Mapping the Milky Way, from the Inside Out, in Color

The Milky Way
(Artist's Conception)

Mapping the Milky Way, from the Inside Out, in Color

Prof. Alyssa A. Goodman
Center for Astrophysics | Harvard & Smithsonian
& Radcliffe Institute for Advanced Study
scholar.harvard.edu/agoodman
@AlyssaAGoodman

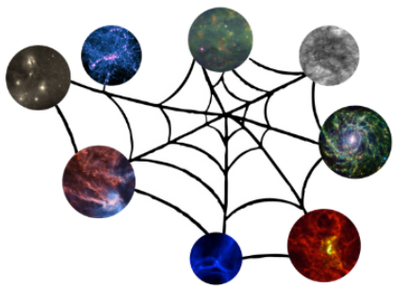
Prof. Alyssa A. Goodman

Center for Astrophysics | Harvard & Smithsonian
& Radcliffe Institute for Advanced Study
scholar.harvard.edu/agoodman
@AlyssaAGoodman

Projects

In my **astrophysical** research, I am primarily interested in how the gas in galaxies constantly rearranges itself over huge time spans to constantly form new stars, and in bringing large data sets and new data science techniques to bear on understanding the structure of the Milky Way. I have also had a long-standing interest in **data visualization**, and in improving the use of computers in all aspects of modern **(21st century) scholarship** and scientific research. My interests in astronomy, visualization, and 21st-century tools combine in the form of WorldWide Telescope, which I help create and maintain, and upon which the WorldWide Telescope Ambassadors **science education** Program I founded often relies. Since 2014, I have become very interested in the history of **Prediction**, as a way to understand modern computer simulations and their interpretation. I have served as coDirector for Science, where I help to bring new scholarship across the sciences to the attention of scholars and the public, at **Radcliffe** since 2017. Someday soon, I may perhaps find time to make custom webpages for each of my interest areas below, but for now, please do follow the links, as many of the projects have entire websites of their own.

Presentations associated with all of the projects below can be found at the Talks Page.



ASTROPHYSICS

- *How do stars really form?*
  - The COMPLETE Survey of Star-Forming Regions (data)
  - The GAS Survey (data, code)
- *What can we learn about the structure of the Milky Way from inside it?*
  - milkyway3d.org

Please see the Publications page, and Alyssa Goodman's pre-2018 website for additional detals.

DATA VISUALIZATION

- glue
- "Astronomical Medicine" (Benefunder Site)
- 10 Questions to Ask when Creating a Visualization
- Viz-e-Lab
- Visualization for Astronomers (Curriculum and Materials, v. Vienna 2017)

- The Timeline Consortium
- WorldWide Telescope
- The ADS All Sky Survey
- Astronomy Rewind
- The "Paper" of the Future
- Data Sharing, Data Ethics
- The Harvard Data Science Initiative (2016-present)
- The Initiative in Innovative Computing (2005-8)
- Seamless Astronomy

SCIENCE EDUCATION

- WorldWide Telescope Ambassadors
- Fetch! Episode using WorldWide Telescope (Imdb link)
- Astronomy PhD Outreach Projects at Harvard
- "The ISM and Star Formation"(online course materials)
- "Outreach" Modules about the Interstellar Medium

PREDICTION: THE PAST & PRESENT OF THE FUTURE

- PredictionX.org
- PredictionX on edX (e.g.John Snow mini course)
- Freshman Seminar (Harvard FS27J)
- Harvard General Education Course (coming 2019-20)

PROJECTS AT RADCLIFFE

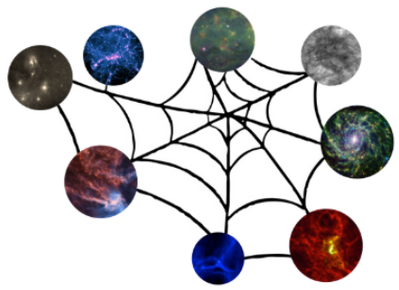
Events Organized as Faculty coDirector for Science

- Next in Data Science (2018)
- Algorithmic Accountability: Designing for Safety (2018)
- The Undiscovered (2018 Science Symposium)
- Climate+Data @ Harvard (2019)
  - An Energy Plan the Earth Can Live With (2019)
- Next in Data Visualization (2019, Coming Soon)

Projects

In my **astrophysical** research, I am primarily interested in how the gas in galaxies constantly rearranges itself over huge time spans to constantly form new stars, and in bringing large data sets and new data science techniques to bear on understanding the structure of the Milky Way. I have also had a long-standing interest in **data visualization**, and in improving the use of computers in all aspects of modern **(21st century) scholarship** and scientific research. My interests in astronomy, visualization, and 21st-century tools combine in the form of WorldWide Telescope, which I help create and maintain, and upon which the WorldWide Telescope Ambassadors **science education** Program I founded often relies. Since 2014, I have become very interested in the history of **Prediction**, as a way to understand modern computer simulations and their interpretation. I have served as coDirector for Science, where I help to bring new scholarship across the sciences to the attention of scholars and the public, at **Radcliffe** since 2017. Someday soon, I may perhaps find time to make custom webpages for each of my interest areas below, but for now, please do follow the links, as many of the projects have entire websites of their own.

Presentations associated with all of the projects below can be found at the Talks Page.



ASTROPHYSICS

- *How do stars really form?*
  - The COMPLETE Survey of Star-Forming Regions (data)
  - The GAS Survey (data, code)
- *What can we learn about the structure of the Milky Way from inside it?*
  - milkyway3d.org

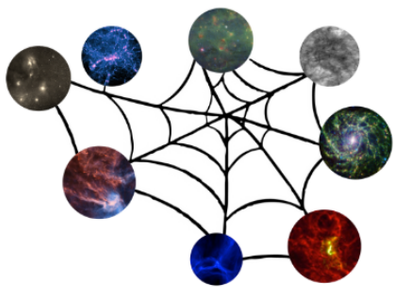
Please see the Publications page, and Alyssa Goodman's pre-2018 website for additional detals.

DATA VISUALIZATION

- glue
- "Astronomical Medicine" (Benefunder Site)
- 10 Questions to Ask when Creating a Visualization
- Viz-e-Lab
- Visualization for Astronomers (Curriculum and Materials, v. Vienna 2017)
- The Art of Numbers (Harvard EMR19)

21st CENTURY SCHOLARSHIP

- The Timeline Consortium
- WorldWide Telescope



ASTROPHYSICS

- *How do stars really form?*
  - The COMPLETE Survey of Star-Forming Regions (data)
  - The GAS Survey (data, code)
- *What can we learn about the structure of the Milky Way from inside it?*
  - milkyway3d.org

ASTROPHYSICS

- *How do stars really form?*
  - The COMPLETE Survey of Star-Forming Regions (data)
  - The GAS Survey (data, code)
- *What can we learn about the structure of the Milky Way from inside it?*
  - milkyway3d.org

- *What can we learn about the structure of the Milky Way from inside it?*
  - milkyway3d.org

The end of the story, first.

The star-forming nebula NGC1333

How did we do that?

Draft version October 18, 2018
Typeset using LaTeX **preprint** style in AASTeX61

MAPPING DISTANCES ACROSS THE PERSEUS MOLECULAR CLOUD USING CO OBSERVATIONS, STELLAR PHOTOMETRY, AND GAIA DR2 PARALLAX MEASUREMENTS

Catherine Zucker,[1] Edward F. Schlafly,[2] Joshua S. Speagle,[1] Gregory M. Green,[3] Stephen K. N. Portillo,[1] Douglas P. Finkbeiner,[1] and Alyssa A. Goodman[1]

[1]*Harvard Astronomy, Harvard-Smithsonian Center for Astrophysics, 60 Garden St., Cambridge, MA 02138, USA*
[2]*Lawrence Berkeley National Laboratory, One Cyclotron Road, Berkeley, CA 94720, USA*
[3]*Kavli Institute for Particle Astrophysics and Cosmology, Physics and Astrophysics Building, 452 Lomita Mall, Stanford, CA 94305, USA*

Abstract

We present a new technique to determine distances to major star-forming regions across the Perseus Molecular Cloud, using a combination of stellar photometry, astrometric data, and ^{12}CO spectral-line maps. Incorporating the Gaia DR2 parallax measurements when available, we start by inferring the distance and reddening to stars from their Pan-STARRS1 and 2MASS photometry, based on a technique presented in Green et al. (2014, 2015) and implemented in their 3D "Bayestar" dust map

Draft version February 6, 2019
Typeset using LaTeX default style in AASTeX62

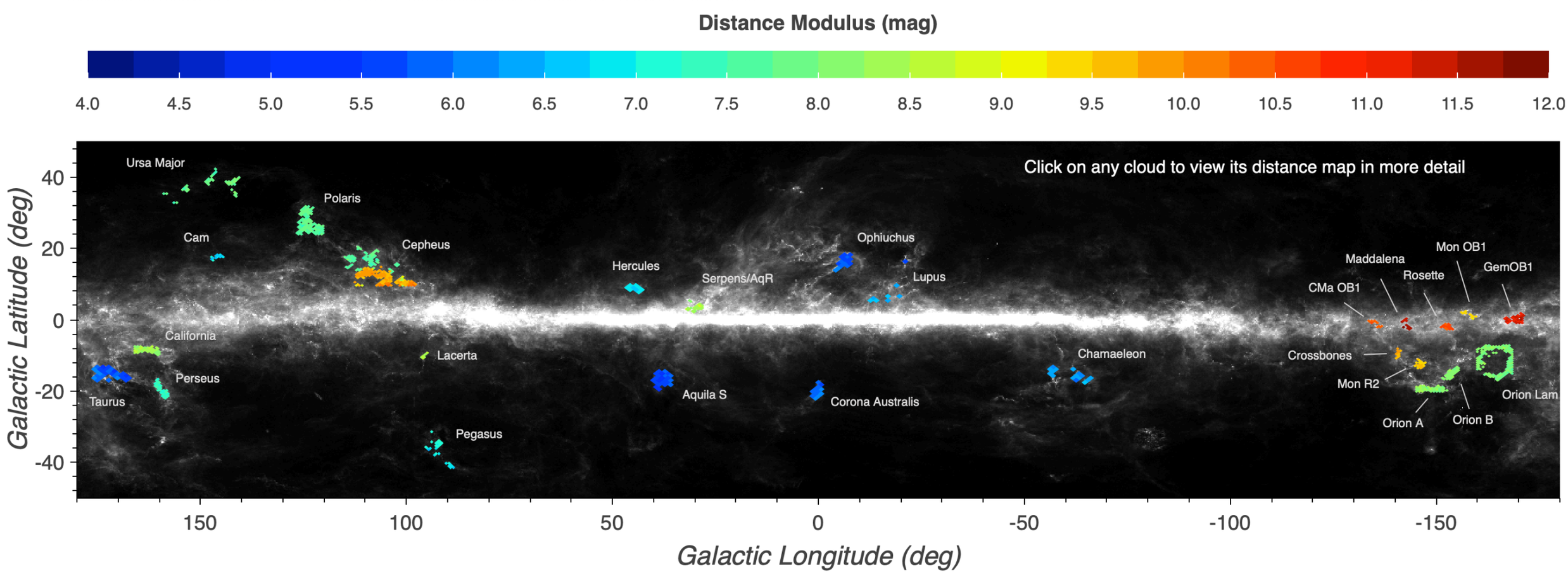
A Large Catalog of Accurate Distances to Local Molecular Clouds: The Gaia DR2 Edition

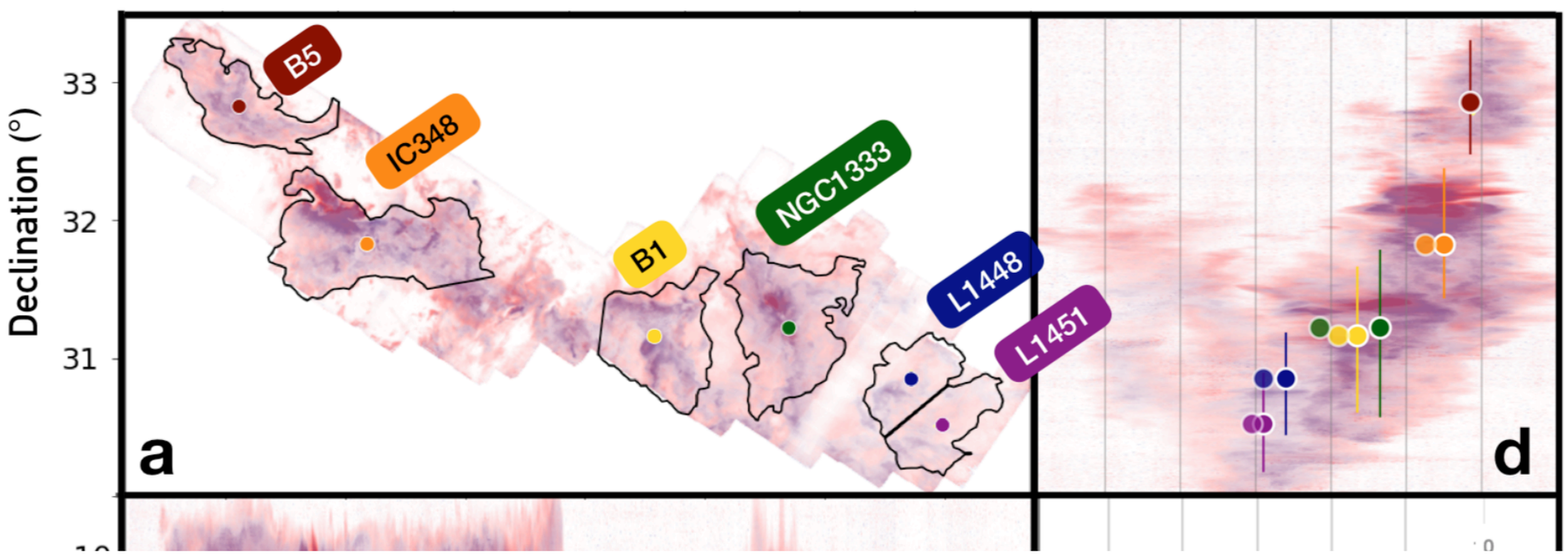
Catherine Zucker,[1,*] Joshua S. Speagle,[1,*] Edward F. Schlafly,[2] Gregory M. Green,[3] Douglas P. Finkbeiner,[1] Alyssa A. Goodman,[1,4] and João Alves[4,5]

[1]*Harvard Astronomy, Harvard-Smithsonian Center for Astrophysics, 60 Garden St., Cambridge, MA 02138, USA*
[2]*Lawrence Berkeley National Laboratory, One Cyclotron Road, Berkeley, CA 94720, USA*
[3]*Kavli Institute for Particle Astrophysics and Cosmology, Physics and Astrophysics Building, 452 Lomita Mall, Stanford, CA 94305, USA*
[4]*Radcliffe Institute for Advanced Study, Harvard University, 10 Garden St, Cambridge, MA 02138*
[5]*University of Vienna, Department of Astrophysics, Türkenschanzstraße 17, 1180 Vienna, Austria*

ABSTRACT

We present a uniform catalog of accurate distances to local molecular clouds informed by the Gaia DR2 data release. Our methodology builds on that of Schlafly et al. (2014). First, we infer the distance and extinction to stars along sightlines towards the clouds using optical and near-infrared photometry. When available, we incorporate knowledge of the stellar distances obtained from Gaia DR2 parallax measurements. We model these per-star distance-extinction estimates as being caused by a dust screen with a 2-D morphology derived from Planck at an unknown distance, which we then fit for using a nested sampling algorithm. We provide updated distances to the Schlafly et al. (2014) sightlines towards the Dame et al. (2001) and Magnani et al. (1985) clouds, finding good agreement with the earlier work. For a subset of 27 clouds, we construct interactive pixelated distance maps to further study detailed cloud structure, and find several clouds which display clear distance gradients and/or





Uh, but how did we do *that*?

