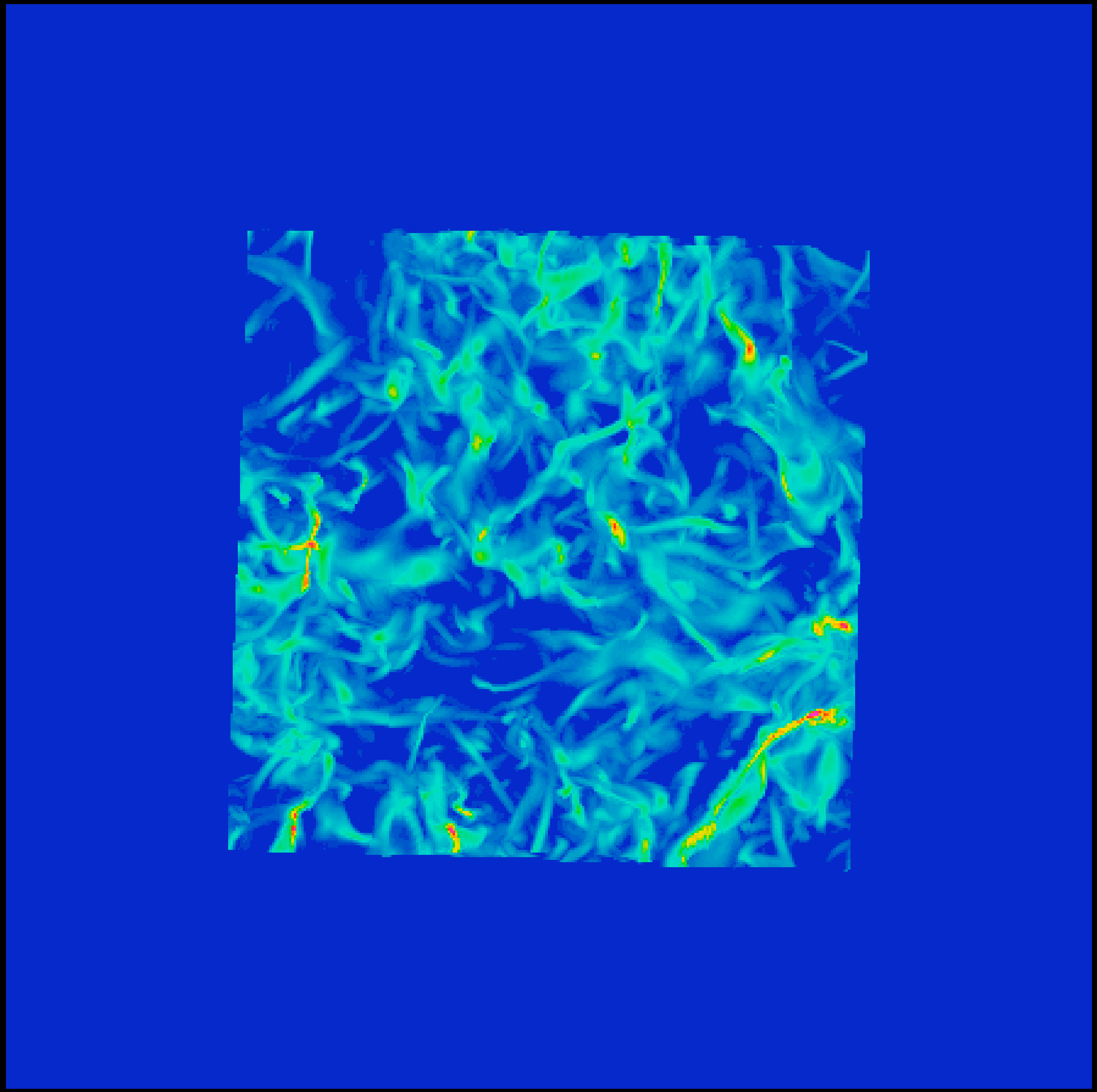
Star Formation Taste Tests

Alyssa A. Goodman
Harvard-Smithsonian Center for Astrophysics
&
Initiative for Innovative Computing at Harvard

What theorists are used to...

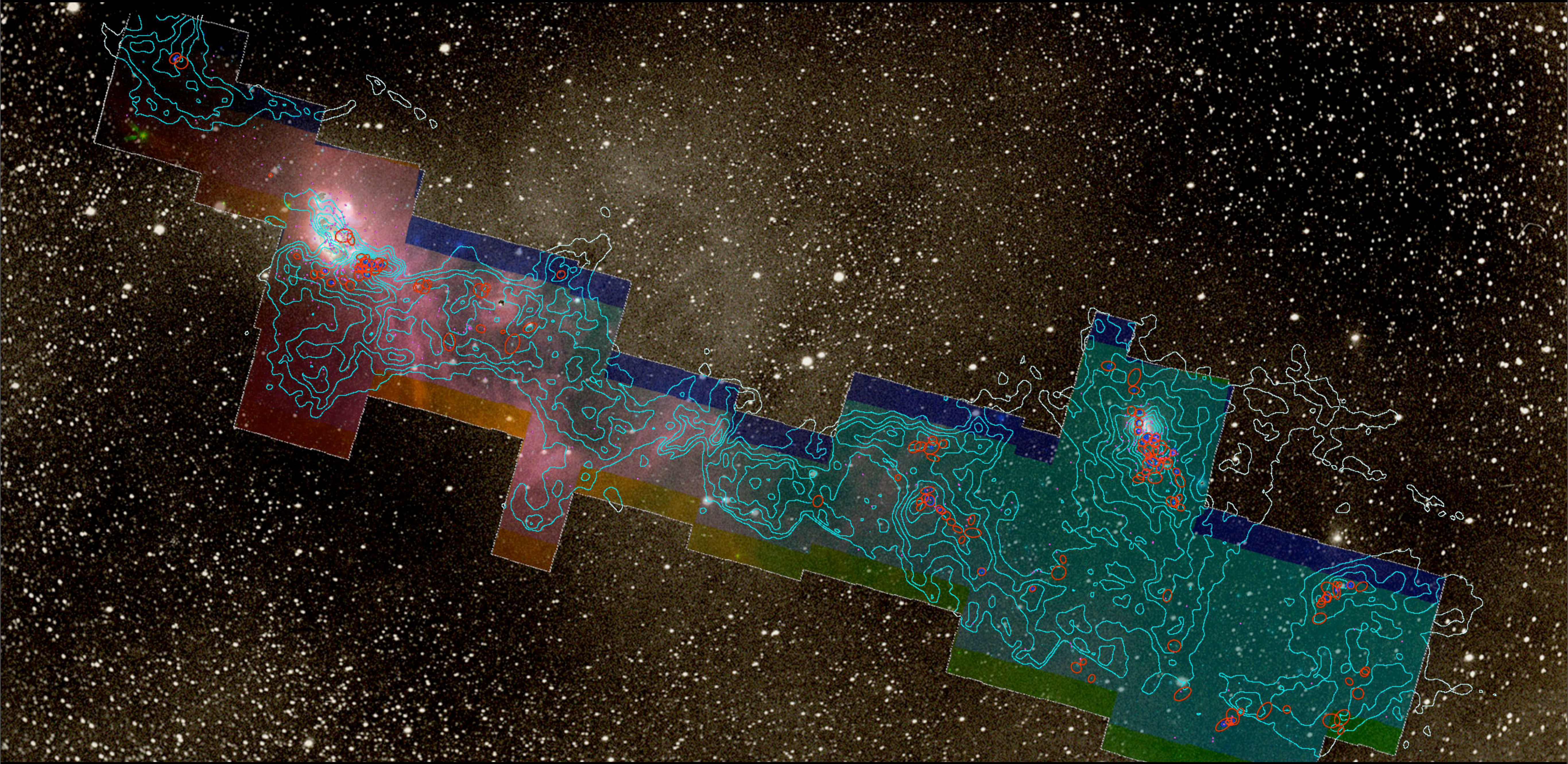


“Three-dimensional visualization of density structure in a turbulent cloud”

Courtesy Eve Ostriker, Jim Stone & Charles Gammie

...but, alas, observers cannot live in that space.

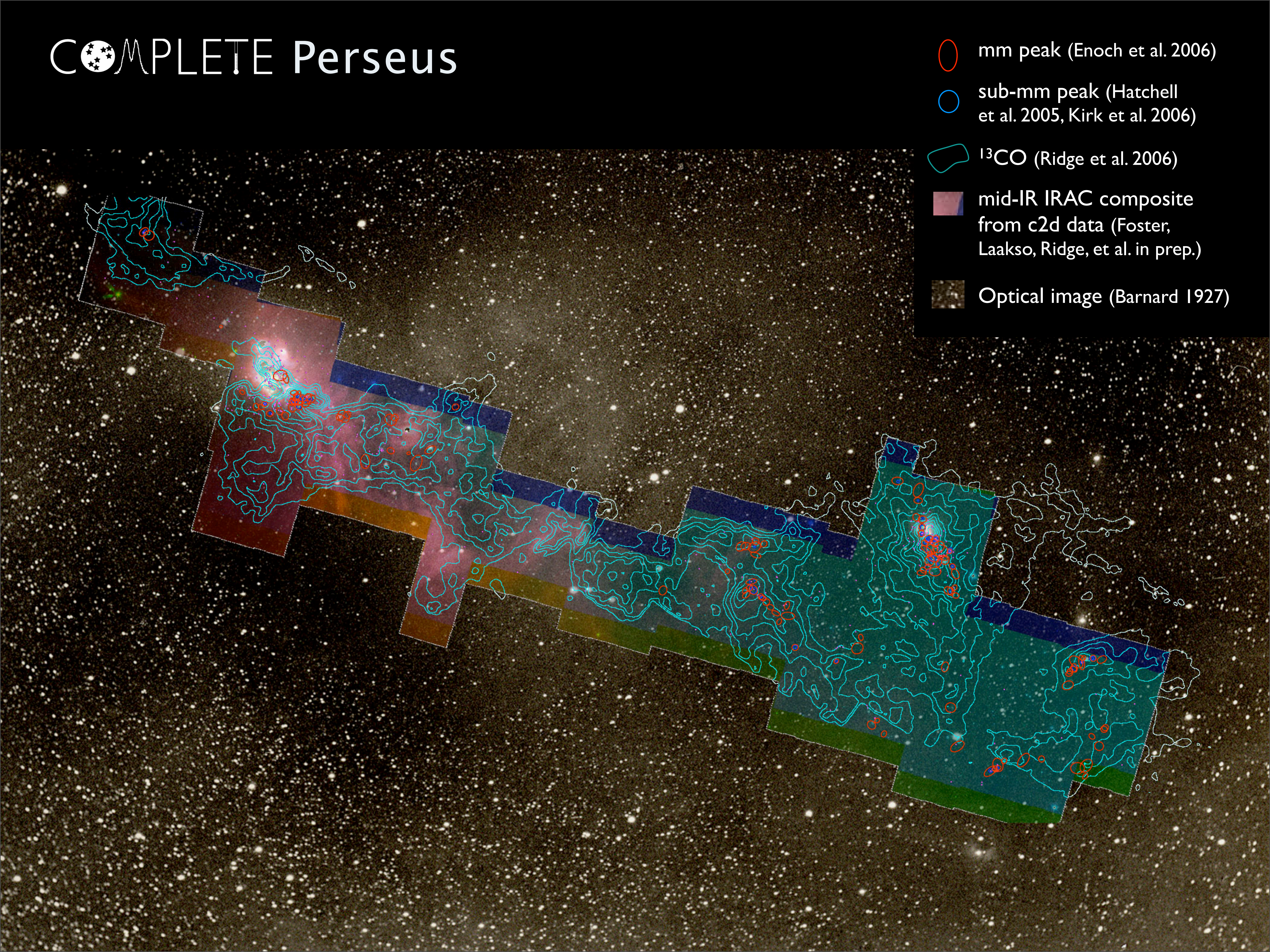
COMPLETE = COordinated Molecular Probe Line Extinction Thermal Emission Survey of Star-Forming Regions



COMPLETE Collaborators, Summer 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)
Mario Tafalla (OAN, Spain)

COMPLETE Perseus



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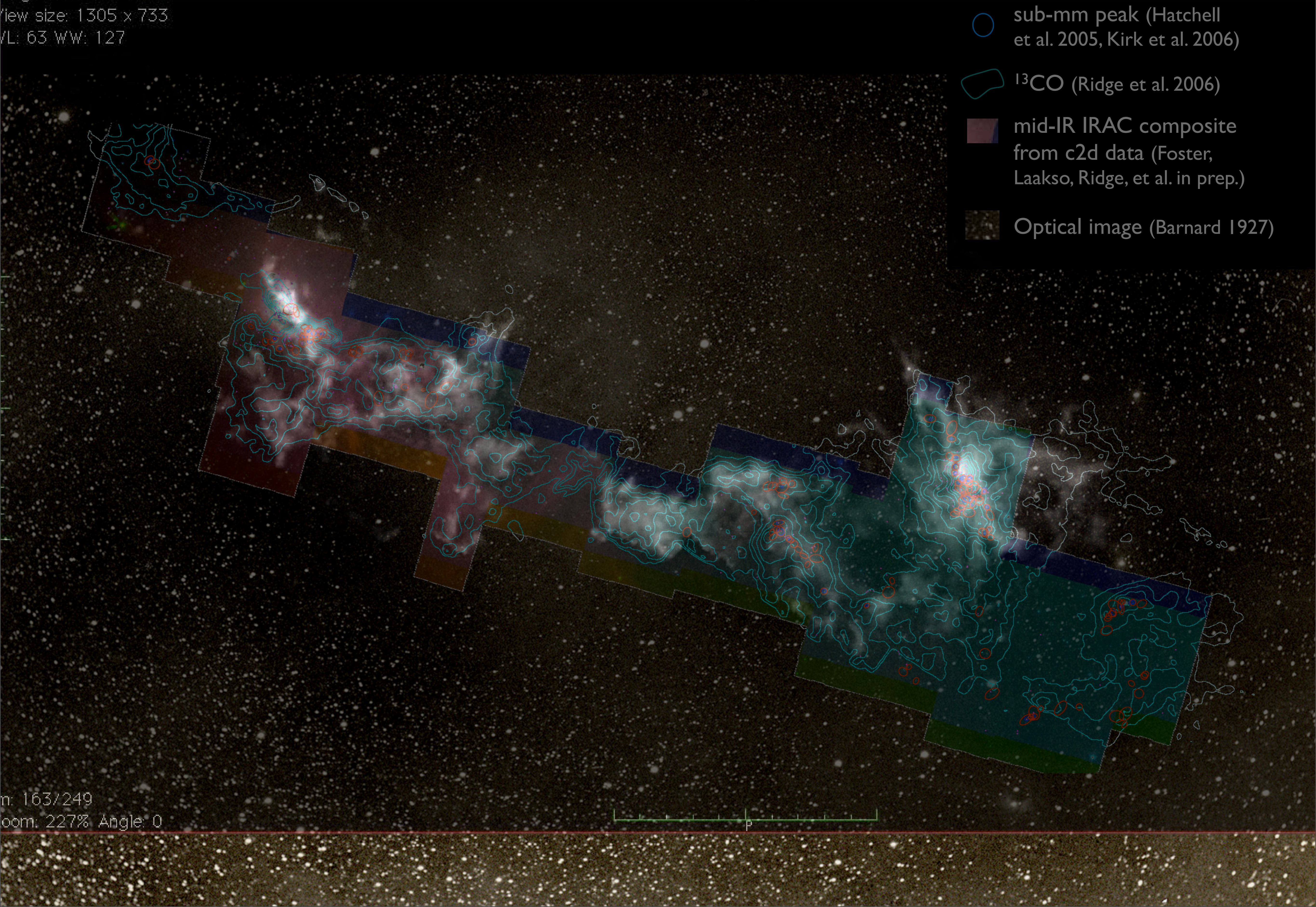

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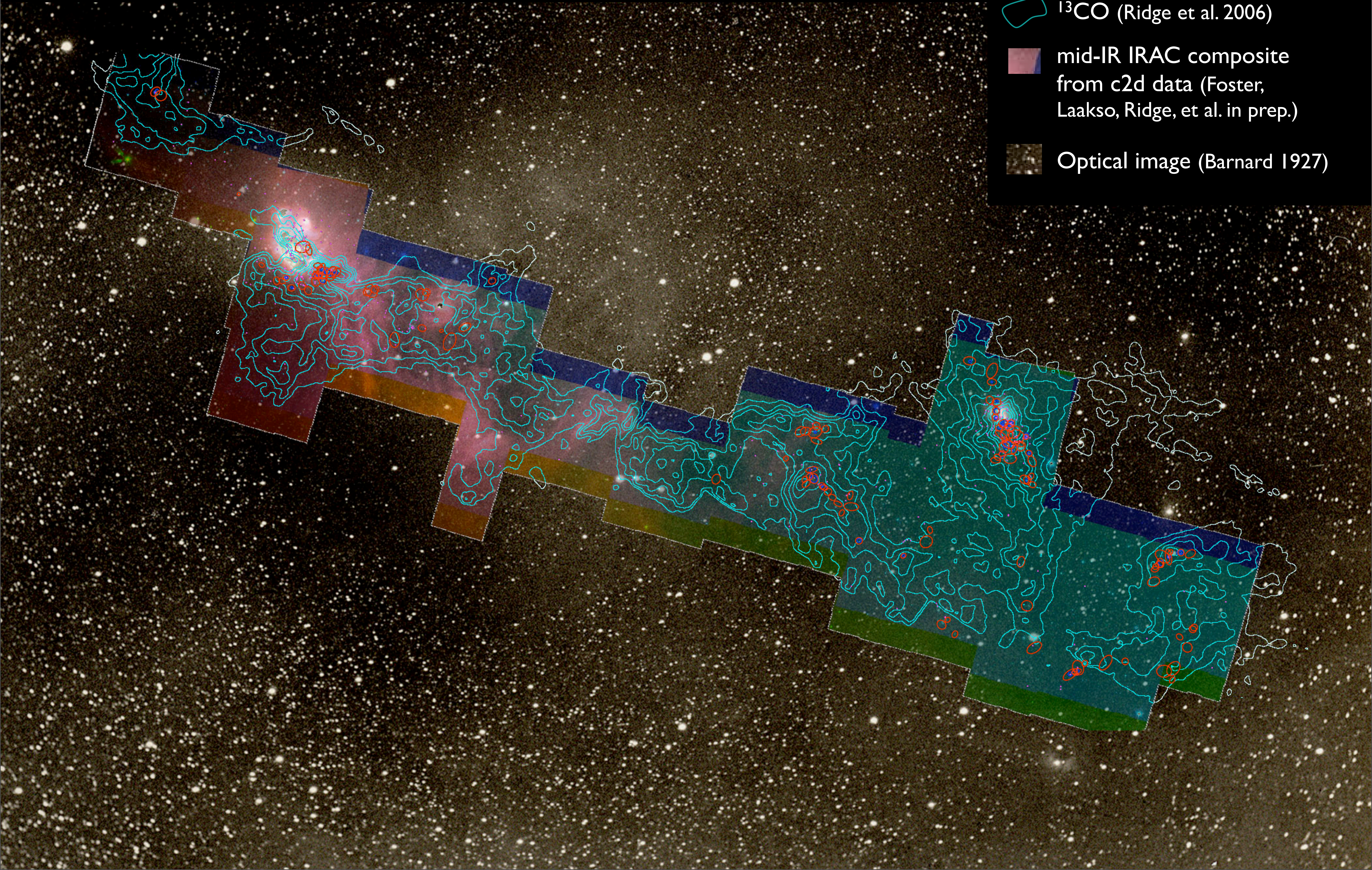


mm peak (Enoch et al. 2006)

sub-mm peak (Hatchell et al. 2005, Kirk et al. 2006)

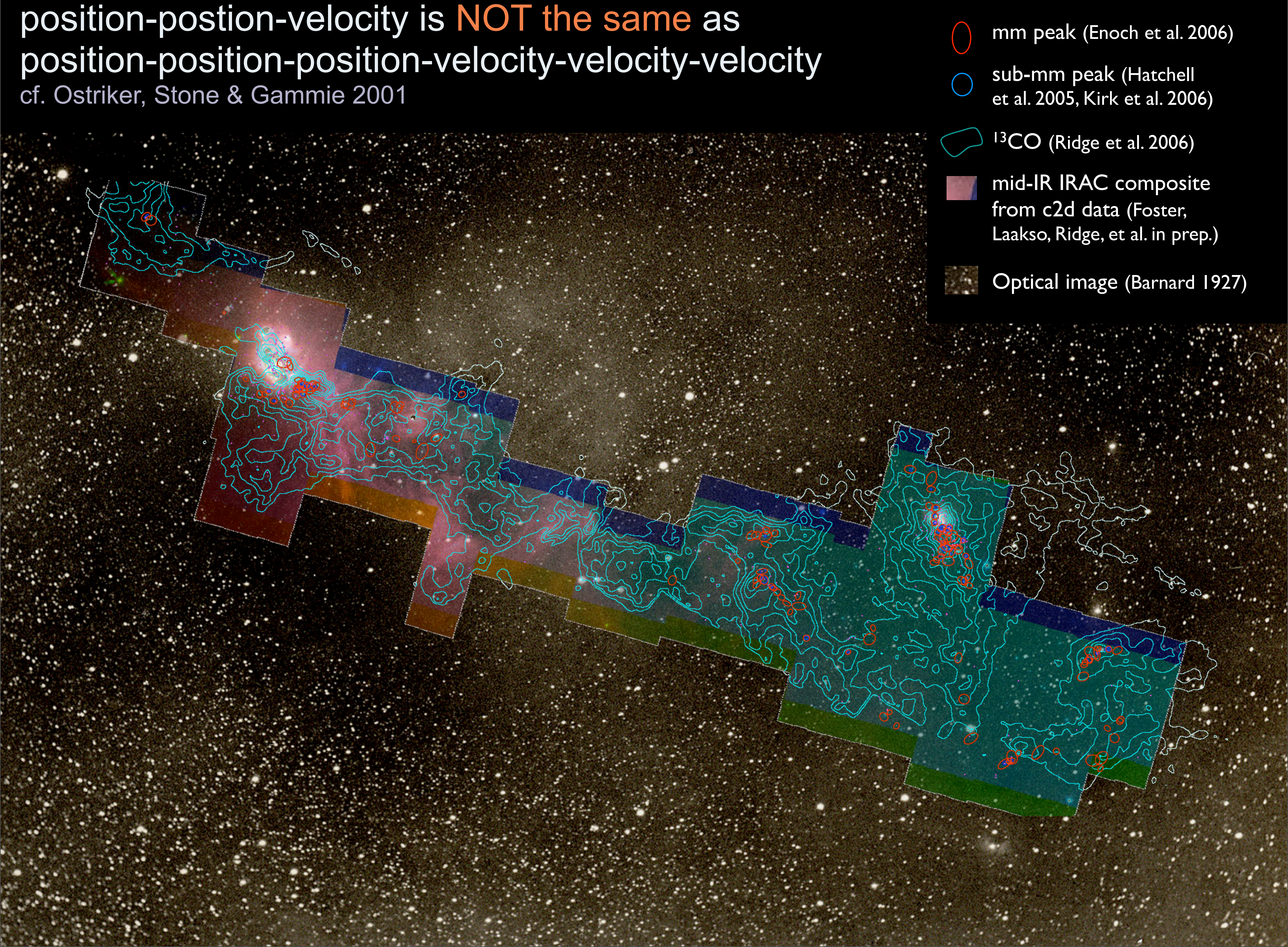
^{13}CO (Ridge et al. 2006)

mid-IR IRAC composite from c2d data (Foster, Laakso, Ridge, et al. in prep.)

Optical image (Barnard 1927)

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

cf. Ostriker, Stone & Gammie 2001



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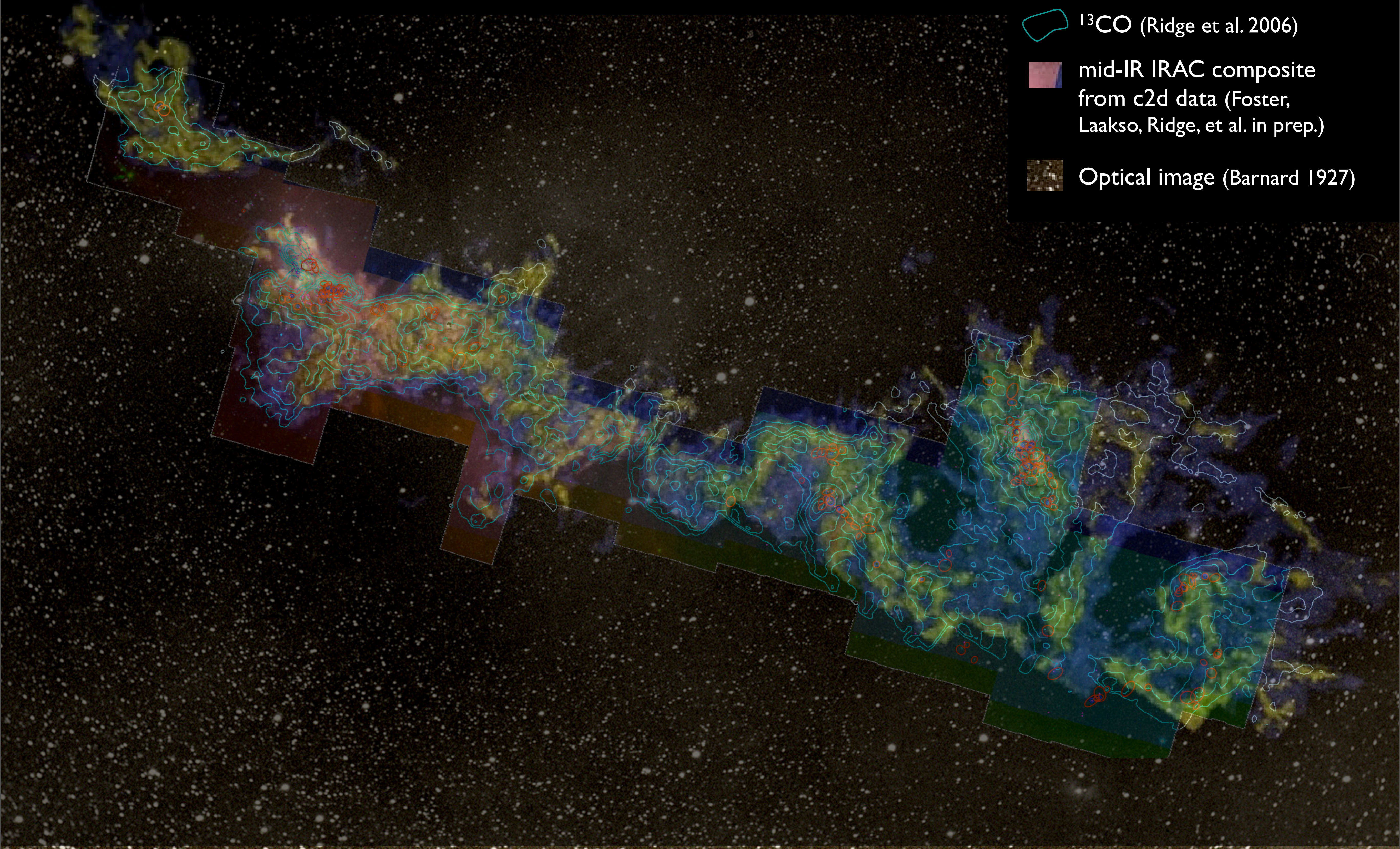

3D rendering courtesy AstroMed team @ IIC & Nick Holliman, Durham, UK

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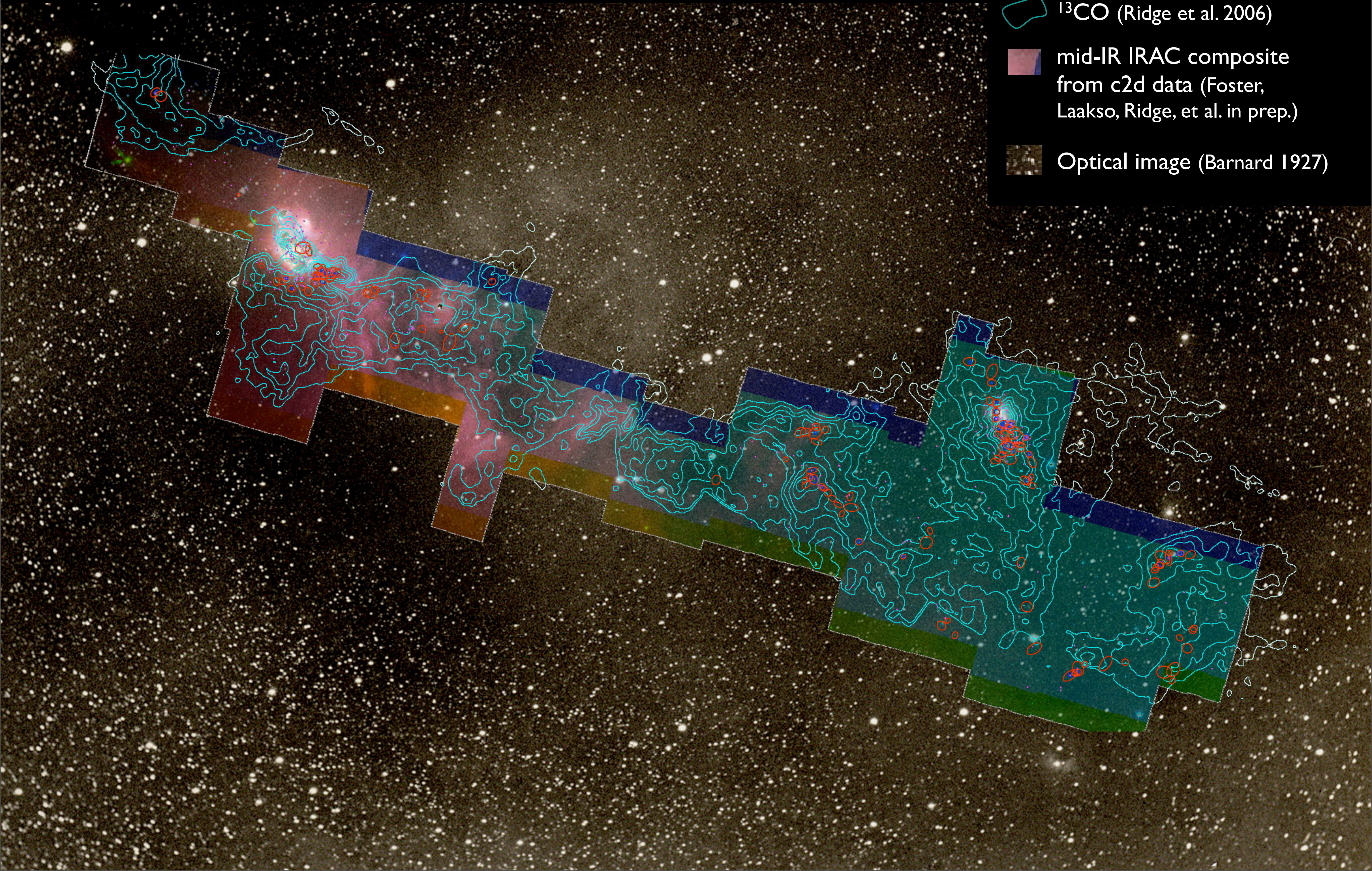

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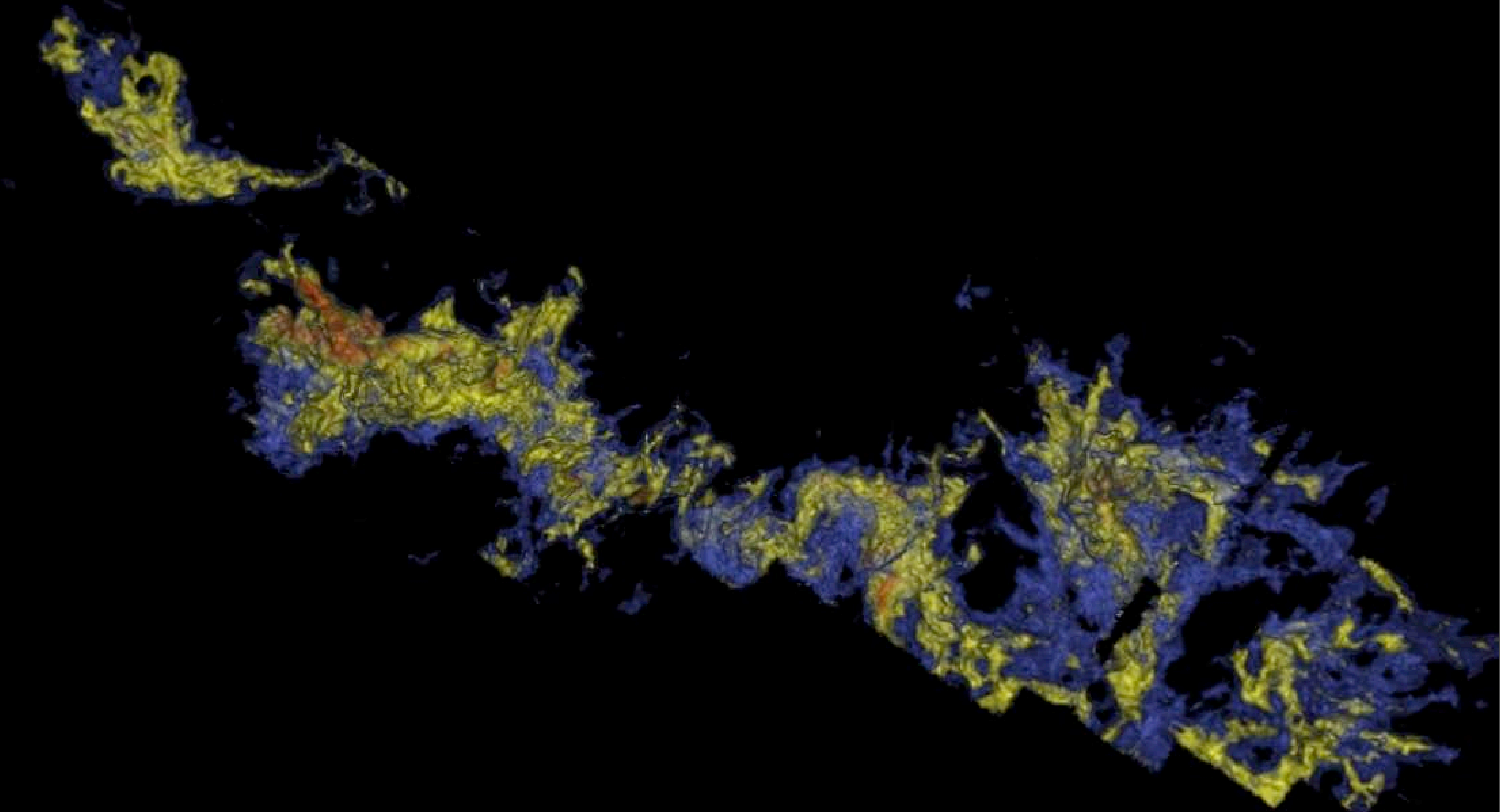

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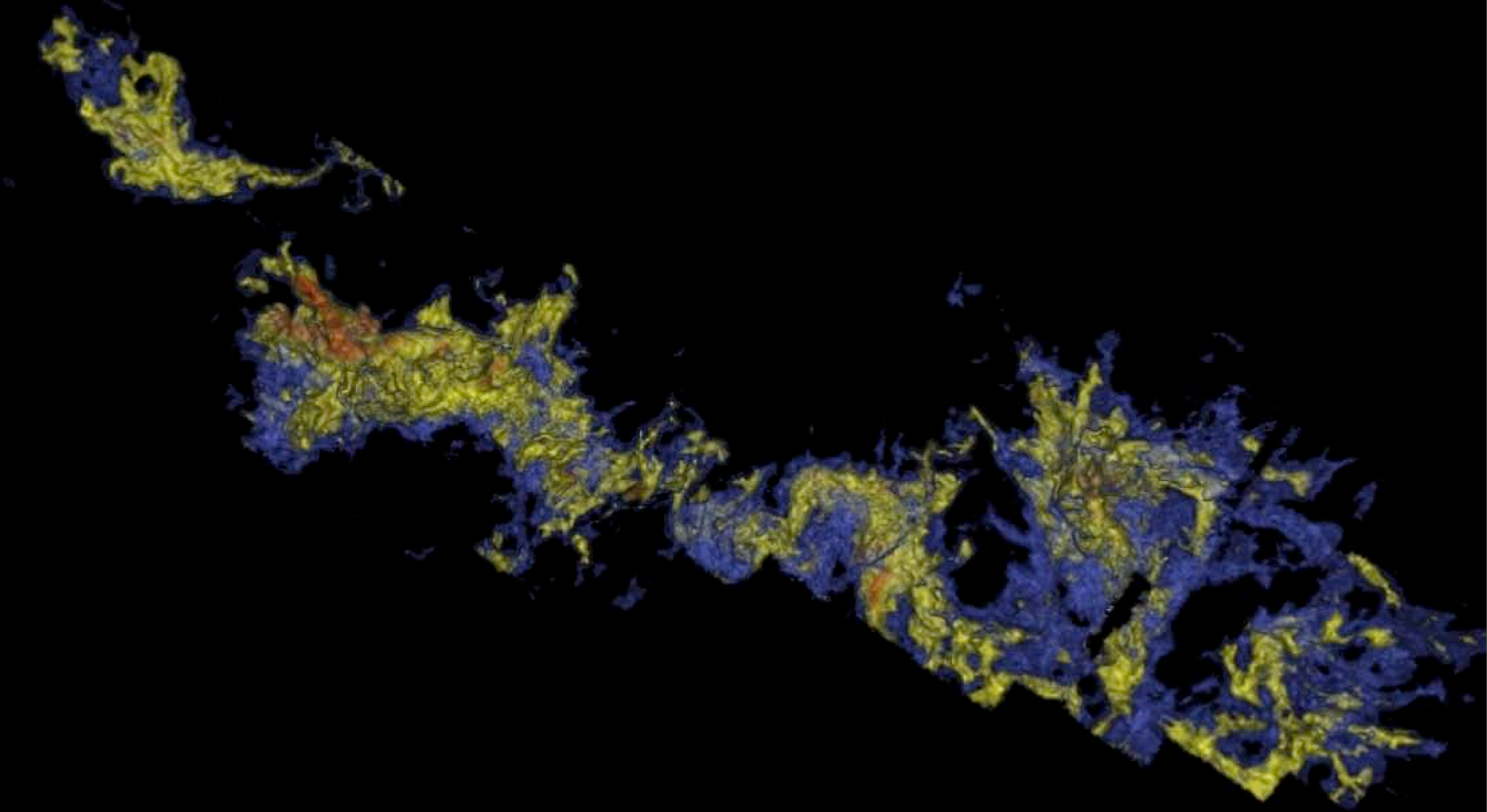
Rendering shows COMPLETE ^{13}CO
(as given in Ridge et al. 2006)
starting frame is plane-of-sky
"z" axis is line-of-sight velocity



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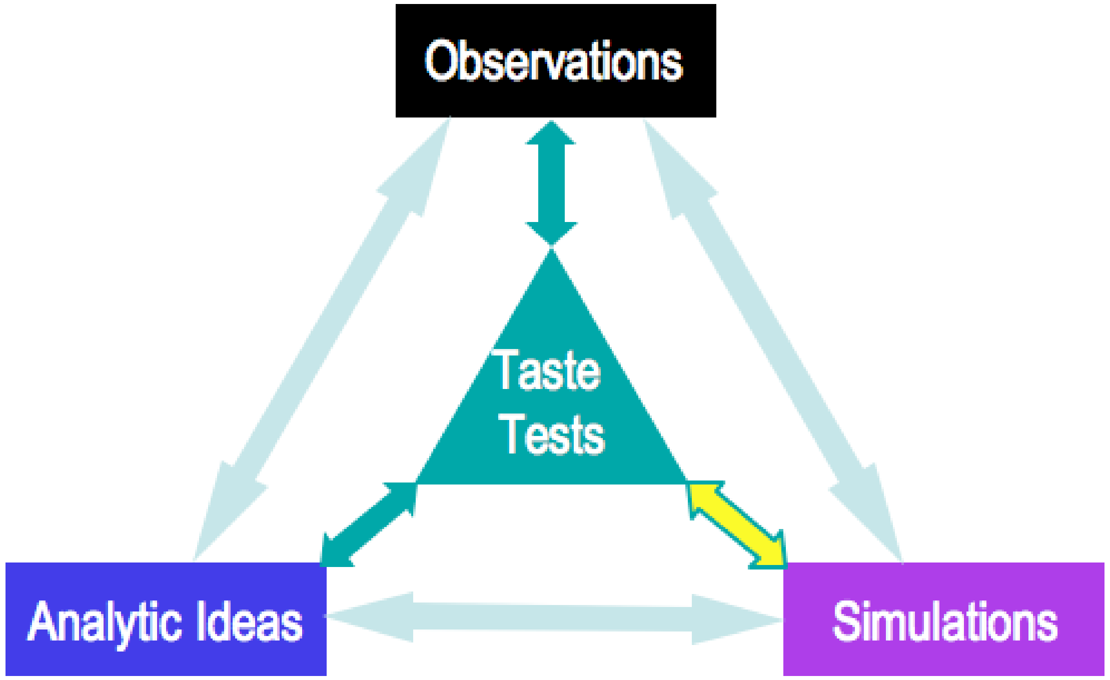
Taste Tests



"Taste Tests"? We frame this project by analogy. How does a great chef, making a complicated dish, know if she has created what she originally intended when she is done cooking? She "tastes." She informs her cooking with her extensive knowledge of food chemistry (analytic theory), uses all the cooking equipment (simulations) she has in the kitchen to try to make something edible and tasty (starforming, and realistic), and then she uses her senses (observations) to see if what she made tastes as intended. *"Tasting" in cooking actually encompasses the joint action of many senses: we propose here a combination of statistical techniques that we call "taste tests."* The tests will allow us to discerningly decide if what we sense (observe) and what we can cook (simulate) might actually be tasty (form stars), and how (analytic theory) that happens.

from: Goodman & Rosolowsky, NSF Proposal Fall 2006

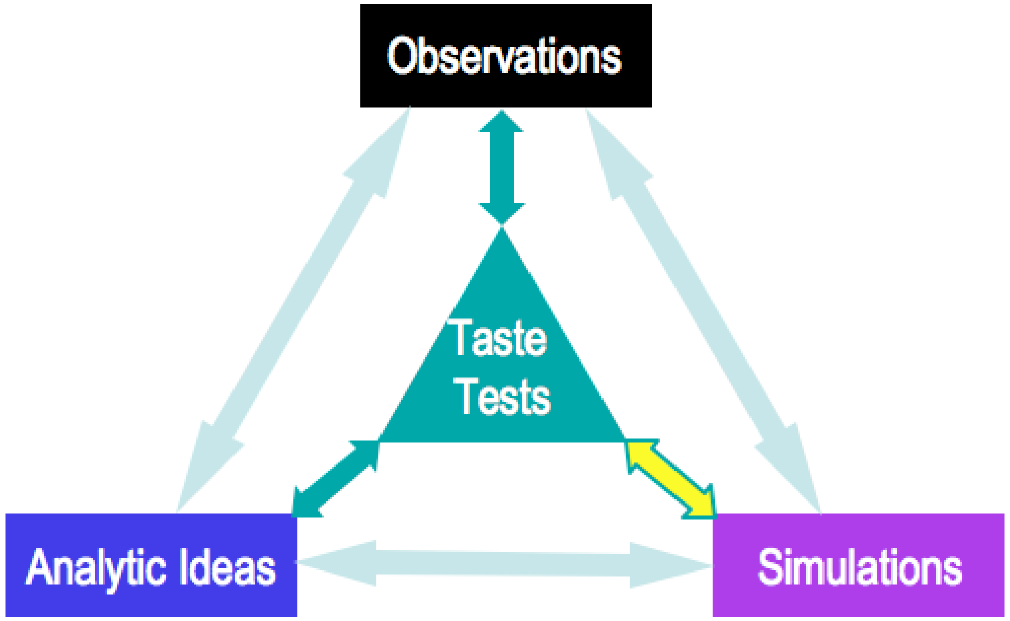
Earlier Tests...

Inspired by the "Theory Cube"

- Power Spectra (of density, velocity)
- pdfs
- Autocorrelation Functions
- Δ–Variance
- Structure Functions

Data-Oriented

- Wavelet Analysis
- Spectral Correlation Function
- Structure Trees
- Velocity Centroid Analysis
  VCA (see also VCS)
- Principal Component Analysis



Today: Take-Out Only

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Column density is **log-normal-ish** on 10's of pc scales

- ★ turbulence prevails, mostly(?)
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Self-gravity matters on a range of scales, at *identifiable* locations

- ★ quantification of hierarchical structure (**dendrograms**)

Full Workshop:
Five-Course In-House Meal

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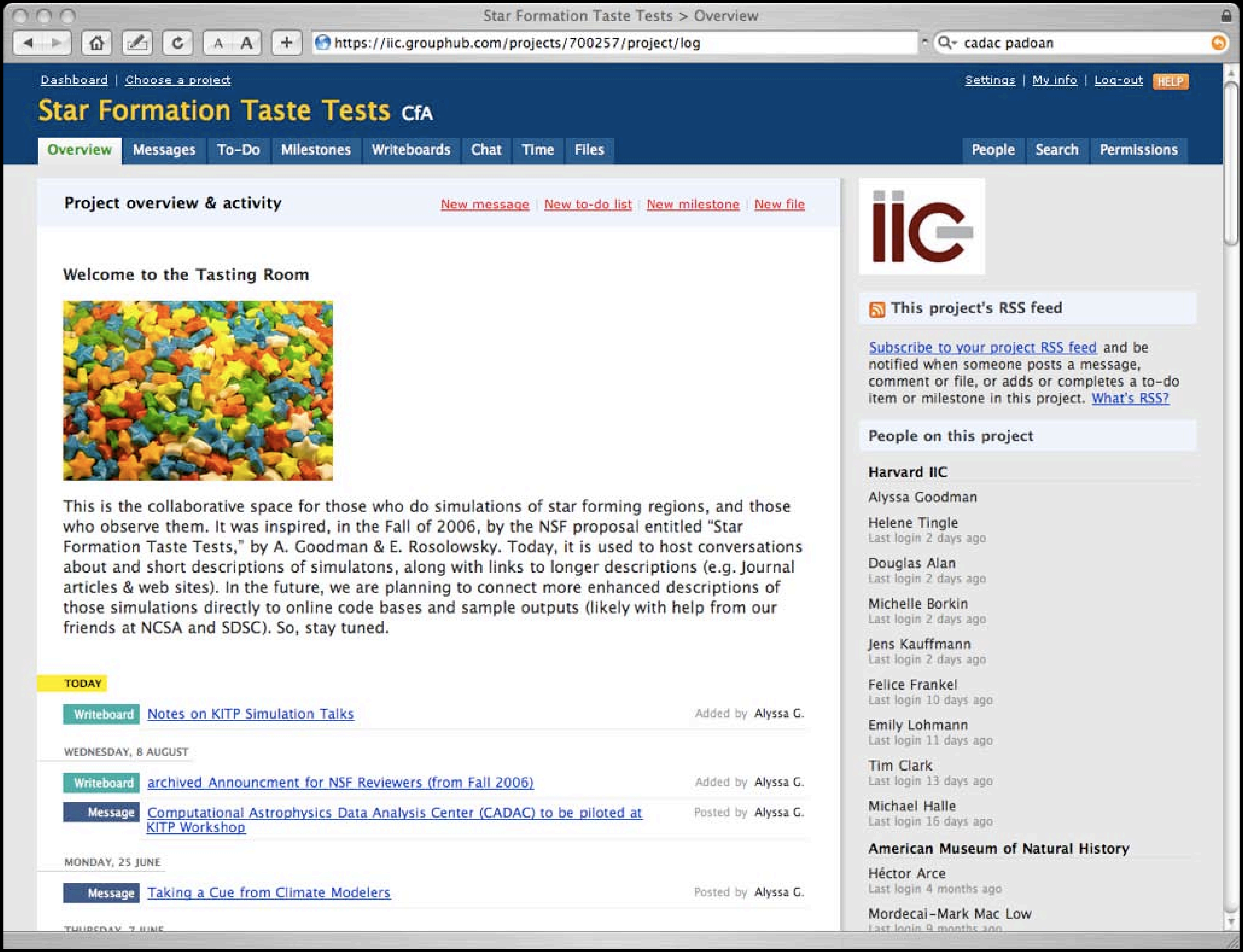

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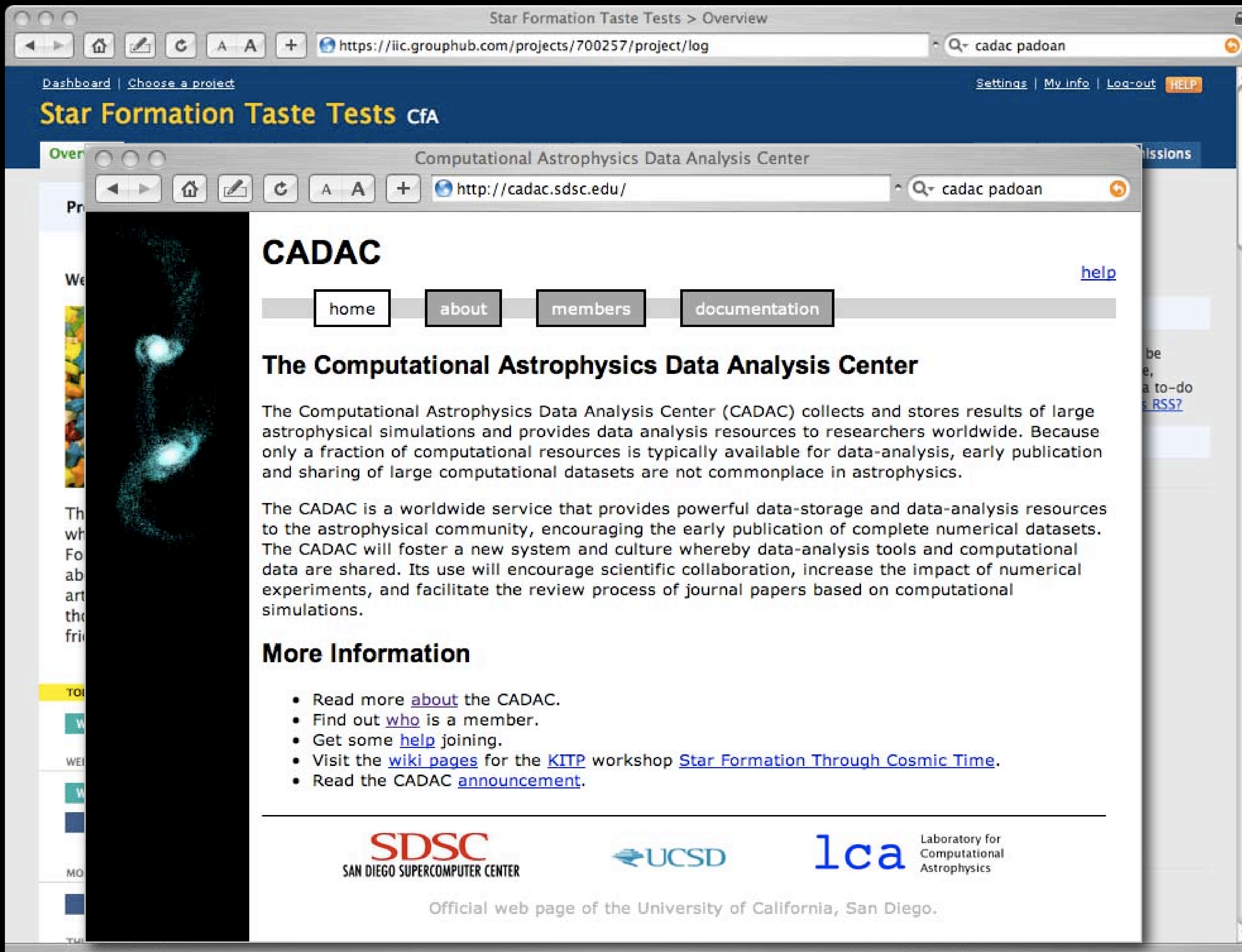

