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 |hōˈlistik|

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

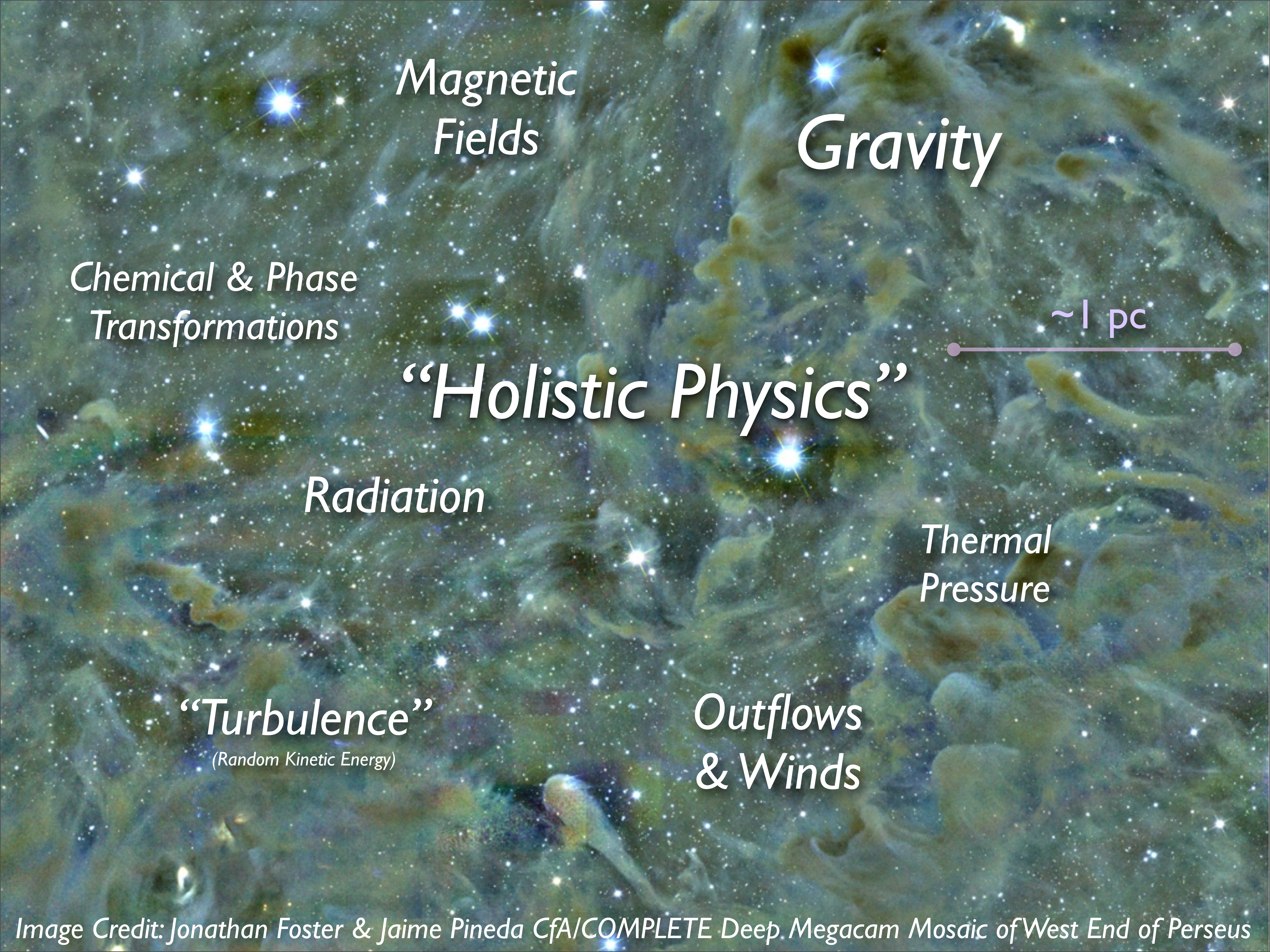
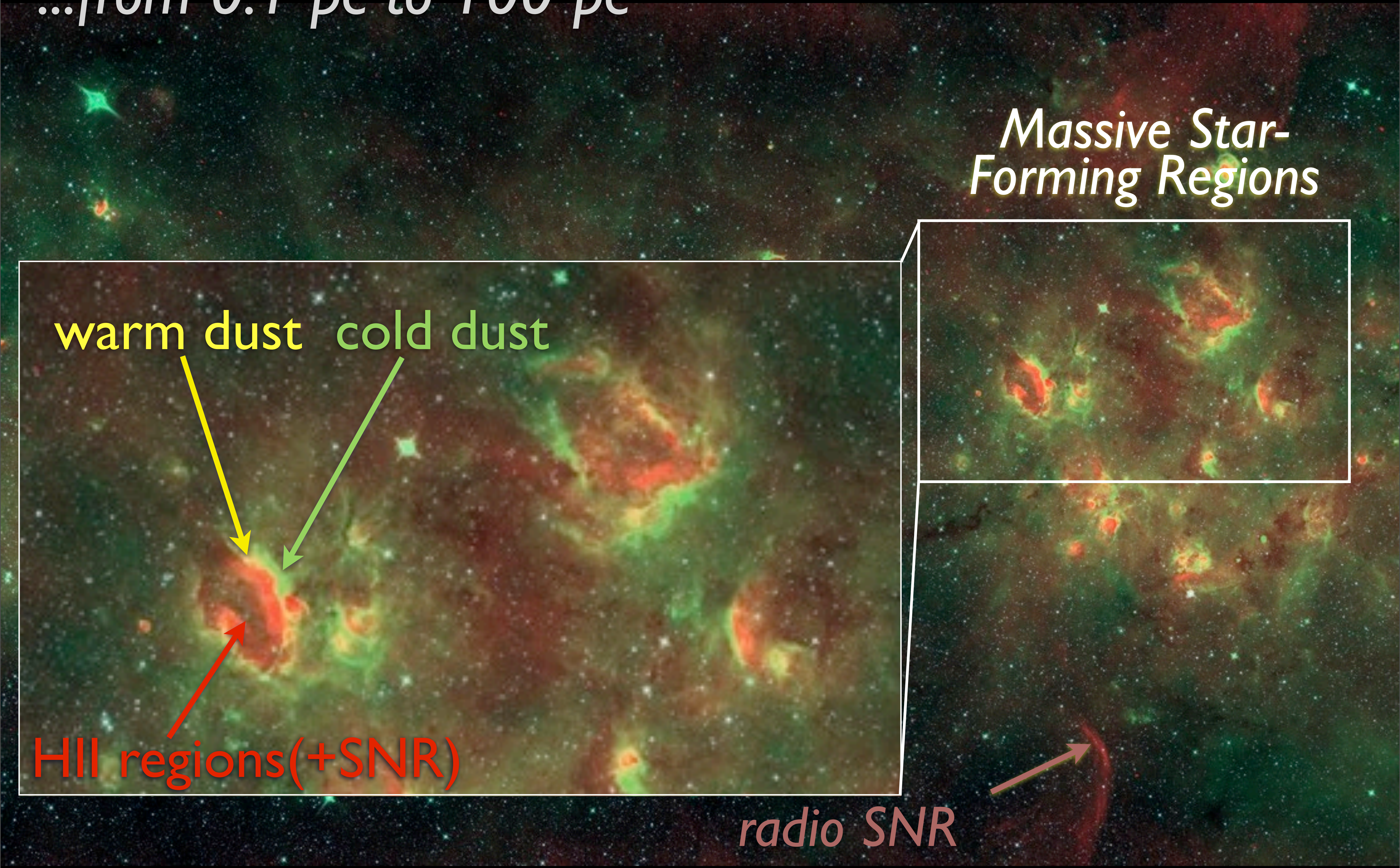


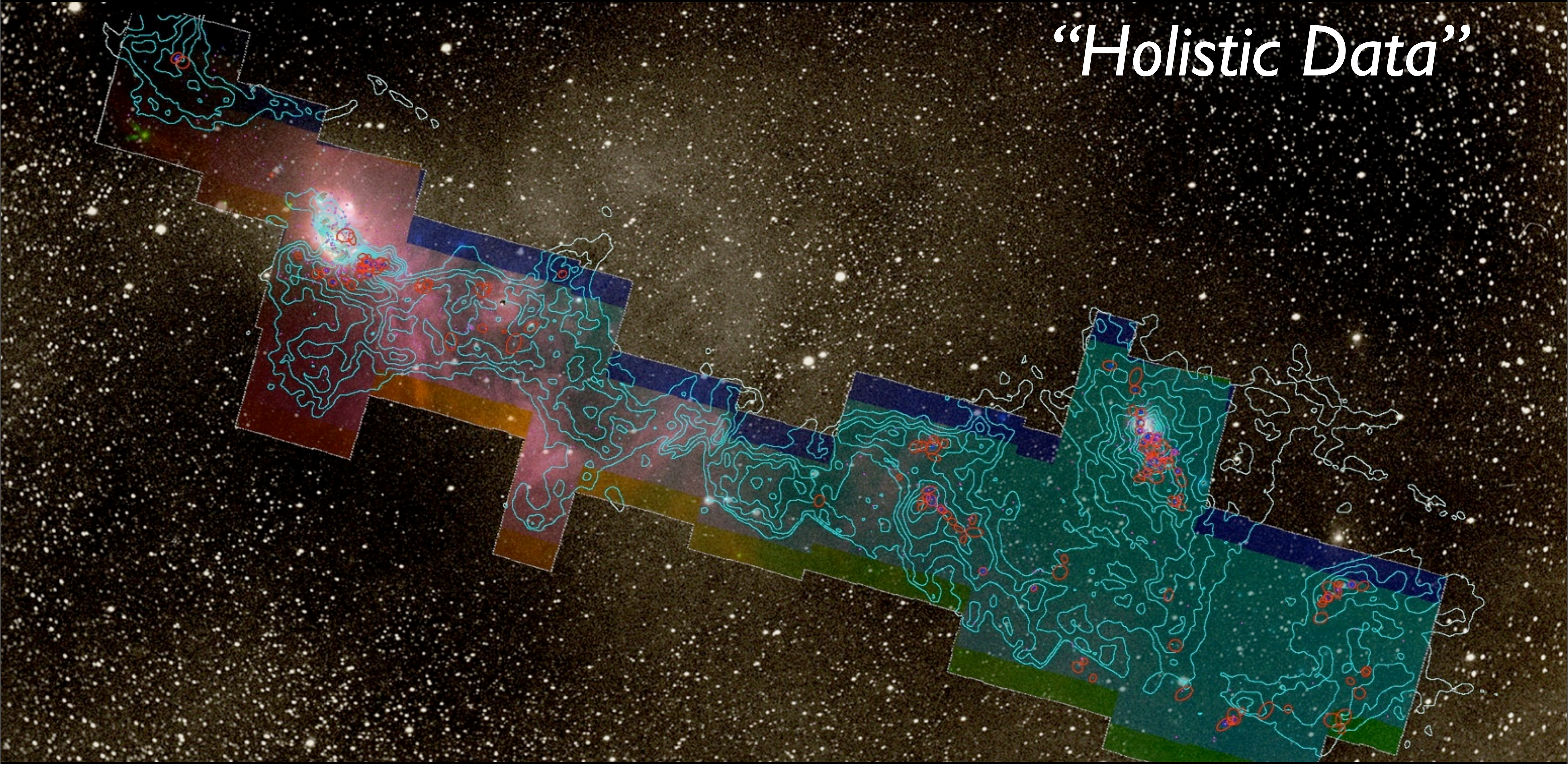
Image Credit: Jonathan Foster & Jaime Pineda CfA/COMPLETE Deep Megacam Mosaic of West End of Perseus

...from 0.1 pc to 100 pc



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



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

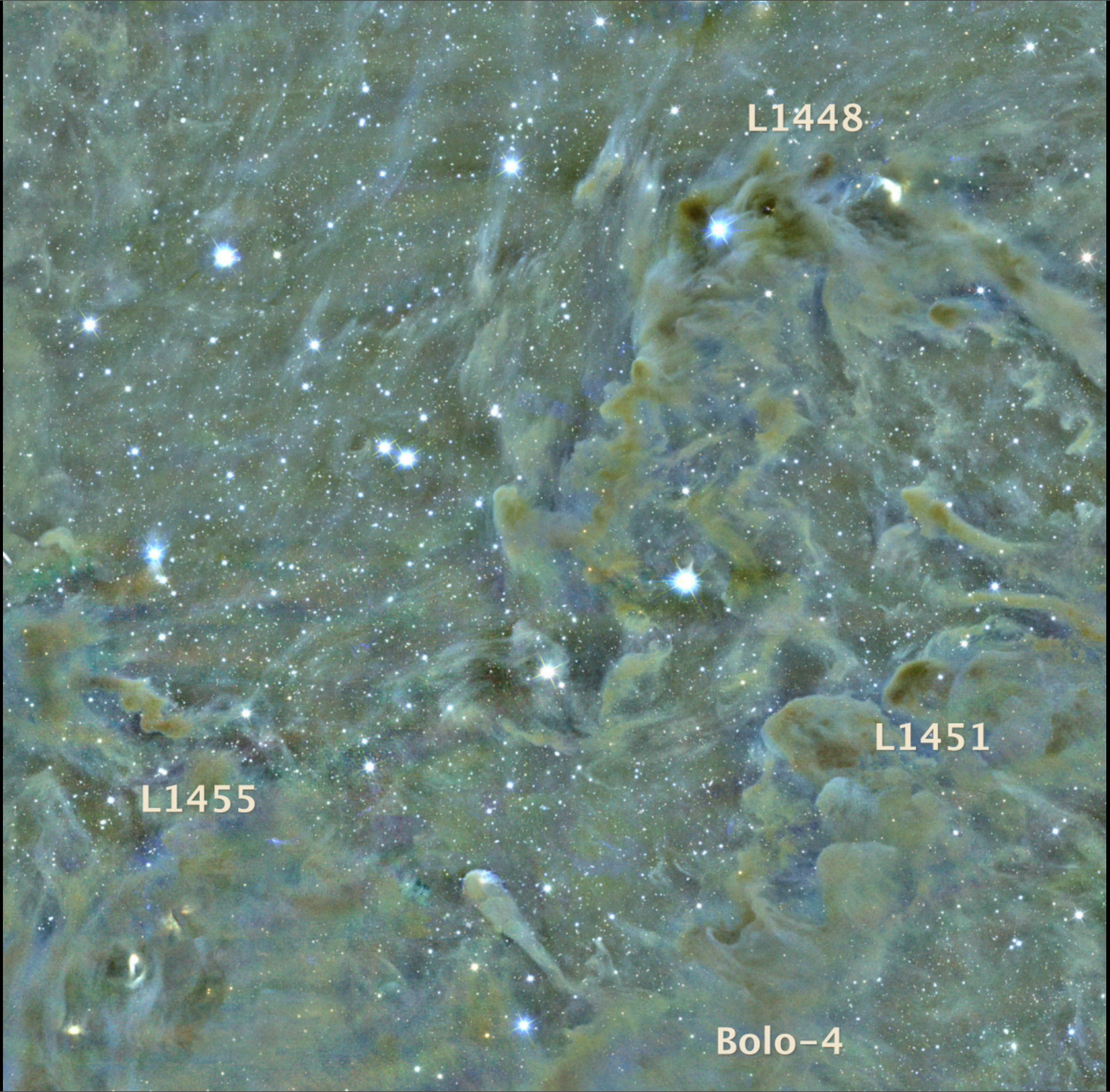
A journey through star-formation in reverse, by Jonthathan Foster.

Main Image:

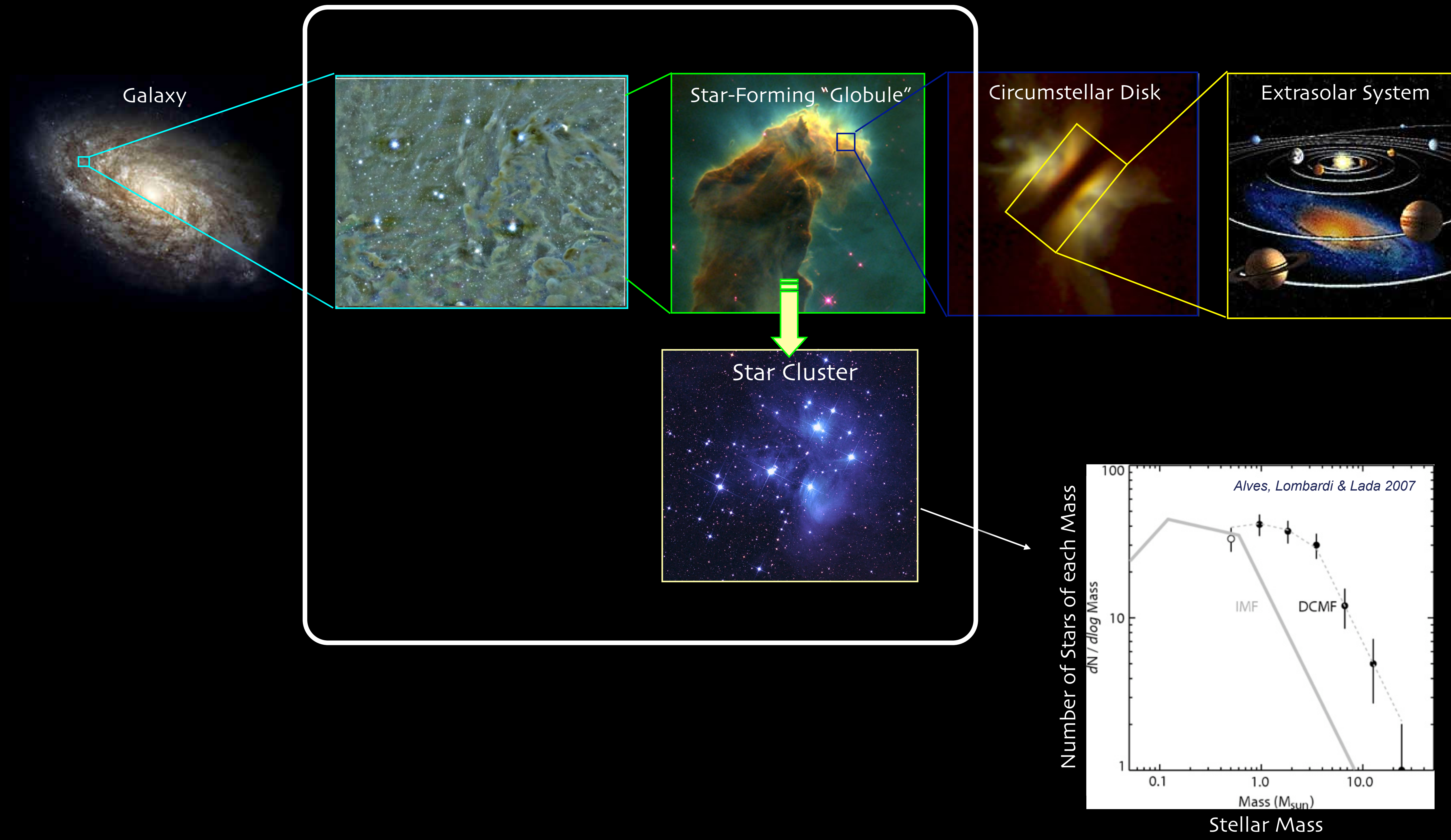
MMT/ Megacam *r,i,z*

Zooms/fades:

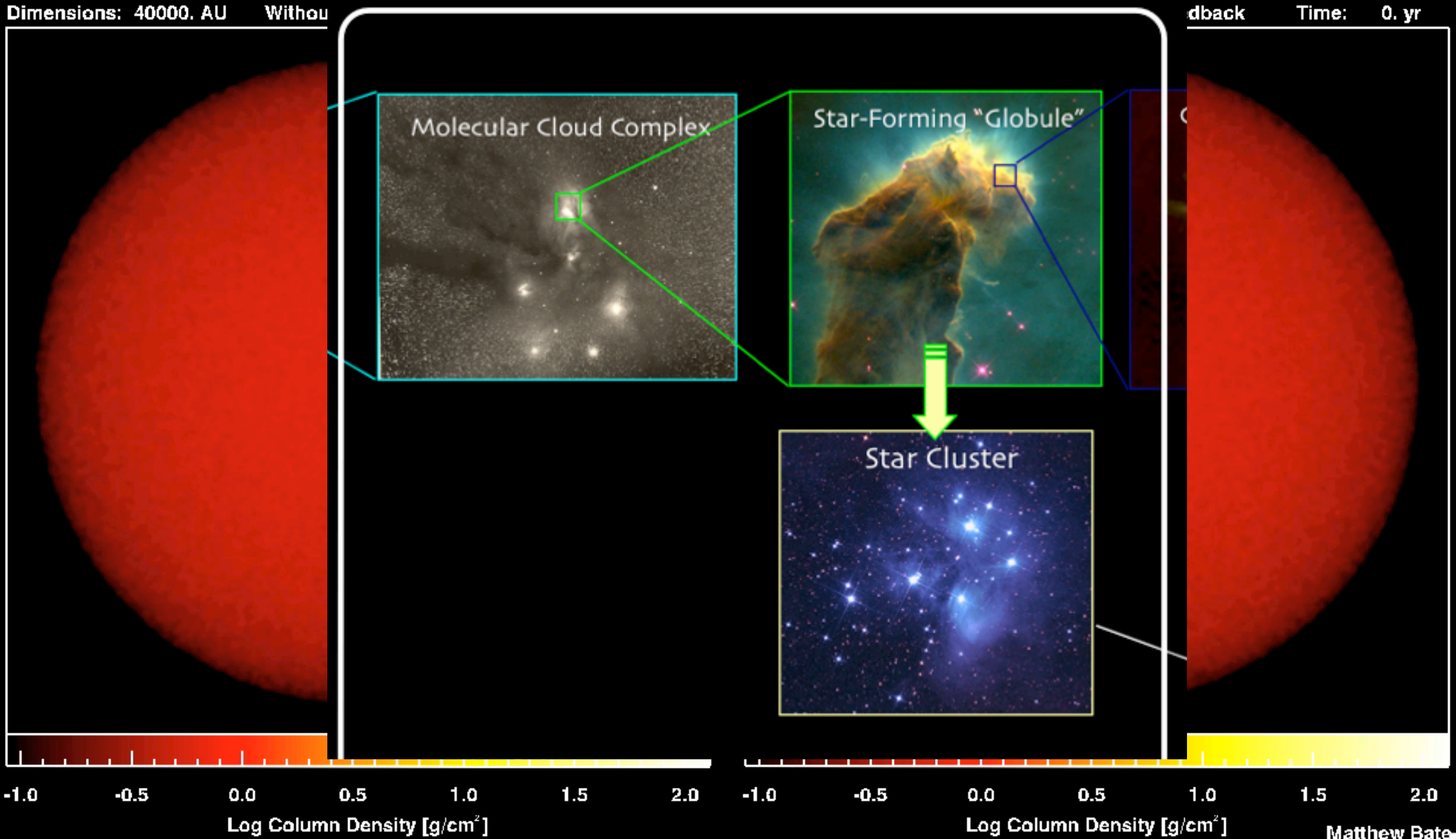
Calar Alto/ OMEGA2000 J,H,K_s



Star (and Planet, and Moon) Formation 301



Our Goal is to "Taste" Star Formation



Simulations of Bate 2009

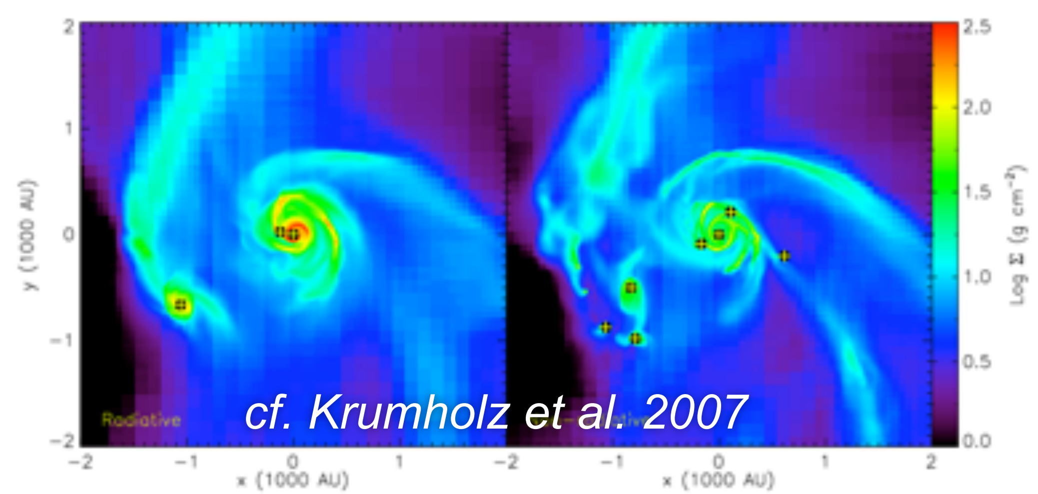
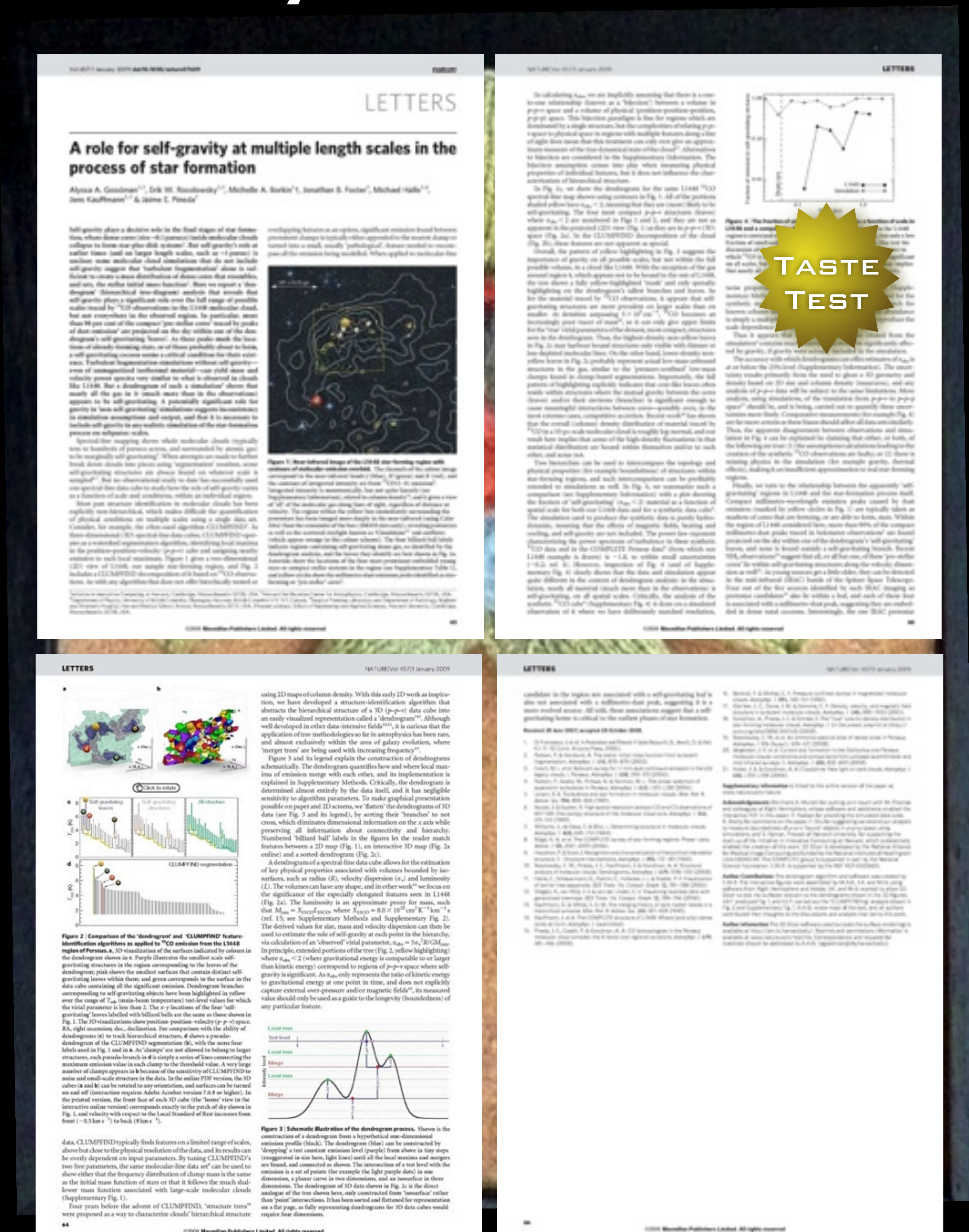


FIG. 9 A comparison of two simulations with identical initial conditions and evolution times, one including radiative transfer (*left panel*) and one done without it (*right panel*). Stars are indicated by plus signs. The simulation without radiative transfer forms a factor of ∼ 4 more stars than the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

Today's Dissection



Goodman, Rosolowsky, Borkin, Foster, Halle, Kauffmann & Pineda 2009, Nature, 457, 63.

