Open Questions in Star Formation

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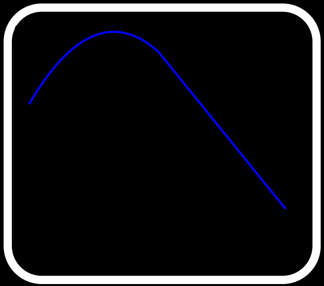
UMass Amherst

Radio Futures, Chicago, 2015

Open Questions

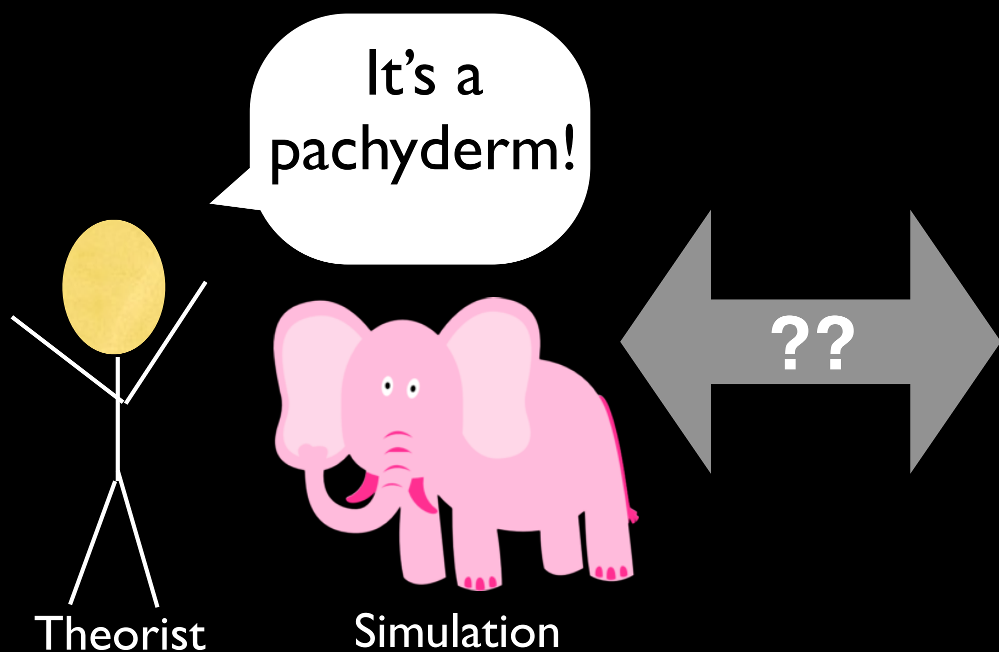


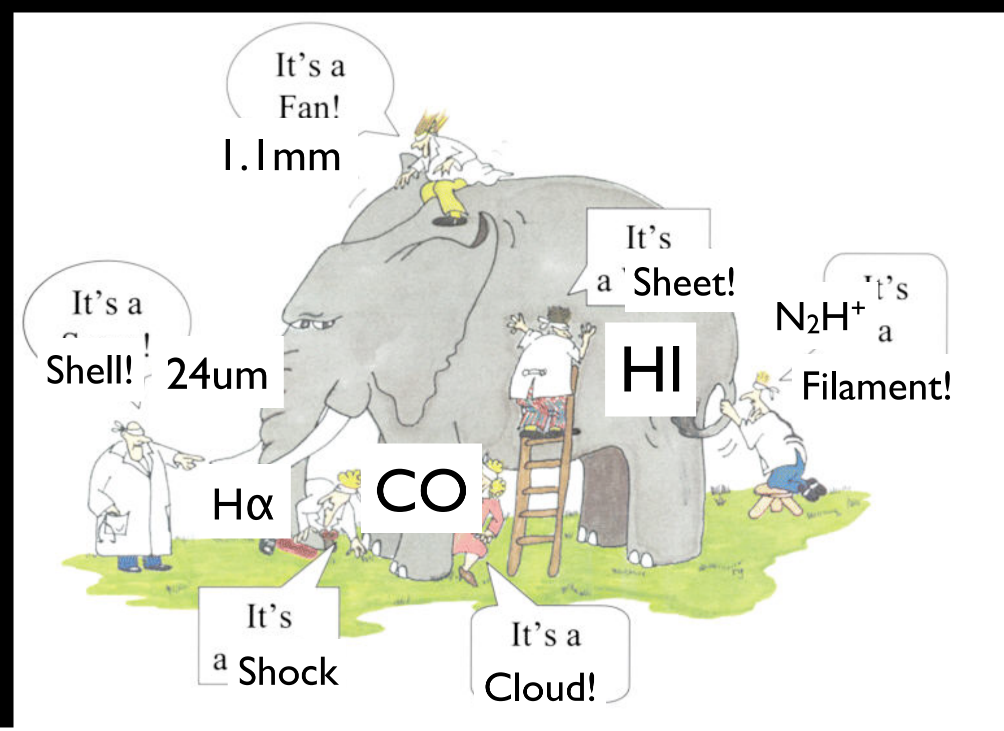
1. What is the origin of the Stellar Initial Mass Function?

2. What is the Role of Star Formation Feedback?

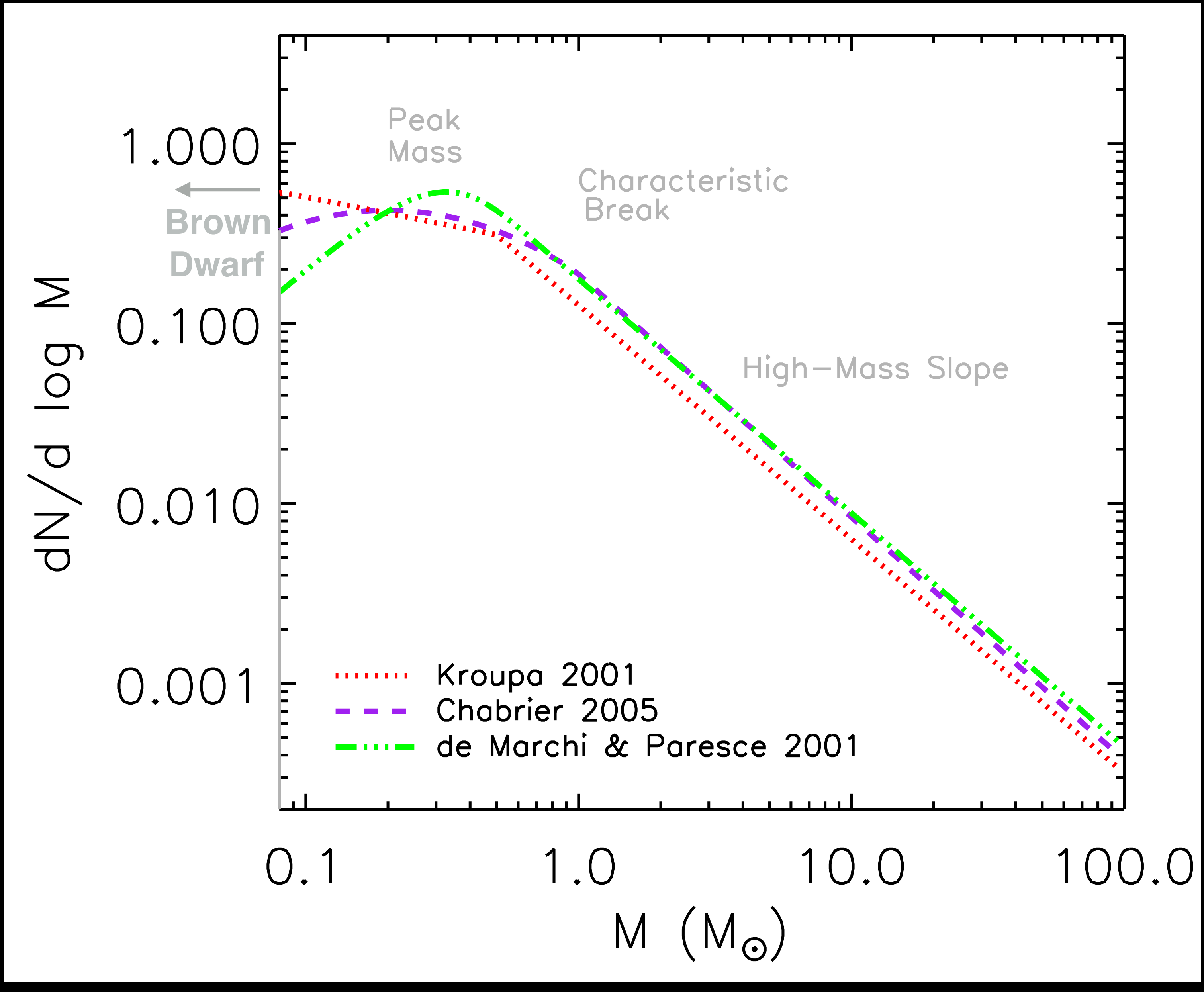
3. How do Molecular Clouds Form?

