Teasing Out the True Milky Way

Alyssa Goodman
Harvard-Smithsonian for Astrophysics
Radcliffe Institute for Advanced Study

space.com/universe-colors-milky-way-photo.html

Teasing Out the True Milky Way

with many thanks to: João **Alves**, Cara Battersby, Gus Beane, Christopher Beaumont, Bob Benjamin, Michelle Borkin, Tom Dame, Jonathan Fay, Douglas **Finkbeiner**, Greg Green, Jens Kauffmann, Mark Reid, Thomas **Robitaille**, Eddie Schlafly, Rowan **Smith**, Josh **Speagle**, Catherine **Zucker** & Curtis **Wong**

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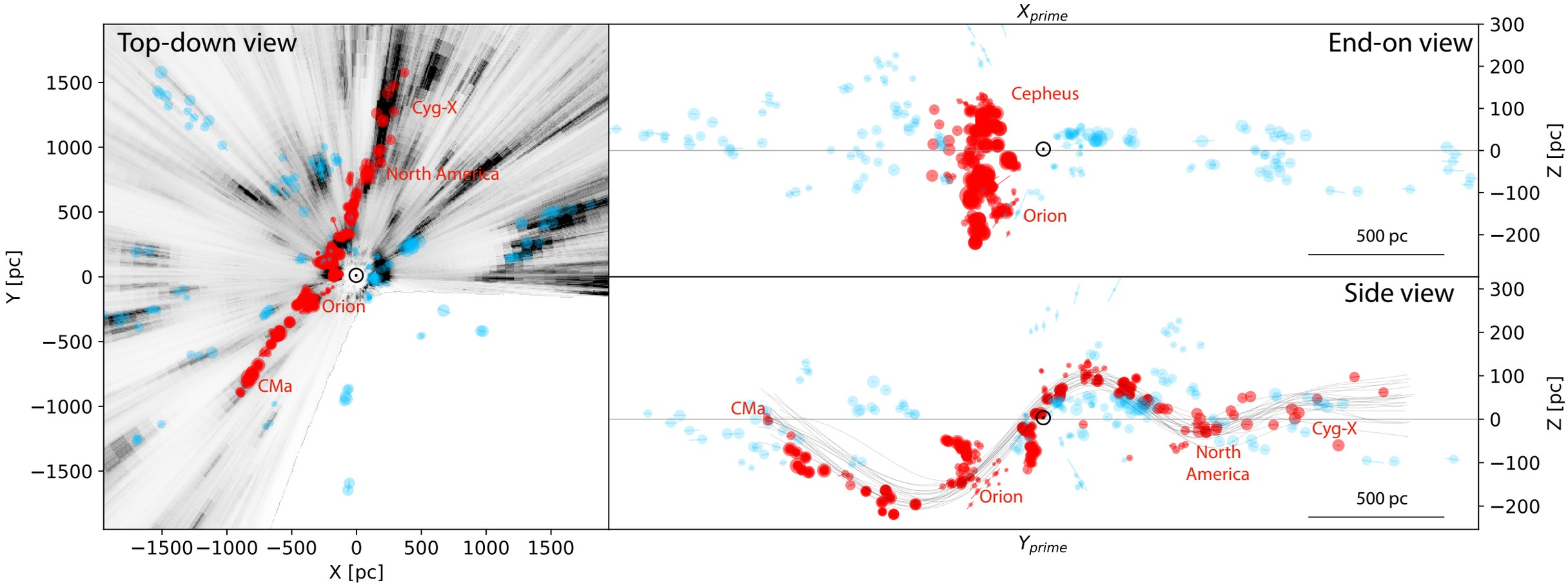
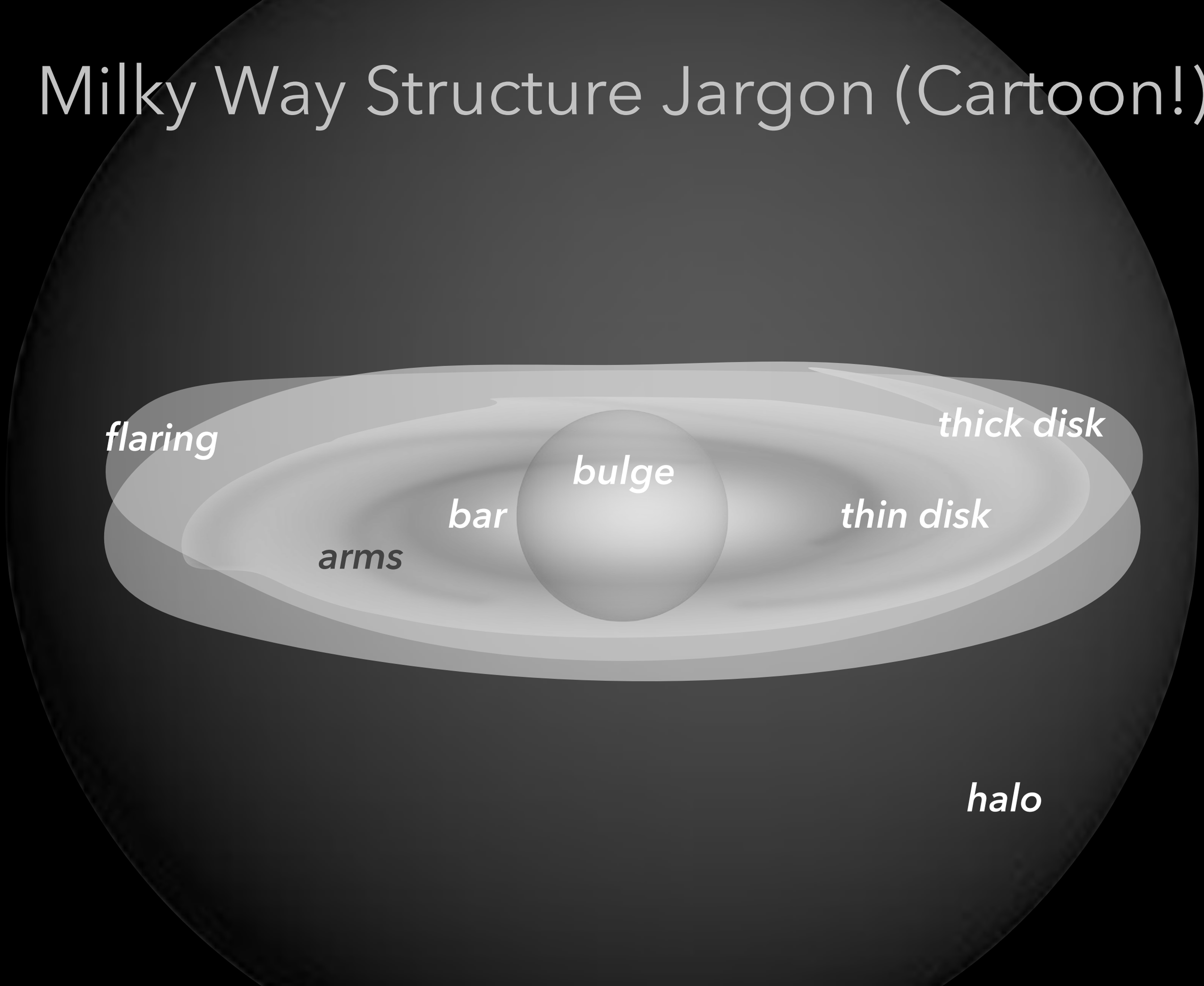
The “Radcliffe” Wave

(embargoed, please do not distribute)



João Alves, Catherine Zucker, Alyssa Goodman, Joshua Speagle, Stefan Meingast, Thomas Robitaille, Douglas Finkbeiner, Edward F. Schlafly, and Gregory Green 2019, *Nature* (soon, we hope)

Milky Way Structure Jargon (Cartoon!)



Aristotle, et al.

Thomas Wright, William Herschel…

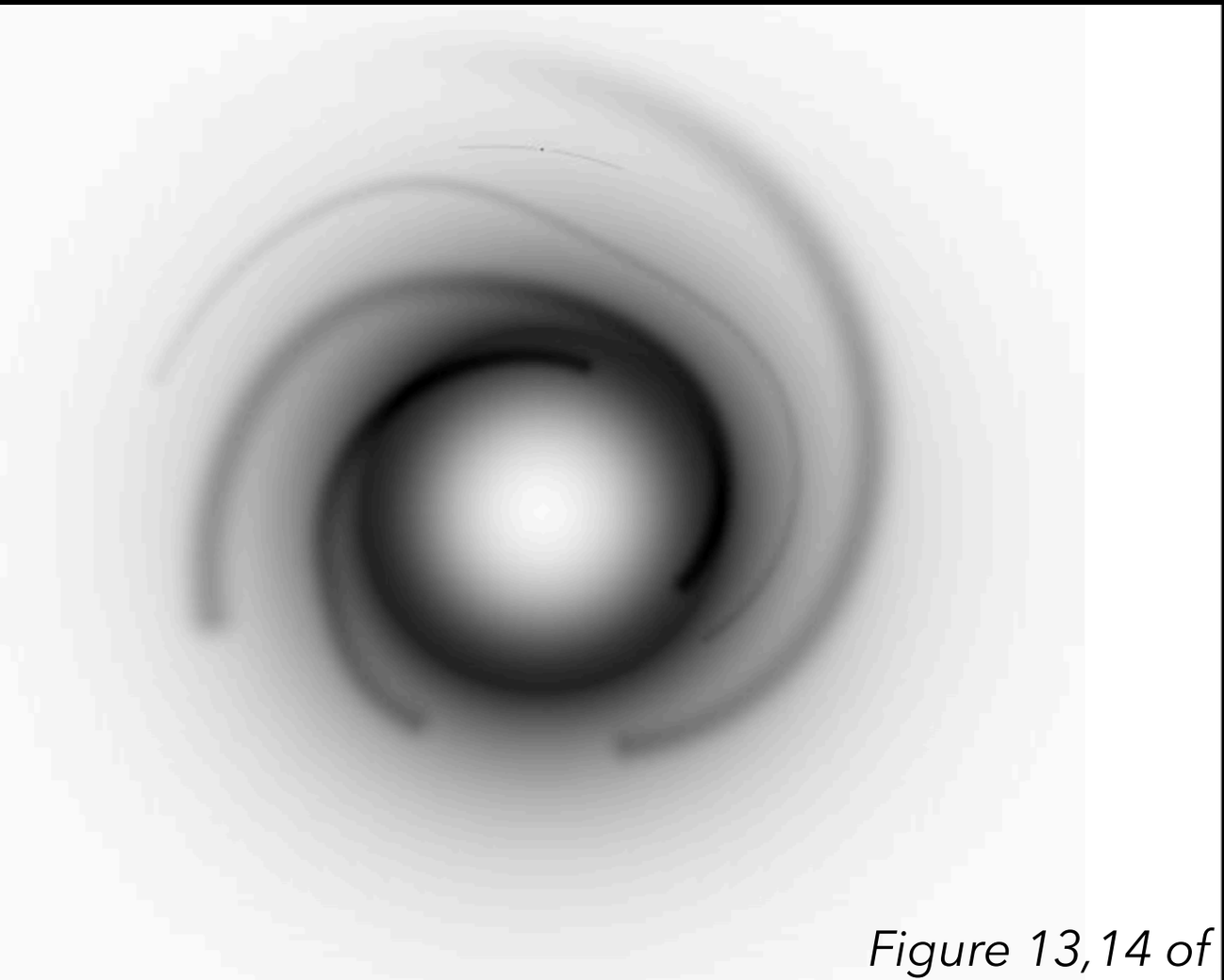


Figure 13,14 of Drimmel & Spergel 1991

Hubble's "Tuning Fork"

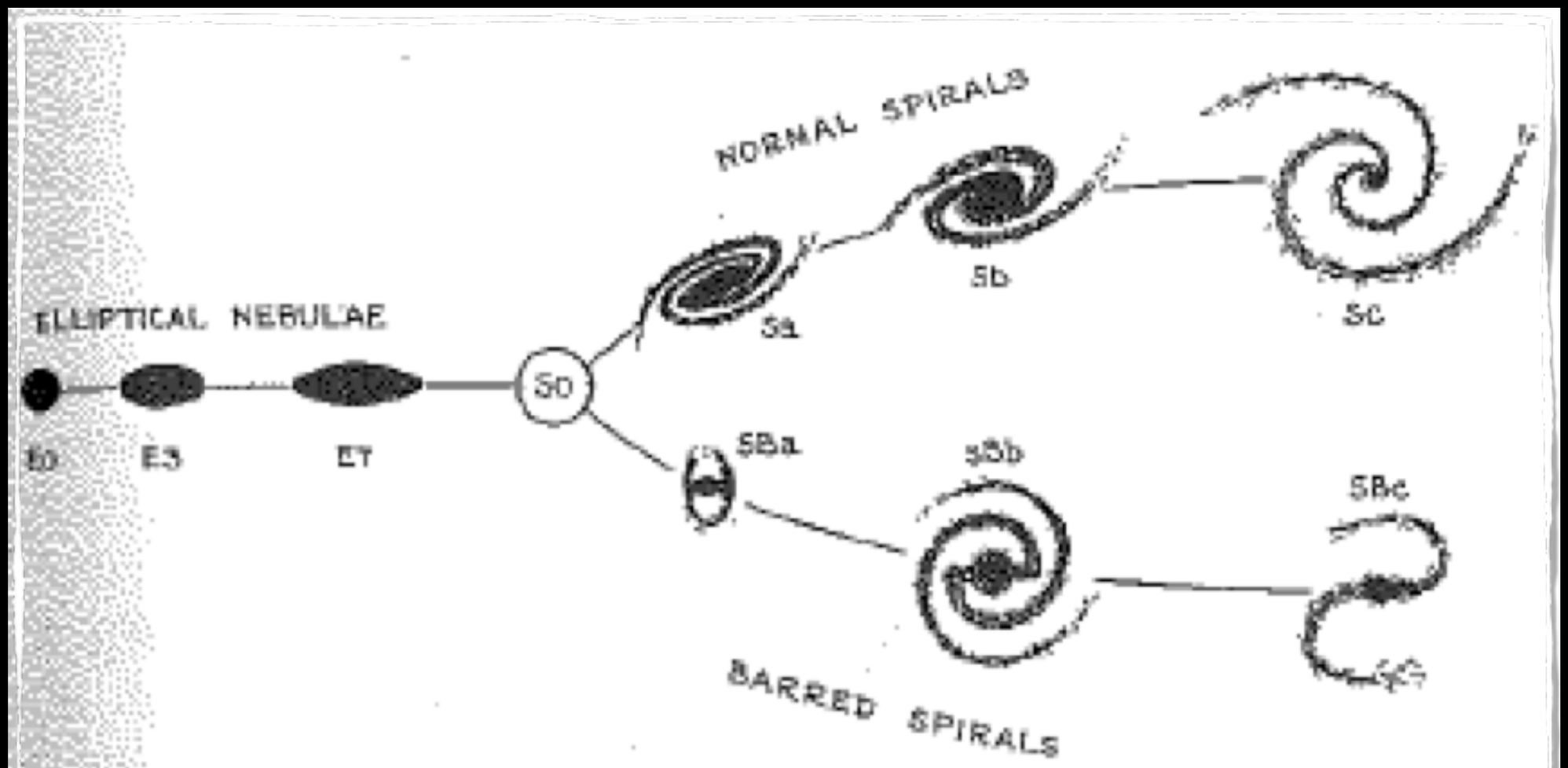
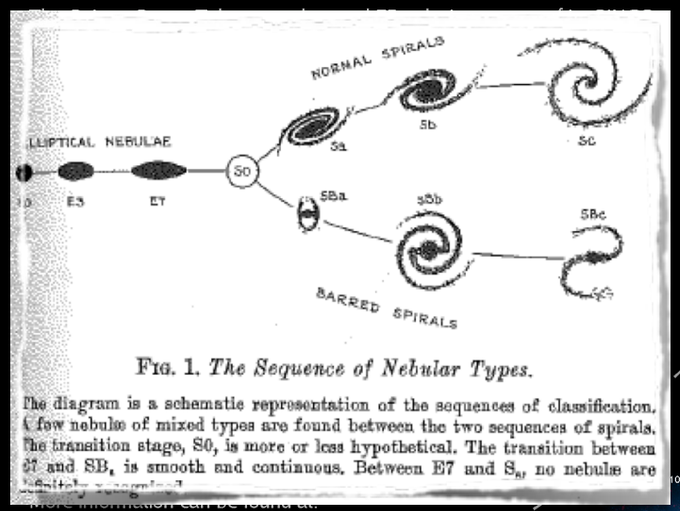


FIG. 1. *The Sequence of Nebular Types.*

The diagram is a schematic representation of the sequences of classification. A few nebulæ of mixed types are found between the two sequences of spirals. The transition stage, S0, is more or less hypothetical. The transition between E7 and SB_a is smooth and continuous. Between E7 and S_a, no nebulæ are definitely recognized.

The Spitzer Infrared Nearby Galaxies Survey (SINGS) Hubble Tuning-Fork



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More information can be found at:
http://sings.stsci.edu/

Unbarred Spirals

Weak Bulge

Intermediate Spirals

Strong Bulge

Ellipticals

Strong Bulge

Irregulars

Weak Bulge

Barred Spirals

Poster and composite images created from SINGS observations by Karl D. Gordon (Oct 2007)
Blue=IRAC 3.6μm (stars)
Green=IRAC 8μm
(aromatic features from dust grains/molecules)
Red=MIPS 24μm (warm dust)

SINGS Team

Robert Kennicutt, Jr. (Principle Investigator), Daniela Calzetti (Deputy Principle Investigator), Charles Engelbracht (Technical Contact), Lee Armus, George Bendo, Caroline Bot, Brent Buckalew, John Cannon, Daniel Dale, Bruce Draine, Karl Gordon, Albert Grauer, David Hollenbach, Tom Jarrett, Lisa Kewley, Claus Leitherer, Aigen Li, Sangeeta Malhotra, Martin Meyer, John Moustakas, Eric Murphy, Michael Regan, George Rieke, Marcia Rieke, Helene Roussel, Kartik Sheth, J.D. Smith, Michele Thornley, Fabian Walter & George Helou

How many arms?

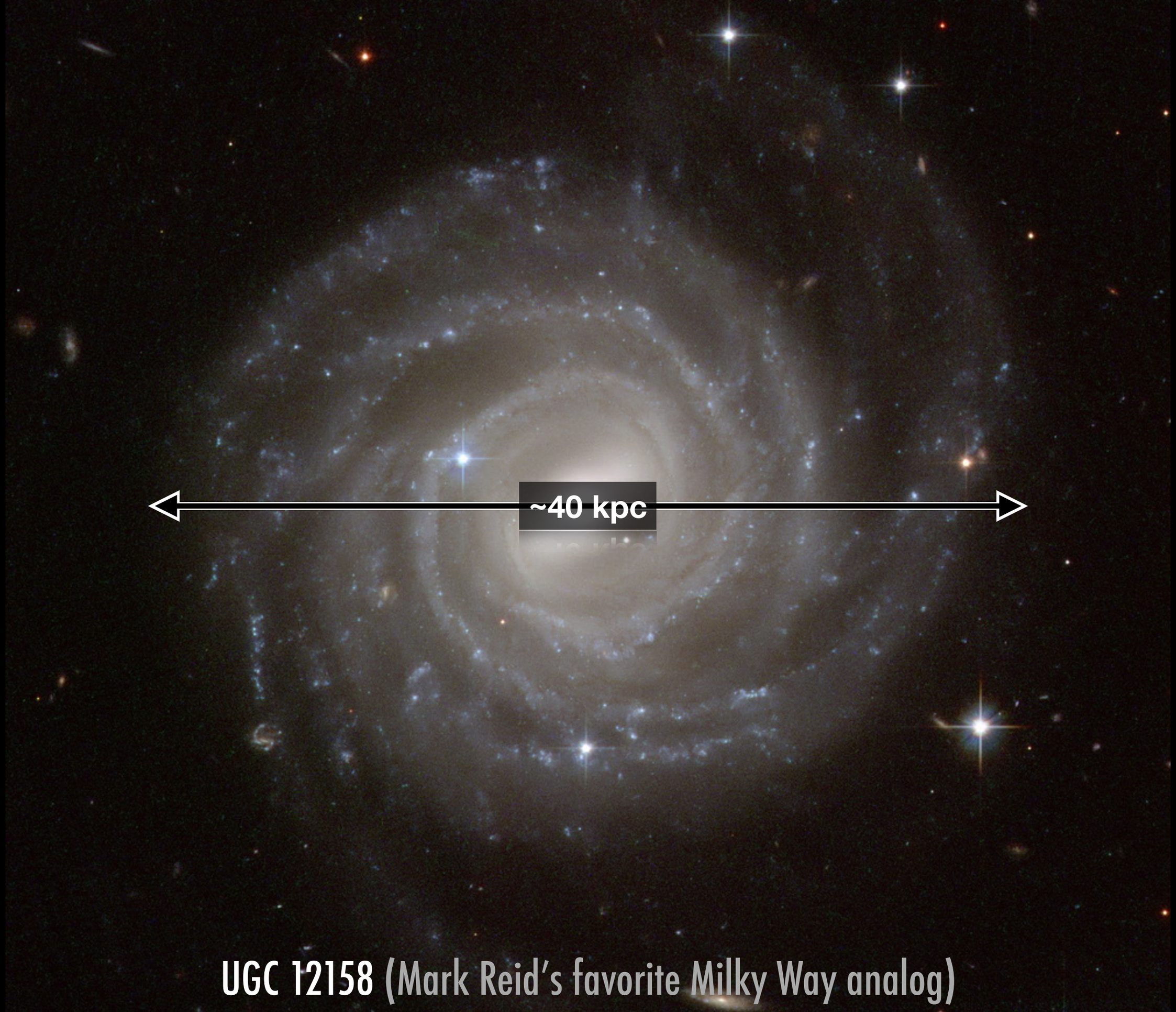
?

long straight bits

bar

?