“turbulent fragmentation”

“L1448”

“(magneto-)hydrodynamic simulation”

“Cloudshine”

“pre-stellar core”

“protostar”

“integrated intensity”

“p-p-v cube”

“segmentation”

“CLUMPFIND”

“Dendrogram”


LETTERS

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

“COMPLETE”

“3D PDF”

“bi-jection”

“virial parameter”

“column density”

“turbulent power spectrum”

“synthetic observation”

“depletion, opacity”

“taste-test”

caveats

"turbulent fragmentation"

"L1448"

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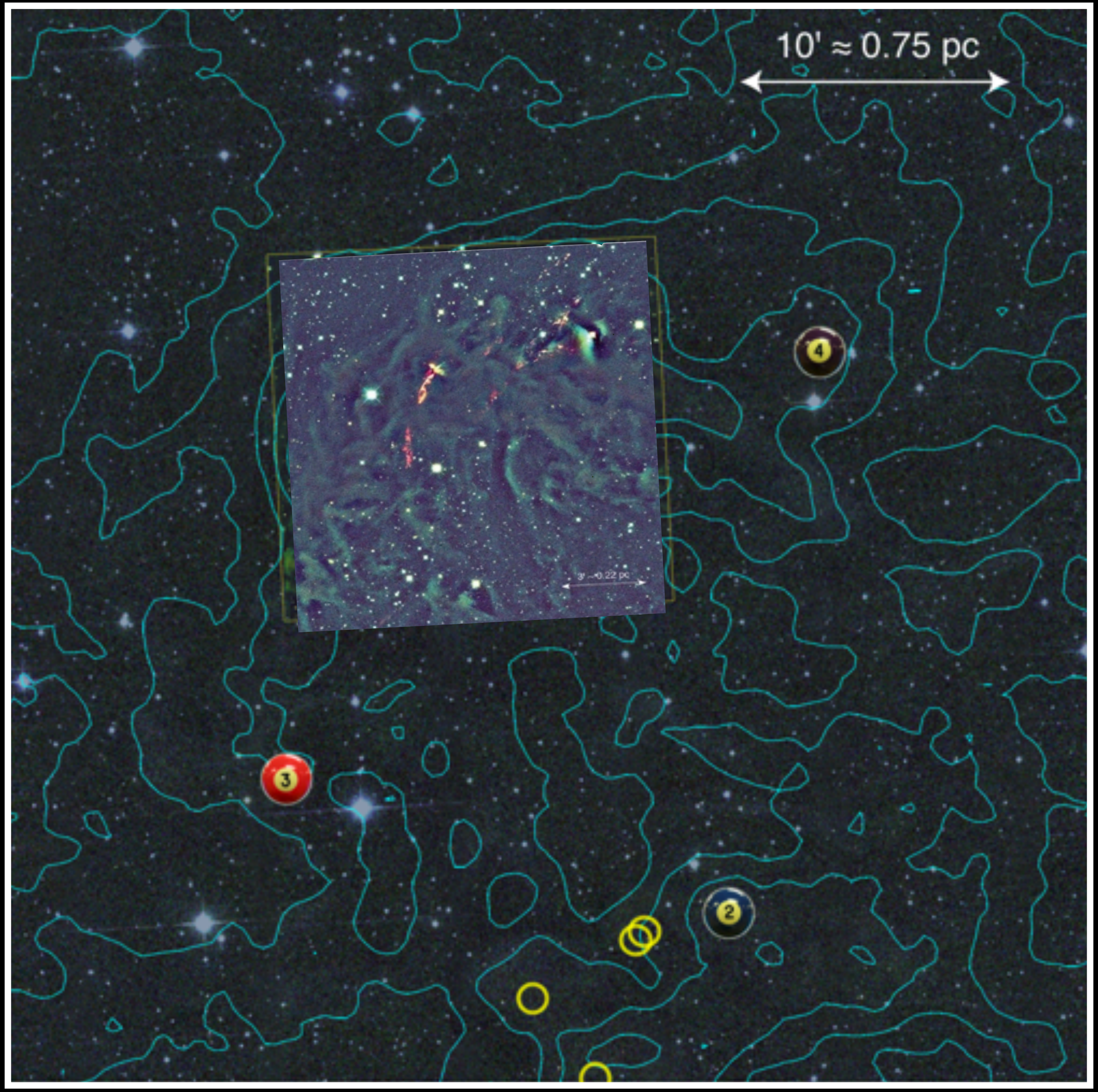
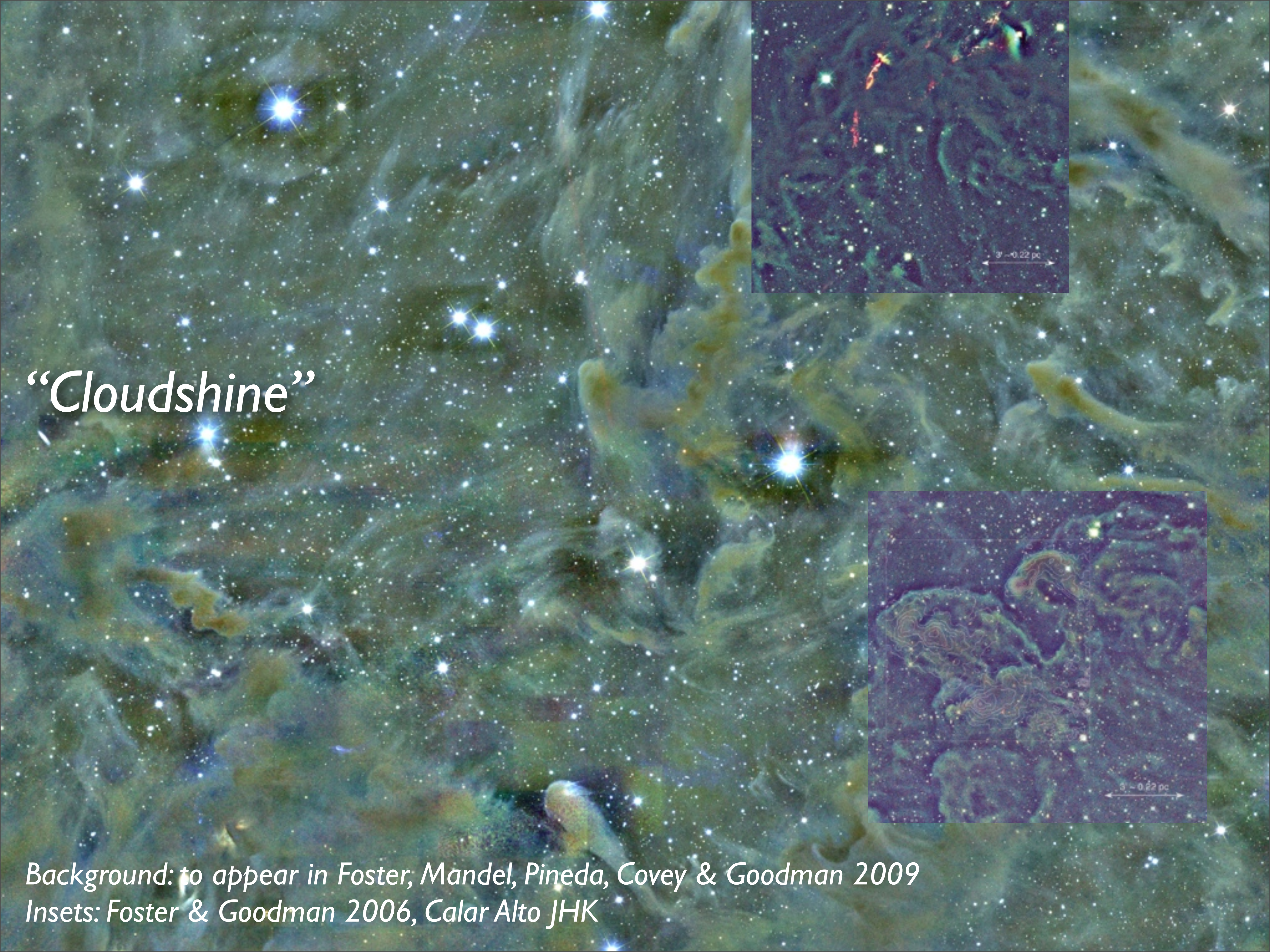


“column density”

“COMPLETE”



“Cloudshine”

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

✔ "L1448"

"Cloudshine" ✔

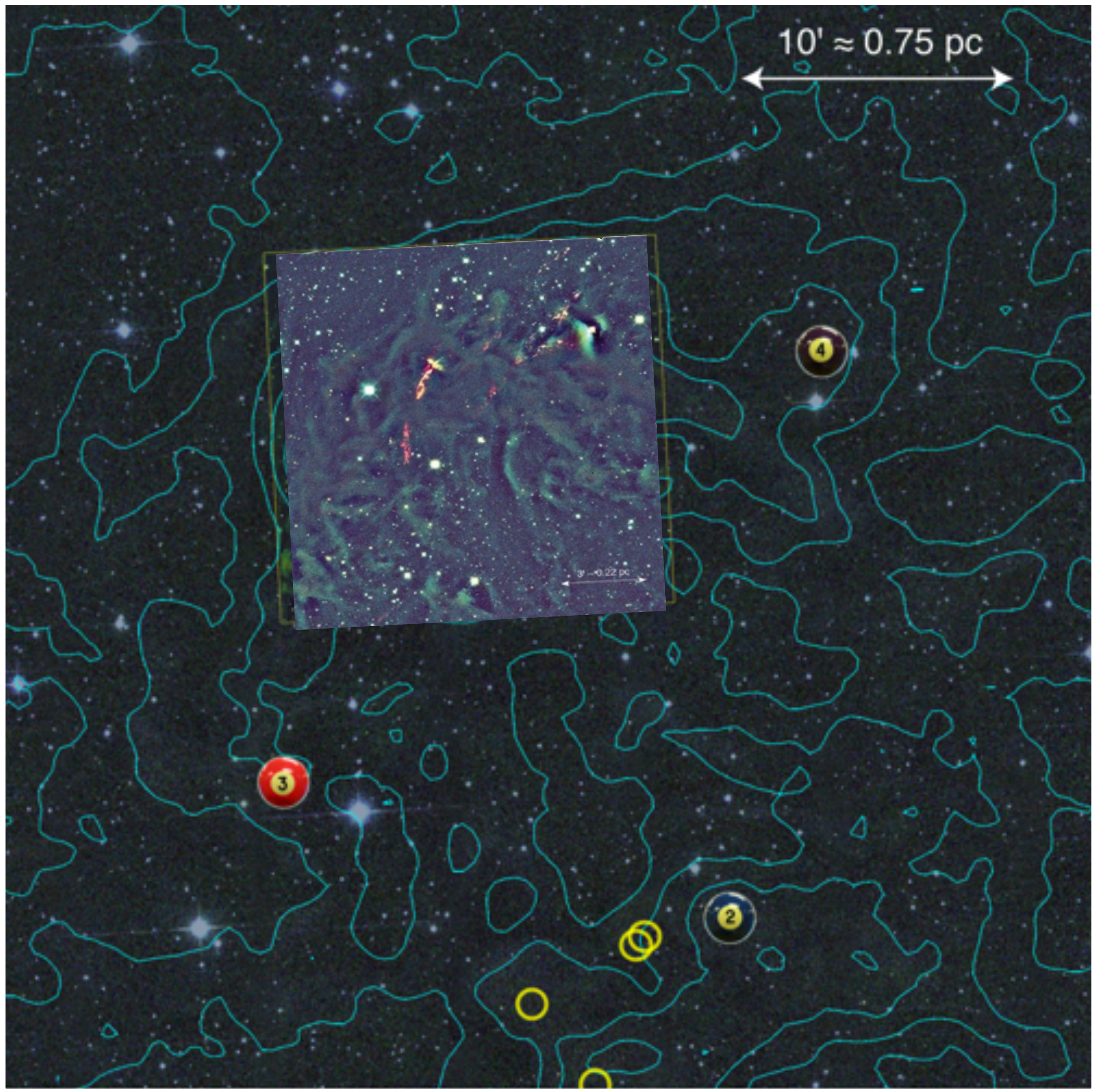
○ "pre-stellar core"

...compact thermal dust peak ✔

* "protostar" ✔

...Spitzer c2d (MIR) point source with "right" SED

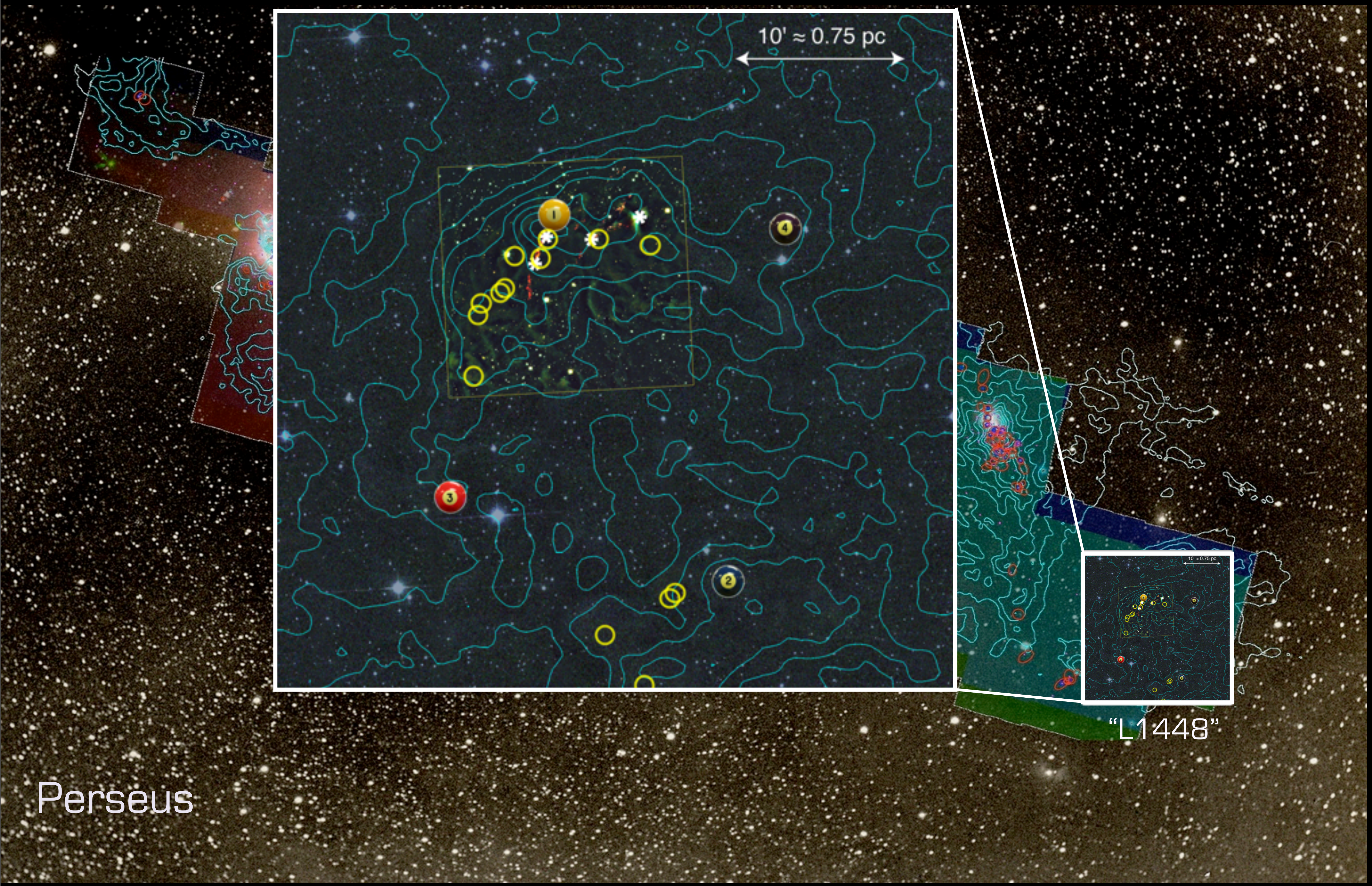
"integrated intensity"



"column density"

"COMPLETE"

(...later)



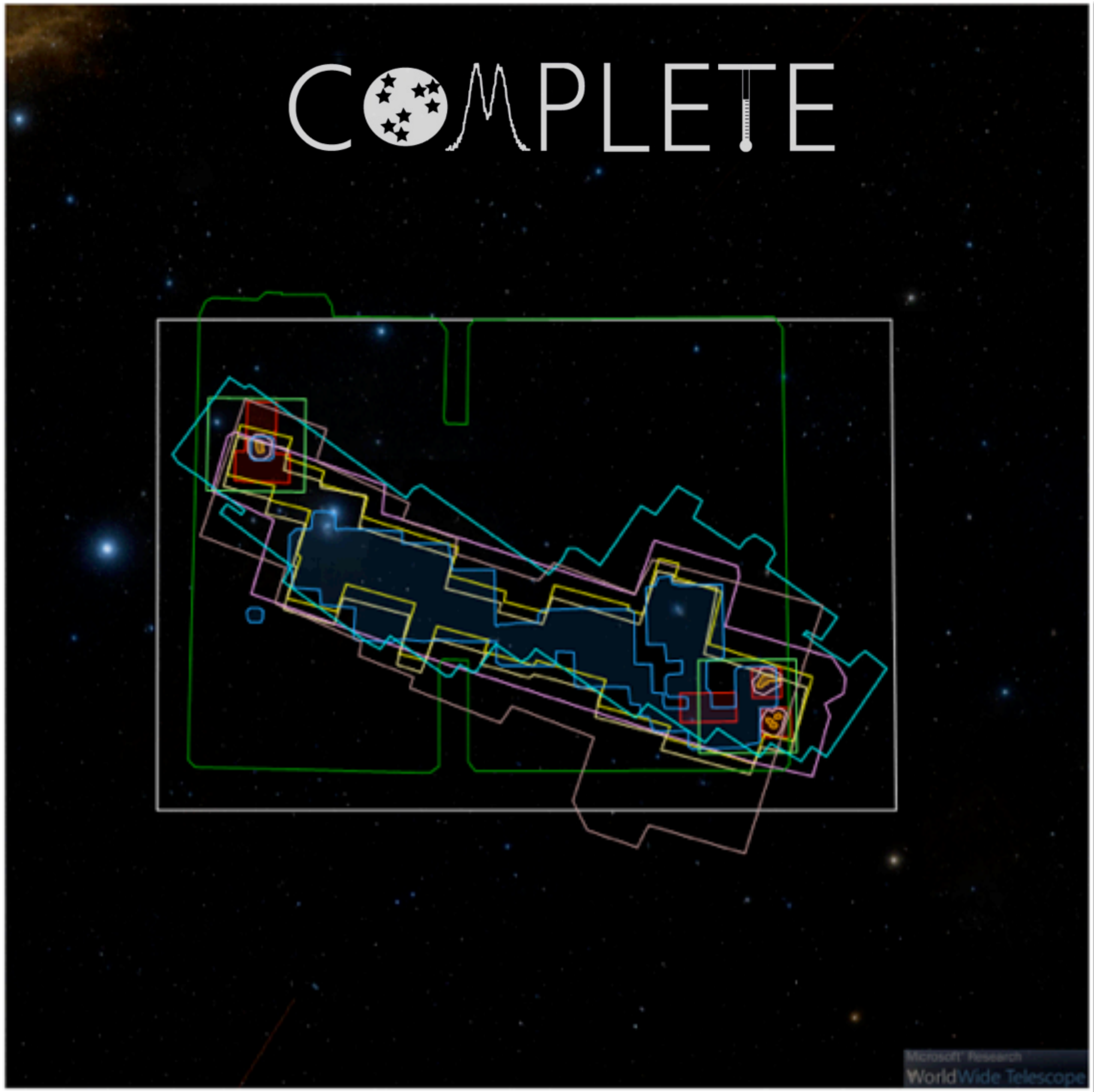
"integrated intensity"

"column density"

COMPLETE

COMPLETE Data Coverage Tool

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



COMPLETE Data Available

Center on Perseus | Center on Ophichus | Center on Serpens

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

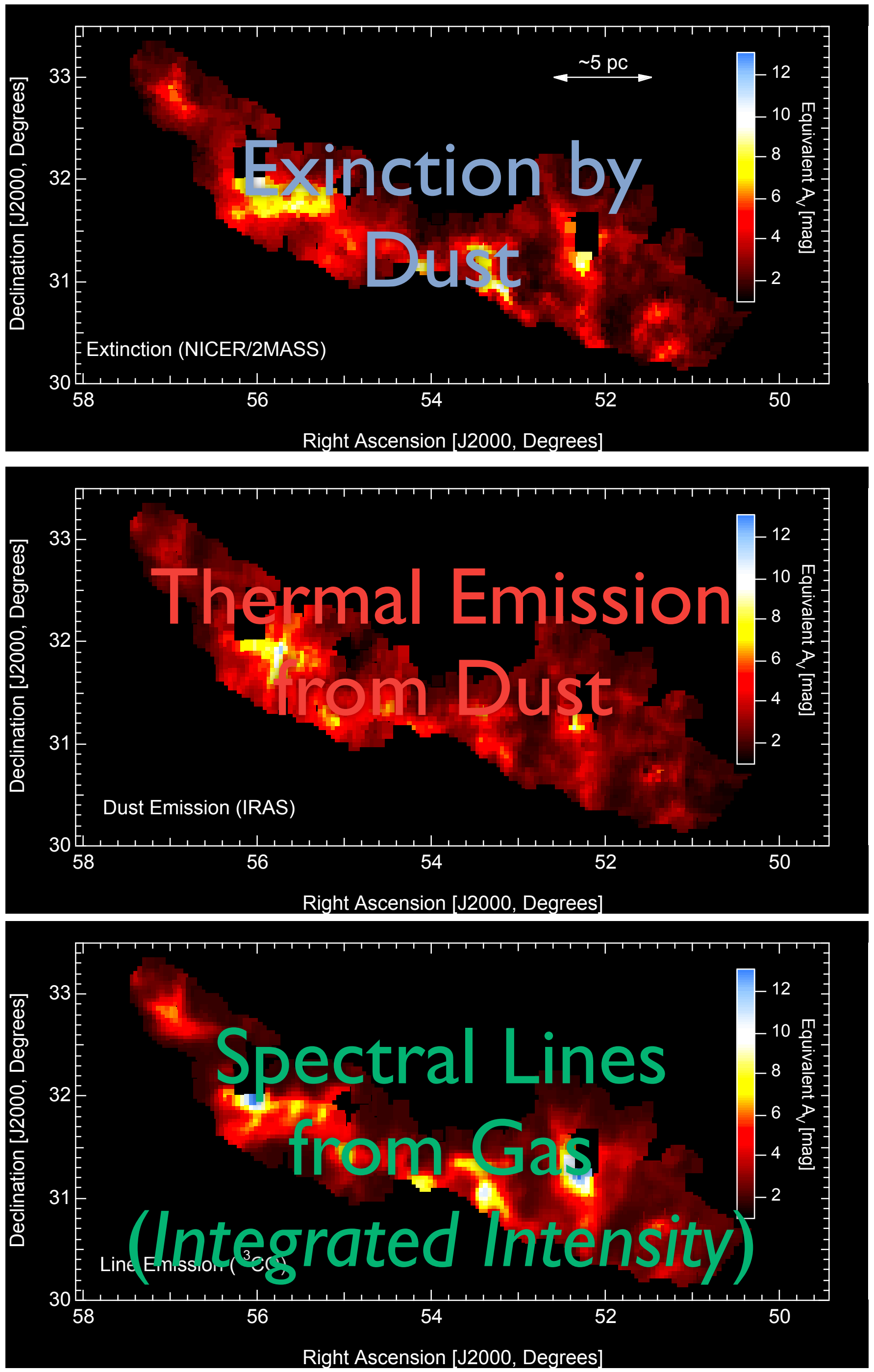
Dataset	Show	Perseus	Ophiuchus	Serpens	Link
GBT: HI Data Cube	☑	√	√	∅	Data
IRAS: Av/Temp Maps	☑	√	√	√	Data
FCRAO: 12CO	☑	√	√	√	Data
FCRAO: 13CO		√	√	√	Data
JCMT: 850 microns	☑	√	√	∅	Data
Spitzer c2d: IRAC 1,3 (3.6,5.8 µm)	☑	√	√	√	Data
Spitzer c2d: IRAC 2,4 (4.5,8 µm)	☑	√	√	√	Data
CSO/Bolocam: 1.2-mm	☑	√	∅	∅	Data
Spitzer MIPS: Derived Dust Map	☑	√	∅	∅	Data
Targeted Regions (Phase II, Some Data Not Yet Available)					
CTIO/Calar Alto: NIR (J,H,Ks)	☑	√	√	∅	Data
IRAM 30-m: N2H+ and C18O	☑	√	∅	∅	Data
IRAM 30-m: 1.1-mm continuum	☑	√	∅	∅	Data
Megacam/MMT: r,i,z images	☑	√	∅	∅	Data
Catalogs & Pointed Surveys					
NH3 Pointed Survey	☐	√	∅	∅	Data
YSO Candidate list (c2d)	☐	√	√	√	Data

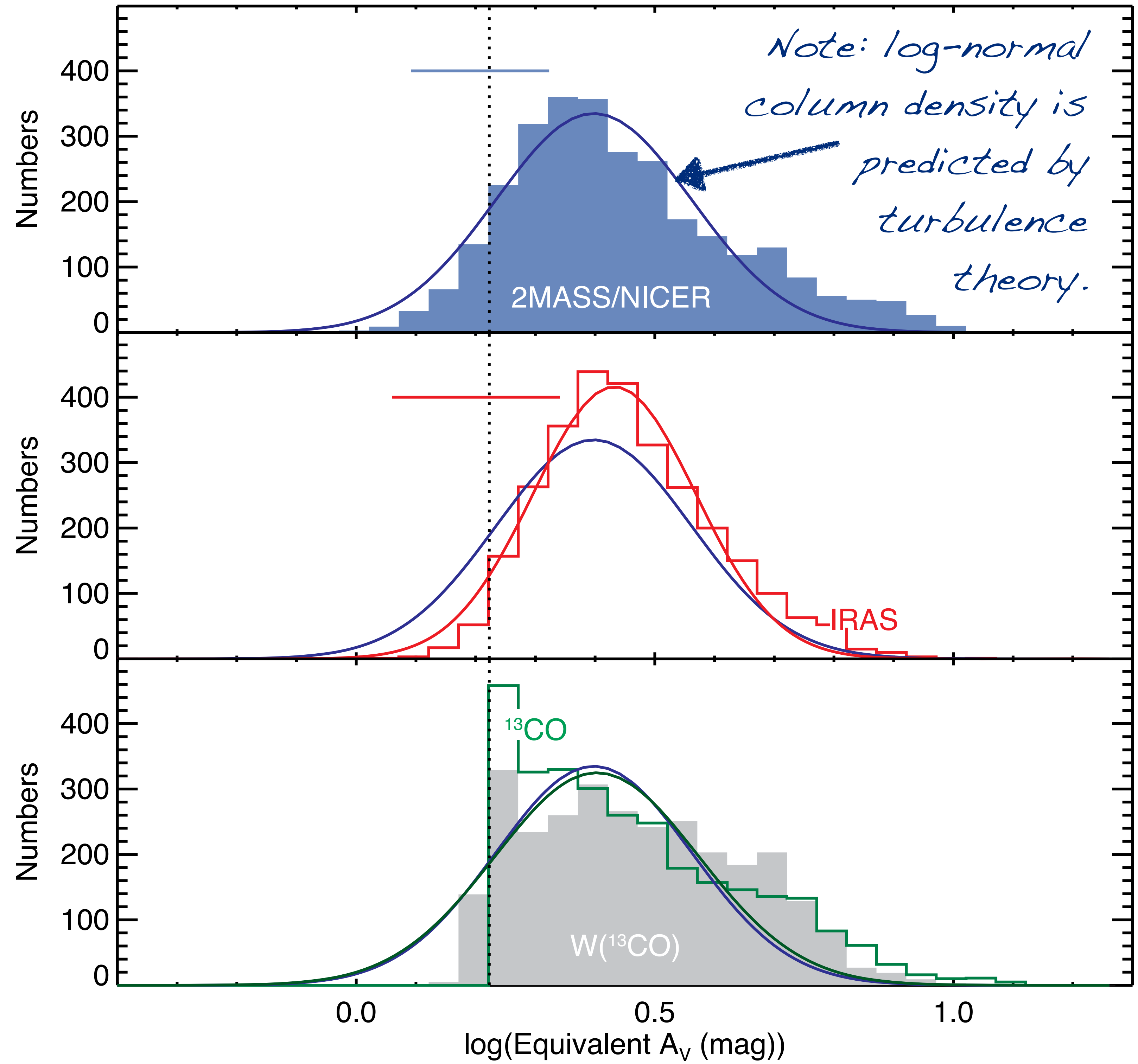
Done

To explore on your own, go to http://www.cfa.harvard.edu/COMPLETE/, then click on **Data** 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



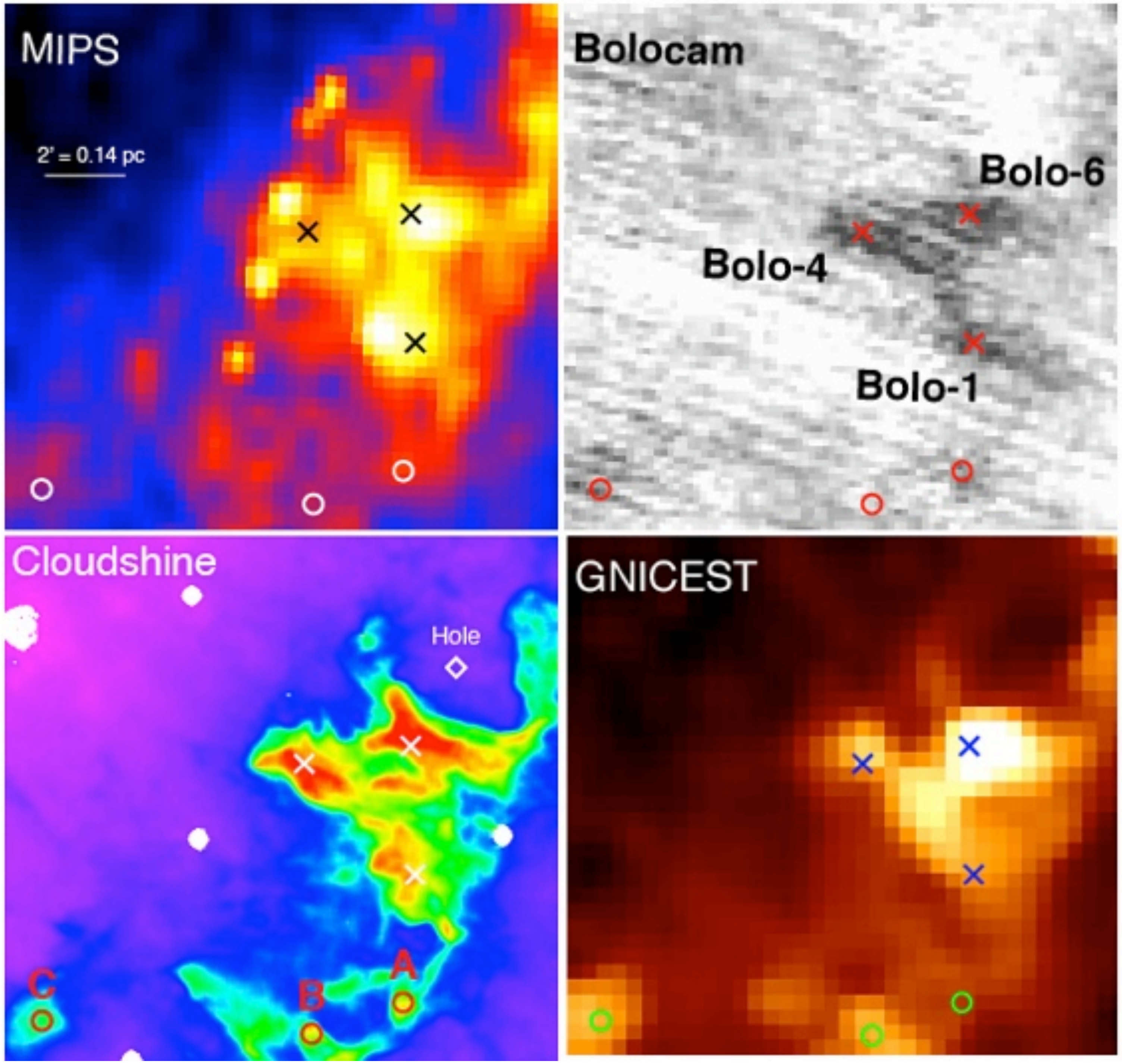


Goodman, Pineda & Schnee 2009, see also Pineda, Caselli & Goodman 2008

COMMERCIAL BREAK:
"Foster's Showdown, v.2009"

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

TASTE TEST



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"integrated intensity*"

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"3D PDF"

"bi-jection"

"virial parameter"

"column density"

"turbulent power spectrum"

"synthetic observation"

"depletion, opacity"

