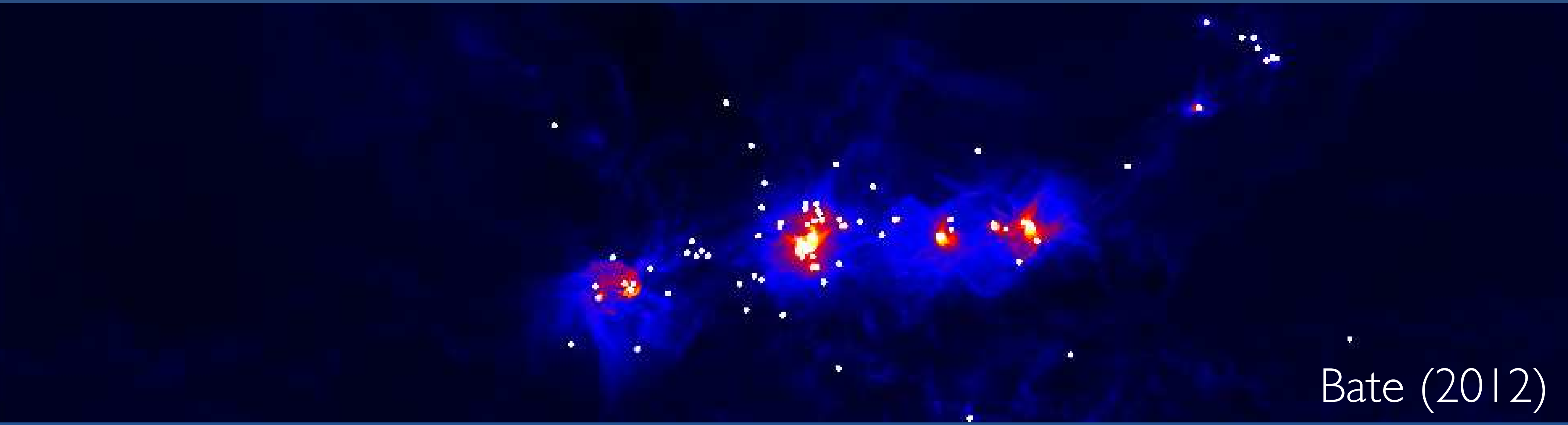
The Origin and Universality of the Stellar Initial Mass Function

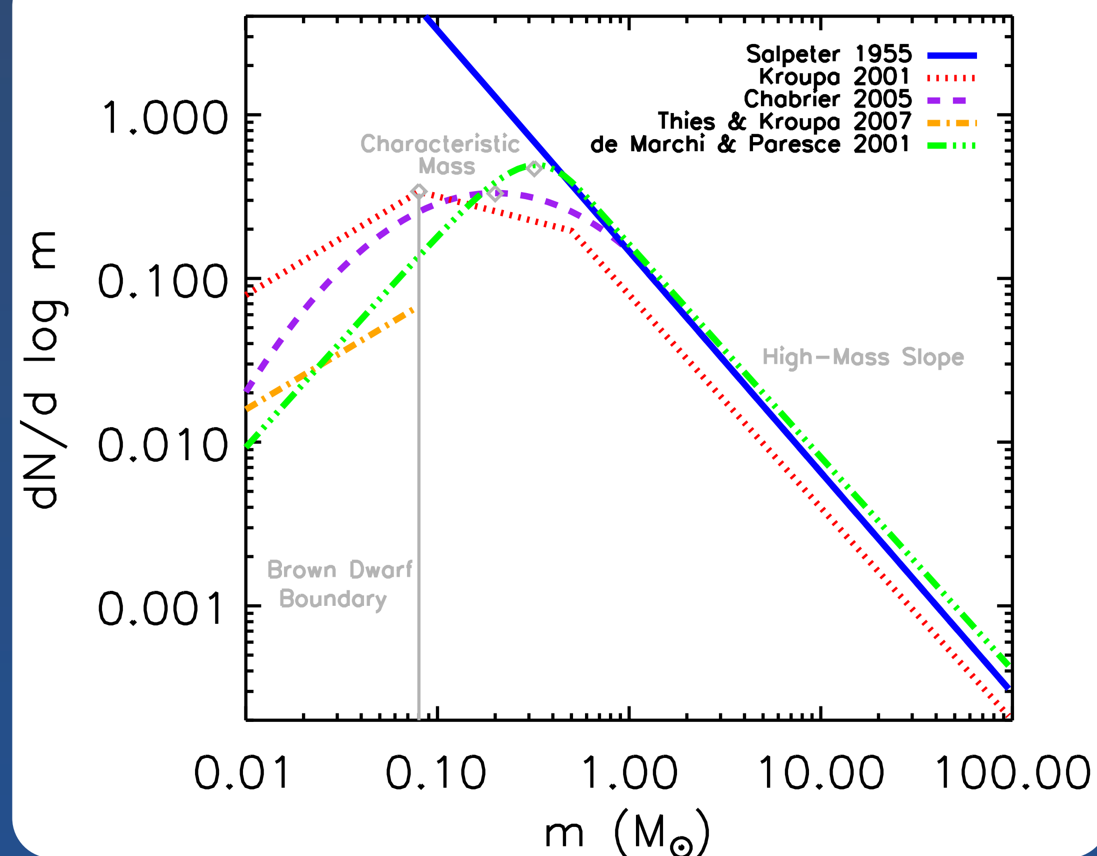
Stella Offner, Paul Clark, Patrick Hennebelle,
Nate Bastian, **Matthew Bate**, Philip Hopkins,
Estelle Moraux, Anthony Whitworth



Bate (2012)

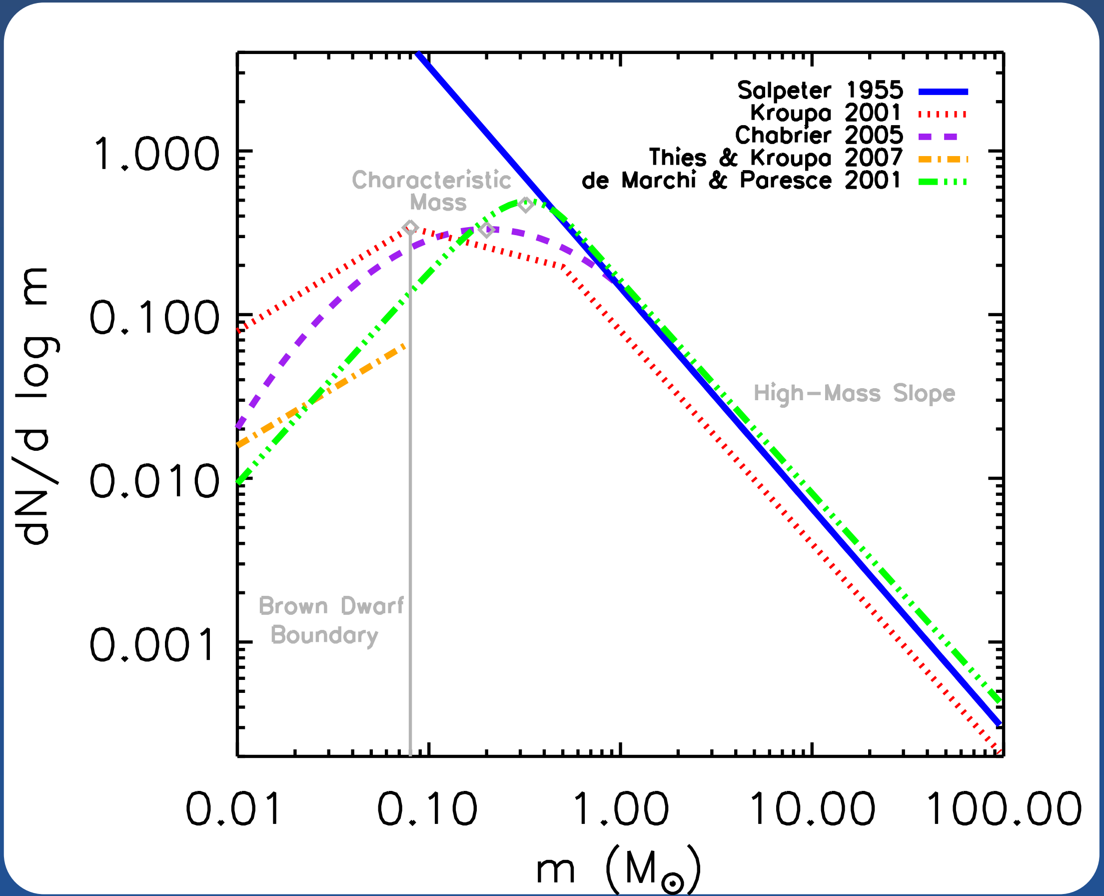
Famous forms of the IMF

- Salpeter (1955) - $N(dM) \sim M^{-\alpha} dM$ - pure power law: $\alpha = 2.35$
- Kroupa (2001) - Multiple power-law segments
- Chabrier (2003/2005) - power-law above a certain mass (~0.8 $M_\odot$), log-normal below
- de Marchi et al. (2005) - Tapered power-law



The importance of the IMF

- Almost every observable property of a galaxy or stellar population depends on the IMF
- SFR indicators only sensitive to small range (high masses) - extrapolate down the IMF



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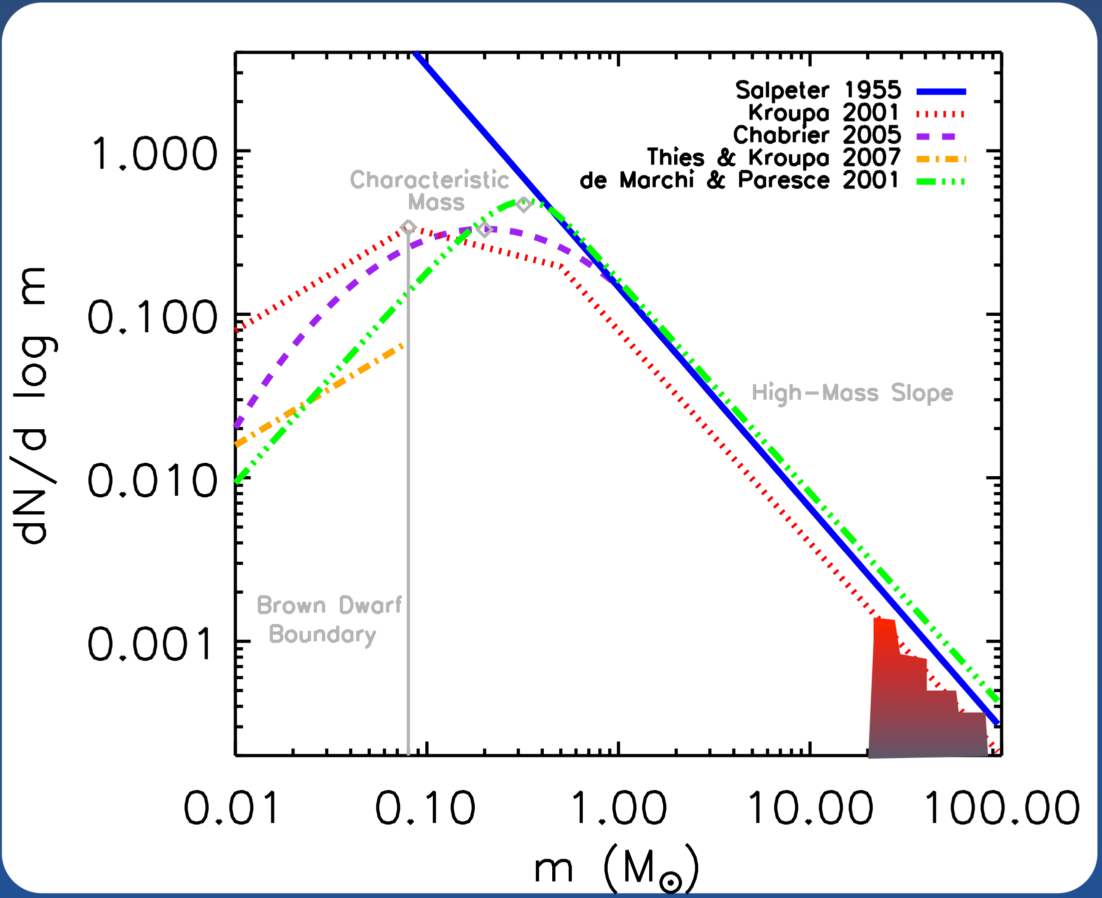

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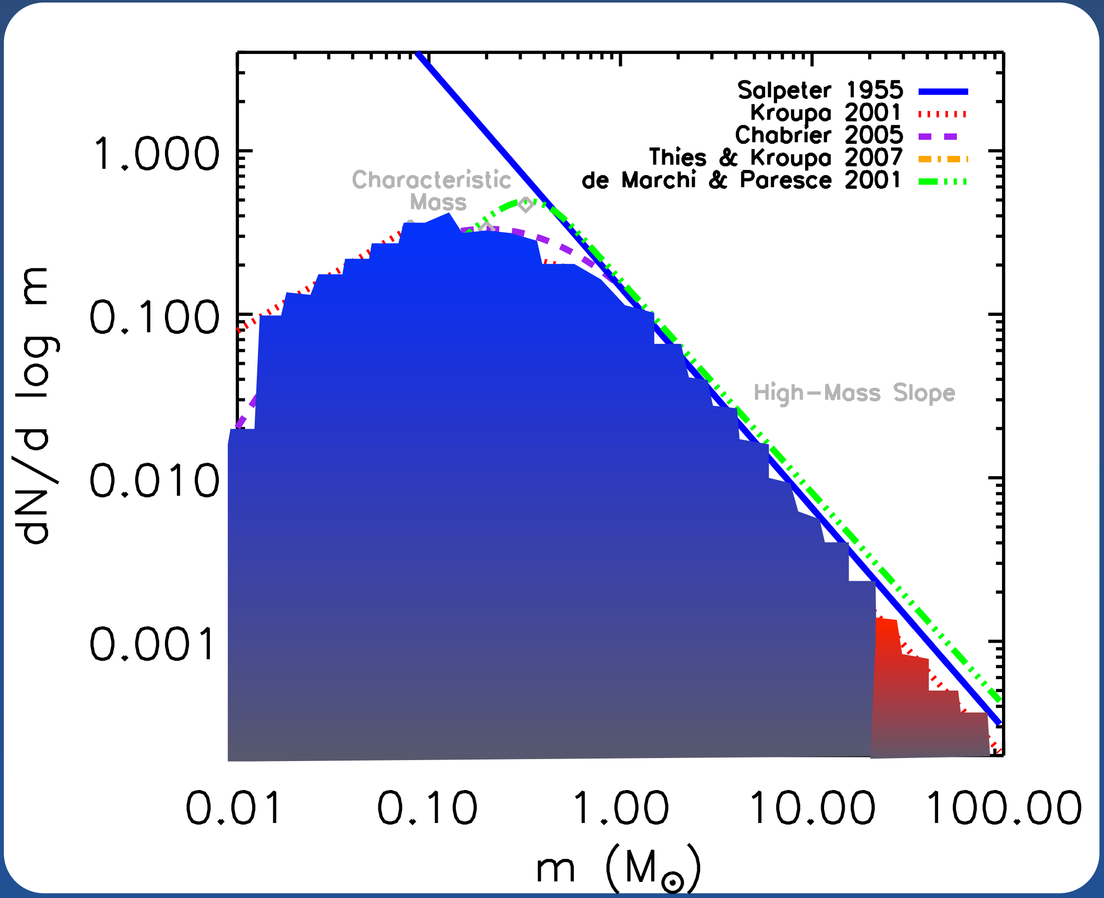
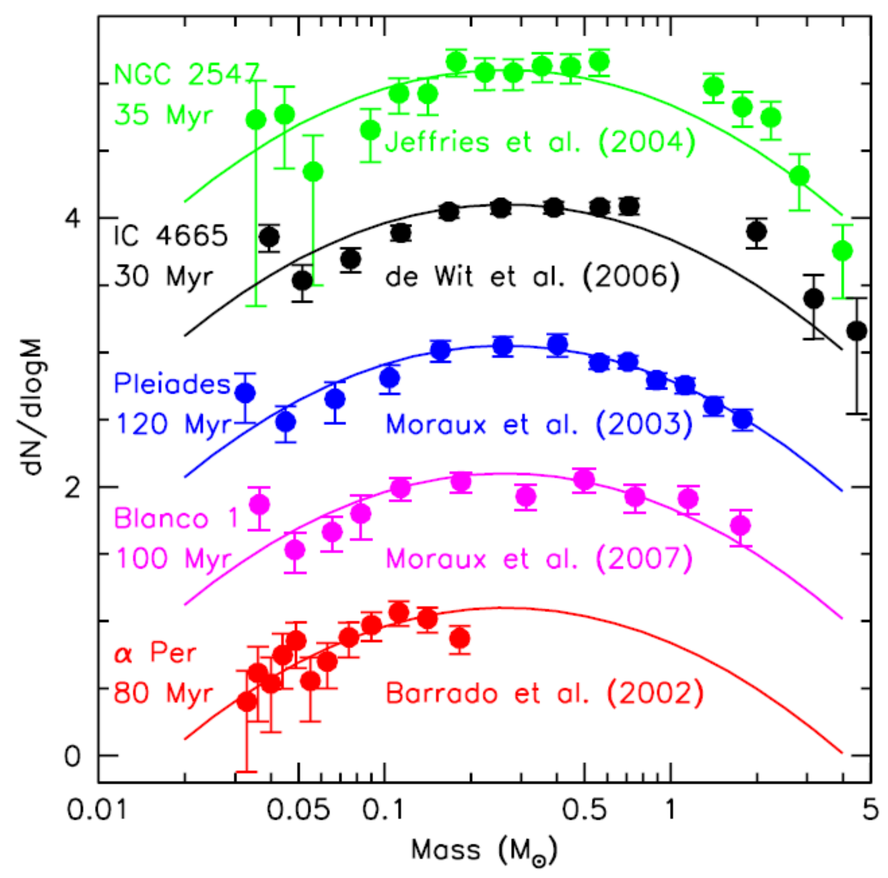


