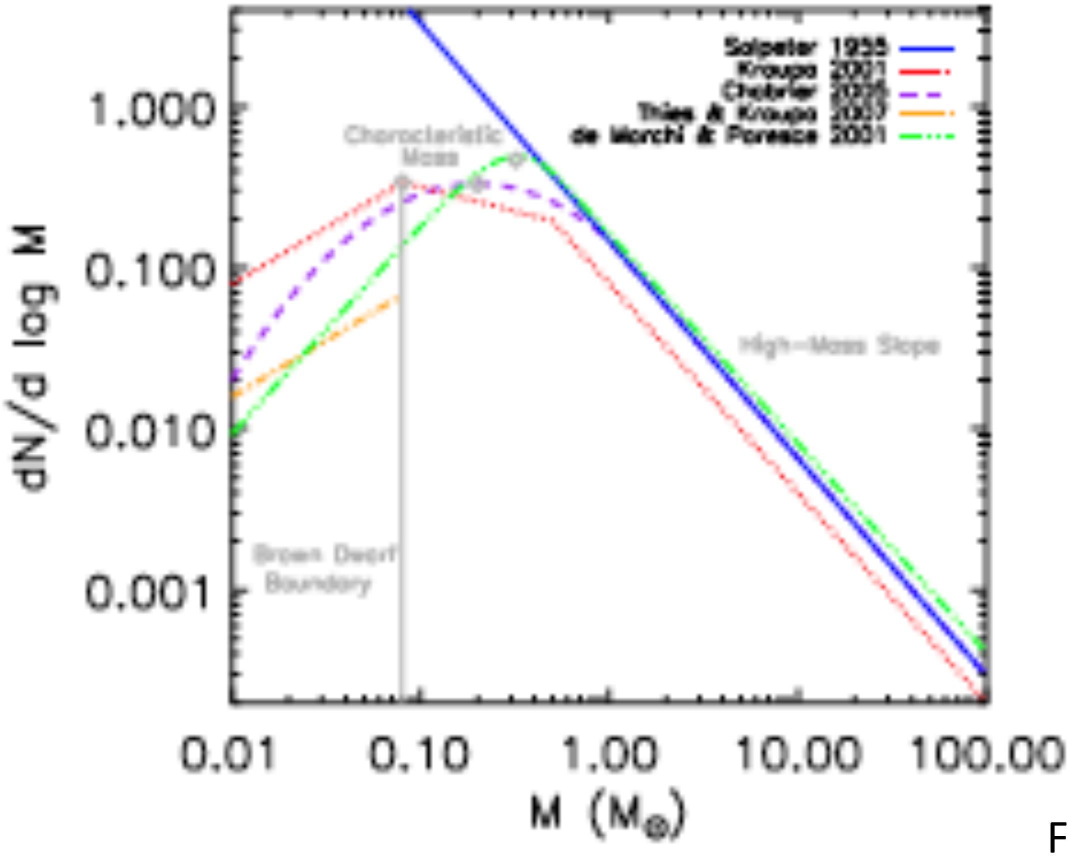
Do we understand the origin of the IMF?

Partially but some fundamental issues are still unclear

IMF theory reviews:

Krumholz 2014, Offner et al 2014 (PPVI) , Clarke (Saas Fee lectures pub. 2015) .

Schematic forms



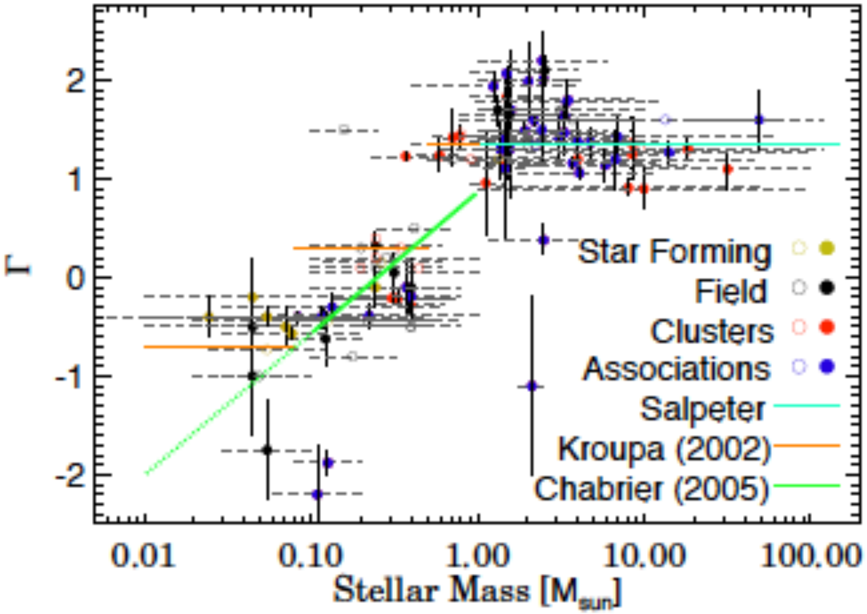
From Offner + 2014

For piece-wise power law parametrisation dN ~ $m^{-\alpha}$ dm, *characteristic mass* is where α makes a transition from < 2 to > 2.

