Molecular Cloud Fragmentation and the IMF

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SS9: Big Data in Star Formation @EWASS2017, Prague, Czech Republic, 28 June 2017

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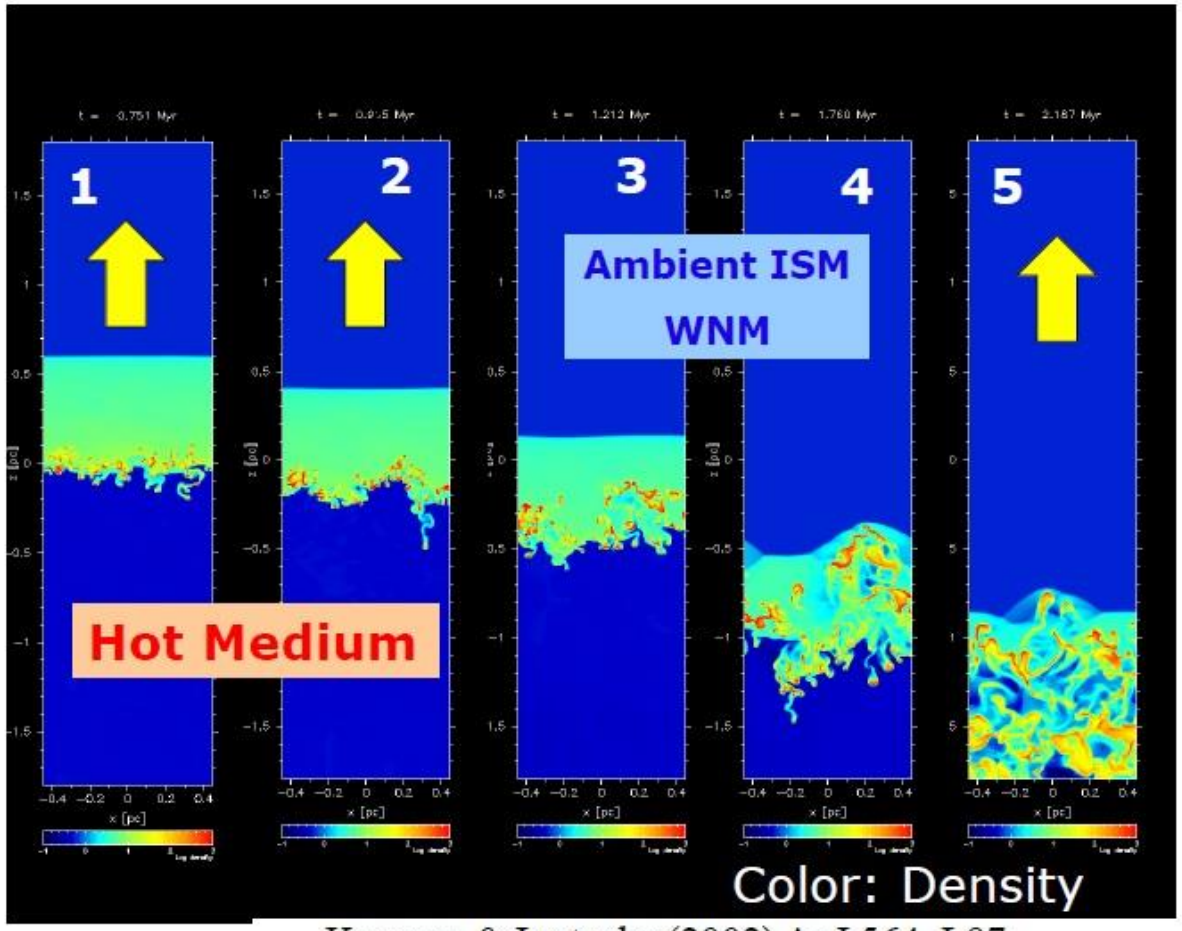
Key Steps

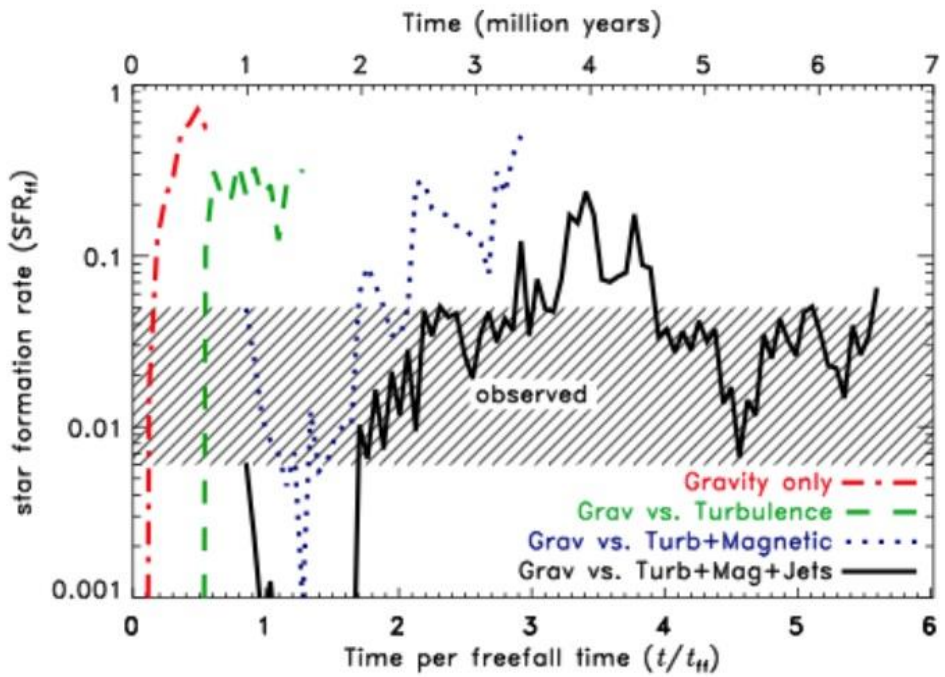
- Set up turbulent initial conditions – shocks, instability. Also initial mass-to-flux ratio
- Fragmentation of cloud into large scale structures (filaments/ribbons, etc.)
- Formation of dense cores within larger structures
- Core collapse to form hydrostatic protostar
- Disk formation, outflows, multiplicity, BDs, planets