"taste-test"

caveats

*...more to come

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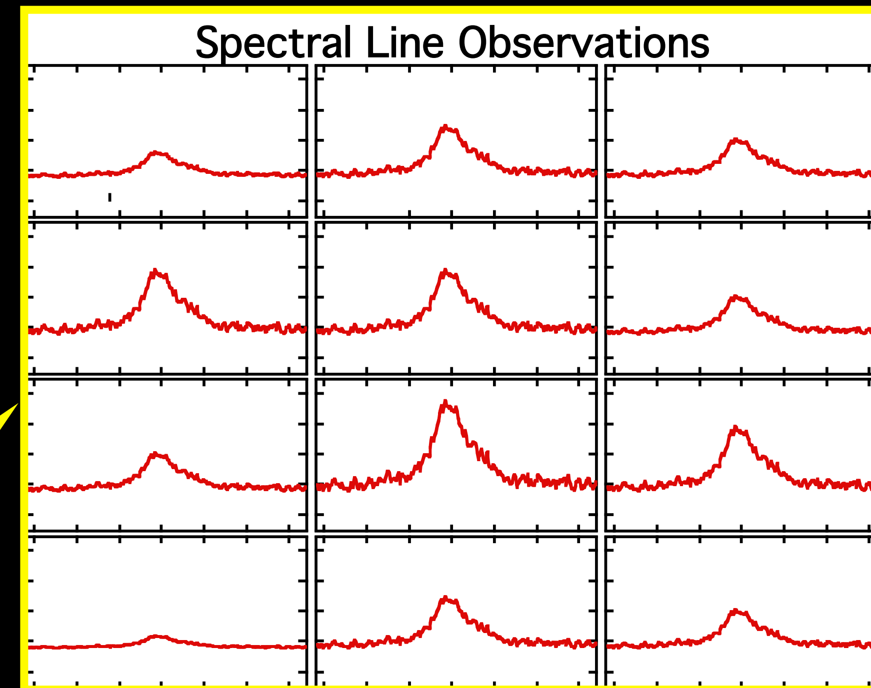
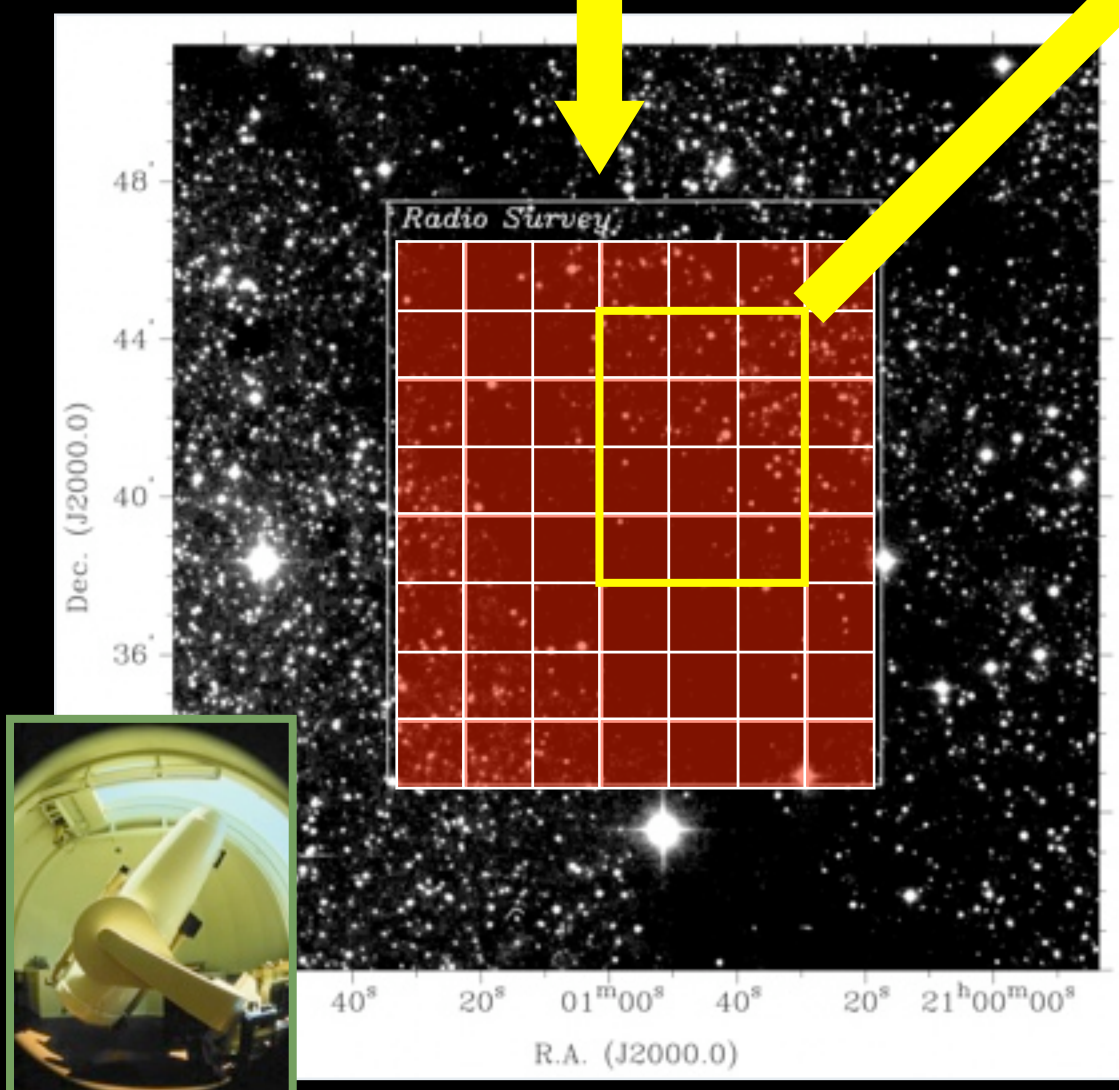
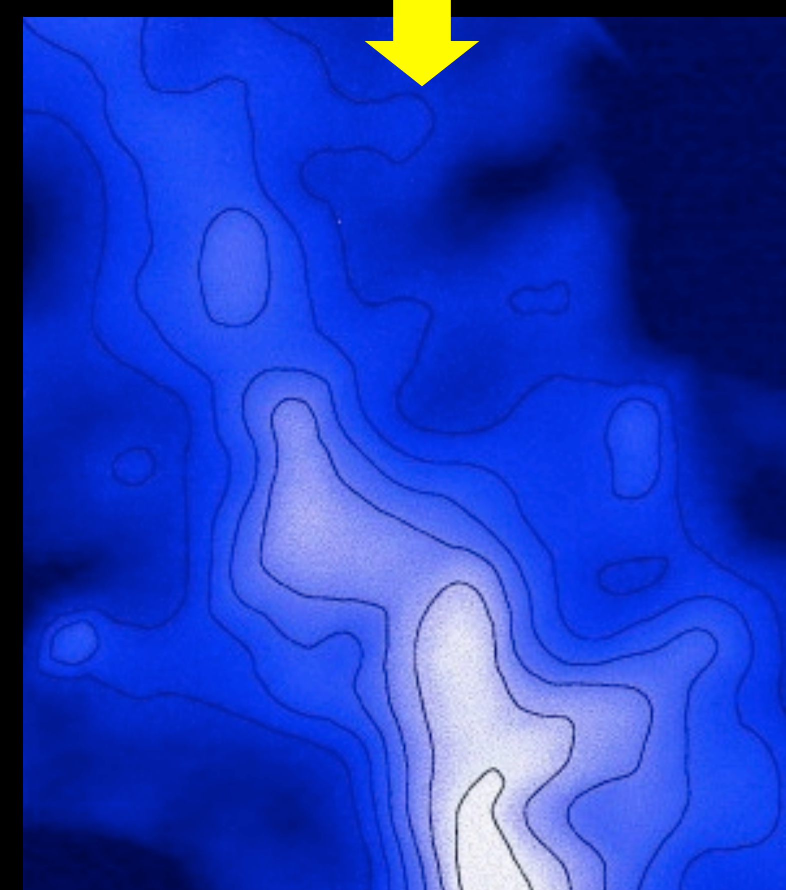
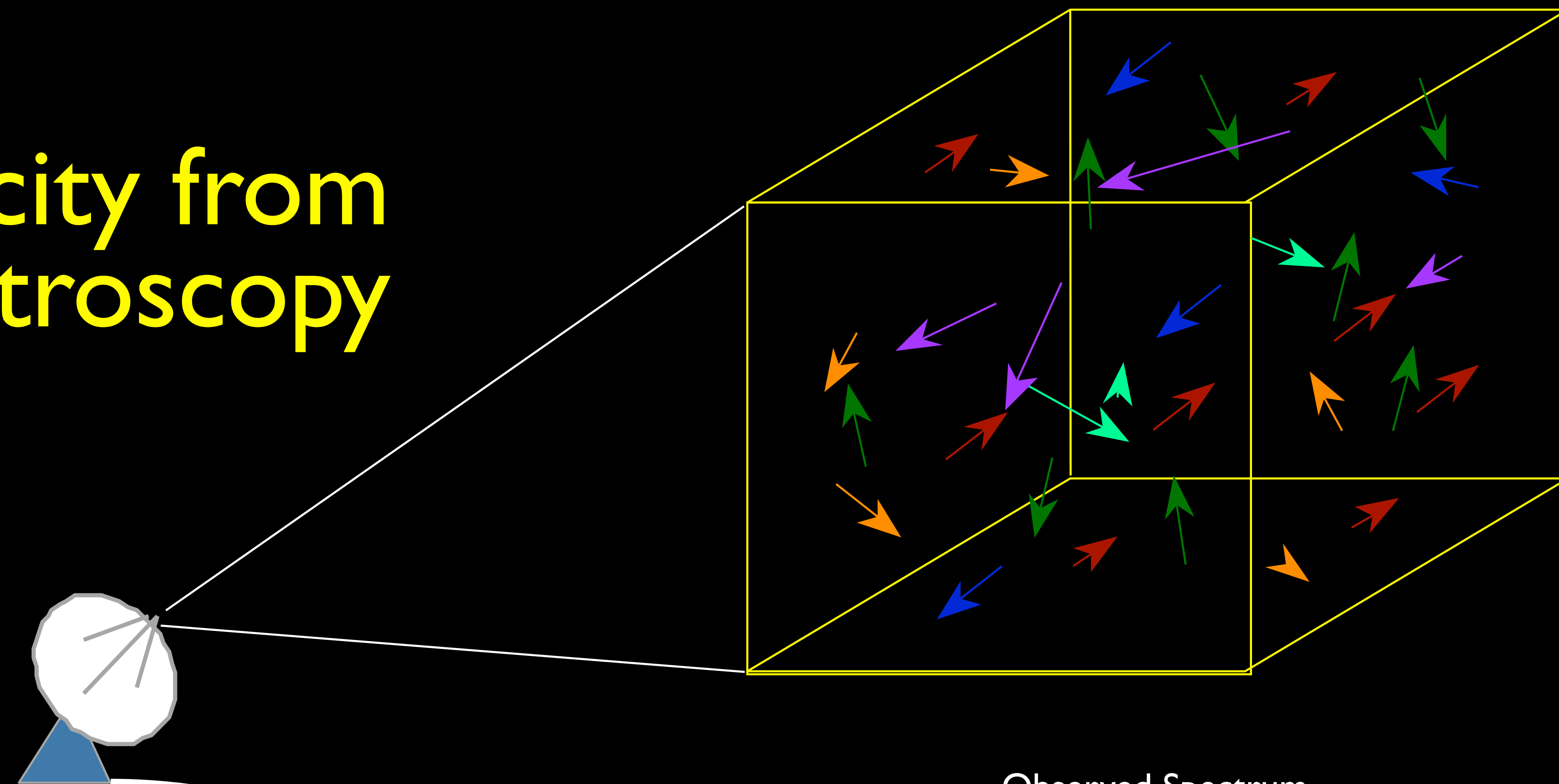
Radio Spectral-line Observations of Interstellar Clouds



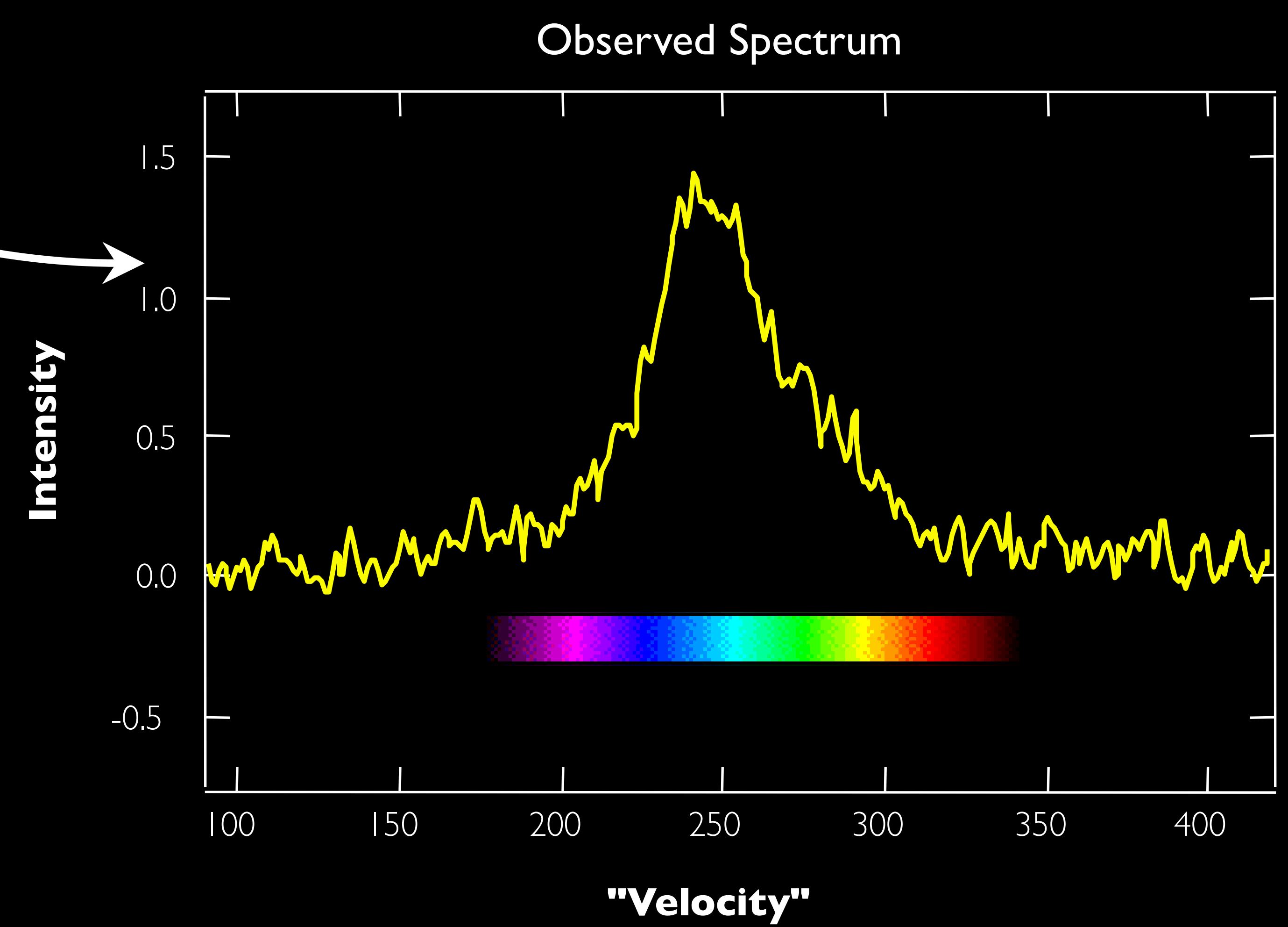




Velocity from Spectroscopy



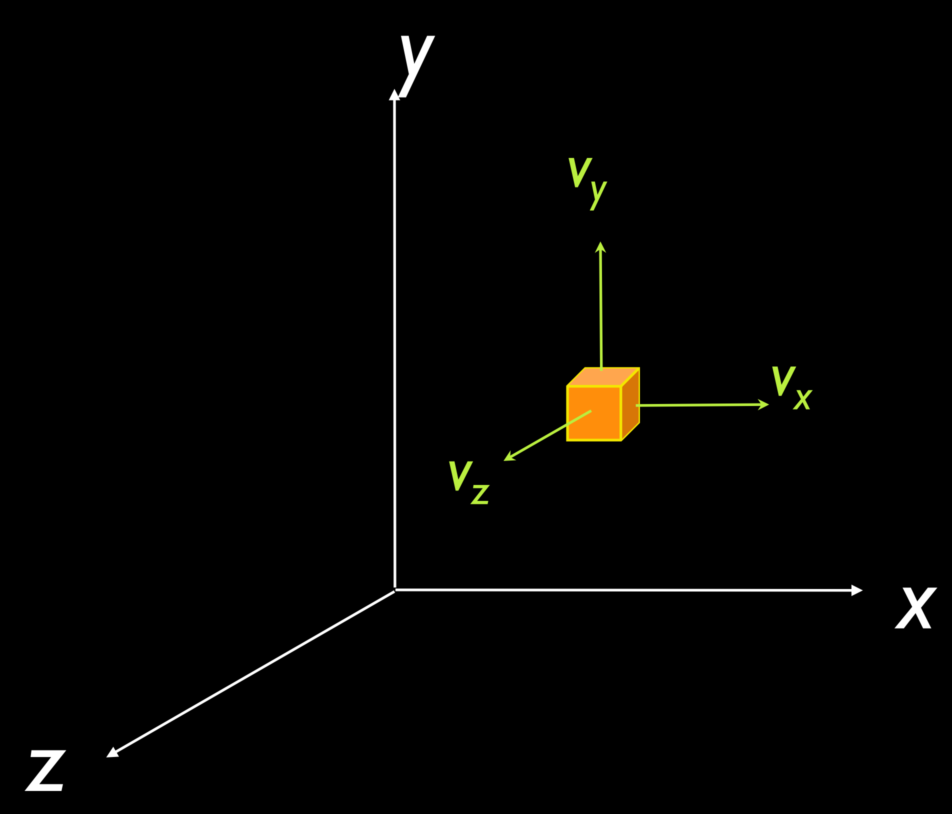
Telescope + Spectrometer



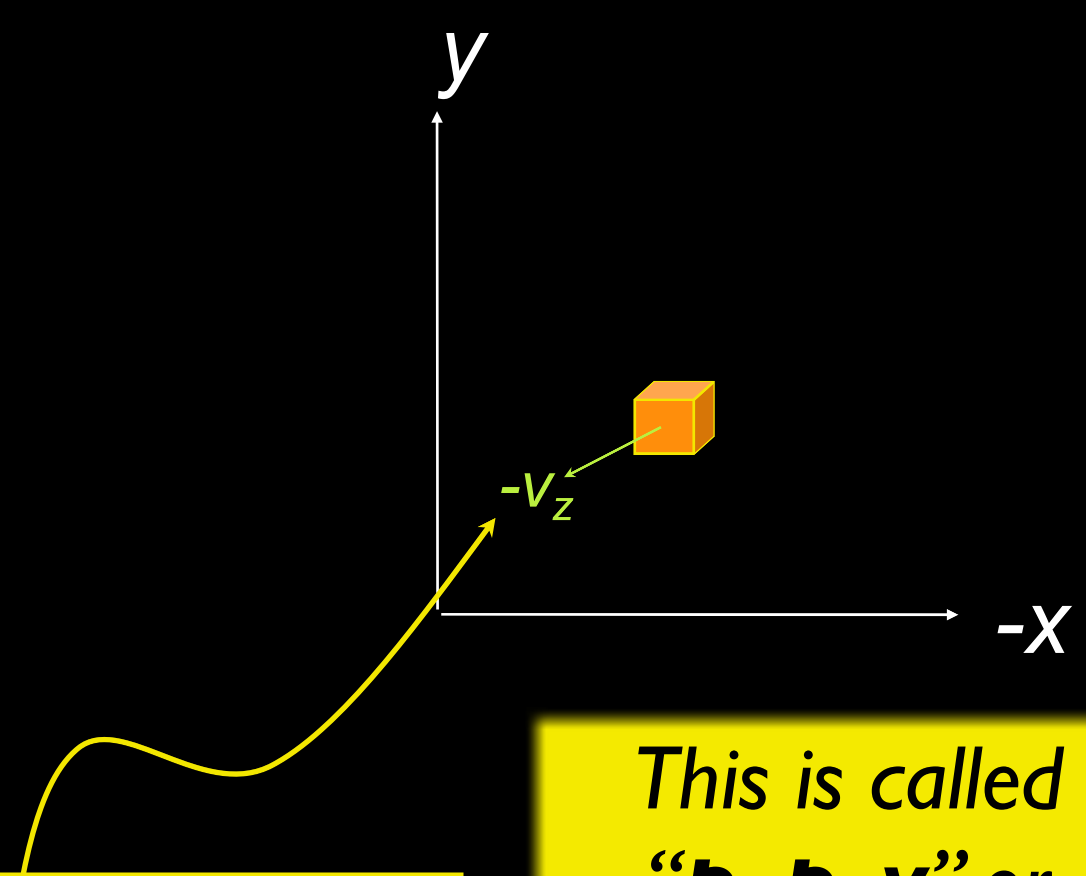
All thanks to Doppler

“Three” Dimensions: Spectral-Line Mapping

We wish we could measure…



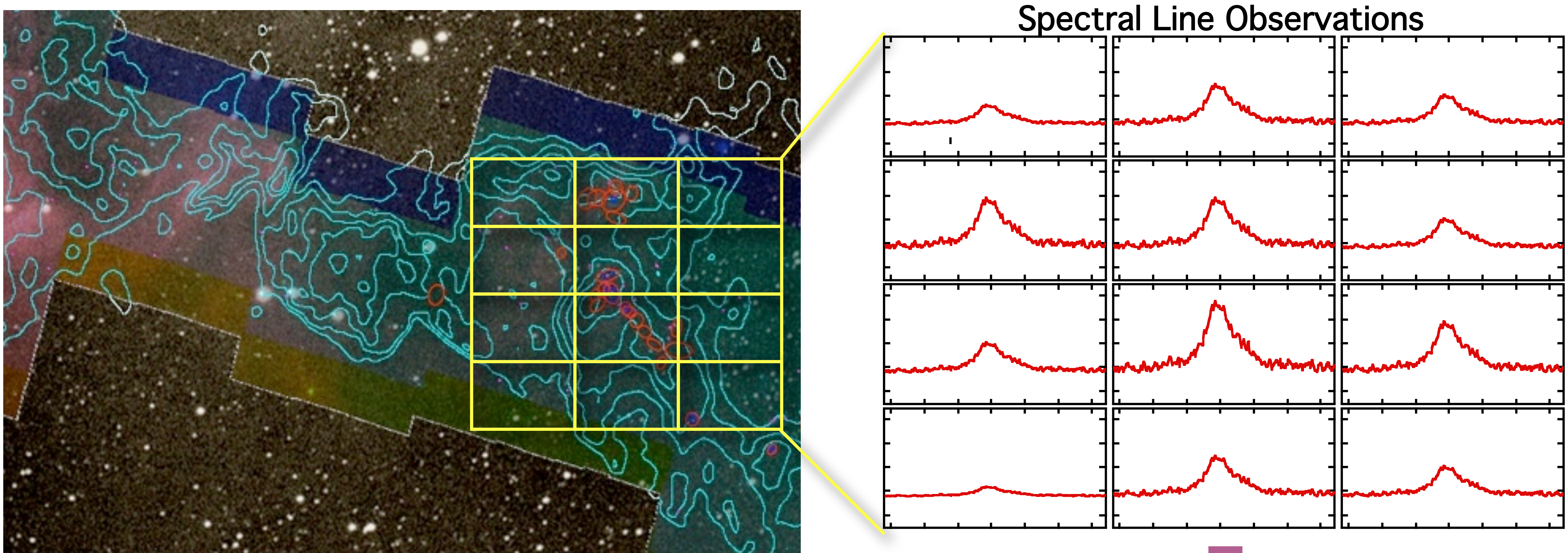
But we can measure…

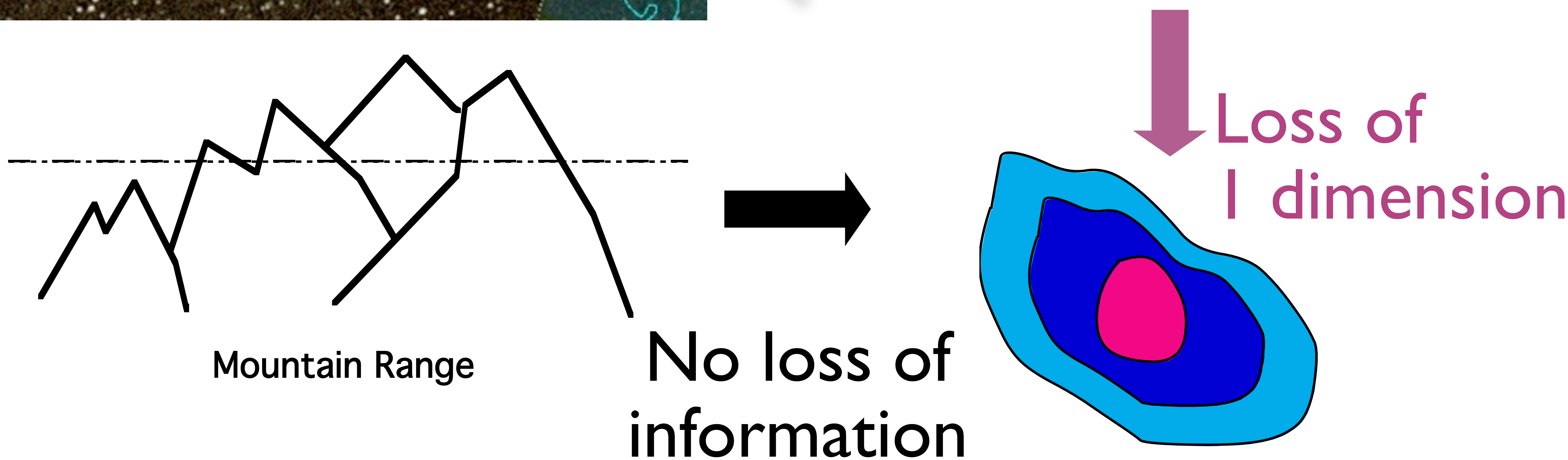


v_z *only* from “spectral-line maps”

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

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





Astronomical Visualization Tools are Traditionally 2D

IDL

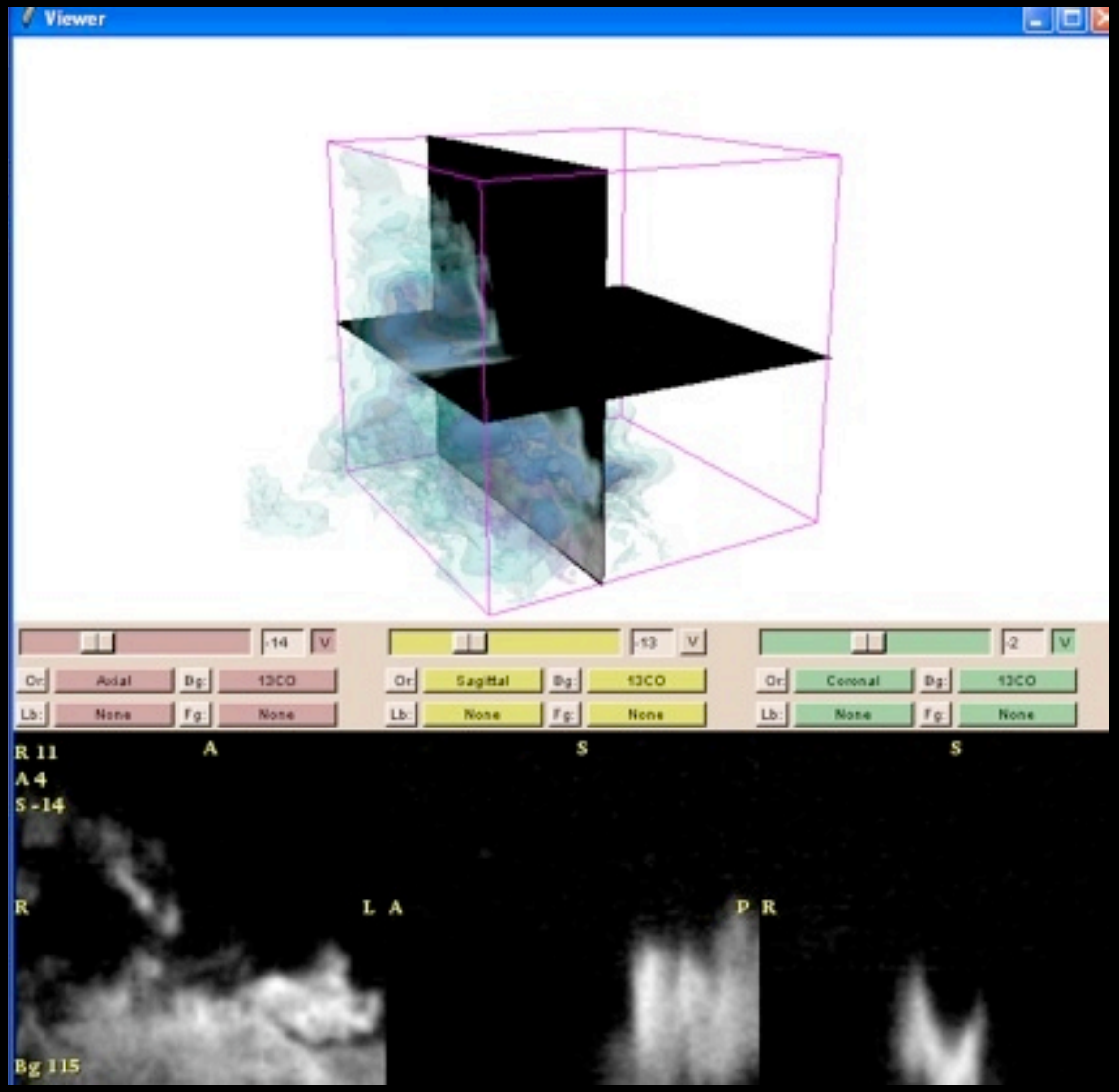
DS9

Karma*

GAIA

Aipsview

3D Slicer



"3D"=movies

COMPLETE Perseus

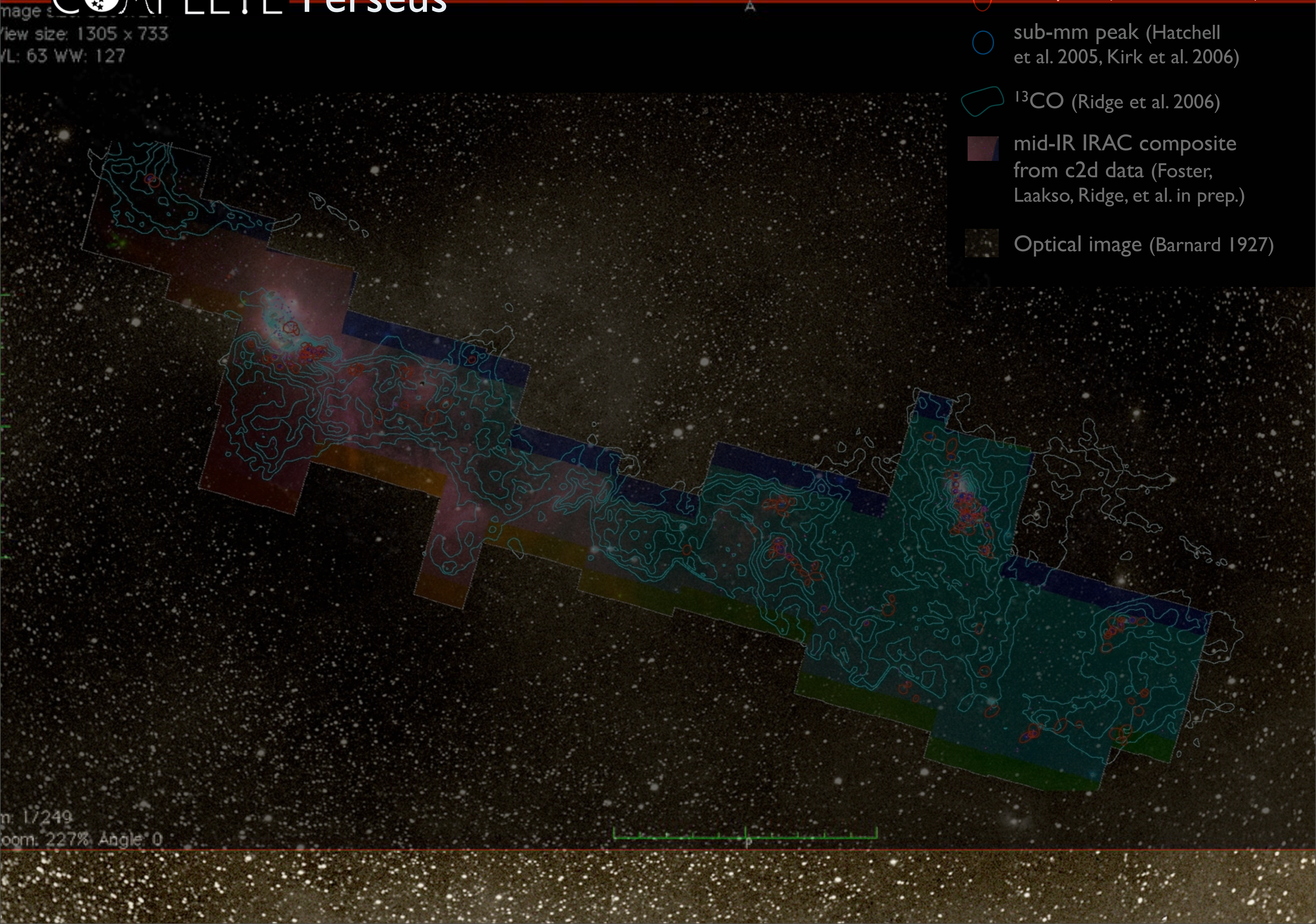
mm peak (Enoch et al. 2006)

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)

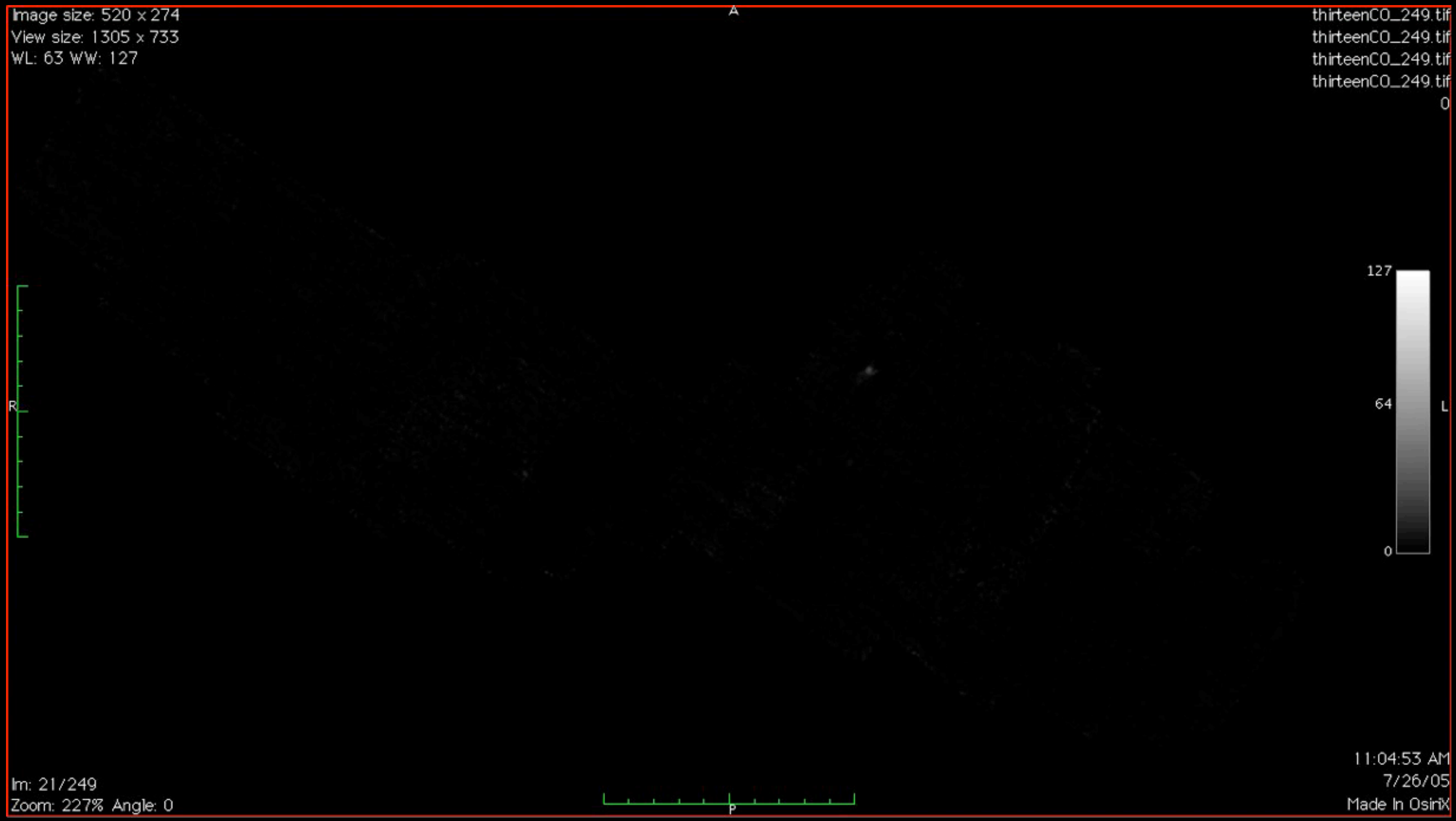


“Astronomical Medicine”