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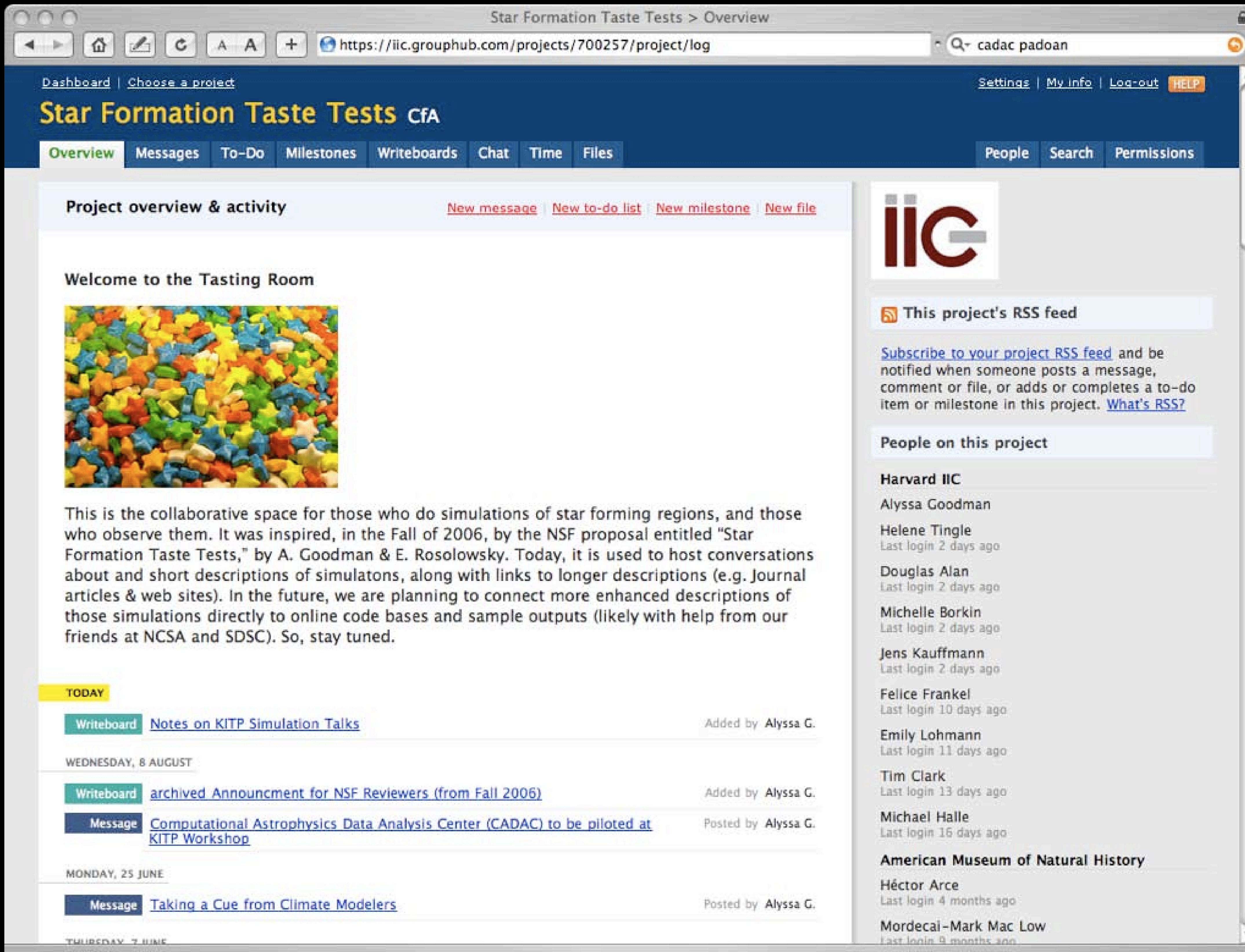

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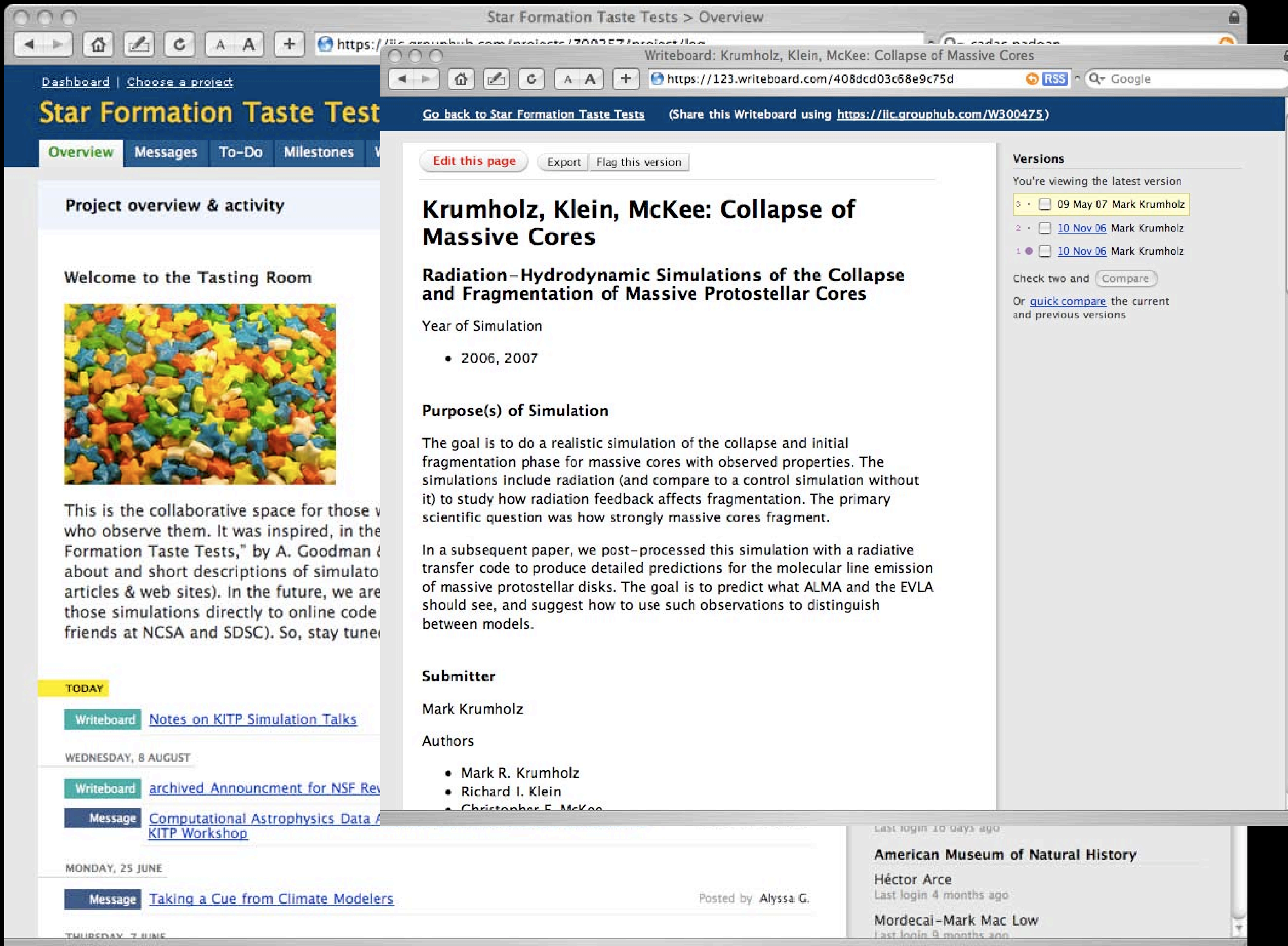

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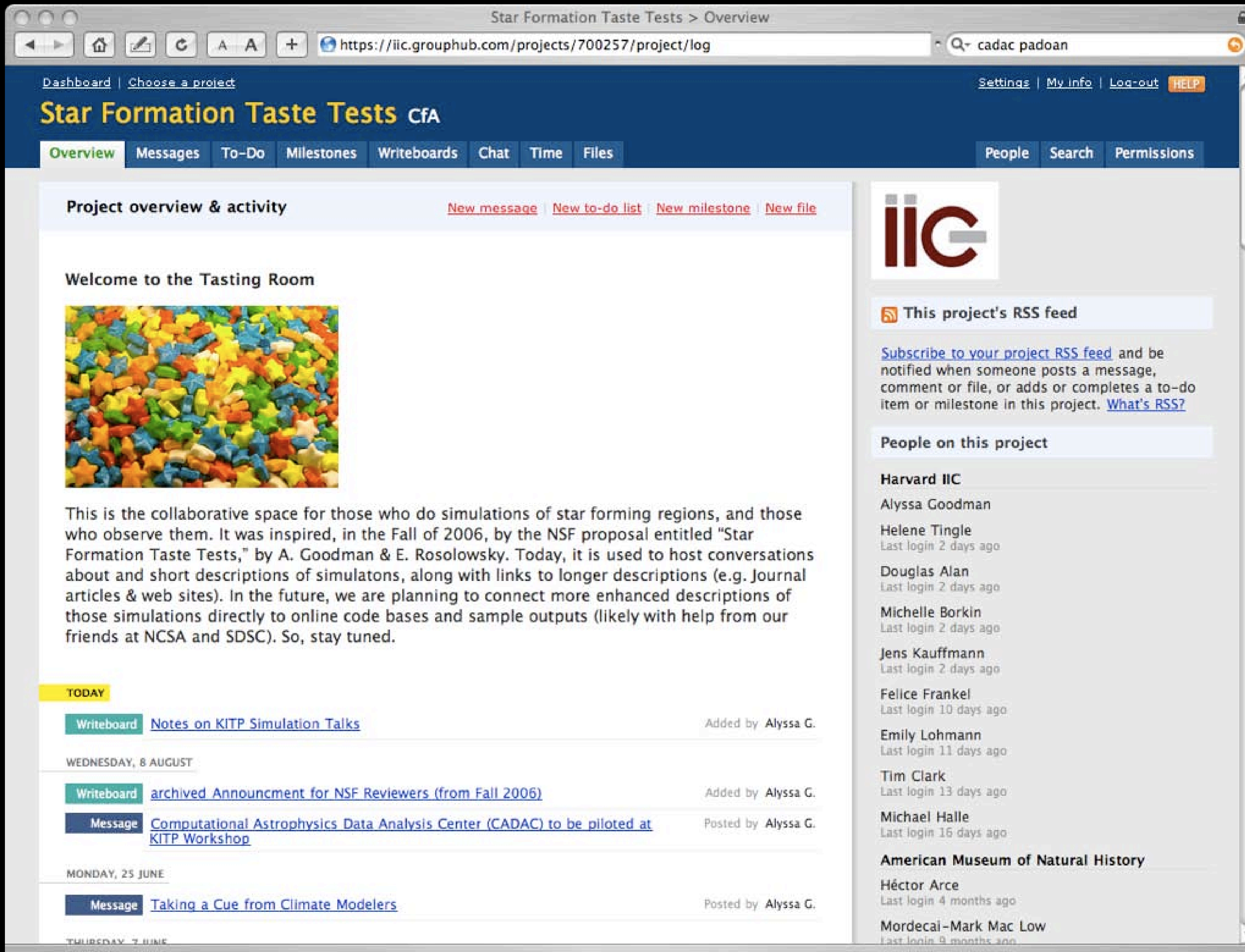
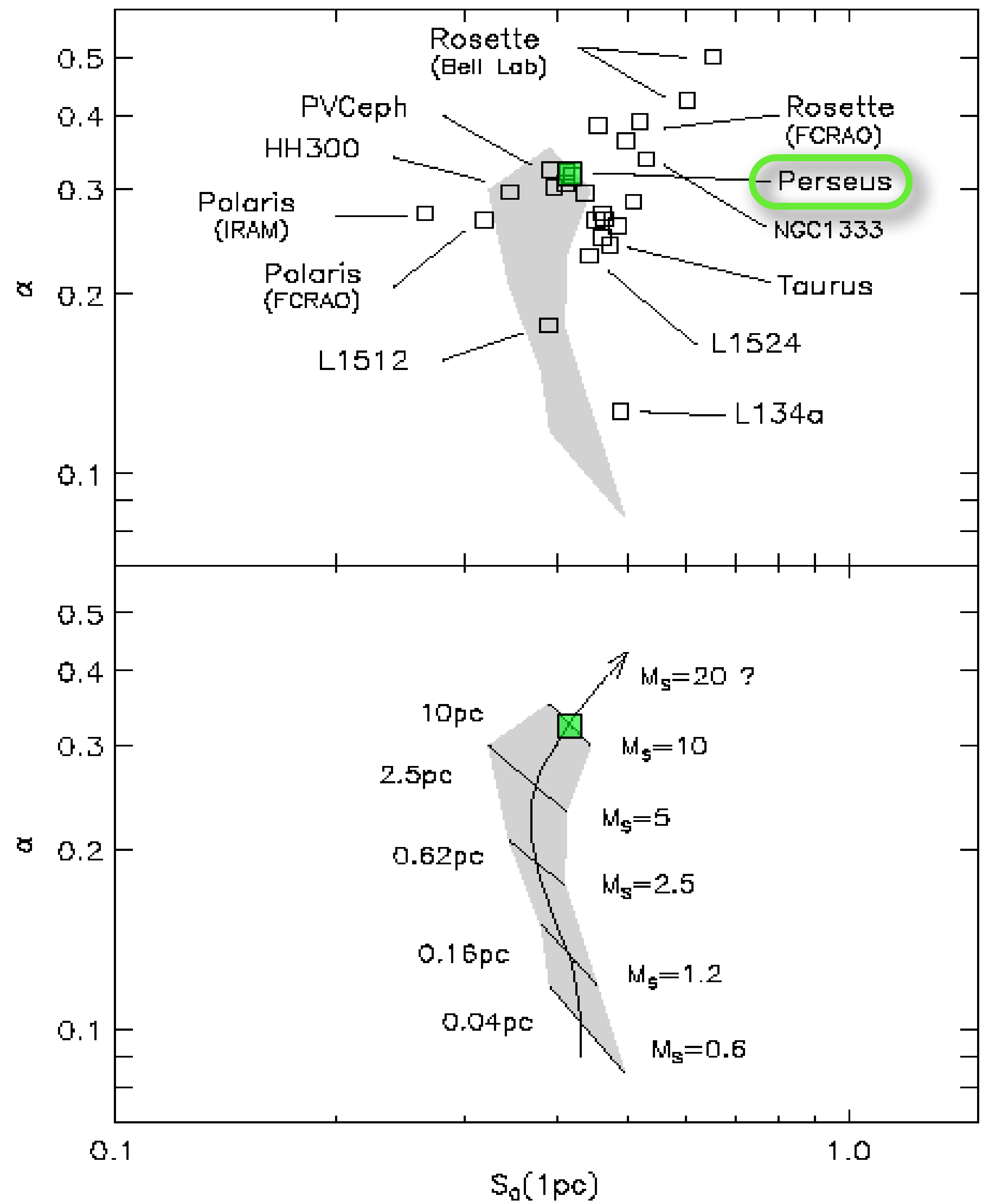


Living in “Observational Space”

Ideally includes...

- Projection to 2D sky plane, or “3D” of spectral-line data cubes
- Radiative Transfer
- Chemical Model
- Adding appropriate noise
- Imposing observing characteristics of a telescope



Example:
The Spectral Correlation Function

(Padoan, Goodman & Juvela 2003)

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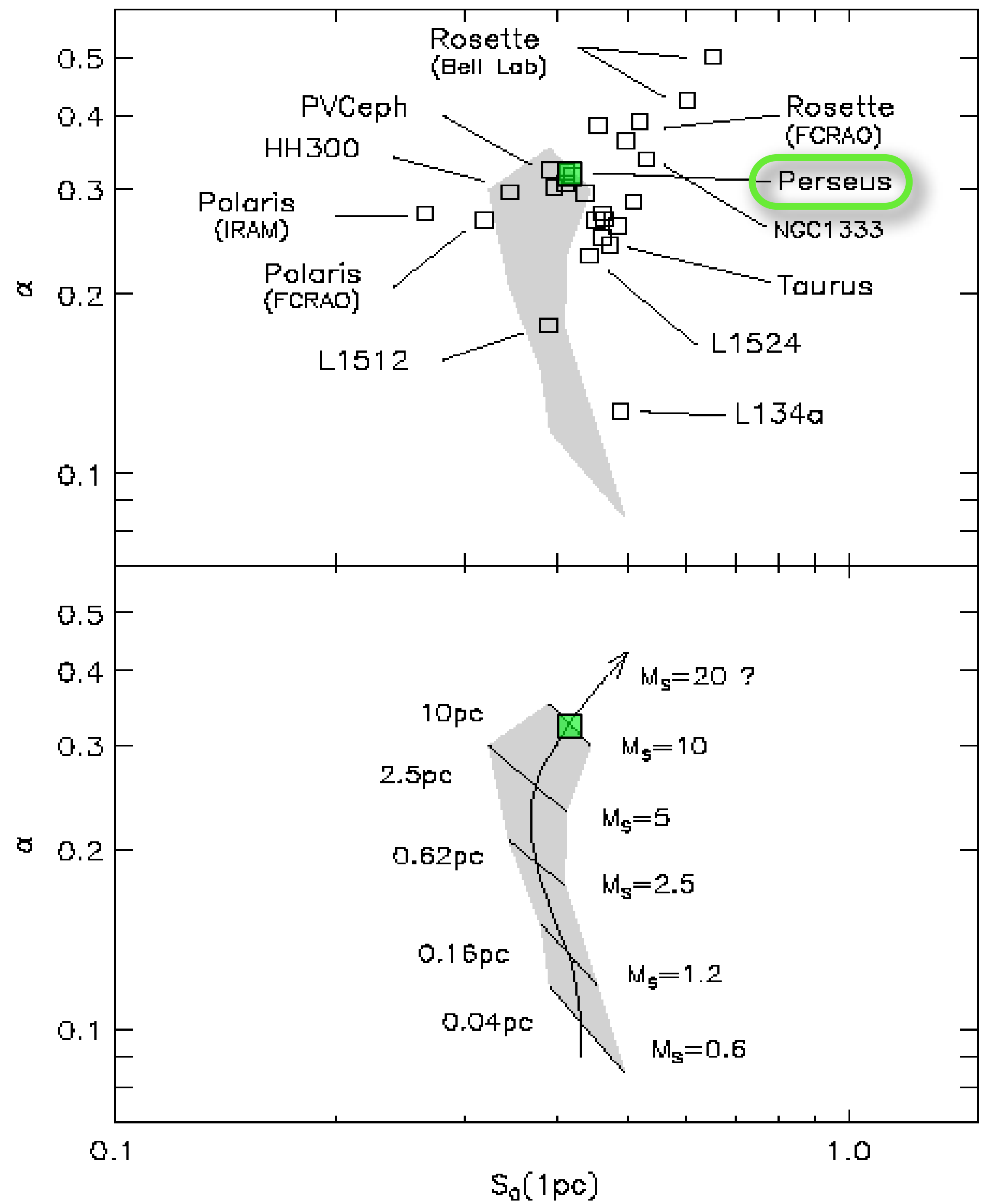

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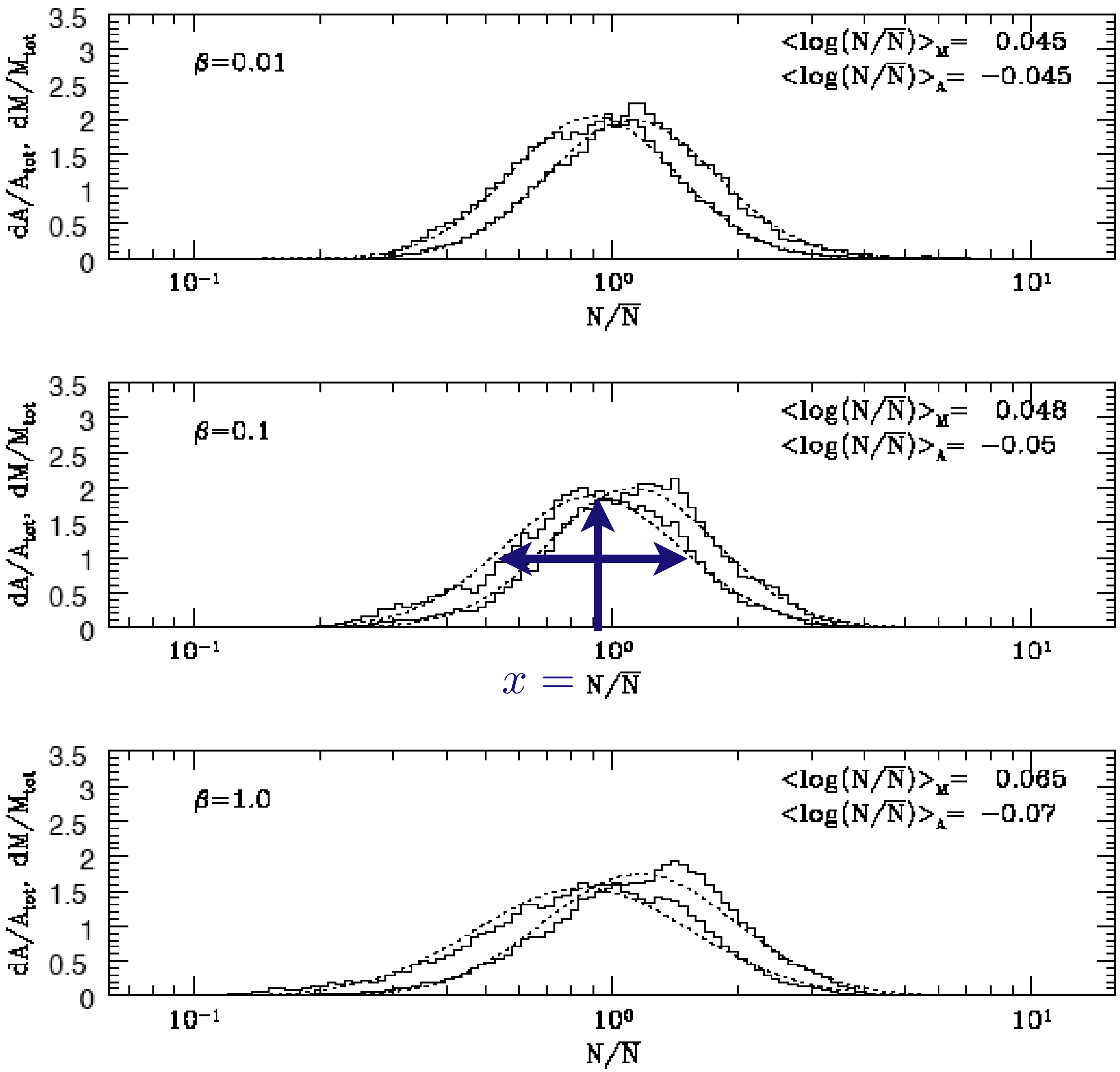
Results from MHD simulations

$$\overline{\ln x} = -\frac{\sigma^2_{lnx}}{2}$$



Strong B-Field

Medium B-Field

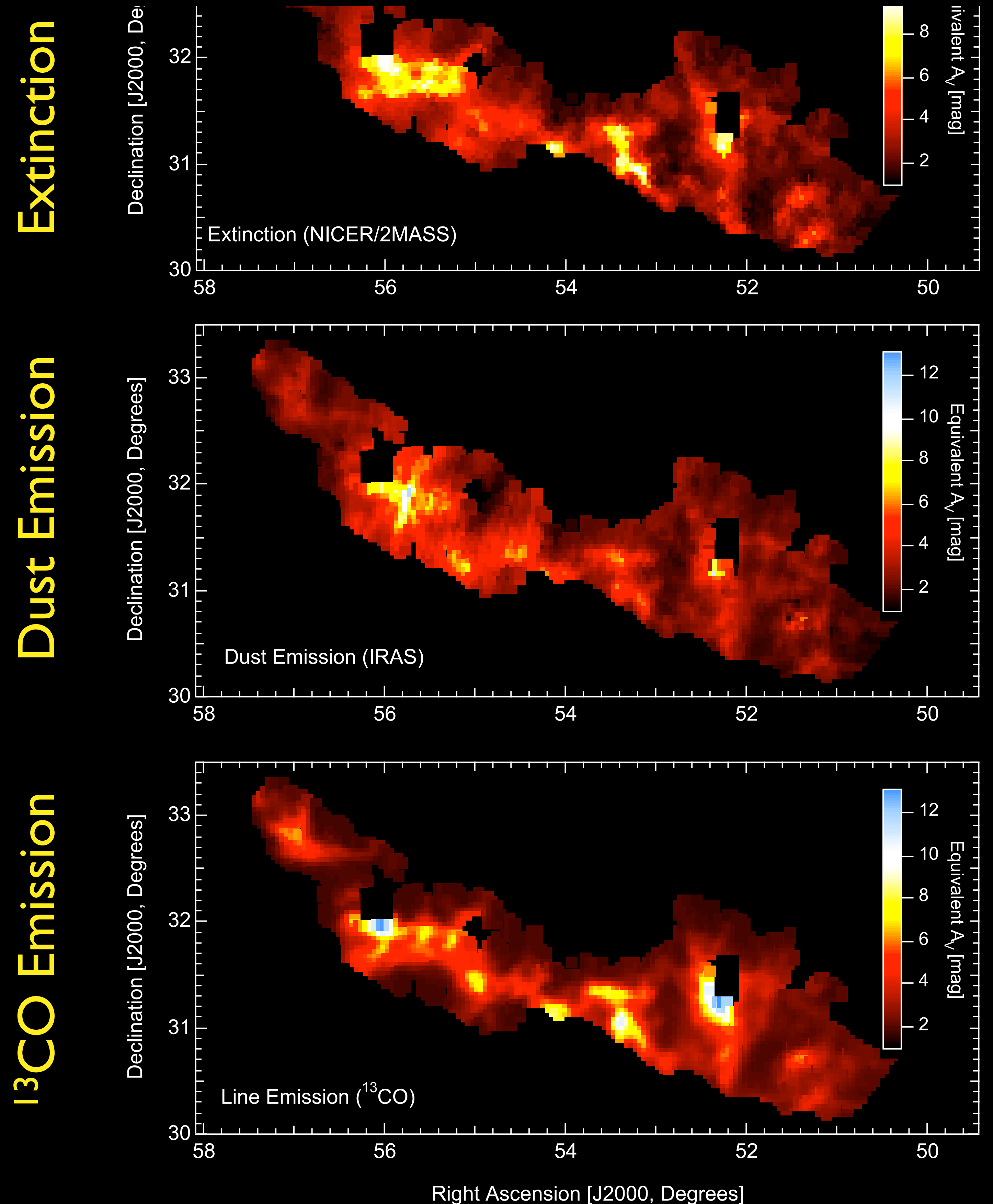
Weak B-Field

Example: log-normal column density distribution

(Ostriker, Stone & Gammie 2001)

Is the gas density distribution lognormal or not? (2D)

The (secret) uncertainties inherent in column density mapping.



Goodman et al. 2007

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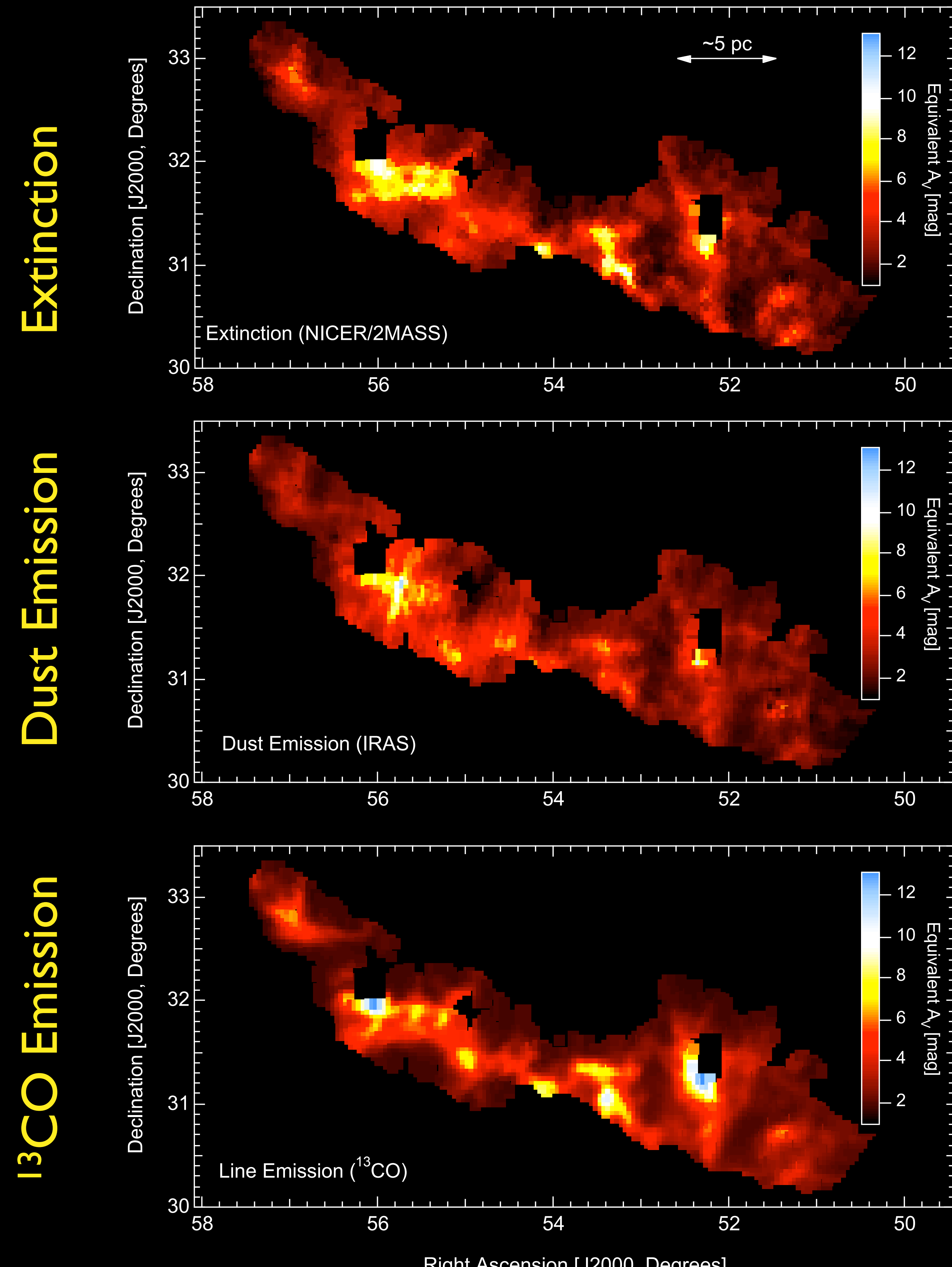

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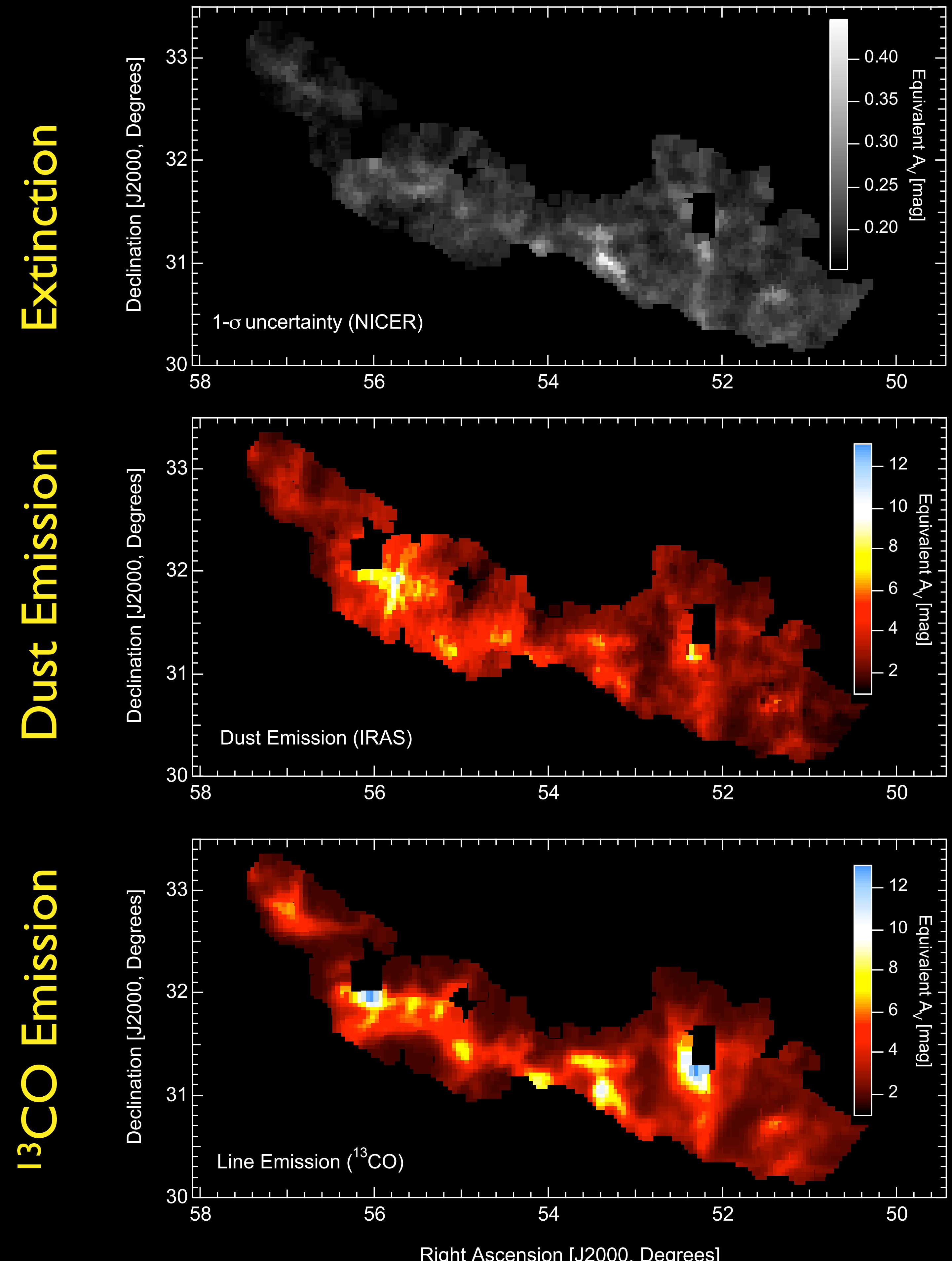

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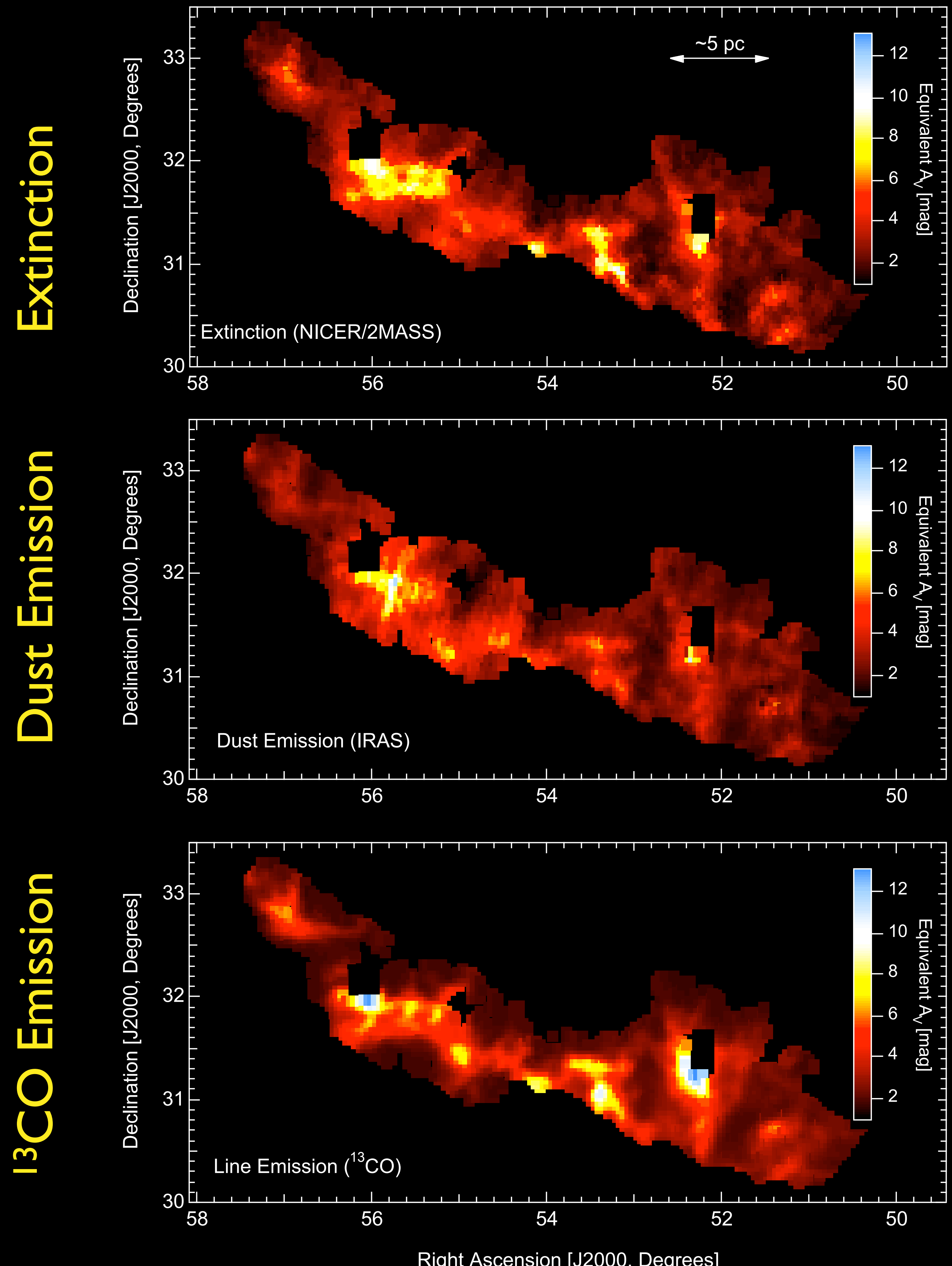

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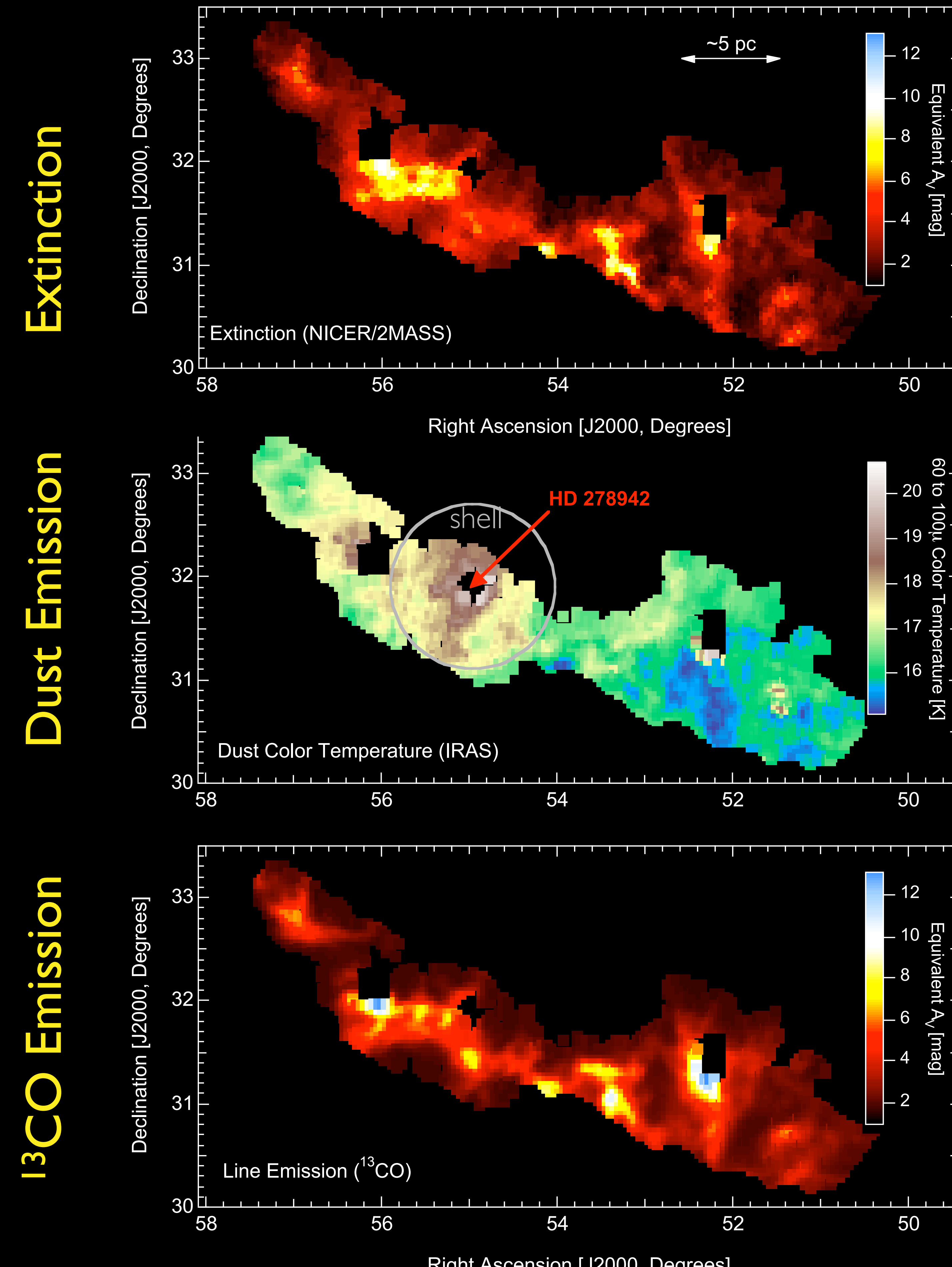

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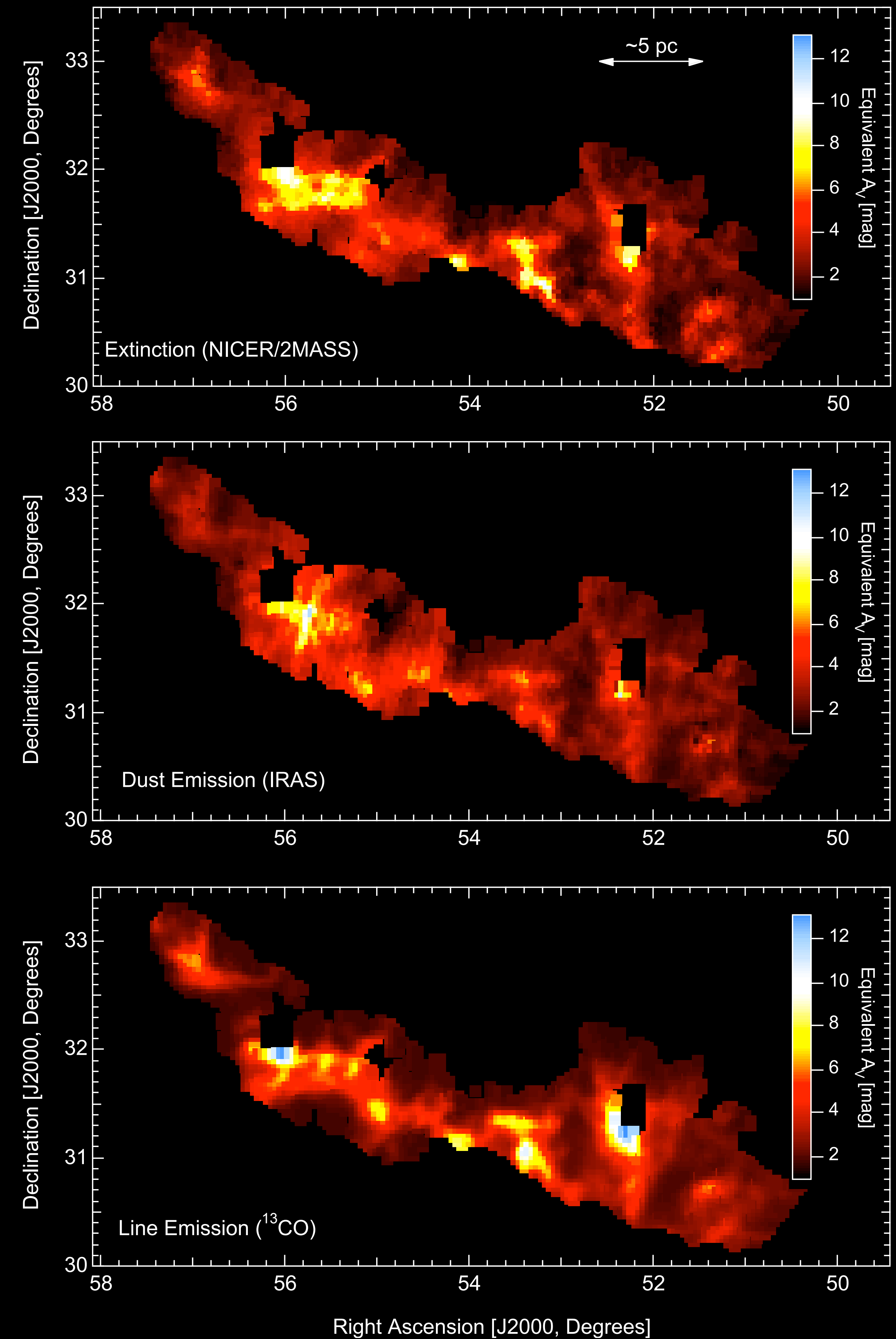
Extinction

Dust Emission

^{13}CO Emission



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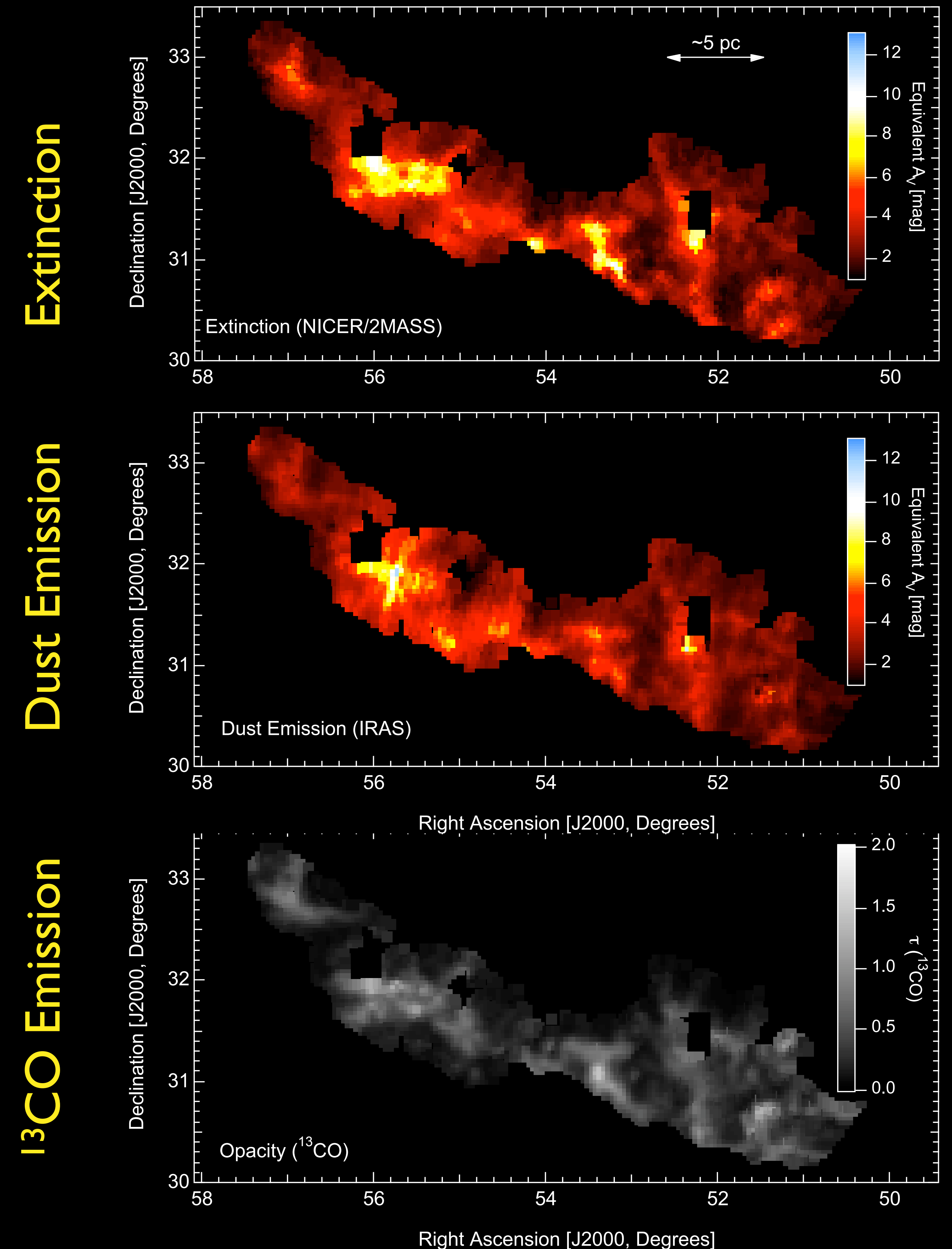

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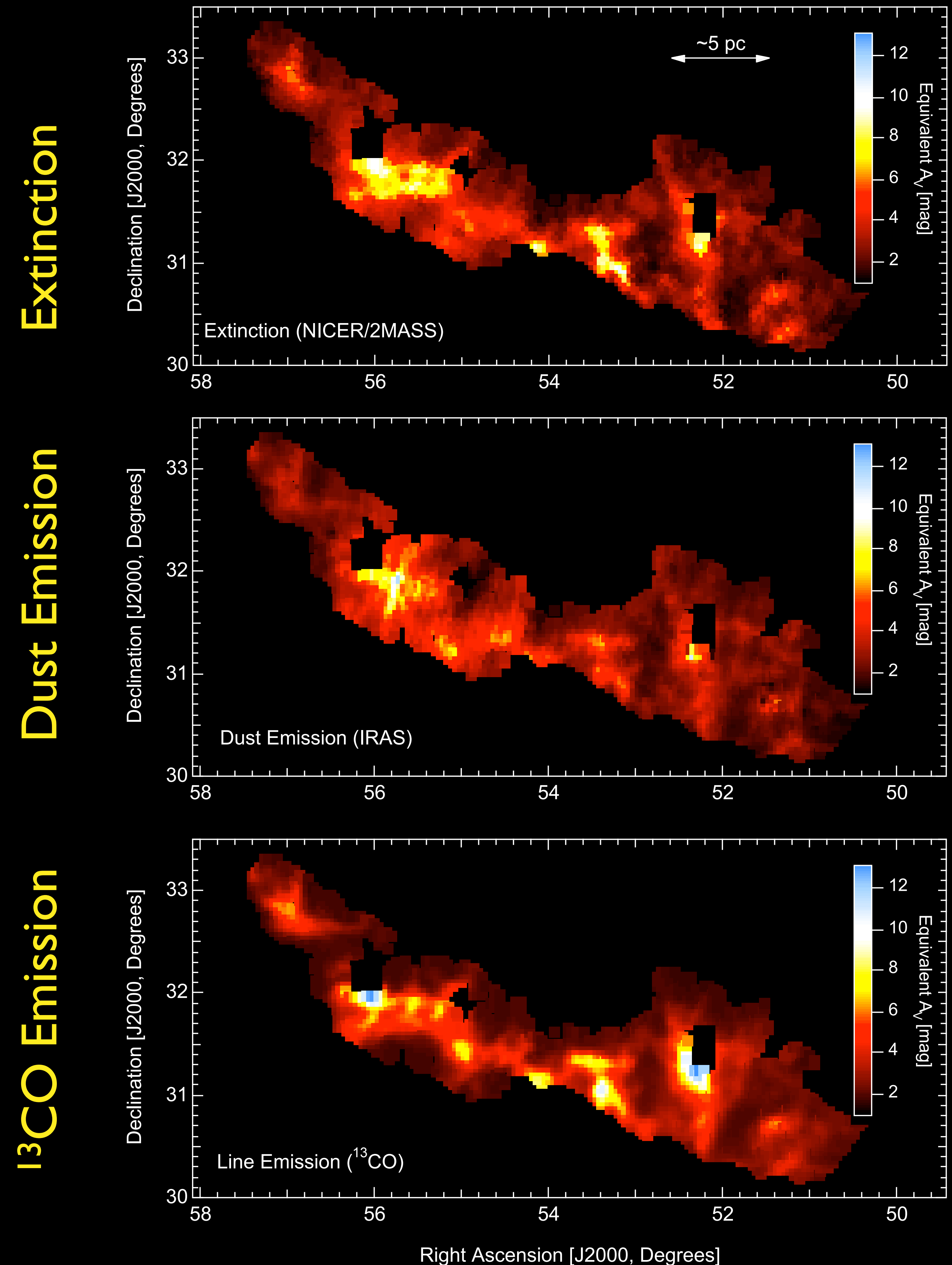
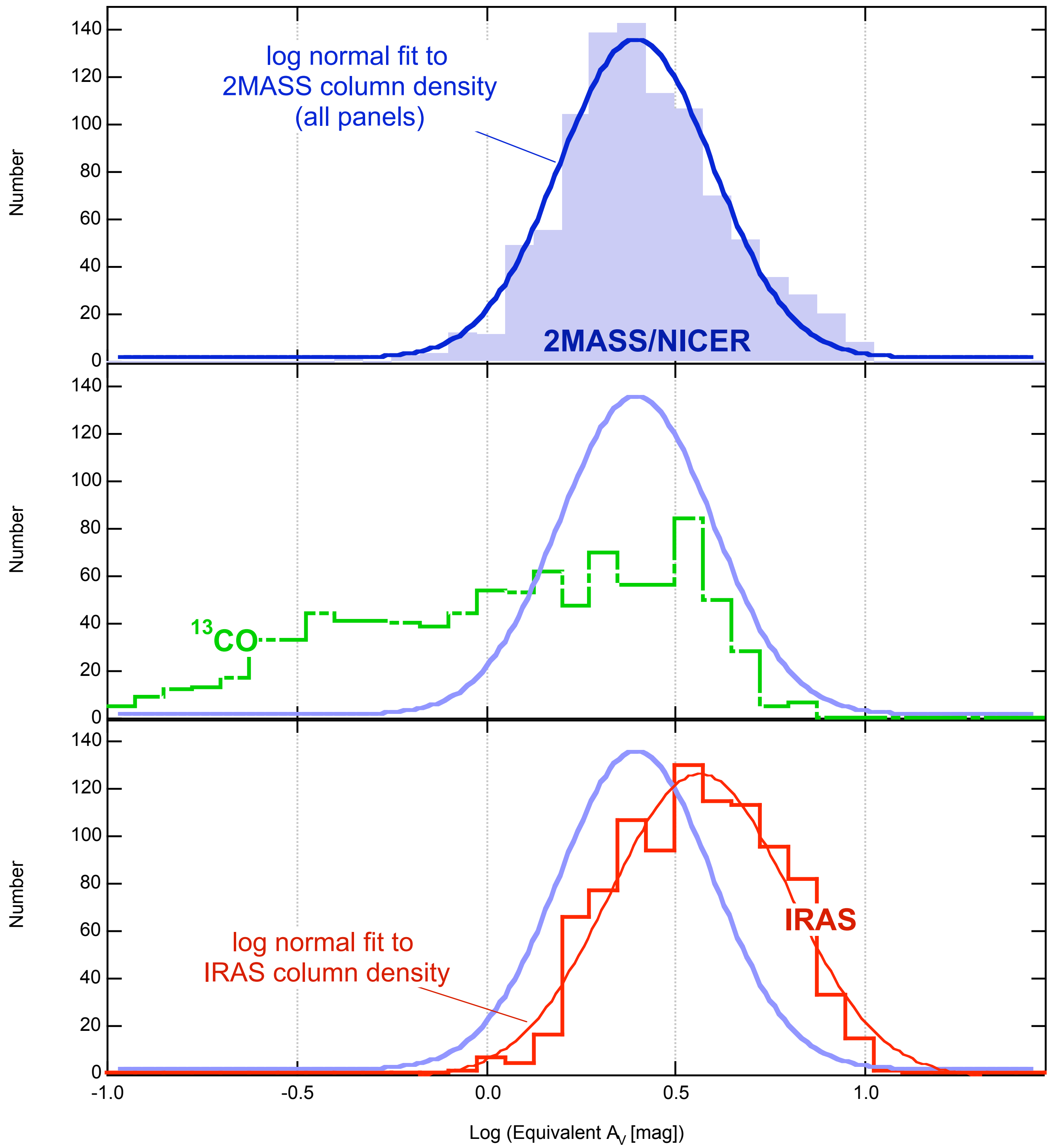


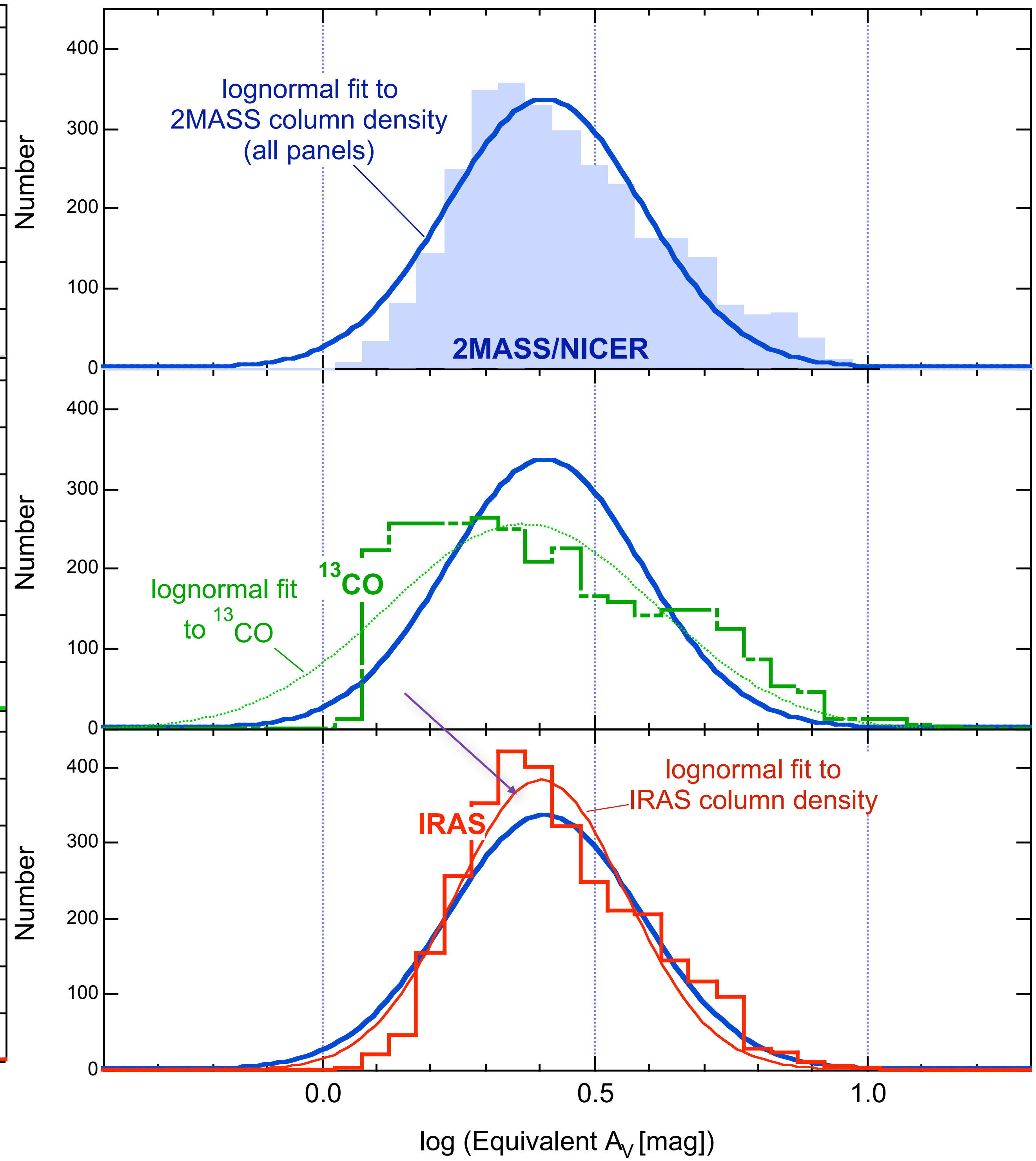
Goodman et al. 2007

“Bias & Uncertainty”: A Never-ending Challenge

State of the Art, 2004



After 2 Years of Refinement…!