All Together Now



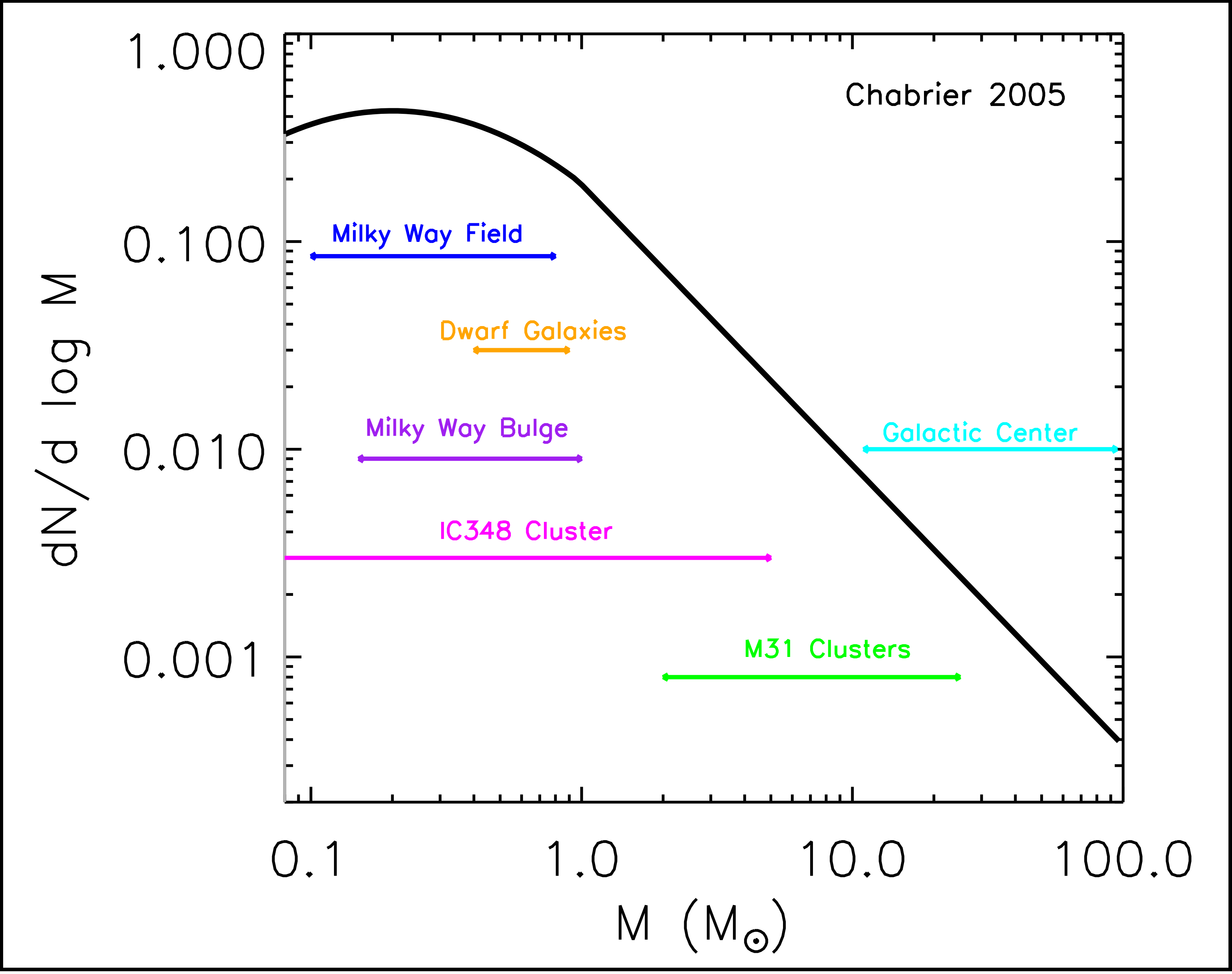


What is the origin of the IMF?



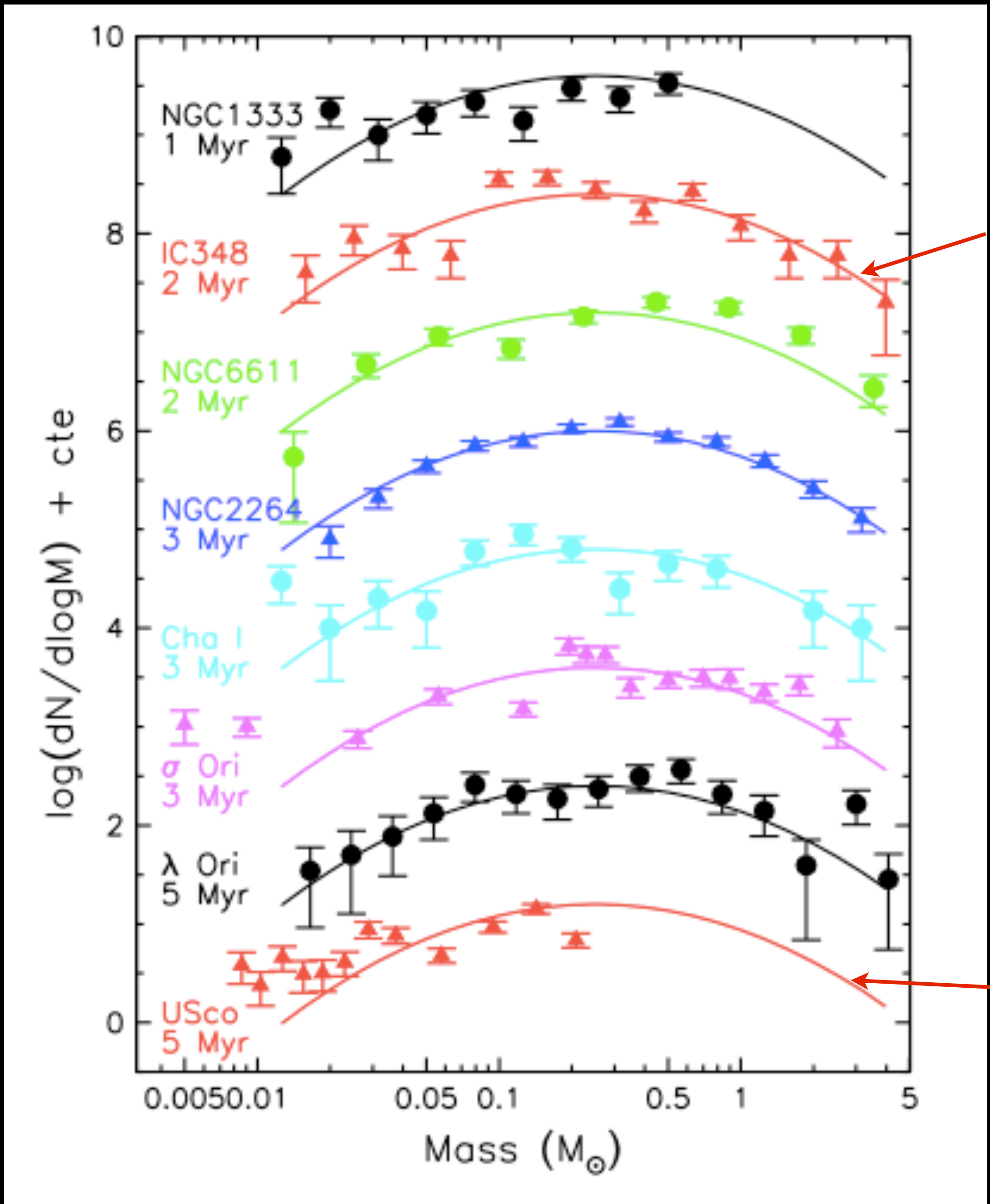
Offner 2015
IAU Review

IMF Sampling



Offner 2015
IAU Review

Resolved IMF: Universal



Poisson errors
- do not include
systematic errors

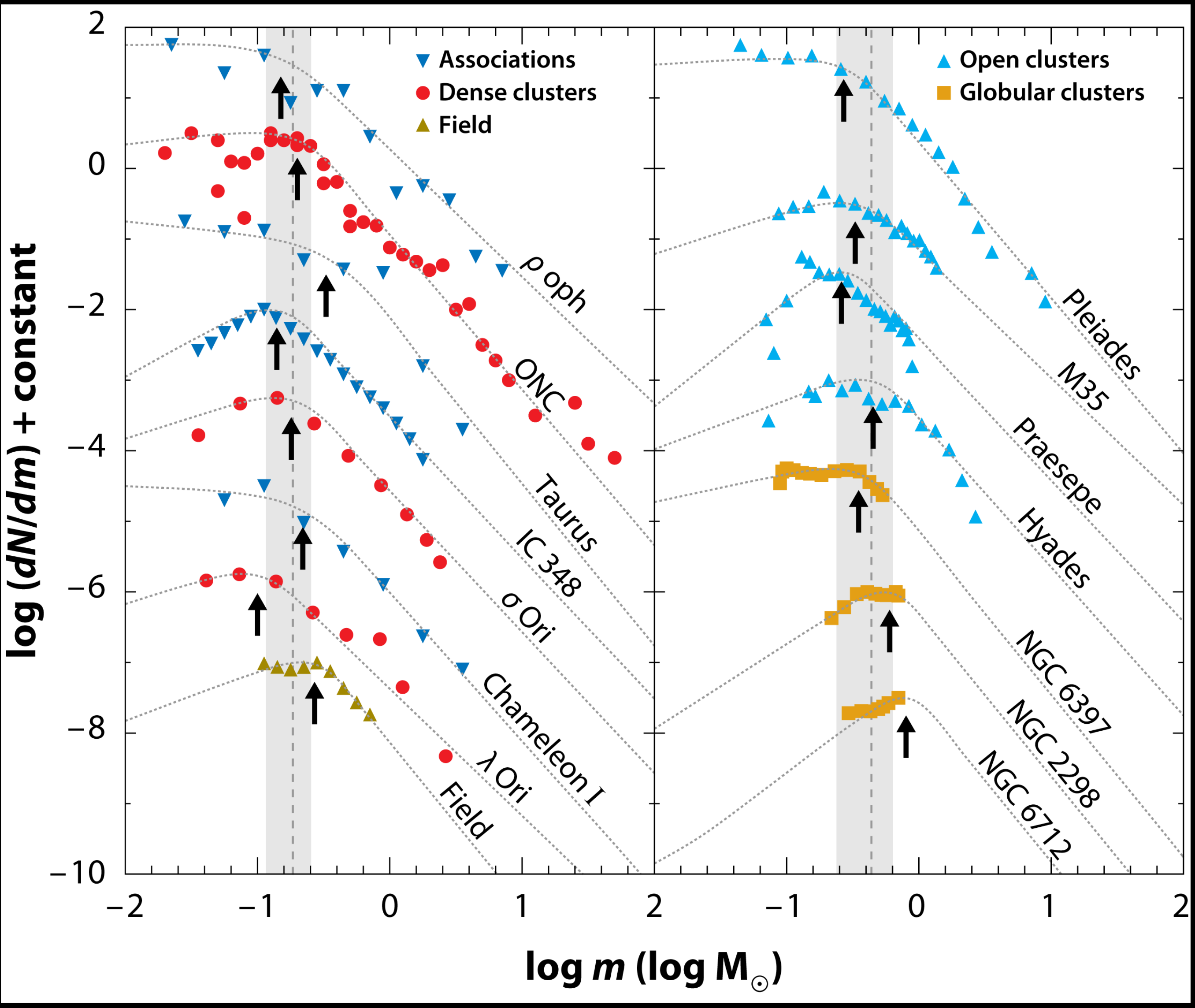
<u>IMF Appears Universal in Young Clusters</u>

