Loren 1989
13CO, 2.4 arcmin

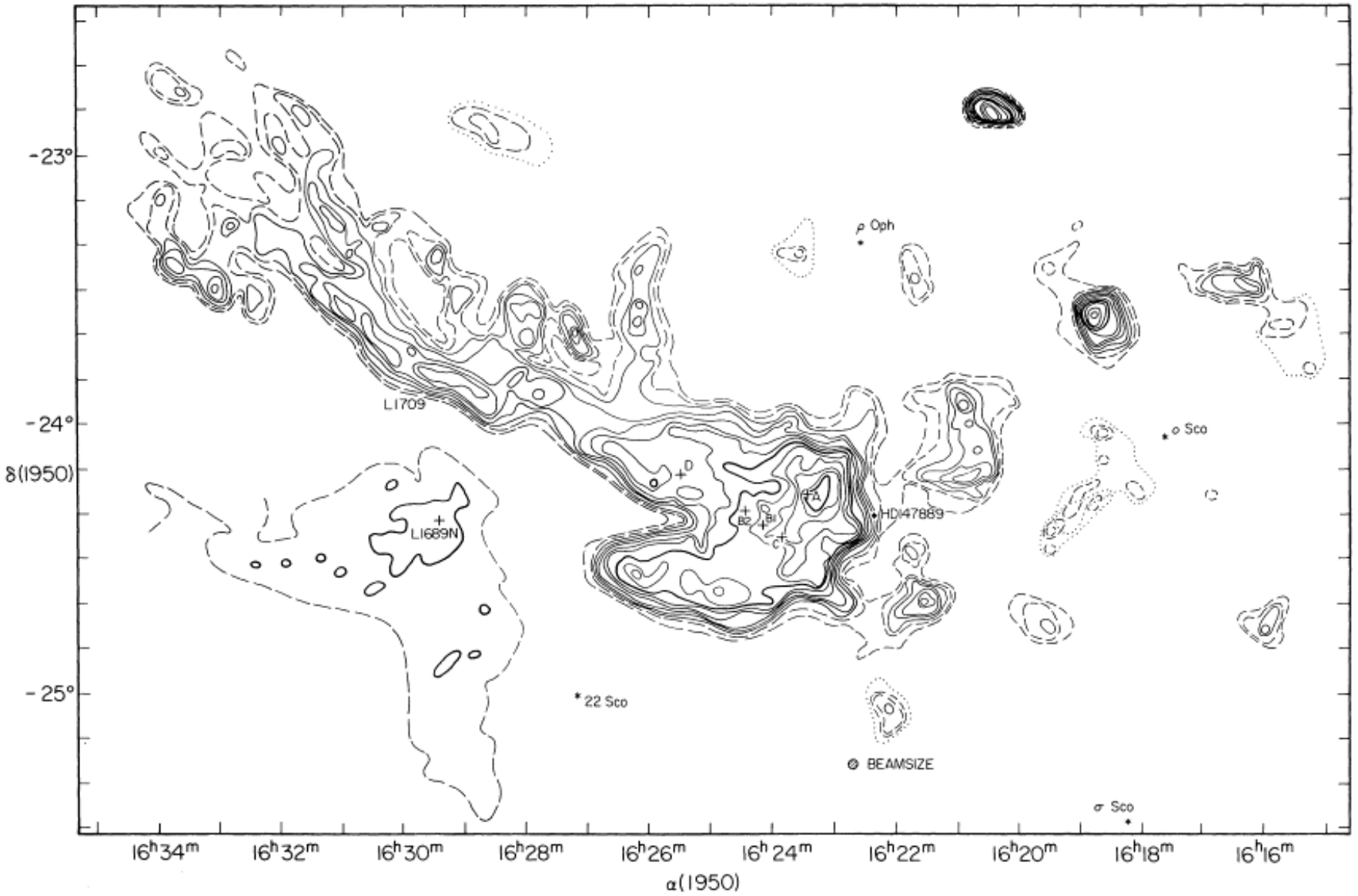


FIG. 1*a*.—Peak $T_R^*(^{13}CO)$ distribution toward the primary mass concentration in the ρ Oph cloud (L1688 and L1709). The relative location of the L1689 cloud is indicated at the lower left. The dashed contours represent the two lowest $T_R^*(^{13}CO)$ contours (2 and 3 K). The solid contours are at $T_R^*(^{13}CO)$ = 4, 5, 6, 7, 8, 10, 12, 14, 16, 18, and 20 K, with the 10 and 20 K contours highlighted as thicker lines. The $T_R^*(^{13}CO)$ = 1 K contour is shown as a dotted line in a few selected regions to locate a few very weak cloud components. The locations of the early B stars in the mapped area are indicated. Dense cores that have been located are labeled by letters.

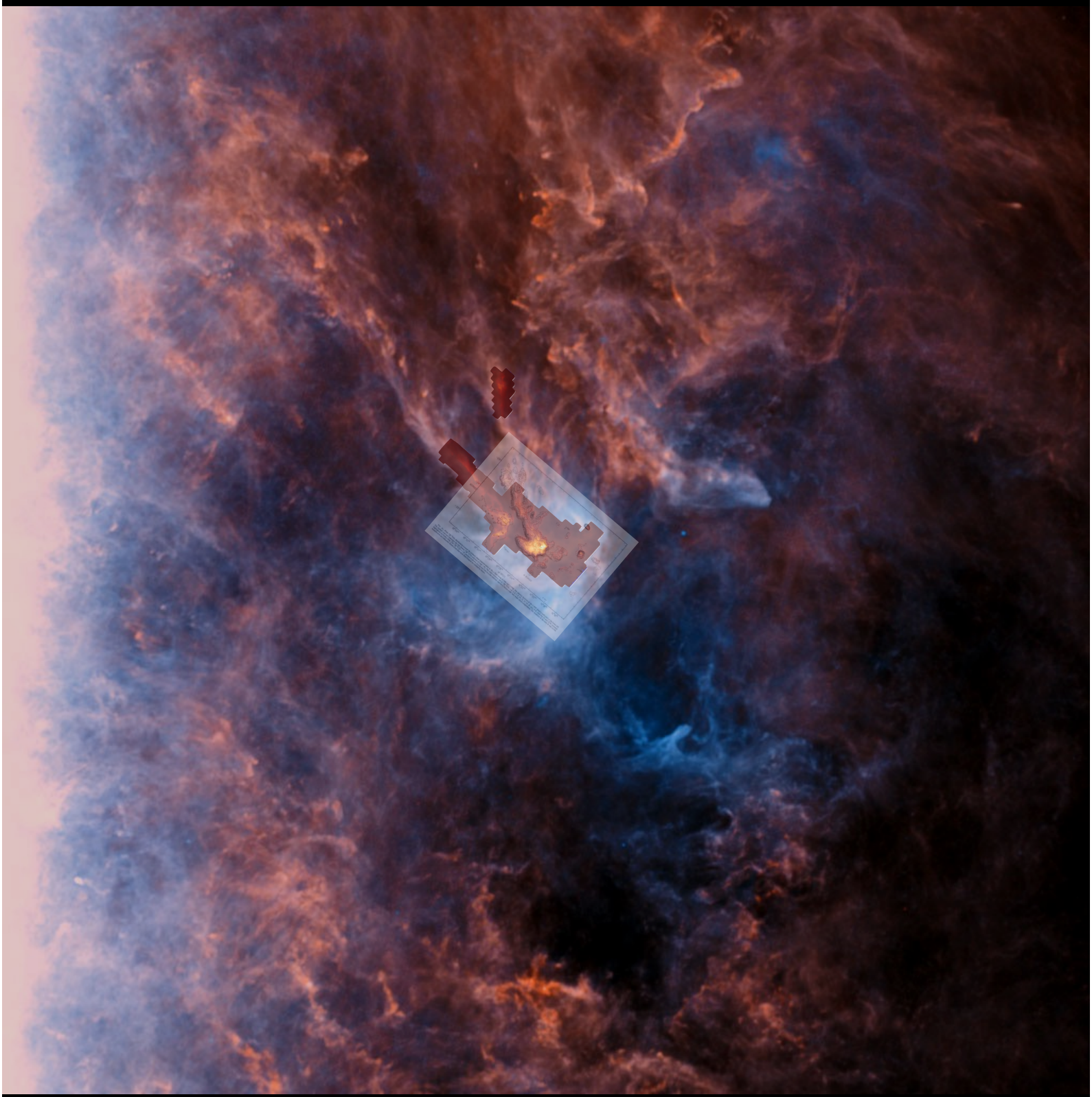
Alves+17
Planck “250”, 350, 500
~5 arcmin

Loren 1989
13CO, 2.4 arcmin

Alves+17
Planck “250”, 350, 500
~5 arcmin

Loren 1989
13CO, 2.4 arcmin

Ridge et al. 2006
13CO, 46 arcsec



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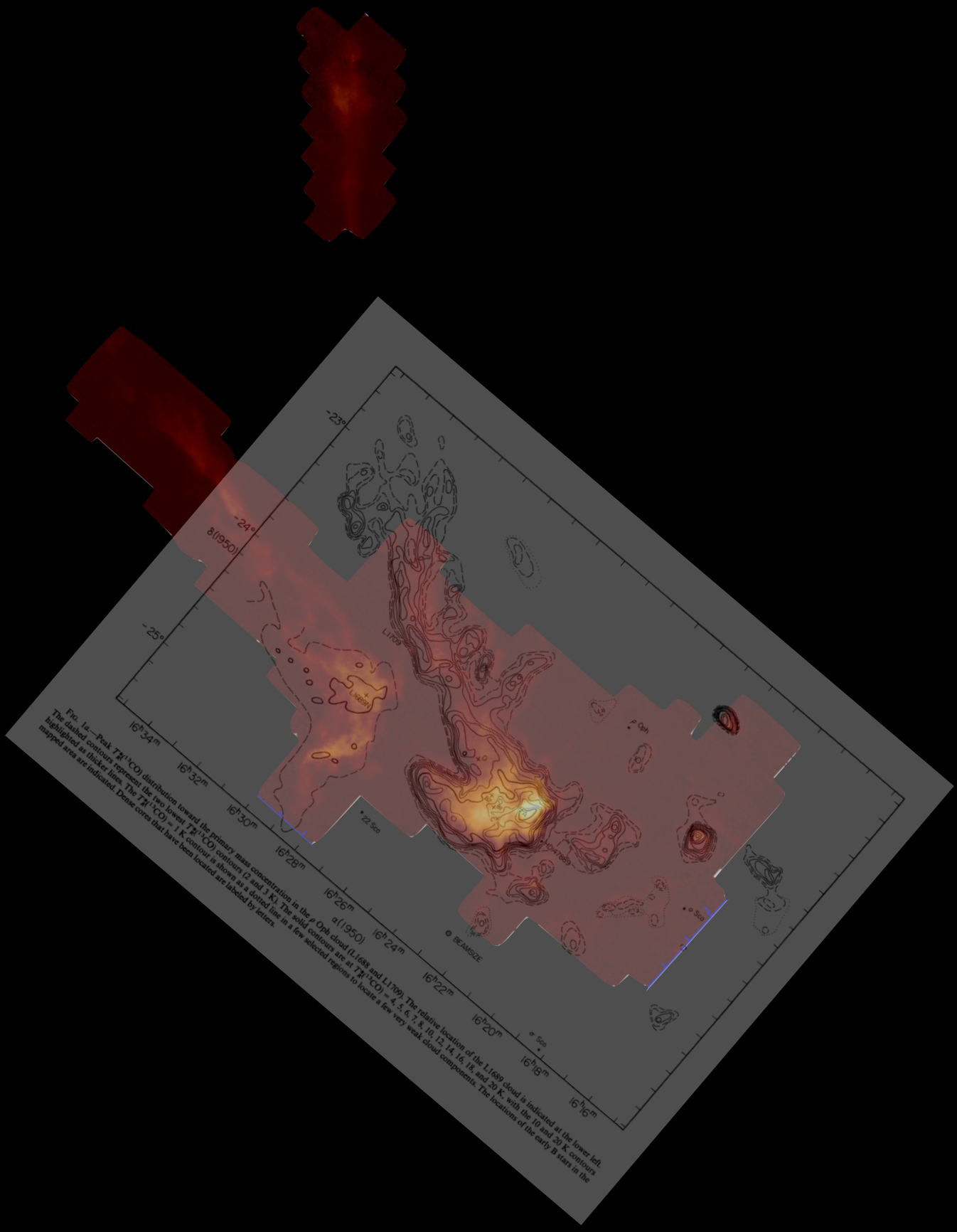

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Loren 1989
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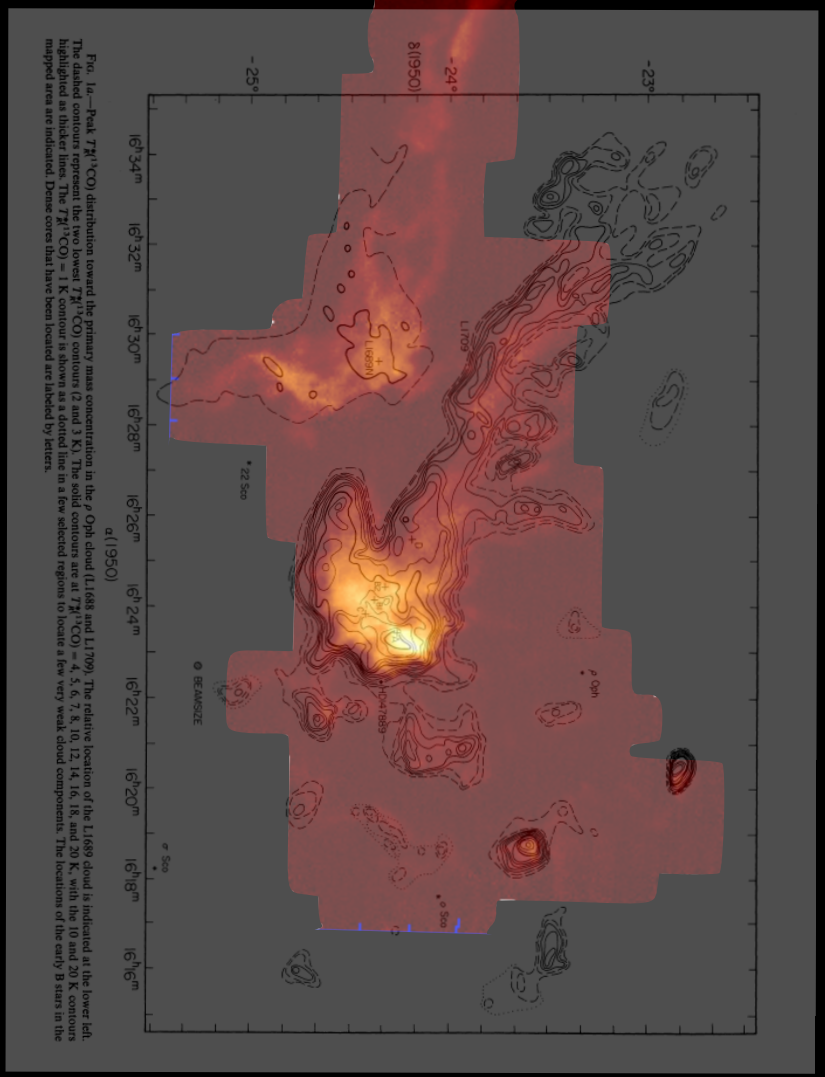

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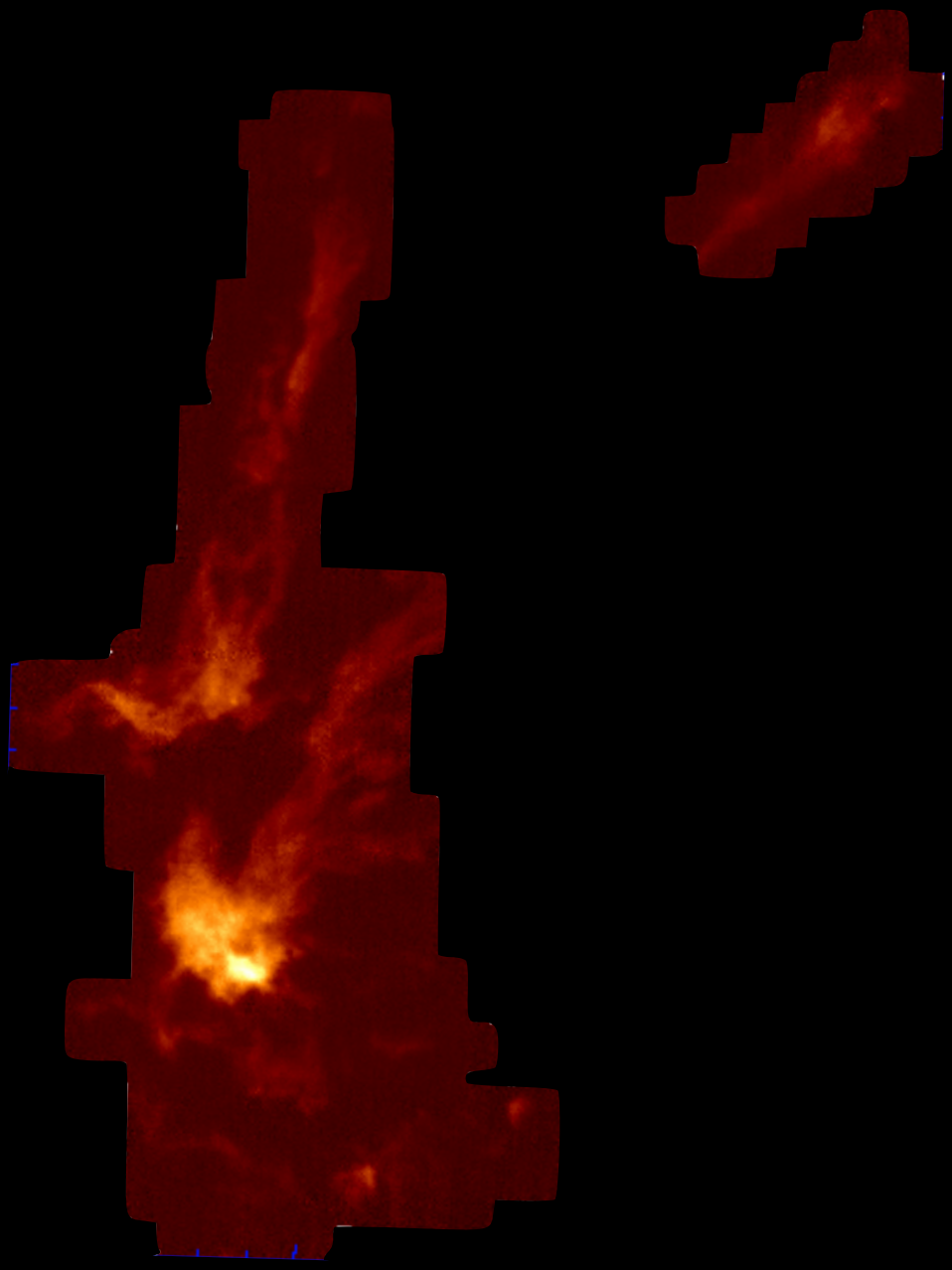

Loren 1989
13CO, 2.4 arcmin

Ridge et al. 2006
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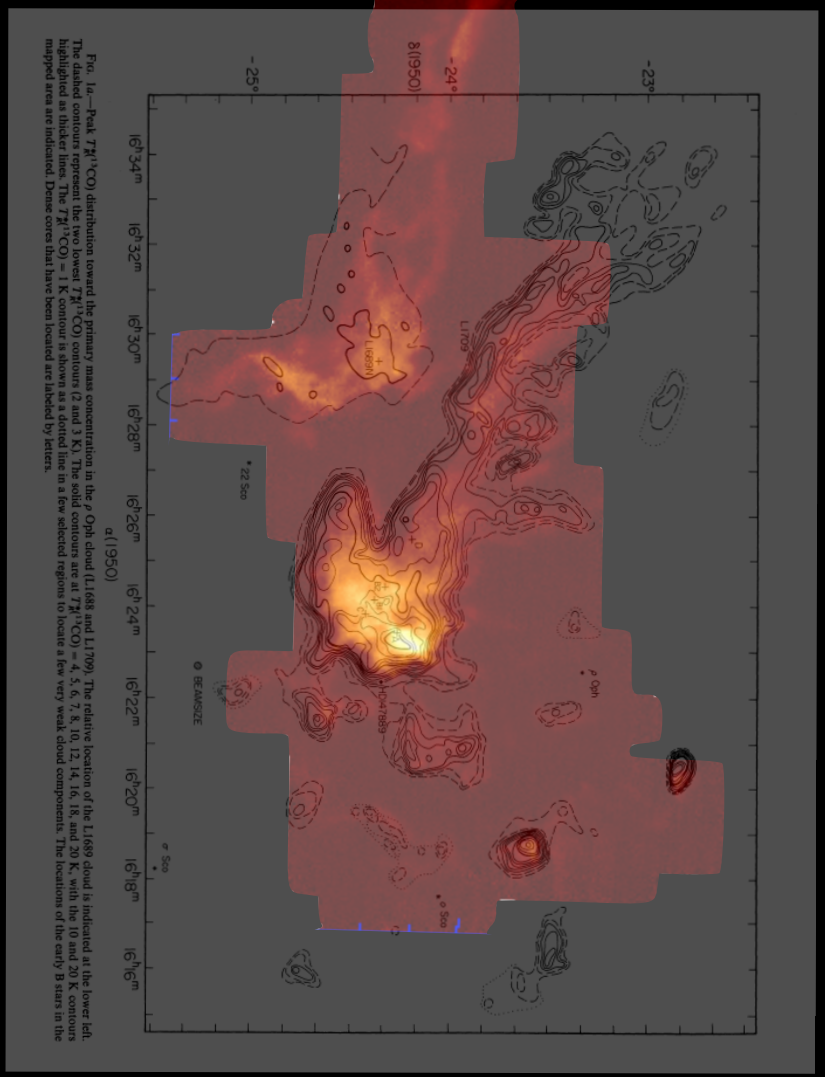

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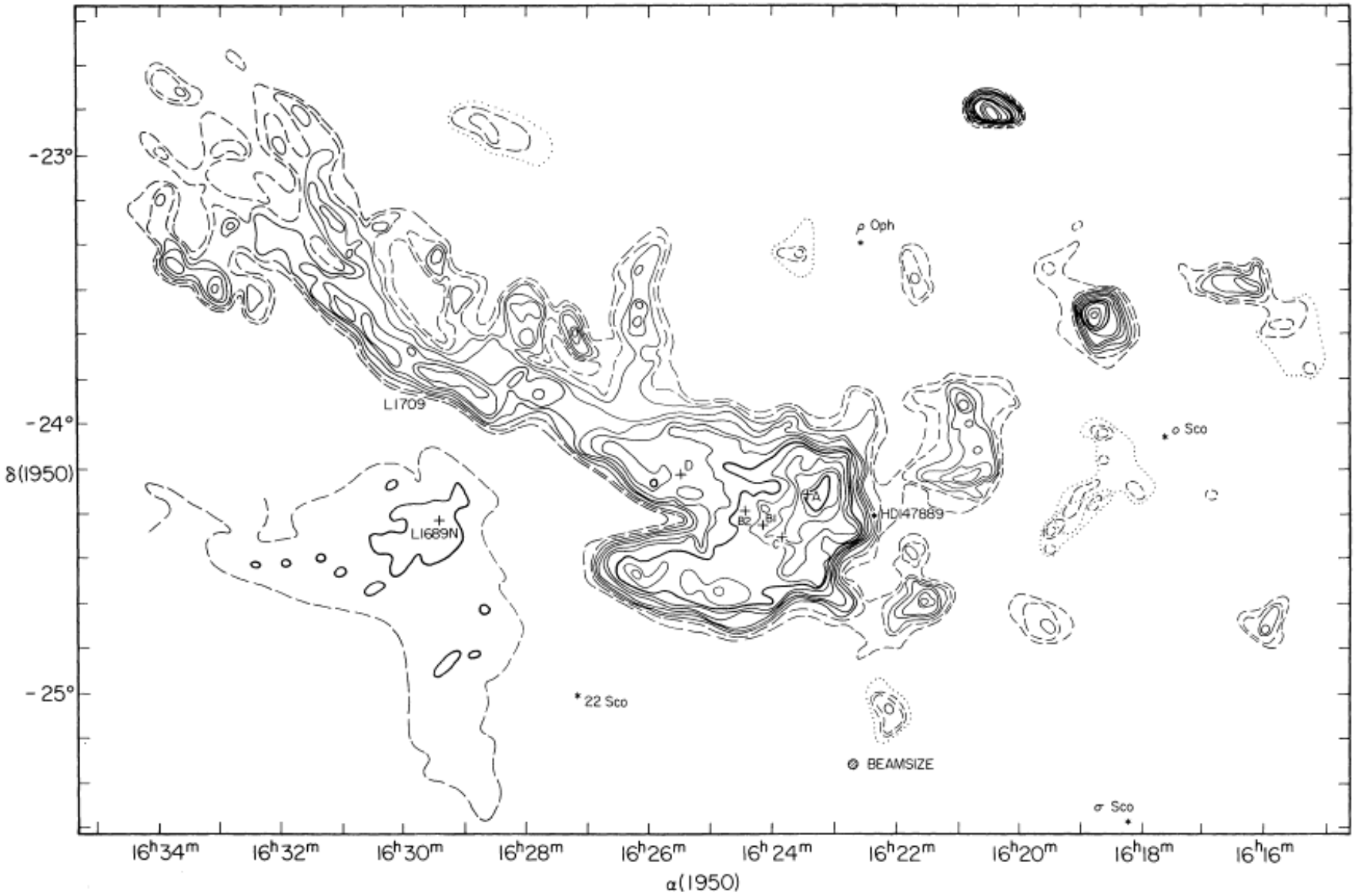

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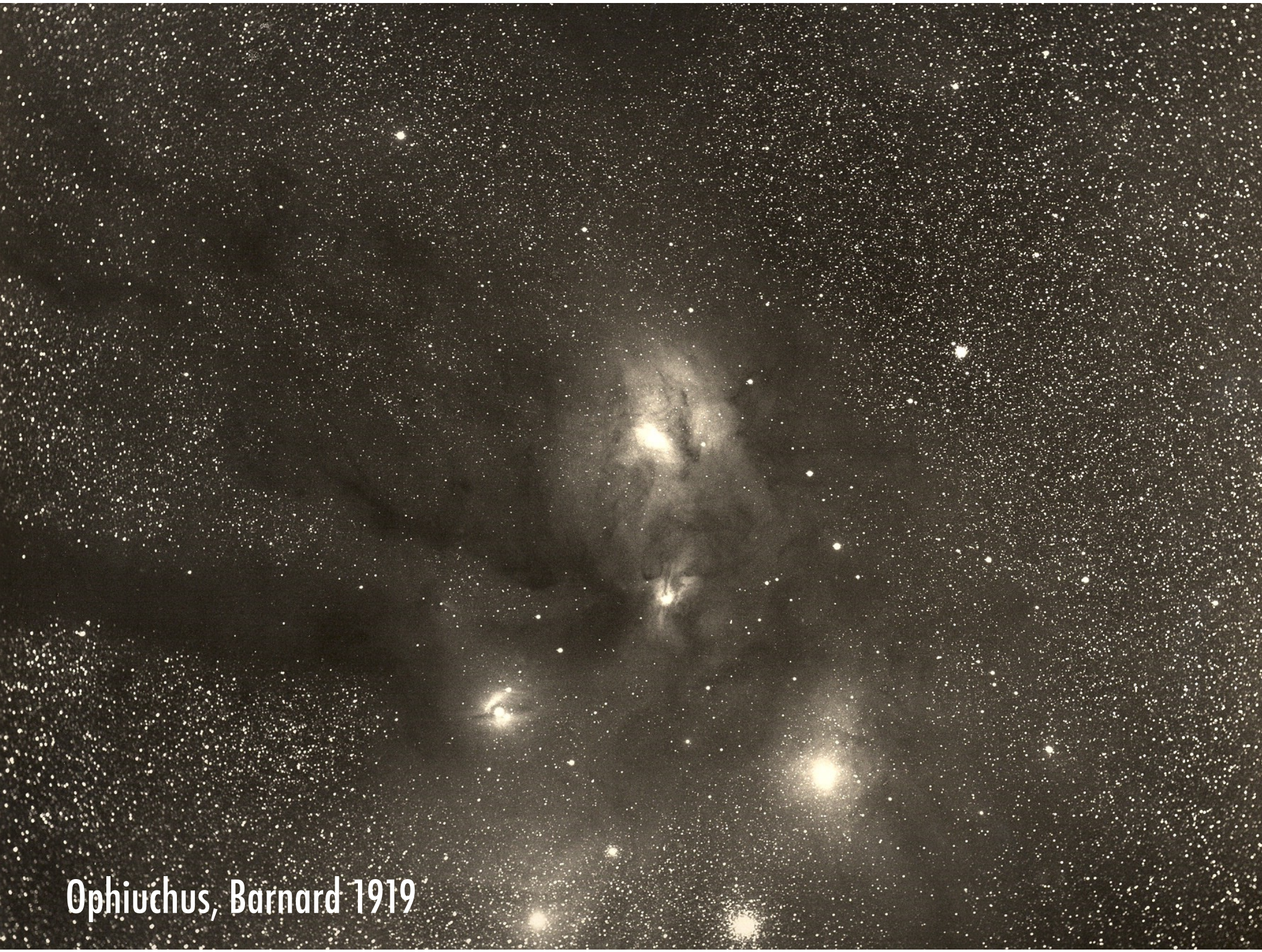
(WHEN) ARE FILAMENTS FUNDAMENTAL?

