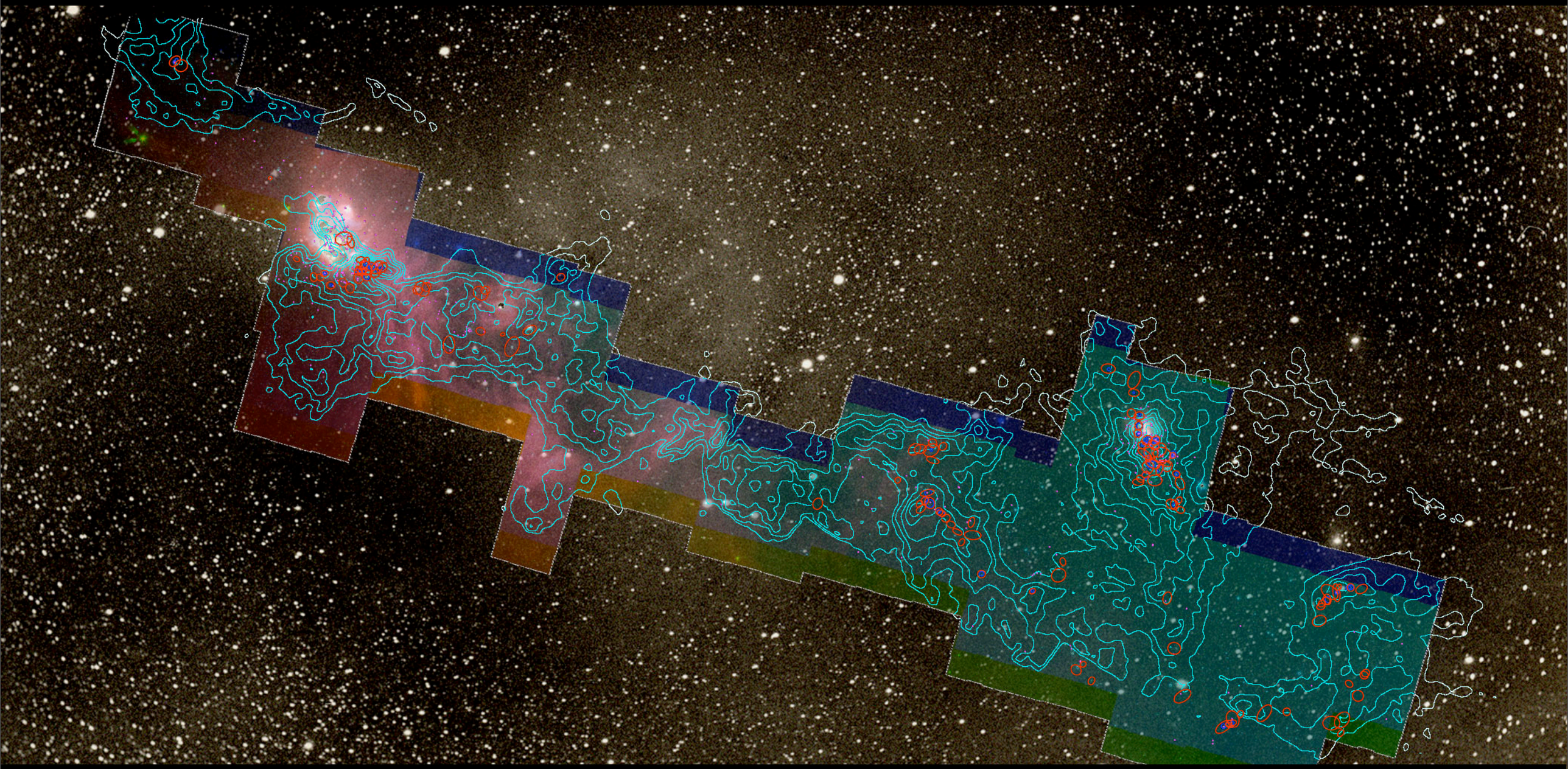
COMPLETE = **CO**ordinated **M**olecular **P**robe **L**ine **E**xtinction **T**hermal **E**mission Survey of Star-Forming Regions



COMPLETE Collaborators, Fall 2007:

Alyssa A. **Goodman** (CfA/IIC)

João Alves (Calar Alto, Spain)

Héctor Arce (AMNH to Yale)

Michelle Borkin (IIC)

Paola Caselli (Leeds, UK)

James DiFrancesco (HIA, Canada)

Jonathan Foster (CfA, PhD Student)

Sebastian Guillot (U. Victoria, Canada)

Mark Heyer (UMASS/FCRAO)

Doug Johnstone (HIA, Canada)

Jens **Kauffmann** (CfA/IIC)

Helen Kirk (HIA, Canada)

Di Li (JPL)

Jason Li (Harvard College)

Jaime **Pineda** (CfA, PhD Student)

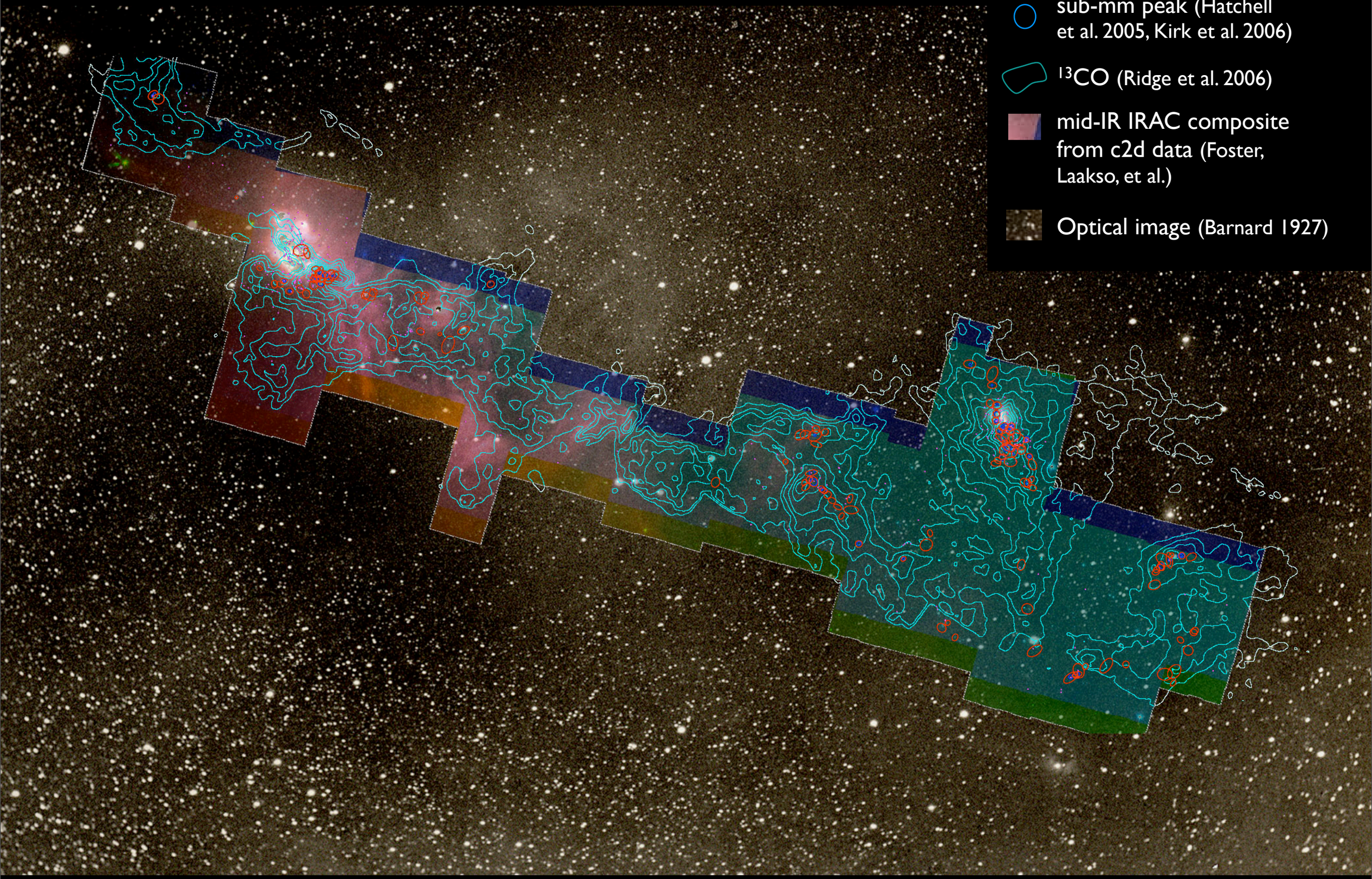
Erik Rosolowsky (CfA)

Scott **Schnee** (Caltech)

Rahul **Shetty** (CfA)

Mario Tafalla (OAN, Spain)

COMPLETE Perseus



COMPLETE

The COordinated Molecular Probe Line Extinction Thermal Emission Survey of Star Forming Regions

Data

Results

Projects

People

Learn

Restricted

Project Description

The COordinated Molecular Probe Line Extinction Thermal Emission Survey of Star Forming Regions (COMPLETE) provides a range of data complementary to the Spitzer Legacy Program "From Molecular Cores to Planet Forming Disks" (c2d) for the Perseus, Ophiuchus and Serpens regions. In combination with the Spitzer observations, COMPLETE will allow for detailed analysis and understanding of the physics of star formation on scales from 500 A.U. to 10 pc.

Phase I, which is now complete, provides fully sampled, arcminute resolution observations of the density and velocity structure of the three regions, comprising: extinction maps derived from the Two Micron All Sky Survey (2MASS) near-infrared data using the NICER algorithm; extinction and temperature maps derived from IRAS 60 and 100um emission; HI maps of atomic gas; 12CO and 13CO maps of molecular gas; and submillimeter continuum images of emission from dust in dense cores.

Click on the "Data" button to the left to access this data.

Phase II (which is still ongoing) uses targeted source lists based on the Phase I data, as it is (still) not feasible to cover every dense star-forming peak at high resolution. Phase II includes high-sensitivity near-IR imaging (for high resolution extinction mapping), mm-continuum imaging with MAMBO on IRAM and high-resolution observations of dense gas tracers such as N2H+. These data are being released as they are validated.

NEW **COMPLETE Movies:** Check-out our movies page for animations of the COMPLETE data cubes in 3D.

COMPLETE

The COordinated Molecular Probe Line Extinction Thermal Emission Survey of Star Forming Regions

Just click on "Data" at www.cfa.harvard.edu/COMPLETE

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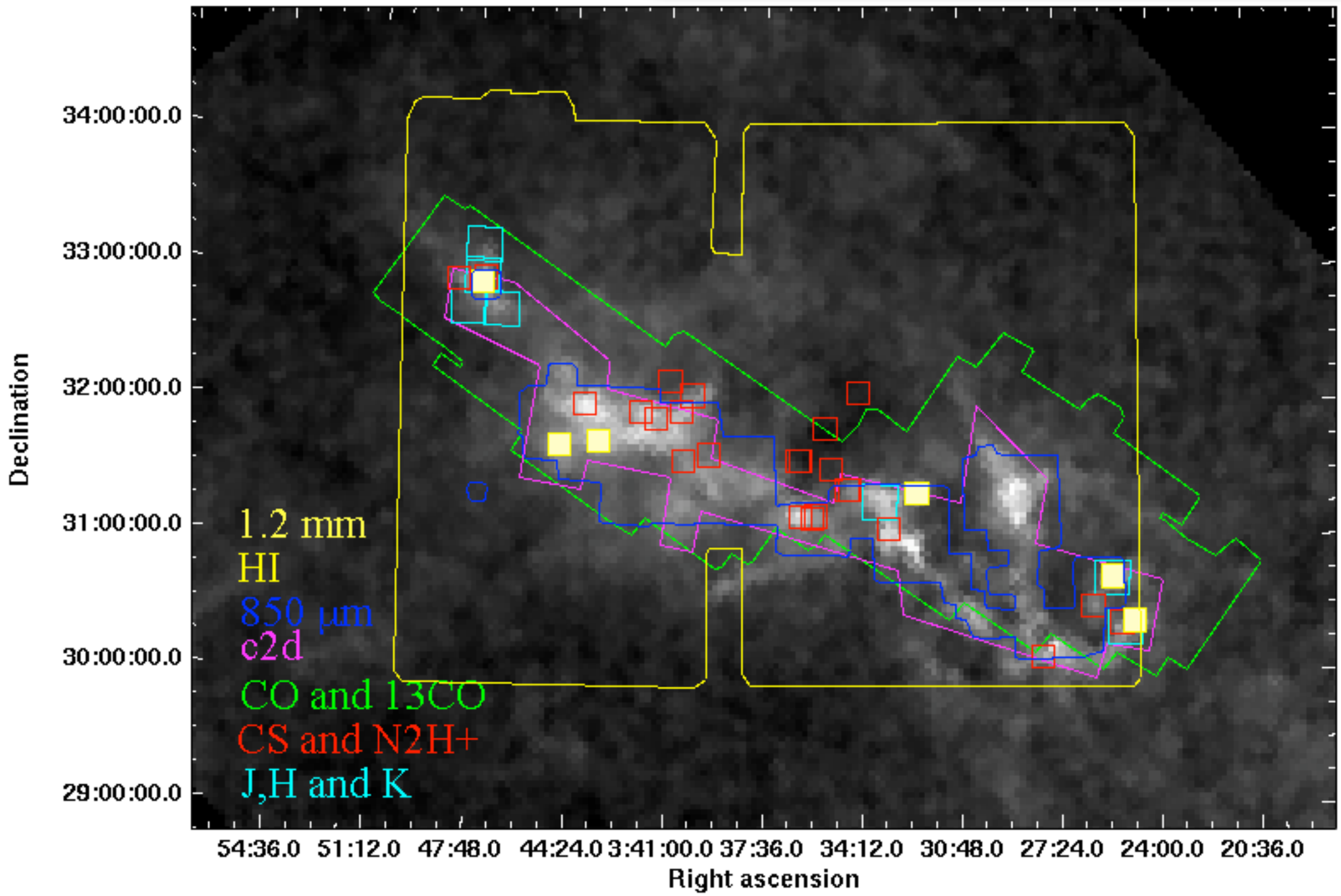
Data Retrieval

www.cfa.harvard.edu/COMPLETE

"1. Interactive Coverage Tool"

Displaying the following data sets for Perseus:

- 850 micron continuum emission (JCMT) Data link
- HI spectral data cube (GBT) Data link
- 1.2-mm continuum emission (IRAM-MAMBO) Data link
- N2H+ and CS (IRAM 30-m and FCRAO) Data link
- Deep near-IR imaging/extinction maps Data link
- c2d IRAC images (Spitzer) Data link
- 12CO,13CO Spectral data cube and integrated intensity map (FCRAO) Data link
- 2MASS-based NICER extinction maps Data link



for
Phase I Data Summary:
See Ridge et al. 2006

Data Retrieval

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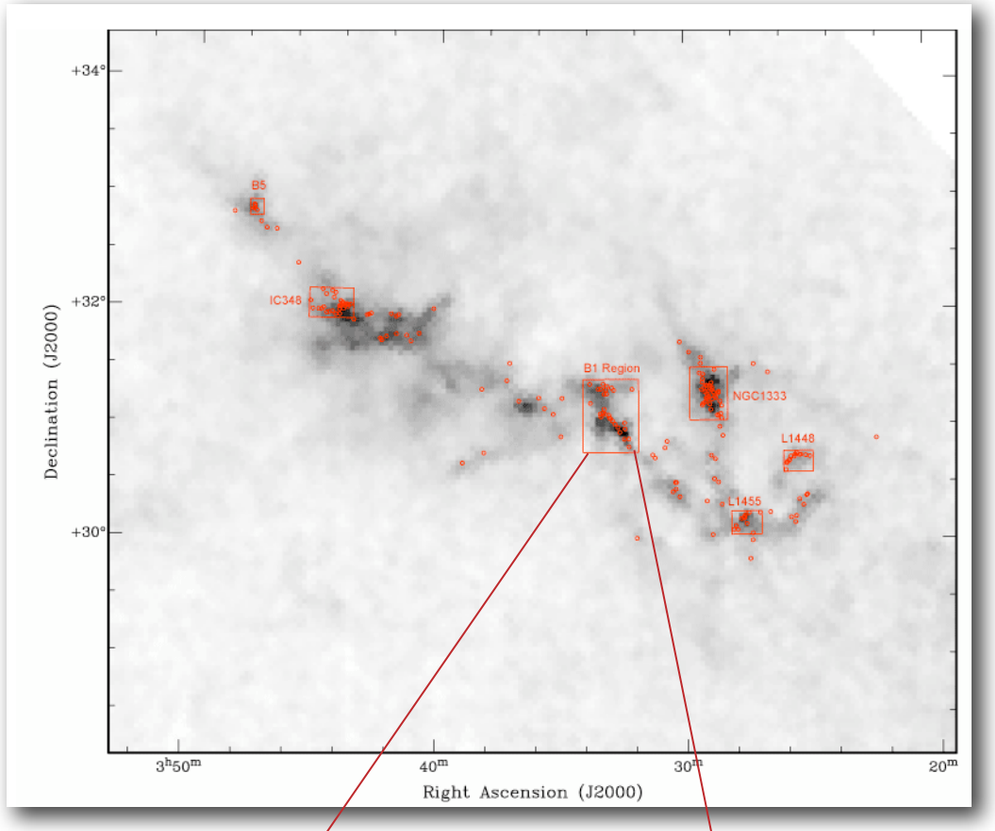
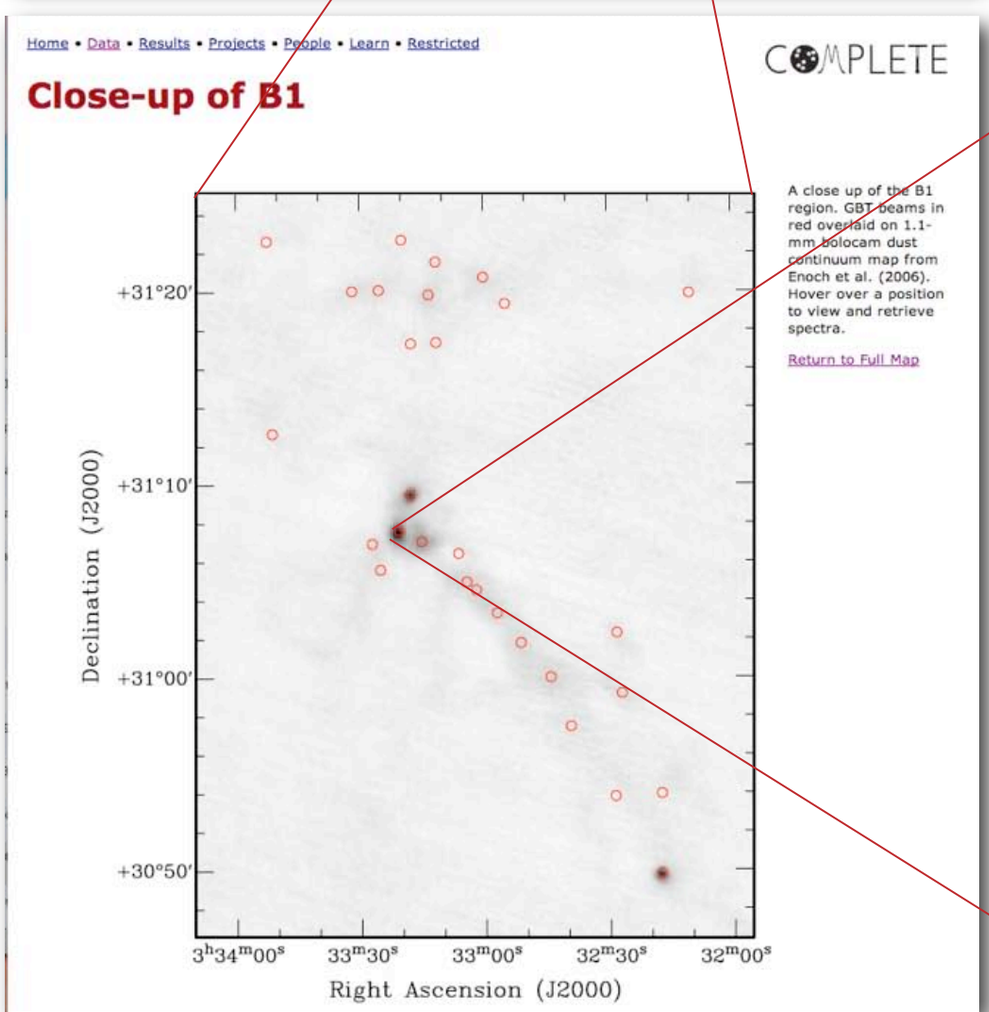
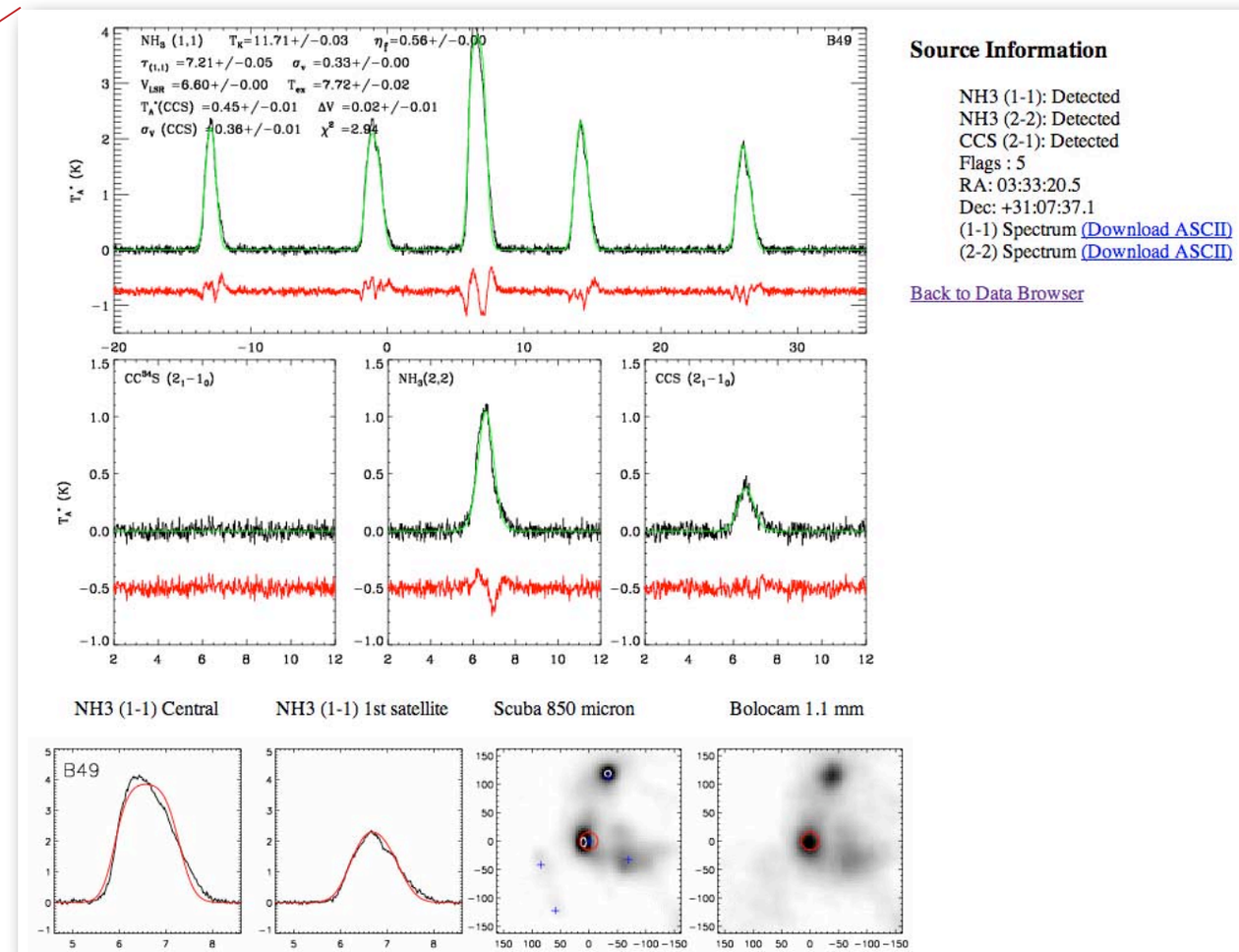
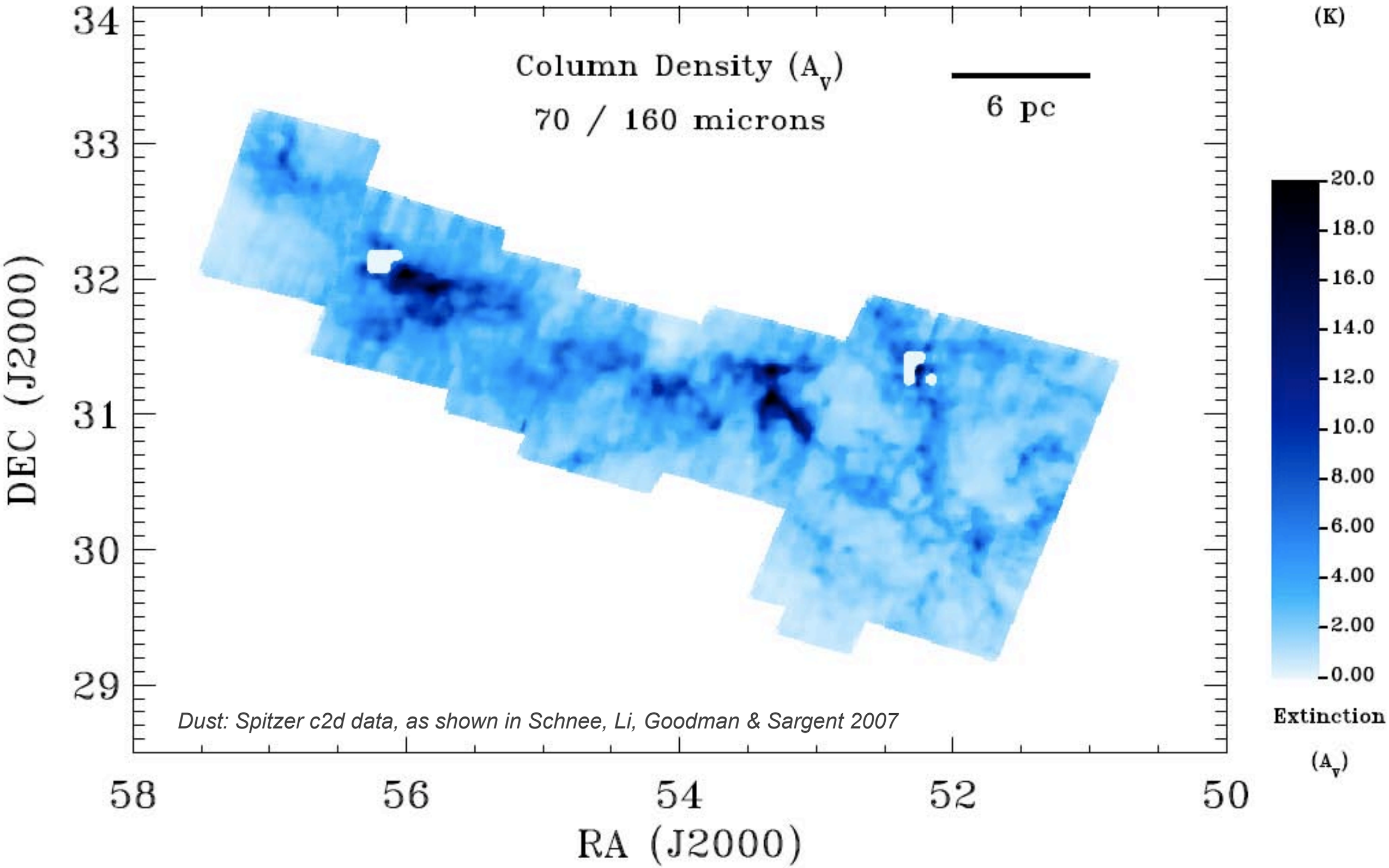
2. Special Ammonia Tool
(for Rosolowsky et al. 2007 survey)







In What Dust Environment(s) are the NH_3 Cores?



