Beauty is in the Eye of the Beholder

Visualization courtesy American Museum of Natural History, Hayden Planetarium

Star Formation, and "Tasting" It

Featuring the work of collaborators:

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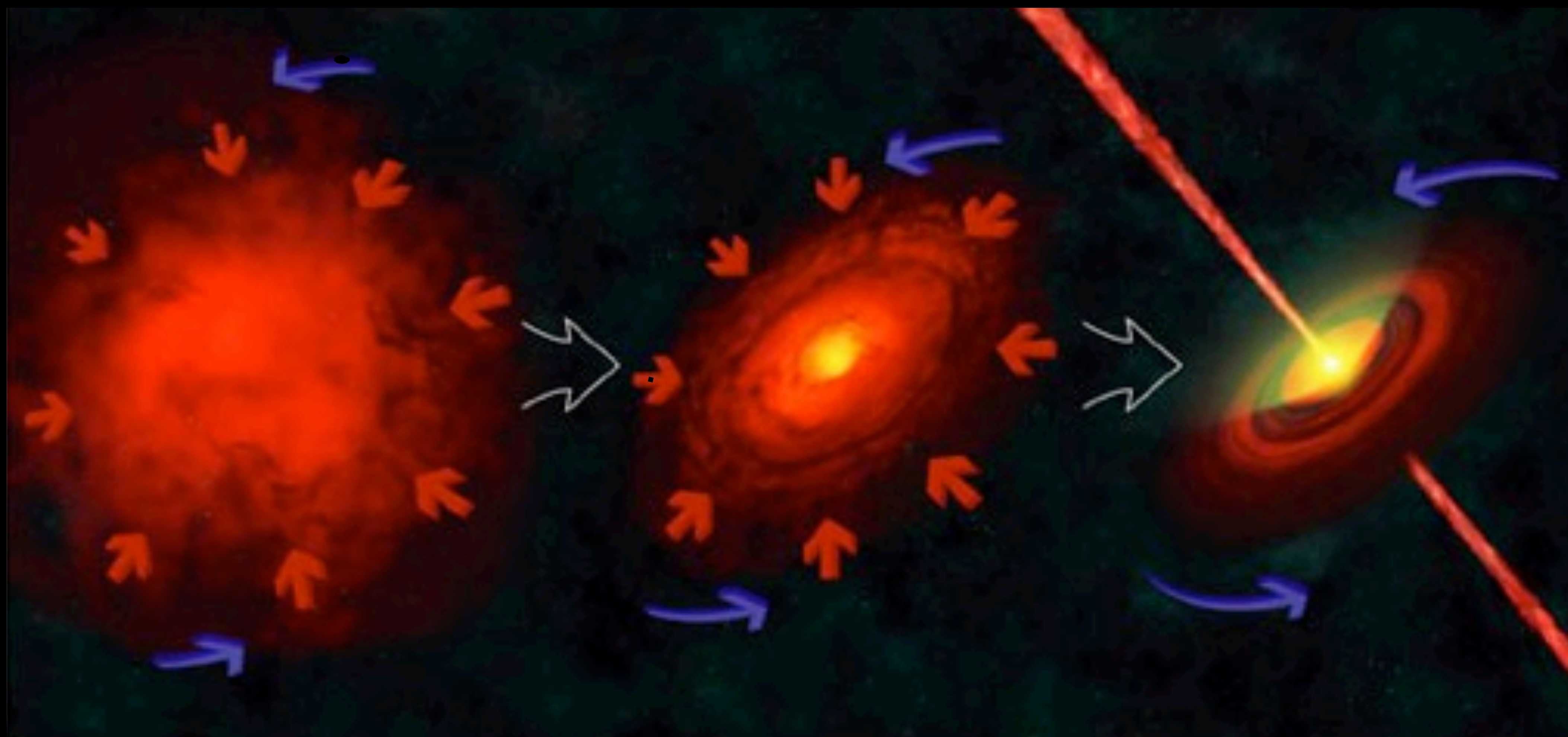
Harvard-Smithsonian Center for Astrophysics
Initiative in Innovative Computing at Harvard

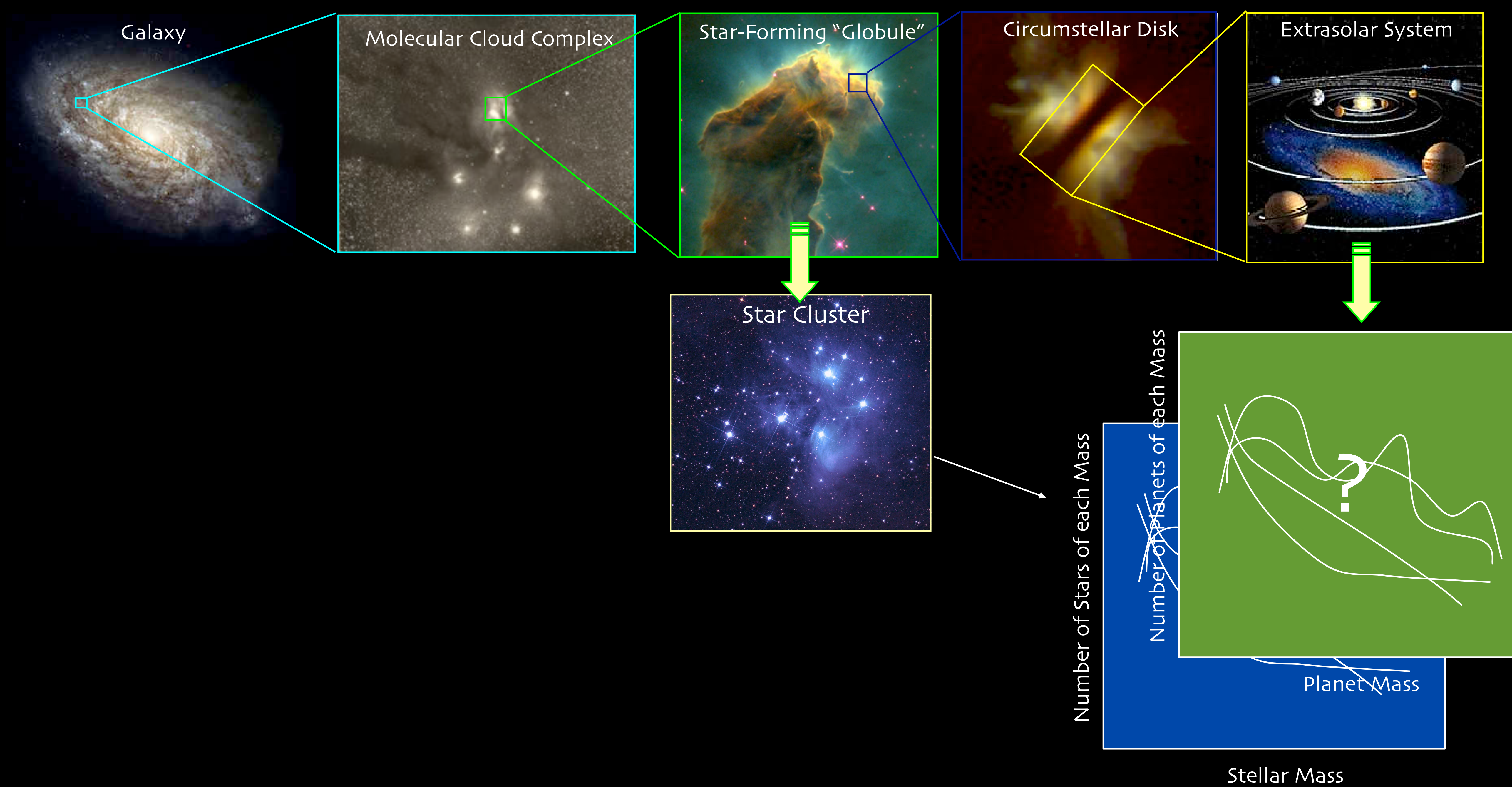
Héctor **Arce**, Michelle **Borkin**, Paola **Caselli**, Jonathan **Foster**, Mike **Halle**, Mark **Heyer**, Jens **Kauffmann**, Jaime **Pineda**, Erik **Rosolowsky**, Scott **Schnee**, Rahul **Shetty**

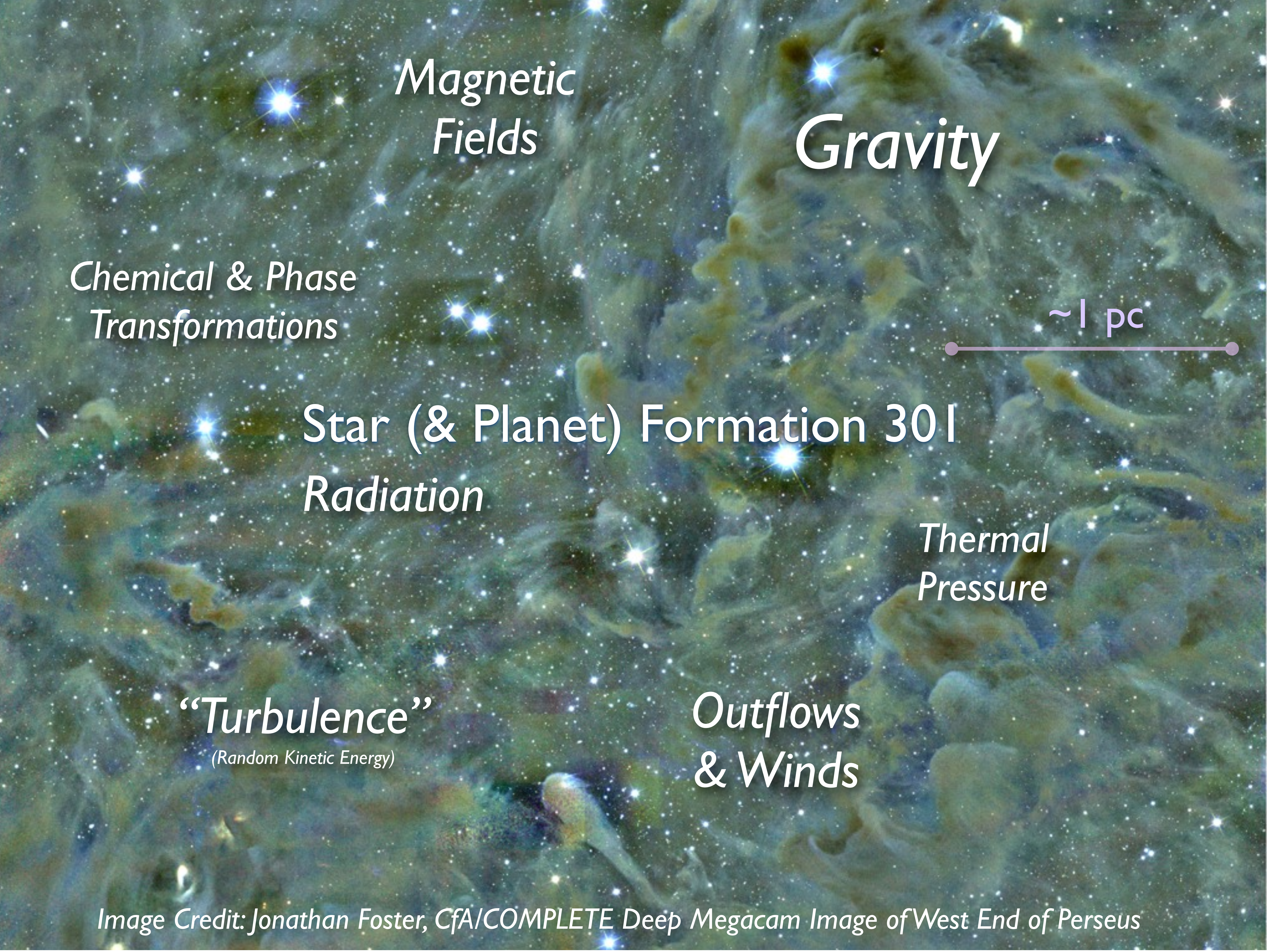
Image Credit: Jonathan Foster, CfA/COMPLETE Deep Megacam Image of West End of Perseus

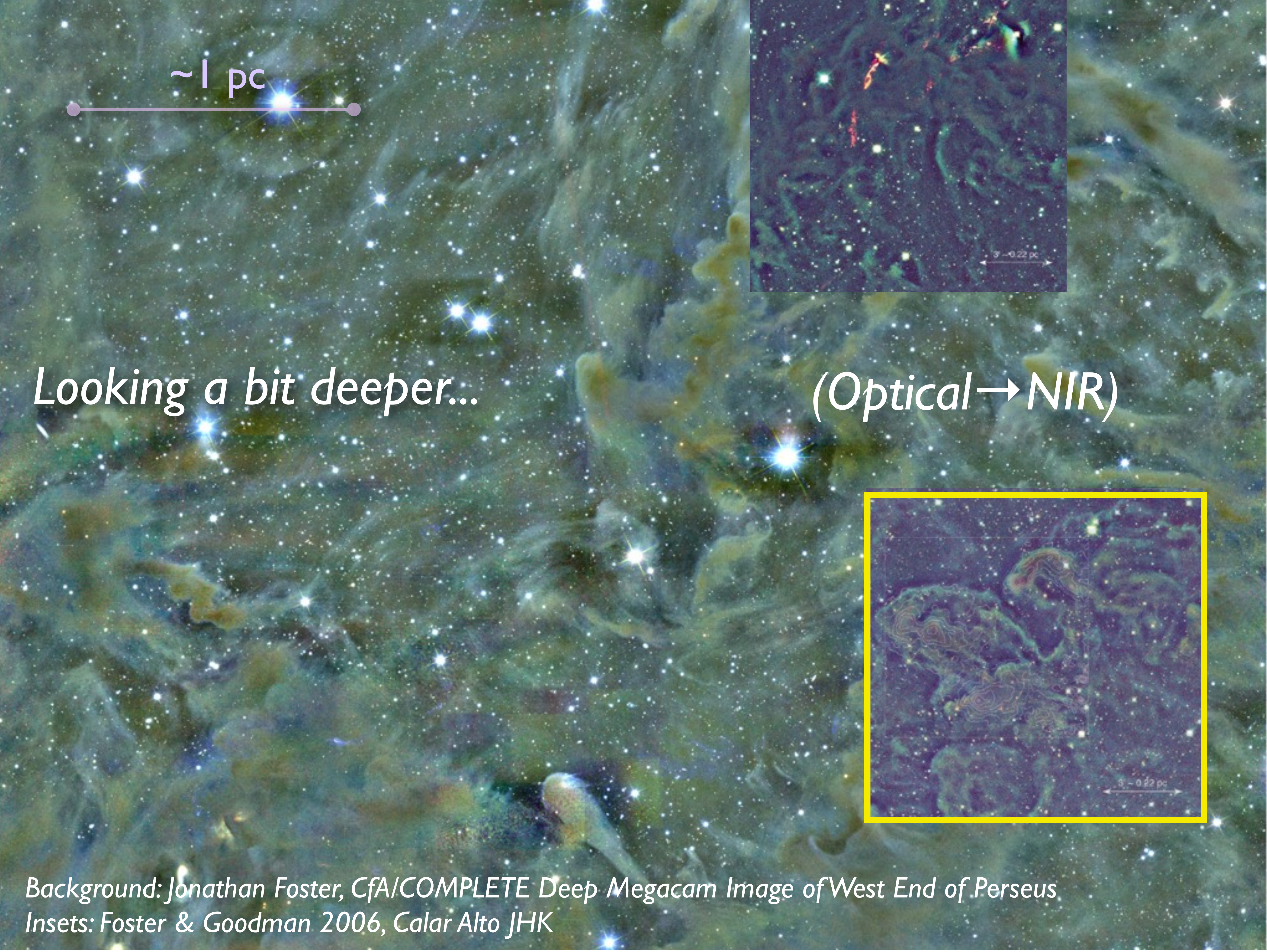
Star Formation 101



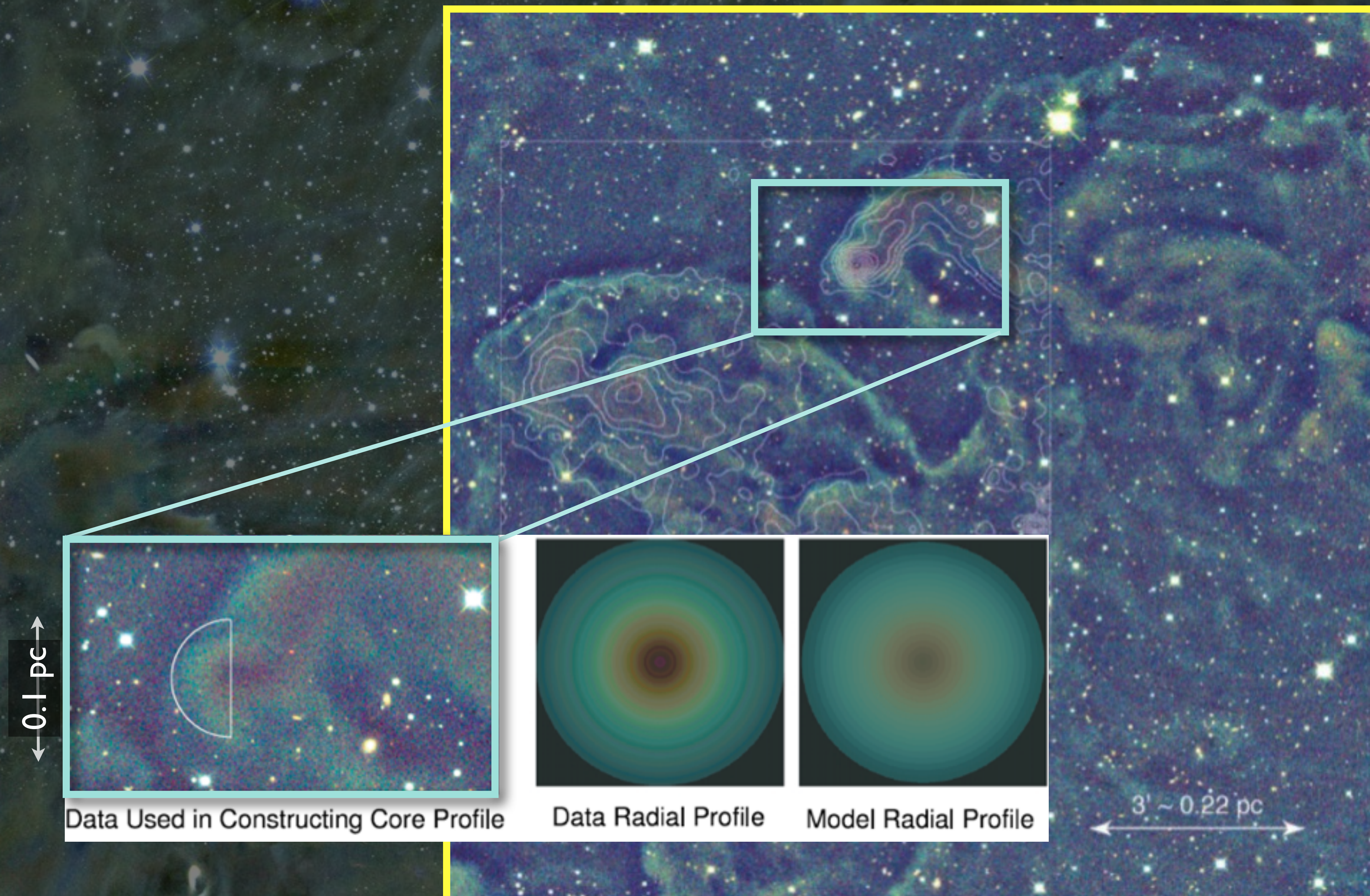
Star (& Planet) Formation 201




Magnetic Fields
Gravity
Chemical & Phase Transformations
~1 pc
Star (& Planet) Formation 301
Radiation
Thermal Pressure
"Turbulence"
(Random Kinetic Energy)
Outflows & Winds
Image Credit: Jonathan Foster, CfA/COMPLETE Deep Megacam Image of West End of Perseus

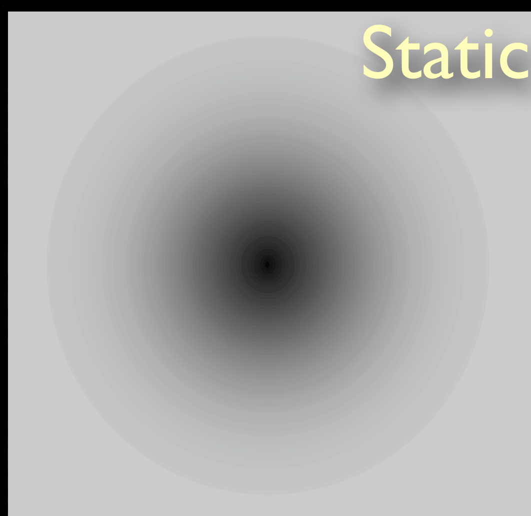

~1 pc
Looking a bit deeper...
(Optical→NIR)
Background: Jonathan Foster, CfA/COMPLETE Deep Megacam Image of West End of Perseus
Insets: Foster & Goodman 2006, Calar Alto JHK

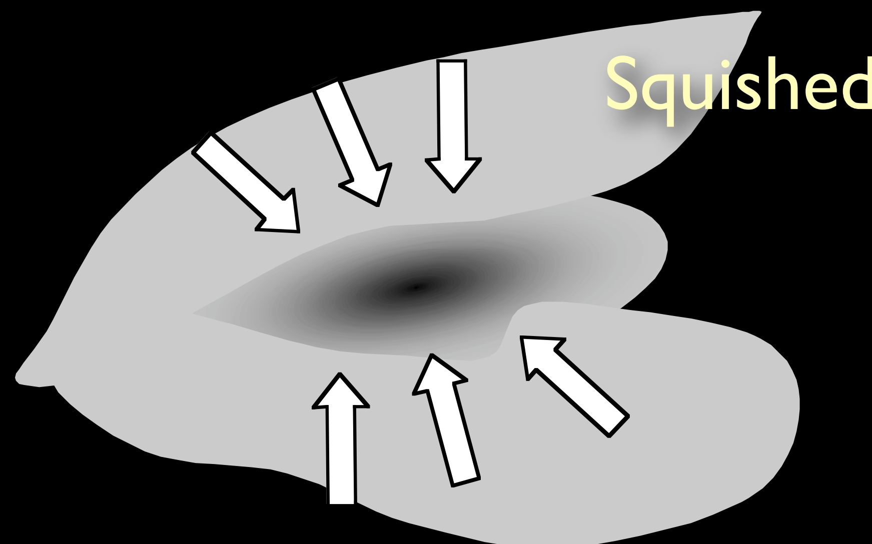
“Islands of Calm in a Turbulent Sea”

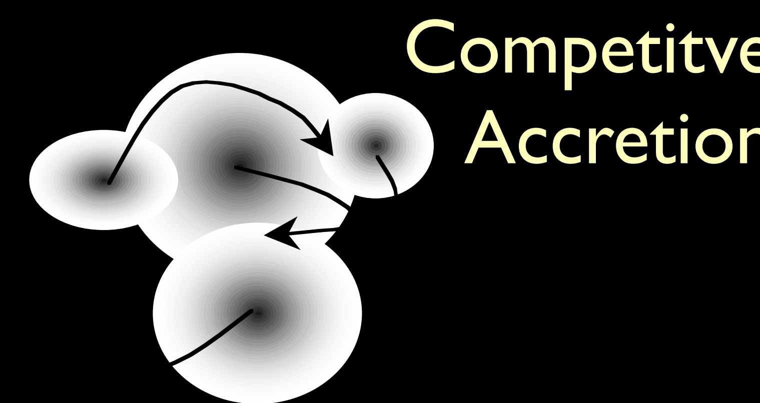


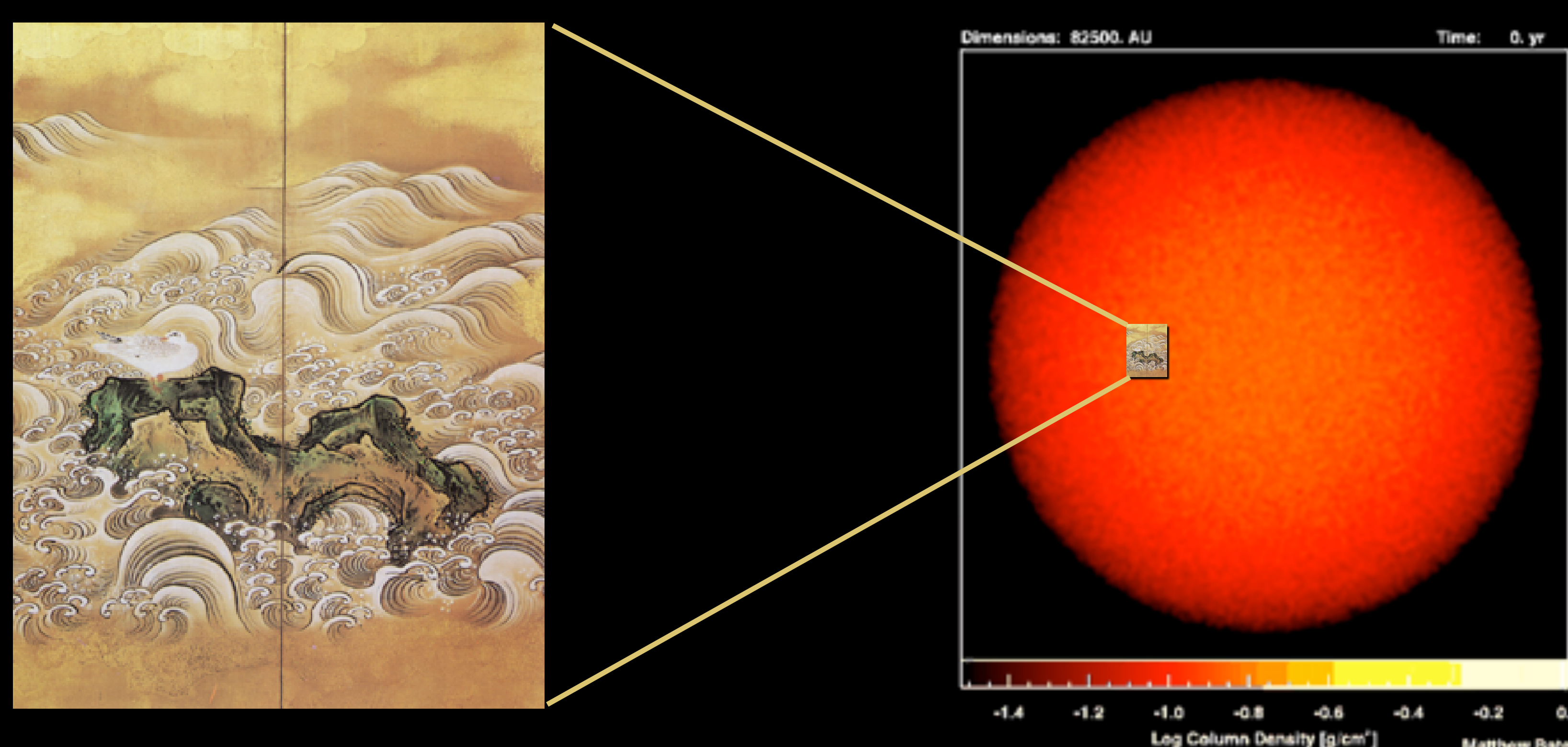
But how calm? And how long-lasting?

Three main views at present...