“KEITH”

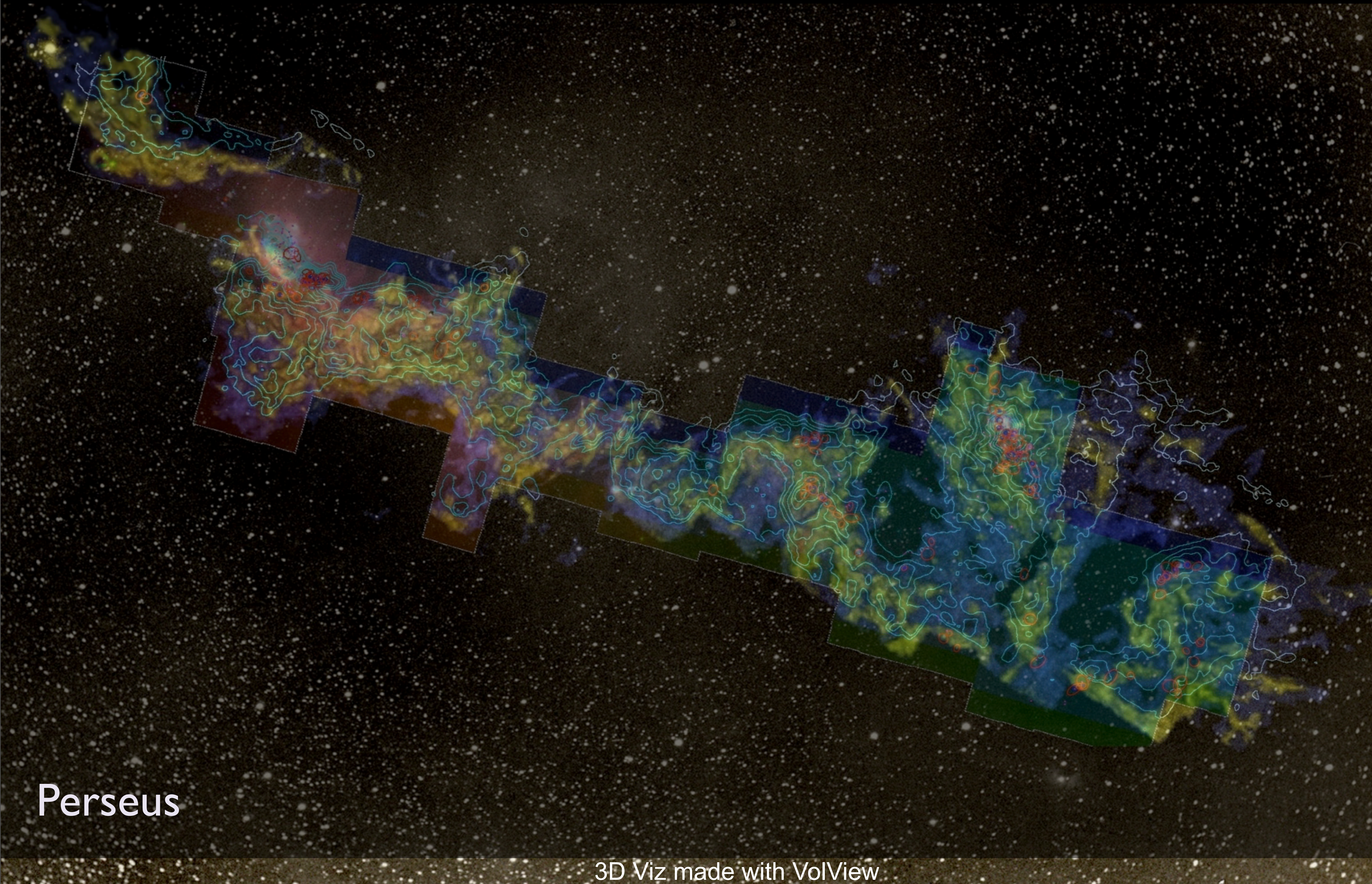
“z” is depth into head

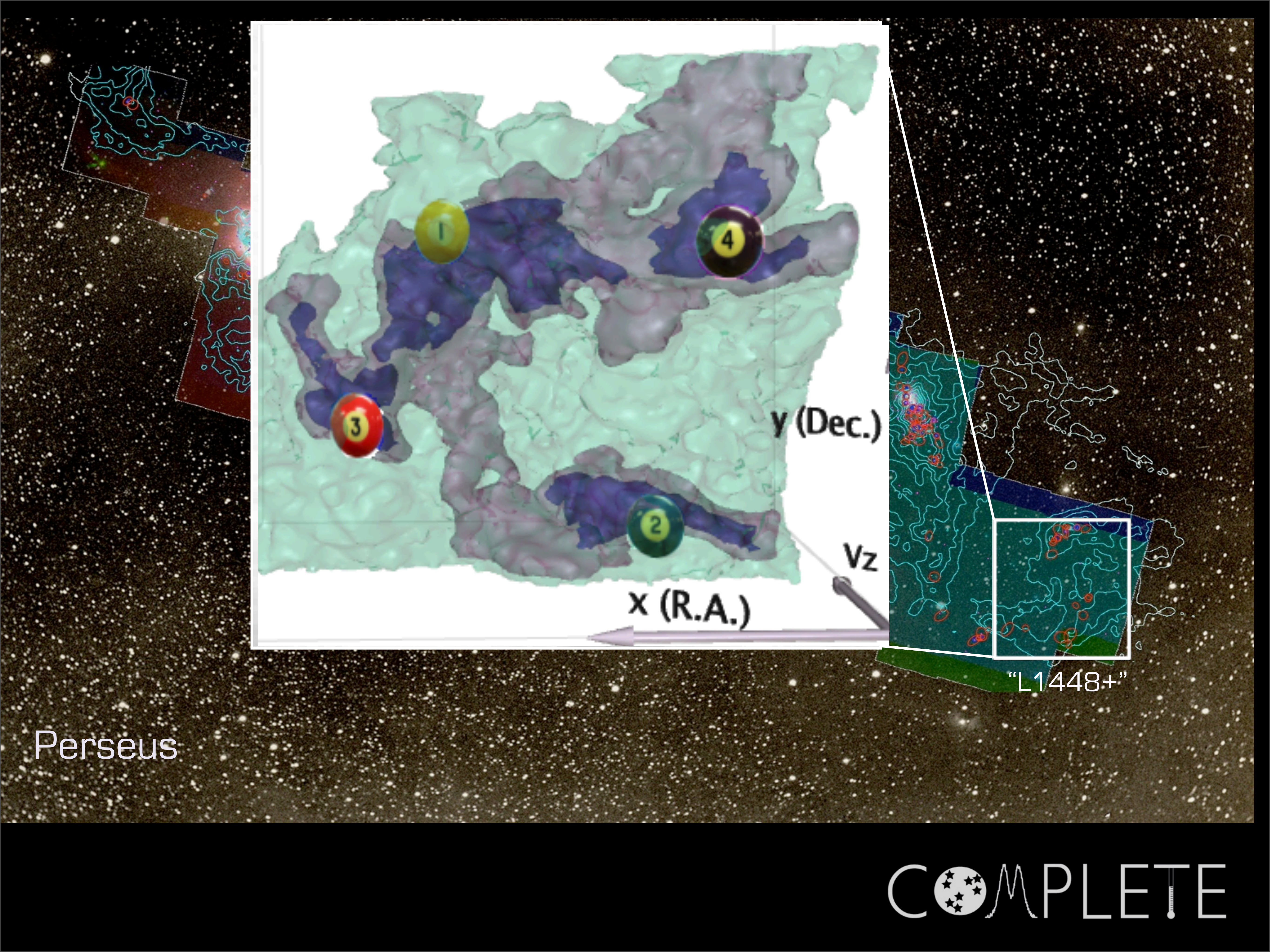
“PERSEUS”



“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



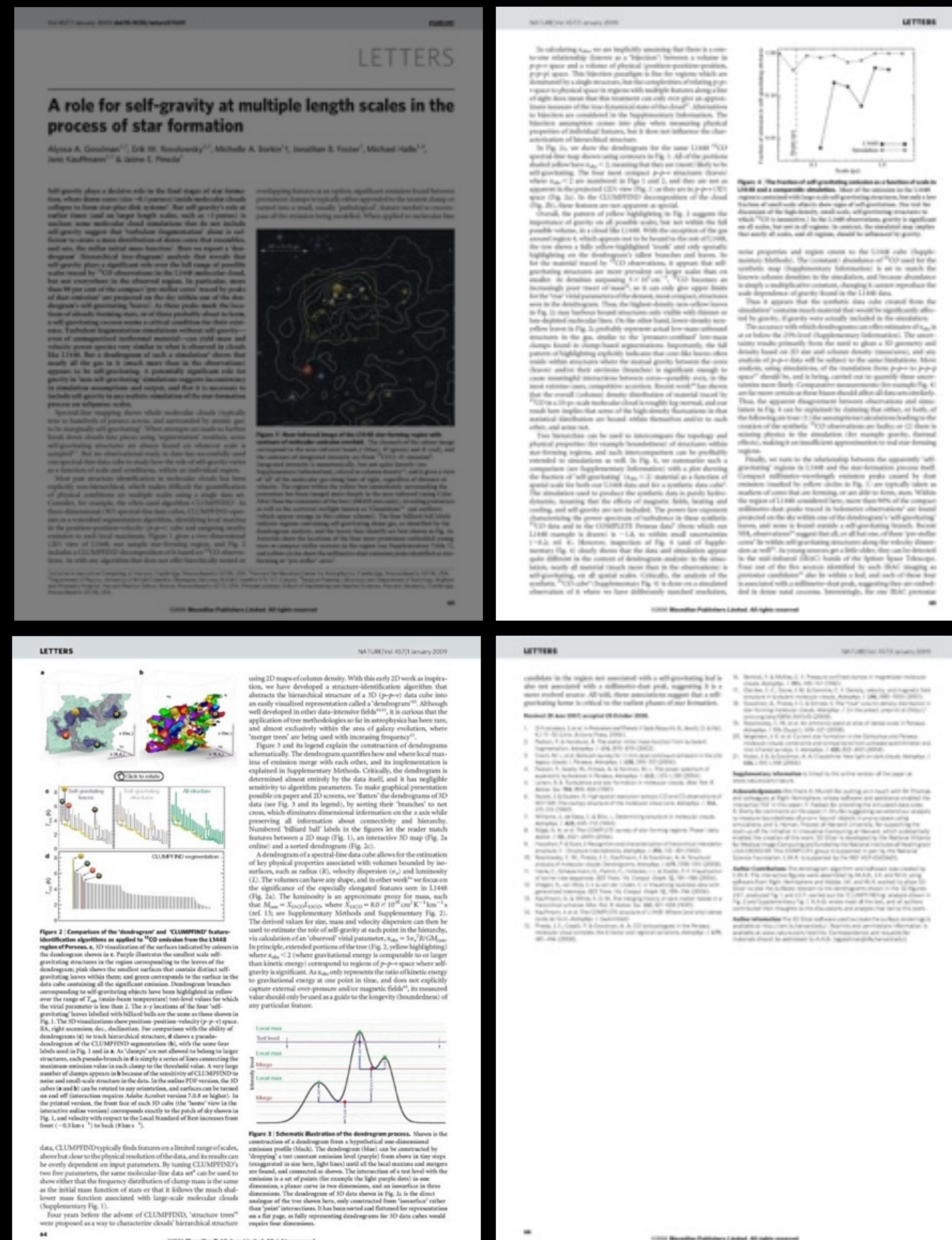
1
4
3
2
y (Dec.)
Vz
x (R.A.)
"L1448+"
Perseus
COMPLETE

"turbulent fragmentation"

"(magneto-)hydrodynamic simulation"

"bi-jection"

"virial parameter"


LETTERS

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✔ "integrated intensity*"

✔ "p-p-v cube"

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"turbulent power spectrum"

"synthetic observation"

"depletion, opacity"

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"3D PDF"

caveats

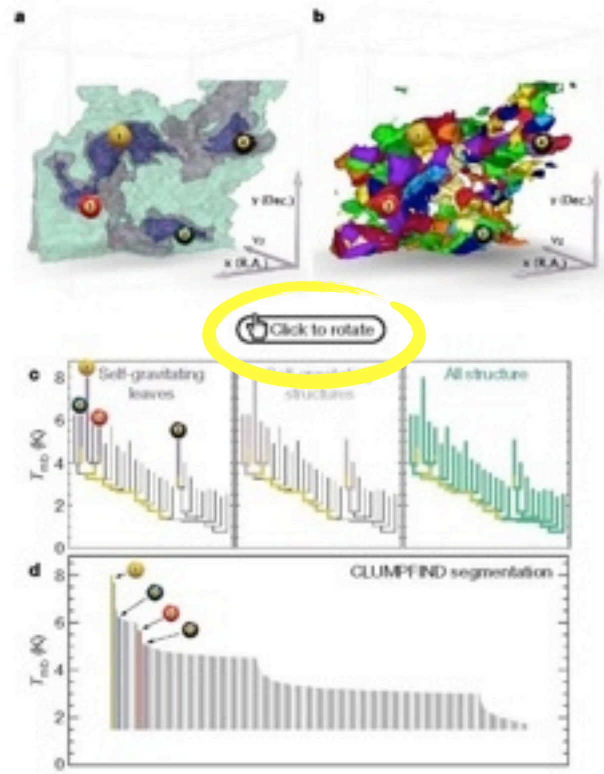

Figure 2 | Comparison of the 'dendrogram' and 'CLUMPFIND' feature-identification algorithms as applied to ^{13}CO emission from the L1448 region of Perseus. a, 3D visualization of the surfaces indicated by colours in the dendrogram shown in **c**. Purple illustrates the smallest scale self-gravitating 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 $T_{\rm mb}$ (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 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 set[8] 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 frequency[13].

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 work[14] 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 $M_{\rm lum} = X_{\rm 13CO} L_{\rm 13CO}$, where $X_{\rm 13CO} = 8.0 \times 10^{20}\,{\rm cm^2\,K^{-1}\,km^{-1}\,s}$ (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, $\alpha_{\rm obs} = 5\sigma_v^2 R/GM_{\rm lum}$. In principle, extended portions of the tree (Fig. 2, yellow highlighting) where $\alpha_{\rm obs} < 2$ (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 $\alpha_{\rm obs}$ 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[16], its measured value should only be used as a guide to the longevity (boundedness) of any particular feature.

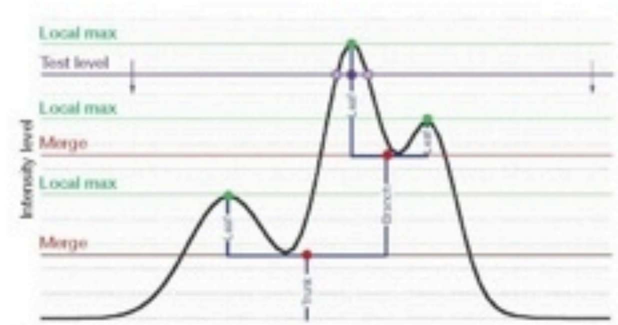

Figure 3 | Schematic illustration of the dendrogram process. Shown is the construction of a dendrogram from a hypothetical one-dimensional emission profile (black). The dendrogram (blue) can be constructed by 'dropping' a test constant emission level (purple) from above in tiny steps (exaggerated in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

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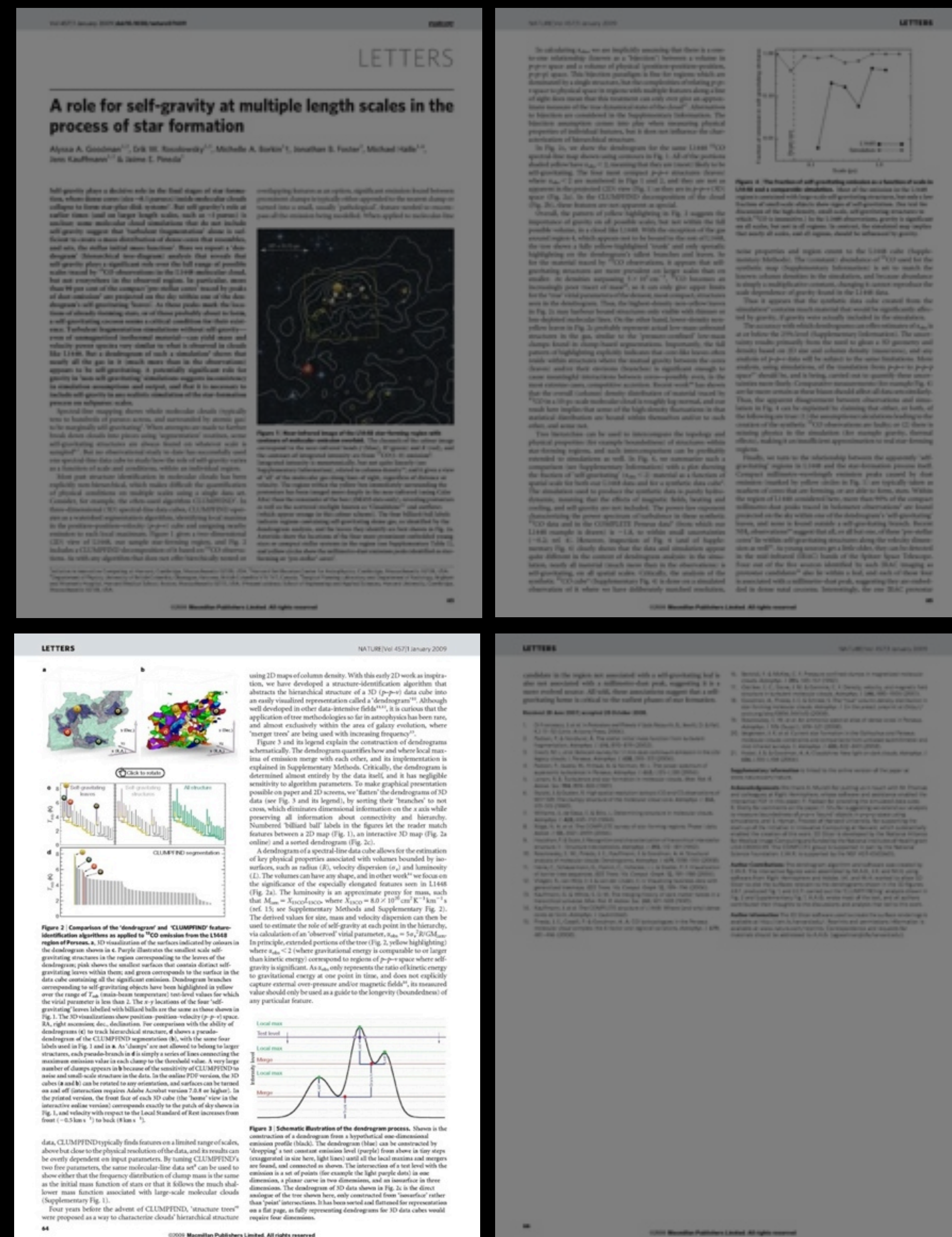

✔ *“integrated intensity*”*

✔ *“p-p-v cube”*

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✔ *“3D PDF”*

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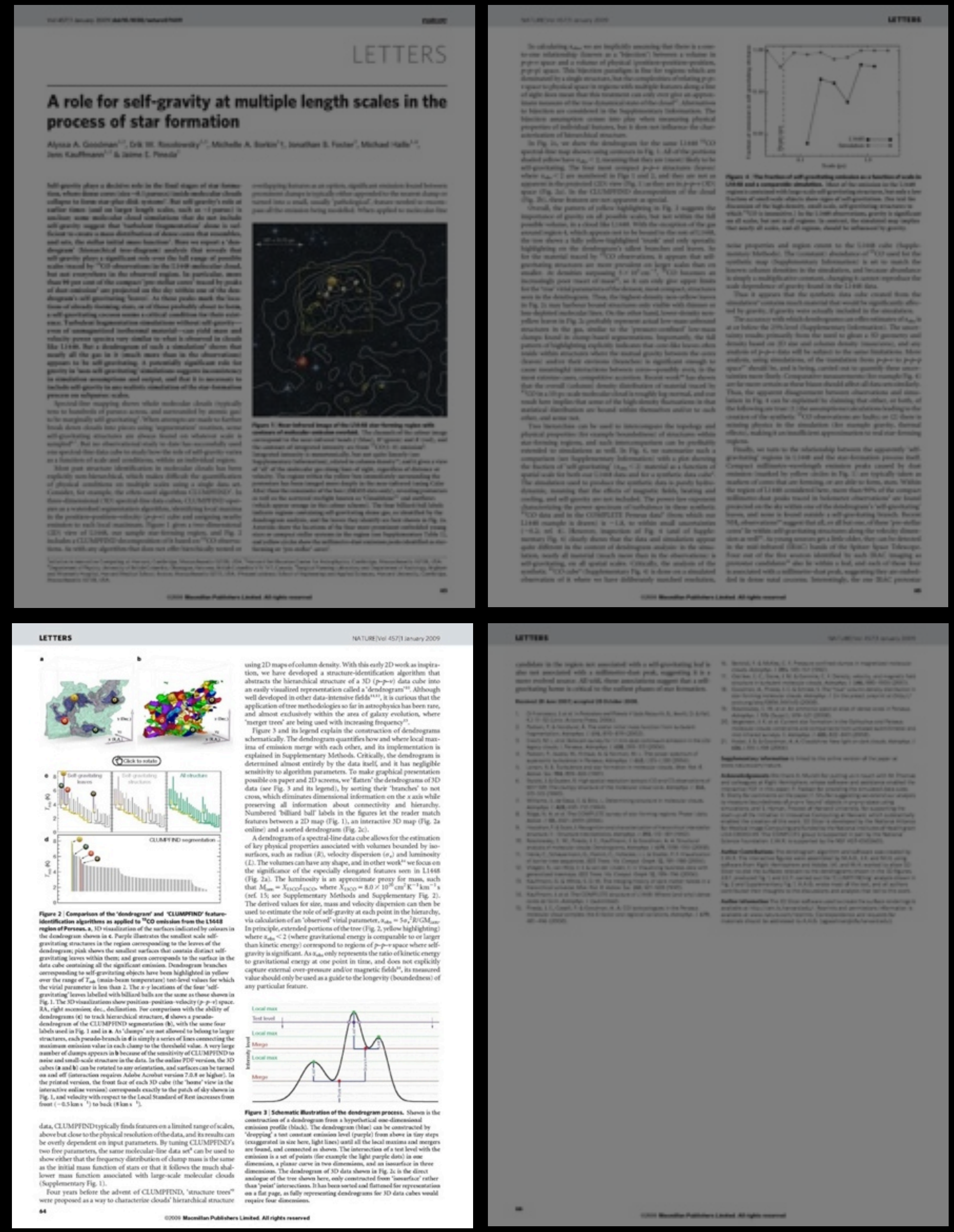
"bi-jection"

"virial parameter"



LETTERS

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

"turbulent power spectrum"

"synthetic observation"

"depletion, opacity"

"taste-test"

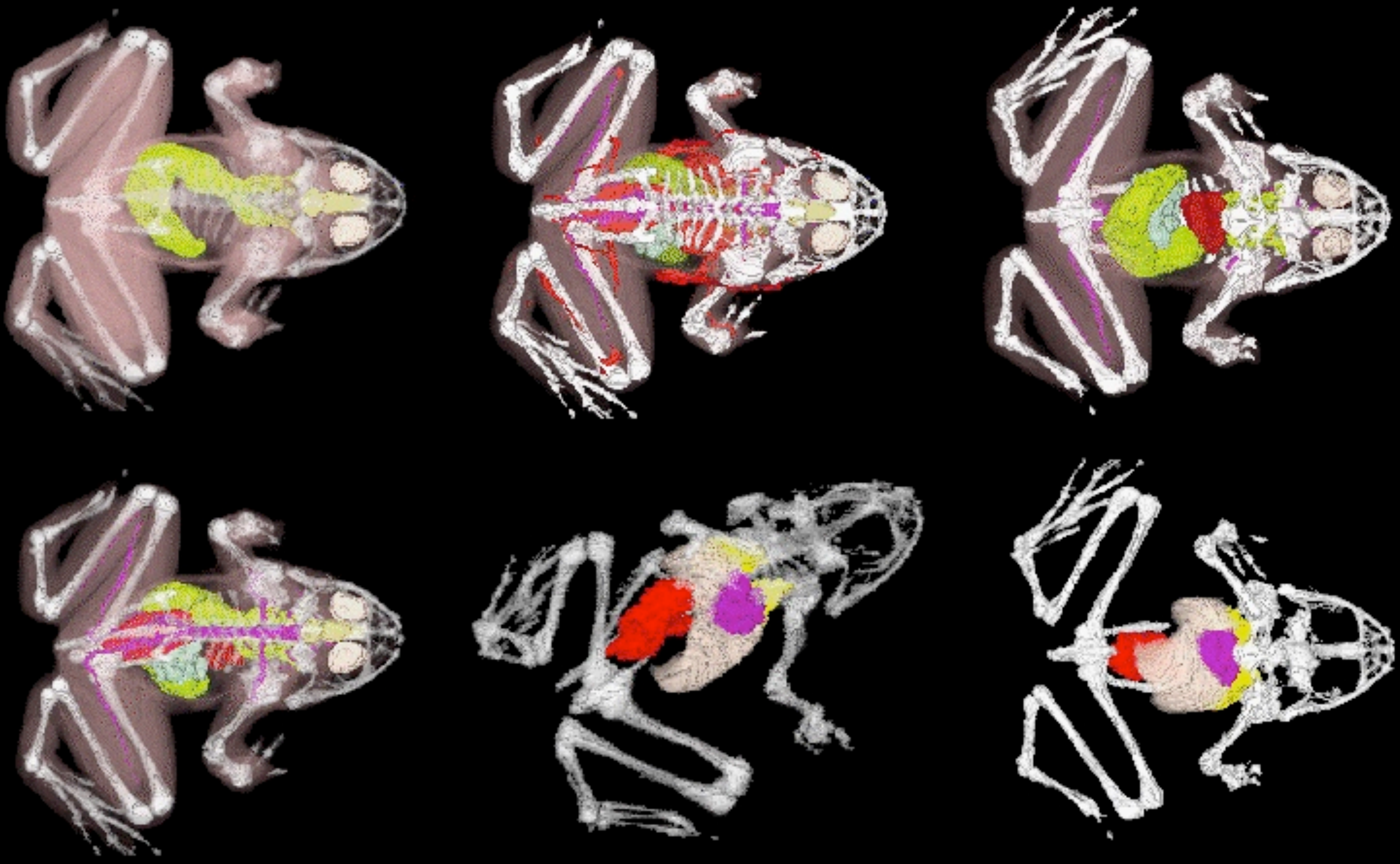
caveats

"segmentation"

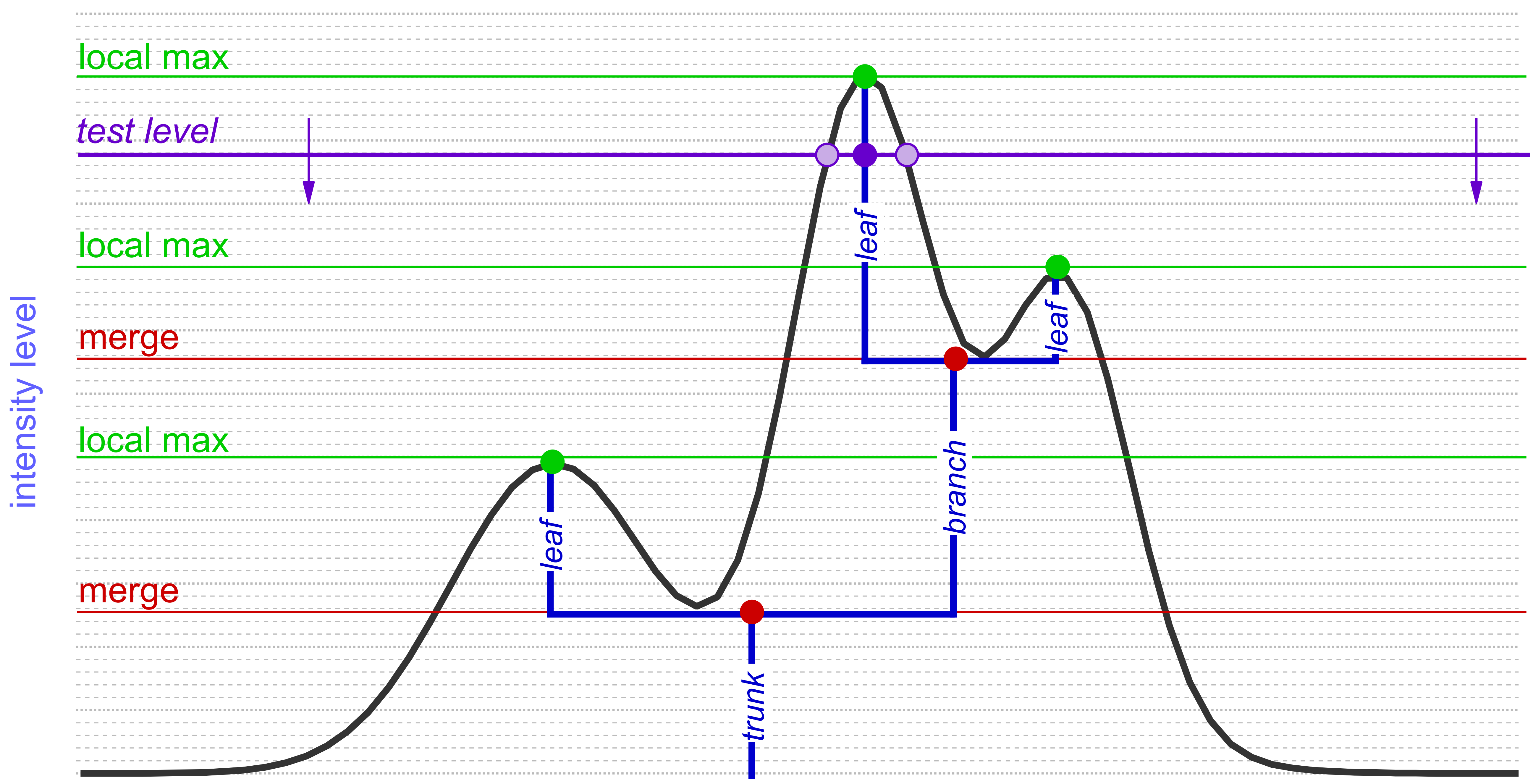
"CLUMPFIND"

"Dendrogram"

“Segmentation”