Alyssa A. Goodman
Harvard-Smithsonan Center for Astrophyscs
Radcliffe Institute for Advanced Study
@aagie

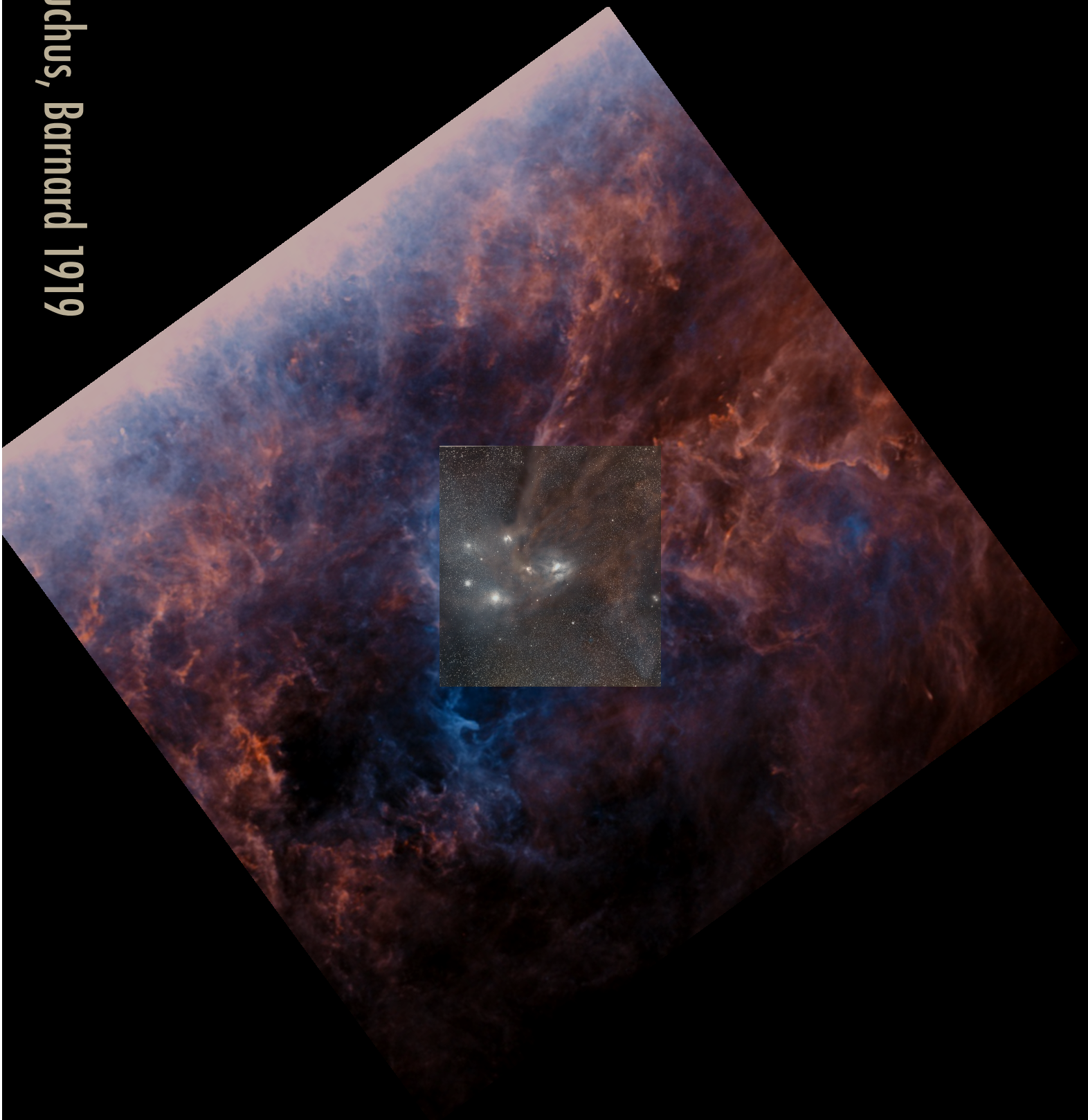
Ophiuchus, Barnard 1919


Ophiuchus, Barnard 1919

Alves+17
Planck “250”, 350, 500
~5 arcmin
Ophiuchus, Barnard 19/19

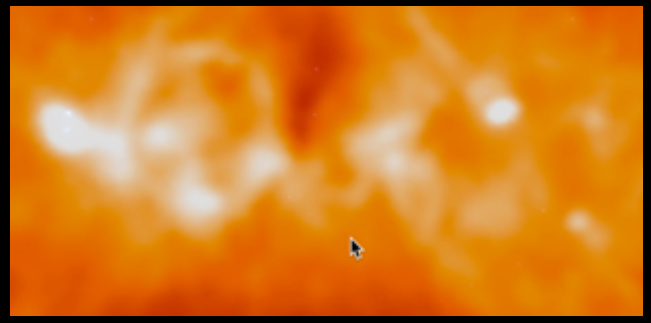
Alves+17
Planck “250”, 350, 500
~5 arcmin

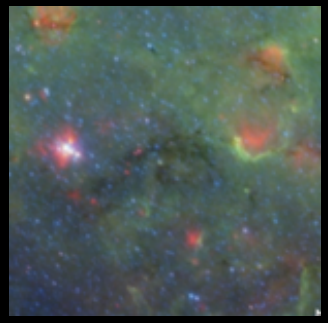
Ophiuchus, Barnard 1919



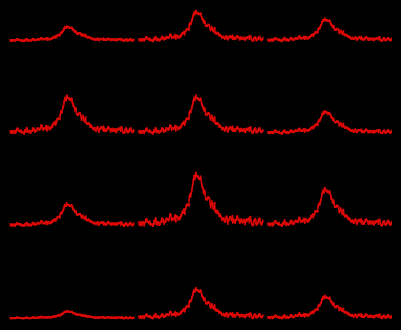
WHAT DO WE "SEE"

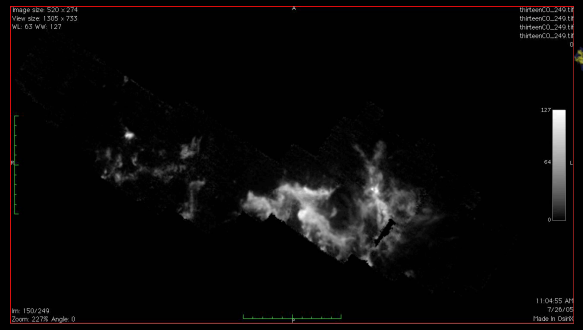
Dust

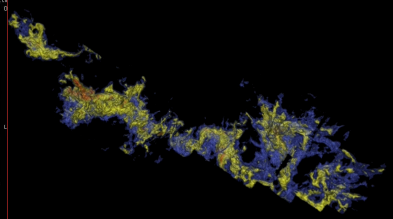




Gas

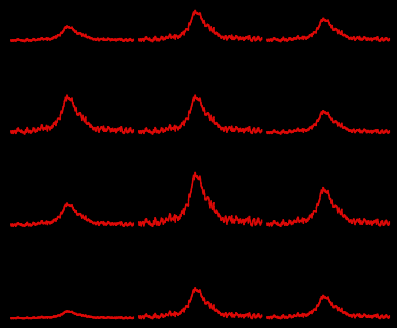


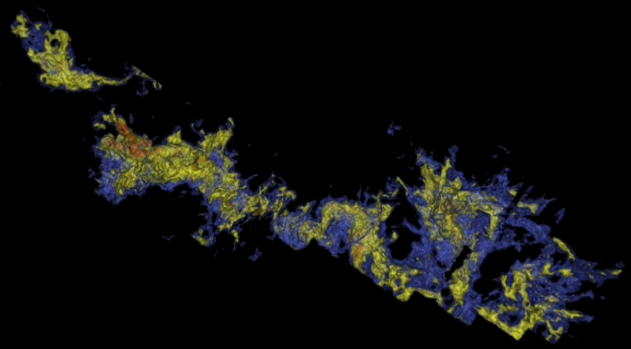




"Stars"

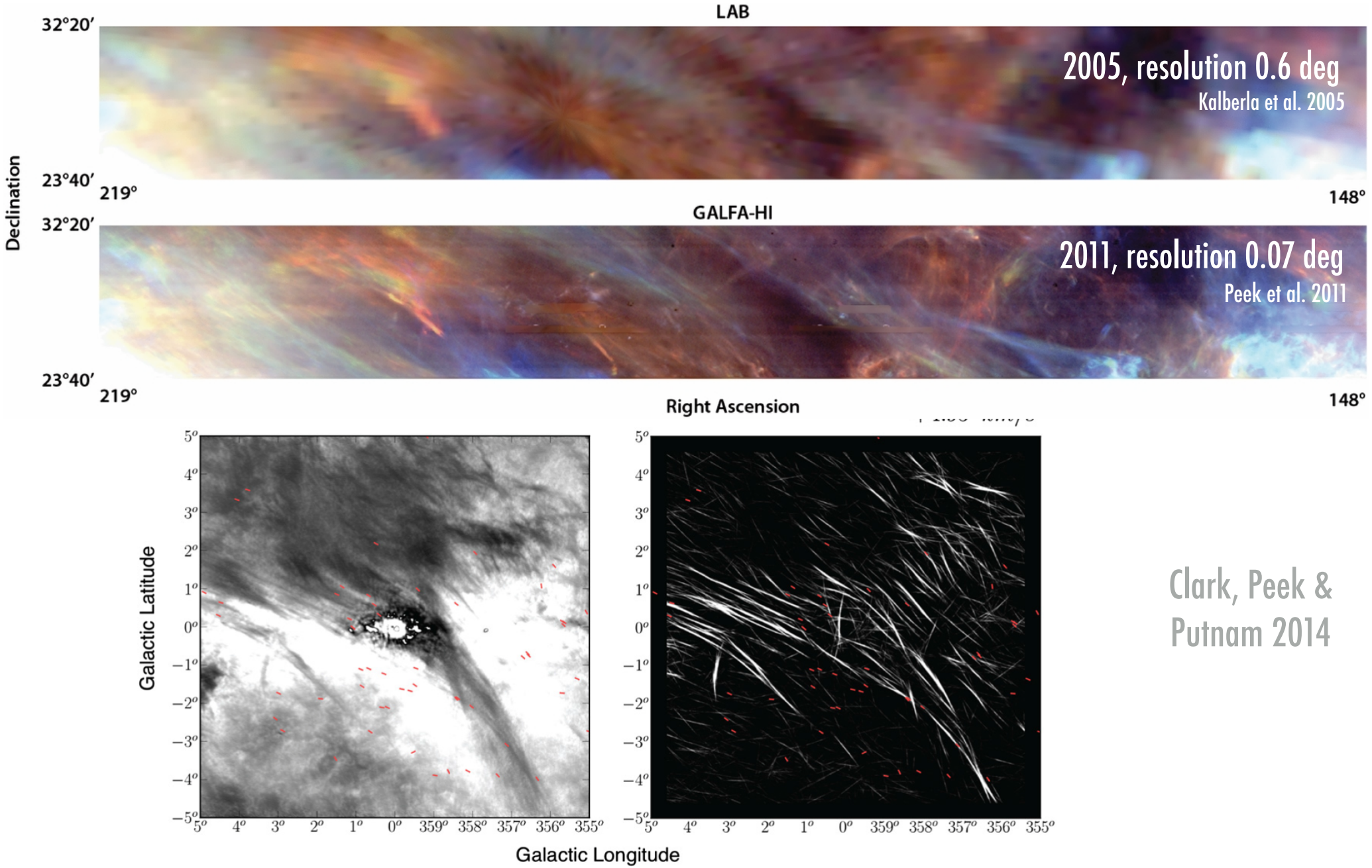
HOW WE "SEE"





IN 3D

Atomic Gas



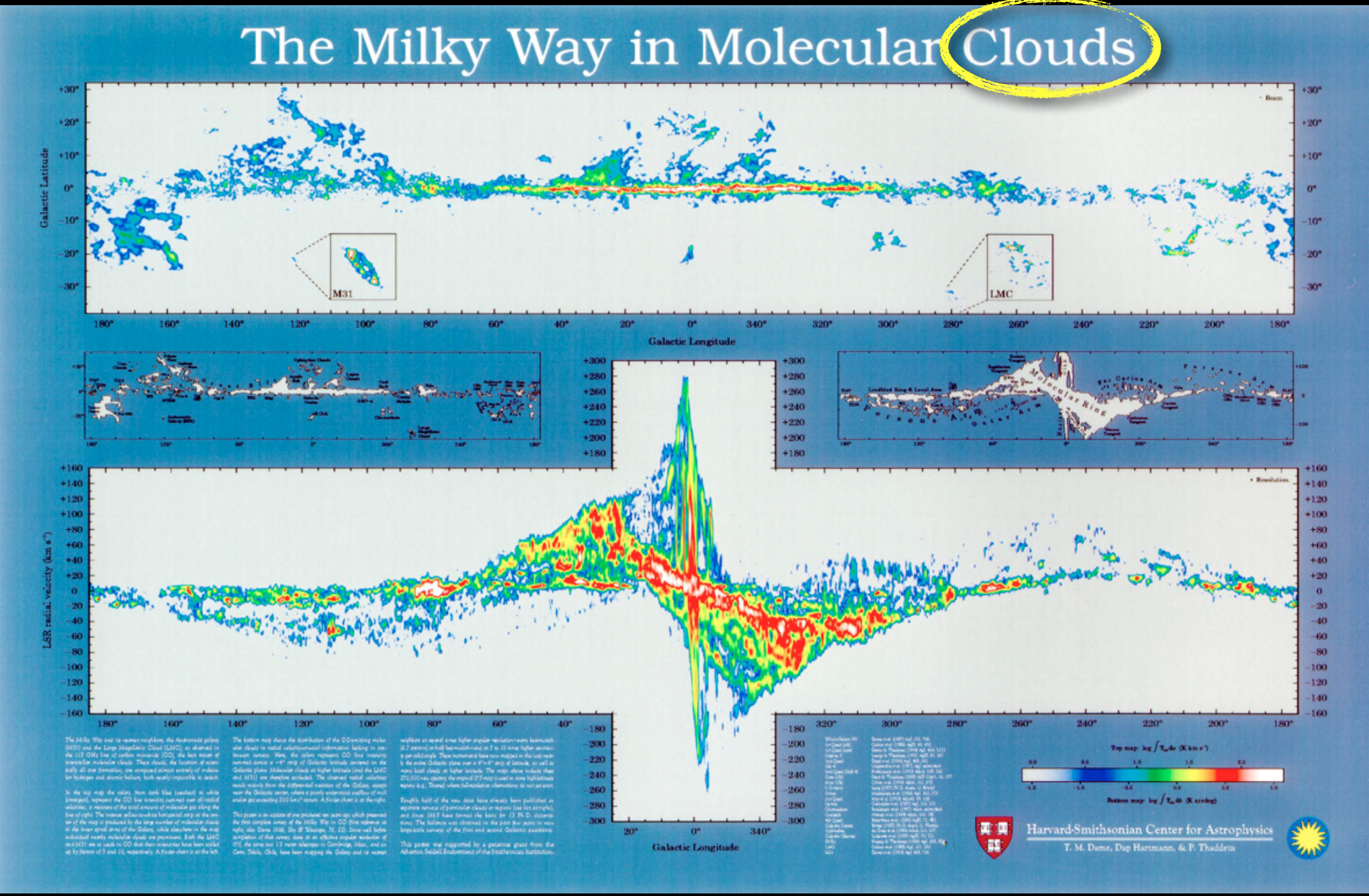
Clark, Peek & Putnam 2014

Figure 10. Riegel–Crutcher cloud (Section 6) in H I absorption (left) and RHT backprojection (right). Overlaid pseudovectors represent polarization angle measurements from the Heiles (2000) compilation. In the left panel, the intensity scale is linear from −20 K (white) to −120 K (black).

(A color version of this figure is available in the online journal.)

Molecular Gas

Dame et al. 2001



Molecular Gas "Clouds"

Rice et al. 2016

video: Matt Pasquini

The Astrophysical Journal, 822:52 (27pp), 2016 May 1 doi:10.3847/0004-637X/822/1/52
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CrossMark

A UNIFORM CATALOG OF MOLECULAR CLOUDS IN THE MILKY WAY

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[1] Department of Astronomy, University of Michigan, 311 West Hall, 1085 South University Avenue, Ann Arbor, MI 48109, USA; tsrice@umich.edu
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Received 2015 July 14; accepted 2016 February 4; published 2016 May 3

ABSTRACT

The all-Galaxy CO survey of Dame et al. is by far the most uniform, large-scale Galactic CO survey. Using a dendrogram-based decomposition of this survey, we present a catalog of 1064 massive molecular clouds throughout the Galactic plane. This catalog contains 2.5×10^8 solar masses, or $25^{+10.7}_{-5.8}$% of the Milky Way's estimated H_2 mass. We track clouds in some spiral arms through multiple quadrants. The power index of Larson's first law, the size-linewidth relation, is consistent with 0.5 in all regions—possibly due to an observational bias—but clouds in the inner Galaxy systematically have significantly (~30%) higher linewidths at a given size, indicating that their linewidths are set in part by the Galactic environment. The mass functions of clouds in the inner Galaxy versus the outer Galaxy are both qualitatively and quantitatively distinct. The inner Galaxy mass spectrum is best described by a truncated power law with a power index of $\gamma = -1.6 \pm 0.1$ and an upper truncation mass of $M_0 = (1.0 \pm 0.2) \times 10^7\,M_\odot$, while the outer Galaxy mass spectrum is better described by a non-truncating power law with $\gamma = -2.2 \pm 0.1$ and an upper mass of $M_0 = (1.5 \pm 0.5) \times 10^6\,M_\odot$, indicating that the inner Galaxy is able to form and host substantially more massive GMCs than the outer Galaxy. Additionally, we have simulated how the Milky Way would appear in CO from extragalactic perspectives, for comparison with CO maps of other galaxies.

Key words: Galaxy: general – ISM: clouds – ISM: molecules

Supporting material: machine-readable table

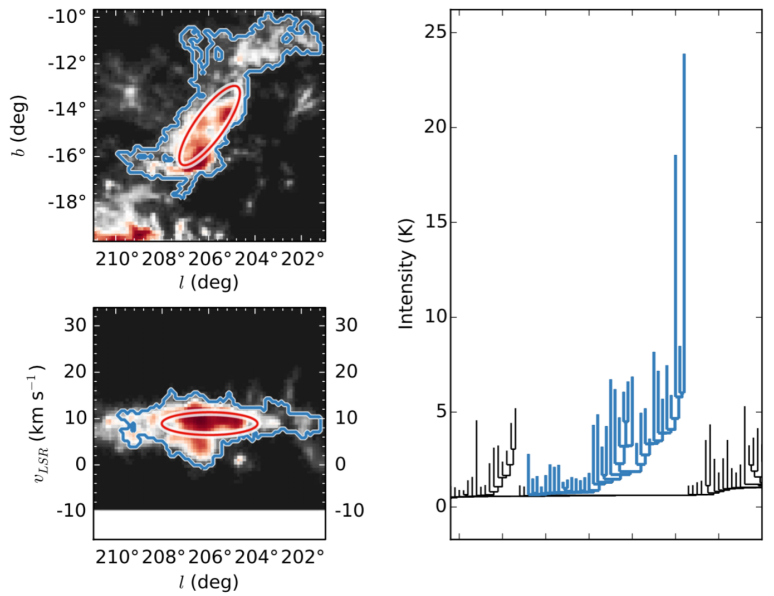
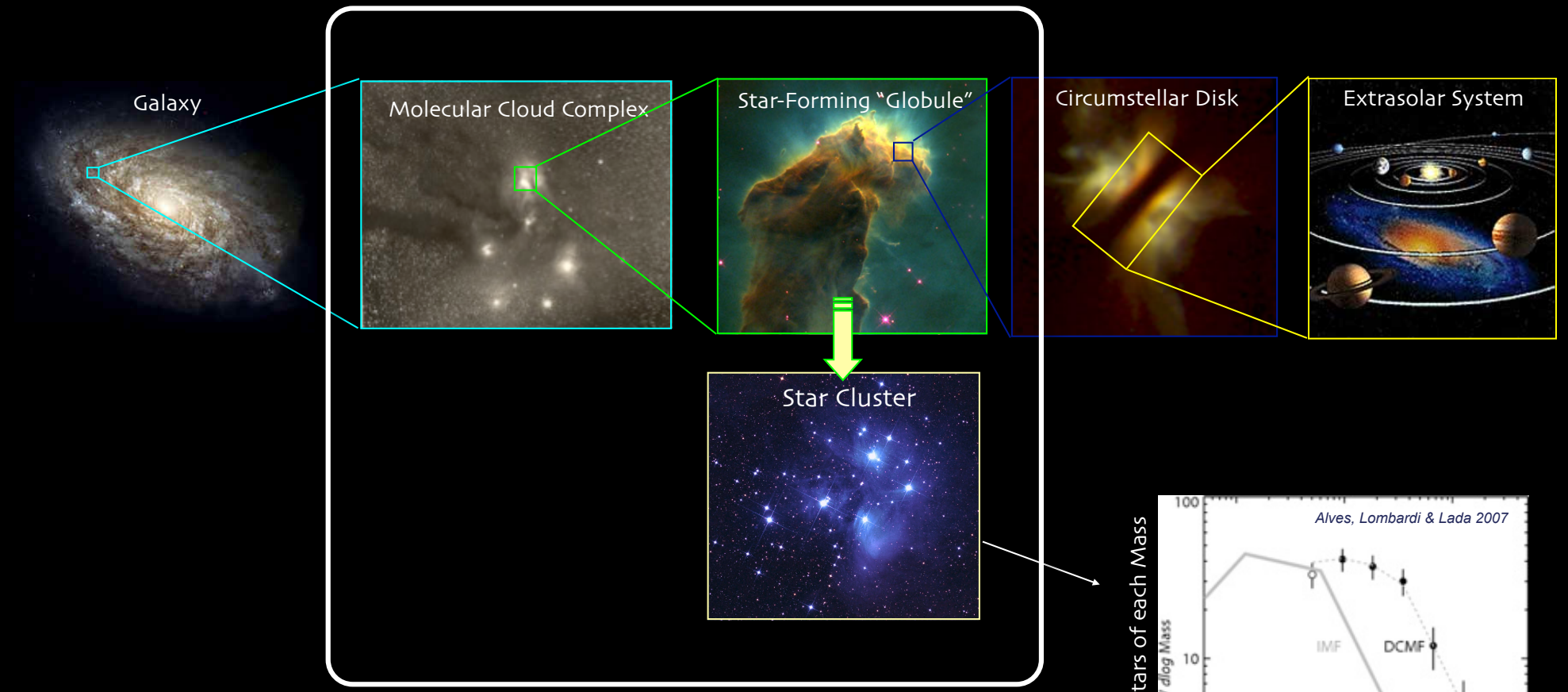
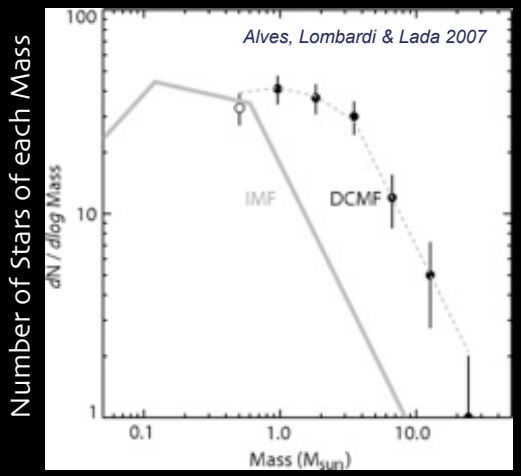


Figure 2. Example dendrogram extraction of Orion B: a nearby, well-studied giant molecular cloud. Top left: (l, b) thumbnail of the cloud and its neighboring region as seen on the sky. Bottom left: (l, v) thumbnail of the same region. Right: dendrogram cutout, with Orion B's structures highlighted in blue. The pixels corresponding to the highlighted dendrogram structures are outlined in the blue contour (in projection); a representative ellipse is drawn in red, with semimajor axis length equal to the second moment along each relevant dimension (as calculated in Section 2.2). Data come from DHT Survey #27 (the Orion complex).

