Beauty is in the Eye of the Beholder

"Tasting" Models of Star Formation

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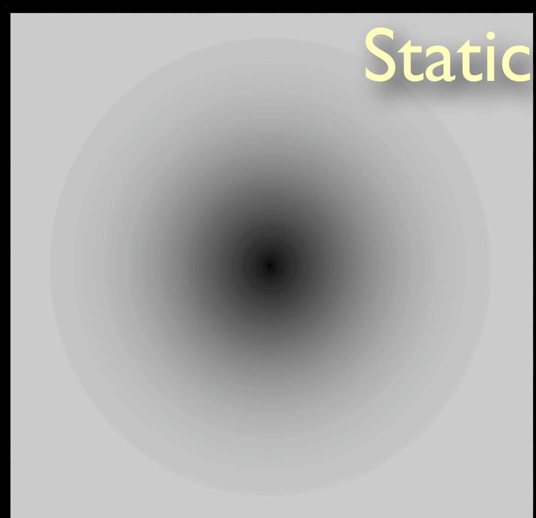
Featuring the work of collaborators:

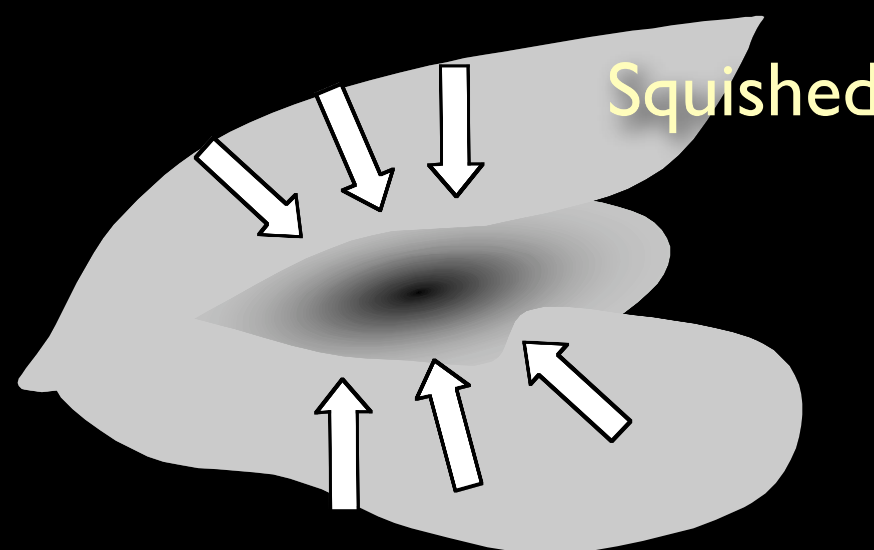
Héctor **Arce**, Michelle **Borkin**, Paola **Caselli**, Jonathan **Foster**, Mike **Halle**, Mark **Heyer**, Jens **Kauffmann**, Jaime **Pineda**, Erik **Rosolowsky**, Scott **Schnee**, Rahul **Shetty**

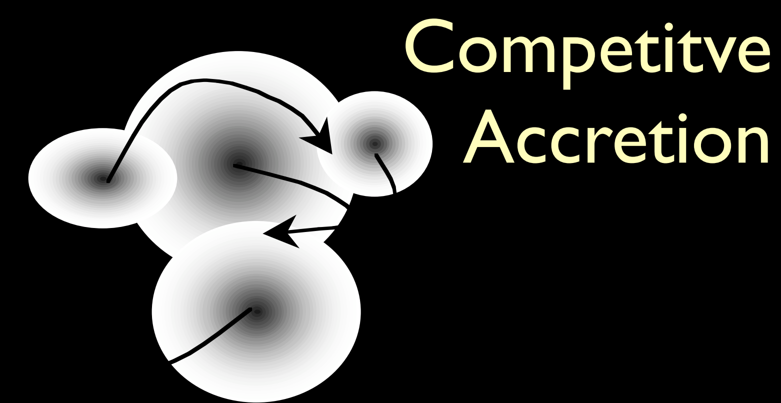
Image Credit: Jonathan Foster, CfA/COMPLETE Deep Megacam Image of West End of Perseus

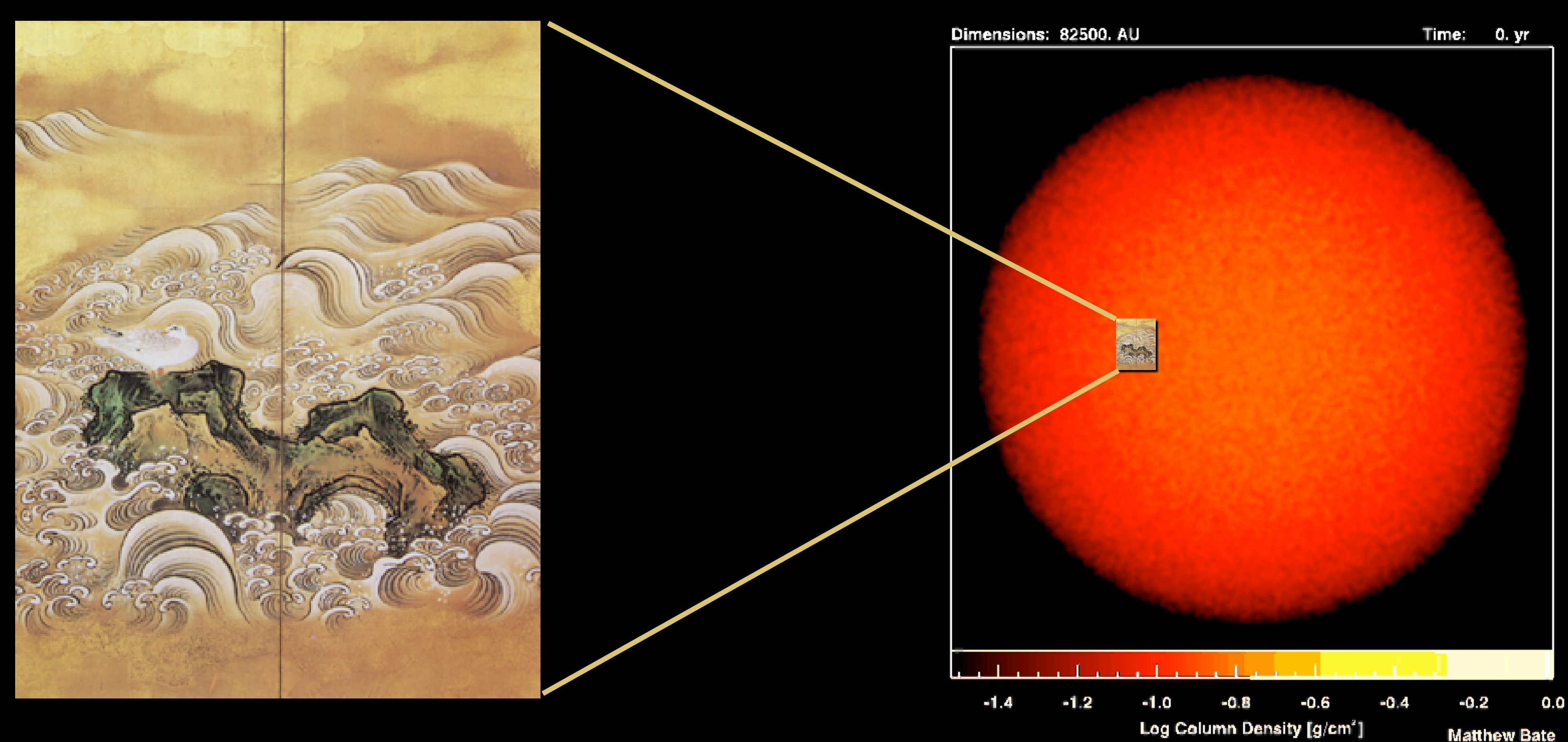
How long does it take to form a star?

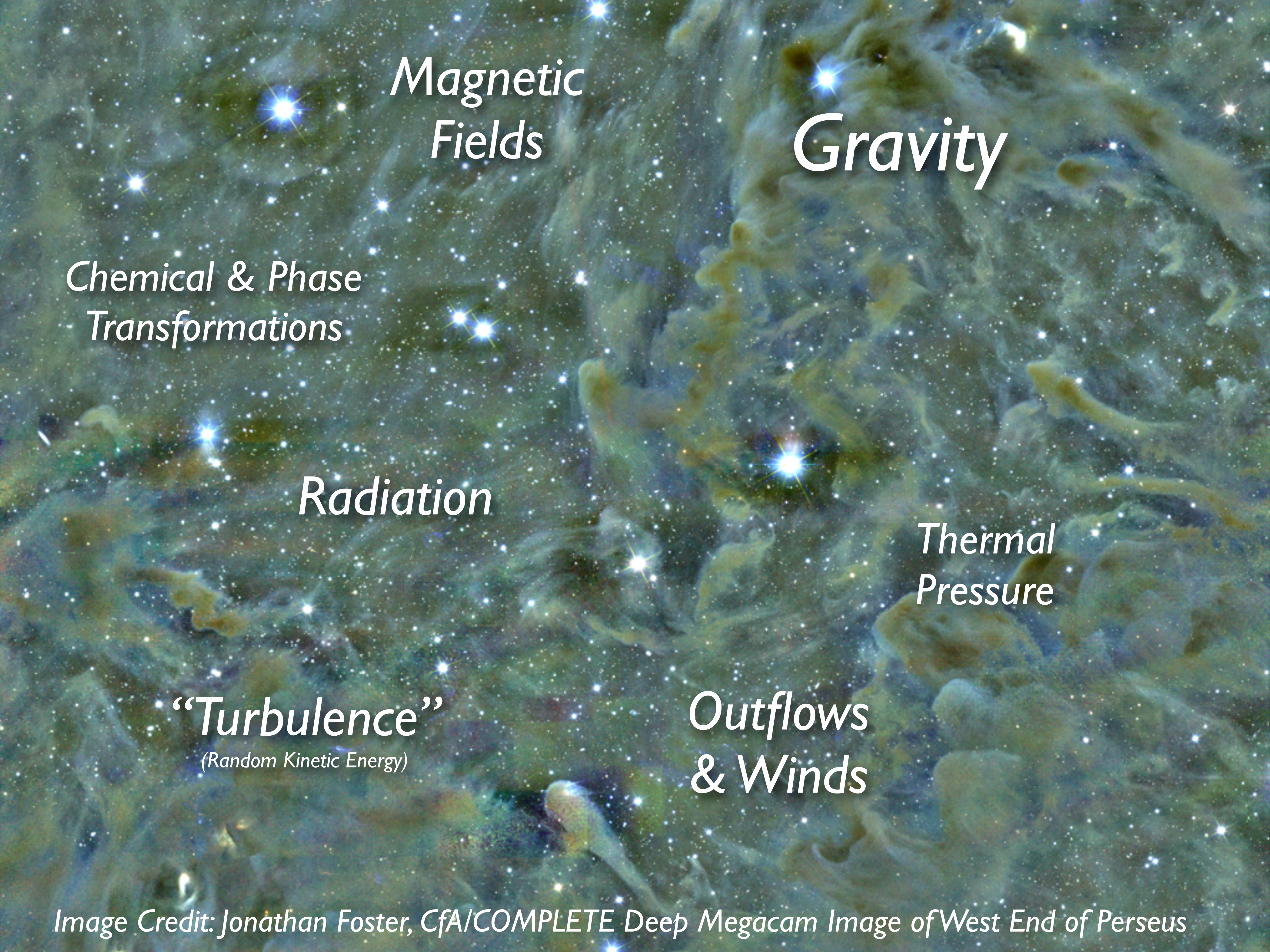
Depends on mass flux onto a forming star/core system, and where it comes from...



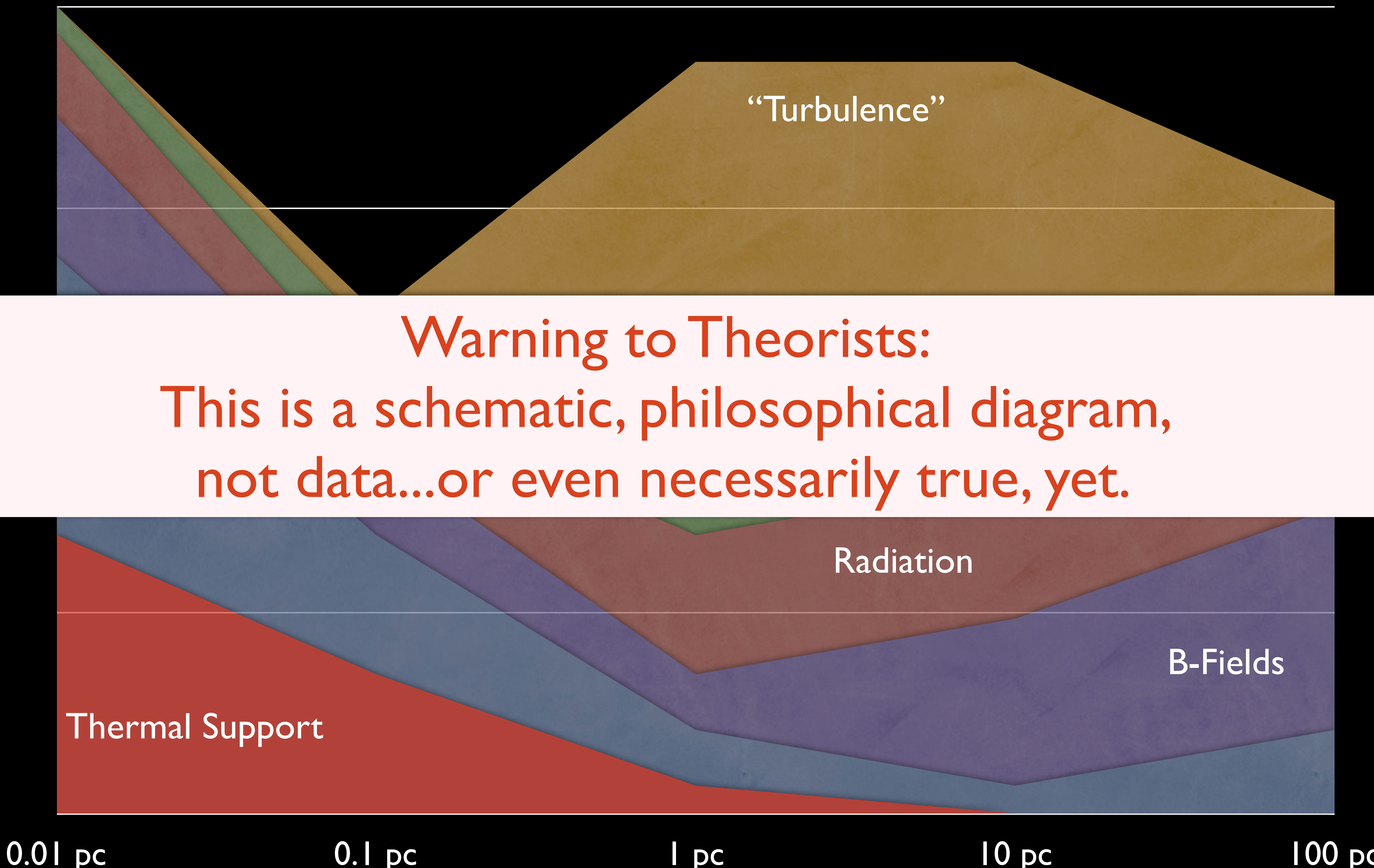






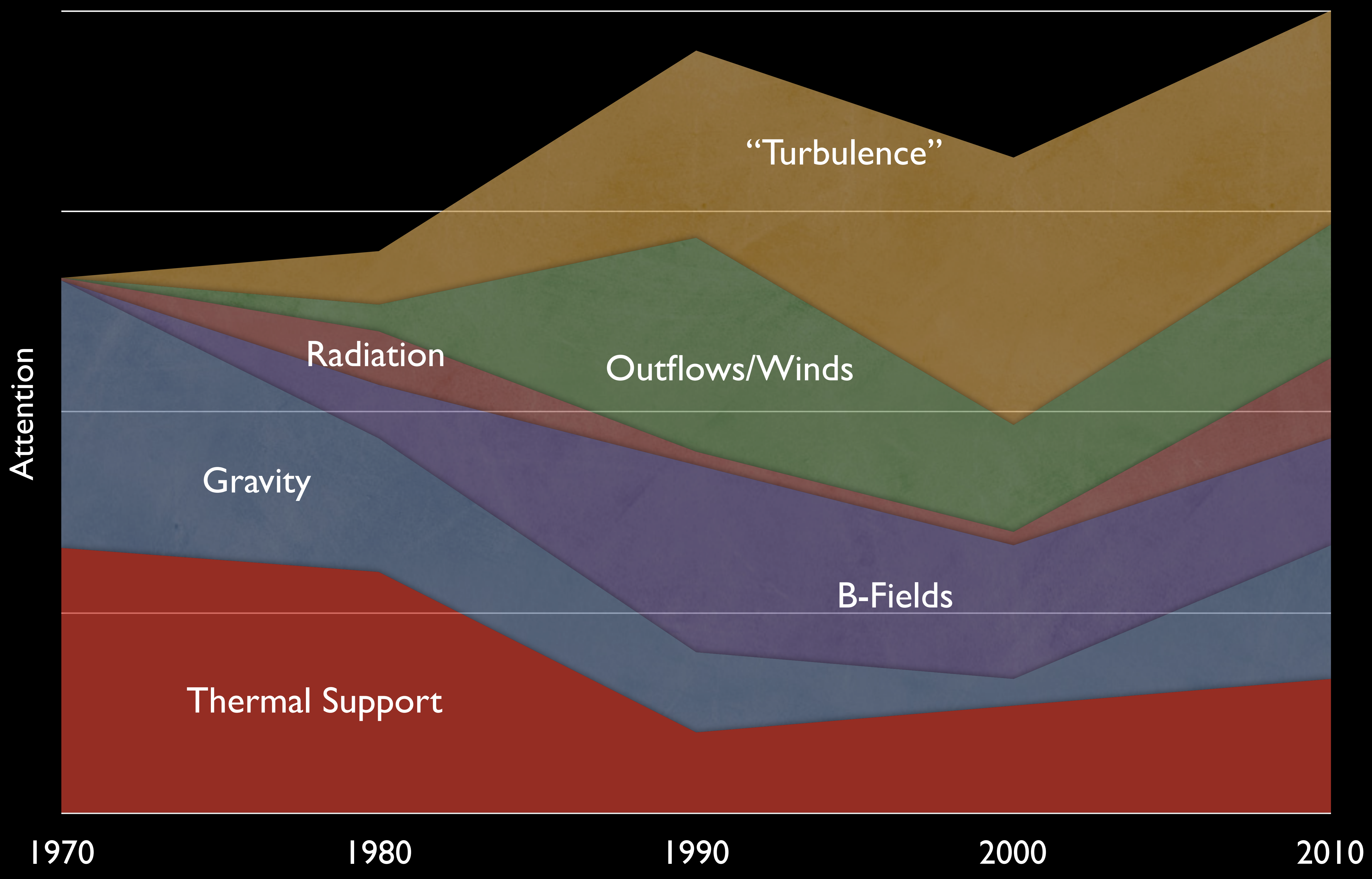

Magnetic Fields
Gravity
Chemical & Phase Transformations
Radiation
Thermal Pressure
"Turbulence"
(Random Kinetic Energy)
Outflows & Winds
Image Credit: Jonathan Foster, CfA/COMPLETE Deep Megacam Image of West End of Perseus

What forces matter most on what scales?

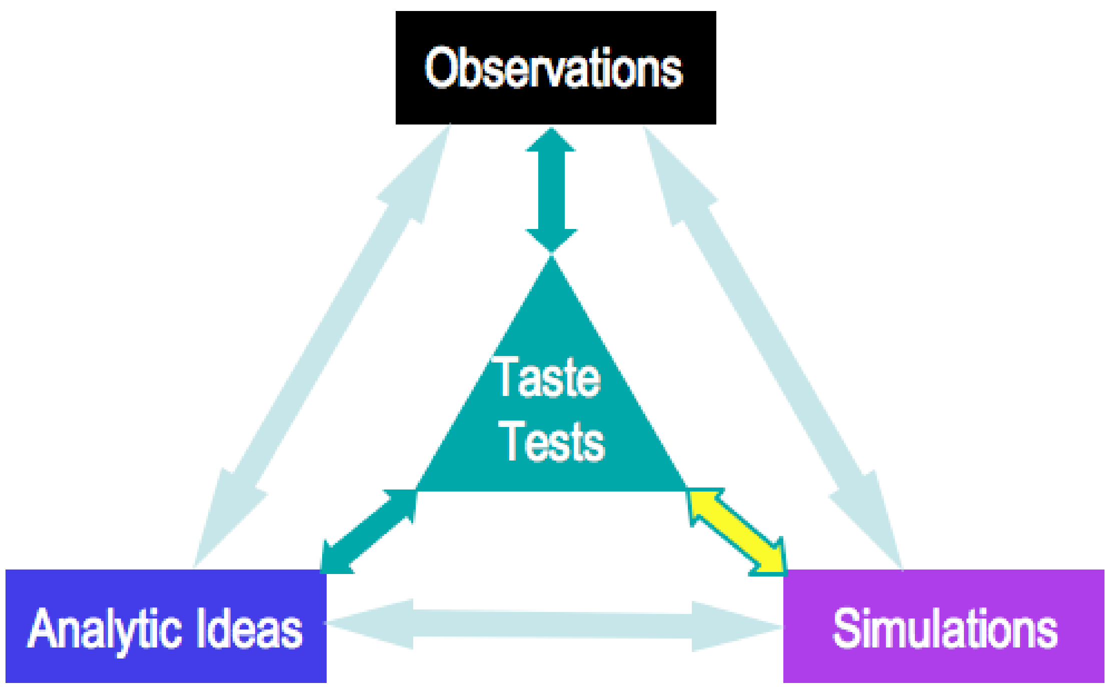


Warning to Theorists:
This is a schematic, philosophical diagram, not data...or even necessarily true, yet.

Changes of Heart, rather than in Physics...



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; Rahul Shetty is now "Taste-Testing" postdoc at Harvard

A Dark Secret of Observer's Kitchens: WYSI(N)WYG

What you see is NOT what you get

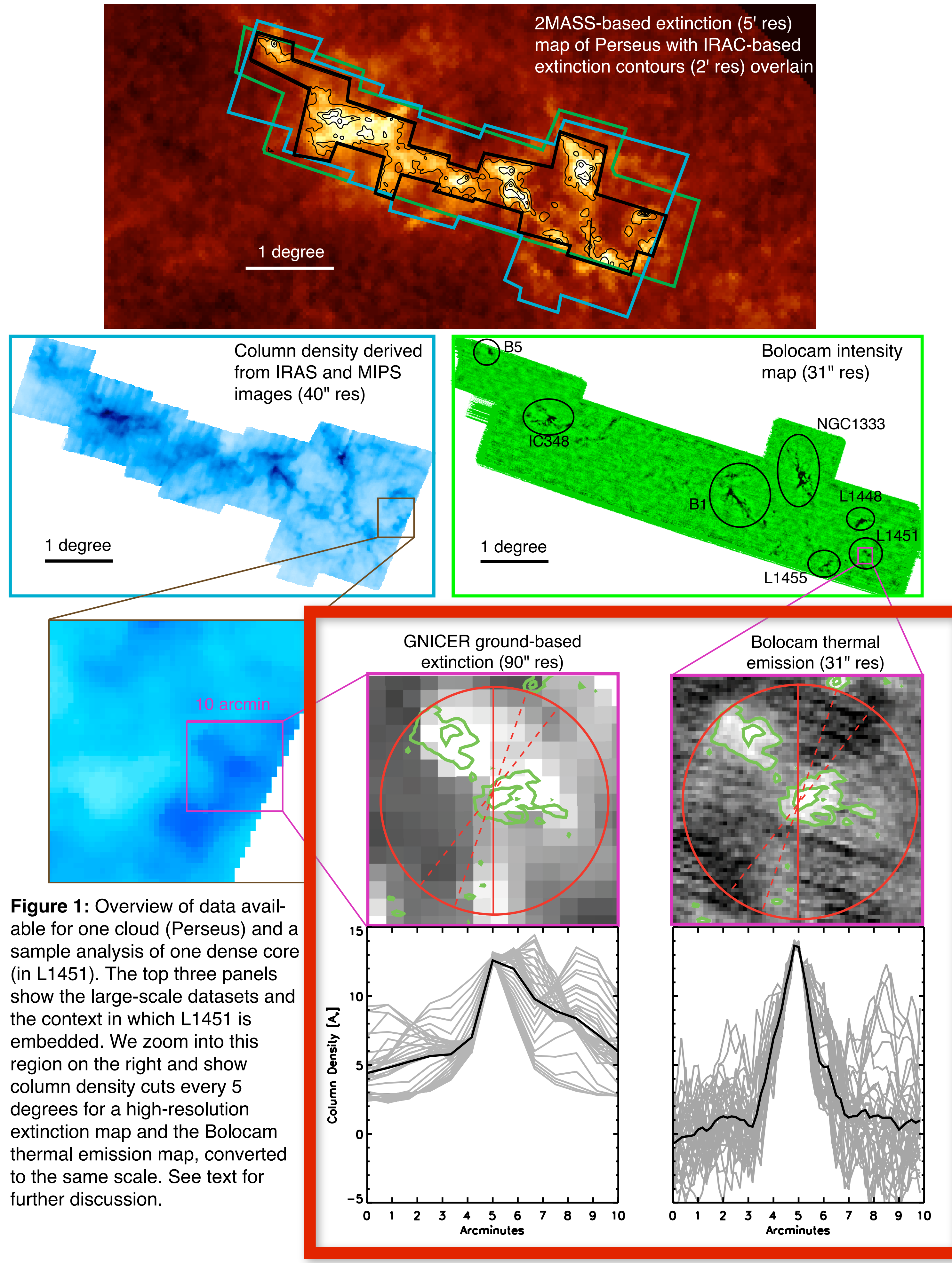
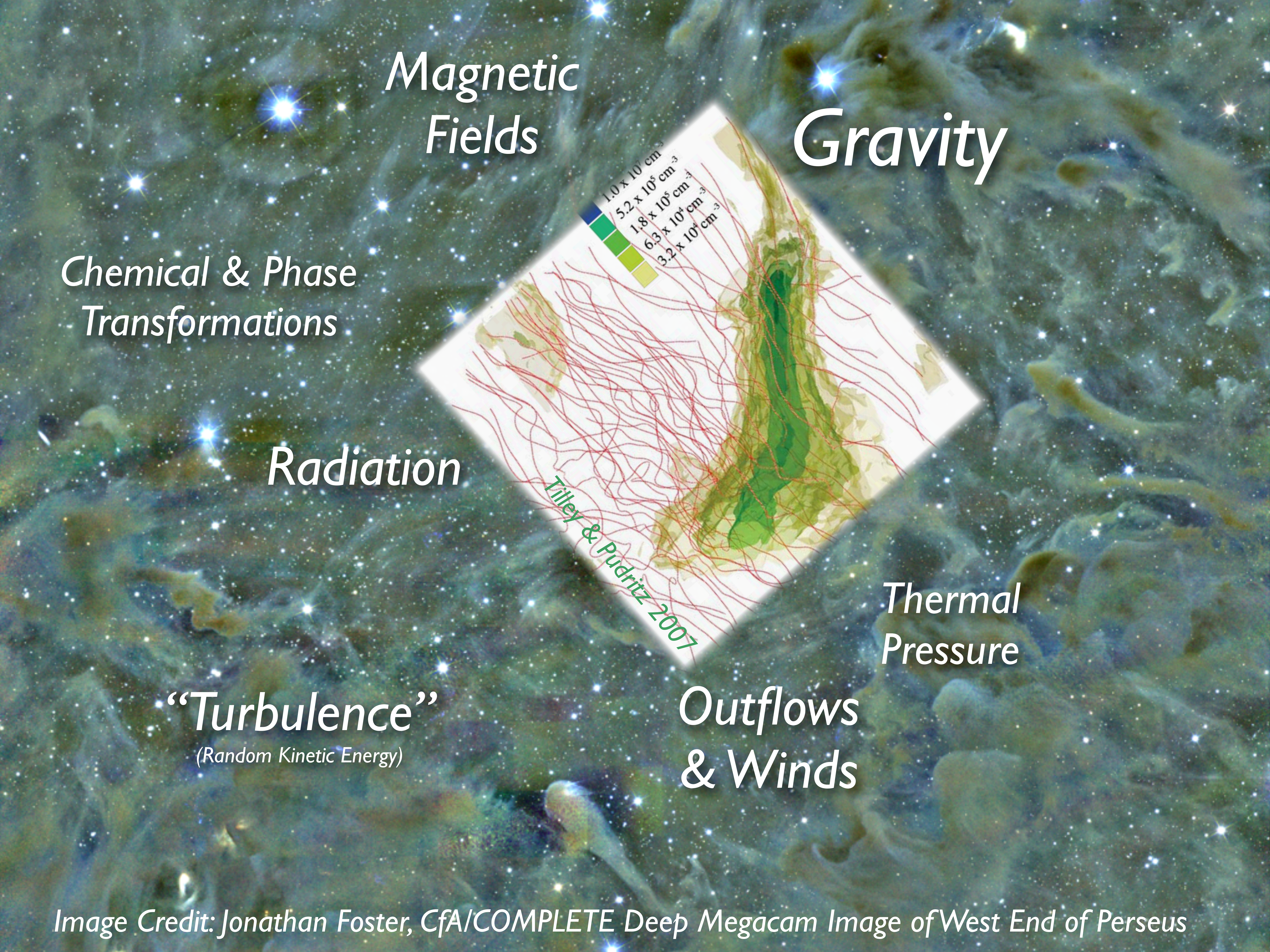
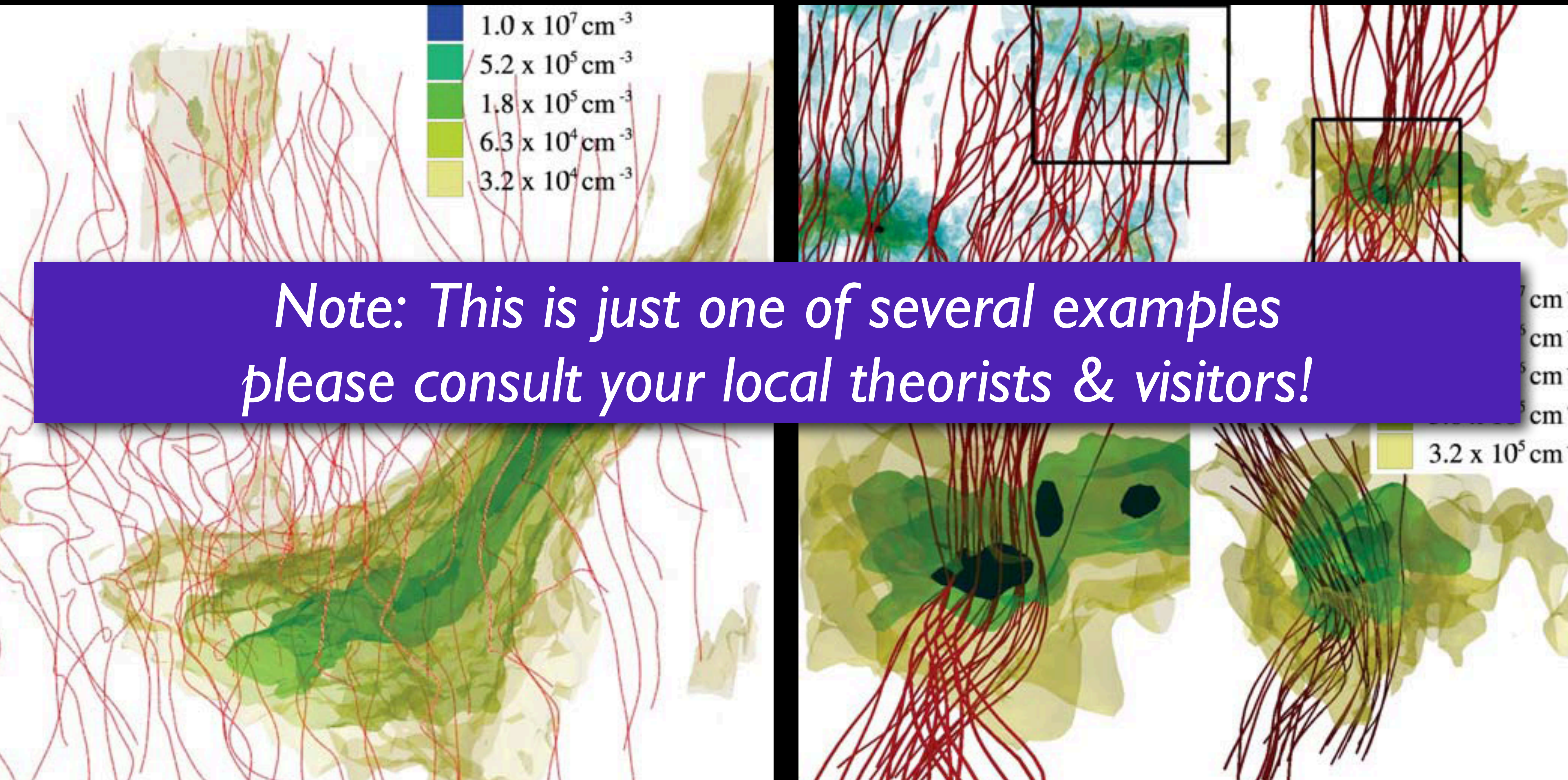


Figure 1: Overview of data available for one cloud (Perseus) and a sample analysis of one dense core (in L1451). The top three panels show the large-scale datasets and the context in which L1451 is embedded. We zoom into this region on the right and show column density cuts every 5 degrees for a high-resolution extinction map and the Bolocam thermal emission map, converted to the same scale. See text for further discussion.


Magnetic Fields
Gravity
5.2 x 10^5 cm^-3
1.8 x 10^5 cm^-3
6.3 x 10^4 cm^-3
3.2 x 10^4 cm^-3
Chemical & Phase Transformations
Radiation
Tilley & Pudritz 2007
Thermal Pressure
"Turbulence"
(Random Kinetic Energy)
Outflows & Winds
Image Credit: Jonathan Foster, CfA/COMPLETE Deep Megacam Image of West End of Perseus

Theorists' Kitchens now cooking *many* Simulations sophisticated enough to "taste"...

