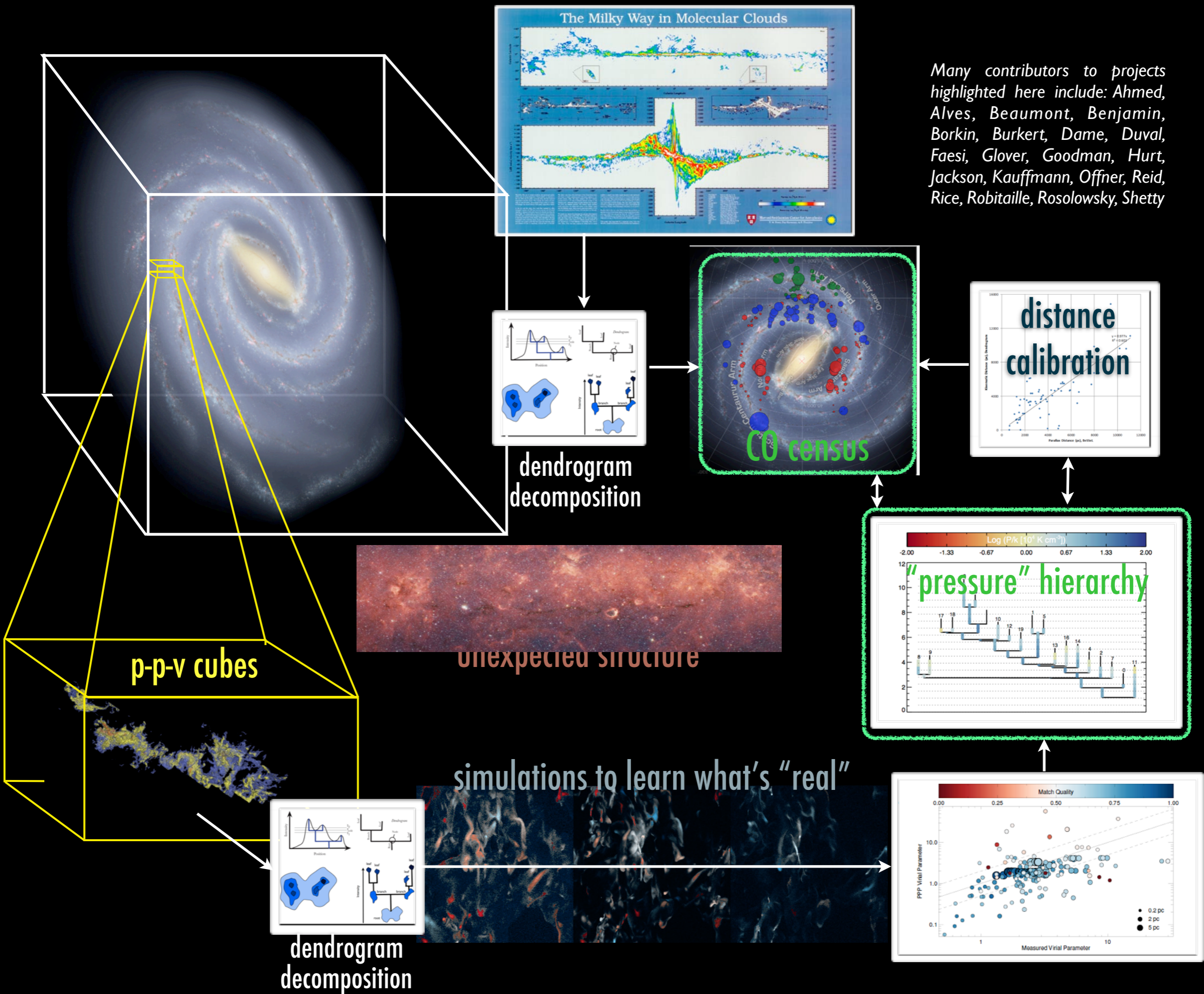


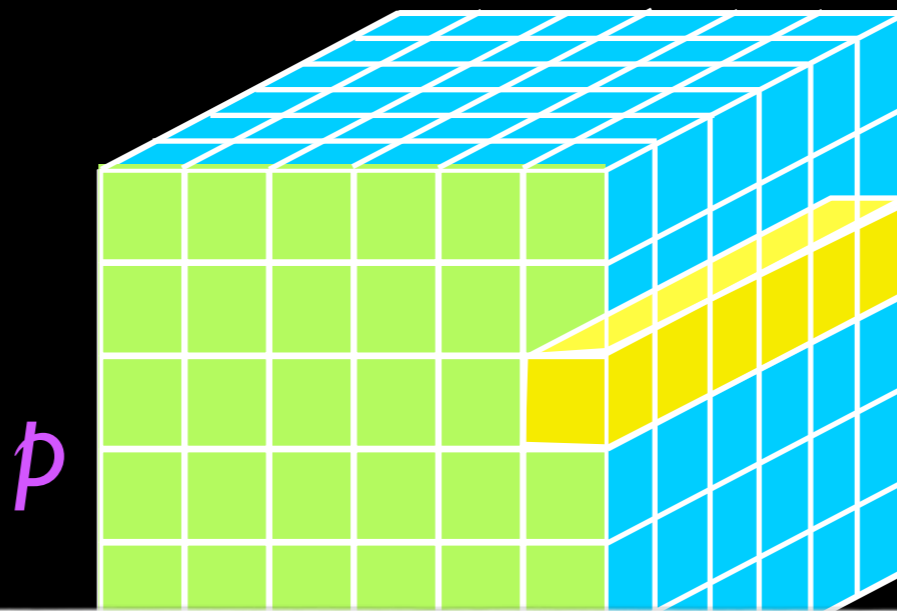
A visualization of the cosmic web, showing a complex network of dark matter filaments and clusters. The filaments are rendered in shades of blue and purple, while the clusters and nodes are highlighted in bright orange and red. The background is black, making the glowing structures stand out.

**Numerically** Constraining  
Star Formation  
in the Real Universe,  
with **Observations**

**Alyssa A. Goodman**

*Harvard-Smithsonian Center for Astrophysics*





de-jargonification

*What's a "p-p-v" cube?*

# GENERALLY

**1D:** Columns

**2D:** Faces or Slices






**3D:** Volumes (e.g. *p-p-v*) = "3D Renderings", "2D Movies"

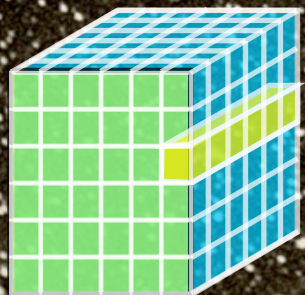
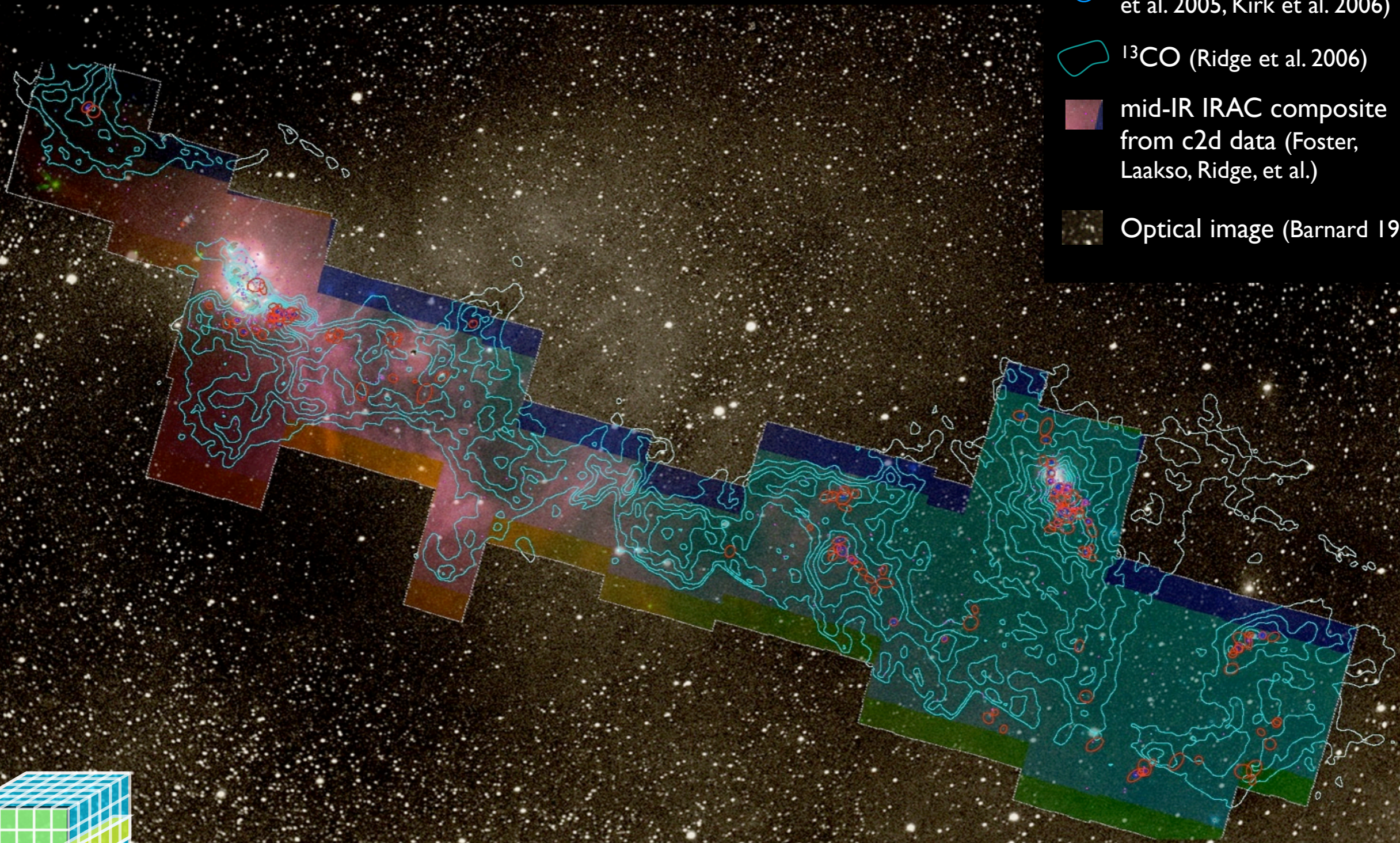
**4D:** Time Series of Volumes = "3D Movies"

Series"

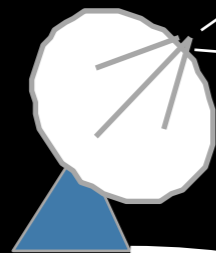
# Perseus Example

COMPLETE

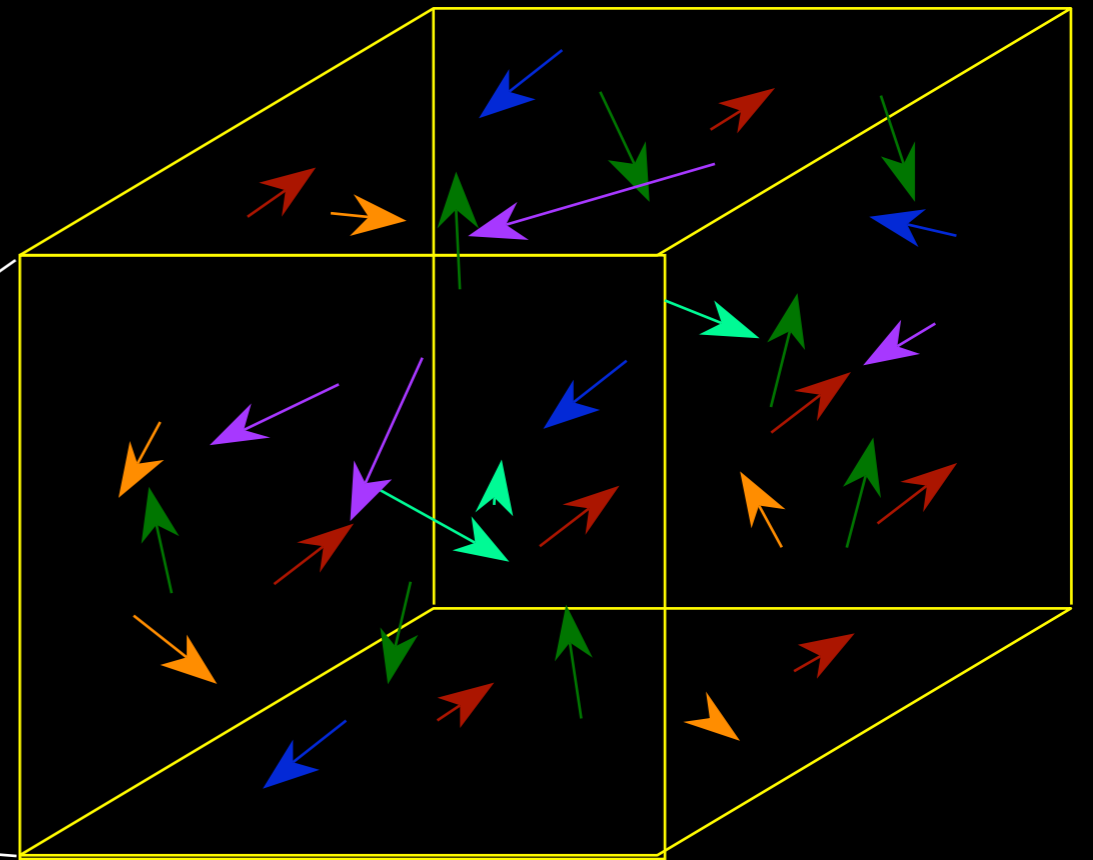
-  mm peak (Enoch et al. 2006)
-  sub-mm peak (Hatchell et al. 2005, Kirk et al. 2006)
-   $^{13}\text{CO}$  (Ridge et al. 2006)
-  mid-IR IRAC composite from c2d data (Foster, Laakso, Ridge, et al.)
-  Optical image (Barnard 1927)



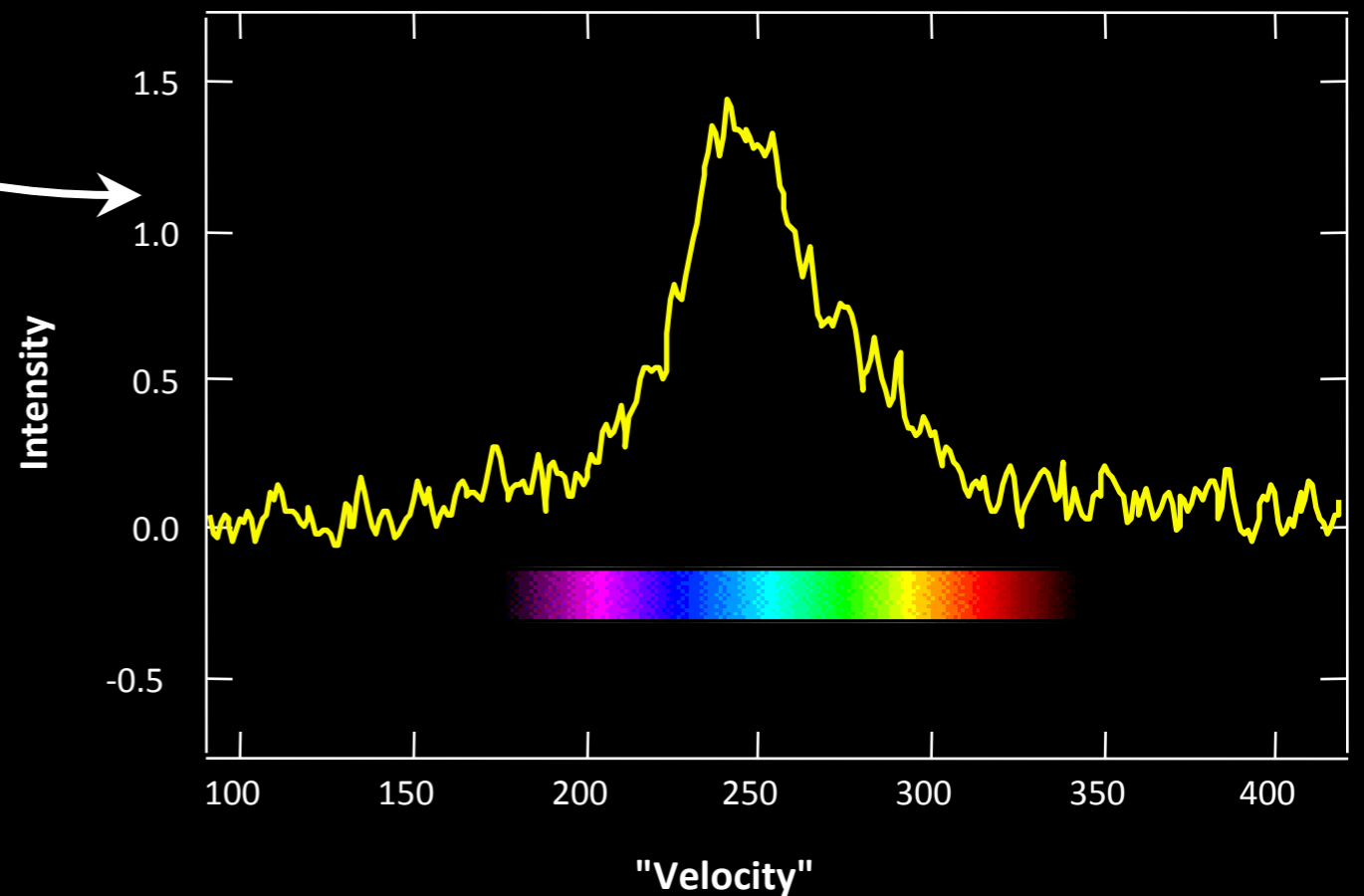
# Velocity from Spectroscopy



Telescope +  
Spectrometer



Observed Spectrum

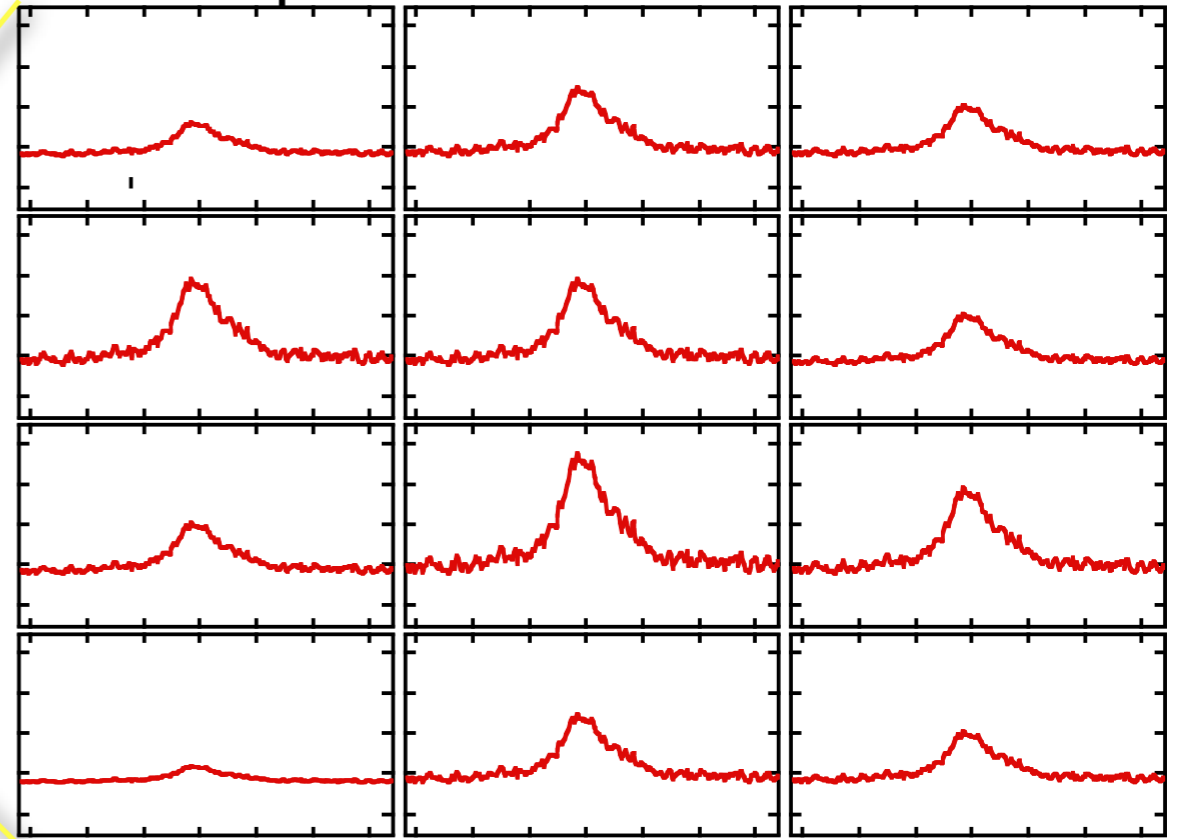


All thanks to Doppler

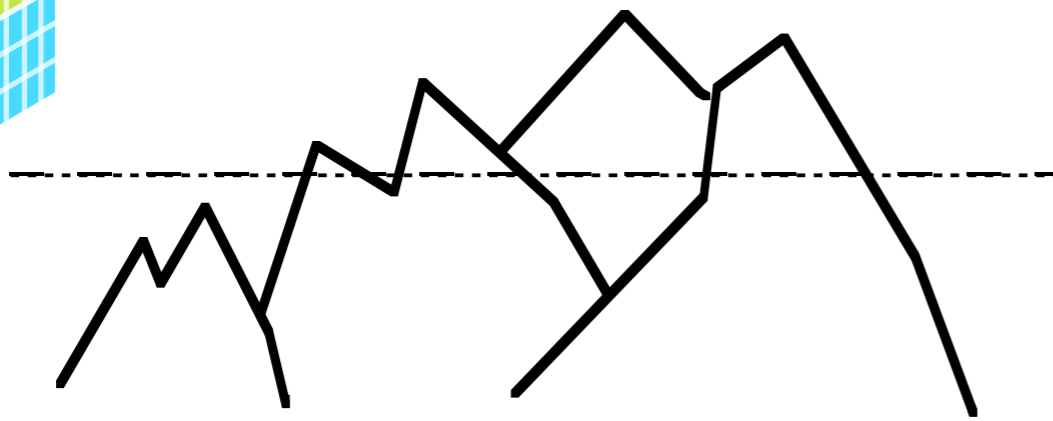
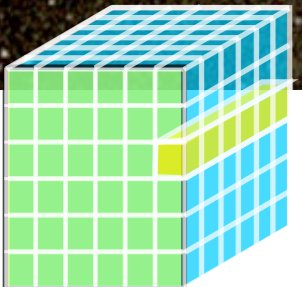
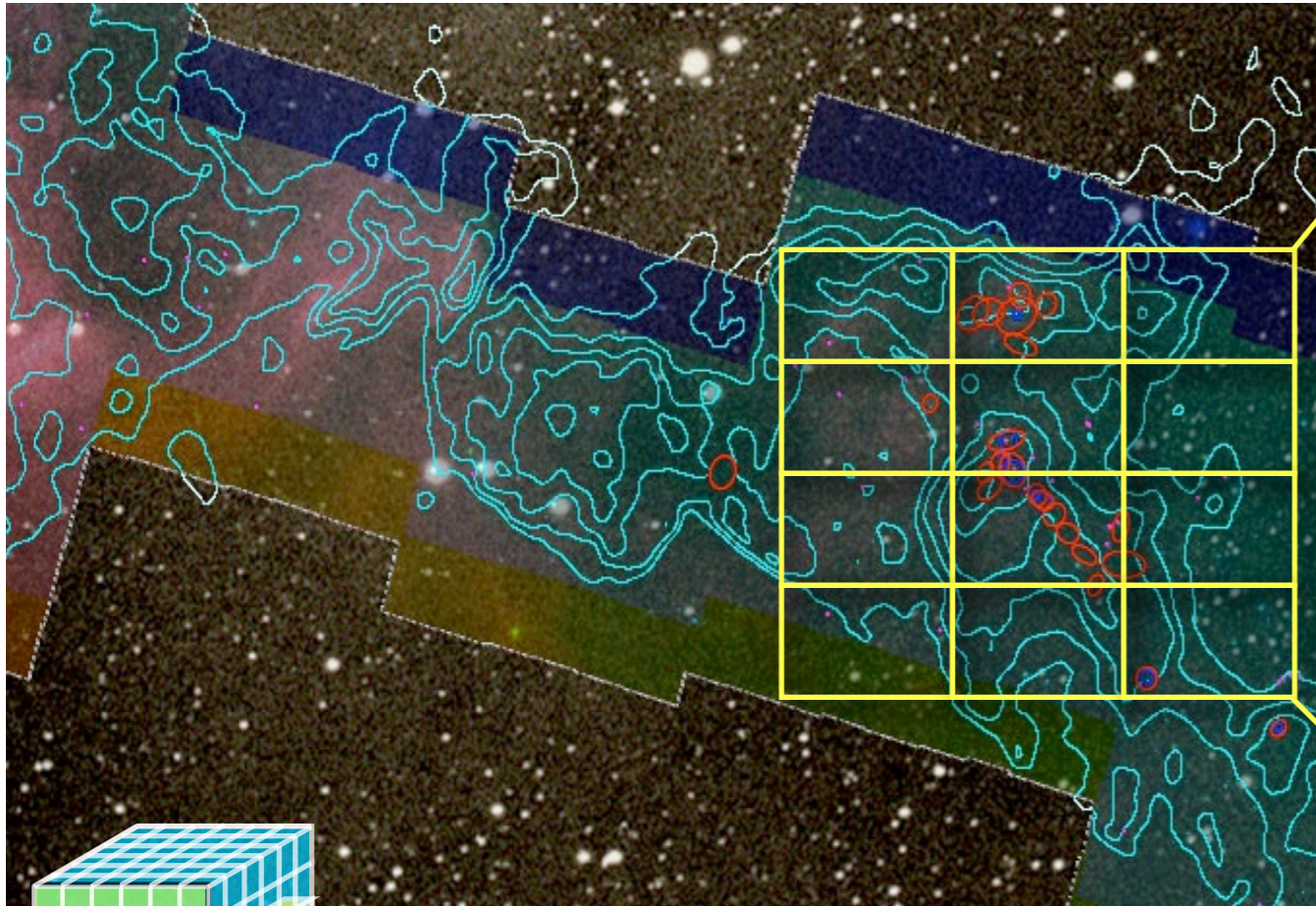
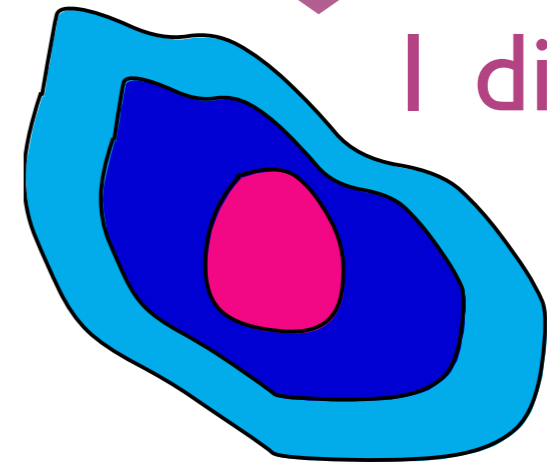


# Spectral-Line Mapping

Spectral Line Observations



Loss of  
1 dimension



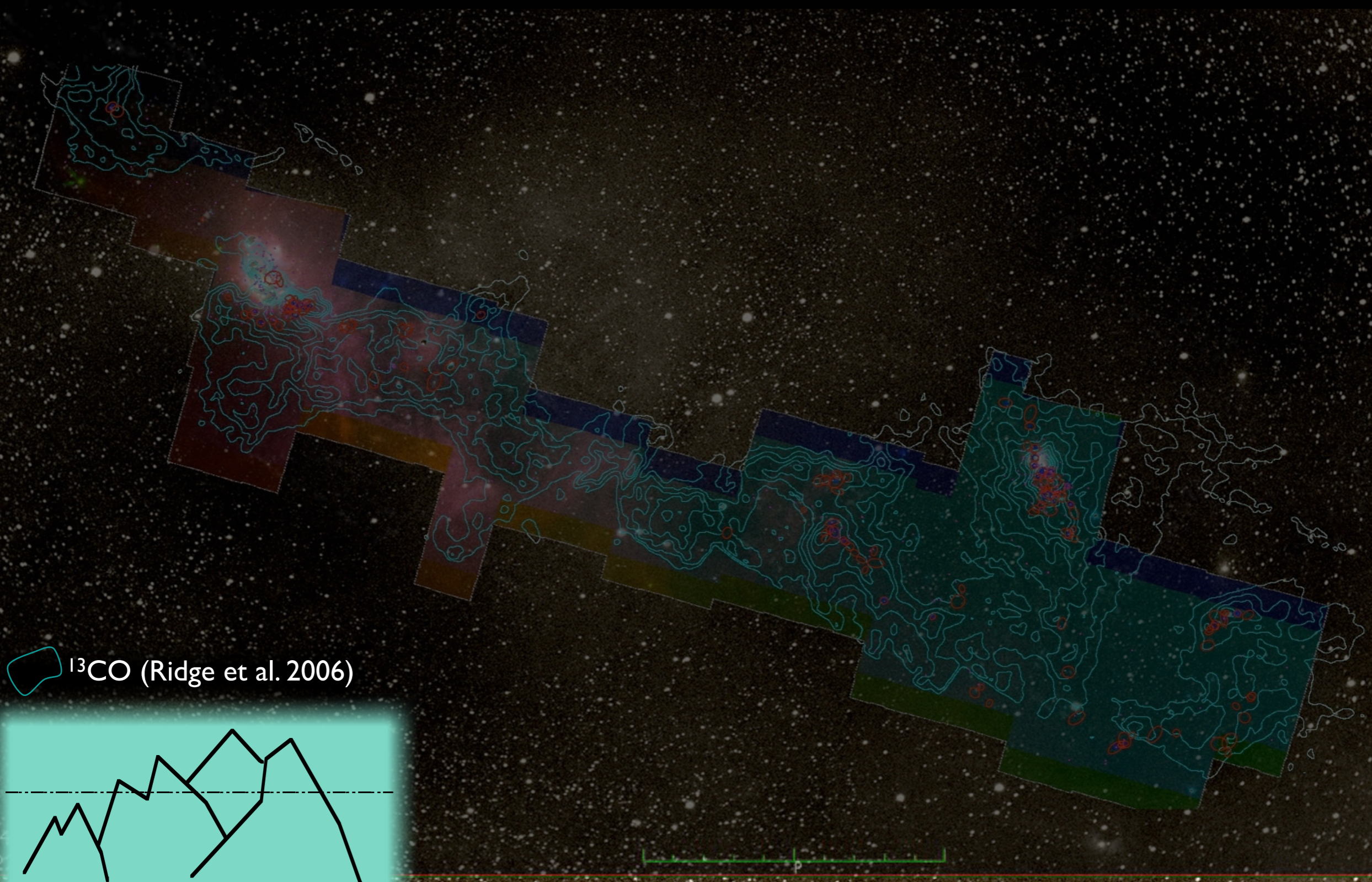
Mountain Range

No loss of  
information

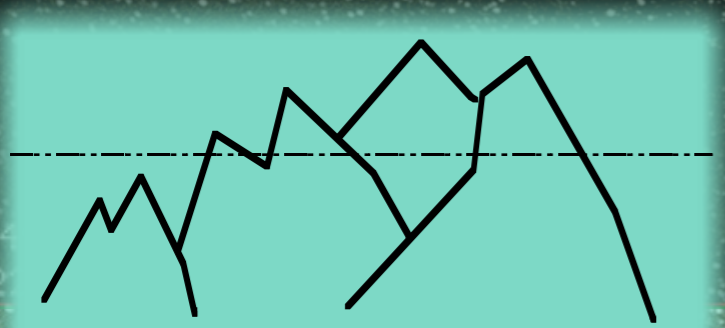


Image size: 520 x 274  
View size: 1305 x 733  
VL: 63 WW: 127

# COMPLETE Perseus



  $^{13}\text{CO}$  (Ridge et al. 2006)

