Origins
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Simulating GMC and star cluster formation: setting the stage for radiative feedback

Ralph E. Pudritz

KITP Stars14: Gravity’s Loyal Opposition
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Collaborators and students

McMaster:

Ph.Ds - Mikhail Klassen and Corey Howard

Samantha Benincasa (former undergrad thesis),

Bill Harris, James Wadsley

Rolf Kuiper (MPIA), Thomas Peters (Zurich), Robi Banerjee (Hamburg), Elizabeth Tasker (Hokkaido U.)

Helen Kirk (NRC – Herzberg, Victoria),

Physical processes: clouds to clusters, and back

I. Galaxy to GMC to Cluster:

II Simulating GMC Formation Comparison to Observed Catalogues

III Feedback on GMC scales: cluster SFR and input

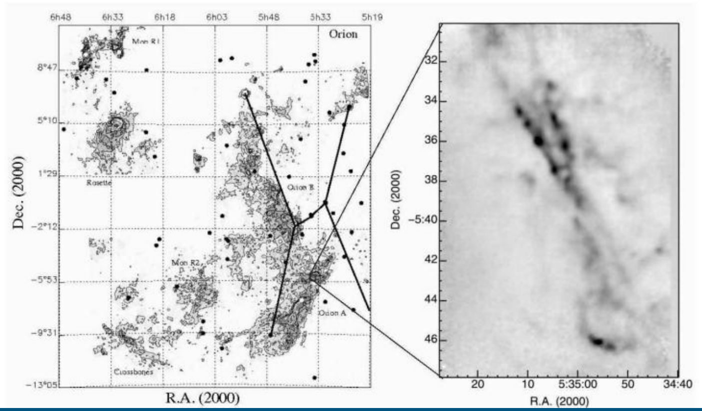
IV. Feedback on Cluster Scale

- RT and MHD, filaments, and a new Hybrid FLASH AMR code

I Galaxy -> GMCs -> Clusters

Diffuse Atomic Hydrogen in Milky Way (Canadian Galactic Plane Survey CGPS) near midplane towards Perseus.

Shocks and filaments on many scales – in diffuse or self-gravitating gas



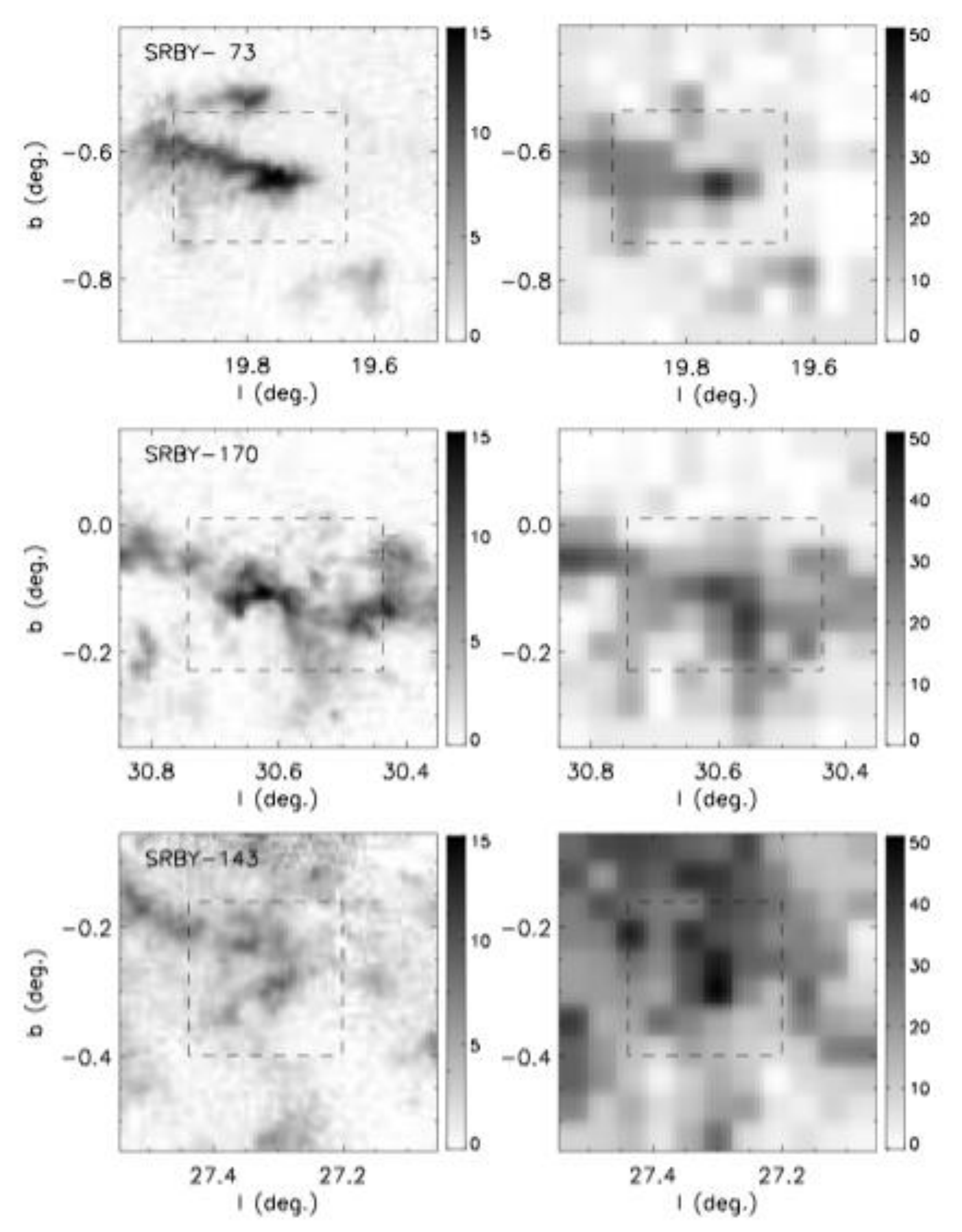
Extinction map of Orion and Mon clouds (Cambresy 1998); right - Scuba continuum 850 micron map of 10 pc portion of cloud (Johnstone & Bally 2006)

