

Holistic Star Formation

Alyssa A. Goodman (Harvard-Smithsonian Center for Astrophysics)

with

*João Alves, Héctor Arce, Frank Bertoldi, **Michelle Borkin**, Paola Caselli, David Collins, **Jonathan Foster**, Katherine Guenthner, Michael Halle, **Jens Kauffmann**, Elizabeth Lada, Phil Myers, **Jaime Pineda**, Naomi Ridge, Carlos Román-Zúñiga, **Erik Rosolowsky**, Sana Sharma, Scott Schnee, & **Rahul Shetty***

& thanks to Douglas Alan, Kevin Covey, Nick Holliman, Doug Johnstone, Helen Kirk, Kaisey Mandel, Gus Muench, Stella Offner, Paolo Padoan, & Tom Robitaille





Holistic

holistic | hō'listik |

adjective chiefly Philosophy
characterized by comprehension of the parts of
something as intimately interconnected and
explicable only by reference to the whole

Magnetic
Fields

Gravity

Chemical & Phase
Transformations

~ 1 pc

“Holistic Physics”

Radiation

Thermal
Pressure

“Turbulence”
(Random Kinetic Energy)

Outflows
& Winds

...from 0.1 pc to 100 pc

Massive Star-Forming Regions

warm dust cold dust

HII regions(+SNR)

radio SNR

20 cm VLA from MAGPIS (Helfand et al. 2006) & MIR from Spitzer GLIMPSE (see Churchwell et al.)

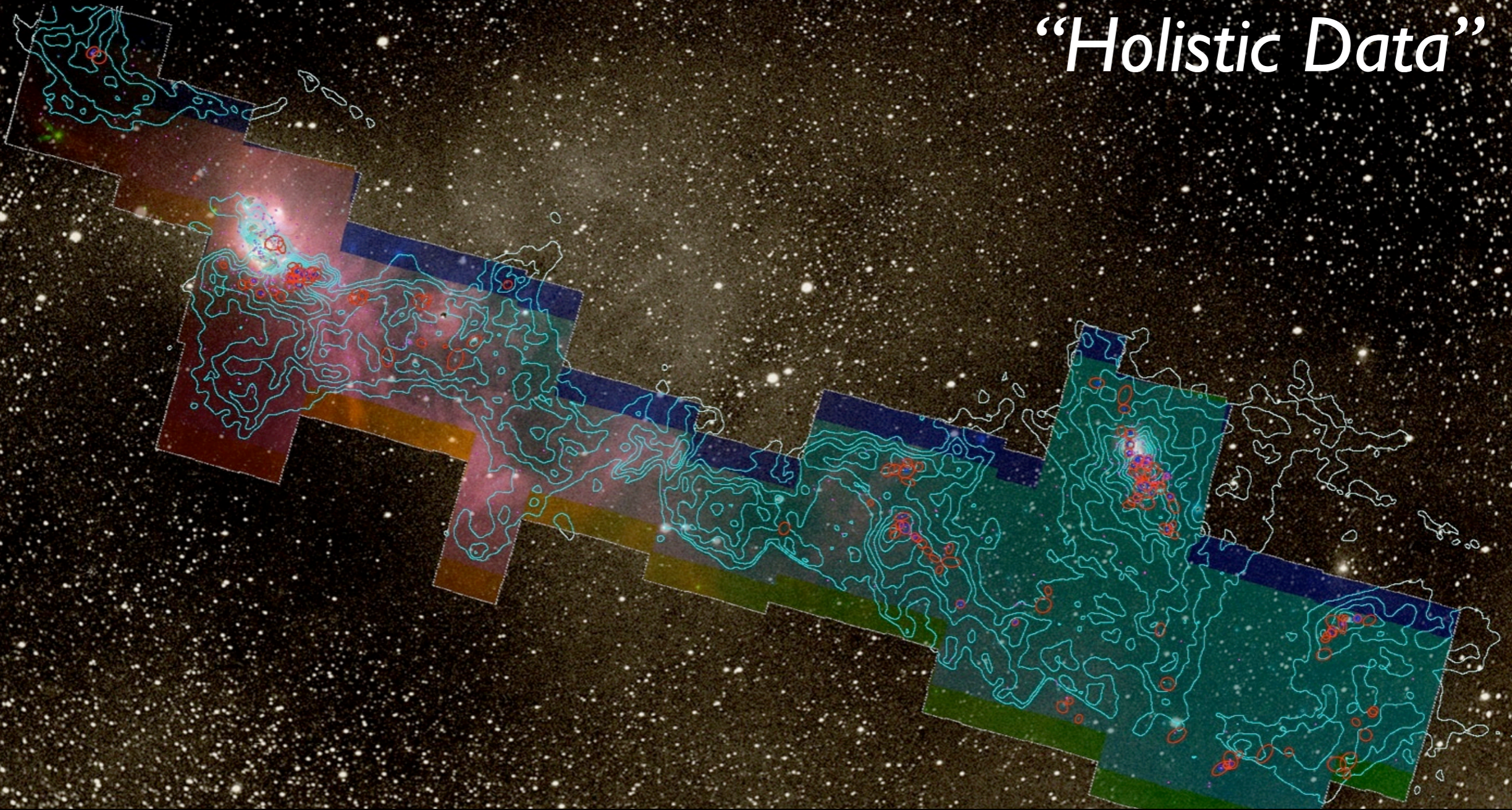
3.6, 4.5, 8.0, 20cm (Luptonized, see Lupton et al. 2004)

image "height" is 1.6 degrees (e.g. 140 pc at 5 kpc)

COMPLETE =

COordinated MOlecular PRobe LIne EXtinction Thermal
Emission Survey of Star-Forming Regions

“Holistic Data”



COMPLETE Collaborators,
2009:

Alyssa A. Goodman (CfA/IIC)

João Alves (Calar Alto, Spain)

Héctor Arce (Yale)

Michelle Borkin (Harvard SEAS/IIC)

Paola Caselli (Leeds, UK)

James DiFrancesco (HIA, Canada)

Jonathan Foster (B.U.)

Mark Heyer (UMASS/FCRAO)

Doug Johnstone (HIA, Canada)

Jens Kauffmann (JPL/Caltech)

Helen Kirk (CfA)

Di Li (JPL/Caltech)

Stella Offner (CfA)

Jaime Pineda (CfA, PhD Student)

Thomas Robitaille (CfA)

Erik Rosolowsky (UBC Okanagan)

Rahul Shetty (ITA Heidelberg)

Scott Schnee (HIA Victoria)

Mario Tafalla (OAN, Spain)

The West-End of Perseus

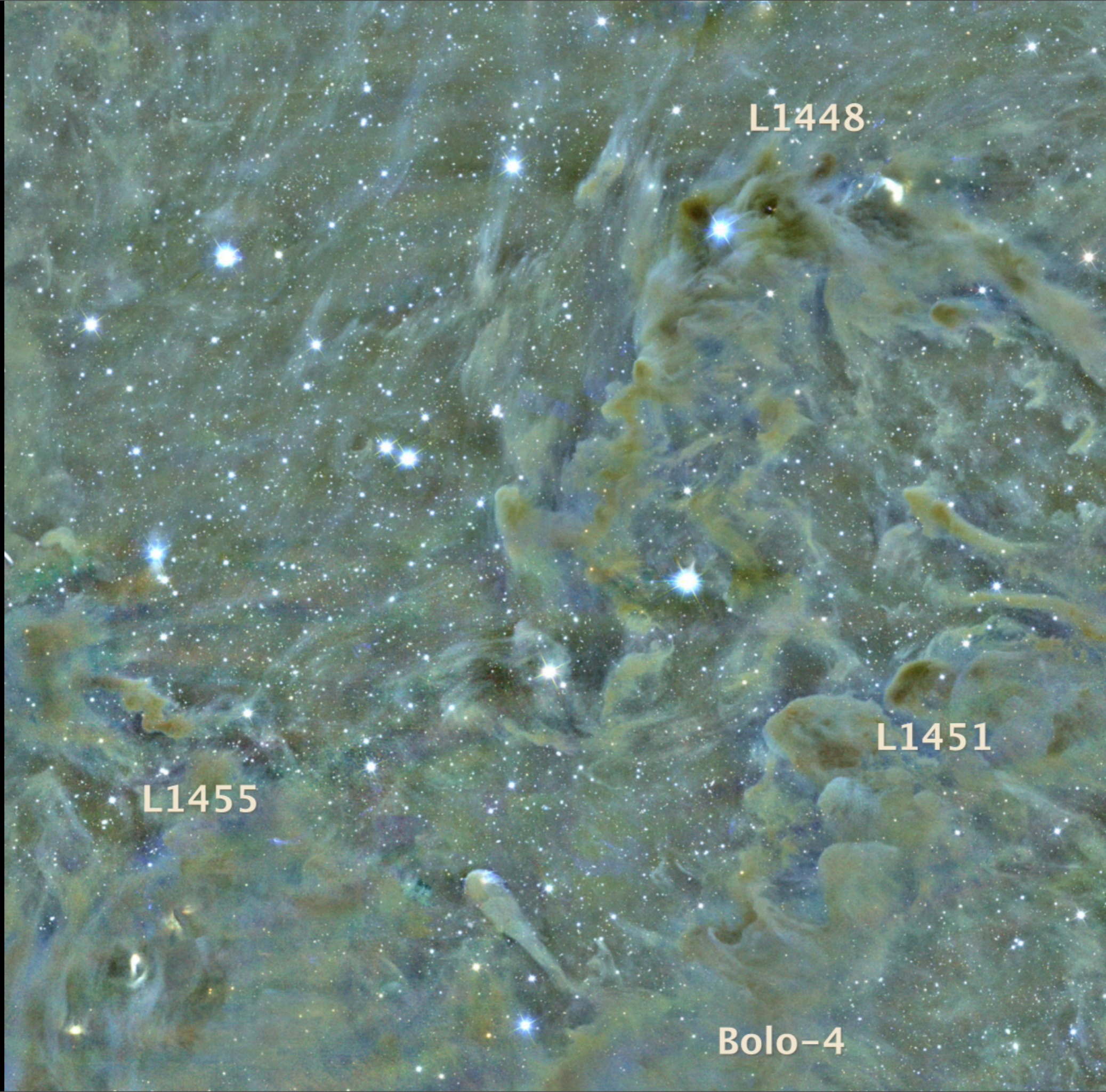
A journey
through star-
formation in
reverse, by
Jonthathan
Foster.

Main Image:

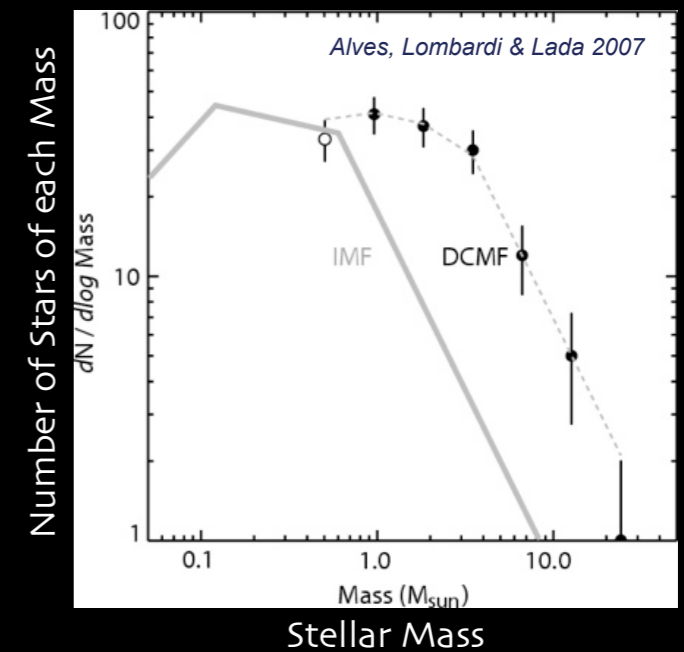
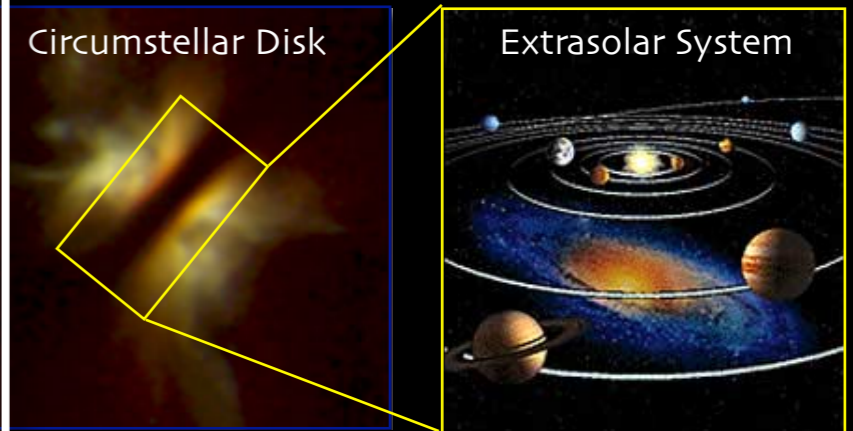
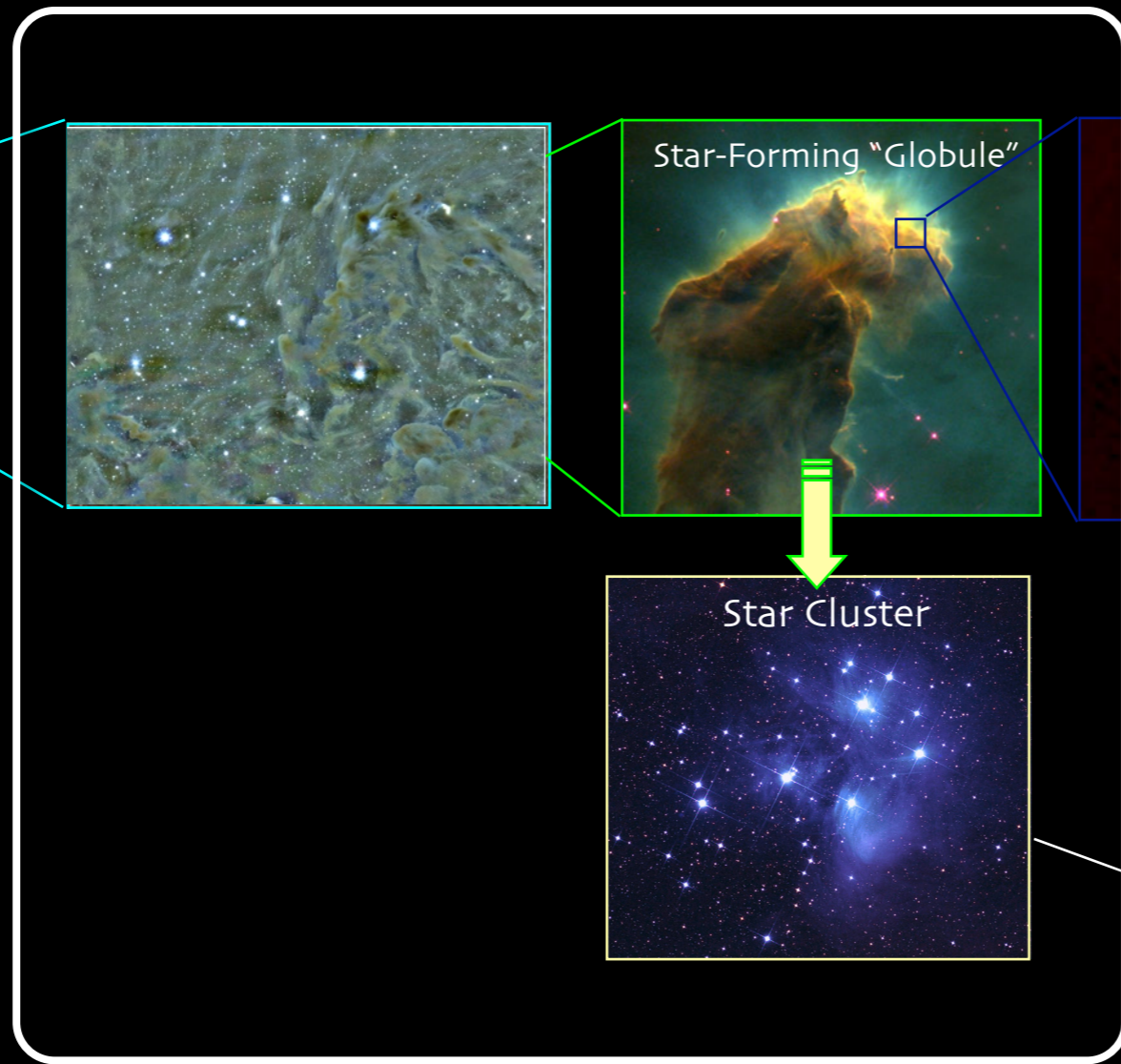
MMT/
Megacam
r,i,z

Zooms/fades:

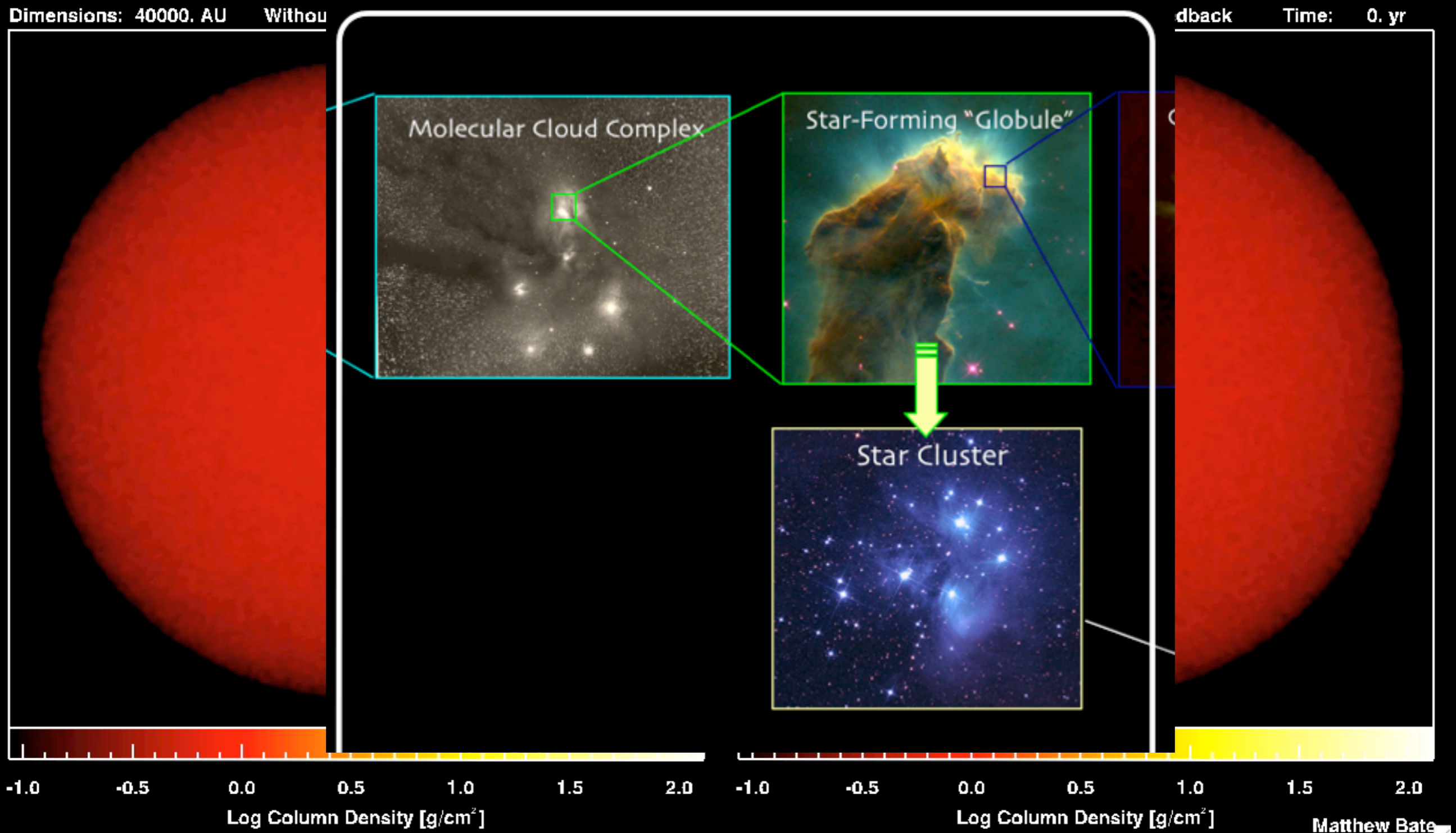
Calar Alto/
OMEGA2000
J,H,K_s



Star (and Planet, and Moon) Formation 30 I



Our Goal is to “Taste” Star Formation



Simulations of Bate 2009

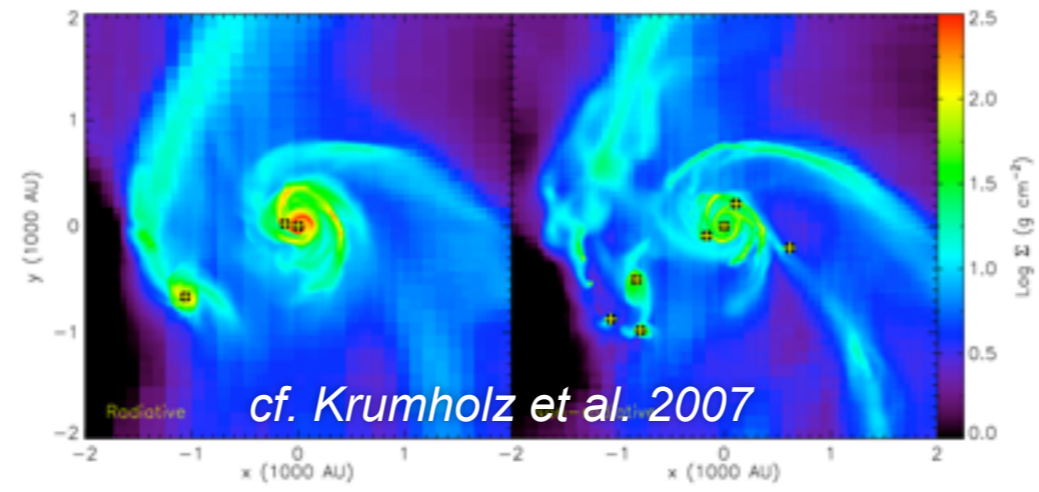


FIG. 9 A comparison of two simulations with identical initial conditions and evolution times, one including radiative transfer (*left panel*) and one done without it (*right panel*). Stars are indicated by plus signs. The simulation without radiative transfer forms a factor of ~ 4 more stars than the one including it, and has significantly less mass in its gaseous disk. (*Images adapted from Krumholz et al. (2007a)*).

“turbulent fragmentation” “LI 448” “(magneto-)hydrodynamic simulation”

“Cloudshine”

“bi-jection”

“pre-stellar core”

“virial parameter”

“protostar”

“column density”

“integrated intensity”

“turbulent power spectrum”

“p-p-v cube”

“synthetic observation”

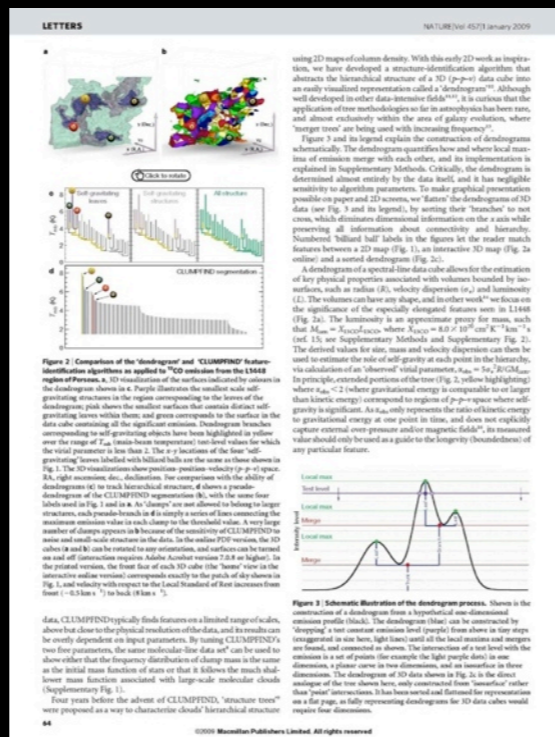
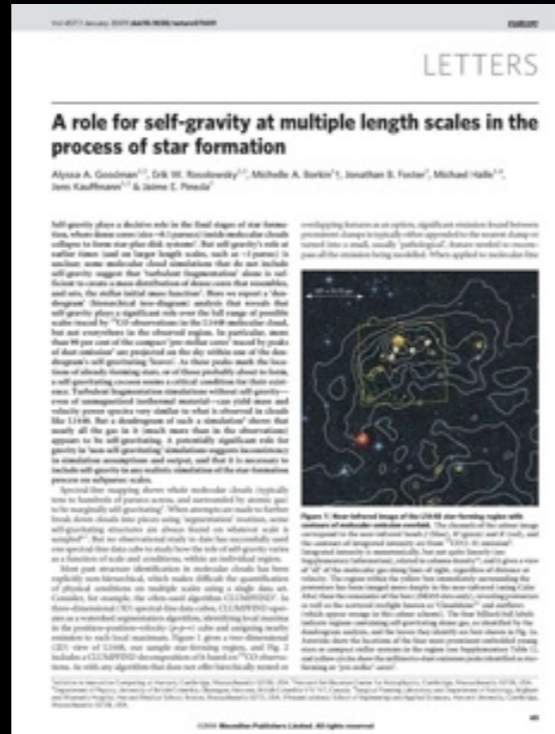
“segmentation”

“depletion, opacity”

“CLUMPFIND”

“taste-test”

“Dendrogram”



“COMPLETE”

“3D PDF”

caveats

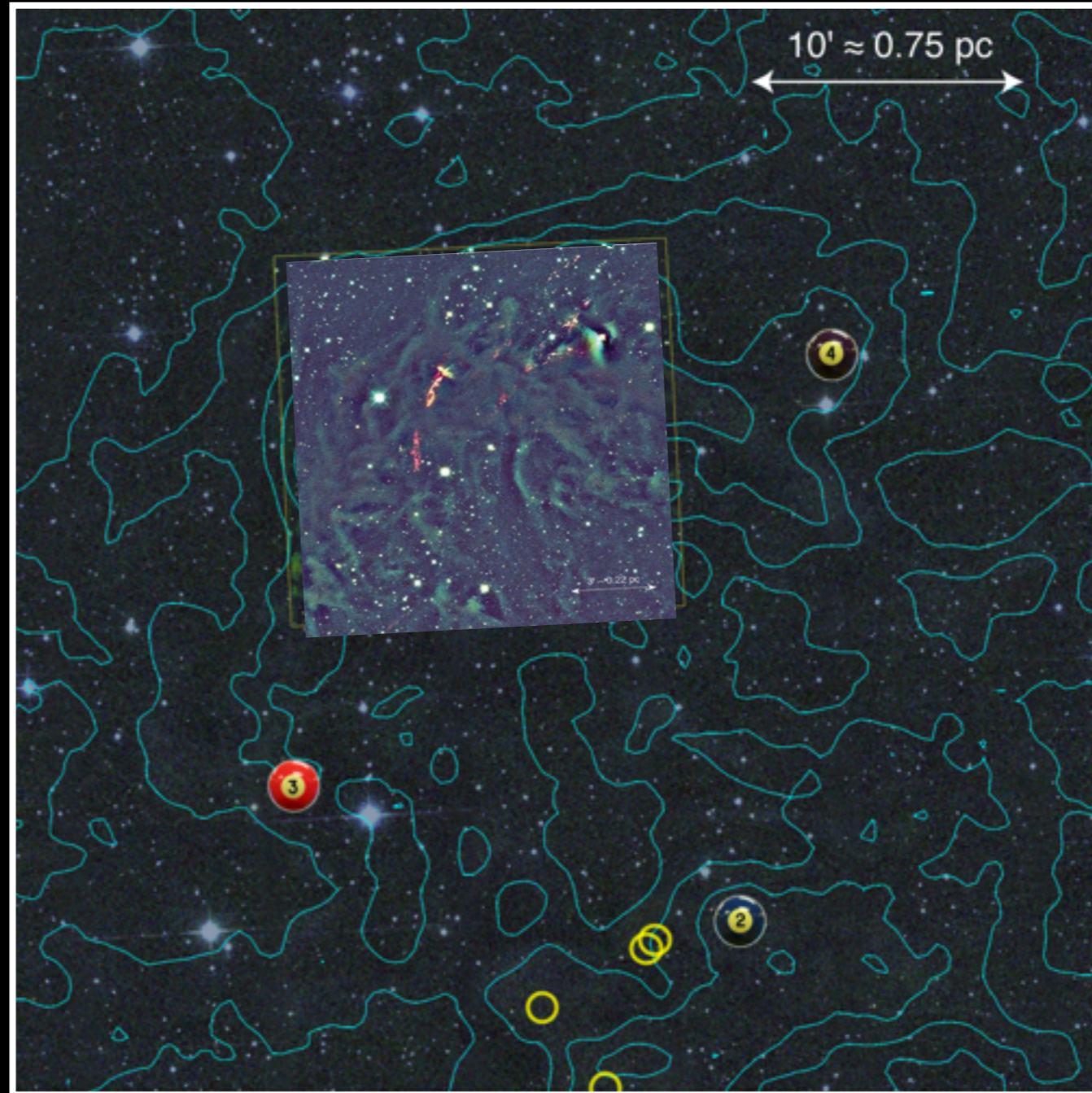
“L1448”

“Cloudshine”

“pre-stellar core”

“protostar”

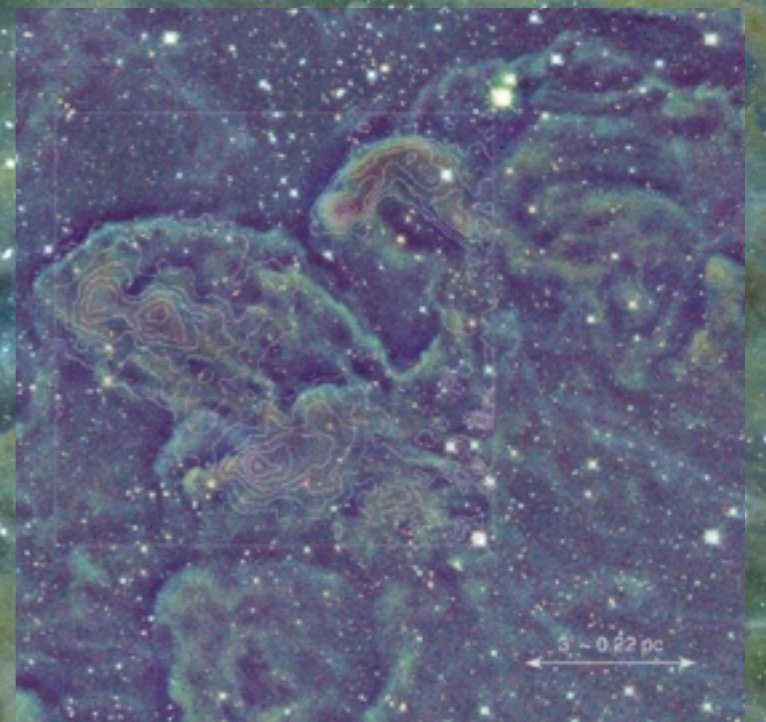
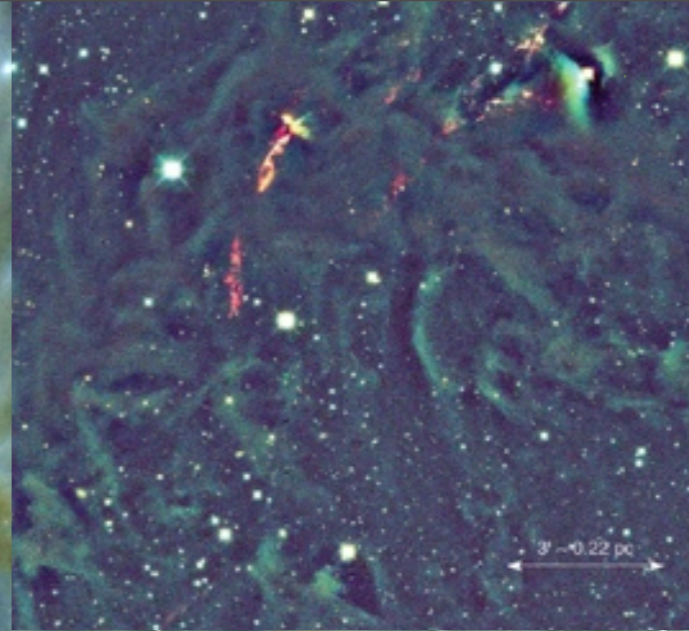
“integrated intensity”