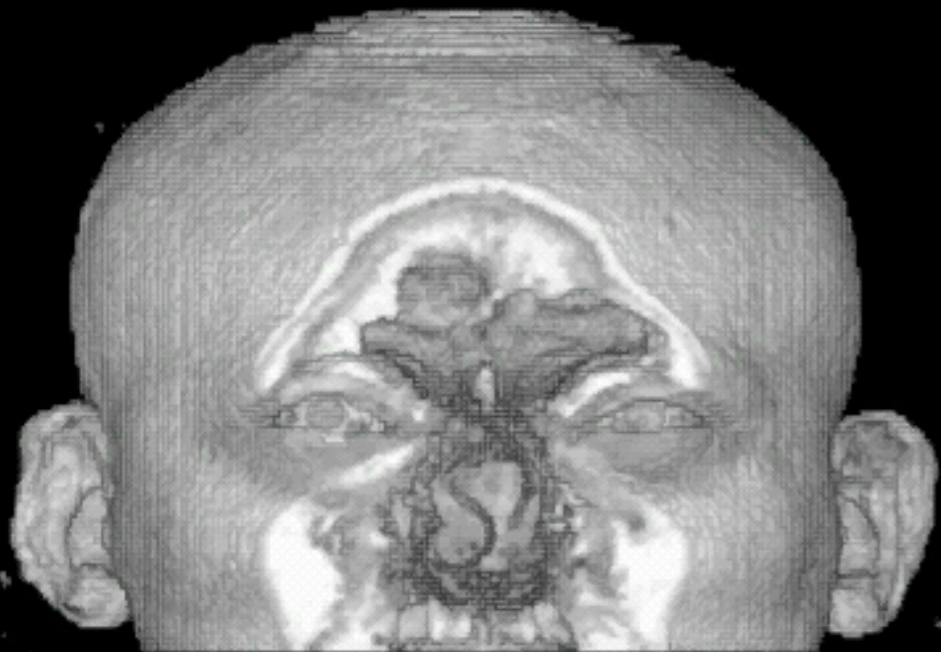


Mountain Range

m: 1724  
oom: 2

# "Astronomical Medicine"

"KEITH"



"z" is depth into head

"PERSEUS"

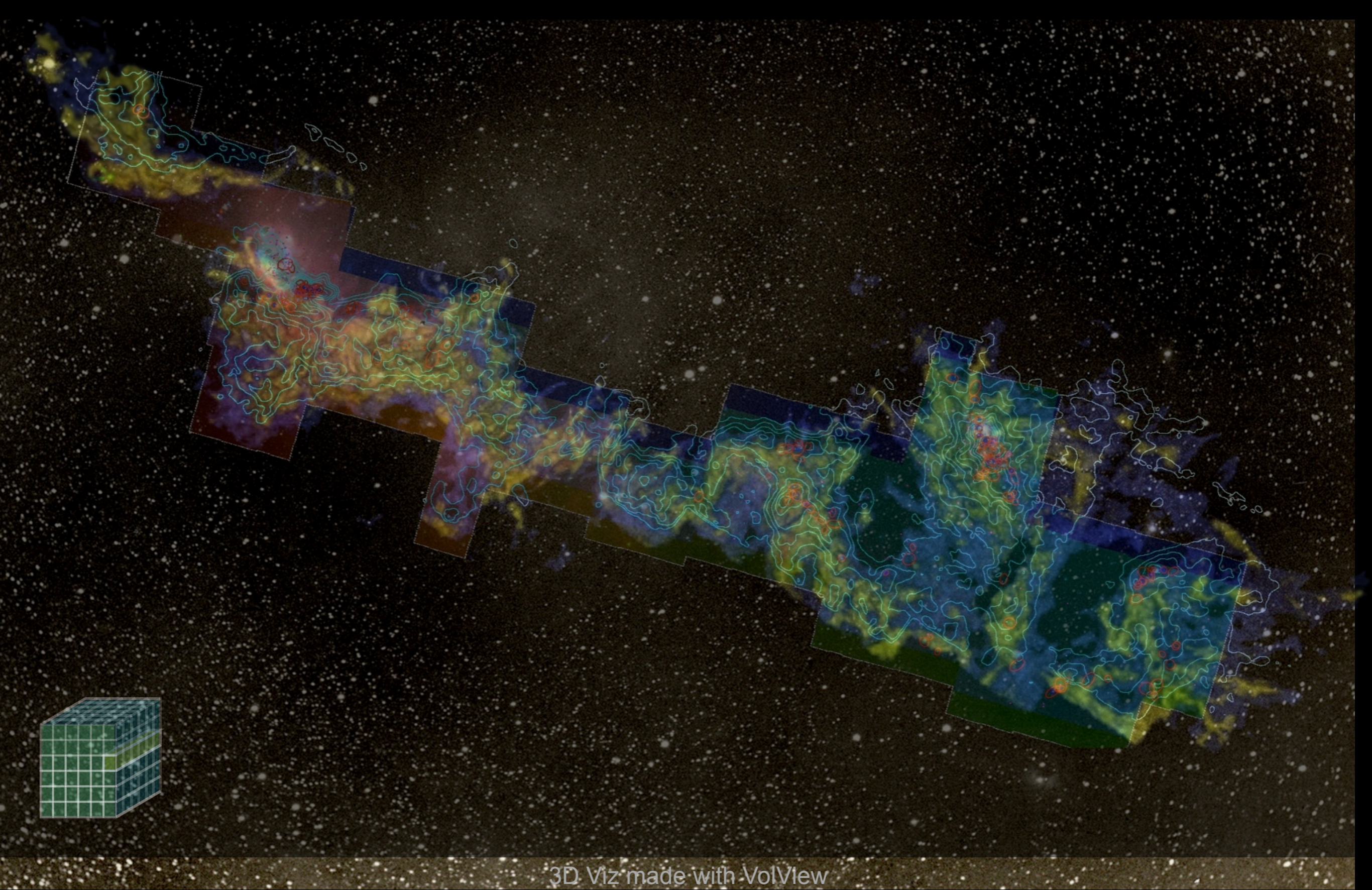


"z" is line-of-sight velocity

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



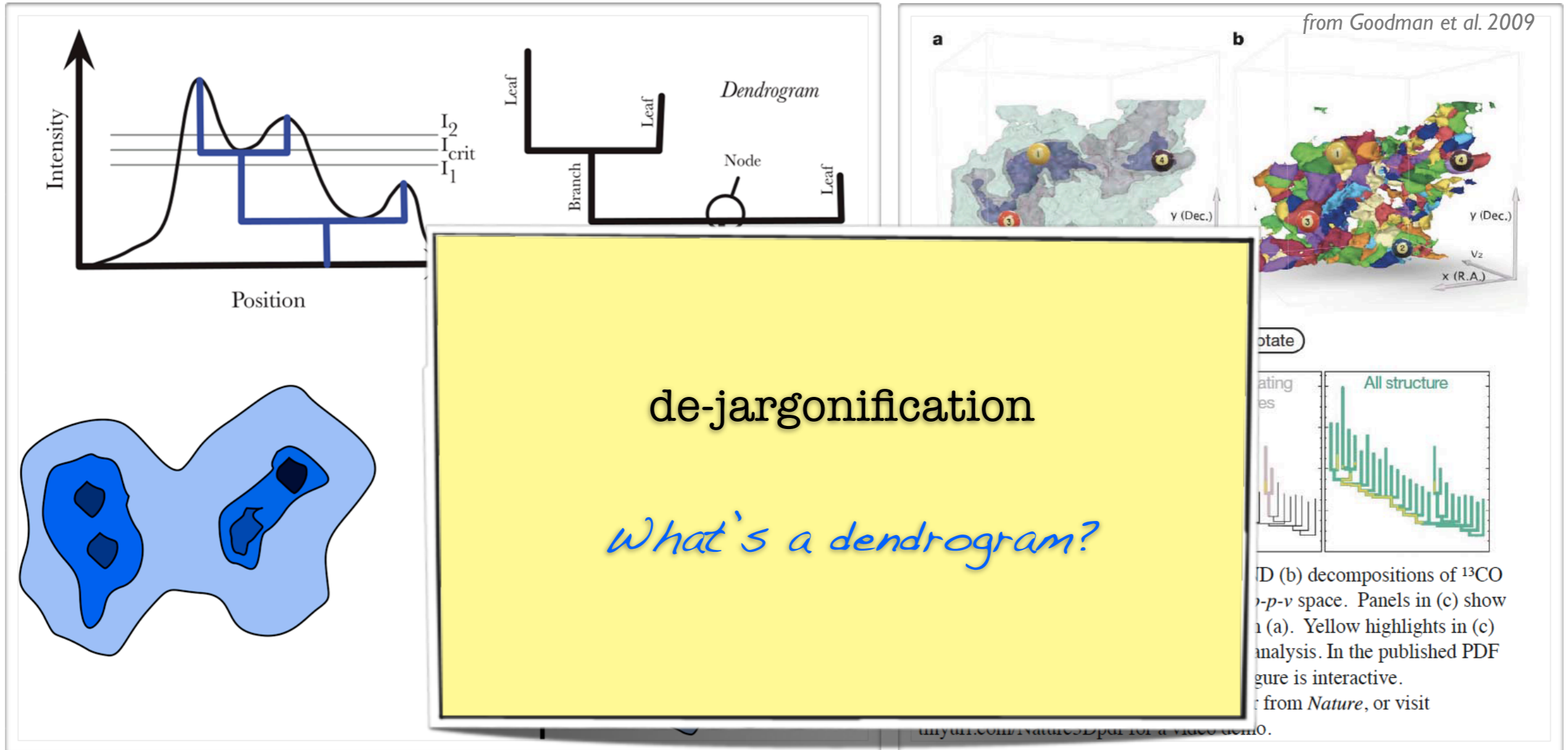




3D Viz made with VolView



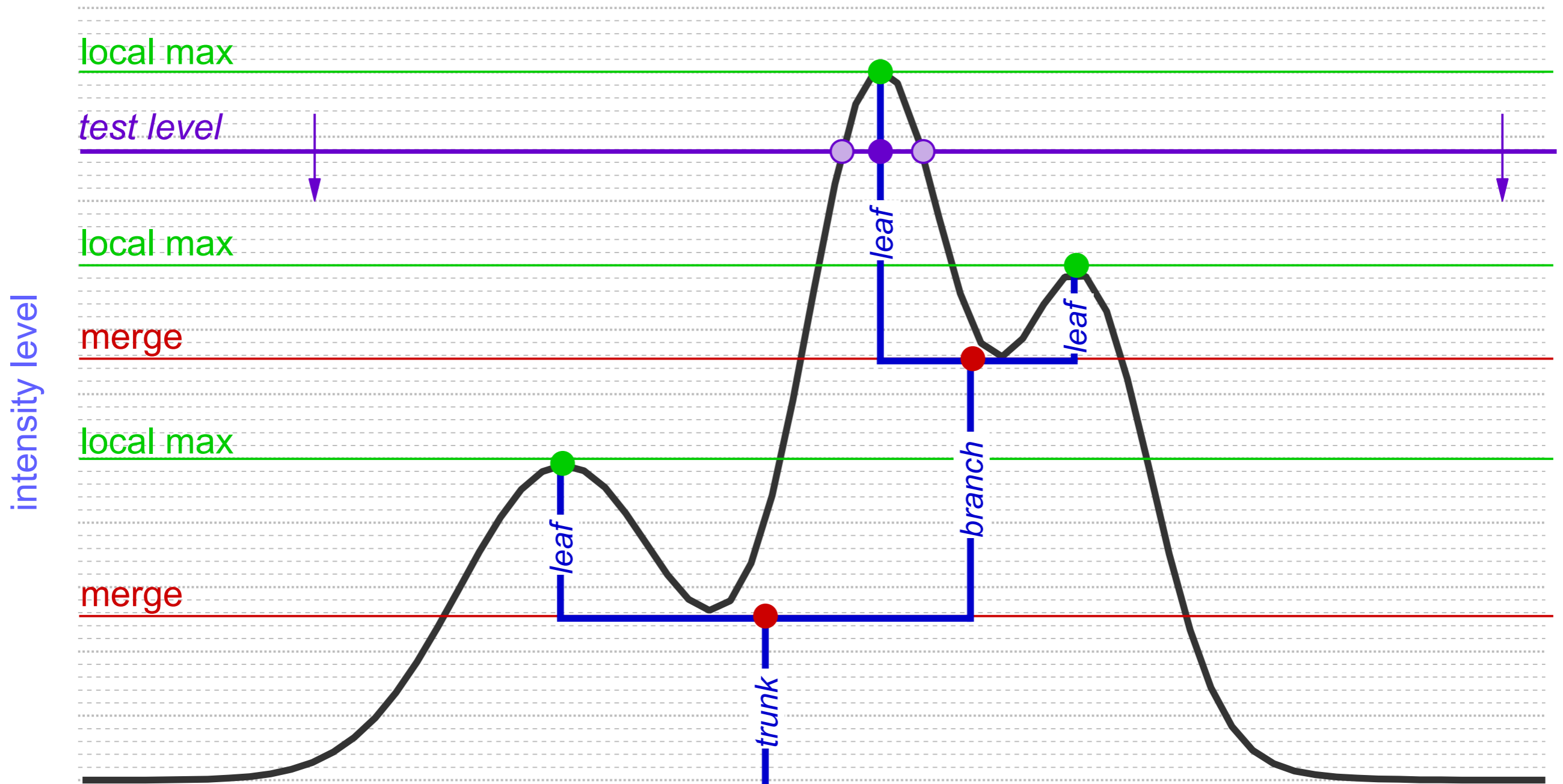
# Dendrograms



## Hierarchical “Segmentation”

Rosolowsky, Pineda, Kauffmann & Goodman 2008; and see Erik Rosolowsky’s talk in a little while!

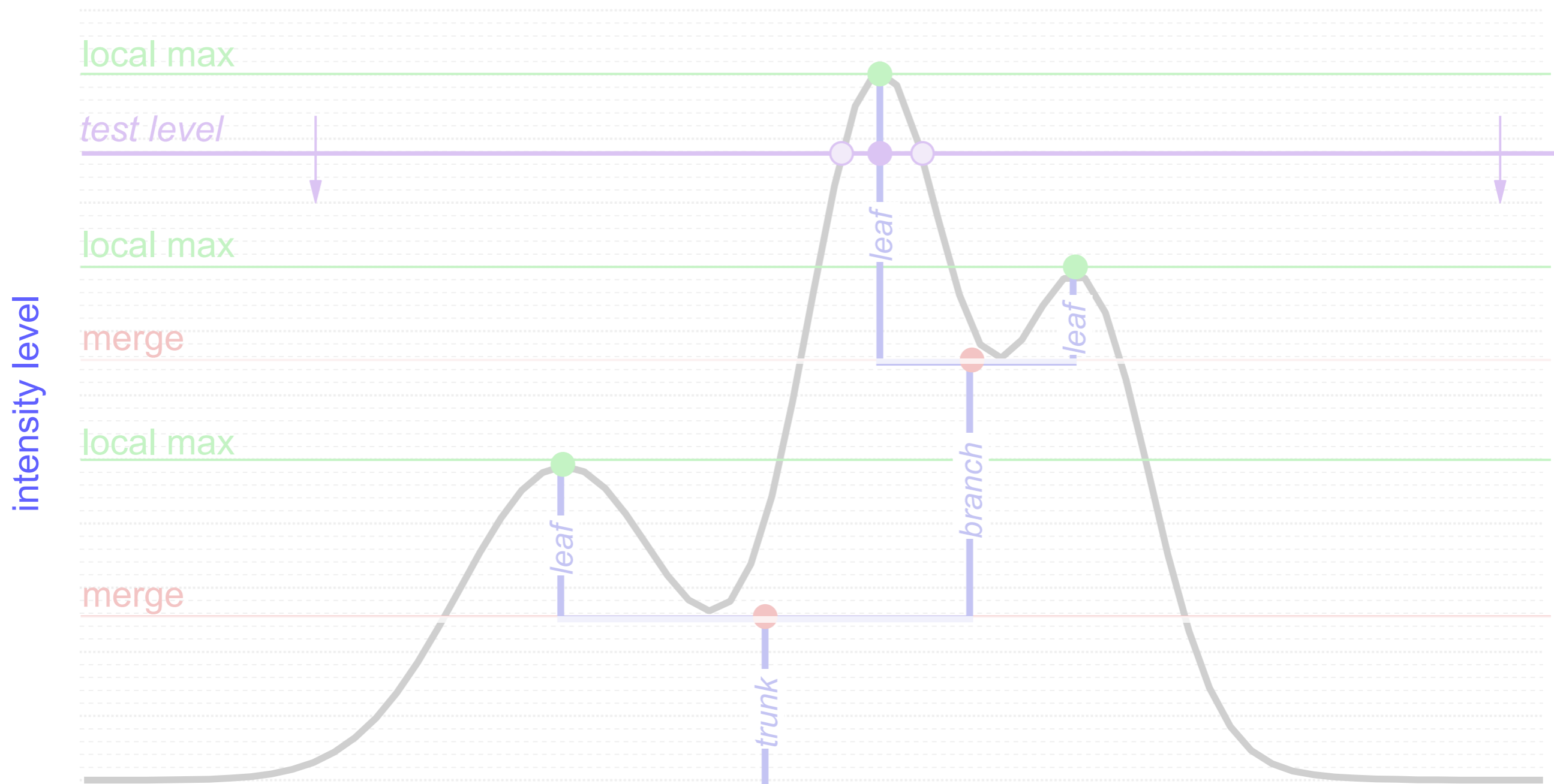
# Dendrograms



## Hierarchical “Segmentation”

*Rosolowsky, Pineda, Kauffmann & Goodman 2008*

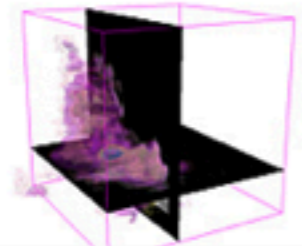
# Dendrograms




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





The Astronomical Medicine Project
Initiative In Innovative Computing at Harvard

**Harvard IIC Home**

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

**Research**  
background  
projects  
papers  
images  
movies

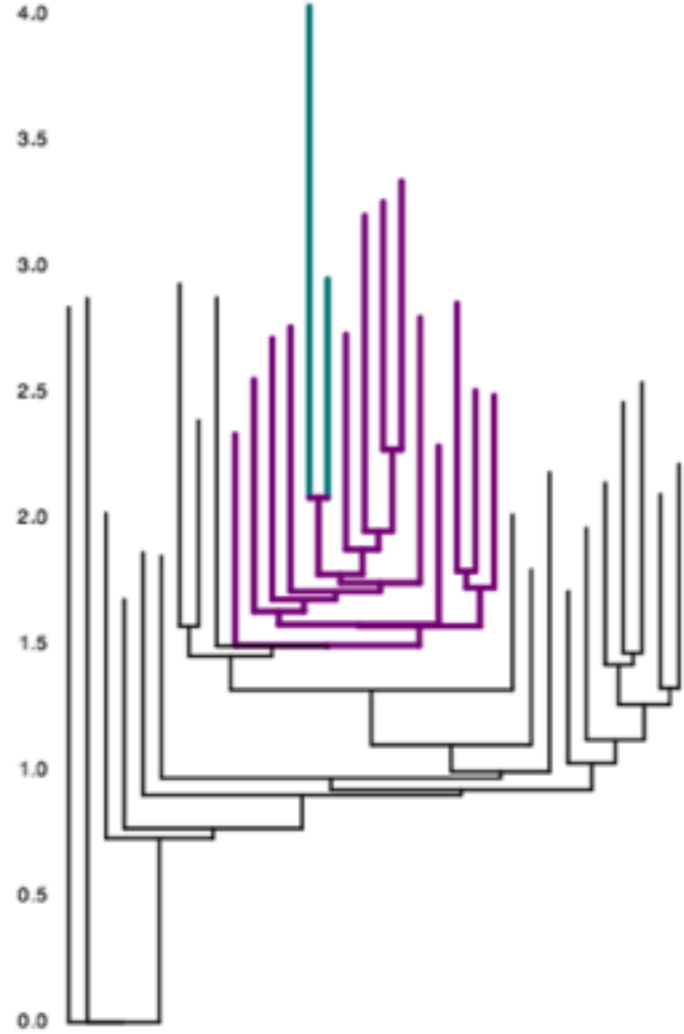
**Software**  
overview  
Slicer: getting started  
Slicer 3  
fits2itk  
OsiriX  
DendroStar

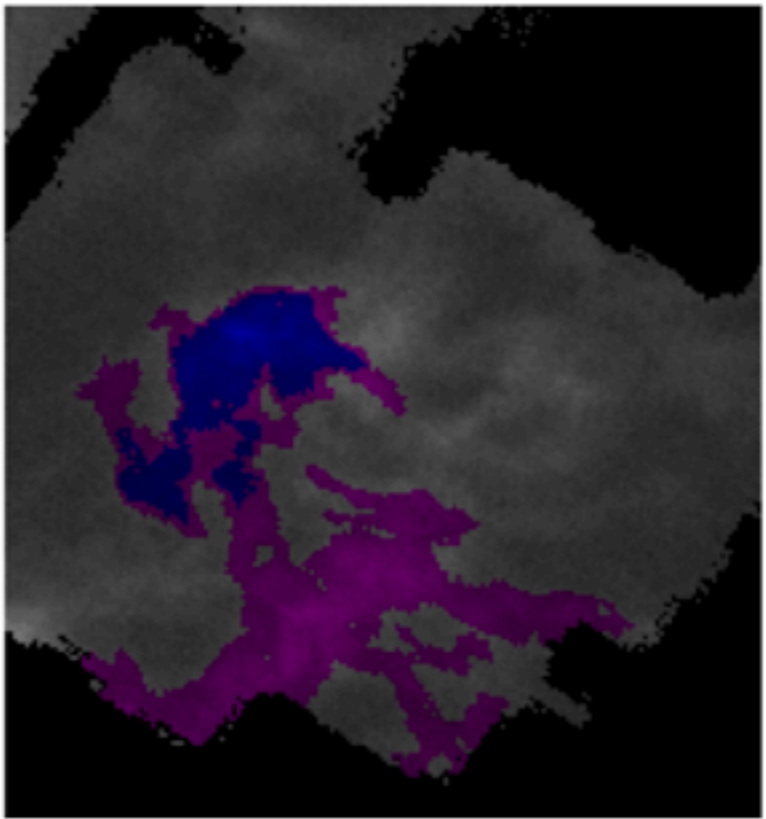
**Links**  
Center for Astrophysics  
COMPLETE Survey  
Surgical Planning Lab  
3D Slicer  
related projects

**User**  
Login

**Search**

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





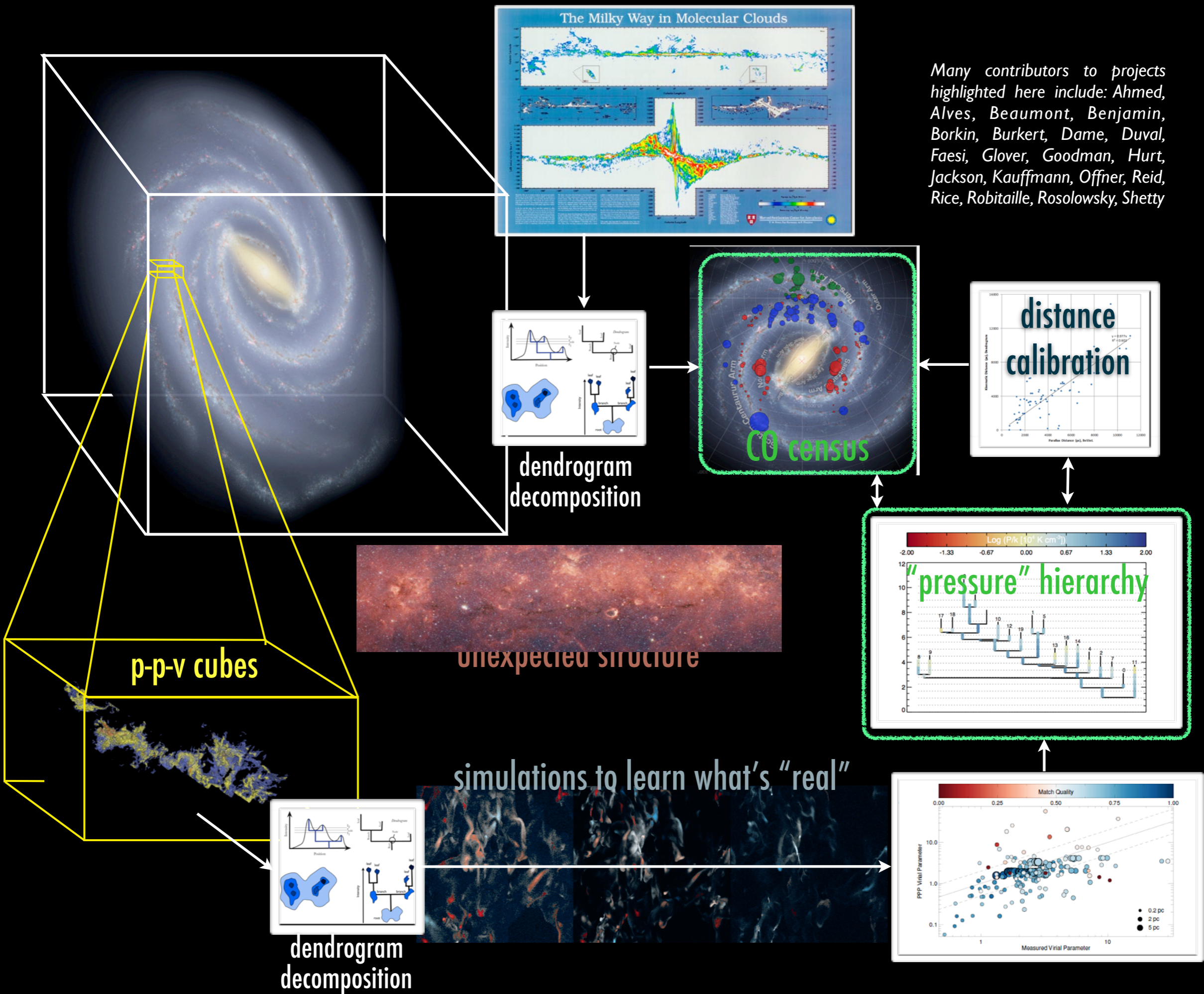
Tint:

Suppress tint:

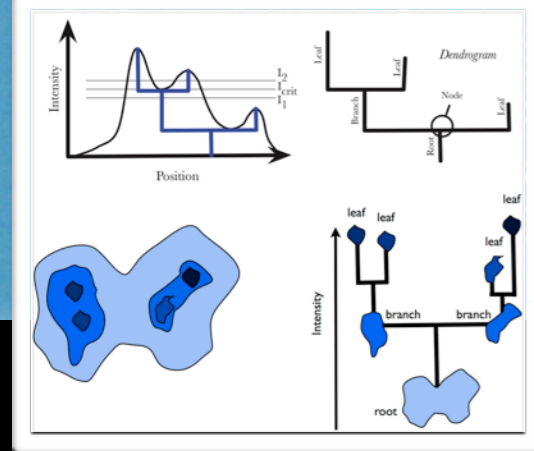
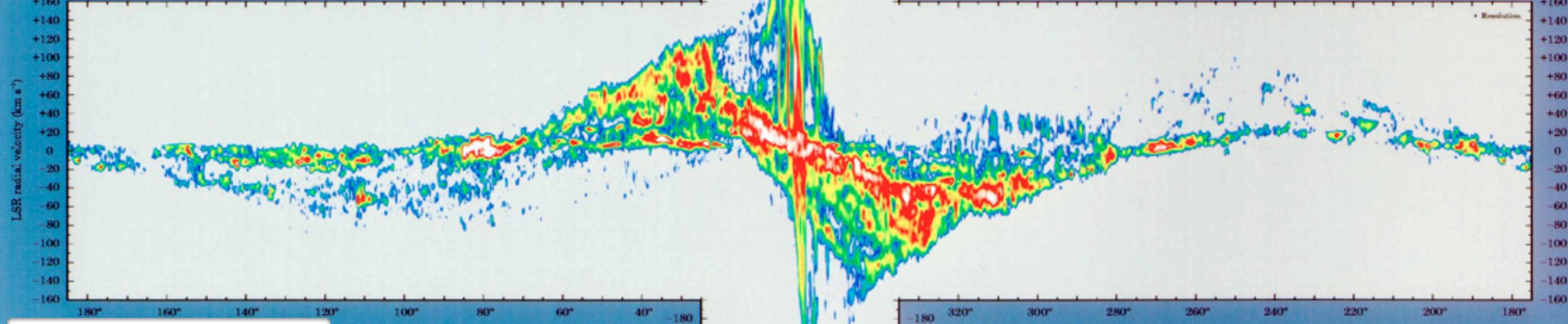
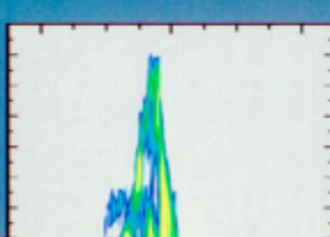
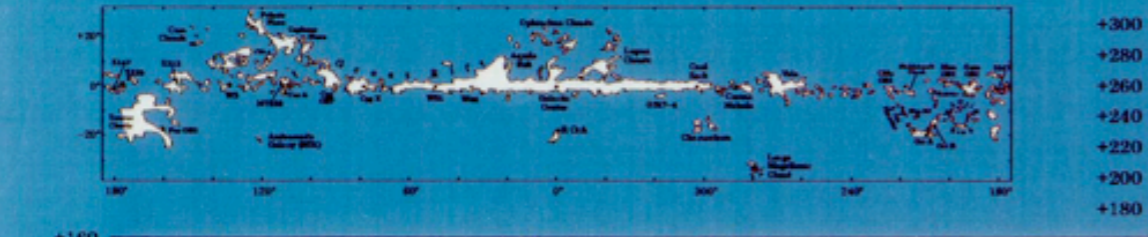
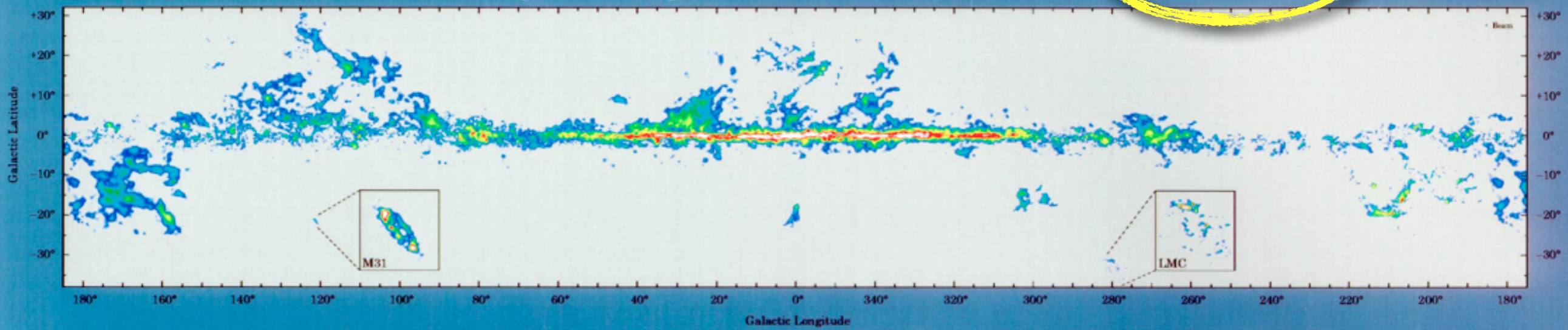
Reset:

Applet DendroStar started

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



# The Milky Way in Molecular Clouds

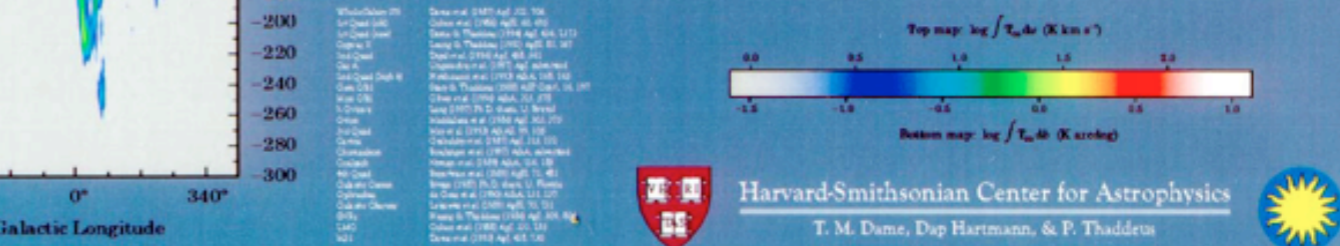


... of the CO-emitting molecular cloud information lacking in our representation. CO line intensity Galactic latitude centered on the Galactic plane is plotted on the y-axis. The observed radial velocities are plotted on the x-axis, except for the poorly understood outflow of molecular gas. A thin disk is at the right.