Zucker et al. 2018

Draft version October 18, 2018
Typeset using LaTeX preprint style in AASTeX61

arXiv:1805.09934v2 [astro-ph.GA] 17 Oct 2018

MAPPING DISTANCES ACROSS THE PERSEUS MOLECULAR CLOUD USING CO OBSERVATIONS, STELLAR PHOTOMETRY, AND GAIA DR2 PARALLAX MEASUREMENTS

Catherine Zucker,[1] Edward F. Schlafly,[2] Joshua S. Speagle,[1] Gregory M. Green,[3] Stephen K. N. Portillo,[1] Douglas P. Finkbeiner,[1] and Alyssa A. Goodman[1]

[1]*Harvard Astronomy, Harvard-Smithsonian Center for Astrophysics, 60 Garden St., Cambridge, MA 02138, USA*
[2]*Lawrence Berkeley National Laboratory, One Cyclotron Road, Berkeley, CA 94720, USA*
[3]*Kavli Institute for Particle Astrophysics and Cosmology, Physics and Astrophysics Building, 452 Lomita Mall, Stanford, CA 94305, USA*

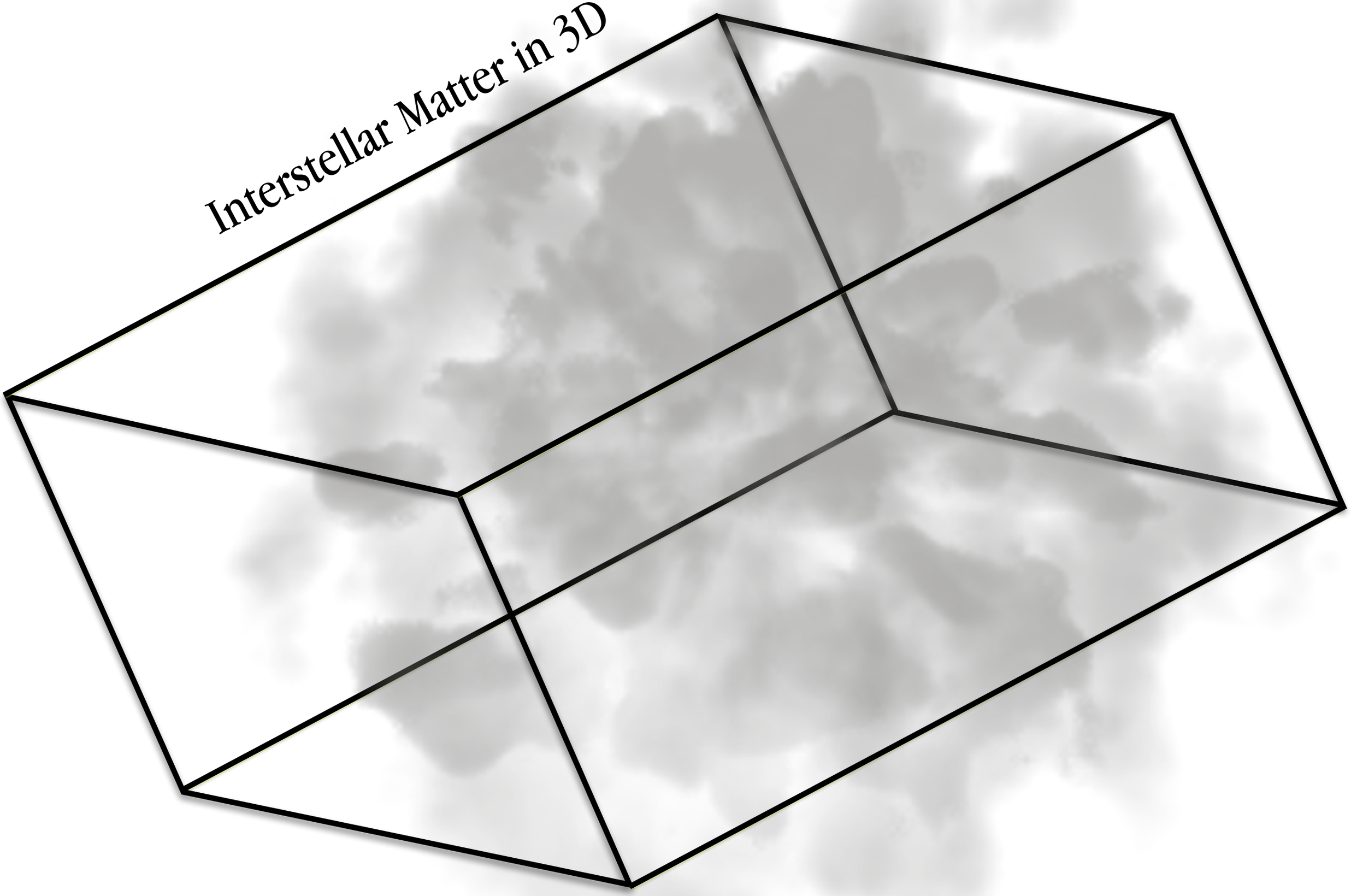
Abstract

We present a new technique to determine distances to molecular star-forming regions across the Perseus Molecular Cloud, using a combination of stellar photometry, astrometric data, and ^{12}CO spectral-line maps. Incorporating the Gaia DR2 parallax measurements when available, we start by inferring the distance and reddening to stars from their Pan-STARRS1 and 2MASS photometry, based on a technique presented in Green et al. (2014, 2015) and implemented in their 3D "Bayestar" dust map of three-quarters of the sky. We then refine the Green et al. technique by using the velocity slices of a CO spectral cube as dust templates and modeling the cumulative distribution of dust along the line of sight towards these stars as a linear combination of the emission in the slices. Using a nested sampling algorithm, we fit these per-star distance-reddening measurements to find the distances to the CO velocity slices towards each star-forming region. This results in distance estimates explicitly tied to the velocity structure of the molecular gas. We determine distances to the B5, IC348, B1, NGC1333, L1448, and L1451 star-forming regions and find that individual clouds are located between $\approx 275 - 300$ pc, with typical combined uncertainties of $\approx 5\%$. We find that the velocity gradient across Perseus corresponds to a distance gradient of about 25 pc, with the eastern portion of the cloud farther away than the western portion. We determine an average distance to the complex of 294 $\pm$ 17 pc, about 60 pc higher than the distance derived to the western portion of the cloud using parallax measurements of water masers associated with young stellar objects. The method we present is not limited to the Perseus Complex, but may be applied anywhere on the sky with adequate CO data in the pursuit of more accurate 3D maps of molecular clouds in the solar neighborhood and beyond.

Matter

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."

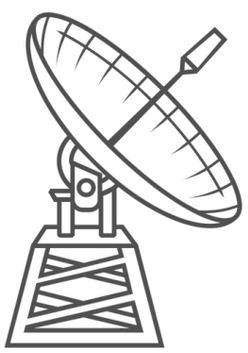
Interstellar Matter in 3D



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

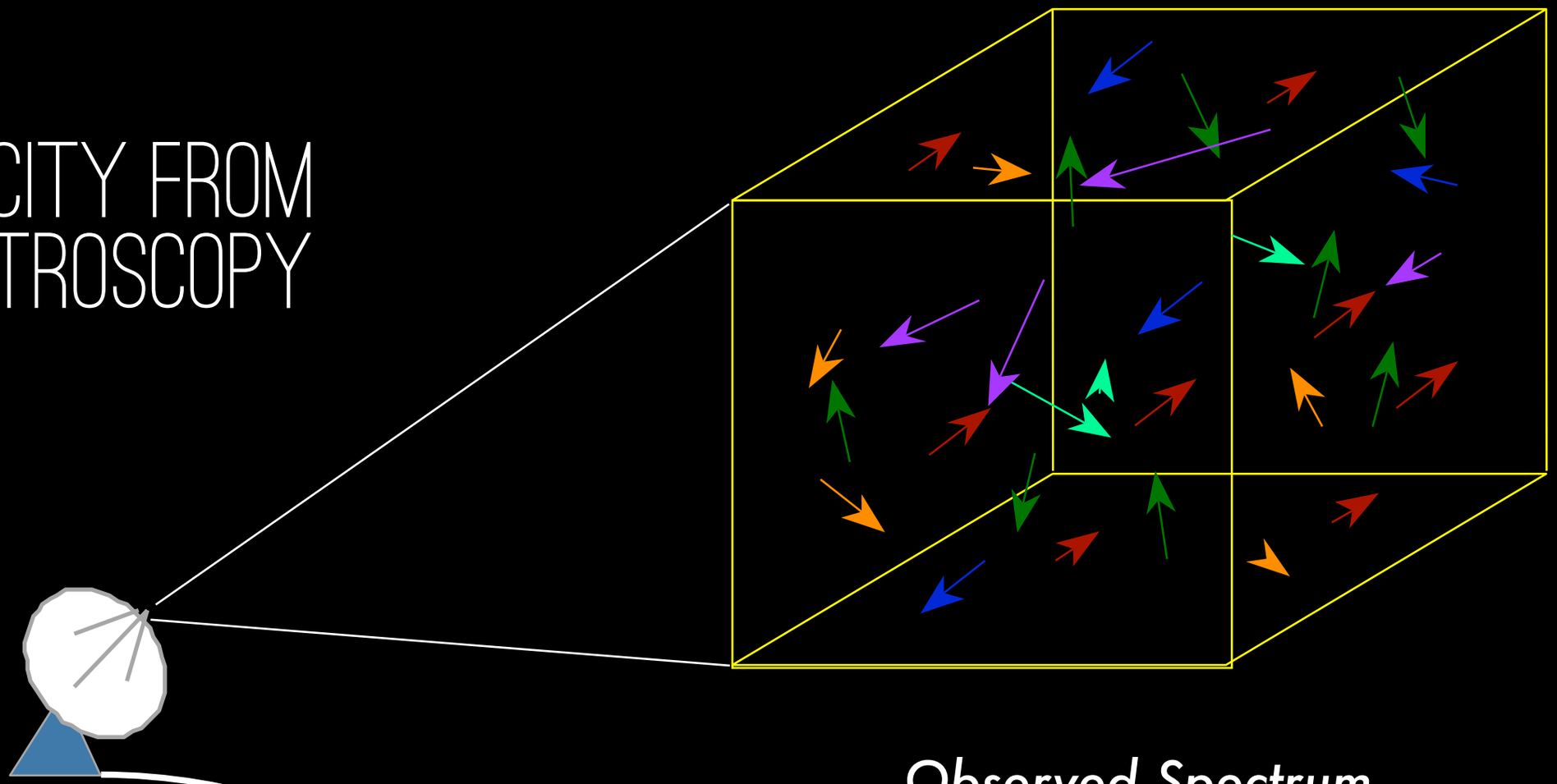
Mapping Interstellar Matter in 3D

"Spectral-Line Data Cubes"

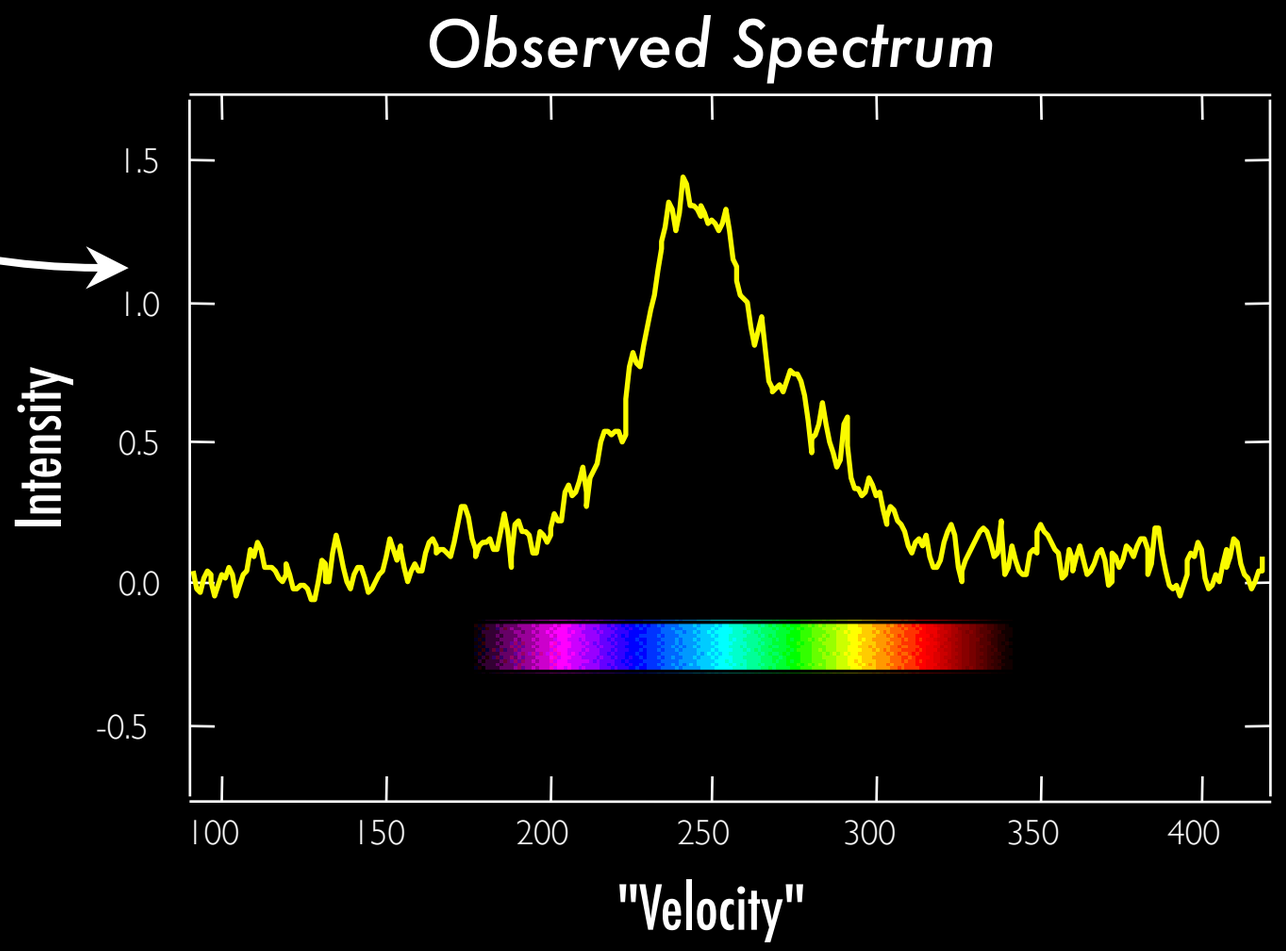


WARNING: schematic diagram, NOT to scale (credit A. Goodman, 2019)