“column density”

“COMPLETE”

“Cloudshine”



Background: to appear in Foster, Mandel, Pineda, Covey & Goodman 2009
Insets: Foster & Goodman 2006, Calar Alto JHK

✓ “L1448”

“Cloudshine” ✓

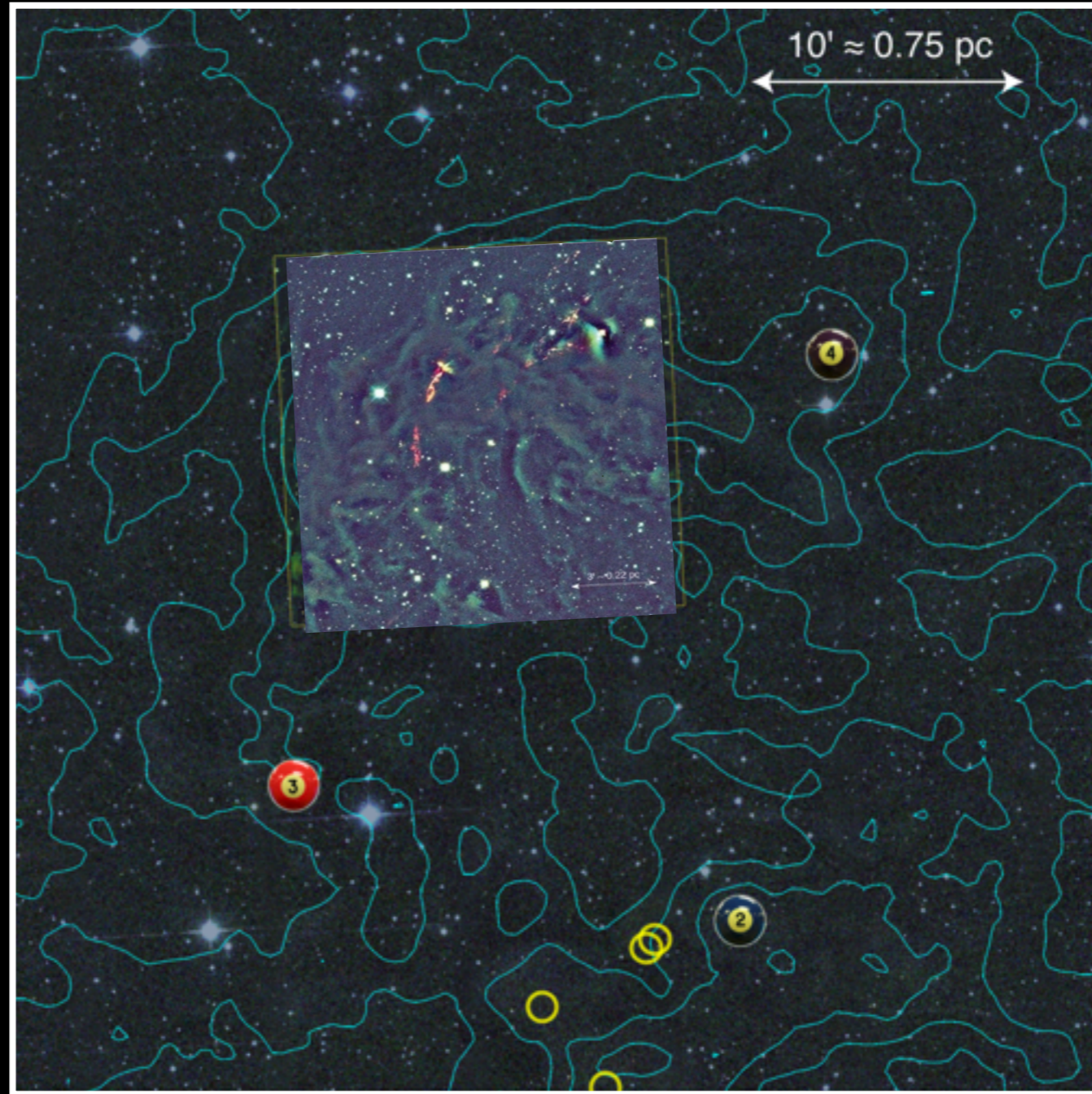
○ “pre-stellar core”

...compact
thermal dust peak ✓

* “protostar” ✓

...Spitzer c2d (MIR) point
source with “right” SED

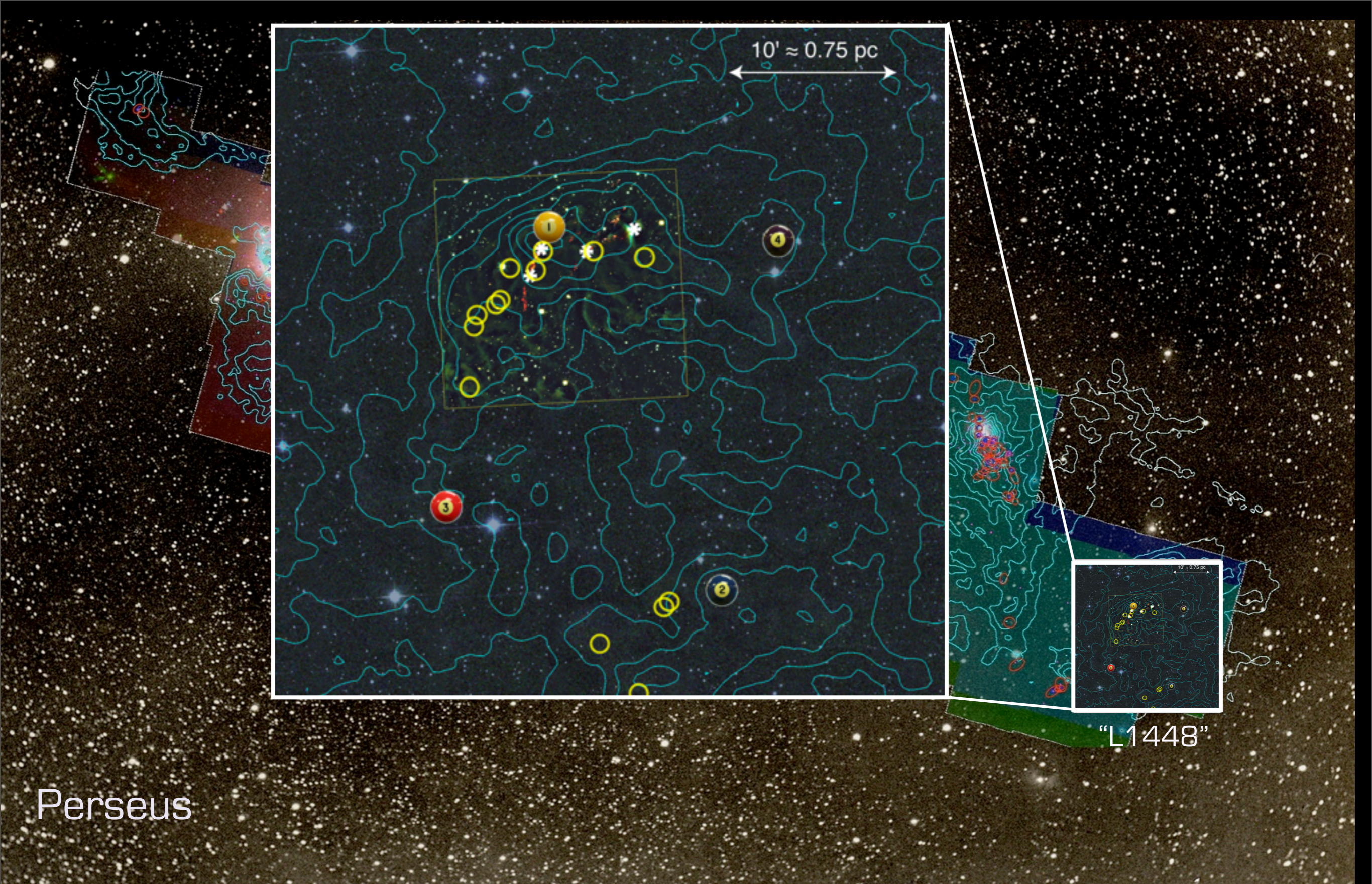
“integrated
intensity”



“column
density”

“COMPLETE”

(3 ...later)



Perseus

"L1448"



"integrated intensity"


"column density"

COMPLETE

COMPLETE Data Coverage Tool

http://www.worldwidetelescope.org/COMPLETE/WWTCoverageTool.htm#

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
GBT: HI Data Cube	<input checked="" type="checkbox"/>	✓	✓	∅	Data
IRAS: Av/Temp Maps	<input checked="" type="checkbox"/>	✓	✓	✓	Data
FCRAO: 12CO	<input checked="" type="checkbox"/>	✓	✓	✓	Data
FCRAO: 13CO	<input checked="" type="checkbox"/>	✓	✓	✓	Data
JCMT: 850 microns	<input checked="" type="checkbox"/>	✓	✓	∅	Data
Spitzer c2d: IRAC 1,3 (3.6,5.8 μm)	<input checked="" type="checkbox"/>	✓	✓	✓	Data
Spitzer c2d: IRAC 2,4 (4.5,8 μm)	<input checked="" type="checkbox"/>	✓	✓	✓	Data
CSO/Bolocam: 1.2-mm	<input checked="" type="checkbox"/>	✓	∅	∅	Data
Spitzer MIPS: Derived Dust Map	<input checked="" type="checkbox"/>	✓	∅	∅	Data

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


CTIO/Calar Alto: NIR (J,H,Ks)	<input checked="" type="checkbox"/>	✓	✓	∅	Data
IRAM 30-m: N2H+ and C18O	<input checked="" type="checkbox"/>	✓	∅	∅	Data
IRAM 30-m: 1.1-mm continuum	<input checked="" type="checkbox"/>	✓	∅	∅	Data
Megacam/MMT: r,i,z images	<input checked="" type="checkbox"/>	✓	∅	∅	Data

Catalogs & Pointed Surveys

NH3 Pointed Survey	<input type="checkbox"/>	✓	∅	∅	Data
YSO Candidate list (c2d)	<input type="checkbox"/>	✓	✓	✓	Data

Microsoft Research
WorldWide Telescope

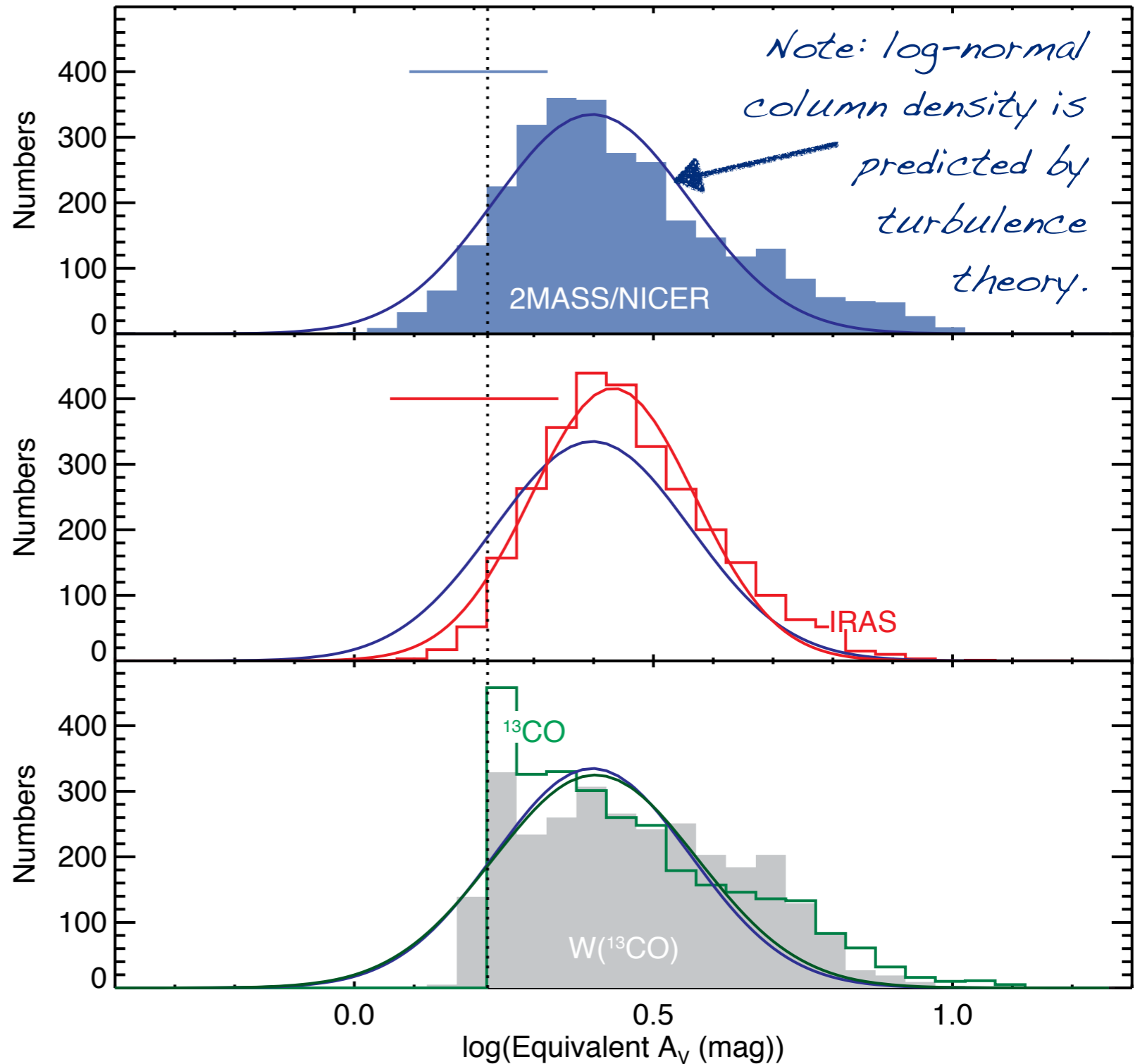
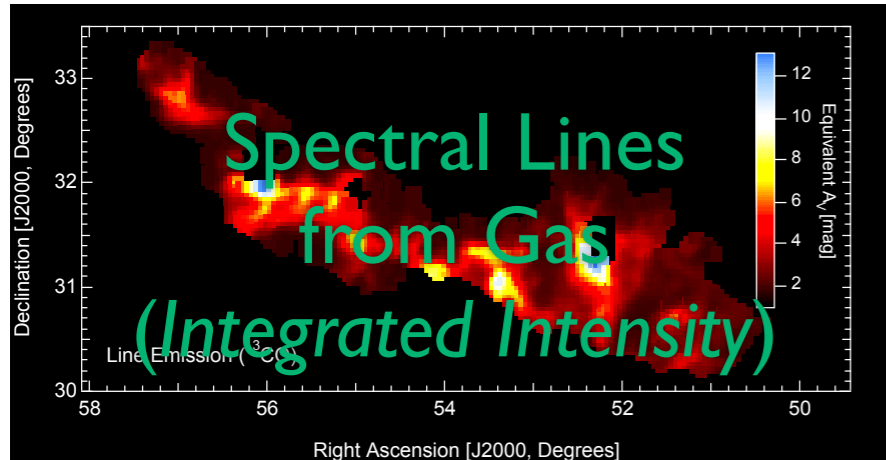
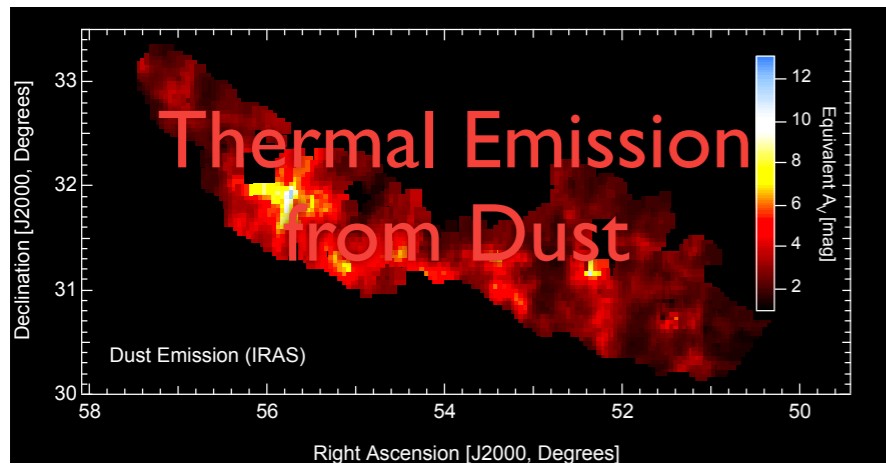
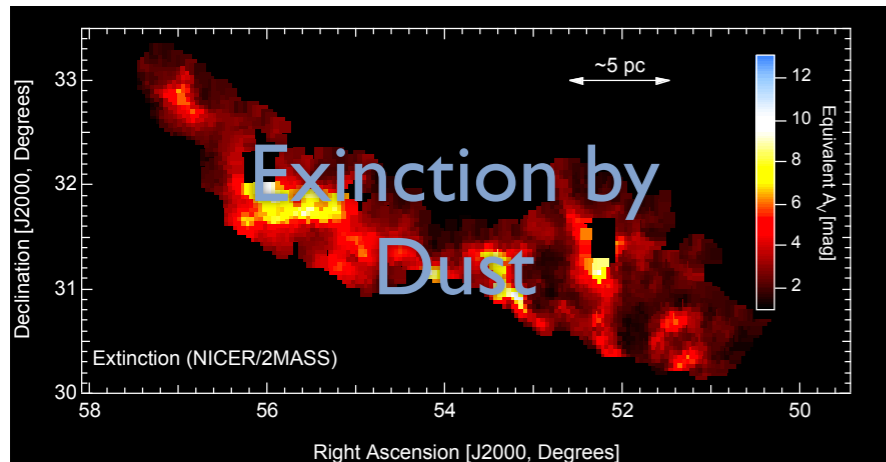
Done

To explore on your own, go to <http://www.cfa.harvard.edu/COMPLETE/>, then click on  and choose to see the Interactive Coverage Tool in either Google Sky or WorldWide Telescope.

Many thanks to Jonathan Foster, Gus Muench & Jonathan Fay (MSR/WWT team) for these tools!

Column Density in Perseus, Measured 3 Ways

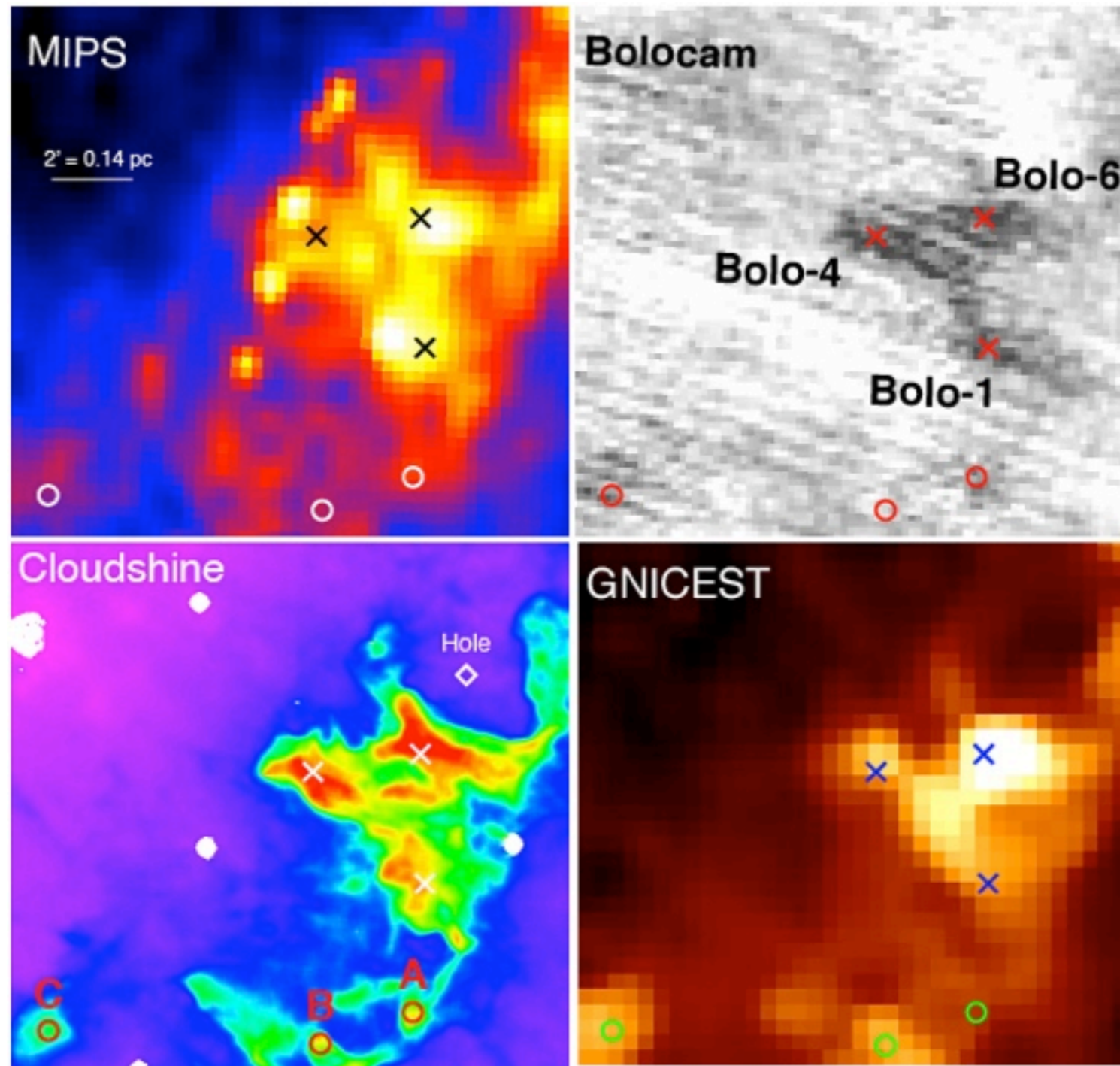
TASTE TEST



COMMERCIAL BREAK:

“Foster’s Showdown, v.2009”

...talk with Foster, Pineda, Offner, Draine and/or me later...



“turbulent fragmentation” “LI 448” “(magneto-)hydrodynamic simulation”

“Cloudshine”

“pre-stellar core”

“protostar”

“integrated intensity*”

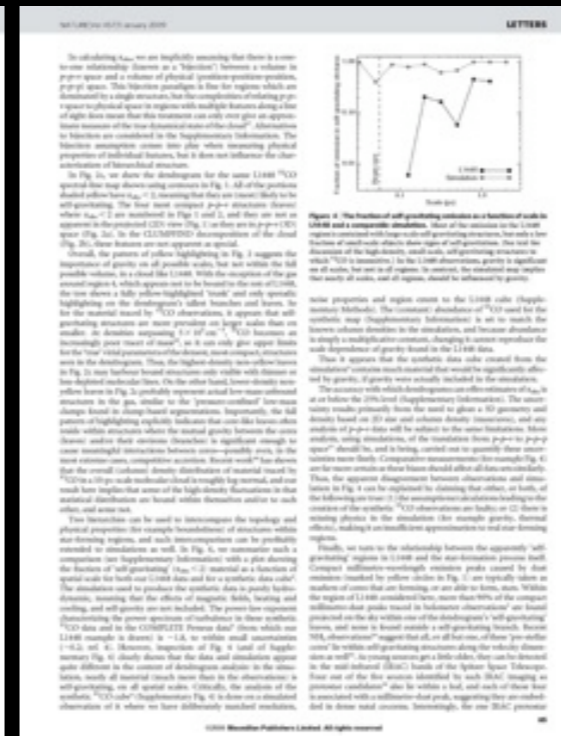
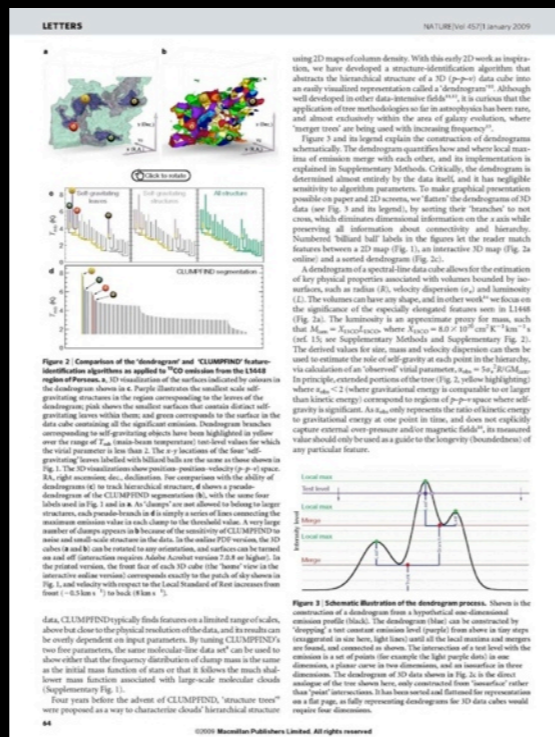
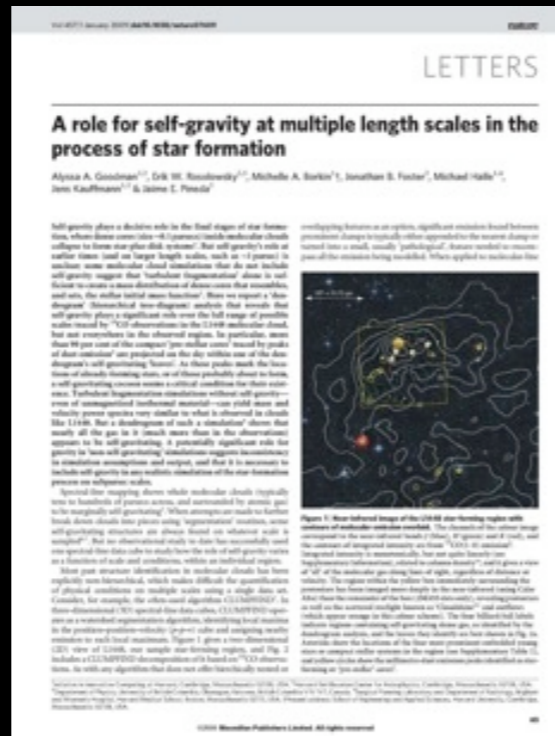
“p-p-v cube”

“segmentation”

“CLUMPFIND”

“Dendrogram”

*...more to come



“COMPLETE”

“3D PDF”

“bi-jection”

“virial parameter”

“column density”

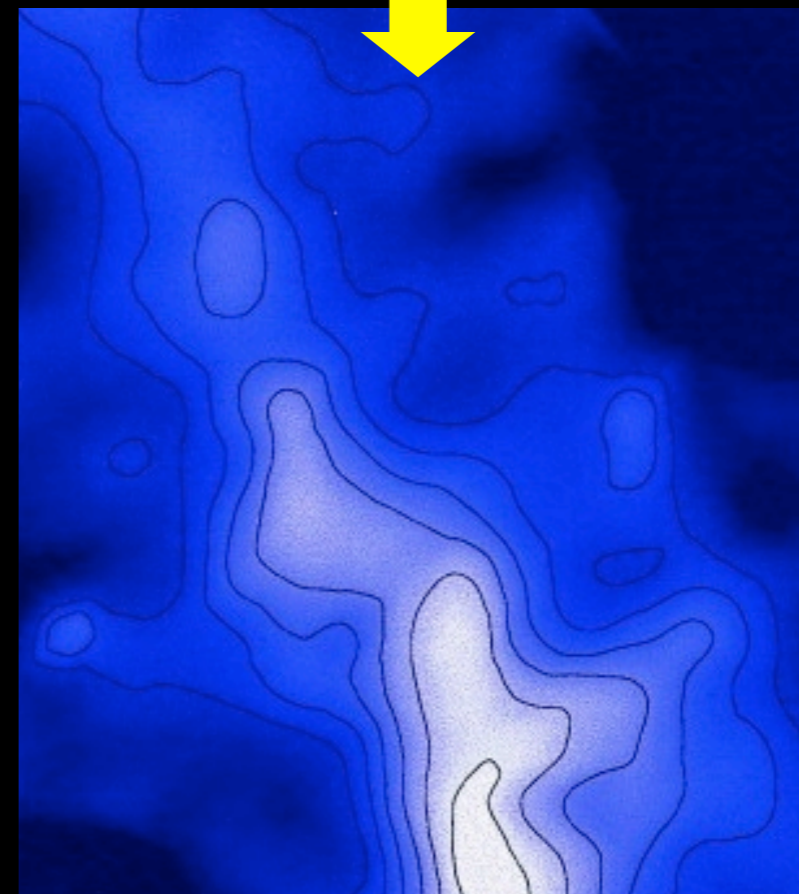
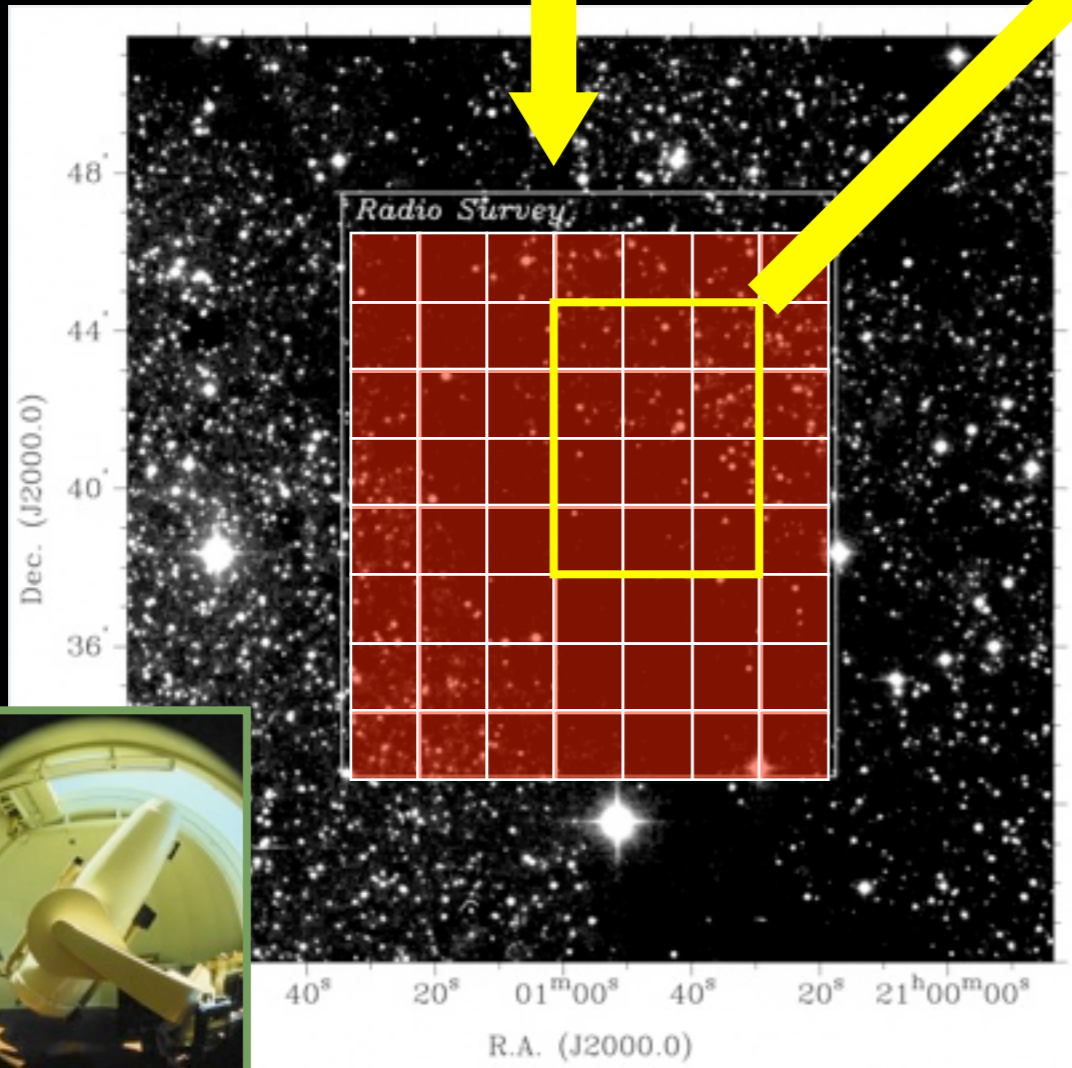
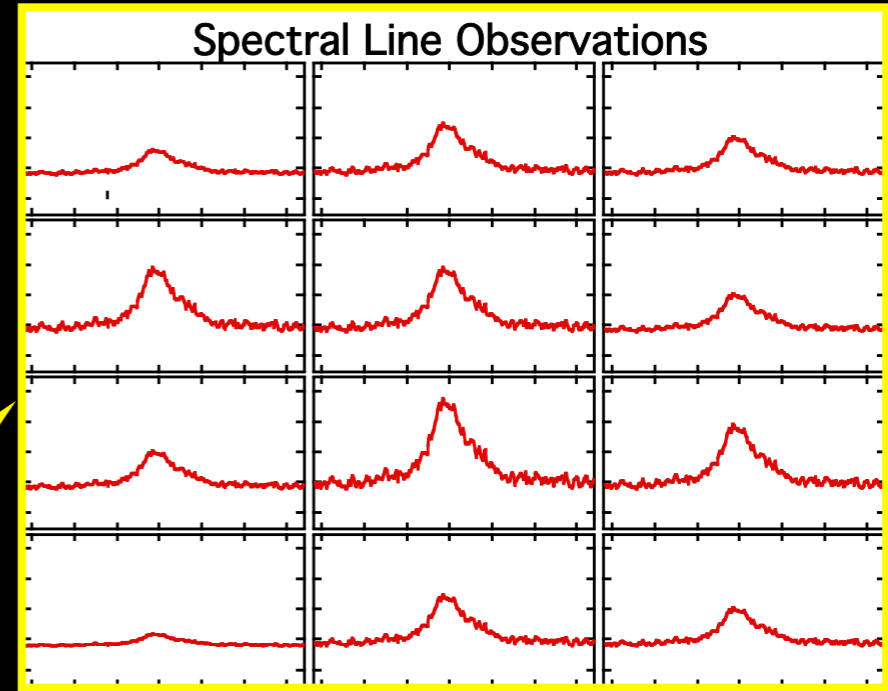
“turbulent power spectrum”