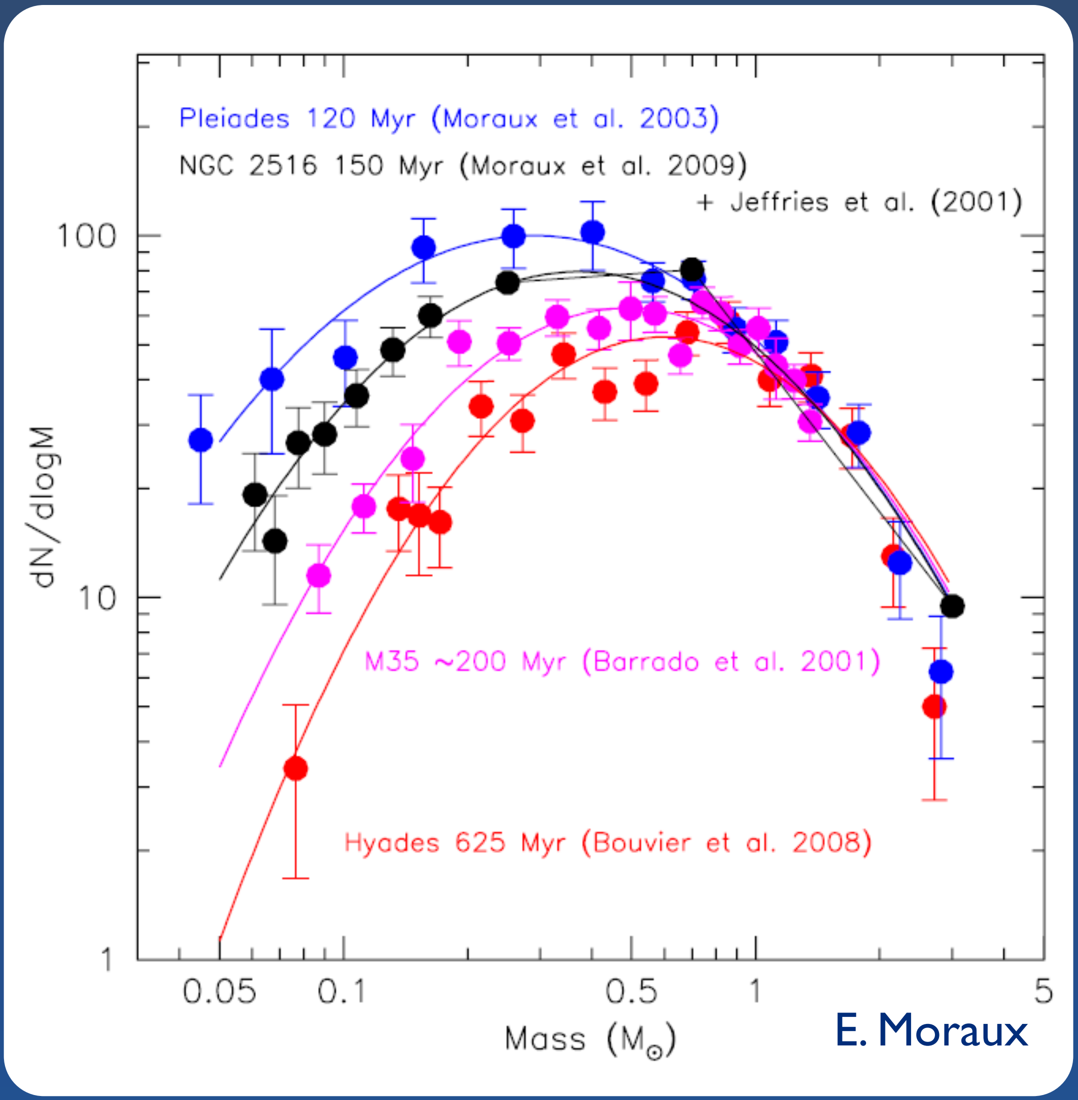
Studies of the IMF in the local Universe

- *"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

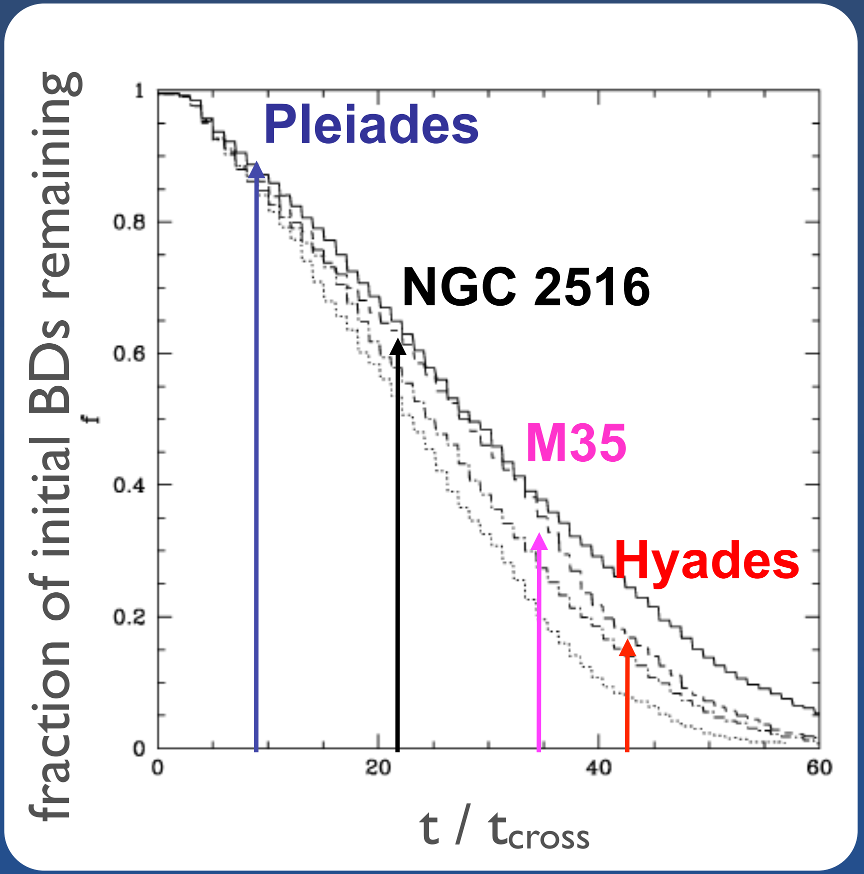


E. Moraux

Dynamical evolution of the Mass Function



Adams et al. 2002, MNRAS, 333, 547



Variations at the low-mass end of the IMF?

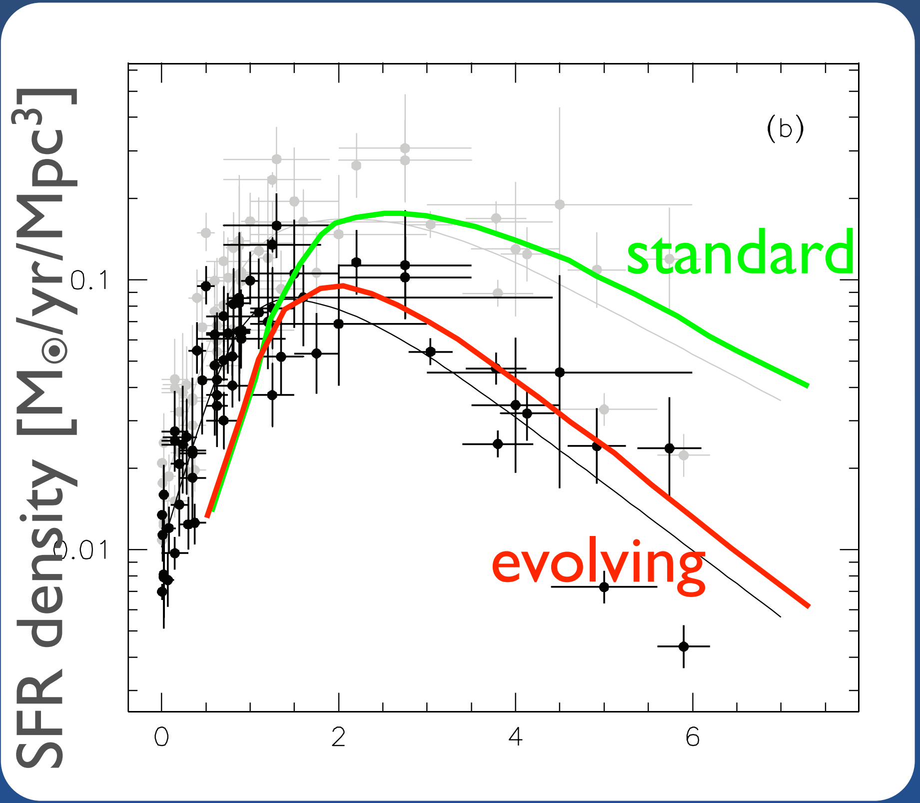
Cluster IMF across the substellar limit (~ 0.03 > 0.3 $M_\odot$)

Cluster	Age (Myr)	α (dn/dm ~ $m^{-\alpha}$)	References
ρ-Ophiuchus	1	0.7 ± 0.3	Alves de Oliveira et al. 2013, Muench et al. 2007, Luhman et al. 2003
ONC	1	0.3-0.6	Weights et al. 2009
NGC 1333	1	0.6 ± 0.1	Scholz et al. 2012, Winston et al. 2009
IC 348	2	0.7 ± 0.4	Alves de Oliveira et al. 2013, Muench et al. 2007, Luhman et al. 2003
σ-Ori	3	0.6 ± 0.2	Peña Ramírez et al. 2012, Caballero et al. 2012, Caballero et al. 2009; Béjar et al. 2011
Cha-I	3	No variation	Muzic et al. 2011, Muench et al. 2008, Luhman et al. 2007
λ-Ori	5	~0.3	Bayo et al. 2011
Upper Sco	5	No variation	Lodieu et al. 2013, Dawson et al. 2011

Alves de Oliveira

Does the IMF vary outside the Milky Way?

- Problem: difficult to observe due to degeneracy with star formation history, extinction, & metallicity



van Dokkum 2008, ApJ, 674, 29

z

Recent Extragalactic IMF determinations

Variations

Baugh et al. 2005
Hopkins & Beacom 2006
Fardal et al. 2007
Pflamm-Altenburg et al. 2007
Davé 2008
van Dokkum 2008
Hoversten & Glazebrook 2008
Wilkins et al. 2008a,b
Meurer et al. 2009
Lee et al. 2009
Pflamm-Altenburg et al. 2009
Treu et al. 2009
Auger et al. 2010
Treu et al. 2010
van Dokkum & Conroy 2010,2011
Spiniello et al. 2011
Weidner et al. 2011
Thomas et al. 2011
Dutton et al. 2011
Capellari et al. 2012

Top heavy

Bottom heavy

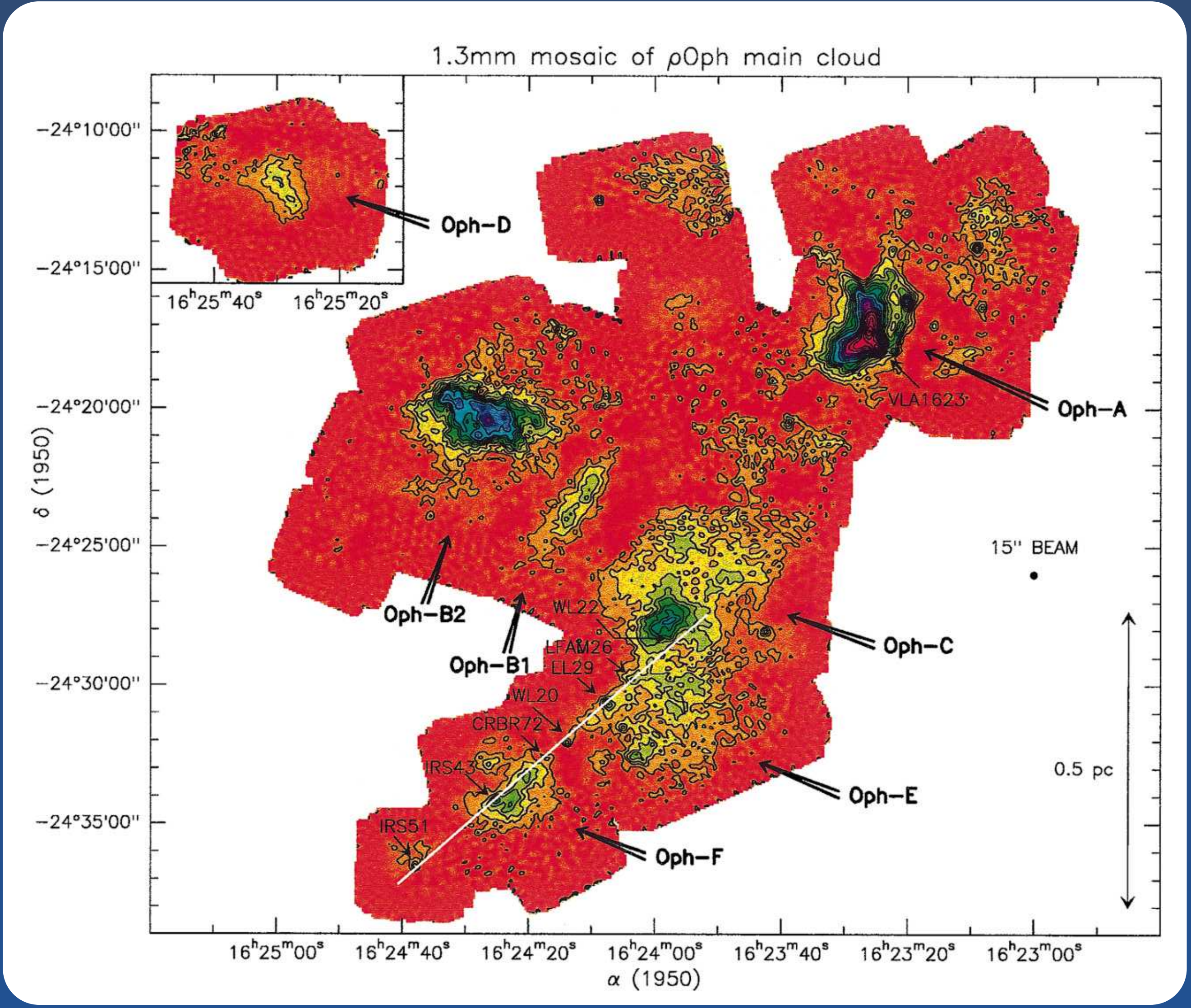
"Universal"

McCrady et al. 2005
Renzini 2005
McGaugh 2005
Cappellari et al. 2006
Bastian et al. 2006
Renzini 2006
Tacconi et al. 2008
Pettini et al. 2008
Banerji et al. 2009
Cappellari et al. 2009
Reddy & Steidel 2009
Quider et al. 2009
Hunter et al. 2010
Gogarten et al. 2010
Goddard et al. 2010
Weisz et al. 2011

What determines the IMF?

The Core Mass Function (CMF)

- Is the IMF related to how clouds fragment?