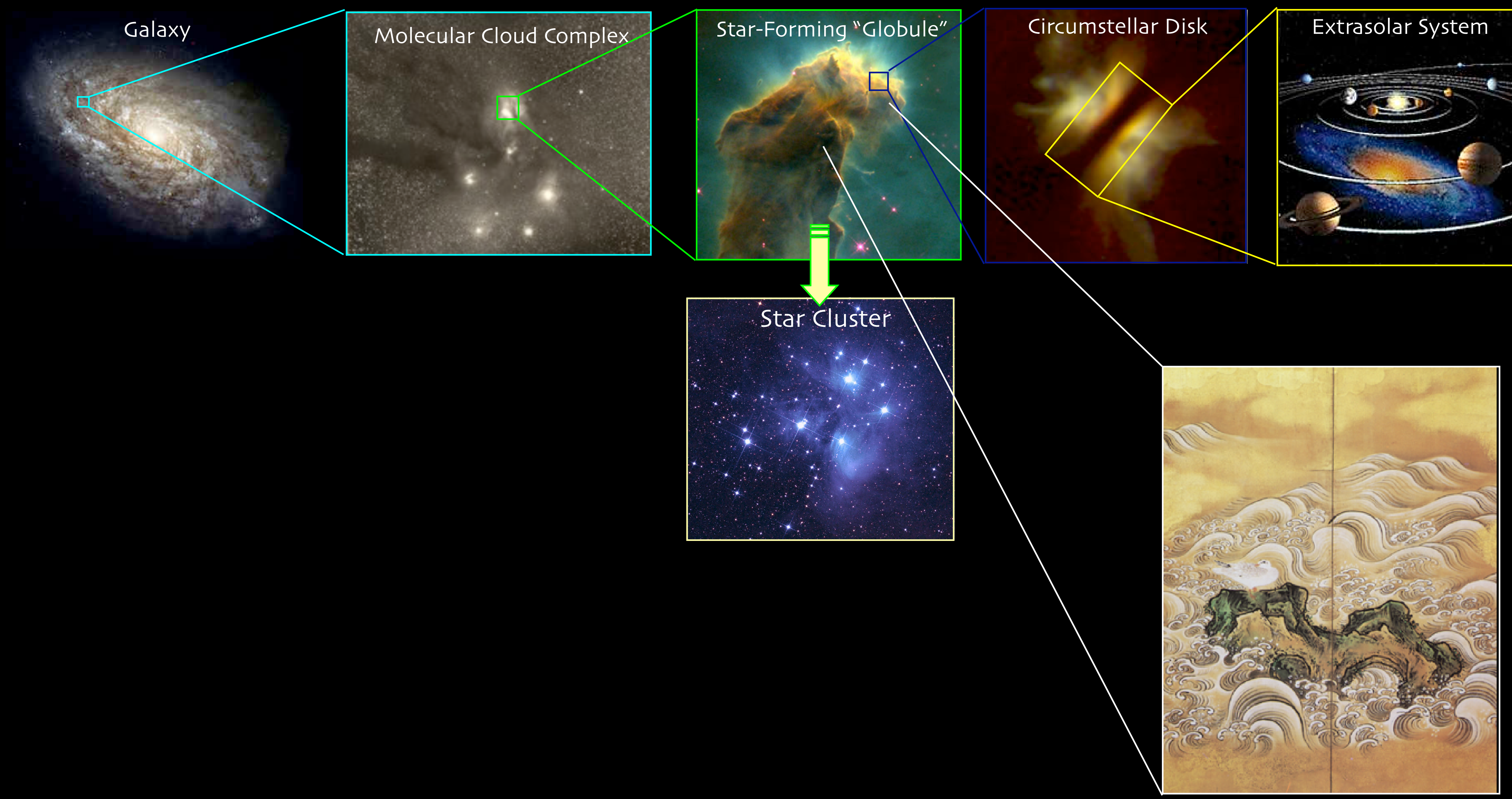






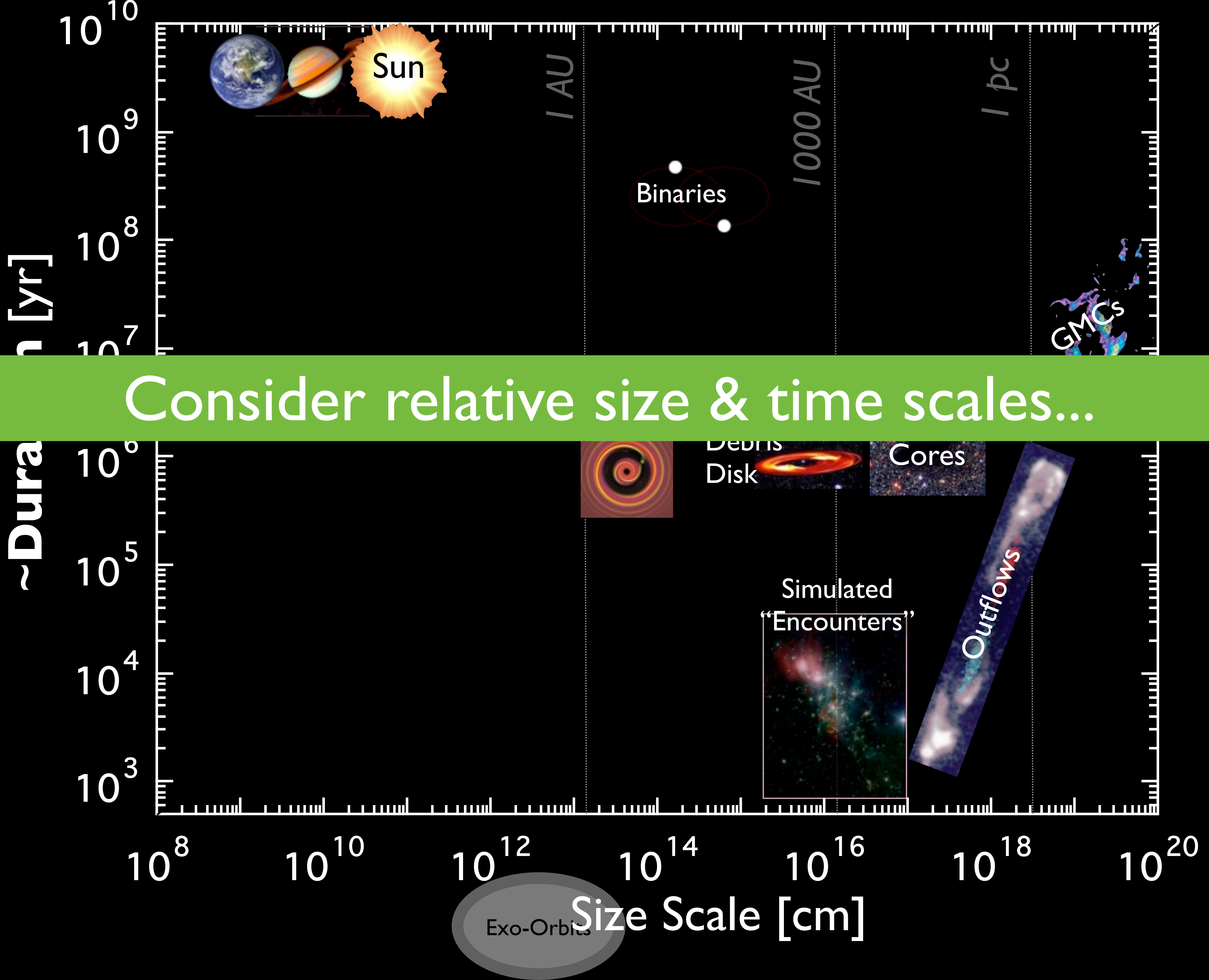


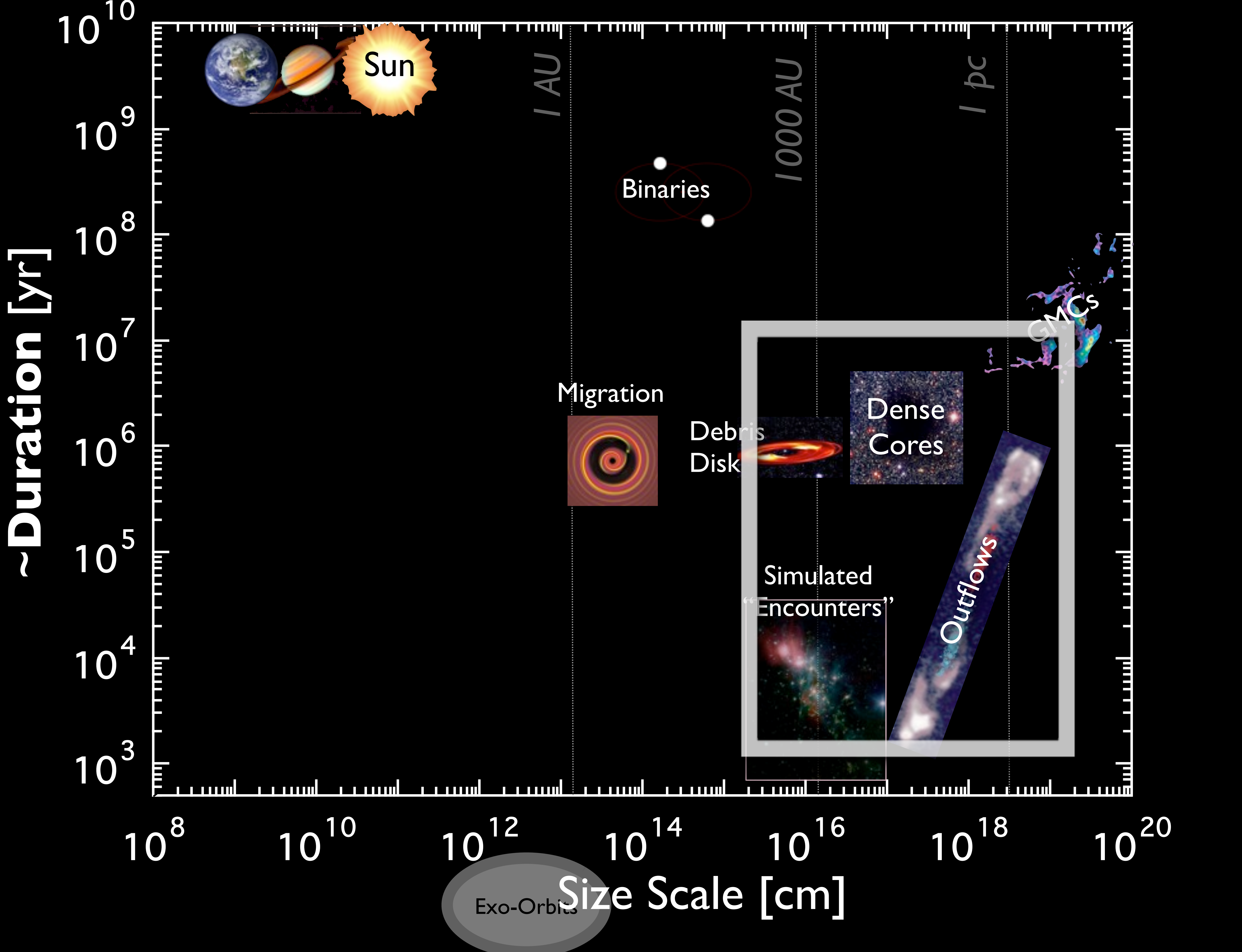
Star (& Planet) Formation 201

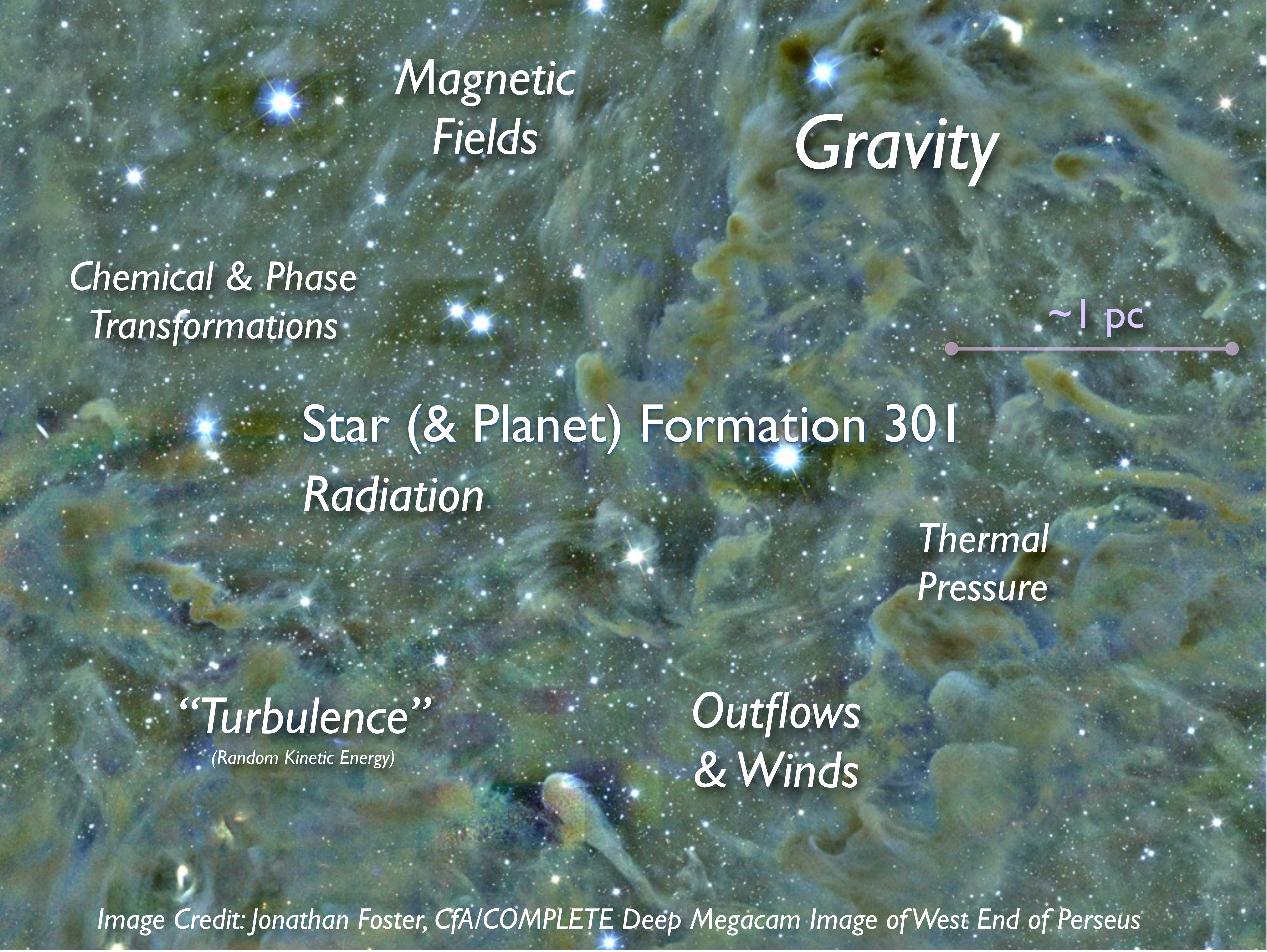


Can the “sea” be shut out, or at least ignored?

Consider relative size & time scales...




Sun
1 AU
1000 AU
1 pc
Binaries
GMCs
Migration
Debris
Disk
Dense
Cores
Simulated
"Encounters"
Outflows
~Duration [yr]
10^{10}
10^{9}
10^{8}
10^{7}
10^{6}
10^{5}
10^{4}
10^{3}
10^{8}
10^{10}
10^{12}
10^{14}
10^{16}
10^{18}
10^{20}
Exo-Orbits
Size Scale [cm]


Magnetic Fields
Gravity
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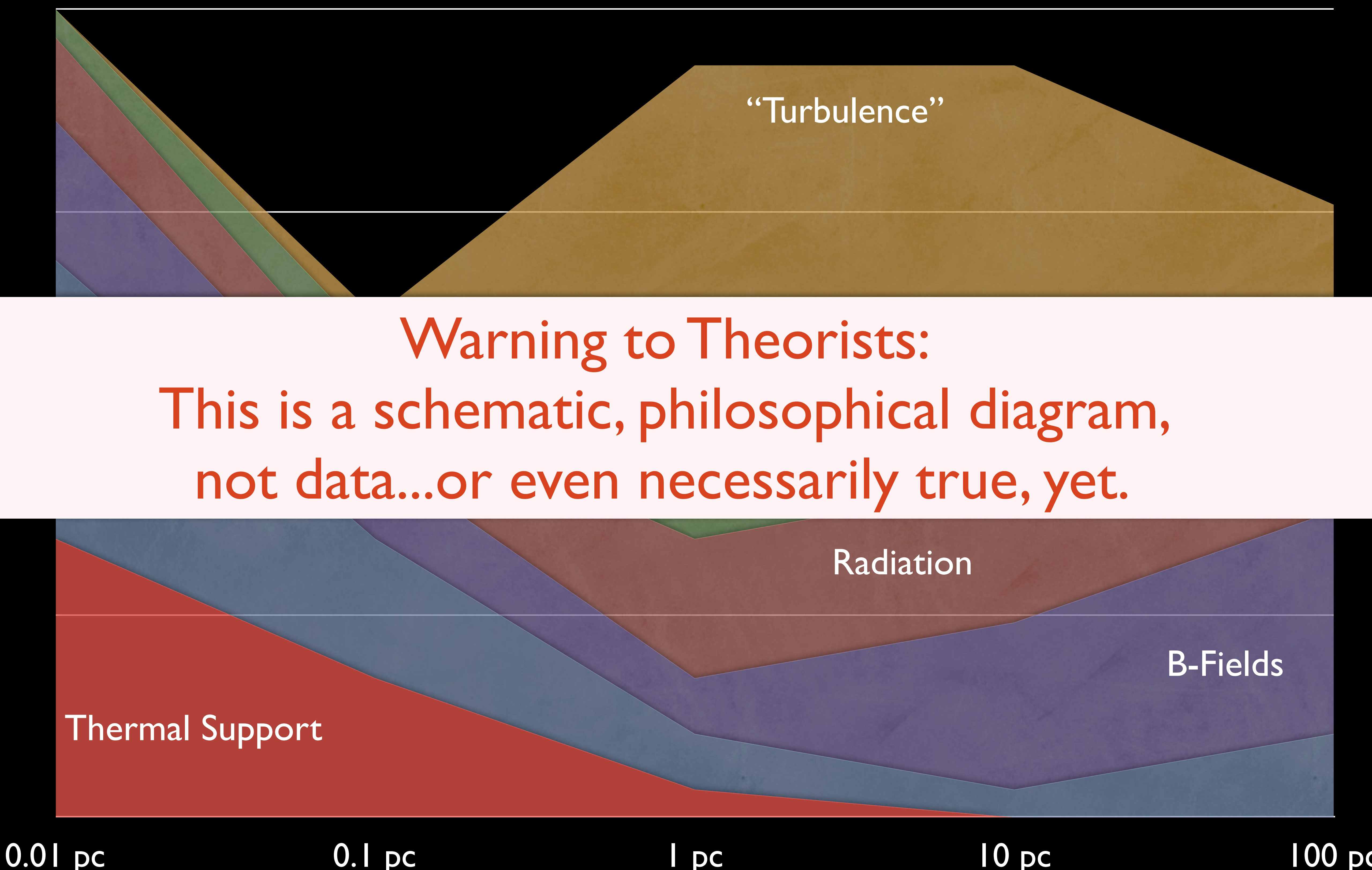
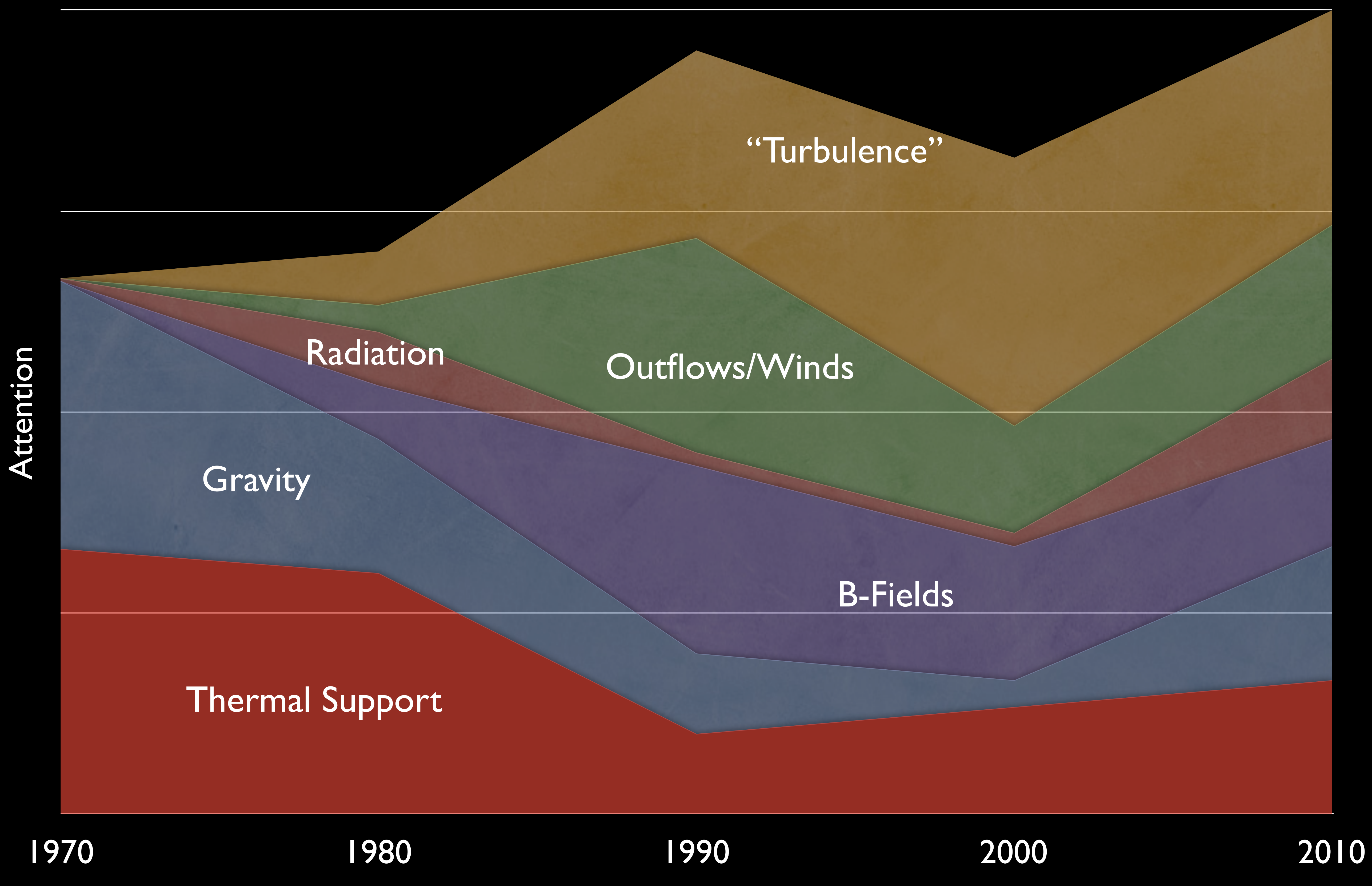
Star (& Planet) Formation 301
Radiation
Thermal Pressure
"Turbulence"
(Random Kinetic Energy)
Outflows & Winds
Image Credit: Jonathan Foster, CfA/COMPLETE Deep Megacam Image of West End of Perseus

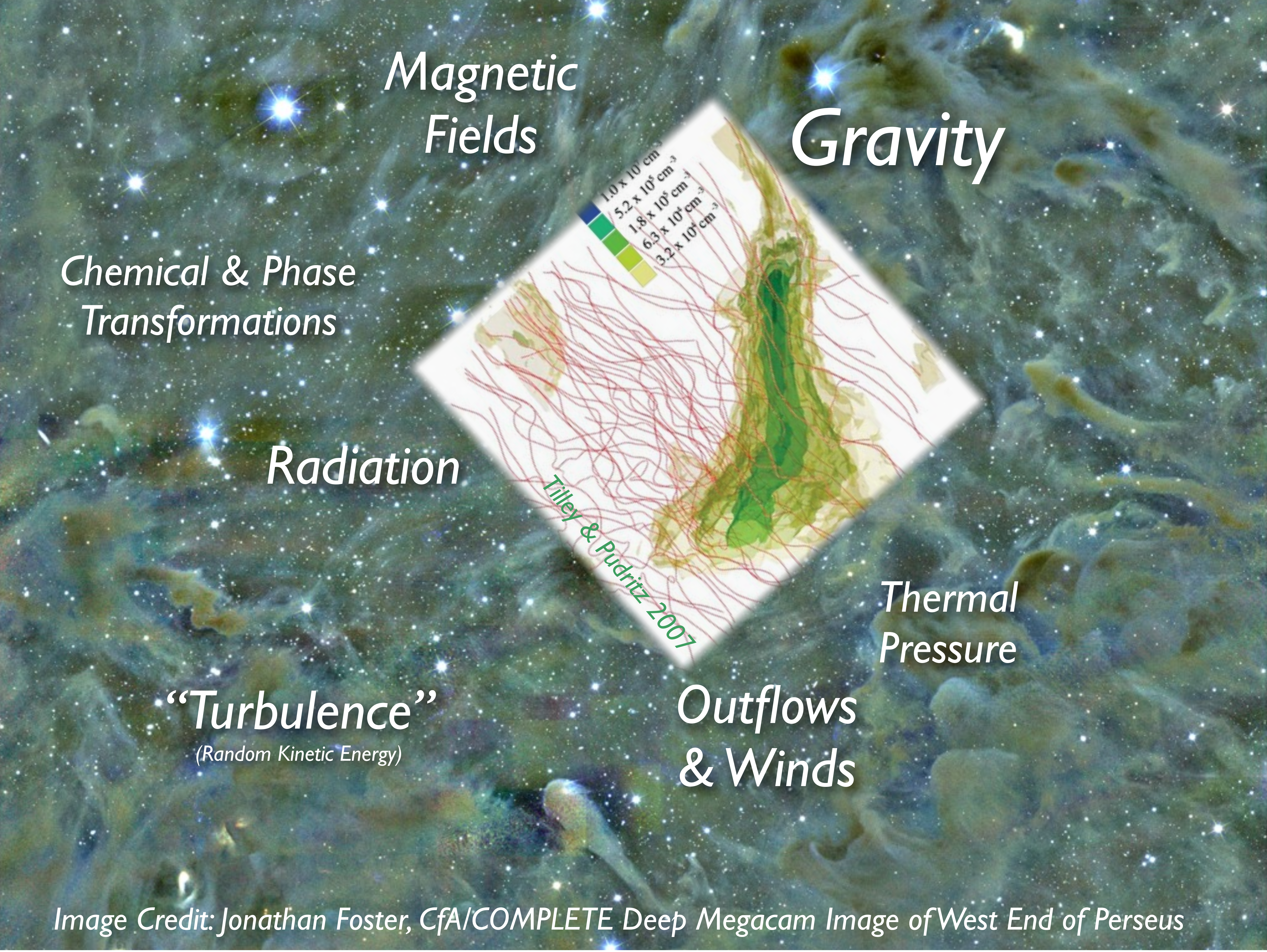
What forces matter most on what scales?



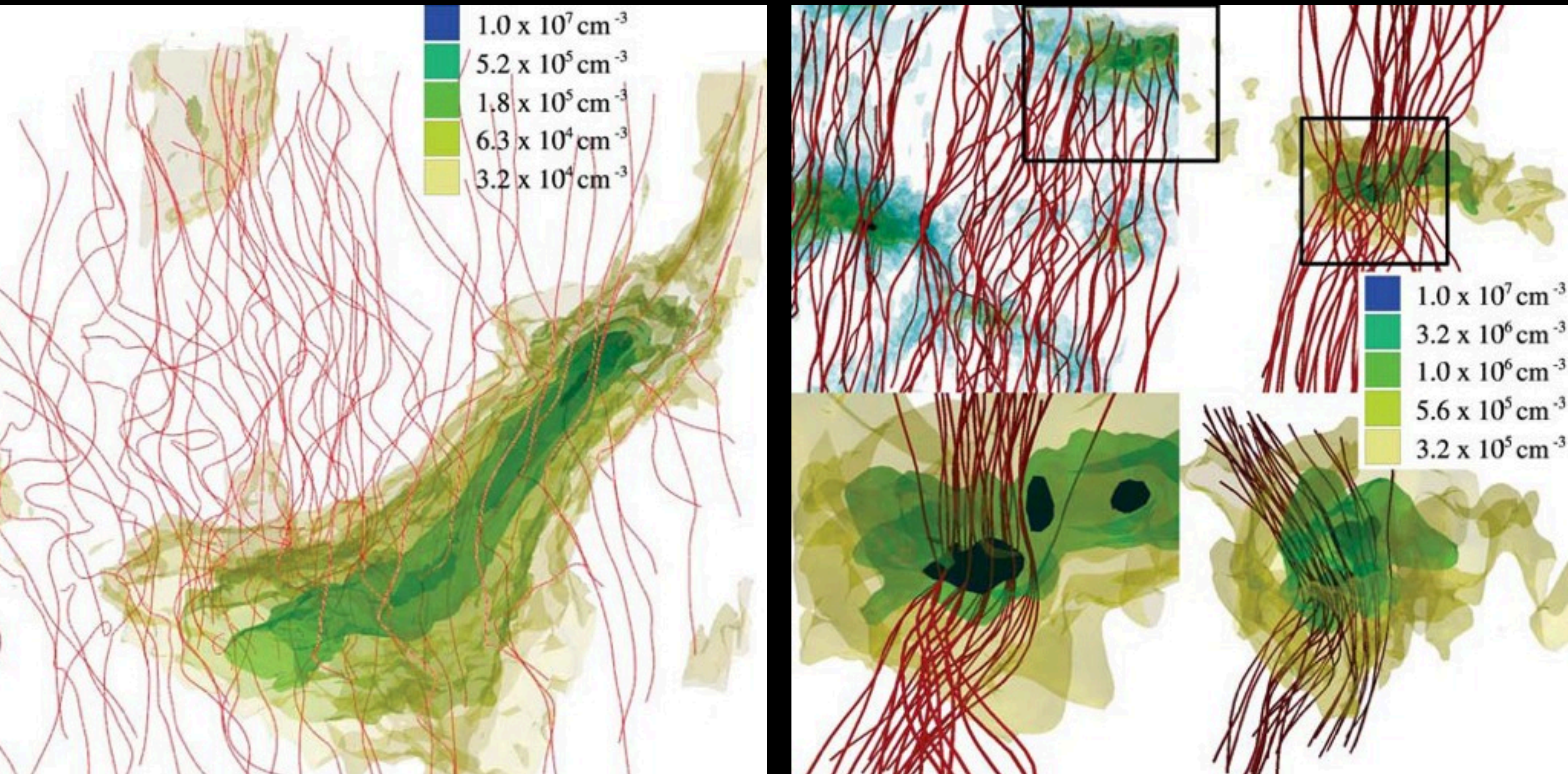
Warning to Theorists:
This is a schematic, philosophical diagram, not data...or even necessarily true, yet.

Changes of Heart, rather than in Physics...




Magnetic
Fields
Gravity
Chemical & Phase
Transformations
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
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

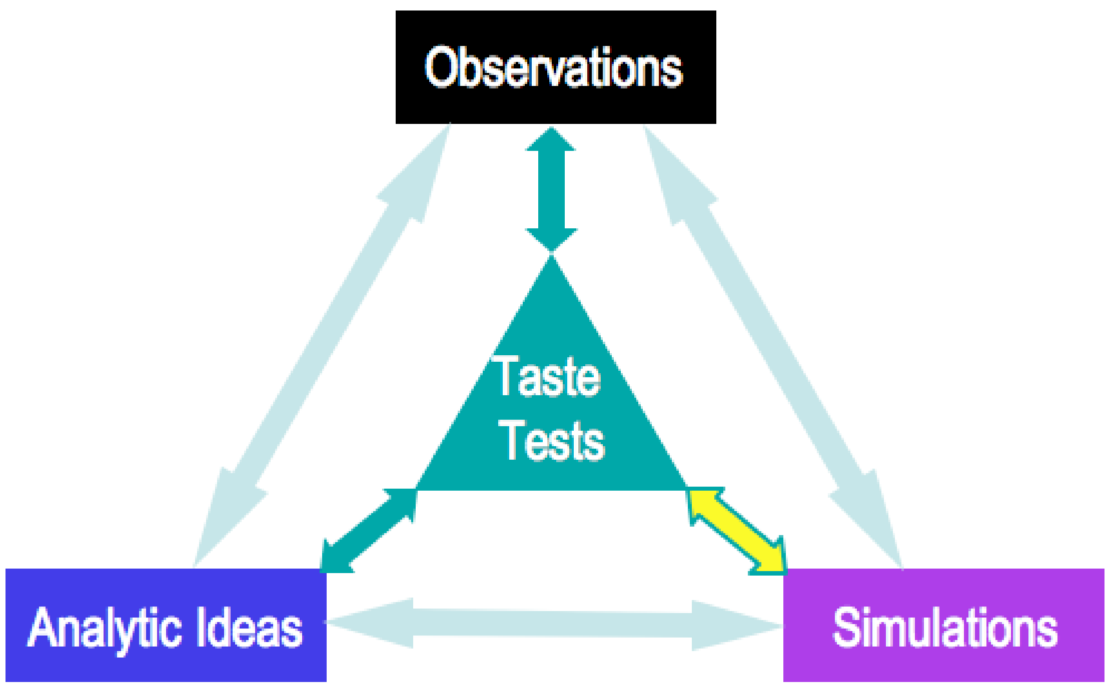
Theorists' Kitchens now cooking *many* Simulations sophisticated enough to "taste"...