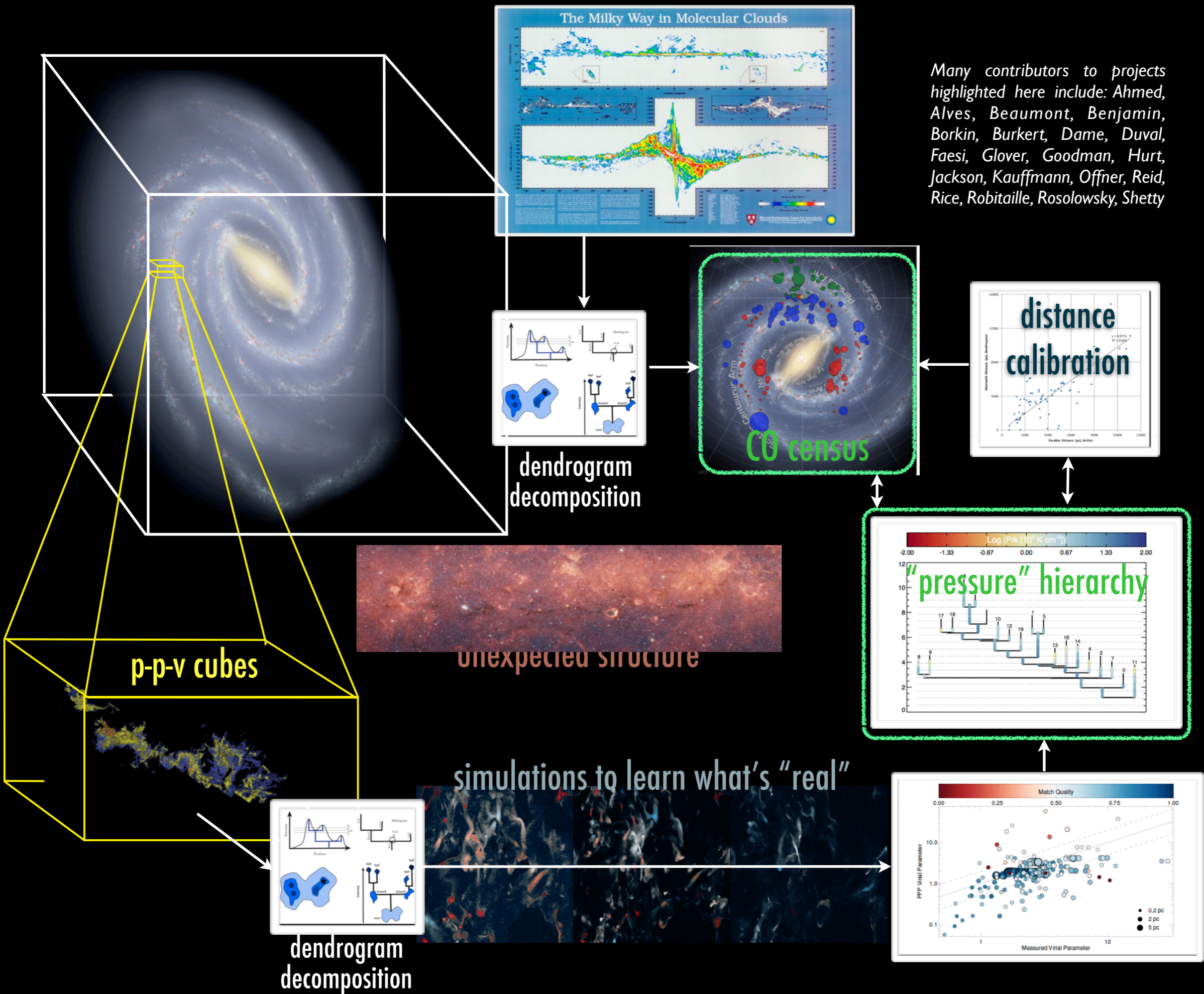
... as several times higher angular resolution (even 100 micron) or half baseline— and at 2 to 33 times higher sensitivity per solid angle. These numbers have now been mapped in the very near to the entire Galactic plane over a 6°-6° range of longitude, as well as many local clouds at higher latitude. The maps above indicate that 250,000 new objects are revealed in some high-latitude regions (e.g., Thore) where full-resolution observations do not exist.

... Roughly half of the new data have already been published as separate volumes of molecular clouds in regions (see list at right), and since 1985 have formed the basis for 13 Ph.D. dissertations. The database was distributed in the past five years in nine long-wavelength surveys of the first and second Galactic quadrants.

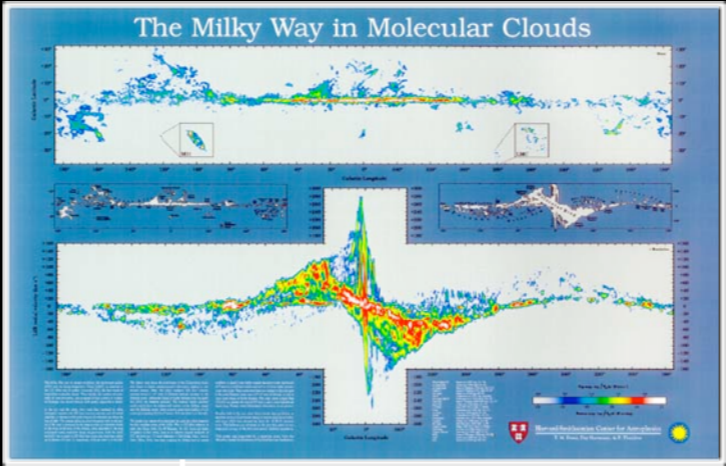
... This paper was supported by a postdoctoral grant from the Adams Foundation, Endowment of the Smithsonian Institution.



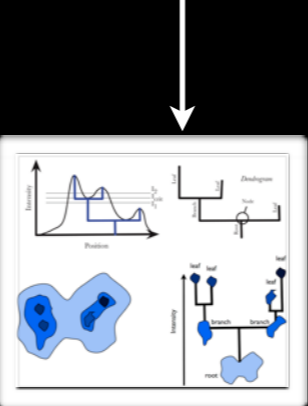
Dame et al. 2001



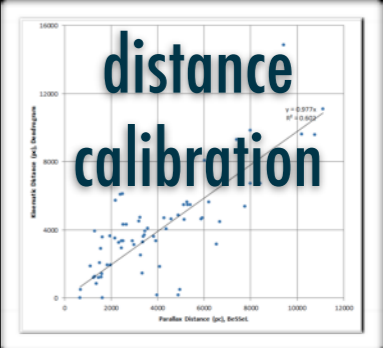
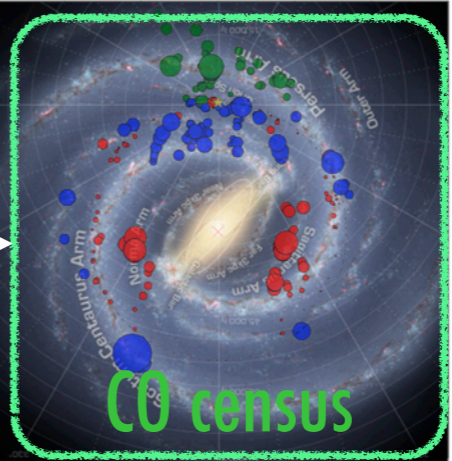




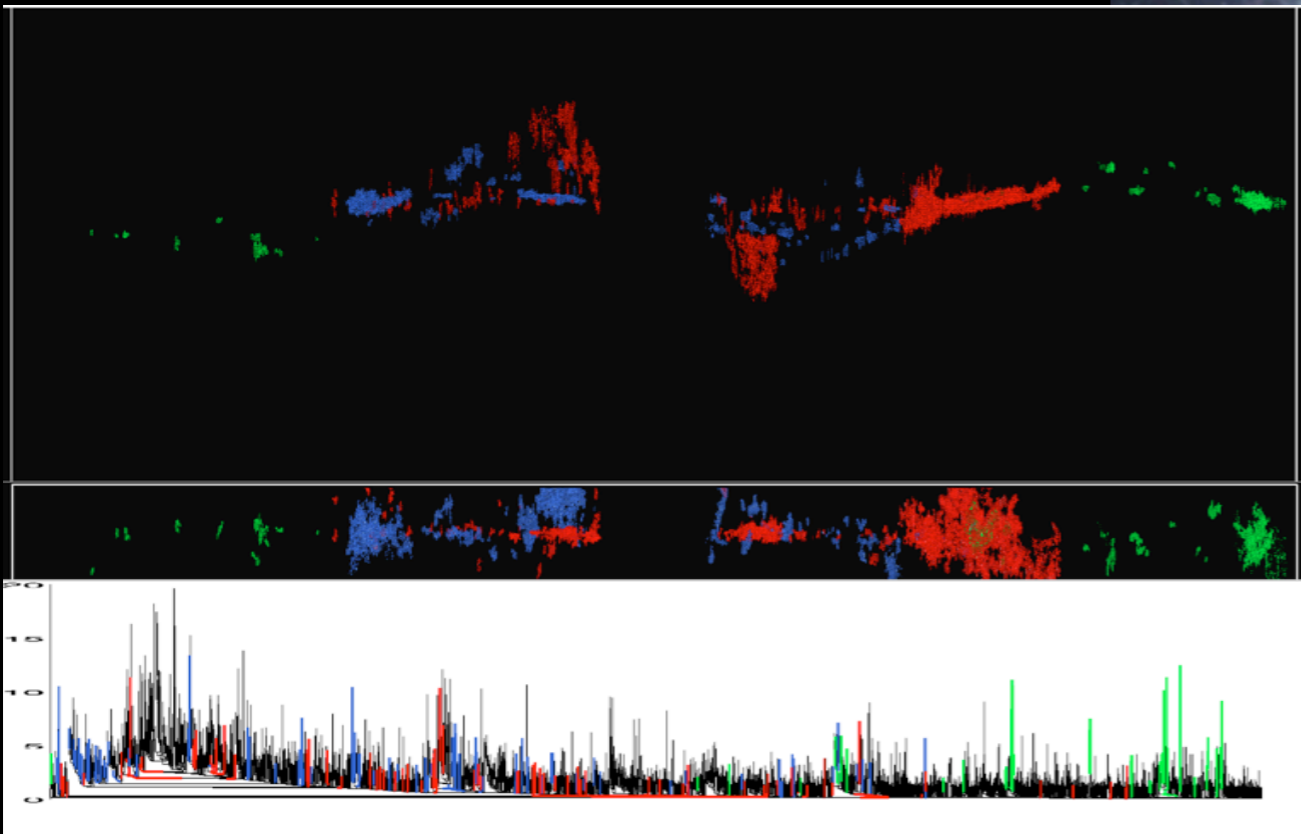
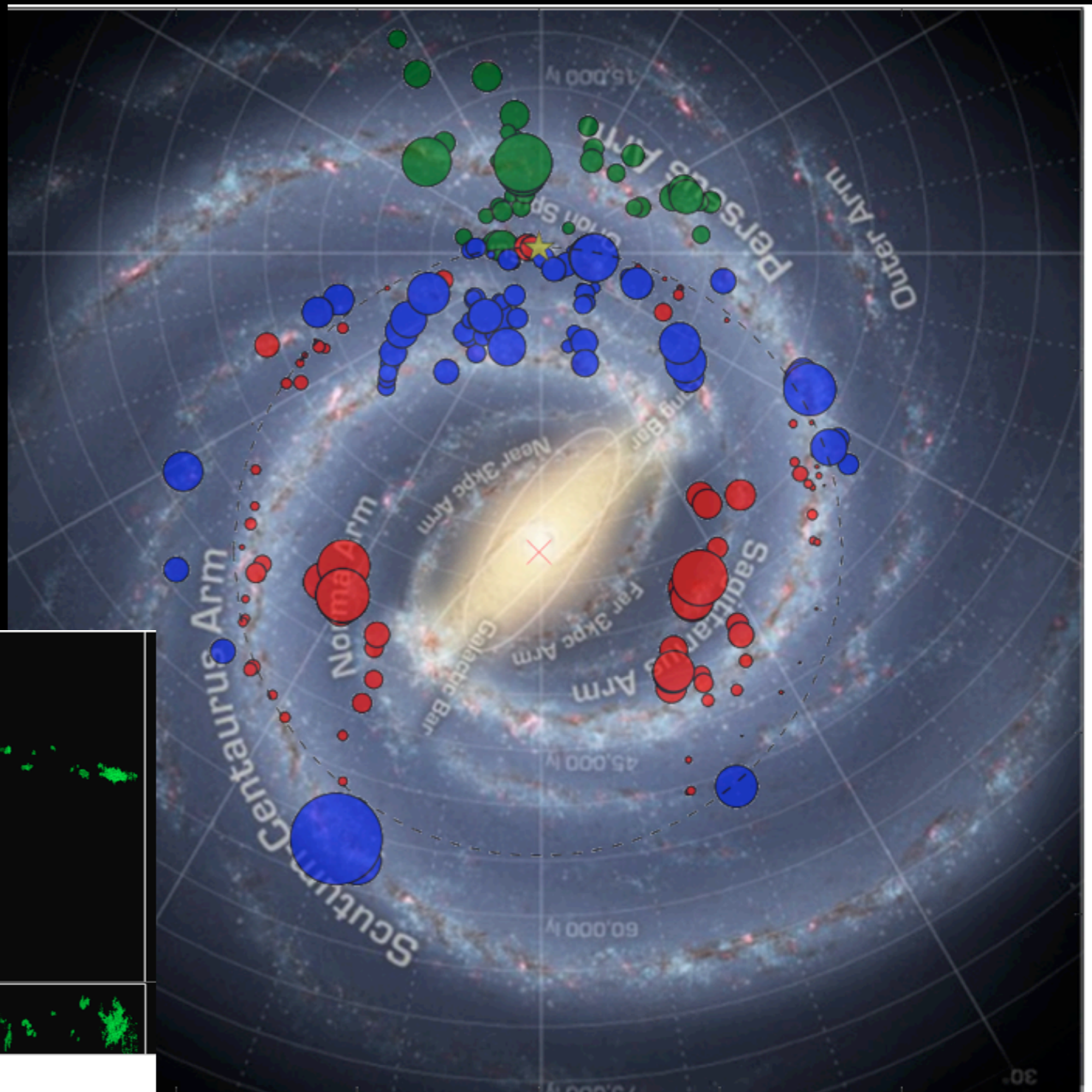
Many contributors to projects highlighted here include: Beaumont, Benjamin, Dame, Duval, Goodman, Offner, Reid, Rice



dendrogram decomposition



# Preliminary Census of "Bound" Features

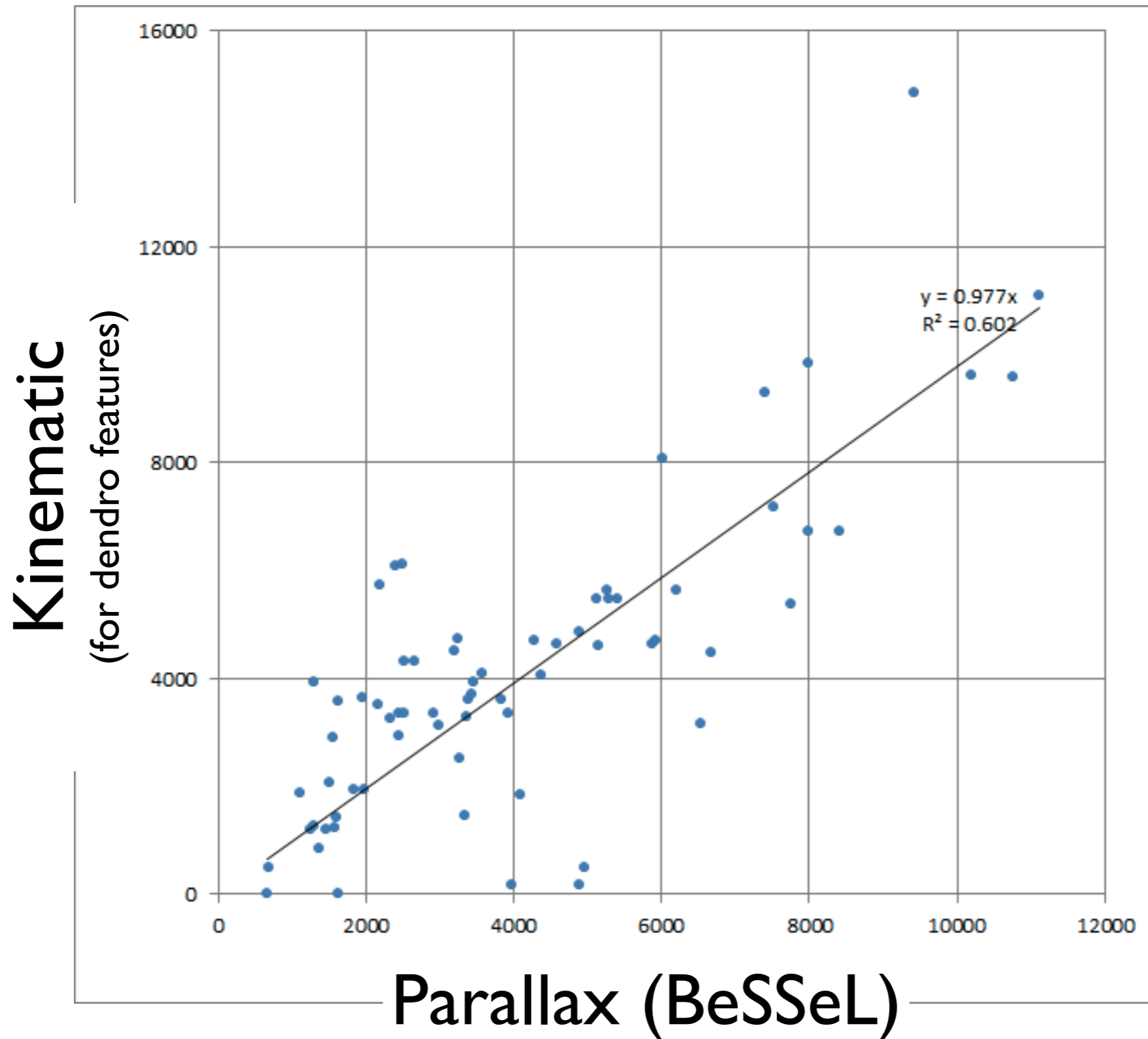


Rice, Beaumont, Dame & Goodman 2014

# What does “bound” mean?

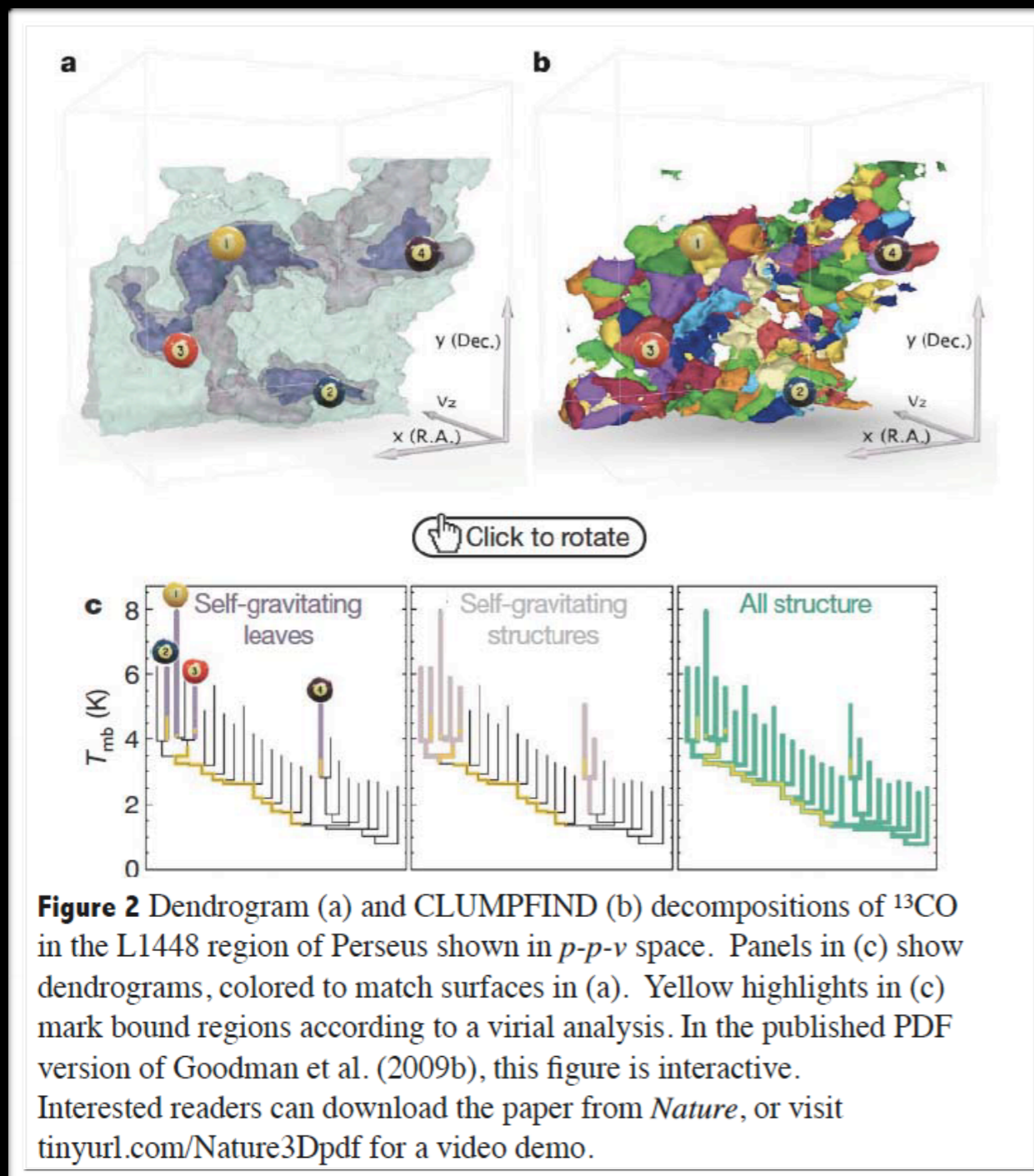
And, how good are distances?

# Kinematic distances are OK, but not fantastic...



*from Sara Duval's Harvard Junior Thesis with AG, 2013 (thanks to Dame & Reid)*

# Bound? (2008: Frank Shu asks for a “test of the test”)



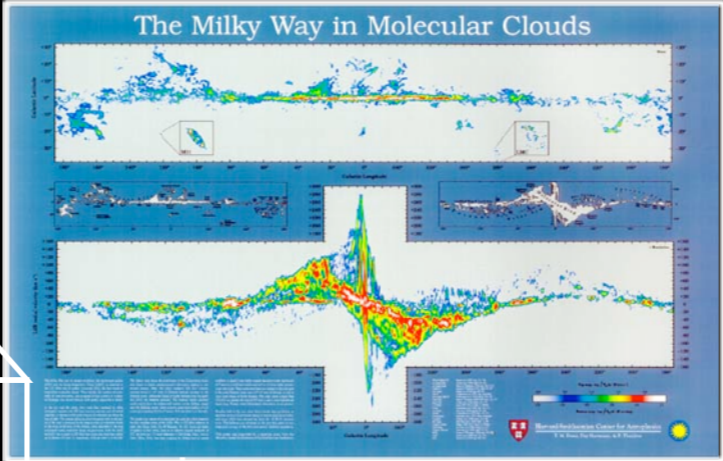
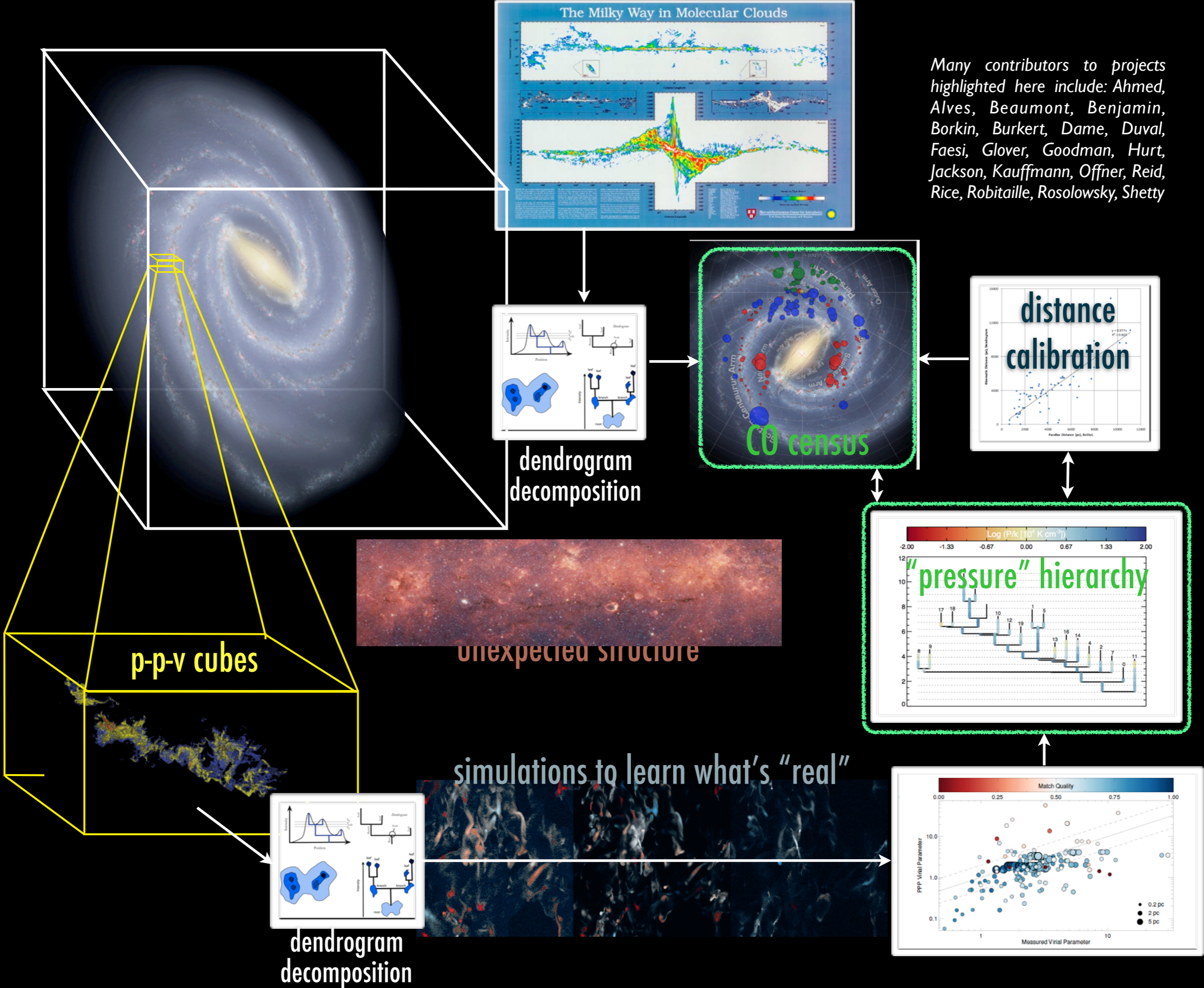
**Yellow** highlighting= “self-gravitating”  
...where “self-gravitating” just means

$$\alpha_{\text{vir}} (=5s_v^2 R/M_{\text{lum}}) < 2$$

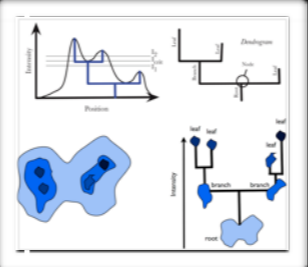
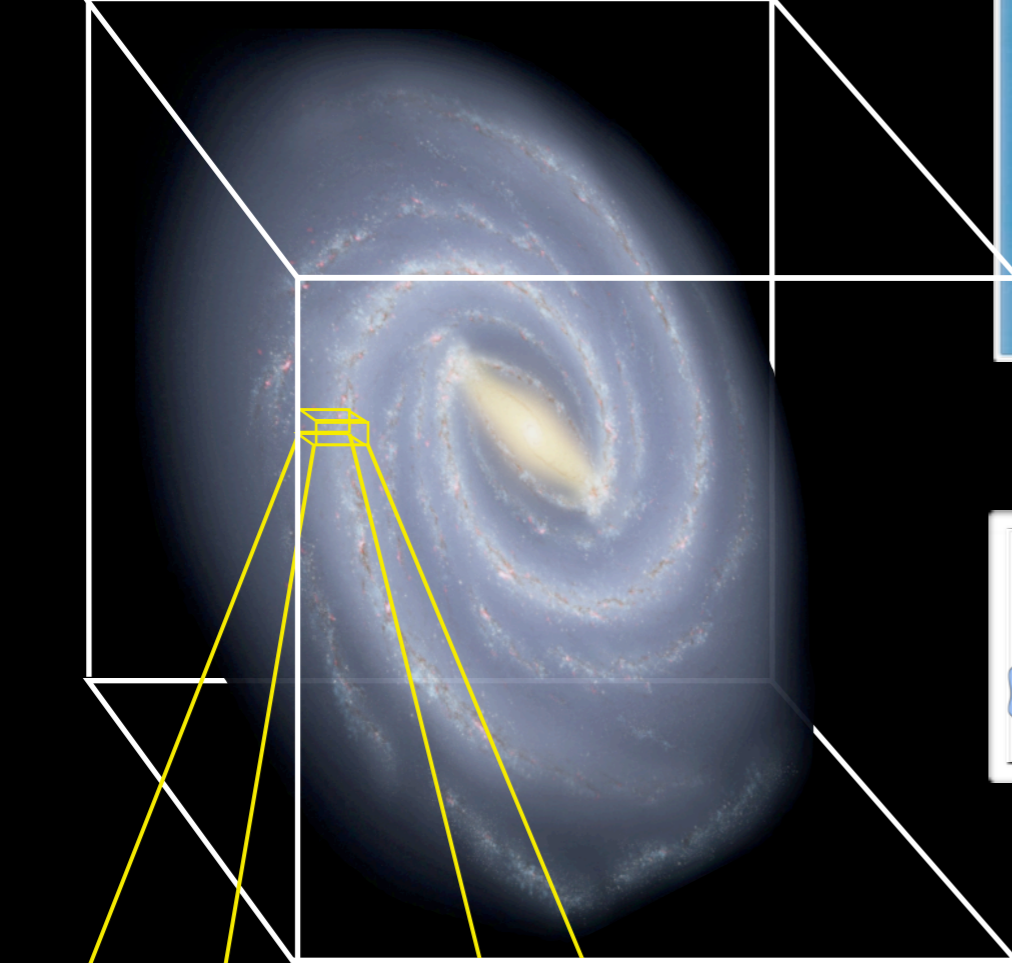
cf. Bertoldi & McKee 1992

## Tests

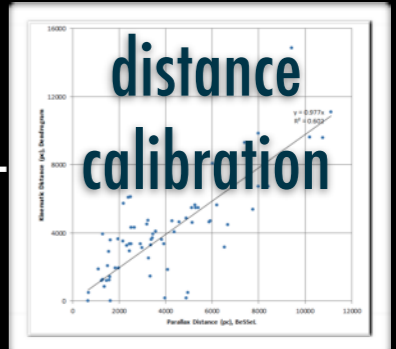
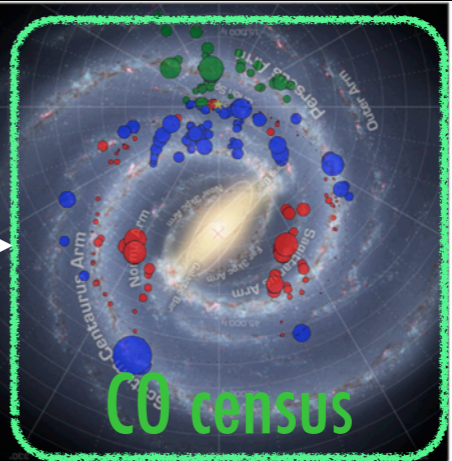
- $p$ - $p$ - $v$  OK for  $p$ - $p$ - $p$ ?
- ignoring all but gravity & random KE OK?
- $^{13}\text{CO}$  good enough?



