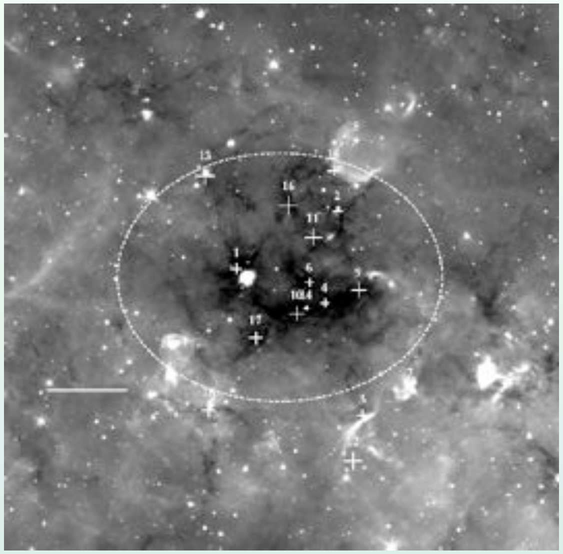
General Theory of Star Formation



Infrared Dark Cloud G28.37 (Butler & Tan)

Orion Nebula Cluster (VLT; JHK) (McCaughrean)

NGC4414 - HST (O. Vallejo)

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What drives star formation? What inhibits star formation?

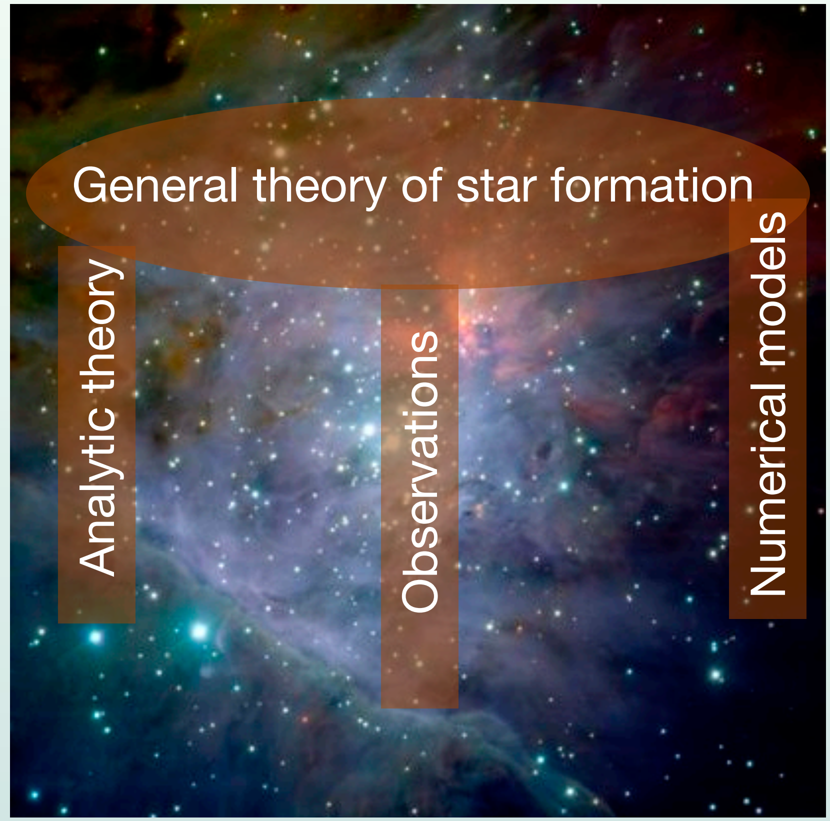
A complicated, nonlinear process

Physics:

Gravity vs pressure (thermal, magnetic, turbulence, radiation, cosmic rays) and shear.

Heating and cooling, generation and decay of turbulence, generation (dynamo) and diffusion of B-fields, etc.

Chemical evolution of dust and gas.



Wide range of scales (~12 dex in space, time) and multidimensional.

Uncertain/unconstrained initial conditions/boundary conditions.

Some notation:

Core -> star or close binary

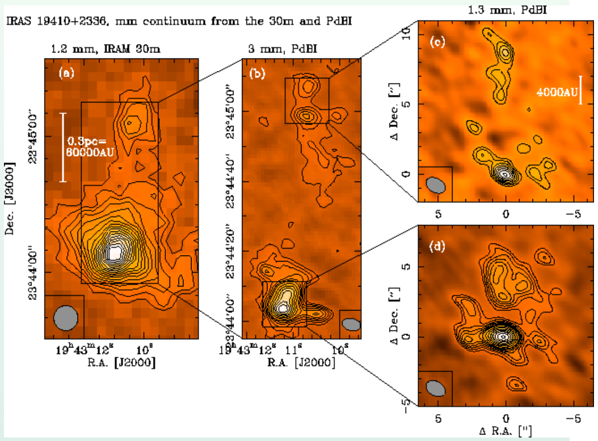
Clump -> star cluster

Star Formation: Open Questions

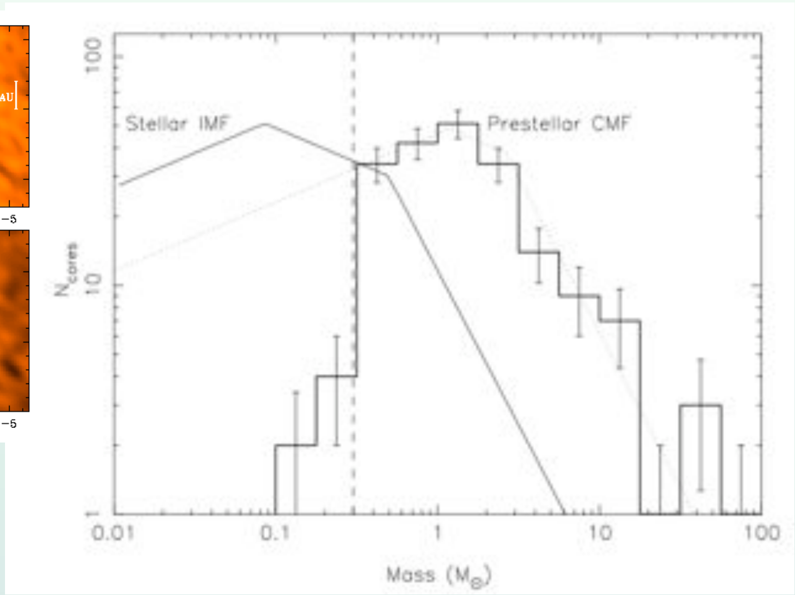
- Causation: external triggering or spontaneous gravitational instability?
- Initial conditions: how close to equilibrium?
- Accretion mechanism: turbulent and/or magnetically regulated fragmentation vs competitive accretion
- Timescale: fast or slow (# of dynamical times)?
- End result
  - Initial mass function (IMF)
  - Binary fraction and properties
  - Initial cluster mass function (ICMF)
  - Efficiency and Rate (& relation to galaxy-scale)

How do these properties vary with environment?

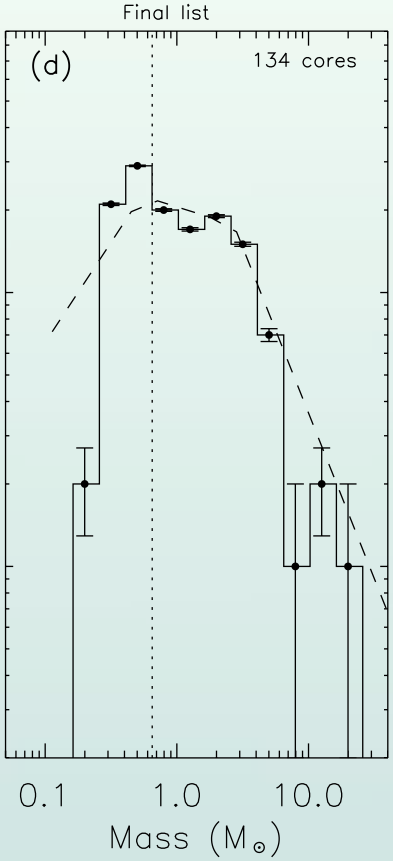
From Cores to Stars:
Individual Stars Appear to Form from Cores



Beuther & Schilke (2004)



Nutter & Ward-Thompson (2007)



Rathborne et al. (2009)

$\epsilon_{core} = m_{*}/m_{core}$ -> ~0.06 0.22+-0.08

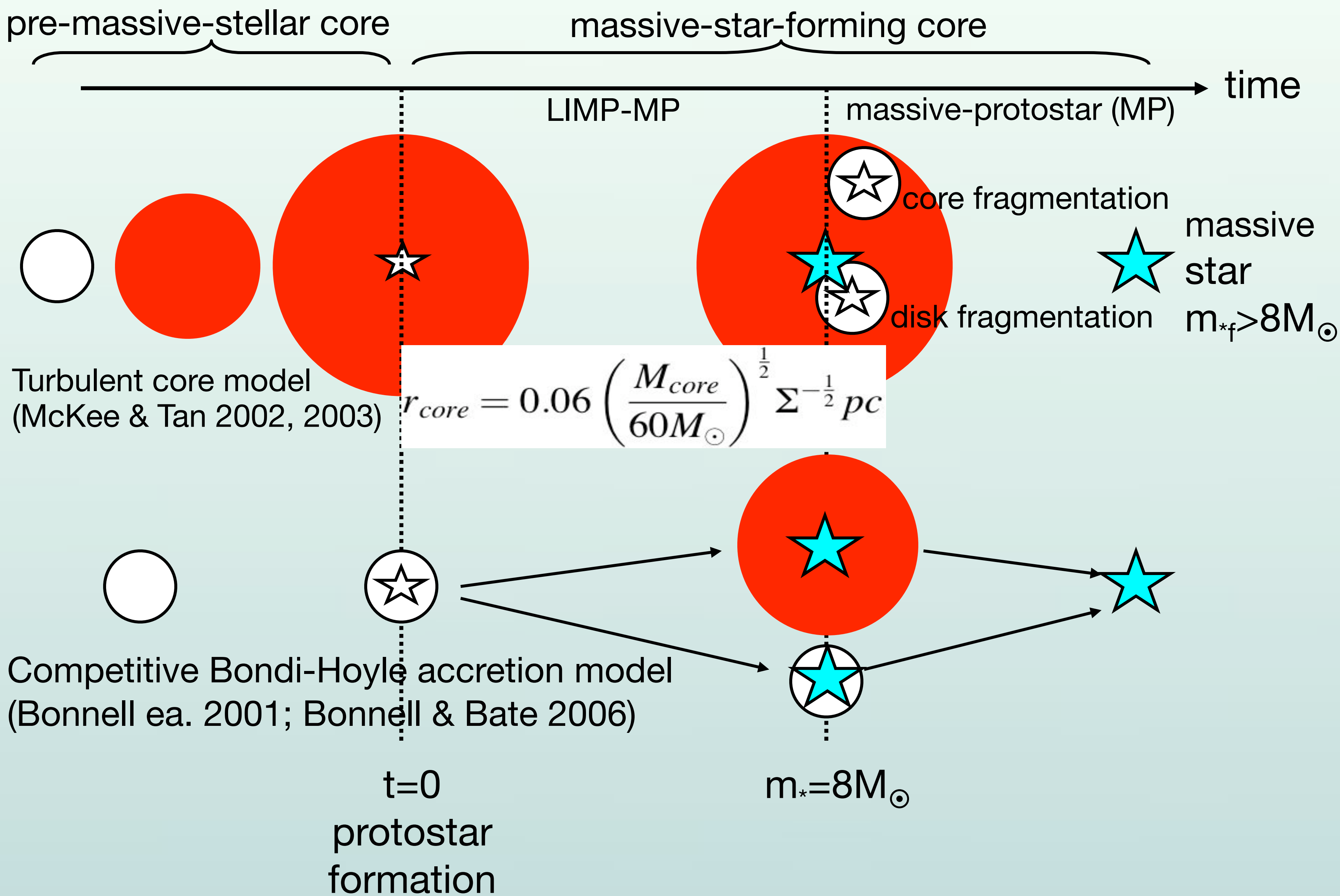
See also: e.g. Testi & Sargent 1998; Motte et al. 2001; Mike Reid & Wilson 2005; Alves et al. 2007; Li et al. 2007; Enoch et al. 2008; Pineda et al. 2009.