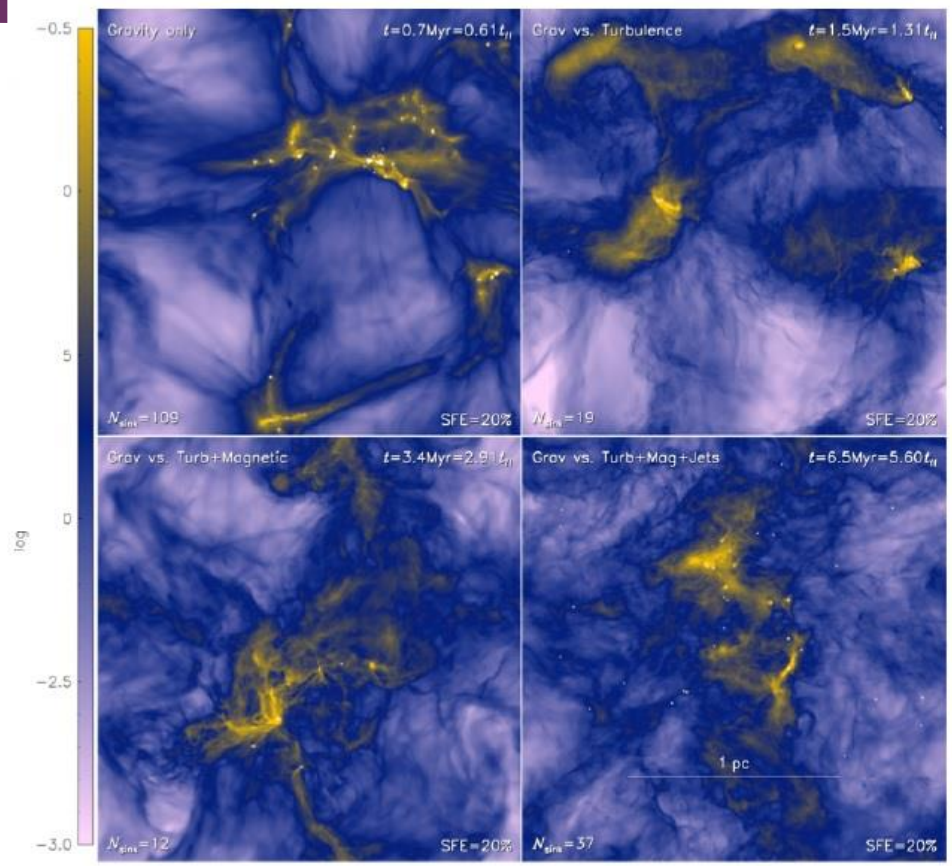
The Turbulent ICs of Molecular Clouds



Koyama & Inutsuka (2002) ApJ 564, L97

Maintaining Turbulence



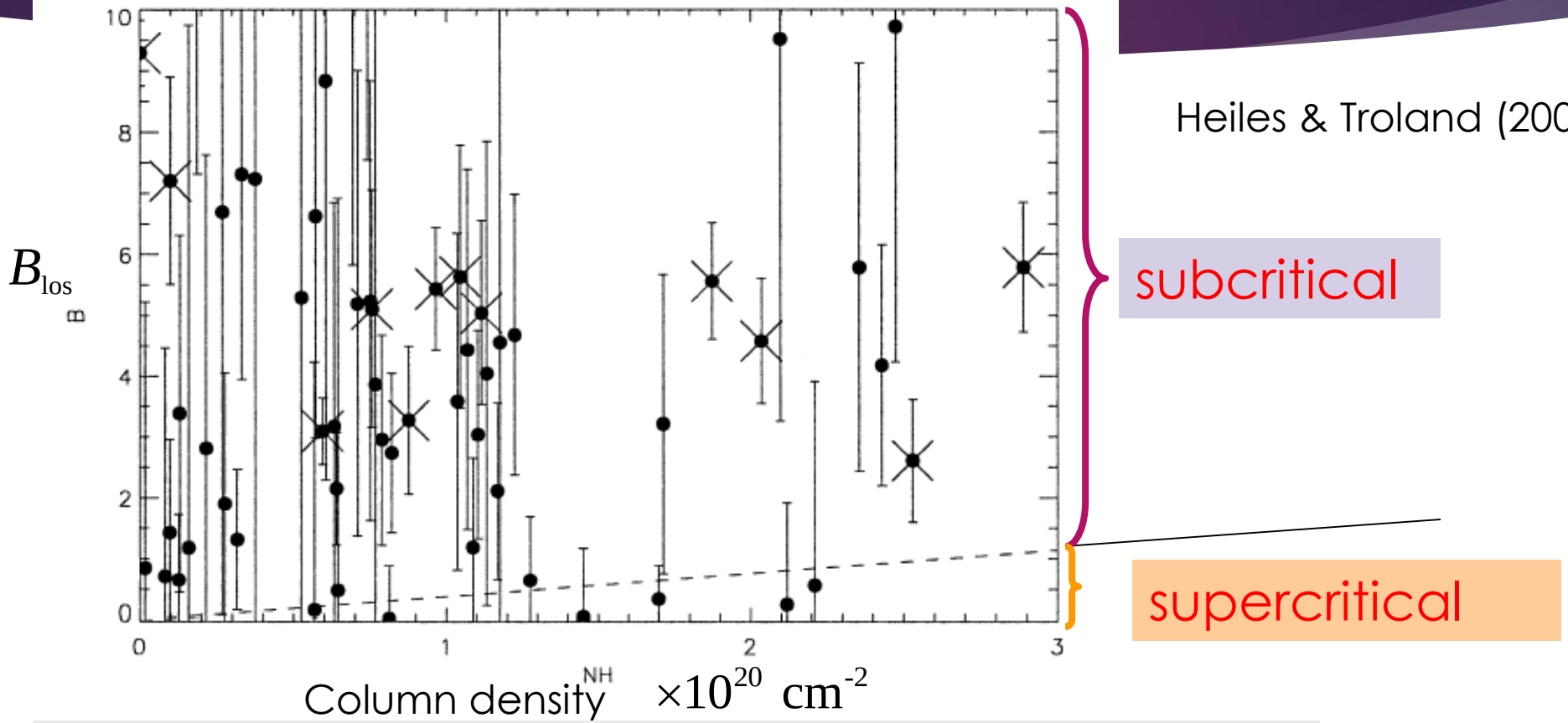


Federrath 2014; also Wang et al. 2011, Li & Nakamura 2007, plus Padoan talk to follow.

Some combination of magnetic fields and protostellar outflows can keep cloud stirred up and lower SFR.

