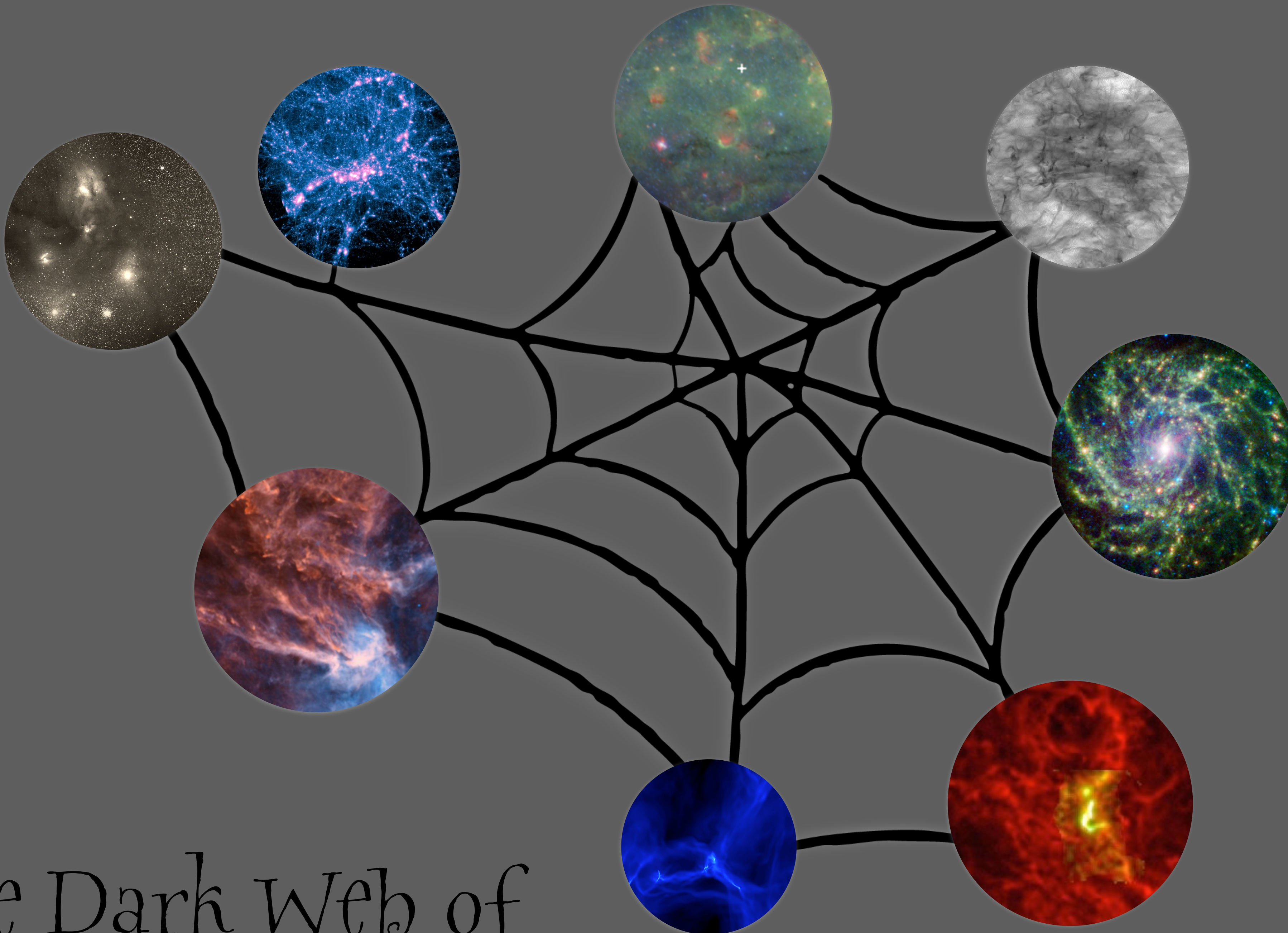


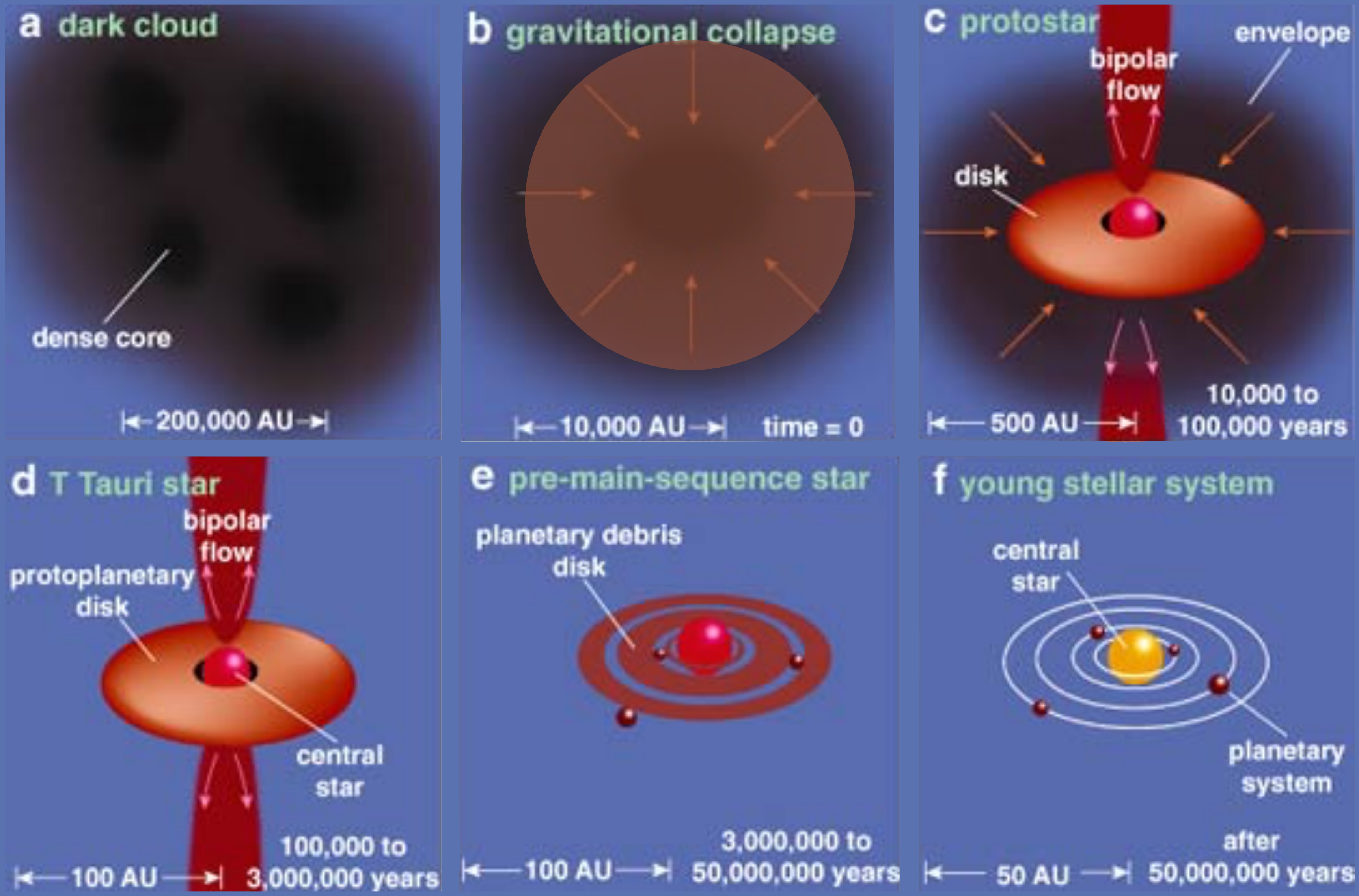
The Dark Web of Star Formation

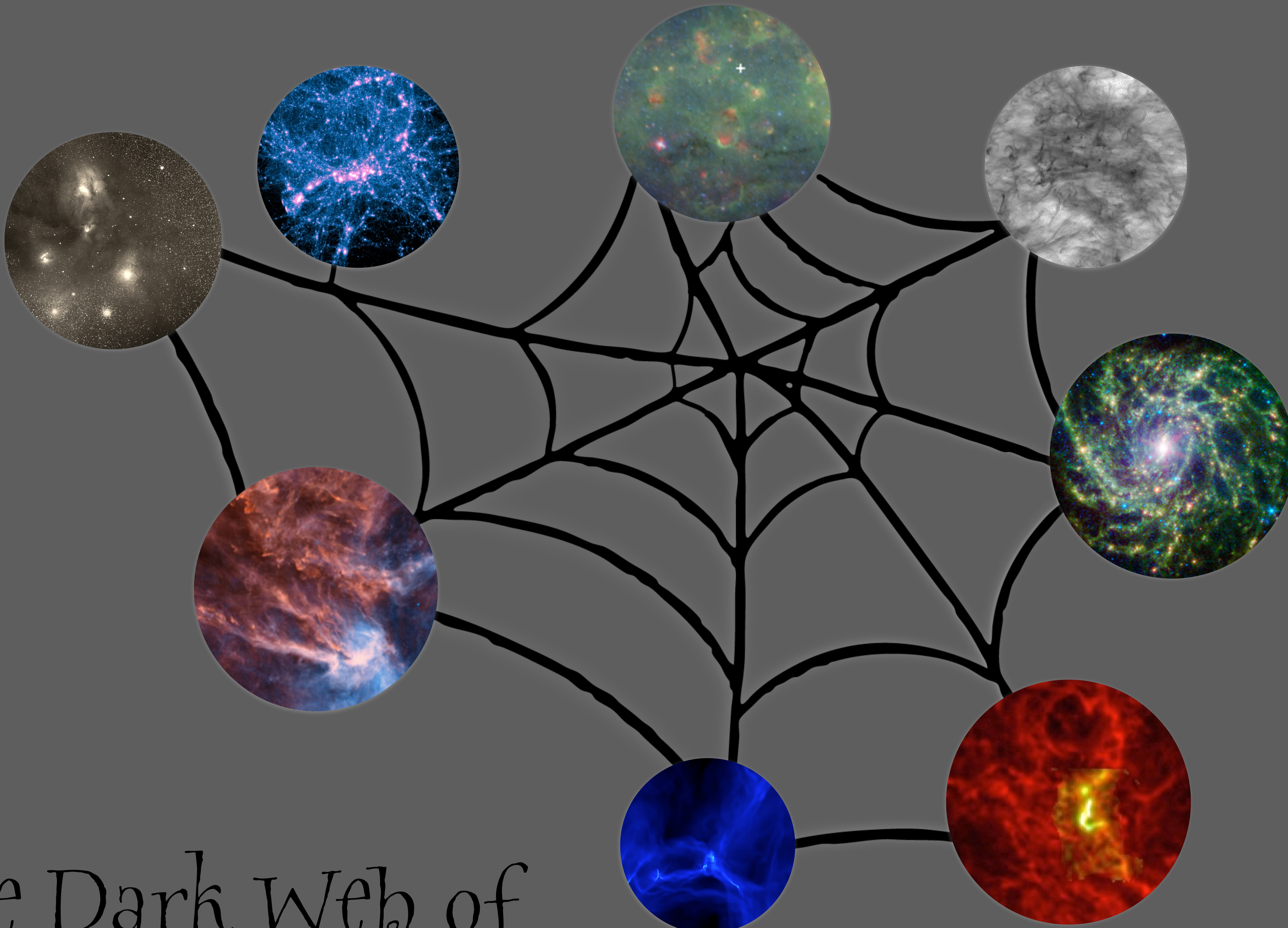
Alyssa A .Goodman
Harvard-Smithsonian Center for Astrophysics
& Radcliffe Institute for Advanced Study

APOD 30 September 2017: NGC 281
© 2017 Eric Coles and Mel Helm

(COLLAPSING SPHERE)

Textbook says…





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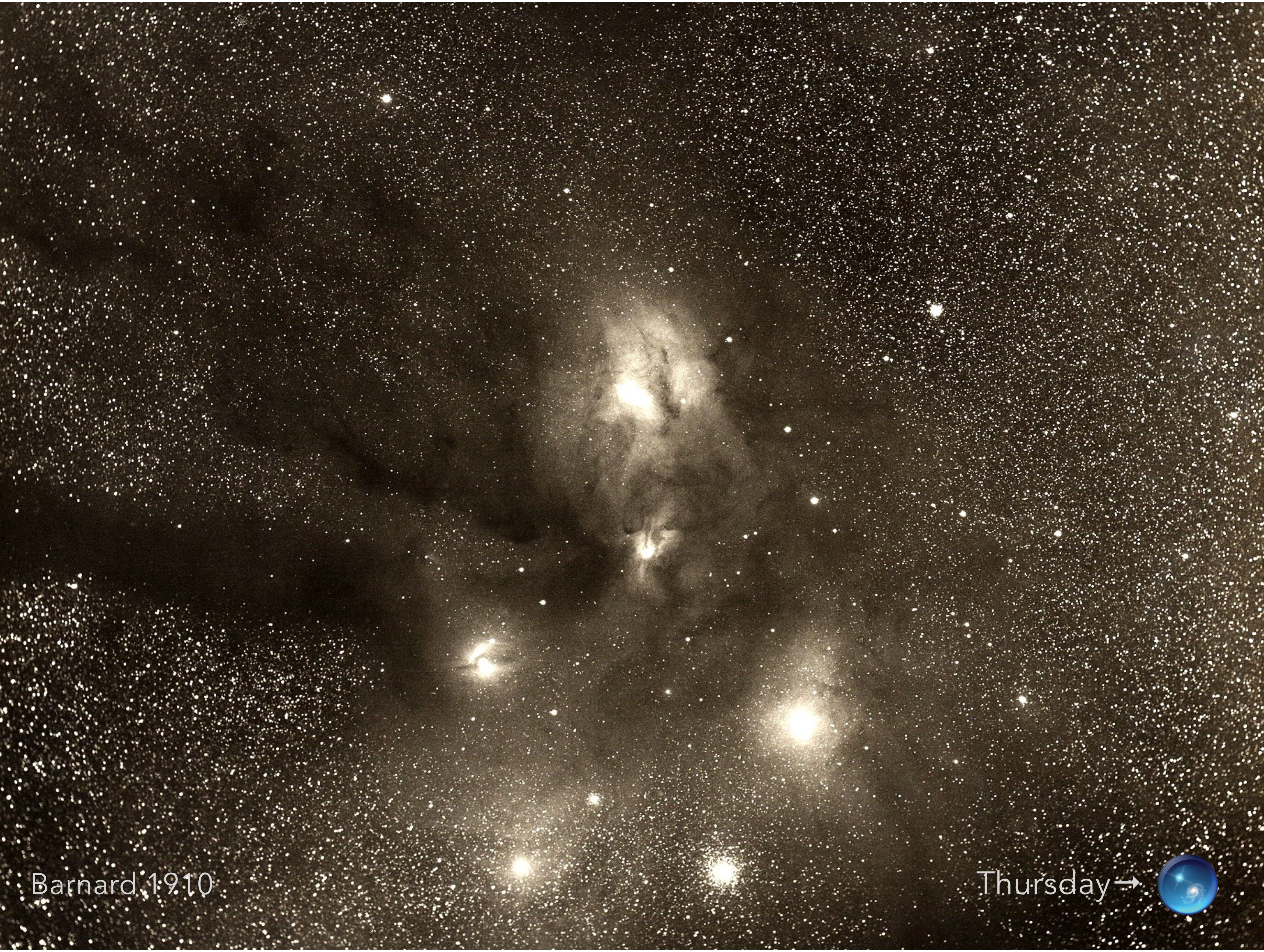

Barnard 1910
Thursday→

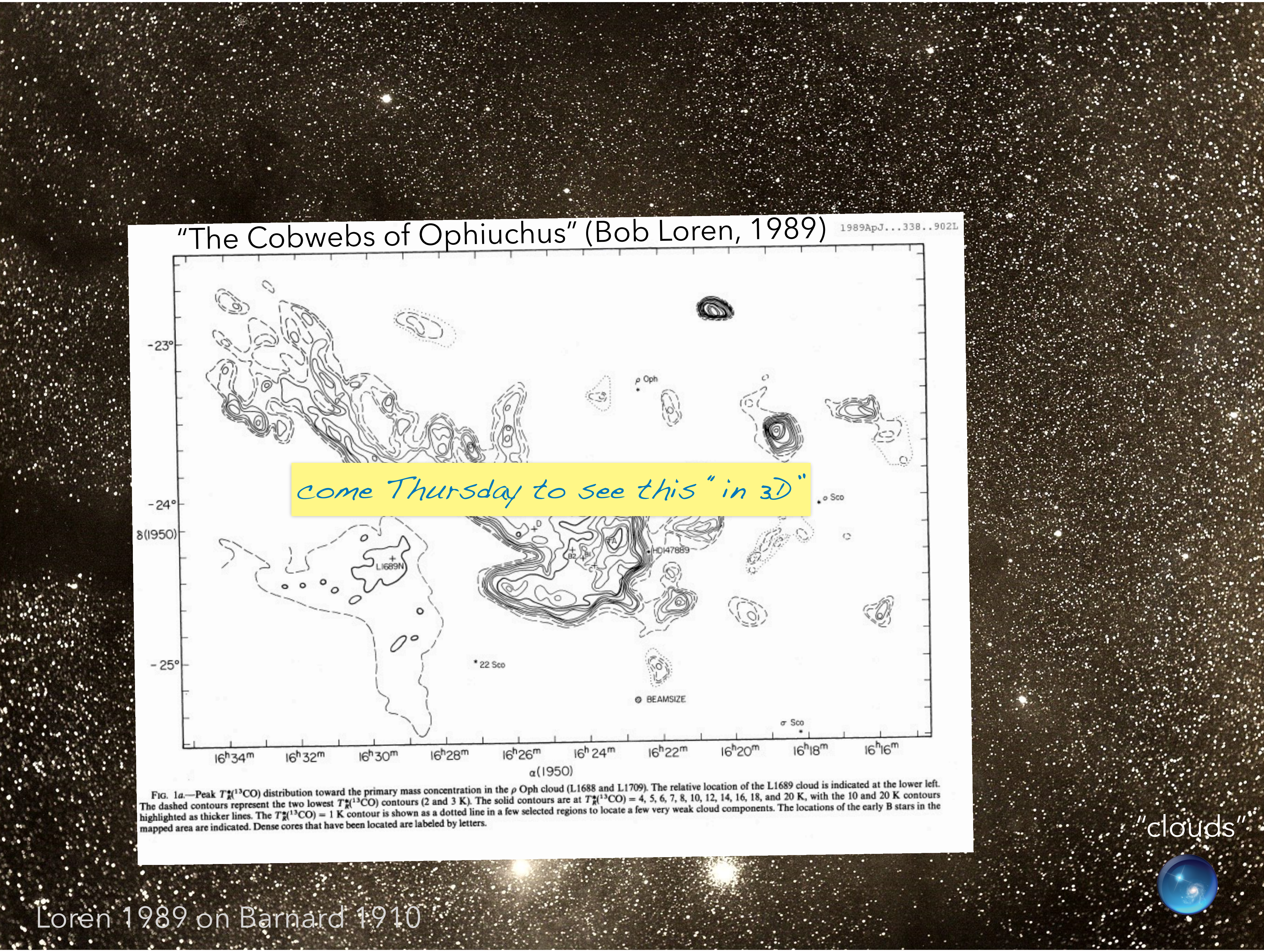
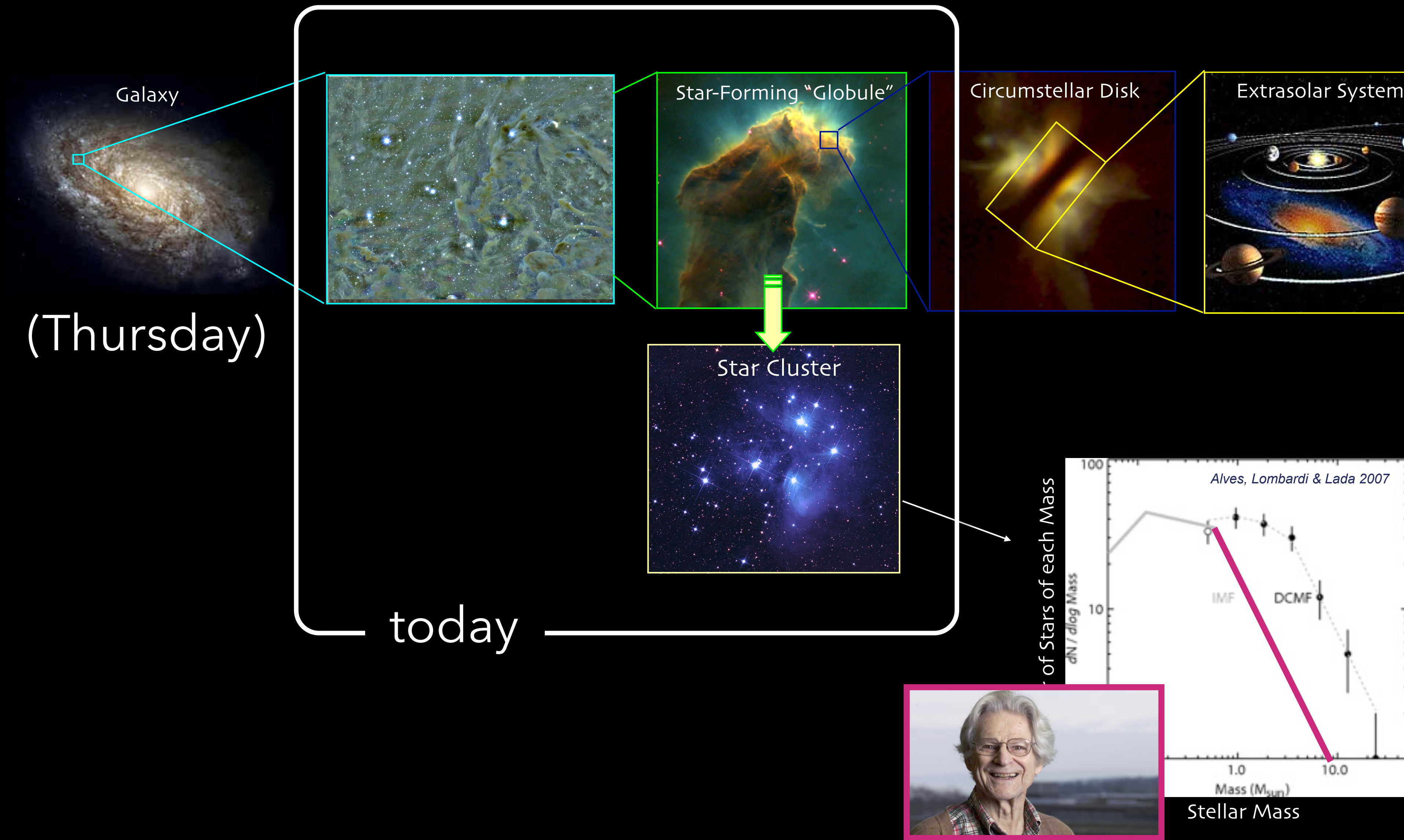
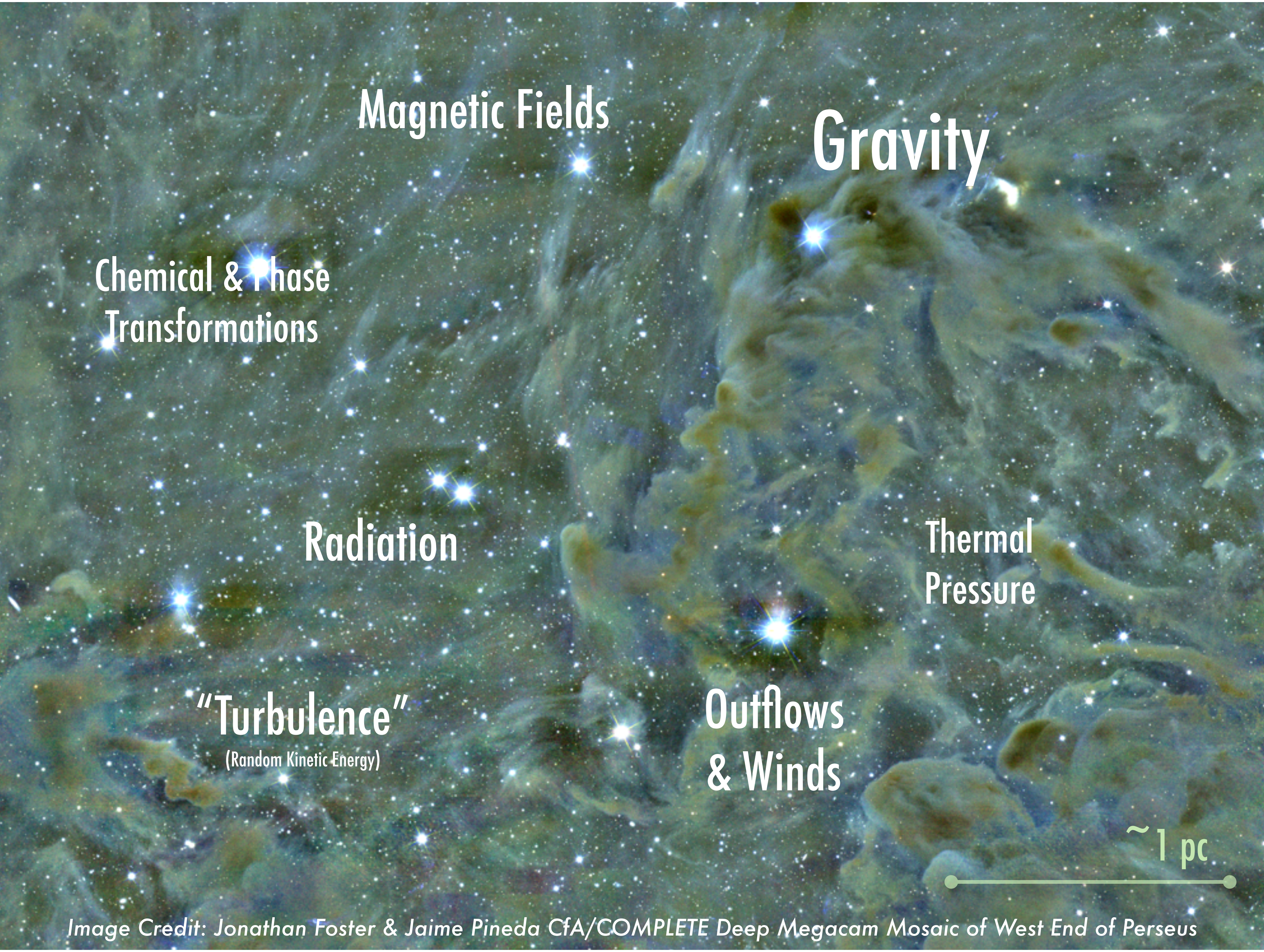


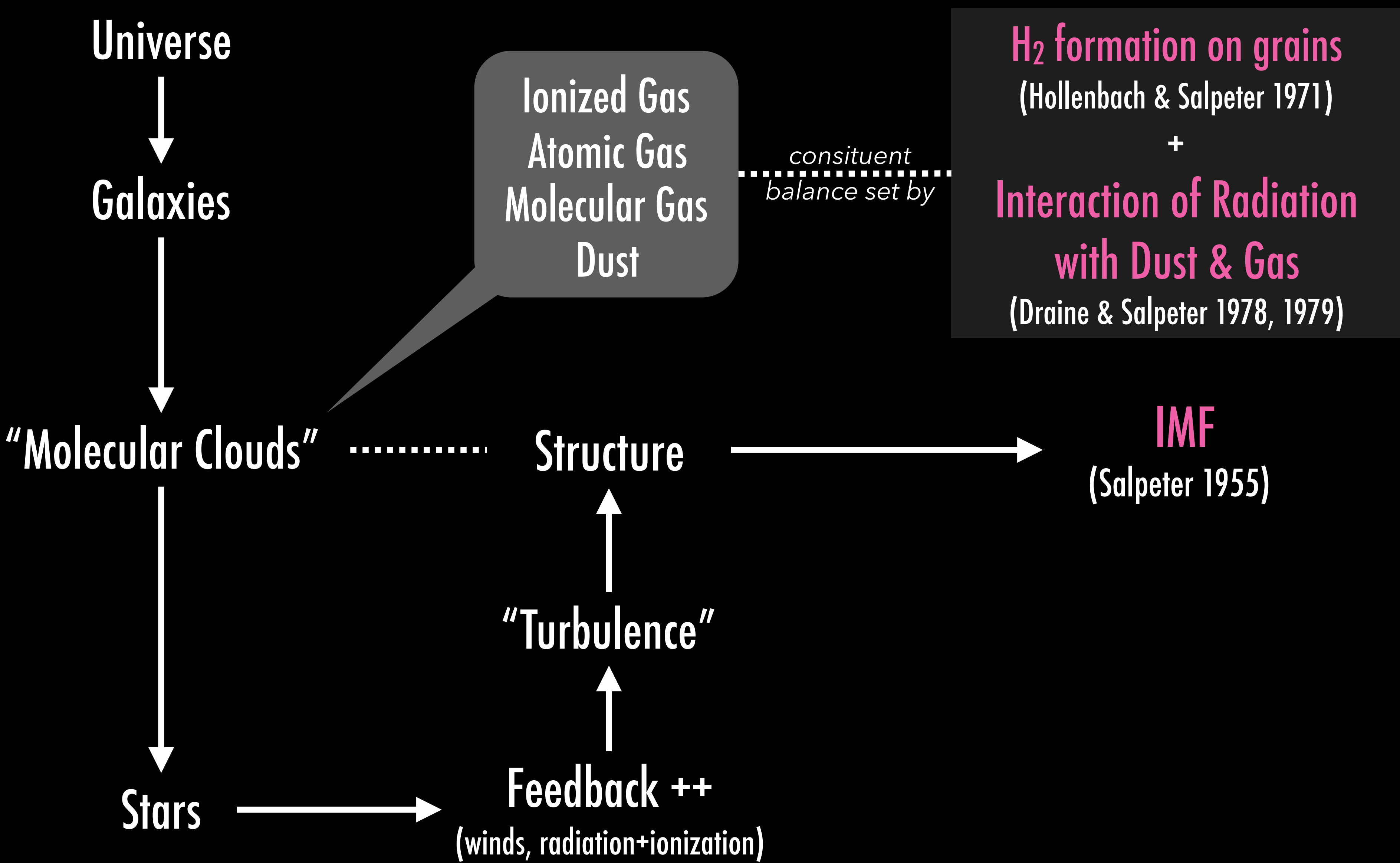
FIG. 1a.—Peak $T_R^*(^{13}CO)$ distribution toward the primary mass concentration in the ρ Oph cloud (L1688 and L1709). The relative location of the L1689 cloud is indicated at the lower left. The dashed contours represent the two lowest $T_R^*(^{13}CO)$ contours (2 and 3 K). The solid contours are at $T_R^*(^{13}CO)$ = 4, 5, 6, 7, 8, 10, 12, 14, 16, 18, and 20 K, with the 10 and 20 K contours highlighted as thicker lines. The $T_R^*(^{13}CO)$ = 1 K contour is shown as a dotted line in a few selected regions to locate a few very weak cloud components. The locations of the early B stars in the mapped area are indicated. Dense cores that have been located are labeled by letters.