“synthetic observation”

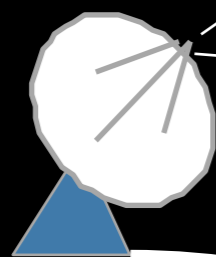
“depletion, opacity”

“taste-test” caveats

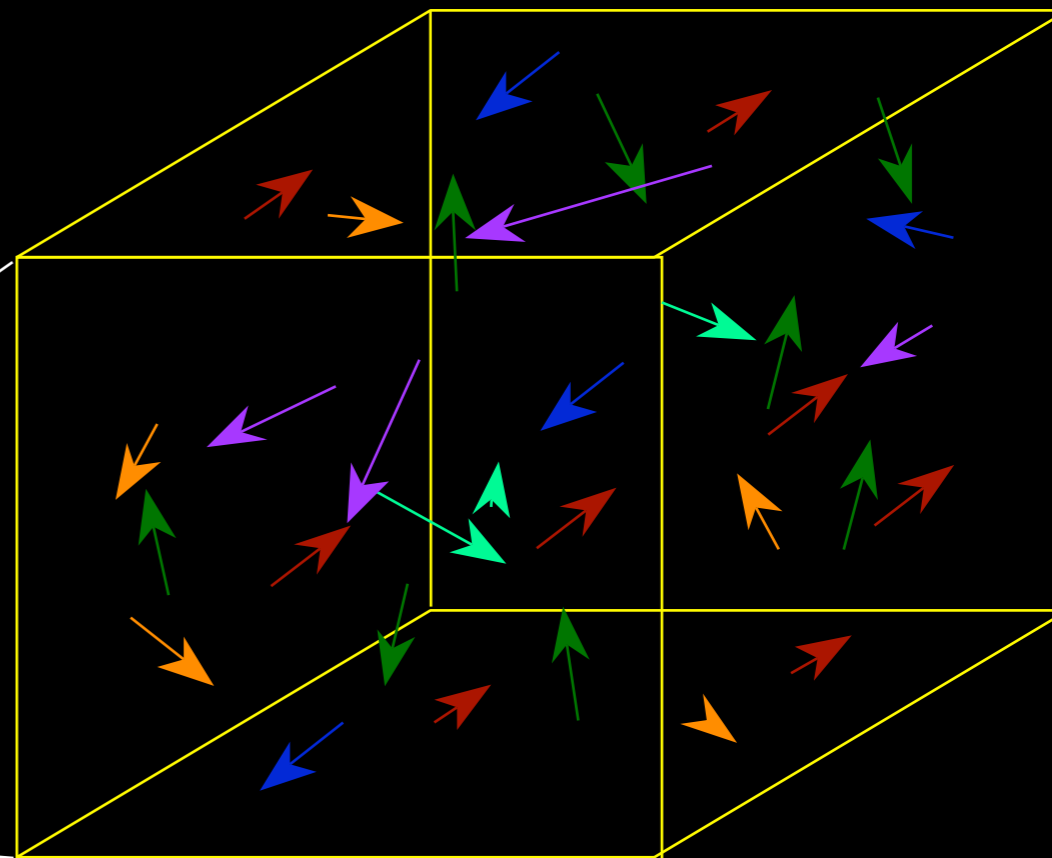
Radio Spectral-line Observations of Interstellar Clouds



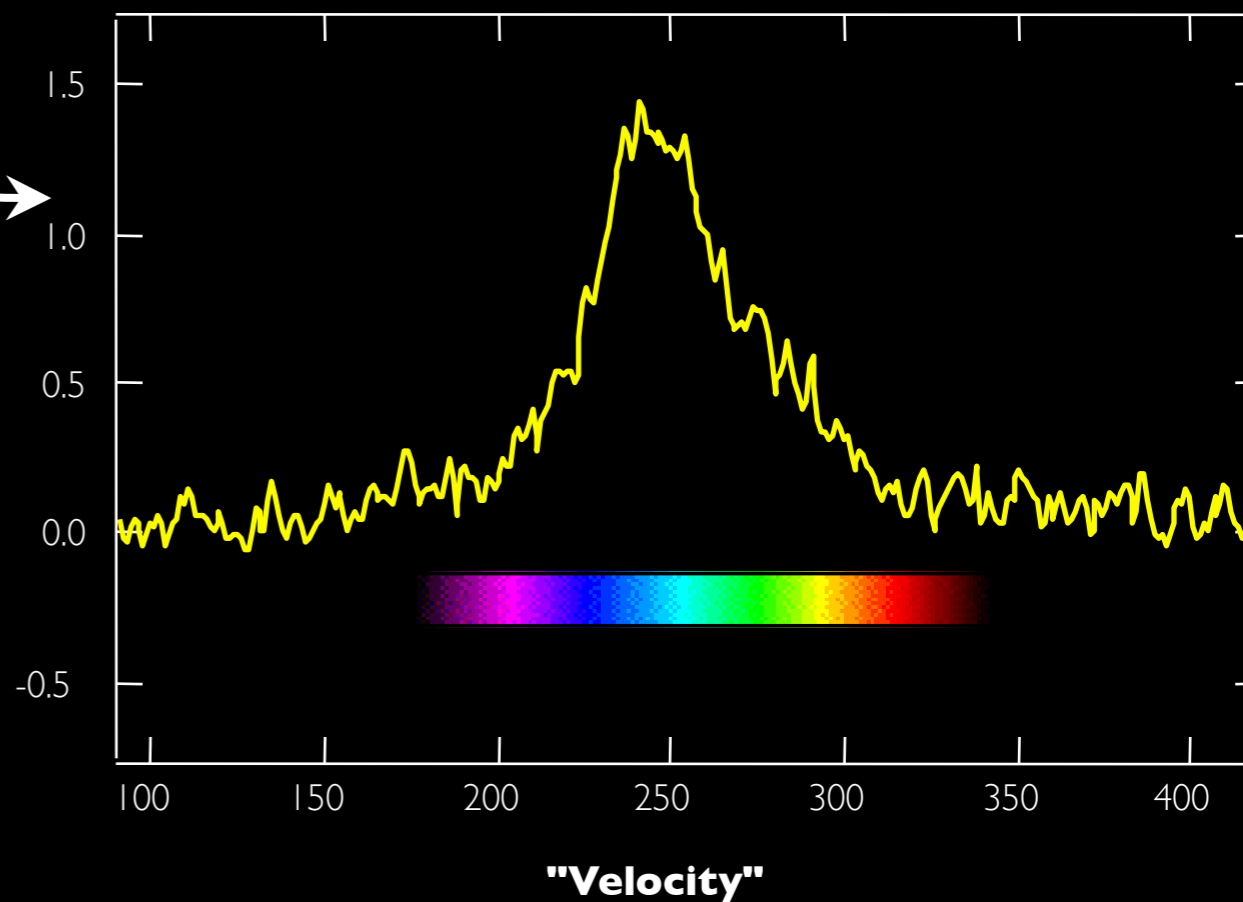
Velocity from Spectroscopy



Telescope +
Spectrometer



Observed Spectrum

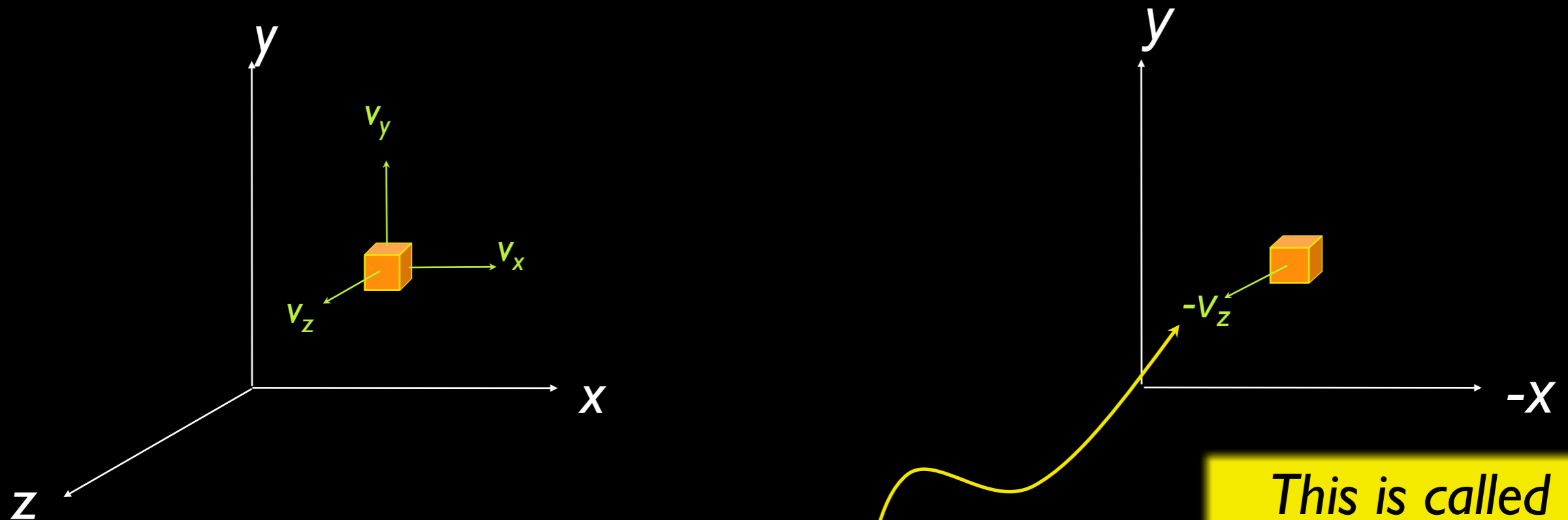


All thanks to Doppler

“Three” Dimensions: Spectral-Line Mapping

We wish we could measure...

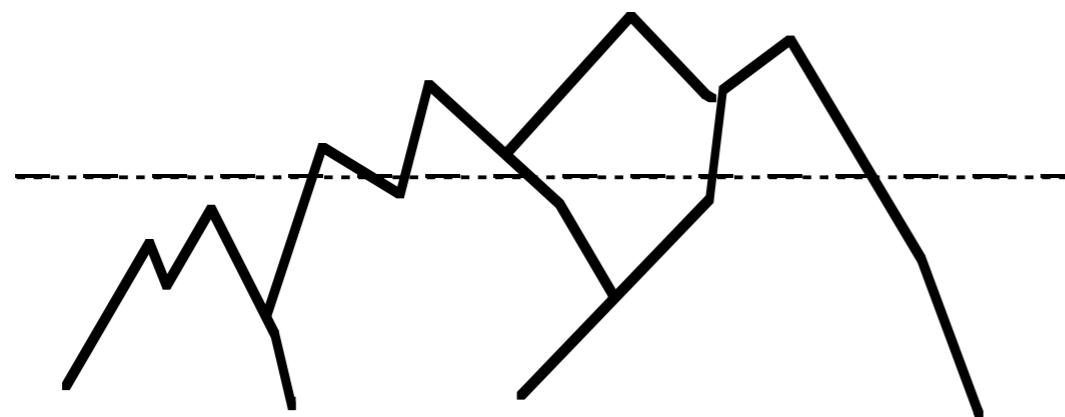
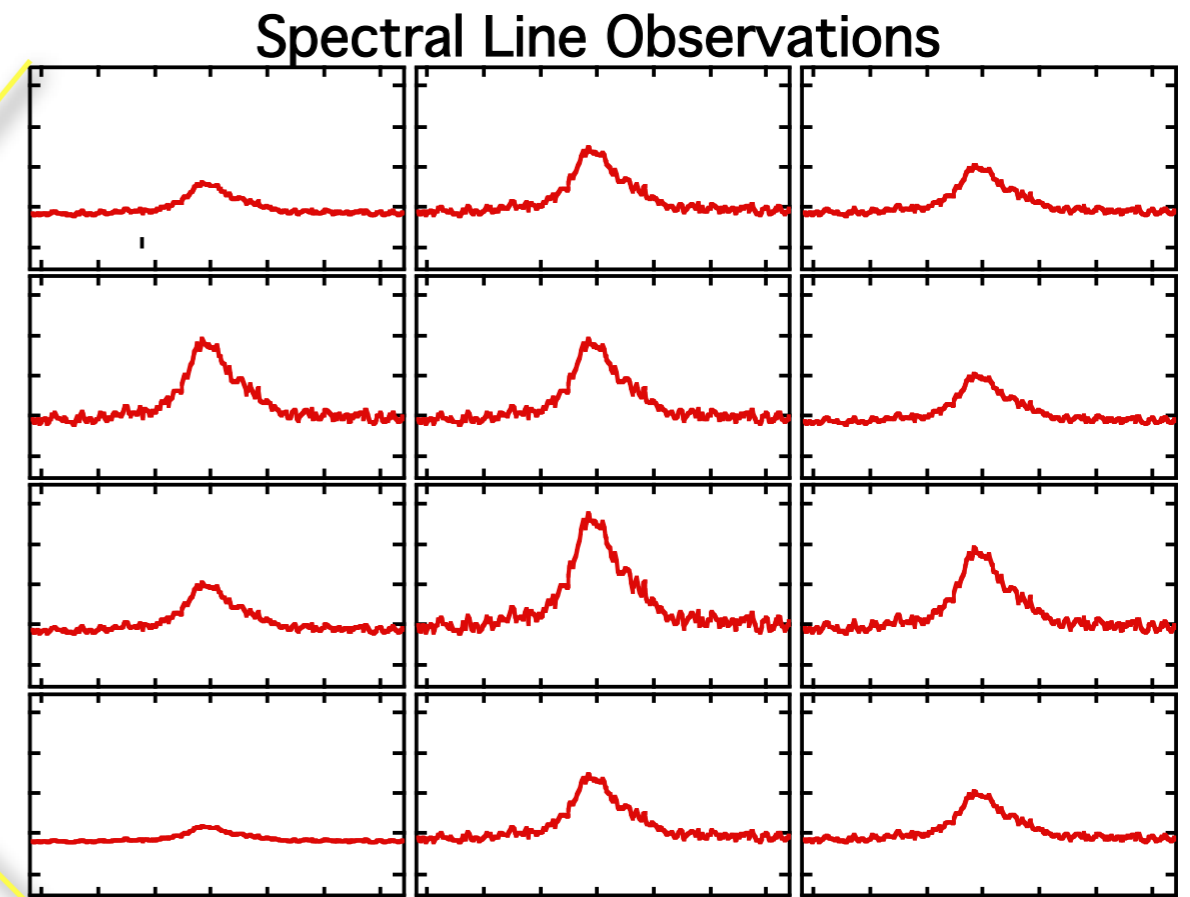
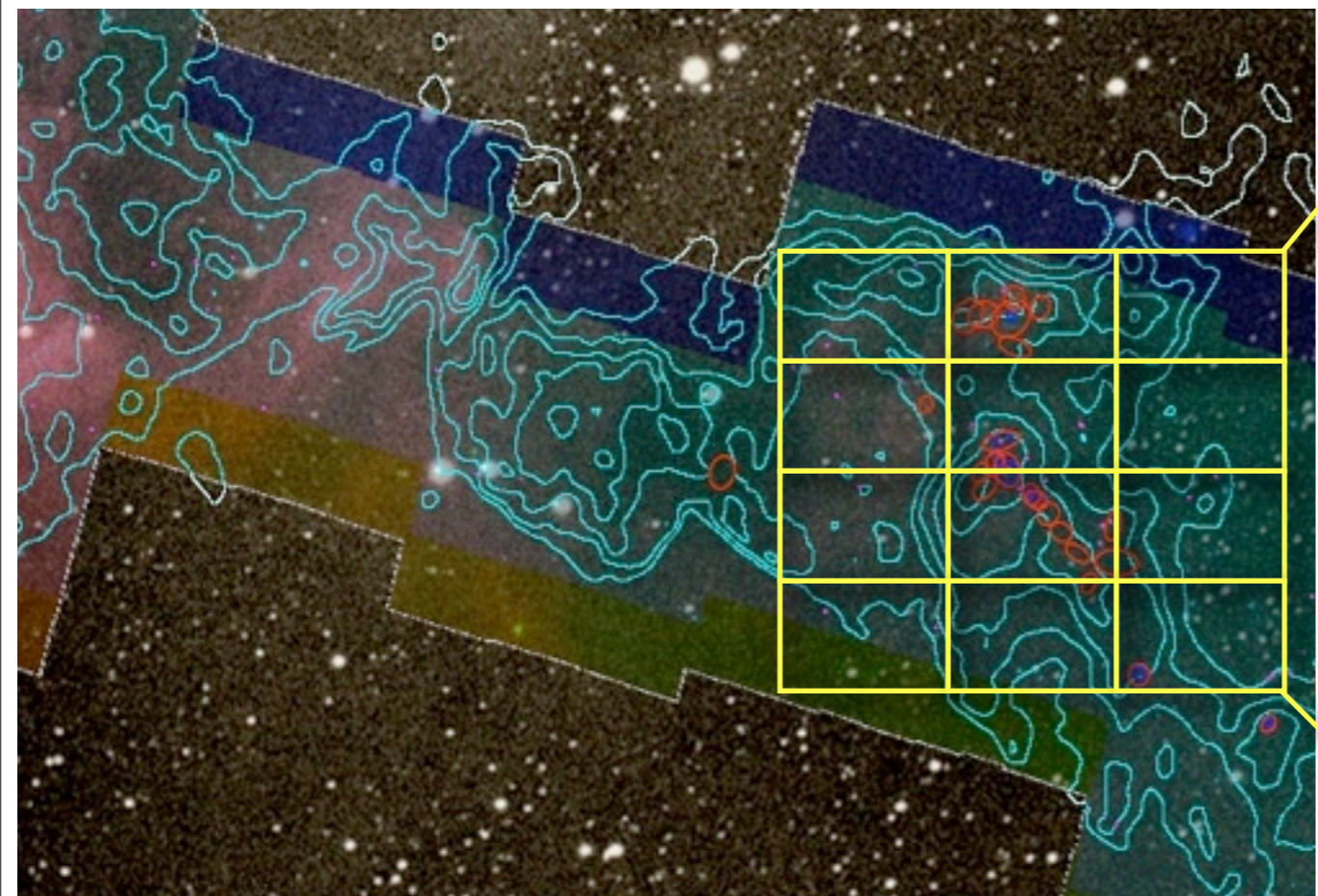
But we can measure...



v_z *only* from
“spectral-line
maps”

This is called
“ **$p-p-v$** ” or
“position-
position-velocity”
space.

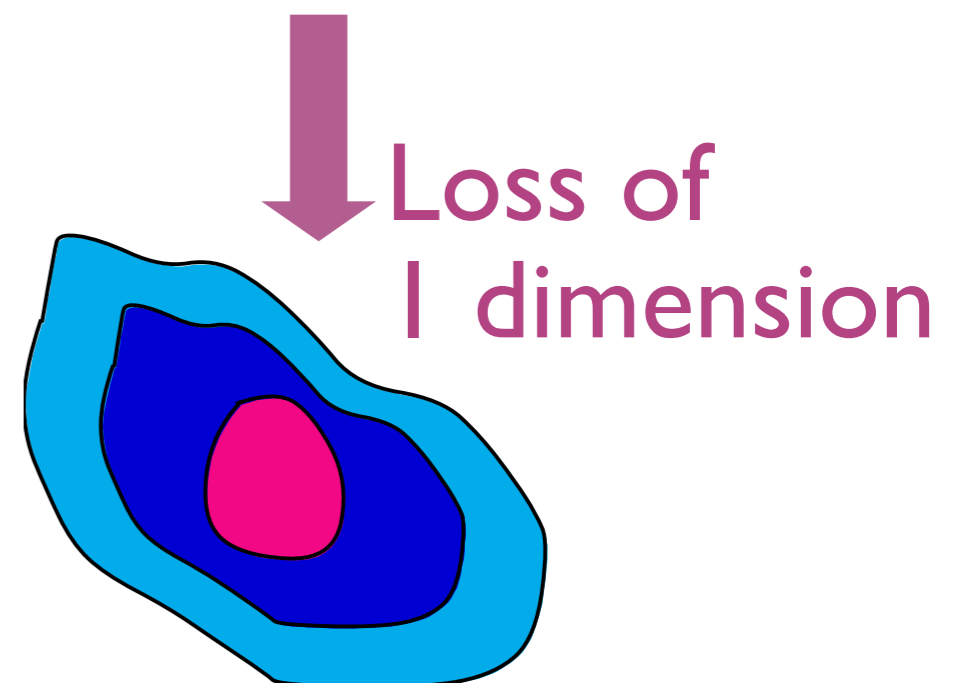
There's much more to life than "integrated intensity"



Mountain Range



No loss of information



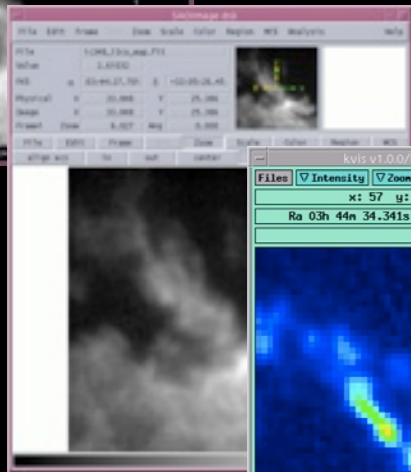
Loss of 1 dimension

Astronomical Visualization Tools are Traditionally 2D

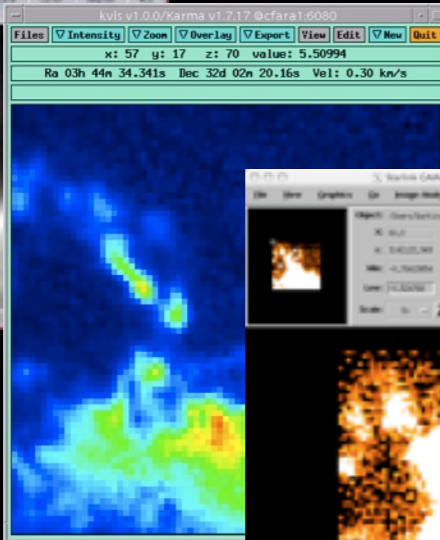
IDL



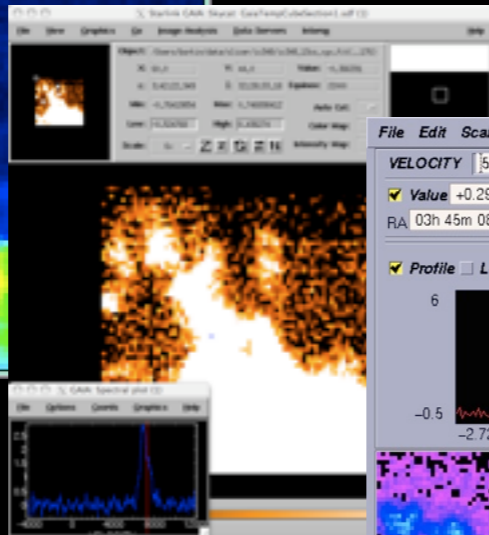
DS9



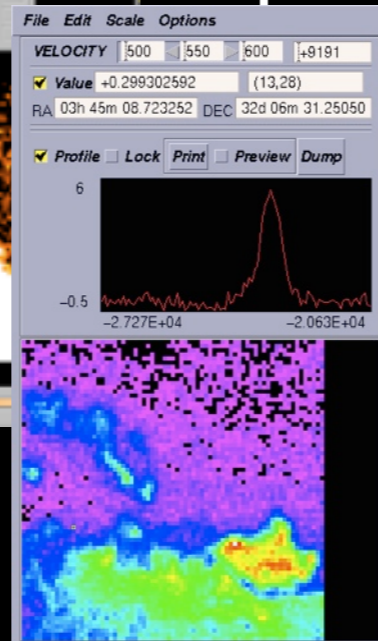
Karma*



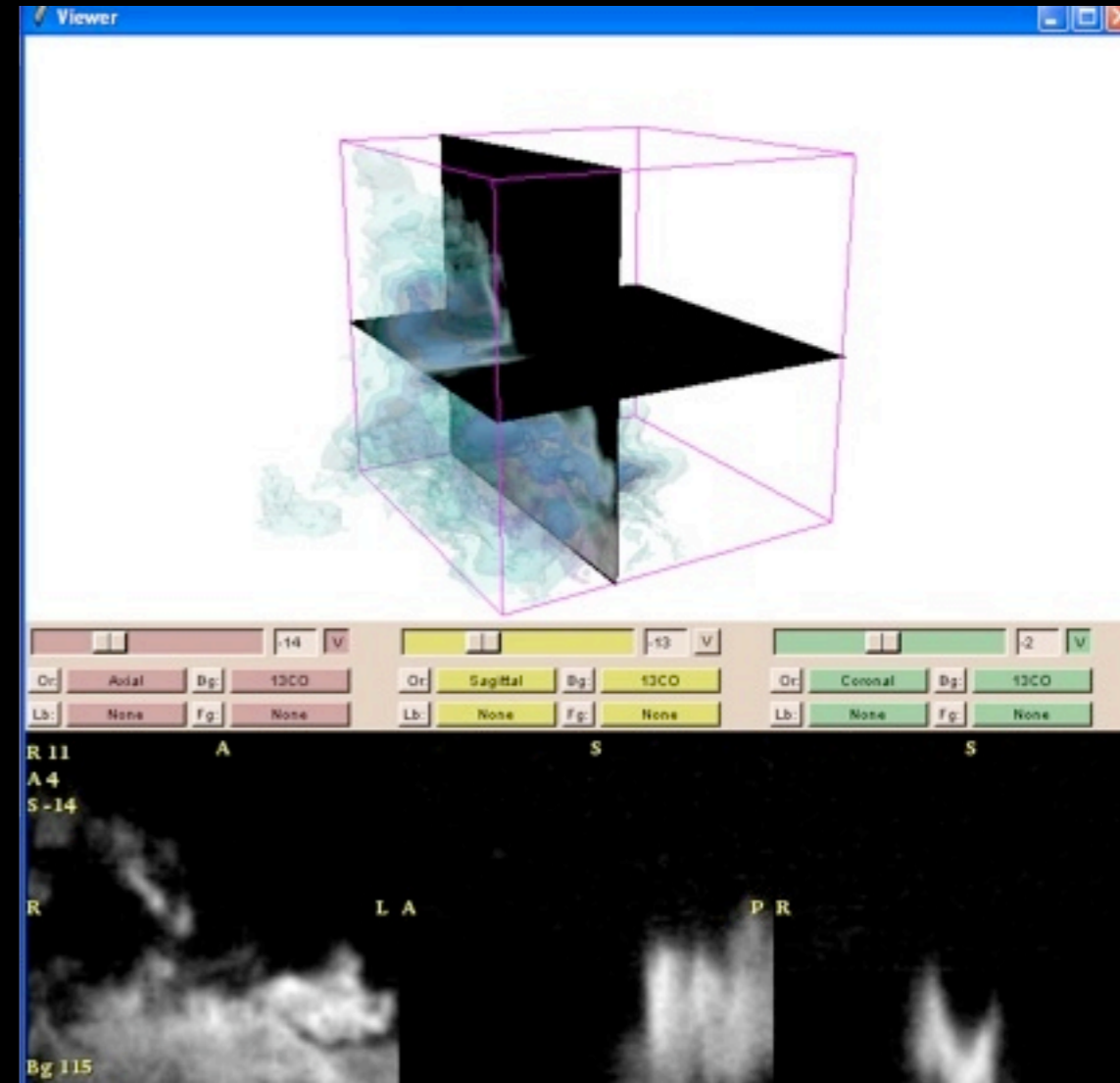
GAIA



Aipsview








3D Slicer

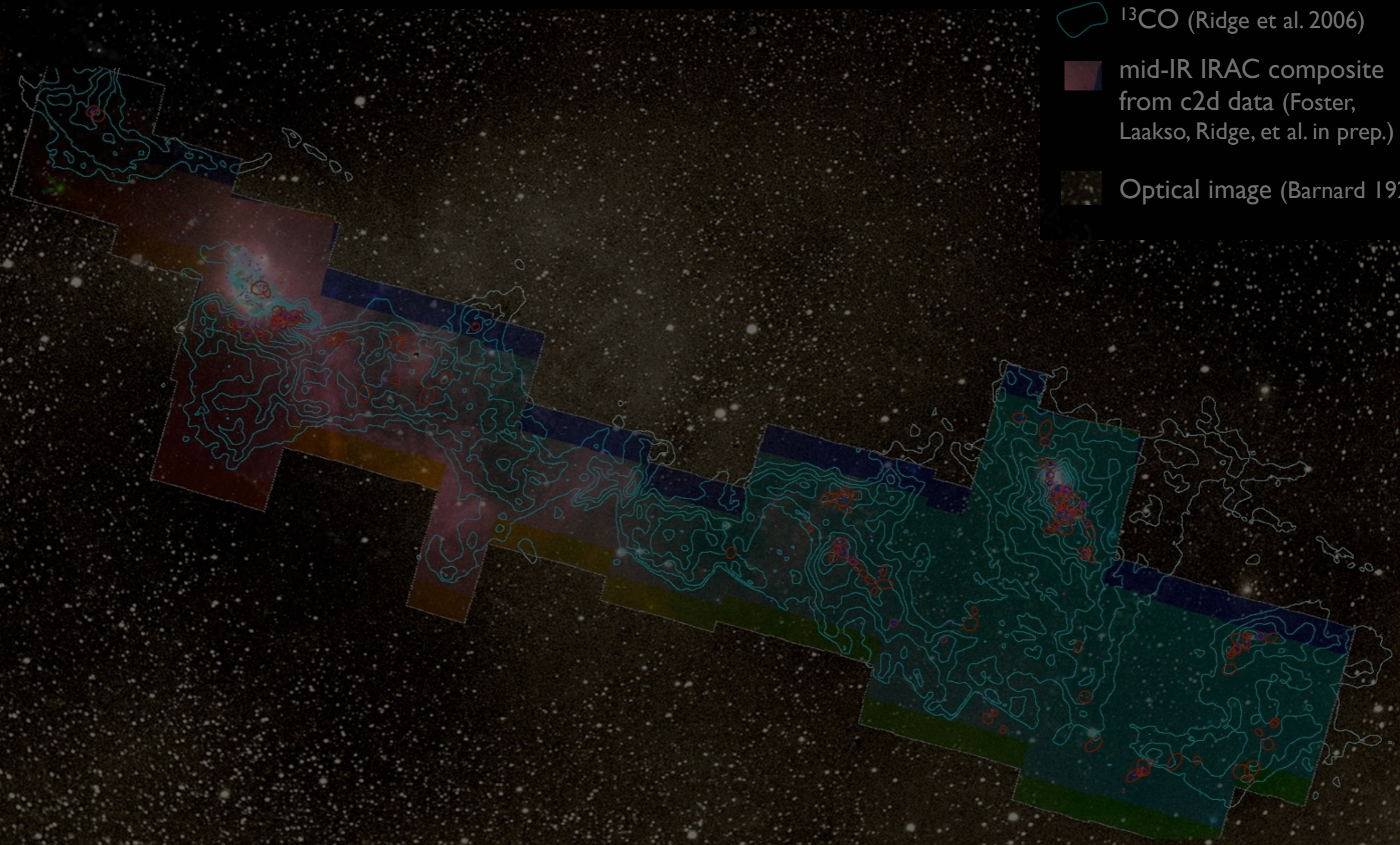


“3D”=movies

COMPLETE Perseus

Image size: 1305 x 733
VL: 63 WW: 127

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

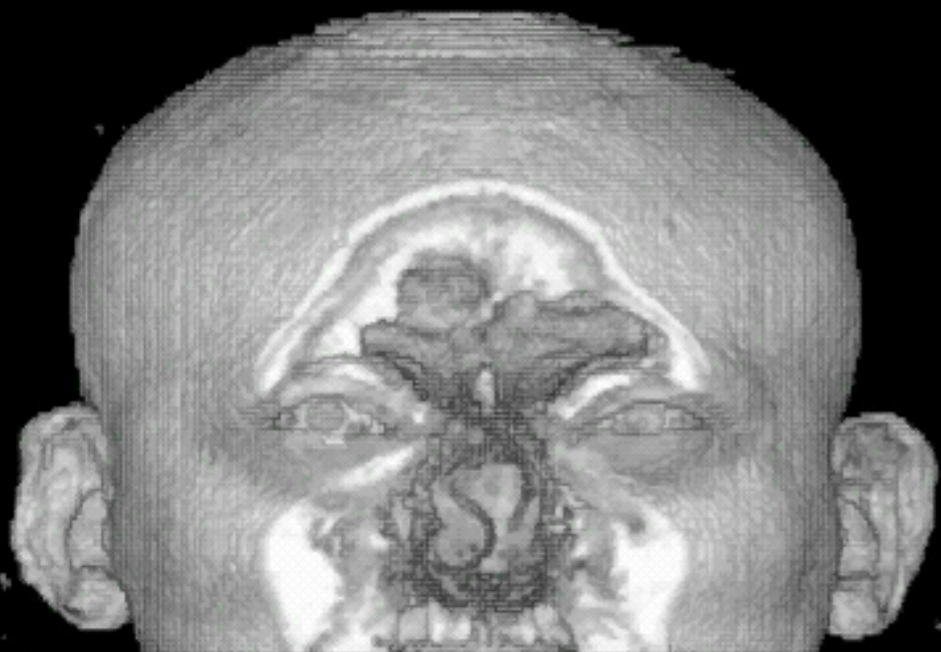


m: 17249
Zoom: 227% Angle: 0



“Astronomical Medicine”