Mol Cloud Progenitors are subcritical H I Clouds

Heiles & Troland (2008)



Heiles & Troland (2005)

Flux freezing in HI gas ➔ Significant regions of molecular clouds may be subcritical.

Molecular Cloud Accumulation Constraints

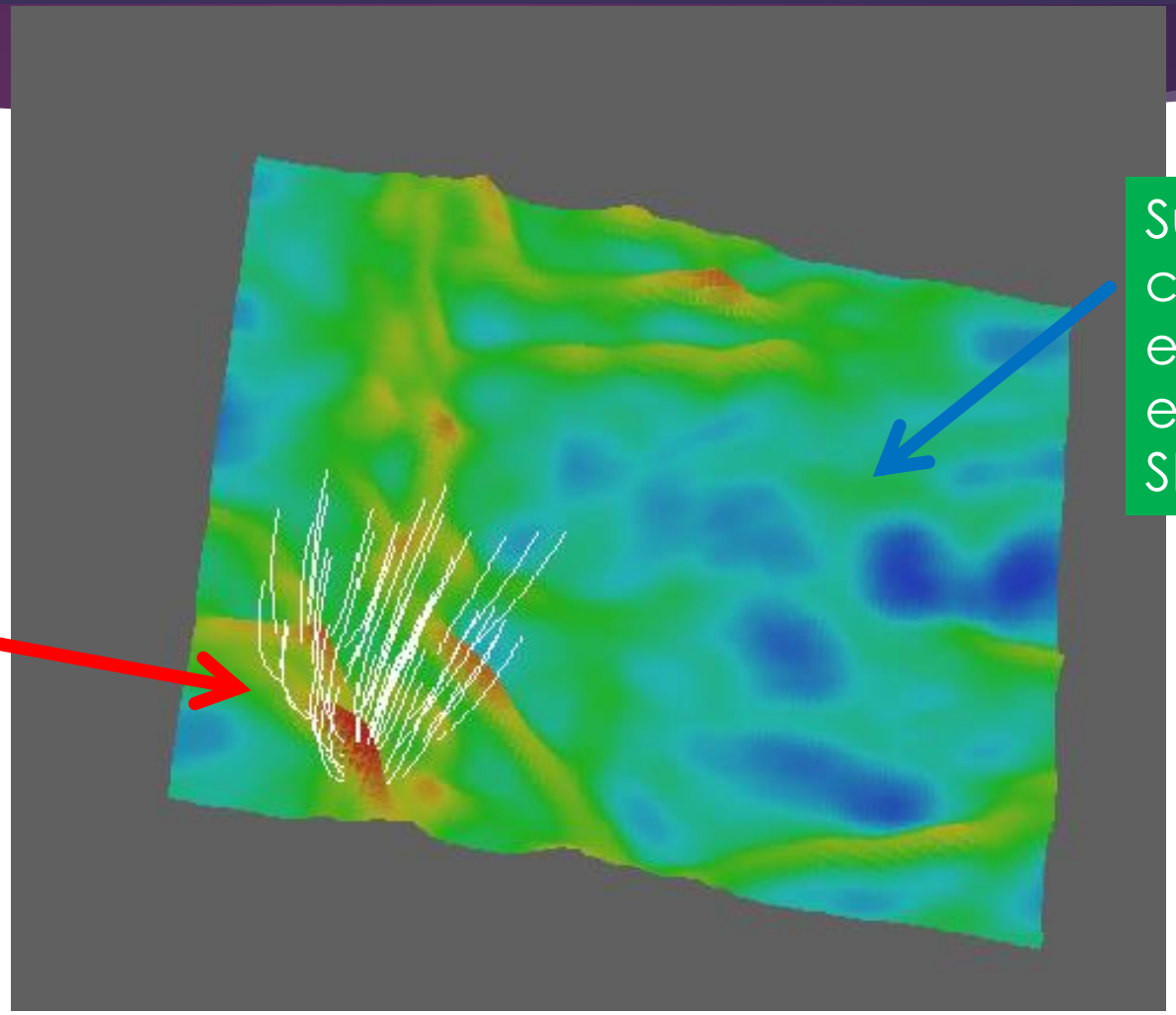
$$L \cong \frac{B}{2\pi G^{1/2}\rho} \cong 150\left(\frac{\mu}{1}\right)\left(\frac{B}{3\times10^{-6}\ \mathrm{G}}\right)\left(\frac{n}{1\ \mathrm{cm}^{-3}}\right)\ \mathrm{pc},$$

$$v \equiv \frac{L}{t} \cong 150\left(\frac{\mu}{1}\right)\left(\frac{B}{3\times10^{-6}\ \mathrm{G}}\right)\left(\frac{n}{1\ \mathrm{cm}^{-3}}\right)\left(\frac{t}{10^{6}\ \mathrm{yr}}\right)^{-1}\ \mathrm{km/s}.$$

Mestel (1999), Stellar Magnetism, and earlier papers quotes 10^3 above, not 150.

Bottom line: Highly supercritical MC and rapid formation time t is unlikely.