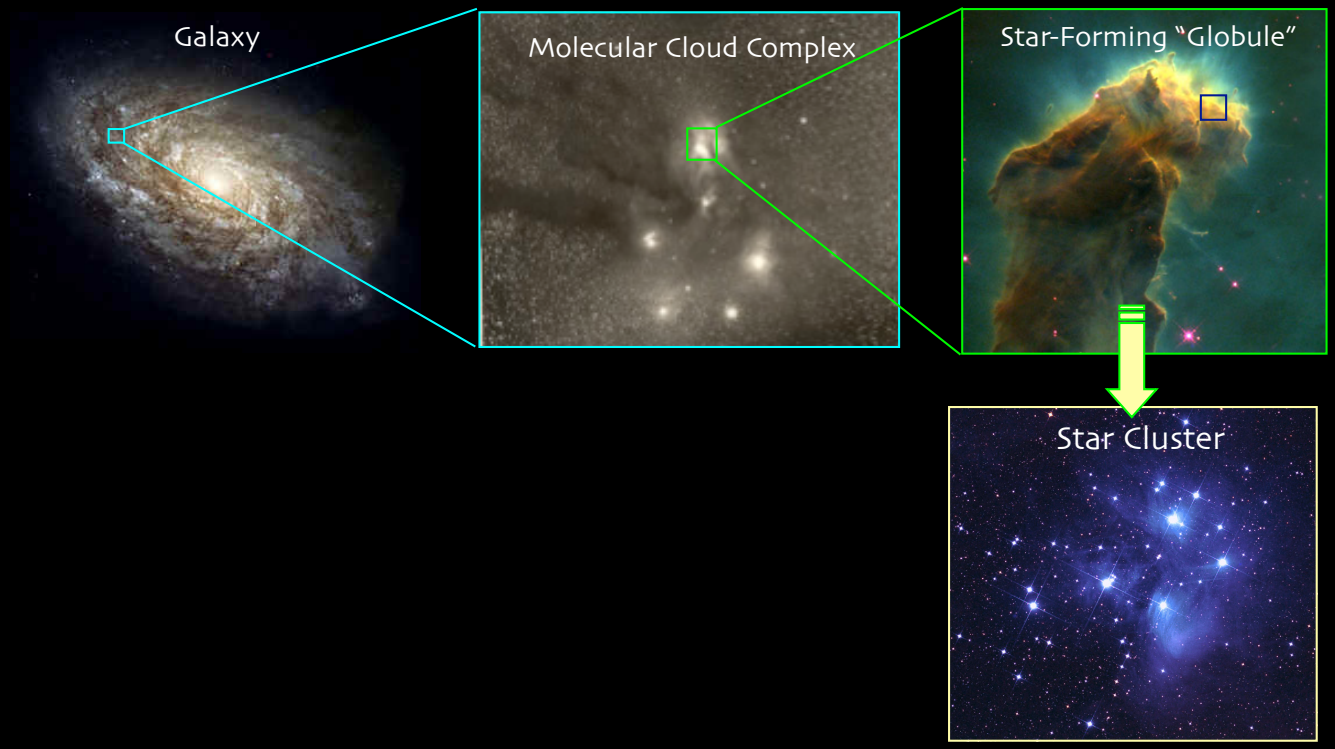
HOW STARS FORM

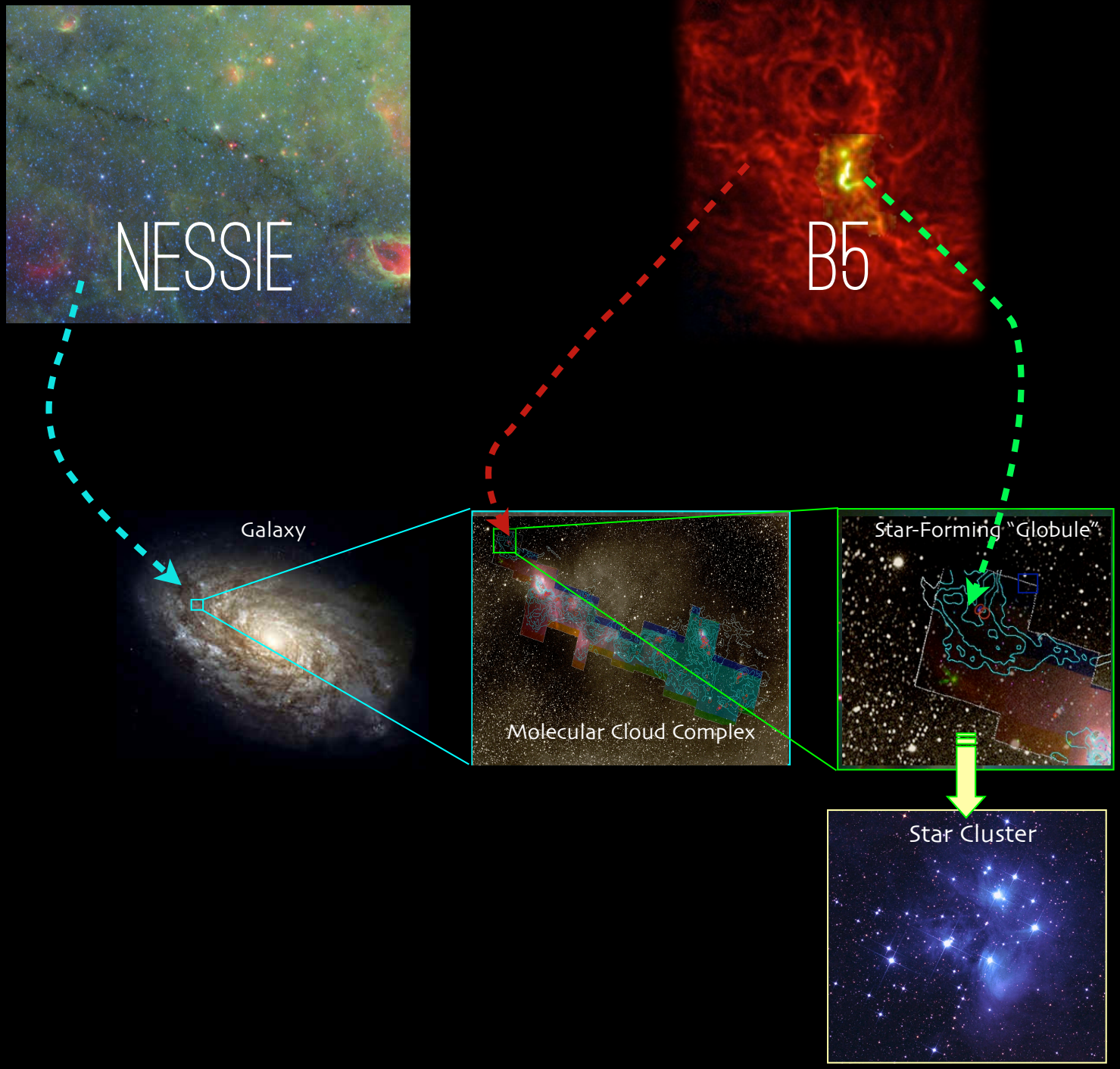


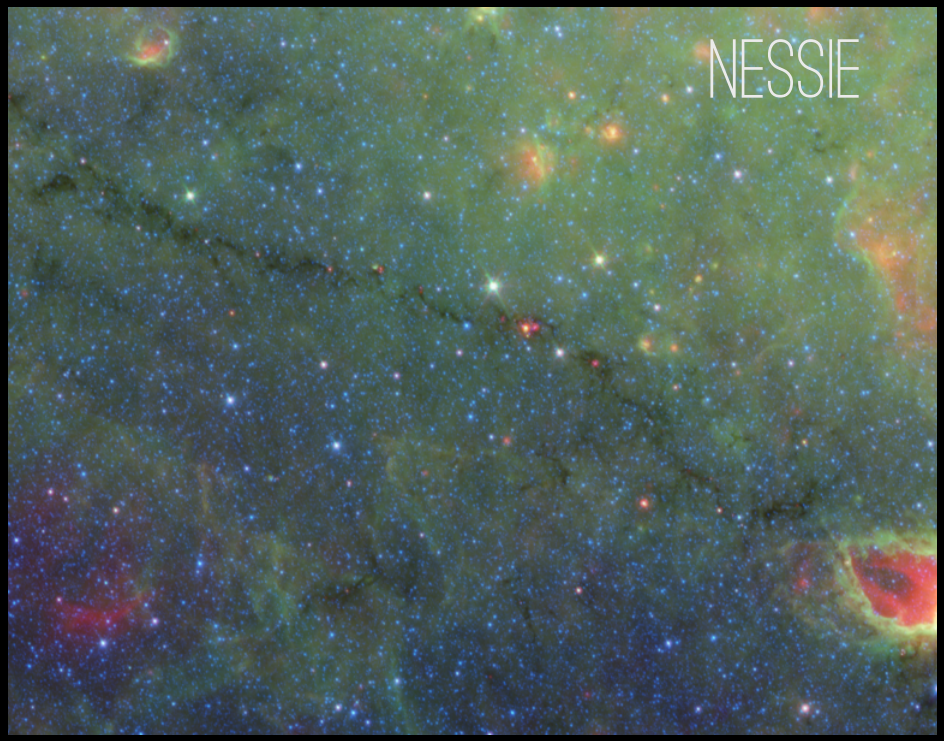


Number of Stars of each Mass

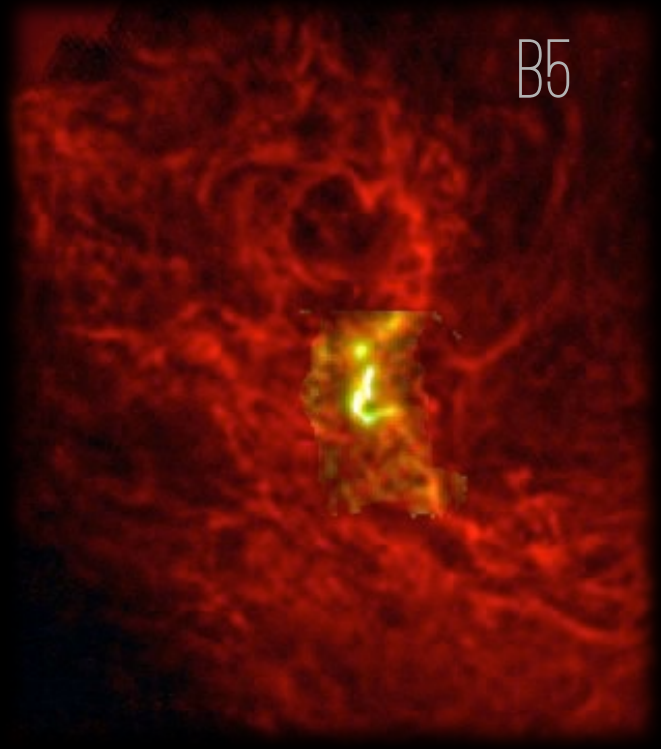
Stellar Mass


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


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



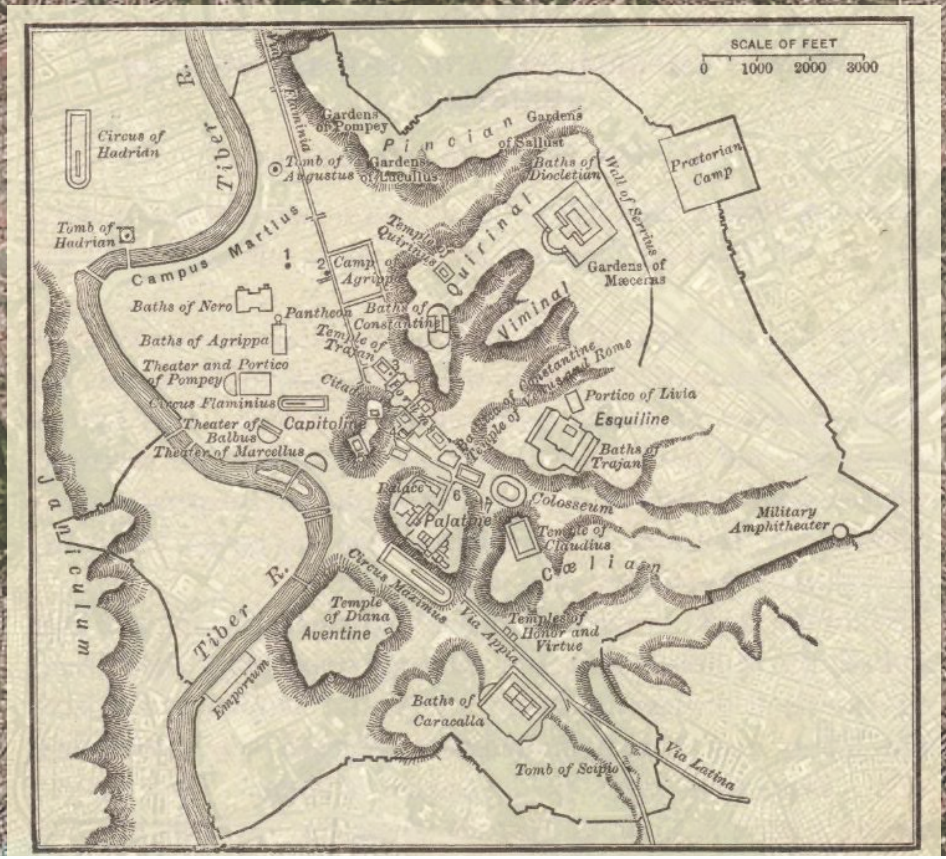
>100 pc



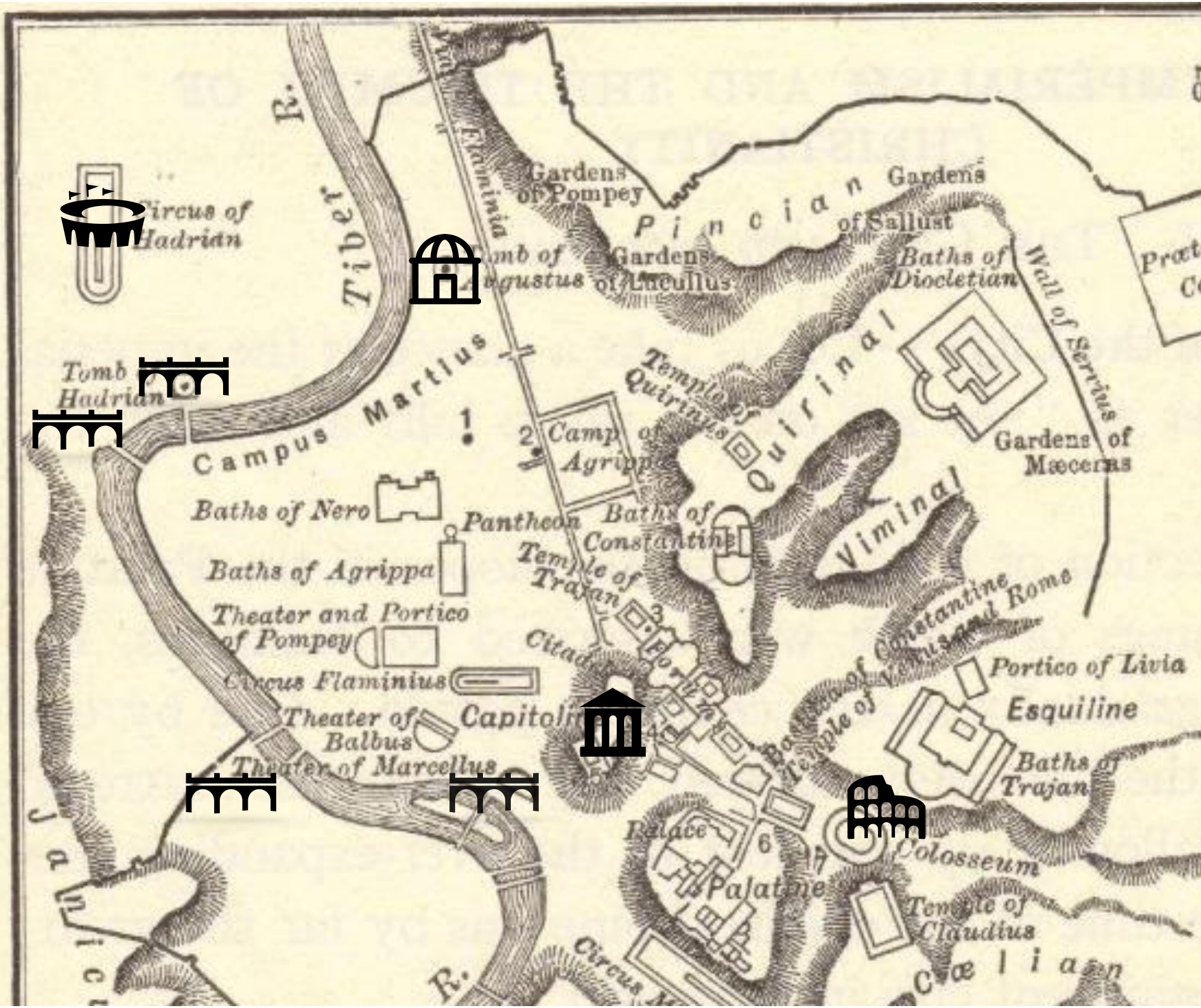
~0.01 to 10 pc

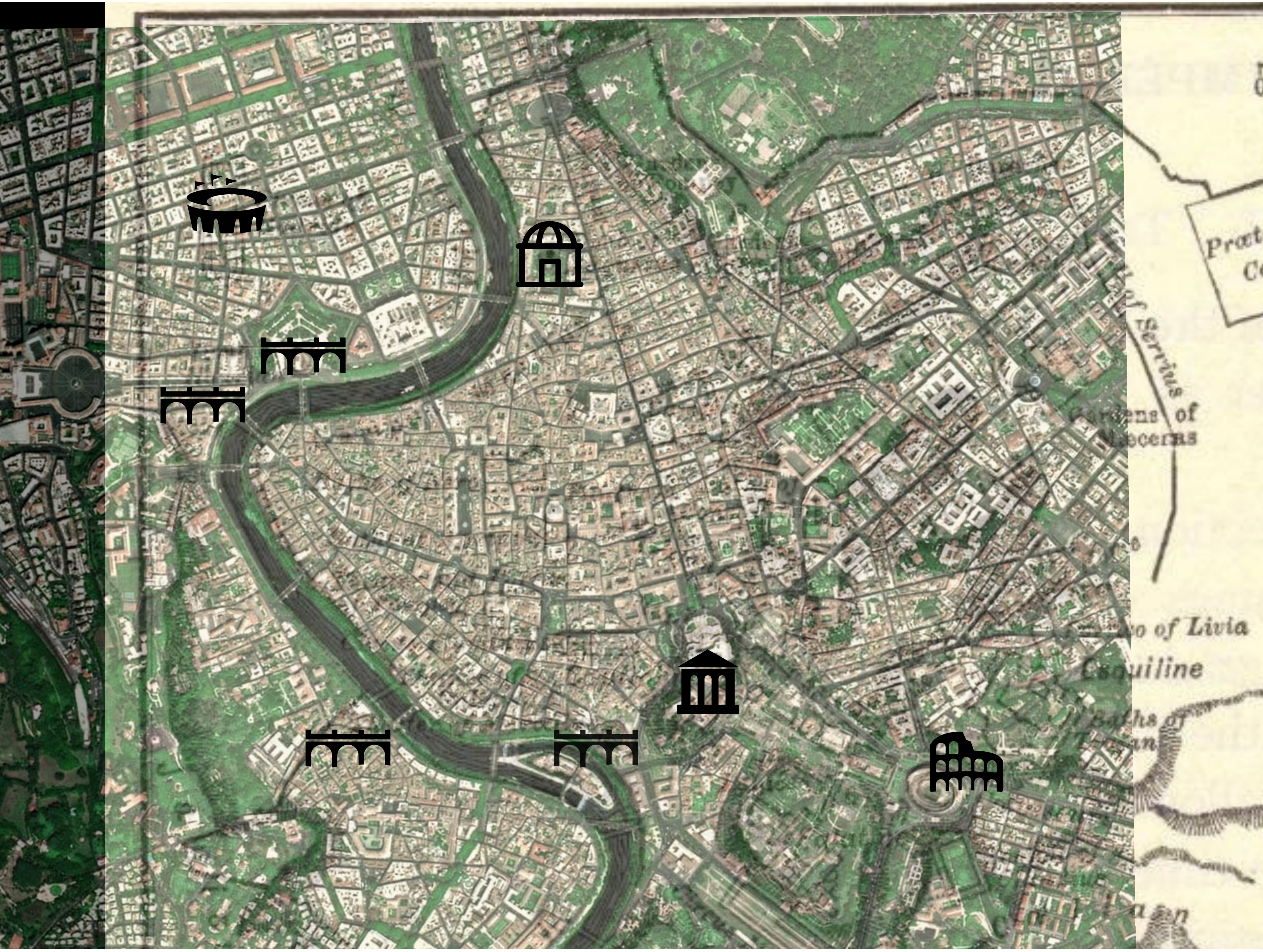
ROME
2017 AD

2000 YEARS AGO...



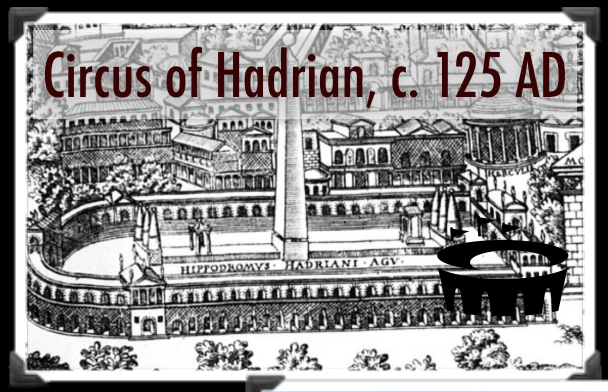
2000 YEARS AGO...

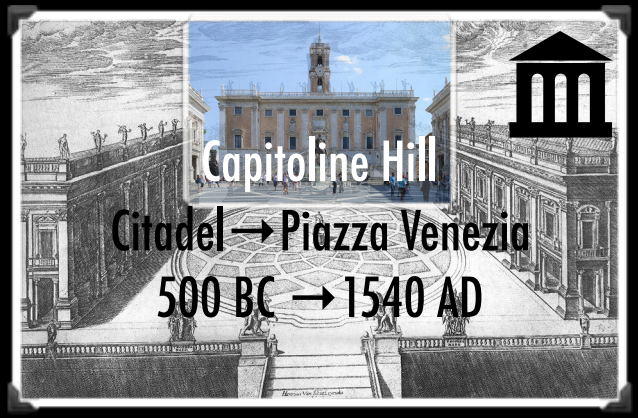


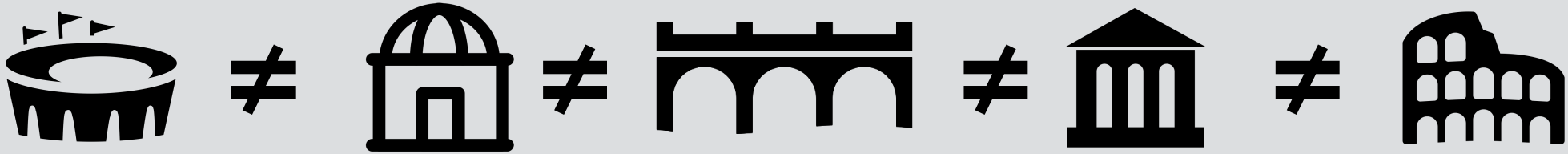


Servius
of Livia

All Stone All in Rome



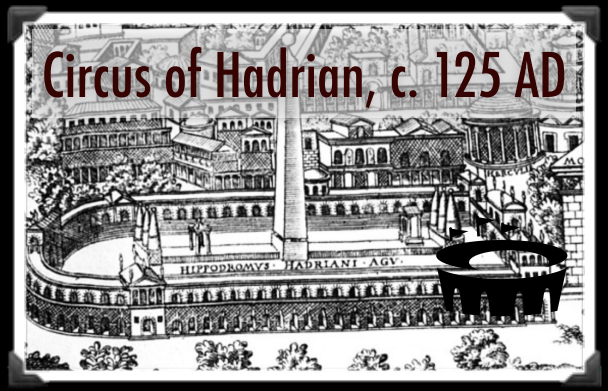




A sequence…
but not of time
…or of type

~~Replaced~~

Erased



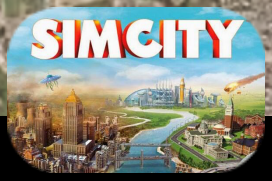
Extant

Disappearing

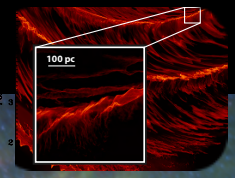
New

ROME

is a mixture of



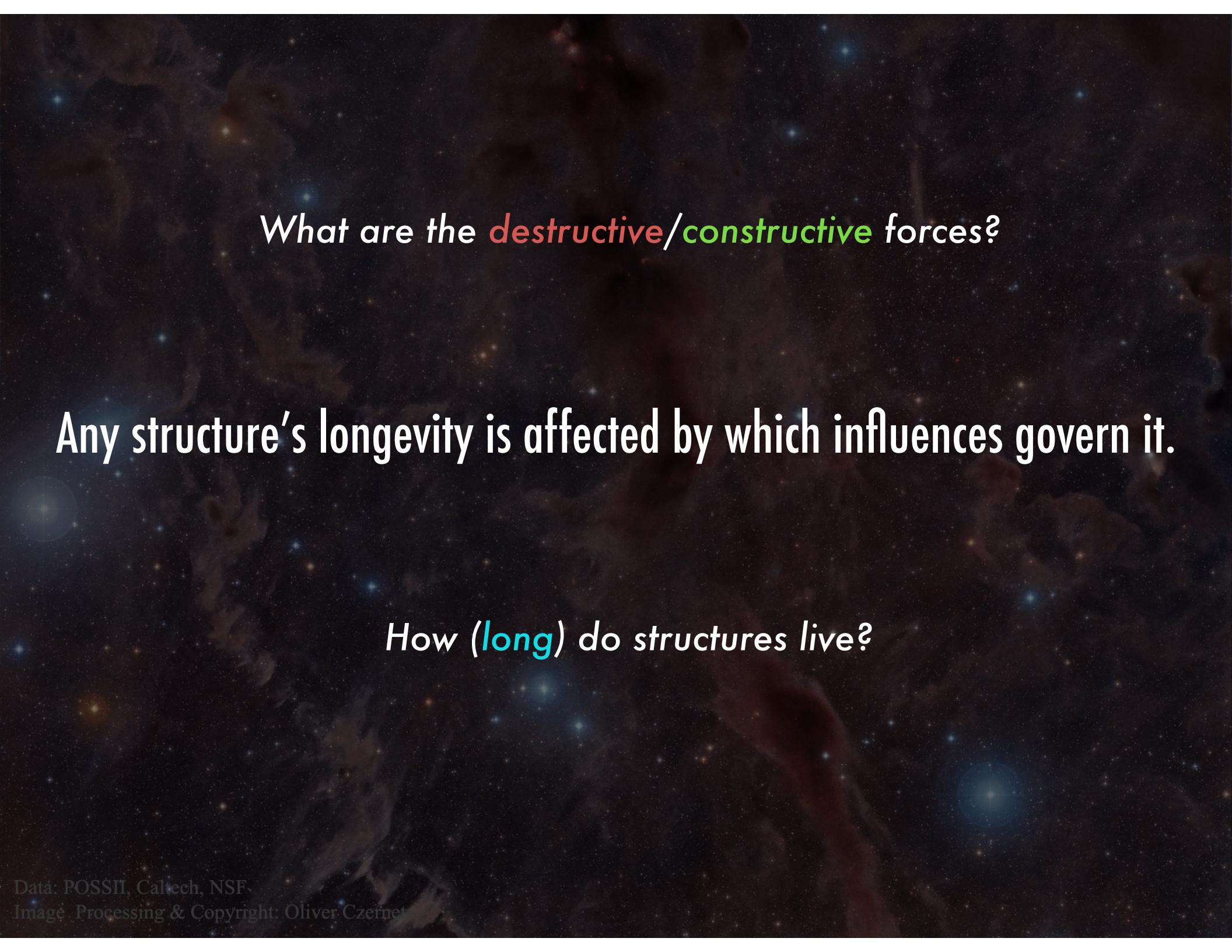
Erased Disappearing ~~Replaced~~* Extant New



and so is

THE STAR-FORMING ISM

*~~Recycled?~~


What are the destructive/constructive forces?
Any structure's longevity is affected by which influences govern it.
How (long) do structures live?
Data: POSSII, Caltech, NSF
Image Processing & Copyright: Oliver Czernetz

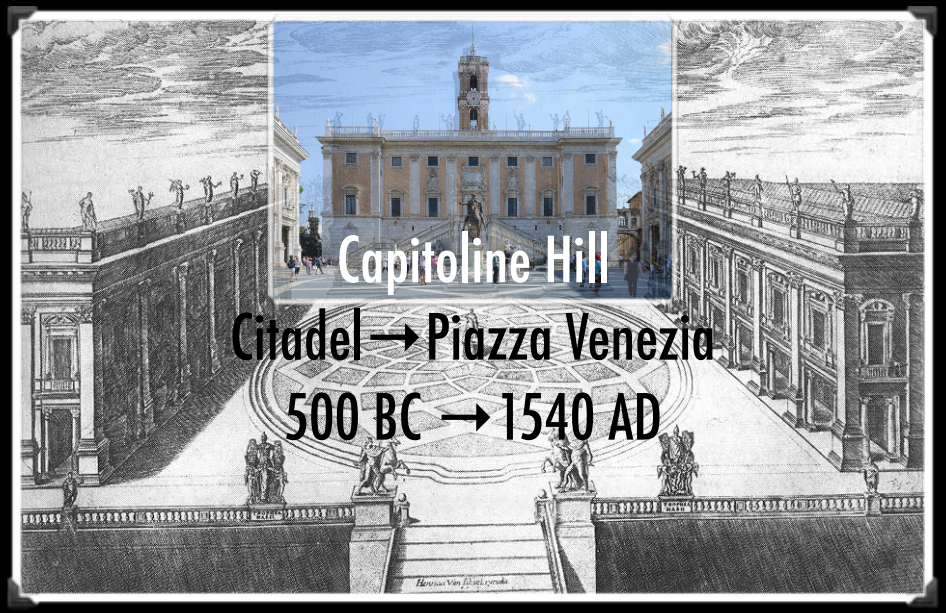
ONLY SIMULATIONS ALLOW US TO BUILD, DESTROY & TIME TRAVEL

C. 80 AD

2016

+"observed" simulations are best

ARE SOME PLACES SPECIAL?



What are "special" places in ISM & how long do they last?

How do "influences" change what is special?

The mid-plane of a spiral galaxy is a special place.

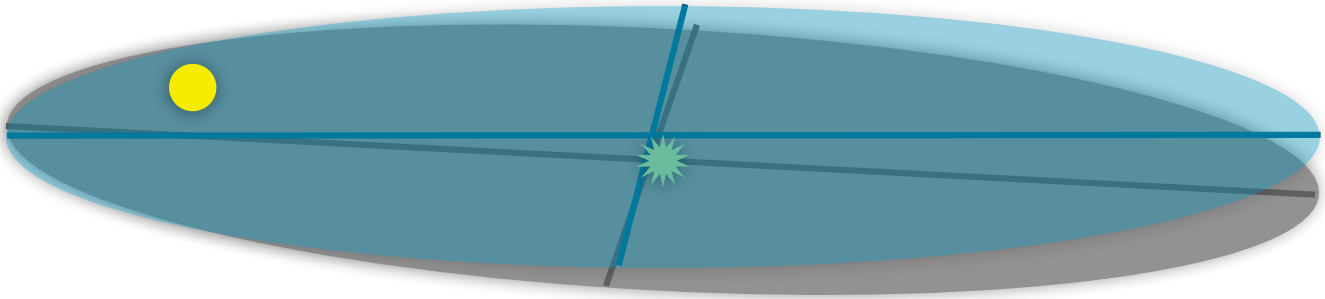
"Is Nessie Parallel to the Galactic Plane?" *-A. Burkert, 2012*

Celestial North

Yes but why not at Zero of Latitude (b=0)?