Tilley & Pudritz 2007;

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

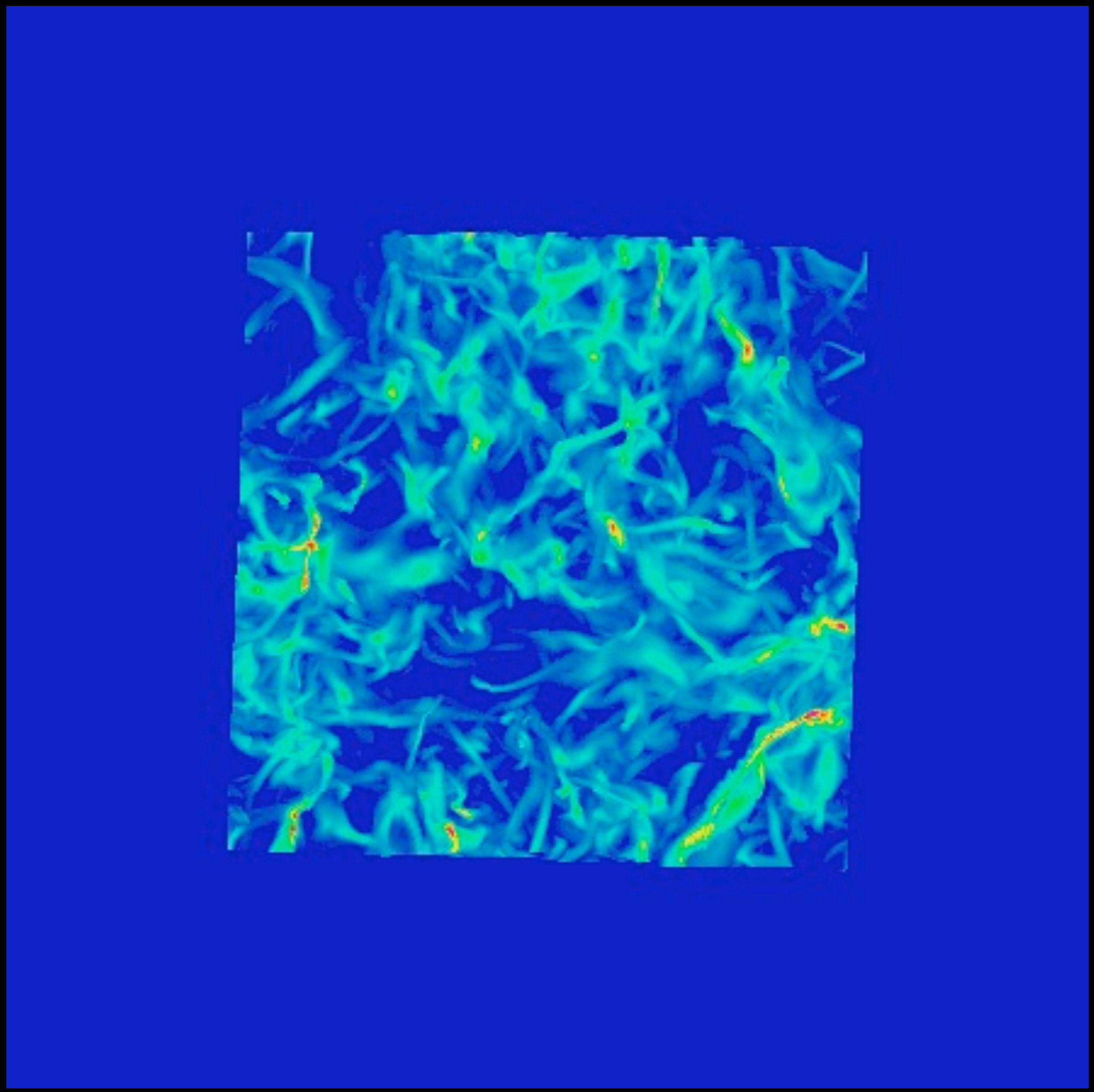
Taste Tests



"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

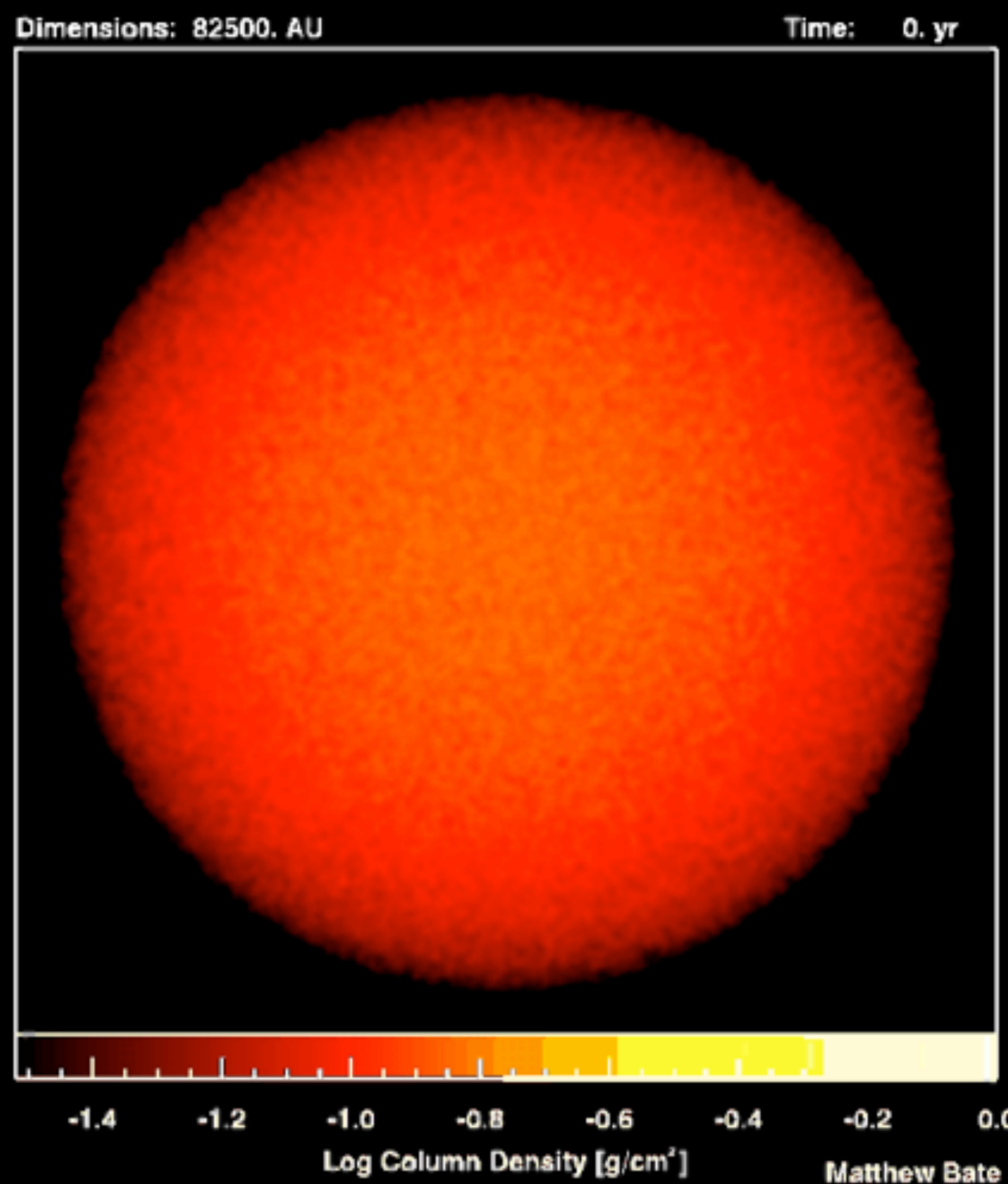
What theorists are used to...



"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?

***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.

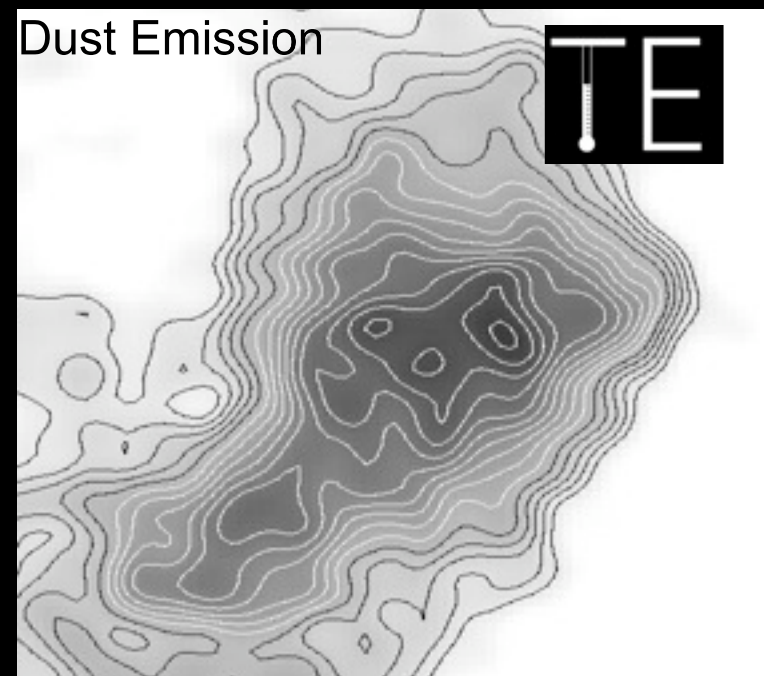
		optical	NIR	MIR	FIR	sub-mm	mm	cm	Density or Mass	Chemical Composition	Temperature	Velocity	Magnetic Fields
Extended Material (Clouds & Cores)	Broadband Emission (Dust)			S	+	C	+						P
	Spectra (Dust)												P
	Spectra (Gas)						C	C					Z
	Background Starlight (Extinction)		C	S									P
	Scattered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

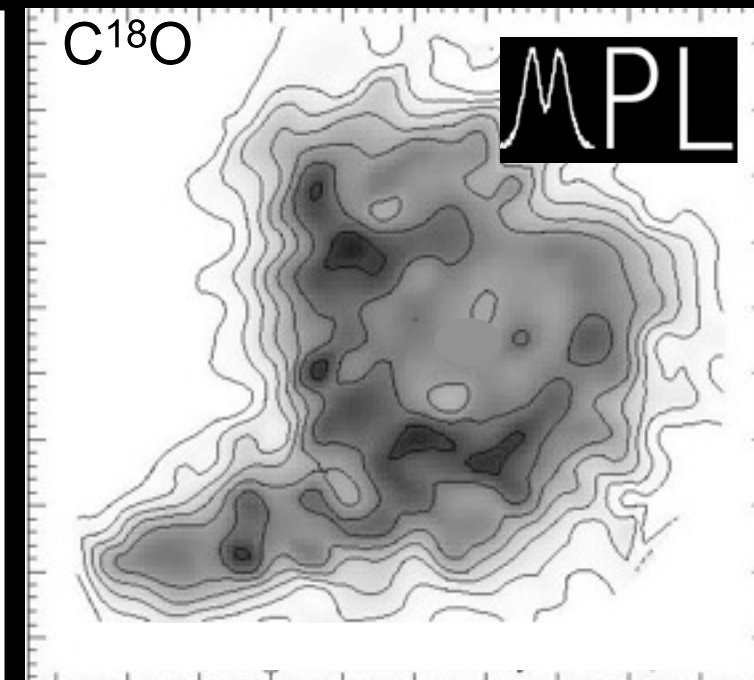
Today, mostly:

•maps of **Emission**, **Extinction** & **Scattering** due to dust (for column density & temperature)

•maps of radio-frequency **spectral lines** from gas (for kinematics & chemistry(!))

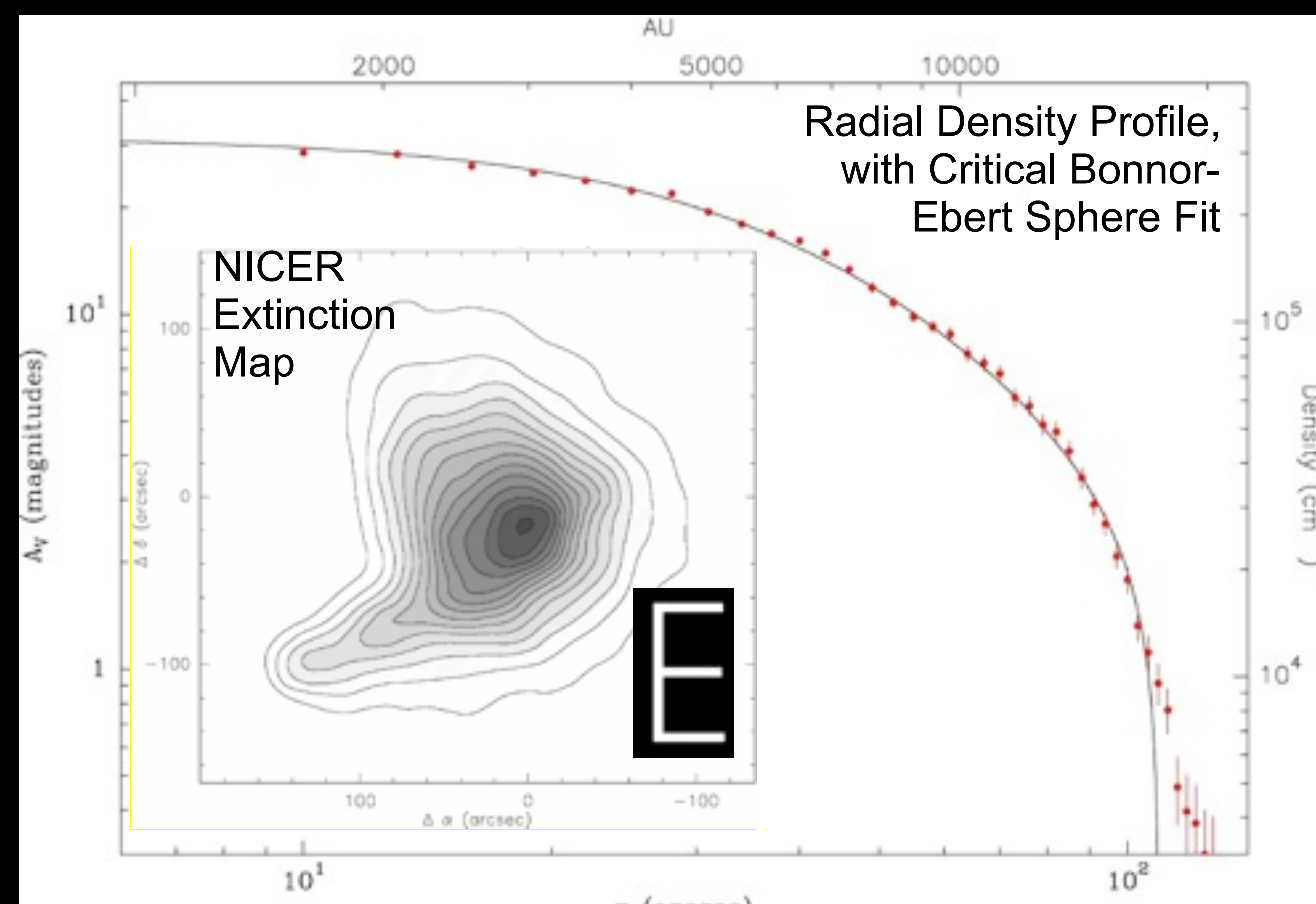
The Value of "COMPLETE" Observations: B68





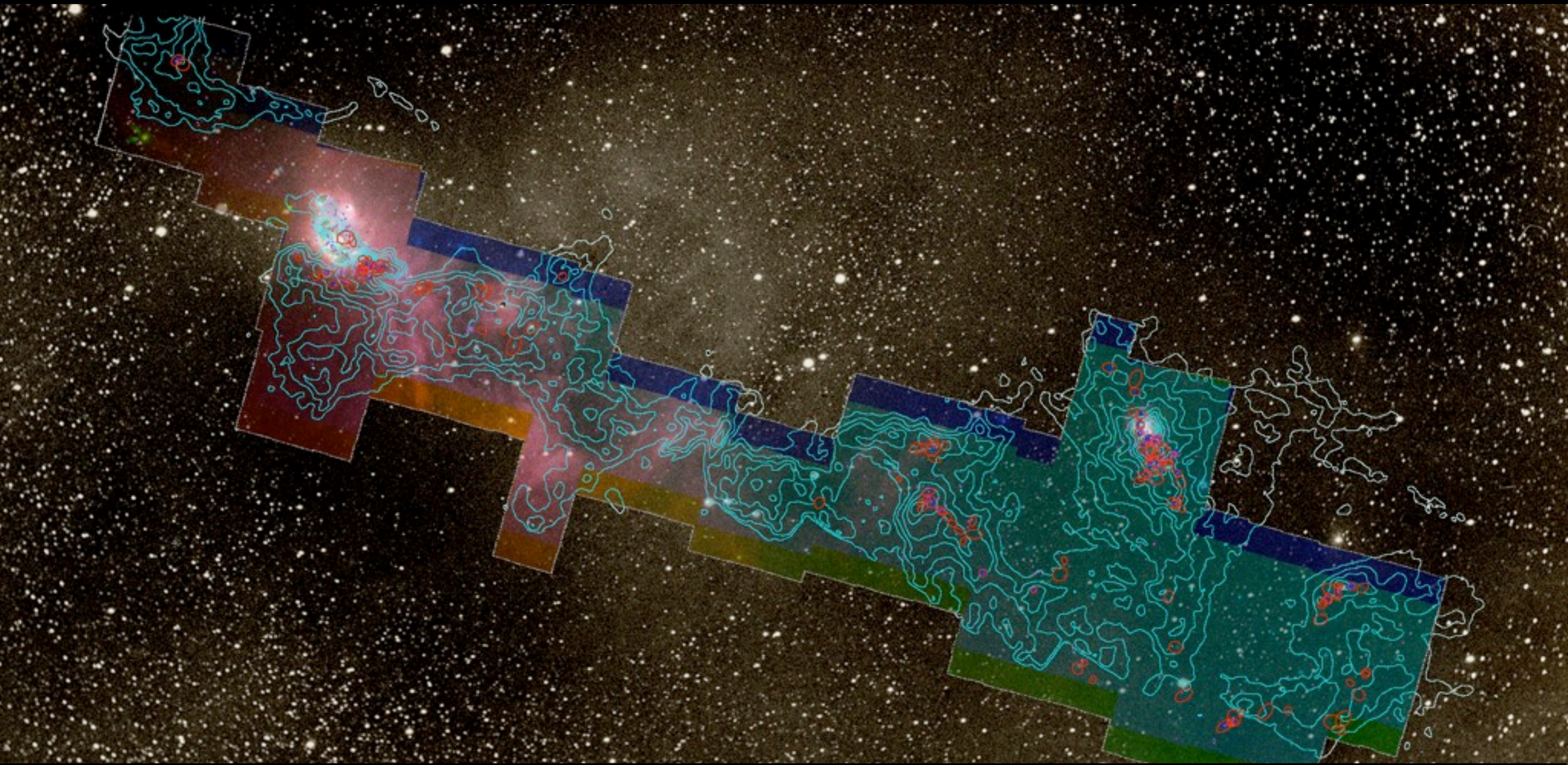
Coordinated Molecular-Probe Line, Extinction & Thermal Emission Observations of Barnard 68

This figure highlights the work of **João Alves** and his collaborators. The *top left* panel shows a deep VLT image (Alves, Lada & Lada 2001). The *middle to*p panel shows the 850 μm continuum emission (Visser, Richer & Chandler 2001) from the dust causing the extinction seen optically. The *top right* panel highlights the extreme depletion seen at high extinctions in $C^{18}O$ emission (Lada et al. 2001). The inset on the *bottom right* panel shows the extinction map derived from applying the NICER method applied to NTT near-infrared observations of the most extinguished portion of B68. The *graph* in the bottom right panel shows the incredible radial-density profile derived from the NICER extinction map (Alves, Lada & Lada 2001). Notice that the fit to this profile shows the inner portion of B68 to be essentially a perfect critical Bonner-Ebert sphere



“Revealing” Outflows

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



COMPLETE Collaborators, 2009:

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Héctor Arce (Yale)

Michelle Borkin (Harvard SEAS)

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)

Thomas Robitaille (CfA)

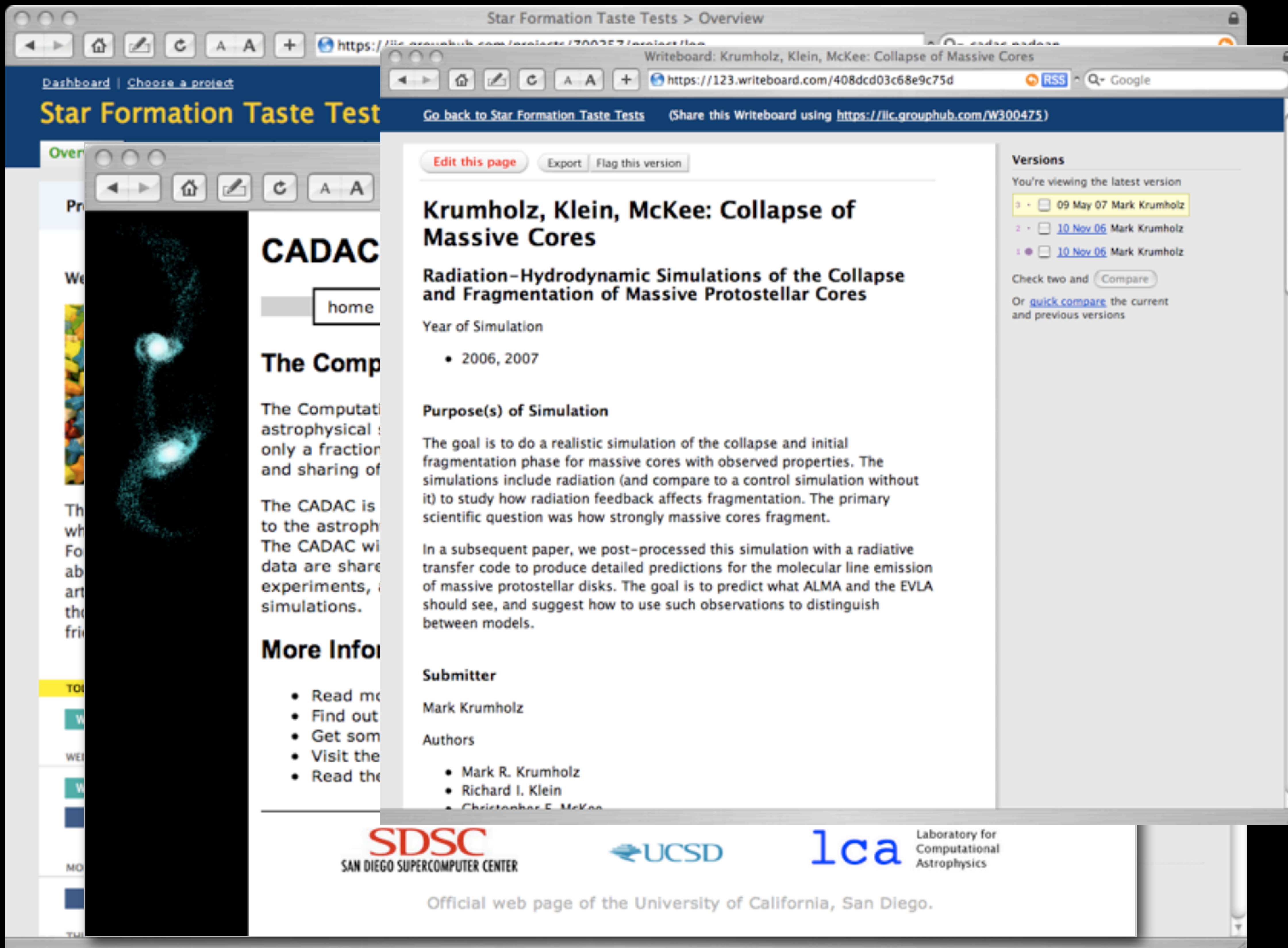
Erik Rosolowsky (UBC Okanagan)

Rahul Shetty (CfA)

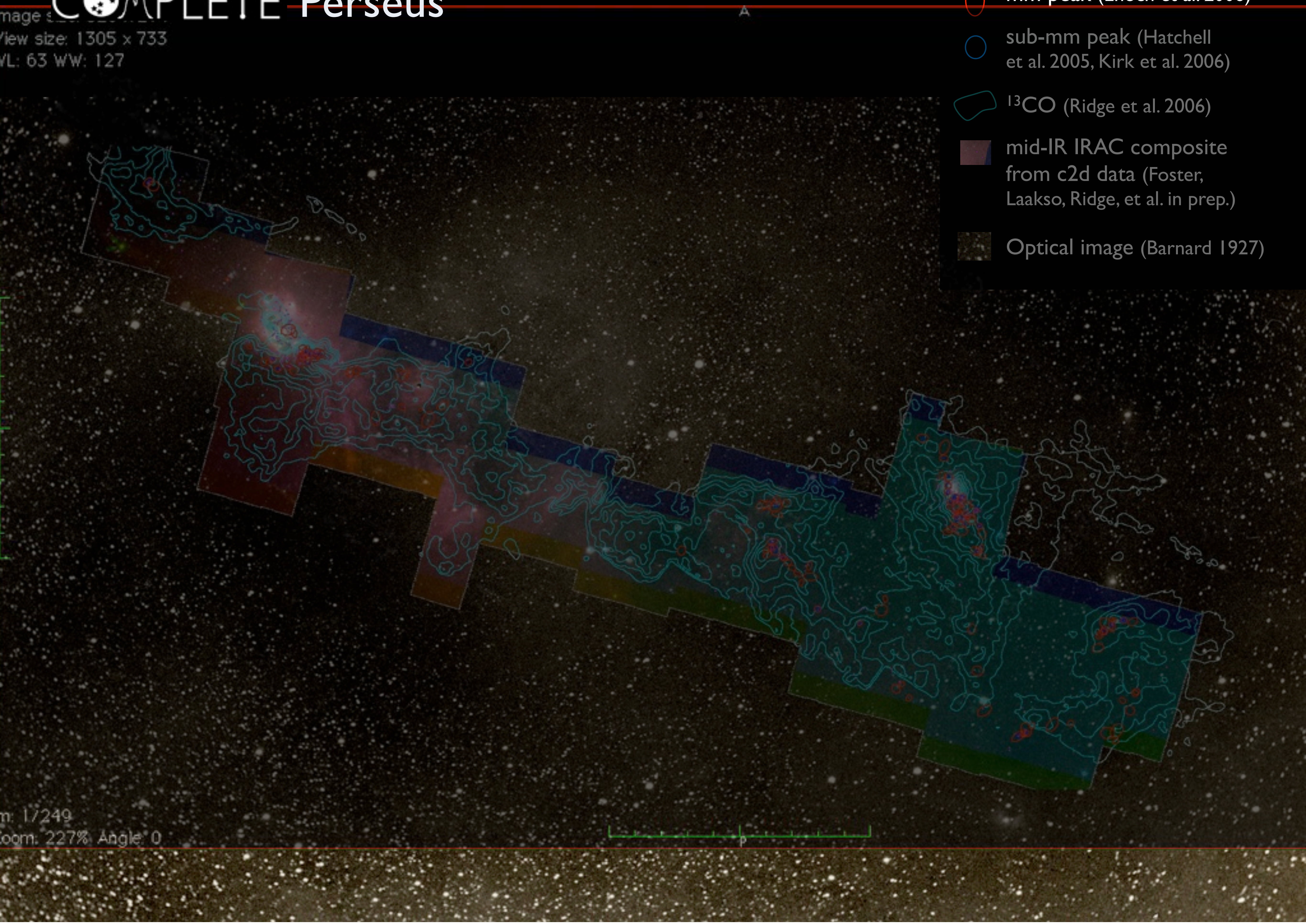
Scott Schnee (Caltech)

Mario Tafalla (OAN, Spain)

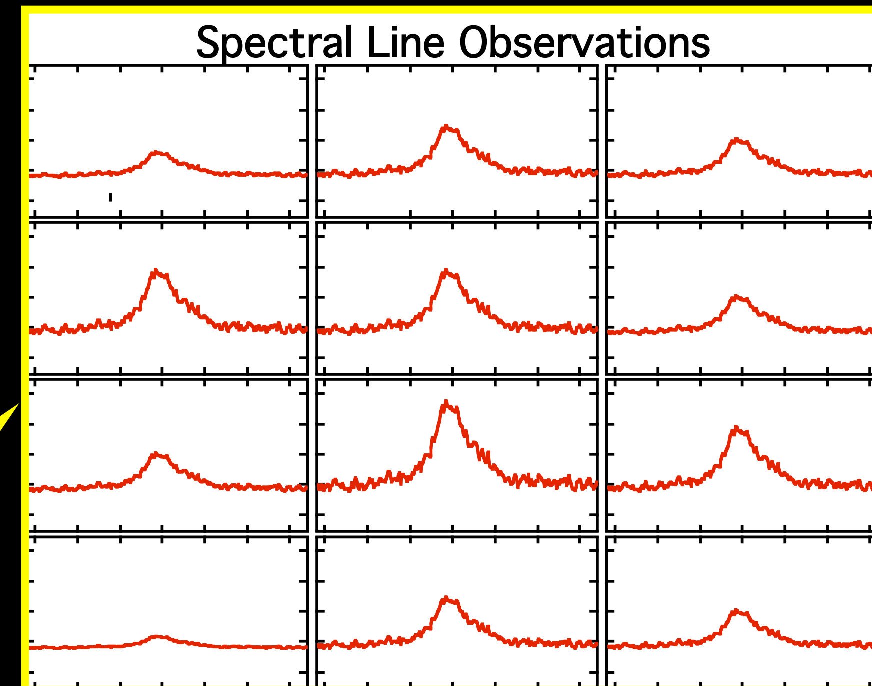
[FYI: Star Formation Taste Tests Site]