Star & Planet Formation




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

Star Formation & Salpeter



Star Formation & Salpeter

Universe

↓

Galaxies

↓

"Molecular Clouds" ········ Structure → **IMF** (Salpeter 1955)

↓

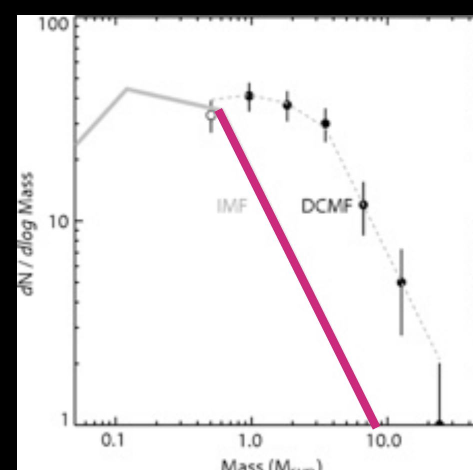
Stars → Feedback ++ (winds, radiation+ionization)

Feedback ++ → "Turbulence" → Structure

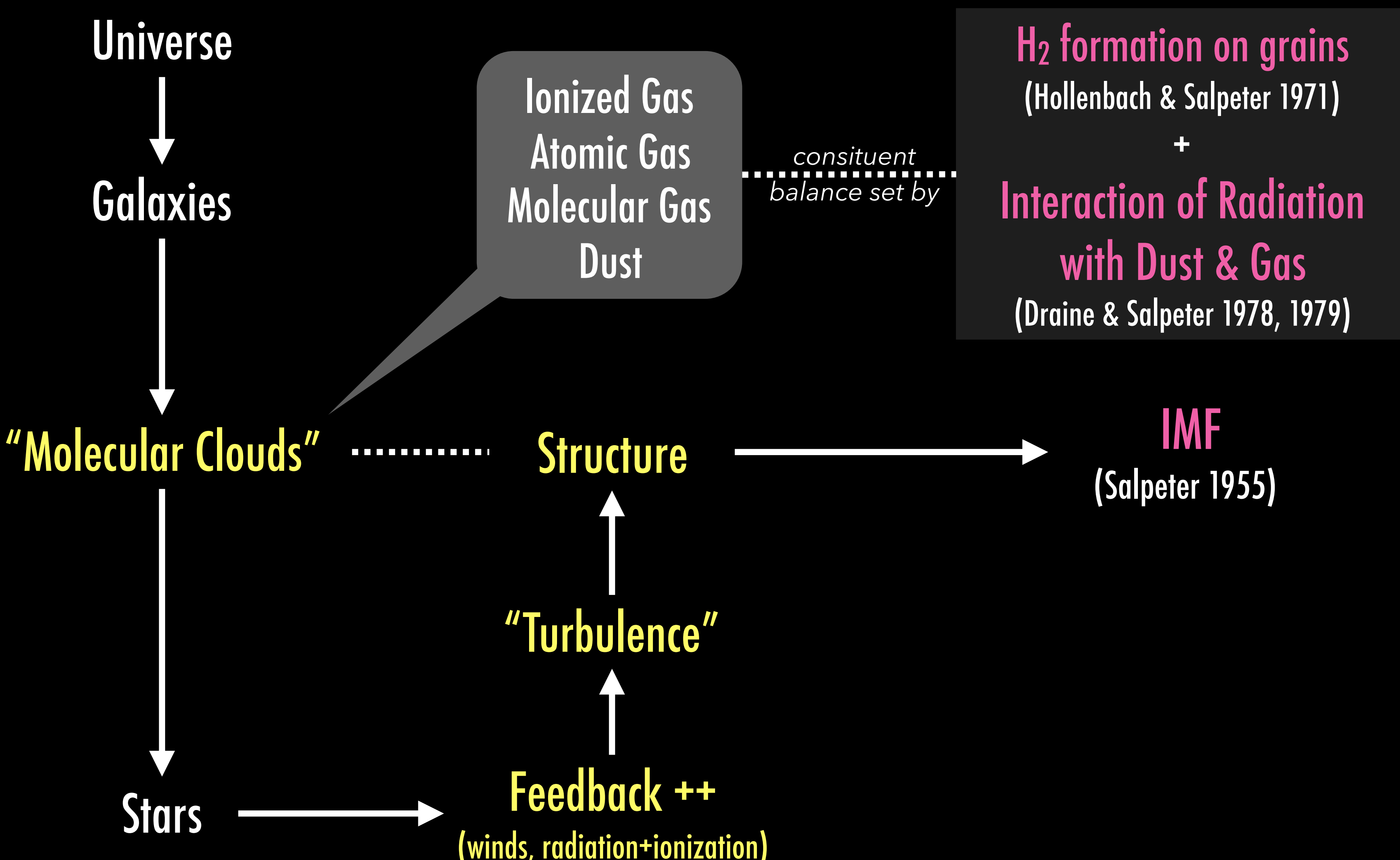
Ionized Gas
Atomic Gas
Molecular Gas
Dust

consituent balance set by

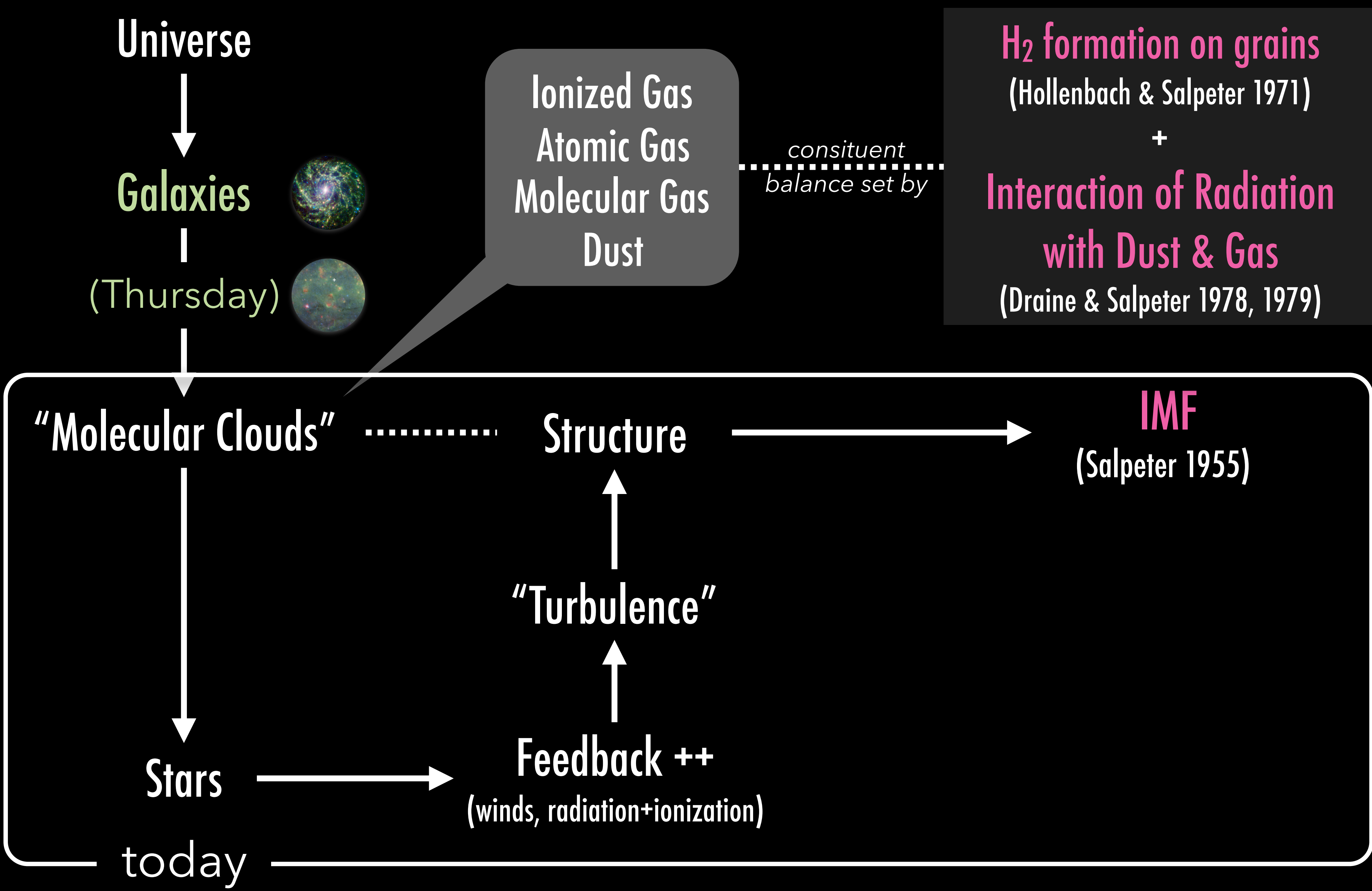
H_2 formation on grains
(Hollenbach & Salpeter 1971)
+
Interaction of Radiation with Dust & Gas
(Draine & Salpeter 1978, 1979)



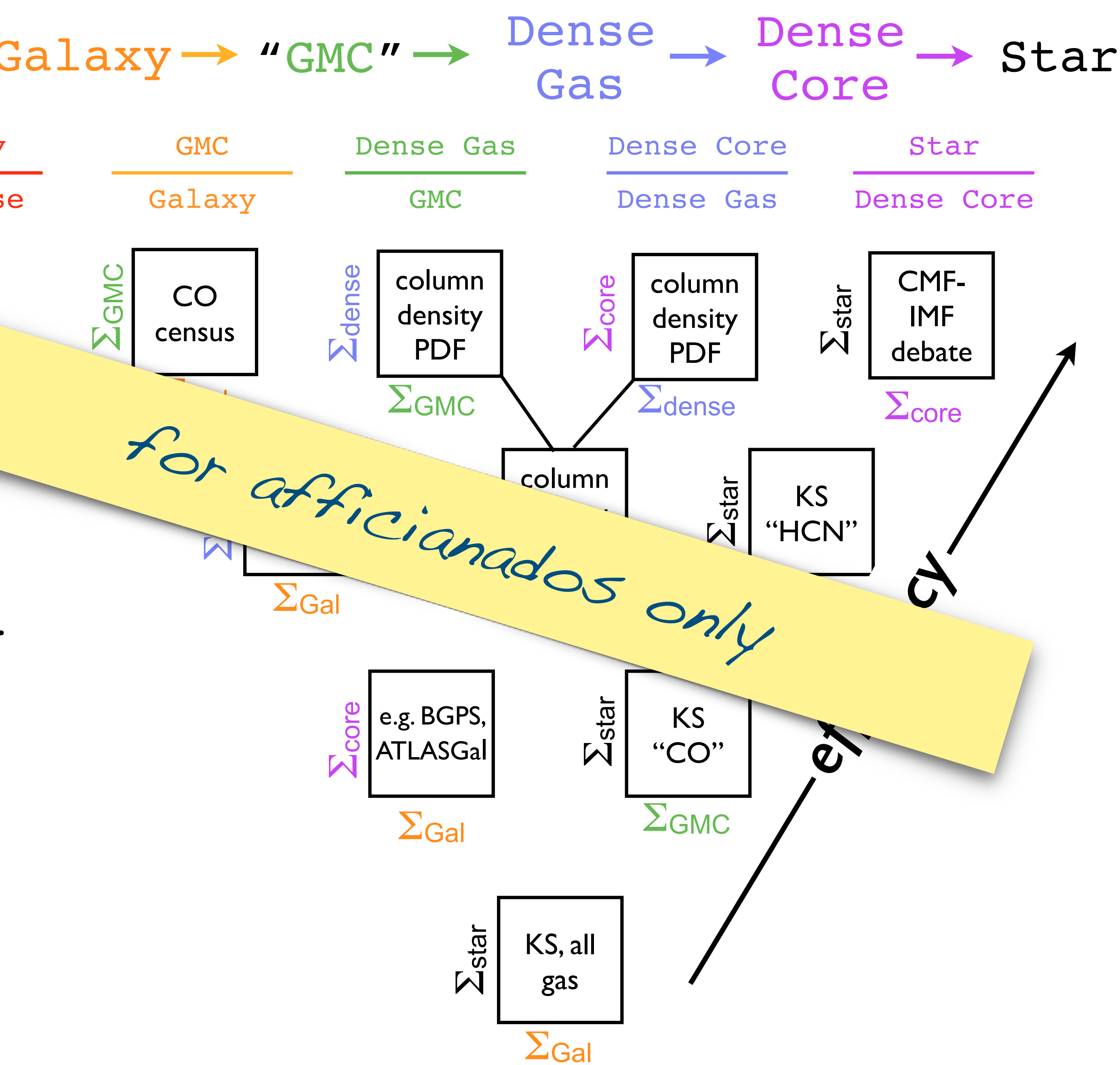
Star Formation & Salpeter



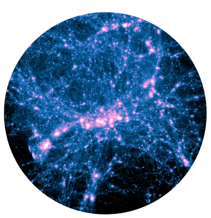
Star Formation & Salpeter

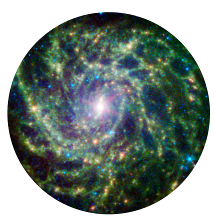


time dependent mass fractions



Star Formation Efficiency Pyramid Scheme

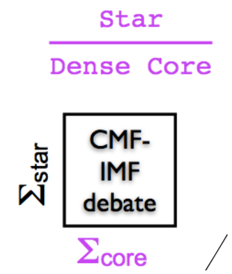




Alyssa Goodman, Ringberg, RSF13

A&A 462, L17–L21 (2007)
DOI: 10.1051/0004-6361:20066389

Astronomy & Astrophysics



LETTER TO THE EDITOR

The mass function of dense molecular cores and the origin of the IMF★

J. Alves[1], M. Lombardi[2,★★], and C. J. Lada[3]

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e-mail: clada@cfa.harvard.edu

Does the "DCMF" give the IMF?

What, really, is a "dense core?"

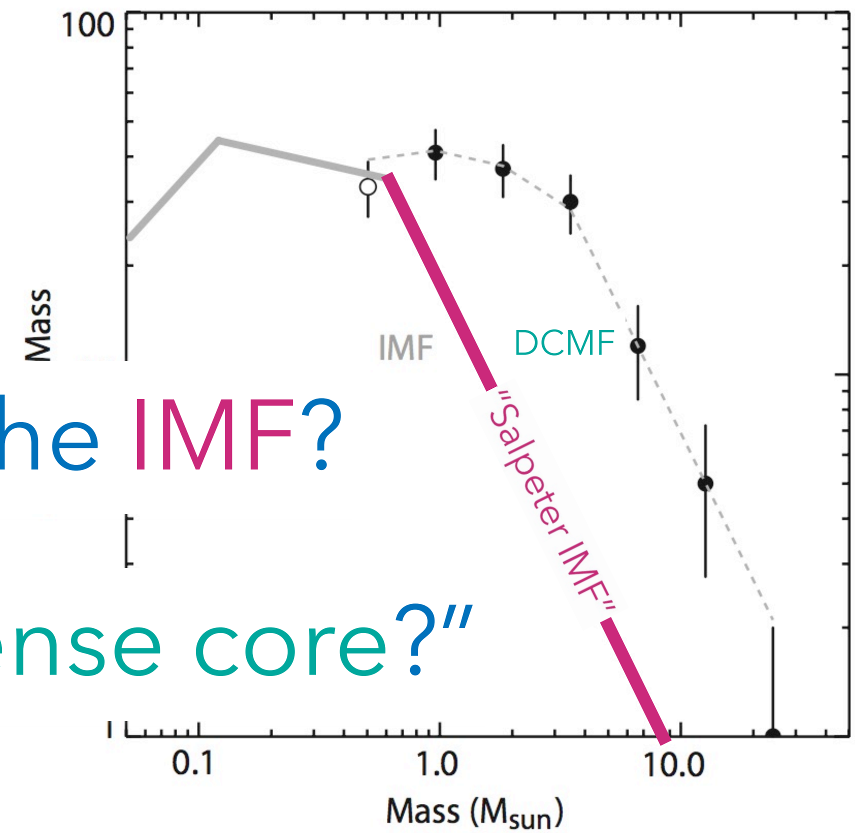
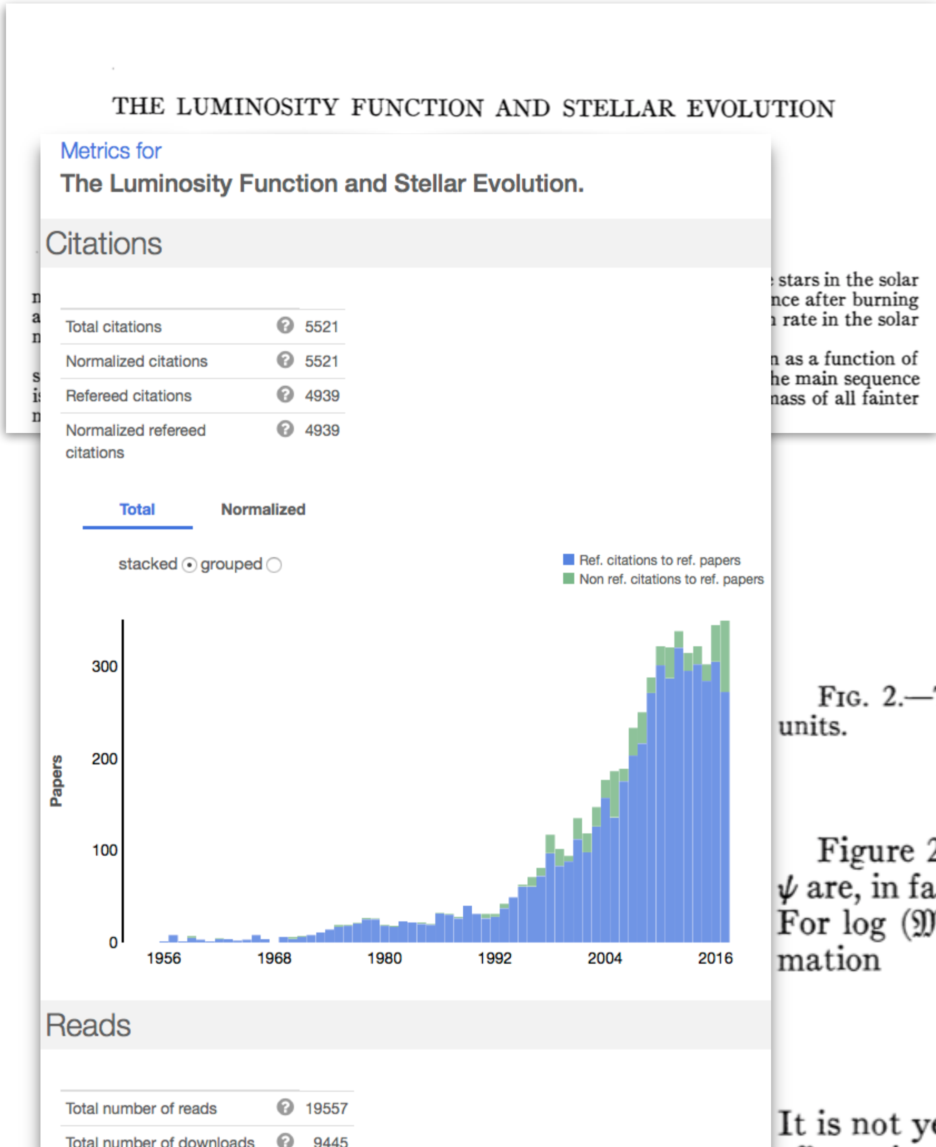


Fig. 2. Mass function of dense molecular cores plotted as filled circles with error bars. The grey line is the stellar IMF for the Trapezium cluster (Muench et al. 2002). The dashed grey line represents the stellar IMF in binned form matching the resolution of the data and shifted to higher masses by about a factor of 4. The dense core mass function is similar in shape to the stellar IMF function, apart from a uniform star formation efficiency factor.

The “Salpeter IMF” (1955)



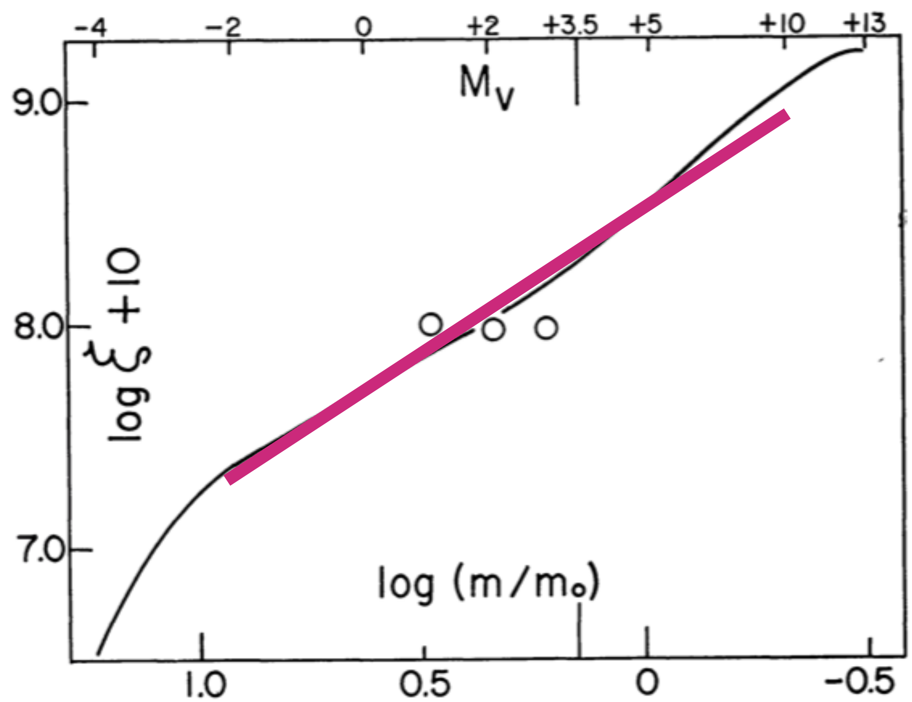


FIG. 2.—The logarithm of the “original mass function,” ξ, plotted against the mass, 𝔐, in solar units.

IV. DISCUSSION

Figure 2 and Table 2 show that the “original” mass and luminosity functions ξ and ψ are, in fact, fairly smoothly varying functions without any very rapid change of slope. For log $(\mathfrak{M}/\mathfrak{M}_\odot)$ between −0.4 and +1.0, ξ is given reasonably well by the approximation

$$\xi(\mathfrak{M}) \approx 0.03 \left(\frac{\mathfrak{M}}{\mathfrak{M}_\odot}\right)^{-1.35}. \quad (5)$$

It is not yet clear whether the steeper drop of ξ for masses larger than 10 $\mathfrak{M}_\odot$ is a real effect, since in this region masses and bolometric corrections are not known very accurately and the number of such stars reasonably near the galactic plane is small.

PUBLICATIONS OF THE ASTRONOMICAL SOCIETY OF THE PACIFIC, 115:763–795, 2003 July

2003

Invited Review

Galactic Stellar and Substellar Initial Mass Function[1]

GILLES CHABRIER
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Received 2003 March 31; accepted 2003 March 31

1.1. Historical Perspective

Since the pioneering paper of Salpeter (1955), several fundamental reviews on the Galactic stellar mass function (MF) have been written by, in particular, Schmidt (1959), Miller & Scalo (1979, hereafter MS79), and Scalo (1986). A shorter, more recent discussion is given by Kroupa (2002). The determination of the stellar MF is a cornerstone in astrophysics, for the stellar mass distribution determines the evolution, surface brightness, chemical enrichment, and baryonic content of galaxies. Determining whether this MF has been constant along the evolution of the universe or varies with redshift bears crucial consequences on the so-called cosmic star formation, i.e., on the universe's light and matter evolution. Furthermore, the knowledge of the MF in our Galaxy yields the complete census of its stellar and substellar population and provides an essential diagnostic to understand the formation of starlike objects. As emphasized by Scalo (1986), the stellar and substellar mass distribution is the link between stellar and galactic evolution.

…

(from the **Conclusions**)

This IMF determination is examined in the context of star formation theory. Theories based on a **pure Jeans-type mechanism**, where fragmentation is due only to gravity, appear to have **difficulties explaining the** determined **IMF** and various observational constraints on star formation. On the other hand, **recent numerical simulations of compressible turbulence, in particular in super-Alfvénic conditions, reproduce qualitatively and reasonably quantitatively the determined IMF** and thus provide an appealing solution. In this picture, **star formation is induced by the dissipation of large-scale turbulence to smaller scales through radiative shocks, producing filamentary structures. These shocks produce local, nonequilibrium structures with large density contrasts. Some of these dense cores then collapse eventually in gravitationally bound objects under the combined action of turbulence and gravity.** The concept of a single Jeans mass, however, is replaced by a **distribution of local Jeans masses, representative of the lognormal probability density function of the turbulent gas.** Cores exceeding the average Jeans mass (1 $M_\odot$) naturally collapse into stars under the action of gravity, whereas objects below this limit still have a possibility to collapse, but with a decreasing probability, as gravity selects only the densest cores in a certain mass range (the ones such that the mass exceeds the local Jeans mass m_J). This picture, combining turbulence as the initial mechanism for fragmentation and gravity, thus provides a natural explanation for a scale-free power-law IMF at large scales and a broad lognormal form below about 1 $M_\odot$. **Additional mechanisms such as accretion, subfragmentation of the cores, and multiplicity will not significantly affect the high-mass power-law part of the mass spectrum but can modify the extension of its low-mass part.** The initial level of turbulence in the cloud and its initial density can also affect the low-mass part of the IMF.

