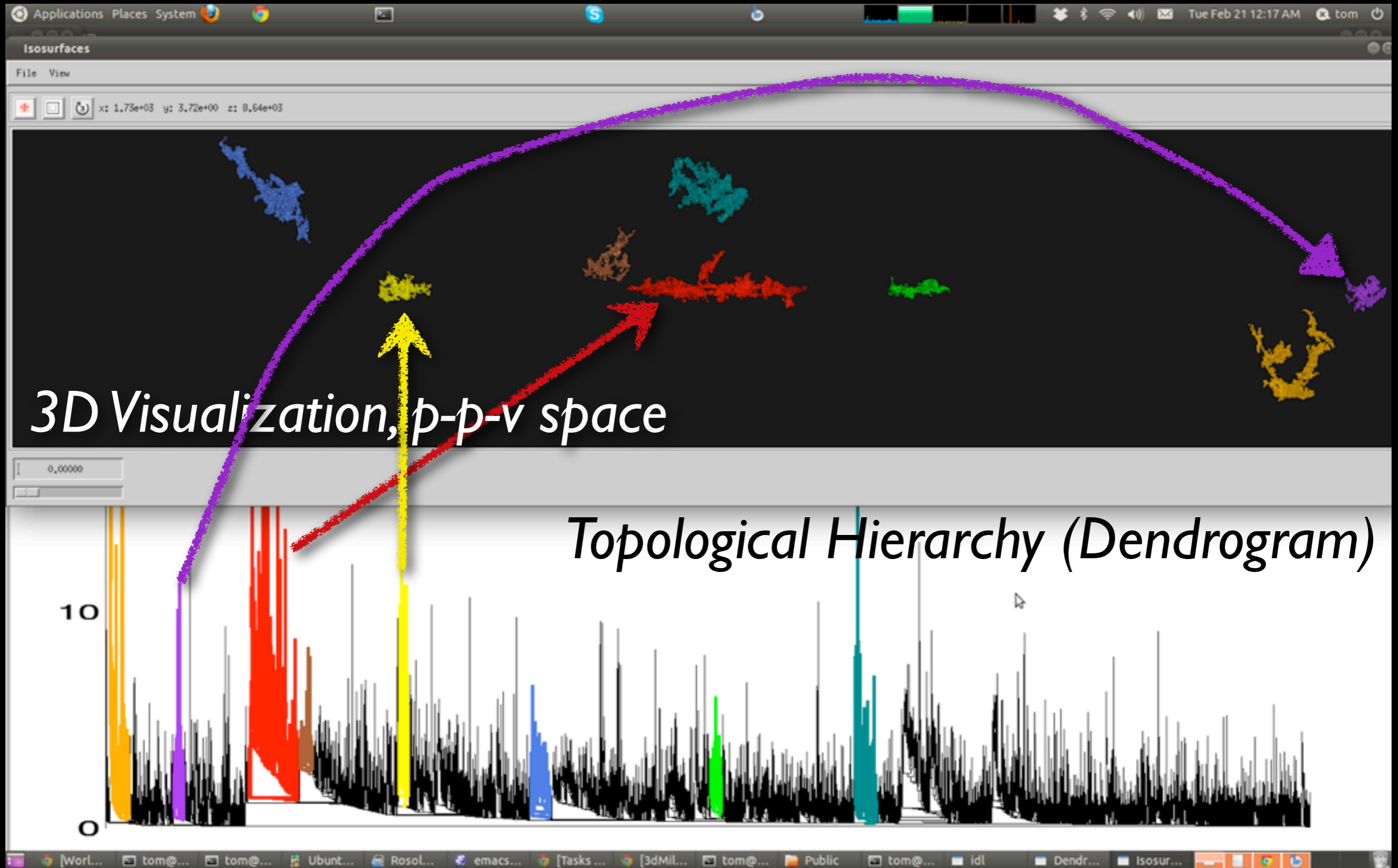
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 Dame, T.M., 2001, *ApJ*, 55, 107  
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Harvard-Smithsonian Center for Astrophysics  
 T. M. Dame, Dap Hartmann, & P. Thaddeus