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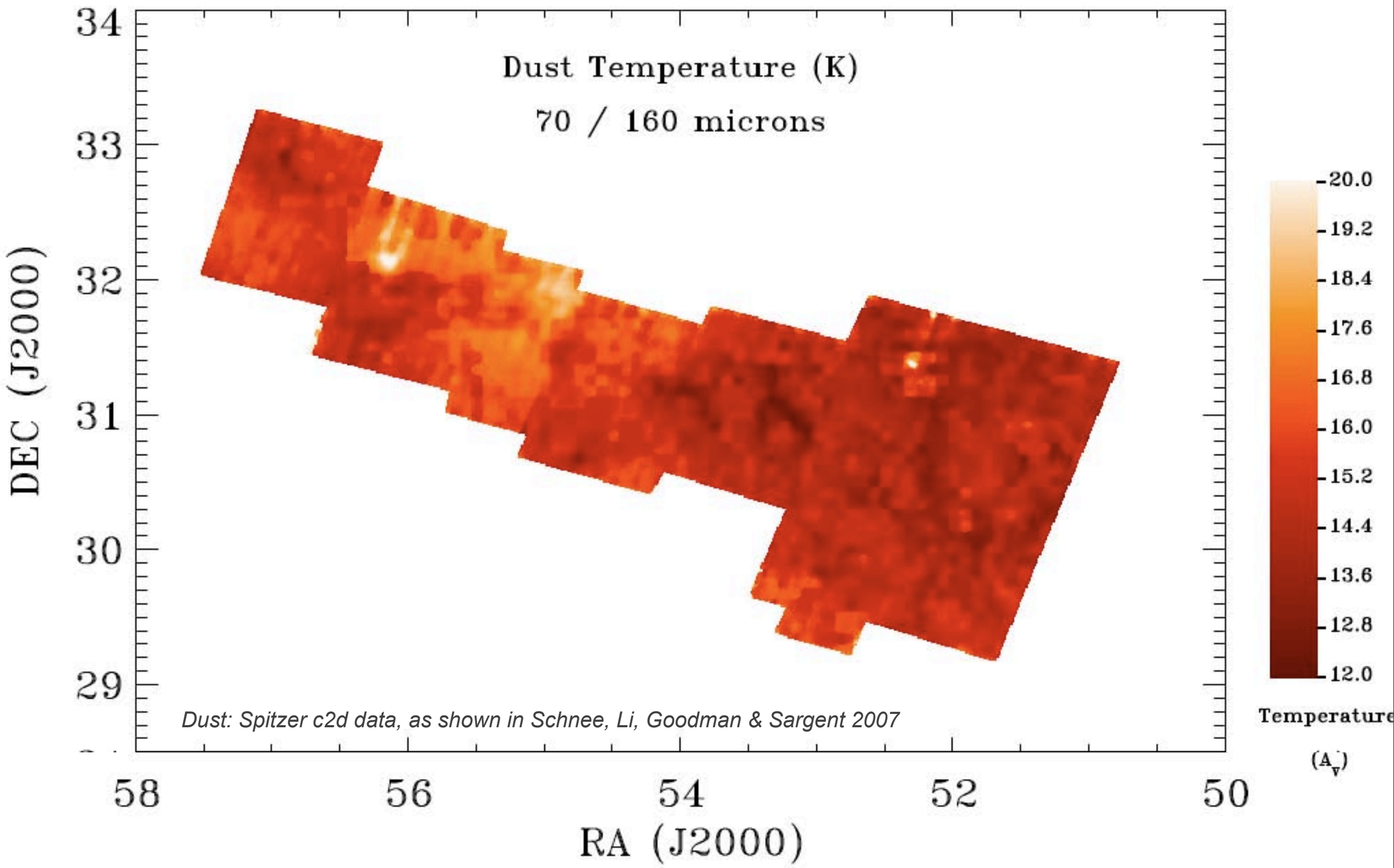

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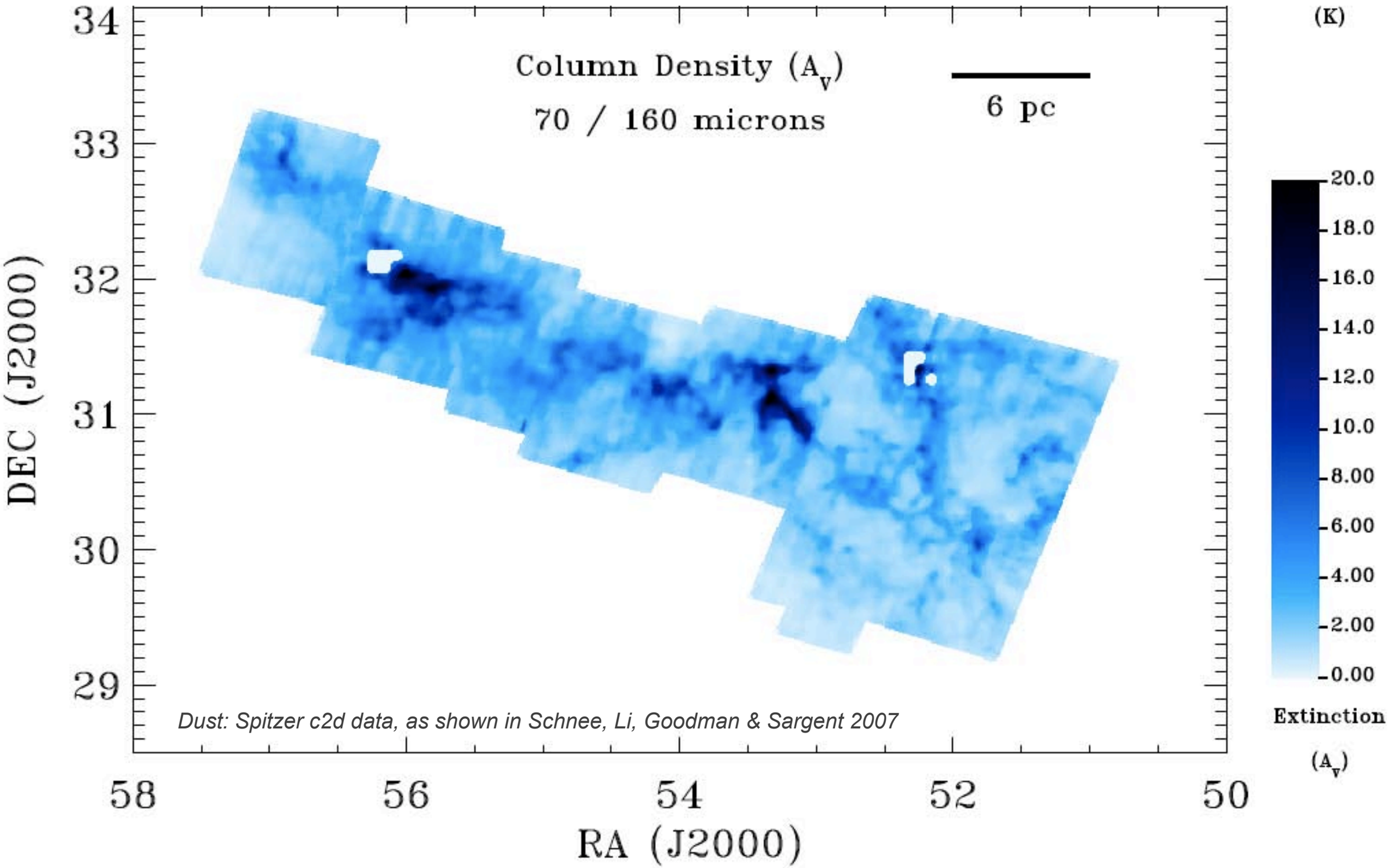

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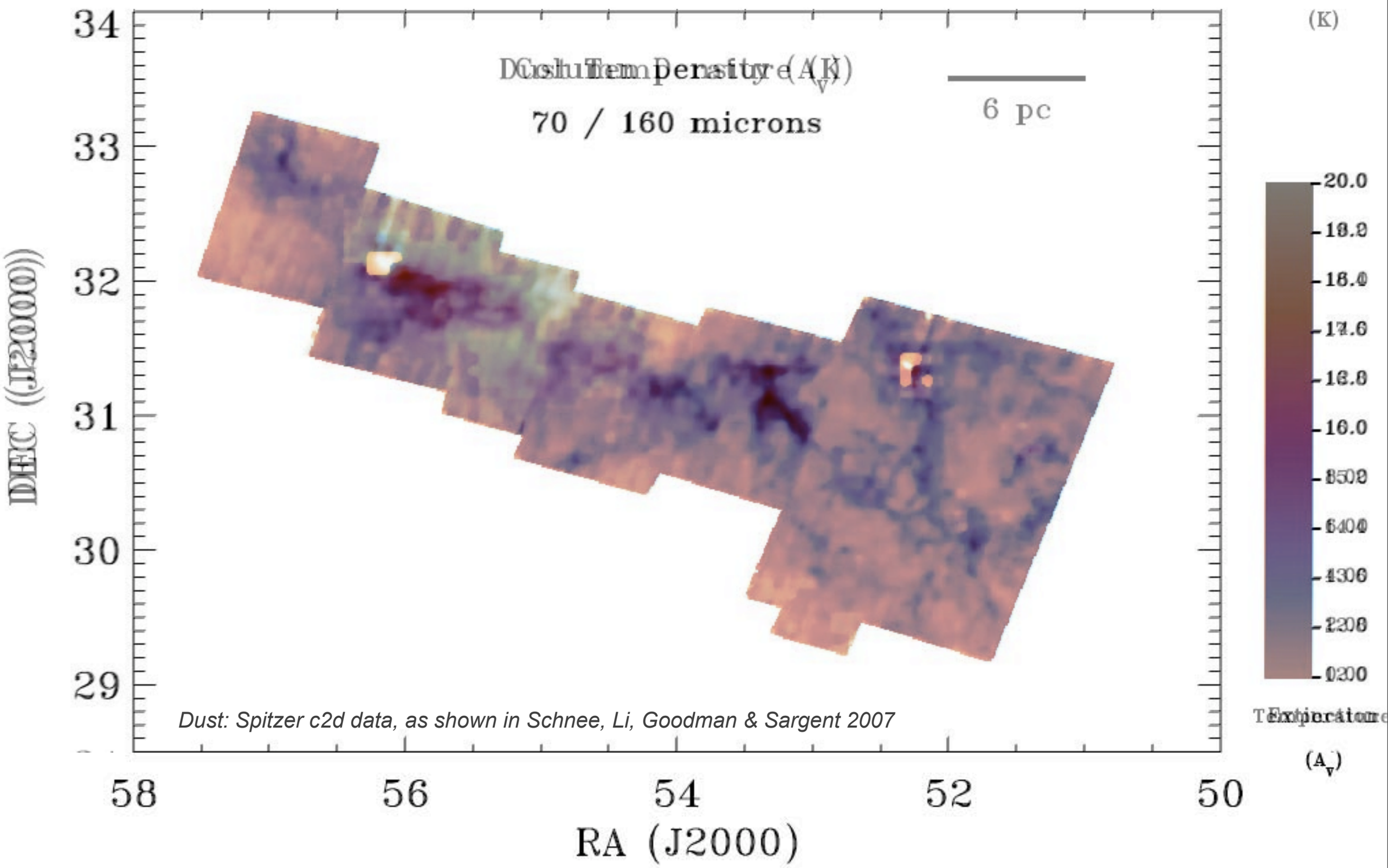

Dust: Spitzer c2d data, as shown in Schnee, Li, Goodman & Sargent 2007

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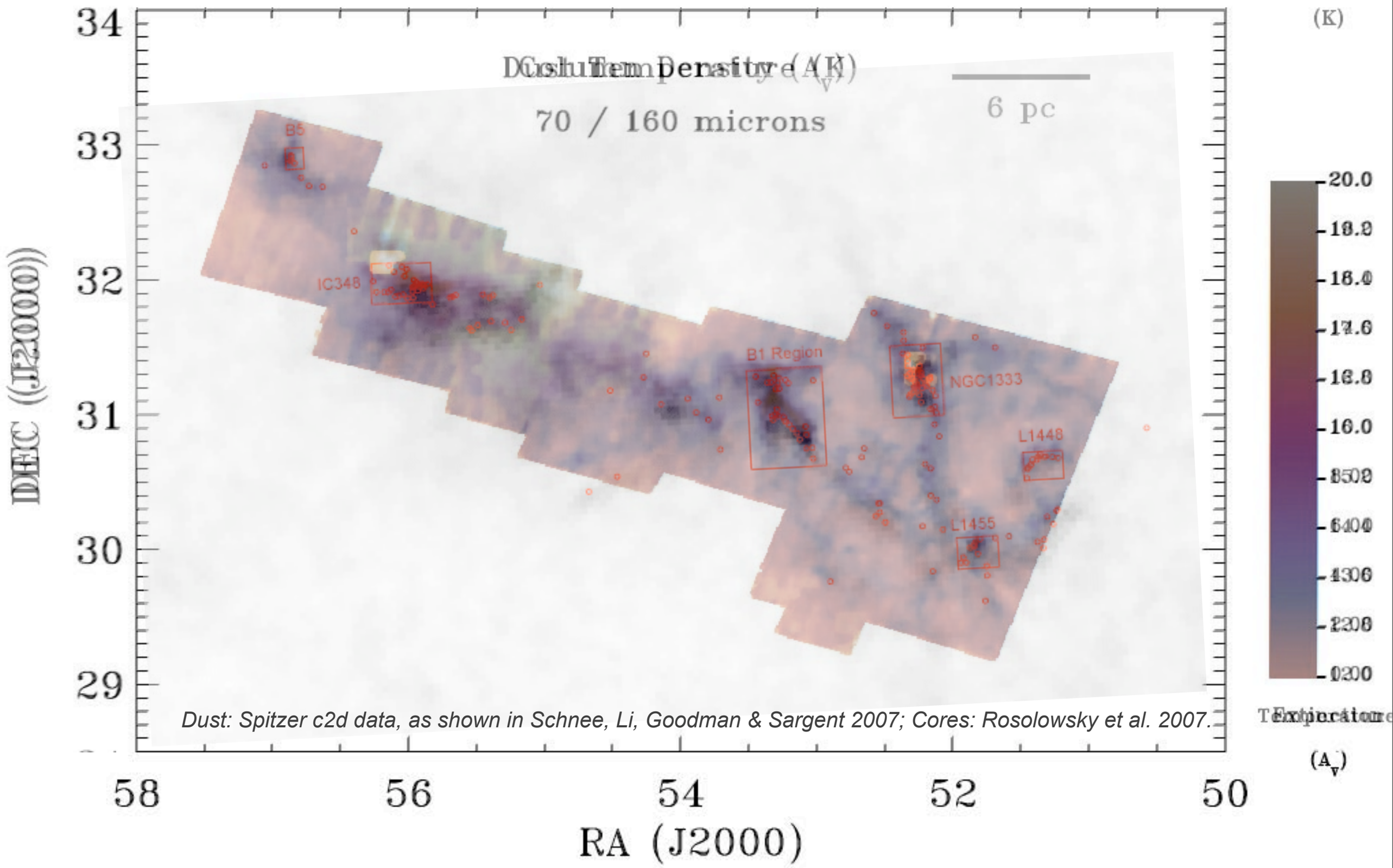


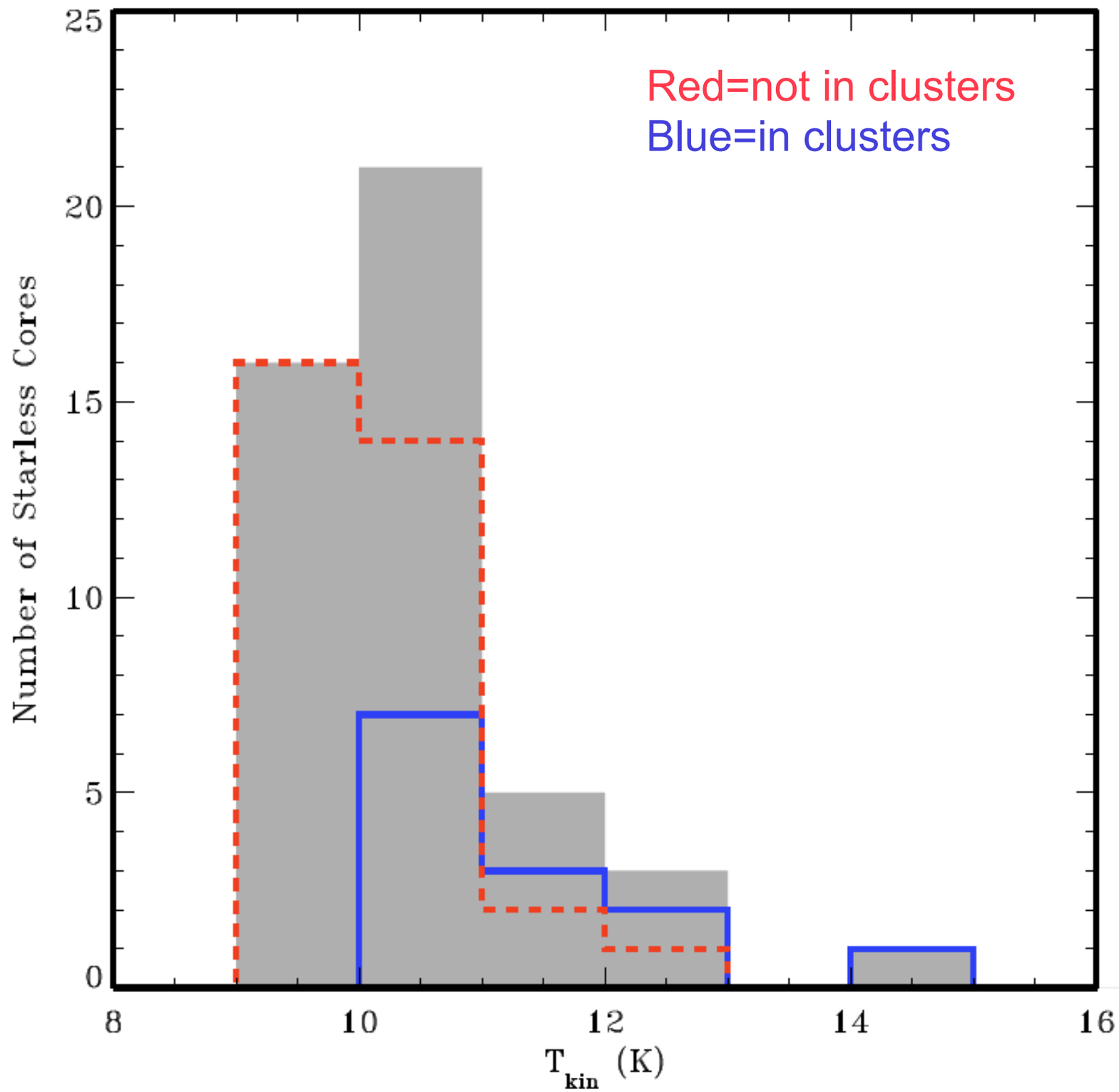
Dust: Spitzer c2d data, as shown in Schnee, Li, Goodman & Sargent 2007; Cores: Rosolowsky et al. 2007.

Perseus Core Temperatures from NH_3:

Slightly Warmer in Clusters

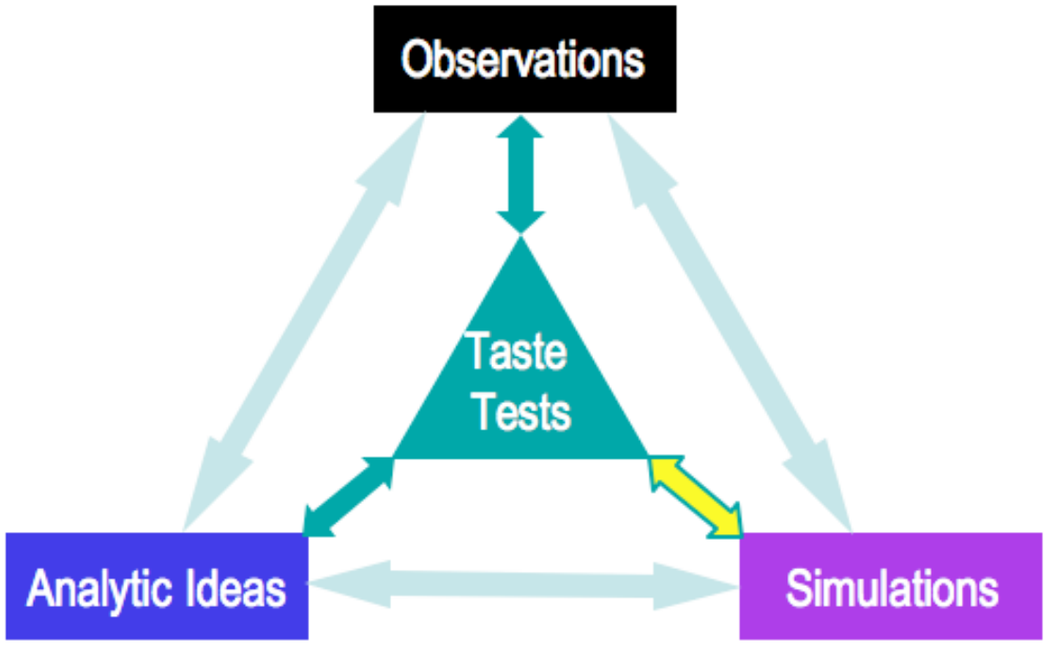
&

No Strong Correlation of Gas Temperature with Dust Temperature



Schnee, Rosolowsky, Foster, Enoch & Sargent 2007

Promised in August:
"Five Course Meal" +
More about Taste Tests
(from Rahul, in a bit)



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5. Stellar Distribution may be useful in figuring out which stars form when & where, but observational biases are CENTRAL (...see Neal's talk, yesterday!)

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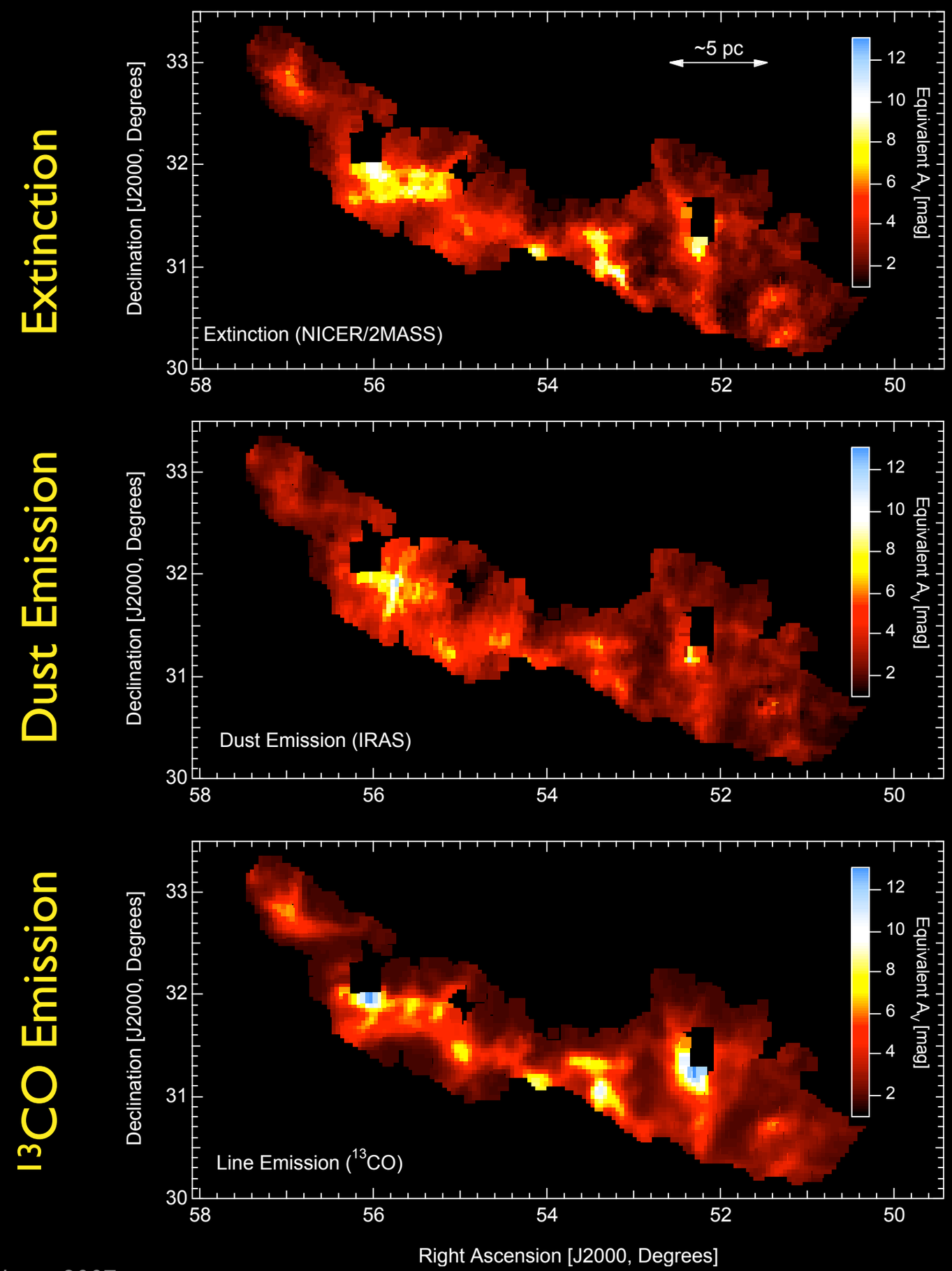
The (secret) uncertainties inherent in column density mapping.



Goodman, Pineda & Schnee,2007; see also Pineda, Caselli & Goodman 2007.

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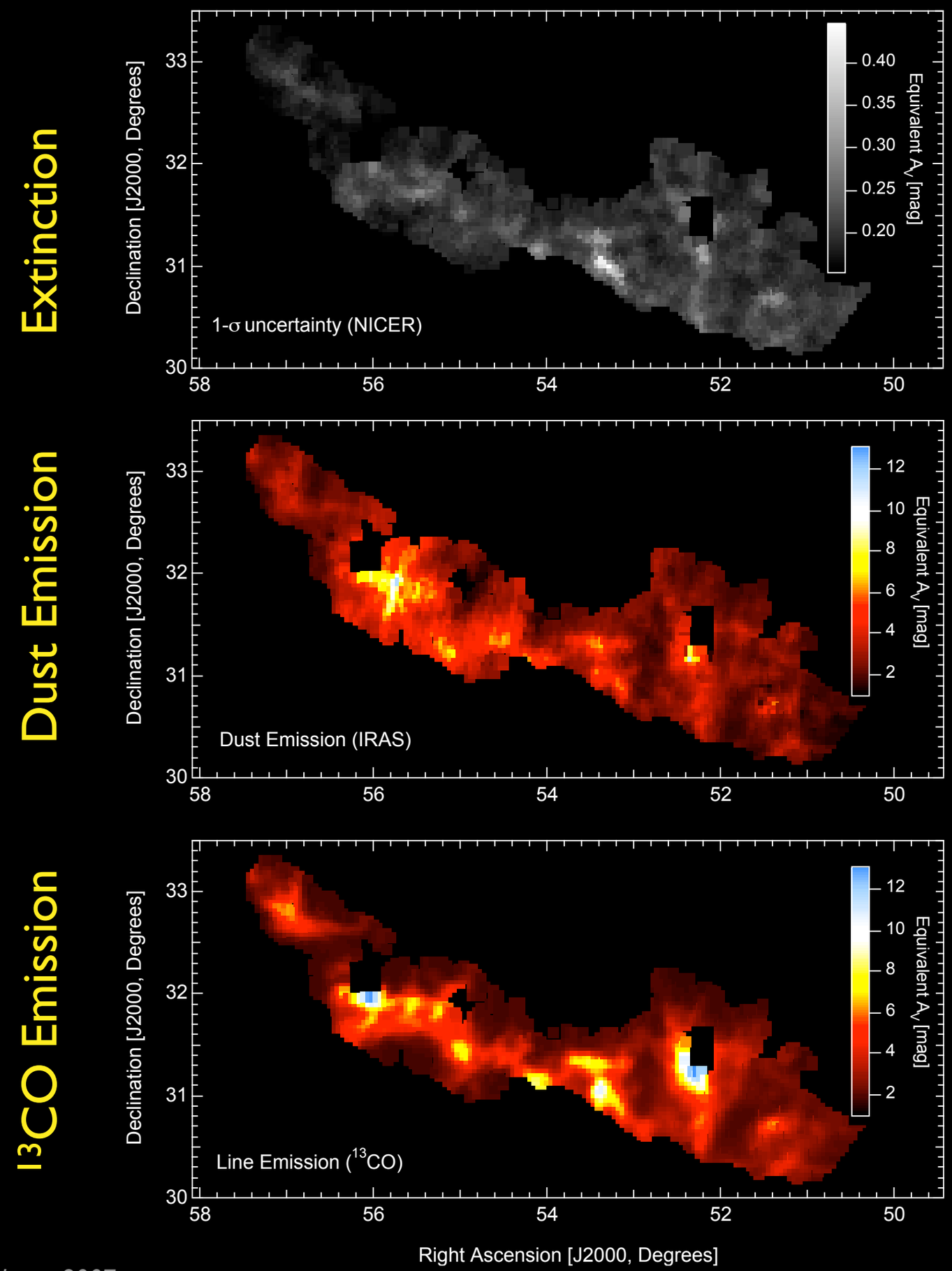

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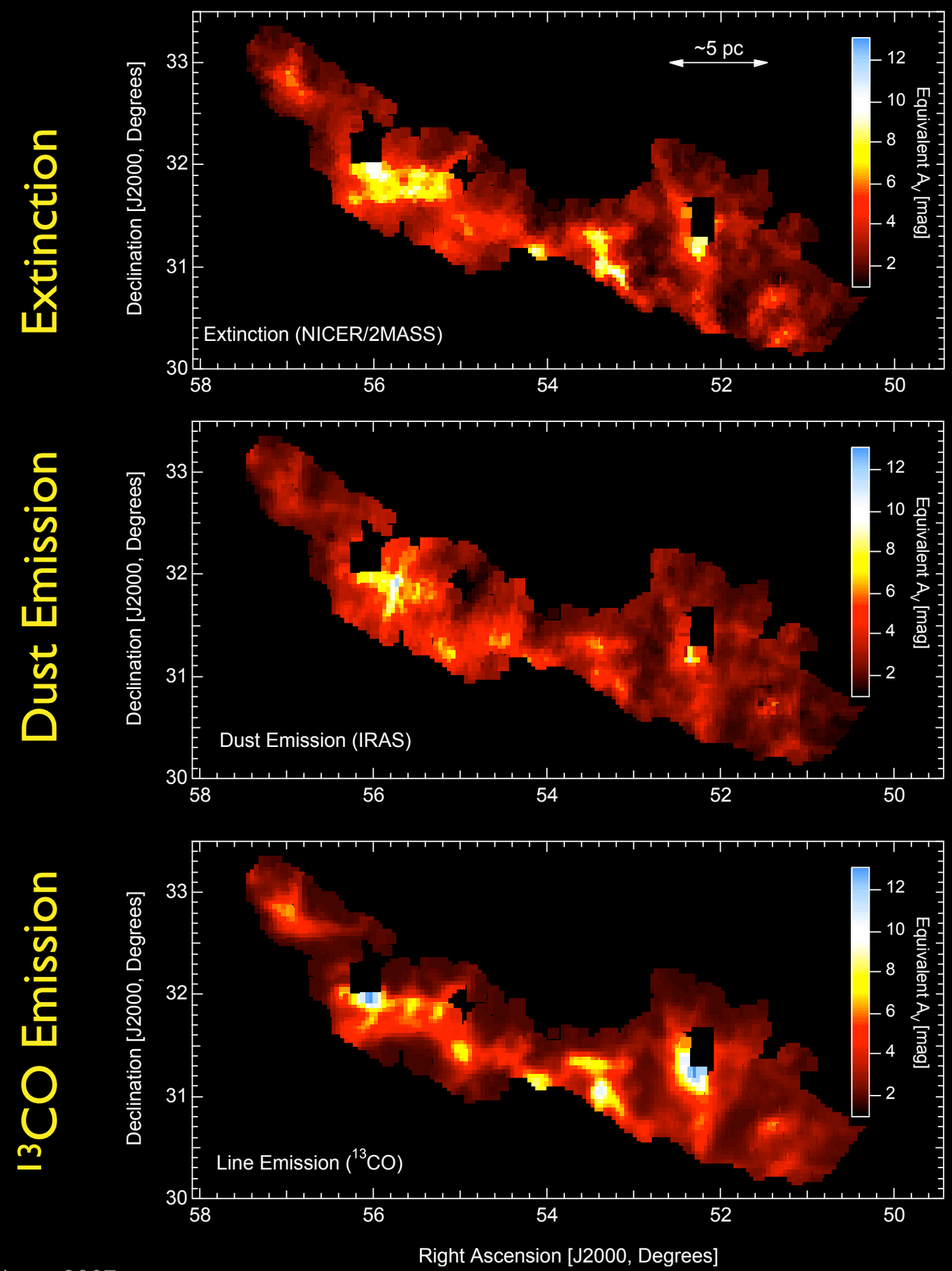

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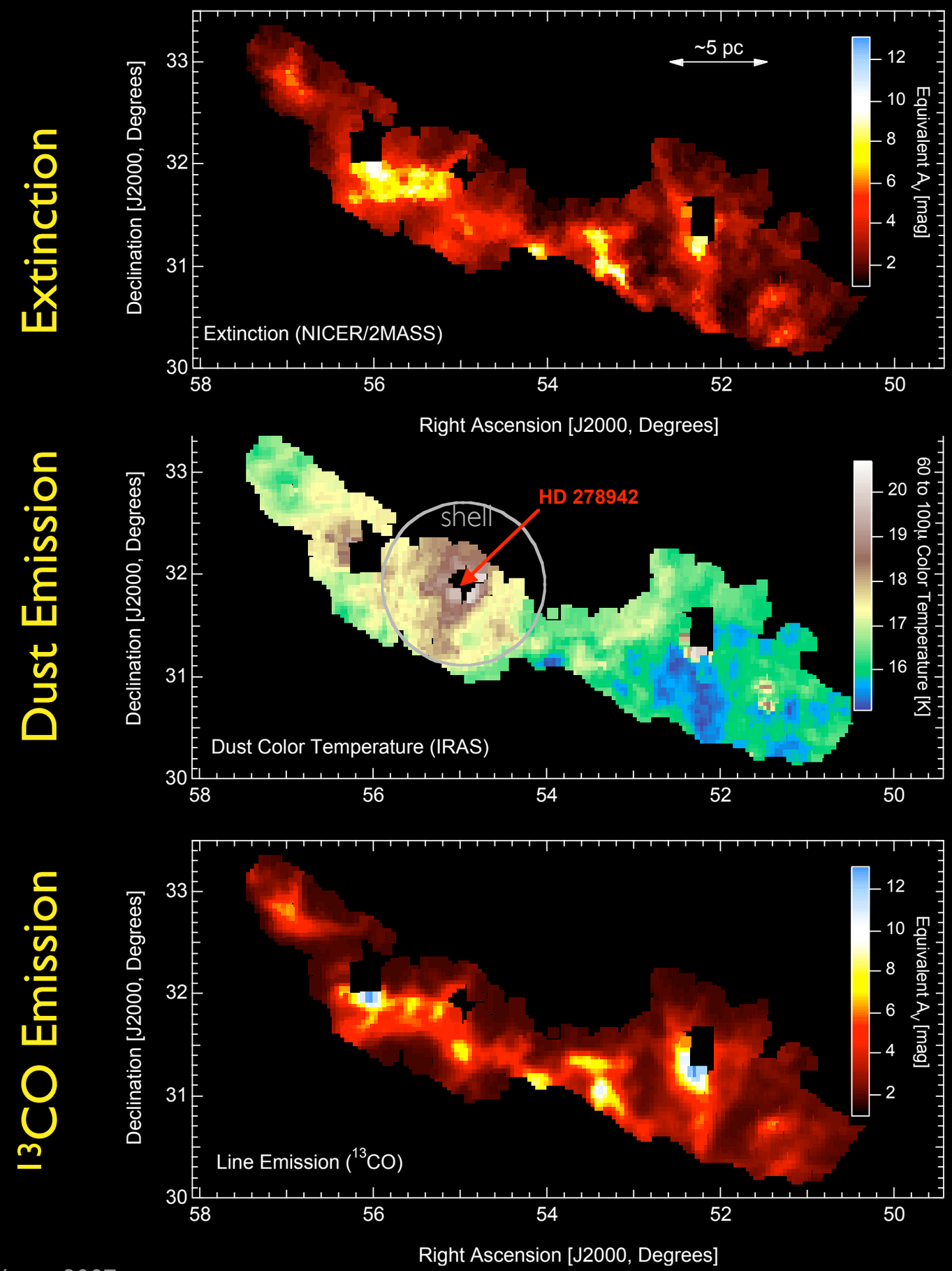