Goodman, Schnee, Pineda, 2007, in prep; see also Pineda, Caselli & Goodman 2007, in press.

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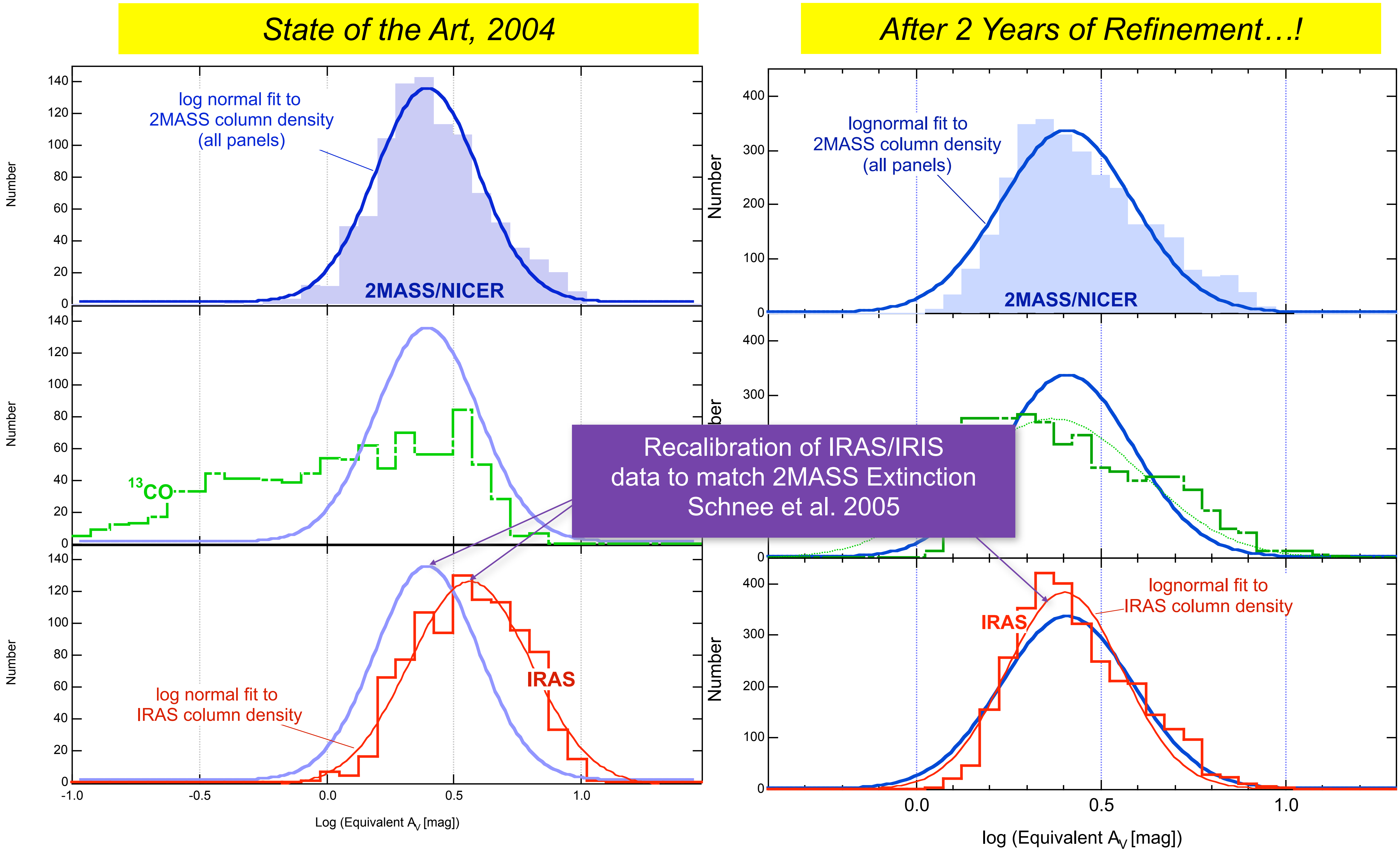

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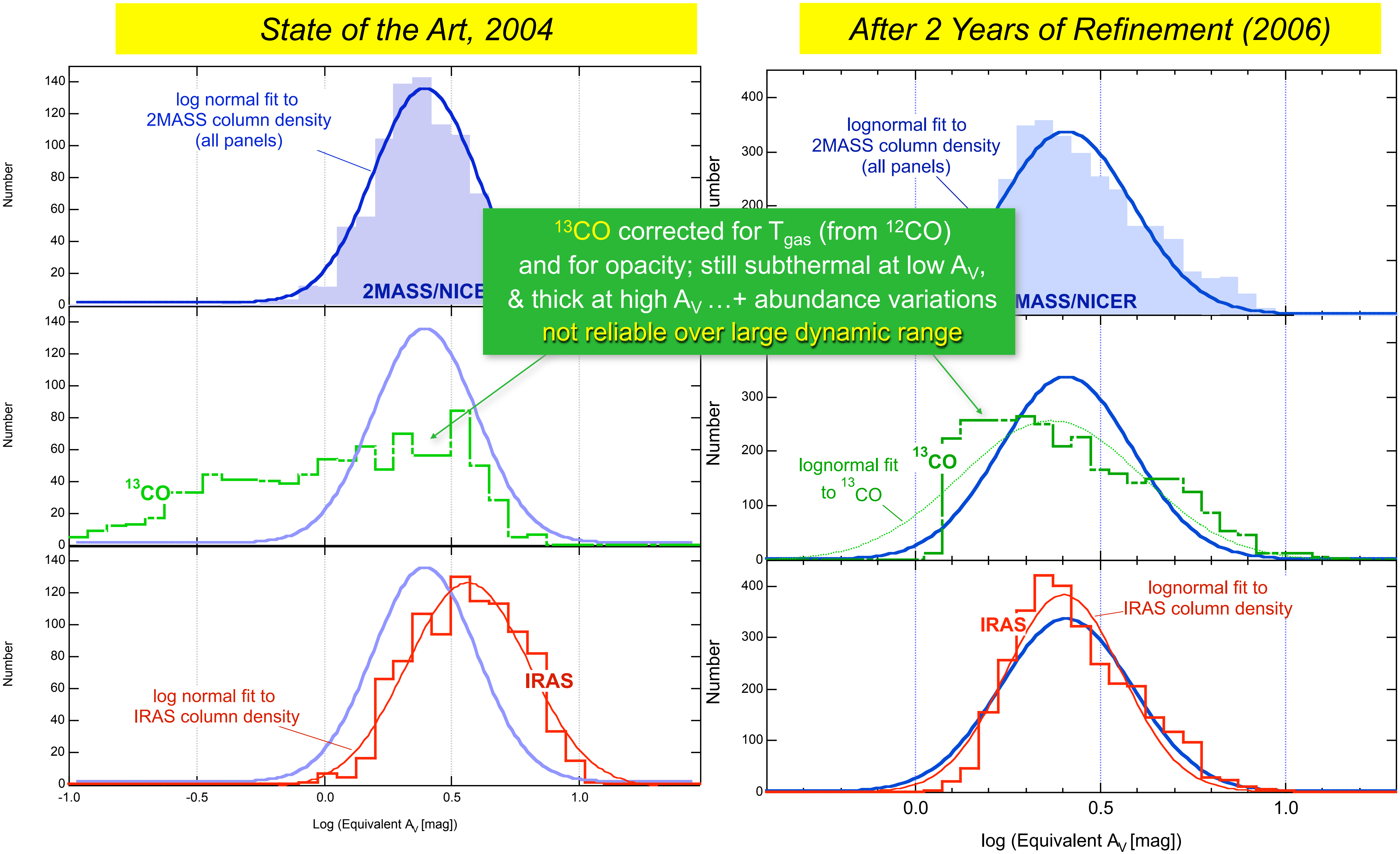

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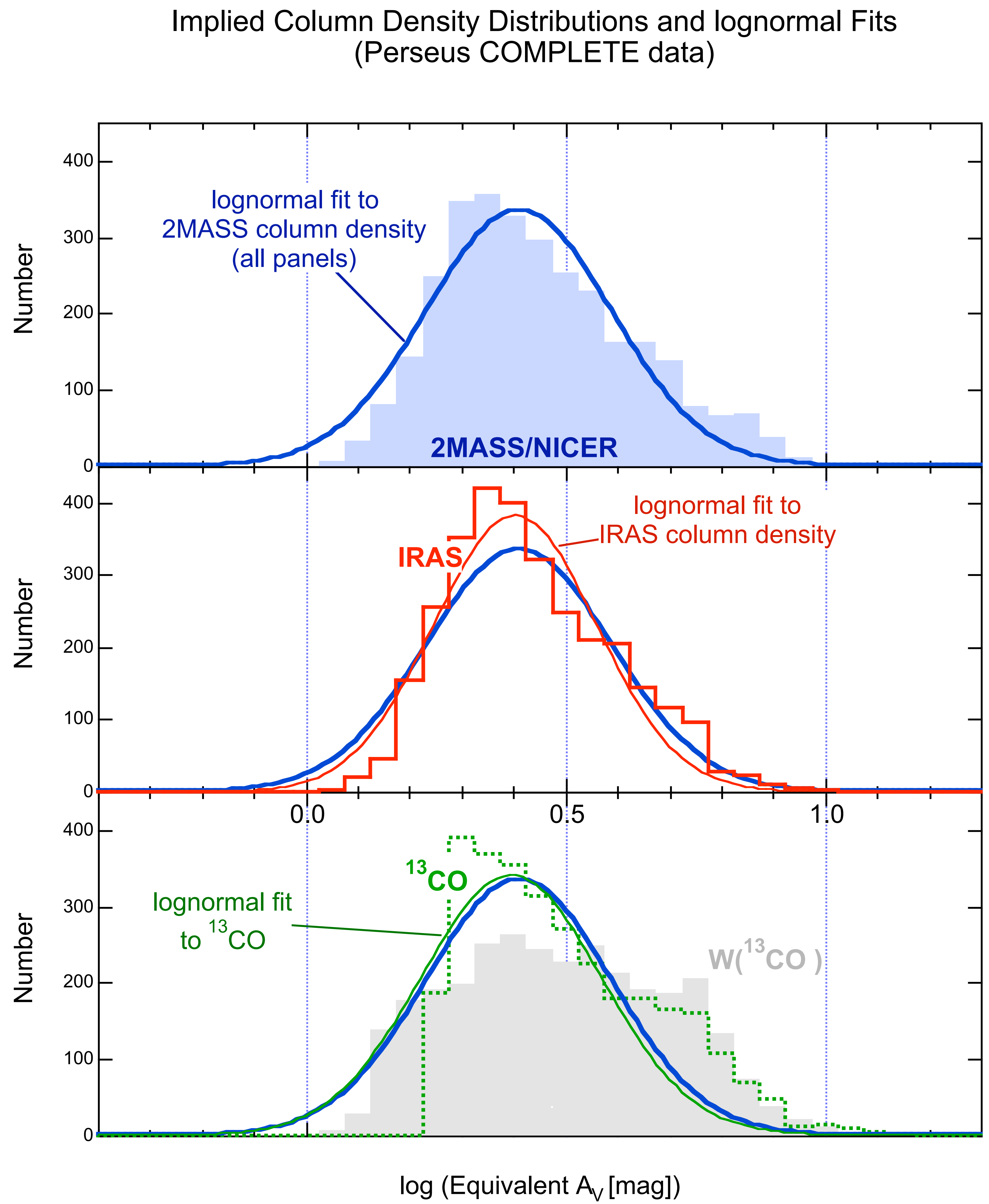
Some results...

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

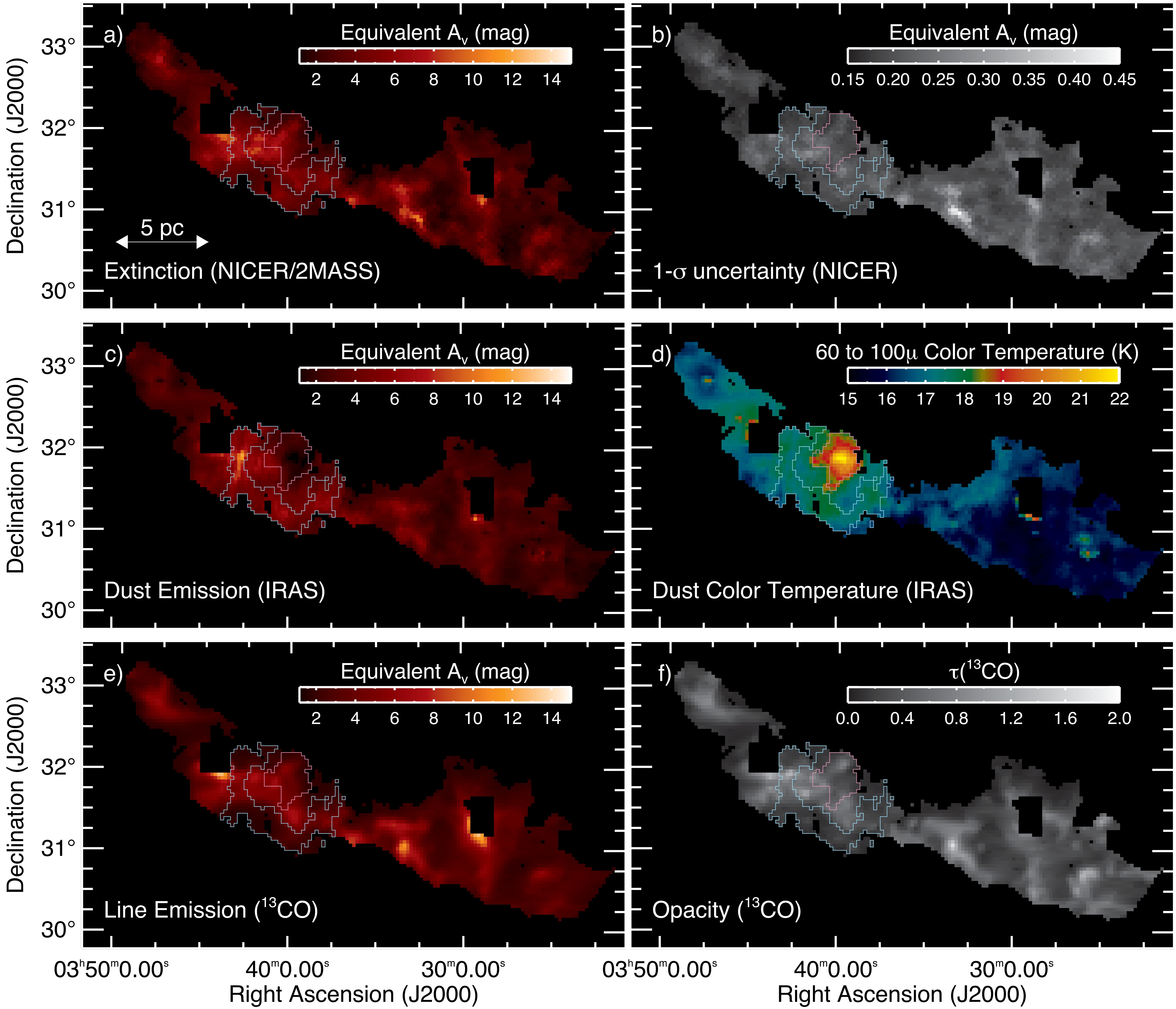
^{13}CO is not a very faithful tracer of column density

But, we're not done...



Today

"Bias & Uncertainty": A **Never-ending** Challenge



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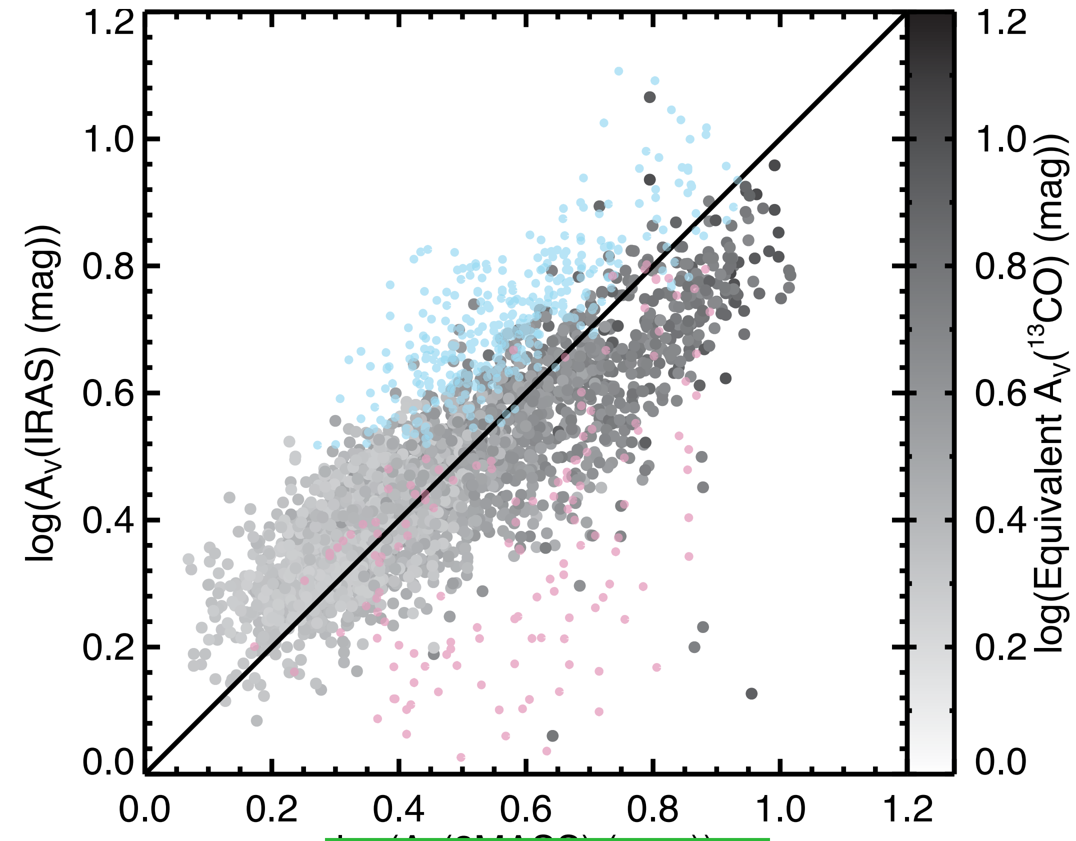
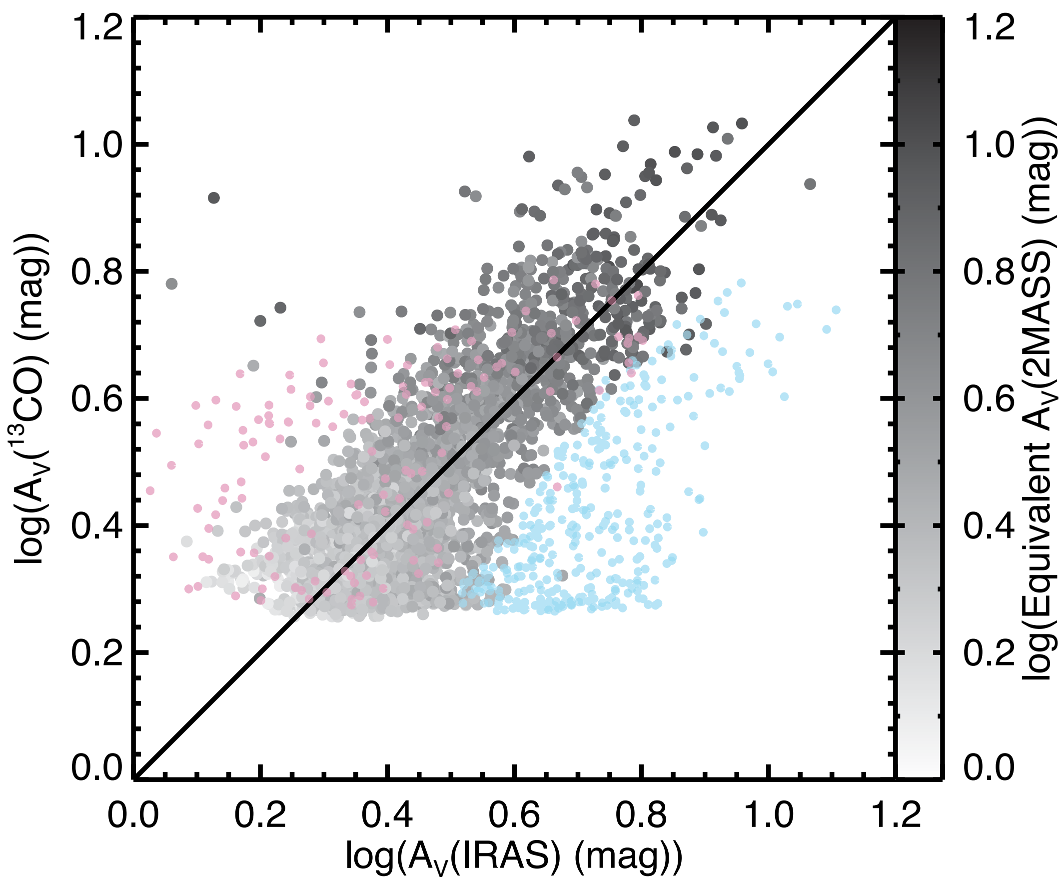
IRIS



2MASS/NICER

^{13}CO



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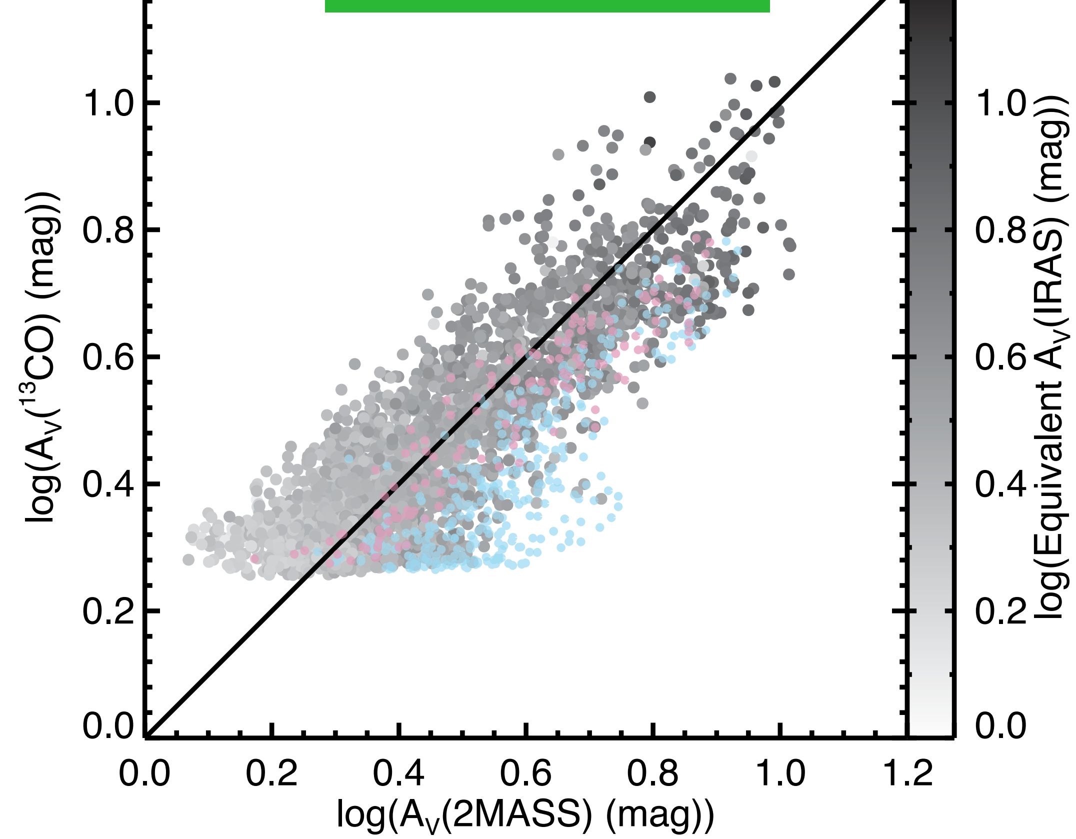

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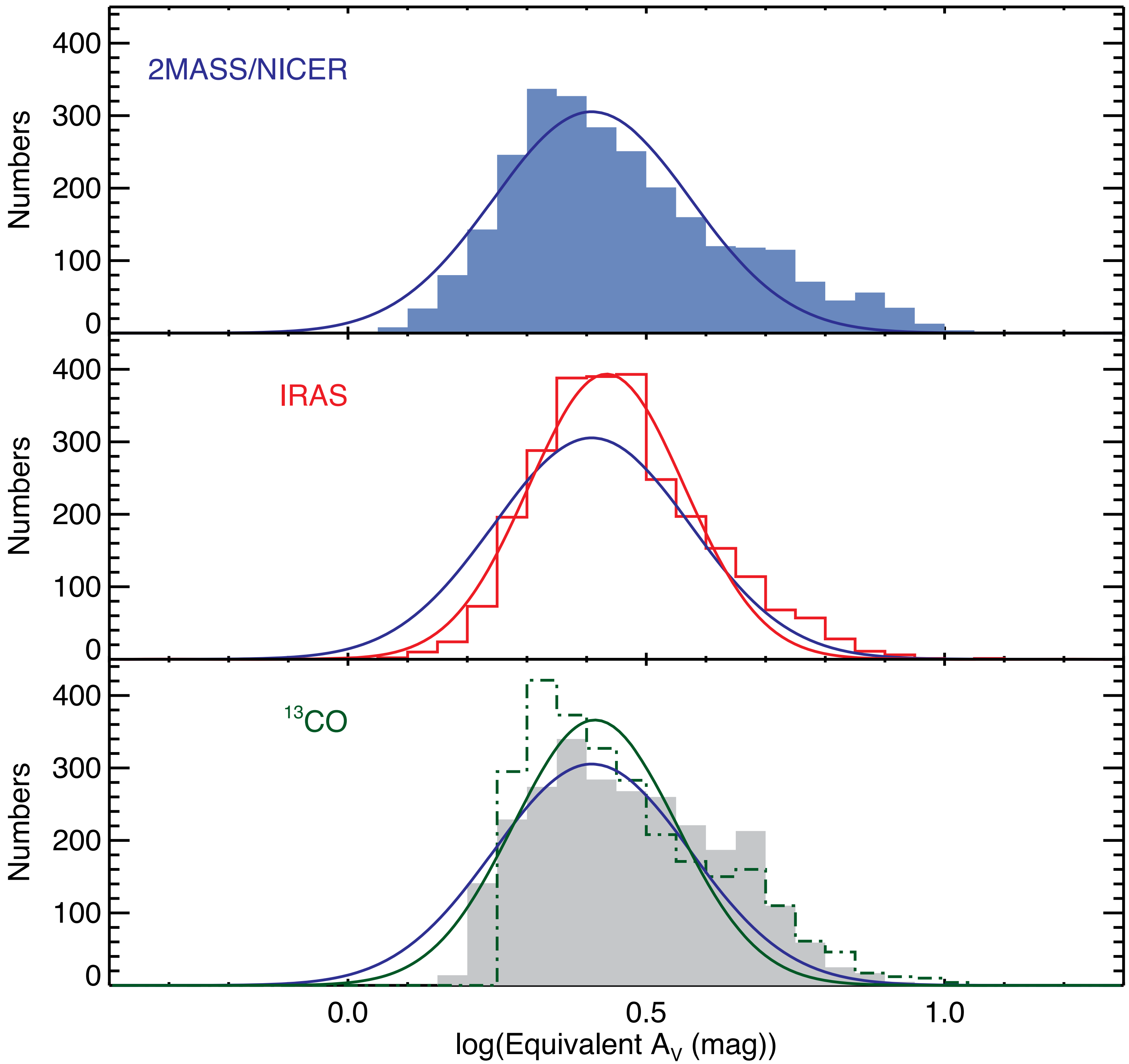

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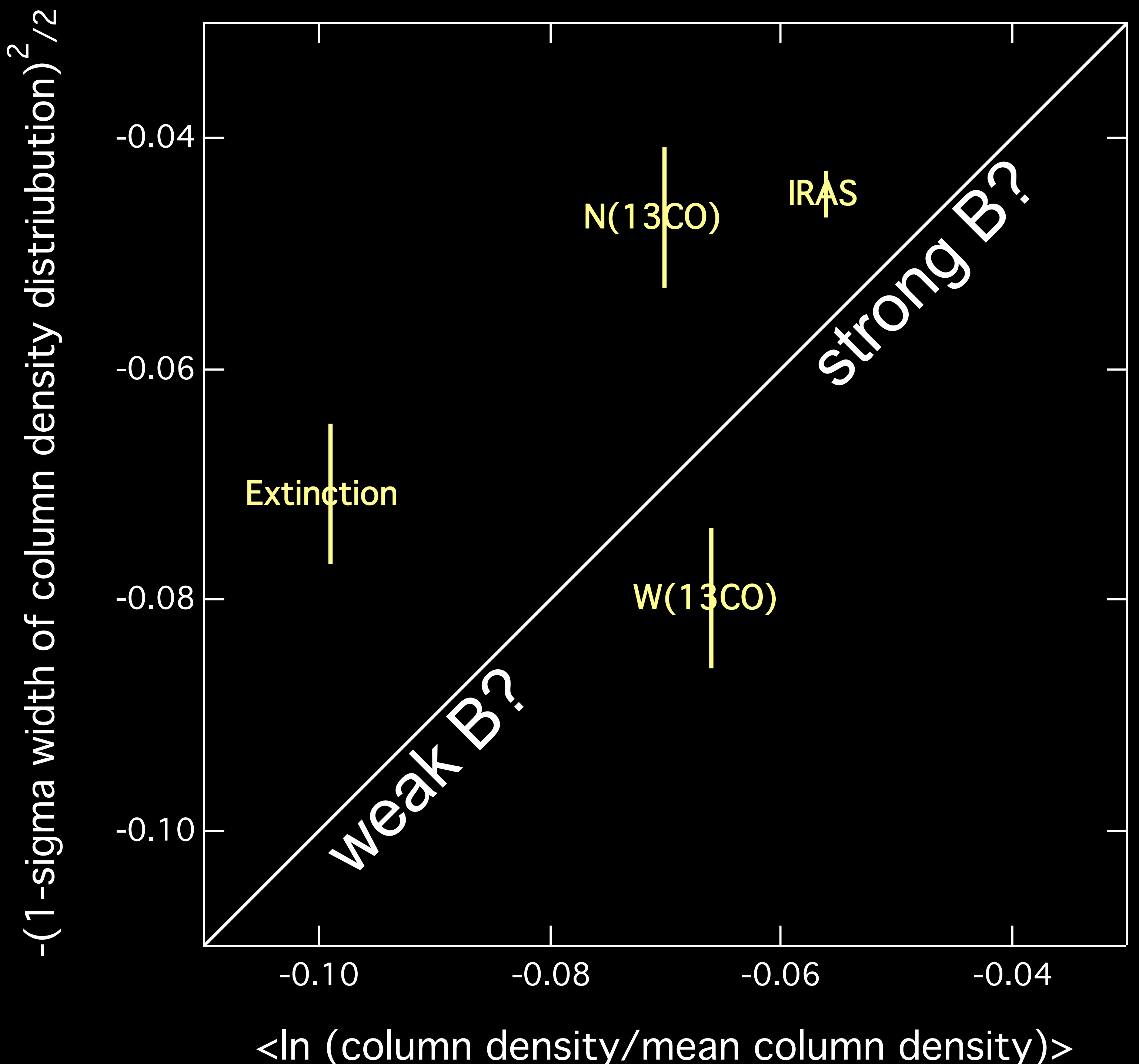
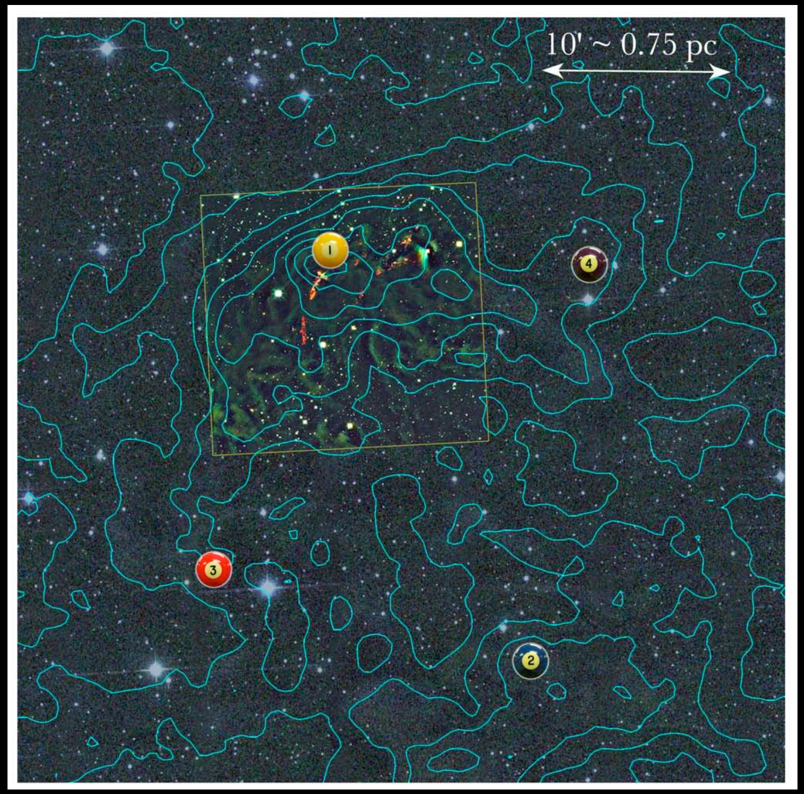
Can we say what these distributions mean, quantitatively?



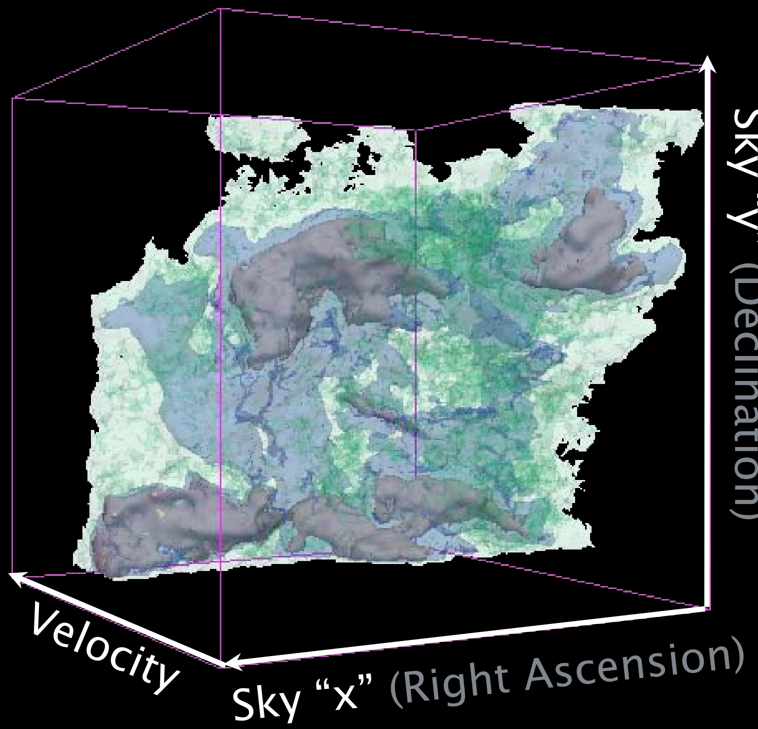
Notes: 1:1 line is predicted for turbulence & log-normal distribtion, and "weak" and "strong" markers are based on (some, but not all!) simulations in Ostriker, Stone & Gammie 2001--an illustrative example. (cf. Vazquez-Semadeni et al.; Padoan et al.)

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

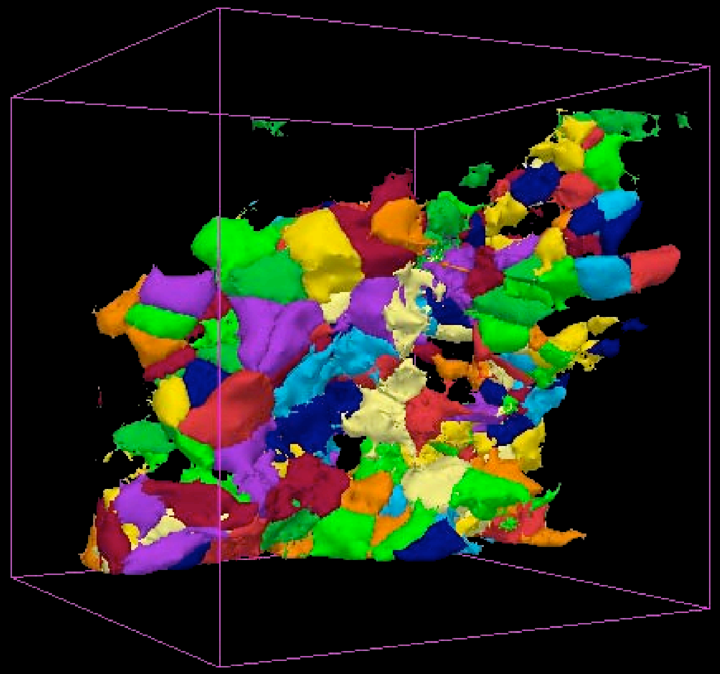
What's at issue?



(Dendro)Surfaces



"CLUMPFIND"



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

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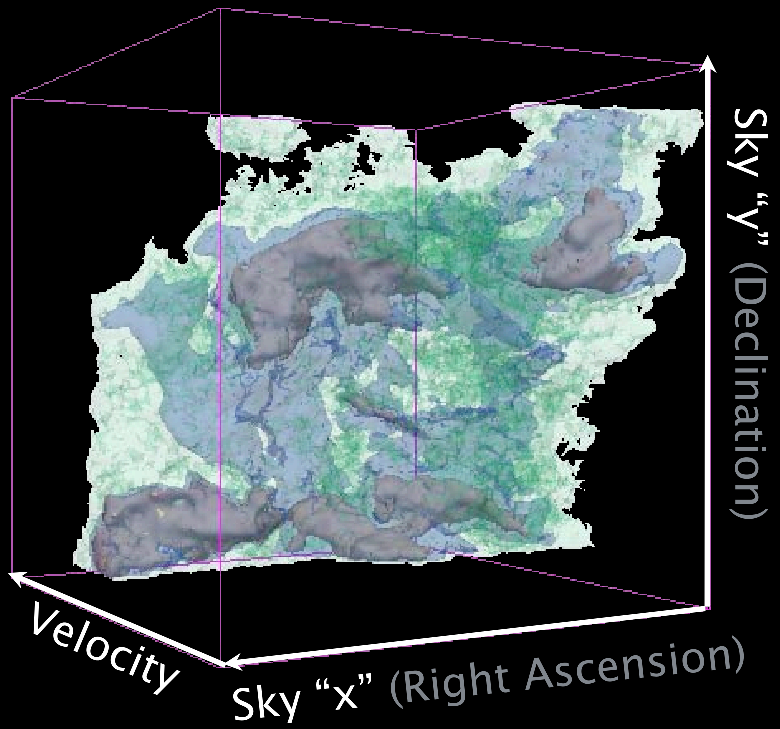

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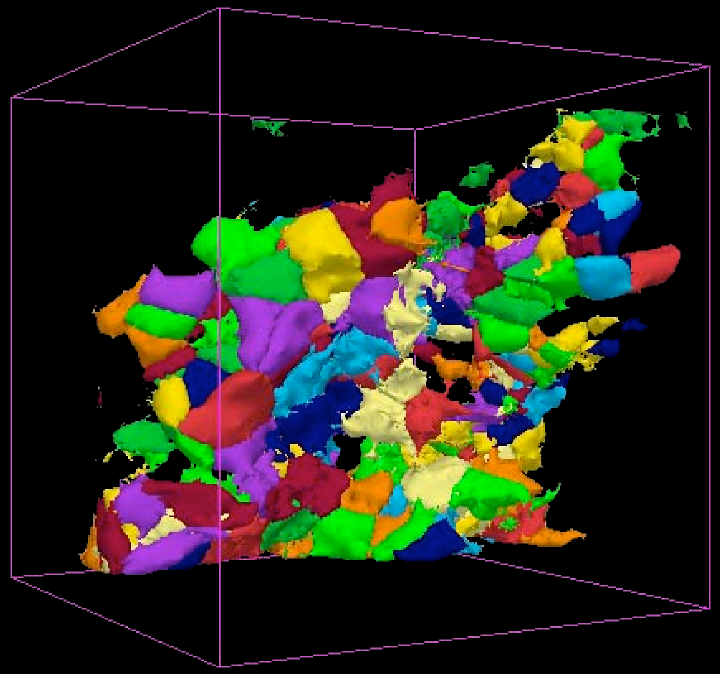
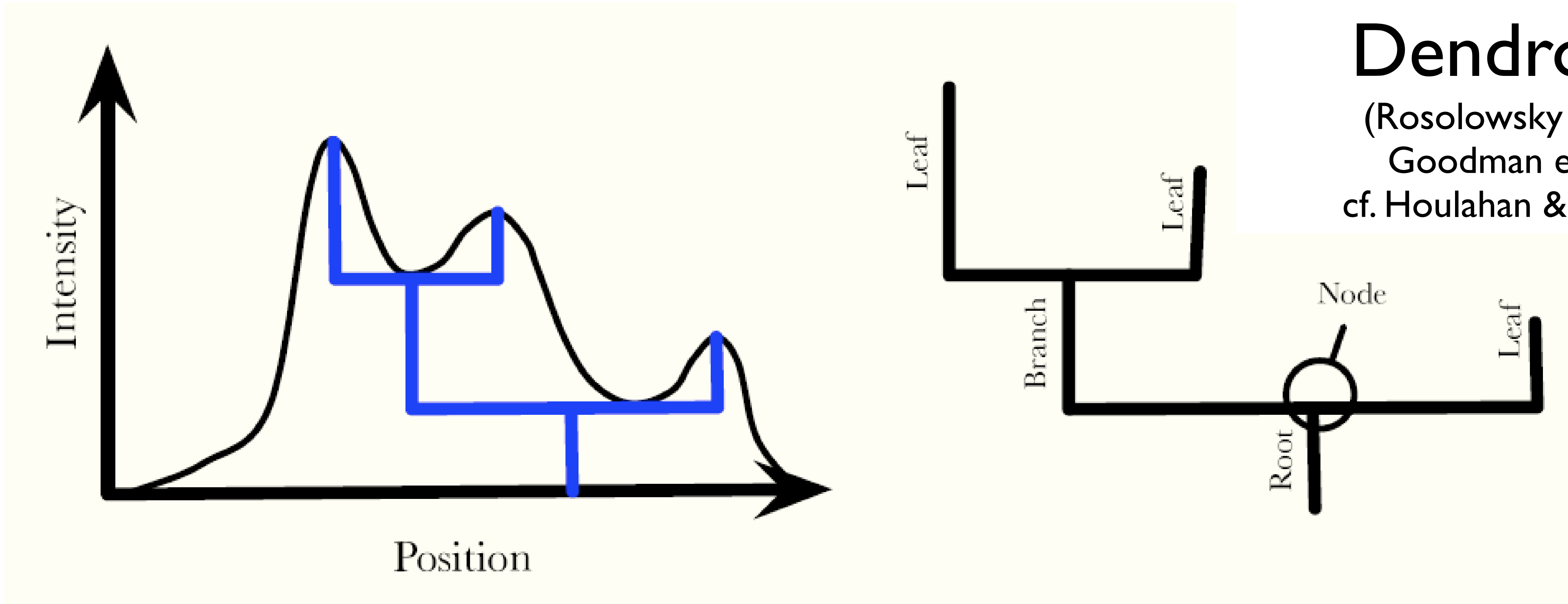


work of Rosolowsky, Foster, Pineda, Kauffmann, Borkin,Padoan, Halle & Goodman; figures based on Foster & Goodman 2006; Goodman et al. 2007

Meaningful structure in position-position-velocity space (3D)