Galaxy GMC surveys - Milky Way

High res maps in ^{13}CO (J=1->0) of clouds in the galactic ring, first studied by Solomon et al (1987).

Res: 0.2 pc at distance of 1kpc

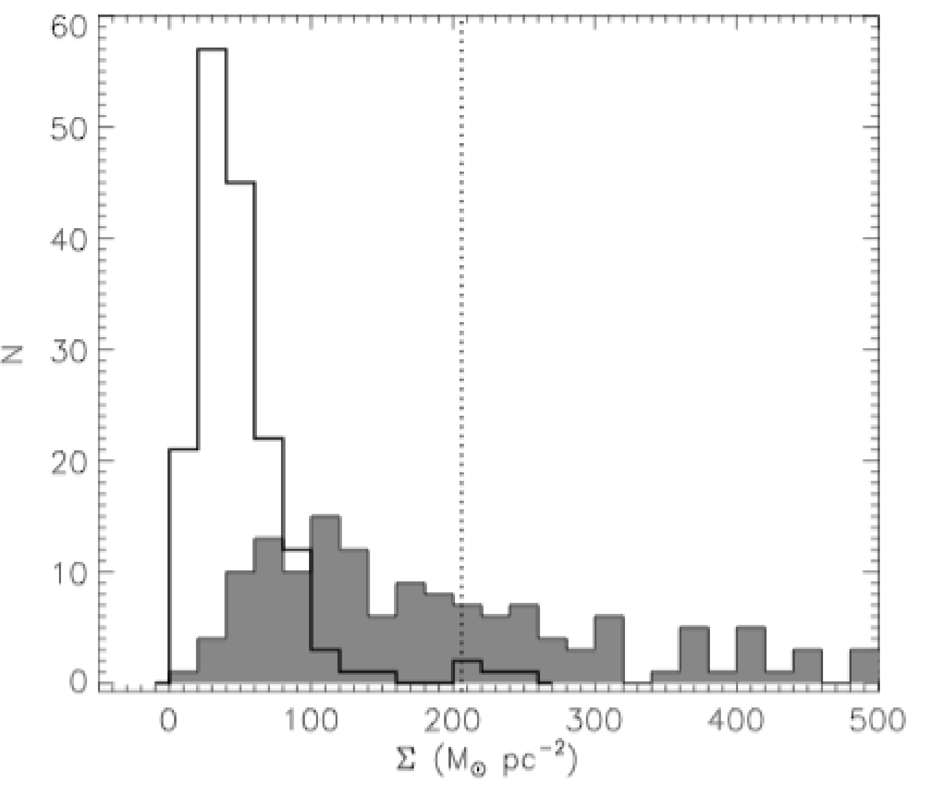
Clumpfind used to identify clouds