Dame et al. 2001 1.3-m "Mini" Telescope Survey of the Milky Way in CO

Hot off the Press

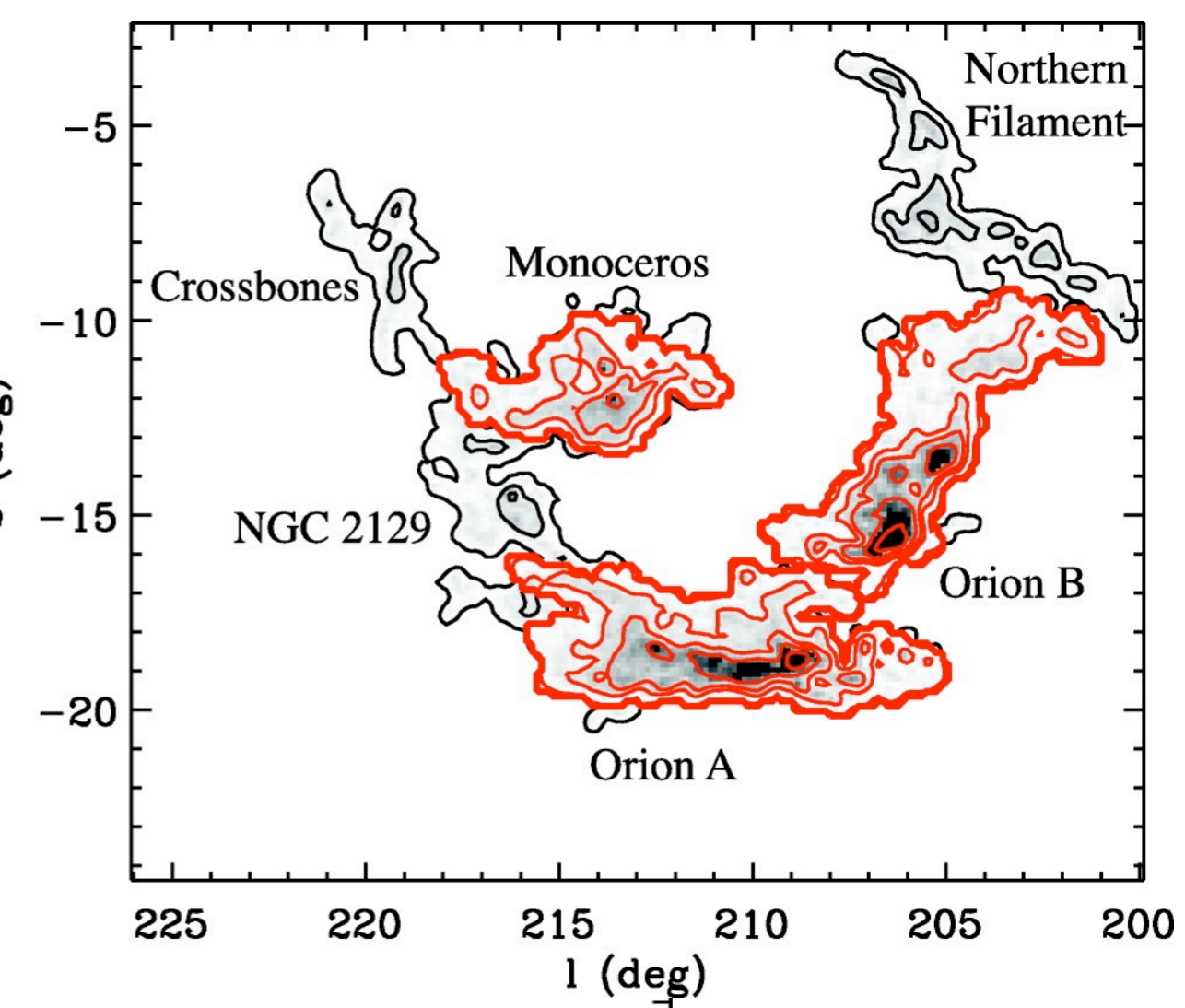
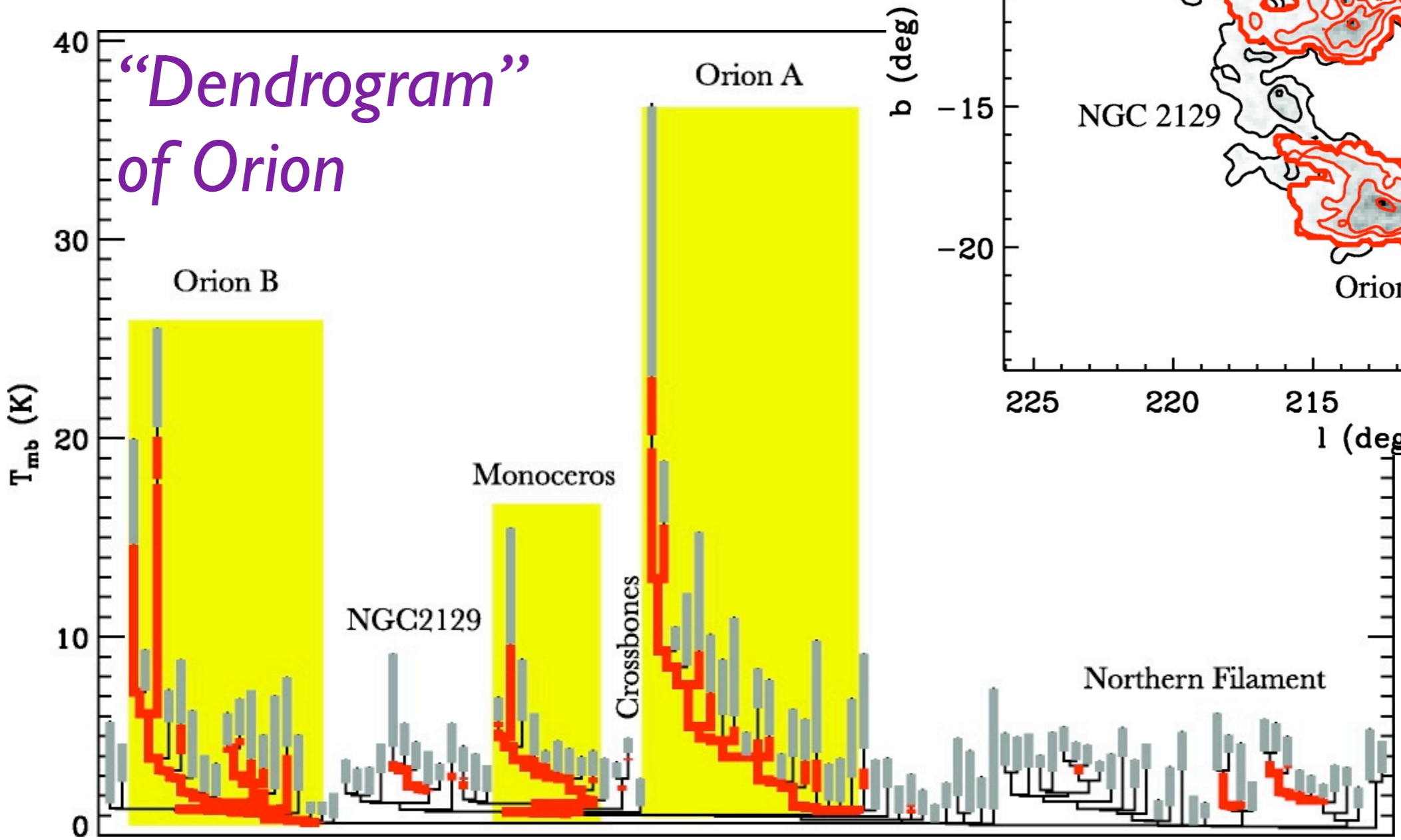
# Nearby Star Forming Regions in The Milky Way



2012 Senior thesis of Tom Rice, Harvard, in collaboration with AG, Chris Beaumont & Tom Dame  
(data from Dame et al. 2001 1.3-m "Mini" Telescope Survey of the Milky Way in CO)