UGC 12158 (Mark Reid's favorite Milky Way analog)



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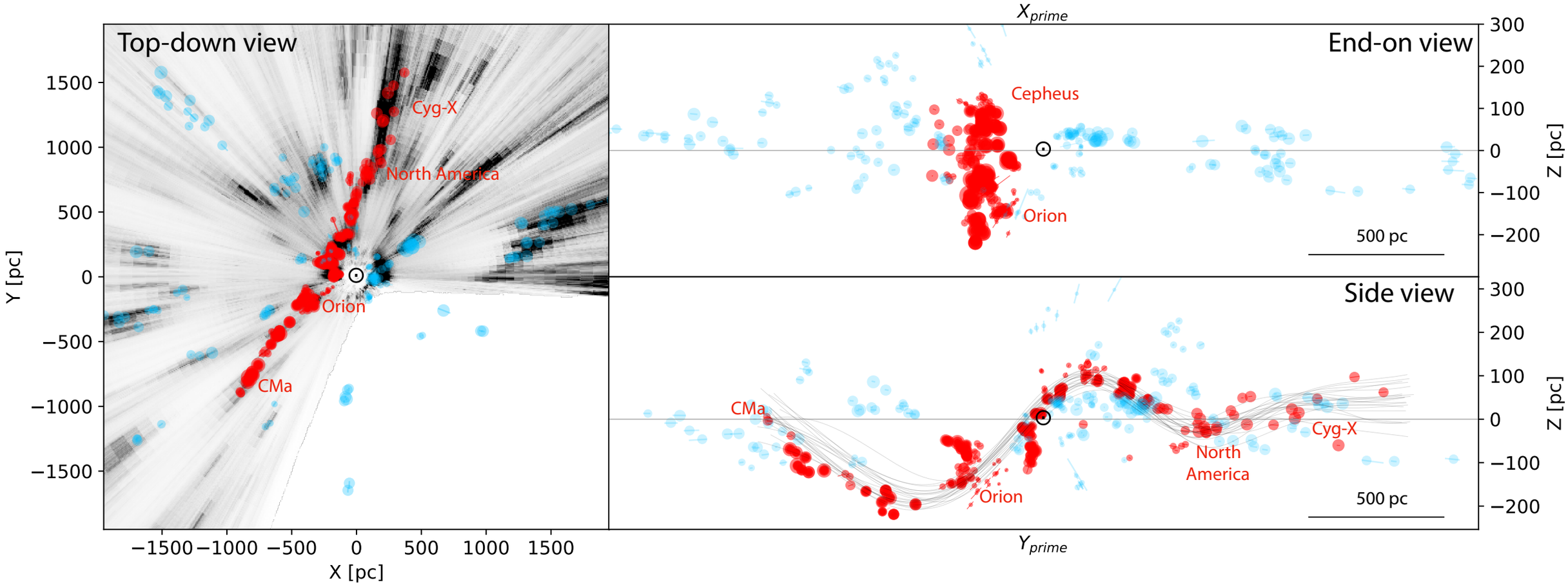
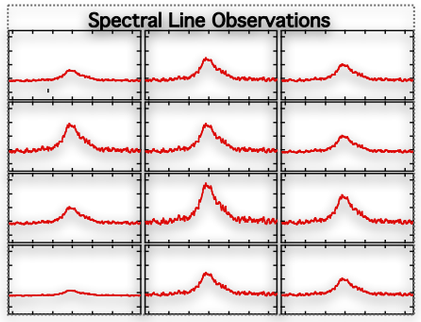
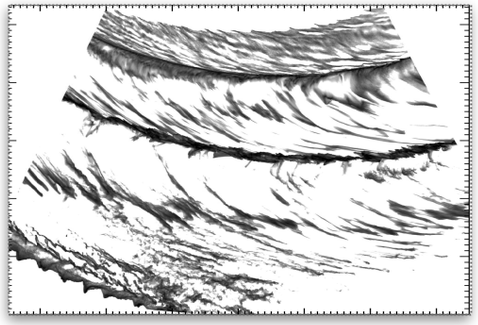


João Alves, Catherine Zucker, Alyssa Goodman, Joshua Speagle, Stefan Meingast, Thomas Robitaille, Douglas Finkbeiner, Edward F. Schlafly, and Gregory Green 2019, *Nature* (soon, we hope)

“Data”= 3D cubes, 2D images, 1D catalogs, from…

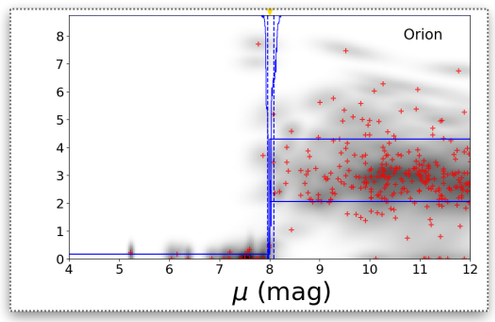


spectral-line mapping

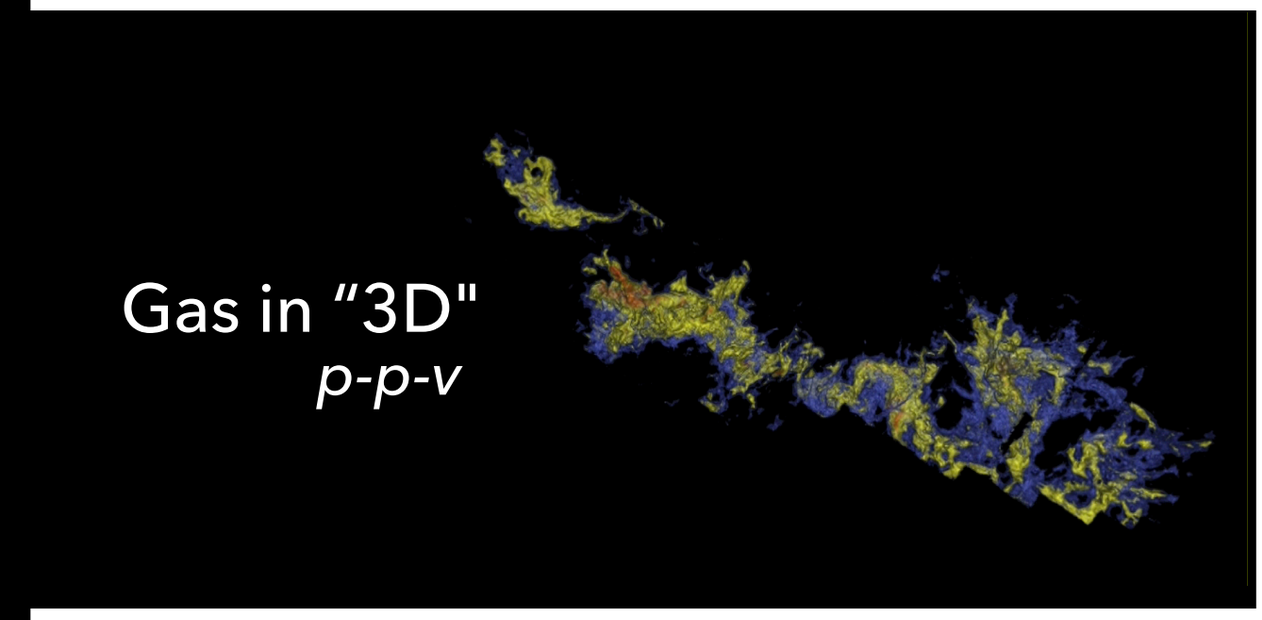


numerical simulation

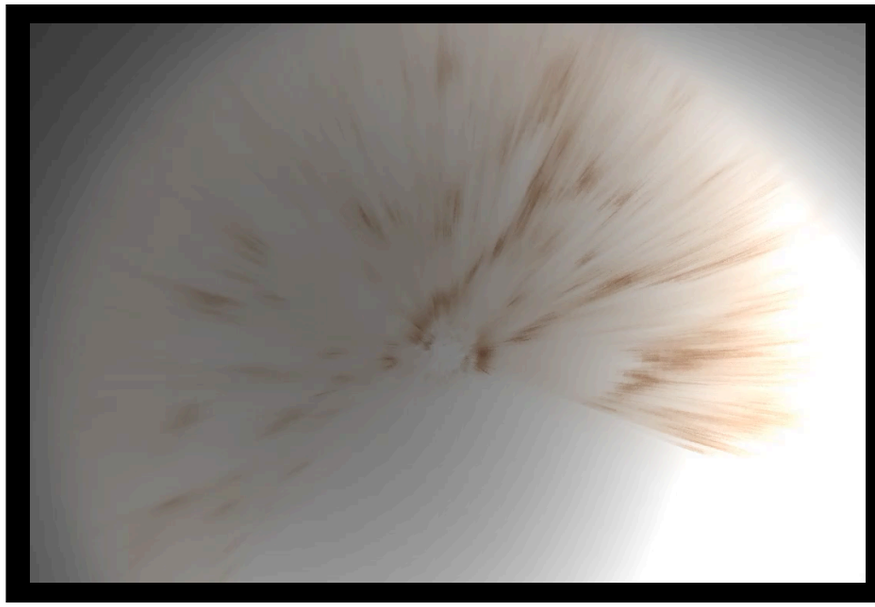
photometric imaging (over time)



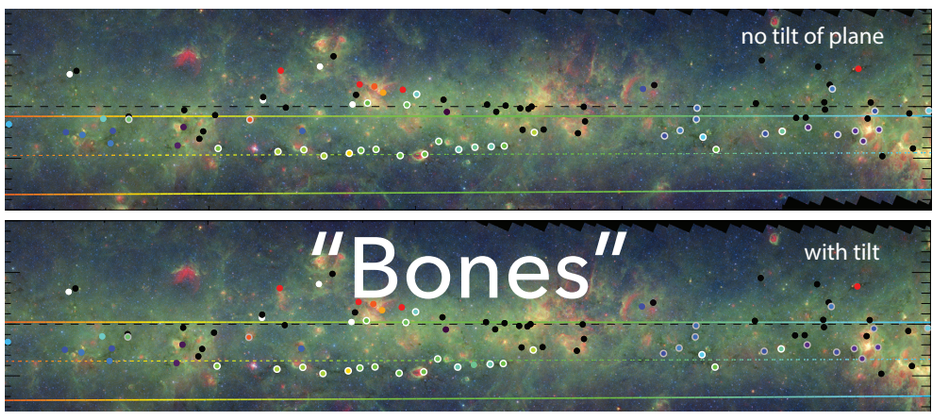
statistical reconstruction

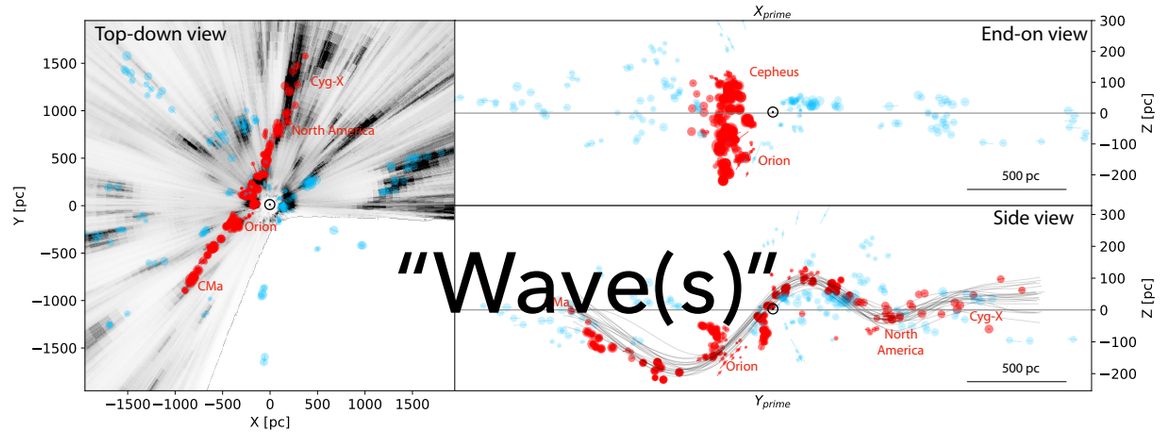


Gas in “3D"
p-p-v



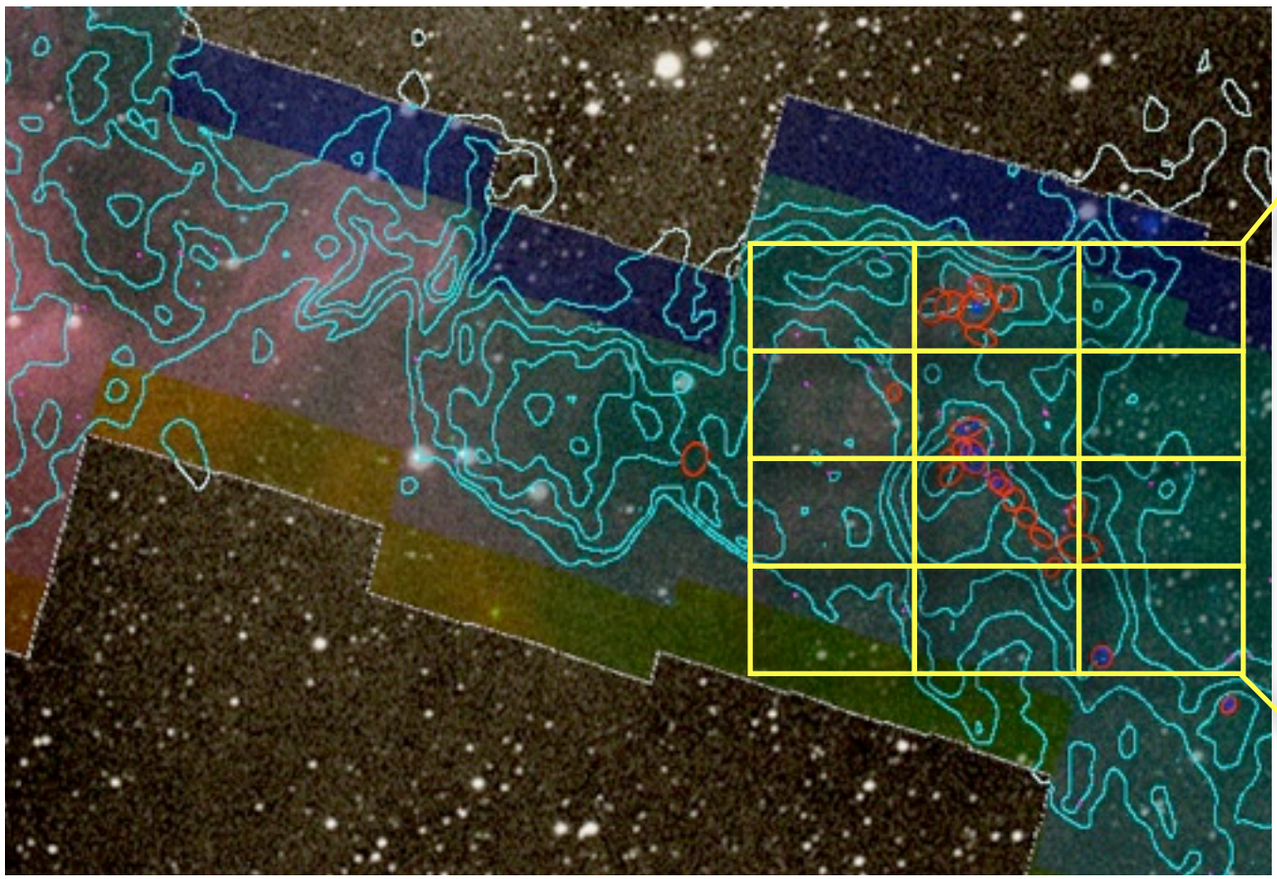
Dust in 3D
p-p-p

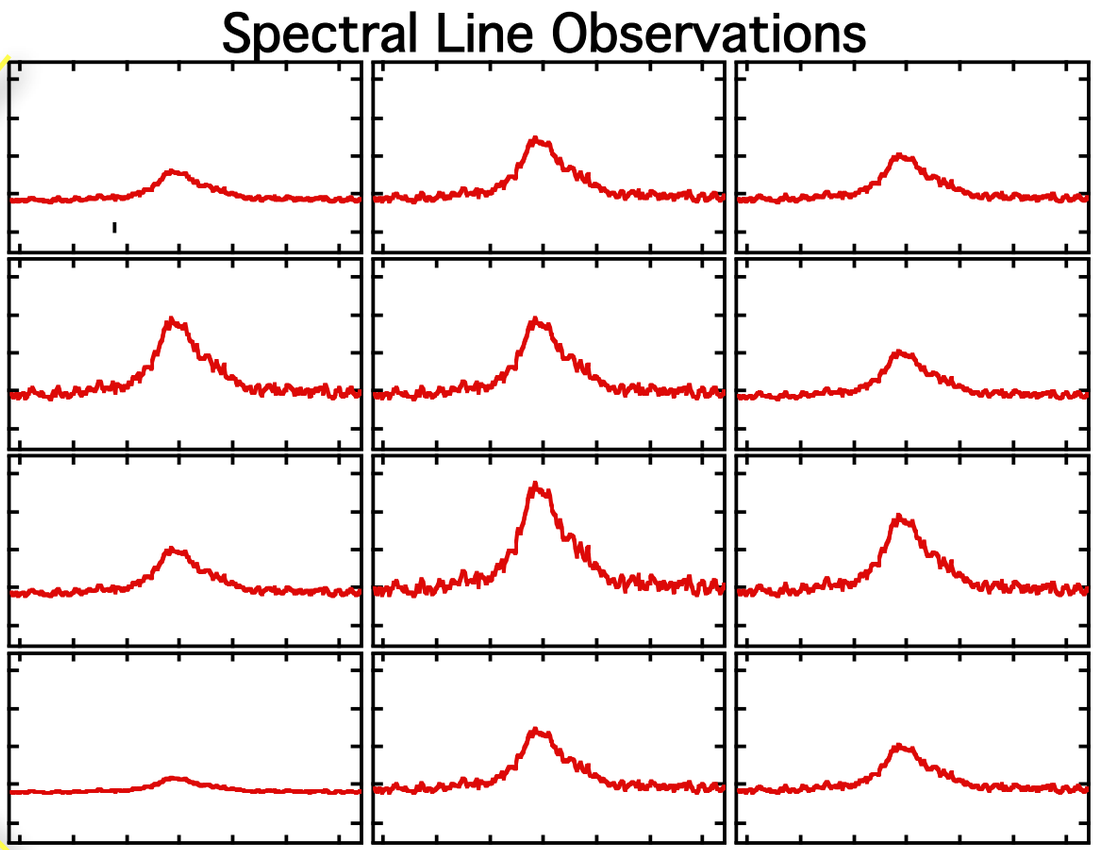


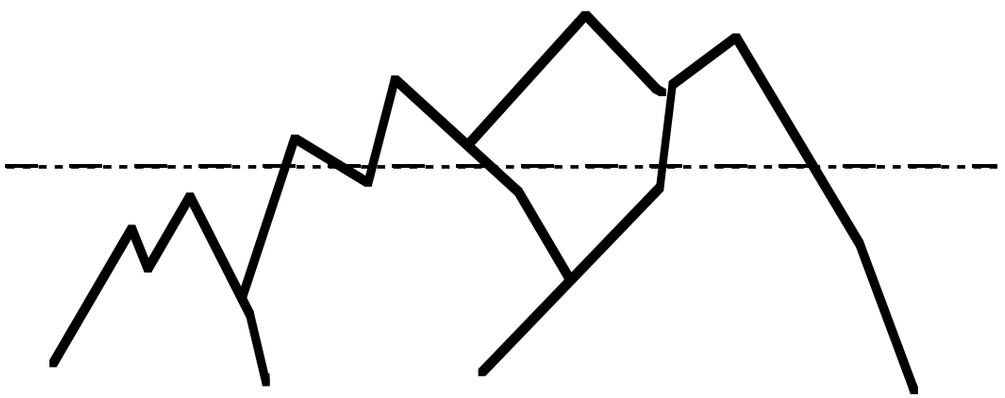


“Theory” questions re: magnetic fields, feedback, collisions, oscillations, dark matter…