Motte et al. 1998, A&A, 336, 150

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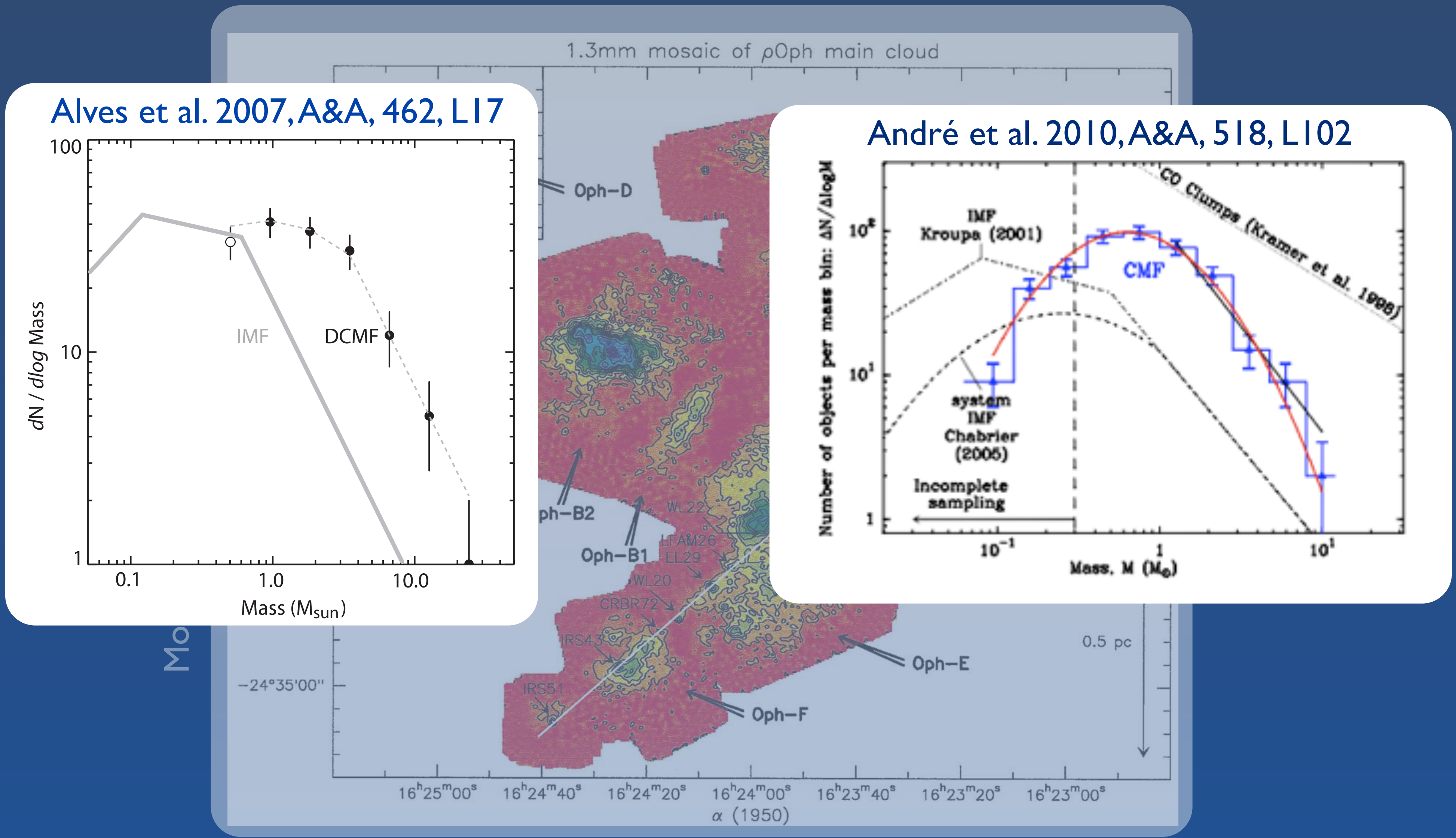
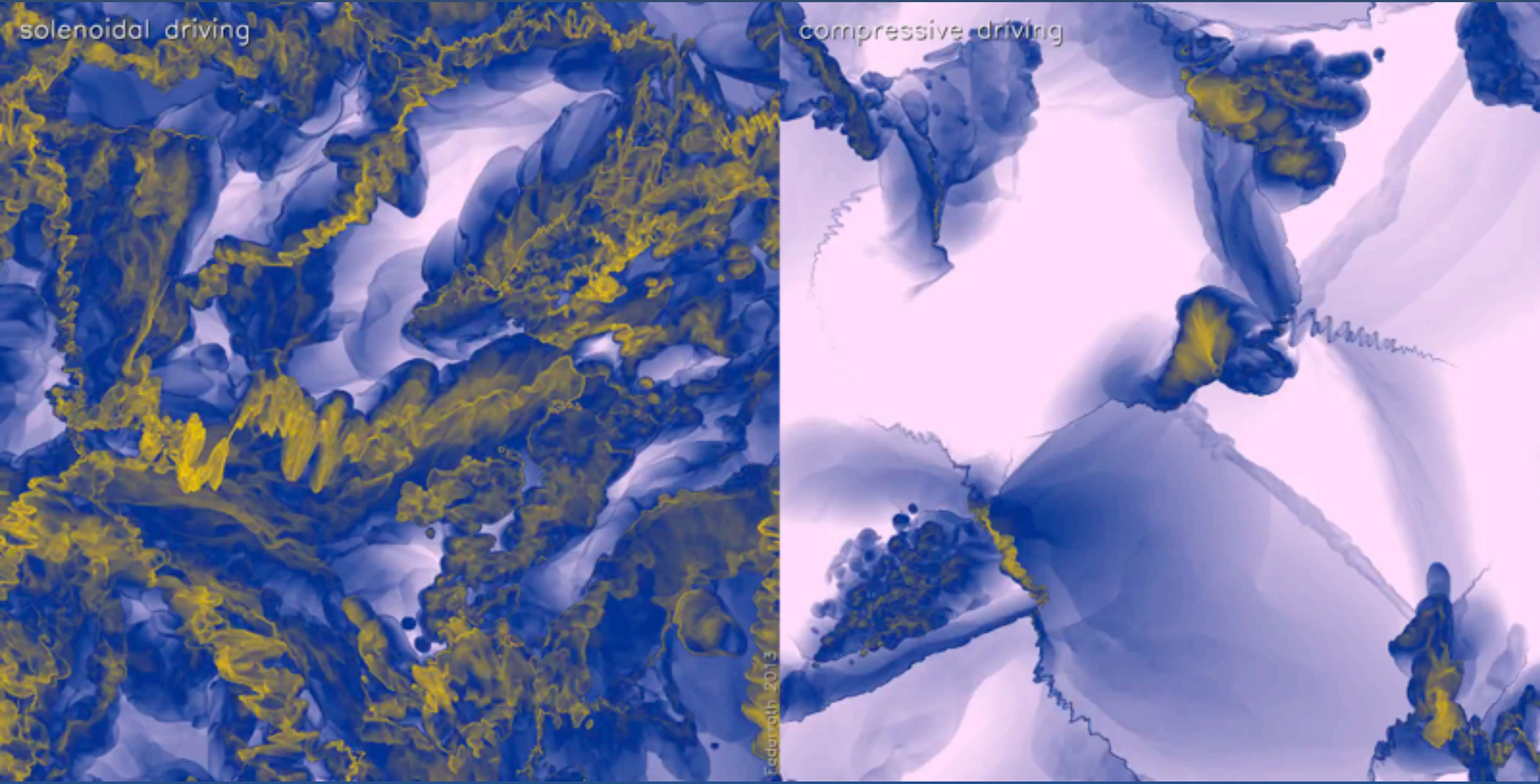


Does supersonic turbulence regulate cloud structure?

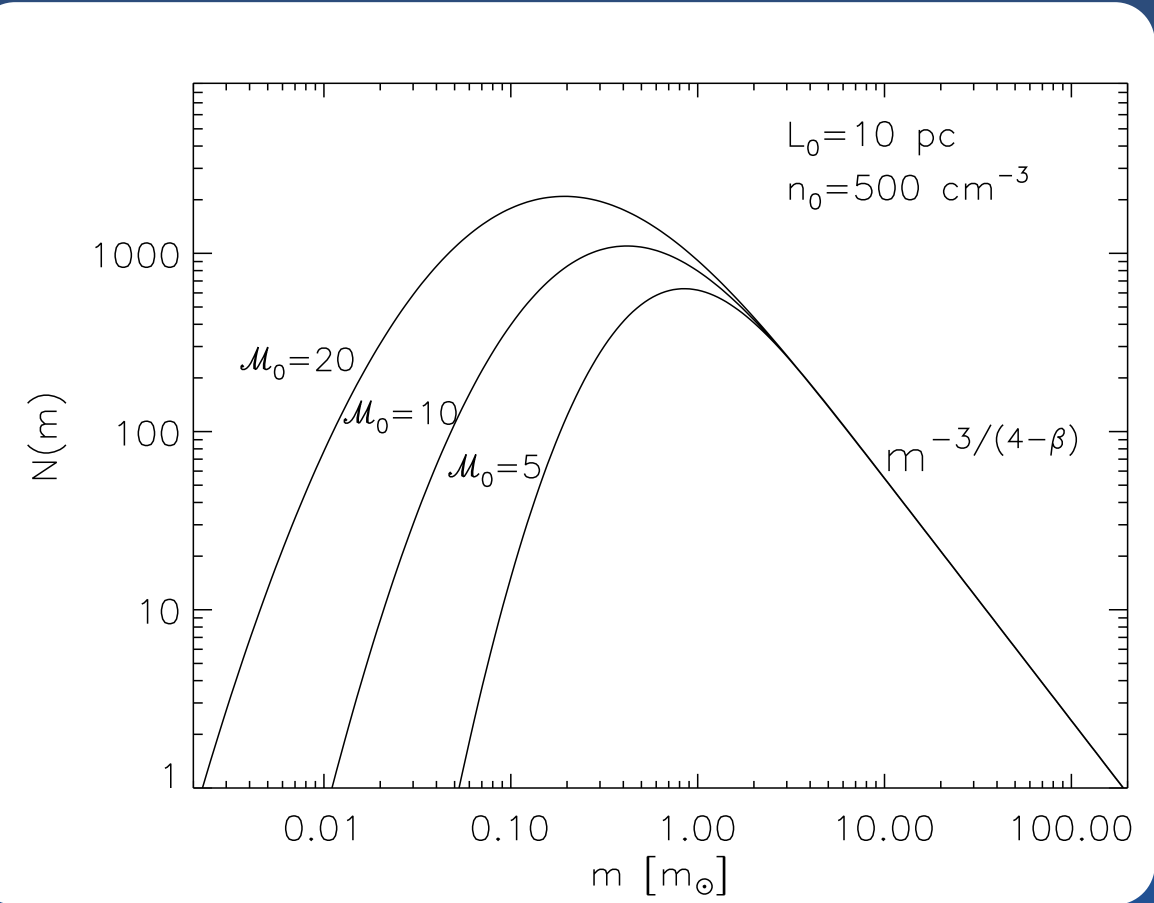


C. Federrath

The CMF from turbulent fragmentation

- Predict that location of CMF depends on Mach number + density of region
- Only considered thermal support
- Suffers from "cloud-in-cloud" problem

Padoan & Nordlund 2002, ApJ, 576, 870



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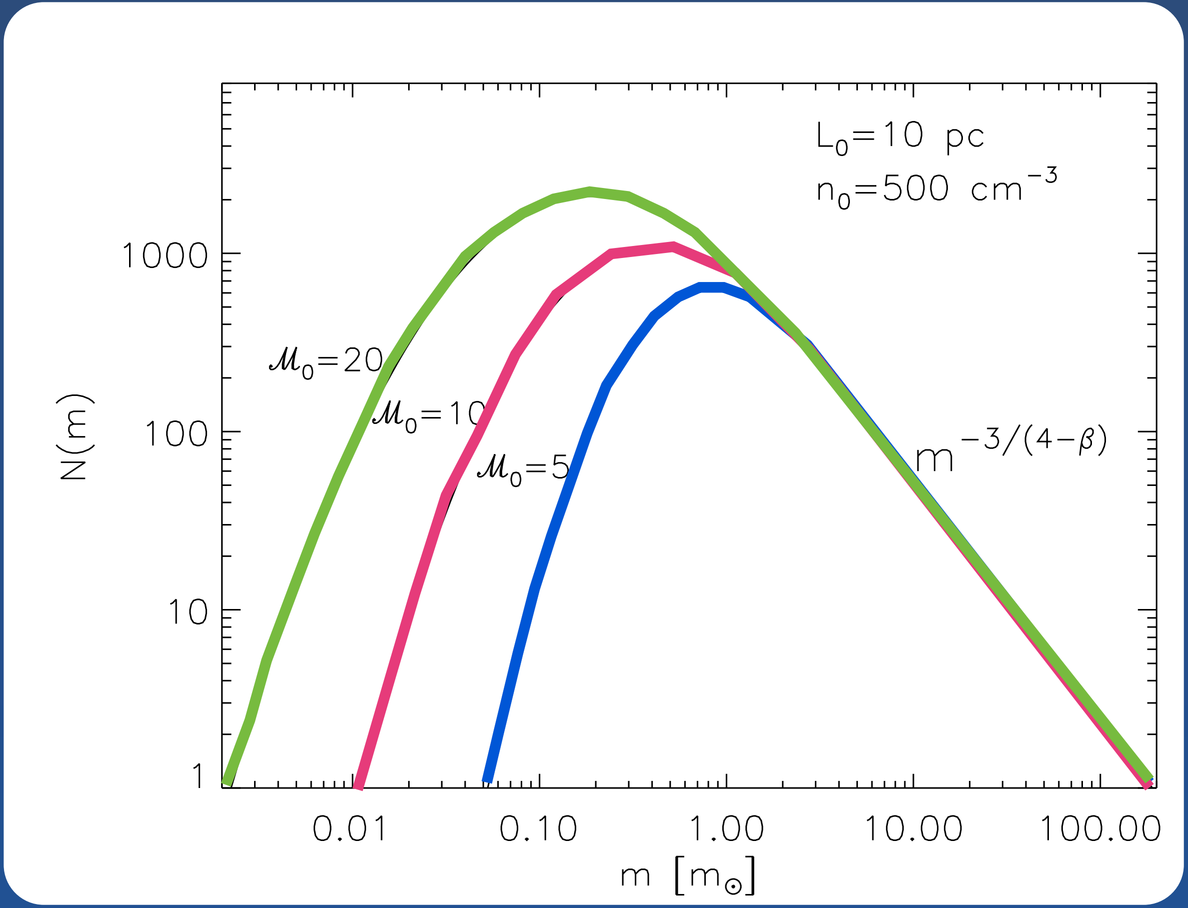
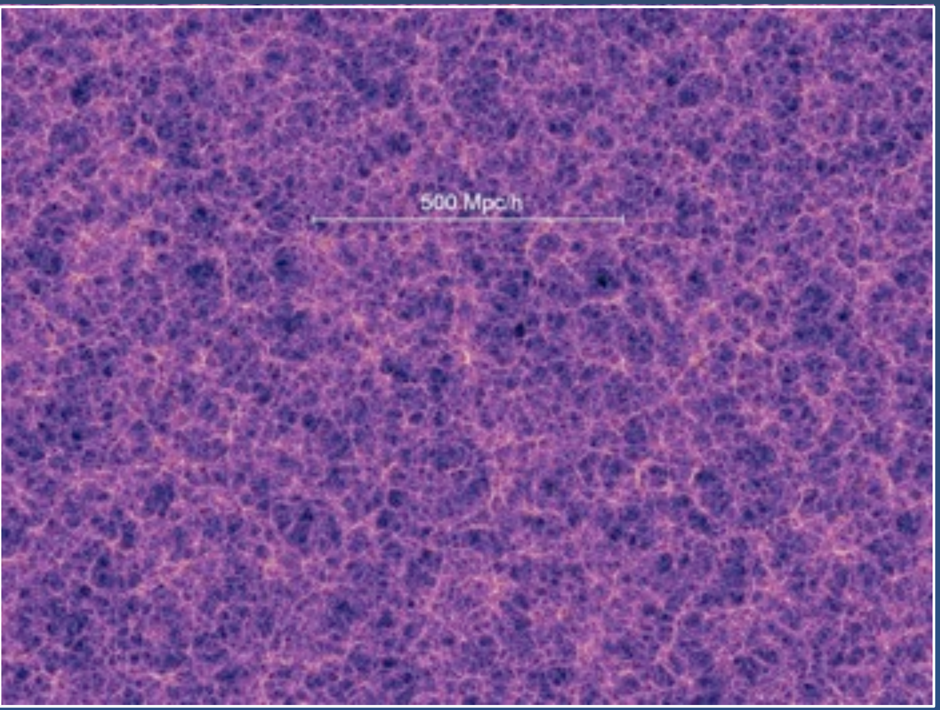


A solution from cosmology?