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 ~25 pc "above" the IAU Milky Way Plane

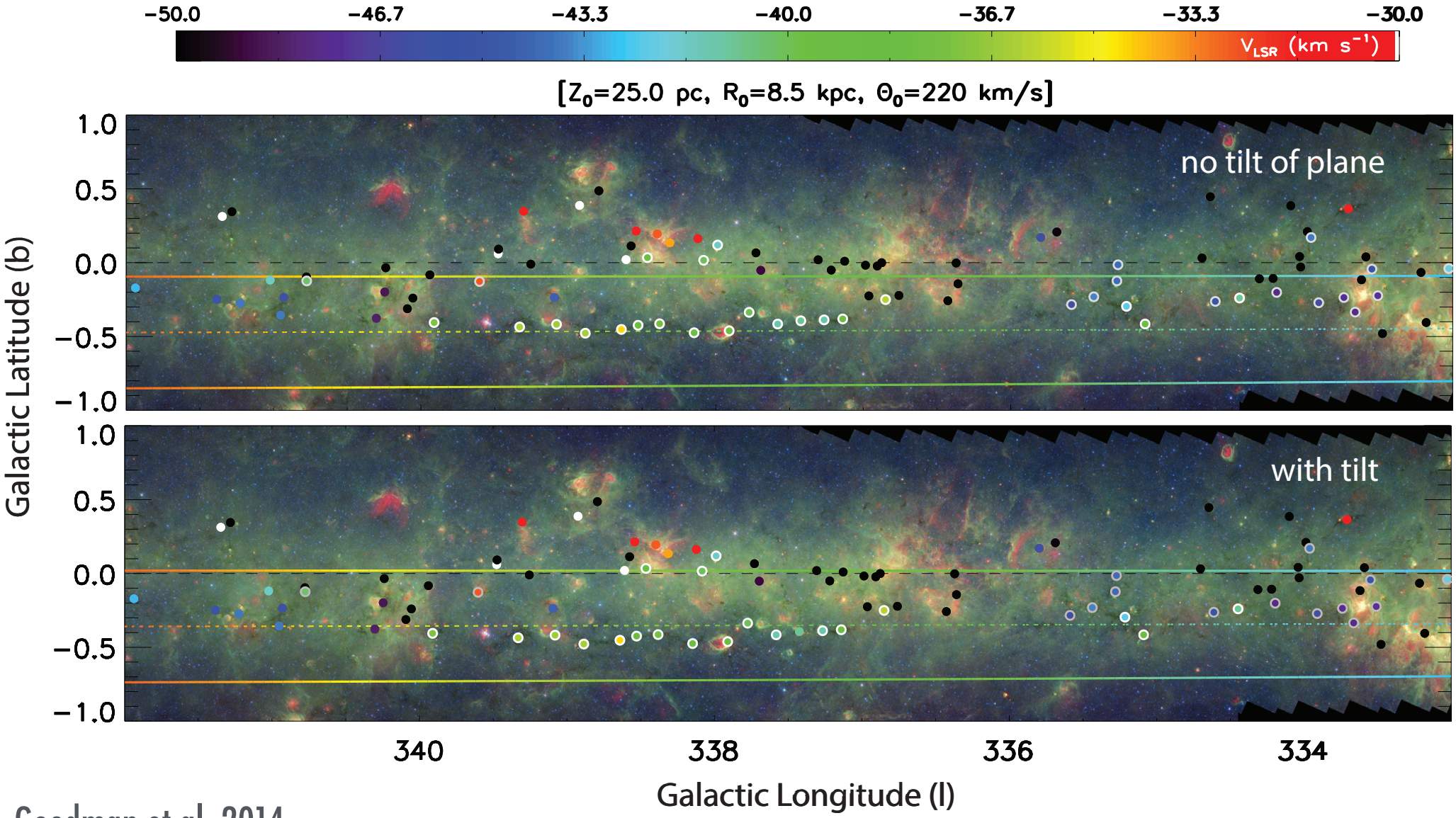
+

Galactic Center is ~7 pc offset from the IAU Milky Way Center

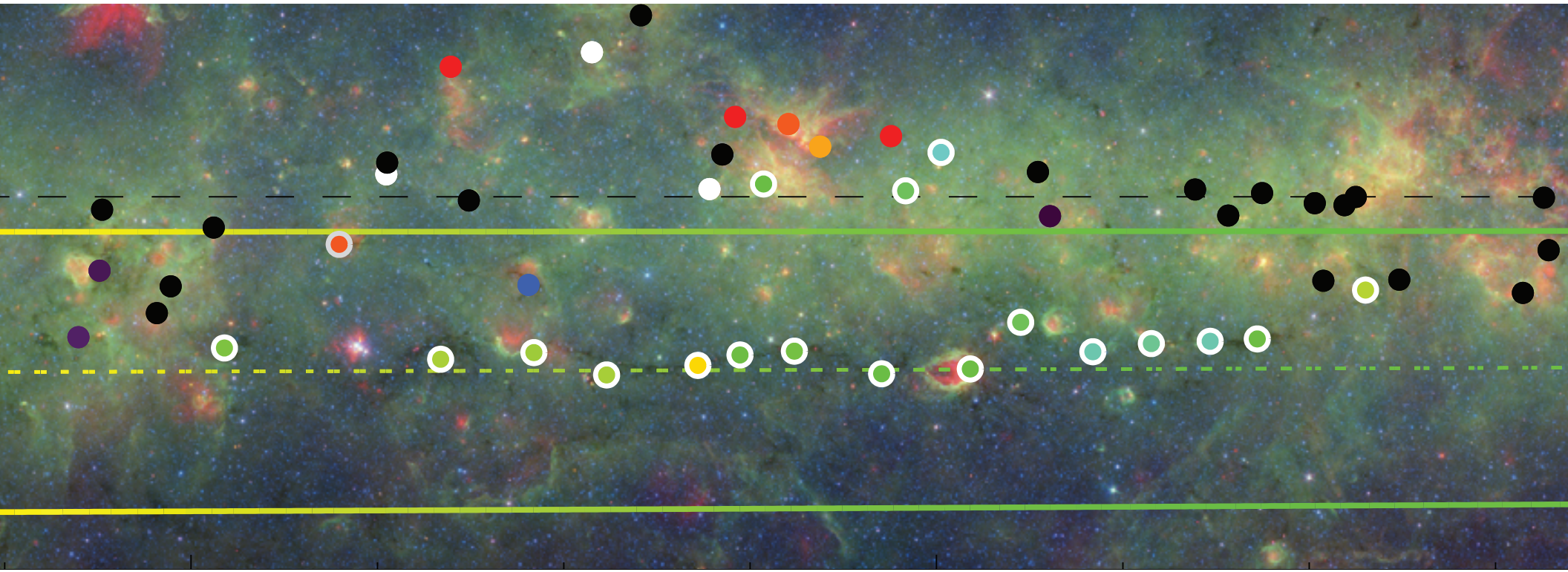
=

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!



Goodman et al. 2014



...eerily precisely...

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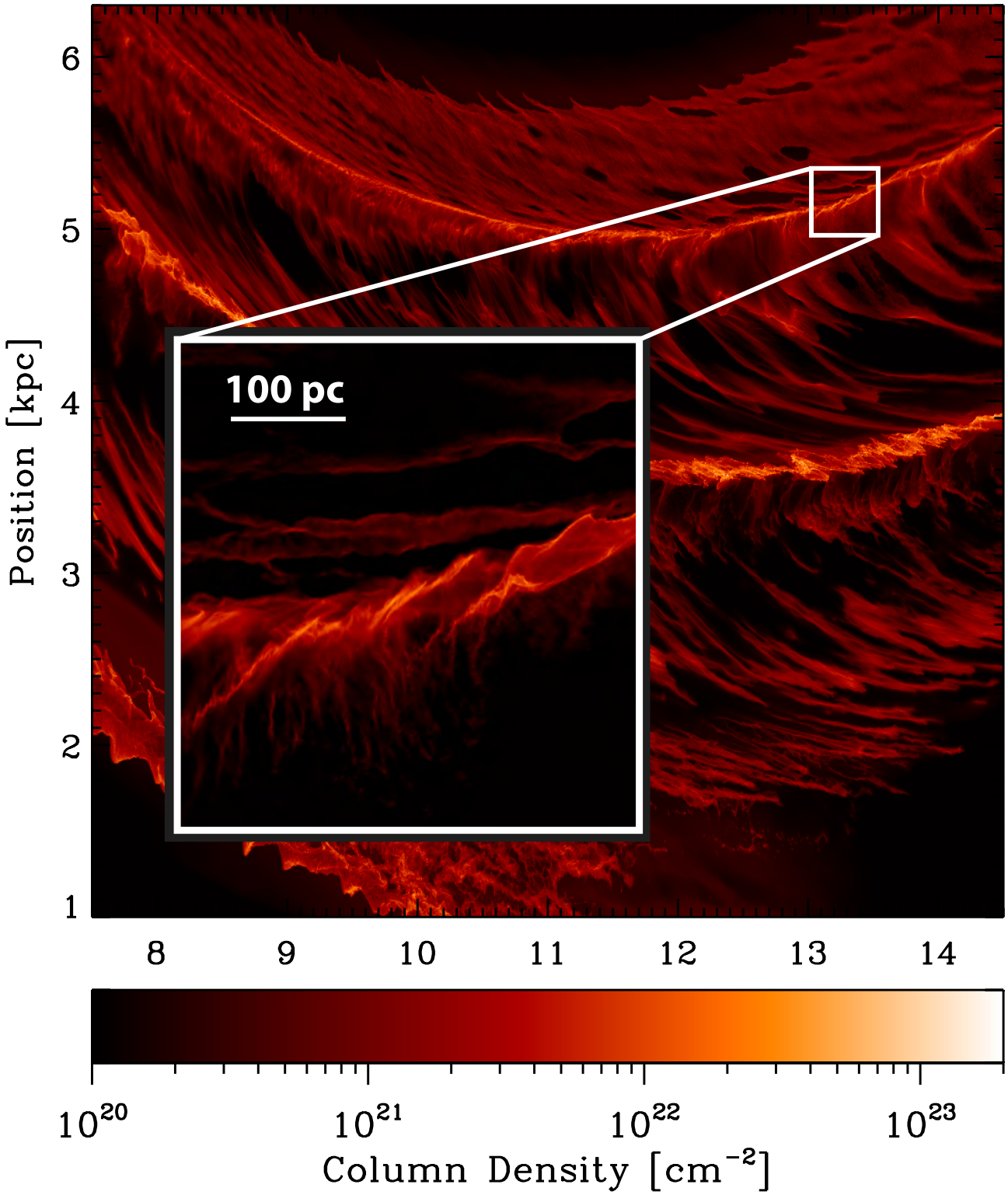
2014 Simulation



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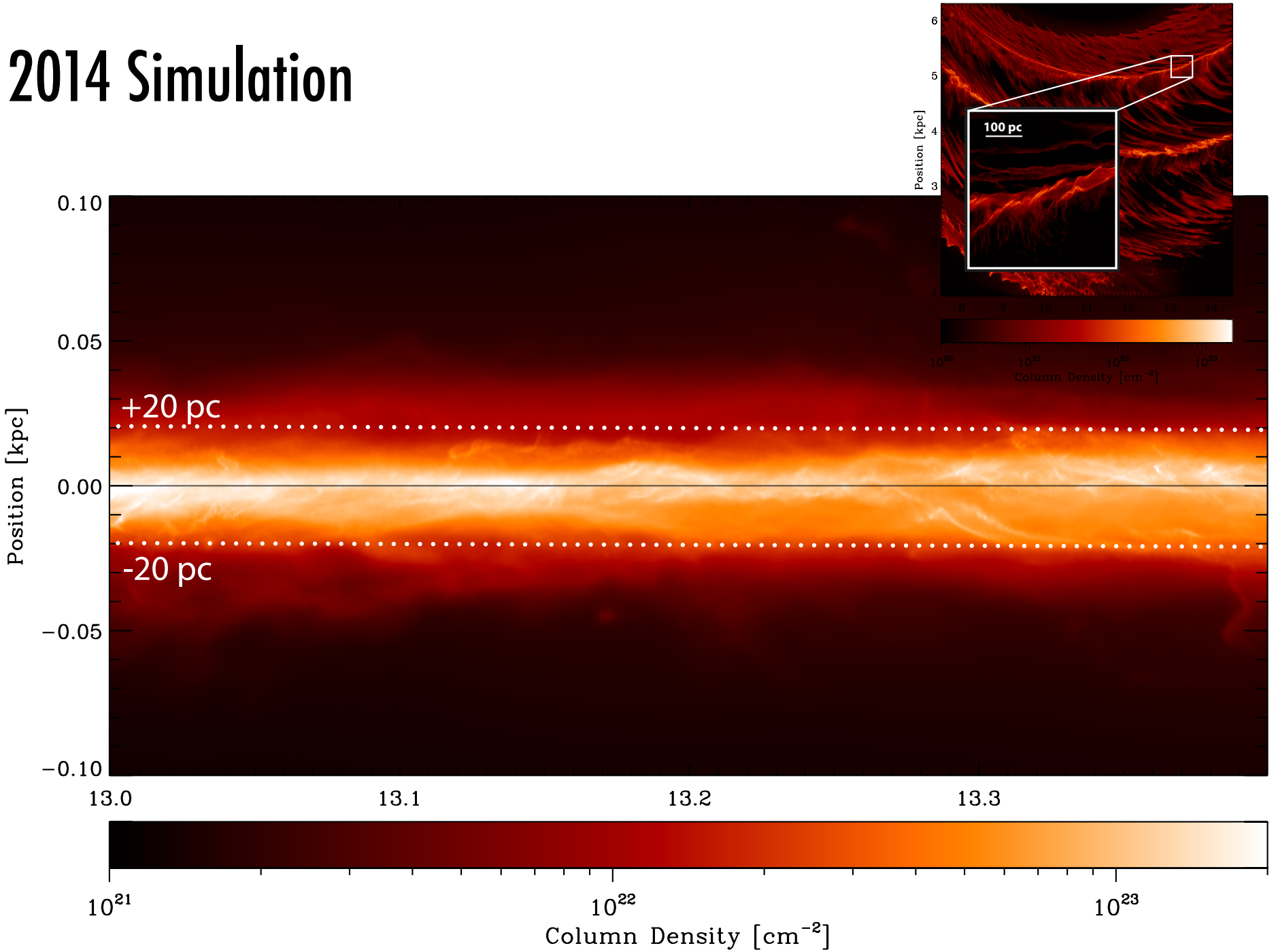

Smith et al. 2014, using AREPO (hydro+chemistry, imposed potential, no B-fields, no local (self-)gravity, no feedback)

The Physical Properties of Large-Scale Galactic Filaments

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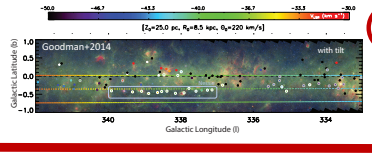

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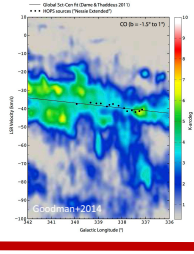

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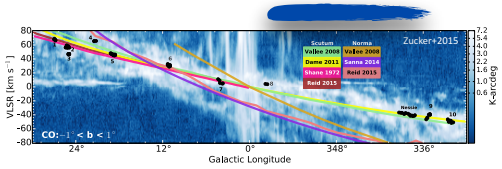

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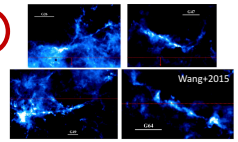

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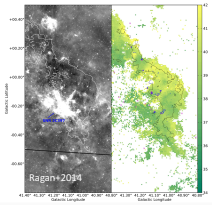

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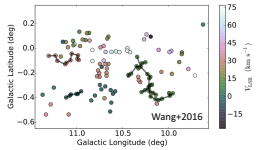

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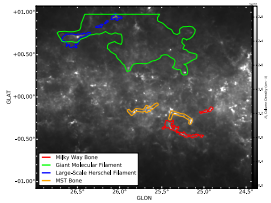

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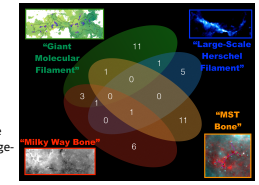

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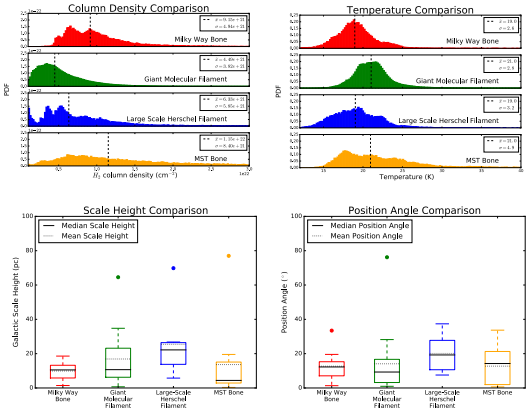

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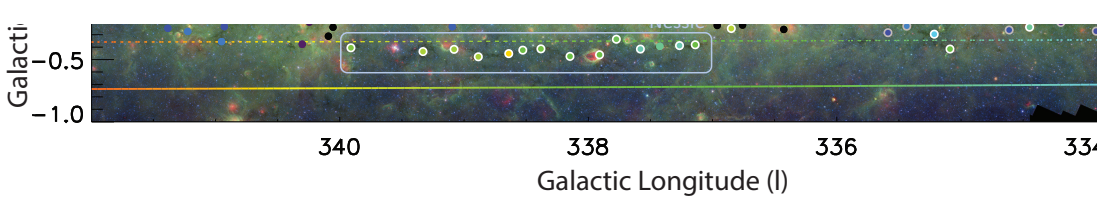

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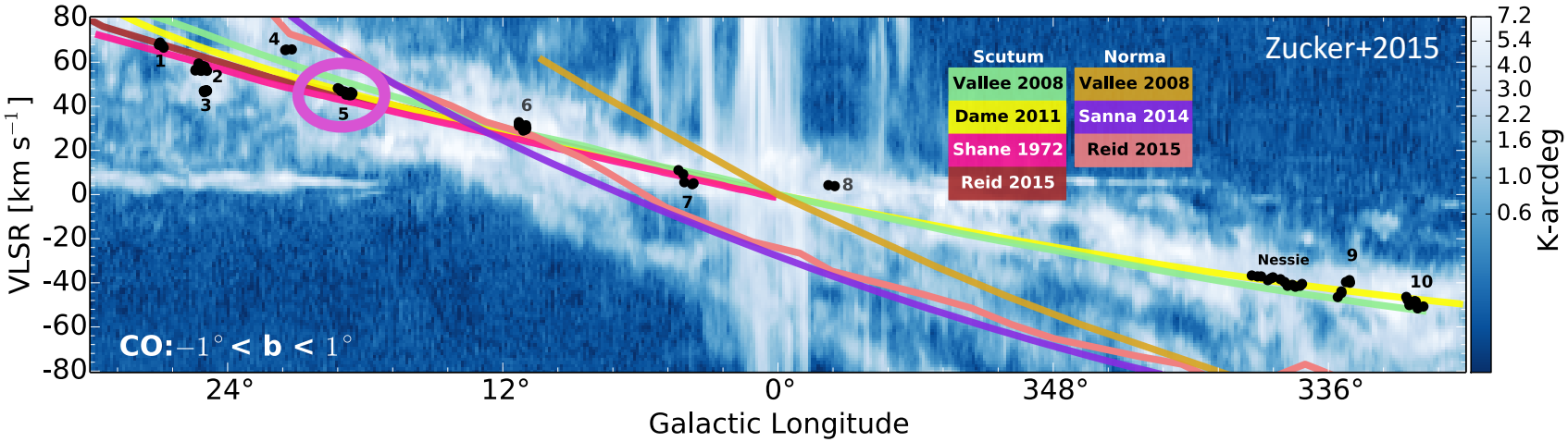

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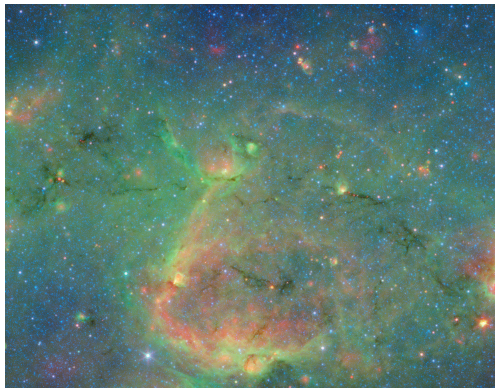

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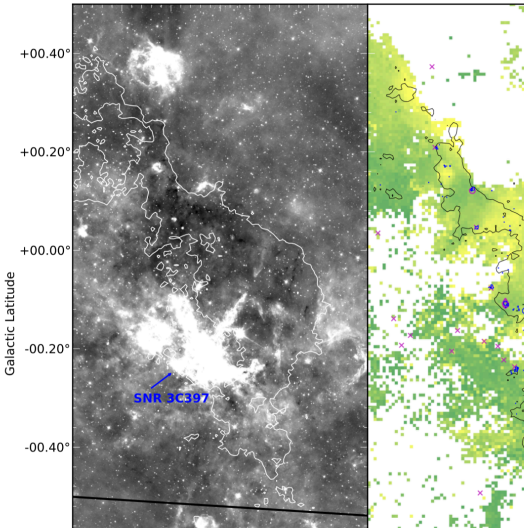

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Battersby, Goodman, Zucker et al. in prep.

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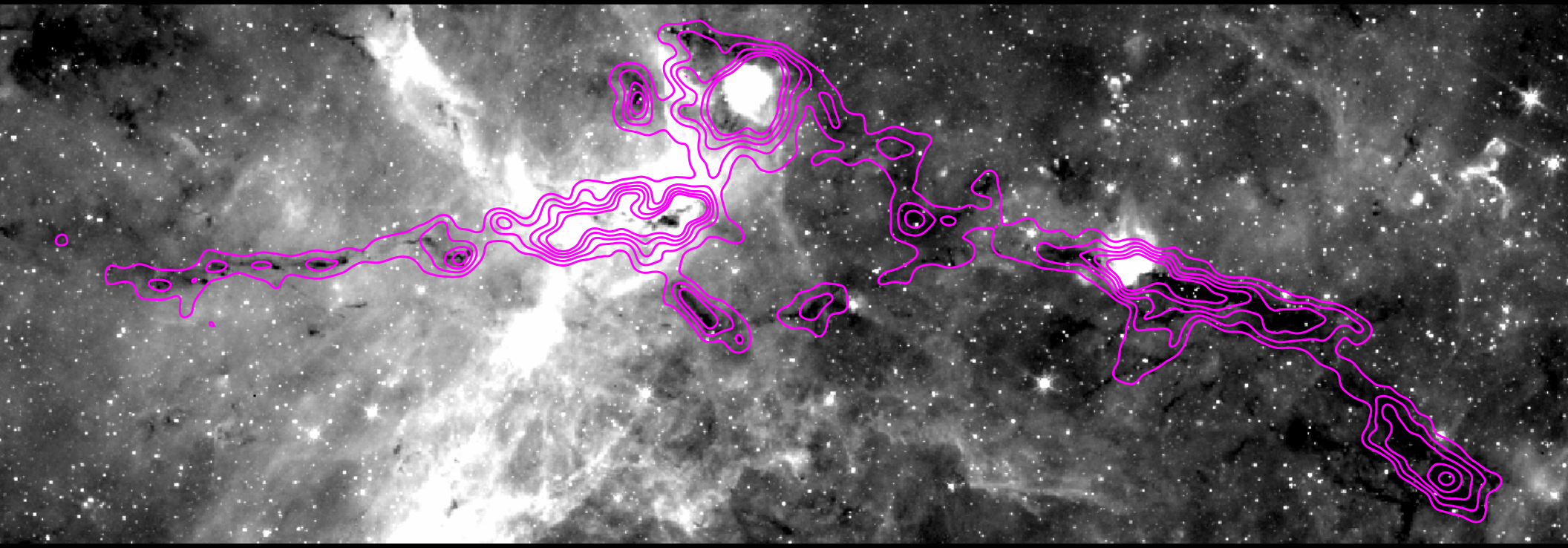

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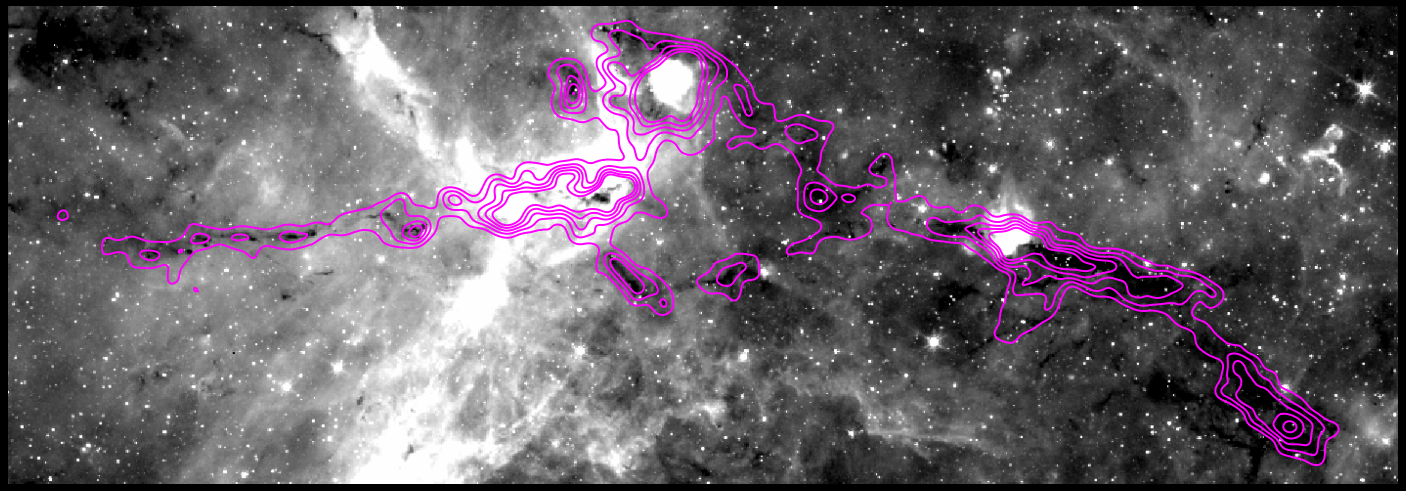

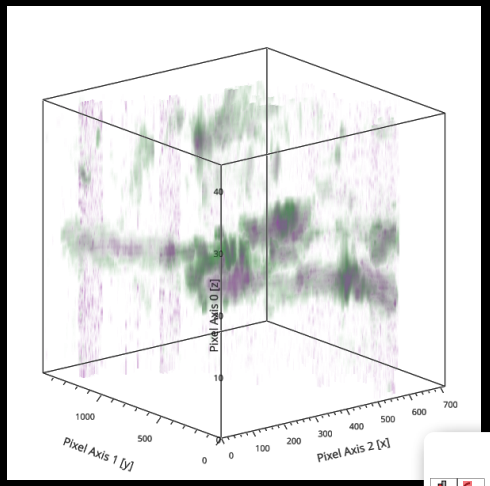

glue 3-D volume rendering of ^{13}CO and $C^{18}O$

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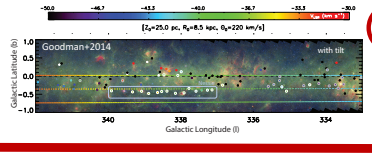

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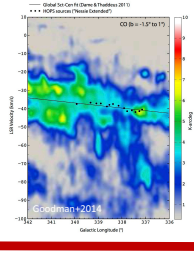

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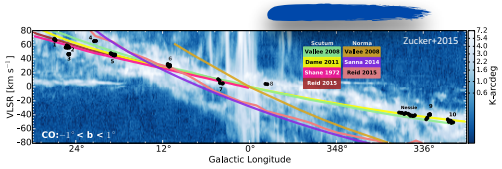