“KEITH”



“z” is depth into head

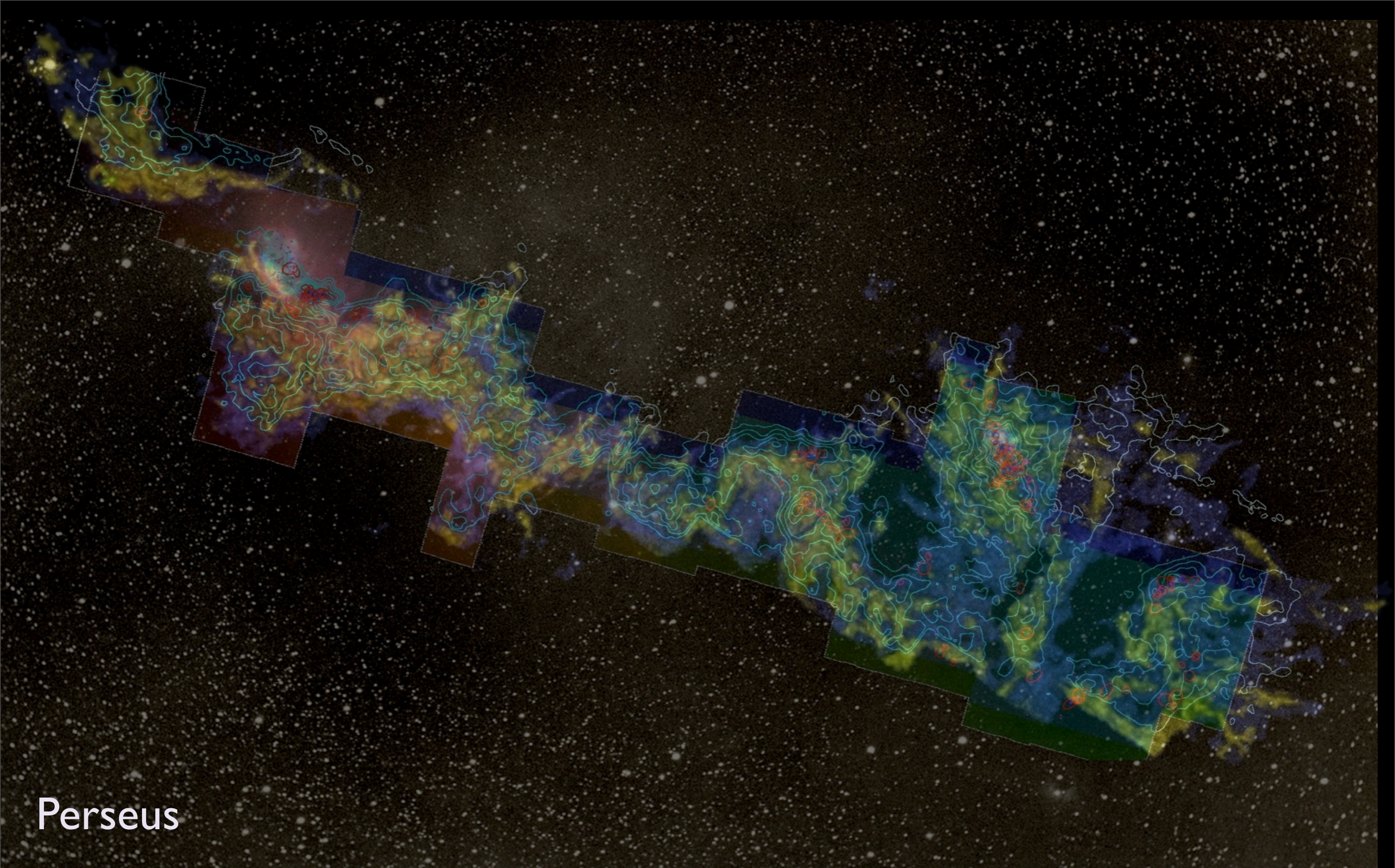
“PERSEUS”



“z” is line-of-sight velocity

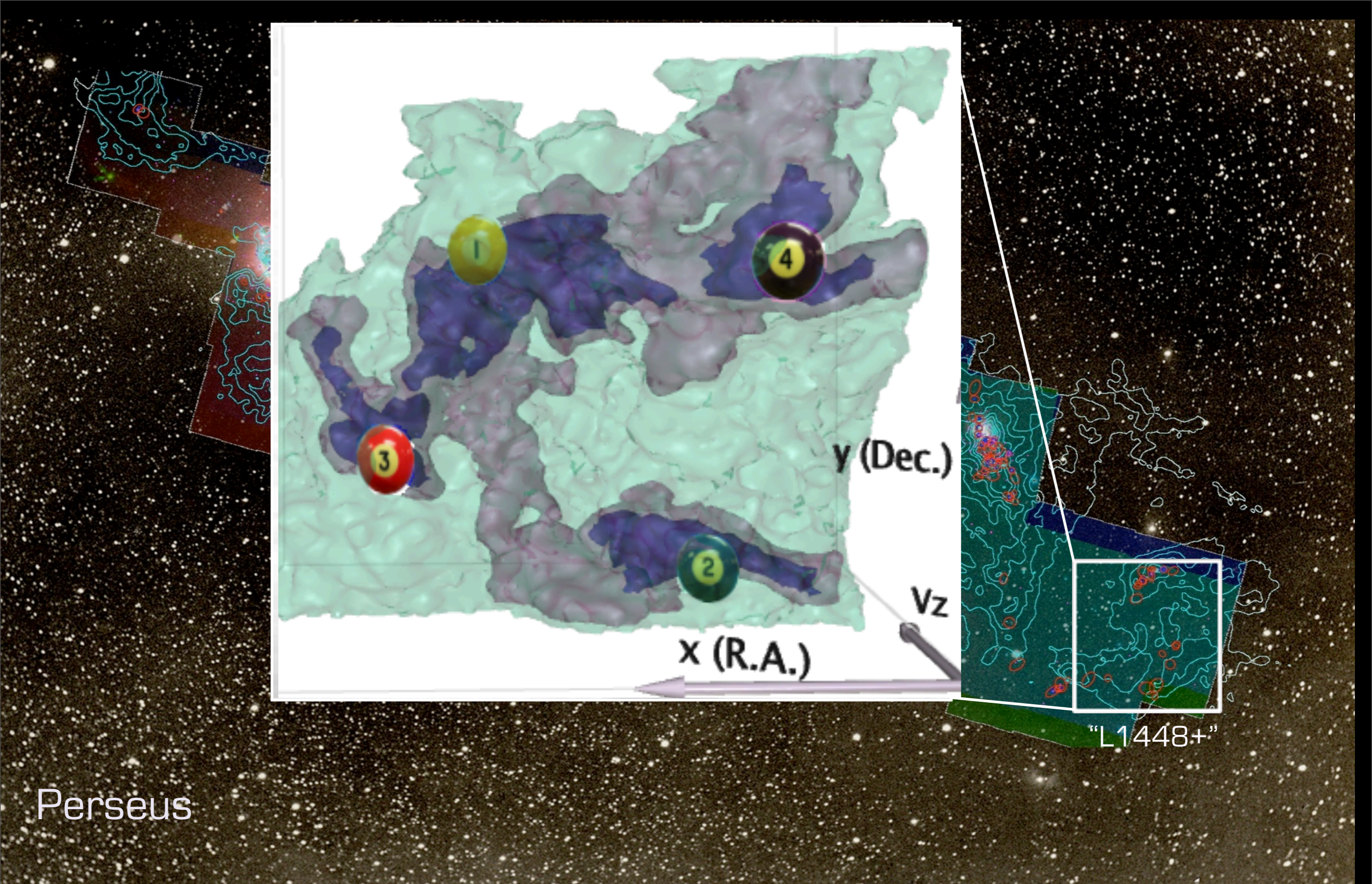
(This kind of “series of 2D slices view” is known in the Viz as “the grand tour”)





Perseus

3D Viz made with VolView



Perseus

“turbulent fragmentation”

“(magneto-)hydrodynamic simulation”

“bi-jection”

“virial parameter”

“virial parameter”

“turbulent power spectrum”

“synthetic observation”

“depletion, opacity”

“taste-test” caveats

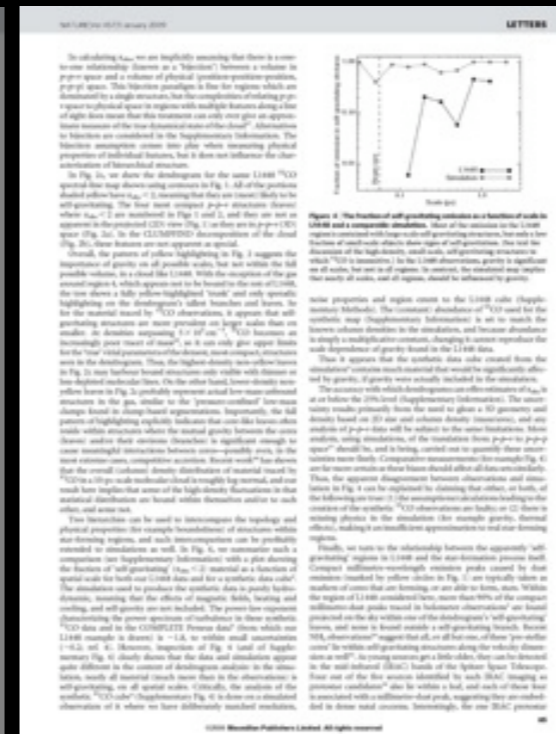
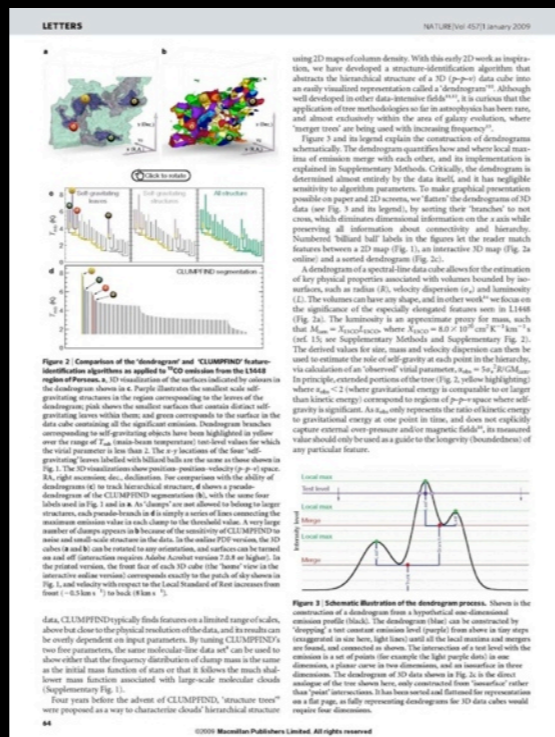
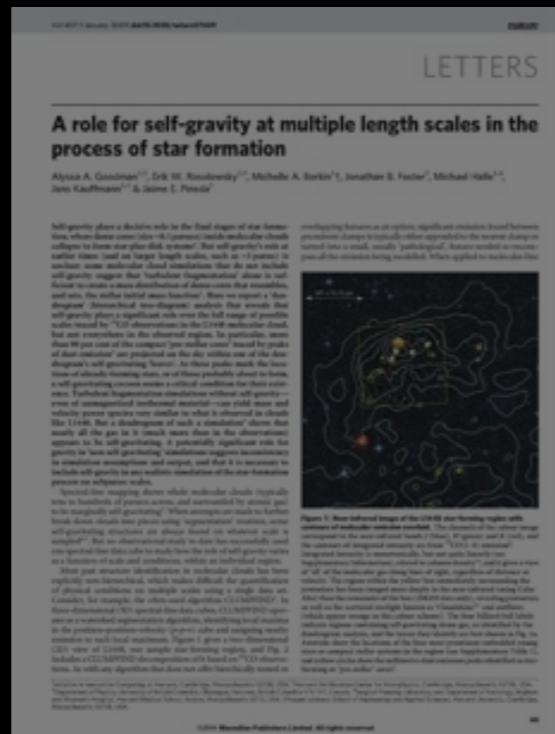
✓ “integrated intensity*”

✓ “p-p-v cube”

“segmentation”

“CLUMPFIND”

“Dendrogram”



“3D PDF”

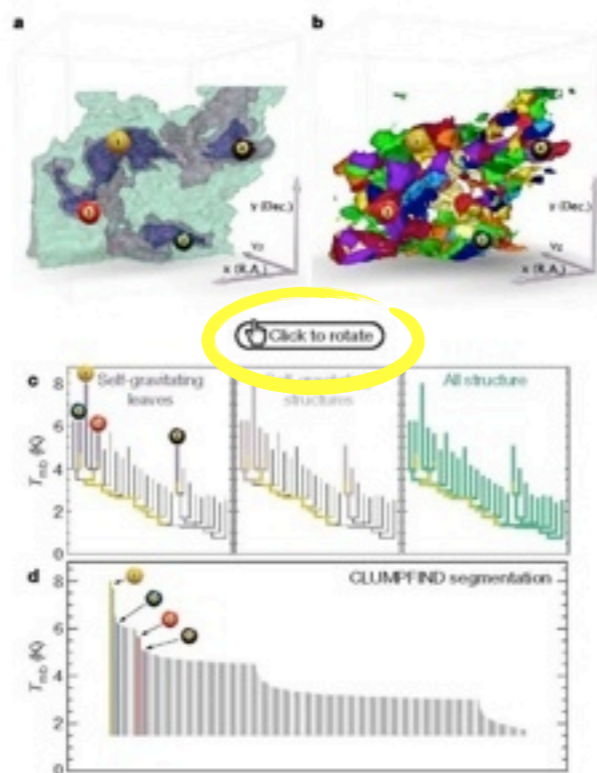


Figure 2 | Comparison of the 'dendrogram' and 'CLUMPFIND' feature-identification algorithms as applied to ^{13}CO emission from the L1448 region of Perseus. **a**, 3D visualization of the surfaces indicated by colours in the dendrogram shown in **c**. Purple illustrates the smallest scale self-gravitating 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_{sub} (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 'dumps' 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 dumps 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 km s^{-1}) to back (8 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 set⁸ 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'⁹ 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'¹⁰. Although well developed in other data-intensive fields^{11,12}, 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 frequency¹³.

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 (σ_v) and luminosity (L). The volumes can have any shape, and in other work¹⁴ 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 $M_{\text{gas}} = X_{13\text{CO}} L_{13\text{CO}}$, where $X_{13\text{CO}} = 8.0 \times 10^{26} \text{ cm}^2 \text{ K}^{-1} \text{ km}^{-1} \text{ s}$ (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, $\alpha_{\text{obs}} = 5\sigma_v^2 R / GM_{\text{gas}}$. 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 α_{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 fields¹⁶, its measured value should only be used as a guide to the longevity (boundedness) of any particular feature.

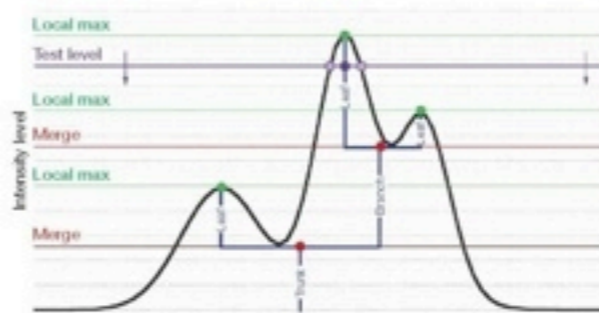
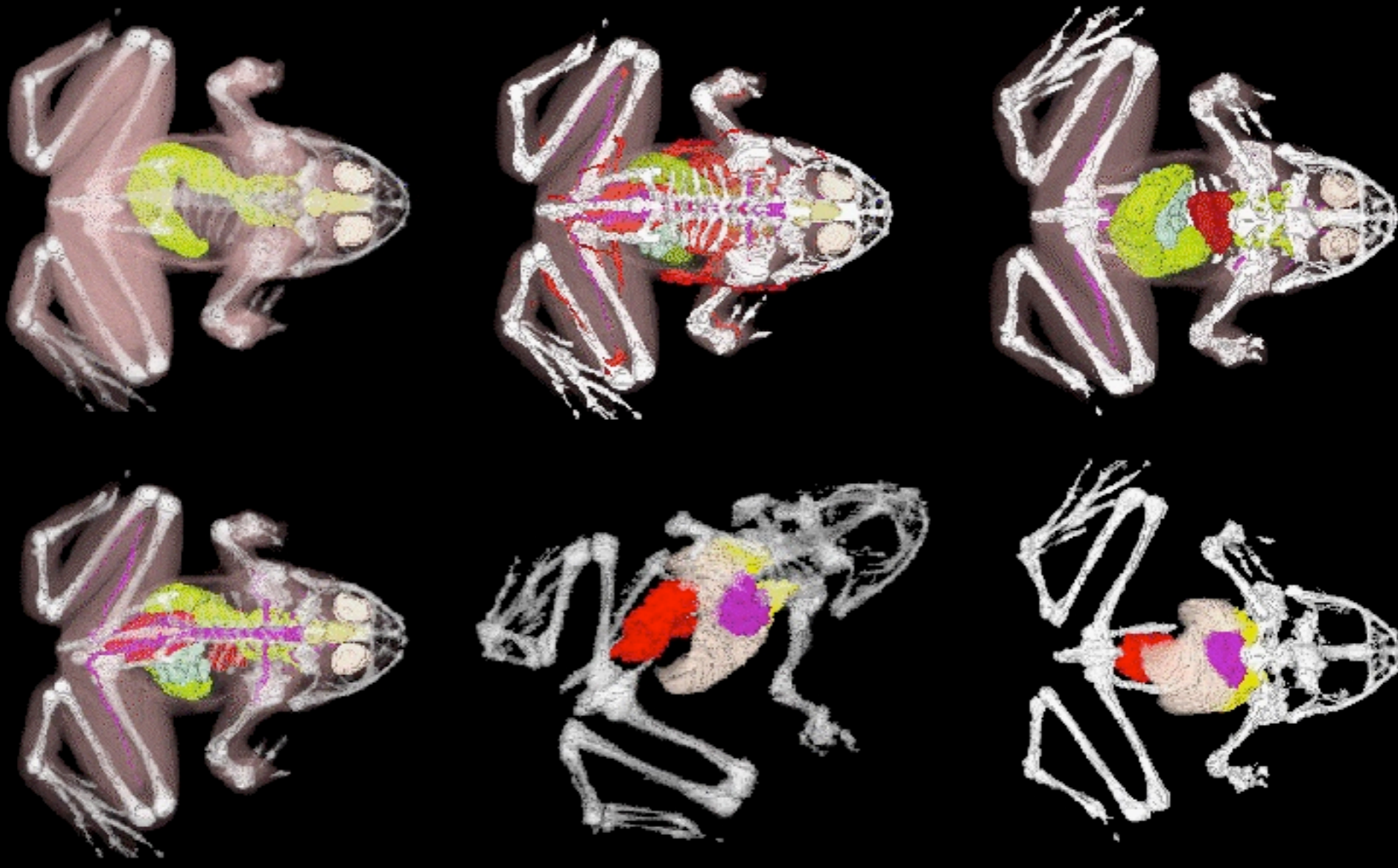
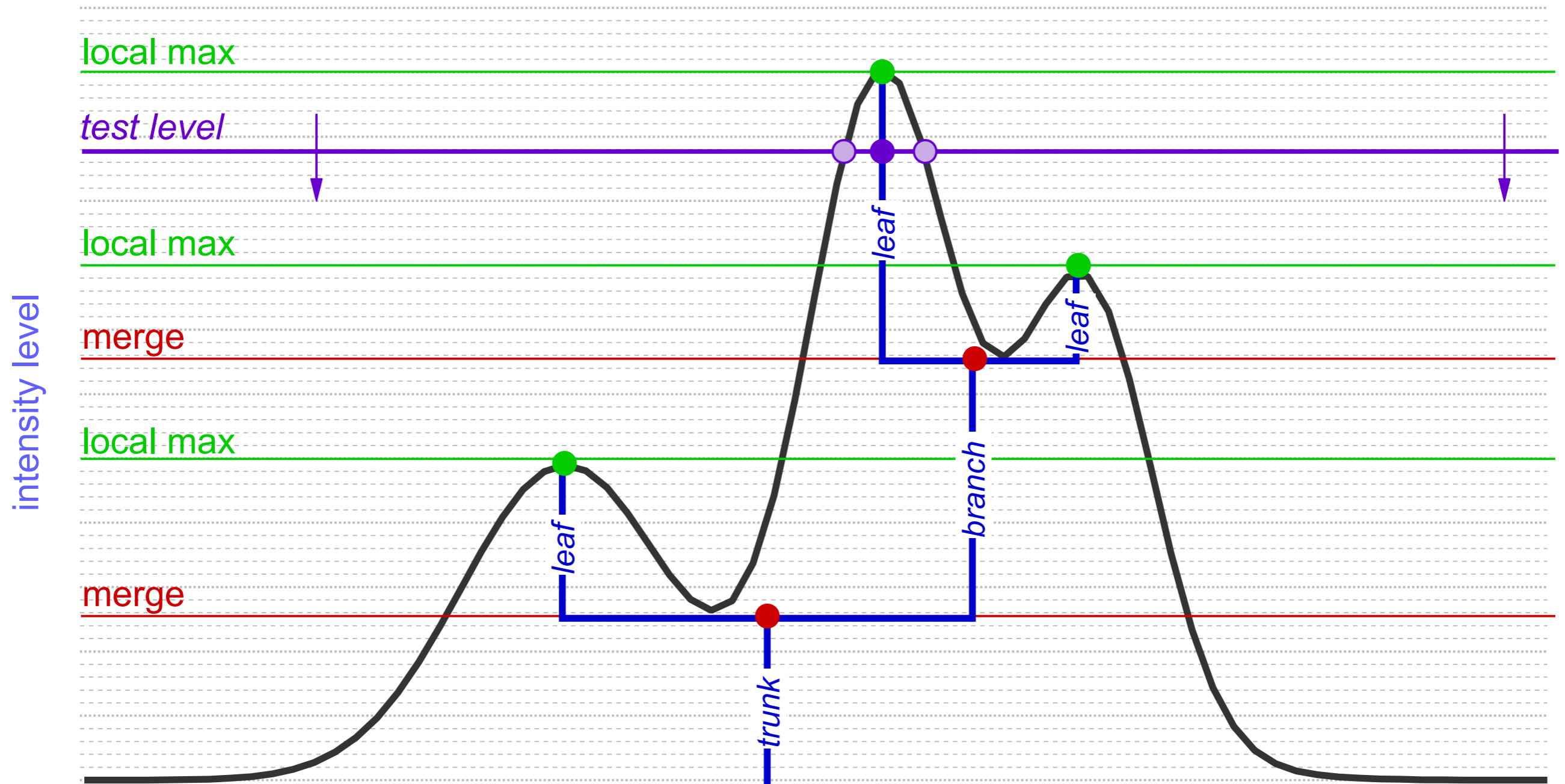


Figure 3 | Schematic illustration of the dendrogram process. Shown is the construction of a dendrogram from a hypothetical one-dimensional emission profile (black). The dendrogram (blue) can be constructed by 'dropping' a test constant emission level (purple) from above in tiny steps (exaggerated in 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.

“Segmentation”



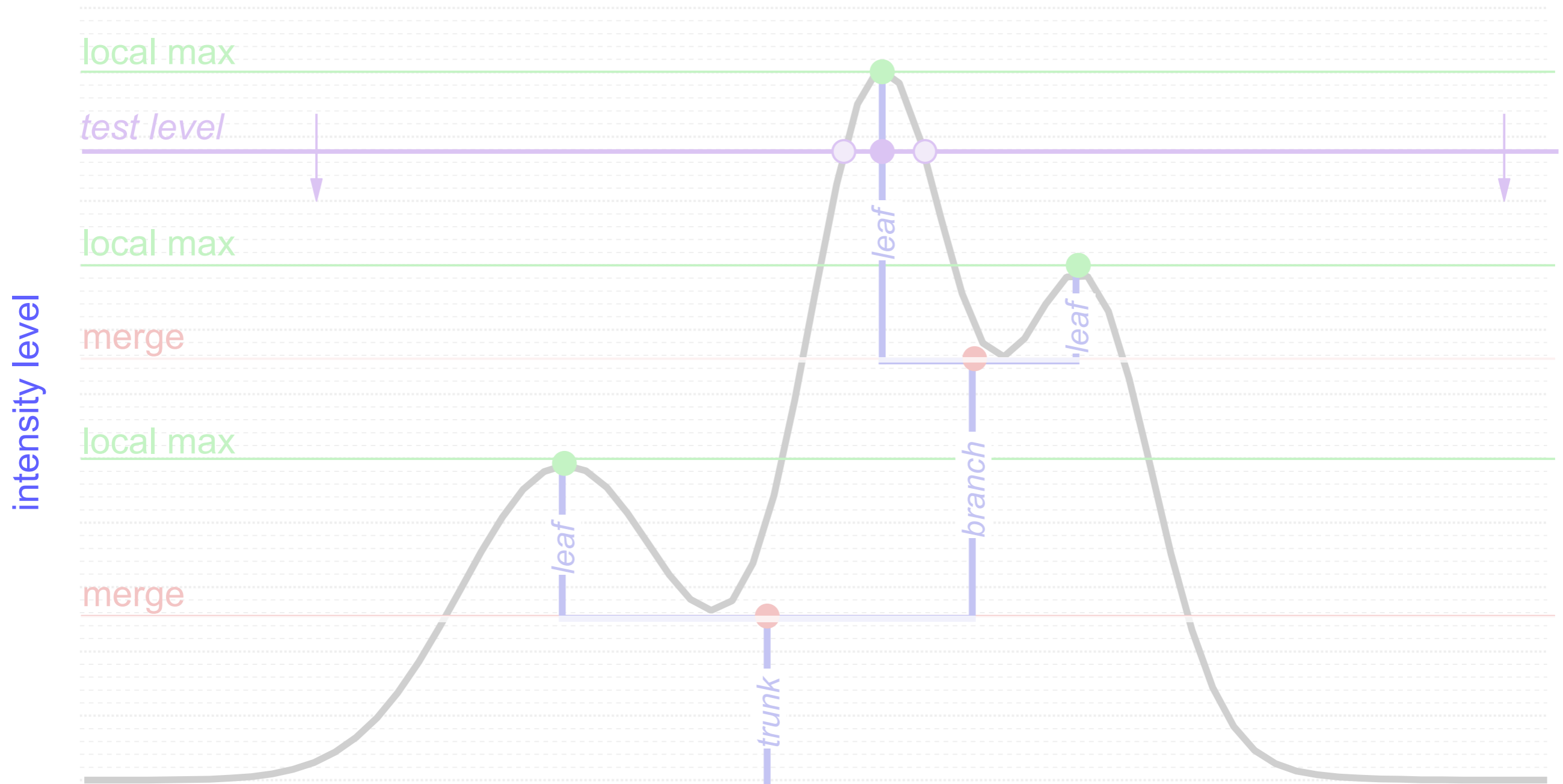
Dendrograms



Hierarchical “Segmentation”

Rosolowsky, Pineda, Kauffmann & Goodman 2008

Dendrograms



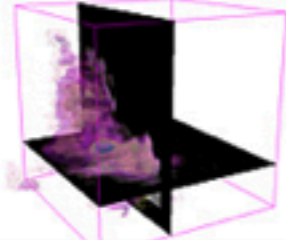

1-D: points; 2-D closed curves (contours); 3-D surfaces enclosing volumes

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:

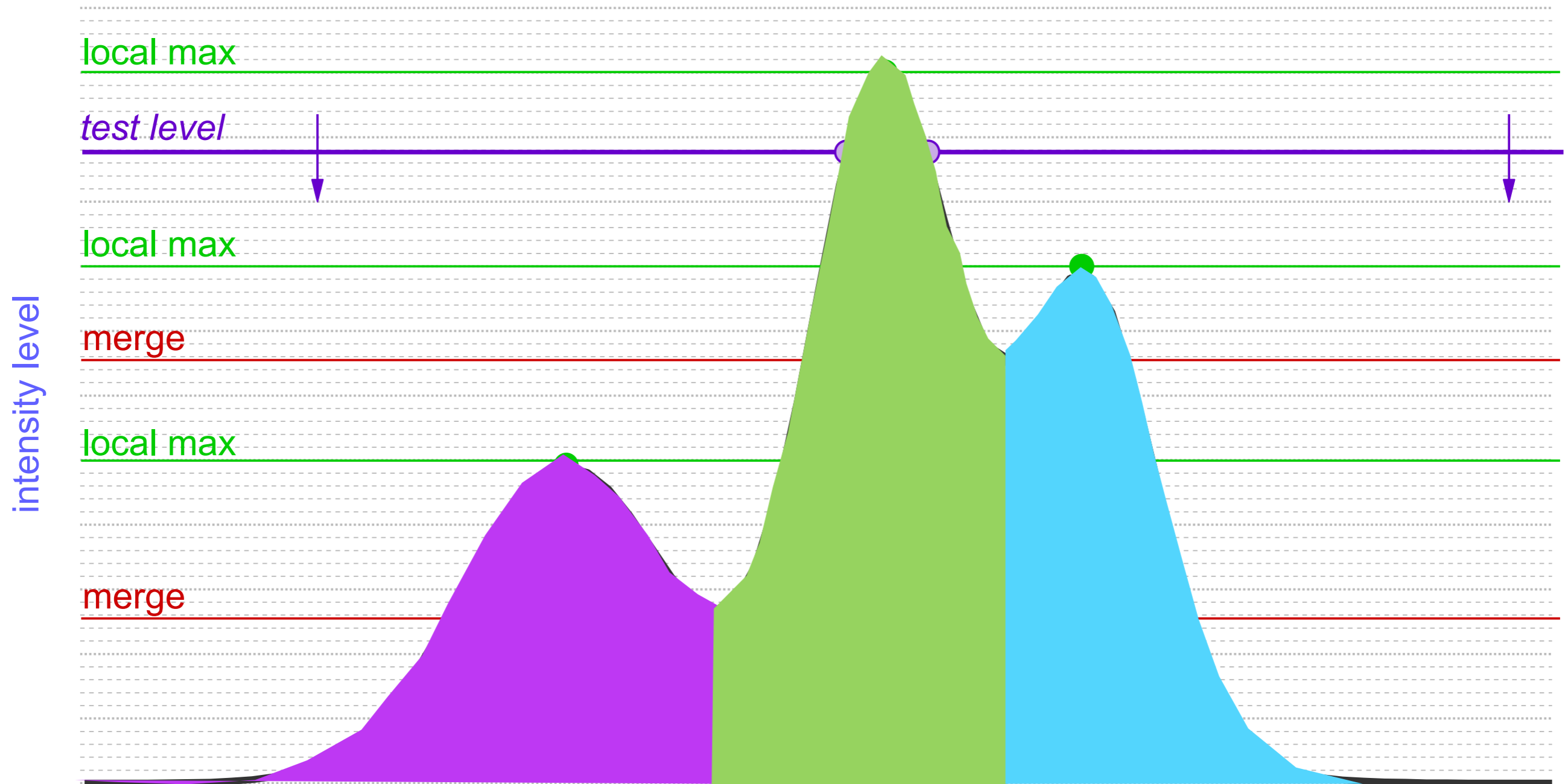
Reset:

Applet DendroStar started

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

3D, see PDF...