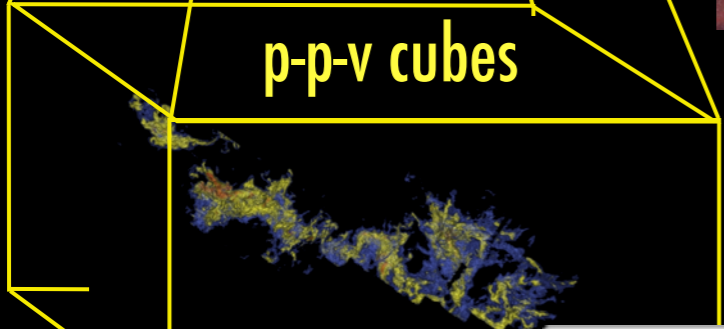
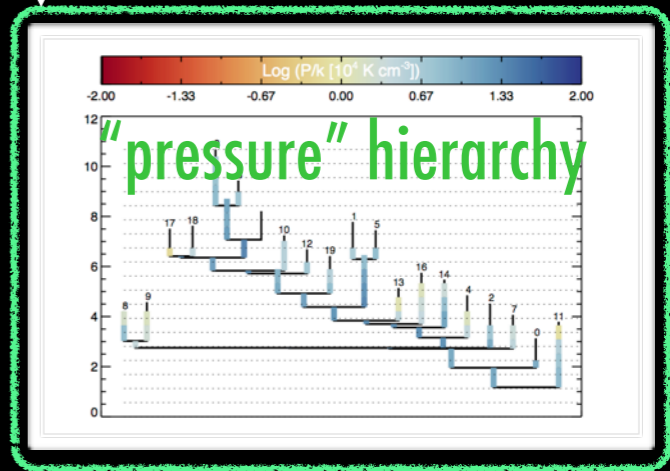
Many contributors to projects highlighted here include: Ahmed, Alves, Beaumont, Benjamin, Borkin, Burkert, Dame, Duval, Faesi, Glover, Goodman, Hurt, Jackson, Kauffmann, Offner, Reid, Rice, Robitaille, Rosolowsky, Shetty



dendrogram decomposition

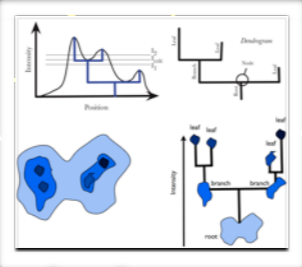


unexpected structure

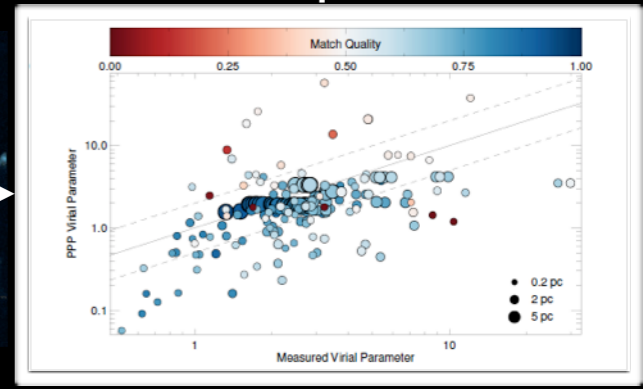
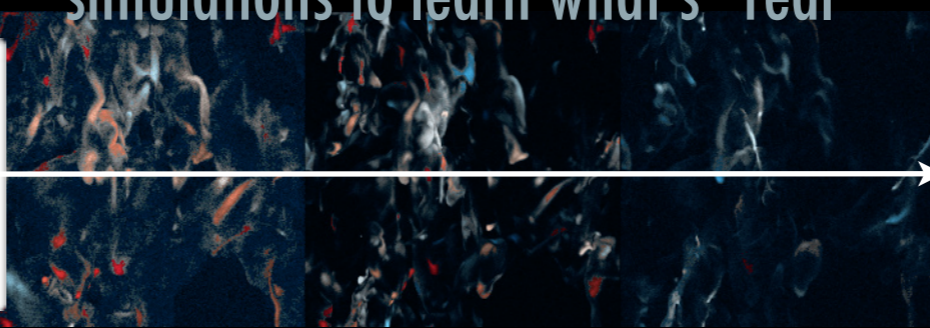


p-p-v cubes

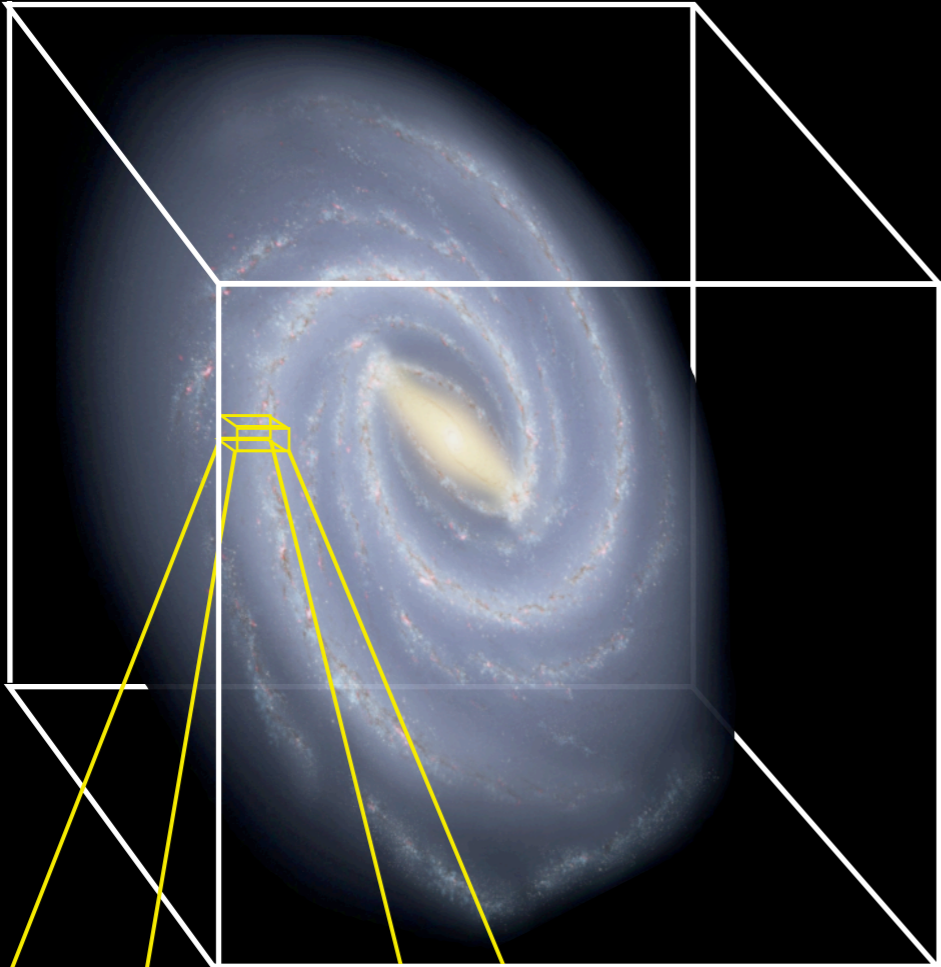
simulations to learn what's "real"



dendrogram decomposition



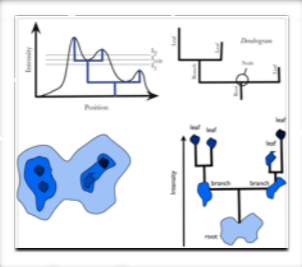
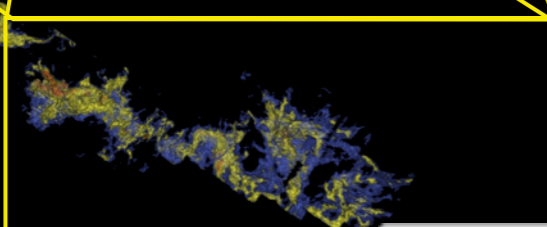
Many contributors to projects highlighted here include: Alves, Beaumont, Benjamin, Borkin, Glover, Goodman, Hurt, Offner, Rosolowsky, Shetty



# What to believe?

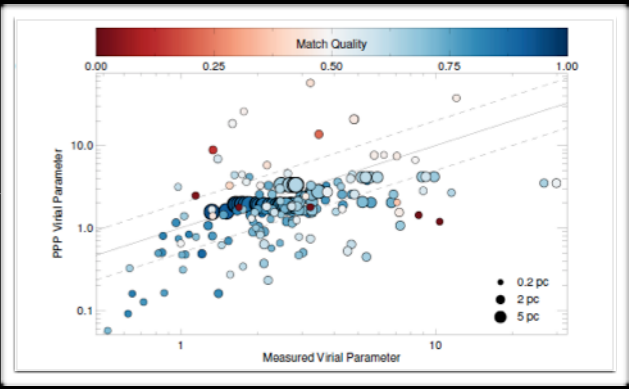
How well does *p-p-v* represent *p-p-p*?

*p-p-v* cubes



dendrogram decomposition

simulations to learn what's "real"



# What to believe?



**Taste test:** Using simulations, and synthetic observations of those simulations, measure “match quality” (indicating  $p$ - $p$ - $v$  space overlap of “real”  $p$ - $p$ - $p$  dendrogram features projected in to  $p$ - $p$ - $v$  space, and structures found in  $p$ - $p$ - $v$  dendrogram).

*Beaumont, Offner, Shetty, Glover & Goodman 2013, using RADMC-3D from Dullemond et al. cf. prior work of Stella Offner, Rowan Smith, Erik Rosolowsky, Paolo Padoan, Rahul Shetty, et al.*



# p-p-v views, $^{13}\text{CO}$

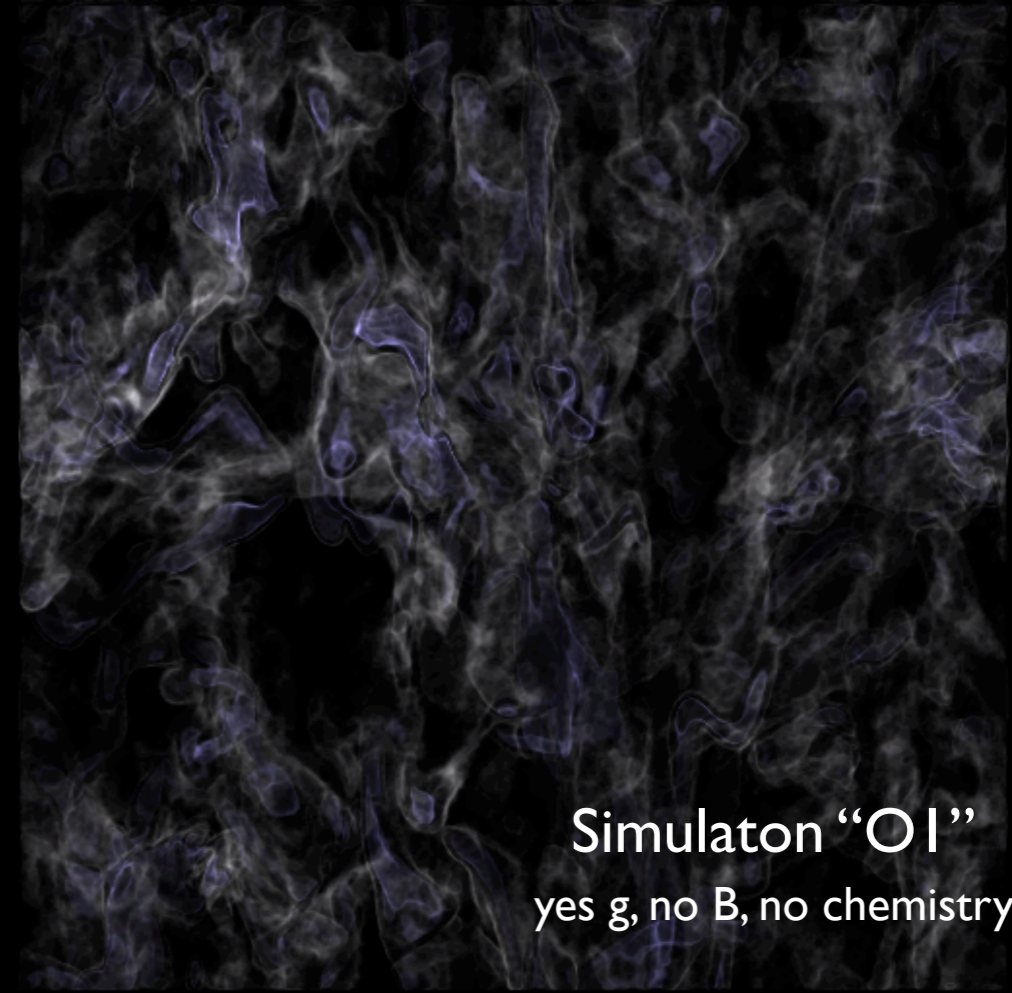
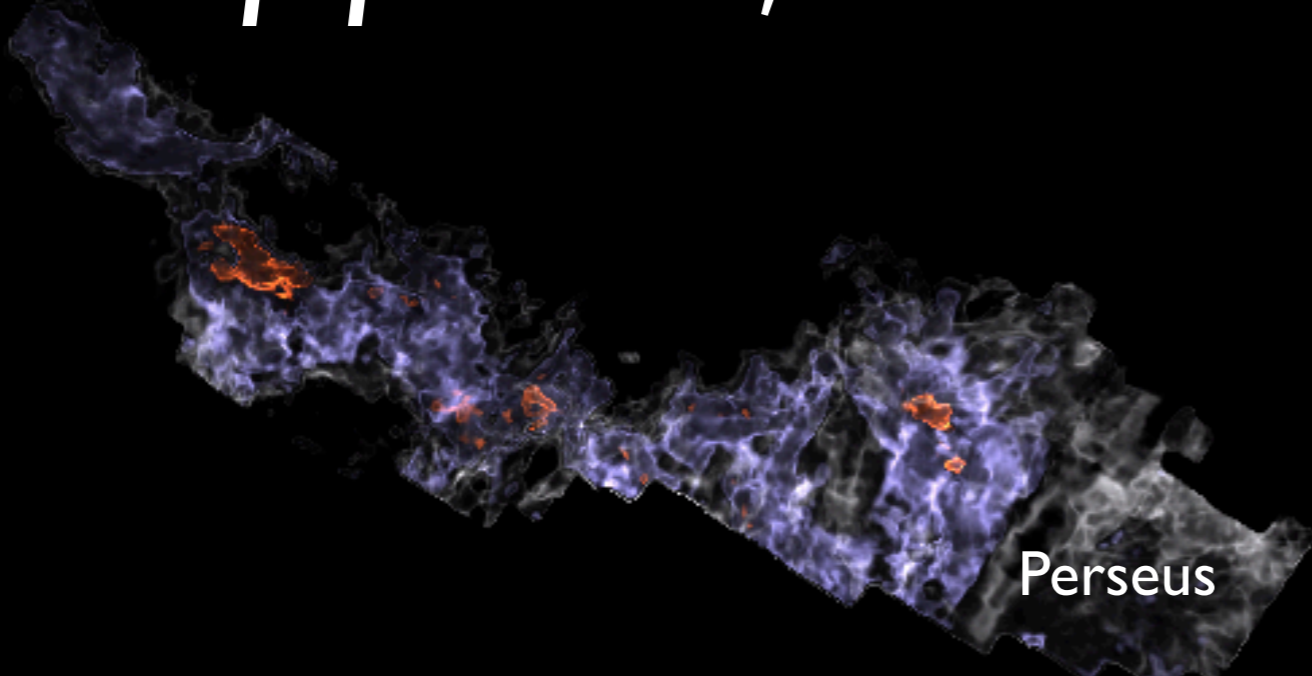
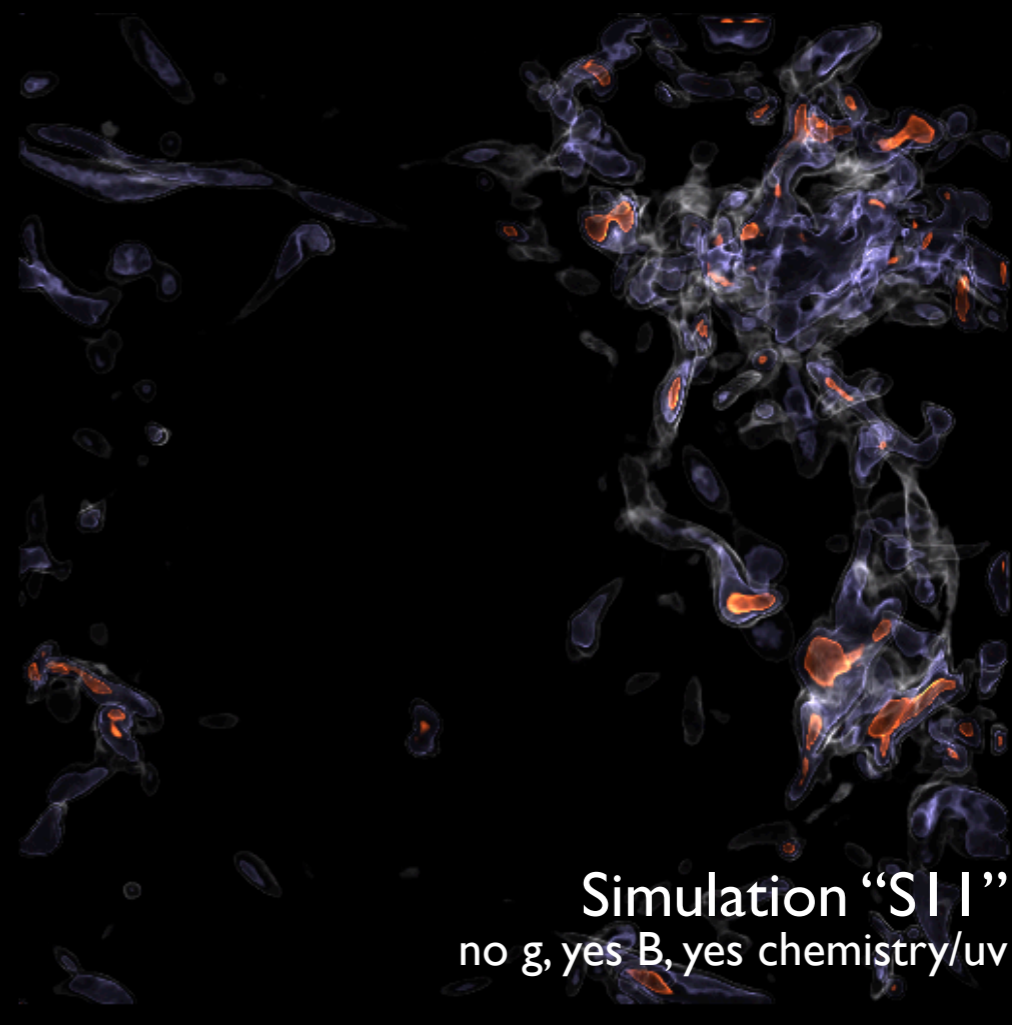


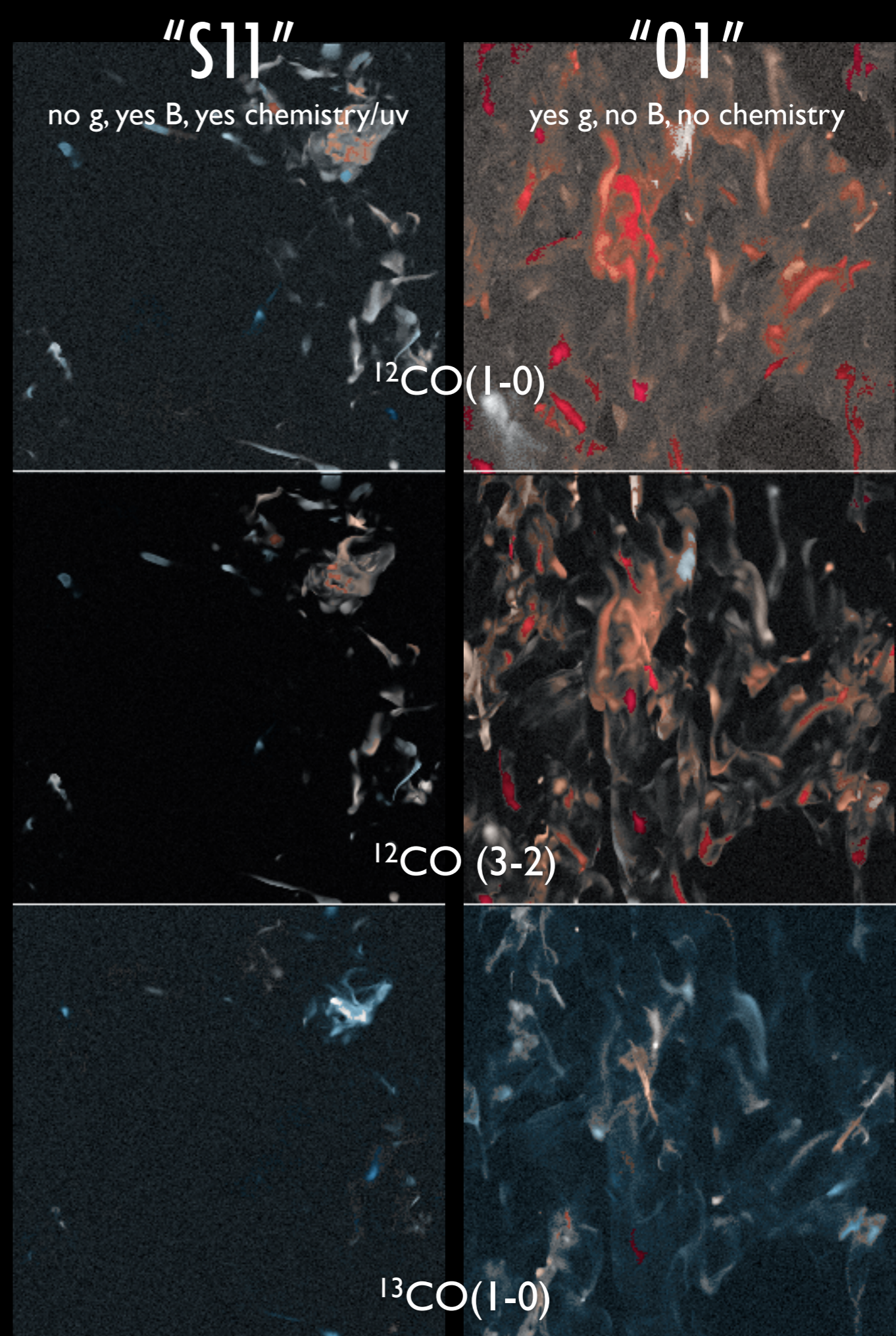
Table 2. Summary of each simulation

	S11	O1
Box Size	20 pc	25 pc
Simulation Code	Zeus-MP	ORION
Gridding	$256^3$	$256^3$ + 4 levels of AMR refinement
Driven Turbulence?	Yes	Yes
Driving Power Spectrum	Uniform $1 < k < 2$	Uniform $1 < k < 2$
Gravity?	No	Yes
B field?	5.85 uG	0
Gas Temperature	Variable (10-200K)	15K
Chemistry	H, O, C	None
Background UV	$2.7e-3 \text{ erg cm}^{-2} \text{ s}^{-1}$	No
Constant CO Abundance	No	$1.75 e-4$
$^{12}\text{CO}/^{13}\text{CO}$ abundance	70	70
Radiative Transfer Code	RADMC 3D	RADMC 3D
Microturbulence	$0.2 \text{ km s}^{-1}$	$0.2 \text{ km s}^{-1}$
Metallicity	Solar	N/A
Mean number density (nH)	$100 \text{ cm}^{-3}$	$58 \text{ cm}^{-3}$
Mach Number	$\sim 6$	22
Isothermal?	No	Yes
Output time(s)	5.7 Myr	2.5 Myr
Mass in stars	N/A	722 Msun (2.4%)



# Match Quality

good  
bad



*movies include a noise model, in both cases*

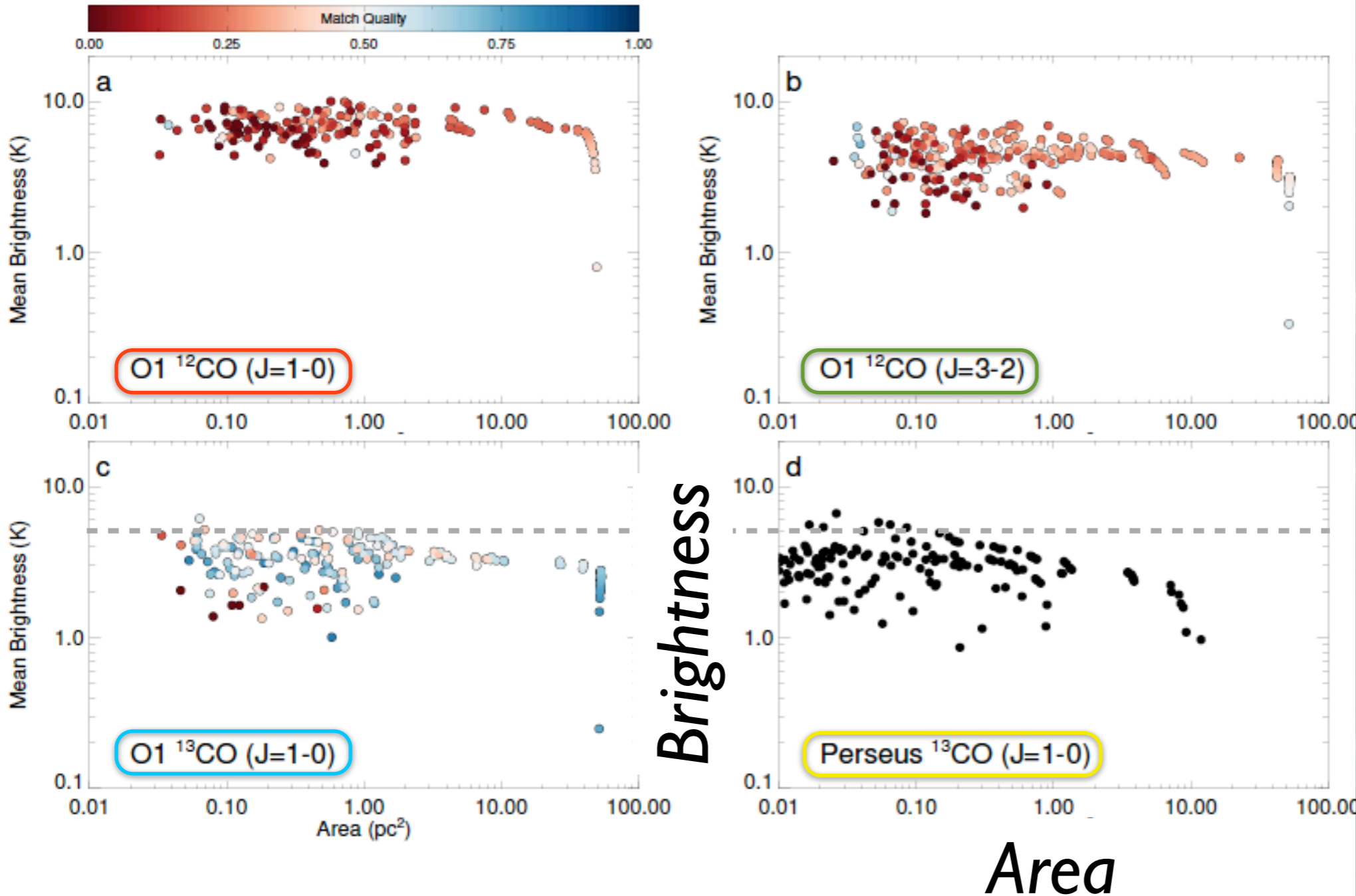
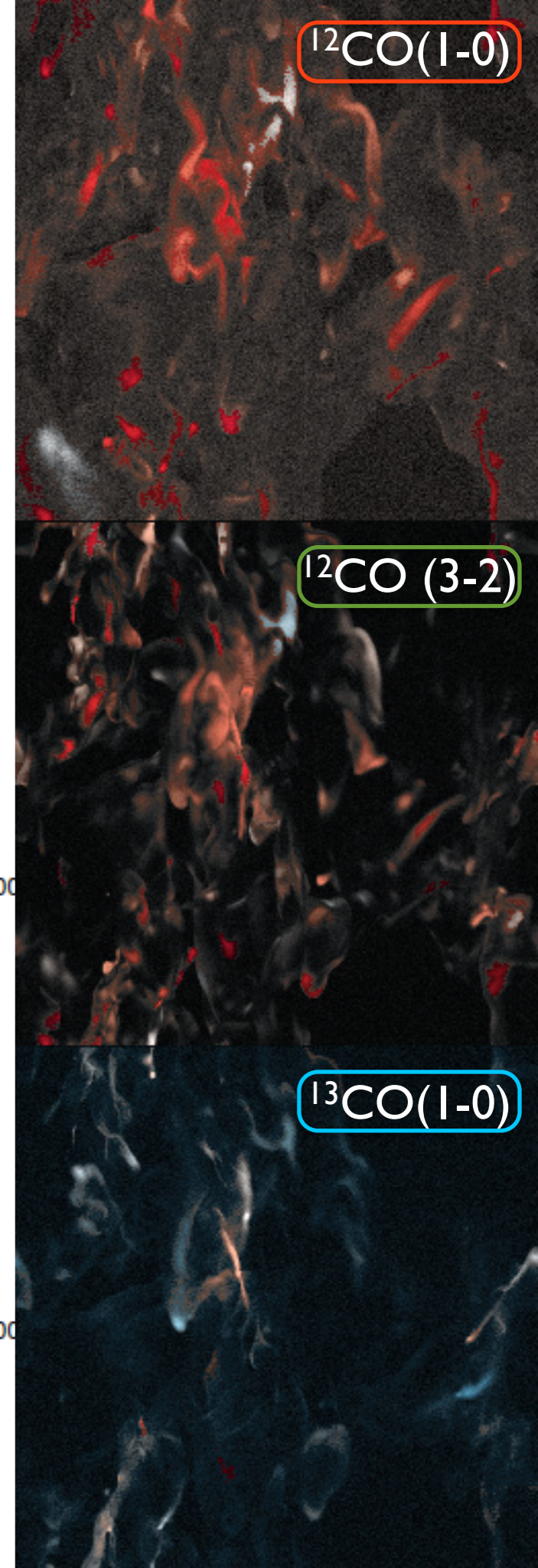
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Gas Temperature	Variable (10-200K)	15K
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Microturbulence	$0.2 \text{ km s}^{-1}$	$0.2 \text{ km s}^{-1}$
Metallicity	Solar	N/A
Mean number density (nH)	$100 \text{ cm}^{-3}$	$58 \text{ cm}^{-3}$
Mach Number	~ 6	22
Isothermal?	No	Yes
Output time(s)	5.7 Myr	2.5 Myr
Mass in stars	N/A	722 Msun (2.4%)