VELOCITY FROM SPECTROSCOPY



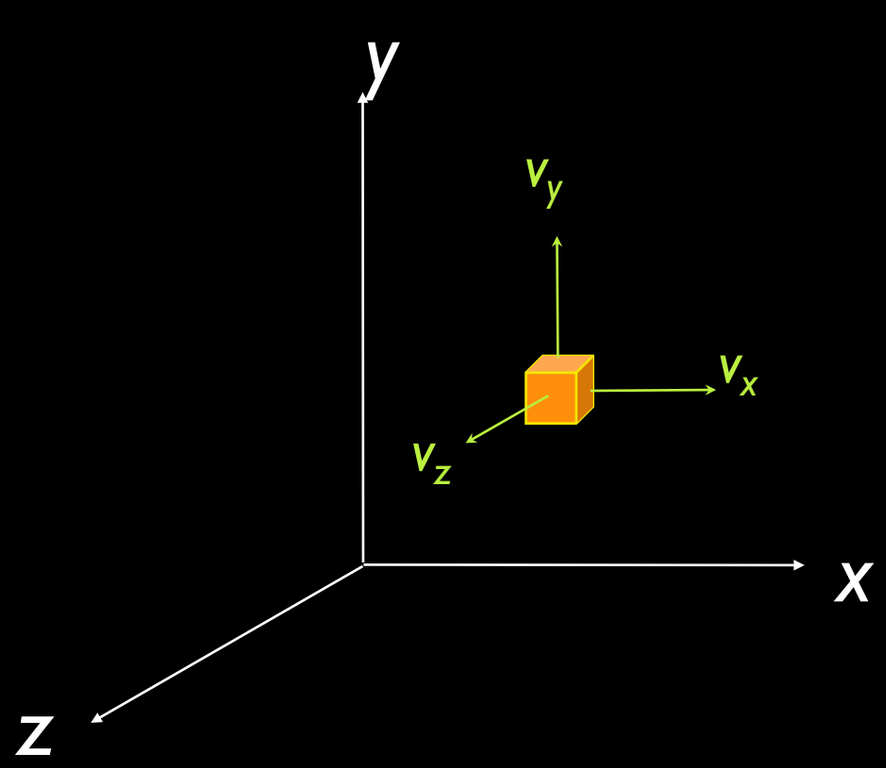
Telescope +
Spectrometer



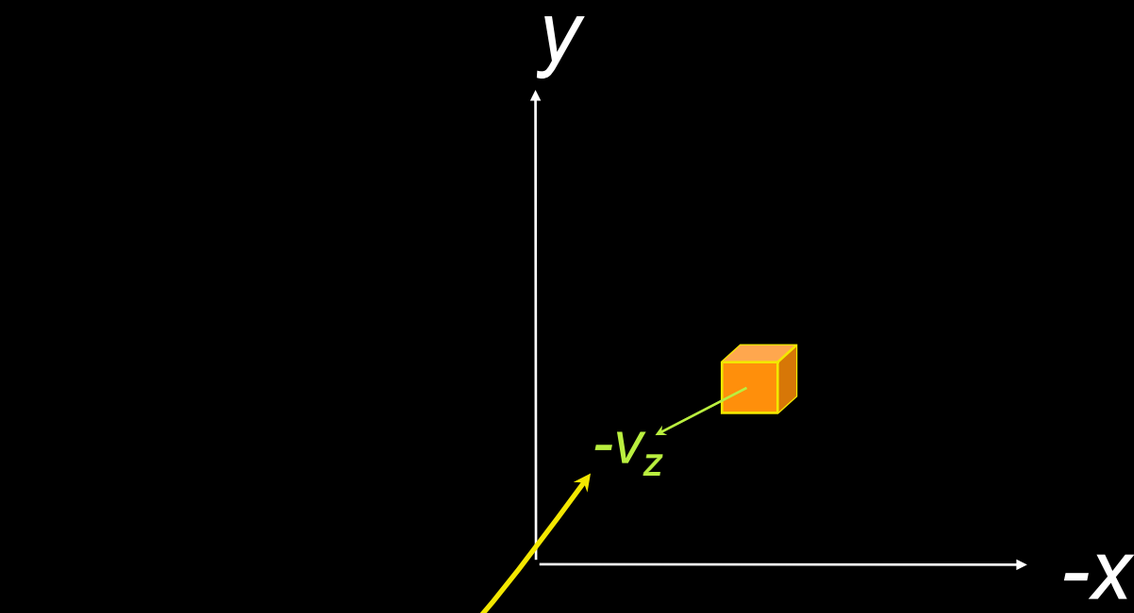
All thanks to Doppler

SPECTRAL-LINE MAPPING

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



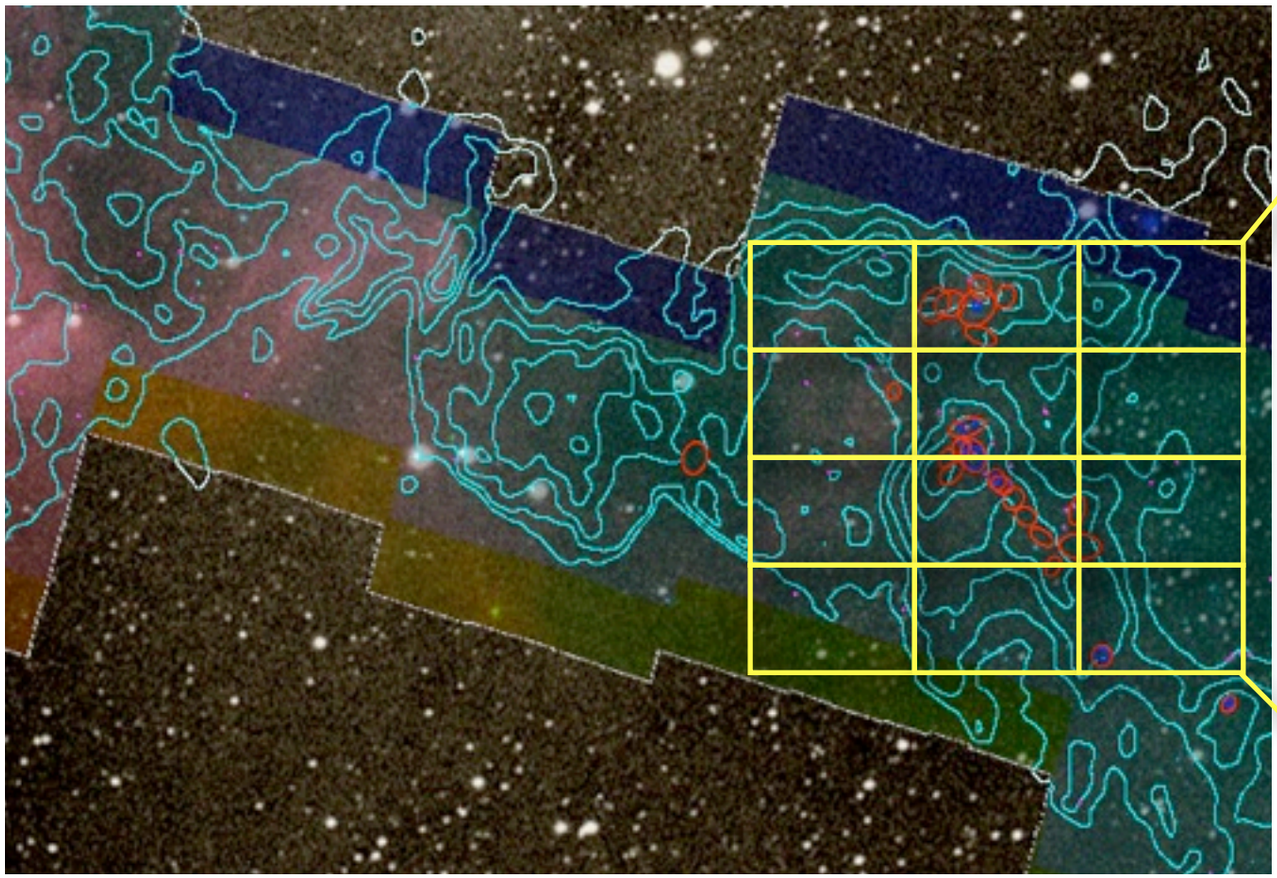
But we <u>can</u> measure...

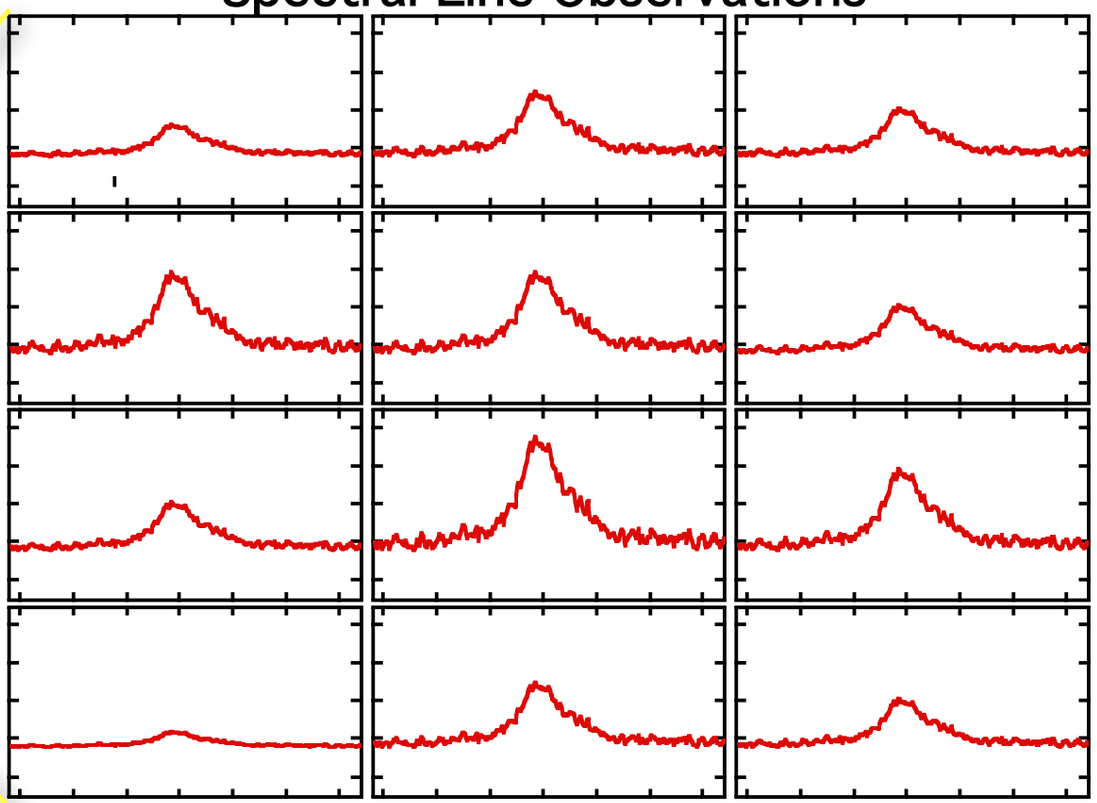


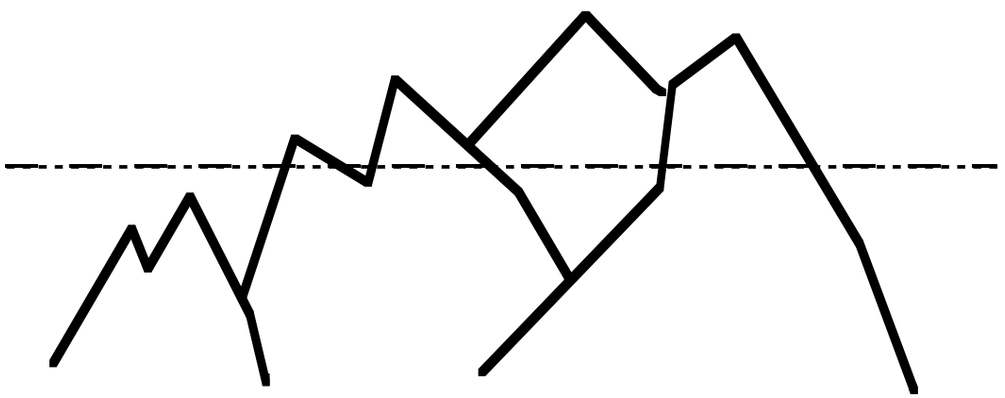
v_z *only* from "spectral-line maps"

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

SEEING IN P-P-V SPACE







Mountain Range

No loss of information

Loss of 1 dimension

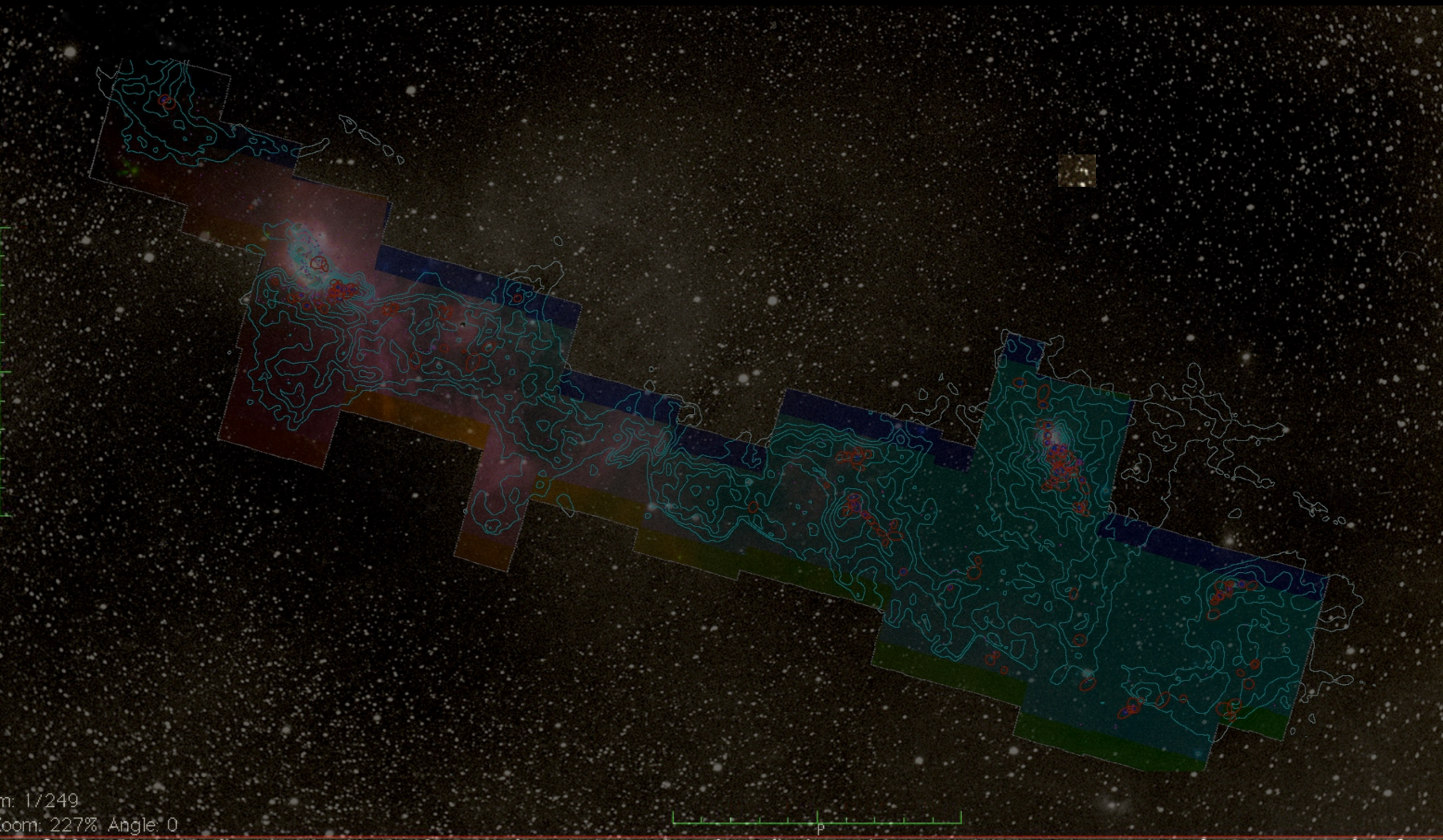
SEEING WIDE DATA IN "3D"

COMPLETE

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

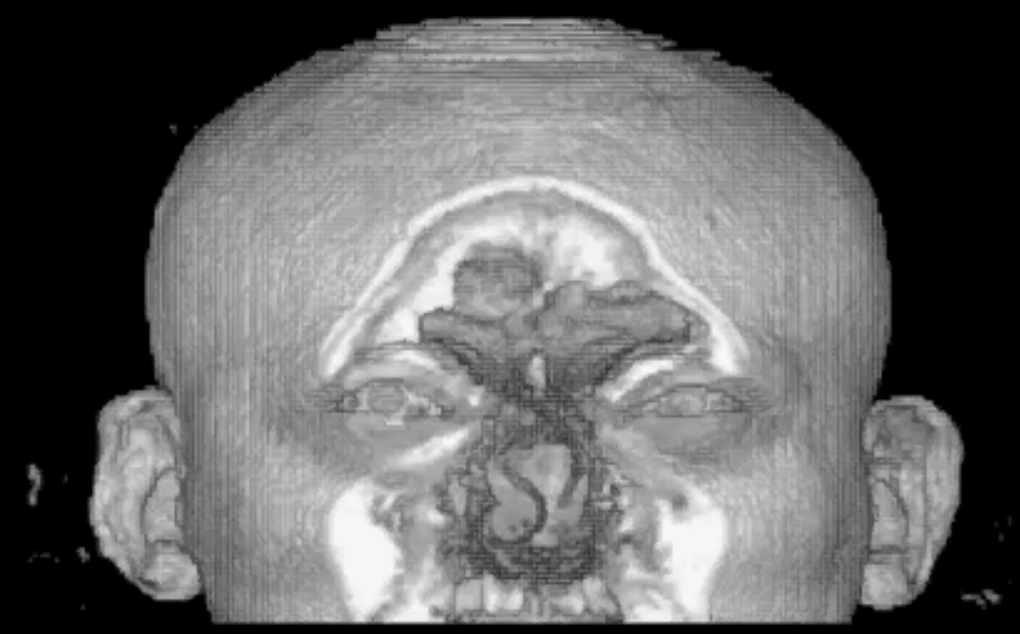
SEEING WIDE DATA IN "3D"