Apparent universality of IMF (?*)

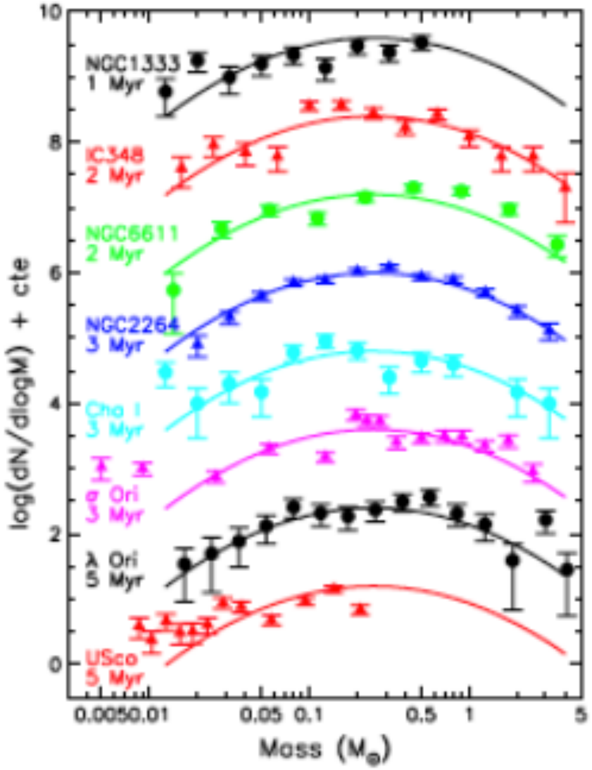
- The Γ plot (power law index as function of stellar mass)

Bastian +2010



WHY IS CHARACTERISTIC MASS ~ 10^33 g?

The IMF peak in nearby SF regions (Offner et al 2014)



* Controversial suggestions of bottom heavy IMF in early type galaxies: van Dokkum & Conroy 2010,Capellari +2012,Ferreras +2013, Weidner+2013

IMF ingredients on which all would agree

- I Need `turbulence’

Disordered velocity field: produces structure

- II Need amplification of structure by self-gravity

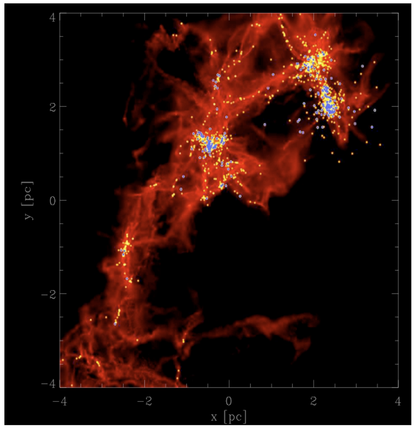
Gravito-turbulent models e.g. Padoan& Nordlund 2002; Hennebelle & Chabrier 2008,2009,2013; Hopkins 2012, 2013, Guszjenov & Hopkins 2015,2016 emphasise I and II

The following also all play a role:

- III Further fragmentation

Inc. in discs

- Binary/multiple system dynamics



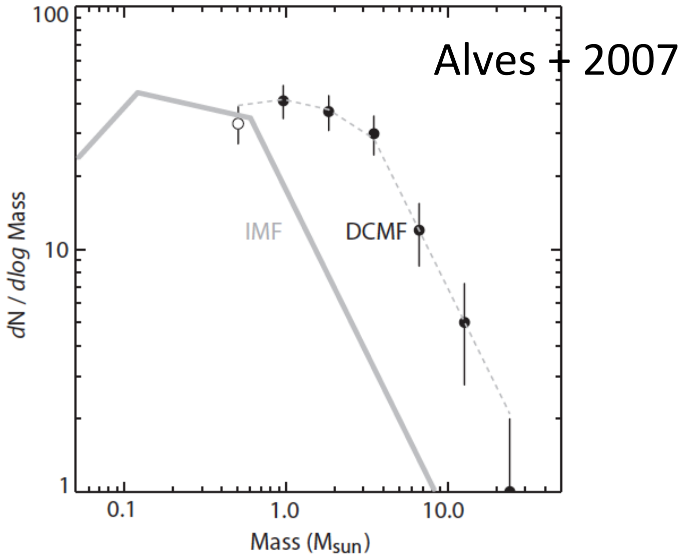
- Accretion

Simulations often point to importance of III

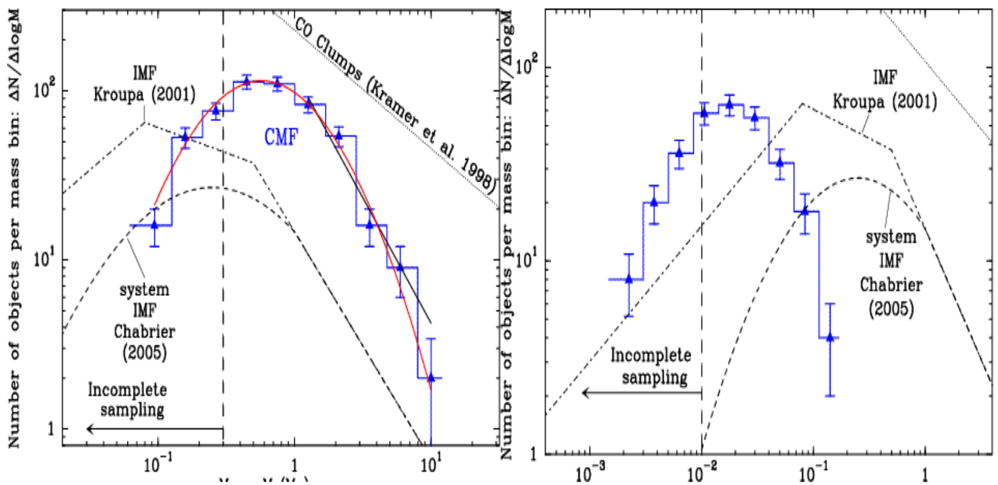
Observational motivation for ignoring III *

* = fragmentation,multiple system dynamics, accretion

- Similarity between core mass function (CMF) and IMF… constant scaling factor?



Andre + 2010



Aquila Polaris

See also Nutter & Ward Thompson 2007, Andre + 2010, Konyves + 2010 , Roman Zuniga + 2010

- *Most* simulations find III* to be very important to shaping of IMF and find that a similarity between simulated CMFs and IMFs doesn't imply straightforward evolutionary connection (e.g. Smith + 09)
- Some indication that strong magnetic fields and radiative feedback may suppress III* and imprint CMF <-> IMF connection (Myers + 2013)

FOCUS ON 3 QUESTIONS:

- What sets the characteristic stellar mass?
- What sets the slope of the upper IMF?
- How do VLM stars/brown dwarfs fit into the star formation picture?

Will avoid topics where simulations do not yet yield robust statistics

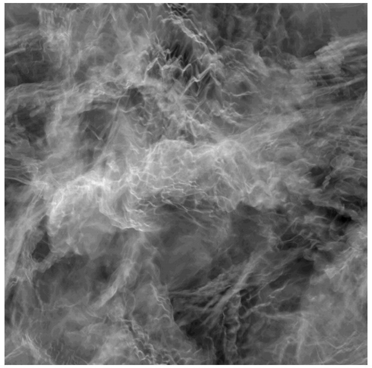
An after-word on interactions in sparse environments

Q1: What sets the characteristic stellar mass?

- Plausible to link to characteristic Jeans mass:

$$M_J = \left(\frac{kT}{Gm_{H_2}}\right)^{1.5} \rho^{-0.5} = 0.9\left(\frac{T}{10\ \mathrm{K}}\right)^{1.5} \left(\frac{n_{H_2}}{10^4\ \mathrm{cm}^{-3}}\right)^{-0.5} M_\odot,$$

- Is this inherited from gravitoturbulent structures?



Padoan & Nordlund 2002, Hennebelle & Chabrier 2008

- If so, ρ distn. depends on Mach number and mixture of compressive/solenoidal modes

Federrath + 2008,2010

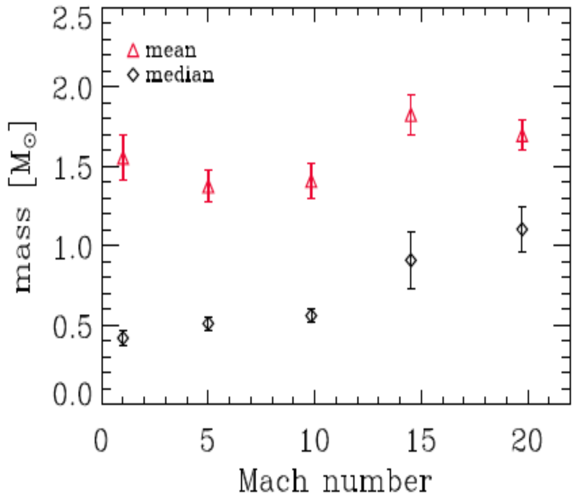
Q1: What sets the characteristic stellar mass?

- Simulations with decaying turbulence find IMF is insensitive to:

  Spectrum of velocity field (Bate 2009)
  Mixture of compressive versus solenoidal modes (Liptai + 2016). See also Girichidis +2011

- Simulations with driven turbulence find IMF is likewise insensitive to

  Mach number of turbulence (Klessen 2001, Bertelli Motta + 2016)