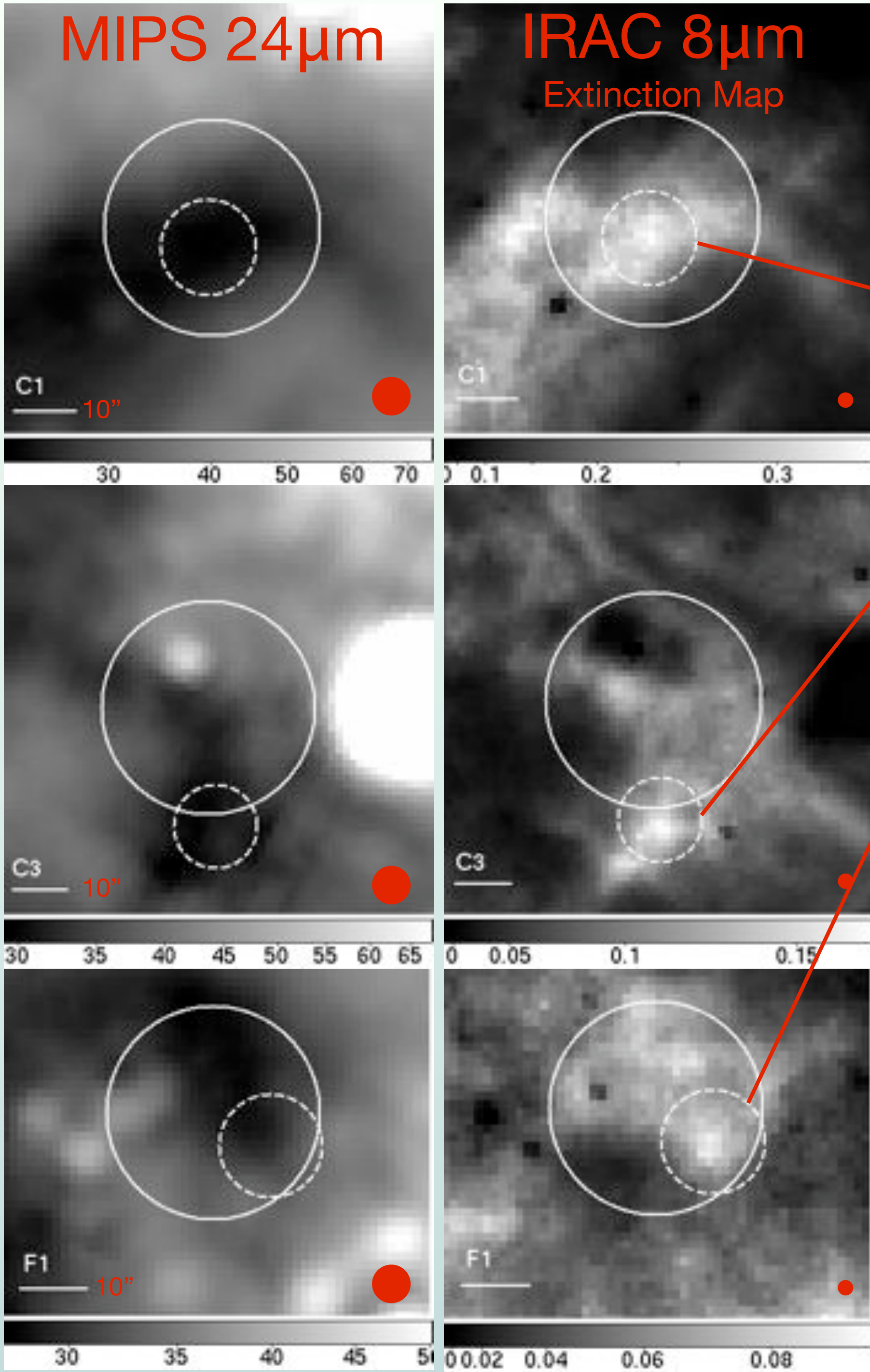
Implications

- The IMF may be partially set by CMF
- There are massive, starless, apparently near equilibrium cores: supported by magnetic fields or turbulence?
- The formation of stars from cores may be relatively inefficient:
  - Protostellar outflow feedback is likely to be important for low-mass cores (Matzner & McKee 1999: ε_{core} ~0.3-0.5) and maybe for high-mass cores also.
  - However, still need to understand effects of binarity, core definition and resolution

Schematic Differences Between Massive Star Formation Theories

Beuther, Churchwell, McKee, Tan (2007); Tan (2008)





Massive Starless Cores

Butler & Tan (2009), Butler & Tan, in prep.

$\Sigma = 0.26$ g cm^{-2} $m_{core} = 205\ M_\odot$

$\Sigma = 0.12$ g cm^{-2} $m_{core} = 94\ M_\odot$

$\Sigma = 0.12$ g cm^{-2} $m_{core} = 50\ M_\odot$

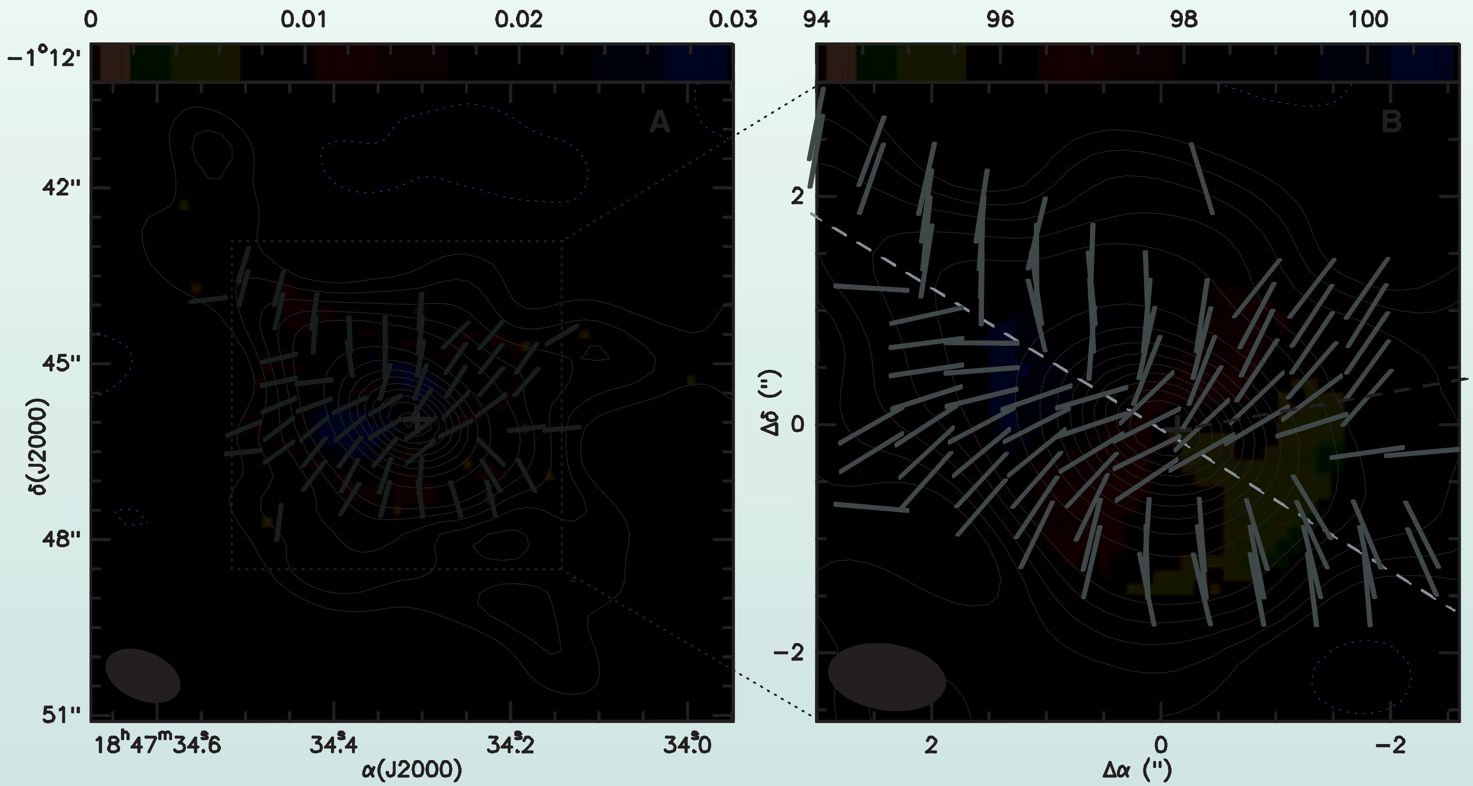
Cores show central concentration, approximately Bonnor-Ebert radial profiles. They contain many thermal Jeans masses. Magnetic fields may be suppressing fragmentation within the core.

$$M_{\rm BE} = 1.182 \frac{c_{\rm th}^4}{(G^3 P_{s,\rm core})^{1/2}} \rightarrow 0.0504 \left(\frac{T}{20\ {\rm K}}\right)^2 \frac{1}{\Sigma_{\rm cl}} M_\odot$$