Chabrier 2005 IMF
-- not a fit

Offner et al. PPVI
Figure credit: E. Moraux

Resolved IMF: Universal

Bastian, Covey, Meyer 2010



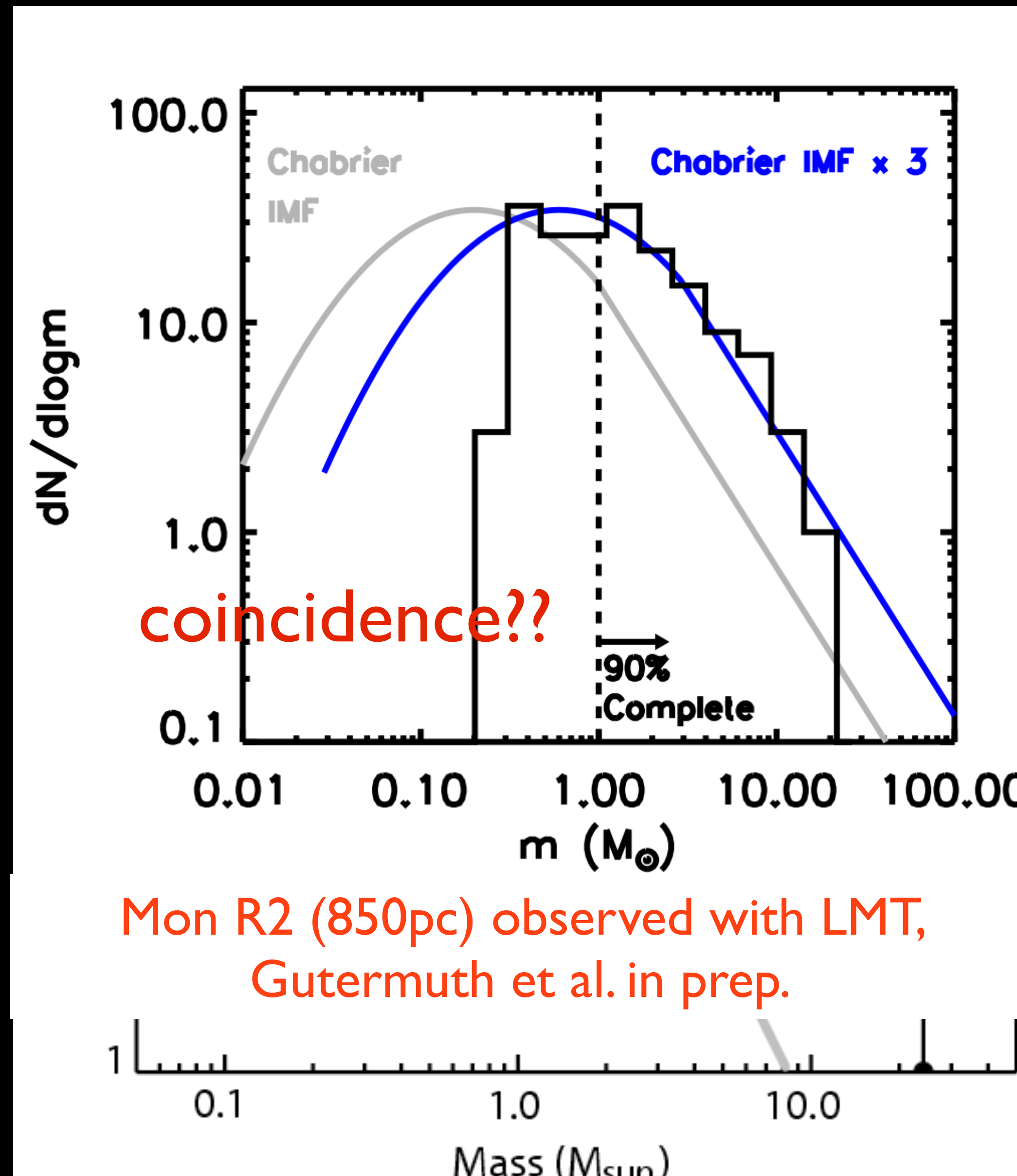
-*"Studies of the field, local young clusters and associations, and old globular clusters suggest that the vast majority were drawn from a "universal" IMF"* ***- Bastian, Covey, Meyer 2010, ARAA***

- No systematic variations found in High-Mass end in M31 ***(Weisz et al. 2015)***

Arrows = completeness limit

CMF and the IMF

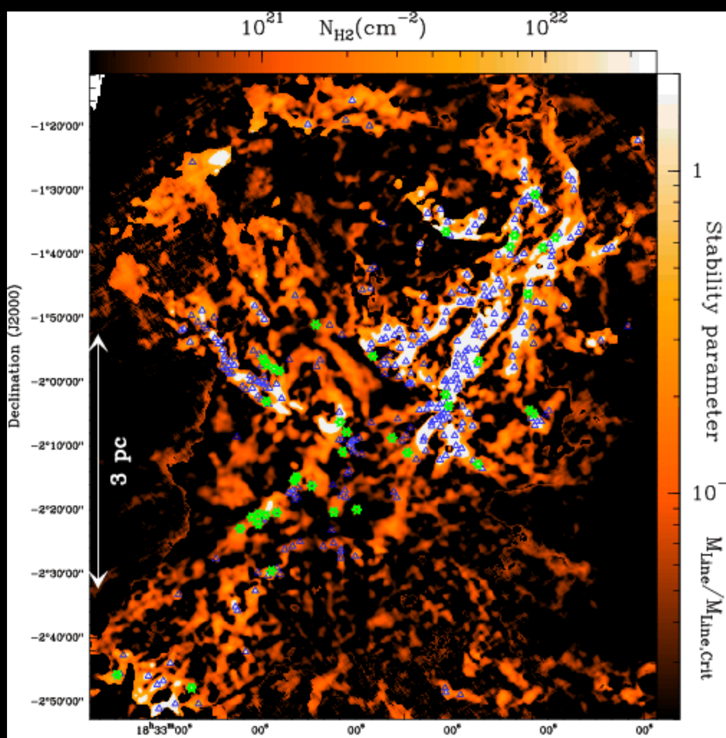
- Dense cores are suspected precursors of stars (star systems)
- Core mass function (CMF) is shifted by ~1/3 compared to the stellar IMF



Mon R2 (850pc) observed with LMT, Gutermuth et al. in prep.

Alves ea 2007; also Nutter & Ward-Thompson 2007, Enoch ea 2008, Andre ea 2010

Cores identified in Aquila Andre et al. 2010



How much does Turbulence matter?

The IMF...

is	is sort of	is not
Padoan & Nordlund Hennebelle & Chabrier Hopkins Myers, McKee, Klein	Cartwright & Whitworth P. Myers Adams & Futuzzo Offner & McKee Krumholz	Clark, Bonnell, Klessen, Smith Stamatellos & Whitworth B. Elmegreen

Manifest Destiny

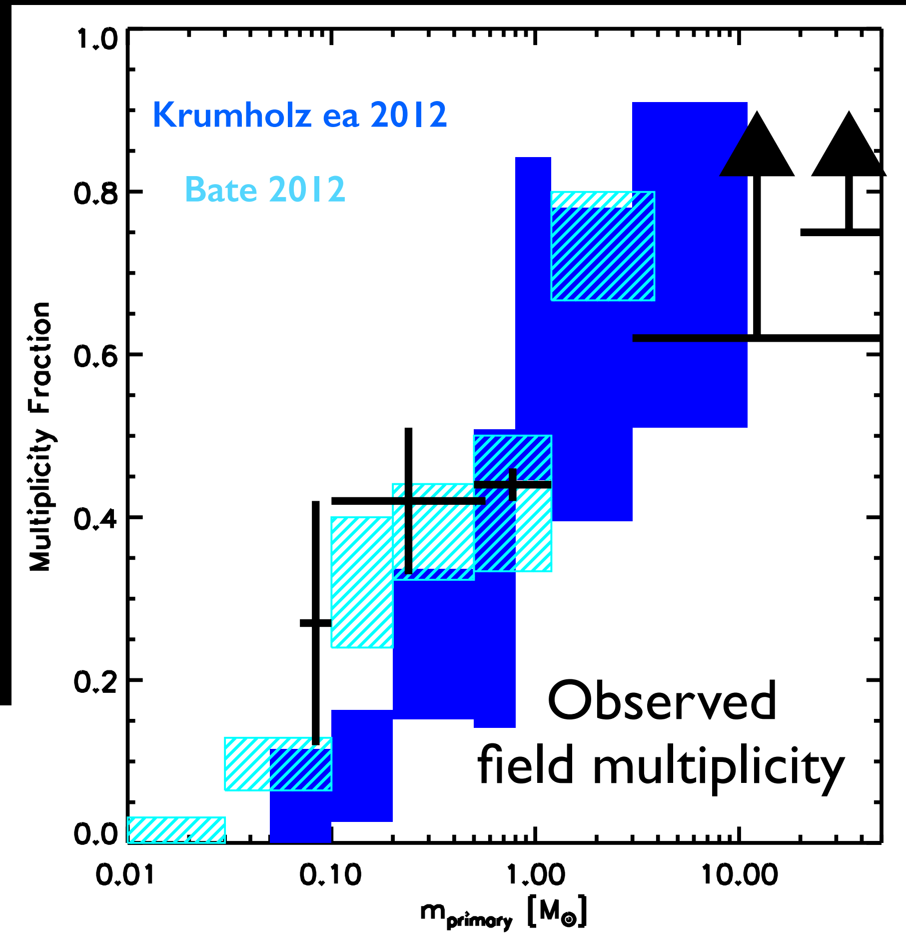
Central Limit Theorem

...determined by the Core Mass Function (CMF)

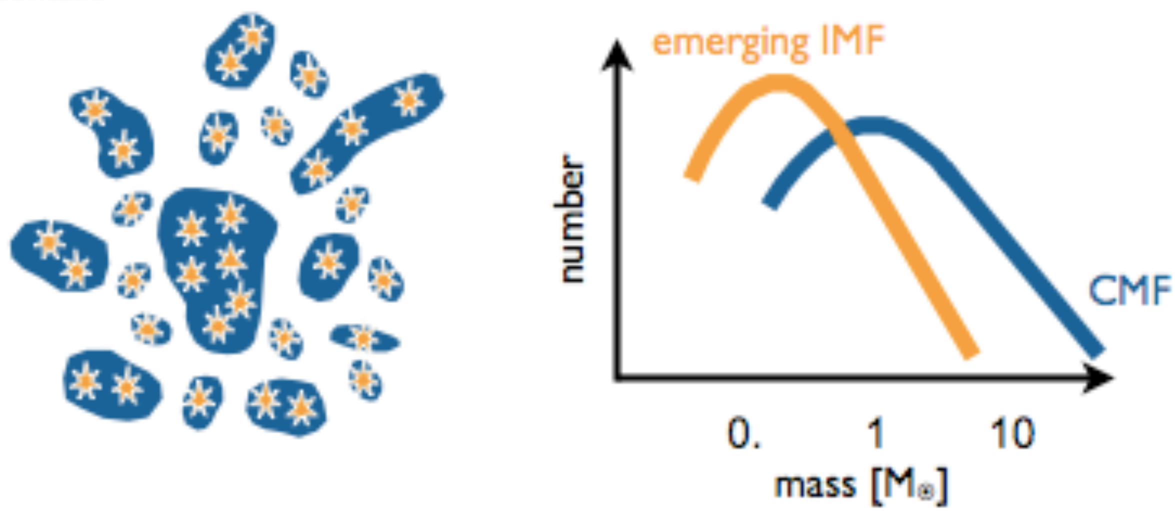
Multiplicity

Cores form multiple stellar systems.