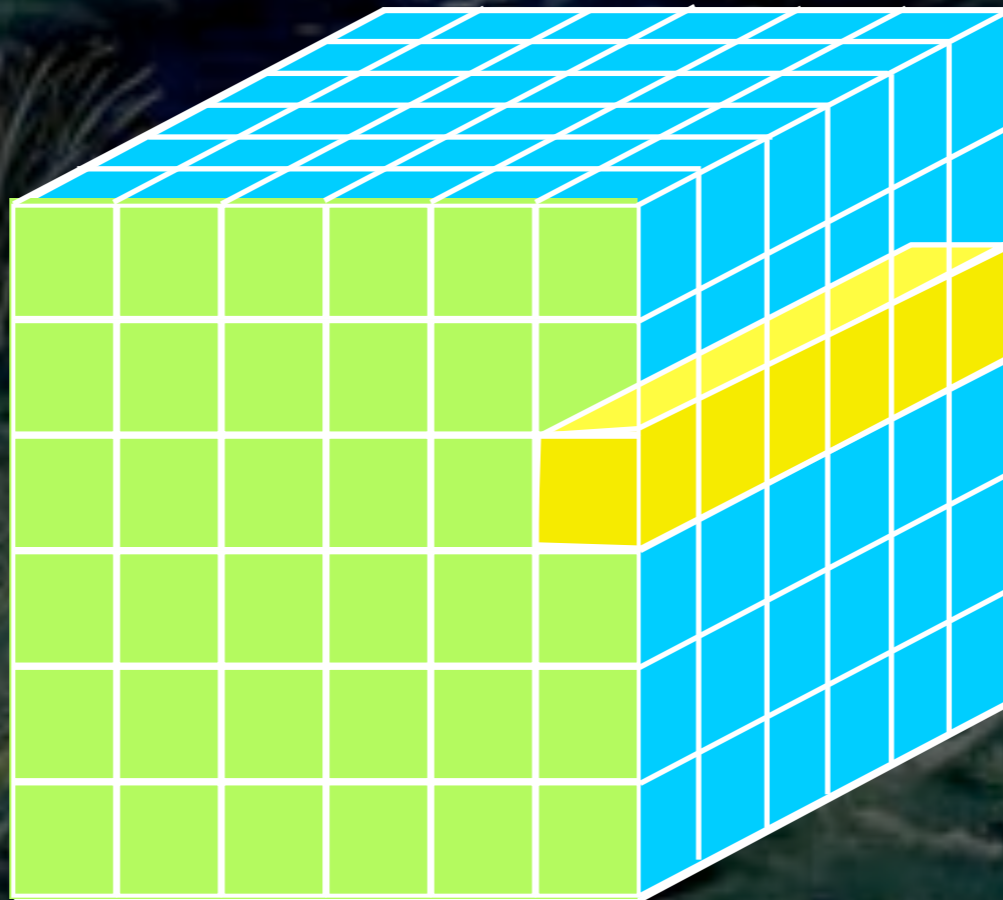


# Large (100 pc) Scales: Does Gravity Define GMCs?



Figures from  
Rosolowsky et al. 2008

# The dream scenario...



# “Astronomers” Saving Lives?

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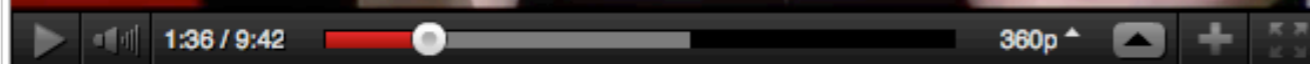
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TEDxBoston 2011, Filmed Jun 2011; Posted Jan 2012

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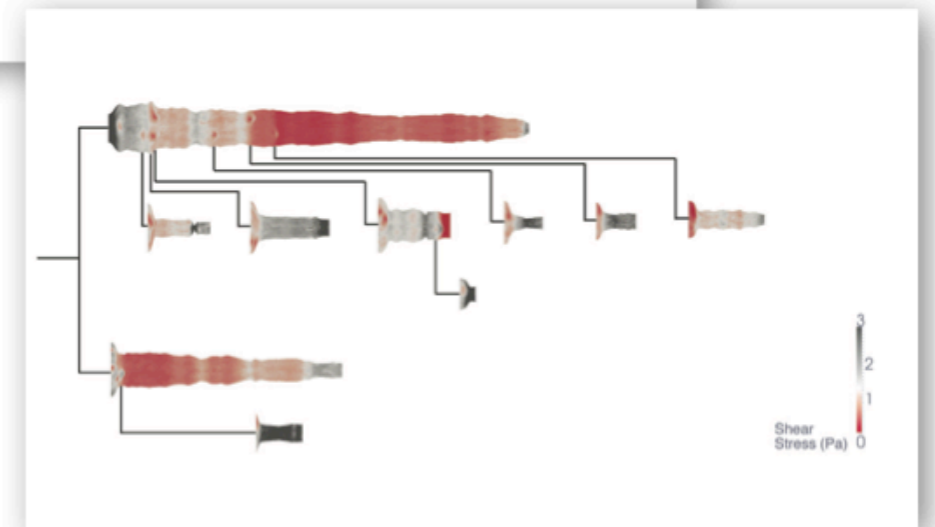
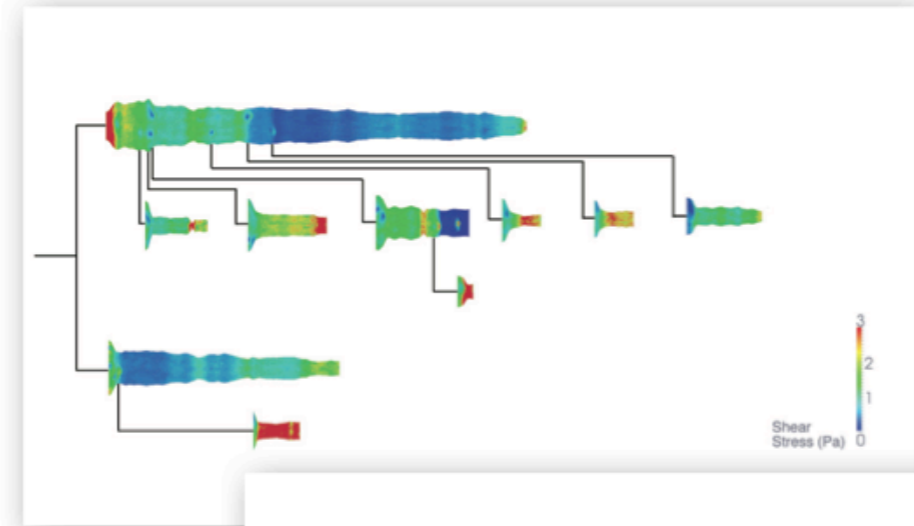
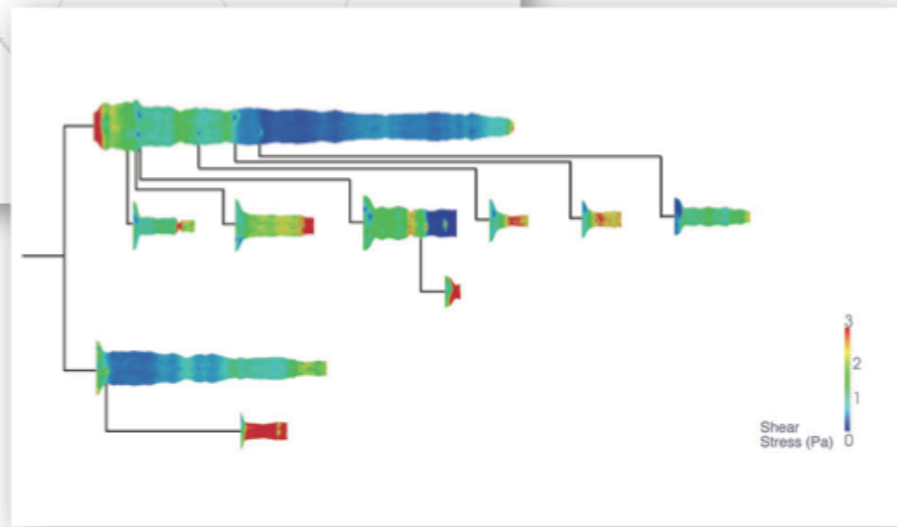
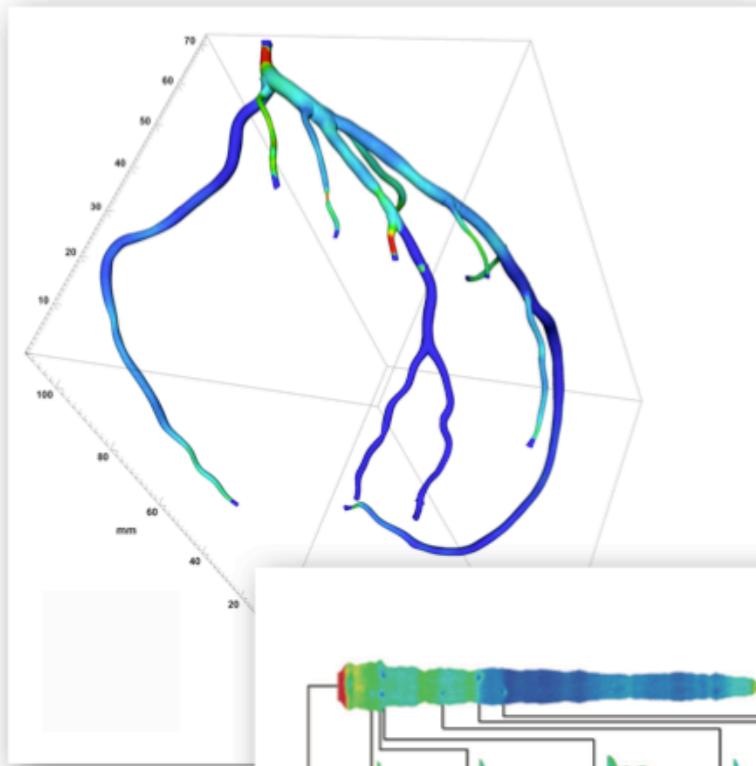
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# “Astronomers” Saving Lives?