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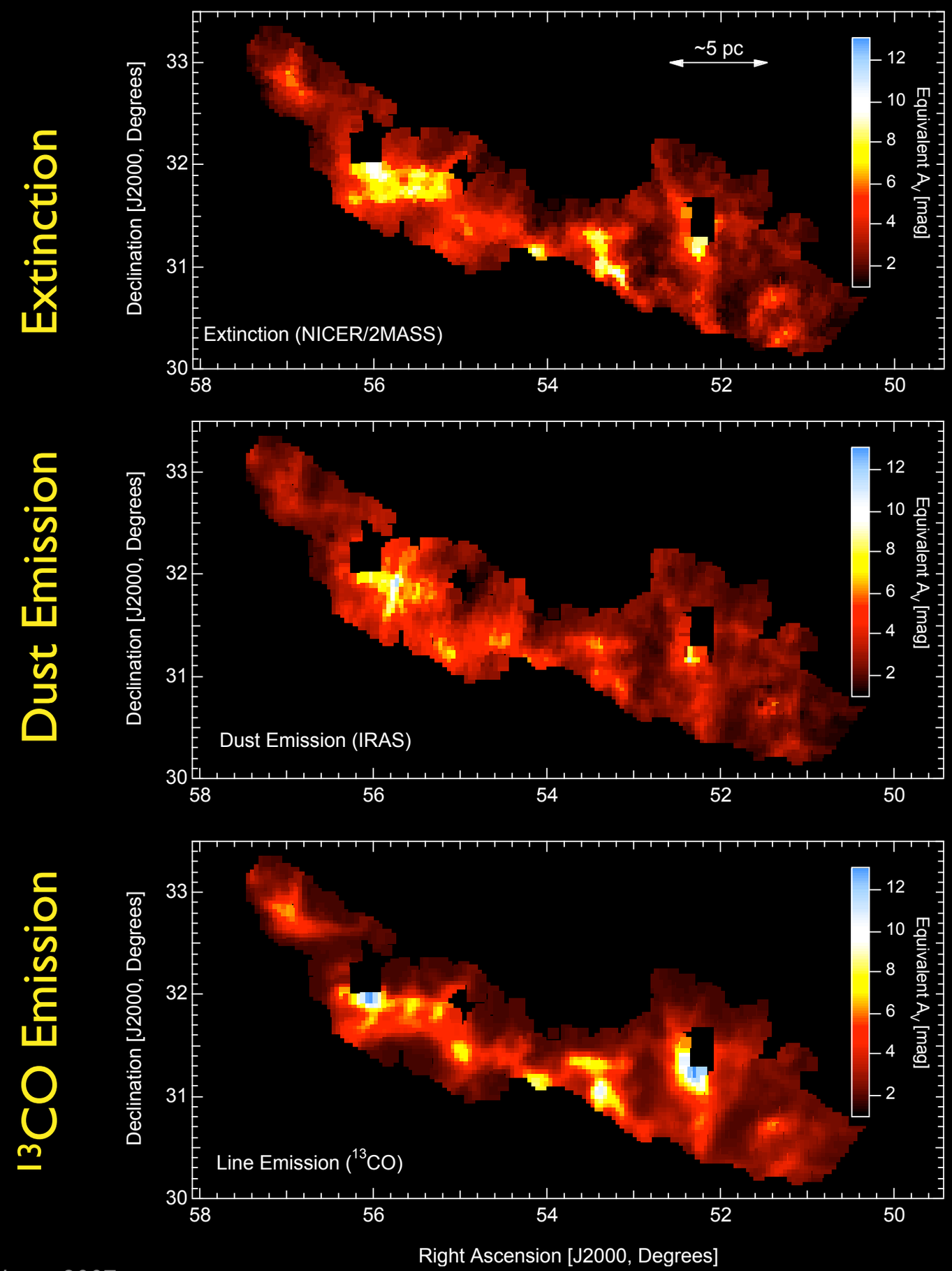

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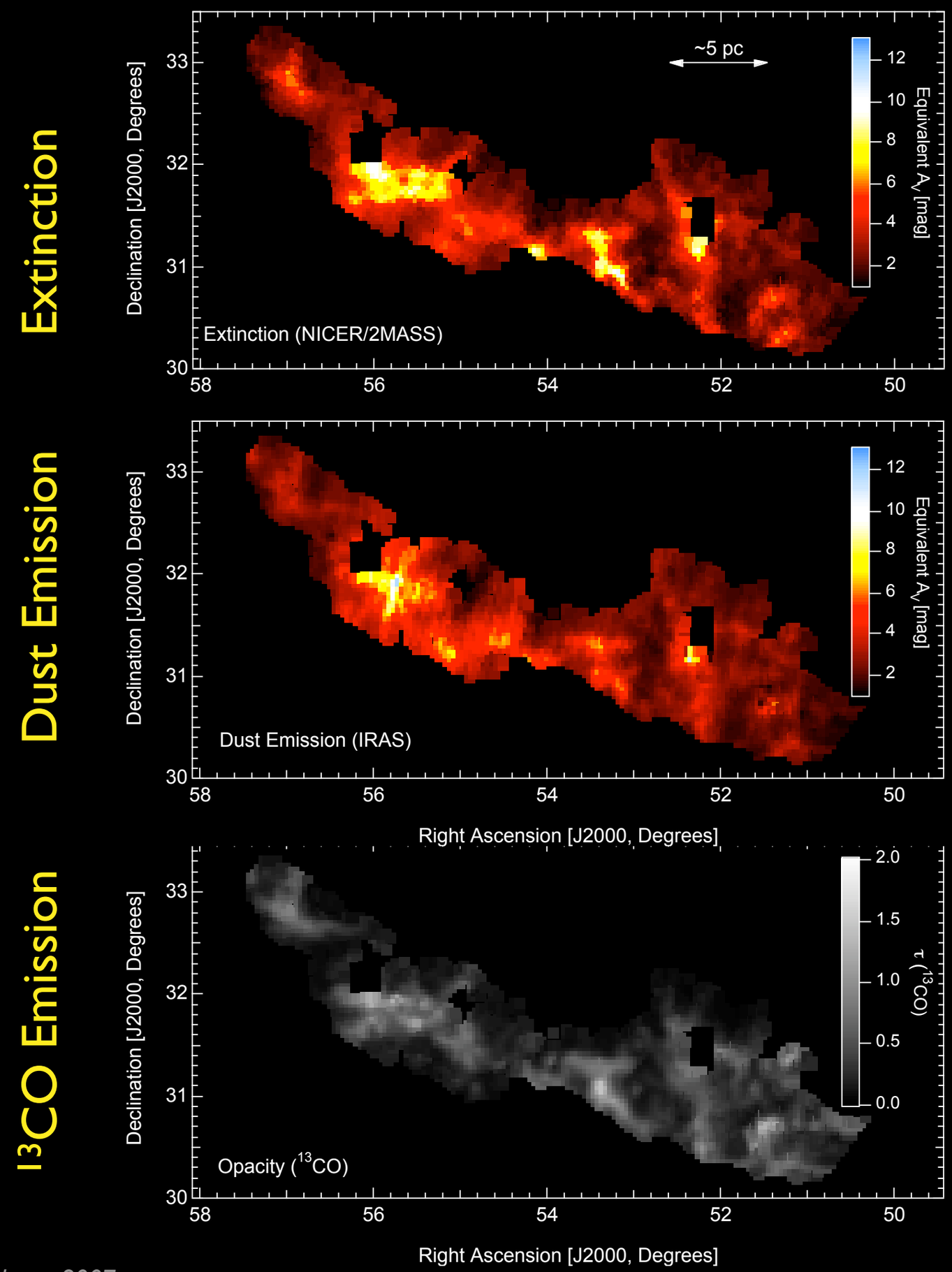

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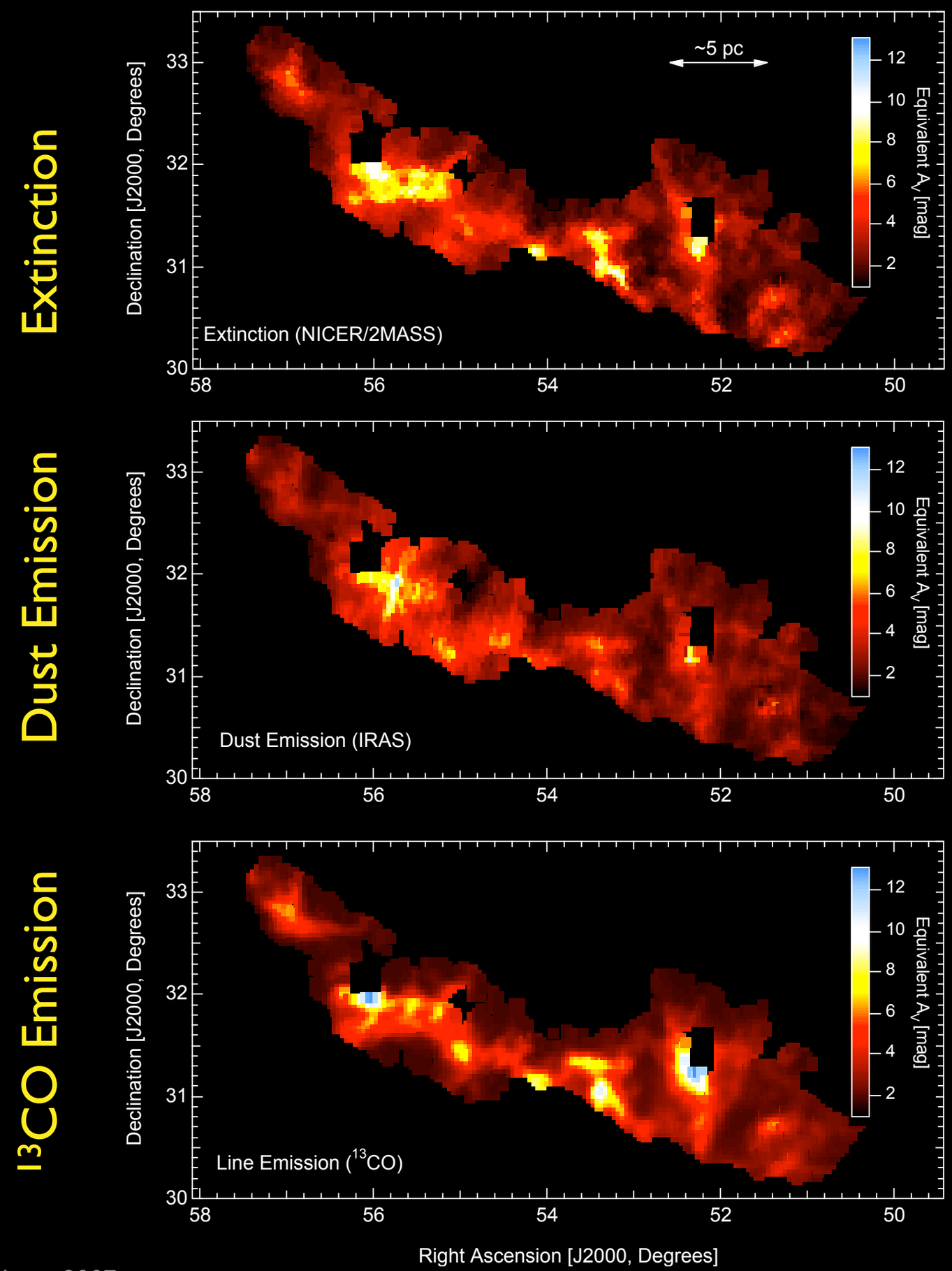

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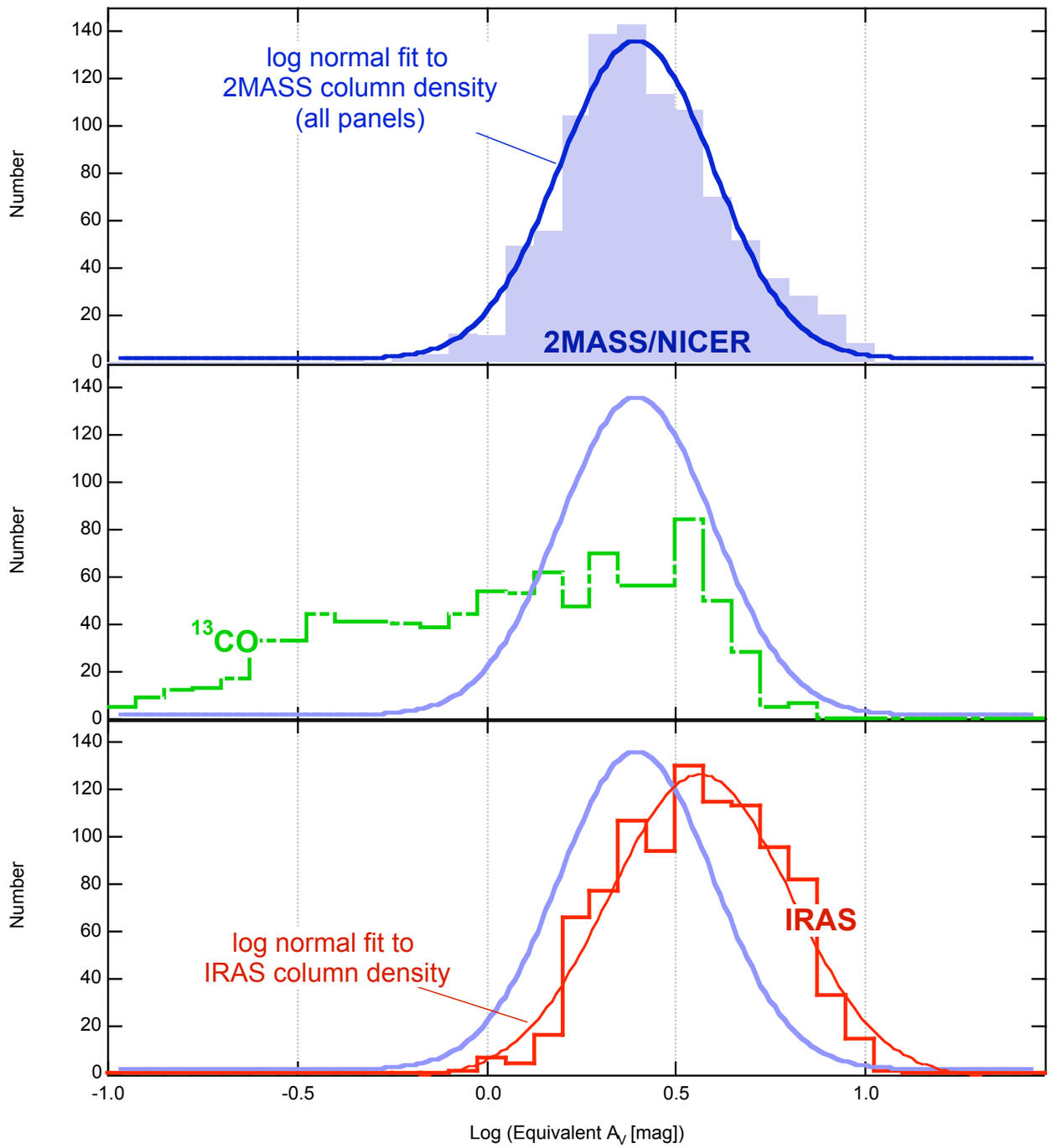
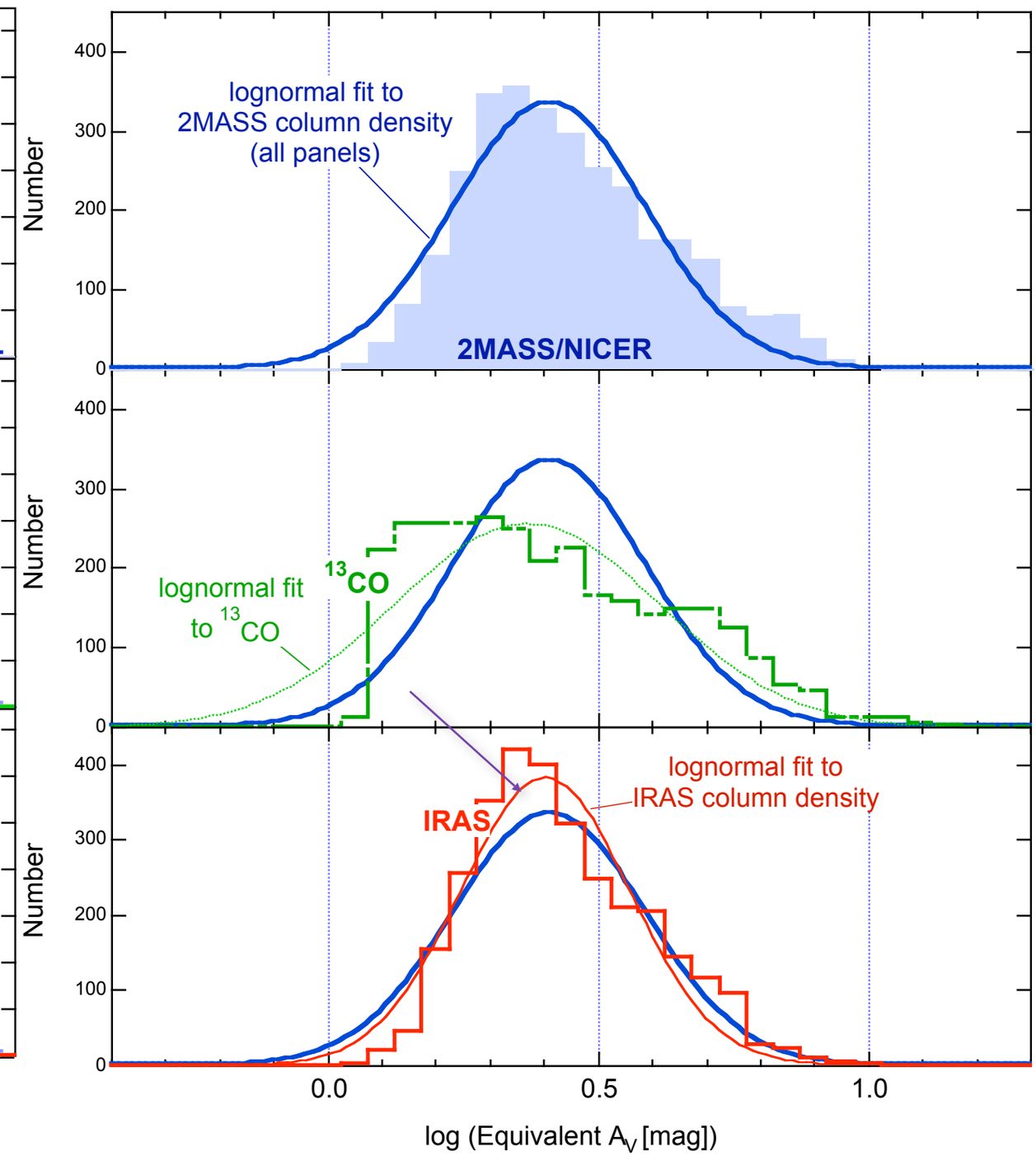
“Bias & Uncertainty”: A Never-ending Challenge

State of the Art, 2004



After 2 Years of Refinement…!



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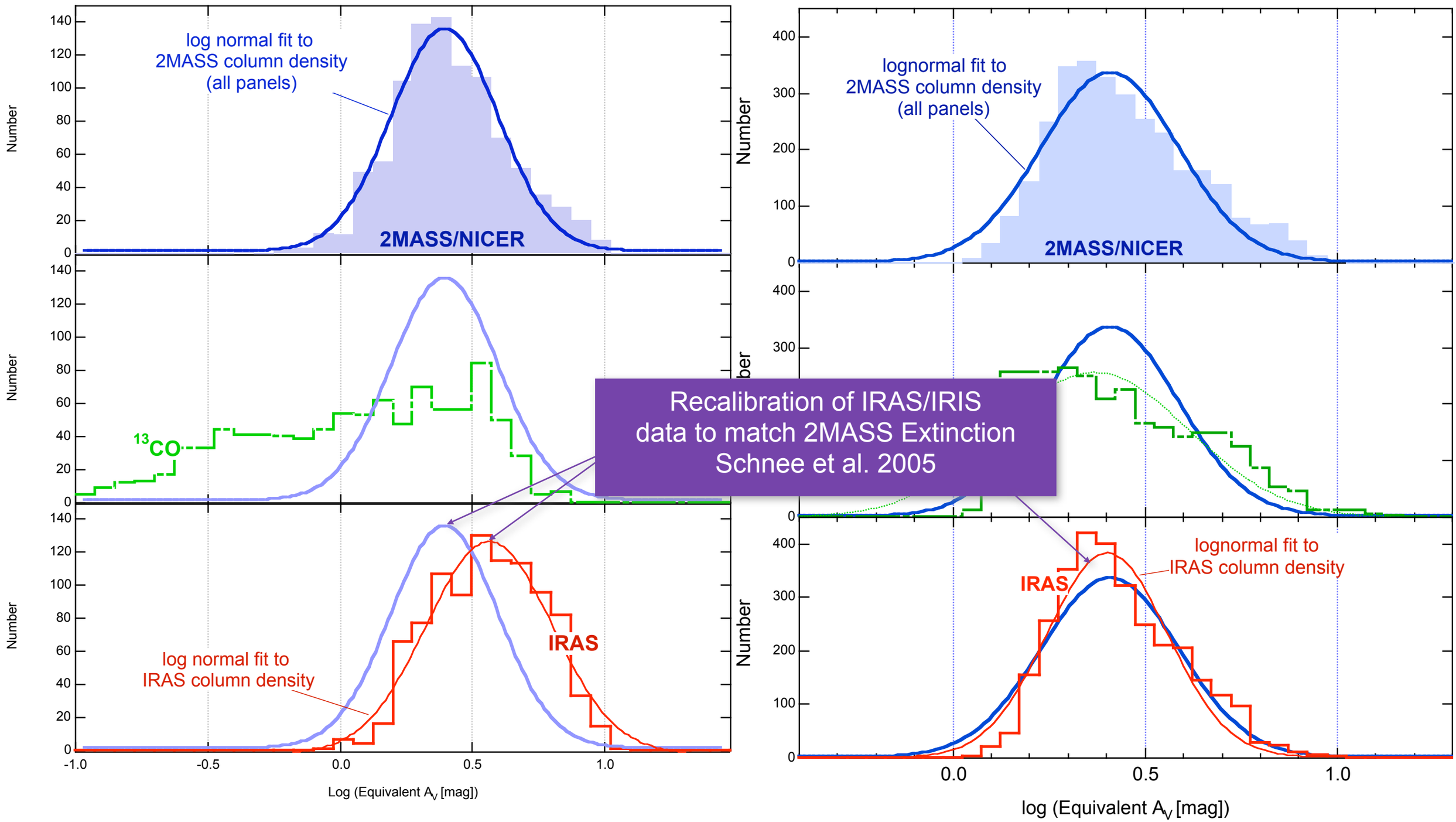

Recalibration of IRAS/IRIS
data to match 2MASS Extinction
Schnee et al. 2005

Goodman, Pineda & Schnee,2007; see also Pineda, Caselli & Goodman 2007.

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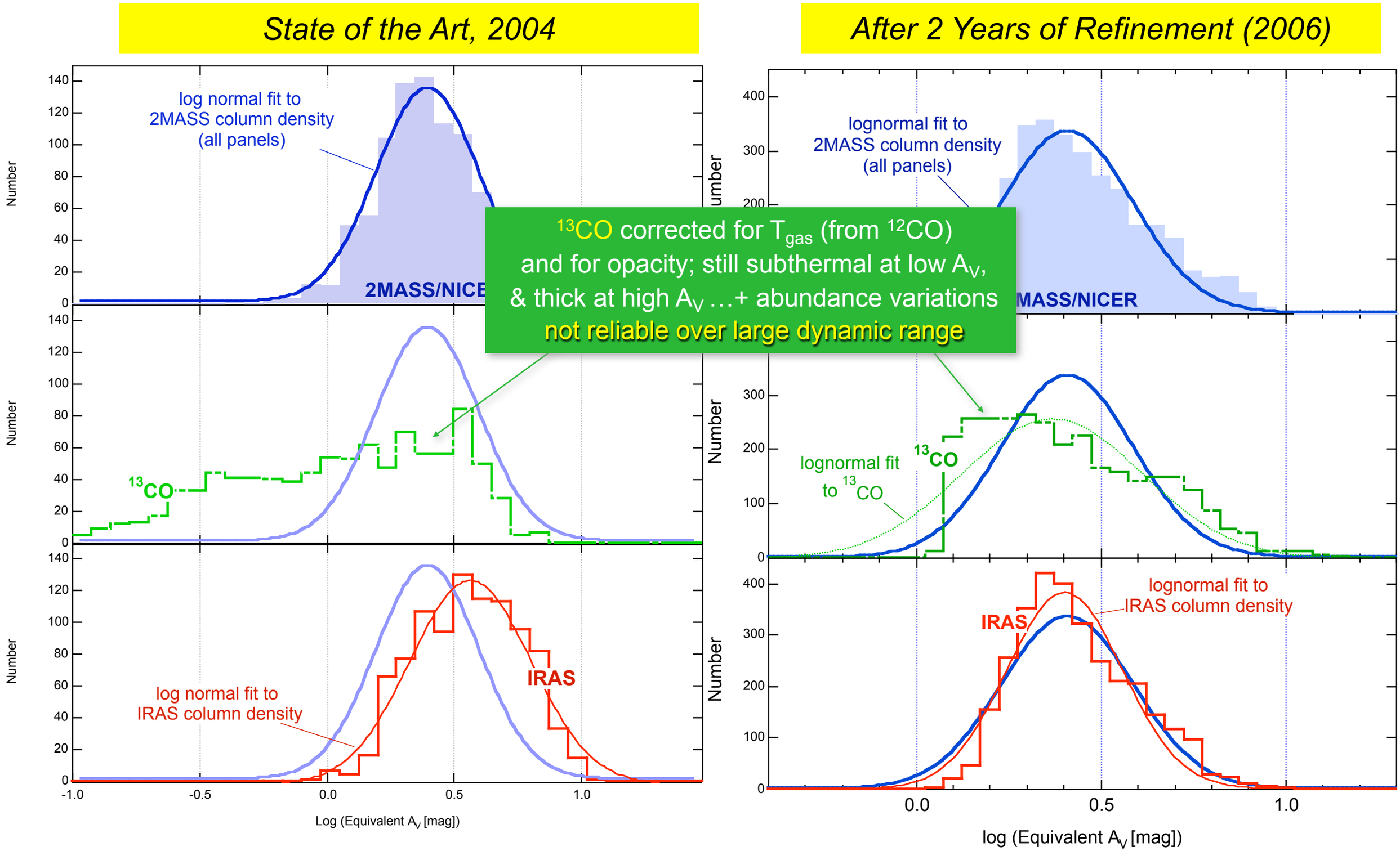


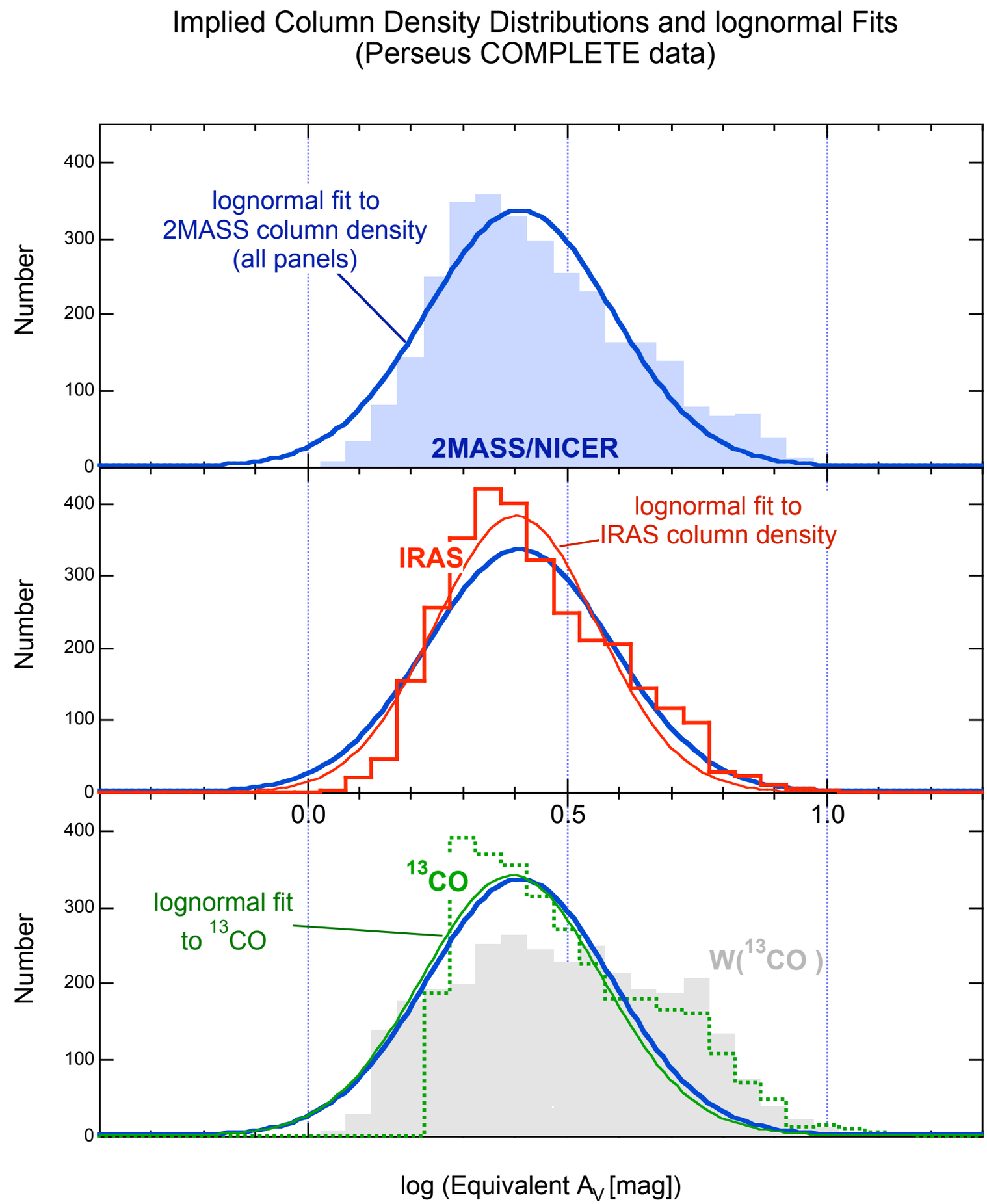
Goodman, Pineda & Schnee,2007; see also Pineda, Caselli & Goodman 2007.

Intermediate results...

Extinction & thermal emission are log-normal-ish (& more so when points undetected in ^{13}CO are included.)

^{13}CO is not a very faithful tracer of column density

...but, that's not all...