Heyer et al 2009; BU-FCRAO Survey

High res ^{13}CO maps show a large range of cloud column densities…

This is at odds with one of Larson’s relations

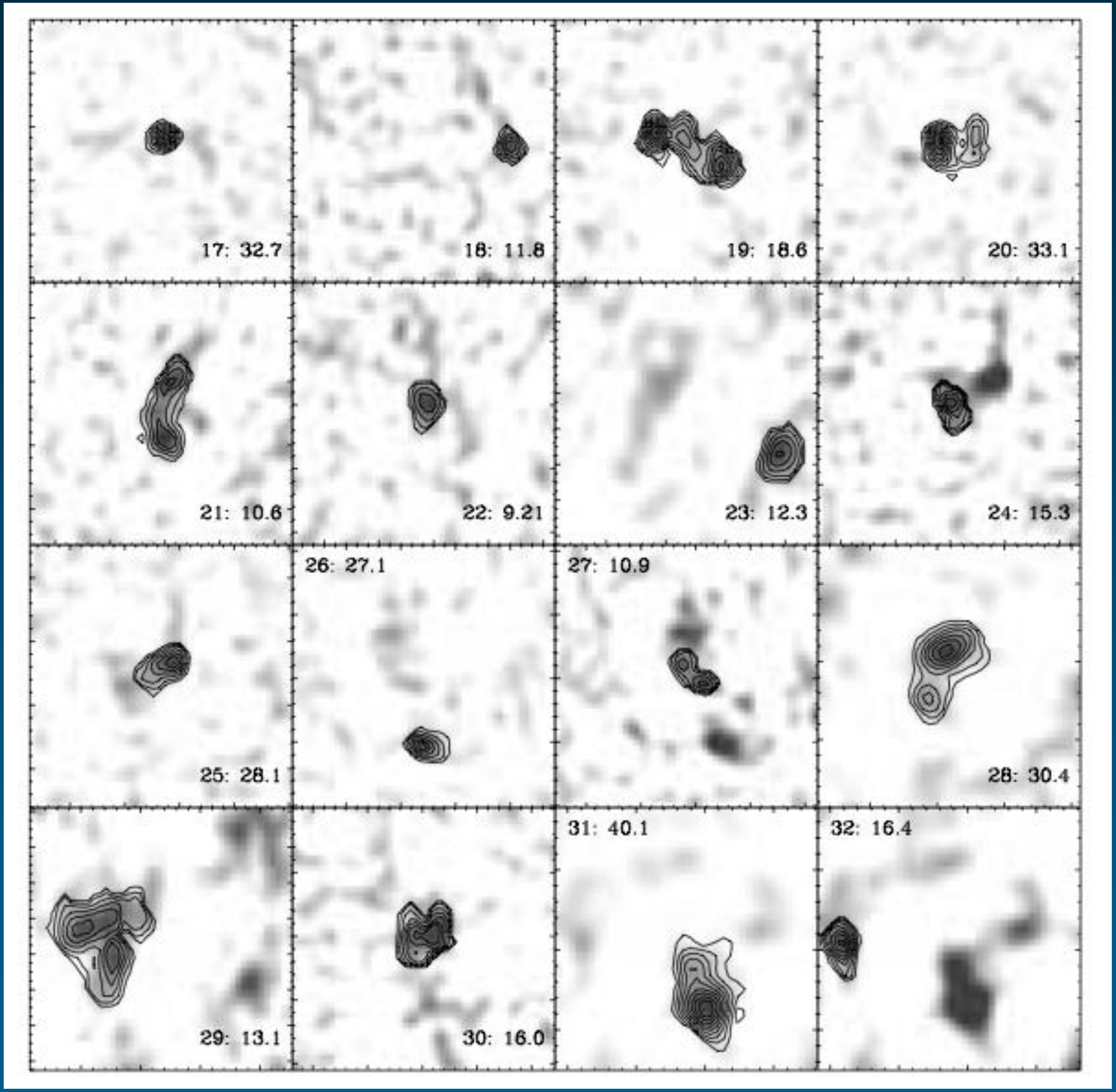


Galaxy GMC surveys – M33

From BIMA All-Disk survey ^{13}CO (J=1->0)