What would *CLUMPFIND* do?



No hierarchy is allowed, all clumps go to the baseline.
(Williams, De Geus & Blitz 1994)



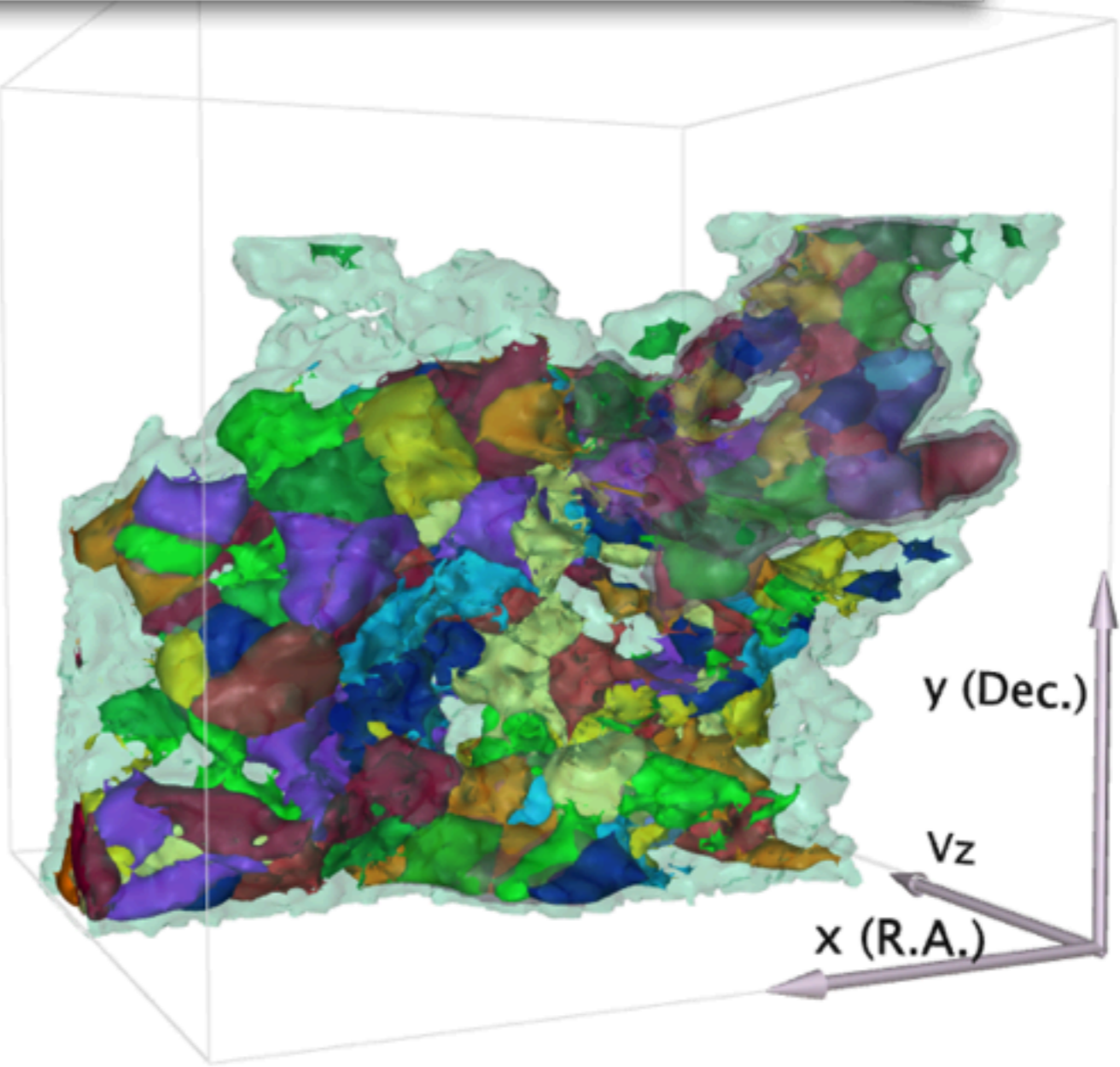
Model Tree

- Highlight Color
- Options
- model
 - Dendrogram decomposition
 - self-gravitating leaves
 - self-gravitating structures
 - all structure
 - CLUMPFIND decomposition
 - peaks within leaves
 - other clumps
 - billiard markers
 - axes

Options

- CLUMPFIND: peaks within leaves
- CLUMPFIND: R.A.-Dec.
- CLUMPFIND: R.A.-Vz
- CLUMPFIND: Vz-Dec.
- Combined: all structure
- Combined: self-grav. and peaks within le

Combined: all structure



This interactive 3D figure shows the result of the dendrogram hierarchical feature-identification algorithm applied to a data cube of ^{13}CO emission of the L1448 region of Perseus. Purple areas are the smallest scale self-gravitating structures in the region, pink shows the smallest regions that contain distinct self-gravitating sub-regions, and green depicts all regions with significant emission. Different views of the data cube can be selected from the Views menu. In addition, results of the alternative

<http://iic.harvard.edu/sites/all/files/interactive.pdf>

with many thanks to Mike Halle, Michelle Borkin, Jens Kauffmann & Douglas Alan

“Crowded” 3D data
(very dangerous)

“Sparse” 2D data
(OK)

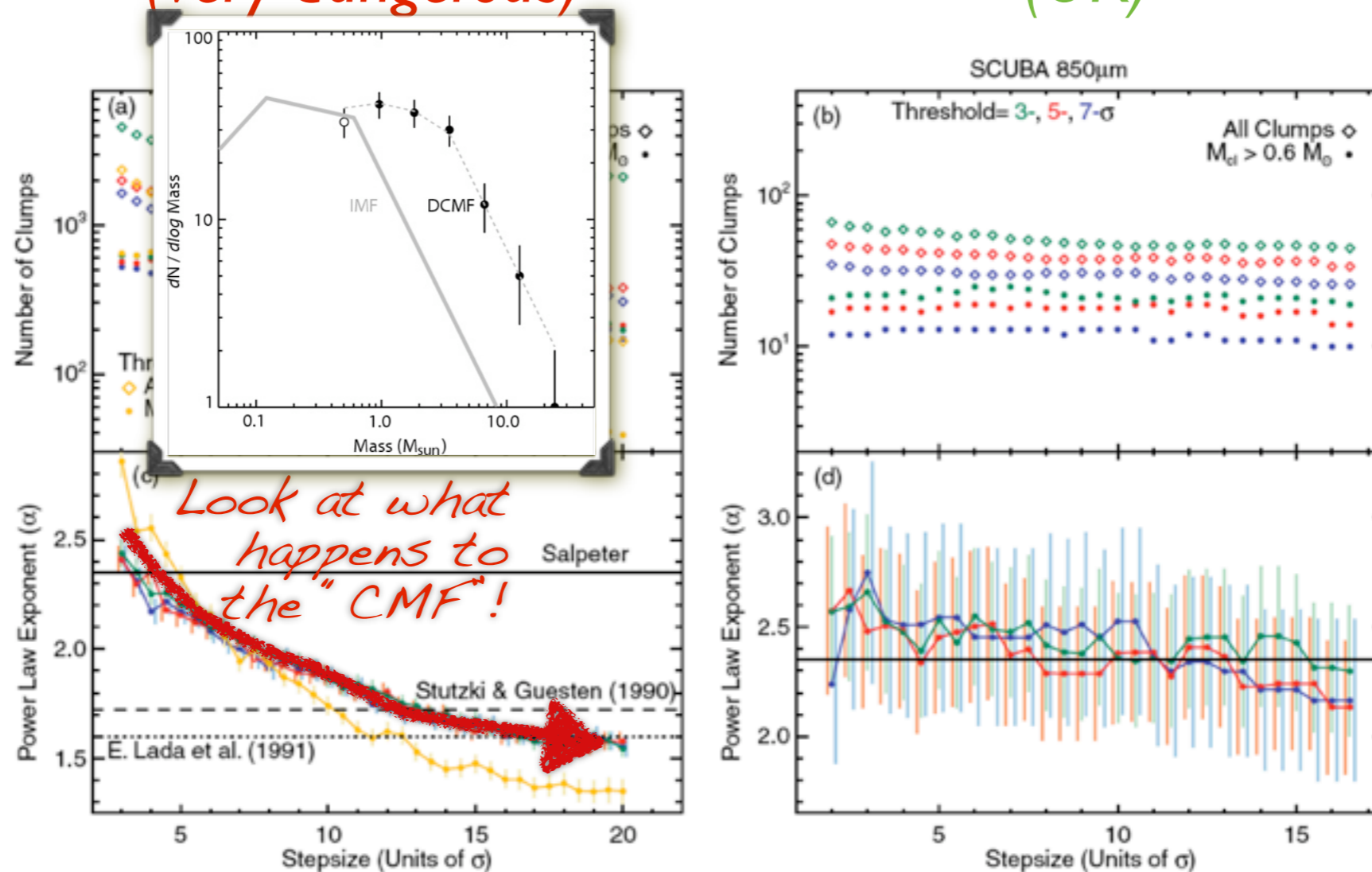


Figure 2. Summary of all Clumpfind runs as a function of stepsize. Color represent different thresholds: blue, red, and green for 3σ , 5σ , and 7σ , respectively; we also show in orange results with a threshold of 5σ for ^{13}CO data with added noise. Left and right columns show results for ^{13}CO and SCUBA data, respectively. Panels (a) and (b) show the number of clumps under a given category per model. Total number of clumps found, and total number of clumps with mass larger than the completeness limit are shown in open diamonds and filled circles, respectively. Panels (c) and (d) show the exponent of the fitted mass spectrum of clumps above the completeness limit, $dN/dM \propto M^{-\alpha}$, with error bars estimated from Equation (6). Horizontal black lines show some fiducial exponents for comparison. Average noise in ^{13}CO , ^{13}CO with added noise, and SCUBA data is 0.1 K , 0.2 K , and 0.06 Jy beam^{-1} , respectively. Completeness limit is estimated to be $4 M_{\odot}$, $3 M_{\odot}$, and $0.6 M_{\odot}$ for ^{13}CO , ^{13}CO with added noise, and SCUBA data. Panel (c) also shows that for different noise level in the data, if a threshold of $\sim 2\text{ K}$ (20σ and 10σ for original and noise-added data, respectively) is used, then the fitted power-law exponents are closer to previous works.

from “**The Perils of CLUMPFIND**” by Pineda, Rosolowsky & Goodman 2009

“turbulent fragmentation”

“(magneto-)hydrodynamic simulation”

“bi-jection”

“virial parameter”

“turbulent power spectrum”

“synthetic observation”

“depletion, opacity”

“taste-test”

caveats

LETTERS

A role for self-gravity at multiple length scales in the process of star formation

Alyssa A. Goodman^{1,2}, Erik R. Rosenow^{1,2}, Michelle A. Barkin¹, Jonathan S. Foster¹, Michael Hebb^{1,2}, Jim Kaufman^{1,2} & James E. Pringle¹

Self-gravity plays a decisive role in the final stages of star formation, where dense cores (or clumps) rapidly radiate and collapse to form star-planet disk systems. But self-gravity acts on smaller scales and on larger length scales, such as 10 parsecs to kiloparsecs, in molecular cloud simulations that do not include self-gravity. We investigate the role of self-gravity at multiple length scales in the formation of star-forming regions. We use a new self-gravity solver to simulate the evolution of a star-forming region at multiple length scales. We find that self-gravity is important on scales from 0.1 to 10 parsecs, and that it is essential for the formation of star-forming regions. We show that self-gravity is important on scales from 0.1 to 10 parsecs, and that it is essential for the formation of star-forming regions. We show that self-gravity is important on scales from 0.1 to 10 parsecs, and that it is essential for the formation of star-forming regions.

Figure 1. 3D visualization of the L1448 star-forming region with a dendrogram overlaid. The dendrogram shows hierarchical clustering of the gas, with colors representing different physical properties like density and velocity dispersion.

LETTERS

The formation of self-gravitating vortices in a turbulent medium

...the vorticity ω_z is an important quantity that is a conserved quantity in the inviscid limit. In the presence of self-gravity, the vorticity is not conserved, but it is still an important quantity. We investigate the formation of self-gravitating vortices in a turbulent medium. We show that self-gravity is important on scales from 0.1 to 10 parsecs, and that it is essential for the formation of star-forming regions. We show that self-gravity is important on scales from 0.1 to 10 parsecs, and that it is essential for the formation of star-forming regions.

Figure 2. Schematic illustration of the dendrogram process. It shows a hierarchical tree structure with nodes and edges, representing the merging of smaller structures into larger ones. The diagram is labeled with 'Local view', 'Global view', and 'Global view'.

LETTERS

Comparison of the dendrogram and CLUMPFIND algorithms as applied to CO emission from the L1448 star-forming region

...the dendrogram and CLUMPFIND algorithms as applied to CO emission from the L1448 star-forming region. We compare the results of the two algorithms and find that the dendrogram is more robust to noise and better at identifying the hierarchical structure of the gas. We show that self-gravity is important on scales from 0.1 to 10 parsecs, and that it is essential for the formation of star-forming regions. We show that self-gravity is important on scales from 0.1 to 10 parsecs, and that it is essential for the formation of star-forming regions.

Figure 3. Comparison of the dendrogram and CLUMPFIND algorithms. The figure shows two dendrograms side-by-side, with the dendrogram on the left and the CLUMPFIND dendrogram on the right. The dendrogram shows a more complex and hierarchical structure than CLUMPFIND.

LETTERS

Self-gravitating vortices in a turbulent medium

...self-gravitating vortices in a turbulent medium. We show that self-gravity is important on scales from 0.1 to 10 parsecs, and that it is essential for the formation of star-forming regions. We show that self-gravity is important on scales from 0.1 to 10 parsecs, and that it is essential for the formation of star-forming regions.

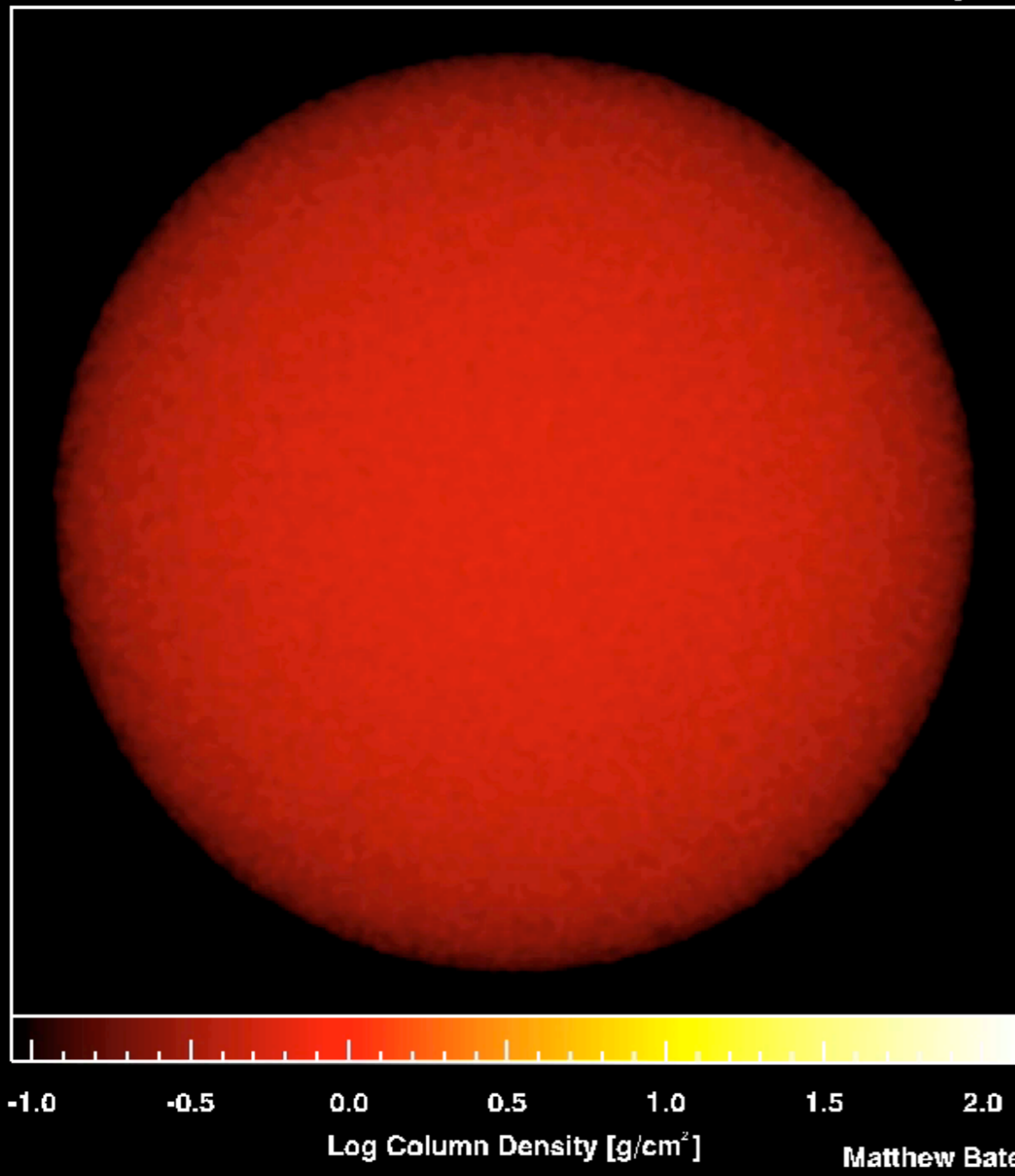
Figure 4. Self-gravitating vortices in a turbulent medium. The figure shows a 3D visualization of a turbulent medium with vortices highlighted in yellow. The vortices are shown as elongated structures with a central core. The figure is labeled with 'Local view', 'Global view', and 'Global view'.

data, CLUMPFIND typically finds features on a limited range of scales, above but below the physical resolution of the data, and its results can be overly dependent on input parameters. By contrast, CLUMPFIND's two free parameters, the noise threshold and the minimum mass function, can be used to tune the algorithm to find features on a wide range of scales. The minimum mass function can be used to tune the algorithm to find features on a wide range of scales. The minimum mass function can be used to tune the algorithm to find features on a wide range of scales.

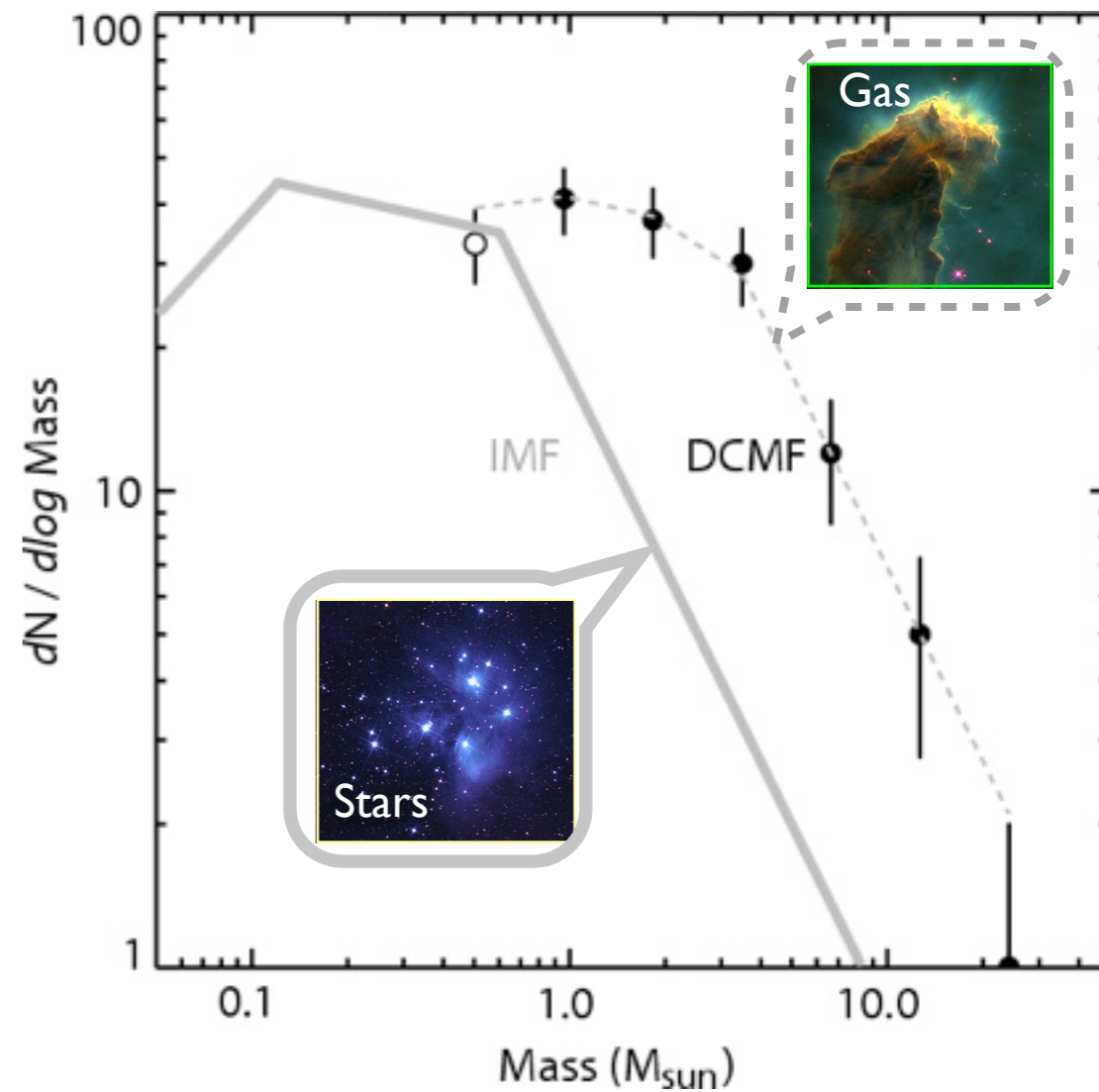
conclude that the regions are associated with a self-gravitating lead in the star formation process. We show that self-gravity is important on scales from 0.1 to 10 parsecs, and that it is essential for the formation of star-forming regions. We show that self-gravity is important on scales from 0.1 to 10 parsecs, and that it is essential for the formation of star-forming regions.

(MHD) Simulations, Turbulent Fragmentation

Dimensions: 40000. AU With Radiative Feedback Time: 0. yr



cf. Padoan & Nordlund 2002



Alves, Lombardi & Lada 2007

LETTERS

A role for self-gravity at multiple length scales in the process of star formation

Allyssa A. Goodman^{1,2}, Erik W. Rosser^{1,2}, Michelle A. Barkin¹, Jonathan S. Foster¹, Michael Hebb^{1,2}, Jim Kaufman^{1,2} & James E. Probst¹

Self-gravity plays a decisive role in the final stages of star formation, where dense cores (or self-gravitating molecular clouds) collapse to form star-planet systems. But self-gravity's role in earlier stages (and on larger length scales, such as 10³ parsecs) is unclear. Some molecular cloud simulations that do not include self-gravity suggest that turbulent fragmentation alone is sufficient to create a mass distribution of dense cores that resembles, and sets, the stellar initial mass function. Here we report a three-dimensional hierarchical tree diagram analysis that reveals that self-gravity plays a significant role over the full range of possible scales tested by CLUMPFIND decomposition of the 13448 molecular cloud, and at scales in the observed regime. In particular, more than 90 per cent of the compact 'pre-stellar cores' traced by peaks of dust emission are projected on the sky within one of the dendrogram's self-gravitating 'blobs'. As these peaks mark the locations of already-forming stars, as well as those predicted about to form, self-gravitating cores meet a critical condition: their mass-to-flux ratio exceeds the critical value for magnetic flux to be converted into self-gravitating, non-linear self-gravitating cores of magnetized interstellar material. Our study shows that self-gravity is important at multiple length scales, from the parsec to the kiloparsec, and that self-gravity is essential to the formation of the stellar initial mass function.

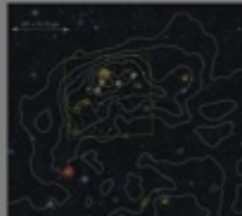


Figure 1. Three infrared images of the L1448 star-forming region with dendrogram overlays. The dendrogram highlights self-gravitating structures at various scales. The images show the spatial distribution of dust emission, and the dendrogram highlights self-gravitating structures at various scales.

LETTERS

“bi-jection”

“virial parameter”

conclude that the regions are associated with a self-gravitating lead in the star-forming process. We conclude that the regions are associated with a self-gravitating lead in the star-forming process.



Figure 2. Comparison of the 'dendrogram' and 'CLUMPFIND' feature-identification algorithms. The figure shows two maps of the L1448 region, one using the dendrogram algorithm and one using CLUMPFIND, with corresponding histograms of mass and velocity dispersion.

LETTERS

“turbulent power spectrum”

“synthetic observation”

“depletion, opacity”

“taste-test”

caveats

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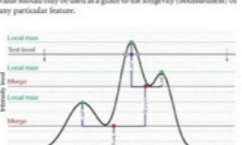


Figure 3. Schematic illustration of the dendrogram process. The diagram shows a hierarchical tree structure with labels for 'Local mass', 'Local velocity', 'Merge', and 'Split' at different levels of the hierarchy.

LETTERS

“turbulent power spectrum”

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caveats

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Figure 4. The fraction of self-gravitating volumes as a function of scale. The plot shows the fraction of self-gravitating volumes (y-axis) versus scale in parsecs (x-axis). The fraction increases with scale, reaching a plateau at larger scales.

“bi-jection”

“virial parameter”

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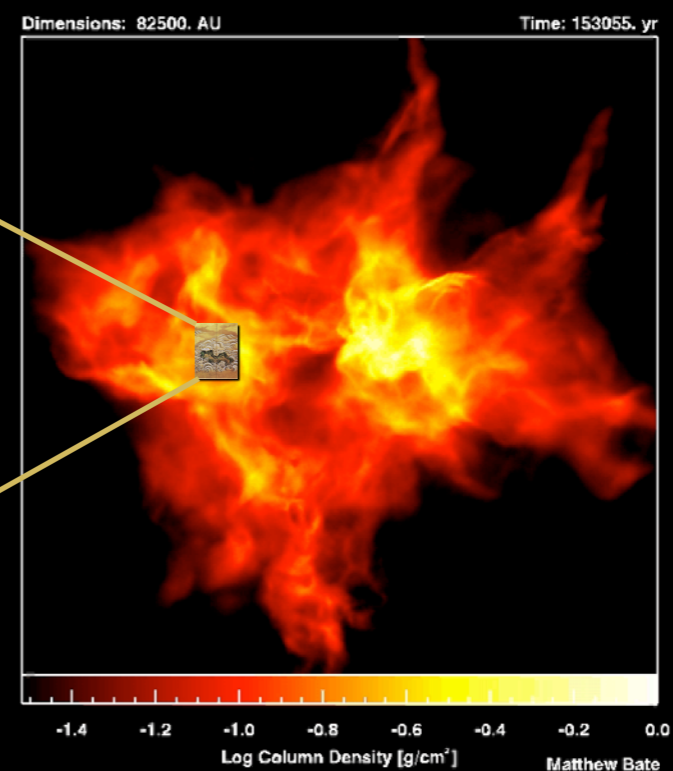
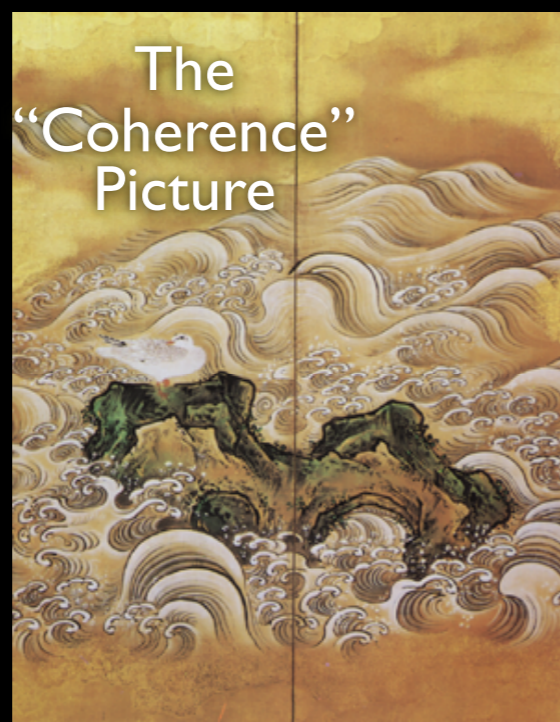
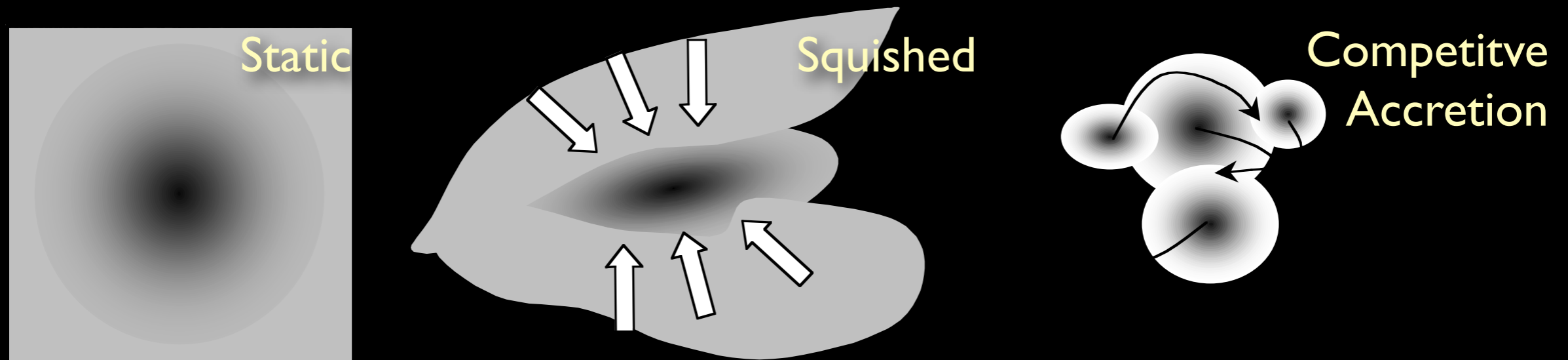
“taste-test”

caveats

How calm, and how long-lasting are cores?