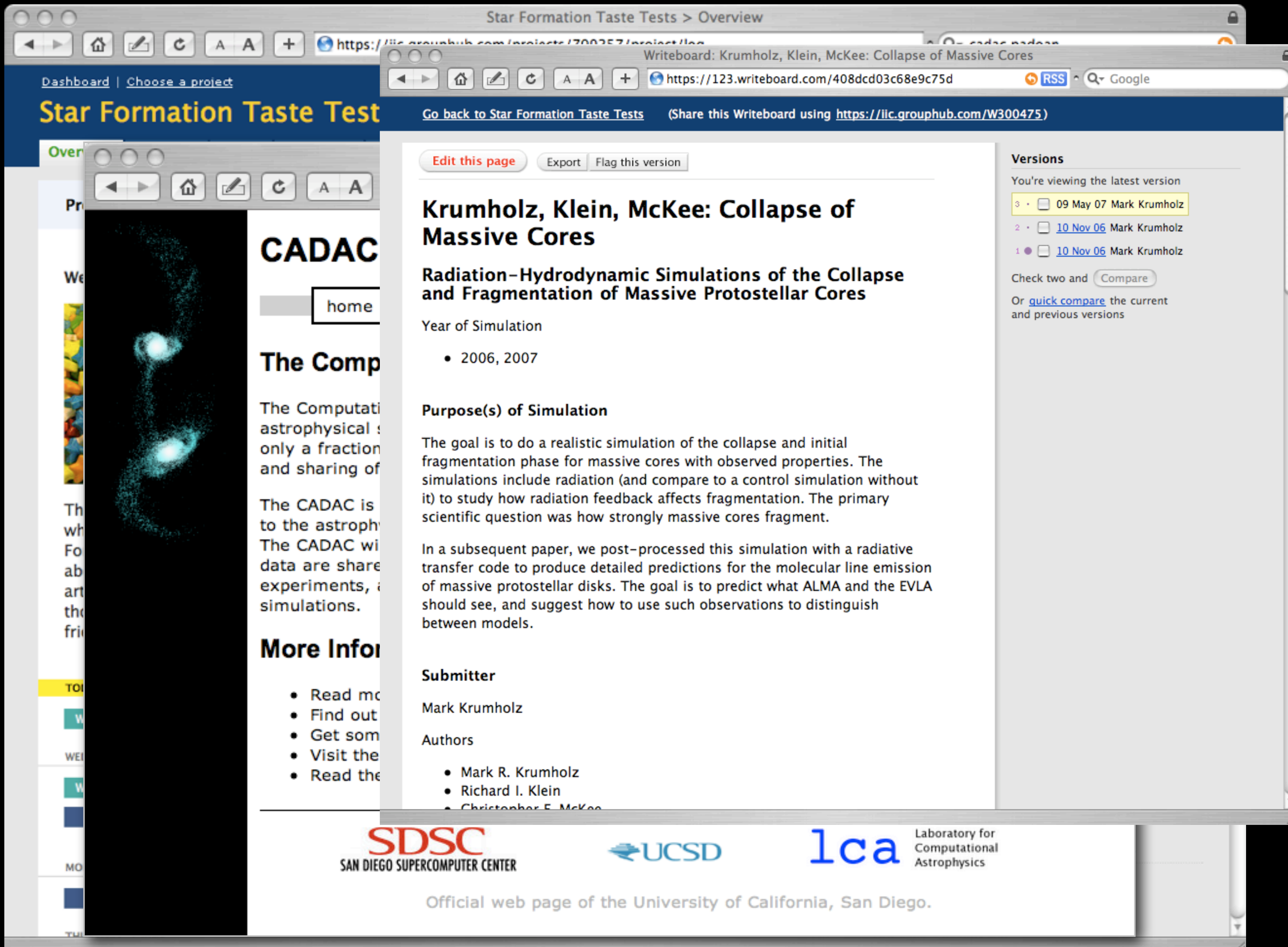


Note: This is just one of several examples please consult your local theorists & visitors!

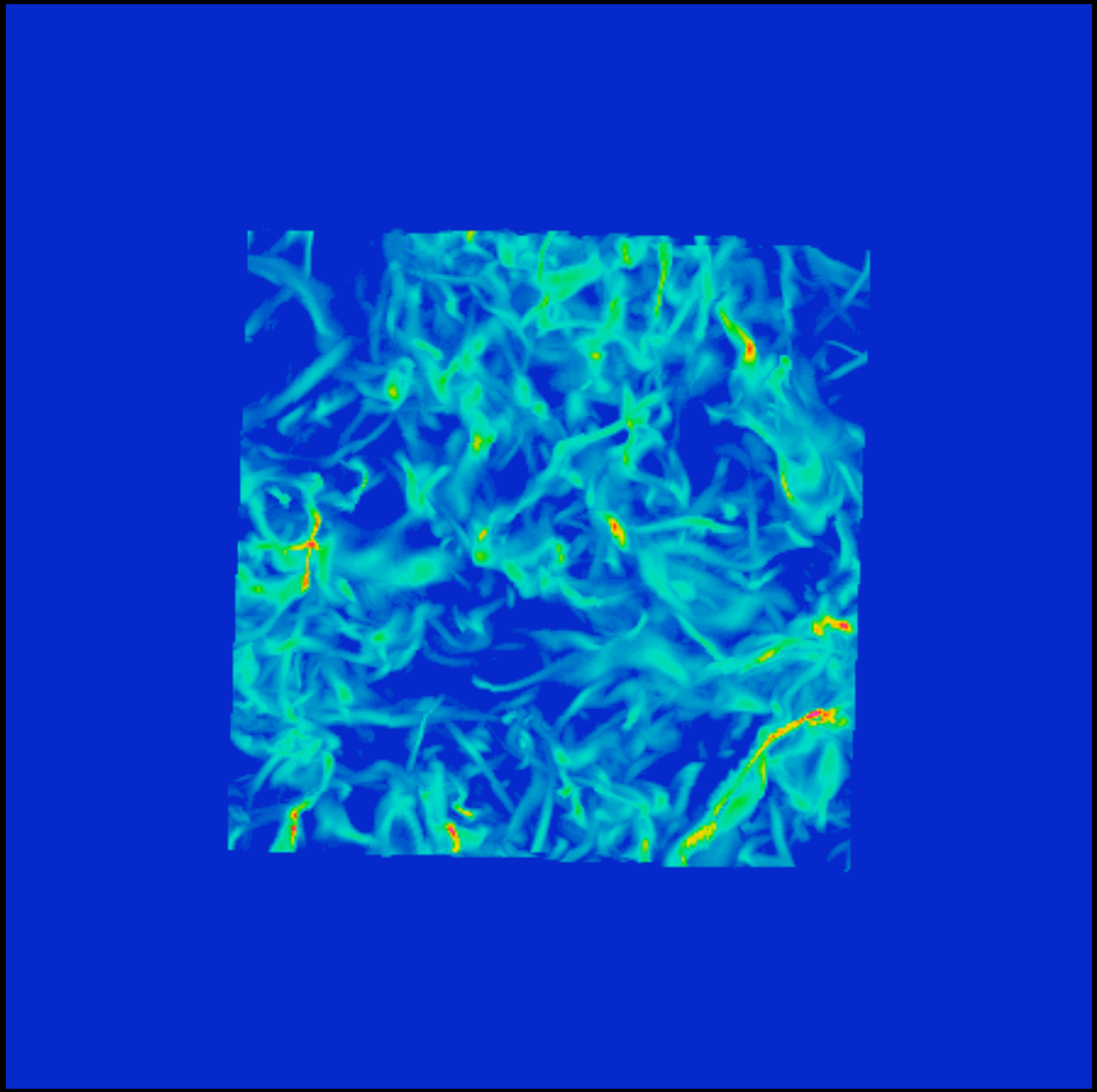
Tilley & Pudritz 2007;

see Padoan, P., Goodman, A., Draine, B., Juvela, M., Nordlund, A. and Rognvaldsson, O.E. 2001 for polarimetry "tastes"

Star Formation Taste Tests



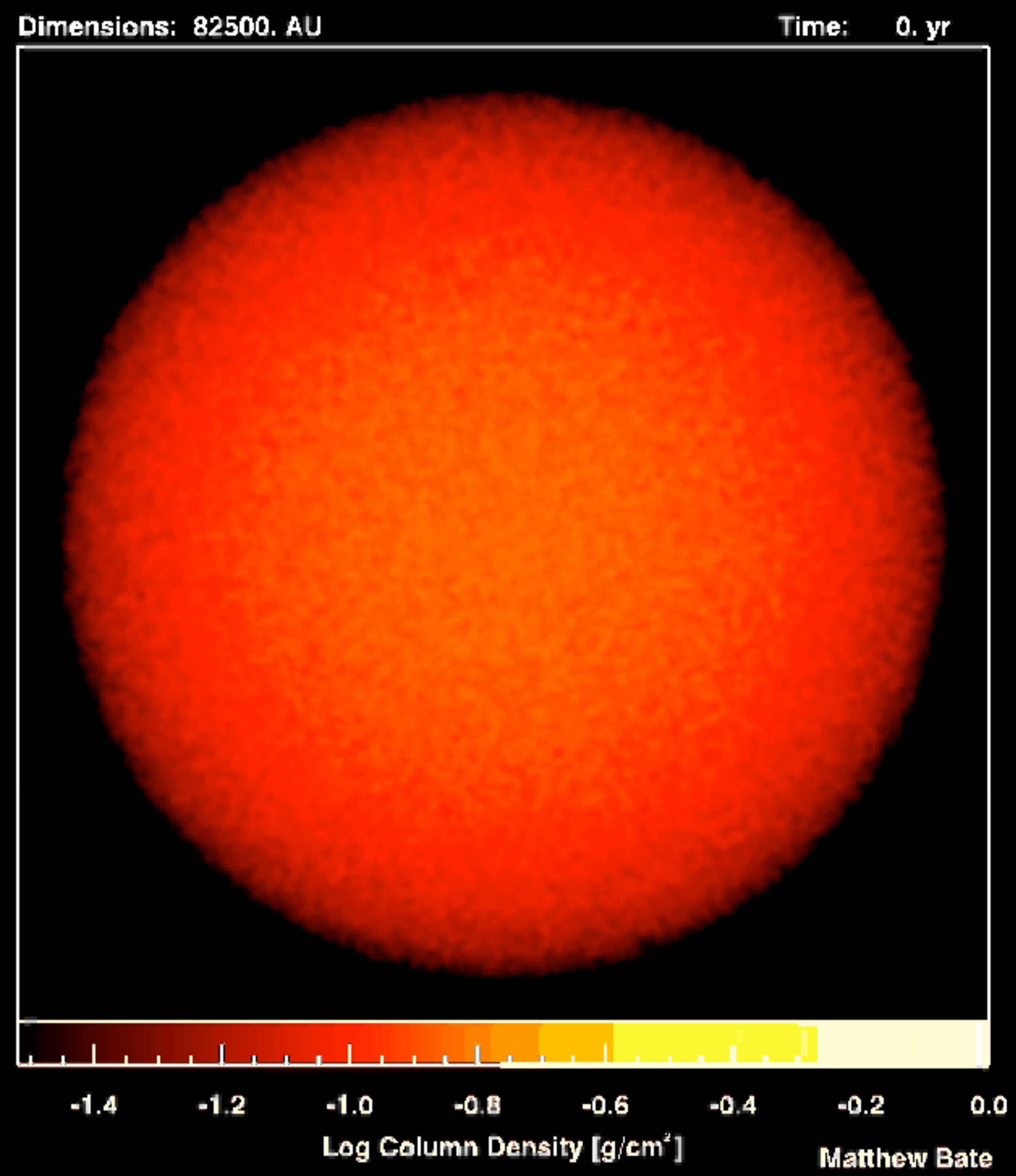
What theorists are used to...



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

Courtesy Eve Ostriker, Jim Stone & Charles Gammie

What theorists are used to...



Competitive Accretion Model for Star Formation

Bate, Bonnell & Bromm, 2002

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

What can we (observers) offer for tasting?

Today, mostly:

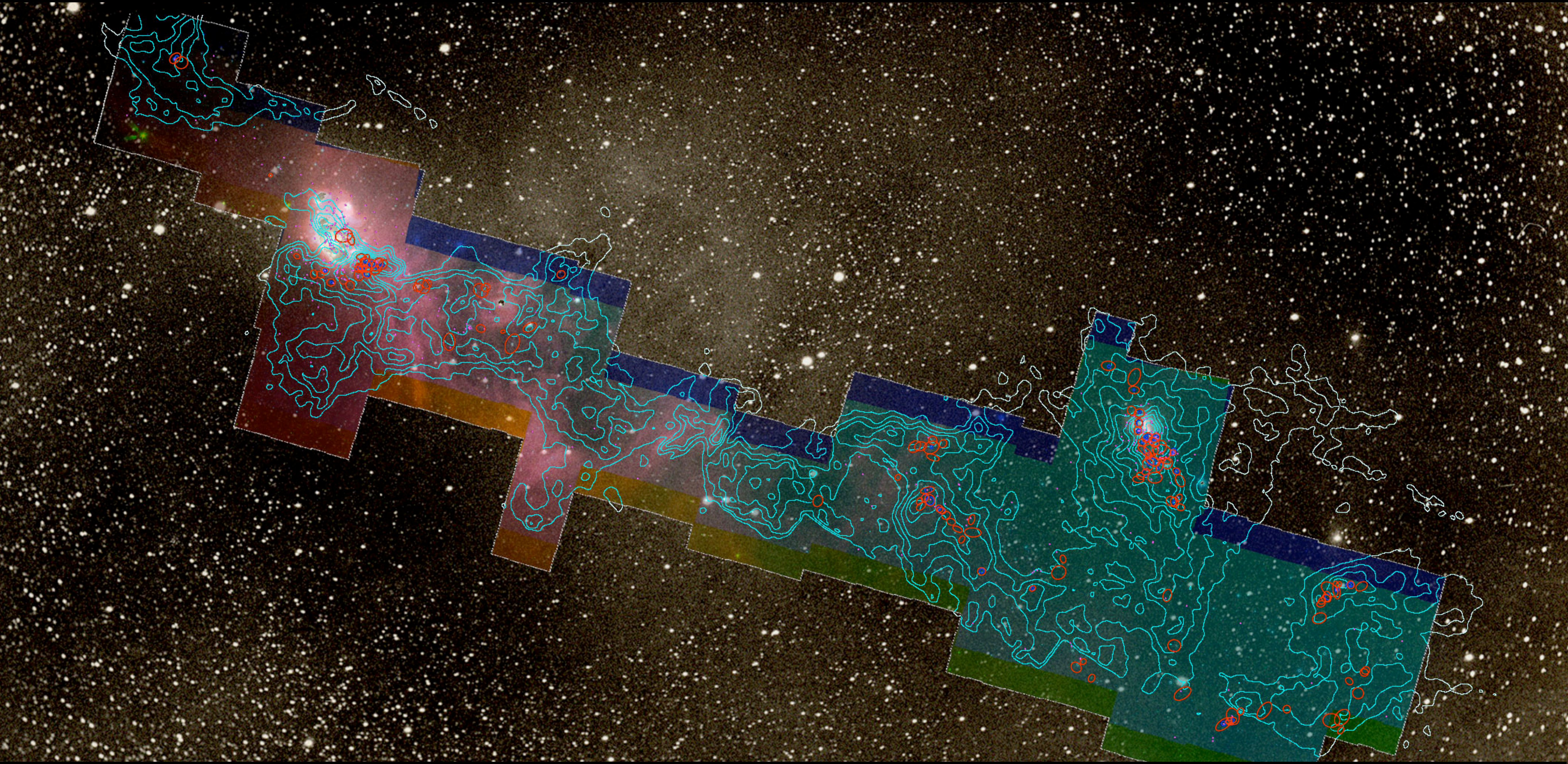
- maps of **Emission**, **Extinction** & **Scattering** due to dust (for column density & temperature)
- maps of radio-frequency **spectral lines** from gas (for kinematics)

Table 2: **Reading Nature's Menu** This table shows which tools are best for deteriming particular physical quantities. Grey shows possible wavelengths, and darker grey emphasizes the best wavelengths. Green means "yes," and yellow means "yes, but not usually very well." *Many subtleties cannot be shown here.* For example, stellar mass determinations are always model-dependent unless an orbit is known; some techniques give line-of-sight velocity, while others give plane-of-the-sky; chemistry is always very model dependent, and so-on.

Notes: C=included in COMPLETE; S=included in Spitzer c2d; +=included in both COMPLETE & c2d; Magnetic Fields: P=by polarimetry; Z=(primarily by) Zeeman, at same wavelengths shown

		optical	NIR	MIR	FIR	sub-mm	mm	cm	Density or Mass	Chemical Composition	Temperature	Velocity	Magnetic Fields
Extended Material (Clouds & Cores)	Broadband Emission (Dust)			S	+	C	+						P
	Spectra (Dust)												P
	Spectra (Gas)						C	C					Z
	Background Starlight (Extinction)		C	S									P
	Scattered Light ("Cloudshine")		C	S									
Disks & Envelopes (spatially filtered obsv'ns.)	Broadband Emission (Dust)			S	S	+							
	Spectra (Dust)			S	S								
	Spectra (Gas)												Z
Optically-Revealed (Proto) Stars	Broadband Emission			S									
	Spectra			S									Z
	Astrometry												

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



COMPLETE Collaborators, Summer 2008:

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João Alves (Calar Alto, Spain)

Héctor Arce (Yale)

Michelle Borkin (IIC)

Paola Caselli (Leeds, UK)

James DiFrancesco (HIA, Canada)

Jonathan Foster (CfA, PhD Student)

Katherine Guenthner (CfA/Leipzig)

Mark Heyer (UMASS/FCRAO)

Doug Johnstone (HIA, Canada)

Jens Kauffmann (CfA/IIC)

Helen Kirk (HIA, Canada)

Di Li (JPL)

Jaime Pineda (CfA, PhD Student)

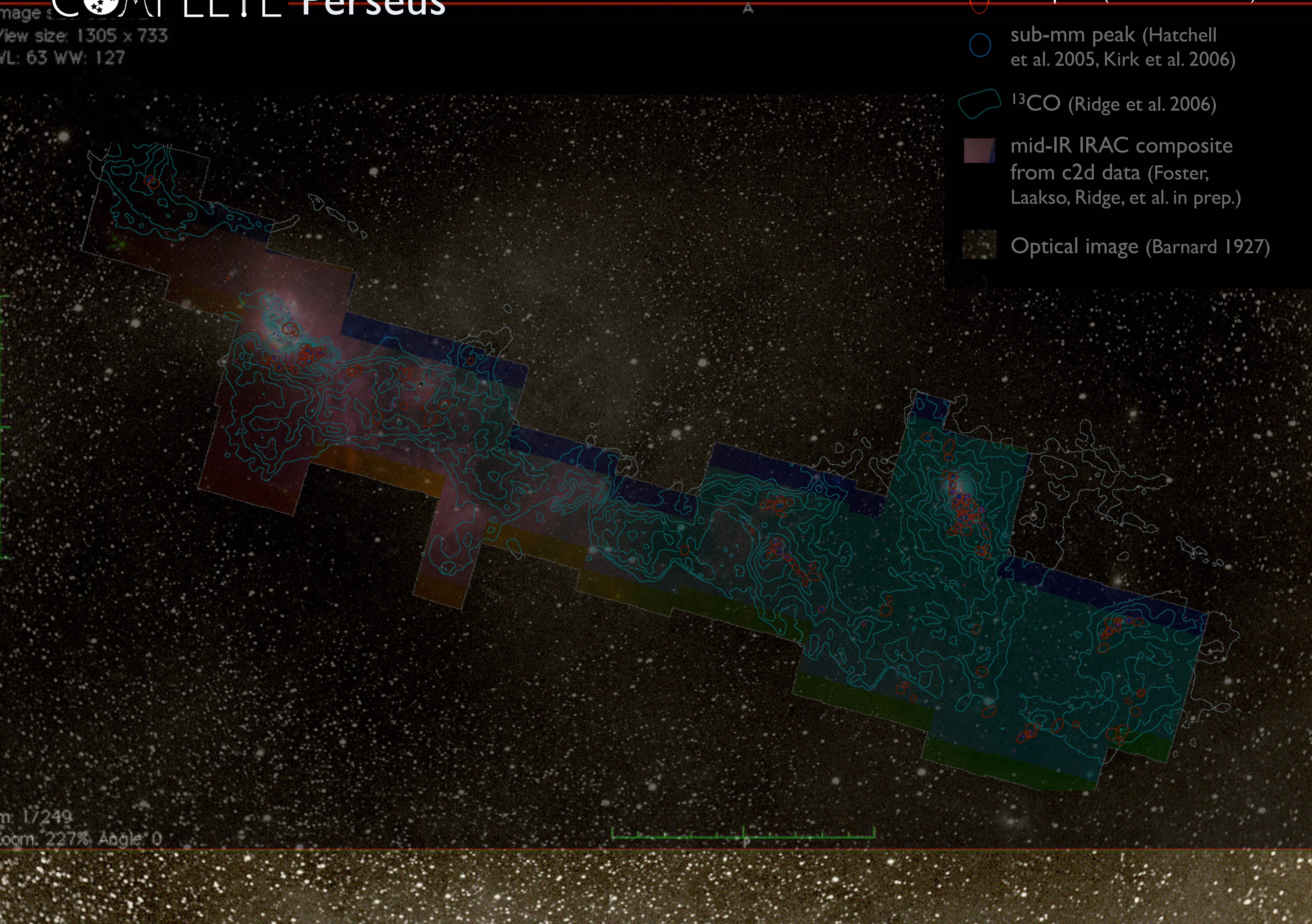
Erik Rosolowsky (UBC Okanagan)

Rahul Shetty (CfA)

Scott Schnee (Caltech)

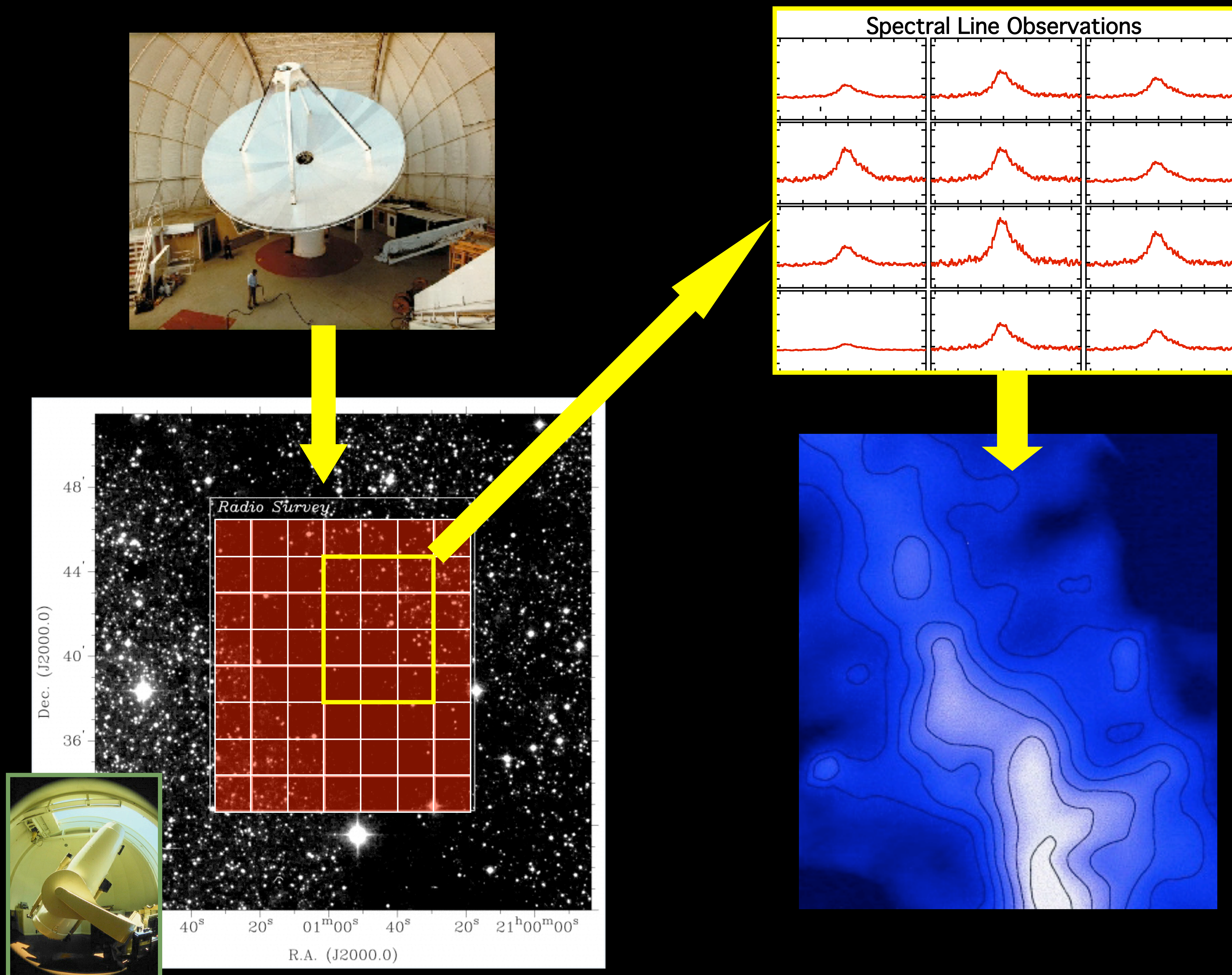
Mario Tafalla (OAN, Spain)

COMPLETE Perseus

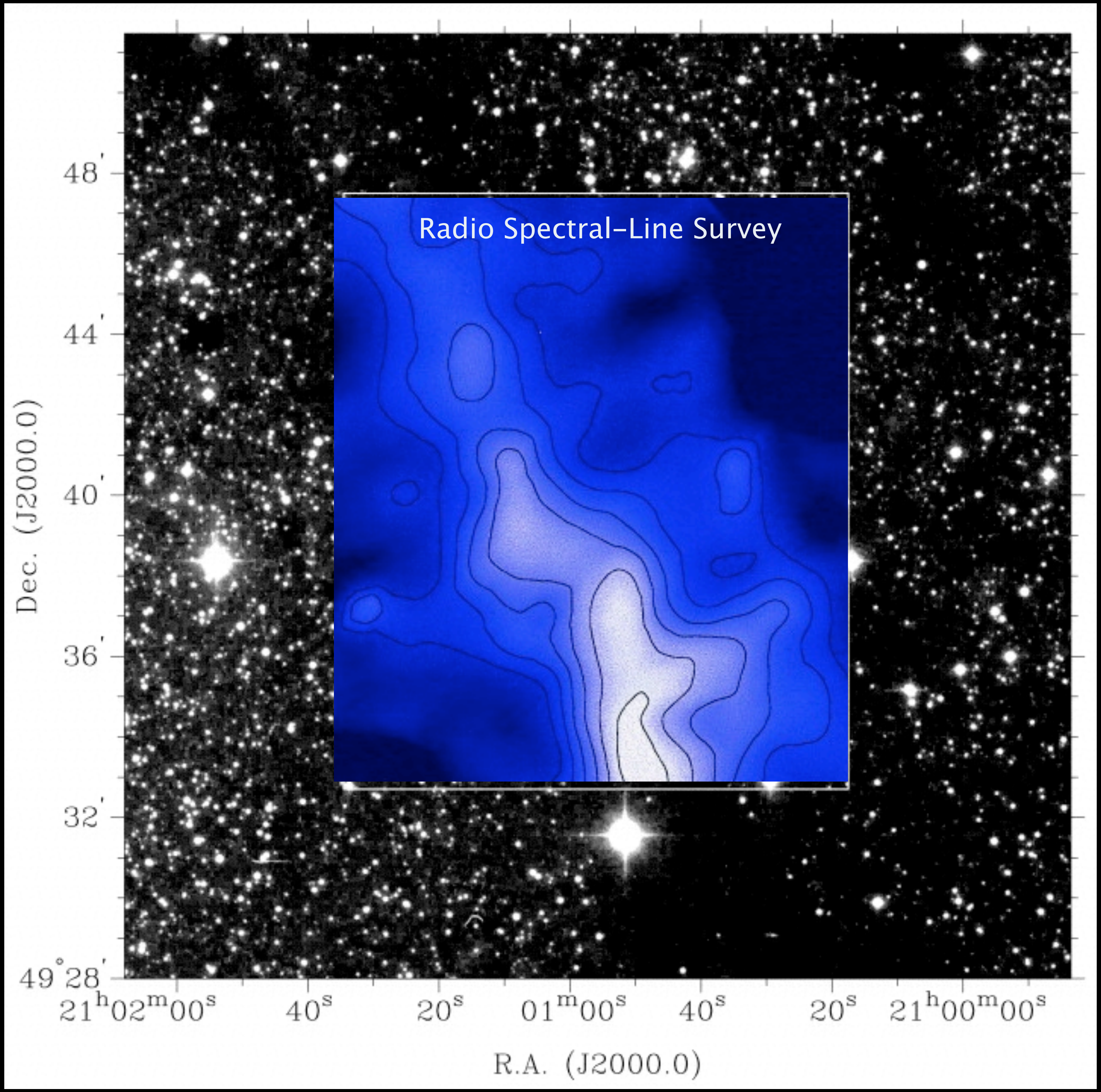


- mm peak (Enoch et al. 2006)
- sub-mm peak (Hatchell et al. 2005, Kirk et al. 2006)
- ^{13}CO (Ridge et al. 2006)
- mid-IR IRAC composite from c2d data (Foster, Laakso, Ridge, et al. in prep.)
- Optical image (Barnard 1927)

Radio Spectral-line Observations of Interstellar Clouds

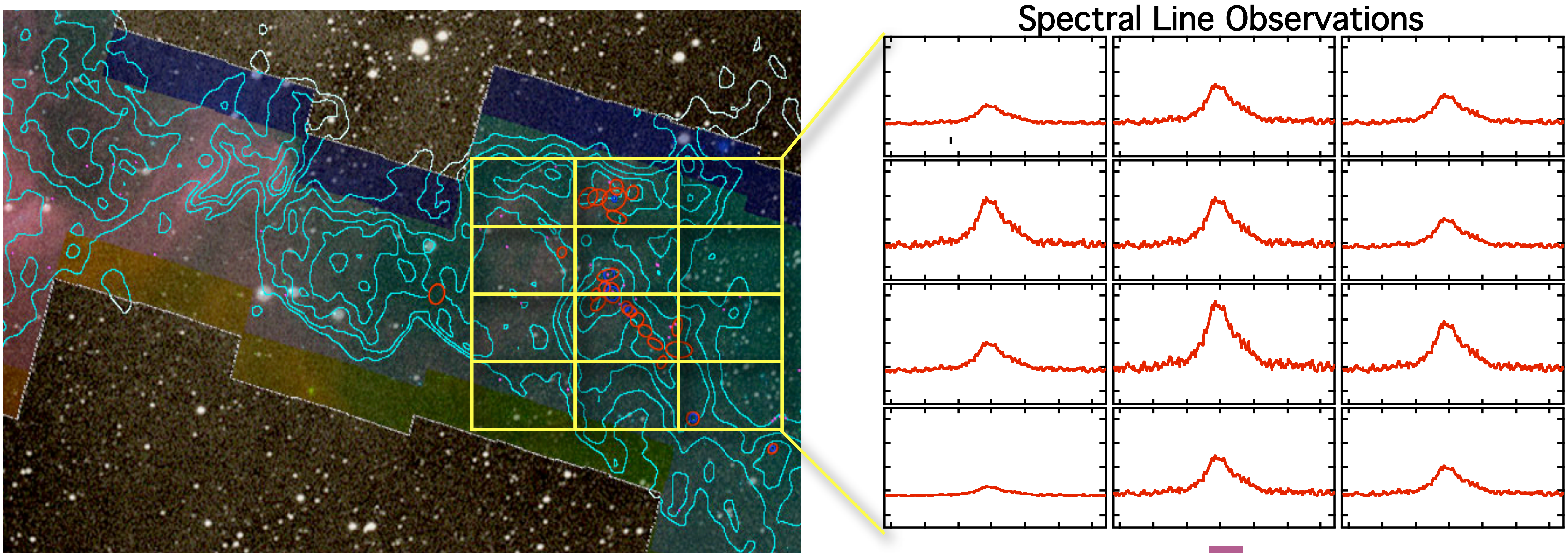


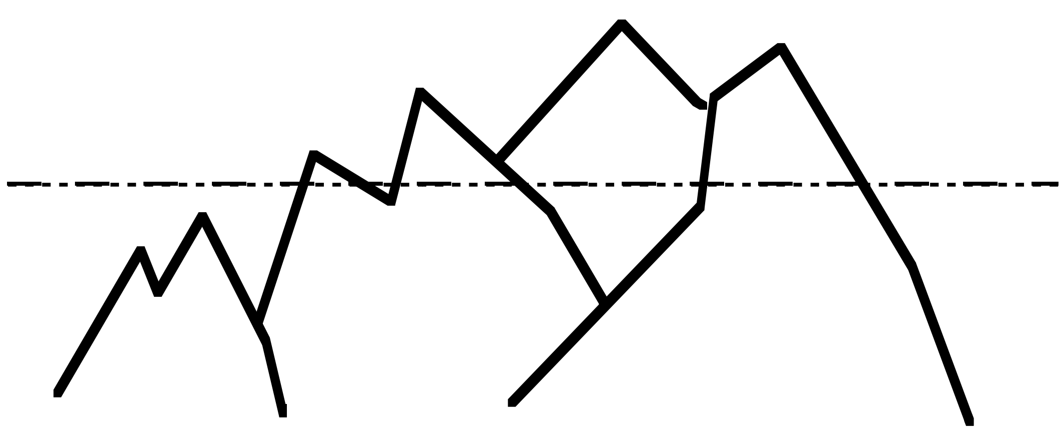
Radio Spectral-line Observations of Interstellar Clouds



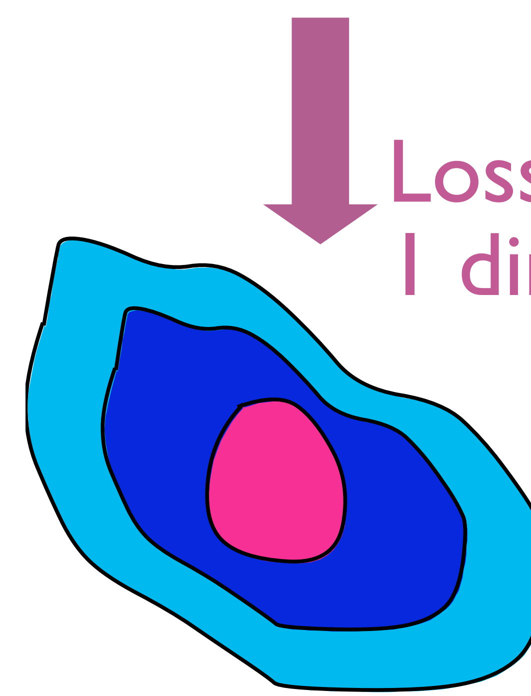
Alves, Lada & Lada 1999

Velocity as a "Fourth" Dimension

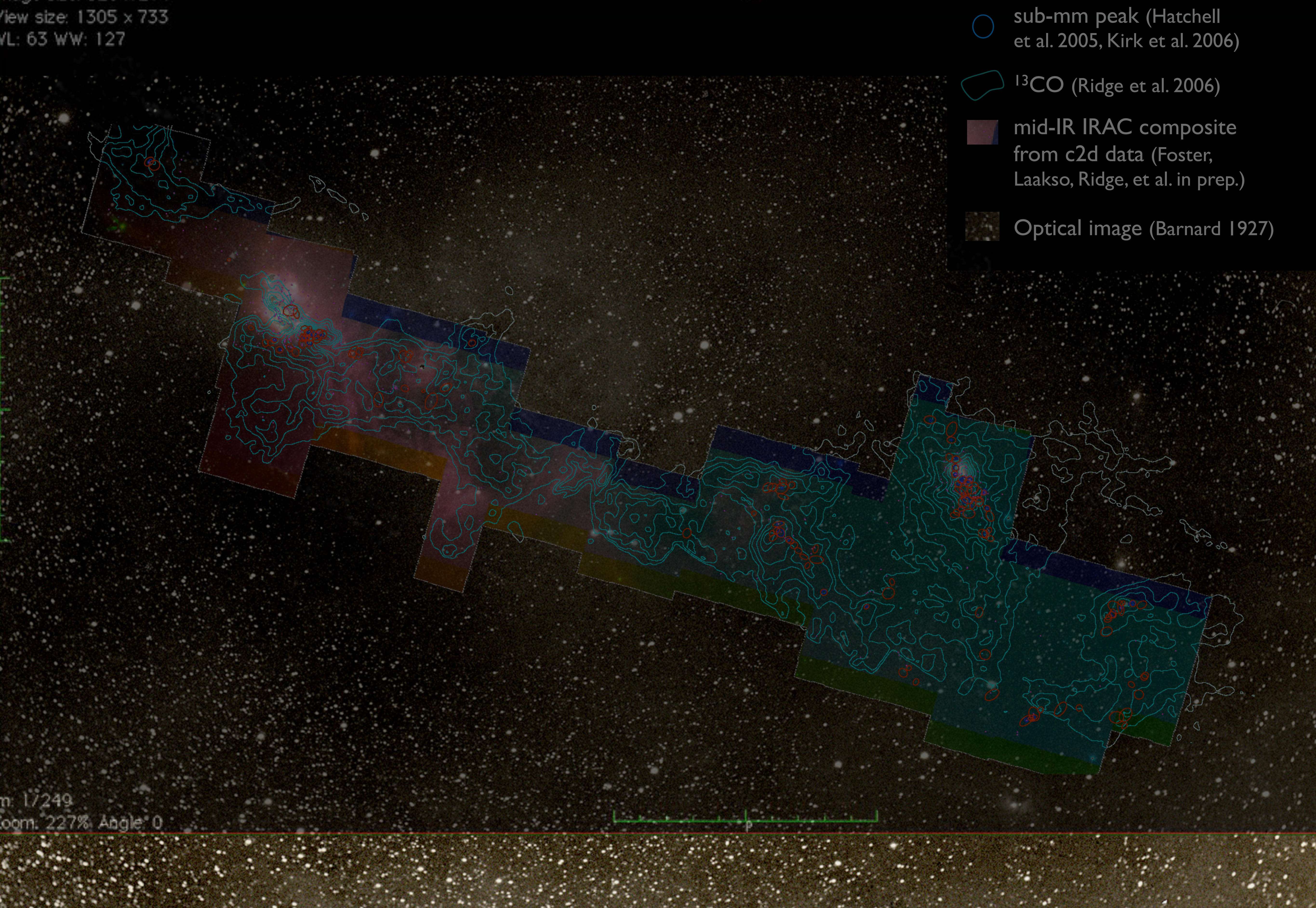




No loss of information



COMPLETE Perseus



mm peak (Enoch et al. 2006)