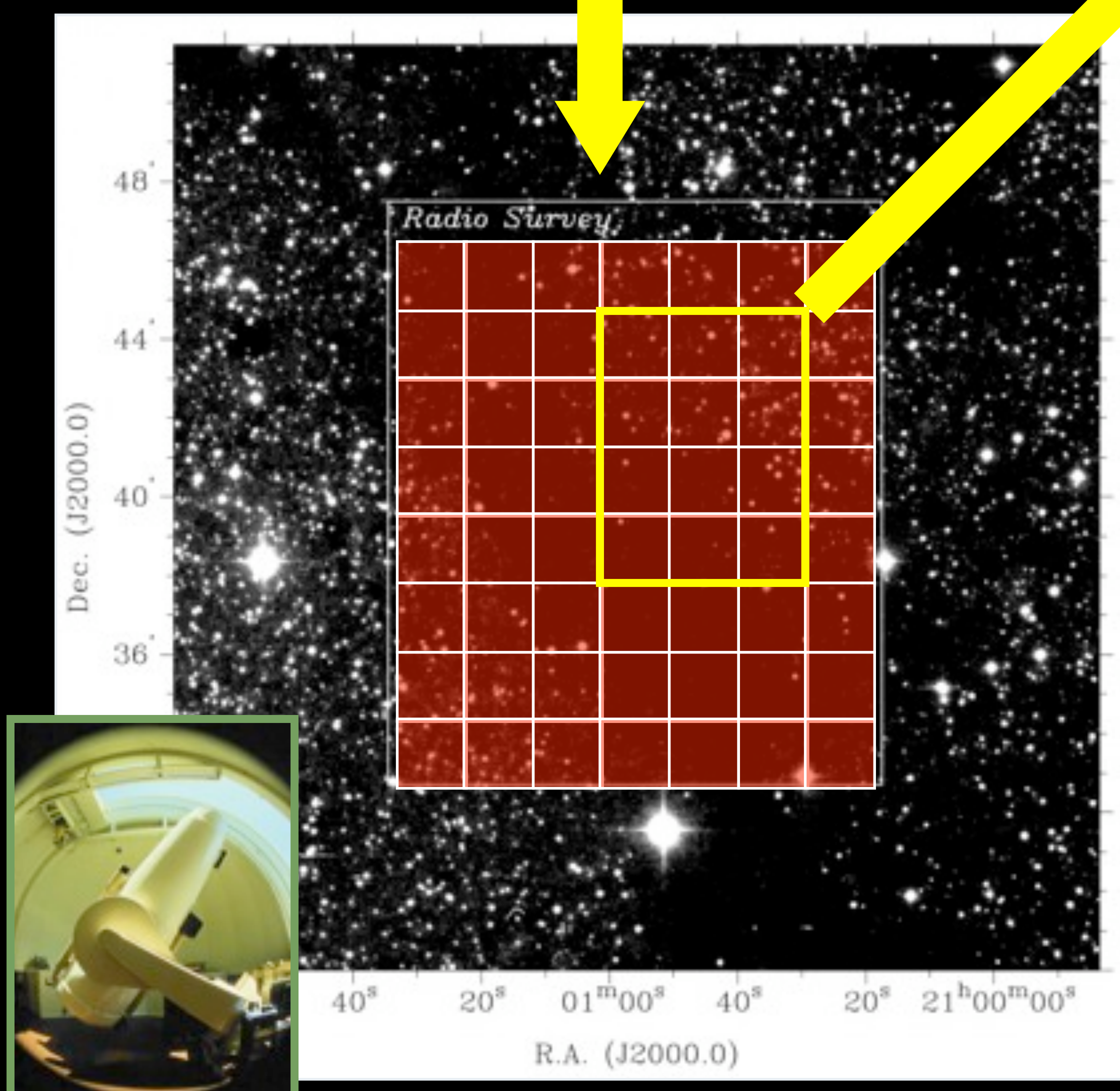


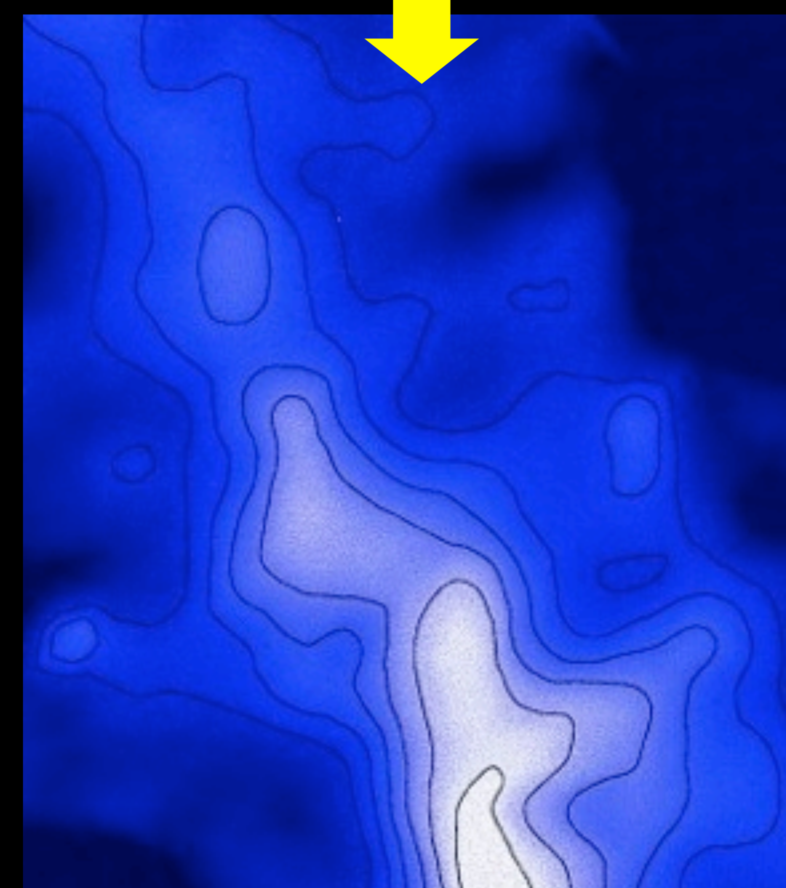
COMPLETE Perseus



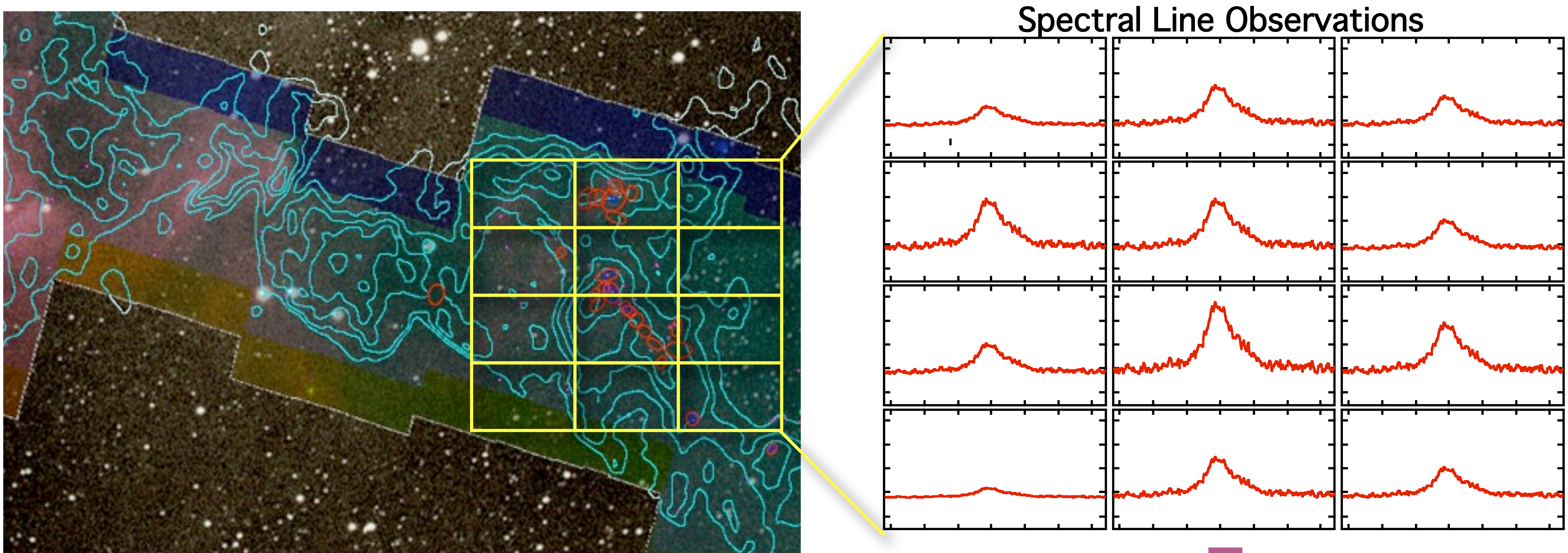
Radio Spectral-line Observations of Interstellar Clouds

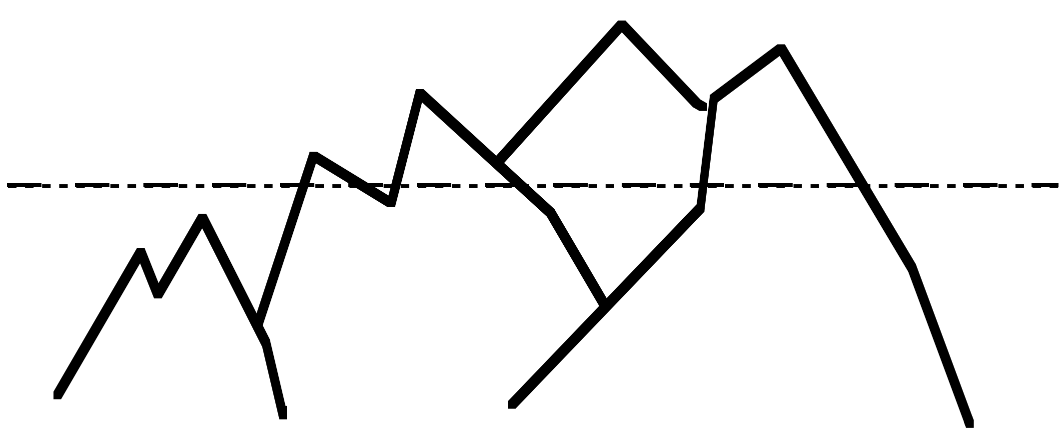






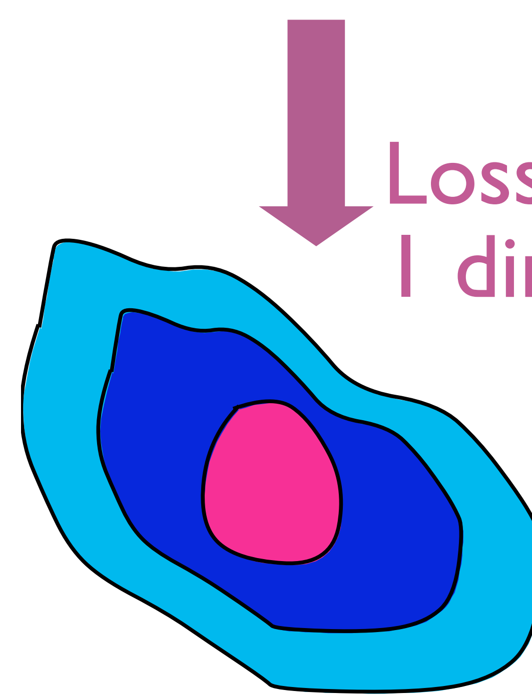
Velocity as a "Fourth" Dimension





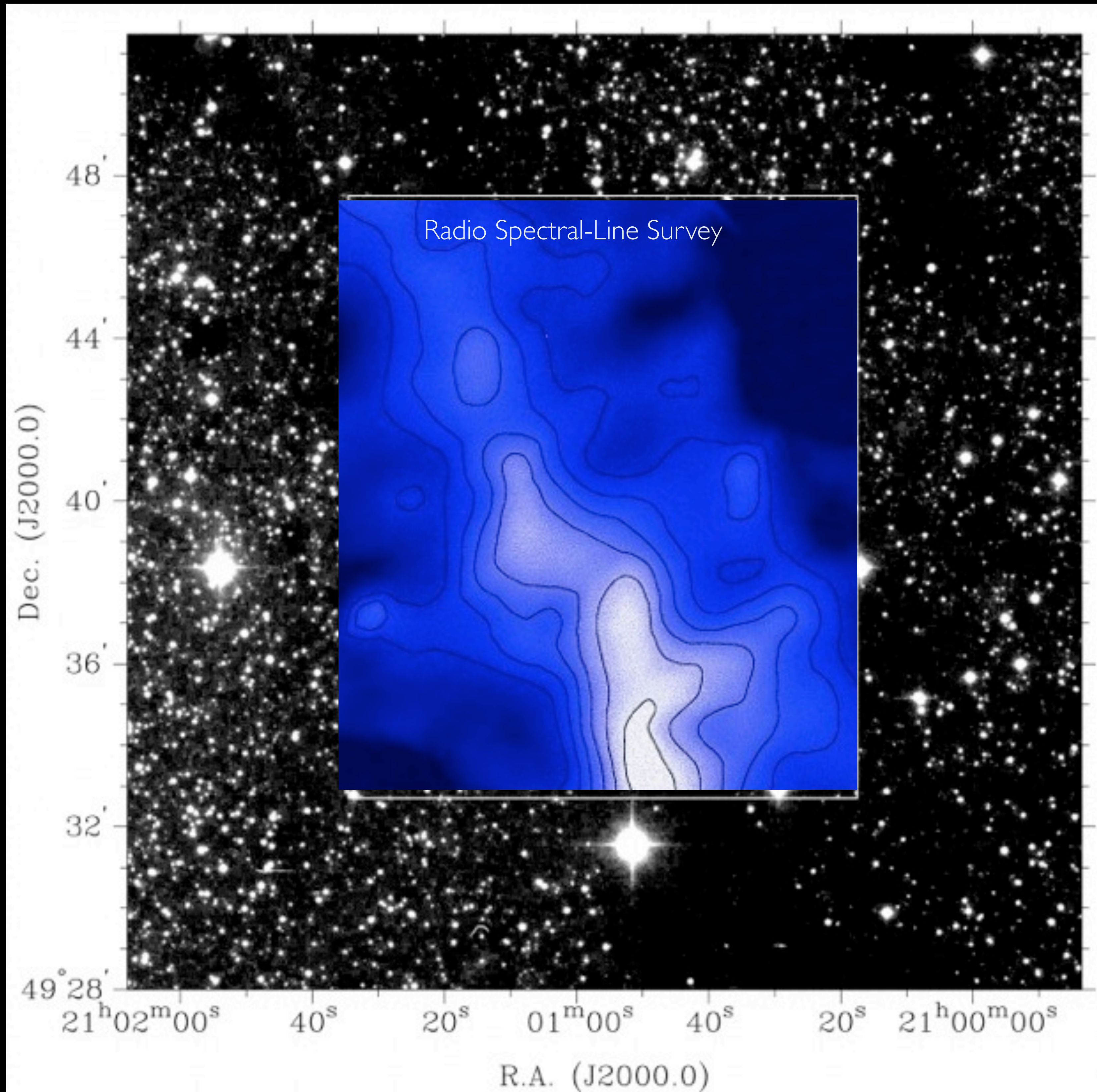
Mountain Range

No loss of information



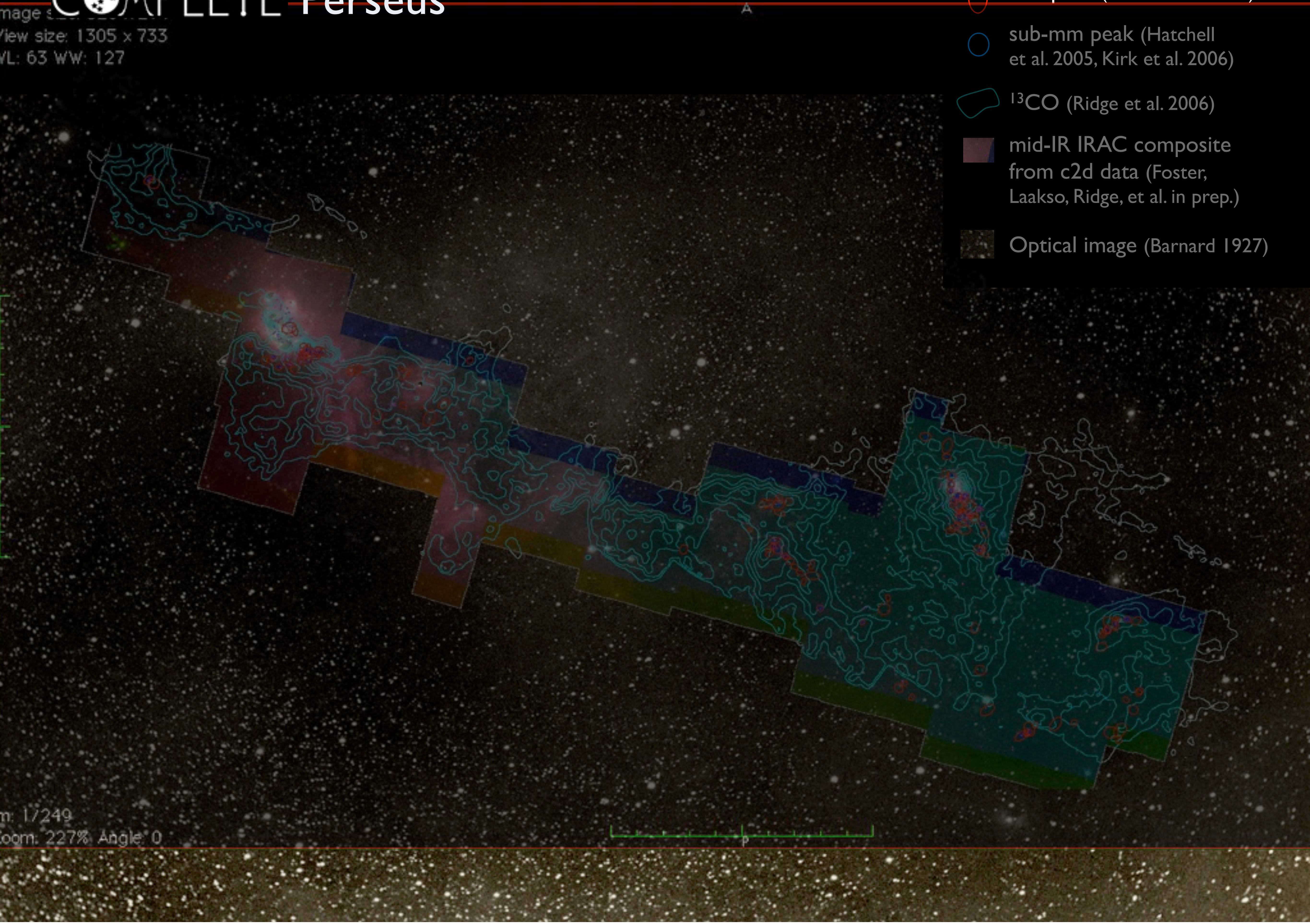
Loss of 1 dimension

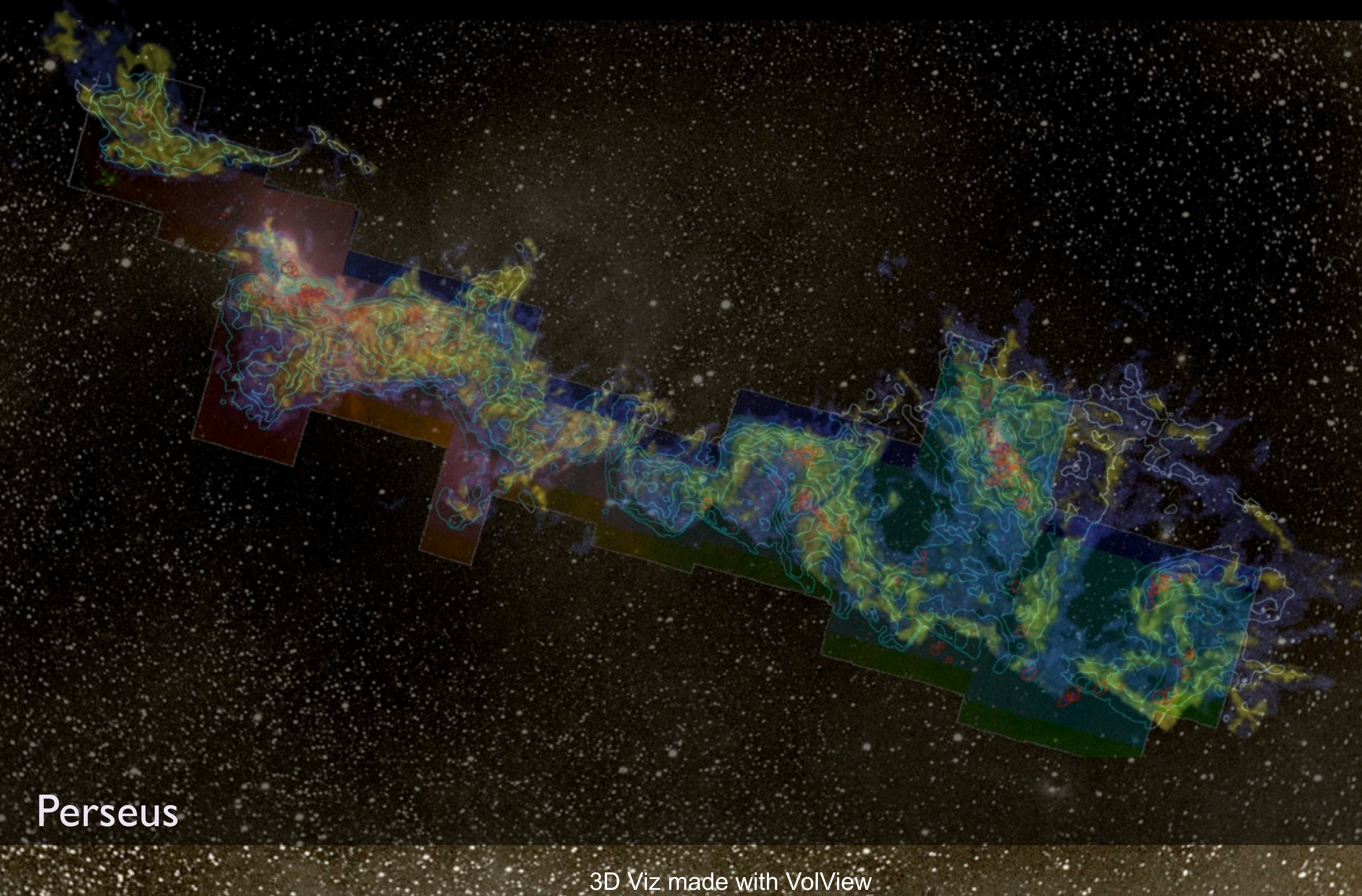
Radio Spectral-line Observations of Interstellar Clouds



Alves, Lada & Lada 1999

COMPLETE Perseus

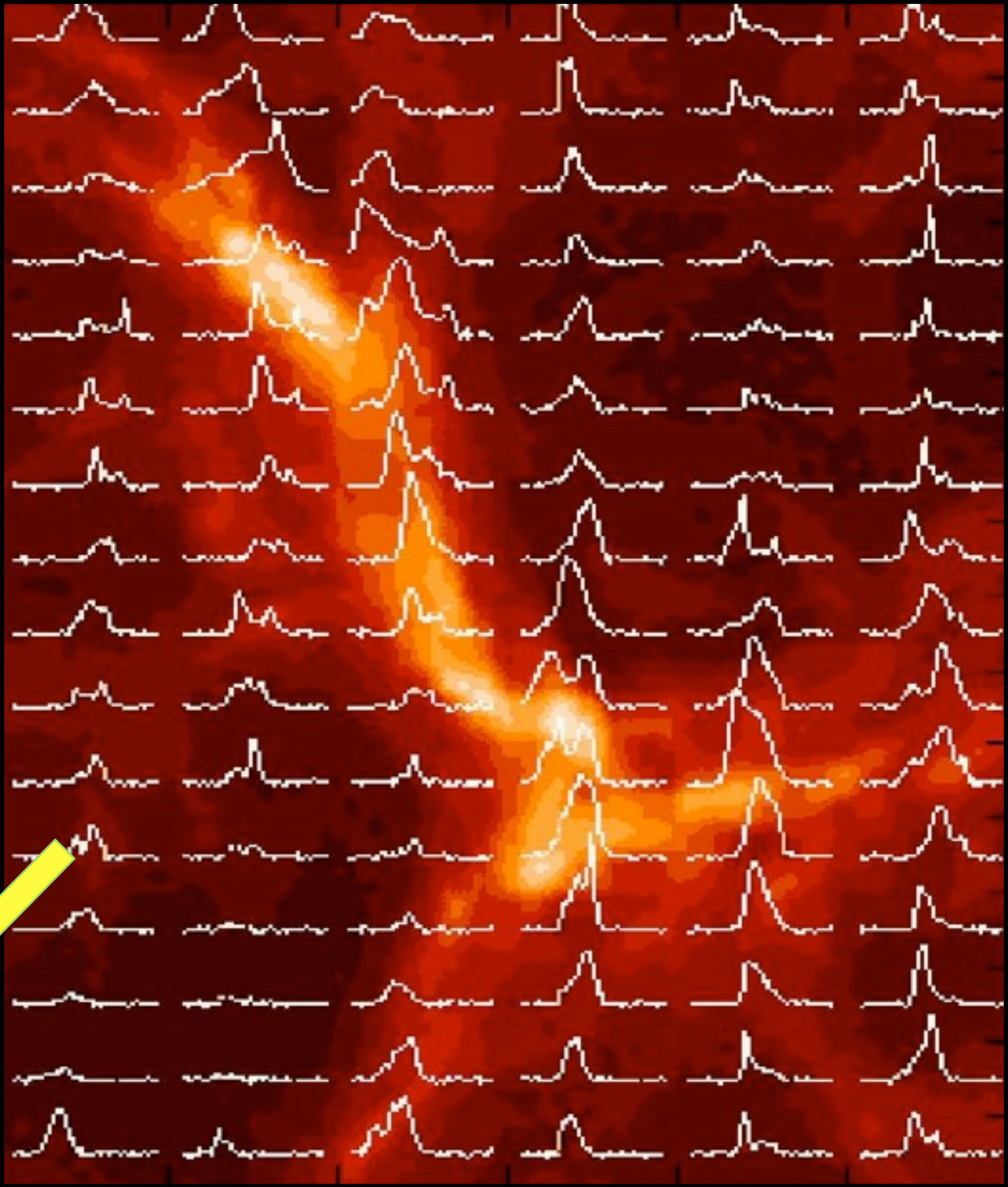




AstroMed@IIC

COMPLETE

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



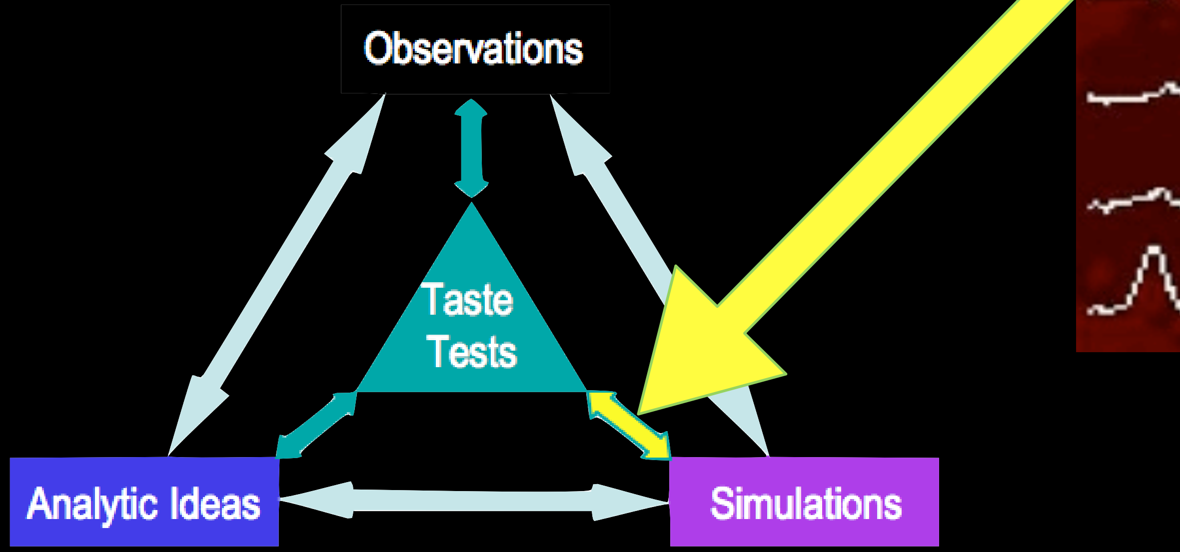


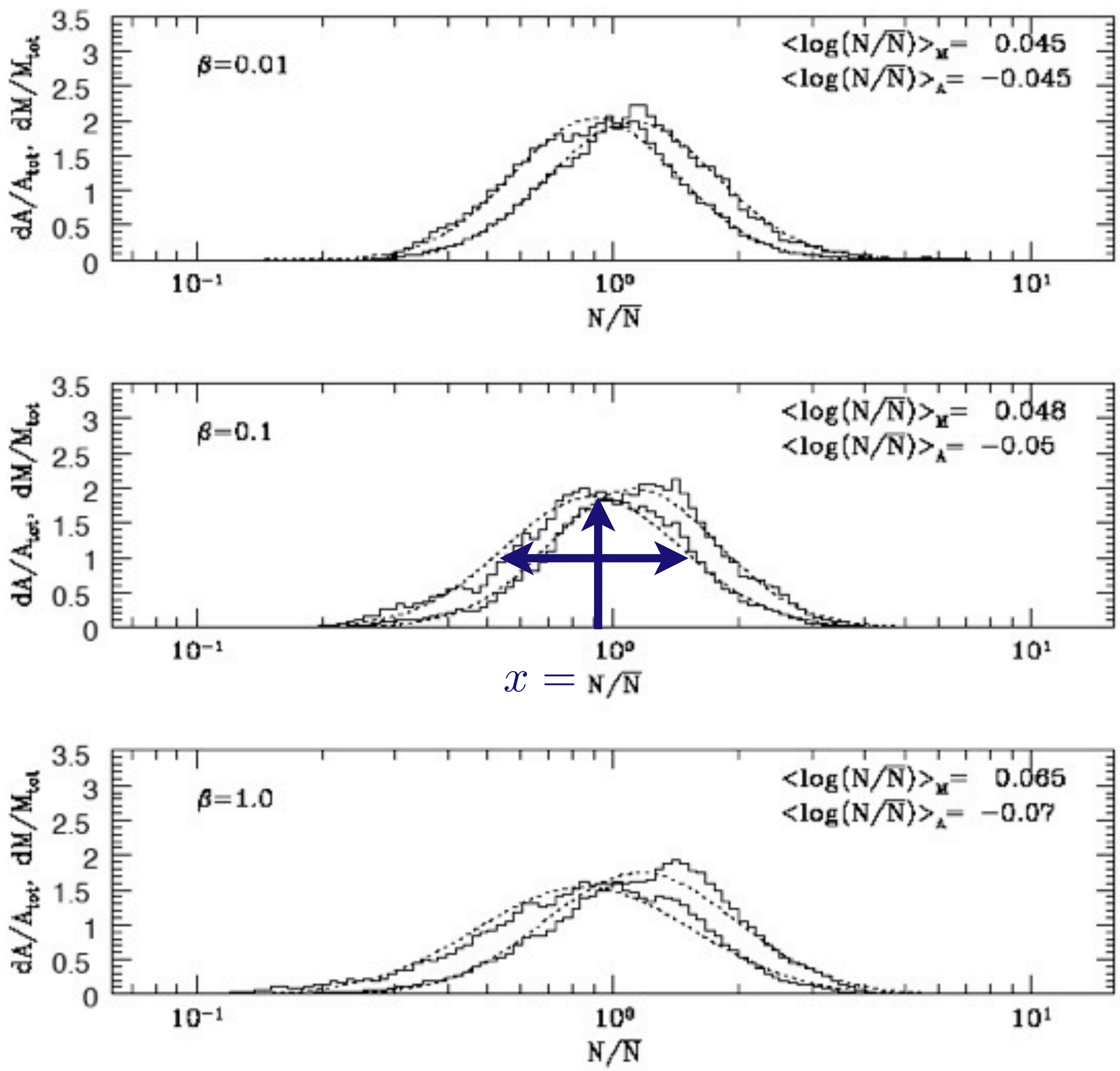
Figure based on work of Padoan, Nordlund, Juvela, et al.
Excerpt from realization used in Padoan & Goodman 2002.