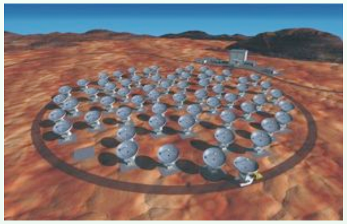
$$M_B = 79 c_\Phi^3 \left(\frac{R}{Z}\right)^2 \frac{\bar{v}_A^3}{(G^3 \bar{\rho})^{1/2}} = 1020 \left(\frac{R}{Z}\right)^2 \left(\frac{\bar{B}}{30\ \mu{\rm G}}\right)^3 \left(\frac{10^3\ {\rm cm}^{-3}}{\bar{n}_{\rm H}}\right)^2 M_\odot$$

$n_H \sim 10^5$ cm^{-3}, B~1mG -> $M_B \sim 100\ M_\odot$

Evidence for strong magnetic fields in massive star-forming cores



Girart et al. (2009)



ALMA Opportunity

Measure the Pre-stellar CMF down to the thermal Jeans mass (or ~$0.1 M_\odot$) in a range of GMC environments across the Galaxy.

$$M_{\rm BE} = 1.182 \frac{c_{\rm th}^4}{(G^3 P_{s,\rm core})^{1/2}} \rightarrow 0.0504 \left(\frac{T}{20\ \rm K}\right)^2 \frac{1}{\Sigma_{\rm cl}}\ M_\odot$$

$$R_{\rm core} = 0.057 \left(\frac{m_{*f}}{30\ M_\odot}\right)^{1/2} \Sigma_{\rm cl}^{-1/2}\ \rm pc$$

-> 3.3×10^{-3}pc for $m_*=0.1M_\odot$

-> ~0.1” at d=8kpc

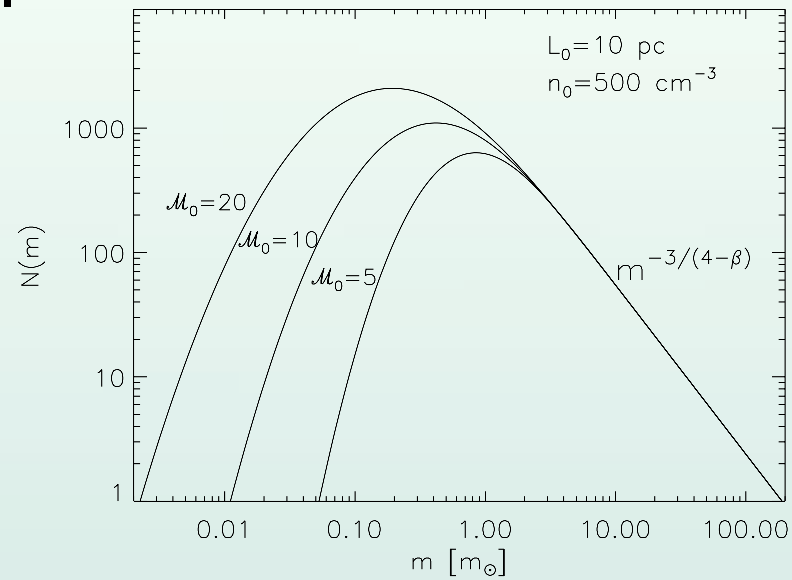
- Determine “core” boundaries based on kinematics. Find gravitationally bound structures.

- Resolve internal structure of massive cores, including B-field strengths (Zeeman).

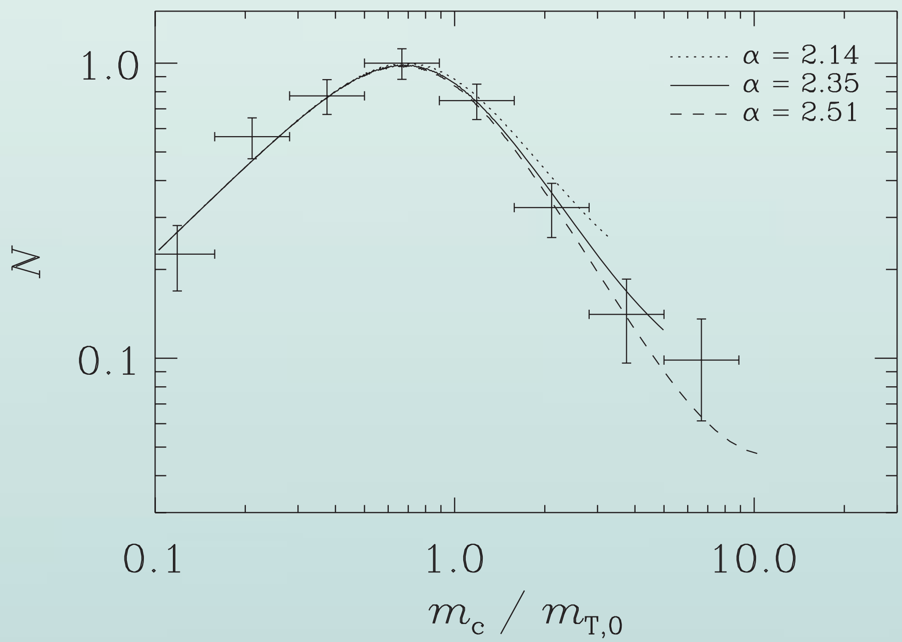
- Resolve core and disk fragmentation in star-forming cores.

From Clumps to Cores: Theories to Explain the CMF

Turbulence-Regulated Fragmentation:
Padoan & Nordlund (2002); Tilley & Pudritz (2004); Hennebelle & Chabrier (2009); See also talk by B. Elmegreen.



Magnetically-Regulated Fragmentation
(Kunz & Mouschovias 2009)



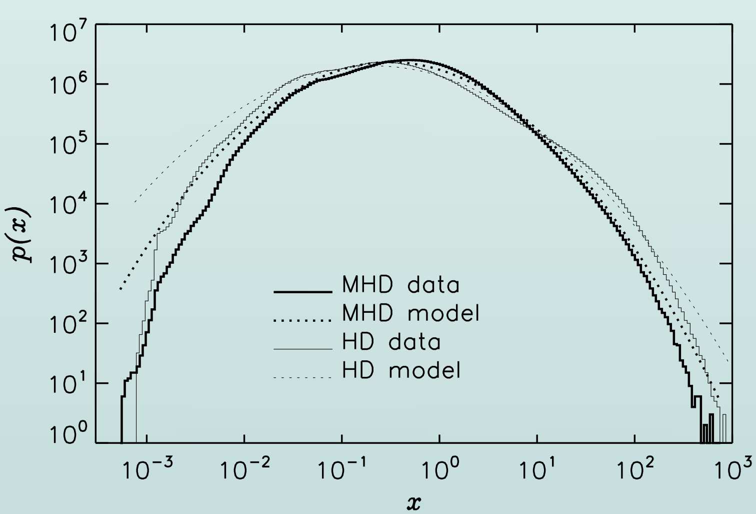
The Rate of Core & Star Formation in Turbulent and Magnetized Gas

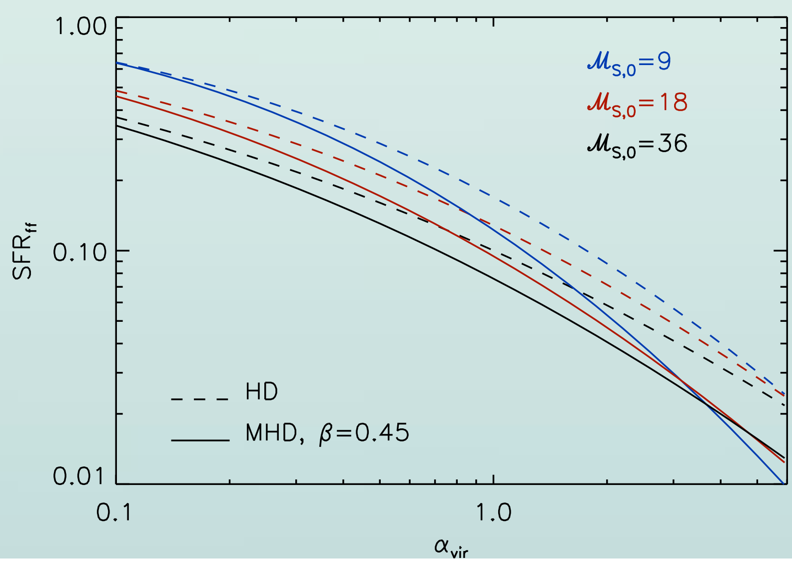
Krumholz & McKee (2005)

$$\varepsilon_{ff} \equiv \dot{M}_* t_{ff} / M_g \approx 0.014 \left(\frac{\alpha_{\mathrm{vir}}}{1.3}\right)^{-0.68} \left(\frac{\mathcal{M}}{100}\right)^{-0.32}$$

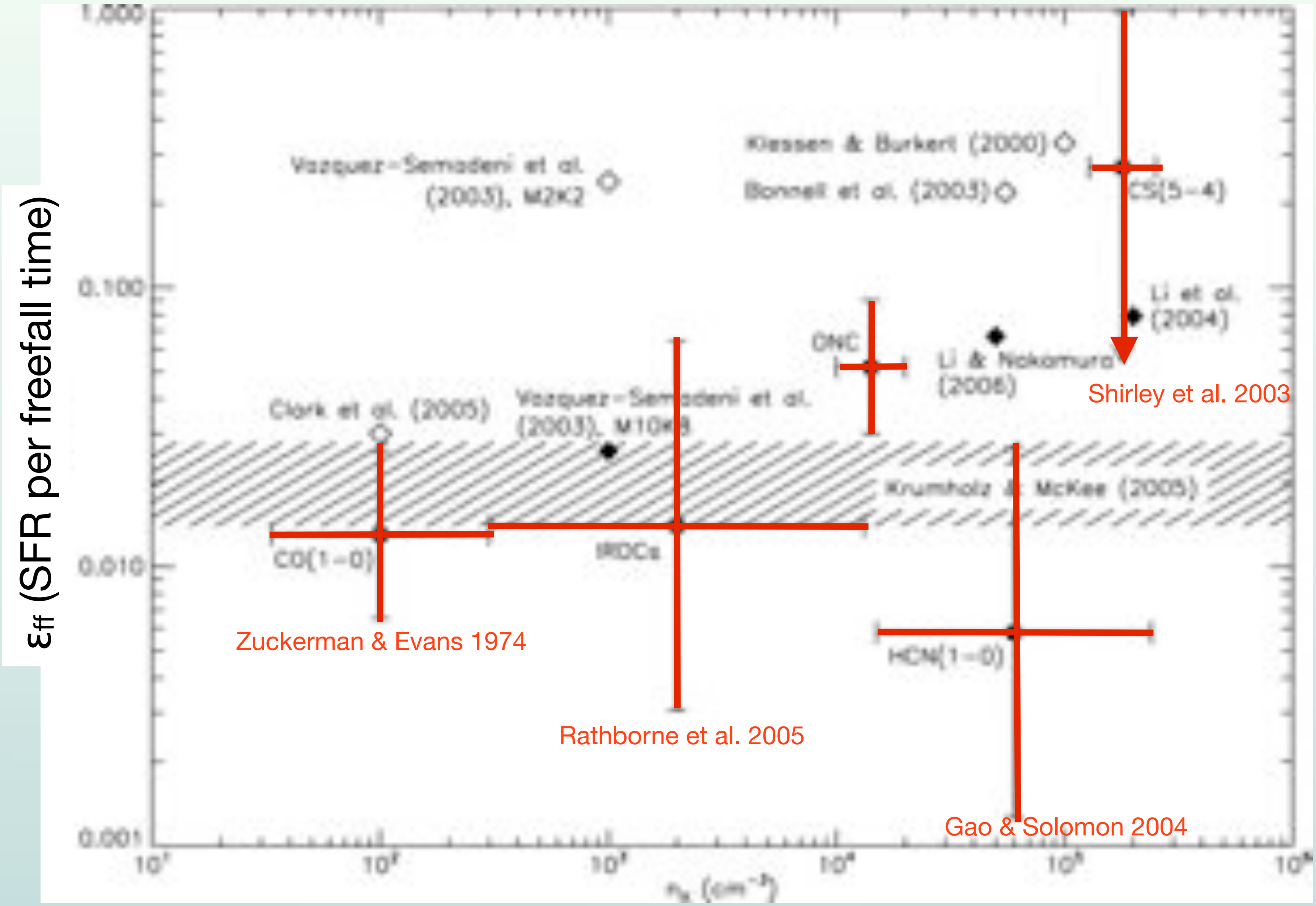
Based on the fraction of gas in gravitationally bound cores (i.e. above some density threshold) given the log-normal distribution of densities produced by supersonic turbulence.