Spectral-line mapping: "*p-p-v*" space



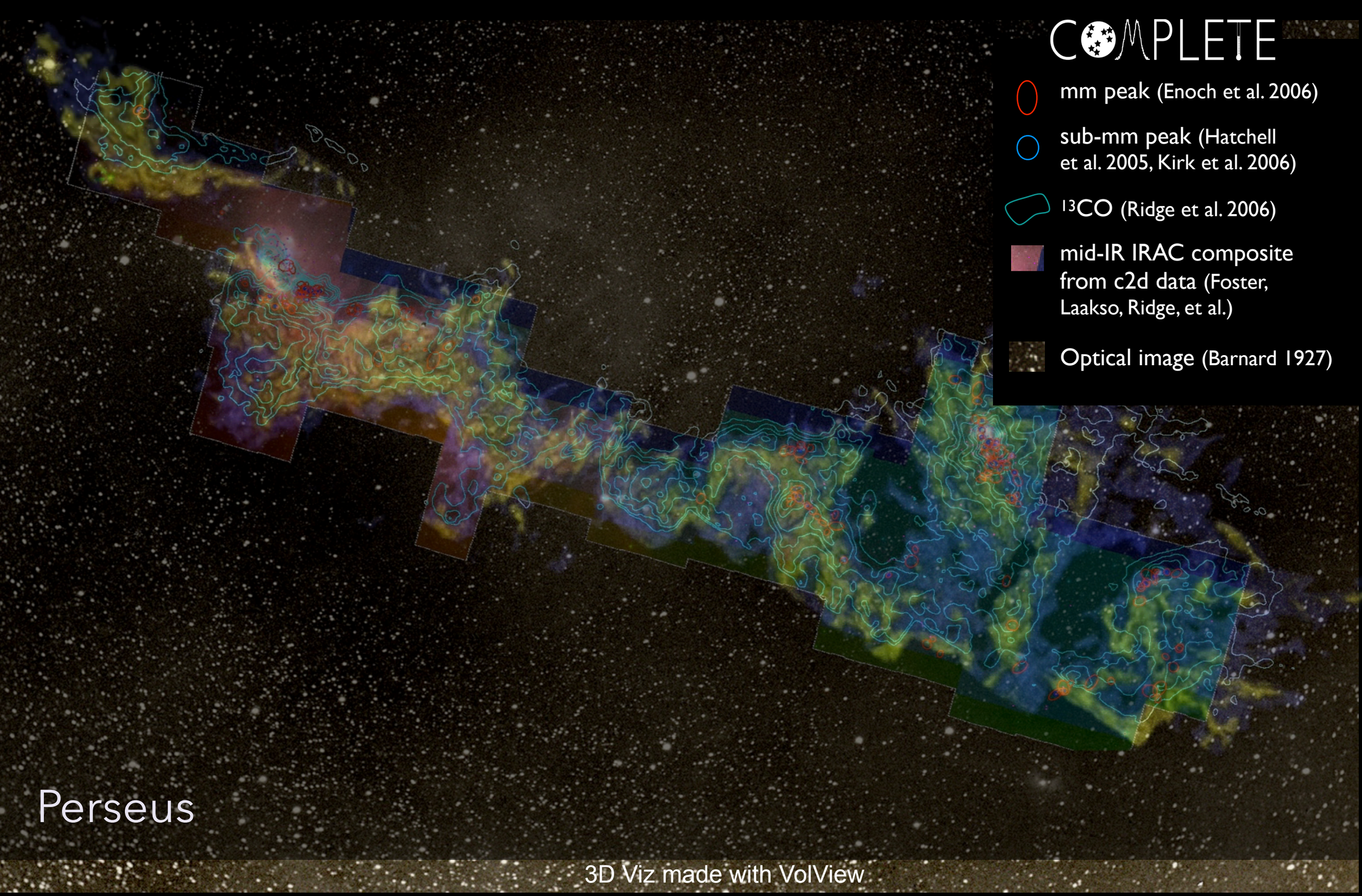




Mountain Range

No loss of information

Loss of 1 dimension

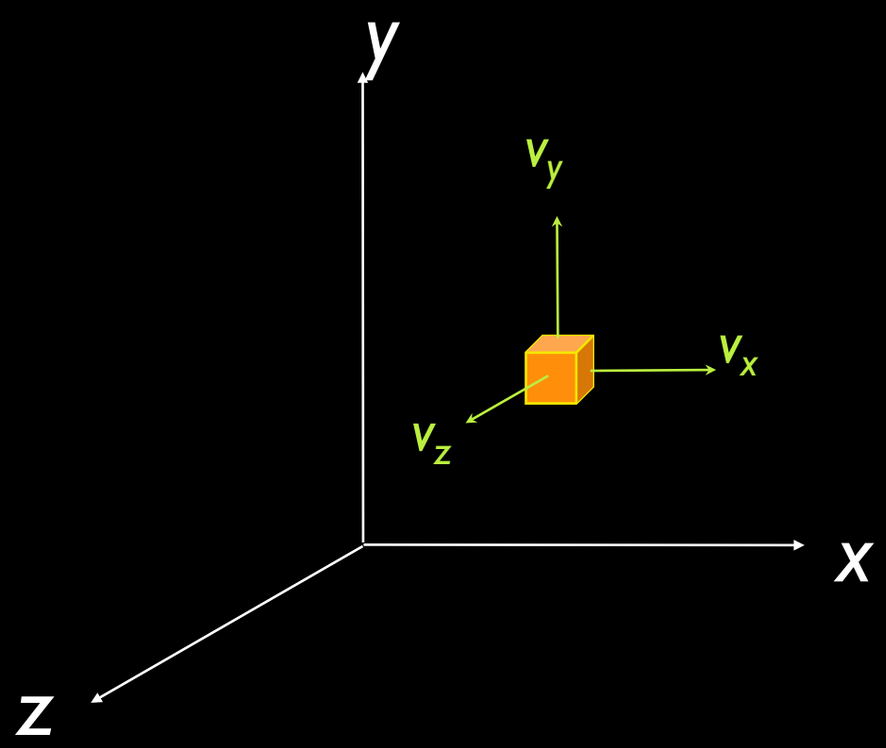


AstronomicalMedicine@

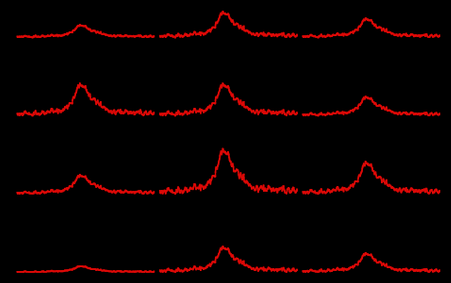
COMPLETE

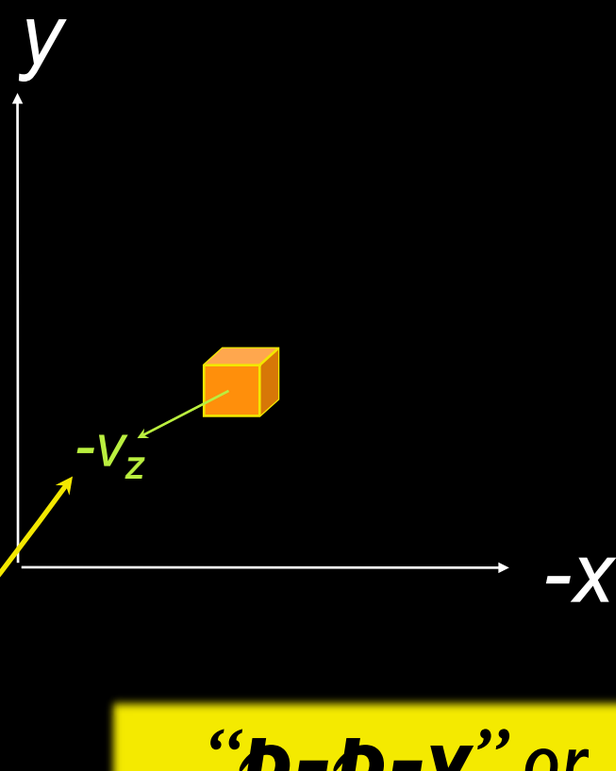
Spectral-line mapping: *p-p-v* space

We <u>wish</u> we could measure...



But we <u>can</u> measure...

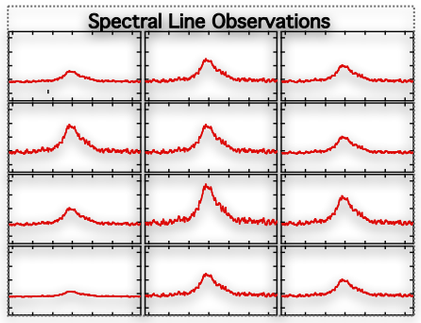




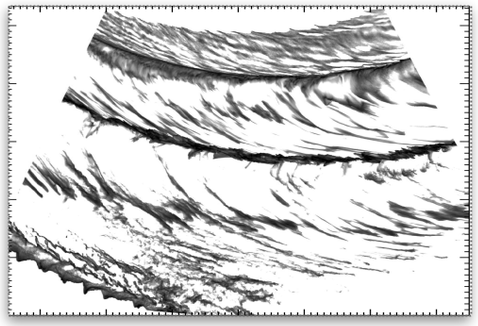
v_z *only* from "spectral-line maps"

"p-p-v" *or "position-position-velocity" space*

“Data”= 3D cubes, 2D images, 1D catalogs, from…

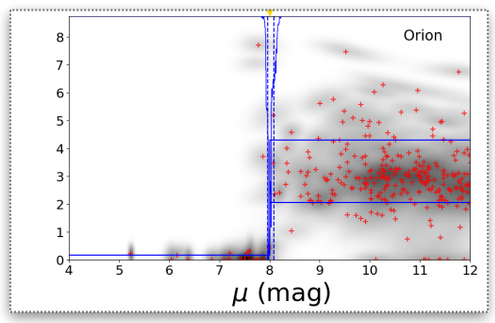


spectral-line mapping



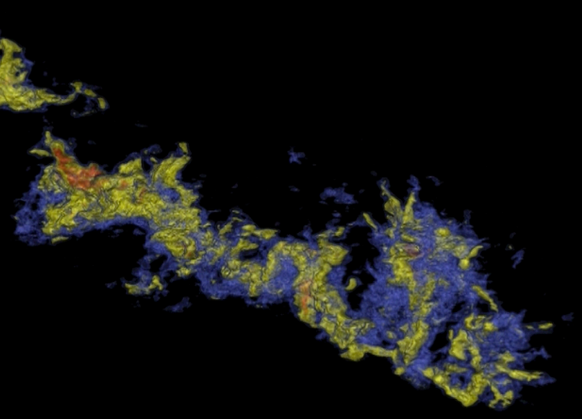
numerical simulation

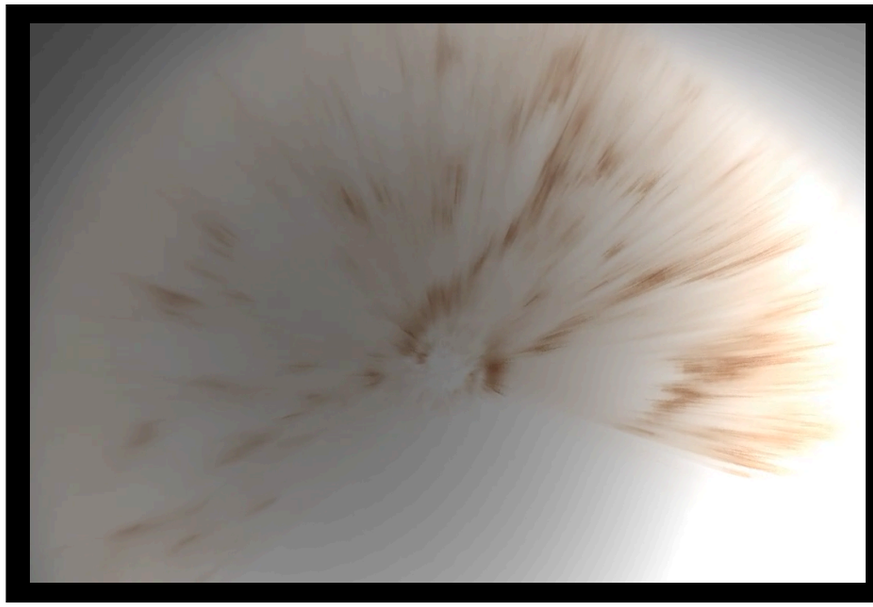
photometric imaging (over time)



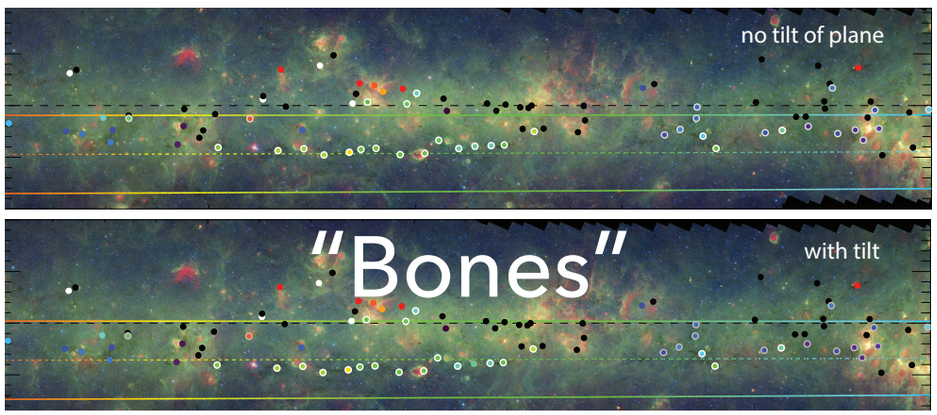
statistical reconstruction

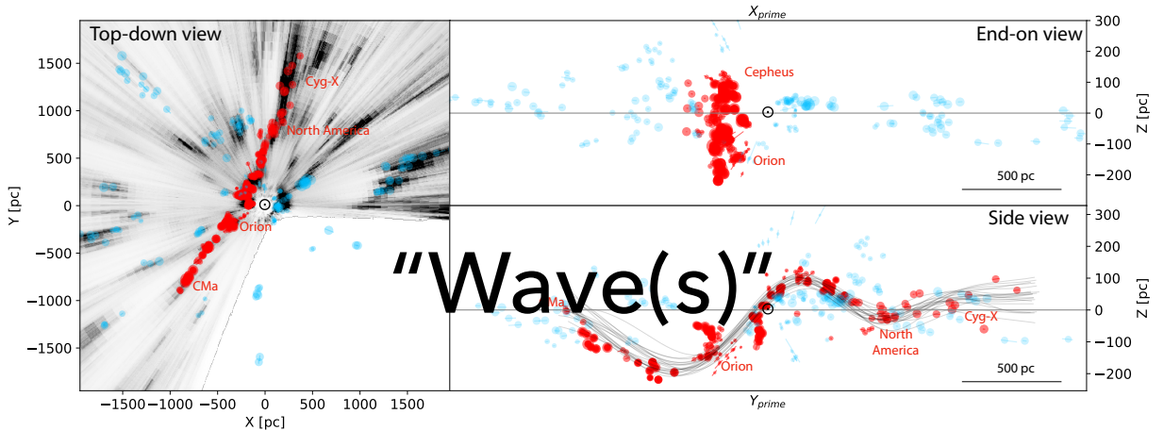
Gas in “3D"
p-p-v





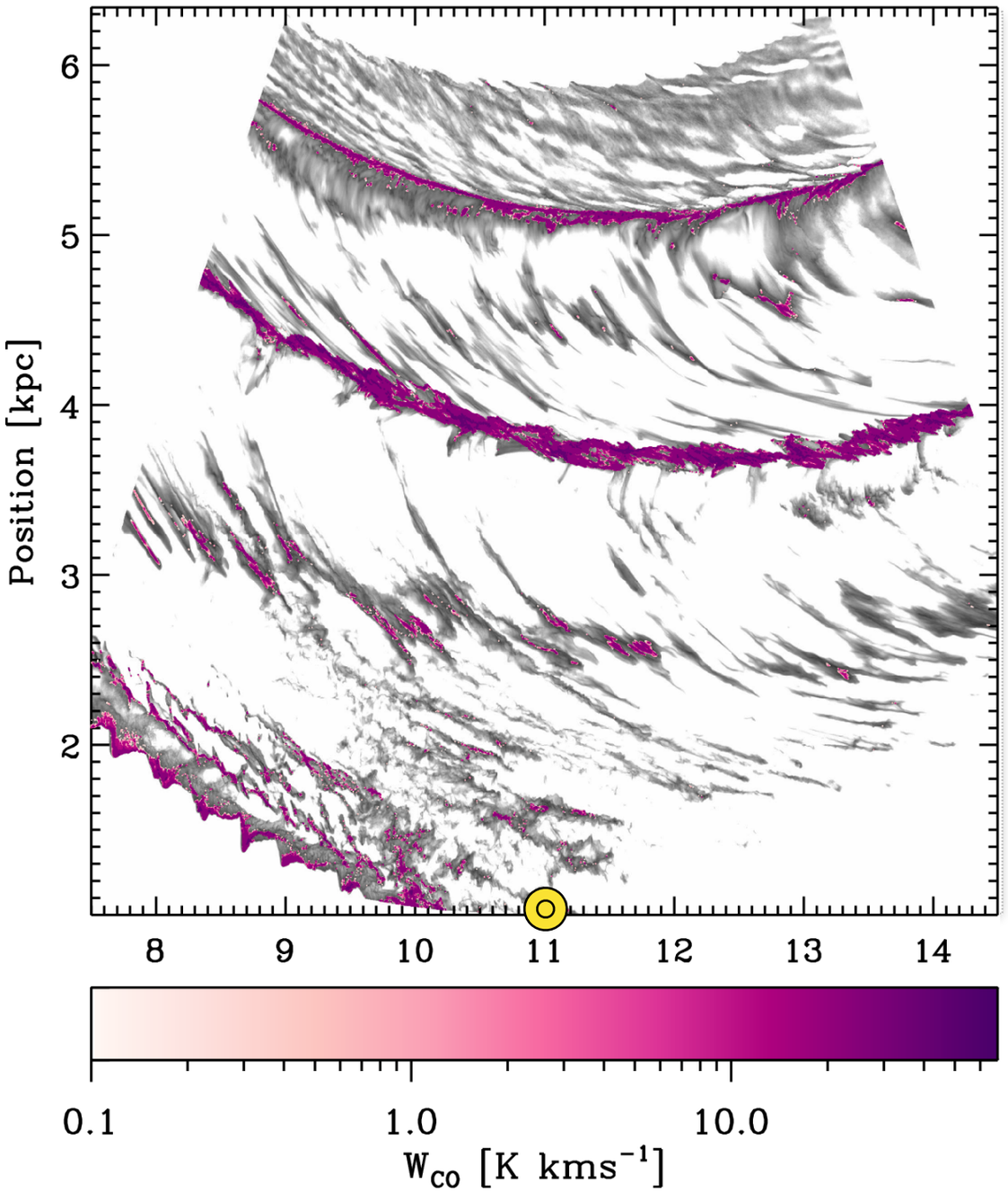
Dust in 3D
p-p-p

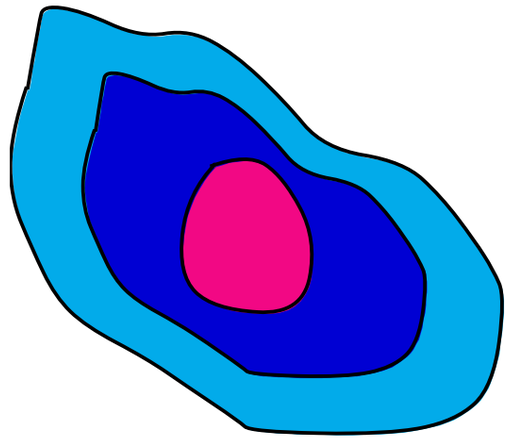




“Theory” questions re: magnetic fields, feedback, collisions, oscillations dark matter…

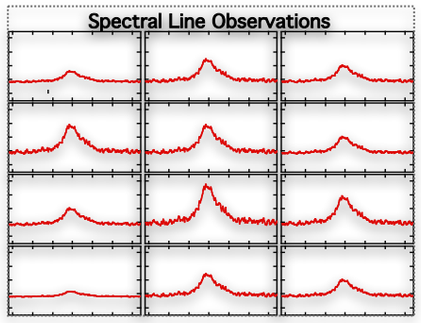
Synthetic *p-p* Maps



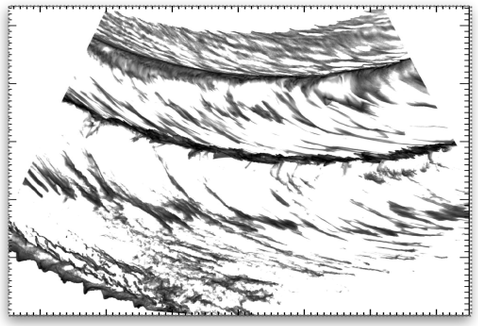


Milky-way-like simulation from Smith et al. 2014

“Data”= 3D cubes, 2D images, 1D catalogs, from…

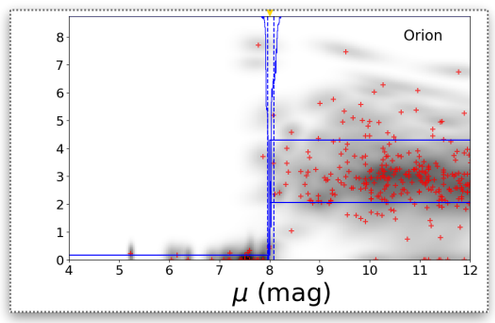


spectral-line mapping



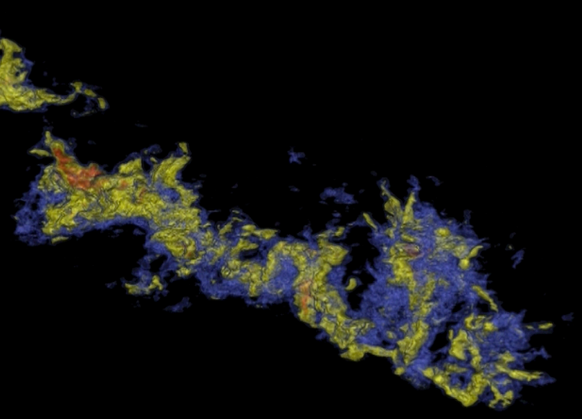
numerical simulation

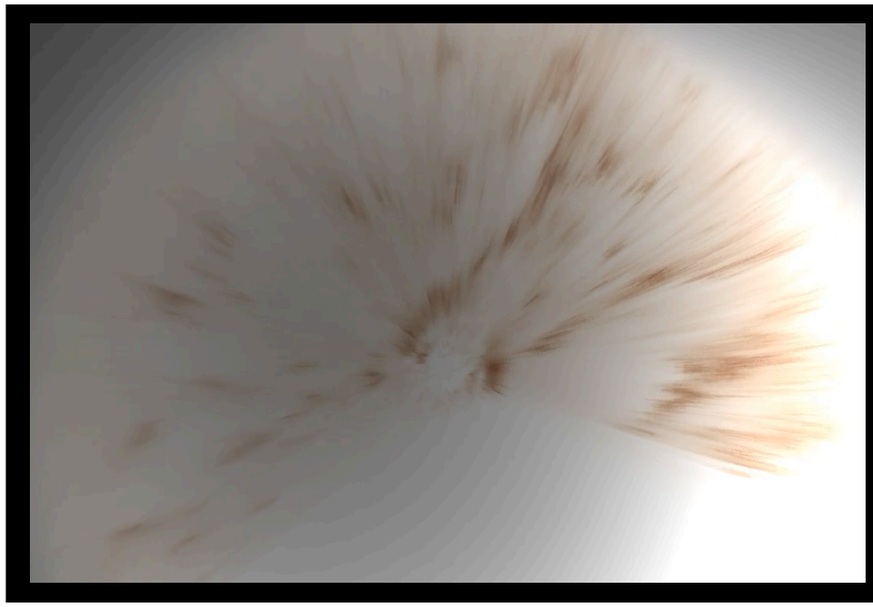
photometric imaging (over time)



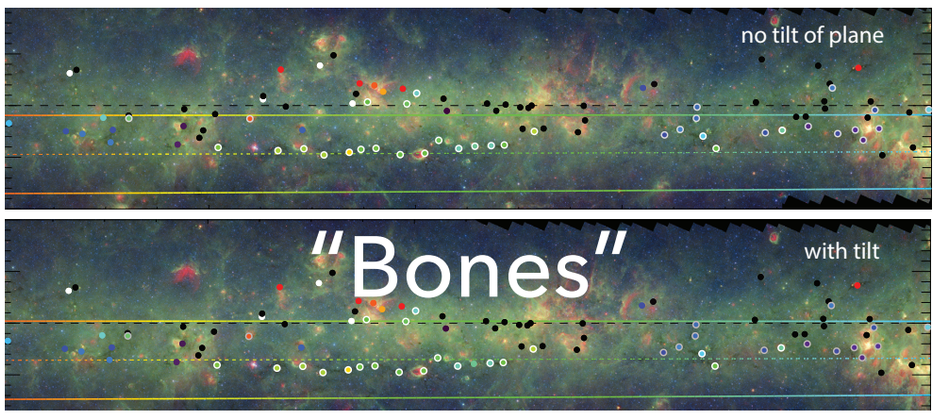
statistical reconstruction

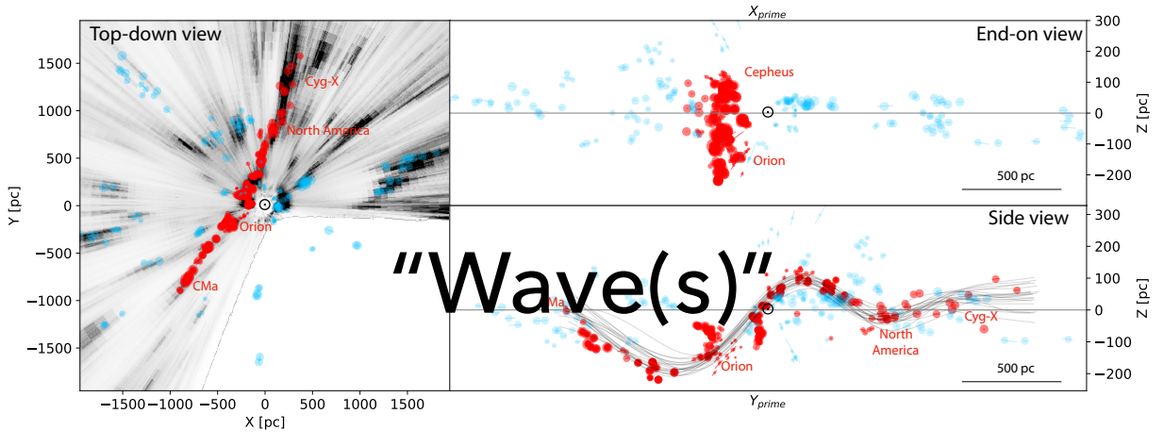
Gas in “3D"
p-p-v





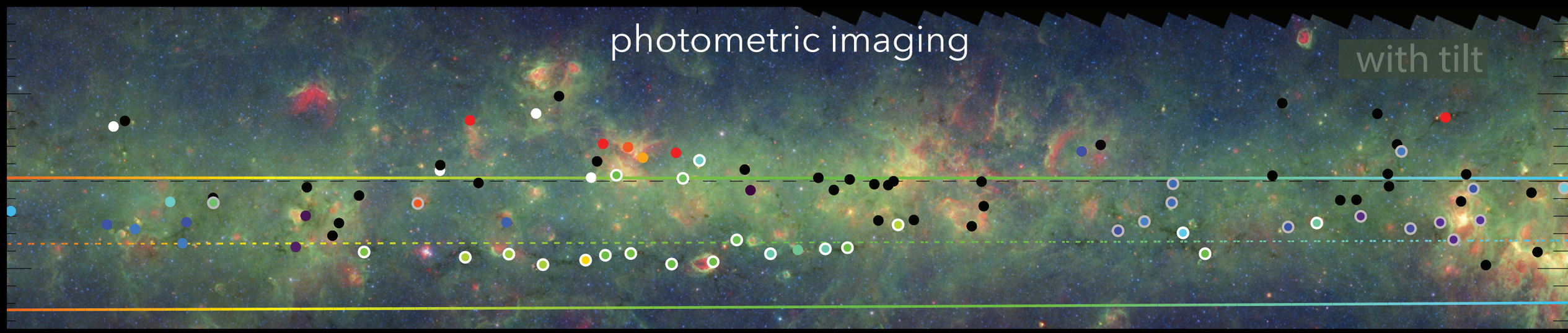
Dust in 3D
p-p-p





“Theory” questions re: magnetic fields, feedback, collisions, oscillations dark matter…