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

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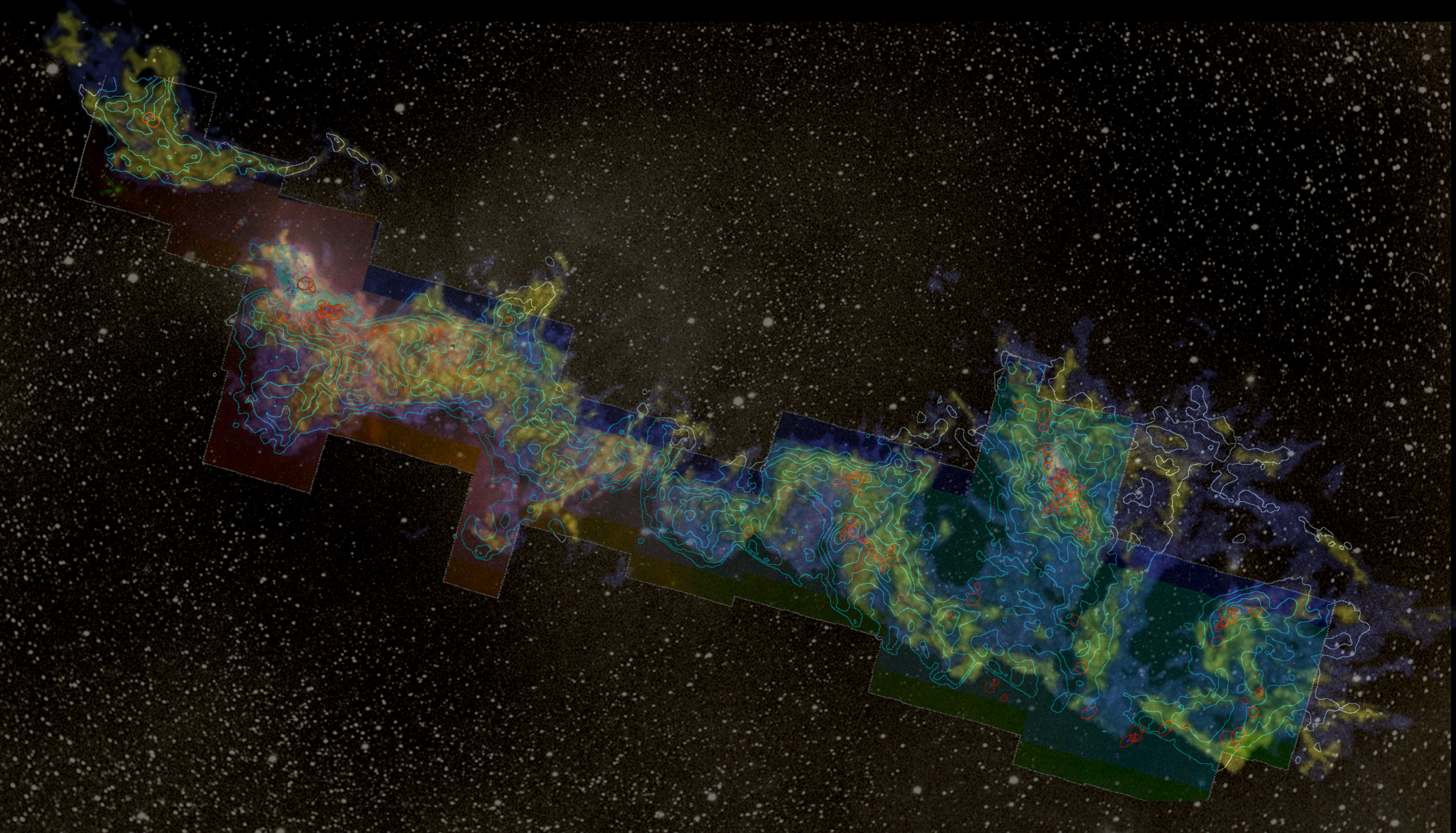


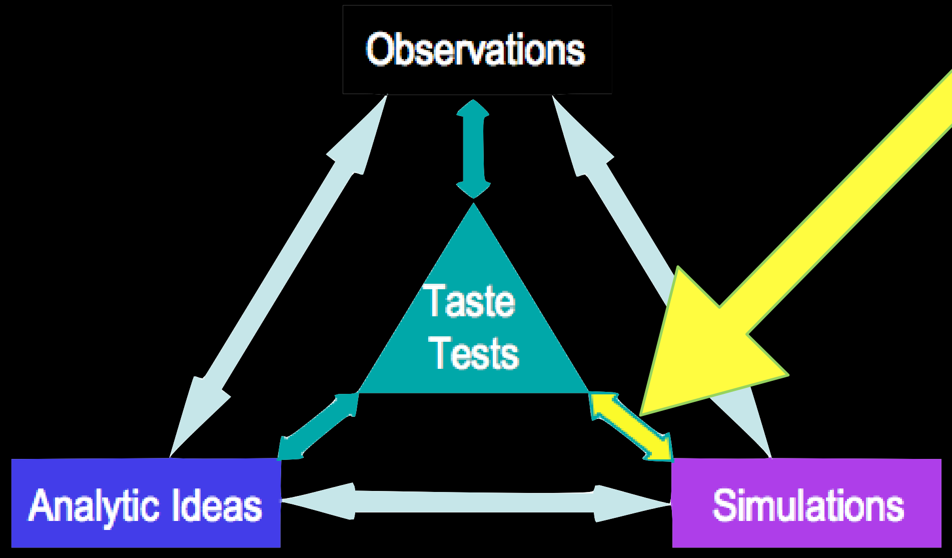
Perseus

3D Viz made with VolView

AstroMed@IIC

COMPLETE

For Taste Testing, we can use Synthetic Spectral Line Maps from Simulations



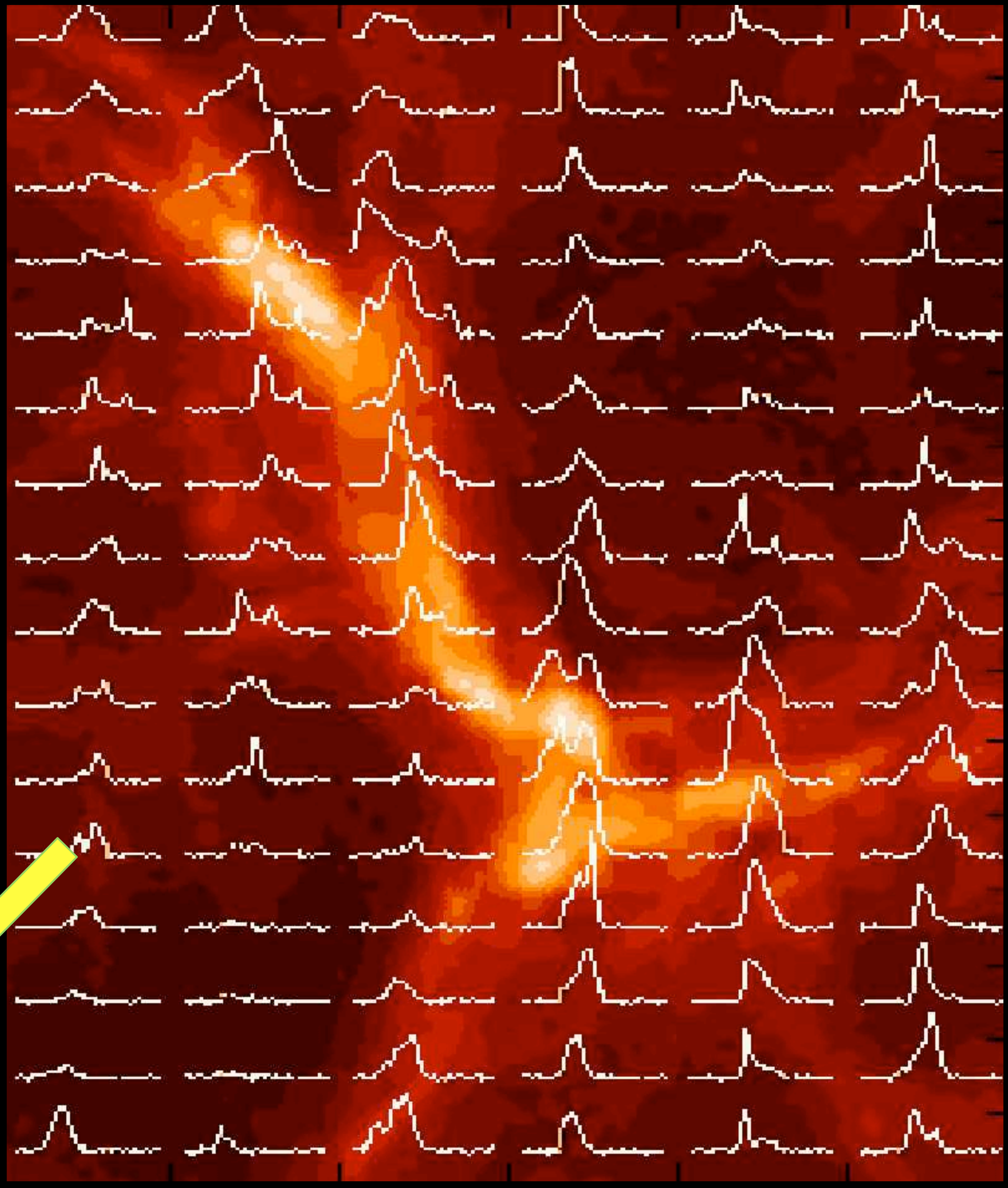
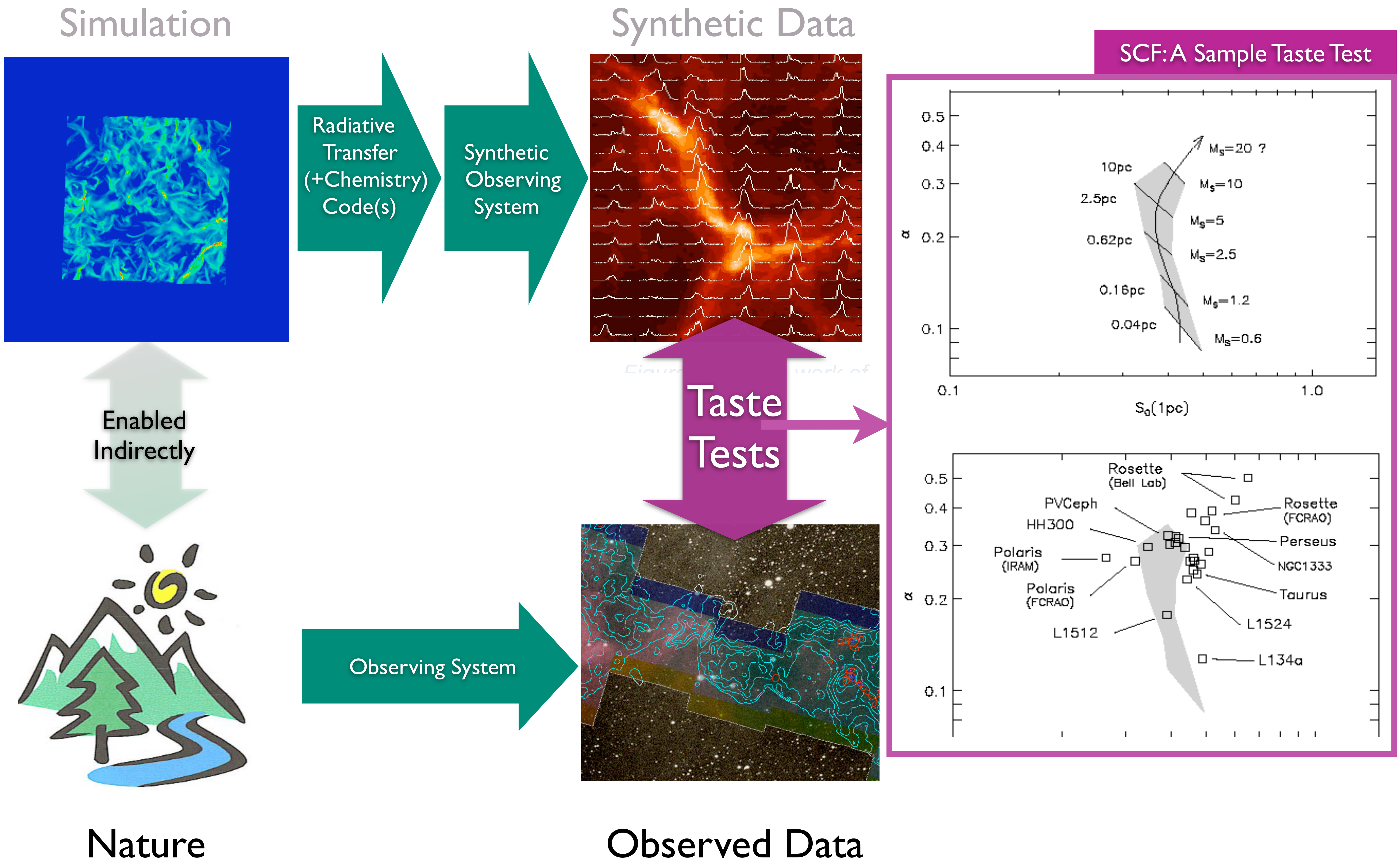


Figure based on work of Padoan, Nordlund, Juvela, et al.
Excerpt from realization used in Padoan & Goodman 2002.

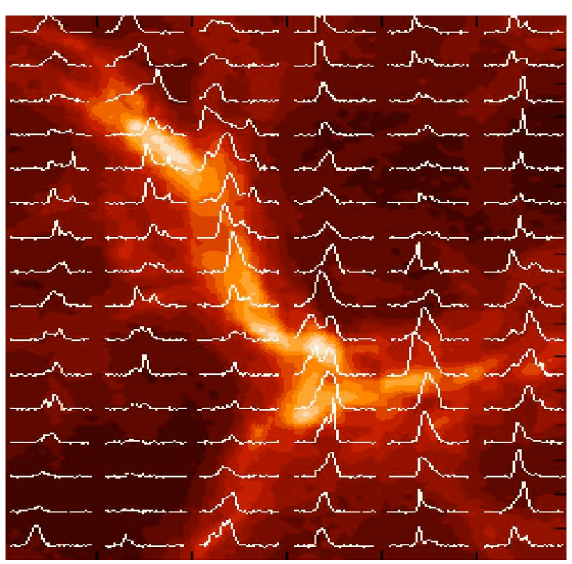
The Taste-Testing Process



Appetizer #1 : The "Spectral Correlation Function"

SCF tastes included...

- Projection to 2D sky plane, or "3D" of spectral-line data cubes
- Radiative Transfer for a variety of chemical "tracers"
- Adding appropriate noise
- Imposing observing characteristics of a telescope



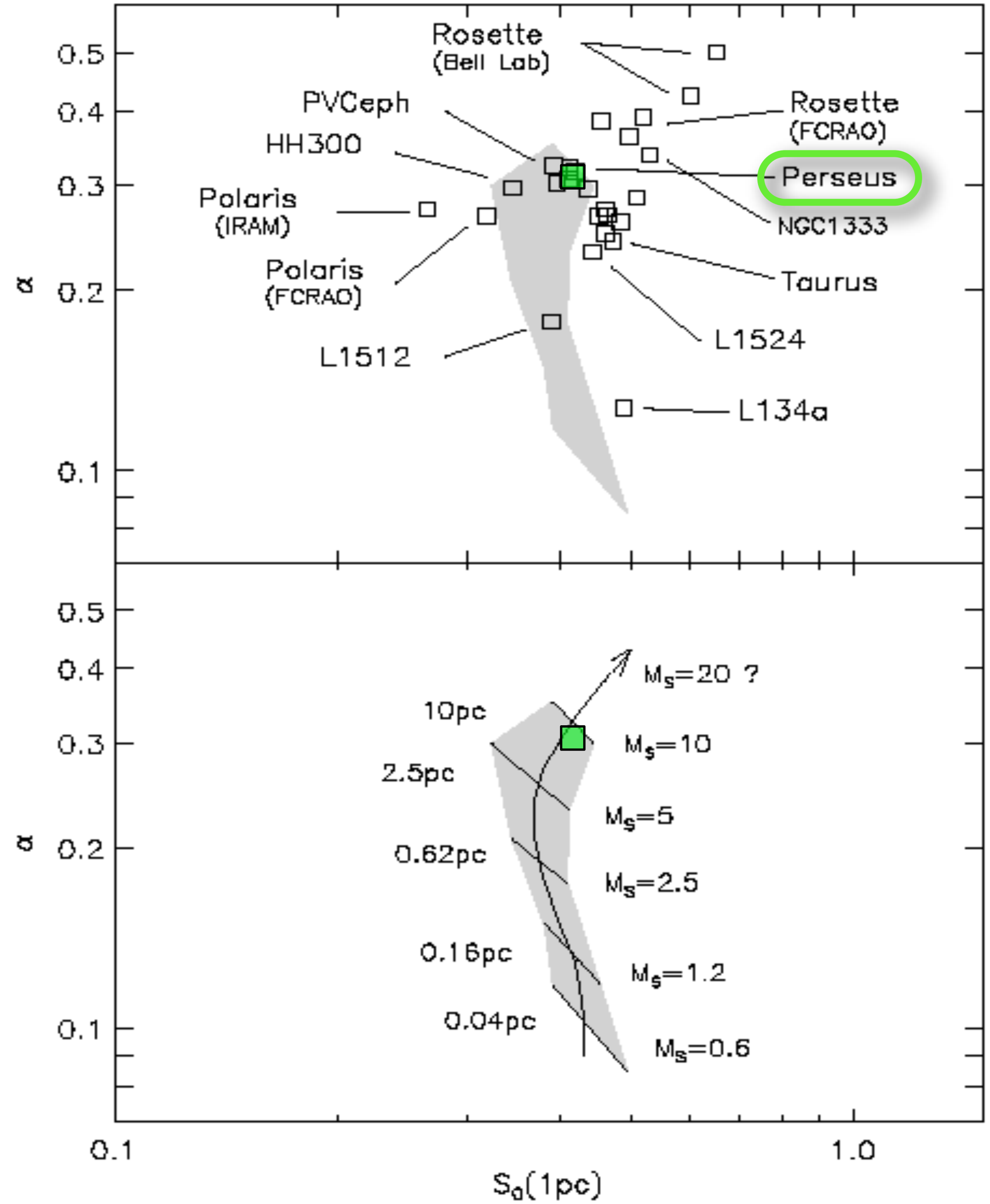


Figure: Padoan, Goodman & Juvela 2003; original SCF: Rosolowsky et al. 1999.

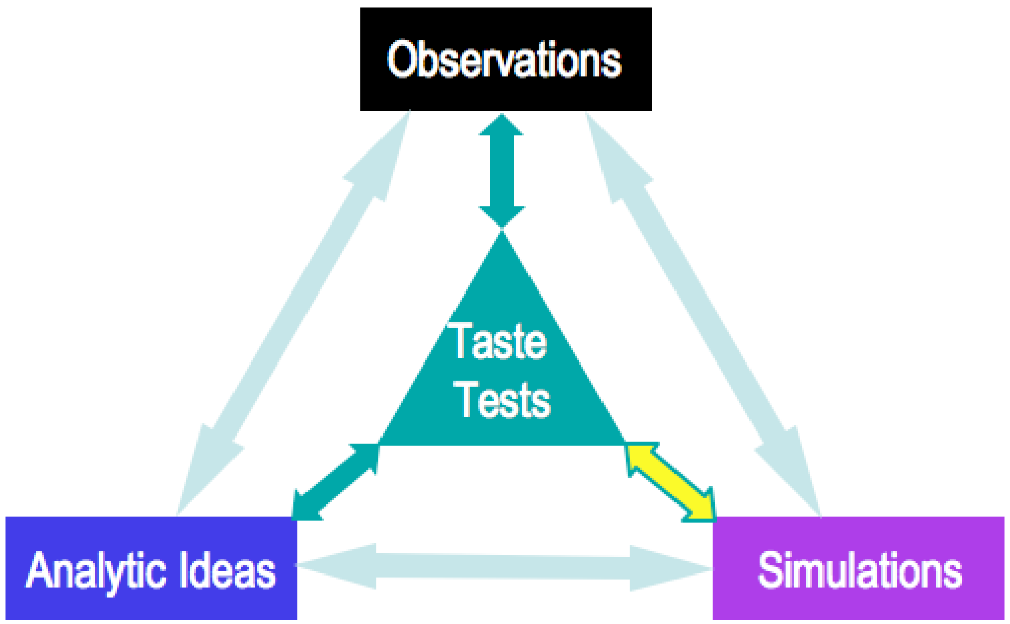
Note: SCF is One of Many...

Inspired by the "Theory Cube"

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

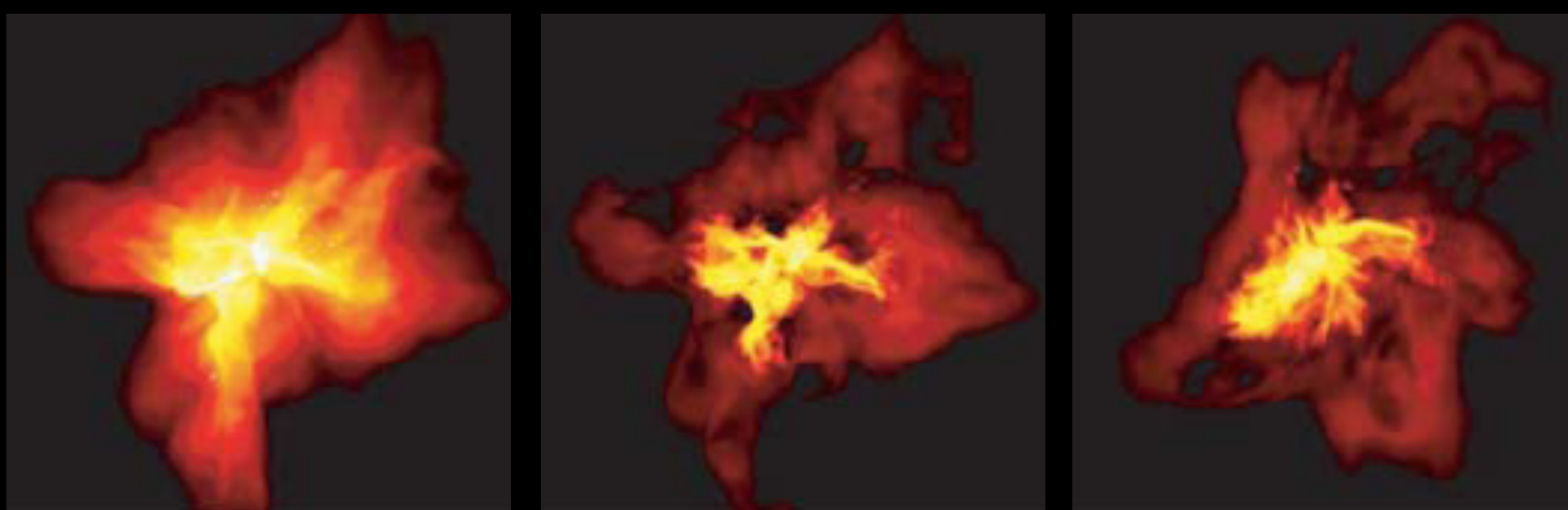
Data-Oriented

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



Appetizer #2: “Taste Test” of Competitive Accretion

By comparing decaying SPH hydrodynamic simulations to *Walsh et al. 2004* results for NGC 1333, *Ayliffe et al. (2007)* show that motions indicative of competitive accretion may not be obvious in tracer-to-tracer velocity offsets,



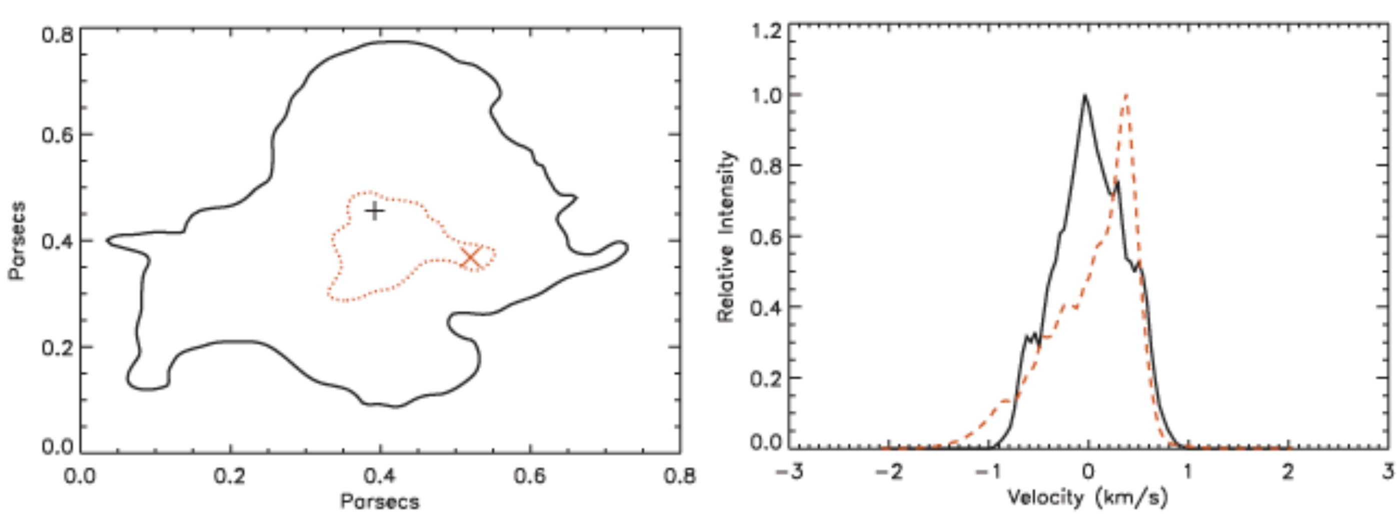
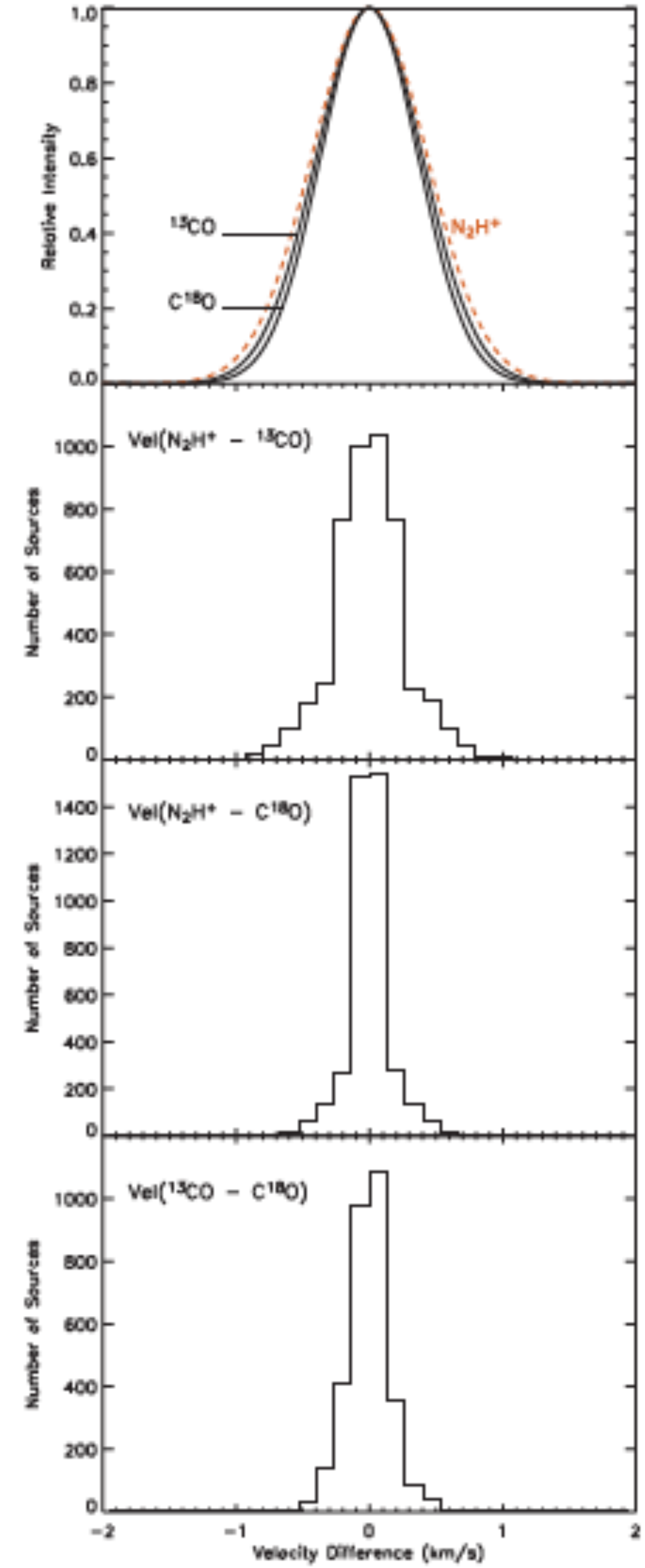
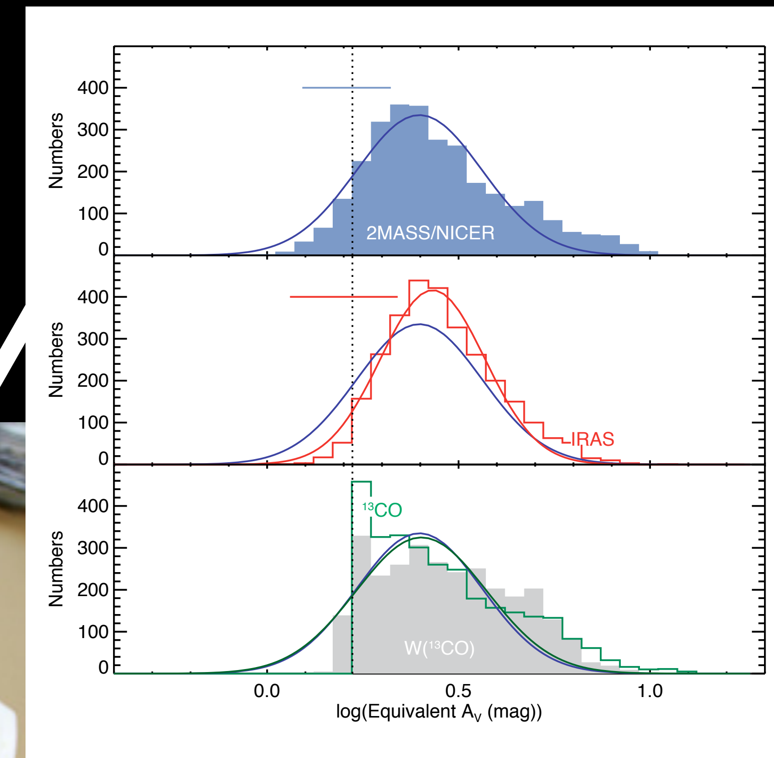


Figure 3. As in Fig. 2, except that the simulation has been smoothed to mimic the resolution of the observational taken by Walsh et al. (we assumed a FWHM resolution of 50 arcsec at 140 pc). Both the column-density contours (left-hand panel) and velocity spectra (right-hand panel) are smoothed slightly from those in Fig. 2.

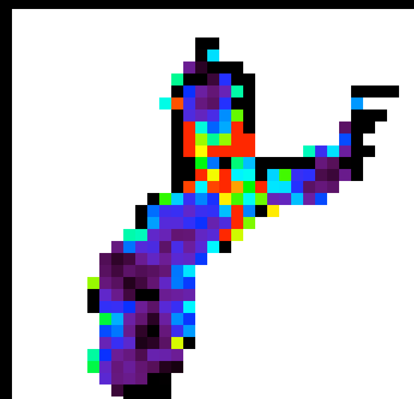


What's for Dinner?

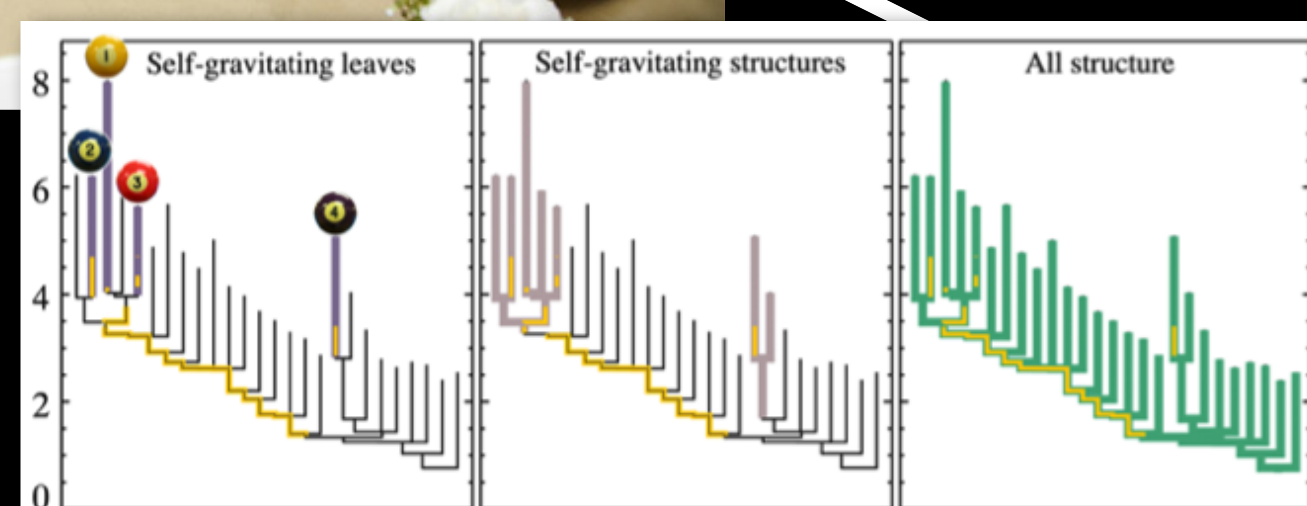
Entree 1: Column Density "Lognormals?"