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

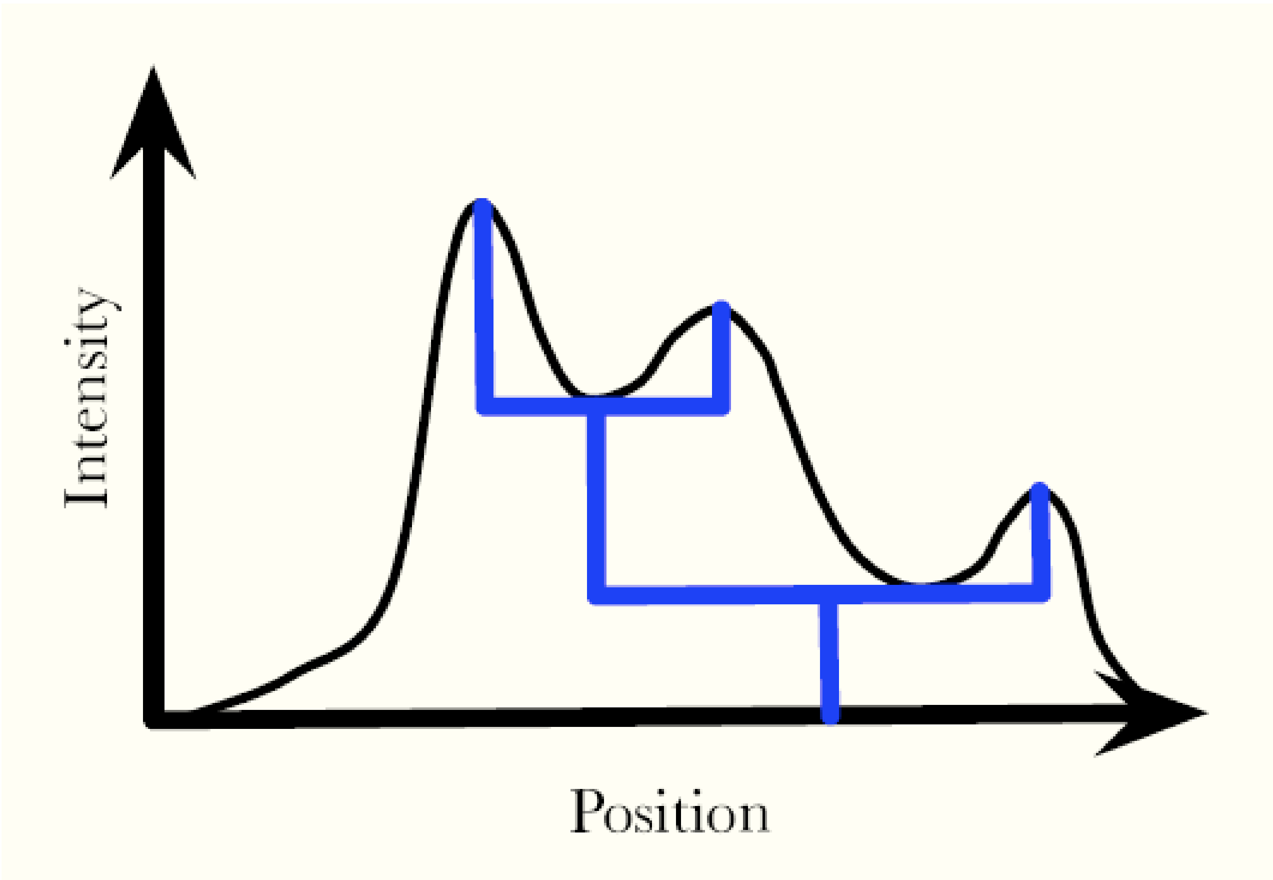
Dendrograms (Hierarchical) vs. CLUMPFIND (Non-hierarchical)

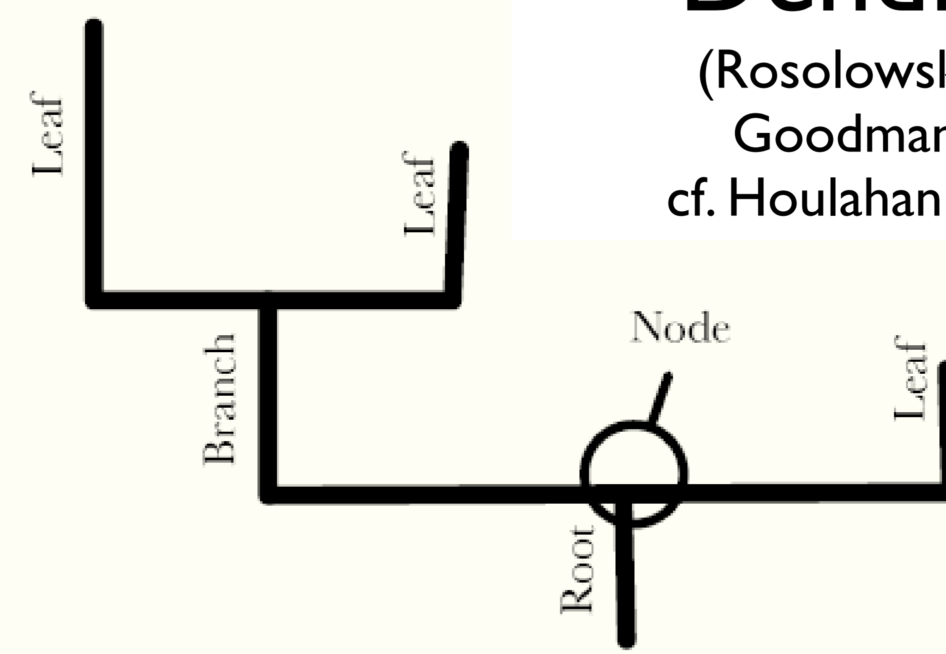


Dendrogram

(Rosolowsky et al. 2007;
Goodman et al. 2007
cf. Houlahan & Scalo 1992)

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





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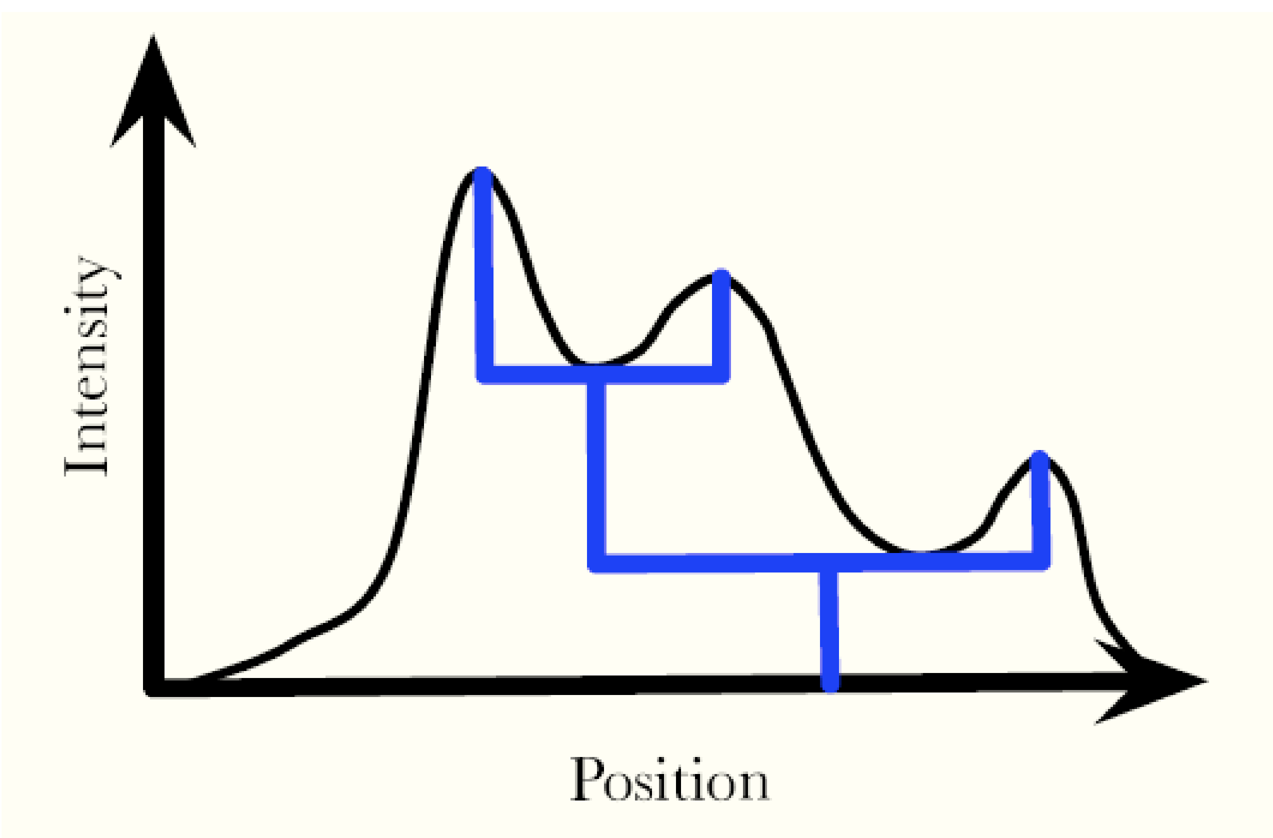
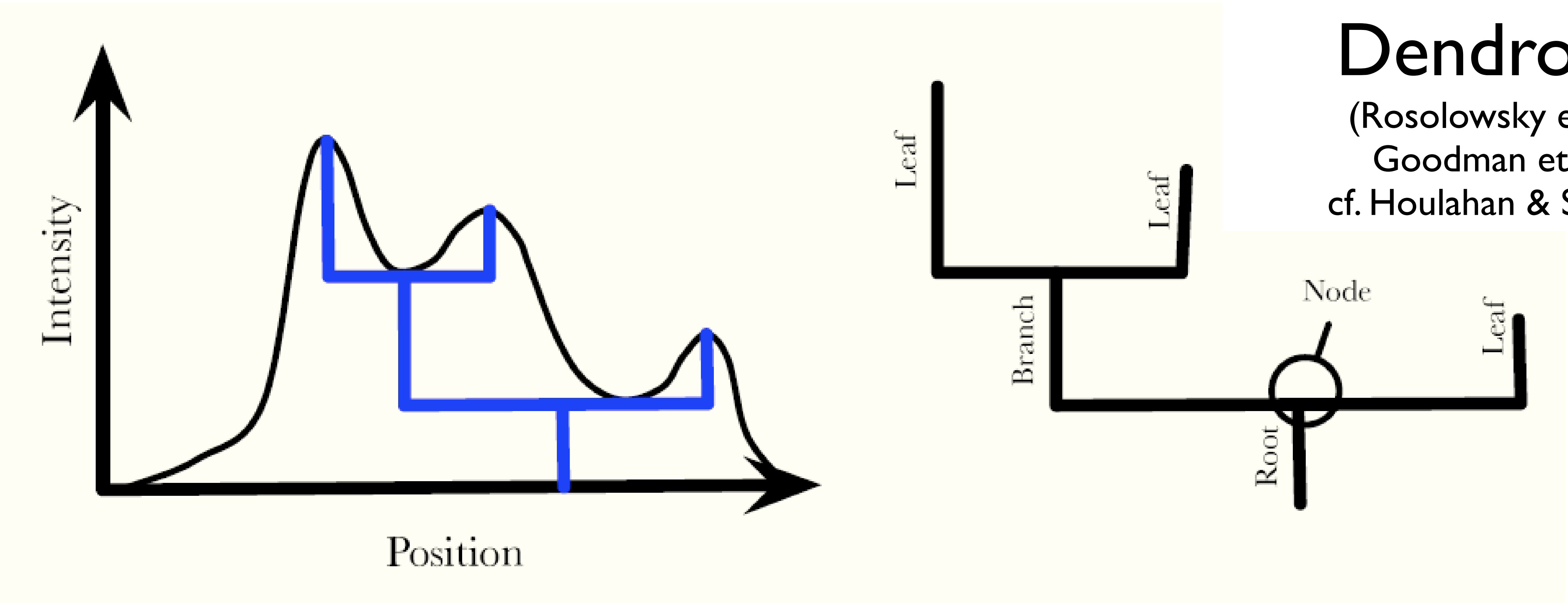


CLUMPFIND

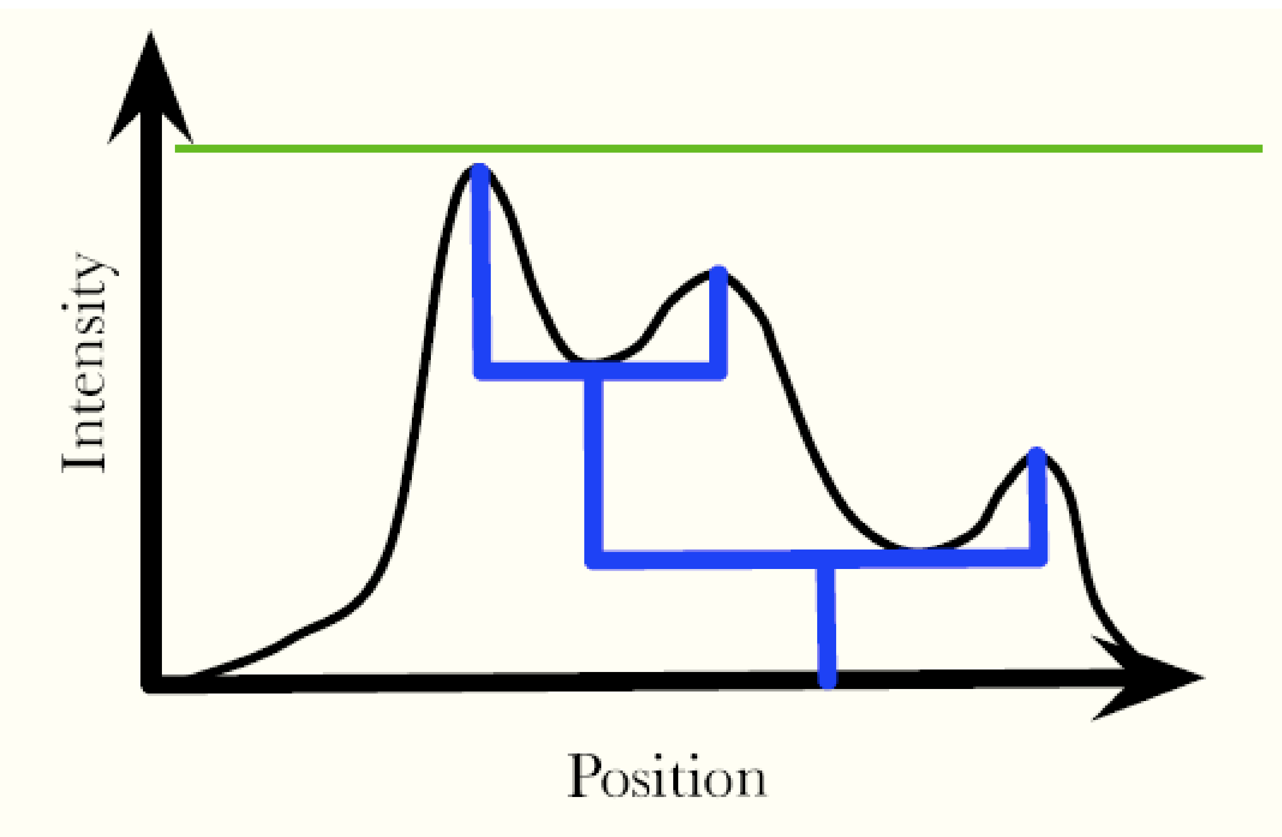
(Williams et al. 1994)

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



Dendrogram

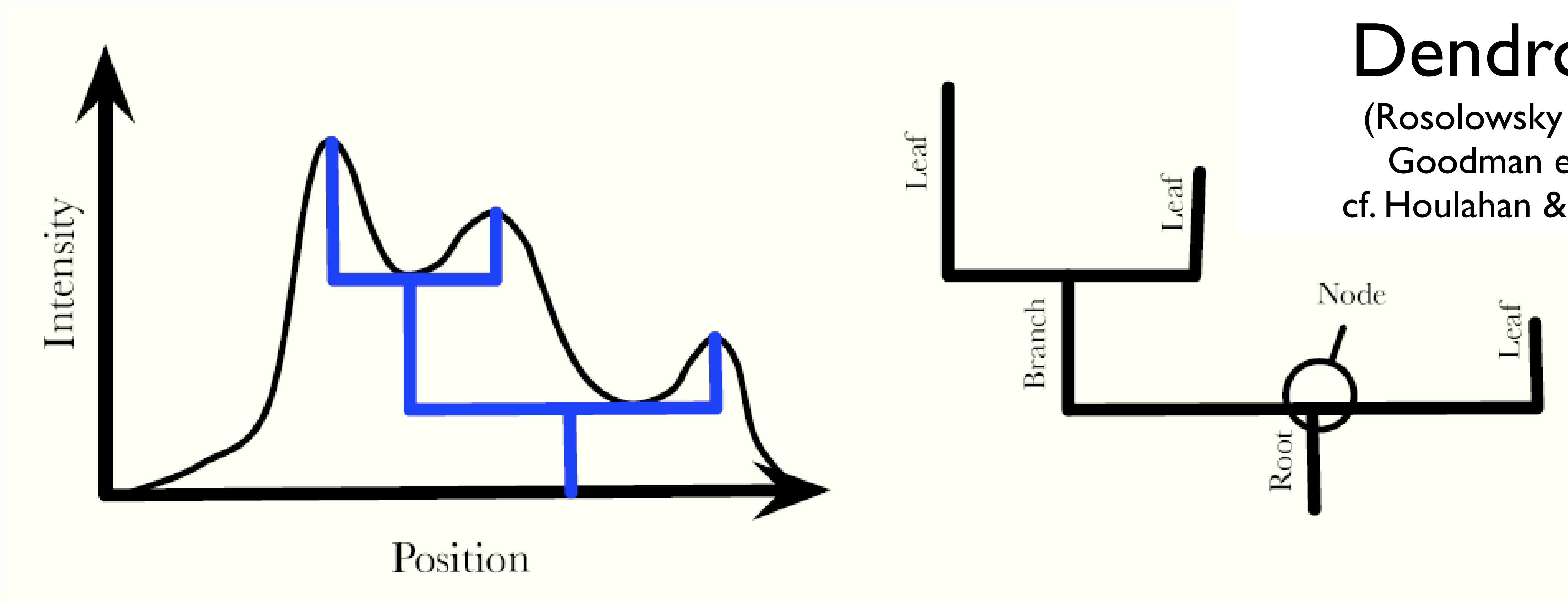
(Rosolowsky et al. 2007;
Goodman et al. 2007
cf. Houlahan & Scalo 1992)



CLUMPFIND

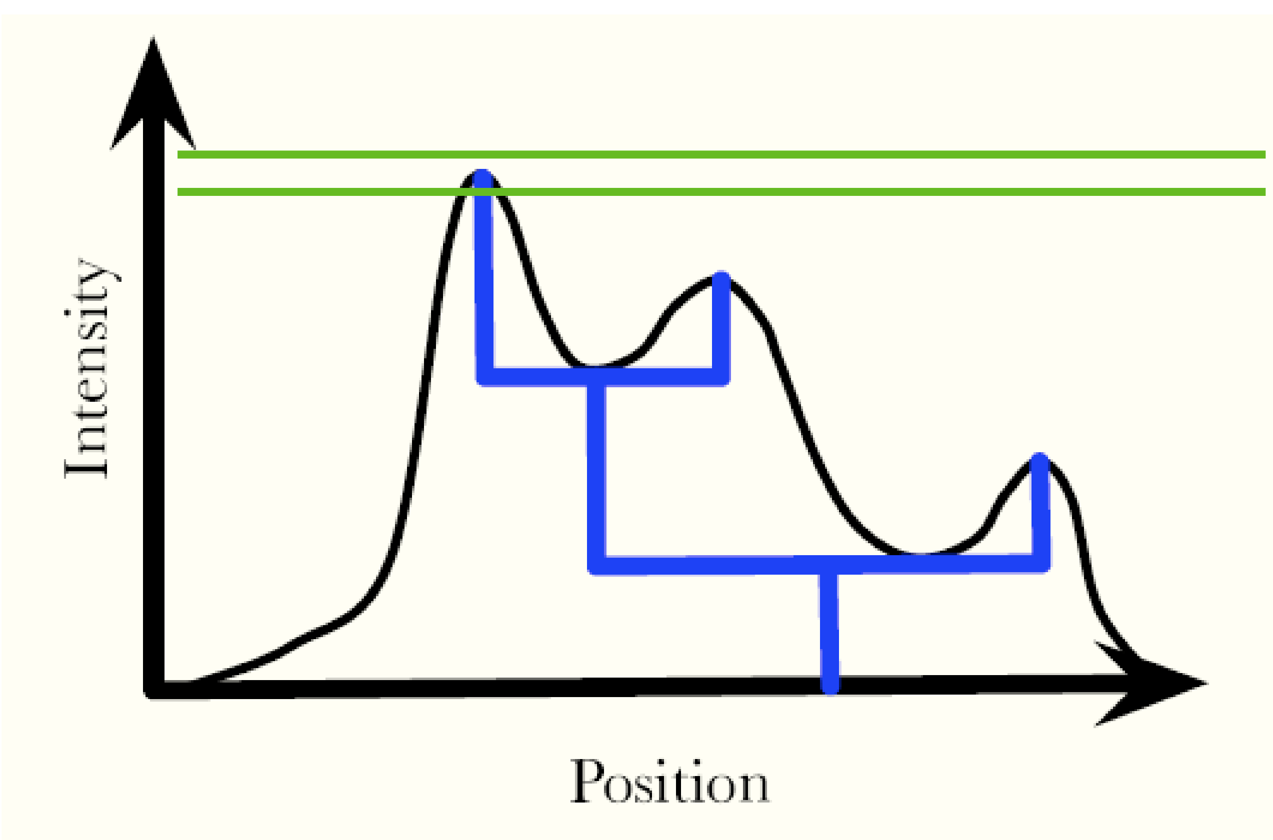
(Williams et al. 1994)

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



Dendrogram

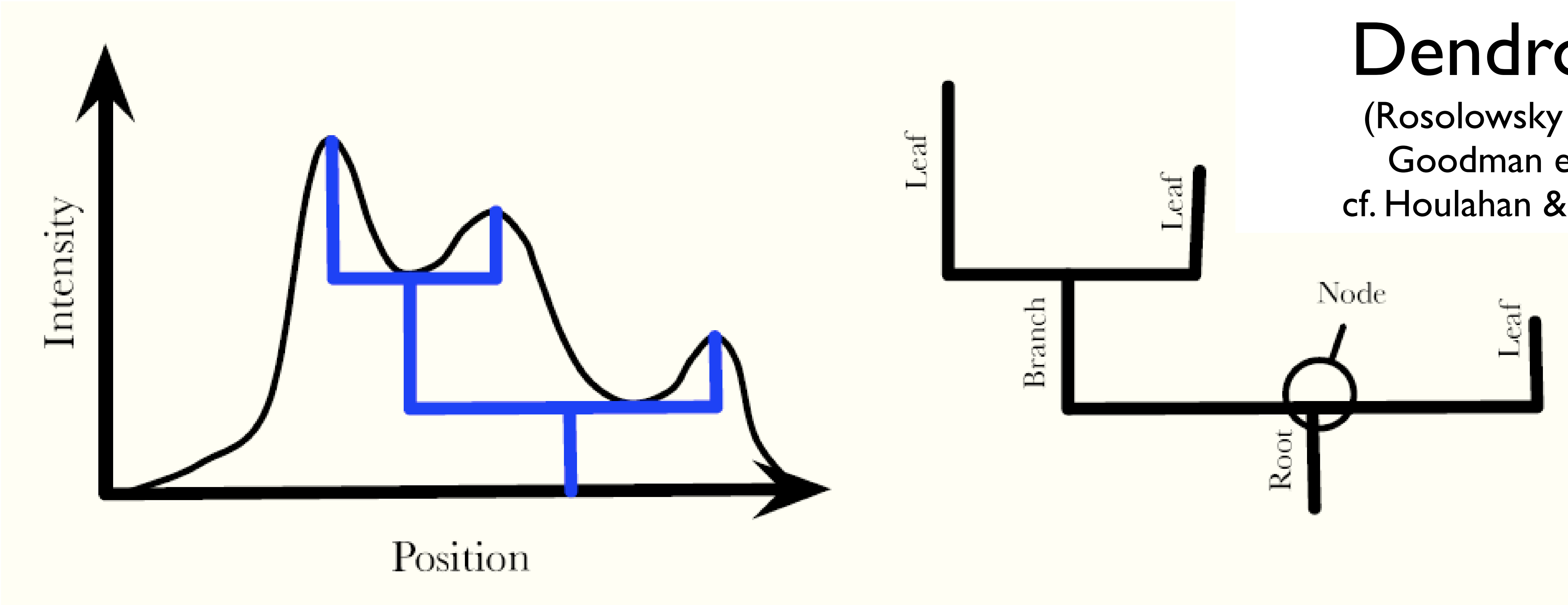
(Rosolowsky et al. 2007;
Goodman et al. 2007
cf. Houlahan & Scalo 1992)



CLUMPFIND

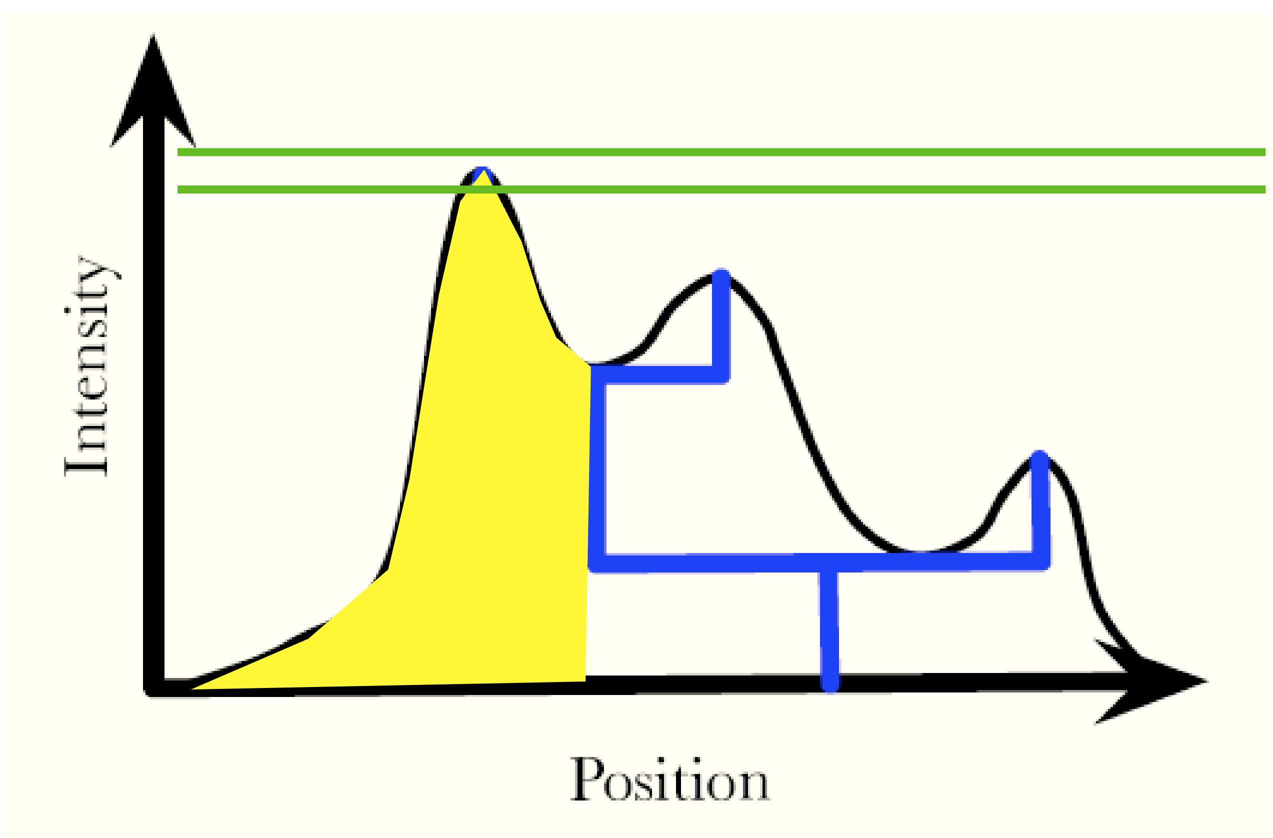
(Williams et al. 1994)

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



Dendrogram

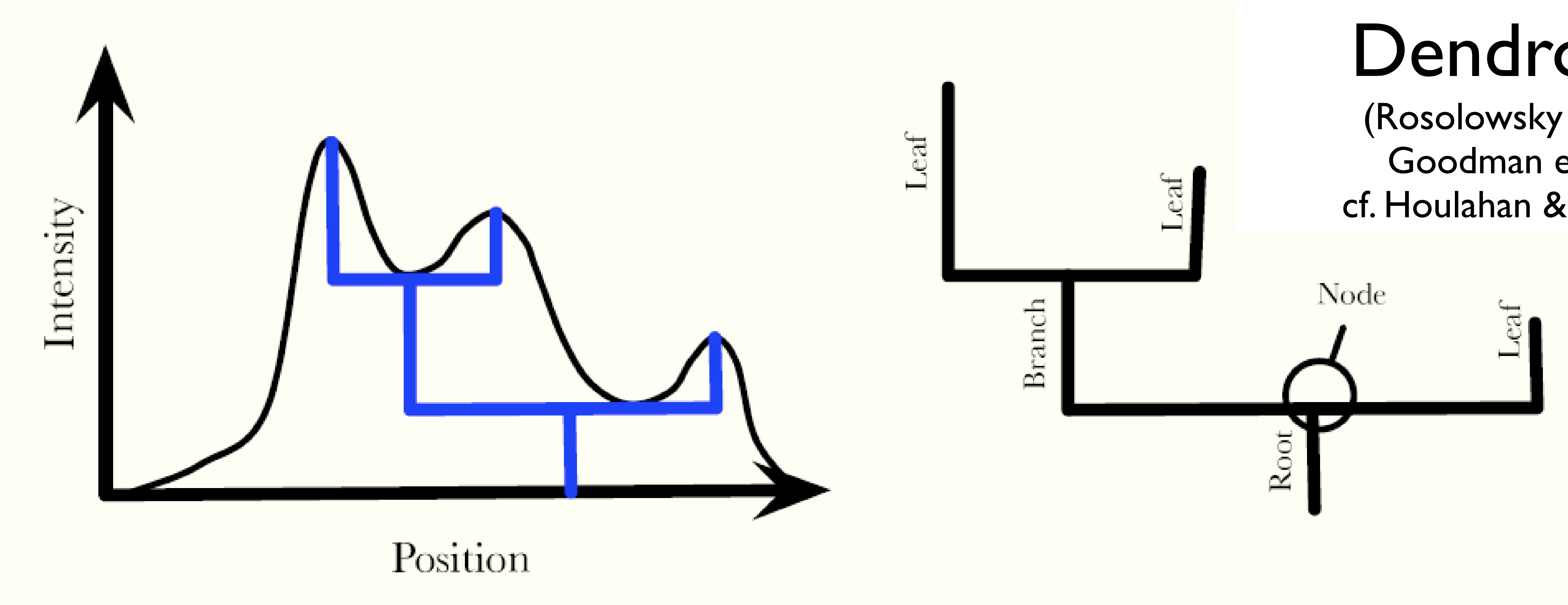
(Rosolowsky et al. 2007;
Goodman et al. 2007
cf. Houlahan & Scalo 1992)



CLUMPFIND

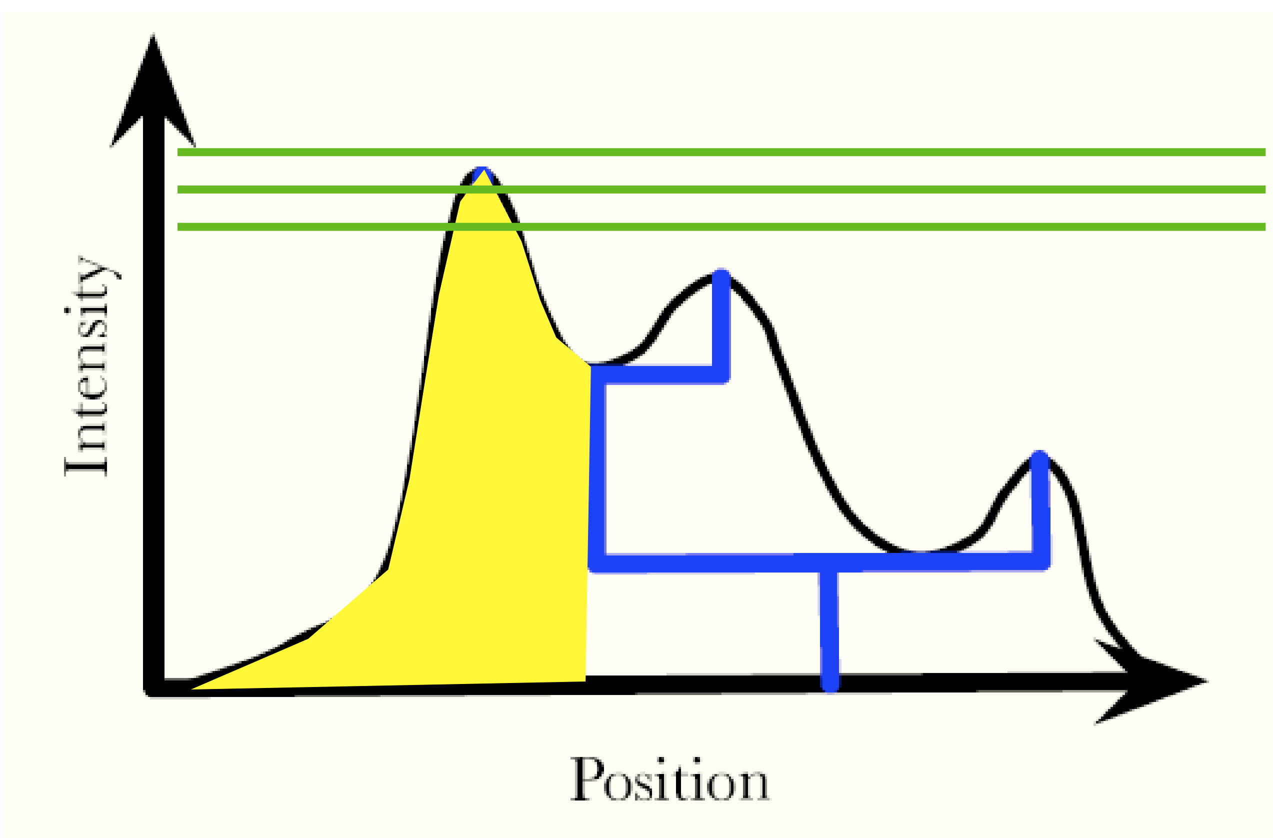
(Williams et al. 1994)

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



Dendrogram

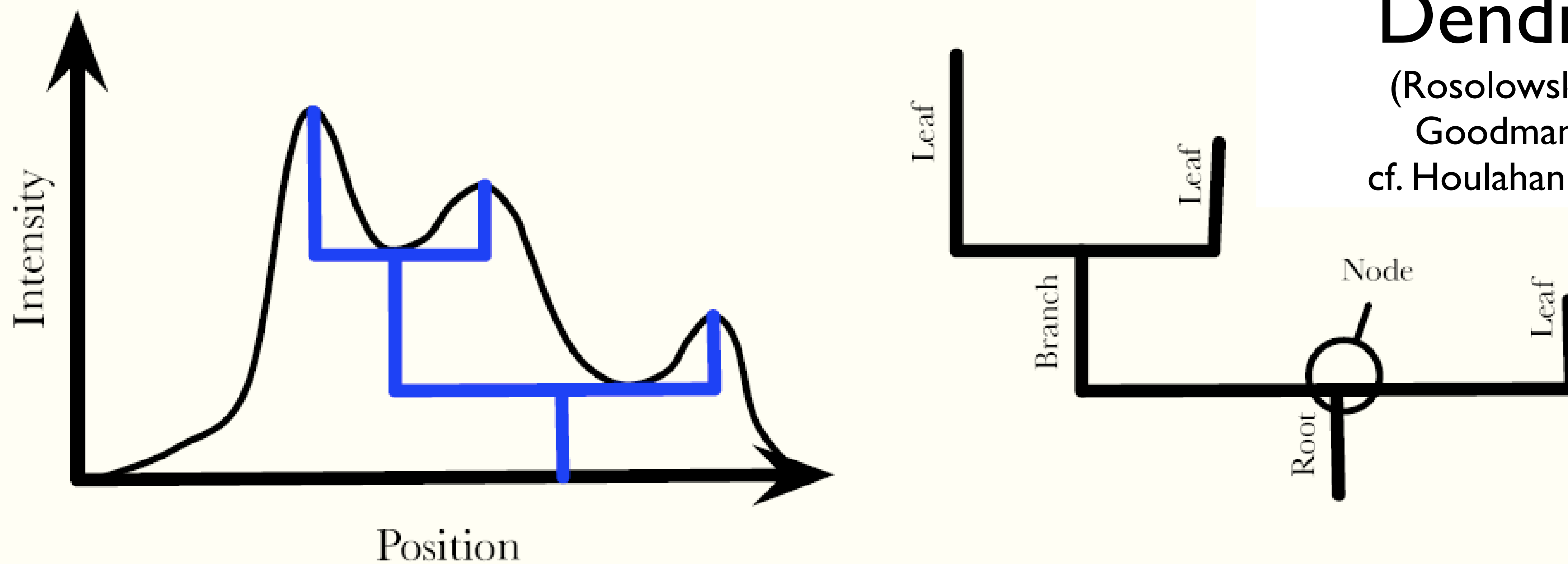
(Rosolowsky et al. 2007;
Goodman et al. 2007
cf. Houlahan & Scalo 1992)



CLUMPFIND

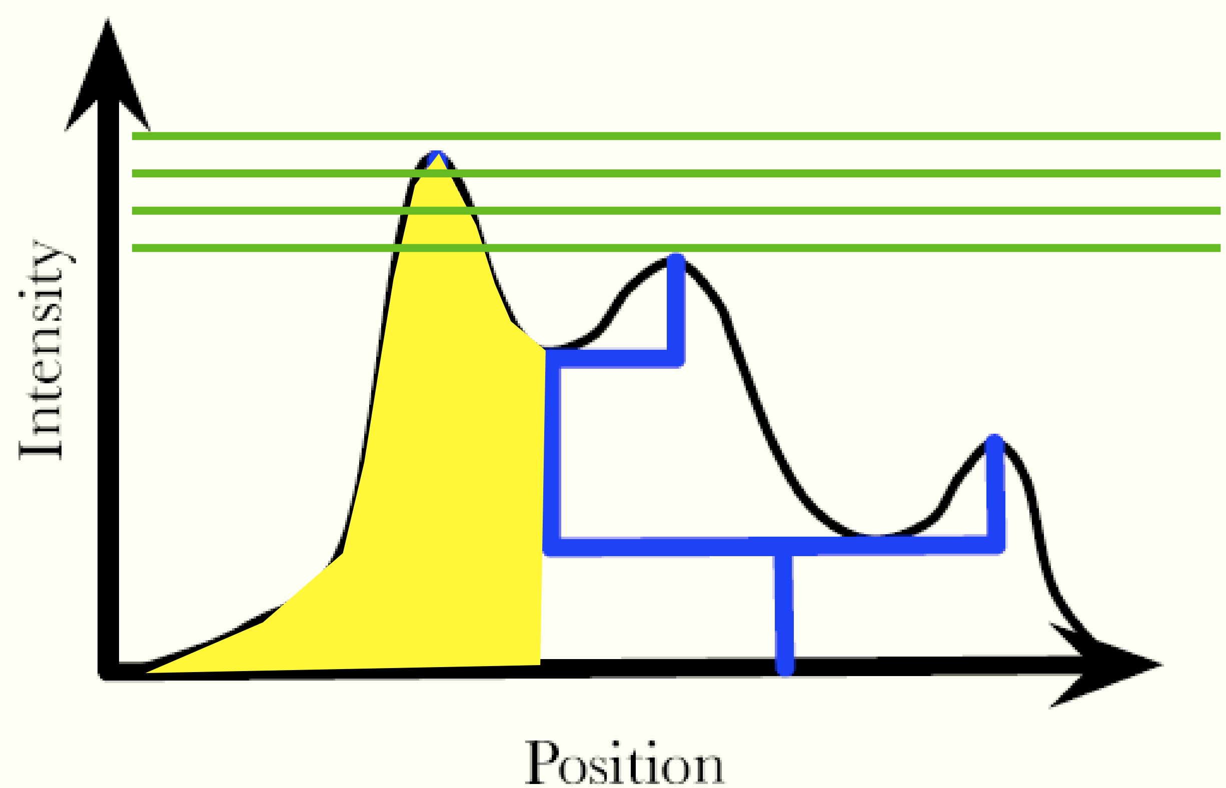
(Williams et al. 1994)

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



Dendrogram

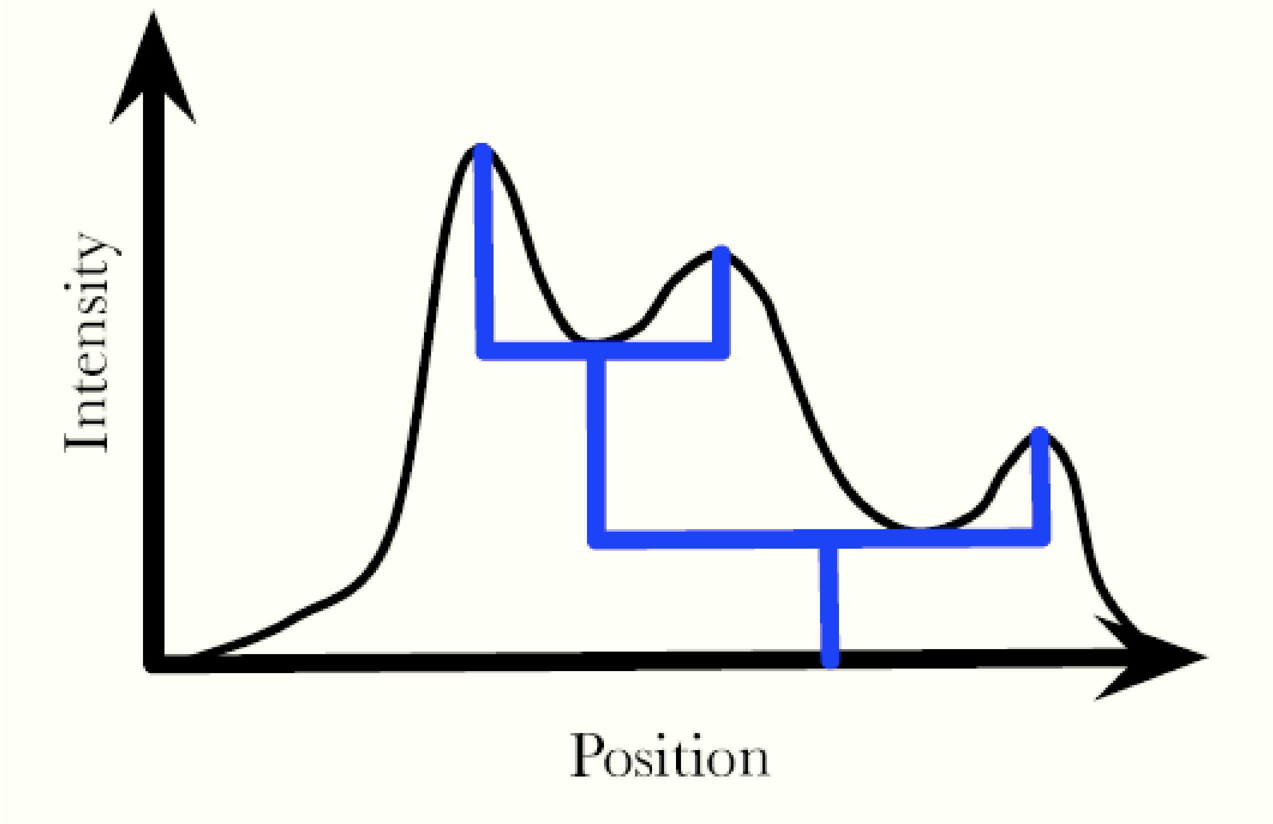
(Rosolowsky et al. 2007;
Goodman et al. 2007
cf. Houlahan & Scalo 1992)

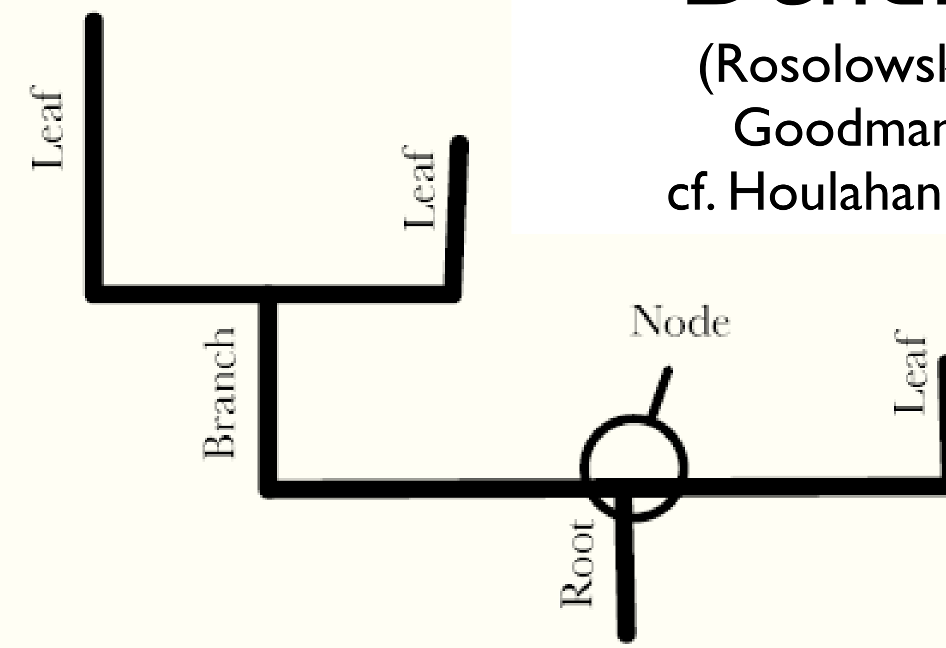


CLUMPFIND

(Williams et al. 1994)

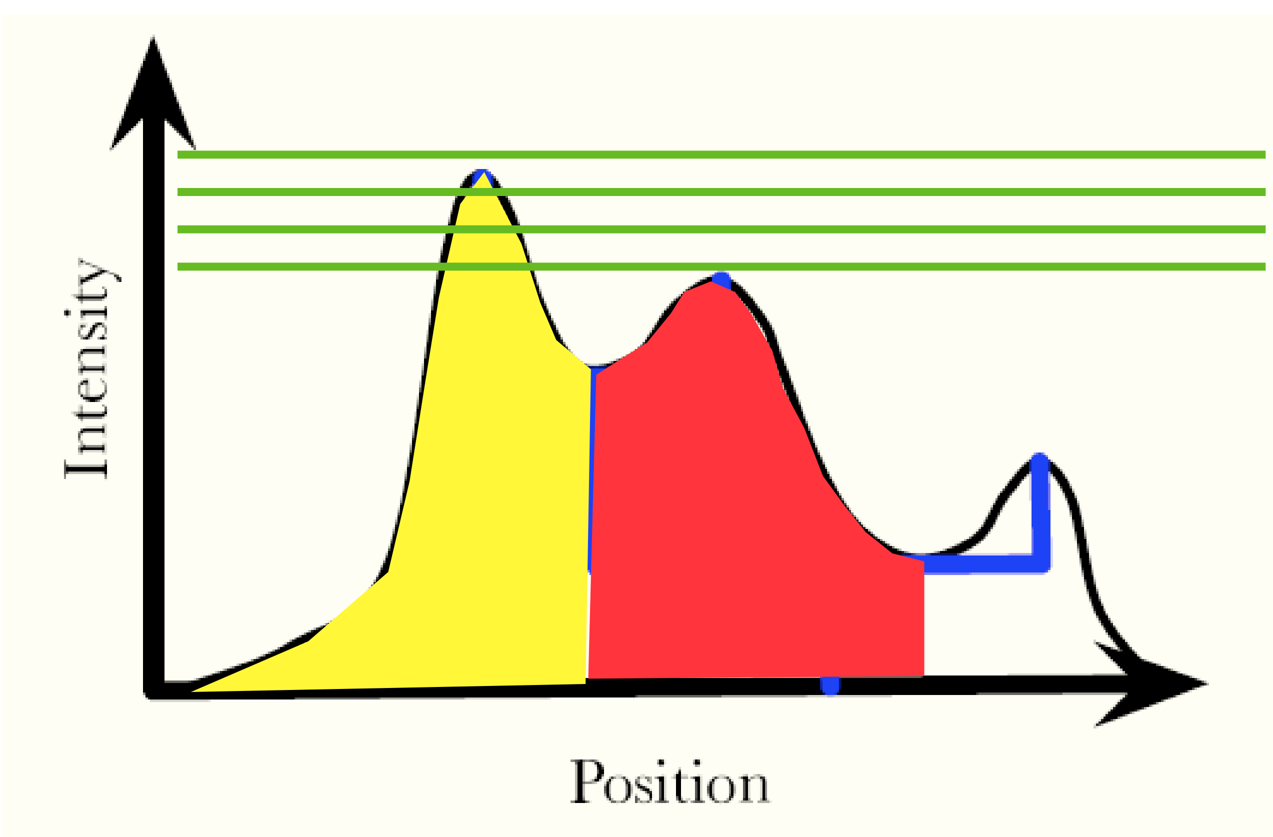
Dendrograms (Hierarchical) vs. CLUMPFIND (Non-hierarchical)





Dendrogram

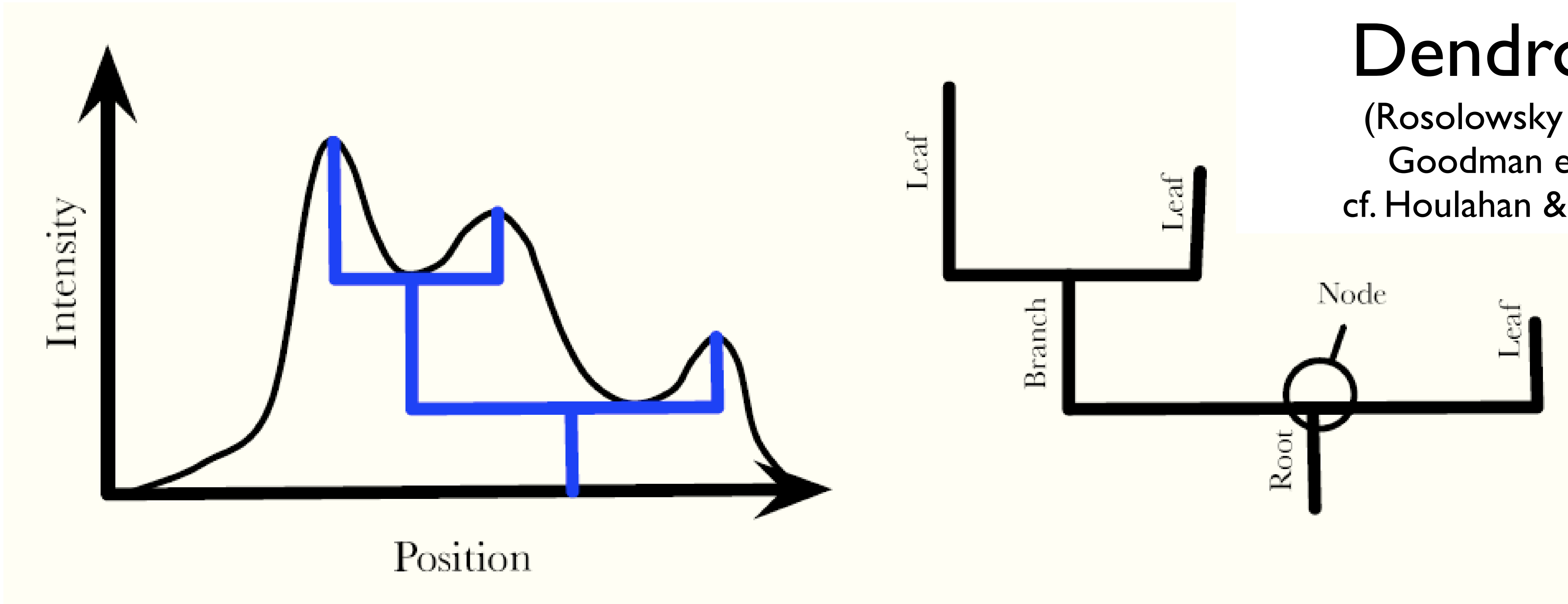
(Rosolowsky et al. 2007;
Goodman et al. 2007
cf. Houlahan & Scalo 1992)