# Match Quality

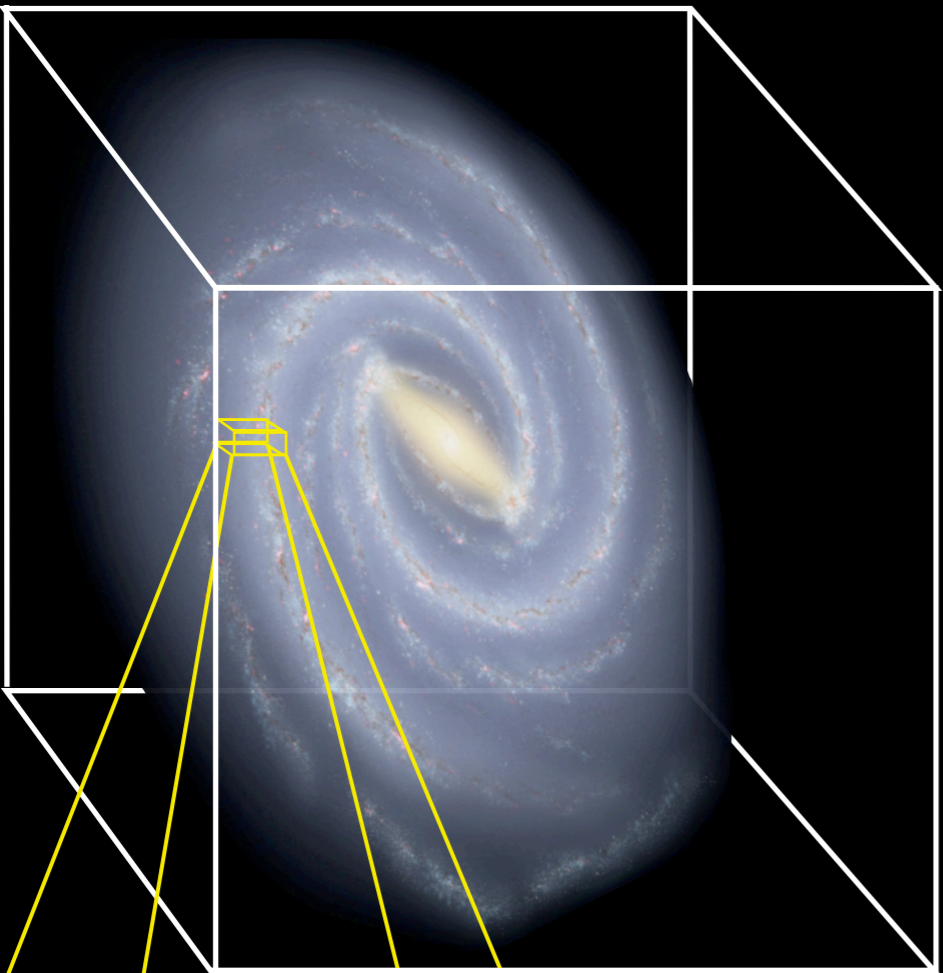
"O1"  
yes g, no B, no chemistry

good  
bad

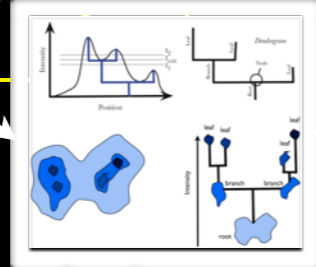
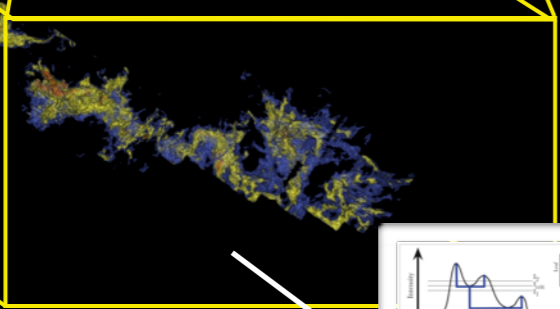


Many contributors to projects highlighted here include: Alves, Beaumont, Benjamin, Borkin, Glover, Goodman, Hurt, Offner, Rosolowsky, Shetty

# What to believe?

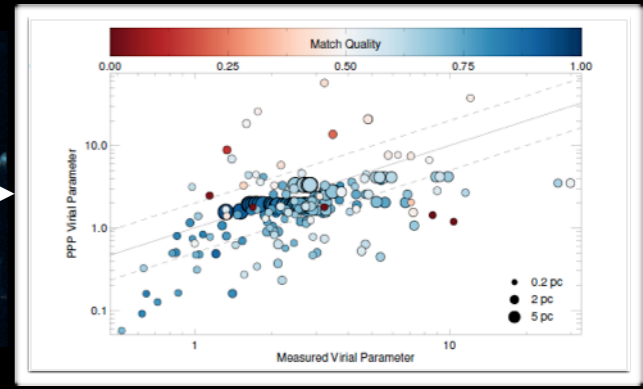


p-p-v cubes



dendrogram decomposition

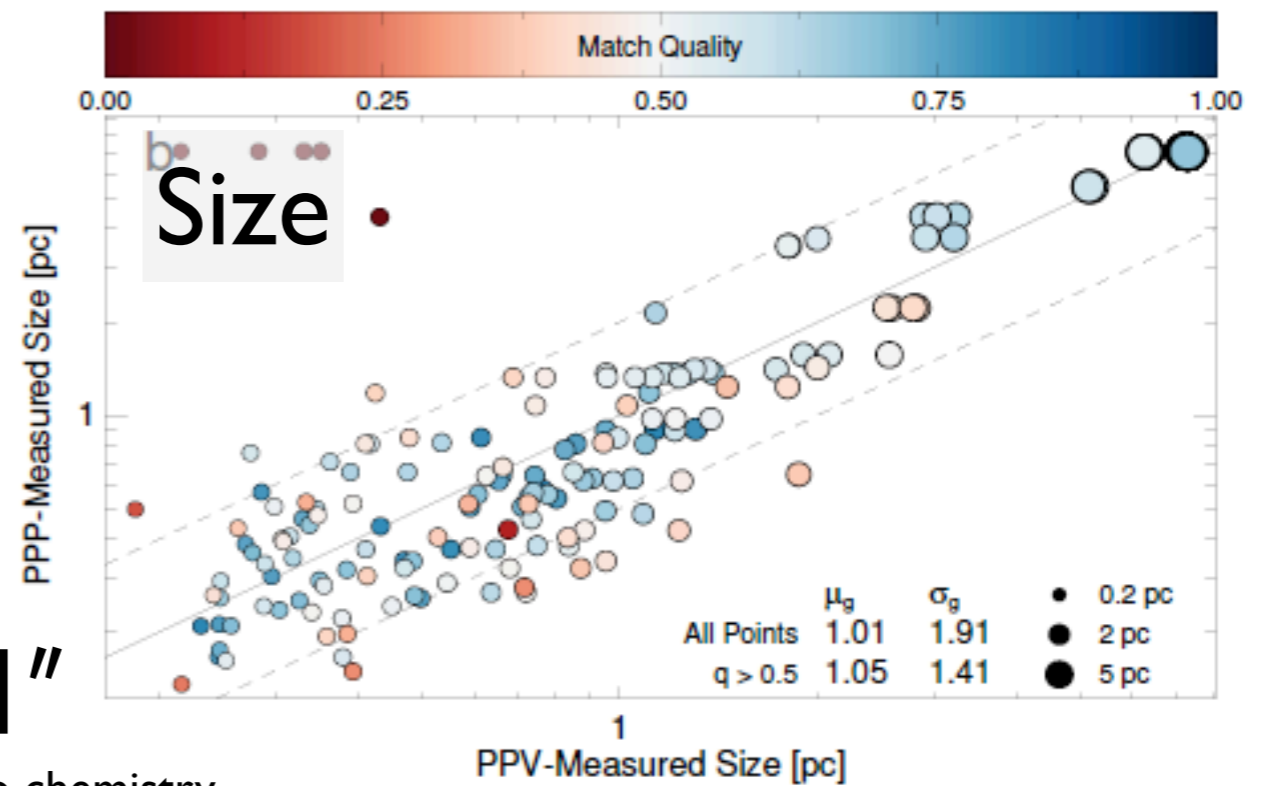
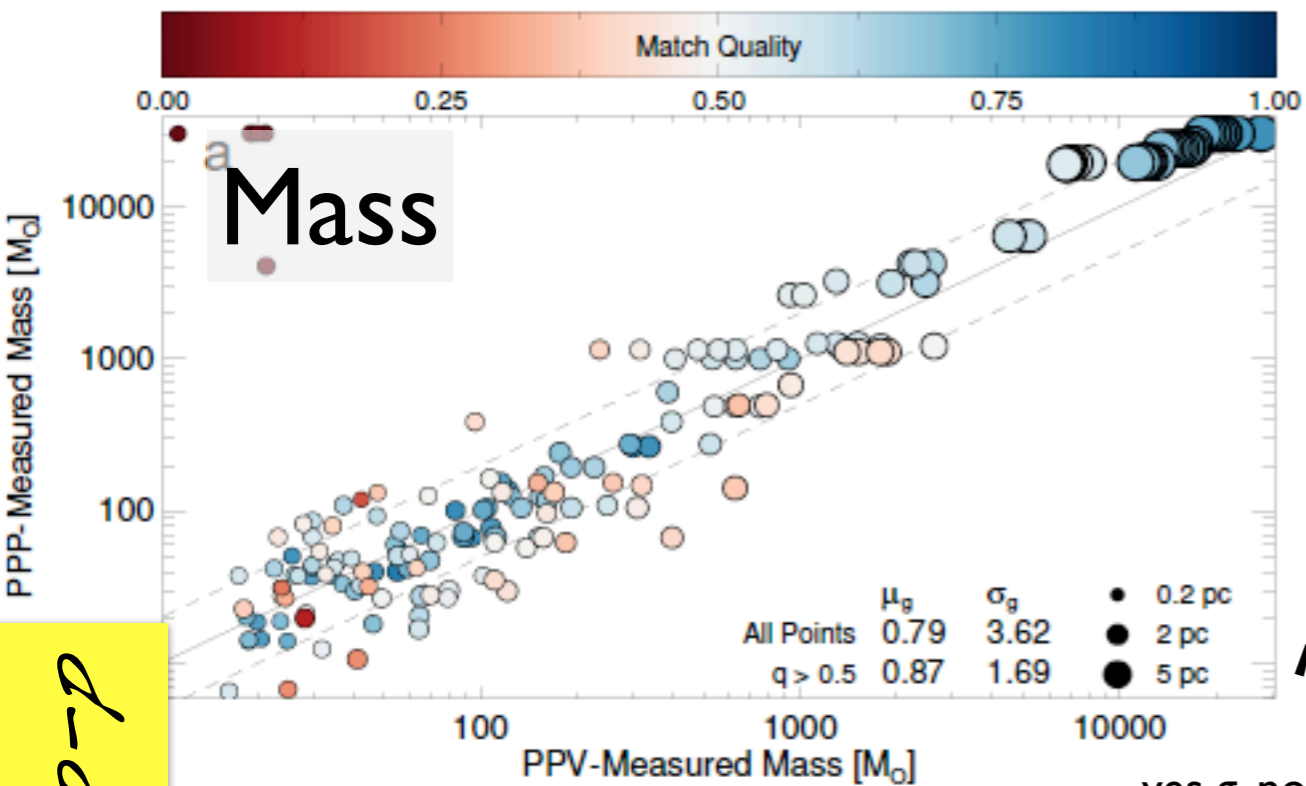
simulations to learn what's "real"



# Match Quality

good  
bad

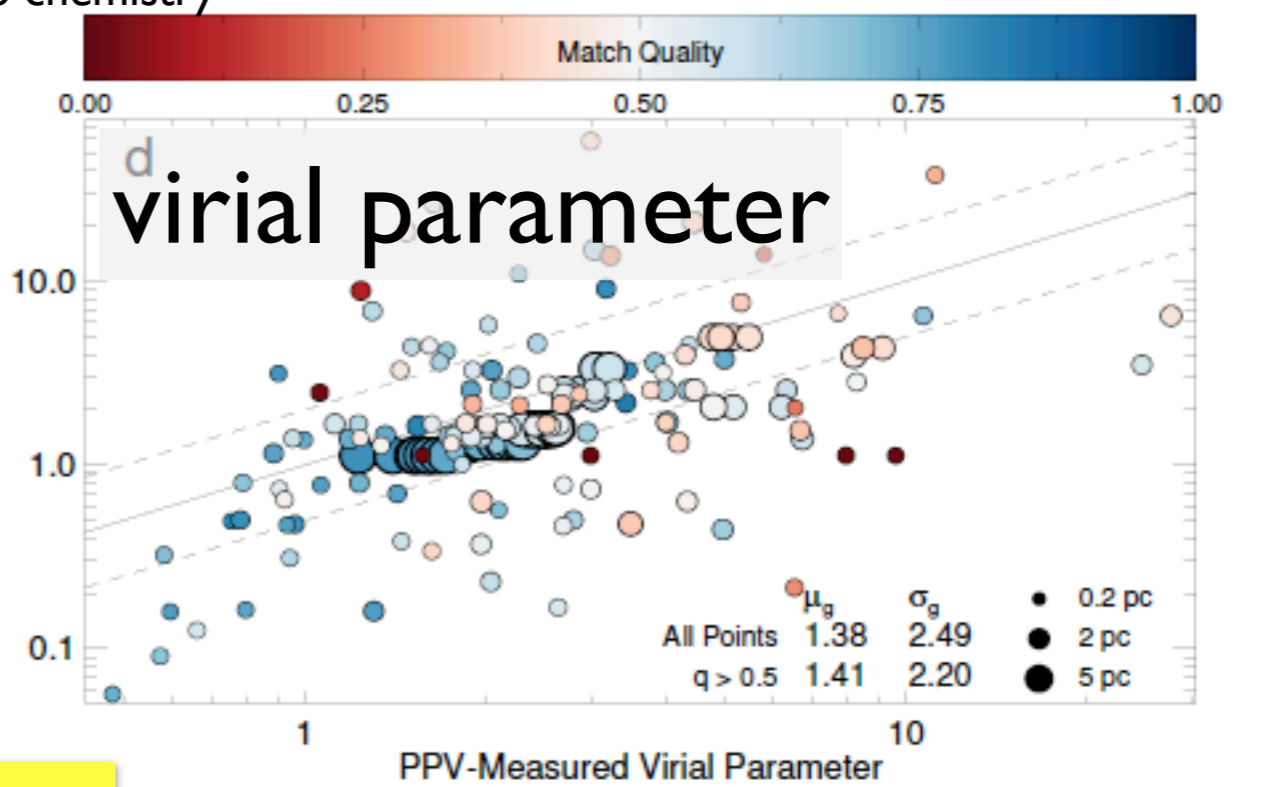
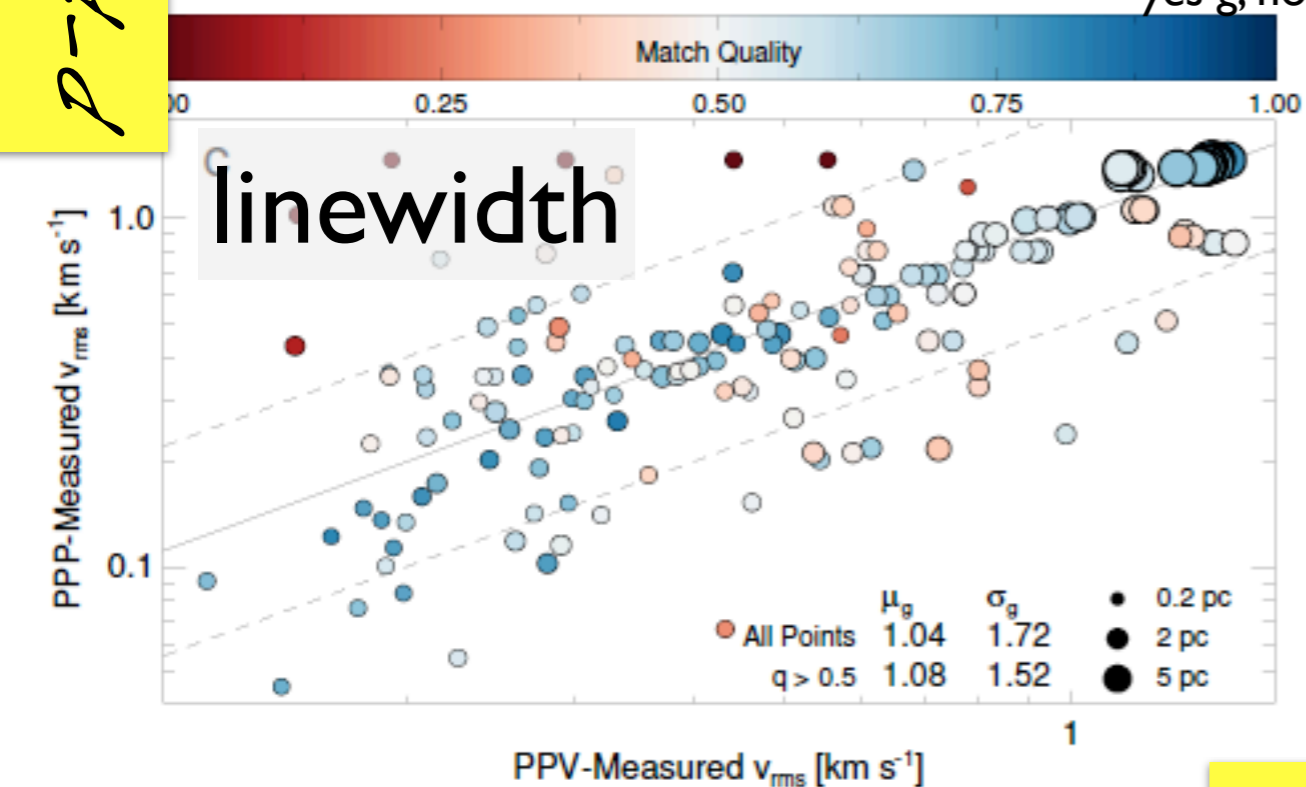
$^{13}\text{CO}(1-0)$



"01"

yes g, no B, no chemistry

*p-p-p*

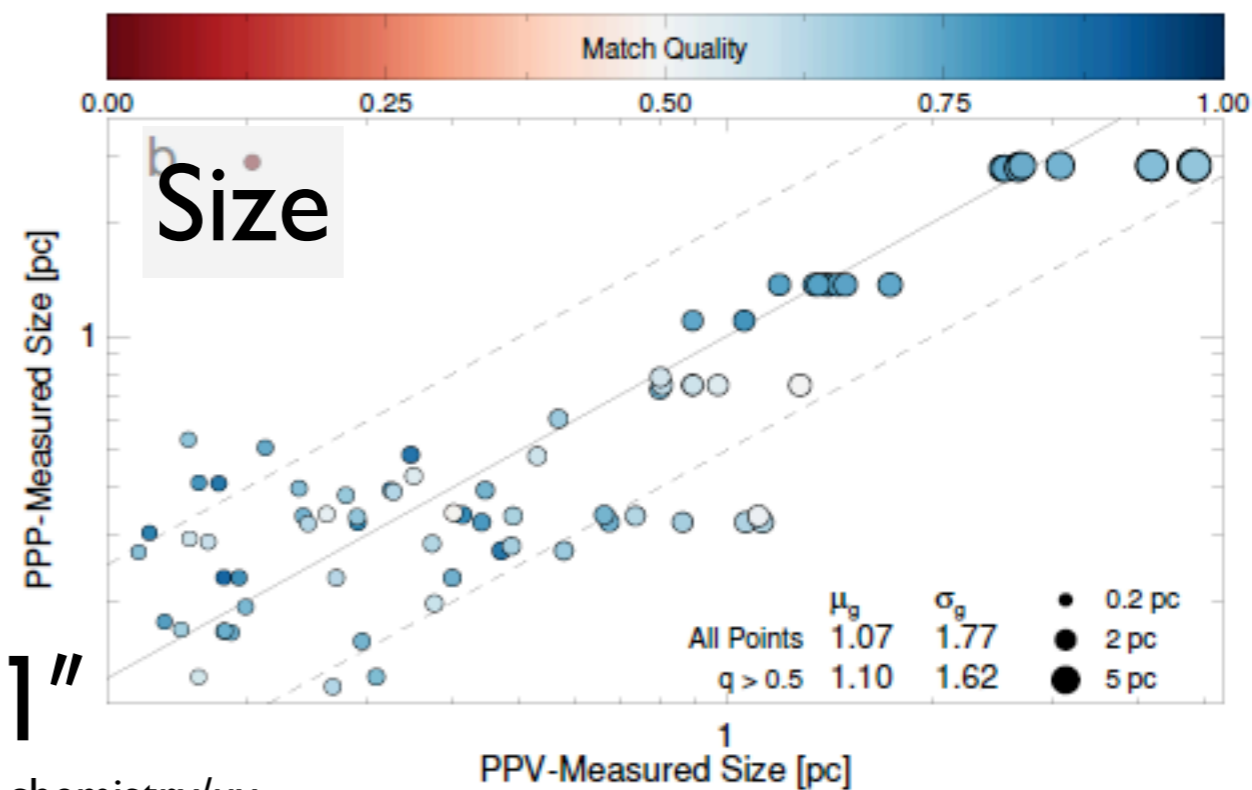
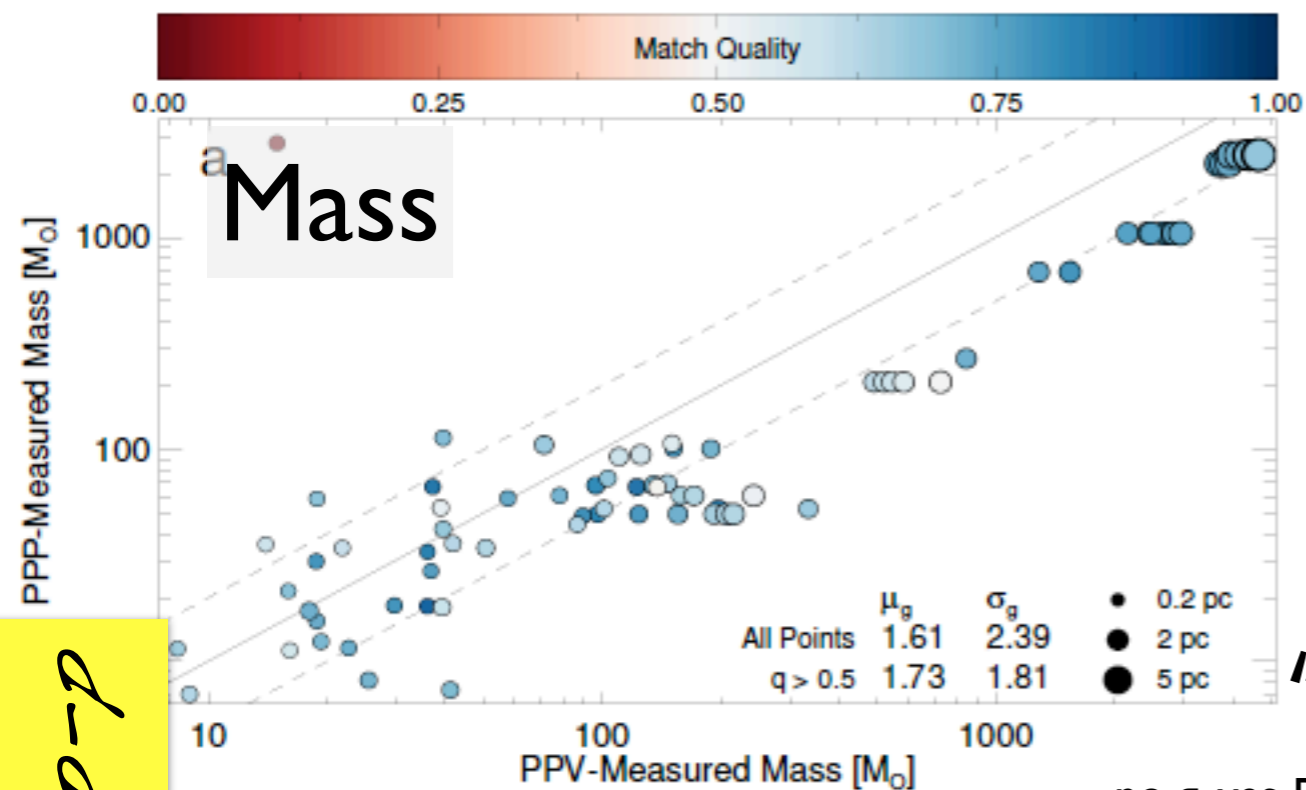


*p-p-v*

# Match Quality

good  
bad

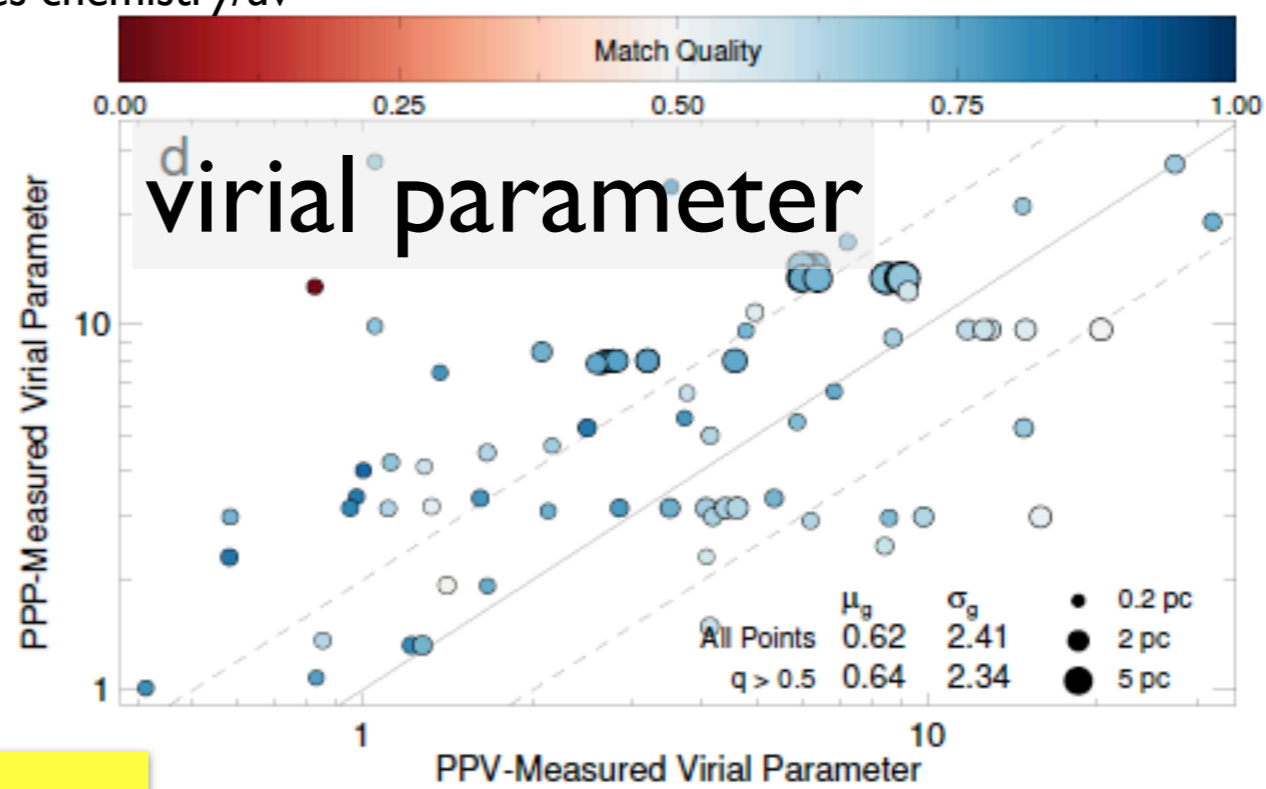
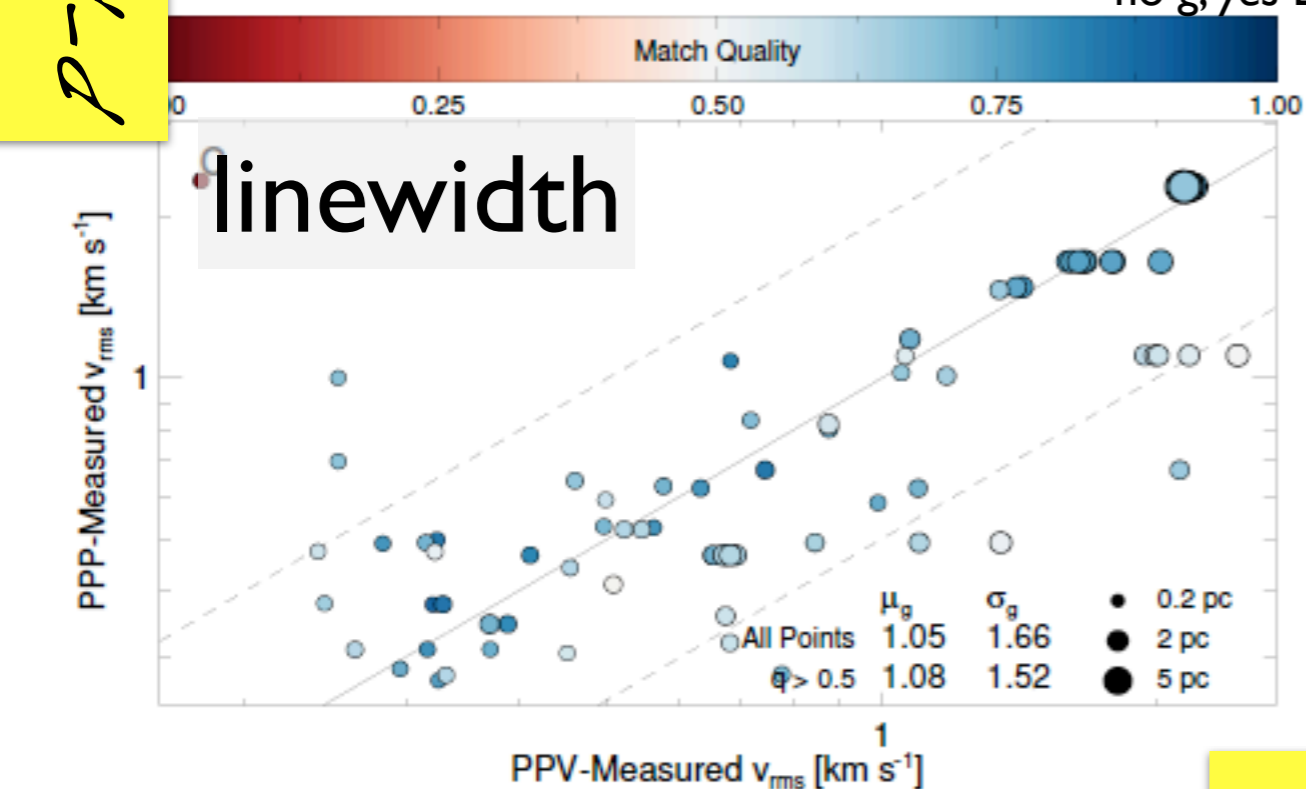
$^{13}\text{CO}(1-0)$