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

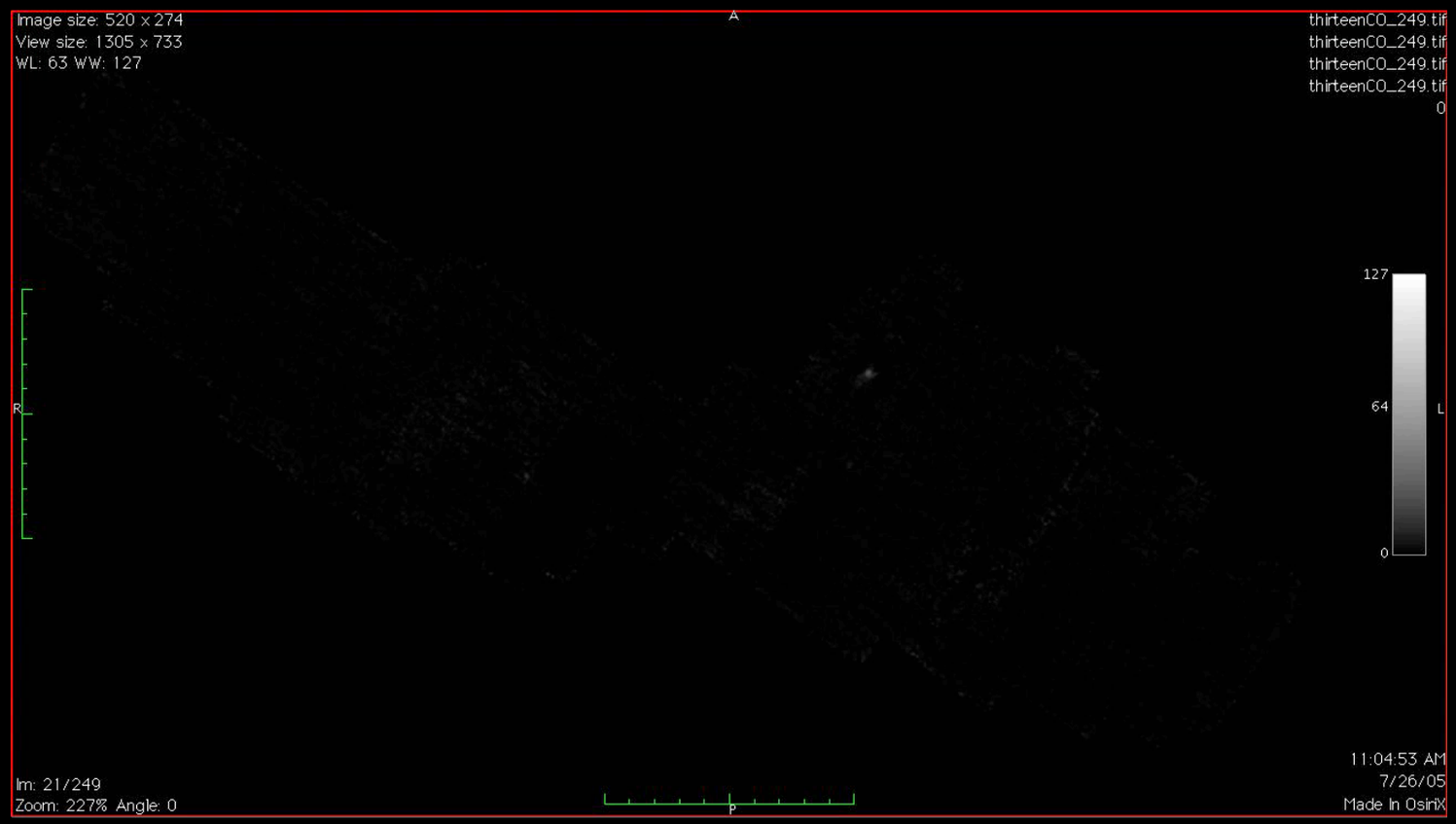


ASTRONOMICAL MEDICINE

"KEITH"



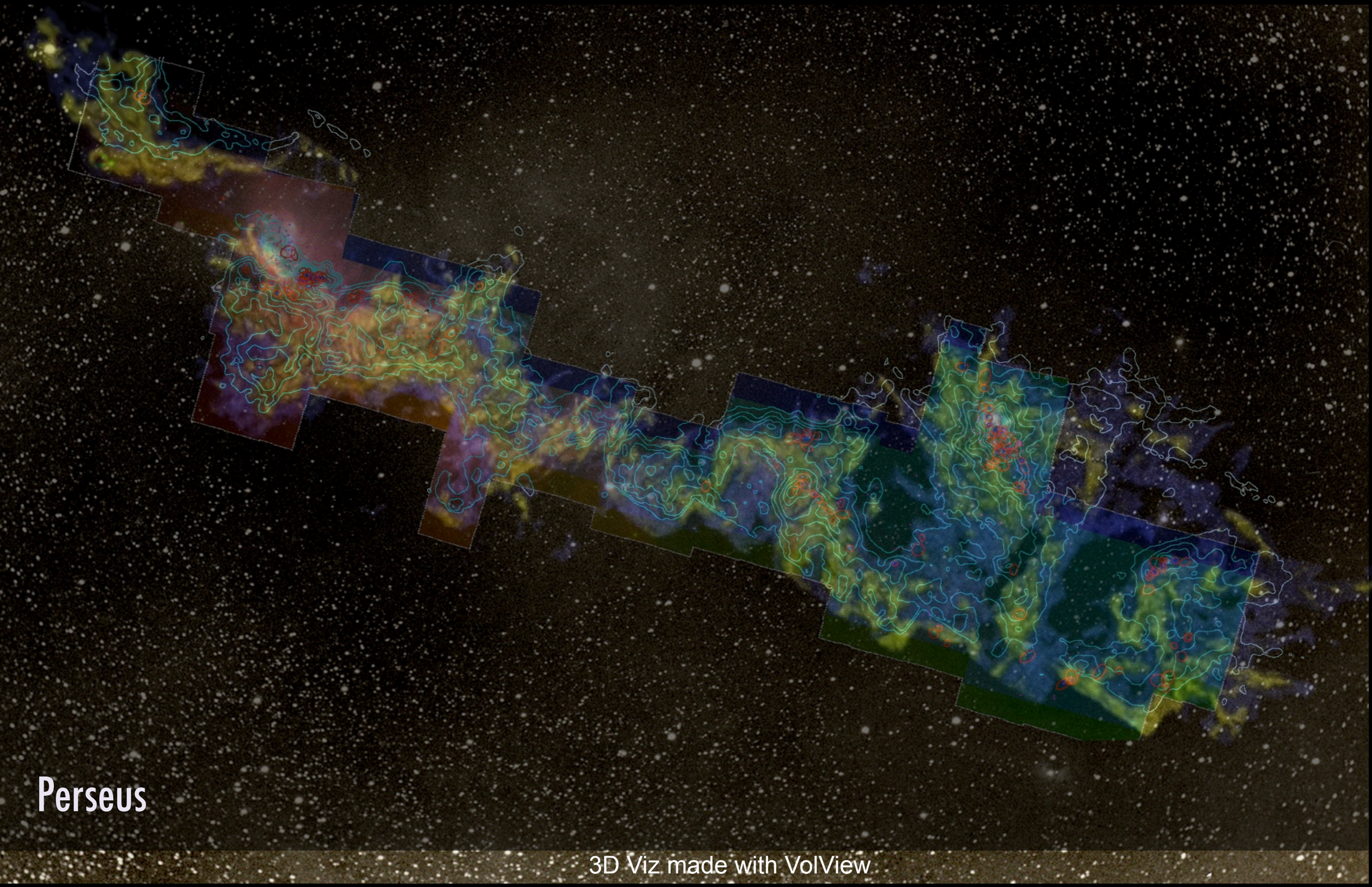
"PERSEUS"



"z" is depth into head

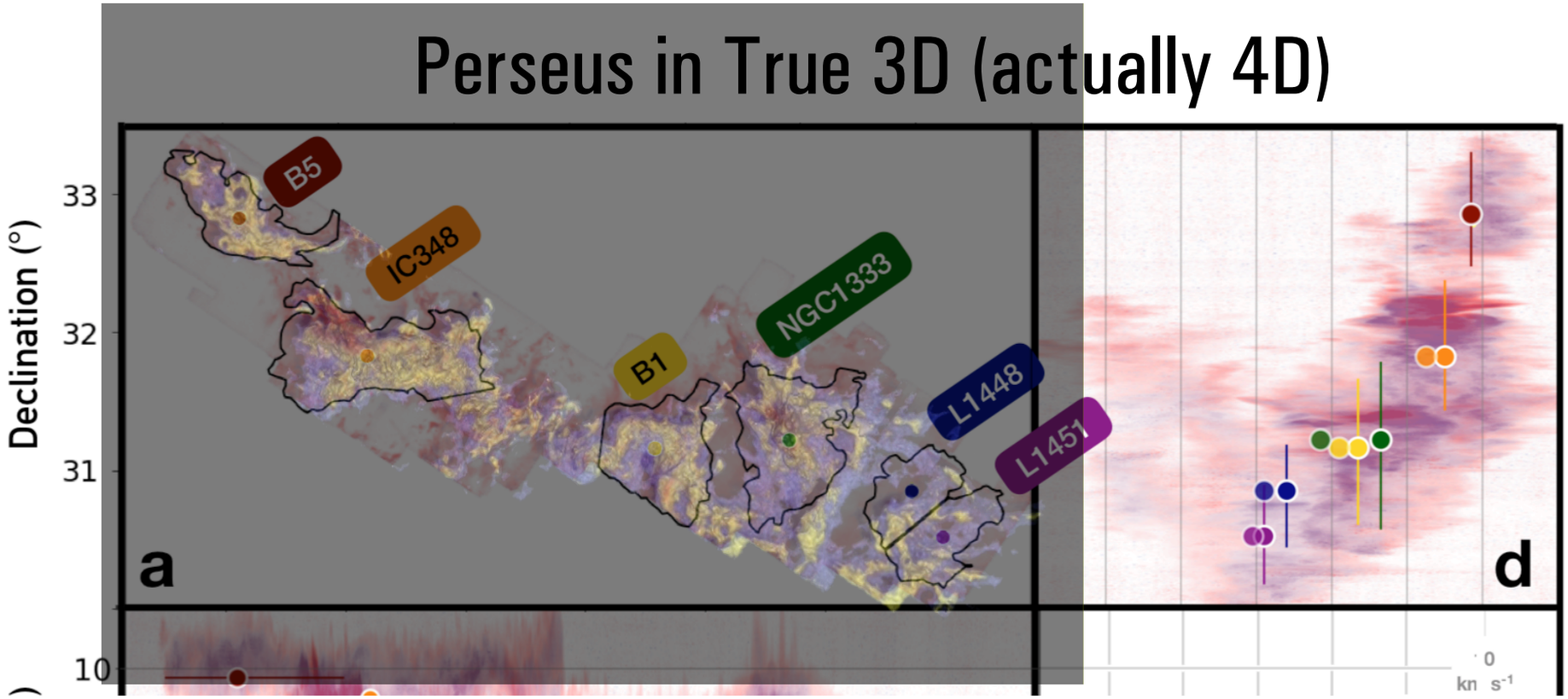
"z" is line-of-sight velocity

"AstroMed" collaborators include Douglas Alan, Chris Beaumont, Michelle Borkin, Jonathan Foster, Michael Halle, Nick Holliman, Jens Kauffmann, Jaime Pineda, Tudor Platon, Erik Rosolowsky, and more

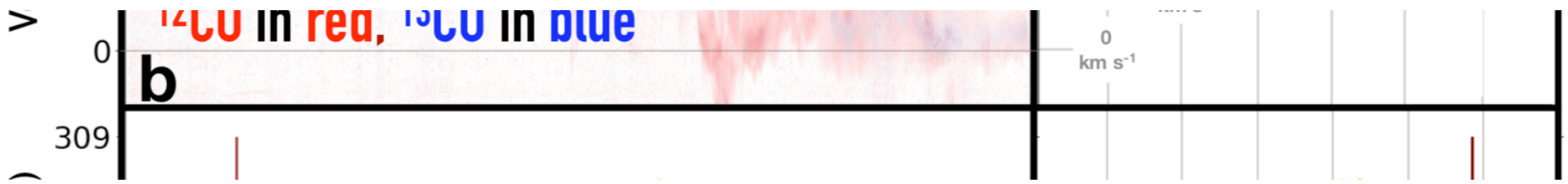


AstronomicalMedicine@IIG

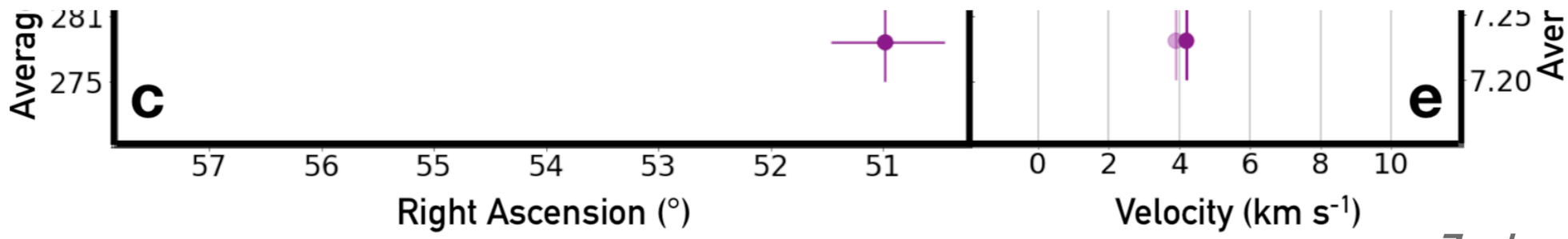
COMPLETE



Velocity is from Spectroscopy



What about actual distance??




Draft version October 18, 2018
Typeset using LaTeX preprint style in AASTeX61

MAPPING DISTANCES ACROSS THE PERSEUS MOLECULAR CLOUD USING CO OBSERVATIONS, STELLAR PHOTOMETRY, AND GAIA DR2 PARALLAX MEASUREMENTS

Catherine Zucker,[1] Edward F. Schlafly,[2] Joshua S. Speagle,[1] Gregory M. Green,[3] Stephen K. N. Portillo,[1] Douglas P. Finkbeiner,[1] and Alyssa A. Goodman[1]

[1]Harvard Astronomy, Harvard-Smithsonian Center for Astrophysics, 60 Garden St., Cambridge, MA 02138, USA
[2]Lawrence Berkeley National Laboratory, One Cyclotron Road, Berkeley, CA 94720, USA
[3]Kavli Institute for Particle Astrophysics and Cosmology, Physics and Astrophysics Building, 452 Lomita Mall, Stanford, CA 94305, USA

Abstract

We present a new technique to determine distances to major star-forming regions across the Perseus Molecular Cloud, using a combination of stellar photometry, astrometric data, and ^{12}CO spectral-line maps. Incorporating the Gaia DR2 parallax measurements when available, we start by inferring the distance and reddening to stars from their Pan-STARRS1 and 2MASS photometry, based on a technique presented in Green et al. (2014, 2015) and implemented in their 3D "Bayestar" dust map of three-quarters of the sky. We then refine the Green et al. technique by using the velocity slices of a CO spectral cube as dust templates and modeling the cumulative distribution of dust along the line of sight towards these stars as a linear combination of the emission in the slices. Using a nested sampling algorithm, we fit these per-star distance-reddening measurements to find the distances to the CO velocity slices towards each star-forming region. This results in distance estimates explicitly tied to the velocity structure of the molecular gas. We determine distances to the B5, IC348, B1, NGC1333, L1448, and L1451 star-forming regions and find that individual clouds are located between $\approx 275 - 300$ pc, with typical combined uncertainties of $\approx 5\%$. We find that the velocity gradient across Perseus corresponds to a distance gradient of about 25 pc, with the eastern portion of the cloud farther away than the western portion. We determine an average distance to the complex of 294 $\pm$ 17 pc, about 60 pc higher than the distance derived to the western portion of the cloud using parallax measurements of water masers associated with young stellar objects. The method we present is not limited to the Perseus Complex, but may be applied anywhere on the sky with adequate CO data in the pursuit of more accurate 3D maps of molecular clouds in the solar neighborhood and beyond.