*The Future of “Astronomical Medicine”..*

# Watching Stars Form

*(or “The Importance of p-p-v Data and Linked Views in Understanding Star Formation”)*

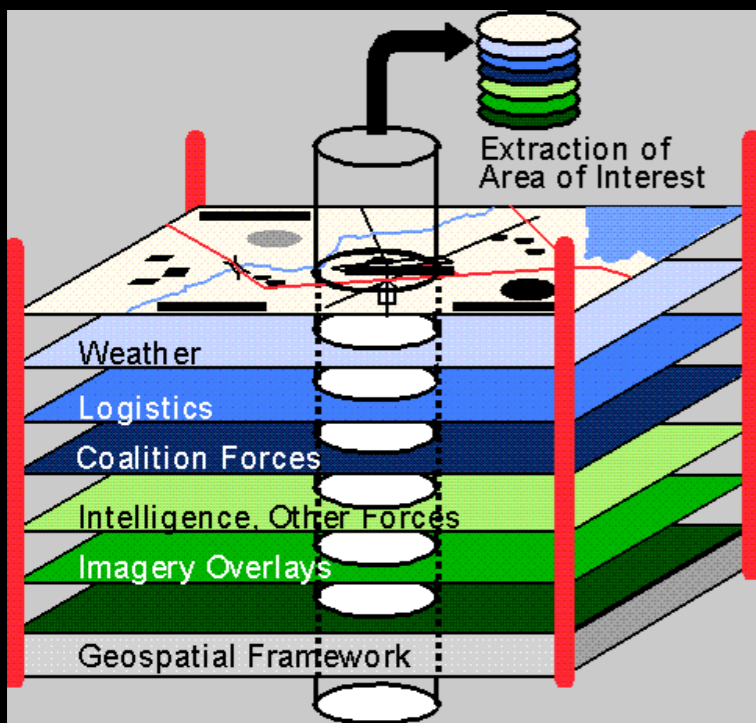
Alyssa A. Goodman

*Harvard-Smithsonian Center for Astrophysics*

*Modern Hydrodynamic AMR Simulation, (B=0), courtesy Stella Offner*







# COMPLETE

## COMPLETE Data Available

Center on Perseus Center on Ophiuchus Center on Serpens

### Full-Cloud Data (Phase I, All Data Available)

Dataset	Show	Perseus	Ophiuchus	Serpens	Link
<a href="#">GBT: HI Data Cube</a>	<input checked="" type="checkbox"/>	✓	✓	∅	<a href="#">Data</a>
<a href="#">IRAS: Av/Temp Maps</a>	<input checked="" type="checkbox"/>	✓	✓	✓	<a href="#">Data</a>
<a href="#">FCRAO: 12CO</a>	<input checked="" type="checkbox"/>	✓	✓	✓	<a href="#">Data</a>
<a href="#">FCRAO: 13CO</a>	<input checked="" type="checkbox"/>	✓	✓	✓	<a href="#">Data</a>
<a href="#">JCMT: 850 microns</a>	<input checked="" type="checkbox"/>	✓	✓	∅	<a href="#">Data</a>
<a href="#">Spitzer c2d: IRAC 1,3 (3.6,5.8 μm)</a>	<input checked="" type="checkbox"/>	✓	✓	✓	<a href="#">Data</a>
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<a href="#">CSO/Bolocam: 1.2-mm</a>	<input checked="" type="checkbox"/>	✓	∅	∅	<a href="#">Data</a>
<a href="#">Spitzer MIPS: Derived Dust Map</a>	<input checked="" type="checkbox"/>	✓	∅	∅	<a href="#">Data</a>

### Targeted Regions (Phase II, Some Data Not Yet Available)

<a href="#">CTIO/Calar Alto: NIR (J,H,Ks)</a>	<input checked="" type="checkbox"/>	✓	✓	∅	<a href="#">Data</a>
<a href="#">IRAM 30-m: N2H+ and C18O</a>	<input checked="" type="checkbox"/>	✓	∅	∅	<a href="#">Data</a>
<a href="#">IRAM 30-m: 1.1-mm continuum</a>	<input checked="" type="checkbox"/>	✓	∅	∅	<a href="#">Data</a>
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### Catalogs & Pointed Surveys