CLUMPFIND

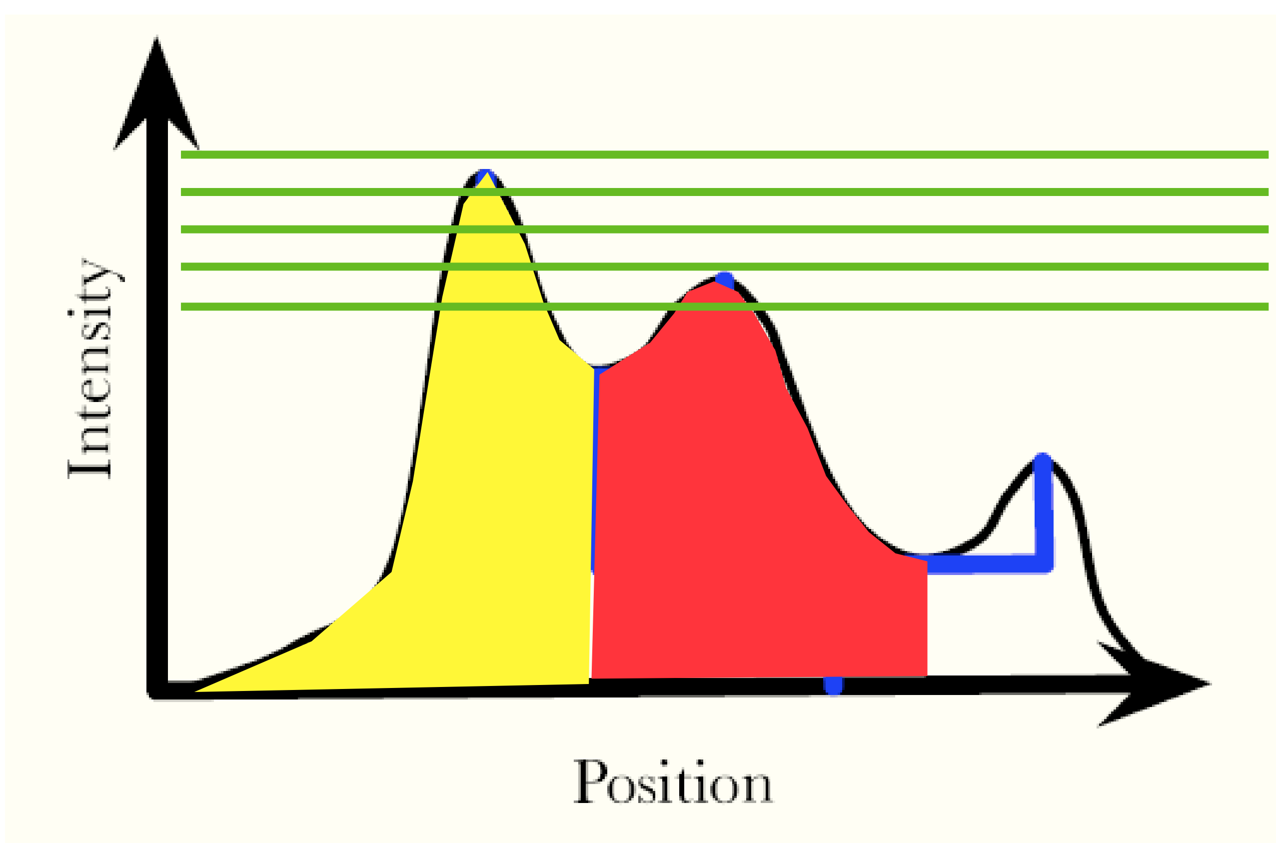
(Williams et al. 1994)

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



Dendrogram

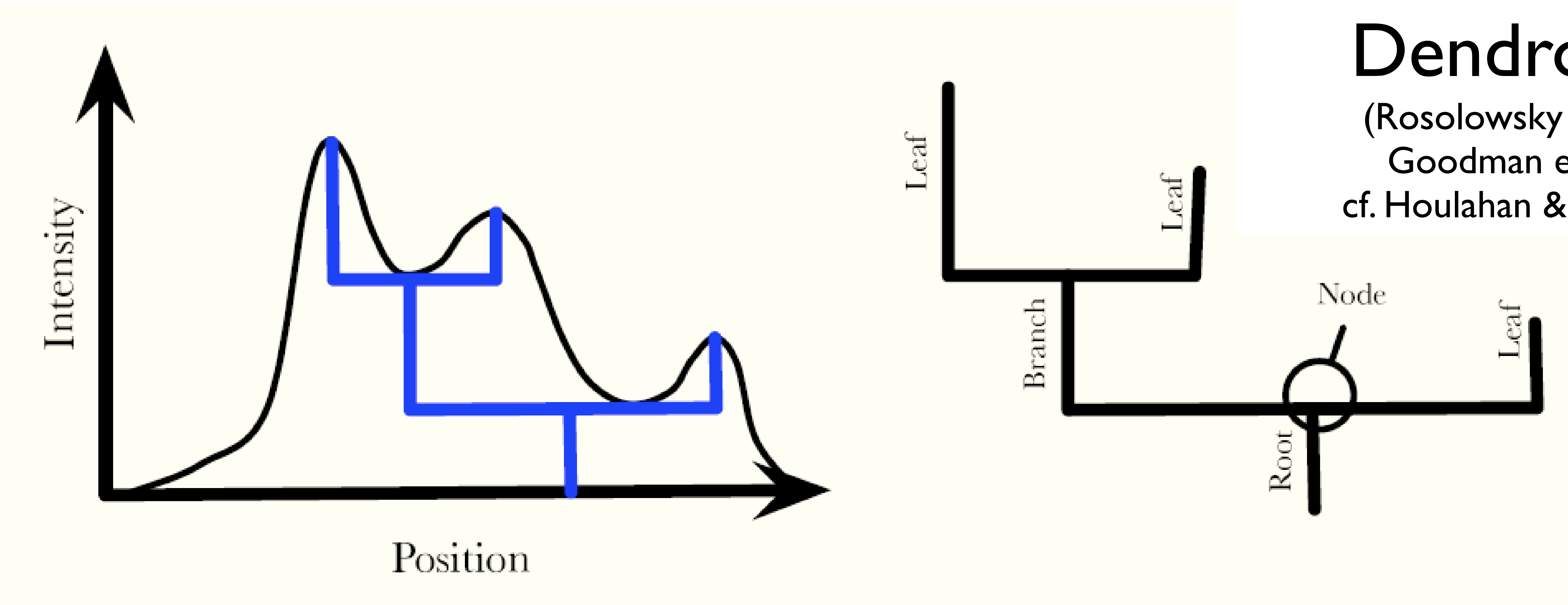
(Rosolowsky et al. 2007;
Goodman et al. 2007
cf. Houlahan & Scalo 1992)



CLUMPFIND

(Williams et al. 1994)

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



Dendrogram

(Rosolowsky et al. 2007;
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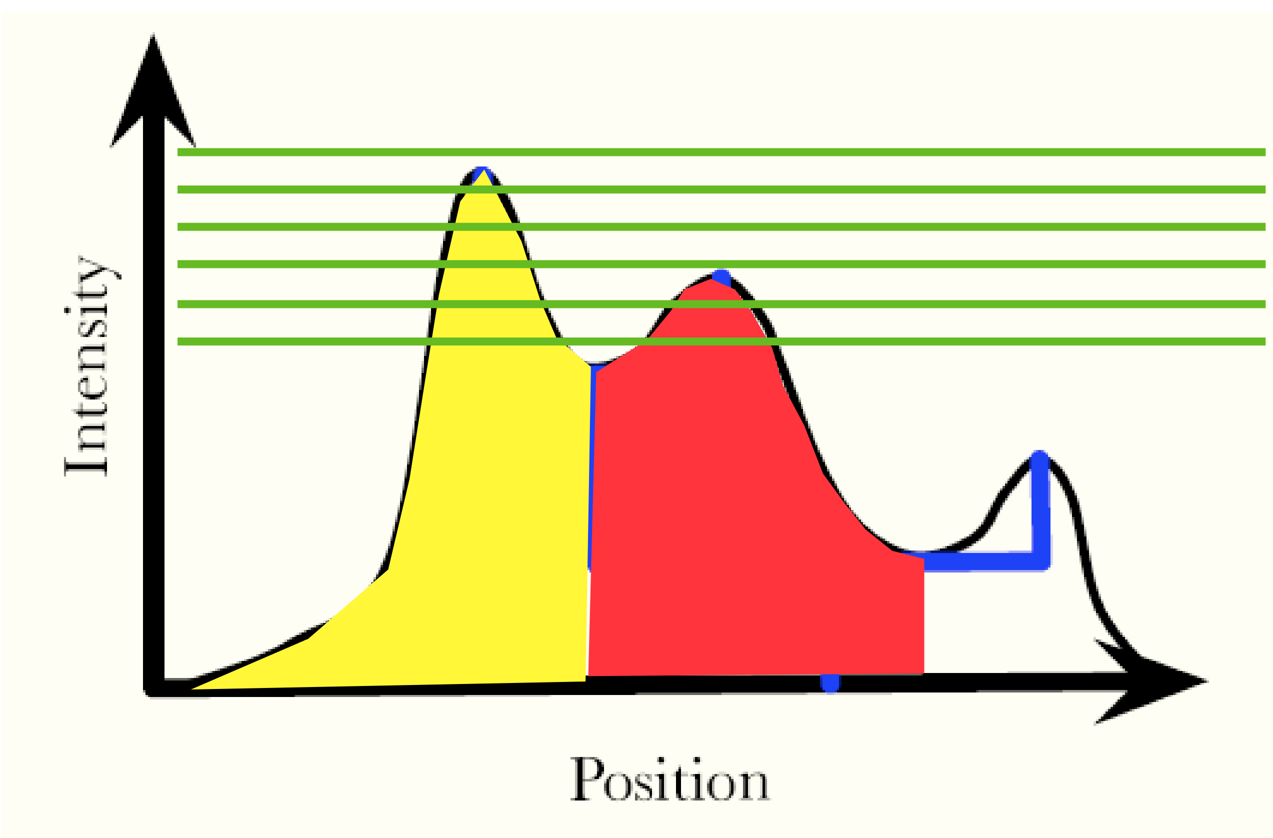
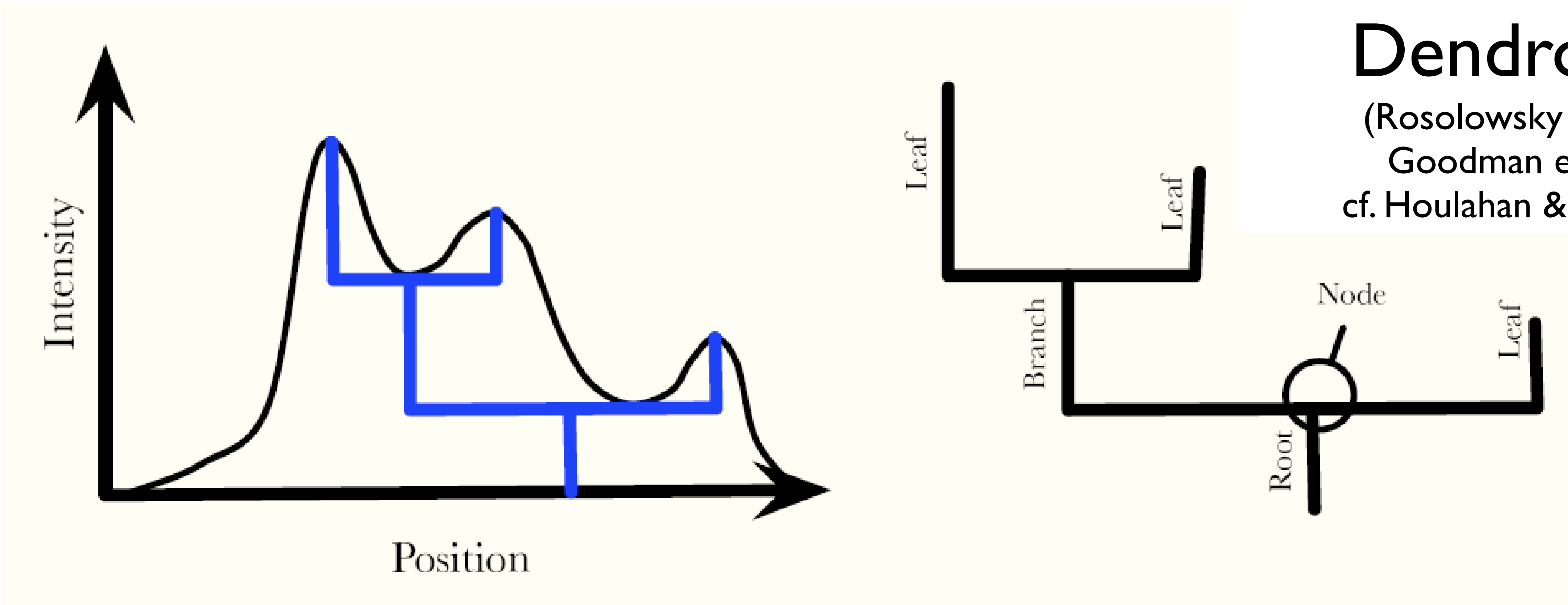


CLUMPFIND

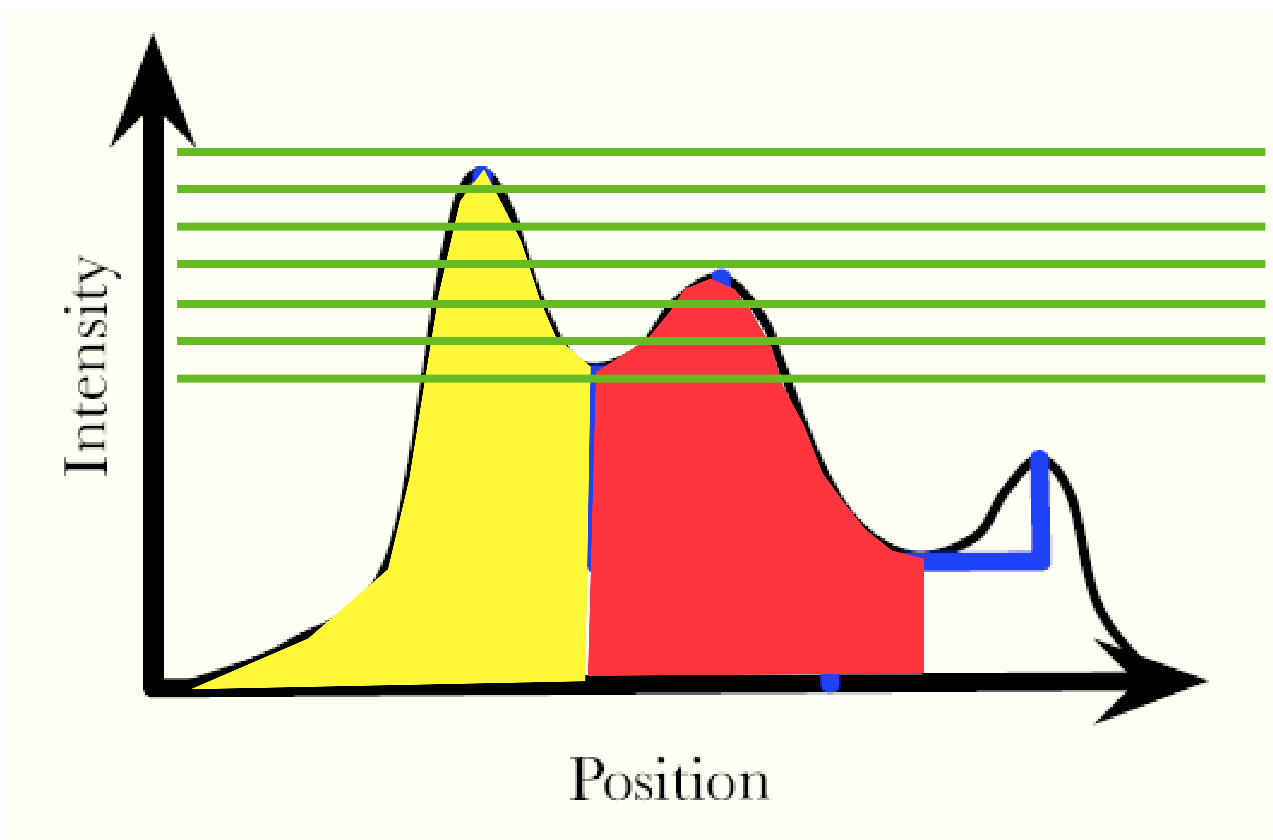
(Williams et al. 1994)

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



Dendrogram

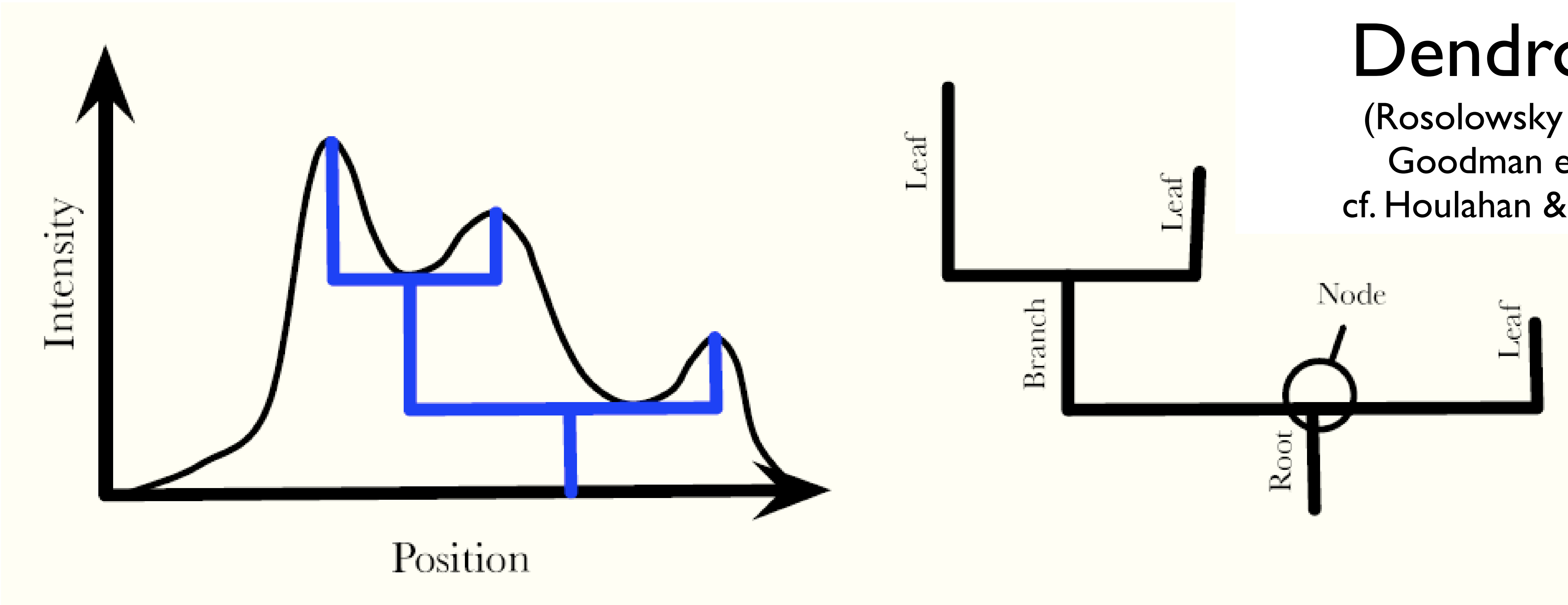
(Rosolowsky et al. 2007; Goodman et al. 2007 cf. Houlahan & Scalo 1992)



CLUMPFIND

(Williams et al. 1994)

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



Dendrogram

(Rosolowsky et al. 2007;
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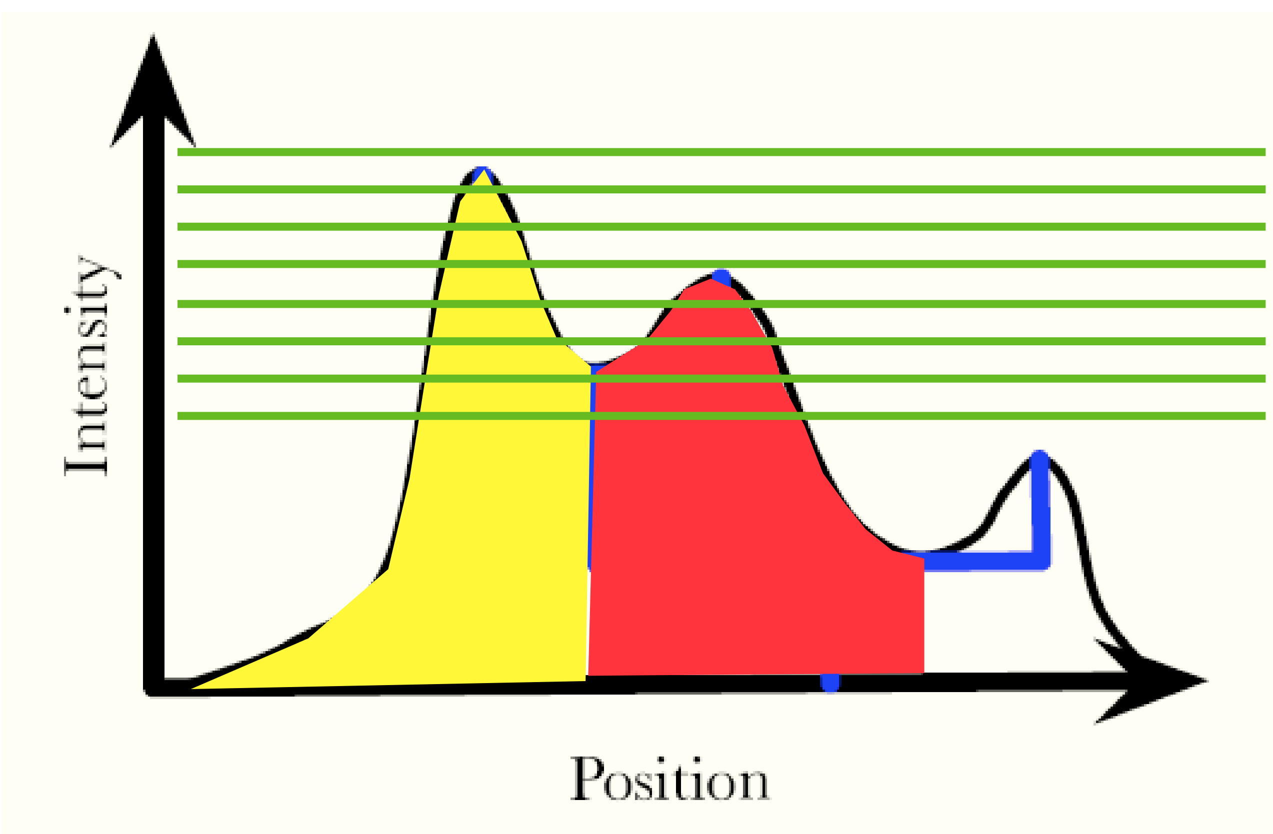
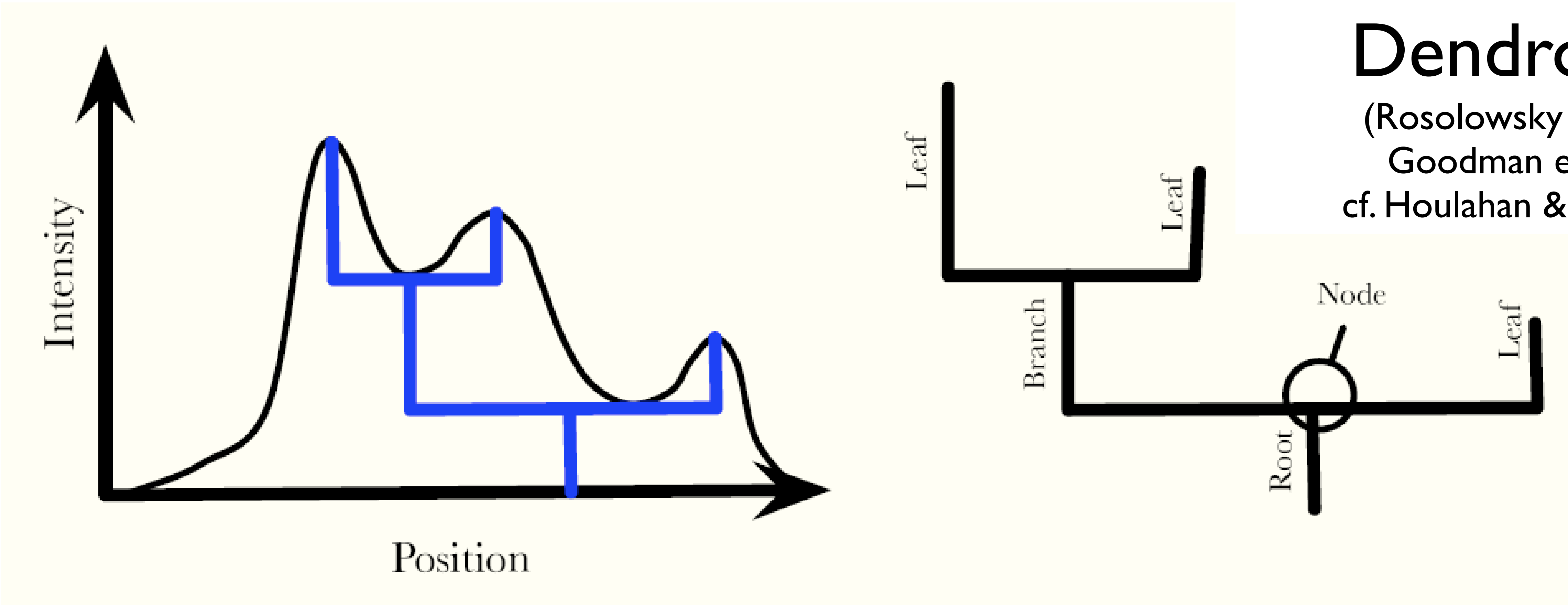


CLUMPFIND

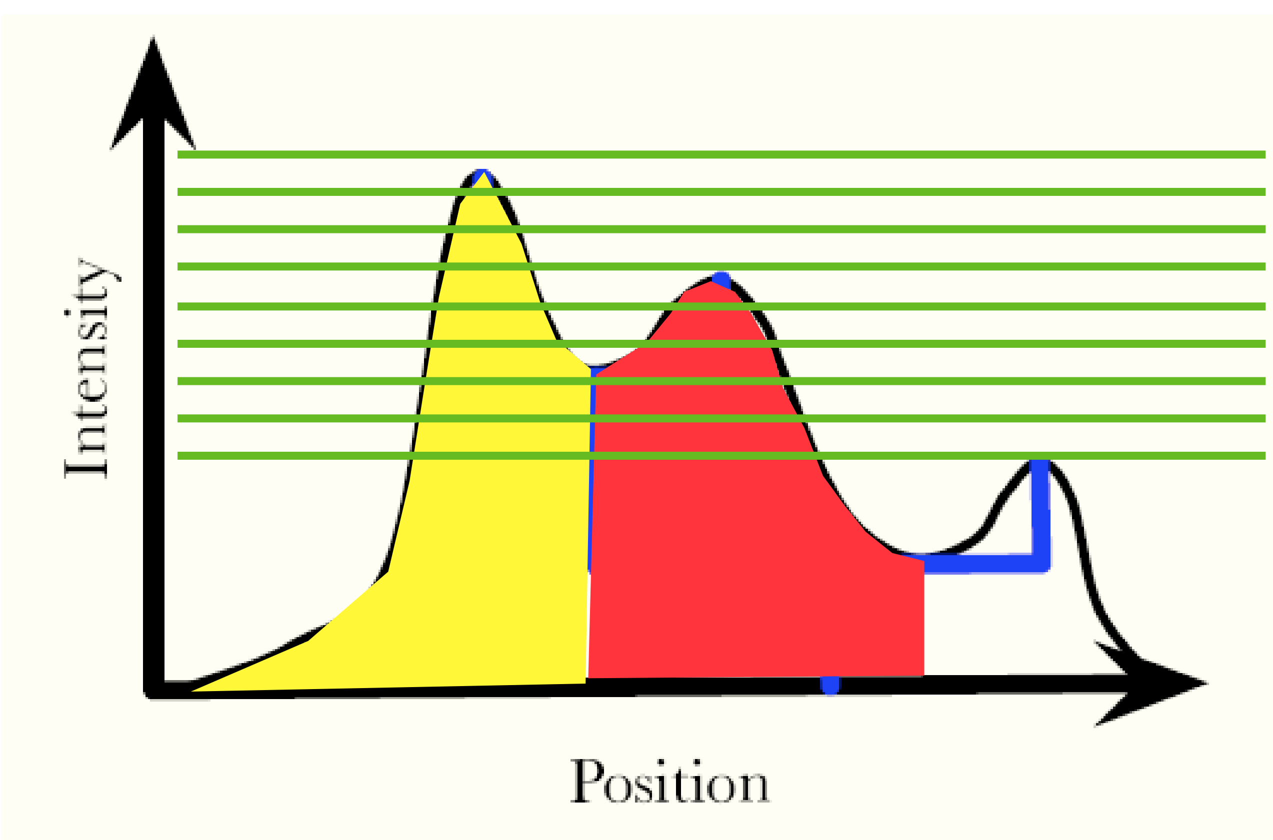
(Williams et al. 1994)

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



Dendrogram

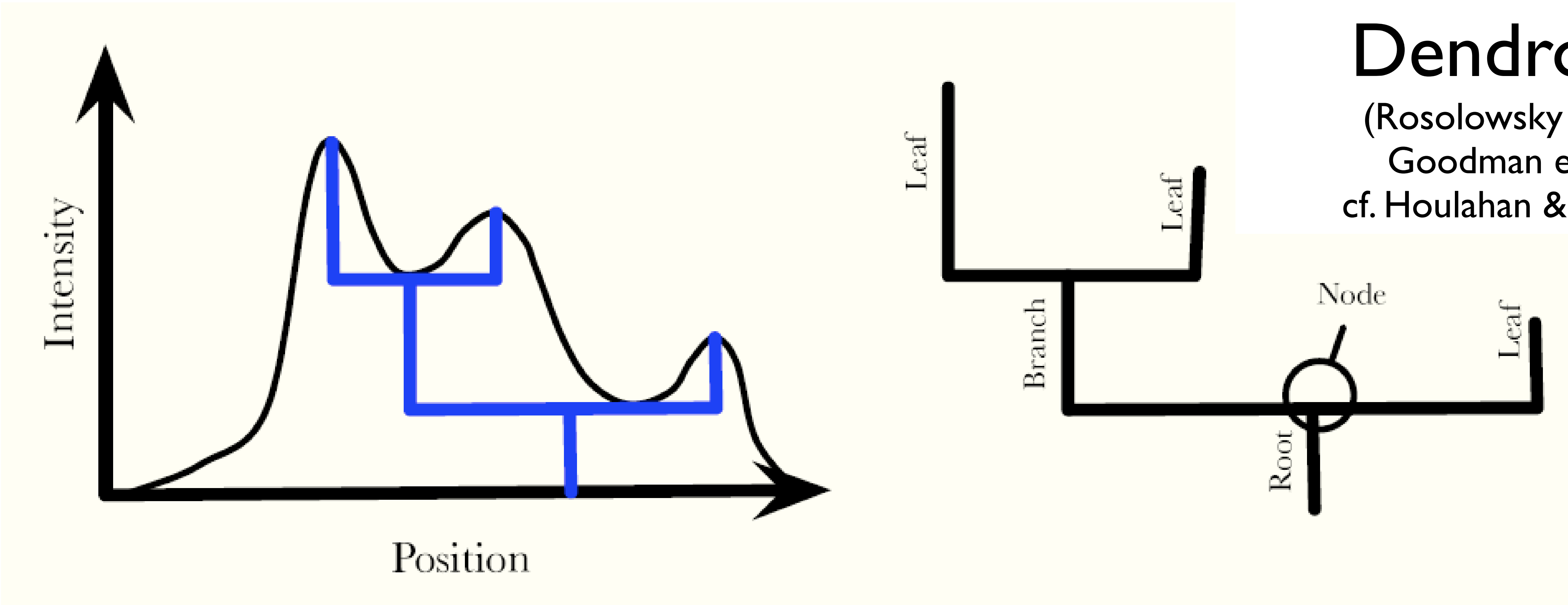
(Rosolowsky et al. 2007;
Goodman et al. 2007
cf. Houlahan & Scalo 1992)



CLUMPFIND

(Williams et al. 1994)

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



Dendrogram

(Rosolowsky et al. 2007;
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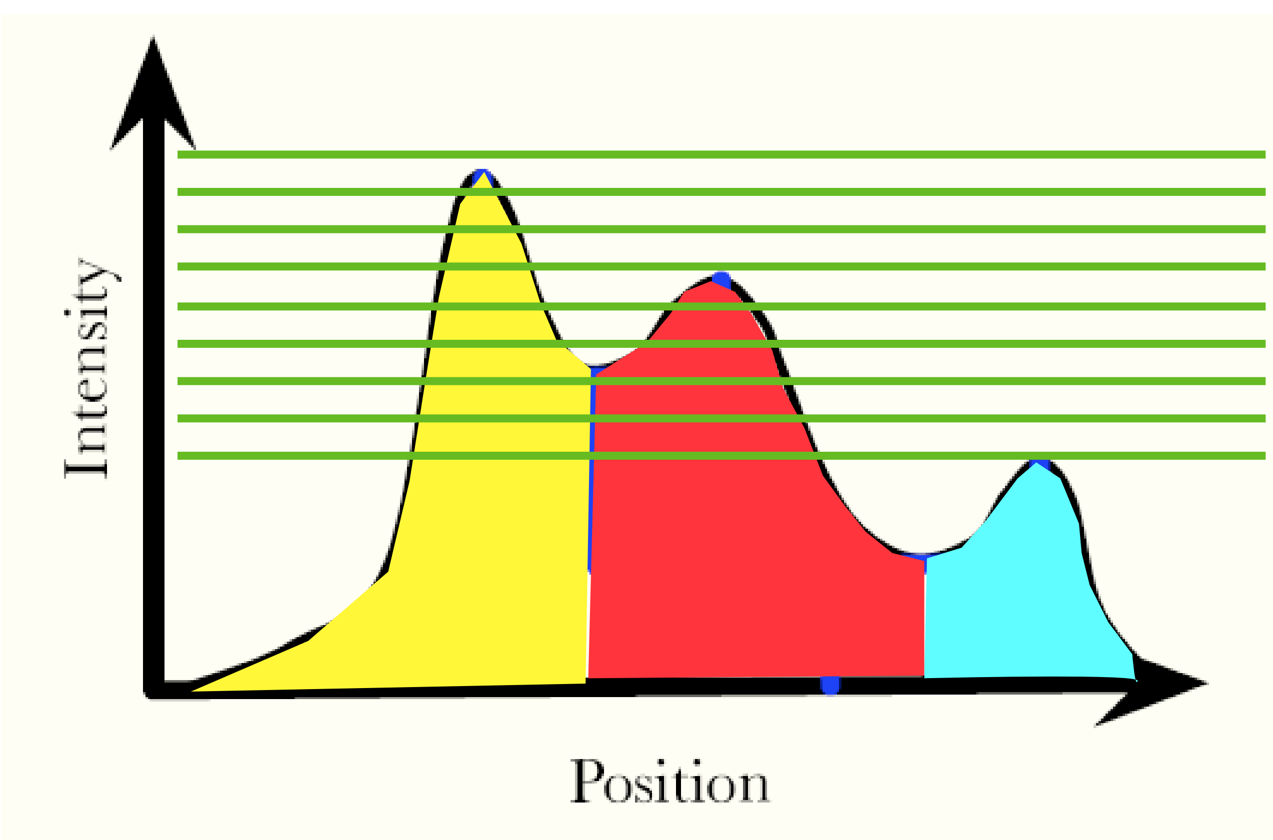
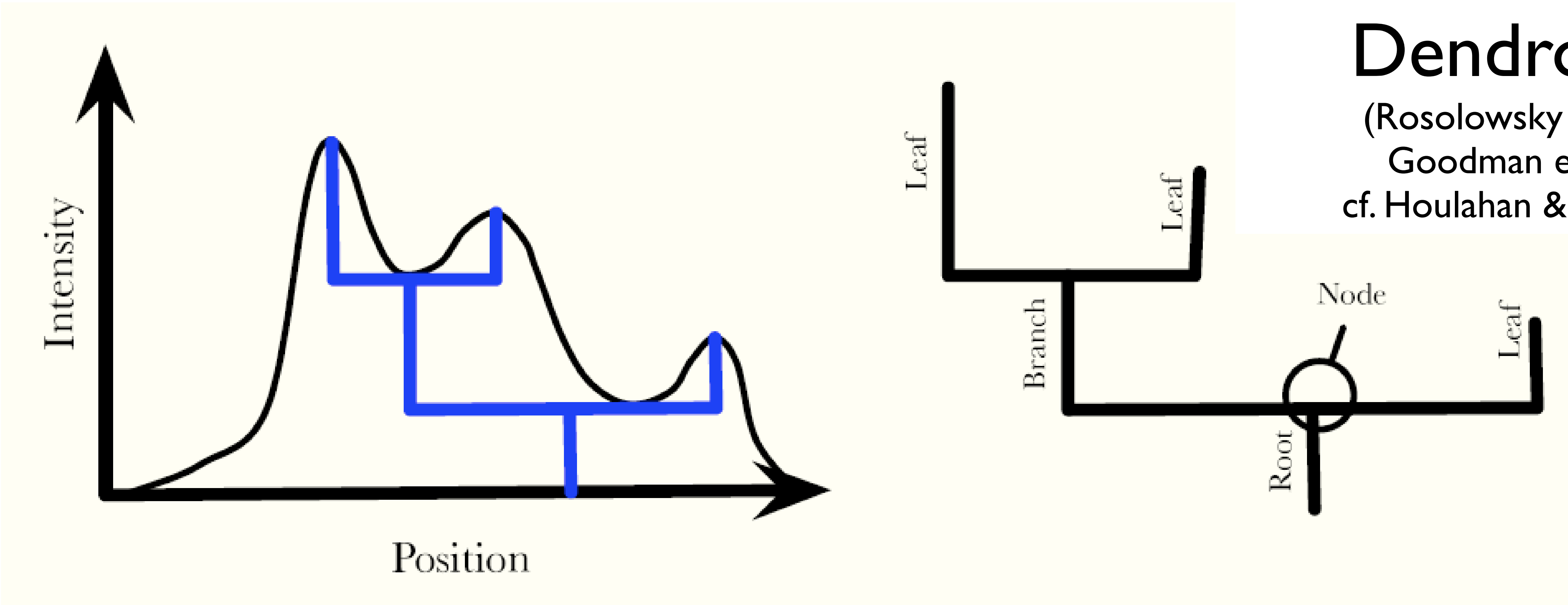


CLUMPFIND

(Williams et al. 1994)

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



Dendrogram

(Rosolowsky et al. 2007;
Goodman et al. 2007
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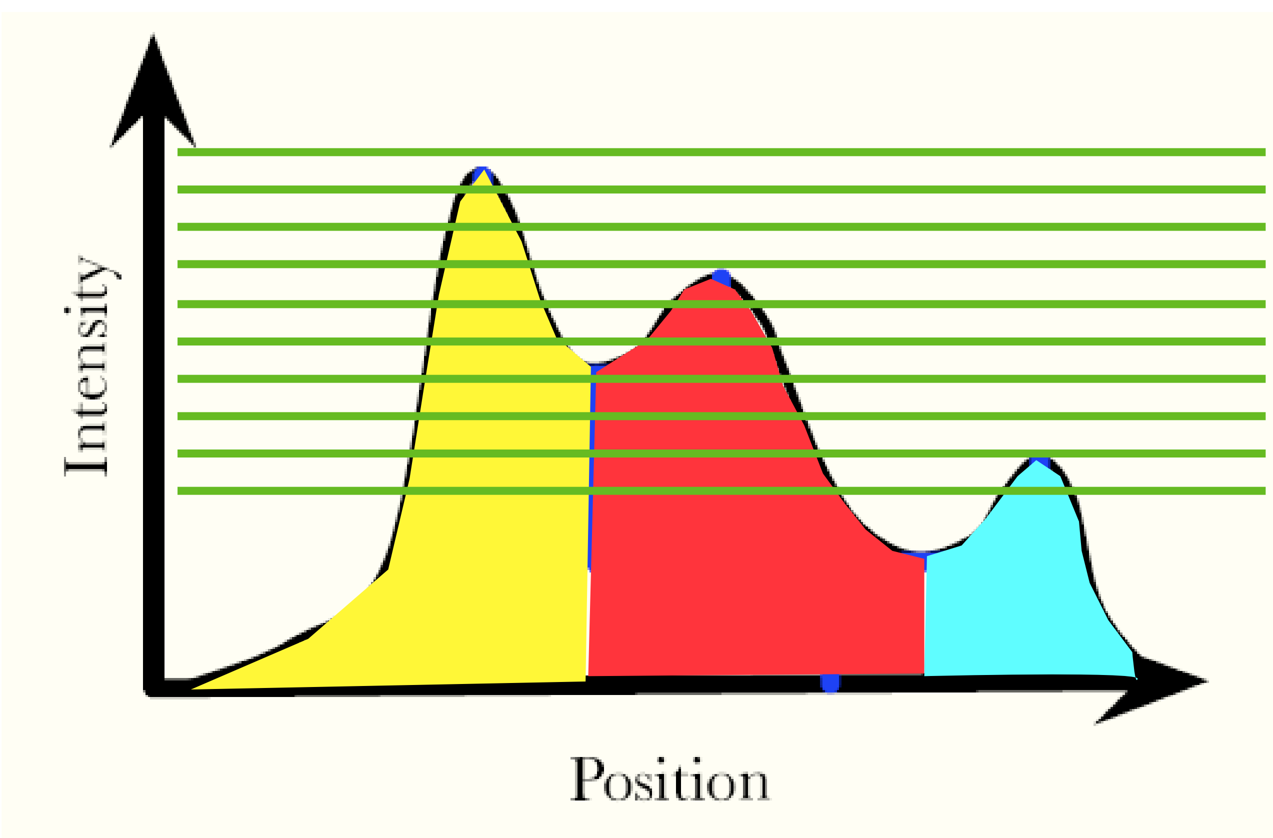
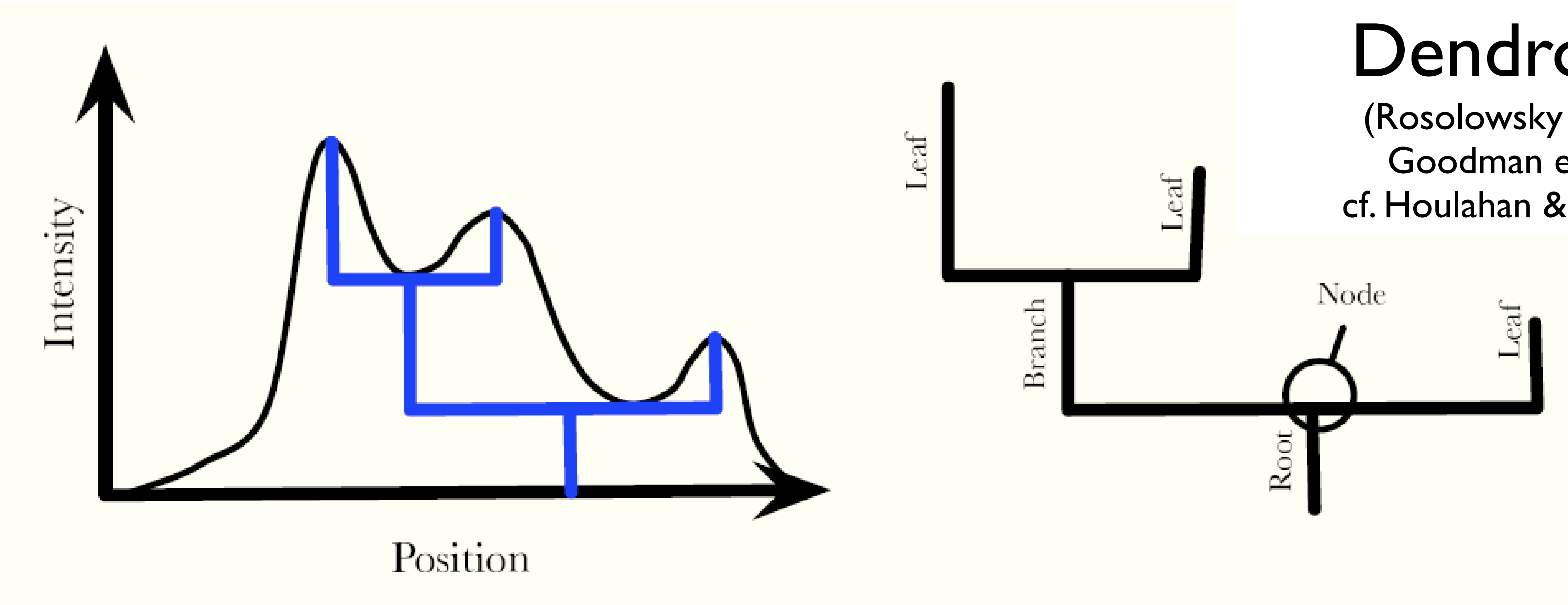


CLUMPFIND

(Williams et al. 1994)

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



Dendrogram

(Rosolowsky et al. 2007;
Goodman et al. 2007
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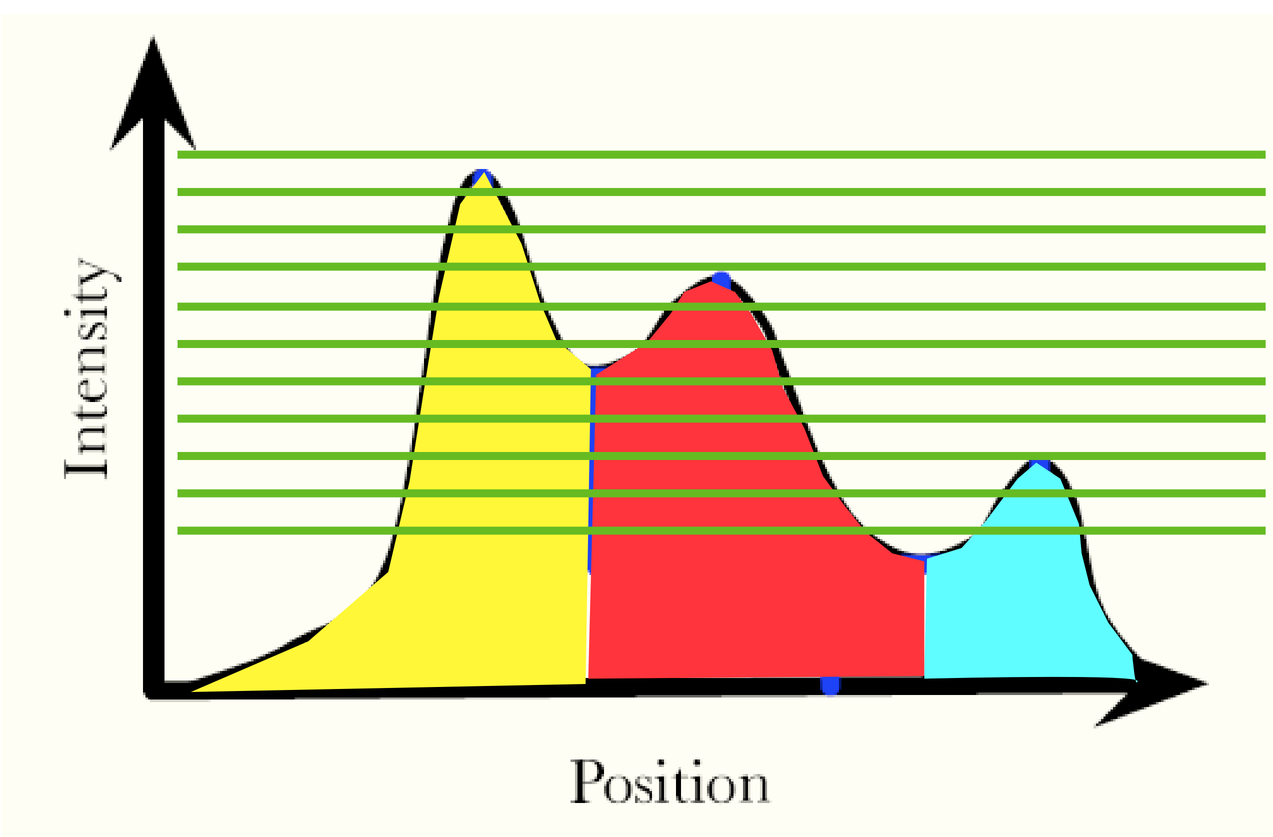
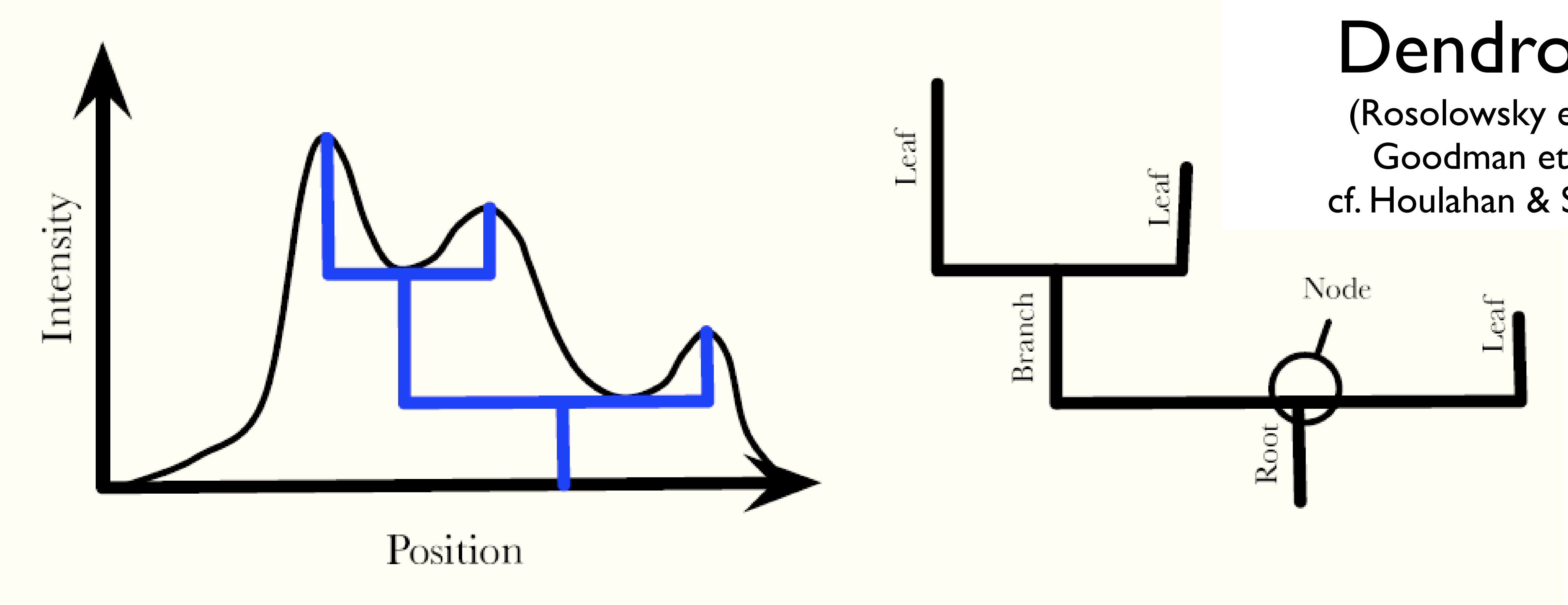


CLUMPFIND

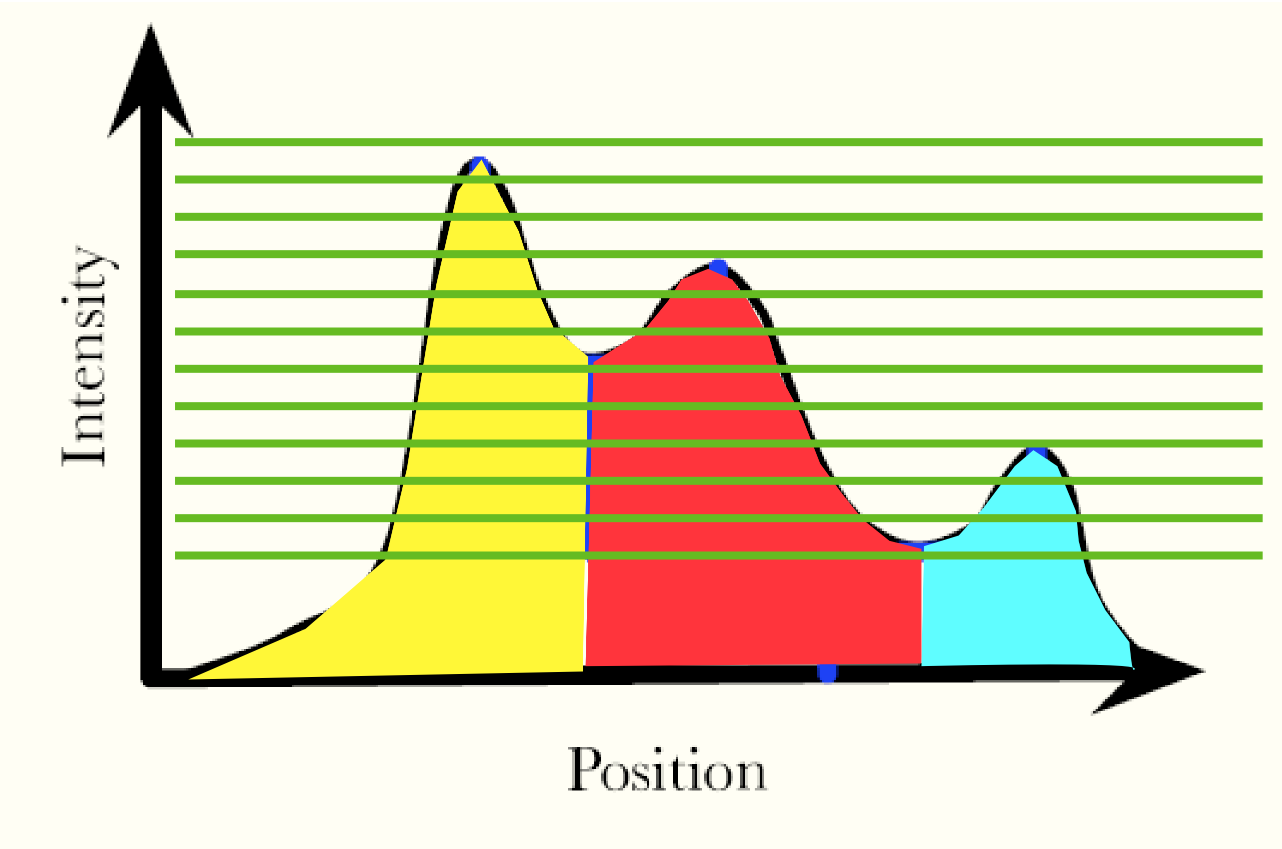
(Williams et al. 1994)