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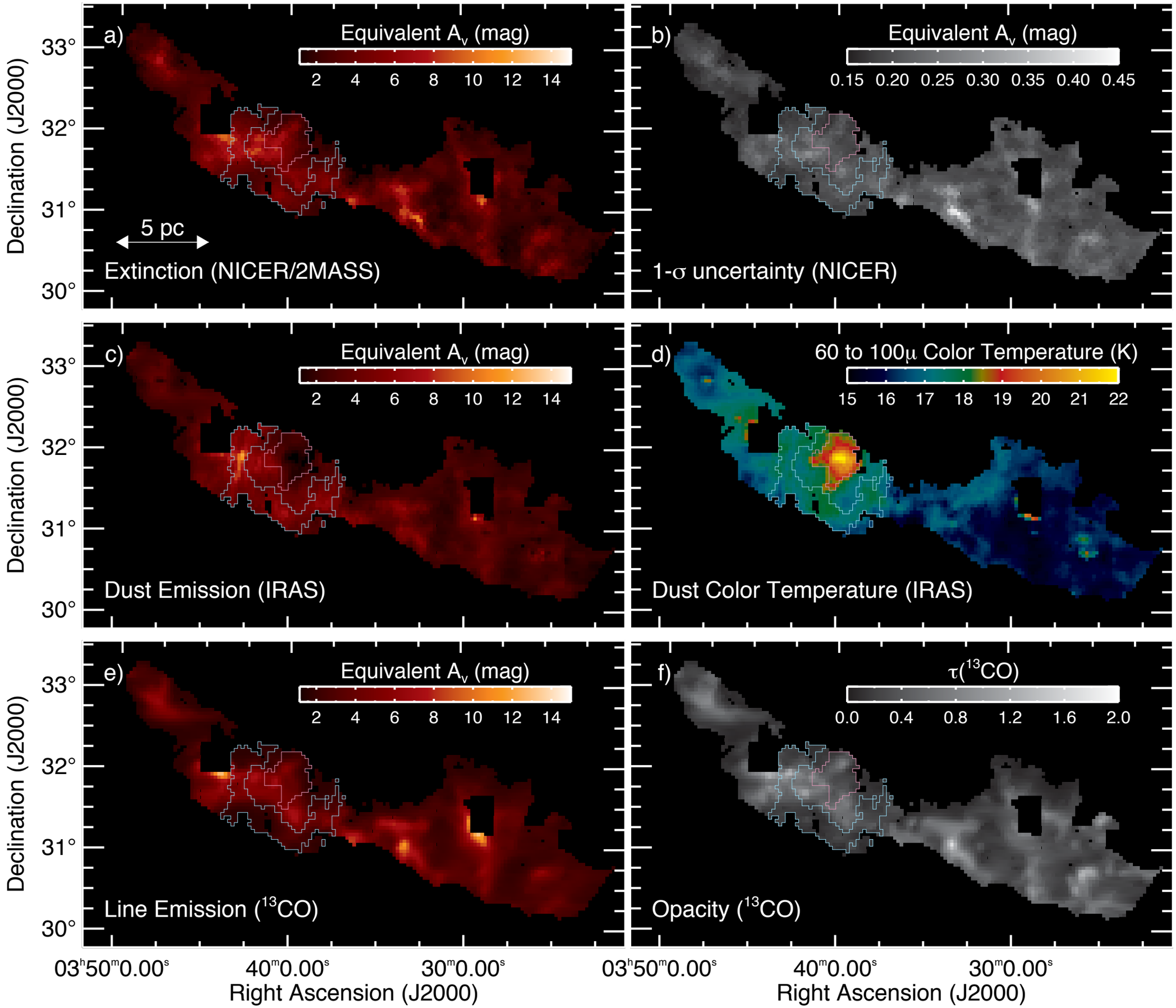
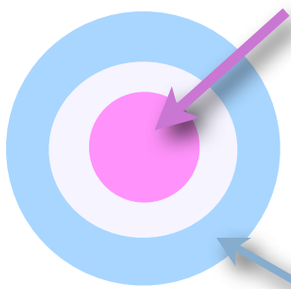


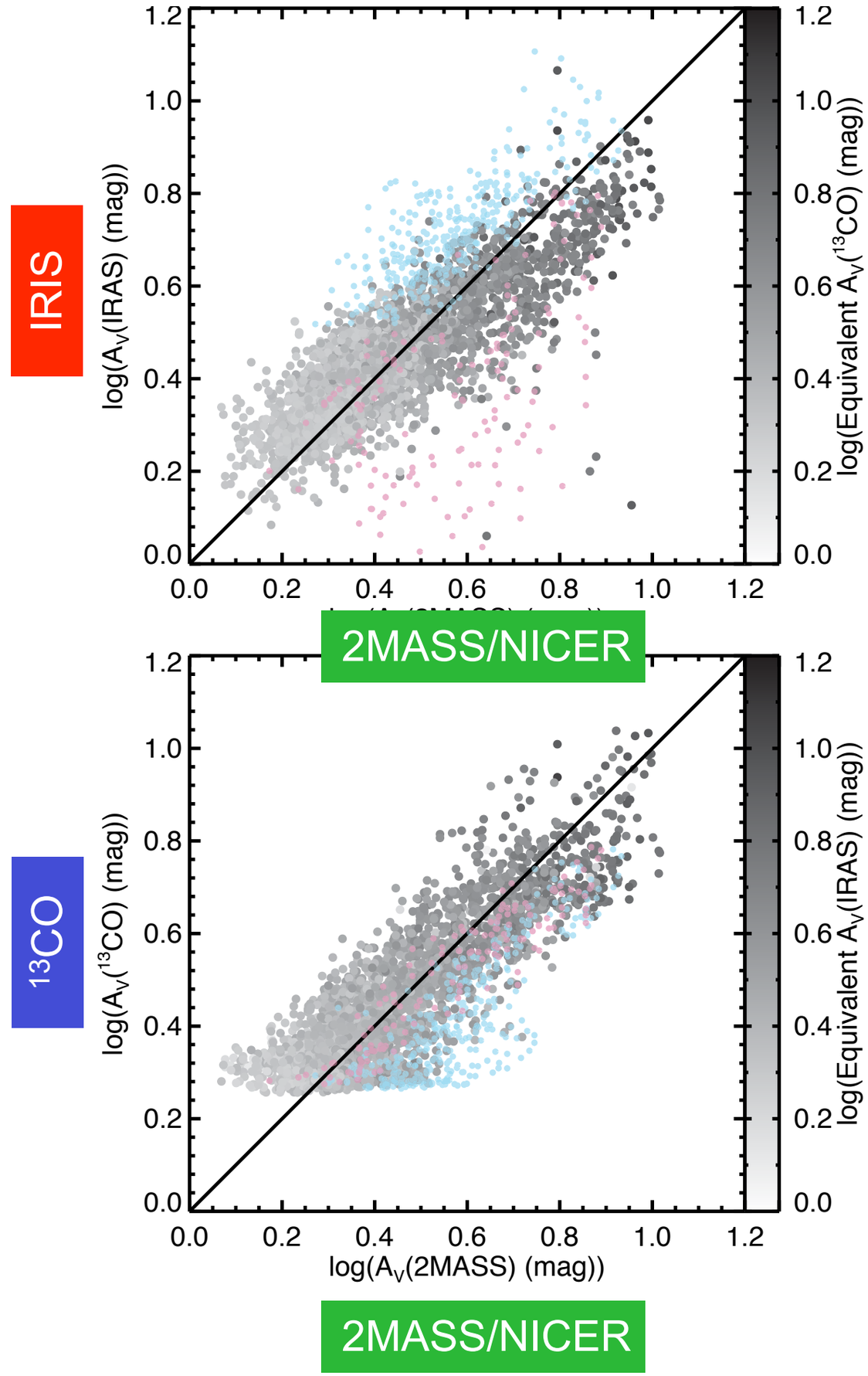
Goodman, Schnee, Pineda, Ridge 2007; see also Pineda, Caselli & Goodman 2007.

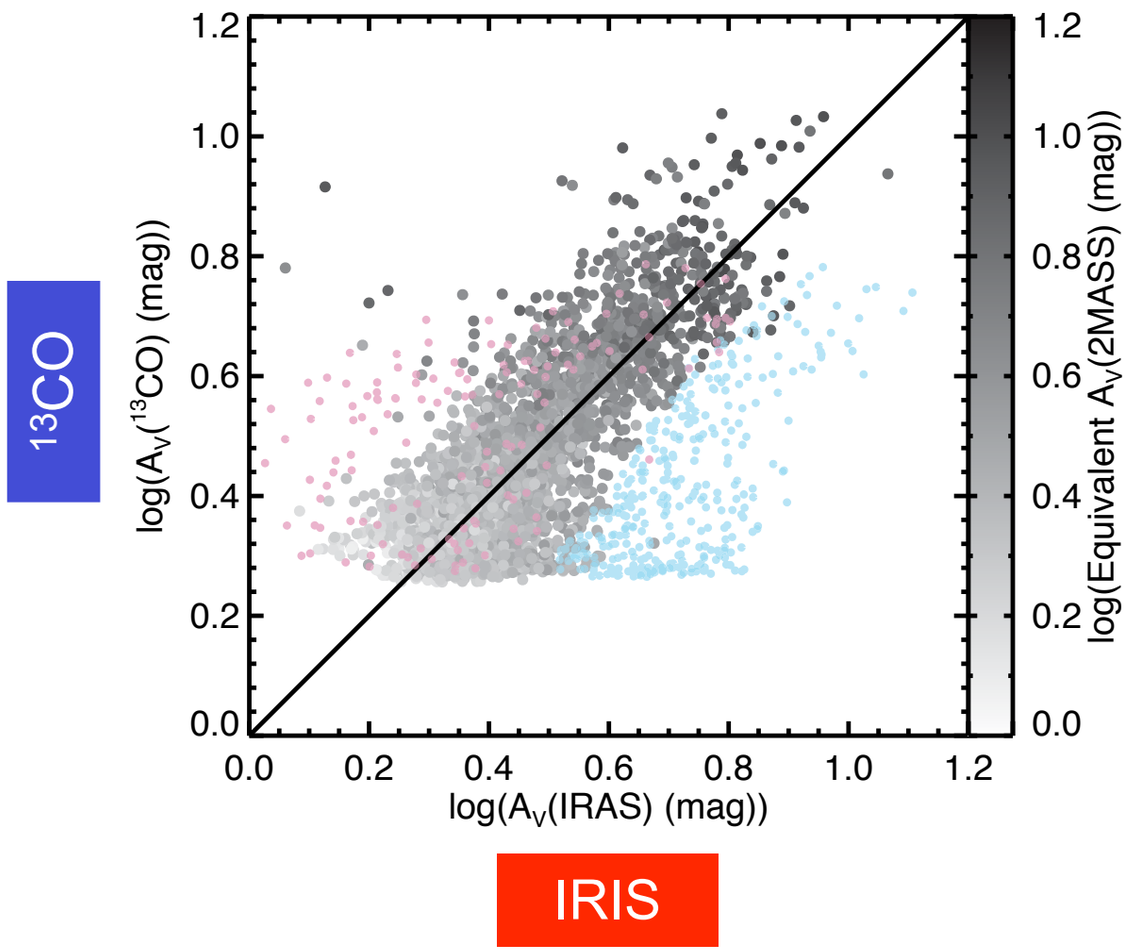
Detailed Correlations,
and that Pesky Shell



Hot, tenuous interior, ^{13}CO only sees cold stuff (OK) and N_{IRAS} too low (b/c of local high T)

Warm, dense ring, **^{13}CO missing**, and N_{IRAS} too high





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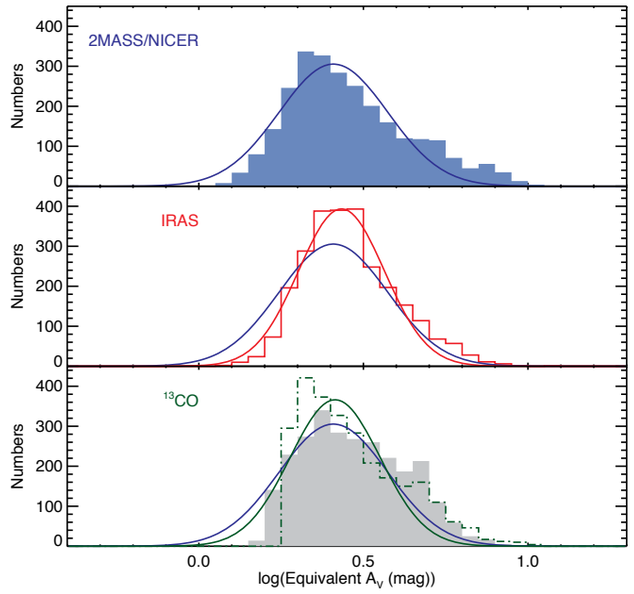
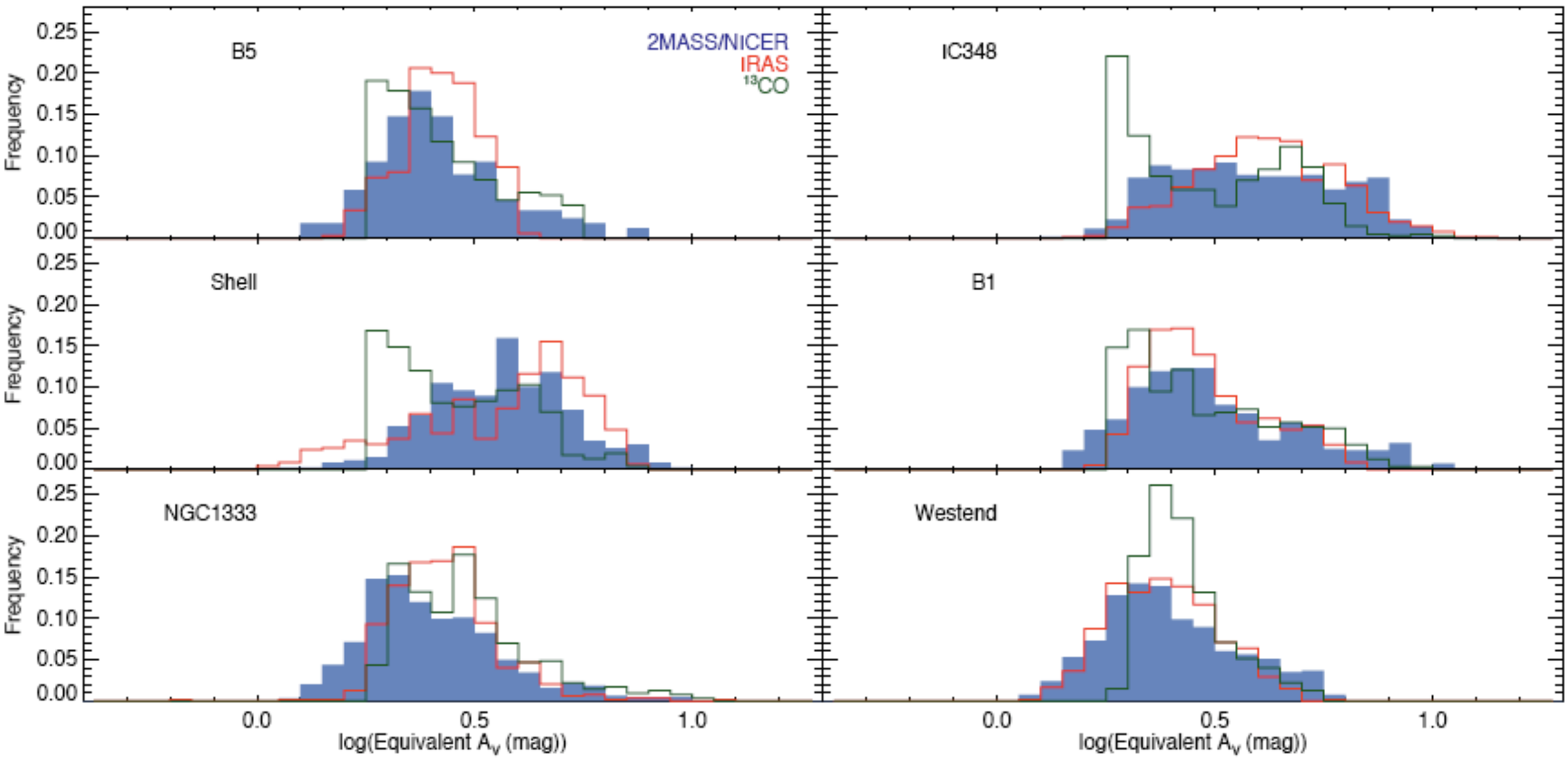


Regional Variations are Significant

(and predicted, with meaning, see Vazquez-Semadeni 1994)



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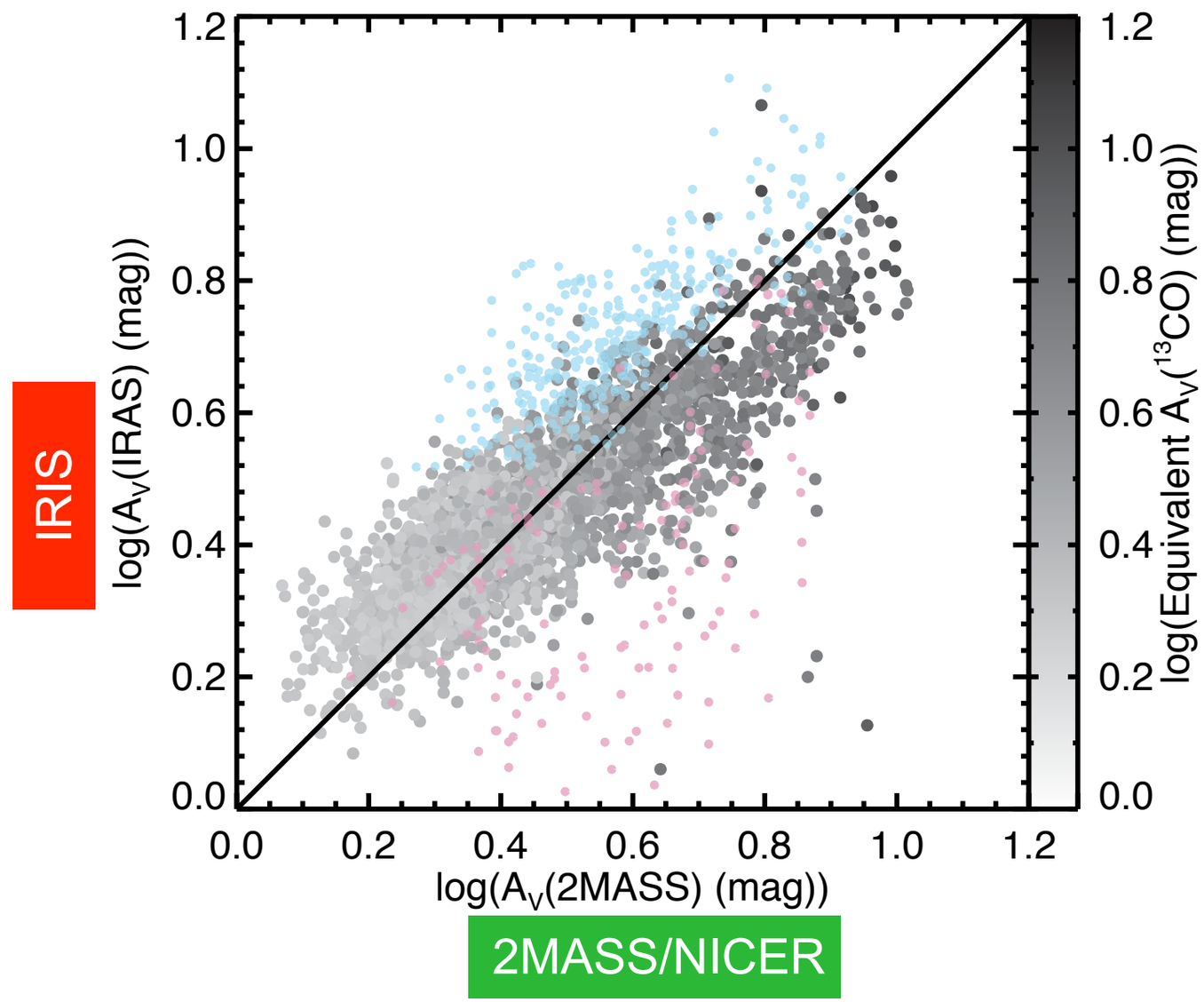
4. Plane-of-the-Sky Temperature Maps, even carefully made, are deceiving due to l.o.s temperature variations

Sources of Scatter

Errors introduced by the assumption of isothermal dust along each line of sight

Variable fraction of emission from transiently heated very small dust grains

Variable dust properties (e.g. emissivity or emissivity spectral index)



Schnee, Bethell & Goodman 2006

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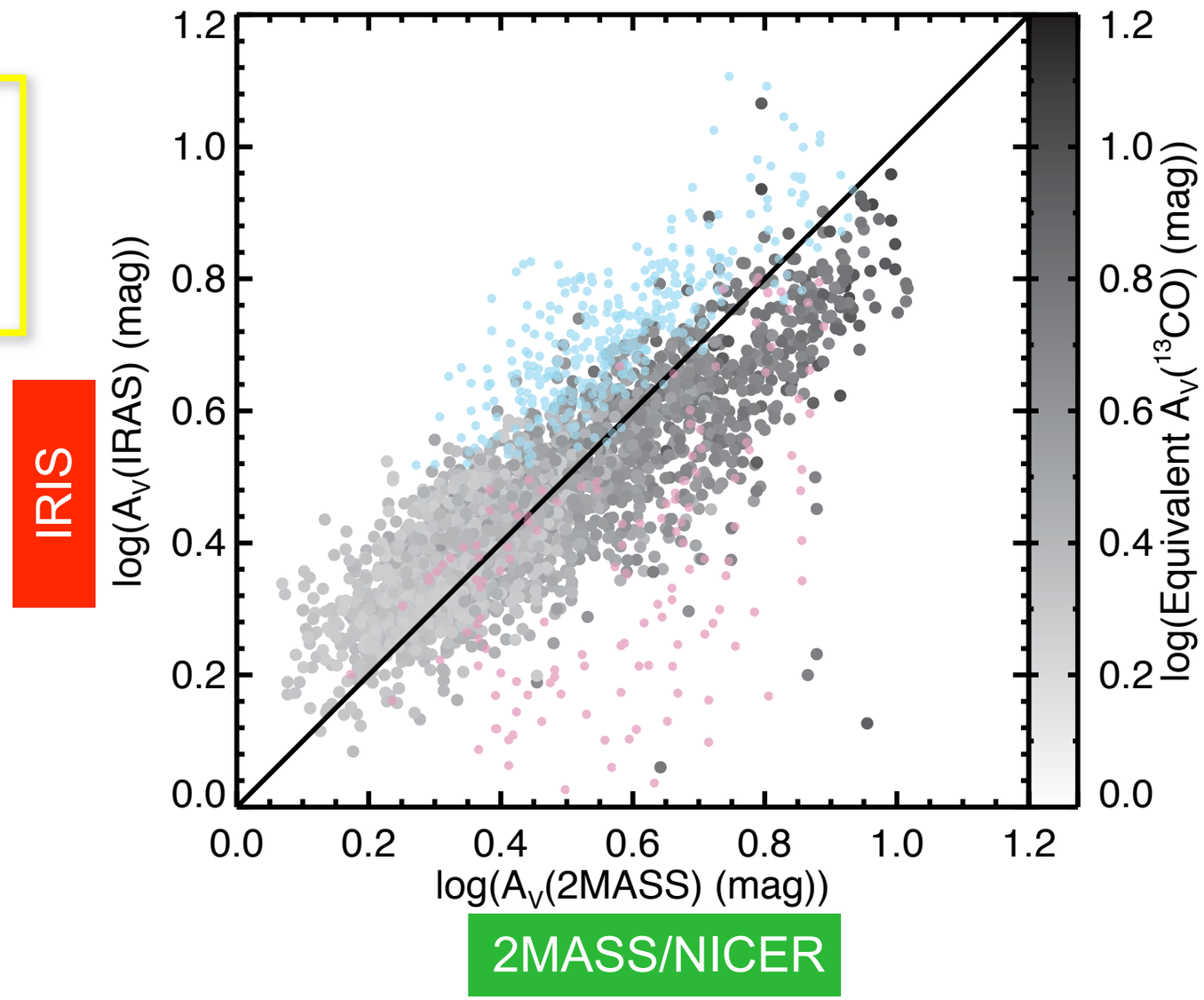
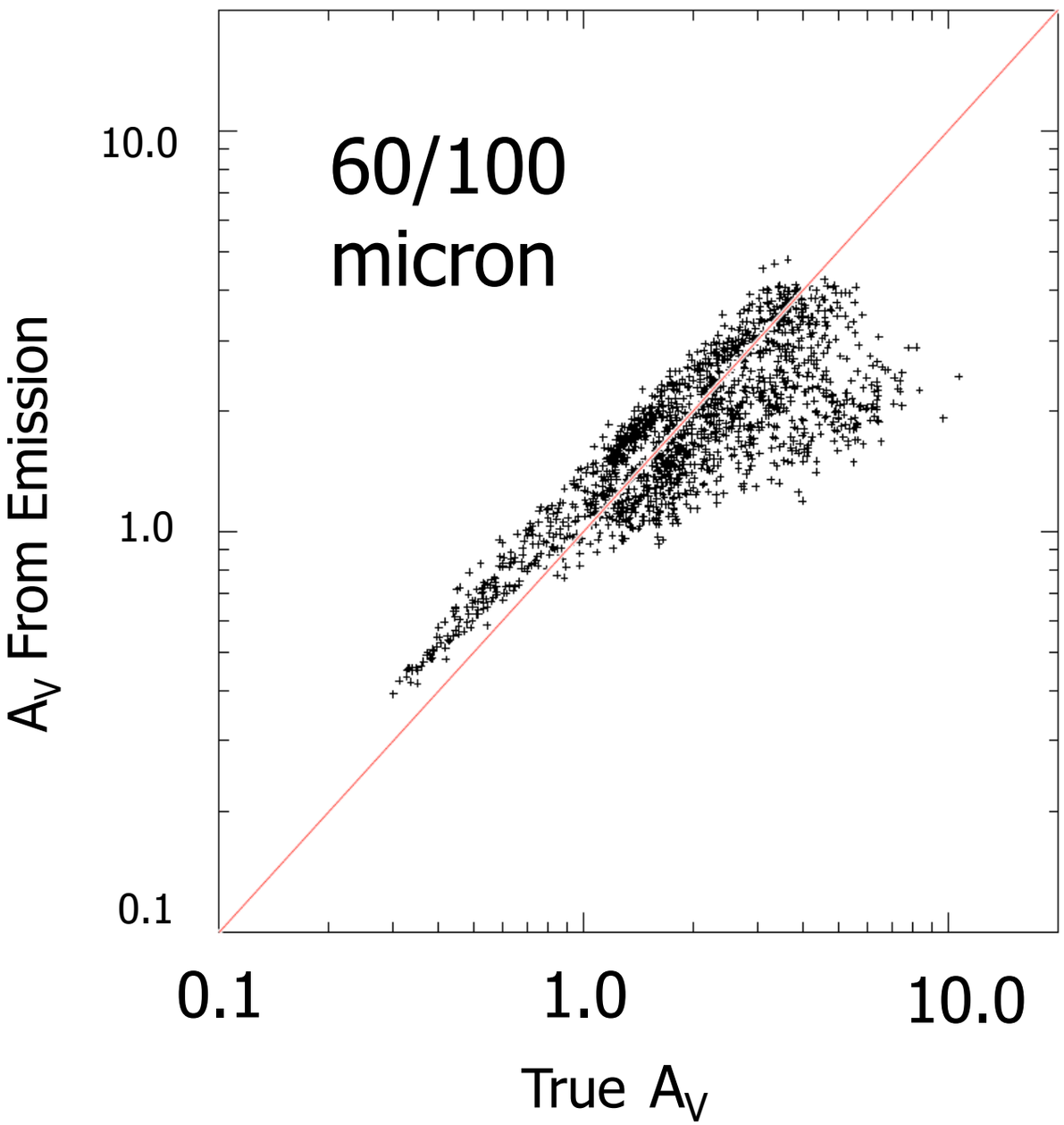
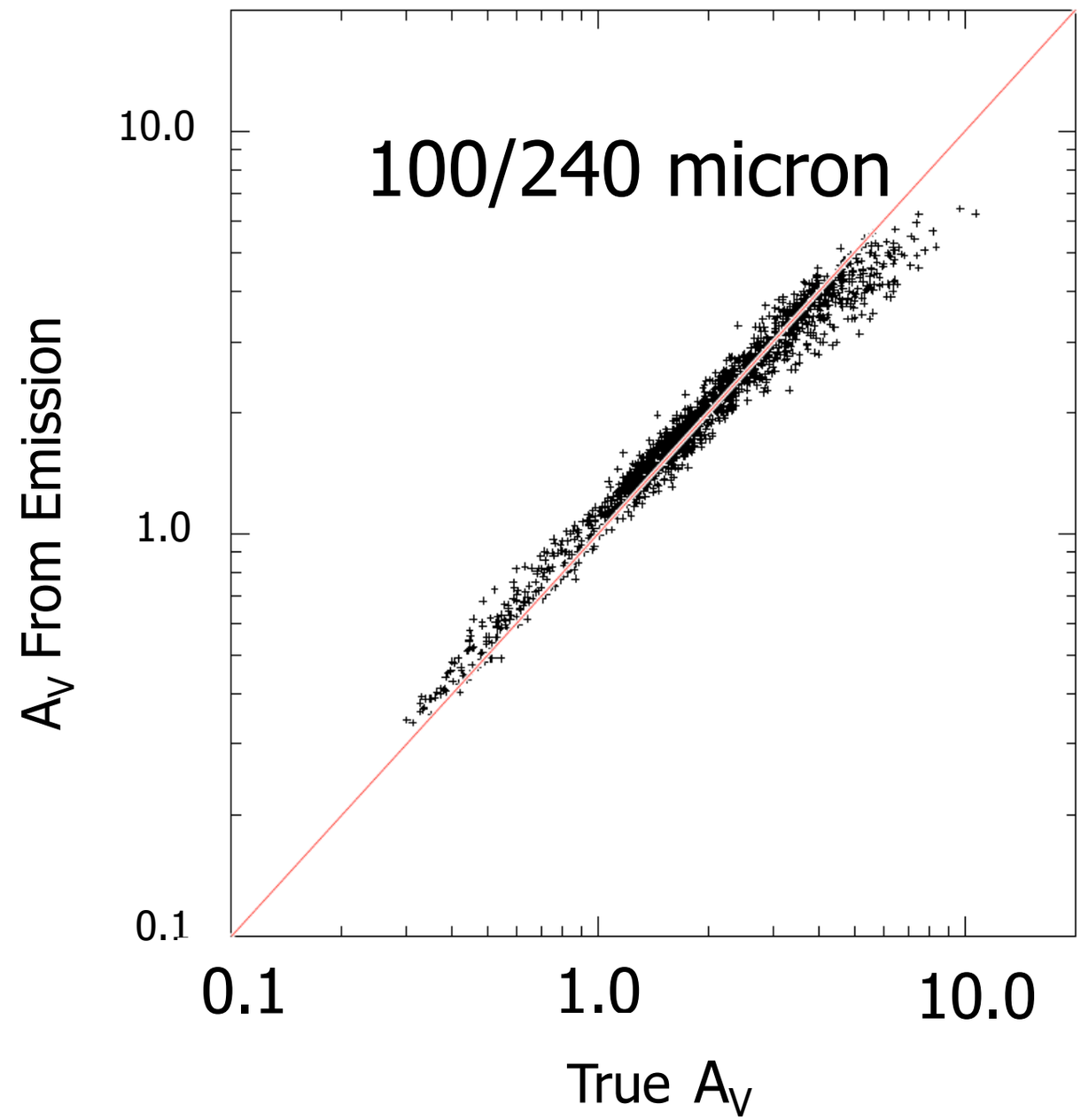