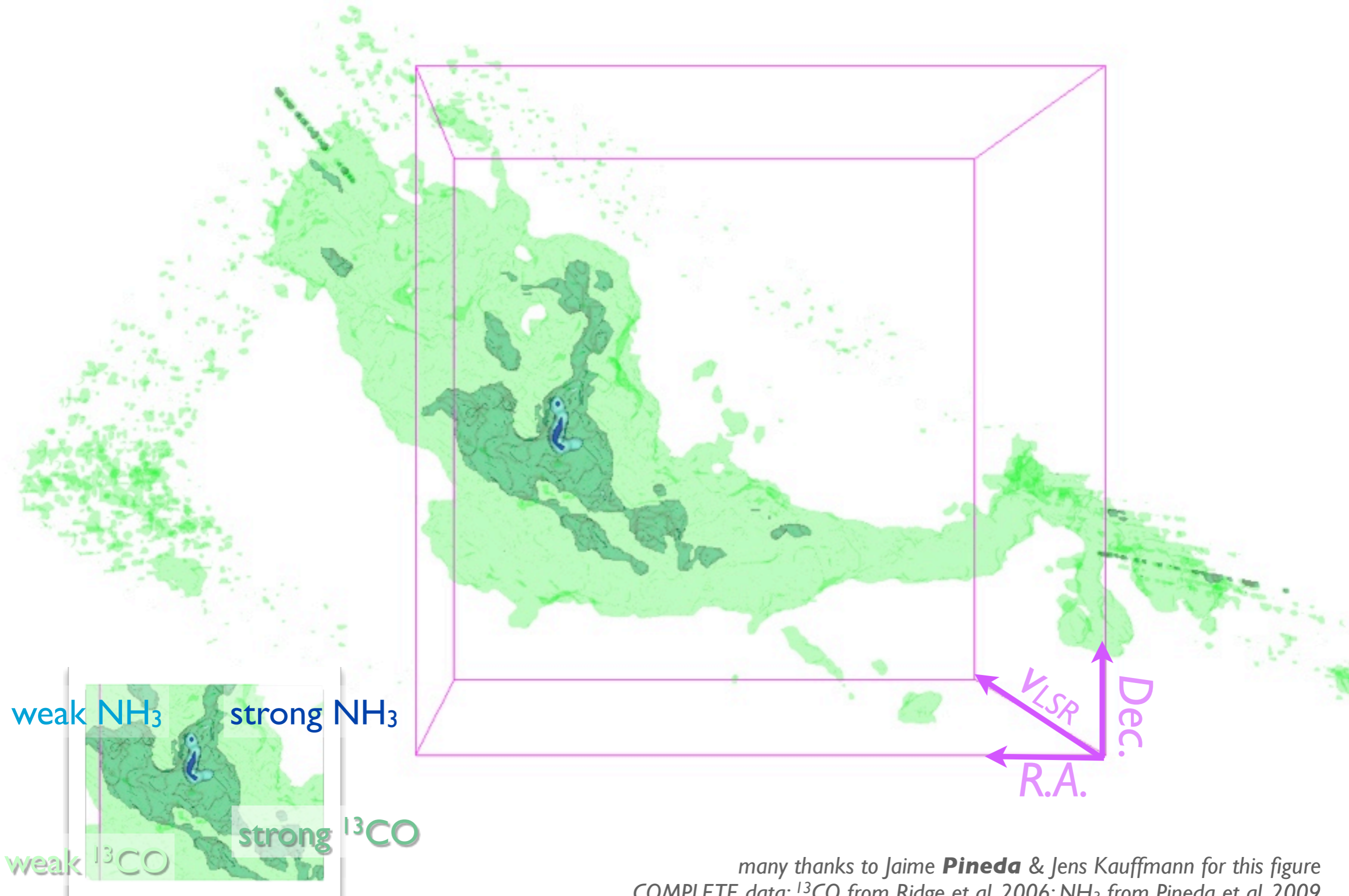
(relevant motions/forces & the “virial parameter”)

Three main views at present...



The “bijection” problem... this is $p-p-p$, but we have only $p-p-v$...

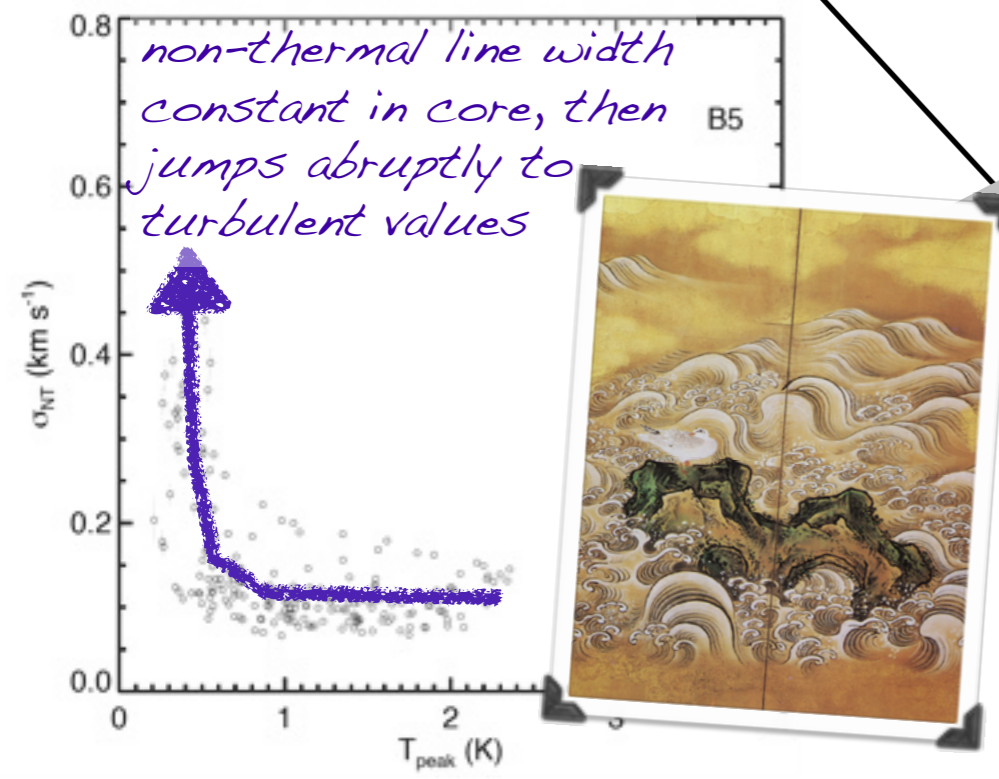
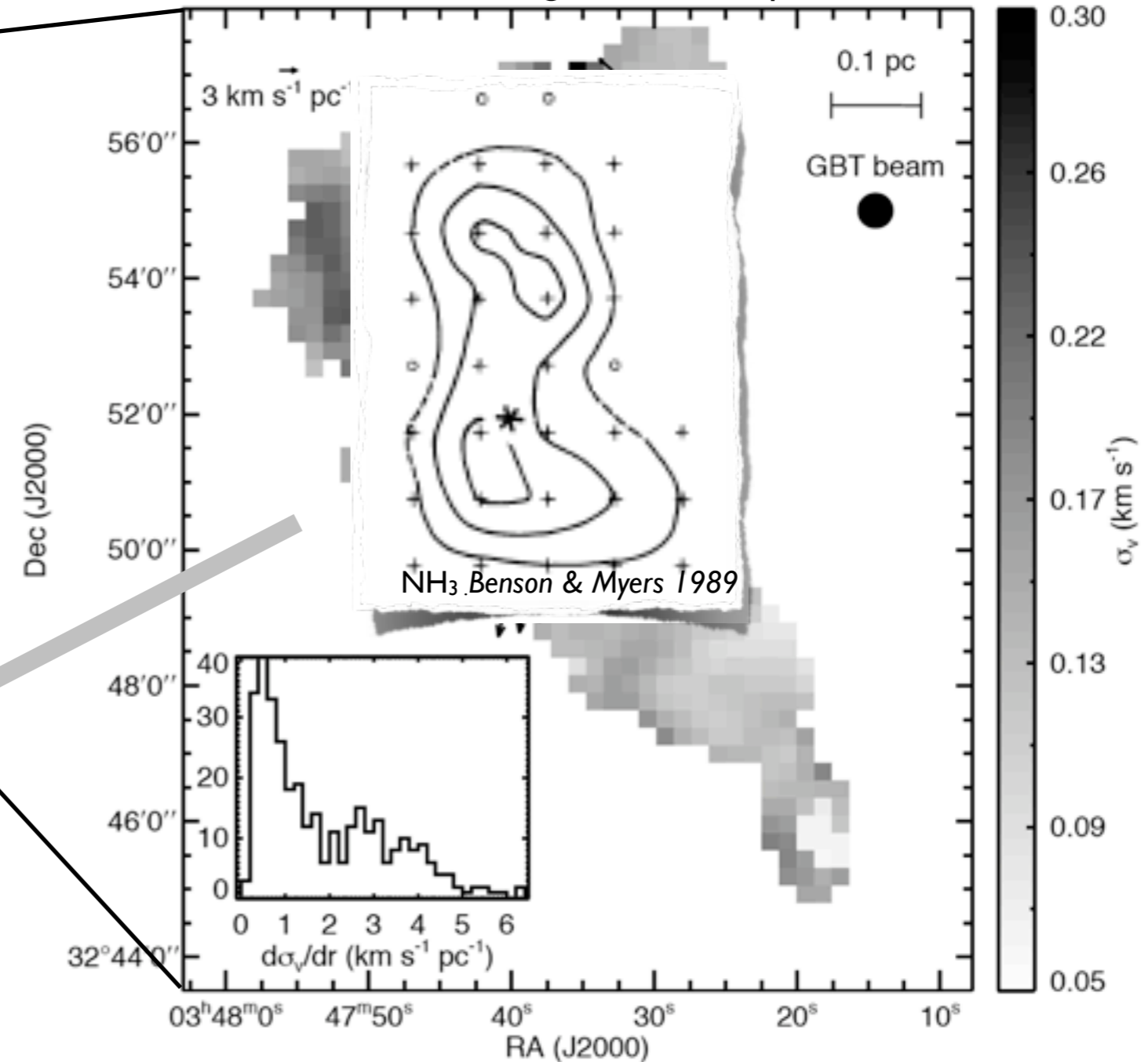
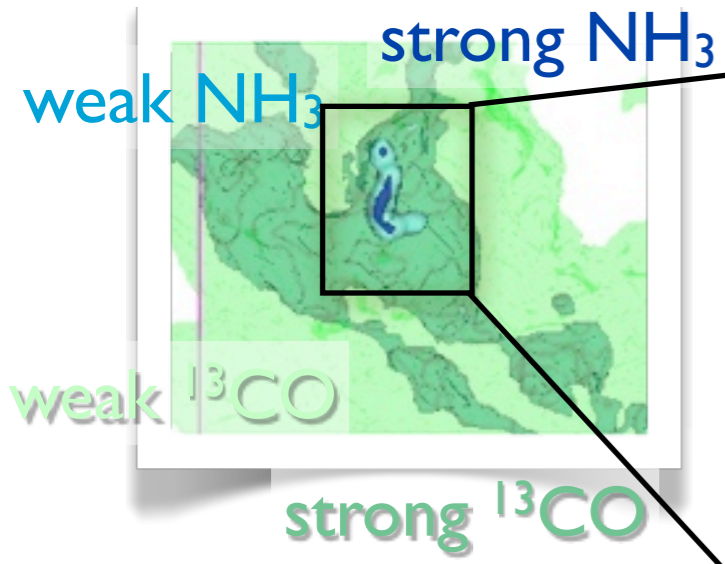
p - p - v structure of the B5 region in Perseus



many thanks to Jaime **Pineda** & Jens Kauffmann for this figure
COMPLETE data: ^{13}CO from Ridge et al. 2006; NH_3 from Pineda et al. 2009

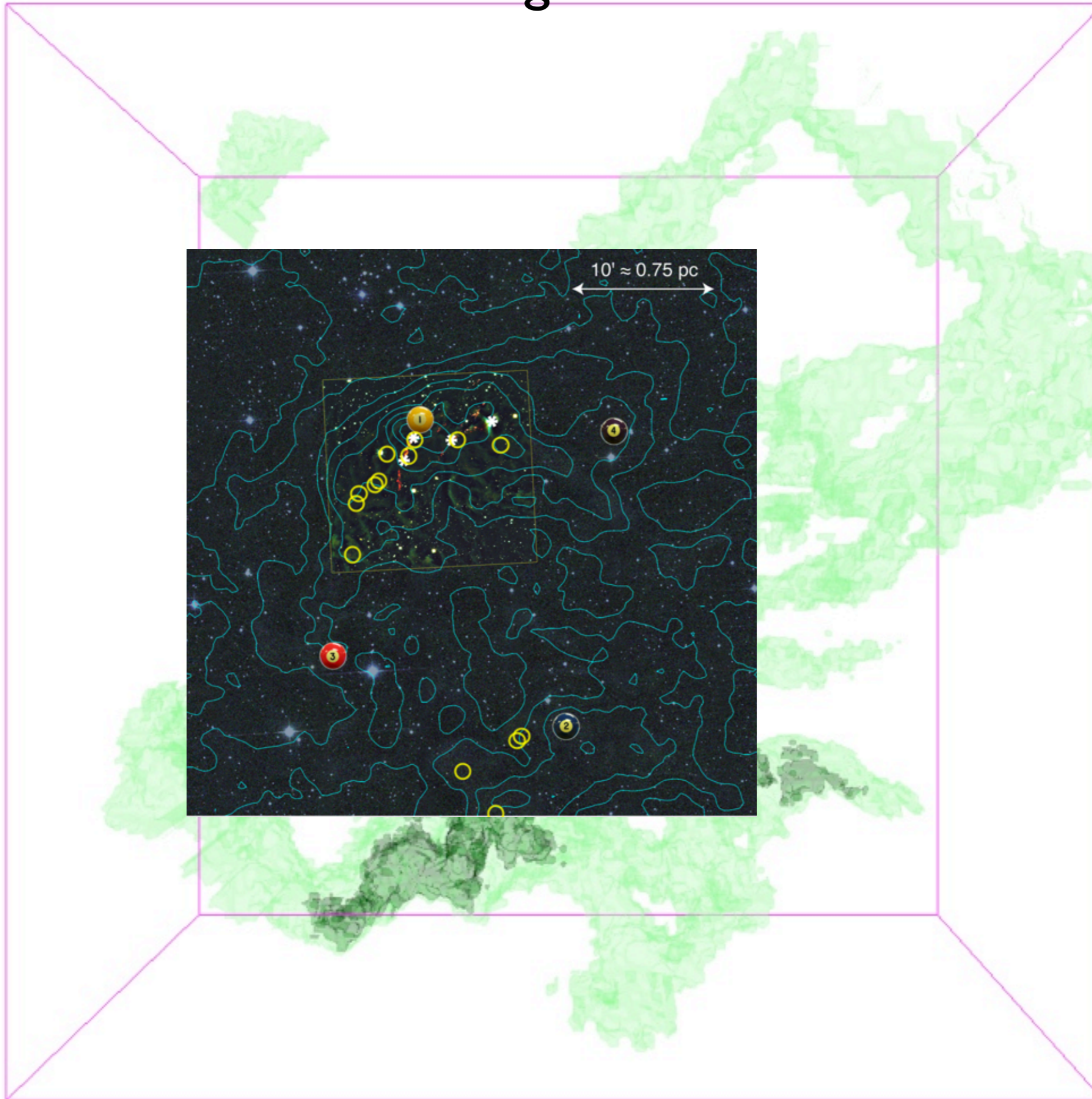
STRONG Evidence for Coherence in Dense Cores

greyscale shows NH_3 velocity dispersion, arrows show gradient in dispersion

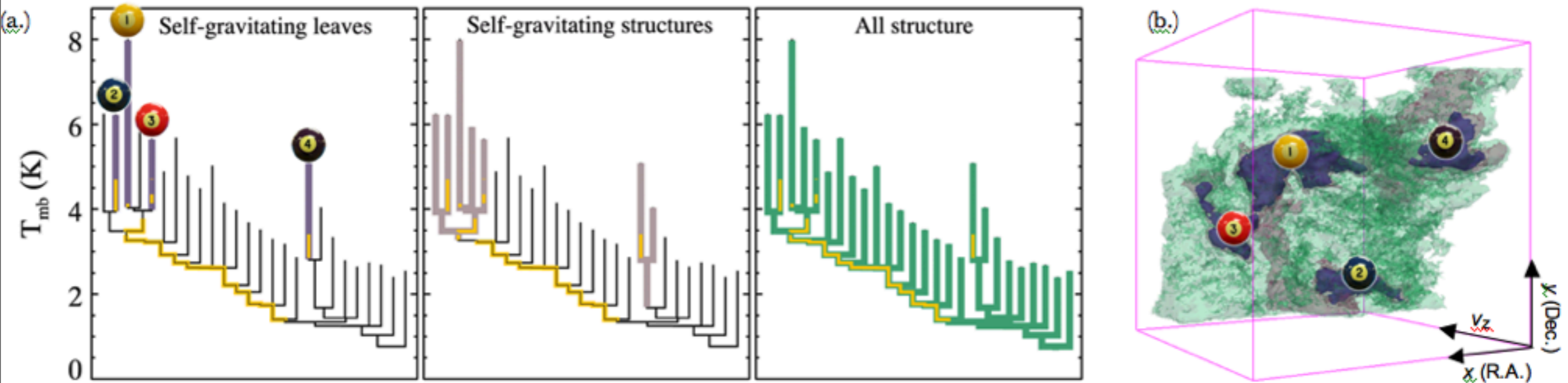


Brand-new GBT NH_3 observations of the B5 core, work of Jaime Pineda

Returning to *L1448*..



Dendrograms & “Self-Gravity”



Yellow highlighting= “self-gravitating”

“Self-gravitating” here just means α_{vir} ($=5\sigma_v^2 R/GM_{lum}$) < 2
(à la Bertoldi & McKee 1992)

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

see PDF...

LETTERS

A role for self-gravity at multiple length scales in the process of star formation

Allyssa A. Goodman^{1,2}, Erik W. Rosolowsky^{1,2}, Michelle A. Barkin¹, Jonathan S. Foster¹, Michael Hebb^{1,3}, Jim Kaufman^{1,2} & James E. Pringle¹

Self-gravity plays a decisive role in the final stages of star formation, where dense cores (or self-gravitating molecular clouds) collapse to form star-planet disk systems. But self-gravity's role in earlier stages (and on larger length scales, such as 10³ parsecs) is unclear. Some molecular cloud simulations that do not include self-gravity suggest that turbulent fragmentation alone is sufficient to create a mass distribution of dense cores that resembles, and may be the initial seed for, star formation. However, our simulations show that self-gravity plays a significant role over the full range of possible scales (and in the observed regime, in particular, more than 90 per cent of the compact 'pre-stellar cores' found by peaks of dust emission) are produced on the day within one of the densest stages of self-gravitating 'cores'. As these cores reach the final stage of star formation, we find that self-gravity is essential to the formation of the final protostar. Turbulent fragmentation combined with self-gravity even of unorganized interstellar material can yield more and denser cores than self-gravitating 'cores' alone. Our results suggest that self-gravity is a crucial component of the process of star formation, and that self-gravity is essential to the formation of the final protostar.



Figure 1. Three infrared images of the L1448 star-forming region with the dendrogram overlaid. The dendrogram is a hierarchical tree structure that shows the relationship between different regions of the cloud. The dendrogram is overlaid on the three infrared images of the L1448 star-forming region. The dendrogram is a hierarchical tree structure that shows the relationship between different regions of the cloud. The dendrogram is overlaid on the three infrared images of the L1448 star-forming region.

LETTERS

The relationship between α_{eff} and α_{vir} is an important question. It is a common relationship between a volume in phase space and a volume of physical position-position-position, (p, q, q) space. This relationship is the key to understanding the relationship between a volume in phase space and a volume of physical position-position-position, (p, q, q) space. This relationship is the key to understanding the relationship between a volume in phase space and a volume of physical position-position-position, (p, q, q) space.

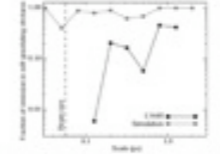


Figure 4. The fraction of self-gravitating volume as a function of scale in the L1448 star-forming region. The plot shows a sharp increase in the fraction of self-gravitating volume at a scale of approximately 0.1 pc, followed by a plateau and then a slight decrease at larger scales.

Our simulations show that self-gravity plays a significant role over the full range of possible scales (and in the observed regime, in particular, more than 90 per cent of the compact 'pre-stellar cores' found by peaks of dust emission) are produced on the day within one of the densest stages of self-gravitating 'cores'. As these cores reach the final stage of star formation, we find that self-gravity is essential to the formation of the final protostar. Turbulent fragmentation combined with self-gravity even of unorganized interstellar material can yield more and denser cores than self-gravitating 'cores' alone. Our results suggest that self-gravity is a crucial component of the process of star formation, and that self-gravity is essential to the formation of the final protostar.

LETTERS

Using 2D maps of column density. With this early 2D work as inspiration, we have developed a structure-identification algorithm that extracts the hierarchical structure of a 2D (p-p) data cube into an easily visualized representation called a 'dendrogram'. Although well developed in other data-intensive fields^{1,2}, it is curious that the application of tree methods to astrophysics has been rare, and almost exclusively within the area of galaxy evolution, where 'merger trees' are being used with increasing frequency^{3,4}.

Figure 3 and its legend explain the construction of dendrograms schematically. The dendrogram quantifies how and where local masses 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 setting their 'branches' to rest on a horizontal axis, which discards directional information on the x axis while preserving all information about connectivity and hierarchy. Nonetheless, 'folded' 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 (σ), and luminosity (L). The volumes can have any shape, and in other work⁵ 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 $M_{\text{star}} \approx \chi_{\text{H}\alpha} L_{\text{H}\alpha}$, where $\chi_{\text{H}\alpha} \approx 0.07 \times 10^6 \text{ cm}^{-2} \text{ K}^{-1} \text{ km}^{-1}$ (ref. 1); 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, $\alpha_{\text{vir}} = 2GM_{\text{star}} / (R\sigma^2)$. In principle, extended portions of the tree (Fig. 2c, yellow highlighting) where $\alpha_{\text{vir}} < 2$ (where gravitational energy is comparable to or larger than kinetic energy) correspond to regions of p-p space where self-gravity is significant. As α_{vir} 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 fields⁶, its measured value should only be used as a guide to the longevity (boundariness) of any particular feature.

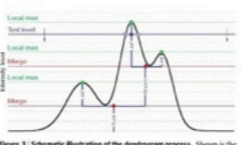


Figure 3. Schematic illustration of the dendrogram process. The diagram shows a hierarchical tree structure with nodes and branches. The nodes are labeled 'Local mass', 'Local mass', 'Local mass', and 'Local mass'. The branches are labeled 'Merge', 'Merge', and 'Merge'. The diagram illustrates how local masses merge into larger structures.

data, CLUMPTO 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 using CLUMPTO's two free parameters, the same molecular-line data set can be used to show either that the frequency distribution of clump sizes 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 CLUMPTO, 'structure trees' were proposed as a way to characterize clouds' hierarchical structure

LETTERS

combine in the regions are associated with a self-gravitating lead in the star formation rate, and these associations suggest that self-gravitating cores are critical to the surface phases of star formation.

Our simulations show that self-gravity plays a significant role over the full range of possible scales (and in the observed regime, in particular, more than 90 per cent of the compact 'pre-stellar cores' found by peaks of dust emission) are produced on the day within one of the densest stages of self-gravitating 'cores'. As these cores reach the final stage of star formation, we find that self-gravity is essential to the formation of the final protostar. Turbulent fragmentation combined with self-gravity even of unorganized interstellar material can yield more and denser cores than self-gravitating 'cores' alone. Our results suggest that self-gravity is a crucial component of the process of star formation, and that self-gravity is essential to the formation of the final protostar.

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✓ “bi-jection”

✓ “virial parameter”

“turbulent power spectrum”

“synthetic observation”

“depletion, opacity”

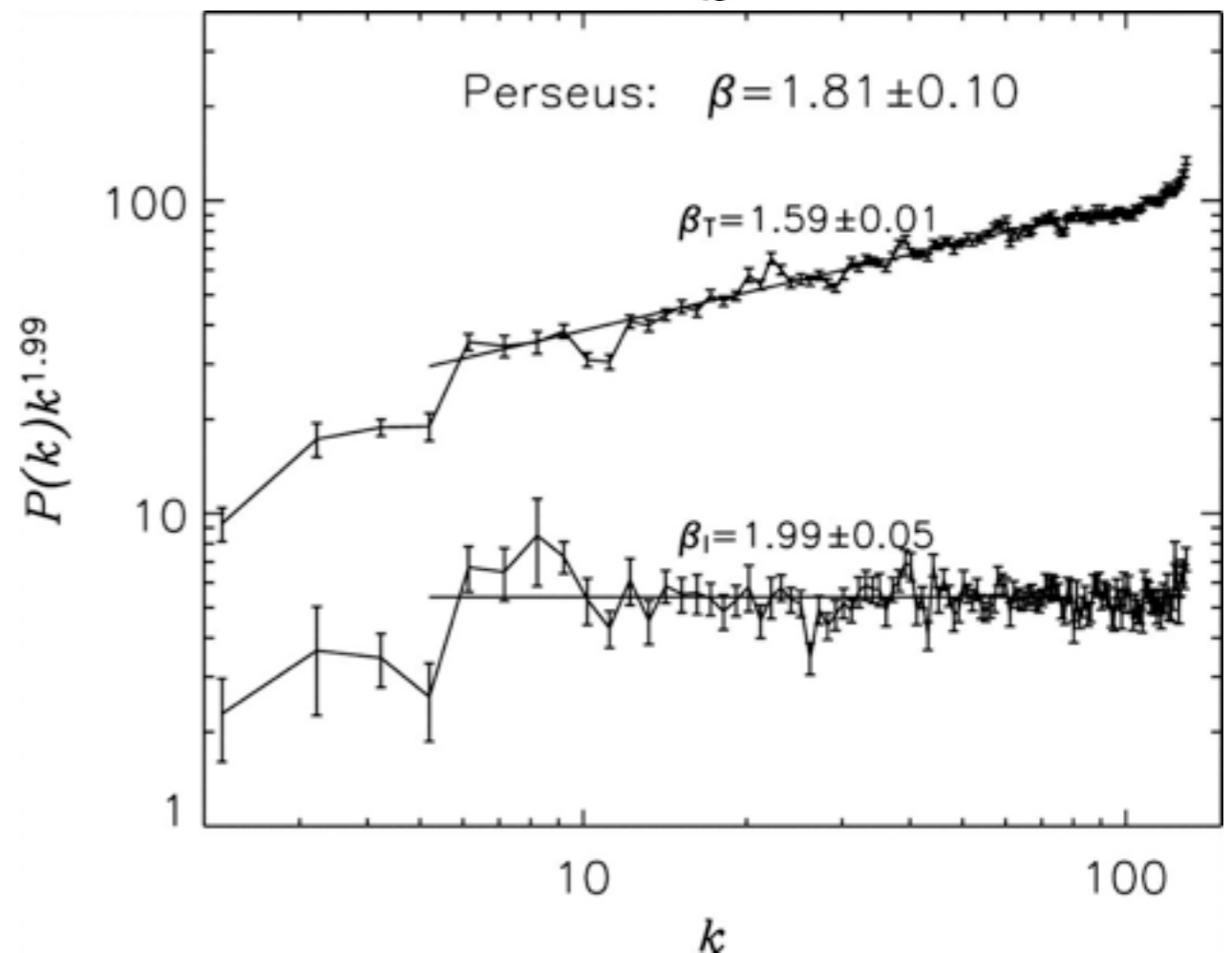
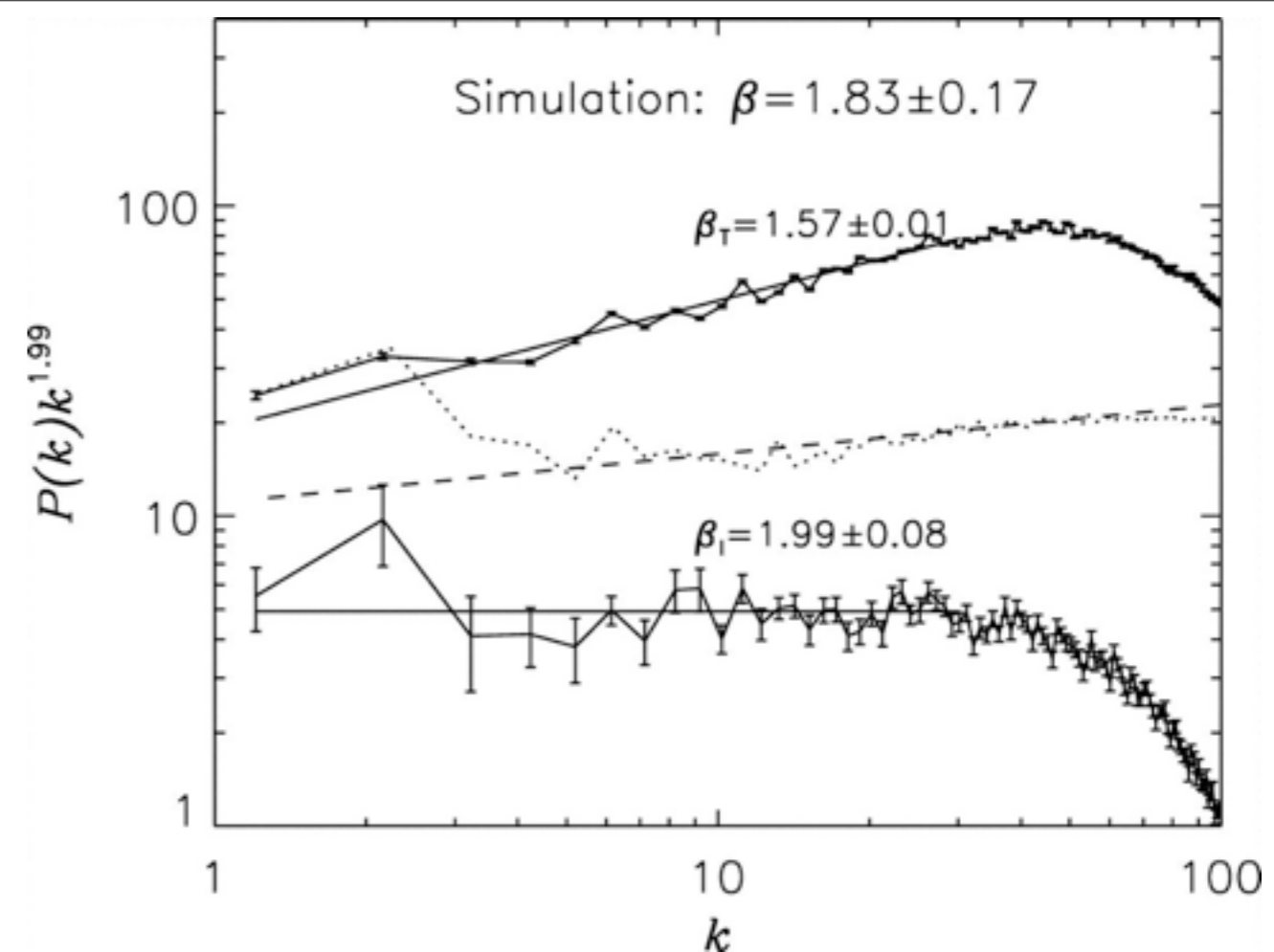
“taste-test”

caveats

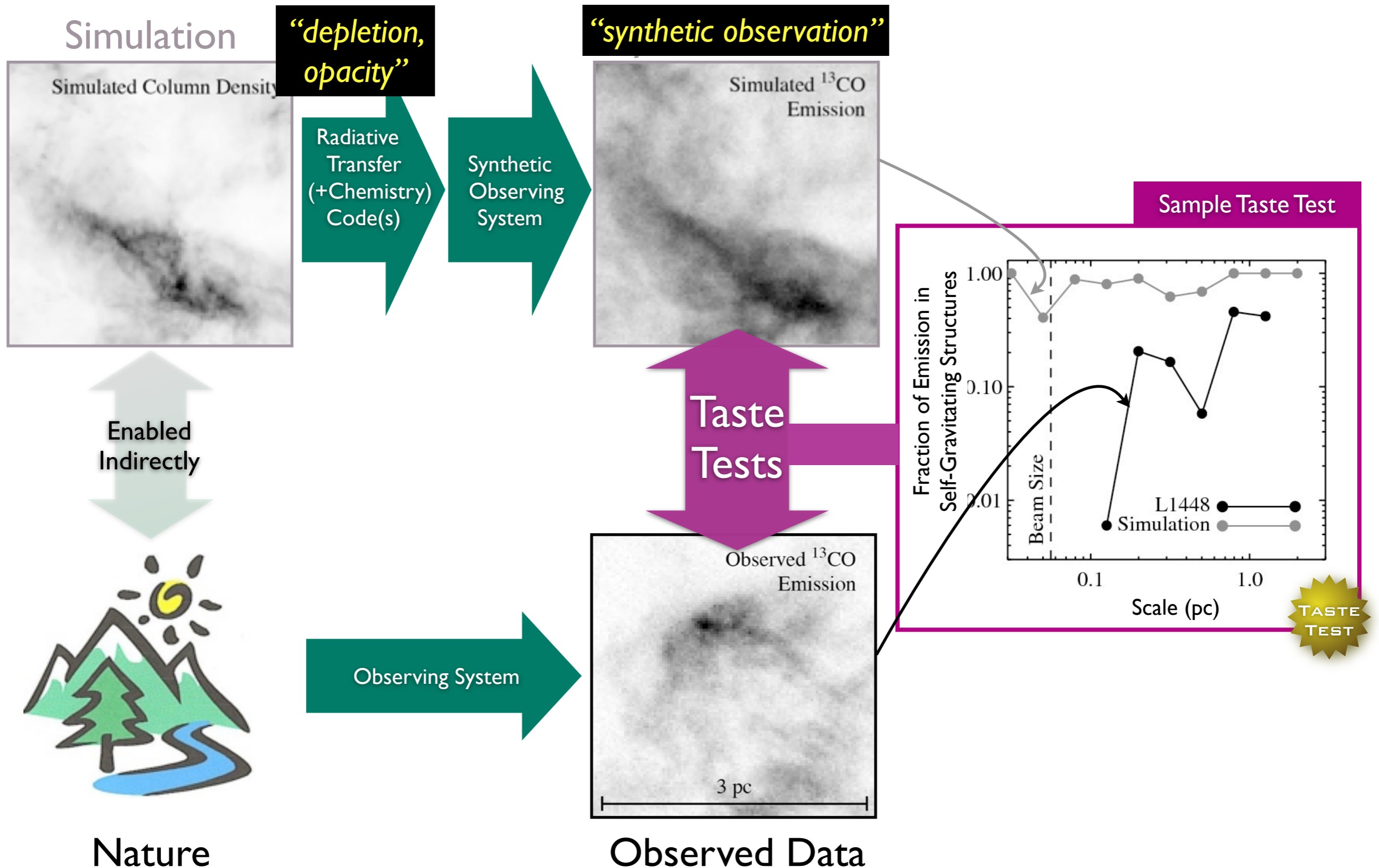
Choosing a relevant simulation to taste...