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



Dendrogram

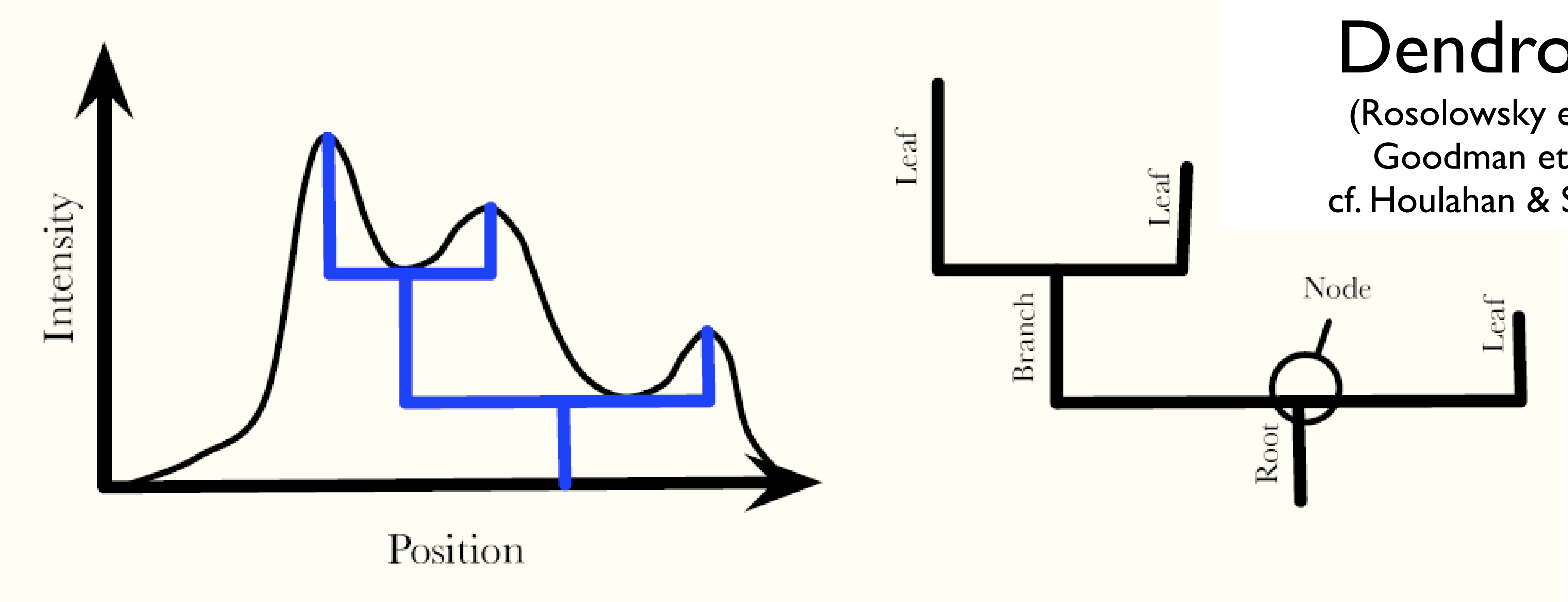
(Rosolowsky et al. 2007; Goodman et al. 2007 cf. Houlahan & Scalo 1992)



CLUMPFIND

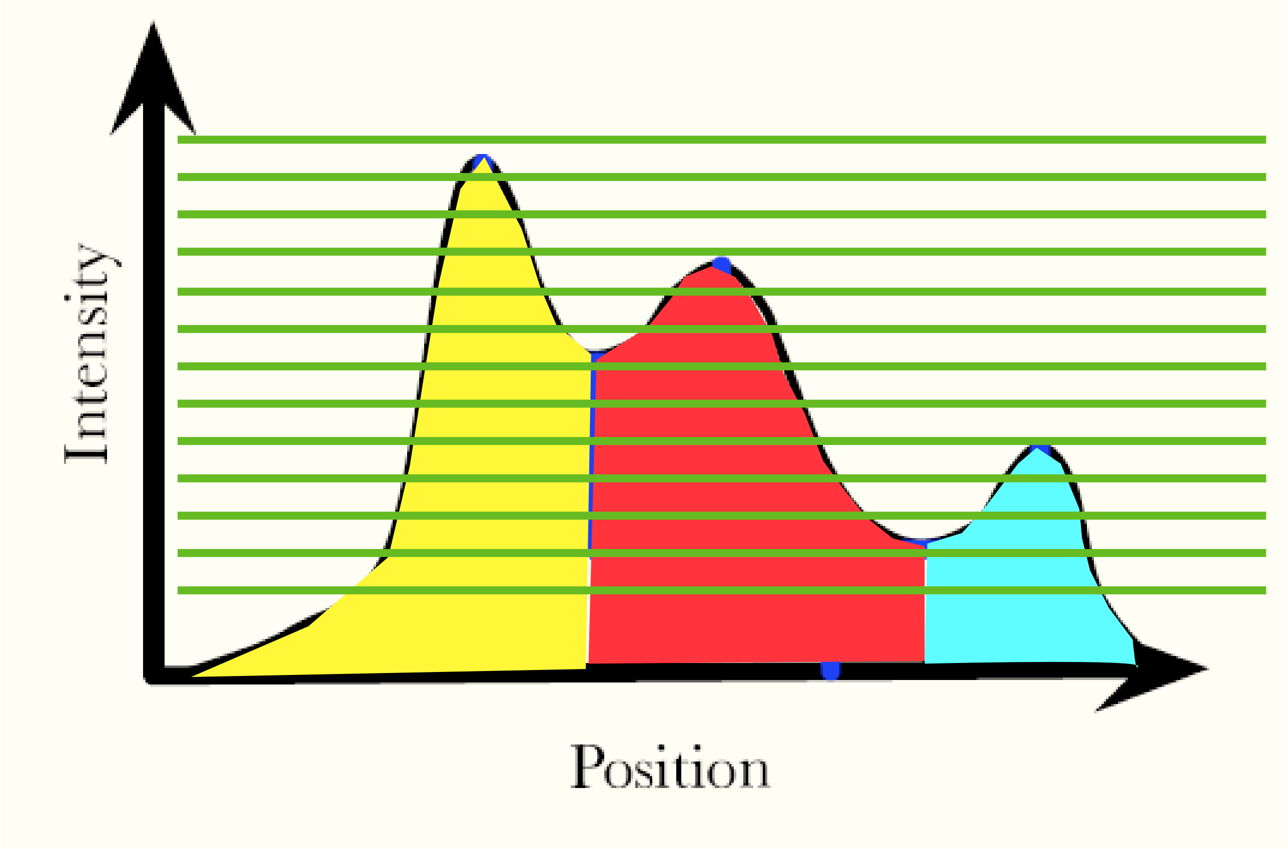
(Williams et al. 1994)

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



Dendrogram

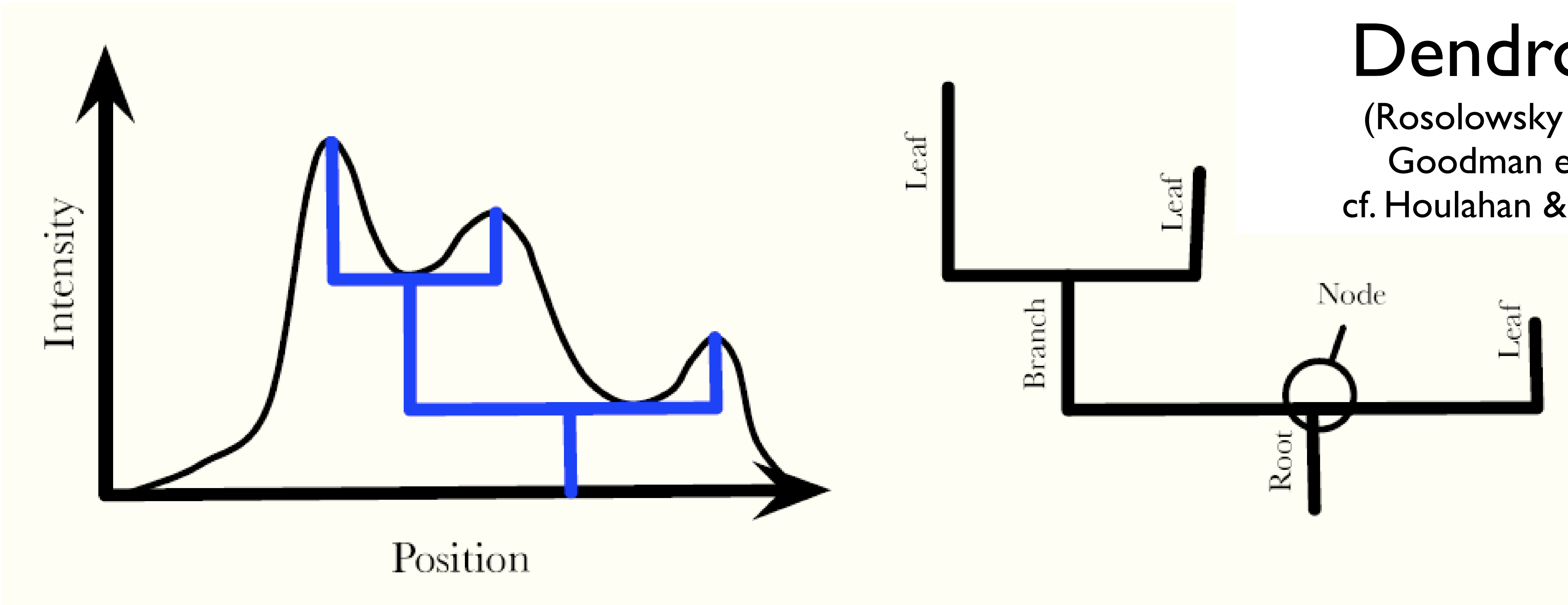
(Rosolowsky et al. 2007;
Goodman et al. 2007
cf. Houlahan & Scalo 1992)



CLUMPFIND

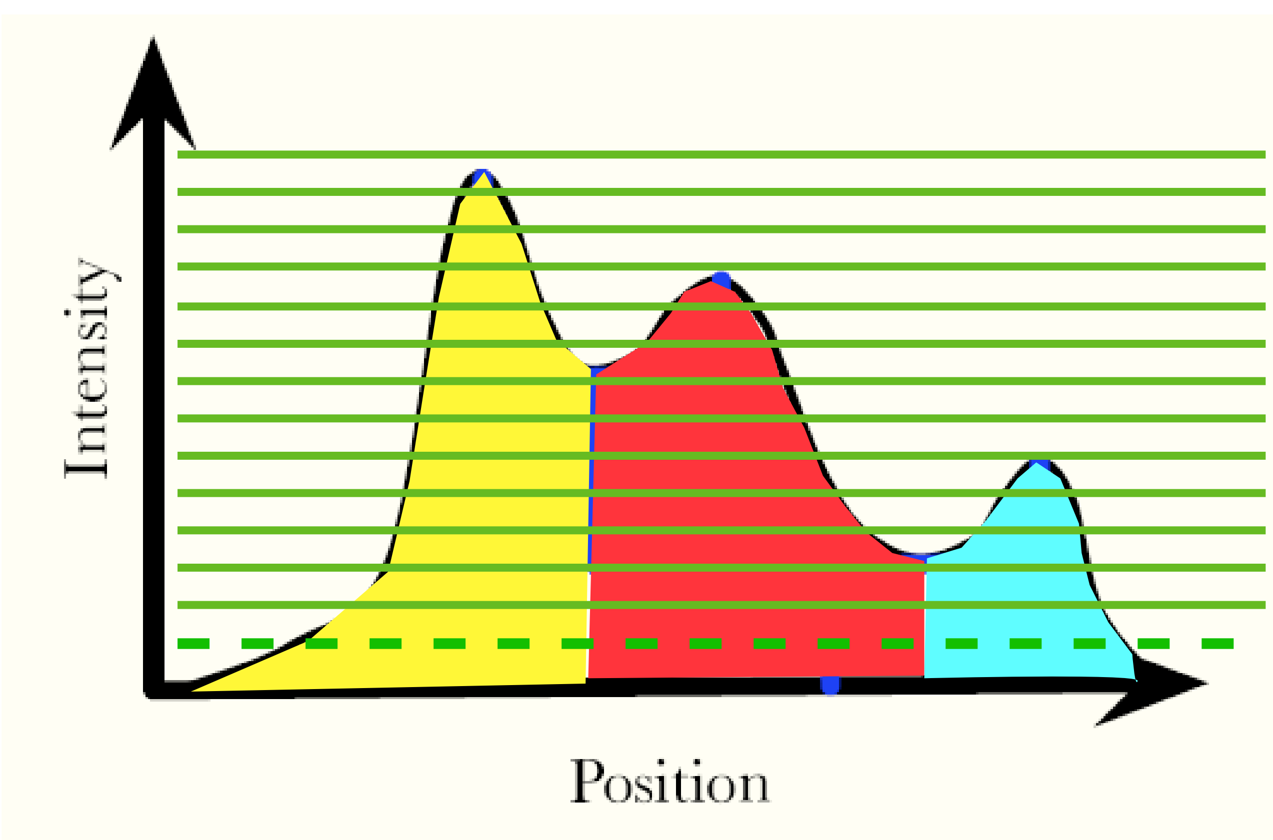
(Williams et al. 1994)

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



Dendrogram

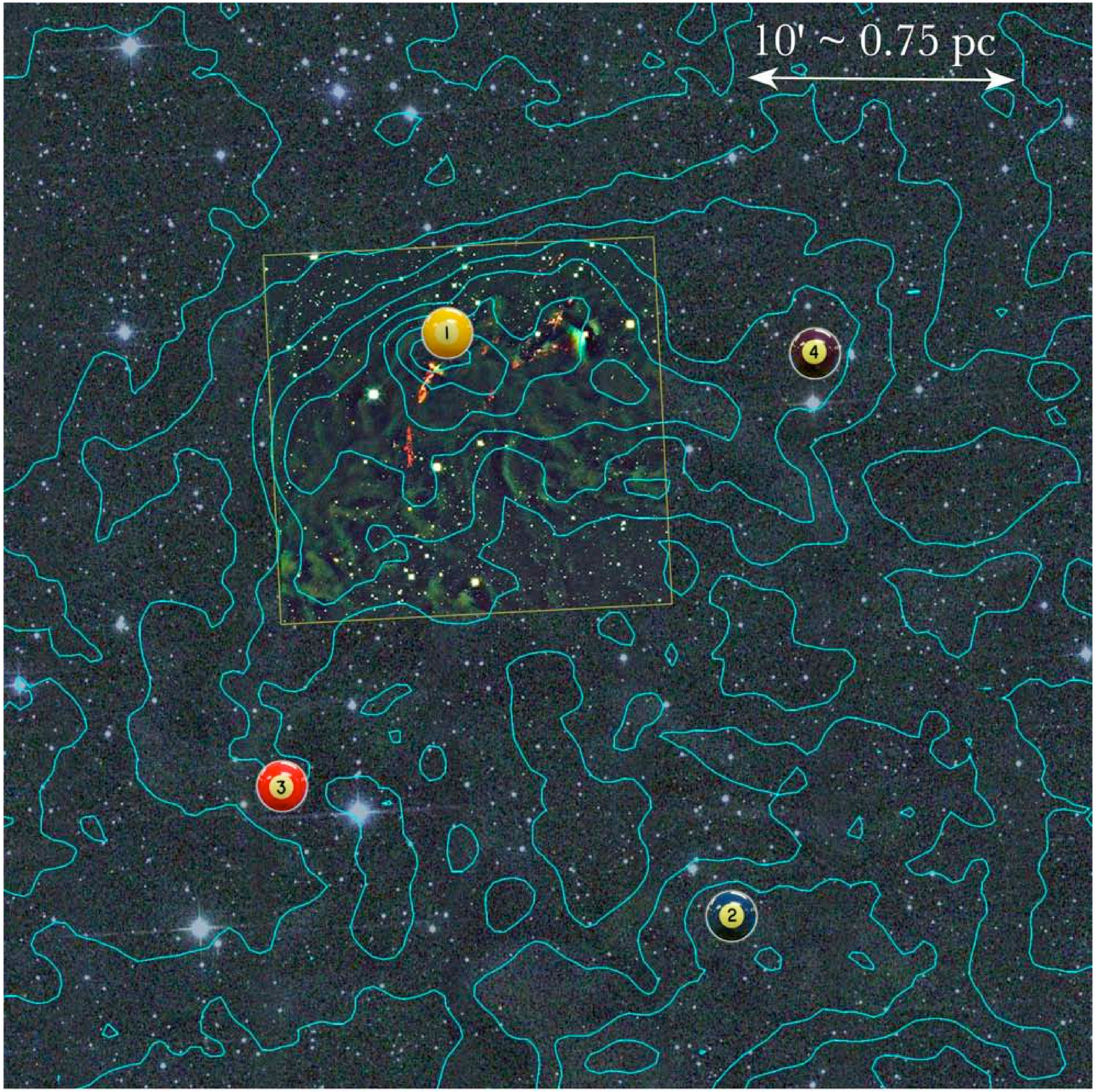
(Rosolowsky et al. 2007; Goodman et al. 2007 cf. Houlahan & Scalo 1992)



CLUMPFIND

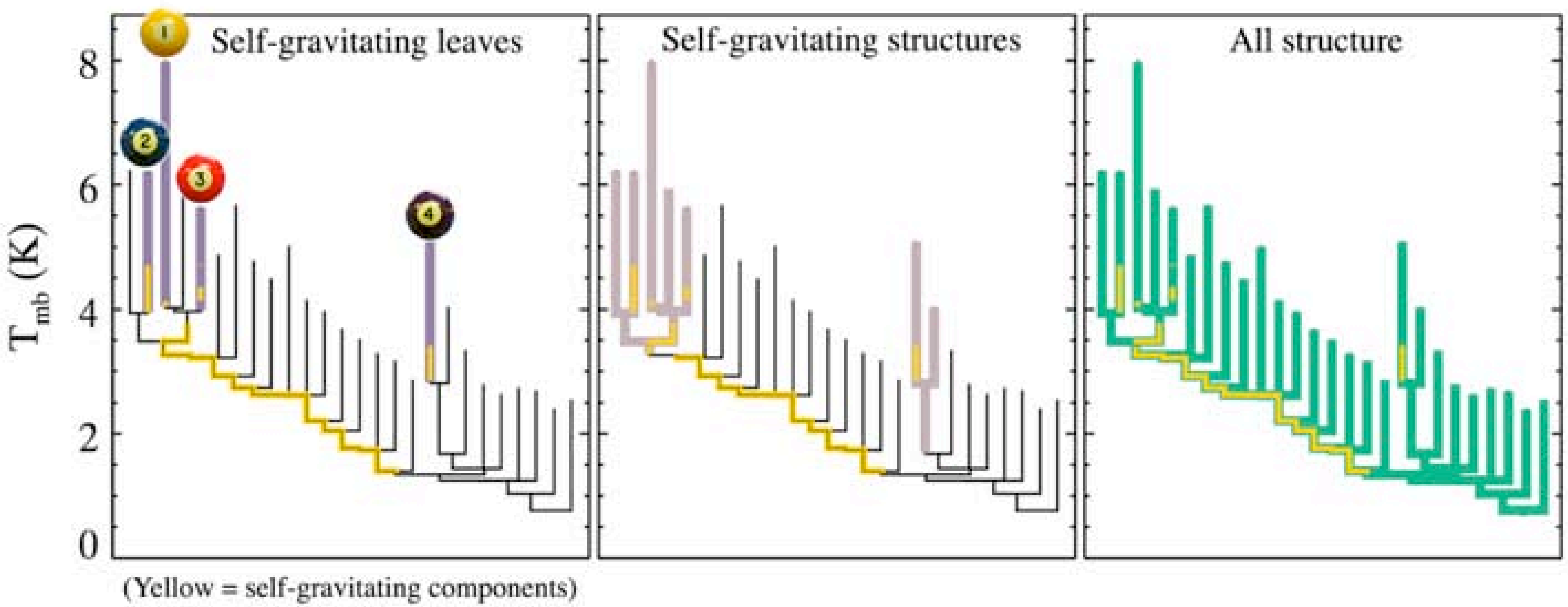
(Williams et al. 1994)

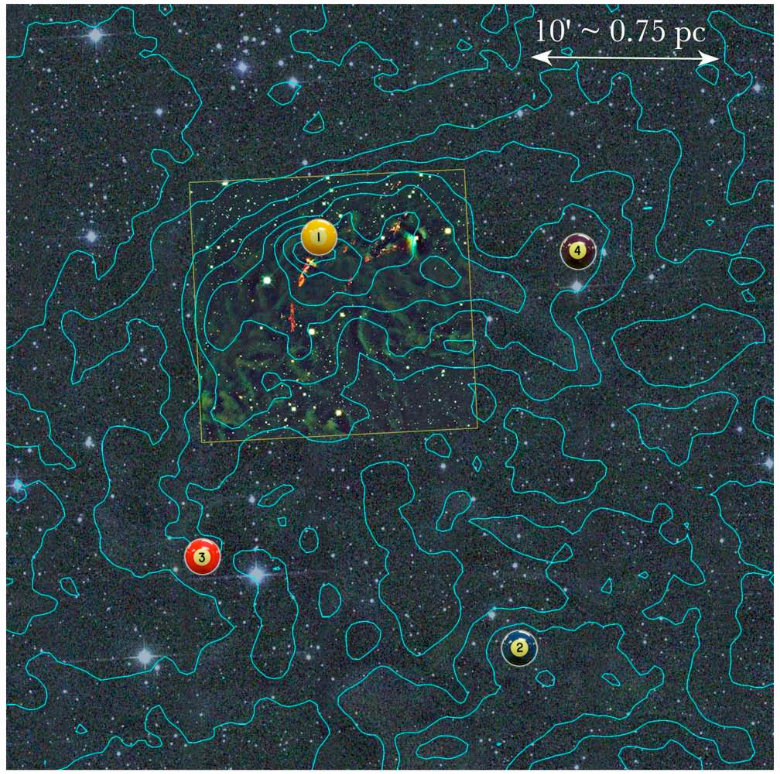
2D View of L1448: Cloudshine + Integrated ^{13}CO



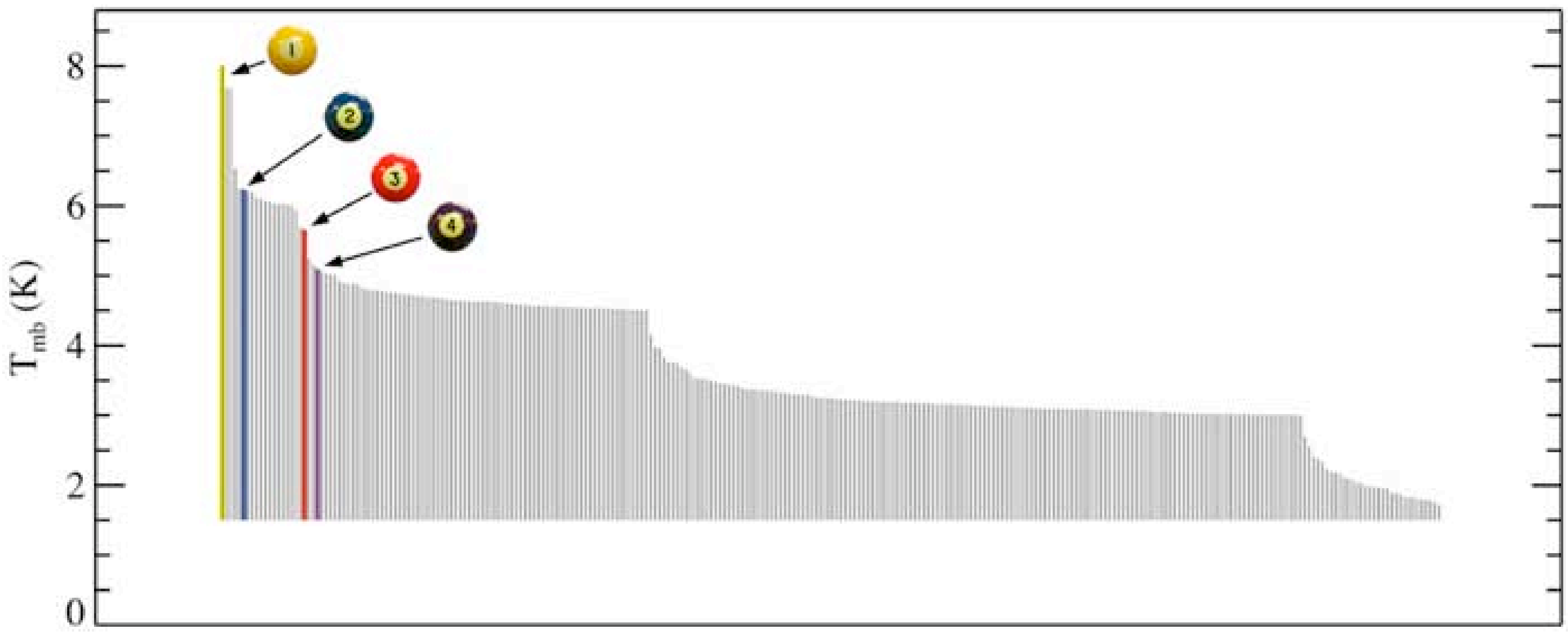
Foster & Goodman 2006; Goodman et al. 2007

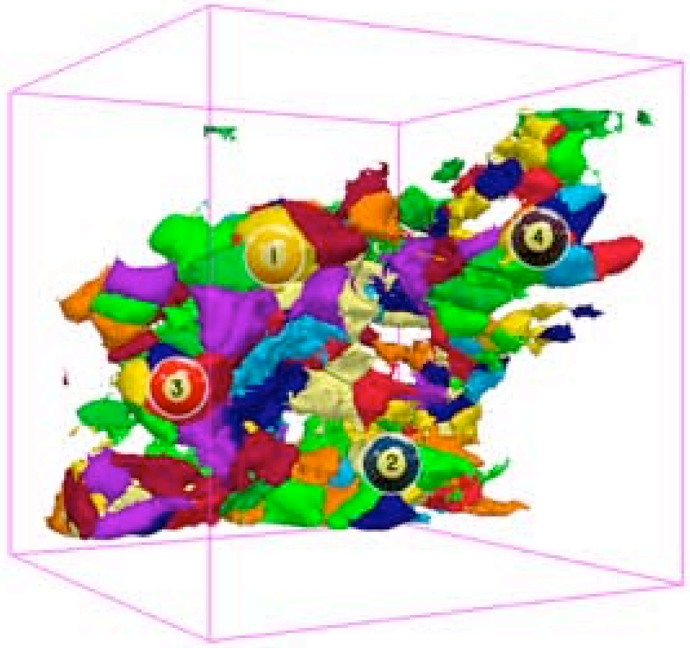
Dendrograms (Hierarchical) vs. CLUMPFIND (Non-hierarchical)



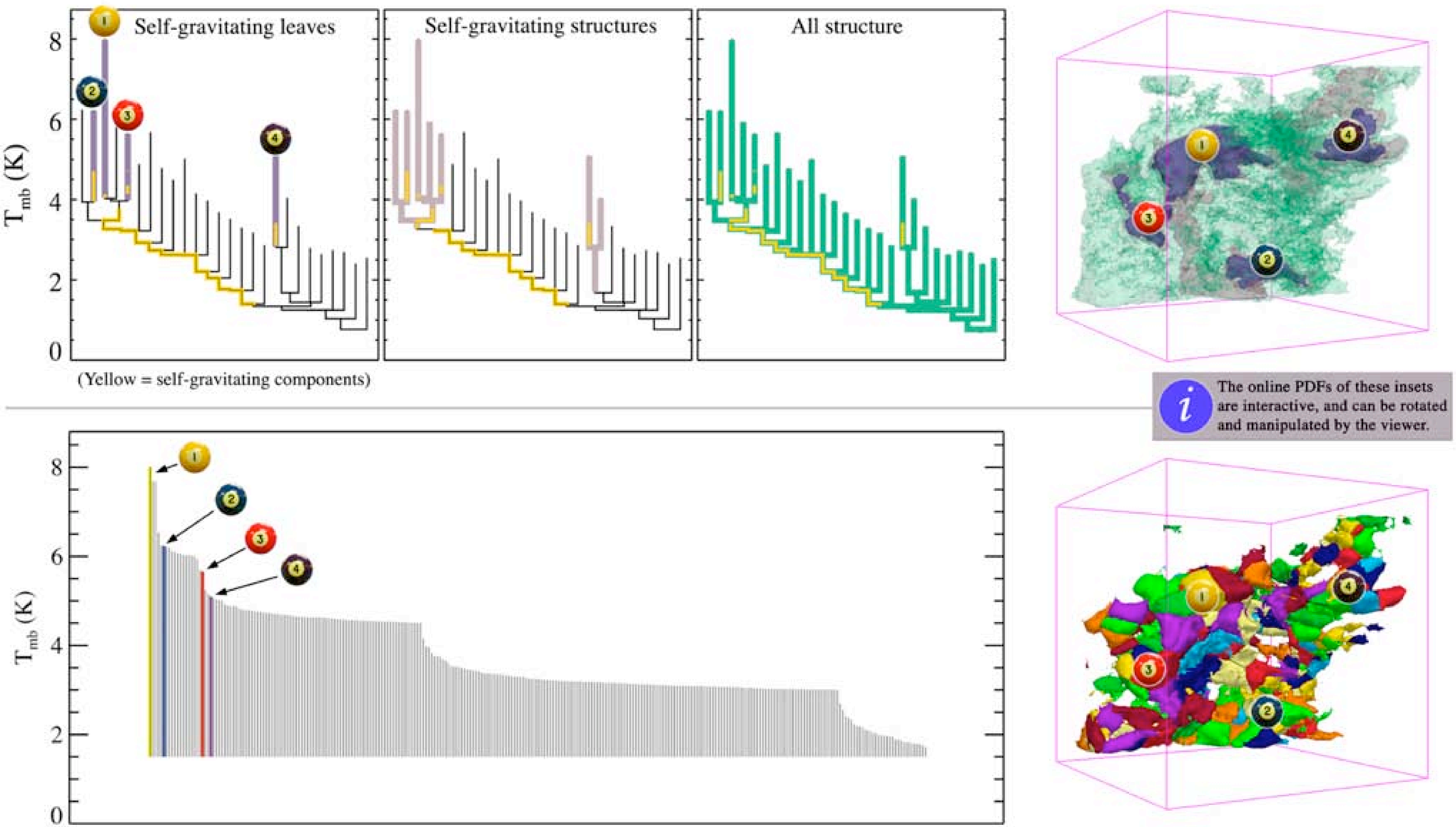


The online PDFs of these insets are interactive, and can be rotated and manipulated by the viewer.

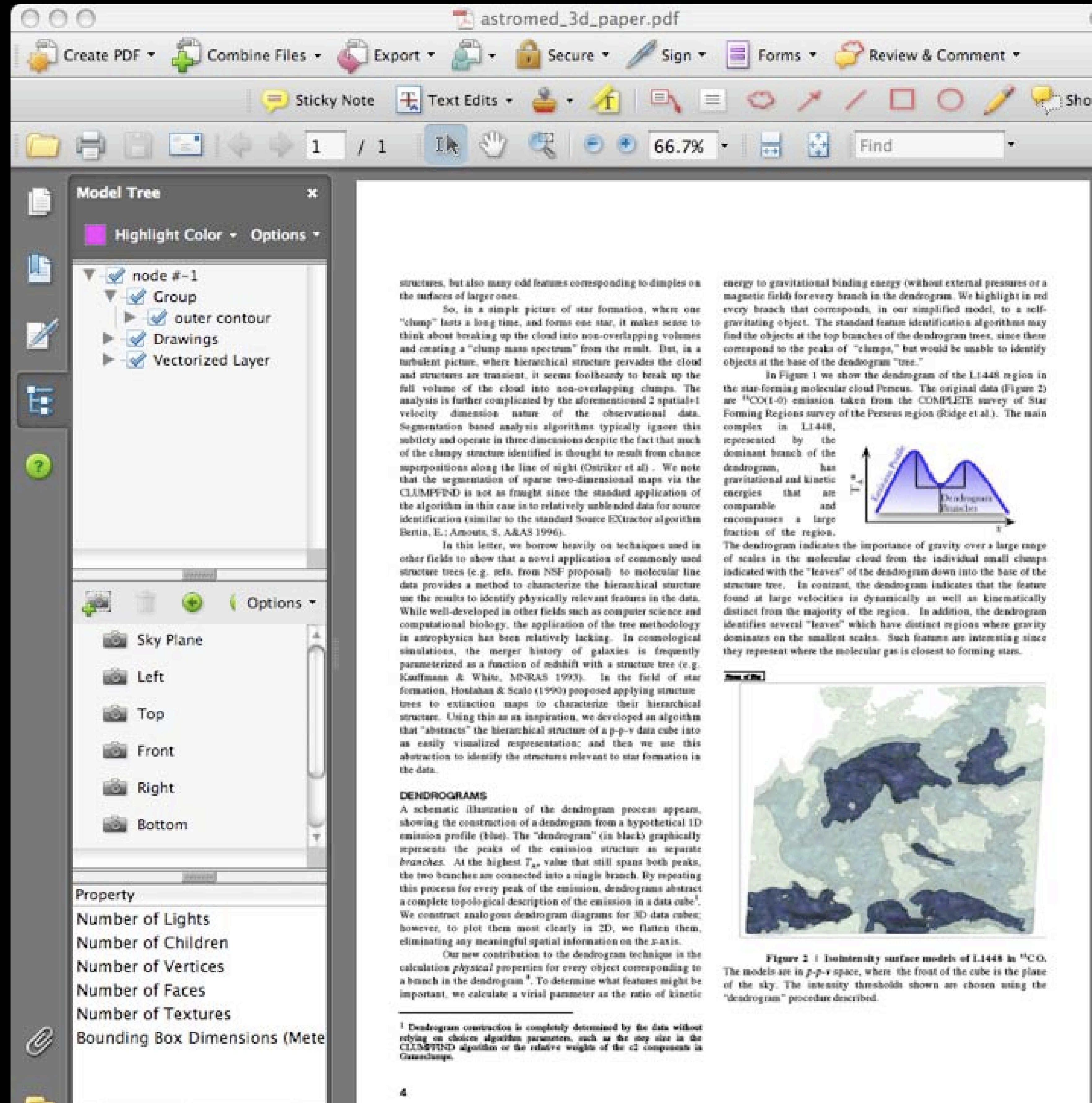




Dendrograms (Hierarchical) vs. CLUMPFIND (Non-hierarchical)



And, coming soon, to a cookbook (Journal) near you... (3D PDF)

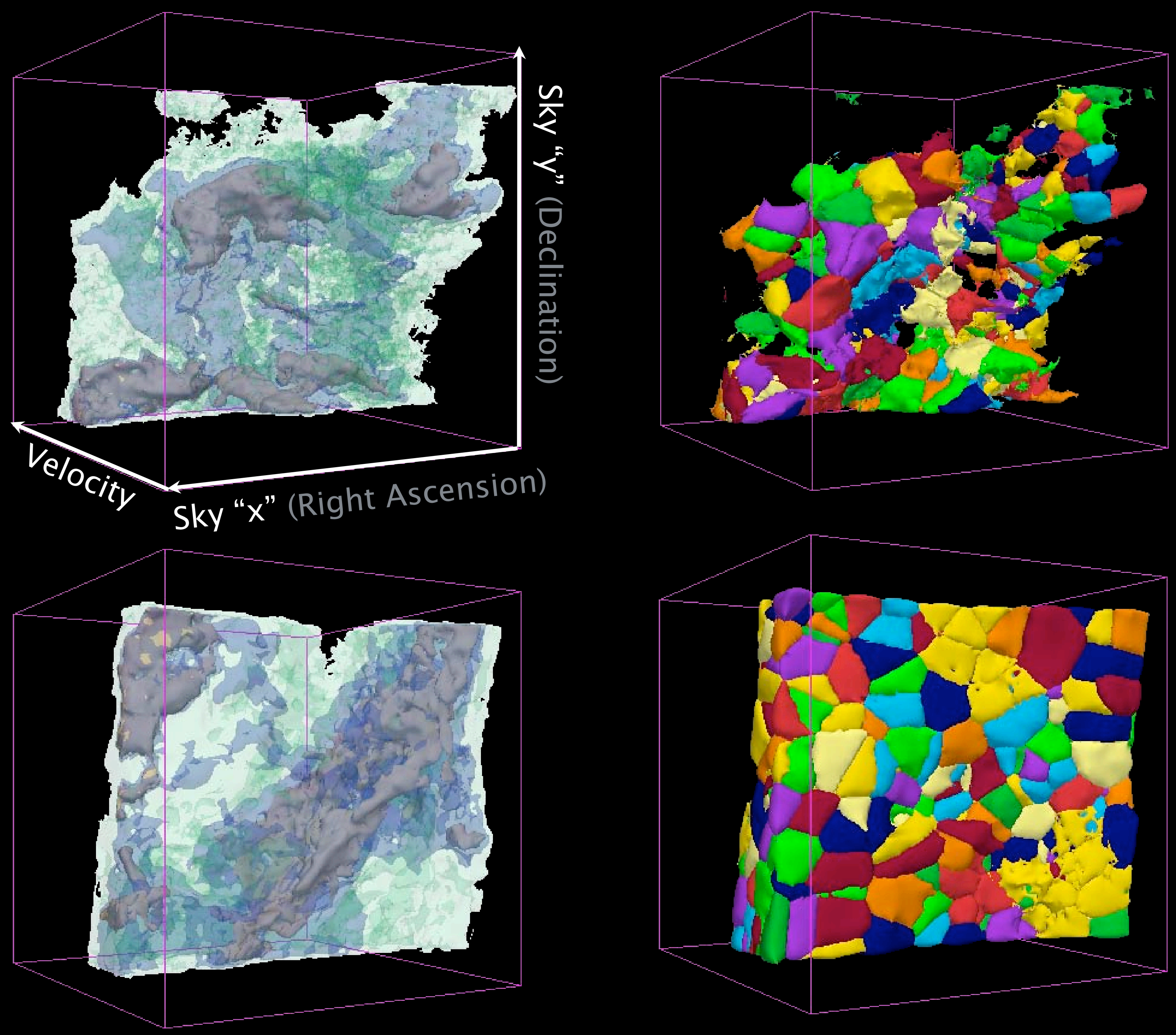


Taste-Test

(Dendro)Surfaces | "CLUMPFIND"

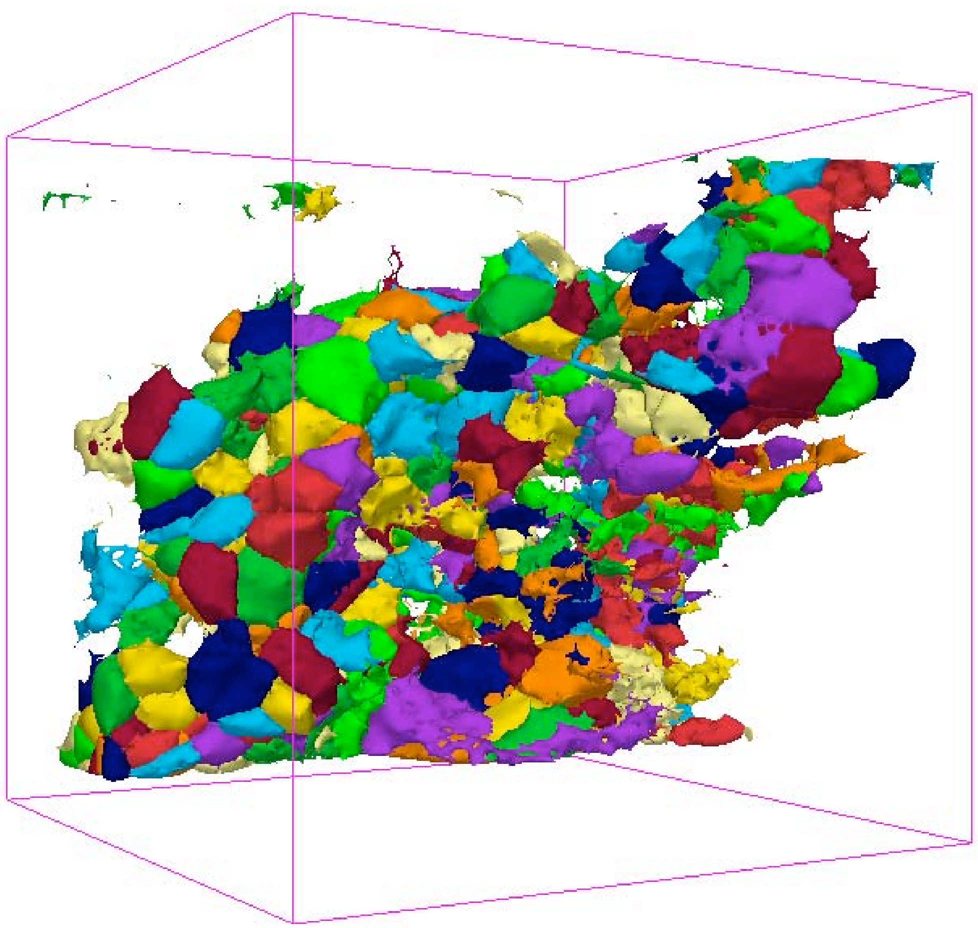
Observed Reality

"Observed" Simulations



work of Rosolowsky, Pineda, Kauffmann, Borkin,Padoan, Halle & Goodman;
figure from Goodman & Rosolowsky NSF "Star Formation Taste Tests" Proposal, Fall 2006

Is CLUMPFIND OK as a Statistic? (Like Cayenne Pepper?)

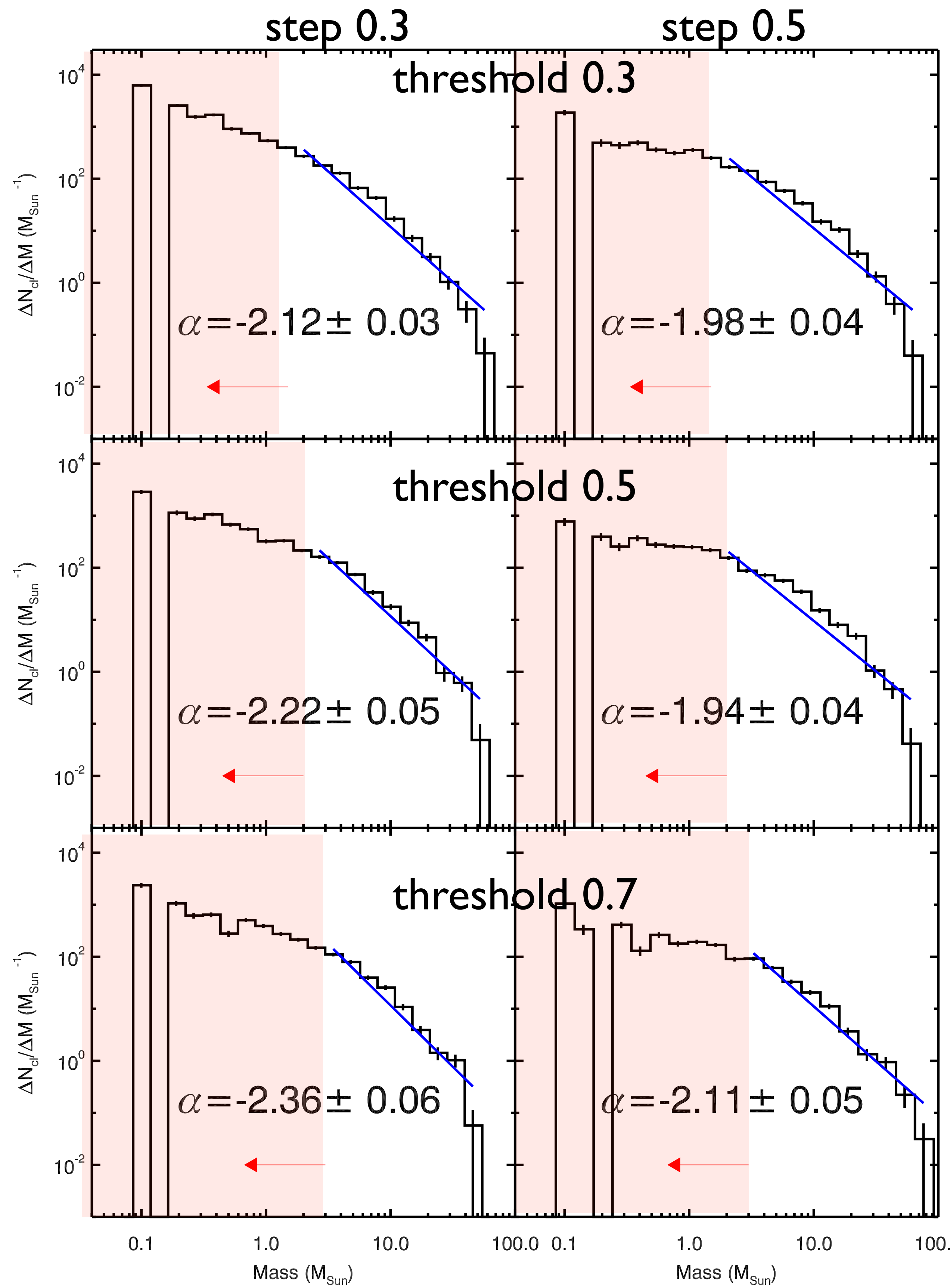


CLUMPFIND output for L1448

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

Results for full Perseus Map

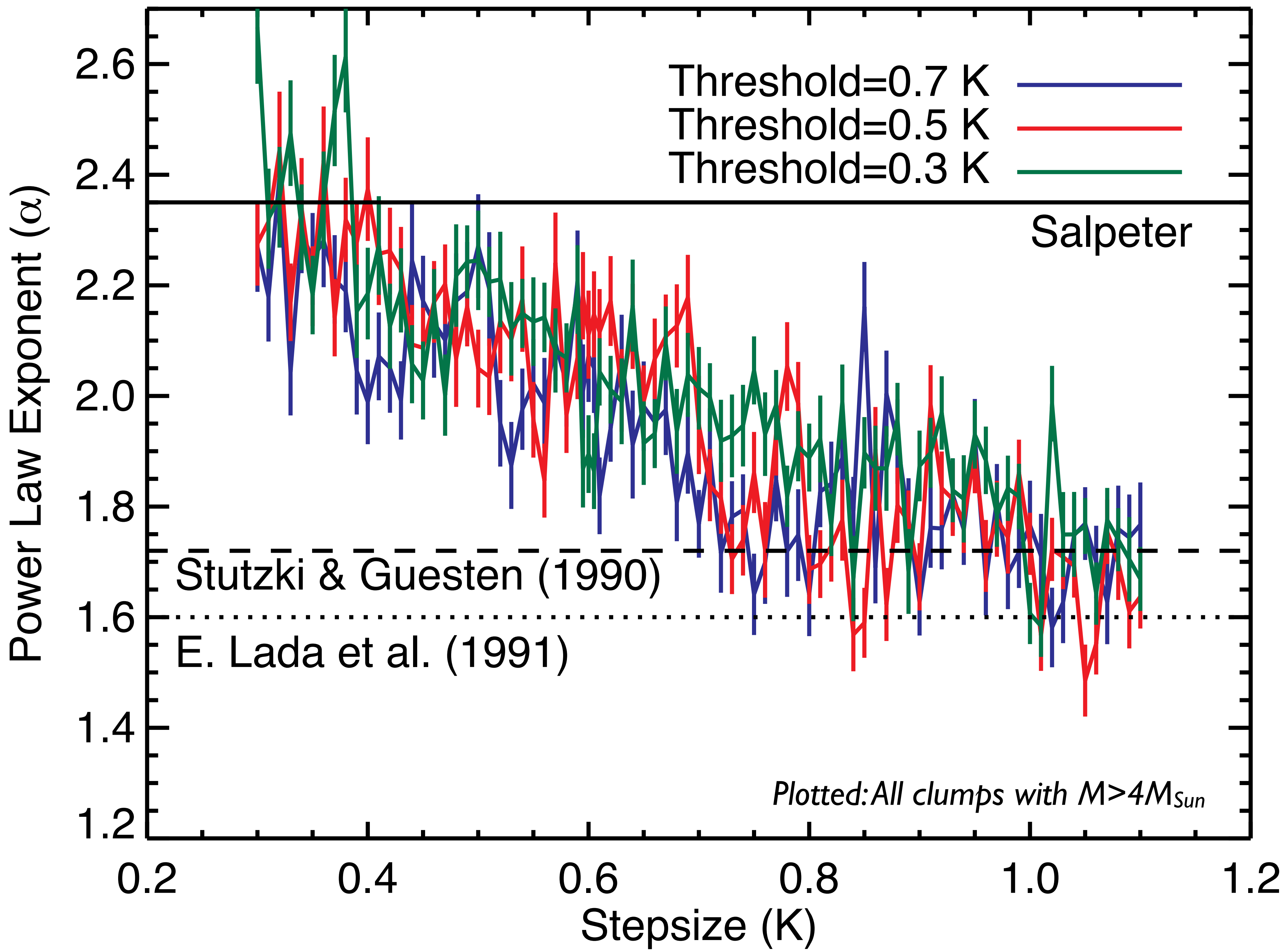
Threshold	Step size	total number of Clump	% above sensitivity limit Mass v/s Radius	% above sensitivity limit FWHM v/s Radius	% above both curves
0.3	0.3	5199	47.32%	58.03%	46.59%
0.3	0.5	3844	40.74%	46.96%	40.30%
0.5	0.3	2141	79.12%	89.72%	78.14%
0.5	0.5	1420	86.83%	89.01%	86.20%
0.7	0.3	1748	79.06%	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?
Be VERY careful of the recipe.

Slope of Mass Spectrum



Pineda, Goodman & Rosolowsky 2007

Advice for Cooks & Tasters

The menu may offer something for everyone, but taste carefully to be sure you got what you ordered.

Also, be careful to mind the difference between “numerical experiments” and “simulations”: don’t taste them in life–threatening ways.

E Extinction and scattering! (Cloudshine)

2006

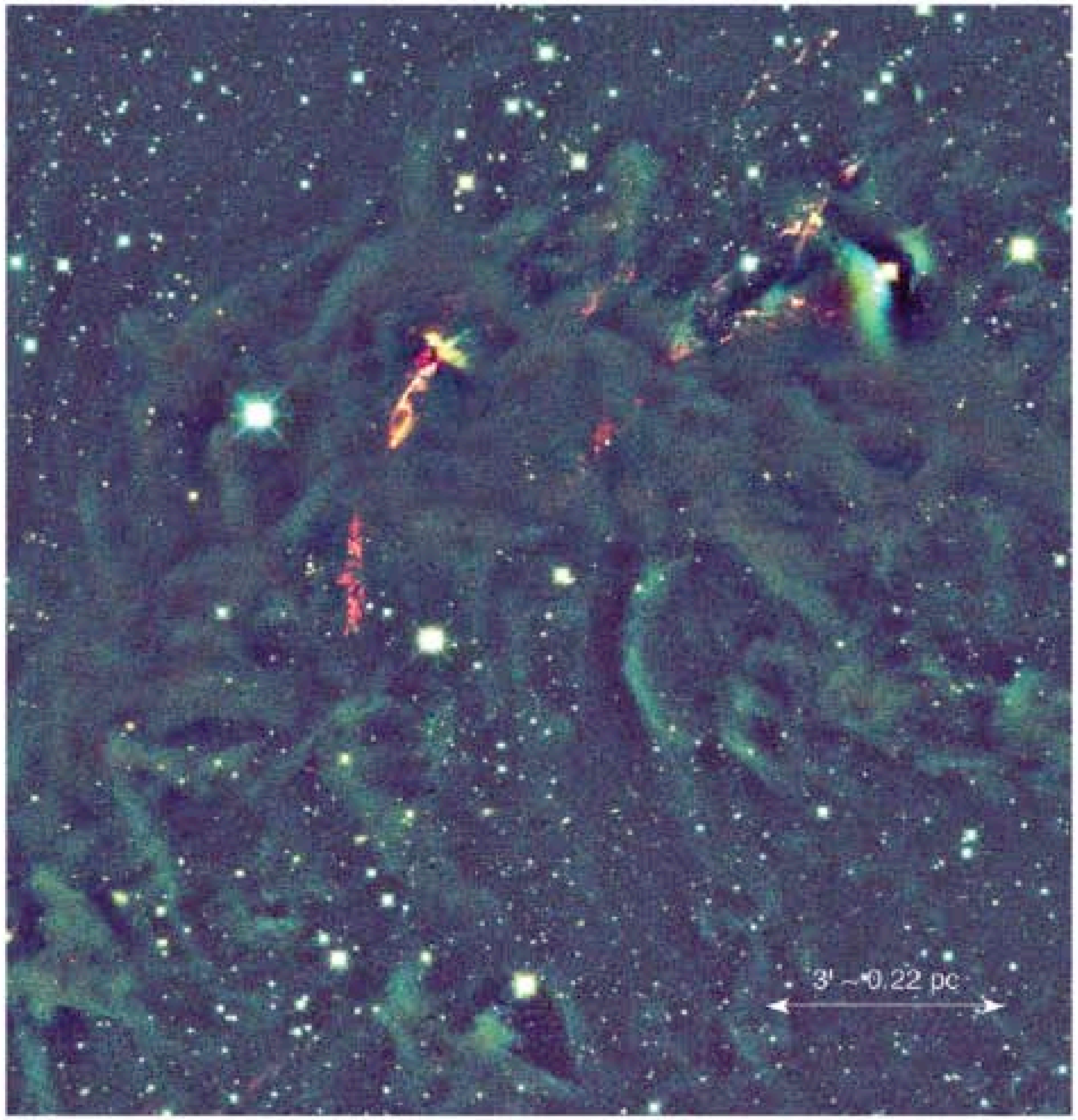


FIG. 1.—L1448 in false color. Component images have been weighted according to their flux in units of MJy sr^{-1}. J is blue, H is green, and K_s is red. Outflows from young stars glow red, while a small fan-shaped reflection nebula in the upper right is blue-green. Cloudshine, in contrast, is shown 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.