Molecular Cloud Scenario

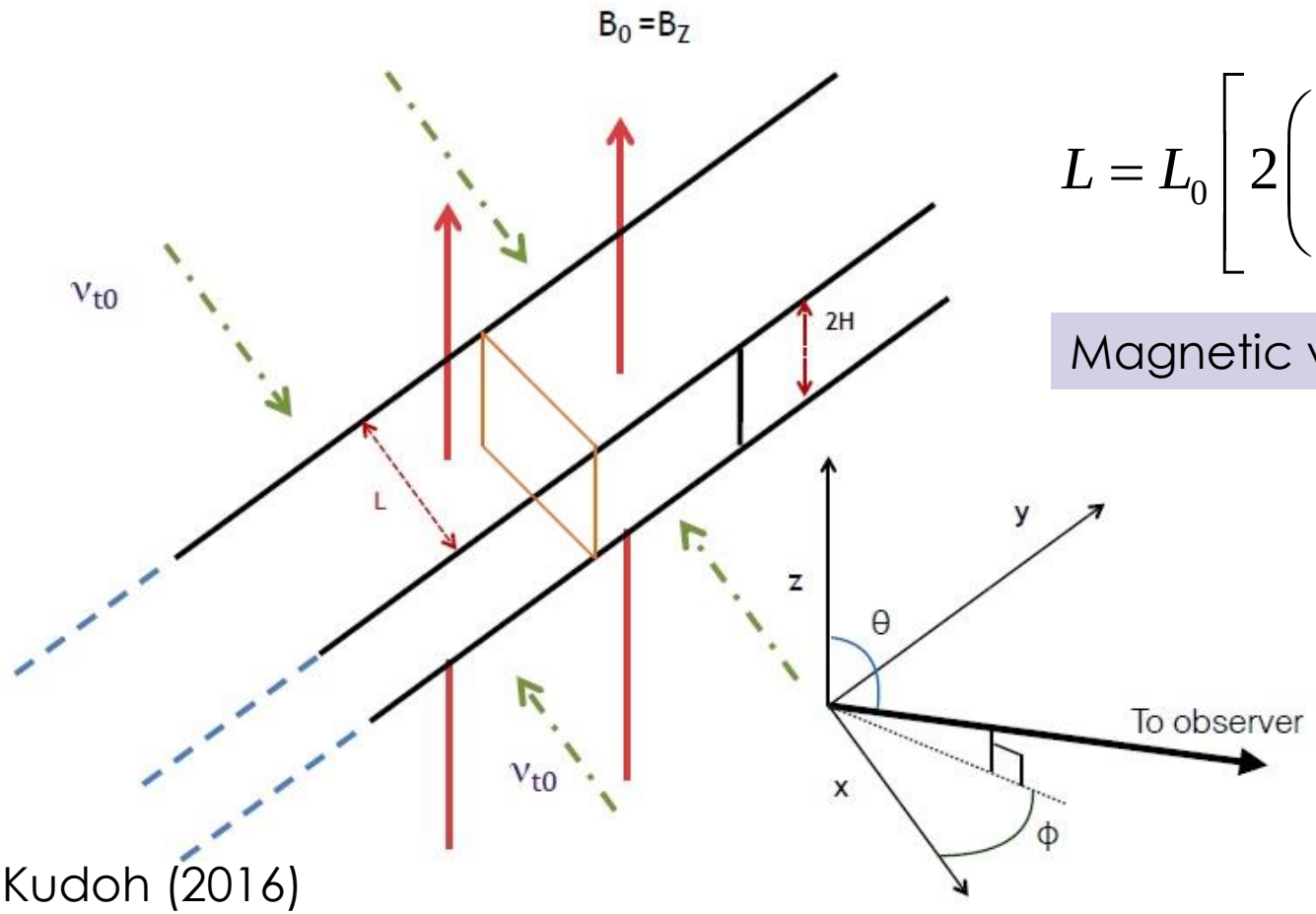


Subcritical common envelope; can enforce low SFR/SFE

Supercritical high-density regions assembled by large scale flows/turbulence

cf. Nakamura & Li (2005), Elmegreen (2007), Kudoh & Basu (2008), Nakamura & Li (2008), Basu , Ciolek, Dapp, & Wurster (2009; model shown here).

Magnetic Ribbon Model



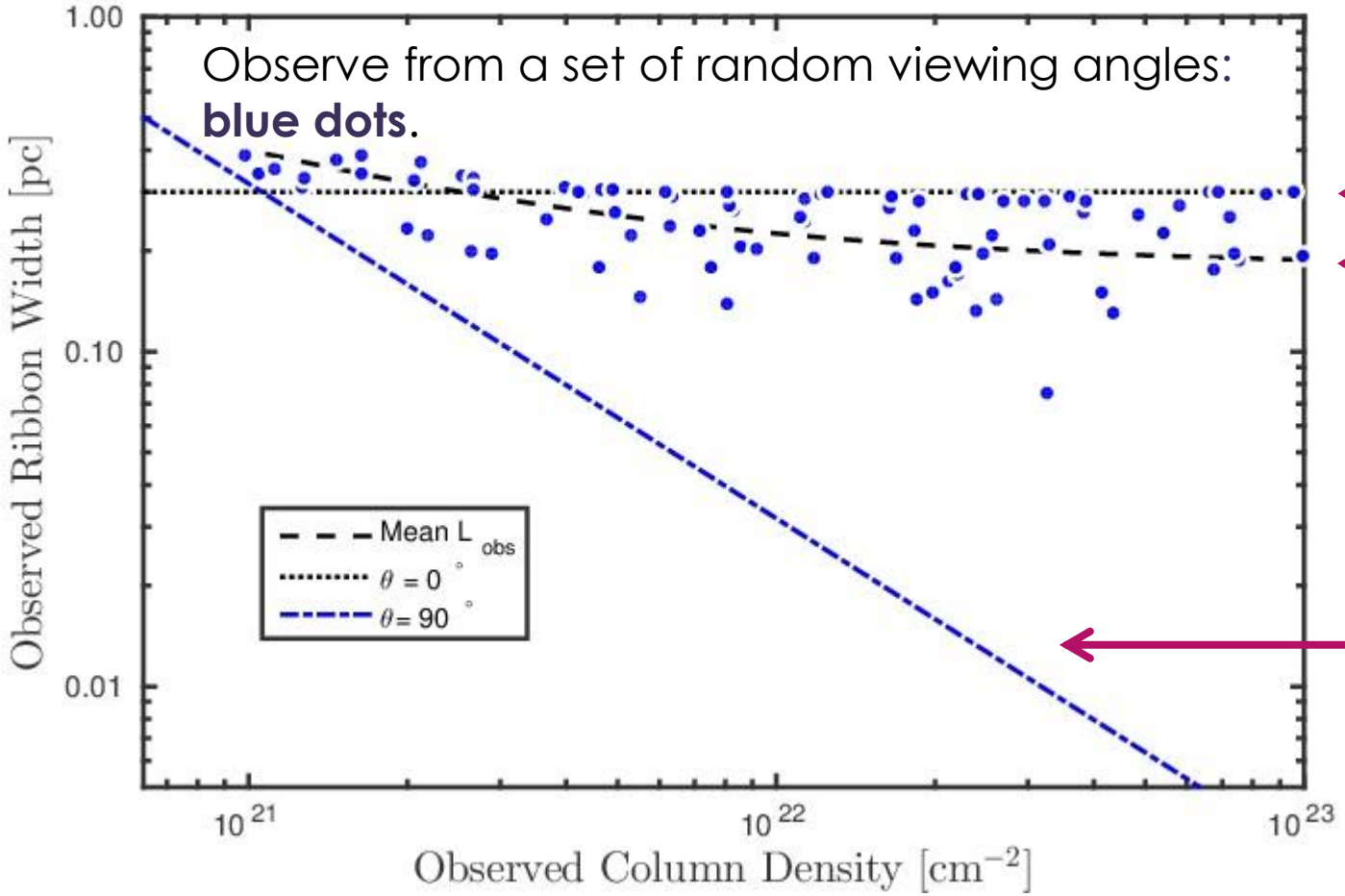
$$L = L_0 \left[2\left(\frac{v_{t0}}{v_{A0}}\right)^2 + 1 \right]^{-1}$$

Magnetic vs. turbulent pressure

Observed width depends on turbulent compression scale, Aflvénic Mach number, and viewing angle.