What if protostellar multiplicity varies with core mass?



iv) Fragmentation is not self-similar. Here we show the emerging IMF that could arise if the cores in the CMF fragment based on the number of initial Jeans masses they contain.

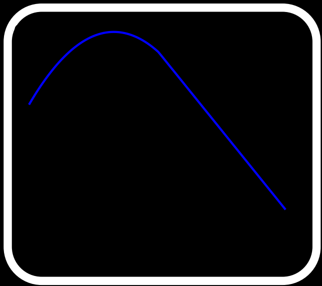


Offner et al. PPVI

What is the Origin of the Stellar IMF?

- Cores: High-sensitivity (M<0.08 Msun), high-resolution (Δx ≤ 0.01pc out to 500 pc) continuum (≥850 um) observations
- Cores: High-resolution, spectroscopic dense gas surveys (Δv ≤ 0.05 km/s): e.g., NH_3, N_2H+
- Protostars: <0.1” resolution to study multiplicity
- Synthetic Observations: evidence of CMF universality or systematic variation

Open Questions

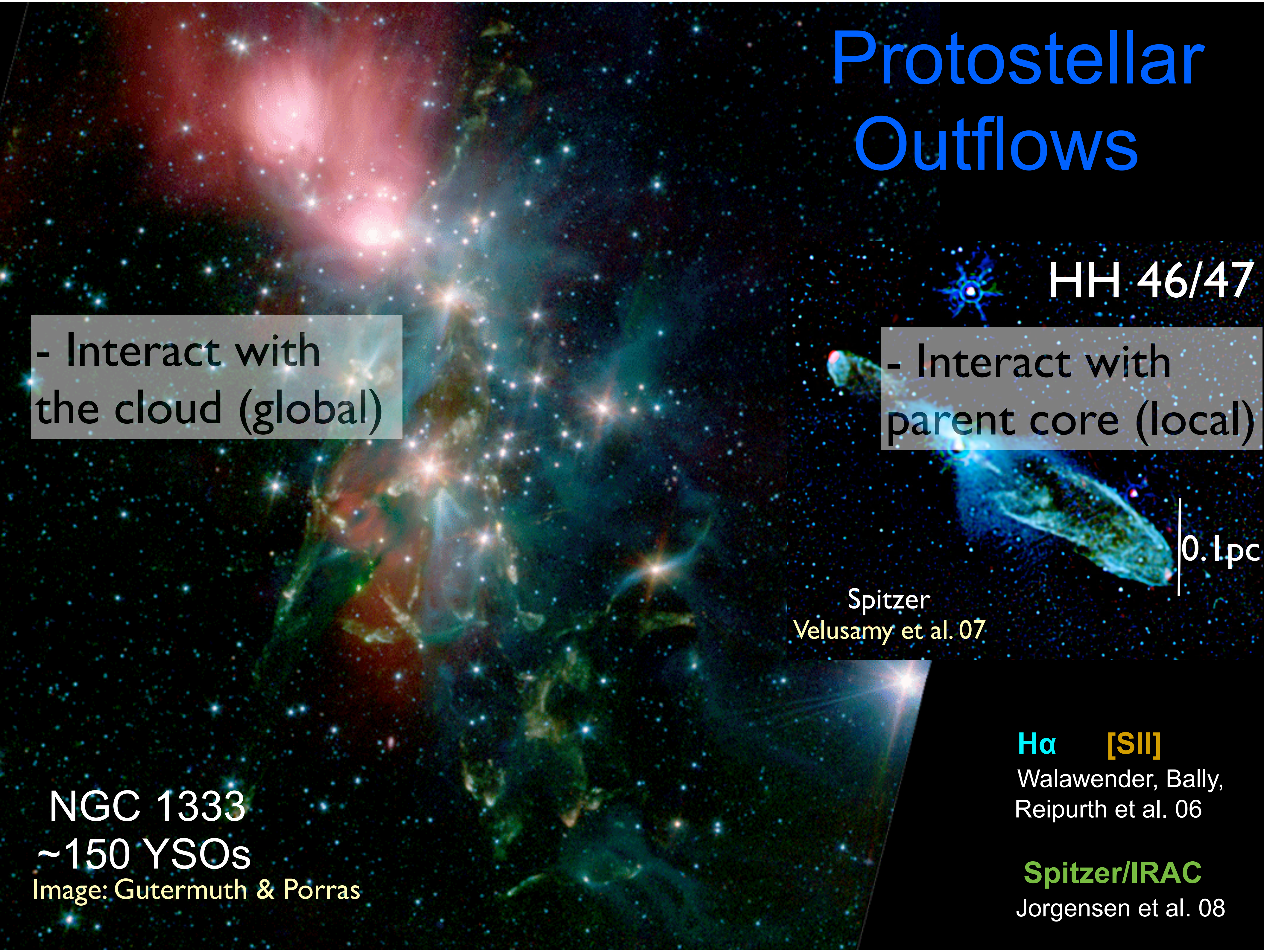


1. What is the origin of the Stellar Initial Mass Function?

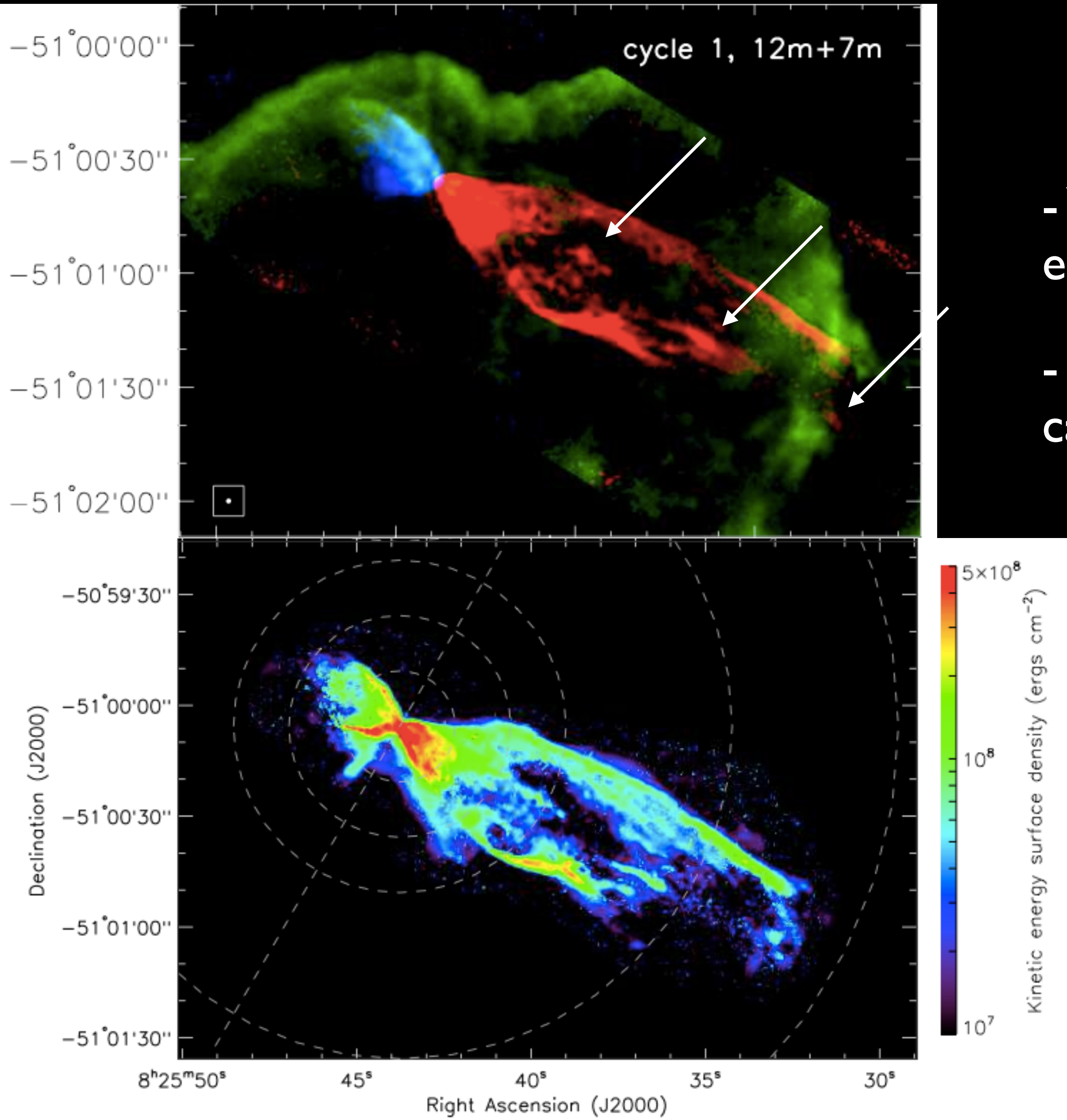
2. What is the Role of Star Formation Feedback?