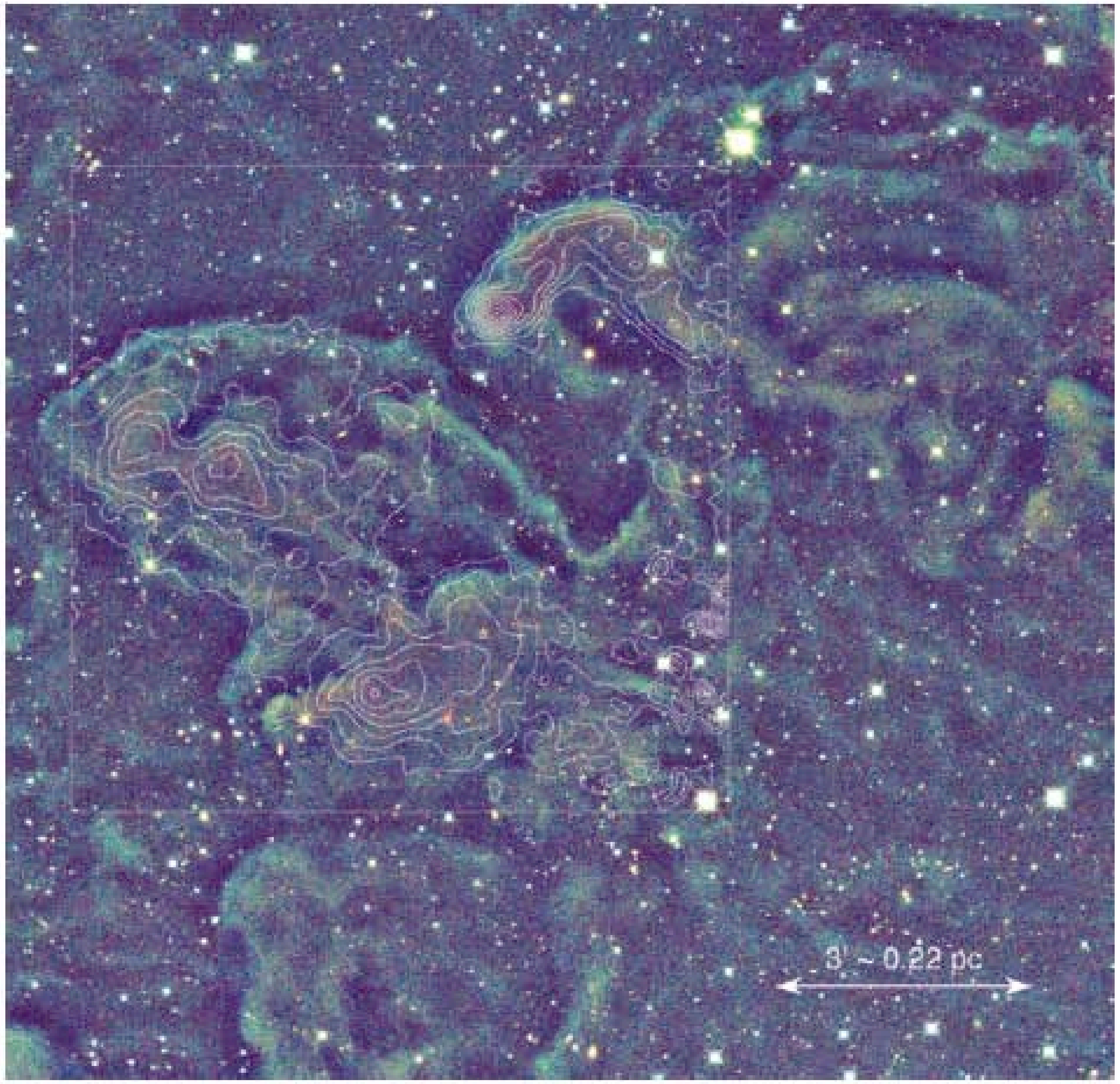
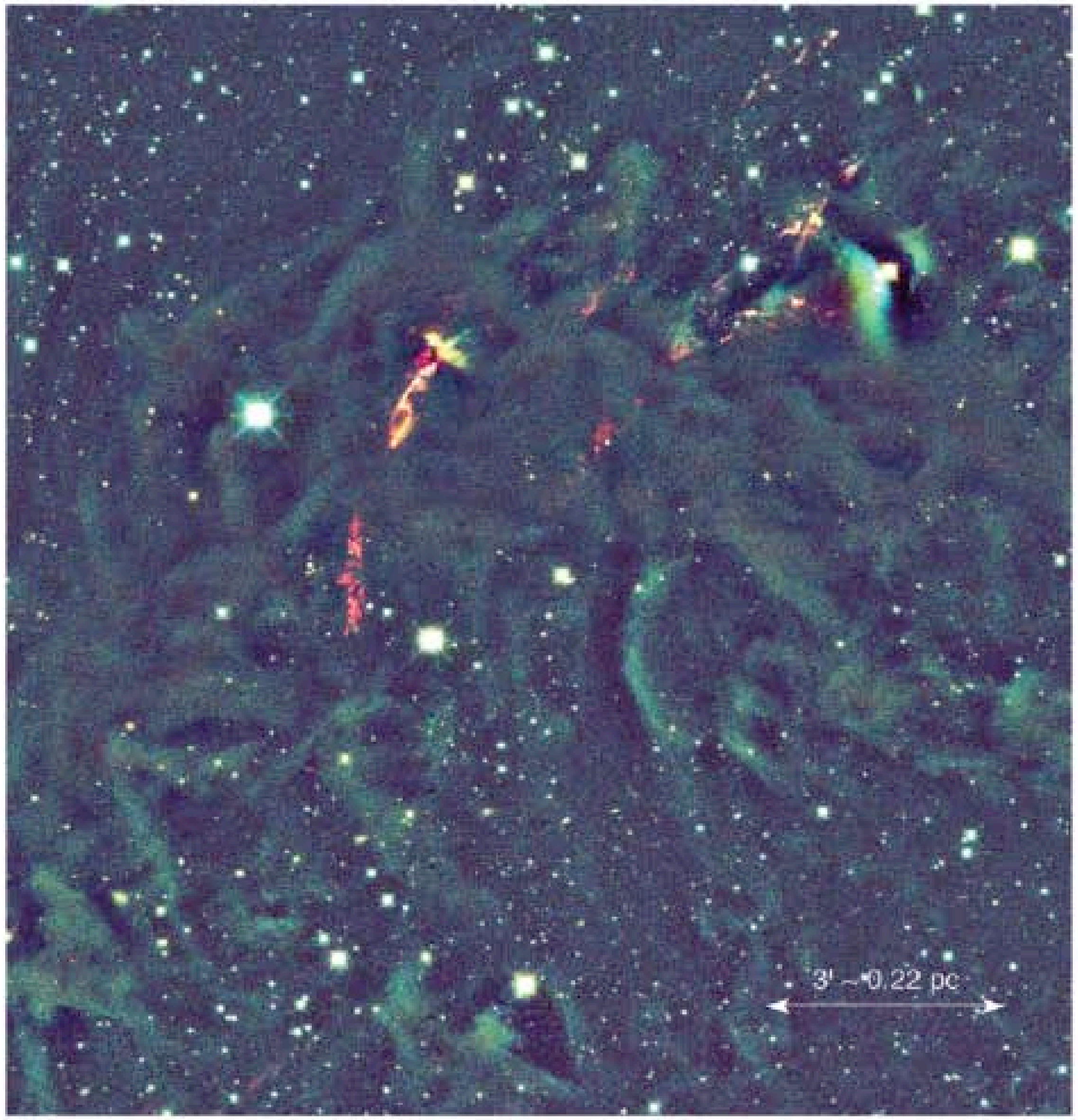


FIG. 2.—L1451 in false color. Again, each component image has been scaled to the same flux scale in units of MJy sr^{-1}; and J is blue, H is green, and K_s is red. A smaller map of 1.2 mm dust emission contours from COMPLETE (M. Tafalla 2006, in preparation) has been overlaid, showing that the color 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.

“Cloudshine”=Scattered Ambient Starlight

2006



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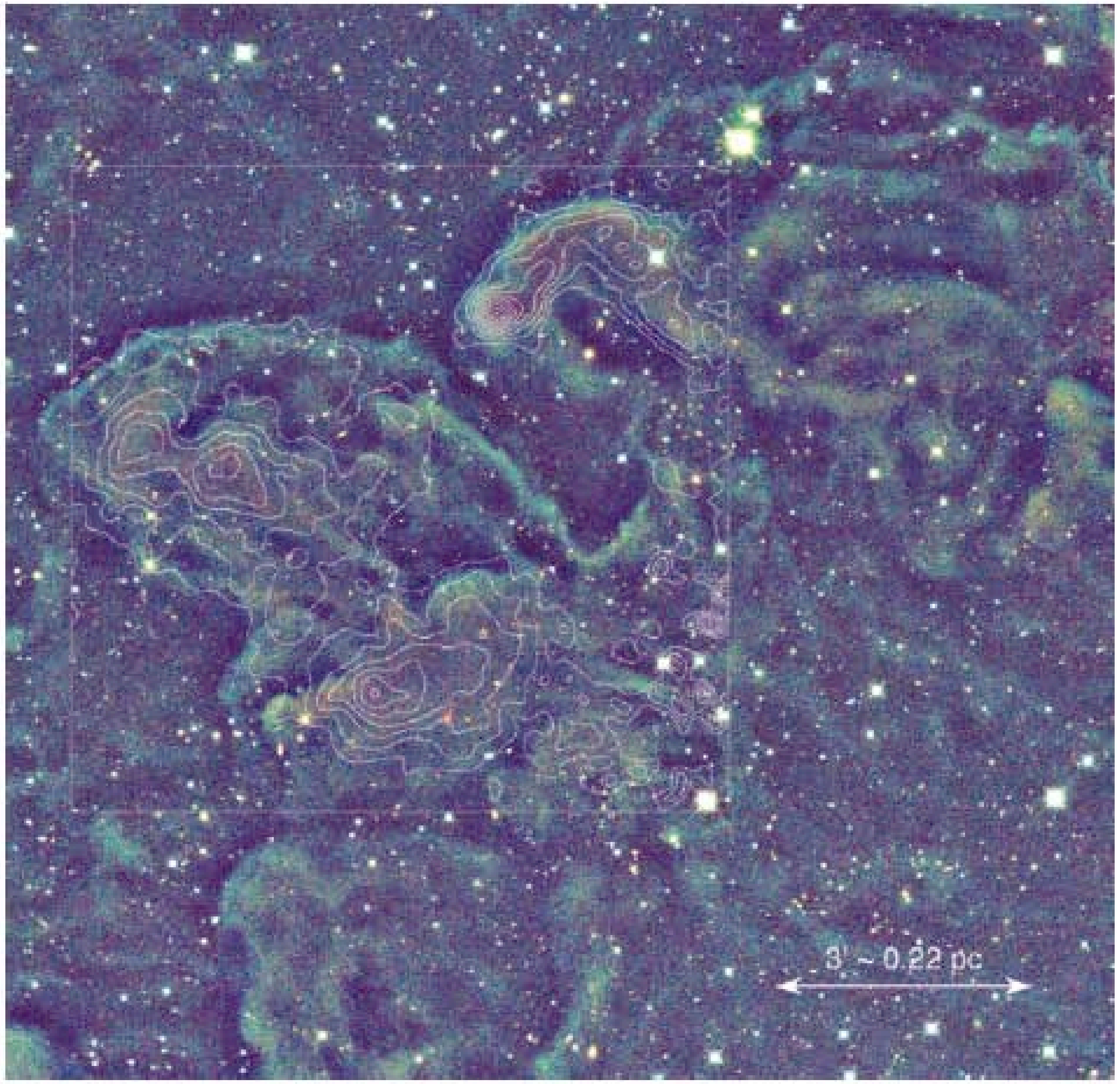

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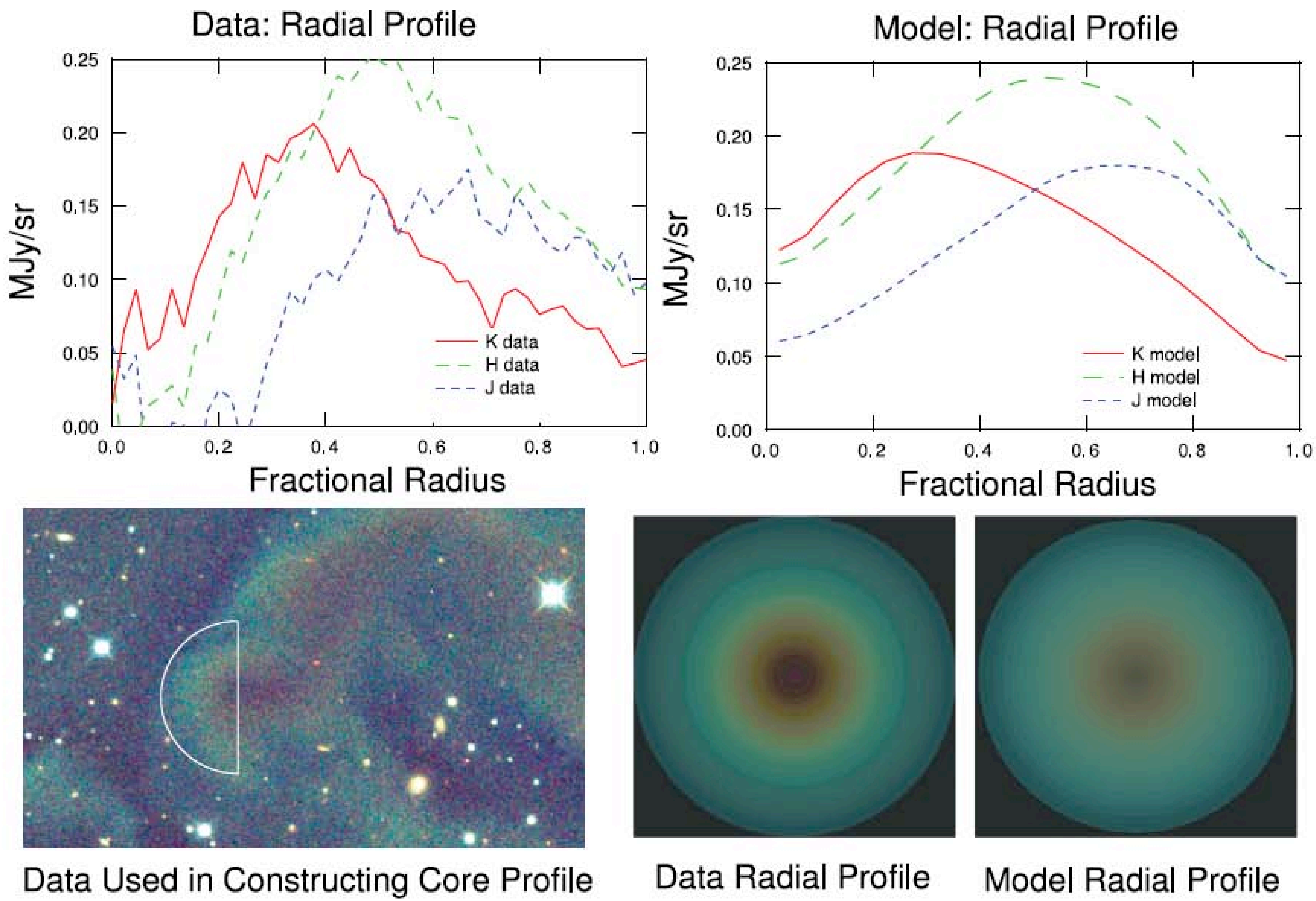
Extra Slides Only
Beyond Here

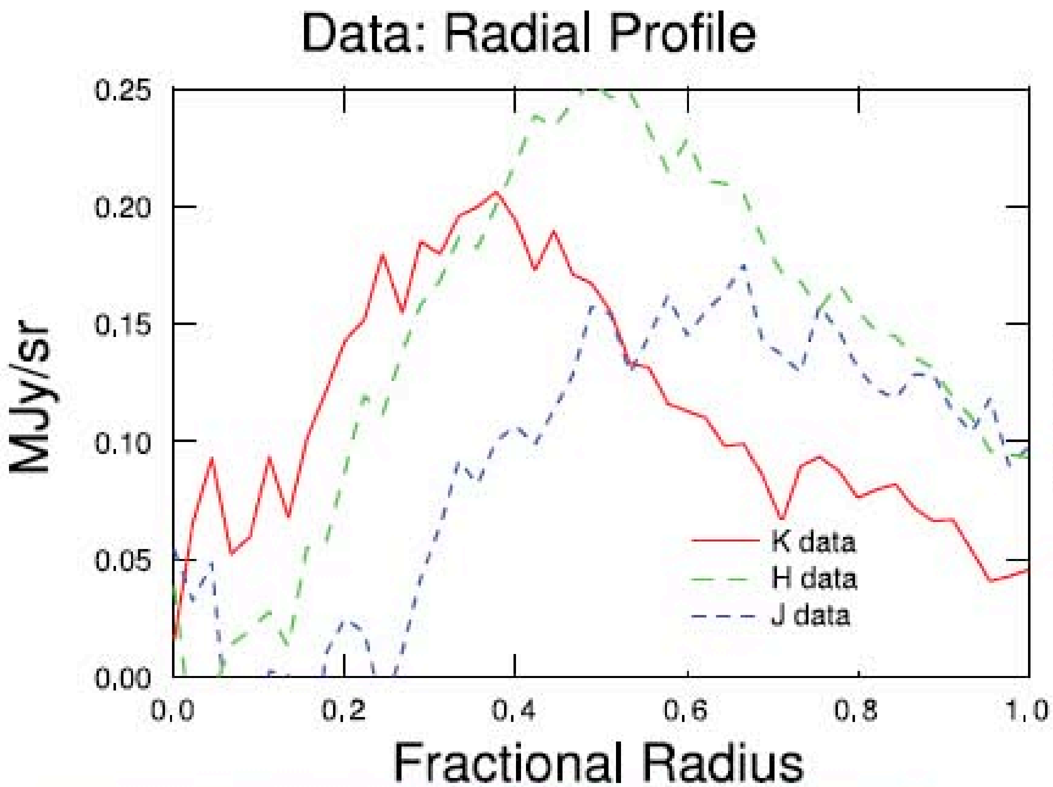
E Extinction and scattering! (Cloudshine)

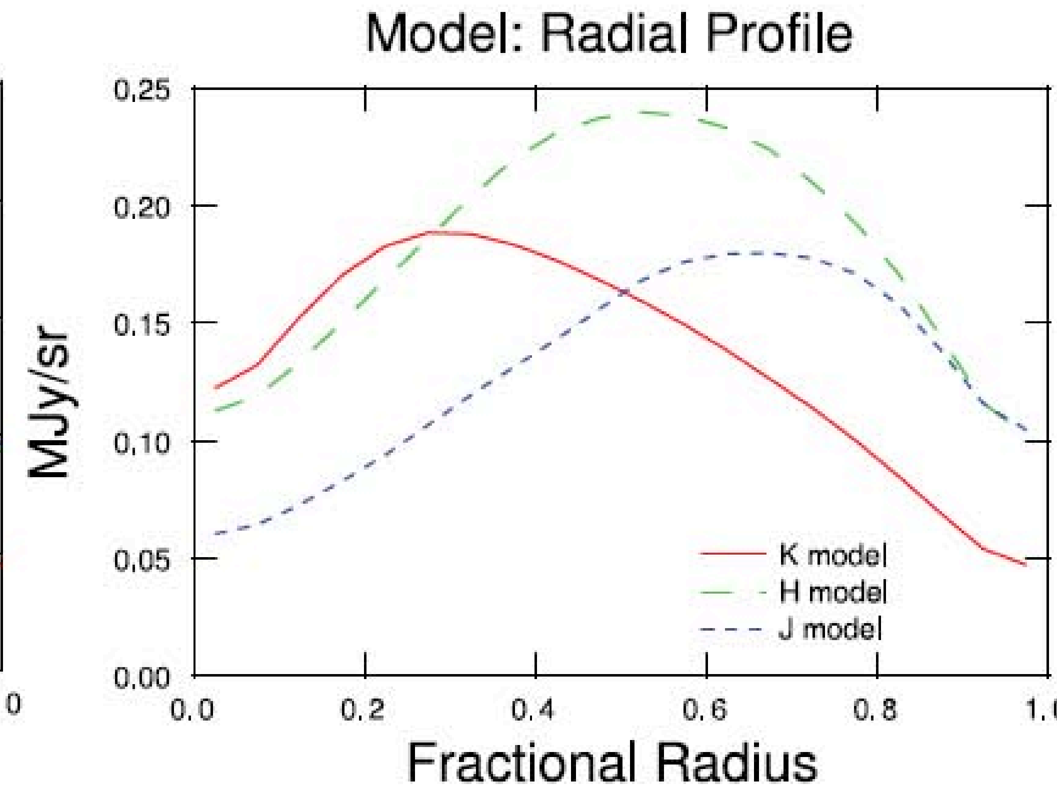


Foster & Goodman 2006

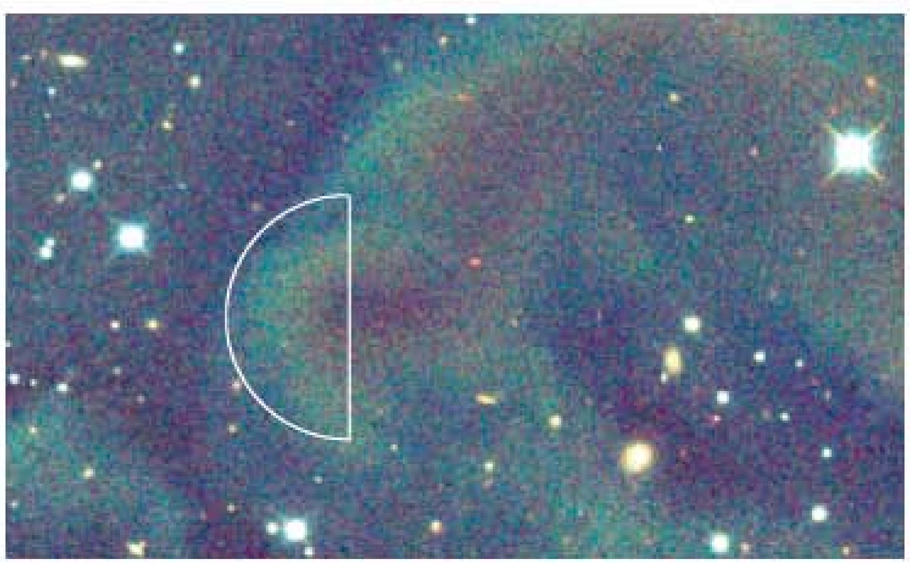
FIG. 3.—Model of cloudshine in one core as reflected interstellar radiation. The lower left panel shows the roughly circular feature we chose to model as a sphere. Due to the surrounding structure, only the left half of the circle was used to derive an angle-averaged radial profile. The comparison between 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.

Almost Tasting a Very Simple Recipe

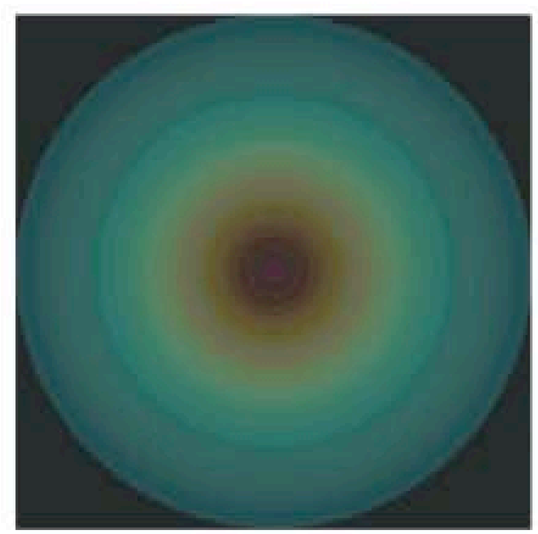




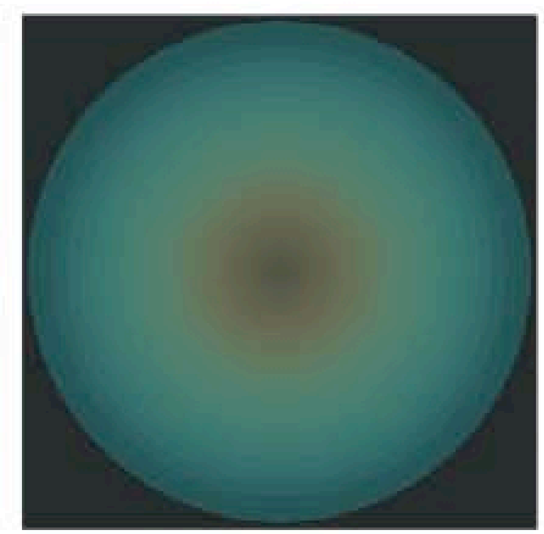
Foster & Goodman 2006



Data Used in Constructing Core Profile



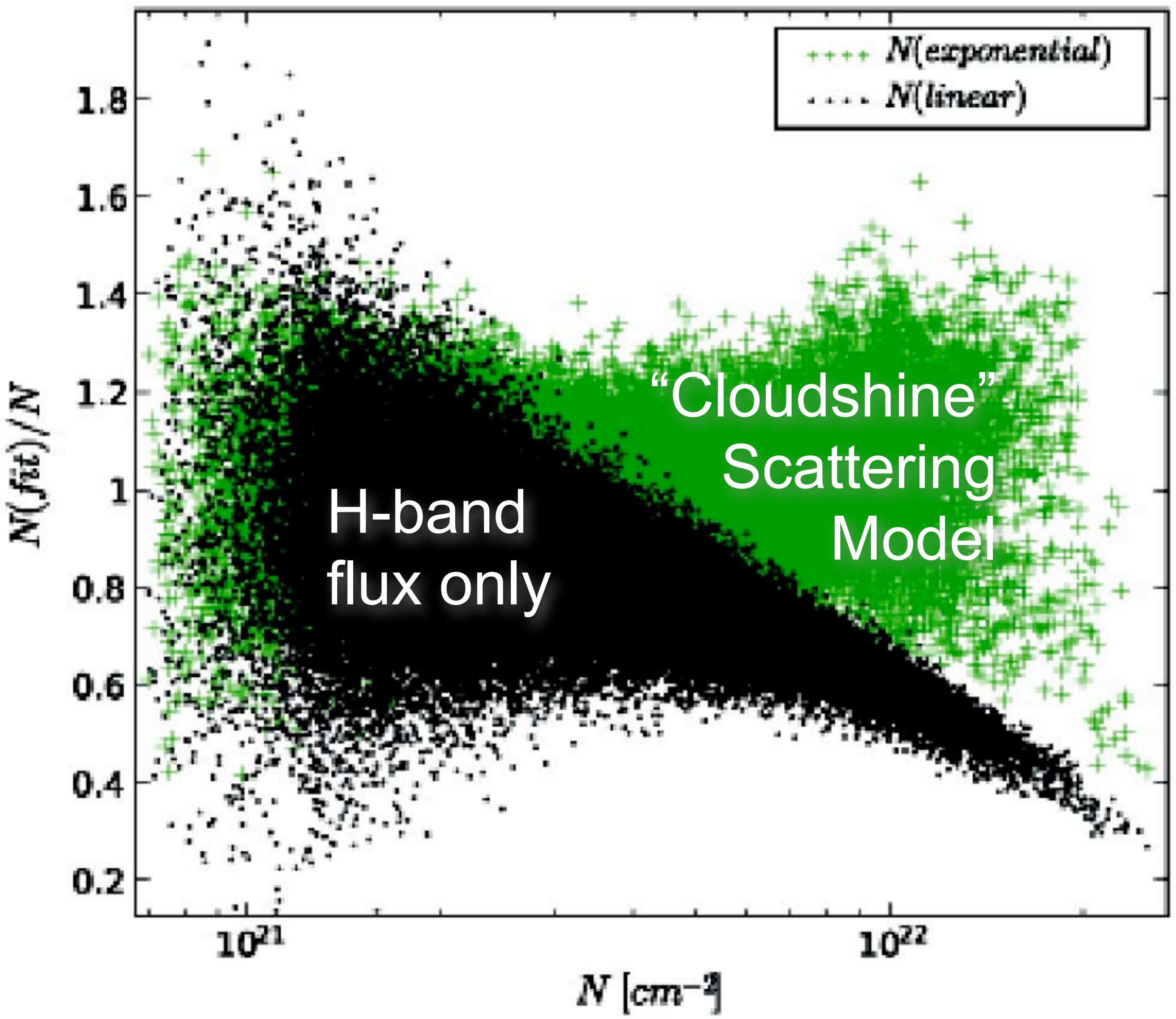
Data Radial Profile



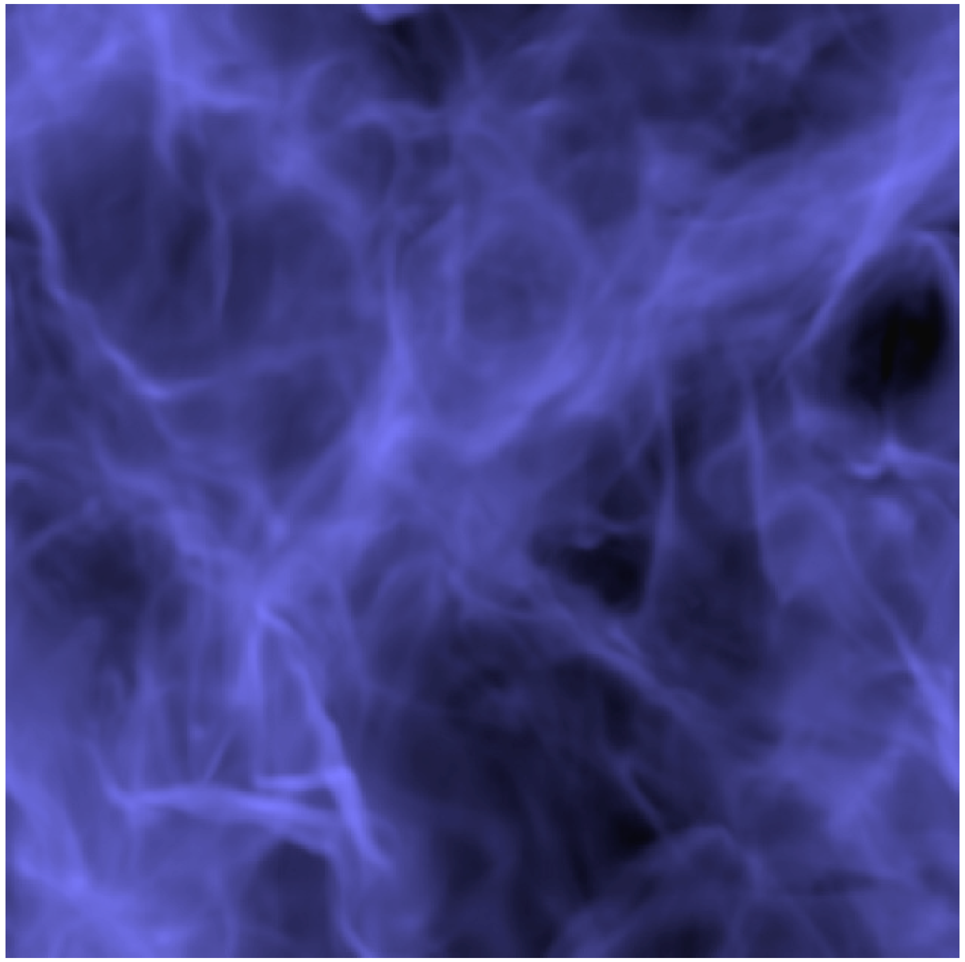
Model Radial Profile

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.

Extinction and scattering! (Cloudshine)



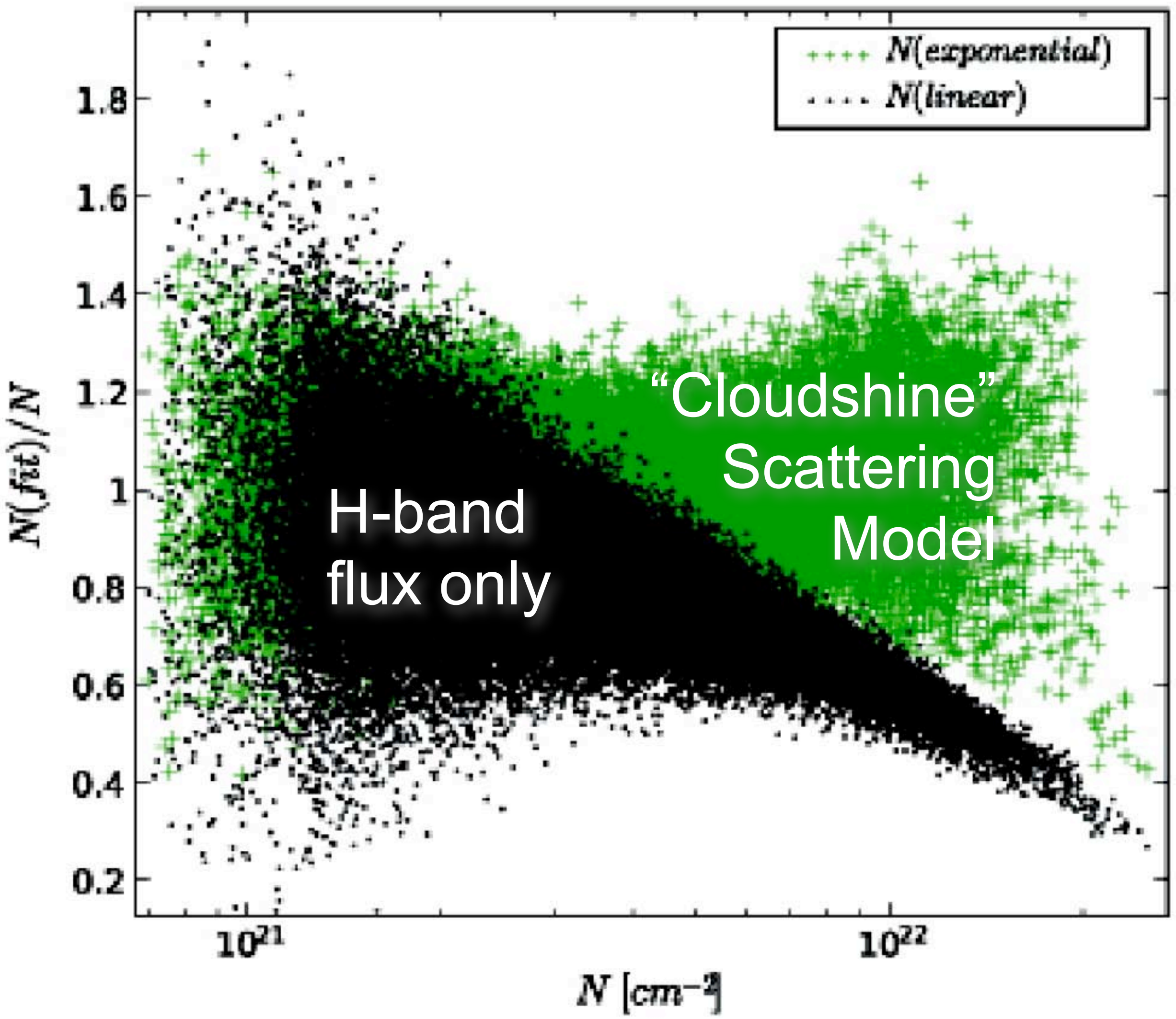
Simulation



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

Padoan et al. 2006

Theorists doing the Tasting!



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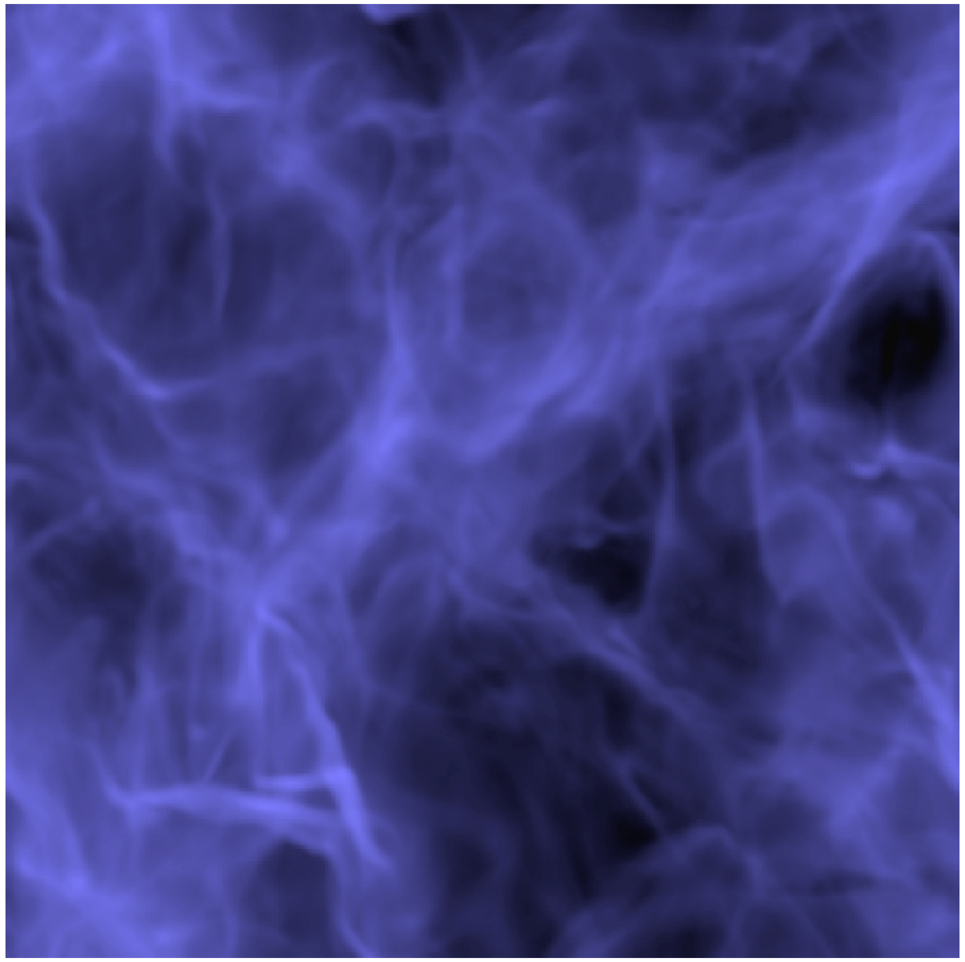

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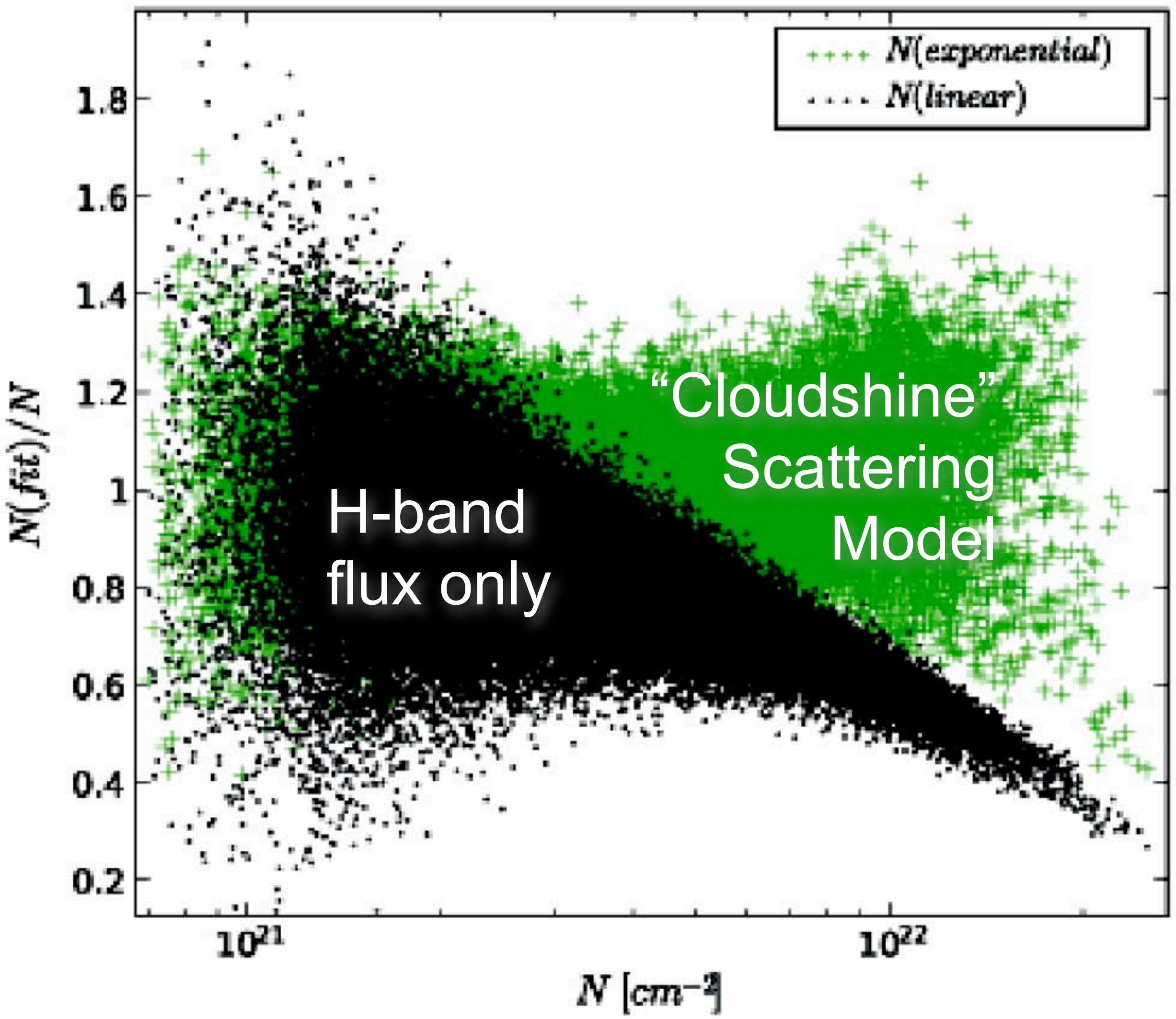
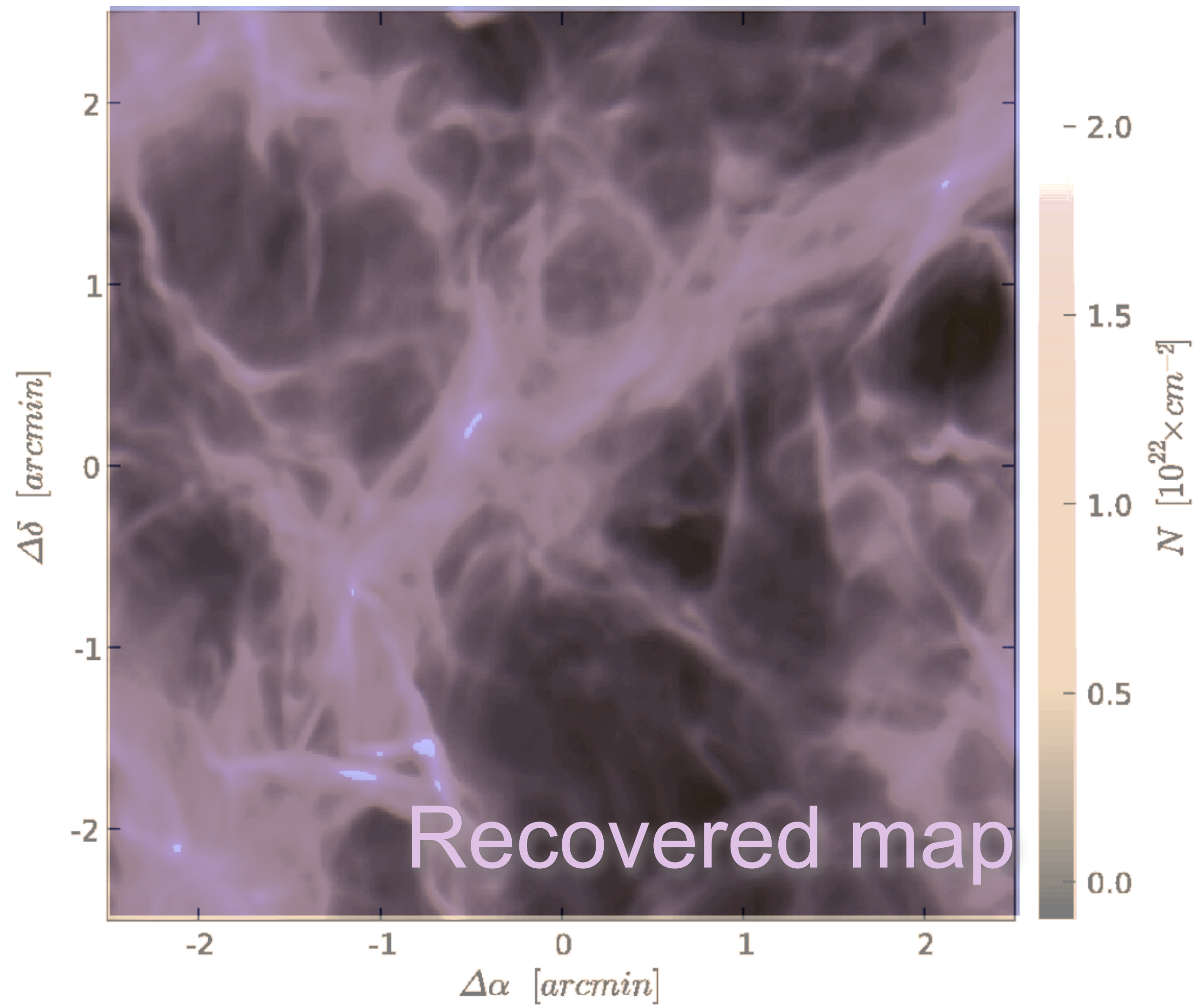


Simulation



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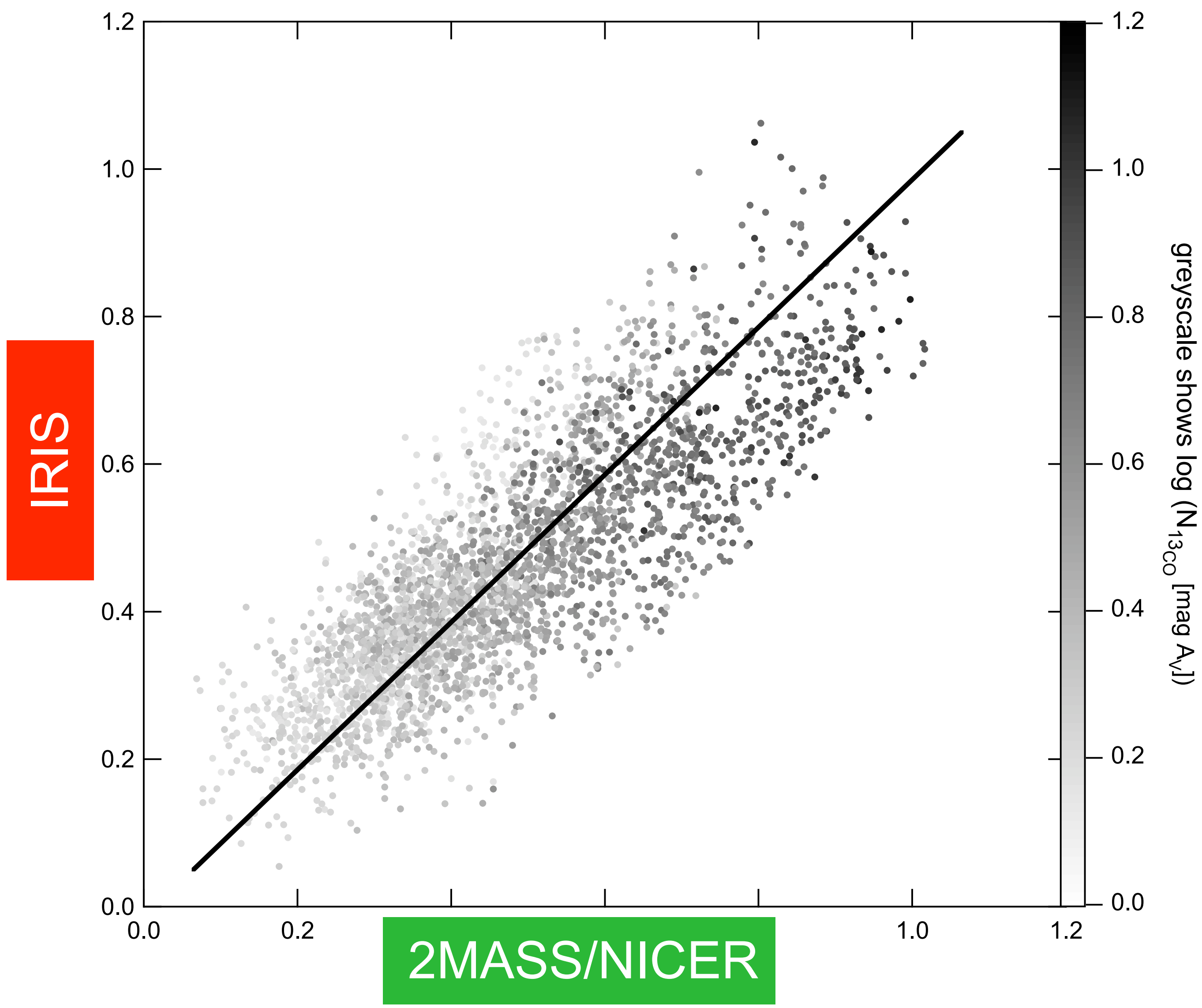
Padoan et al. 2006