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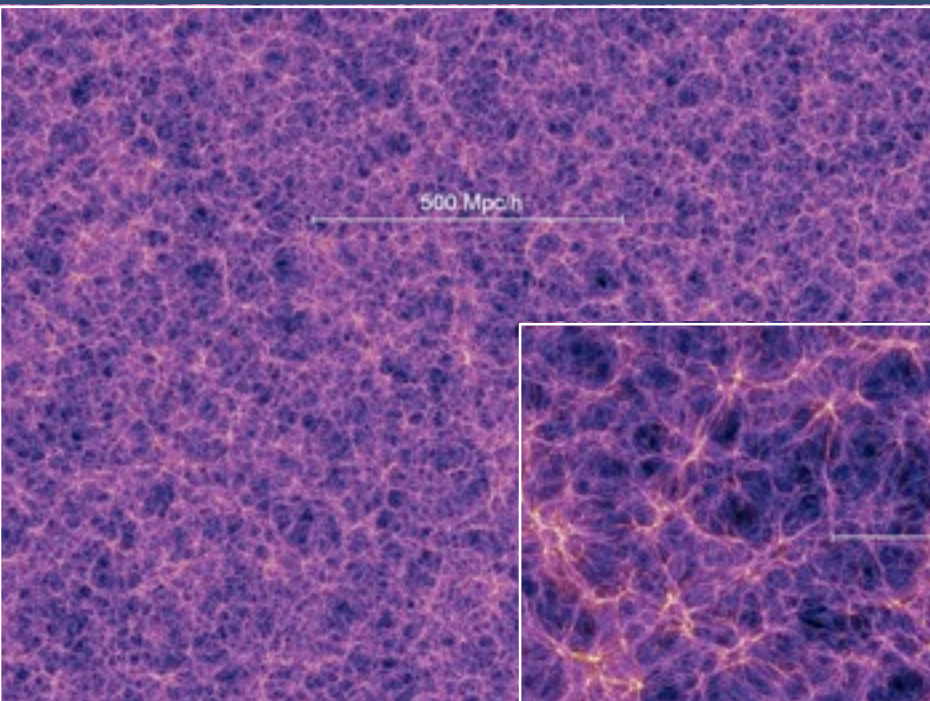
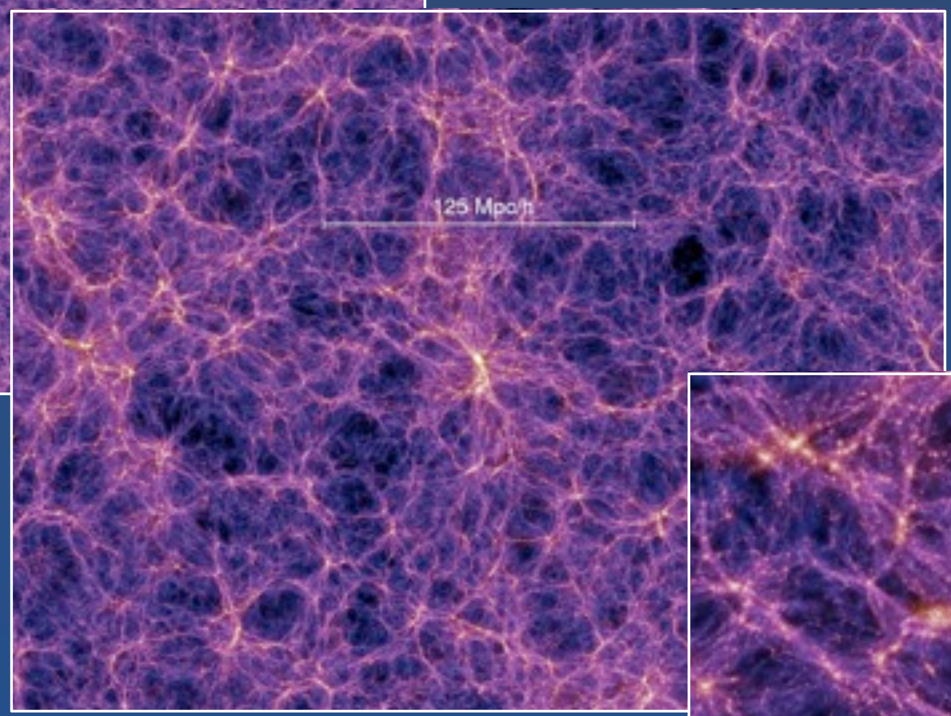
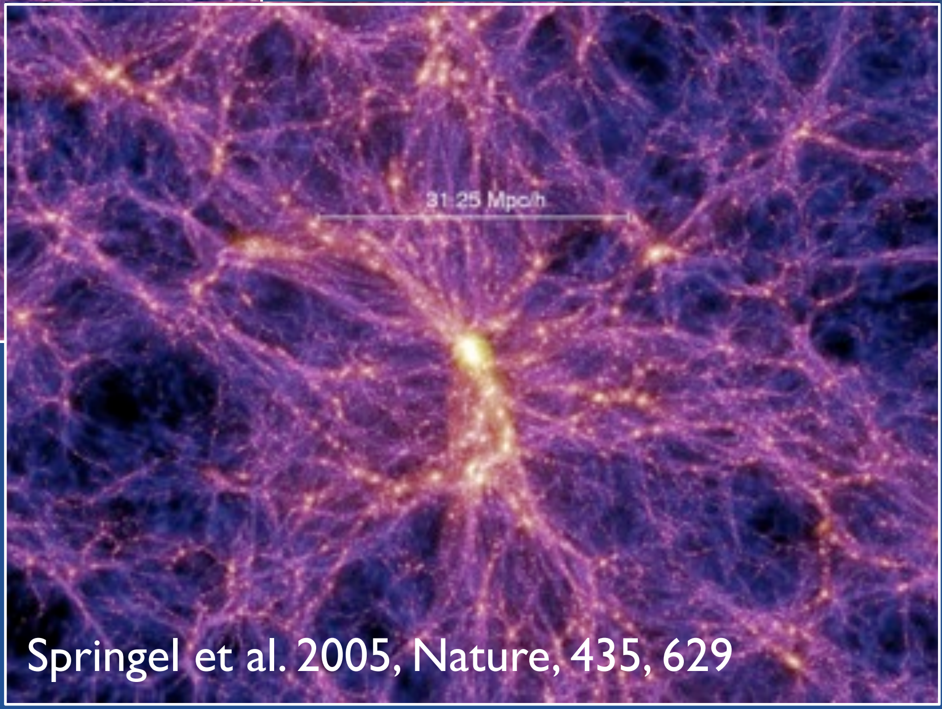


- Press & Schechter (1974)
- Excursion set (Bond et al. 1991)



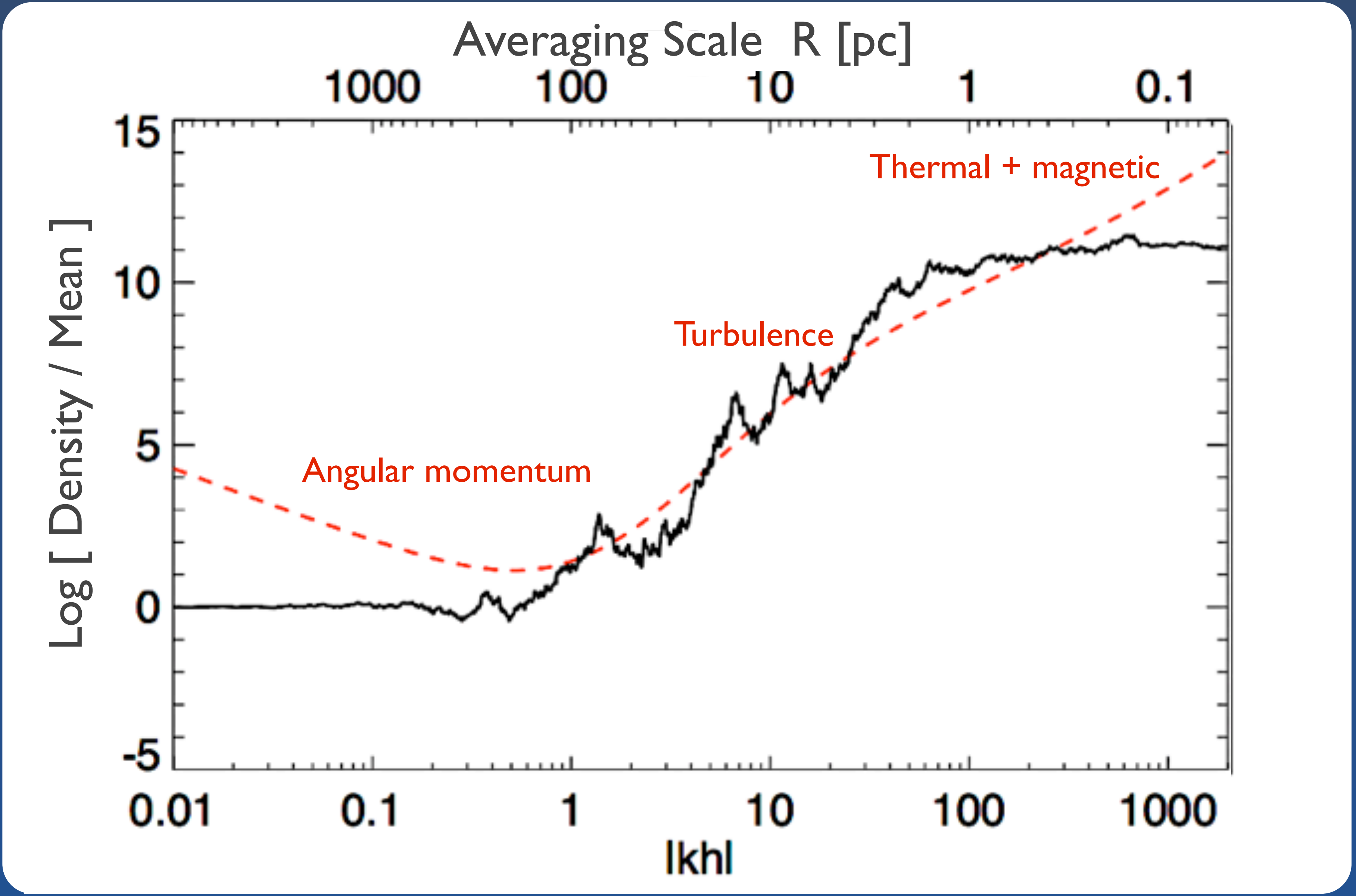


Springel et al. 2005, Nature, 435, 629

- “Count” mass above critical fluctuations
- Decouple from flow and gravitational collapse:

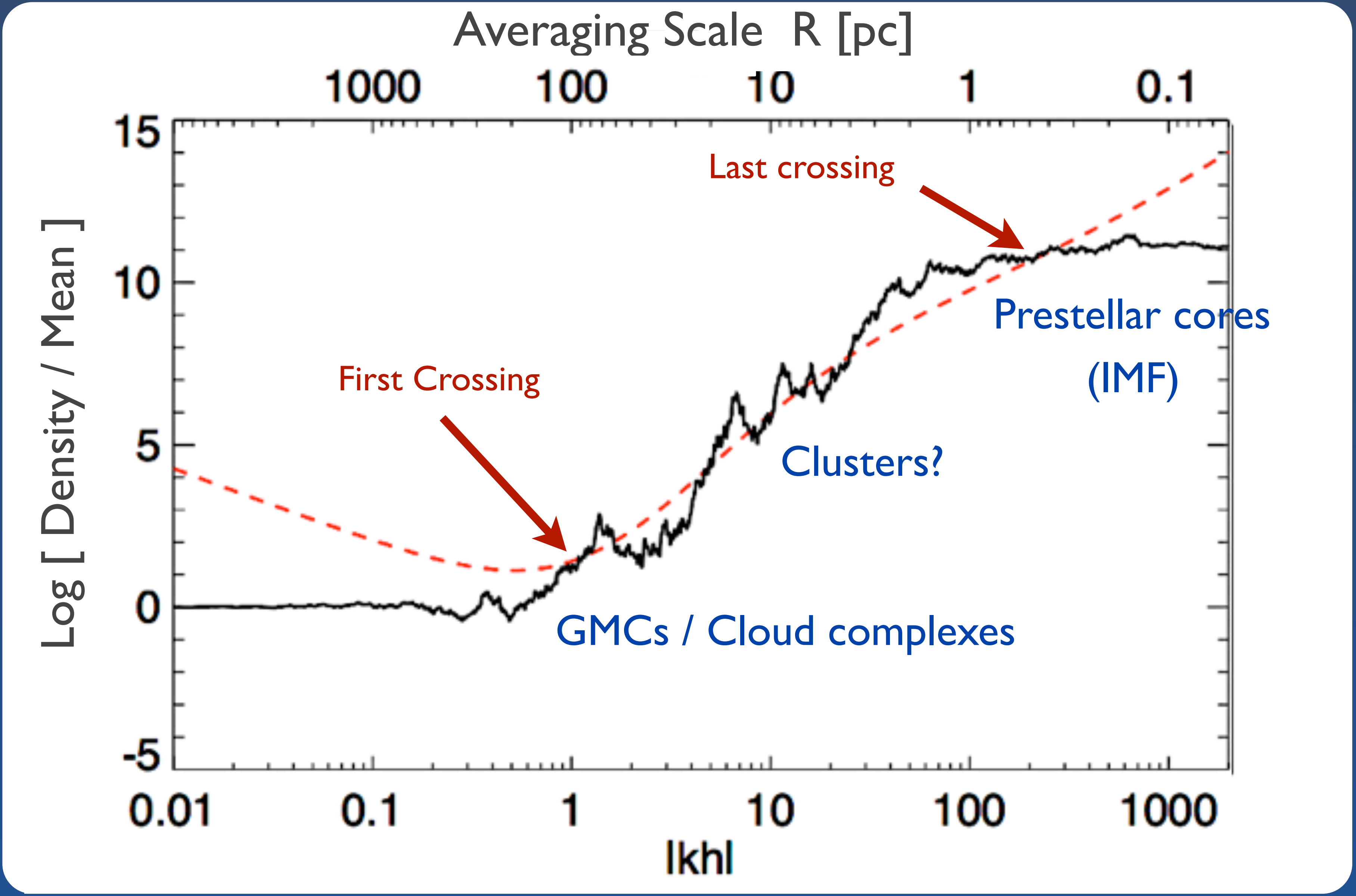
$$\bar{\rho}\ (< R \sim 1/k\ ) > \rho_{crit}$$

Breaking the density barrier



P. Hopkins

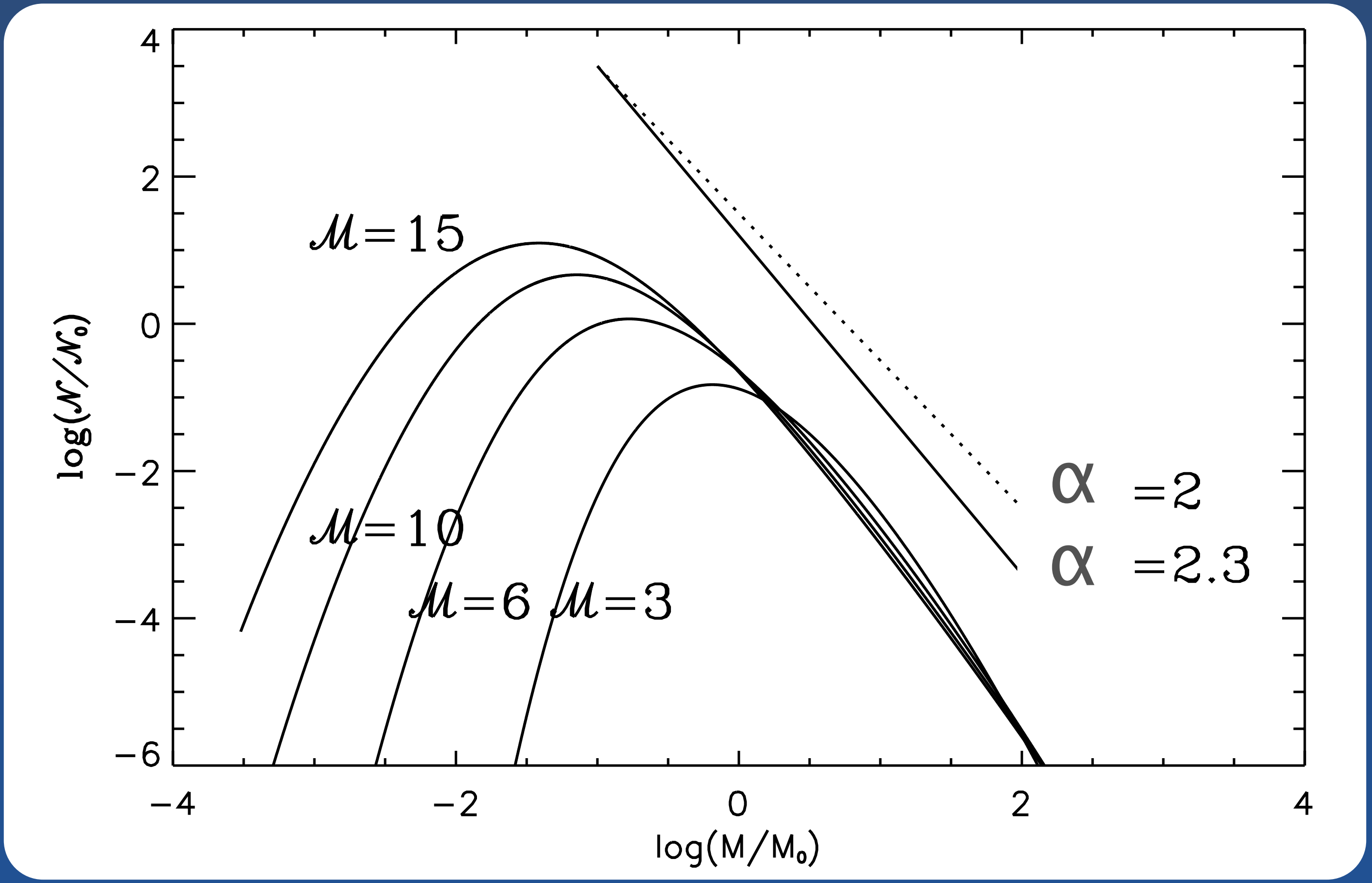
The "crossing" events



P. Hopkins

Hennebelle & Chabrier (2008)