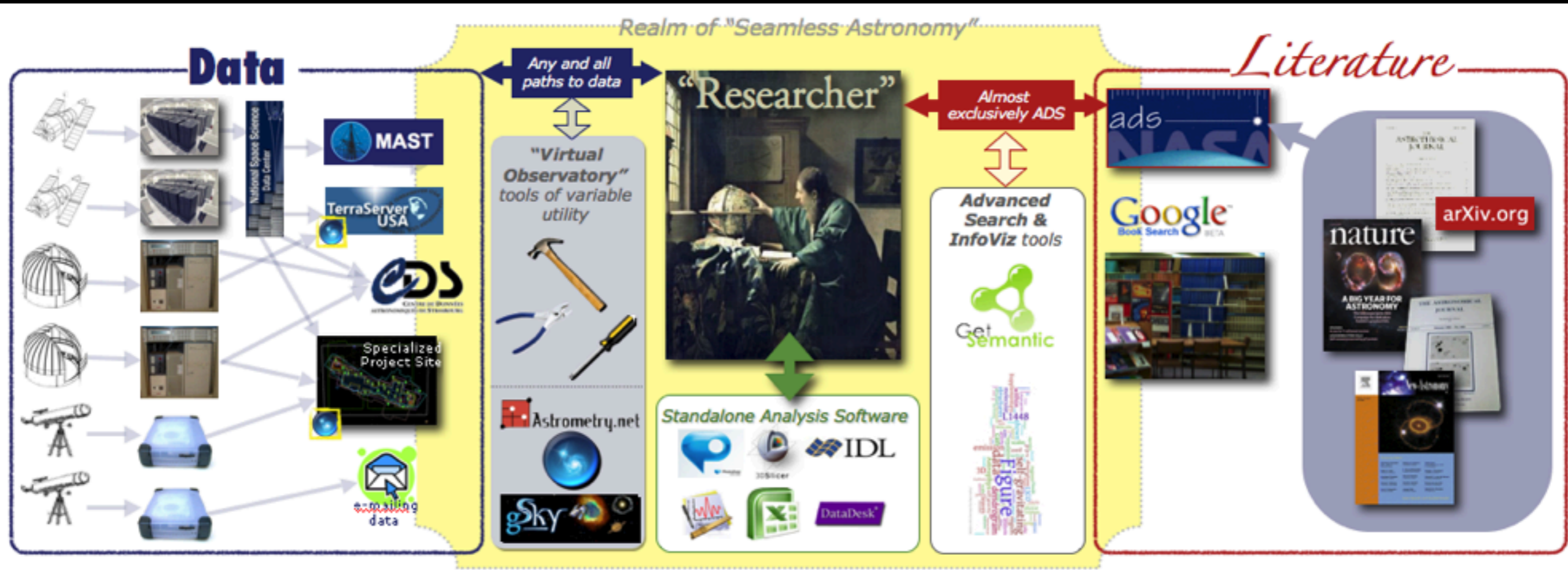
<a href="#">NH3 Pointed Survey</a>	<input checked="" type="checkbox"/>	✓	∅	∅	<a href="#">Data</a>
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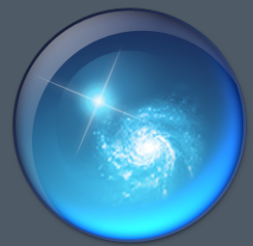
Microsoft Research  
WorldWide Telescope

# Seamless Astronomy

Alberto Accomazzi, Doug Burke, Alberto Conti, Carol Christian, Mercé Crosas, Raffaele D'Abrusco, Rahul Davé, Christopher Erdmann, Jonathan Fay, Jay Luker, Alyssa Goodman, Michael Kurtz, Gus Muench, Alberto Pepe, Curtis Wong







# Microsoft® Research WorldWide Telescope

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The screenshot displays the WWT interface with a top navigation bar containing 'Explore', 'Guided Tours', 'Search', 'View', and 'Settings'. Below this is a 'Collections > All-Sky Surveys >' section with a row of eight thumbnails: 'Digitized Sky Survey', 'VLSS: VLA Low-frequency Sky Survey', 'WMAP ILC 5-Year Cosmic Microwave Background', 'SFD Dust Map (Infrared)', 'IRIS: Improved Resolution', '2MASS: Two Micron All Sky Survey', and 'Hydrogen Alpha Filter'. The main view shows a starry field with a circular 'Finder Scope' centered on a bright object. A 'Context bar' at the bottom shows 'NGC221' and 'M31'. A 'Context globe' on the right shows the current field of view on a celestial sphere. A 'Finder Scope' window is open, displaying details for 'NGC224', including its classification as a 'Spiral Galaxy in Andromeda', RA (00h42m42s), Dec (41:16:00), and a link to research data.

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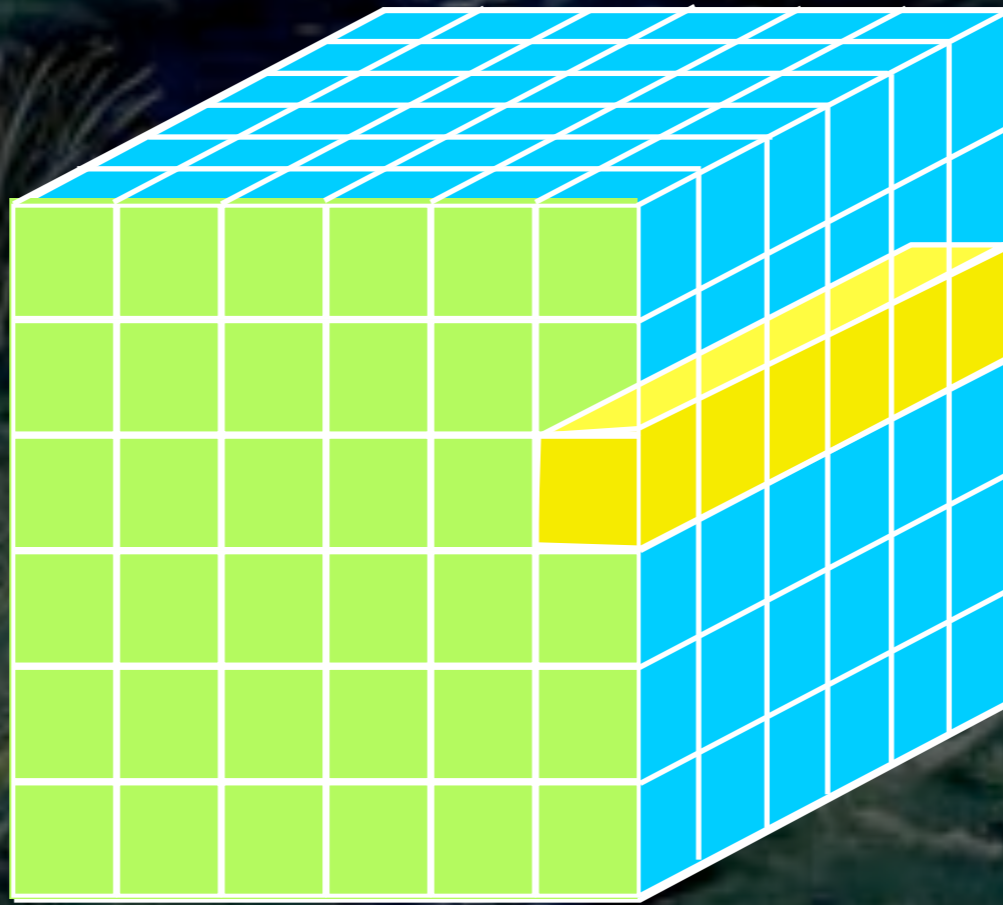
Much more than "just" the sky at night! 3D features can take you to other planets, stars & galaxies.