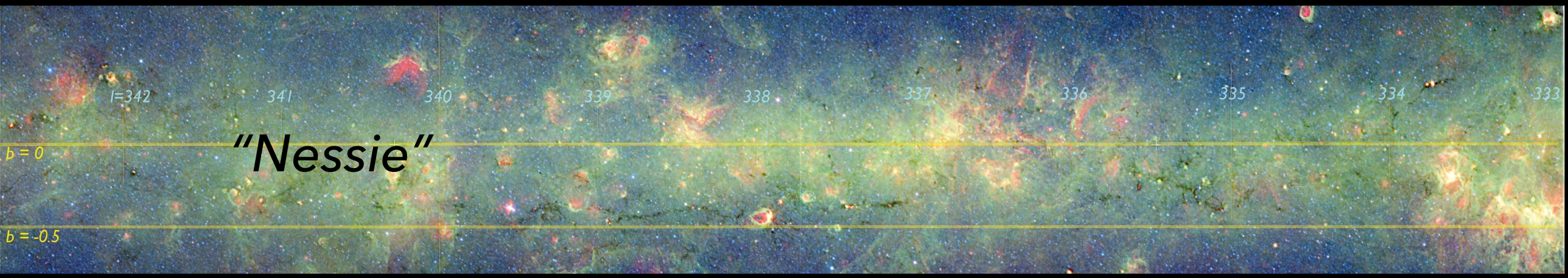
“Bones”

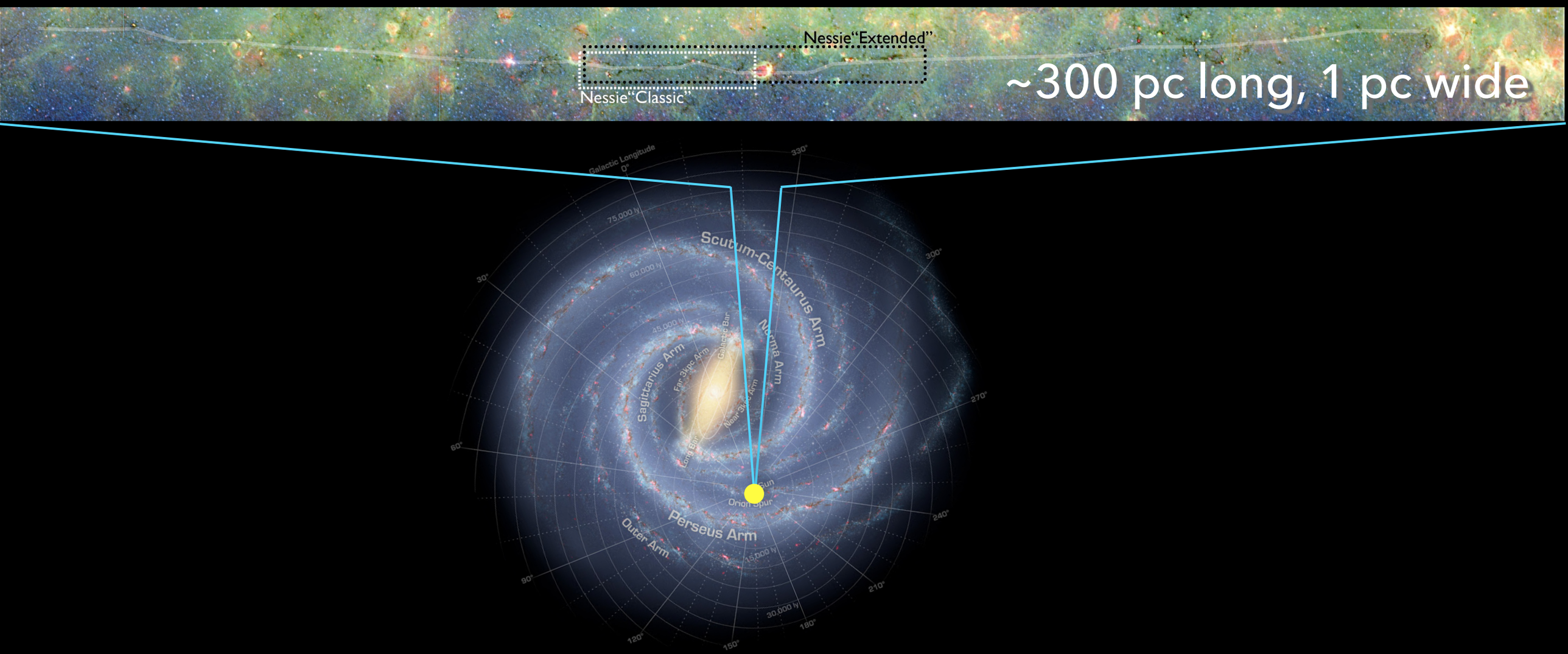


colored dots show spectral line measurements’ agreement w/Galactic rotation;
velocity-colored lines show ±20 pc from true Galactic plane

Goodman et al. 2014

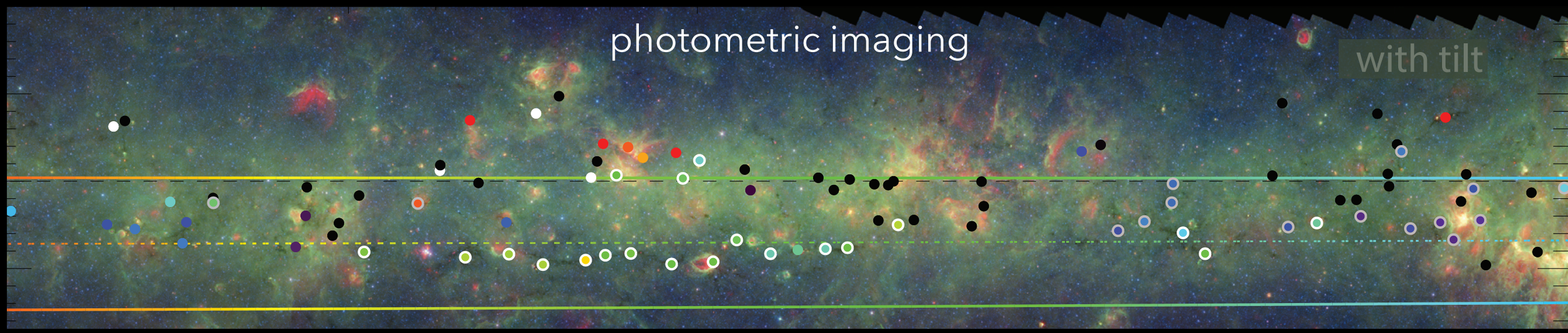
"Bones"





Goodman et al. 2014

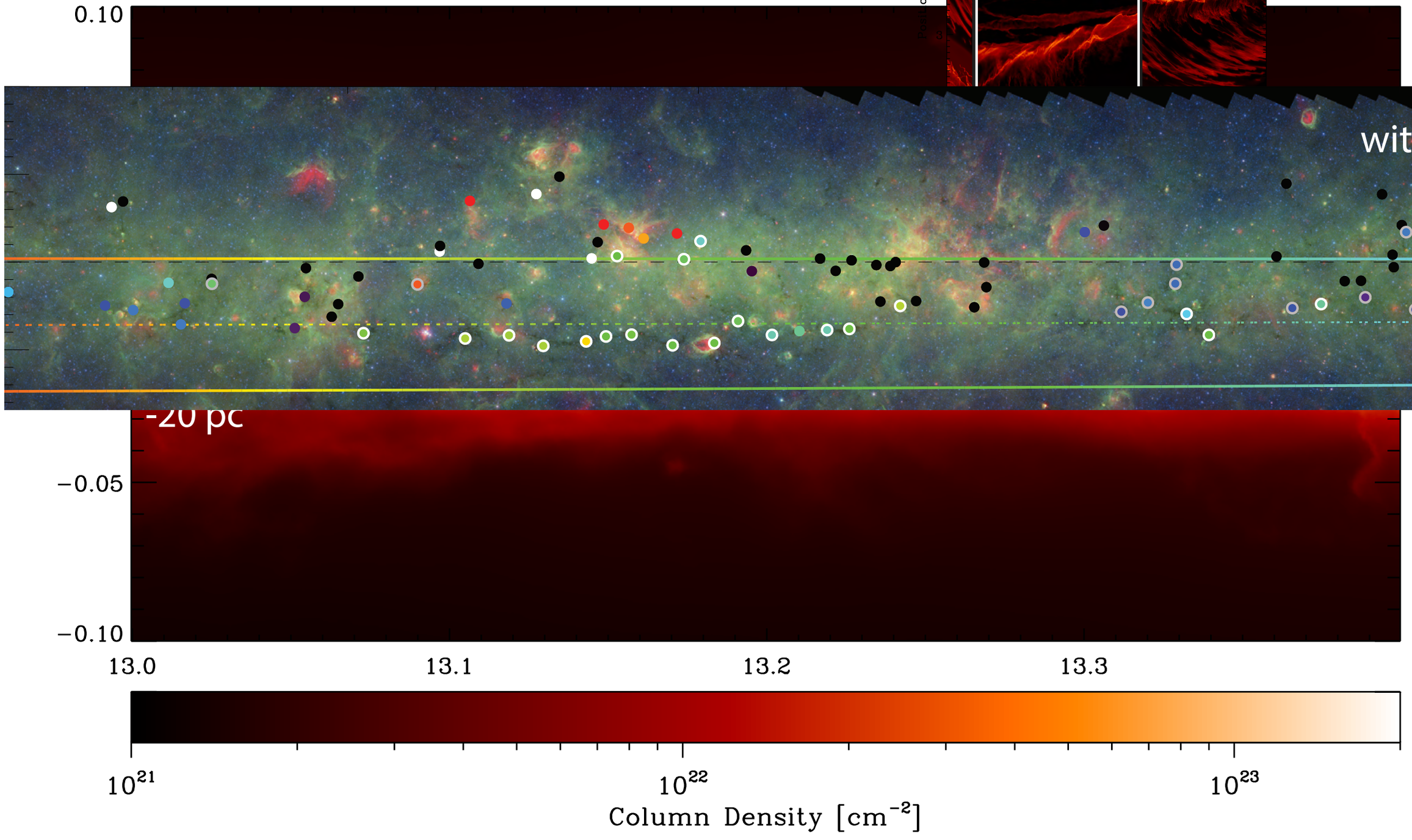
“Bones”



colored dots show spectral line measurements’ agreement w/Galactic rotation;
velocity-colored lines show ±20 pc from true Galactic plane

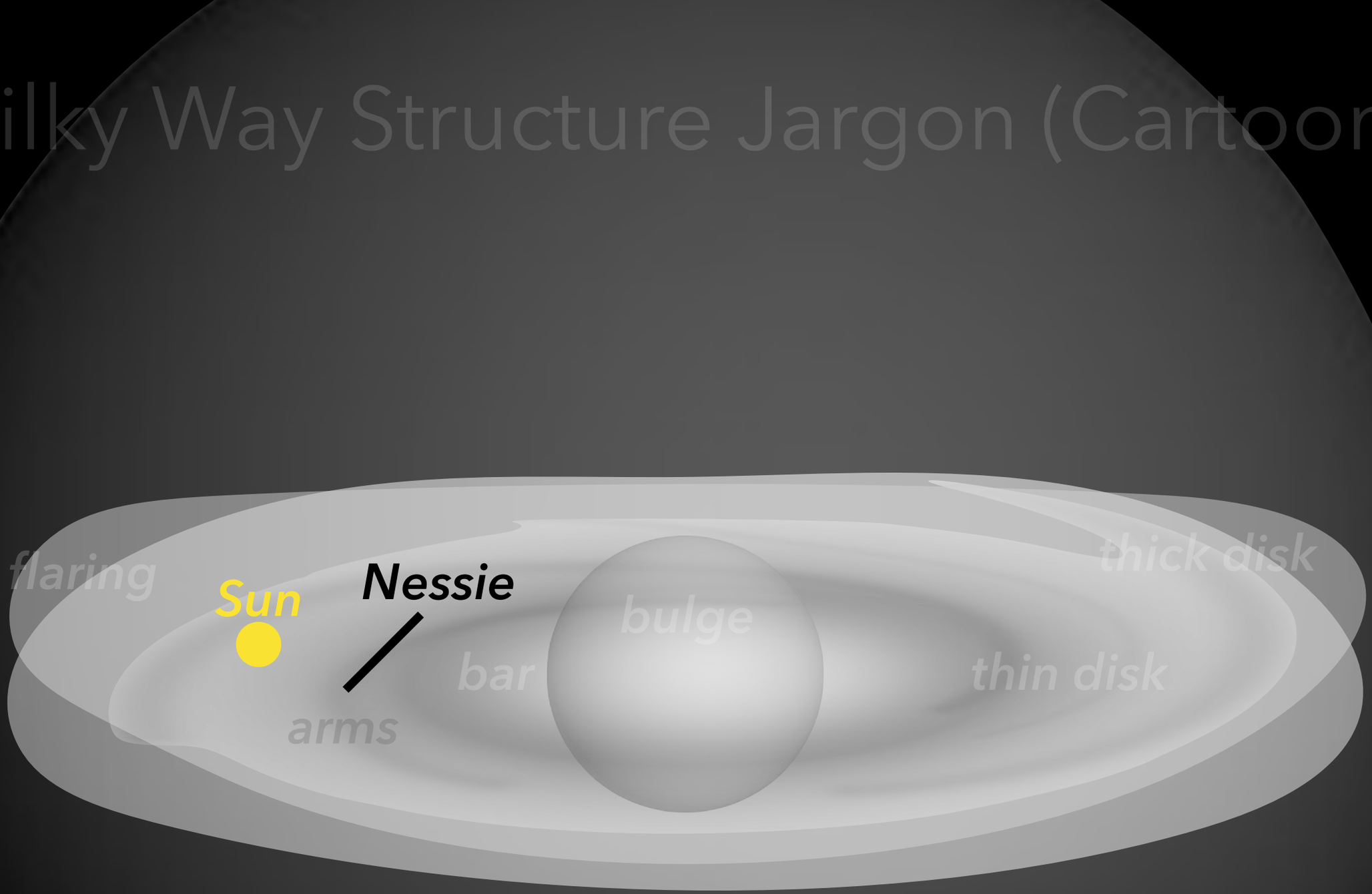
Goodman et al. 2014

AREPO Simulation (2014)



Smith et al. 2014

Milky Way Structure Jargon (Cartoon!)



2014: How many more Nessie-like Bones?

The Astrophysical Journal, 815:23 (25pp), 2015 December 10 doi:10.1088/0004-637X/815/1/23
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2015

THE SKELETON OF THE MILKY WAY

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Received 2015 June 27; accepted 2015 September 21; published 2015 December 3

ABSTRACT

Recently, Goodman et al. argued that the very long, very thin infrared dark cloud "Nessie" lies directly in the Galactic midplane and runs along the Scutum–Centaurus Arm in position–position–velocity (*p–p–v*) space as traced by lower-density CO and higher-density NH_3 gas. Nessie was presented as the first "bone" of the Milky Way, an extraordinarily long, thin, high-contrast filament that can be used to map our Galaxy's "skeleton." Here we present evidence for additional bones in the Milky Way, arguing that Nessie is not a curiosity but one of several filaments that could potentially trace Galactic structure. Our 10 bone candidates are all long, filamentary, mid-infrared extinction features that lie parallel to, and no more than 20 pc from, the physical Galactic mid-plane. We use CO, N_2H^+, HCO^+, and NH_3 radial velocity data to establish the three-dimensional location of the candidates in *p–p–v* space. Of the 10 candidates, 6 also have a projected aspect ratio of $\geqslant$50:1; run along, or extremely close to, the Scutum–Centaurus Arm in *p–p–v* space; *and* exhibit no abrupt shifts in velocity. The evidence presented here suggests that these candidates mark the locations of significant spiral features, with the bone called filament 5 ("BC_18.88-0.09") being a close analog to Nessie in the northern sky. As molecular spectral-line and extinction maps cover more of the sky at increasing resolution and sensitivity, it should be possible to find more bones in future studies.

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

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2018

RadFil: A Python Package for Building and Fitting Radial Profiles for Interstellar Filaments

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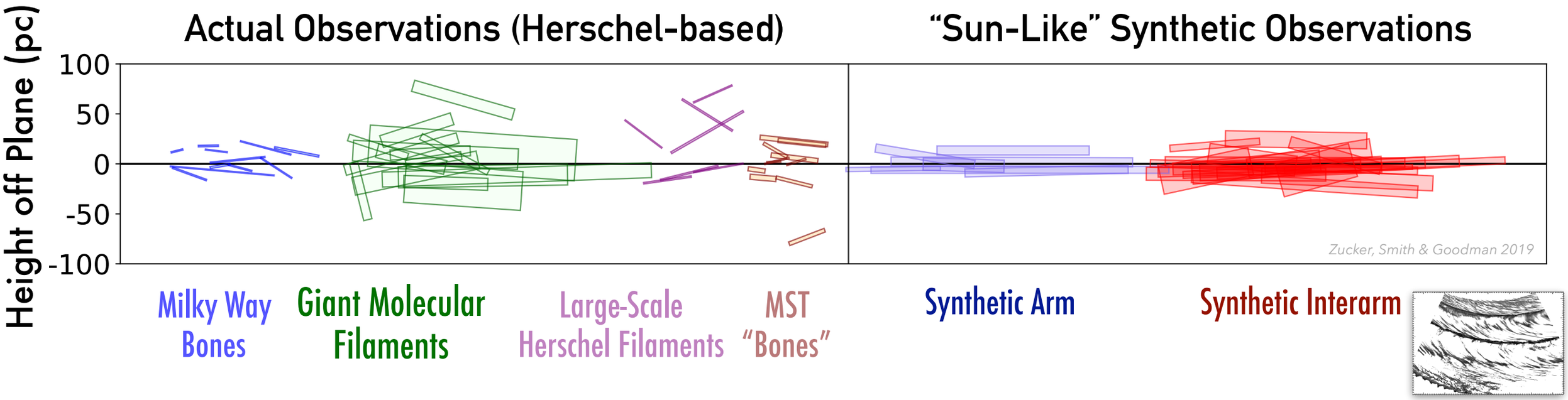
(co-PIs)
Harvard-Smithsonian Center for Astrophysics, 60 Garden St., Cambridge, MA 02138, USA; catherine.zucker@cfa.harvard.edu
Received 2018 February 12; revised 2018 July 6; accepted 2018 July 12; published 2018 September 11

Abstract

We present `RadFil`, a publicly available Python package that gives users full control over how to build and fit radial profiles for interstellar filaments. `RadFil` builds filament profiles by taking radial cuts across the spine of a filament, thereby preserving the radial structure of the filament across its entire length. Pre-existing spines can be inputted directly into `RadFil`, or can be computed using the `FilFinder` package as part of the `RadFil` workflow. We provide Gaussian and Plummer built-in fitting functions, in addition to a background subtraction estimator, which can be fit to the entire ensemble of radial cuts or an average radial profile for the filament. Users can tweak parameters like the radial cut sampling interval, the background subtraction estimation radii, and the Gaussian/Plummer fitting radii. As a result, `RadFil` can provide treatment of how the resulting filament properties rely on systematics in the building and fitting process. We walk through the typical `RadFil` workflow and compare our results to those from an independent radial profile code obtained using the same data; we find that our results are entirely consistent. `RadFil` is open source and available on GitHub. We also provide a complete working tutorial of the code available as a Jupyter notebook, which users can download and run themselves.

Key words: ISM: clouds – methods: data analysis – methods: statistical



The Astrophysical Journal, 864:153 (34pp), 2018 September 10 https://doi.org/10.3847/1538-4357/aacc66
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2018

Physical Properties of Large-scale Galactic Filaments

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Received 2017 December 27; revised 2018 May 7; accepted 2018 May 28; published 2018 September 11

Abstract

The characterization of our Galaxy's longest filamentary gas features has been the subject of several studies in recent years, producing not only a sizable sample of large-scale filaments, but also confusion as to whether all these features (e.g., "Bones," "Giant Molecular Filaments") are the same. They are not. We undertake the first standardized analysis of the physical properties (H_2 column densities, dust temperatures, morphologies, radial column density profiles) and kinematics of large-scale filaments in the literature. We expand and improve upon prior analyses by using the same data sets, techniques, and spiral arm models to disentangle the filaments' inherent properties from selection criteria and methodology. Our results suggest that the myriad filament-finding techniques are uncovering different physical structures, with length (11–269 pc), width (1–40 pc), mass ($3 \times 10^3\,M_\odot$–$1.1 \times 10^6\,M_\odot$), aspect ratio (3:1–117:1), and high column density fraction (0.2%–100%) varying by over an order of magnitude across the sample of 45 filaments. We develop a radial profile-fitting code, `RadFil`, which is publicly available. We also perform a position–position–velocity (*p–p–v*) analysis on a subsample and find that while 60%–70% lie spatially in the plane of the Galaxy, only 30%–45% concurrently exhibit spatial *and* kinematic proximity to spiral arms. In a parameter space defined by aspect ratio, dust temperature, and column density, we broadly distinguish three filament categories, which could indicate different formation mechanisms or histories. Highly elongated "Bone-like" filaments show the most potential for tracing gross spiral structure (e.g., arms, spurs), while other categories could be large concentrations of molecular gas (giant molecular clouds, core complexes).