Schnee, Bethell & Goodman 2006

MHD Simulation+Radiative Xfer Code





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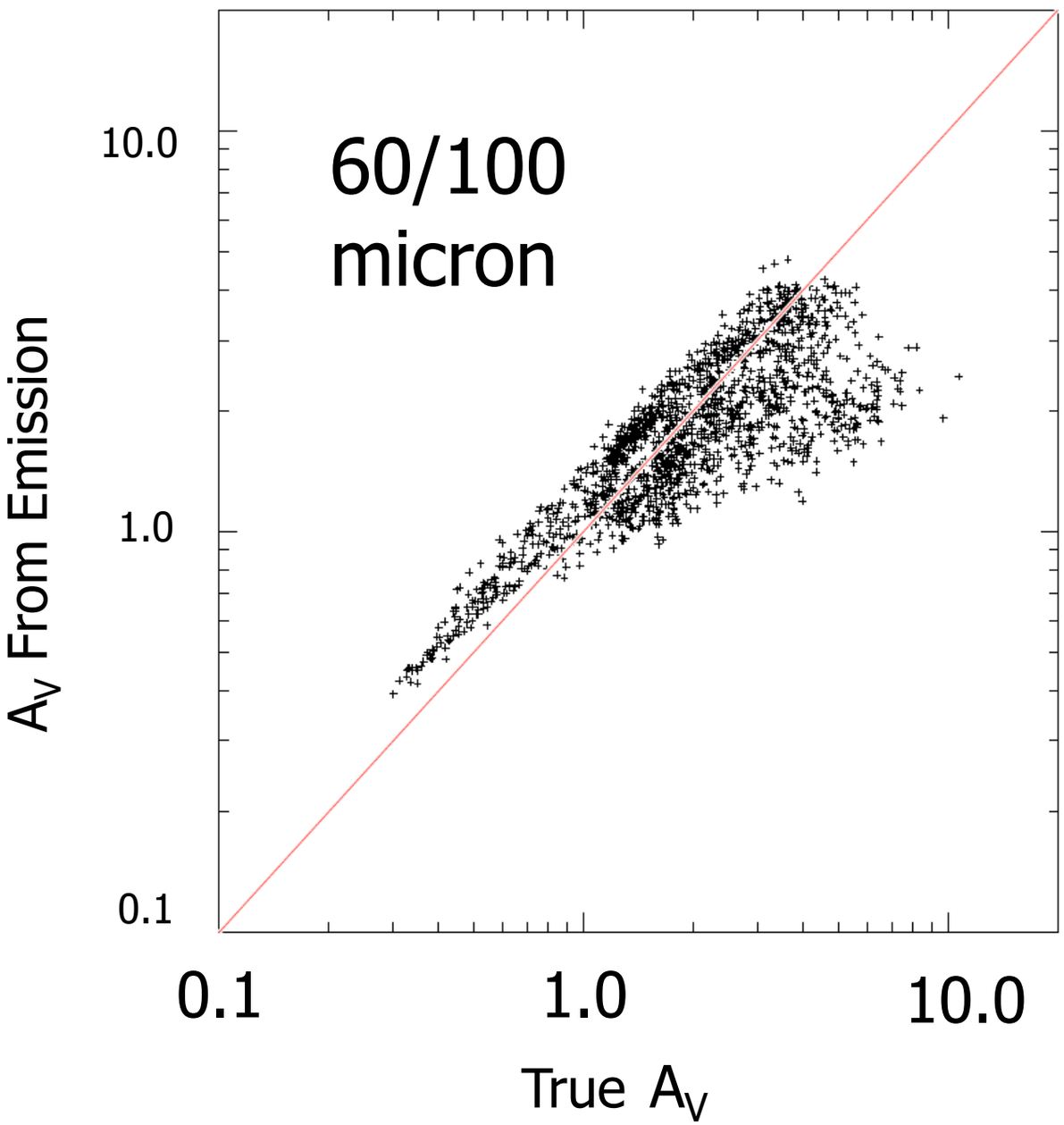
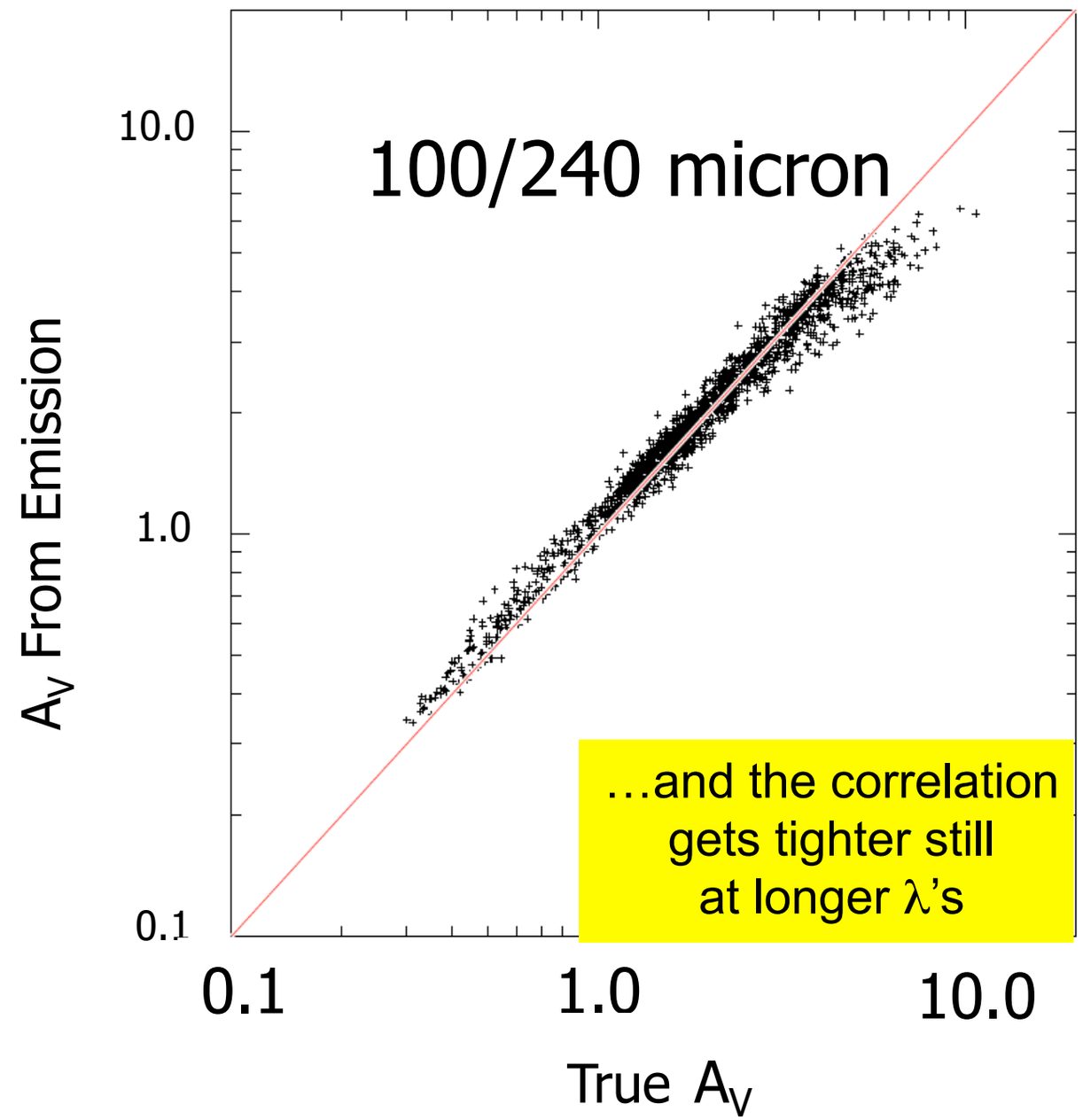
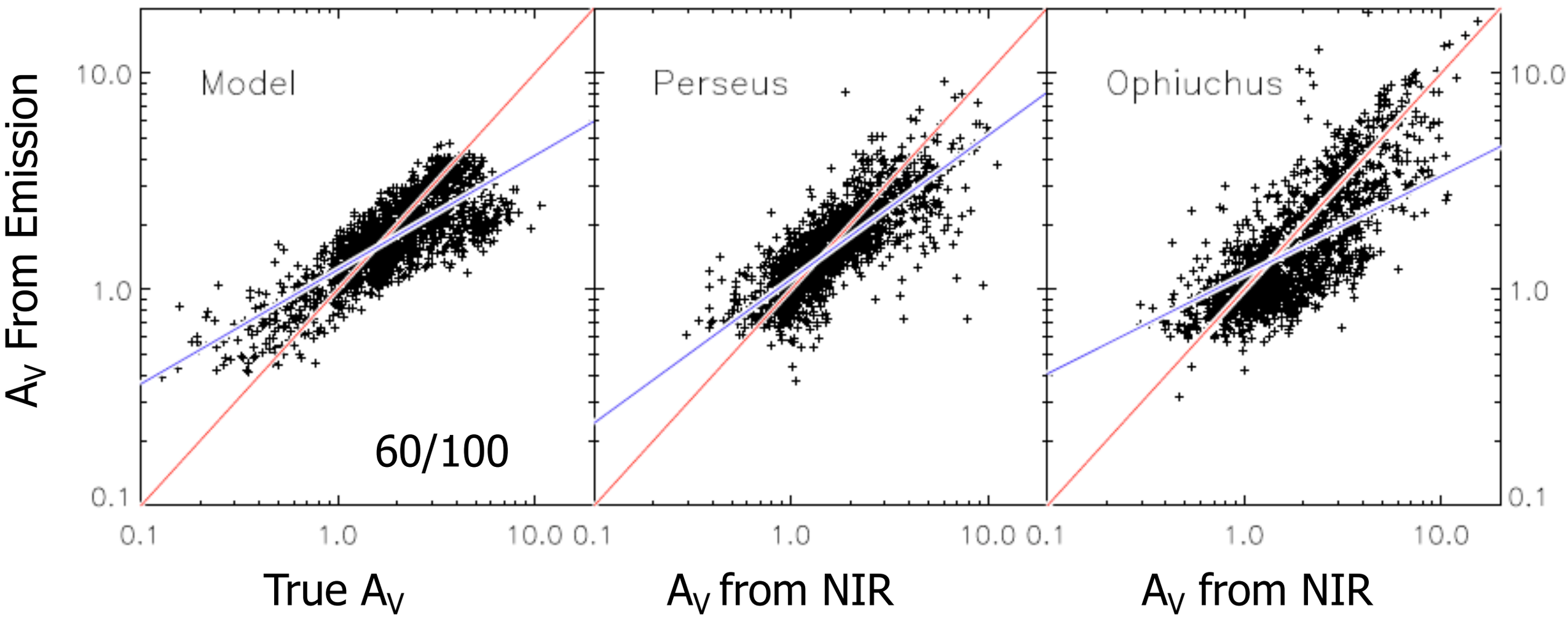




…and the correlation gets tighter still at longer λ's

Schnee, Bethell & Goodman 2006

With Realistic Noise



Schnee, Bethell & Goodman 2006

3. Scattered light ("Cloudshine") is potentially a GREAT way to improve resolution of dust maps, and potentially a big headache for JWST

COMPLETE Extinction Mapping Bonus #1:

"Cloudshine"=Scattered Ambient Starlight

L106 FOSTER & GOODMAN Vol. 636
2006

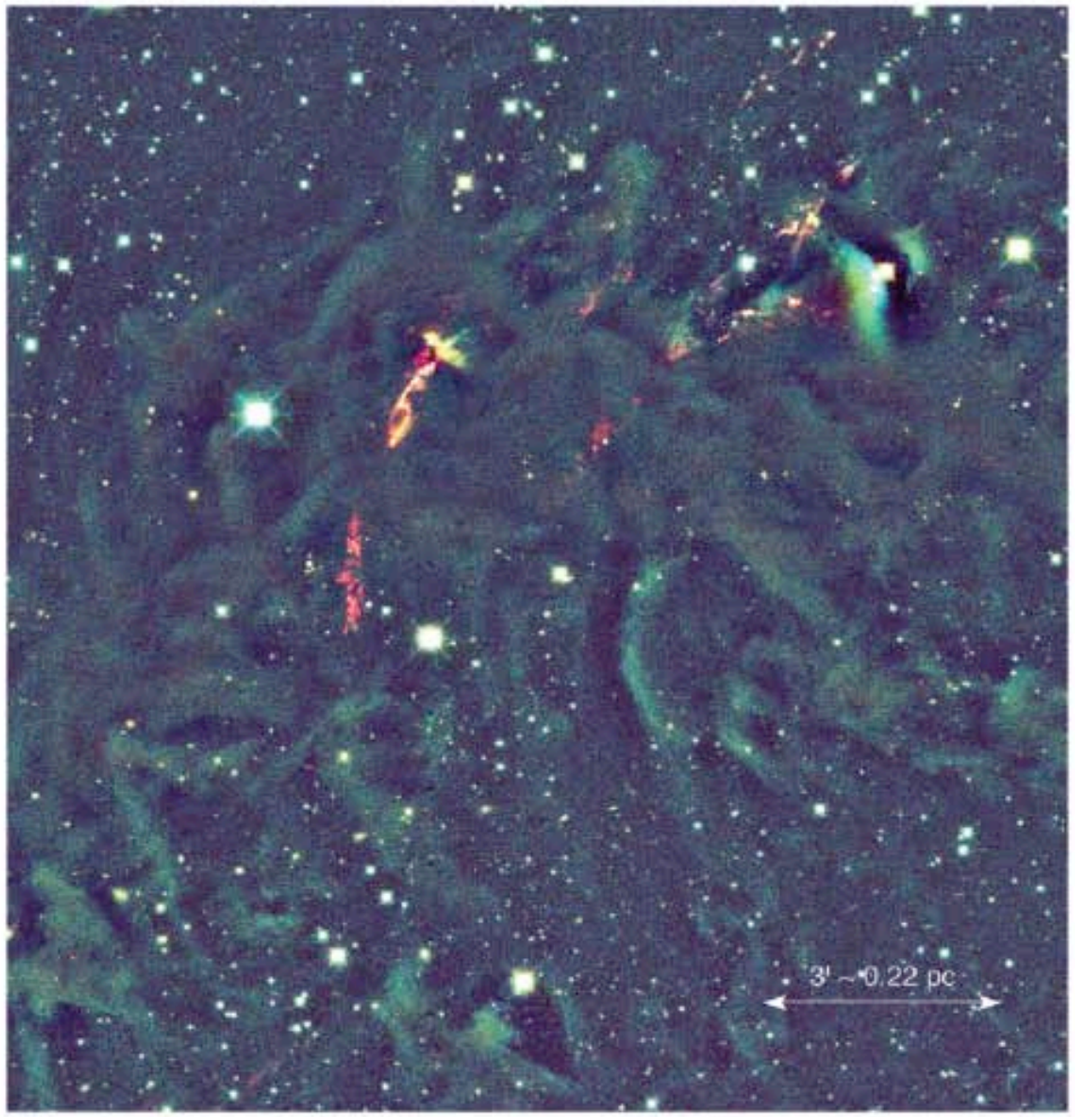


FIG. 1.—L1448 in false color. Component images have been weighted according to their flux in units of MJy sr^{-1}. J is blue, H is green, and K_s is red. Outflows from young stars glow red, while a small fan-shaped reflection nebula in the upper right is blue-green. Cloudshine, in contrast, is shown here as a muted glow with green edges. Dark features around extended bright objects (such as the reflection nebula) are the result of self-sky subtraction.

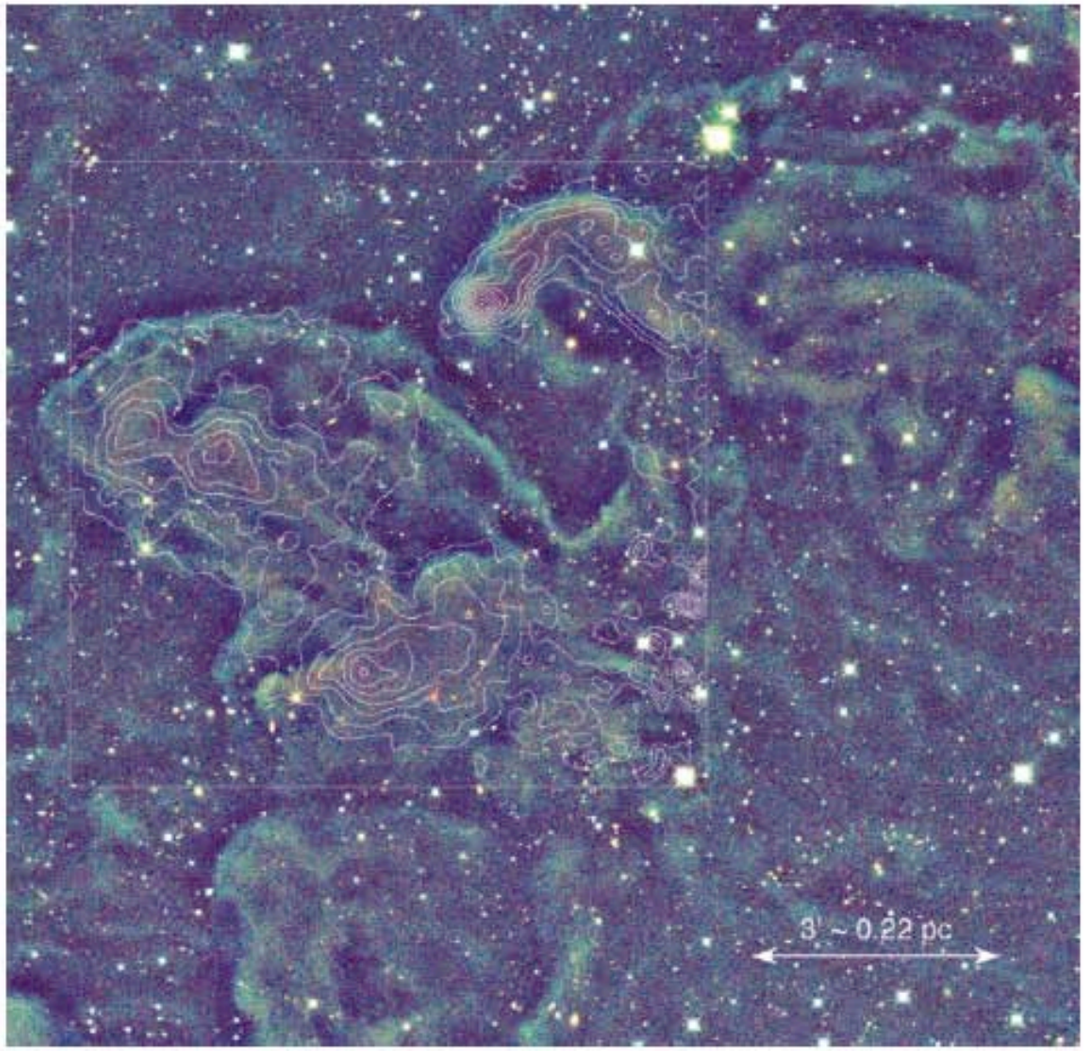
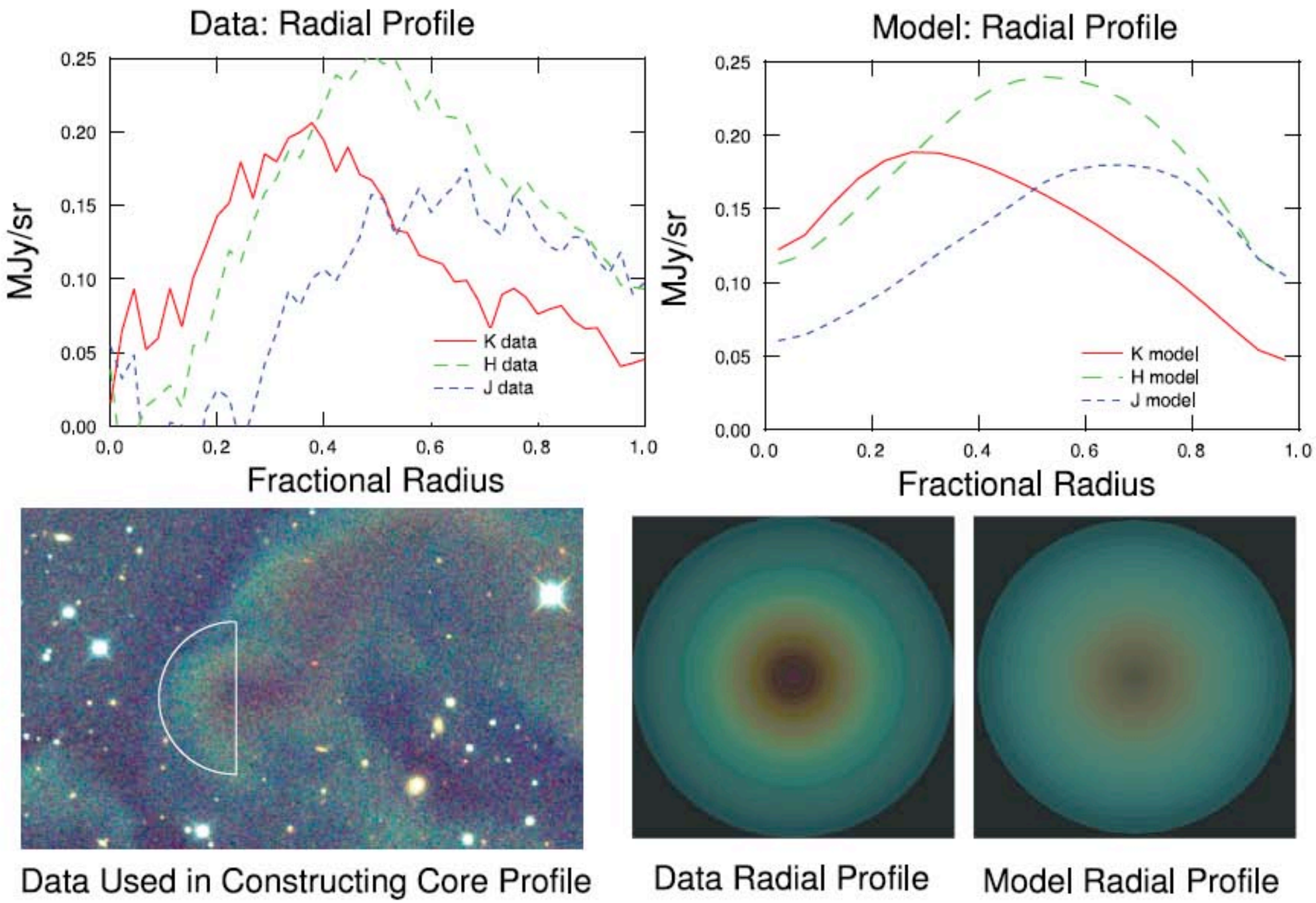


FIG. 2.—L1451 in false color. Again, each component image has been scaled to the same flux scale in units of MJy sr^{-1}; and J is blue, H is green, and K_s is red. A smaller map of 1.2 mm dust emission contours from COMPLETE (M. Tafalla 2006, in preparation) has been overlaid, showing that the color of cloudshine is a tracer of density. Redder regions have high dust continuum flux, and the edges of cloudshine match the edges of the dust emission. Dark edges around bright features (particularly noticeable along the northern edges) are the result of self-sky subtraction.

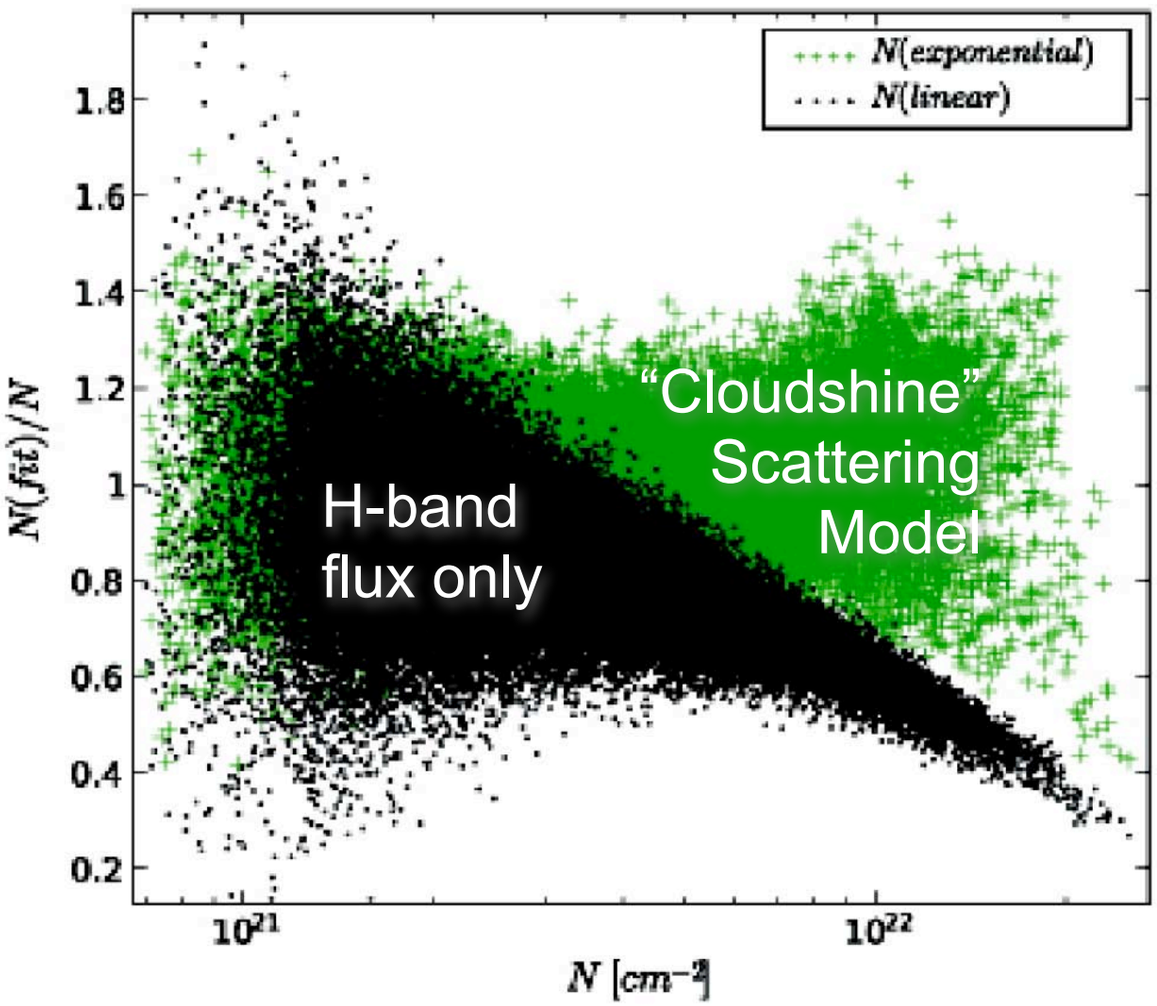
Tasting a Very Simple Recipe



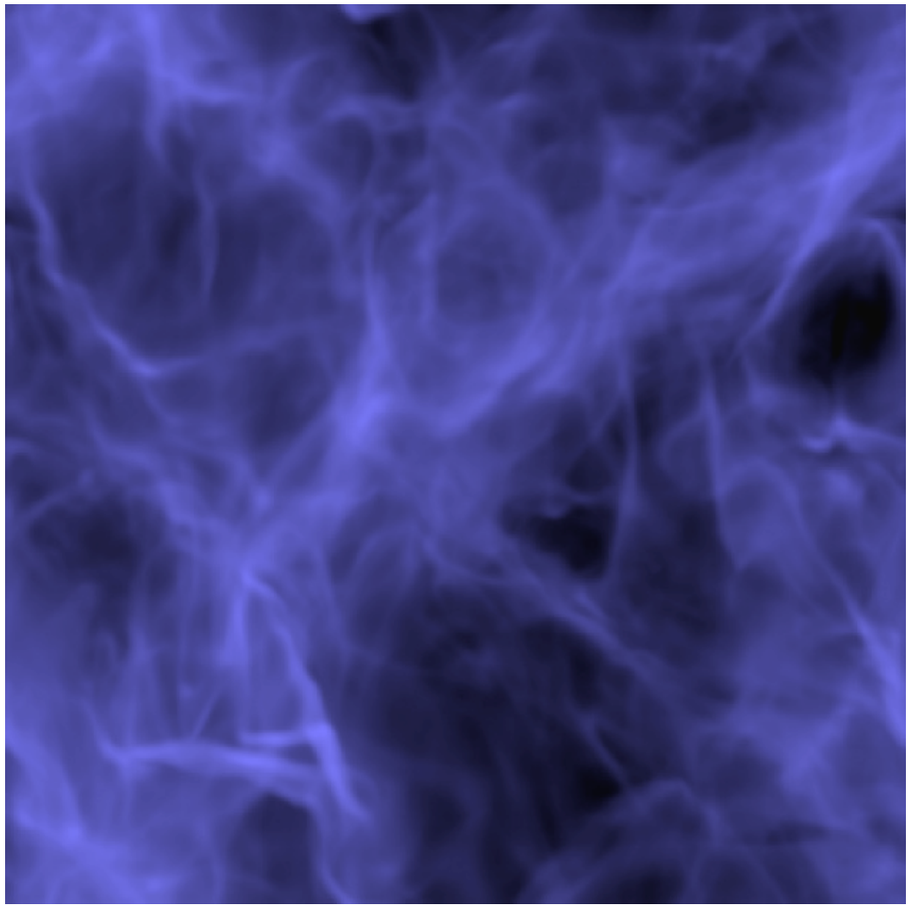
Foster & Goodman 2006

FIG. 3.—Model of cloudshine in one core as reflected interstellar radiation. The lower left panel shows the roughly circular feature we chose to model as a sphere. Due to the surrounding structure, only the left half of the circle was used to derive an angle-averaged radial profile. The comparison between this radial profile and our best-fit model (an r^{-2} density profile and a total optical depth of 120 mag of visual extinction) is shown in two ways: above as radial flux profiles in individual bands and in the lower right as a synthetic color-composite image that allows for an overall comparison. Although the fit is good, the central region of the core is darker than predicted by the model. Some of this may be due to self-sky subtraction in the image (which causes dark edges around bright features) and a nonspherical, nonisotropically illuminated core, and some may be due to a failure to adequately model the density structure at the center of the core.

Tasting a Turbulence Theorist's Recipe



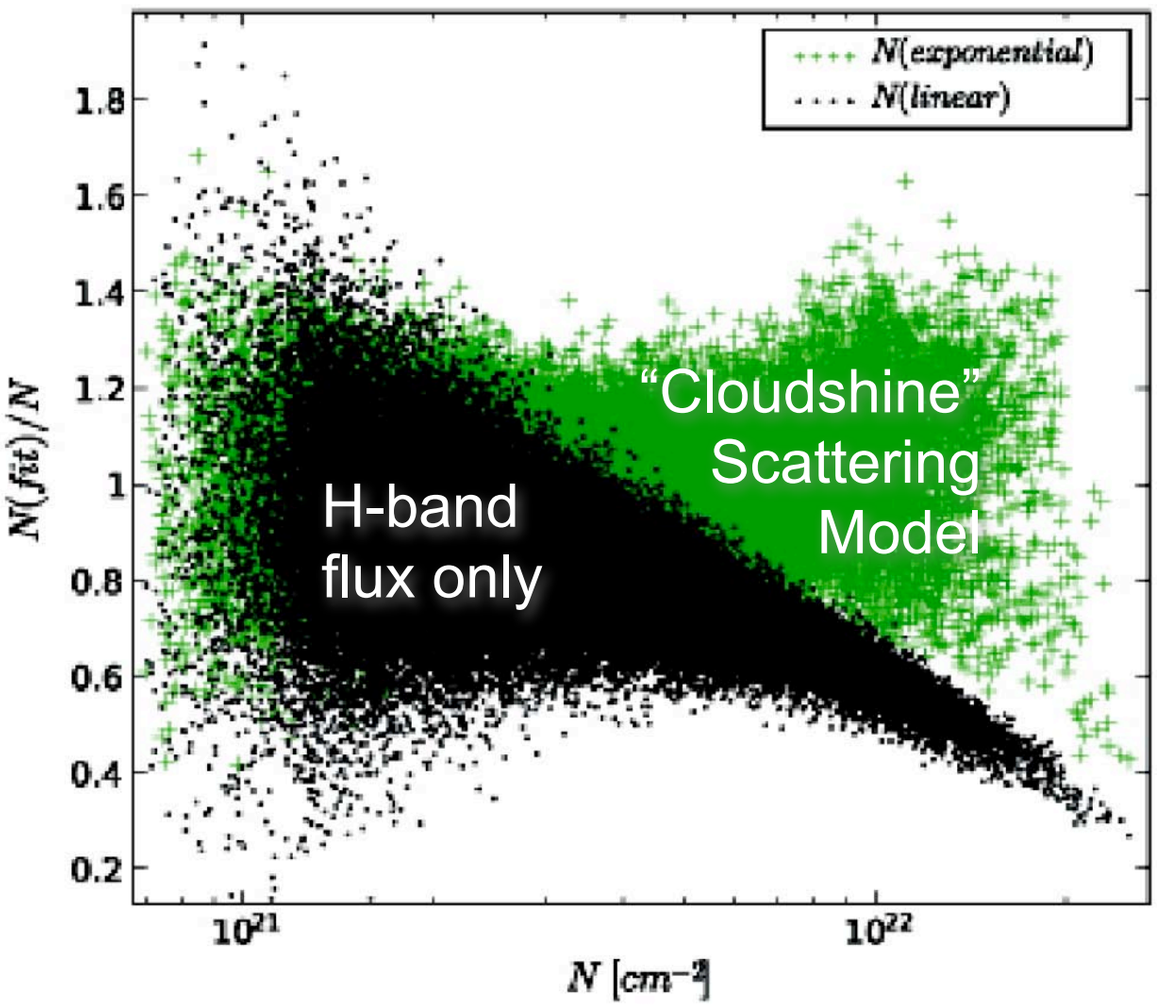
Simulation



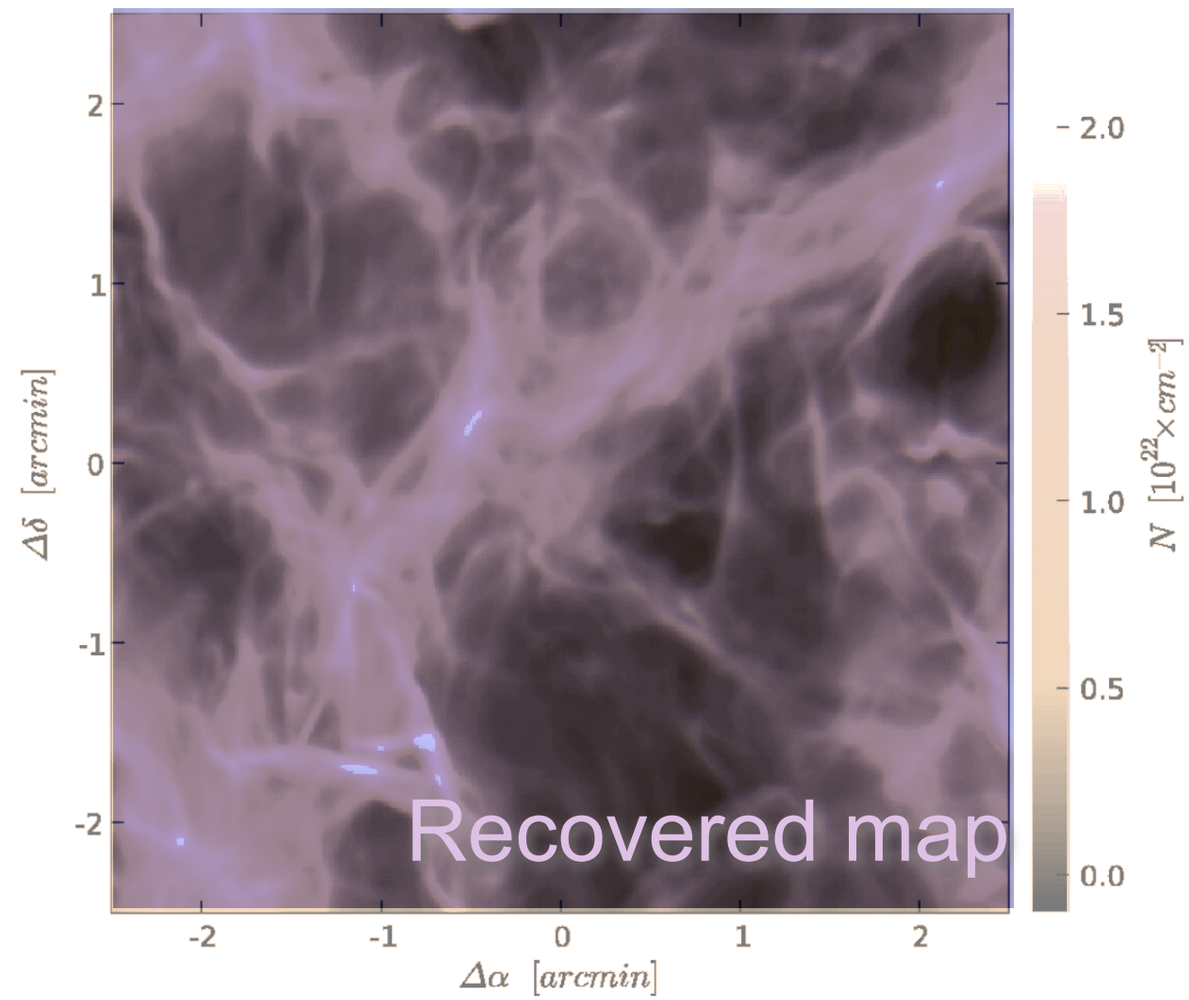
Tastes "right", with 20% scatter, at $1<A_V<10$, for NIR.