How about one with a
“*turbulent power spectrum*” shown
to match COMPLETE data?
from Padoan et al. 2006
(see Lazarian & Pogosyan 2000 for
methodology)

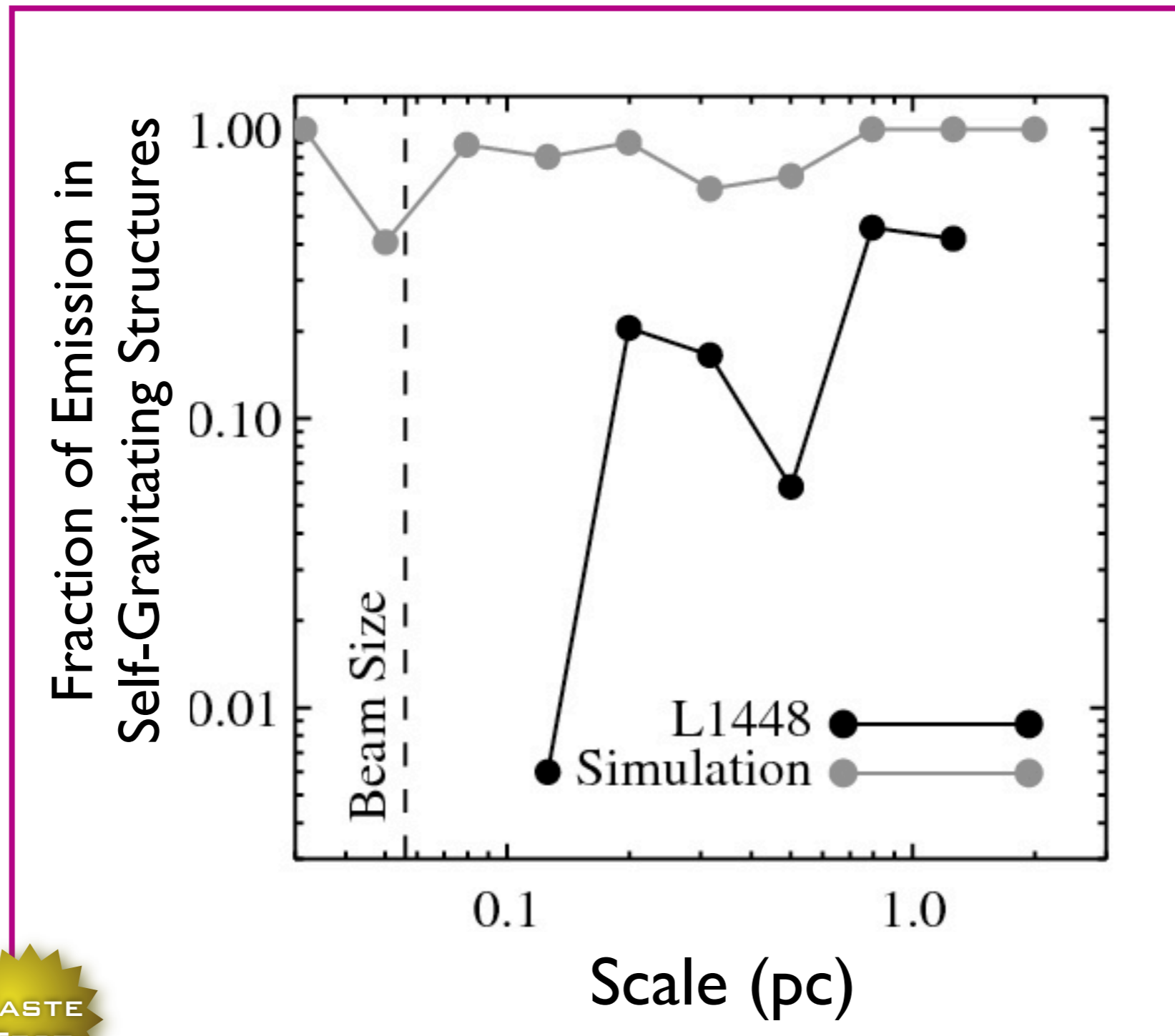
Note: This simulation does NOT include *gravity*,
magnetic fields, radiative effects, or explicit
heating & cooling—it is pure hydrodynamics.



The Taste-Testing Process

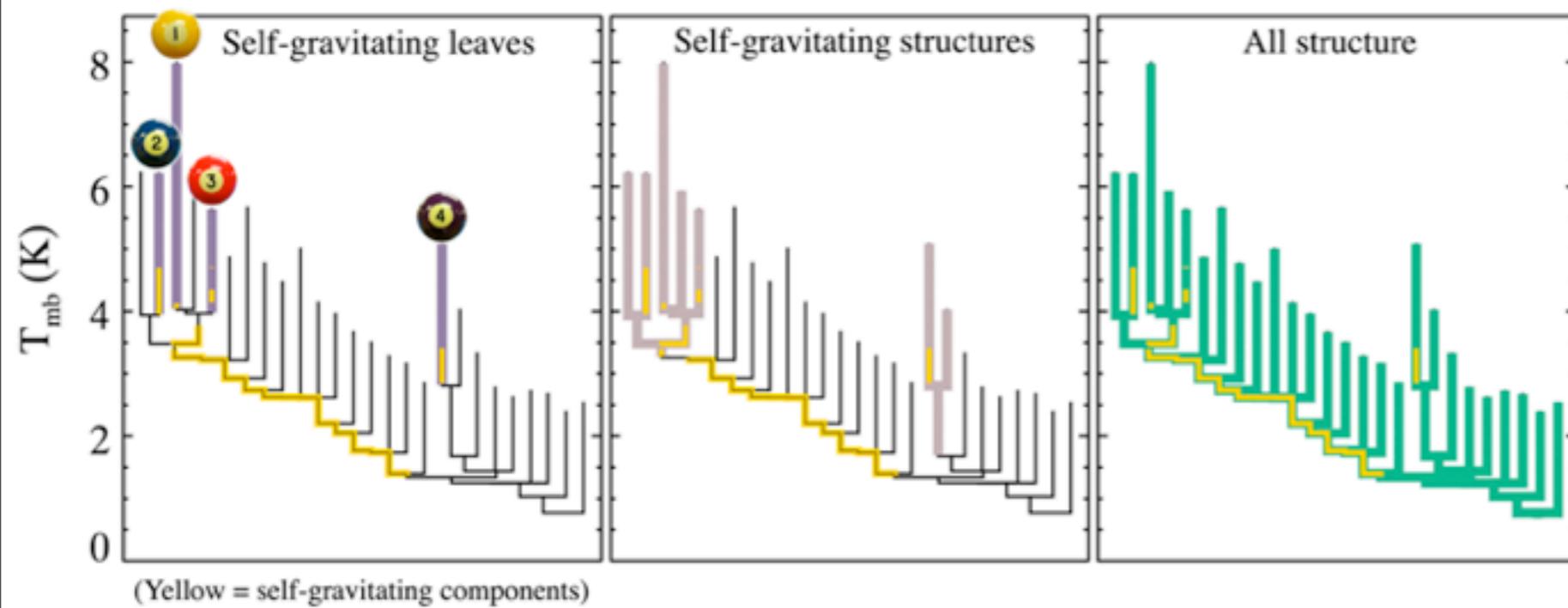


Taste-Testing Gravity

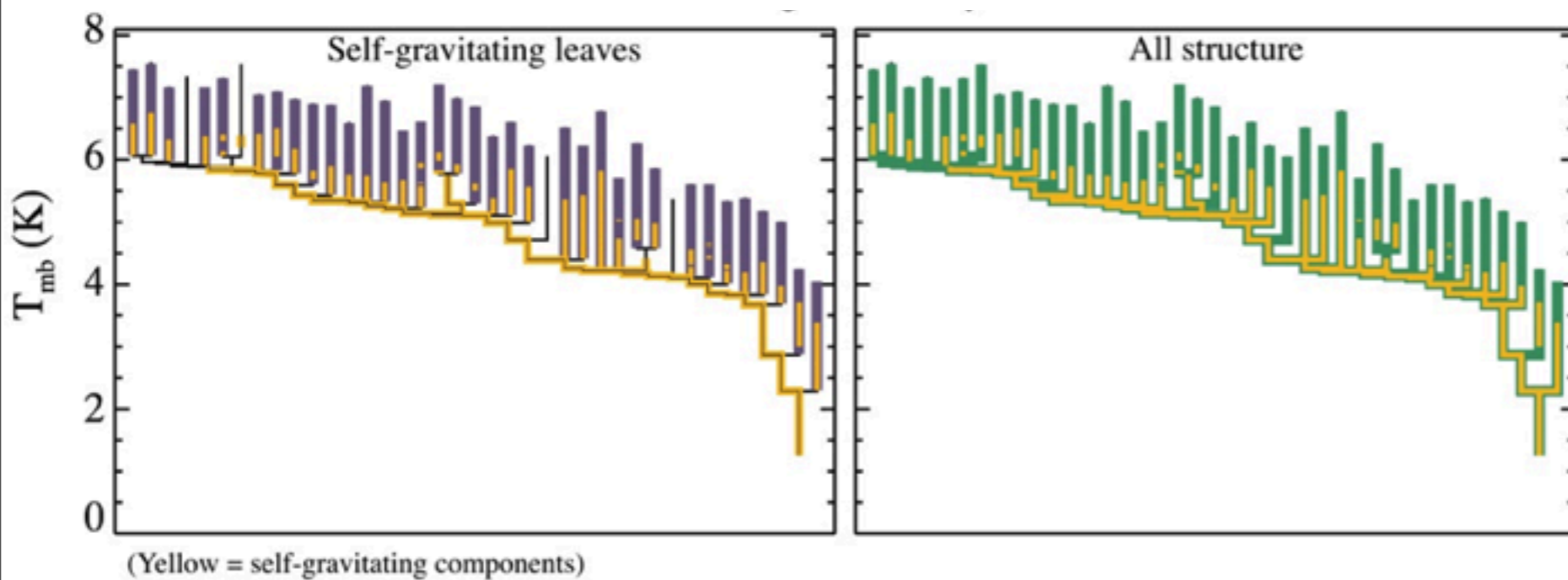


Gravity-free HD Simulations from Padoan et al. 2006;
L1448 analysis from Rosolowsky et al. 2008
both lines derived from ^{13}CO “observations”

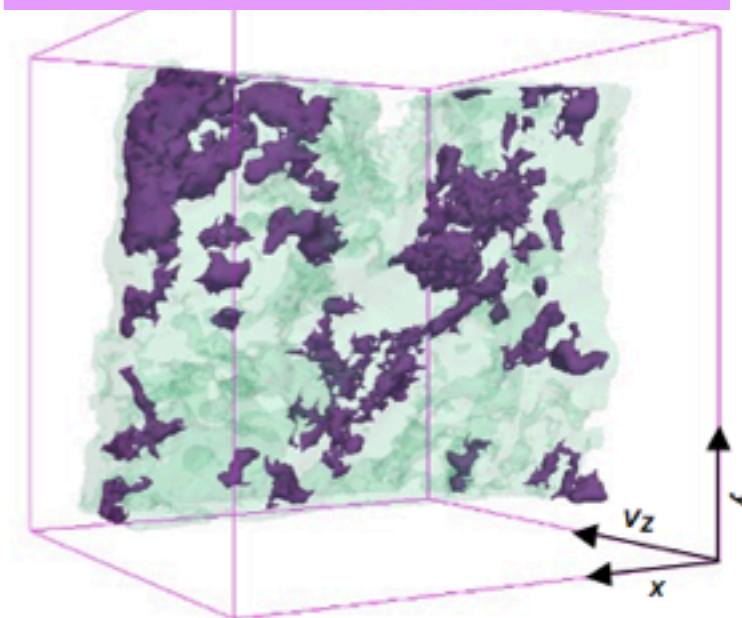
Real vs. Simulated ^{13}CO



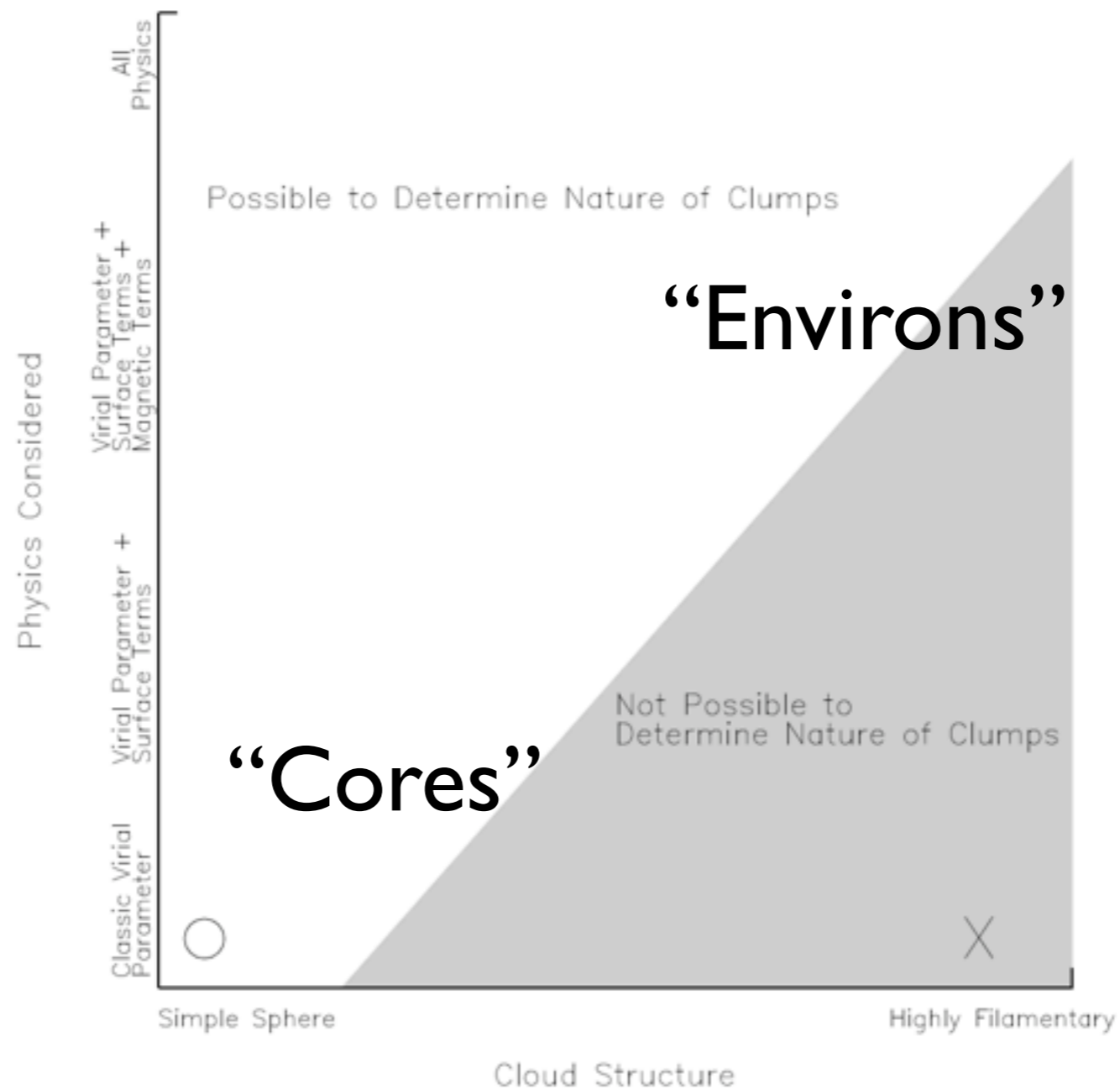
Real



Simulated



Caveats/Worries about p - p - v (bijection) ... and the virial parameter



from **Shetty**, Collins, Kauffmann, Goodman, Rosolowsky 2009;
see also recent work of Ostriker et al., Ballesteros-Paredes et al., Myers, and Smith, Clark & Bonnell

What (else) keeps me up at night now...

“Bi-jection” or “ $p-p-p$ to/from $p-p-v$ ” & the impact
of missing terms in **virial analysis** in each space
[Shetty, Collins, et al.]

Projection effects in analyzing **spatial & velocity
offsets**
[Kirk, Pineda, Offner, et al.]

When/how can we best **measure YSO velocities**
& what should they be?
[Covey, Offner, et al.]

How much excess column is there **beyond “log-
normal”**?
[Foster, Offner, et al.]

Effects of **Cloudshine** on **Deep NIR Point Source
Photometry** (e.g. JWST) [Foster!]

Can we **differentiate** simulations **with** known &
simple new “**taste tests**”
[Rosolowsky, Shetty, et al.]
...for example, how do **cores connect to** their
environment?
[Kauffmann, Myers, Pineda, Alves, Foster,
Rosolowsky, Offner, et al.]?

Can we do better than **Kennicutt-Schmidt**,
really?
[Cox, Narayanan, Shetty, Rosolowsky et al.]

Effects of **B-Star Winds** on Cloud Evolution
[Covey, Sharma, Valverde, Dupree, Borkin, Arce et al.]

Do **dendrograms** give a different **CMF**?
[Alves, Rosolowsky, Pineda et al.]

And, what about **magnetic fields**?!
[Li et al.]

...and WWT, IIC, 3D Data Desk, WGBH, VAO...and my family.

“turbulent fragmentation” “LI 448” “(magneto-)hydrodynamic simulation”

“Cloudshine”

“bi-jection”

“pre-stellar core”

“virial parameter”

“protostar”

“column density”

“integrated intensity”

“turbulent power spectrum”

“p-p-v cube”

“synthetic observation”

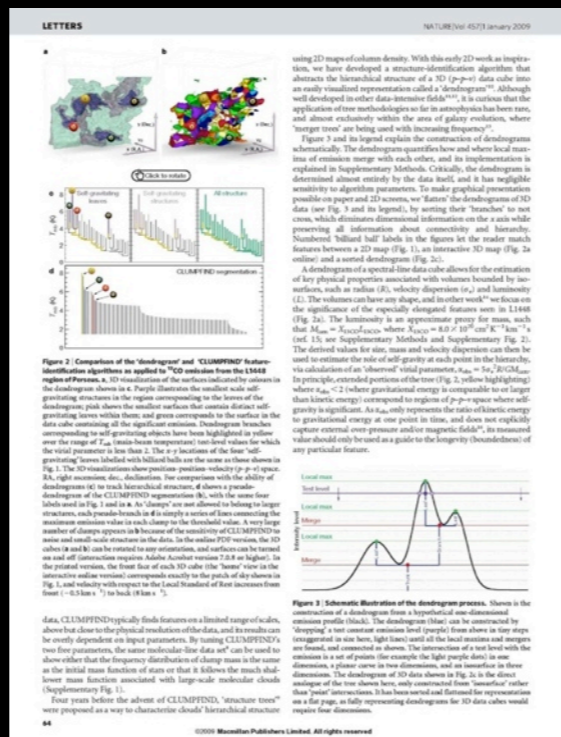
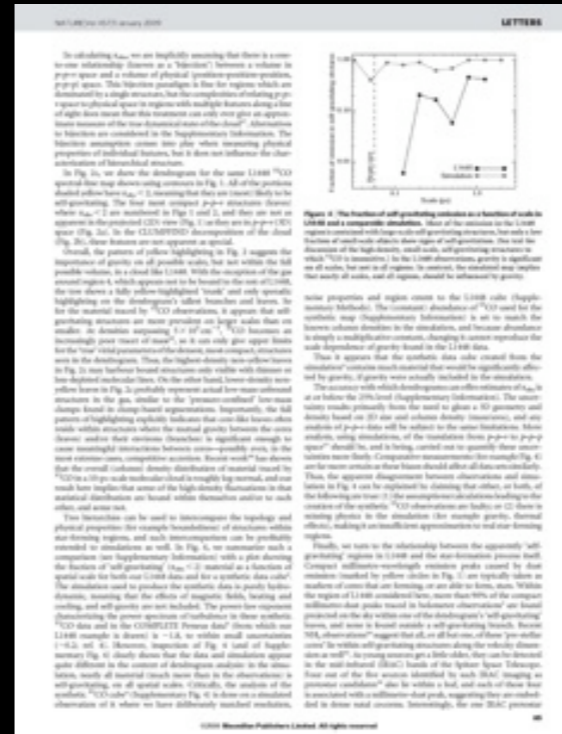
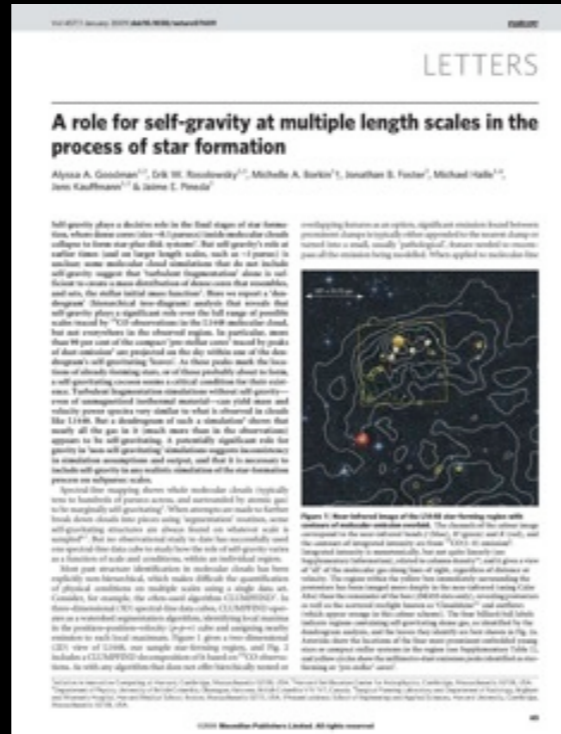
“segmentation”

“depletion, opacity”

“CLUMPFIND”

“taste-test”

“Dendrogram”



“COMPLETE”

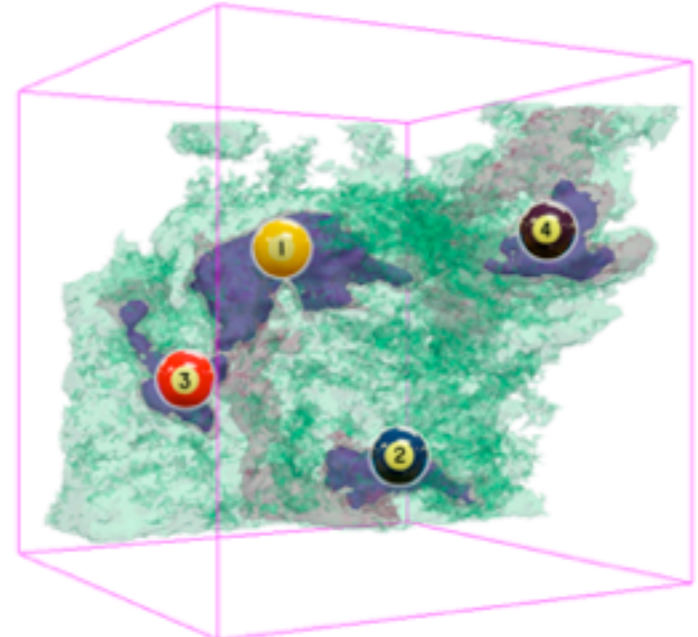
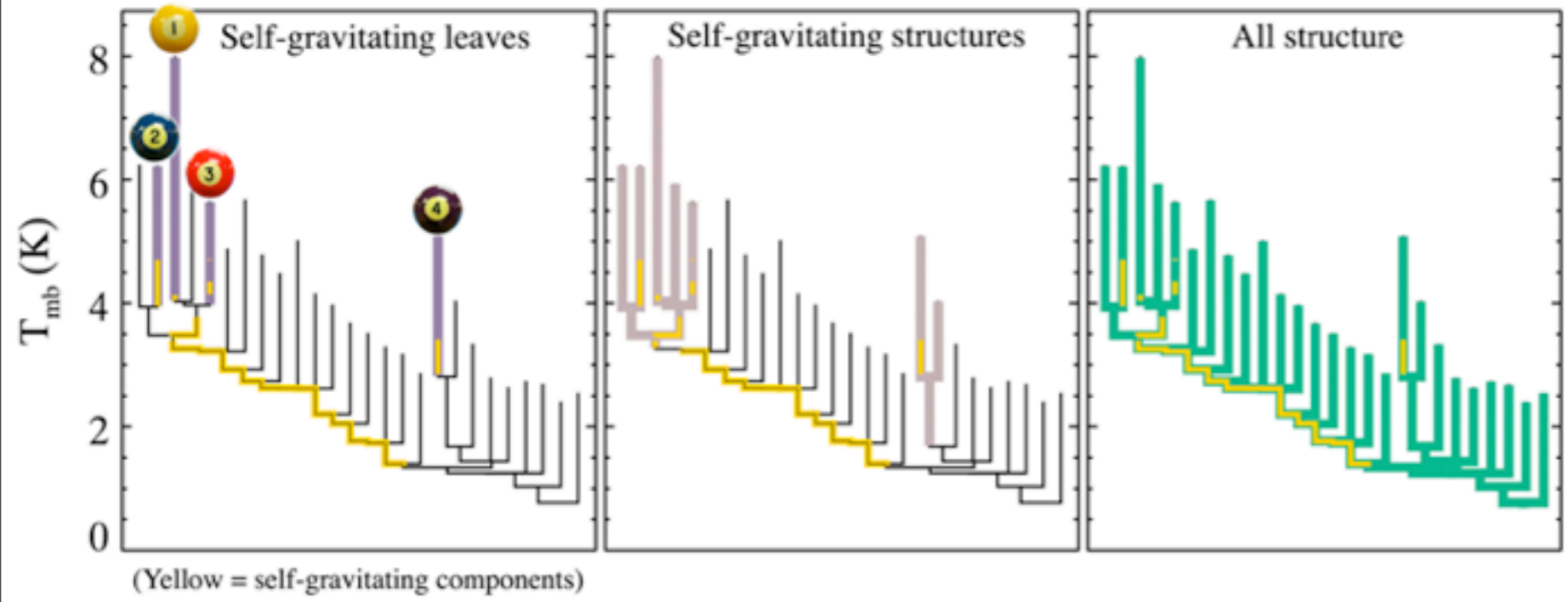
“3D PDF”

caveats

Extra Slides

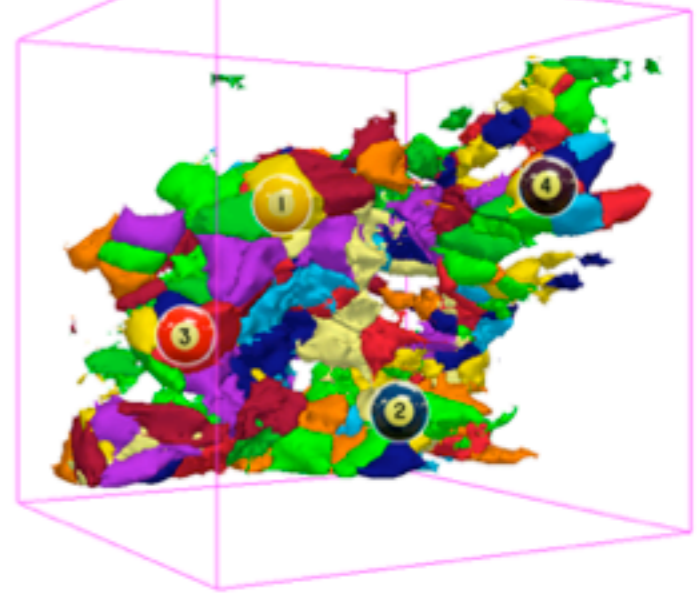
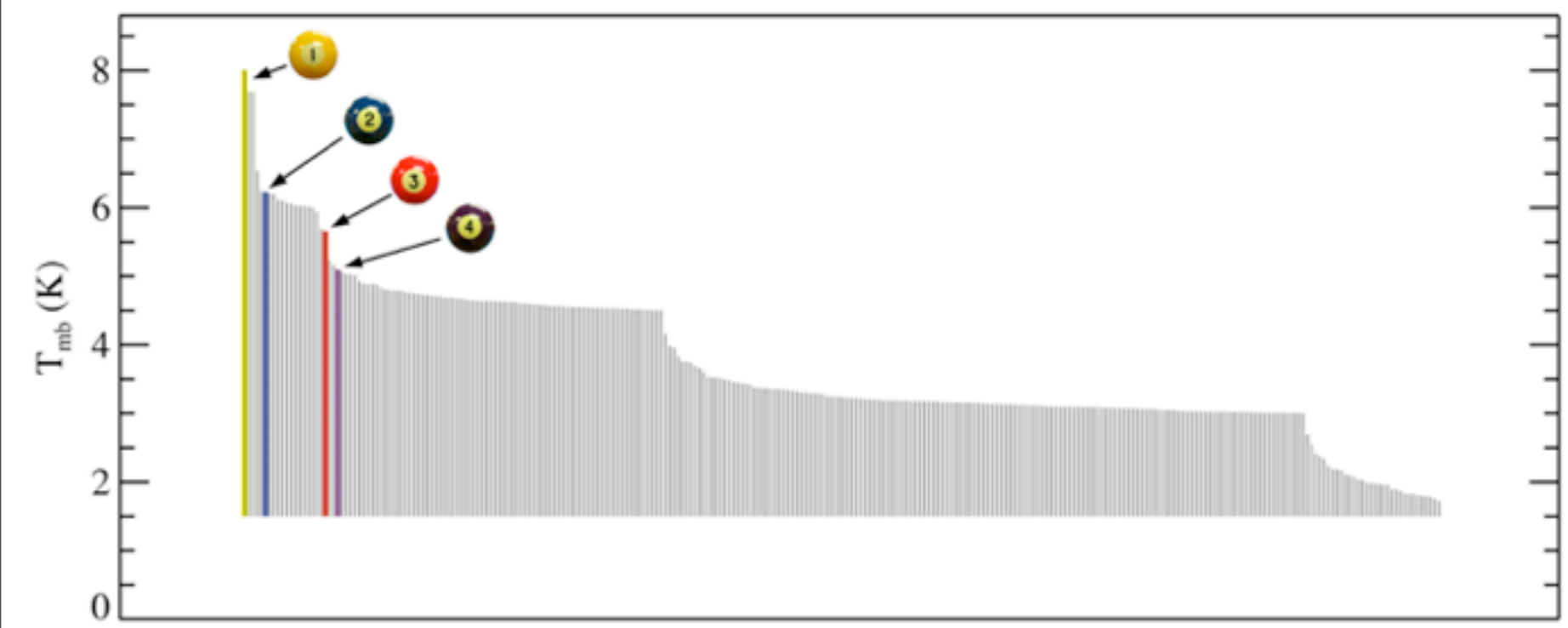
CLUMPFIND vs. Dendrograms: LI 448