A “Simple” Example:
Column Density Distributions

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

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

Example: log-normal column density distribution

(Ostriker, Stone & Gammie 2001)

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

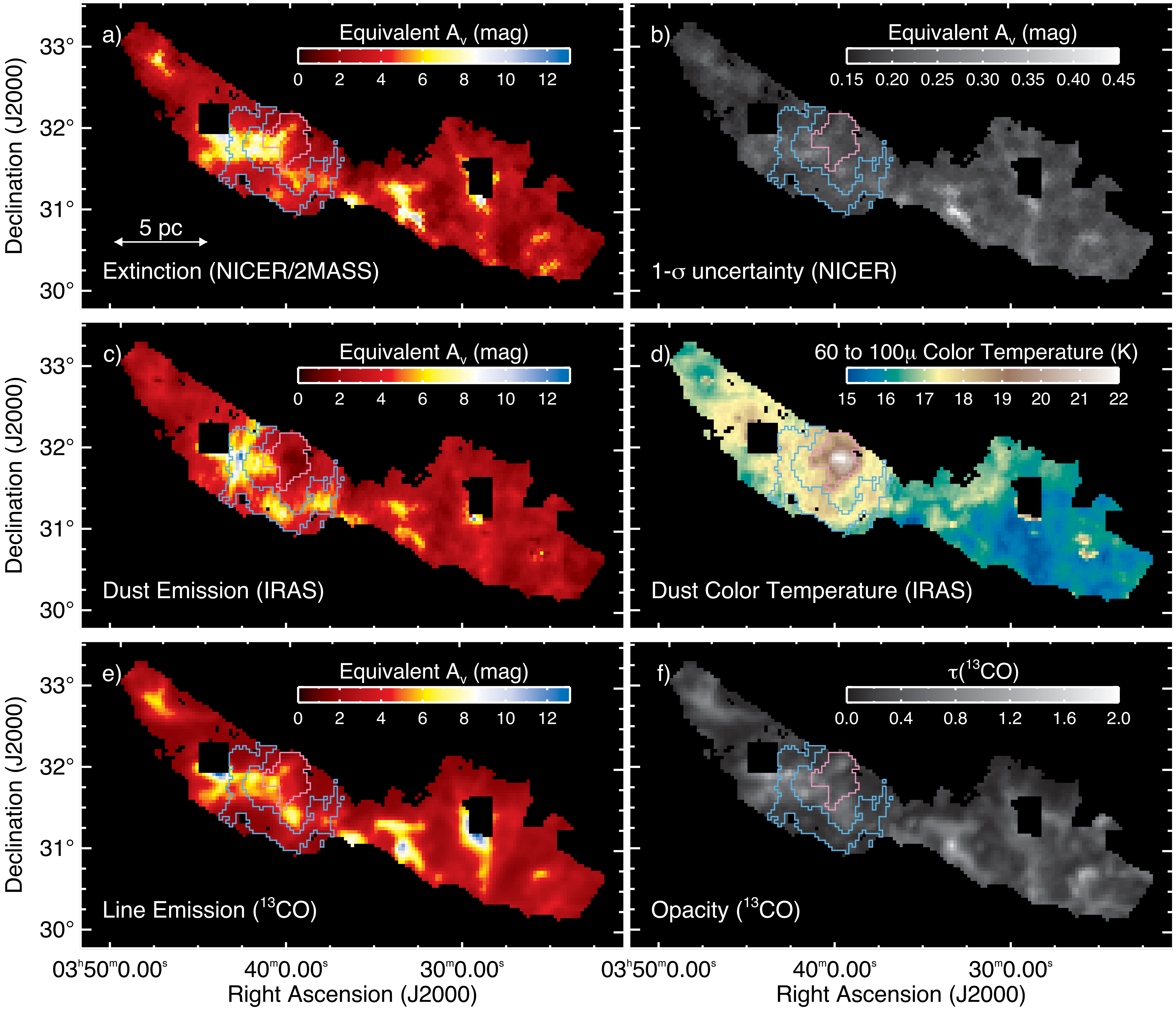


figure from Goodman, Pineda & Schnee 2008; see also Pineda et al. 2008

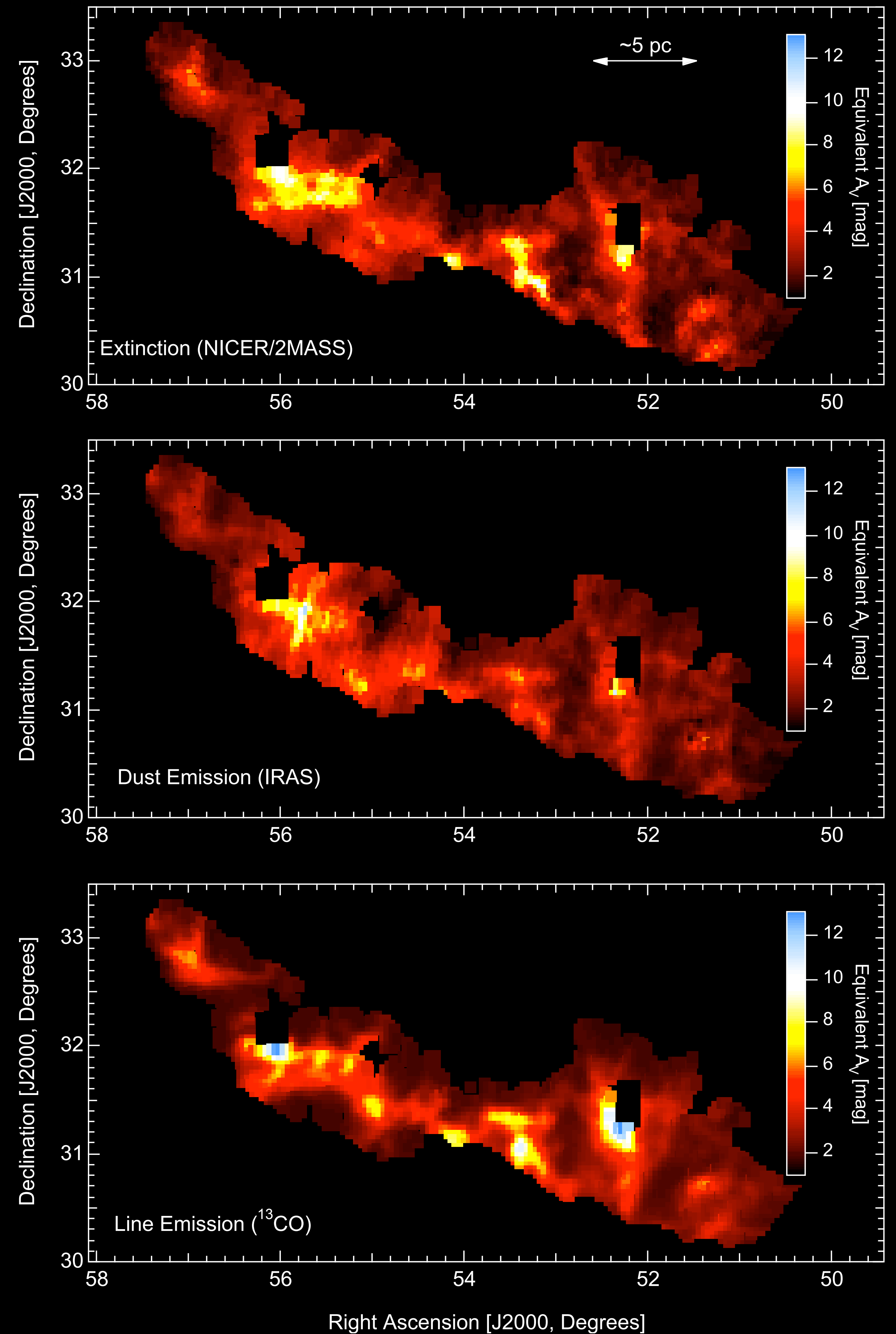
The (secret) uncertainties inherent in column density mapping.

Goodman, Pineda & Schnee 2008

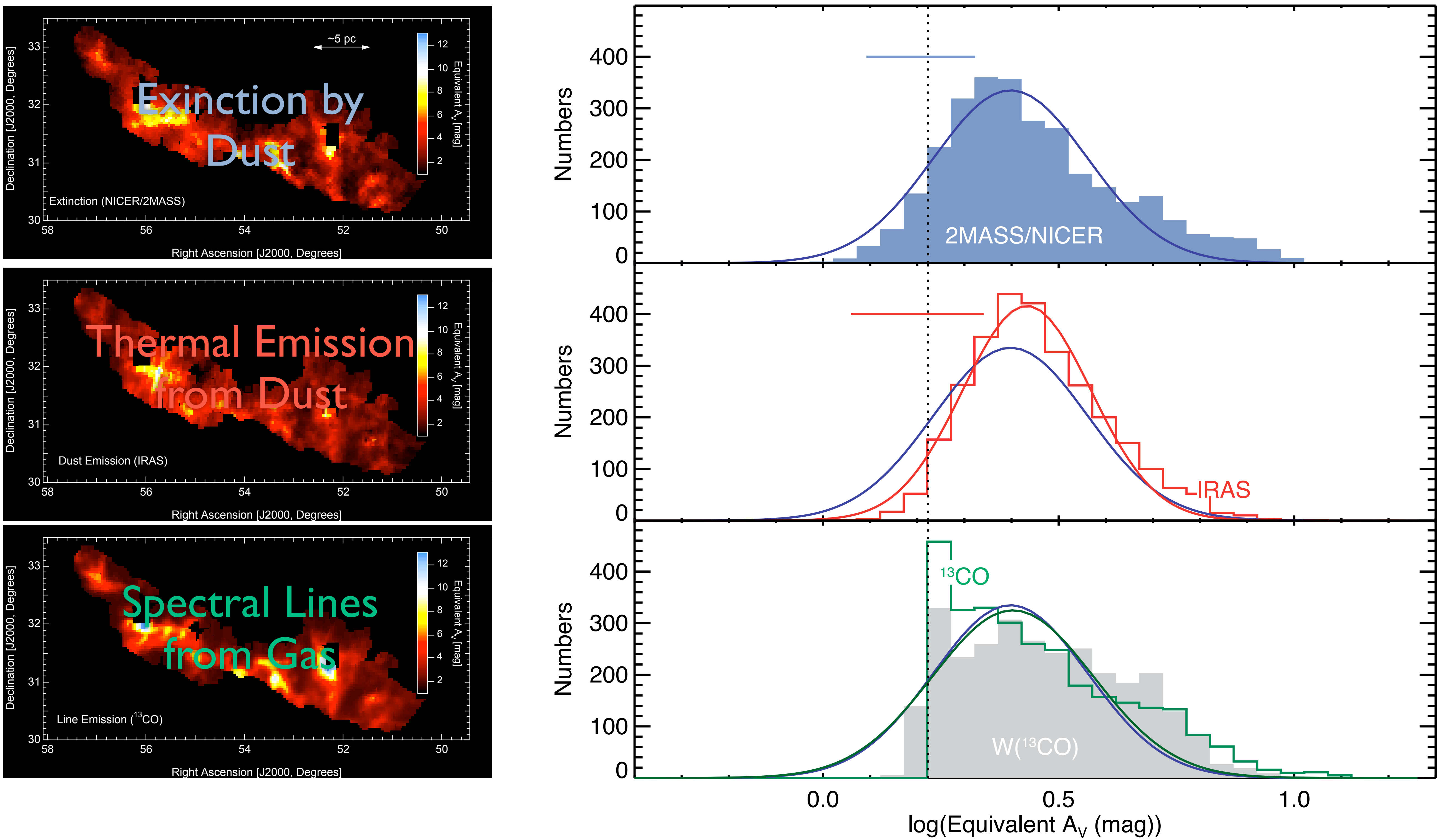
Extinction

Dust Emission

^{13}CO Emission

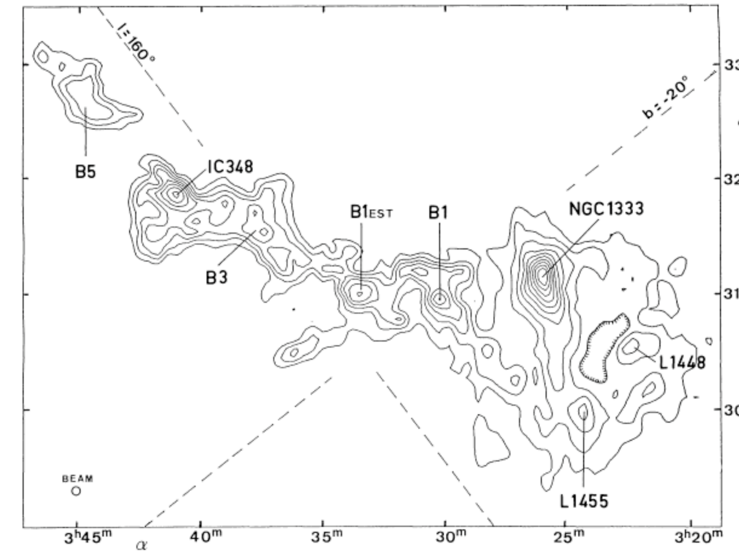


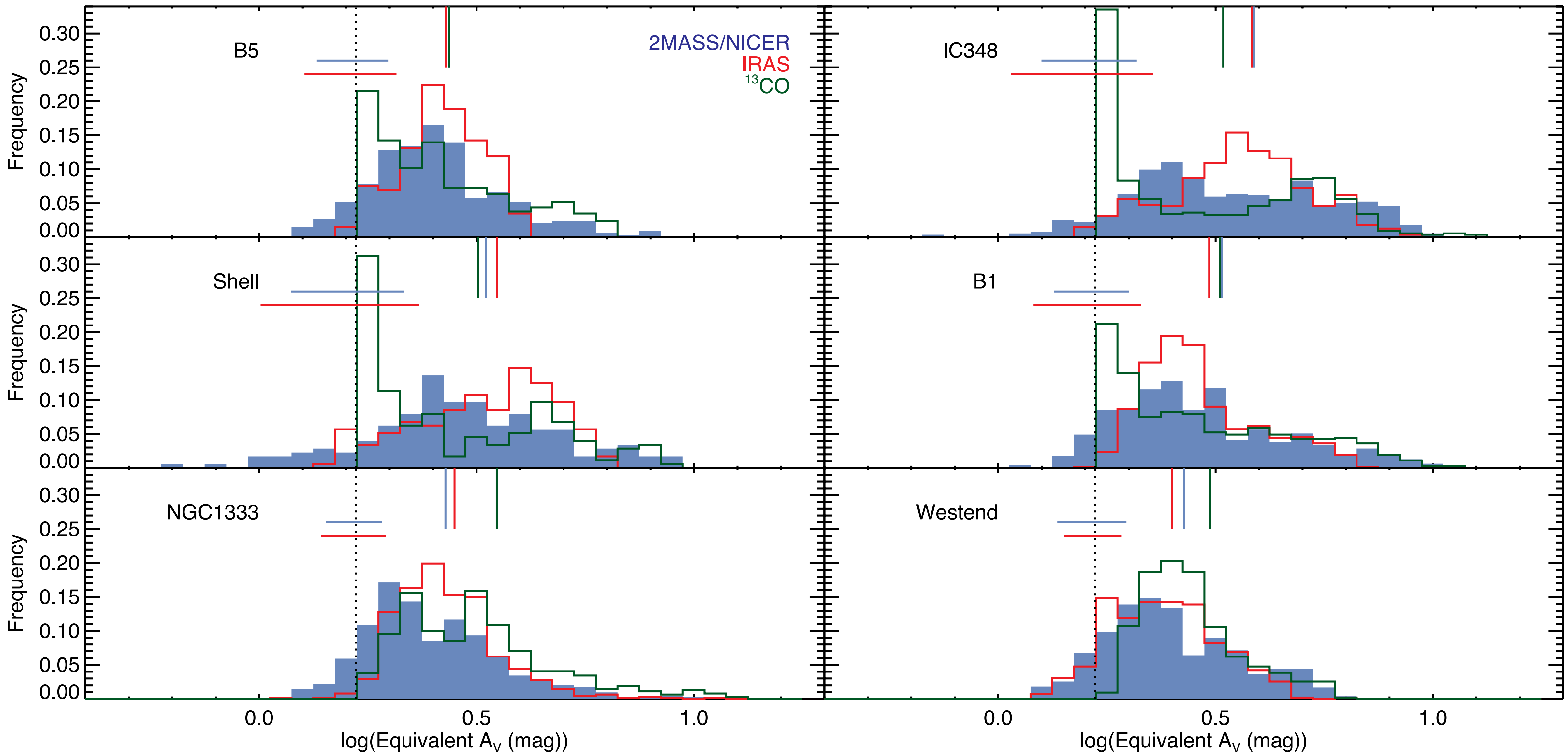
Column Density in Perseus, Measured 3 Ways



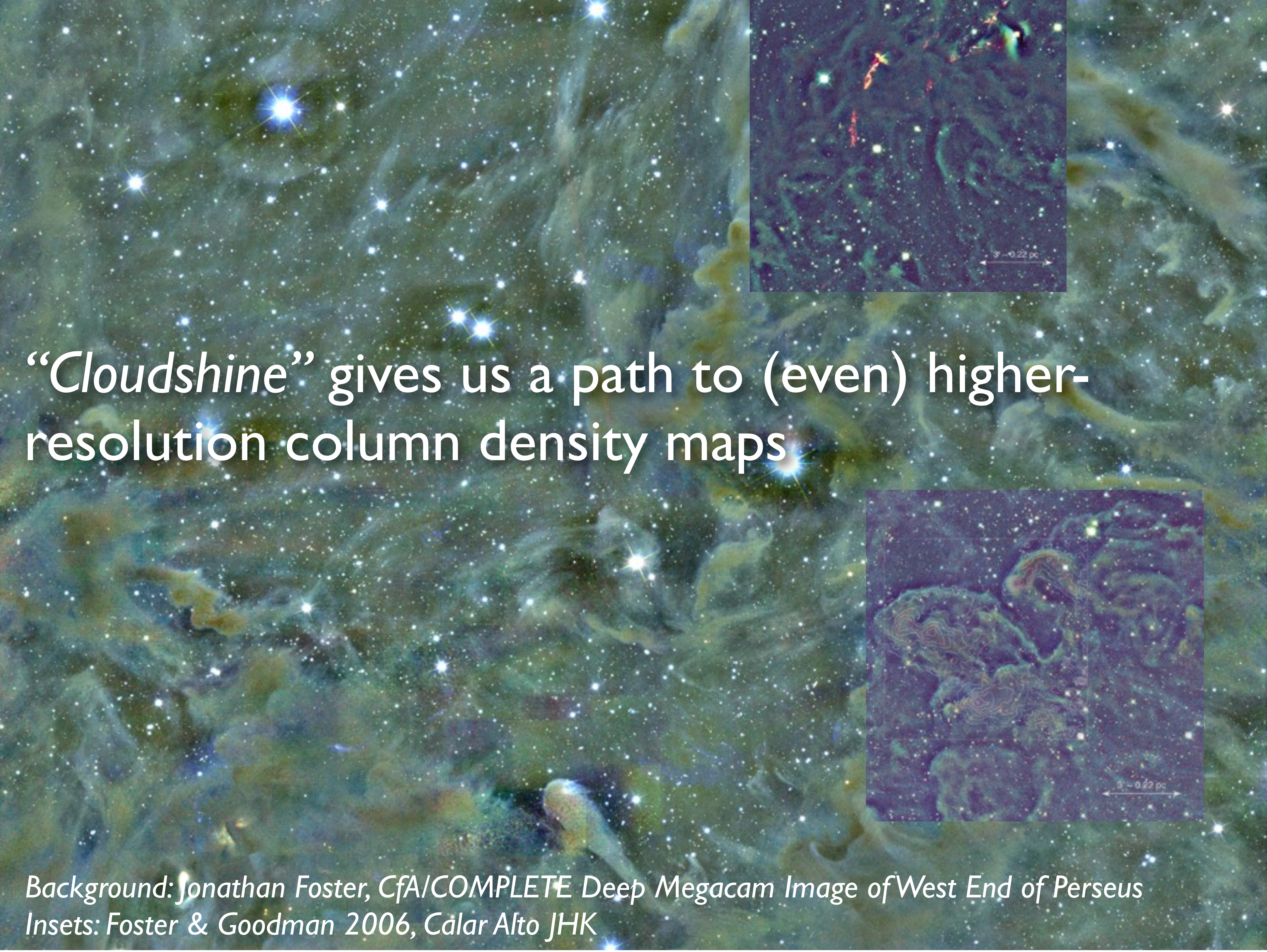
Goodman, Pineda & Schnee 2008

Regional Variations within Perseus





Goodman, Pineda & Schnee 2008; Pineda, Caselli & Goodman 2008



"*Cloudshine*" gives us a path to (even) 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

"Cloudshine"=Scattered Ambient Starlight

2006

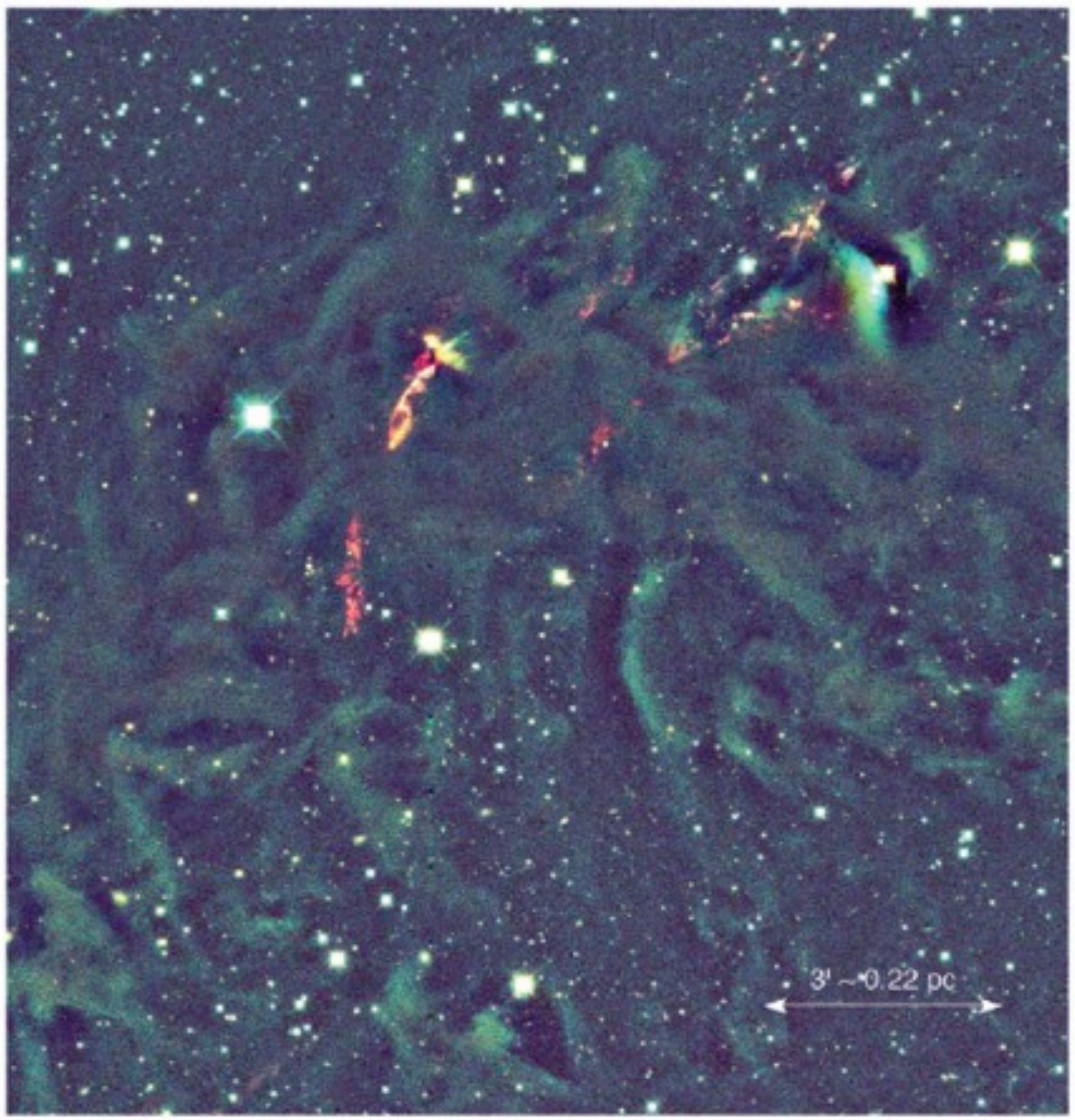


FIG. 1.—L1448 in false color. Component images have been weighted according to their flux in units of MJy sr^{-1}. J is blue, H is green, and K_s is red. Outflows from young stars glow red, while a small fan-shaped reflection nebula in the upper right is blue-green. Cloudshine, in contrast, is shown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

