Fundamental, (?), Fragmenting, Filaments & Fibers

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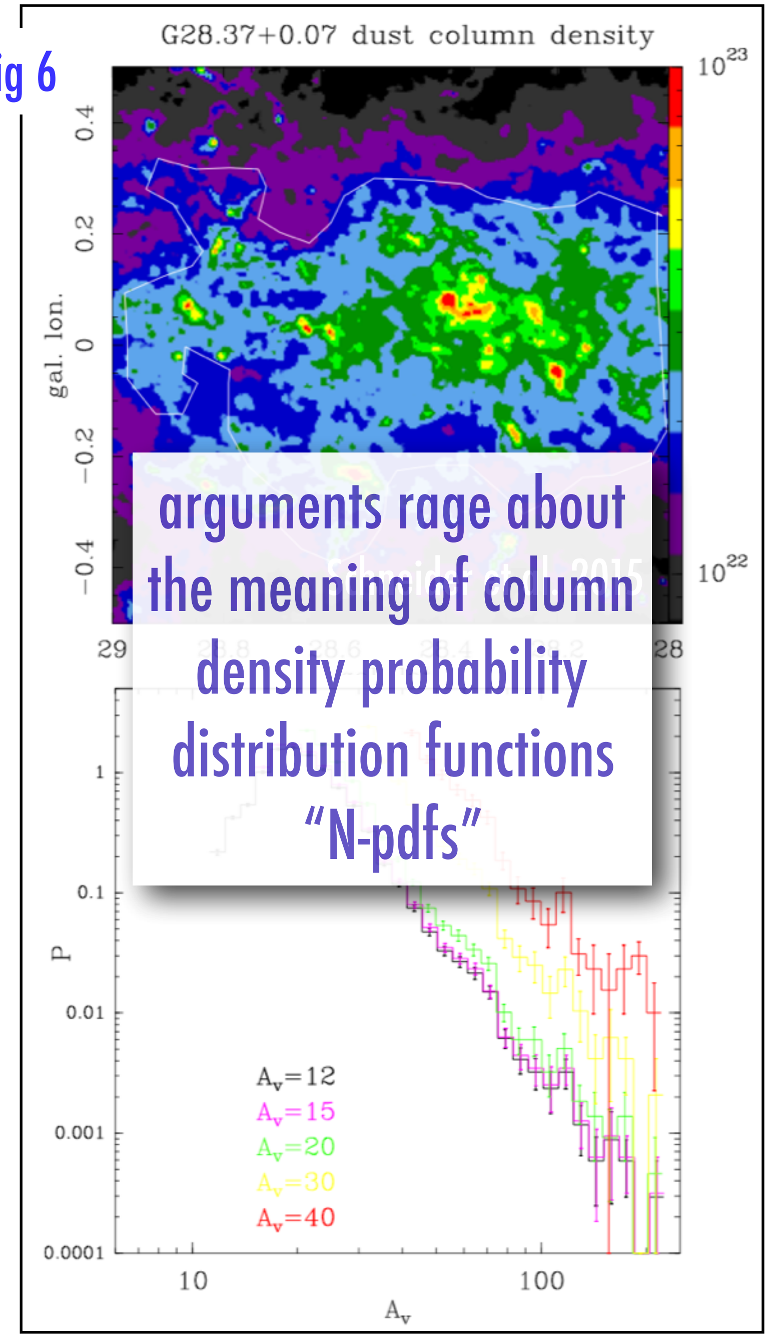
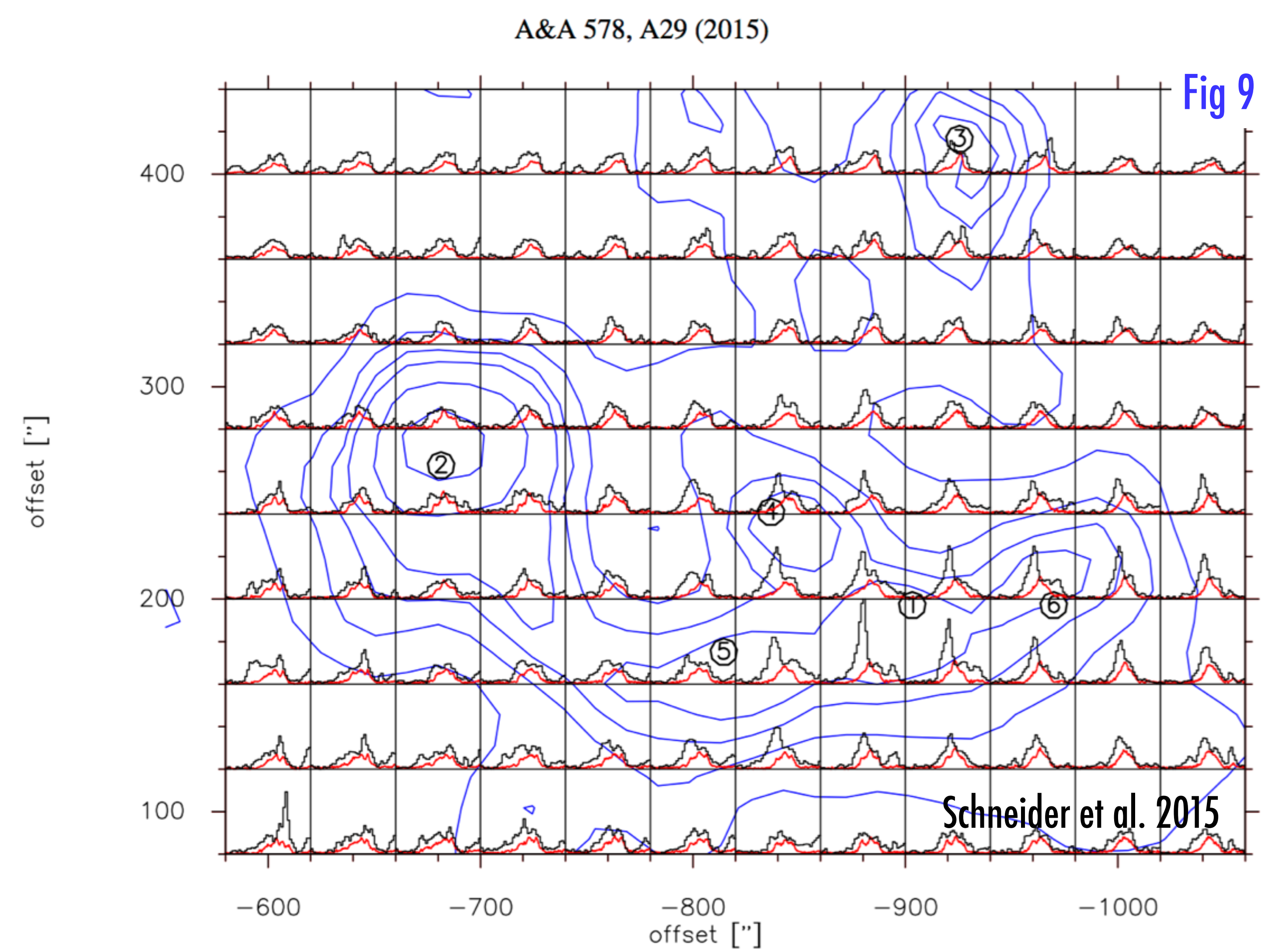
NGC3521, APOD 11-30-15

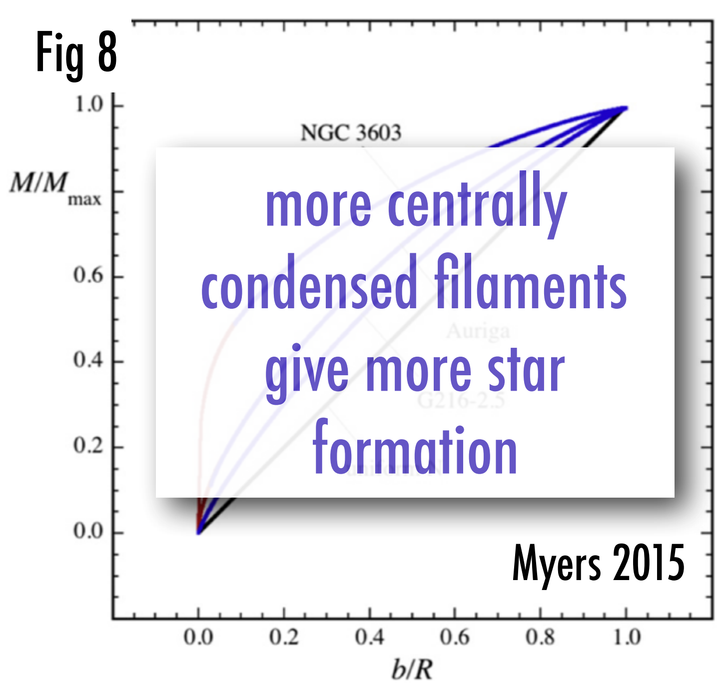
ESA/Hubble & NASA and S. Smartt (Queen's University Belfast)
Acknowledgement: Robert Gendler

FUNDAMENTAL?



arguments rage about the meaning of column density probability distribution functions “N-pdfs”





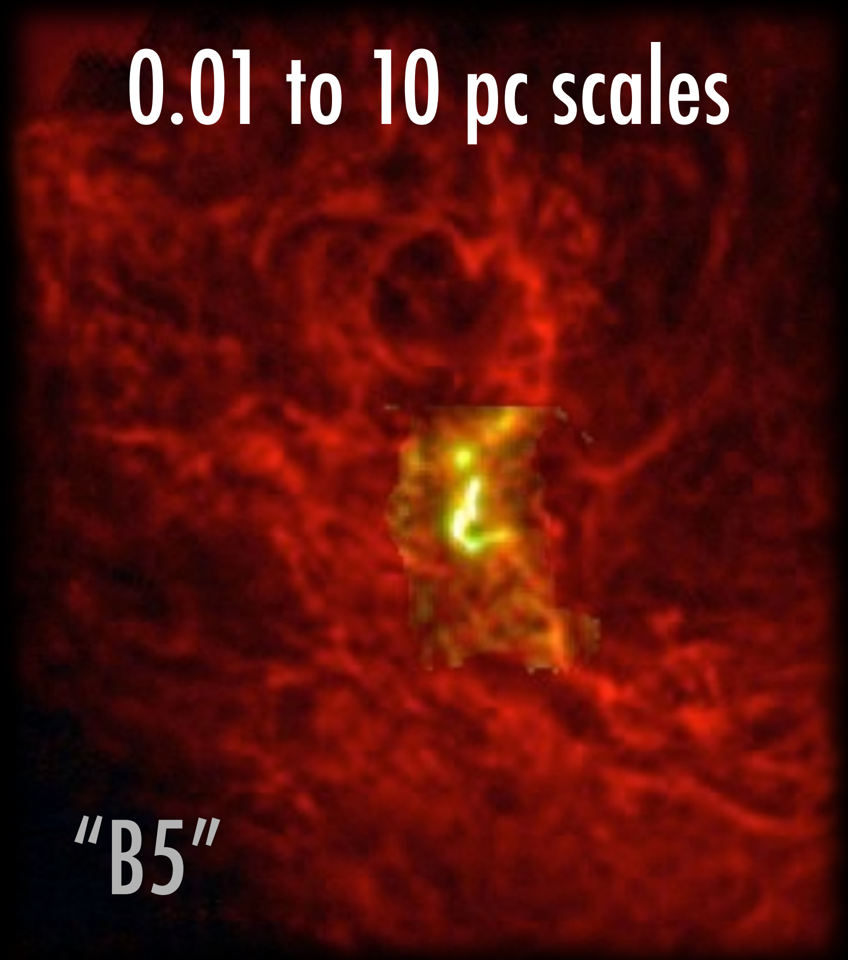
more centrally condensed filaments give more star formation

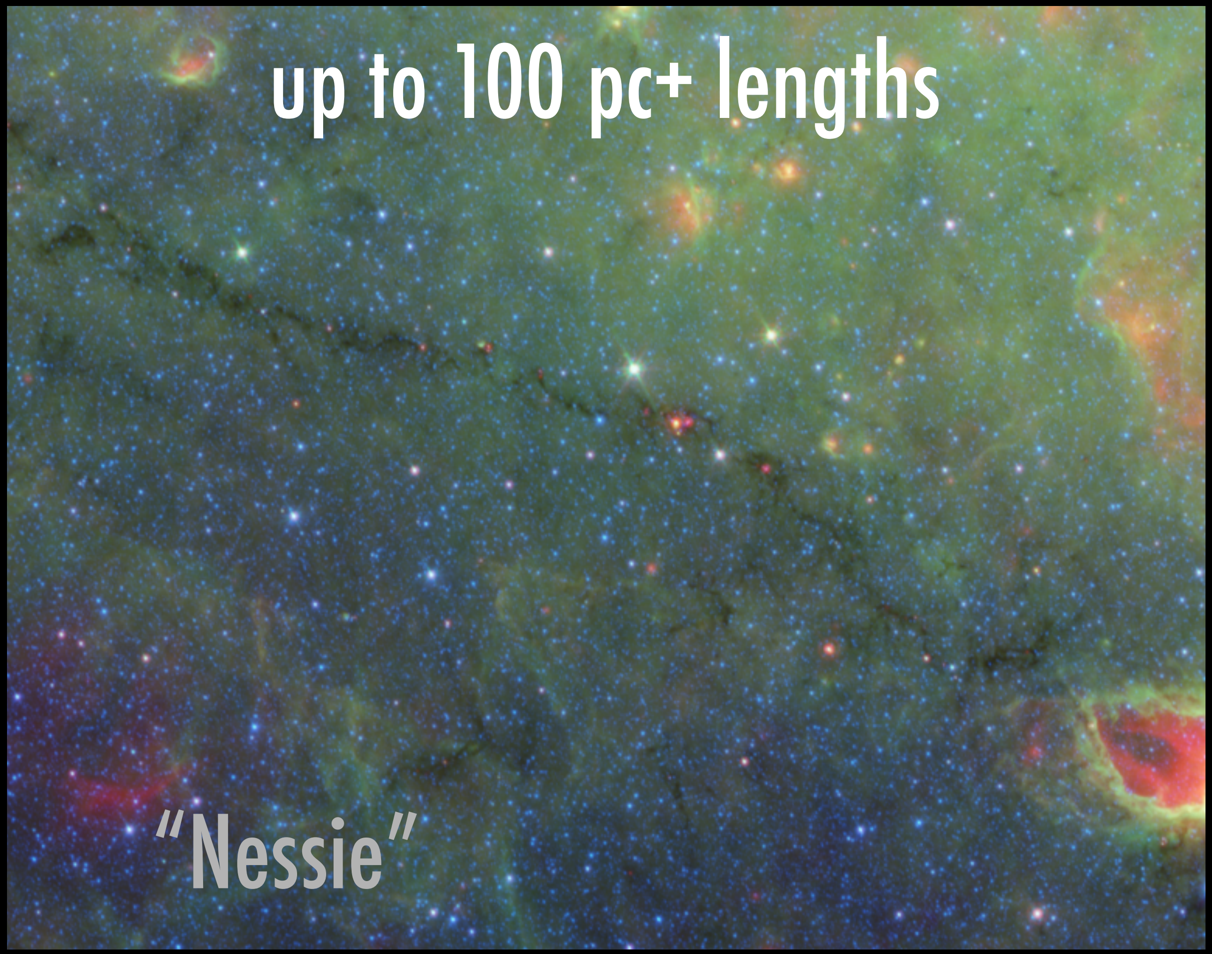
Fig. 9. Main beam brightness temperature spectra of ^{12}CO 3 → 2 (black) and ^{13}CO 1→0 (red) emission in the velocity range 55 to 95 km s^{-1} and temperature range −0.2 to 12 K. The area corresponds to the centre region of the IRDC G28.37+0.07, outlined in Fig. 8. The dust column density from *Herschel* is overlaid as blue contours (levels 4, 5, 7, 10, 16 × 10^{22} cm^{-2}), and the numbering from 1 to 6 indicates the position of submm-continuum sources labelled using ATLASGAL and subsequently observed in N_2H^+ (Tackenberg et al. 2014).

Figure 8. Enclosed mass profiles for characteristic filaments of star-forming regions NGC 3603, Auriga, and G216-2.5, whose *N*-pdfs are based on *Herschel* observations (Schneider et al. 2014b). Each colored curve is based on the LNPL fit by Schneider et al. (2014b) to the observed *N*-pdf. The red part of each mass profile arises from the PL component of the *N*-pdf and the blue part arises from the LN component. The black line shows the enclosed mass profile of a filament having uniform column density. The degree of central concentration of each profile increases with the star formation activity of each region.

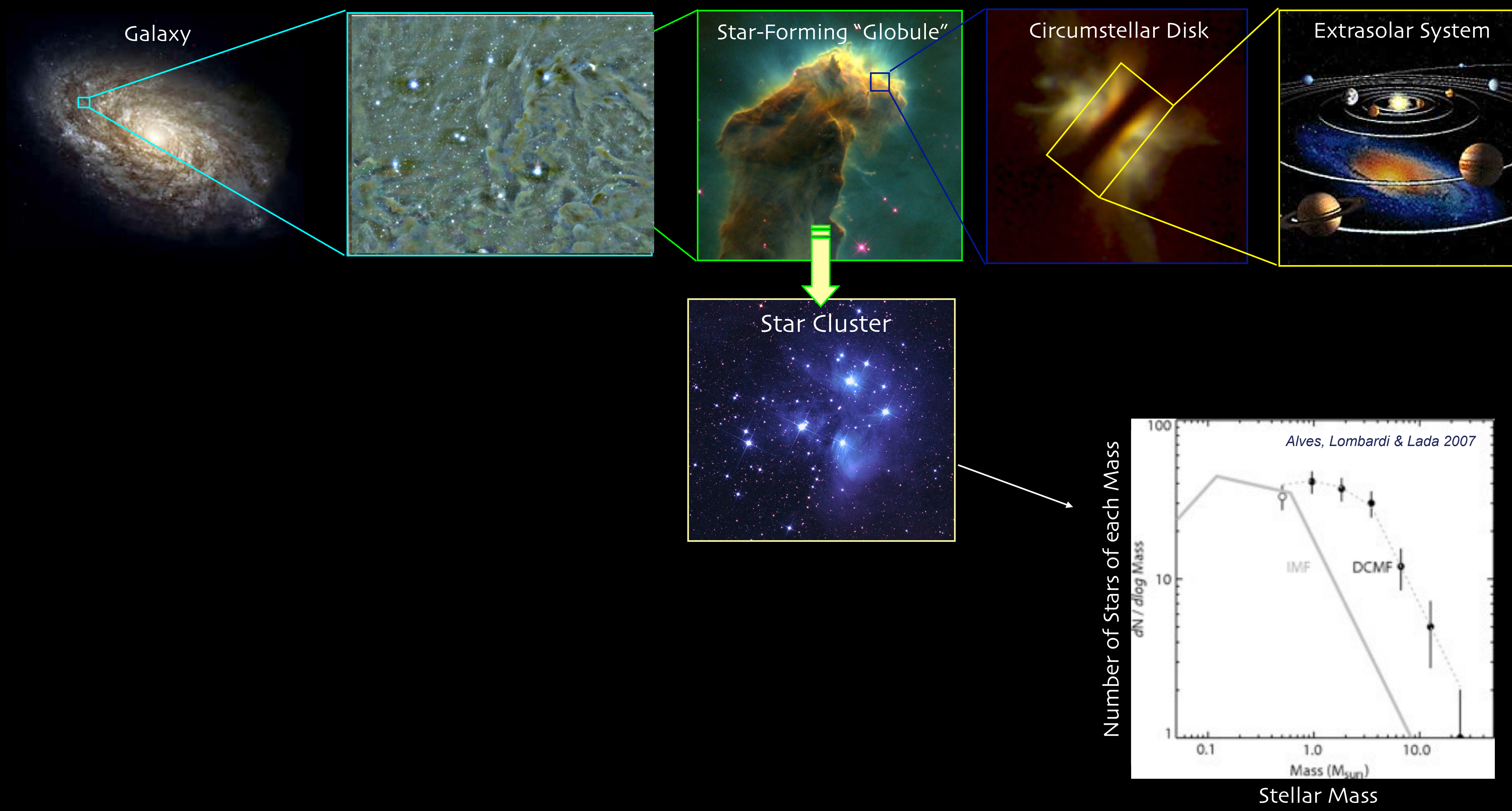
Fig. 6. *Top*: H_2 column density from dust continuum with the white contour, roughly outlining the GMC in which G28.37+0.07 is embedded. *Bottom*: PDFs of the GMC, derived from the dust column density map from the left above different A_v-thresholds (indicated with different colours and given in the panel).

...FRAGMENTING FILAMENTS & FIBERS



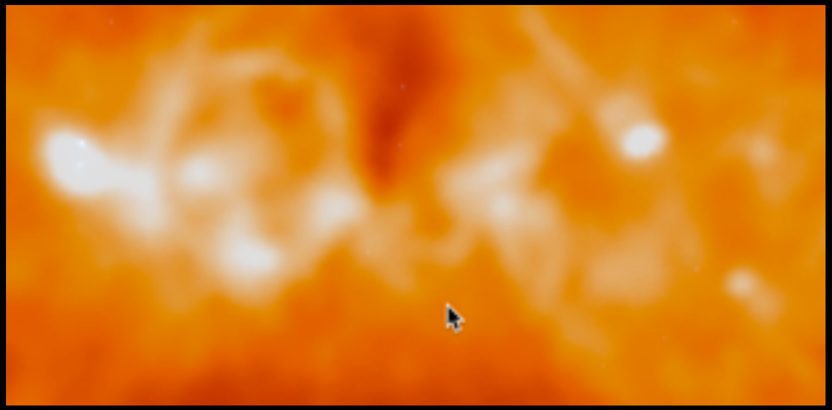


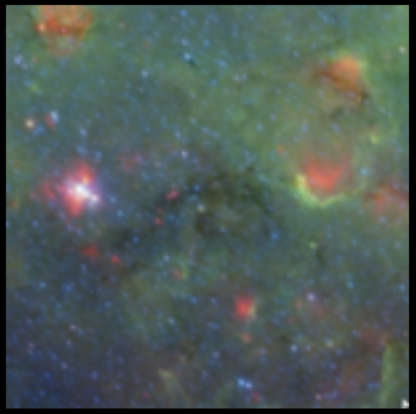
"STAR FORMATION"



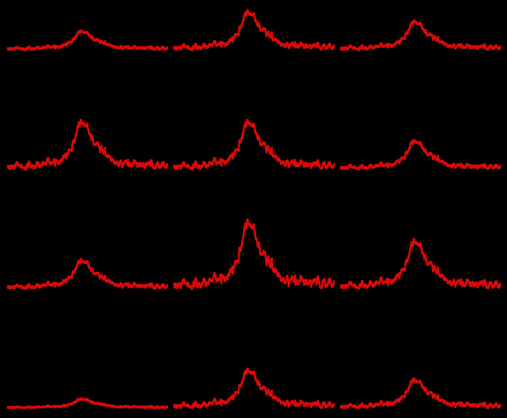
OBSERVATIONS

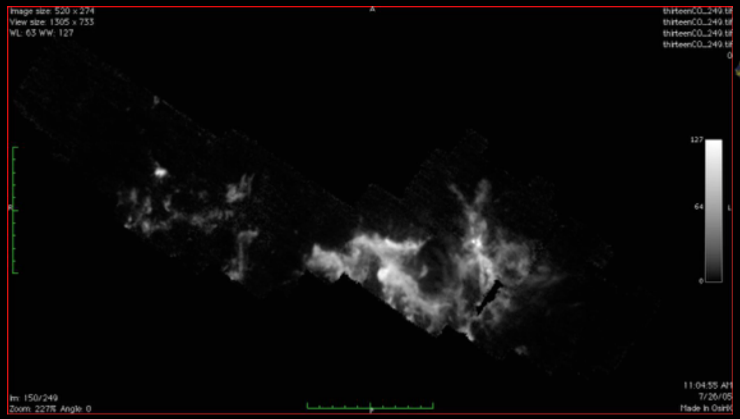
Dust

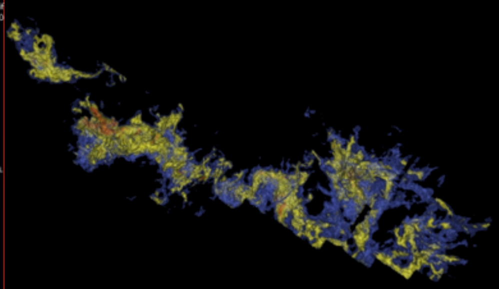




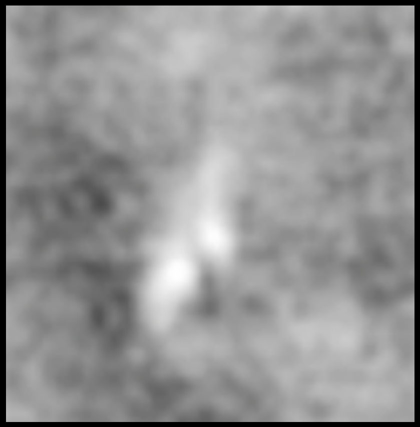
Gas





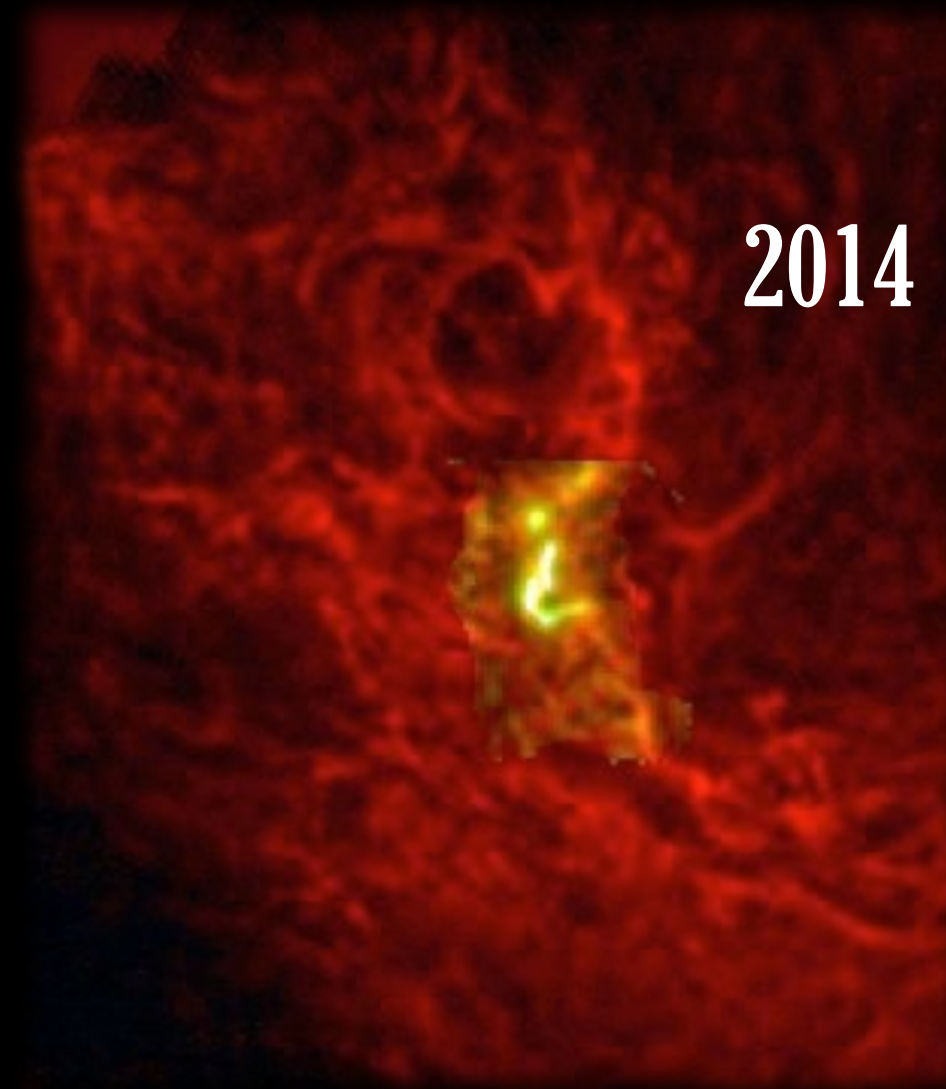


“Stars”

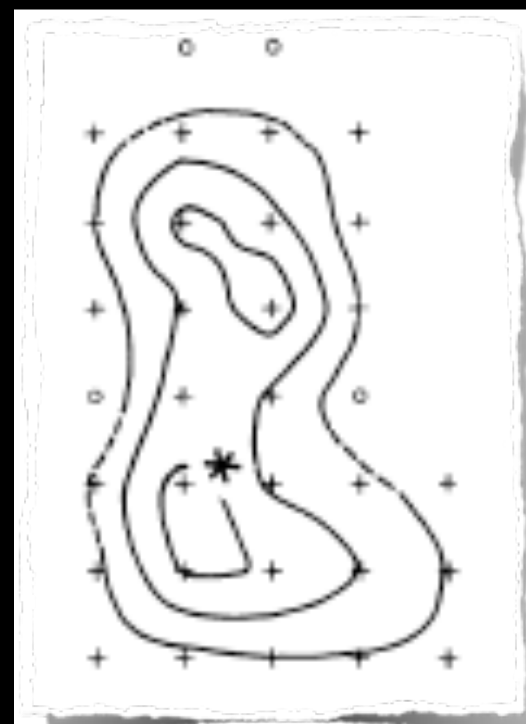


"BLOBS" TO "FILAMENTS"