Padoan & Nordlund (2009): extension to turbulent, magnetized gas.





ε_{ff} appears to be independent of density



Krumholz & Tan (2007)

If ε_{ff} is small ($\sim 10^{-2}$), then high ε star clusters need many free-fall times to form

($t_{form} >> t_{ff} \sim$ few x 10^5yr)

This is one motivation for models of slow star cluster formation from gas clumps in near virial equilibrium (Tan, Krumholz, McKee 2006).

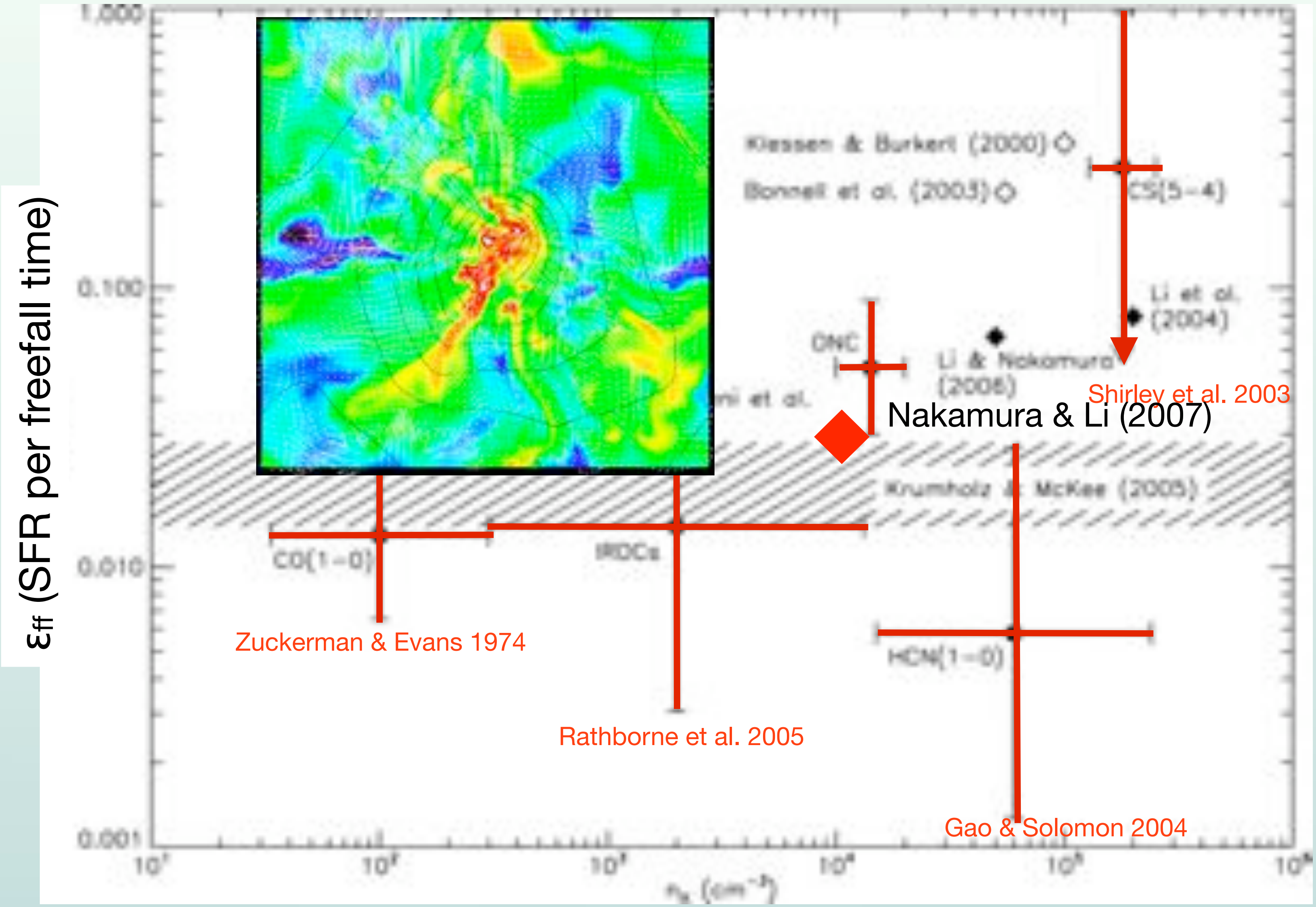
Other evidence for this scenario includes

- Morphologies of gas and young stars
- Momentum flux of protostellar outflows
- Age spreads of pre-main sequence stars
- Estimates of the Orion Nebula Cluster age from ejected stars

However, this issue is still debated (see Elmegreen 2007; Hartmann & Burkert 2007).

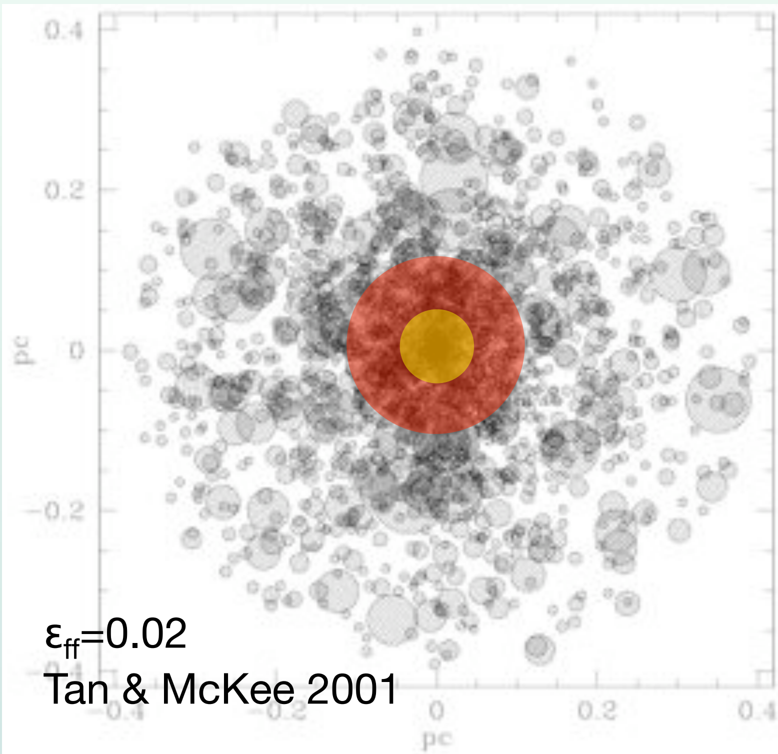
Since turbulence decays in $\sim 1 t_{ff}$, to maintain turbulent virial equilibrium, momentum must be injected into the clump: protostellar outflows.

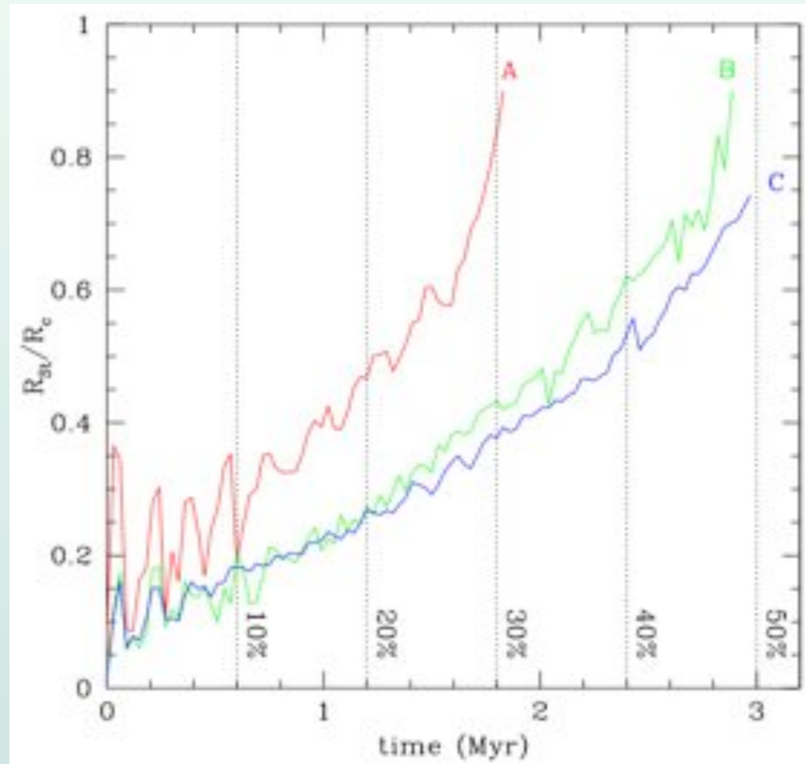
If ε_{ff} is small (~10^{-2}), then high ε star clusters need many free-fall times to form



Krumholz & Tan (2007)

Eventually Ionizing Feedback Will Disperse the Clump Gas and Halt Star Formation





See also Krumholz & Matzner (2009)

From GMCs to Star-forming Clumps:

Star formation is highly clustered: (Lada & Lada 2003; Gutermuth et al. 2009)