Auddy, Basu, & Kudoh (2016)

Magnetic Ribbon Model



L

Average over random viewing angles

$2H \approx \lambda_J$

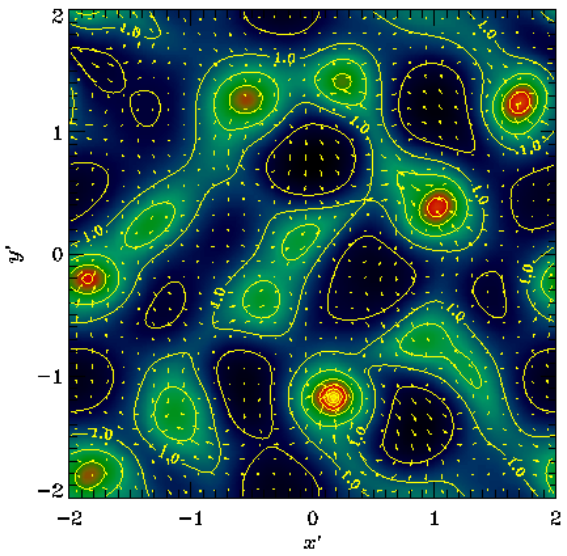
Assuming trans-Alfvénic turbulence and turbulent scale $L_0 \sim 1$ pc.

Auddy, Basu, & Kudoh (2016)

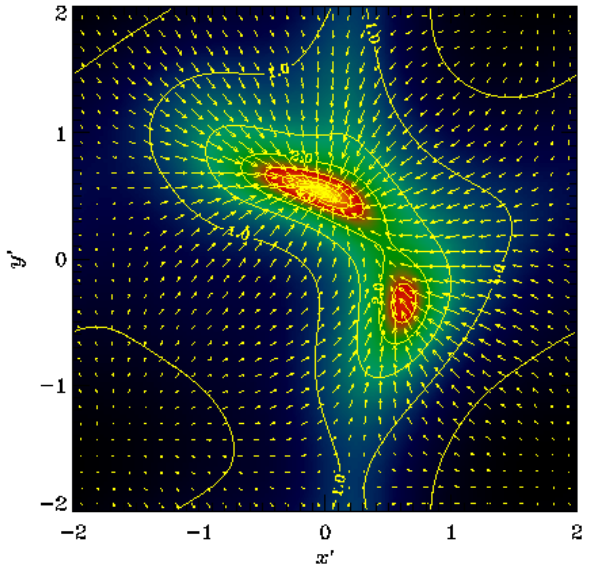
Probability Functions in Star Formation – Universal or Varying?

- Core Mass Function
- Column Density PDF
- Stellar (and substellar) Initial Mass Function