Key words: Galaxy: structure – ISM: clouds
Supporting material: figure sets

Draft version July 19, 2019
Typeset using LaTeX default style in AASTeX62

Synthetic Large-Scale Galactic Filaments – on their Formation, Physical Properties, and Resemblance to Observations

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[3] *Radcliffe Institute for Advanced Study, Harvard University, 10 Garden St, Cambridge, MA 02138*

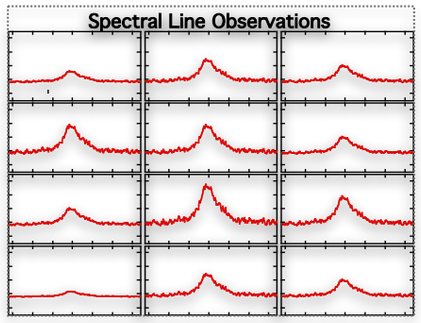
Submitted to ApJ

ABSTRACT

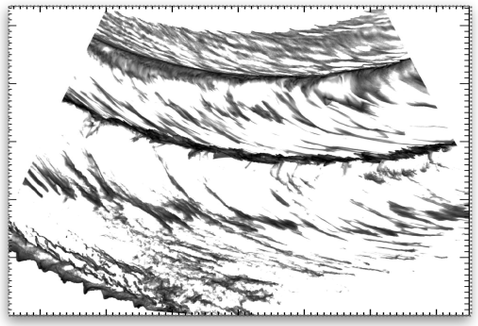
Using a population of large-scale filaments extracted from an AREPO simulation of a Milky Way-like galaxy, we seek to understand the extent to which observed large-scale filaments properties (with lengths $\gtrsim$ 100 pc) can be explained by galactic dynamics alone. We identify filaments from an observer's perspective in the disk of the galaxy, which are forming purely to due to galactic dynamics without the effects of feedback or local self-gravity. We find that large-scale Galactic filaments are intrinsically very rare, and estimate that at maximum approximately one filament per kpc^2 should be identified in our Milky Way. In this idealized scenario, we find filaments forming in both the arm and interarm regions, the former due to gas compression in the spiral potential wells and the latter due to Galactic shear. Using the same analysis pipeline applied previously to observations, we analyze the physical properties of large-scale Galactic filaments, and quantify their sensitivity to projection effects and galactic environment (i.e. formation in the arm or interarm regions). We find that observed "Giant Molecular Filaments" are consistent with being non-self-gravitating structures dominated by large-scale galactic dynamics. "Bone-like" filaments, like the paradigmatic Nessie filament, have similar column densities, velocity gradients, and Galactic plane heights ($z \approx 0$ pc) to those in our simple model, but additional physical effects (such as feedback and self-gravity) must be invoked to explain their lengths and widths.

2019

“Data”= 3D cubes, 2D images, 1D catalogs, from…



spectral-line mapping



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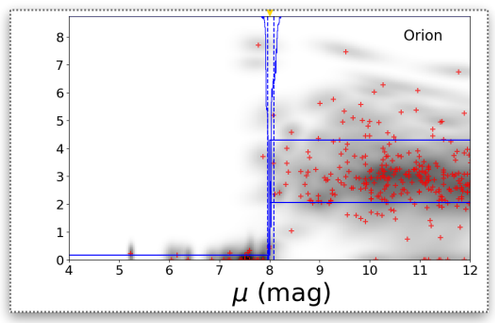
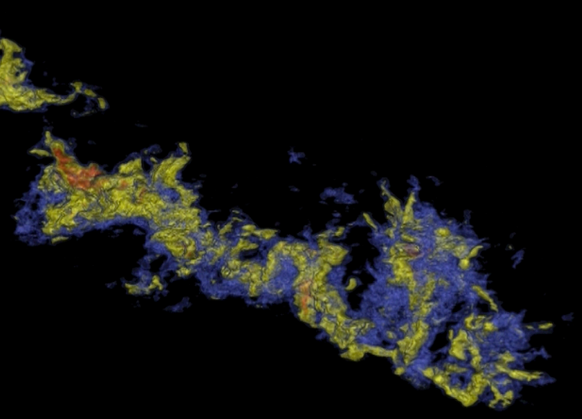
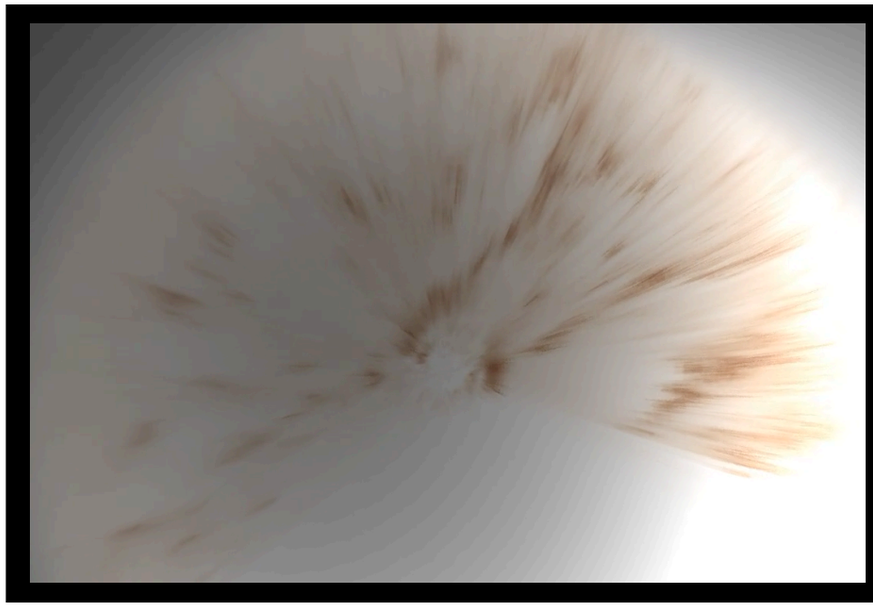


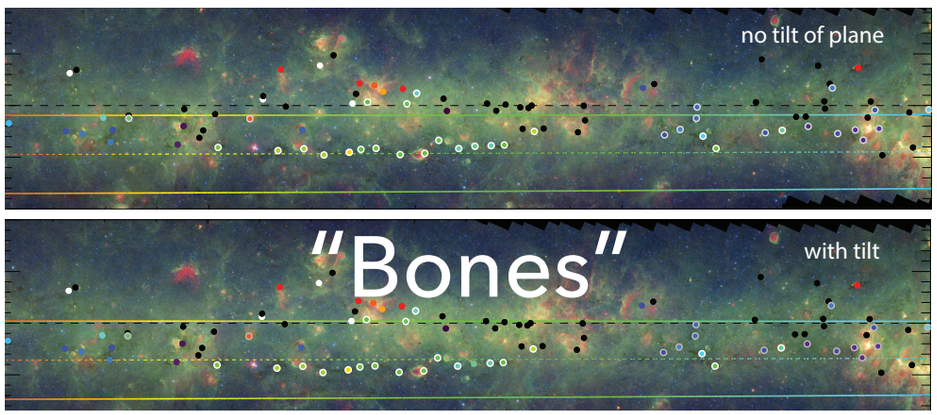
statistical reconstruction

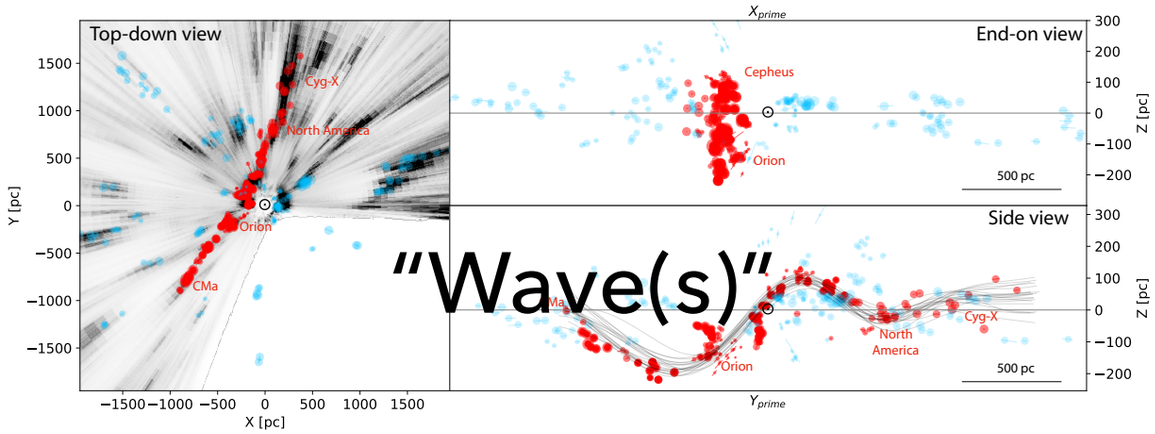
Gas in “3D"
p-p-v





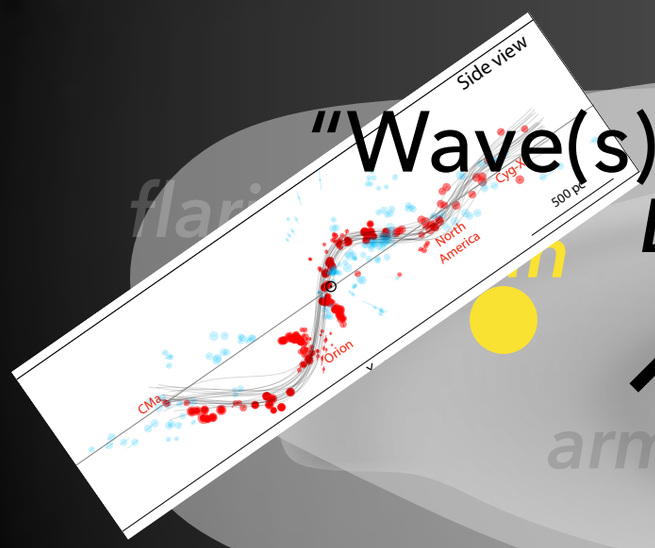
Dust in 3D
p-p-p





“Theory” questions re: magnetic fields, feedback, collisions, oscillations dark matter…

Milky Way Structure Jargon (Cartoon!)



"Wave(s)"

Bone(s)

flari

thick disk

bulge

bar

thin disk

arms

halo

2019: The “Radcliffe” Wave

The “Radcliffe” Wave – Live at Princeton

Data Collection

Data
- Possible Wave Models
- Best Fit Wave Model
- CO Gas (Local)
- Gould's Belt (Perrot & Grenier 2003)
- Green 2019 3D Dust
- Local Arm Fit (Reid+2016)
- Major Cloud Catalog
- Maser Catalog (Reid+2014,2016)
- Sagittarius Arm Fit (Reid+2016)
- Tenuous Connections
- Sun

Subsets

Plot Layers - 3D Volume Rendering
- [ ] RadWave (Sun)
- [ ] Local Arm Masers (Sun)
- [ ] Sagittarius Arm Masers (Sun)
- [x] Sun
- [ ] RadWave (Major Cloud Catalog)
- [ ] Tenuous Connections

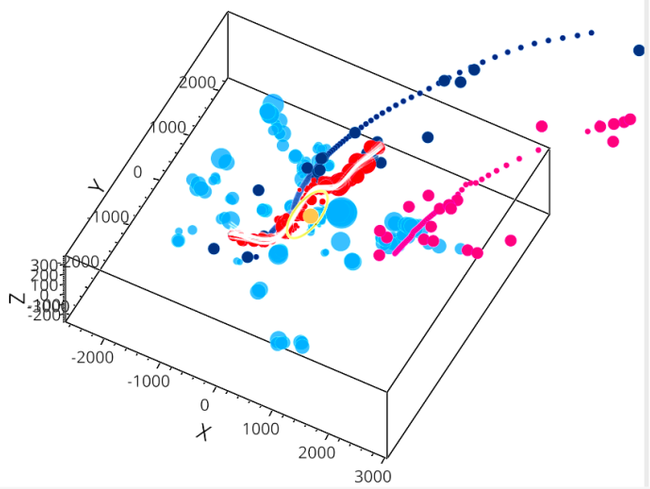
Attribute: PRIMARY
Limits: 1 5
Color:

Plot Options - 3D Volume Rendering

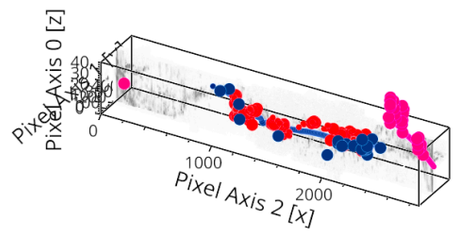
x axis	Pixel Axis 2 [x]		
min/max:	38.2241	⇄	1160.78
stretch:			1.00
y axis	Pixel Axis 1 [y]		
min/max:	38.2241	⇄	1160.78
stretch:			1.00
z axis	Pixel Axis 0 [z]		
min/max:	5.95402	⇄	193.046
stretch:			1.00
reference:	Green 2019 3D Dust		
resolution:	256		

Tab 1

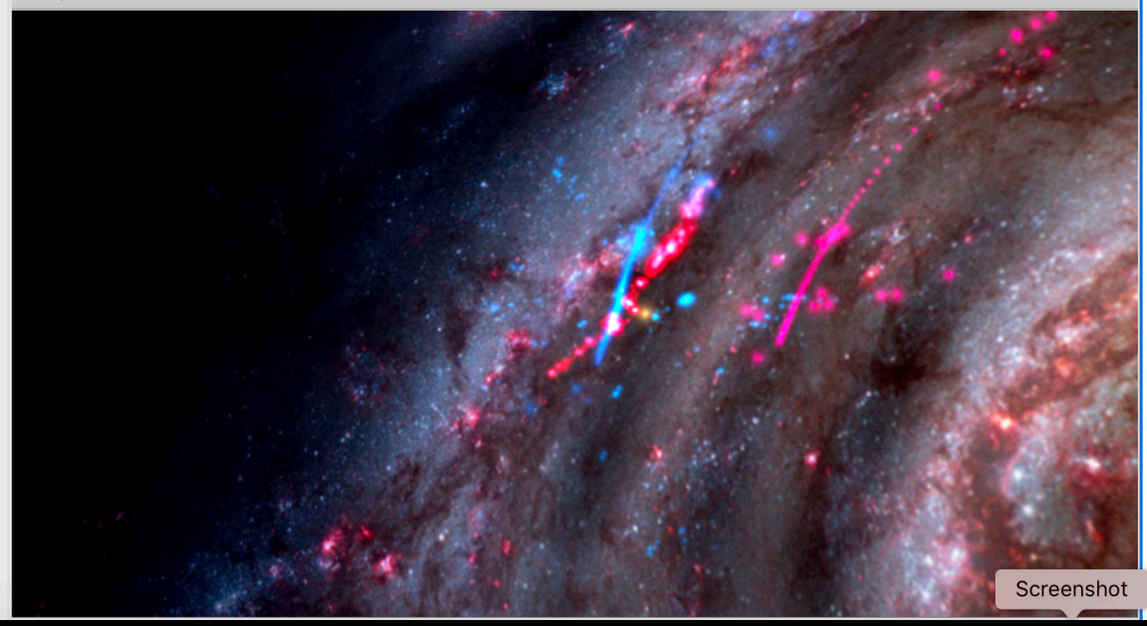
3D Scatter



3D Volume Rendering

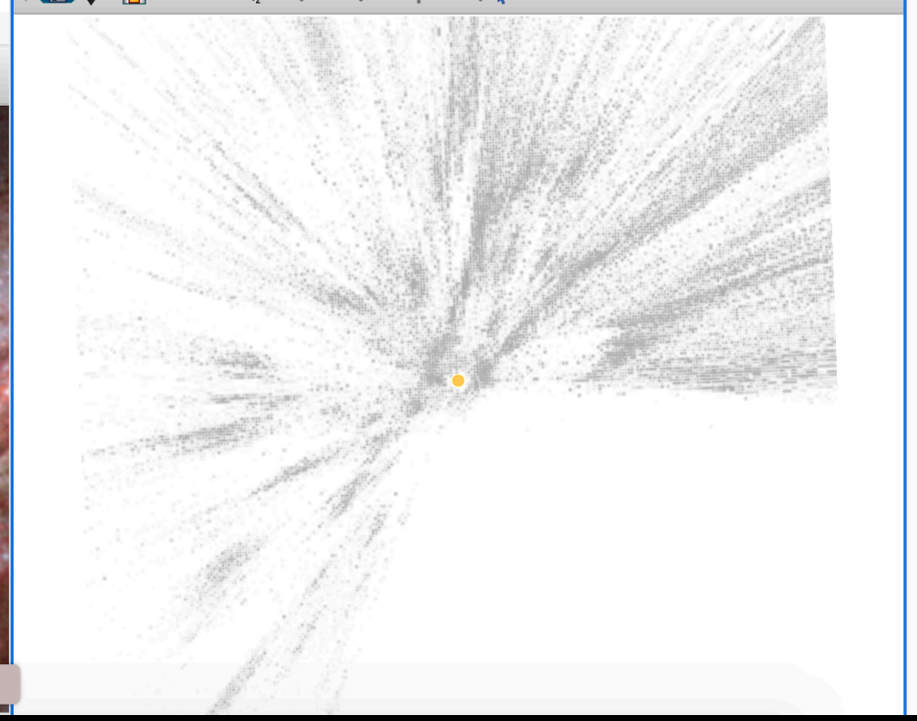


WorldWideTelescope



Screenshot

3D Volume Rendering

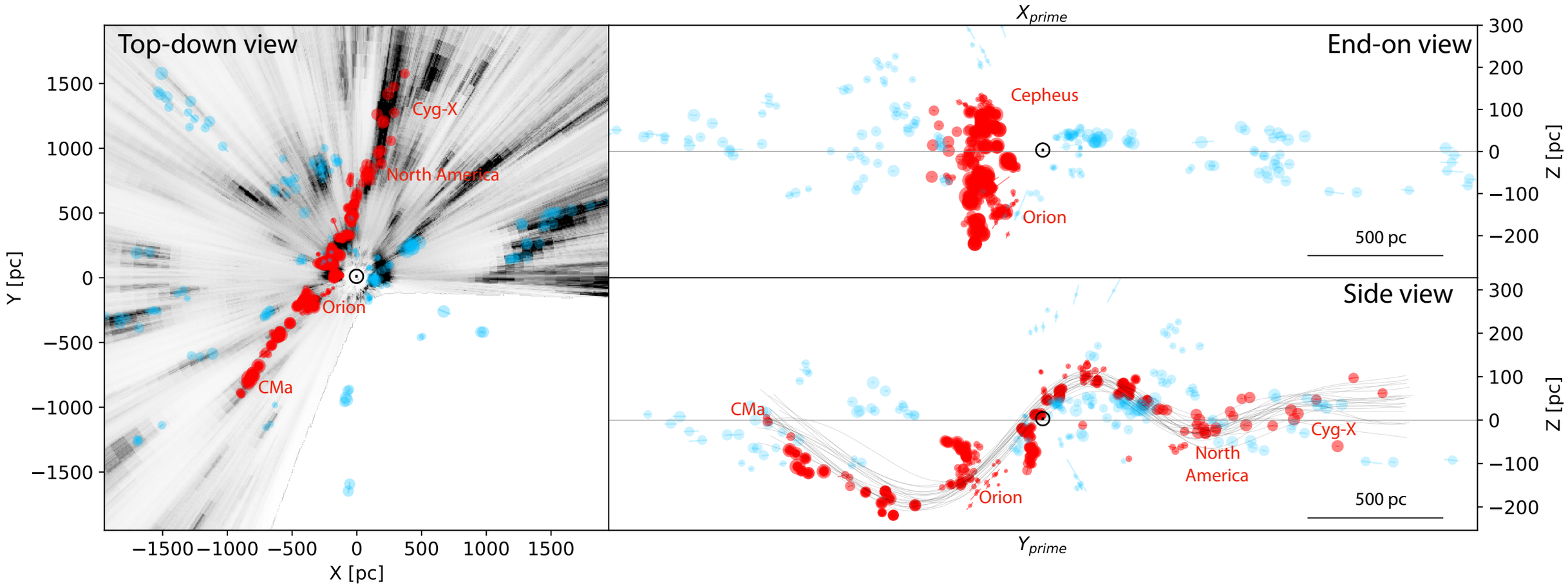


glue: glueviz.org WorldWide Telescope: worldwidetelescope.org

The “Radcliffe“ Wave – Live at Princeton

The “Radcliffe” Wave

(embargoed, please do not distribute)



João Alves, Catherine Zucker, Alyssa Goodman, Joshua Speagle, Stefan Meingast, Thomas Robitaille, Douglas Finkbeiner, Edward F. Schlafly, and Gregory Green 2019,
Nature (soon, we hope)

Table 3: Physical Properties of the Radcliffe Wave

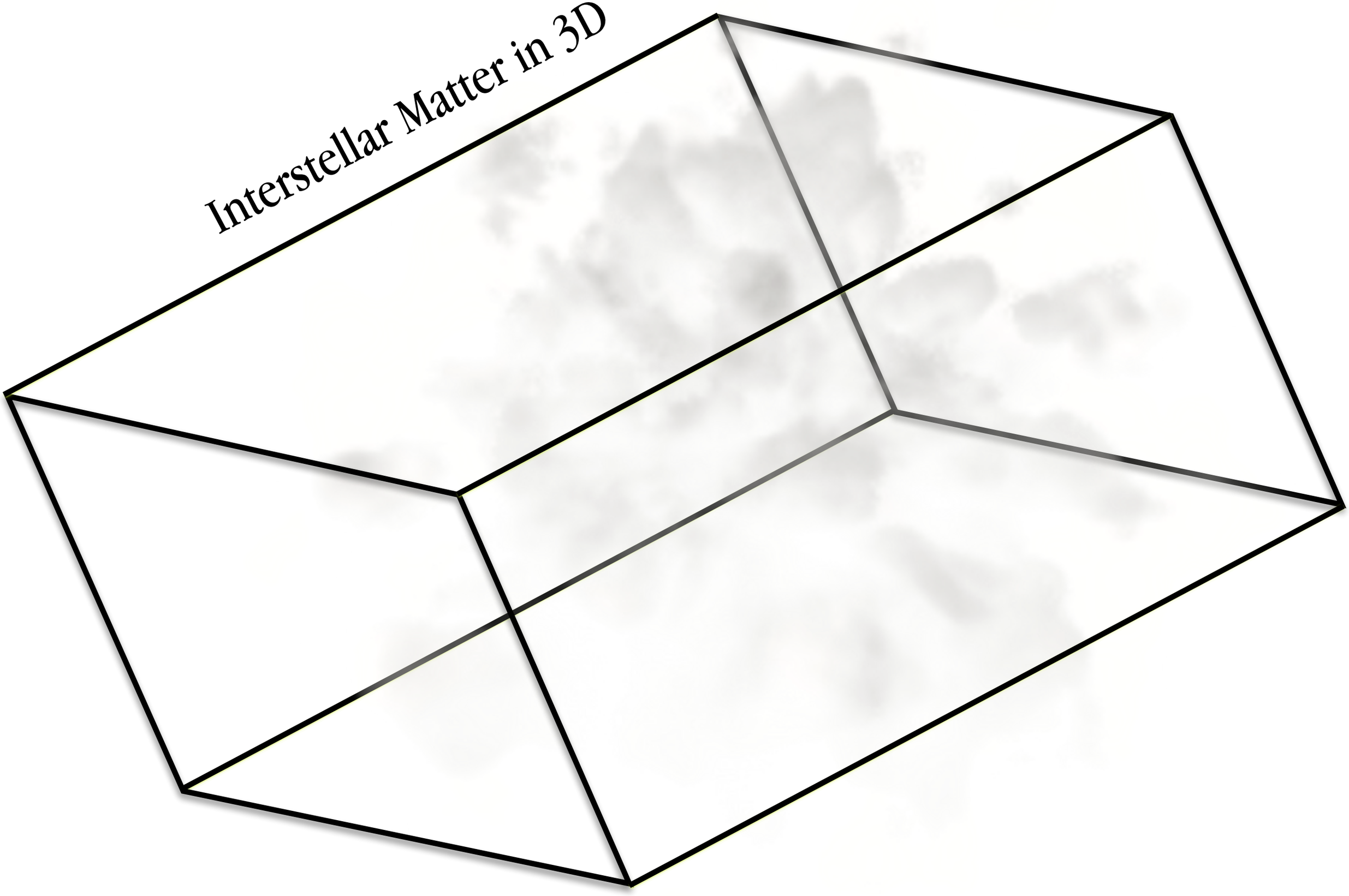
Name	Median with 95% CI
Length	2.7 ± 0.2 kpc
Scatter	60 ± 15 pc
Amplitude	160 ± 30 pc
Mass	$\geq 3 \times 10^6$ $M_\odot$

Where did the distances come from?

hard work over a decade by the “3D Dust Mapping” team of Doug Finkbeiner,
Eddie Schlafly, Greg Green, Catherine Zucker, Josh Speagle et al.,
+ Pan-STARRS 1 & Gaia teams & many(!) others (see argonaut.skymaps.info)

NERD NOTE: "Matter" is actually "Gas" and "Dust," which are not distributed in EXACTLY the same way, but for this cartoon, we'll say "close enough."