Tasty Side: "Hot Sauce"



Tasty Side: "Cloudshine"



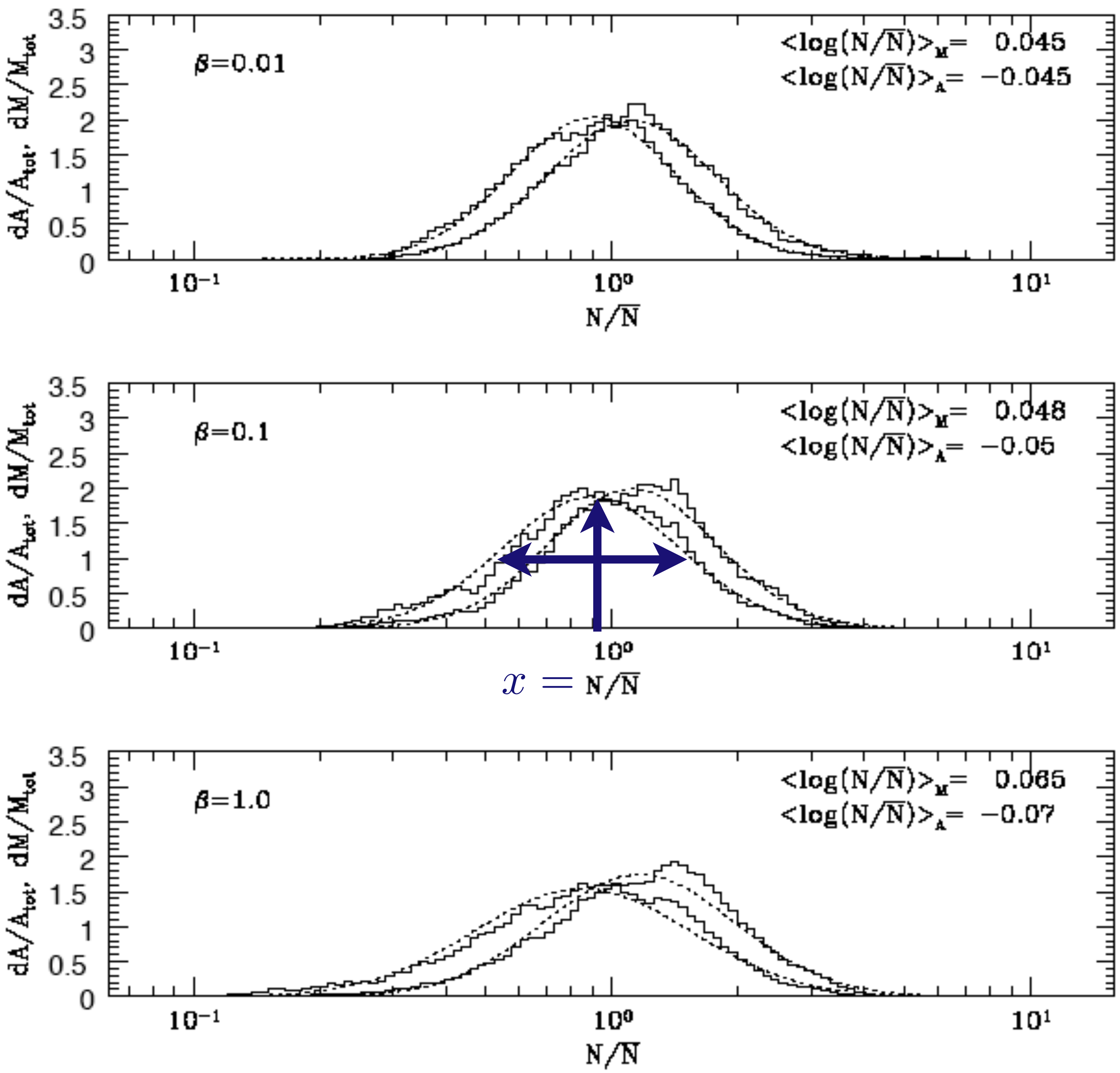
Entree 2: Dendrograms & Gravity

...if there's time

Turbulence theory & simulations generally predict that

Column density "tastes" log-normal(ish) on 10's of pc scales

Results from MHD simulations



Strong B-Field

Medium B-Field

Weak B-Field

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

Example: log-normal column density distribution

(Ostriker, Stone & Gammie 2001)

But which measure of ***Column Density*** *gives the* ***"Truest" Taste****?*

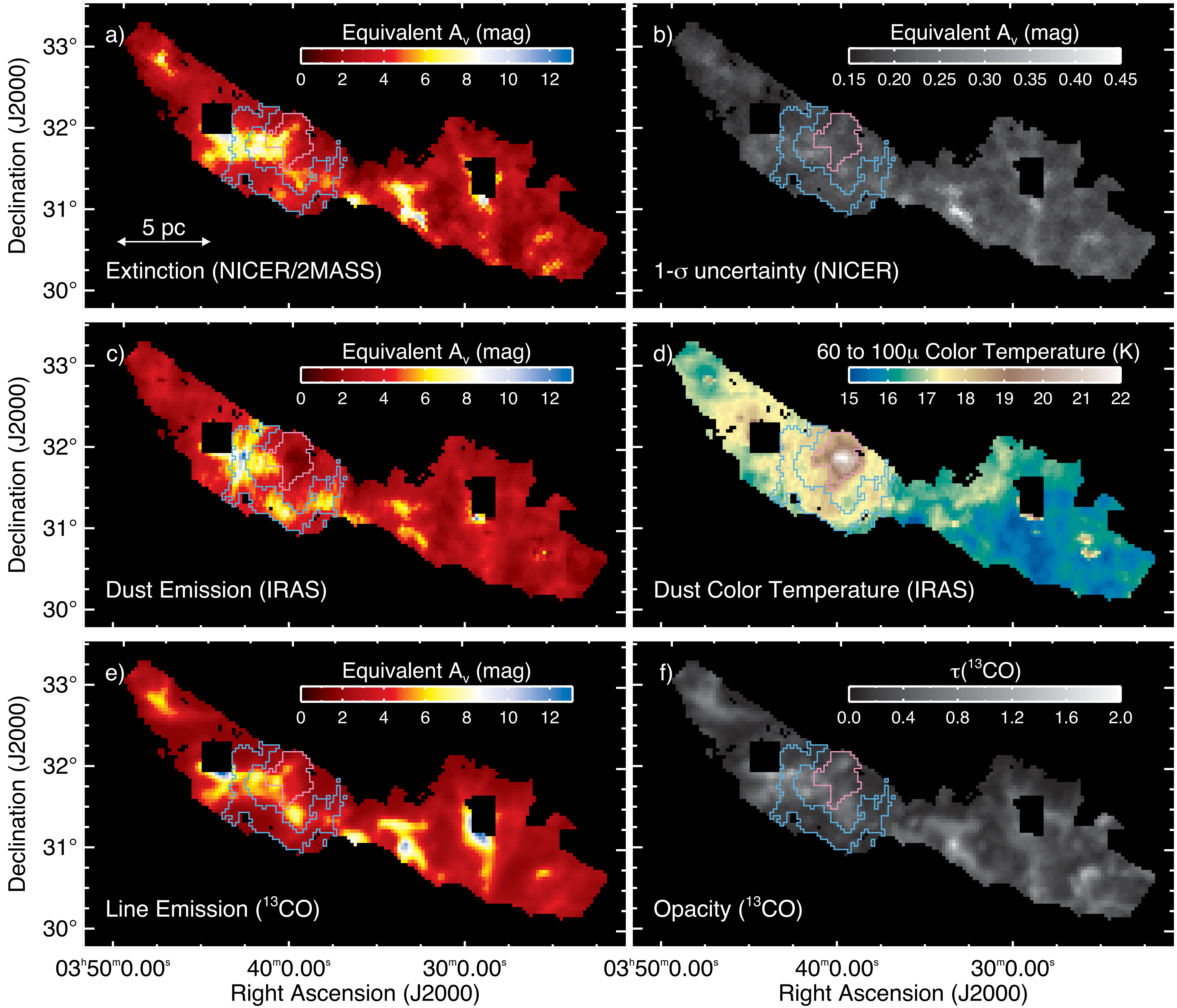
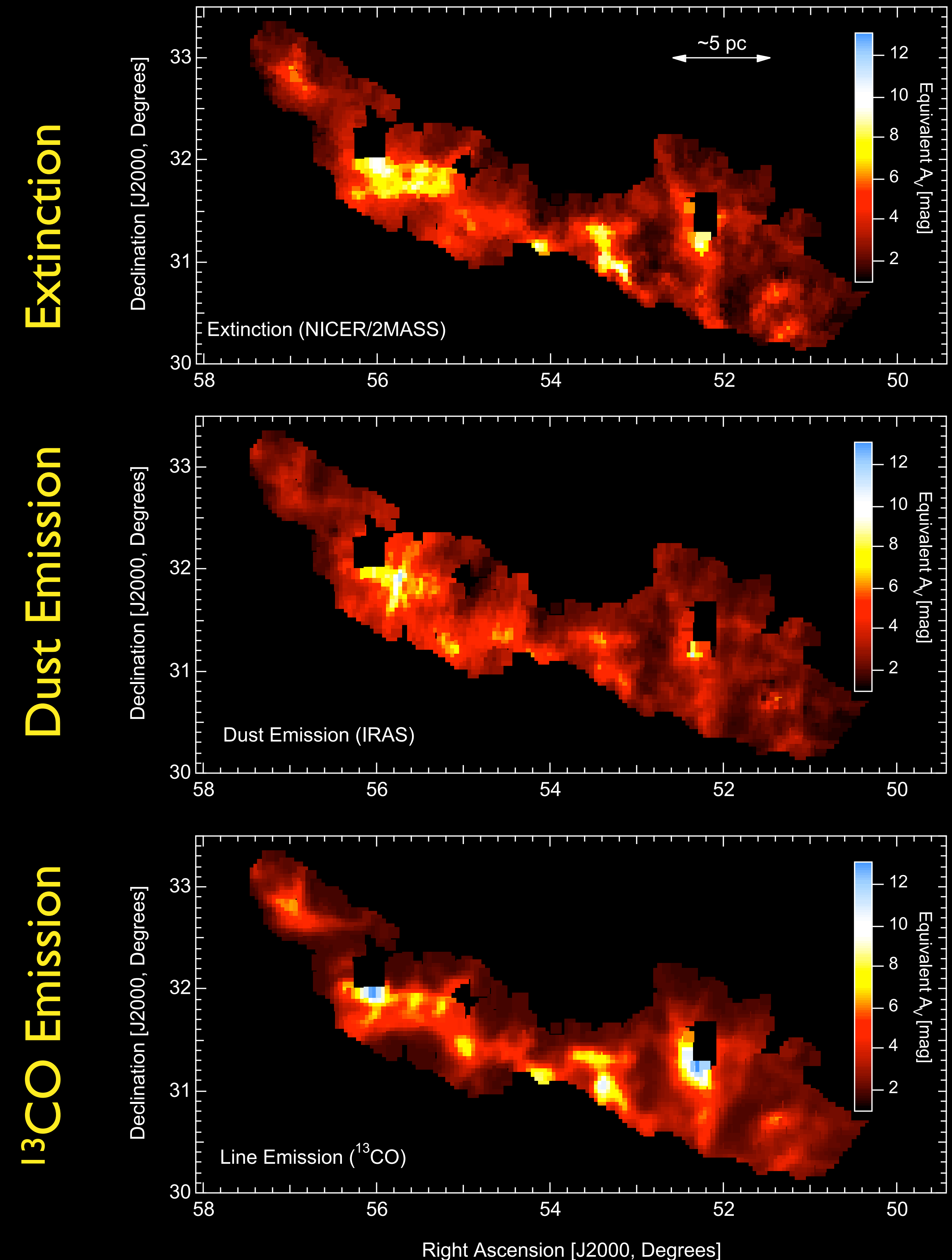


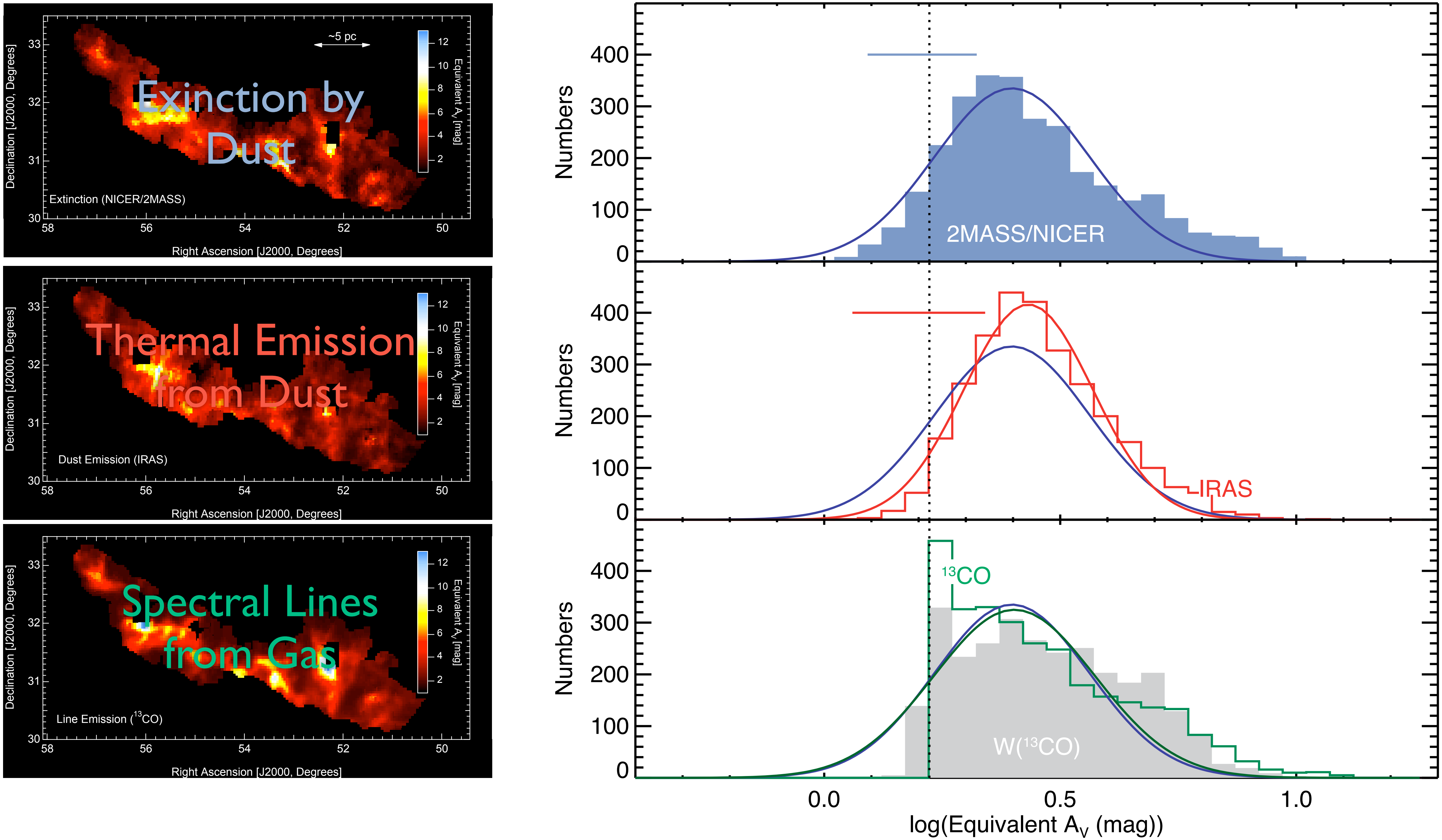
figure from Goodman, Pineda & Schnee 2008; see also Pineda et al. 2008

The (secret) uncertainties inherent in column density mapping.



Goodman, Pineda & Schnee 2008

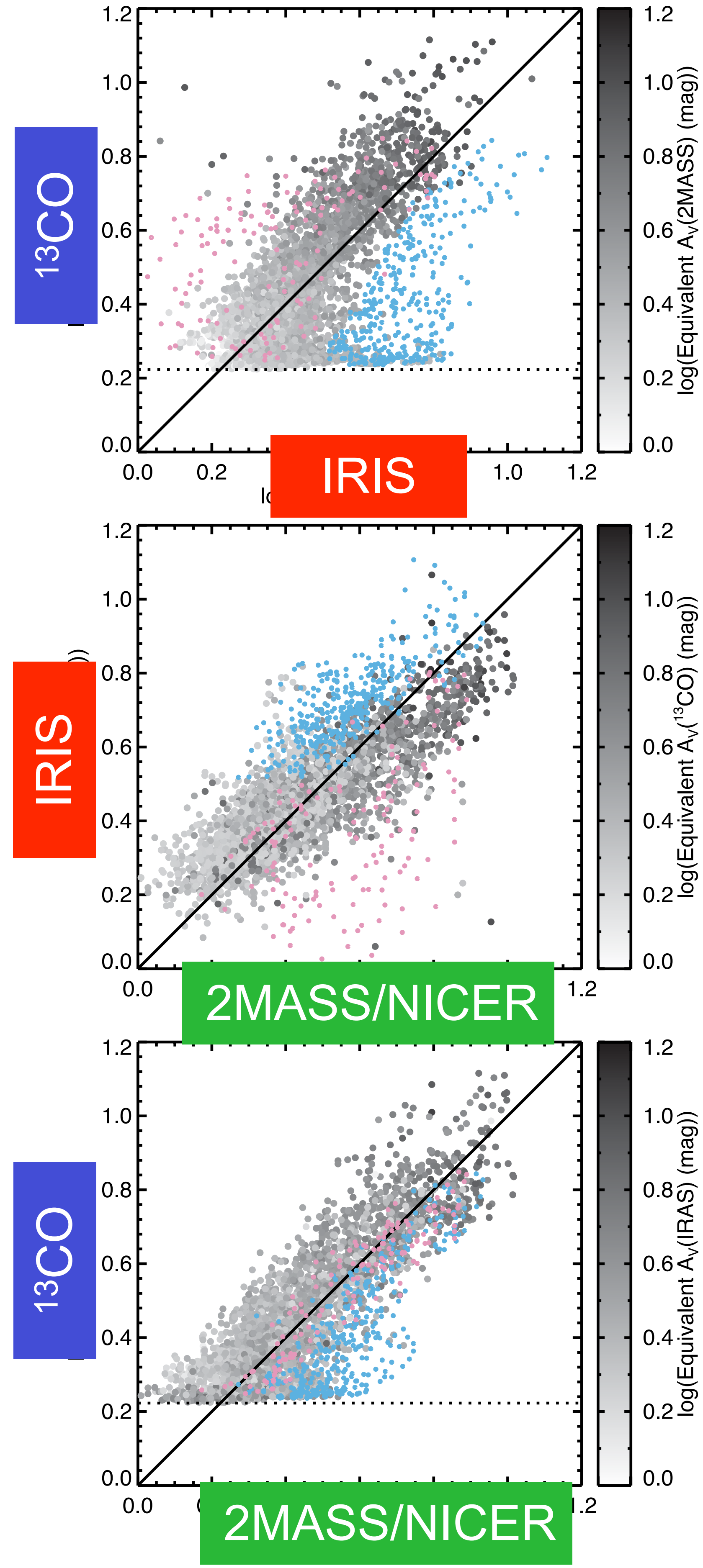
Column Density in Perseus, Measured 3 Ways



Goodman, Pineda & Schnee 2008

What Causes the Variations?

Tasty Side:
"Hot Sauce"



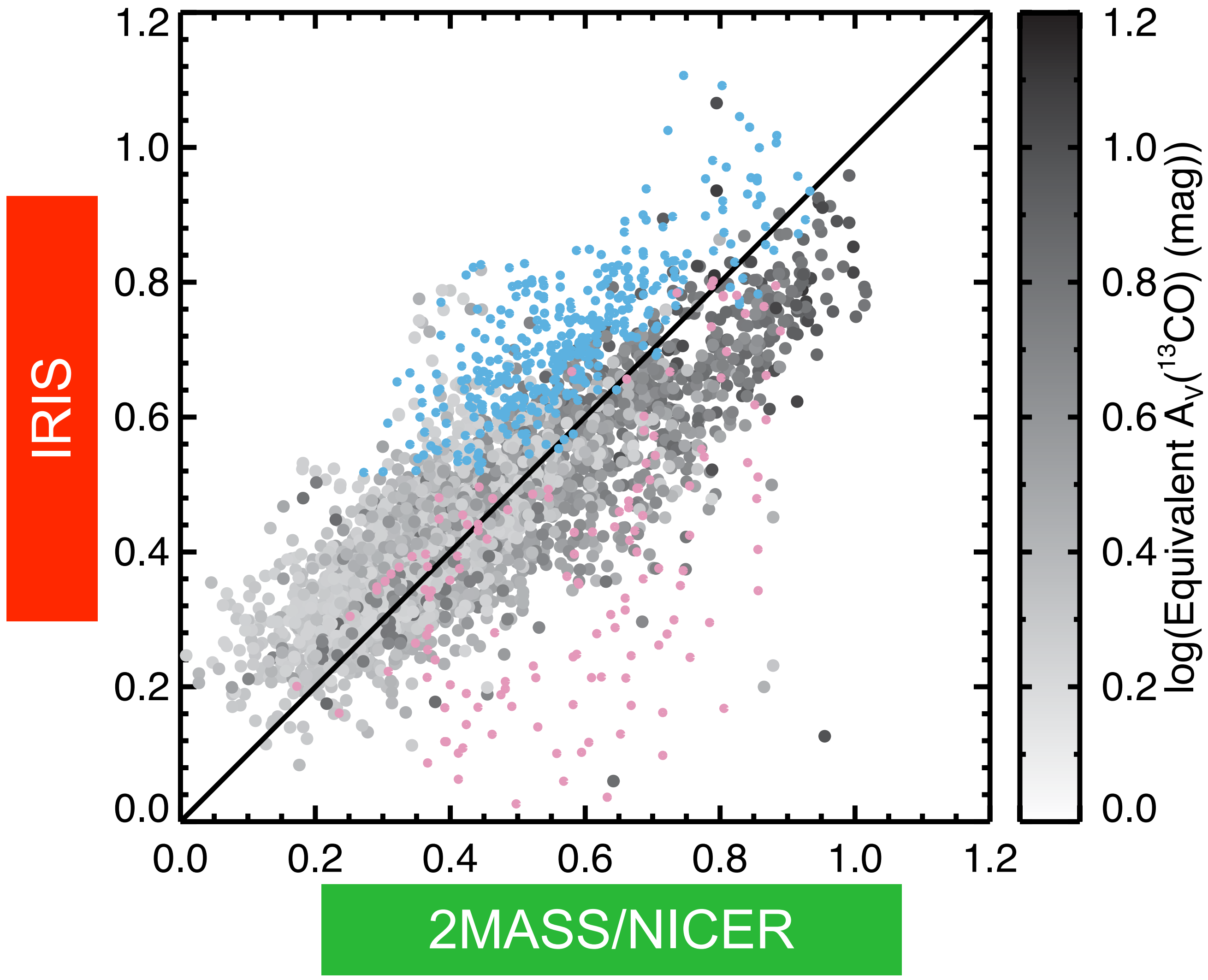
Goodman, Pineda & Schnee 2008

What Causes the Variations?

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

Variable fraction of emission from transiently heated very small dust grains

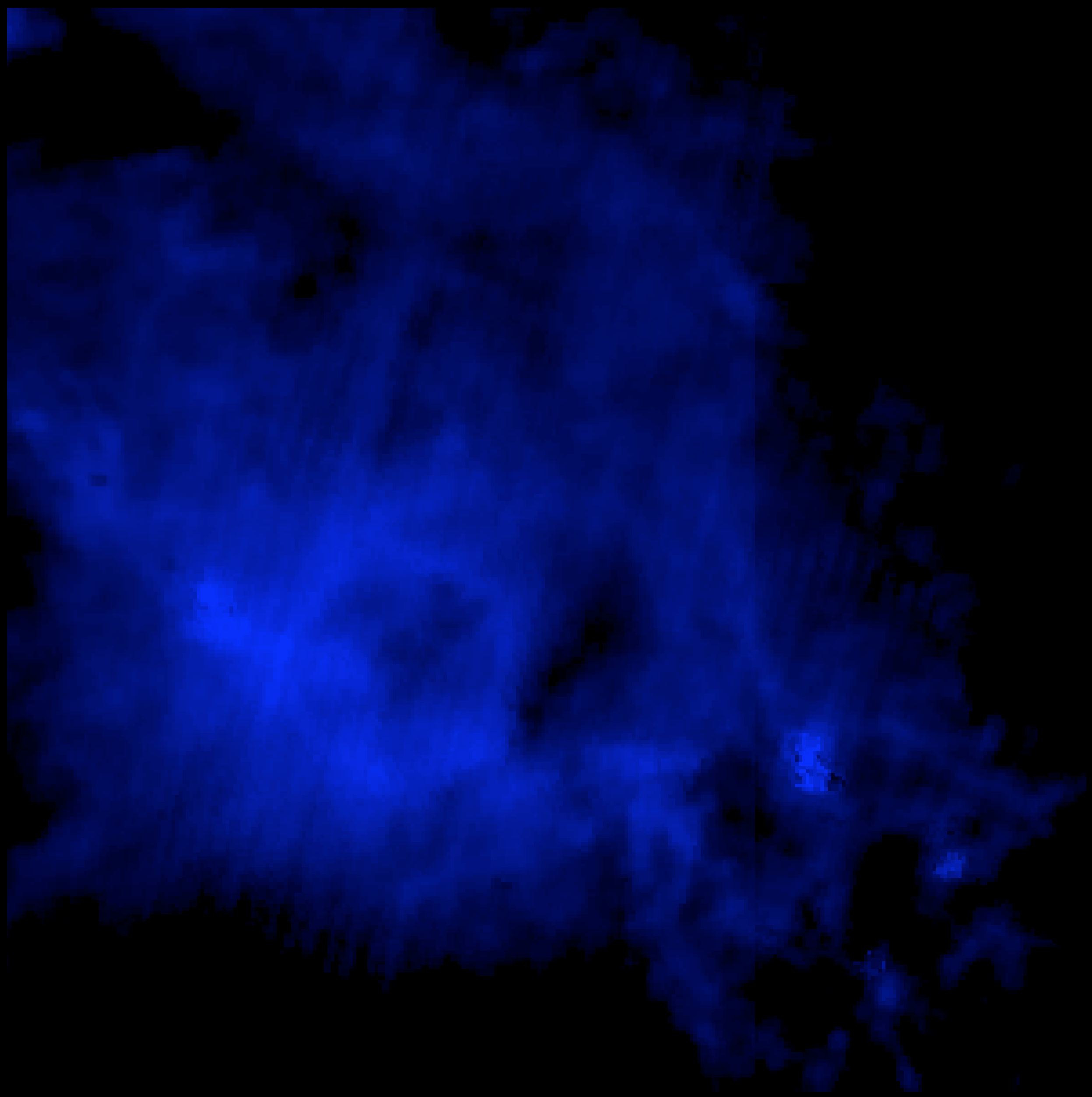
Variable dust properties (e.g. emissivity or emissivity spectral index)



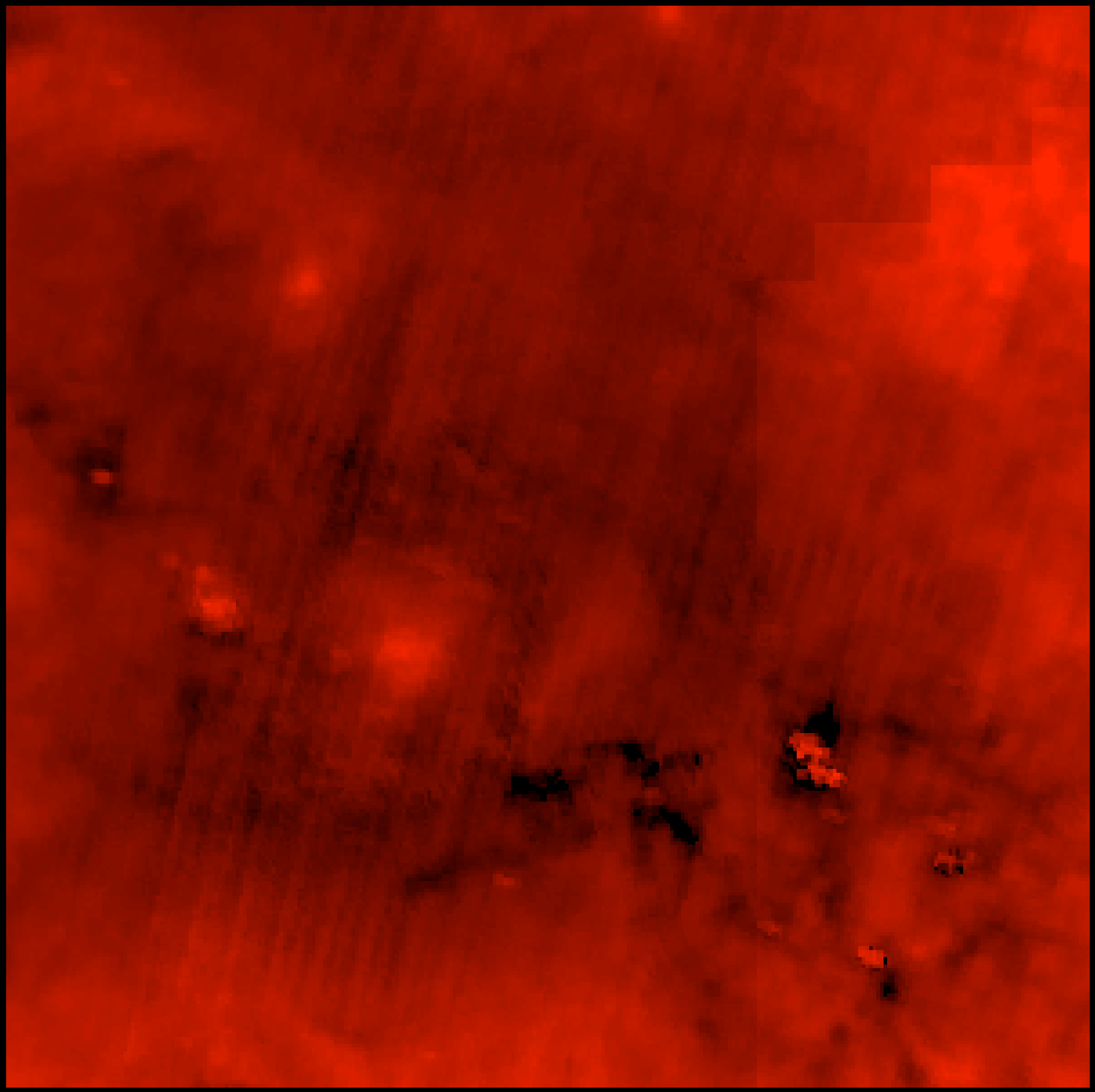
Schnee, Bethell & Goodman 2006

Perseus

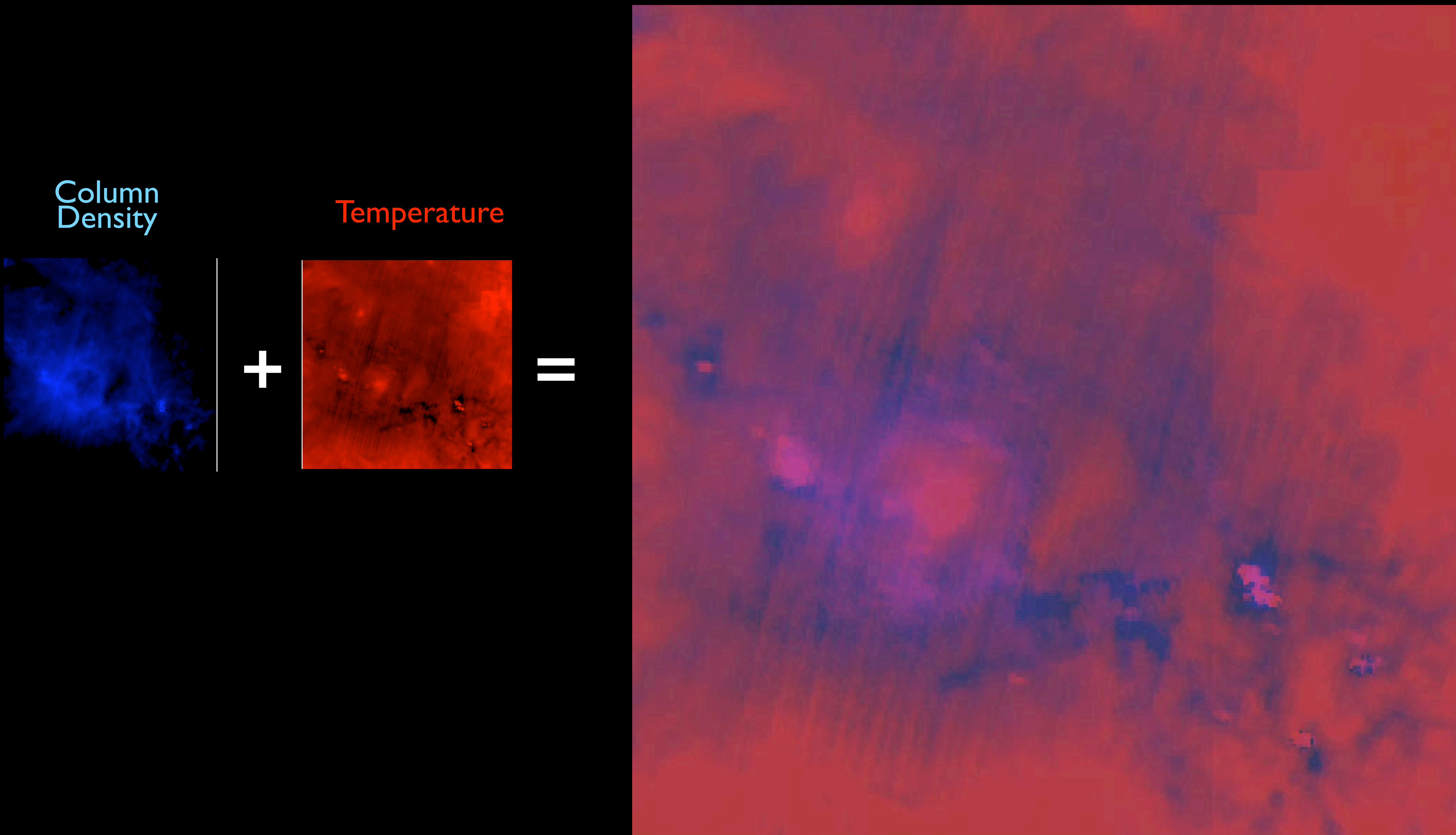
Total Dust Column (0 to 15 mag A_V)
(Based on 60/100 microns)



Dust Temperature (25 to 45 K)
(Based on 60/100 microns)

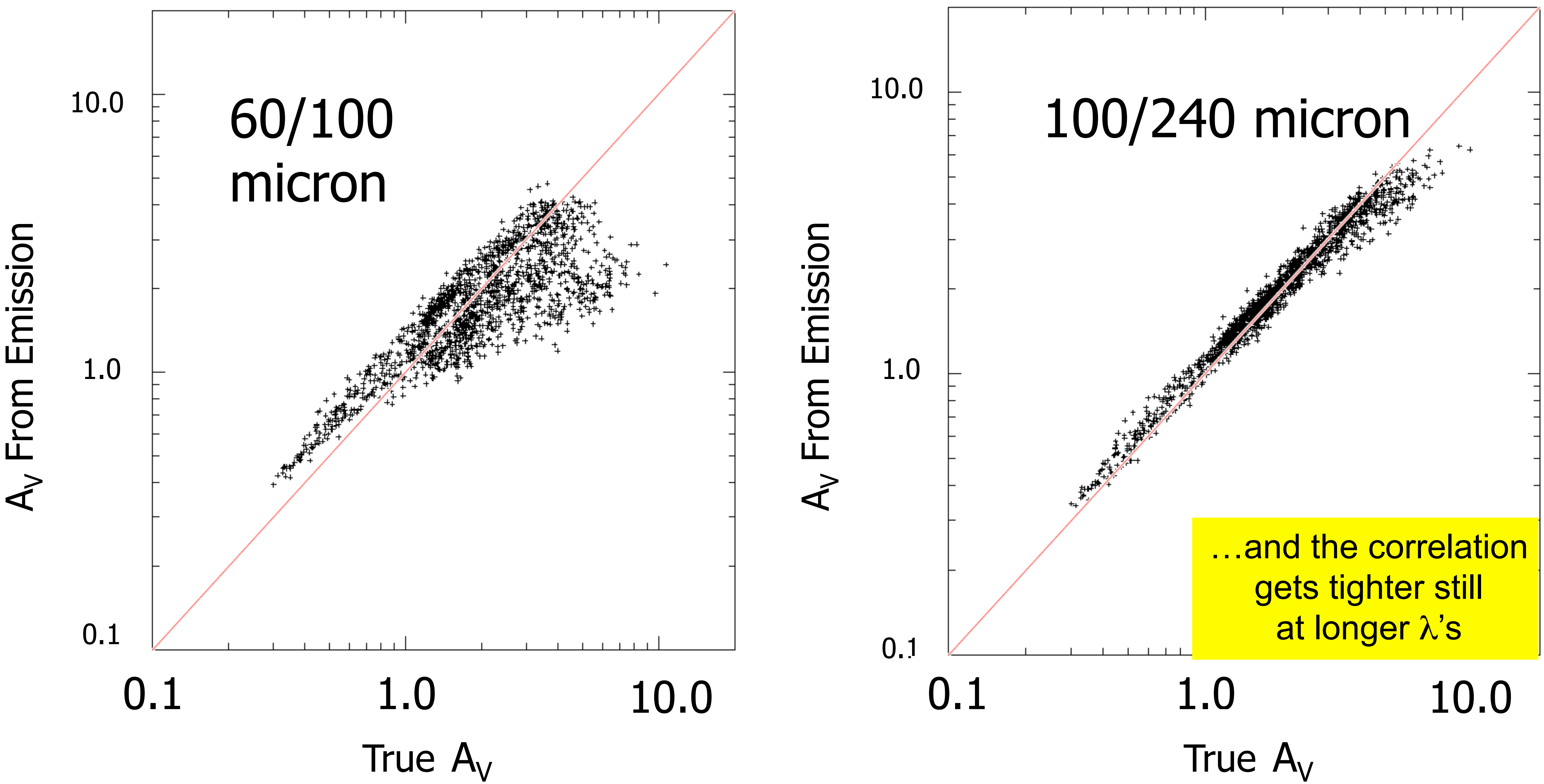


Imagine you look from the "side"...