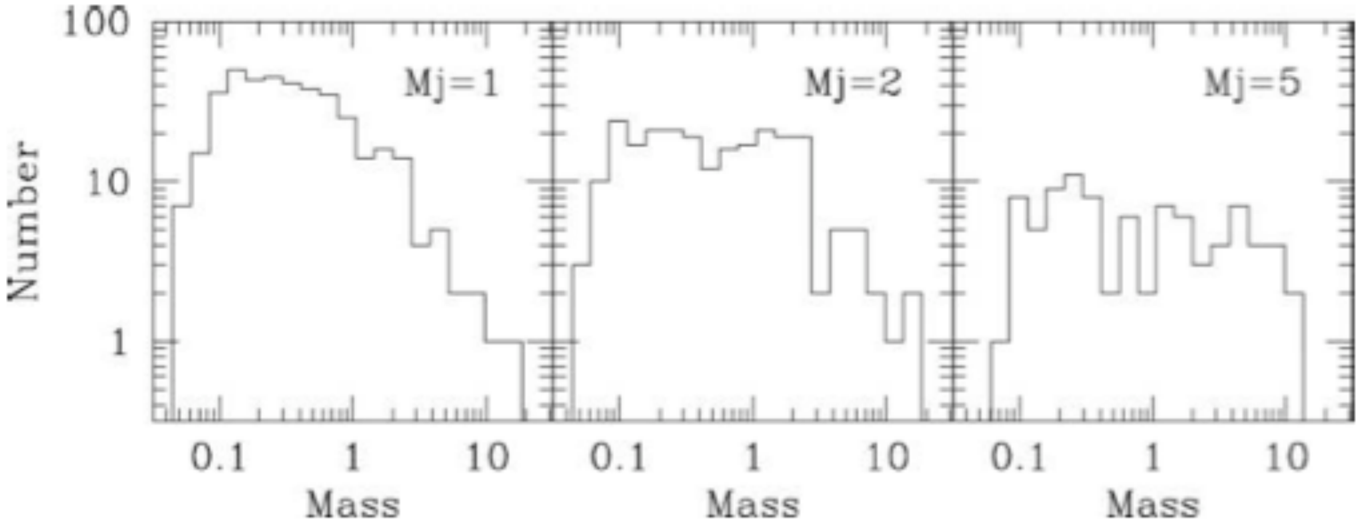


- Ascribe this to IMF being set by sub-fragmentation (e.g. in discs) + strong turbulence disrupts low mass structures

Q1: What sets the characteristic stellar mass?

- Plausible to link to characteristic Jeans mass:

$$M_J = \left(\frac{kT}{Gm_{H_2}}\right)^{1.5} \rho^{-0.5} = 0.9\left(\frac{T}{10\ \mathrm{K}}\right)^{1.5} \left(\frac{n_{H_2}}{10^4\ \mathrm{cm}^{-3}}\right)^{-0.5} M_\odot,$$

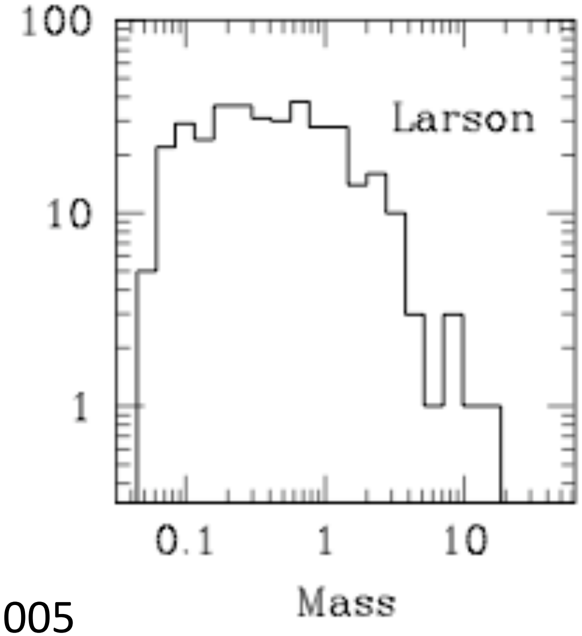


Bonnell + 2006 found for isothermal simulations the characteristic mass depended on mean Jeans mass in the initial cloud….too dependent on initial conditions…

Q1: What sets the characteristic stellar mass?

Breaking the dependence on initial conditions

- Need instead to imprint Jeans mass at particular values of T and ρ (e.g. T,ρ associated with transition from line cooling to dust cooling)



Barotropic e.o.s.

T ~ ρ^-0.25

↓

T ~ ρ^0.1

Larson 2005; see also Jappsen + 2005

Stablises IMF irrespective of initial cloud density

Q1: What sets the characteristic stellar mass?

- Elmegreen + 2008 argued that critical Jeans mass is weakly dependent on Z and ambient conditions

Cf Guszenjov + 2016

- Need to supplant calculations that put in a barotropic equation of state by those modeling thermal evolution from diffuse cloud to dense core conditions

See e.g Bate & Keto 2015

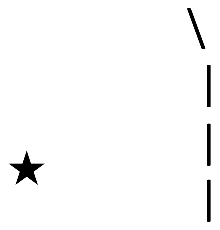
Most calculations either use barotropic e.o.s. or perform radiative transfer in the dust and impose T_gas = T_dust

Q1: What sets characteristic stellar mass?