Modeling line-of-sight temperature fluctuations

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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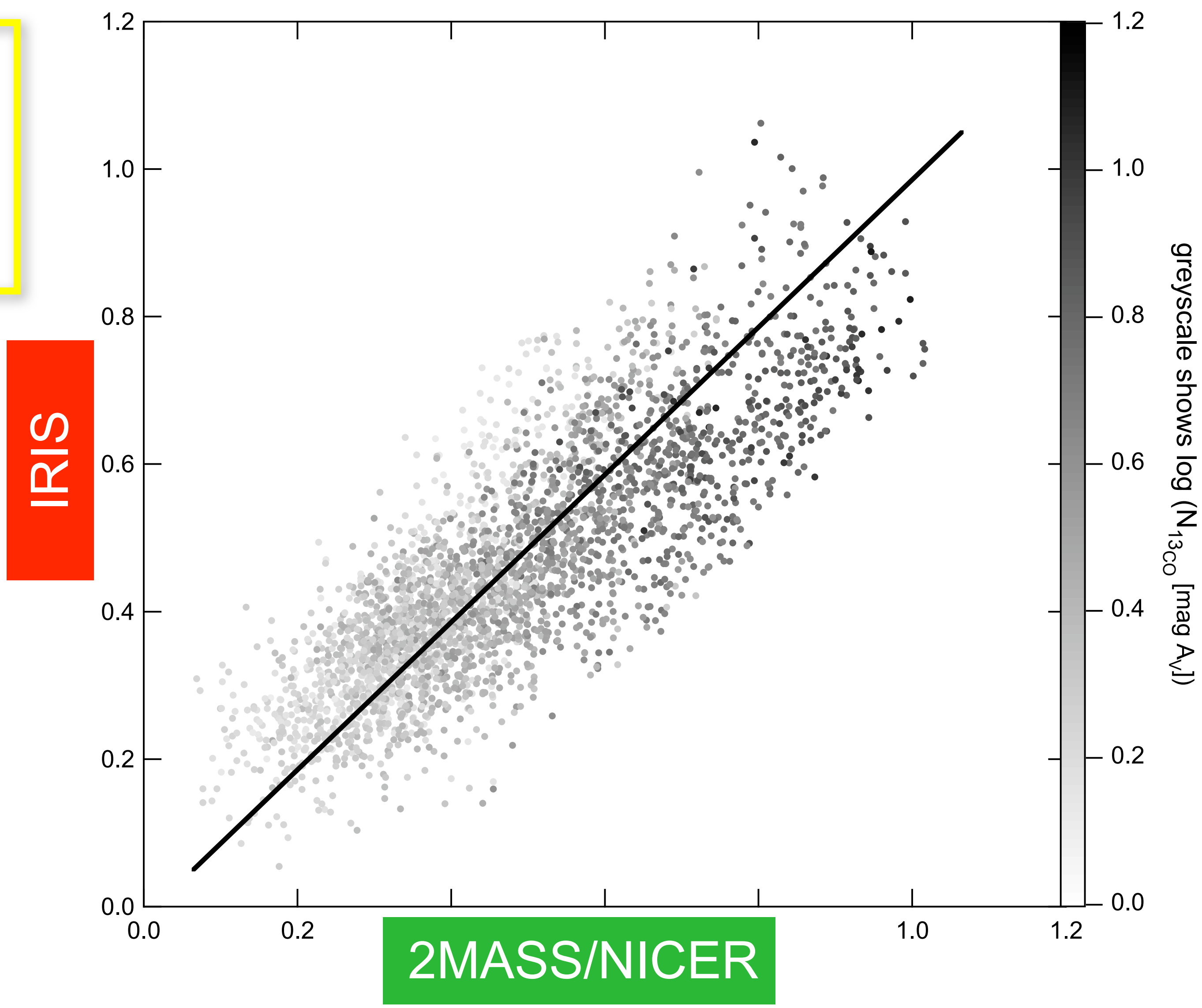
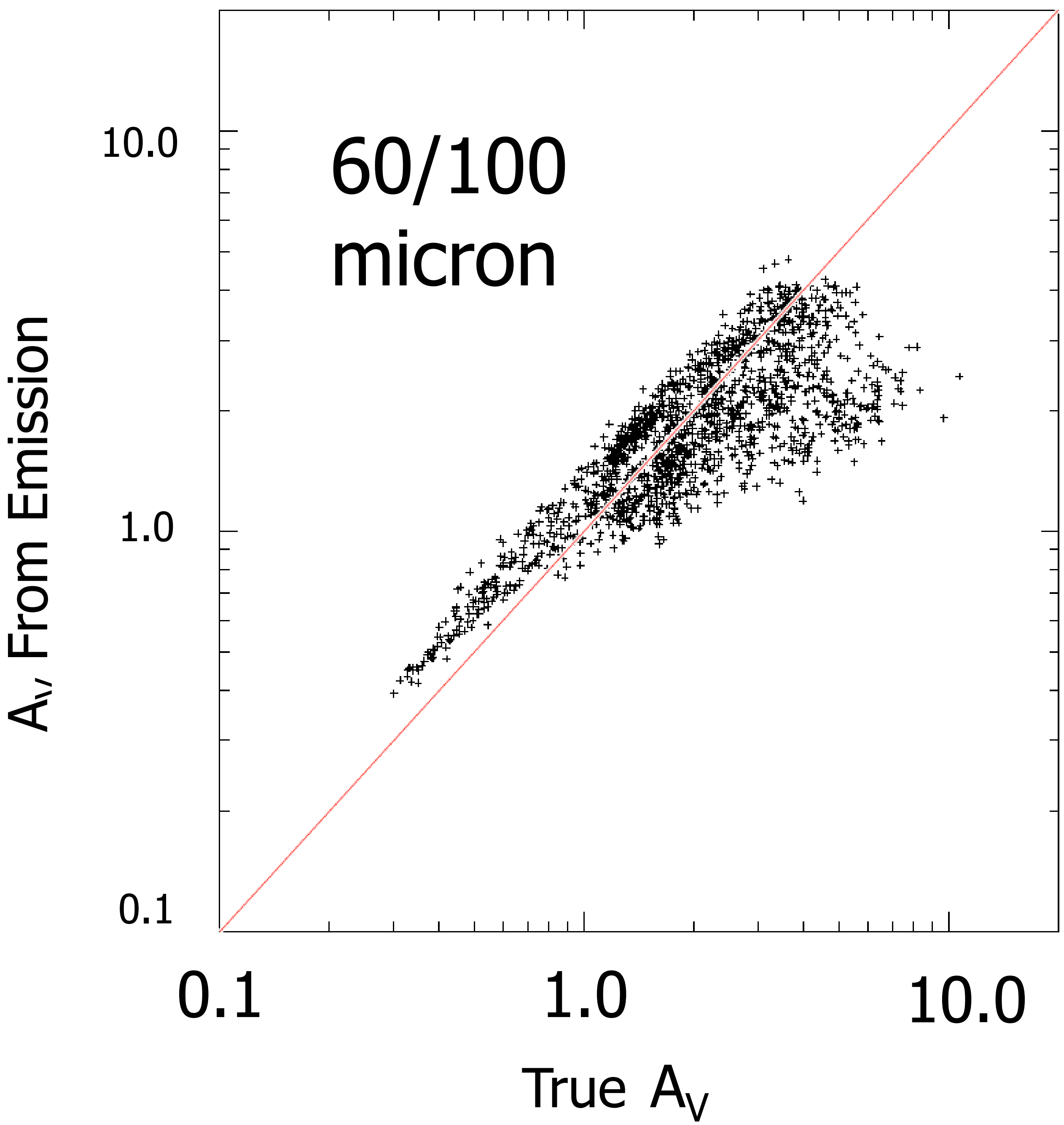
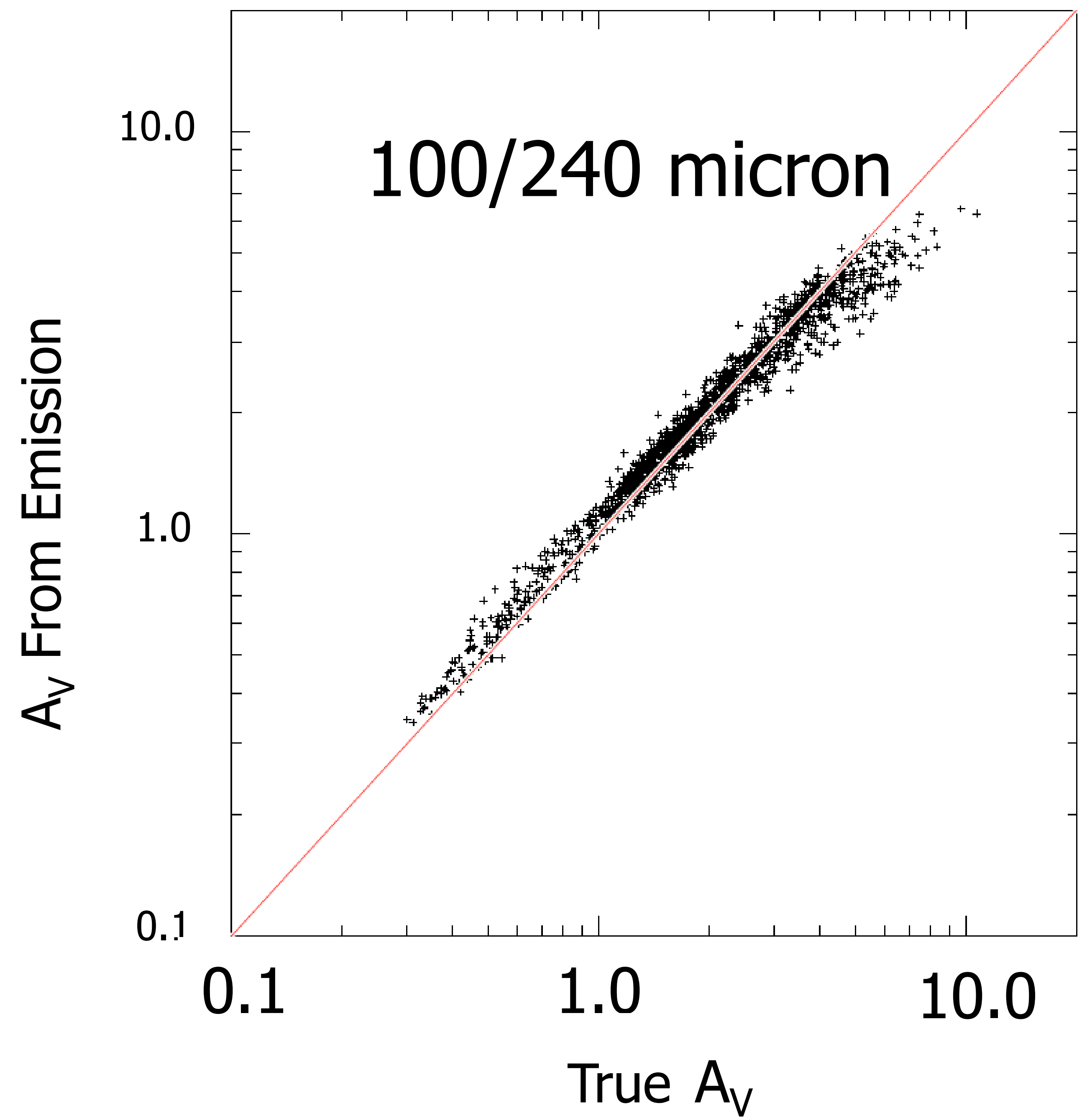


Schnee, Bethell & Goodman 2006

Modeling line-of-sight temperature fluctuations

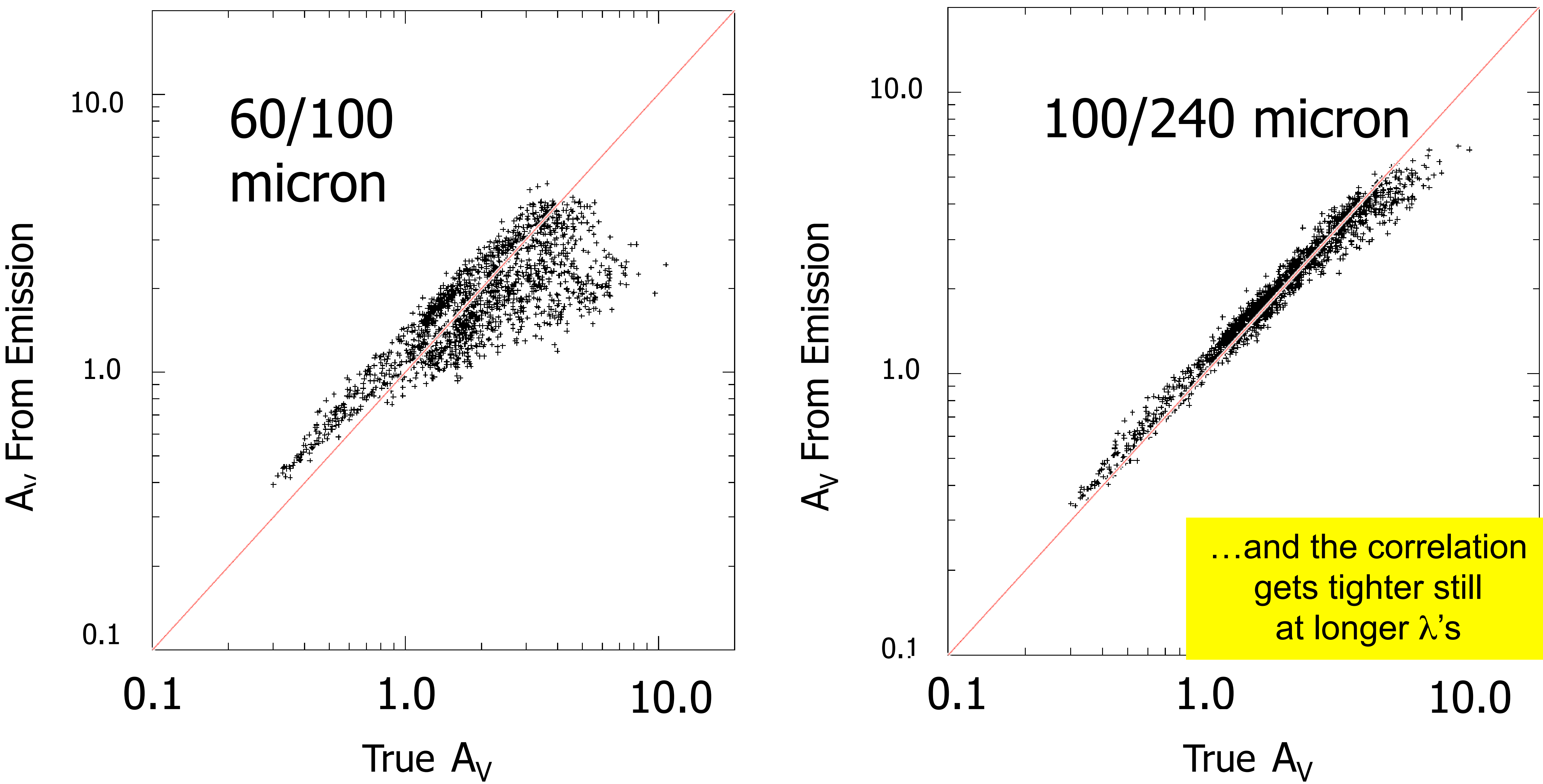
MHD Simulation+Radiative Xfer Code (No NOISE)





Schnee, Bethell & Goodman 2006

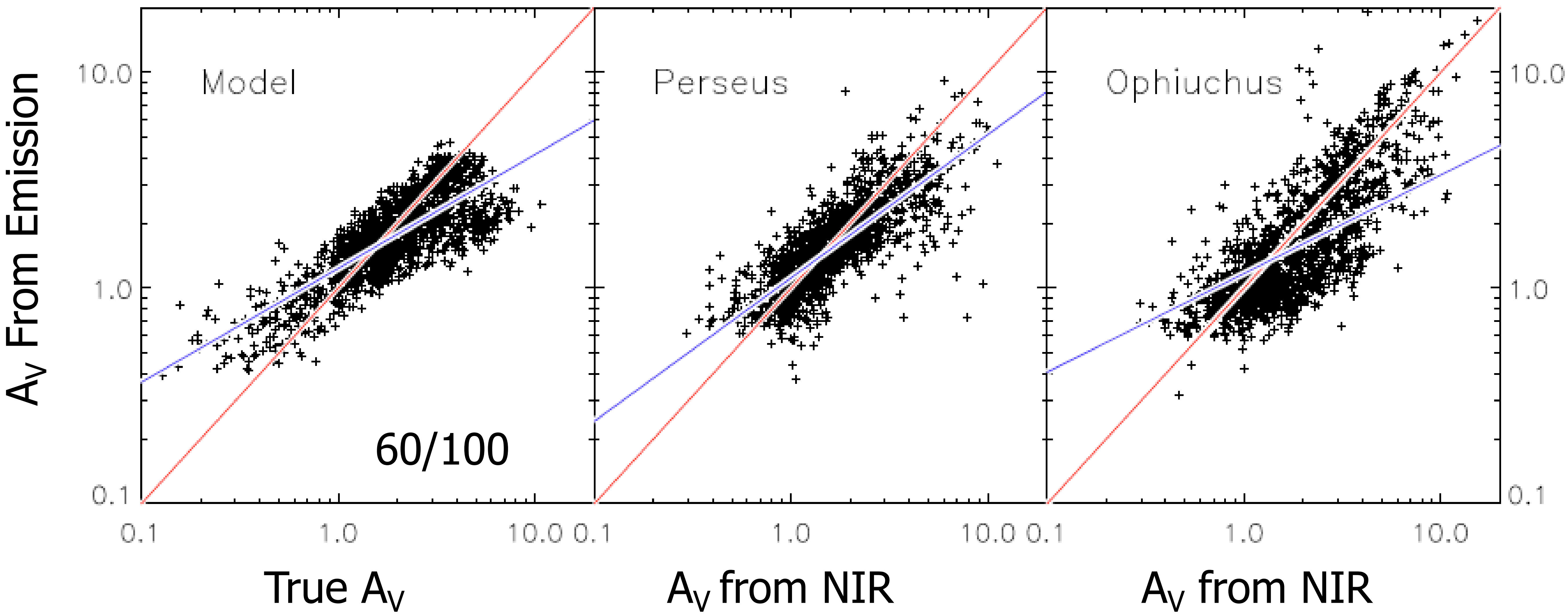
MHD Simulation+Radiative Xfer Code (No NOISE)



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

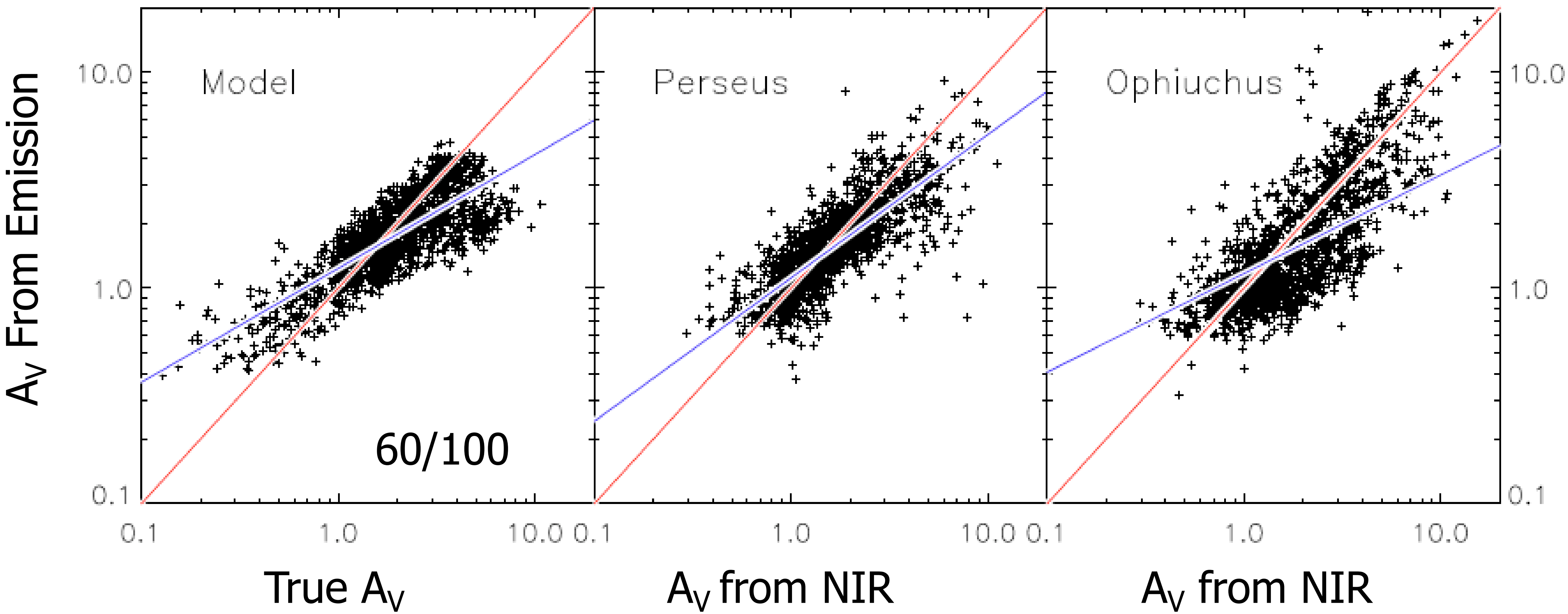
Schnee, Bethell & Goodman 2006

Tasting the Simulations



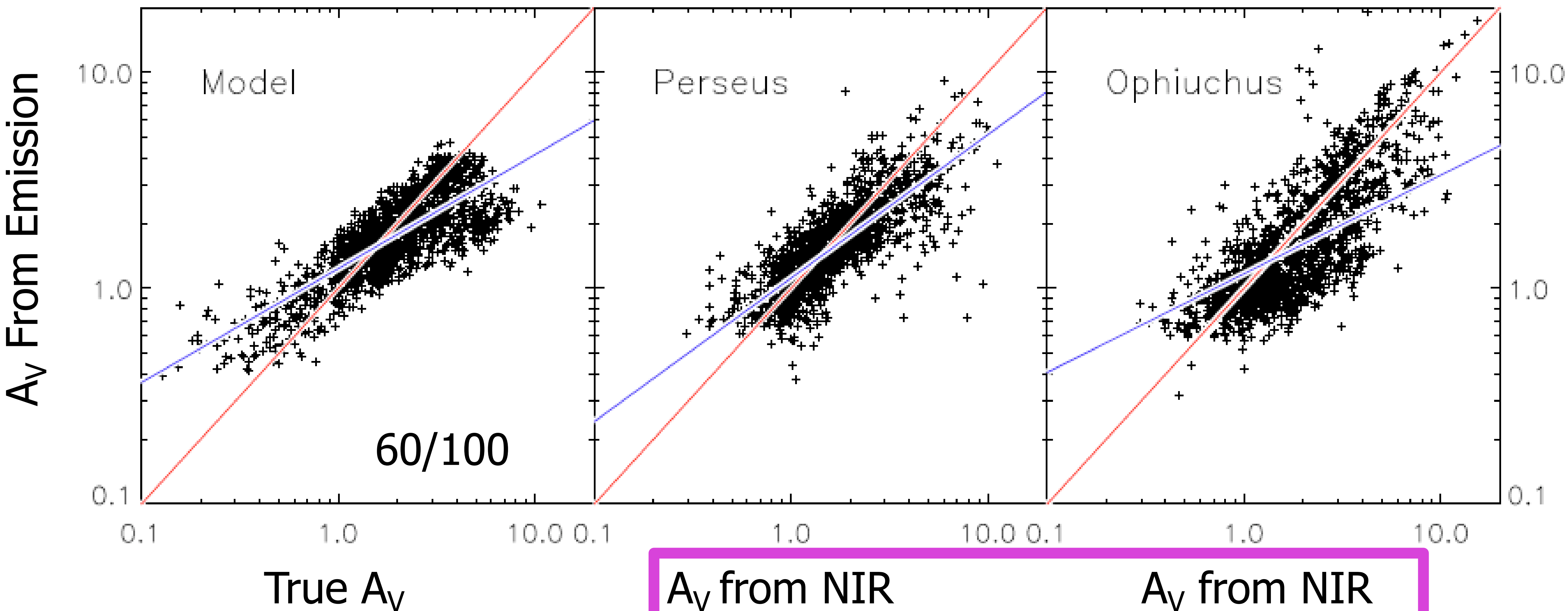
Schnee, Bethell & Goodman 2006

Tasting the Simulations



Schnee, Bethell & Goodman 2006

Tasting the Simulations

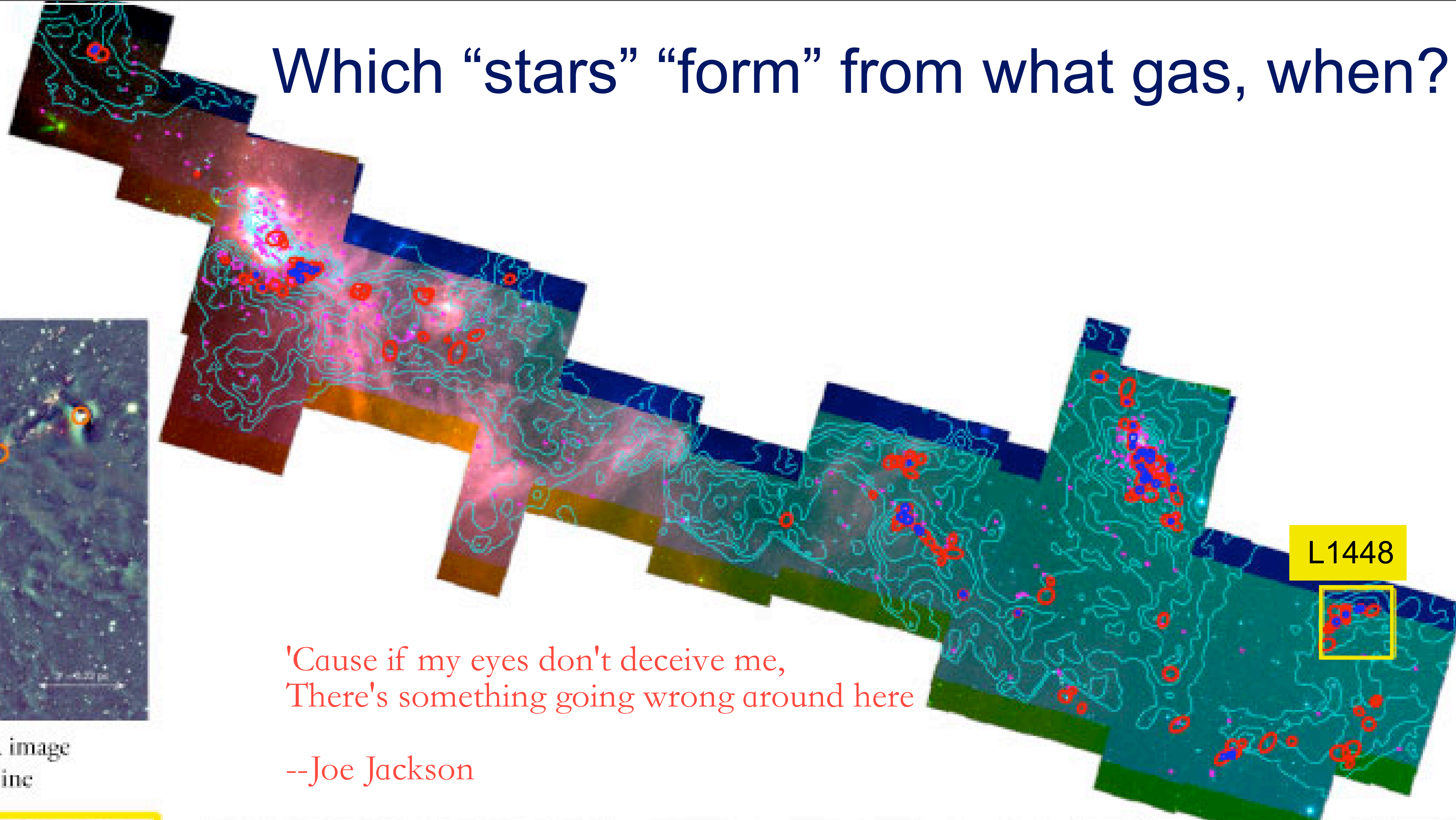


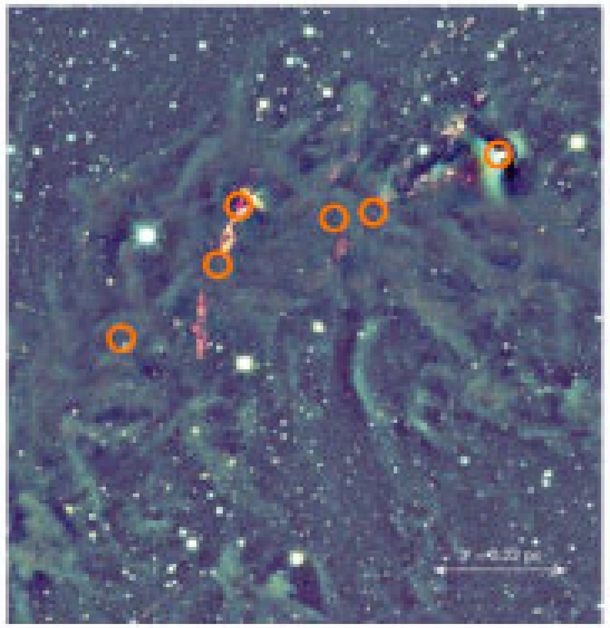
I'll show you later why that's "True Av"

Schnee, Bethell & Goodman 2006

Which "stars" "form" from what gas, when?

Figure Credit: Jonathan Foster

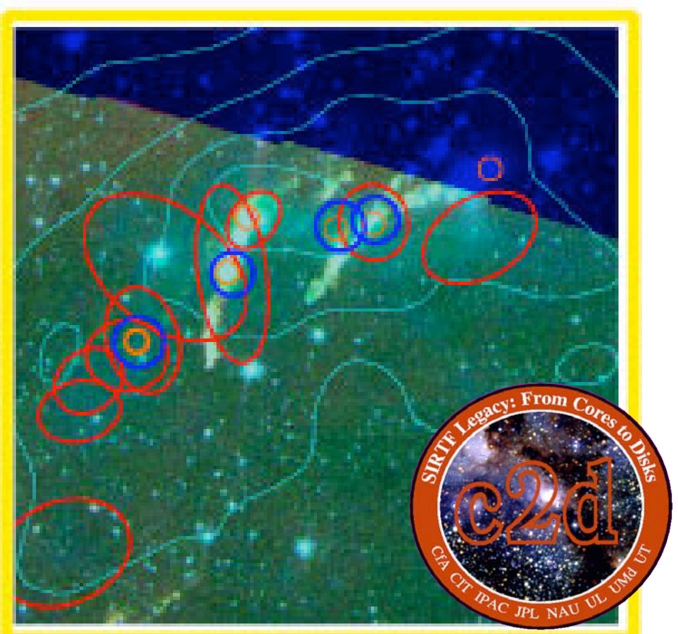




J,H,K Near-IR image
of Cloudshine

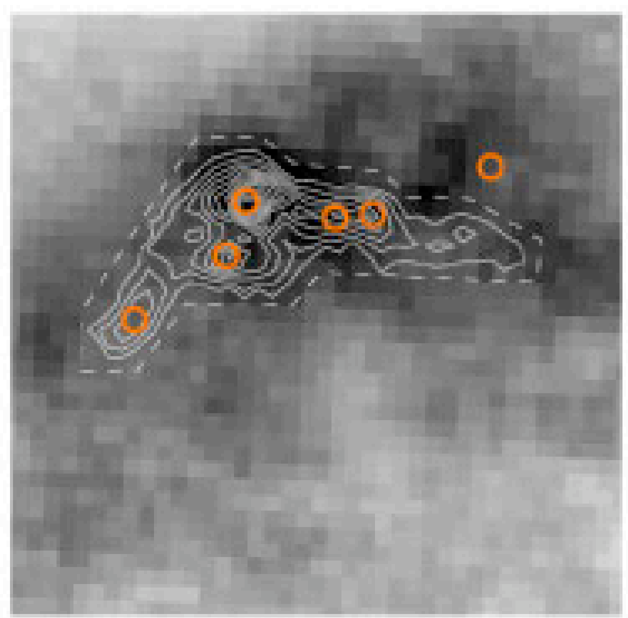
'Cause if my eyes don't deceive me,
There's something going wrong around here

--Joe Jackson



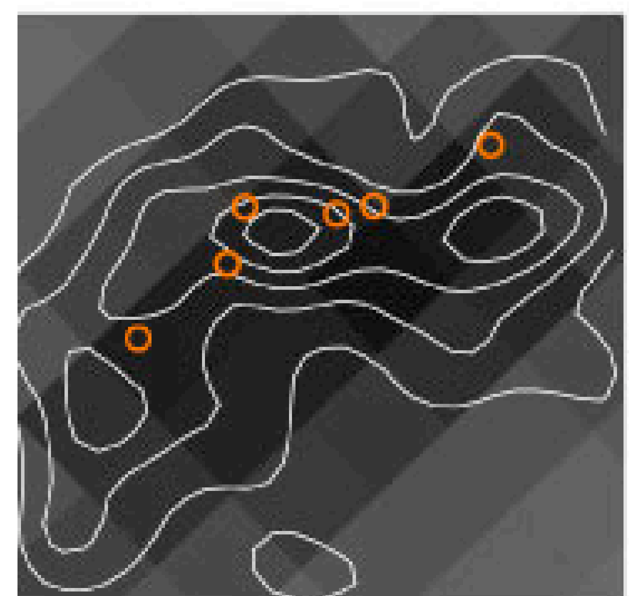
C

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

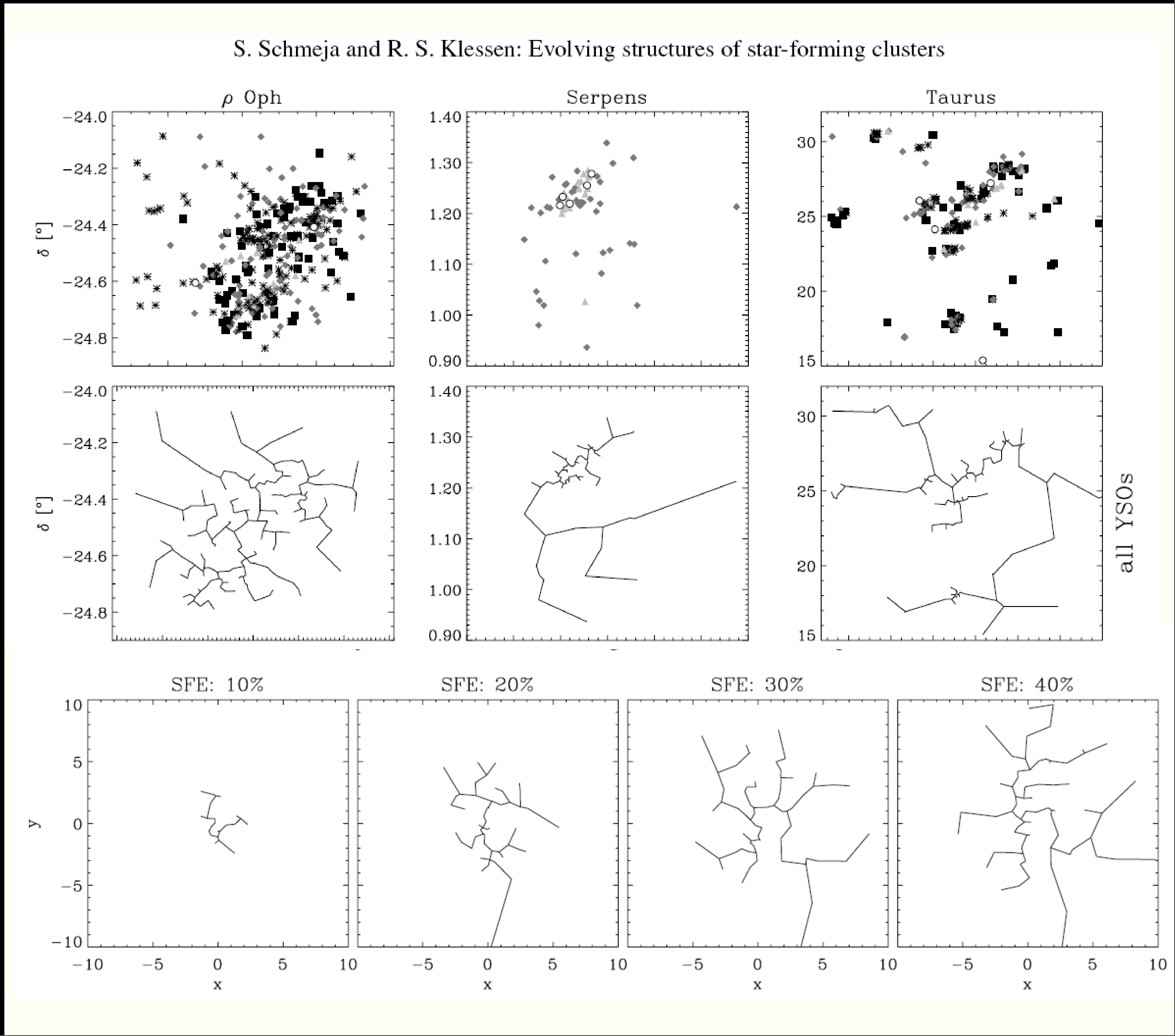
TE

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

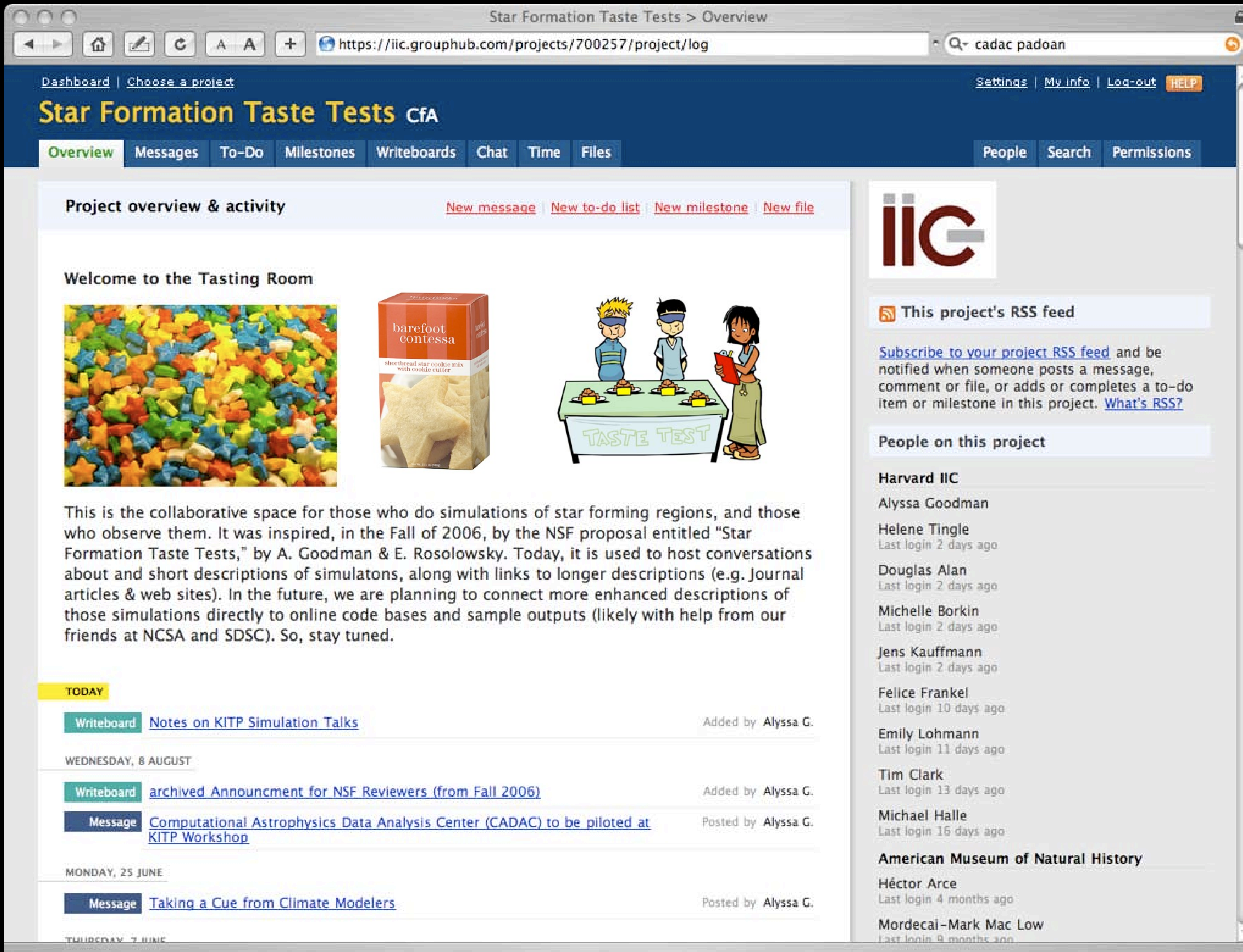
What stars form from what gas, when?

Theorists using Observers Ingredients

e.g. Schmeja & Klessen 2006



Are you hungry yet?



Let's not let food go to waste, even if it is full of artificial ingredients...

The Astrophysics Simulation Collaboratory:
A Science Portal Enabling Community Software Development

Michael Russell[†] Gabrielle Allen[*] Greg Daues[§] Ian Foster[†¶] Tom Goodale[*]
Edward Seidel[*] Jason Novotny[‡] John Shalf[‡§] Wai-Mo Suen[||]
Gregor von Laszewski[¶]

April 4, 2001

http://ascl.net/

Abstract

We describe the design and implementation of the Astrophysics Simulation Collaboratory Web Portal.

Data formats, software, middleware, and infrastructure matter.

Let's not let food go to waste, even if it is full of artificial ingredients...

Computational Astrophysics Data Analysis Center

http://cadac.sdsc.edu/ cadac padoan

CADAC

help

home | about | members | documentation

The Computational Astrophysics Data Analysis Center

The Computational Astrophysics Data Analysis Center (CADAC) collects and stores results of large astrophysical simulations and provides data analysis resources to researchers worldwide. Because only a fraction of computational resources is typically available for data-analysis, early publication and sharing of large computational datasets are not commonplace in astrophysics.

The CADAC is a worldwide service that provides powerful data-storage and data-analysis resources to the astrophysical community, encouraging the early publication of complete numerical datasets. The CADAC will foster a new system and culture whereby data-analysis tools and computational data are shared. Its use will encourage scientific collaboration, increase the impact of numerical experiments, and facilitate the review process of journal papers based on computational simulations.

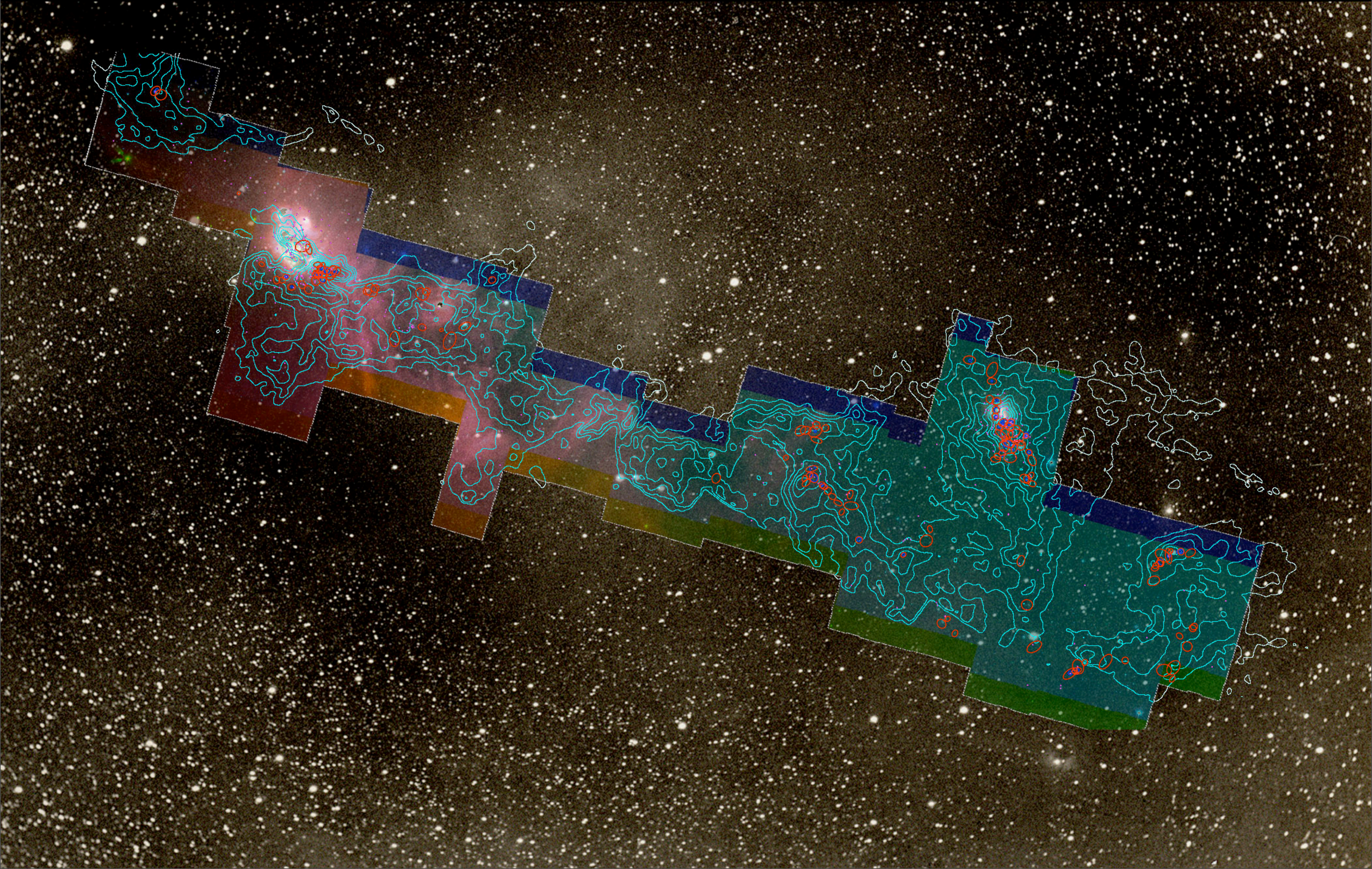
More Information

- Read more about the CADAC.
- Find out who is a member.
- Get some help joining.
- Visit the wiki pages for the KITP workshop Star Formation Through Cosmic Time.
- Read the CADAC announcement.

SDSC SAN DIEGO SUPERCOMPUTER CENTER UCSD lca Laboratory for Computational Astrophysics

Official web page of the University of California, San Diego.

Who can make this?



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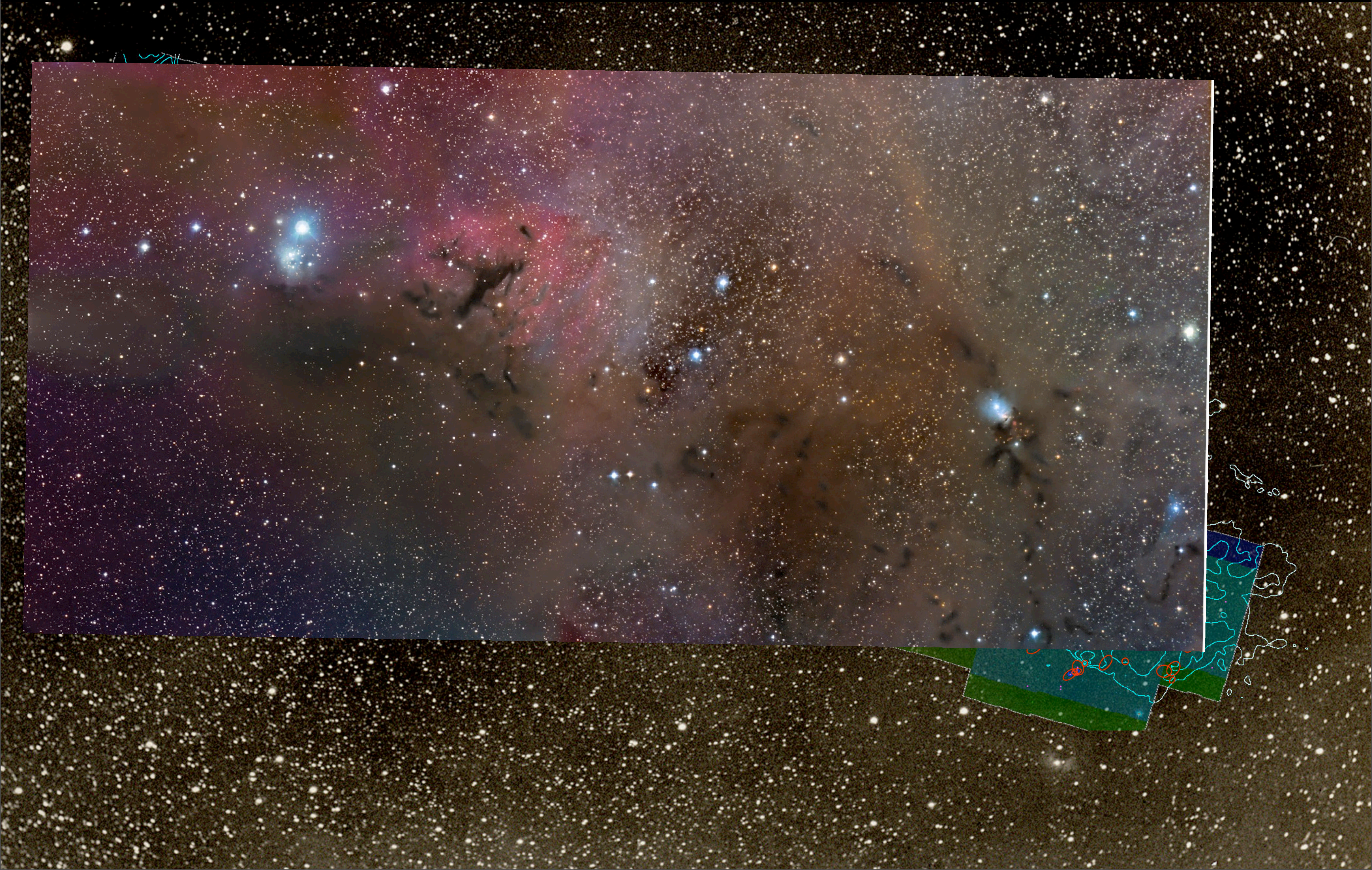

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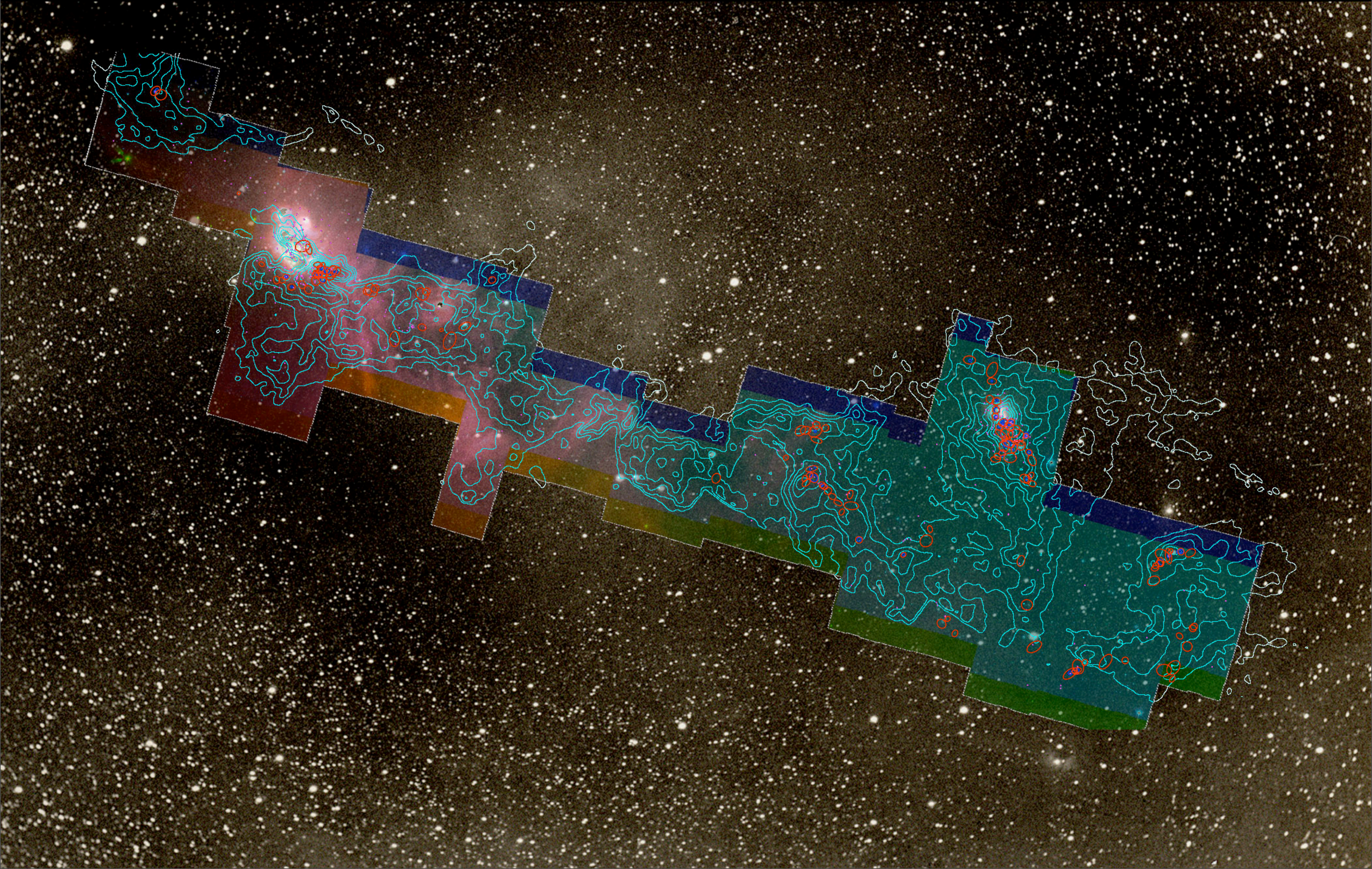

Who can make this?