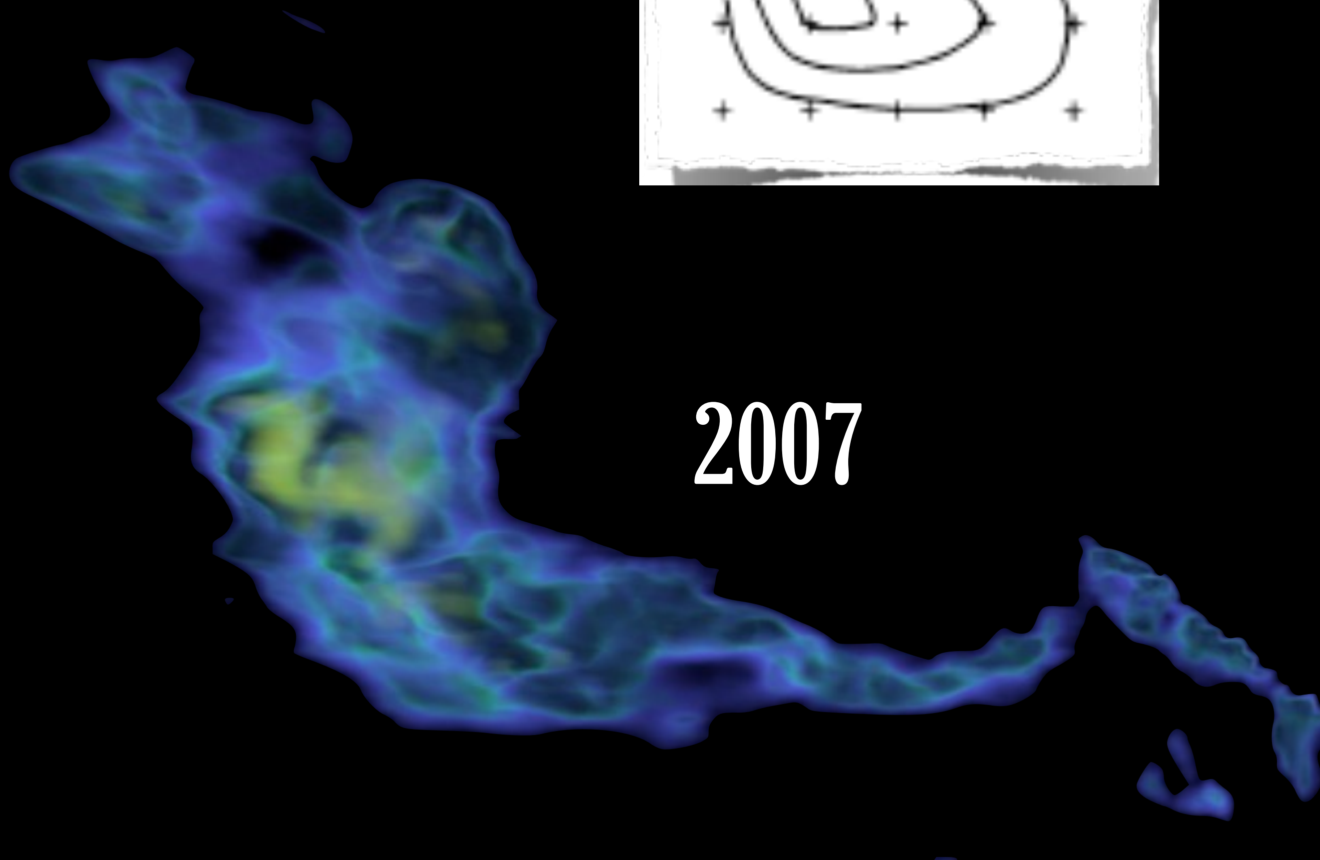
2014



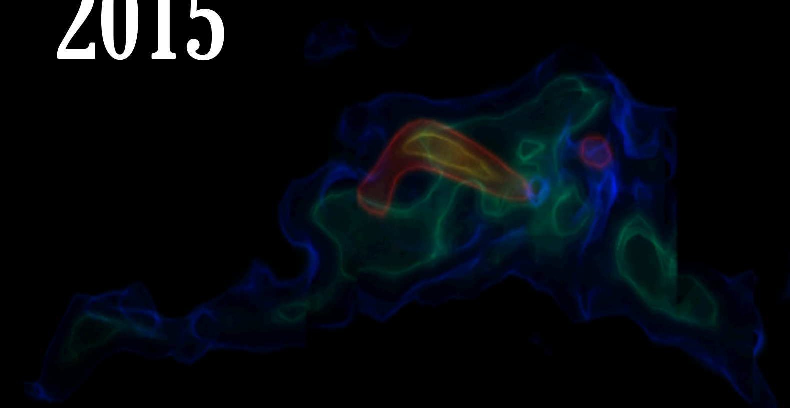
1989



2007

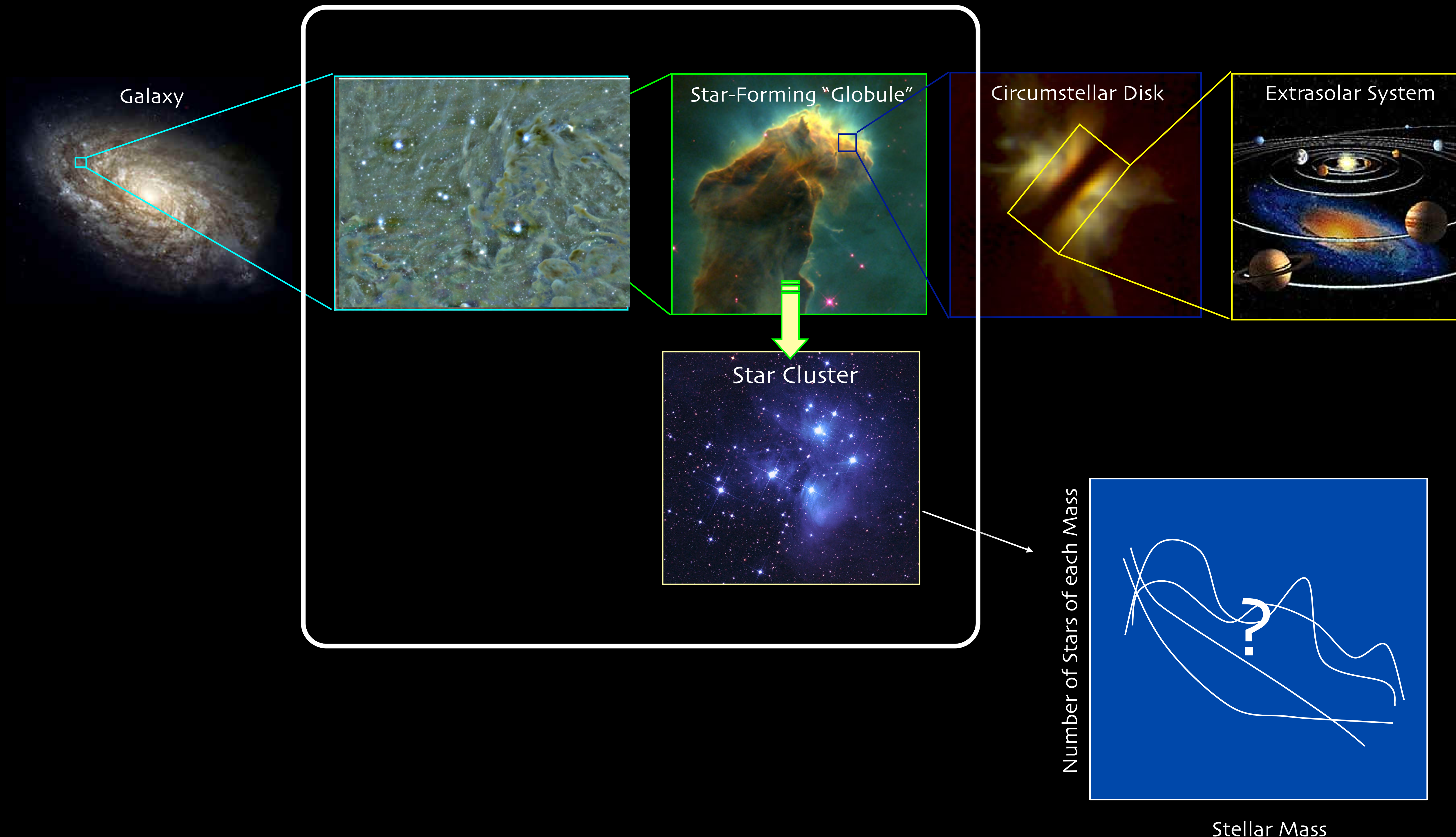


2015

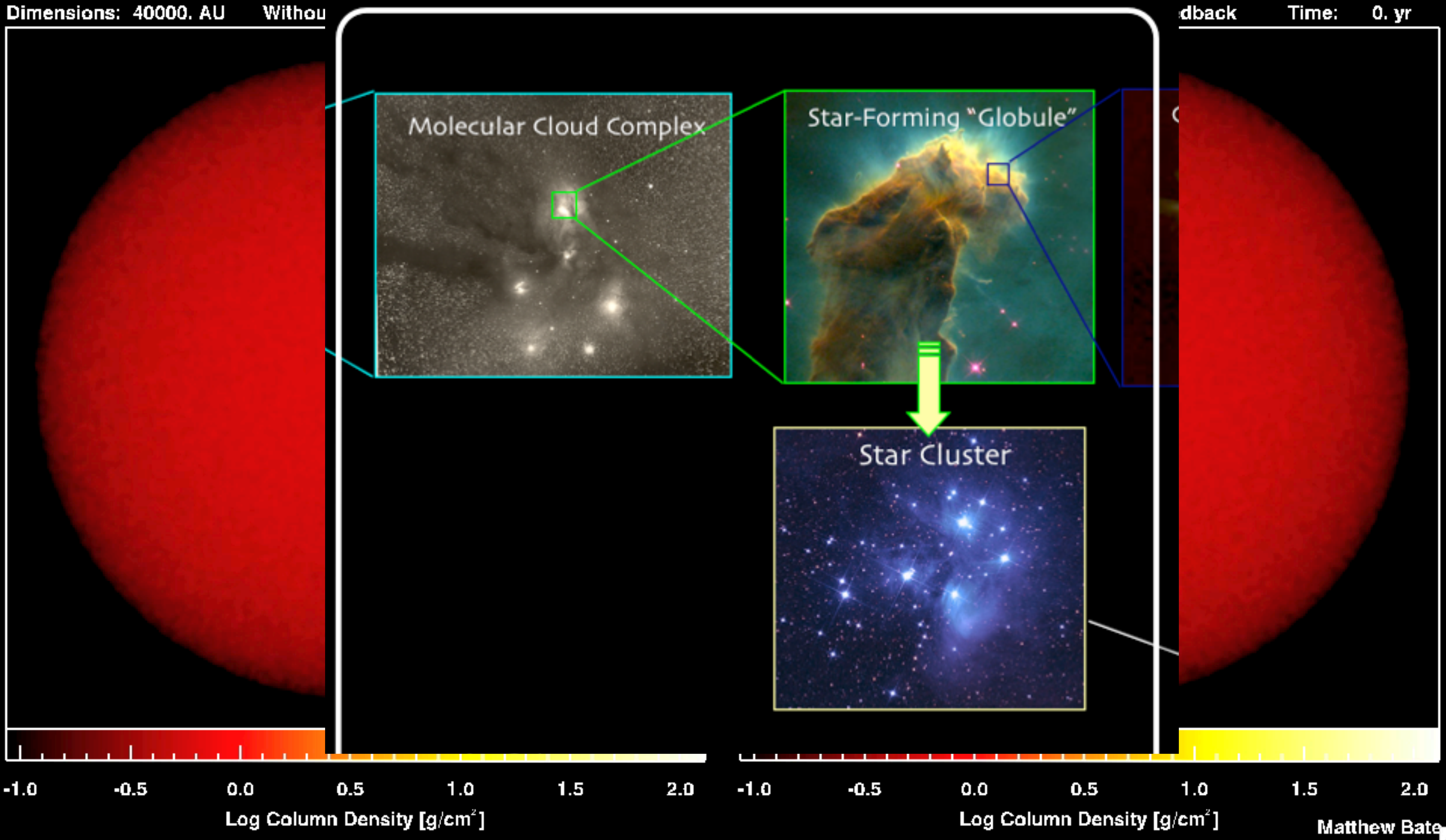


representative images, not to scale

"STAR FORMATION"



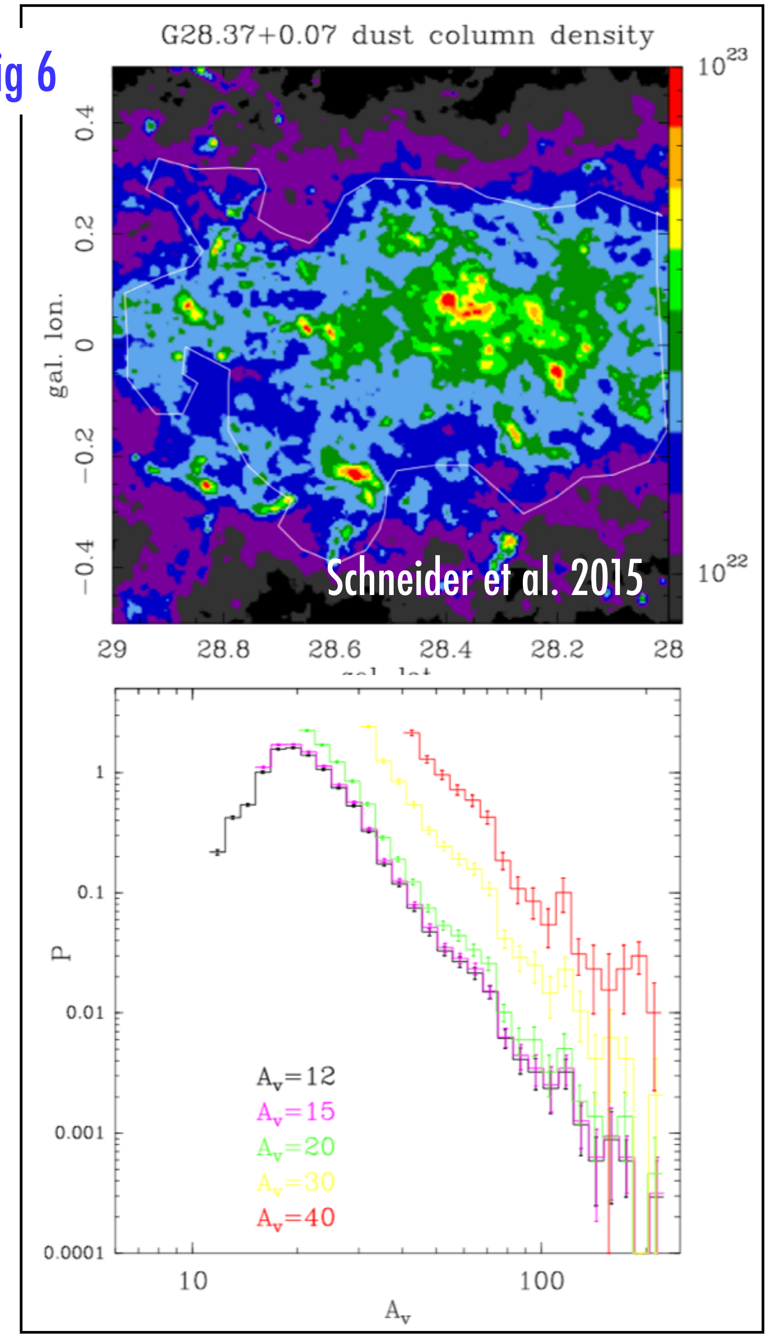
MAYBE THE THEORISTS WERE FIRST?



Simulations of Bate 2009

FUNDAMENTAL?

Fig 6



A&A 578, A29 (2015)

Fig 9

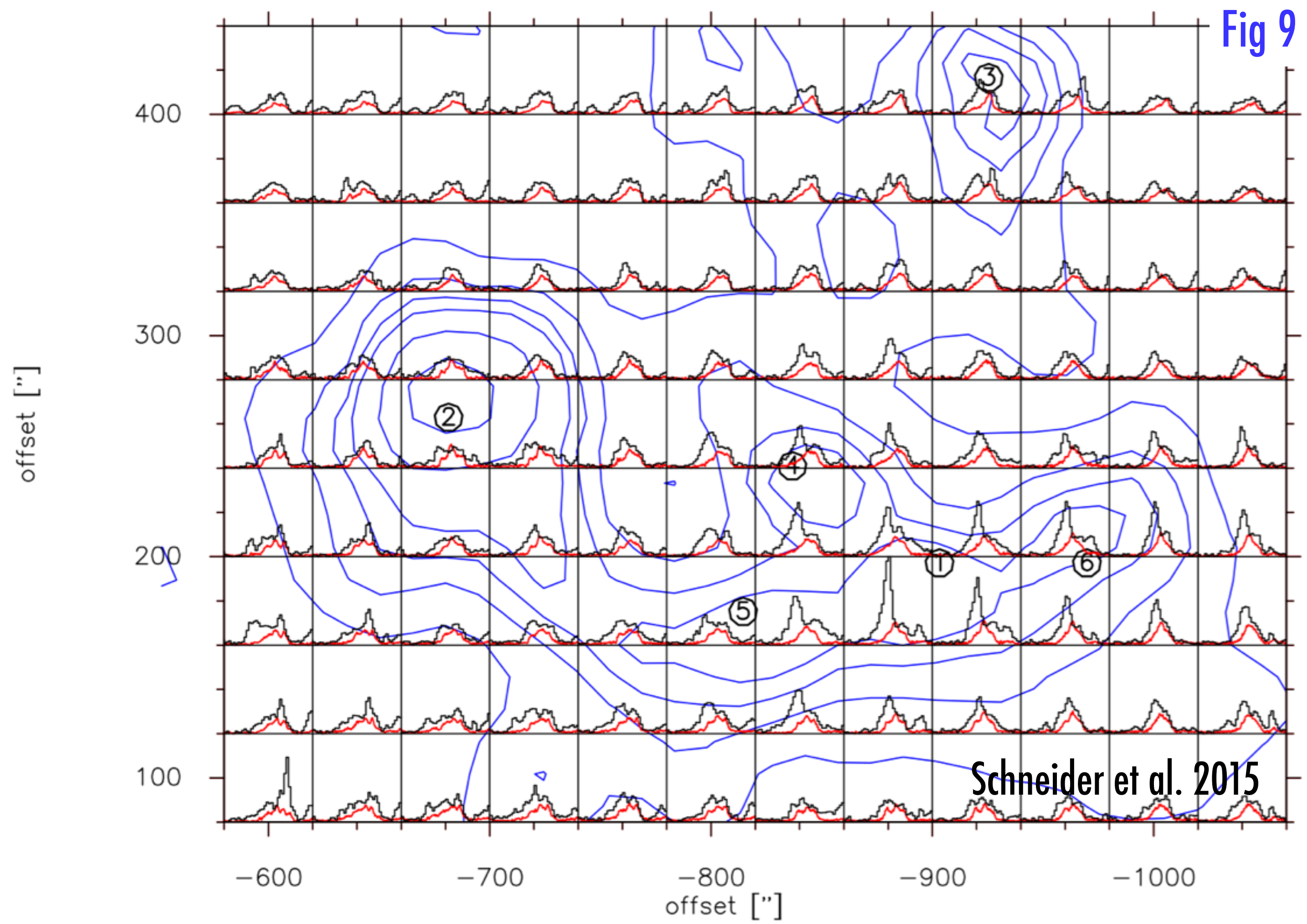


Fig 8

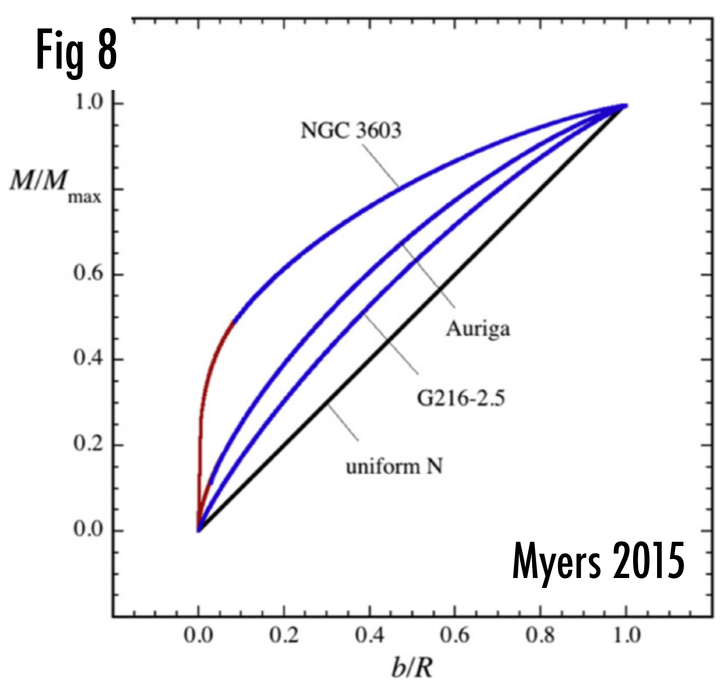


Fig. 9. Main beam brightness temperature spectra of ^{12}CO 3 → 2 (black) and ^{13}CO 1→0 (red) emission in the velocity range 55 to 95 km s^{-1} and temperature range −0.2 to 12 K. The area corresponds to the centre region of the IRDC G28.37+0.07, outlined in Fig. 8. The dust column density from *Herschel* is overlaid as blue contours (levels $4, 5, 7, 10, 16 \times 10^{22}$ cm^{-2}), and the numbering from 1 to 6 indicates the position of submm-continuum sources labelled using ATLASGAL and subsequently observed in N_2H^+ (Tackenberg et al. 2014).

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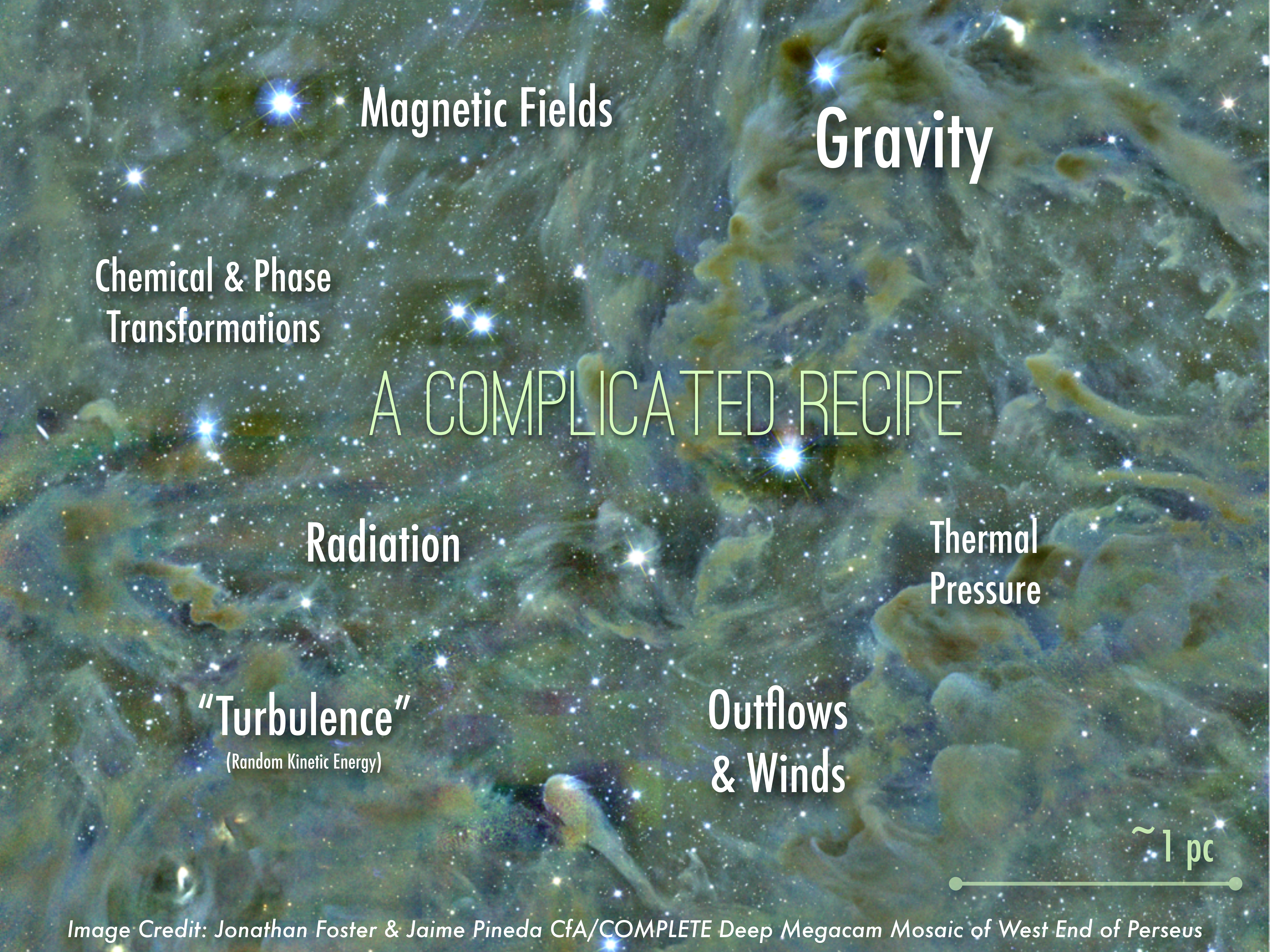
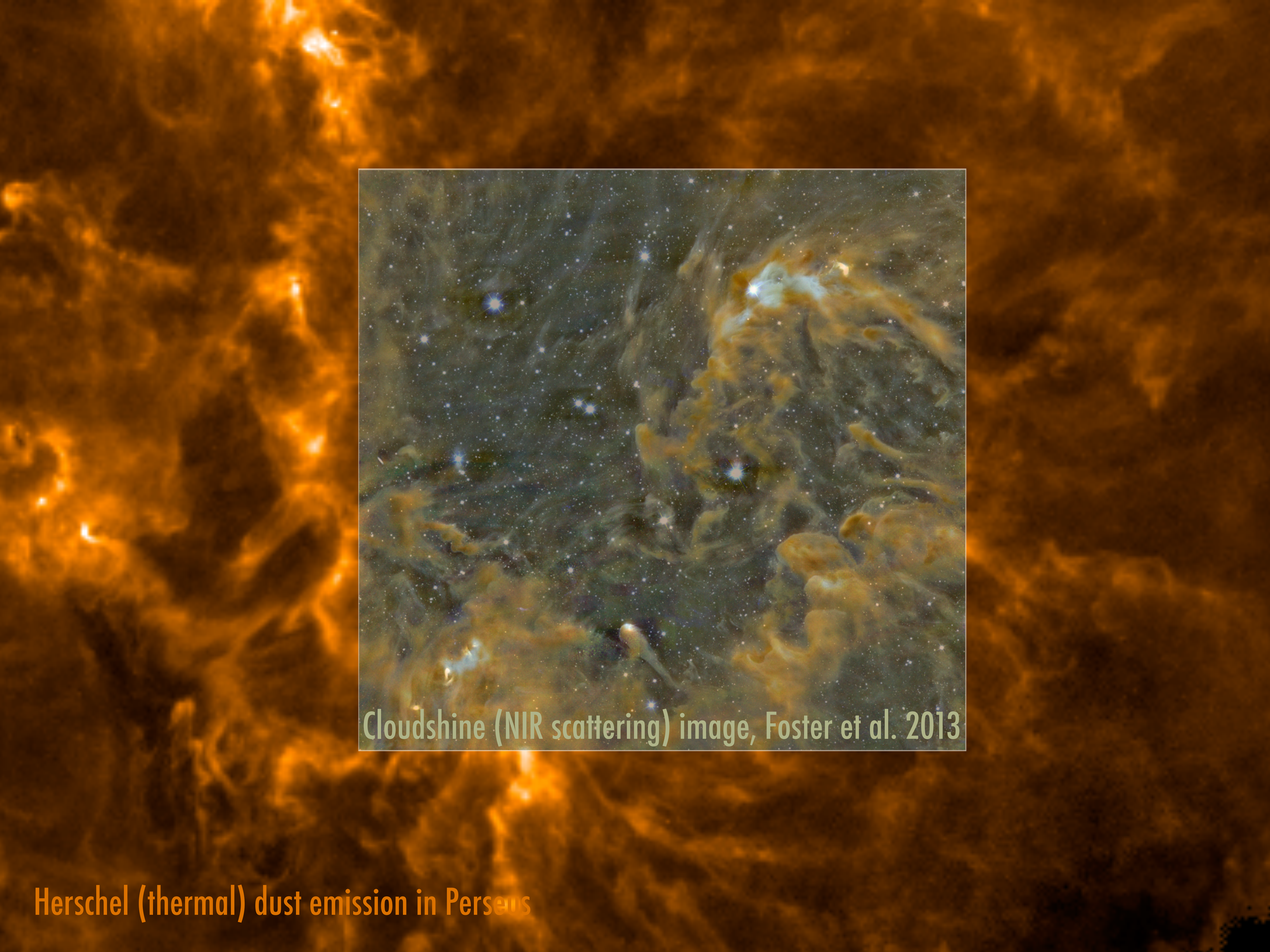
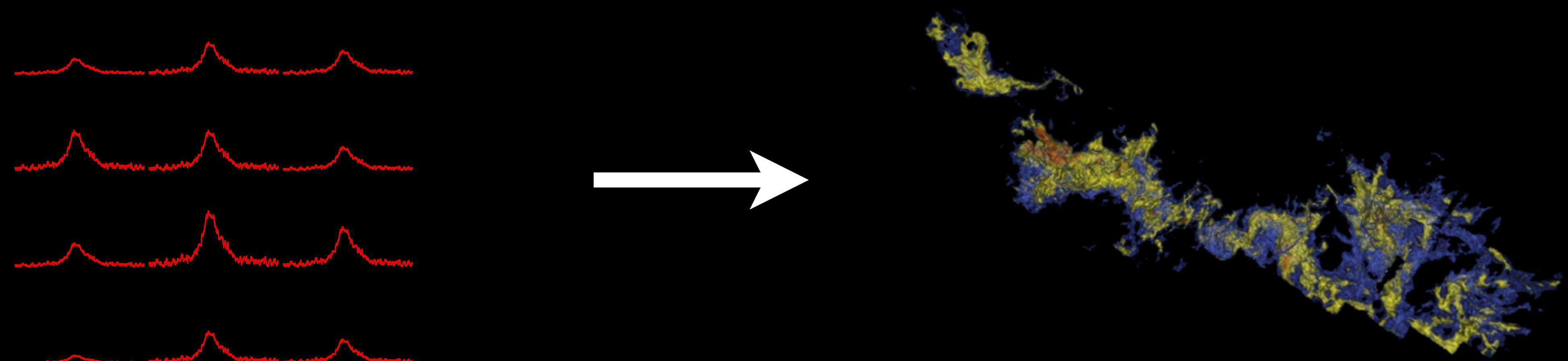


Image Credit: Jonathan Foster & Jaime Pineda CfA/COMPLETE Deep Megacam Mosaic of West End of Perseus

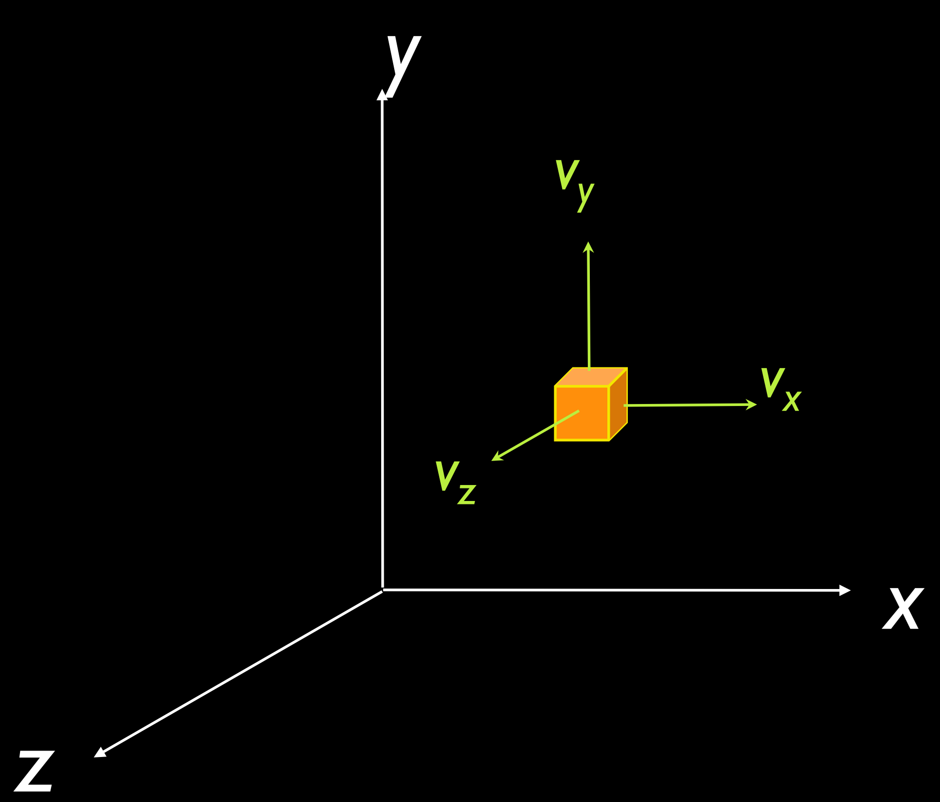

Cloudshine (NIR scattering) image, Foster et al. 2013
Herschel (thermal) dust emission in Perseus

CAN WE SEE IN 3D?

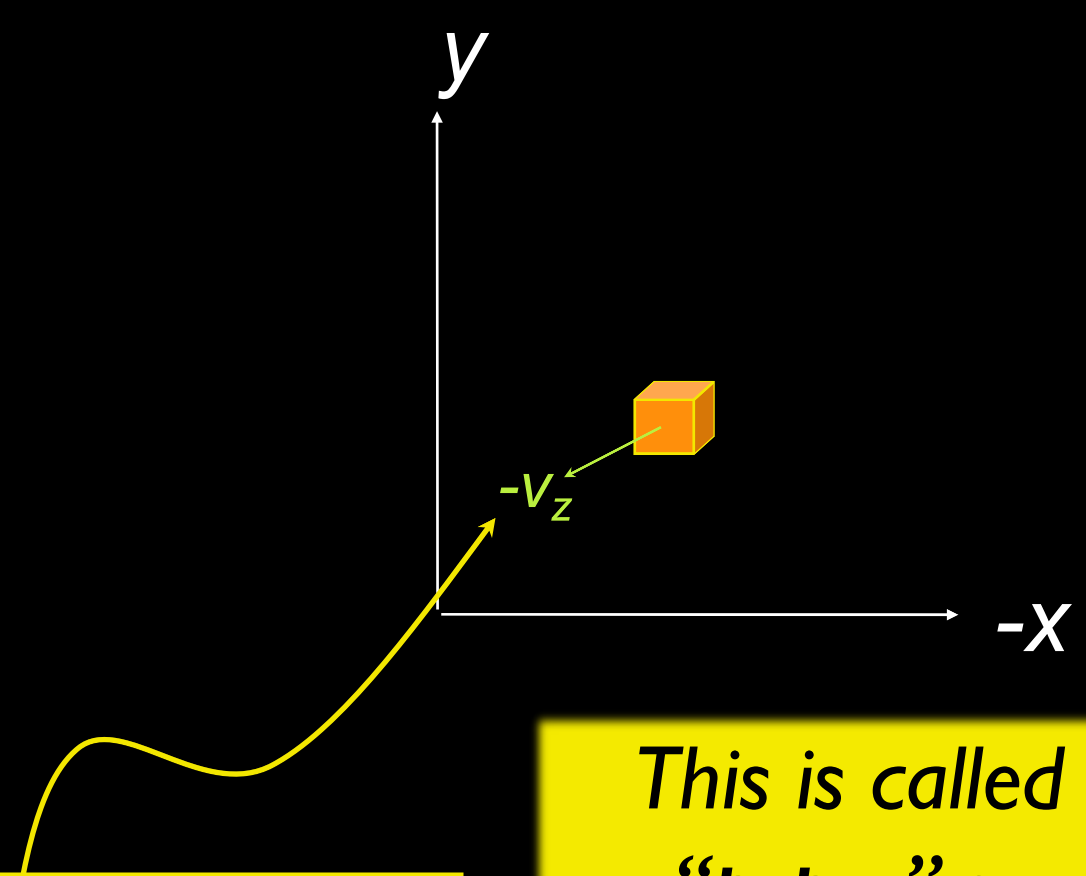


SPECTRAL-LINE MAPPING

We <u>wish</u> we could measure…



But we <u>can</u> measure…

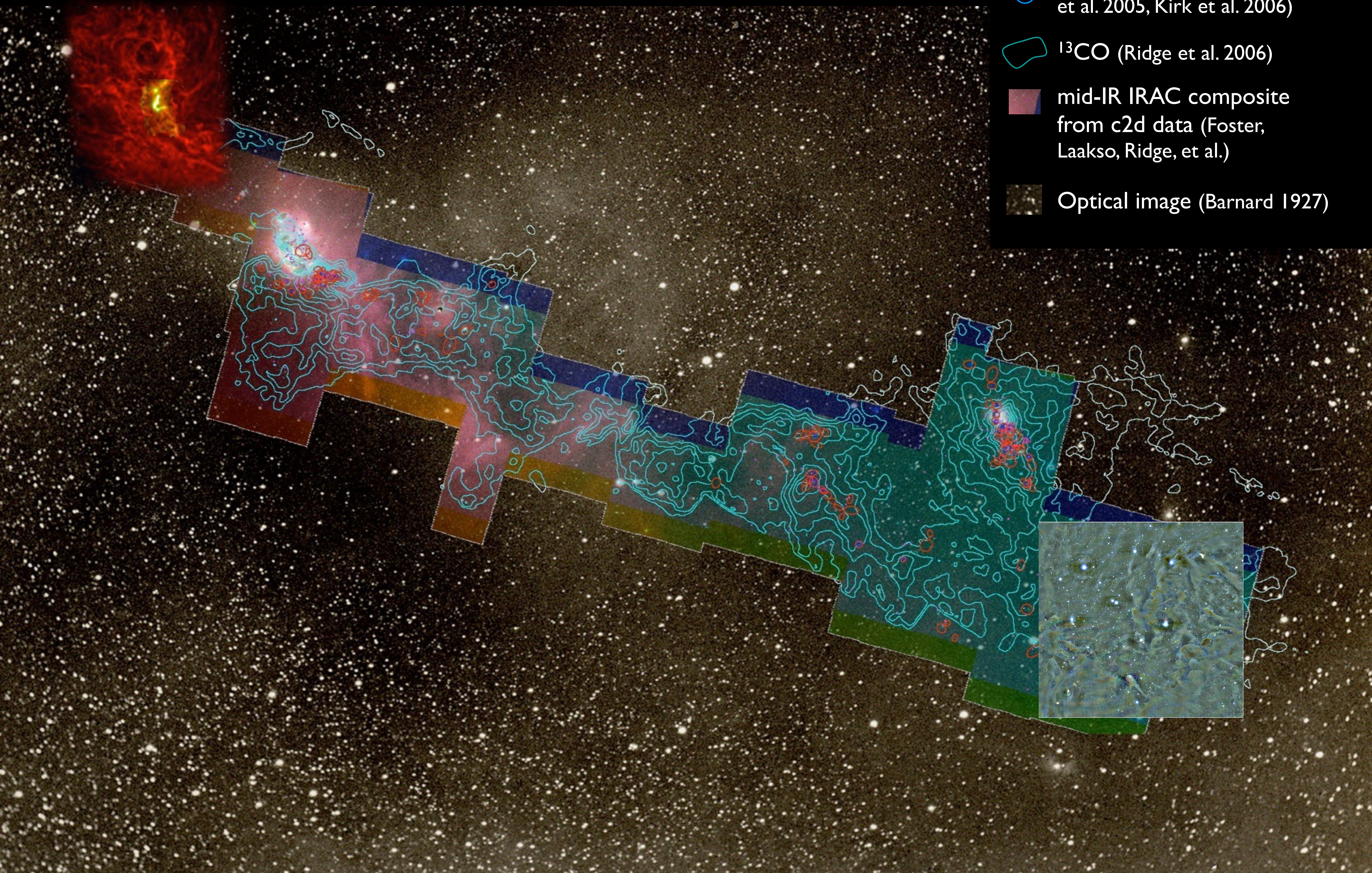


v_z *only* from "spectral-line maps"

This is called "p-p-v" or "position-position-velocity" space.