Recovering Temperature from "Color" of Dust Emission

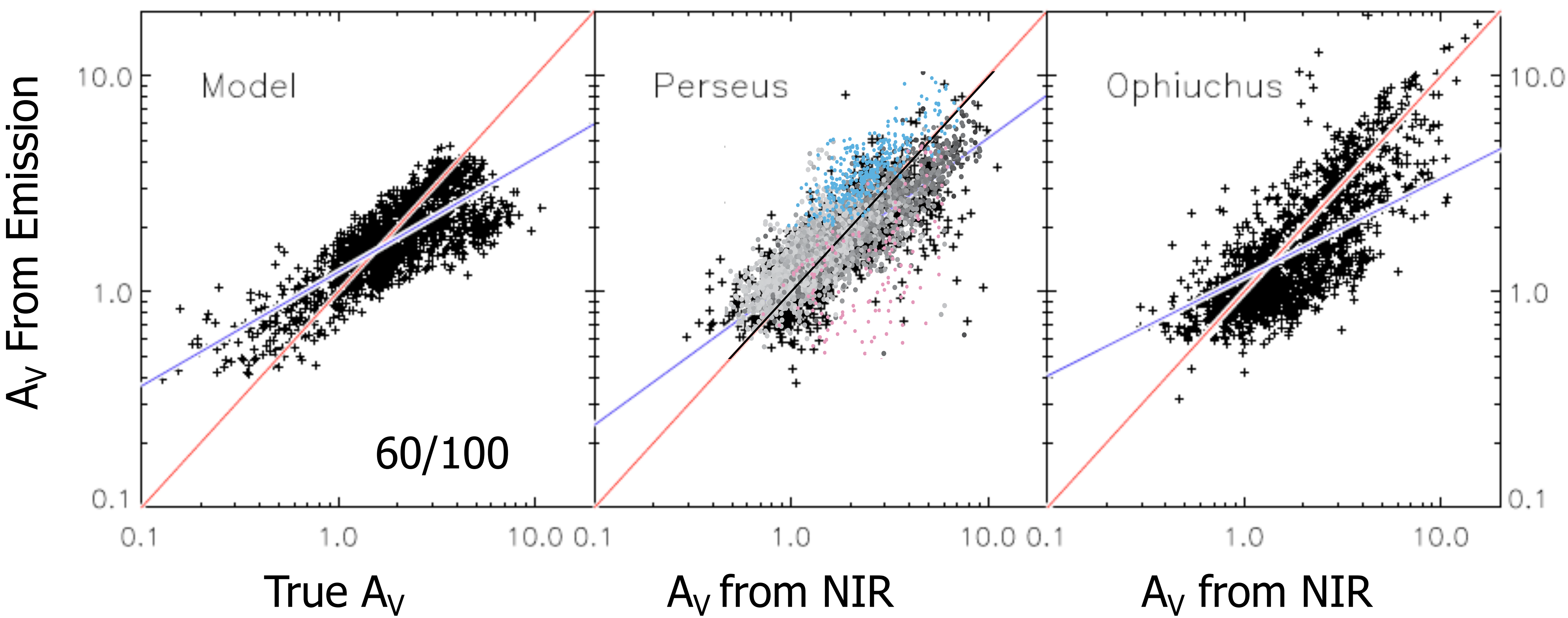
MHD Simulation + Radiative Transfer + NO NOISE gives...



Schnee, Bethell & Goodman 2006

Tasting Line of Sight Temperature Fluctuations

simulation + radiative transfer + realistic NOISE

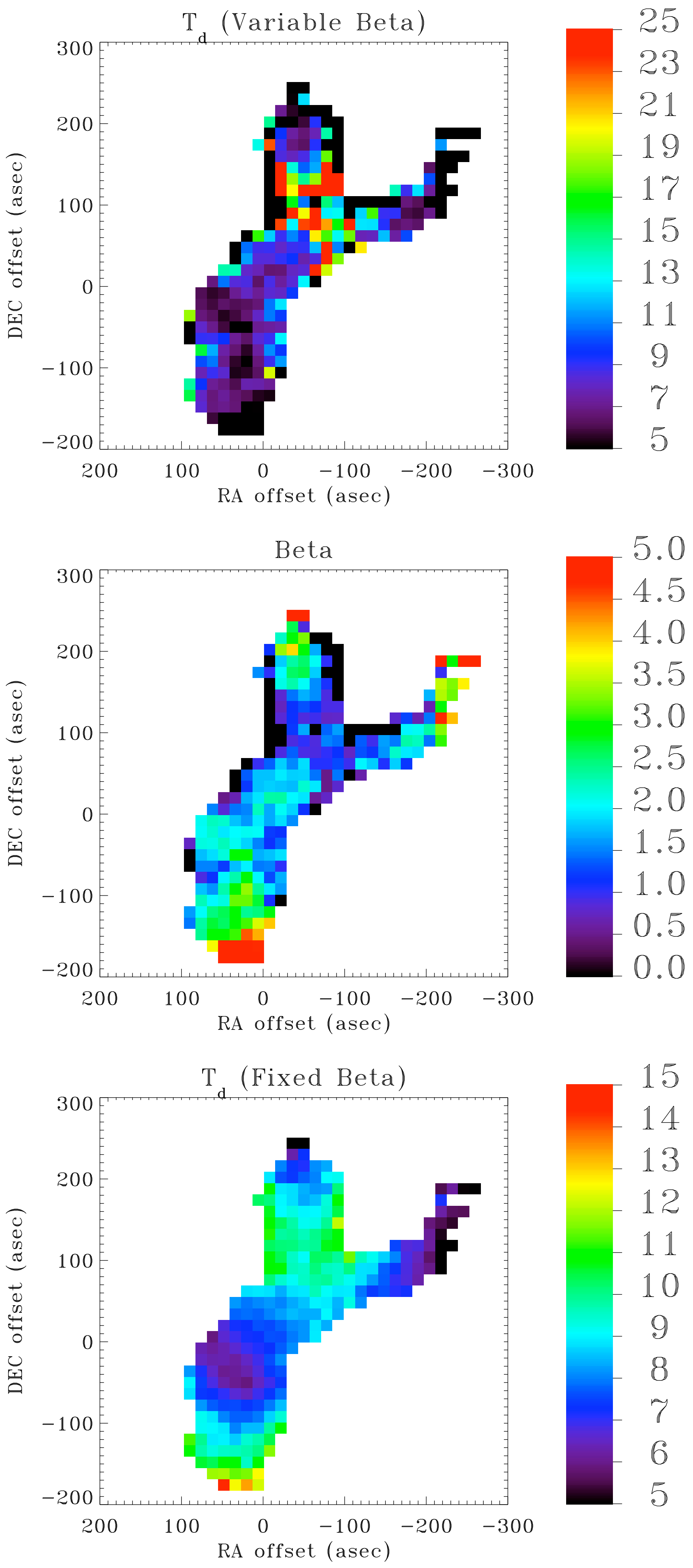


✓ ~all scatter is introduced by the assumption of isothermal dust along each line of sight

Schnee, Bethell & Goodman 2006

“Hot Sauce”
on
TMC-1C

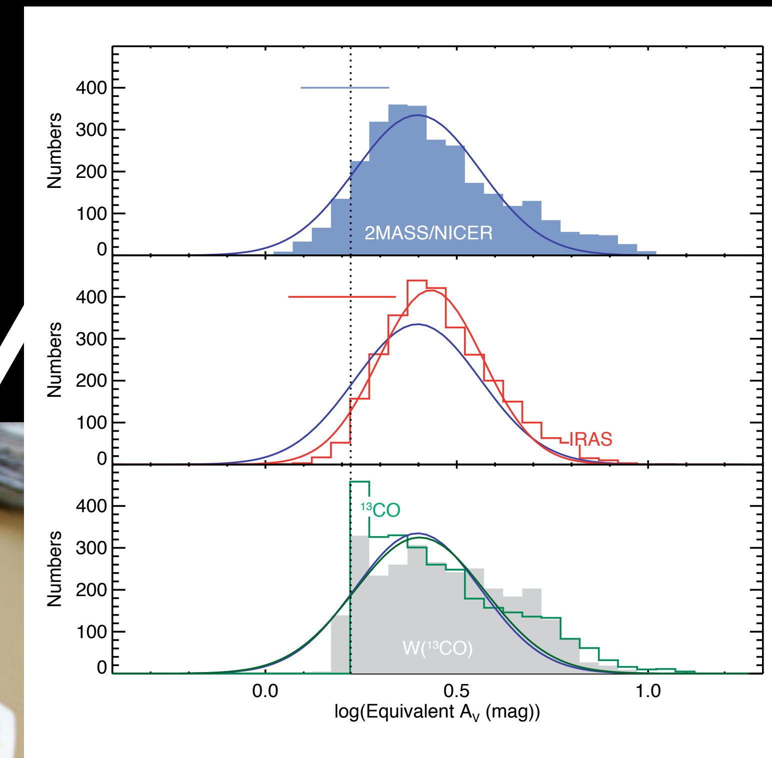
(only for those who are really ready...)



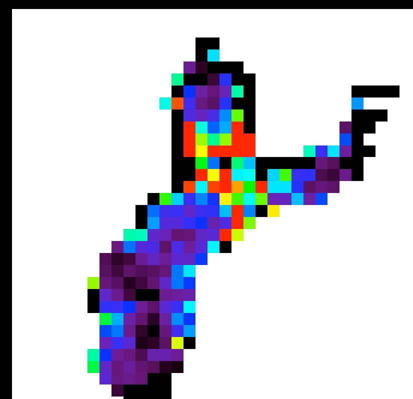
Shetty et al. 2008; Schnee et al. 2007

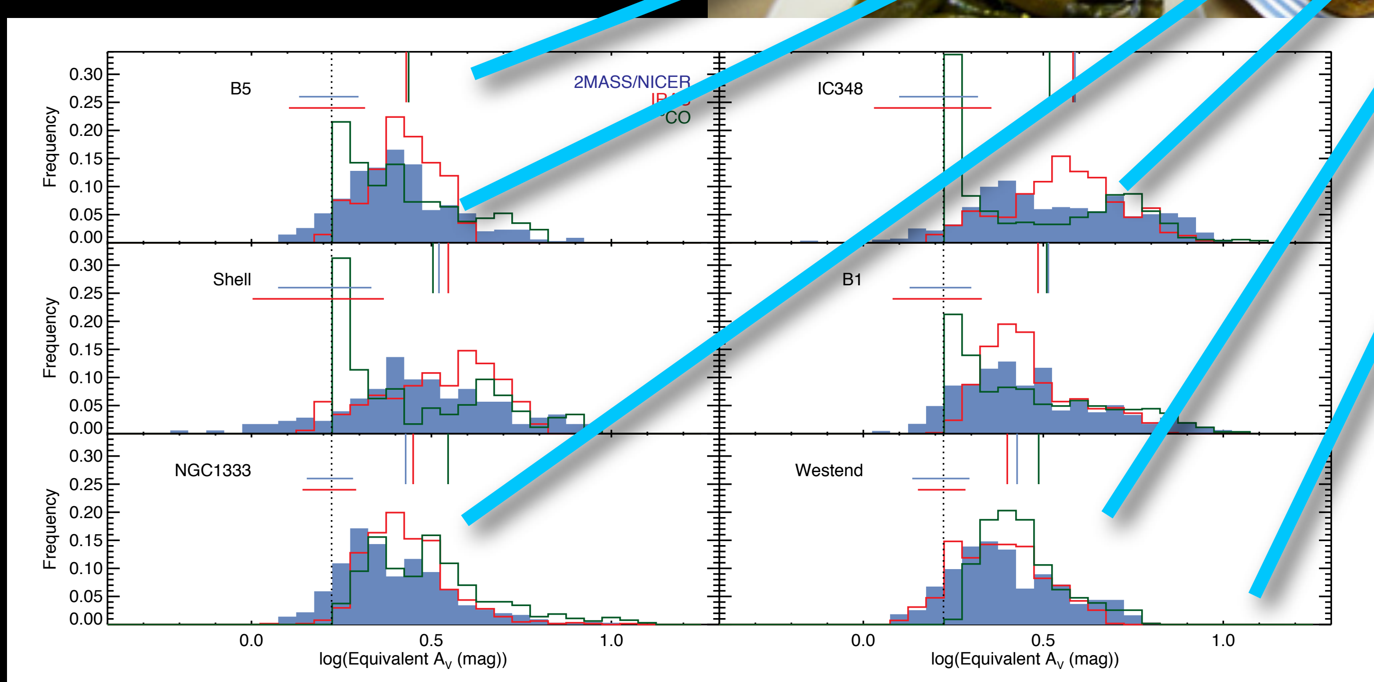
Back to the Main Dish...

Entree 1: Column Density "Lognormals?"



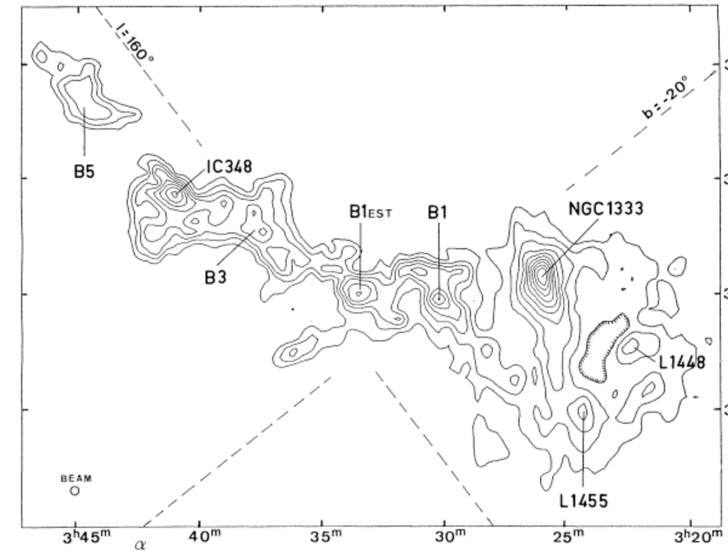
Tasty Side: "Hot Sauce"

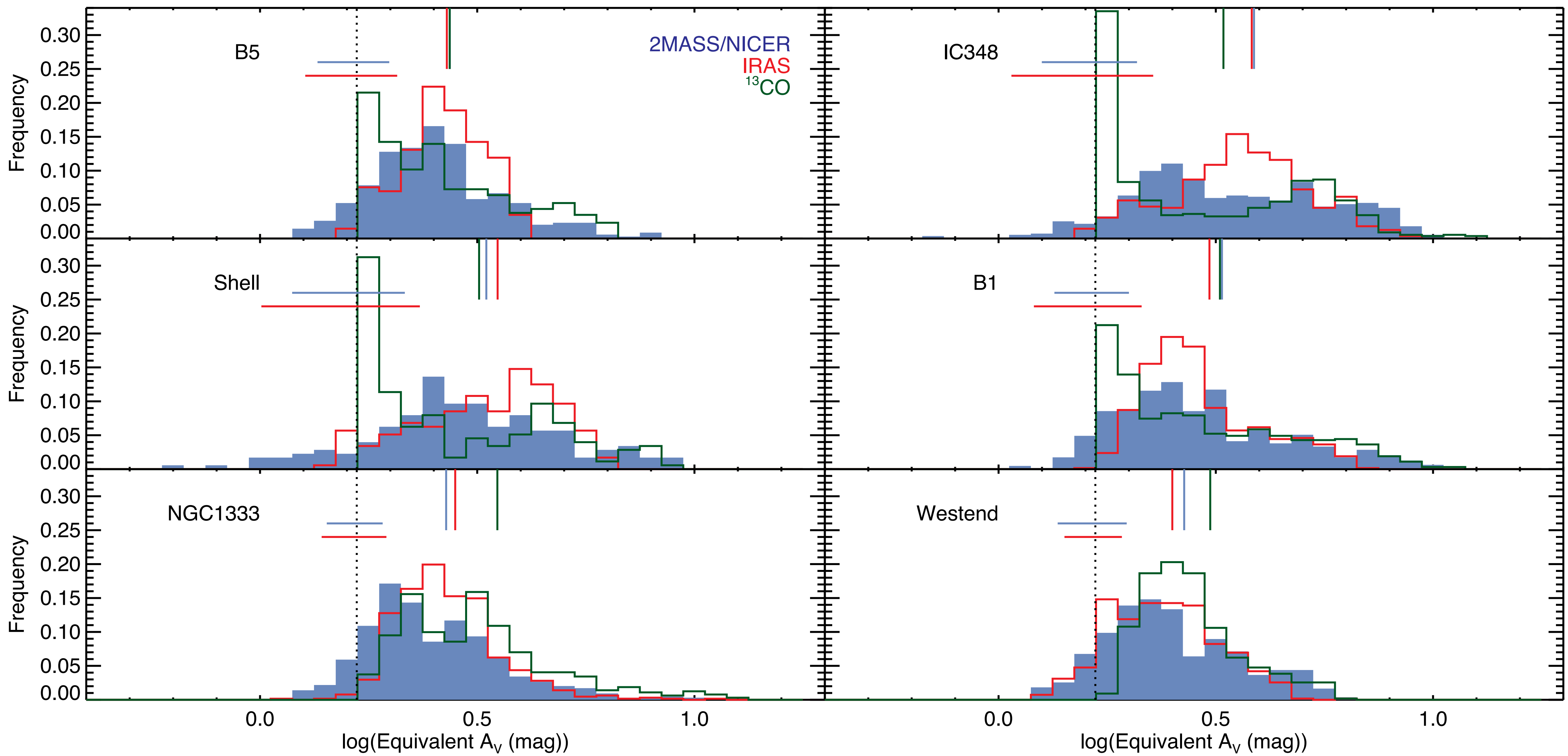




Does each ball taste different?

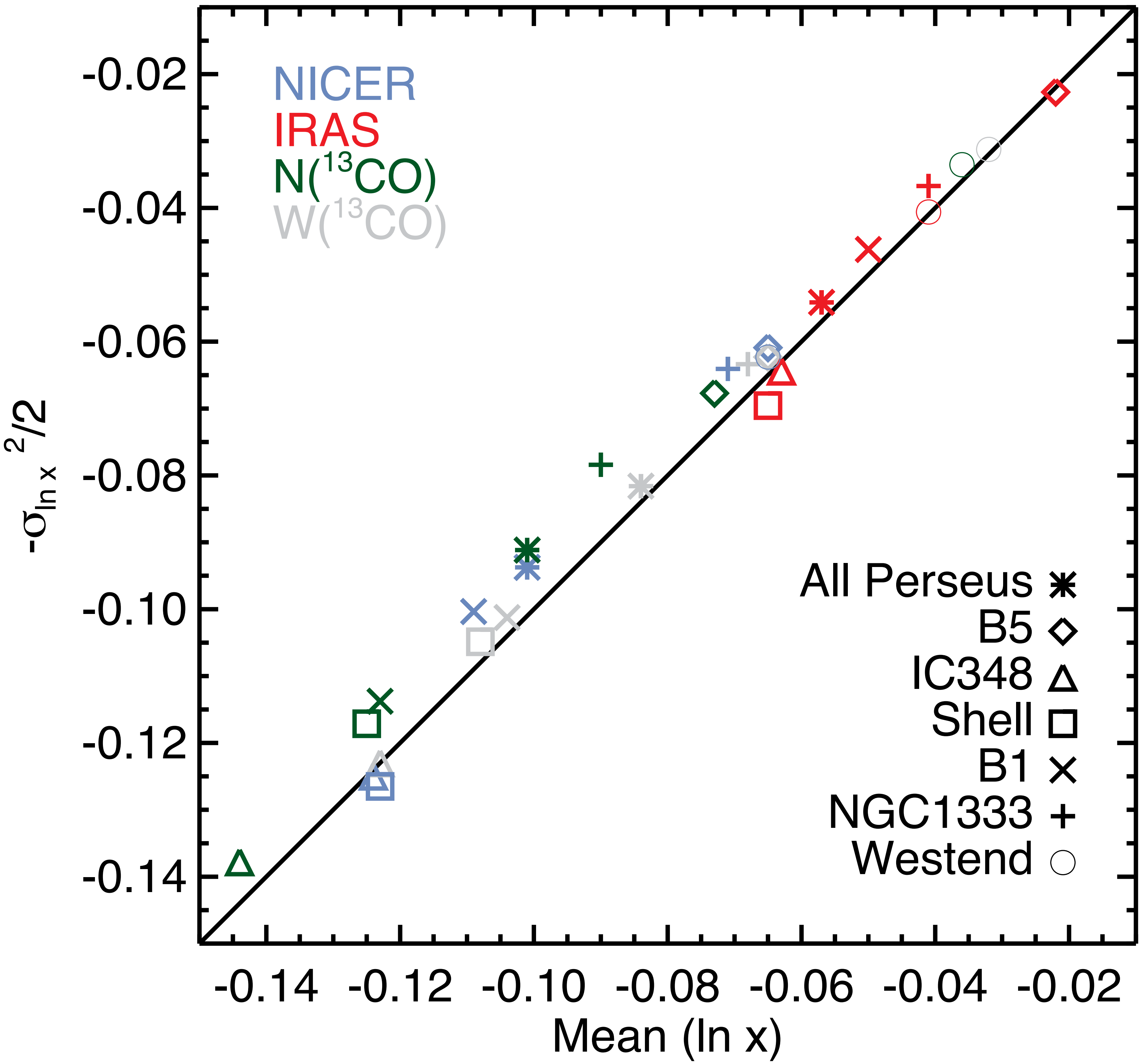
Regional Variations within Perseus





Goodman, Pineda & Schnee 2008; Pineda et al. 2008

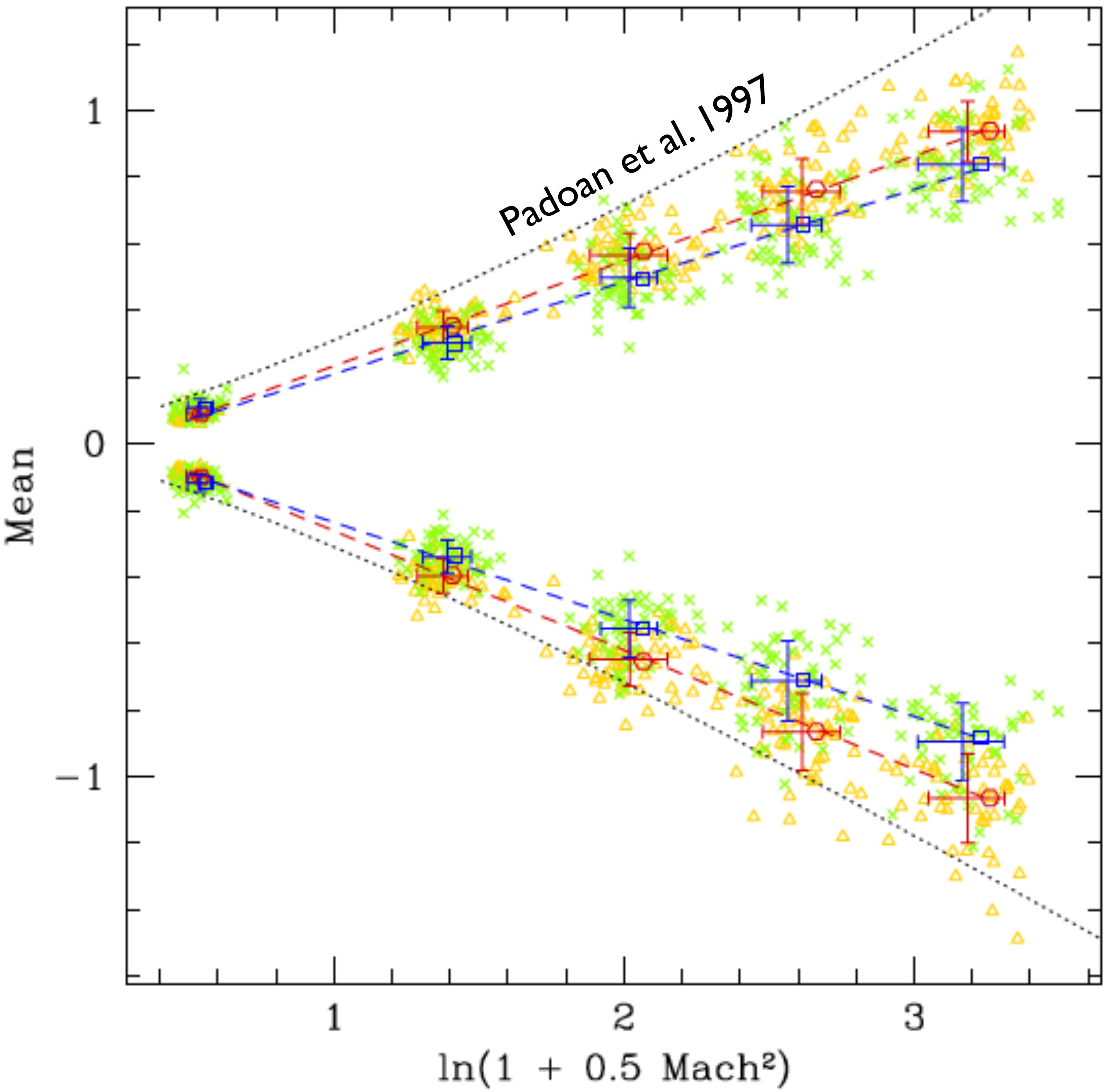
log-normal: $\overline{\ln x} = -\frac{\sigma_{lnx}^2}{2}$



Goodman, Pineda & Schnee 2008

Brand New Results from 512^3 "ATHENA" Simulations

(Lemaster & Stone 2008)



Similar level of variation seen...big enough that magnetized case **not** distinguishable from unmagnetized, using PDFs alone

driven

strong-field

sub-region

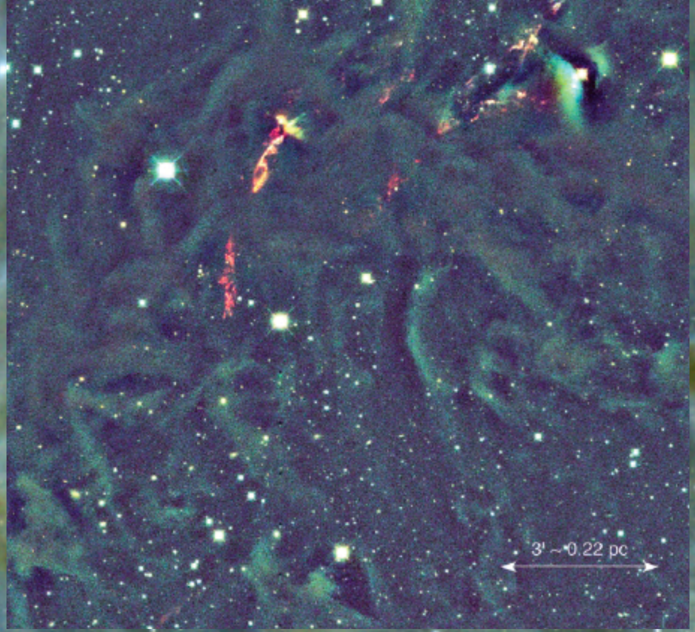
sub-region

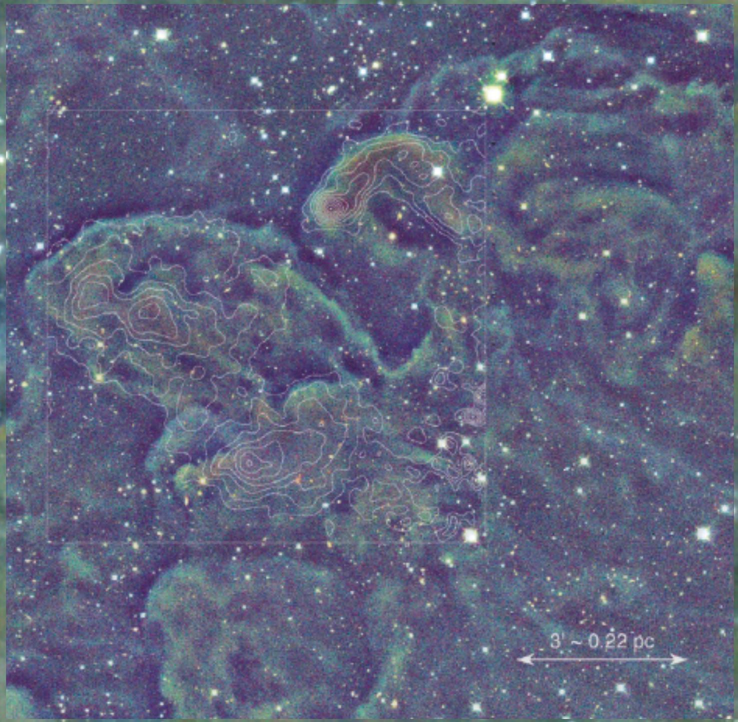
$$\overline{\ln x} = -\frac{\sigma^2_{lnx}}{2} \qquad \sigma^2_{\ln x} = \ln(1 + \beta^2 \mathscr{M}^2)\,?$$

Side dish for those with a fine palette...

Tasty Side: "Cloudshine"

Cloudshine:
(Problem for JWST)
Opportunity for Fine Dining...