2017

THE STELLAR IMF FROM ISOTHERMAL MHD TURBULENCE

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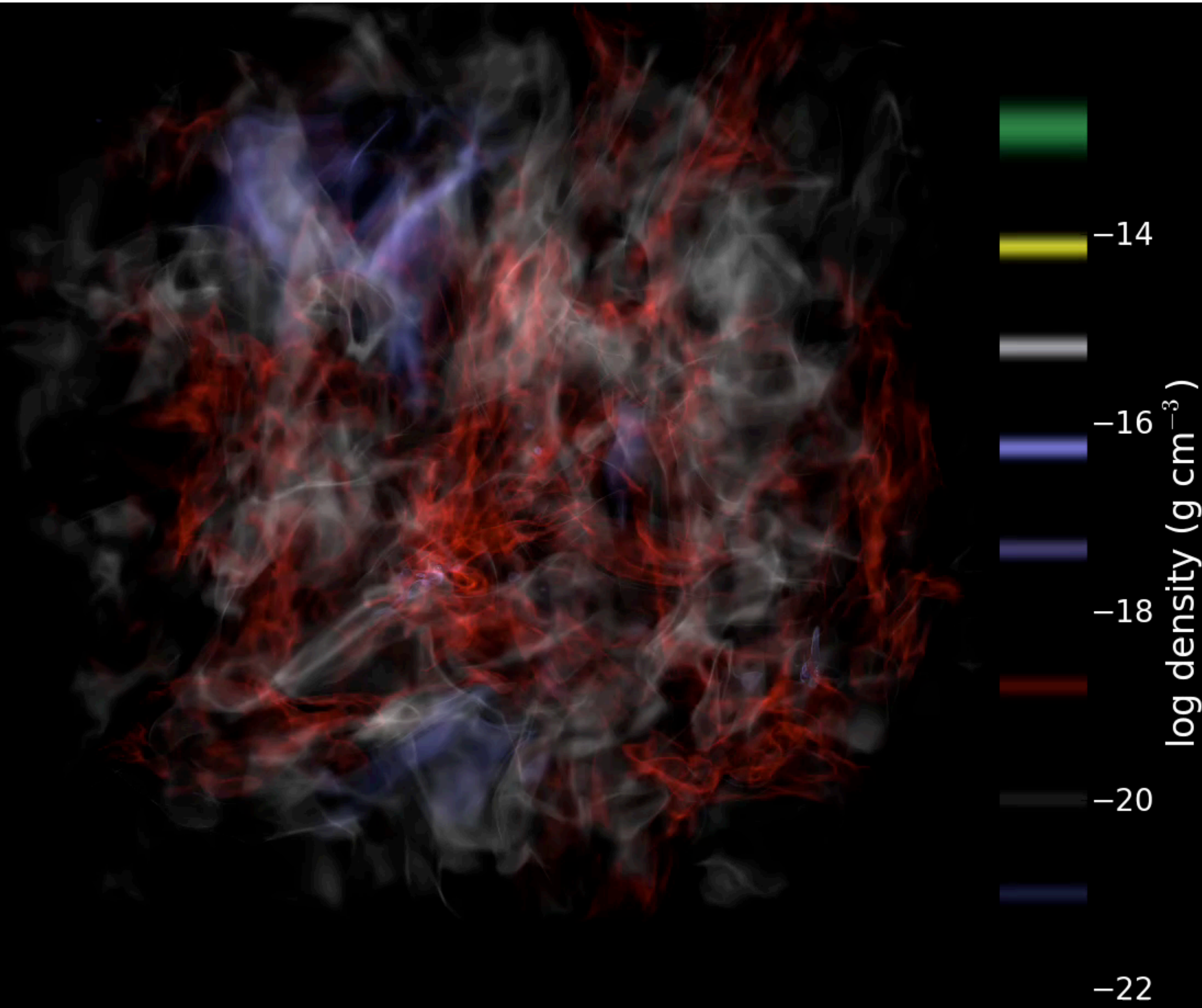
Åke Nordlund
Centre for Star and Planet Formation, Niels Bohr Institute & Natural History Museum of Denmark, University of Copenhagen, Øster

Details are very interesting, but for today
—any kind of turbulence-inducing process
seems to give a "Salpeter" IMF

(as high-mass end of underlying log-normal distribution, caused by...central limit theorem)

IMF. A large set of medium-size simulations is used to test the sink particle scheme, while larger simulations are used to test the numerical convergence of the IMF and the dependence of the IMF turnover on physical parameters predicted by the turbulent-fragmentation model. We find clear evidence of numerical convergence and strong support for the model predictions, including the initial time evolution of the IMF. We conclude that the physics of isothermal MHD turbulence is sufficient to explain the origin of the IMF.

Keywords: ISM: kinematics and dynamics – MHD – stars: formation – turbulence



Offner et al. 2009

(Is there a sensible) Cloud Mass Function(?)

in a webby, filamentary, ISM

The Astrophysical Journal, 699:L134–L138, 2009 July 10
doi:10.1088/0004-637X/699/2/L134

THE PERILS OF CLUMPFIND: THE MASS SPECTRUM OF SUBSTRUCTURES IN MOLECULAR CLOUDS

Jaime E. Pineda[1], Erik W. Rosolowsky[2], and Alyssa A. Goodman[1]
[1] Harvard-Smithsonian Center for Astrophysics, 60 Garden Street, Cambridge, MA 02138, USA; jpineda@cfa.harvard.edu
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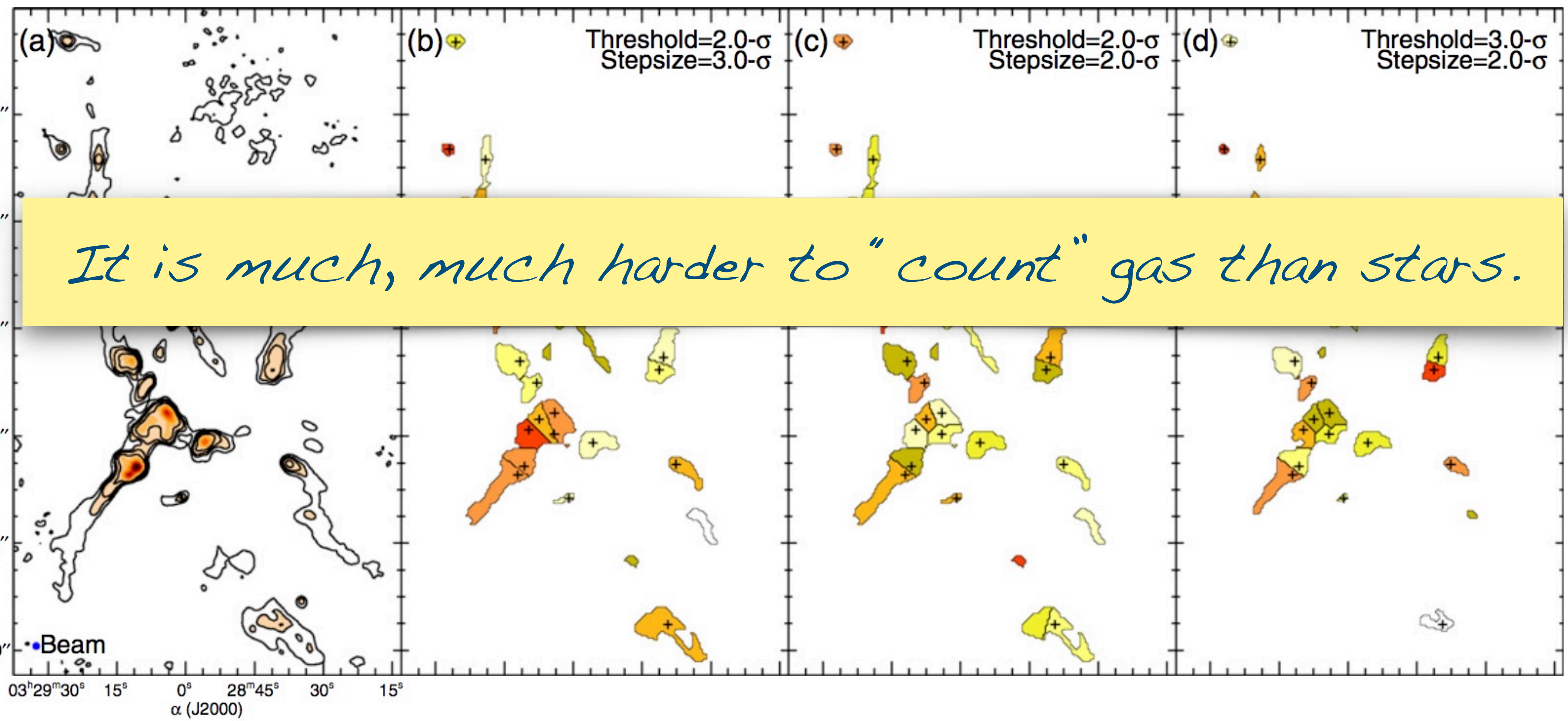
Received 2009 January 27; accepted 2009 June 1; published 2009 June 22

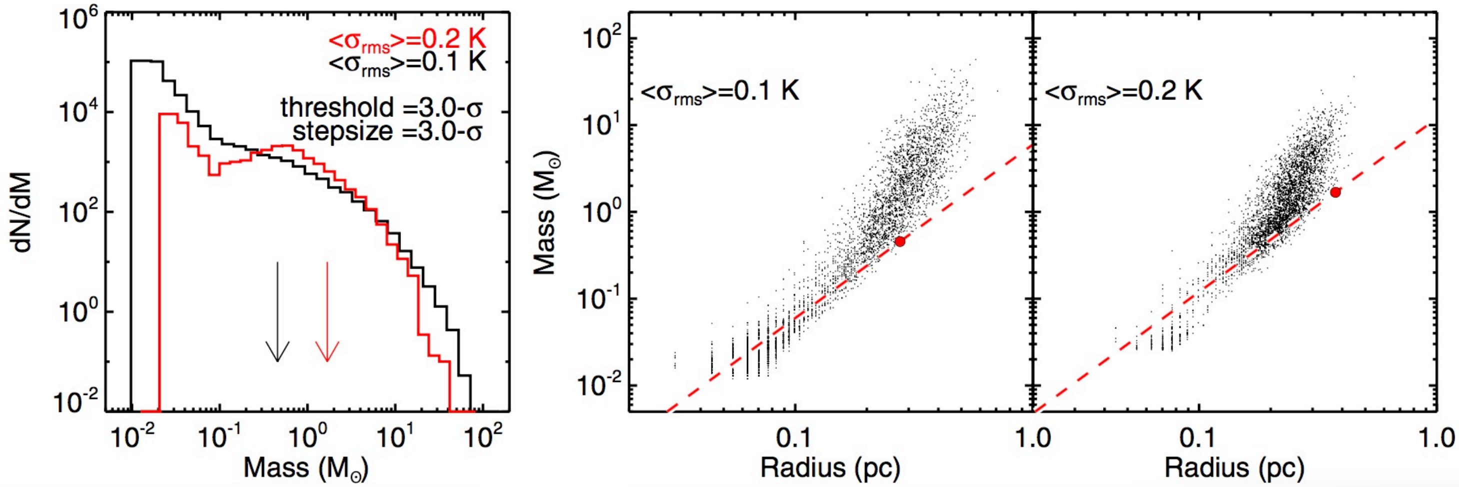


It is much, much harder to "count" gas than stars.

"The Perils of CLUMPFIND"

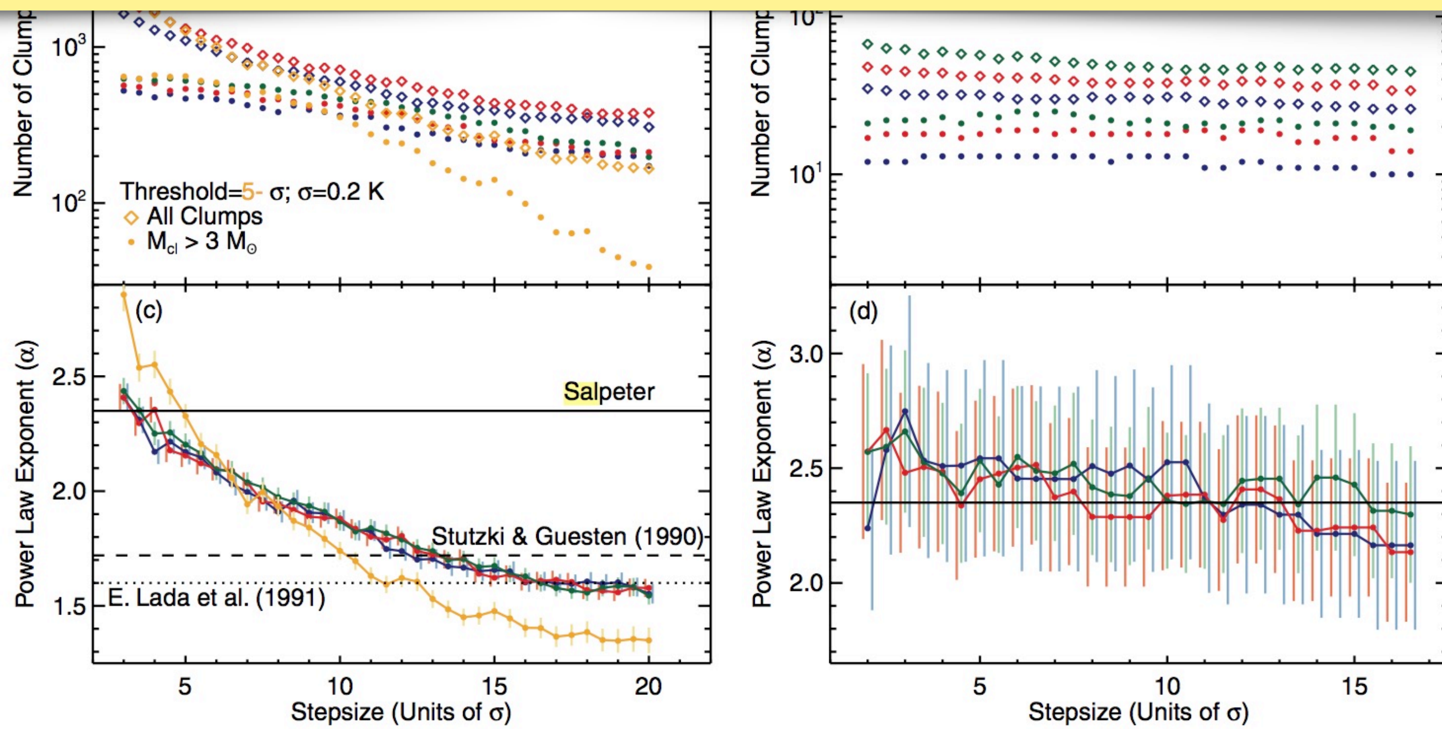
Pineda, Rosolowsky & Goodman 2009

Mass spectrum changes dramatically based on algorithm parameters.



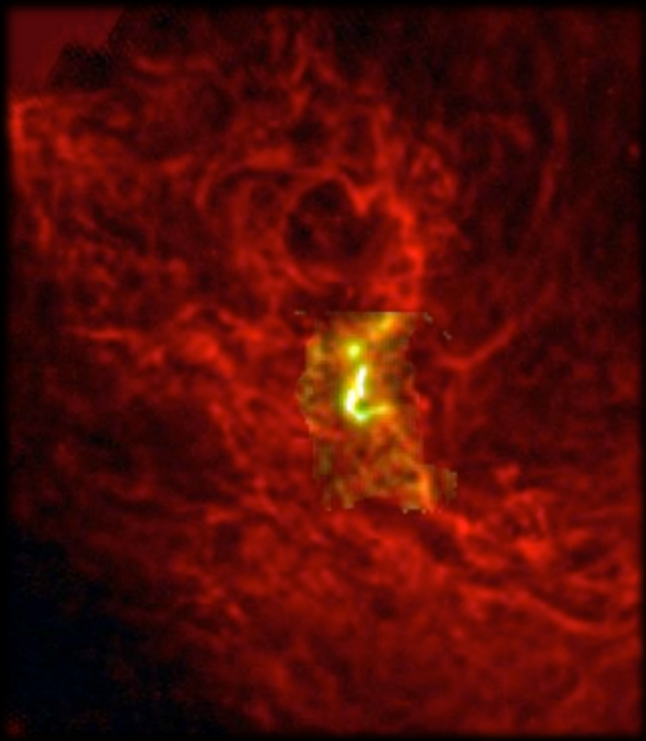
You can get almost any CMF exponent you want.

Problem especially bad for "crowded" emission– exponent "adjustable" with step size.



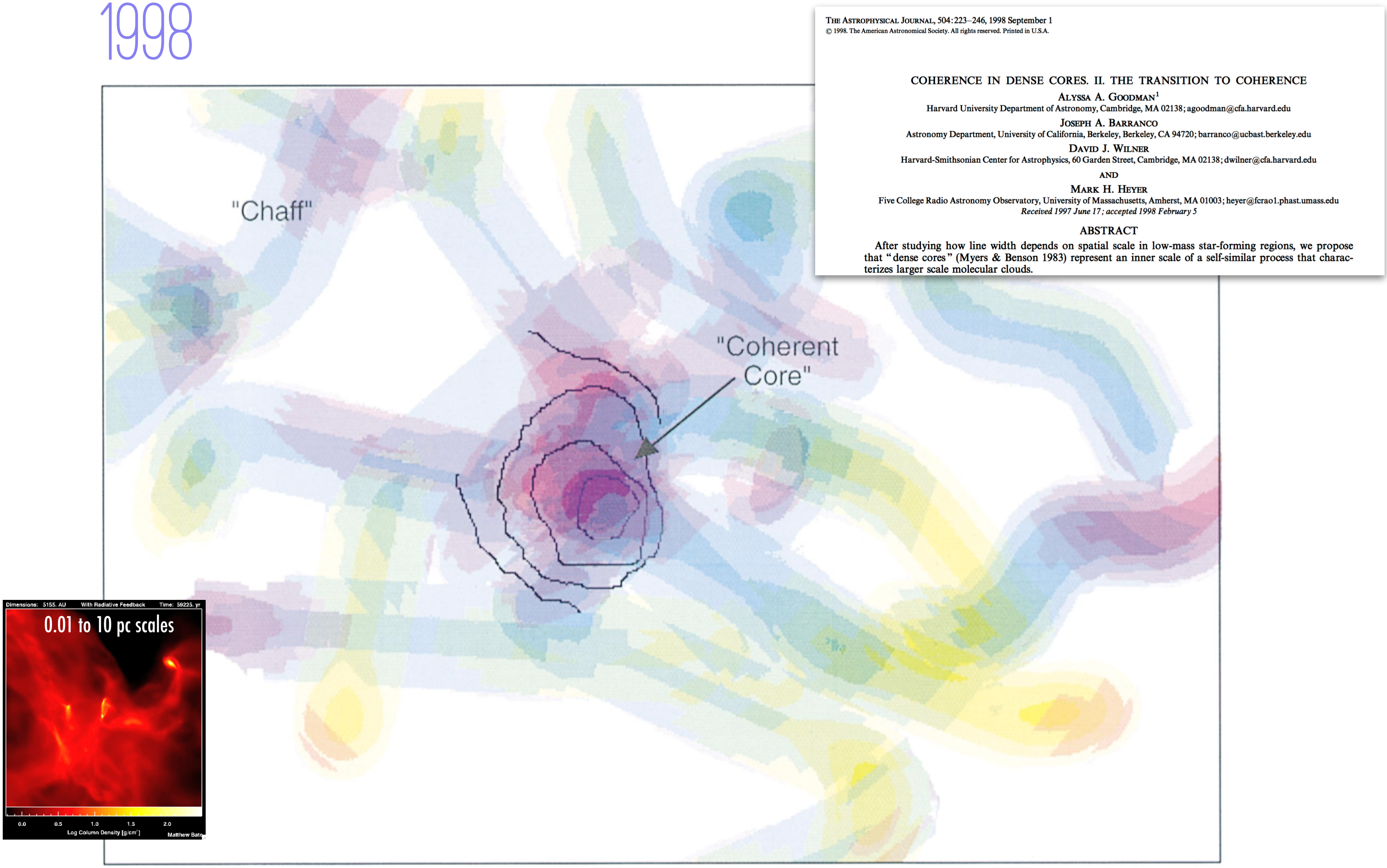
Until this decade, I thought (coherent) ***cores*** *were real, countable, entities, whose mass one could measure –but I am less sure now.* (AG, 2017)

COHERENT CORES
ISLANDS OF CALM IN TURBULENT SEAS(?)



The 30-year story: Myers & Benson 1983, Goodman et al. 1998, Pineda et al. 2010, 2011, 2014

1998



The Astrophysical Journal, 504:223–246, 1998 September 1

COHERENCE IN DENSE CORES. II. THE TRANSITION TO COHERENCE

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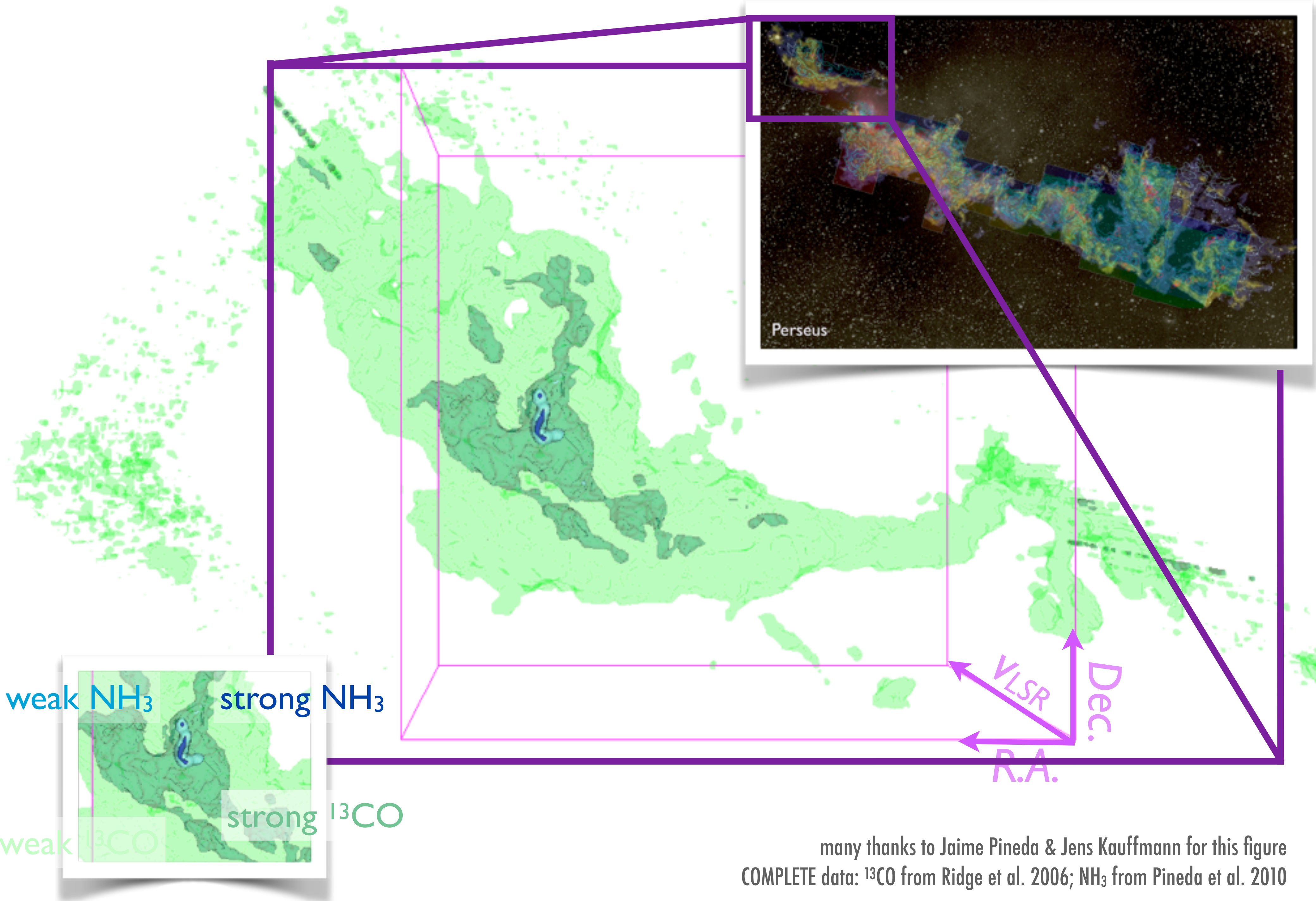
Received 1997 June 17; accepted 1998 February 5

ABSTRACT

After studying how line width depends on spatial scale in low-mass star-forming regions, we propose that "dense cores" (Myers & Benson 1983) represent an inner scale of a self-similar process that characterizes larger scale molecular clouds.

Fig. 10.—An illustration of the transition to coherence. Color and shading schematically represent velocity and density in this figure. On large scales, material (labeled chaff) is distributed in a self-similar fashion, and its filling factor is low. On scales smaller than some fiducial radius, the filling factor of gas increases substantially, and a coherent dense core, which is not self-similar, is formed. Due to limitations in the authors' drawing ability, the figure emphasizes a particular size scale in the chaff, which should actually exhibit self-similar structure on all scales ranging from the size of an entire molecular cloud complex down to a coherent core.

POSITION-VELOCITY STRUCTURE OF THE B5 REGION IN PERSEUS

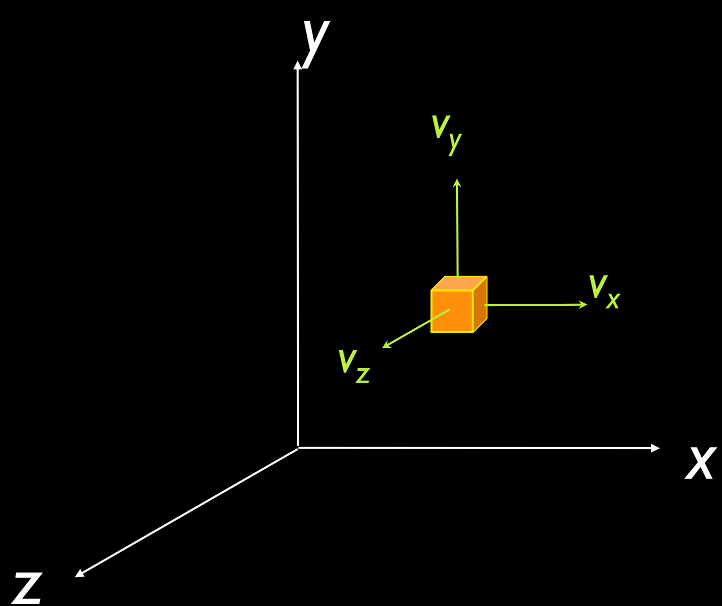


many thanks to Jaime Pineda & Jens Kauffmann for this figure

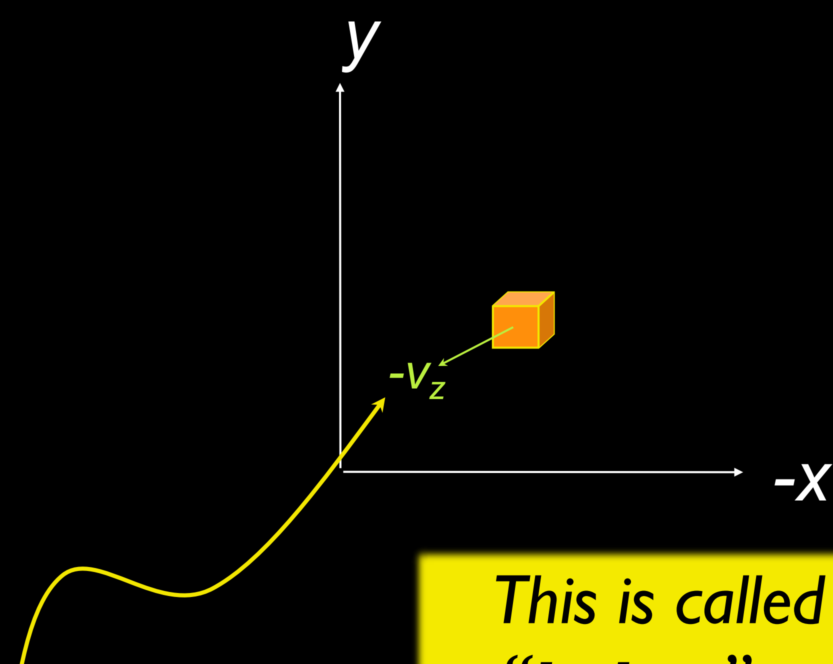
COMPLETE data: ^{13}CO from Ridge et al. 2006; NH_3 from Pineda et al. 2010

POSITION-VELOCITY SPACE & SPECTRAL-LINE MAPPING (Thursday!)