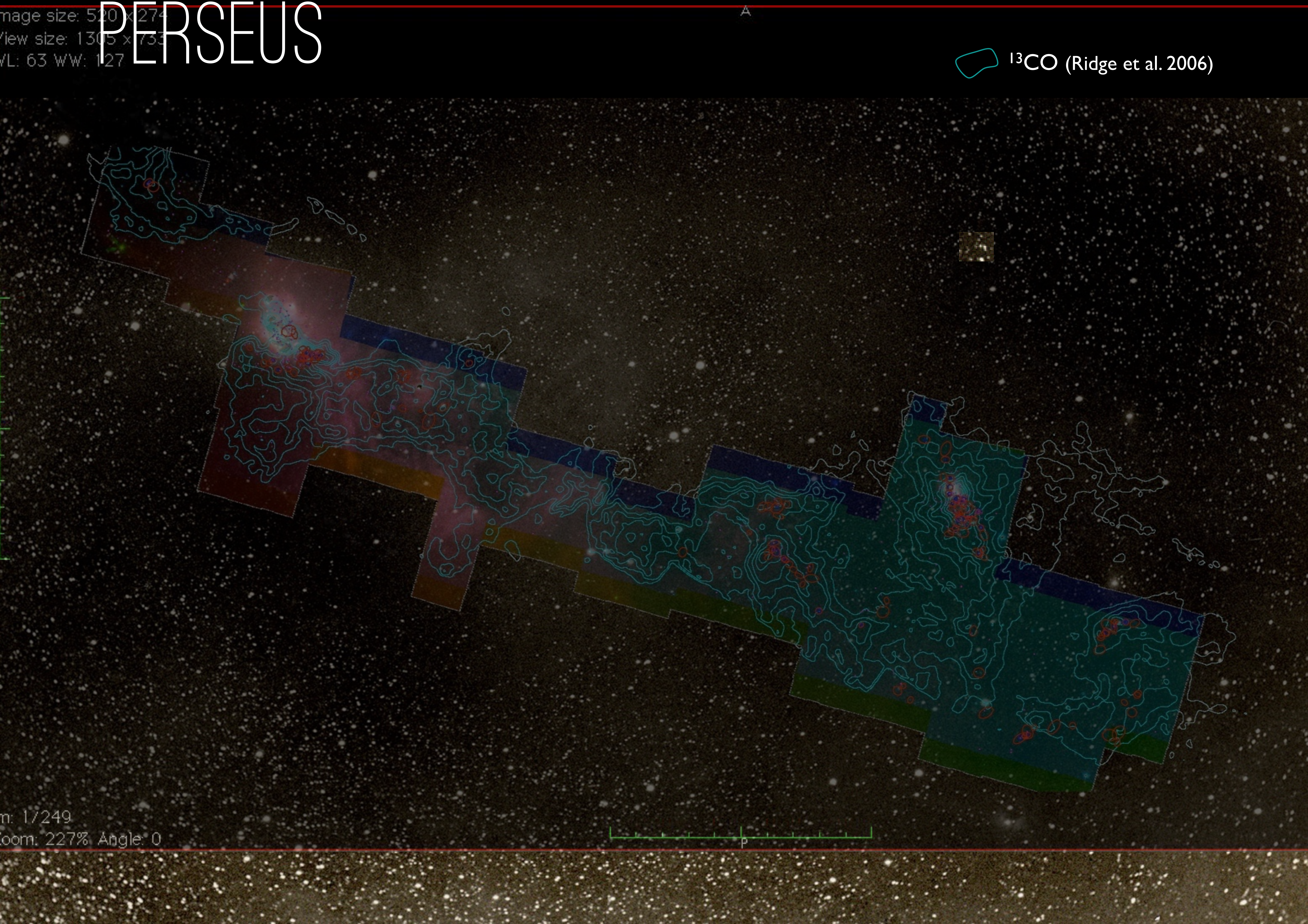
PERSEUS

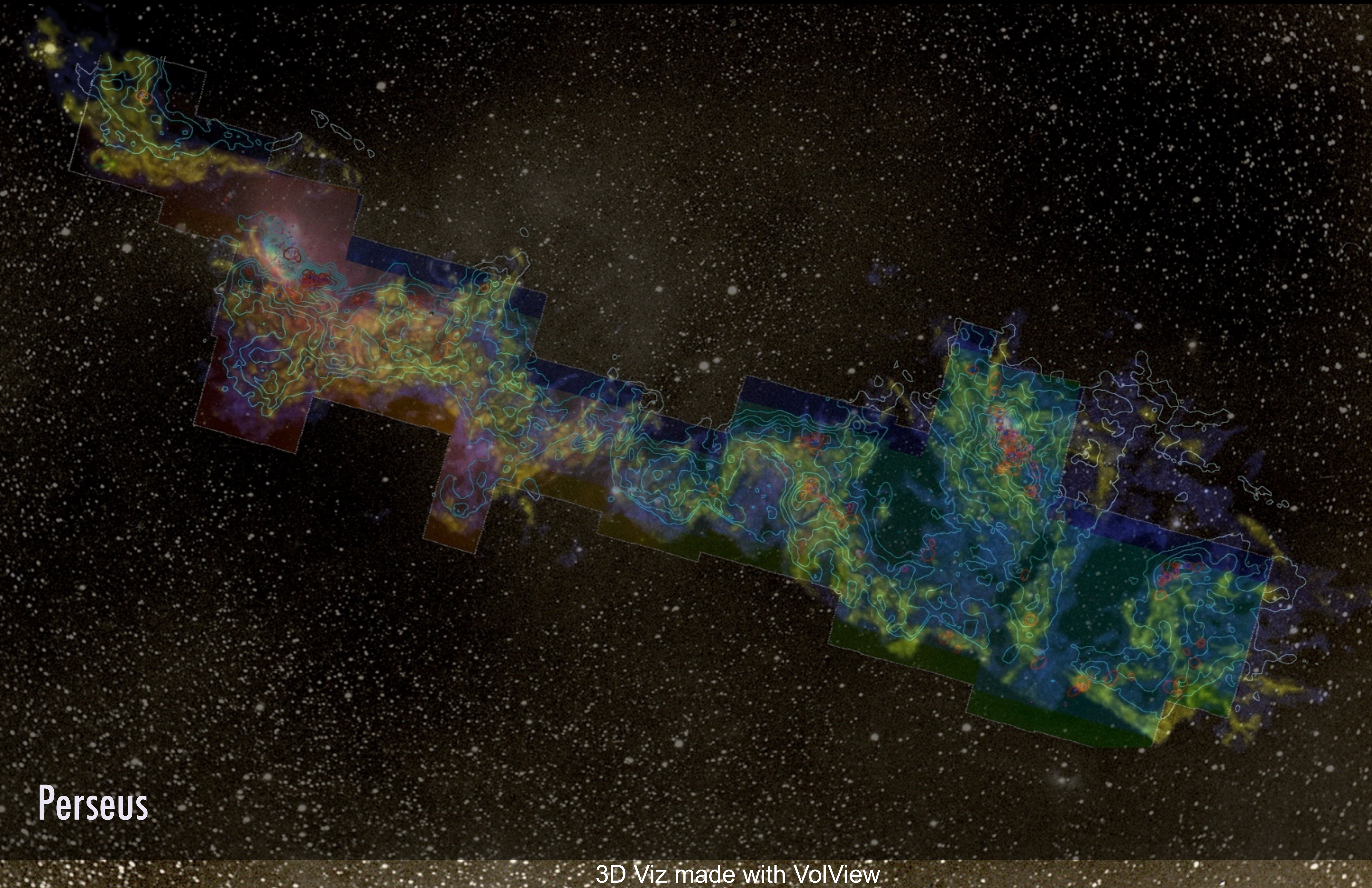
COMPLETE



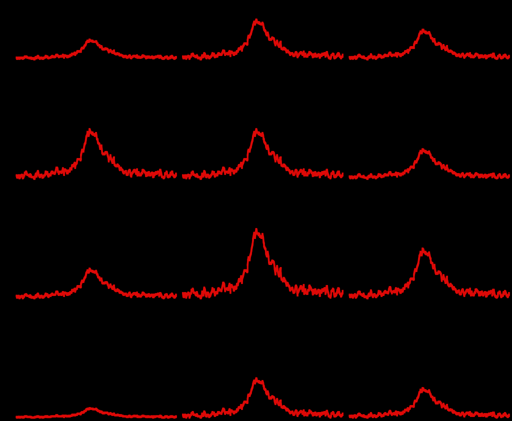
- mm peak (Enoch et al. 2006)
- sub-mm peak (Hatchell et al. 2005, Kirk et al. 2006)
- ^{13}CO (Ridge et al. 2006)
- mid-IR IRAC composite from c2d data (Foster, Laakso, Ridge, et al.)
- Optical image (Barnard 1927)

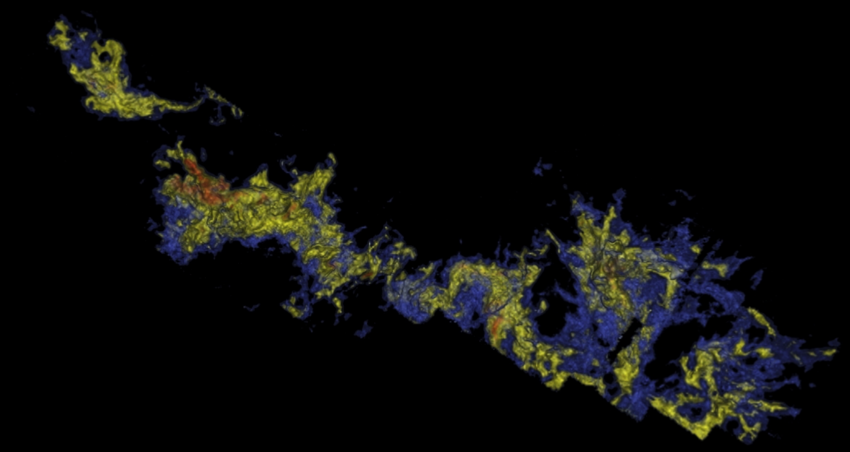
PERSEUS




Perseus
3D Viz made with VolView

CAN WE SEE IN 3D?





BUT...CHEMISTRY, PROJECTION, OPACITY (SEE BEAUMONT ET AL. 2013)

Projection

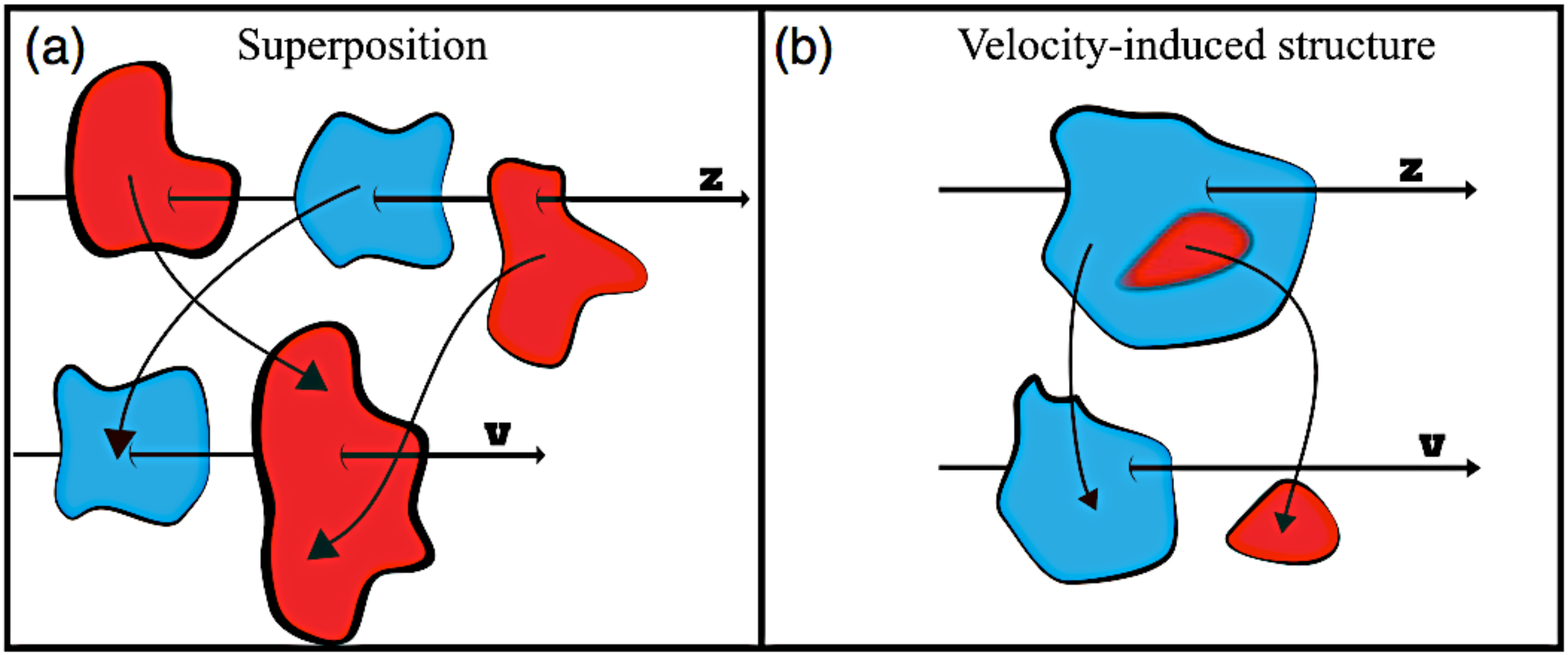


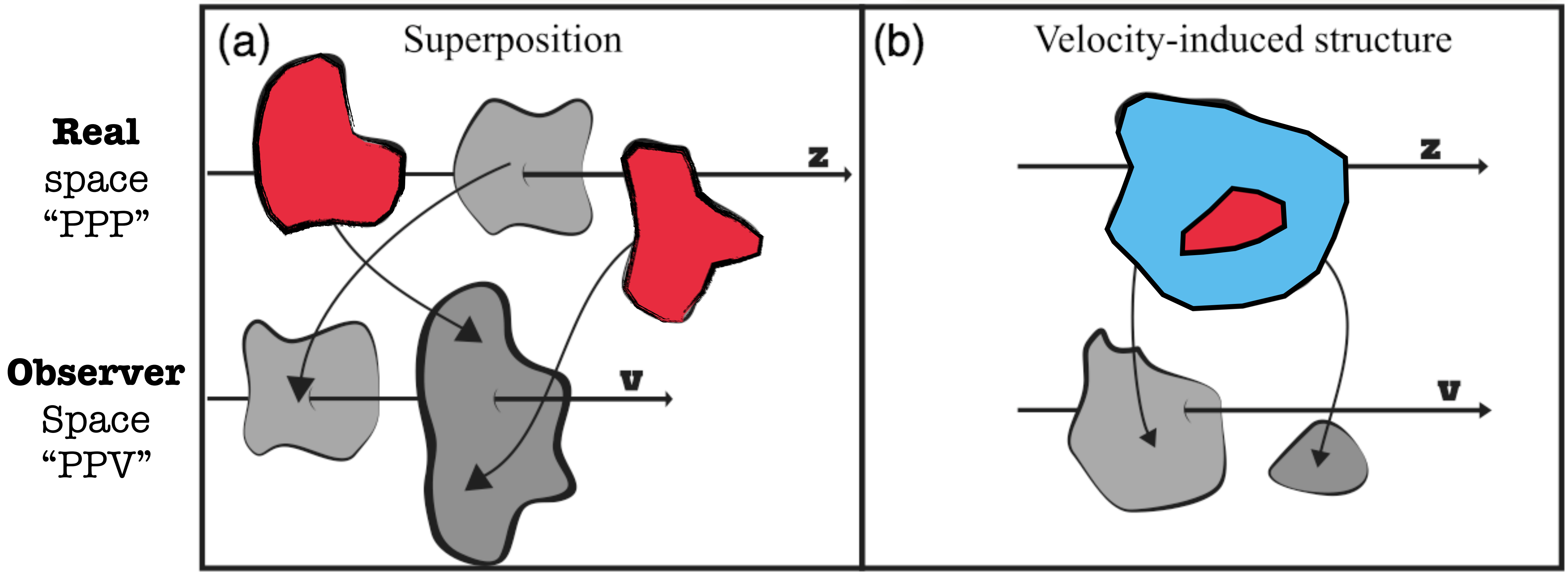
Figure 1. Schematic representation of superposition and velocity-induced structures. Colors indicate velocity. Left: three PPP structures (top) merge into 2 PPV structures (bottom), due to the similar velocity of the front and back structures. Right: a single density structure with internal velocity gradients (top) splits into two PPV structures (bottom).

Beaumont et al. 2013

“PPP” to “PPV”

“Destruction” of Real Structures

“Creation” of Unreal Structures



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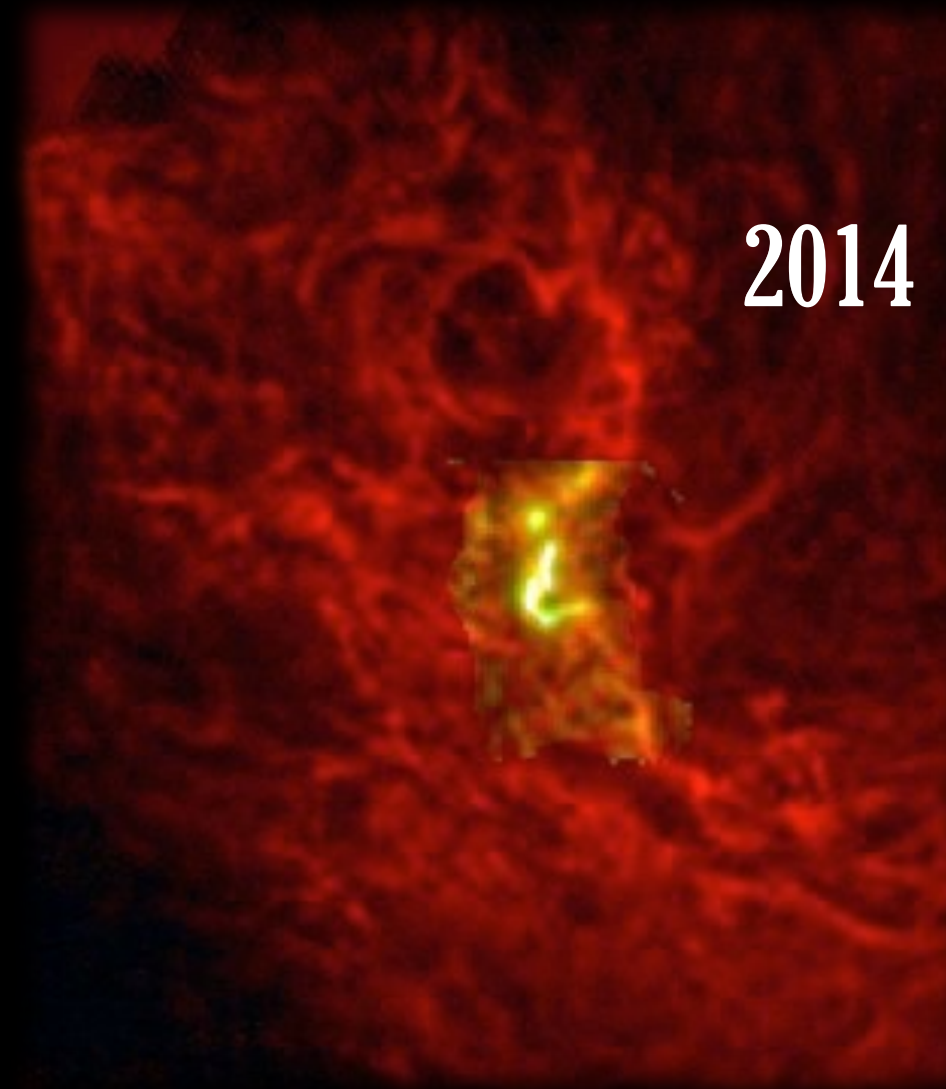
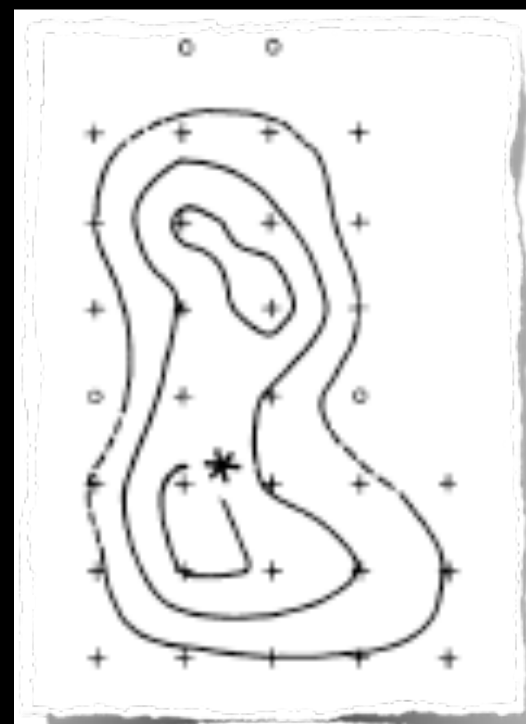
Beaumont et al. 2013

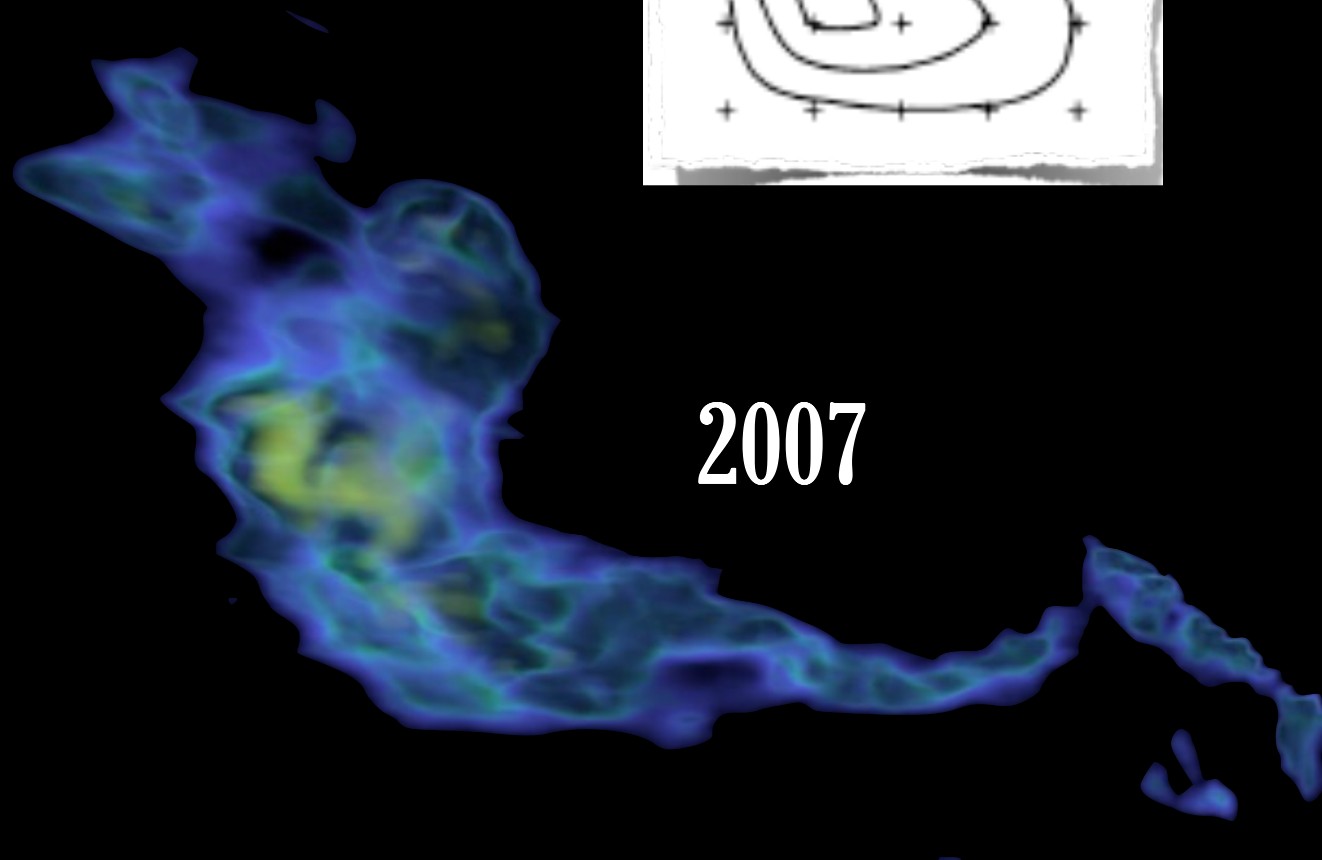
OK–SO WHY THEN DO I CARE SO MUCH ABOUT B5?

2014



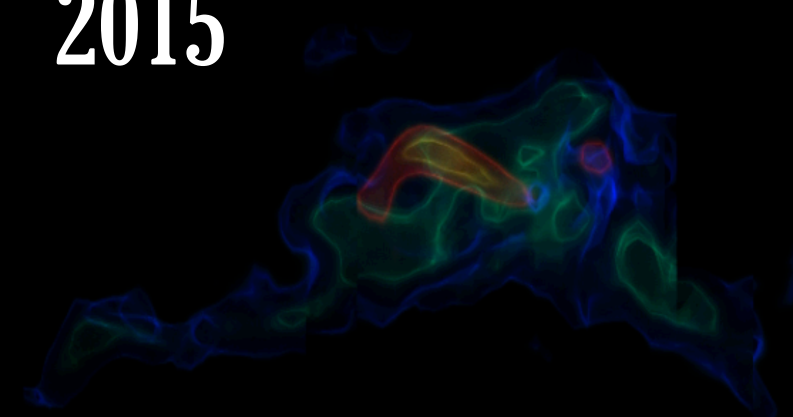
1989



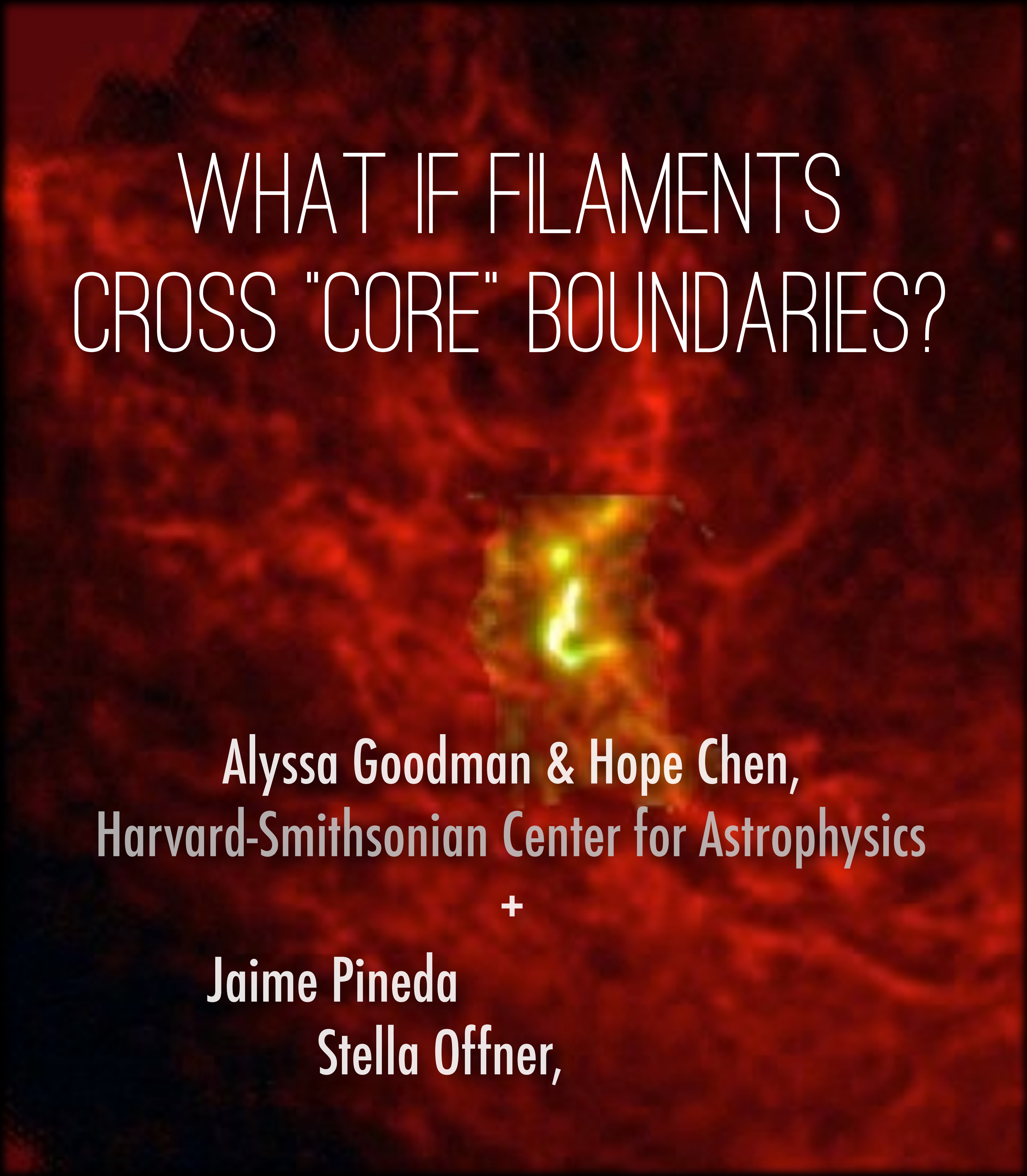


2007

2015



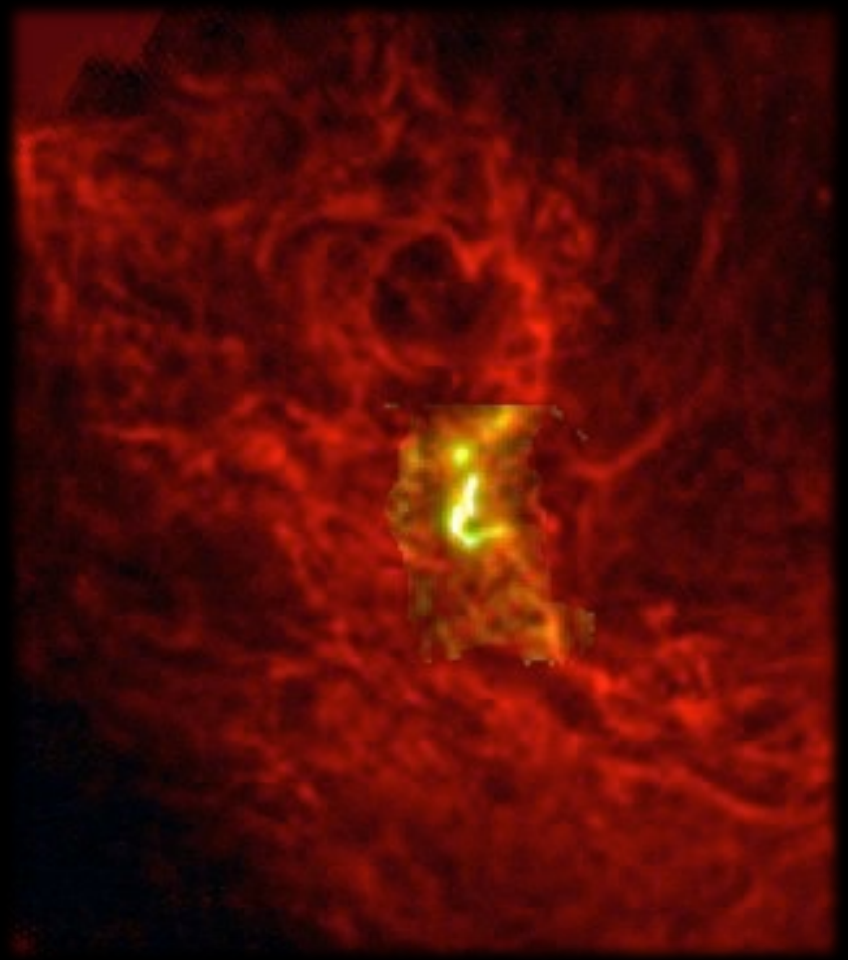
representative images, not to scale



WHAT IF FILAMENTS CROSS "CORE" BOUNDARIES?