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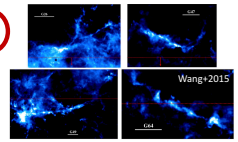

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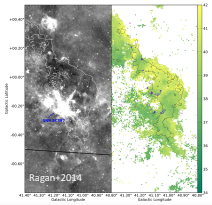

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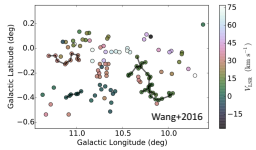

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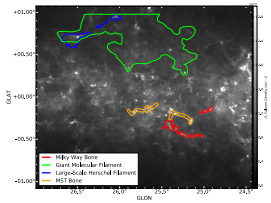

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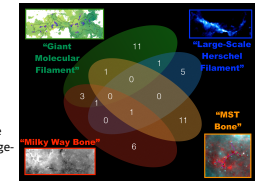

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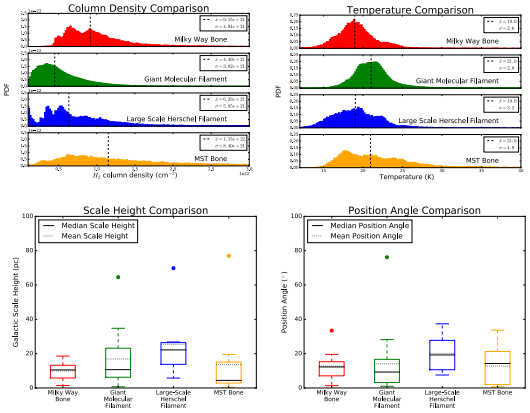

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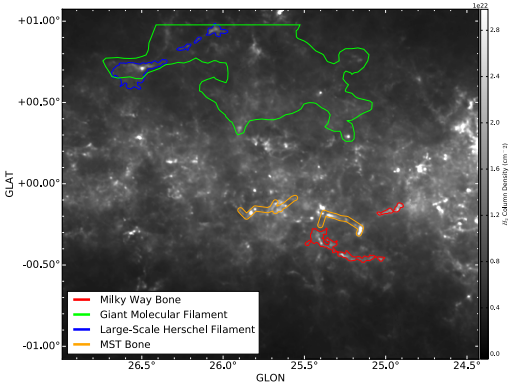

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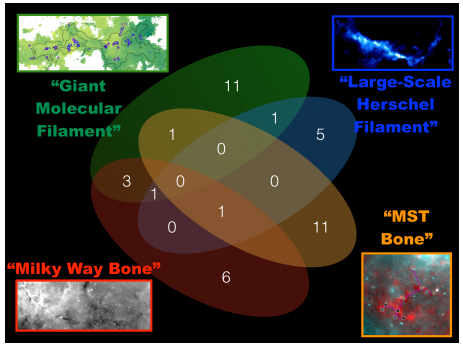

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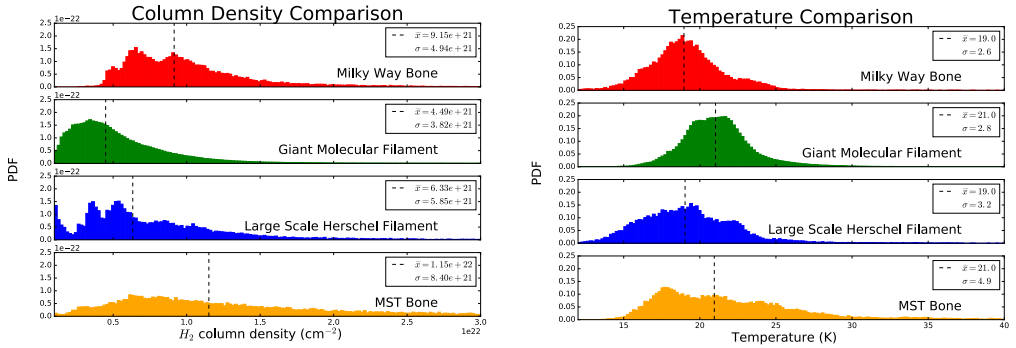

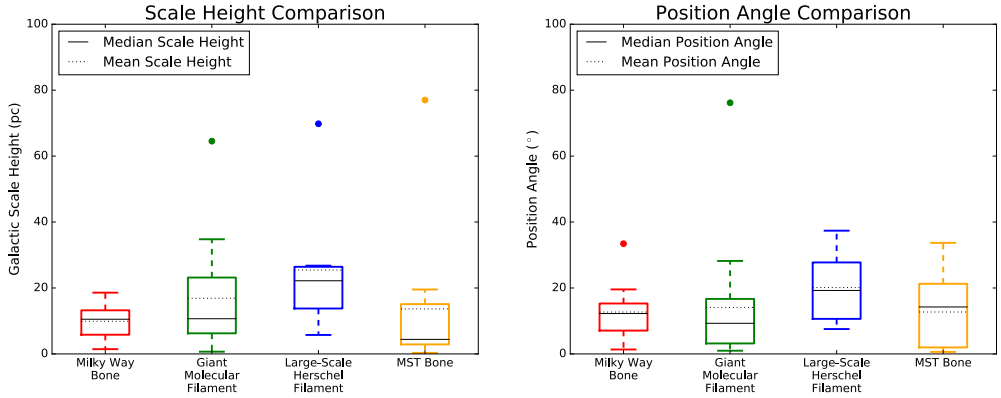

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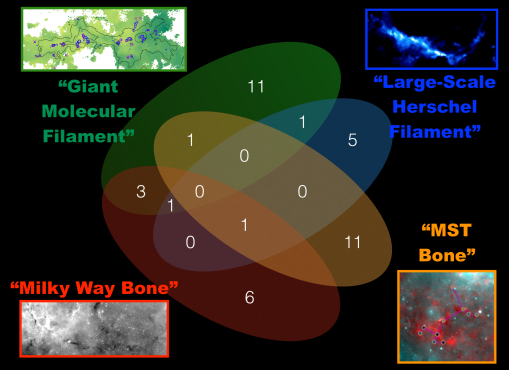


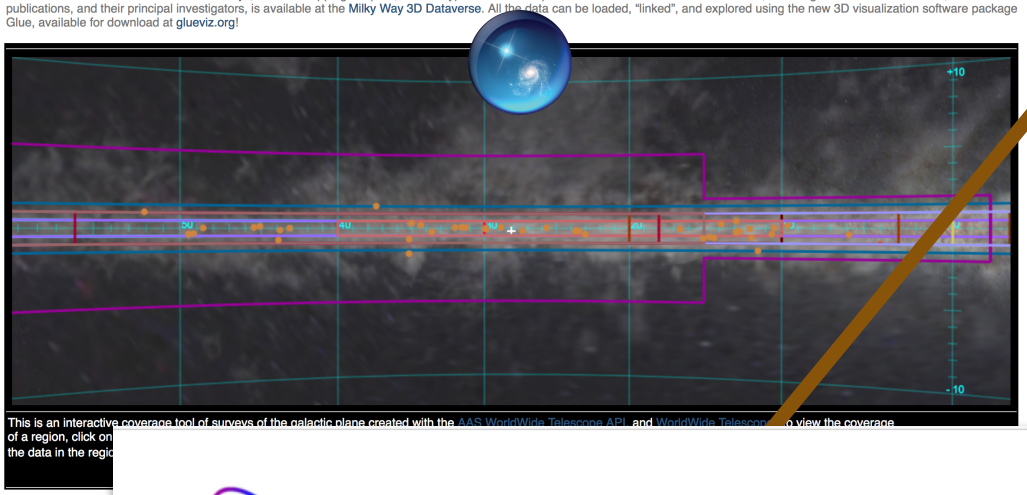
Filament Class	References	λ of Initial Detection	Velocity Reference	Spectral Lines	Velocity Contiguity Criterion	Aspect Ratio or Linearity Criterion	Min. Length	Spiral Arm Association Criterion	Spiral Arm Reference	Galactic scale height criterion	Position angle criterion
GMF	Ragan et al. 2014, Abreu-Vicente et	Mid-IR, Near-IR	GRS, ThrUMMS	^{13}CO	"Continuous" velocity gradient		1°	Intersects *p-v* fit within arm errors	Vallee 2008, Reid et al. 2014		
Herschel	Wang et al. 2015	Far-IR	GRS	^{13}CO	"Continuous, not broken" emission in p-v diagram	>>10		Intersects *p-p* fit within arm/	Reid et al. 2014		
Bone	Goodman et al. 2014, Zucker et	Mid-IR	HOPS, MALT90, BGPS, GRS,	NH_3, N_2H+, HCO+, ^{13}CO	$\Delta v < 3$ km/s per 10 pc	>50:1		Within 10 km/s of *p-v* fit	Dame et al. 2011, Reid et al. 2016	<20 pc	<30° from midplane
ATLASGAL	Li et al. 2016	Submm	HOPS, MALT90, BGPS, COHRS,	NH_3, N_2H+, HCO+, ^{13}CO,	Std. Dev. of clumps < 10 km/s	>3:1		Within 10 km/s of *p-v* fit	Taylor & Cordes 1993		
MST	Wang et al. 2016	Radio	BGPS	N_2H+, HCO+	$\Delta v < 2$ km/s between connected clumps	$\sigma_{major}/\sigma_{minor} > 1.5$	10 pc	Within 5 km/s of *p-v* fit	Reid et al. 2016	<20 pc	< 30° from midplane

milkyway3d.org

Milky Way 3D

Galactic Plane Coverage Tool

MilkyWay3D.org is a tool intended to organize and curate links to information about data sets relevant to our 3D understanding of the Milky Way. For any given longitude range, we provide the means to determine the available surveys, their overlapping footprint, and the type of data each provides. Information about each dataset, including how to access the data, their hallmark publications, and their principal investigators, is available at the Milky Way 3D Dataverse. All the data can be loaded, "linked", and explored using the new 3D visualization software package Glue, available for download at glueviz.org!



View Region	Link to Survey	Wavelength	Extended Observations: Continuum (2D)	Extended Observations: Spectral Line (3D)	Catalogs and Pointed Surveys: Source-Based Lists	Catalogs and Pointed Surveys: Spectral Line
☑	THOR	21 cm, 300 mm, 174-186 mm		★		
☑	BESSEL	1-3 cm			★	
☑	RAMPS*	1 cm		★		
☑	CORNISH*	60 mm	★		★	
☑	HOPS	12 mm		★		★
☑	GRS	3 mm		★		
☑	MALT90	3 mm				★
☑	THRUMMS	3 mm		★		
☑	Dame CO	2.6 mm		★		
☑	BGPS	1 mm	★		★	★
☑	CHIMPS	1 mm		★		
☑	COHRS	1 mm		★		
☑	ATLASGAL	870 μm	★		★	
☑	JCMT*	850 μm	★		★	
☑	HIGAL*	70-500 μm	★			
☑	MIPSGAL	24, 70 μm	★			
☑	WISE	3.4, 4.6, 12, 22.0 μm	★			
☑	GLIMPSE	3.6, 4.5, 5.8, 8.0 μm	★			
☑	UKIDSS-GPS*	1.3, 1.6, 2.2 μm	★			
☑	GPIPS*	1.6 μm			★	

Admin | Alyssa Ann Goodman

VIALACTEA Science Gateway

Welcome | Workflow | Storage | Settings | Security | Statistics | Information | Data Avenue | Help | End User | PBS Monitoring

Data Avenue

DataAvenue

and coming soon!

Two panel view | Edit favorites | History

Powered By Liferay

Author Name

Simon Bihr (1)

Developed at the Institute for Quantitative Social Science | Dataverse Project on | Code available at

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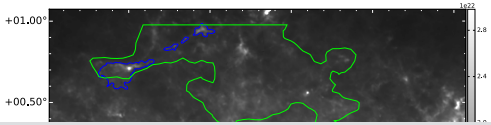
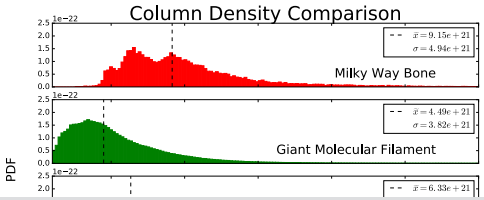
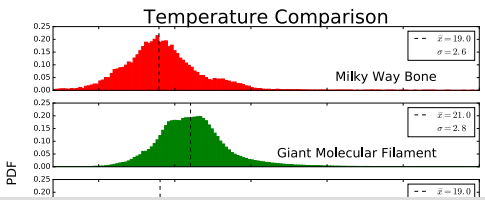
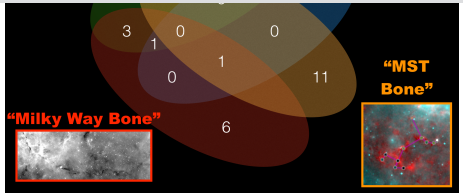


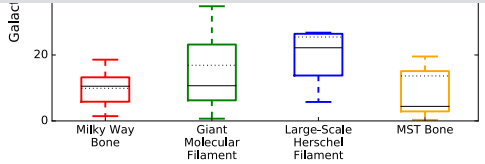
10 Systematic offsets in column density (top left), temperature (top

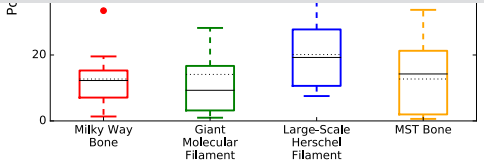




Filament Venn Diagram: Only 18% of large-scale filaments share any overlap with other large-scale filament catalogs



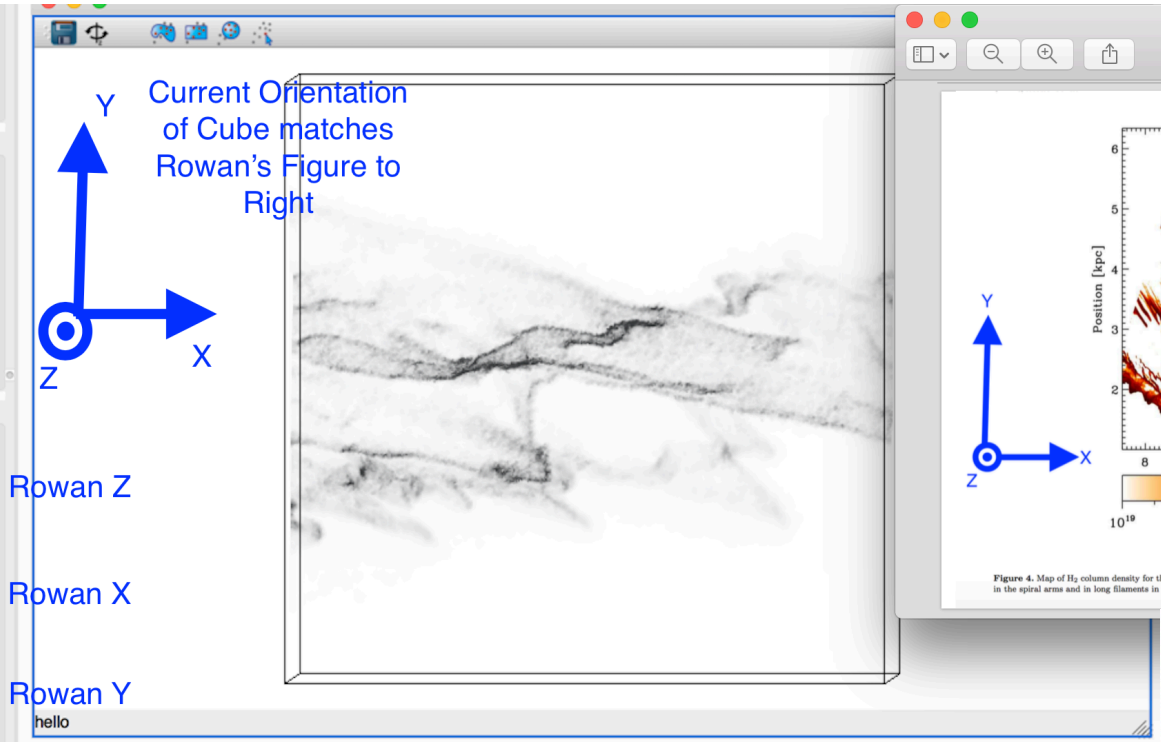


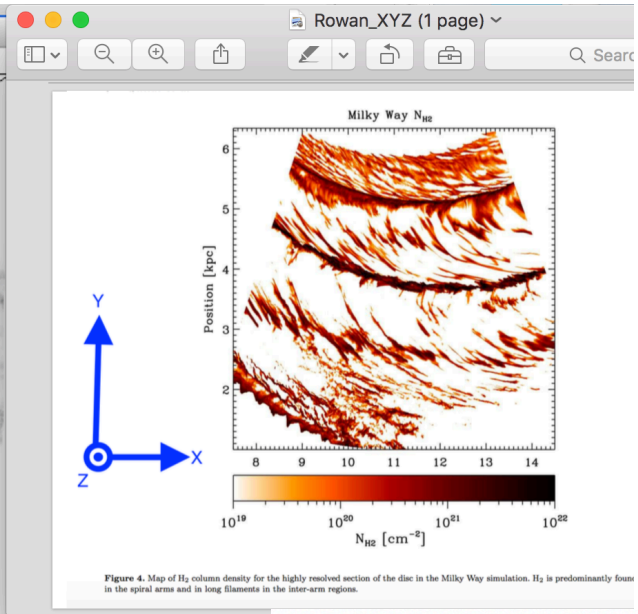


"Bones" are most likely to trace structure in/of the Galaxy's plane.

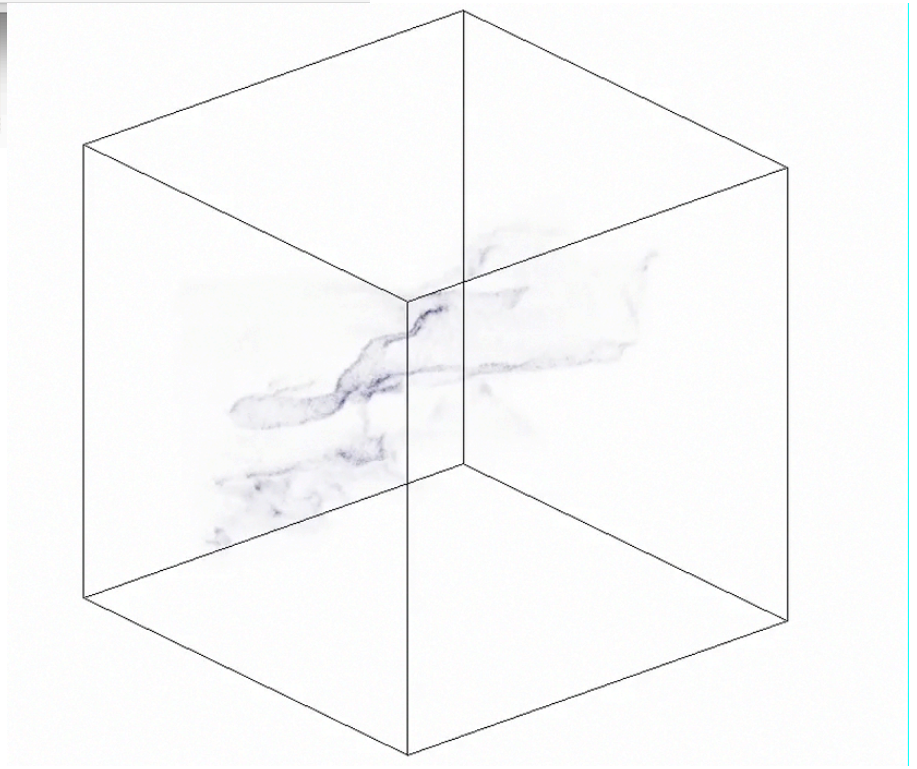
But what creates the Bones we observe?

brand new AREPO work...look for Zucker, Smith, Battersby, Goodman 2017

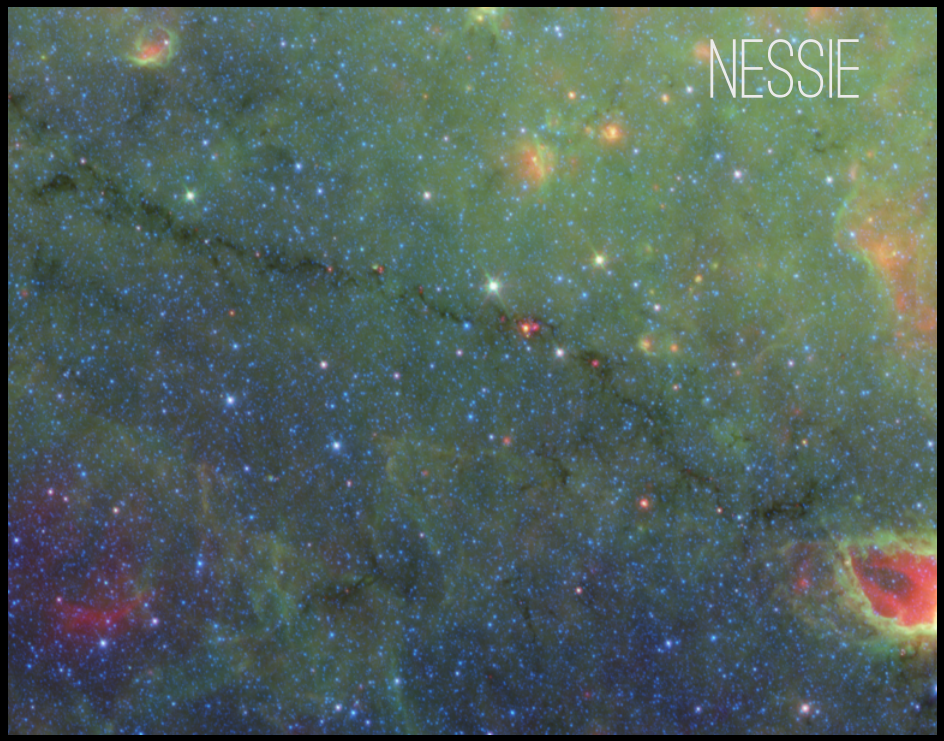




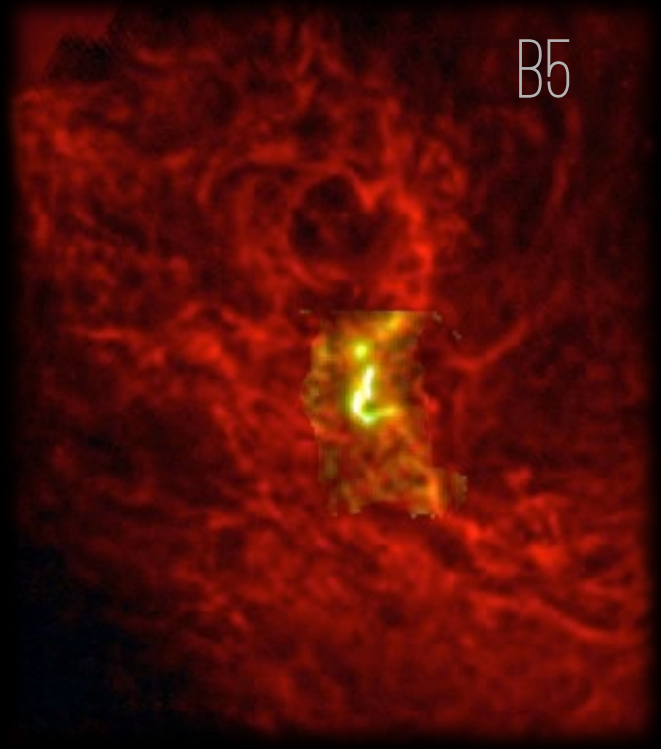
glue
multidimensional data exploration



cf. simulation work by Moeckl & Burkert 2015, Duarte-Cabral & Dobbs 2016; + AREPO MHD simulation -ALMA polarimetry comparison from Hull et al. 2016, more...

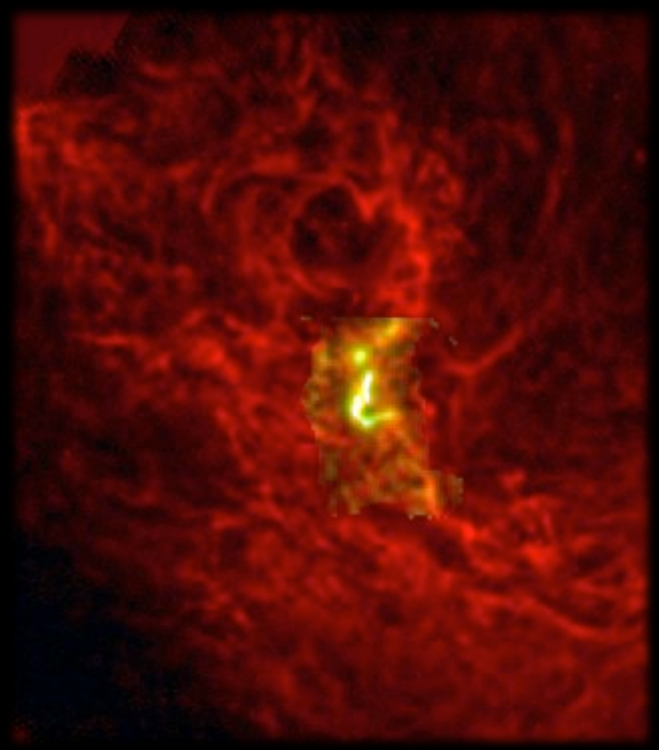


>100 pc



~0.01 to 10 pc

COHERENT CORES
ISLANDS OF CALM IN TURBULENT SEAS(?)



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

1998

THE ASTROPHYSICAL JOURNAL, 504:223–246, 1998 September 1
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COHERENCE IN DENSE CORES. II. THE TRANSITION TO COHERENCE

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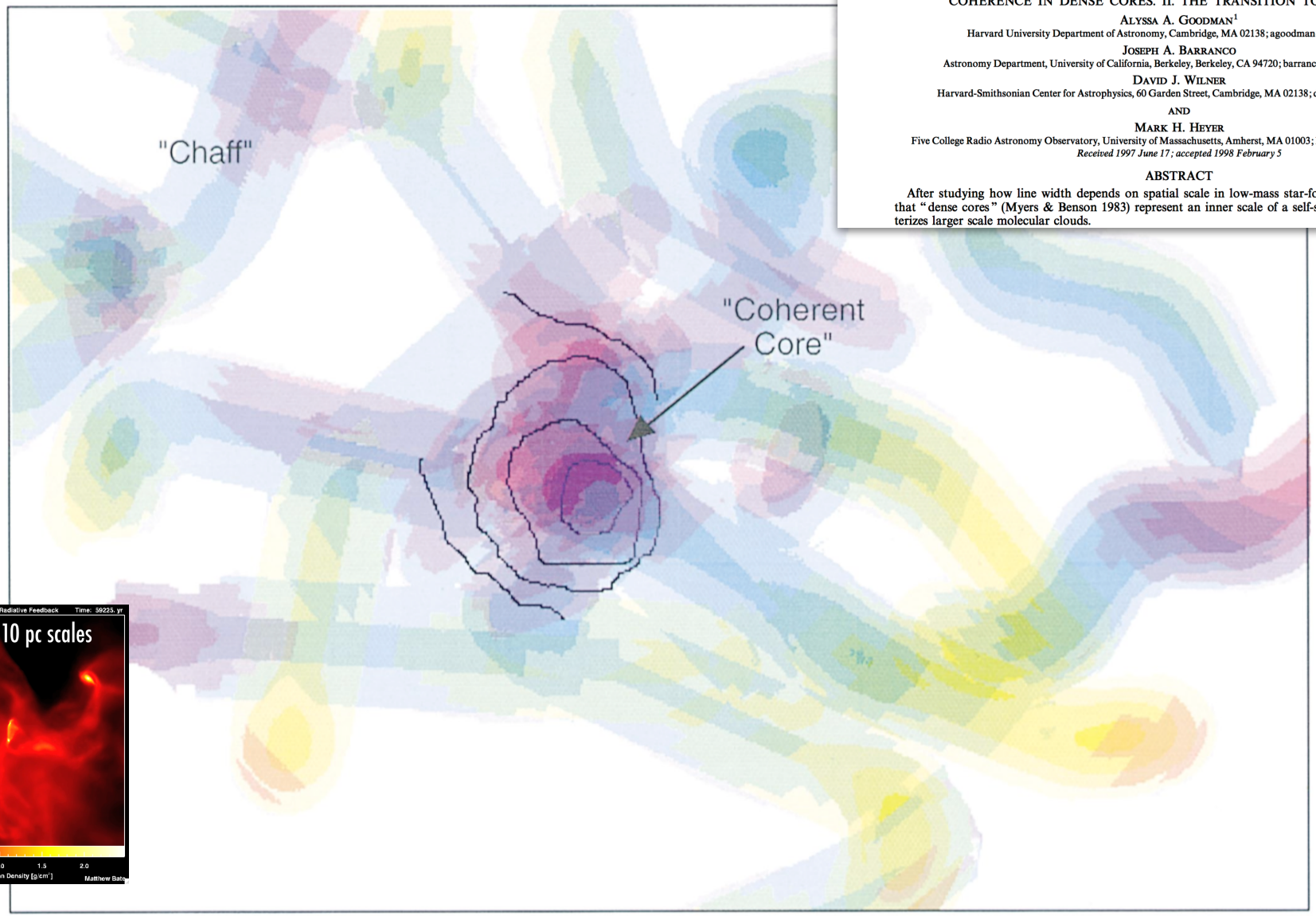
Received 1997 June 17; accepted 1998 February 5

ABSTRACT

After studying how line width depends on spatial scale in low-mass star-forming regions, we propose that "dense cores" (Myers & Benson 1983) represent an inner scale of a self-similar process that characterizes larger scale molecular clouds.