Finder Scope links to Wikipedia, publications, and data, so you can learn more

Context bar shows items of interest in current field of view

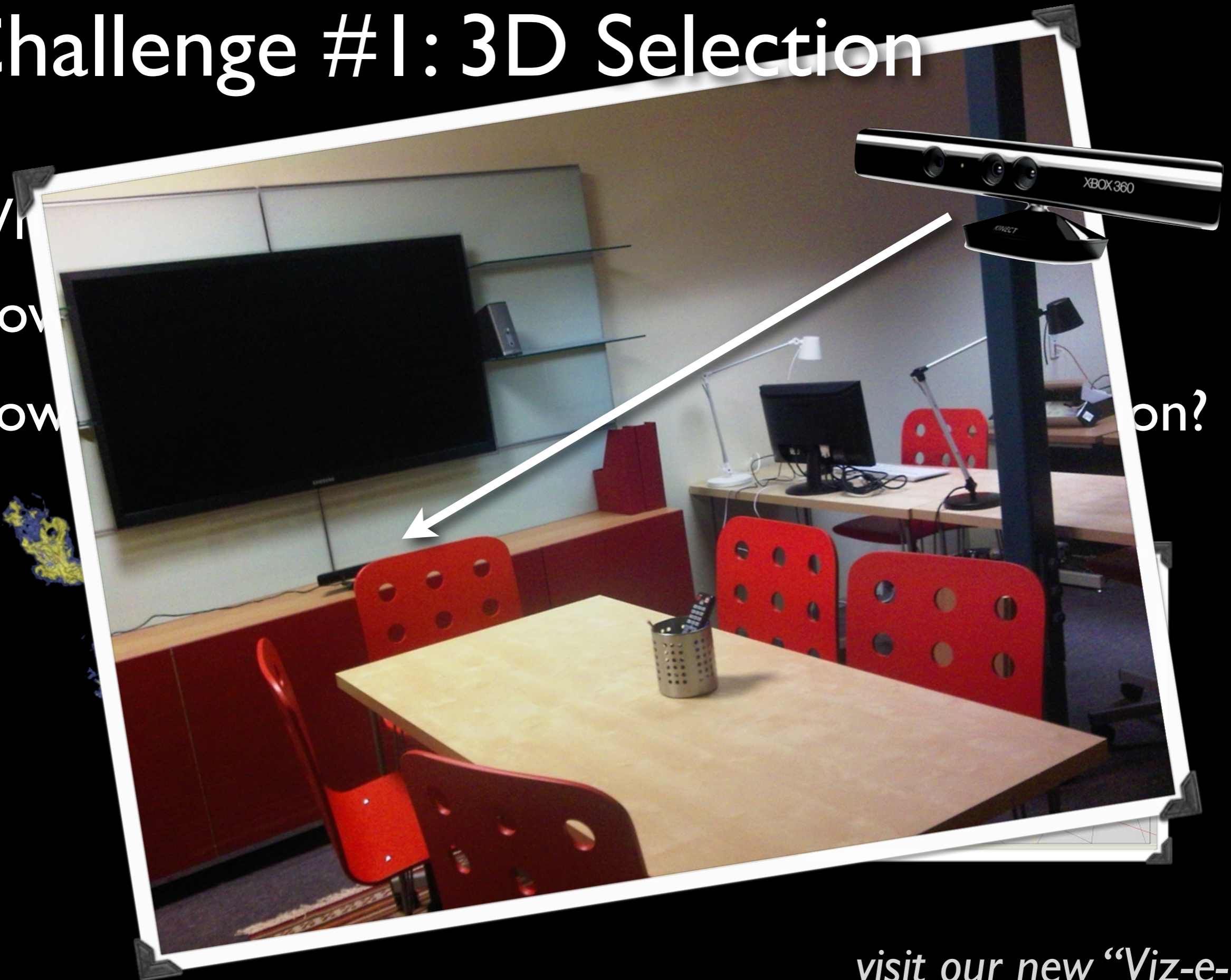
Context globe shows where you're looking.

# The dream scenario...



# Challenge #1: 3D Selection

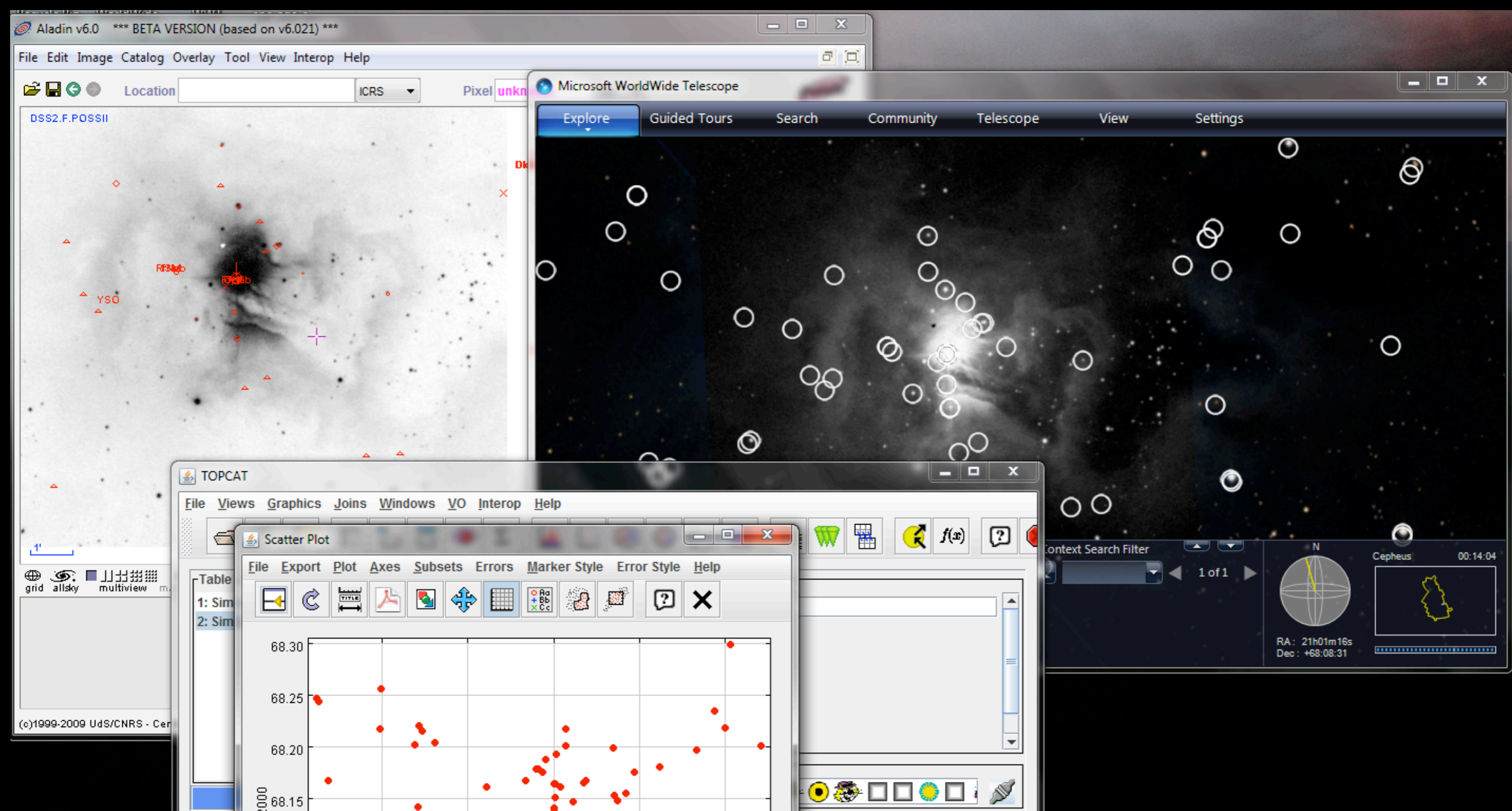
Why?  
How?  
How?