- Radiative feedback from protostars

Bate 2009, Krumholz 2011

Each star sets up heated zone in which can't form another star



Model T(R,L); can't form another star until R > R_Jeans

Resulting mass scale very weakly dependent on ρ

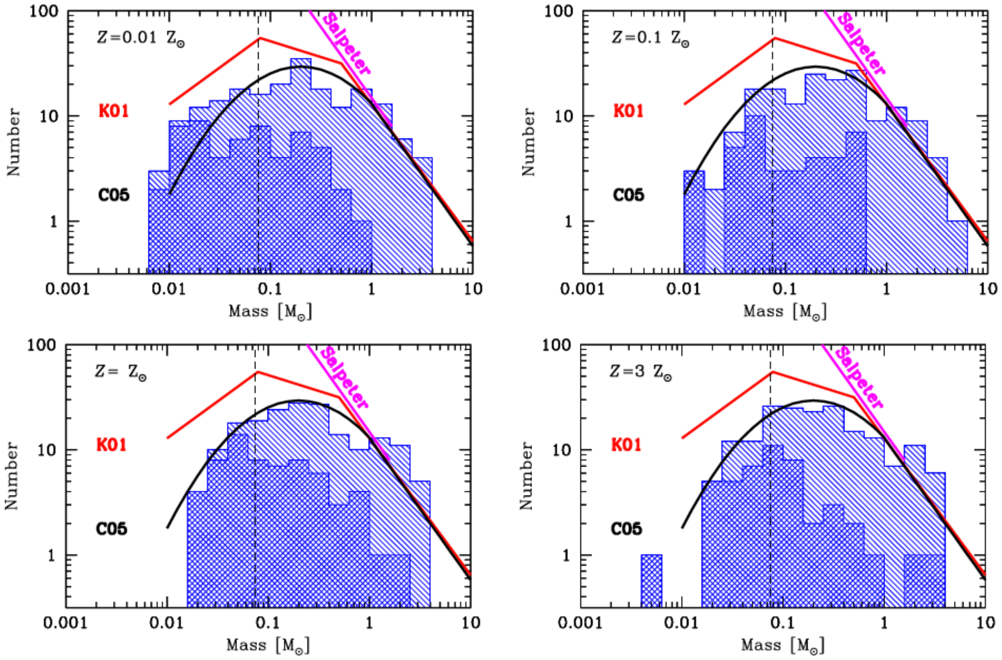
$$M_{\rm eff} = \rho^{-1/5} L_*^{3/10} \frac{4\pi}{3} \left(\frac{3\mathcal{R}}{4\pi \mu G} \right)^{6/5} (4\pi\sigma)^{-3/10}.$$

Even weaker when consider L_*(ρ)

Q1: what sets initial mass?

- Radiative feedback stabilises IMF against variations in initial conditions
- …and opacity

See also Myers + 11



But note assumption that dust and gas are well coupled (as in simulation) breaks down at sub-solar Z.

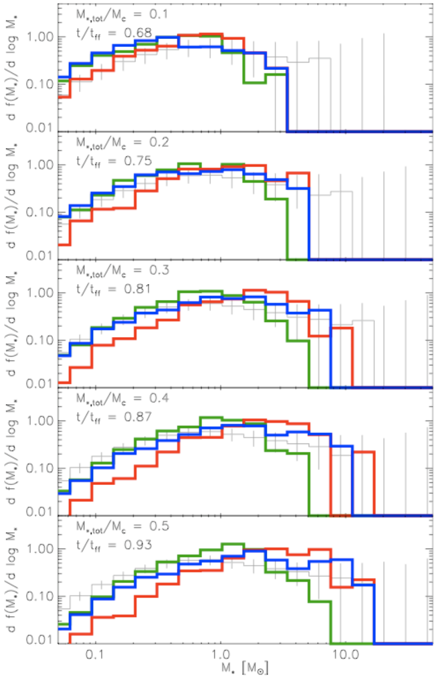
Bate 2014

Q1: what sets characteristic mass?

- Likely to involve thermodynamical effects associated with either onset of dust coupling and/or radiative feedback from protostars

  Simulations currently rely on either barotropic e.o.s. or assumption T_gas= T_dust: improvements needed

- Note that at high density radiative feedback can lead to top-heavy IMF:



Feedback suppresses new fragmentation but not acccretion onto existing stars

Green= no feedback
Blue/red= feedback

↓

time

Krumholz et al 2011

Q2: What sets slope of upper IMF?

(α ~2)

Some analytic suggestions:

- Argument that self-similar fragmentation should produce equal mass in equal logarithmic stellar mass intervals => $\alpha = 2$

Guszjenov + 2016

Not what's setting the upper IMF in simulations: high mass stars acquire most of their mass by **accretion**

Bonnell et al 2004

Q2: What sets slope of upper IMF?

(α =2)

Some analytic suggestions:

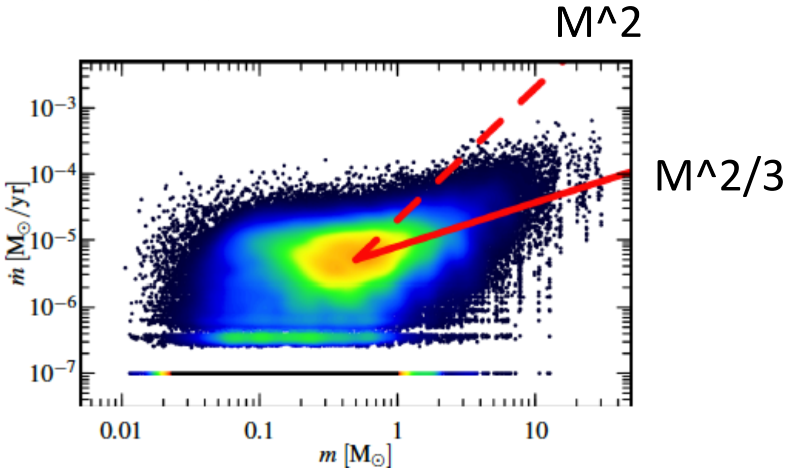
- Bondi-Hoyle accretion from *smooth* background ?