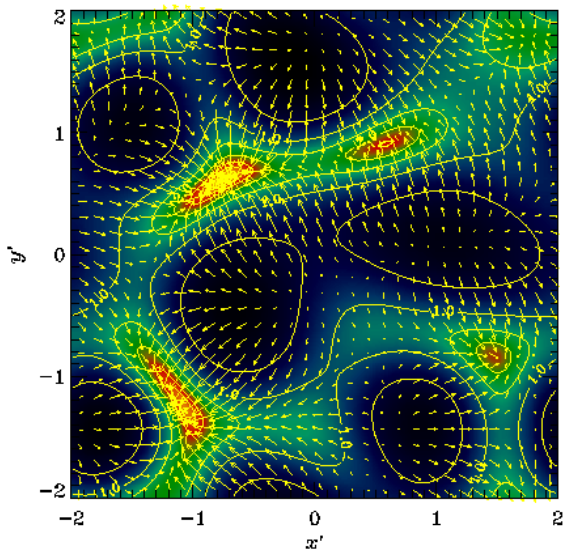
Magnetic Field affects the CMF



$\mu_0 = 0.5$



$\mu_0 = 1.1$



$\mu_0 = 2.0$

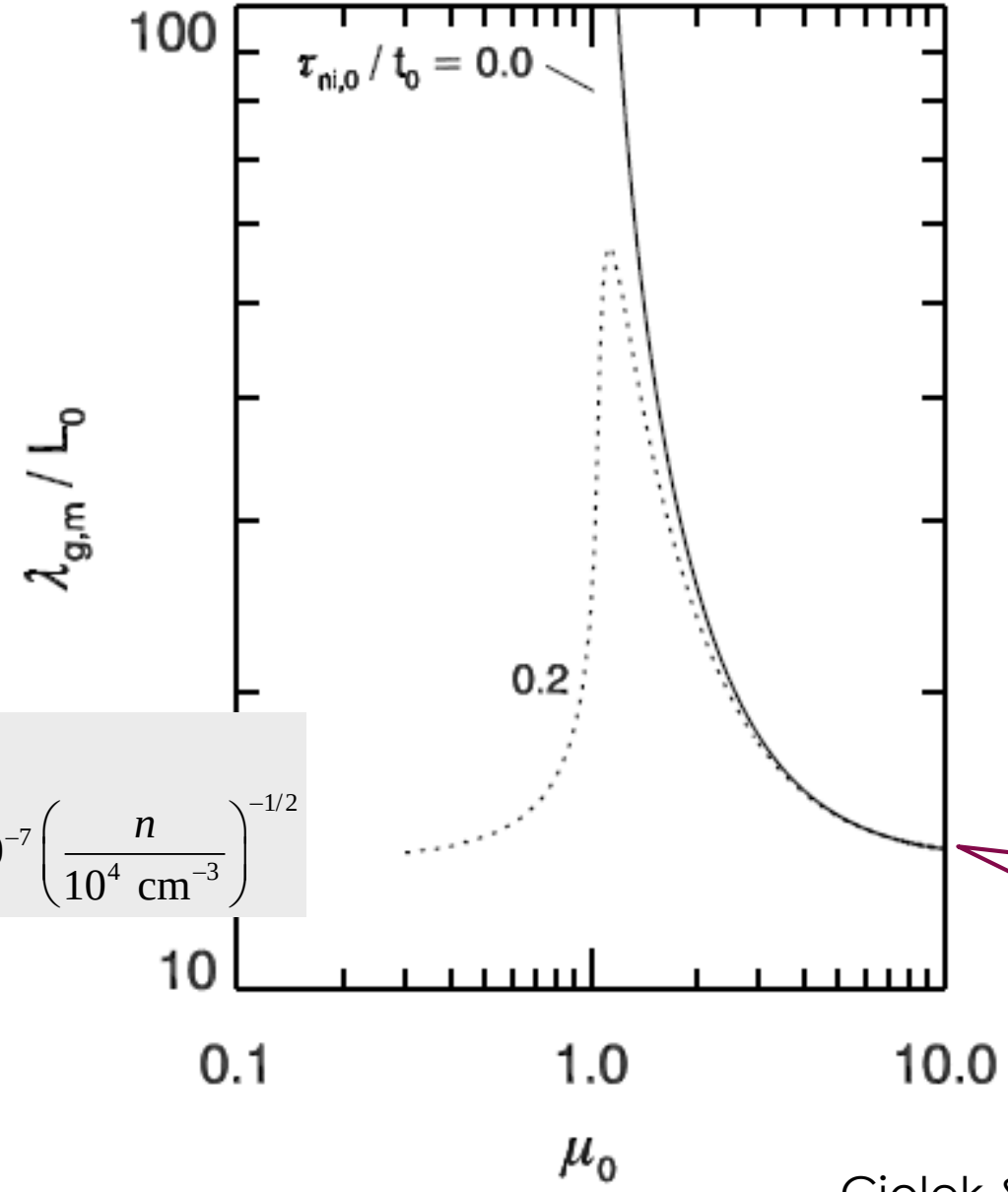
$x' = x/(2\pi Z_0)$, etc.

Periodic isothermal thin-sheet model. Initial small amplitude perturbations. B is initially normal to sheet.

Column density and velocity vectors (unit 0.5 c_s)
Note variation in sizes, shapes, velocity fields.

Basu, Ciolek & Wurster (2009, NewA, 14, 221)

B Field and CMF



$$\tilde{\tau}_{ni,0} = 0.2$$

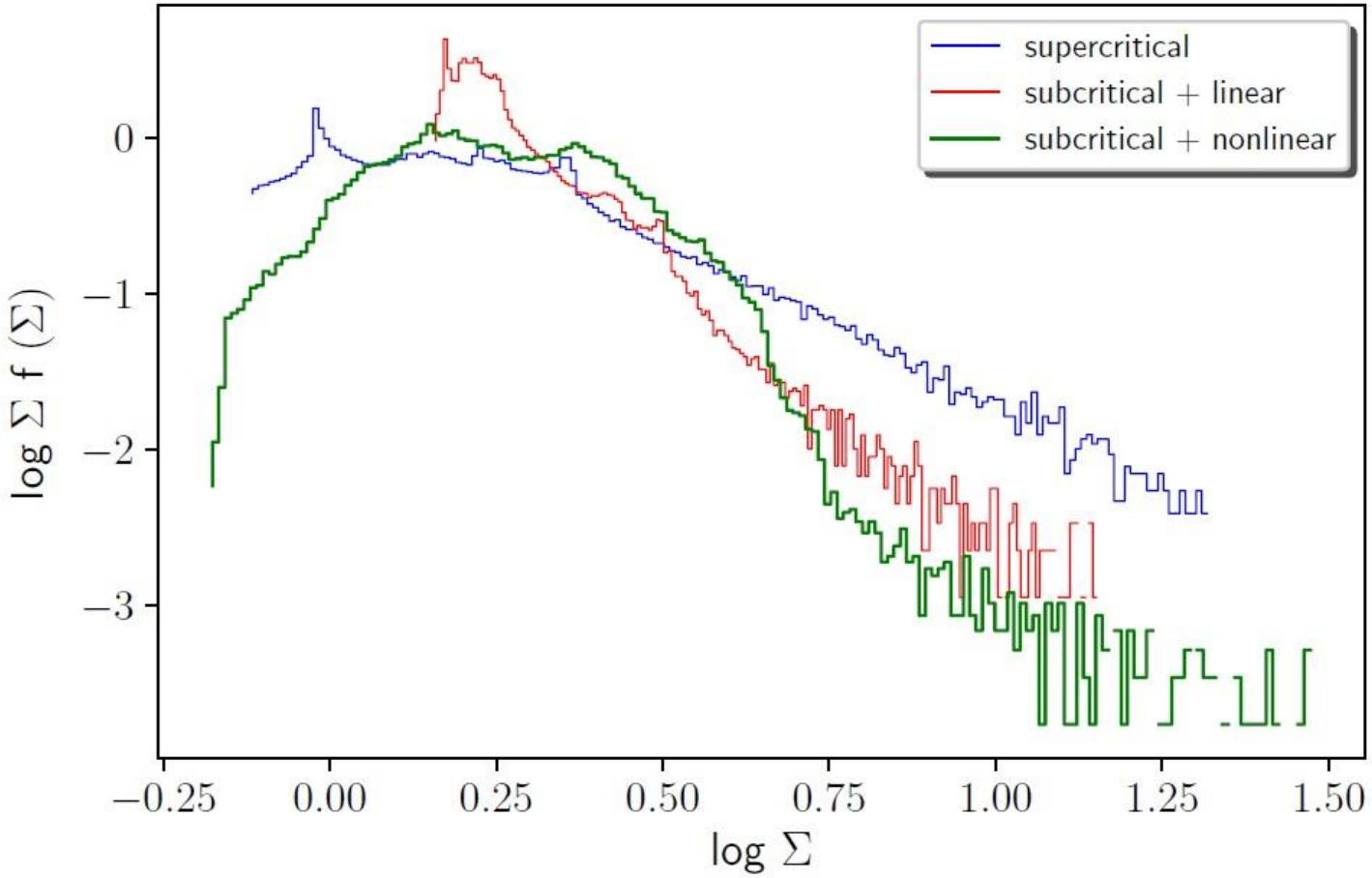
$$\Leftrightarrow x_i = 10^{-7}\left(\frac{n}{10^4\ \mathrm{cm}^{-3}}\right)^{-1/2}$$