Padoan et al. 2006

Tasting a Turbulence Theorist's Recipe



Simulation



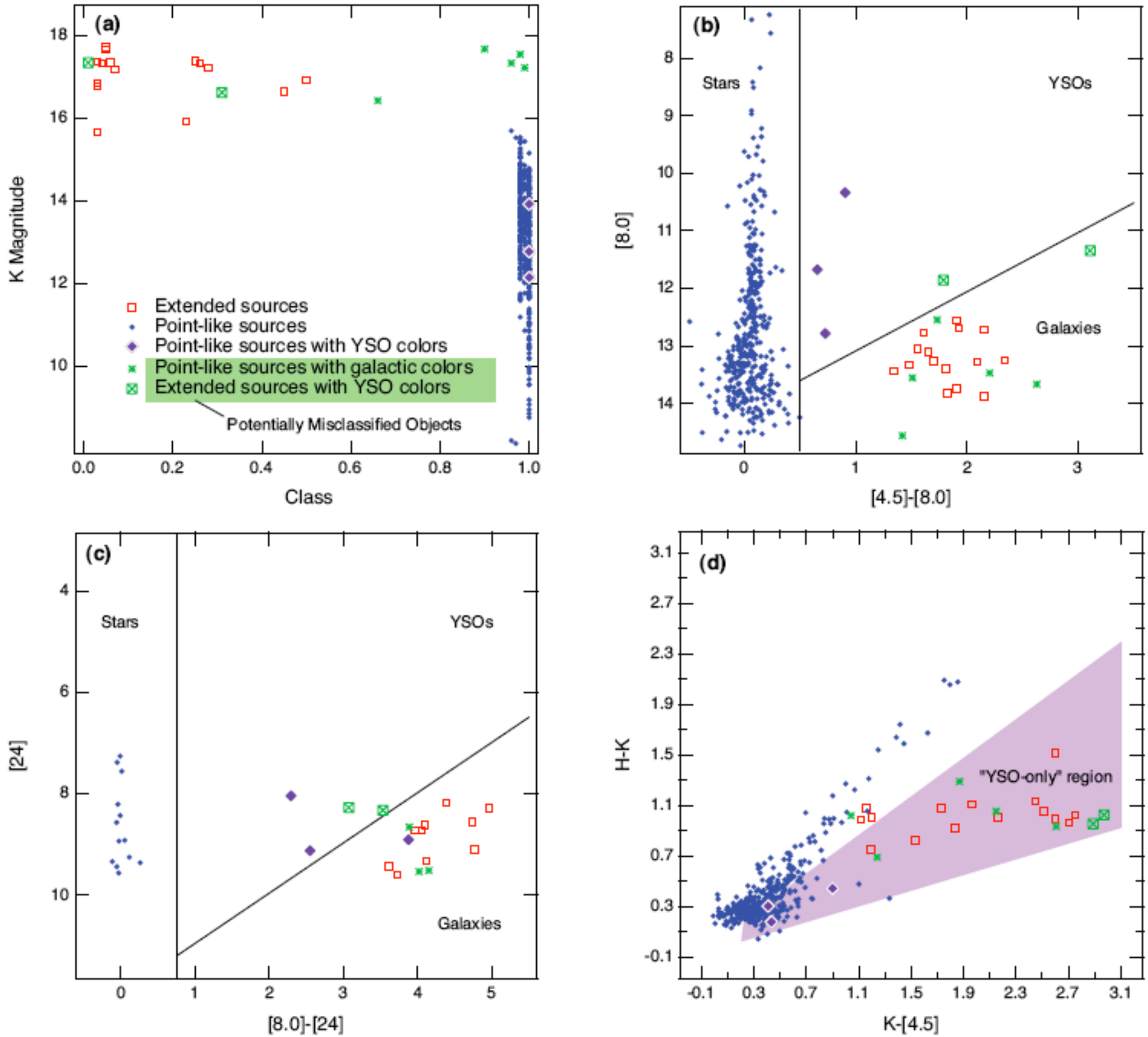
Tastes "right", with 20% scatter, at $1<A_V<10$, for NIR.

Padoan et al. 2006

COMPLETE Extinction Mapping Bonus #2:

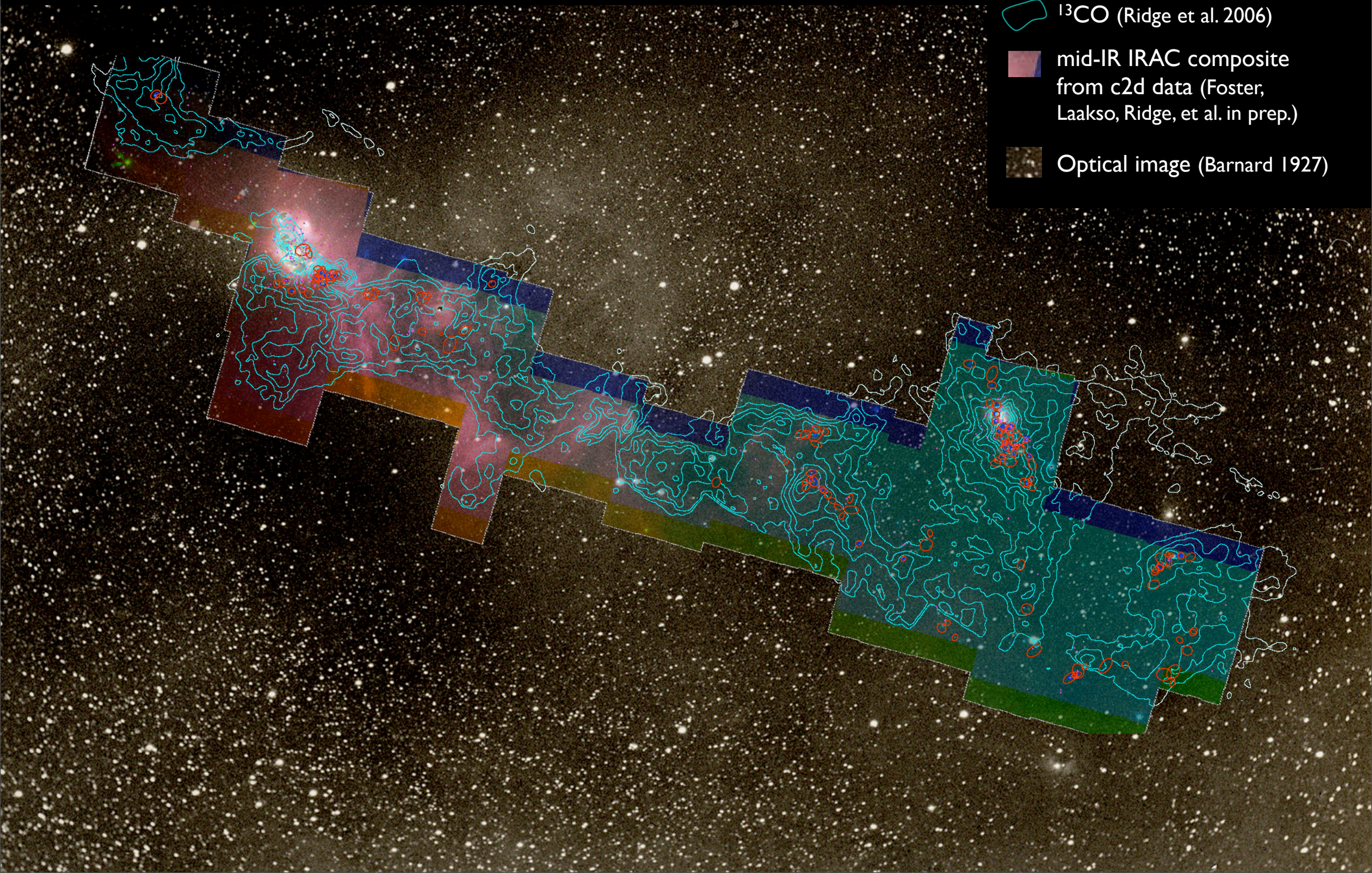
Hunting Galaxies to (and for) Extinction

see Foster et al. 2007

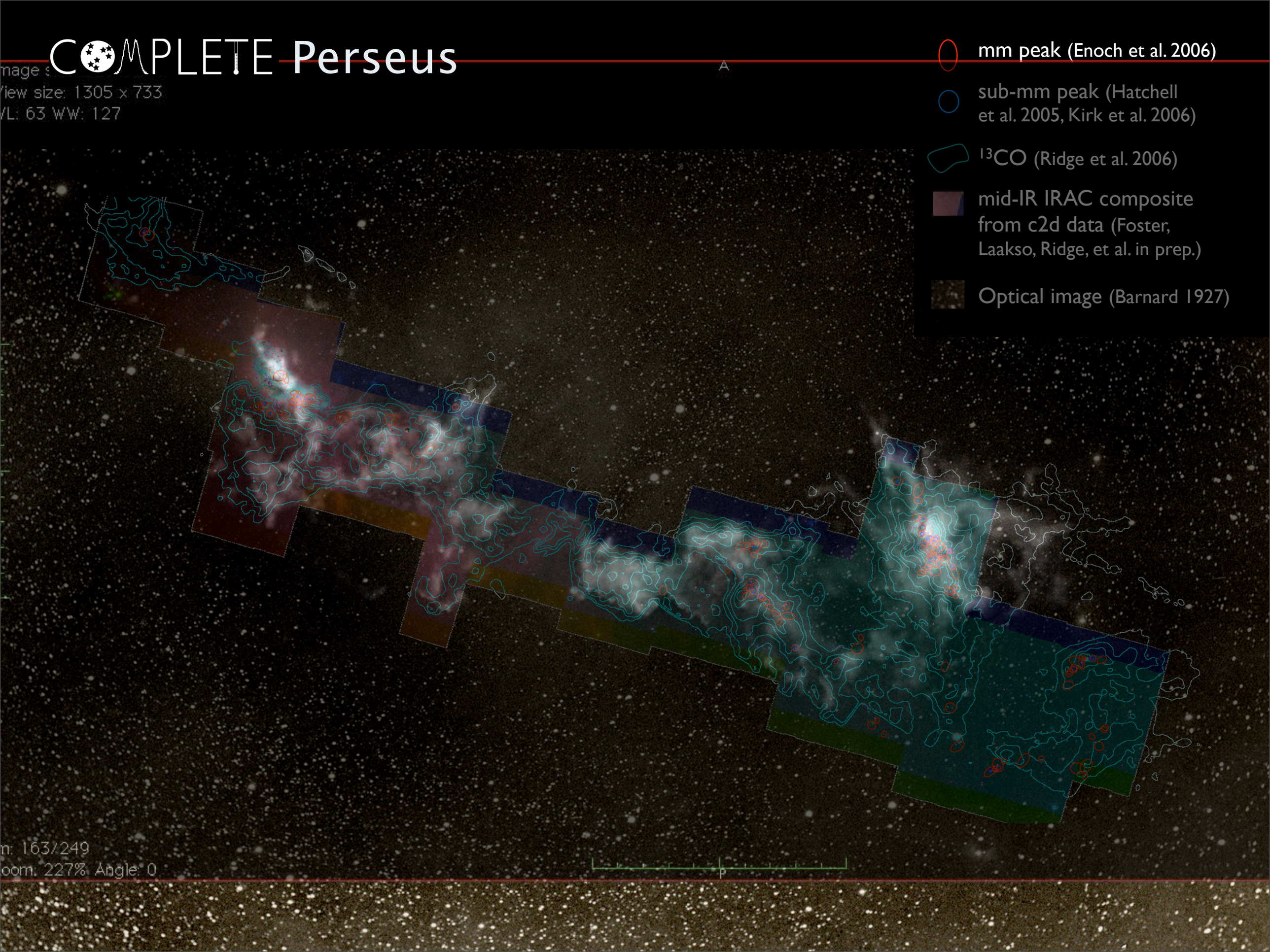


2. Self-gravity matters on a range of scales, at *identifiable* locations

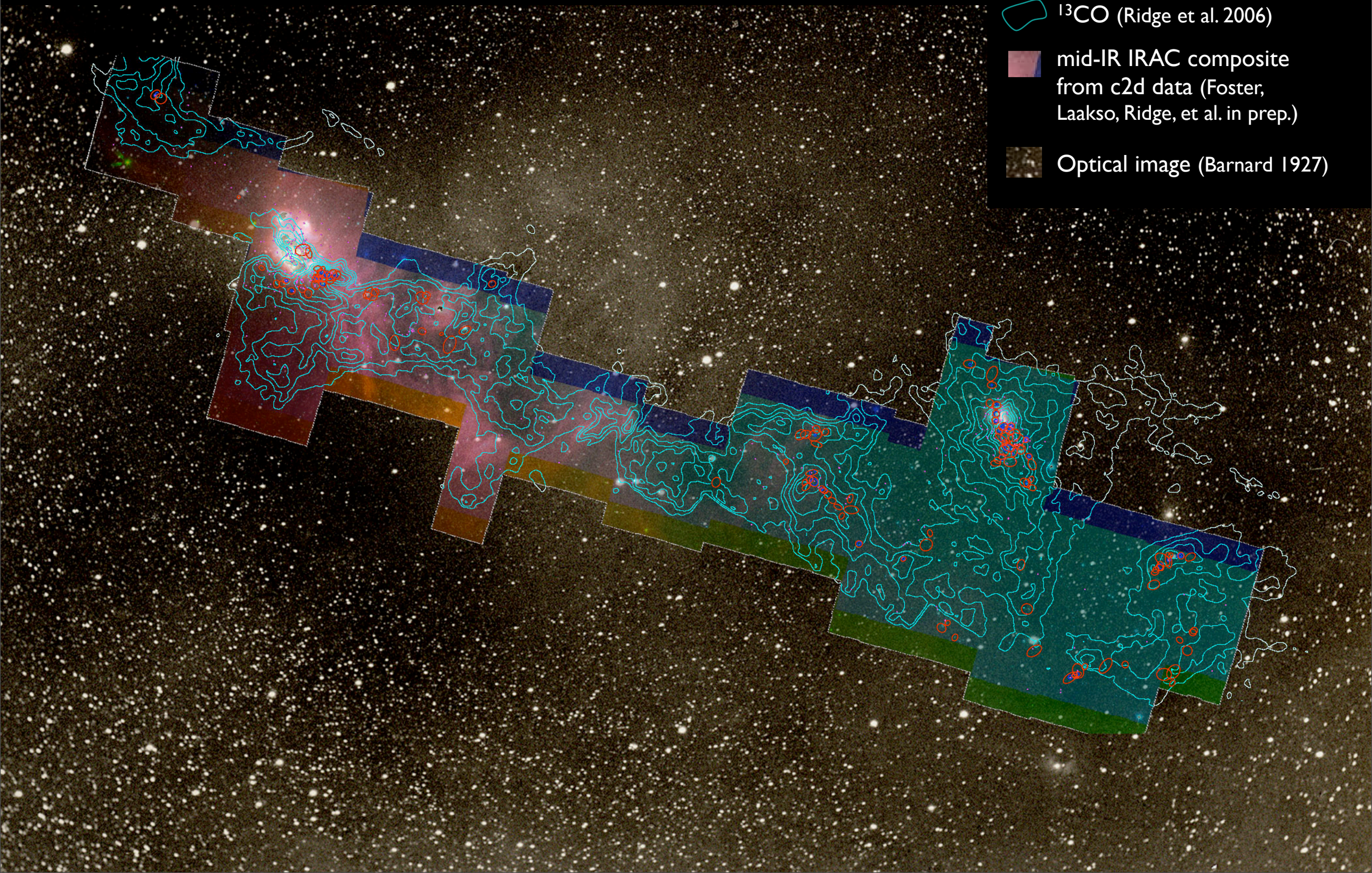
COMPLETE Perseus



COMPLETE Perseus

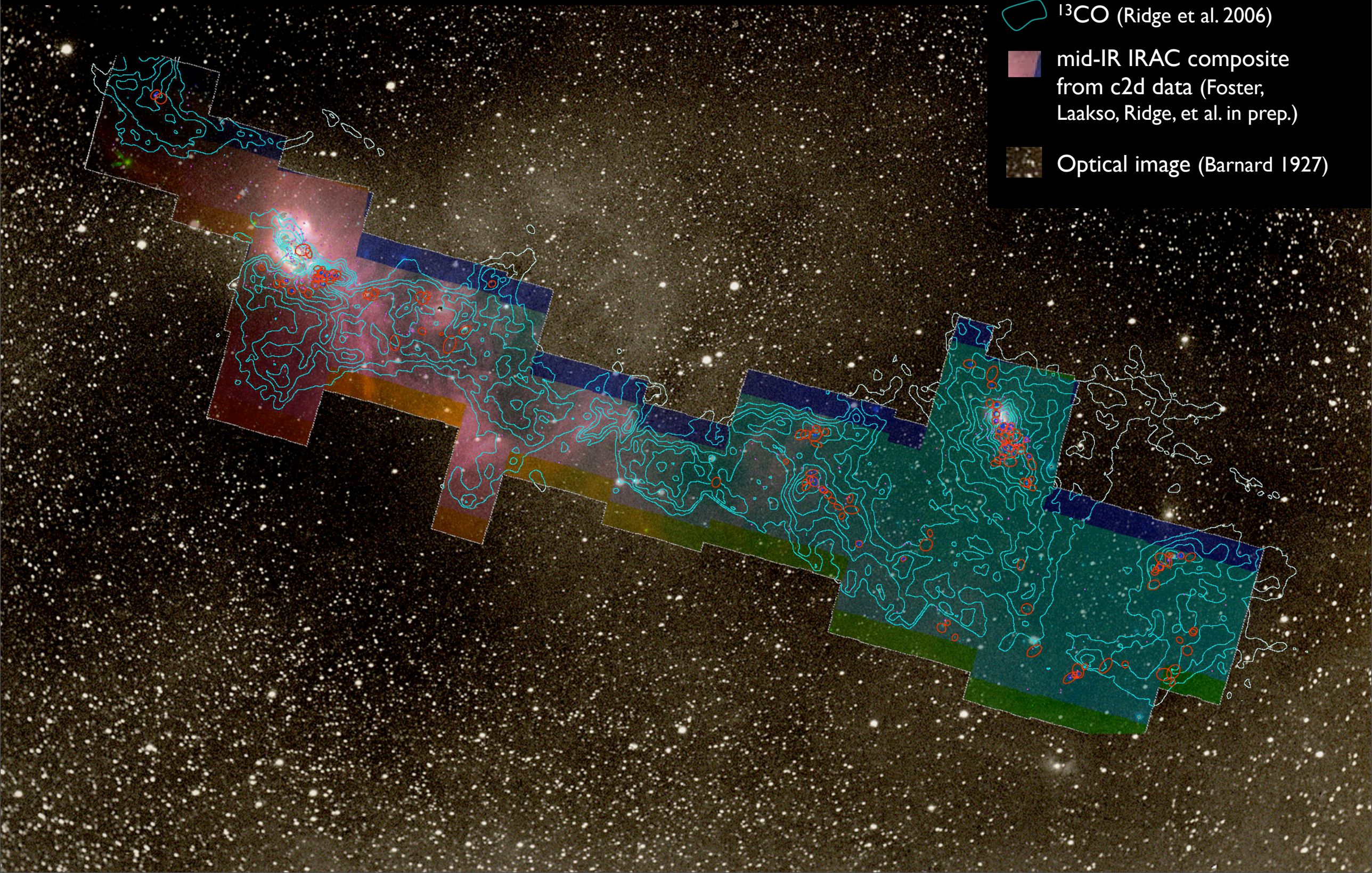


COMPLETE Perseus



position-postion-velocity is NOT the same as position-position-position-velocity-velocity-velocity

cf. Ostriker, Stone & Gammie 2001



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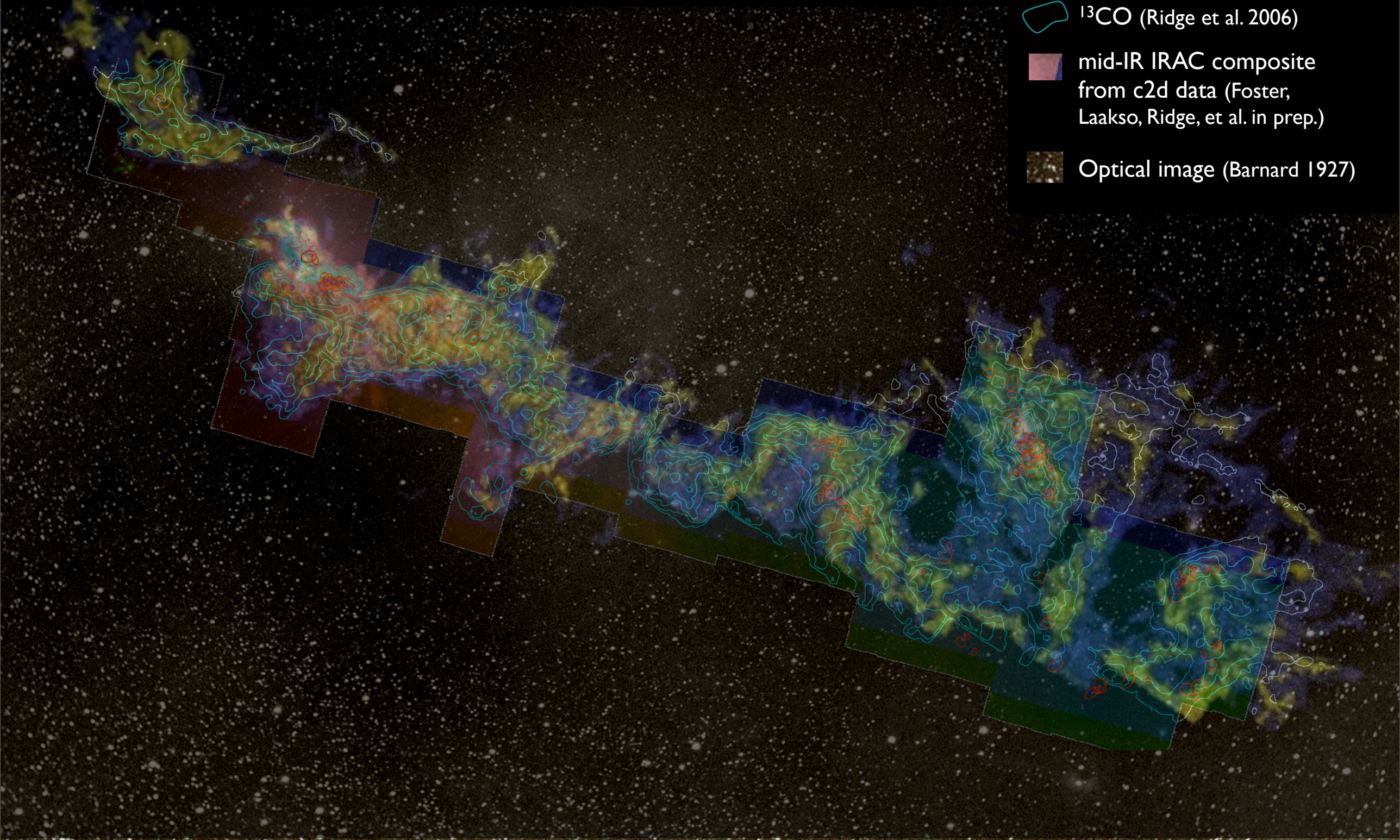
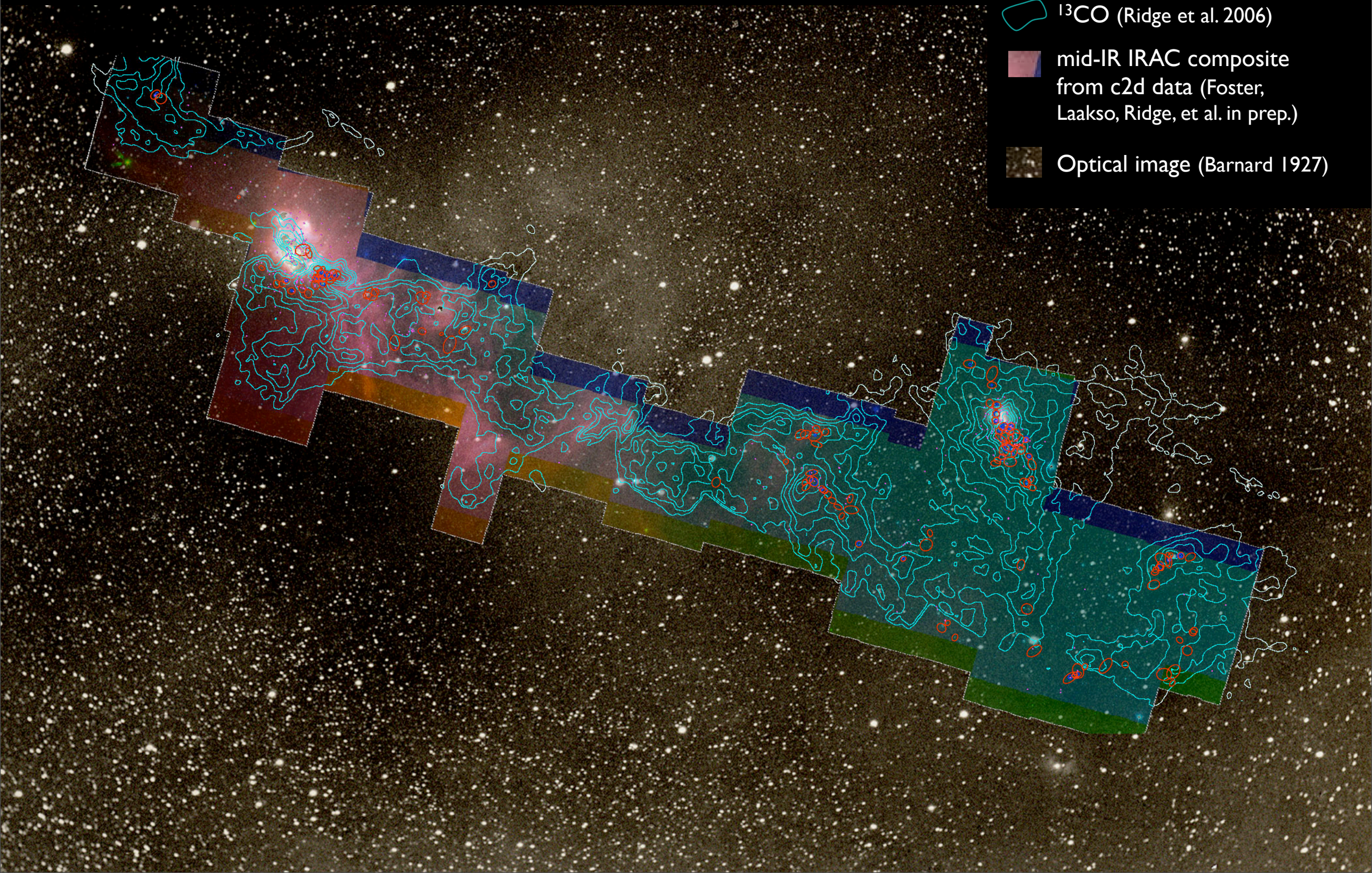