"S11"

no g, yes B, yes chemistry/uv

*P-P-P*



*P-P-V*

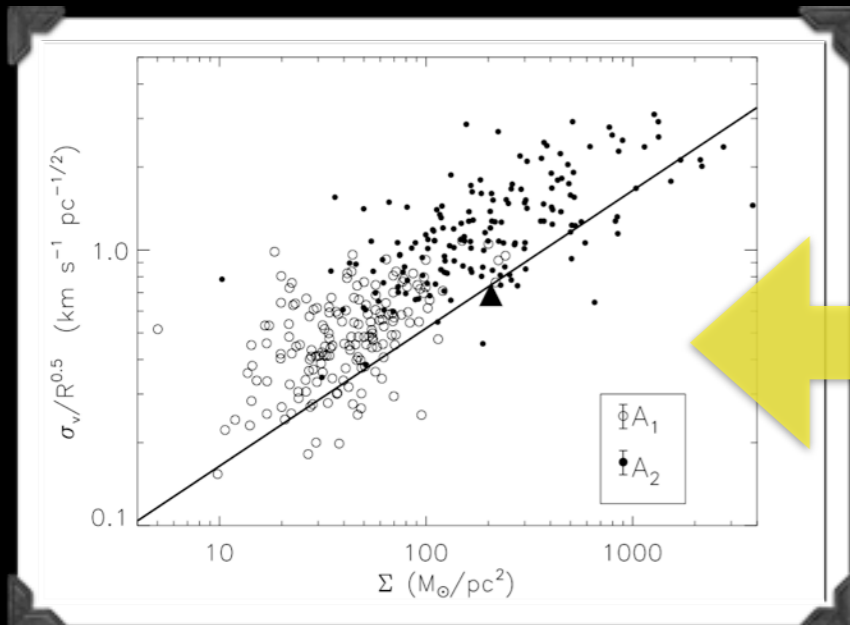
# Match Quality

“Larson Relations”

$$\alpha_{\text{vir}} (=5s_v^2 R/M_{\text{lum}})$$

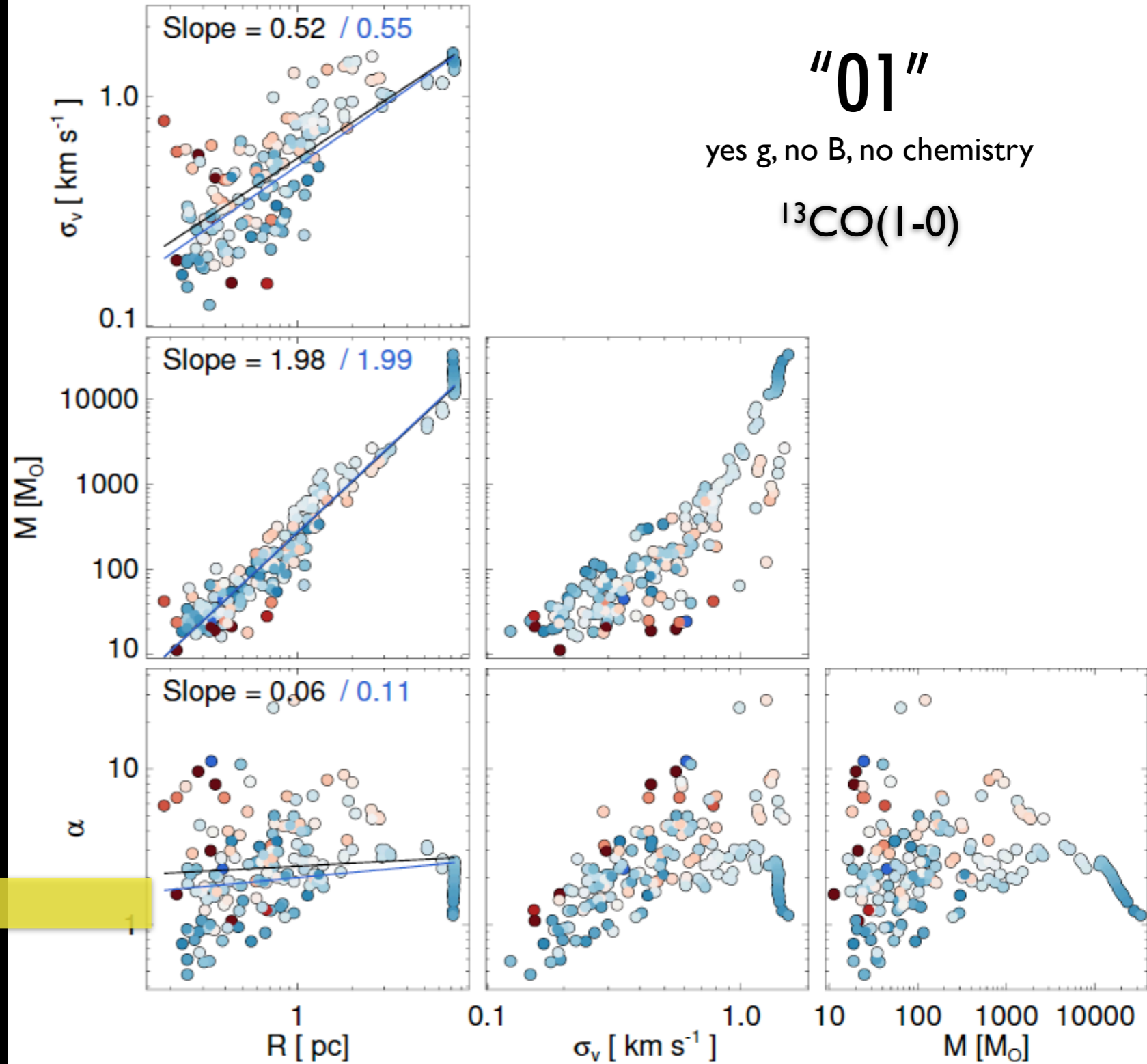
so, note, then if  $M \sim R^2$ ,

$$\alpha_{\text{vir}} \sim s_v^2 / R$$



Heyer et al. 2009

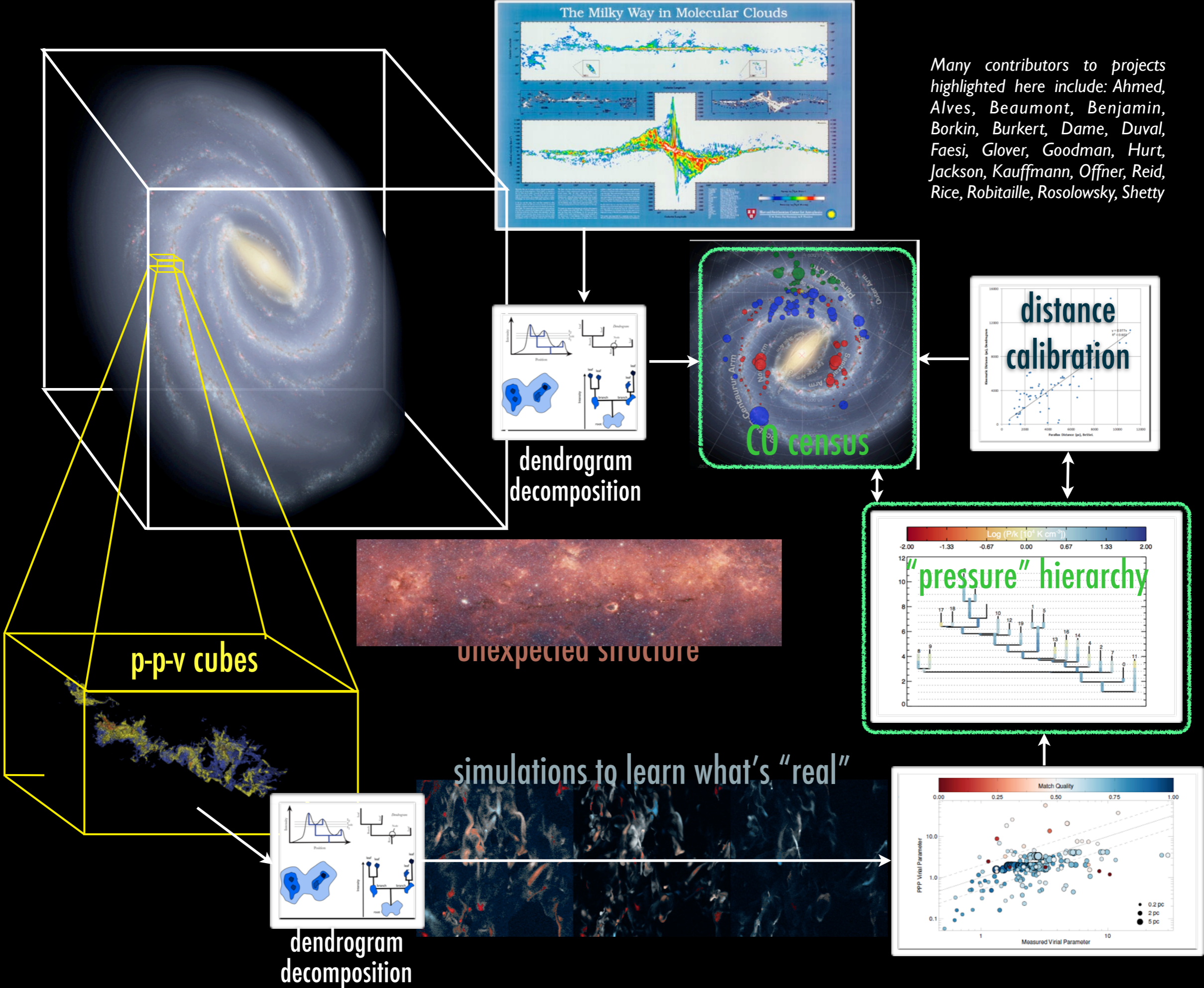
good  
bad



“01”

yes g, no B, no chemistry

$^{13}\text{CO}(1-0)$

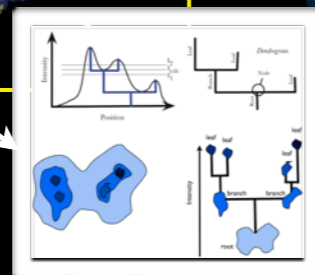
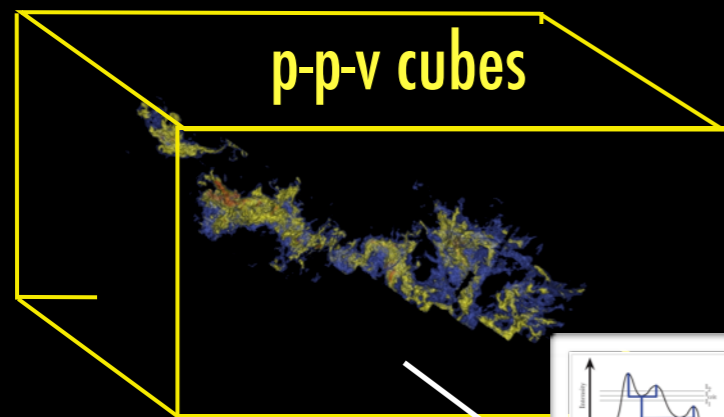




# Role of Pressure

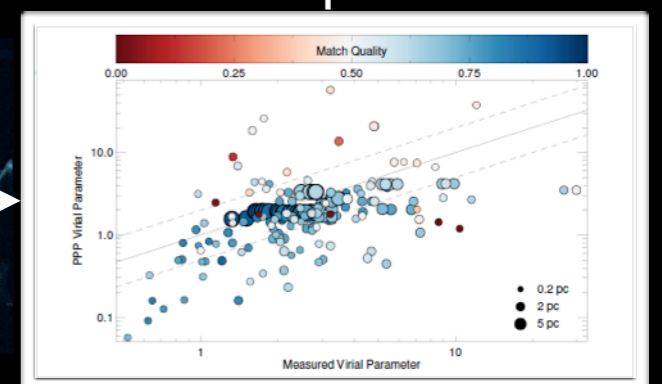
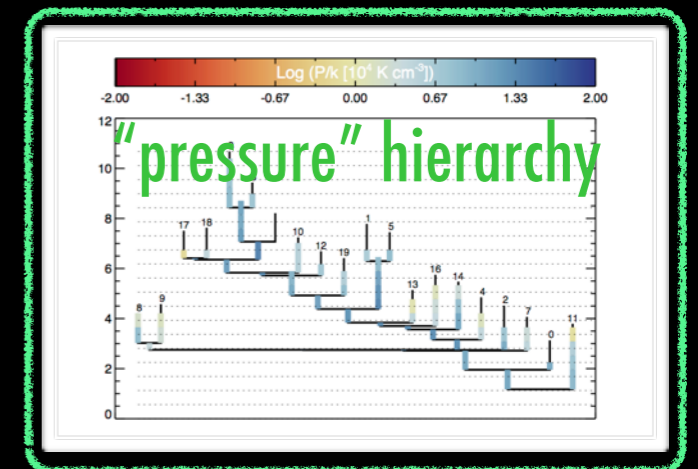
## Can we measure it?

Contributors to projects highlighted here include Beaumont, Borkin, Faesi, Glover, Goodman, Offner, Shetty



dendrogram decomposition

simulations to learn what's "real"



$$\text{OBSERVED "Pressure"} = P = \rho \sigma_v^2$$

**density** ( $r$ ) is derived from column density ( $N$ ), which is derived from CO luminosity & "X-factor" assumptions

**1-D velocity dispersion** ( $S_v$ ) is taken to be 2<sup>nd</sup> moment of velocity along the line of sight.  
(Can also assume 3D=3<sup>1/2</sup>  $S_v$ .)

*Operationally*

$$\rho = (6.7 \mu m_H L X_{CO}) / (\sqrt{\pi} * r)^3$$

$$r = 1.91 \sqrt{x_{rms} y_{rms}}$$

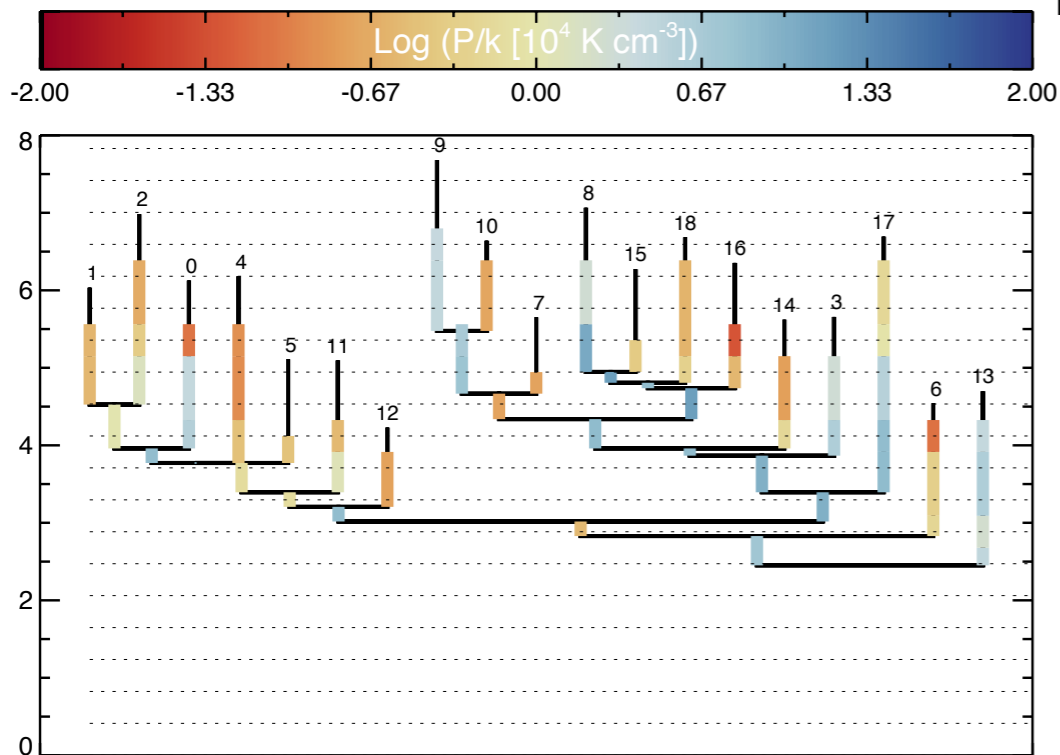
$$\sigma_v^2 = \sum_i (I_i (v_i - v_0)^2) / (\sum_i I_i)$$

$$\sigma_v = \left[ \frac{\sum (I_j v_j^2) - (\sum I_j v_j)^2 / \sum (I_j)}{\sum (I_j)} \right]^{1/2}$$

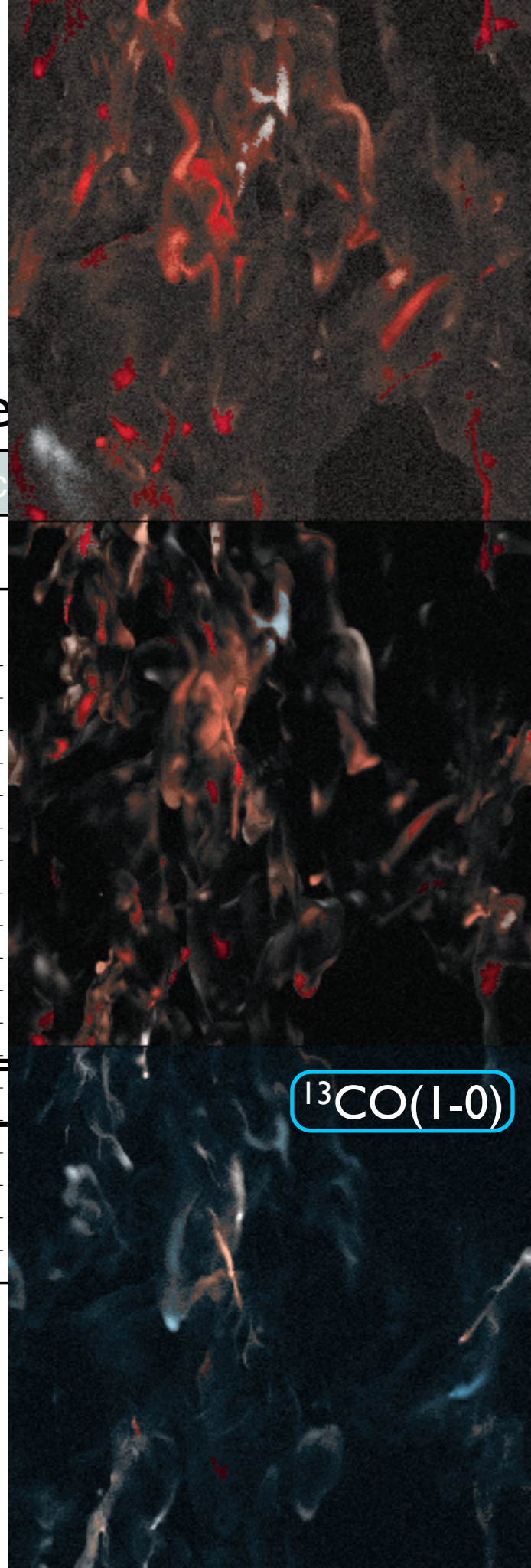
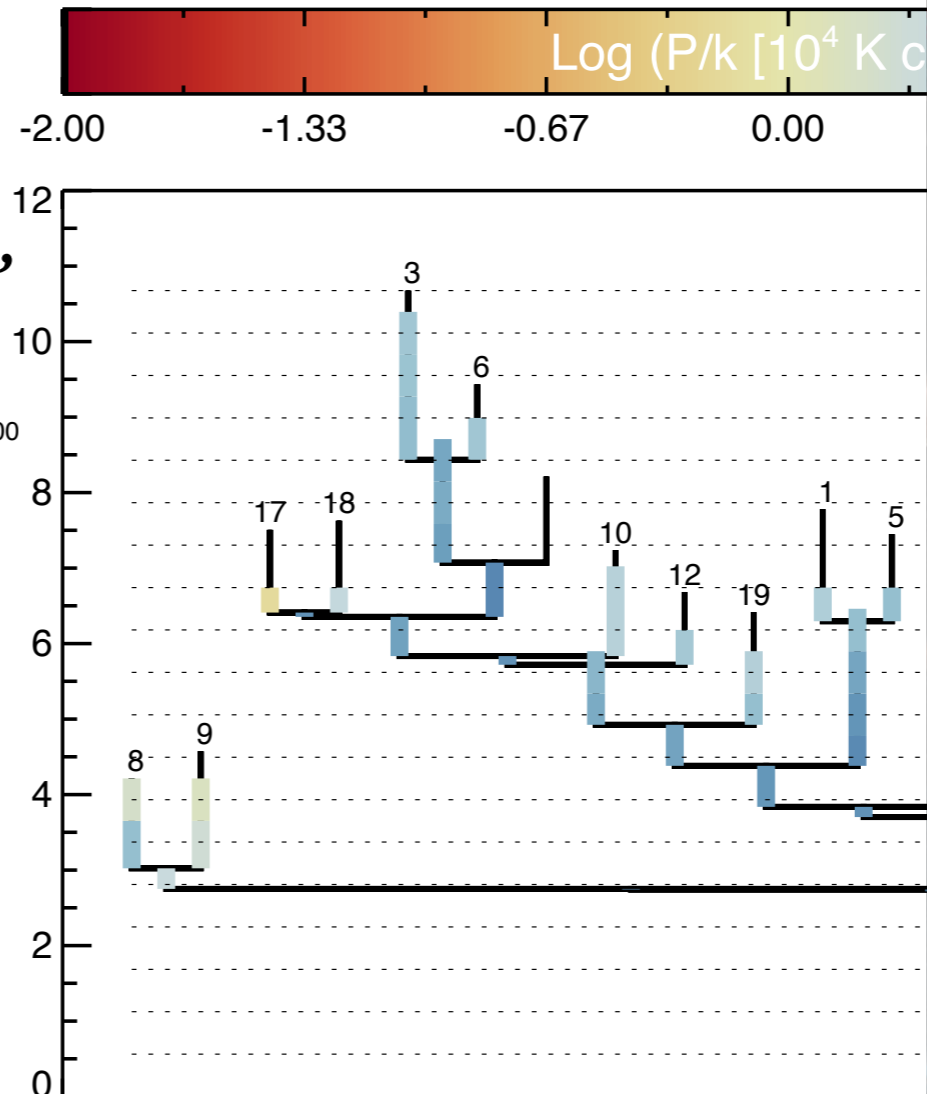
# $^{13}\text{CO}$ "Pressure"-Encoded Dendrograms

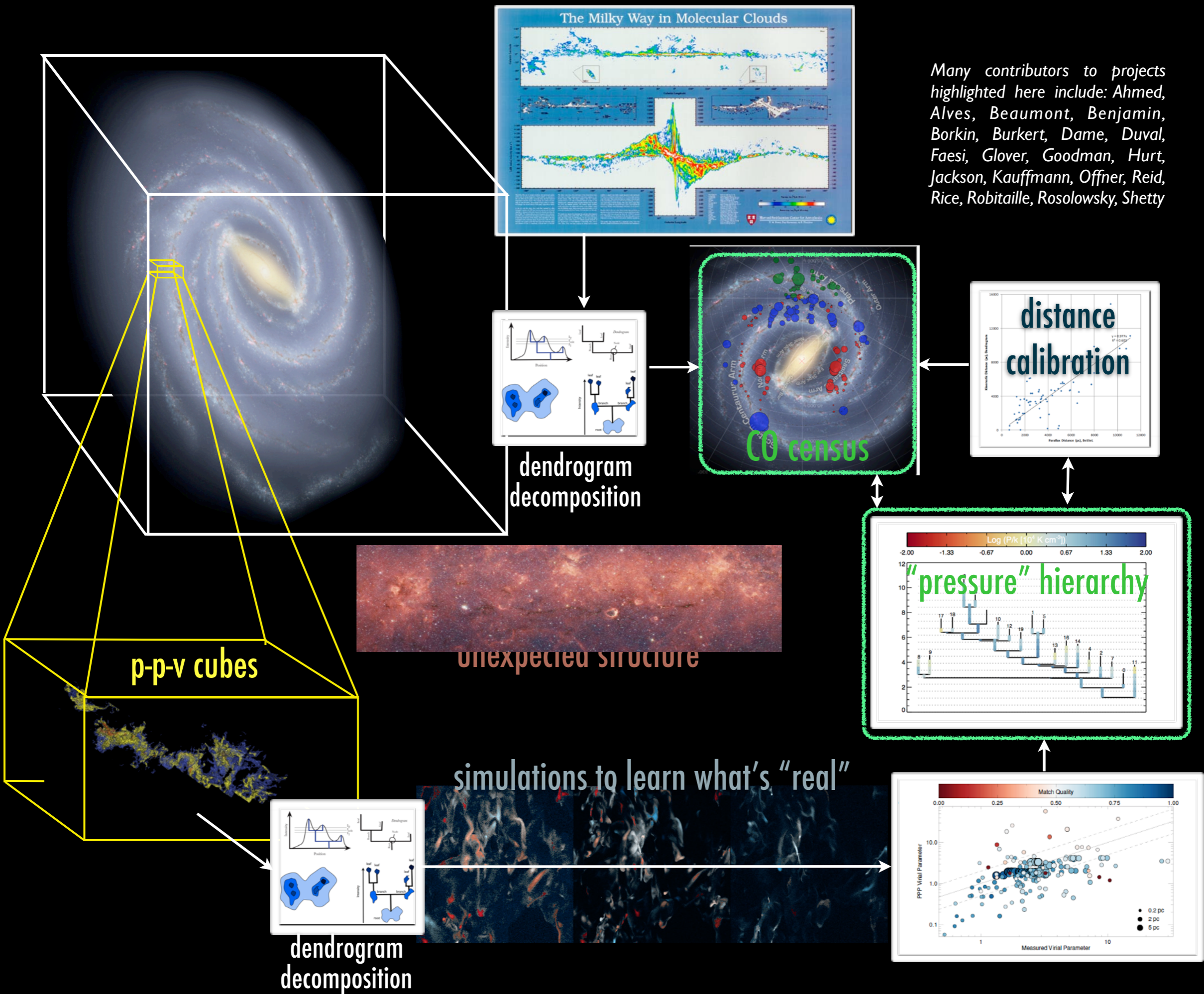
does pressure really "drop" at peaks? (*unlikely!*)

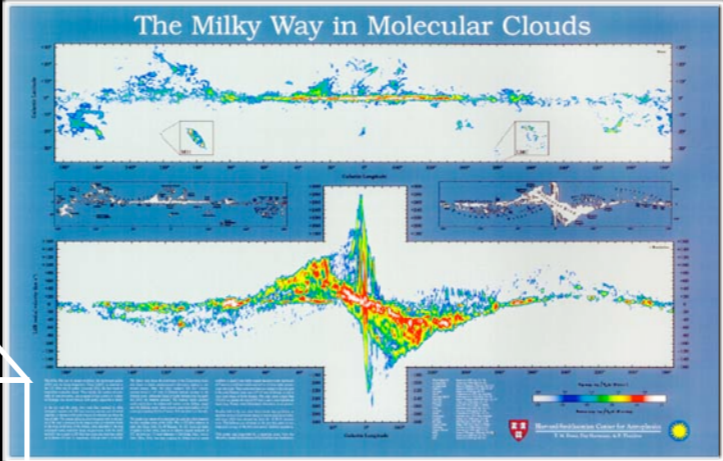
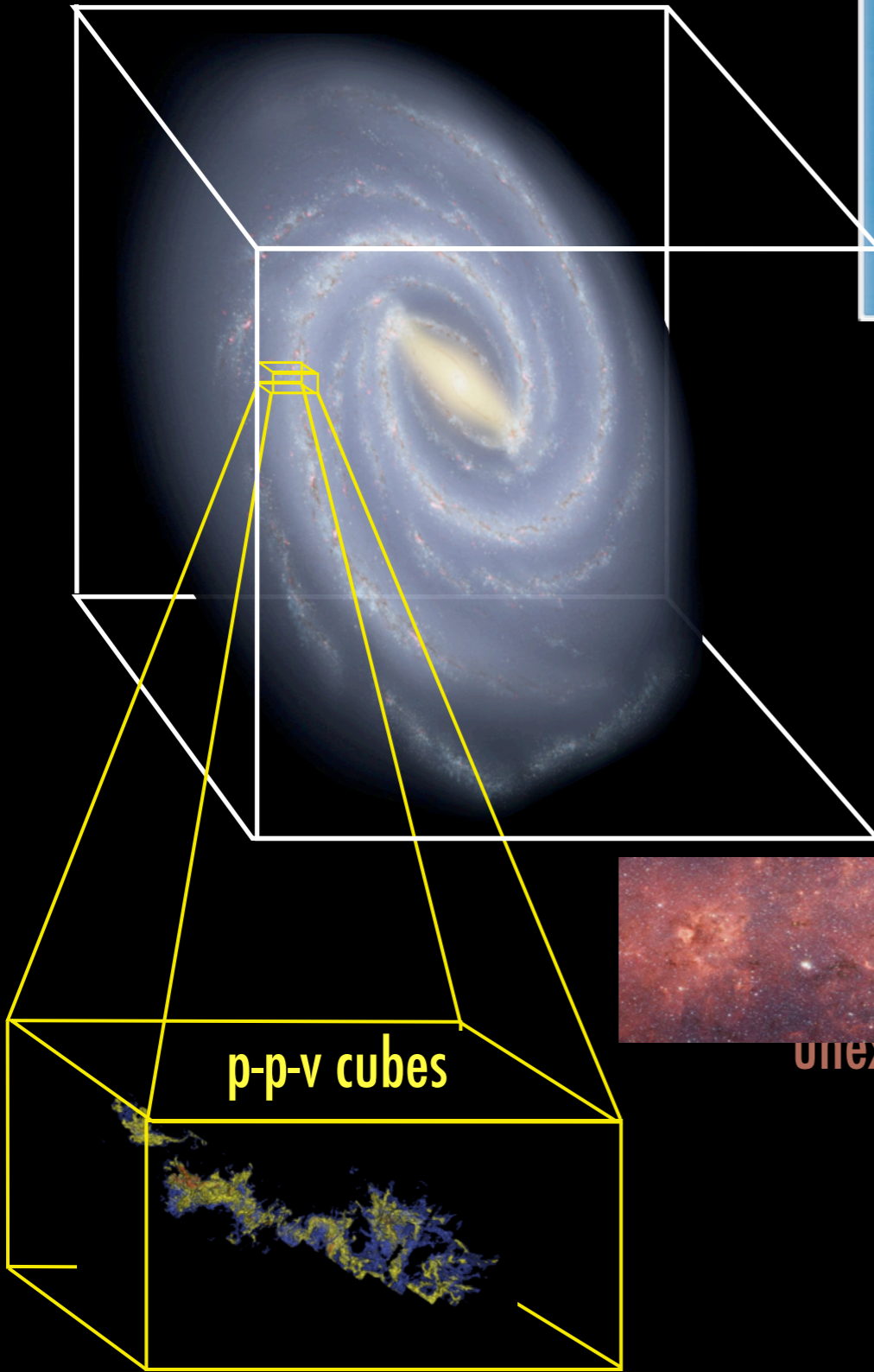
Simulation like "O I"  
underluminous, under "pressured"



IC348 (cluster-forming re







Many contributors to projects highlighted here include: Ahmed, Alves, Beaumont, Benjamin, Borkin, Burkert, Dame, Goodman, Hurt, Jackson, Kauffmann, Robitaille



unexpected structure










p-p-v cubes

Article view

Folder view

Newsfeed view

Article index

- > Introduction 1
- > Nessie longer
- >  1nessie findingchart
- >  Table1 mass nessie
- > 3d position
- >  2galactic coords
- > Using rotation curves
- >  6drafttopview
- >  3draftnessie vrad 21
- > Co velocities
- >  4draft co sky
- > Nh3 velocities
- >  5draft side view
- >  7draftnessie co lv
- > Significance
- >  Bones dobbs
- > Can we map full skeleton
- >  9ic342 jarrett lowres

WORKING DRAFT OPEN SCIENCE ARTICLE AUTHOREA.COM/249

# The Bones of the Milky Way

Alyssa Goodman, Joao Alves, Chris Beaumont, Tom Dame, James Jackson, Jens Kauffmann, Thomas Robitaille, Alberto Pepe, Michelle Borkin, Andreas Burkert, Bob Benjamin

+ Add author

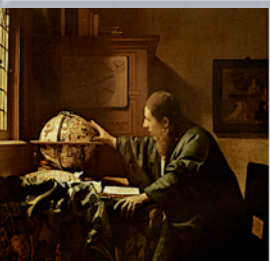
Export article

**Abstract.** The very long, thin infrared dark cloud “Nessie” is even longer than had been previously claimed, and an analysis of its Galactic location suggests that it lies directly in the Milky Way’s mid-plane, tracing out a highly elongated bone-like feature within the prominent Scutum-Centaurus spiral arm. Re-analysis of mid-infrared imagery from the Spitzer Space Telescope shows that this IRDC is at least 2, and possibly as many as 8 times longer than had originally been claimed by Nessie’s discoverers, Jackson et al. (2010); its aspect ratio is therefore at least 150:1, and possibly as large as 800:1. A careful accounting for both the Sun’s offset from the Galactic plane ( $\sim 25$  pc) and the Galactic center’s offset from the  $(l'', b'') = (0, 0)$  position defined by the IAU in 1959 shows that the latitude of the true Galactic mid-plane at the 3.1 kpc distance to the Scutum-Centaurus Arm is not  $b = 0$ , but instead closer to  $b = -0.5$ , which is the latitude of Nessie to within a few pc. Apparently, Nessie lies in the Galactic mid-plane. An analysis of the radial velocities of low-density (CO) and high-density (NH<sub>3</sub>) gas associated with the Nessie dust feature suggests that Nessie runs along the Scutum-Centaurus Arm in position-position-velocity space, which means it likely forms a dense ‘spine’ of the arm in real space as well. No galaxy-scale simulation to date has the spatial resolution to predict a Nessie-like feature, but extant simulations do suggest that highly elongated over-dense filaments should be associated with a galaxy’s spiral arms. Nessie is situated in the closest major spiral arm to the Sun toward the inner Galaxy, and appears almost perpendicular to our line of sight, making it the easiest feature of its kind to detect from our location (a shadow of an Arm’s bone, illuminated by the Galaxy beyond). Although the Sun’s offset from the Galactic plane is not significant compared with the thickness of the plane as traced by Population I objects such as GMCs and HII regions, it may be significant compared with an extremely thin layer that might be traced out by Nessie-like objects. Future high-resolution extinction and molecular line data may therefore allow us to exploit the Sun’s position above the plane to gain a small amount of perspective on the Galactic disk.