on?

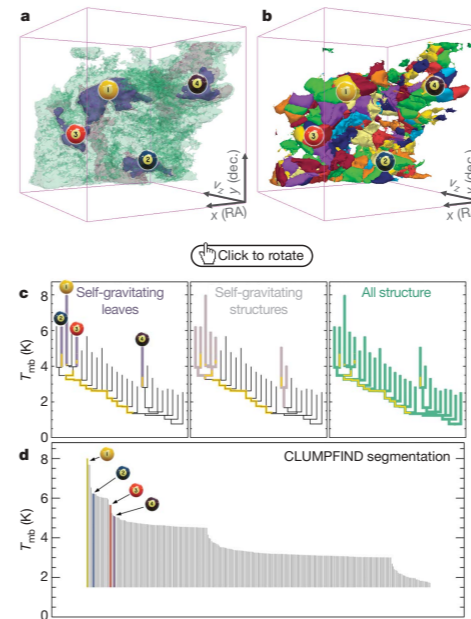
*visit our new "Viz-e-Lab"!*

# Challenge #2: Too many windows...



# Challenge #3:

## What does “Publication-Quality” Graphics Mean in an Interactive 3D World?



**Figure 2** | Comparison of the ‘dendrogram’ and ‘CLUMPFIND’ feature-identification algorithms as applied to  $^{13}\text{CO}$  emission from the L1448 region of Perseus. **a**, 3D visualization of the surfaces indicated by colours in the dendrogram shown in **c**. Purple illustrates the smallest scale self-gravitating structures in the region corresponding to the leaves of the dendrogram; pink shows the smallest surfaces that contain distinct self-gravitating leaves within them; and green corresponds to the surface in the data cube containing all the significant emission. Dendrogram branches corresponding to self-gravitating objects have been highlighted in yellow over the range of  $T_{\text{mb}}$  (main-beam temperature) test-level values for which the virial parameter is less than 2. The  $x$ - $y$  locations of the four ‘self-gravitating’ leaves labelled with billiard balls are the same as those shown in Fig. 1. The 3D visualizations show position–position–velocity ( $p$ - $p$ - $v$ ) space. RA, right ascension; dec., declination. For comparison with the ability of dendrograms (**c**) to track hierarchical structure, **d** shows a pseudo-dendrogram of the CLUMPFIND segmentation (**b**), with the same four labels used in Fig. 1 and in **a**. As ‘clumps’ are not allowed to belong to larger structures, each pseudo-branch in **d** is simply a series of lines connecting the maximum emission value in each clump to the threshold value. A very large number of clumps appears in **b** because of the sensitivity of CLUMPFIND to noise and small-scale structure in the data. In the online PDF version, the 3D cubes (**a** and **b**) can be rotated to any orientation, and surfaces can be turned on and off (interaction requires Adobe Acrobat version 7.0.8 or higher). In the printed version, the front face of each 3D cube (the ‘home’ view in the interactive online version) corresponds exactly to the patch of sky shown in Fig. 1, and velocity with respect to the Local Standard of Rest increases from front ( $-0.5 \text{ km s}^{-1}$ ) to back ( $8 \text{ km s}^{-1}$ ).

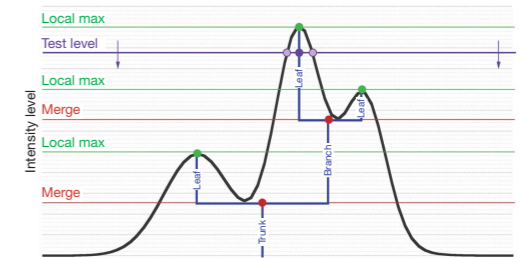
data, CLUMPFIND typically finds features on a limited range of scales, above but close to the physical resolution of the data, and its results can be overly dependent on input parameters. By tuning CLUMPFIND’s two free parameters, the same molecular-line data set<sup>9</sup> can be used to show either that the frequency distribution of clump mass is the same as the initial mass function of stars or that it follows the much shallower mass function associated with large-scale molecular clouds (Supplementary Fig. 1).

Four years before the advent of CLUMPFIND, ‘structure trees’<sup>9</sup> were proposed as a way to characterize clouds’ hierarchical structure

using 2D maps of column density. With this early 2D work as inspiration, we have developed a structure-identification algorithm that abstracts the hierarchical structure of a 3D ( $p$ - $p$ - $v$ ) data cube into an easily visualized representation called a ‘dendrogram’<sup>10</sup>. Although well developed in other data-intensive fields<sup>11,12</sup>, it is curious that the application of tree methodologies so far in astrophysics has been rare, and almost exclusively within the area of galaxy evolution, where ‘merger trees’ are being used with increasing frequency<sup>13</sup>.