Zucker et al. 2018

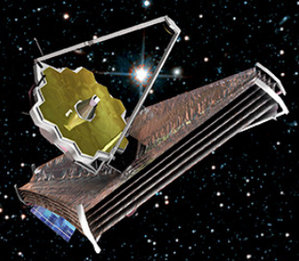
→ ESA'S FLEET ACROSS THE SPECTRUM

esa

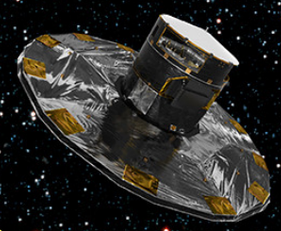
Thanks to cutting edge technology, astronomy is unveiling a new world around us. With ESA's fleet of spacecraft, we can explore the full spectrum of light and probe the fundamental physics that underlies our entire Universe. From cool and dusty star formation revealed only at infrared wavelengths, to hot and violent high-energy phenomena, ESA missions are charting our cosmos and even looking back to the dawn of time to discover more about our place in space.

herschel
Unveiling the cool and dusty Universe

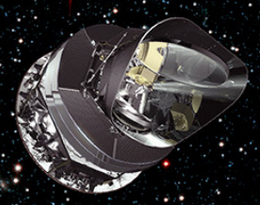
jwst
Observing the first light



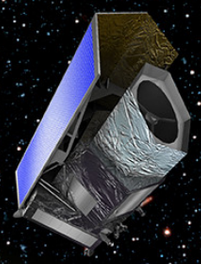
gaia
Surveying a billion stars



planck
Looking back at the dawn of time



euclid
Probing dark matter, dark energy and the expanding Universe



hst
Expanding the frontiers of the visible Universe

xmm-newton
Seeing deeply into the hot and violent Universe

lisa pathfinder
Testing the technology for gravitational wave detection

"In Color"

microwaves
sub-millimetre
infrared
optical
ultraviolet
x-rays
gamma rays

integral
Seeking out the extremes of the Universe

www.esa.int

European Space Agency

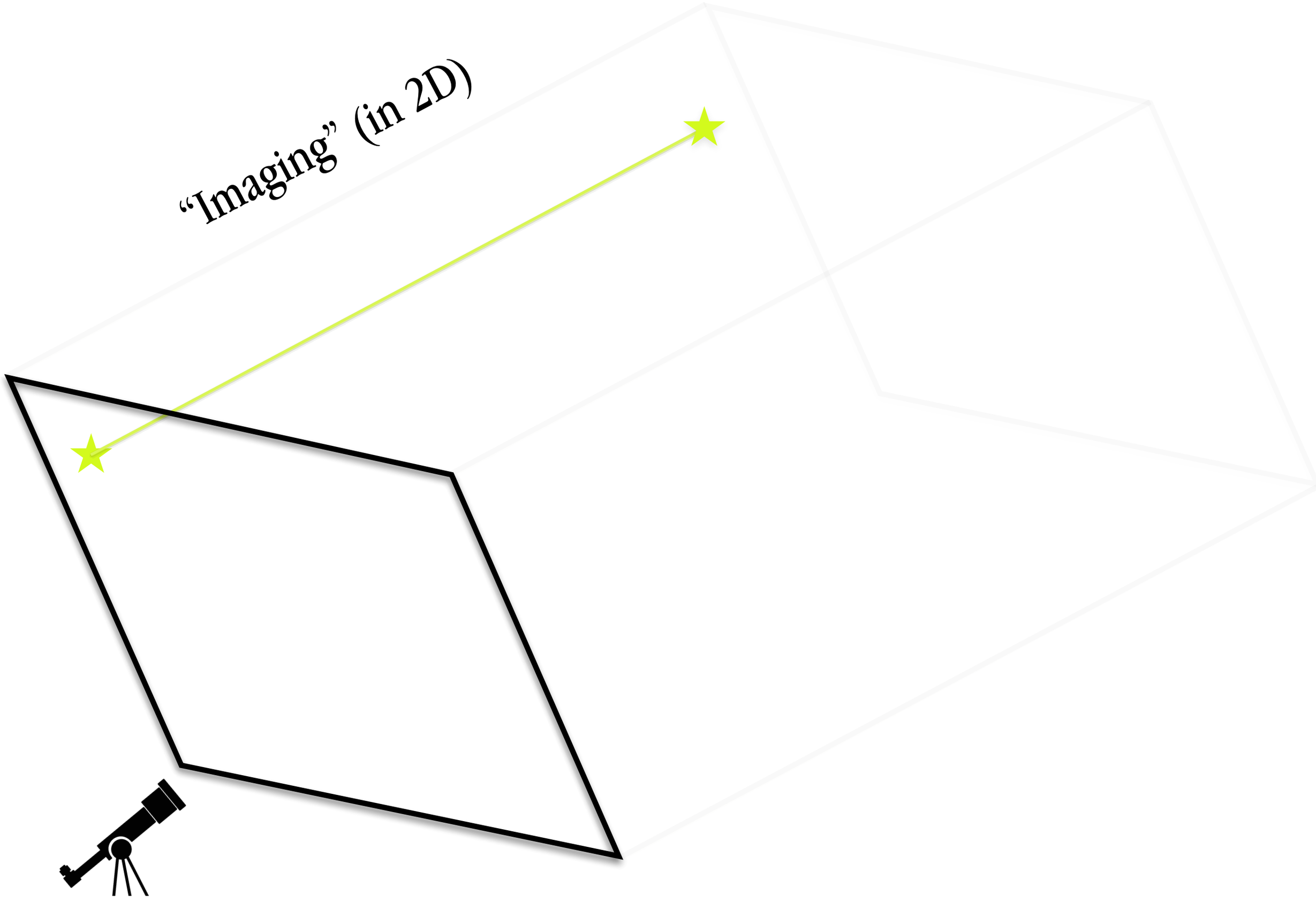
Stars in 3D

"Radial Velocity"

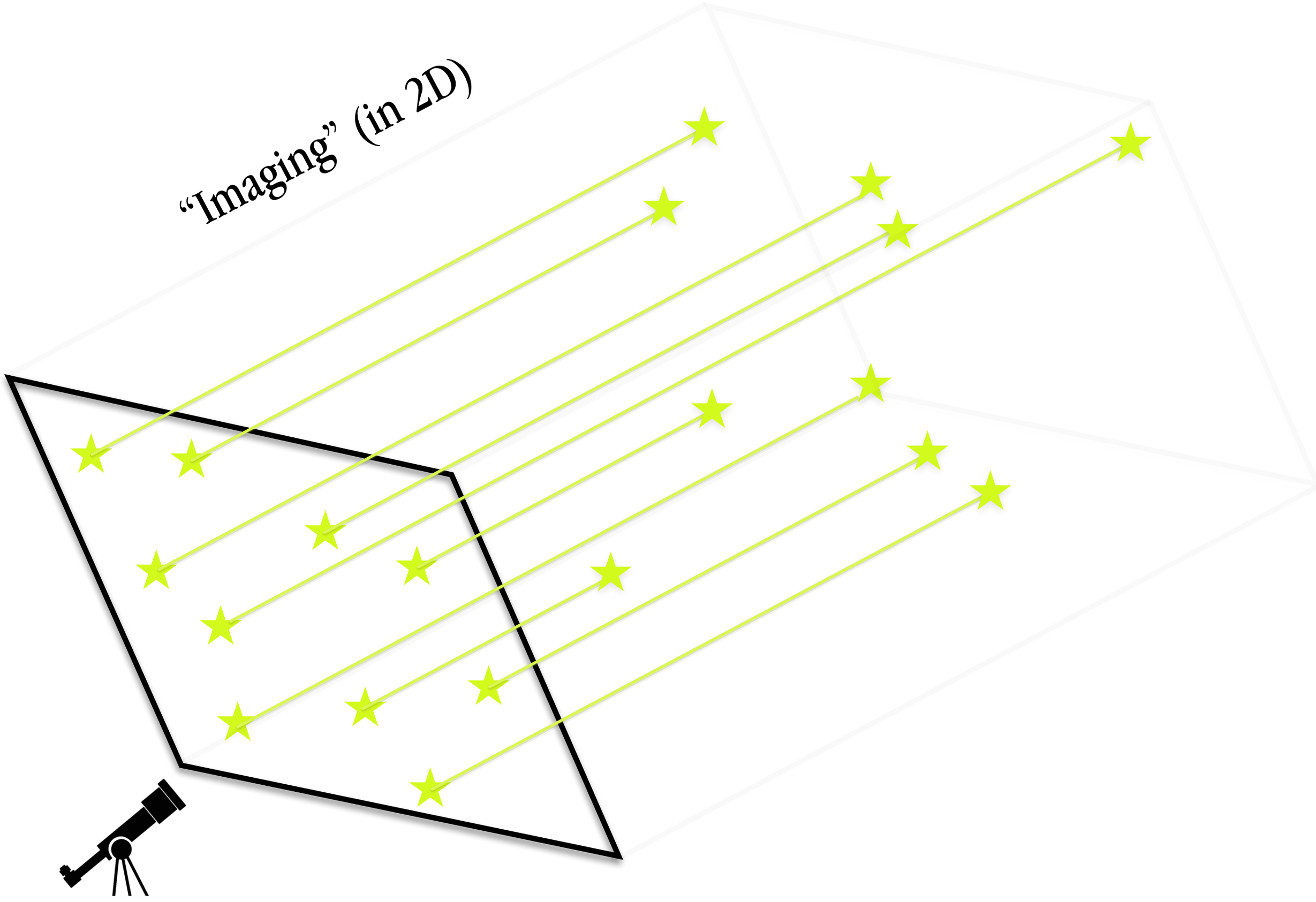
&

"Proper Motion"

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

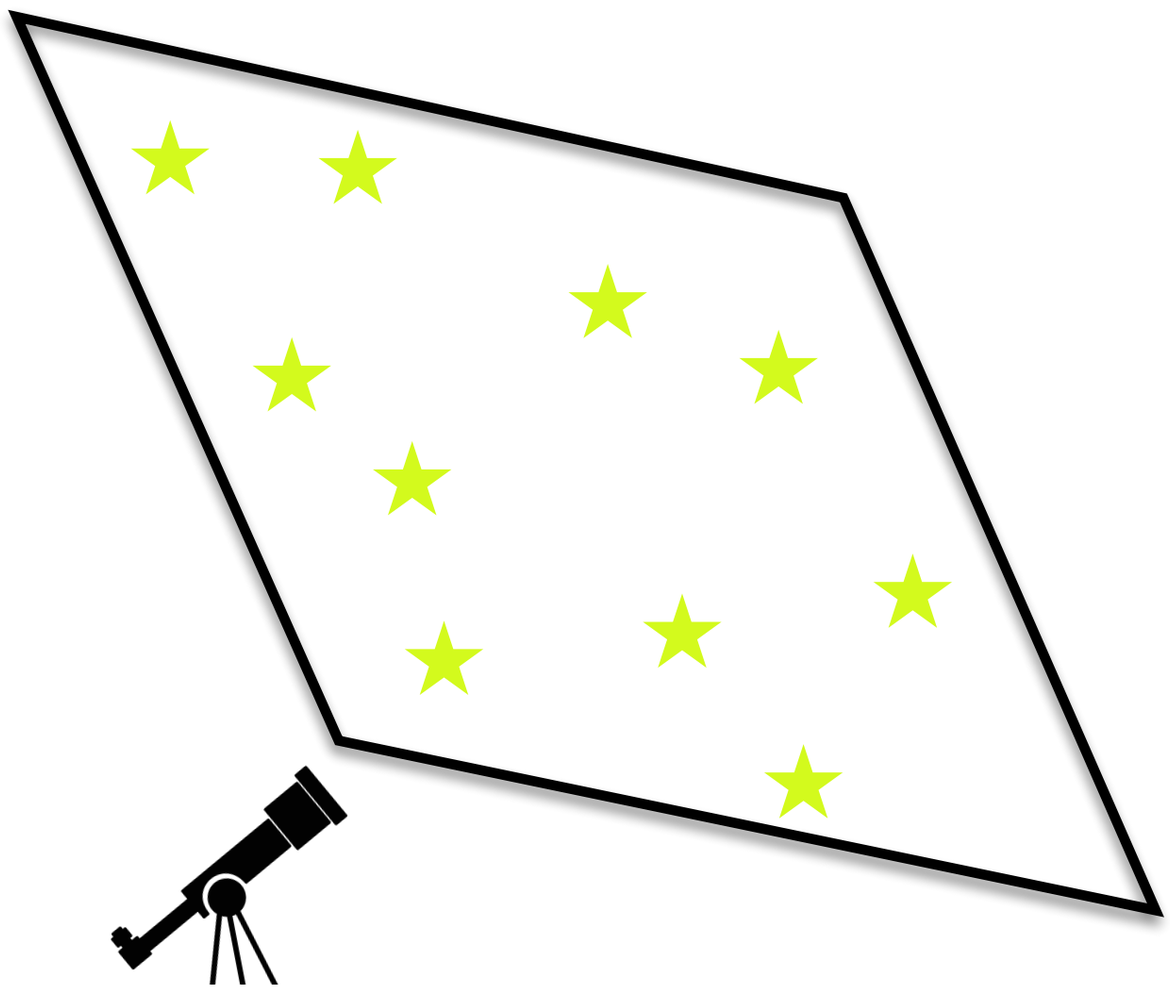


WARNING: schematic diagram, NOT to scale (credit A. Goodman, 2019)