Background: Jonathan Foster, CfA/COMPLETE Deep Megacam Image of West End of Perseus
Insets: Foster & Goodman 2006, Calar Alto JHK

"Cloudshine"=Scattered Ambient Starlight

2006

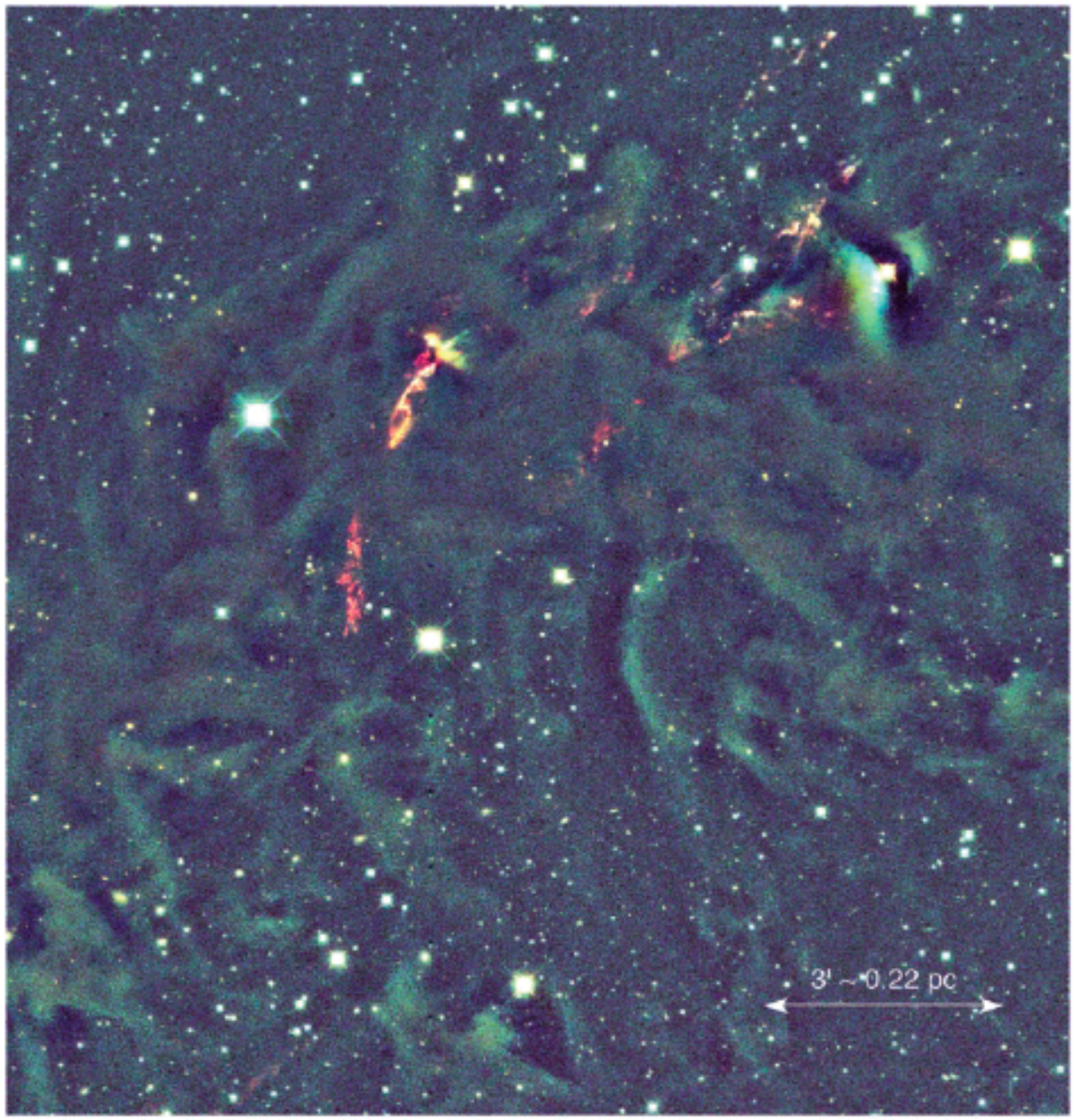


FIG. 1.—L1448 in false color. Component images have been weighted according to their flux in units of MJy sr^{-1}. J is blue, H is green, and K_s is red. Outflows from young stars glow red, while a small fan-shaped reflection nebula in the upper right is blue-green. Cloudshine, in contrast, is shown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

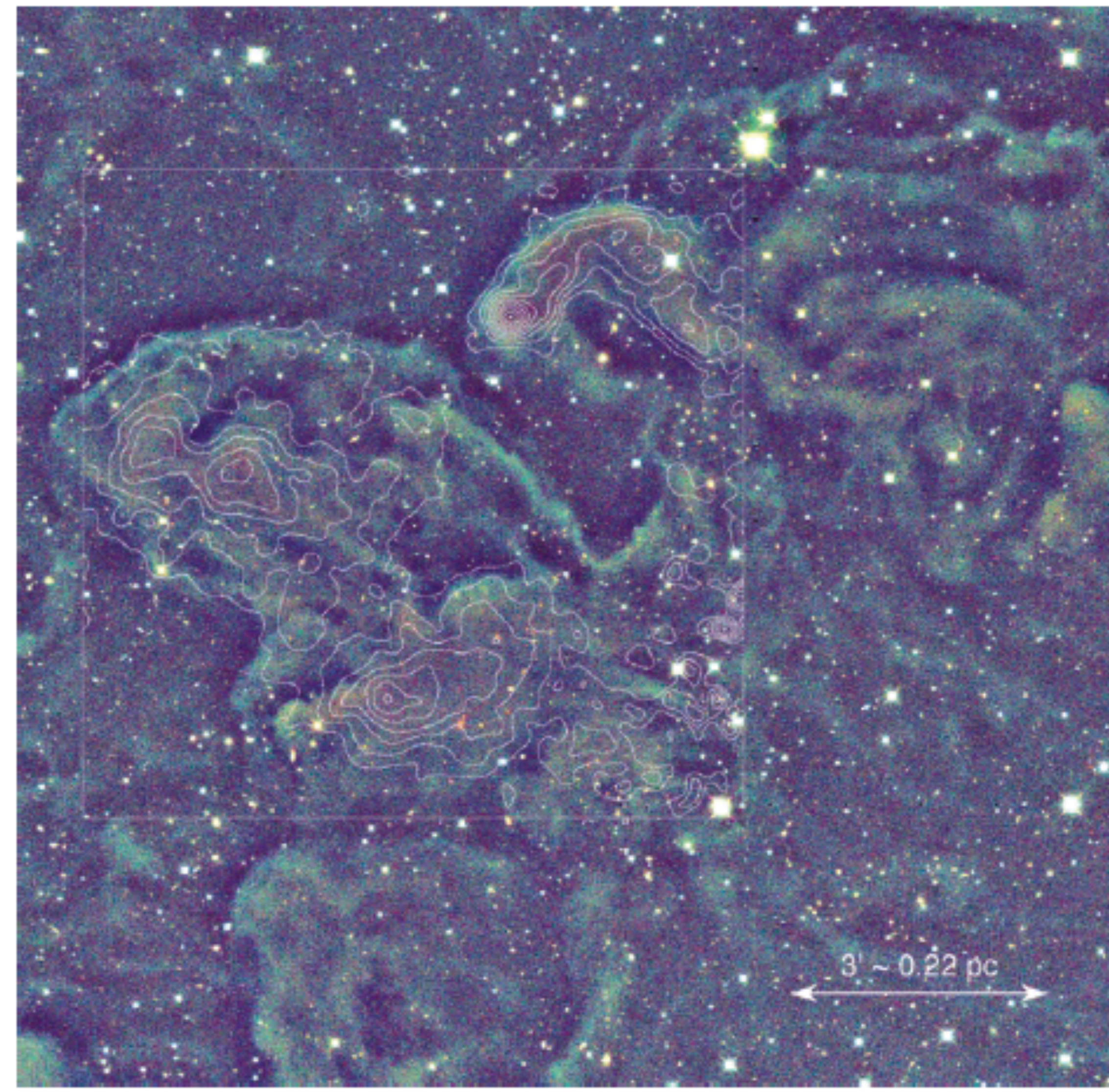
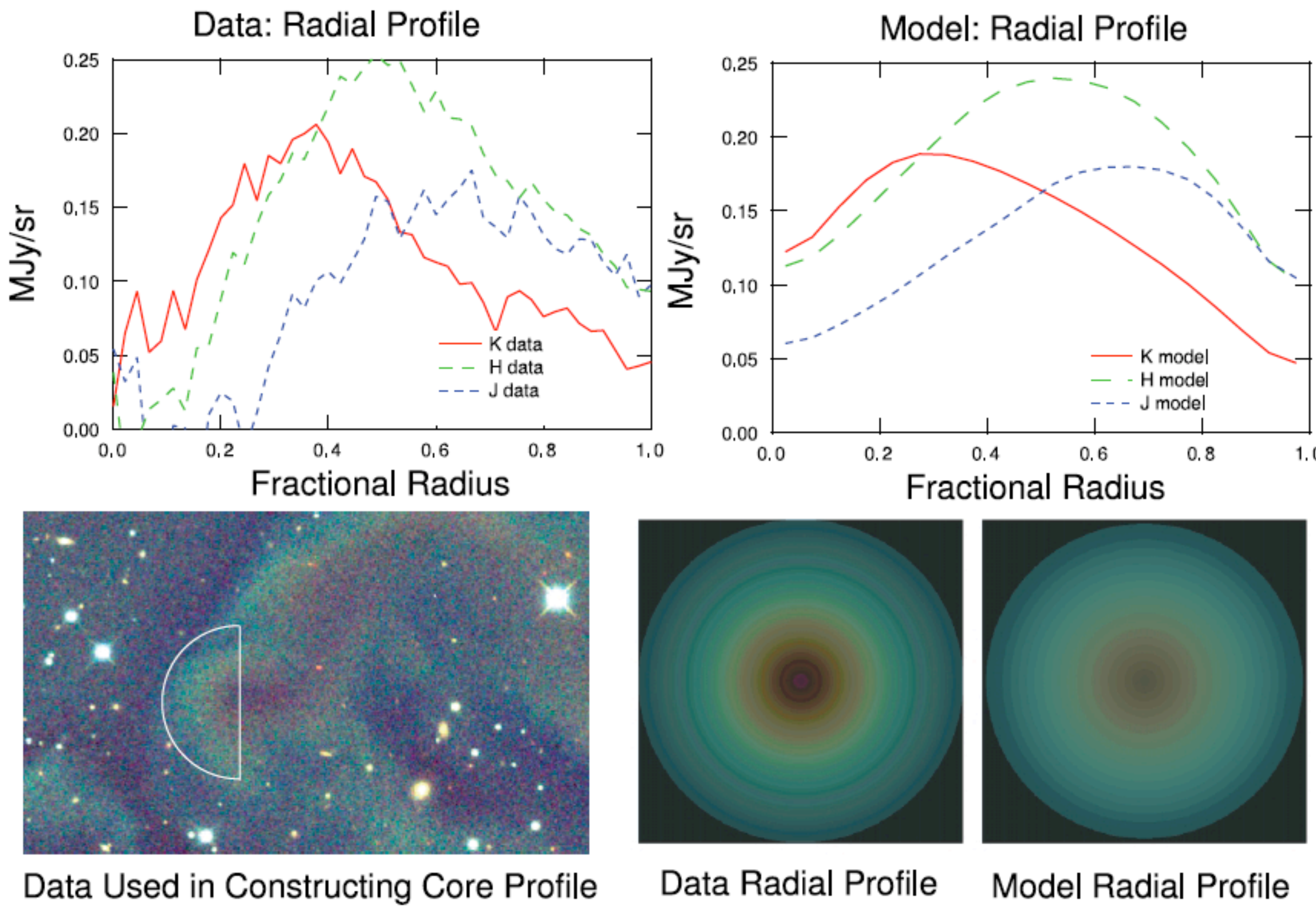


FIG. 2.—L1451 in false color. Again, each component image has been scaled to the same flux scale in units of MJy sr^{-1}; and J is blue, H is green, and K_s is red. A smaller map of 1.2 mm dust emission contours from COMPLETE (M. Tafalla 2006, in preparation) has been overlaid, showing that the color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

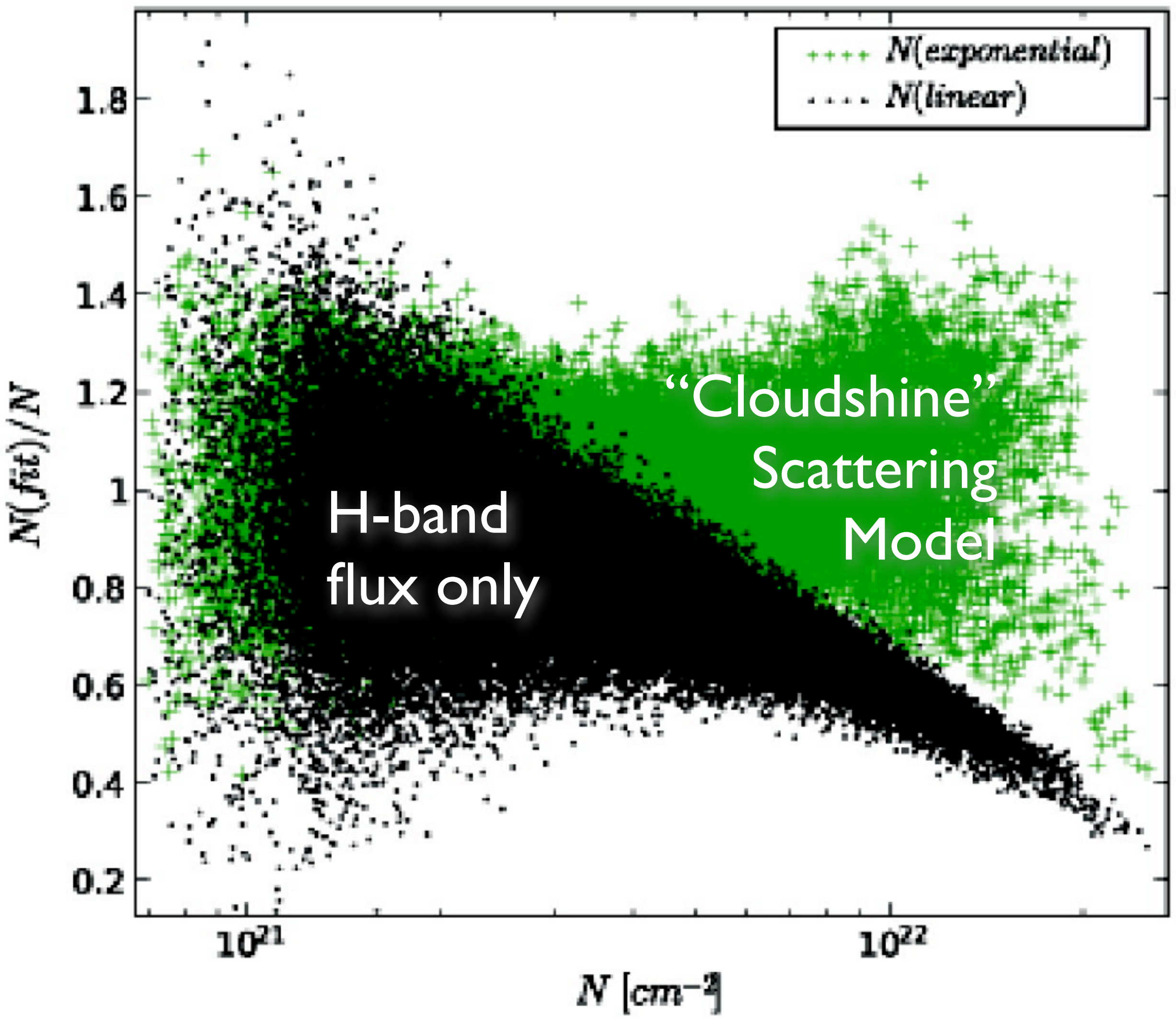
“Tasting” a Very Simple Recipe



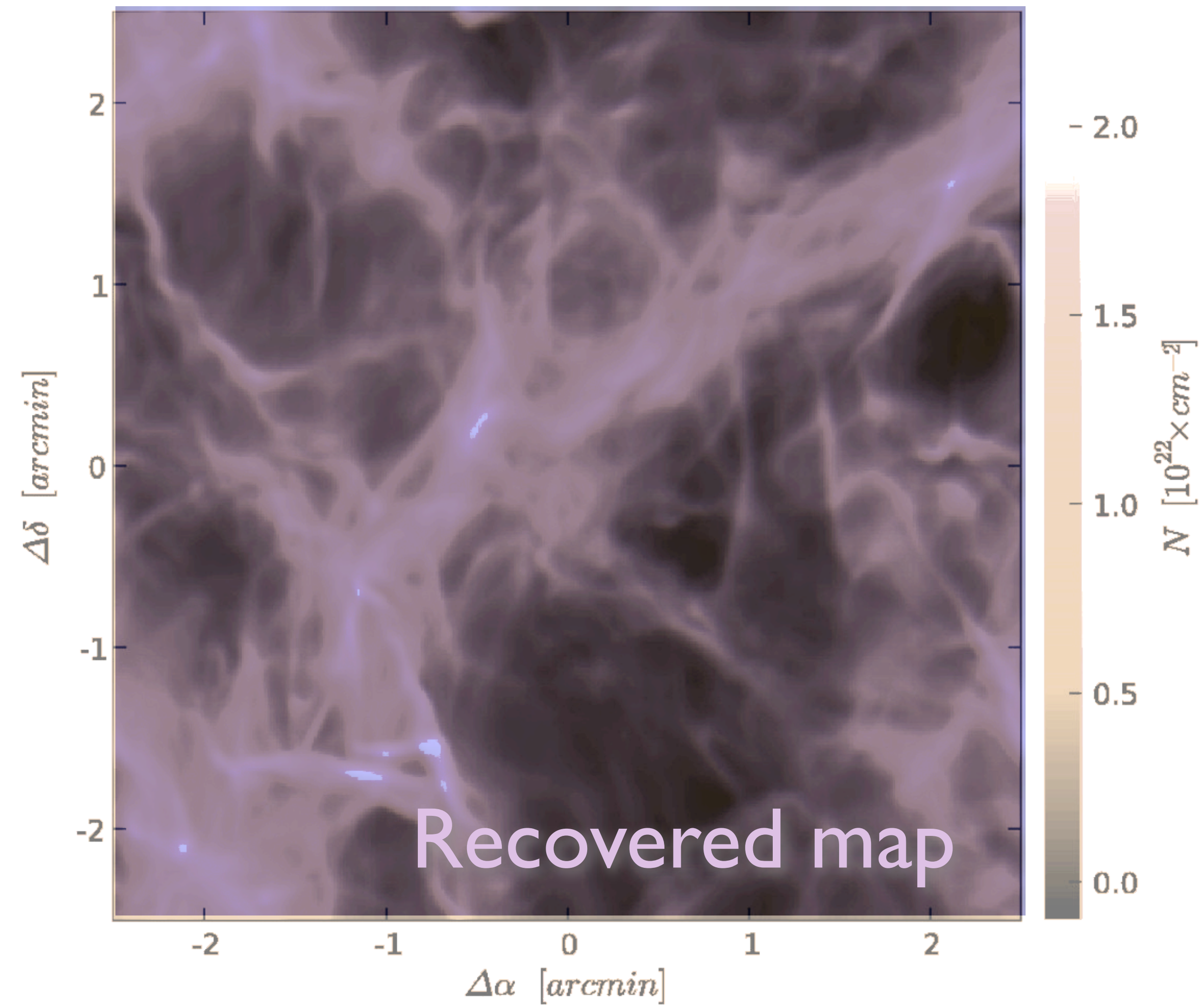
Foster & Goodman 2006

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.

Theorists doing the Tasting!



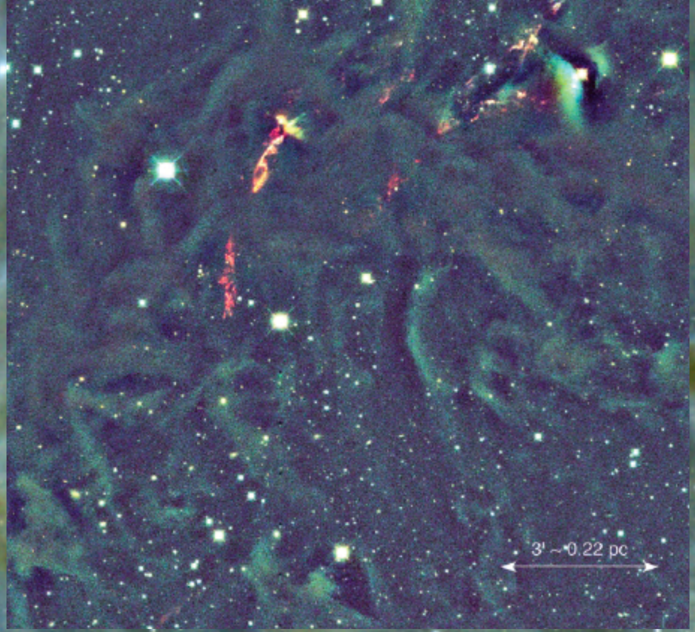
Simulation

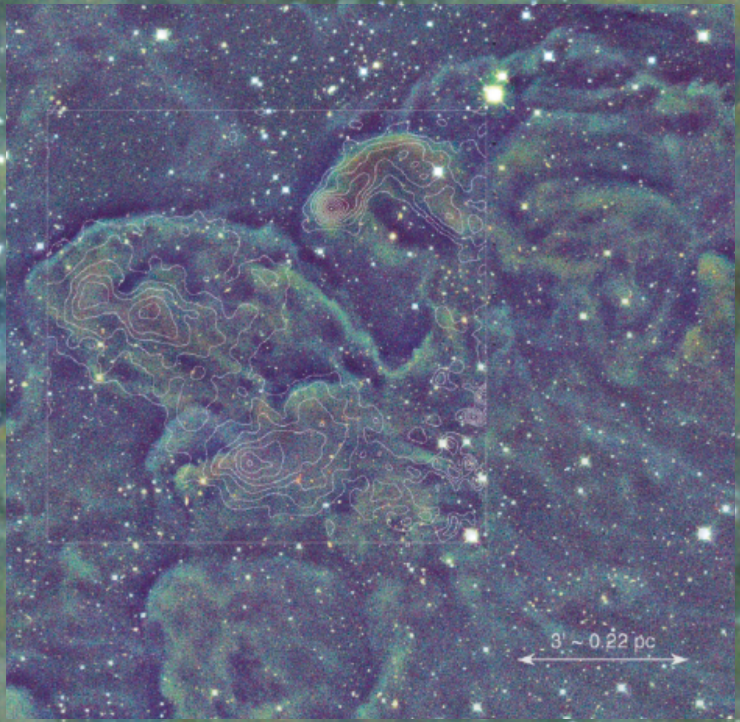


Tastes "right", with 20% scatter, at $1<A_V<10$, for NIR.

Padoan et al. 2006

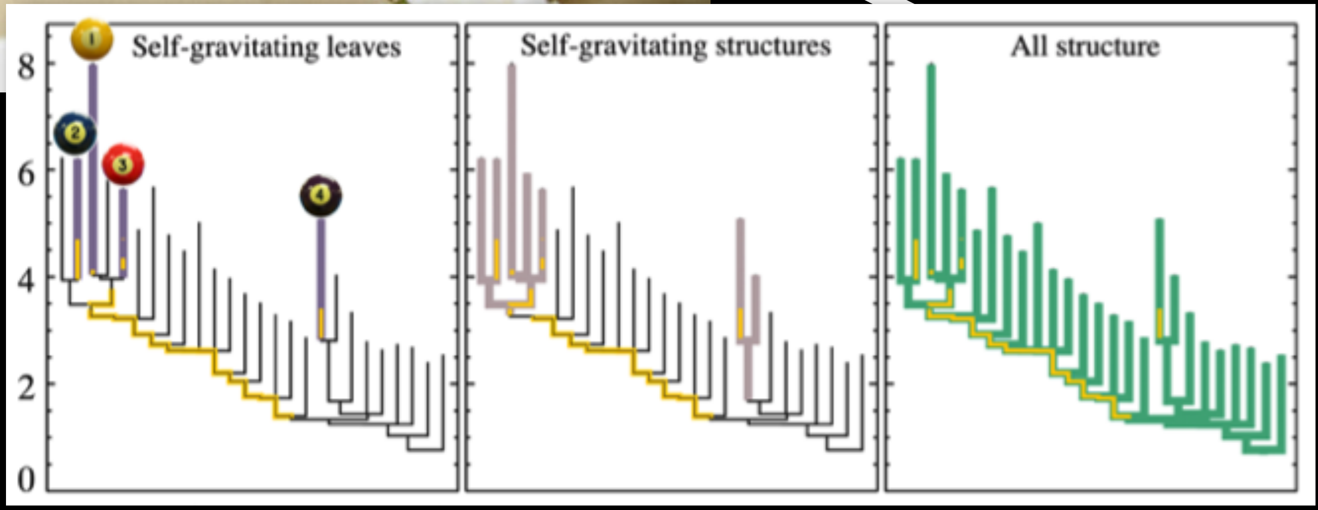
Cloudshine gives us a path to (much) higher-resolution column density maps



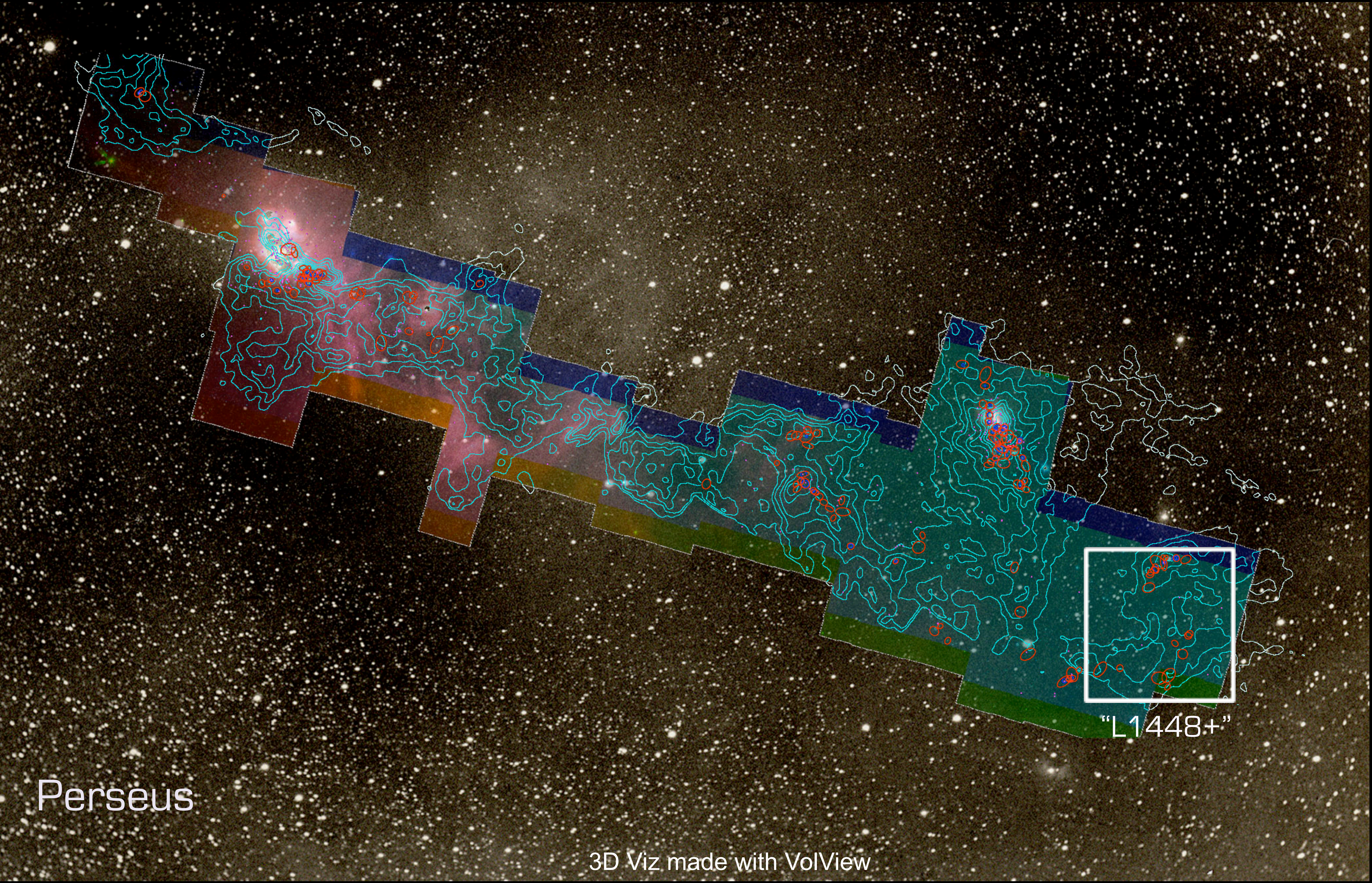


Background: Jonathan Foster, CfA/COMPLETE Deep Megacam Image of West End of Perseus
Insets: Foster & Goodman 2006, Calar Alto JHK

Let’s finish Dinner...



Entree 2: Dendrograms & Gravity



AstroMed@ IIC

COMPLETE

Tasting L1448
(The Role of Gravity)

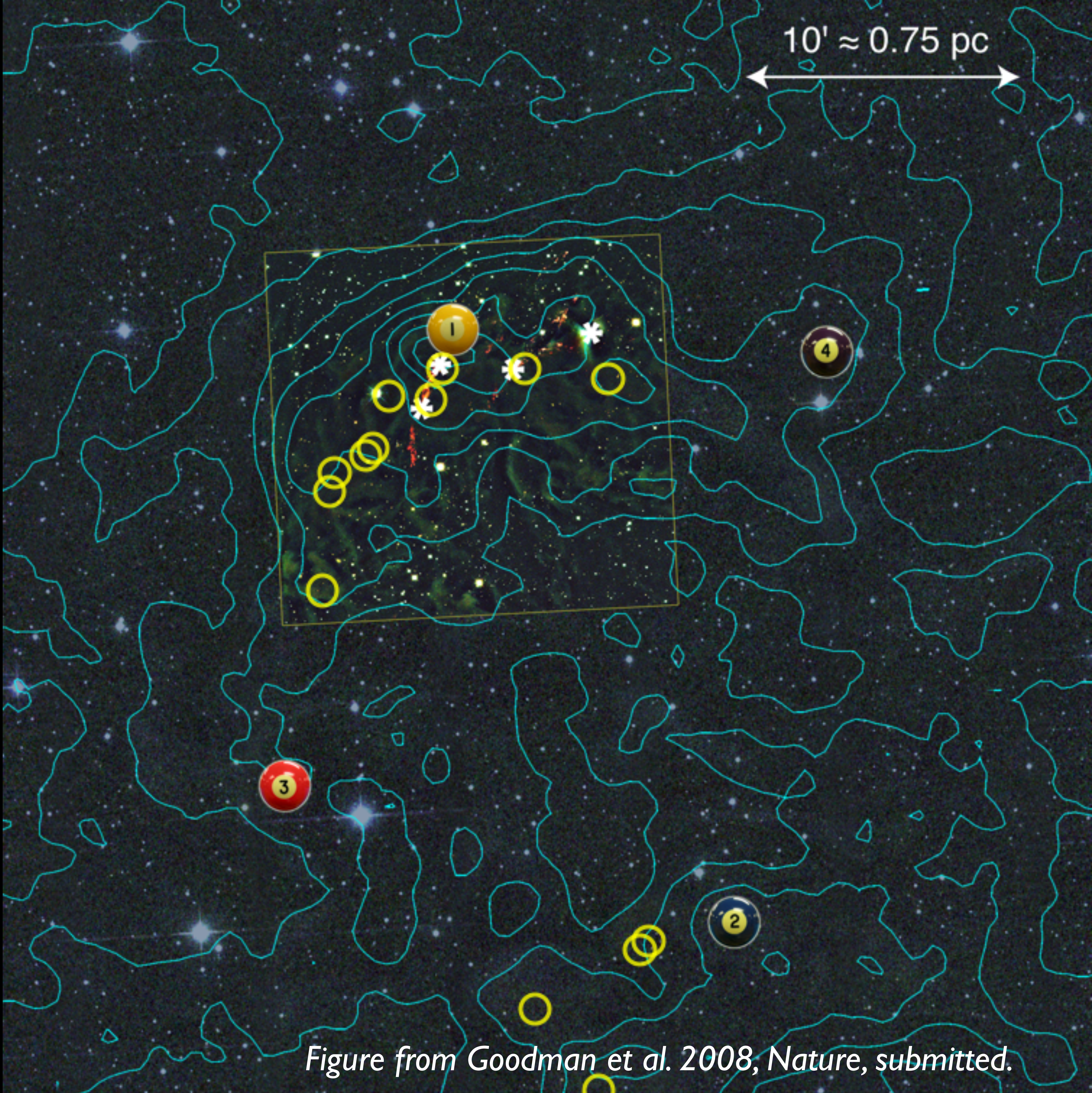
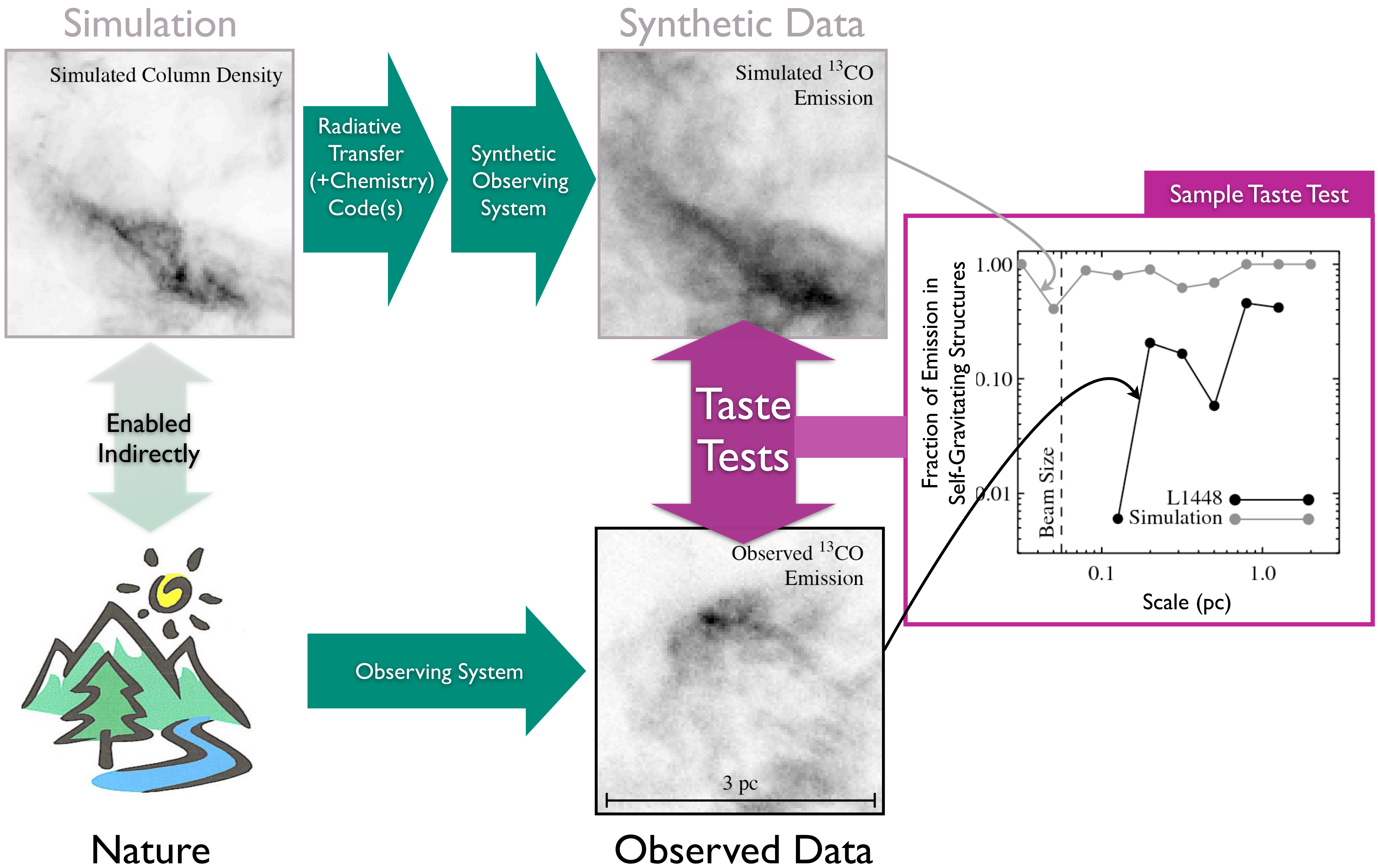
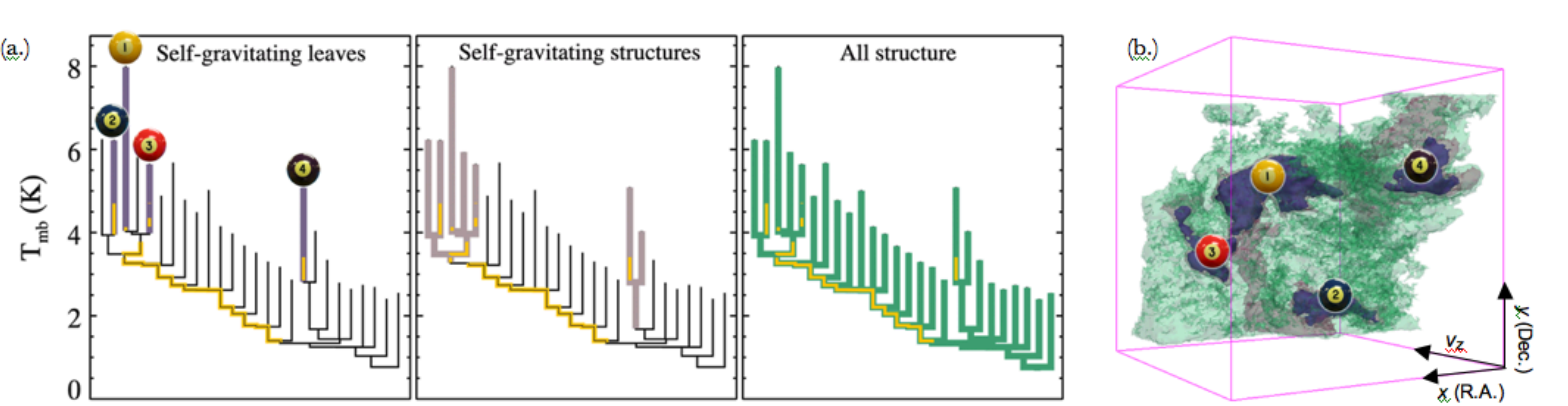


Figure from Goodman et al. 2008, Nature, submitted.