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



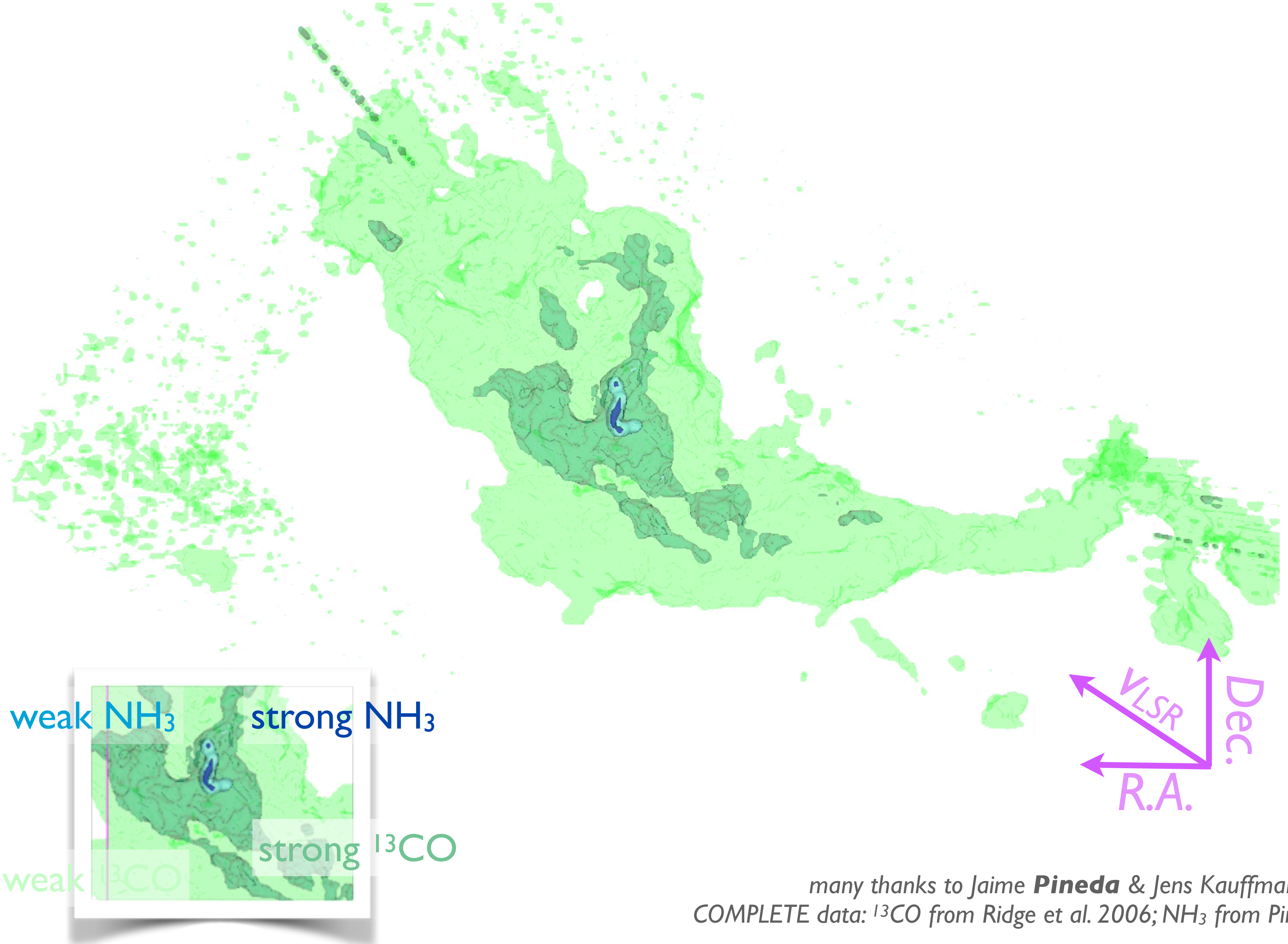
But we <u>can</u> measure...



v_z *only* from "spectral-line maps"

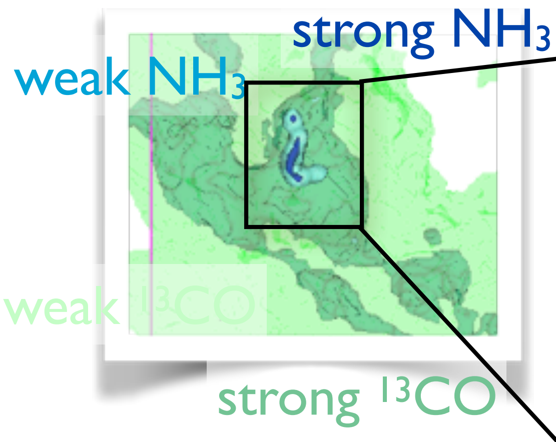
*This is called "**p-p-v**" or "(position-) position-velocity" space.*

POSITION-VELOCITY STRUCTURE OF THE B5 REGION IN PERSEUS

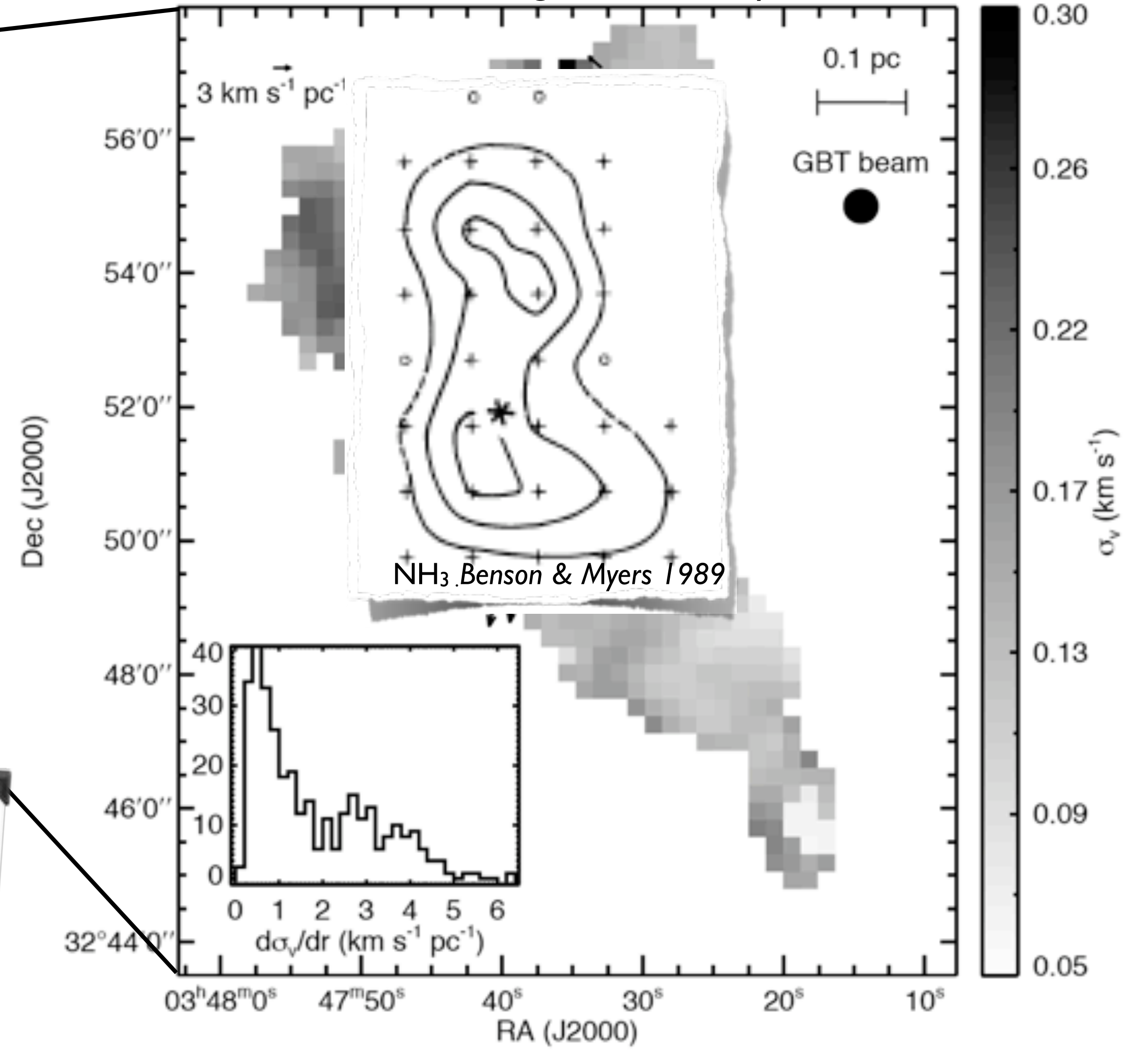


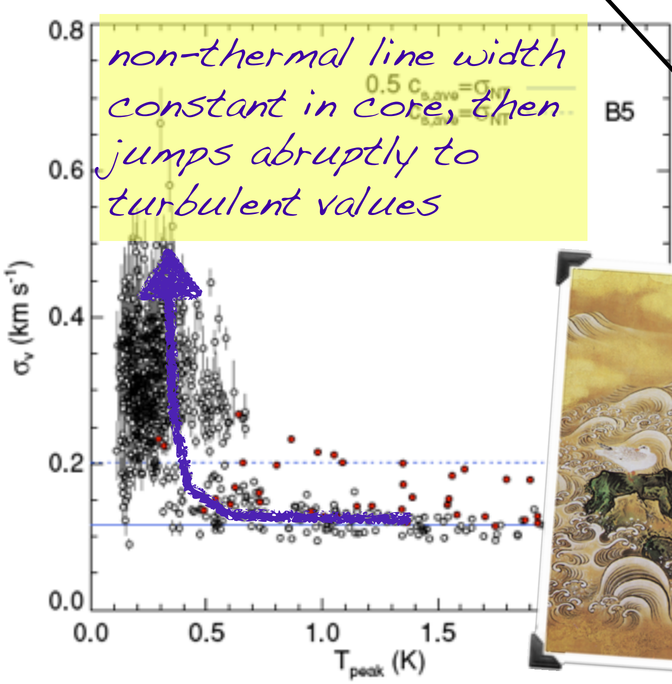
*many thanks to Jaime **Pineda** & Jens Kauffmann for this figure*
COMPLETE data: ^{13}CO from Ridge et al. 2006; NH_3 from Pineda et al. 2010

STRONG EVIDENCE FOR "VELOCITY COHERENCE" IN DENSE CORES



greyscale shows NH_3 velocity dispersion, arrows show gradient in dispersion





GBT NH_3 observations of the B5 core (Pineda et al. 2010)

BUT THEN… WE FOUND SUB-STRUCTURE

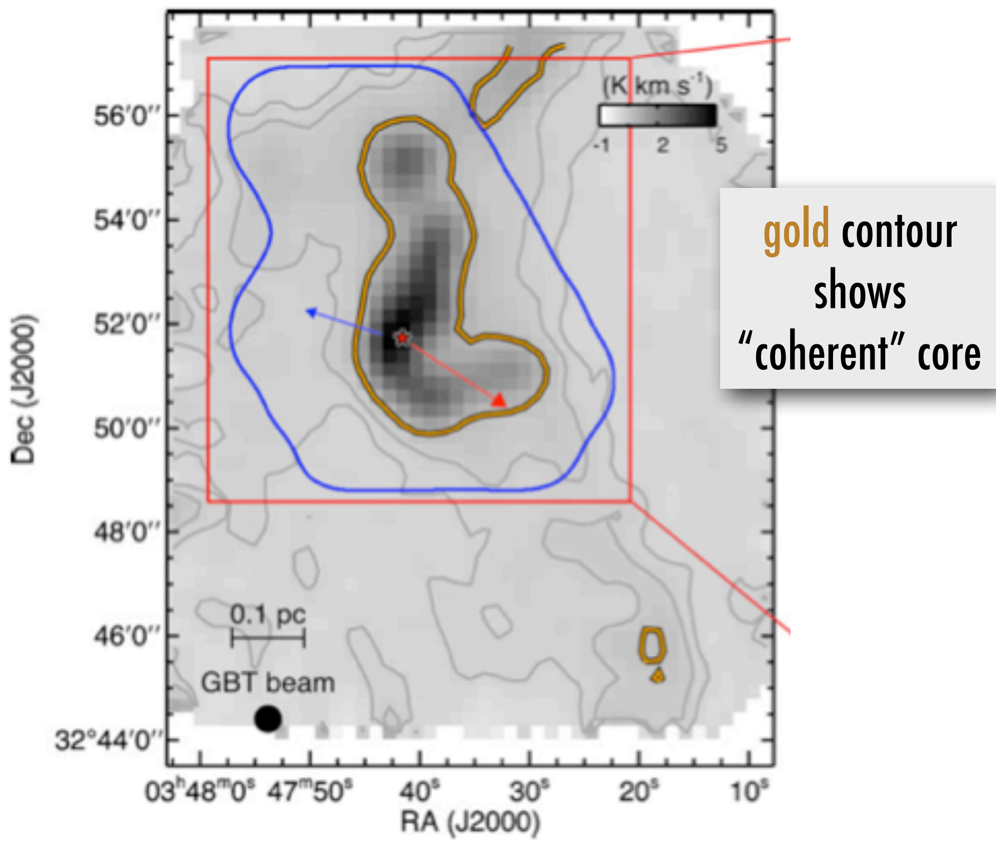
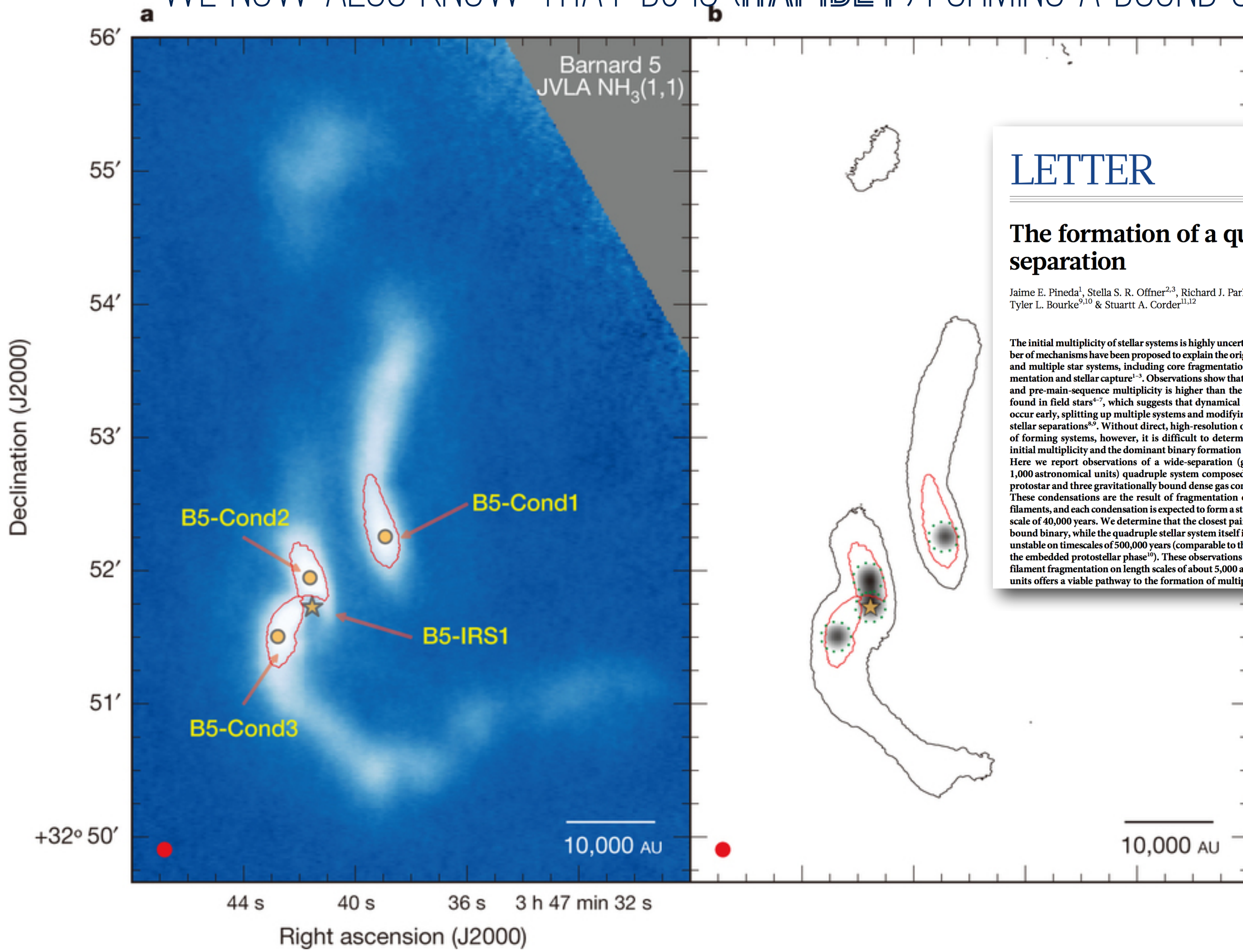


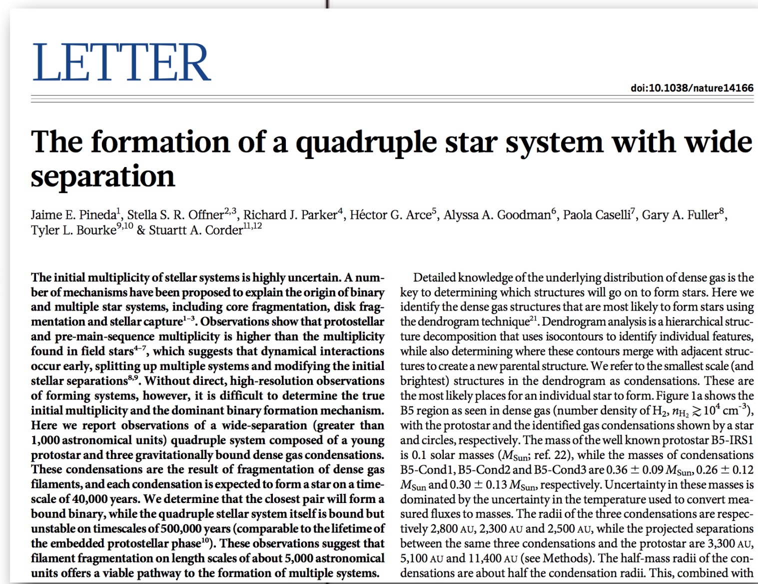
Figure 1. Left panel: integrated intensity map of B5 in NH_3 (1,1) obtained with GBT. Gray contours show the 0.15 and 0.3 K km s^{-1} level in NH_3 (1,1) integrated intensity. The orange contours show the region in the GBT data where the non-thermal velocity dispersion is subsonic. The young star, B5–IRS1, is shown by the star in both panels. The outflow direction is shown by the arrows. The blue contour shows the area observed with the EVLA and the red box shows the area shown in the right panel. Right panel: integrated intensity map of B5 in NH_3 (1,1) obtained combining the EVLA and GBT data. Black contour shows the 50 mJy $beam^{-1}$ km s^{-1} level in NH_3 (1,1) integrated intensity. The yellow box shows the region used in Figure 4. The northern starless condensation is shown by the dashed circle.

Pineda et al. 2011

AND SUB-SUB STRUCTURE

WE NOW ALSO KNOW THAT B5 IS (RAPIDLY) FORMING A BOUND CLUSTER





LETTER

doi:10.1038/nature14166

The formation of a quadruple star system with wide separation

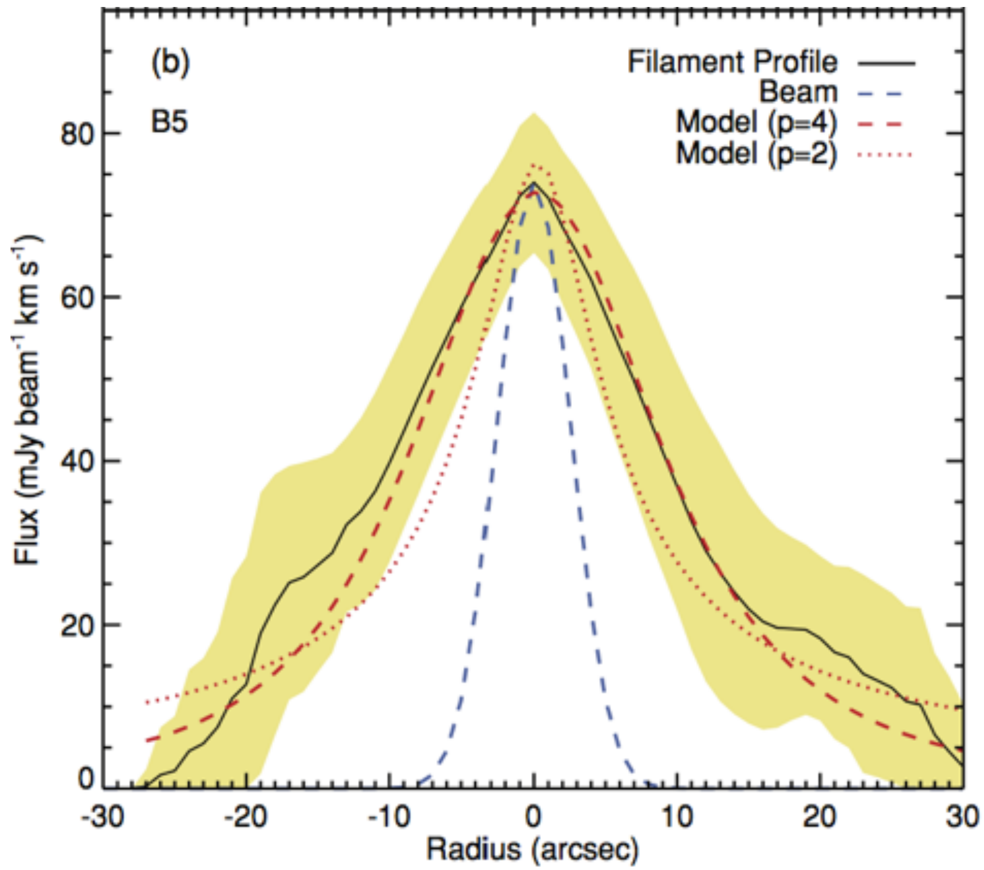
Jaime E. Pineda[1], Stella S. R. Offner[2,3], Richard J. Parker[4], Héctor G. Arce[5], Alyssa A. Goodman[6], Paola Caselli[7], Gary A. Fuller[8], Tyler L. Bourke[9,10] & Stuartt A. Corder[11,12]

The initial multiplicity of stellar systems is highly uncertain. A number of mechanisms have been proposed to explain the origin of binary and multiple star systems, including core fragmentation, disk fragmentation and stellar capture[1–3]. Observations show that protostellar and pre-main-sequence multiplicity is higher than the multiplicity found in field stars[4–7], which suggests that dynamical interactions occur early, splitting up multiple systems and modifying the initial stellar separations[8,9]. Without direct, high-resolution observations of forming systems, however, it is difficult to determine the true initial multiplicity and the dominant binary formation mechanism. Here we report observations of a wide-separation (greater than 1,000 astronomical units) quadruple system composed of a young protostar and three gravitationally bound dense gas condensations. These condensations are the result of fragmentation of dense gas filaments, and each condensation is expected to form a star on a timescale of 40,000 years. We determine that the closest pair will form a bound binary, while the quadruple stellar system itself is bound but unstable on timescales of 500,000 years (comparable to the lifetime of the embedded protostellar phase[10]). These observations suggest that filament fragmentation on length scales of about 5,000 astronomical units offers a viable pathway to the formation of multiple systems.

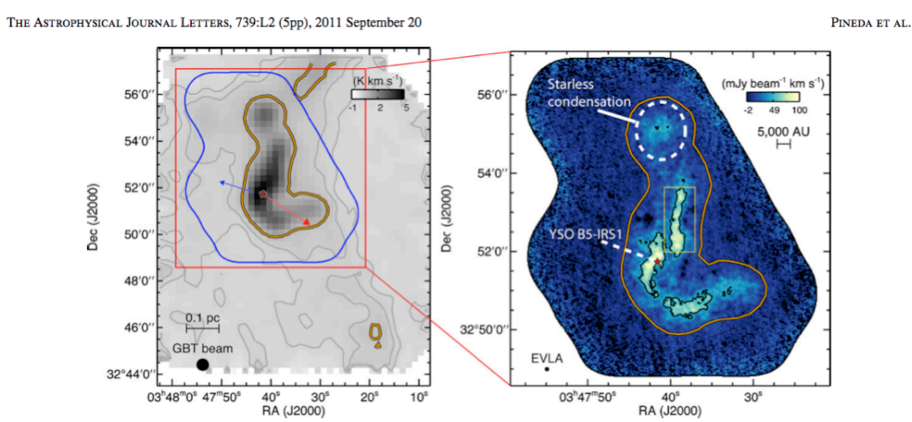
Detailed knowledge of the underlying distribution of dense gas is the key to determining which structures will go on to form stars. Here we identify the dense gas structures that are most likely to form stars using the dendrogram technique[21]. Dendrogram analysis is a hierarchical structure decomposition that uses isocontours to identify individual features, while also determining where these contours merge with adjacent structures to create a new parental structure. We refer to the smallest scale (and brightest) structures in the dendrogram as condensations. These are the most likely places for an individual star to form. Figure 1a shows the B5 region as seen in dense gas (number density of H_2, $n_{H_2} \gtrsim 10^4$ cm^{-3}), with the protostar and the identified gas condensations shown by a star and circles, respectively. The mass of the well known protostar B5-IRS1 is 0.1 solar masses (M_{Sun}; ref. 22), while the masses of condensations B5-Cond1, B5-Cond2 and B5-Cond3 are 0.36 ± 0.09 M_{Sun}, 0.26 ± 0.12 M_{Sun} and 0.30 ± 0.13 M_{Sun}, respectively. Uncertainty in these masses is dominated by the uncertainty in the temperature used to convert measured fluxes to masses. The radii of the three condensations are respectively 2,800 AU, 2,300 AU and 2,500 AU, while the projected separations between the same three condensations and the protostar are 3,300 AU, 5,100 AU and 11,400 AU (see Methods). The half-mass radii of the condensations are about half the condensation radii. This, combined with

Pineda, Offner, Parker, Arce, Goodman, Caselli, Fuller, Bourke & Corder 2015

BUT MAYBE IT'S DIFFERENT?



isothermal, hydrostatic filaments, not turbulent ones?

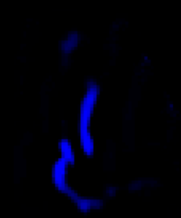


Pineda et al. 2011

Here’s the fun/crazy part.