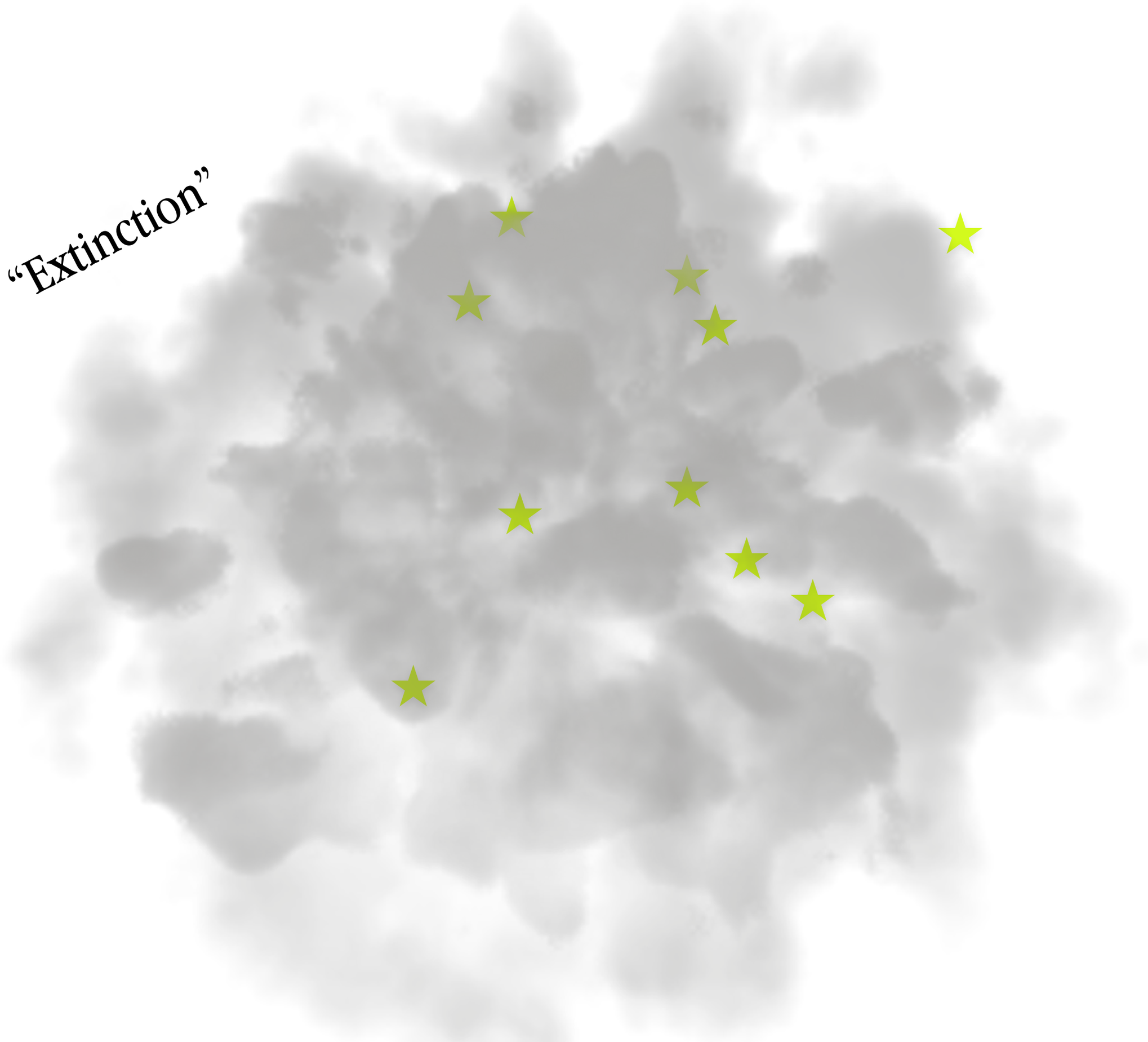


WARNING: schematic diagram, NOT to scale (credit A. Goodman, 2019)

"Imaging" (in 2D)



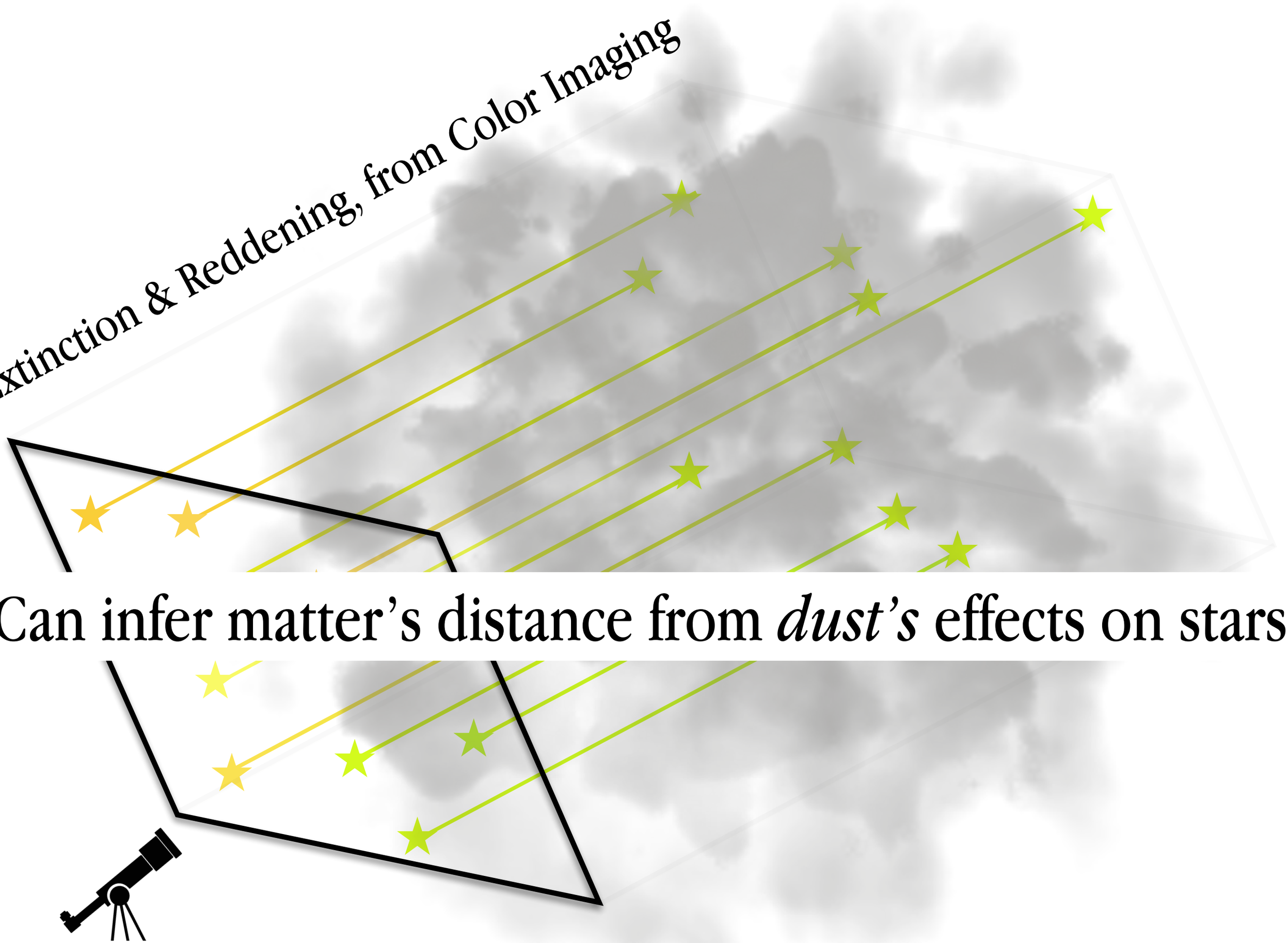
WARNING: schematic diagram, NOT to scale (credit A. Goodman, 2019)



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

“Reddening”

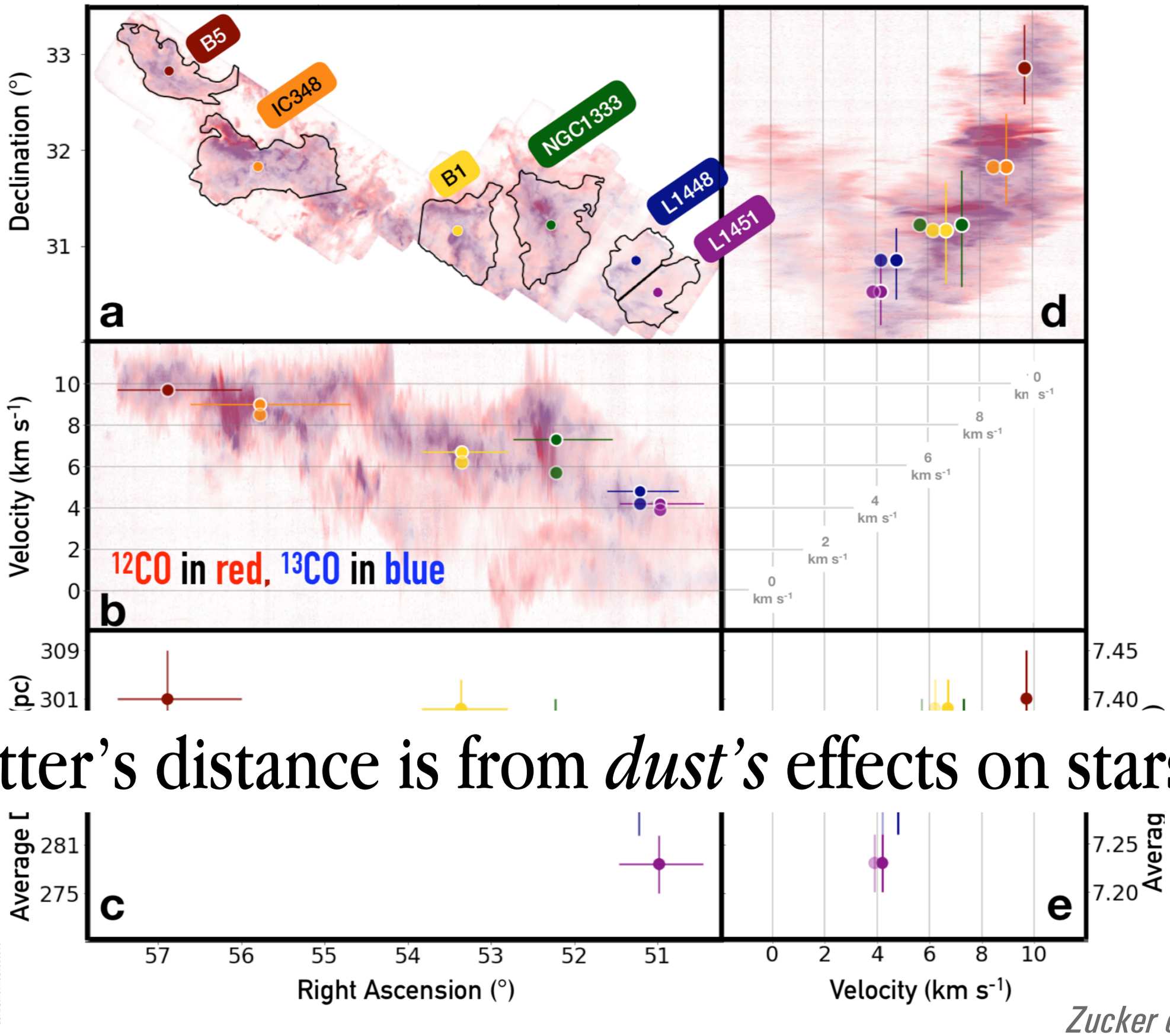
Extinction & Reddening, from Color Imaging



Can infer matter's distance from *dust's* effects on stars

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

Perseus in True 3D (actually 4D)



Matter's distance is from *dust's* effects on stars.

Draft version October 18, 2018
Typeset using LaTeX **preprint** style in AASTeX61

arXiv:1805.09931v2 [astro-ph.GA] 17 Oct 2018

MAPPING DISTANCES ACROSS THE PERSEUS MOLECULAR CLOUD USING CO OBSERVATIONS, STELLAR PHOTOMETRY, AND GAIA DR2 PARALLAX MEASUREMENTS

Catherine Zucker,[1] Edward F. Schlafly,[2] Joshua S. Speagle,[1] Gregory M. Green,[3] Stephen K. N. Portillo,[1] Douglas P. Finkbeiner,[1] and Alyssa A. Goodman[1]

[1]*Harvard Astronomy, Harvard-Smithsonian Center for Astrophysics, 60 Garden St., Cambridge, MA 02138, USA*
[2]*Lawrence Berkeley National Laboratory, One Cyclotron Road, Berkeley, CA 94720, USA*
[3]*Kavli Institute for Particle Astrophysics and Cosmology, Physics and Astrophysics Building, 452 Lomita Mall, Stanford, CA 94305, USA*

Abstract

We present a new technique to determine distances to molecular star-forming regions across the Perseus Molecular Cloud, using a combination of stellar photometry, astrometric data, and ^{12}CO spectral-line maps. Incorporating the Gaia DR2 parallax measurements when available, we start by inferring the distance and reddening to stars from their Pan-STARRS1 and 2MASS photometry, based on a technique presented in Green et al. (2014, 2015) and implemented in their 3D "Bayestar" dust map of three-quarters of the sky. We then refine the Green et al. technique by using the velocity slices of a CO spectral cube as dust templates and modeling the cumulative distribution of dust along the line of sight towards these stars as a linear combination of the emission in the slices. Using a nested sampling algorithm, we fit these per-star distance-reddening measurements to find the distances to the CO velocity slices towards each star-forming region. This results in distance estimates explicitly tied to the velocity structure of the molecular gas. We determine distances to the B5, IC348, B1, NGC1333, L1448, and L1451 star-forming regions and find that individual clouds are located between $\approx 275 - 300$ pc, with typical combined uncertainties of $\approx 5\%$. We find that the velocity gradient across Perseus corresponds to a distance gradient of about 25 pc, with the eastern portion of the cloud farther away than the western portion. We determine an average distance to the complex of 294 $\pm$ 17 pc, about 60 pc higher than the distance derived to the western portion of the cloud using parallax measurements of water masers associated with young stellar objects. The method we present is not limited to the Perseus Complex, but may be applied anywhere on the sky with adequate CO data in the pursuit of more accurate 3D maps of molecular clouds in the solar neighborhood and beyond.