Interstellar Matter in 3D



WARNING: schematic diagram, NOT to scale (credit A. Goodman, 2019)

Stars in 3D

[z:"Radial Velocity"]

&

x,y: "Proper Motion"

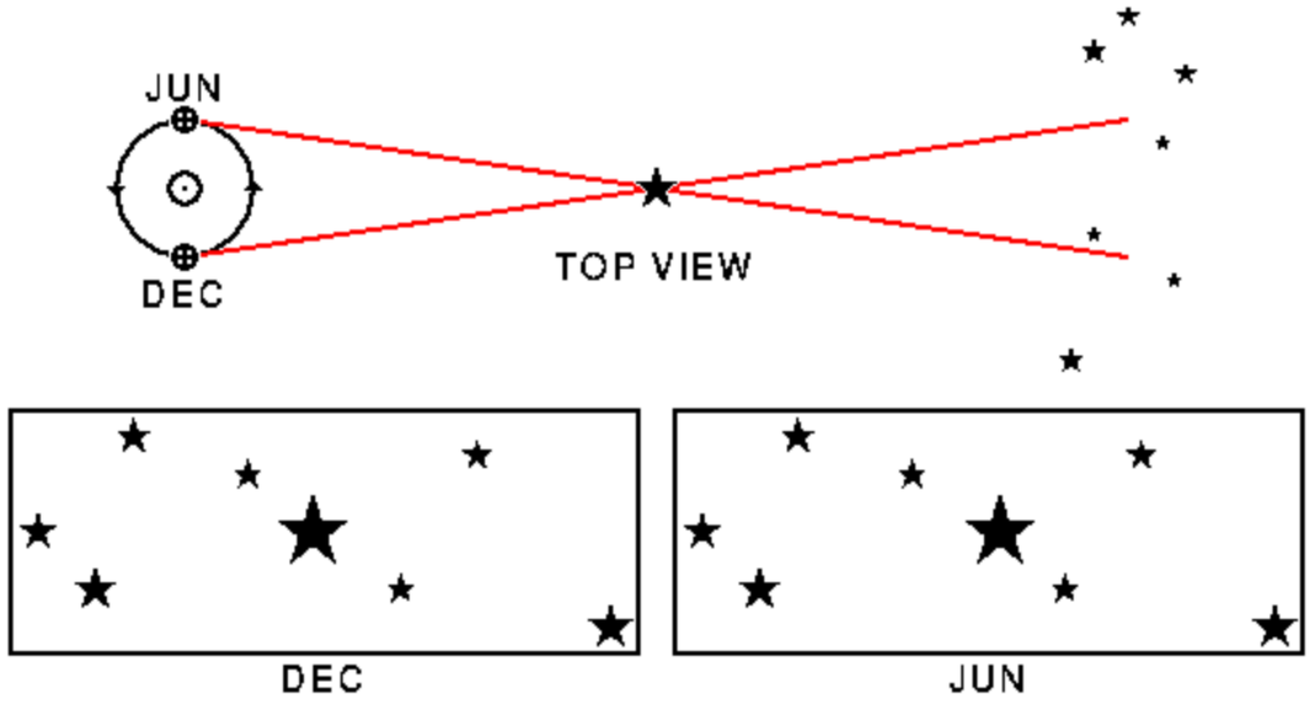
WARNING: schematic diagram, NOT to scale (credit A. Goodman, 2019)

The ABC's of Distances

It is almost impossible to tell the distances of objects we see in the sky. Almost, but not quite, and astronomers have developed a large variety of techniques. Here I will describe 26 of them. I will ignore the work that went into determining the astronomical unit: the scale factor for the Solar System, and just consider distances outside of the Solar System.

A. TRIGONOMETRIC PARALLAX

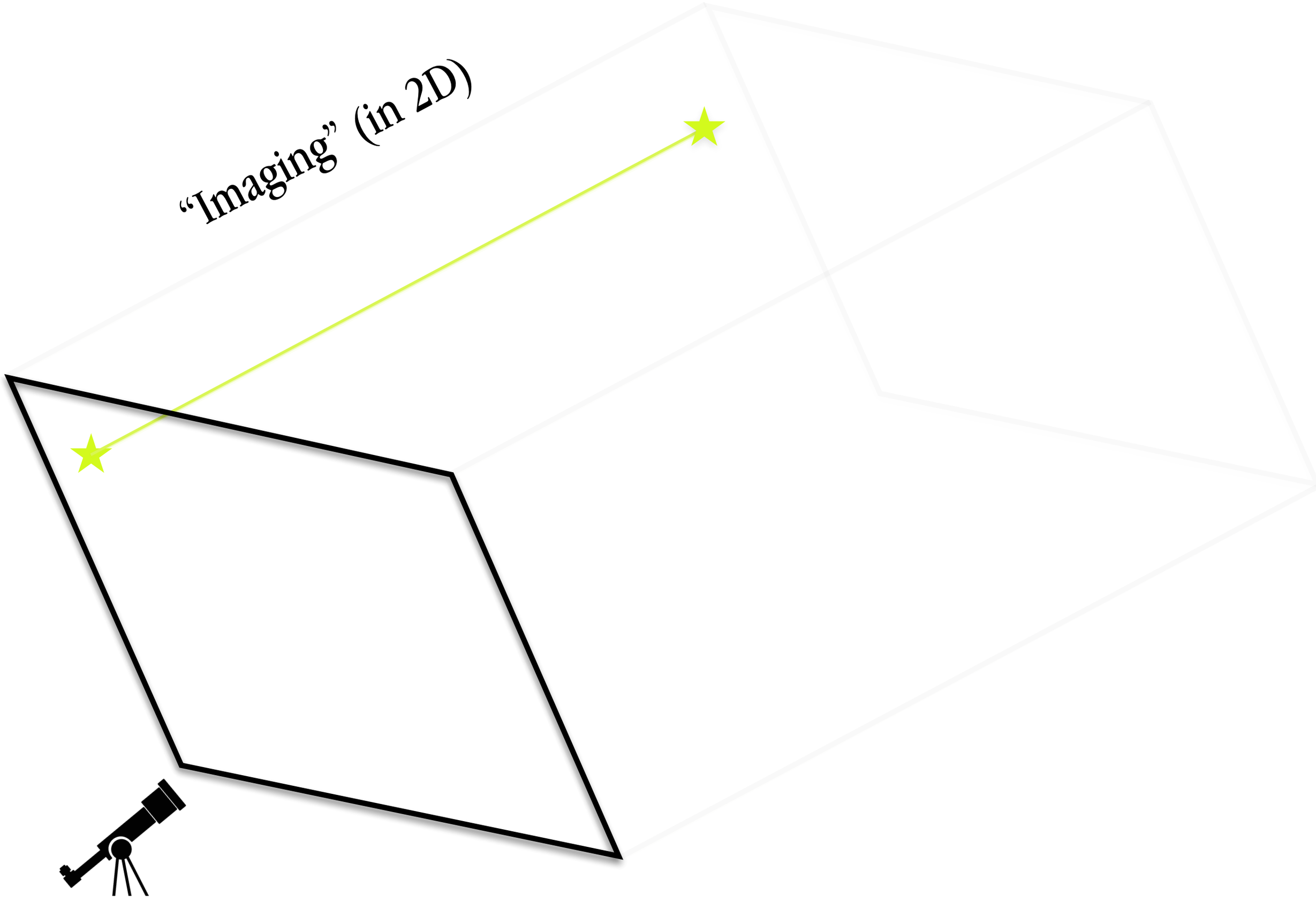
This method rates an A because it is the gold standard for astronomical distances. It is based on measuring two angles and the included side of a triangle formed by 1) the star, 2) the Earth on one side of its orbit, and 3) the Earth six months later on the other side of its orbit.



The top part of the diagram above shows the Earth at two different times, and the triangle formed with a nearby star and these two positions of the Earth. The bottom part shows two pictures of the nearby star projected onto more distant stars taken from the two sides of the Earth's orbit. If you cross your eyes to merge these two pictures, you will either see the nearby star standing in front of the background in 3-D, or else get a headache.

The *parallax* of a star is one-half the angle at the star in the diagram above. Thus the parallax is the angle at the star in an Earth-Sun-star triangle. Since this angle is always very small, the sine and tangent of the parallax are very well approximated by the parallax angle measured in radians. Therefore the distance to a star is

```
D[in cm] = [Earth-Sun distance in cm]/[parallax in radians]
```



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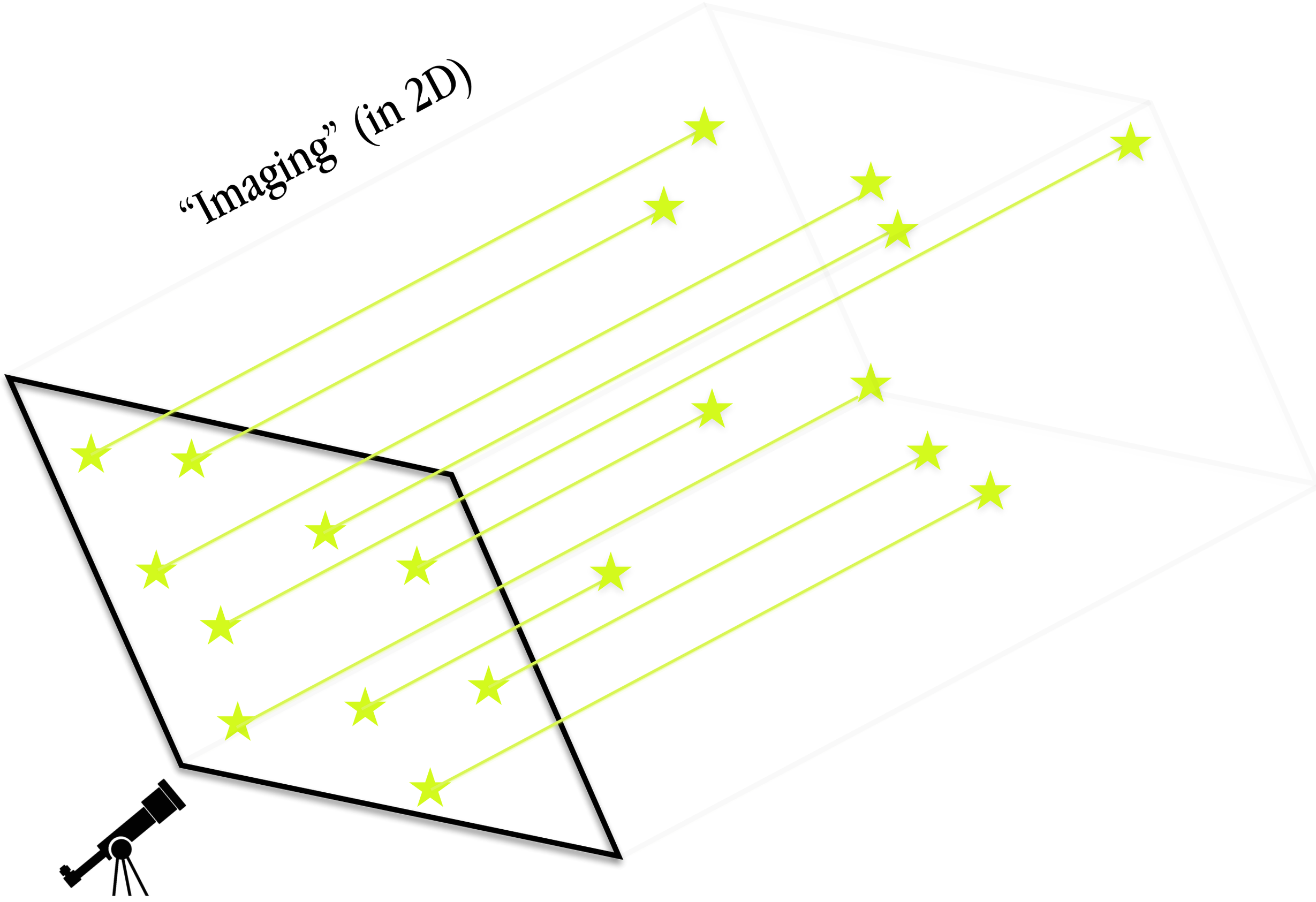
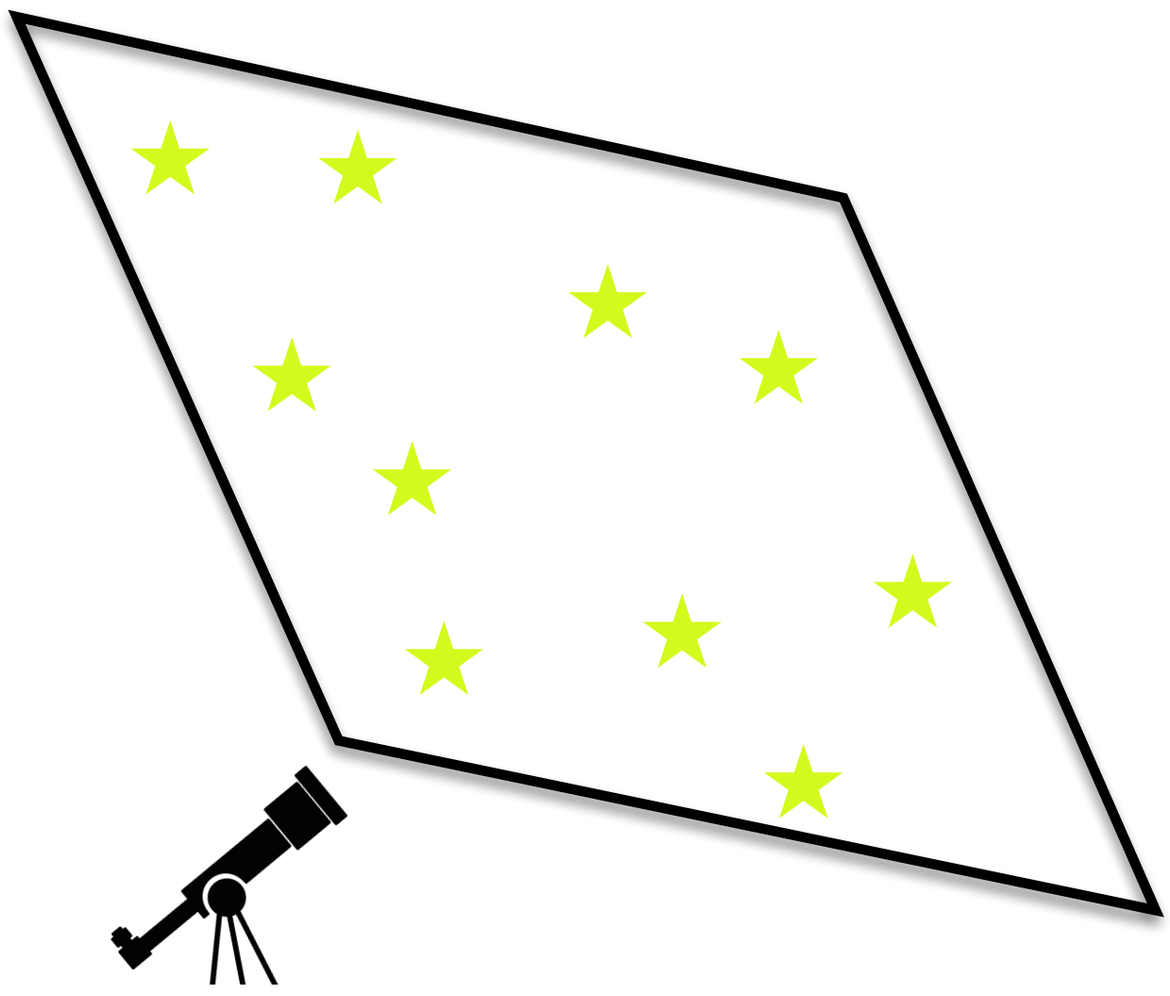


WARNING: schematic diagram, NOT to scale (credit A. Goodman, 2019)

"Imaging" (in 2D)



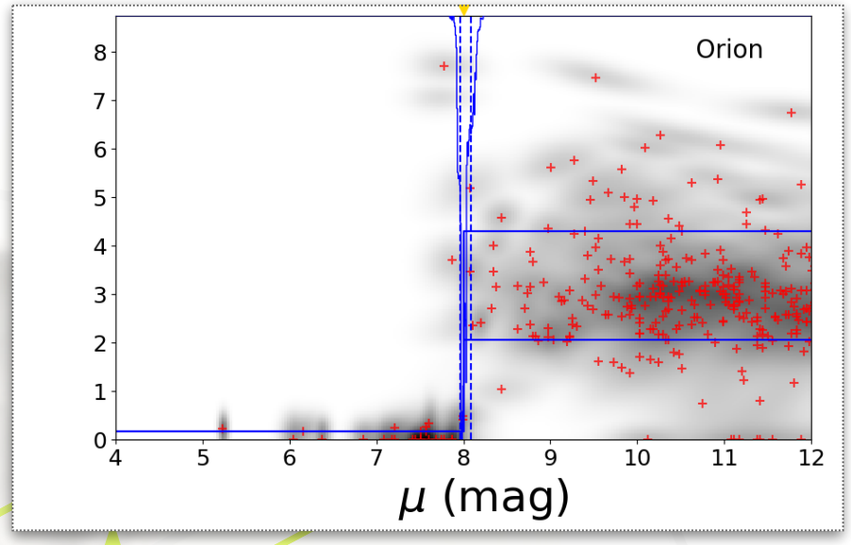
WARNING: schematic diagram, NOT to scale (credit A. Goodman, 2019)

“Extinction”

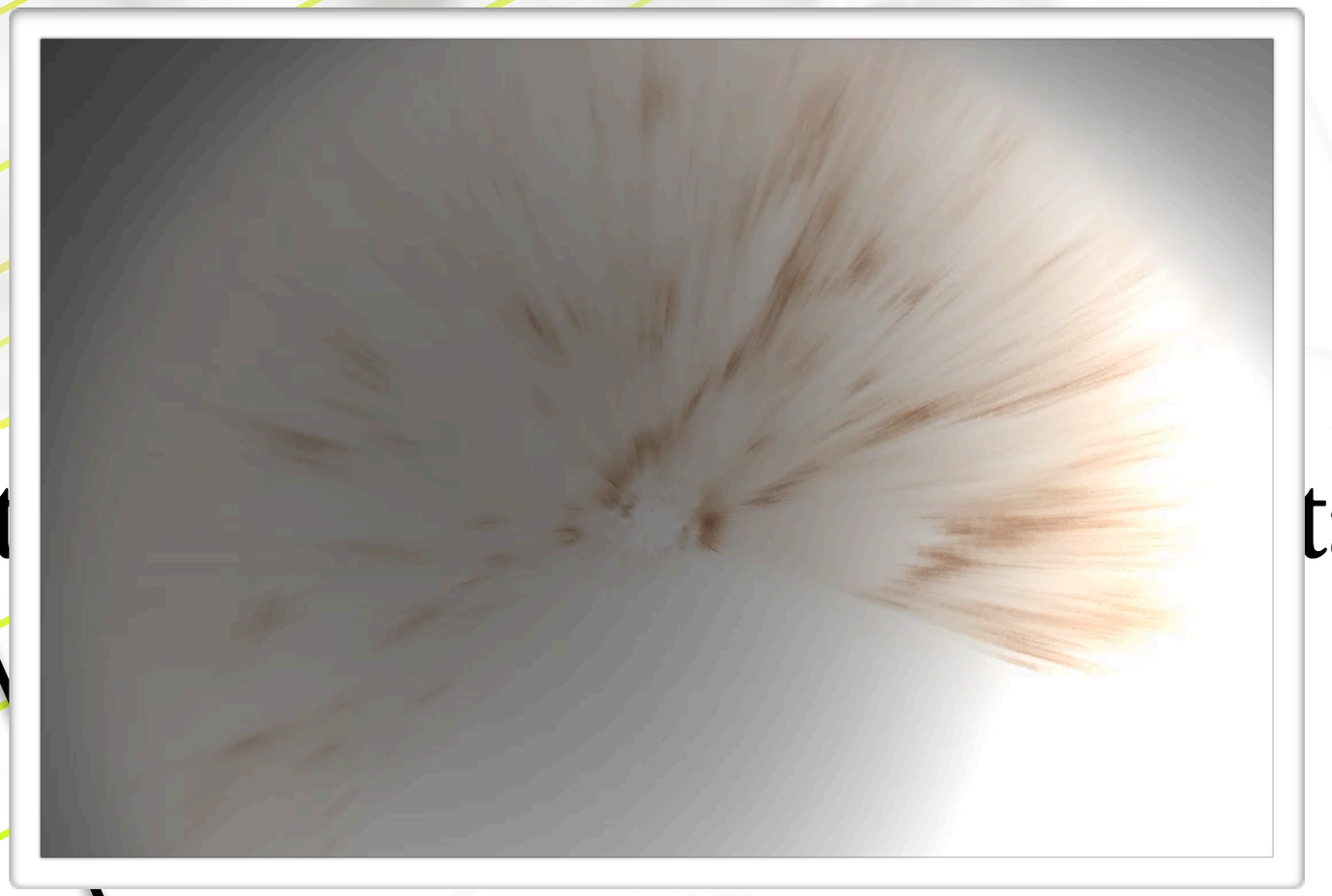
WARNING: schematic diagram, NOT to scale (credit A. Goodman, 2019)

“Reddening”

Extinction & Reddening, from Color Imaging



Zucker et al. 2019



Green et al. 2019

Can infer matter's dist tars

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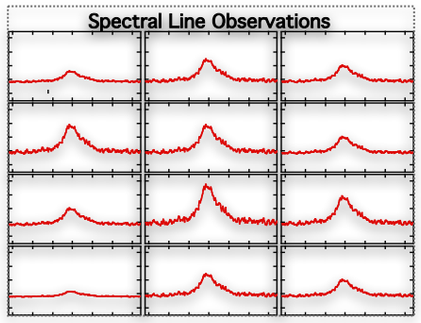