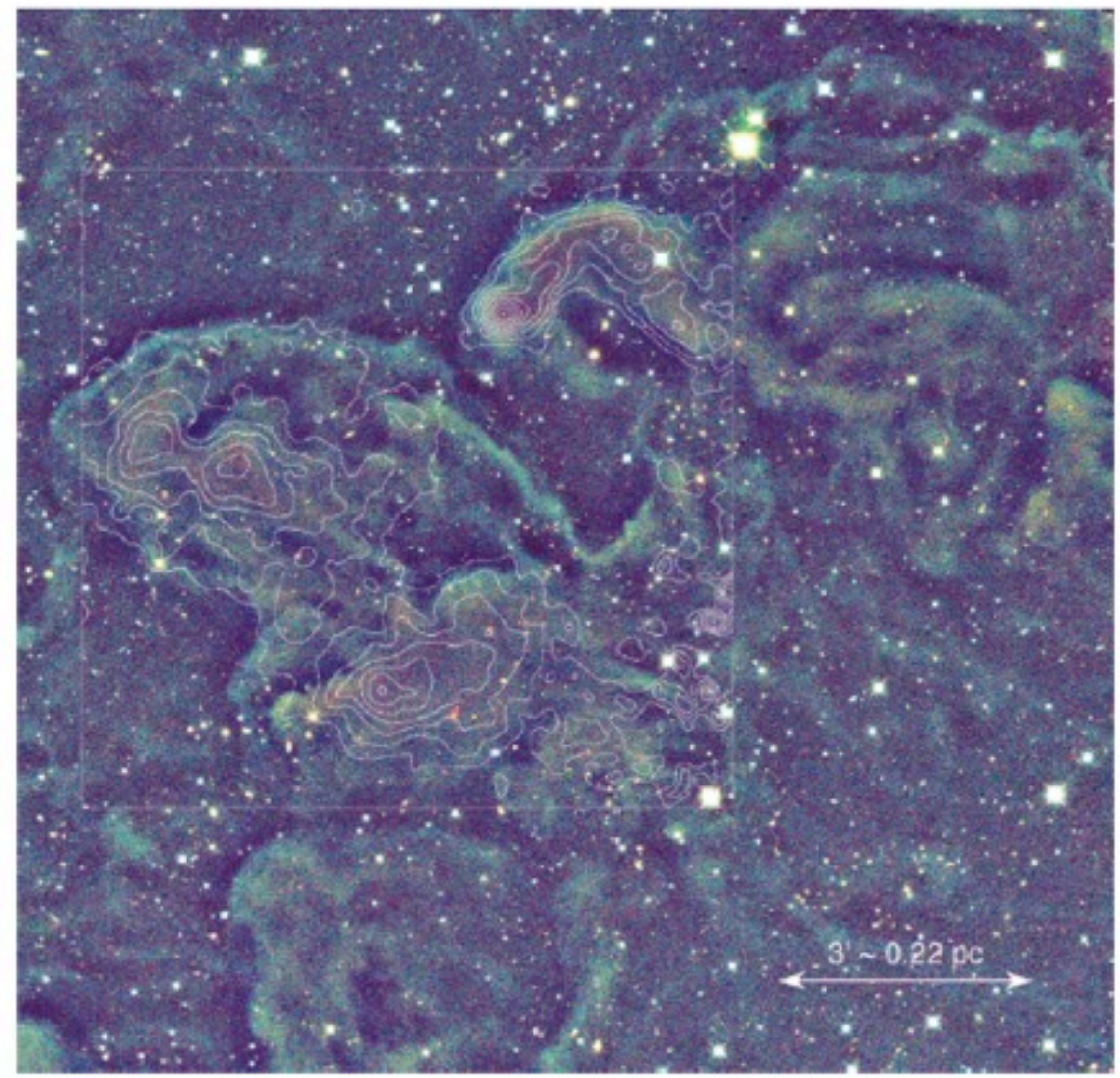
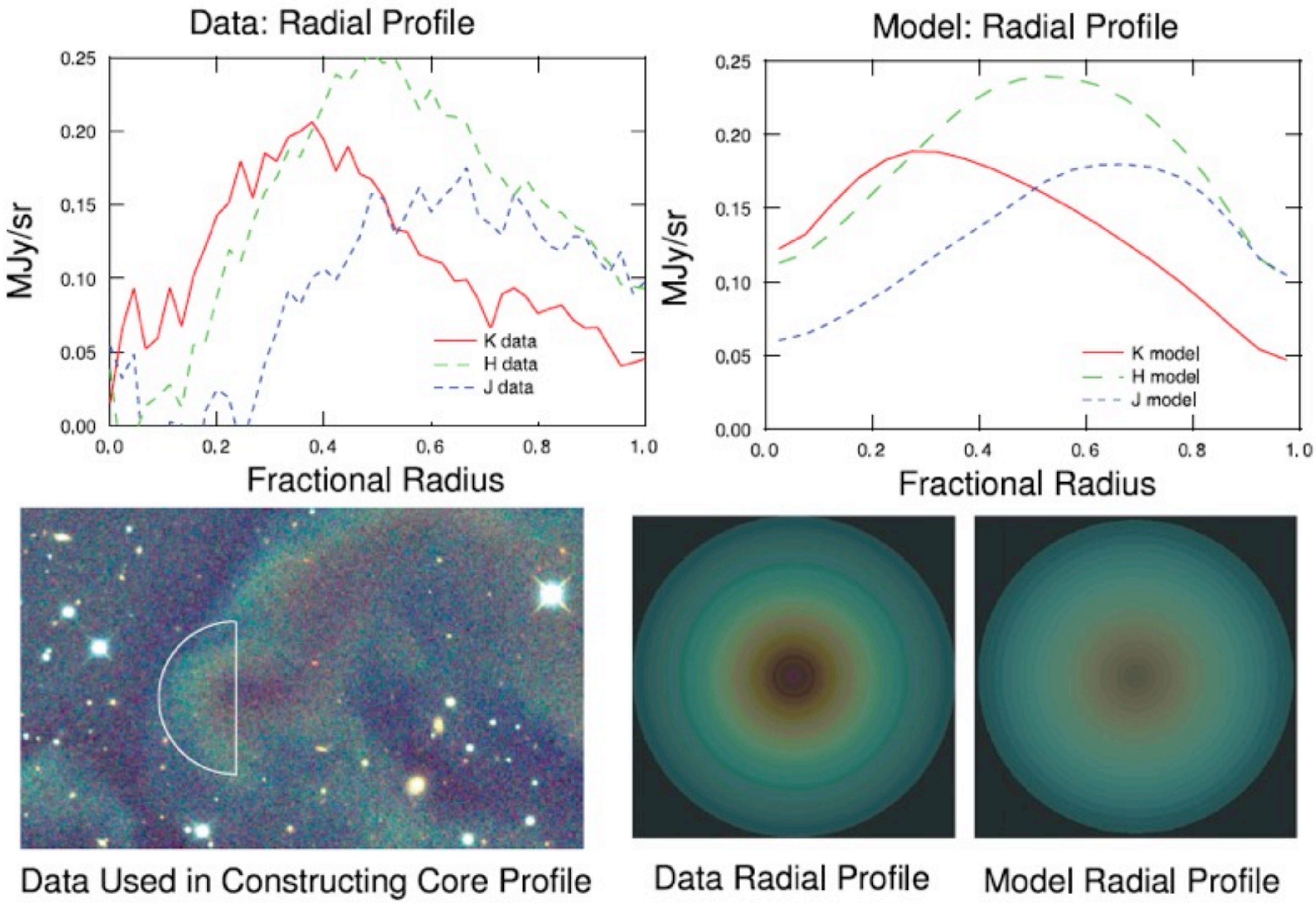


FIG. 2.—L1451 in false color. Again, each component image has been scaled to the same flux scale in units of MJy sr^{-1}; and J is blue, H is green, and K_s is red. A smaller map of 1.2 mm dust emission contours from COMPLETE (M. Tafalla 2006, in preparation) has been overlaid, showing that the color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

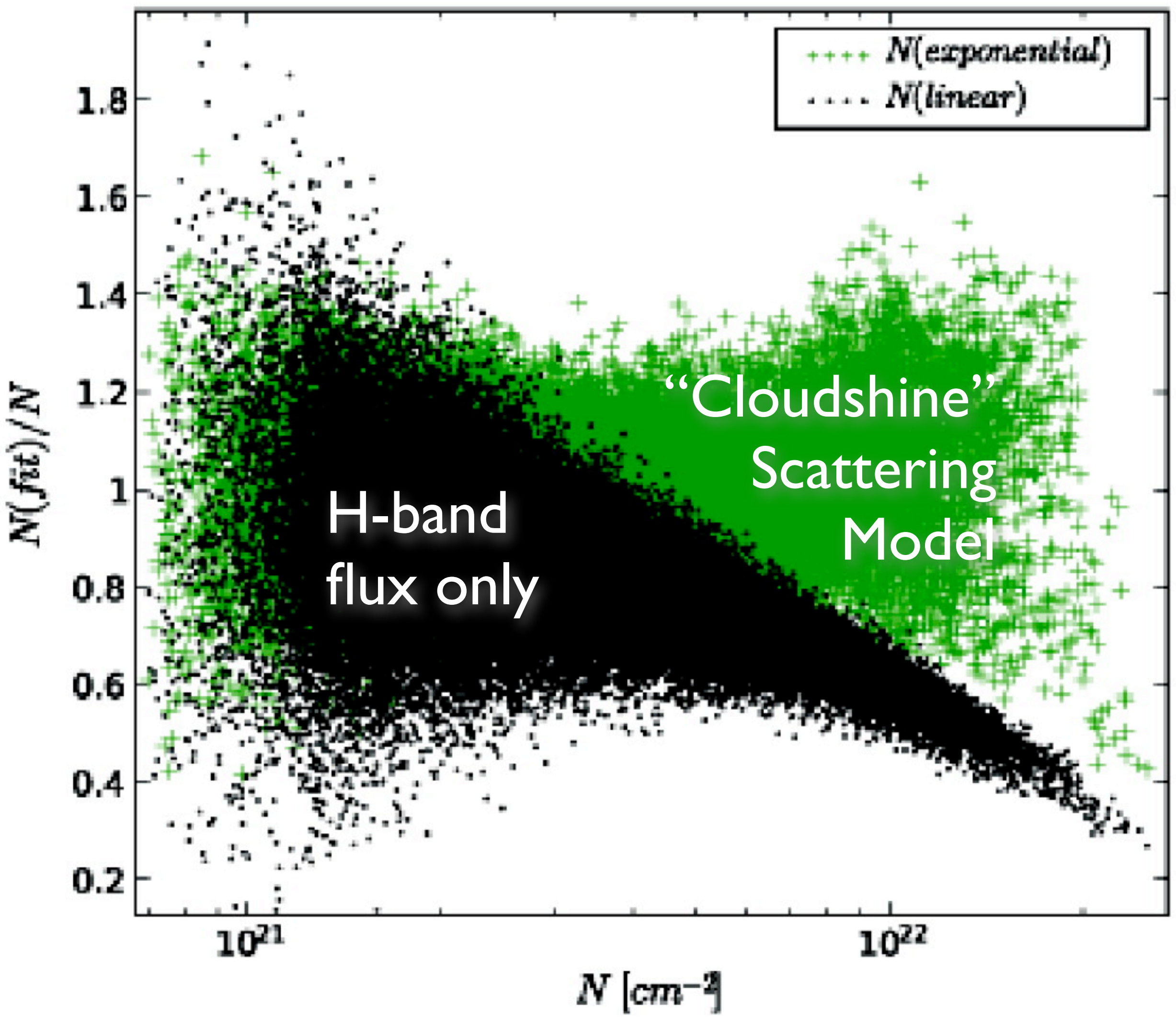
“Tasting” a Very Simple Recipe



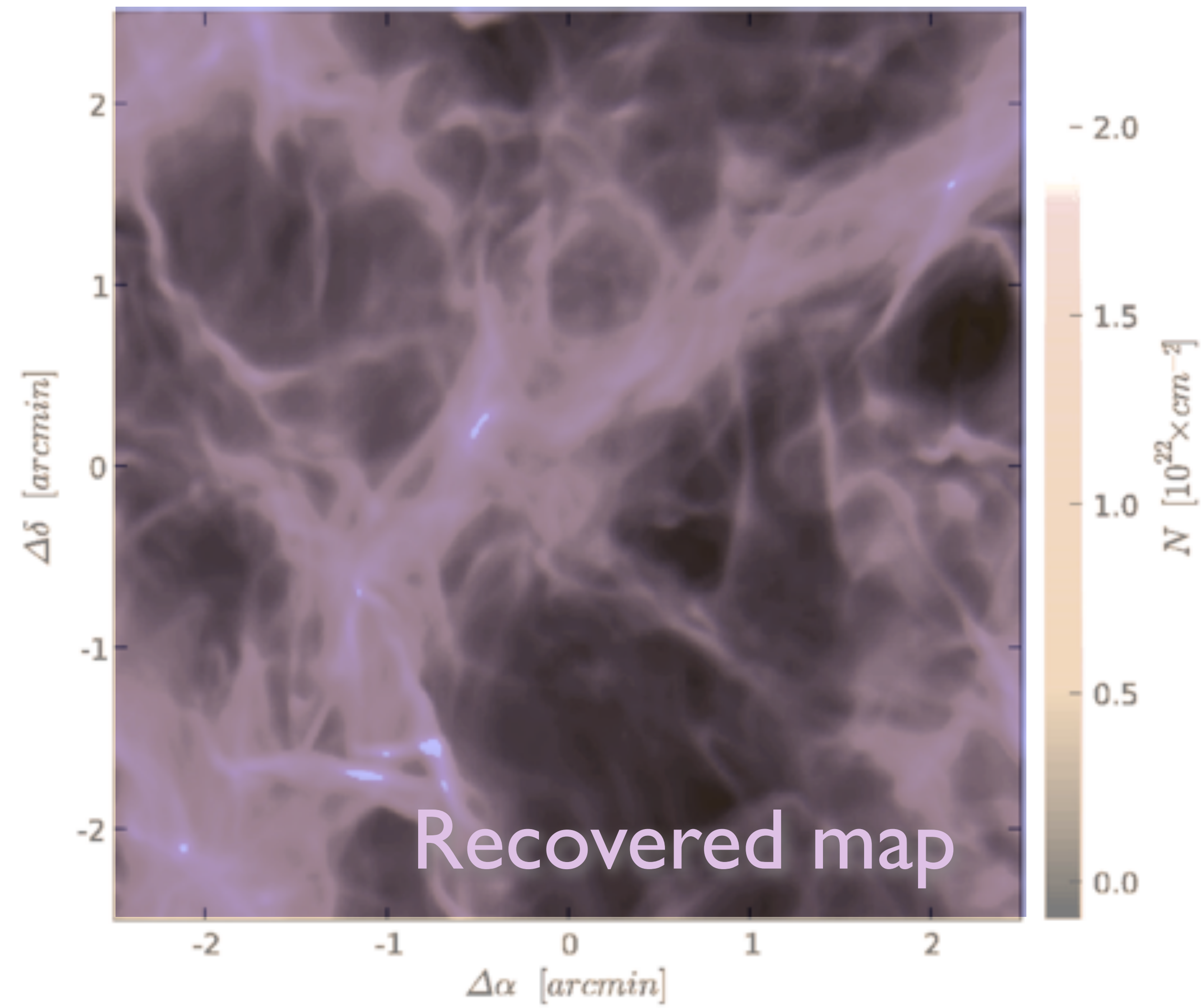
Foster & Goodman 2006

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!



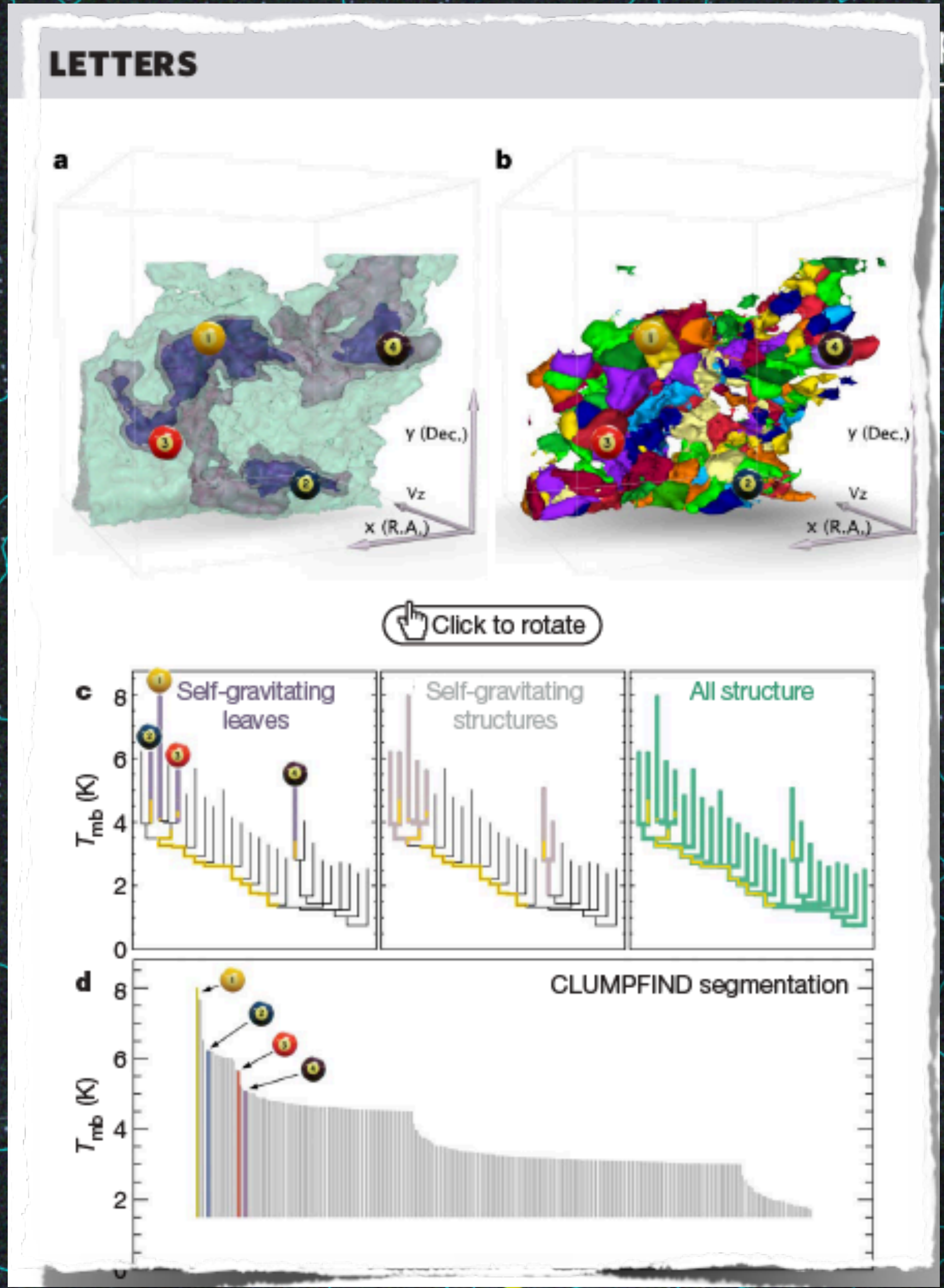
Simulation



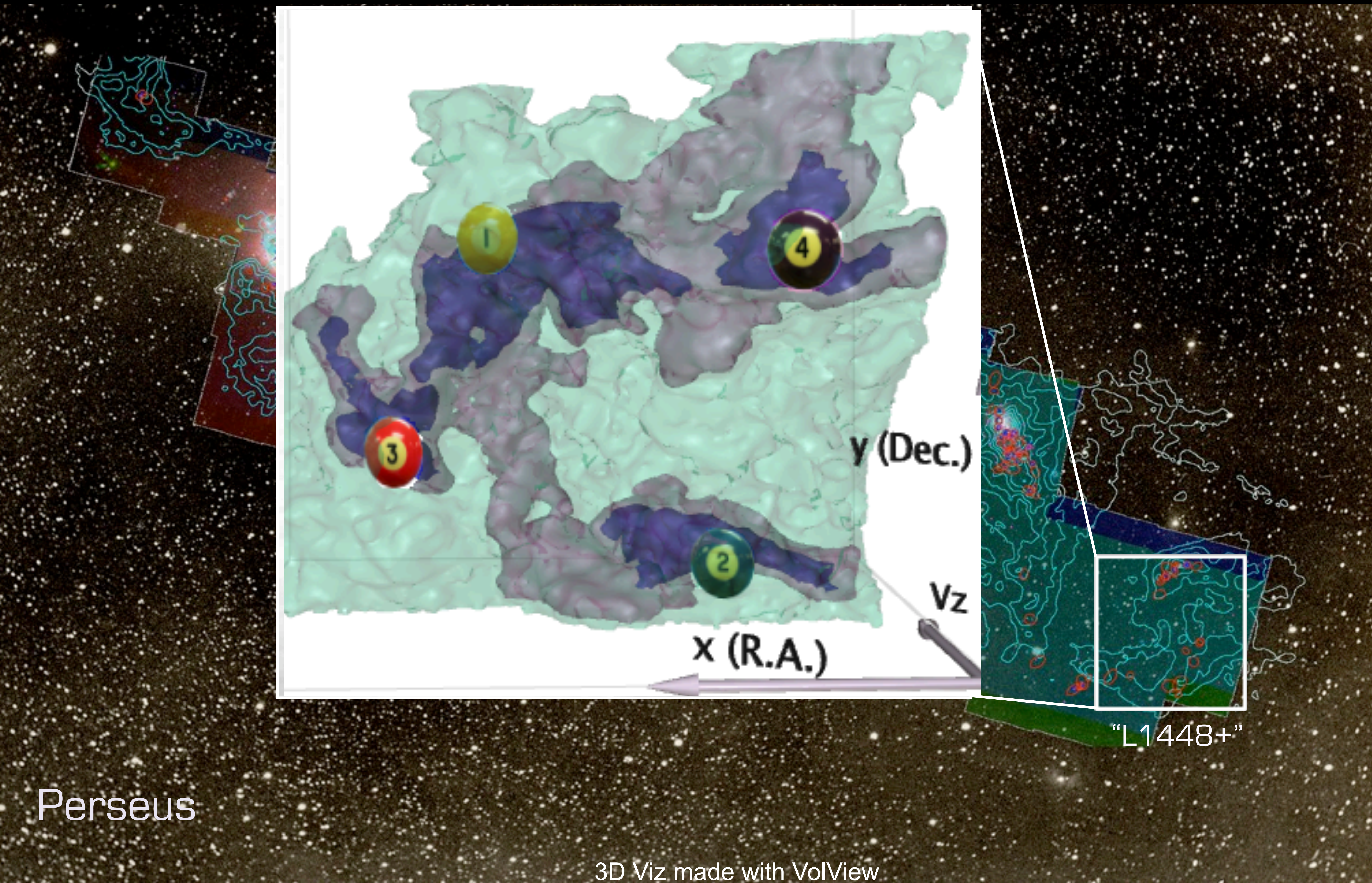
Tastes "right", with 20% scatter, at $1<A_V<10$, for NIR.

Padoan et al. 2006

Tasting Gravity (in L1448)

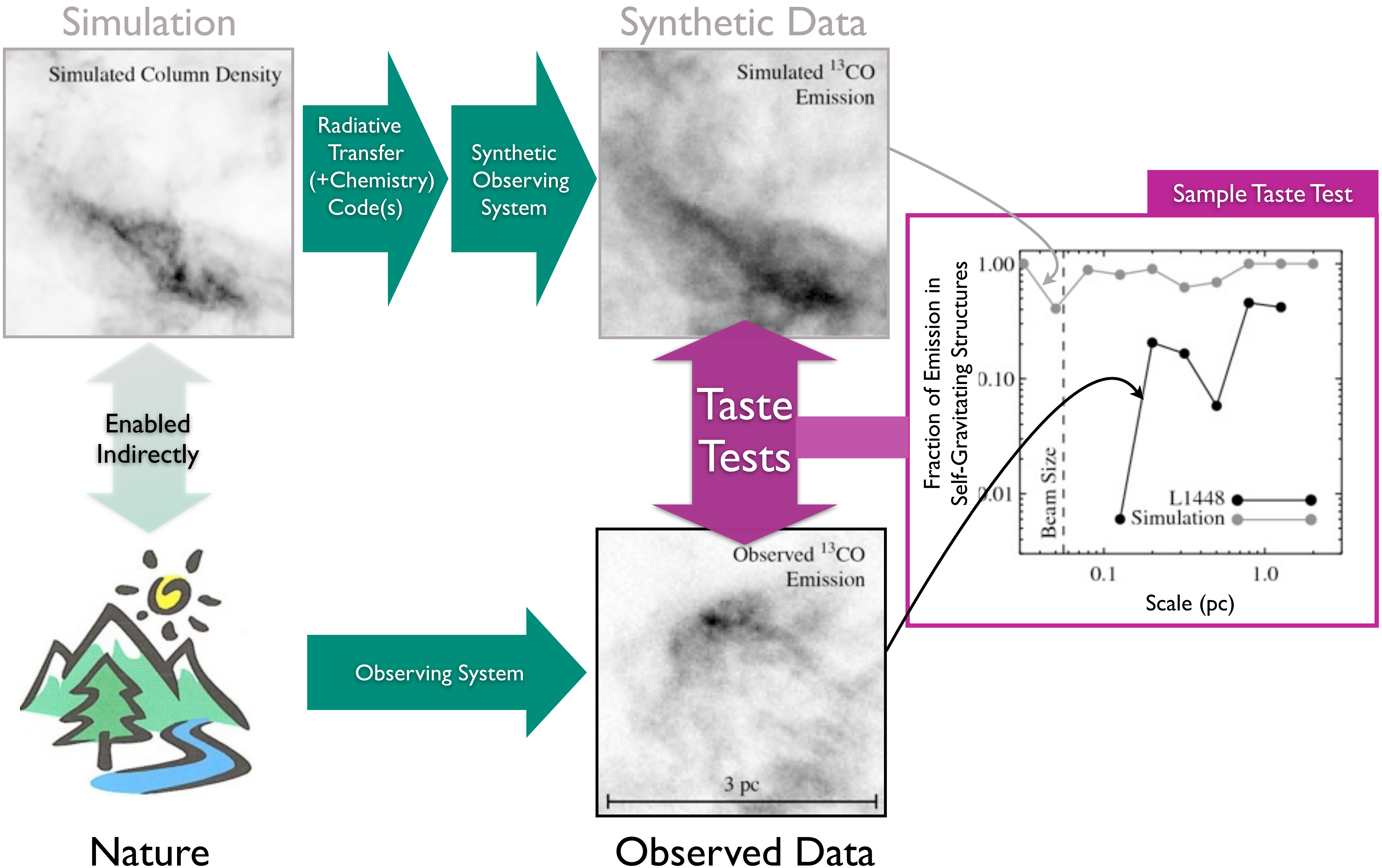


Figures from Goodman et al. 2009 (Nature's First 3D PDF!)

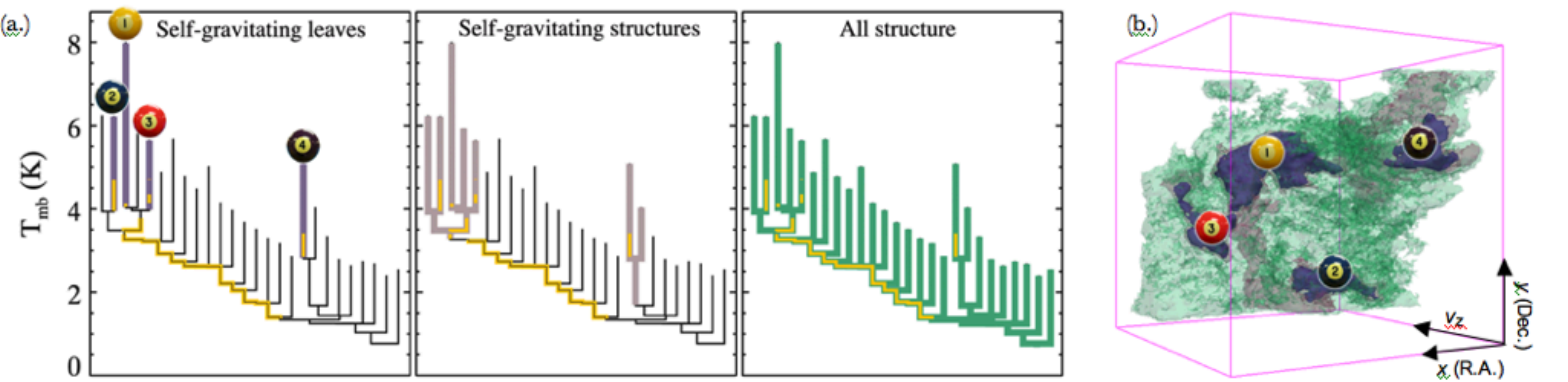


AstroMed@IIC COMPLETE

The Taste-Testing Process



Value of Dendrograms

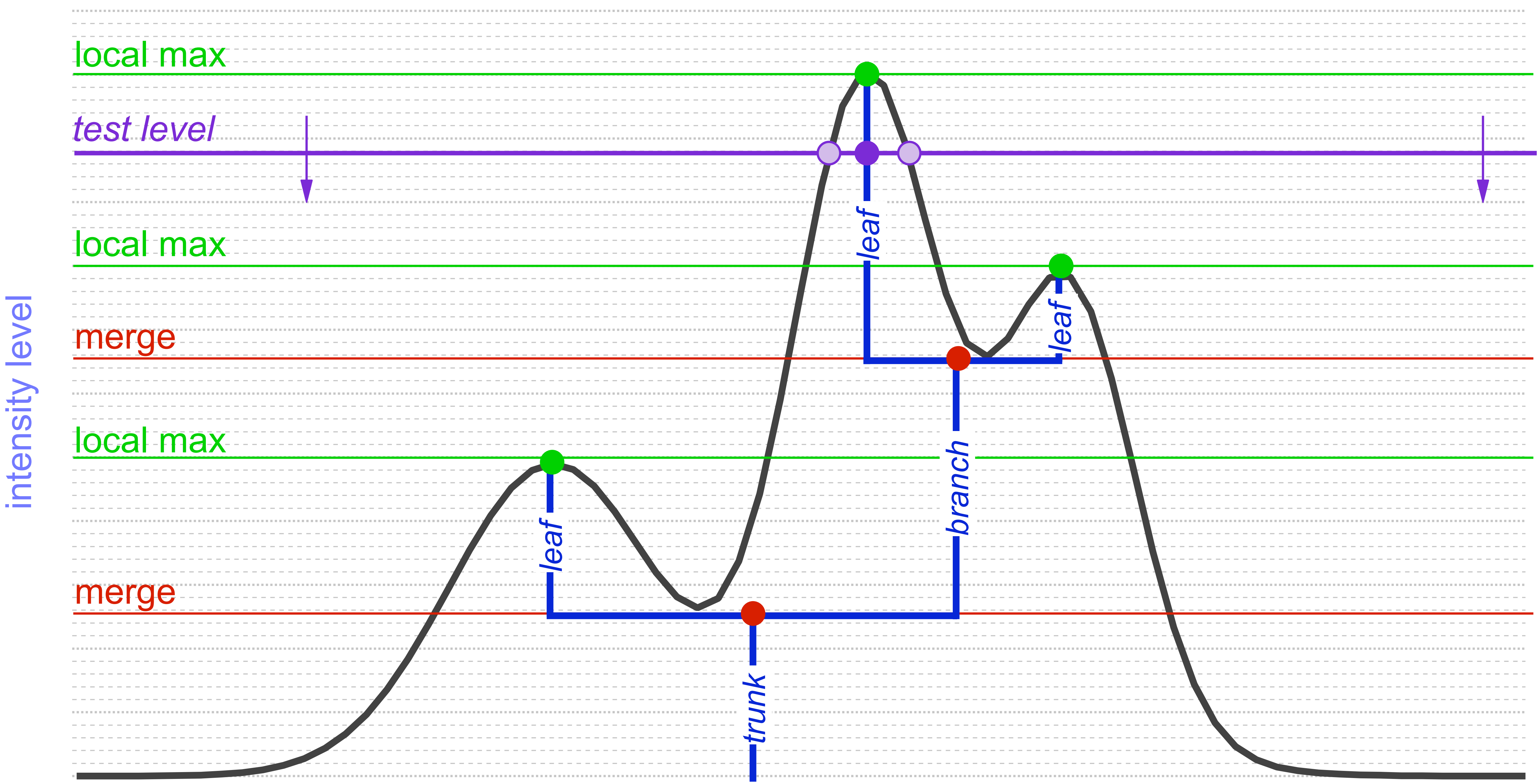


Yellow highlighting= "self-gravitating"

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

Rosolowsky et al. 2008 (*ApJ*) &
Goodman et al. 2009 (*Nature*)