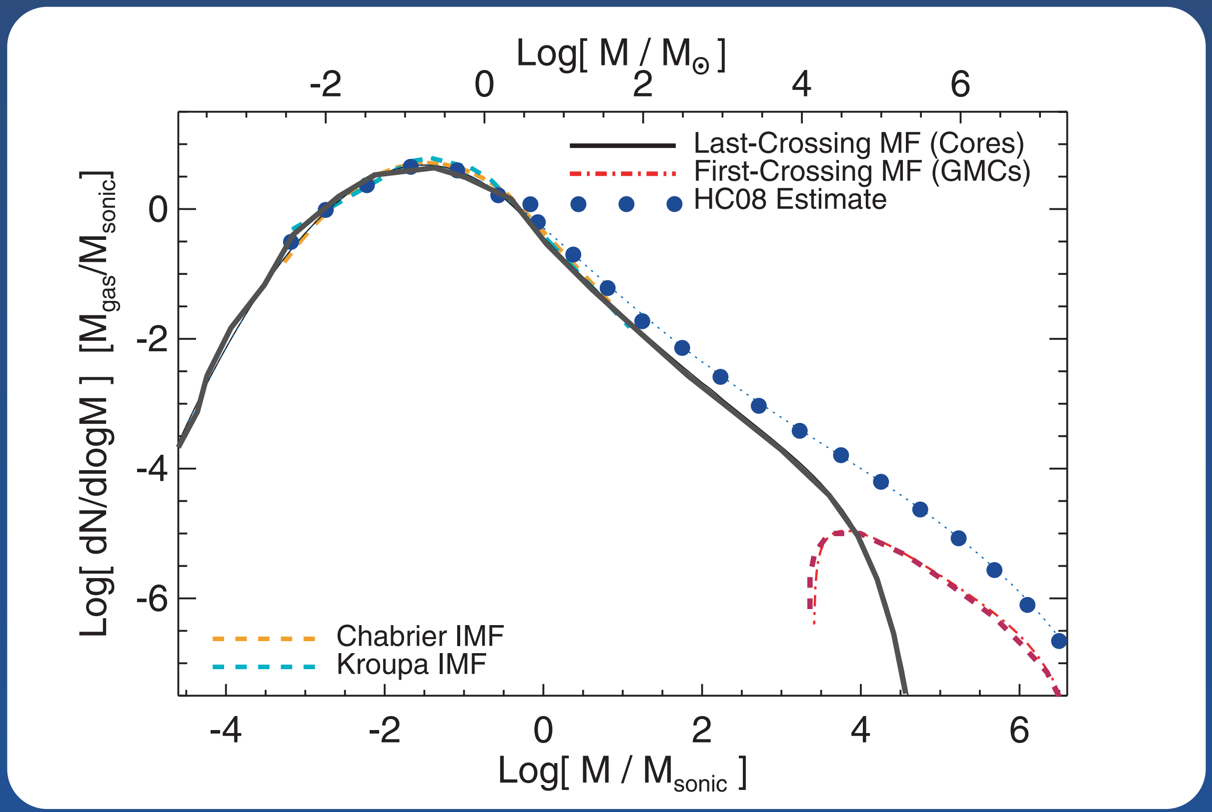
- Used Press-Schechter (1974) formalism to construct a mass function of gravitationally bound structures.
- Account for non-thermal support
- Again found IMF dependency on cloud parameters



Hennebelle & Chabrier 2008, ApJ, 684, 395

Hopkins (2012a,b, 2013)

- Excursion-set version formalism -- designed to deal with cloud-in-cloud problem
- Can look at multiple "crossings" in the energy hierarchy
- Separates bound GMC complexes from clusters and stars



Hopkins 2012, MNRAS, 423, 2016

Summary of turbulent fragmentation

- Turbulent fragmentation theories predict a population of cores (or "reservoirs") than have a mass function (the CMF) that resembles the IMF.
- However, in some theories, the characteristic mass for star formation changes with the Mach number/cloud properties.
- Potential to make a powerful prediction.

So is the IMF solved?!

What is the relation between CMF and IMF ?

A connection between CMF and IMF implies...

Cores must:

- Neither accrete nor merge with siblings (or they must do so in a way that preserves the shape of the CMF)
- Fragment self-similarly (i.e. into roughly the same number of fragments)
- Have the same star formation efficiency, regardless of mass
- Form stars on a similar timescale
- Actually be capable of forming stars... (i.e. gravitationally bound)

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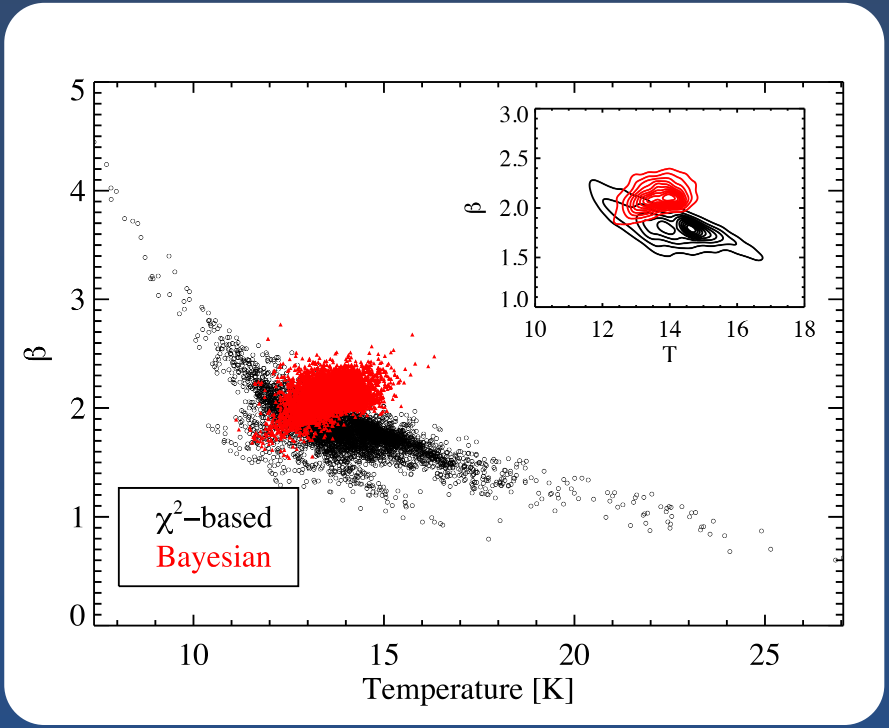
Are observed cores "prestellar" ?

- Mass derived from column densities.
- Obtained mainly from dust emission
- Problem: flux from dust depends on T and dust properties
- Number of "Jeans masses" $\propto T^{-3}$

Kelly et al. 2012, ApJ, 752, 55



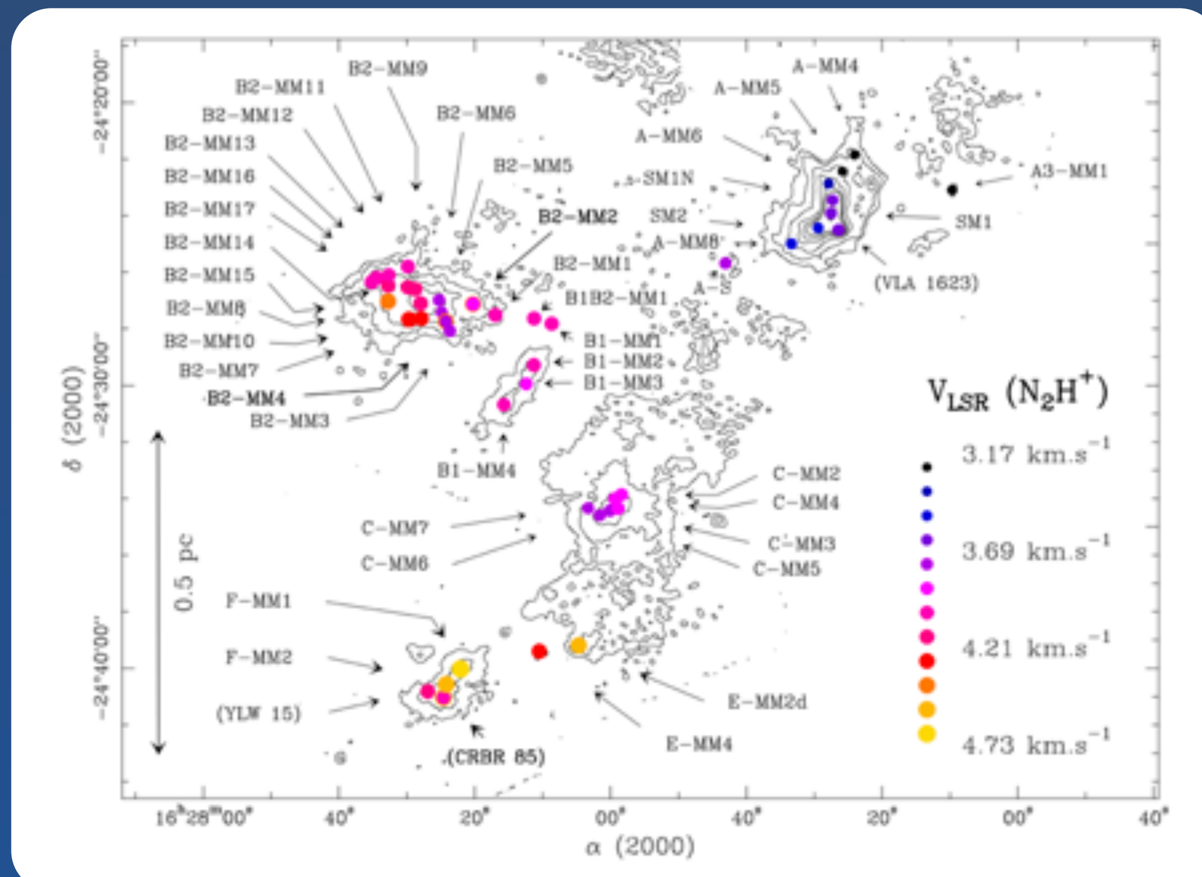
Ragan et al. 2012, A&A, 5 547, 49

Are observed cores "prestellar"...?

• Magnetic field estimates are extremely difficult

• Tend to be consistent with $E_{mag} < E_{therm}$ -- but perhaps only marginally (Crutcher et al. 2009).

• Kinetic energy estimates are easier to obtain ... but only exist for small fraction of cores



André et al. 2007, A&A, 472, 519

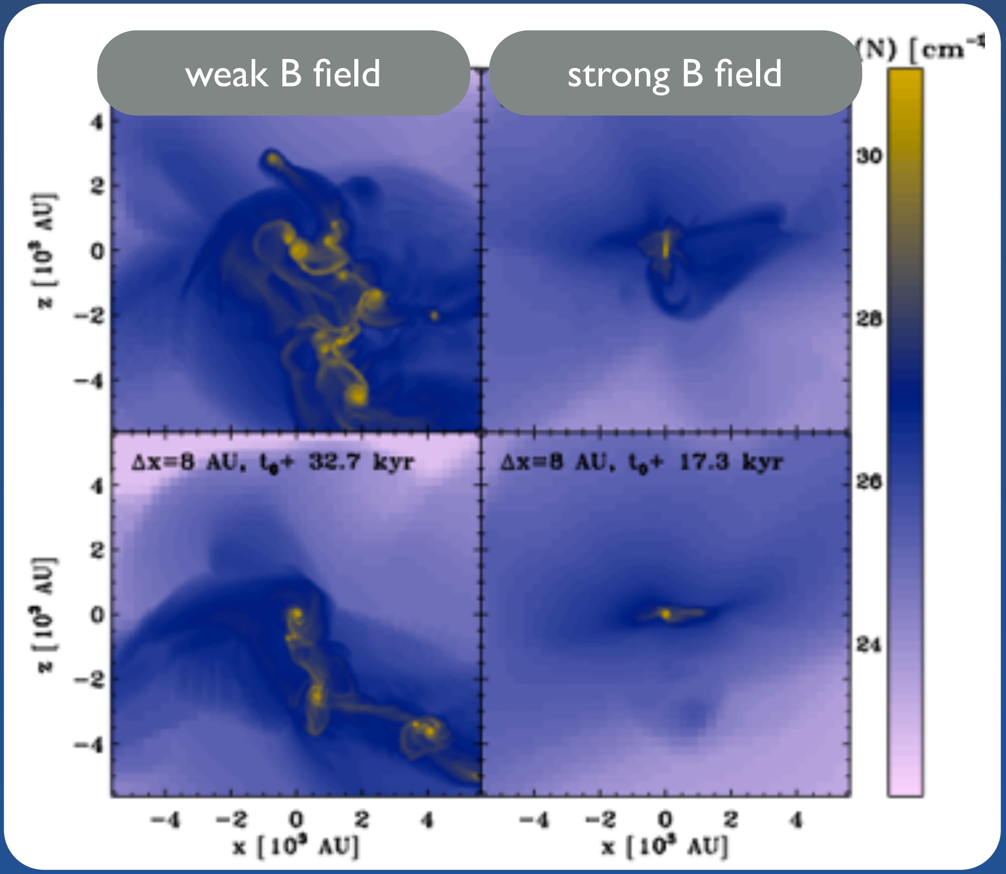
Fragmentation within cores?

• Cores need to fragment self-similarly if the mapping between CMF and IMF is to be preserved

• Need to prevent high-mass cores fragmenting into full clusters if the Jeans mass is low!

• Radiative feedback and magnetic fields can inhibit fragmentation

• However can depend on the geometry and properties (e.g. turbulence)

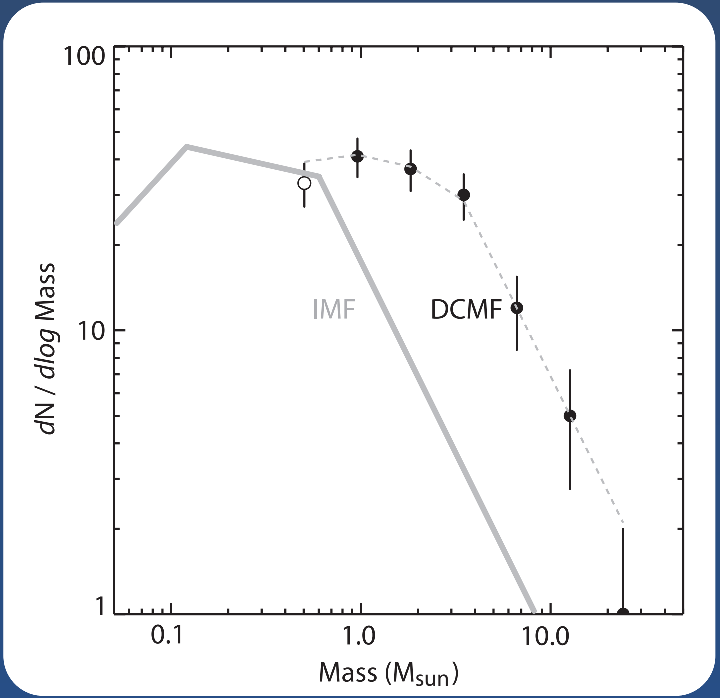


Commerçon et al. 2011, ApJL 742, L9

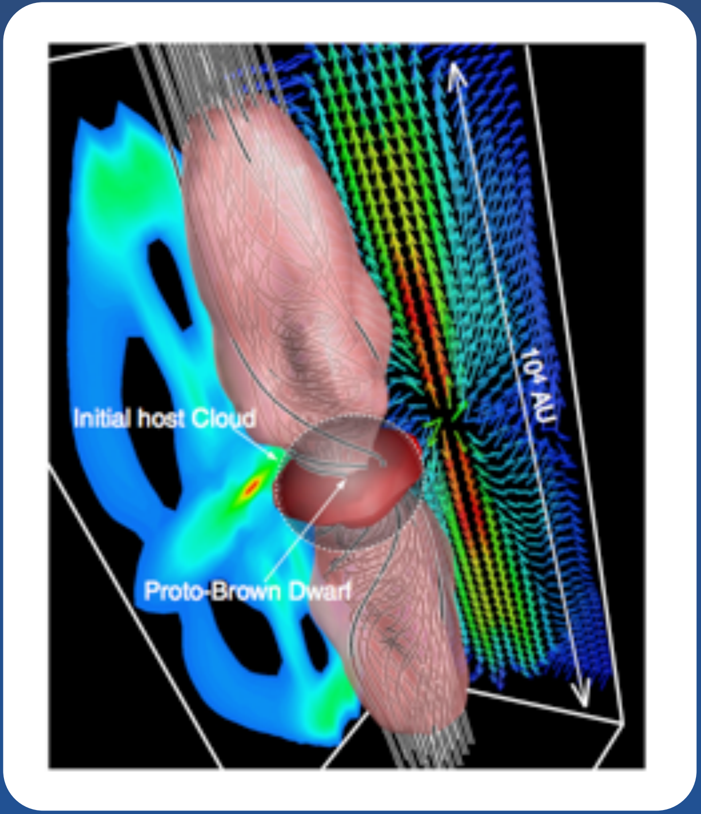
Star formation efficiency within cores

- CMF peaks at higher masses than IMF
(Alves et al. 2007; Nutter et al. 2007; Enoch et al. 2008, André et al. 2010)
- Implies a 30% to 50% efficiency (for single stars or binaries/multiples)

Alves et al. 2007, A&A, 462, L17



Machida et al. 2009, ApJL, 699, L157



- Self-regularisation of the efficiency has only been tested in a few cases (e.g Machida et al. 2009, Seifried et al. 2012, Price et al. 2012) and for idealised physics.