Heating, Ionization, Pressure, **Outflows, Winds**…

3. How do Molecular Clouds Form?


Protostellar
Outflows
- Interact with
the cloud (global)
HH 46/47
- Interact with
parent core (local)
0.1pc
Spitzer
Velusamy et al. 07
Hα
[SII]
Walawender, Bally,
Reipurth et al. 06
Spitzer/IRAC
Jorgensen et al. 08
NGC 1333
~150 YSOs
Image: Gutermuth & Porras

ALMA



- Wide angle wind + episodic jet

- Outflow momentum can disperse parent core

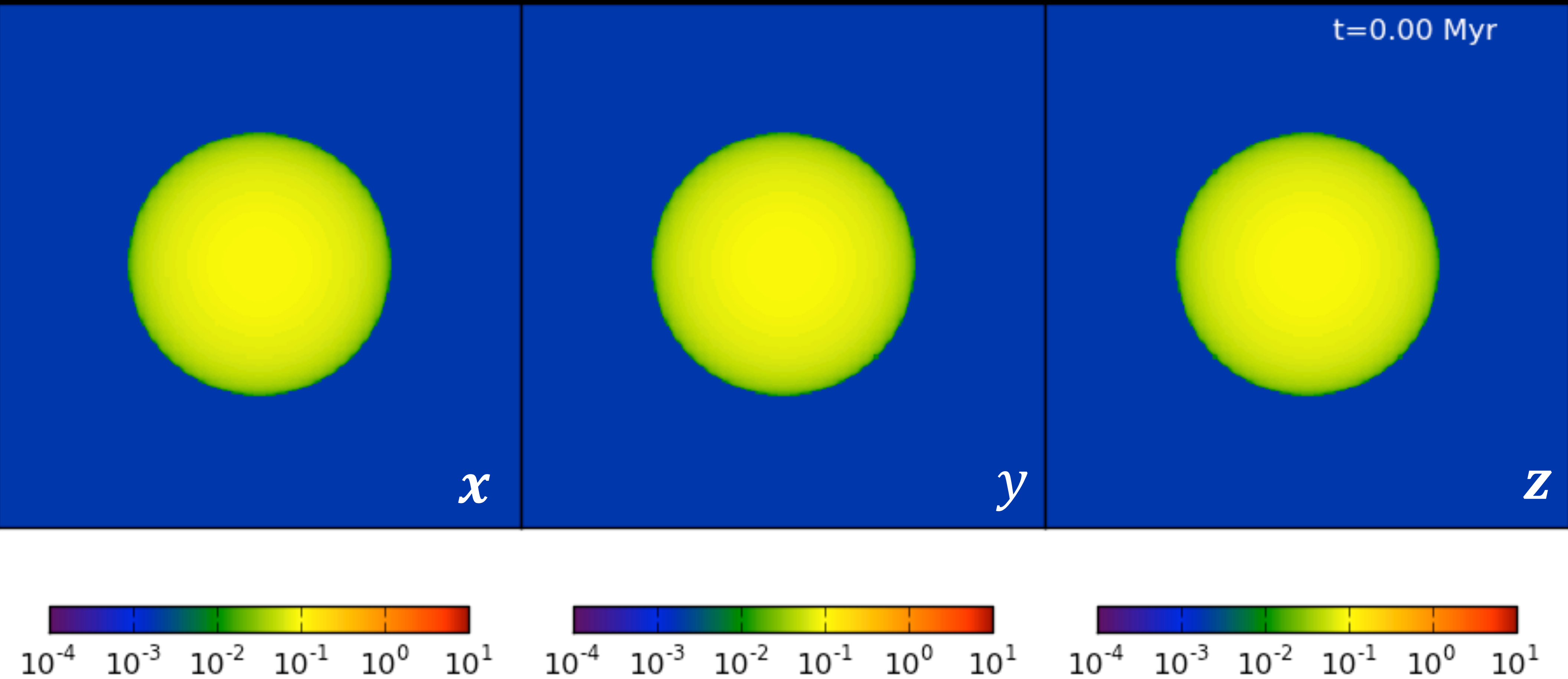
HH 46/47, ^{12}CO, ^{13}CO, $C^{18}O$, CS

Zhang, Arce, Mardones et al. in prep.

Protostellar Outflows & Cores

"Isolated" Star Forming Core

M_{core} = 4 Msun

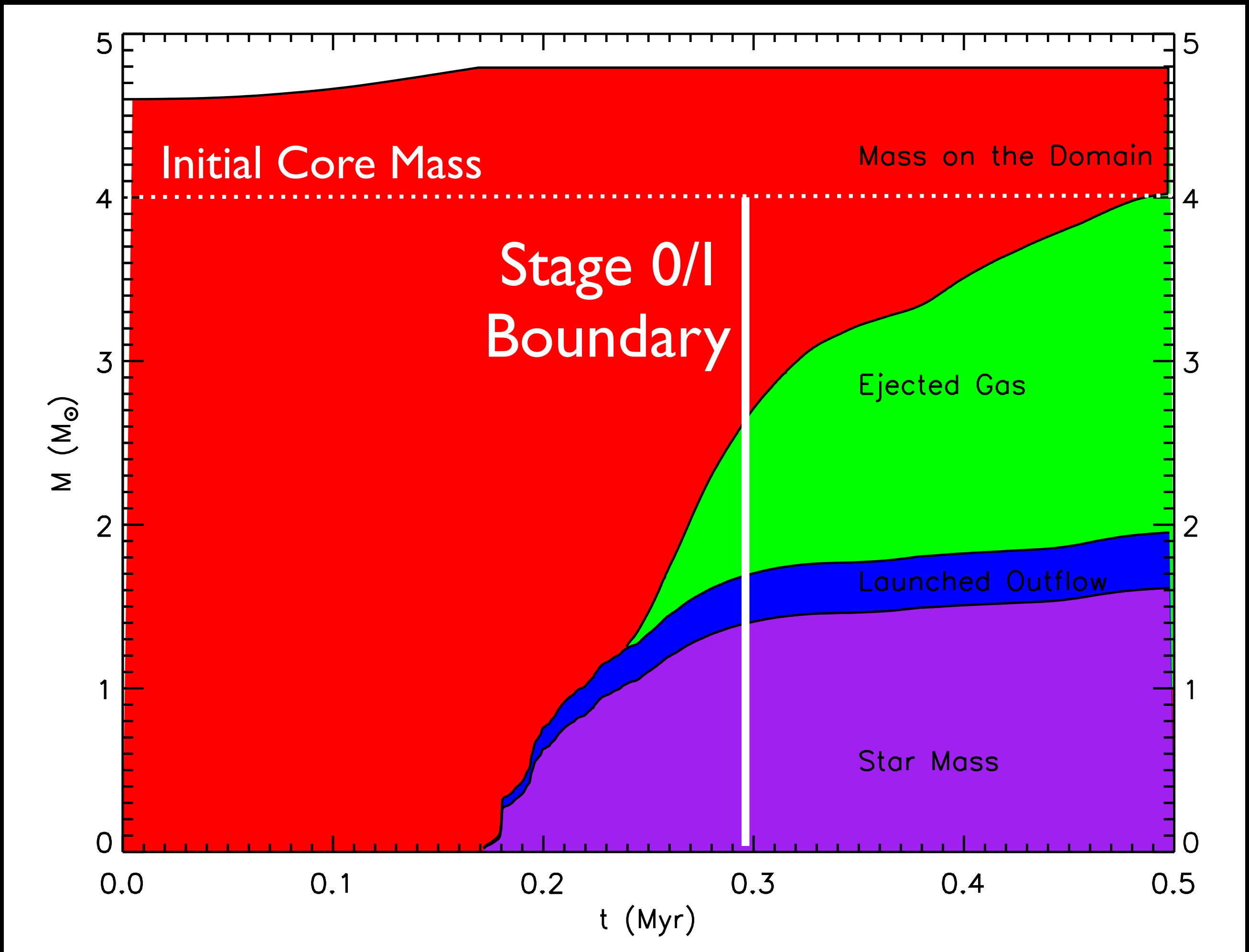


Column Density (g cm^{-2})