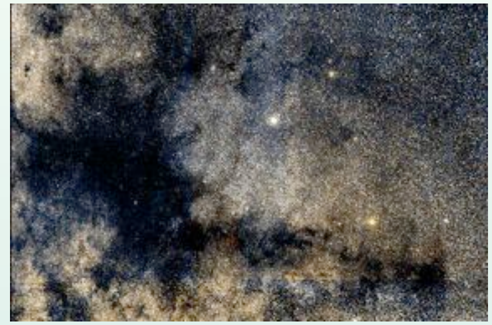
Most mass in GMCs has hardly any star formation ($\varepsilon, \varepsilon_{ff} << 0.01$)

Pipe Nebula (Forbrich et al. 2009)

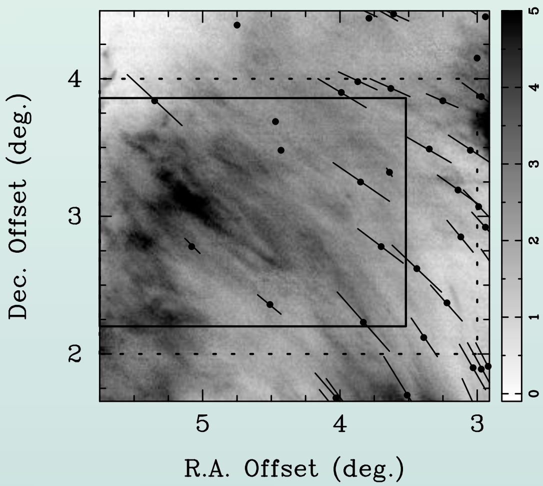
$M_g \sim 10^4 M_\odot$

$\varepsilon \sim 0.0006$

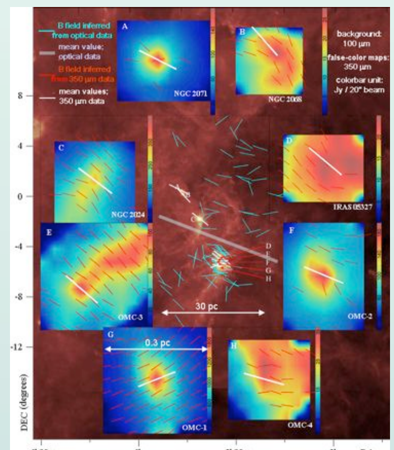
$\varepsilon_{ff} \sim 0.0006$ (assuming $t_{cloud} = 1 t_{ff}$)

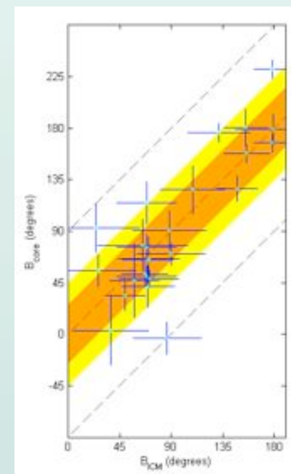


Magnetic fields appear to be strong:



Taurus (Heyer et al. 2008)





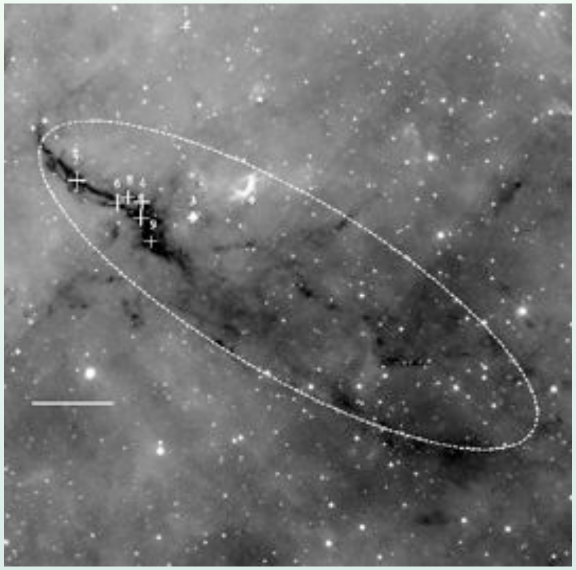
Correlation of field orientations from ~100pc to <1pc scales (Hua-bai Li et al. 2009)

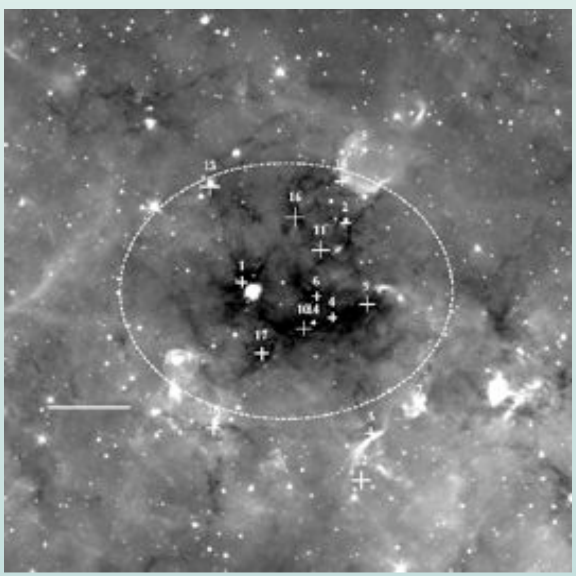
Magnetic critical mass (Mouschovia & Spitzer 1976; Bertoldi & McKee 1992)

$$M_B = 79 c_\Phi^3 \left(\frac{R}{Z}\right)^2 \frac{\bar{v}_A^3}{(G^3 \bar{\rho})^{1/2}} = 1020 \left(\frac{R}{Z}\right)^2 \left(\frac{\bar{B}}{30\,\mu\mathrm{G}}\right)^3 \left(\frac{10^3\ \mathrm{cm}^{-3}}{\bar{n}_\mathrm{H}}\right)^2 \quad M_\odot$$

From GMCs to Star-forming Clumps: IRDCs

Butler & Tan (2009); Hernandez & Tan, in prep.





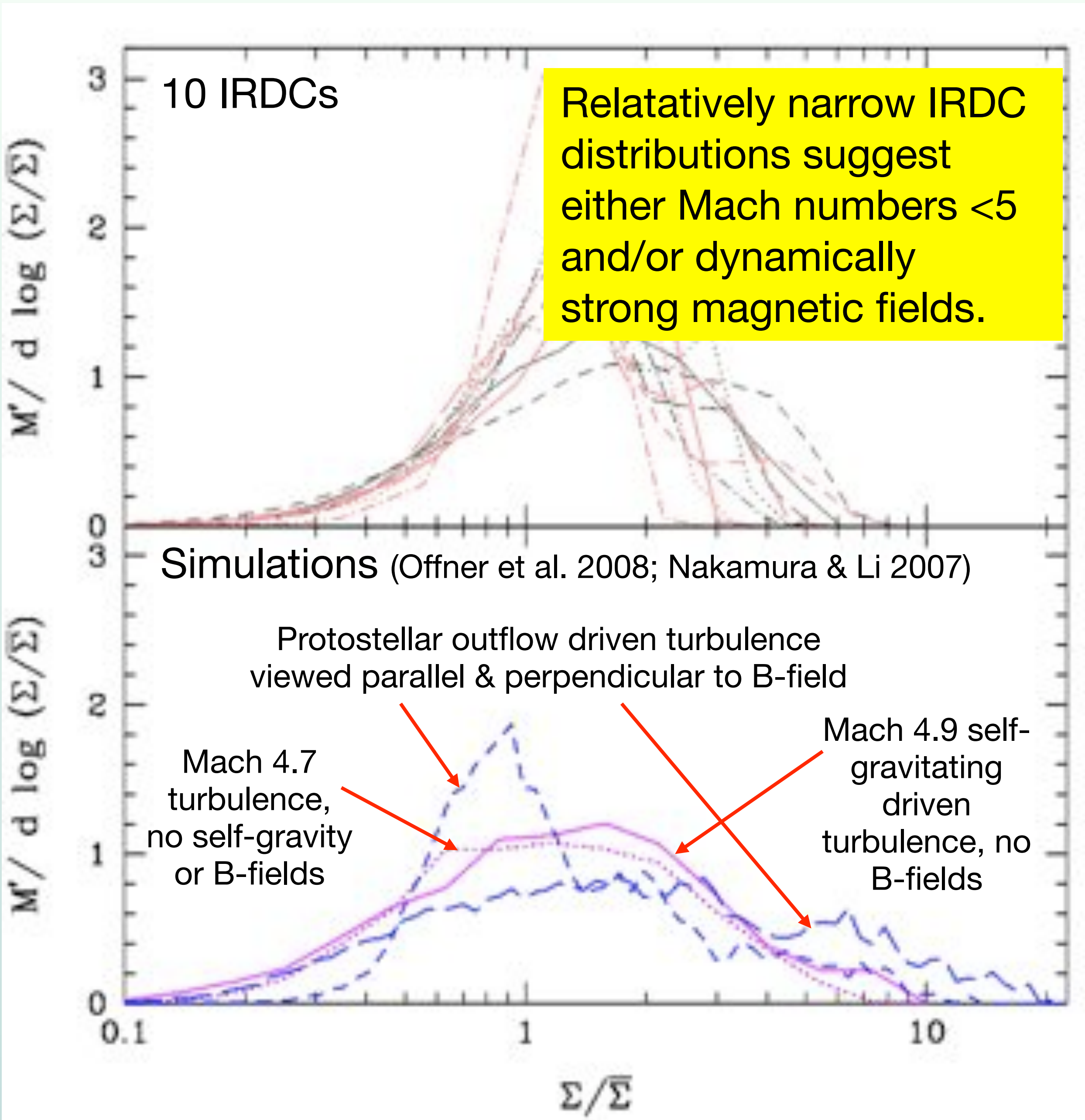
Variety of morphologies: filamentary to near spherical.

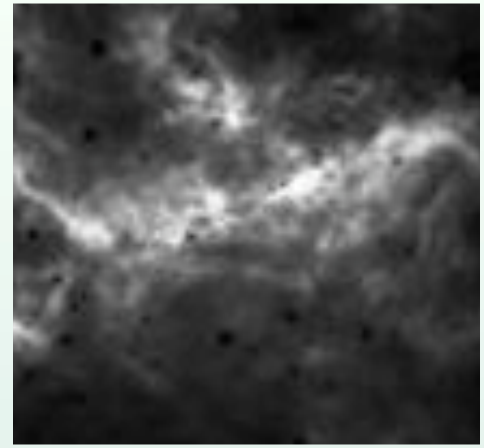
Mass estimates from MIR extinction mapping, CO emission, and assuming virial equilibrium are in reasonable agreement.