WHAT IF FILAMENTS CONTINUE ACROSS "CORE" BOUNDARIES?!

blue =VLA ammonia (high-density gas); green=GBT ammonia (lower-res high-density gas); red=Herschel 250 micron continuum (dust)



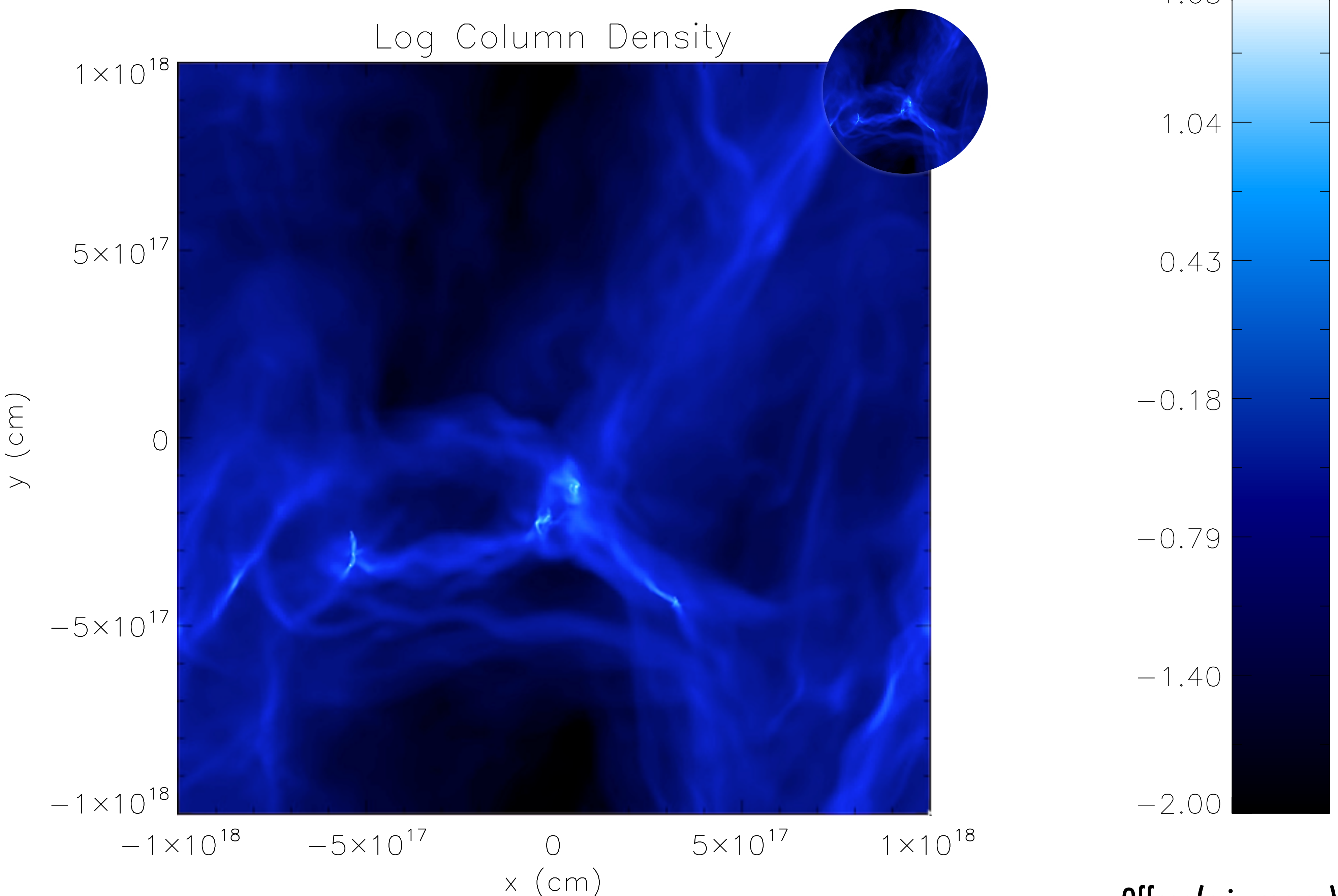
Goodman, Chen, Offner & Pineda 2017 in prep.

Herschel data from Gould Belt Survey

1998

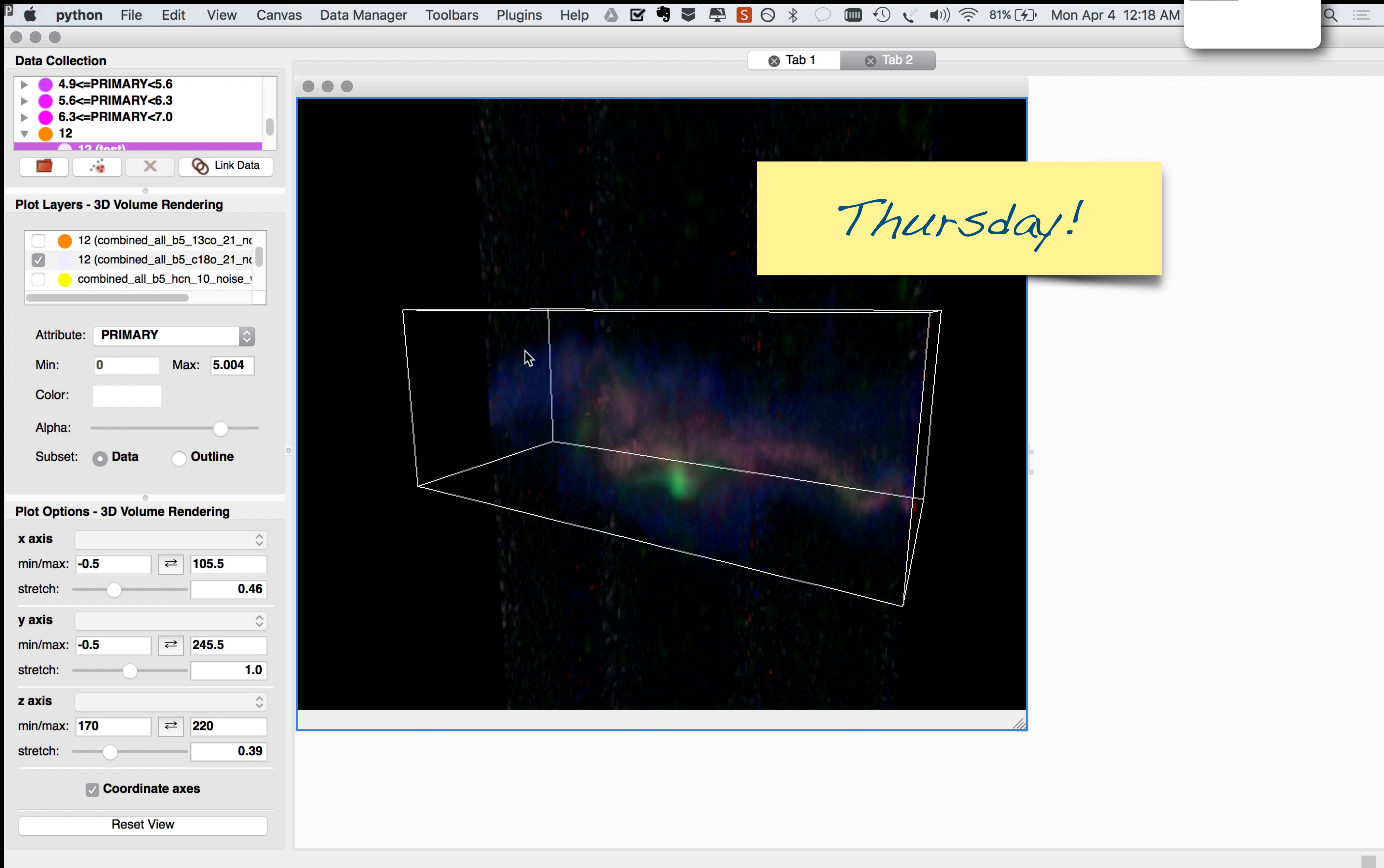
2008

B5-ISH SIMULATION (NO MAGNETIC FIELD)



Offner (priv. comm.)

B5/GLUE (NEW IRAM 30-M DATA)

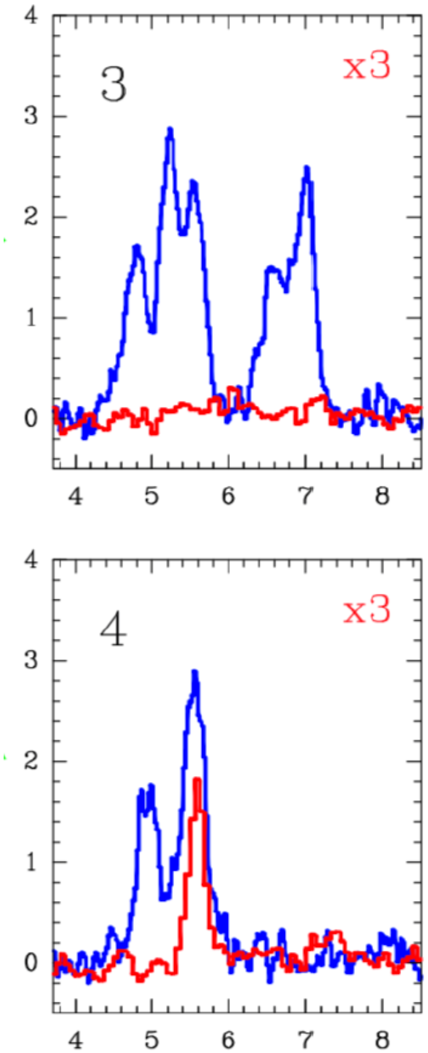


Goodman, Chen, Offner & Pineda 2017 in prep.

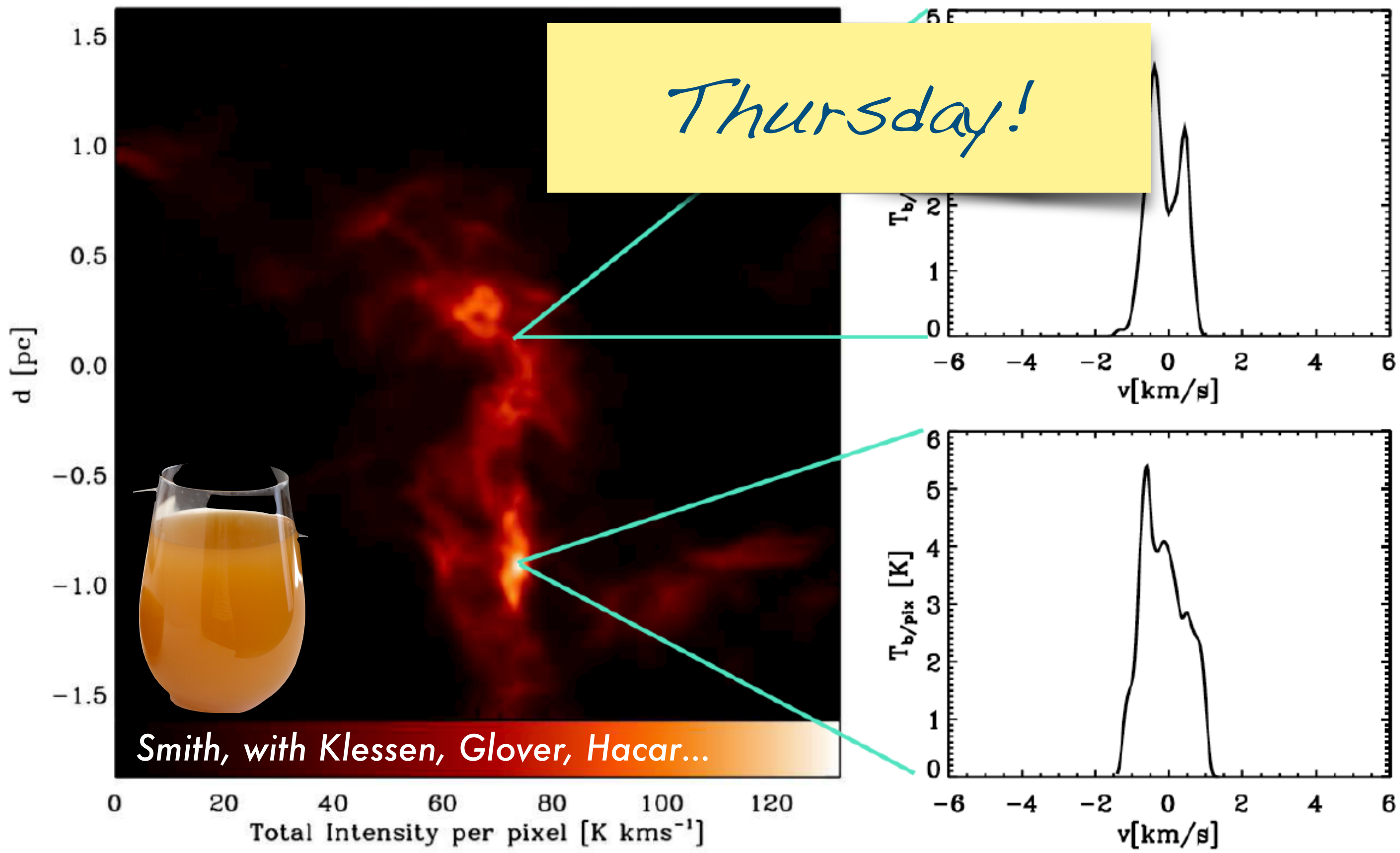
glueviz.org

Simulators are *almost* observing enough lines…

Filaments in Filaments



Observed C^{18}O emission in blue.



Synthetic observation of C^{18}O emission from our time-dependent chemical model post-processed with radmc-3d

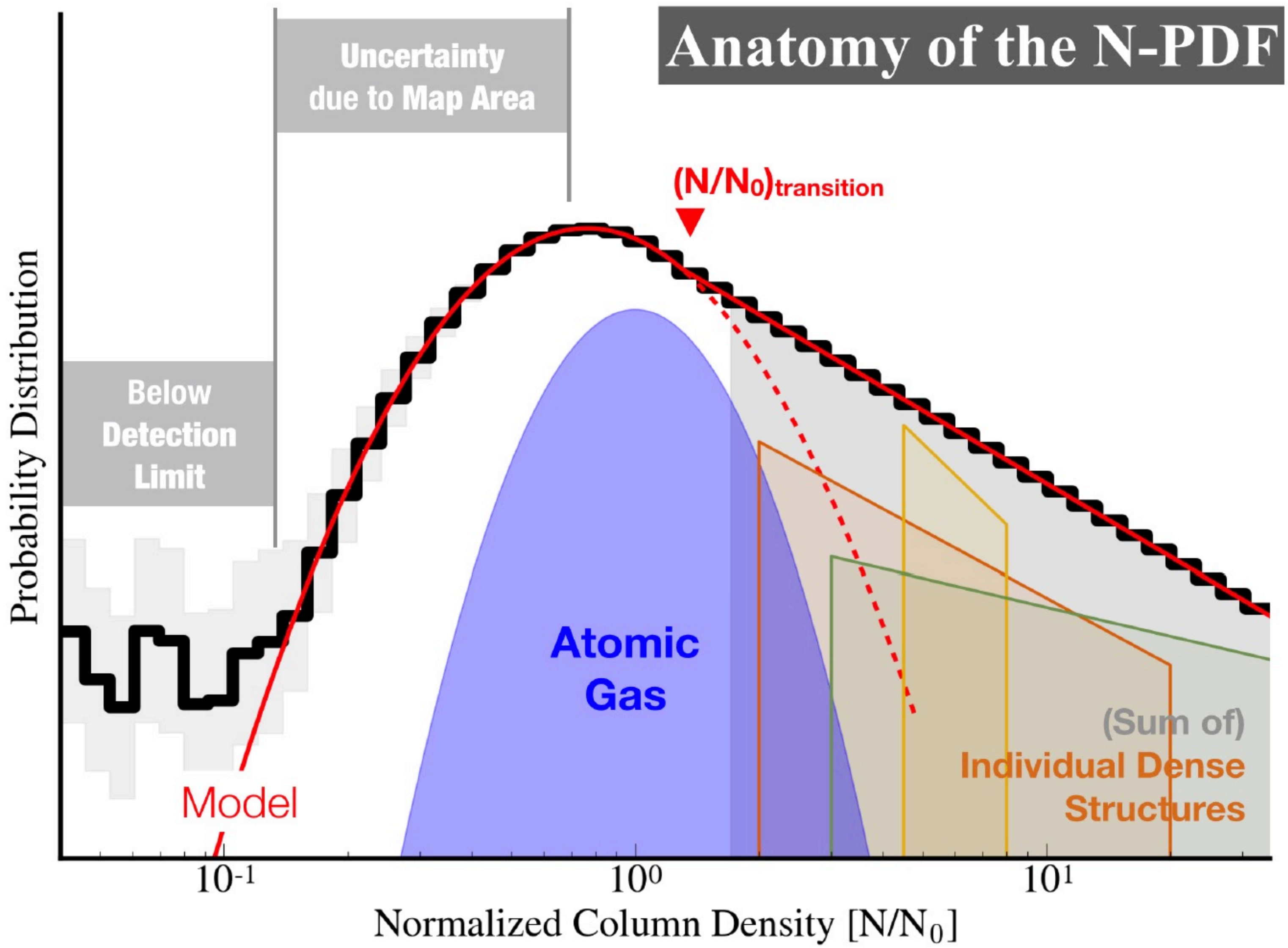
slide courtesy of Rowan Smith, from CfA-ITC talk, 2016
cf. Moeckl & Burkert 2015, work of Hacar et al…


"Taste-Testing"

Taste Test: Dendrogram Decomposition of Column Density PDF

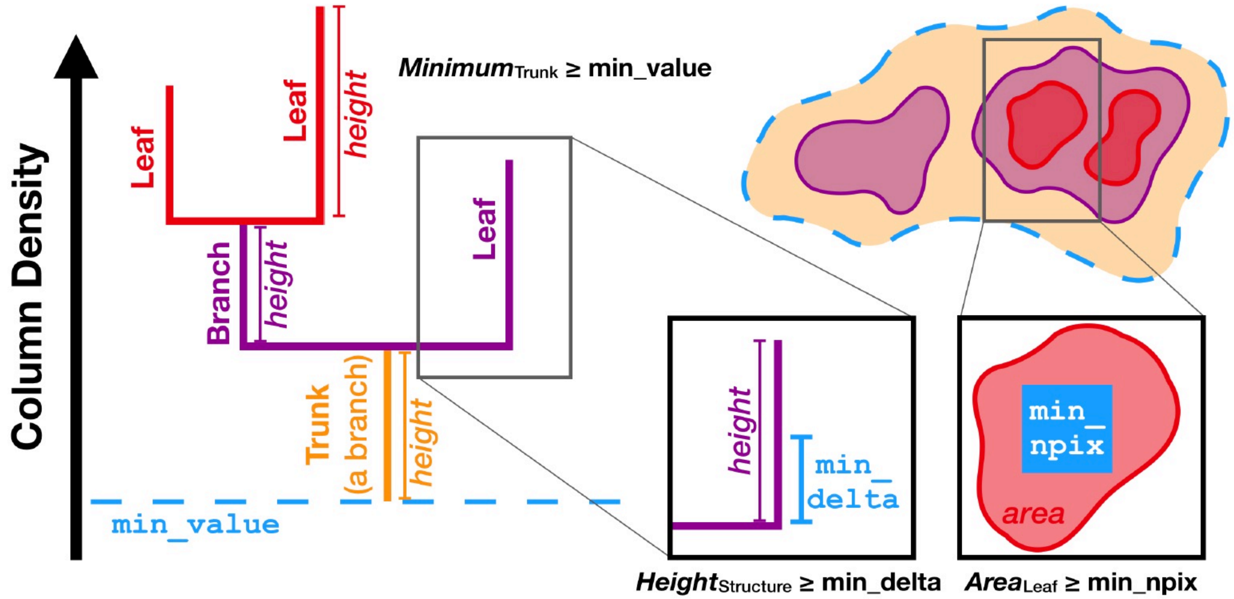
Chen, Burkhart, Goodman & Collins 2017

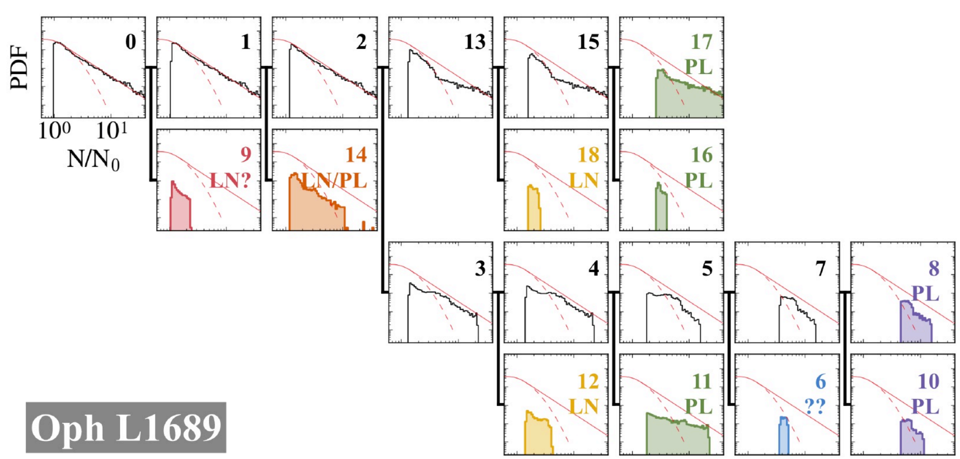
PDF=Probability Density (or Distribution) Function