The Taste-Testing Process



Value of Dendrograms

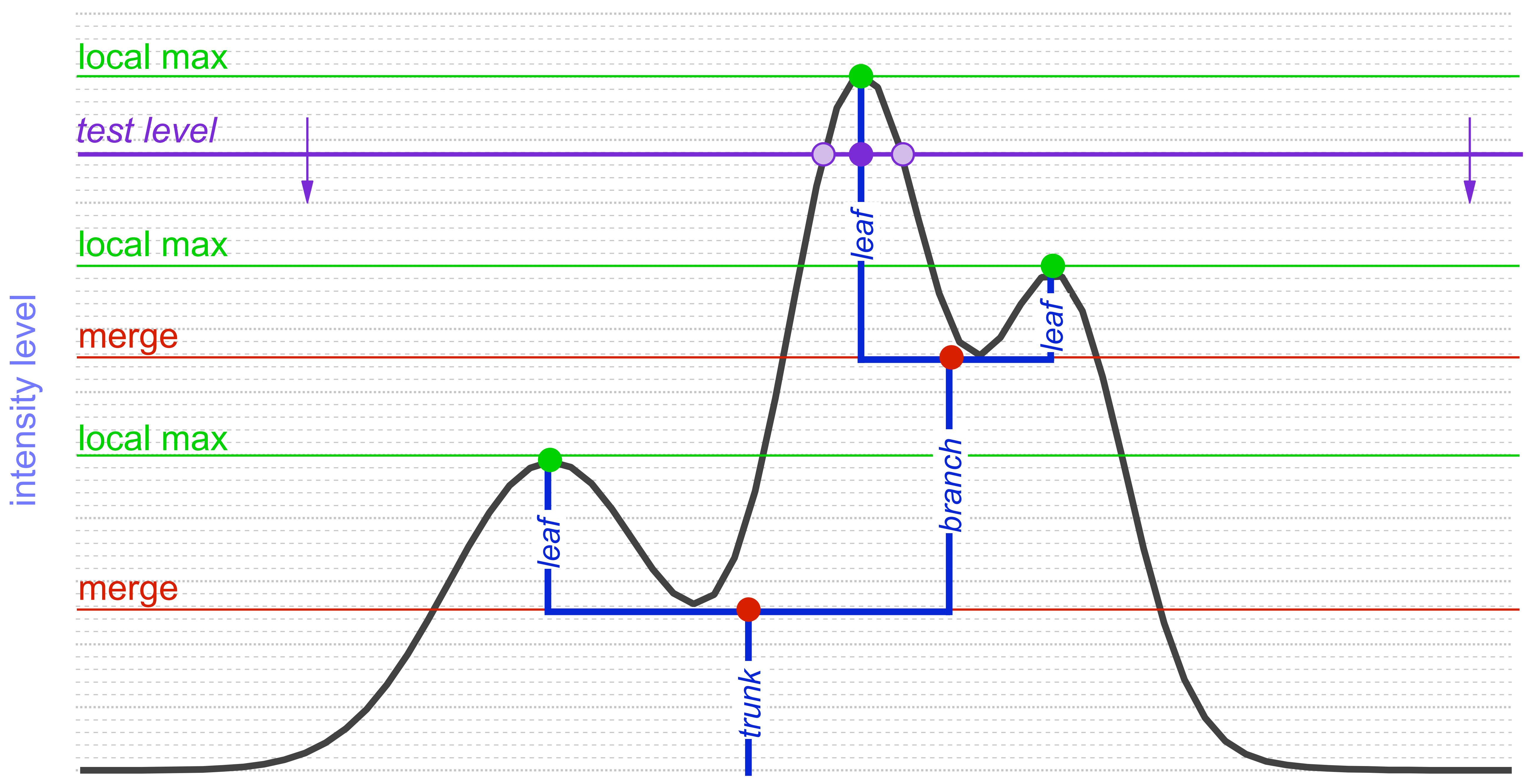


Yellow highlighting= “self-gravitating”

“Self-gravitating” here just means α_{vir} $(=5\sigma_v^2 R/GM_{lum}) < 2$
(à la Bertoldi & McKee 1992)

Rosolowsky et al. 2008 (ApJ);
Goodman et al. 2008 (Nature, submitted)

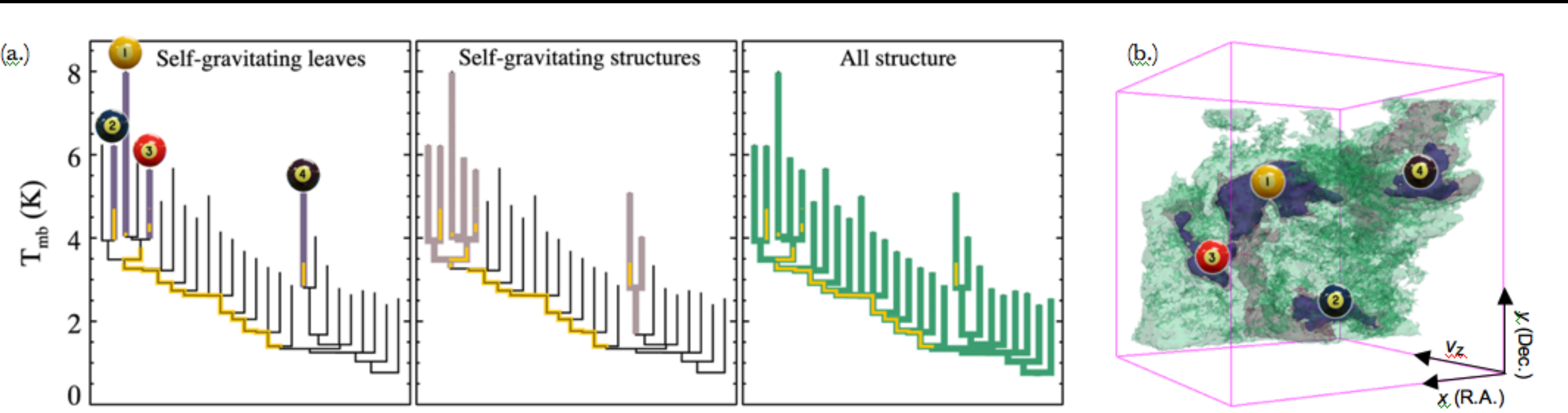
Dendrograms



1-D: points; 2-D closed curves (contours); 3-D surfaces enclosing volumes

see demo at http://aerial.client.fas.harvard.edu/~nessus/dendrostar/

Value of Dendrograms



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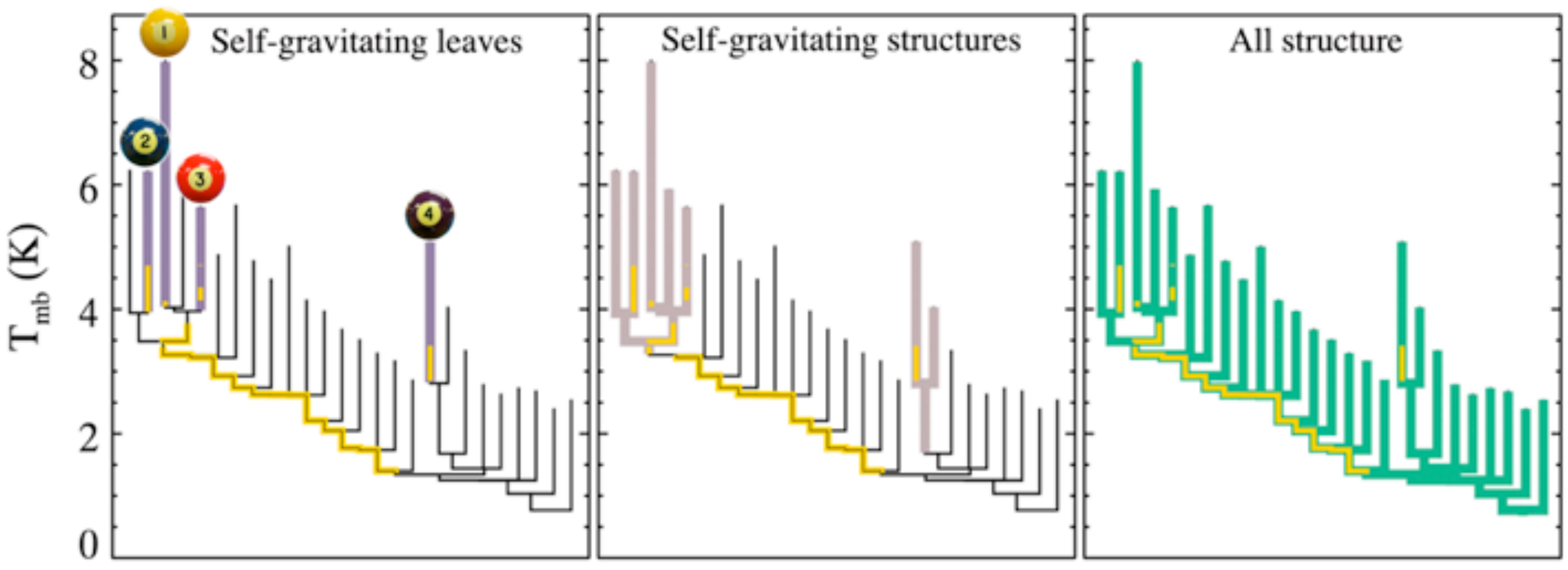
(à la Bertoldi & McKee 1992)

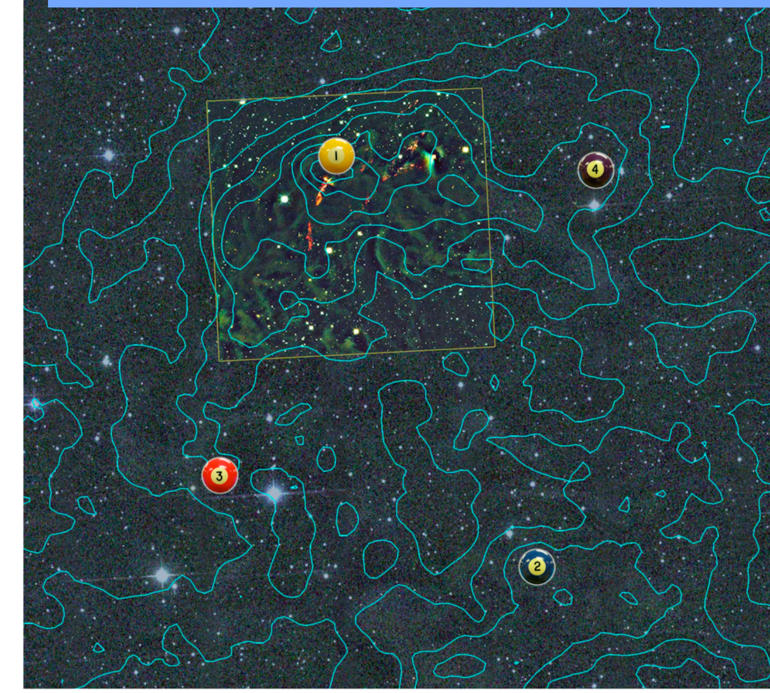
Rosolowsky et al. 2008 (ApJ);
Goodman et al. 2008 (Nature, submitted)

CLUMPFIND vs. Dendrograms: L1448

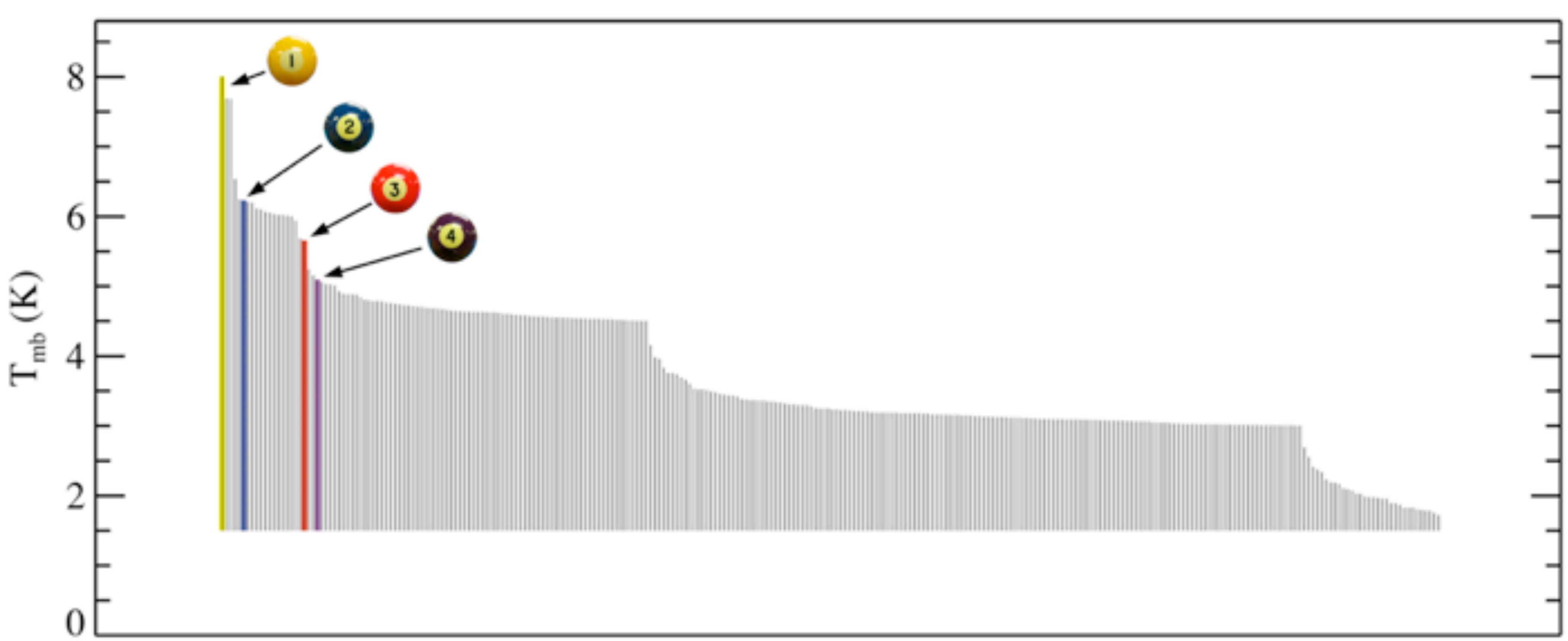


(Yellow = self-gravitating components)

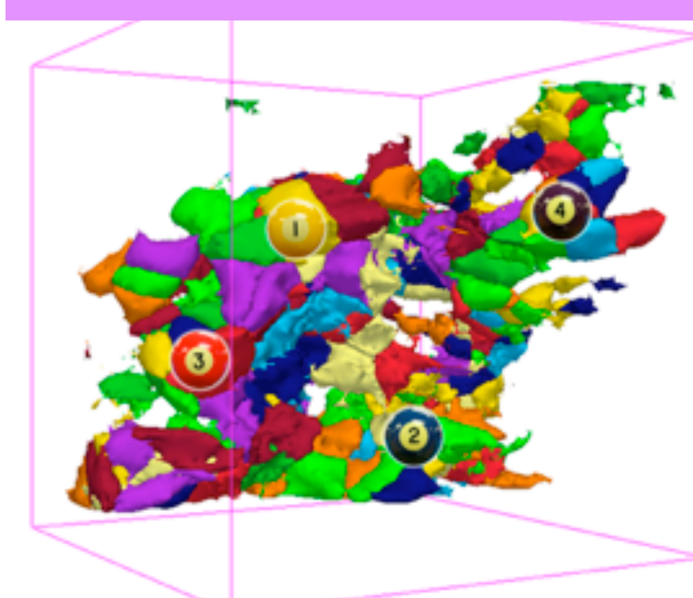
Dendrograms



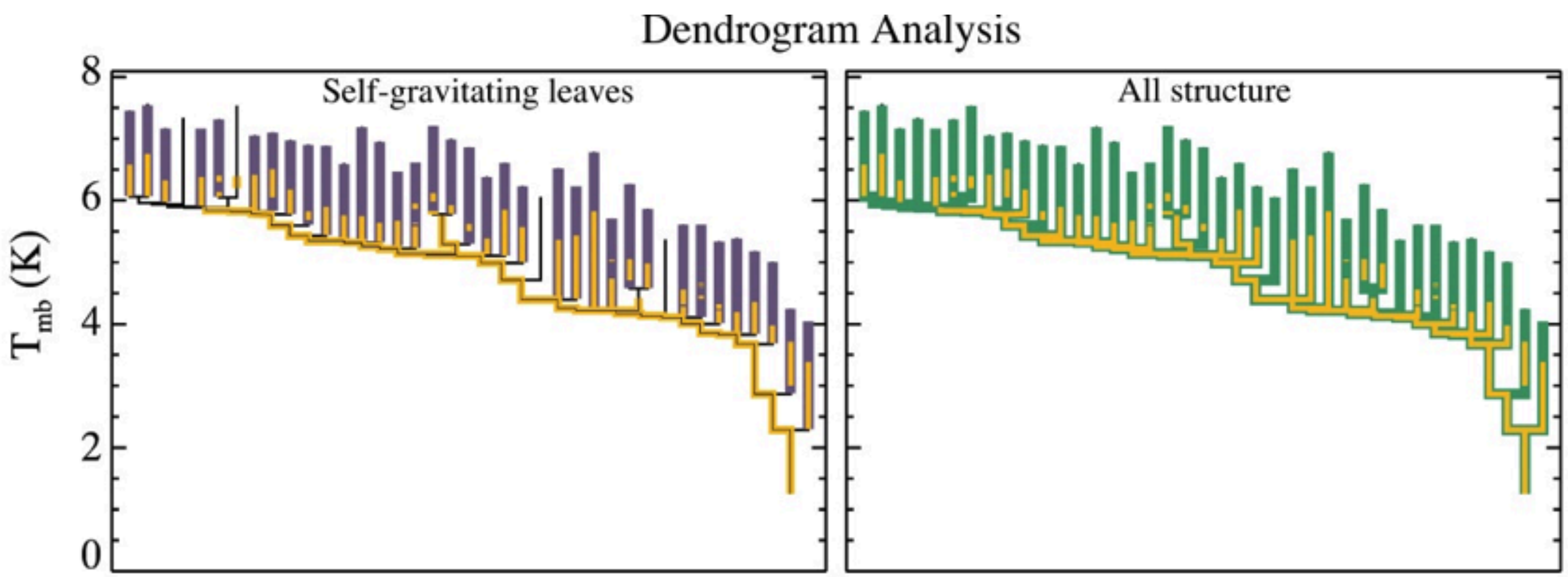
The online PDFs of these insets



"CLUMPFIND"

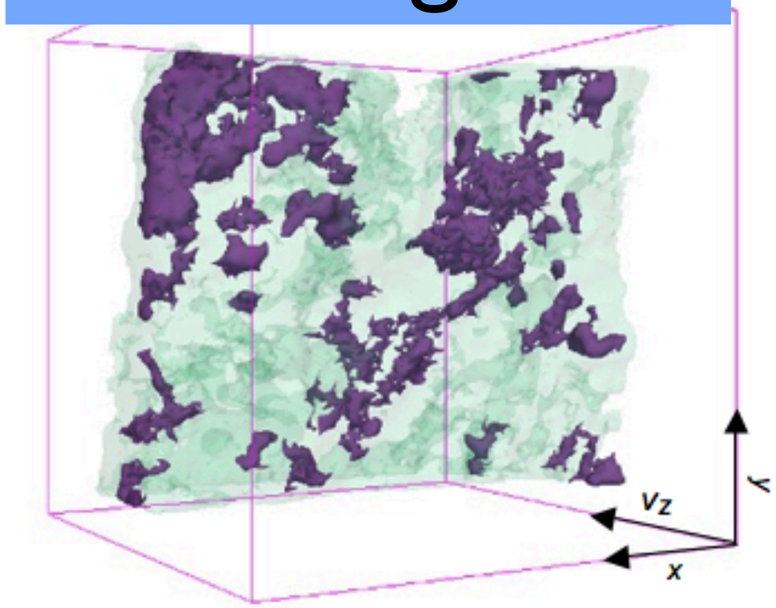


CLUMPFIND vs. Dendrograms: Synthetic Data

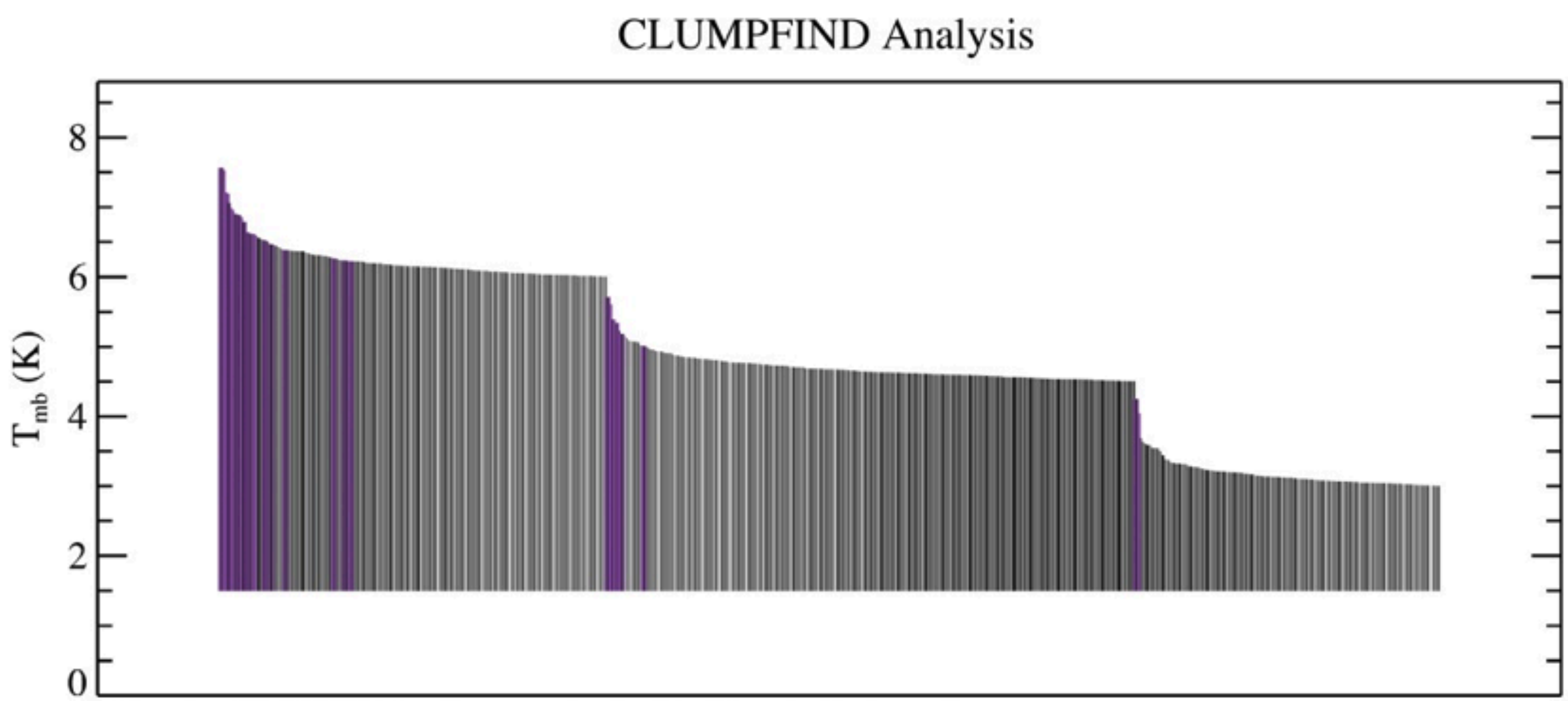


(Yellow = self-gravitating components)

Dendrograms

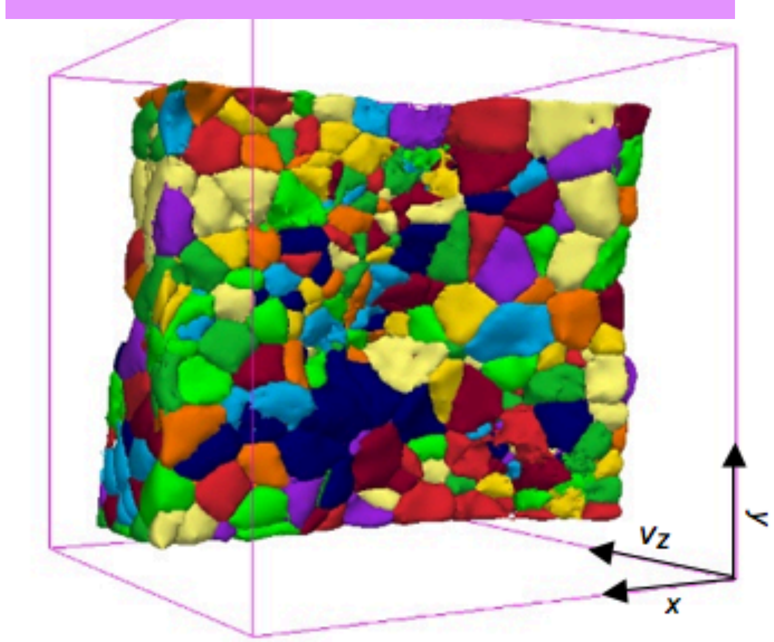


The online PDFs of these insets are interactive, offer additional surfaces, and can be rotated and manipulated by

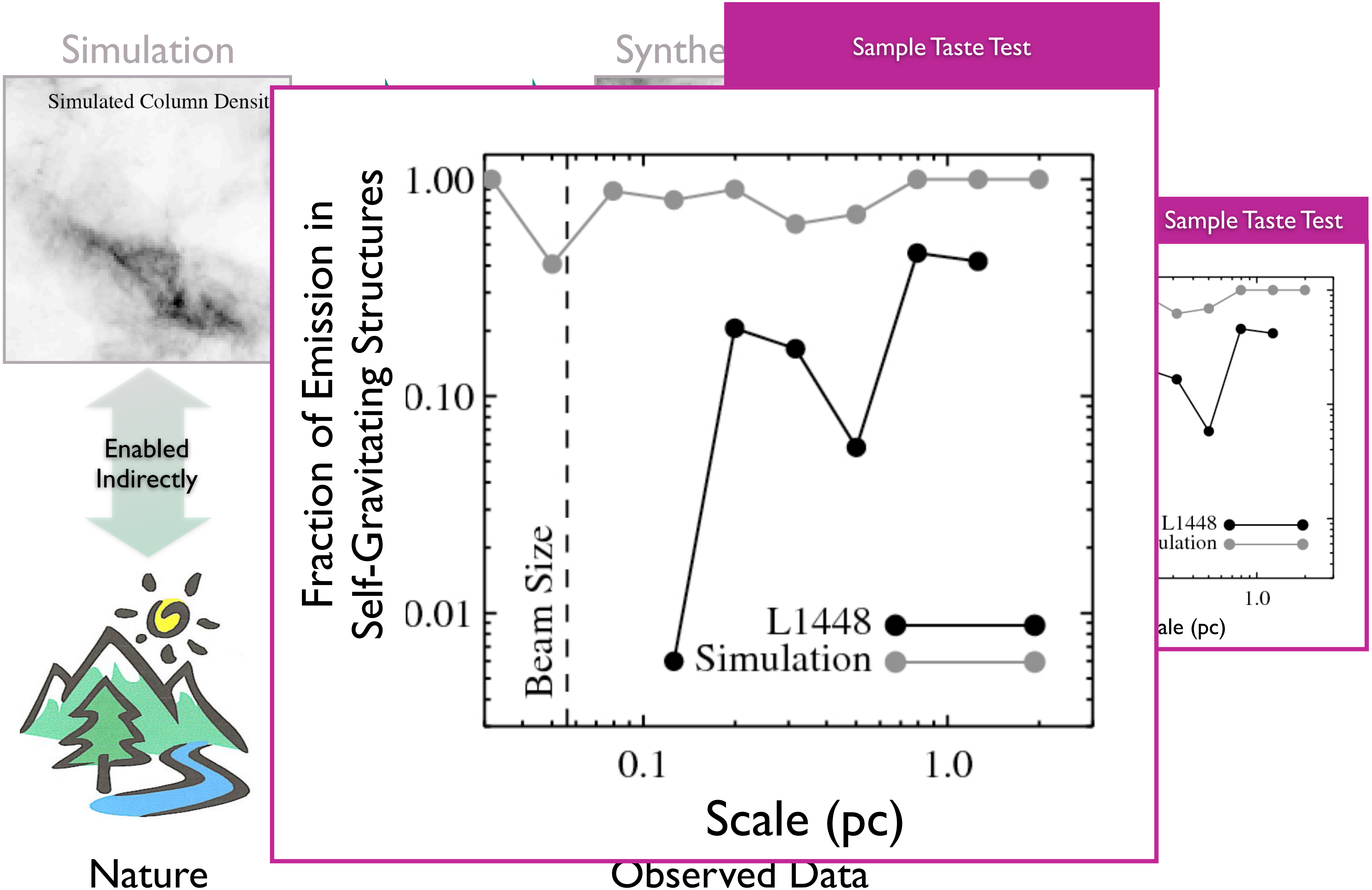


(Purple = CLUMPFIND regions associated with self-gravitating leaves)

"CLUMPFIND"



Taste-Testing Gravity



A tasty challenge from Frank Shu...

Star Formation Taste Tests > All Messages

https://iic.grouphub.com/projects/700257/msg/all

Back to Dashboard | Switch to a different project

Star Formation Taste Tests CfA

Overview | Messages | To-Do | Milestones | Writeboards | Chat | Time | Files

All Messages

Expanded view | List view

THURSDAY, 19 JUNE 2008

Column Density Paper

A paper entitled: "The "True" Column Density Distribution in Star-Forming Molecular Clouds", by Goodman, Pineda & Schnee, is now available, on astro-ph, at http://adsabs.harvard.edu/cgi-bin/nph-data_query?bibcode=2008arXiv0806.3441G&db_key=PRE&link_type=ABSTRACT&high=485efe37dd27343. Here's a copy.

goodman_pineda_schnee08.pdf (PDF, 927K)

Posted by Rahul Shetty in Publications | Edit | Post the first comment

THURSDAY, 10 APRIL 2008

Frank Shu's "Test of the Test" Idea: Are Dendrogram Identified Cores really Self-Gravitating?

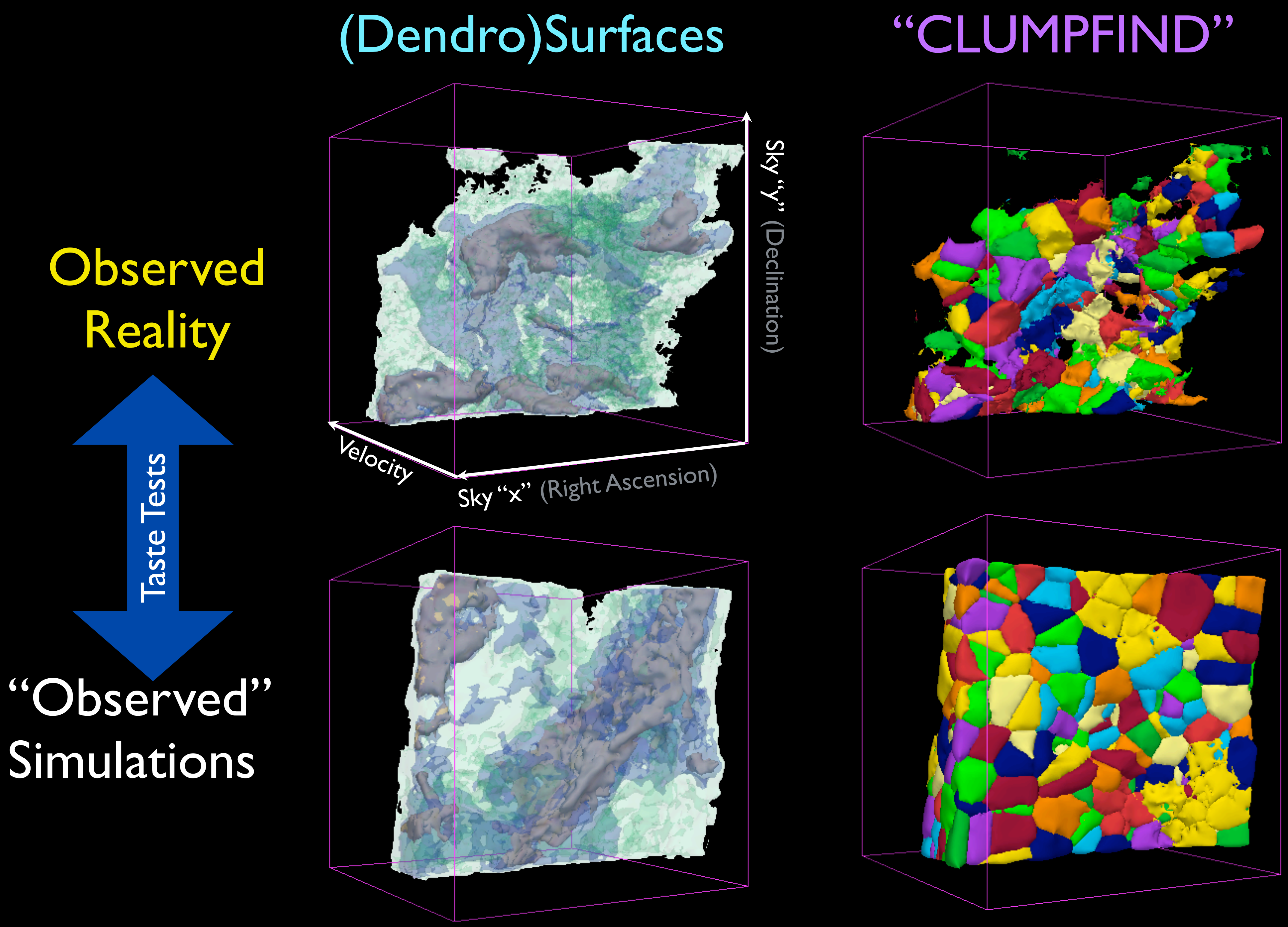
We have been investigating the use of Dendrograms (http://arxiv.org/abs/0802.2944) to identify self-gravitating regions in molecular clouds. As a test, Frank Shu has suggested that we apply this method to simulation cubes of molecular clouds. We can perform a dendrogram analysis on simulation cubes at early times, before the clumps have completely collapsed. We will then verify whether the dendrogram identified self-gravitating clumps do indeed collapse by inspecting the simulation cubes at later times. In order to carry out this test, we are requesting simulation data cubes of star forming clouds (where the calculation of self-gravity is included); we would certainly appreciate a wide variety of simulations for a thorough test of the dendrogram analysis. Please let us know if you are able to contribute your simulation data cubes for this test. We are also happy to collaborate if you'd like to go through this kind of analysis with us together.