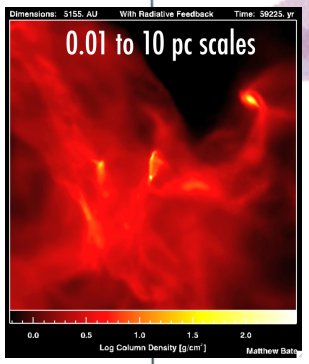
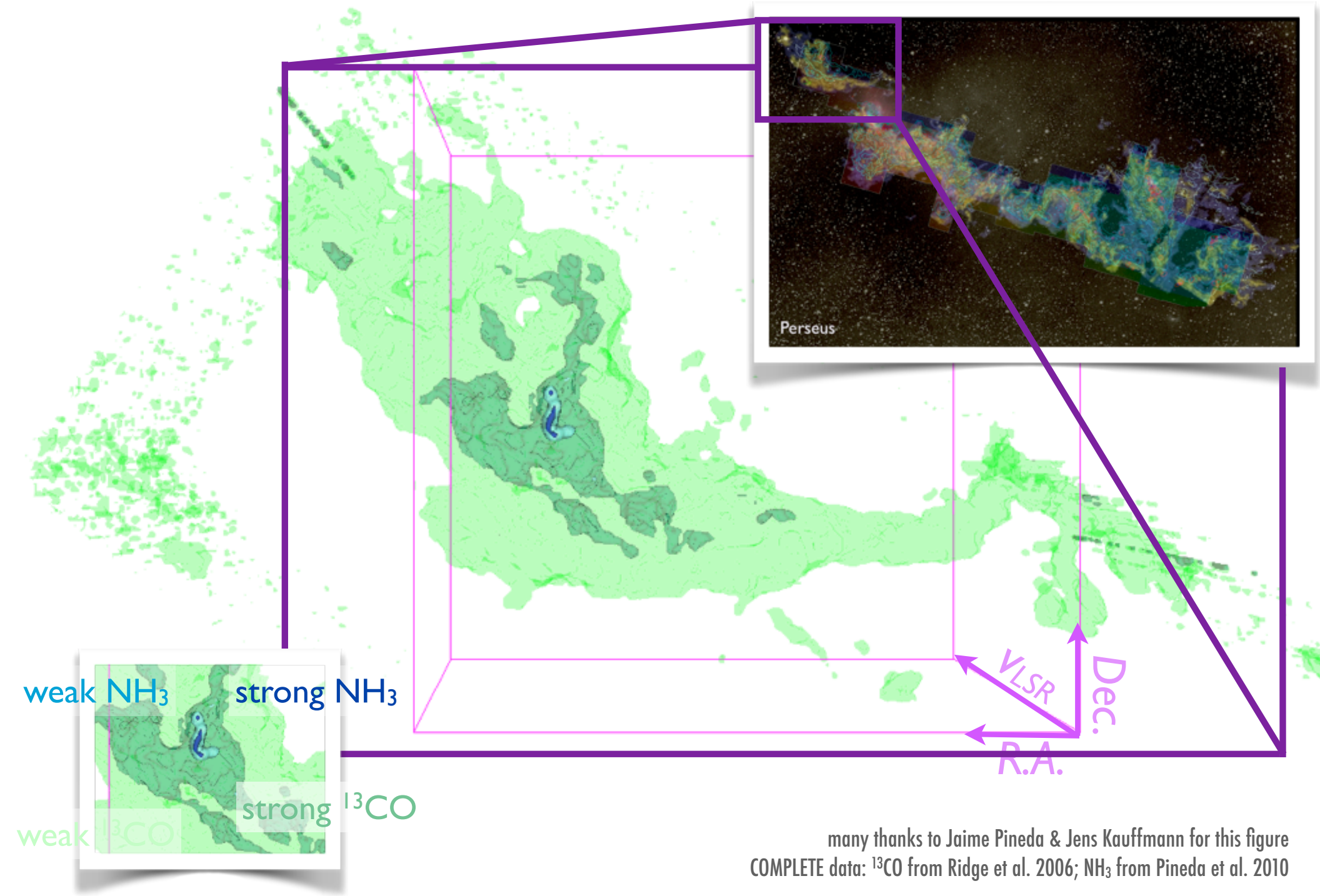


FIG. 10.—An illustration of the transition to coherence. Color and shading schematically represent velocity and density in this figure. On large scales, material (labeled chaff) is distributed in a self-similar fashion, and its filling factor is low. On scales smaller than some fiducial radius, the filling factor of gas increases substantially, and a coherent dense core, which is not self-similar, is formed. Due to limitations in the authors' drawing ability, the figure emphasizes a particular size scale in the chaff, which should actually exhibit self-similar structure on all scales ranging from the size of an entire molecular cloud complex down to a coherent core.

?

POSITION-VELOCITY STRUCTURE OF THE B5 REGION IN PERSEUS

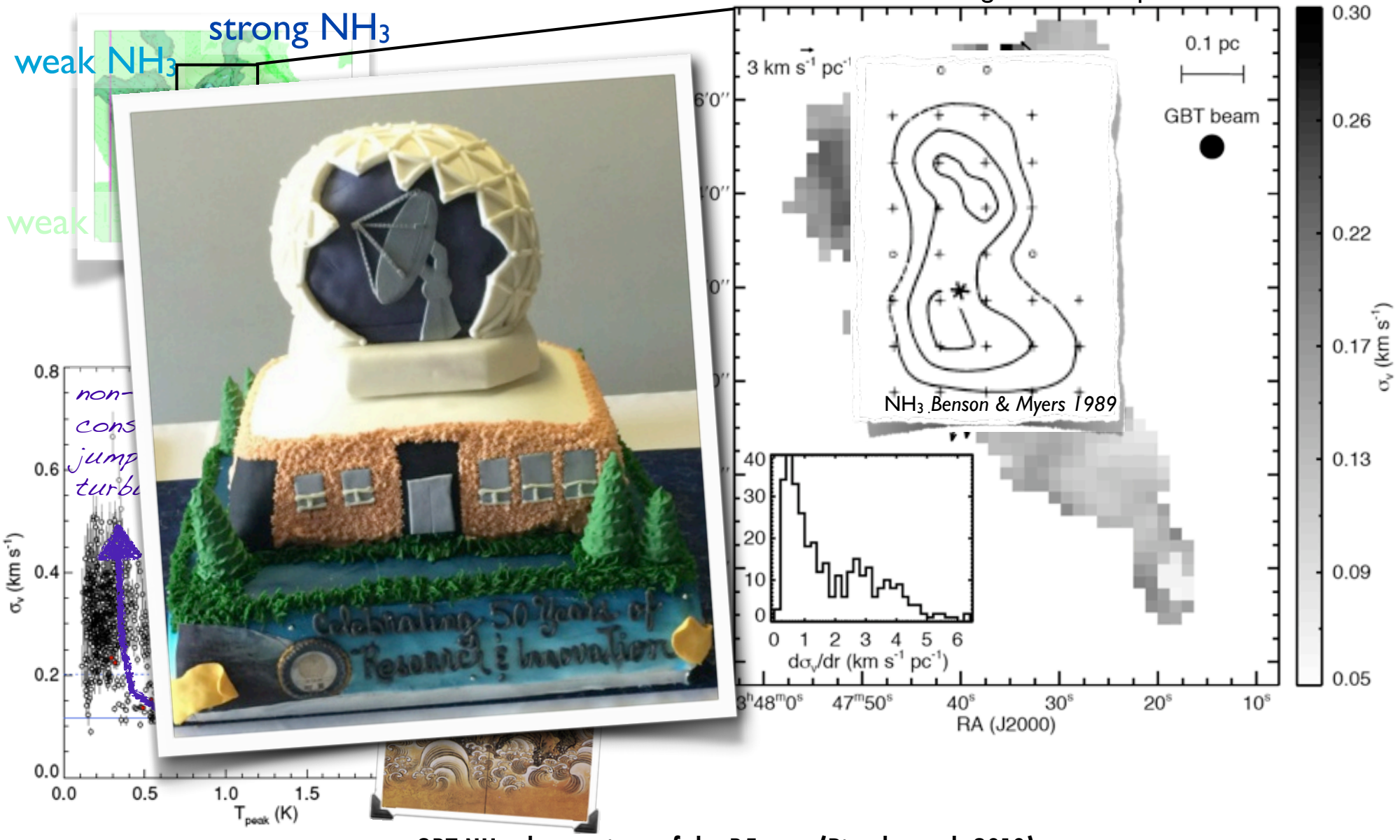


many thanks to Jaime Pineda & Jens Kauffmann for this figure

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

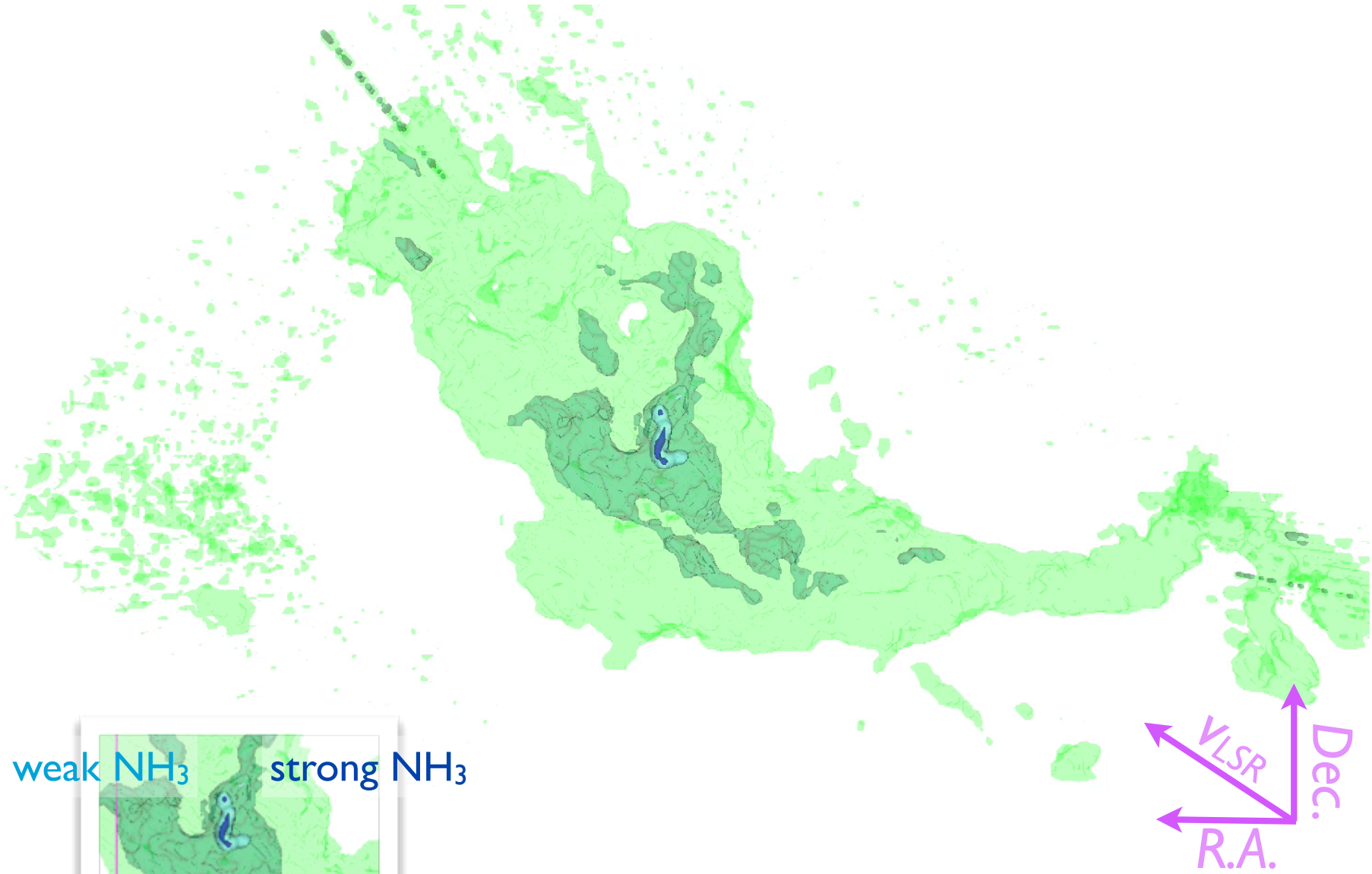
STRONG EVIDENCE FOR "VELOCITY COHERENCE" IN DENSE CORES

greyscale shows NH_3 velocity dispersion,
arrows show gradient in dispersion



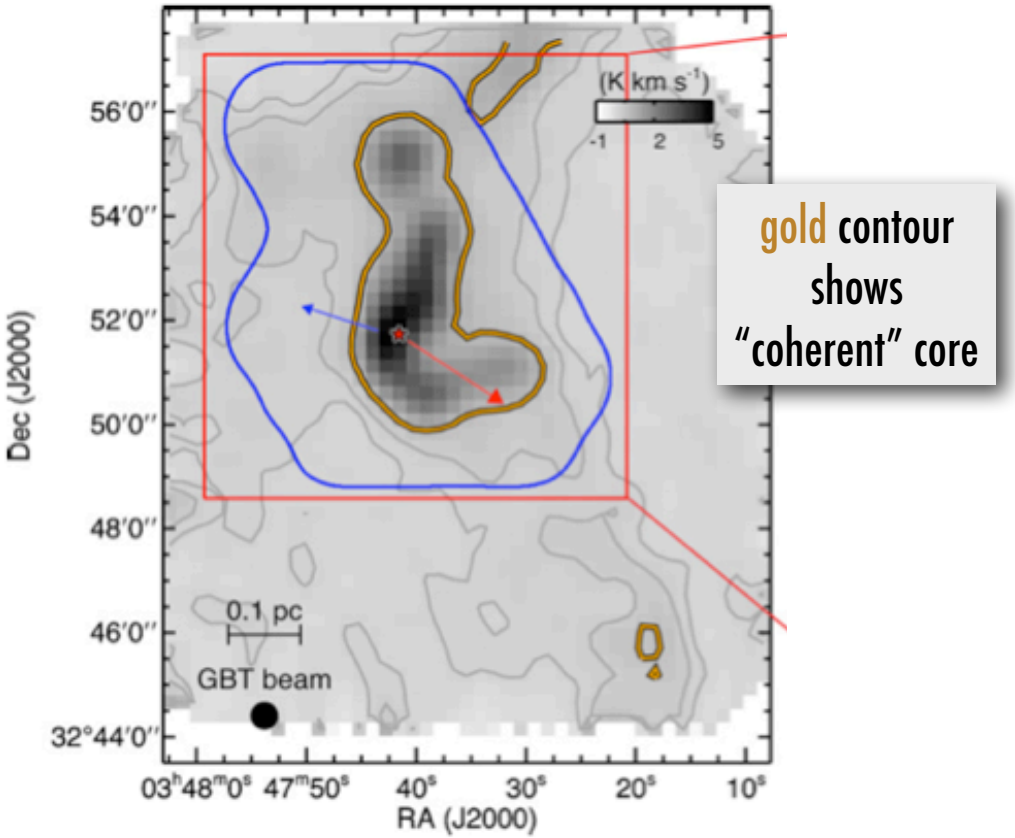
GBT NH_3 observations of the B5 core (Pineda et al. 2010)

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... WE FOUND SUB-STRUCTURE



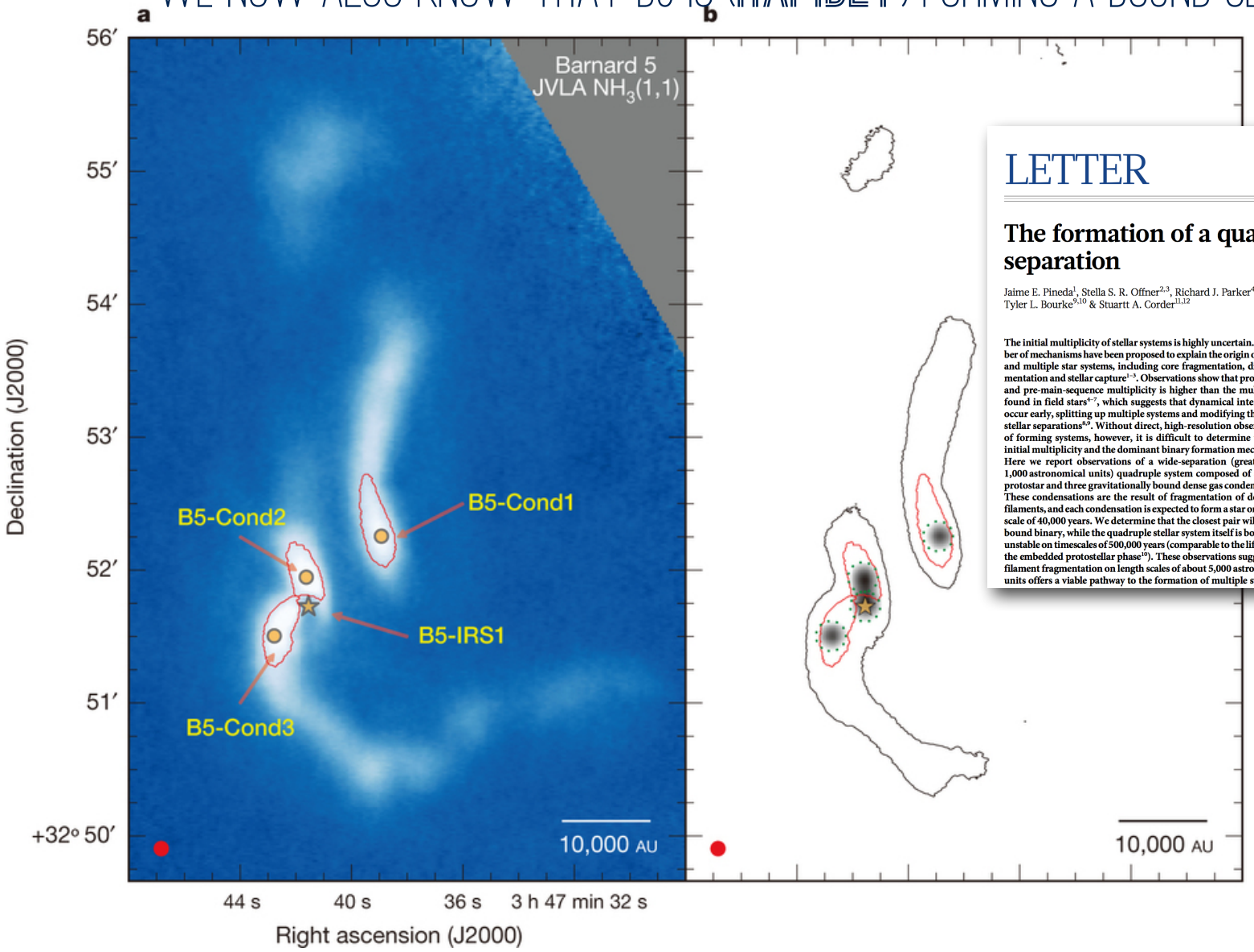
gold contour shows "coherent" core

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

AND SUB-SUB STRUCTURE

WE NOW ALSO KNOW THAT B5 IS (RAPIDLY) FORMING A BOUND CLUSTER



LETTER

doi:10.1038/nature14166

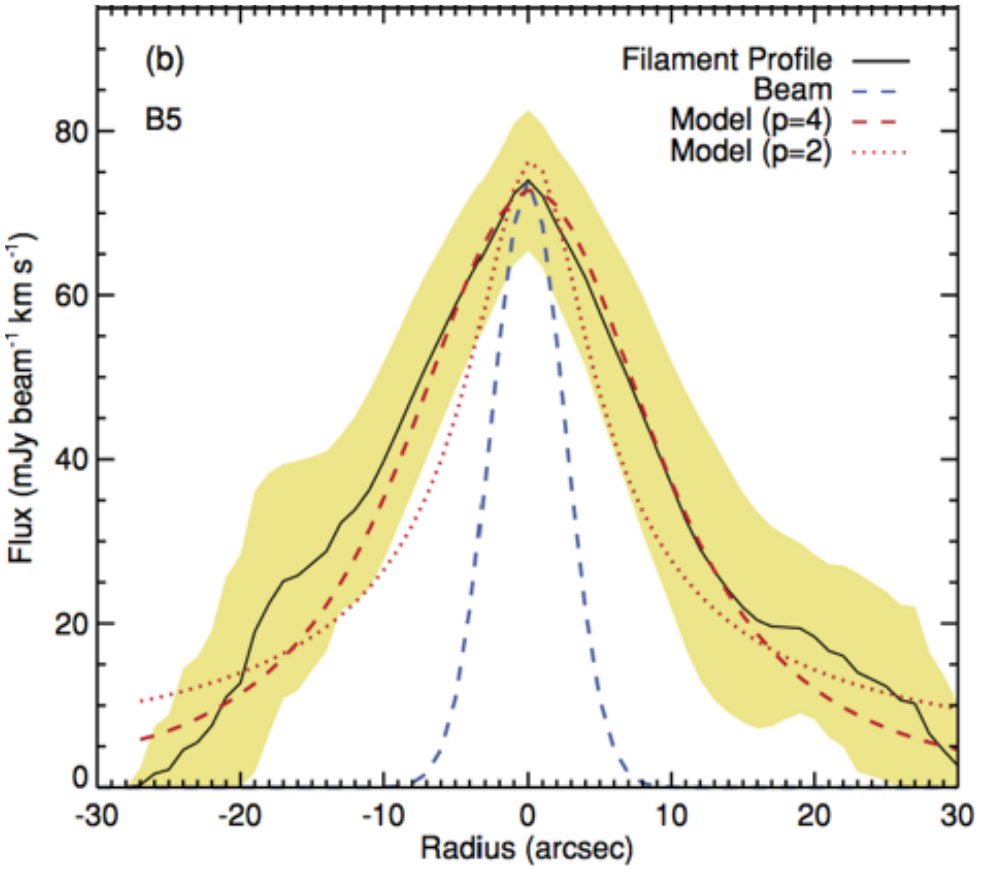
The formation of a quadruple star system with wide separation

Jaime E. Pineda[1], Stella S. R. Offner[2,3], Richard J. Parker[4], Héctor G. Arce[5], Alyssa A. Goodman[6], Paola Caselli[7], Gary A. Fuller[8], Tyler L. Bourke[9,10] & Stuart A. Corder[11,12]

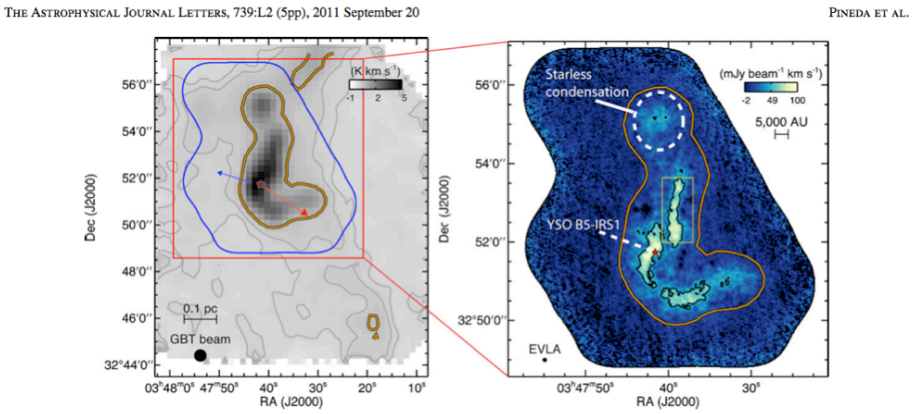
The initial multiplicity of stellar systems is highly uncertain. A number of mechanisms have been proposed to explain the origin of binary and multiple star systems, including core fragmentation, disk fragmentation and stellar capture[1–3]. Observations show that protostellar and pre-main-sequence multiplicity is higher than the multiplicity found in field stars[4–7], which suggests that dynamical interactions occur early, splitting up multiple systems and modifying the initial stellar separations[8,9]. Without direct, high-resolution observations of forming systems, however, it is difficult to determine the true initial multiplicity and the dominant binary formation mechanism. Here we report observations of a wide-separation (greater than 1,000 astronomical units) quadruple system composed of a young protostar and three gravitationally bound dense gas condensations. These condensations are the result of fragmentation of dense gas filaments, and each condensation is expected to form a star on a timescale of 40,000 years. We determine that the closest pair will form a bound binary, while the quadruple stellar system itself is bound but unstable on timescales of 500,000 years (comparable to the lifetime of the embedded protostellar phase[10]). These observations suggest that filament fragmentation on length scales of about 5,000 astronomical units offers a viable pathway to the formation of multiple systems.

Detailed knowledge of the underlying distribution of dense gas is the key to determining which structures will go on to form stars. Here we identify the dense gas structures that are most likely to form stars using the dendrogram technique[21]. Dendrogram analysis is a hierarchical structure decomposition that uses isocontours to identify individual features, while also determining where these contours merge with adjacent structures to create a new parental structure. We refer to the smallest scale (and brightest) structures in the dendrogram as condensations. These are the most likely places for an individual star to form. Figure 1a shows the B5 region as seen in dense gas (number density of H_2, $n_{H_2} \gtrsim 10^4$ cm^{-3}), with the protostar and the identified gas condensations shown by a star and circles, respectively. The mass of the well known protostar B5-IRS1 is 0.1 solar masses (M_{Sun}; ref. 22), while the masses of condensations B5-Cond1, B5-Cond2 and B5-Cond3 are $0.36 \pm 0.09\ M_{Sun}$, $0.26 \pm 0.12\ M_{Sun}$ and $0.30 \pm 0.13\ M_{Sun}$, respectively. Uncertainty in these masses is dominated by the uncertainty in the temperature used to convert measured fluxes to masses. The radii of the three condensations are respectively 2,800 AU, 2,300 AU and 2,500 AU, while the projected separations between the same three condensations and the protostar are 3,300 AU, 5,100 AU and 11,400 AU (see Methods). The half-mass radii of the condensations are about half the condensation radii. This, combined with

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



isothermal,
hydrostatic filaments,
not turbulent ones?

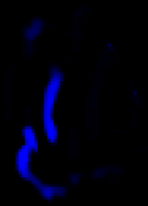


Pineda et al. 2011

Here's the fun/crazy part.