Quick edit

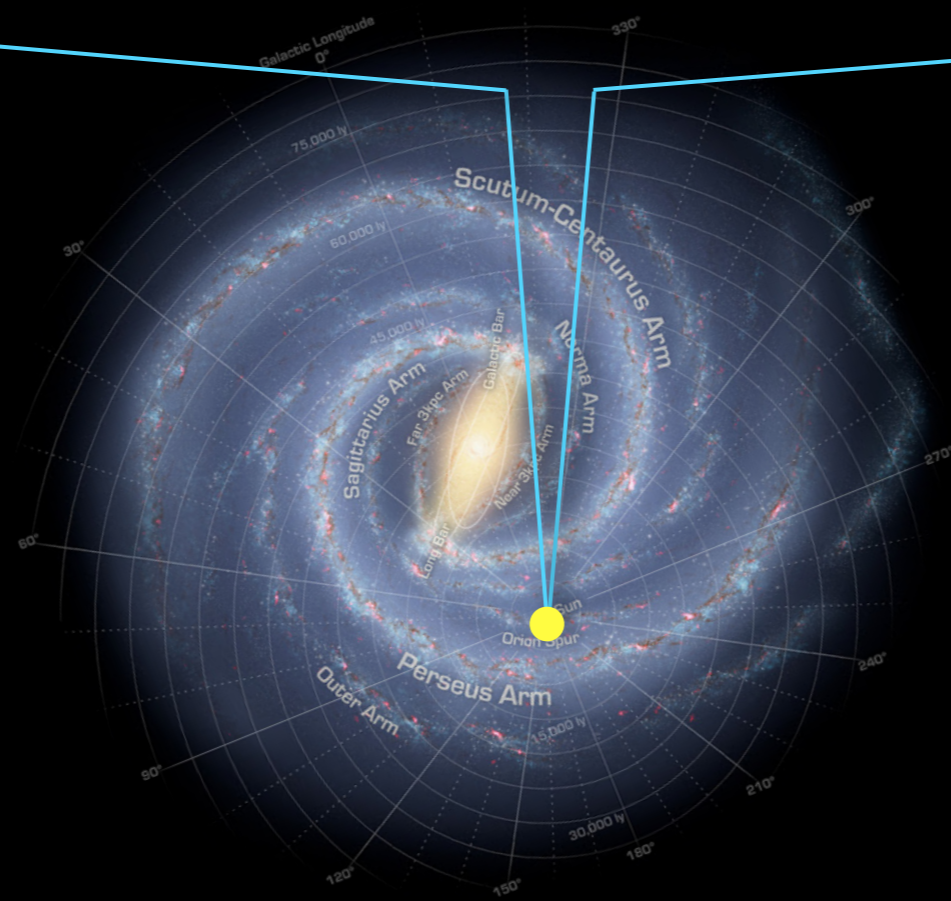
How do I..?

Settings



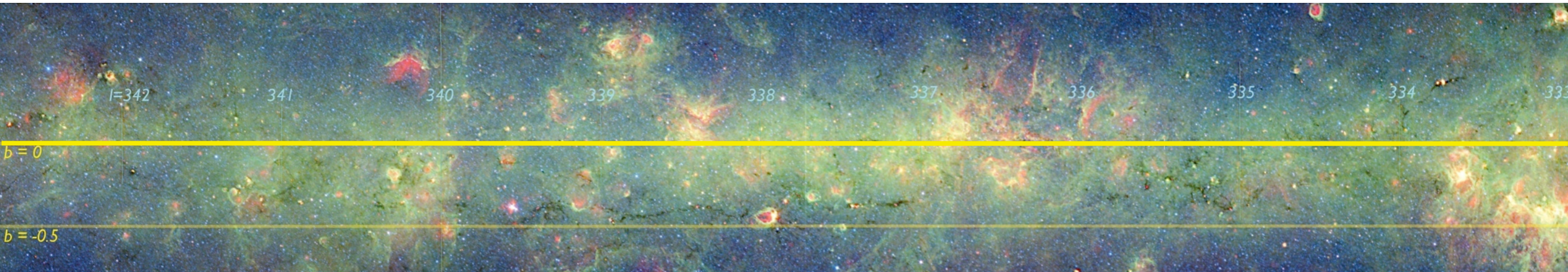
# "Is Nessie Parallel to *the Galactic Plane*?" -A. Burkert, Ringberg 2012



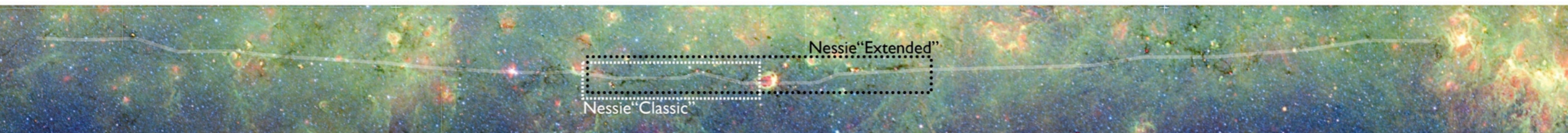




# Why $b < 0$ ?! Galactic Geometry: 1959 and Now



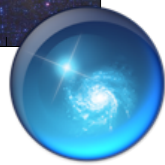
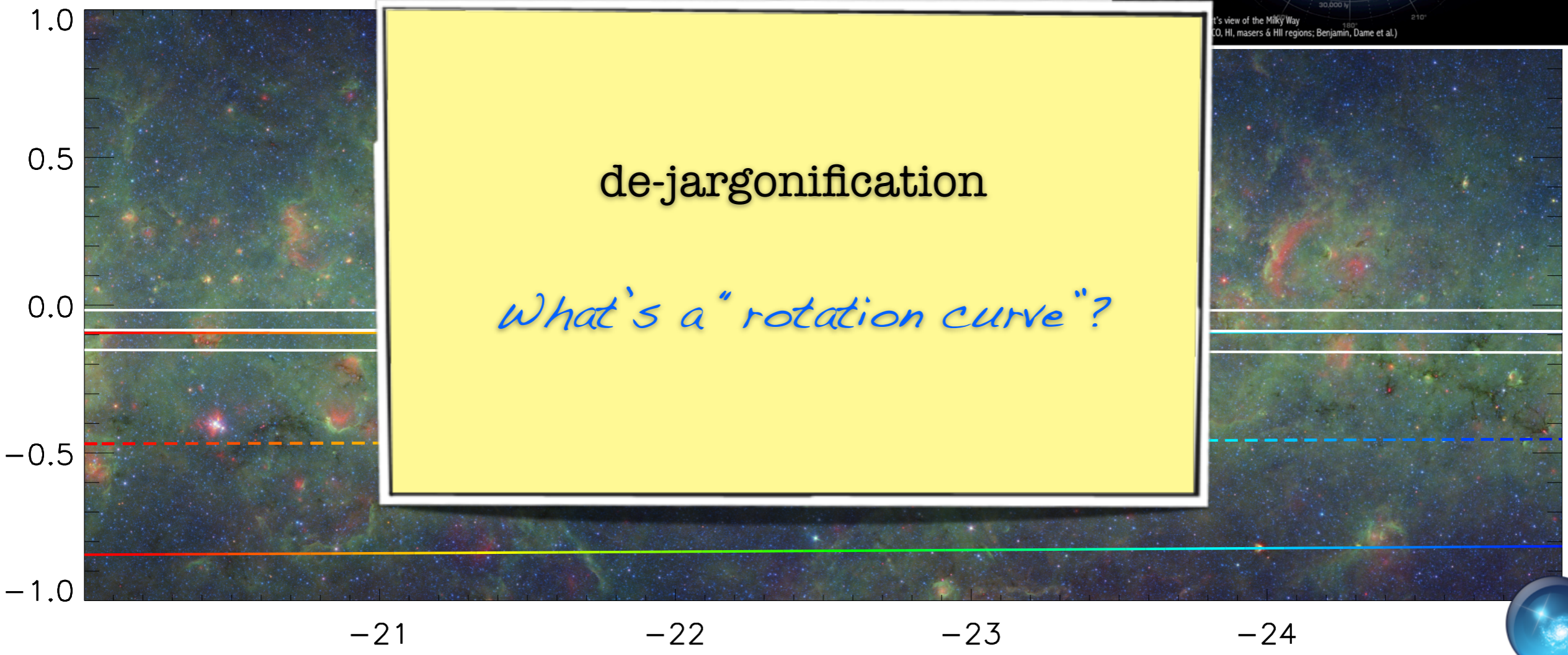
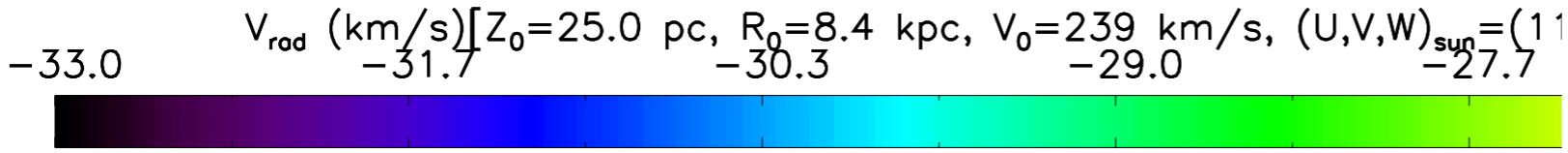
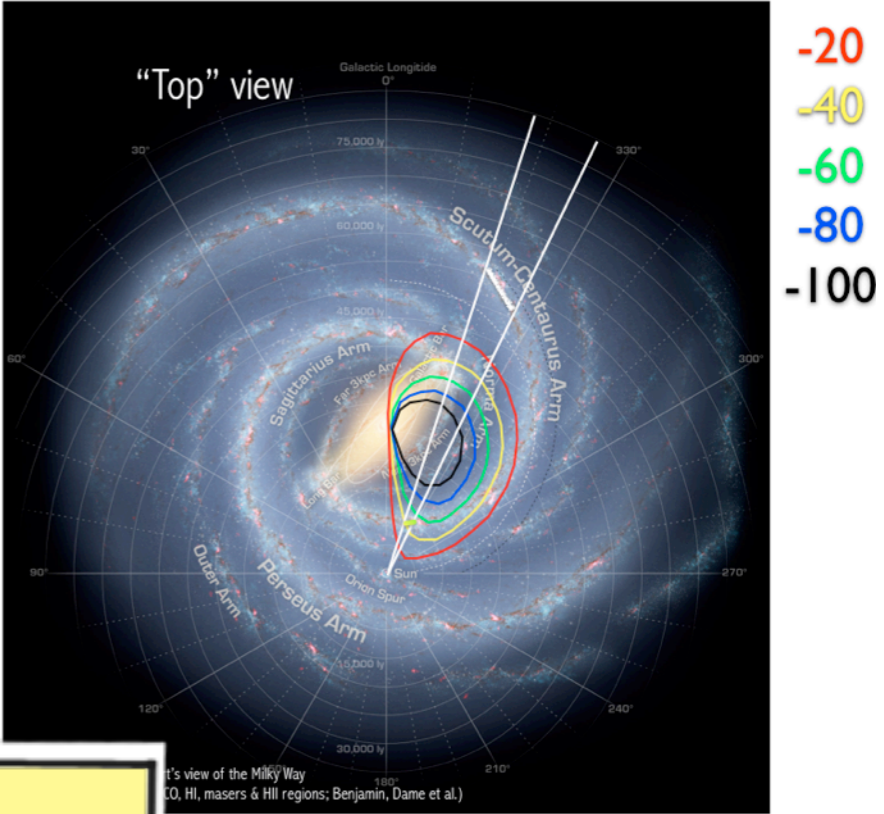
1 degree  $\sim$  60 pc at 3.5 kpc



The equatorial plane of the new co-ordinate system must of necessity pass through the sun. It is a fortunate circumstance that, within the observational uncertainty, both the sun and Sagittarius A lie in the mean plane of the Galaxy as determined from the hydrogen observations. If the sun had not been so placed, points in the mean plane would not lie on the galactic equator.

[Blaauw et al. 1959]

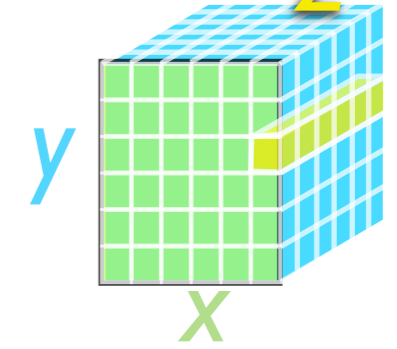
# Predicted Near & Far Scutum-Centaurus Arm



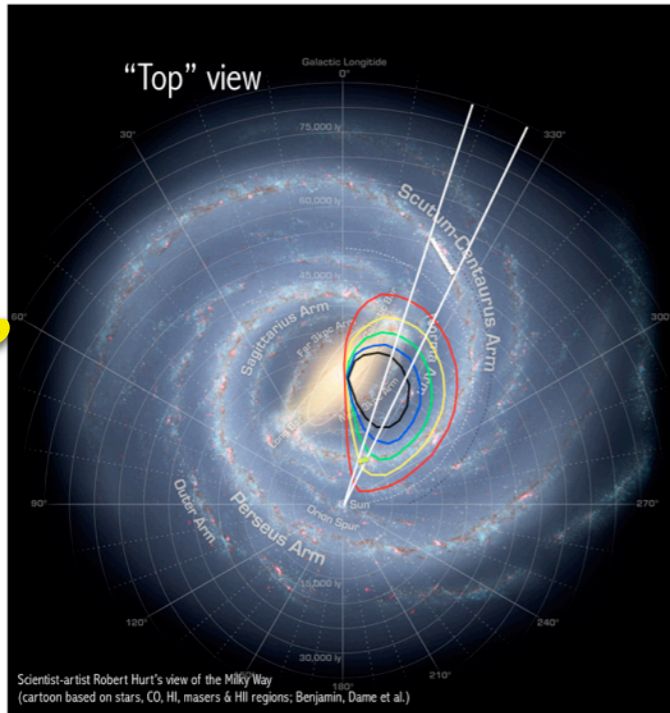
# Velocity Constraints

“X”

“Z”



“Z”