$\dot{M}$ ~ M^2 => α =2

Bonnell + 2001
Zinnecker 1982

Not what's setting the upper IMF in simulations using *turbulent* initial conditions:

Maschberger et al 2015



Upper IMF in simulations driven by *stochastic accretion*

(exponential distribution of accretion times driven by few-body dynamics; see also Basu & Jones 2004, Bate & Bonnell 2005)

Q3: How do VLM stars/bds fit into the star formation picture?

- Bds/VLMs are collapse products of low mass high density cores?

Generic expectation of gravitoturbulent `core mapping' models

- They instead derive from fragmentation within discs/multiple systems

Variants on this theme:

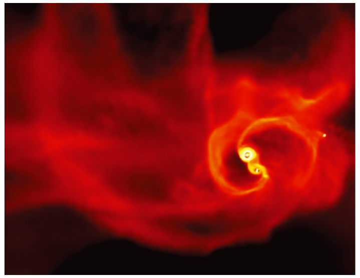
Reipurth & Clarke 2001; Rice et al 2003;
Stamatellos & Whitworth 2009;Bate 2009;
Basu & Vorobyov 2012, Forgan et al 2015

Q3: How do VLM stars/bds fit into the star formation picture?

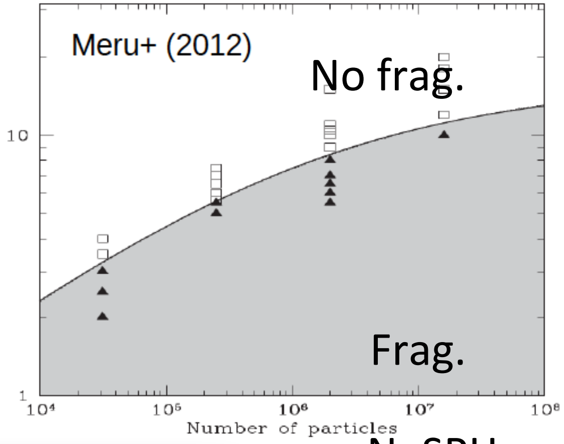
- Simulations favour latter path

..but do we understand numerical convergence issues with disc fragmentation?

Bate 2009

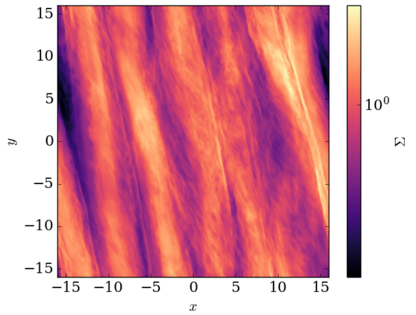


Cooling time/ dynamical time

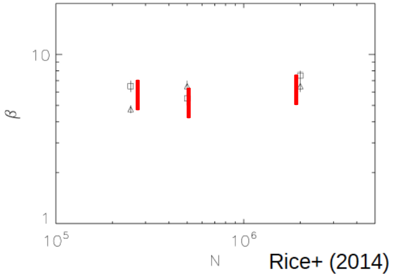


N_SPH

Not converged



Booth & Clarke in prep



Converged

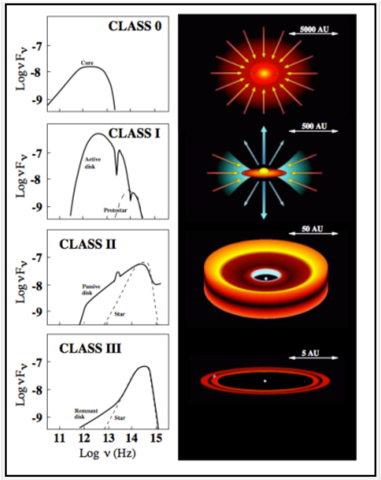
Q3: How do VLM stars/bds fit into star formation picture?