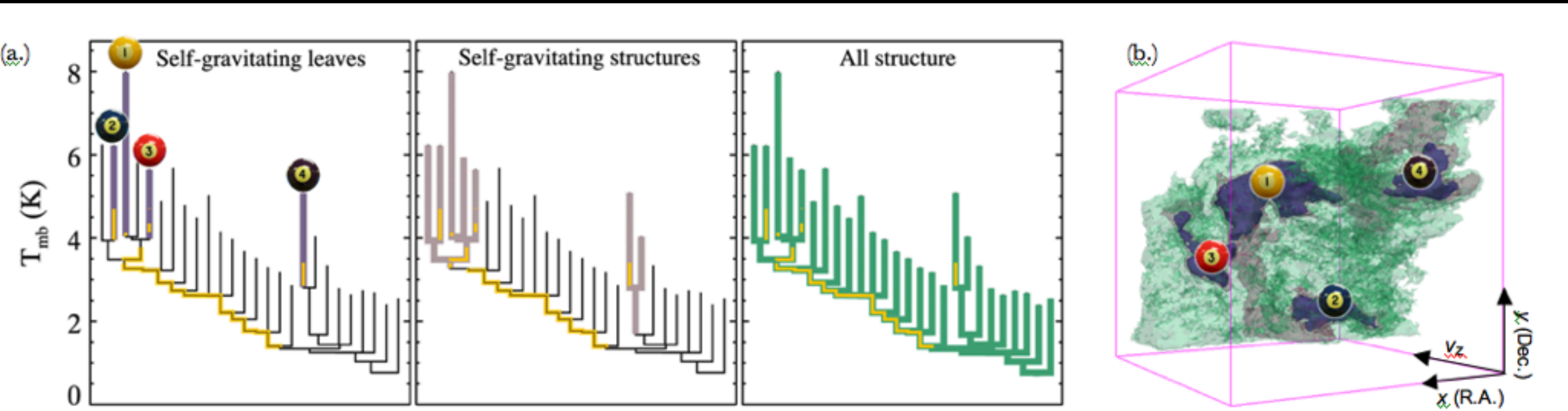
Dendrograms



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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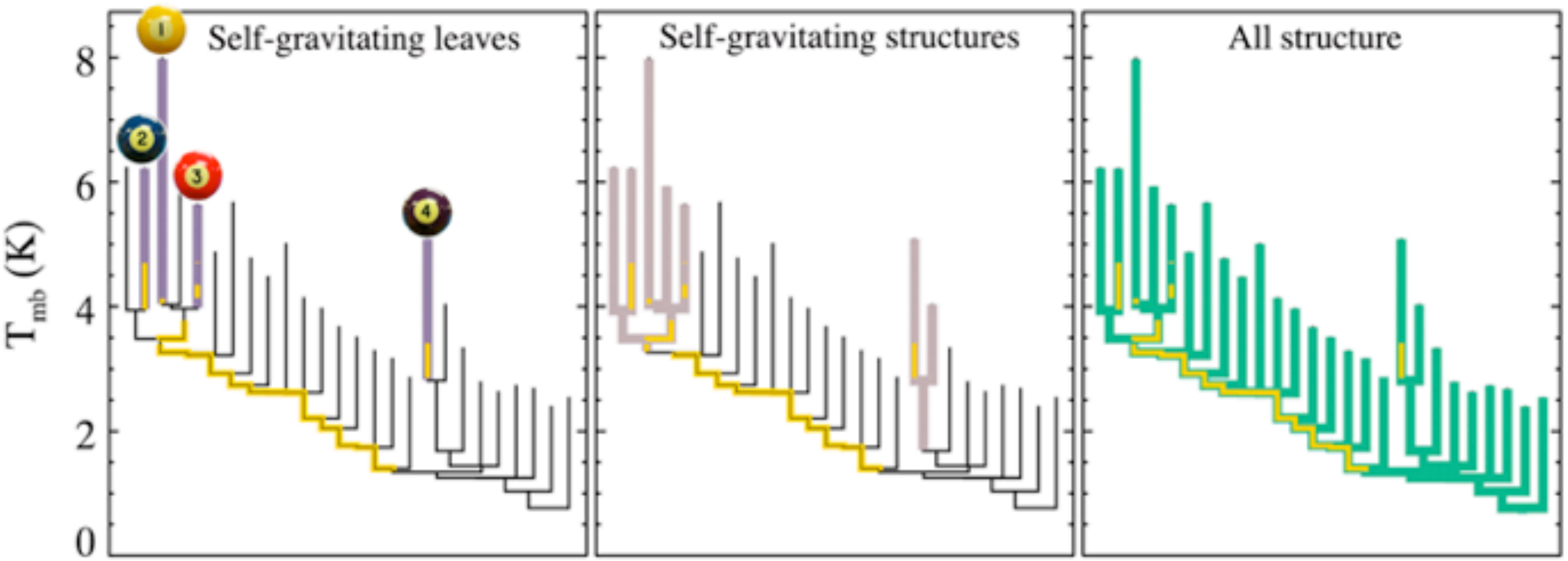
(à la Bertoldi & McKee 1992)

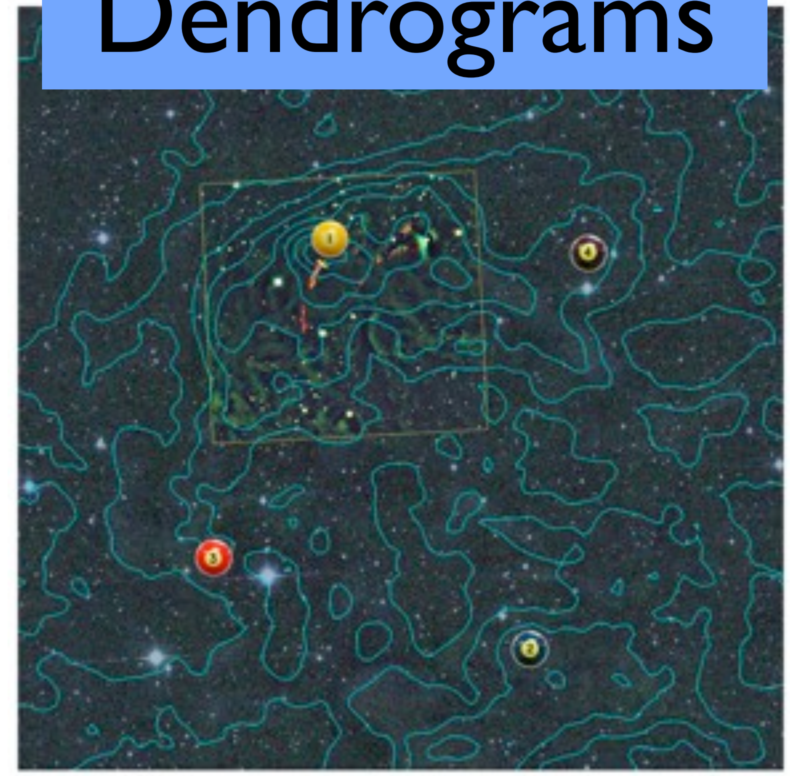
Rosolowsky et al. 2008 (*ApJ*) &
Goodman et al. 2009 (*Nature*)

CLUMPFIND vs. Dendrograms: L1448

Dendrograms

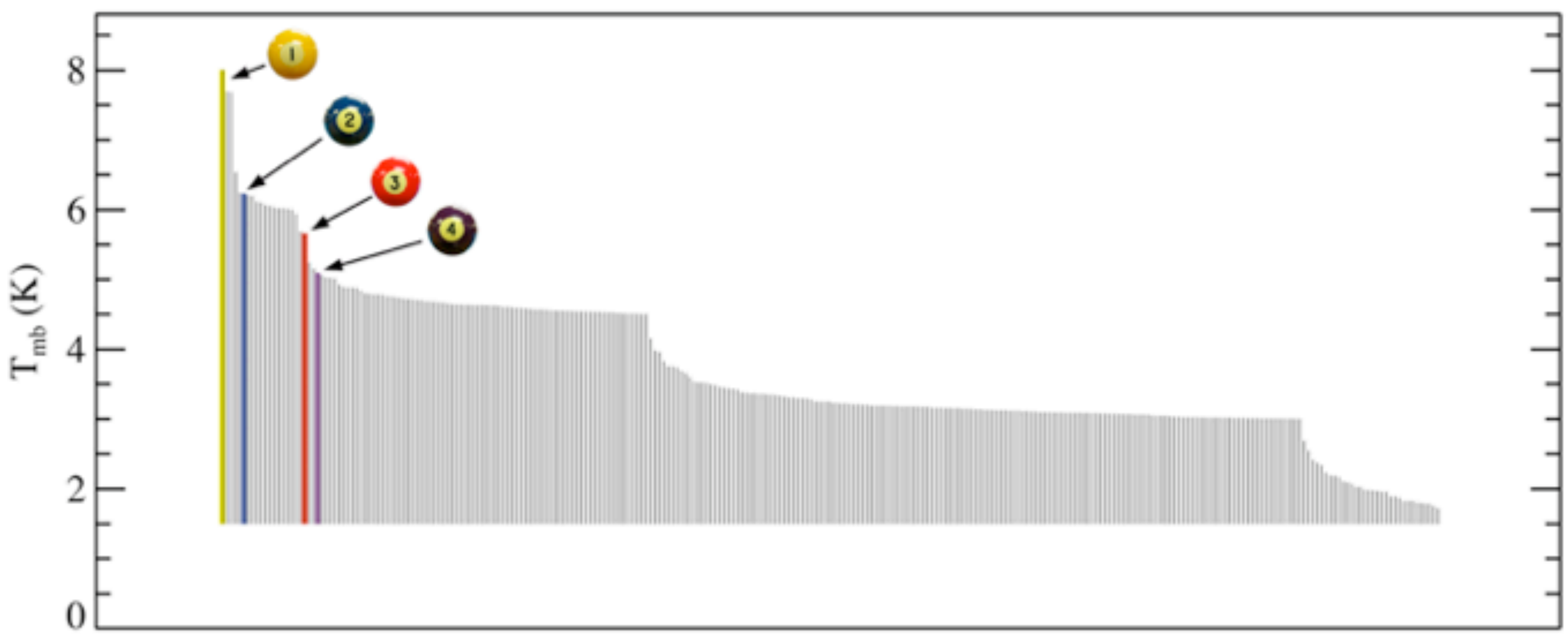


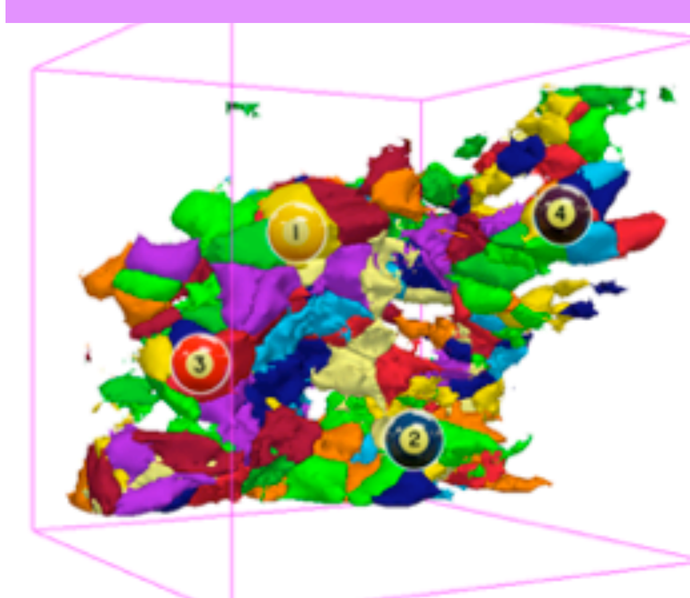
(Yellow = self-gravitating components)



The online PDFs of these insets

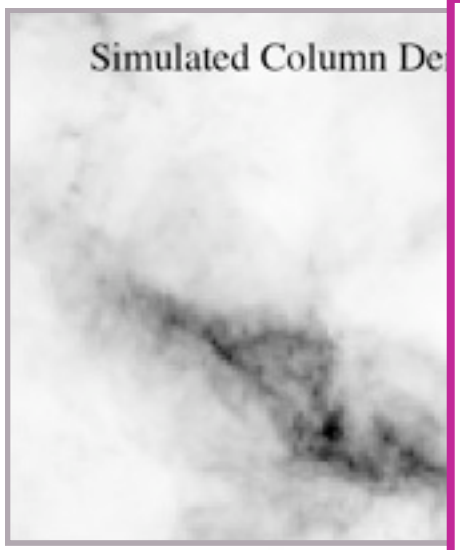
“CLUMPFIND”



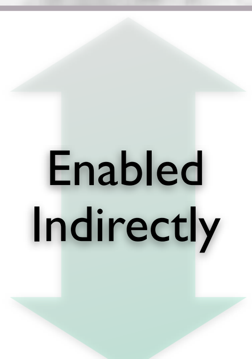


Taste-Testing Gravity

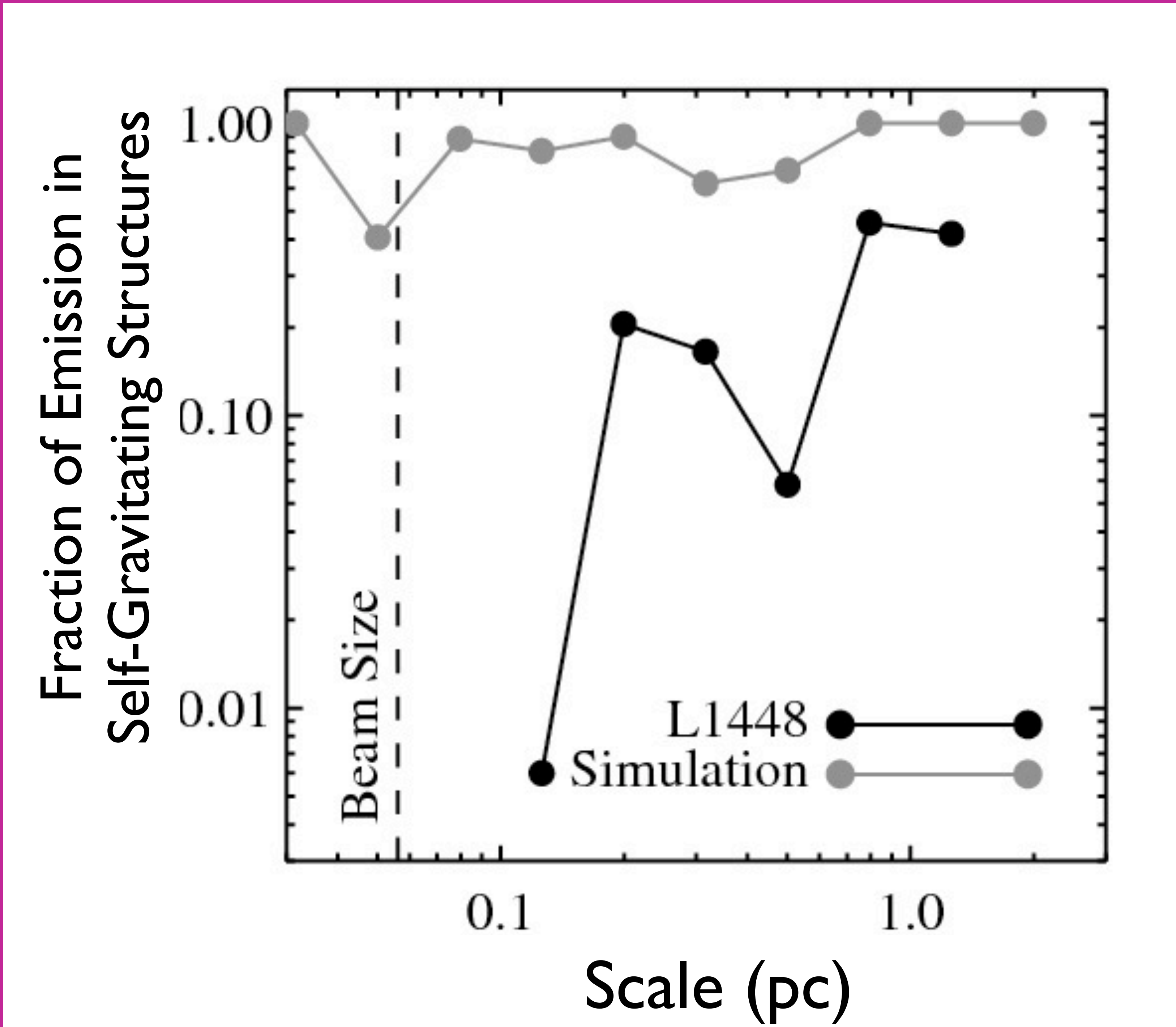
Simulation



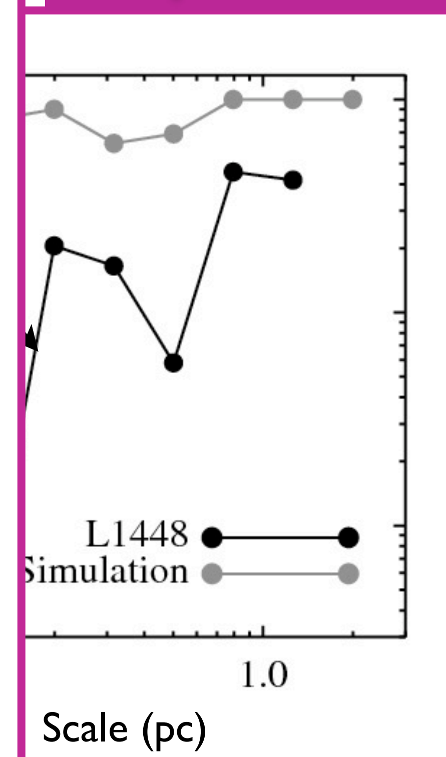
Synth



Sample Taste Test



Sample Taste Test



Nature

Observed Data

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)

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/

More to Taste in the Future...

Core shapes...

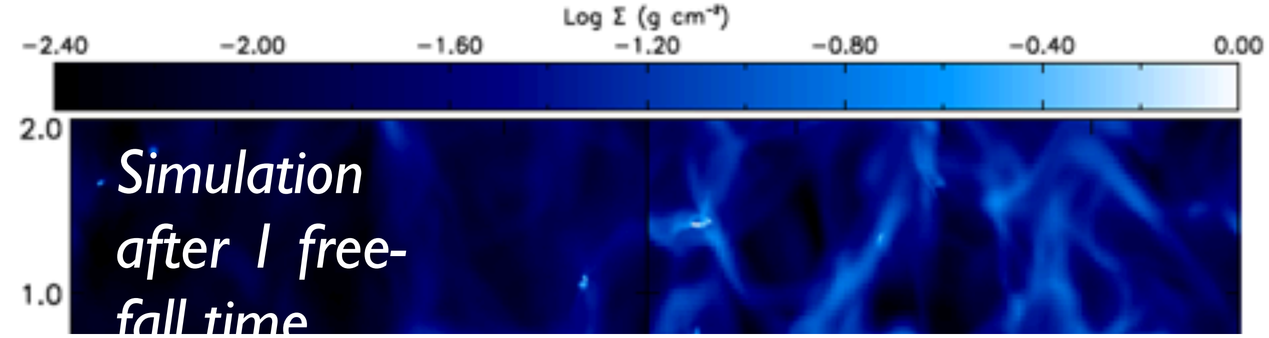
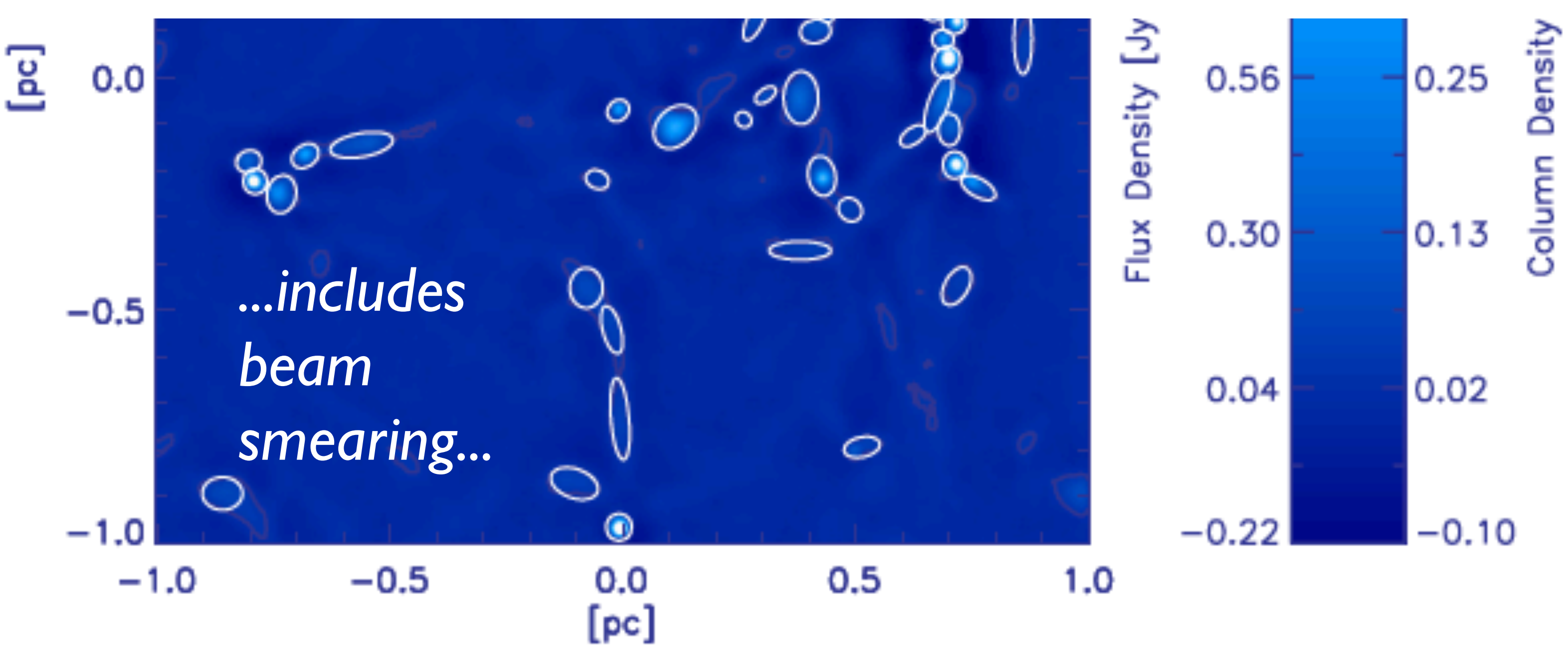


Table 1
Core Axis Ratio b/a Minimum, Median, and Mean and Median Core Sizes

	All					Starless					Protostellar				
	O[a]	D_1[b]	$D_{\frac{1}{2}}$[c]	U_1[d]	$U_{\frac{1}{2}}$[e]	O	D_1	$D_{\frac{1}{2}}$	U_1	$U_{\frac{1}{2}}$	O	D_1	$D_{\frac{1}{2}}$	U_1	$U_{\frac{1}{2}}$
N_{cores}	393	161	152	78	66	286	114	103	45	50	107	47	49	33	16
Minimum $\frac{b}{a}$	0.24	0.22	0.23	0.18	0.23	0.24	0.22	0.23	0.18	0.23	0.34	0.23	0.26	0.28	0.66
Median $\frac{b}{a}$	0.66	0.68	0.58	0.65	0.65	0.66	0.66	0.55	0.68	0.57	0.68	0.68	0.74	0.79	0.76
Mean $\frac{b}{a}$	0.67	0.66	0.61	0.66	0.62	0.66	0.64	0.56	0.58	0.57	0.68	0.68	0.73	0.77	0.80
Median a_{100}[f]	100	76	84	80	92	96	88	88	80	104	120	64	68	72	64
Median b_{100}[f]	64	48	48	52	56	64	54	48	48	56	76	48	48	52	48

Notes.
[a] Observed Orion molecular cloud cores (NWT).
[b] Driven turbulence simulation at $1t_{ff}$.
[c] Driven turbulence simulation at $\frac{1}{2}t_{ff}$.
[d] Undriven turbulence simulation at $1t_{ff}$.
[e] Undriven turbulence simulation at $\frac{1}{2}t_{ff}$.
[f] Median projected semi-major (a) and semi-minor (b) size in units of 100 AU.

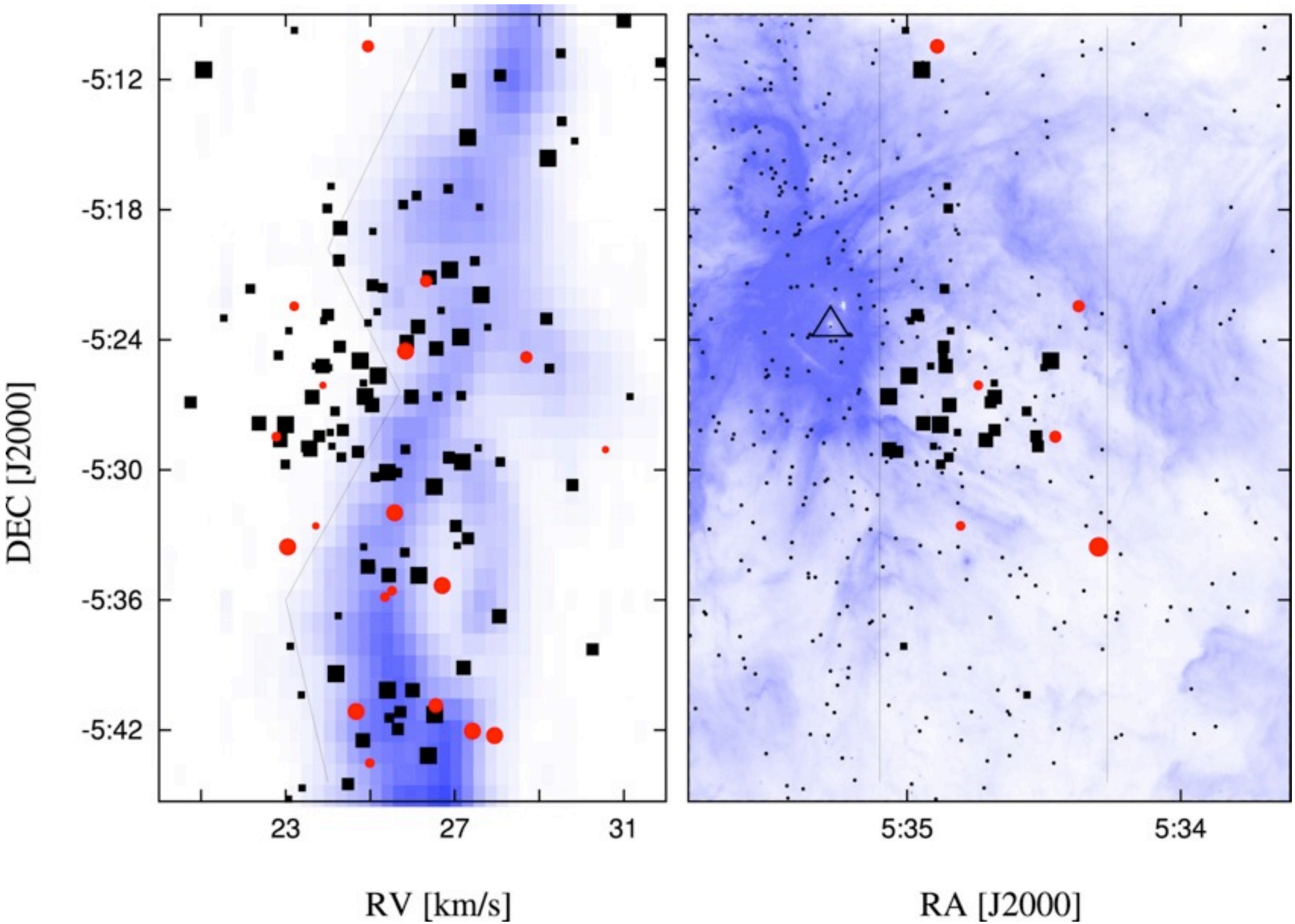


...not tasty enough.

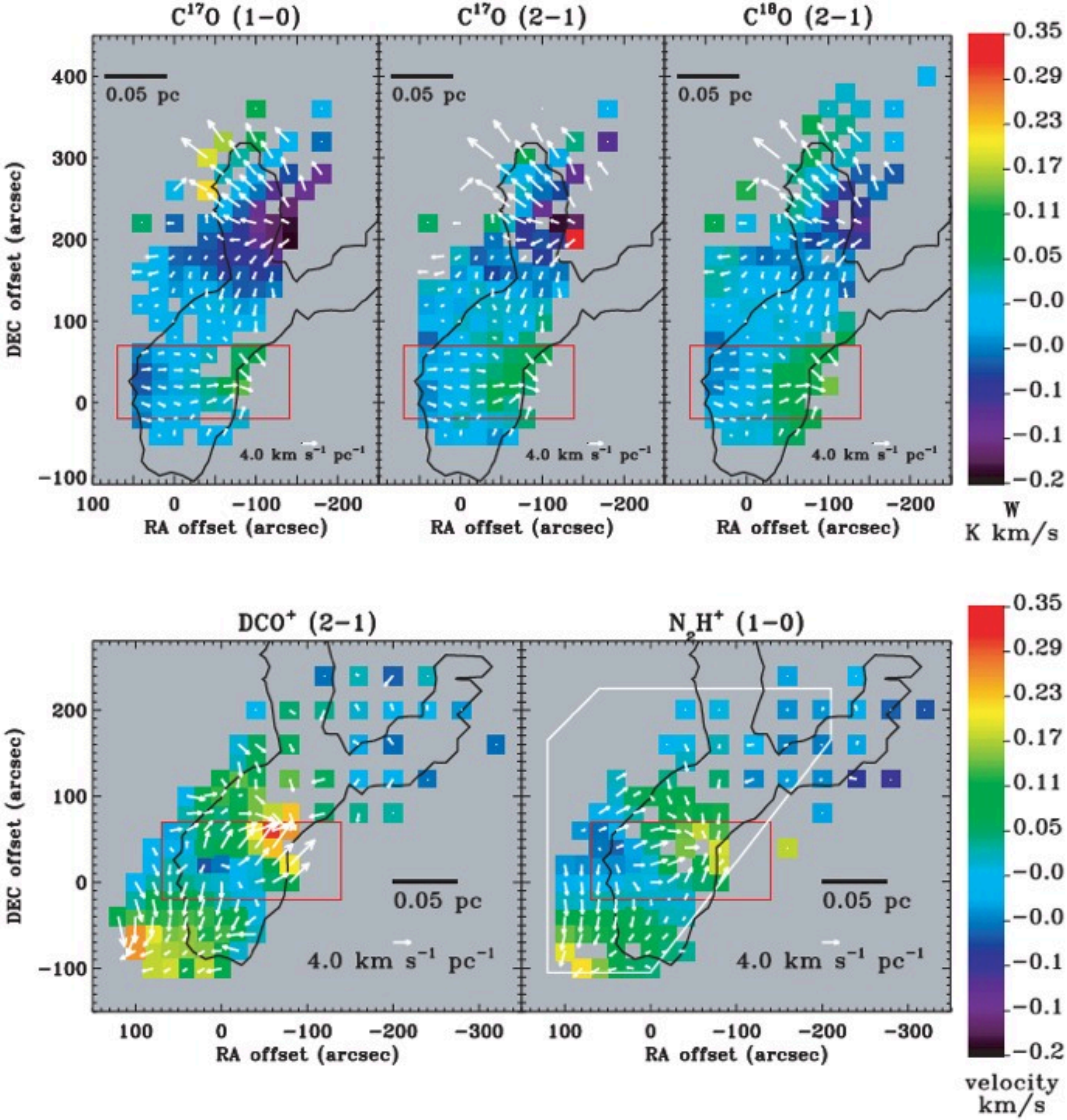
Offner & Krumholtz 2009

What stars form from what gas, when... and where do they go?