3D rendering courtesy AstroMed team @ IIC & Nick Holliman, Durham, UK

position-postion-velocity is NOT the same as position-position-position-velocity-velocity-velocity

cf. Ostriker, Stone & Gammie 2001



position-postion-velocity is NOT the same as
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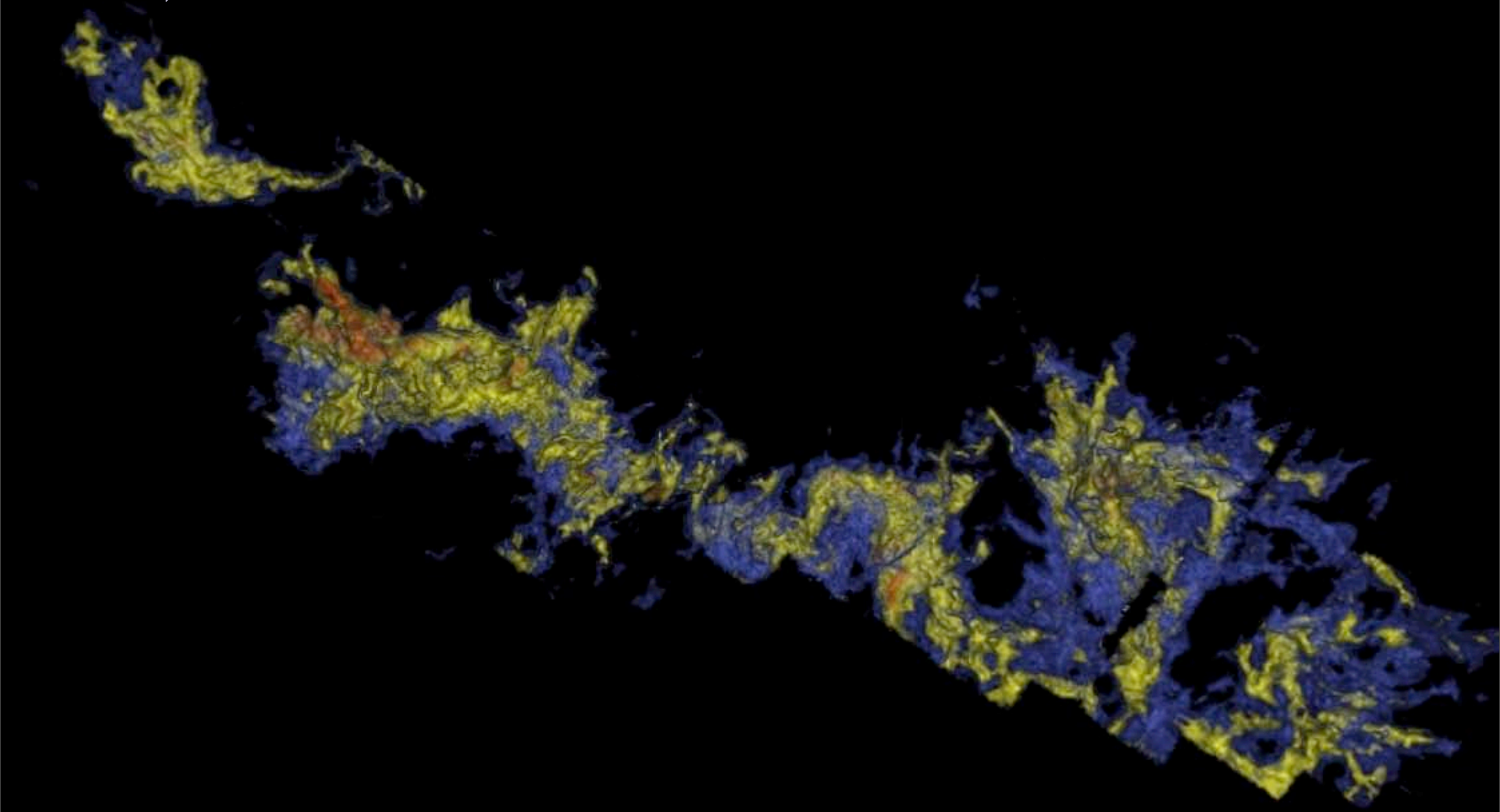
cf. Ostriker, Stone & Gammie 2001

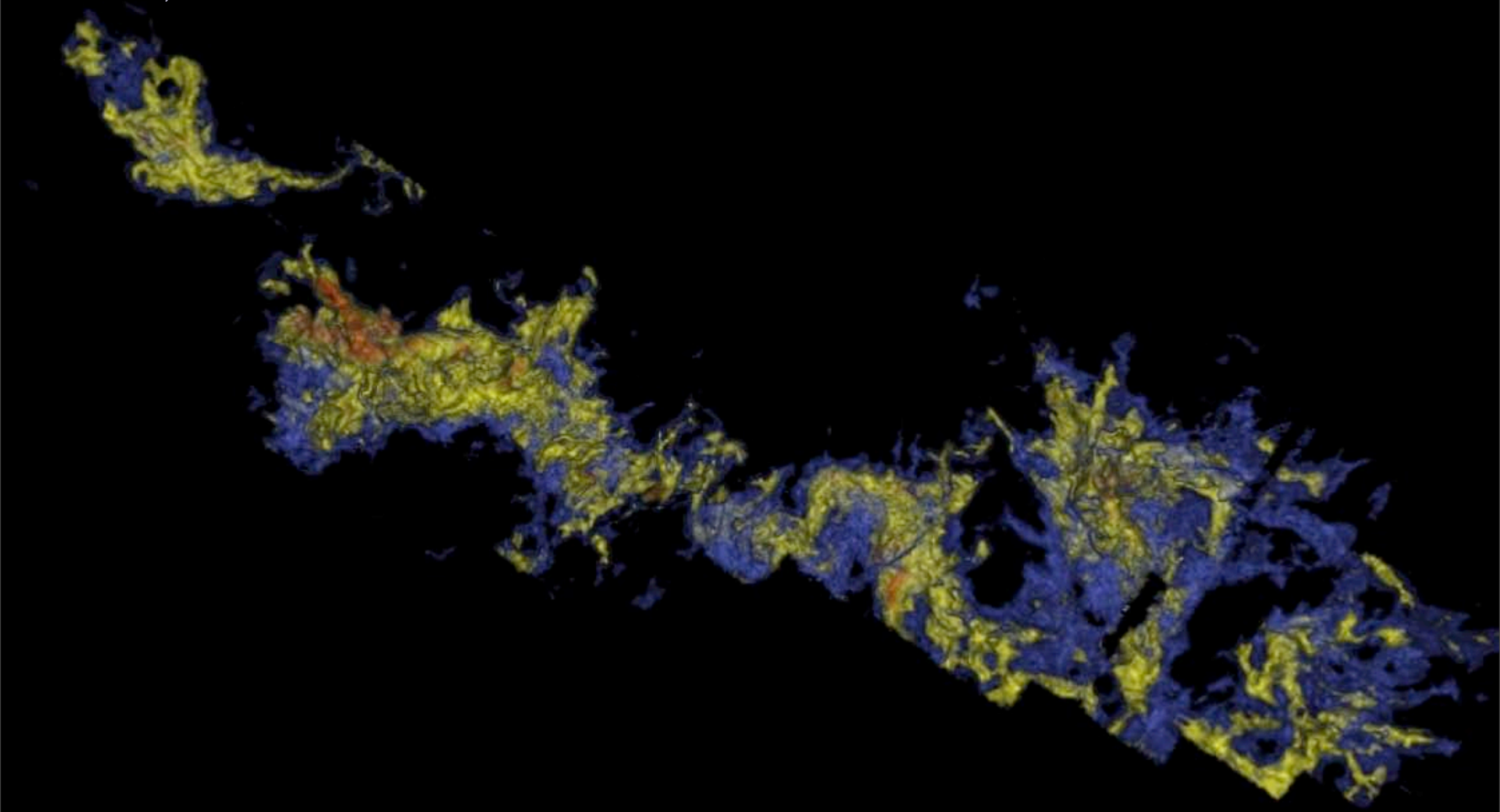


....ask me later about ^{12}CO & Outflows; see Borkin, Arce & Goodman 2007

position-postion-velocity is NOT the same as position-position-position-velocity-velocity-velocity

cf. Ostriker, Stone & Gammie 2001

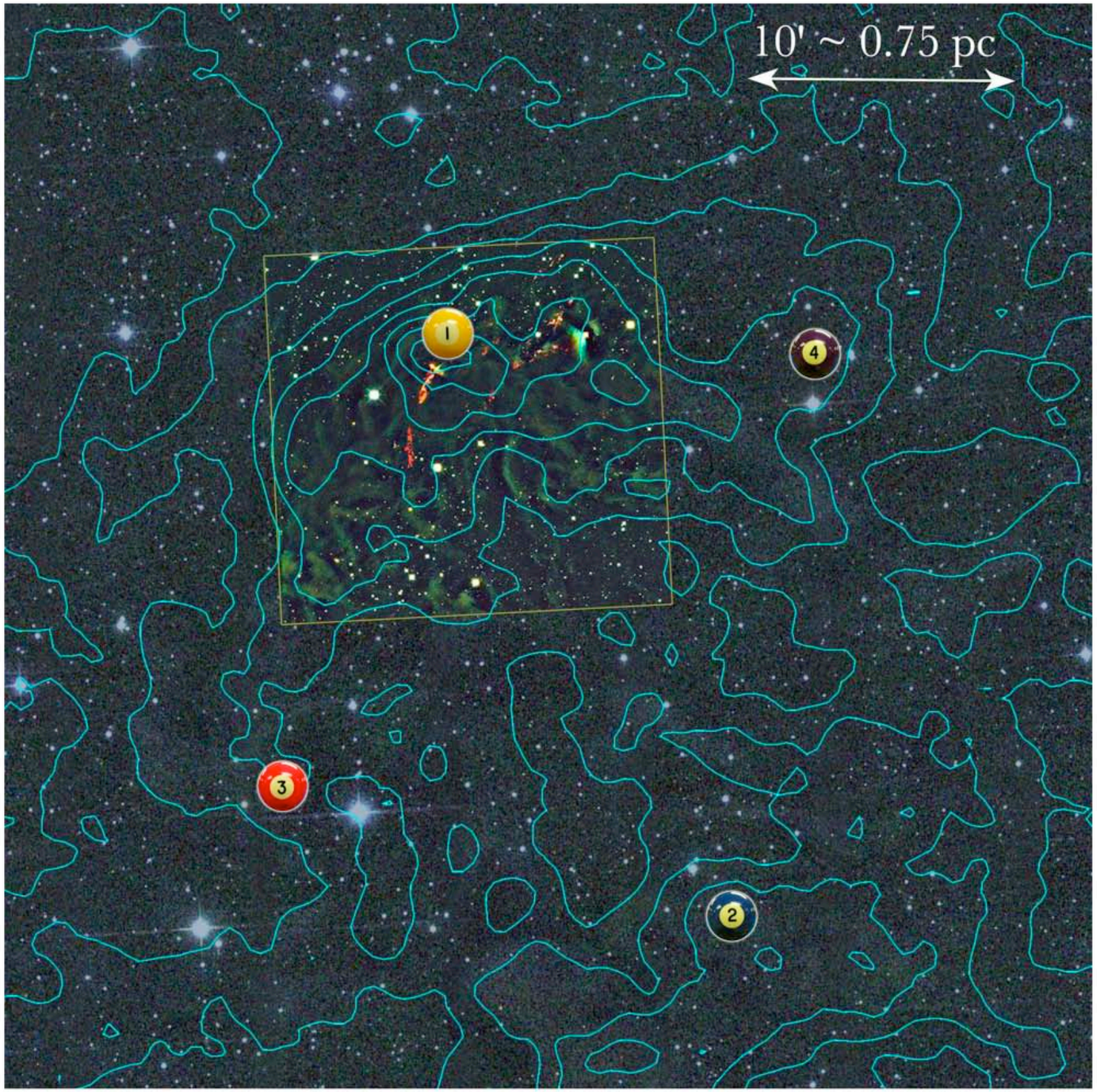
Rendering shows COMPLETE ^{13}CO
(as given in Ridge et al. 2006)
starting frame is plane-of-sky
"z" axis is line-of-sight velocity



....ask me later about ^{12}CO & Outflows; see Borkin, Arce & Goodman 2007

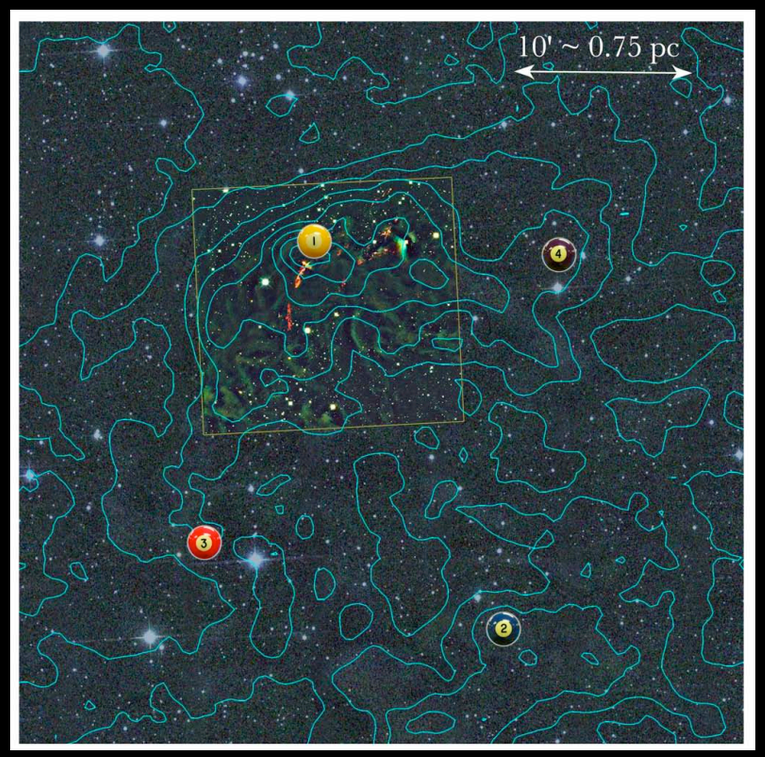
3D rendering courtesy AstroMed team @ IIC & Nick Holliman, Durham, UK

2D View of L1448: Cloudshine + Integrated ^{13}CO

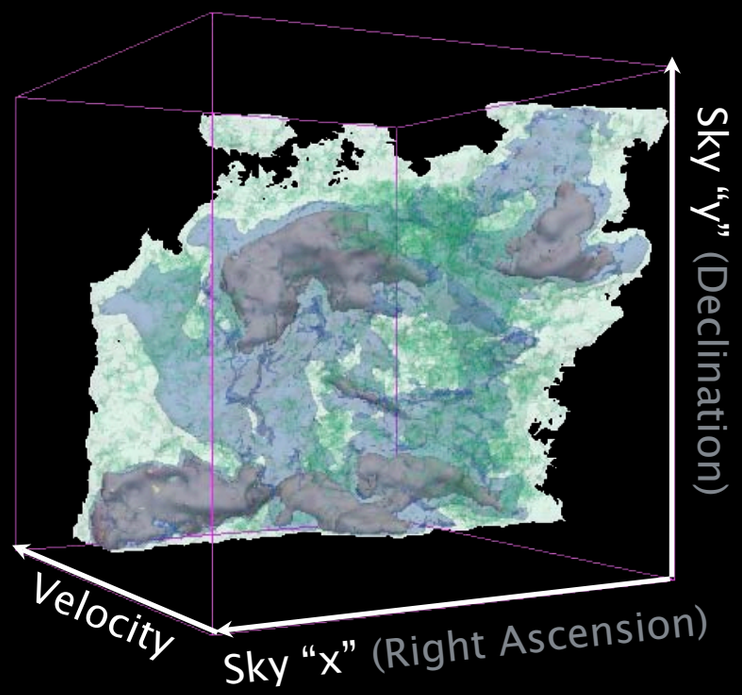


Foster & Goodman 2006; Goodman et al. 2007

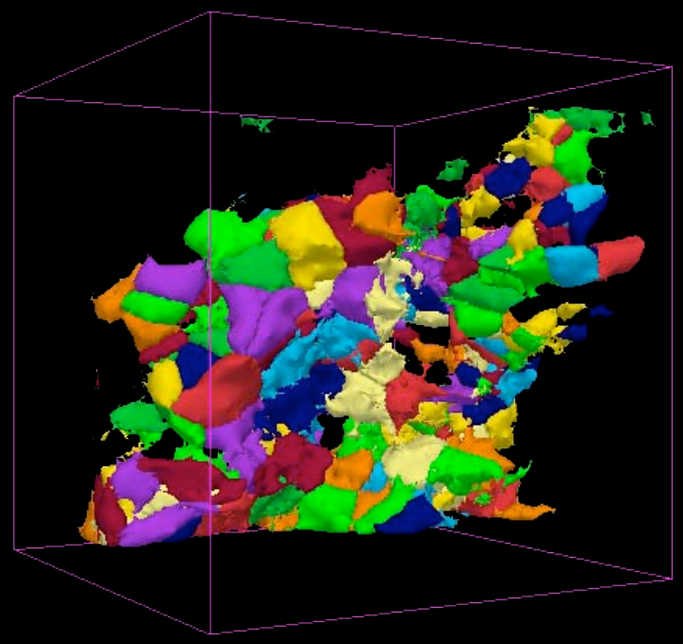
What's at issue?



(Dendro)Surfaces

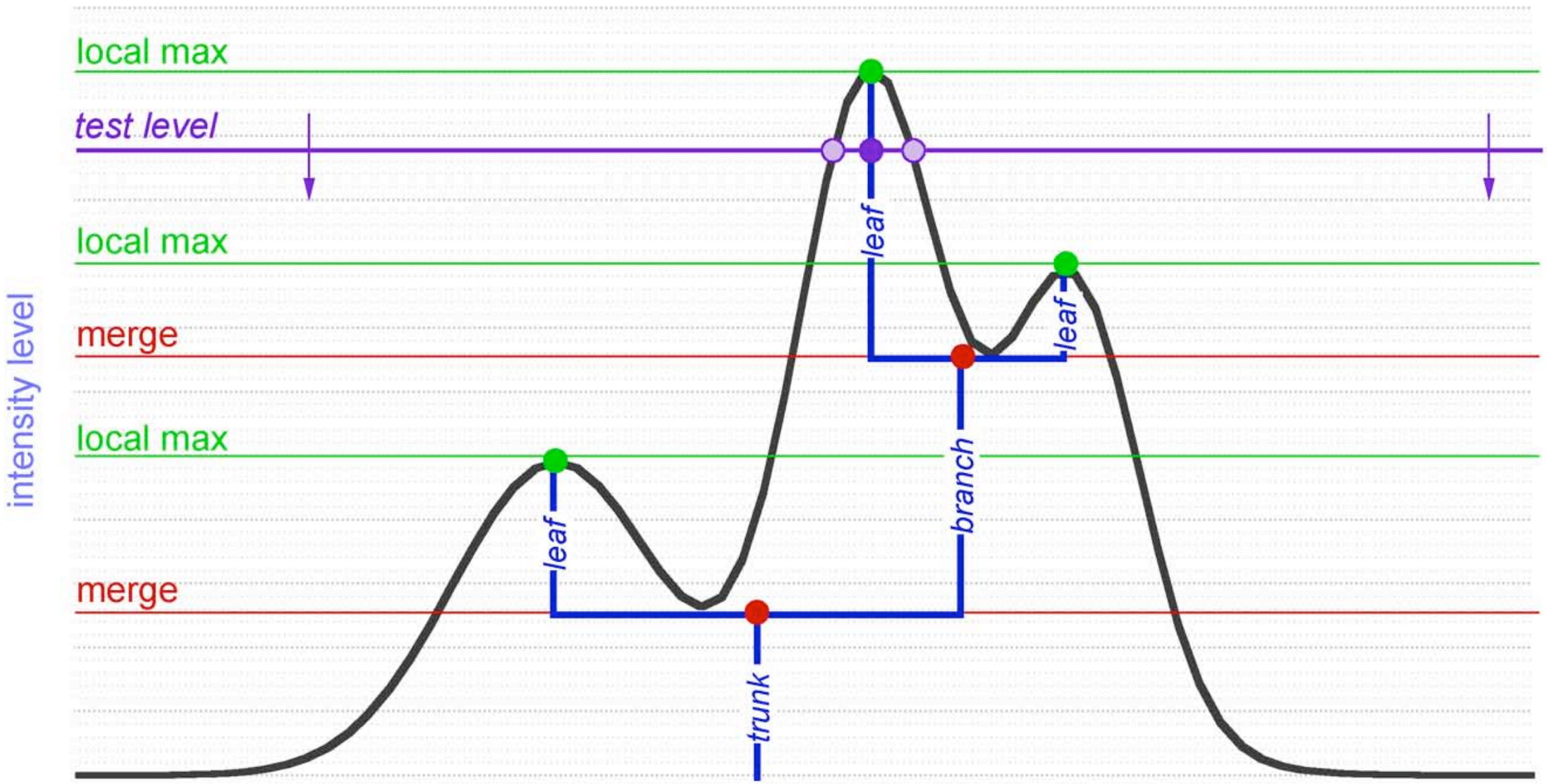


"CLUMPFIND"

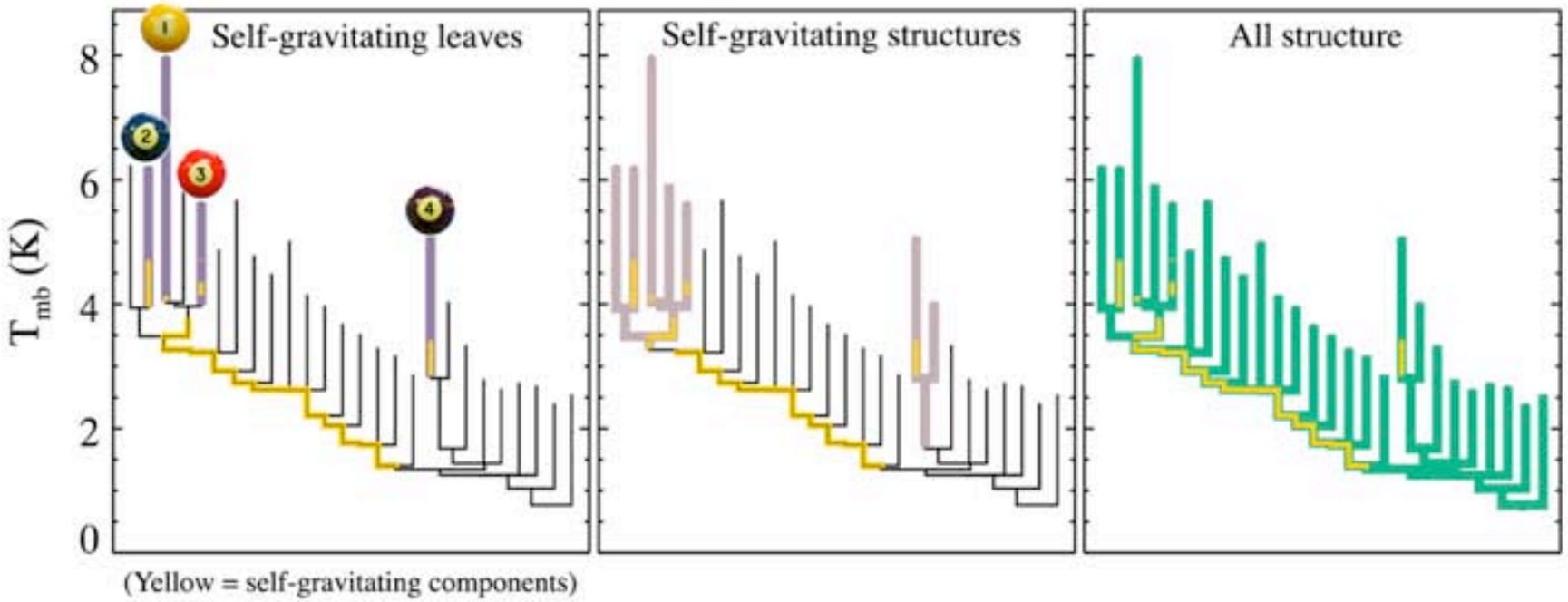


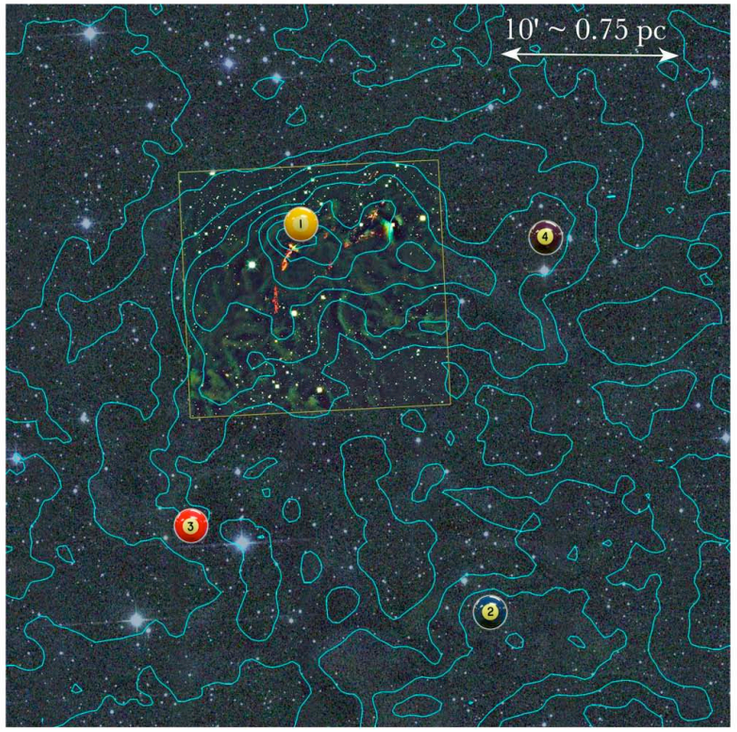
work of Rosolowsky, Foster, Pineda, Kauffmann, Borkin,Padoan, Halle & Goodman;
figures based on Foster & Goodman 2006; Goodman et al. 2007

Dendrograms

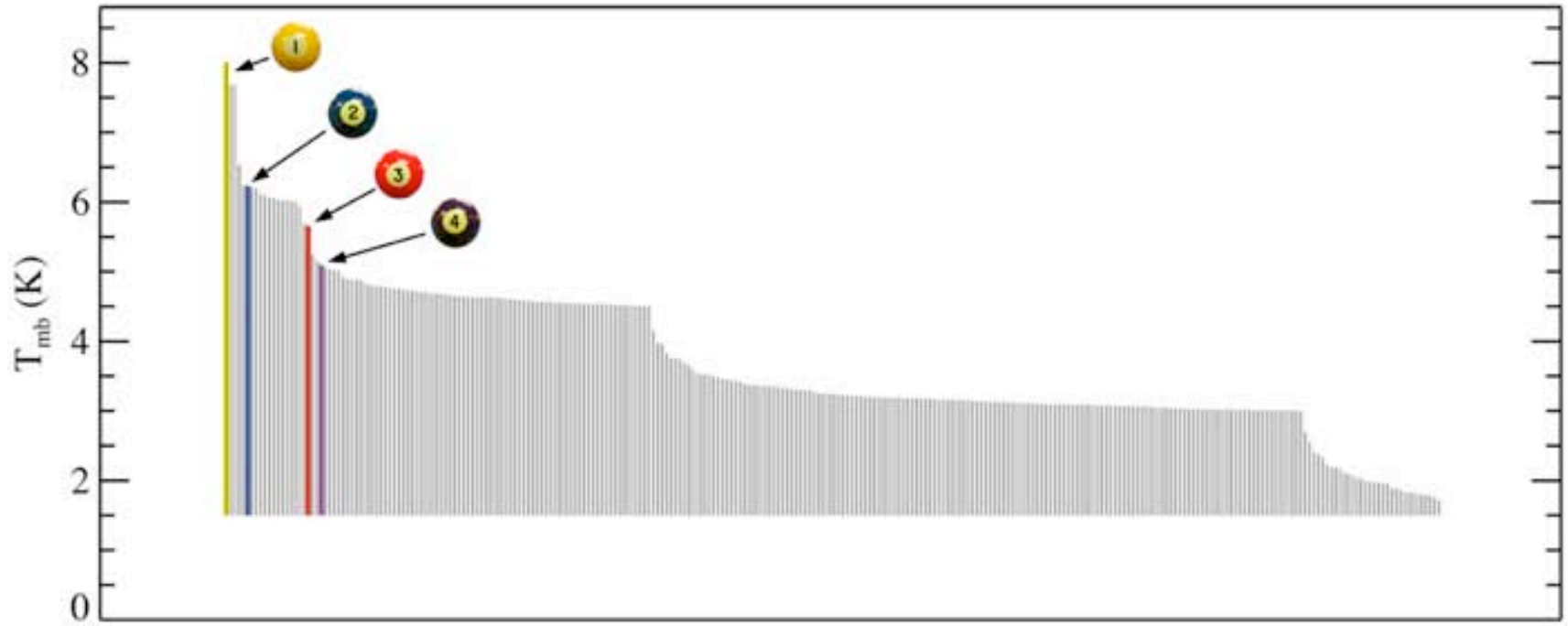


Dendrograms (Hierarchical) vs. CLUMPFIND (Non-hierarchical)



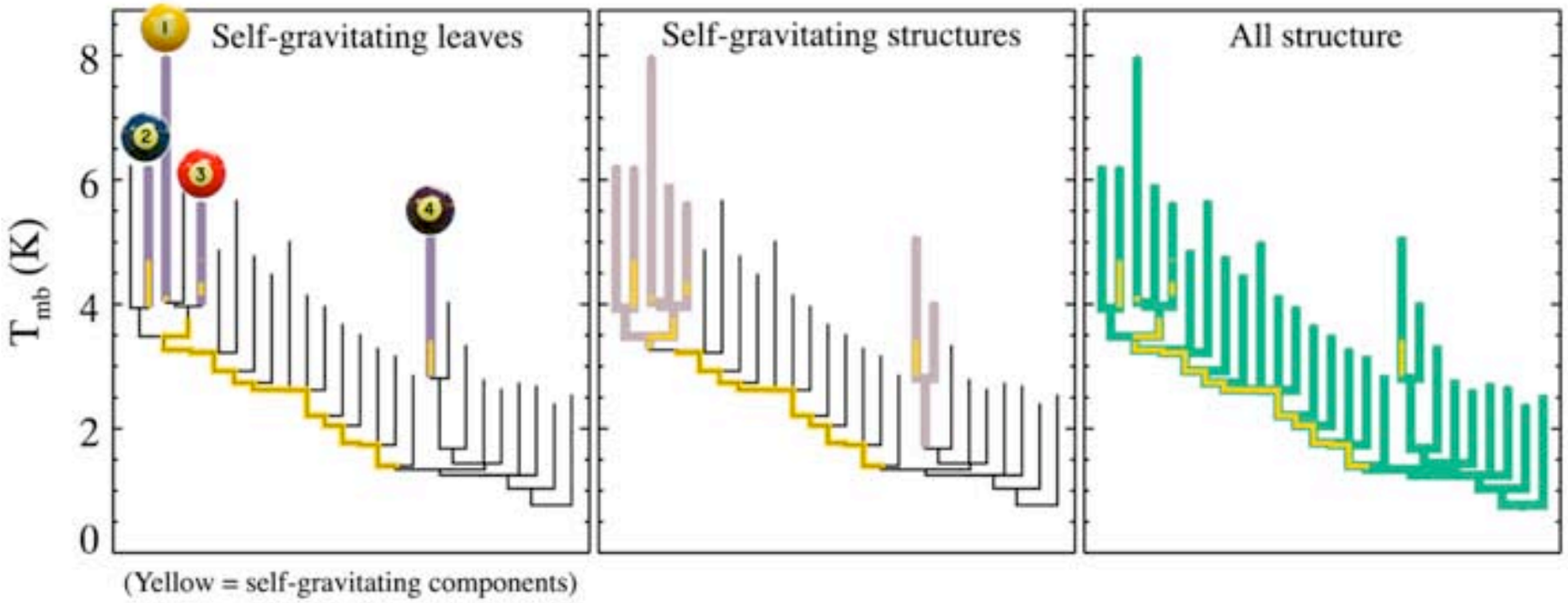


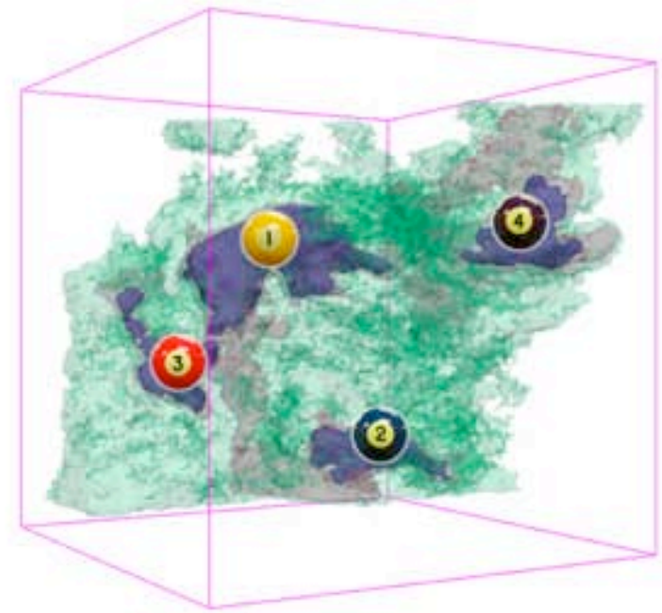
The online PDFs of these insets are interactive, and can be rotated and manipulated by the viewer.