L=0.26pc

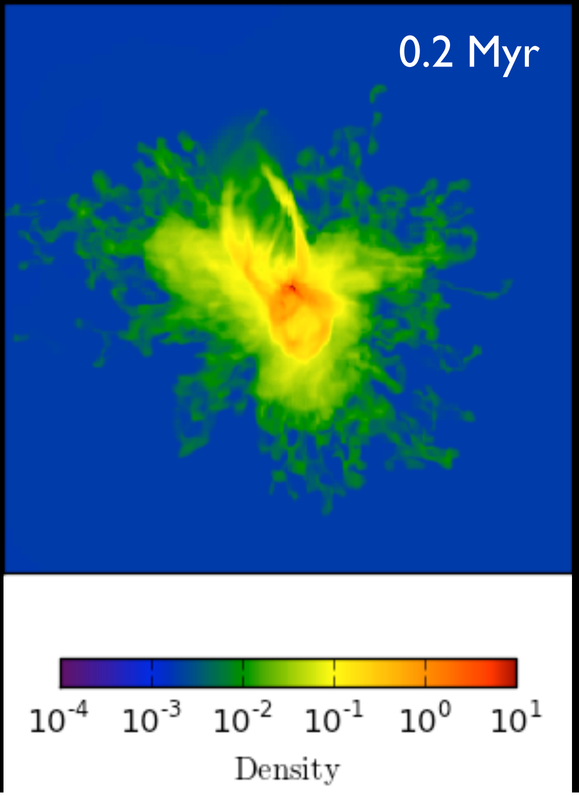
Offner & Arce 2014

Outflow Mass Evolution



Offner & Arce 2014

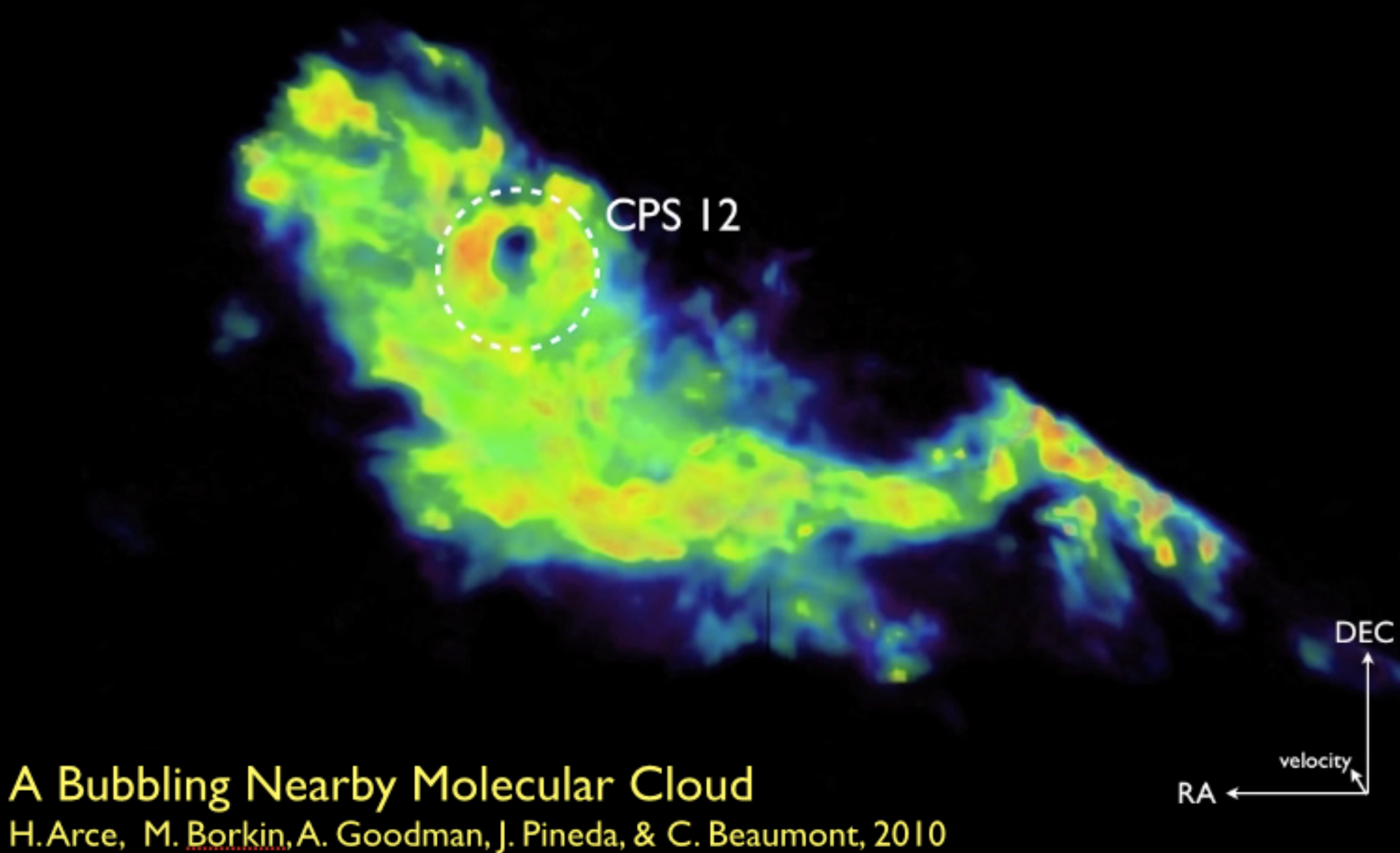
- Stage 0 Defn: $M_* < M_{env}$
- Sim. Stage 0 ~ 0.1 Myr
- Obs. Class 0 ~ 0.1 Myr
  (Enoch et al. 08)



$f_{wind} = 0.2$
theta = 0.01

Shells

B5 Star-Forming Region in 13CO(1-0)

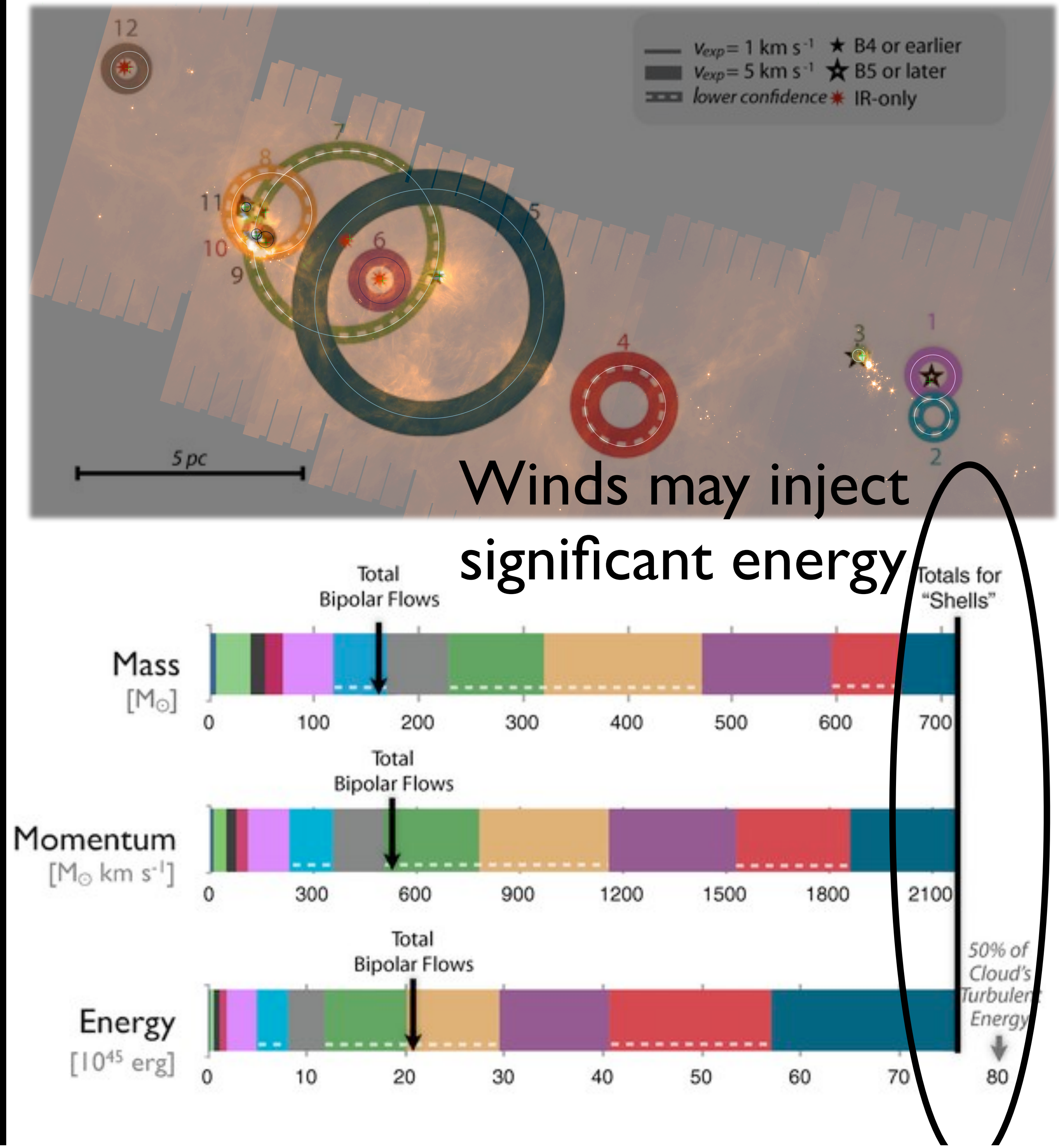


Stellar Winds

Perseus

Molecular Cloud

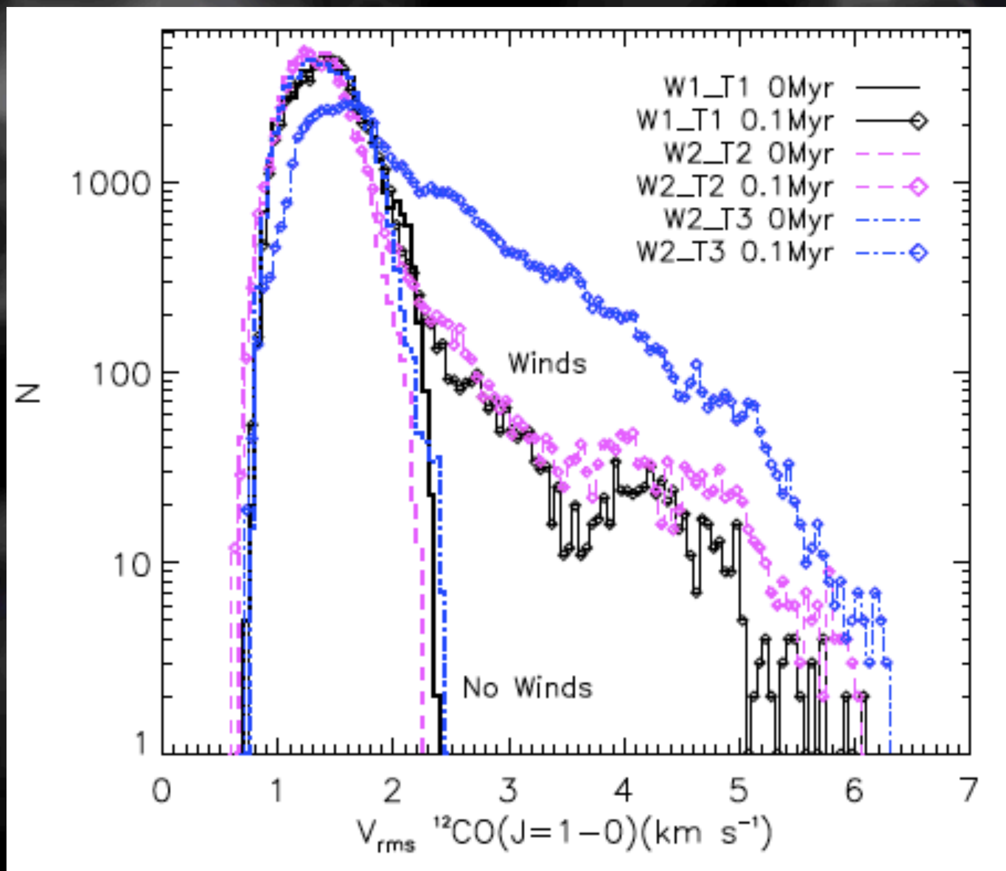
Arce et al. 2011



See also:
Swift & Welsch 2008,
Narayanan et al. 2008,
Nakamura et al. 2012
Lei et al. 2015