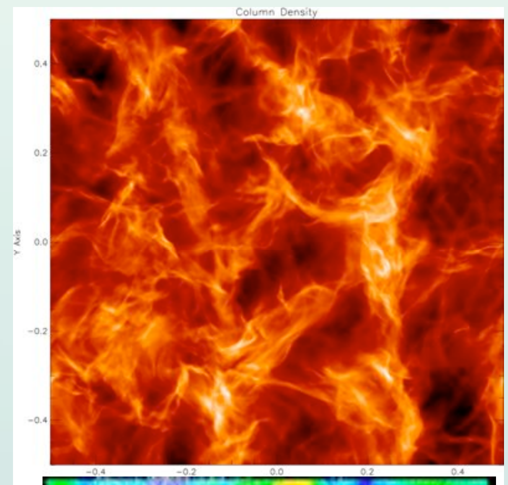
Relatively narrow distribution of centroid velocities of “cores”.

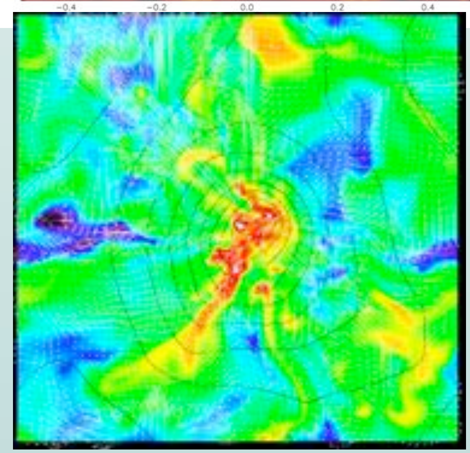
Distribution of mass surface densities indicates Mach no. of turbulence <~5 and/or relatively strong B-fields.

Distribution of M with $\Sigma/\bar{\Sigma}$









What drives galactic-scale star formation? What is the rate limiting step?

$$\Sigma_{\rm sfr} = A_g \Sigma_g^{\alpha_g}$$

Empirical: α_g=1.4+-0.15 Molecular-dominated regions (Kennicutt 1998)
Theoretical: growth of large scale grav. instabilities (for constant scaleheight disks) (Larson 1988; Elmegreen 1994; Wang & Silk 1994)

$$\Sigma_{\rm sfr} = A_{\rm H2} \Sigma_{\rm H2}$$

Empirical: normal spirals (Leroy et al. 2008; Bigiel et al. 2008)
Theoretical: GMC properties independent of galactic environment; constant density, constant $\epsilon_{\rm ff}$. Cannot hold in starburst regime.

$$\Sigma_{\rm sfr} = A_{\rm KM} f_{\rm GMC} \phi_{\bar{P},6}^{0.34} Q_{1.5}^{-1.32} \Omega_0^{1.32} \Sigma_{g,2}^{0.68}$$

Krumholz & McKee (2005): GMCs are virialized and their surfaces in pressure equilibrium with Q~1 disk.

$$\Sigma_{\rm sfr} = A_{\rm KMT} f_{\rm GMC} \Sigma_{g,2} \times \begin{cases} (\Sigma_g / 85 M_\odot {\rm pc}^{-2})^{-0.33}, & \Sigma_g < 85\ M_\odot {\rm pc}^{-2} \\ (\Sigma_g / 85 M_\odot {\rm pc}^{-2})^{0.33}, & \Sigma_g > 85\ M_\odot {\rm pc}^{-2} \end{cases}$$

Krumholz, McKee, Tumlinson (2009): GMCs are virialized and their surfaces in pressure equilibrium with Q~1 disk for high Σ_g regime. Pressure set by internal feedback in low Σ_g regime.

$$\Sigma_{\rm sfr} = B_\Omega \Sigma_g \Omega$$

Empirical: molecular dominated regions (Kennicutt 1998)
Theoretical: Spiral arm passage; swing amplifier (Wyse & Silk 1989)

$$\Sigma_{\rm sfr} = B_{\rm CC} Q^{-1} \Sigma_g \Omega (1 - 0.7\beta), \quad (\beta \ll 1)$$

Theoretical: GMC collisions in a shearing, thin, molecular-dominated, Q~1 disk (Tan 2000)

Why GMC collisions can be important for driving galactic SFRs:

In the molecular-dominated regions, the rate limiting step for star formation should be the creation of star-forming clumps in GMCs, rather than the formation of GMCs themselves. (In the atomic-dominated regions, it can also depend on the formation of GMCs from the CNM and/or WNM.)

Converging flows of dense gas are a natural mechanism to create high density regions. In the molecular-dominated regime, these converging flows will often result from GMC-GMC collisions (Scoville et al. 1986; Tan 2000).

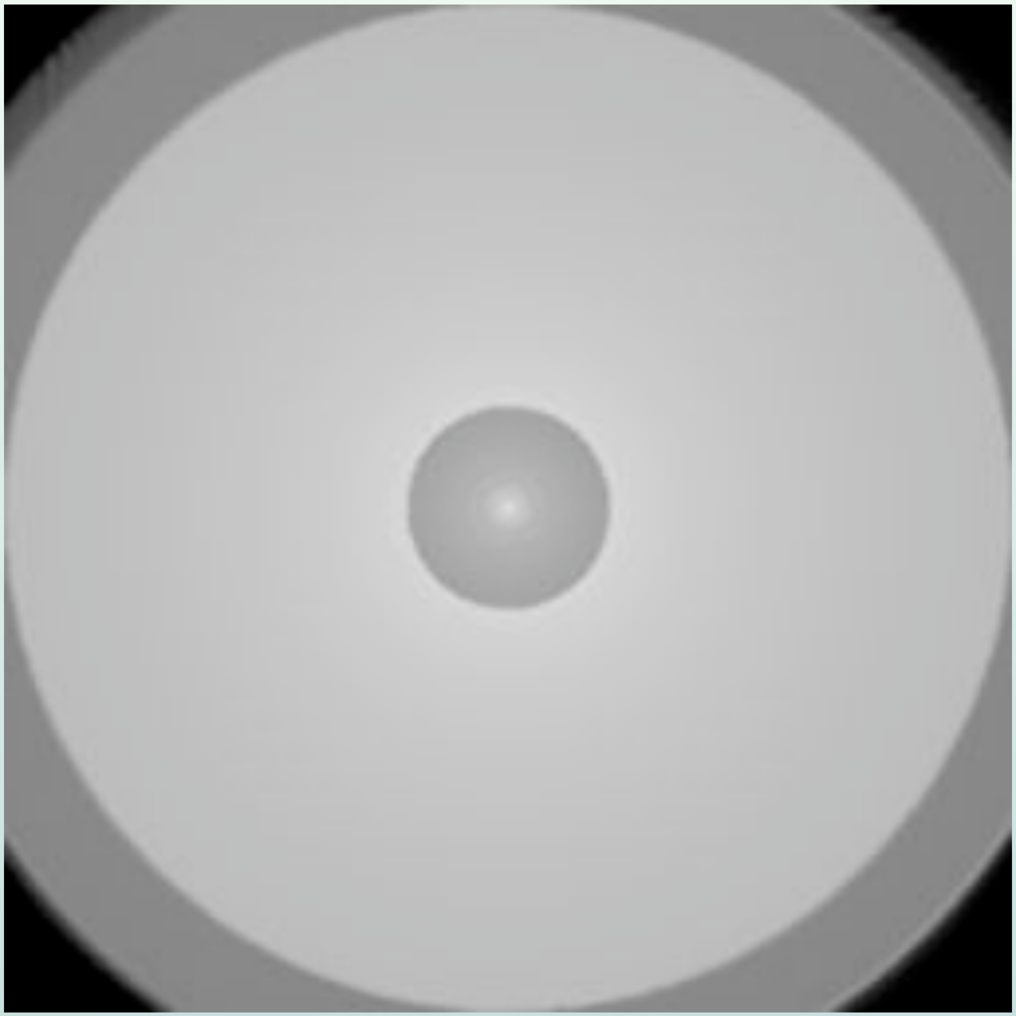
Spiral density waves will concentrate this process, but are not necessary.

Compressions can also result from gravitational instability; internal GMC turbulence; HII region and supernova feedback.

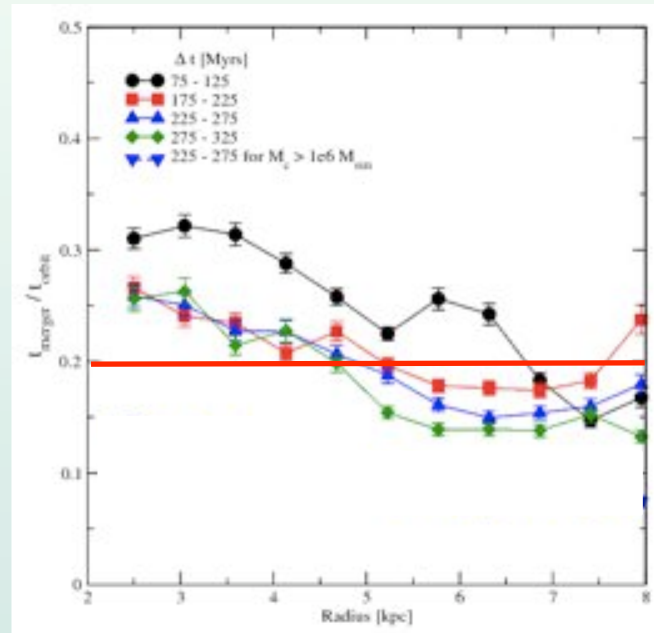
-Dependence of SFRs on galactic shear. GMC collisions are driven by shear.
-Dispersion in GMC star formation efficiencies
-Disturbed kinematics or GMCs, especially around IRDCs

Dependence of SFRs on shear rate: GMC collisions are driven by shear.