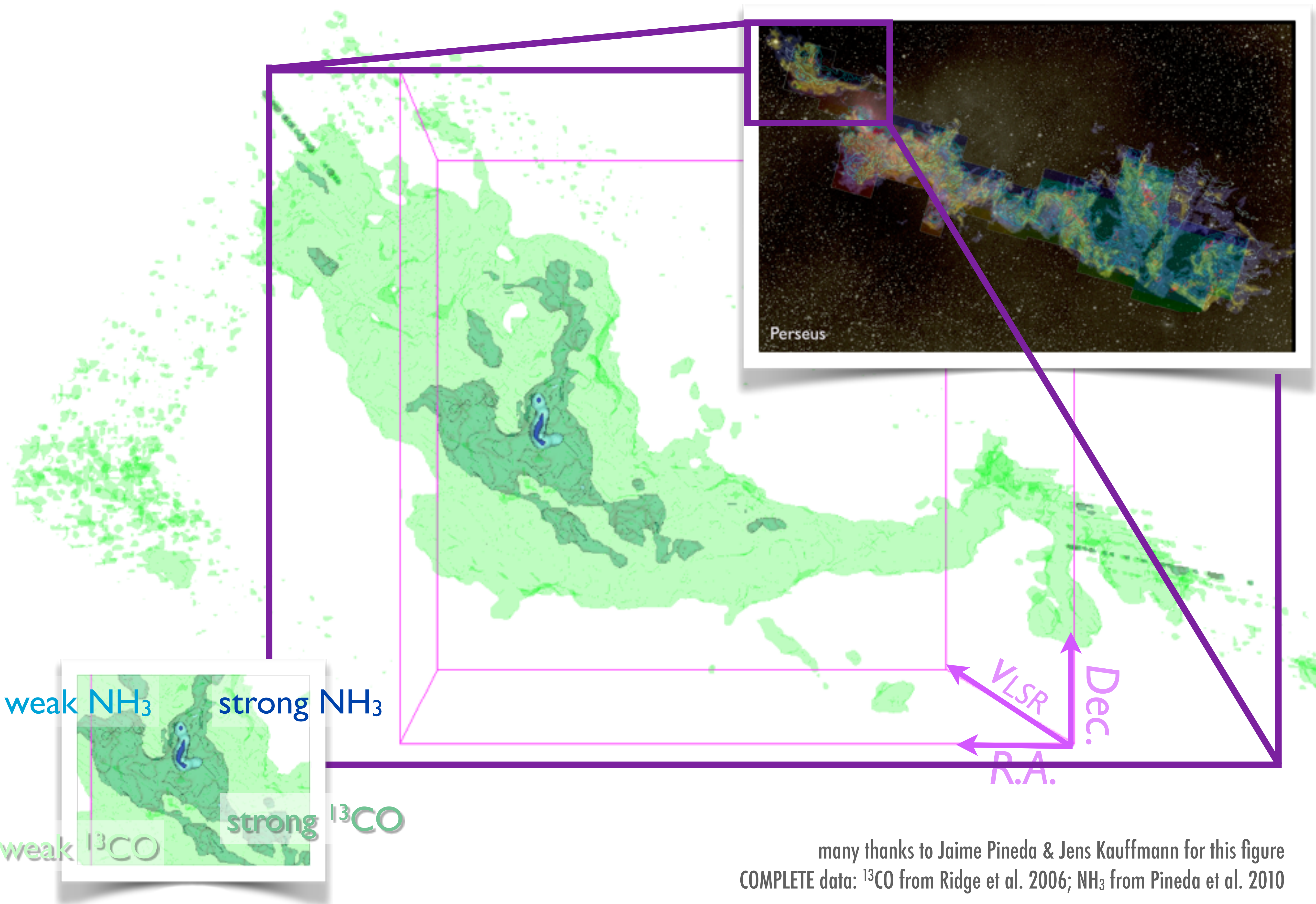
Alyssa Goodman & Hope Chen,
Harvard-Smithsonian Center for Astrophysics
+
Jaime Pineda
Stella Offner,

COHERENT CORES
ISLANDS OF CALM IN TURBULENT SEAS(?)



30-year story: Myers & Benson 1983, Goodman et al. 1998, Pineda et al. 2010, 2011, 2014

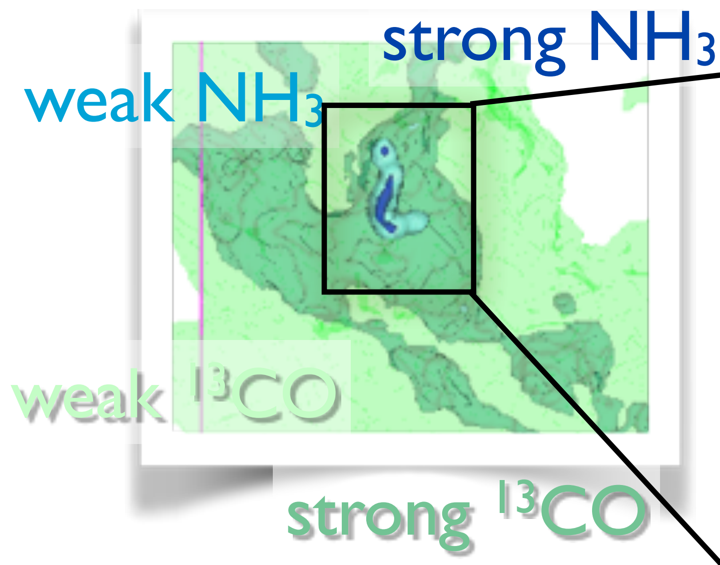
THE B5 REGION, IN PERSEUS



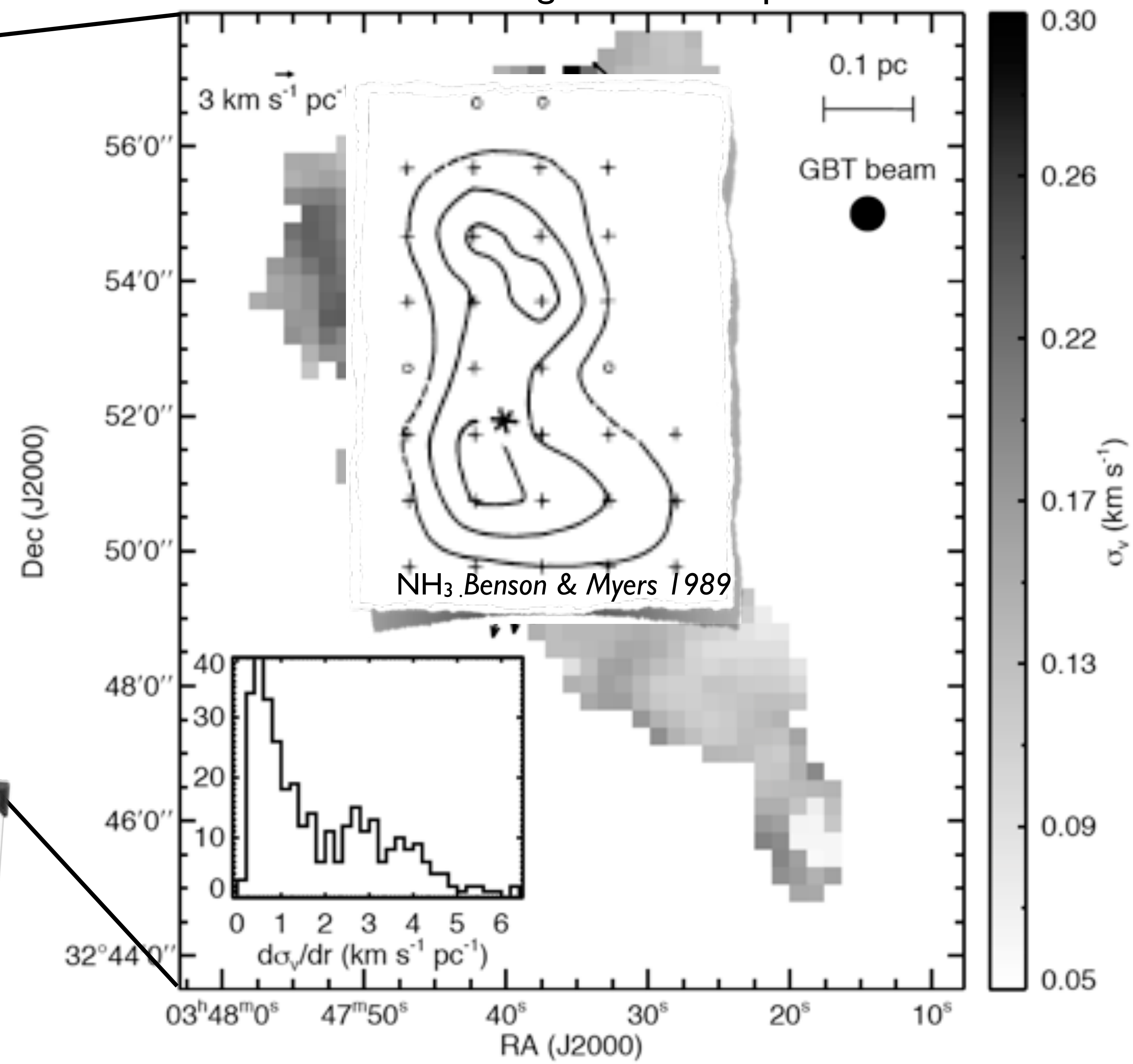
many thanks to Jaime Pineda & Jens Kauffmann for this figure

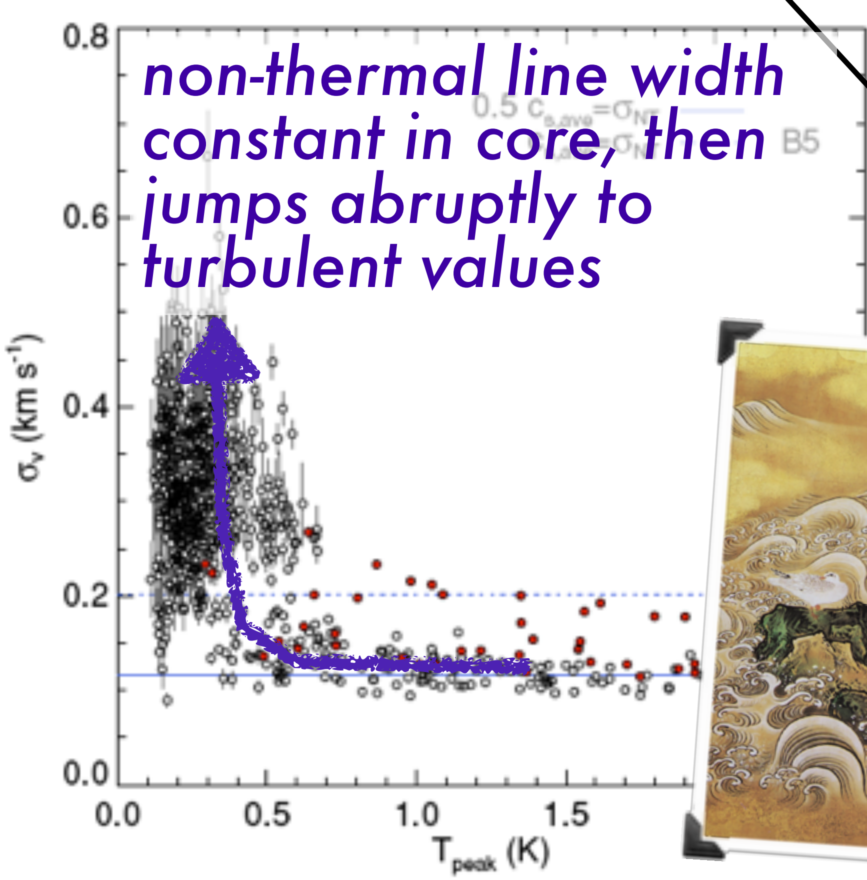
COMPLETE data: ^{13}CO from Ridge et al. 2006; NH_3 from Pineda et al. 2010

STRONG EVIDENCE FOR "VELOCITY COHERENCE" IN DENSE CORES



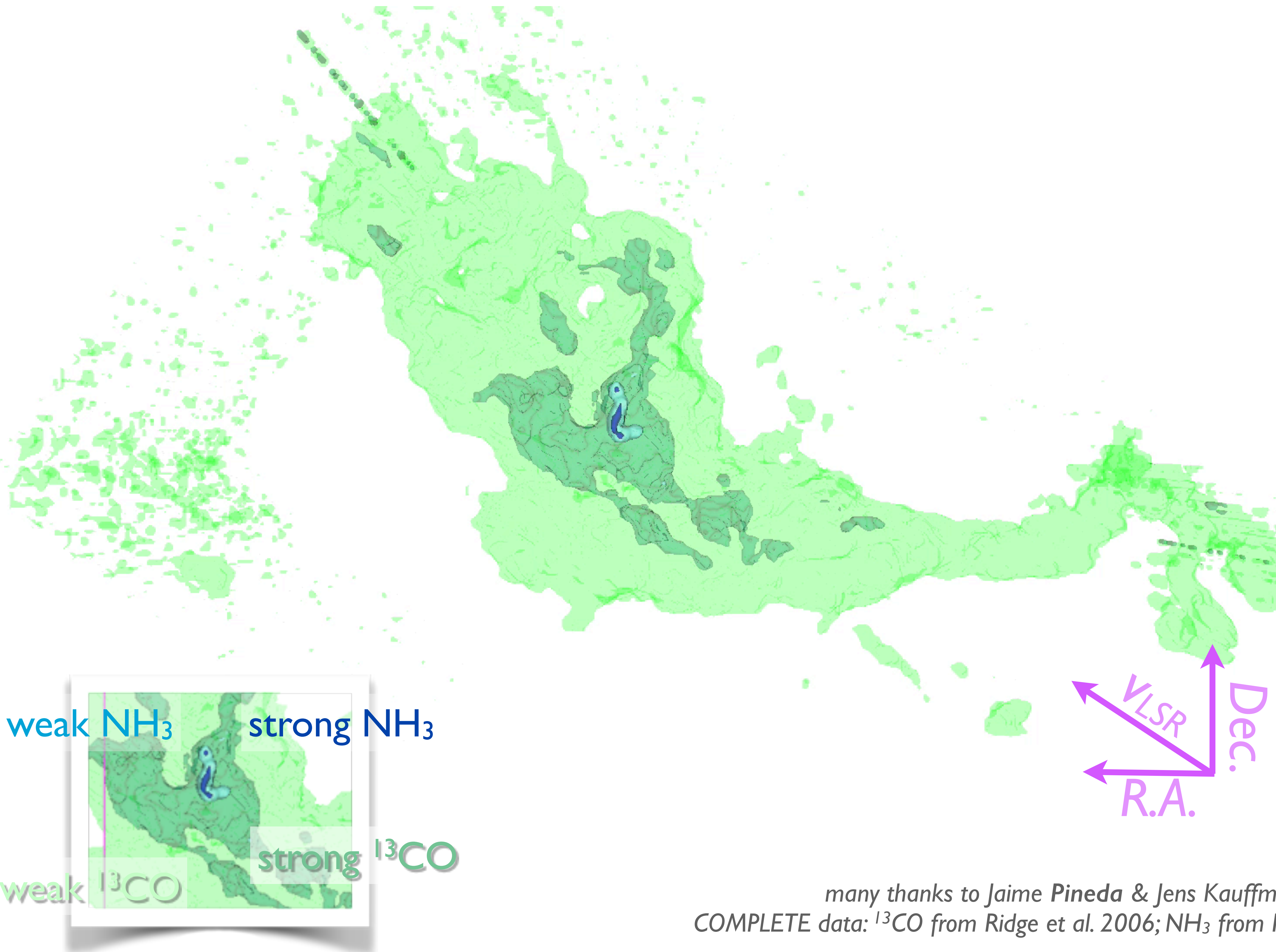
greyscale shows NH_3 velocity dispersion, arrows show gradient in dispersion





GBT NH_3 observations of the B5 core (Pineda et al. 2010)

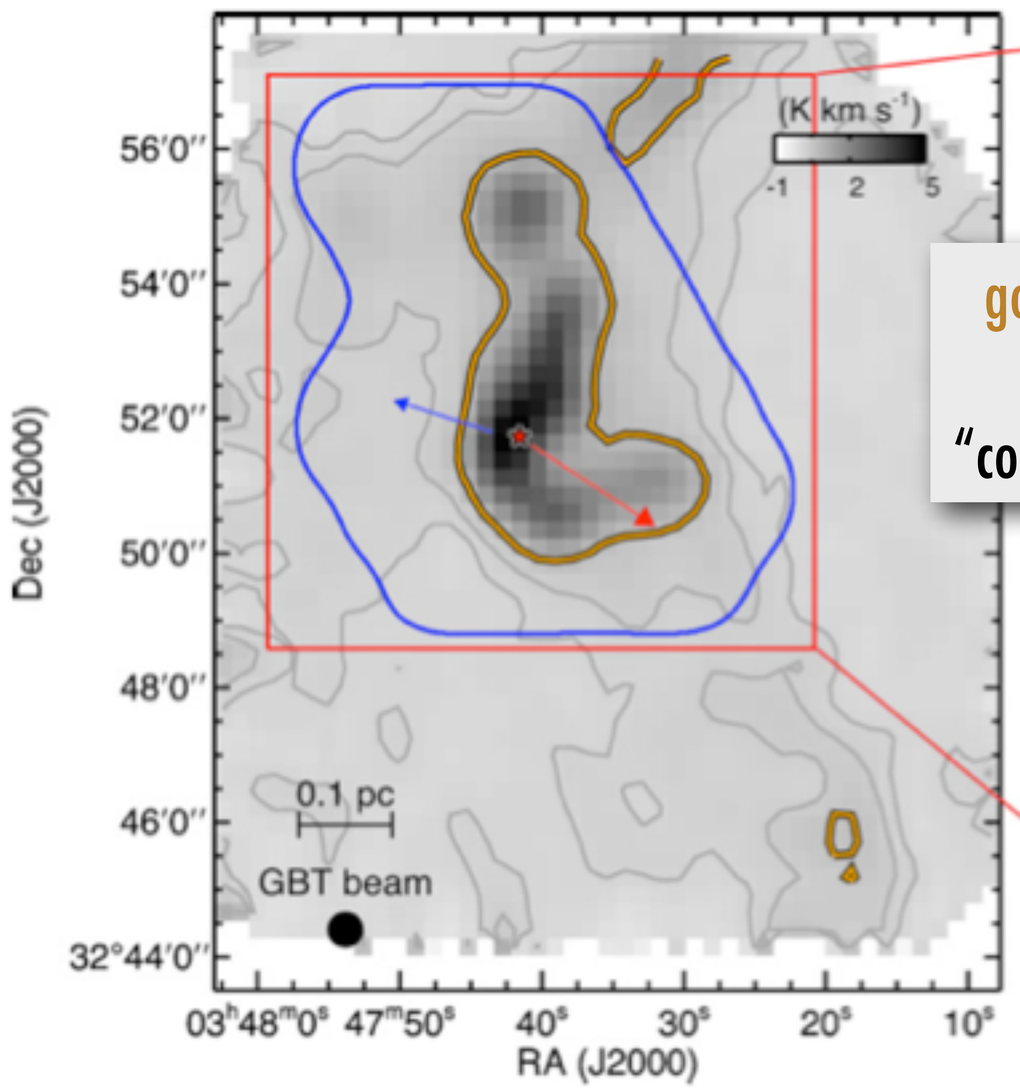
POSITION-VELOCITY STRUCTURE OF THE B5 REGION IN PERSEUS



*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. 2010

BUT THEN... VLA (JAIME) FOUND SUB-STRUCTURE

THE ASTROPHYSICAL JOURNAL LETTERS, 739:L2 (5pp), 2011 September 20 — PINEDA ET AL.

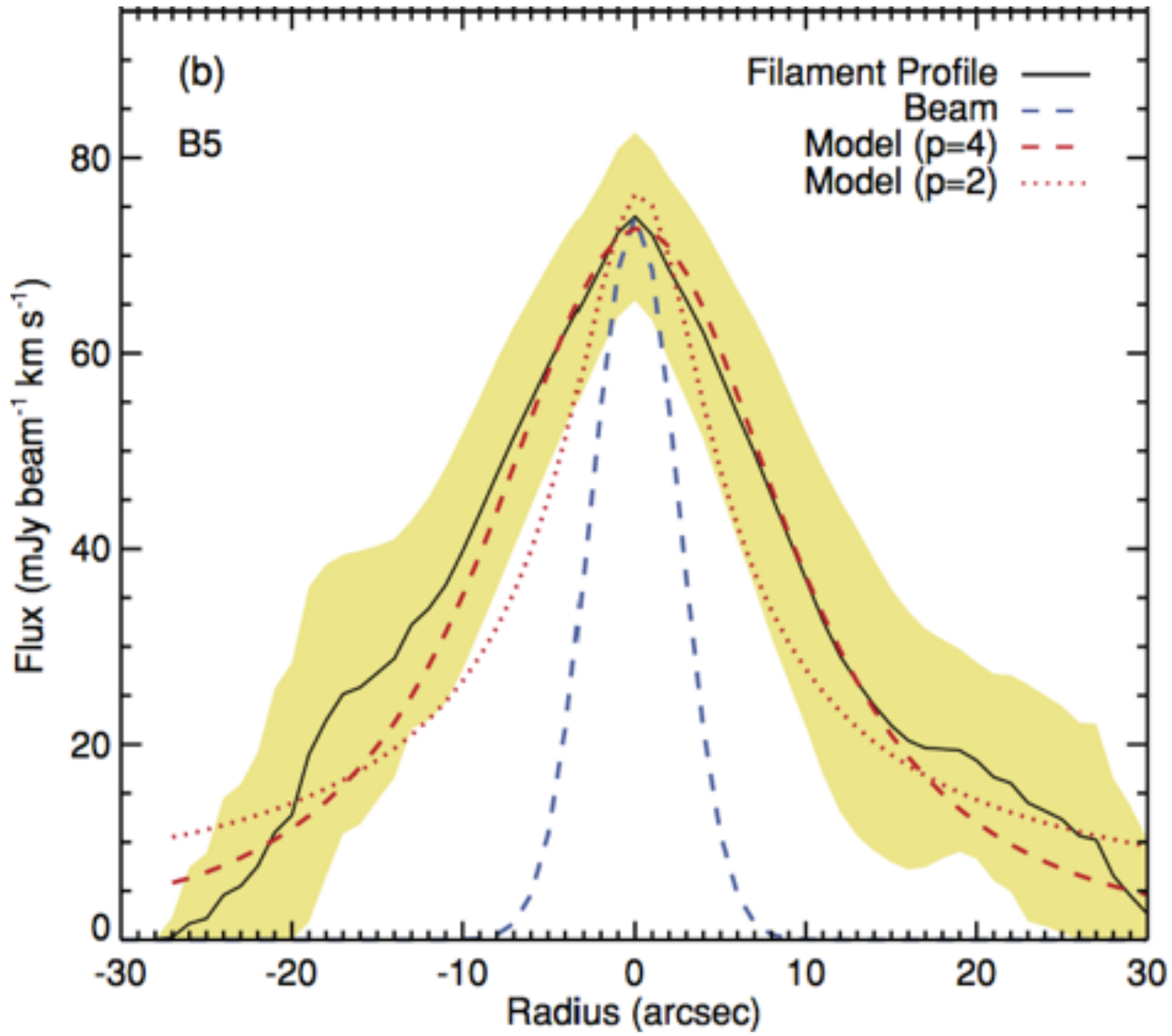


gold contour shows "coherent" core

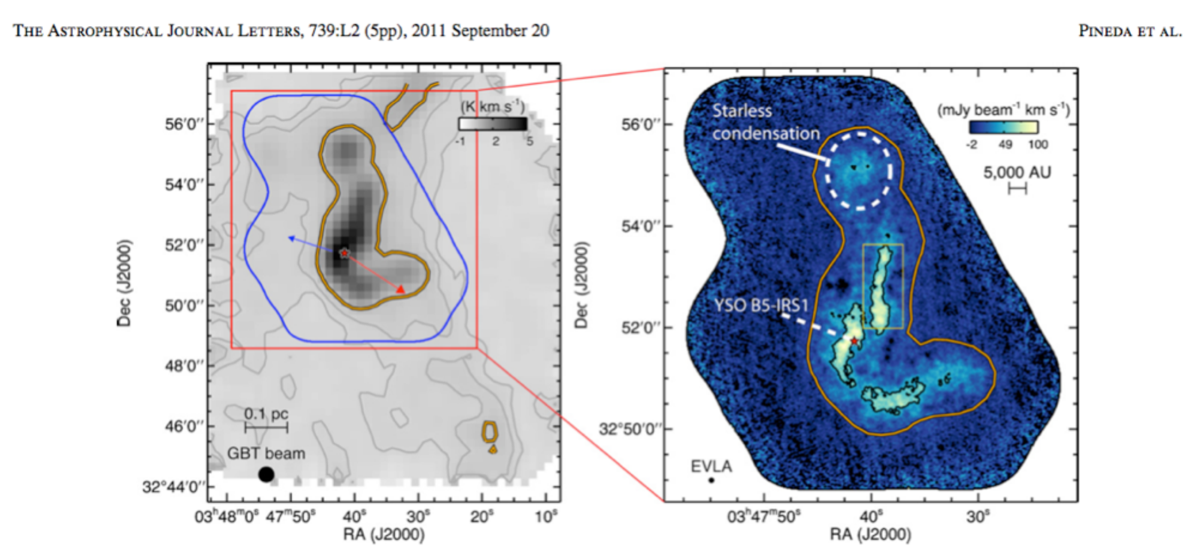
Figure 1. Left panel: integrated intensity map of B5 in NH_3 (1,1) obtained with GBT. Gray contours show the 0.15 and 0.3 K km s^{-1} level in NH_3 (1,1) integrated intensity. The orange contours show the region in the GBT data where the non-thermal velocity dispersion is subsonic. The young star, B5–IRS1, is shown by the star in both panels. The outflow direction is shown by the arrows. The blue contour shows the area observed with the EVLA and the red box shows the area shown in the right panel. Right panel: integrated intensity map of B5 in NH_3 (1,1) obtained combining the EVLA and GBT data. Black contour shows the 50 mJy beam^{-1} km s^{-1} level in NH_3 (1,1) integrated intensity. The yellow box shows the region used in Figure 4. The northern starless condensation is shown by the dashed circle.

Pineda et al. 2011

BUT MAYBE IT'S DIFFERENT?



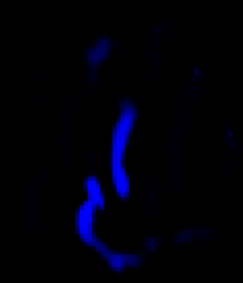
isothermal, hydrostatic filaments, not turbulent ones?



Pineda et al. 2011

BUT WHAT IF FILAMENTS CONTINUE ACROSS "CORE" BOUNDARIES?!

blue =VLA ammonia (high-density gas); green=GBT ammonia (lower-res high-density gas); red=Herschel 250 micron continuum (dust)

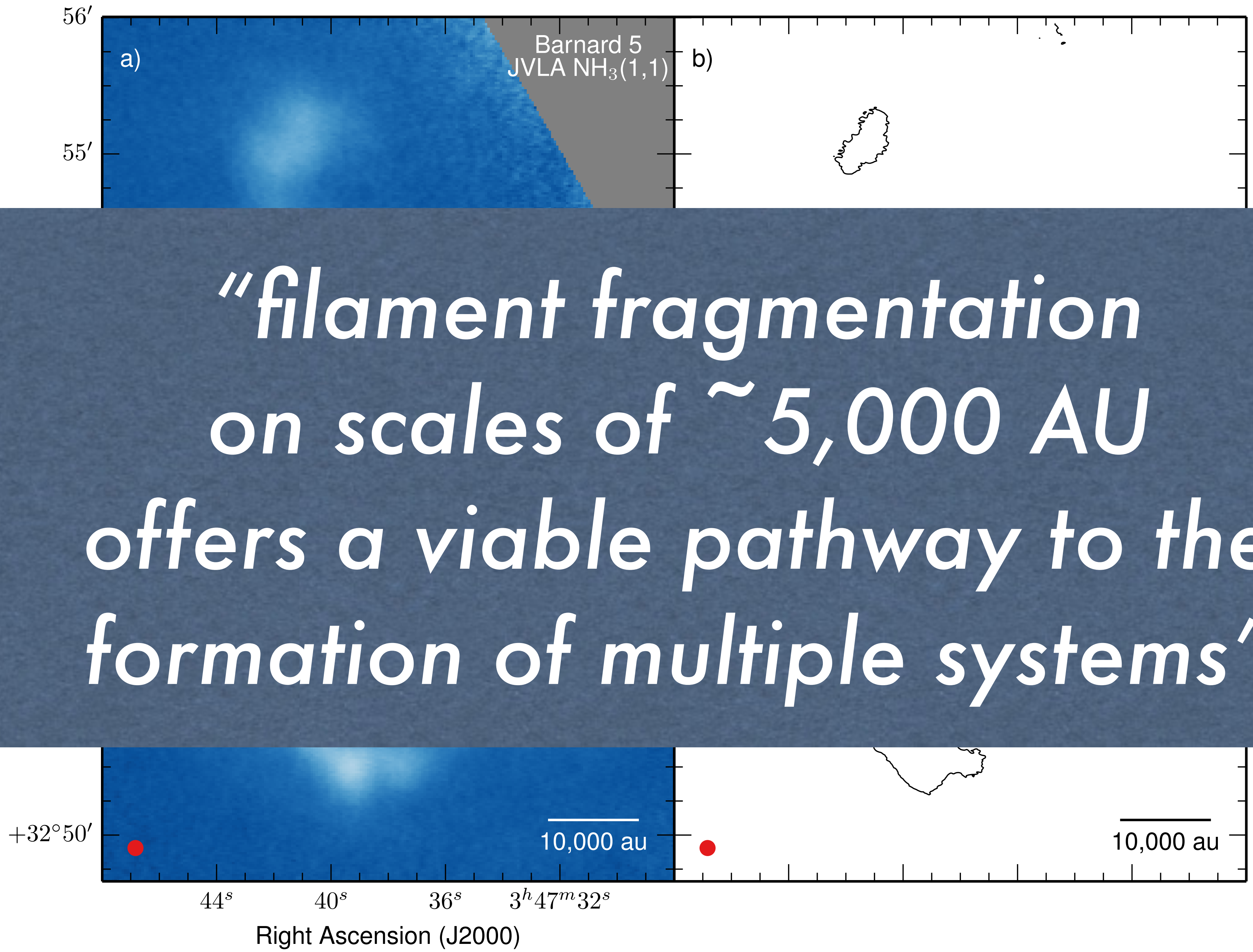


Goodman, Chen, Offner & Pineda 2014 in prep.

Herschel data from Gould Belt Survey

FILAMENT FRAGMENTATION → STAR FORMATION?