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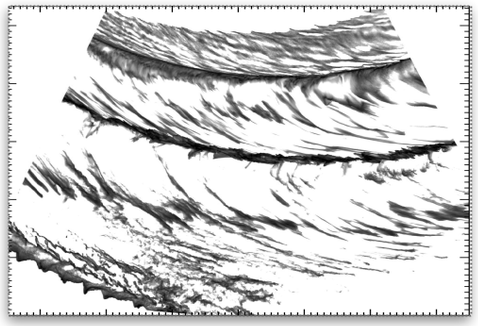

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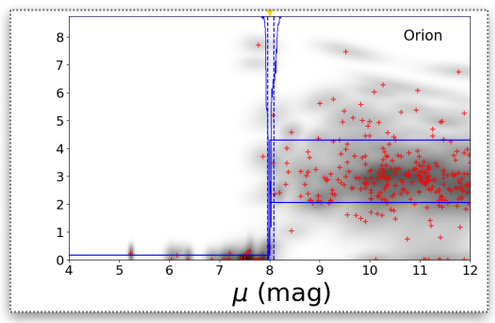
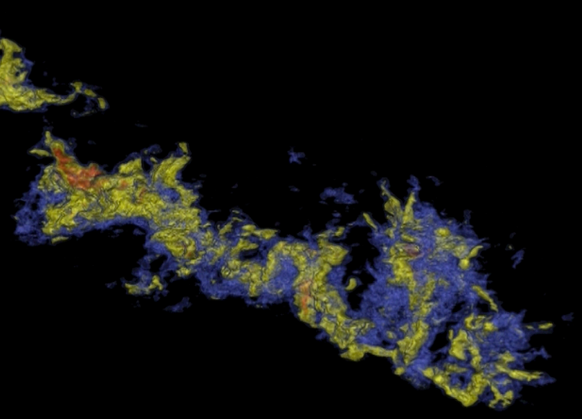
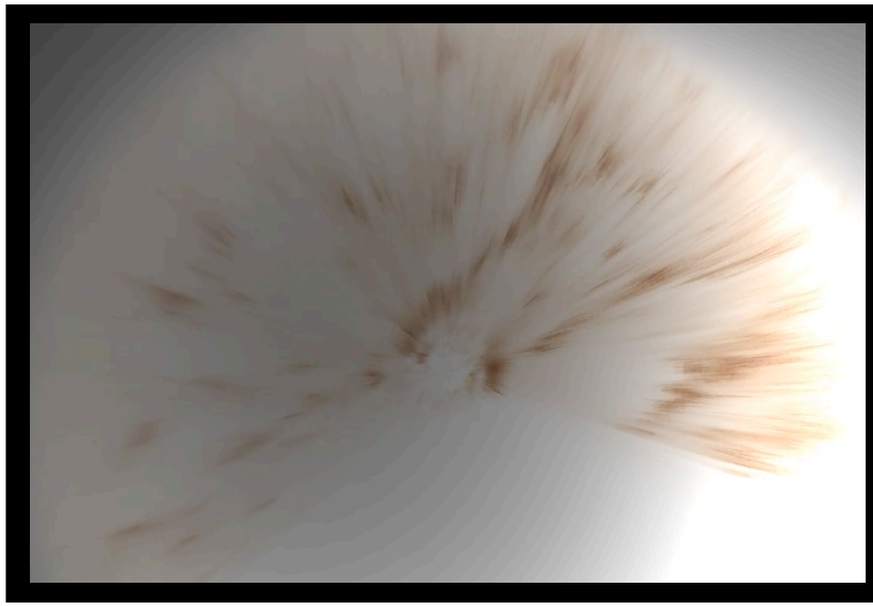


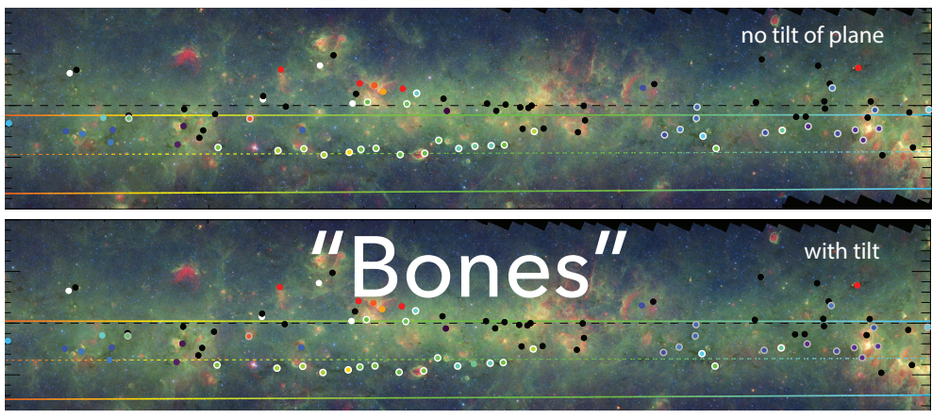
statistical reconstruction

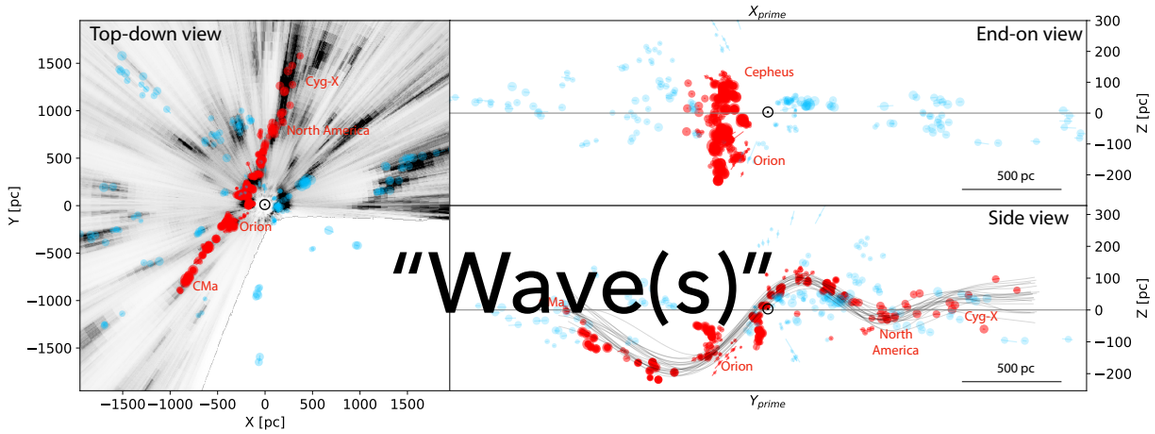
Gas in “3D"
p-p-v





Dust in 3D
p-p-p





“Theory” questions re: magnetic fields, feedback, collisions, oscillations dark matter…

Draft version August 26, 2019
Typeset using LaTeX **twocolumn** style in AASTeX62

The Implications of Local Fluctuations in the Galactic Midplane for Dynamical Analysis in the *Gaia* Era

Angus Beane,[1,2] Robyn E. Sanderson,[2,1] Melissa K. Ness,[3,1] Kathryn V. Johnston,[3,1] Douglas Grion Filho,[3] Mordecai-Mark Mac Low,[4,1] Daniel Anglés-Alcázar,[1] David W. Hogg,[5,6,1,7] and Chervin F. P. Laporte[8,*]

[1] *Center for Computational Astrophysics, Flatiron Institute, 162 5th Ave., New York, NY 10010, USA*
[2] *Department of Physics & Astronomy, University of Pennsylvania, 209 South 33rd St., Philadelphia, PA 19104, USA*
[3] *Department of Astronomy, Columbia University, 550 West 120th St., New York, NY 10027, USA*
[4] *Department of Astrophysics, American Museum of Natural History, Central Park West at 79th St., New York, NY 10024, USA*
[5] *Center for Cosmology and Particle Physics, Department of Physics, New York University, 726 Broadway, New York, NY 10003, USA*
[6] *Center for Data Science, New York University, 60 5th Ave., New York, NY 10011, USA*
[7] *Max-Planck-Institut für Astronomie, Königstuhl 17, 69117 Heidelberg, Germany*
[8] *Department of Physics & Astronomy, University of Victoria, 3800 Finnerty Rd., Victoria, BC, V8P 4HN, Canada*

Submitted to ApJ

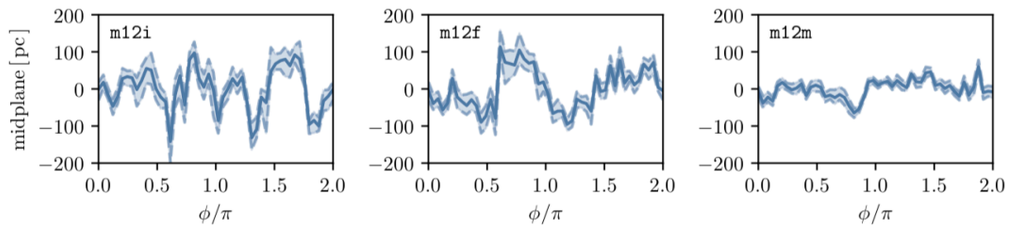
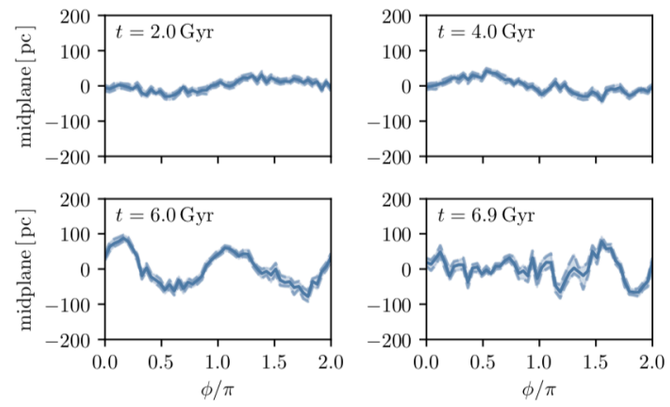


Figure 6. The local midplane determined at the fiducial solar circle ($R_0 = 8.2\,\mathrm{kpc}$) for the three FIRE galaxies `m12i`, `m12f`, and `m12m` (left, center, and right panels) as a function of azimuthal angle, at cosmological redshift $z_r = 0$. The local midplane is determined at a position ϕ by taking the median height of all stars within $R = 0.5\,\mathrm{kpc}$ and $z = 1\,\mathrm{kpc}$ (in cylindrical coordinates). In order to allow for the possibility that the fiducial galactocentric coordinate system is incorrect, we subtract the best fit sine curve from each panel. We then bootstrap resample 1000 times to determine $1\,\sigma$ error bars, which we report as dashed lines.



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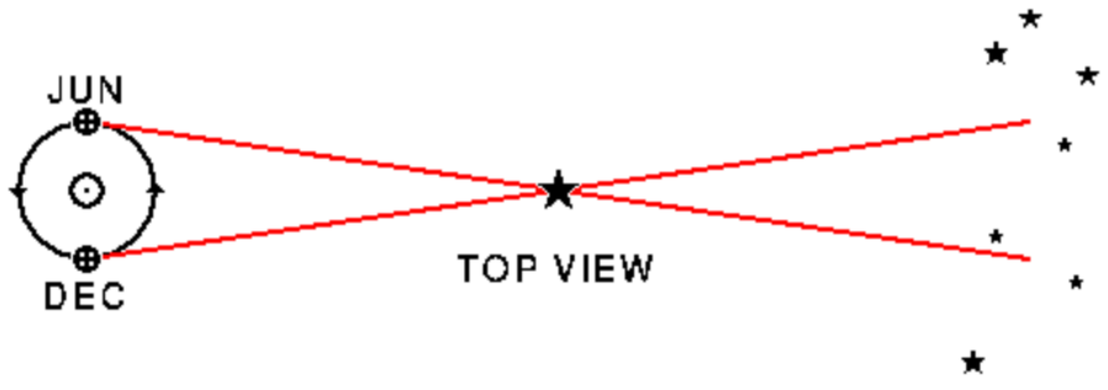
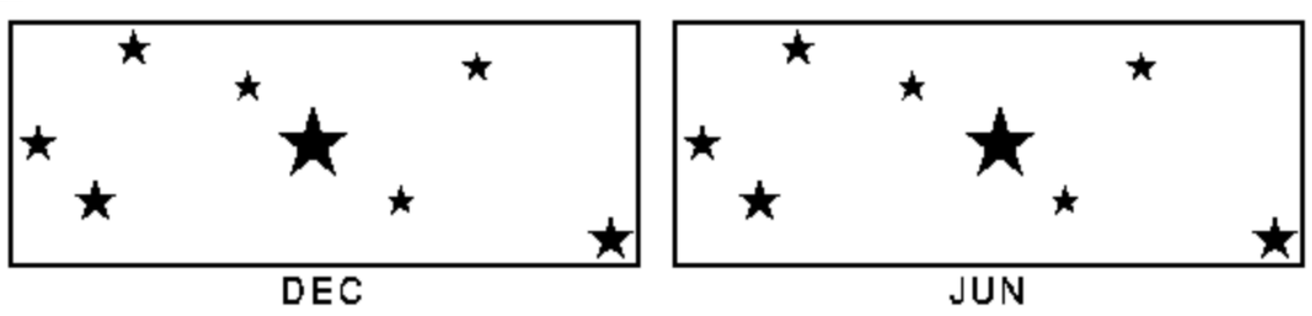


“maser” distances

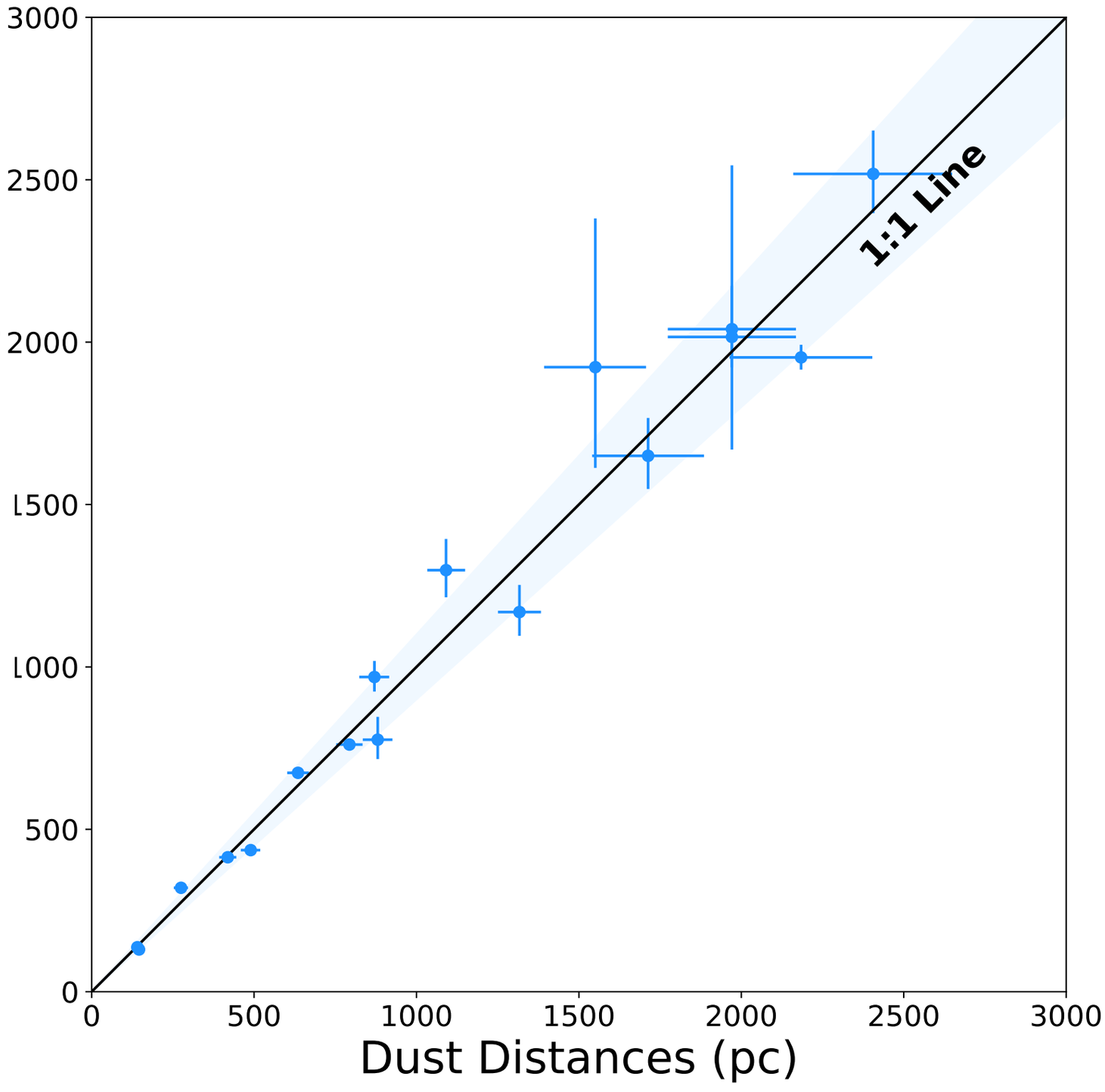


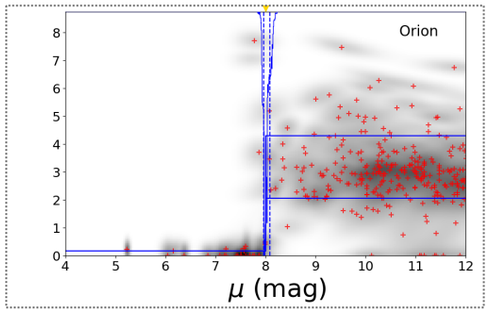
The top part of the diagram above shows the Earth at two different times, and the triangle formed with a nearby star and these two positions of the Earth. The bottom part shows two pictures of the nearby star projected onto more distant stars taken from the two sides of the Earth's orbit. If you cross your eyes to merge these two pictures, you will either see the nearby star standing in front of the background in 3-D, or else get a headache.

The *parallax* of a star is one-half the angle at the star in the diagram above. Thus the parallax is the angle at the star in an Earth-Sun-star triangle. Since this angle is always very small, the sine and tangent of the parallax are very well approximated by the parallax angle measured in radians. Therefore the distance to a star is

```
D[in cm] = [Earth-Sun distance in cm]/[parallax in radians]
```

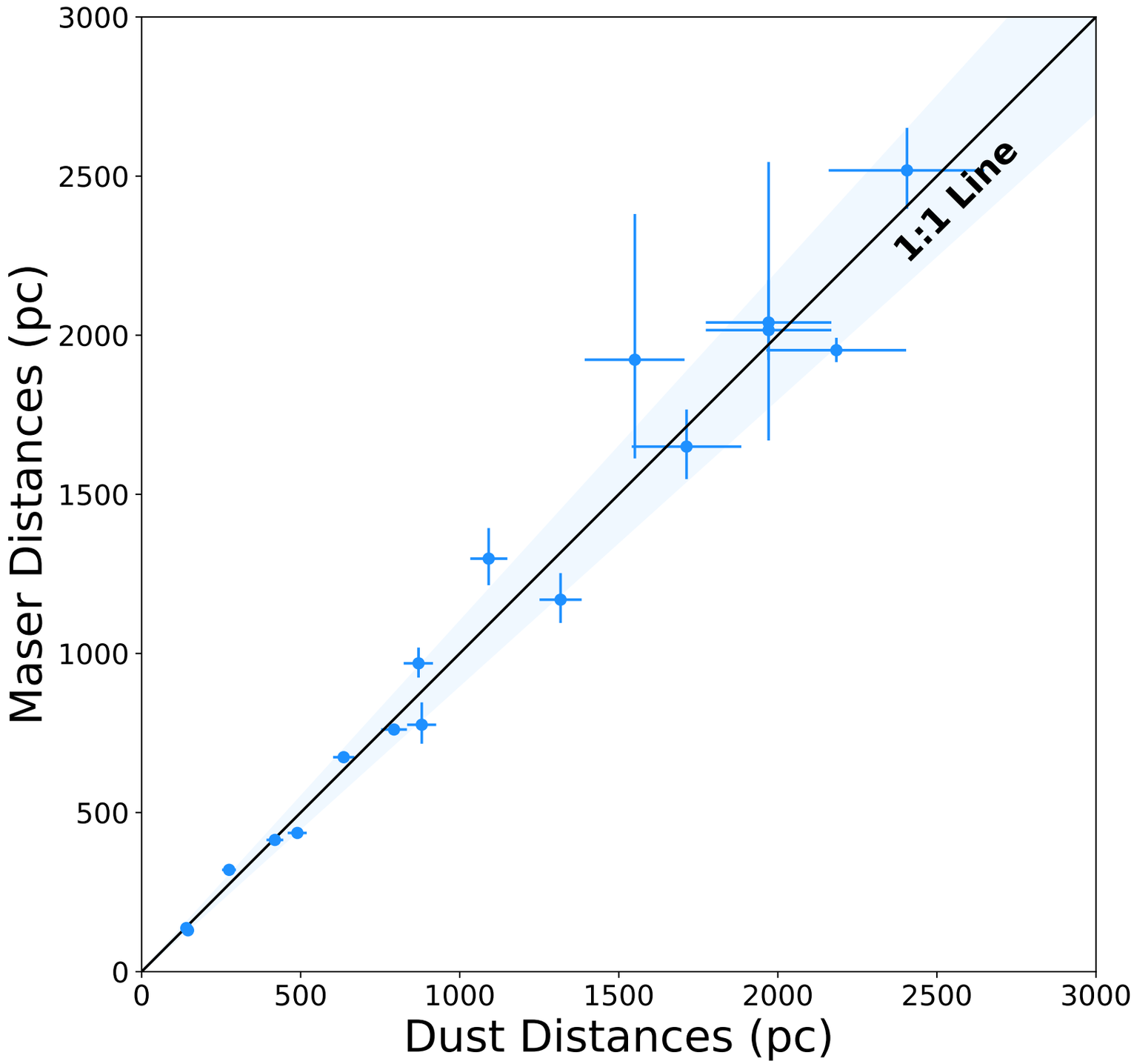
www.astro.ucla.edu/~wright/distance.htm





Zucker et al. 2019

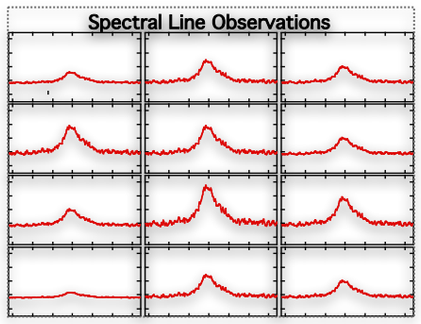
requires
special regions
on the Sky
(HII regions
with masers)