Spatial resolution of 20 pc., closer to our own simulation res of 7.8 pc.

Paper suggest that clouds made by instability rather than agglomeration.



Rosolowsky et al 2003 – GMCs in M33

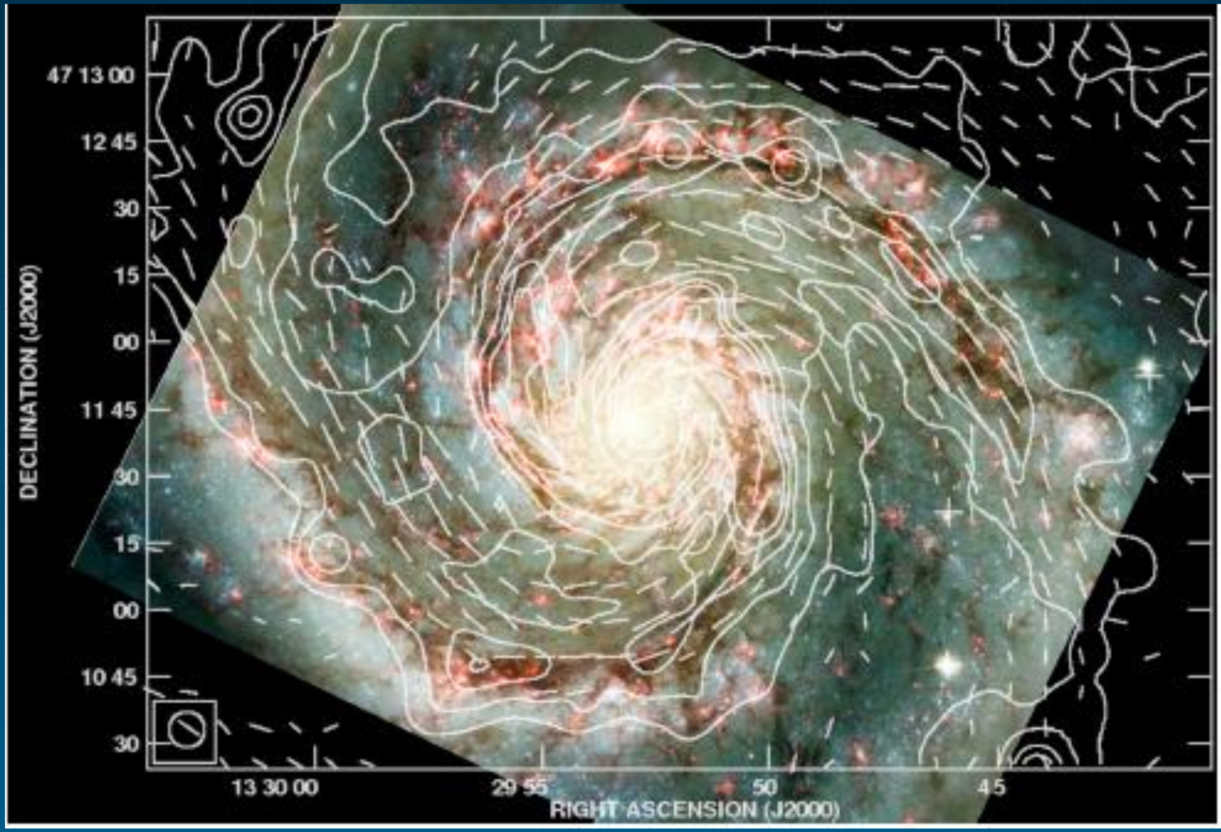
Galactic B fields

Full gas dynamics; spiral waves, B field compression: spiral field along density wave.