WE NOW ALSO KNOW THAT B5 IS FORMING A BOUND CLUSTER



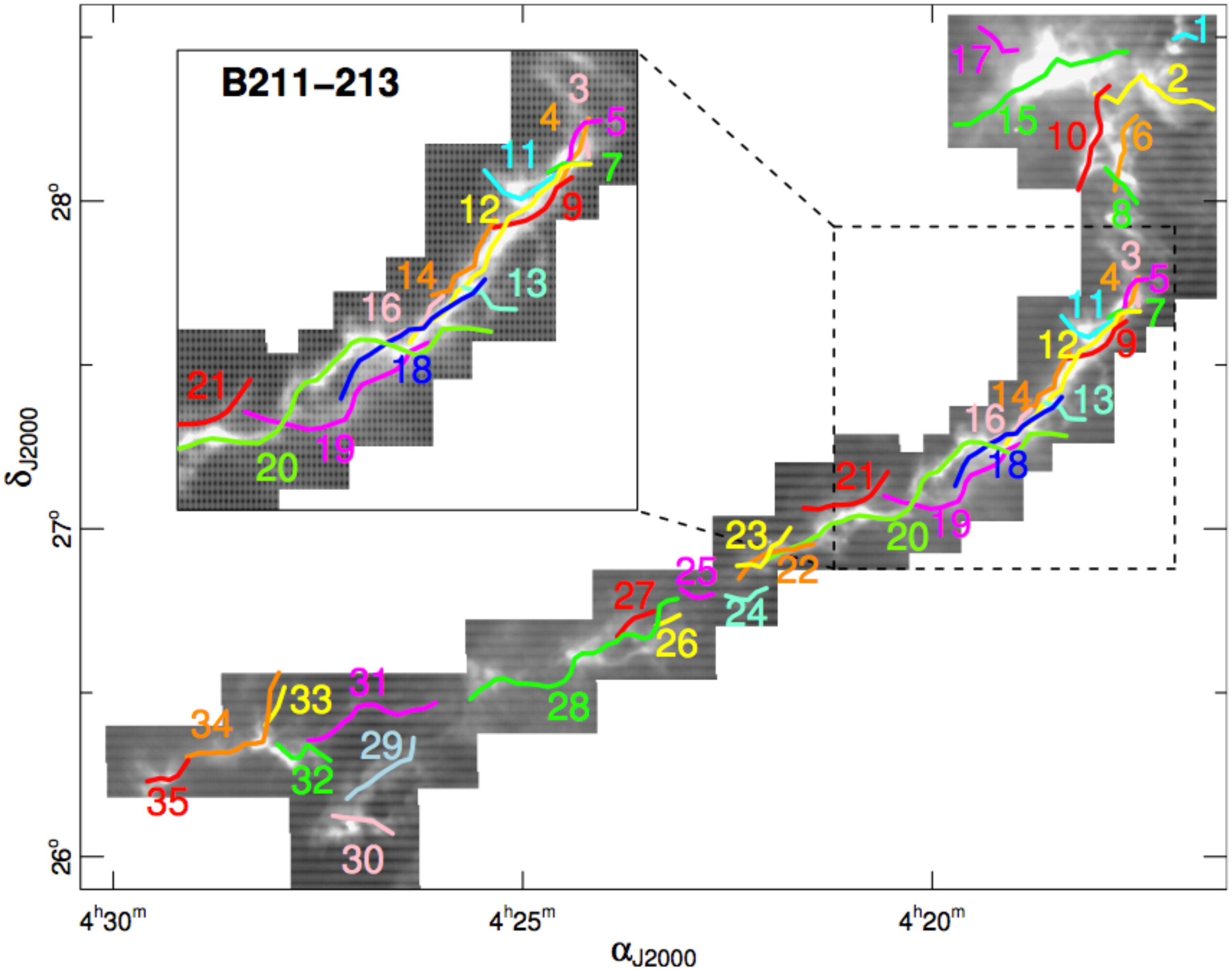
"filament fragmentation on scales of ~5,000 AU offers a viable pathway to the formation of multiple systems"

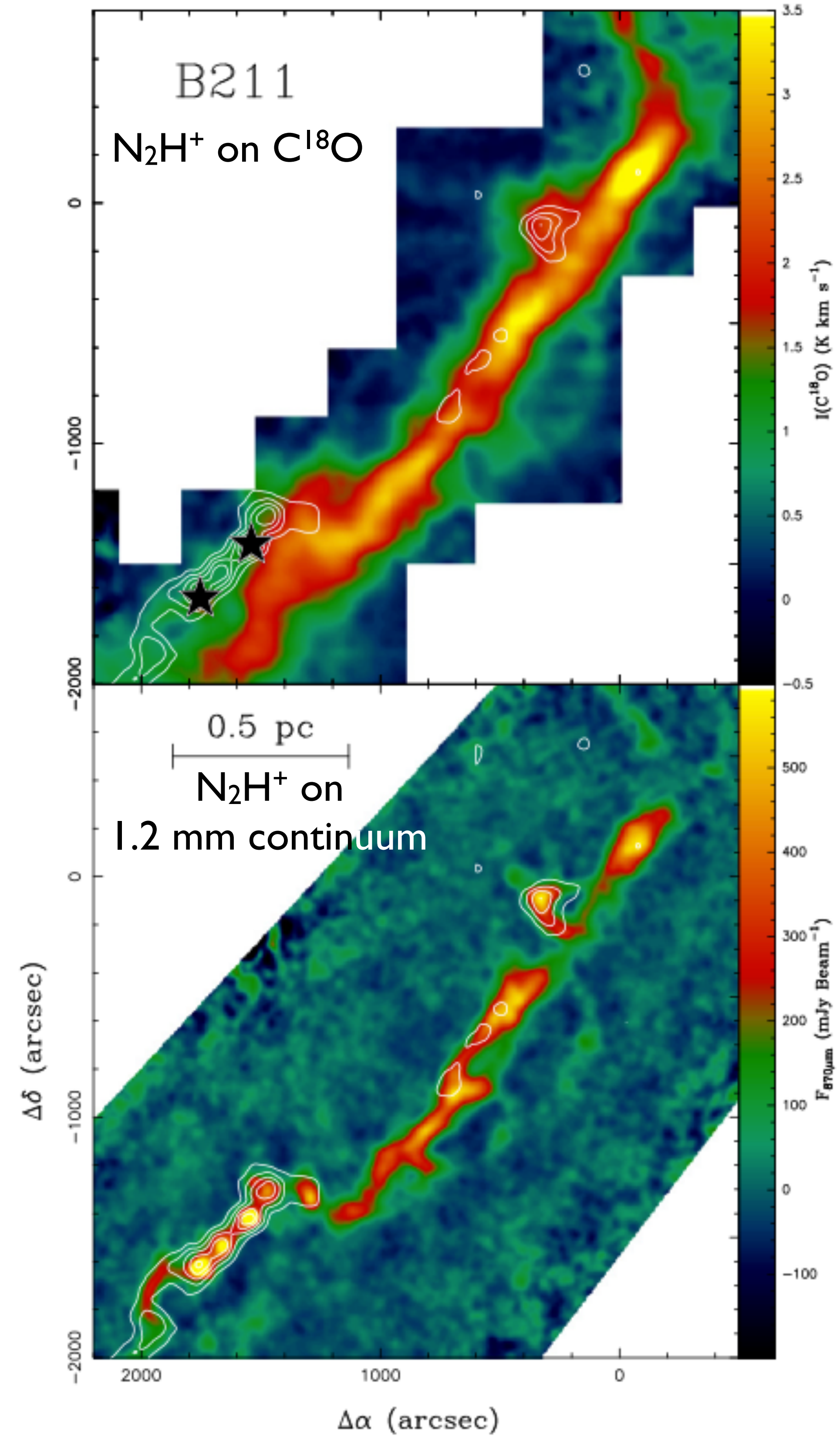
Pineda, Offner, Parker, Arce, Goodman, Caselli, Fuller, Bourke & Corder 2015 (Nature)

Filaments offer pre-existing density enhancement.

Collapse is rapid enough that aboriginal filament is not erased, even within a “coherent core.”

In B5, small bound cluster will form c. 40K years from now.





Now, we (all!) need to try FIVe, from Hacar et al. 2013, to study "coherent" core-filament relation.

Filaments offer pre-existing density enhancement.

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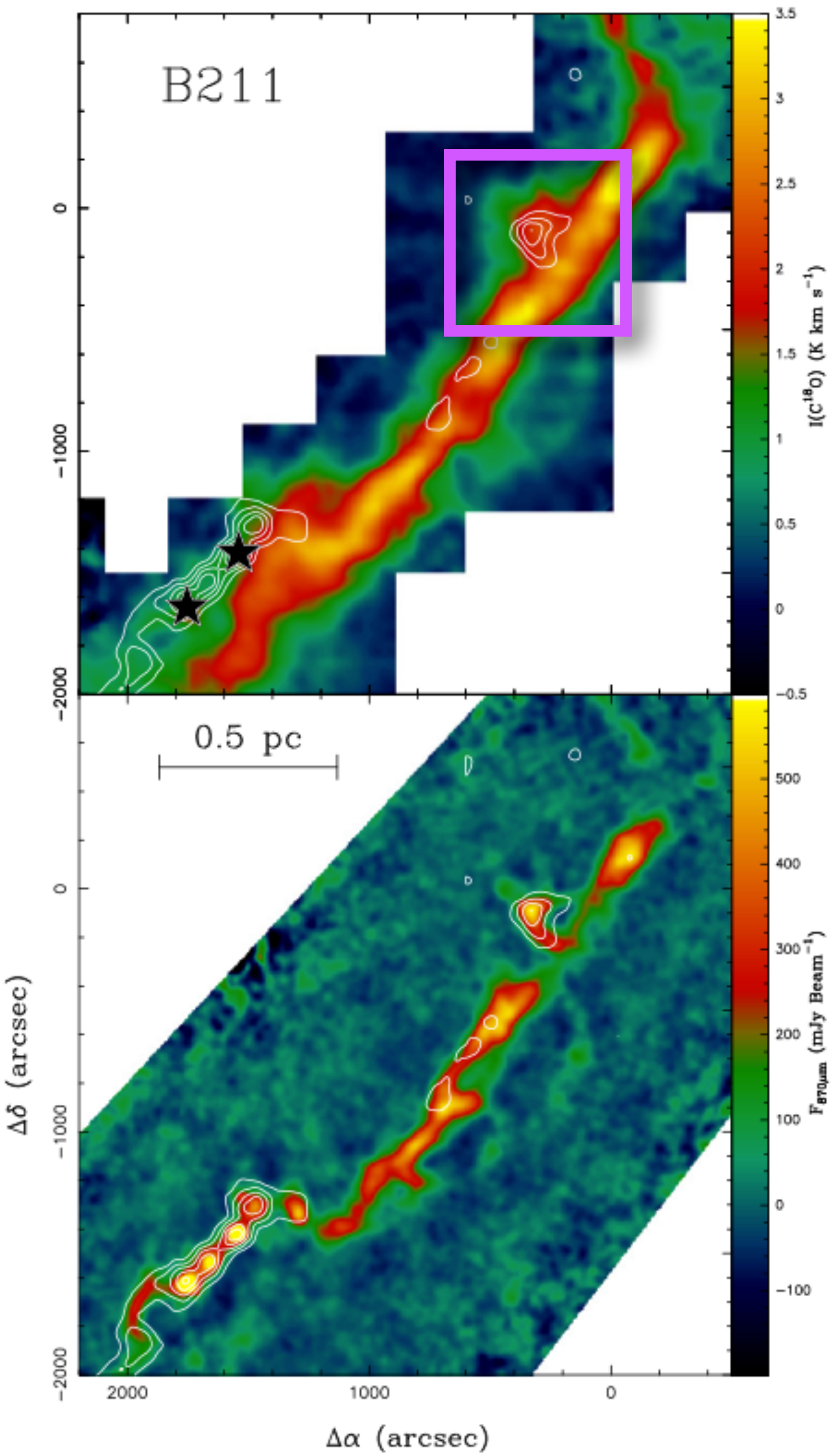
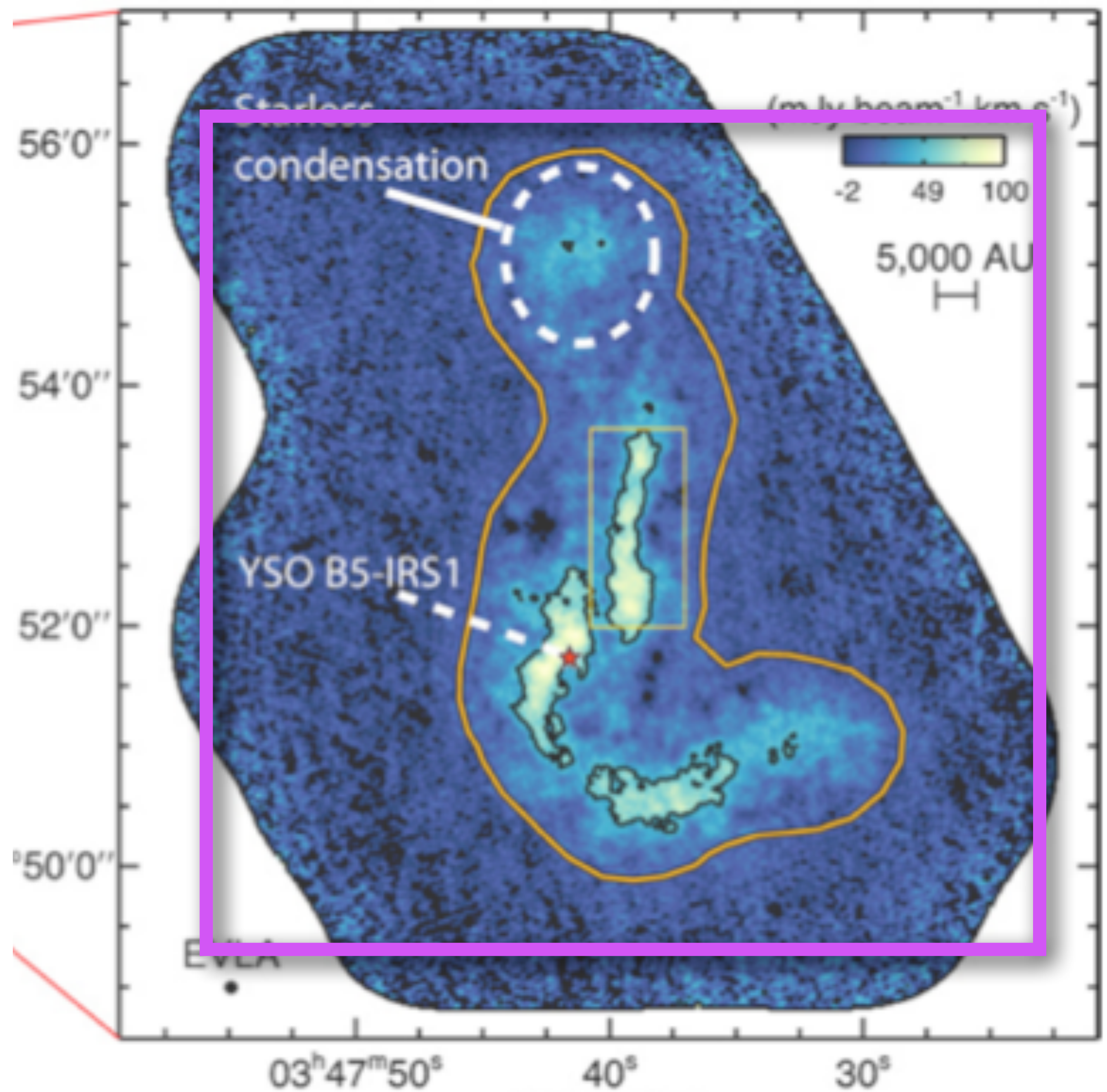
In B5, small bound cluster will form c. 40K years from now.

COMPARING SCALES

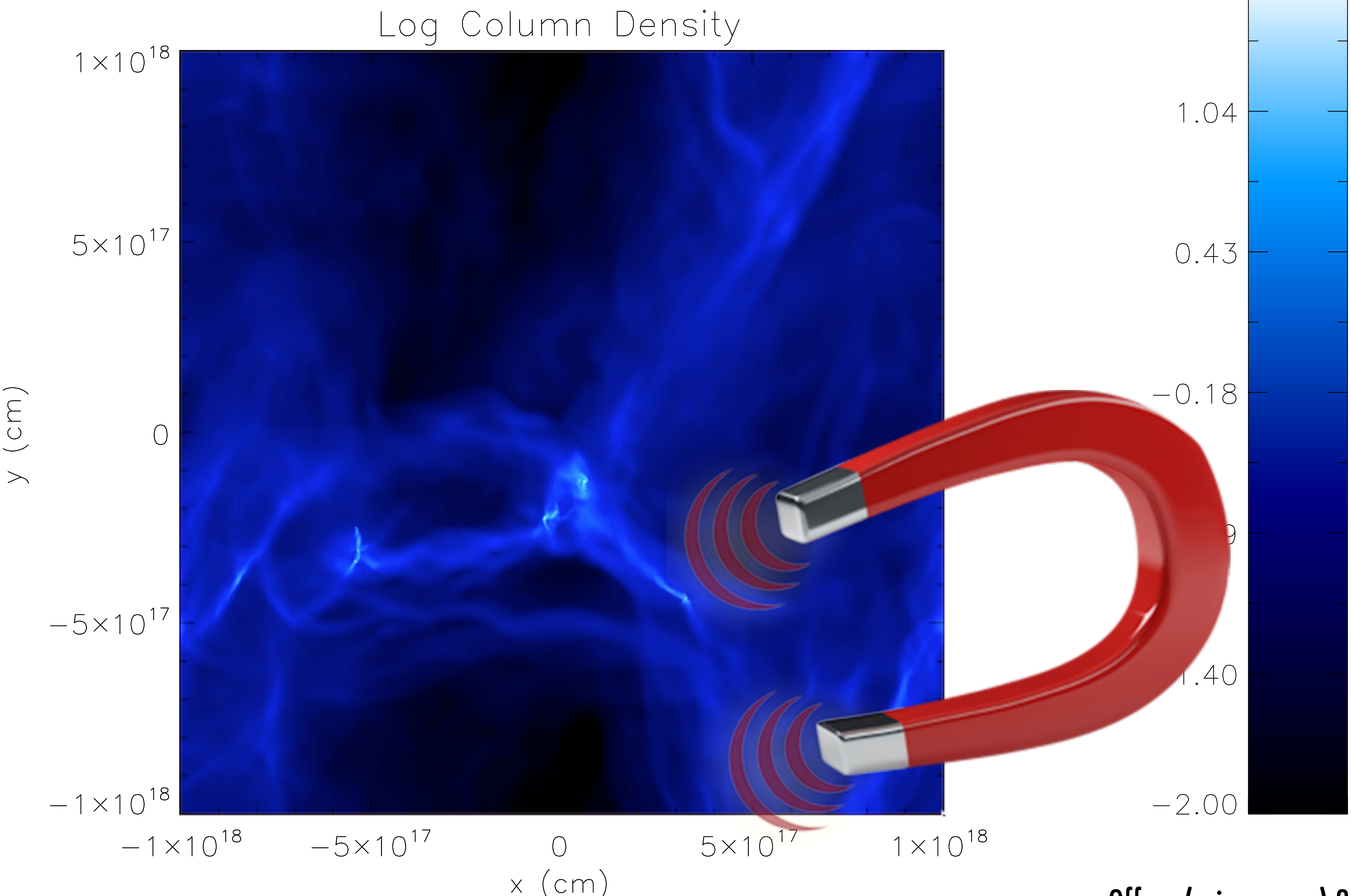


Taurus (Hacar et al.)



B5 (Pineda et al.)

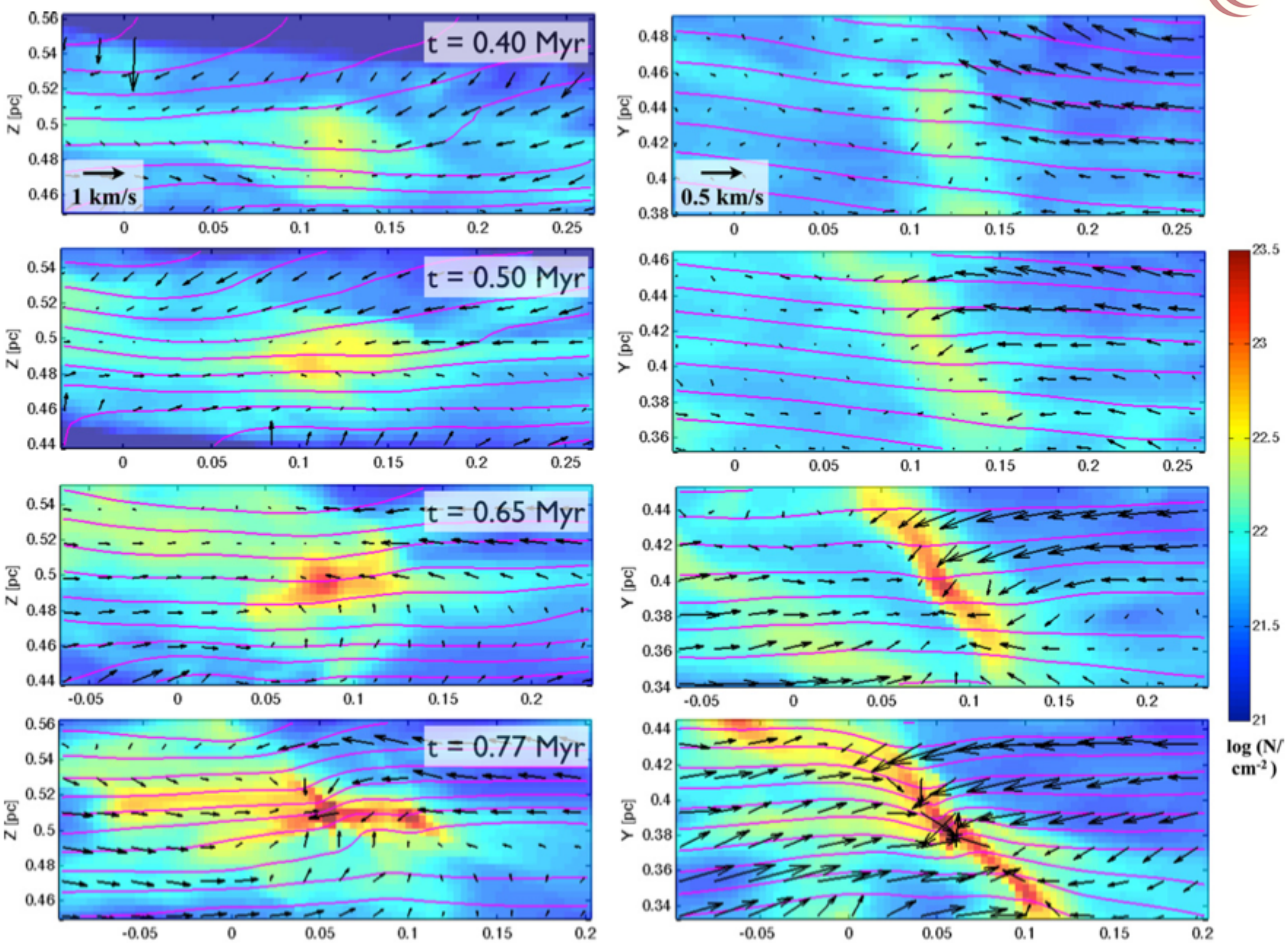
B5-ISH SIMULATION (NO MAGNETIC FIELD)



Offner (priv. comm.) 2014

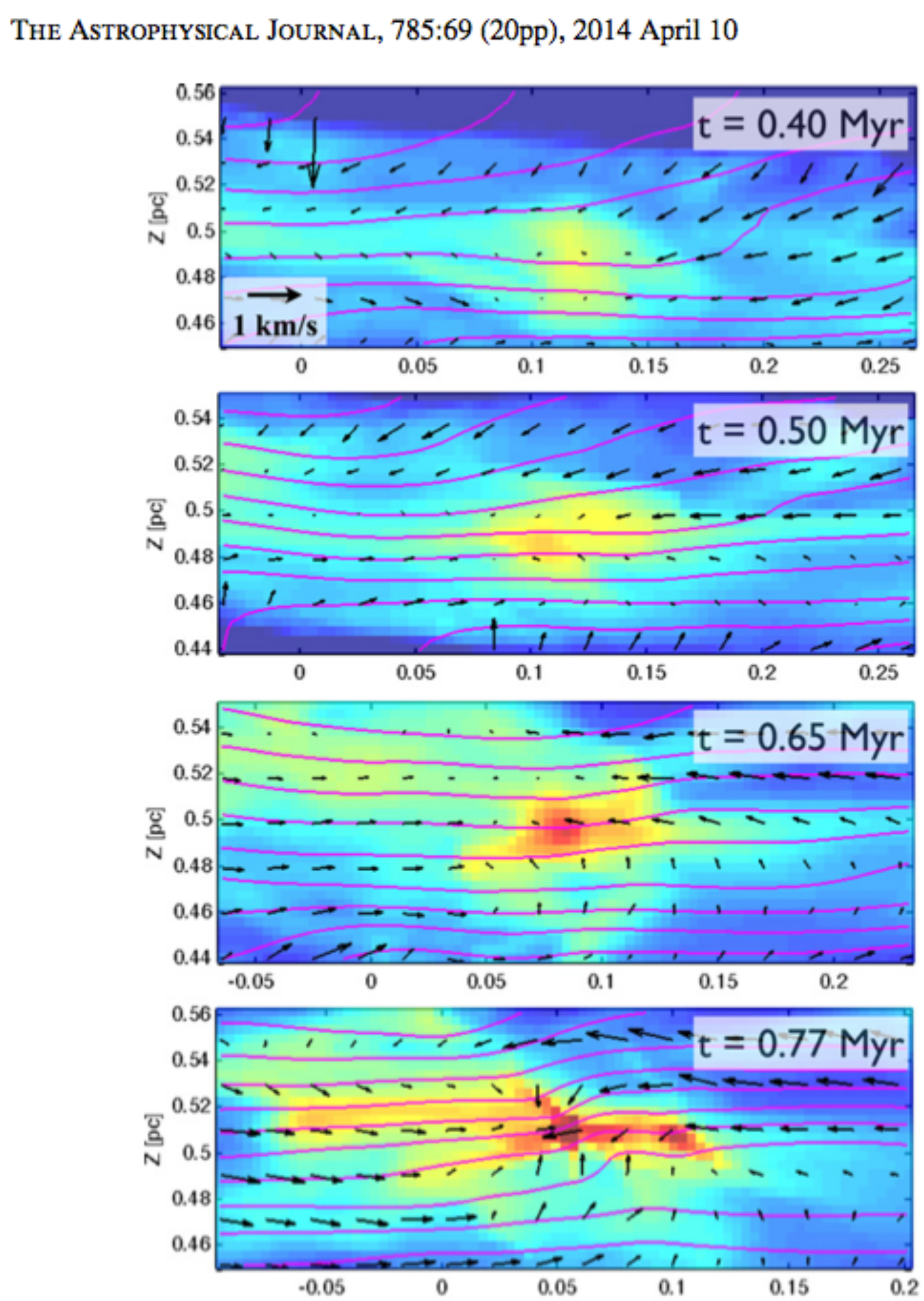
B5-ish? Simulation (with magnetic field)

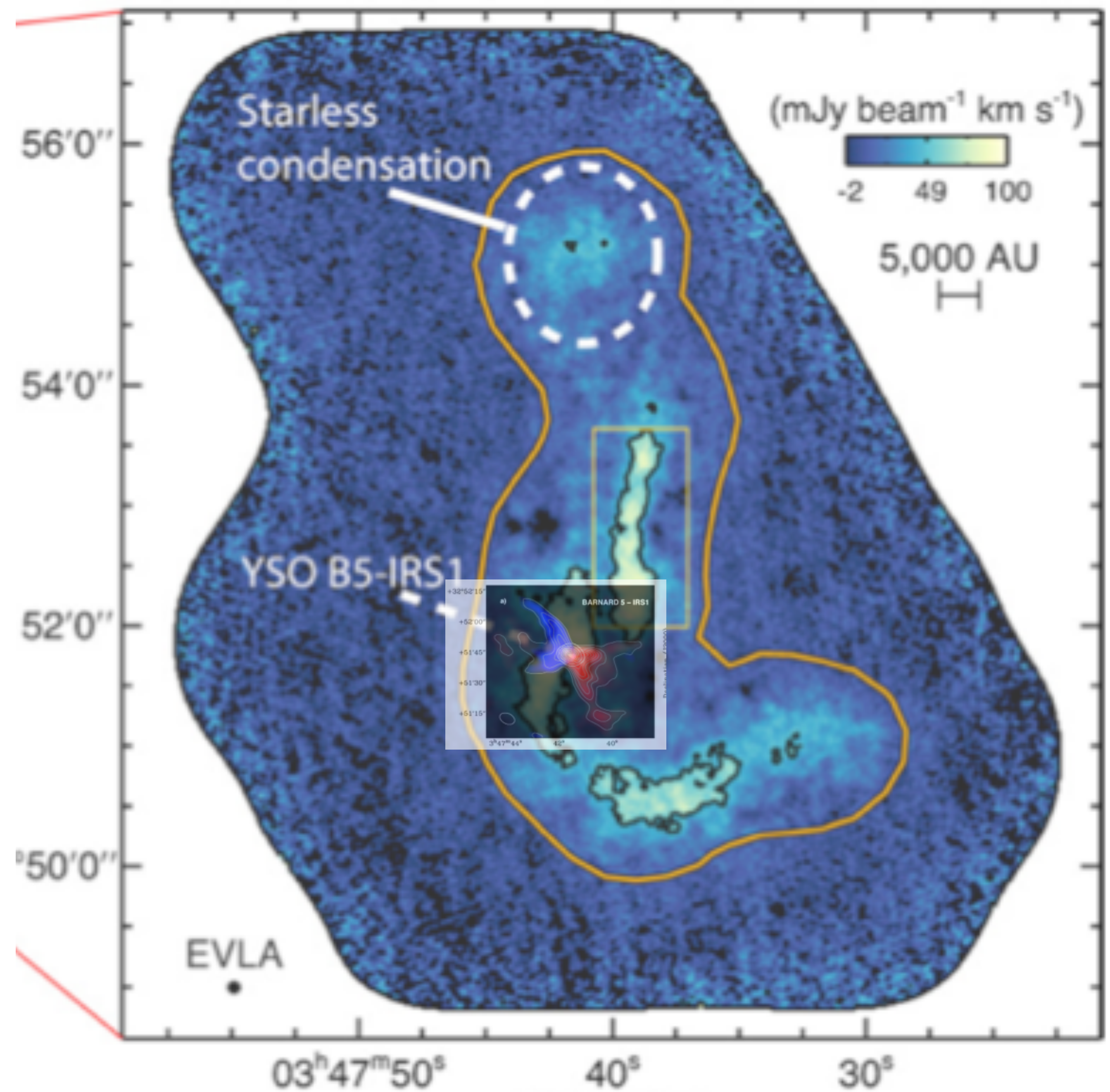
The Astrophysical Journal, 785:69 (20pp), 2014 April 10



Chen & Ostriker 2014

TO THE SAME SCALE...

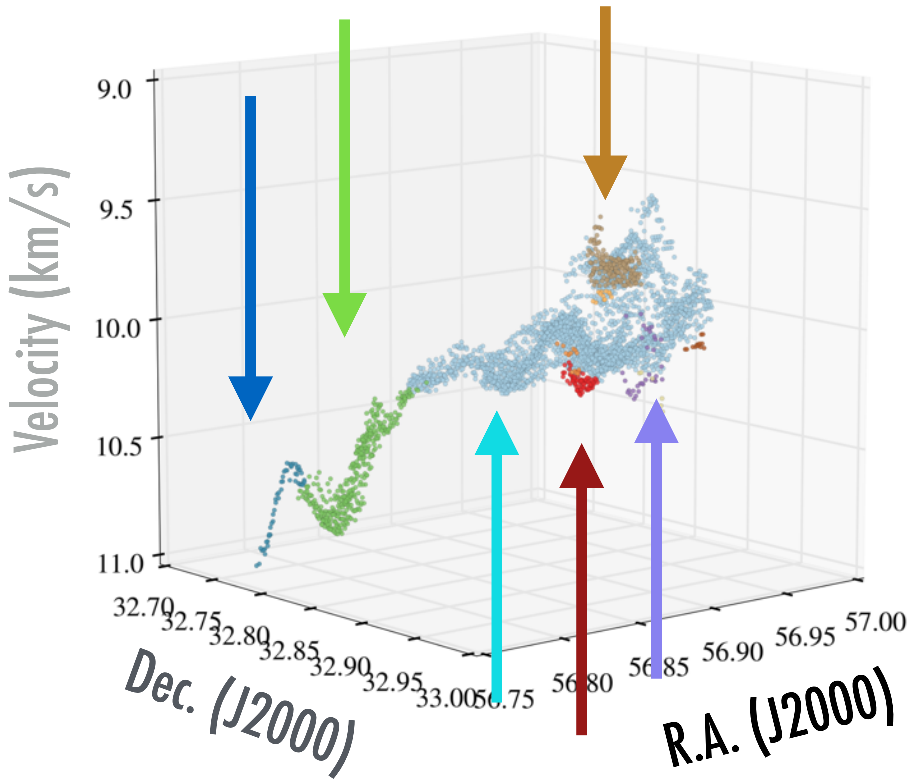




MHD (Chen & Ostriker 2014) B5 (Pineda et al.)+Zapata et. al. 2013

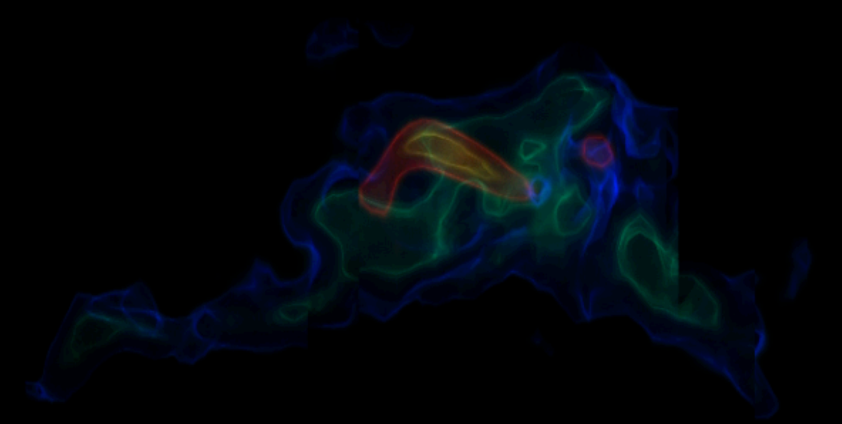
THE LATEST ON B5: IRAM LINE-MAPPING OF "FIBERS" WITHIN

There are at least three different components in the position-position-velocity space.



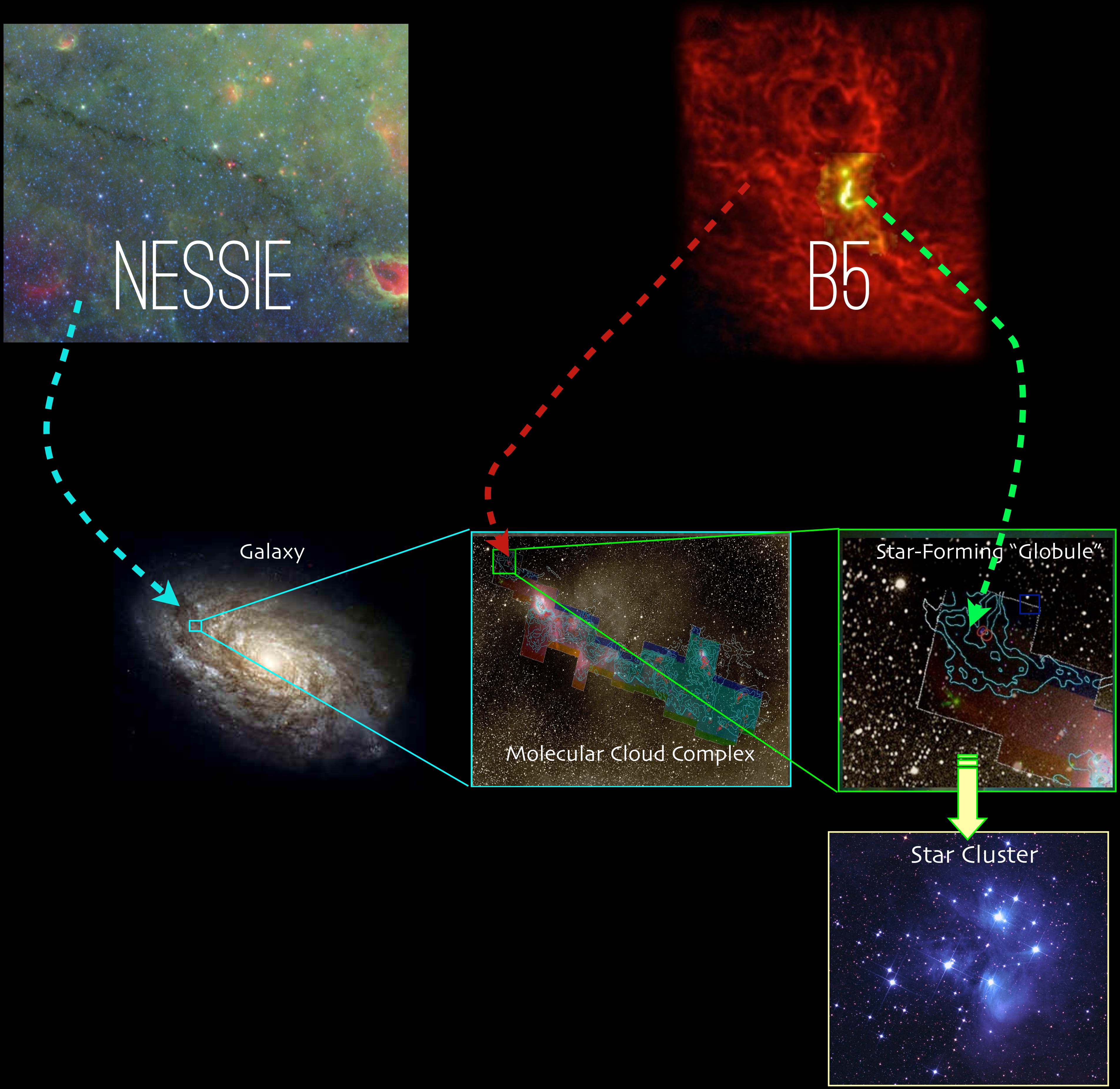
And potentially, many more...