Observational clues:

- Bd progenitors at star-less core or protostellar stage are proving elusive

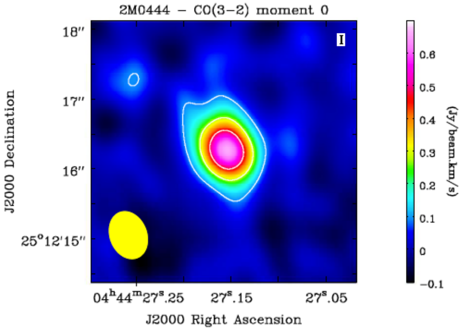
“There are, however, very few discoveries reported to date on the early-stage Class 0/I objects at the very low-mass end, with Lbol . 0.1 L⊙.“ Riaz + 2014

See however Palau +2012 for Class 0 proto-brown dwarf candidate



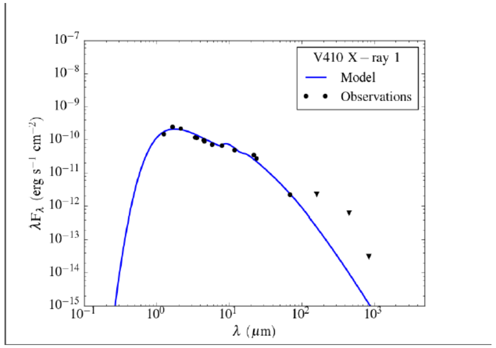
- There are plenty of bd/VLM stars at subsequent Class II (T Tauri analogue) phase

These have discs with a range of sizes:



2M0444 R ~ 140 AU Ricci+2014

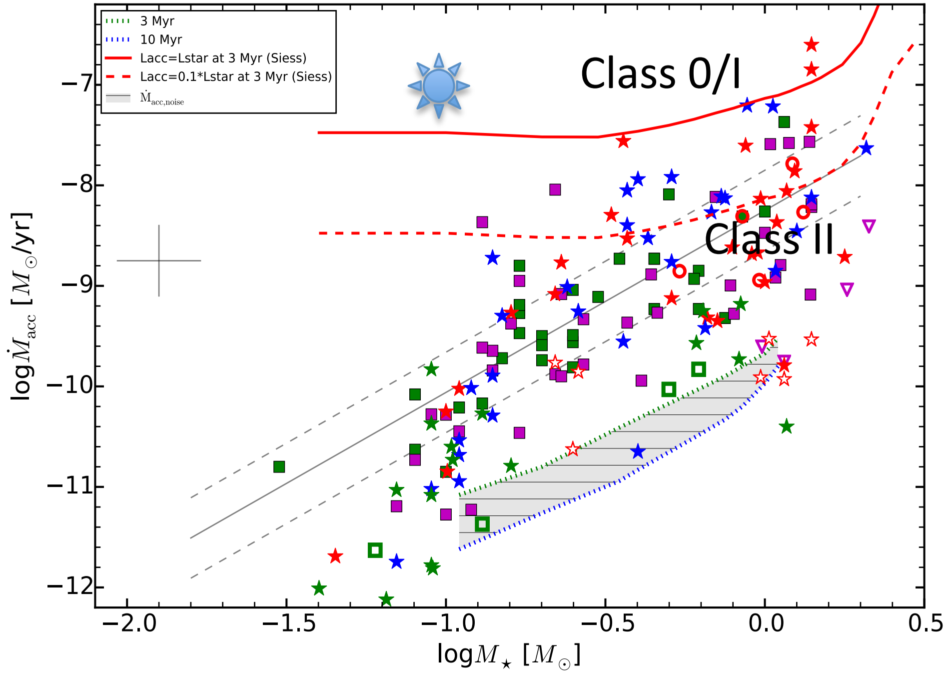
cf



SED fit implies R ~ 1 AU, Boneberg + in prep.

Q3: How do VLM stars/bds fit into the star formation picture?

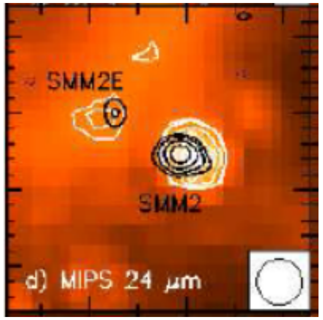
- Some evidence that they `appear' at later evolutionary phases cf higher mass stars:



Manara et al in prep; data for Lupus

☀ = position of Class 0 proto-brown dwarf candidate SMM2E ; *Palau et al 2012*

Are these VLM/bds hidden in discs or proto-multiples?

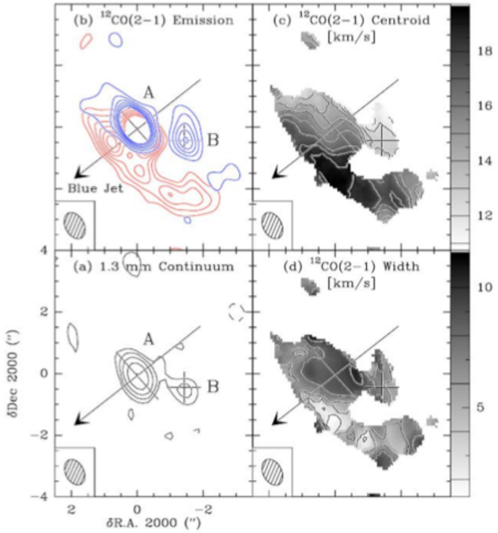


☀ = wide triple companion

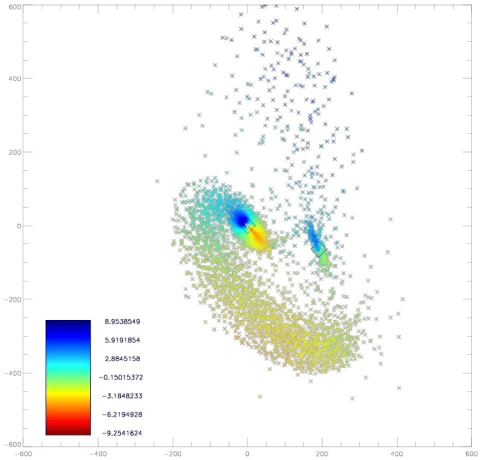
Afterword: are *stellar aggregates* important even in sparse environments?