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



Velocity Gradients

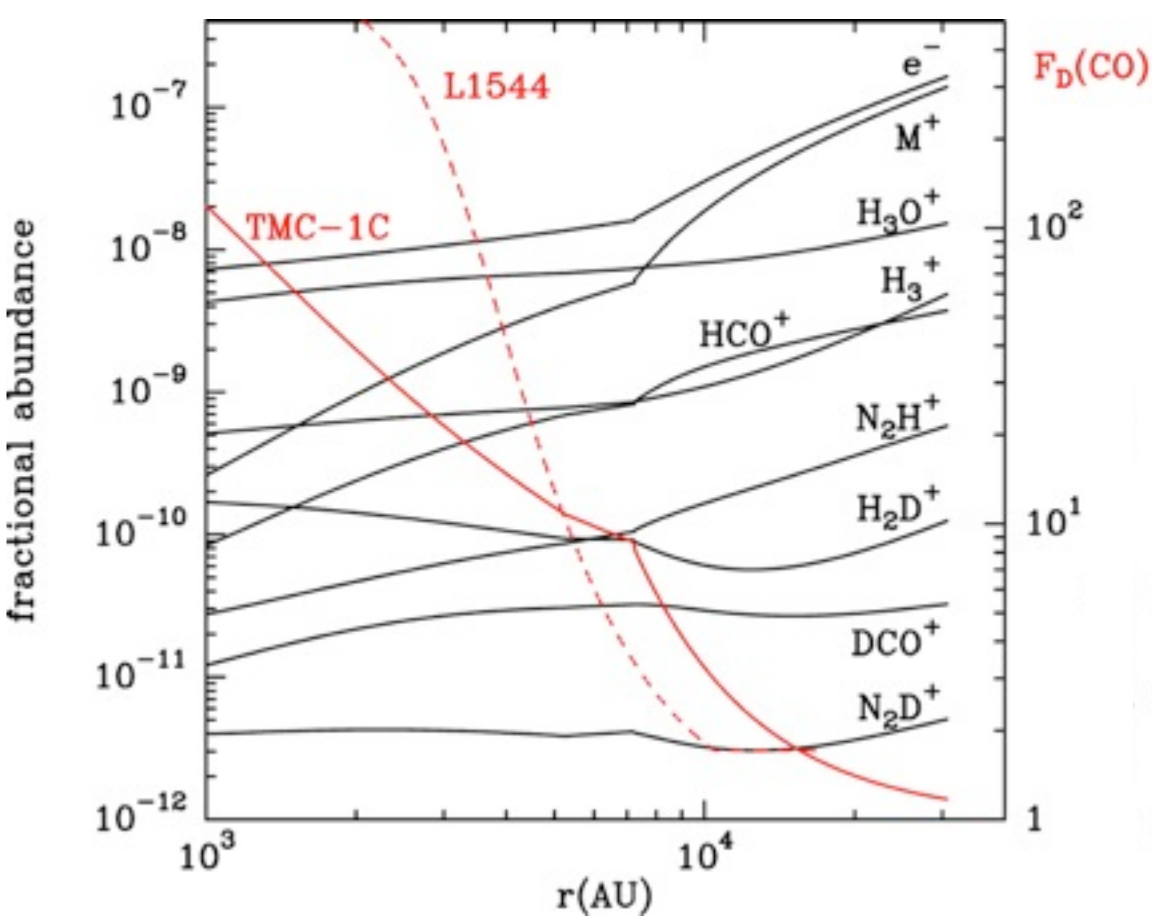


Schnee et al. 2007

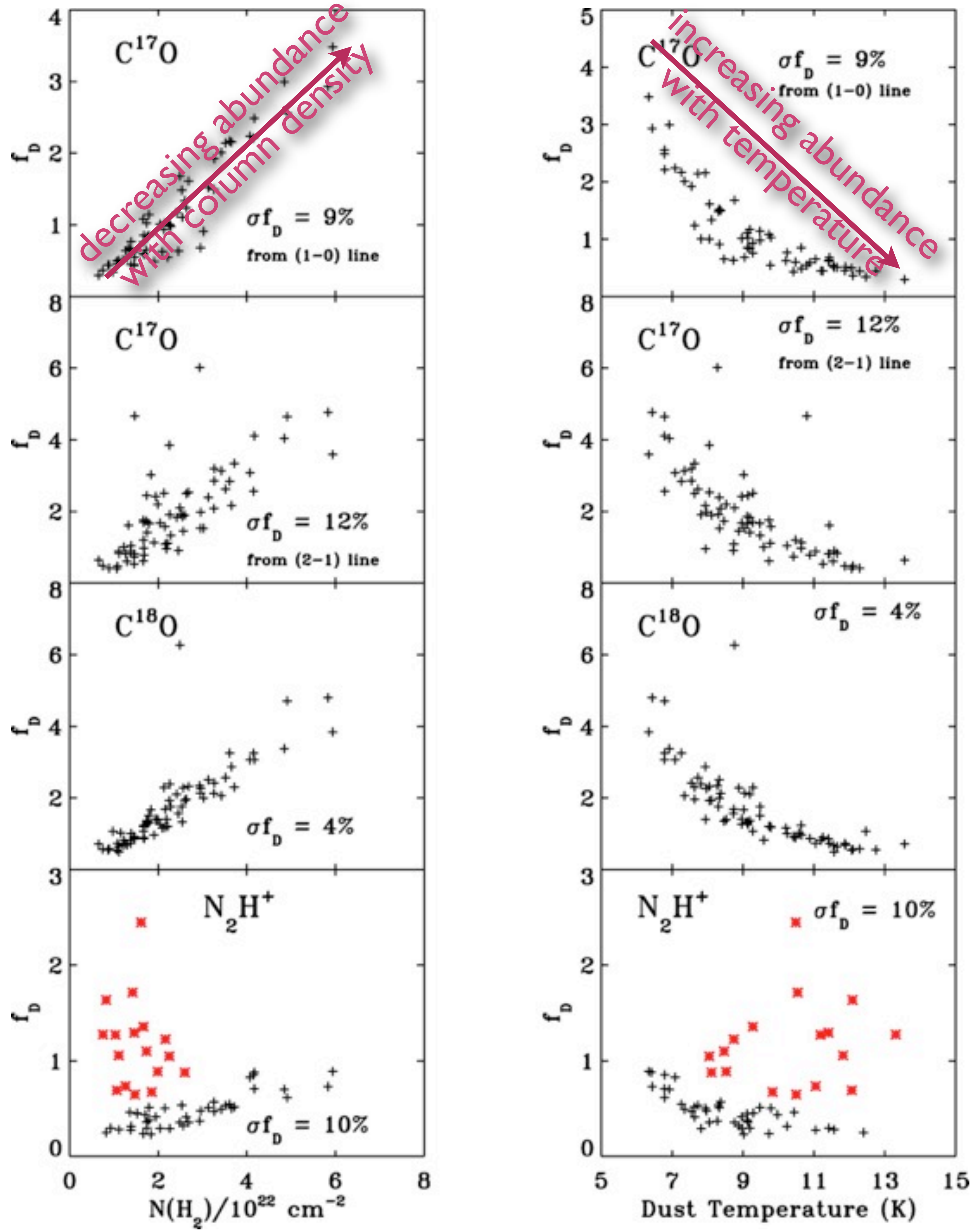
lines + dust continuum constrain

Chemistry in (Starless) Cores

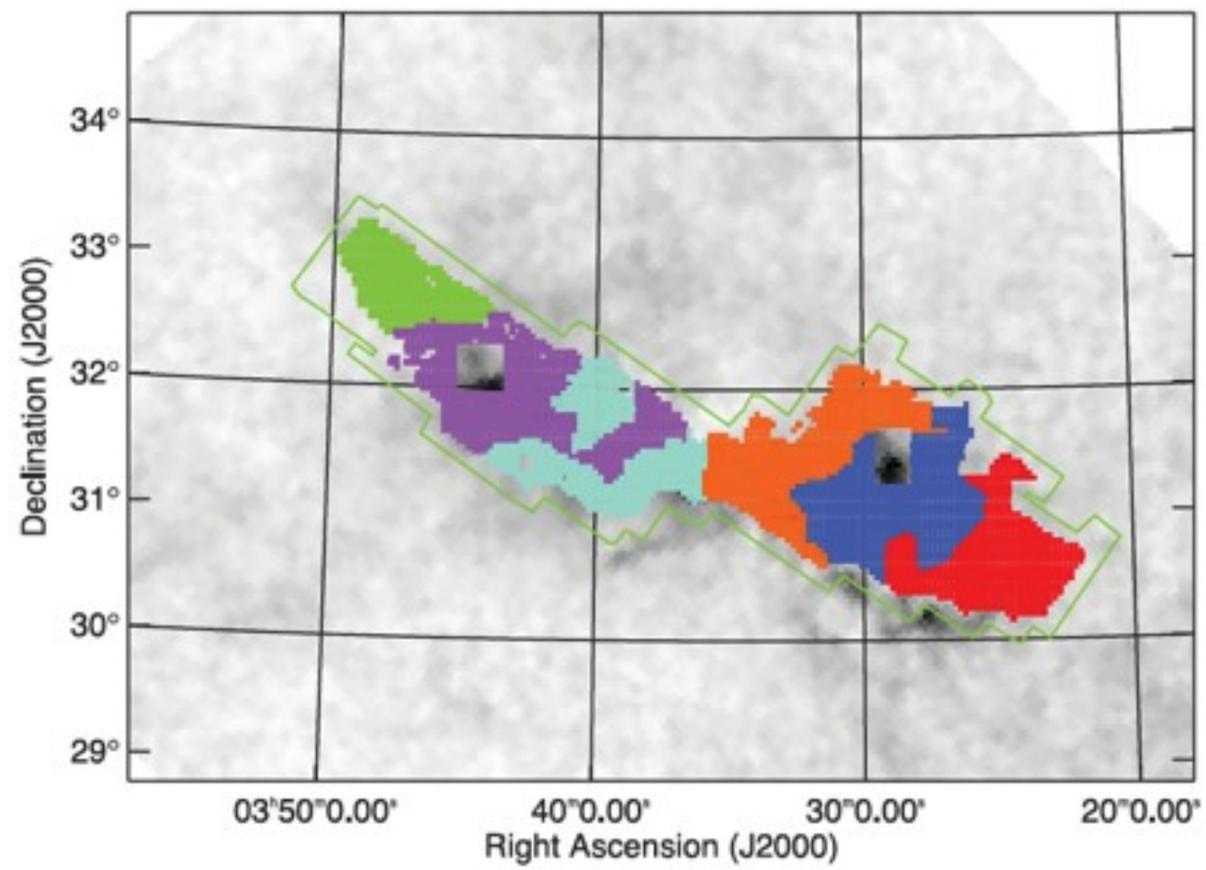
Carbon decreases as *N* rises and T falls



Schnee, Caselli, Goodman et al. 2007



Starting-point abundances can vary significantly (X 2) on large scales...ask Paola



Pineda, Caselli & Goodman 2008

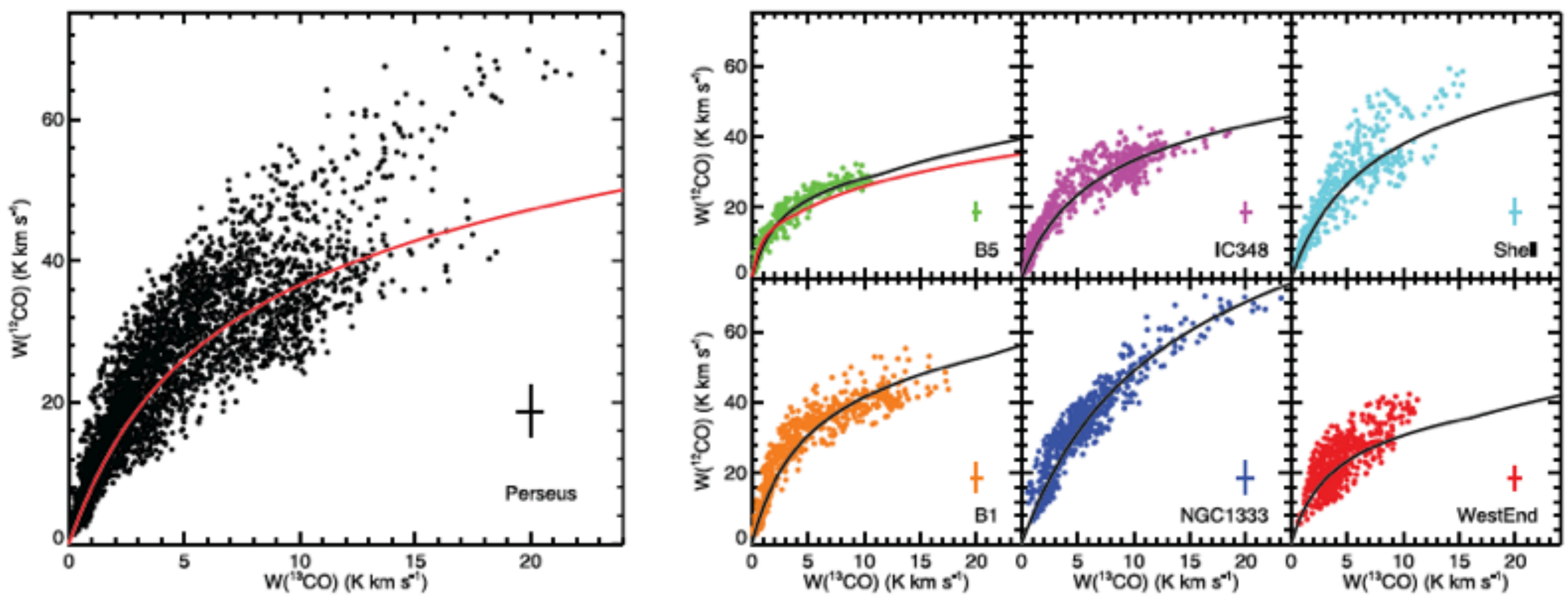
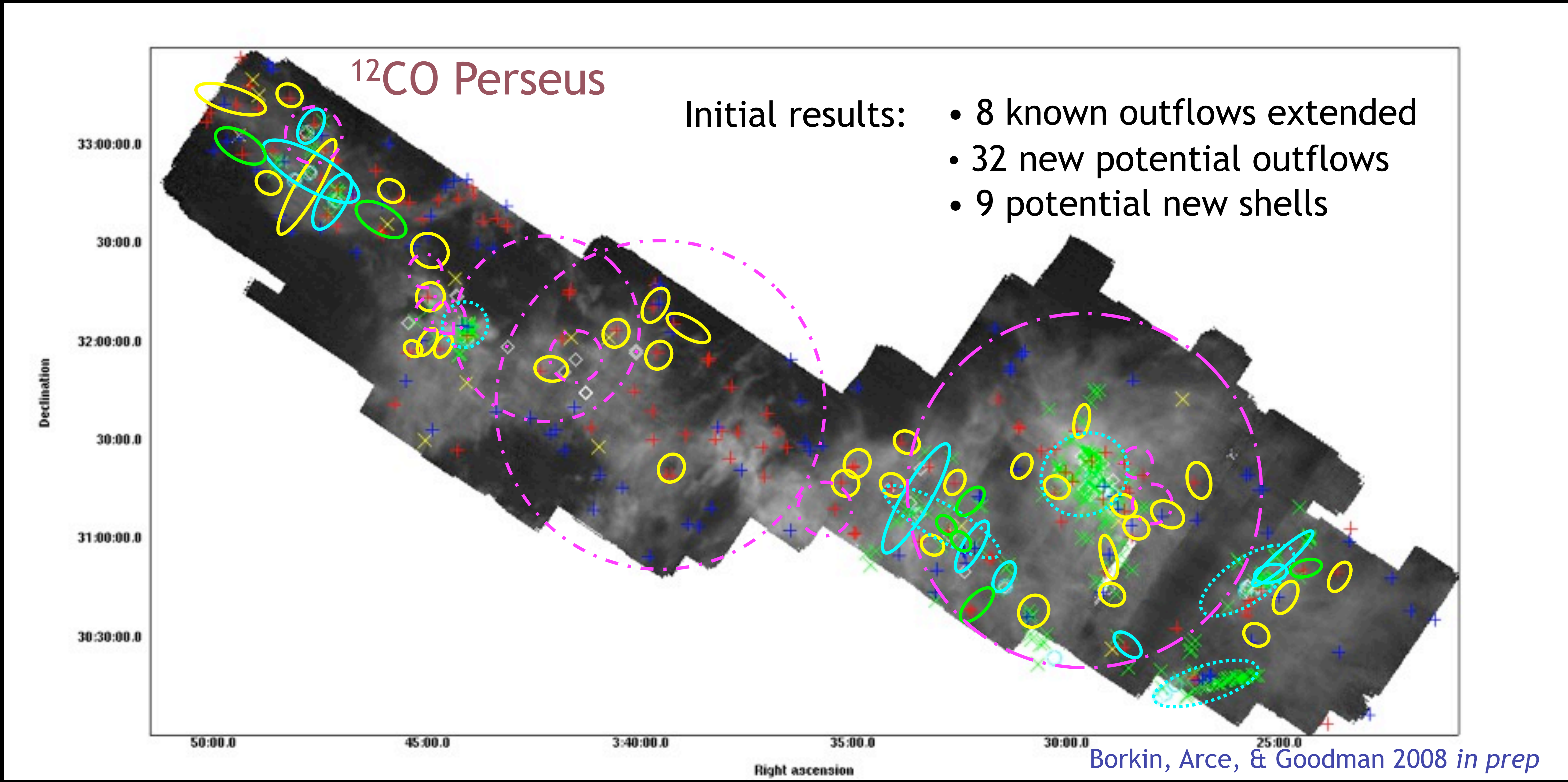


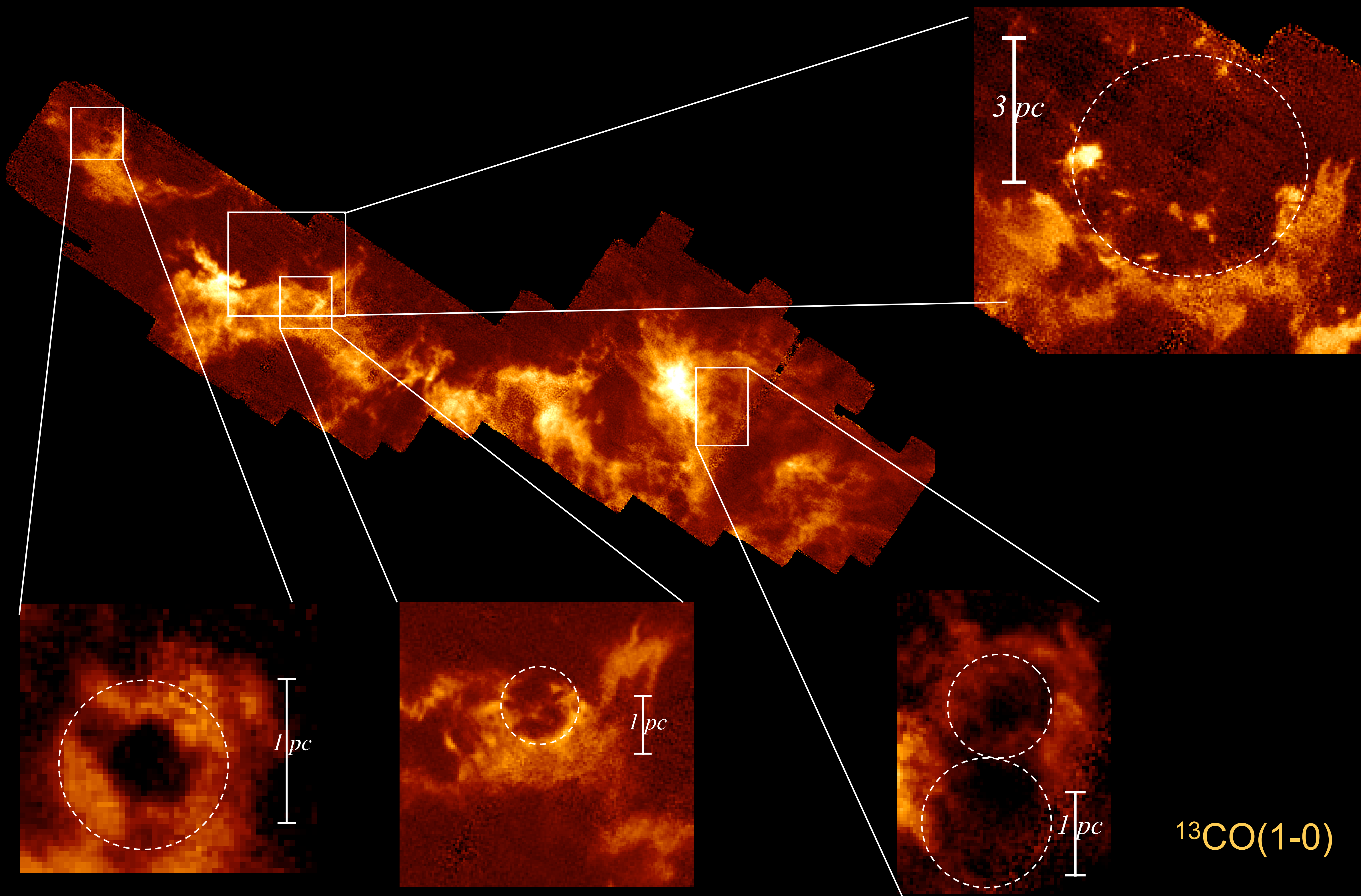
FIG. 5.—Integrated intensity of ^{12}CO is plotted against the integrated intensity of ^{13}CO. The left panel shows all data used while right panel shows each region separately, using the same colors as in Fig. 3. The median of the 1 σ errors are shown in bottom right of each plot. Solid lines are the growth curve fit, while the red curve in B5 is the fit from Langer et al. (1989).

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

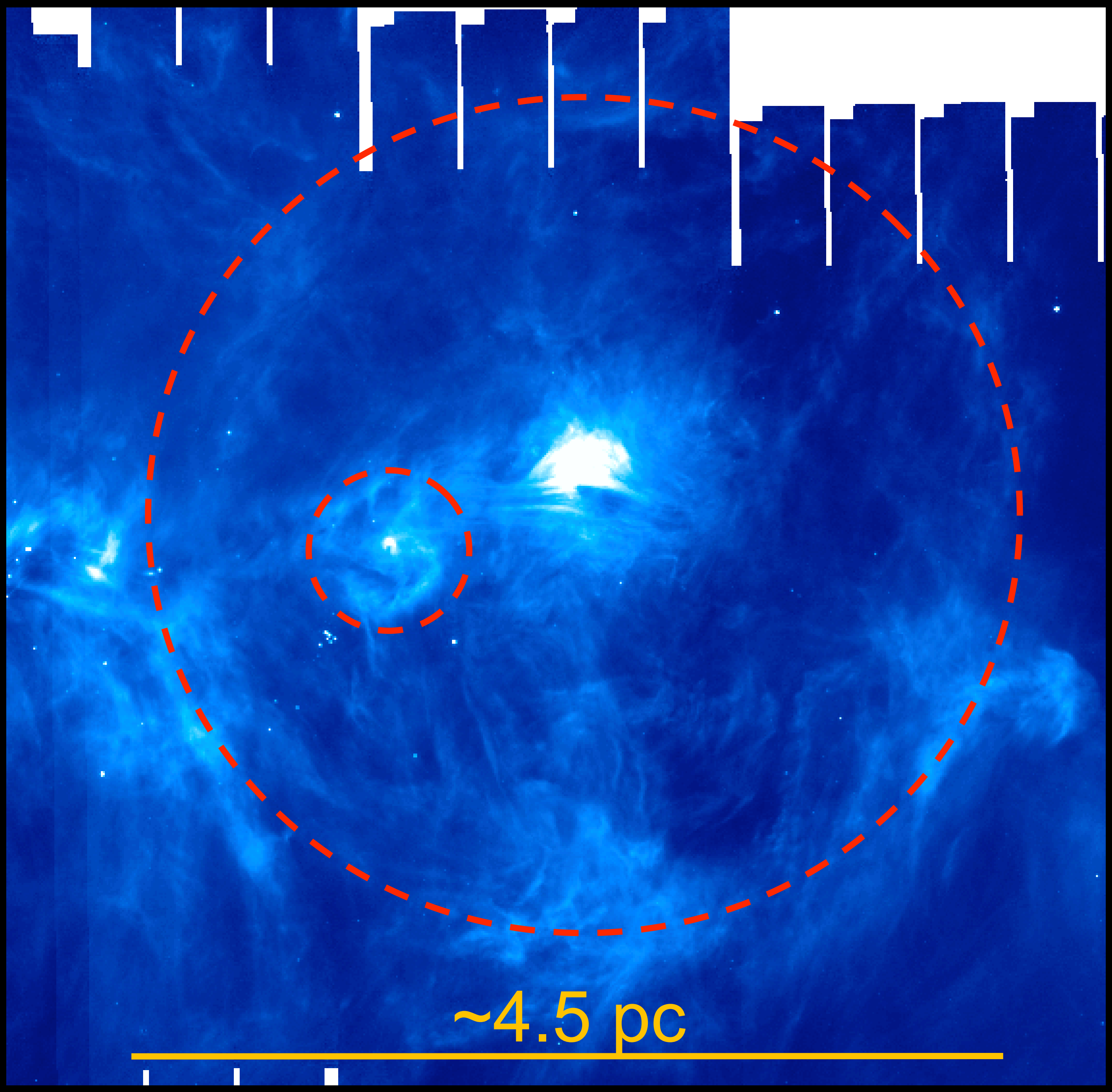


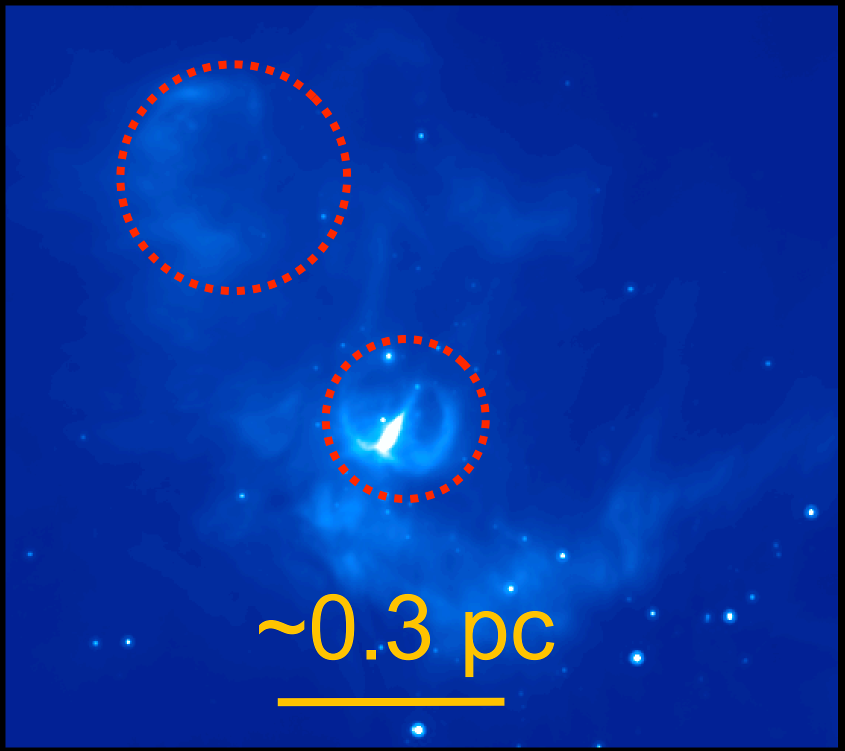
$^{13}CO(1-0)$

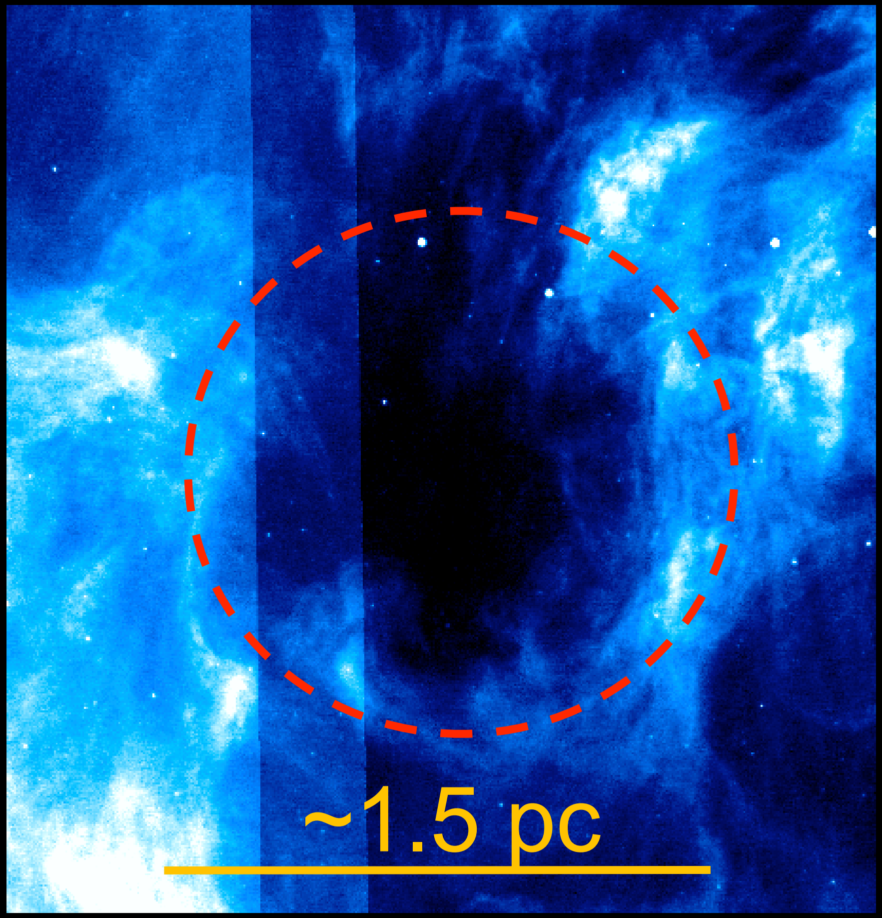
Borkin, Arce & Goodman 2008

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*