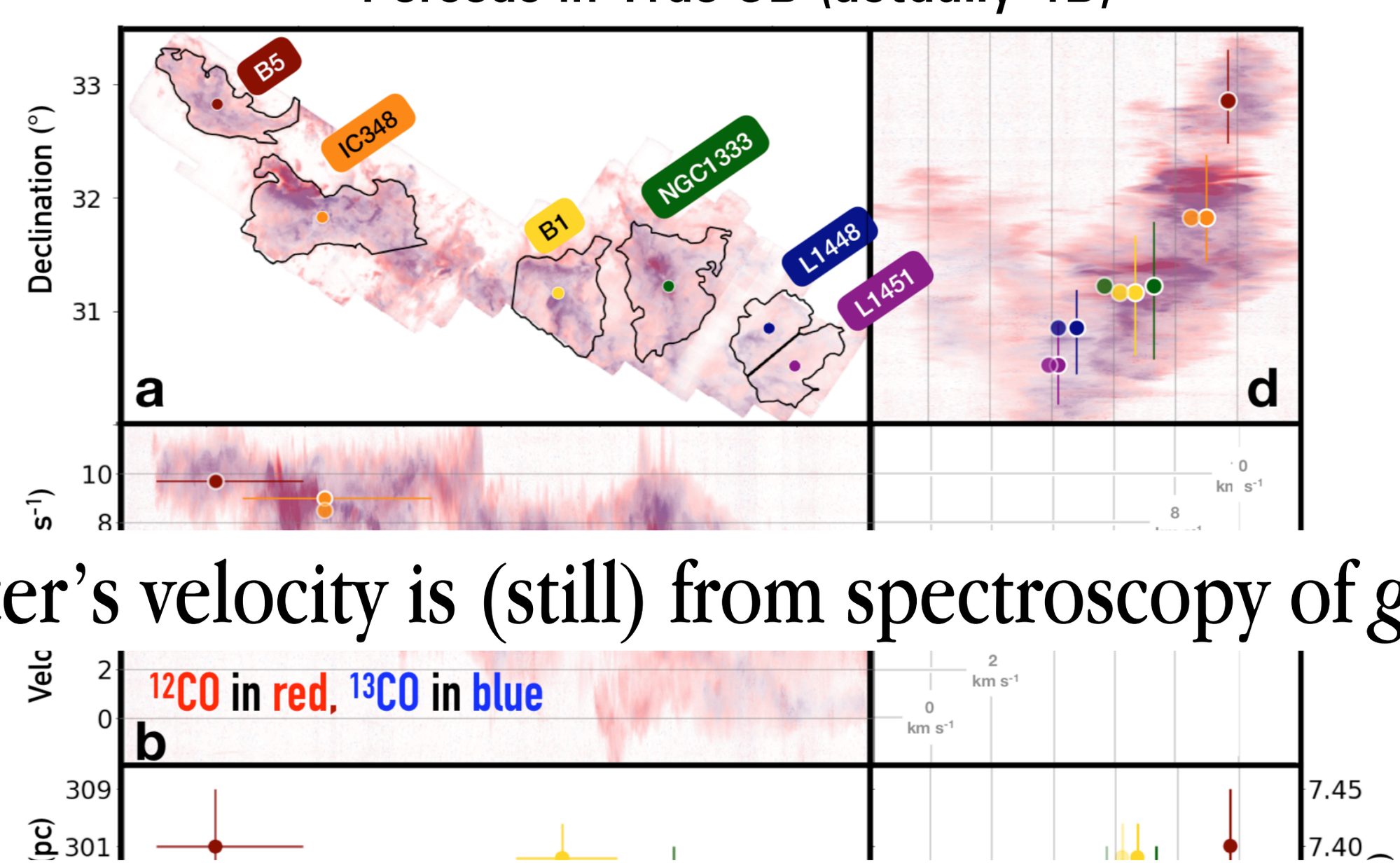
Zucker et al. 2018

Mapping Interstellar Matter in 3D

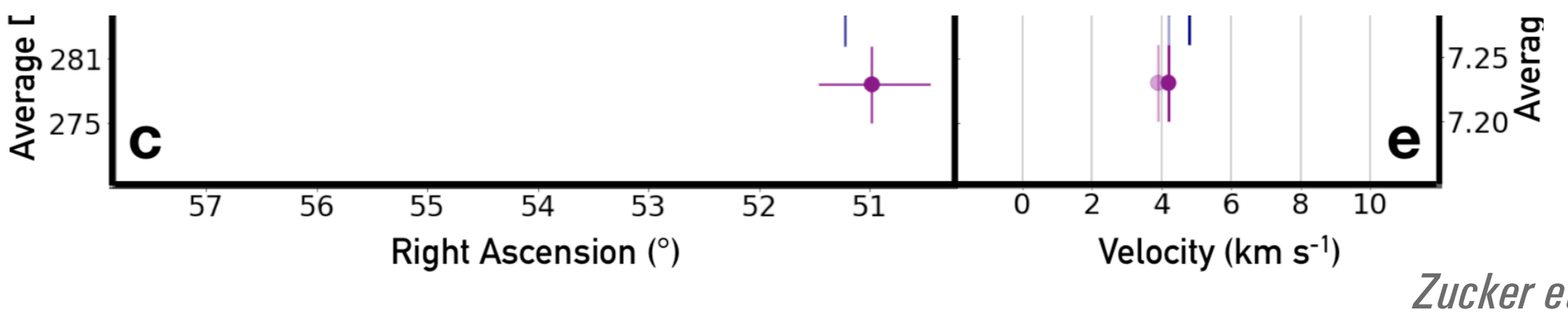
WARNING: schematic diagram, NOT to scale (credit A. Goodman, 2019)

Perseus in True 3D (actually 4D)

Matter's velocity is (still) from spectroscopy of *gas*.



Matter's distance is from *dust's* effects on stars.



arXiv:1803.08931v2 [astro-ph.GA] 17 Oct 2018

Draft version October 18, 2018
Typeset using LaTeX preprint style in AASTeX61

MAPPING DISTANCES ACROSS THE PERSEUS MOLECULAR CLOUD USING CO OBSERVATIONS, STELLAR PHOTOMETRY, AND GAIA DR2 PARALLAX MEASUREMENTS

Catherine Zucker,[1] Edward F. Schlafly,[2] Joshua S. Speagle,[3] Gregory M. Green,[4] Stephen K. N. Portillo,[1] Douglas P. Finkbeiner,[1] and Alyssa A. Goodman[1]

[1]Harvard Astronomy, Harvard-Smithsonian Center for Astrophysics, 60 Garden St., Cambridge, MA 02138, USA
[2]Lawrence Berkeley National Laboratory, One Cyclotron Road, Berkeley, CA 94720, USA
[3]Department for Particle Astrophysics and Cosmology, Physics and Astrophysics Building, 452 Lomita Mall, Stanford, CA 94305, USA

Abstract

We present a new technique to determine distances to major star-forming regions across the Perseus Molecular Cloud, using a combination of stellar photometry, astrometric data, and ^{12}CO spectral-line maps. Incorporating the Gaia DR2 parallax measurements when available, we start by inferring the distance and reddening to stars from their Pan-STARRS1 and 2MASS photometry, based on a technique presented in Green et al. (2015, 2015) and implemented in their 3D "Bayestar" dust map of three-quarters of the sky. We then refine the Green et al. technique by using the velocity slices of a CO spectral cube as dust templates and modeling the cumulative distribution of dust along the line of sight towards these stars as a linear combination of the emission in the slices. Using a nested sampling algorithm, we fit these per-star distance-reddening measurements to find the distances to the CO velocity slices towards each star-forming region. This results in distance estimates explicitly tied to the velocity structure of the molecular gas. We determine distances to the B5, IC348, B1, NGC1333, L1448, and L1451 star-forming regions and find that individual clouds are located between $\approx 275 - 300$ pc, with typical combined uncertainties of $\approx 5\%$. We find that the velocity gradient across Perseus corresponds to a distance gradient of about 25 pc, with the eastern portion of the cloud farther away than the western portion. We determine an average distance to the complex of 294 ± 17 pc, about 60 pc higher than the distance derived to the western portion of the cloud using parallax measurements of water masers associated with young stellar objects. The method we present is not limited to the Perseus Complex, but may be applied anywhere on the sky with adequate CO data in the pursuit of more accurate 3D maps of molecular clouds in the solar neighborhood and beyond.

Zucker et al. 2018

How we did this.

Draft version October 18, 2018
Typeset using LaTeX **preprint** style in AASTeX61

MAPPING DISTANCES ACROSS THE PERSEUS MOLECULAR CLOUD USING CO OBSERVATIONS, STELLAR PHOTOMETRY, AND GAIA DR2 PARALLAX MEASUREMENTS

Catherine Zucker,[1] Edward F. Schlafly,[2] Joshua S. Speagle,[1] Gregory M. Green,[3] Stephen K. N. Portillo,[1] Douglas P. Finkbeiner,[1] and Alyssa A. Goodman[1]

[1]*Harvard Astronomy, Harvard-Smithsonian Center for Astrophysics, 60 Garden St., Cambridge, MA 02138, USA*
[2]*Lawrence Berkeley National Laboratory, One Cyclotron Road, Berkeley, CA 94720, USA*
[3]*Kavli Institute for Particle Astrophysics and Cosmology, Physics and Astrophysics Building, 452 Lomita Mall, Stanford, CA 94305, USA*

Abstract

We present a new technique to determine distances to major star-forming regions across the Perseus Molecular Cloud, using a combination of stellar photometry, astrometric data, and ^{12}CO spectral-line maps. Incorporating the Gaia DR2 parallax measurements when available, we start by inferring the distance and reddening to stars from their Pan-STARRS1 and 2MASS photometry, based on a technique presented in Green et al. (2014, 2015) and implemented in their 3D "Bayestar" dust map

Draft version February 6, 2019
Typeset using LaTeX default style in AASTeX62

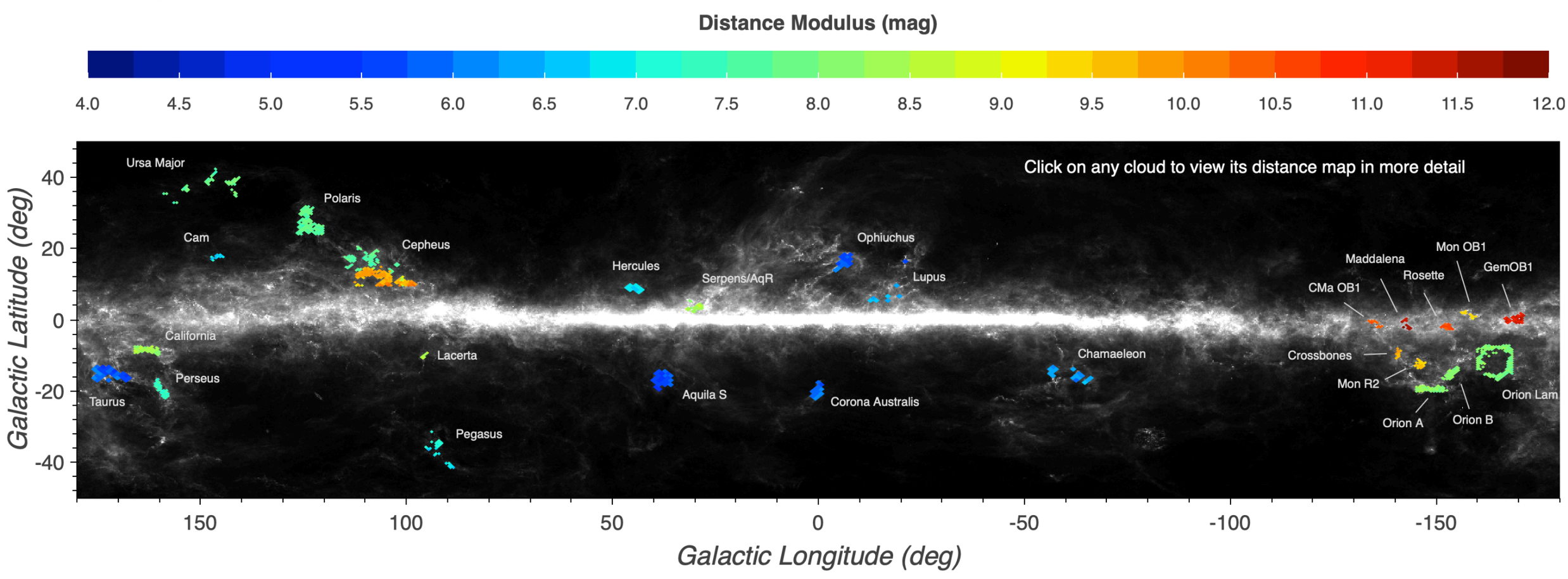
A Large Catalog of Accurate Distances to Local Molecular Clouds: The Gaia DR2 Edition

Catherine Zucker,[1,*] Joshua S. Speagle,[1,*] Edward F. Schlafly,[2] Gregory M. Green,[3] Douglas P. Finkbeiner,[1] Alyssa A. Goodman,[1,4] and João Alves[4,5]

[1]*Harvard Astronomy, Harvard-Smithsonian Center for Astrophysics, 60 Garden St., Cambridge, MA 02138, USA*
[2]*Lawrence Berkeley National Laboratory, One Cyclotron Road, Berkeley, CA 94720, USA*
[3]*Kavli Institute for Particle Astrophysics and Cosmology, Physics and Astrophysics Building, 452 Lomita Mall, Stanford, CA 94305, USA*
[4]*Radcliffe Institute for Advanced Study, Harvard University, 10 Garden St, Cambridge, MA 02138*
[5]*University of Vienna, Department of Astrophysics, Türkenschanzstraße 17, 1180 Vienna, Austria*

ABSTRACT

We present a uniform catalog of accurate distances to local molecular clouds informed by the Gaia DR2 data release. Our methodology builds on that of Schlafly et al. (2014). First, we infer the distance and extinction to stars along sightlines towards the clouds using optical and near-infrared photometry. When available, we incorporate knowledge of the stellar distances obtained from Gaia DR2 parallax measurements. We model these per-star distance-extinction estimates as being caused by a dust screen with a 2-D morphology derived from Planck at an unknown distance, which we then fit for using a nested sampling algorithm. We provide updated distances to the Schlafly et al. (2014) sightlines towards the Dame et al. (2001) and Magnani et al. (1985) clouds, finding good agreement with the earlier work. For a subset of 27 clouds, we construct interactive pixelated distance maps to further study detailed cloud structure, and find several clouds which display clear distance gradients and/or



The end of the story, again.

Draft version February 6, 2019
Typeset using LaTeX default style in AASTeX62

A Large Catalog of Accurate Distances to Local Molecular Clouds: The Gaia DR2 Edition

Catherine Zucker,[1,*] Joshua S. Speagle,[1,*] Edward F. Schlafly,[2] Gregory M. Green,[3] Douglas P. Finkbeiner,[1] Alyssa A. Goodman,[1,4] and João Alves[2,5]

[1] *Harvard Astronomy, Harvard-Smithsonian Center for Astrophysics, 60 Garden St., Cambridge, MA 02138, USA*
[2] *Lawrence Berkeley National Laboratory, One Cyclotron Road, Berkeley, CA 94720, USA*
[3] *Kavli Institute for Particle Astrophysics and Cosmology, Physics and Astrophysics Building, 452 Lomita Mall, Stanford, CA 94305, USA*
[4] *Radcliffe Institute for Advanced Study, Harvard University, 10 Garden St, Cambridge, MA 02138*
[5] *University of Vienna, Department of Astrophysics, Türkenschanzstraße 17, 1180 Vienna, Austria*

ABSTRACT

We present a uniform catalog of accurate distances to local molecular clouds informed by the Gaia DR2 data release. Our methodology builds on that of Schlafly et al. (2014). First, we infer the distance and extinction to stars along sightlines towards the clouds using optical and near-infrared photometry. When available, we incorporate knowledge of the stellar distances obtained from Gaia DR2 parallax measurements. We model these per-star distance-extinction estimates as being caused by a dust screen with a 2-D morphology derived from Planck at an unknown distance, which we then fit for using a nested sampling algorithm. We provide updated distances to the Schlafly et al. (2014) sightlines towards the Dame et al. (2001) and Magnani et al. (1985) clouds, finding good agreement with the earlier work. For a subset of 27 clouds, we construct interactive pixelated distance maps to further study detailed cloud structure, and find several clouds which display clear distance gradients and/or are comprised of multiple components. We use these maps to determine robust average distances to these clouds. The characteristic combined uncertainty on our distances is $\approx 5-6\%$, though this can be higher for clouds at farther distances, due to the limitations of our single-cloud model.