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)

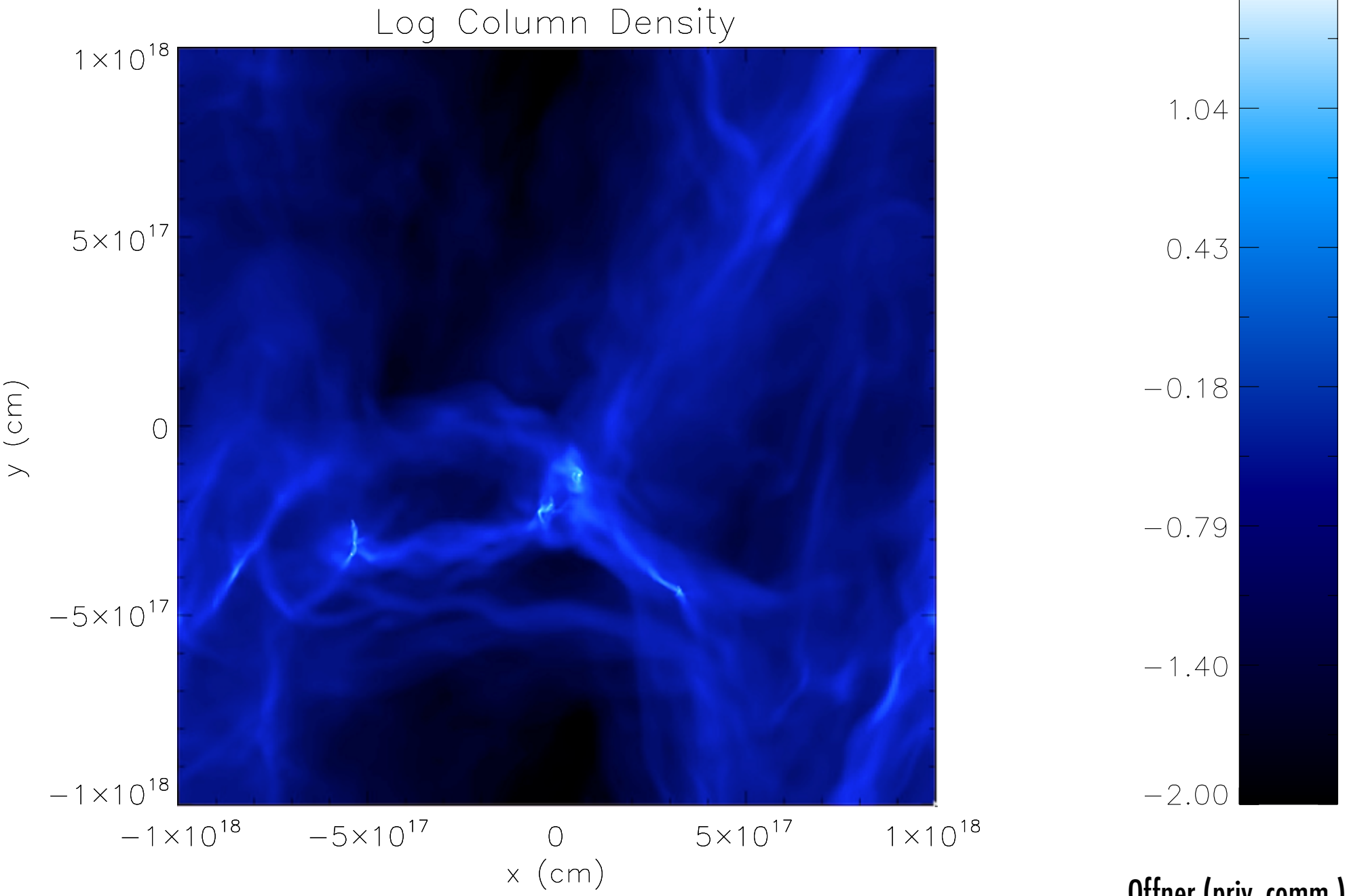


Goodman, Chen, Offner & Pineda 2016 in prep.

Herschel data from Gould Belt Survey

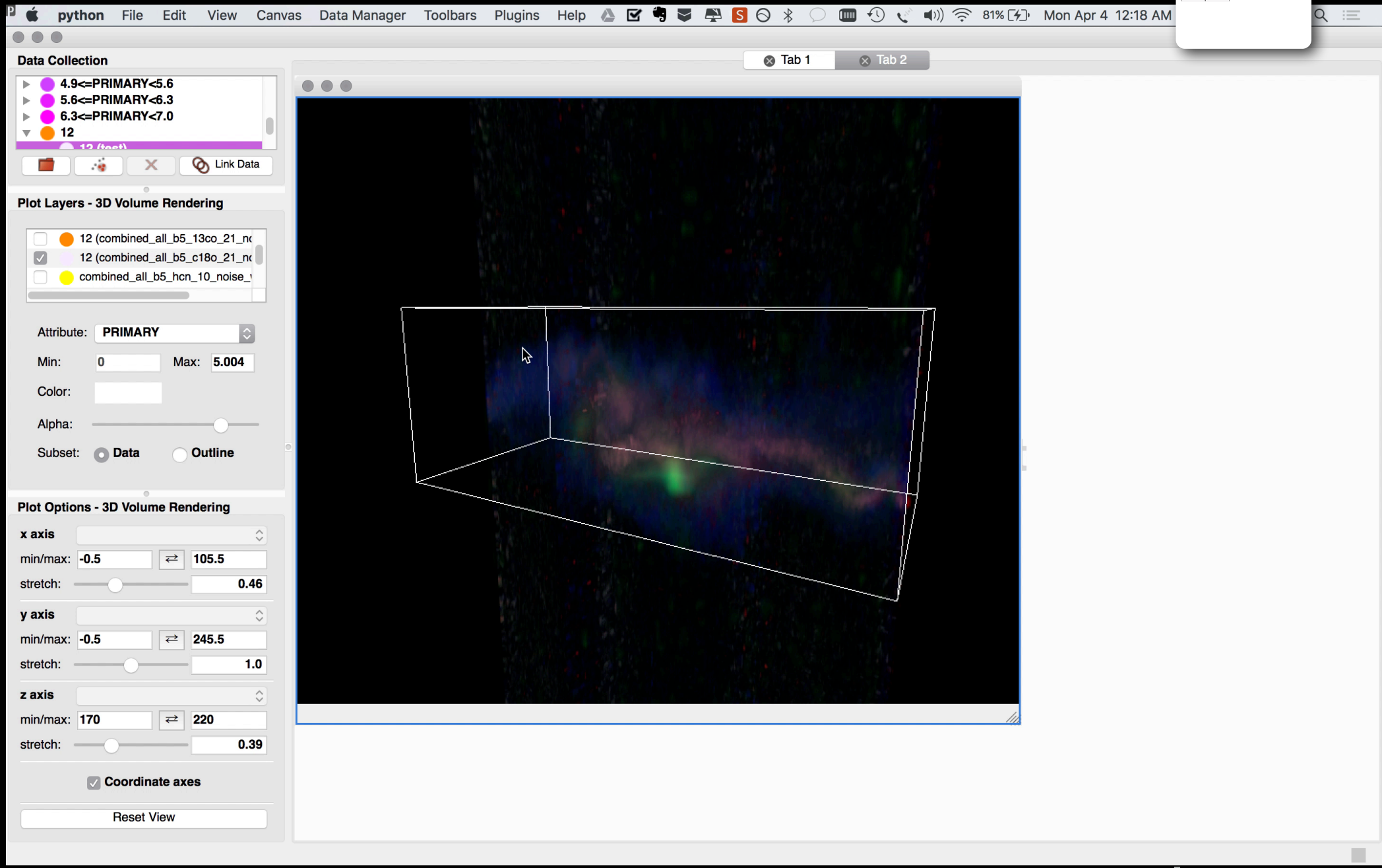
1998 2008

B5-ISH SIMULATION (NO MAGNETIC FIELD)



Offner (priv. comm.)

B5/GLUE (NEW IRAM 30-M DATA)

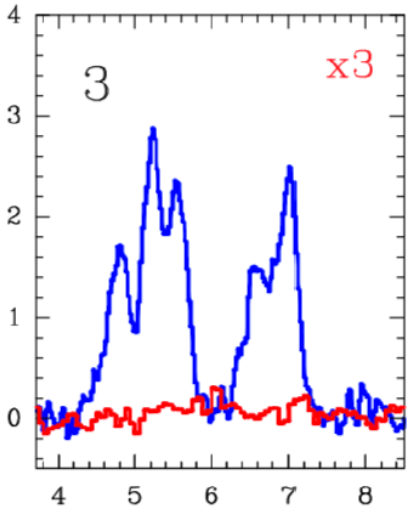


Chen, Offner, Pineda & Goodman 2017 in prep.

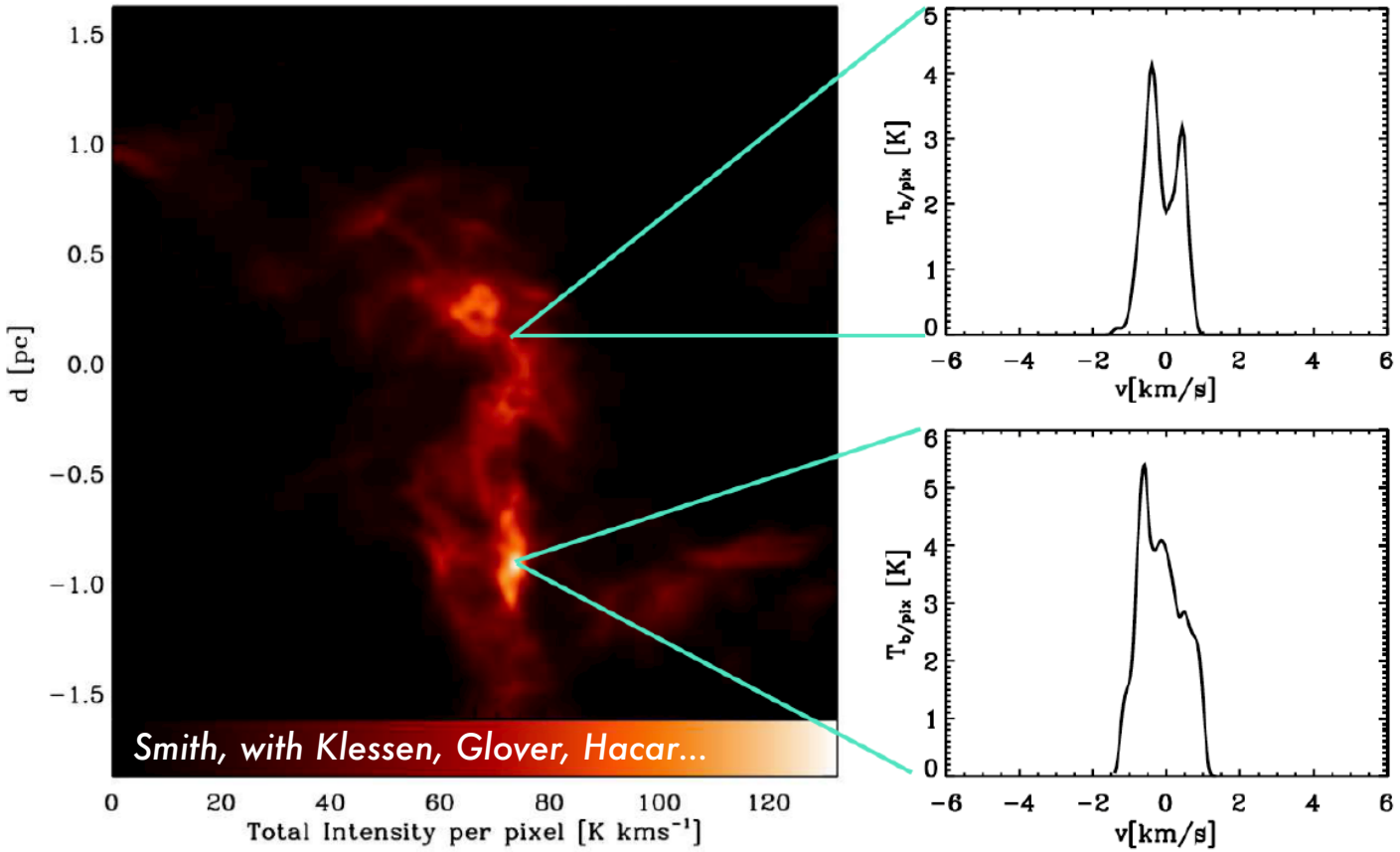
glueviz.org

Simulators are almost observing enough lines...

Filaments in Filaments



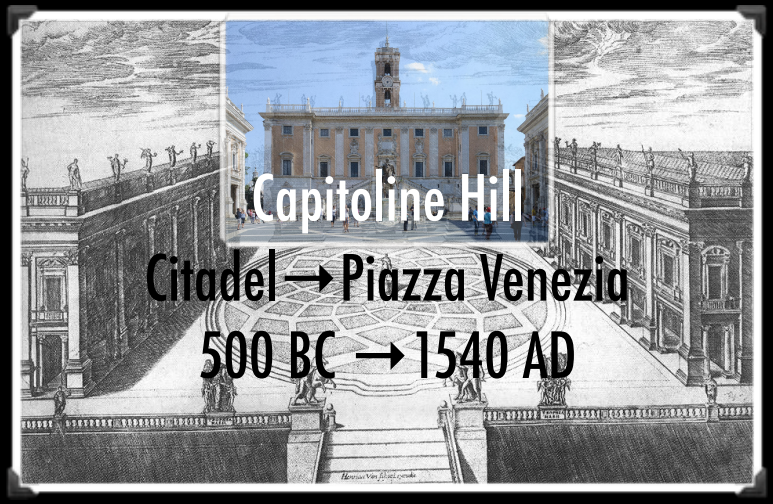
Observed $C^{18}O$ emission in blue.



Synthetic observation of $C^{18}O$ emission from our time-dependent chemical model post-processed with radmc-3d

slide courtesy of Rowan Smith, from CfA-ITC talk, March 31, 2016
cf. Moeckl & Burkert 2015, work of Hacar et al...

SOME PLACES ARE SPECIAL



What are "special" places in ISM & how long do they last?

–galactic plane, Bones

–filaments' influence may last into cores–how long, and when, simulators?

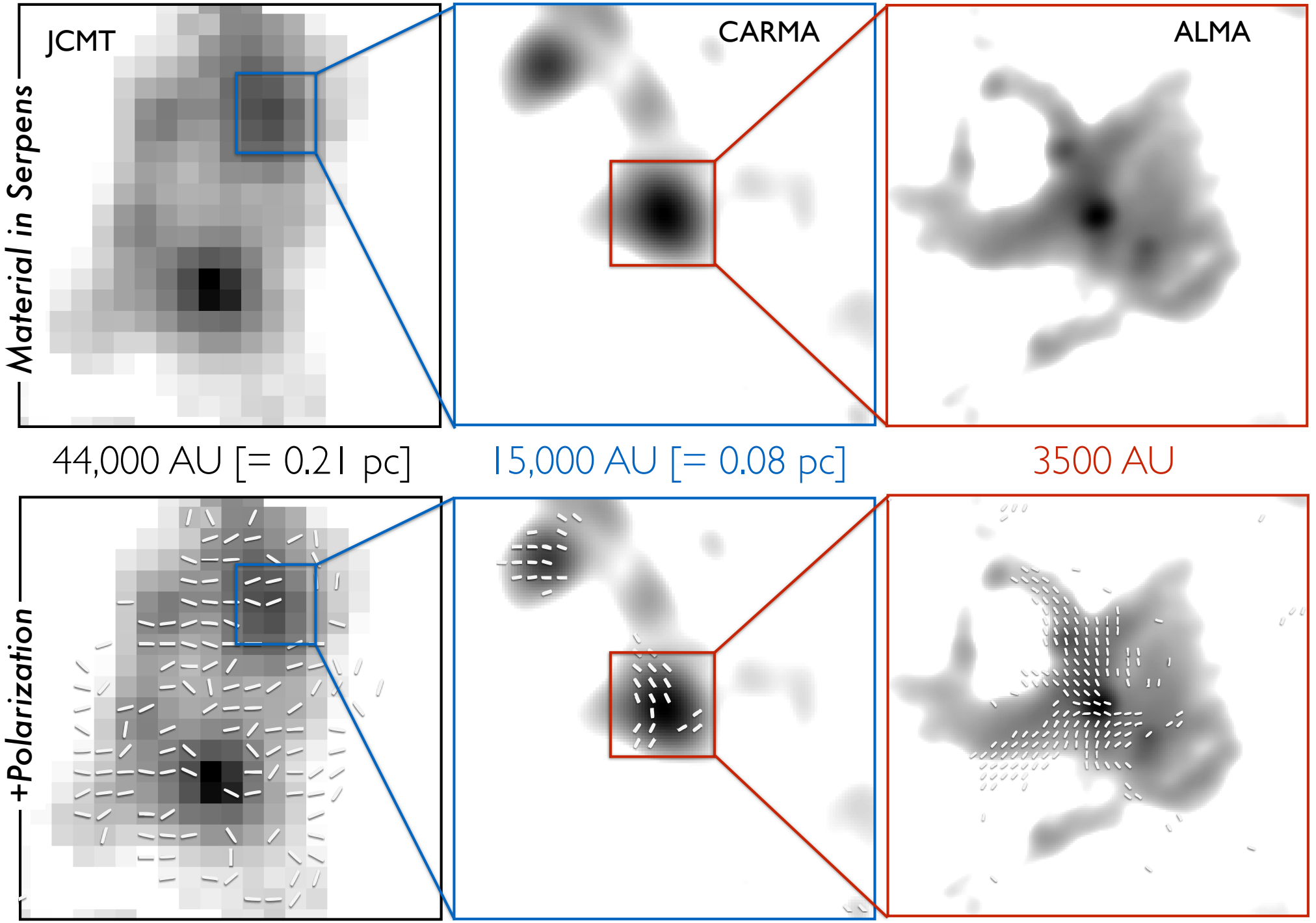
How do "influences" change what is special?

–magnetic fields, feedback, "collisions," but when, how & where, simulators?

Sneak Preview of ALMA+AREPO B-field insights...

Hull, Mocz, Burkhart, Goodman, Girart, Cortes, Hernquist, Lai, Li, Springel 2017, *ApJL*, submitted.

Hull, Mocz, Burkhart, Goodman, Girart, Cortes, Hernquist, Lai, Li, Springel 2017, *ApJL*, submitted.



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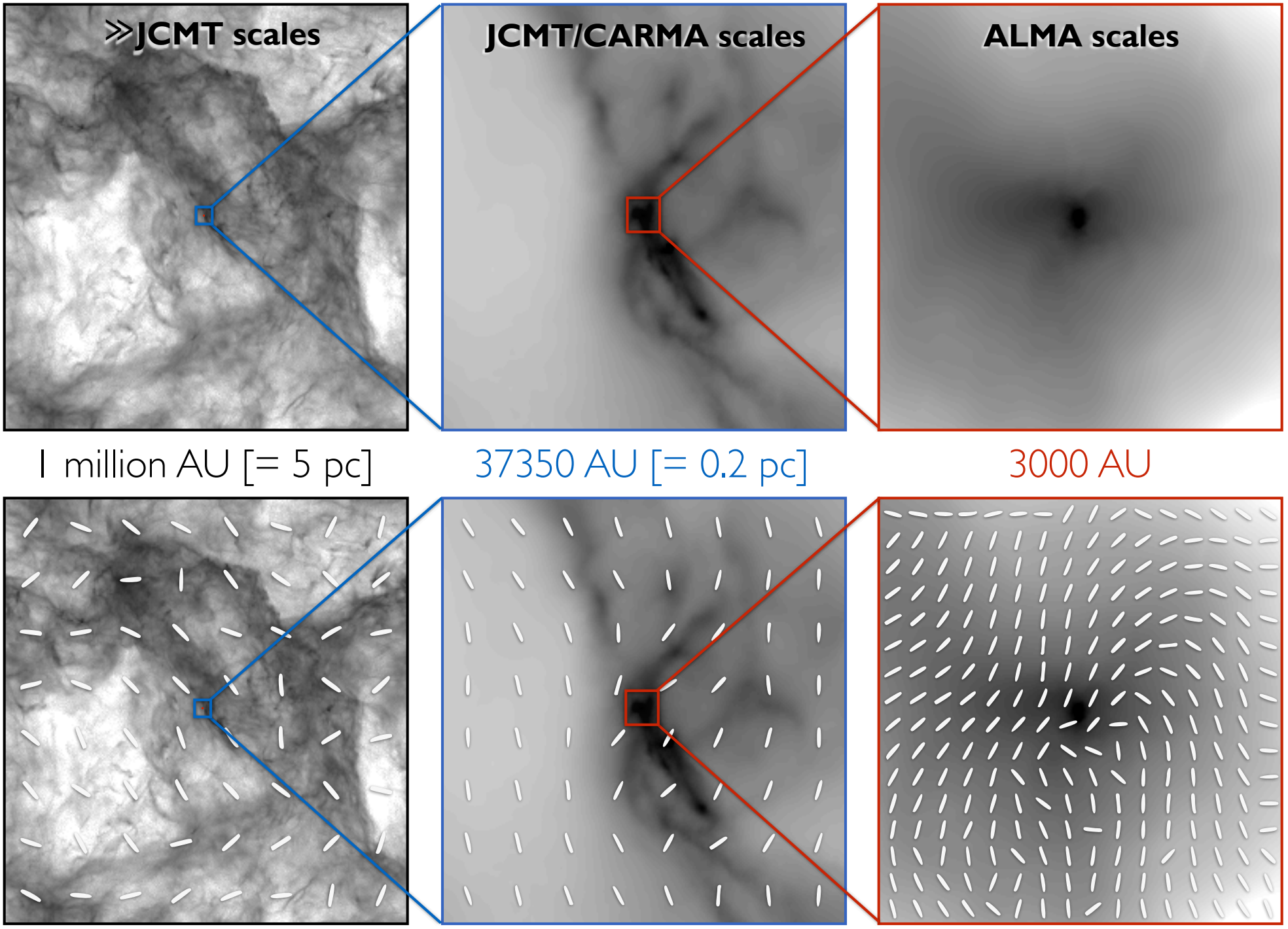
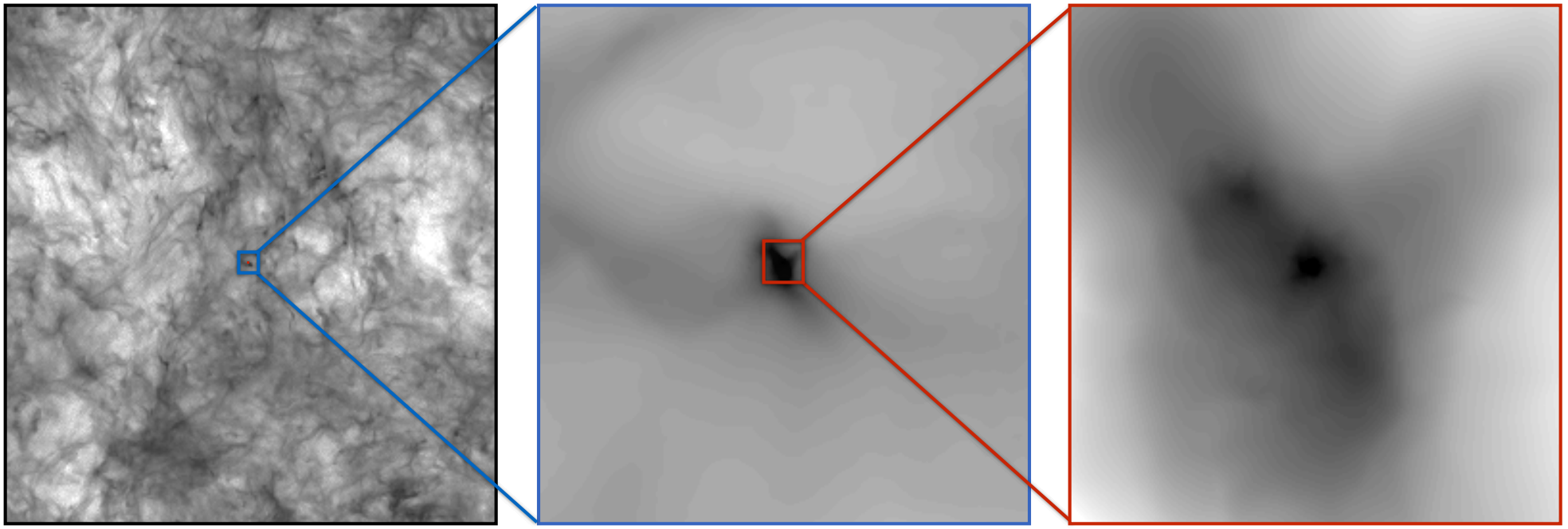

≫JCMT scales
JCMT/CARMA scales
ALMA scales
1 million AU [= 5 pc]
37350 AU [= 0.2 pc]
3000 AU

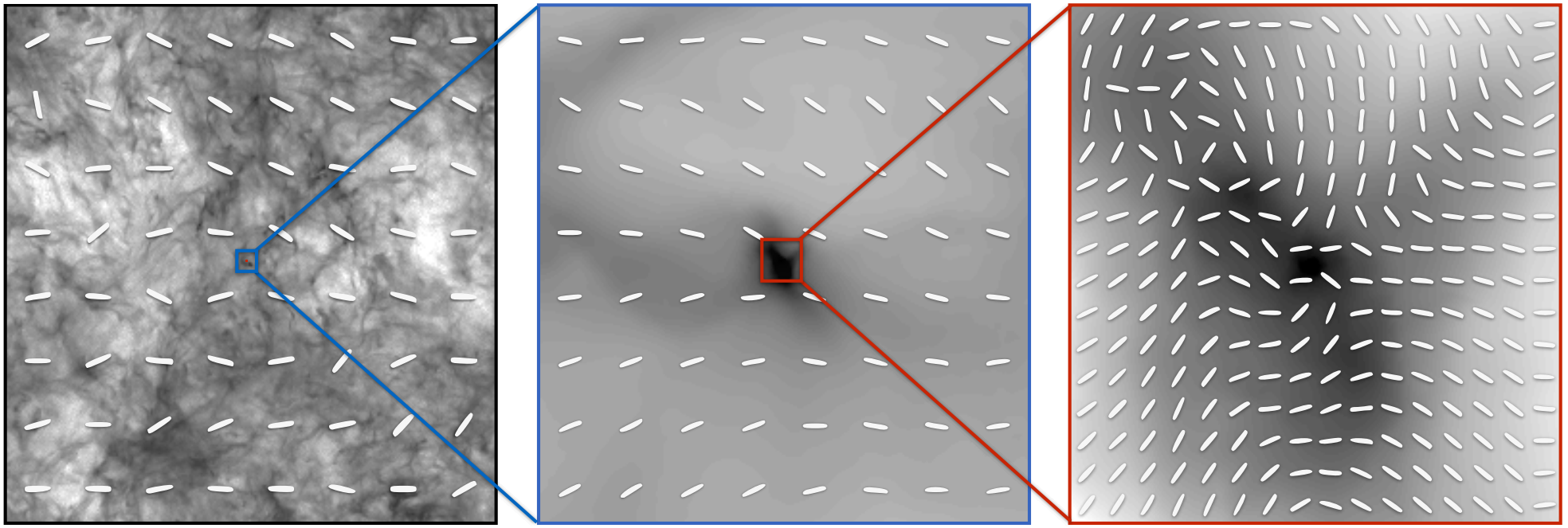
B=10



1 million AU [= 5 pc]