Wind Simulation

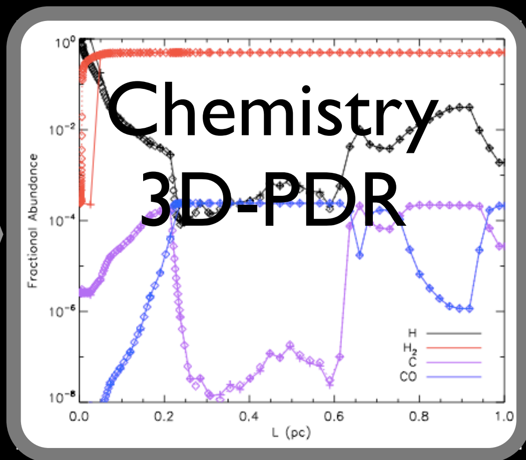
t = 4.947 Myr

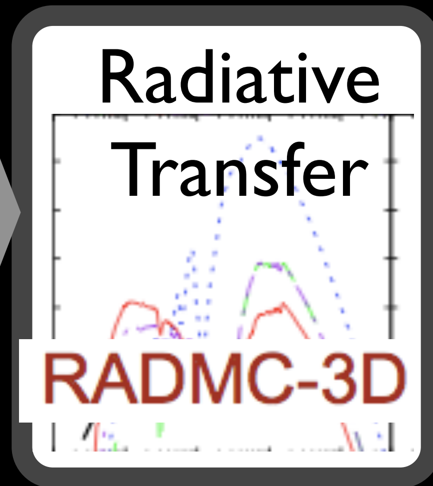


1pc

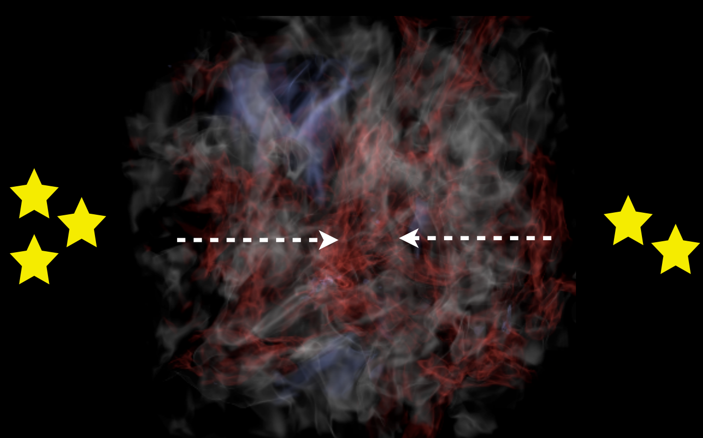
Offner & Arce 2015

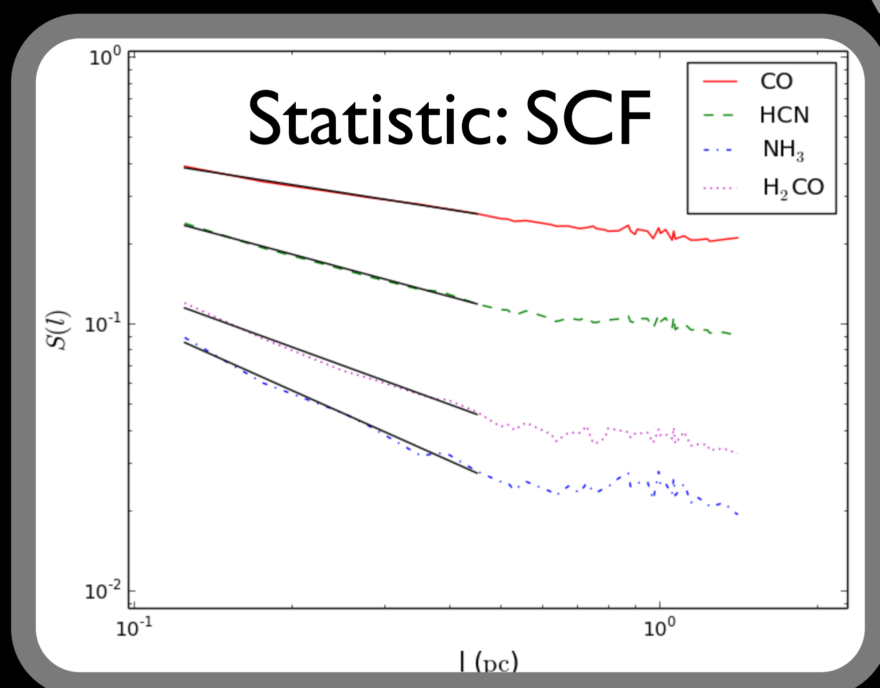
Which statistics can identify feedback?





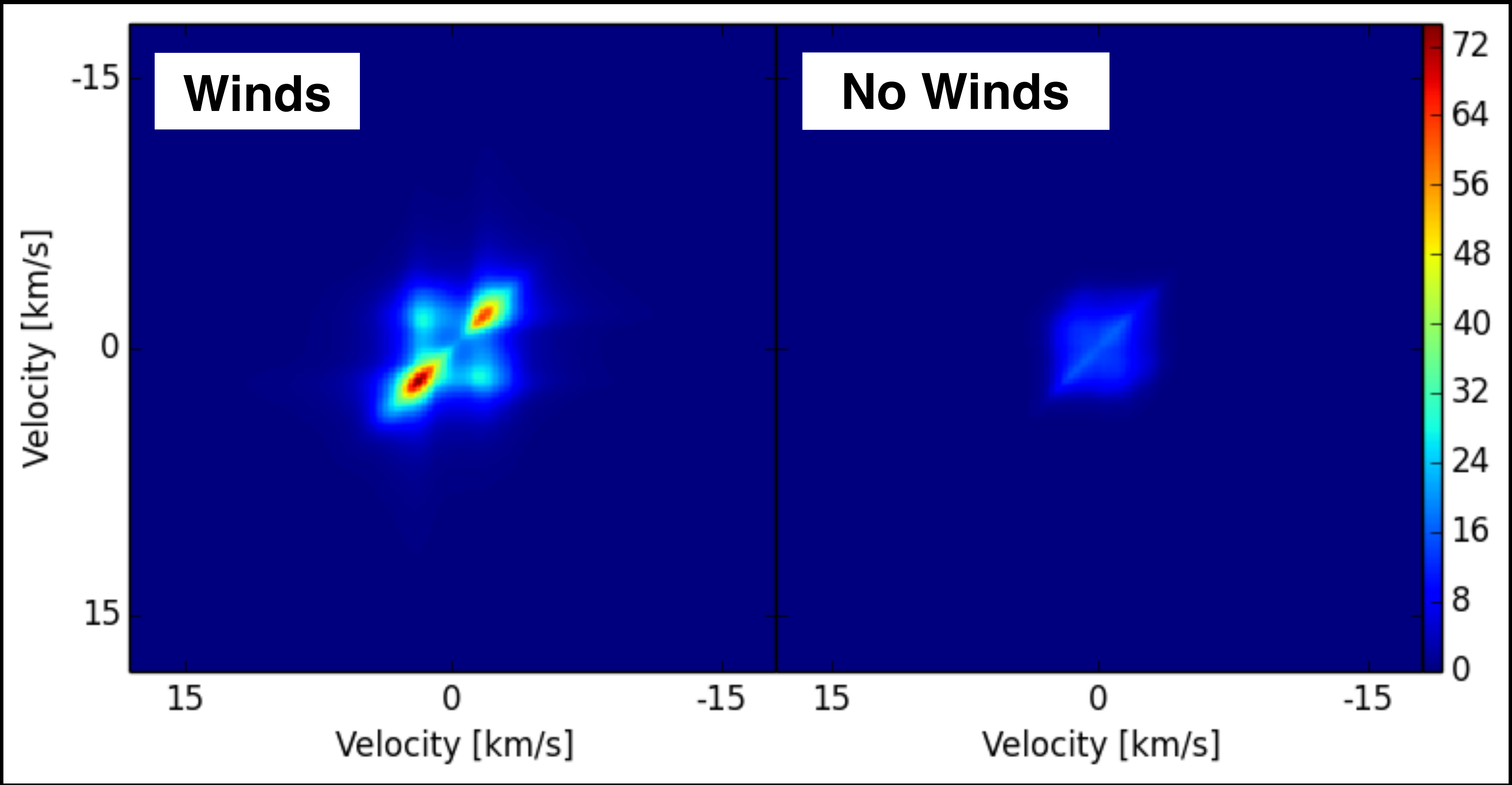
Gaches, Offner, Rosowlosky, Bisbas 2015





Proof of Concept: Winds

Wind features appear in Principle Component Analysis



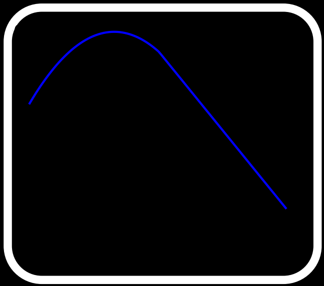
Boyden, Offner et al. in prep

Covariance: $S_1(v, v') = \sum_{x,y} O_1(x, y, v) O_1(x, y, v'),$

What is the Role of Stellar Feedback?

- Outflows: High-sensitivity, high-resolution ($\Delta x \leq 2''$) continuum ($\geq$850 um) and spectroscopic ($\Delta v \leq 0.2$km/s) observations
- Turbulence: High-resolution ($\Delta v \leq 0.05$km/s, $\Delta x \leq 0.01$pc) ^{12}CO and ^{13}CO maps
- Synthetic Observations: robust statistics, parameter studies

Open Questions



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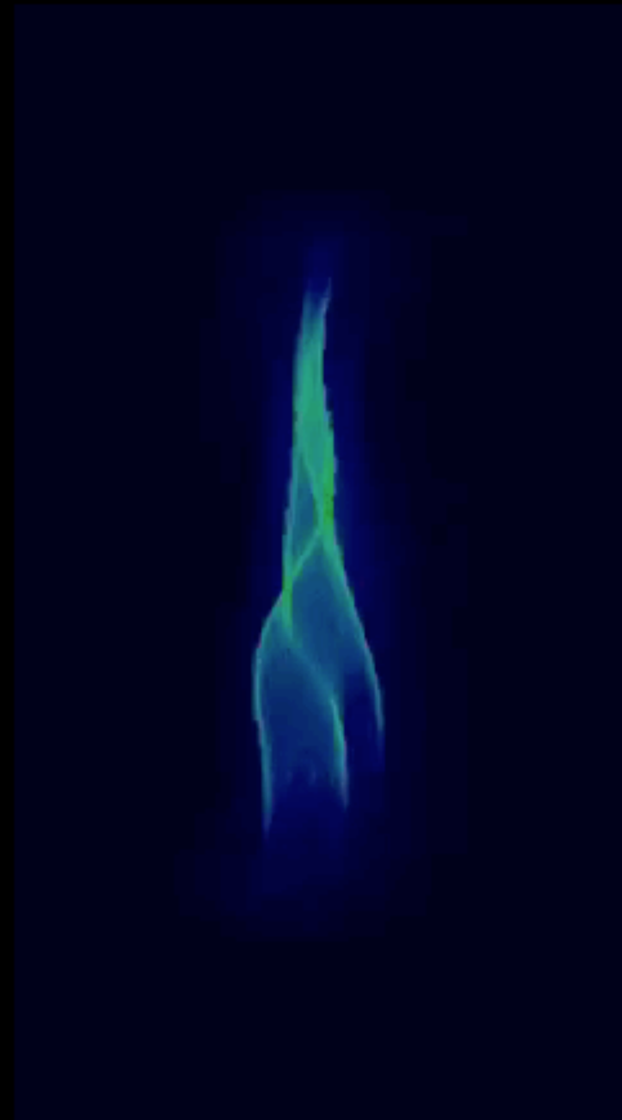
Origin Scenarios