20kpc



Tasker & Tan (2009): ENZO AMR 3D Hydro Atomic Cooling



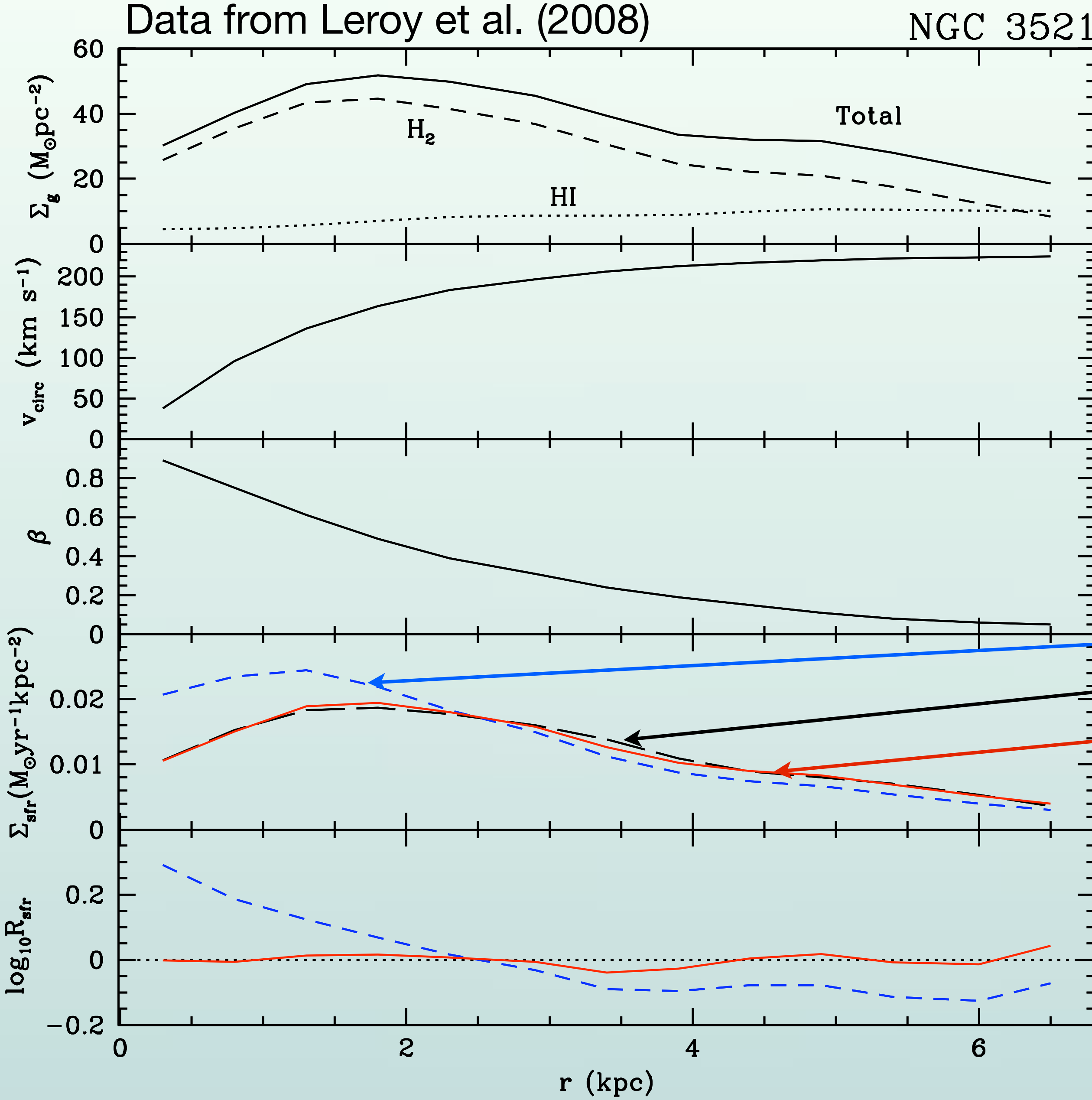
$$\bar{\Sigma}_{\rm sfr} \simeq B_{\rm CC}\bar{\Sigma}_g \Omega(1 - 0.7\beta),$$

$$\beta \equiv \frac{d\ln v_{\rm circ}}{d\ln r},$$

Empirical Effect of Shear on Σ_{sfr}

Tan (2009)

Data from Leroy et al. (2008)



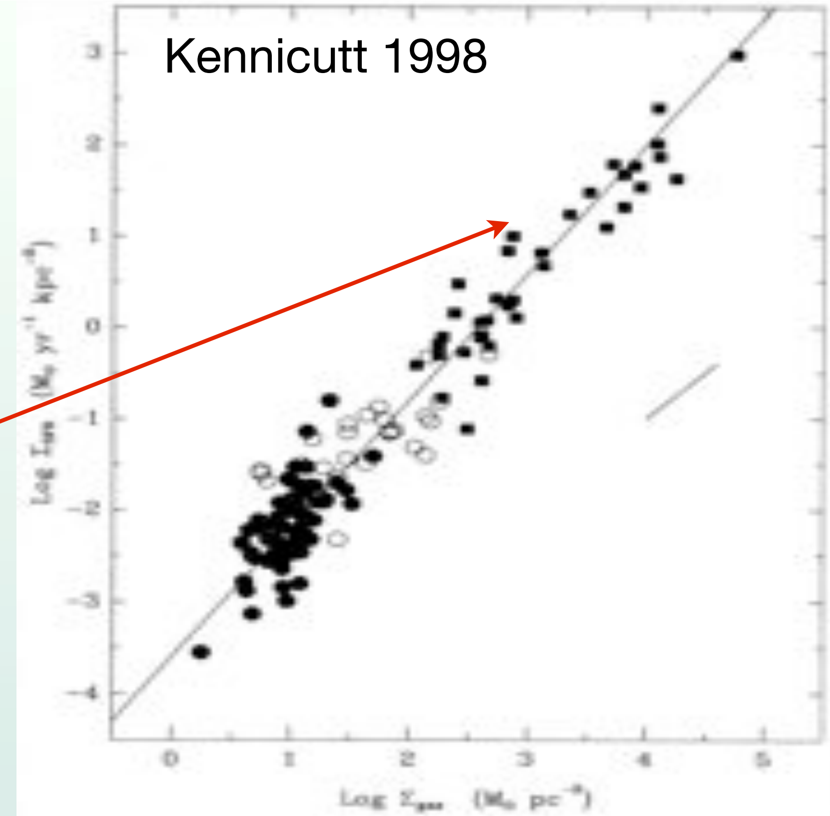
$\Sigma_{sfr} = B\,\Sigma_g\,\Omega$

Observed Σ_{sfr}

$\Sigma_{sfr} = B\,\Sigma_g\,\Omega(1\text{-}0.7\beta)$

Comparison of 6 SF laws:

Tan (2009)



Schmidt-Kennicutt power law:

$$\Sigma_{\rm sfr} = A_g \Sigma_{g,2}^{\alpha_g},$$

Constant molecular law:

$$\Sigma_{\rm sfr} = A_{\rm H2} \Sigma_{\rm H2,2},$$

Krumholz-McKee (2005) turbulence law:

$$\Sigma_{\rm sfr} = A_{\rm KM} f_{\rm GMC} \phi_{\bar{P},6}^{0.34} Q_{1.5}^{-1.32} \Omega_0^{1.32} \Sigma_{g,2}^{0.68}$$

Krumholz-McKee-Tumlinson (2009) turbulence law

$$\Sigma_{\rm sfr} = A_{\rm KMT} f_{\rm GMC} \Sigma_{g,2} \times \begin{cases} \left(\Sigma_g / 85 M_\odot {\rm pc}^{-2}\right)^{-0.33}, & \Sigma_g < 85\ M_\odot {\rm pc}^{-2} \\ \left(\Sigma_g / 85 M_\odot {\rm pc}^{-2}\right)^{0.33}, & \Sigma_g > 85\ M_\odot {\rm pc}^{-2} \end{cases}$$

Omega law:

$$\Sigma_{\rm sfr} = B_\Omega \Sigma_g \Omega$$

8.0×10^{-3}, $\epsilon_{\rm CC} = 0.02$

GMC collisions law:

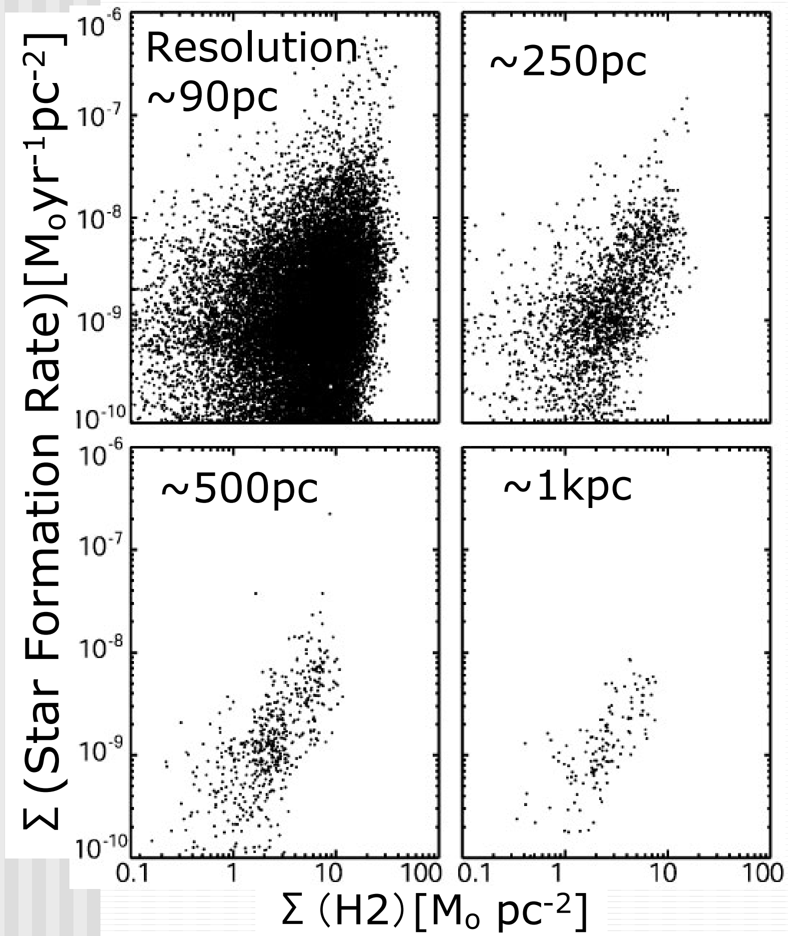
$$\Sigma_{\rm sfr} = B_{\rm CC} Q^{-1} \Sigma_g \Omega (1 - 0.7\beta), \quad (\beta \ll 1)$$

A single value of $B_{\rm CC} = 8 \times 10^{-3}$ predicts SFRs to RMS error of factor of 1.8

These laws predict the radial profiles with an RMS error of a factor of 1.5

Dispersion in GMC Star Formation Efficiencies

Slide from Sachiko Onodera:



- Correlation evident in 1kpc, 500pc
- Becomes looser with higher resolution
- GMC scale is where S-K law becomes invalid

(Onodera Ph.D thesis 2009)