Jeans scale is a sensitive function of mass-to-flux ratio and peaks at transcritical values.

$$\lambda_{g,m} = 2\pi Z_0$$

Ciolek & Basu (2006)

Column Density PDF (ΣPDF/NPDF) from 3D non-ideal MHD simulations

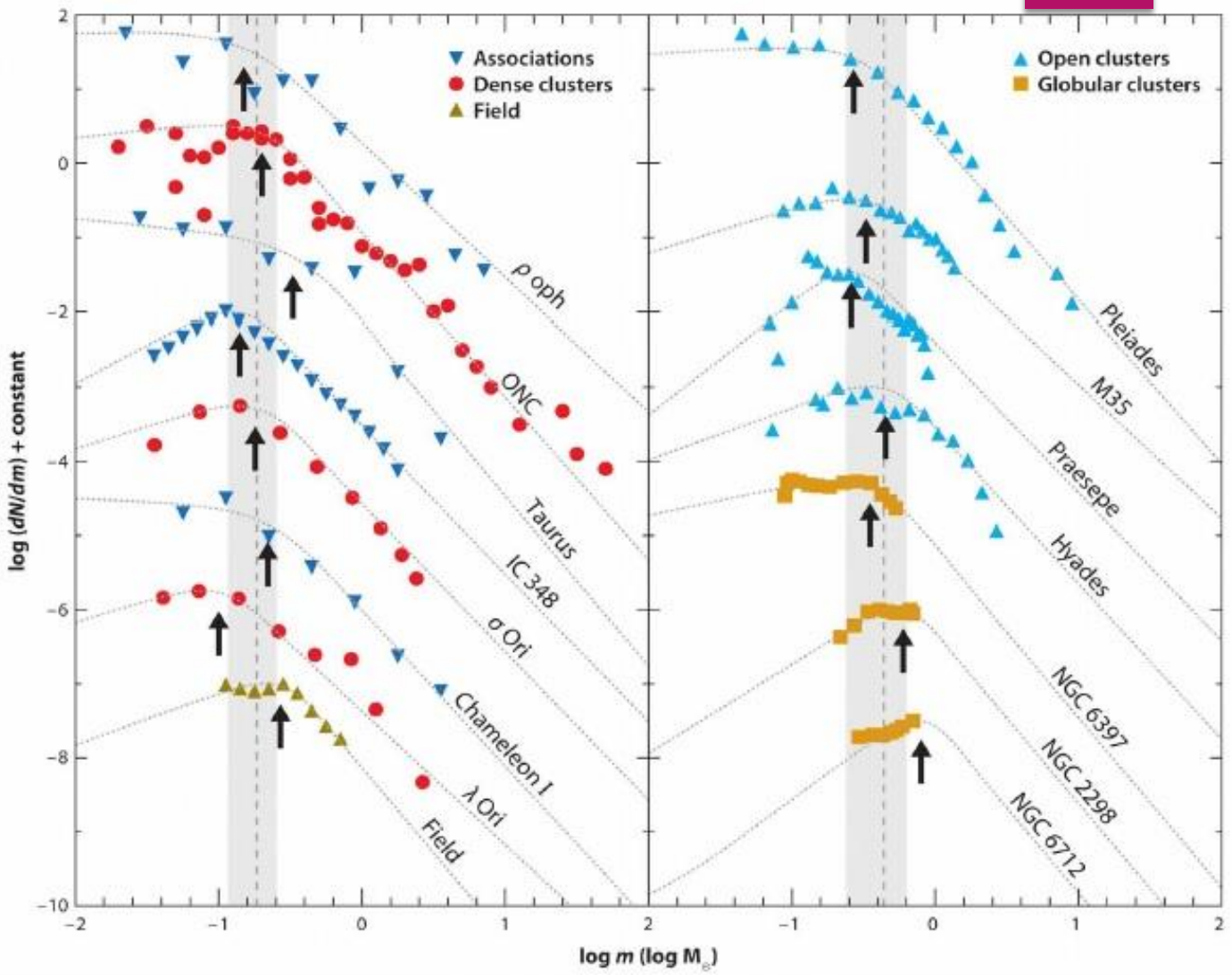


- Supercritical → shallow power-law Npdf consistent with B-E spheres
- Subcritical → steeper power-law from ambipolar diffusion regulated evolution
- Subcritical+turbulence → lognormal plus shallow power law at high column density

Auddy, Basu, & Kudoh (2017)

IMF in clusters

- Significant substellar population generally detected
- Stars/BD ratio ~ 2-5
- New paper by Drass et al. (2016) finds 1:1 ratio in ONC. Not spectroscopically confirmed



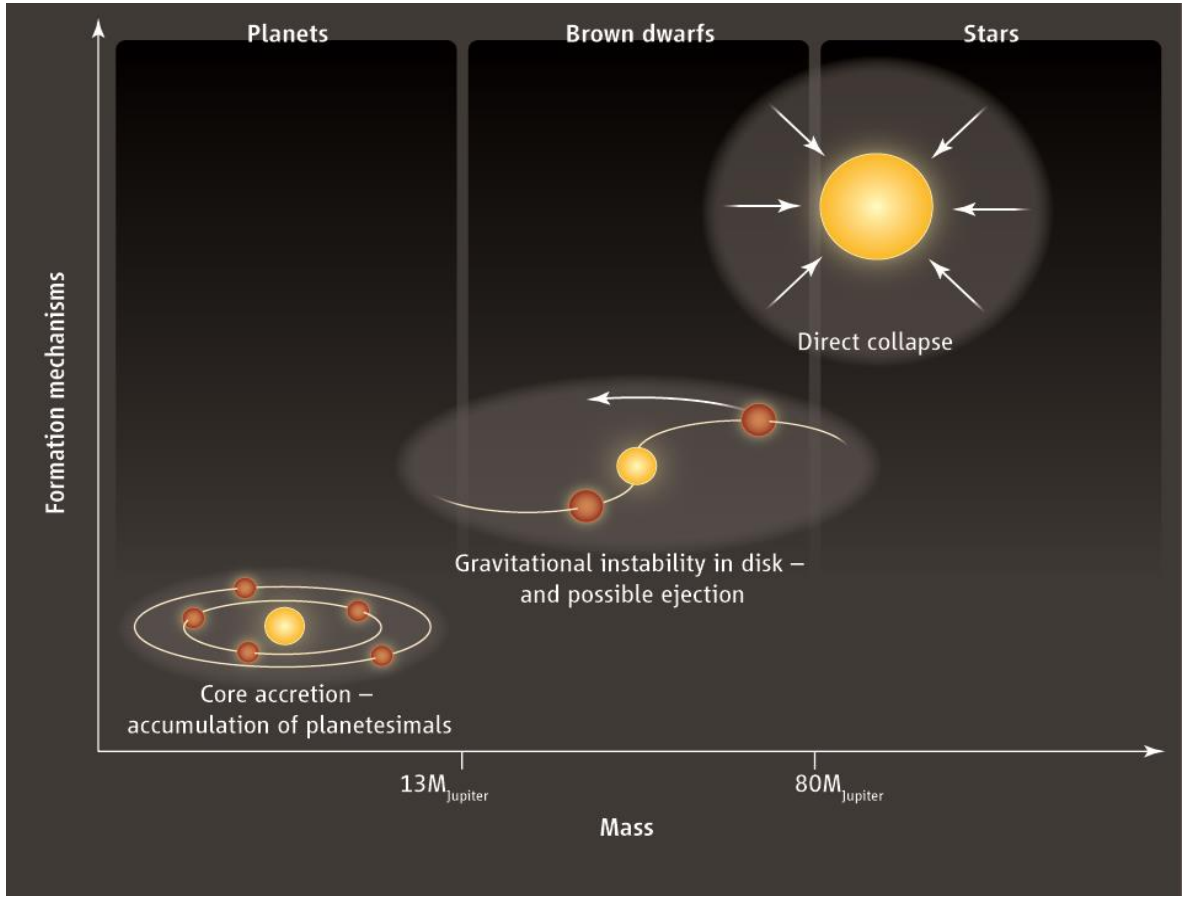
Bastian et al. (2010)