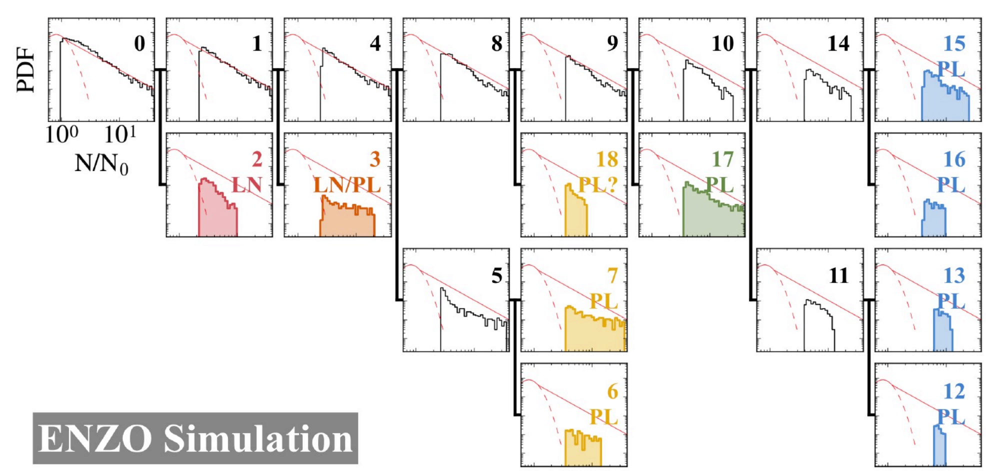


Taste Test: Dendrogram Decomposition of Column Density PDF

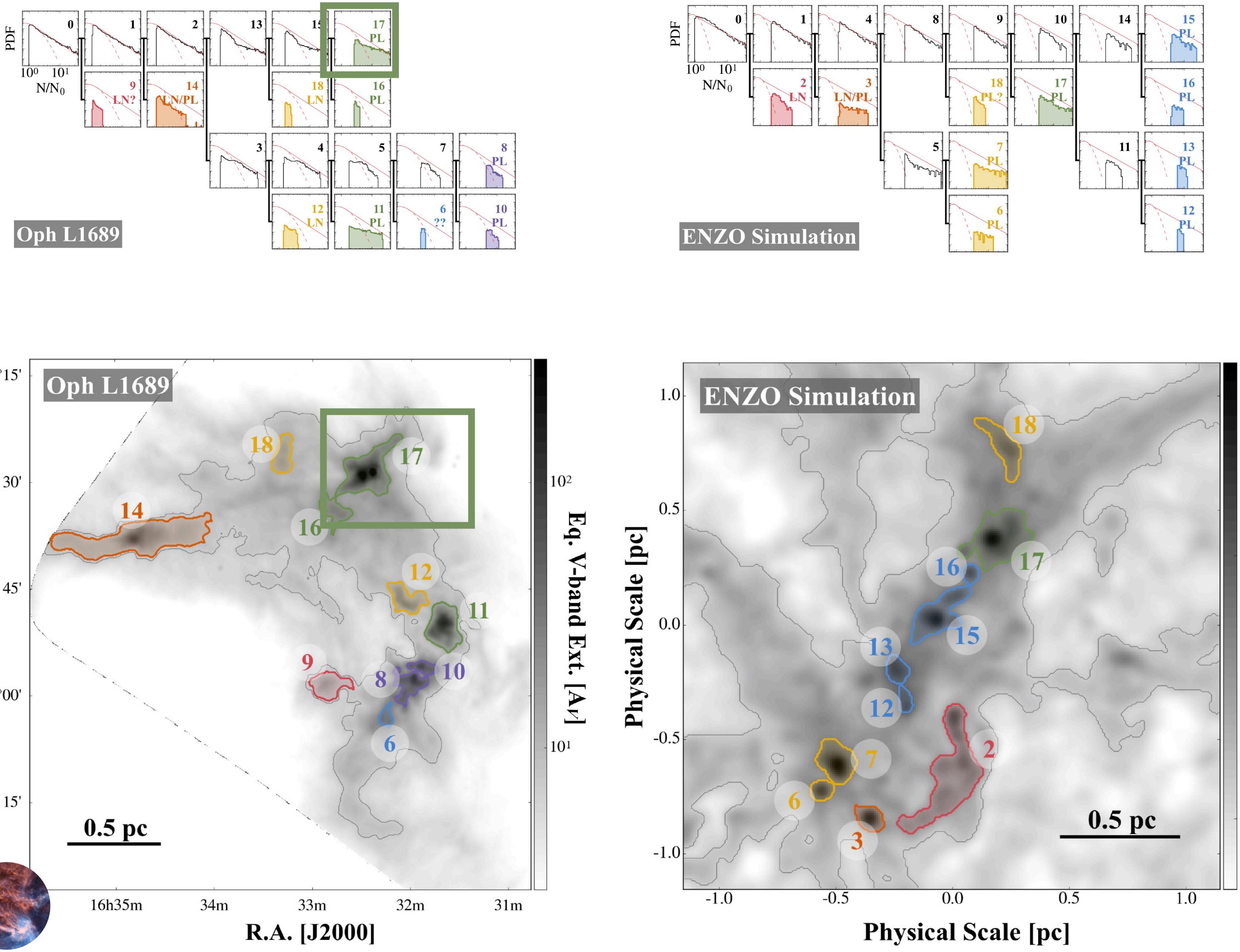
Chen, Burkhart, Goodman & Collins 2017





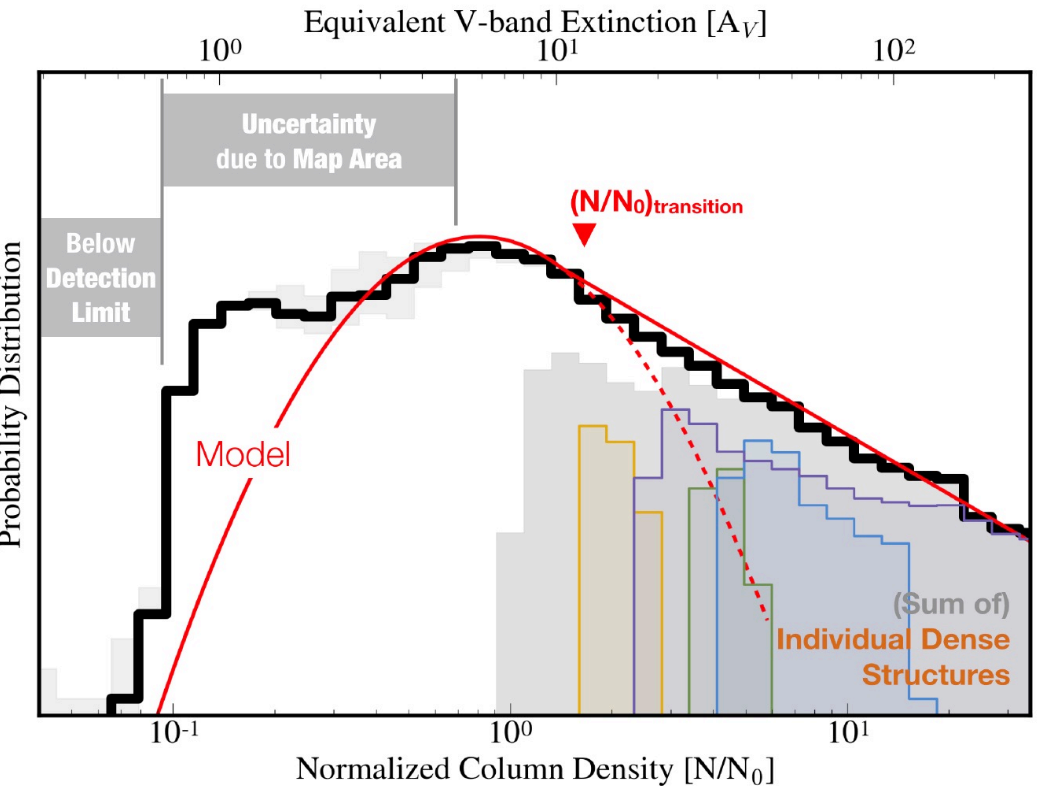


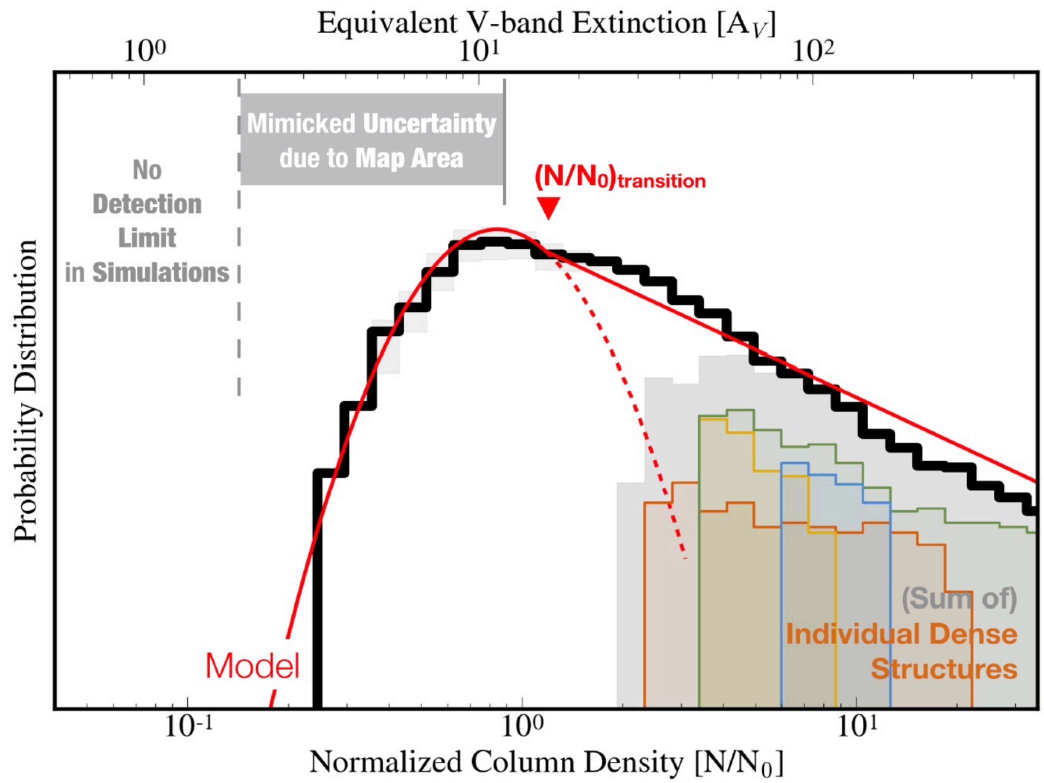

“L1689” in Ophiuchus

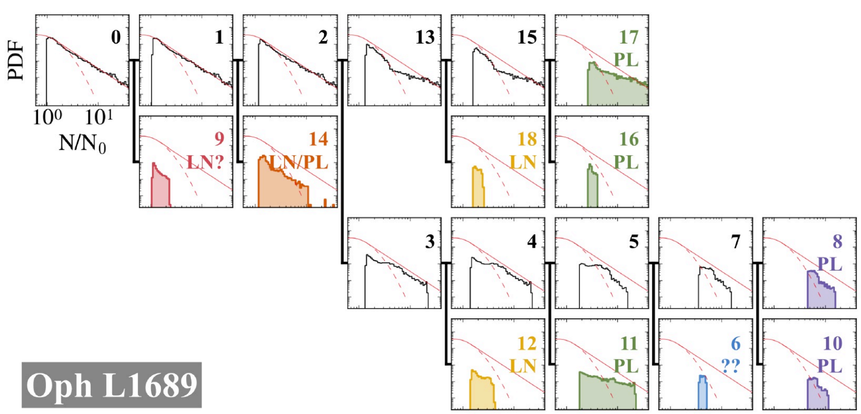


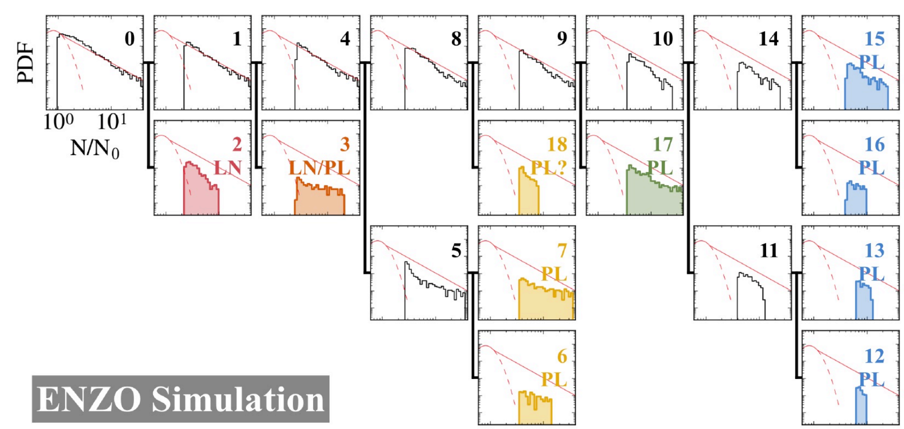
PDF
N/N$_0$
10^0 10^1
9 LN?
14 LN/PL
18 LN
16 PL
17 PL
12 LN
11 PL
6 ??
8 PL
10 PL
Oph L1689
2 LN
3 LN/PL
18 PL.?
17 PL
15 PL
16 PL
7 PL
6 PL
13 PL
12 PL
ENZO Simulation
Oph L1689
Dec. [J2000]
R.A. [J2000]
-24°15'
30'
45'
-25°00'
15'
16h35m
34m
33m
32m
31m
0.5 pc
Eq. V-band Ext. [A$_V$]
10^2
10^1
ENZO Simulation
Physical Scale [pc]
Physical Scale [pc]
-1.0
-0.5
0.0
0.5
1.0
0.5 pc
Eq. V-band Ext. [A$_V$]

Are the dense structures "cores"? Are they gravitationally bound?



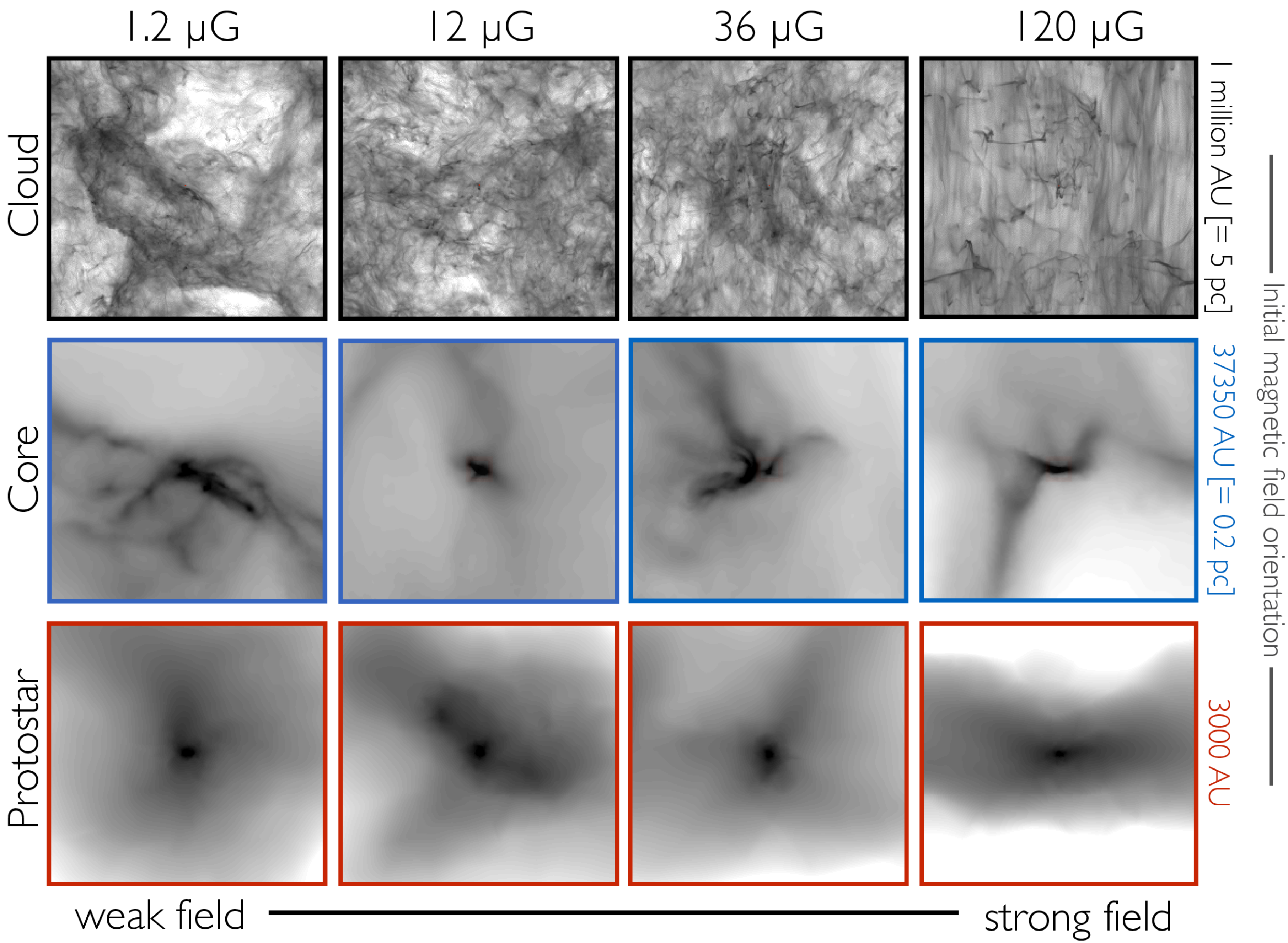




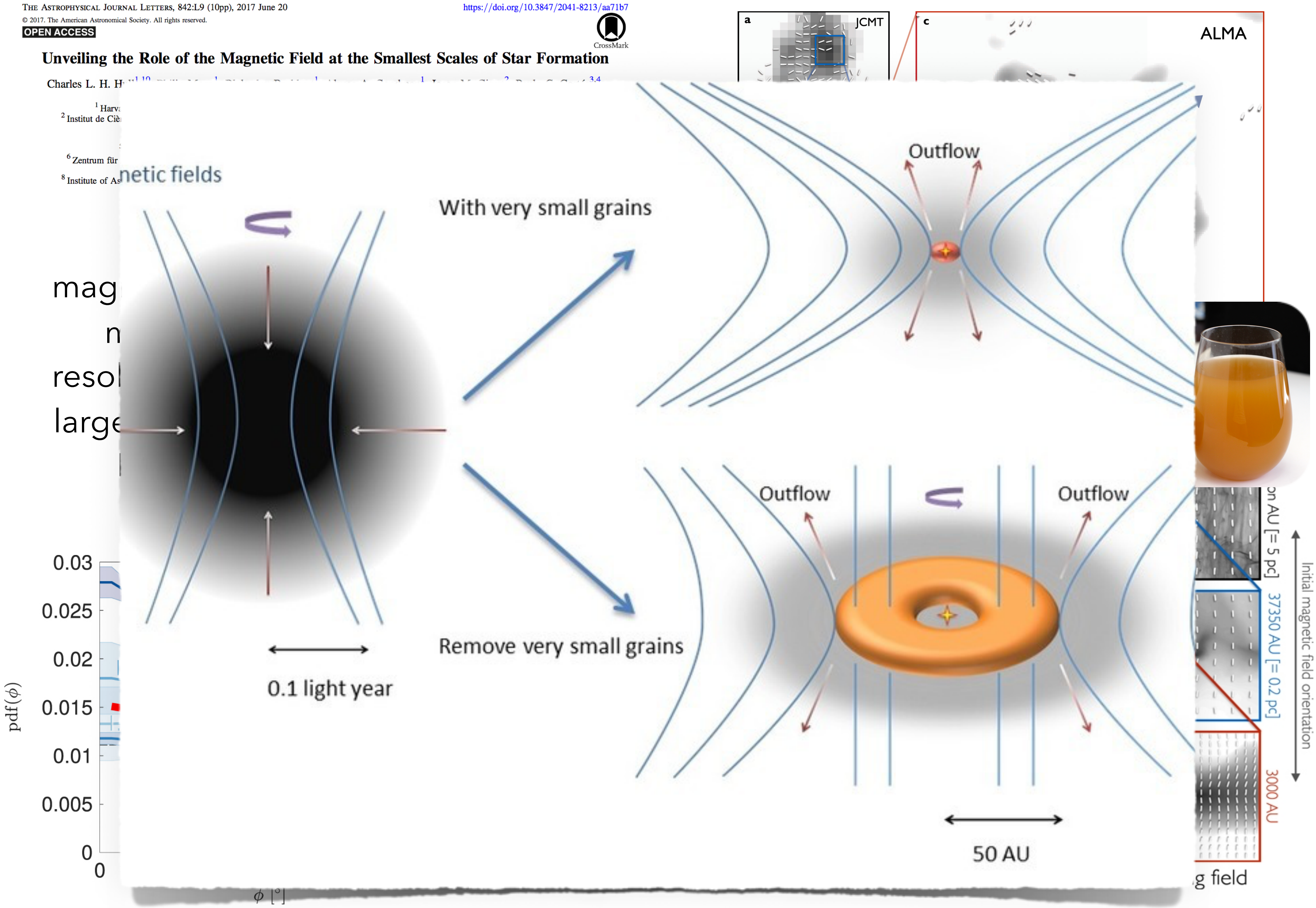


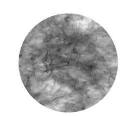
Chen, Burkhart, Goodman & Collins 2017

What, really, is a "dense core?"



Hull, Mocz, Burkhart, Goodman, Girart, Cortes, Hernquist, Springel, Li & Lai 2017.





Hull, Mocz, Burkhart, Goodman, Girart, Cortes, Hernquist, Springel, Li & Lai 2017.

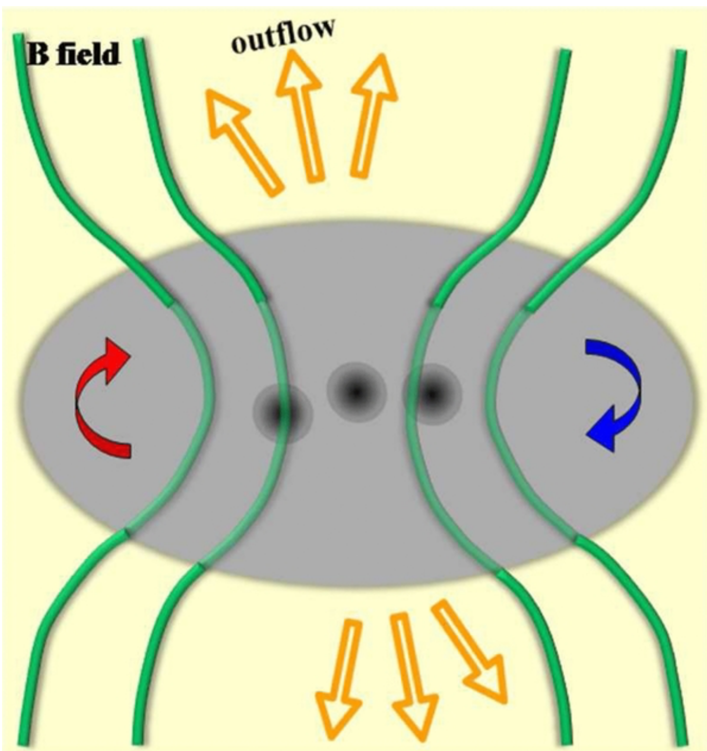
tinyurl.com/ApJ-B-Interactive

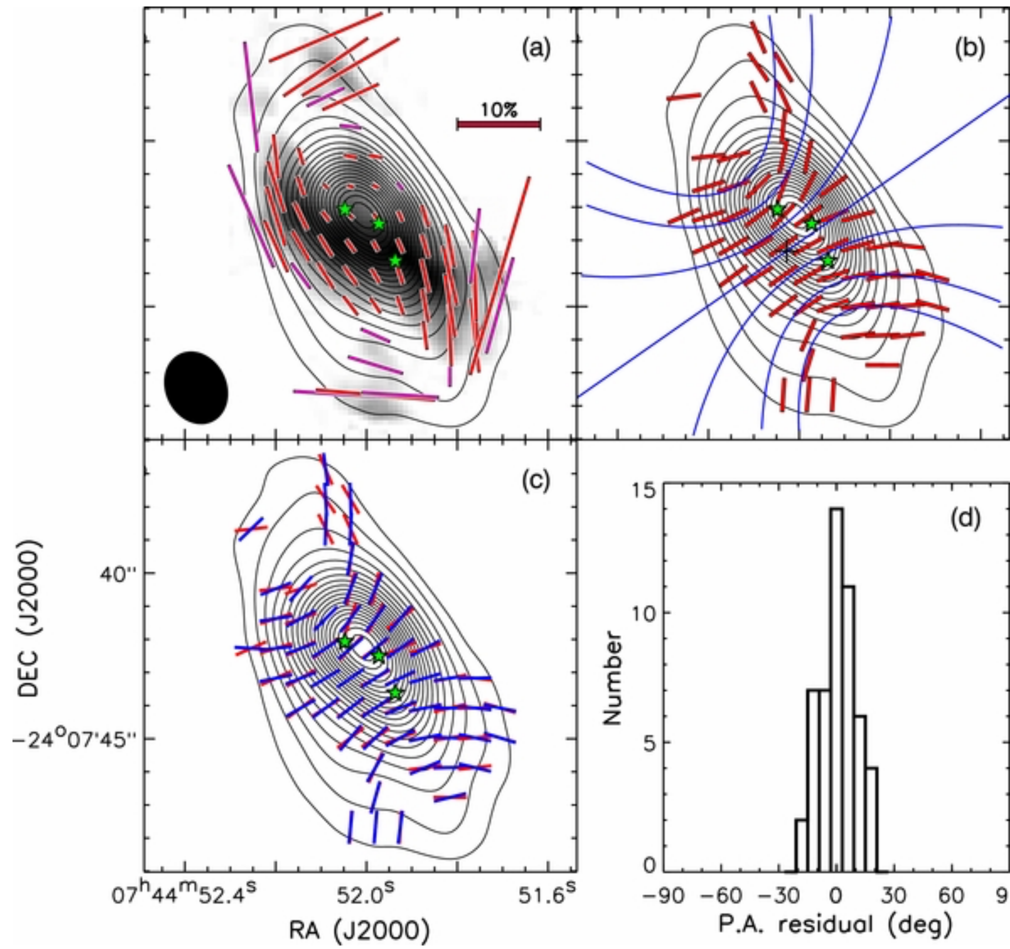
SUBMILLIMETER ARRAY OBSERVATIONS OF MAGNETIC FIELDS IN G240.31+0.07: AN HOURGLASS IN A MASSIVE CLUSTER-FORMING CORE

Keping Qiu[1,2], Qizhou Zhang[3], Karl M. Menten[4], Hauyu B. Liu[5], Ya-Wen Tang[5], and Josep M. Girart[6]

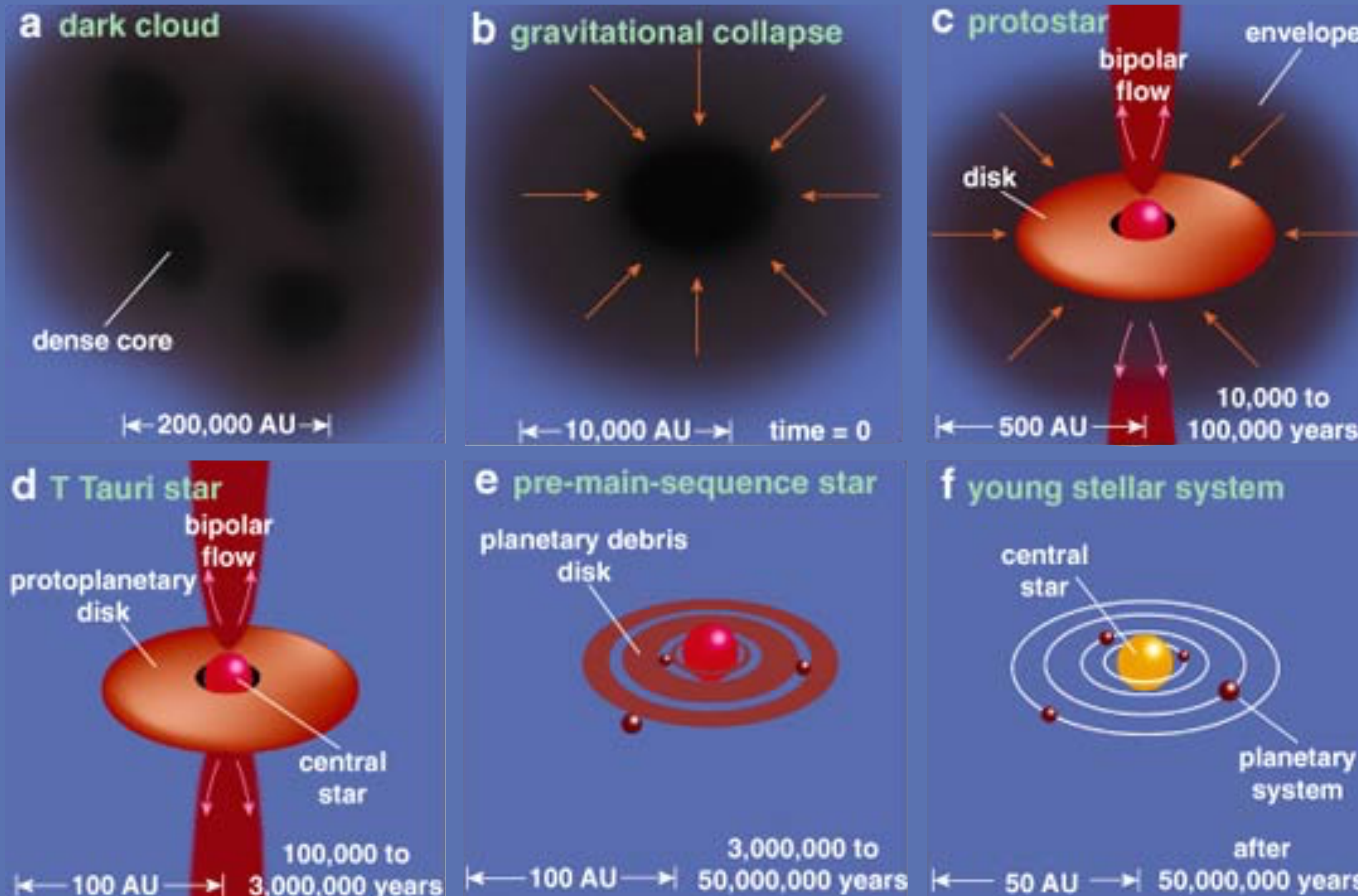
Published 2014 September 30 •

The Astrophysical Journal Letters, Volume 794, Number 1

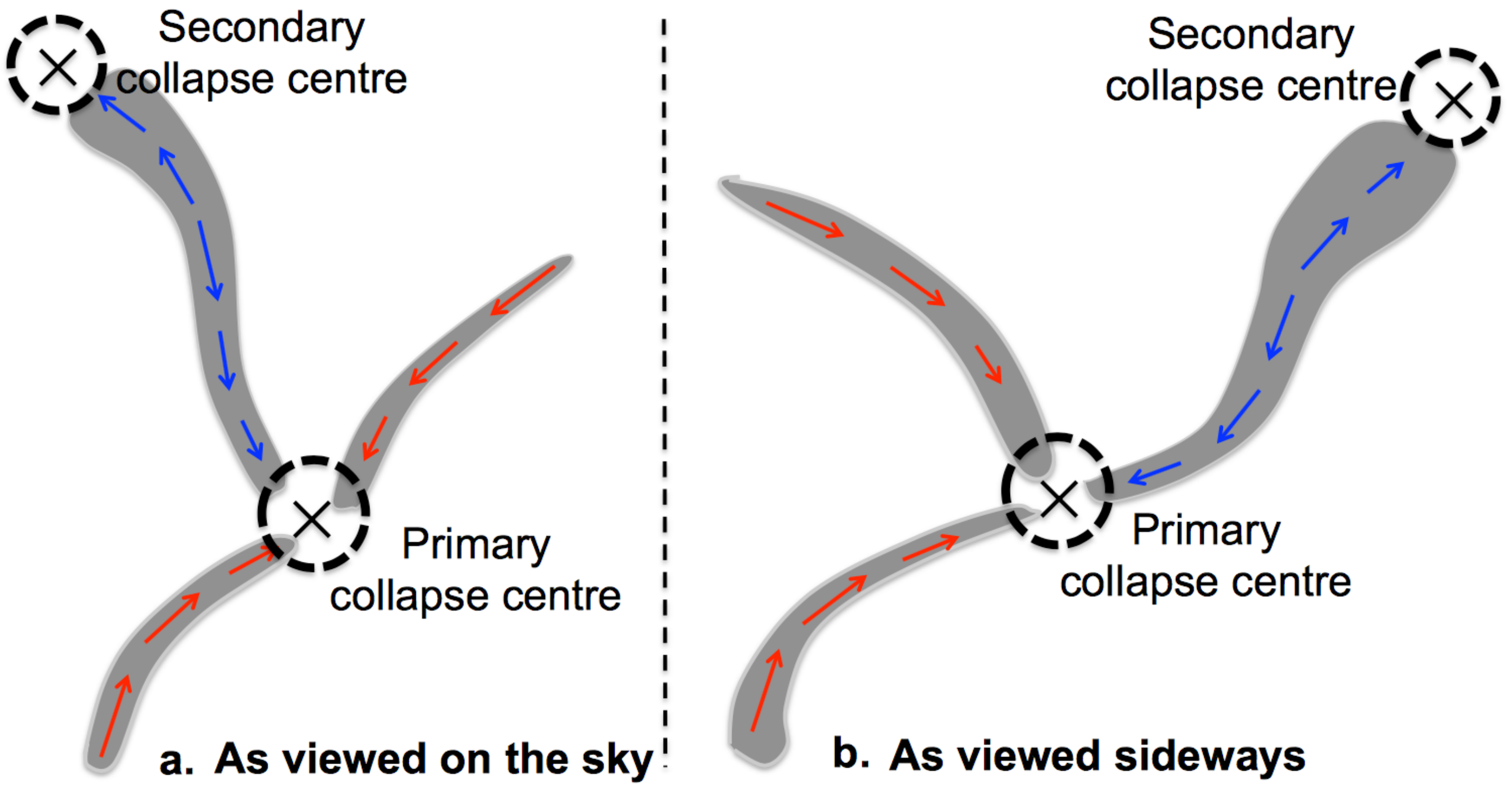




(When) does spherical collapse happen? Ever?

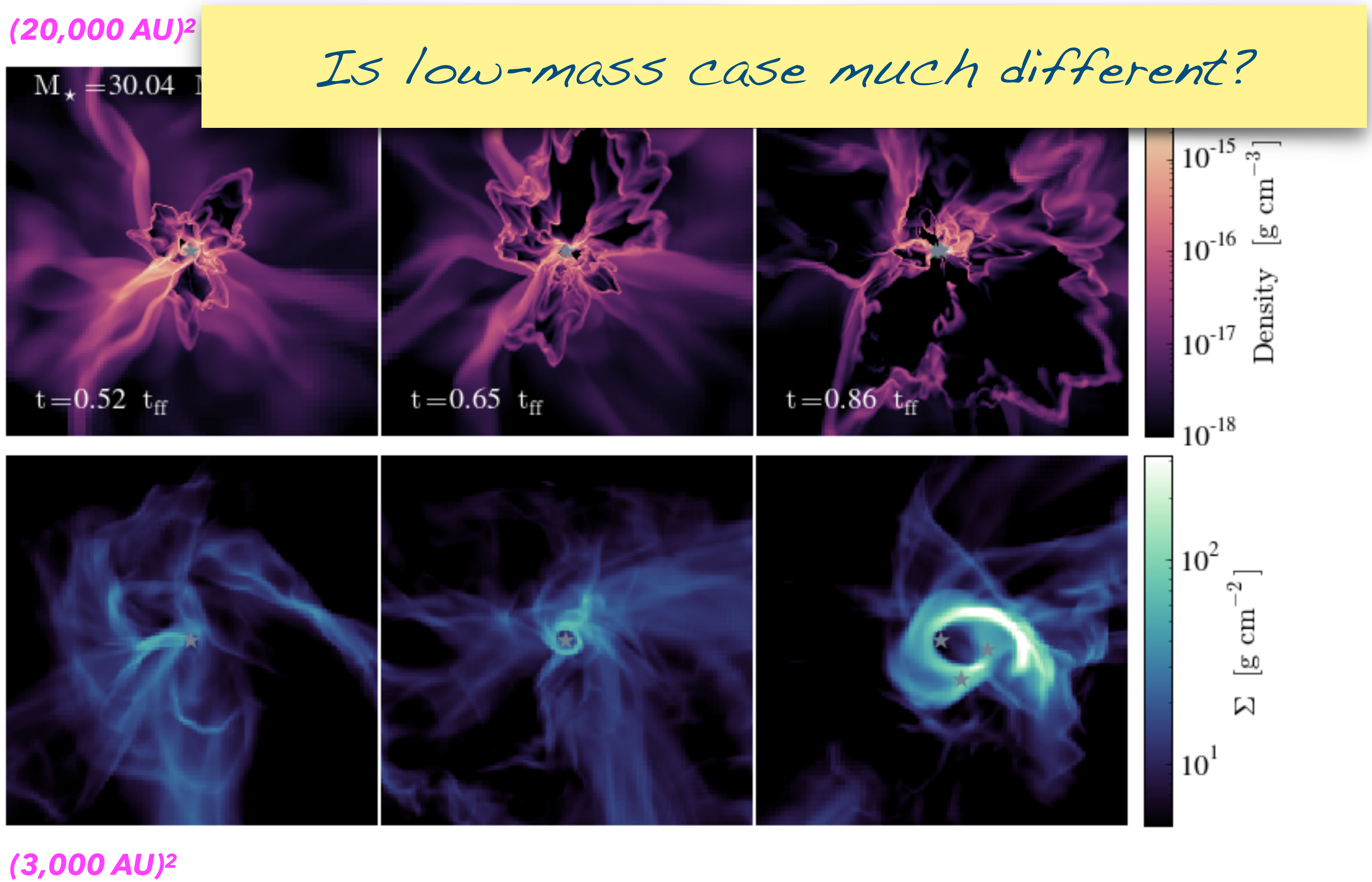


Is it all about non-spherical accretion in filaments & flows?