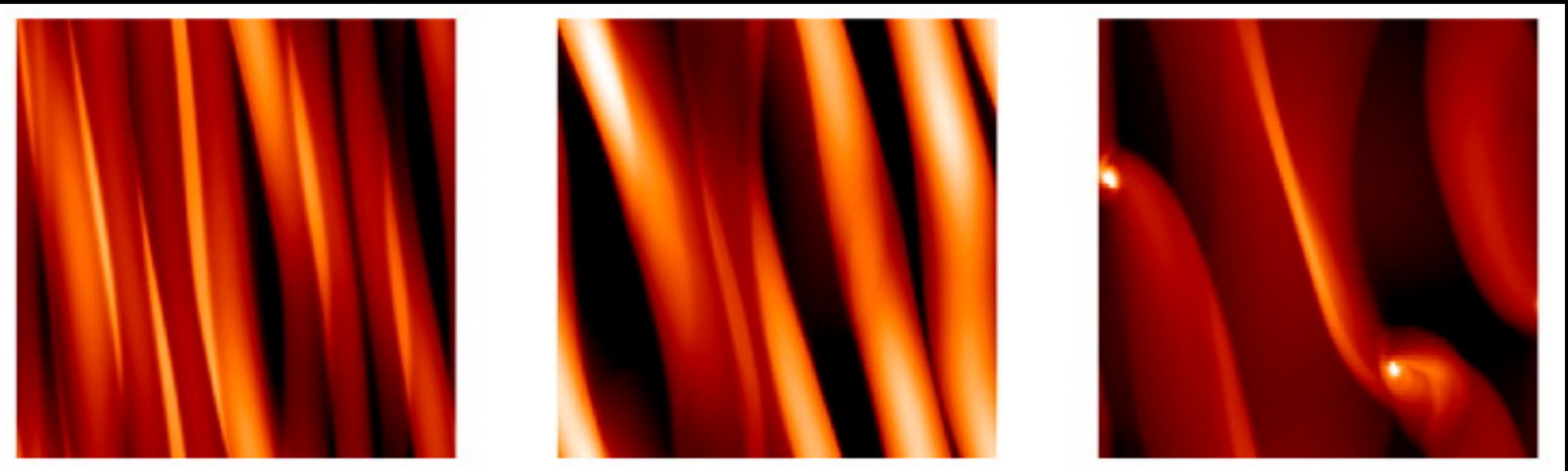
Colliding Flows / GMC collisions



Heitsch et al. 2008

(see also Audit & Hennebelle 2005, Vazquez-Semadeni et al. 2007, Tasker & Tan 2009)

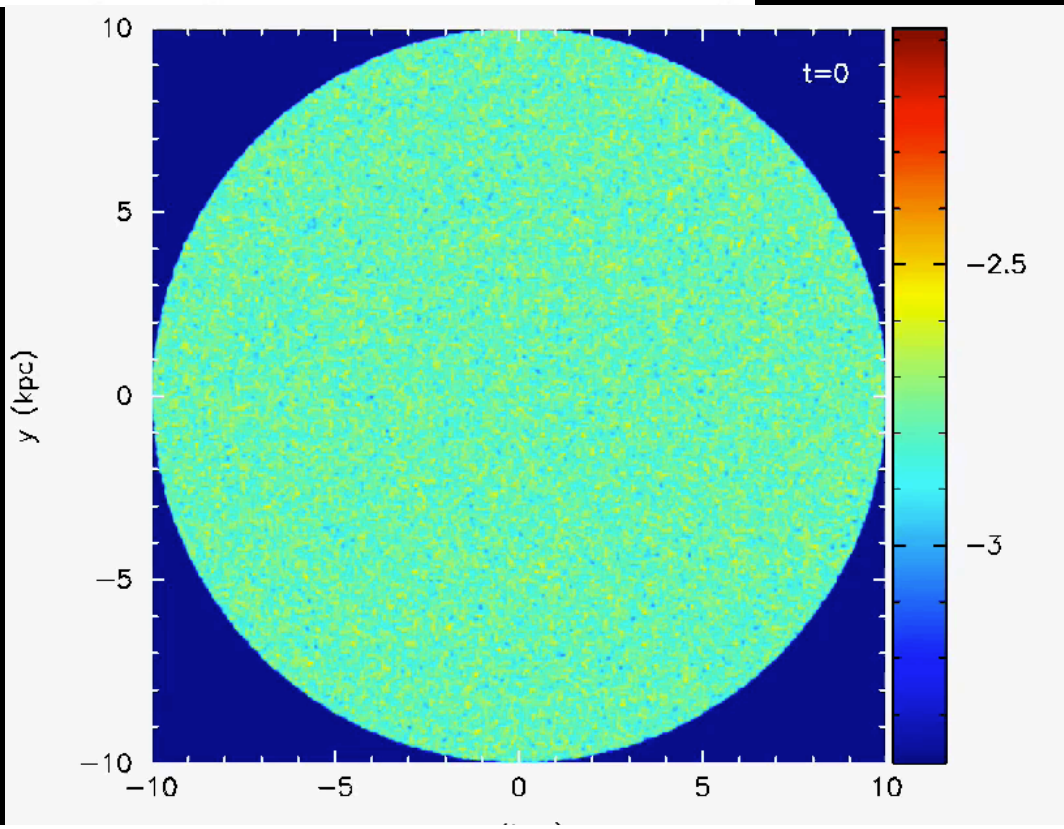
Origin Scenarios



Kim, Ostriker, & Stone 2002

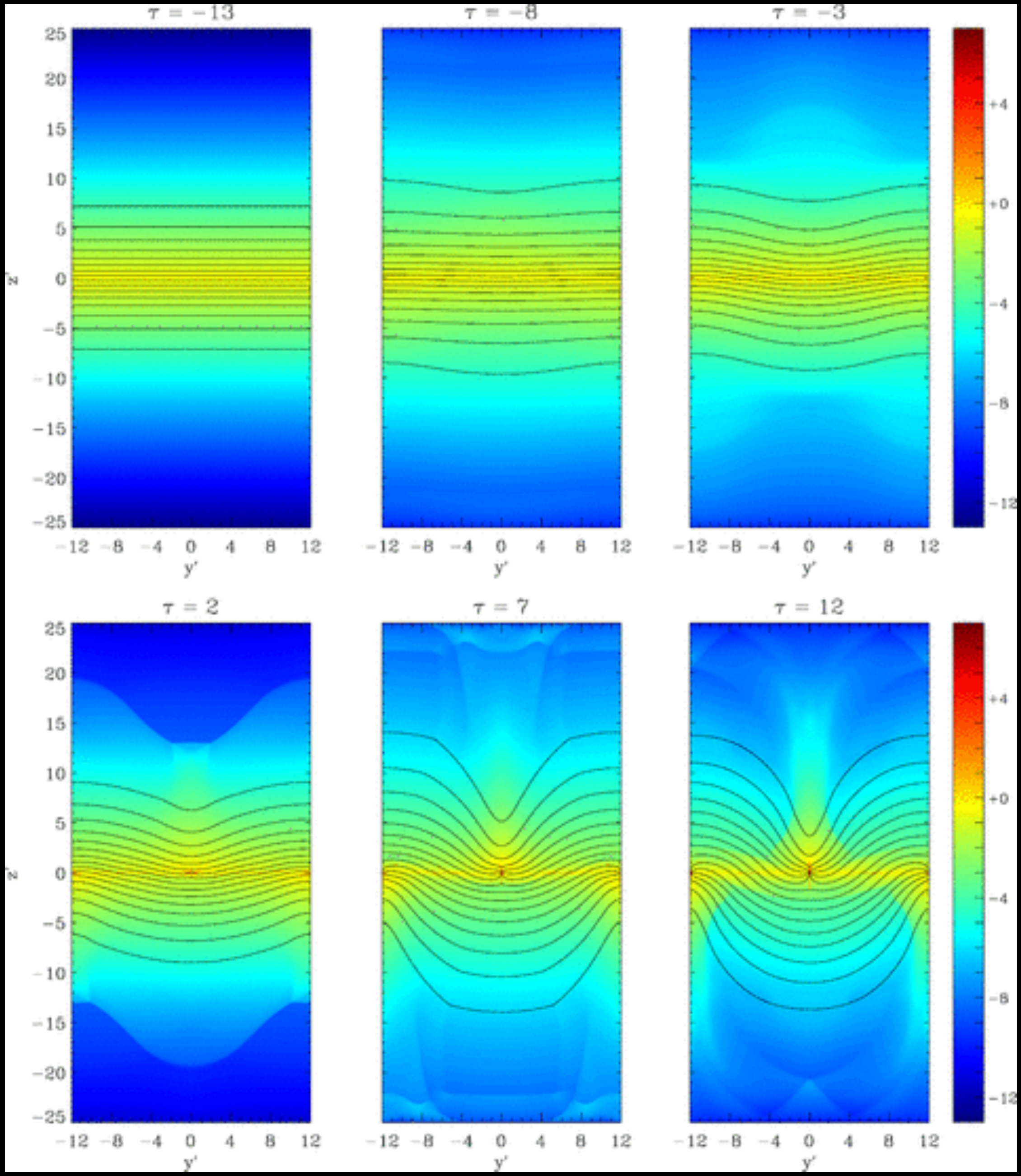
Gravitational Instability /
Magnto-Jeans Instabiliy

Dobbs, Pringle &
Burkert 2011



Origin Scenarios

Parker Instability

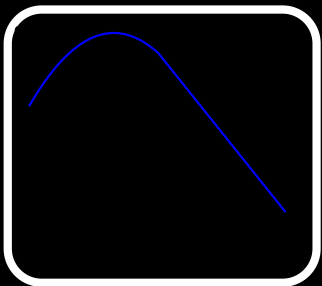


Mouschovias et al. 2009
(see also Franco et al. 2002
Kim & Ostriker 2006)

How Do Molecular Clouds Form?

- Simulations: Full physics (gravity,radiation,MHD) modeling from galaxies down to sub-pc scales; emission predictions for each scenario
- Context: HI/CO/HCN emission maps of *other galaxies*
- Transition to Molecular Gas: Detailed photo-dissociation region (PDR) maps of local clouds in H/C/C+

Open Questions



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