Source of B: large scale dynamo

(Beck, Brandenburg, Moss, Shukurov, Sokolov 1996)

Dominant quadropolar type mode (Heeson et al 2009, Braum et a; 2010)

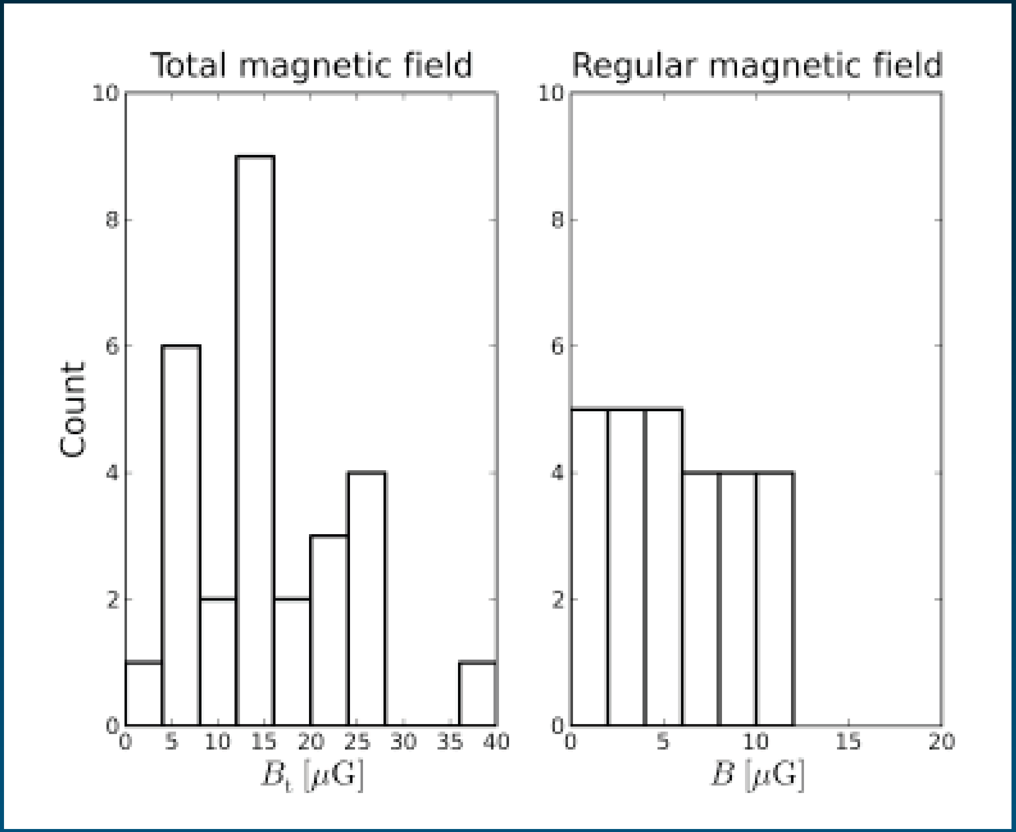


Magnetic fields in spiral galaxies – M51

B fields in spiral galaxies

- Resolution: several 10’s of disk galaxies mapped RM ($B_{||}$) and polarizations ($B_{perp))}$ -Beck et al 1996, Beck 2005, 2011, Fletcher 2011 – down to 100 pc.

- Equipartition: ISM, CR, and B fields on this scale (synchotron emission from CRs in B field)



$$B_{tot} @ 17 \pm 14 mG$$

$$B_{mean} @ 5 \pm 3 mG$$

Fletcher, 2011

Inside GMCs: Stars/clusters form in filaments

Herschel observations: clouds are filamentary

(Andre et al 2010, Menshchikov et al 2011, Henning et al 2010..)