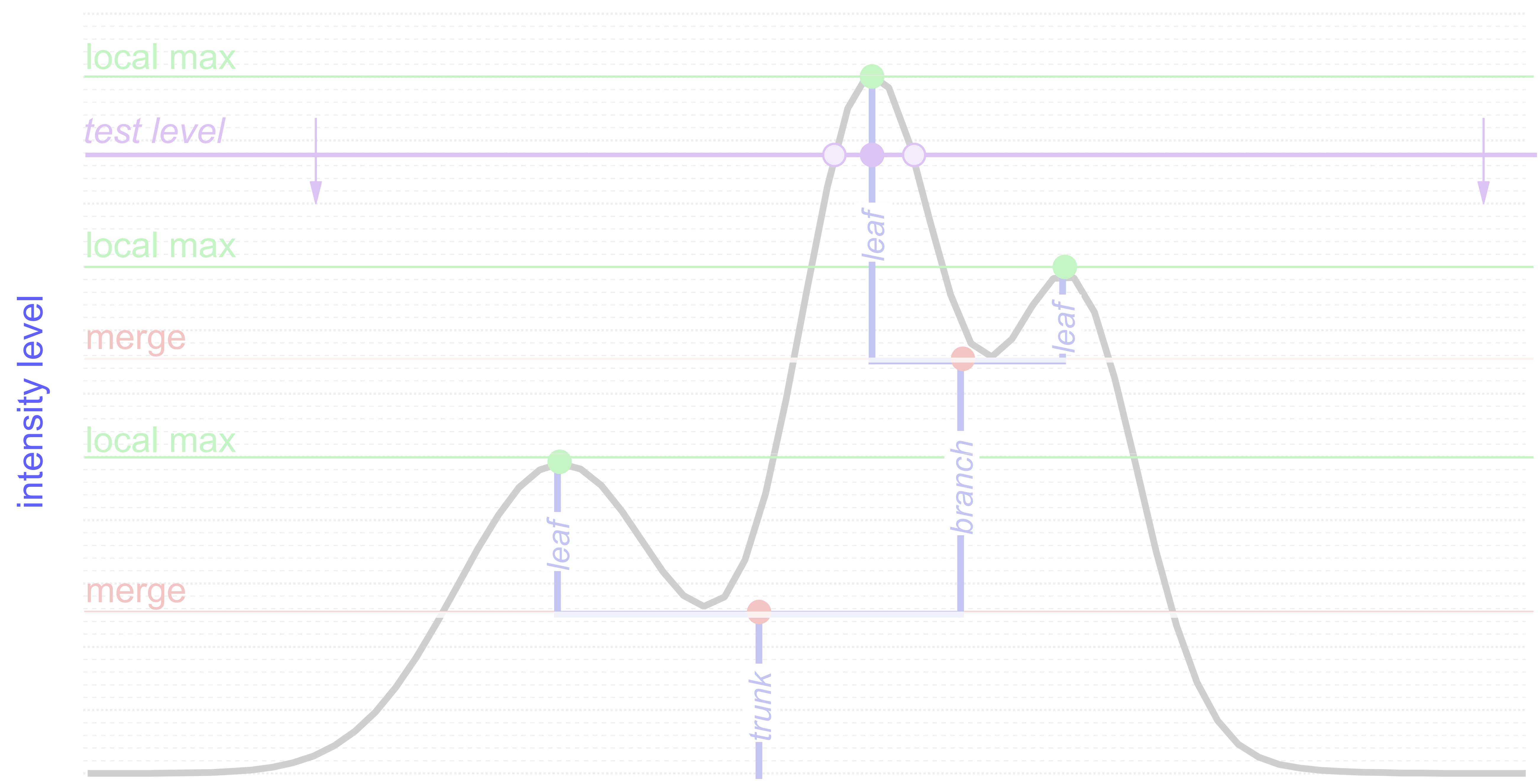
Dendrograms



Hierarchical “Segmentation”

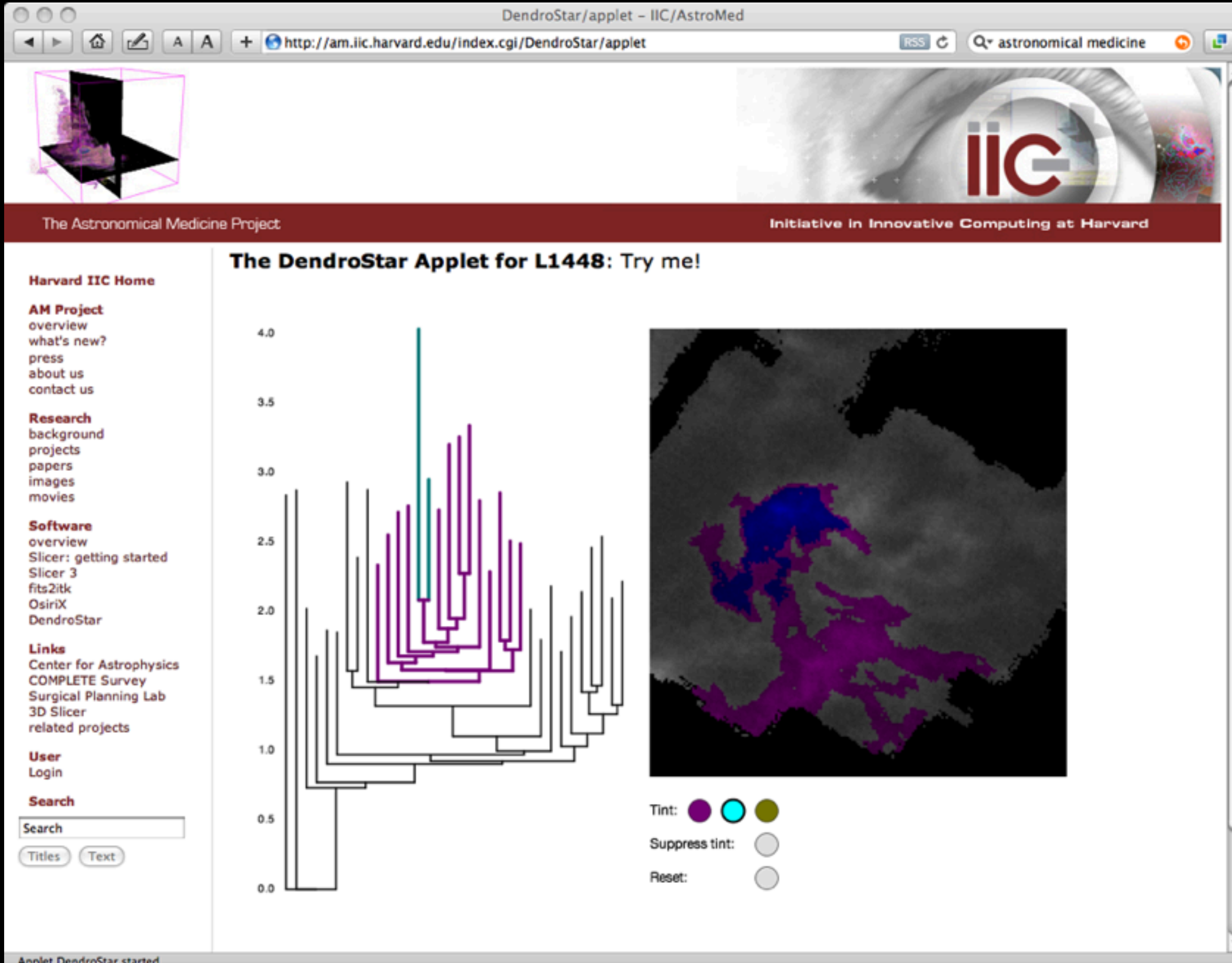
Rosolowsky, Pineda, Kauffmann & Goodman 2008

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*

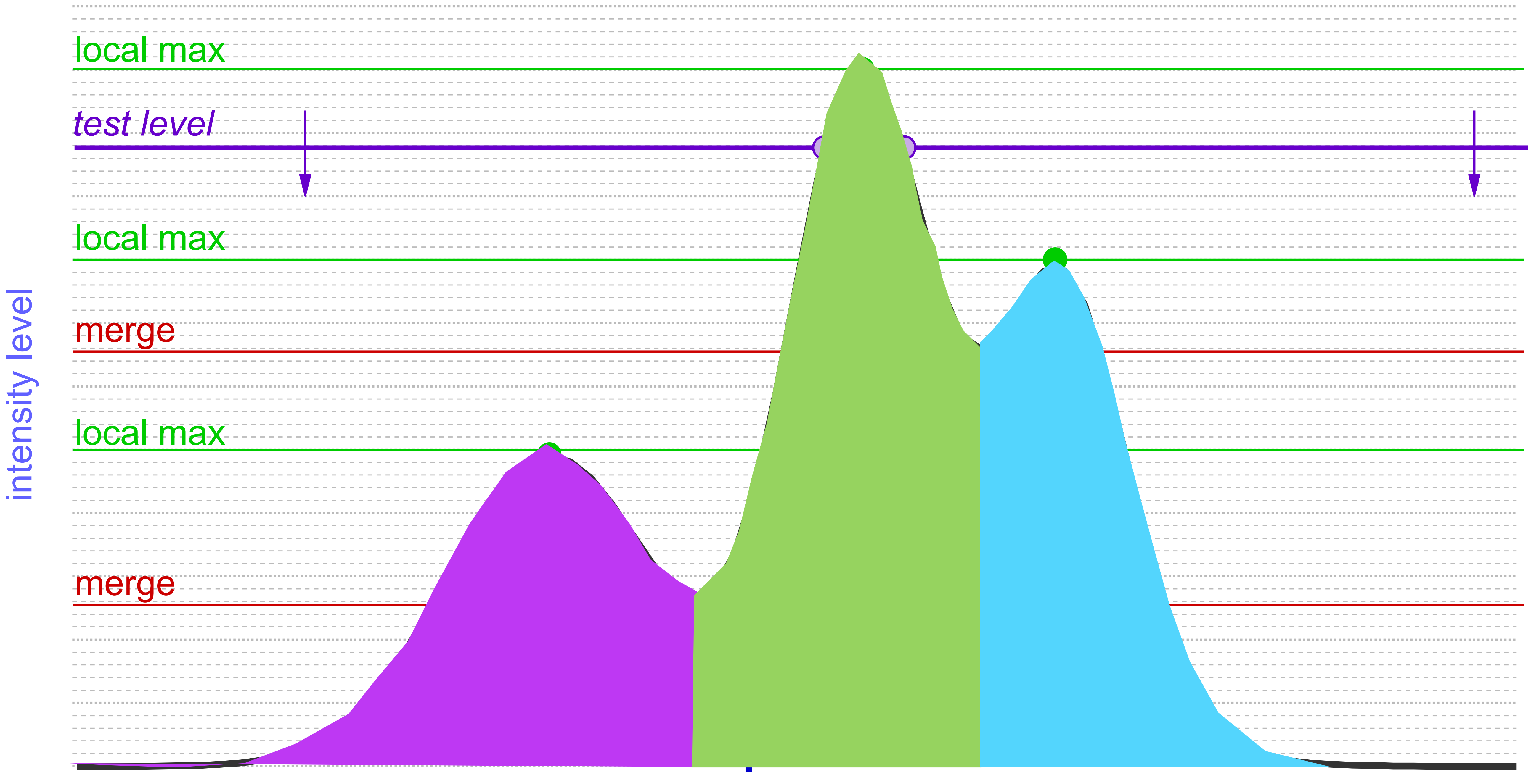


http://am.iic.harvard.edu/index.cgi/DendroStar/applet

Dendrogram Algorithm by Erik Rosolwosky; Applet by Douglas Alan

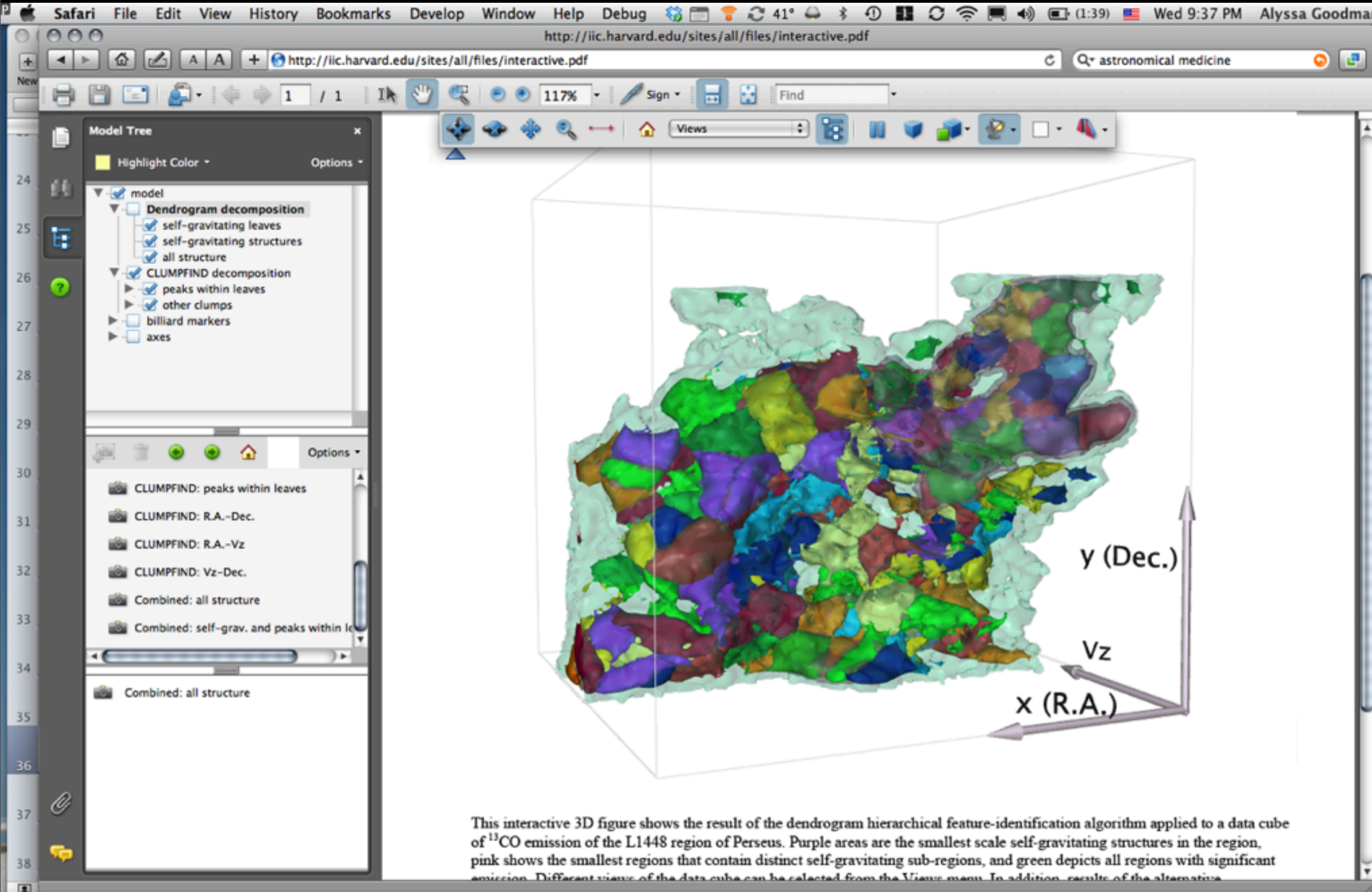
3D, see PDF...

What would *CLUMPFIND* do?



No hierarchy is allowed, all clumps go to the baseline.

(Williams, De Geus & Blitz 1994)



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)*

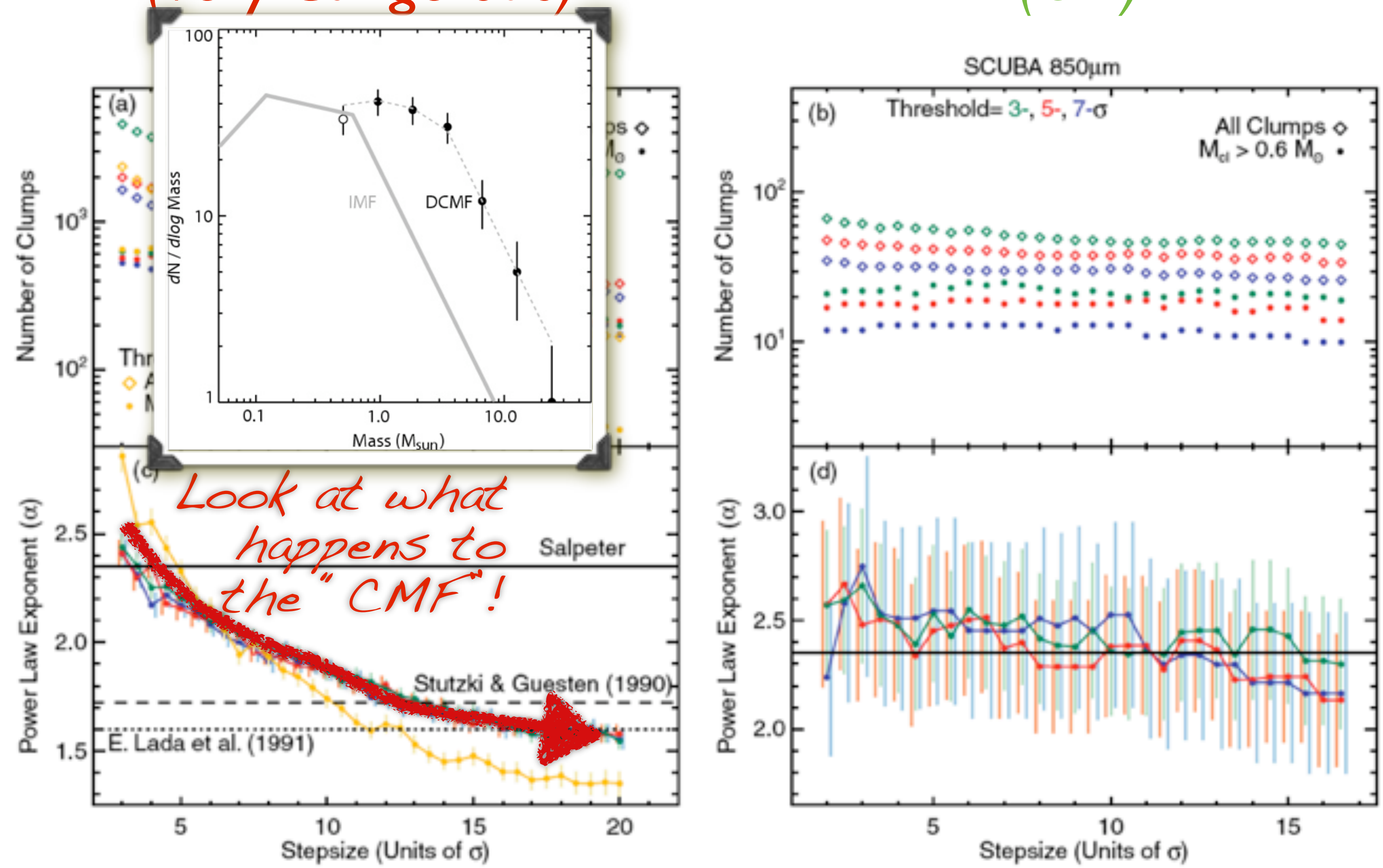


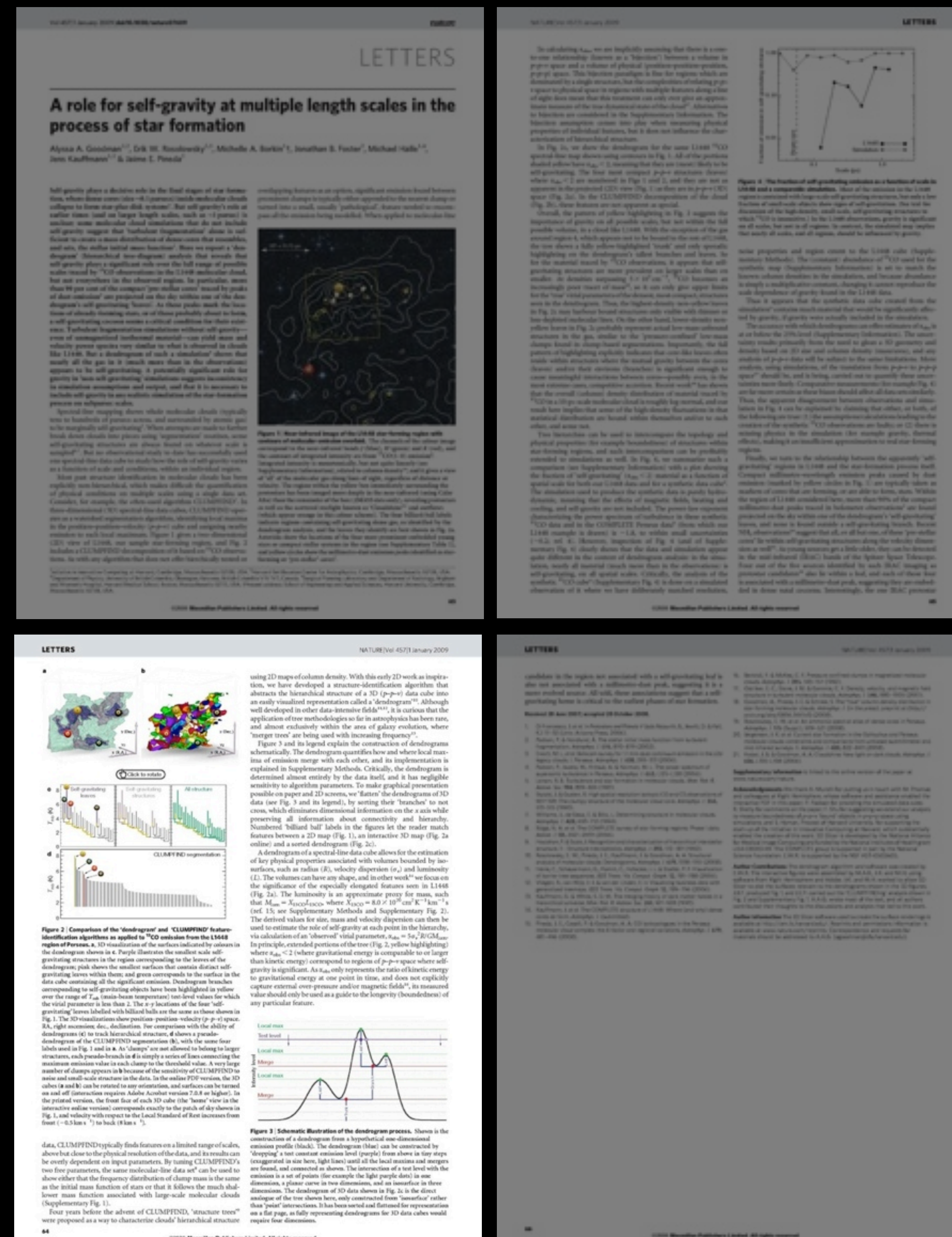
Figure 2. Summary of all Clumpfind runs as a function of stepsize. Color represent different thresholds: blue, red, and green for 3σ, 5σ, and 7σ, respectively; we also show in orange results with a threshold of 5σ for ^{13}CO data with added noise. Left and right columns show results for ^{13}CO and 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 ~2 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”

✔“segmentation”

✔“CLUMPFIND”

✔“Dendrogram”


LETTERS

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

“(magneto-)hydrodynamic simulation”

“bi-jection”

“virial parameter”

“turbulent power spectrum”

“synthetic observation”

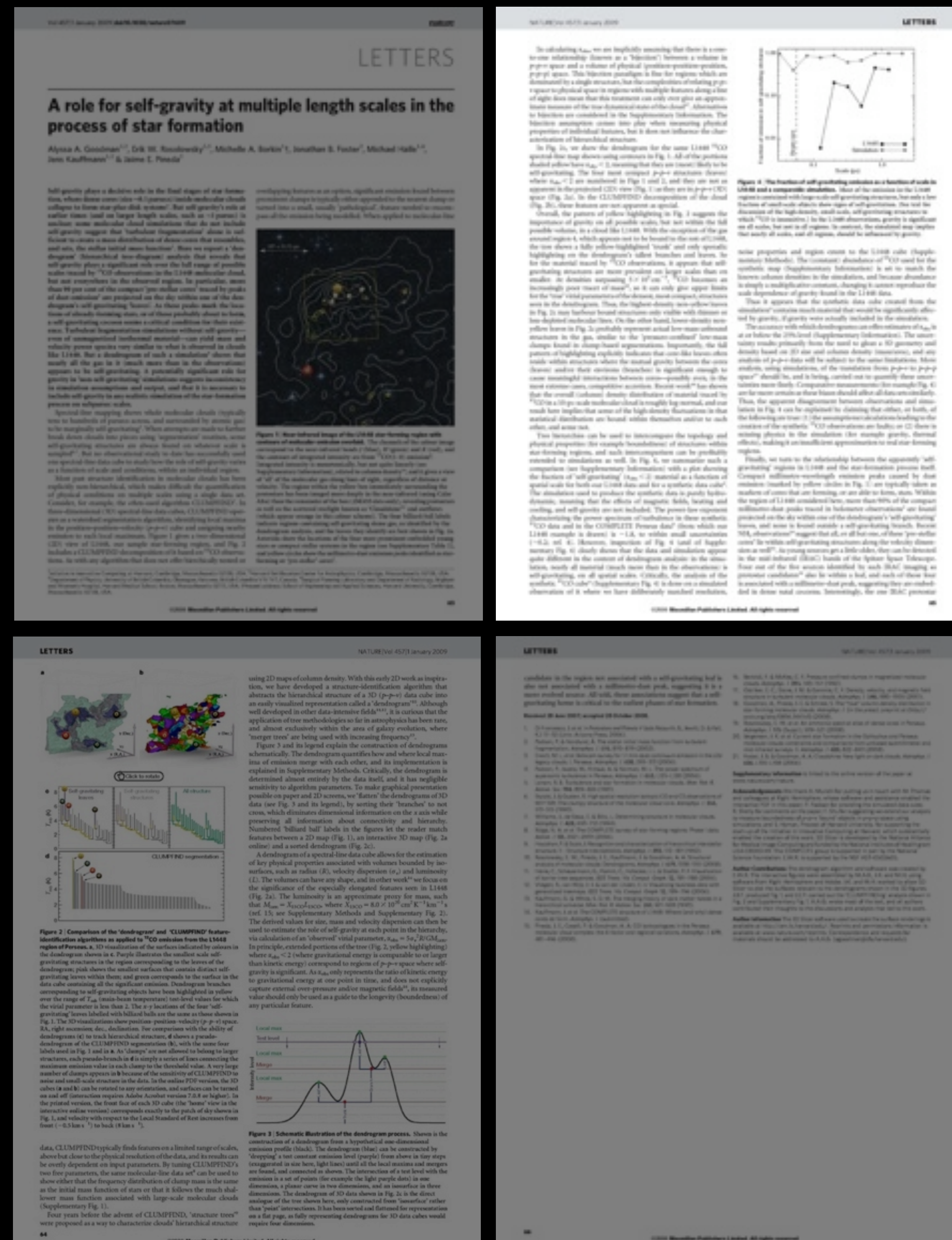
“depletion, opacity”

“taste-test”

caveats

“turbulent fragmentation”

“(magneto-)hydrodynamic simulation”


LETTERS

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

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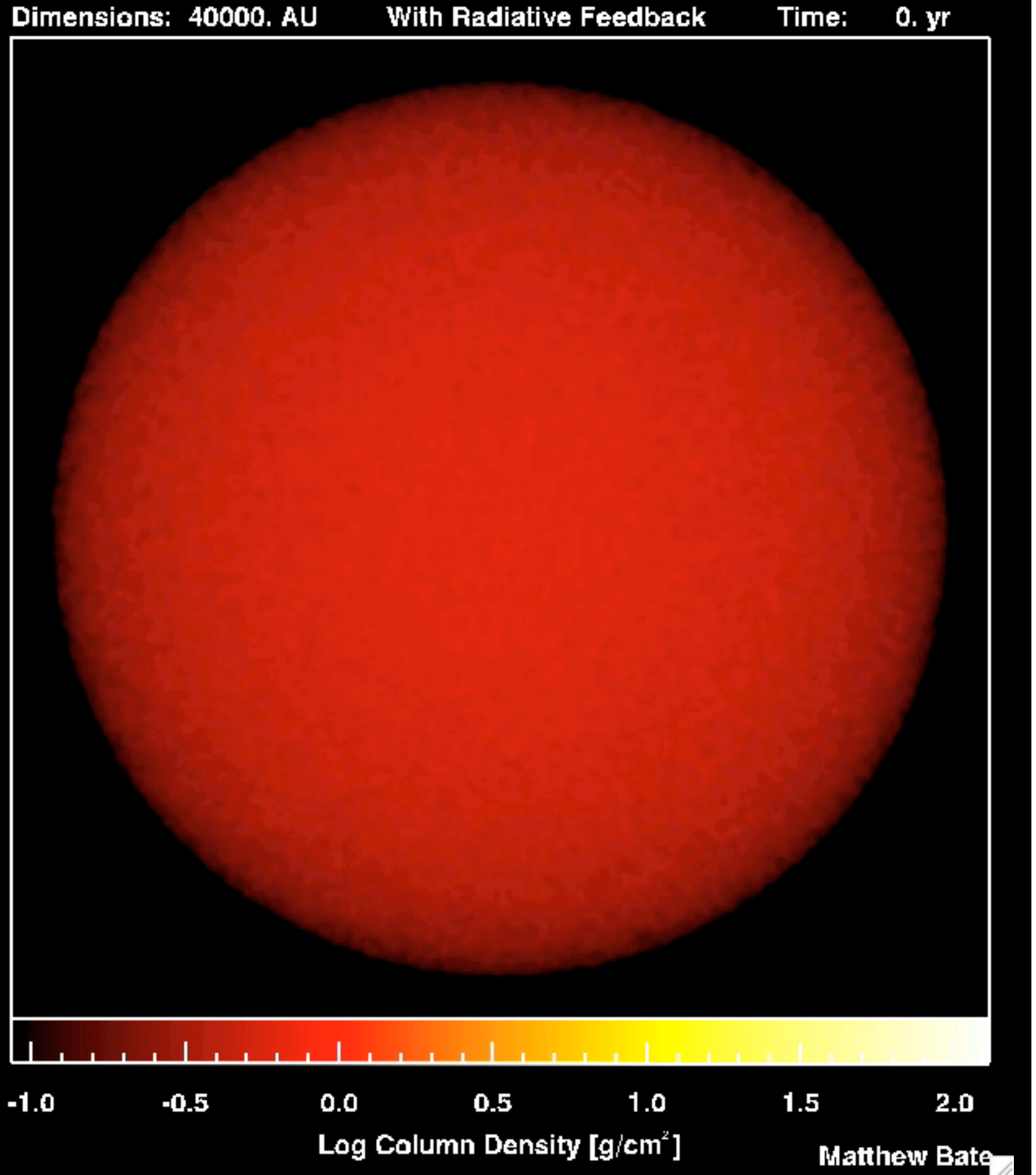
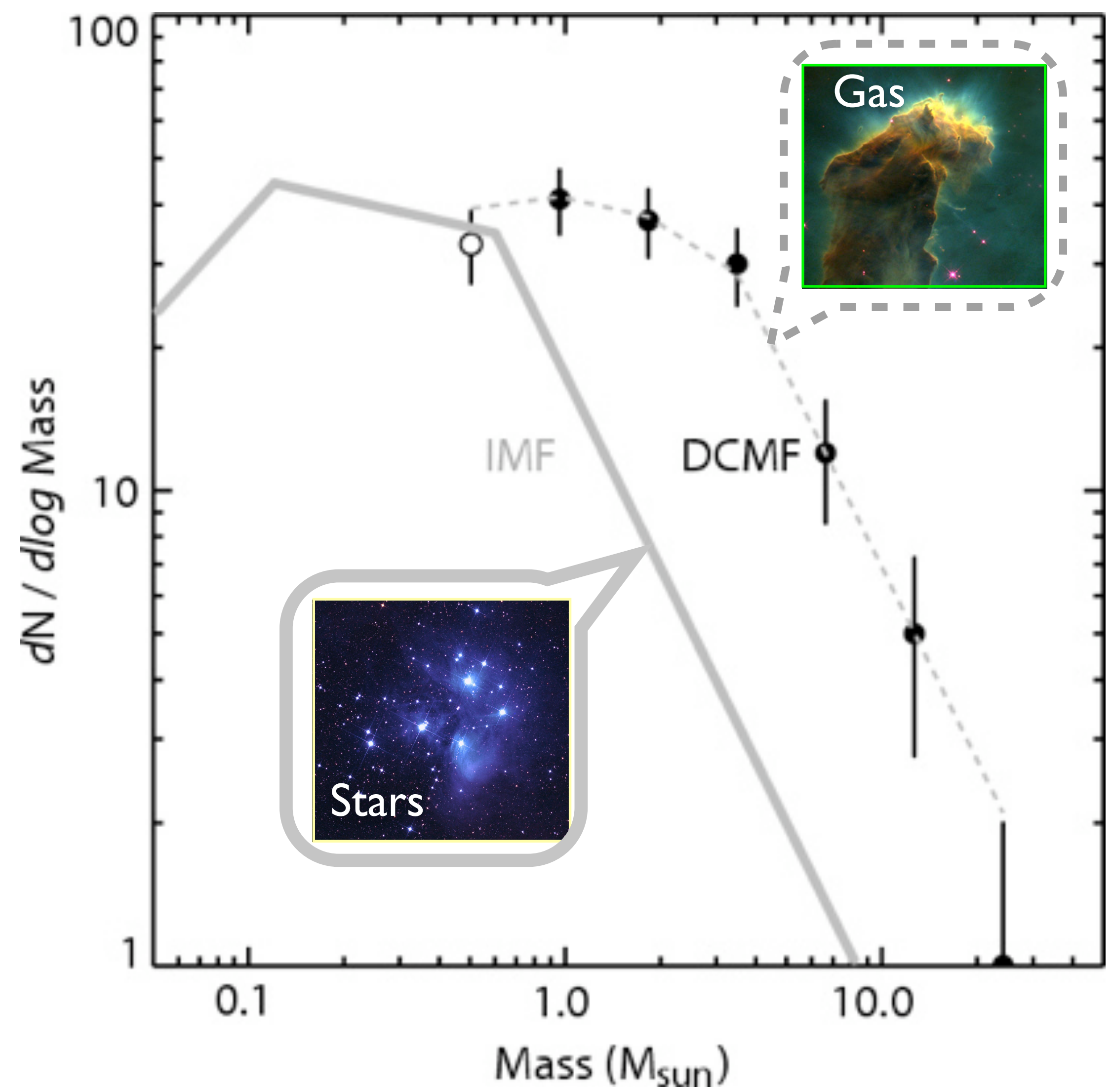
(MHD) Simulations, Turbulent Fragmentation