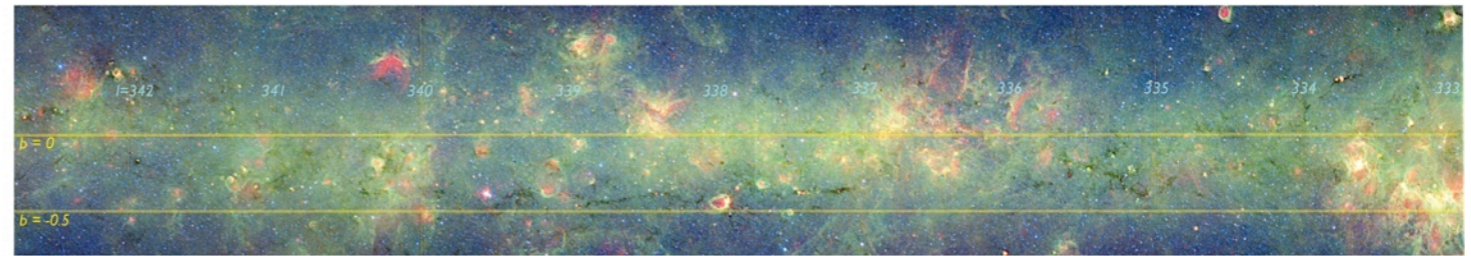


-20  
-40  
-60  
-80  
-100

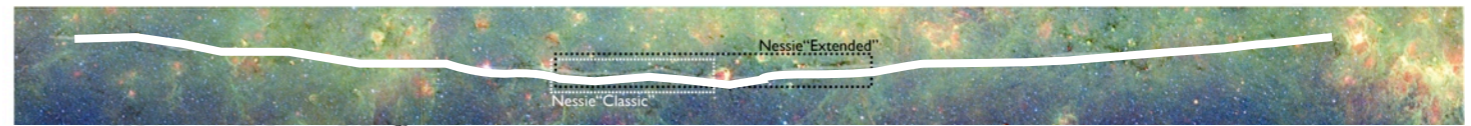
X

X

Y

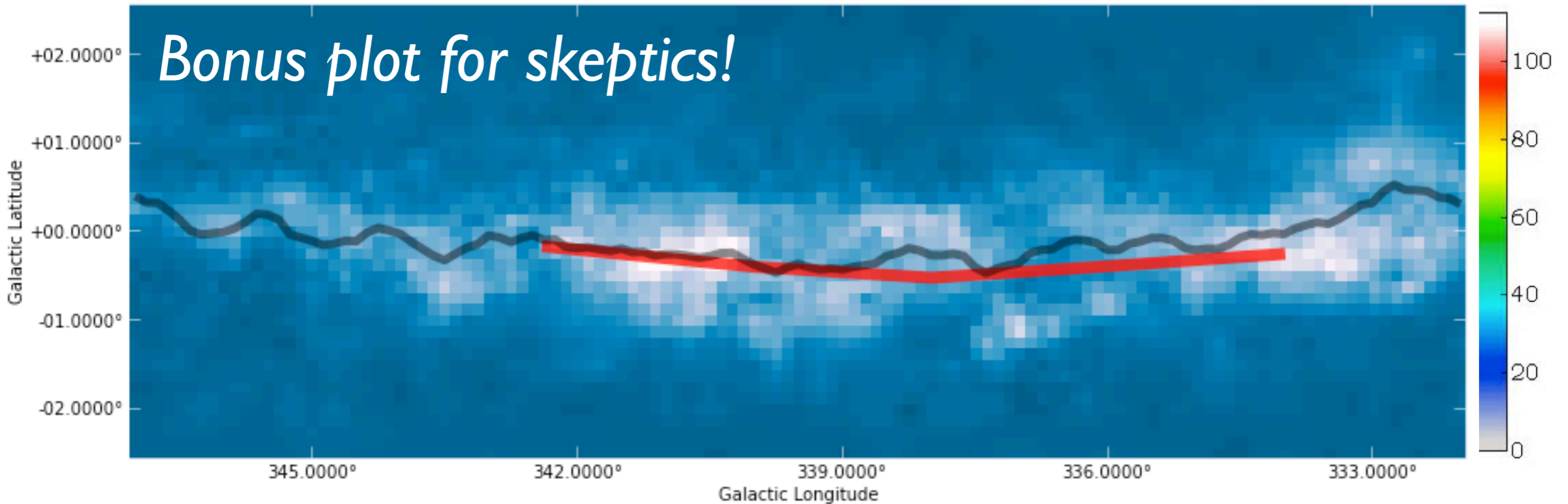


1 degree ~ 60 pc at 3.5 kpc



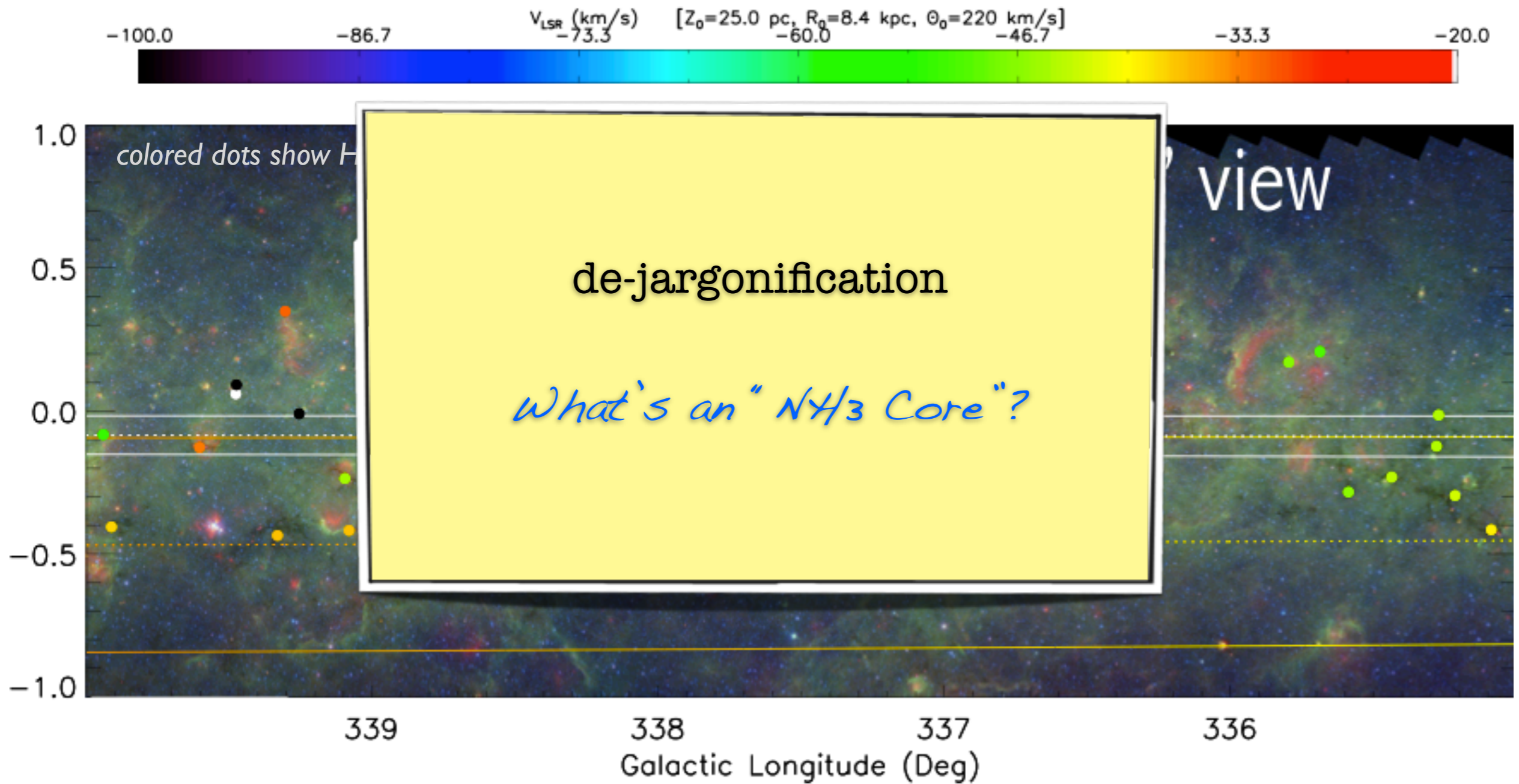
Wco m50 m30.fits

*Bonus plot for skeptics!*

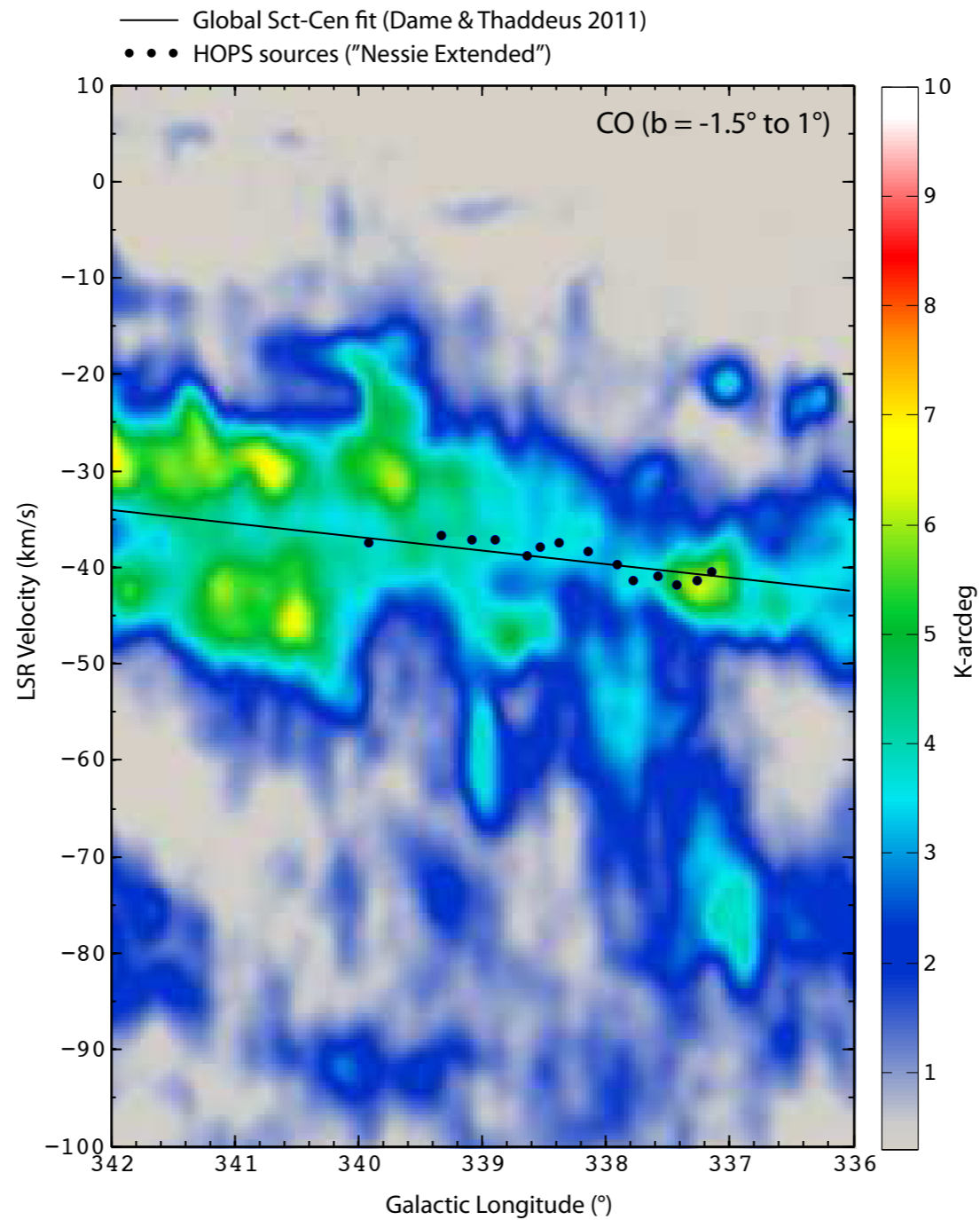




# Predicted Velocities match NH<sub>3</sub> Cores in Nessie Perfectly

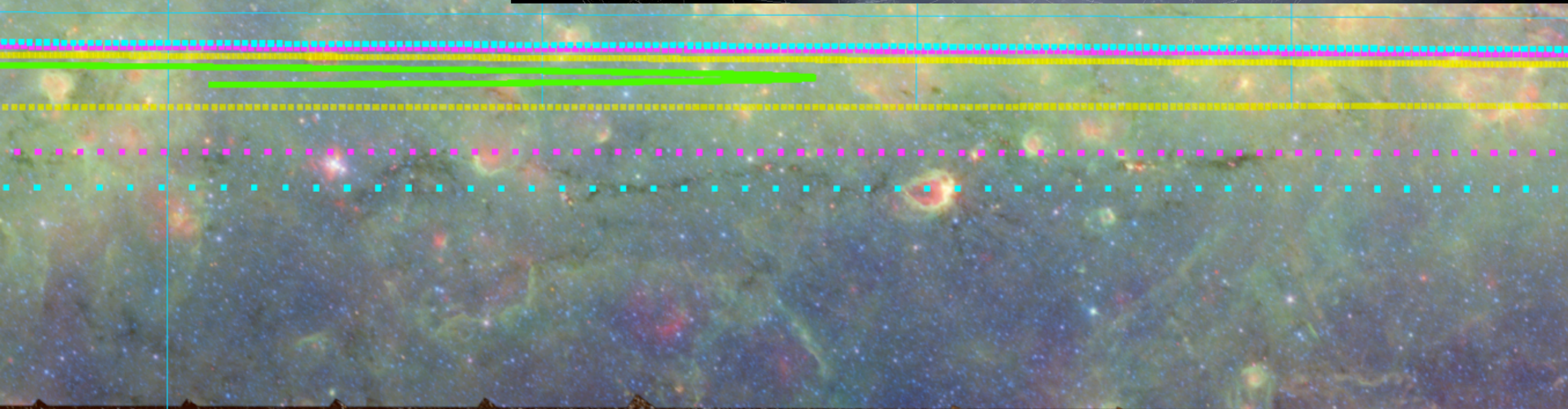
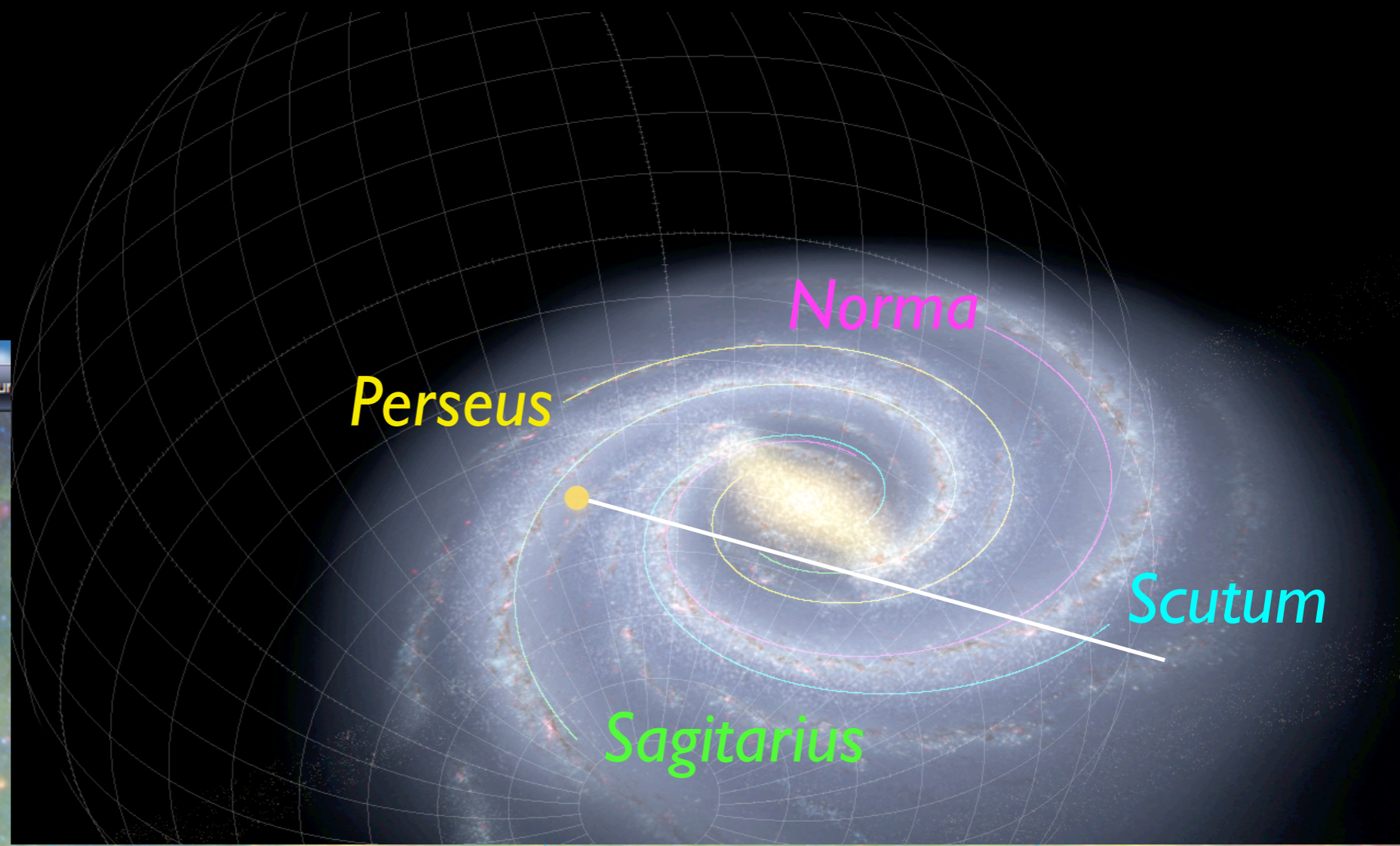
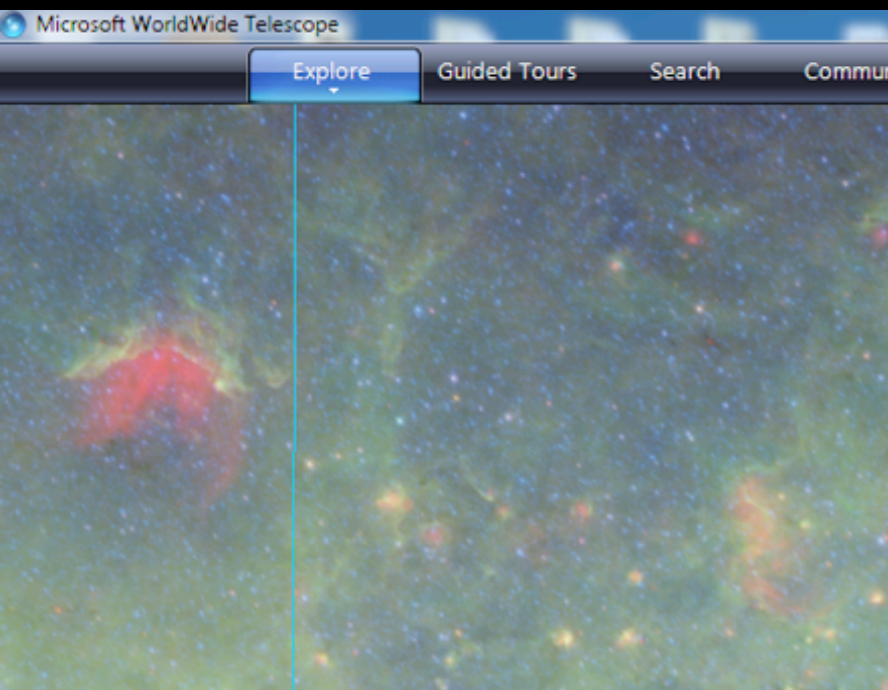


# Predicted Velocities match NH<sub>3</sub> Cores in Nessie Perfectly



*black dots show HOPS NH<sub>3</sub> velocities from Purcell et al. 2012; color is CO; line is log-spiral fit to full Scut-Cen Arm*

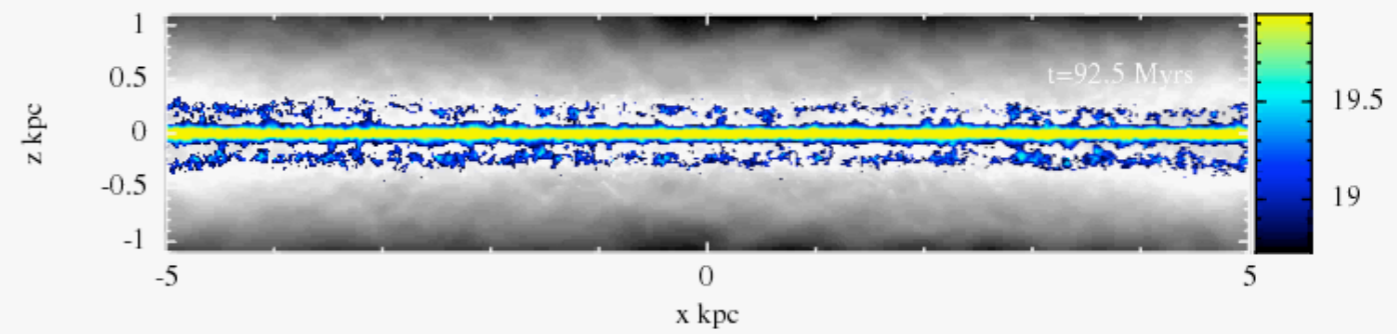
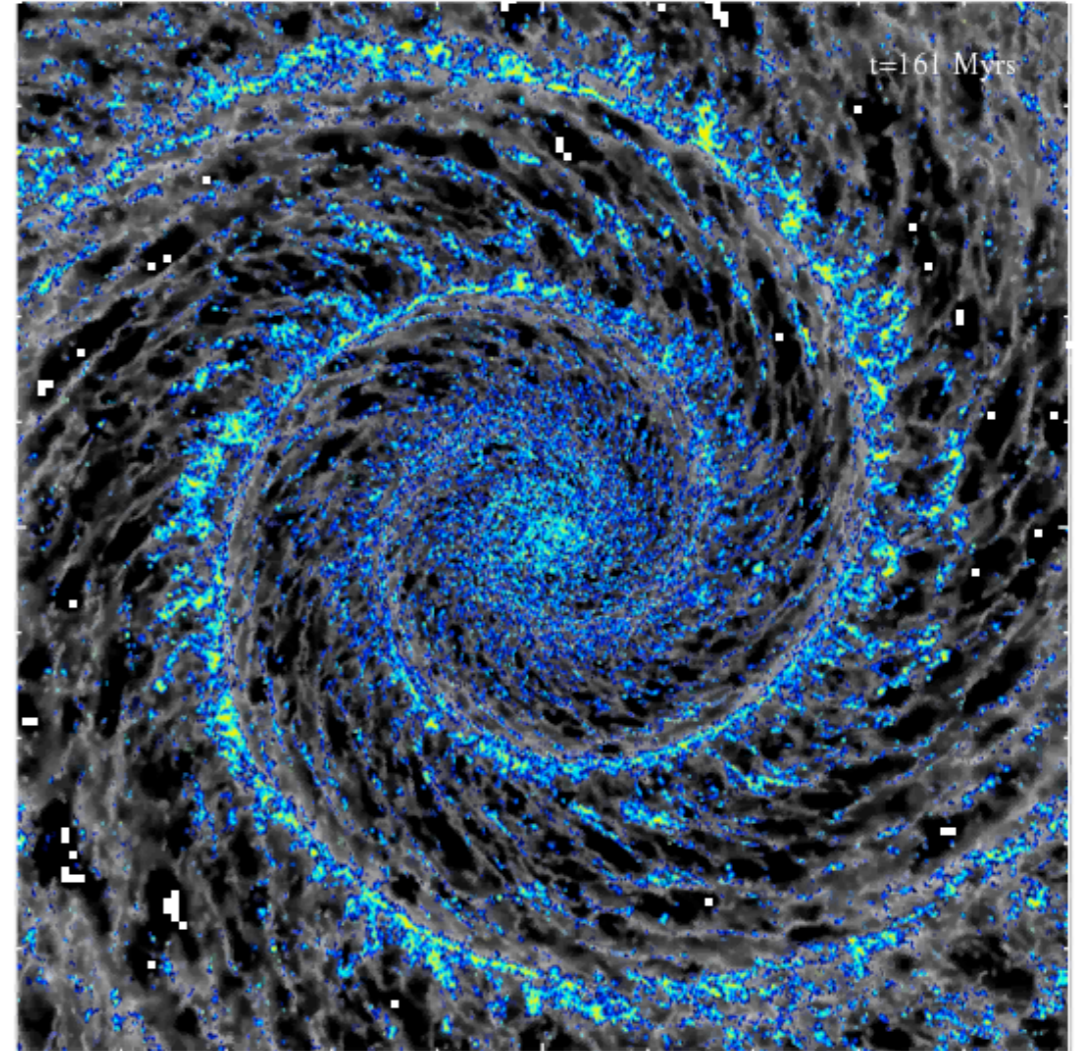
# Other Arms? Other Nessies?



# What's a bone?



(flipped) image of IC342 from Jarrett et al. 2012; WISE Enhanced Resolution Galaxy Atlas



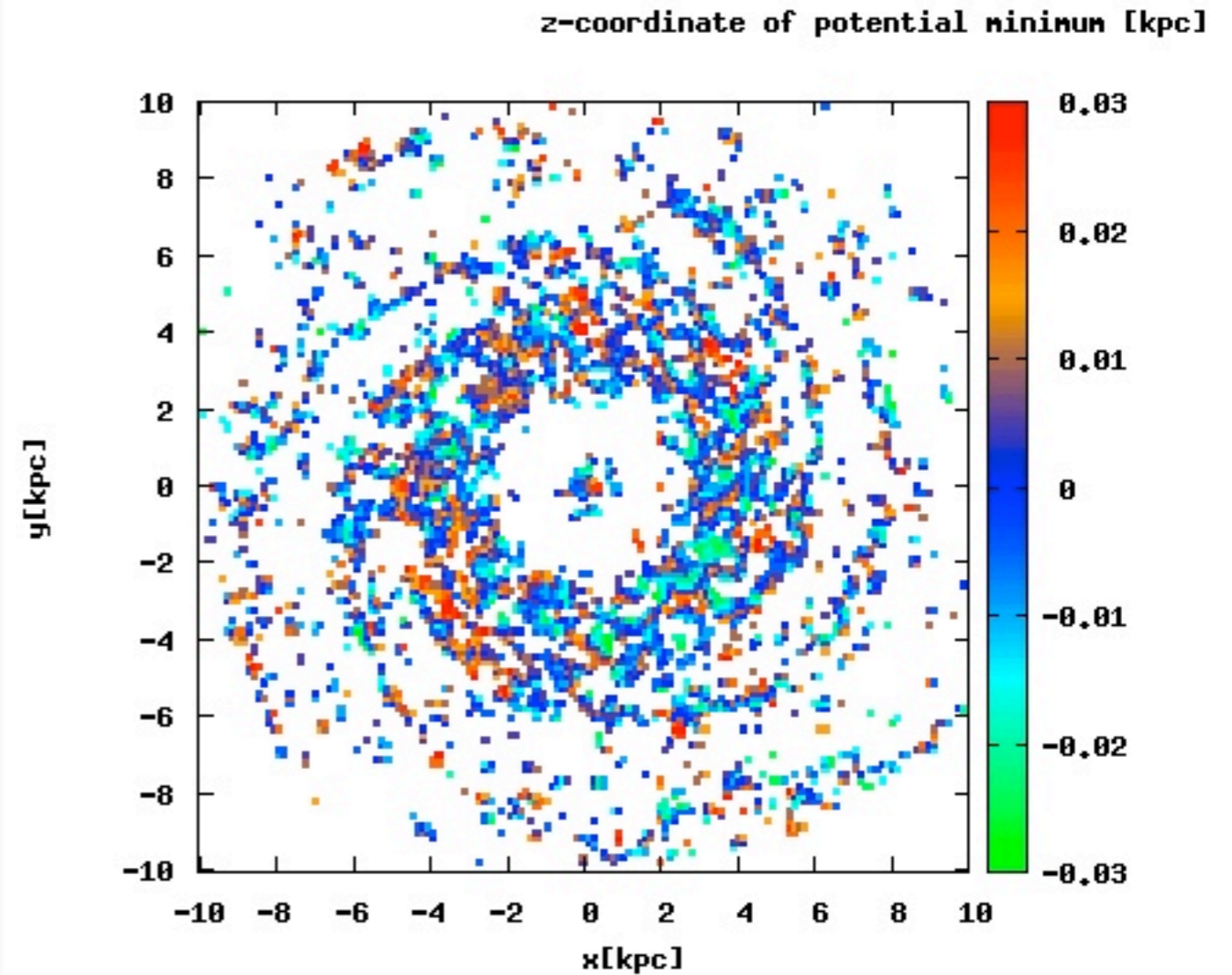
Dobbs & Pringle 2013

# What's a bone?



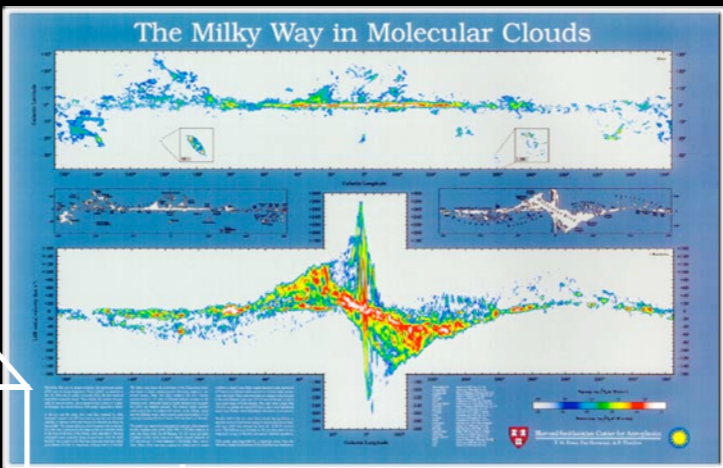
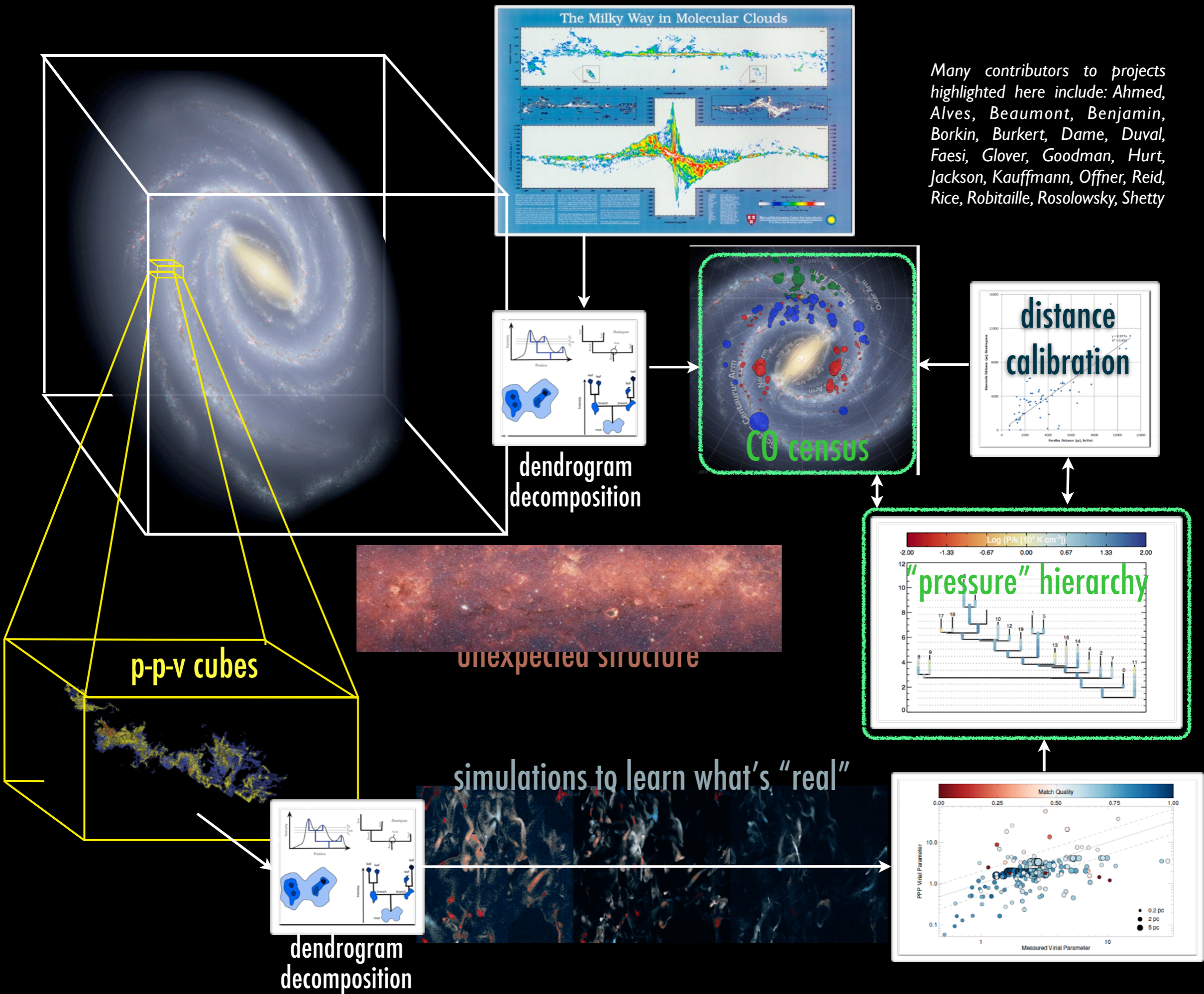
(flipped) image of IC342 from Jarrett et al. 2012; WISE Enhanced Resolution Galaxy Atlas

# What does Nessie mark?

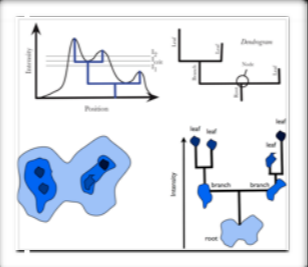
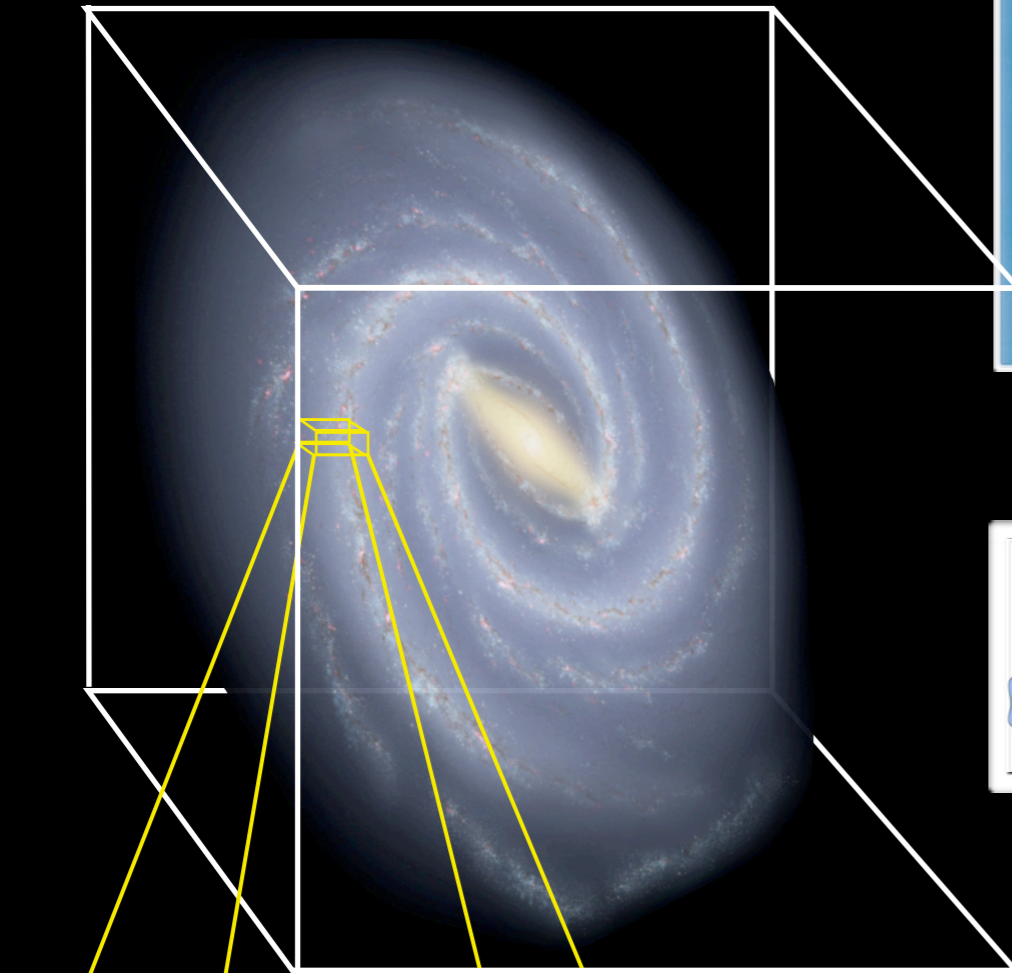


new (June 2013) simulation by Andi Burkert et al., “inspired” by Nessie, but still not high-enough resolution...  
*Andi says we need 1 billion particles to see Nessies...*

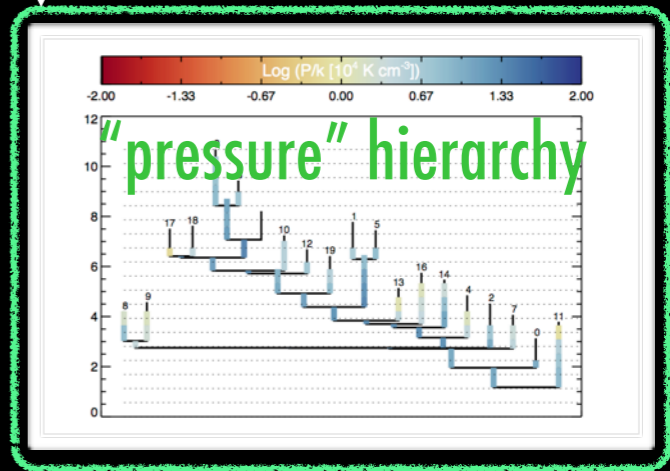
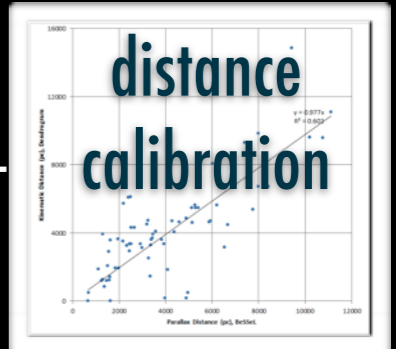
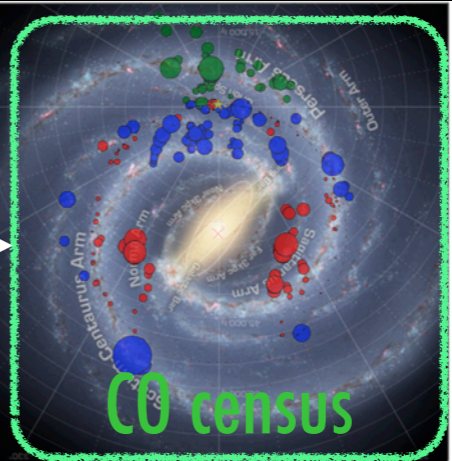




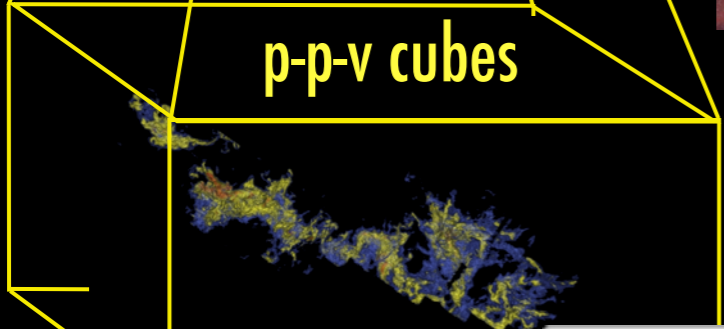
Many contributors to projects highlighted here include: Ahmed, Alves, Beaumont, Benjamin, Borkin, Burkert, Dame, Duval, Faesi, Glover, Goodman, Hurt, Jackson, Kauffmann, Offner, Reid, Rice, Robitaille, Rosolowsky, Shetty



dendrogram decomposition

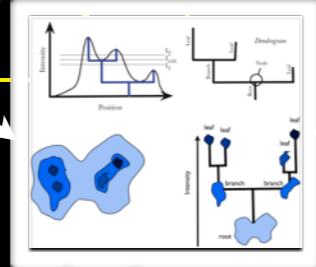


unexpected structure

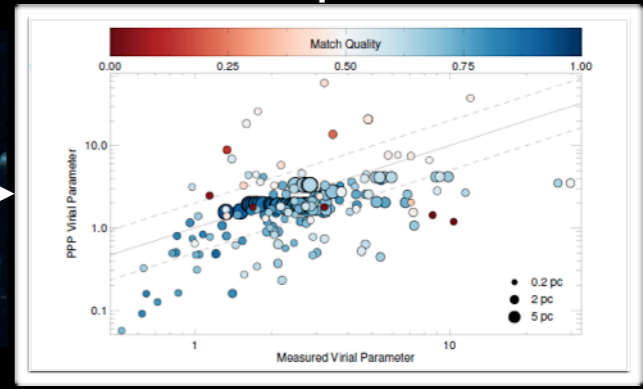
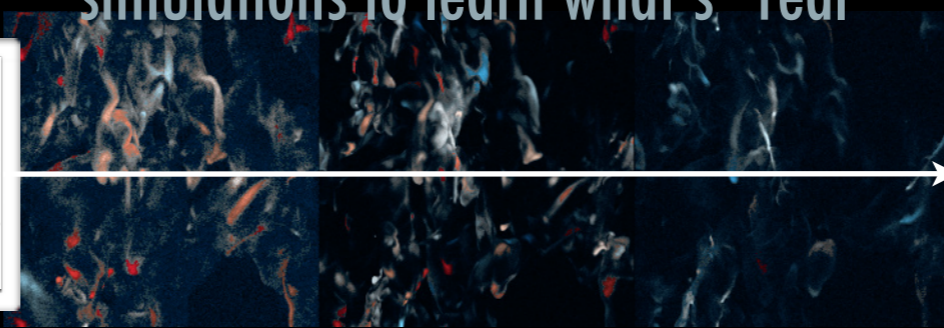


p-p-v cubes

simulations to learn what's "real"



dendrogram decomposition



A visualization of the cosmic web, showing a complex network of dark matter filaments and clusters. The filaments are rendered in shades of blue and purple, while the clusters and nodes are highlighted in bright orange and red. The background is black, making the glowing structures stand out.

# **Numerically** Constraining Star Formation in the Real Universe, with **Observations**

**Alyssa A. Goodman**

*Harvard-Smithsonian Center for Astrophysics*

## Navigation

[Home](#)  
[3D Viewers](#)  
[Datasets](#)  
[Images](#)  
[Videos](#)  
[Publications & Presentations](#)

## More

[About Universe3D.org](#)  
[Related Meetings](#)  
[Contact](#)  
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[What links here](#)  
[Related changes](#)  
[Special pages](#)  
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## What is Universe3D.org?

The intention of Universe3D.org is to host links to web content that enable the enhancement of our three-dimensional view of the Universe. Feel free to join in and edit--Wikipedia-style!

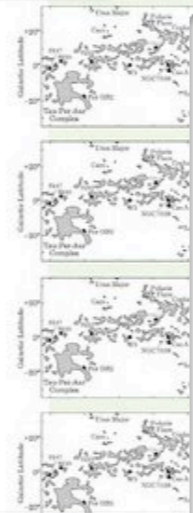
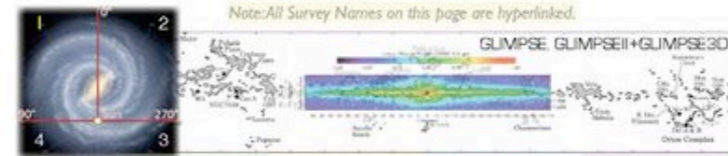
### Recently added Dataset

**Methanol MultiBeam Survey** [↗](#) The Methanol MultiBeam Survey is a sensitive survey of massive young stars in the Milky Way Galaxy to detect methanol masers. The survey is carried out by scanning the telescope in galactic longitude. Spectra cover a 4-MHz band, corresponding to a velocity range of 180 km/s, with 2048 channels each separated by 0.09 km/s. Regions towards the galactic centre are scanned more than once with different velocity settings, so that all likely radial velocities are searched. A second frequency band centred on the 6035-MHz line of hydroxyl (OH) is observed in parallel with the methanol band.

### Astronomy News

**The Week in Pictures: June 15–21, 2013**  
 Astronomy Magazine News Article -  
 Released:6/21/2013  
 Fri, 21 Jun 2013 00:00:00 GMT

### Survey Coverage of the Milky Way



## Datasets

Distance	Wavelength					
	Gamma Ray	X-Ray	Ultraviolet	Optical	Infrared	Radio
Solar System	★	★	★	★	★	★
Nearby Stars	★	★	★	★	★	★
Milky Way	★	★	★	★	★	★
Local Group Galaxies	★	★	★	★	★	★
z ~ 0 Galaxies	★	★	★	★	★	★
z > 0 Galaxies	★	★	★	★	★	★
High Redshift Universe	★	★	★	★	★	★
Early Universe	★	★	★	★	★	★

If you want to add a new dataset [click here](#).

★: Datasets available  
★: No Datasets available yet