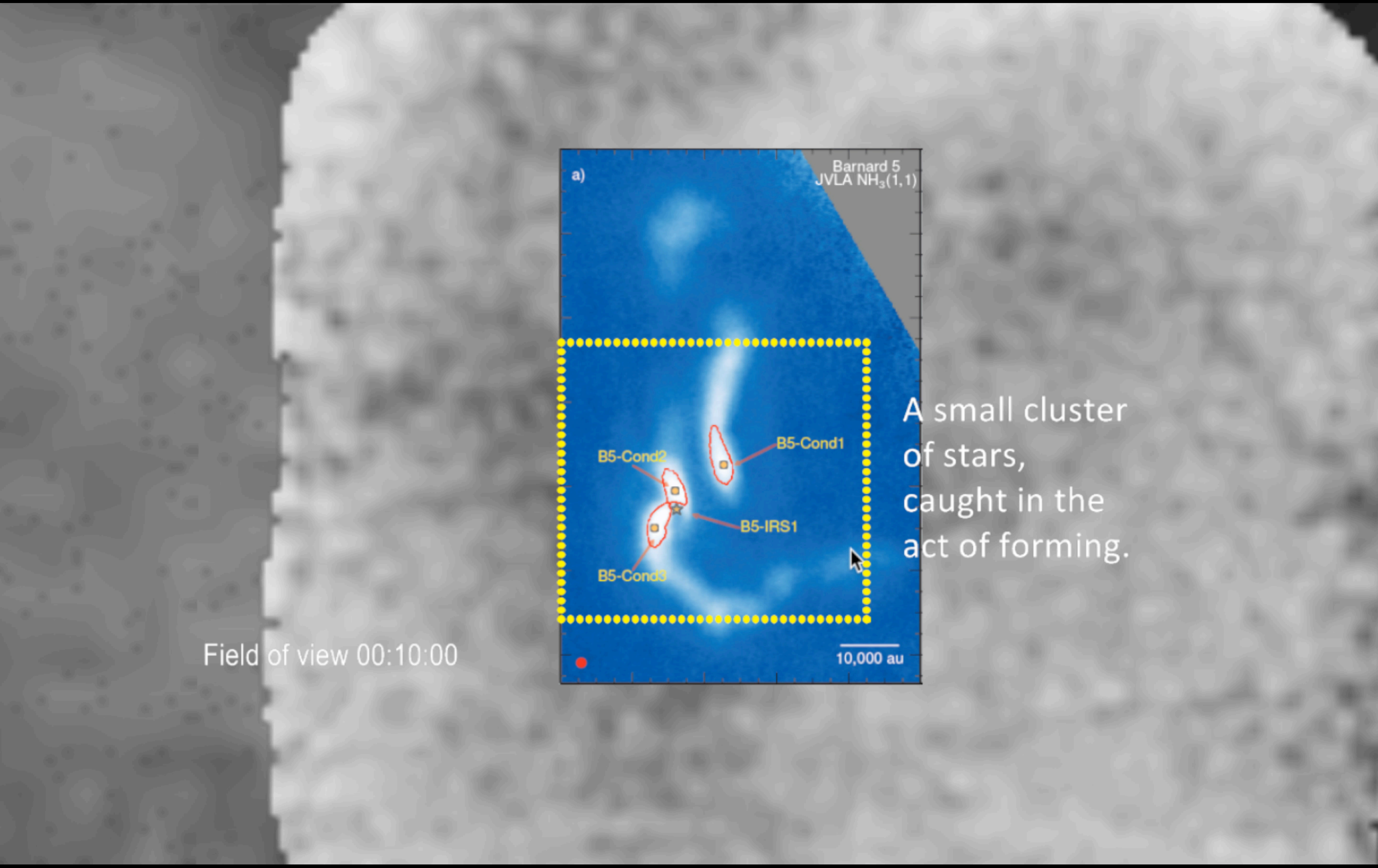
Gaussian fitted C18O (2-1) peaks
with components found using FIVE algorithm (Hacar et al. 2013)

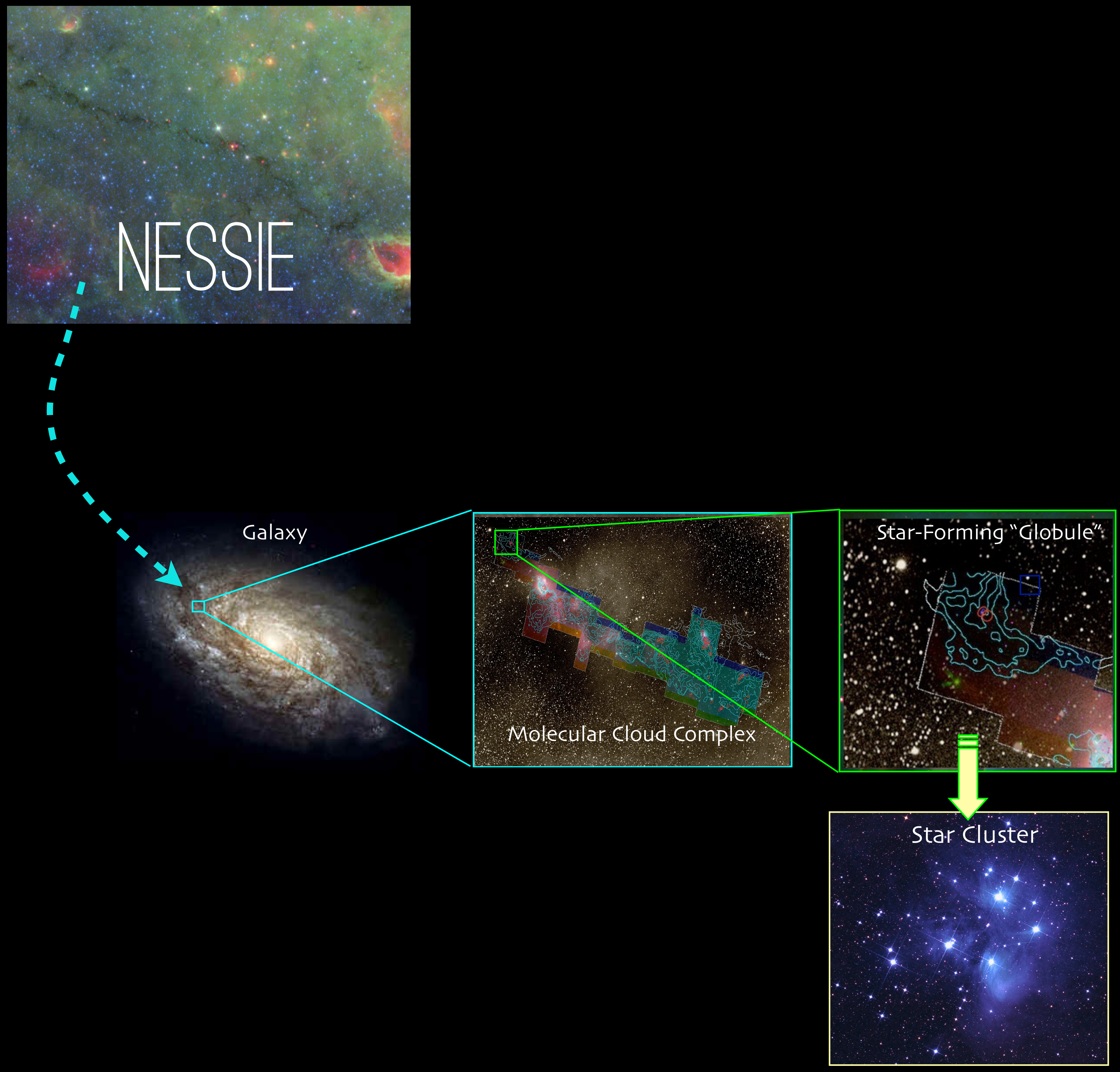


Compact & diffuse C18O (2-1) emission
Compact & diffuse NH3 (1, 1) emission
3D rendering using Python YT

courtesy of Hope Chen

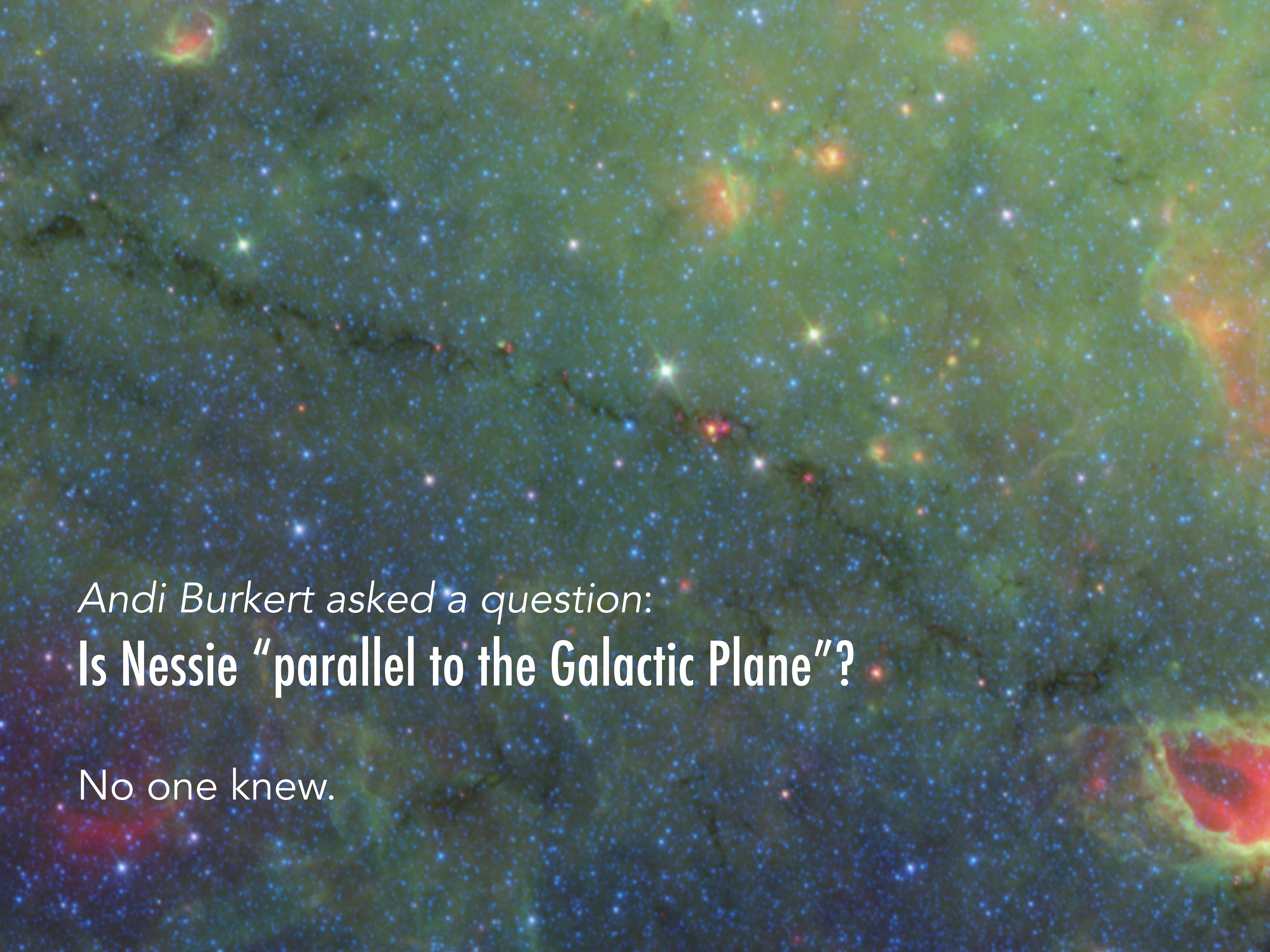

NESSIE
B5
Galaxy
Molecular Cloud Complex
Star-Forming "Globule"
Star Cluster


a)
Barnard 5
JVLA NH_3(1,1)
B5-Cond1
B5-Cond2
B5-IRS1
B5-Cond3
10,000 au
A small cluster of stars, caught in the act of forming.
Field of view 00:10:00


NESSIE
Galaxy
Molecular Cloud Complex
Star-Forming "Globule"
Star Cluster

Once upon a time (2012), in an enchanted castle (in Bavaria)

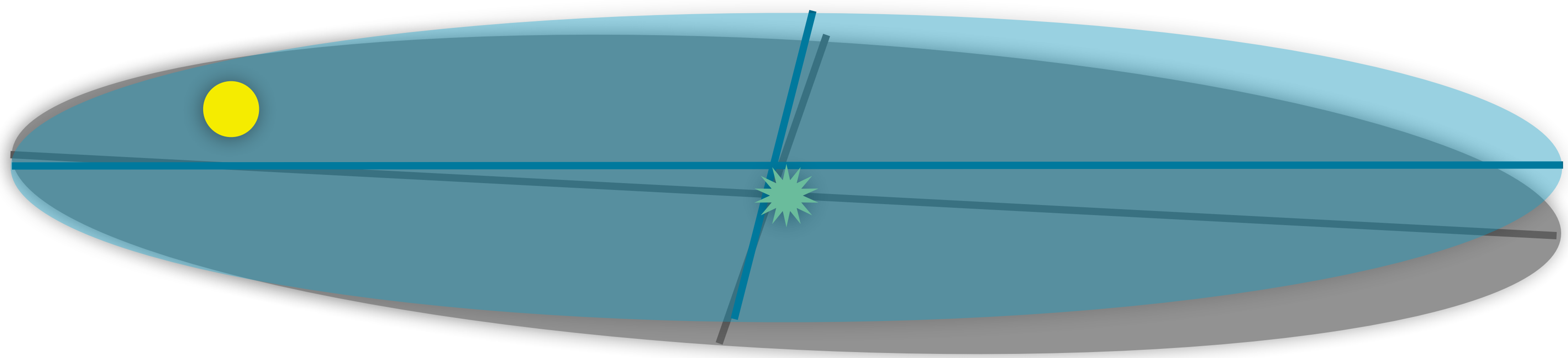
...at a conference about
"The Early Phases of Star Foration"


Andi Burkert asked a question:
Is Nessie "parallel to the Galactic Plane"?
No one knew.

"Is Nessie Parallel to the Galactic Plane?"

Where are we, really?

"IAU Milky Way", est. 1959



True Milky Way, modern

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]

Sun is ~75 light years "above" the IAU Milky Way Plane

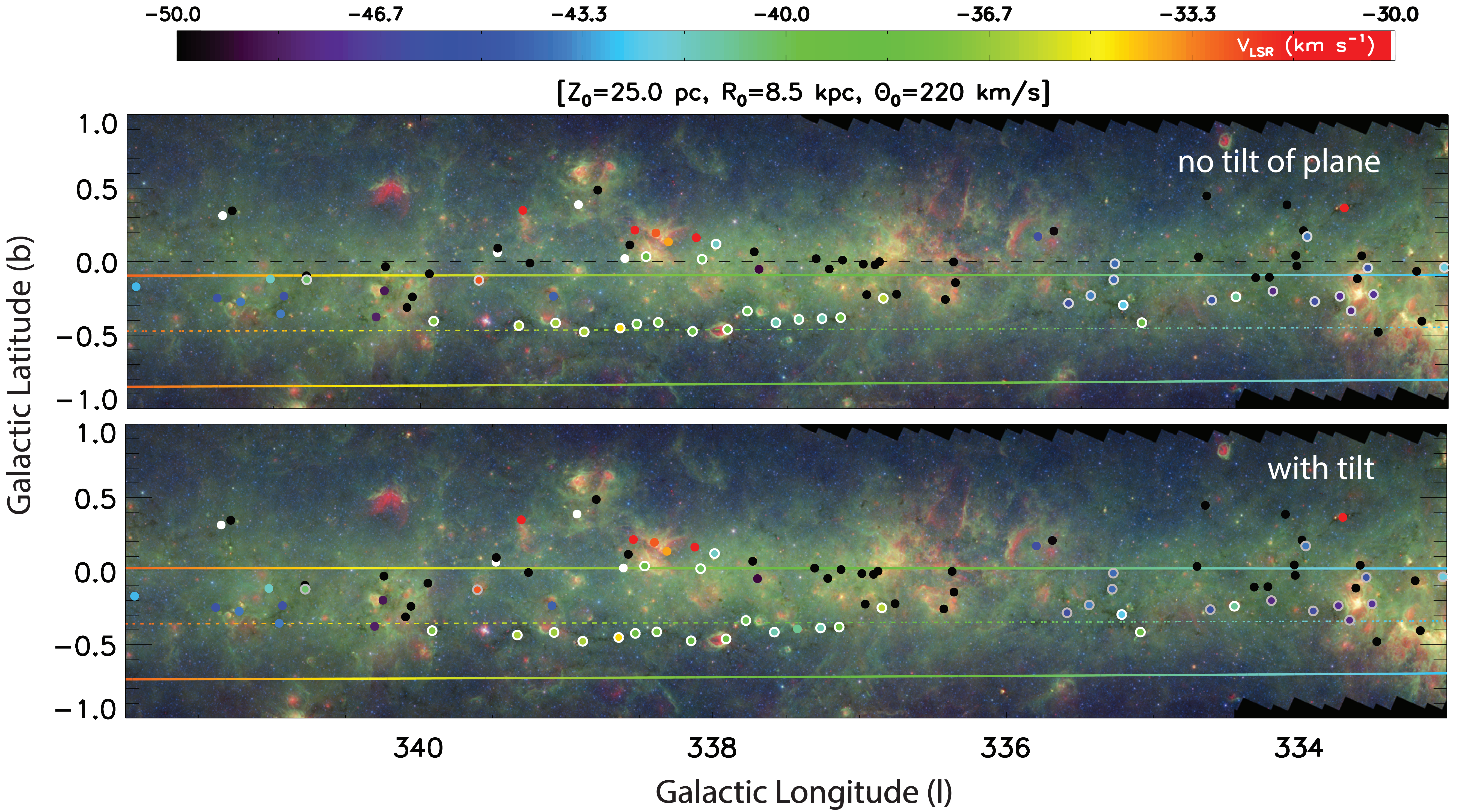
+

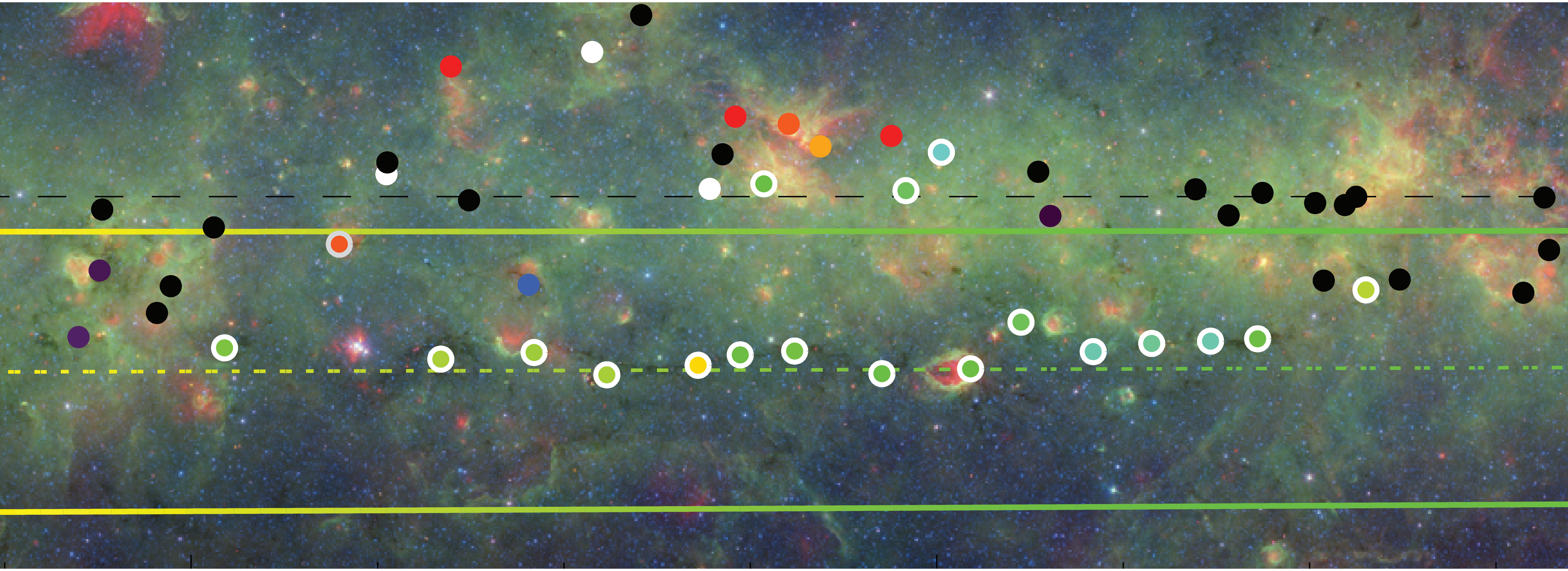
Galactic Center is ~20 light years offset from the IAU Milky Way Center

=

The **Galactic Plane is not quite where you'd think it is** when you look at the sky

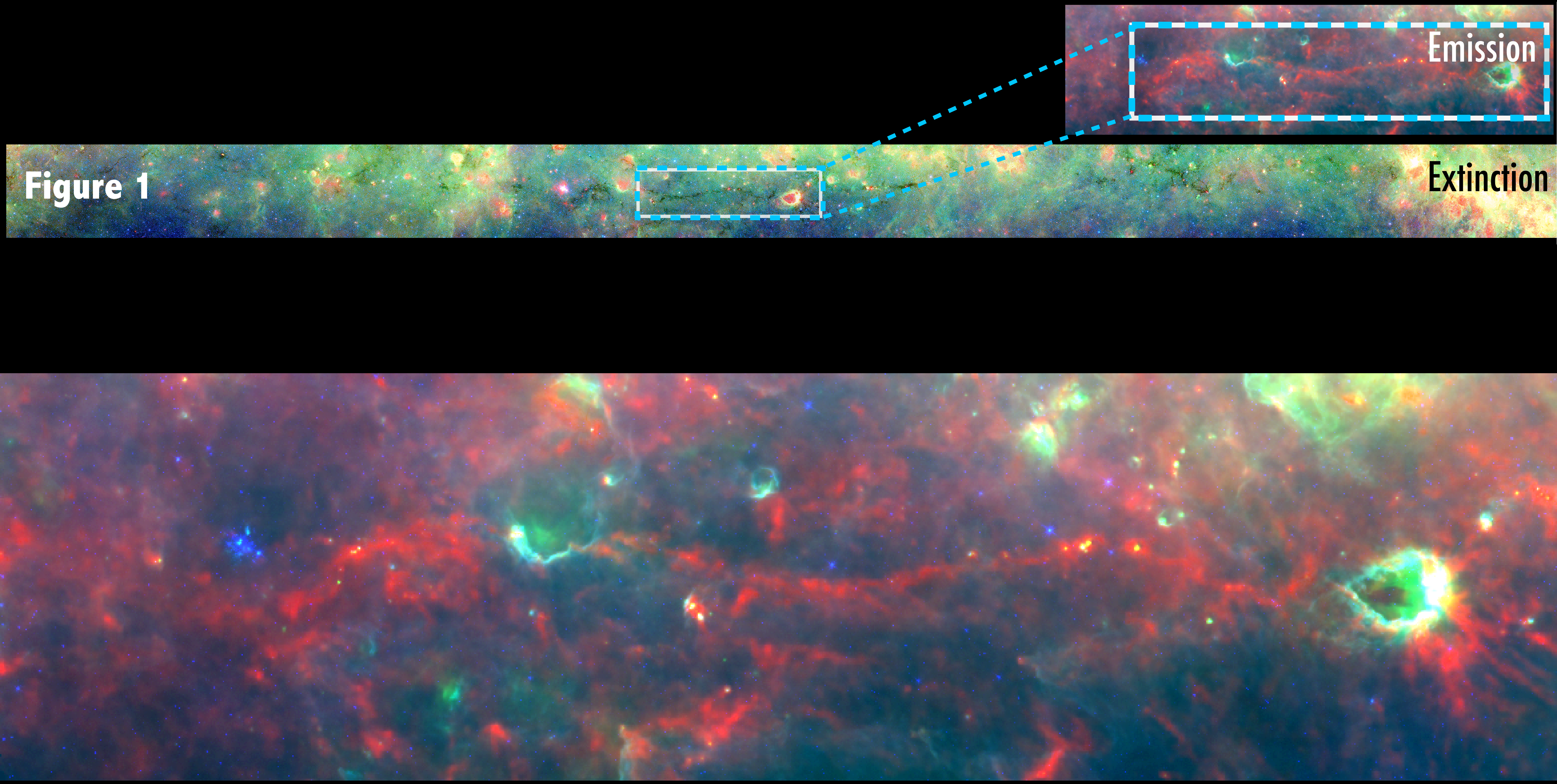
In the plane! And at distance of spiral arm!





...eerily precisely...

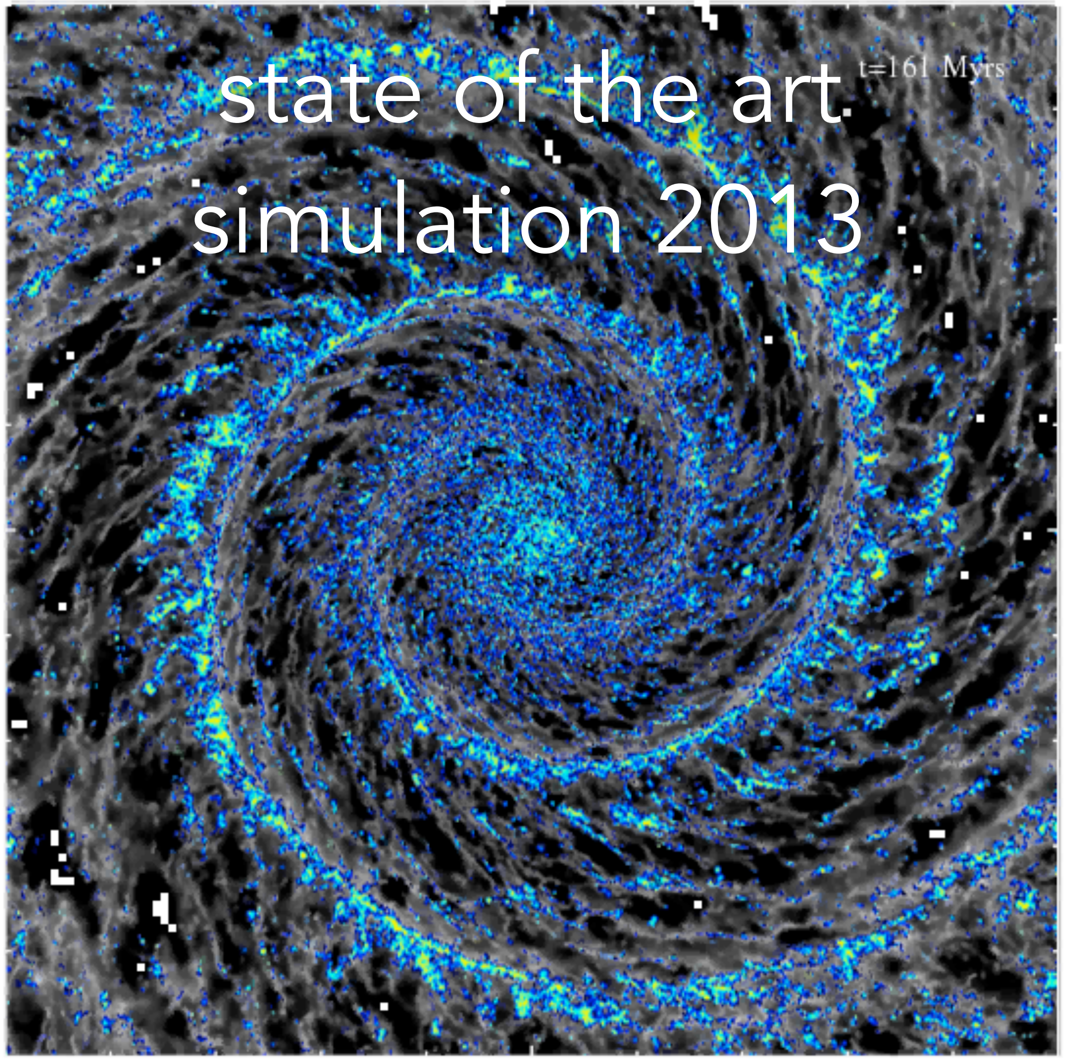
How do we know the velocities?

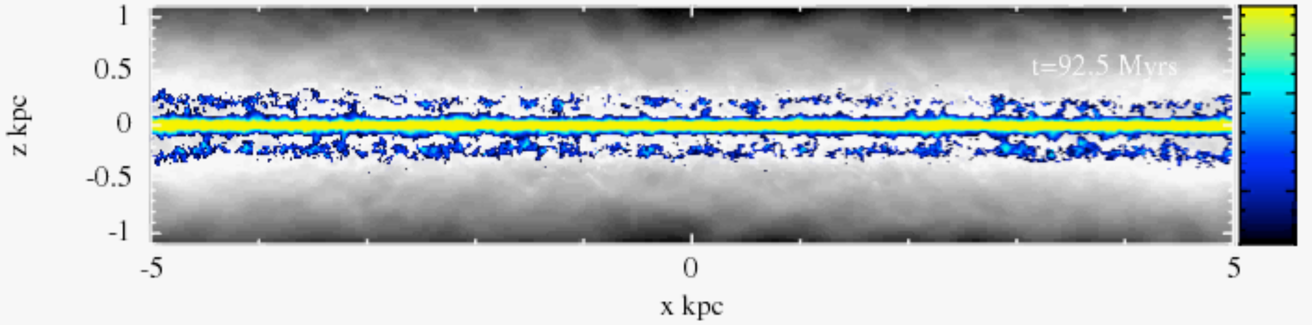


Bottom panel: Red=column density from Herschel, green=70 micron data from Herschel, and blue= 8 micron data image courtesy of Cara Battersby

A full 3D skeleton?