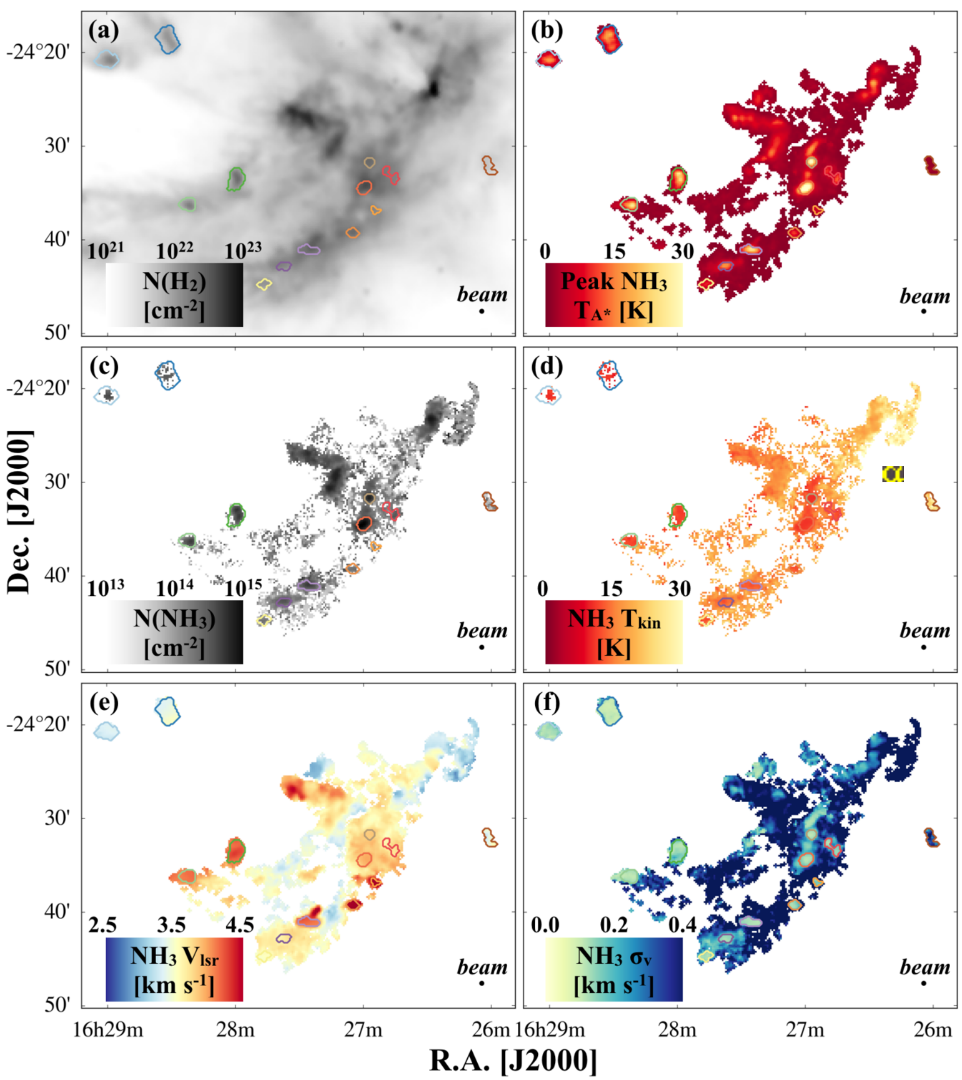
Peretto et al. 2014

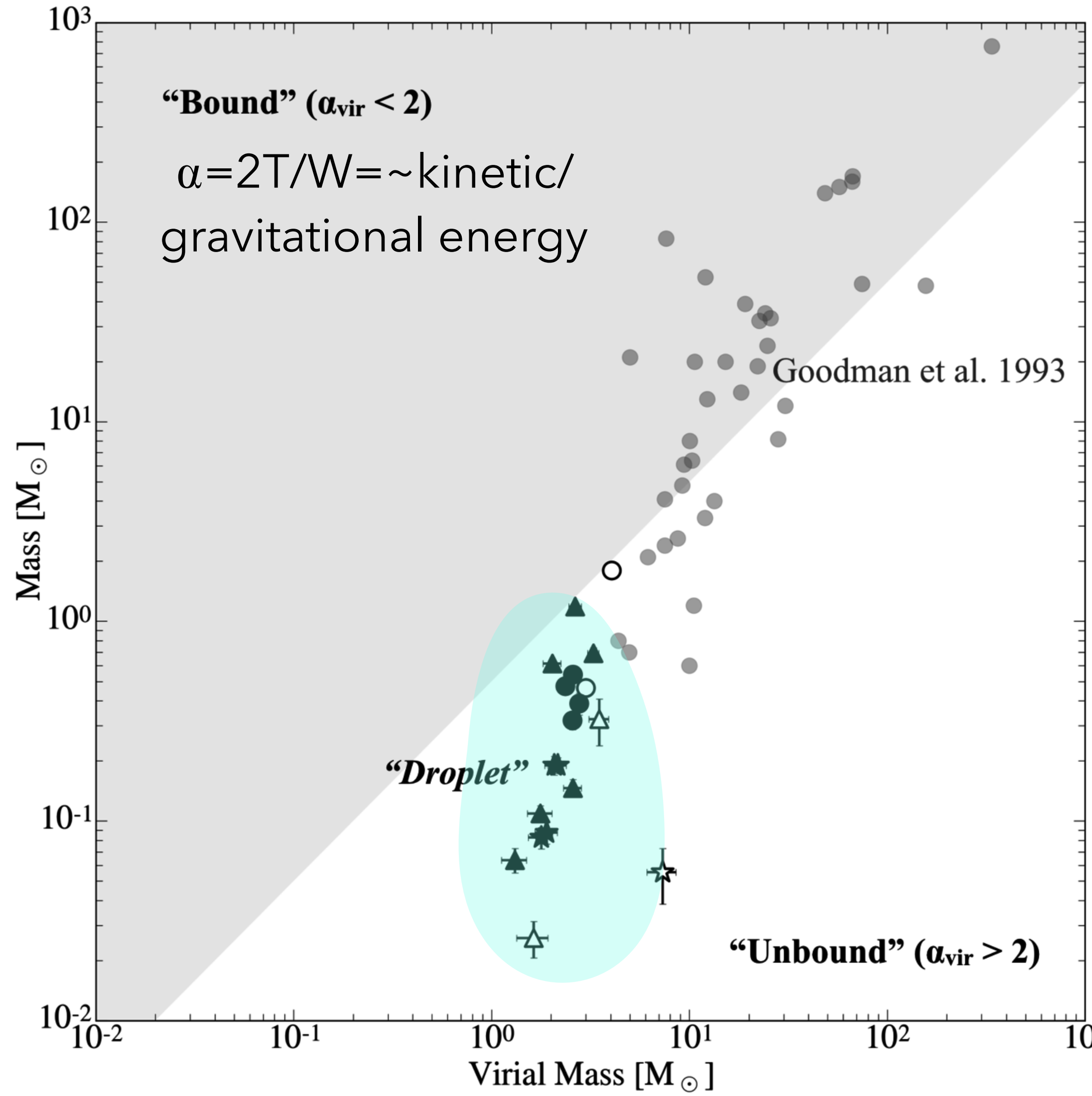
Mass delivered to (high-mass) star via infalling dense filaments, RT instabilities, and disk accretion. (Rosen et al. 2016)



What's next?

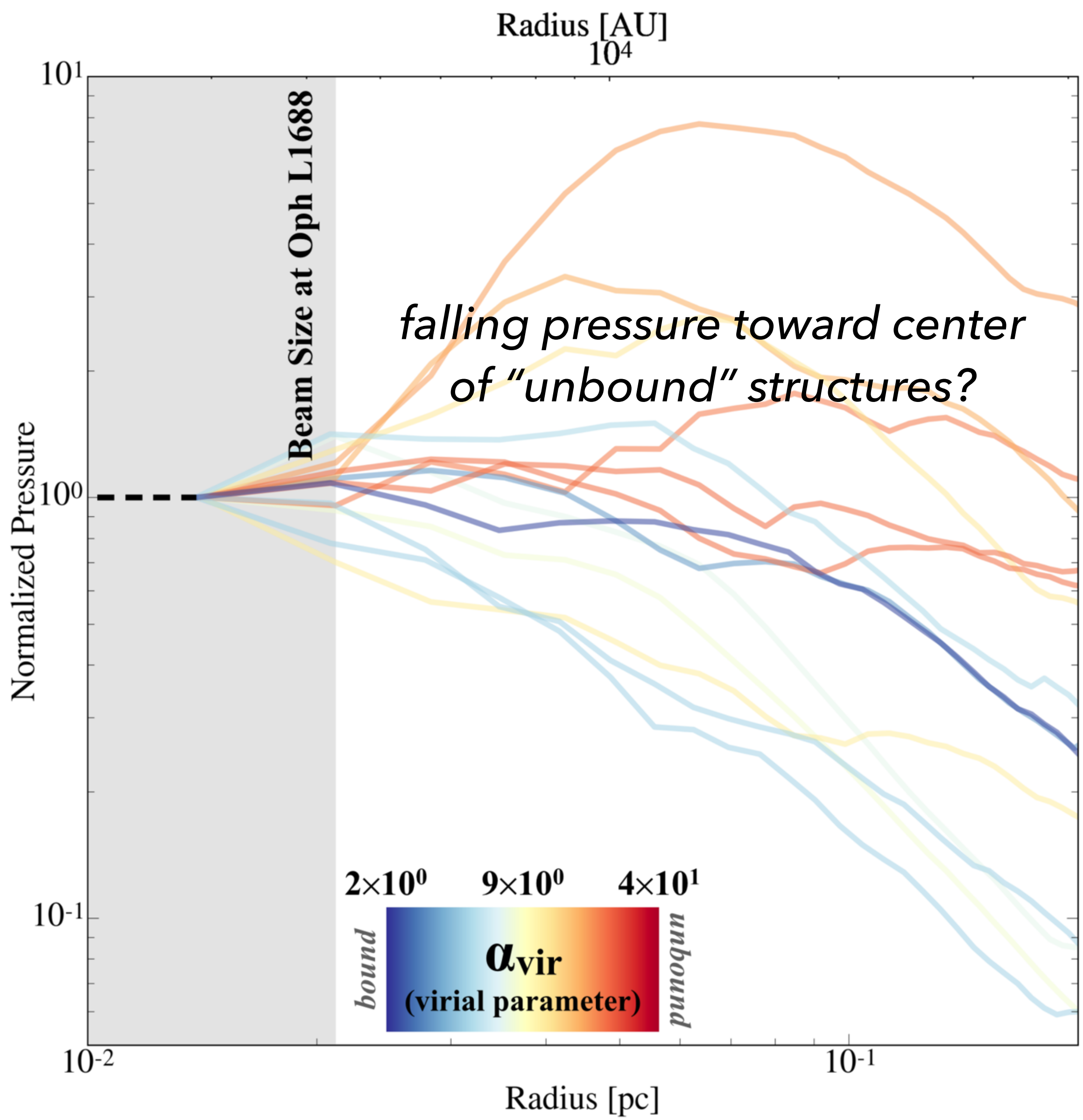
"Droplets"





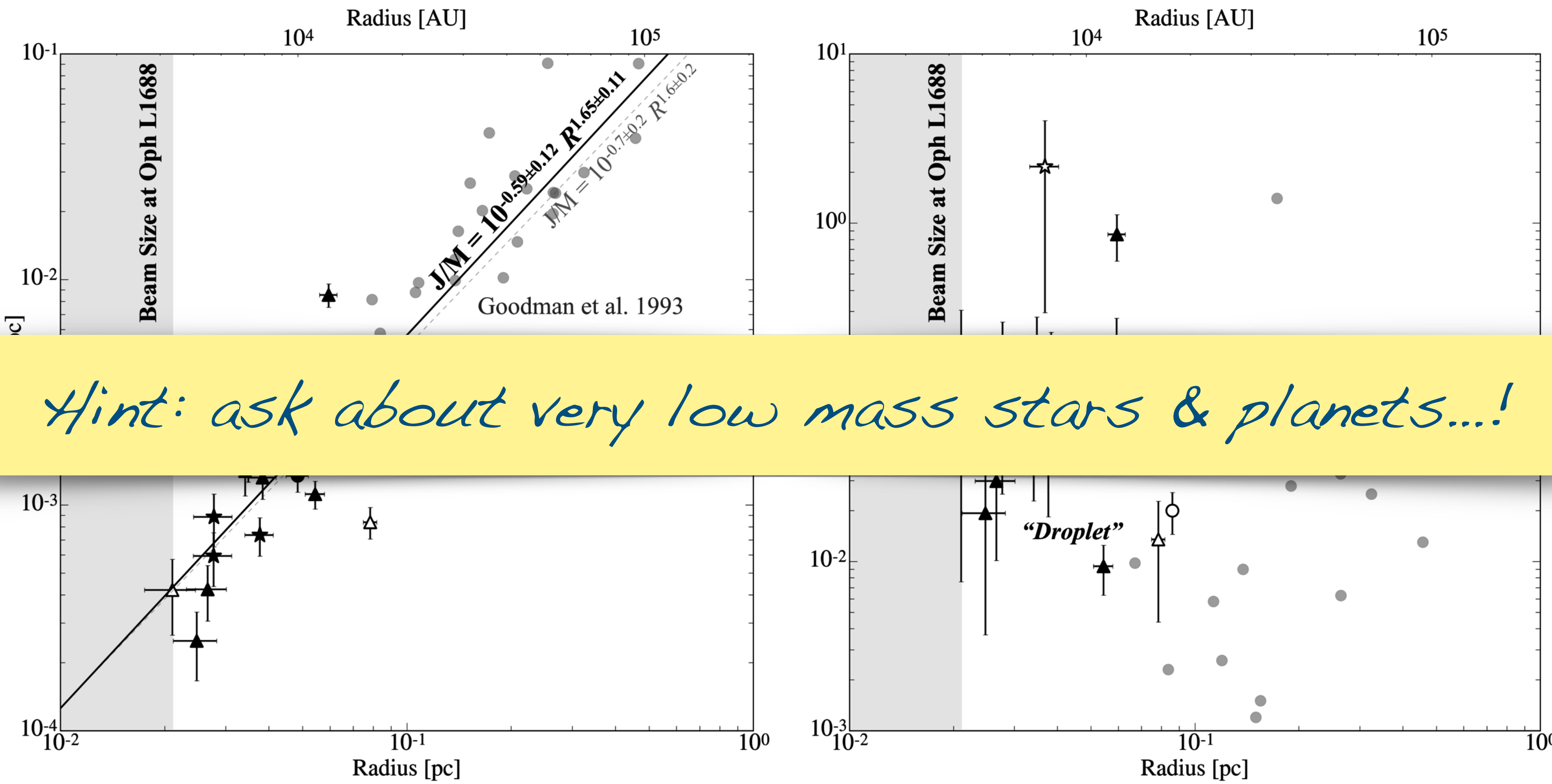
Chen, Burkert, Goodman & Pineda 2017, on Authorea ←*NOT the "dark" web!*

(Pressure Bound) "Droplets"



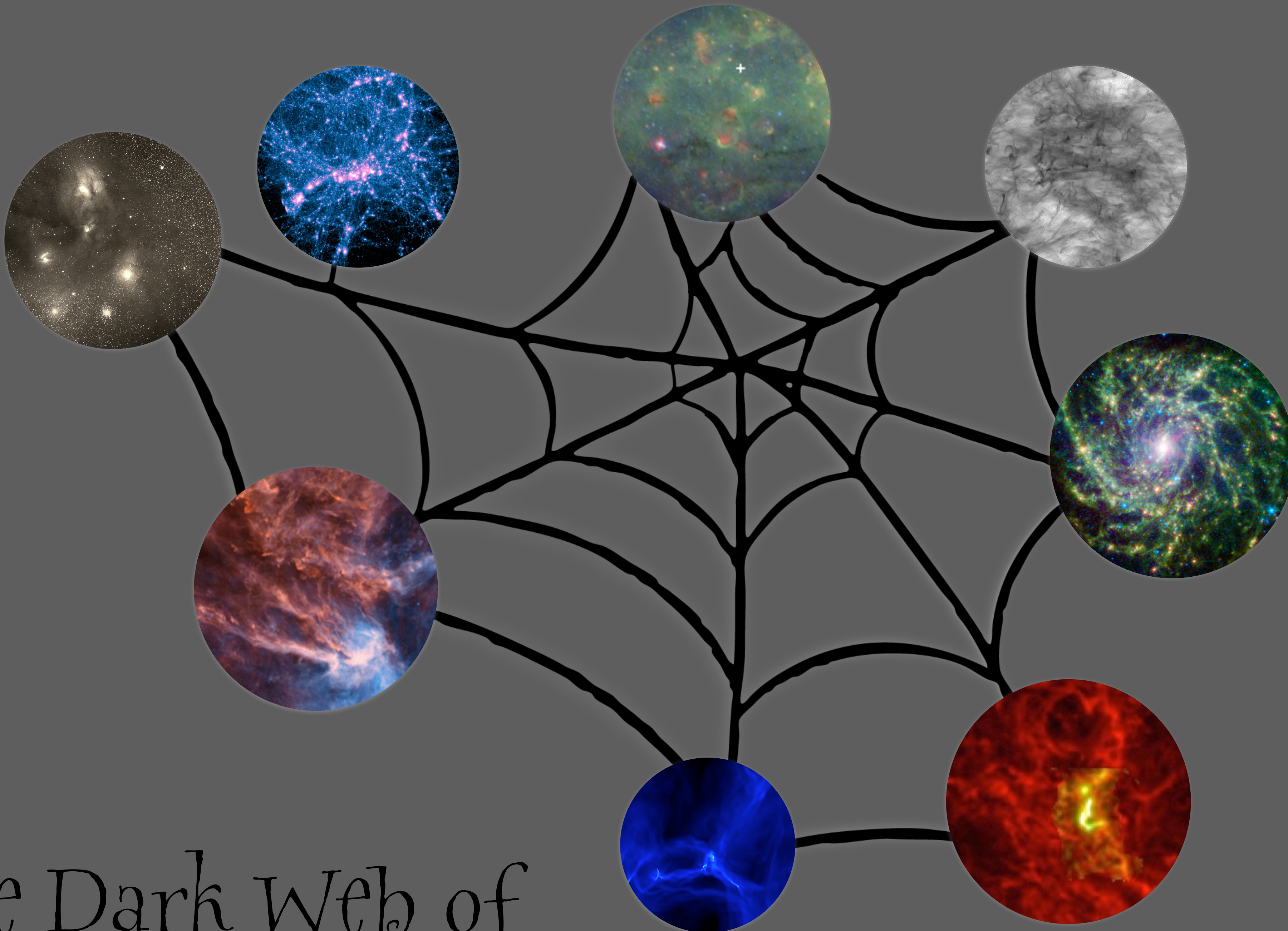
Chen, Burkert, Goodman & Pineda 2017, on Authorea ←*NOT the "dark" web!*

"Droplets"



Hint: ask about very low mass stars & planets…!

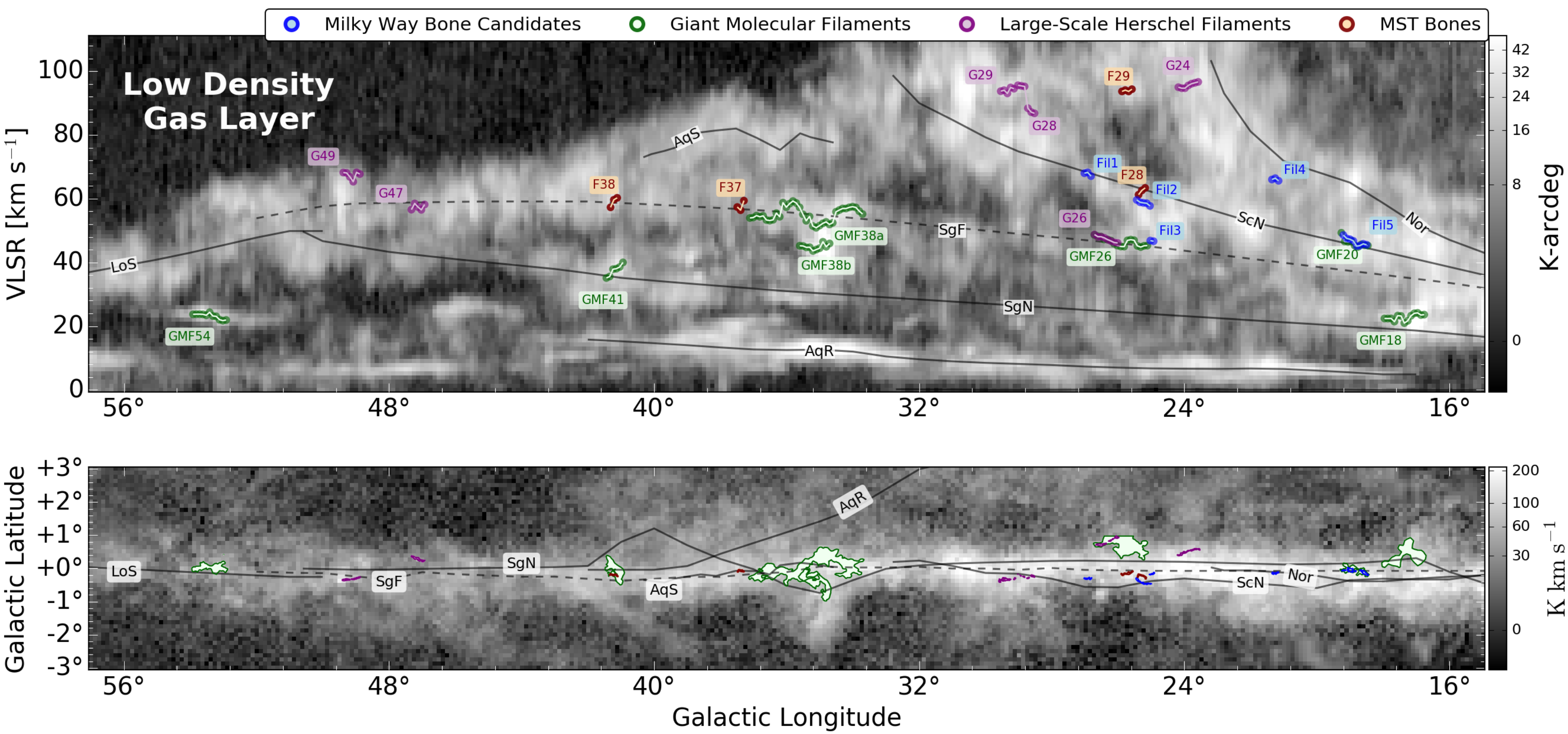
Chen, Burkert, Goodman & Pineda 2017, on Authorea ←*NOT the "dark" web!*



The Dark Web of Star Formation

Alyssa A .Goodman
Harvard-Smithsonian Center for Astrophysics
& Radcliffe Institute for Advanced Study

Preview of Thursday's Sequel… (Bones of) The Milky Way!



Zucker, Battersby & Goodman 2017


CHRISTIAN DOPPLER
1803 - 1853
PROFESSOR DER PHYSIK
AN DER UNIVERSITÄT WIEN
1850 - 1853
ERWIN
SCHRÖDINGE
1887 1961
$i\hbar\dot{\psi} = H\psi$

THE ASTROPHYSICAL JOURNAL, **231**:77–94, 1979 July 1

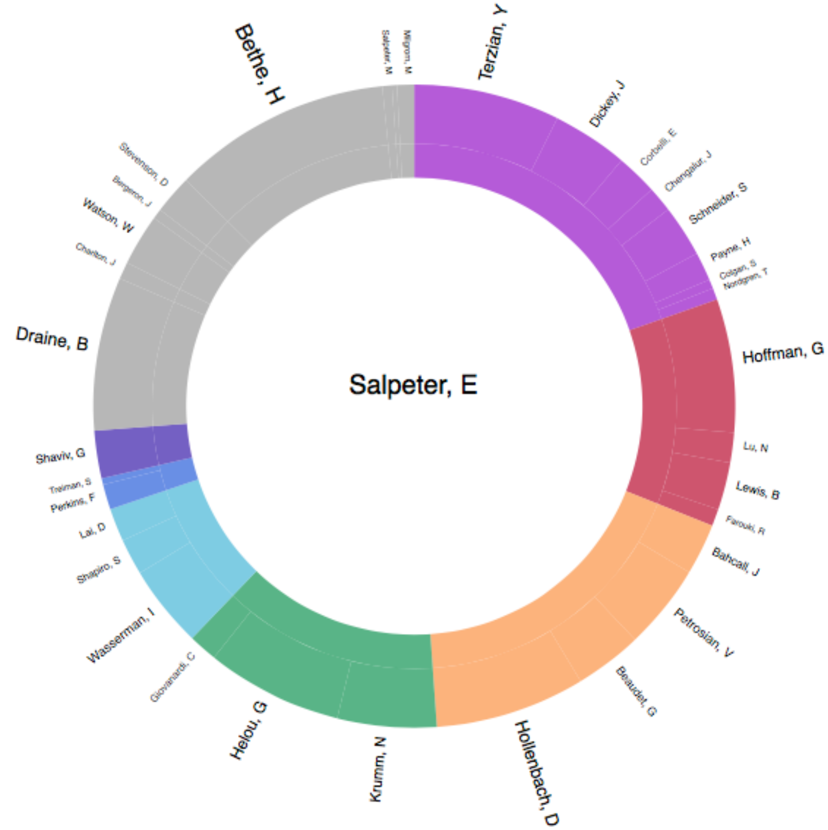
ON THE PHYSICS OF DUST GRAINS IN HOT GAS

B. T. DRAINE
Harvard-Smithsonian Center for Astrophysics
AND
E. E. SALPETER
Departments of Astronomy and Physics, Cornell University
Received 1978 August 7; accepted 1979 January 8

ABSTRACT

Charging of dust grains in hot (10^4–10^9 K) plasma is studied, including photoelectron and secondary electron emission, field emission, and transmission of electrons and ions through the grain; resulting grain potentials are (for $T \gtrsim 10^5$ K) considerably smaller in magnitude than found by Burke and Silk. Even so, large electrostatic stresses can cause ion field emission and rapid destruction of small grains in very hot gas. Rapid rotation can also disrupt small grains, but damping (by microwave emission) usually limits the centrifugal stress to acceptable values for plasma densities $n_H \lesssim 1$ cm^{-3}. Sputtering rates are estimated for grains in hot gas, based upon a semiempirical fit to experimental data. Predicted sputtering rates for possible grain constituents are similar to estimates by Barlow, but in some cases differ significantly. Useful approximation formulae are given for the drag forces acting on a grain with arbitrary Mach number.

Subject headings: interstellar: matter — plasmas



THE ASTROPHYSICAL JOURNAL, **163**:155–164, 1971 January 1

SURFACE RECOMBINATION OF HYDROGEN MOLECULES

DAVID HOLLENBACH
Harvard College Observatory, Cambridge, Massachusetts
AND
E. E. SALPETER
Laboratory of Nuclear Studies, Cornell University, Ithaca, New York
Received 1970 March 24; revised 1970 June 3

ABSTRACT

In this paper we reexamine the problem of the formation of molecular hydrogen on the surfaces of dust grains. We discuss a "recombination efficiency" $\gamma'(T)$, the fraction of adsorbed atoms which form molecules before evaporating from a surface, as a function of the surface temperature T. For grains with a perfectly regular surface, γ' would be small at grain temperatures exceeding about 13° K. We consider an irregular surface with some lattice-defect or impurity sites having enhanced adsorption energies for atomic hydrogen. Our main result is that even a small number of such sites can greatly extend the range of temperatures over which the efficiency of molecular formation is high. On realistic grains, $\gamma' \simeq 1$ for all $T < T_{tr}$, where T_{tr} is some critical value between 25° and 50° K. Since all dust grains in H I regions are likely to be cooler than T_{tr}, we conclude that $\gamma' = 1$ for molecular formation on grains in H I regions.