- Taurus-Auriga is the canonical low density star forming region where probability of *future* interactions is apparently low

e.g. star-disc interaction in RW Aur: almost certainly a binary (prob of hyperbolic encounter < 0.001)



Cabrit + 2006



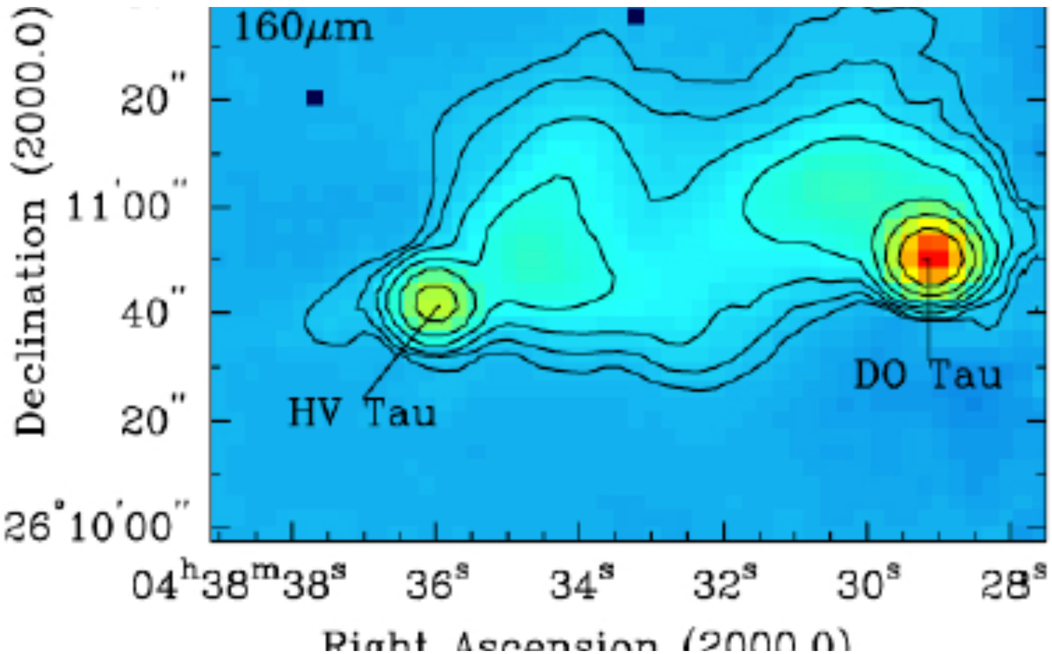
Dai+ 2015

Consider now the case of HV Tau and DO Tau

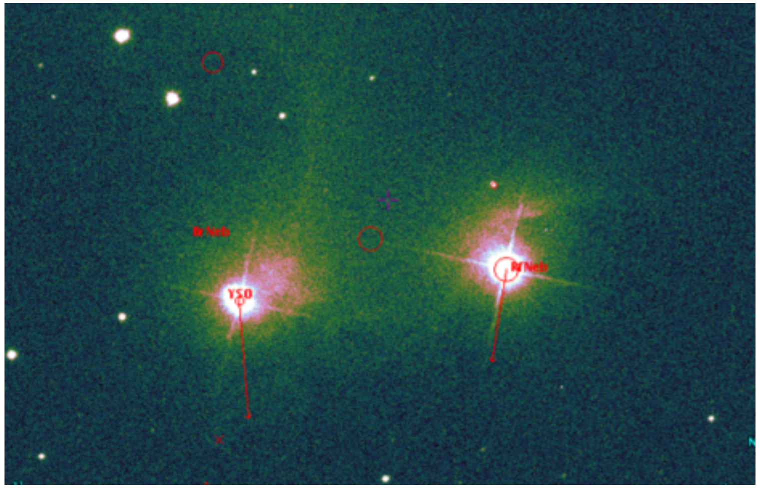
- Separation on the sky is > 10^ 4 A.U.
- HV Tau and DO Tau are almost certainly unbound

…..would expect independent origins…

However….



Herschel map from Howard + 2013



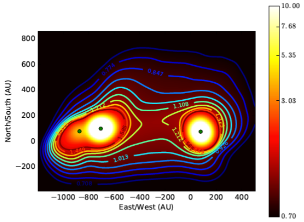
Scattered light image from HST archive

↗

↖

Clearly `know' about each other!

Moreover HV is itself a triple: rich dynamics in a sparse environment…



Winter et al , in prep.

Final thought:

- In a hierarchically structured ISM, which end of the clustering hierarchy determines stellar properties?

- *If* the lower end then naturally explains the relative insensitivity of the IMF to environment