Posted by Rahul Shetty in Collaboration Projects | Edit | Post the first comment

TUESDAY, 1 APRIL 2008

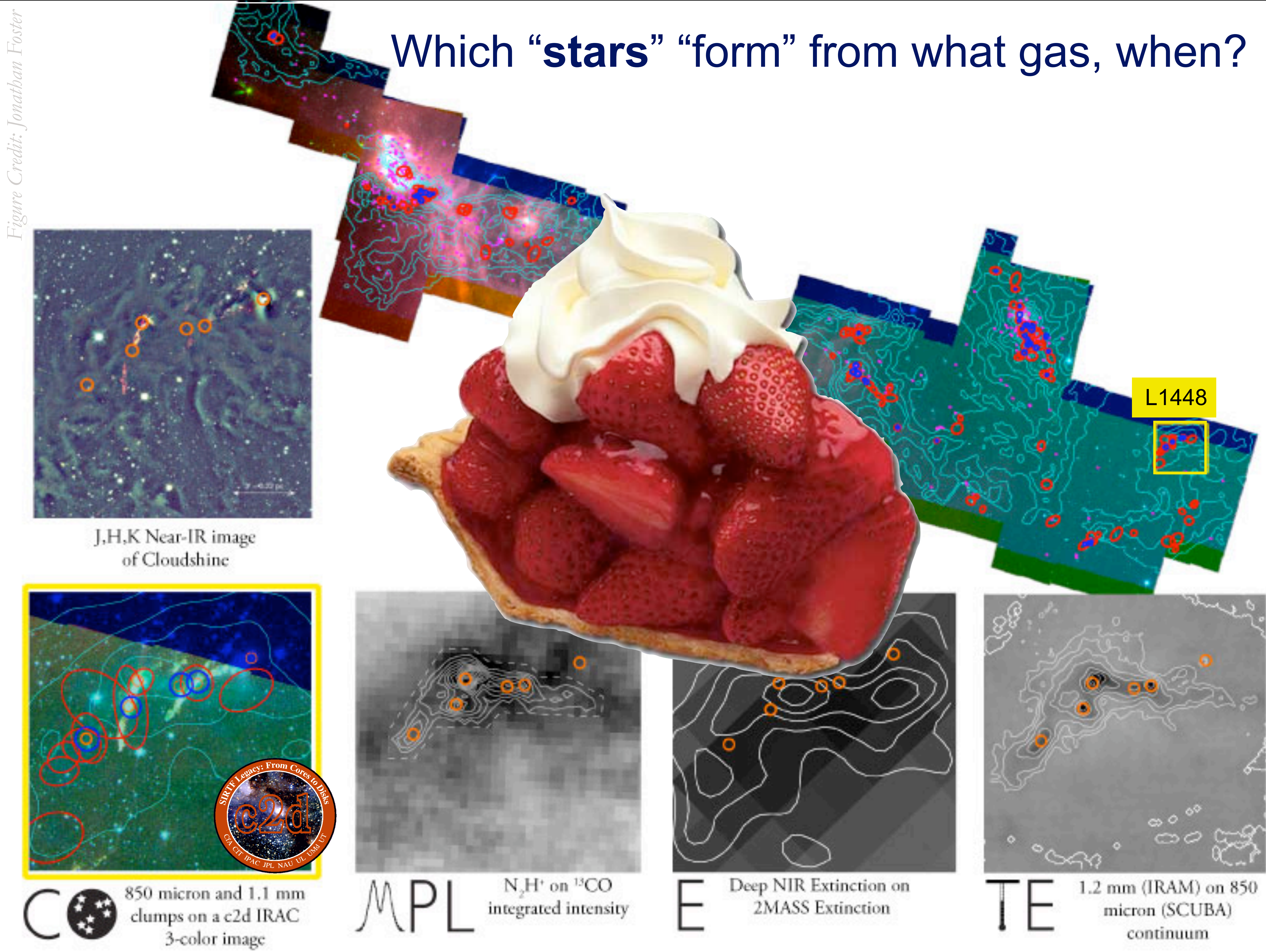
Cosmic Dust & Radiative Transfer
a workshop devoted to radiative transfer coding

Either Algorithm is an Example of Tasting in Observational-Space



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

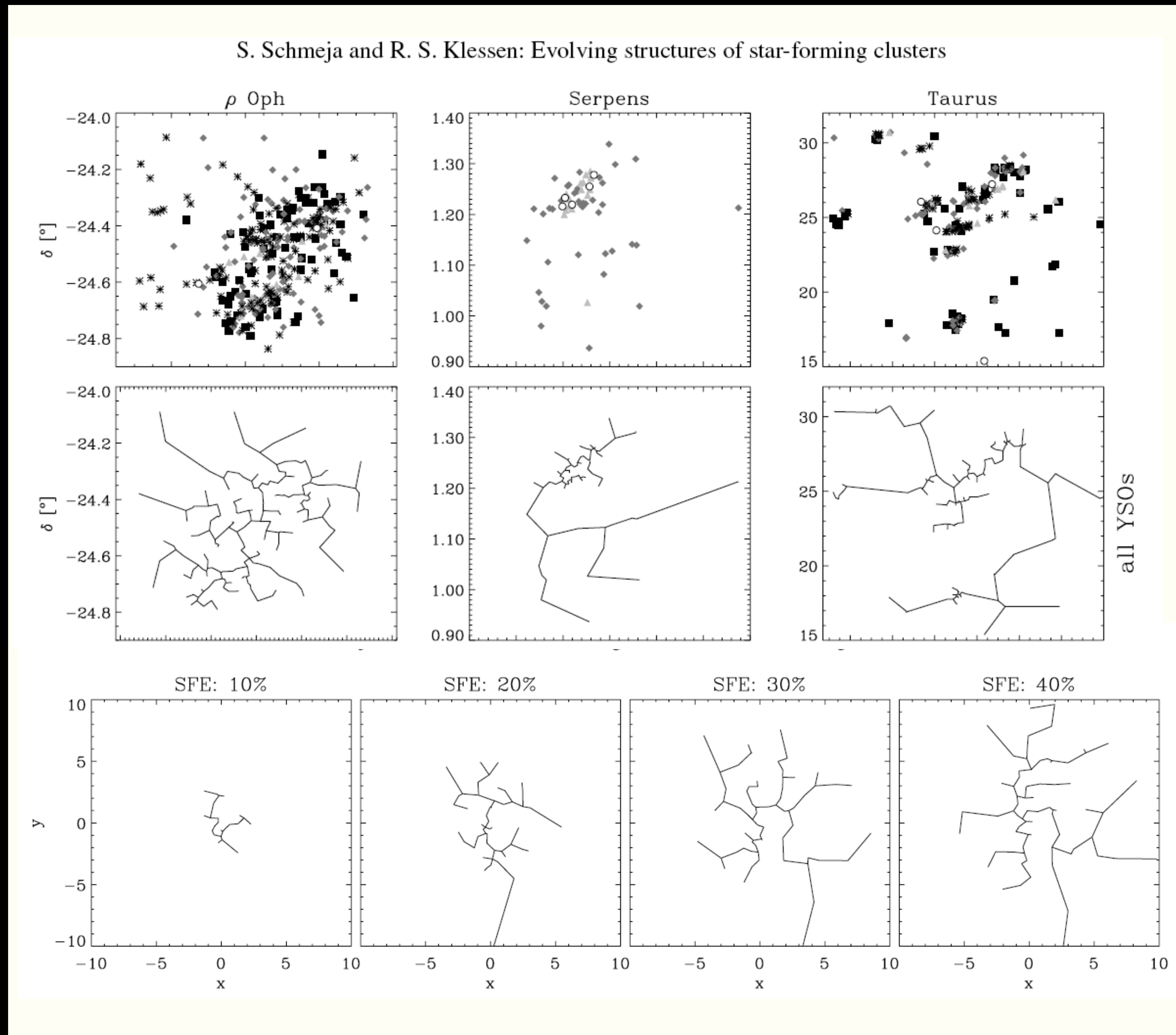
Which “**stars**” “form” from what gas, when?



What stars form from what gas, when?

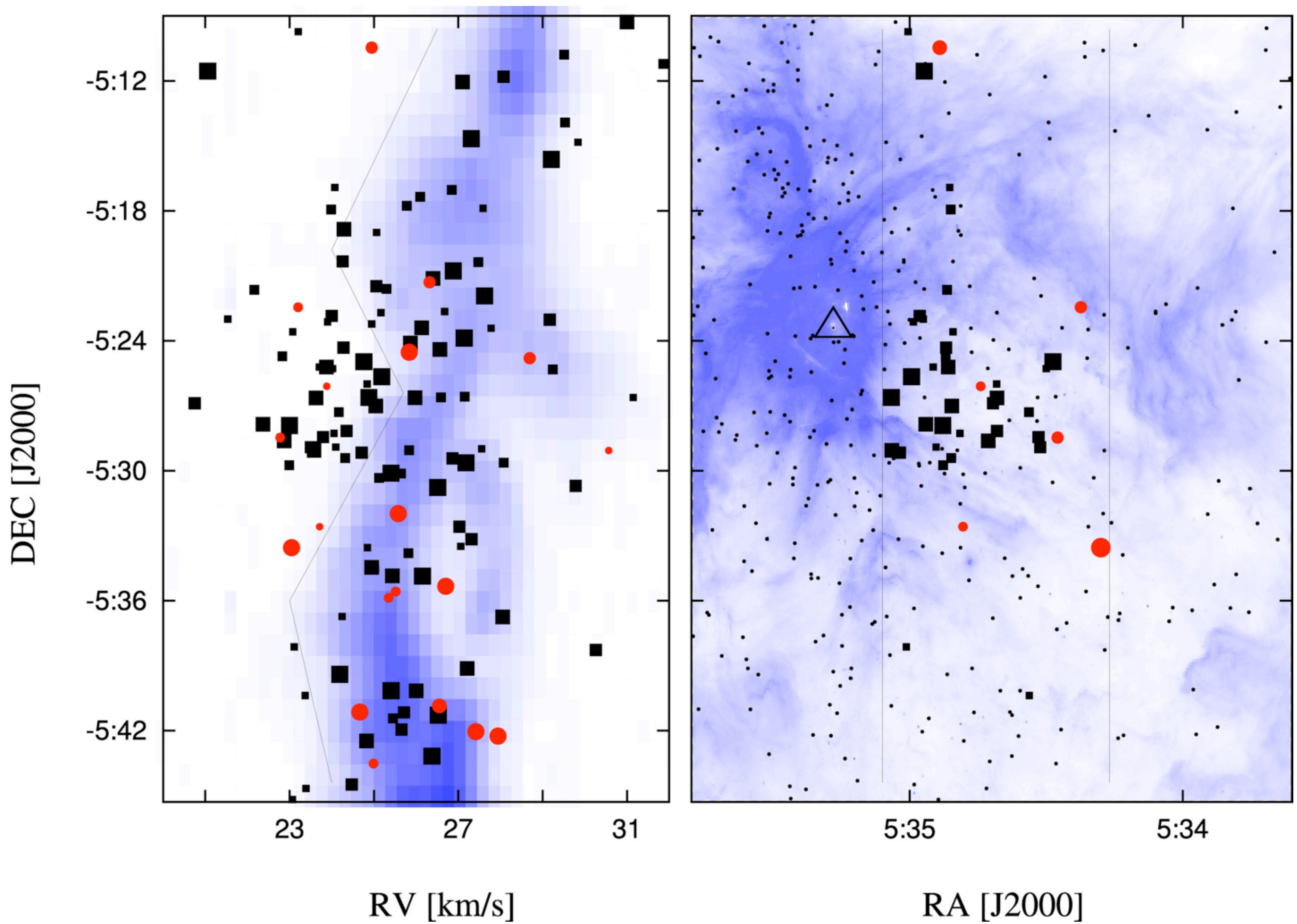
Theorists using Observers Ingredients

e.g. Schmeja & Klessen 2006

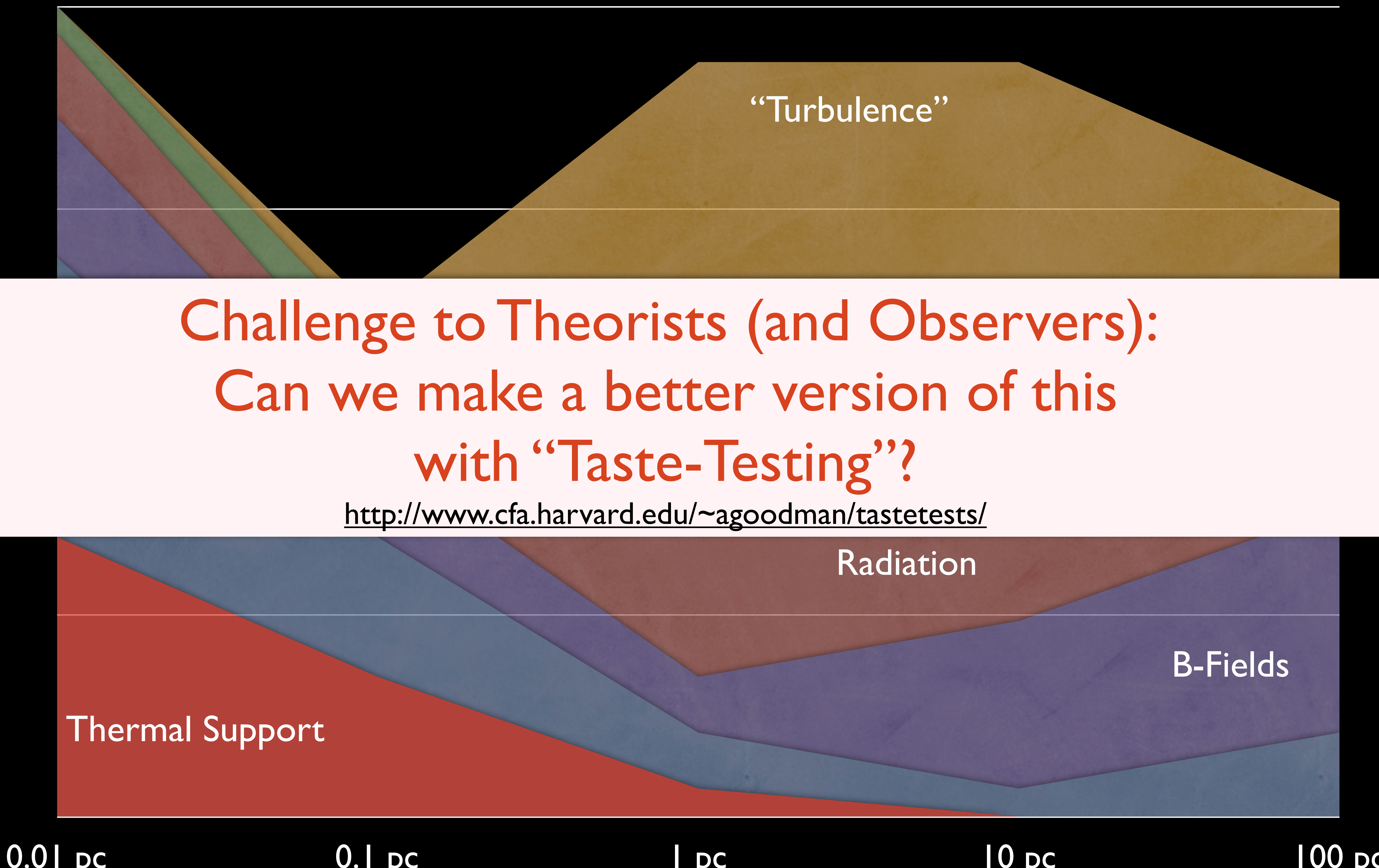


What stars form from what gas, when?

Radial Velocity Study of Orion (Furesz et al. 2008)



What really matters where...and when?



Challenge to Theorists (and Observers):
Can we make a better version of this
with "Taste-Testing"?

http://www.cfa.harvard.edu/~agoodman/tastetests/


"Tasting" Models
of Star Formation
Featuring the work of collaborators:
Alyssa A. Goodman
Harvard-Smithsonian Center for Astrophysics
Initiative in Innovative Computing at Harvard
Héctor Arce, Michelle Borkin, Paola Caselli
Jonathan Foster, Mike Halle, Mark Heyer, Jens
Kauffmann, Jaime Pineda, Erik Rosolowsky,
Scott Schnee, Rahul Shetty
Image Credit: Jonathan Foster, CfA/COMPLETE Deep Megacam Image of West End of Perseus

Optional

State of Affairs, Now

- **Thermal support:** thermal emission and gas excitation measures of dust temperature confirm low temperatures, but show *significant* structure (e.g. Scott Schnee's work)
- **B-fields:** most geometrically relevant at low densities (fluff) and at very high densities (star+disk), less-so in-between (TAURUS example)
- **Turbulence**: apparently dominant (morphologically) at ~all scales bigger than cores...but it must have an energy source. (AGREED.)
- **Radiation:** You don't need H II regions for radiation field to be critical to chemistry, heating/cooling, etc. Asymmetry may be critical. (See CLOUDSHINE....see also recent work by Pineda et al. on **chemical** abundances.)
- **Outflows/Winds:** Oops! What about stars that are not newborn or dying...what are all those spherical winds? We think they are 10x more important than bi-polar flows. (See COMPLETE/3D analysis by Arce, Borkin, et al.)
- **Gravity:** Can and often does matter at *all* scales--but not everywhere! Obviously critical at smallest scales, for collapse. (Taste-Testing with DENDROGRAMS)

Are you hungry yet?

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

The HDF Group

FDA

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

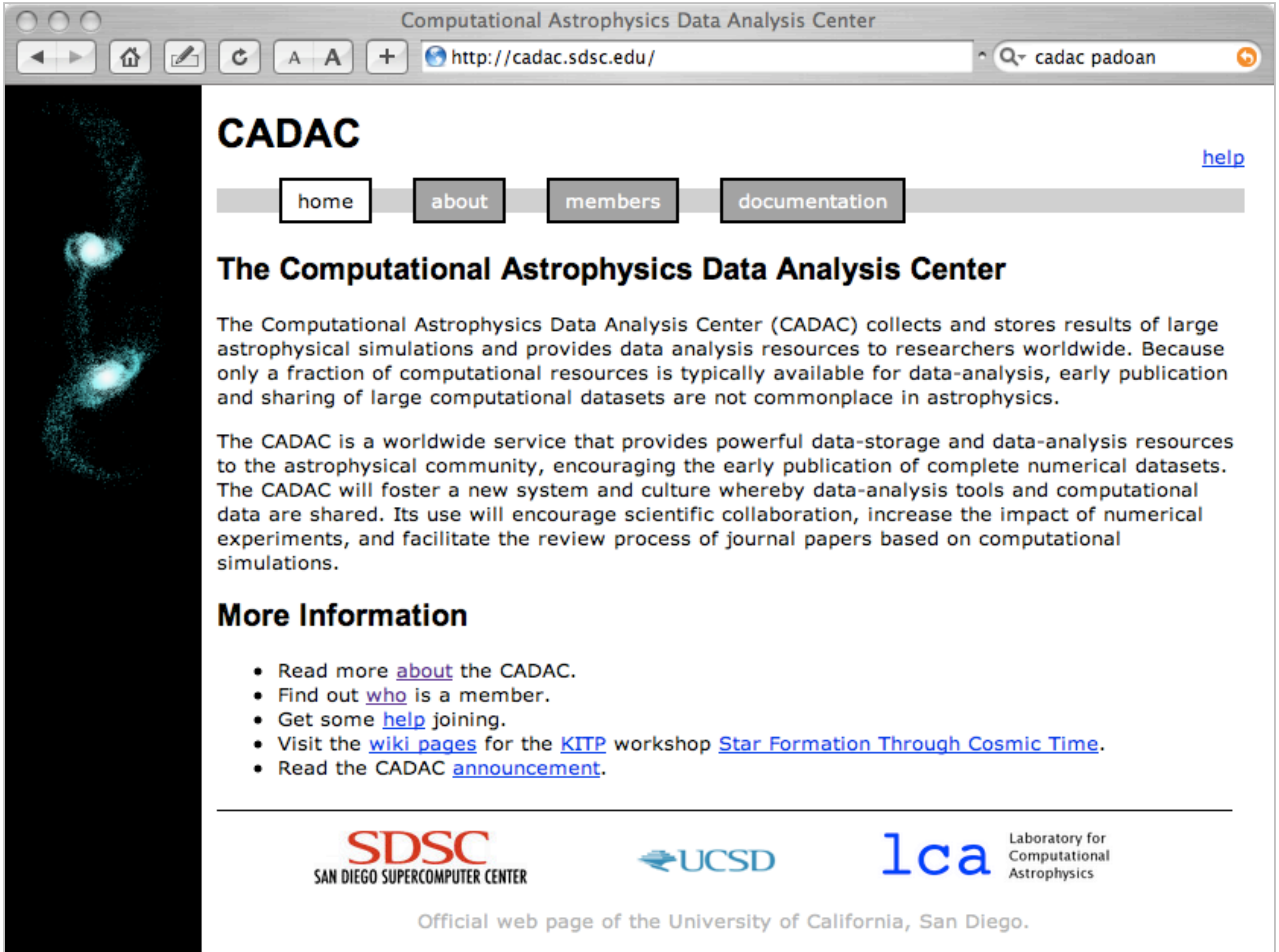
We describe the design and implementation of the Astrophysics Simulation Collaboratory Web Portal.

NVO NATIONAL VIRTUAL OBSERVATORY

US National Virtual Observatory

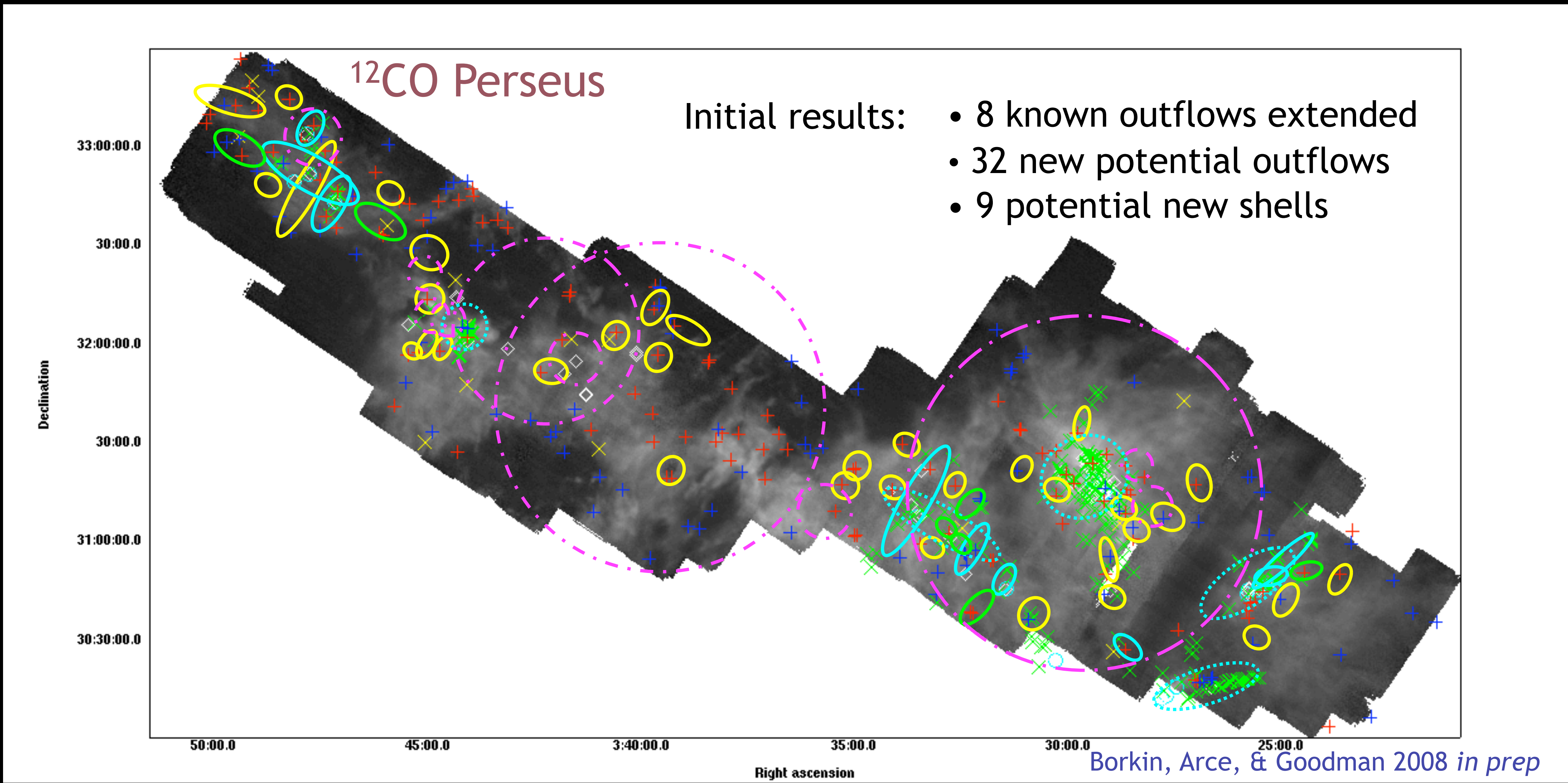
Data formats, software, middleware, and infrastructure matter.

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



A Challenge for the Next Round of Cooking

Perseus Outflows



Red Shifted points

Blue Shifted points

HH Objects

New outflows

Known outflows

Many small known outflows

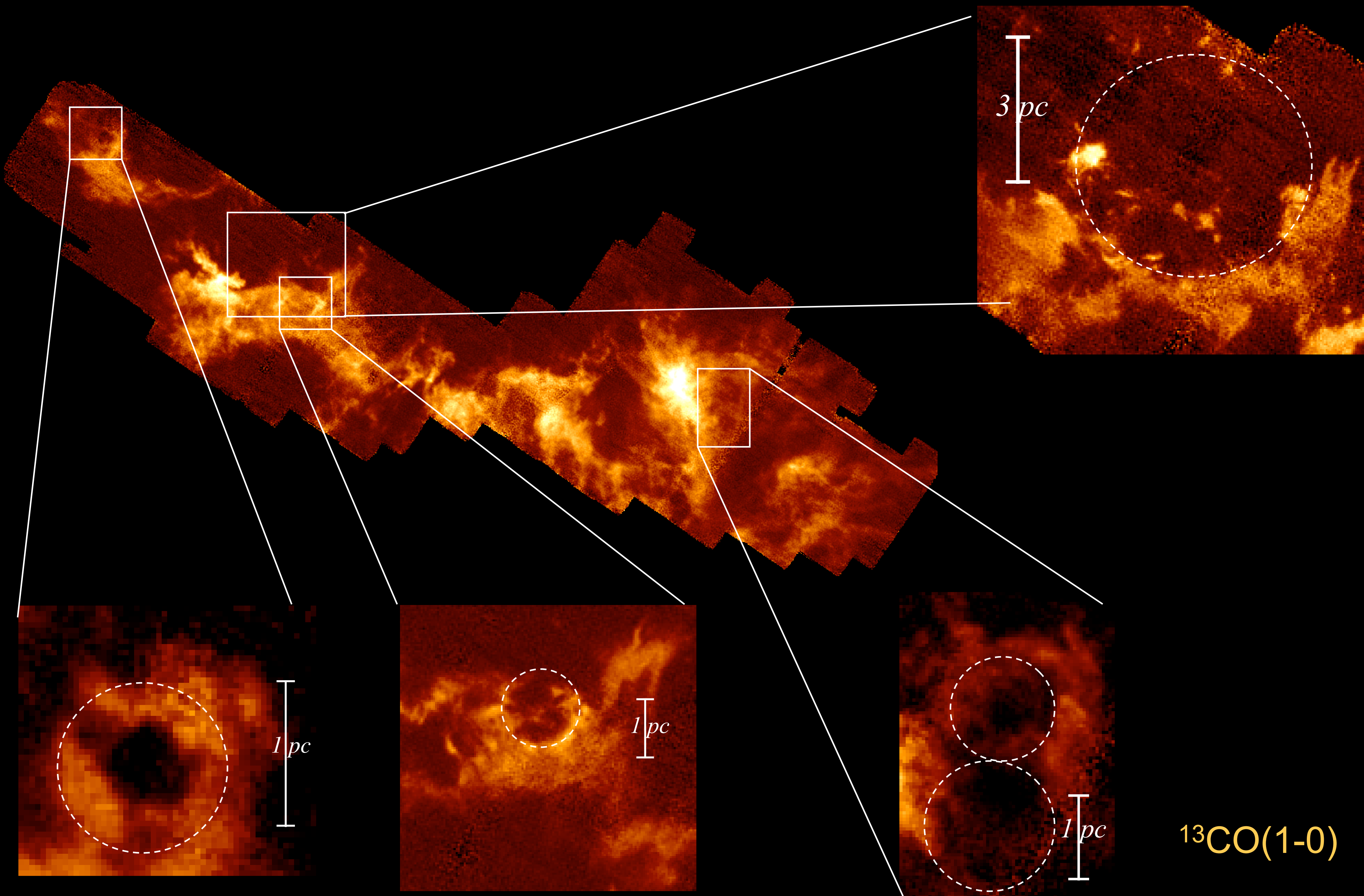
Outflow extensions

IRAS Sources

Known Outflow Sources

New shells

Powerful(!) Shells in Perseus

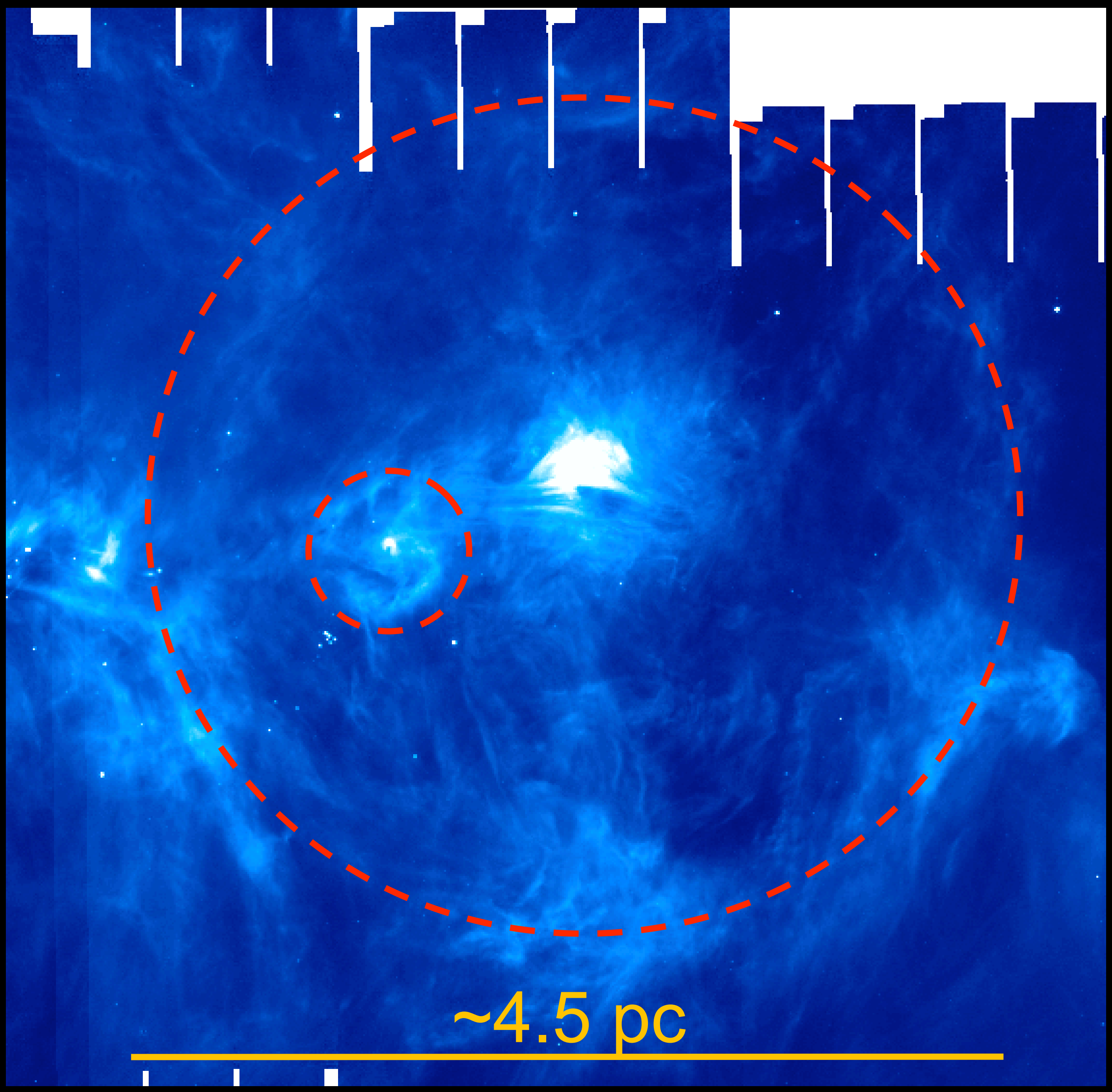


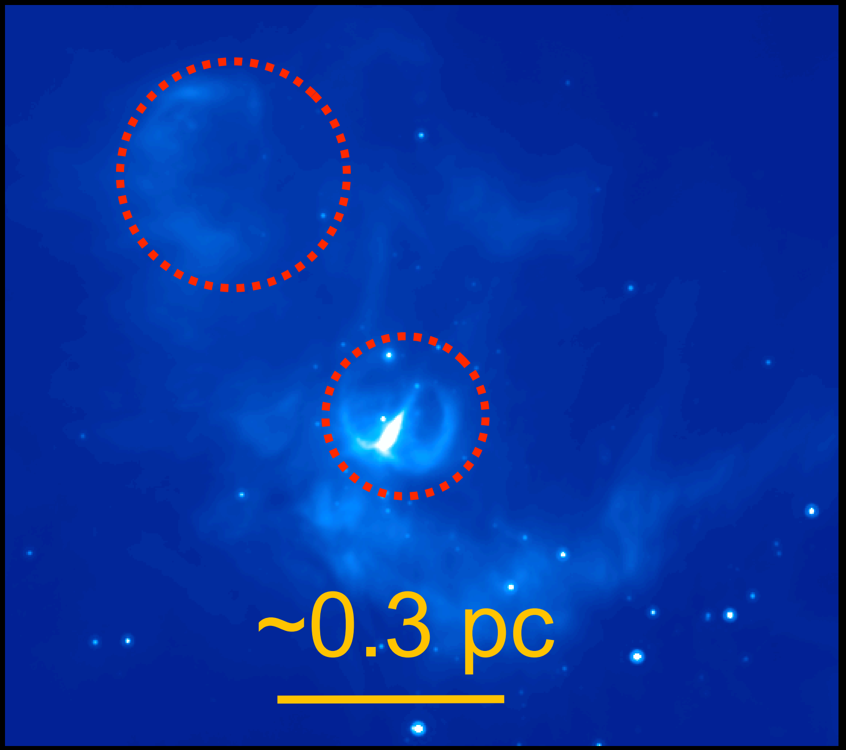
$^{13}CO(1\text{-}0)$

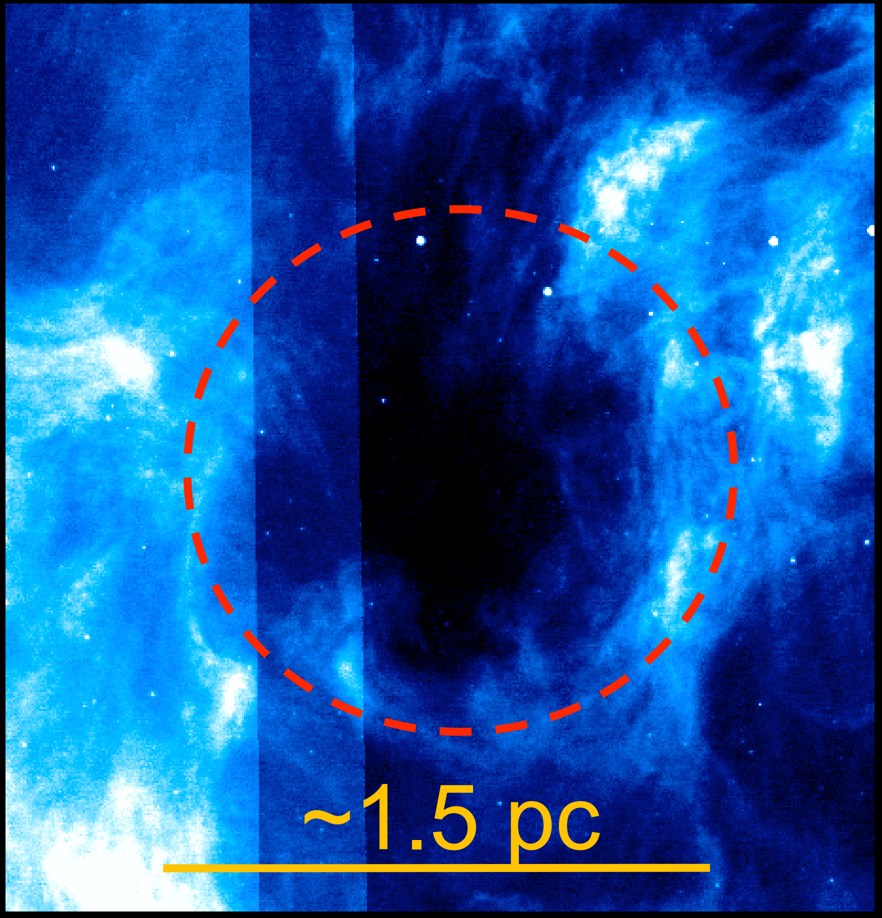
Borkin, Arce & Goodman 2008

Spitzer (MIPS) View

c2d MIPS (24μm) maps of Perseus
Rebull et al. 2007







Preliminary Numbers say Shells are Much MORE Important than Outflows

Table 2. Perseus Cloud Properties

	Mass ($M_\odot$)	Momentum ($M_\odot$ km s^{-1})	Kinetic Energy (10^{42} ergs)
Perseus (Global)	11,050	...	...
All Shells	608	908.24	31,713.43
All Outflows	34.33	79.83	2,373.32
Outflows (New)	17.58	33.44	708.97
Outflows (Known)	14.99	42.24	1,535.98
Outflows (New Extensions)	1.76	4.15	128.37

Note. — Thus outflows comprise 0.31% of the total mass in Perseus, shells comprise 5.5% of the total mass in Perseus, and shells are injecting ~11 times the momentum and ~13 times the energy that outflows are injecting into the cloud.

Borkin, Arce, & Goodman 2008 *in prep*