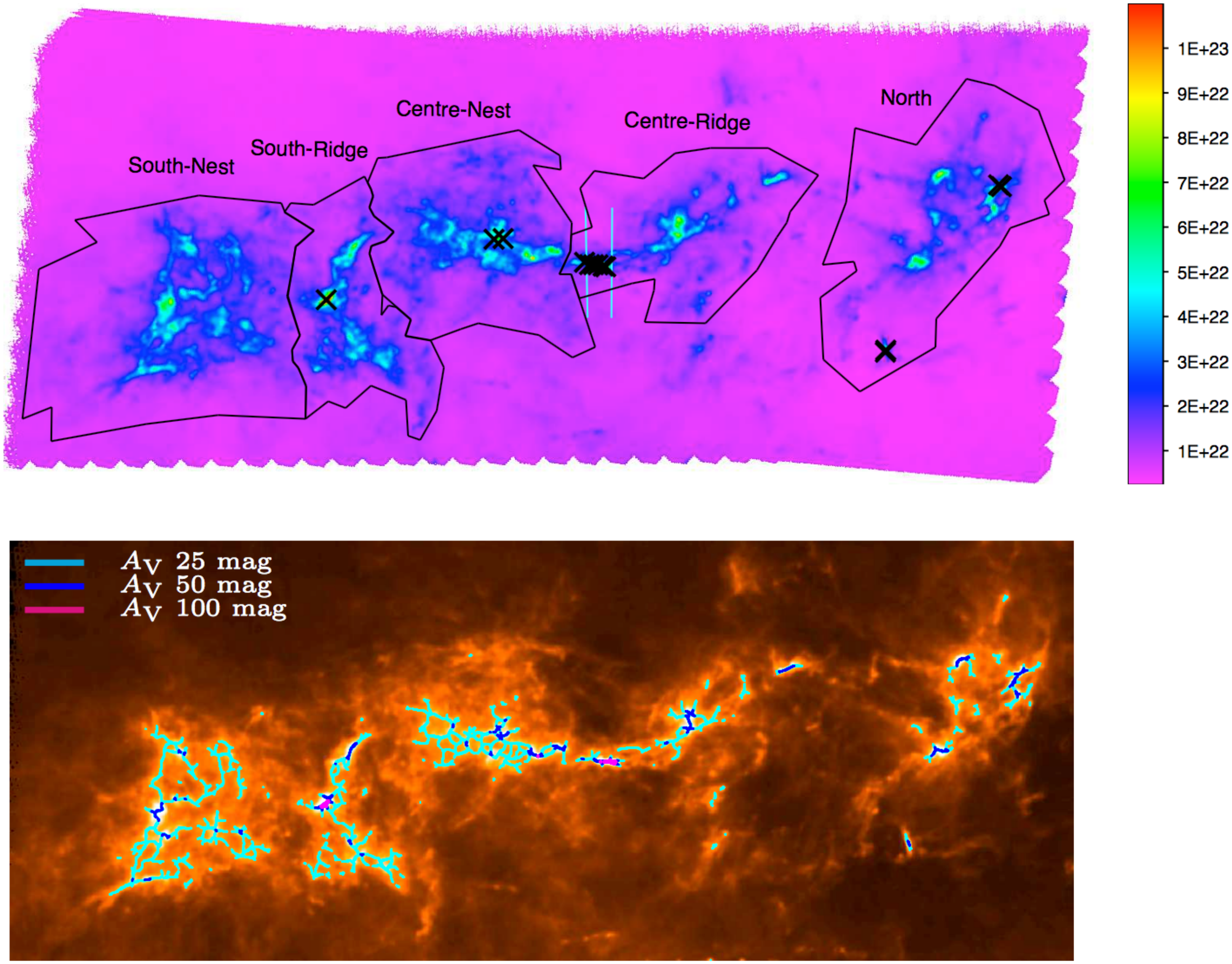
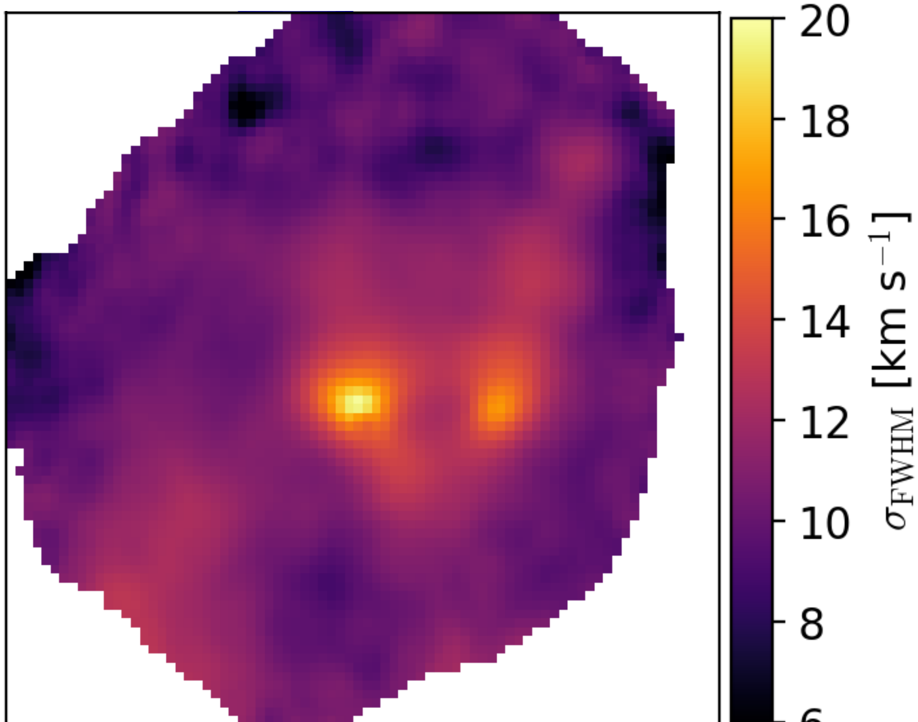


Figure 1: Top: Column Density map with sub-regions, as defined at an $A_V > 7$ mag, overlaid. The black crosses are the 13 most massive sources with (S:N$>$ 50, and Mass 20–60$M_\odot$). Bott Column density with the filamentary structure detected by DisPerSE. Ridges appear mage

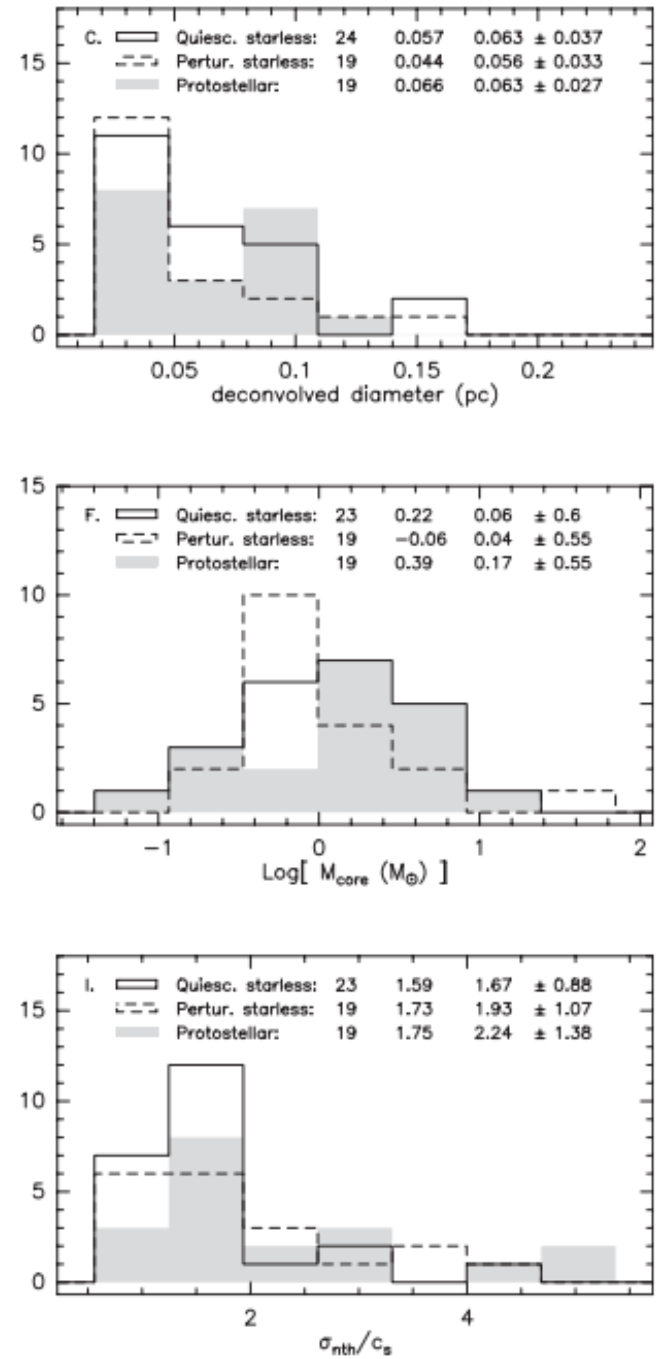
Slides from Anna re: isolated massive star formation from the collapse of a turbulent core (with hybrid radiative transfer).

…but star forming cores are turbulent



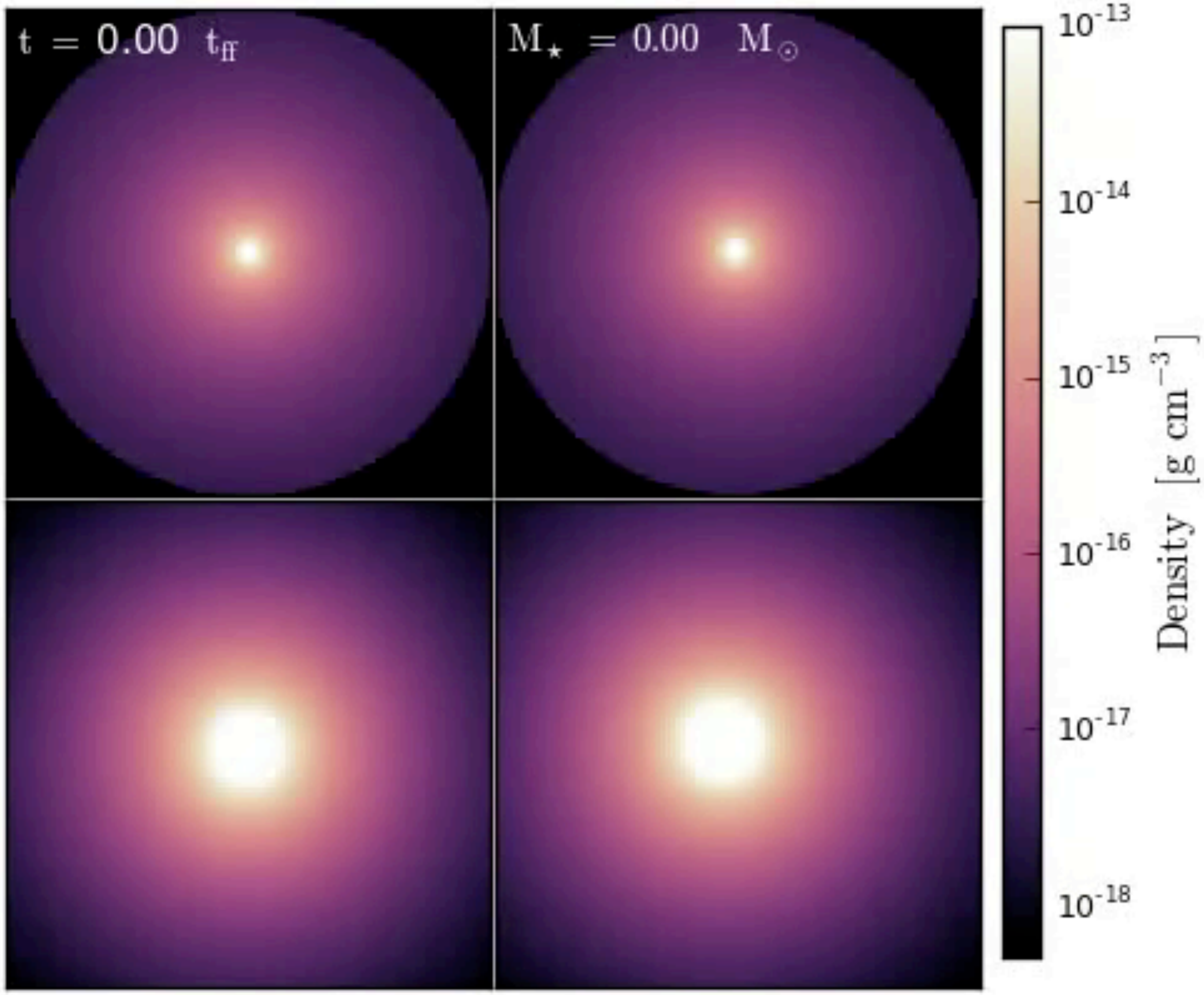
Ginsburg+2017

Turbulence should be initial seeds for RT instabilities.



Sanchez-Monge+2013

Collapse of turbulent core with *HARM*$_2$



Rosen+2016

Top panel: (40,000 AU x 40,000 AU)

Bottom panel: (8,000 AU x 8,000 AU)

Initial Conditions:

M_{core}=150 $M_\odot$

R_{core}=0.1 pc

$\rho(r)\propto r^{-3/2}$

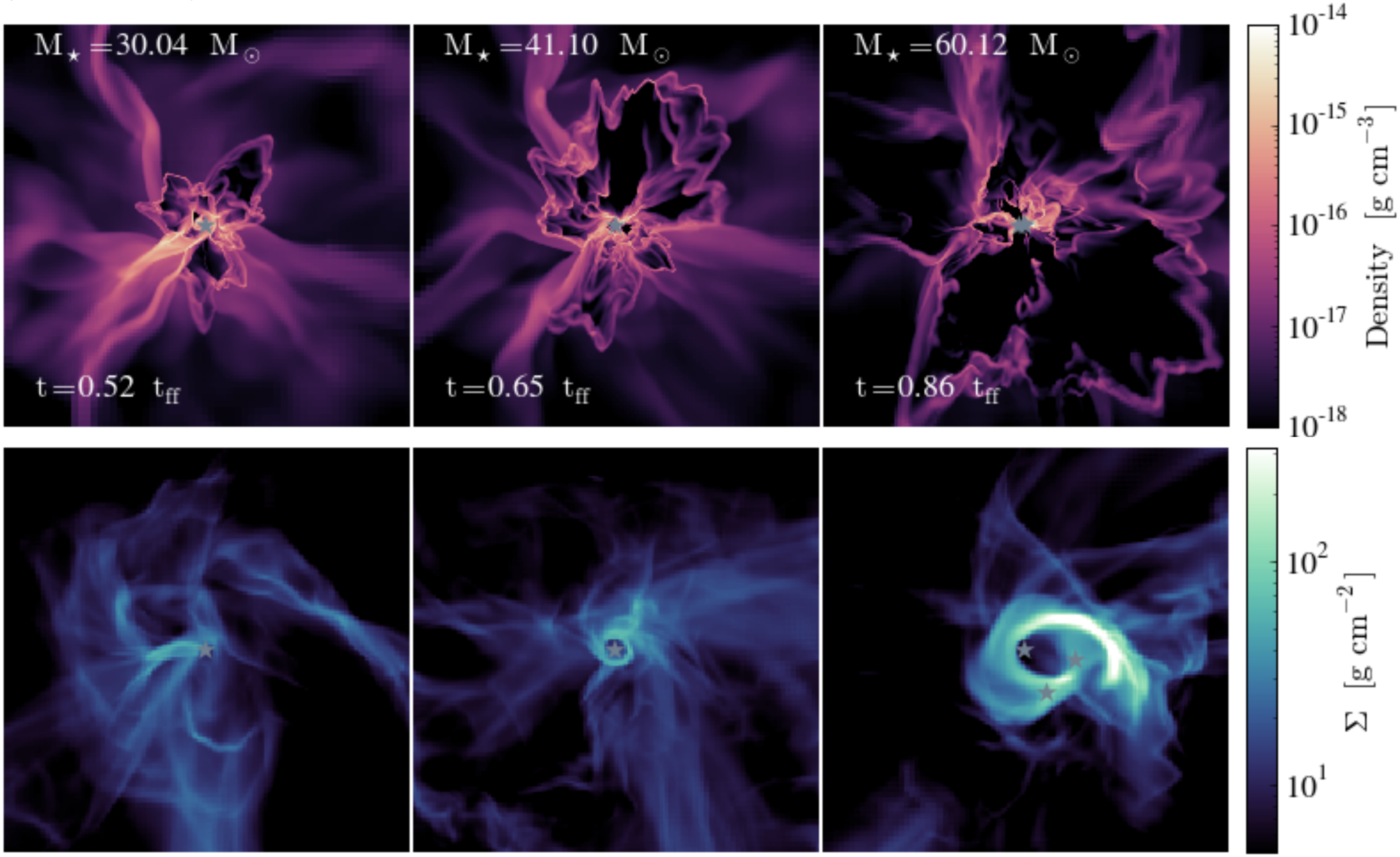
σ_{1D}=0.4 km s^{-1}

Δx_{min}=20 AU

t_{ff}=42,710 yrs

Mass delivered to star via infalling dense filaments, RT instabilities, and disk accretion.

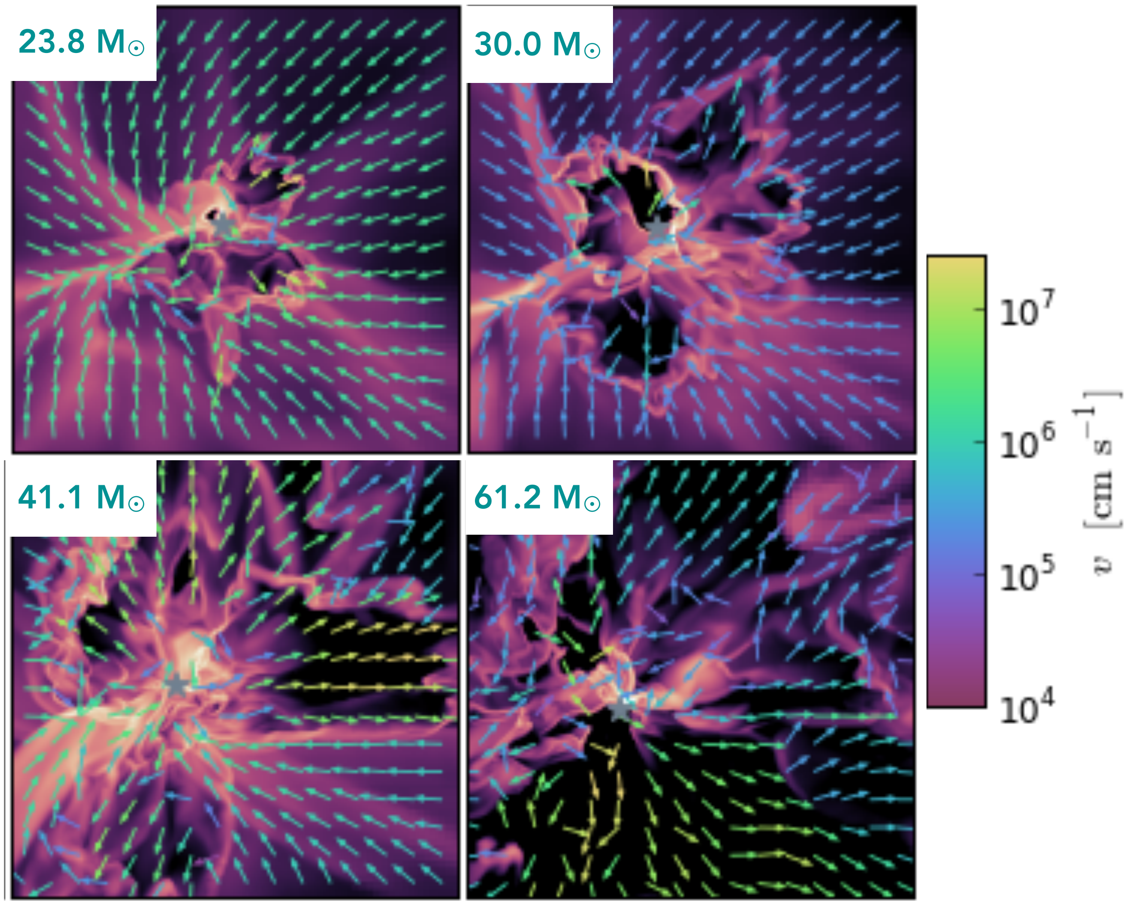
(20,000 AU)²



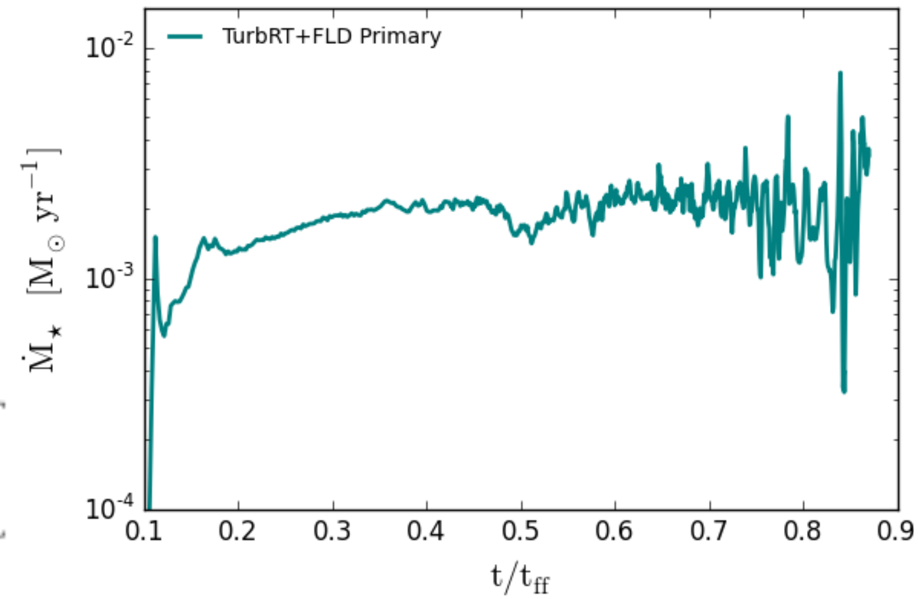
Rosen+2016

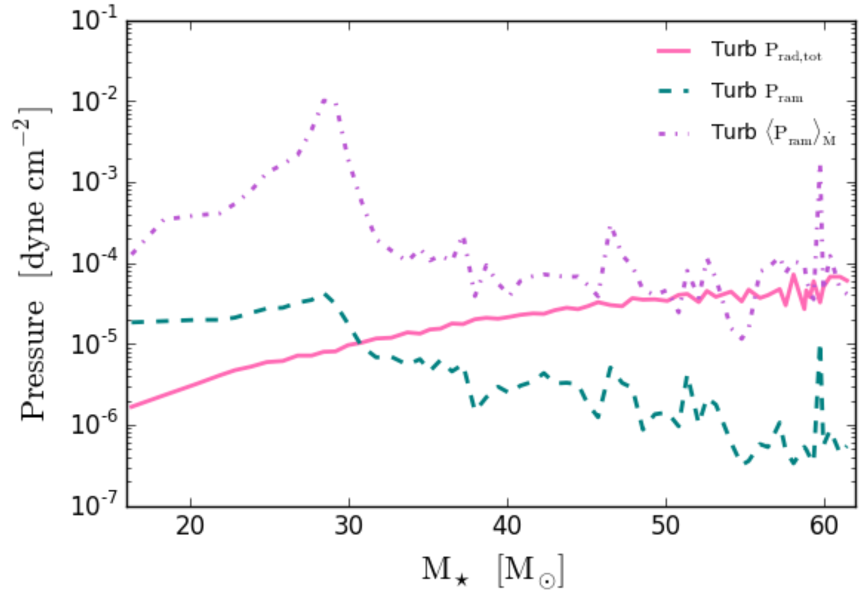
(3,000 AU)²

High accretion rates and infalling filaments provide sufficient ram pressure to overcome radiation pressure.



$(10,000\ AU)^2$

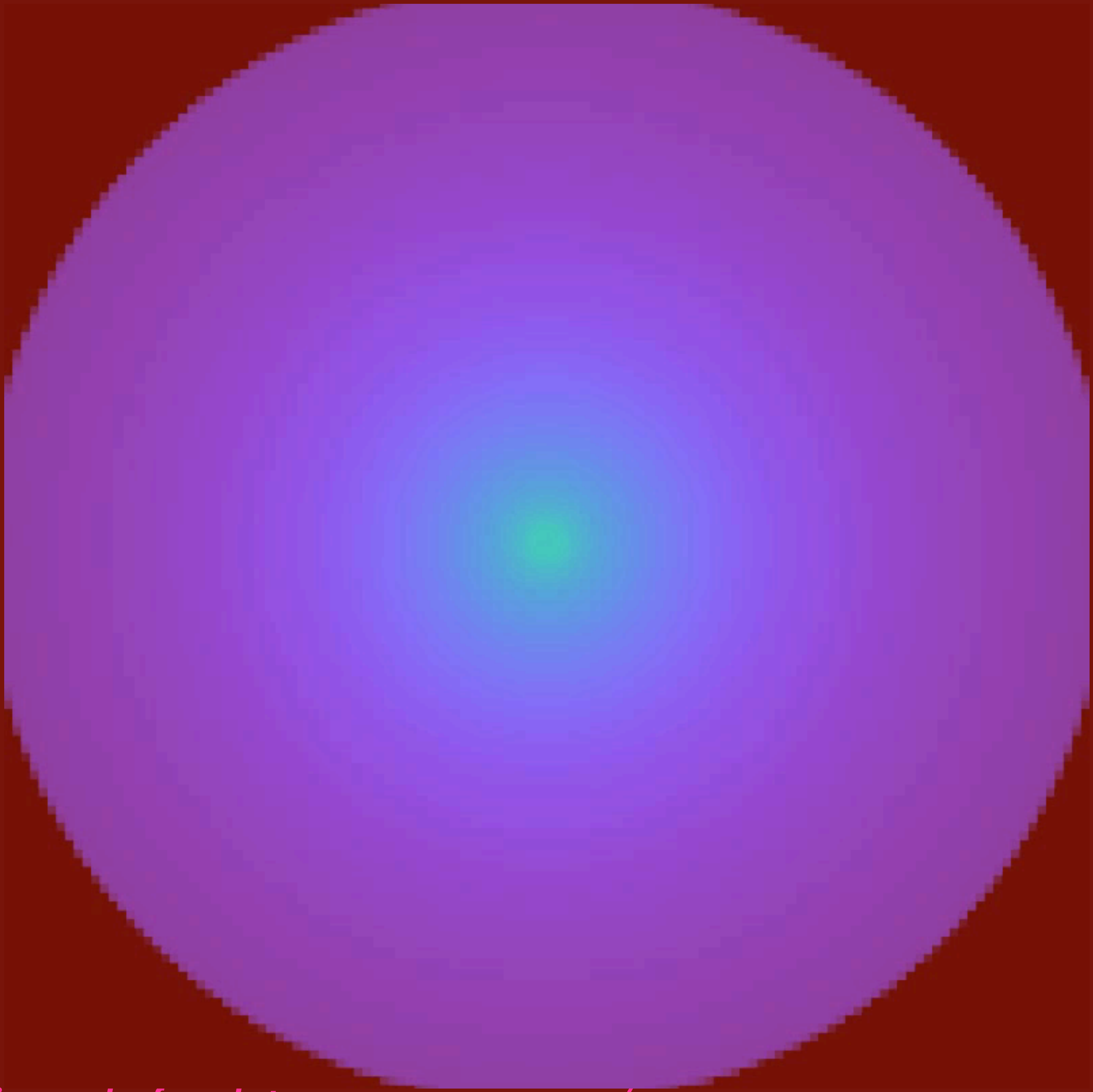




Agrees with turbulent core model for massive star formation

(McKee & Tan, 2003)

Rosen+2016



Simulation movies can be found at www.anna-rosen.com/movies