37350 AU [= 0.2 pc]

3000 AU



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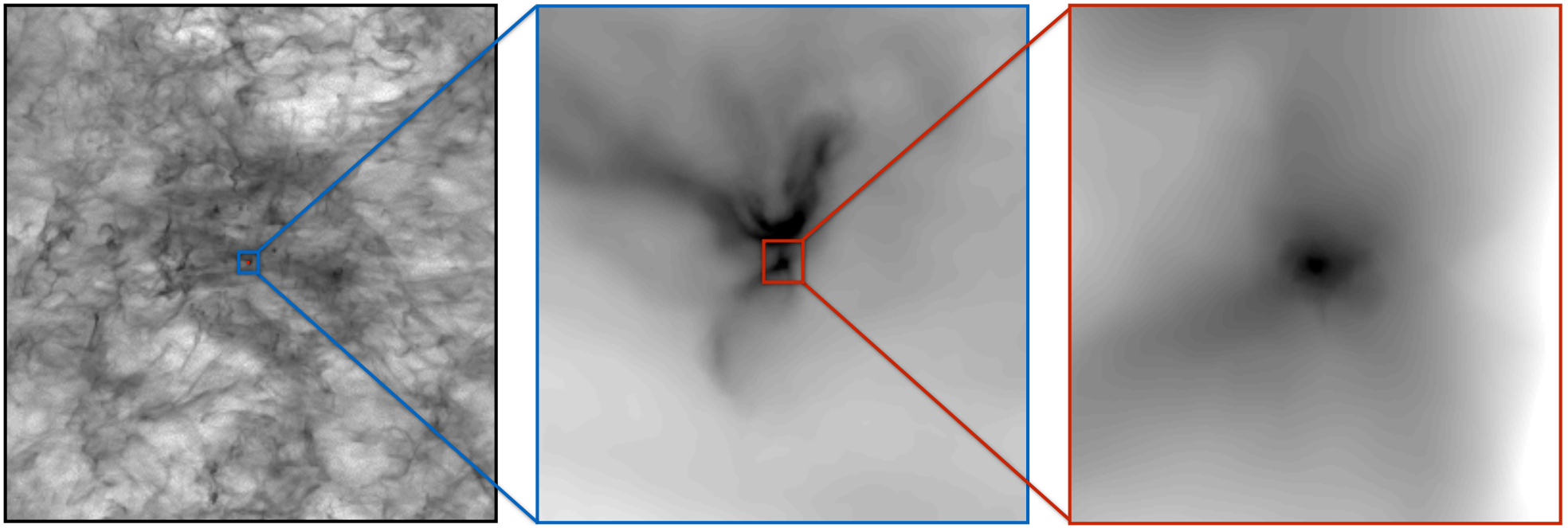
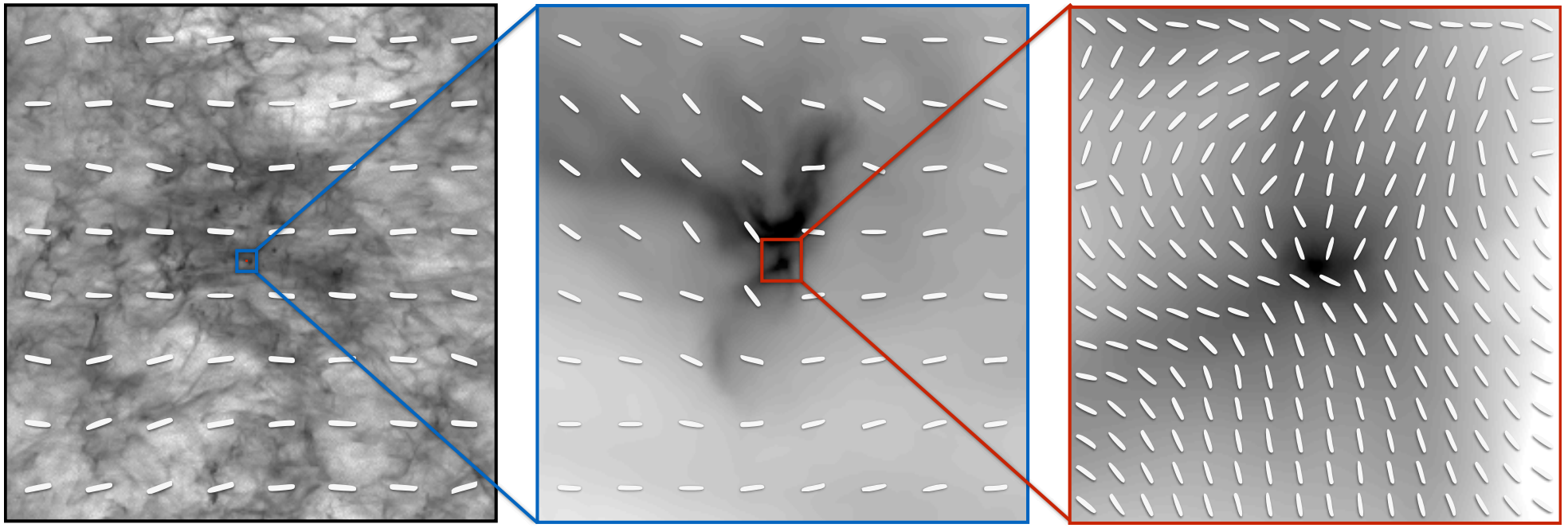
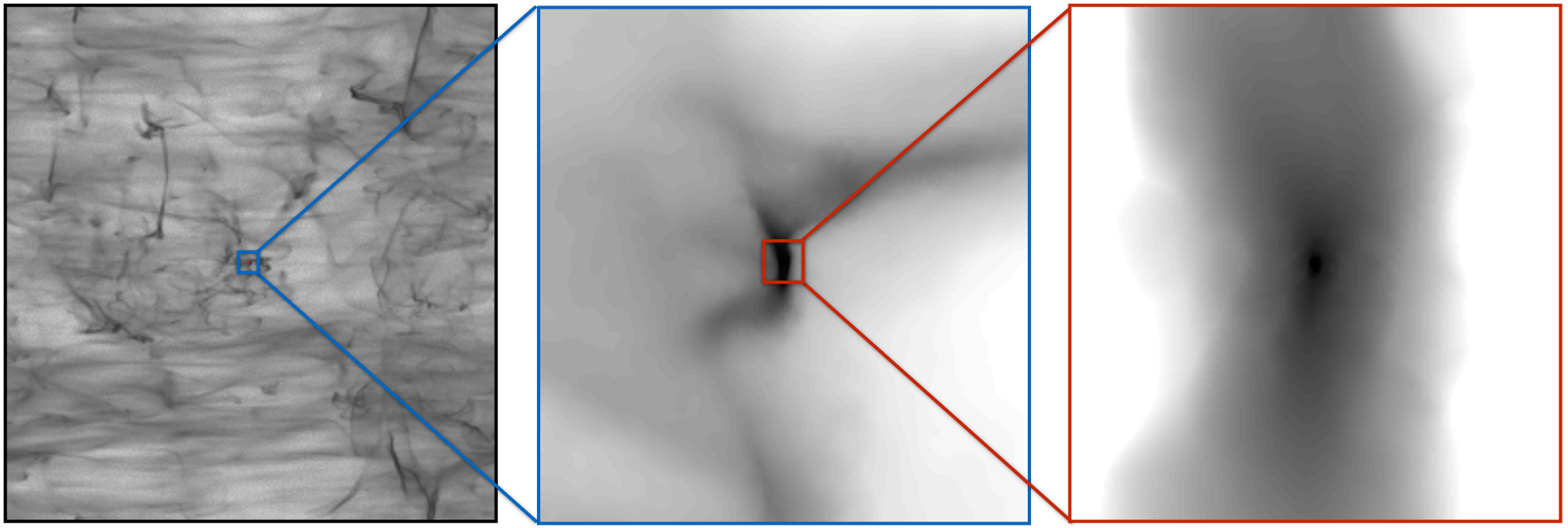


1 million AU [= 5 pc]

37350 AU [= 0.2 pc]

3000 AU

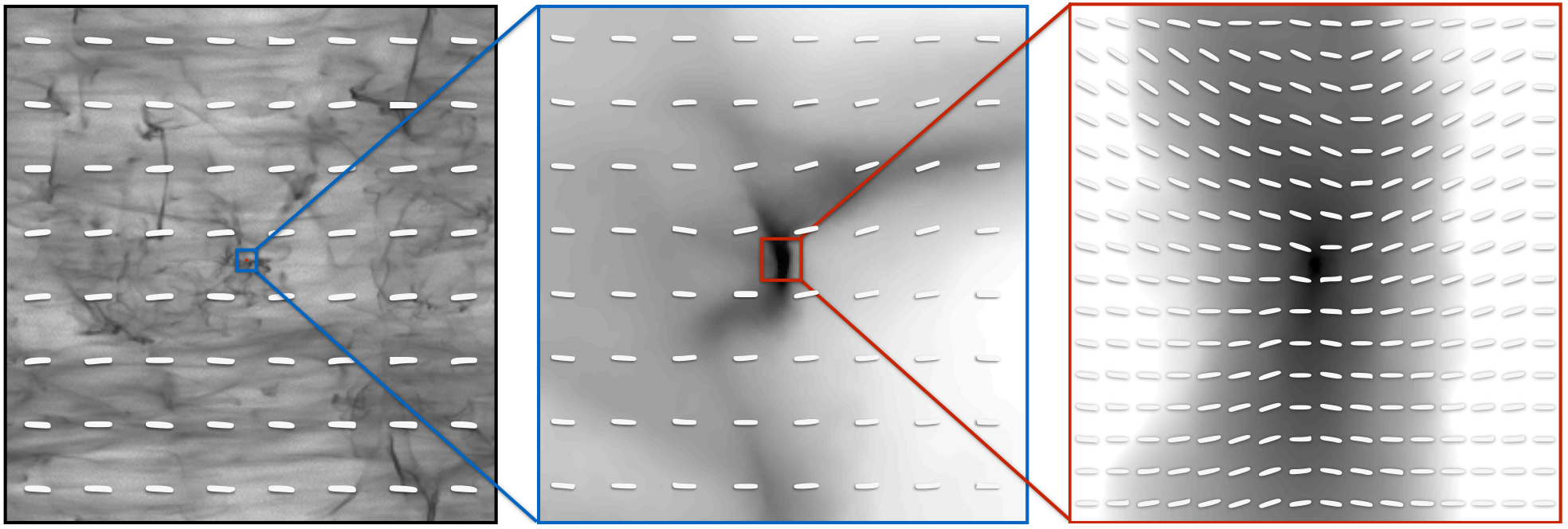




1 million AU [= 5 pc]

37350 AU [= 0.2 pc]

3000 AU



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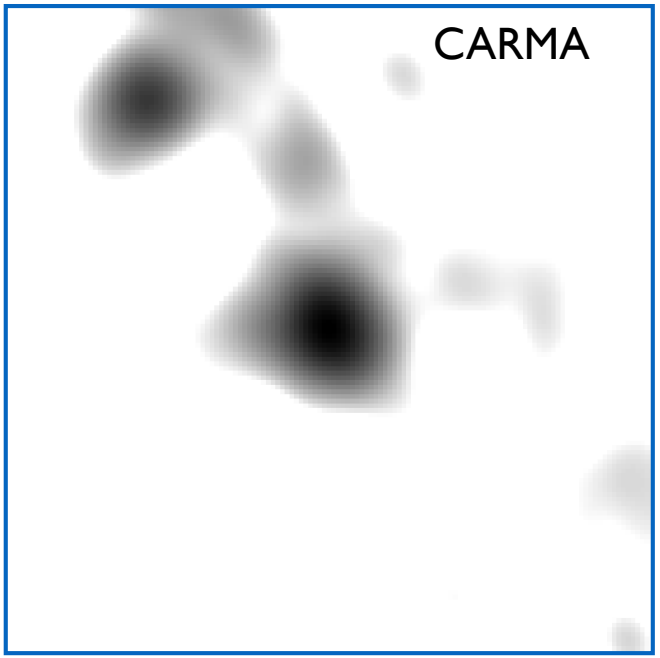
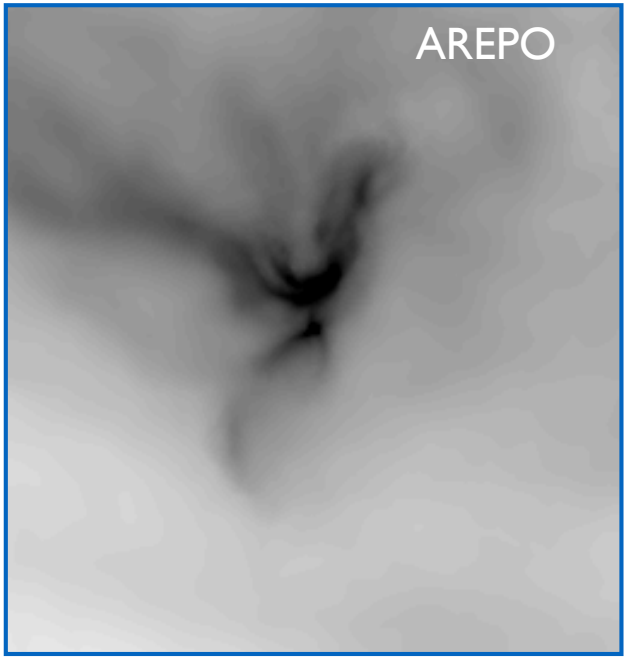
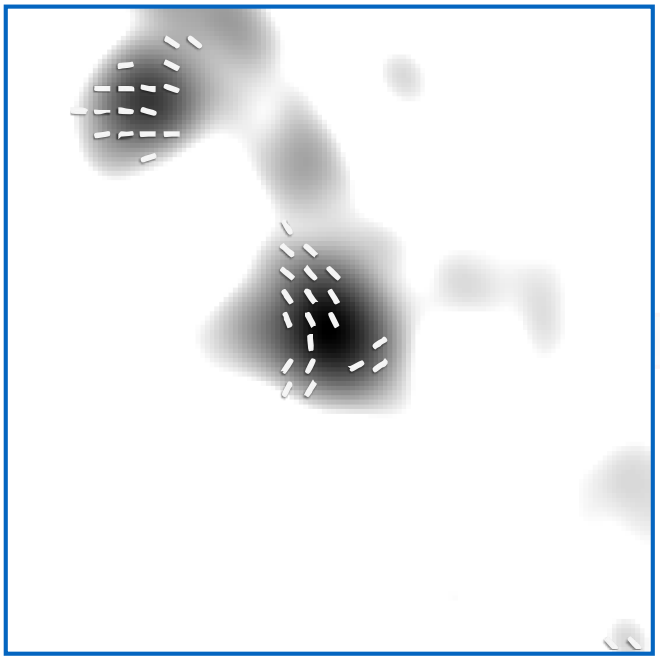
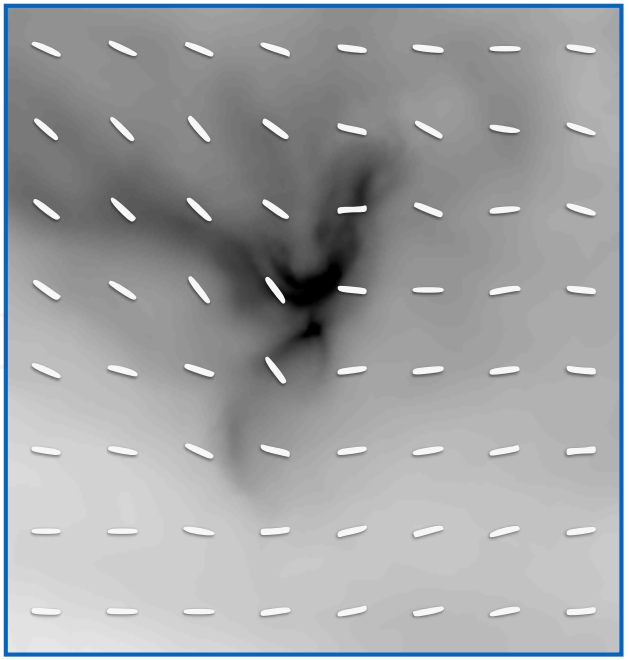




15,000 AU [= 0.08 pc]

37350 AU [= 0.2 pc]





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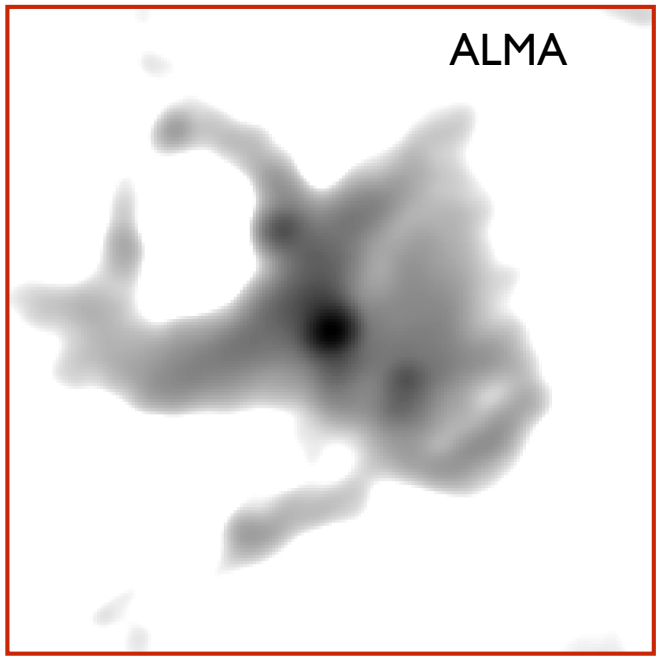
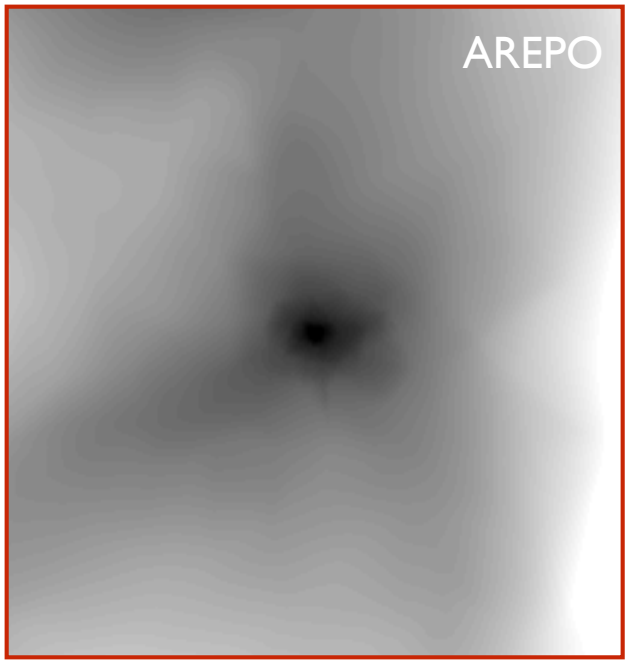
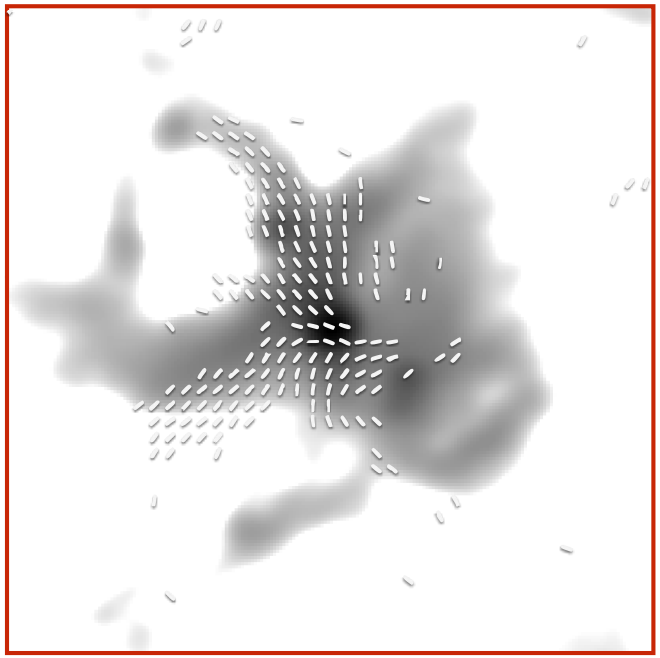
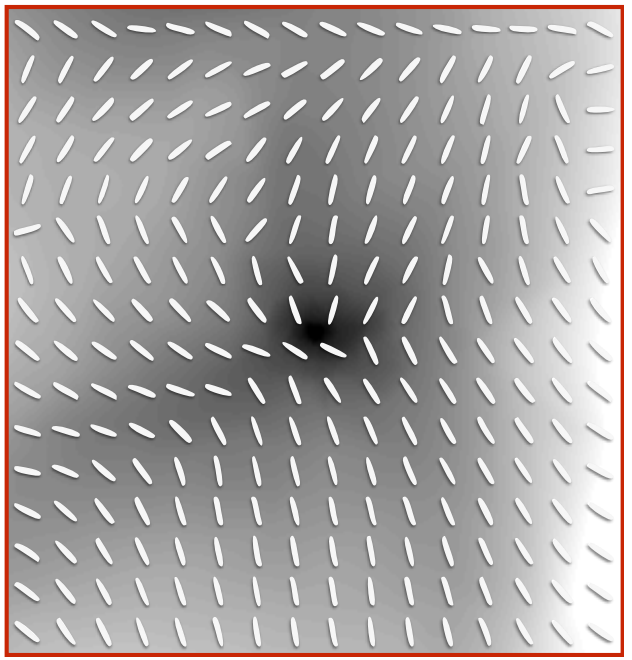




3500 AU

3000 AU





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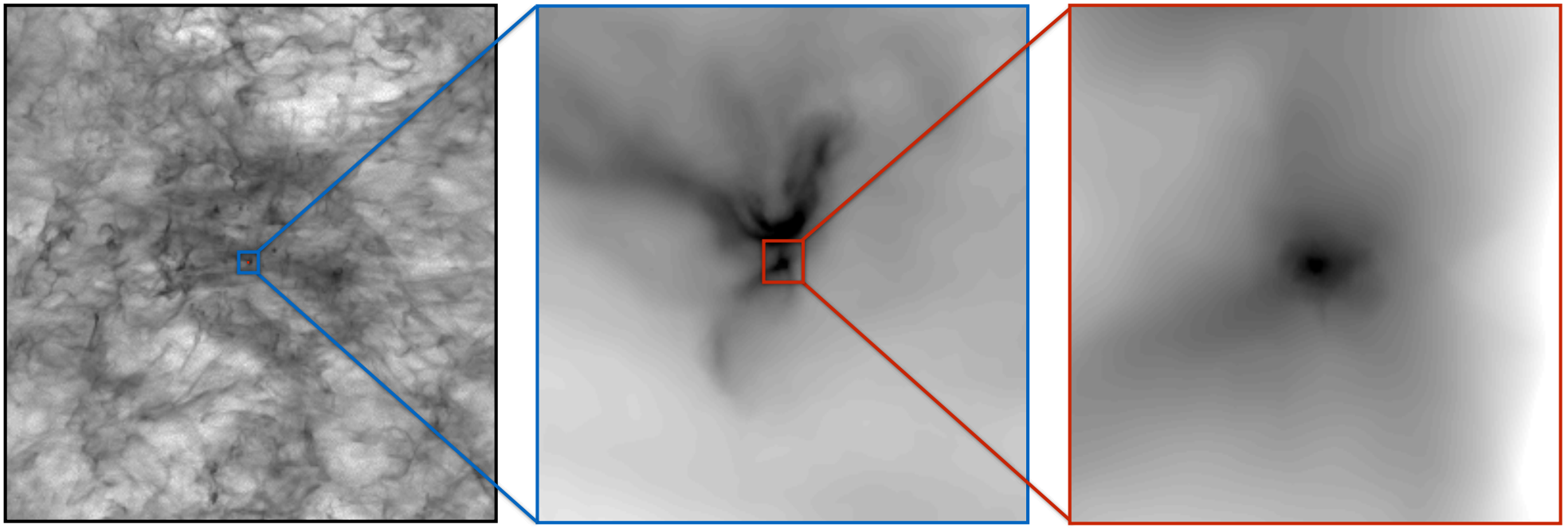
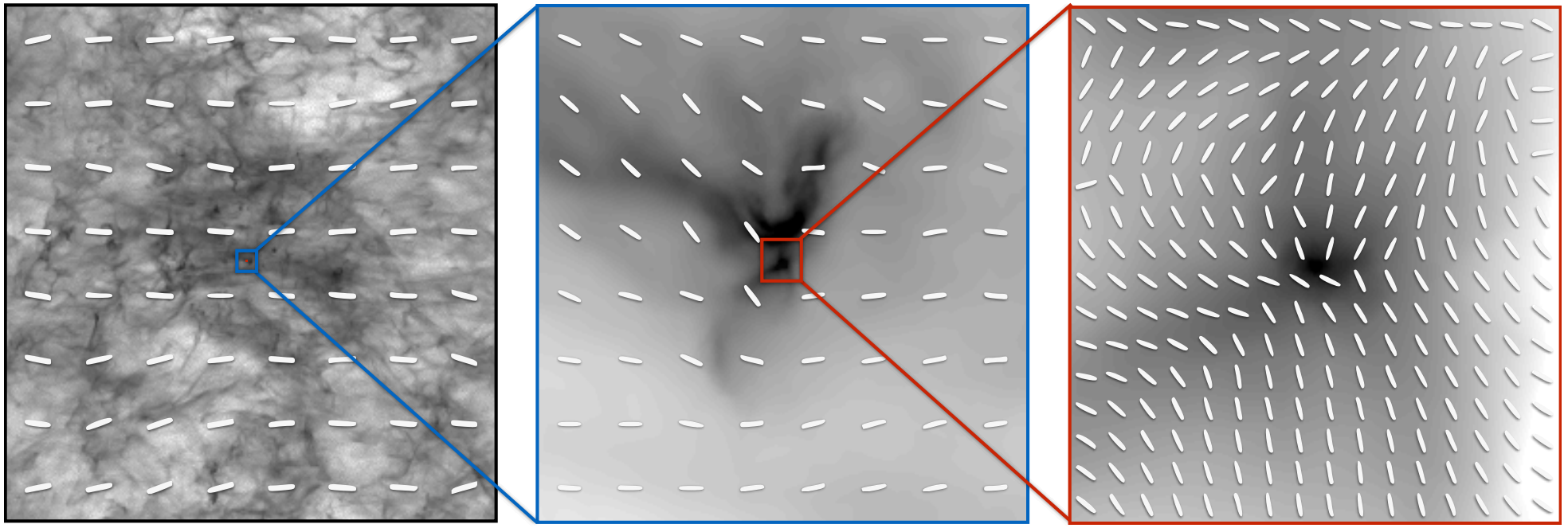


1 million AU [= 5 pc]

37350 AU [= 0.2 pc]

3000 AU



FILAMENTS: FAD OR FUNDAMENTAL?

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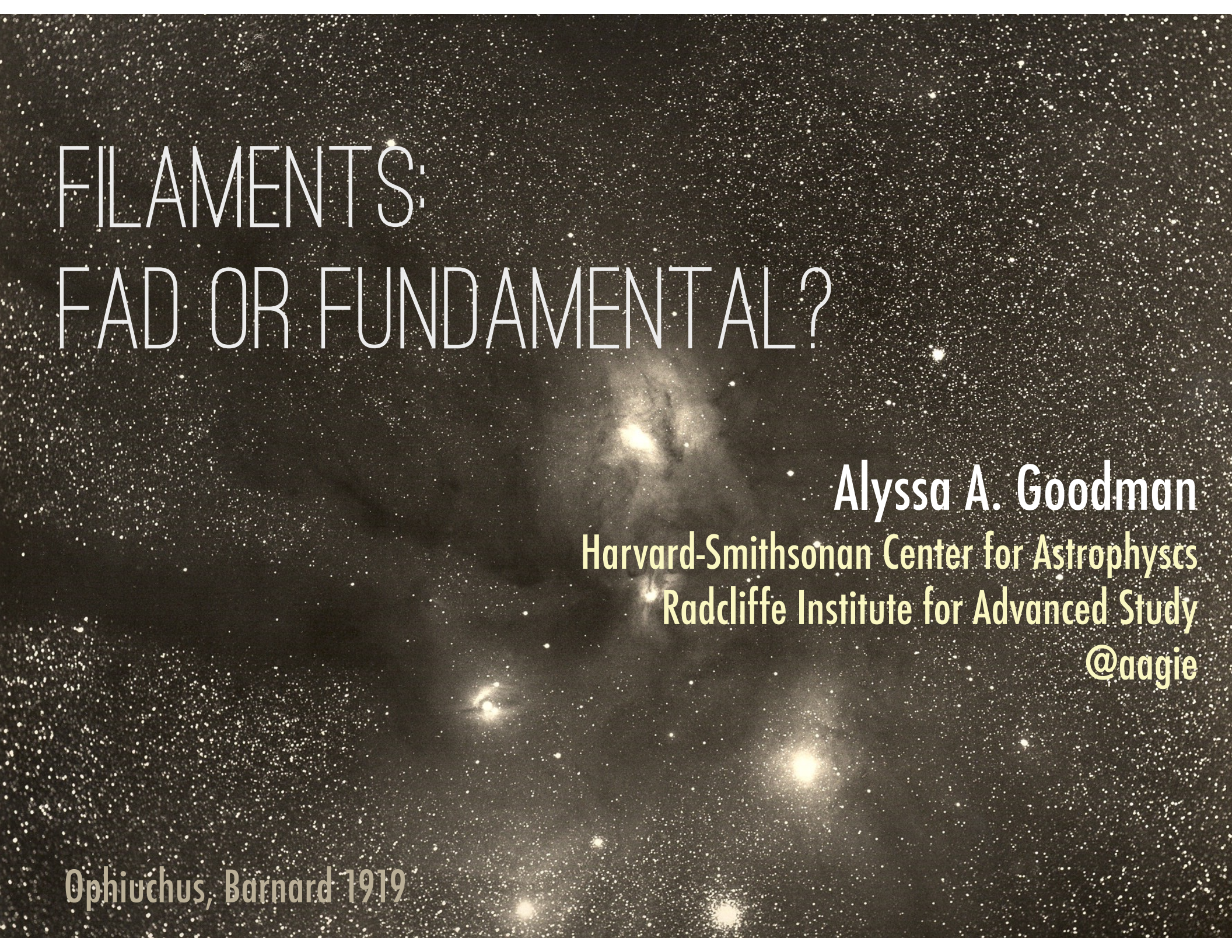

Ophiuchus, Barnard 1919