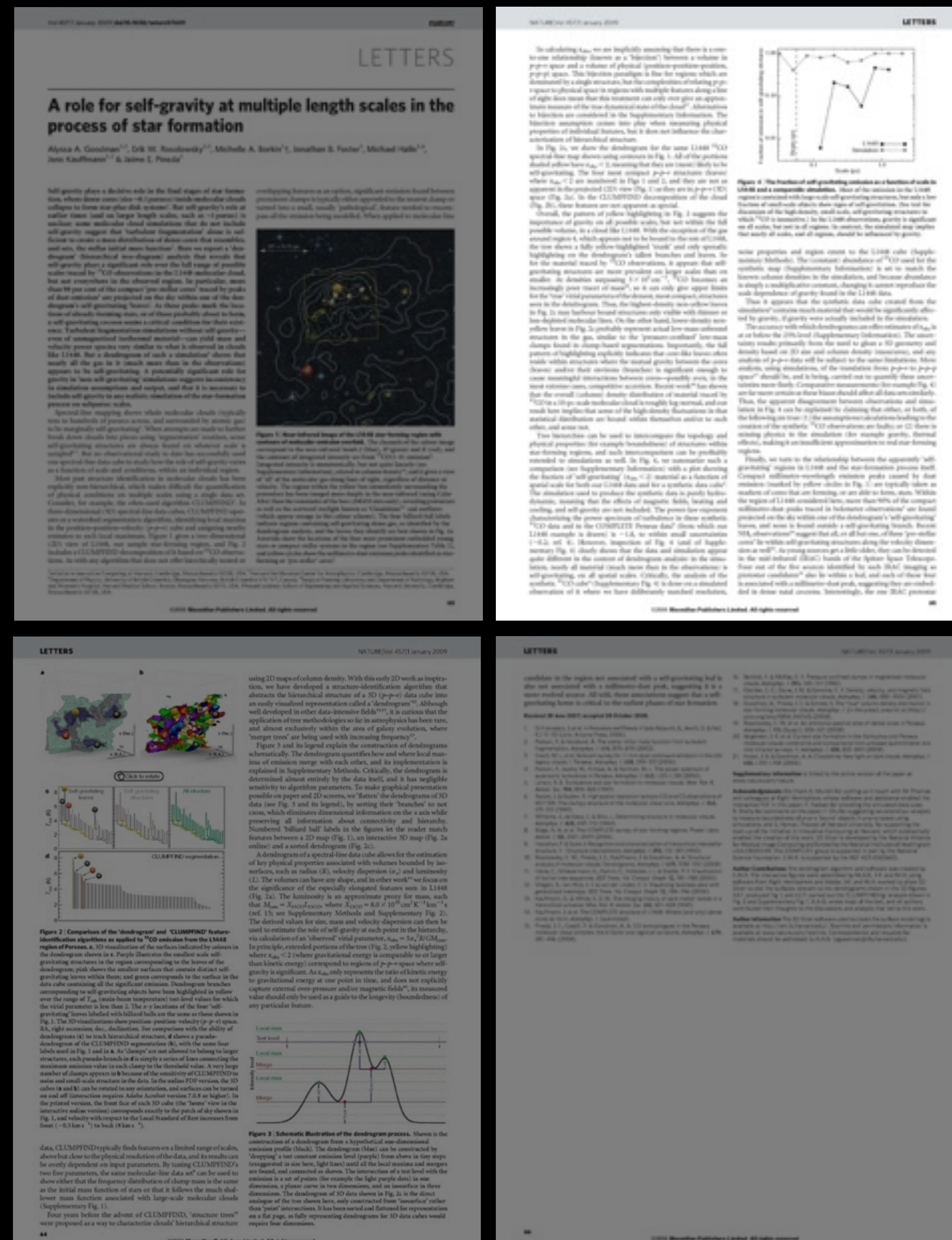
cf. Padoan & Nordlund 2002



Alves, Lombardi & Lada 2007

✔“turbulent fragmentation”

✔“(magneto-)hydrodynamic simulation”



“bi-jection”

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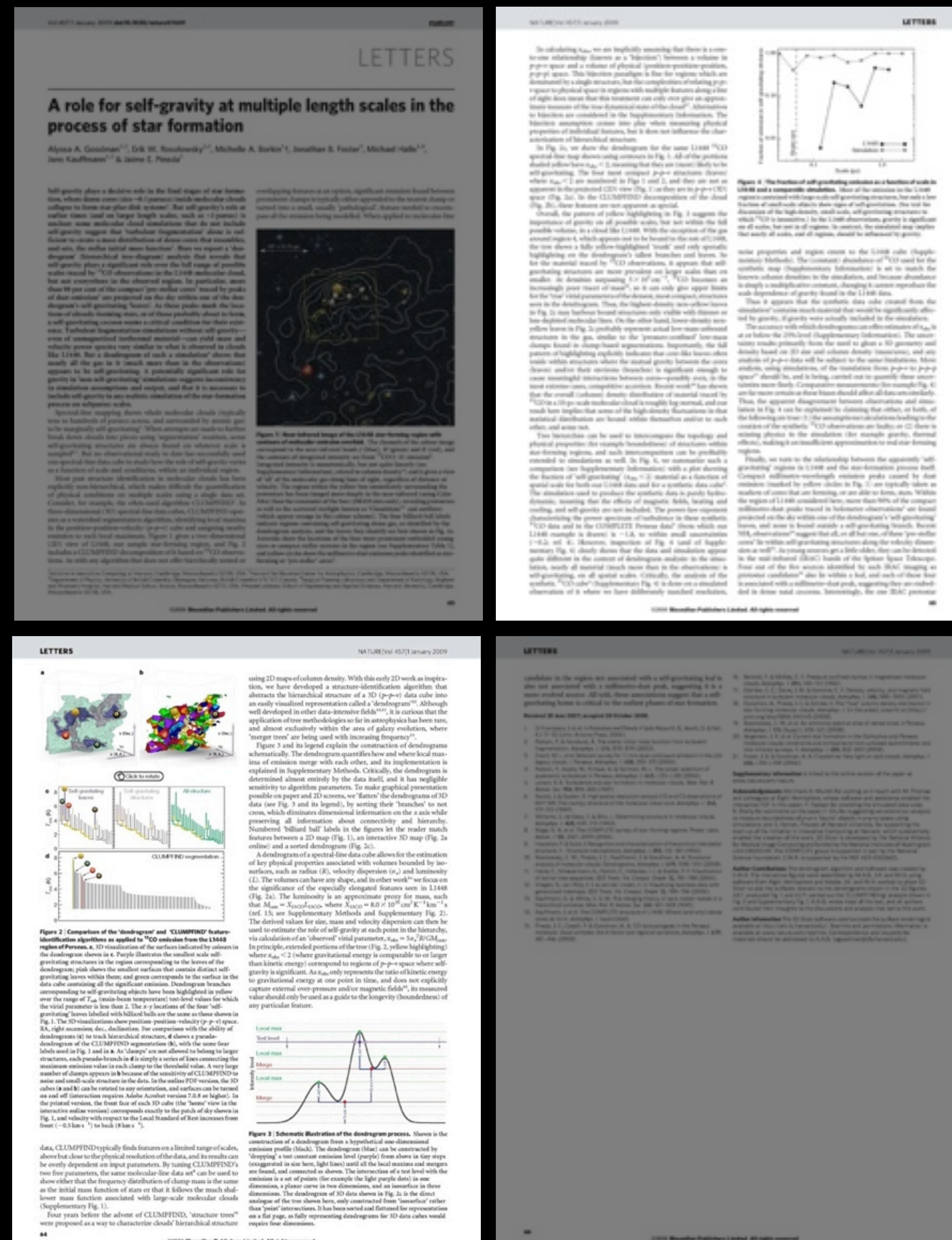
caveats



“bi-jection”

“virial parameter”

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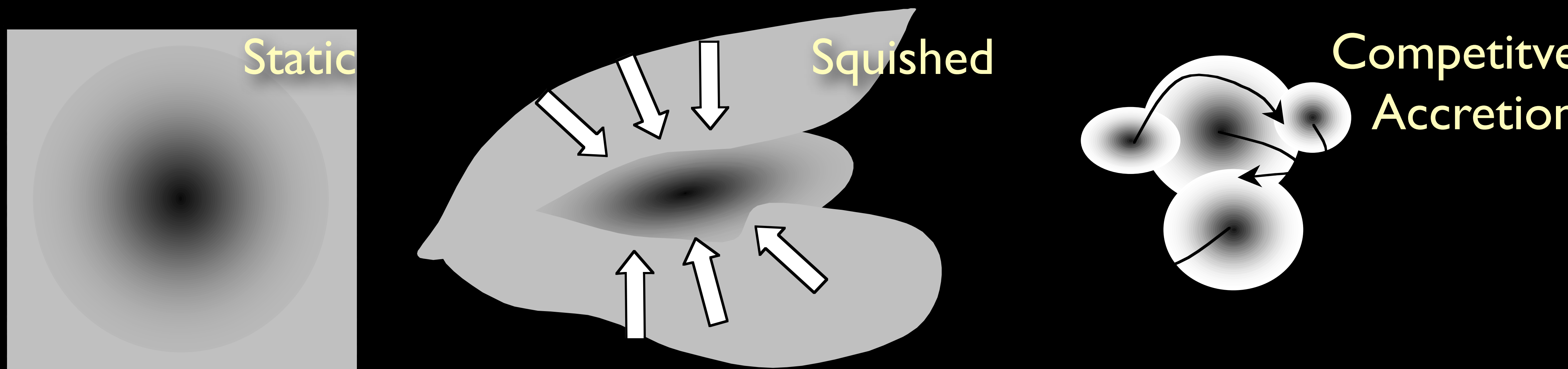
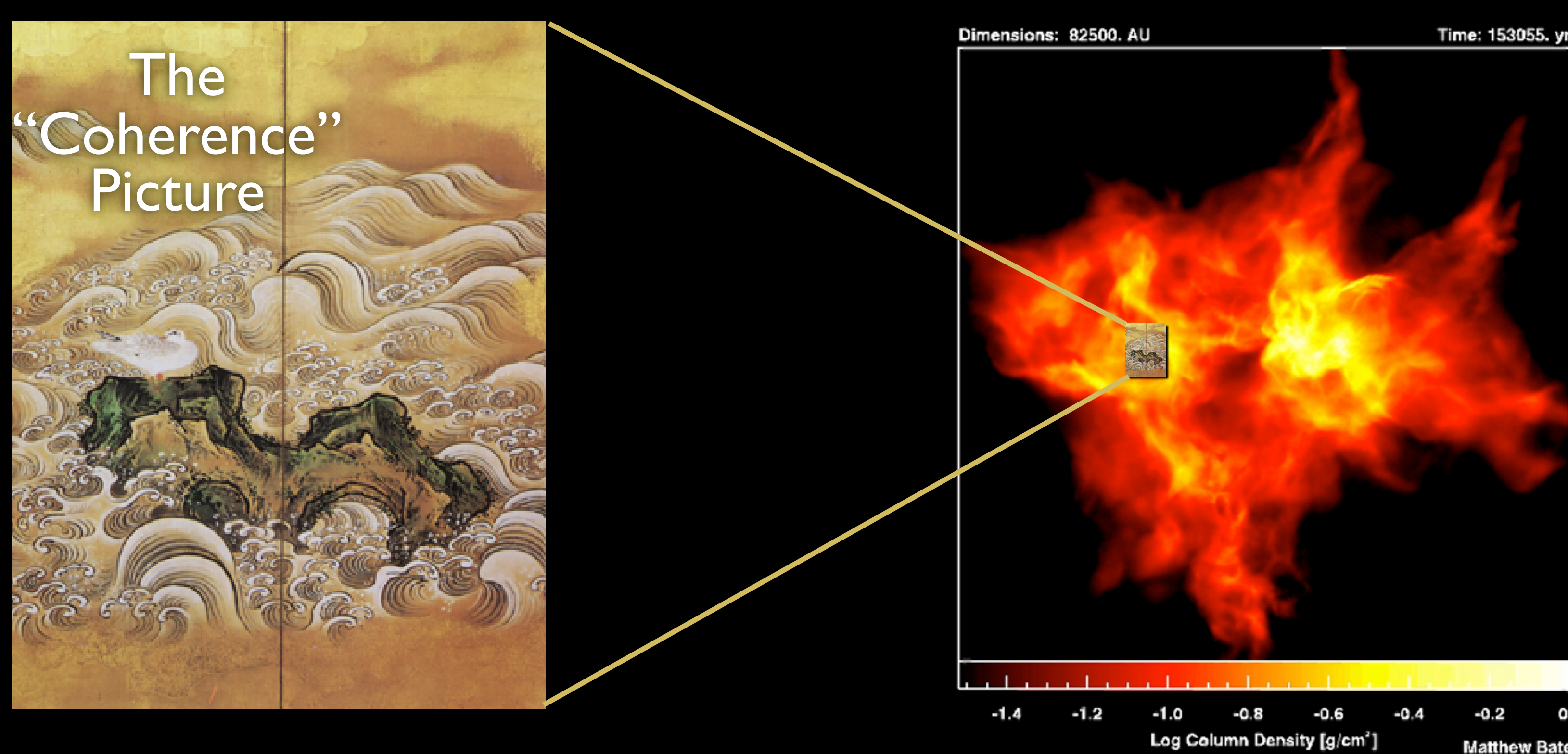
“taste-test”

caveats

How calm, and how long-lasting are cores?
(relevant motions/forces & the "*virial parameter*")

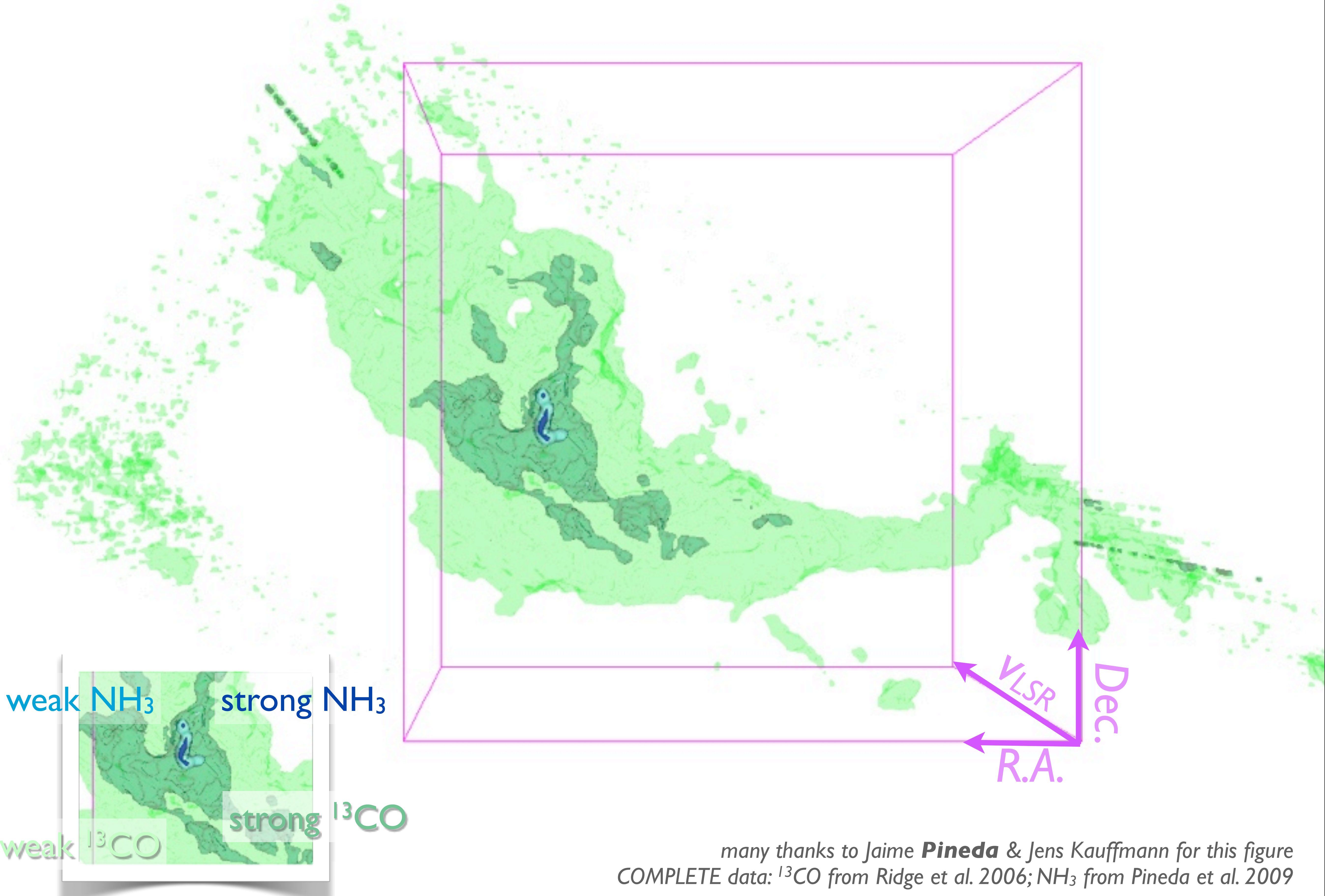
Three main views at present...





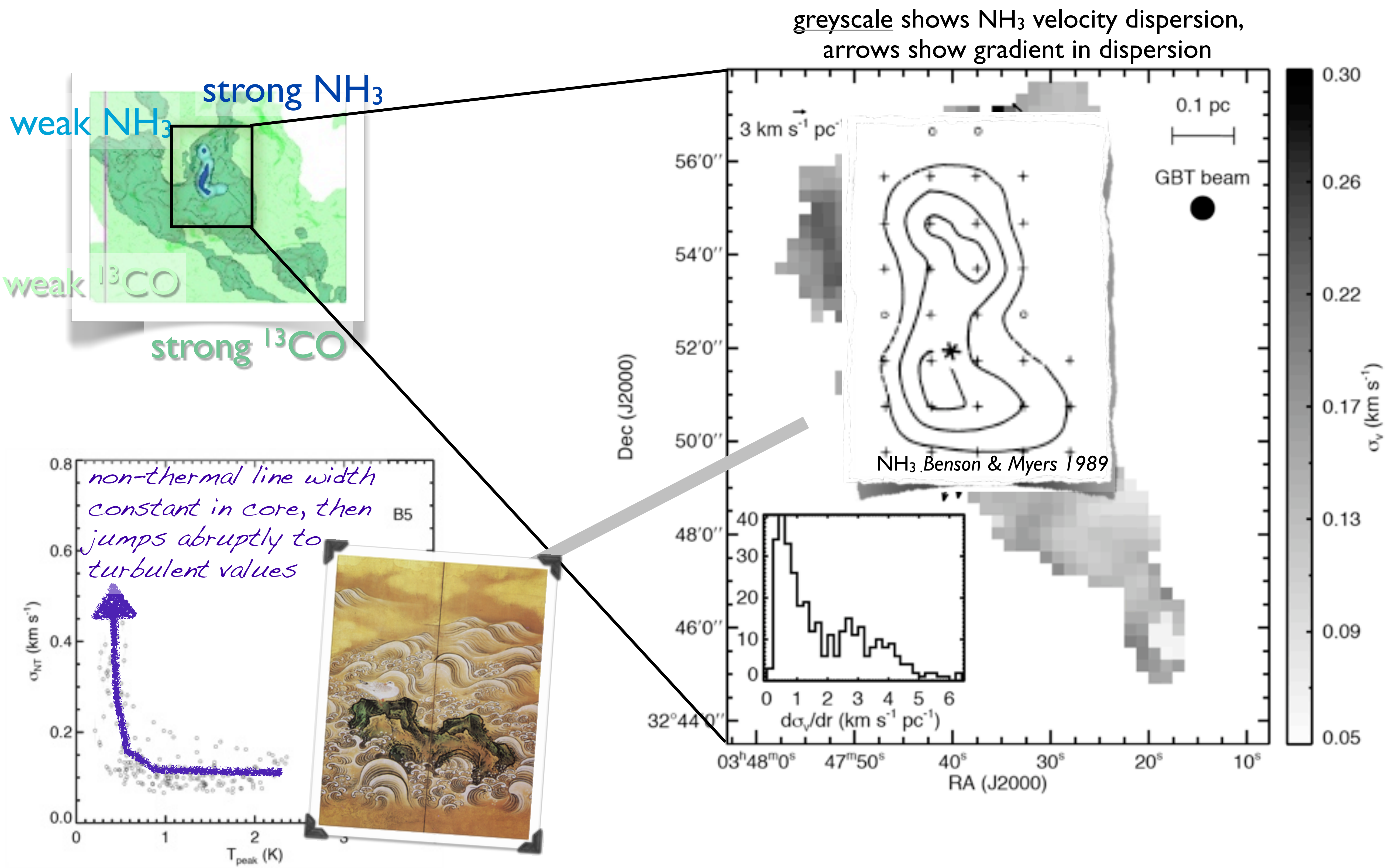
The "bijection" problem... this is p-p-p, but we have only p-p-v...

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



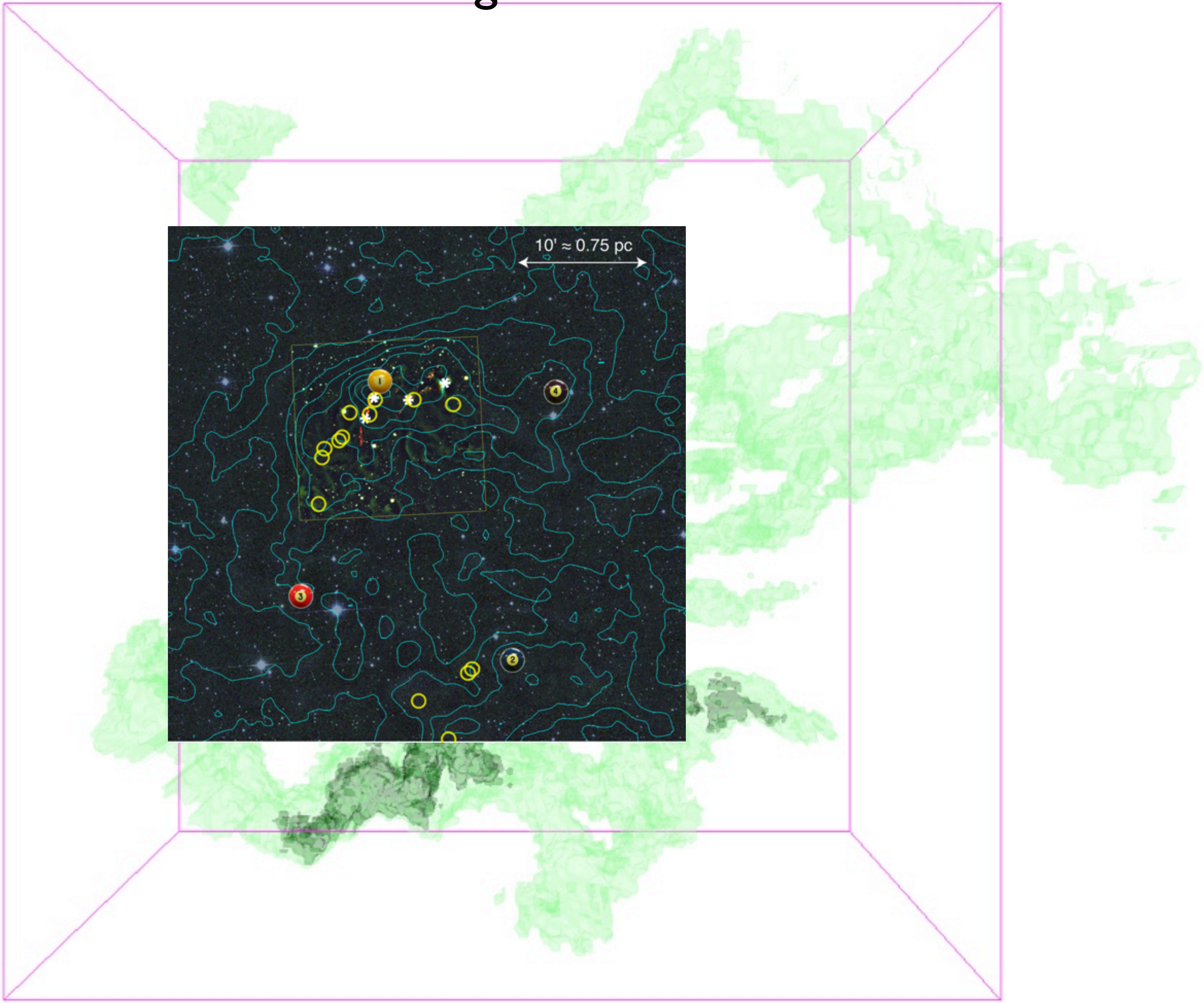
*many thanks to Jaime **Pineda** & Jens Kauffmann for this figure*
COMPLETE data: ^{13}CO from Ridge et al. 2006; NH_3 from Pineda et al. 2009

STRONG Evidence for Coherence in Dense Cores

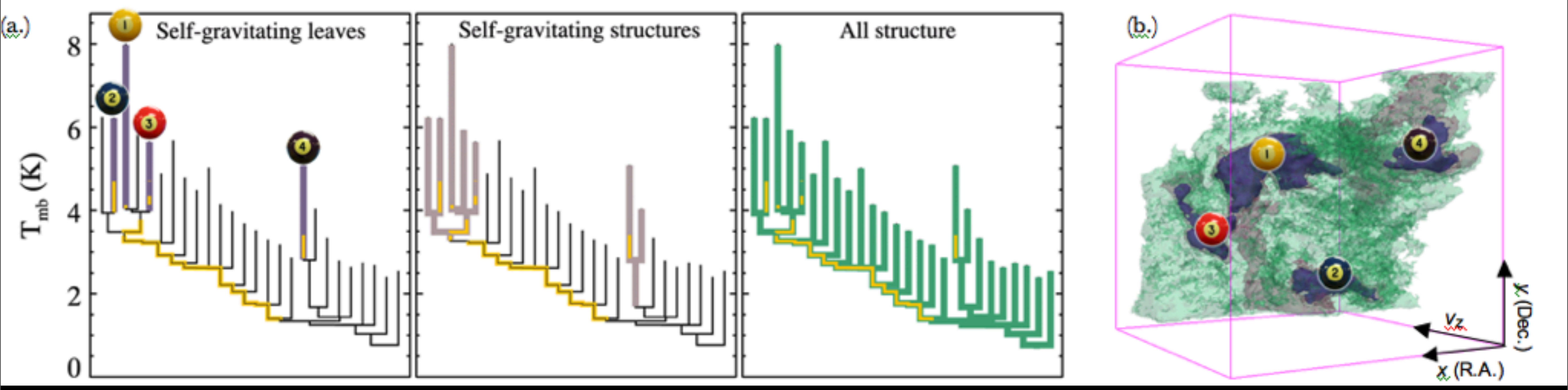


Brand-new GBT NH_3 observations of the B5 core, work of Jaime Pineda

Returning to L1448...