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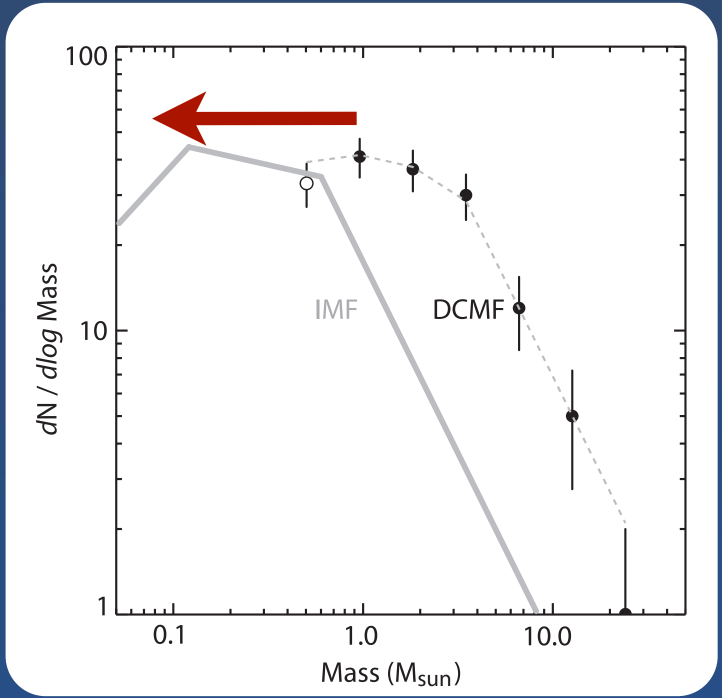

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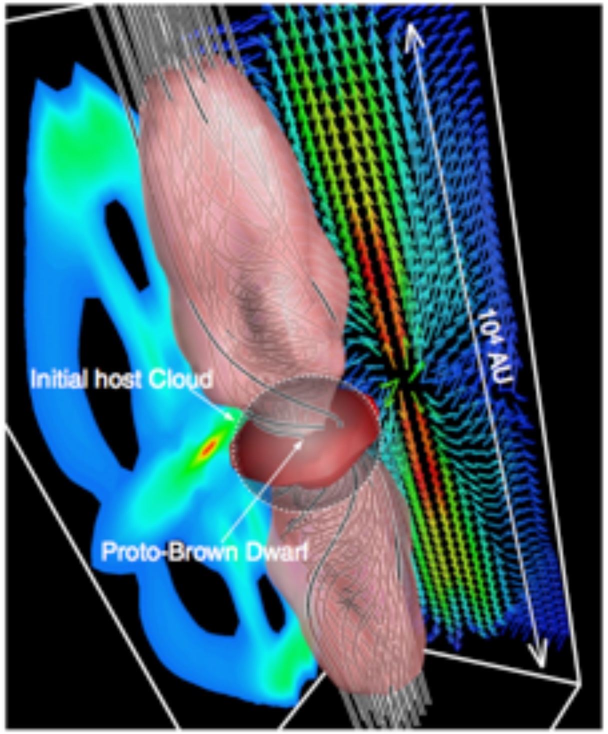

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An emerging picture of the core phase

- Community is still developing a picture of where cores fit into the puzzle.
- Some aspects remain an enigma:
    - Cores in The Pipe look like the IMF... yet are not bound (pressure confined)
    - CMF in Aquila has a (roughly) similar shape to those in nearby regions, yet also unbound, **and** shifted to much lower masses.
- Observationally, the key may be in constraining the Class 0 CMF

Numerical simulations as a test-bed for IMF theory

- Numerical simulations allow us to perform experiments
- Can explore which bits of physics can alter the IMF
- Focus has mainly been on end-products of the simulations (i.e. the properties of the 'sink particles')

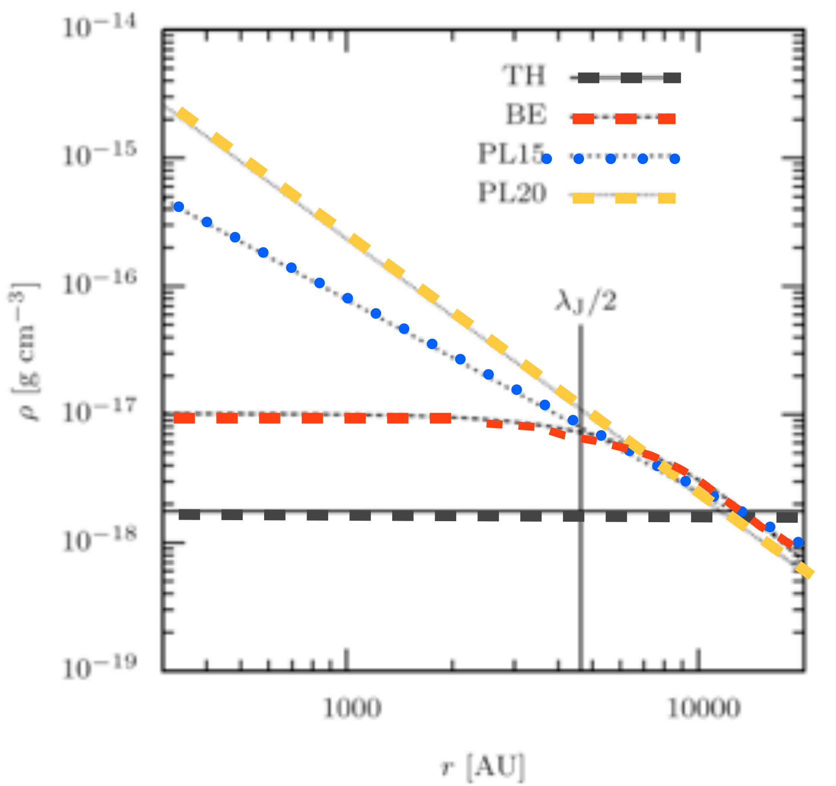
Properties that impact the IMF (in simulations) **but probably shouldn't**

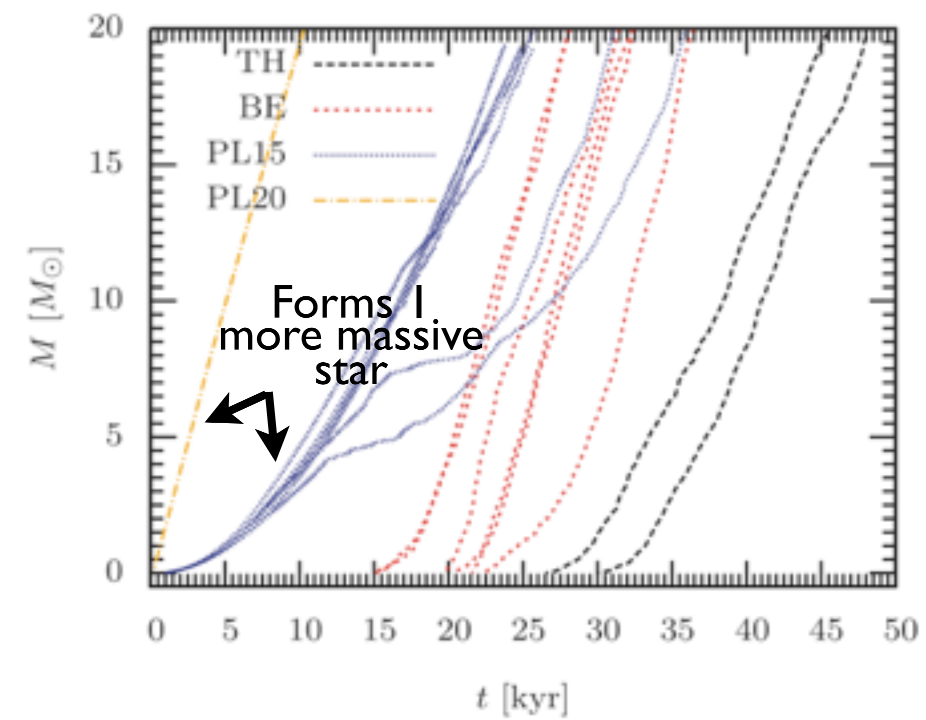
Initial conditions: (temperature, density)

Should not impact the IMF

- Thermal jeans mass (Klessen et al. 1998; Bate & Bonnell 2005; Jappsen et al. 2005; Bonnell et al. 2006, Larson 2005)
- Initial density/cloud profile
- Turbulent driving scale (although not well constrained)

Girichidis et al. 2011, ApJ, 413, 2741





Girichidis et al. 2011, ApJ, 413, 2741

Properties that do not Impact the IMF

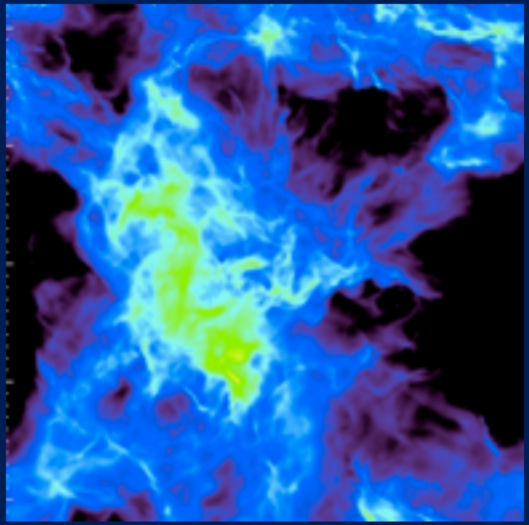
(simulations and observations generally agree)

Cloud initialisation

Does not impact the IMF

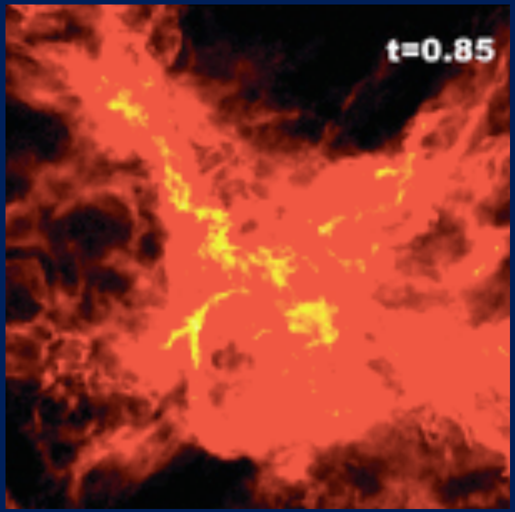
- Simulations of isolated cloud and pieces of clouds can reproduce the observed IMF

Periodic Box



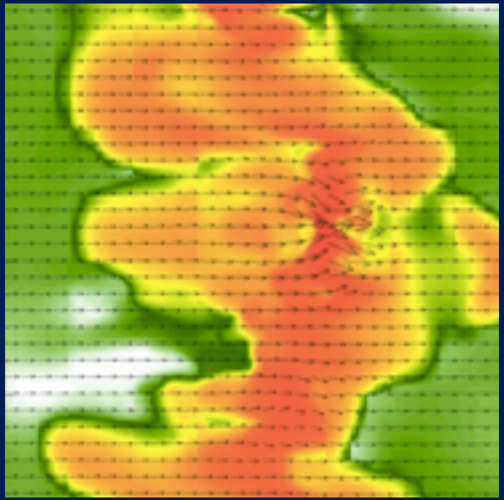
Krumholz et al. 2012, ApJ, 754, 71

Isolated Cloud (Constant Density Sphere)



Bate 2012, MNRAS,419, 3115

Colliding Flows



Vazquez-Semadeni et al 2011, MNRAS, 414, 2511

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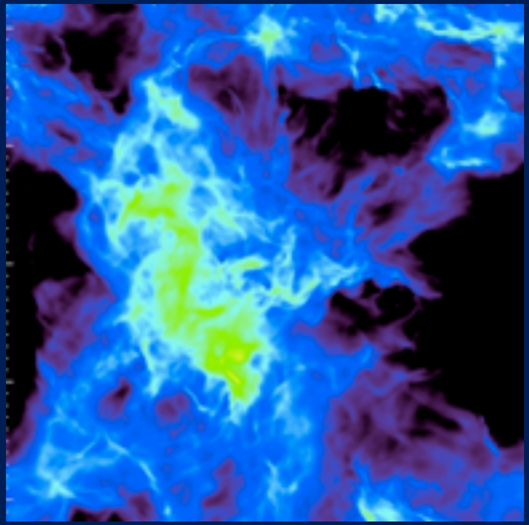

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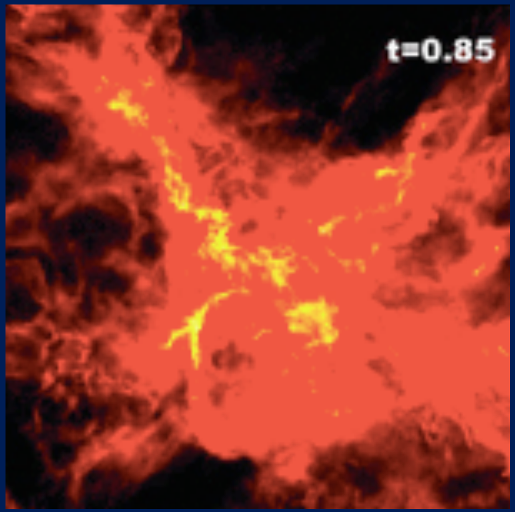

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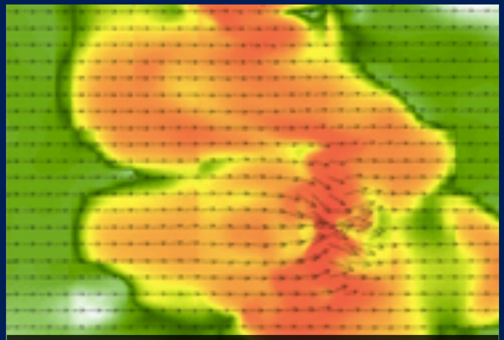


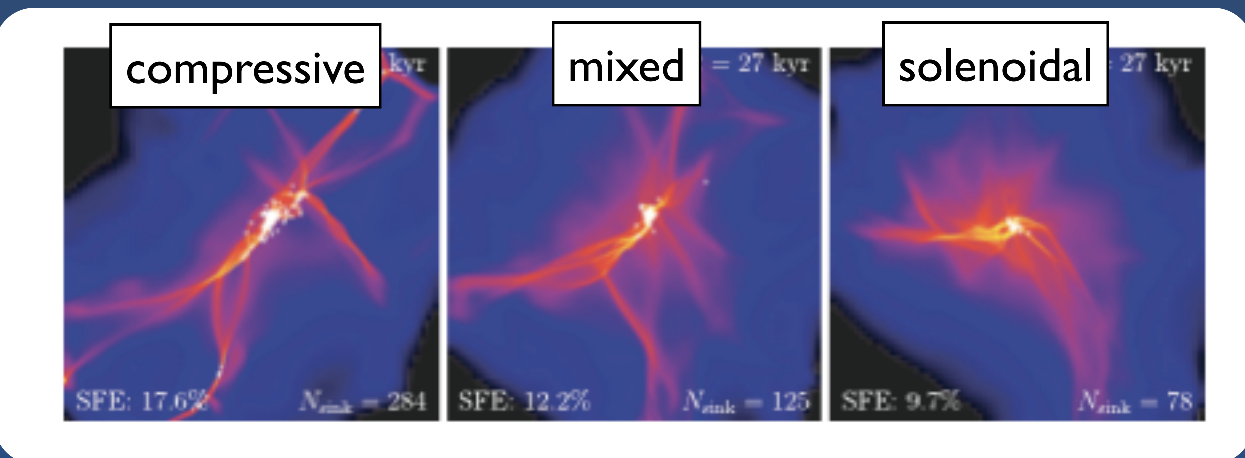
Still need higher resolution to determine an IMF