Figure 3 and its legend explain the construction of dendrograms schematically. The dendrogram quantifies how and where local maxima of emission merge with each other, and its implementation is explained in Supplementary Methods. Critically, the dendrogram is determined almost entirely by the data itself, and it has negligible sensitivity to algorithm parameters. To make graphical presentation possible on paper and 2D screens, we ‘flatten’ the dendrograms of 3D data (see Fig. 3 and its legend), by sorting their ‘branches’ to not cross, which eliminates dimensional information on the  $x$  axis while preserving all information about connectivity and hierarchy. Numbered ‘billiard ball’ labels in the figures let the reader match features between a 2D map (Fig. 1), an interactive 3D map (Fig. 2a online) and a sorted dendrogram (Fig. 2c).

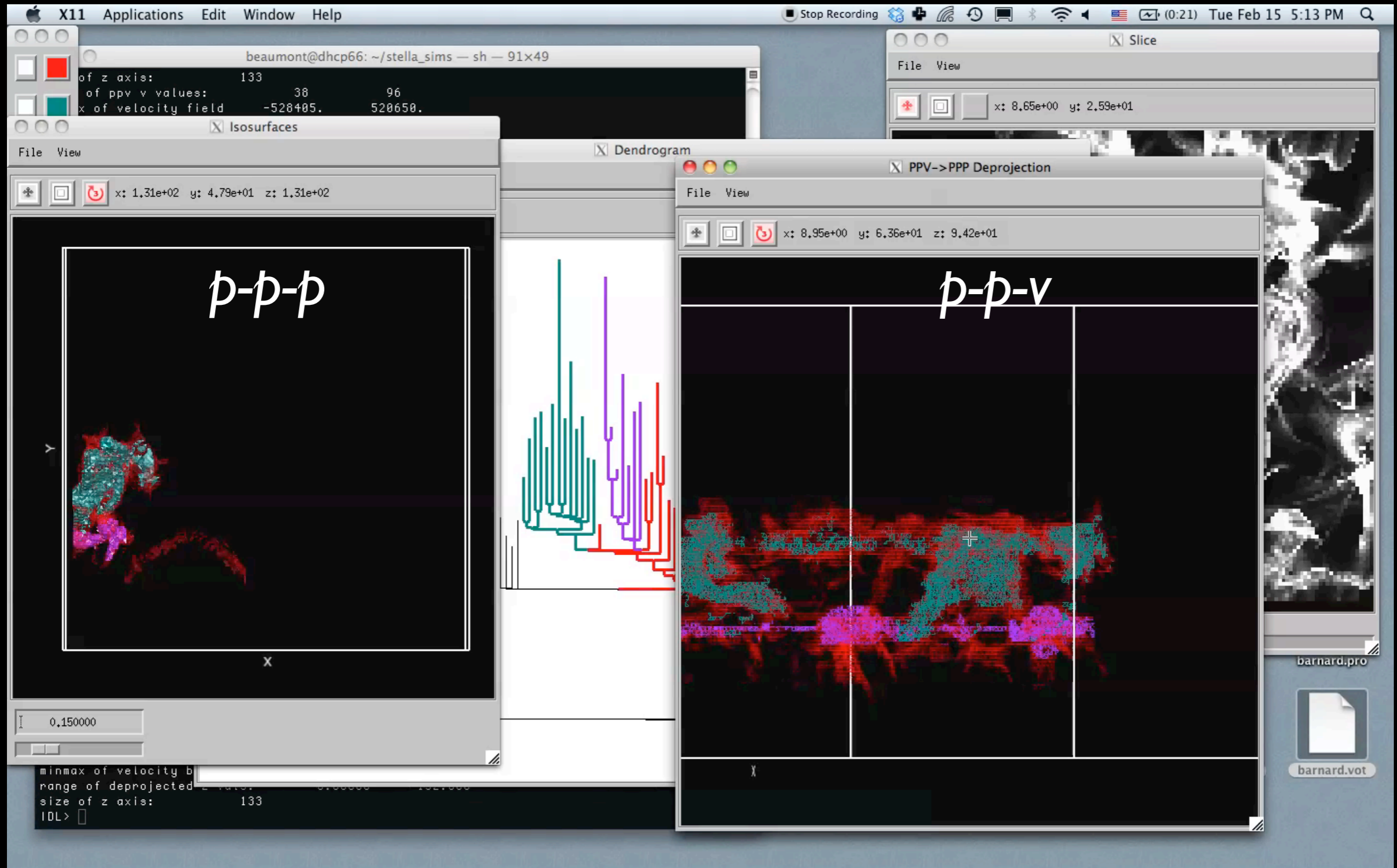
A dendrogram of a spectral-line data cube allows for the estimation of key physical properties associated with volumes bounded by isosurfaces, such as radius ( $R$ ), velocity dispersion ( $\sigma_v$ ) and luminosity ( $L$ ). The volumes can have any shape, and in other work<sup>14</sup> we focus on the significance of the especially elongated features seen in L1448 (Fig. 2a). The luminosity is an approximate proxy for mass, such that  $M_{\text{lum}} = X_{13\text{CO}} L_{13\text{CO}}$ , where  $X_{13\text{CO}} = 8.0 \times 10^{20} \text{ cm}^2 \text{ K}^{-1} \text{ km}^{-1} \text{ s}$  (ref. 15; see Supplementary Methods and Supplementary Fig. 2). The derived values for size, mass and velocity dispersion can then be used to estimate the role of self-gravity at each point in the hierarchy, via calculation of an ‘observed’ virial parameter,  $\alpha_{\text{obs}} = 5\sigma_v^2 R/GM_{\text{lum}}$ . In principle, extended portions of the tree (Fig. 2, yellow highlighting) where  $\alpha_{\text{obs}} < 2$  (where gravitational energy is comparable to or larger than kinetic energy) correspond to regions of  $p$ - $p$ - $v$  space where self-gravity is significant. As  $\alpha_{\text{obs}}$  only represents the ratio of kinetic energy to gravitational energy at one point in time, and does not explicitly capture external over-pressure and/or magnetic fields<sup>16</sup>, its measured value should only be used as a guide to the longevity (boundedness) of any particular feature.



**Figure 3** | Schematic illustration of the dendrogram process. Shown is the construction of a dendrogram from a hypothetical one-dimensional emission profile (black). The dendrogram (blue) can be constructed by ‘dropping’ a test constant emission level (purple) from above in tiny steps (exaggerated in size here, light lines) until all the local maxima and mergers are found, and connected as shown. The intersection of a test level with the emission is a set of points (for example the light purple dots) in one dimension, a planar curve in two dimensions, and an isosurface in three dimensions. The dendrogram of 3D data shown in Fig. 2c is the direct analogue of the tree shown here, only constructed from ‘isosurface’ rather than ‘point’ intersections. It has been sorted and flattened for representation on a flat page, as fully representing dendrograms for 3D data cubes would require four dimensions.

Goodman, Rosolowsky, Borkin, Foster, Halle, Kauffmann & Pineda, **Nature**, 2009

# Linked Dendrogram Views in IDL (2)



# Linked Dendrogram Views in IDL (3)