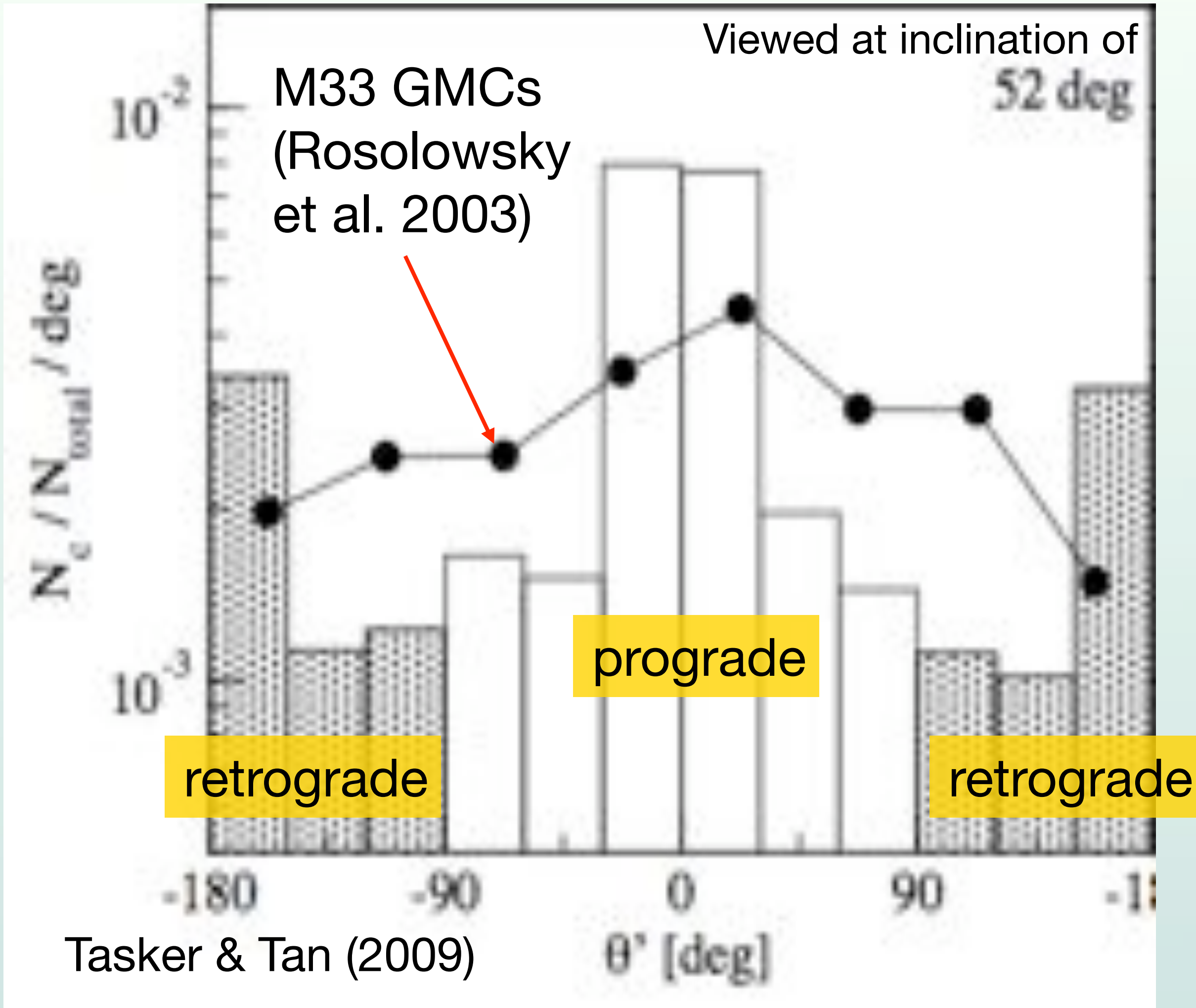
Nobeyama legacy project on M33: Onodera, Kuno et al. 2009, in prep.

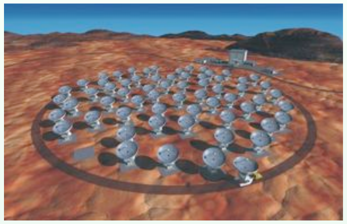
See also Mooney & Solomon (1988) for Galactic GMCs.

Turbulence-regulated law should predict a correlation of Σ_{sfr} with Σ_{H2} in GMCs with smaller dispersion for more massive clouds?

Implications of Frequent GMC Collisions

Frequent mergers can explain the retrograde rotation of GMCs with respect to galactic rotation.



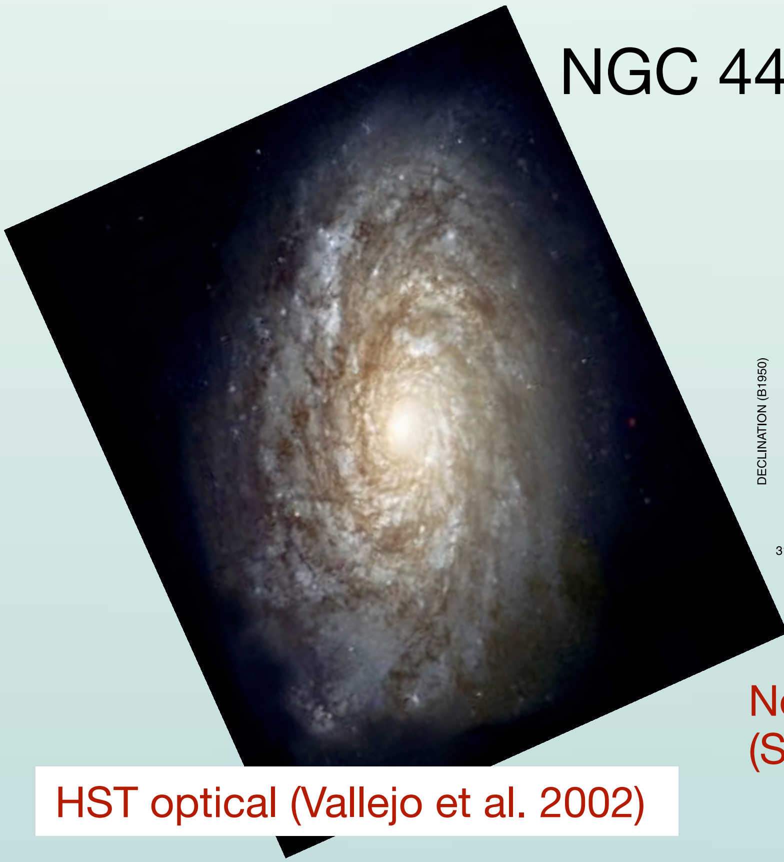


ALMA Opportunity

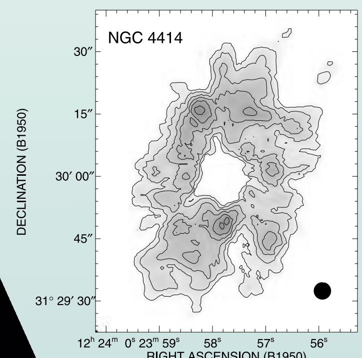
Measure the GMC mass function down to $\sim 10^4 M_\odot$ in a range of galactic environments.

Measure GMC kinematics: virial parameters, rotation directions. Find the precursors to star-forming clumps.

NGC 4414 at 19.2 Mpc

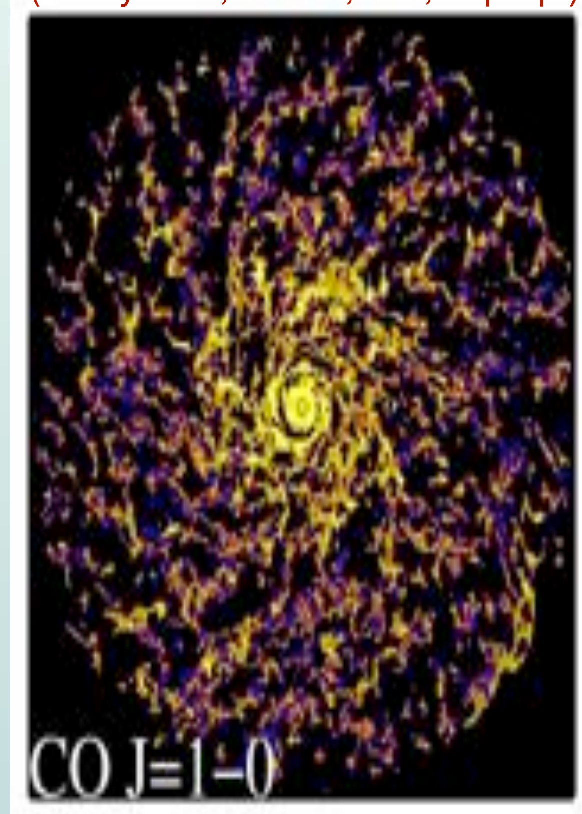


HST optical (Vallejo et al. 2002)

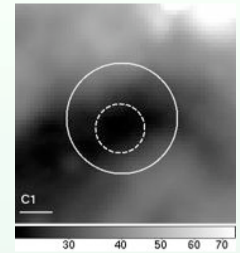


Nobeyama CO(1-0)
(Sakamoto et al. 1999)

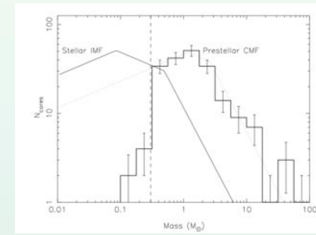
Predicted CO with
ALMA 0.3” beam
(Narayanan, Tasker, Tan, in prep.)



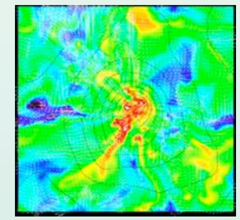
Conclusions:



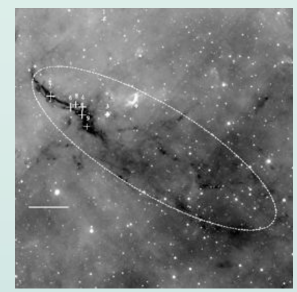
From cores to stars: CMF & IMF similarities are intriguing. Pre-stellar cores appear to be in near virial & pressure equilibrium. Massive cores must be supported by B-fields and/or turbulence. Outflows likely set the core SFE. ALMA will resolve core and disk fragmentation and core disruption.



From clumps to cores: Fragmentation regulated by turbulence and/or B-fields can reproduce observed CMF. Competitive accretion does not produce the high-mass end of CMF. ALMA will measure the CMF, surrounding gas kinematics, and B-fields in a range of environments to test these models.



From clumps to star clusters: Small SFEs per free-fall time, ε_{ff}~0.01-0.05. Clusters forming with high SFE, ε~0.5, must take many free-fall times to form. Turbulence must be maintained in the clump, likely by protostellar outflows.



From GMCs to clumps & star clusters: GMC SFEs per free-fall time are small, ε_{ff}~0.01. Star formation is highly clustered. Most GMC mass has ε,ε_{ff} <<0.01, perhaps because of magnetic support. Converging flows, many from GMC collisions, may initiate star cluster formation by producing magnetically supercritical clumps. Study of GMC kinematics around IRDCs can help test this idea. ALMA can extend these studies to nearby galaxies.

From galaxies to star clusters: In molecular-dominated regions, most gas is in GMCs - their formation from atomic gas is not likely to be the rate limiting step for star formation. Self-regulation by star formation feedback should lead to Q~1 disks, with significant gas mass in bound clouds. Spiral arms do not appear to enhance global SFRs. Models of star formation regulated by turbulence or cloud collisions can explain observed SFRs. Distinguish by dependence on galactic shear, and the dispersion of GMC SFEs.