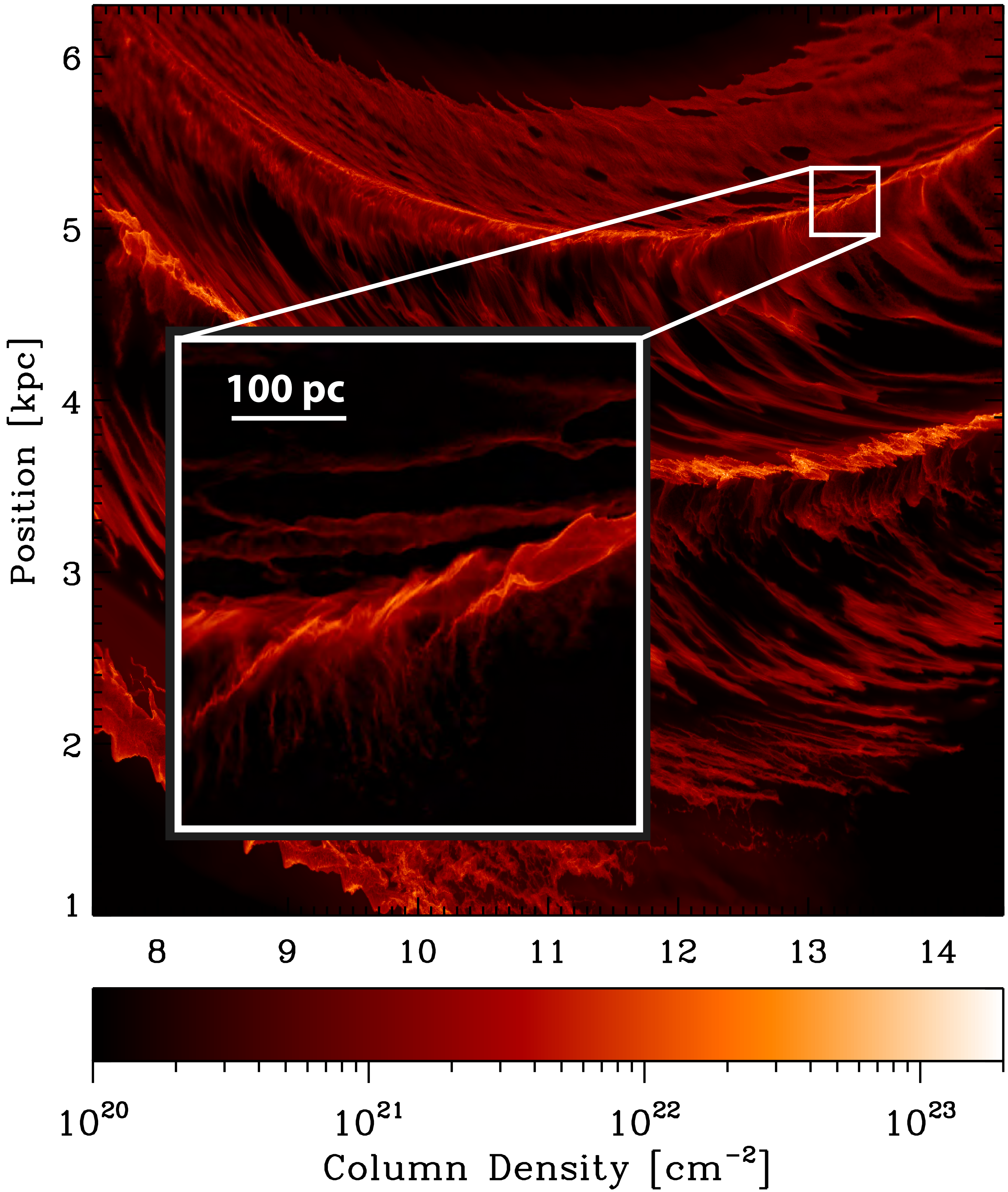
(flipped) image of IC342 from Jarrett et al. 2012; WISE Enhanced Resolution Galaxy Atlas





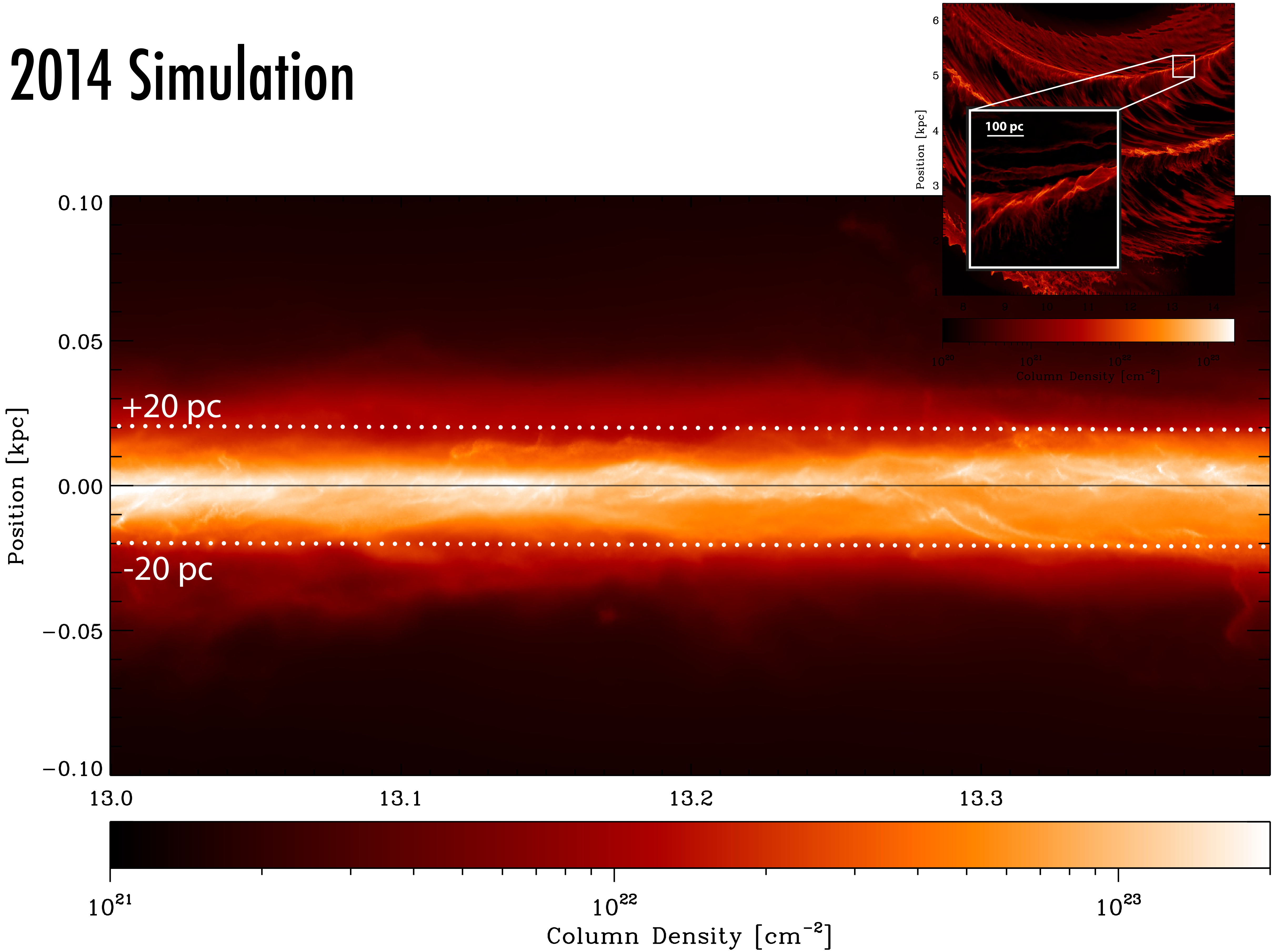
simulations courtesy Clare Dobbs

2014 Simulation



Smith et al. 2014, using AREPO

2014 Simulation



Smith et al. 2014, using AREPO (hydro+chemistry, imposed potential, no B-fields, no local (self-)gravity, no feedback)

But wait—there's more!

THE SKELETON OF THE MILKY WAY

CATHERINE ZUCKER[1], CARA BATTERSBY[2], AND ALYSSA GOODMAN[2]
[1] Astronomy Department, University of Virginia, Charlottesville, VA 22904, USA; catherine.zucker@cfa.harvard.edu
[2] Harvard-Smithsonian Center for Astrophysics, Cambridge, MA 02138, USA
Received 2015 June 27; accepted 2015 September 21; published 2015 MM DD

"We present the first evidence of additional bones in the Milky Way Galaxy, arguing that Nessie is not a curiosity but one of several filaments that could potentially trace Galactic structure."

Key words: Galaxy: kinematics and dynamics – Galaxy: structure – ISM: clouds

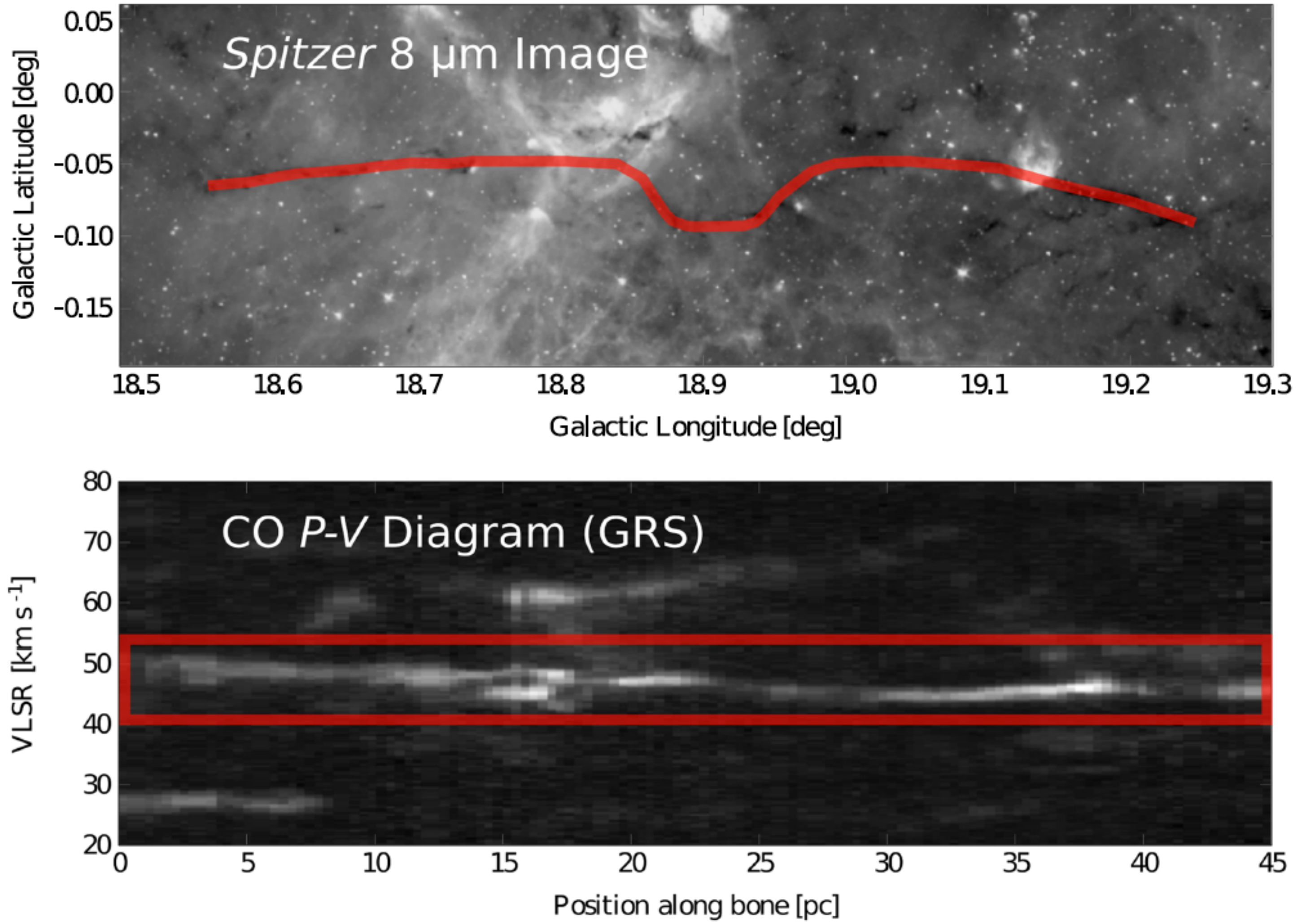


Figure 1. Results of performing a slice extraction along the filamentary extinction feature of our strongest bone candidate, filament 5. The top panel shows a *Spitzer*-GLIMPSE 8 μm image of filament 5, and the red trace indicates the curve (coincident with the extinction feature) along which a p–v slice was extracted. The bottom panel shows the p–v slice, with the red boxed region indicating the emission corresponding to filament 5.

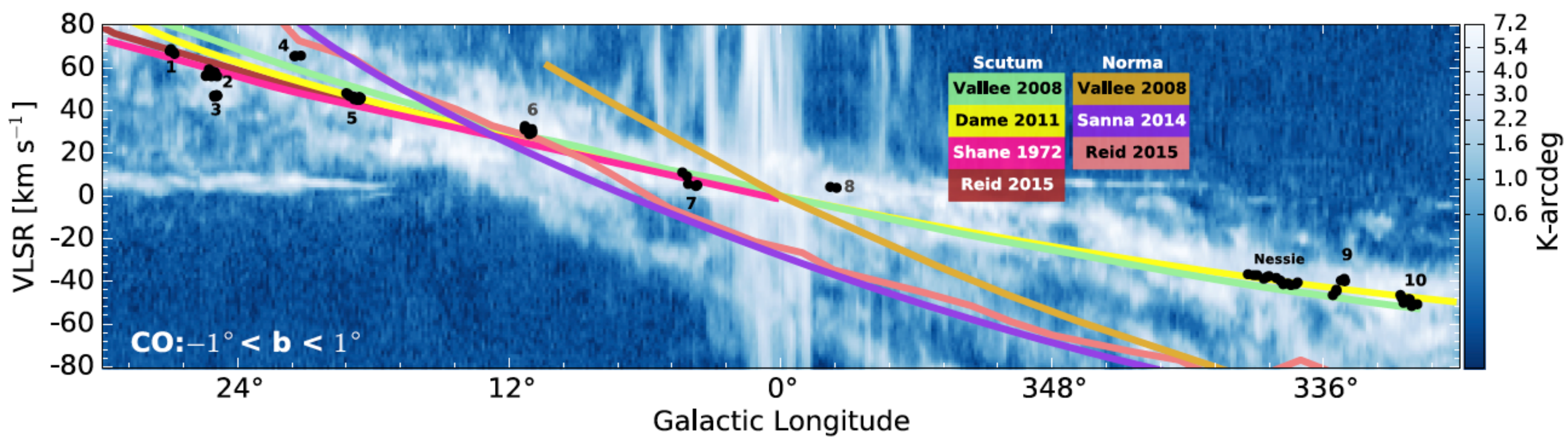
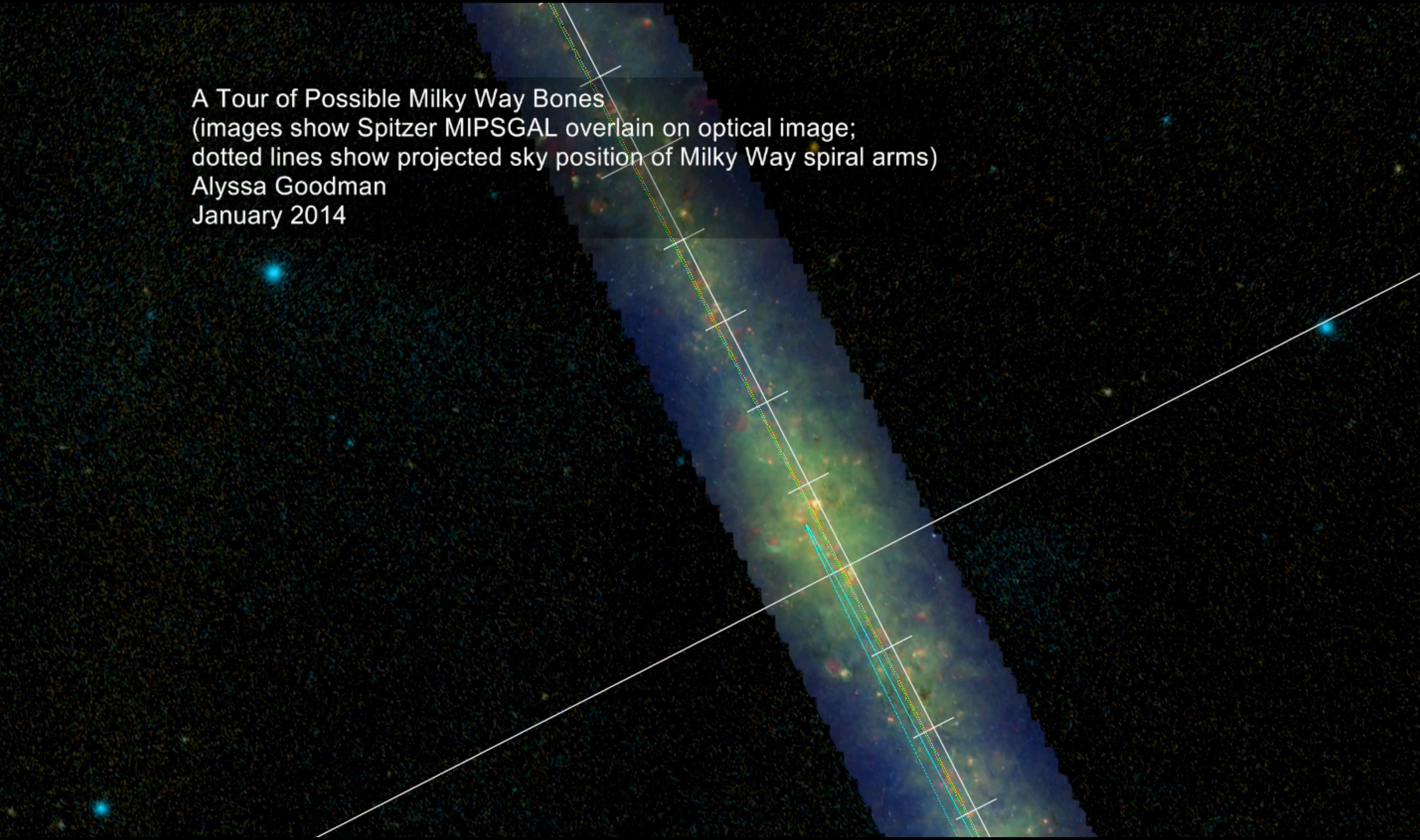
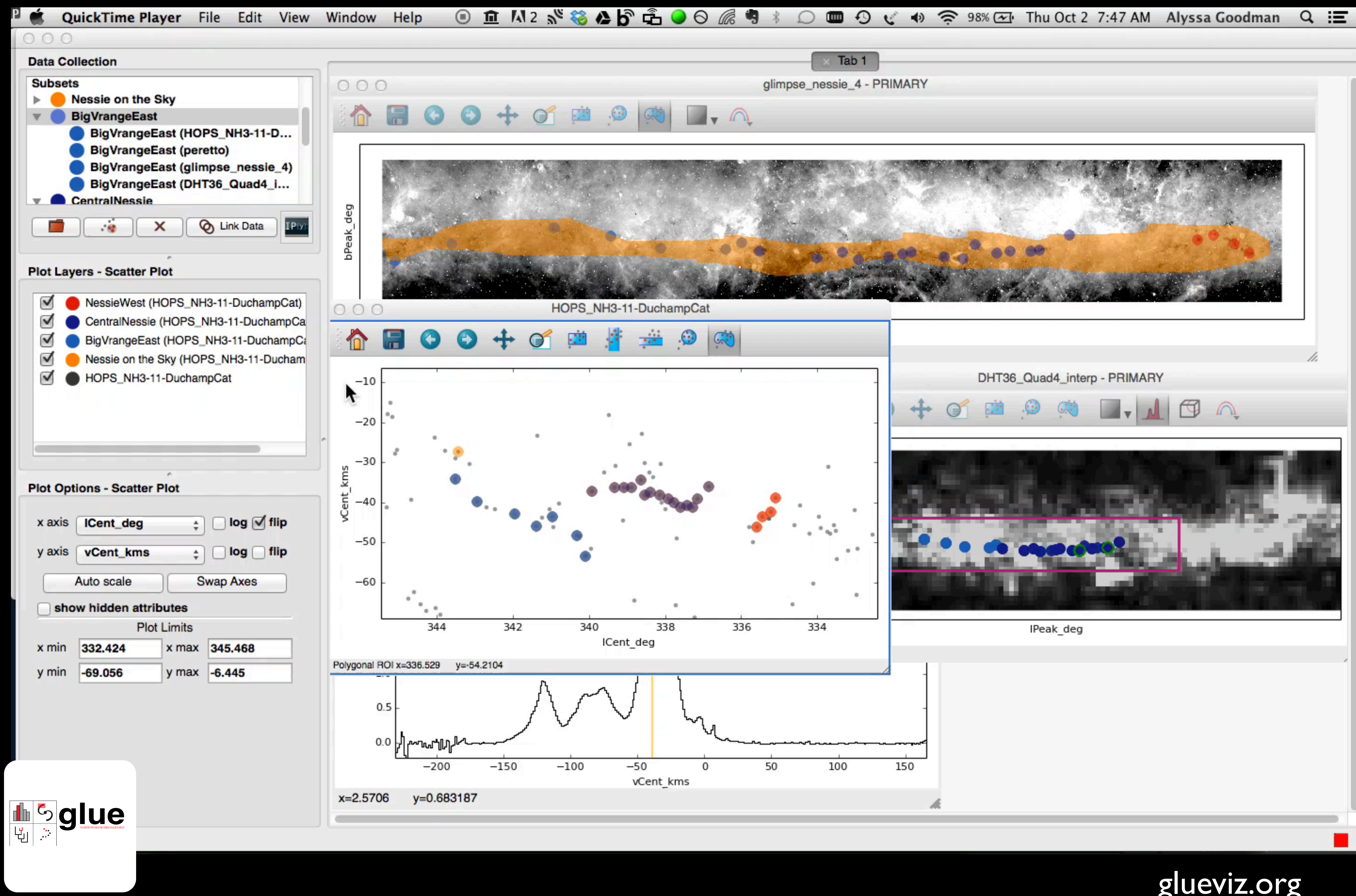


Figure 2. Position–velocity summary of bone candidates and spiral arm models. Blue background shows ^{12}CO emission from Dame et al. (2001), integrated between $-1° < b < 1°$. Black dots show measurements of BGPS-, HOPS-, MALT90-, and GRS-determined velocities, with particular candidate filaments identified by number (see Table 1 for further identification), or, in the case of Nessie, by name. Lines of varying color show predicted p–v spiral arm traces from the literature (see text for references).

SKELETON STEP 1: WHERE "SHOULD" THE BONES BE?



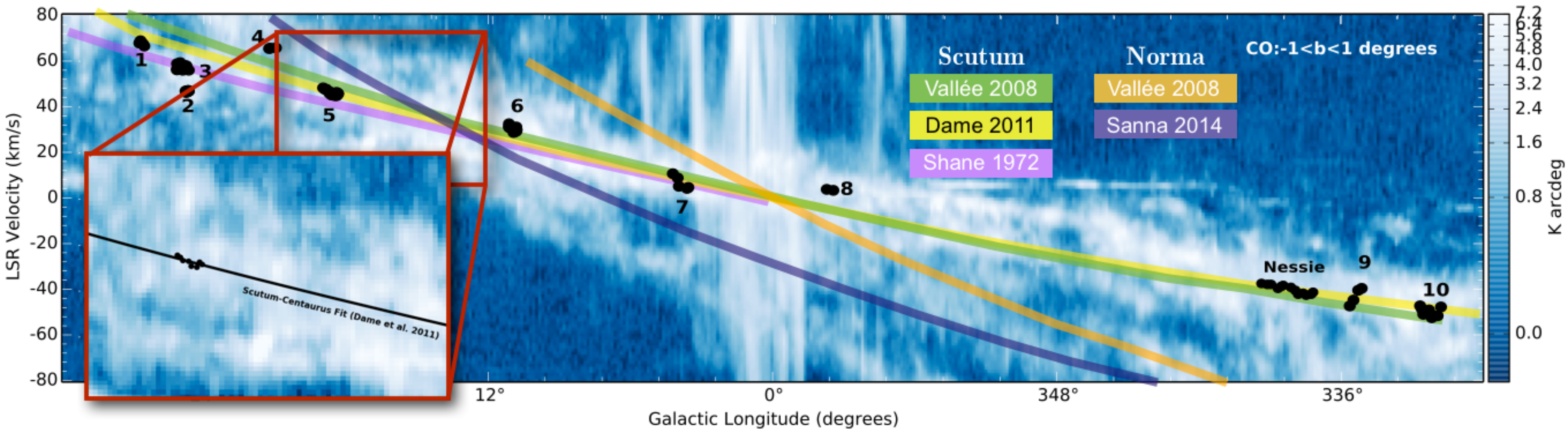
SKELETON STEP 2: ADDING VELOCITY INFORMATION



glueviz.org

6 OUT OF 10 BONE CANDIDATES LOOK EXCELLENT IN "3D"

(POSITION-POSITION-VELOCITY SPACE)



Blue image in the background shows CO position-velocity diagram based on Dame et al. 2001

FOR AFICIONADOS ONLY...

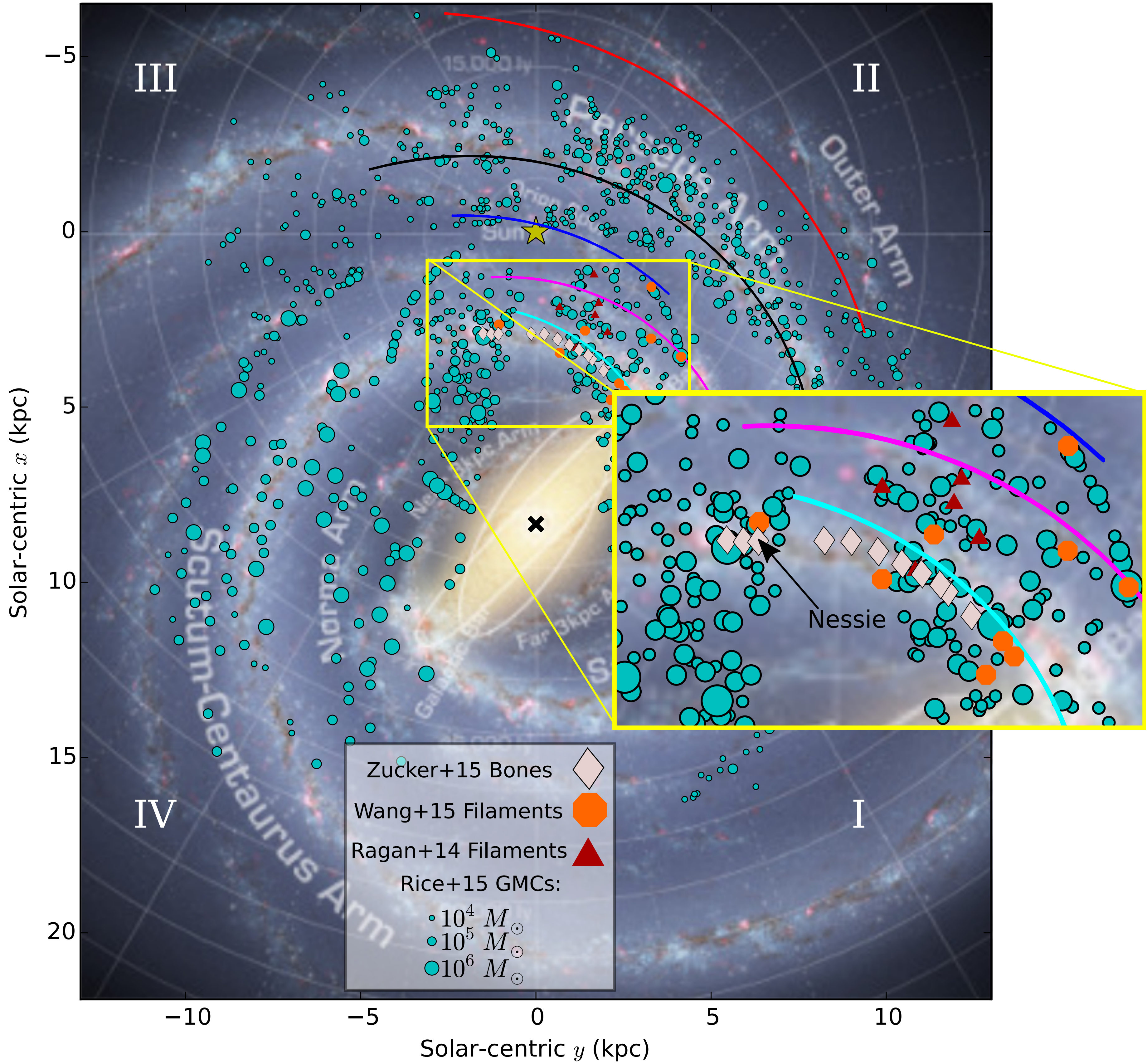
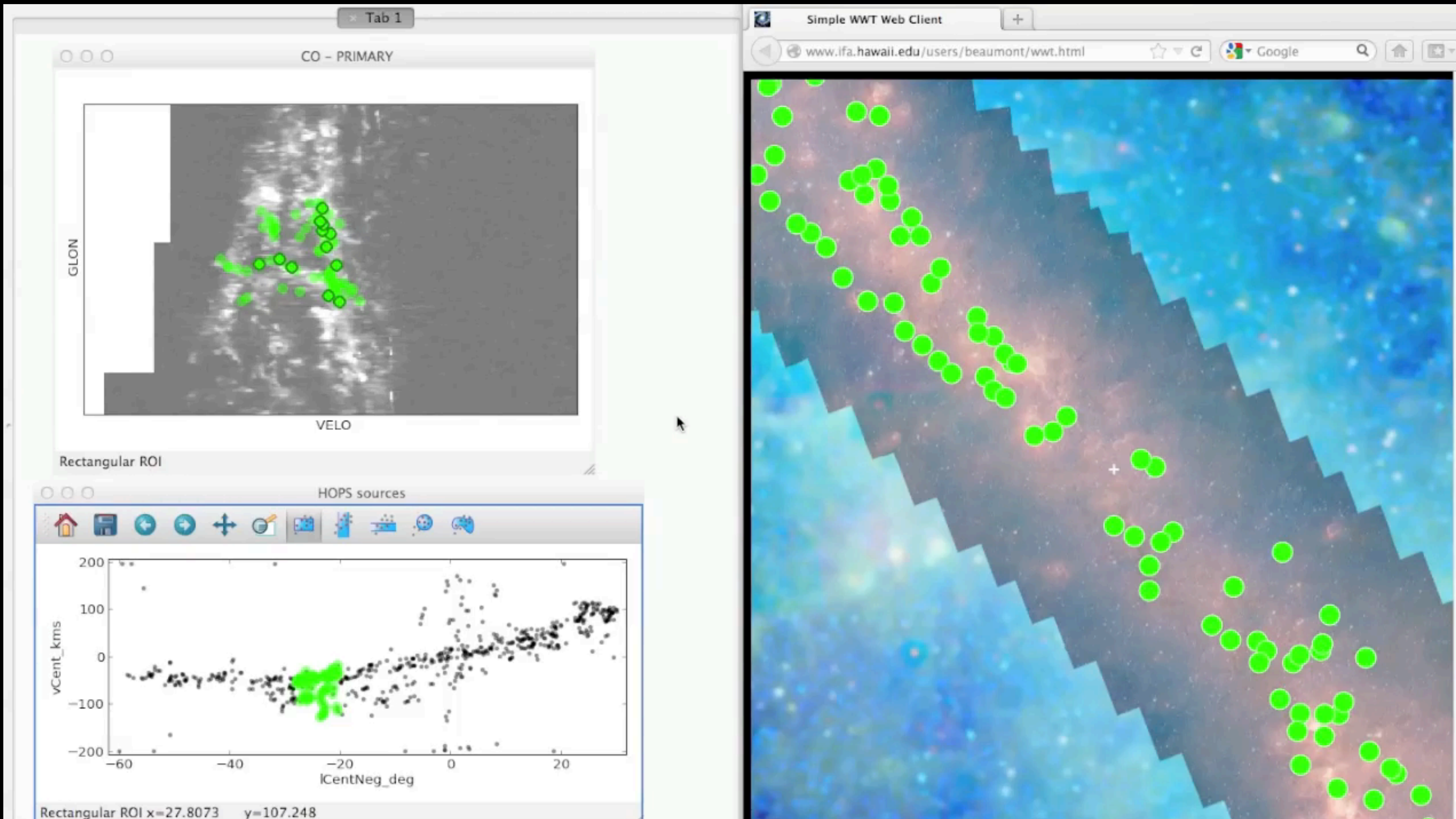


Figure (in prep) courtesy of Catherine Zucker, using Reid, Dame et al. 2015 arm traces (BeSSeL + Bayes)

TOMORROW, AT Google



Video courtesy of Chris Beaumont, Lead Glue Architect

Nessie to B5, the movie.