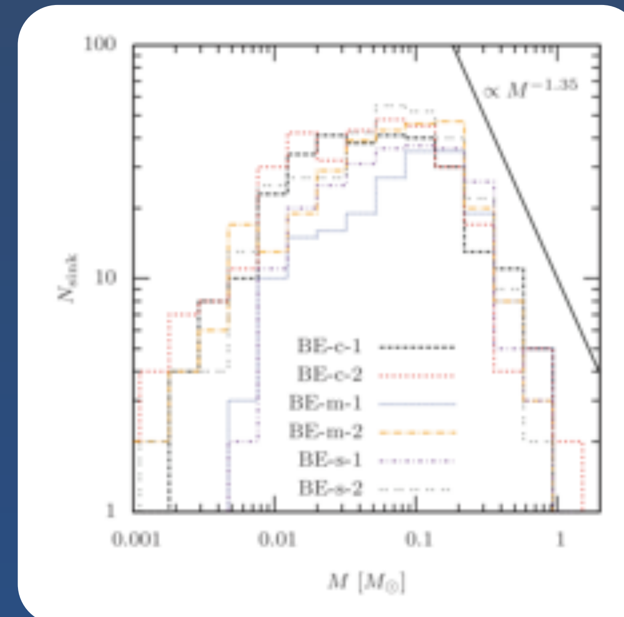
Vazquez-Semadeni et al 2011, MNRAS, 414, 2511

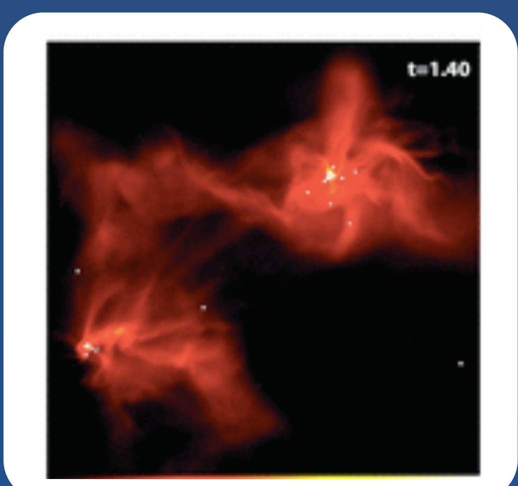
Does not impact the IMF

Turbulence properties

Girichidis et al. 2011, MNRAS, 413, 2741



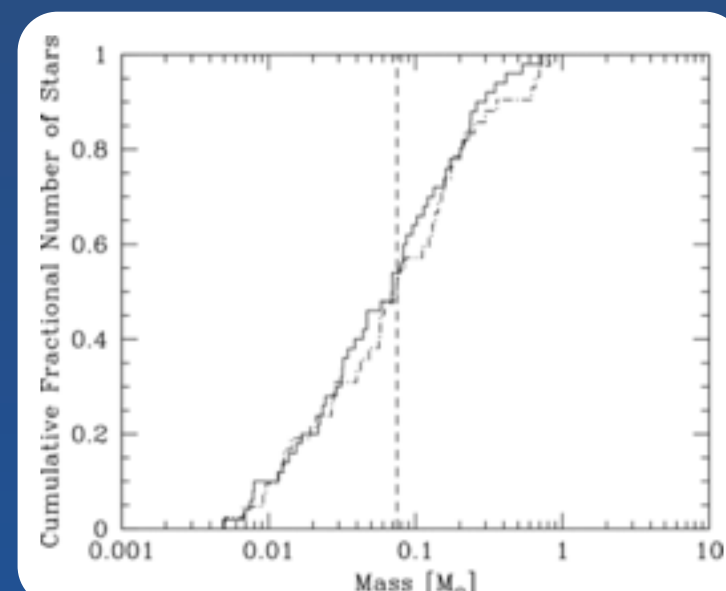




Bate 2009, MNRAS, 397, 232

Turbulent Power Spectrum

$P(k) \propto k^{\beta} : \beta = -4, -6$

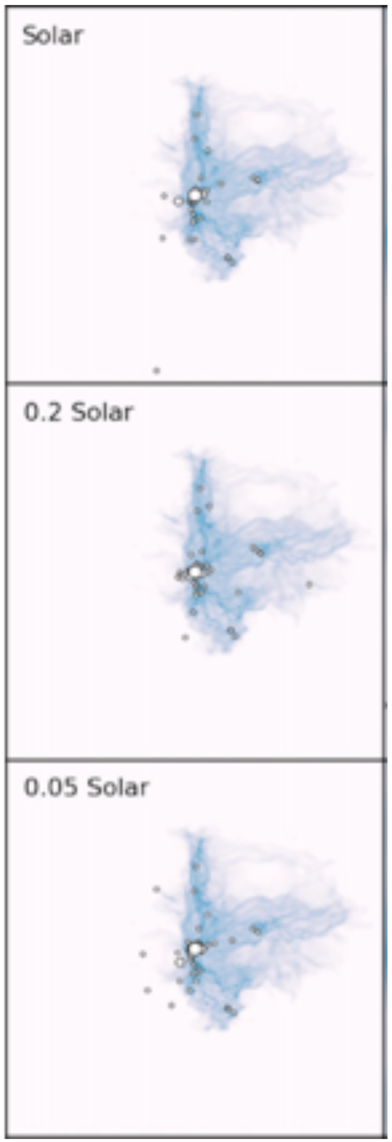


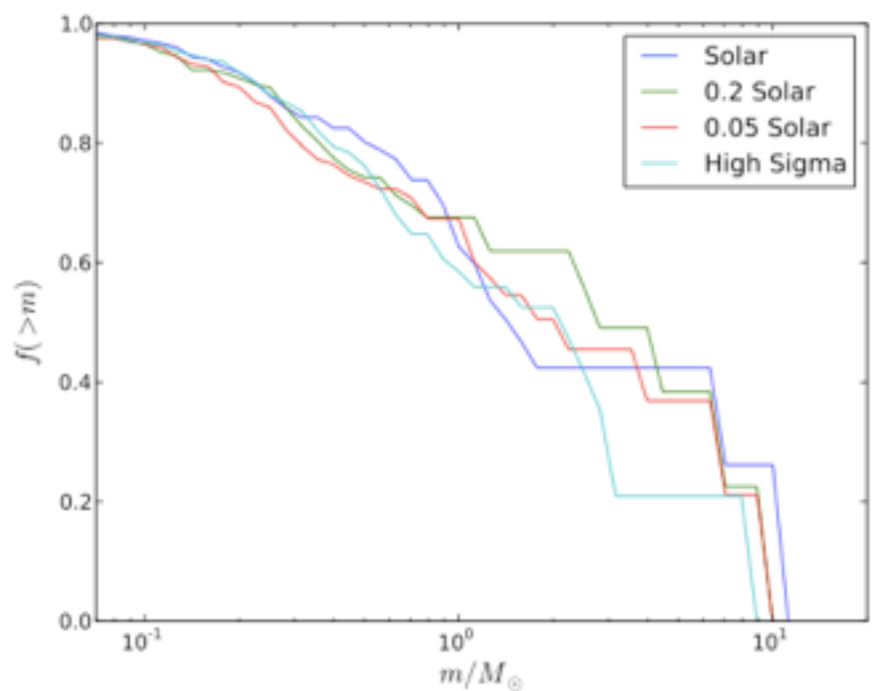
Does not impact the IMF

Thermal assumptions

- Variation in metallicity by a factor of 20 does not change the IMF (see also poster by Bate: 1G018)
- Need to go to much lower metallicities (< 10^{-5} $Z_\odot$) before changes are seen (Clark et al. 2008, 2011; Dopcke et al. 2011, 2012)

Myers et al. 2011, ApJ, 735, 49





Myers et al. 2011, ApJ, 735, 49

Properties that impact IMF

(and simulations suggest are necessary)

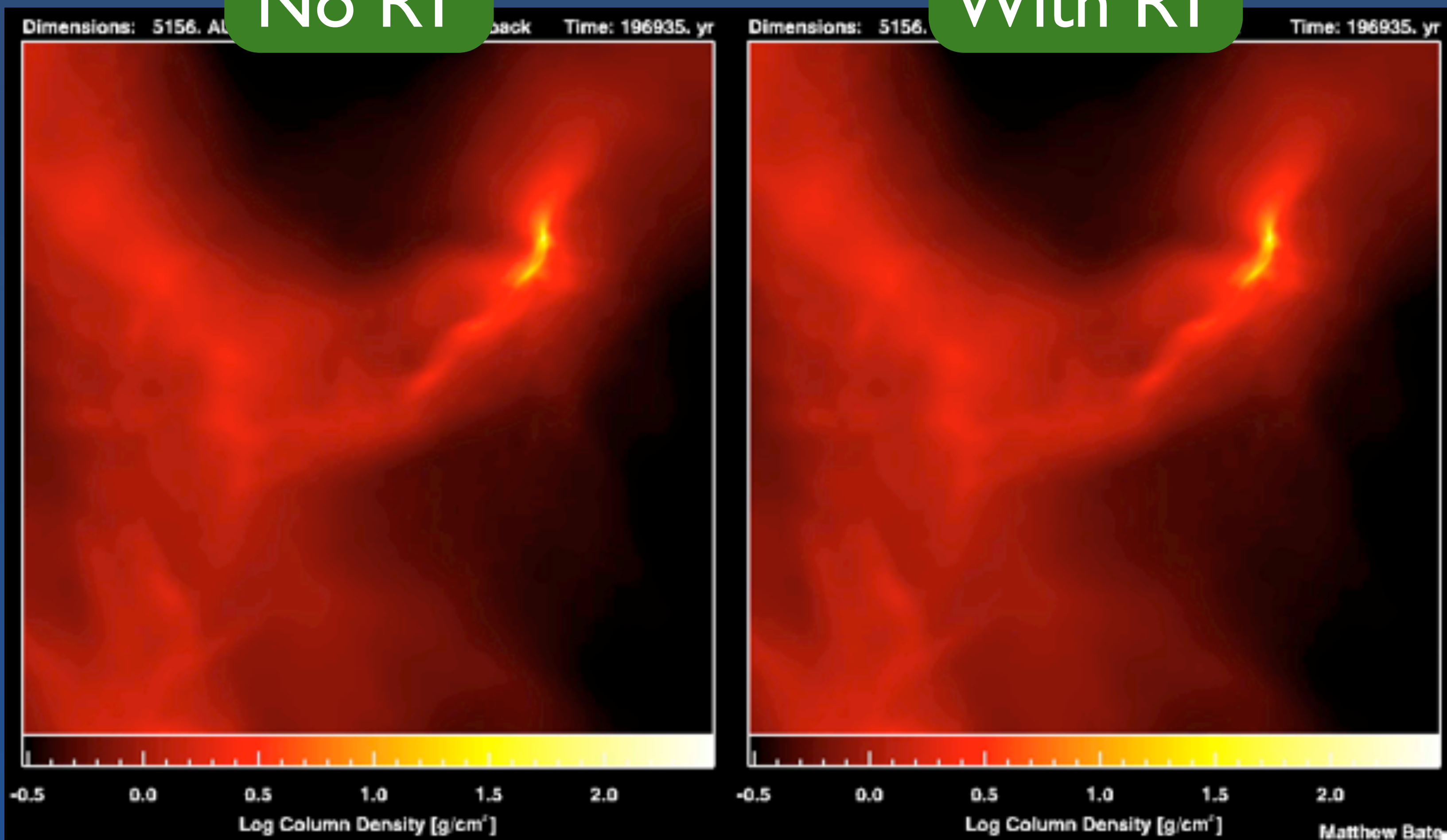
Does impact the IMF

Radiation Transfer (RT)

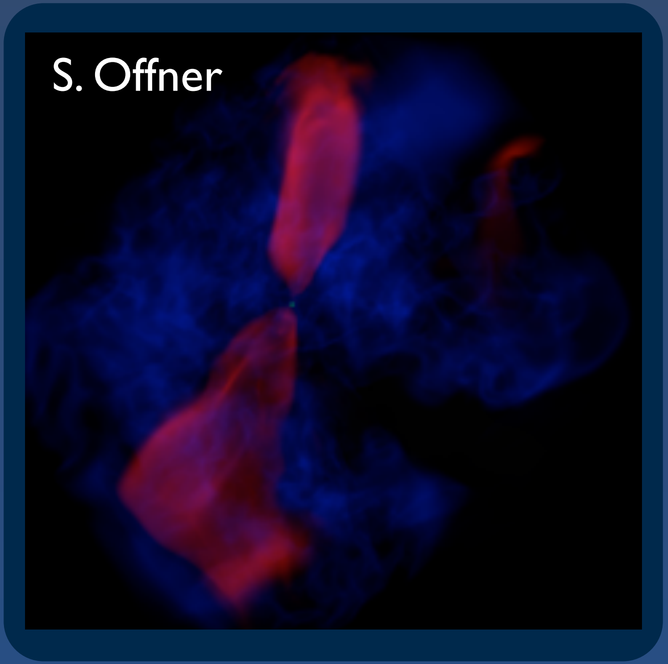
Without radiation transfer there are too many BDs