Dendrograms & "Self-Gravity"

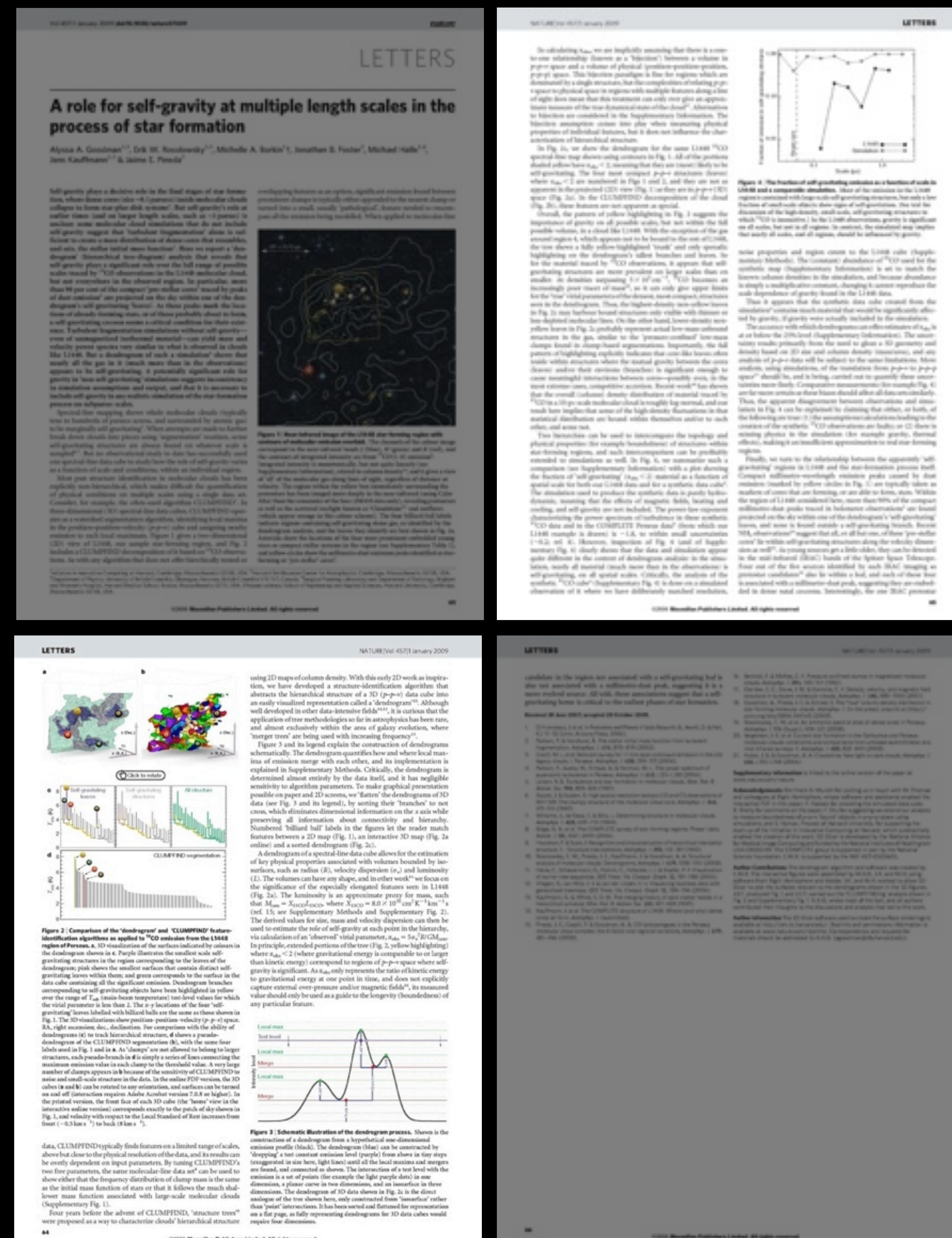


Yellow highlighting= "self-gravitating"

"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

✔ "bi-jection"

✔ "virial parameter"

"turbulent power spectrum"

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"depletion, opacity"

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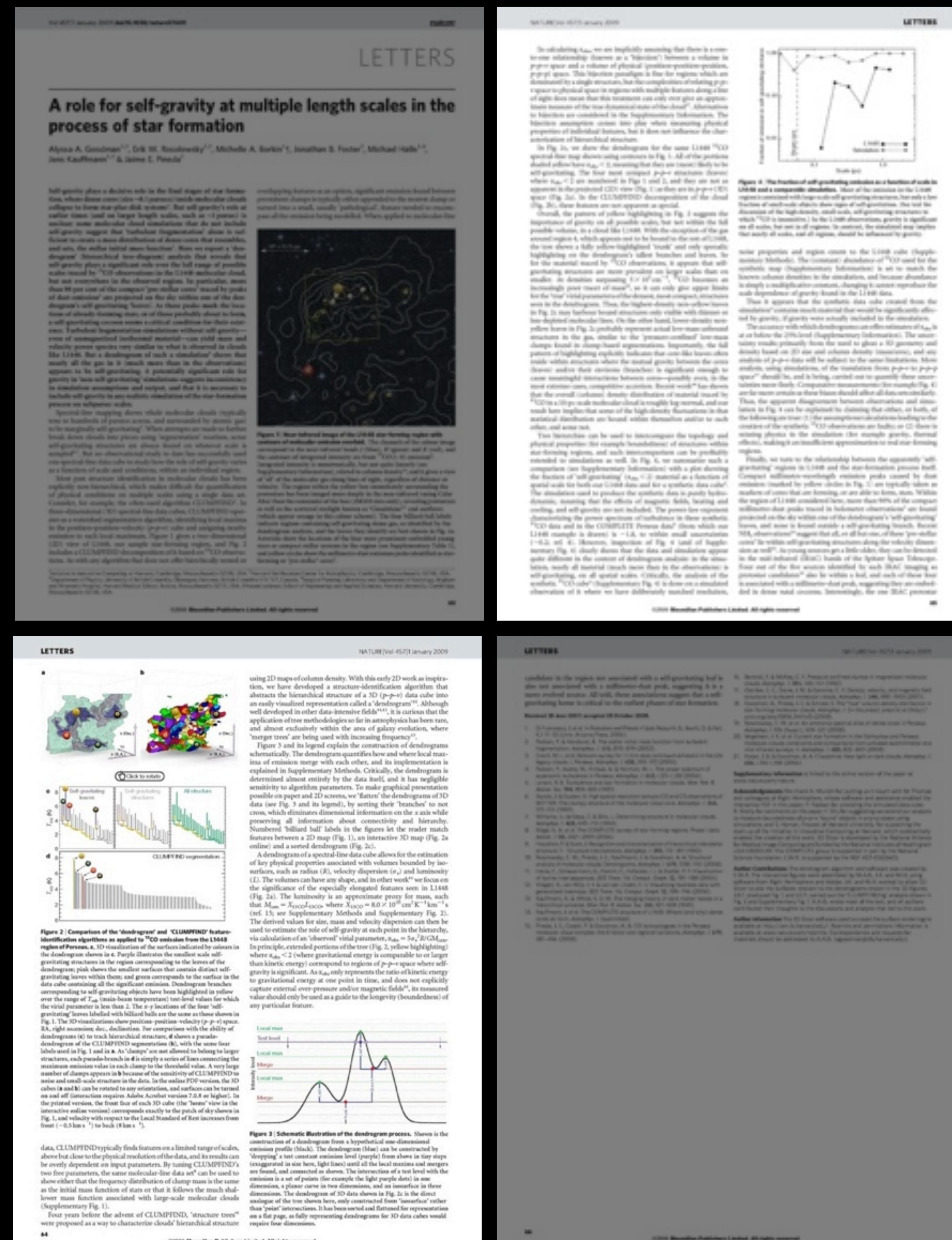
caveats


LETTERS

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

"turbulent power spectrum"

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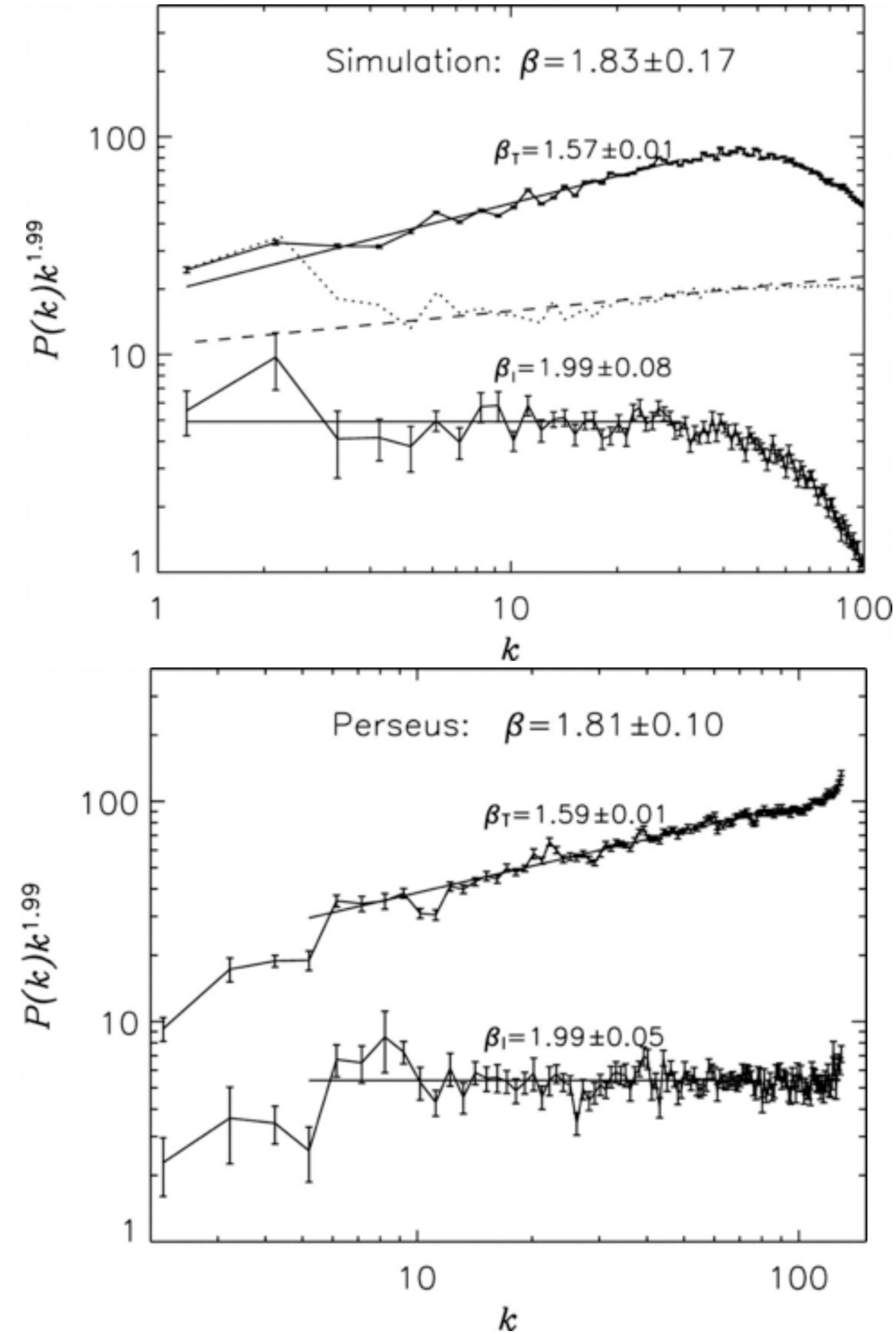
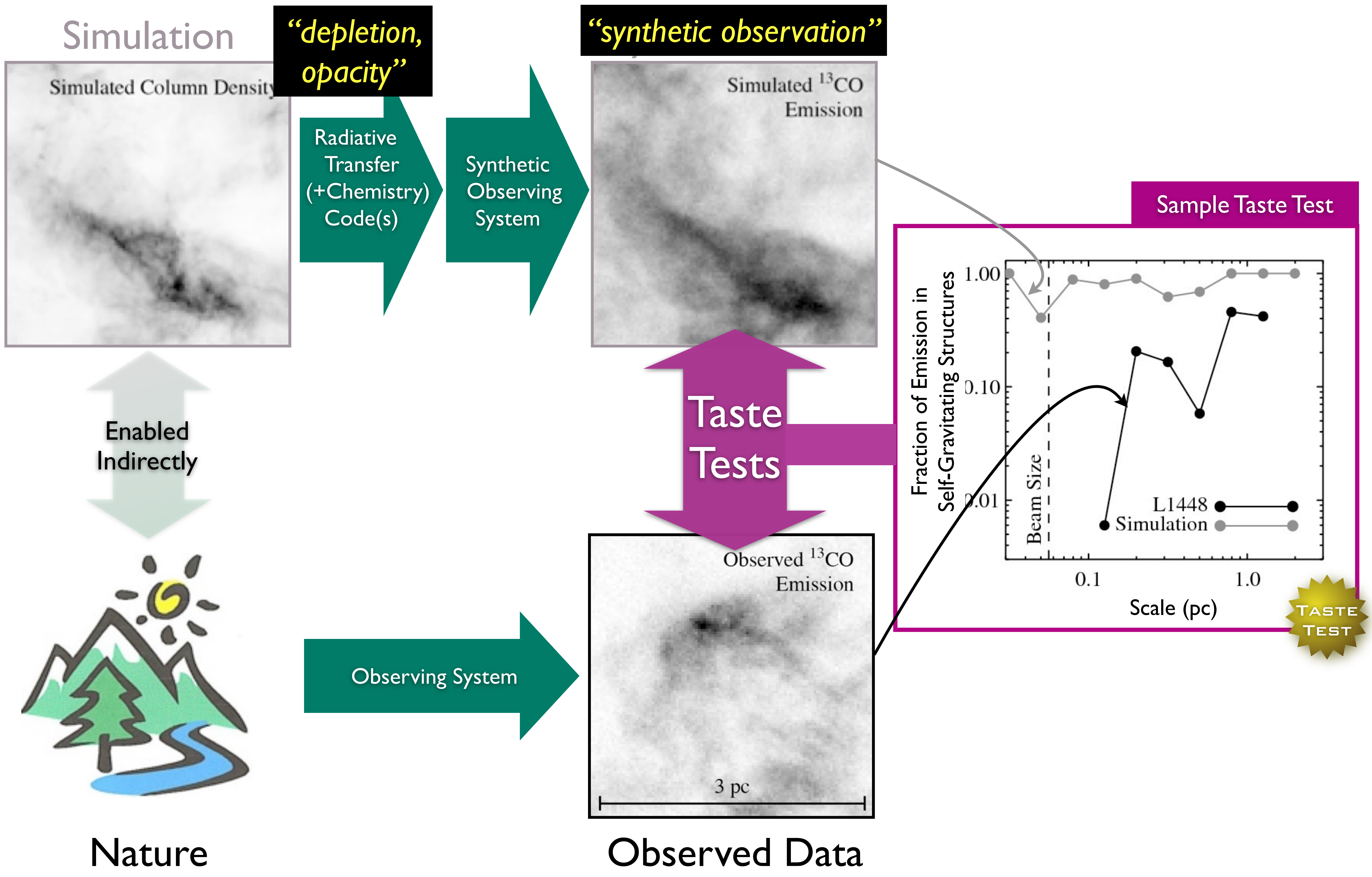
Choosing a relevant simulation to taste...

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

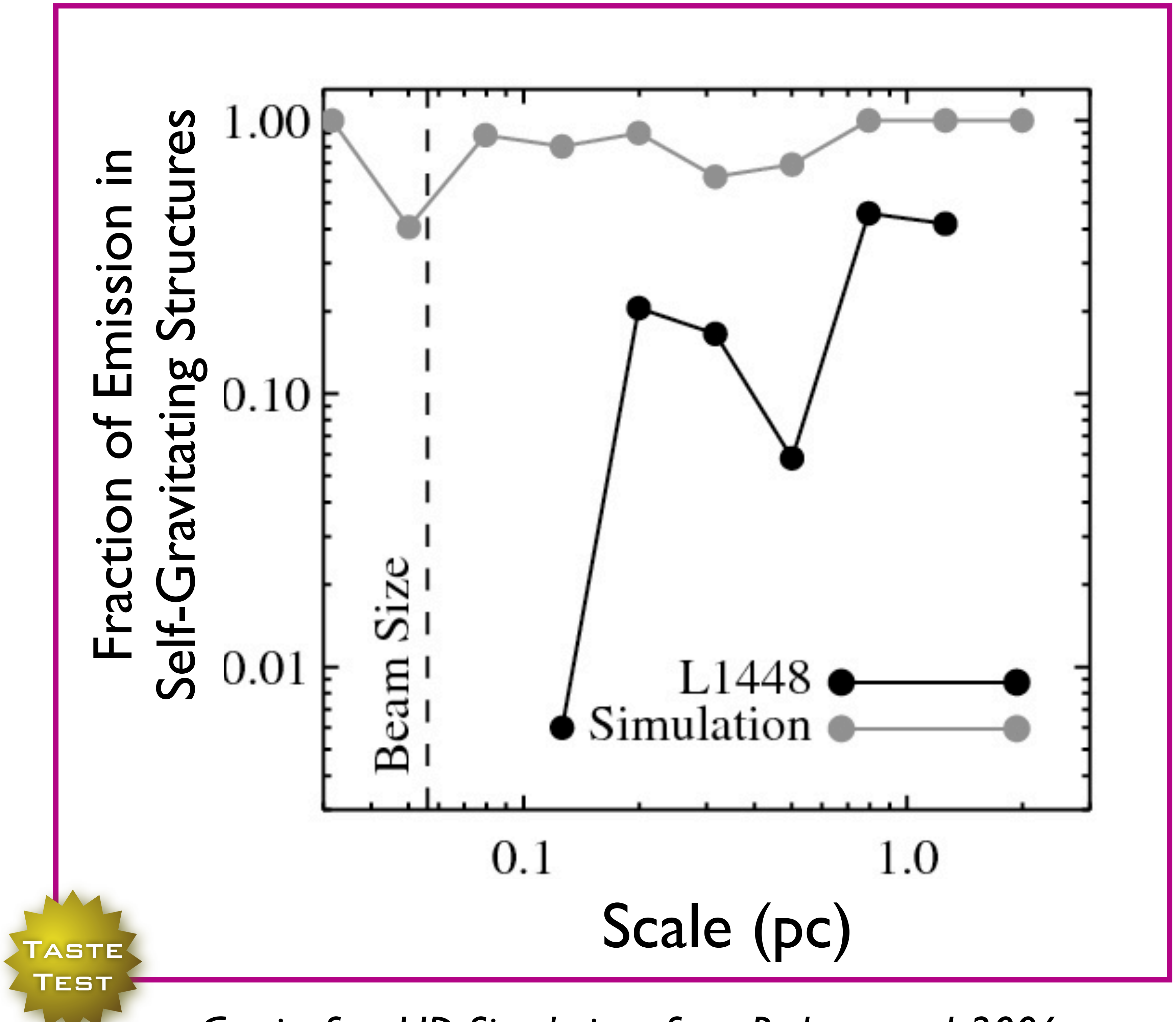


Note: This simulation does NOT include gravity, magnetic fields, radiative effects, or explicit heating & cooling–it is pure hydrodynamics.

The Taste-Testing Process

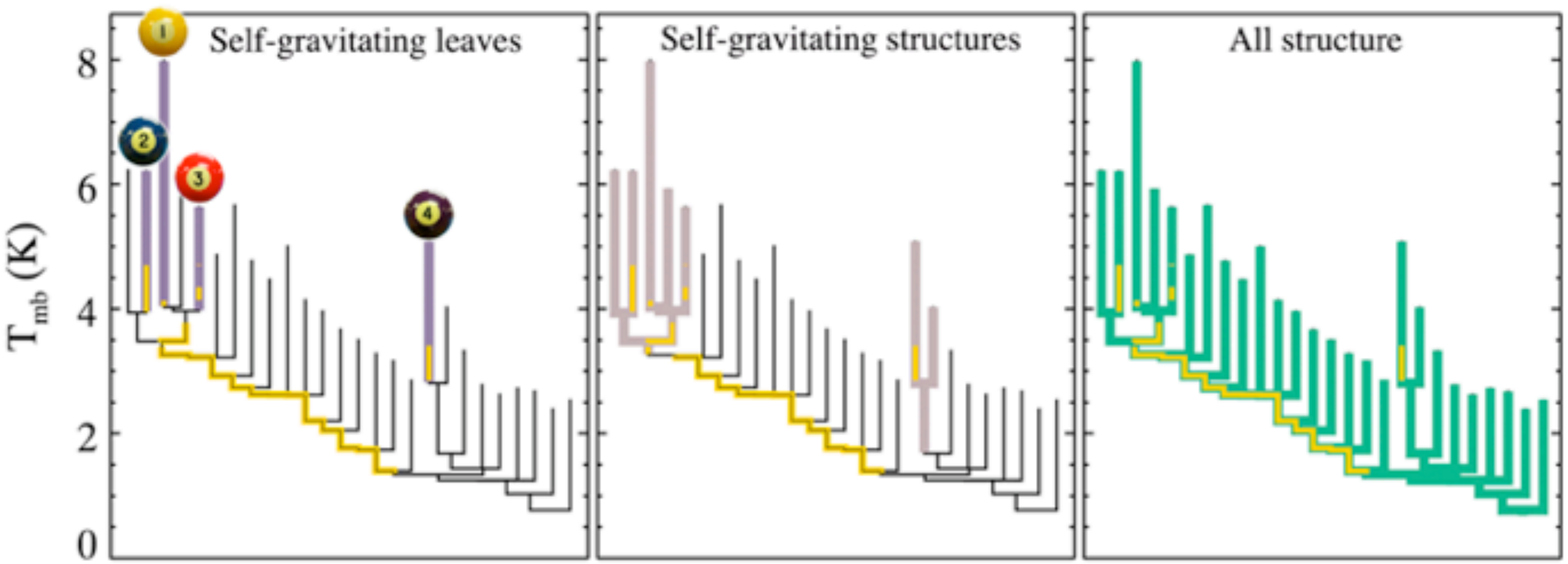


Taste-Testing Gravity



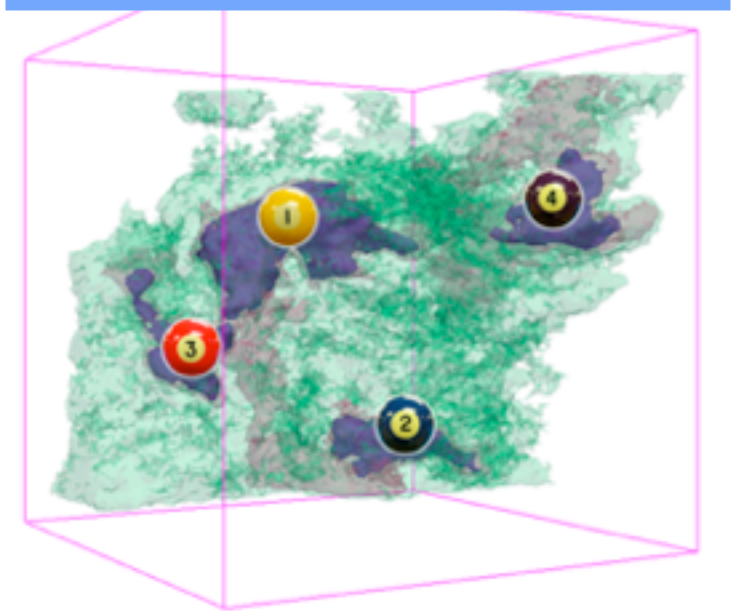
Gravity-free HD Simulations from Padoan et al. 2006;
L1448 analysis from Rosolowsky et al. 2008
both lines derived from ^{13}CO "observations"

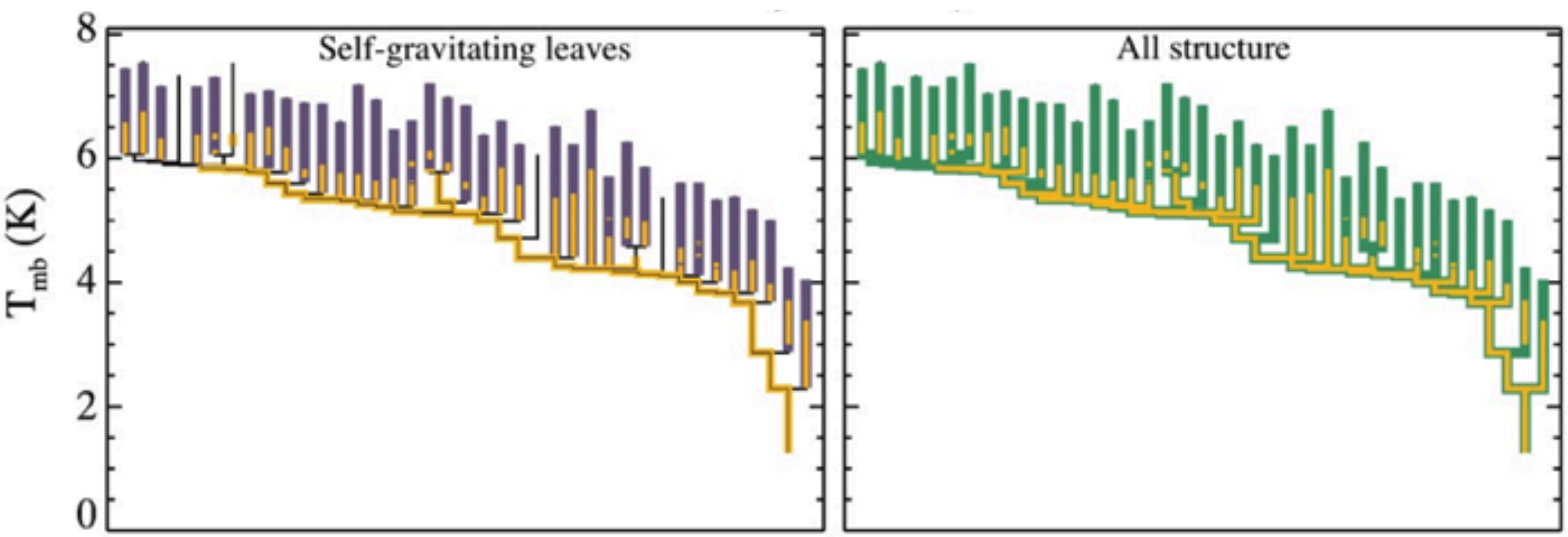
Real vs. Simulated ^{13}CO



(Yellow = self-gravitating components)

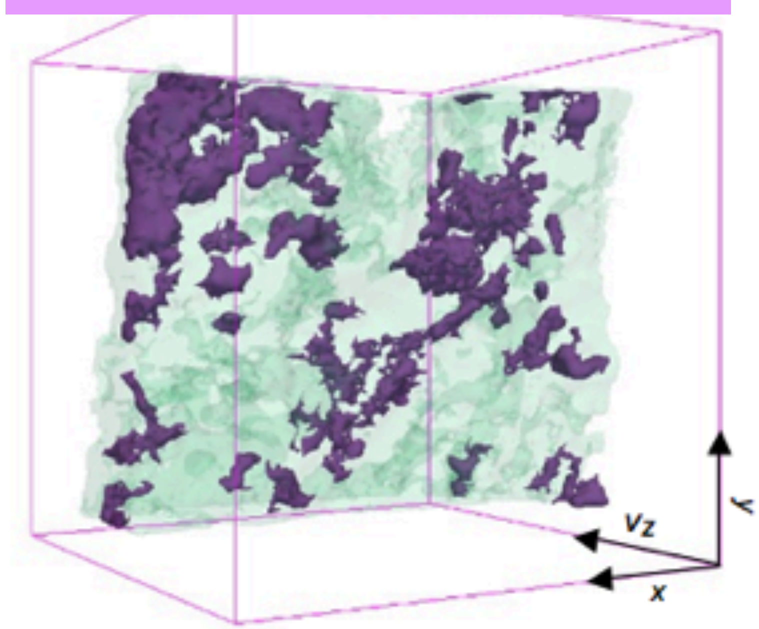
Real





(Yellow = self-gravitating components)

Simulated



✔ "turbulent power spectrum"

✔ "synthetic observation"

✔ "depletion, opacity"

✔ "taste-test"

caveats

3 *conclusions & caveats*

Star formation takes place in self-graviatating "coccoons," and some of those coccoons are bound to each other.

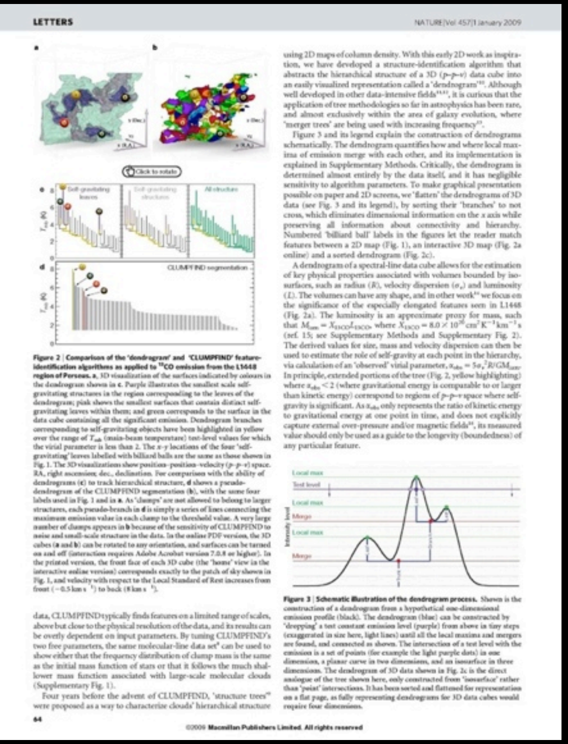


Figure 2 | Comparison of the 'dendrogram' and 'CLUMPFIND' feature-identification algorithms as applied to ^{13}CO emission from the L1448 region of Perseus. a, 3D visualization of the surfaces indicated by colours in the dendrogram shown in c. Purple illustrates the smallest scale self-gravitating structures 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_{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 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 set[8] 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 frequency[13].

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 work[14] 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 $M_{lum} = X_{13CO} L_{13CO}$, where $X_{13CO} = 8.0 \times 10^{20}$ cm^2 K^{-1} km^{-1} 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, $\alpha_{obs} = 5\sigma_v^2 R / GM_{lum}$. In principle, extended portions of the tree (Fig. 2, yellow highlighting) where $\alpha_{obs} < 2$ (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 fields[16], 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.

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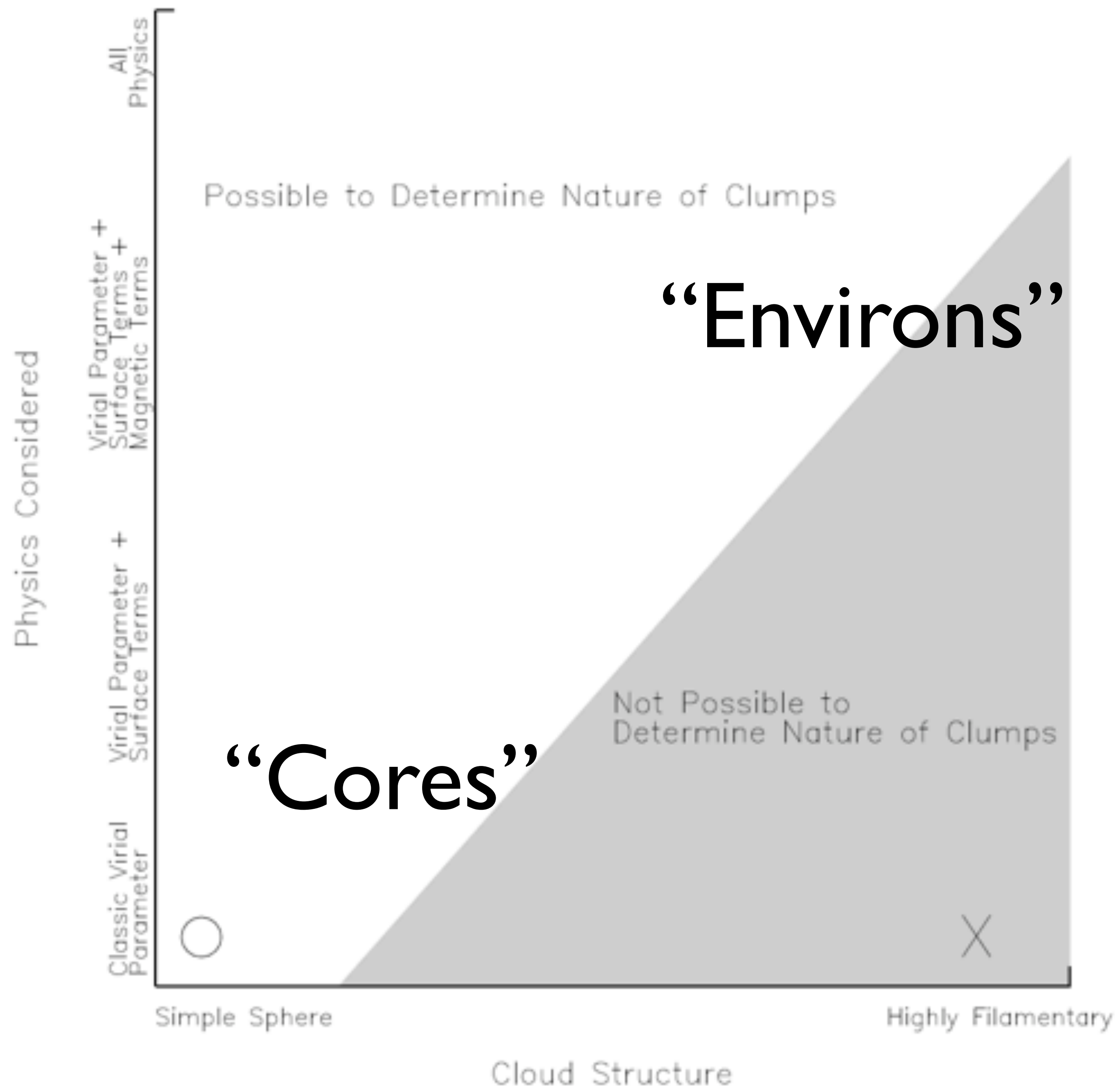
Caveats/Worries about *p-p-v* (bijection) ... and the virial parameter



*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 exess 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” “L1448” “(magneto-)hydrodynamic simulation”

“Cloudshine”

“pre-stellar core”

“protostar”

“integrated intensity”

“p-p-v cube”

“segmentation”

“CLUMPFIND”

“Dendrogram”


LETTERS

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

“COMPLETE” “3D PDF”

“bi-jection”

“virial parameter”

“column density”

“turbulent power spectrum”

“synthetic observation”

“depletion, opacity”

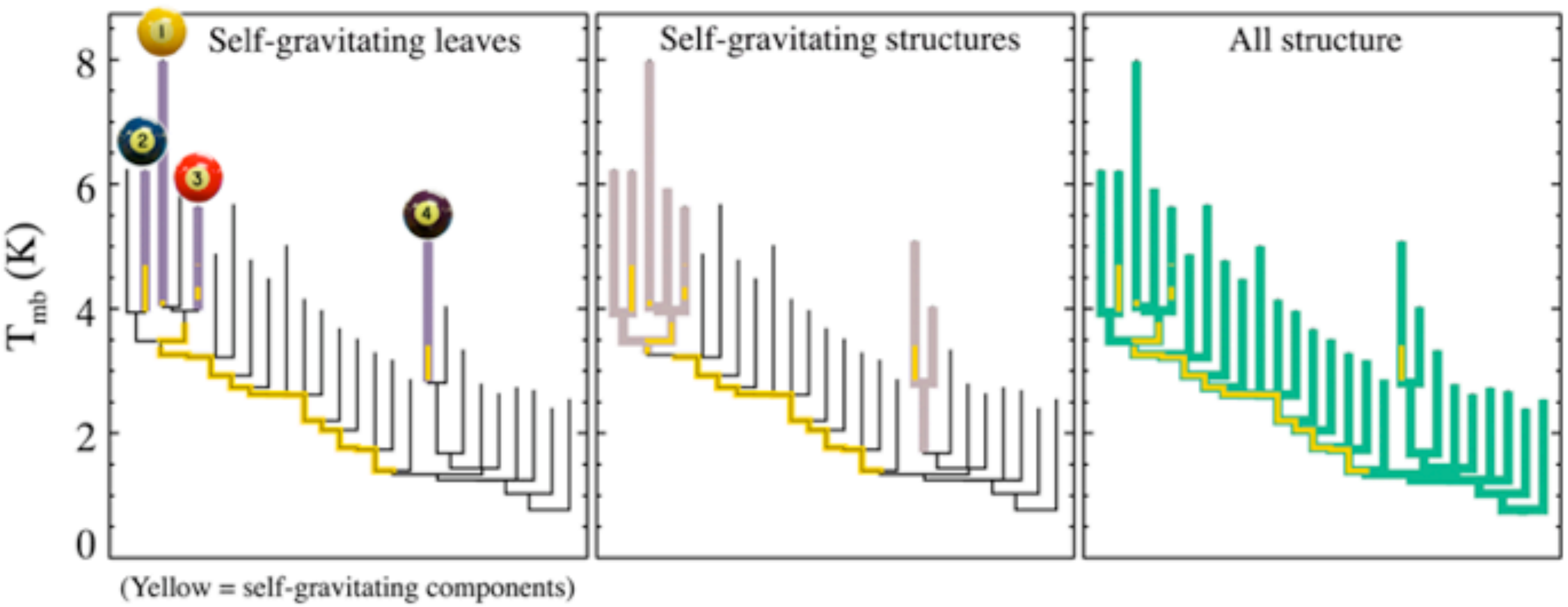
“taste-test”