Keywords: ISM: clouds, ISM: dust, extinction, stars: distances, methods: statistical

Mapping the Milky Way, from the Inside Out, in Color

The Milky Way
(Artist's Conception)

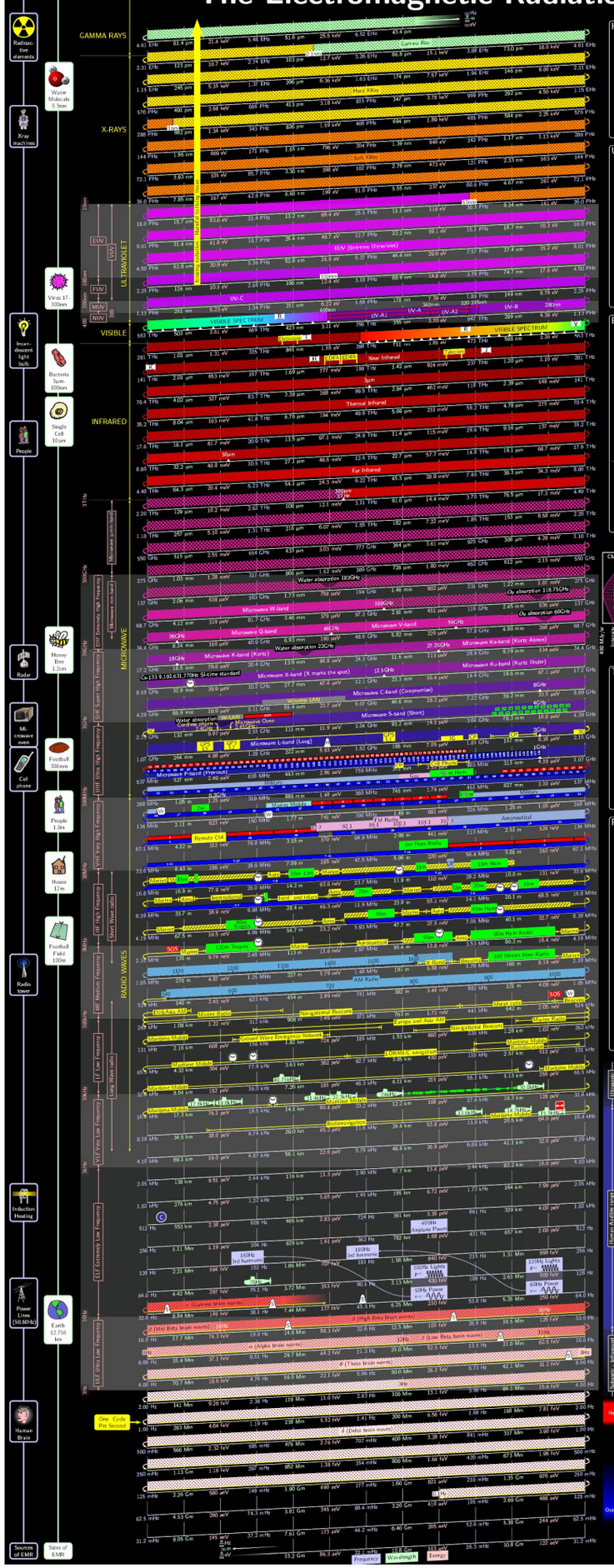
z=0.00

Formation of a Milky-Way-like Galaxy (Stars)

http://www.tapir.caltech.edu/~phopkins/Site/Movies_cosmo.html

Future of the Milky Way
(Collision with Andromeda)

The Electromagnetic Radiation Spectrum



How to read this chart

- This chart is organized in octaves (frequency doubling/halving) starting at 1Hz and going higher (2,4,8, etc) and lower (1/2, 1/4, etc). The octave is a natural way to represent frequency.
- Frequency increases on the vertical scale in the upward direction.
- The horizontal bars wrap around from far right to far left as the frequency increases upwards.
- There is no limit to either end of this chart, however, due to limited space, only the "known" items have been shown here. A frequency of 0Hz is the lowest possible frequency but the method of depicting octaves used here does not allow for ever reaching 0Hz, only approaching it. Also, by the definition of frequency (Cycles per second), there is no such thing as negative frequency.
- Values on the chart have been labelled with the following colours. Frequency measured in Hertz, Wavelength measured in meters, Energy measured in electronVolts

Ultraviolet Light

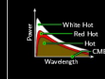
- Ultraviolet light is beyond the range of human vision.
- Physicists have divided ultraviolet light ranges into Vacuum Ultraviolet (VUV), Extreme Ultraviolet (EUV), Far Ultraviolet (FUV), Medium Ultraviolet (MUV), and Near Ultraviolet (NUV)
- UV-A, UV-B and UV-C were introduced in the 1930's by the Commission Internationale de l'Eclairage (CIE, International Commission on Illumination) for photobiological spectral bands.
- Short-term UV-A exposure causes sun-tanning which helps to protect against sunburn. Exposure to UV-B is beneficial to humans by helping the skin produce vitamin D. Excessive UV exposure causes skin damage. UV-C is harmful to humans but is used as a germicide.
- The CIE originally divided UVA and UVB at 315nm, later some photo-dermatologists divided it at 320nm.
- UVA is subdivided into UVA1 and UVA2 for DNA altering effects at 340nm.
- The sun produces a wide range of frequencies including all the ultraviolet light, however, UVB is partially filtered by the ozone layer and UVC is totally filtered out by the earth's atmosphere.
- A bumblebee can see light in the UVA range which helps them identify certain flowers.

Emission and Absorption

- As EMR passes through elements, certain wavelength bands get absorbed and some new ones get emitted. This absorption and emission produces characteristic spectral lines for each element which are useful in determining the makeup of distant stars. These lines are used to prove the red-shift amount of distant stars.
- When a photon hits an atom it may be absorbed if the energy is just right. The energy level of the electron is raised – essentially holding the radiation. A new photon of specific wavelength is created when the energy is released. The jump in energy is a discrete step and many possible levels of energy exist in an atom.
- Johann Balmer created this formula defining the photon emission wavelength (λ); where m is the initial electron energy level and n is the final electron energy level:

$$\lambda = 364.56\text{nm}\left(\frac{m^2}{m^2-n^2}\right)$$

- Much of the interstellar matter is made of the ex-inplext atom hydrogen. The hydrogen visible-spectrum emission and absorption lines are shown below:

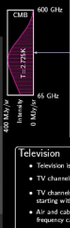


- Max Planck determined the relationship between the temperature of an object and its radiation profile; where B_λ is the radiation power, λ is the wavelength, T is the temperature:

$$B_\lambda = \frac{37418}{\lambda^5\left(e^{\frac{14388}{\lambda T}}-1\right)}$$

Cosmic Microwave Background Radiation

- CMB radiation is the leftover heat from the hot early universe, which last scattered about 400,000 years after the Big Bang.
- CMB permeates the entire universe at a temperature of 2.725 ± 0.001K.
- CMB was predicted in the 1940's by Ralph Alpher, George Gamow and Robert Herman.
- Arno Penzias and Robert Wilson accidentally discovered CMB while working for Bell Telephone Laboratories in 1965.
- The intensity is measured in Mega Jansky (Jy) per steradian. $1Jy = 10^{-20}W/m^2/Hz$
- Close examination of slight CMB intensity variations in different parts of the sky help cosmologists study the formation of galaxies.



Television

- Television is transmitted in the VHF and UHF ranges (30MHz - 3GHz).
- TV channels transmitted over the air are shown as TV
- TV channels transmitted through cable (CATV) are shown as CATV. CATV channels starting with "E" are channels fed back to the cable TV station (for news feeds)
- Air and cable TV stations are broadcast with the separate video, colour, and audio frequency carriers grouped together in a channel band as follows:

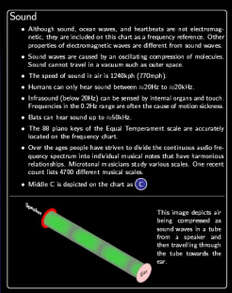
- Satellite channels broadcast in the C-Band as depicted as SAT. These stations are broadcast in alternating polarities (Ex. Ch 1 is vertical and 2 is horizontal and vice versa on neighbouring satellites).
- The 15.7 kHz horizontal sweep signal produced by a TV can be heard by some young people. This common contaminant signal to VLF spectra listening is depicted as

Radio Bands

- The radio spectrum (ELF to EHF) is populated by many more items than can be shown on this chart, only a small sampling of bands used around the world have been shown.
- Communication using EMR is done using either:
  - Amplitude Modulation (AM)
  - OR
  - Frequency Modulation (FM)
- Each country has its own rules and regulations for allotting bands in this region. For more information, look up the radio communications authority in your area (Ex. FCC in the US, DOC in Canada).
- Not all references agree on the ULF band range, the HAARP range is used here.
- RAdio Detecting And Ranging (RADAR) uses EMR in the microwave range to detect the distance and speed of objects.
- Citizens Band Radio (CB) contains 40 stations between 26.965-27.405MHz.
- Schumann resonance is produced in the cavity between the Earth and the ionosphere. The resonant peaks are depicted as
- Hydrogen gas emits radio band EMR at 21cm
- Some individual frequencies are represented as icons:
  - Submarine communications
  - Time and frequency standards
  - Ham radio and international meter bands
  - Miscellaneous short wave radio
  - Weather stations
  - Cellular and PCS Phones (including; FDMA, TDMA, CDMA ranges)

Sound

- Although sound, ocean waves, and heartbeats are not electromagnetic, they are included on this chart as a frequency reference. Other properties of electromagnetic waves are different from sound waves.
- Sound waves are caused by an oscillating compression of molecules. Sound cannot travel in a vacuum such as outer space.
- The speed of sound is air is 1240kph (770mph).
- Humans can only hear sound between ≈20Hz to ≈20kHz.
- Infrasound (below 20Hz) can be sensed by internal organs and touch. Frequencies in the 0.2Hz range are often the cause of motion sickness.
- Bats can hear sound up to ≈50kHz.
- The 88 piano keys of the Equal Temperament scale are accurately located on the frequency chart.
- Over the ages people have striven to divide the continuous audio frequency spectrum into individual musical notes that have harmonious relationships. Microtonal musicians study various scales. One recent count lists 4700 different musical scales.
- Middle C is depicted on the chart as C



Gravity Waves

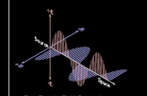
- Gravity is the mysterious force that holds large objects together and binds our planets, stars and galaxies together. Many people have unsuccessfully theorized about the details of gravity and its relationship to other forces. There have been no links between gravity waves and electromagnetic radiation.
- Gravity is theorized to warp space and time. In fact, gravity is responsible for bending light as observed by the gravity-lens example of distant galaxies.
- "Gravity-waves" would appear as ripples in space-time formed by large objects moving through space that might possibly be detected in the future by very sensitive instruments.
- The speed that gravity propagates through space has been theorized to be the same as the speed of light.

Brain Waves

- By connecting electrodes from the human head to an electroencephalograph (EEG), it is possible to measure very small cyclic electrical signals.
- There has been much study on this topic, but like all effects on humans, the science is not as exact as the science of materials.
- Generally, lower brain wave frequencies relate to sleep, and the higher frequencies relate to alertness.
- Devices have been made for measuring and stimulating brain waves to achieve a desired state.

Electromagnetic Radiation (EMR)

- EMR is emitted in discrete units called photons but has properties of waves as seen by the images below. EMR can be created by the oscillation or acceleration of electrical charge or magnetic field. EMR travels through space at the speed of light (2 997 924 58 ×10^8 m/s). EMR consists of an oscillating electrical and magnetic field which are at right angles to eachother and spaced at a particular wavelength. There is some controversy about the phase relationship between the electrical and magnetic fields of EMR, one of the theoretical representations is shown here:



- The particle nature of EMR is exhibited when a solar cell emits individual electrons when struck with very dim light.
- The wave nature of EMR is demonstrated by the famous double slit experiment that shows cancelling and addition of waves.
- Much of the EMR properties are based on theories since we can only see the effects of EMR and not the actual photon or wave itself.
- Albert Einstein theorized that the speed of light is the fastest that anything can travel. So far he has not been proven wrong.
- EMR can have its wavelength changed if the source is receding or approaching as in the red-shift example of distant galaxies and stars that are moving away from us at very high speeds. The emitted spectral light from these receding bodies appears more red than it would be if the object was not moving away from us.
- We only have full electronic control over frequencies in the microwave range and lower. Higher frequencies must be created by waiting for the energy to be released from elements as photons. We can either pump energy into the elements (ex. heating a rock with visible EMR and letting it release infrared EMR) or let it naturally escape (ex. uranium decay)
- We can only see the visible spectrum. All other bands of the spectrum are depicted as hatched colours

Système international d'unité prefixes (SI unit prefixes)

Symbol	Name	Exp.	Multiplier
Y	yotta	10^{24}	1,000,000,000,000,000,000,000,000
Z	zetta	10^{21}	1,000,000,000,000,000,000,000
E	exa	10^{18}	1,000,000,000,000,000,000
P	peta	10^{15}	1,000,000,000,000,000
T	tera	10^{12}	1,000,000,000,000
G	giga	10^{9}	1,000,000,000
M	mega	10^{6}	1,000,000
k	kilo	10^{3}	1,000
		10^{0}	1
m	milli	10^{-3}	0.001
µ	micro	10^{-6}	0.000 001
n	nano	10^{-9}	0.000 000 001
p	pico	10^{-12}	0.000 000 000 001
f	femto	10^{-15}	0.000 000 000 000 001
a	atto	10^{-18}	0.000 000 000 000 000 001
z	zepto	10^{-21}	0.000 000 000 000 000 000 001
y	yocto	10^{-24}	0.000 000 000 000 000 000 000 001

Measurements on this chart

Symbol	Name	Value
c	Speed of Light	2 997 924 58 ×10^8 m/s
h	Planck's Constant	6.626 1 ×10^{-34} J·s
h	Planck's Constant (freq)	1 054 560 ×10^{-34} J·s
f	Frequency (cycles / second)	Hz
λ	Wavelegth (meters)	m
E	Energy (Joules)	J

Conversions

$E = h f$
$\lambda = \frac{c}{f}$
1Å = 0.1nm
1nm = 10Å
1Joule = 6.24 ×10^{18} eV

Gamma Rays

- Gamma radiation is the highest energy radiation (up to ≈ 10^{20} eV) that has been measured. At this energy, the radiation could be from gamma-rays, protons, electrons, or something else.
- Alpha, beta, and delta radiation are not electromagnetic but are actually parts of the atom being released from a radioactive atom. In some cases this can cause gamma radiation. These are not to be confused with brain waves of similar names.

Visible Spectrum

- The range of EMR visible to humans is also called "Light". The visible spectrum also closely resembles the range of EMR that filters through our atmosphere from the sun.
- Other creatures see different ranges of visible light, for example bumble-bees can see ultraviolet light and dogs have a different response to colours than do humans.
- The sky is blue because our atmosphere scatters light and the shorter wavelength blue gets scattered the most. It appears that the entire sky is illuminated by a blue light but in fact that light is scattered from the sun. The longer wavelengths like red and orange more straight through the atmosphere which makes the sun look like a bright white ball containing all the colours of the visible spectrum.
- Interestingly, the visible spectrum covers approximately one octave.
- Astronomers use filters to capture specific wavelengths and reject unwanted wavelengths, the major astronomical (visual) filter bands are depicted as

Infrared Radiation

- Infrared radiation (IR) is sensed by humans as heat and is below the range of human vision. Humans (and anything at room temperature) are emitters of IR.
- IR remote control signals are invisible to the human eye but can be detected by most camcorders.
- Night vision scopes/goggles use a special camera that senses IR and converts the image to visible light. Some IR cameras employ an IR lamp to help illuminate the view.
- IR LASERs are used for burning objects.
- A demonstration of IR is to hold a metal bowl in front of your face. The IR emitted by your body will be reflected back using the parabolic shape of the bowl and you will feel the heat.
- Fiber-optic based infrared communication signals are sometimes amplified with Erbium-Doped Fiber Amplifiers (EDFA)

LASER

- LASER is an acronym for Light Amplification by Stimulated Emission of Radiation.
- A LASER is a device that produces monochromatic EMR of high intensity.
- With proper equipment, any EMR can be made to operate like a LASER. For example, microwaves are used to create a MASER.

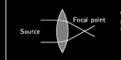
Polarization

- As a photon (light particle) travels through space, its axis of electrical and magnetic fluctuations does not rotate. Therefore, each photon has a fixed linear polarity of somewhere between 0°to 360°. Light can also be circularly and elliptically polarized.
- Some crystals can cause the photon to rotate its polarization.
- Receivers that expect polarized photons will not accept photons that are in other polarities. (ex. satellite dish receivers have horizontal and vertical polarity positions).
- A polarized filter (like Polaroid™sunglasses) can be used to demonstrate polarized light. One filter will only let photons that have one polarity through. Two overlapping filters at right angles will almost totally block the light that exits, however, a third filter inserted between the first two at a 45°angle will rotate the polarized light and allow some light to come out the end of all three filters.
- Light that reflects off an electrical insulator becomes polarized. Conductive reflectors do not polarize light.
- Perhaps the most reliably polarized light is a rainbow.
- Moonlight is also slightly polarized. You can test this by viewing the moonlight through a Polaroid™sunglass lens, then rotate that lens, the moonlight will dim and brighten slightly.

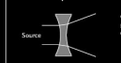
Refraction

- Refraction of EMR is dependent on wavelength as can be seen by the prism example below.

By using a glass prism, white light can be spread by refraction into a spectrum of its composite colours. All wavelengths of EMR can be refracted by using the proper materials.



Convex lenses make objects appear closer and are used to correct far-sightedness.

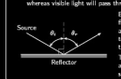


Concave lenses make objects appear farther away and are used to correct near-sightedness.

Heavy objects like dense galaxies and large planets cause light to bend due to gravitational lensing.

Reflection

- Reflection of EMR is dependent on wavelength as demonstrated when visible light and radio waves bounce off objects that X-Rays would pass through. Microwaves, which have a large wavelength compared to visible light, will bounce off metal mesh in a microwave oven whereas visible light will pass through.



EMR of any wavelength can be reflected, however, the reflectivity of a material depends on many factors including the wavelength of the incident beam.

The angle of incidence (A_i) and angle of reflection (A_r) are the same.


GR