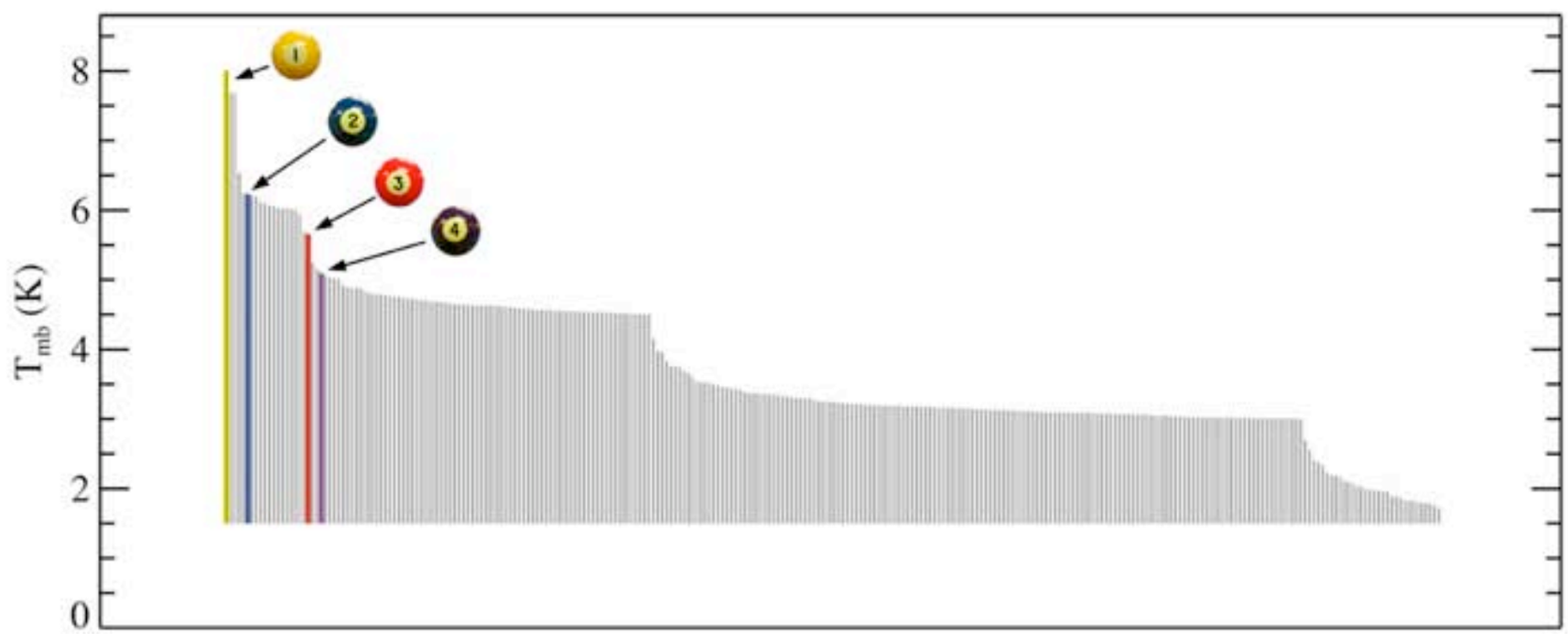
Goodman, Rosolowsky et al. 2007, submitted to Nature.

Dendrograms (Hierarchical) vs. CLUMPFIND (Non-hierarchical)



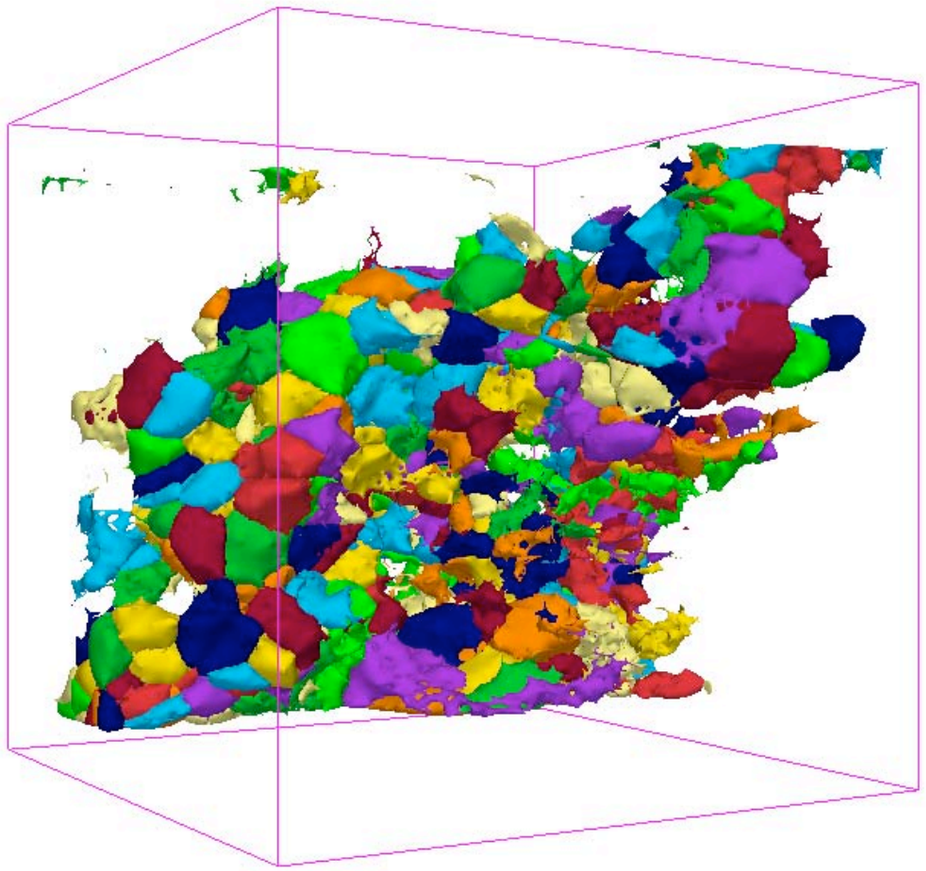


The online PDFs of these insets are interactive, and can be rotated and manipulated by the viewer.



Goodman, Rosolowsky et al. 2007, submitted to Nature.

Is CLUMPFIND OK as a Statistic?

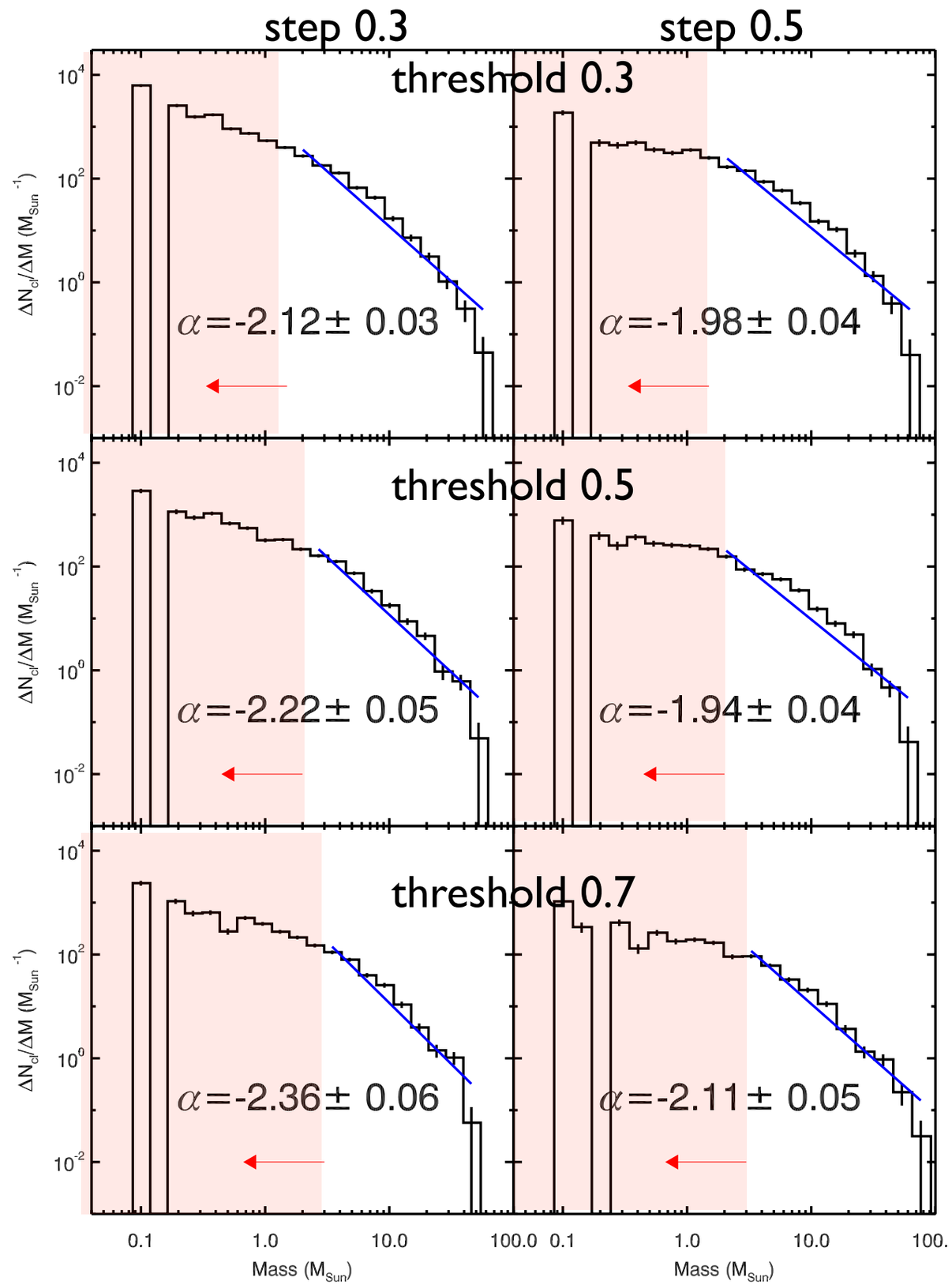


CLUMPFIND output for L1448

(1.2K step & threshold; lower values give too many clumps to show!)

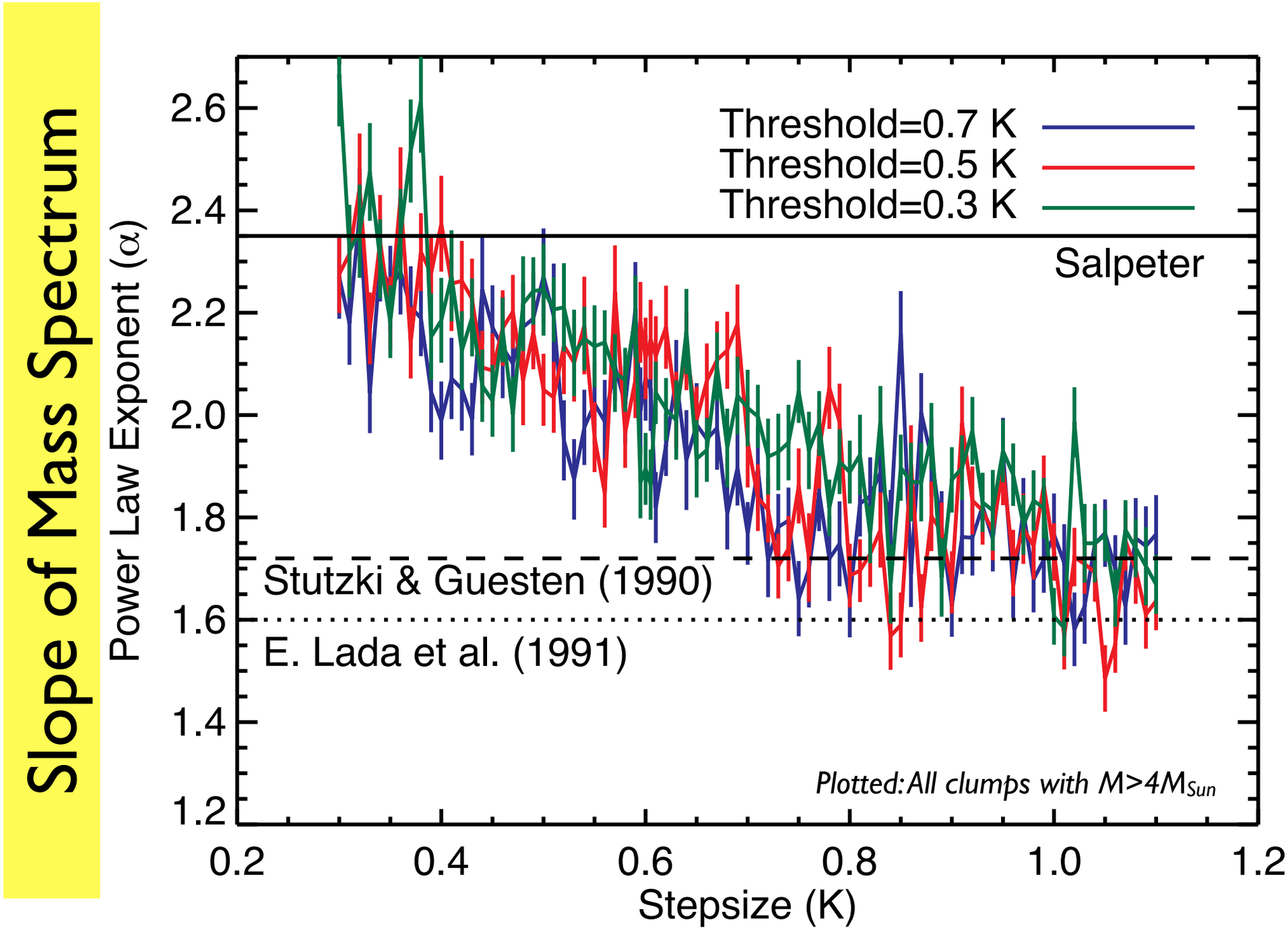
Results for full Perseus Map

Threshold	Step size	total number of Clump	% above sensitivity limit Mass v/s Radius	% above sensitivity limit FWHM v/s Radius	% above both curves
0.3	0.3	5199	47.32%	58.03%	46.59%
0.3	0.5	3844	40.74%	46.96%	40.30%
0.5	0.3	2141	79.12%	89.72%	78.14%
0.5	0.5	1420	86.83%	89.01%	86.20%
0.7	0.3	1748	79.06%	90.79%	78.60%
0.7	0.5	1168	87.07%	90.58%	86.73%



Pineda, Goodman & Rosolowsky 2007

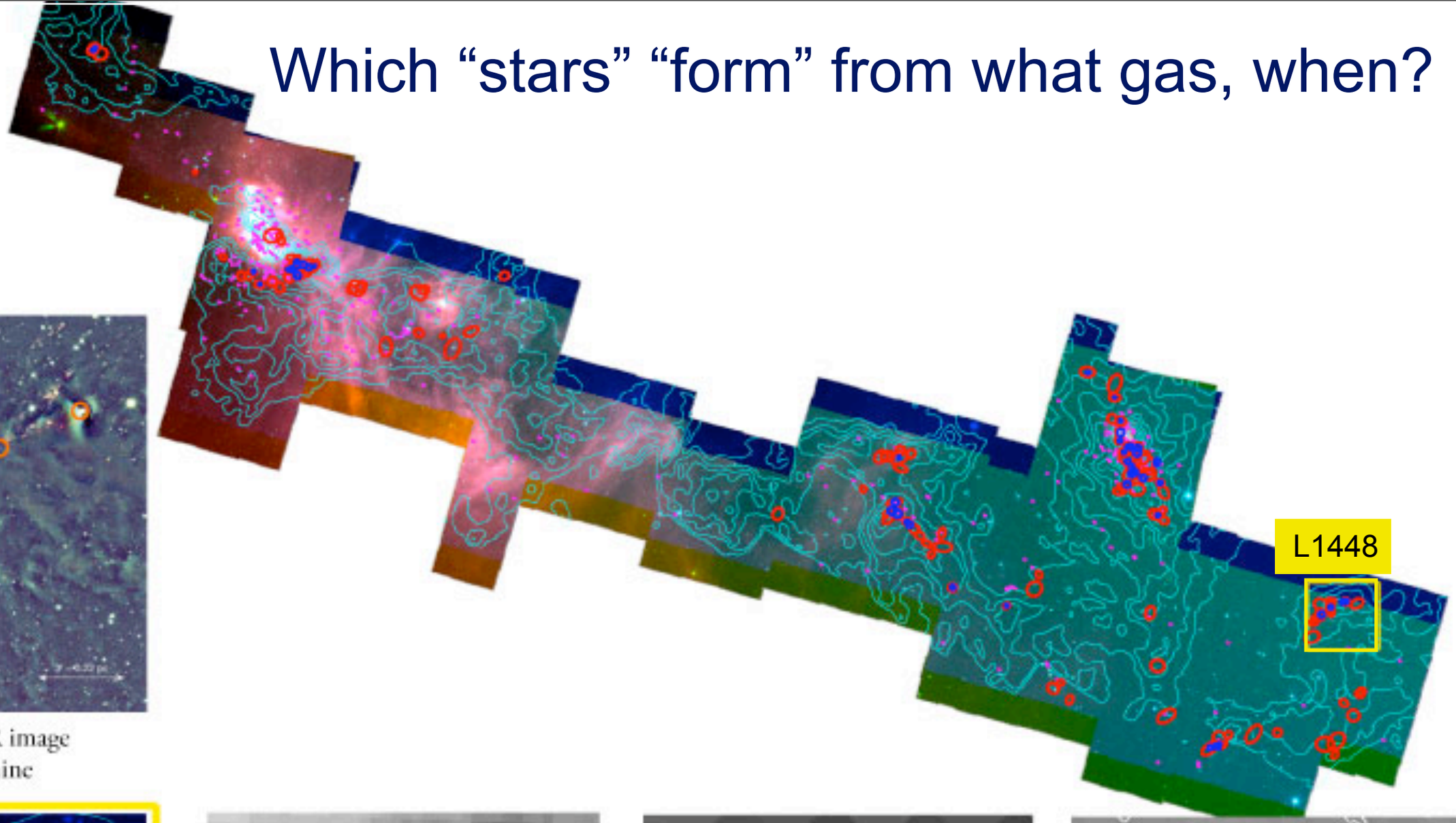
Is CLUMPFIND OK as a Statistic?

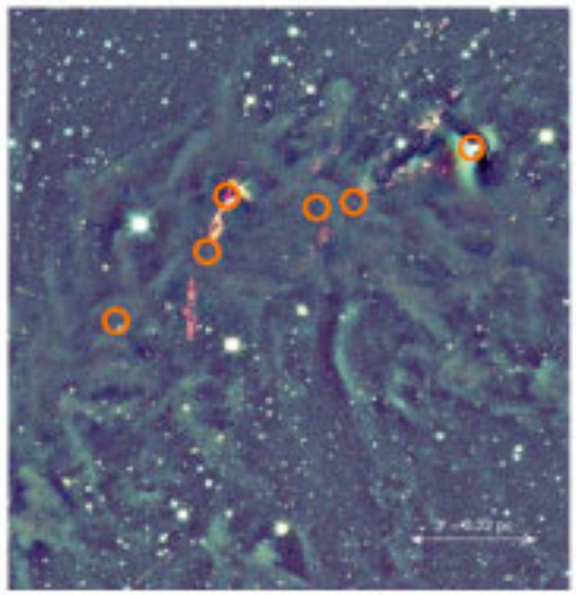


Pineda, Goodman & Rosolowsky 2007

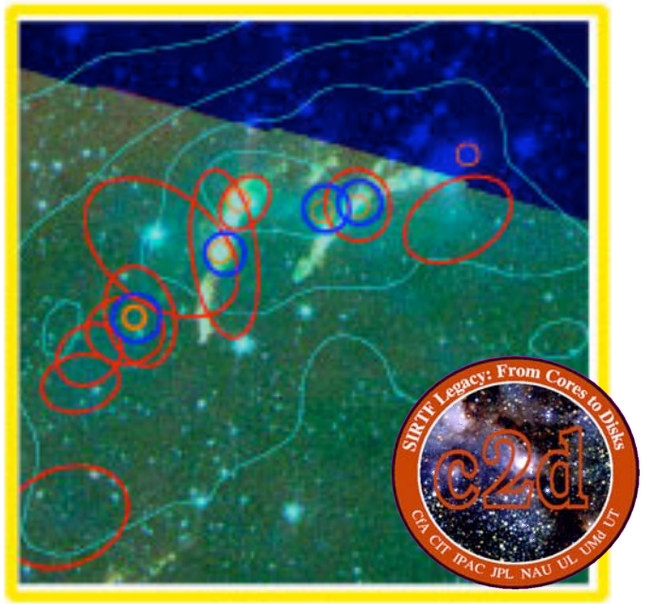
5. Stellar Distribution may be useful in figuring out which stars form when & where, but observational biases are CENTRAL (...see Neal's talk, yesterday!)

Which “stars” “form” from what gas, when?

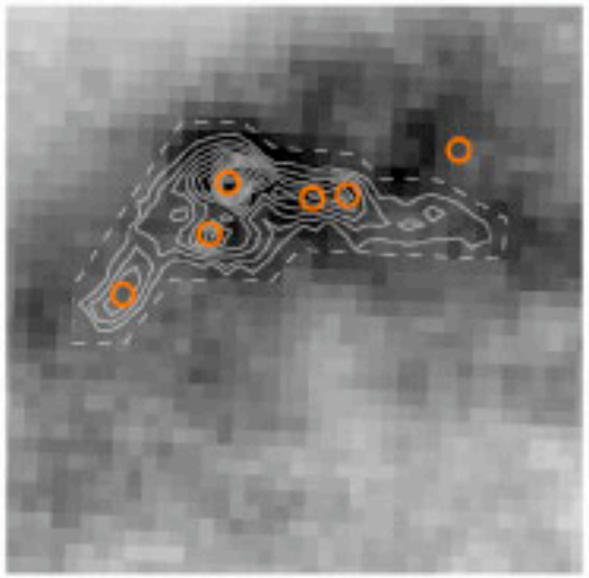




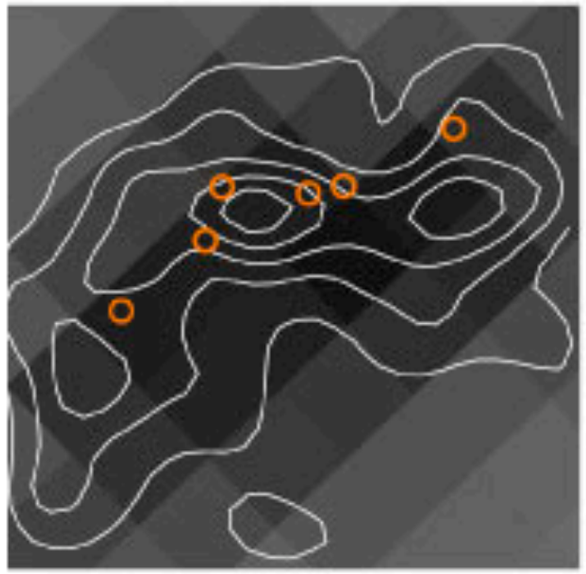
J,H,K Near-IR image of Cloudshine



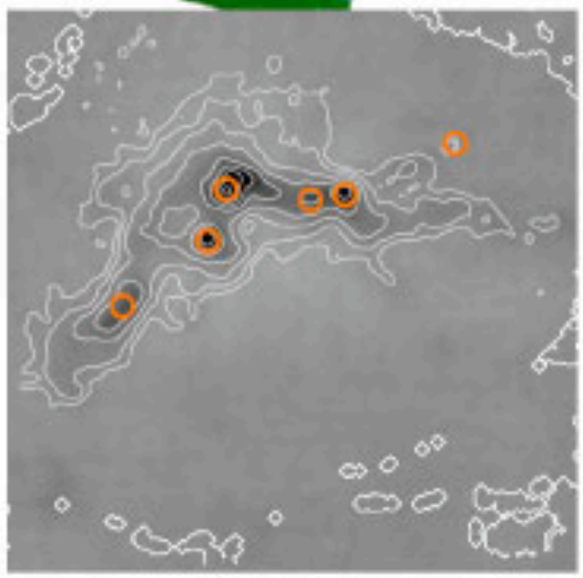
C 850 micron and 1.1 mm clumps on a c2d IRAC 3-color image



MPL N_2H^+ on ^{13}CO integrated intensity



E Deep NIR Extinction on 2MASS Extinction



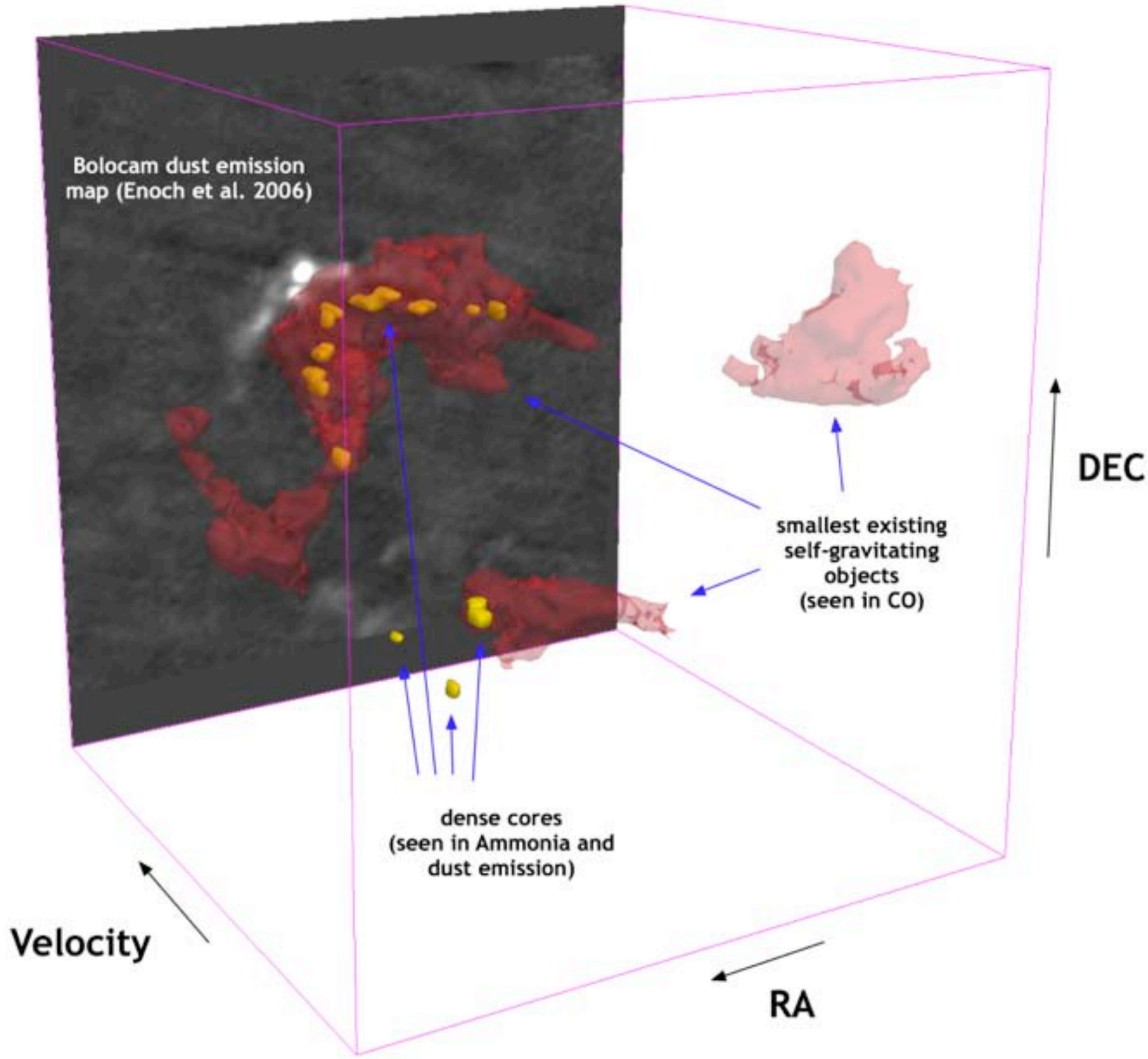
TE 1.2 mm (IRAM) on 850 micron (SCUBA) continuum

Figure Credit: Jonathan Foster

The Innards of L1448

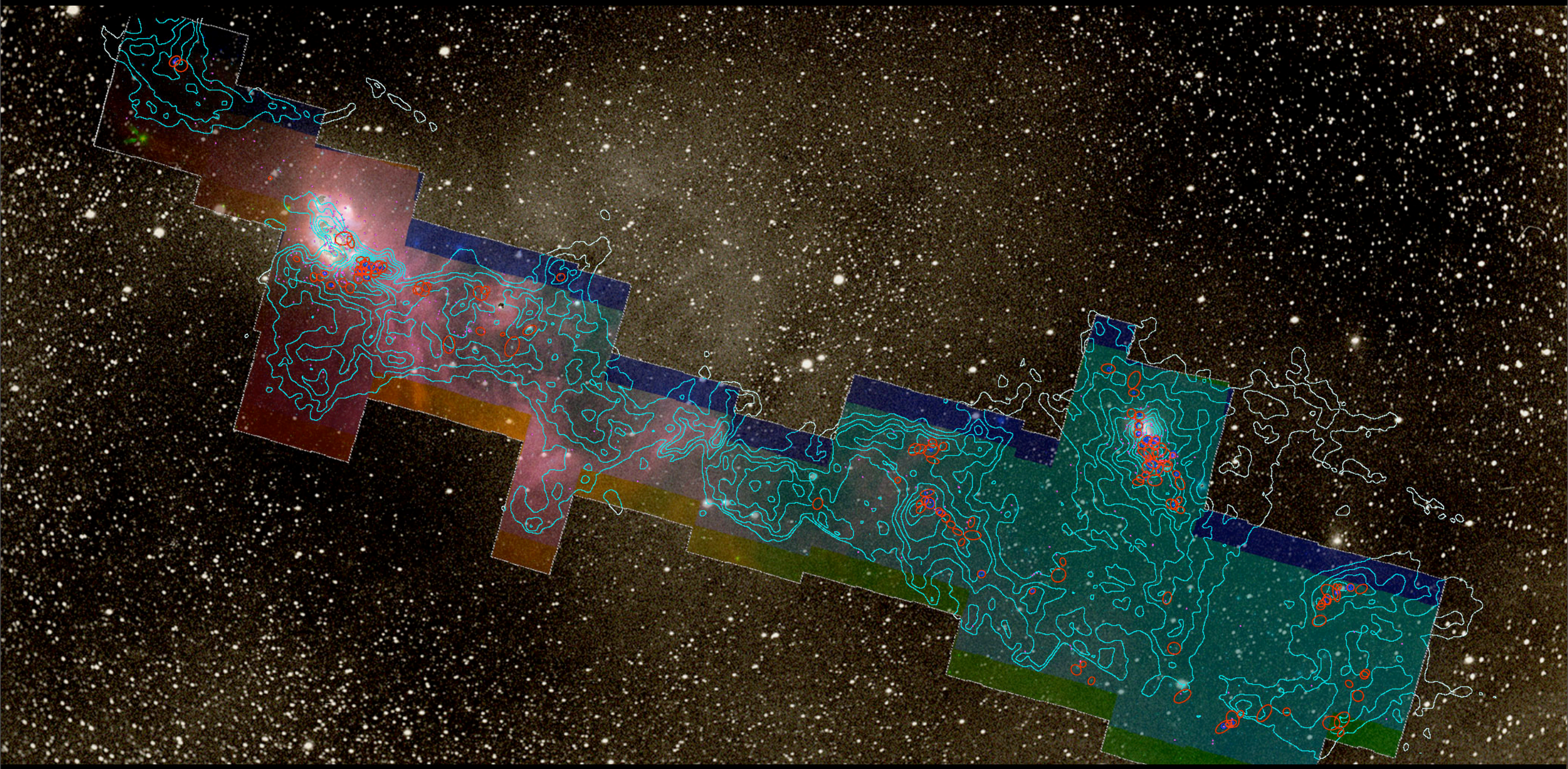
Can we understand it all in context?

(e.g. Kauffmann et al. 2007 “Anatomy of L1448”)



Visualization created by Jens Kauffmann (CfA/IIC) using 3D Slicer

COMPLETE = **CO**ordinated **M**olecular **P**robe **L**ine **E**xtinction **T**hermal **E**mission Survey of Star-Forming Regions



COMPLETE Collaborators, Fall 2007:

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Héctor Arce (AMNH to Yale)

Michelle Borkin (IIC)

Paola Caselli (Leeds, UK)

James DiFrancesco (HIA, Canada)

Jonathan Foster (CfA, PhD Student)

Sebastian Guillot (U. Victoria, Canada)

Mark Heyer (UMASS/FCRAO)

Doug Johnstone (HIA, Canada)

Jens **Kauffmann** (CfA/IIC)

Helen Kirk (HIA, Canada)

Di Li (JPL)

Jason Li (Harvard College)

Jaime **Pineda** (CfA, PhD Student)

Erik Rosolowsky (CfA)

Scott **Schnee** (Caltech)

Rahul **Shetty** (CfA)

Mario Tafalla (OAN, Spain)