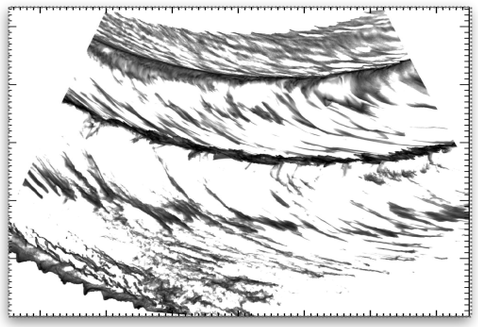
can be used **anywhere**
there's dust & measurable
stellar properties

Zucker et al. 2019

"Data"= 3D cubes, 2D images, 1D catalogs, from…

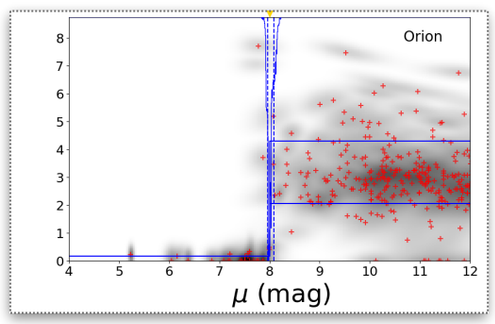


spectral-line mapping



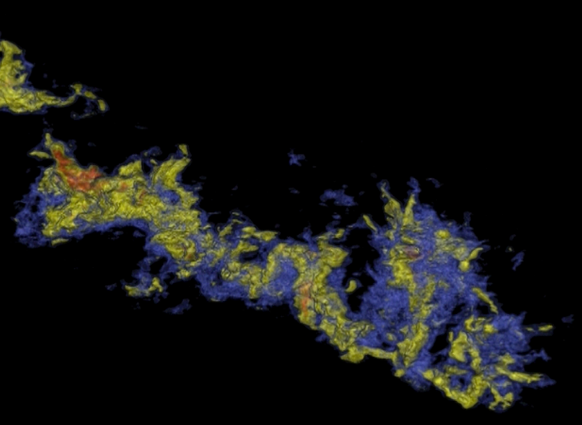
numerical simulation

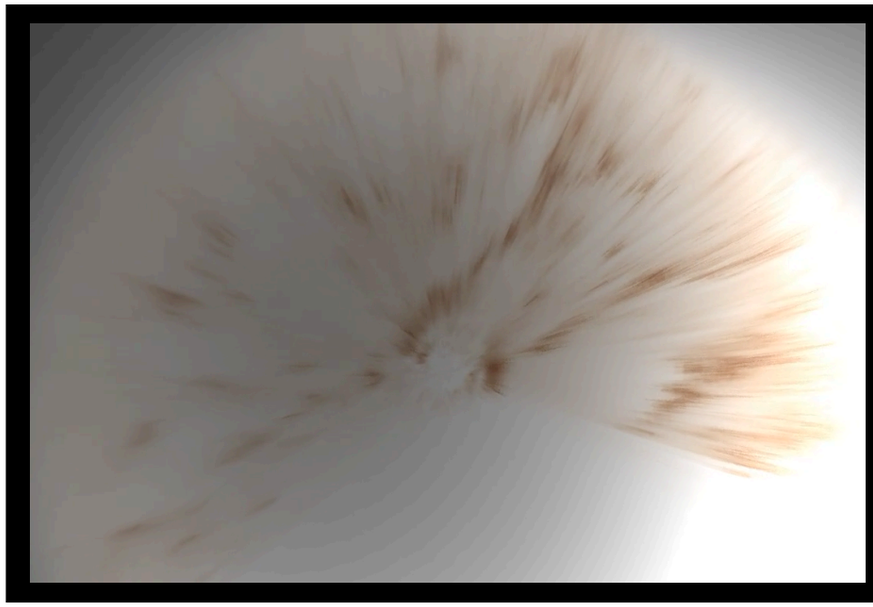
photometric imaging (over time)



statistical reconstruction

Gas in "3D"
p-p-v

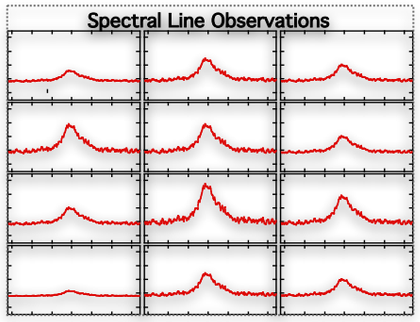




Dust in 3D
p-p-p

What about 4D??

(*p-p-p-*v_z)

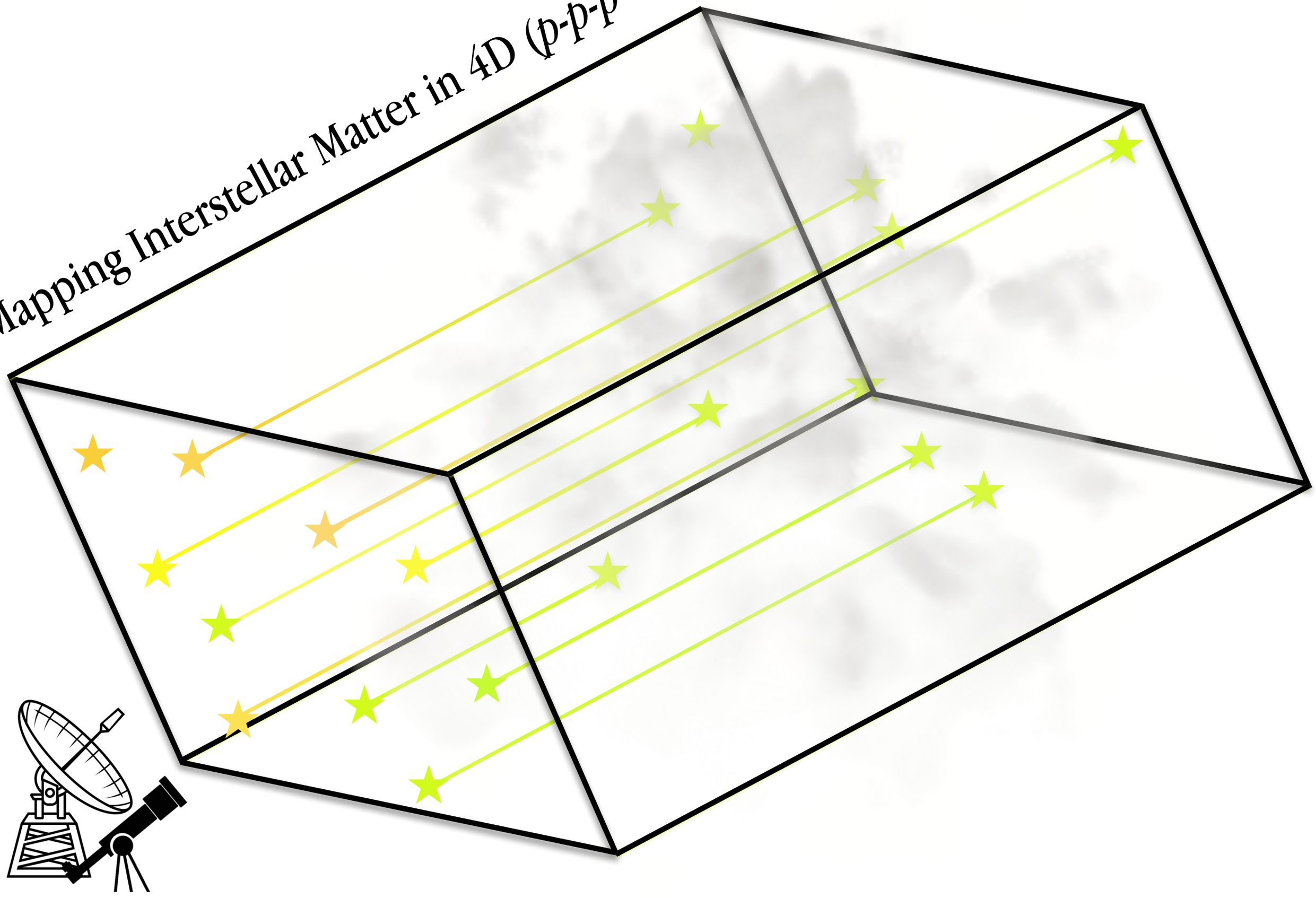


Mapping Interstellar Matter in *p-p-v*

"Spectral-Line Data Cubes"

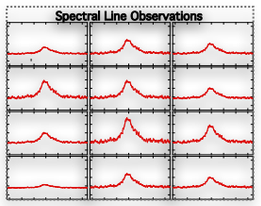
WARNING: schematic diagram, NOT to scale (credit A. Goodman, 2019)

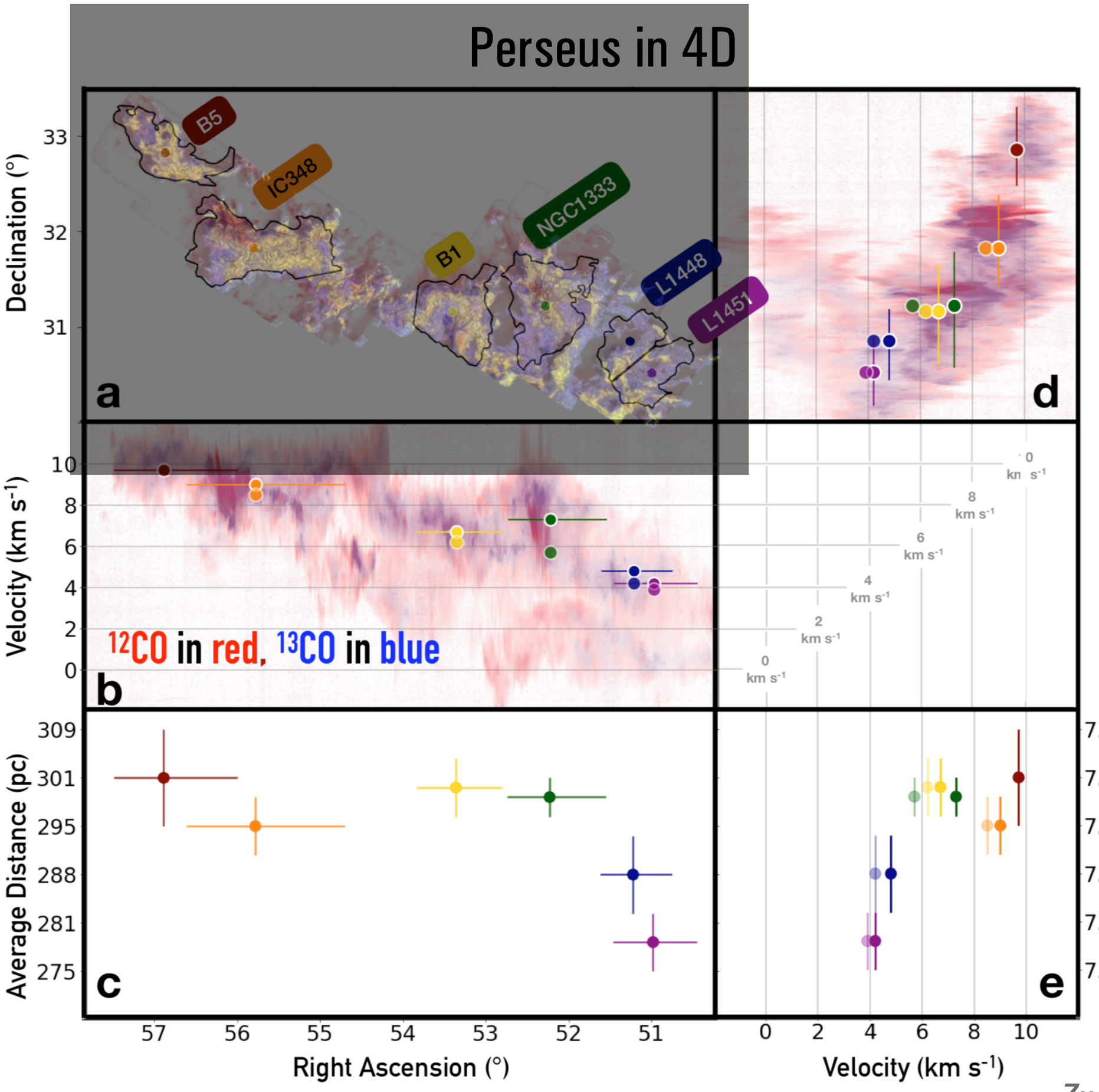
Mapping Interstellar Matter in 4D (p-p-p-v_z)



WARNING: schematic diagram, NOT to scale (credit A. Goodman, 2019)

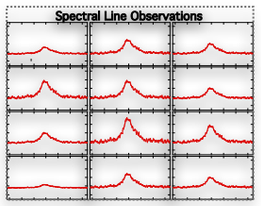
Perseus in 4D

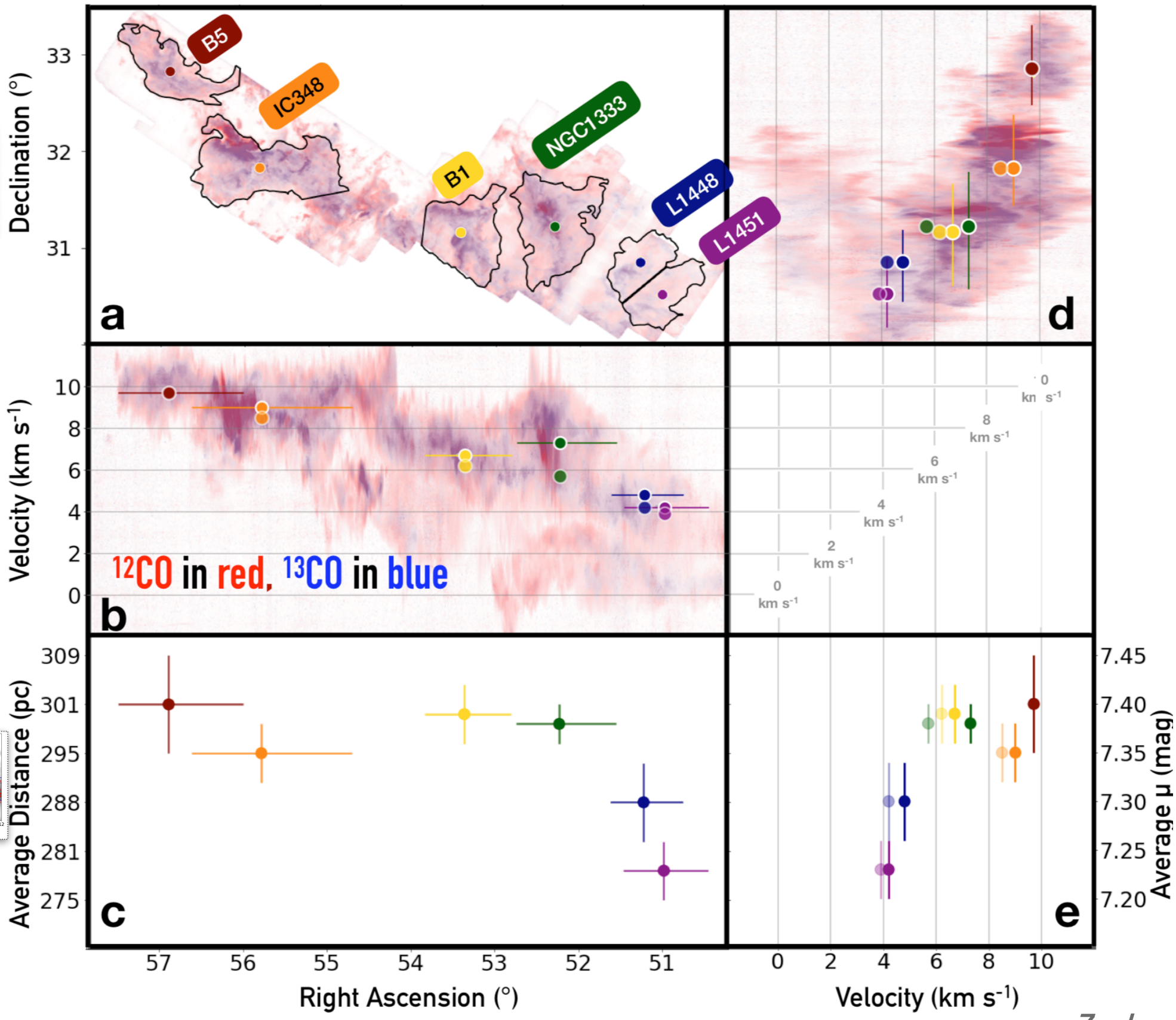


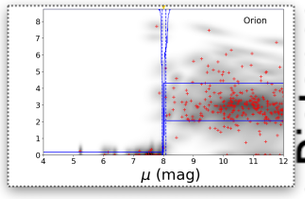


Zucker et al. 2018

Perseus in 4D







Zucker et al. 2018

“Teasing” or “Knitting”?

"Knitting" in 2020 & beyond…

brutus

catalog of 5 billion stars

UKIDSS, VVV, DECaPS GLIMPSE

Pan-STARRS1

2MASS

Gaia

3D Dust v1 "**Bayestar**" Green et al. 2015

3D Dust v4 "**brutus**" **optimized for Galactic Plane**

AREPO **simulations** of Milky Way-like Galaxy (Zucker et al. 2019)

Bayestar

3D Dust v3 "+Gaia" Green et al. 2019

Distance-Velocity knitting demo (Perseus) Zucker et al. 2018b

Distance-Velocity knitting for <5 kpc

4D (3D position-1D velocity) model of nearby arms

(future) **4D** (3D position-1D velocity) model of full **Milky Way**

3D Dust v2 "**Bayestar**" Green et al. 2018a

glue

Dendroviz

Milky Way **CO Dendrogram** (Rice et al. 2016)

dustmaps (query tool)

Spatially-varying reddening (Schlafly et al. 2017)

surveys of gas & dust (CO, masers, HII, and more)

Bones constrain Galactic plane. (Goodman et al. 2014; Zucker et al. 2015, 2018a, 2019)

milkyway3d.org (open data archive tool)

KEY

Prior Work NSF 1739657

Prior Work NSF 1614941

Deliverables from this proposal

Zucker Thesis

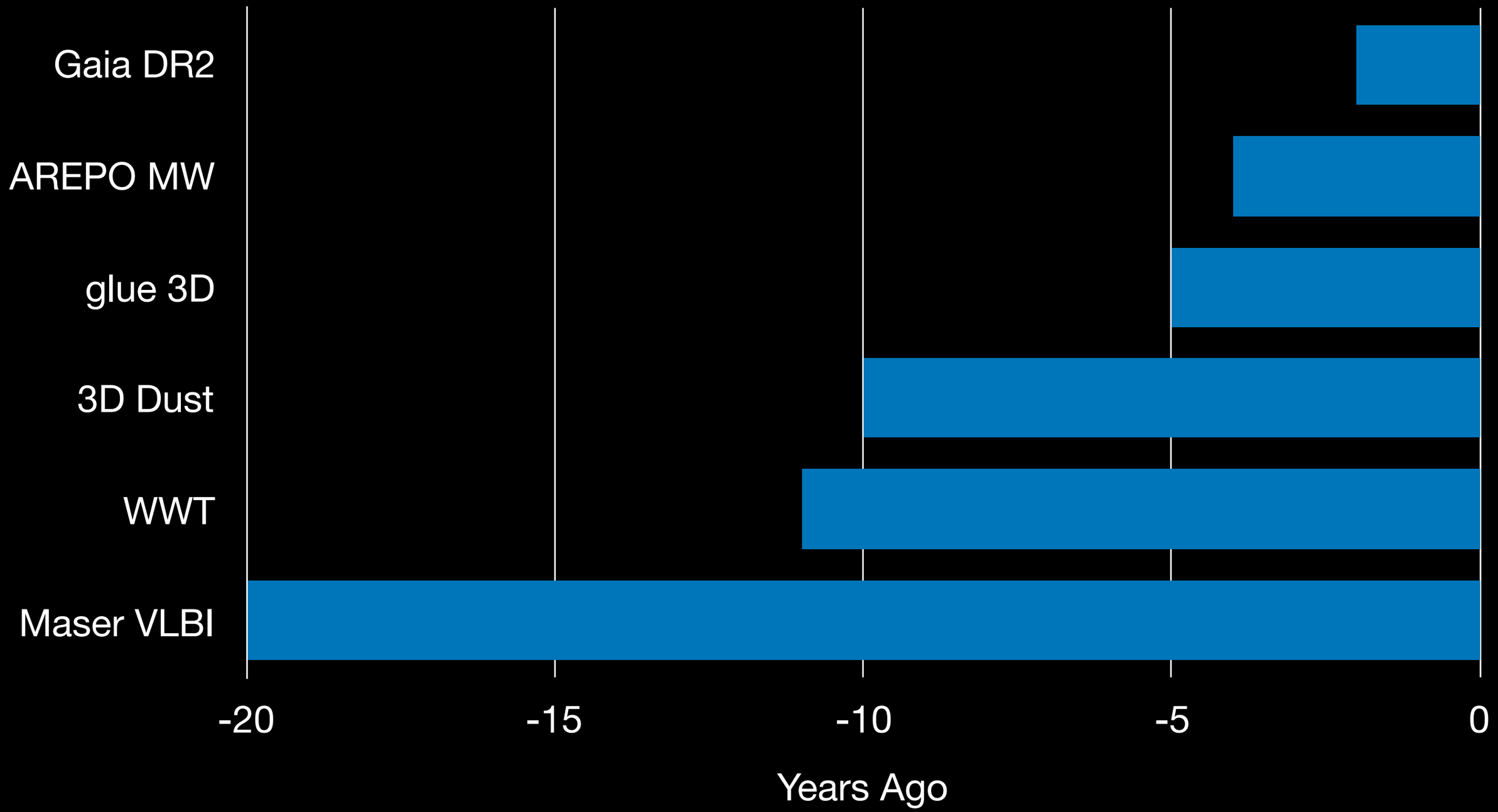
software

data

ancillary benefits

related to WWT

How/why is this all possible now?



Teasing Out the True Milky Way

with many thanks to: João **Alves**, Cara Battersby, Gus Beane, Christopher Beaumont, Bob Benjamin, Michelle Borkin, Tom Dame, Jonathan Fay, Douglas **Finkbeiner**, Greg Green, Jens Kauffmann, Mark Reid, Thomas **Robitaille**, Eddie Schlafly, Rowan **Smith**, Josh **Speagle**, Catherine **Zucker** & Curtis **Wong**

space.com/universe-colors-milky-way-photo.html

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3D Solar System View
Tracking
Sun
Planet Size
Actual
Large
Mercury
Venus
Earth
Mars
Jupiter
Saturn
Uranus
Neptune
Pluto
Sun

tease

/tēz/

verb

gerund or present participle: **teasing**

1. make fun of or attempt to provoke (a person or animal) in a playful way.
   "she was just teasing"
   synonyms: make fun of, poke fun at, chaff, make jokes about, rag, mock, laugh at, guy, satirize, be sarcastic about; More
   - tempt (someone) sexually with no intention of satisfying the desire aroused.
2. gently pull or comb (tangled wool, hair, etc.) into separate strands.
   "she was teasing out the curls into her usual hairstyle"
   - find something out from a mass of irrelevant information.
     "a historian who tries to tease out the truth"
   - NORTH AMERICAN
     comb (hair) in the reverse direction of its natural growth in order to make it appear fuller.
   - ARCHAIC
     comb (the surface of woven cloth) to raise a nap.