No RT

With RT



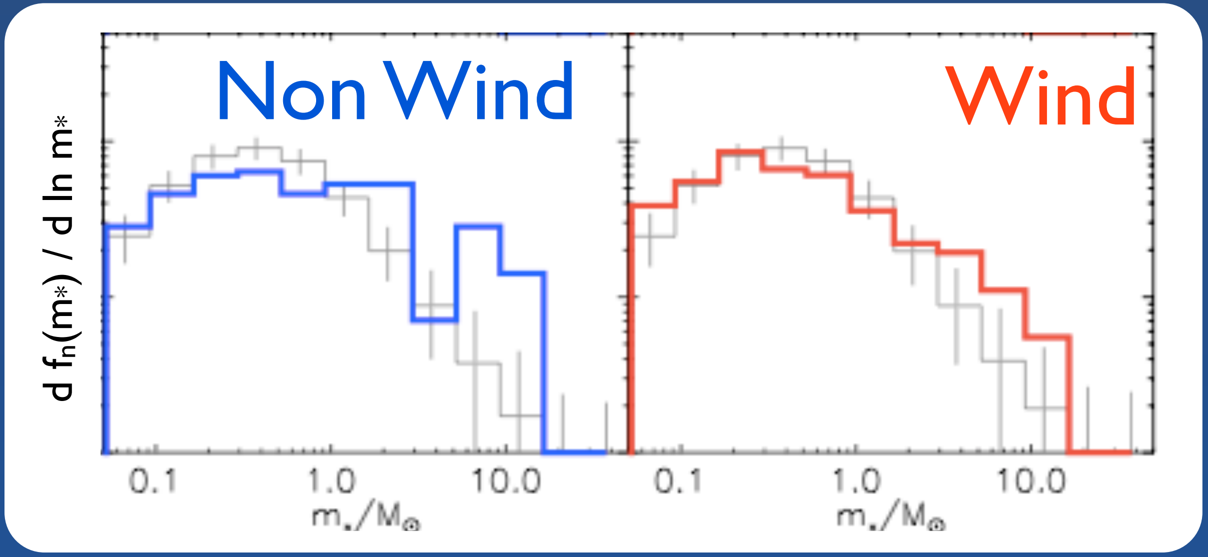
Kinetic feedback

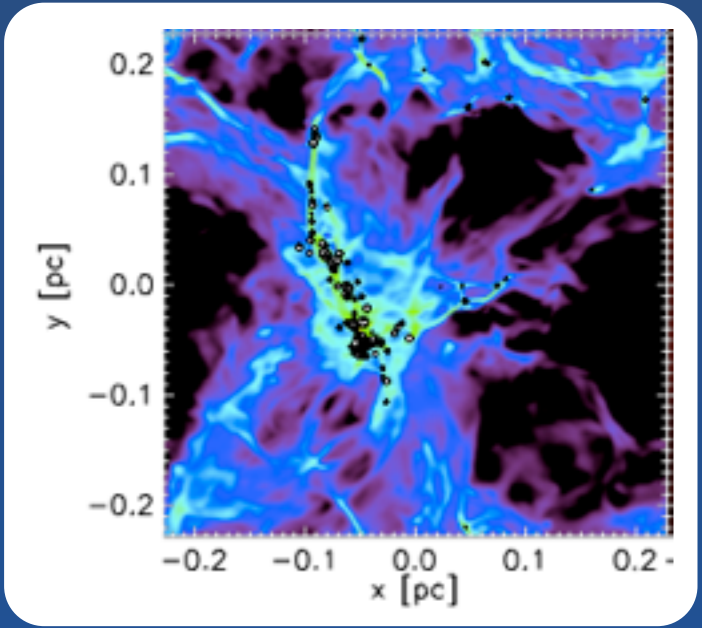


Outflows drive turbulence and lower the characteristic stellar mass

See also: Li et al. 2010; Hansen et al. 2011

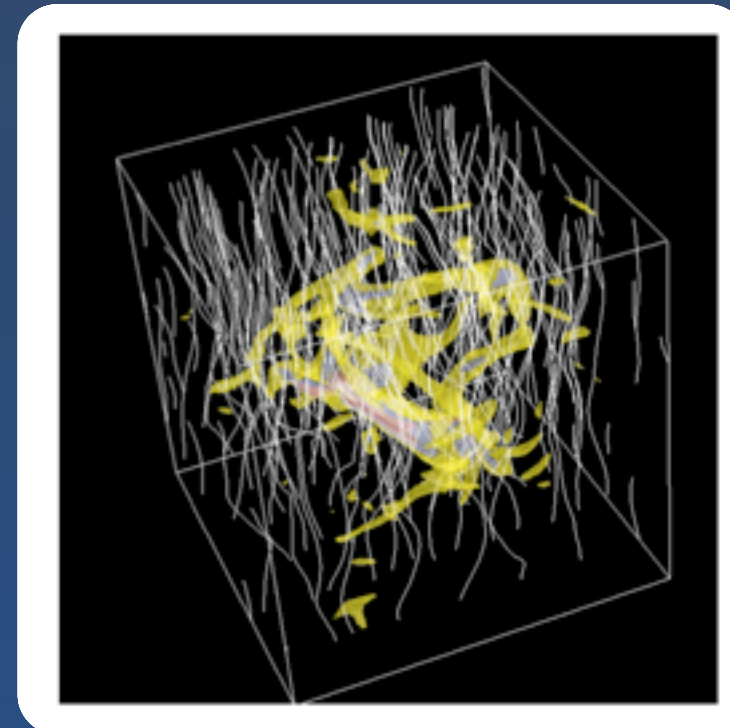
Krumholz et al. 2012, ApJ, 545, 46





Does impact the IMF

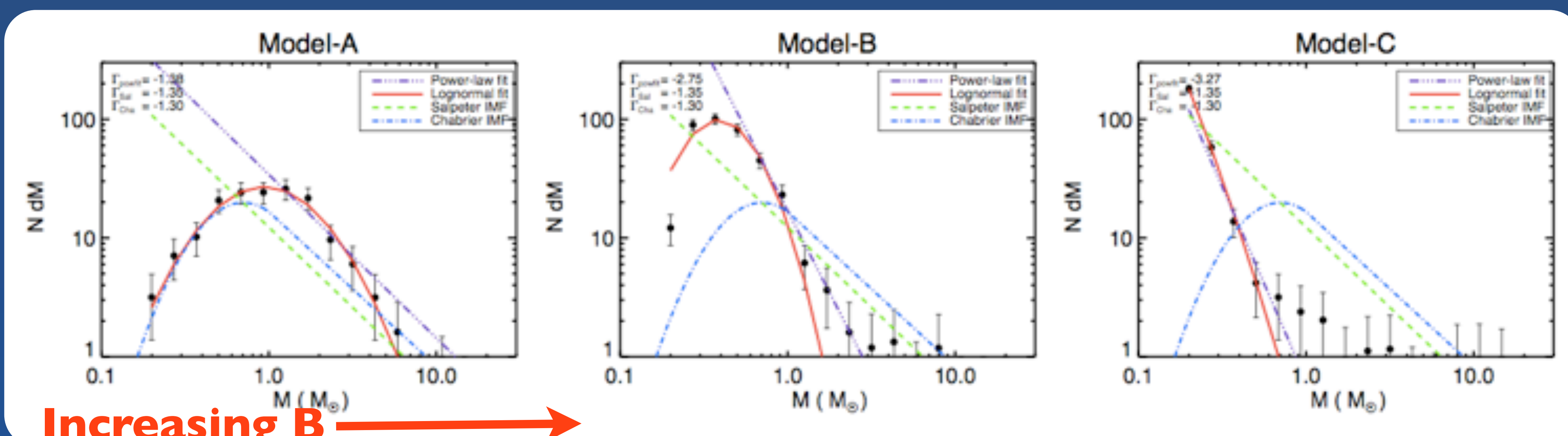
Magnetic fields



Li et al. 2010, ApJ, 720, 26

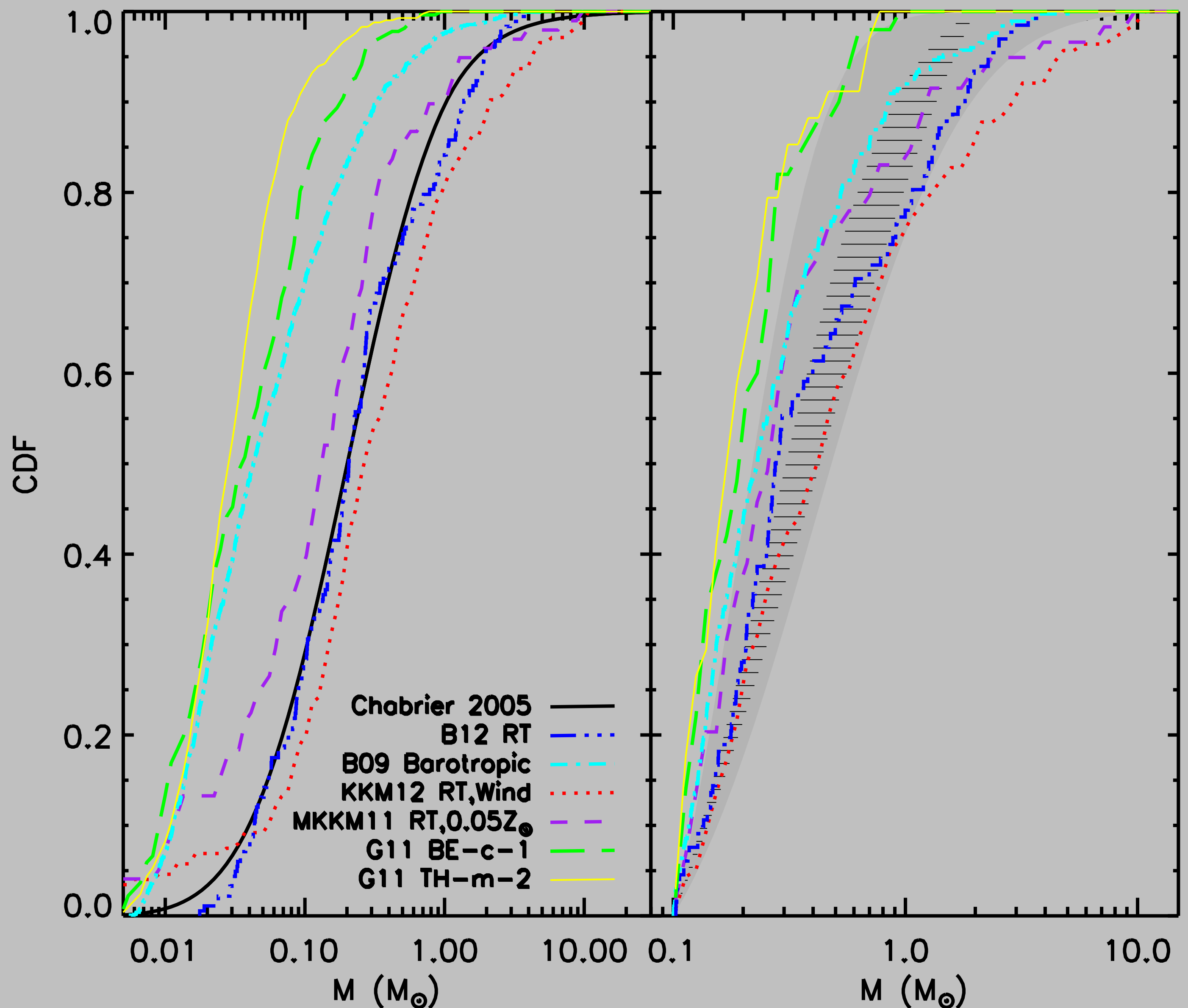
Increasing magnetic field lowers the IMF break mass and characteristic mass

Hocuk et al. 2012, A&A, 545, 46



Simulation summary

Offner et al. PPVI



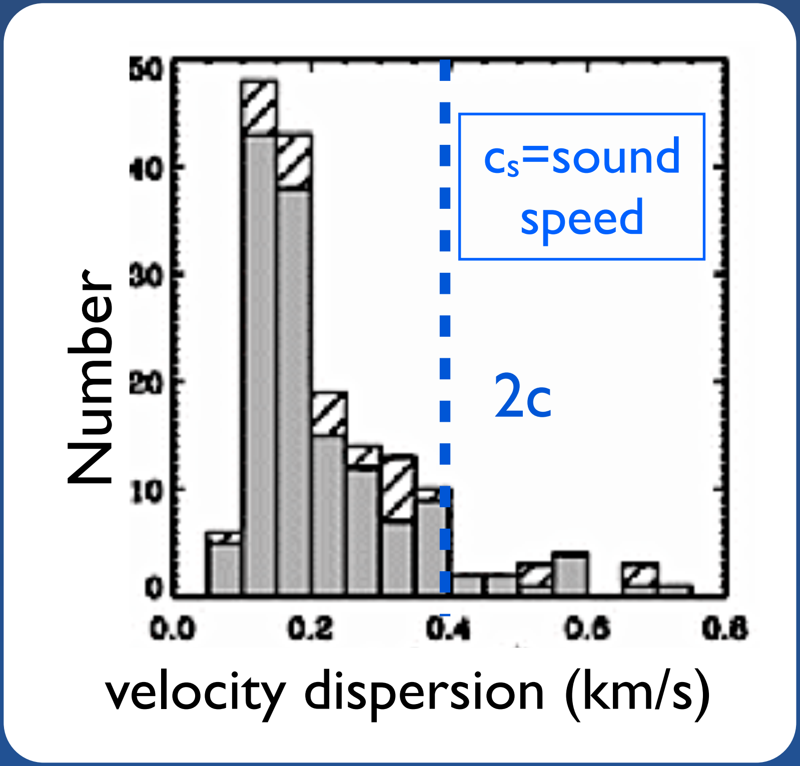
Secondary metrics?

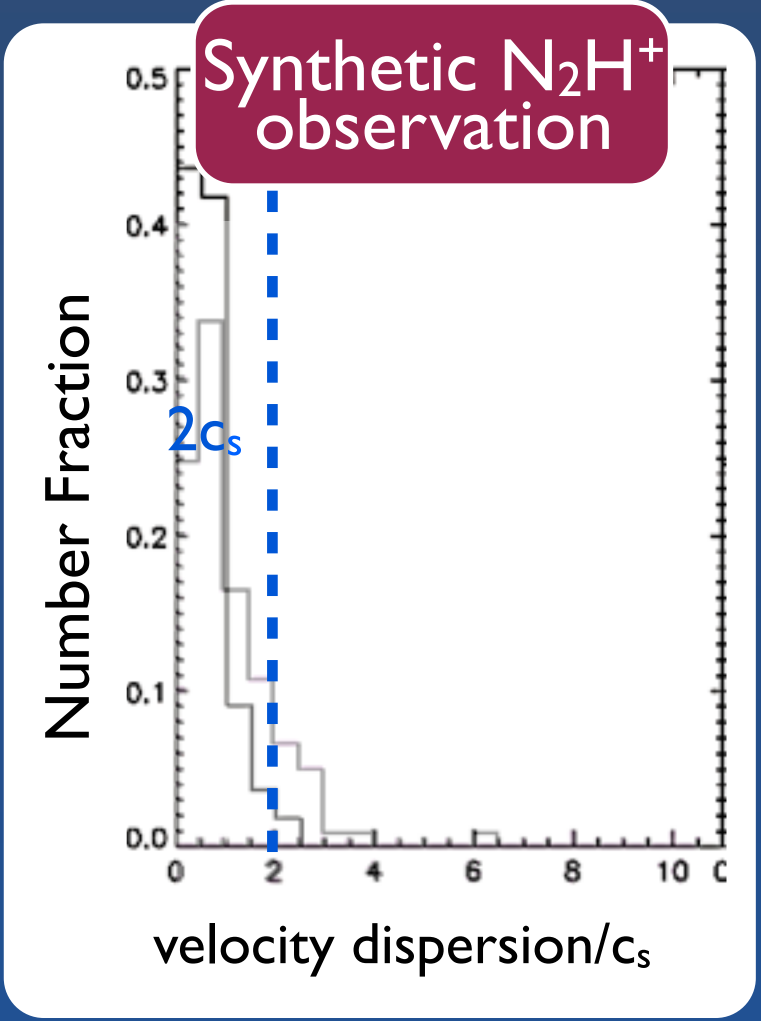
Gas Kinematics

- Low-mass cores have sub-sonic linewidths (see also: Kirk et al. 2007; André et al. 2007; Ayliffe et al. 2007)
- Other gas metrics:

  core los motion, core-envelope velocity offset, core coherence

Rosolowsky et al., 2008, ApJS, 175, 509



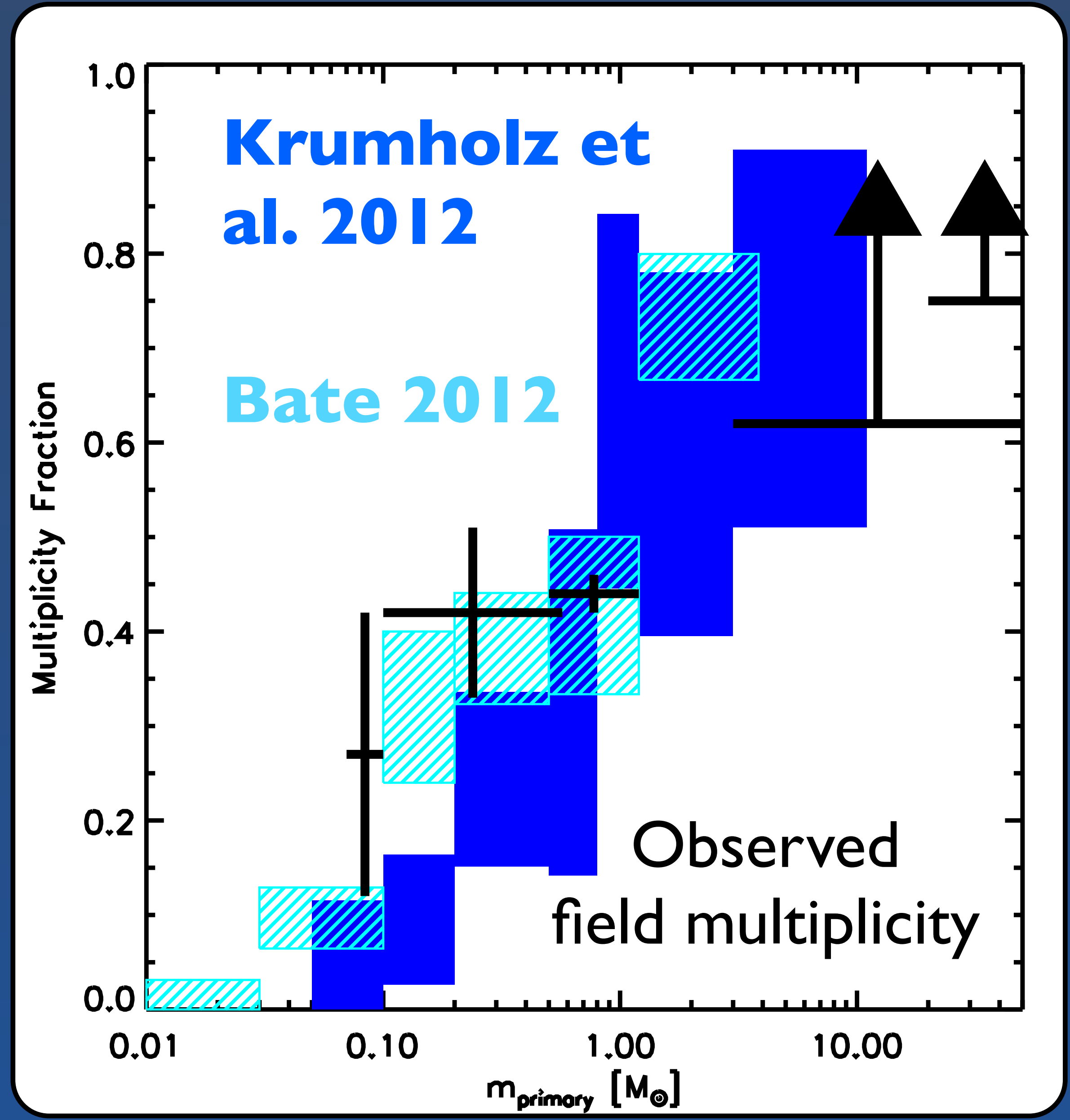


Offner et a. 2008, AJ, 136, 404

Secondary metrics?

Multiplicity

Simulations with RT can reproduce observed multiplicity



Summary
(what's new since PPV)

- Observationally, there is much debate regarding the IMF, particularly beyond the Milky Way.
- However the IMF in local regions appears robust against major changes (except perhaps at the very low mass end)
- Fragmentation theories have advanced considerably in the last decade and can now explain the CMF and cloud structure over a wide variety of scales.
- Simulations are now able to include/test a wide range of physical processes
- The simulations now suggest that both isolated fragmentation and dynamical effects (e.g. "competitive accretion", or feedback) are important for setting the IMF.

Outlook...

- We are getting more information on the IMF in extreme environments, including the Galactic Centre (e.g. Lu et al. 2013).
- Prestellar core properties can now be better constrained by the observations.
- Simulations still need to test the connection between the CMF and IMF.
- Also require more synthetic observations of "cores" and their evolution.