Substellar population: direct collapse, ejection, other processes?

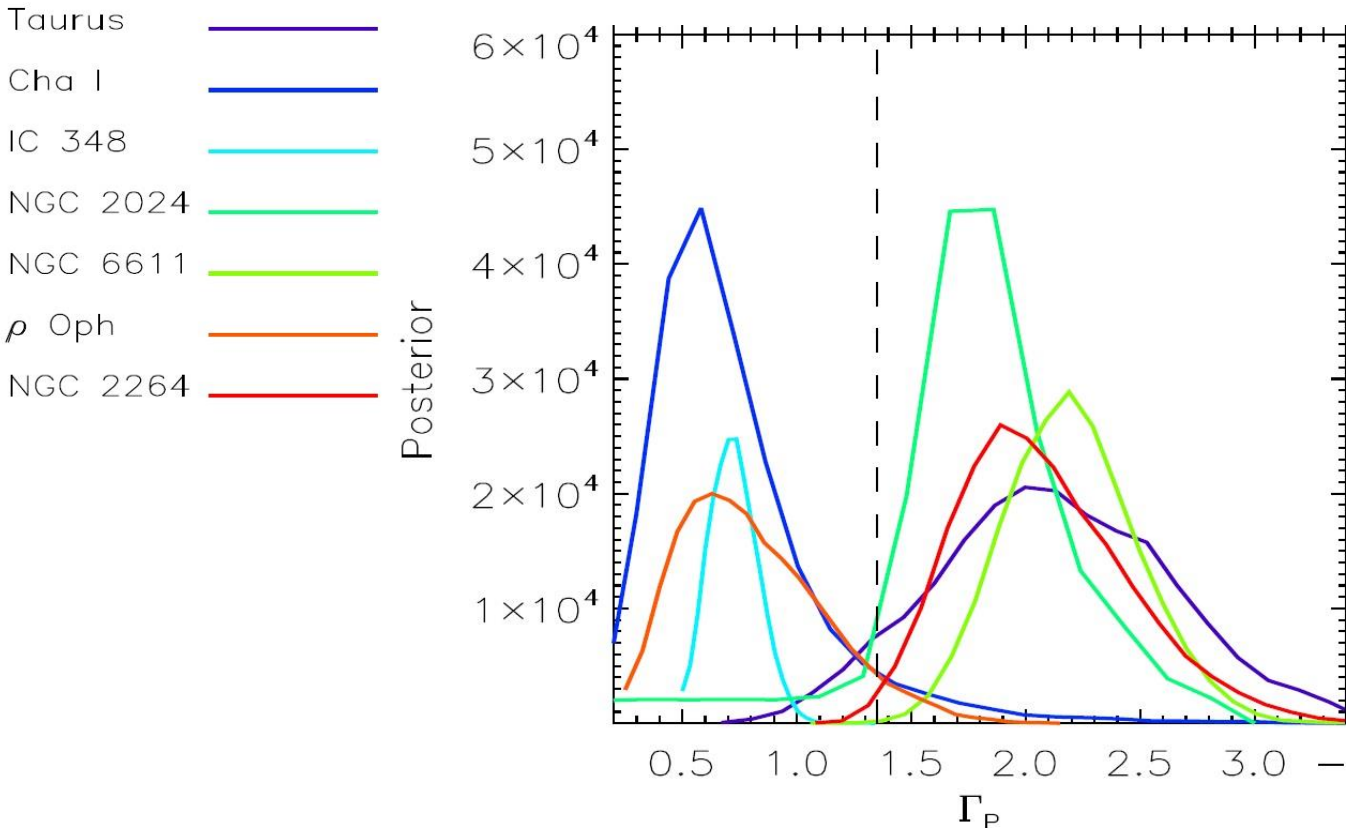
$$M_J = 5.5 M_{sun} \left(\frac{n}{10^4 \mathrm{cm}^{-3}} \right)^{-1/2} \left(\frac{T}{10\,\mathrm{K}} \right)^{3/2}$$

- Star Formation as an accretion process or a fragmentation process?

- Do disks play a role in determining stellar/substellar masses?



Variations in IMF



Intermediate to high mass power-law index

Dib (2014)

Bayesian analysis shows that posterior probability density functions for IMF parameters show a significant variation and do not overlap significantly in many cases.

Summary

- Magnetic fields can play a role in large scale regulation of star formation rate through 1. subcritical mass-to-flux ratio envelopes 2. efficient transport of turbulent energy from outflows
- Big data era leading to calculation of various PDFs in star formation
- Simulations show evidence that CMF and NPDFs will be strongly influenced by ambient magnetic field strength
- IMF: possible significant underlying substellar population
- IMF: Big data era can test and challenge ideas of universality