Dendrograms



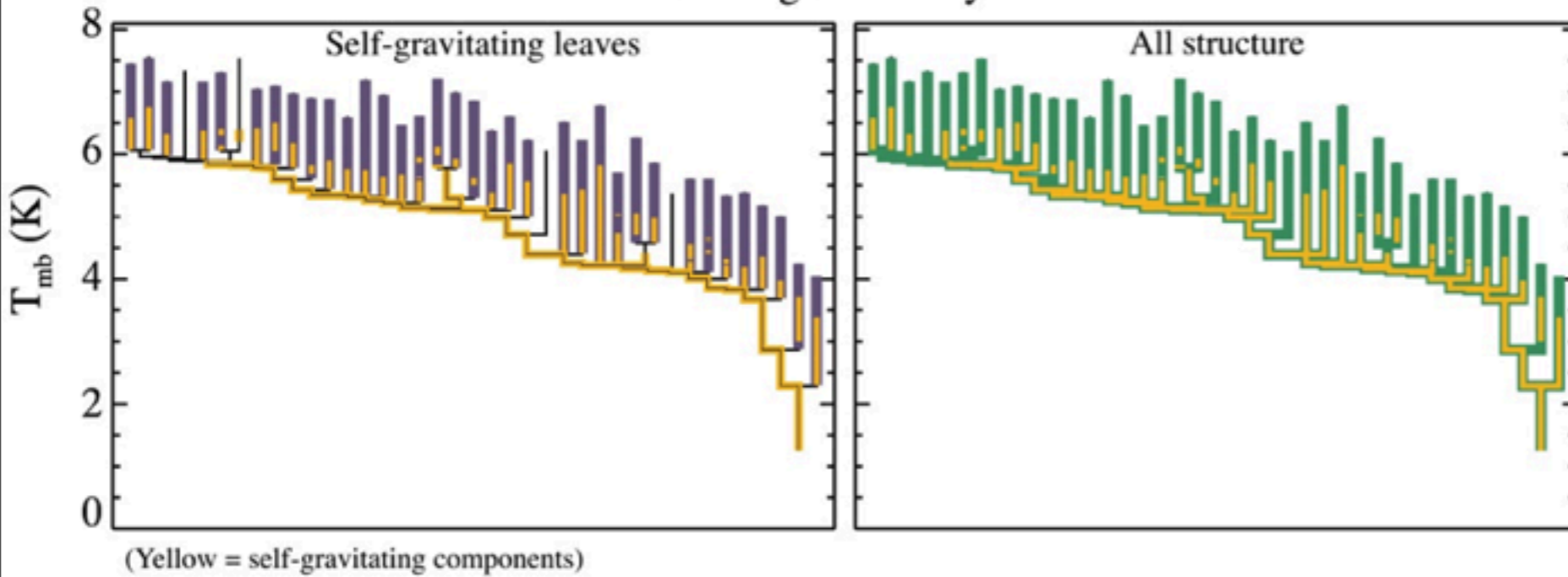
The online PDFs of these insets

“CLUMPFIND”

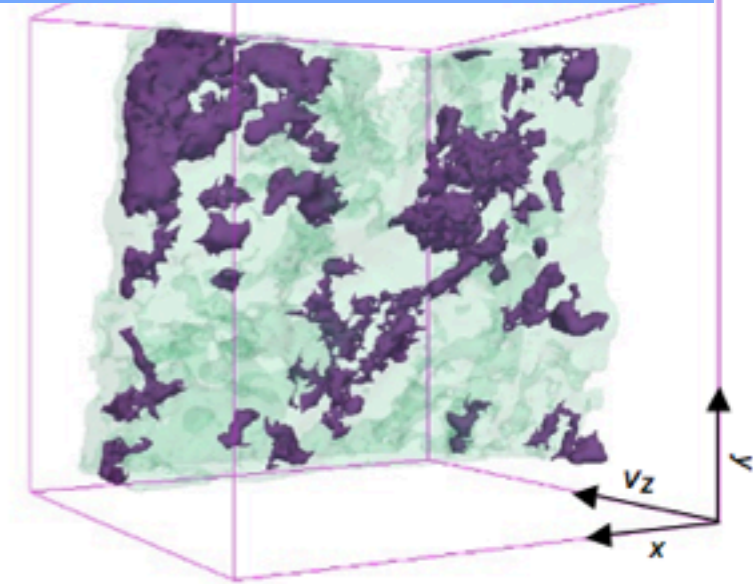


CLUMPFIND vs. Dendrograms: Synthetic Data

Dendrogram Analysis

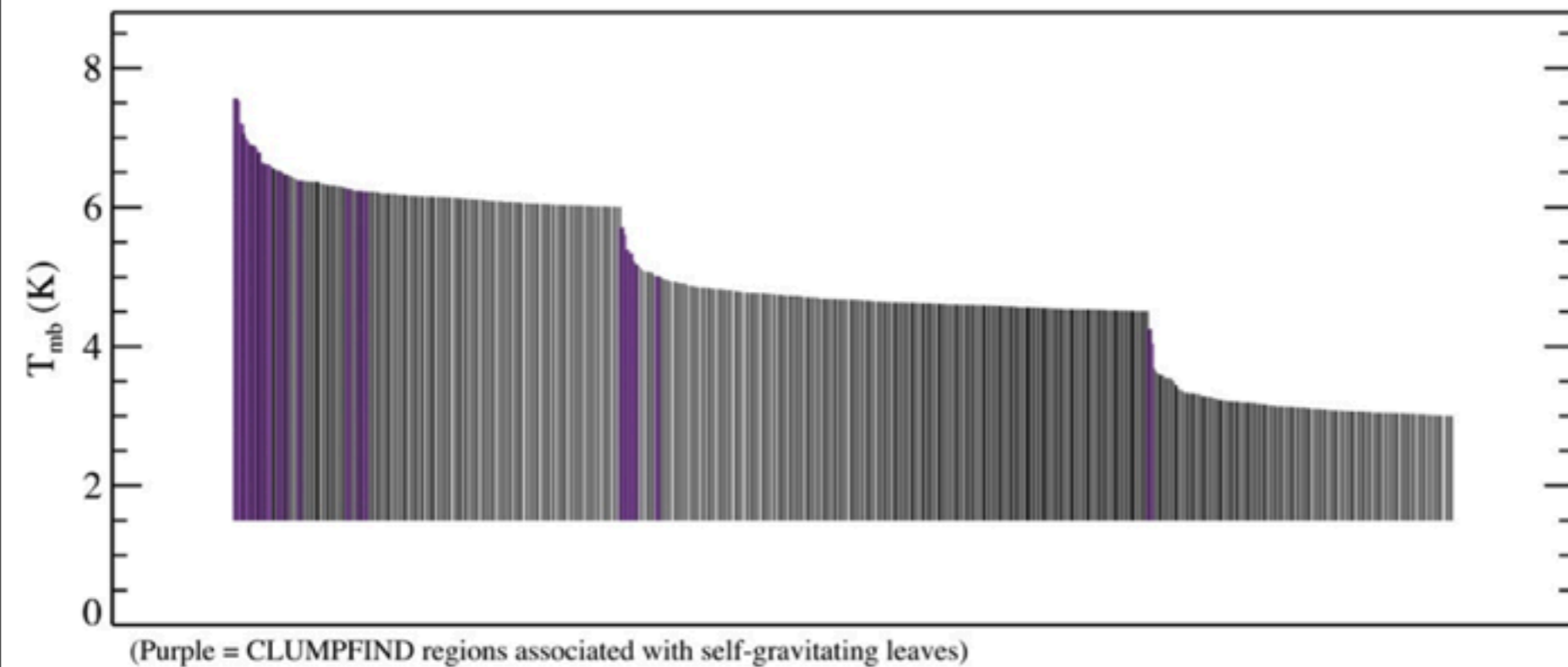


Dendrograms

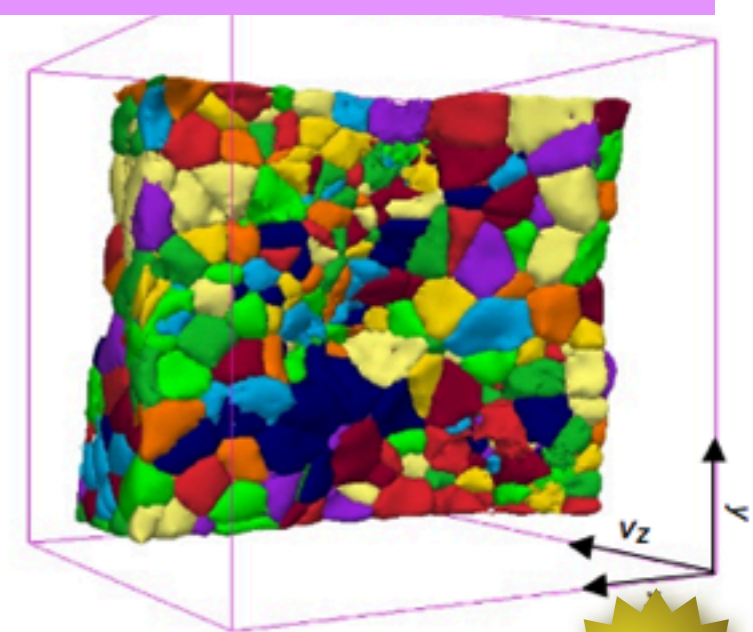


i The online PDFs of these insets are interactive, offer additional surfaces, and can be rotated and manipulated by

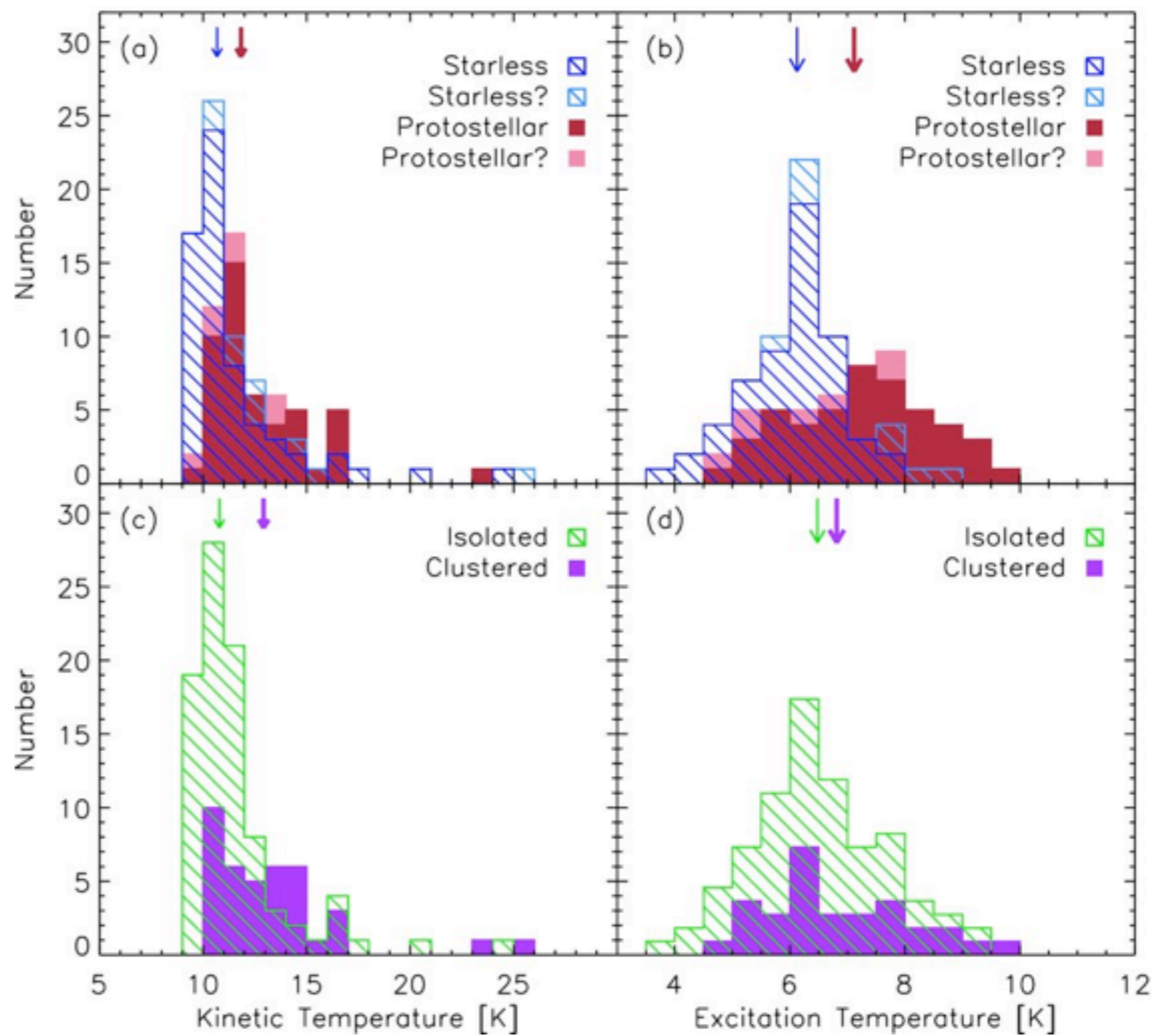
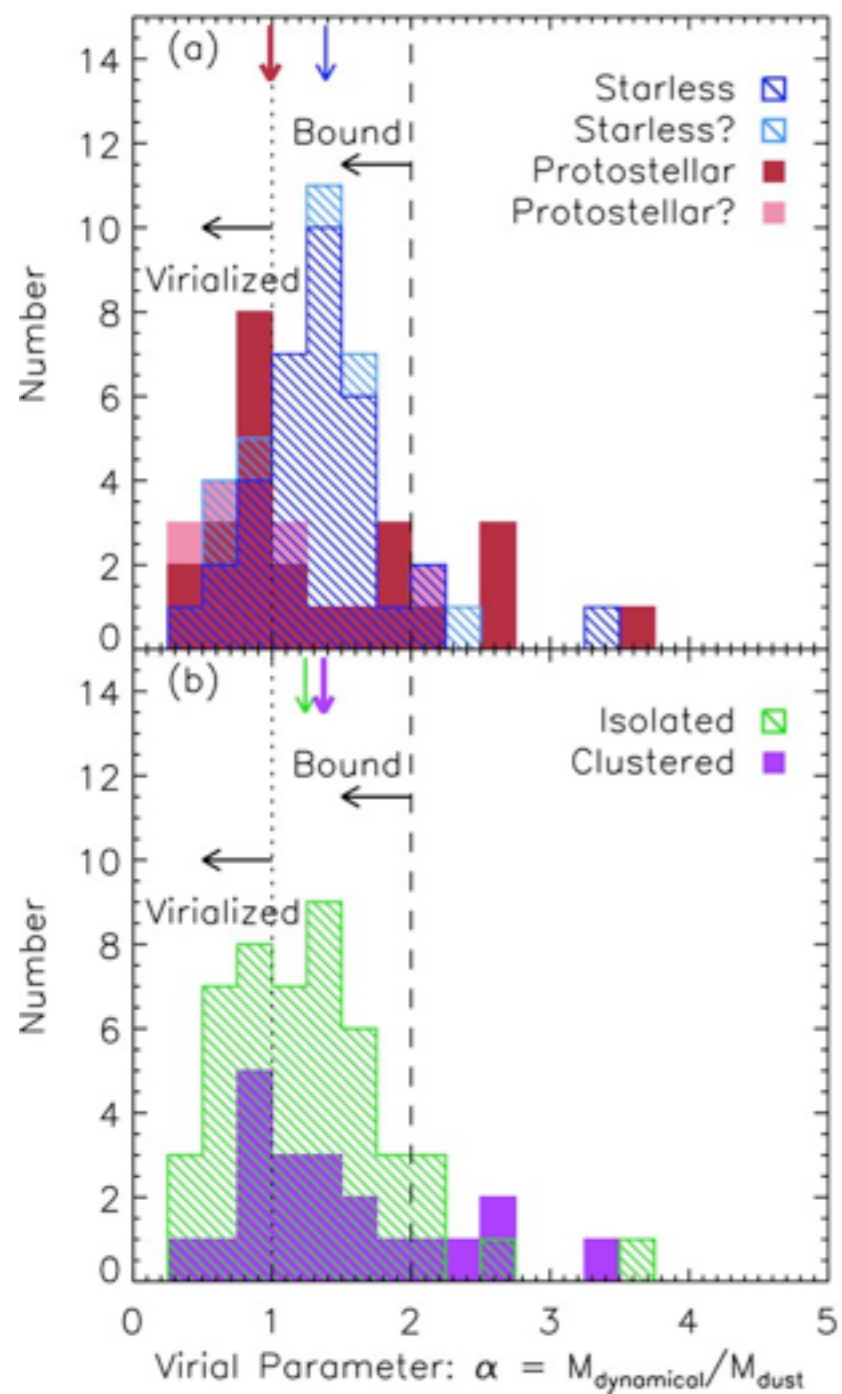
CLUMPFIND Analysis



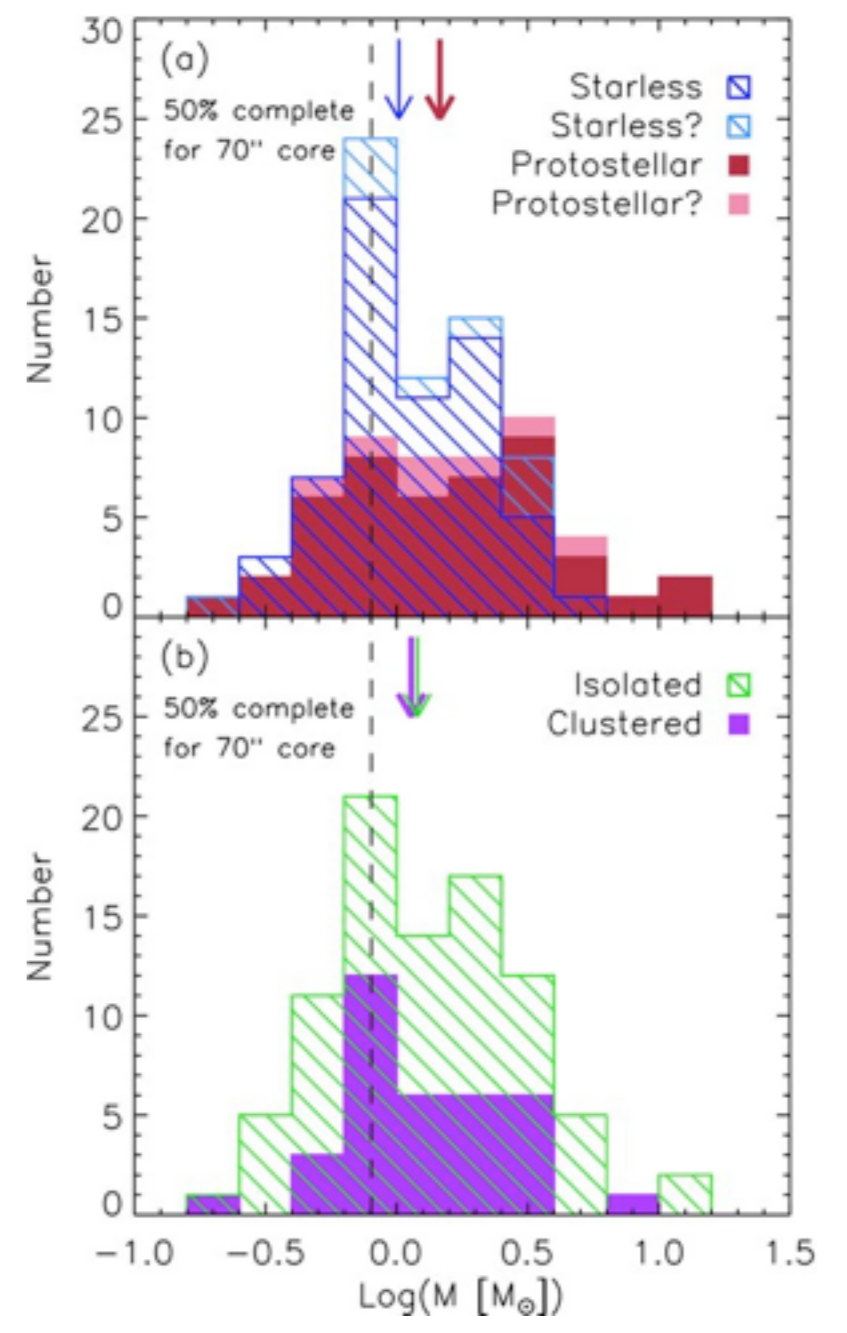
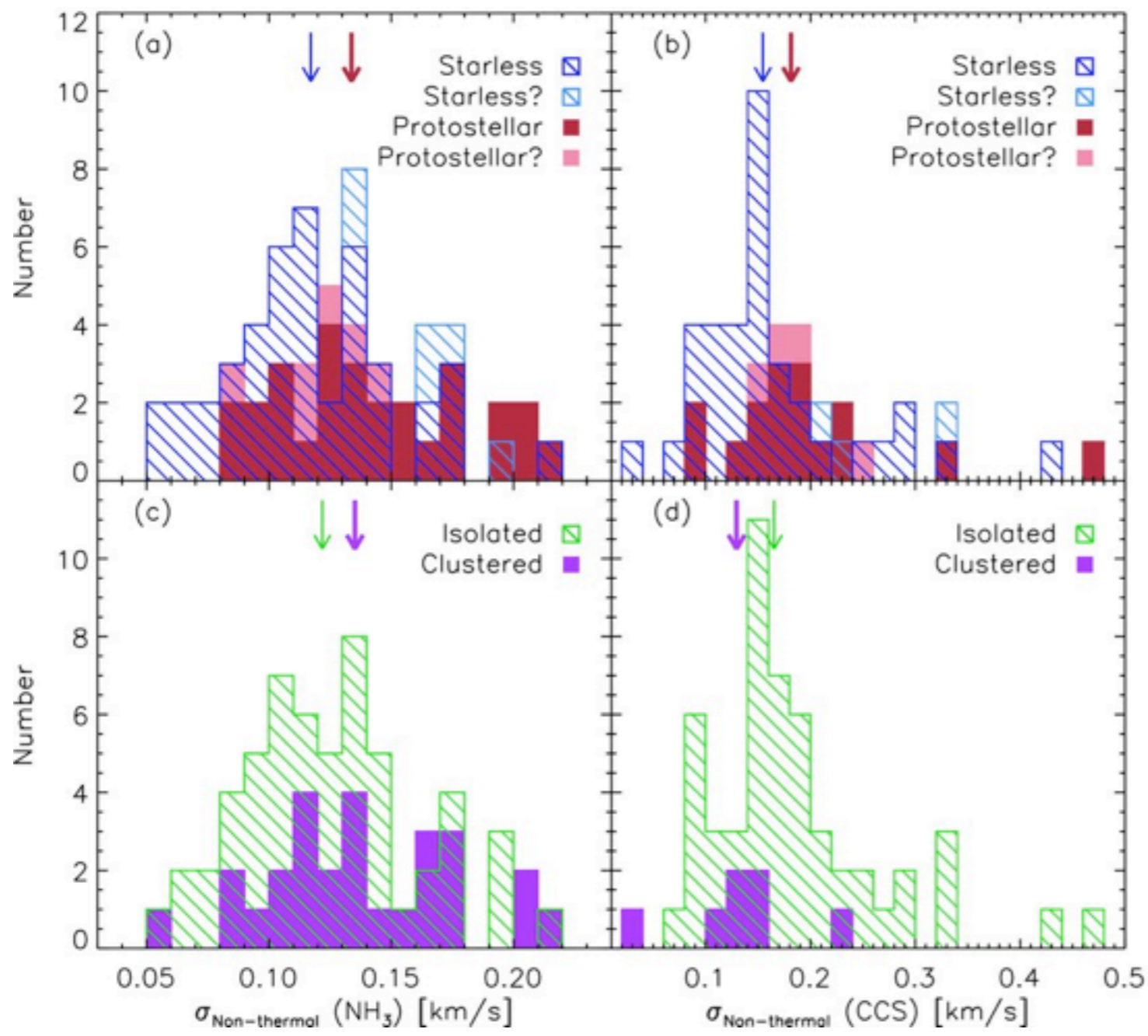
“CLUMPFIND”



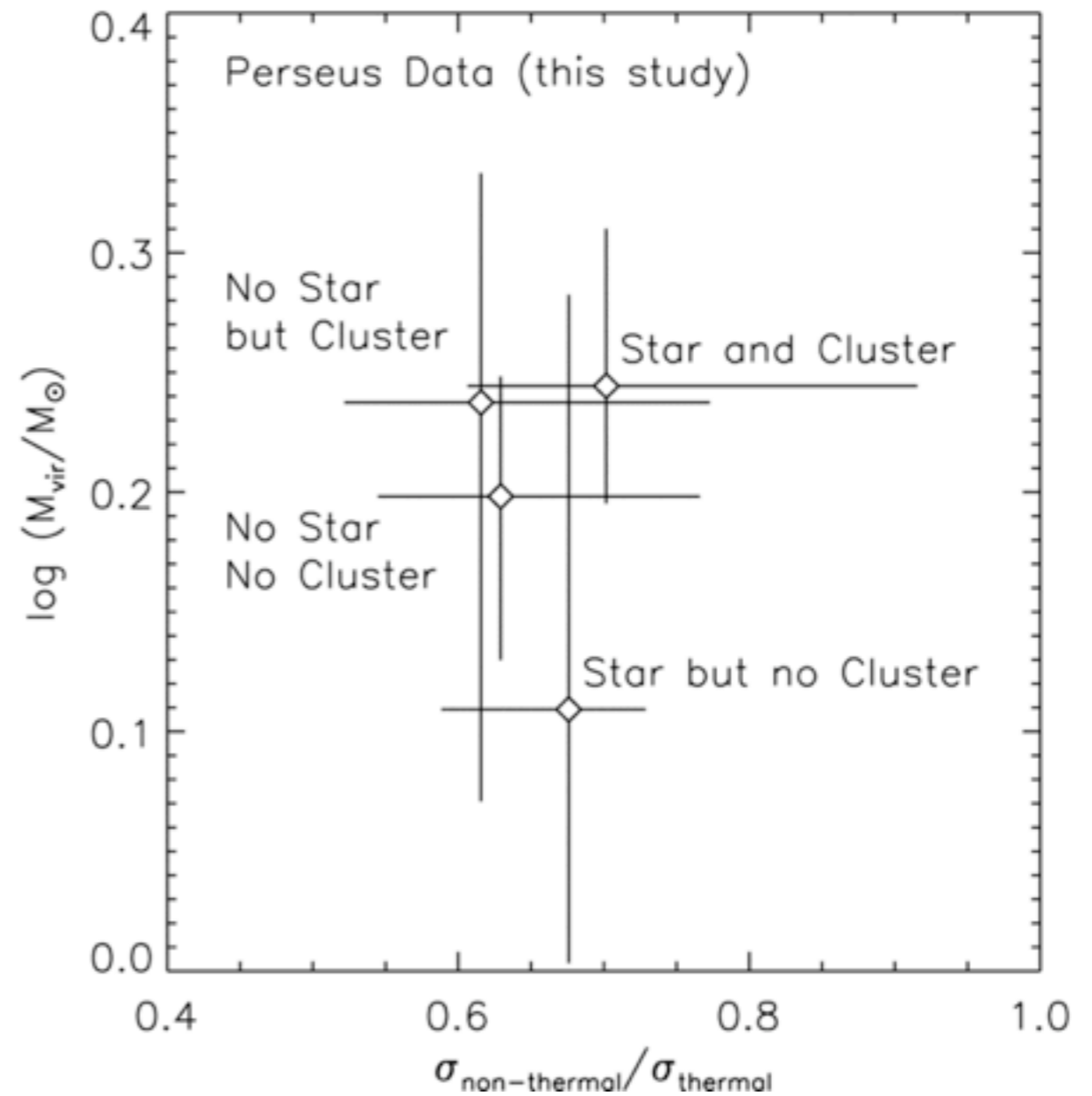
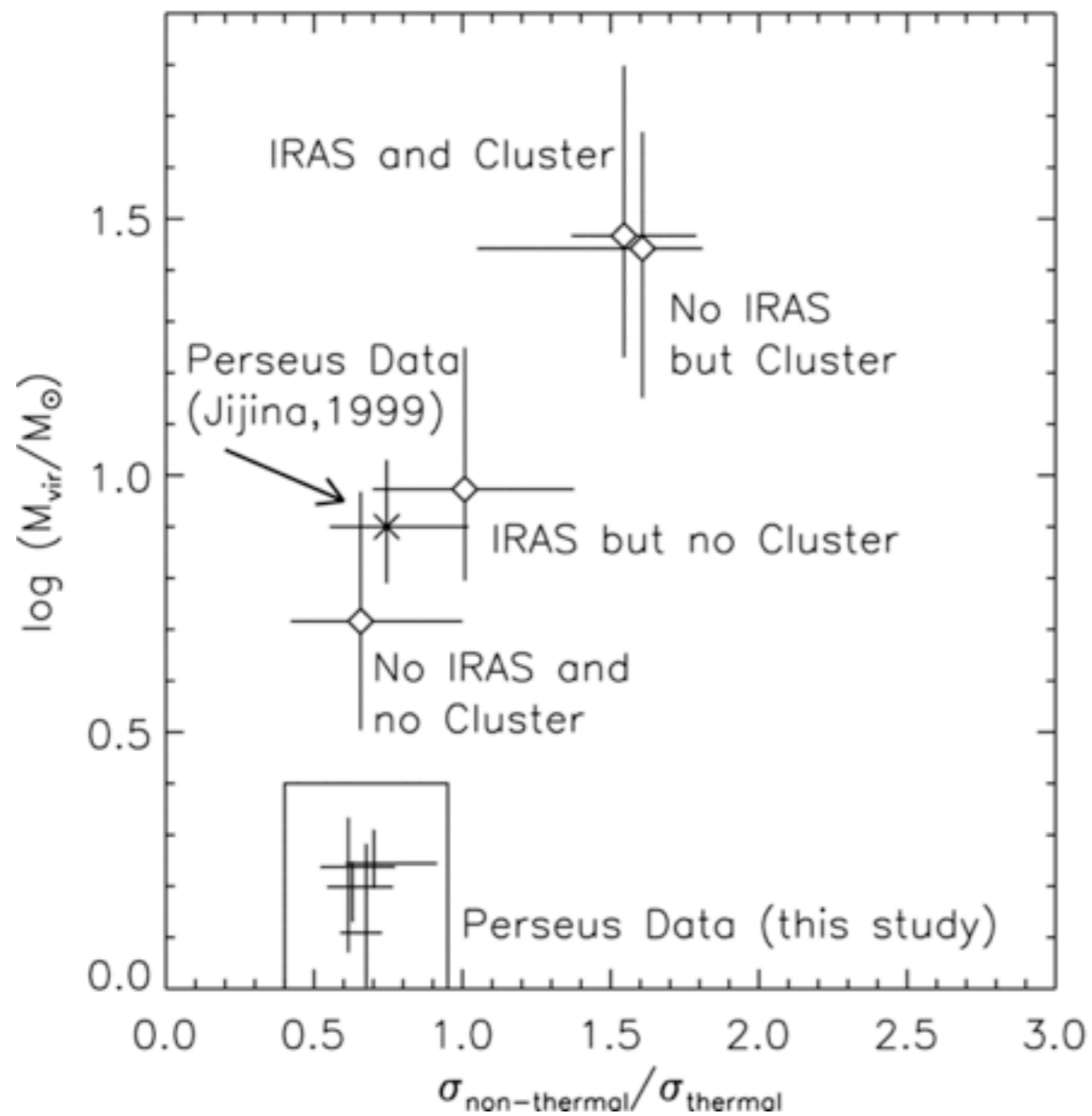
TASTE TEST



Foster et al. 2009



Foster et al. 2009



Foster et al. 2009