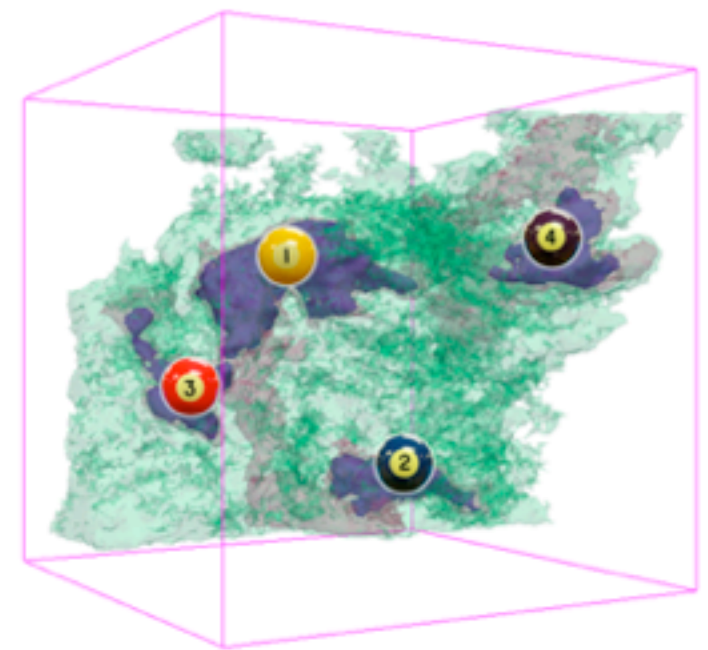
caveats

Extra Slides

CLUMPFIND vs. Dendrograms: L1448

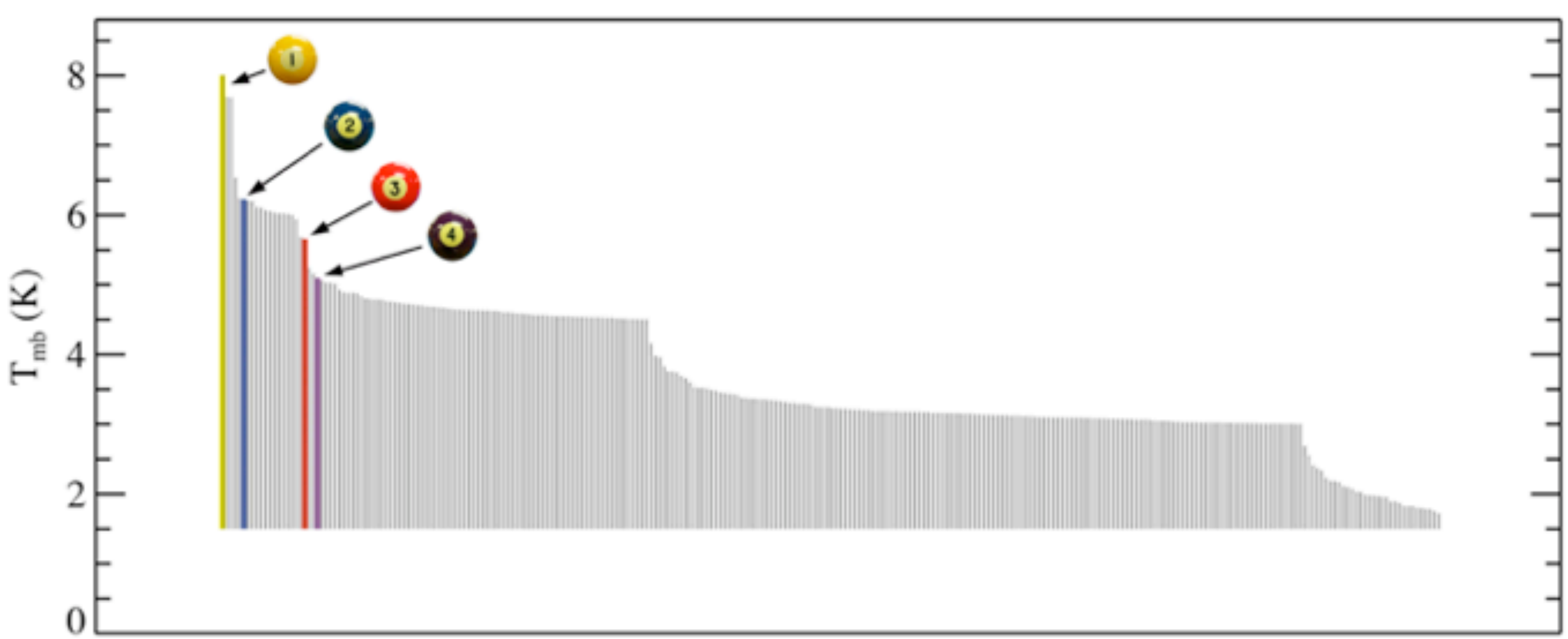
Dendrograms



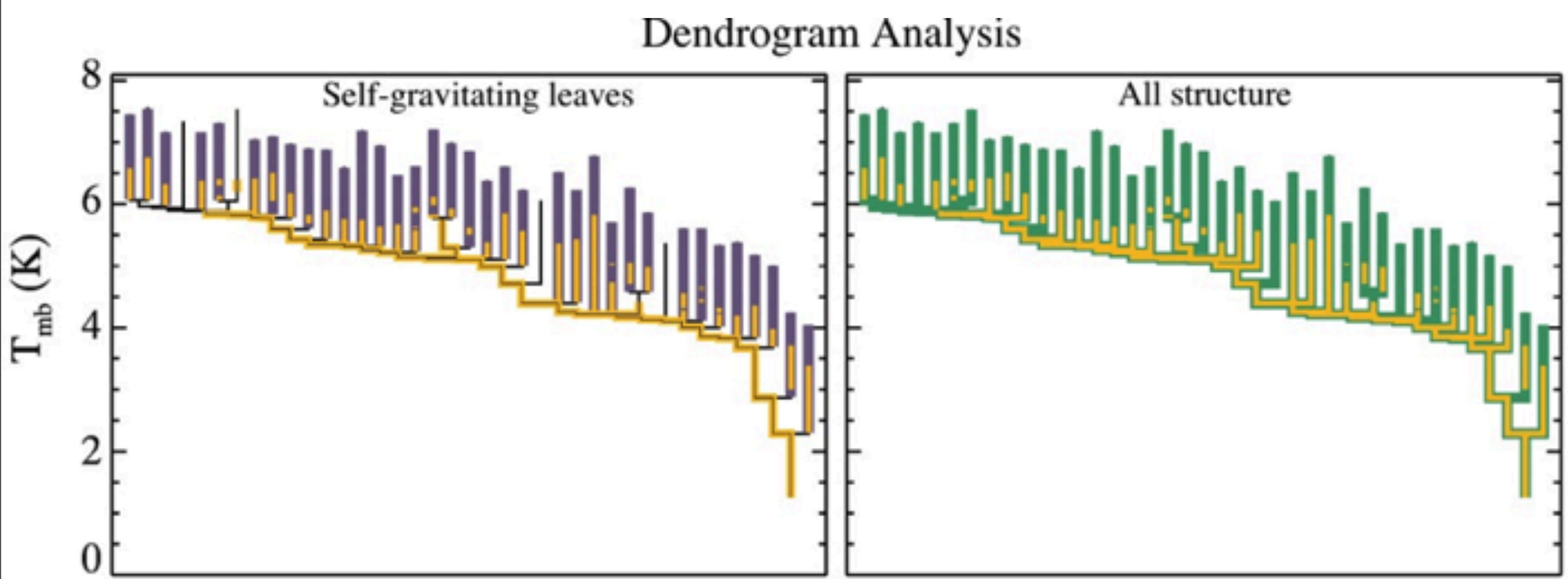


The online PDFs of these insets

“CLUMPFIND”

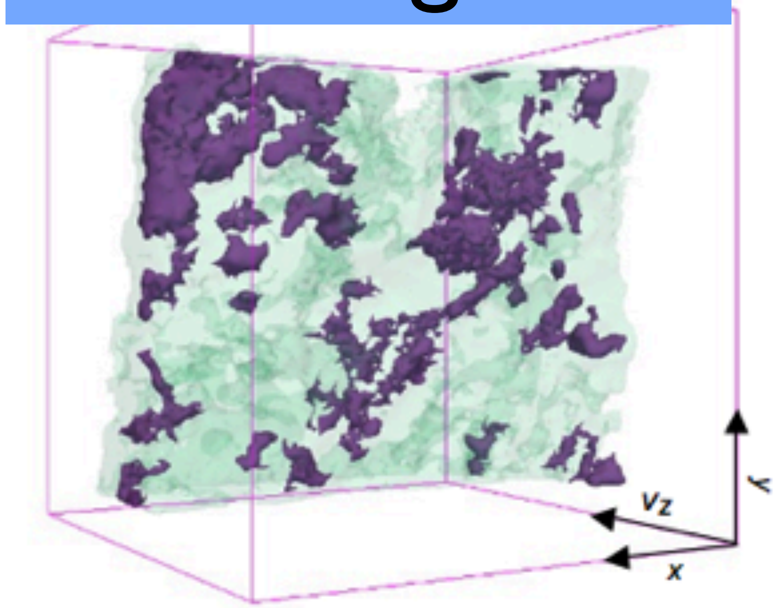


CLUMPFIND vs. Dendrograms: Synthetic Data

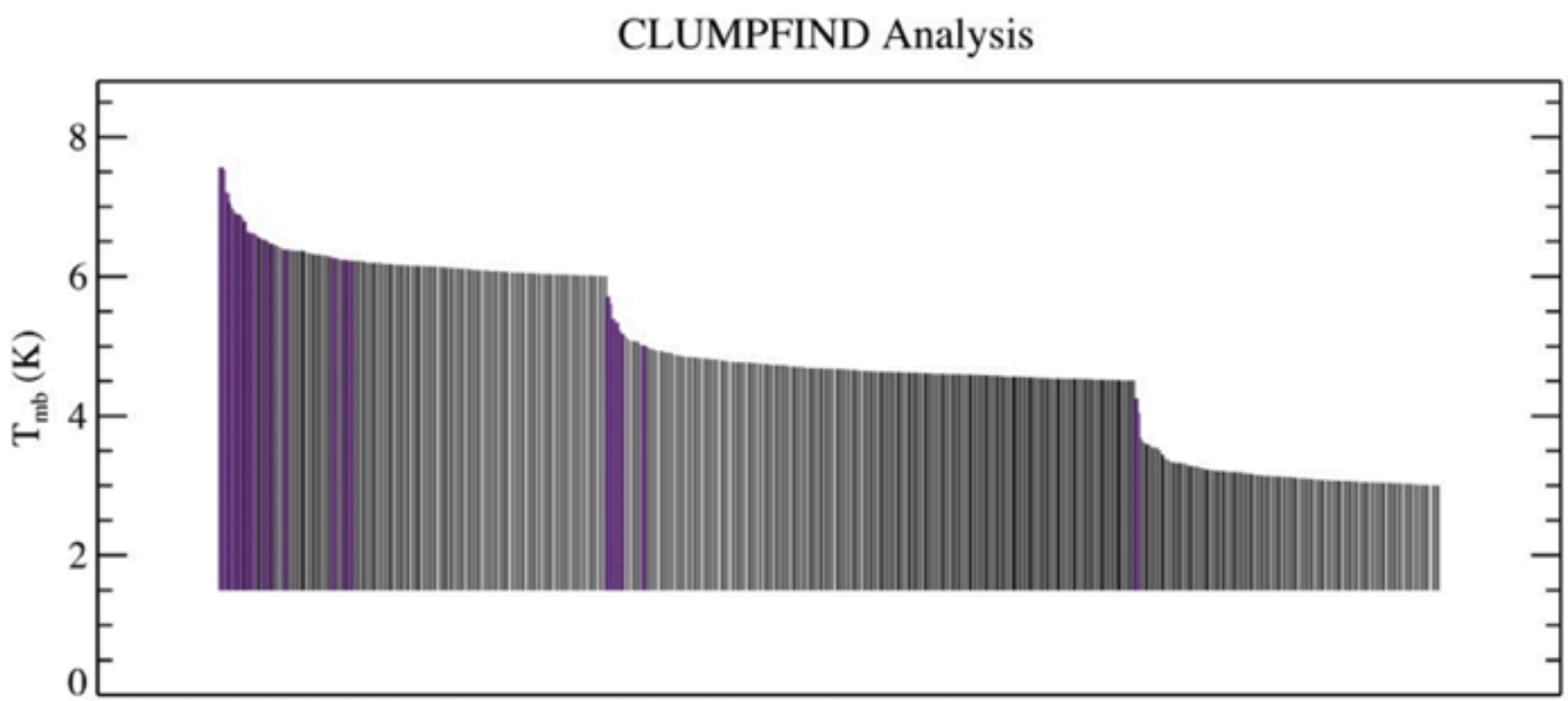


(Yellow = self-gravitating components)

Dendrograms

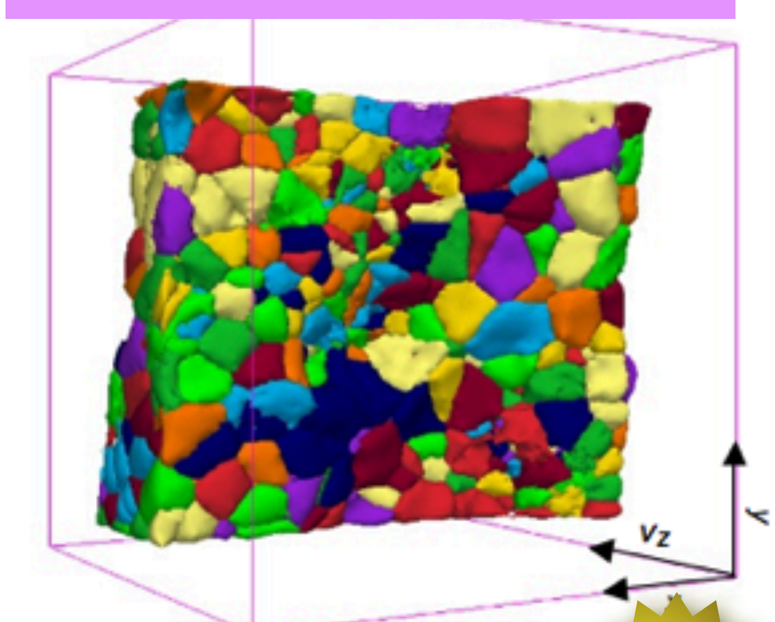


The online PDFs of these insets are interactive, offer additional surfaces, and can be rotated and manipulated by

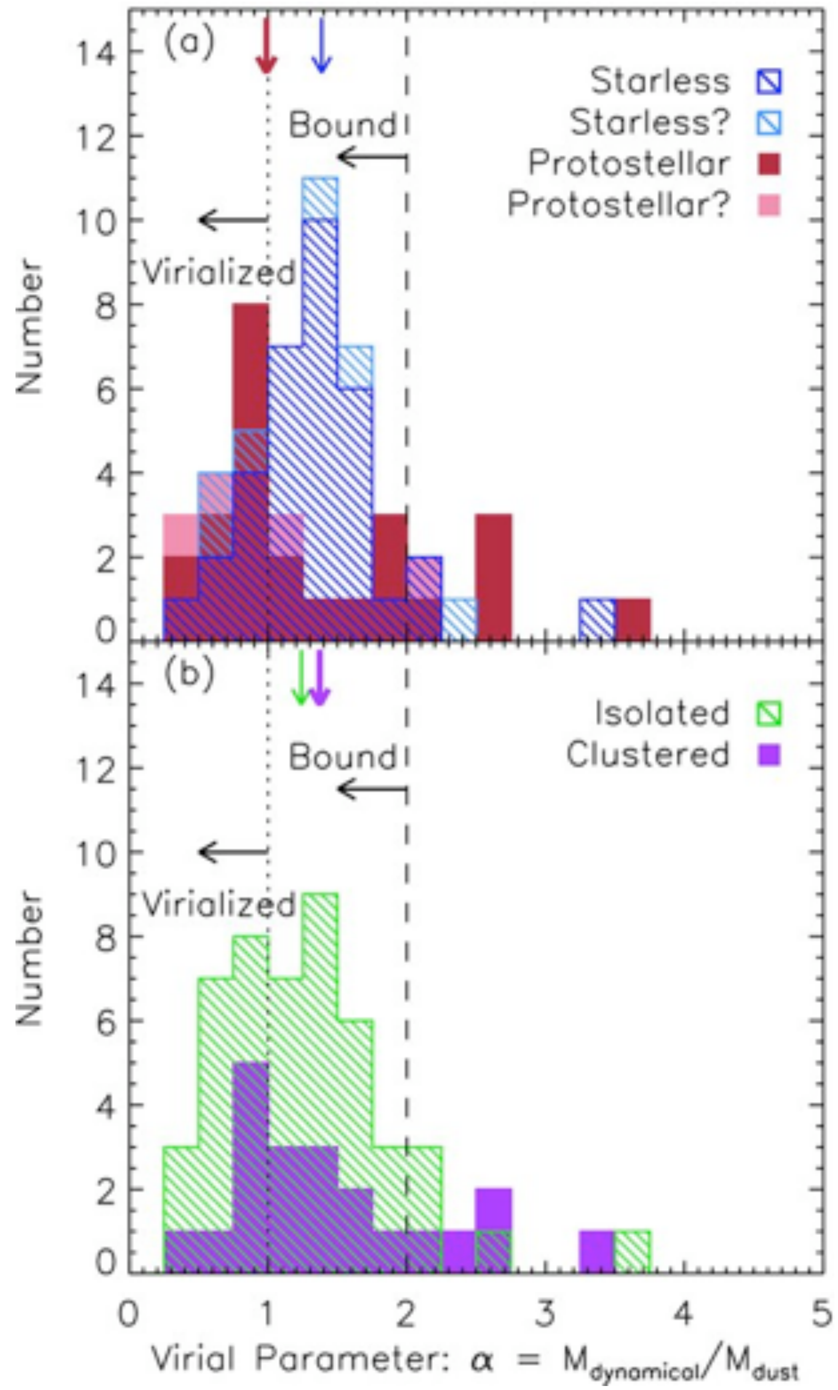


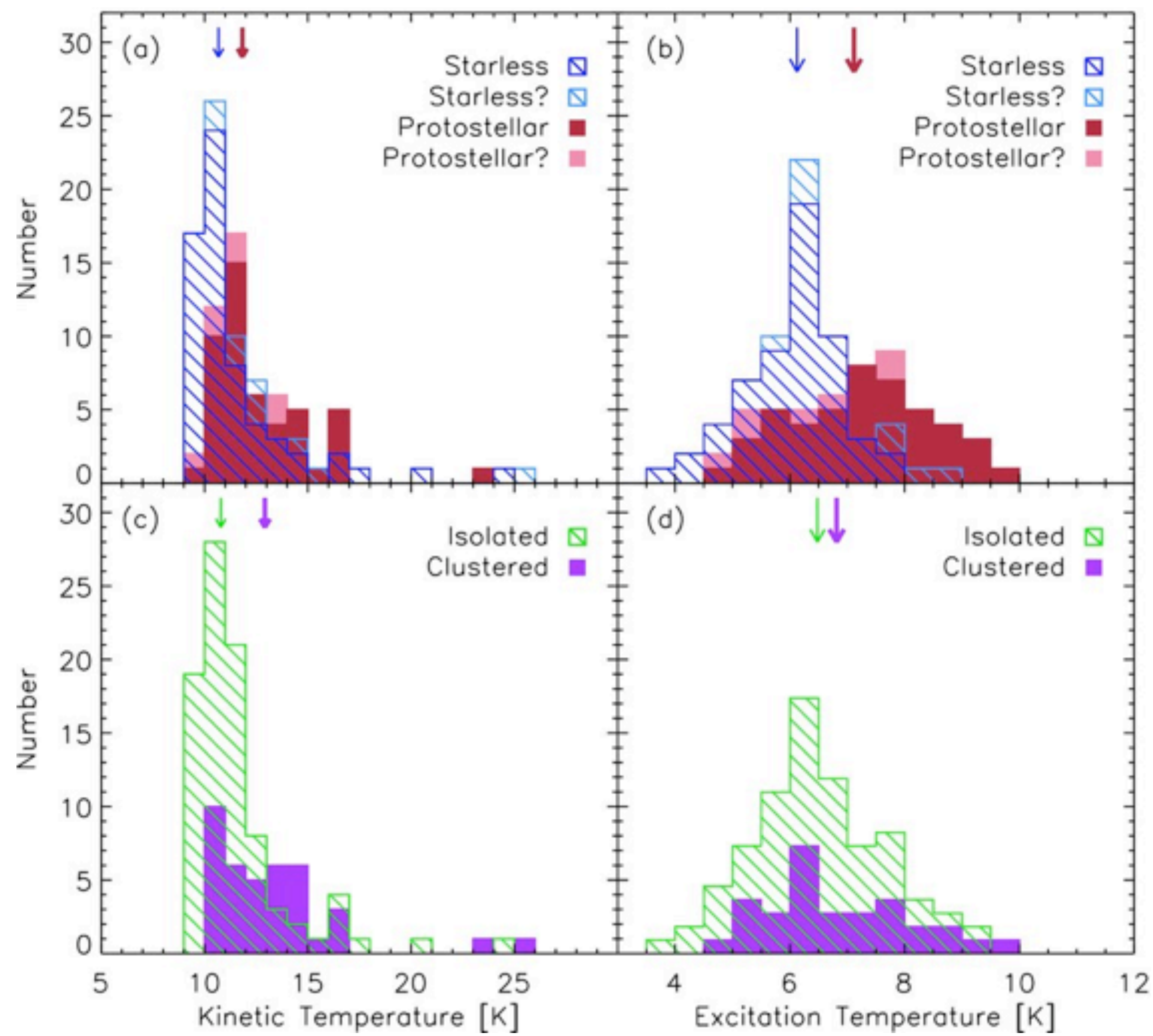
(Purple = CLUMPFIND regions associated with self-gravitating leaves)

"CLUMPFIND"

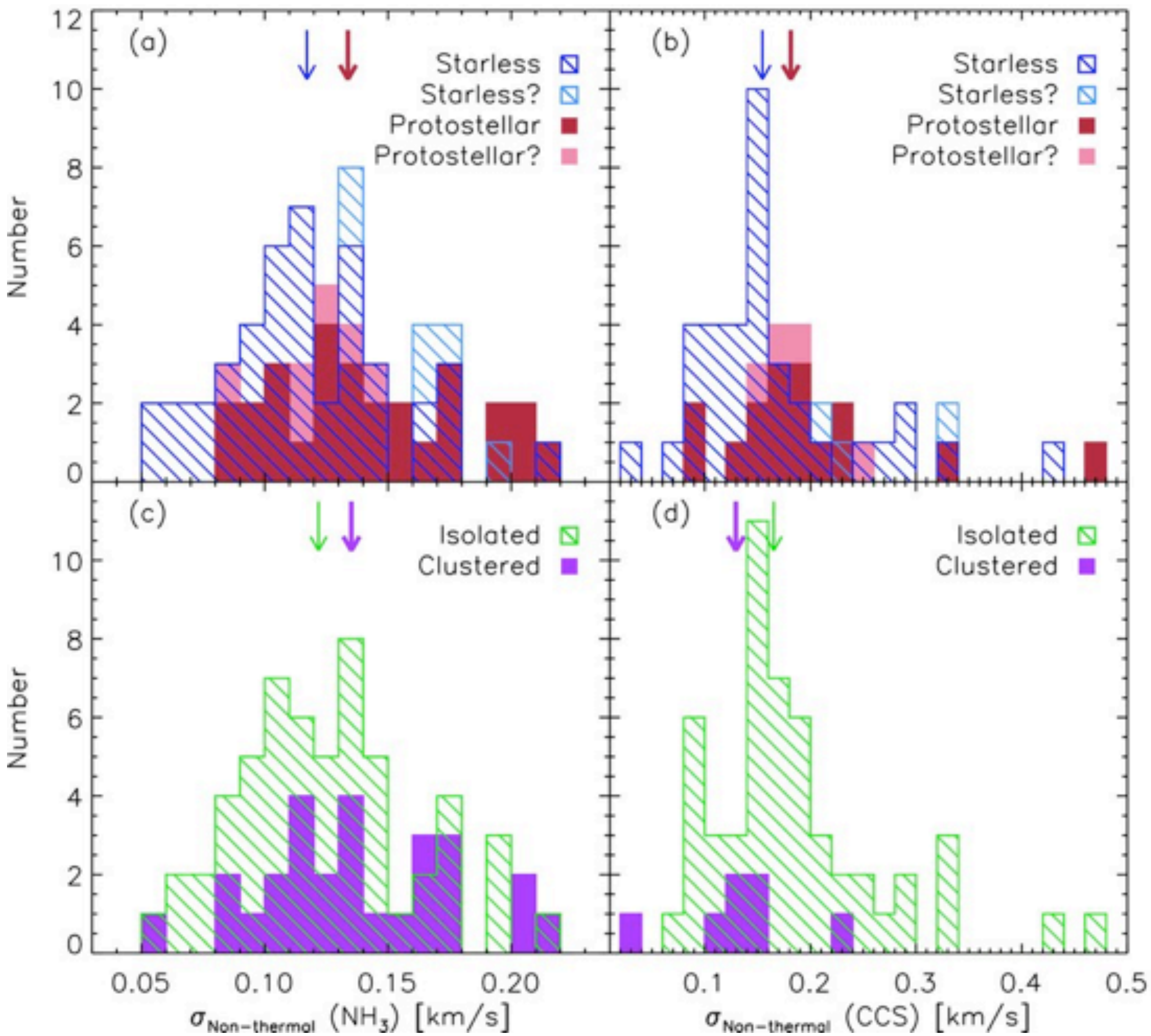


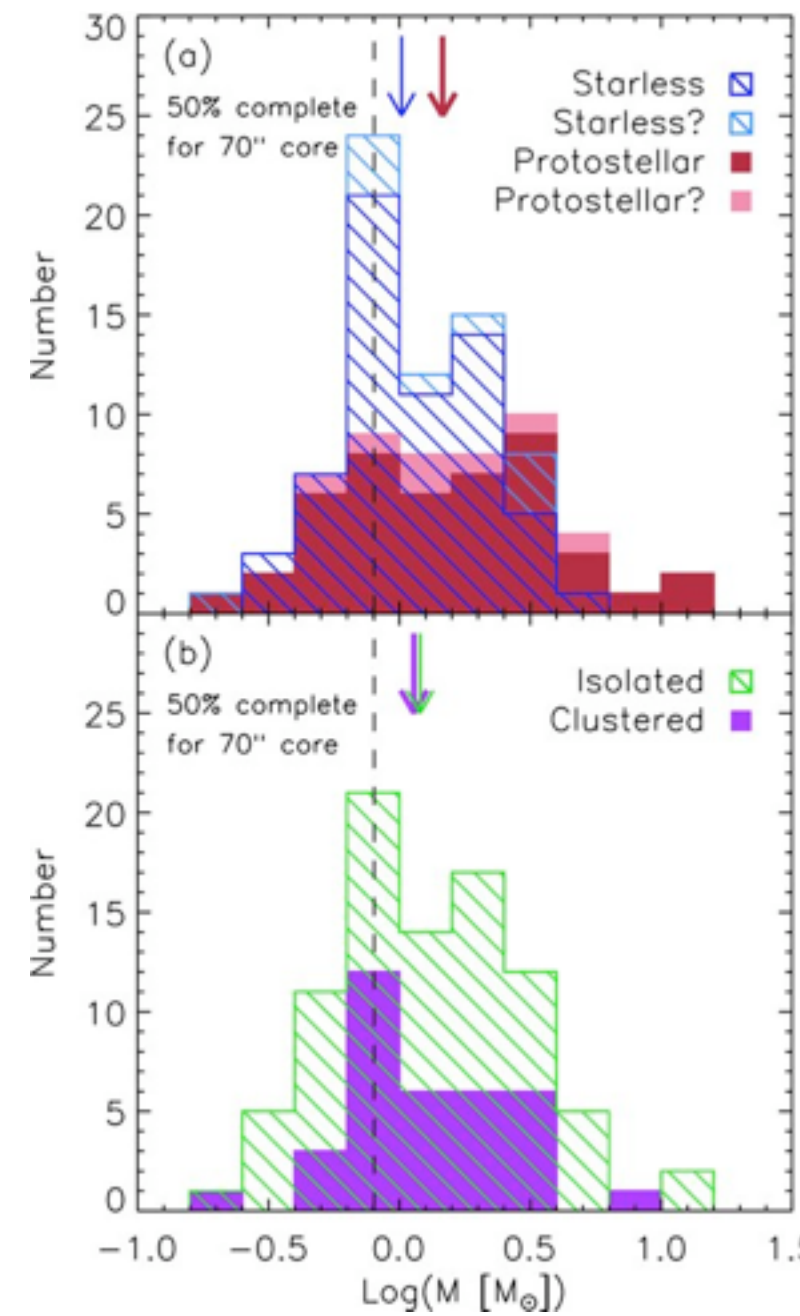
TASTE TEST



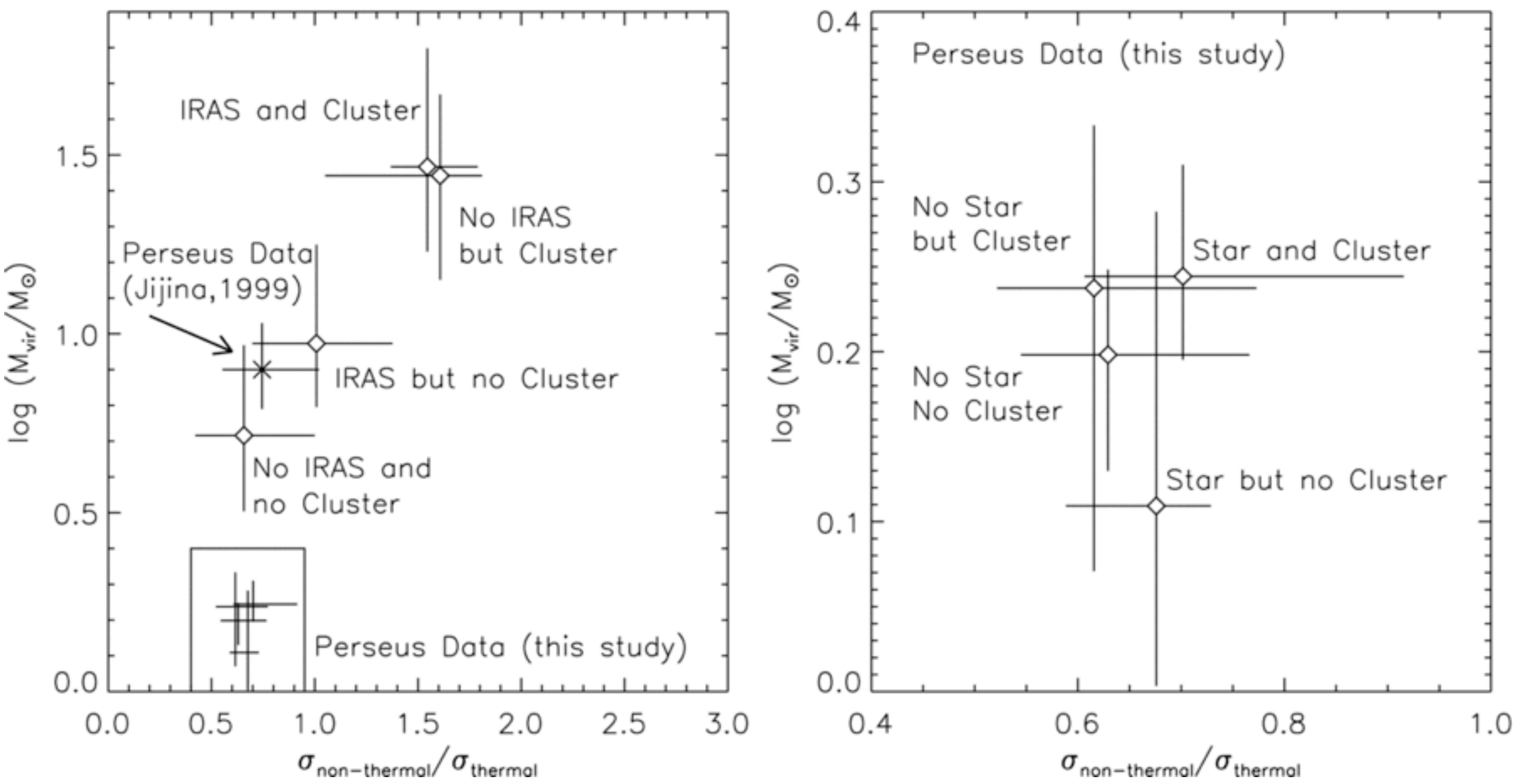


Foster et al. 2009





Foster et al. 2009



Foster et al. 2009