FUNDAMENTAL, (?),
FRAGMENTING,
FILAMENTS
& FIBERS
ALYSSA A. GOODMAN
HARVARD-SMITHSONIAN
CENTER FOR ASTROPHYSICS
@AAGIE
APOD 11-30-15
ESA/Hubble & NASA and S. Smartt (Queen's University Belfast)
Acknowledgement: Robert Gendler

THE MILKY WAY

"Galactic Plane"

The Milky Way
(Artist's Conception)

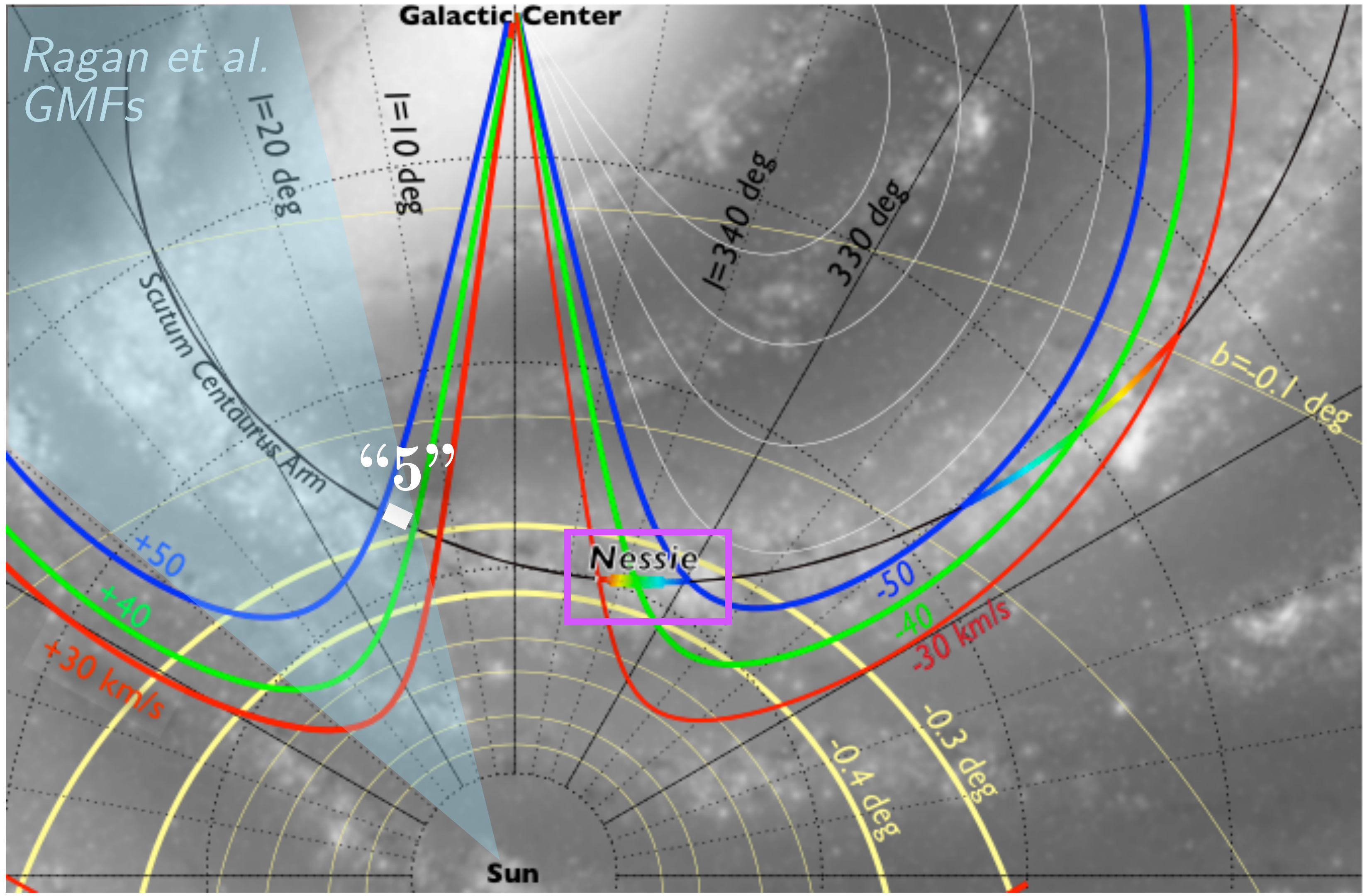
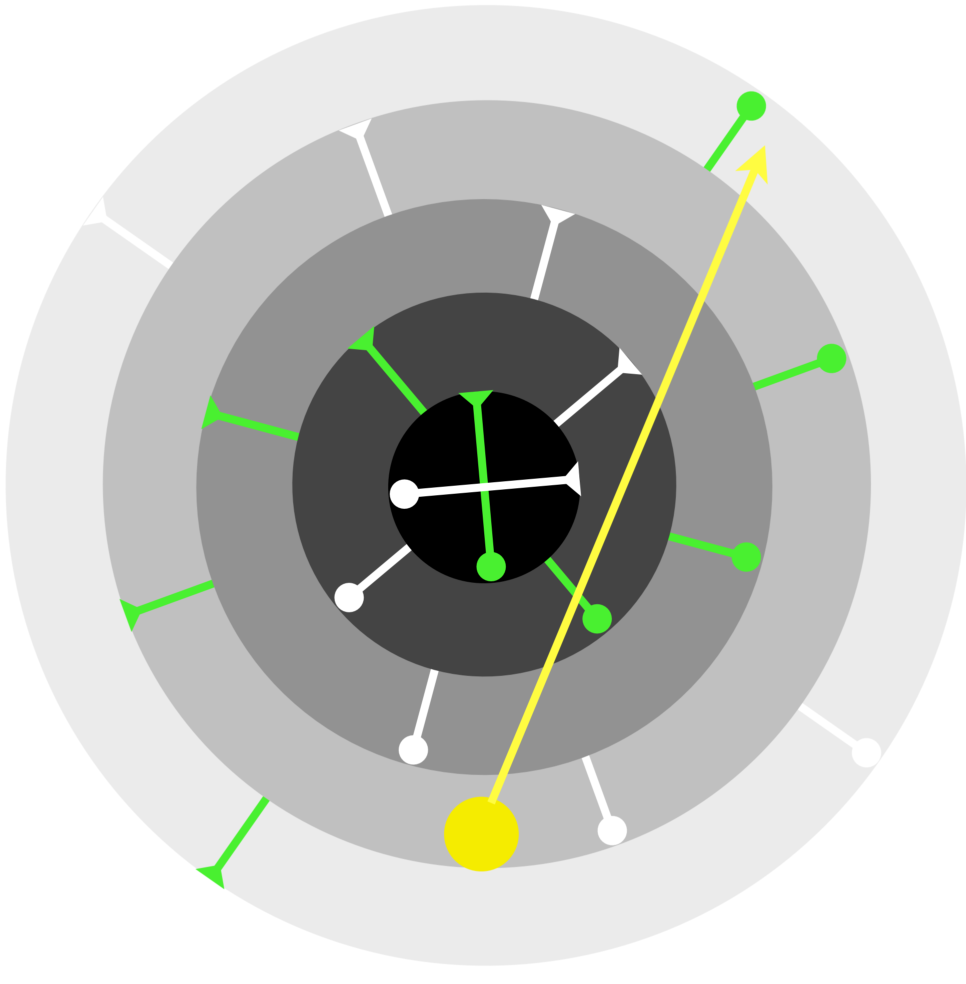
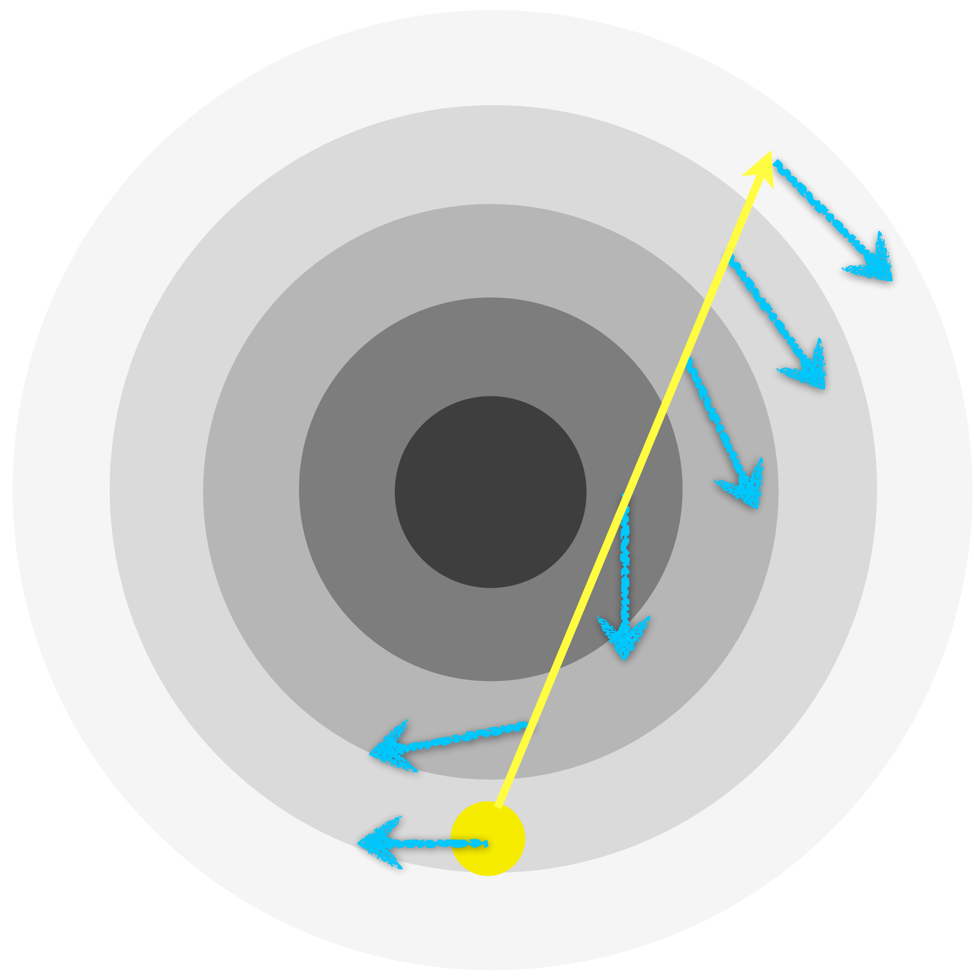
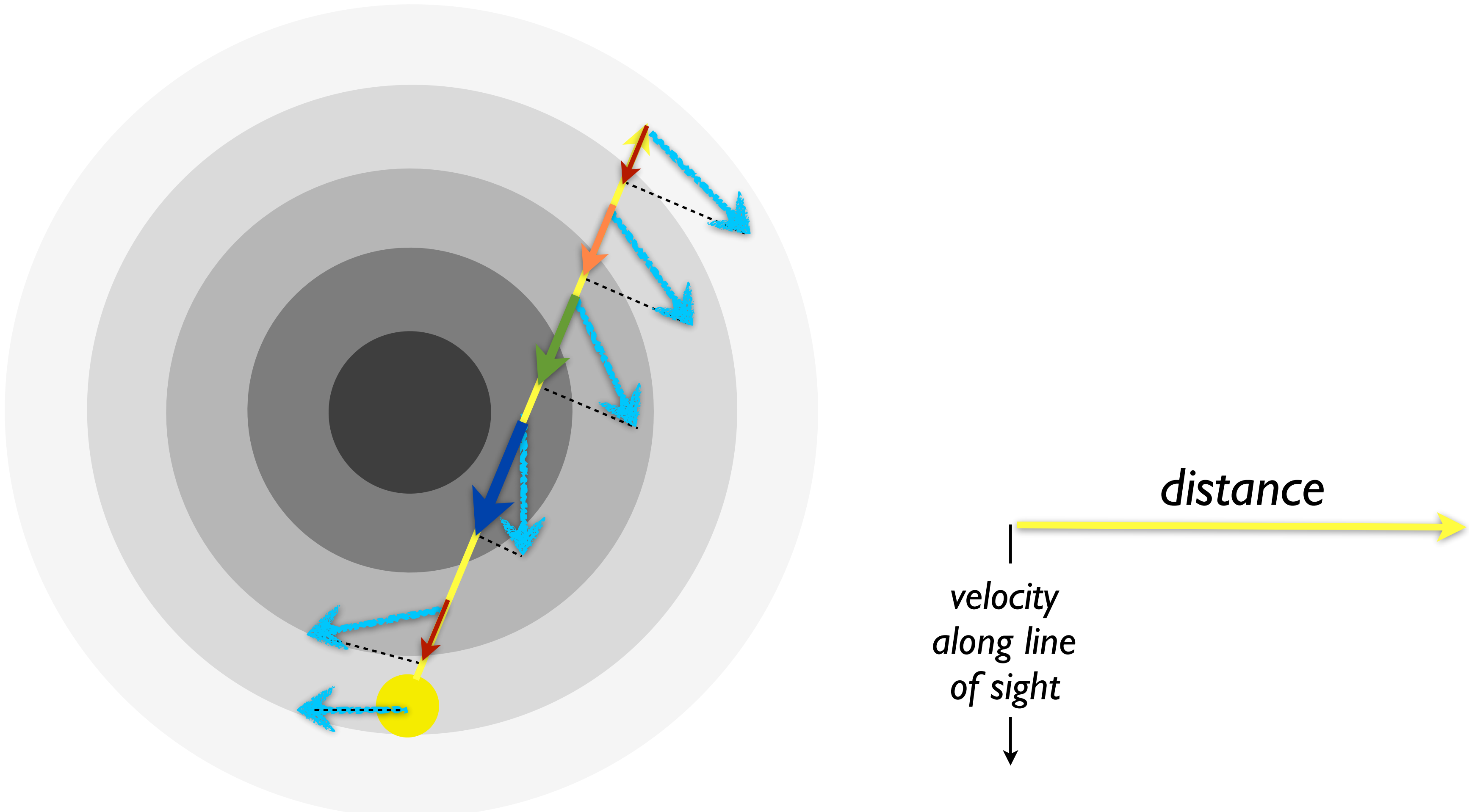


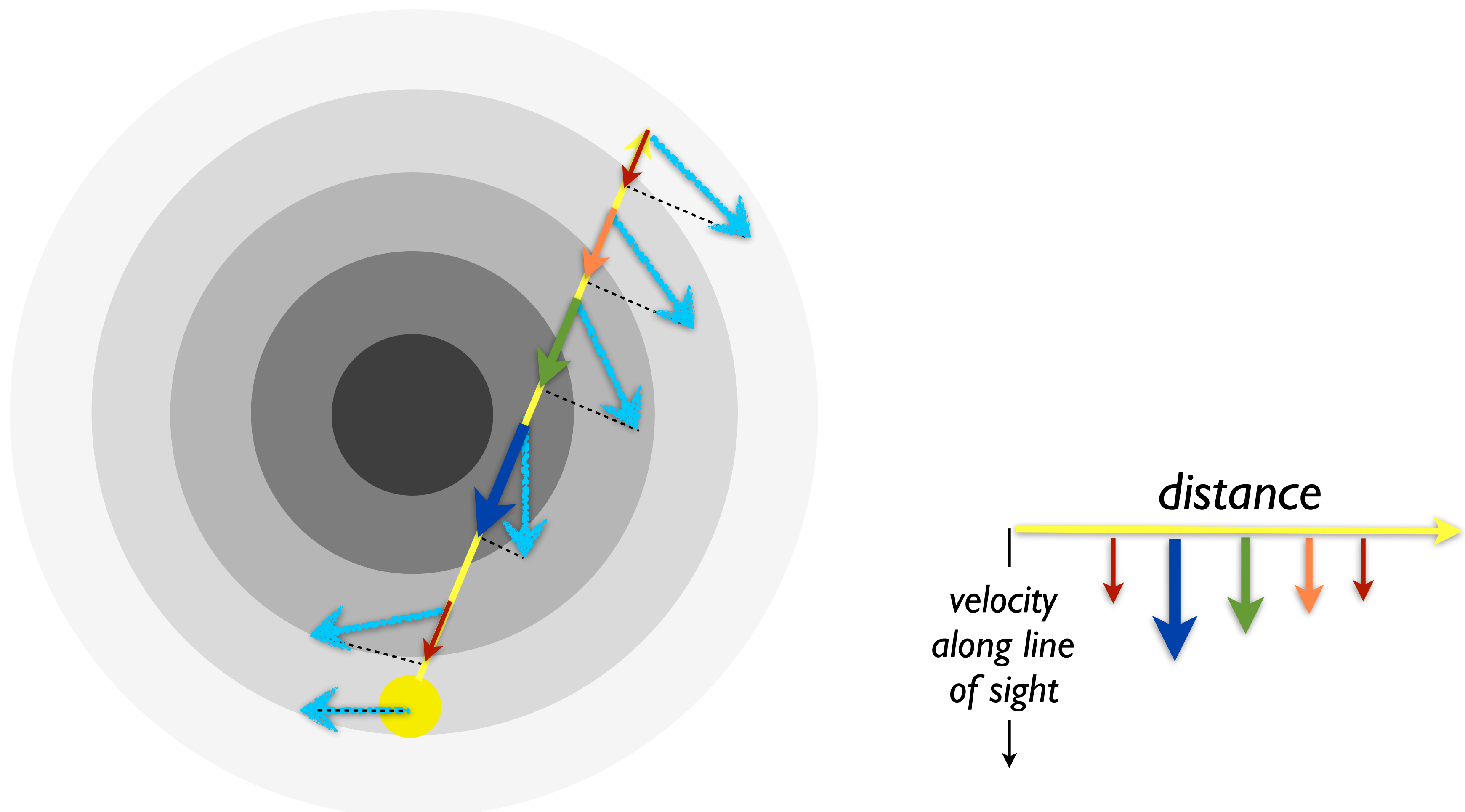
Figure 3 A data-motivated cartoon model of the Milky Way with iso-velocity contours (color) overlain. Yellow iso-latitude contours show the latitude of the Galactic mid-plane, assuming a height of 25 pc for the Sun, and an offset of 7 pc for SgrA*. Nessie's advantageous position is marked by a rainbow, along the Scutum-Centaurus arm. Position of "Filament 5," discussed below, is marked with a "5." (Figure adapted from Goodman et al. 2014.)

A Rotating (Spiral) Galaxy Observed from its Outskirts...






distance
velocity
along line
of sight



back

Tastemaker 1: Chemistry

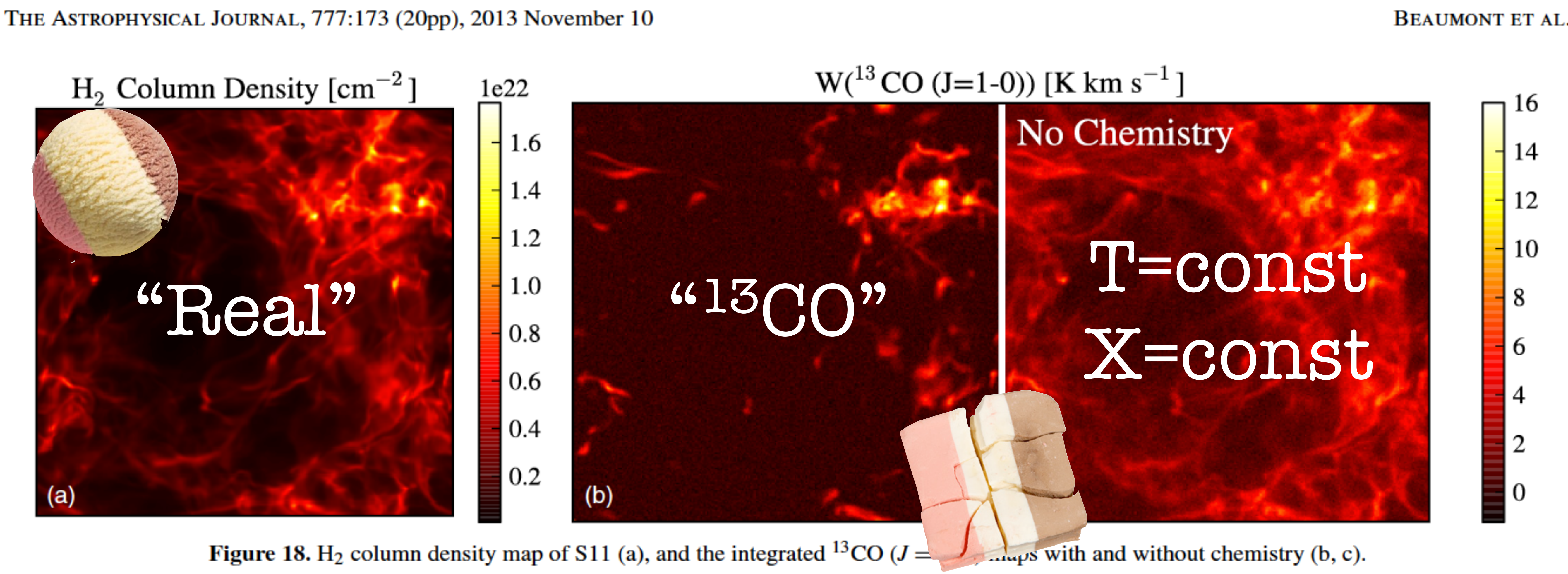


Figure 18. H_2 column density map of S11 (a), and the integrated ^{13}CO (J = ... maps with and without chemistry (b, c).

The Astrophysical Journal, 777:173 (20pp), 2013 November 10 doi:10.1088/0004-637X/777/2/173, 2013.
QUANTIFYING OBSERVATIONAL PROJECTION EFFECTS USING MOLECULAR CLOUD SIMULATIONS

Christopher N. **Beaumont**[1,2], Stella S. R. **Offner**[3,5], Rahul **Shetty**[4], Simon C. O. **Glover**[4], and Alyssa A. **Goodman**[2]

Tastemaker 2: Projection

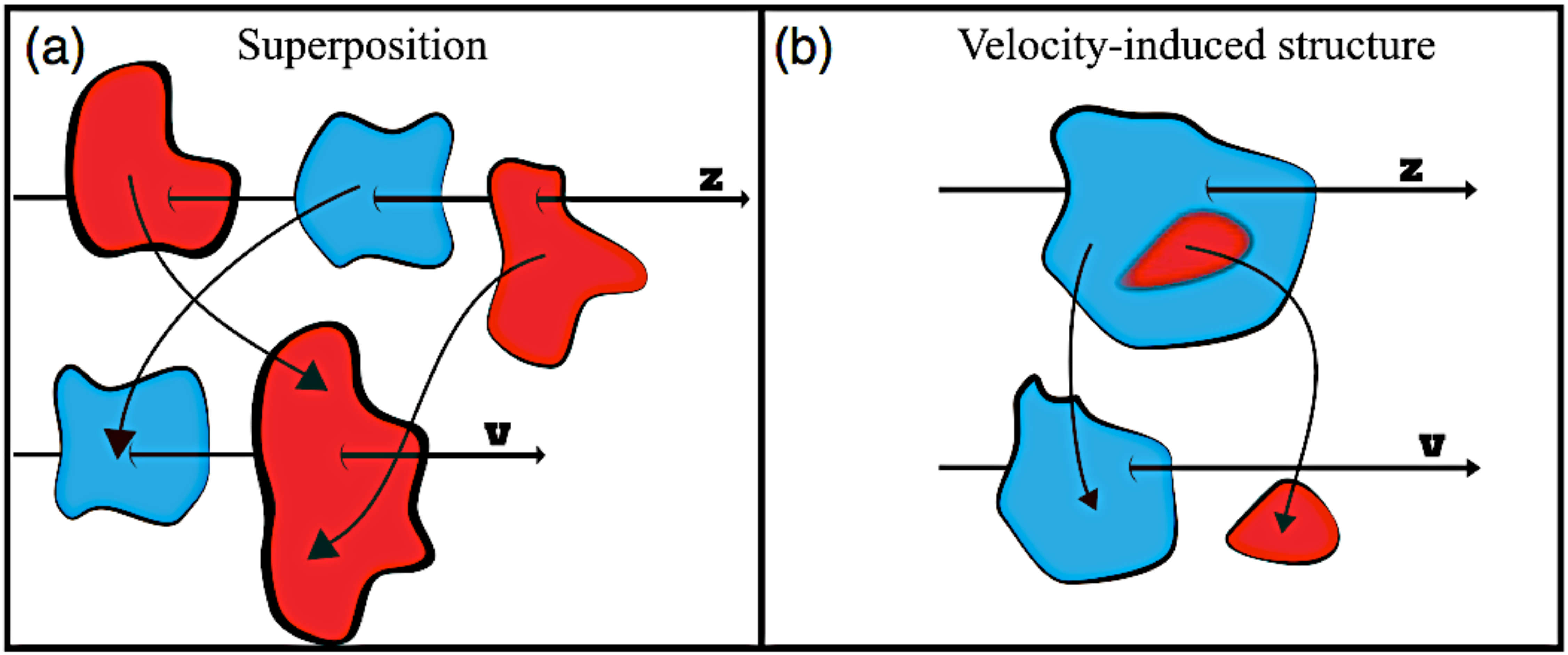


Figure 1. Schematic representation of superposition and velocity-induced structures. Colors indicate velocity. Left: three PPP structures (top) merge into 2 PPV structures (bottom), due to the similar velocity of the front and back structures. Right: a single density structure with internal velocity gradients (top) splits into two PPV structures (bottom).

Beaumont et al. 2013

Tastemaker Part 2: Projection

“PPP” to “PPV”

“Destruction” of Real Structures

“Creation” of Unreal Structures

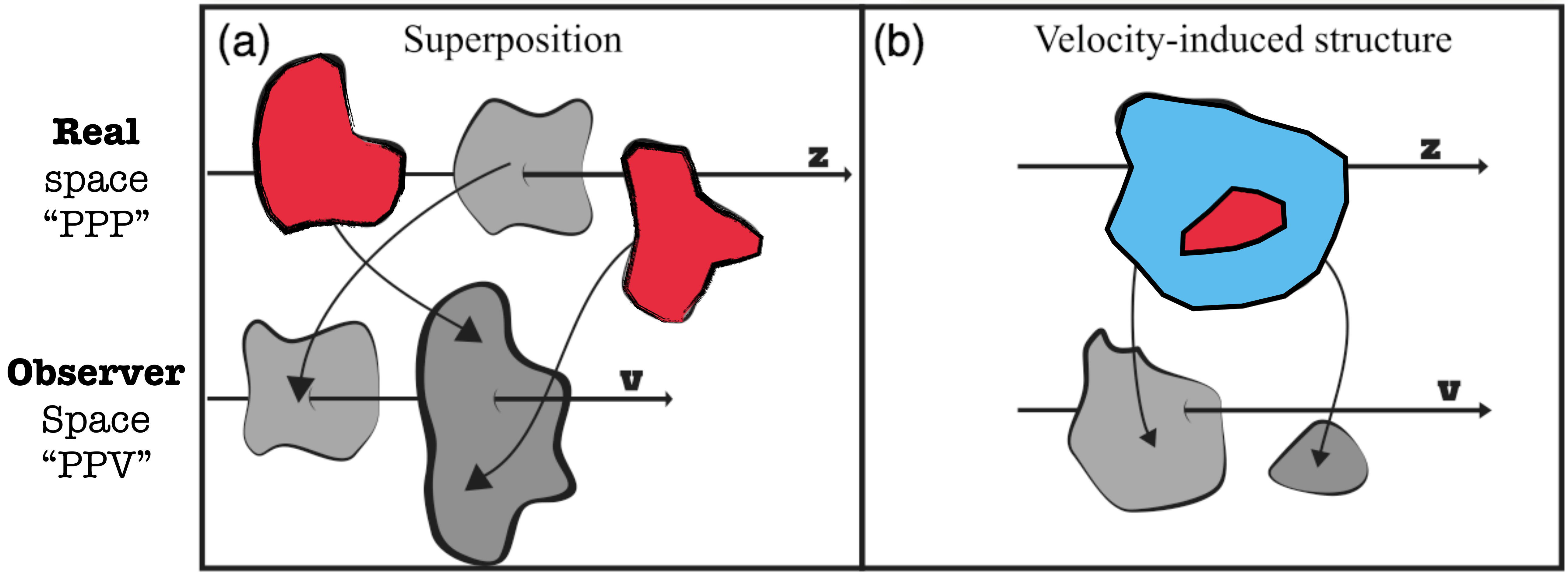


Figure 1. Schematic representation of superposition and velocity-induced structures. Colors indicate velocity. Left: three PPP structures (top) merge into 2 PPV structures (bottom), due to the similar velocity of the front and back structures. Right: a single density structure with internal velocity gradients (top) splits into two PPV structures (bottom).

Beaumont et al. 2013

Tastemaker 3: Opacity

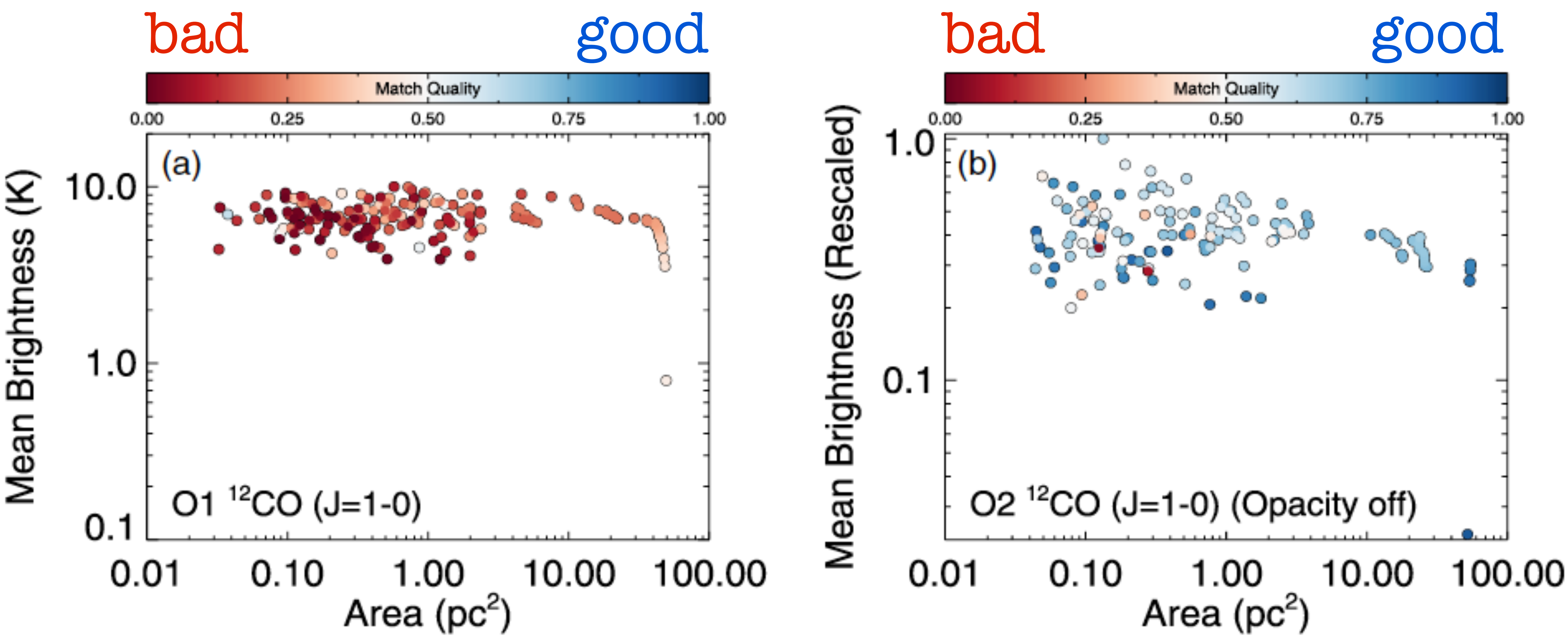
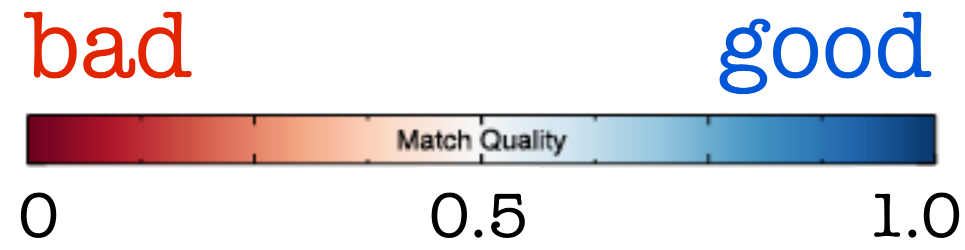
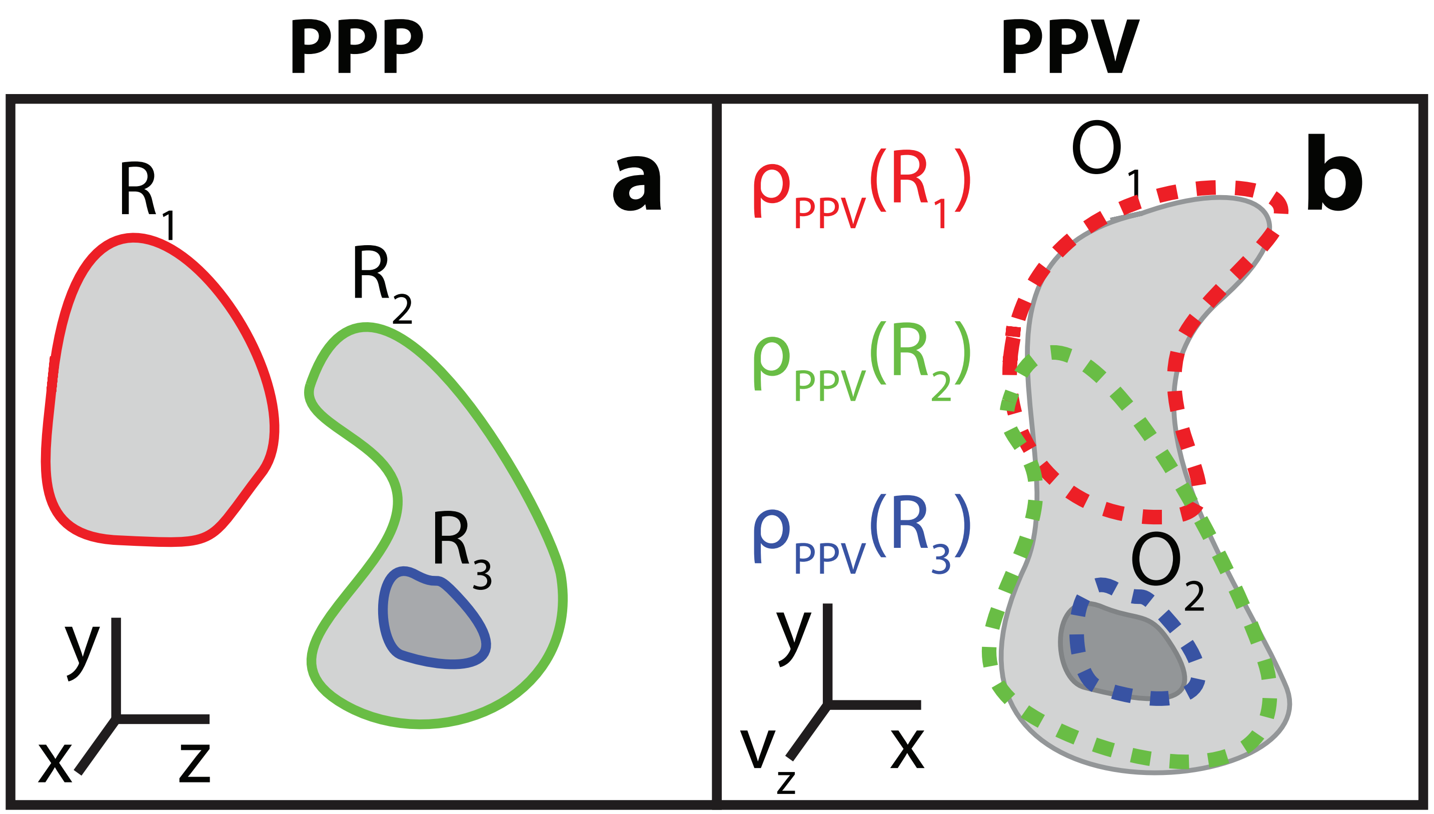


Figure 11. Same as Figure 7, but for the O2 simulation where opacity was disabled during radiative transfer.

Beaumont et al. 2013

Defining "Match Quality", q=





	Similarity R₁	Similarity R₂	Similarity R₃	M	q
O_1	0.4	**0.5**	0	R_2	0.5
O_2	0	0.3	**0.9**	R_3	0.9

1. extract features "R" from ppp dendrogram
2. extract features "O" from ppv dendrogram
3. project features R to ppv, find best matches to "O"
4. measure overlap of best match, assign 0<q<1 quality

Match Quality

good
bad

movies include a noise model, in both cases

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 erg cm^{-2} s^{-1}	No
Constant CO Abundance	No	1.75 e-4
$^{12}CO/^{13}CO$ abundance	70	70
Radiative Transfer Code	RADMC 3D	RADMC 3D
Microturbulence	0.2 km s^{-1}	0.2 km s^{-1}
Metallicity	Solar	N/A
Mean number density (nH)	100 cm^{-3}	58 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%)

Beaumont, Offner, Shetty, Glover & Goodman 2013