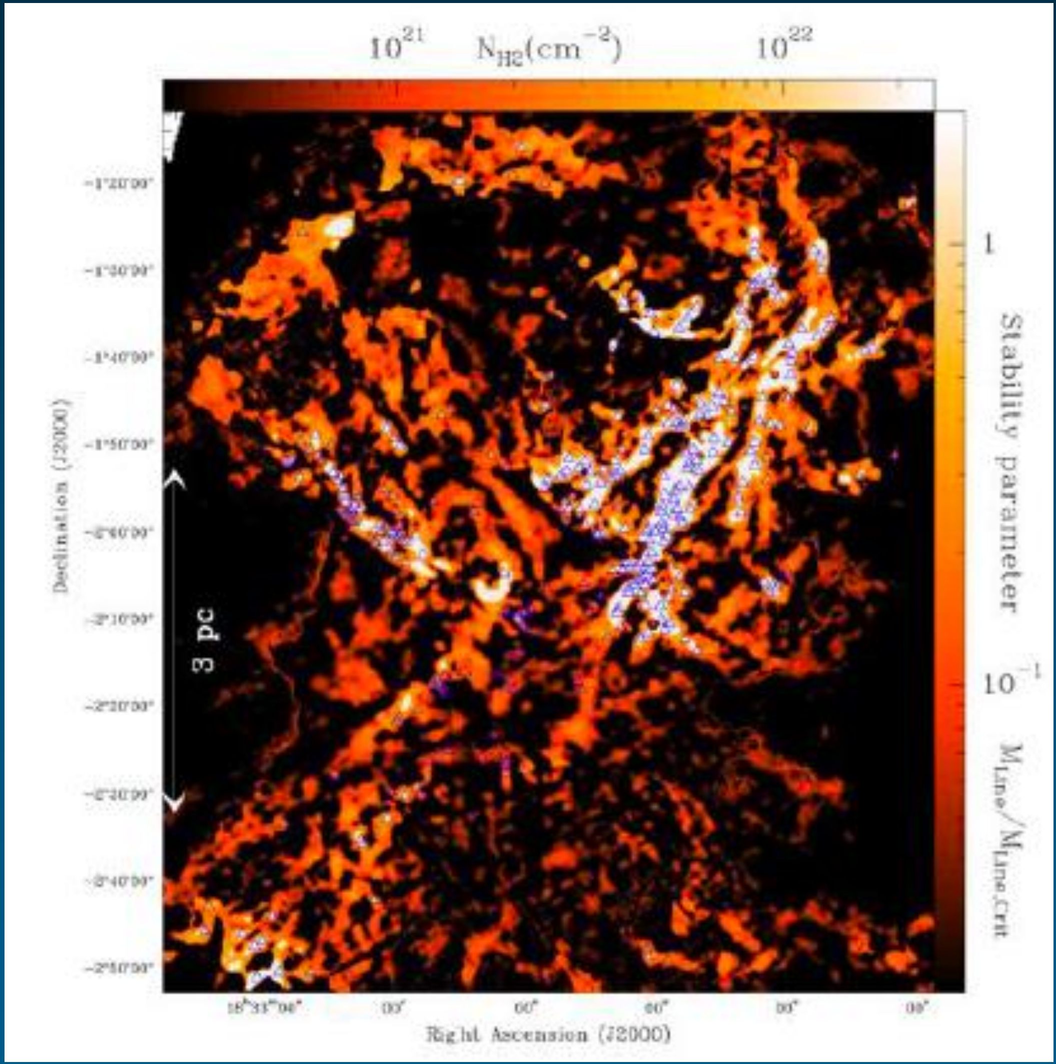
- Cores are strongly associated with filaments

(> 70%; Polychroni et al 2013)

- Cores formation by GI: mass per unit length (m) exceeds:

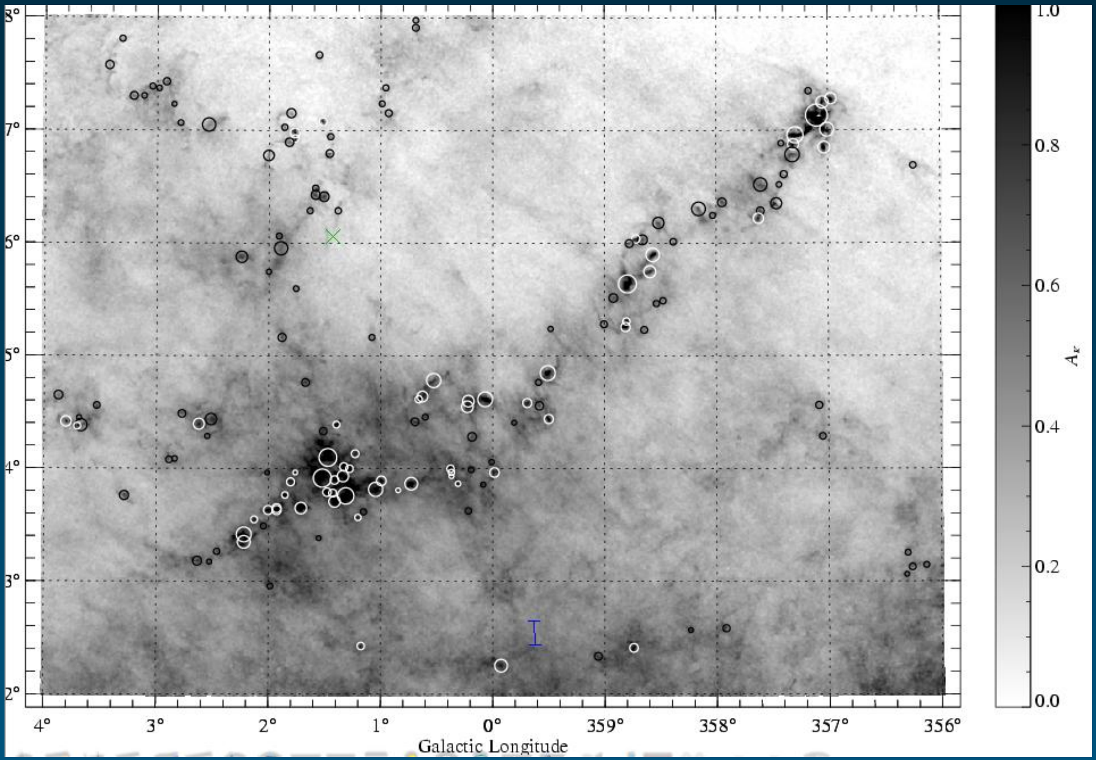
$$m > m_{crit} = 2\ c_s^2\ /\ G$$

(Inutsuka & Miyama 1997, Fiege & Pudritz 2000)



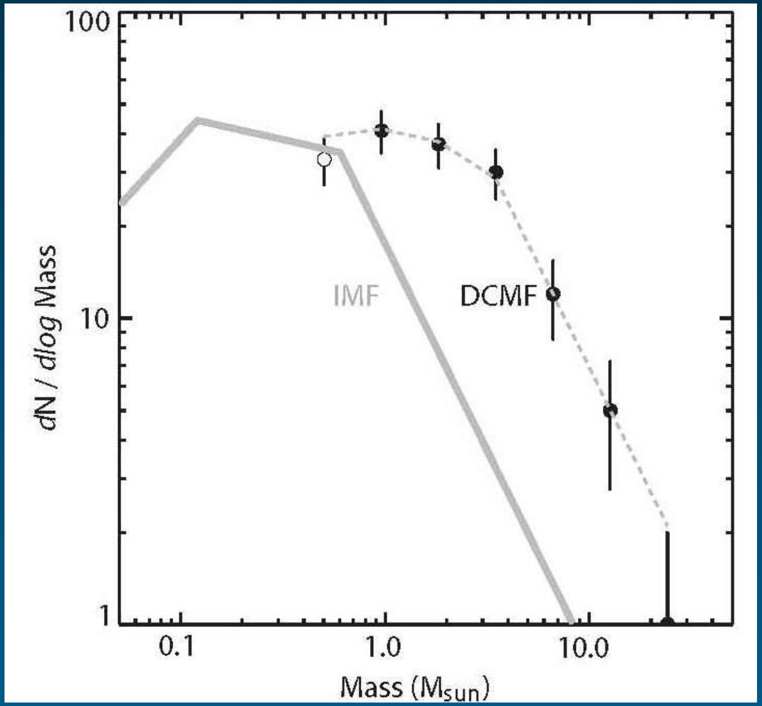
Aquila star forming cloud: Andre et al 2010

Core Mass Functions (CMF) and the IMF:



Dense cores in the Pipe Nebula

Alves et al 2007 (Pipe Nebula)

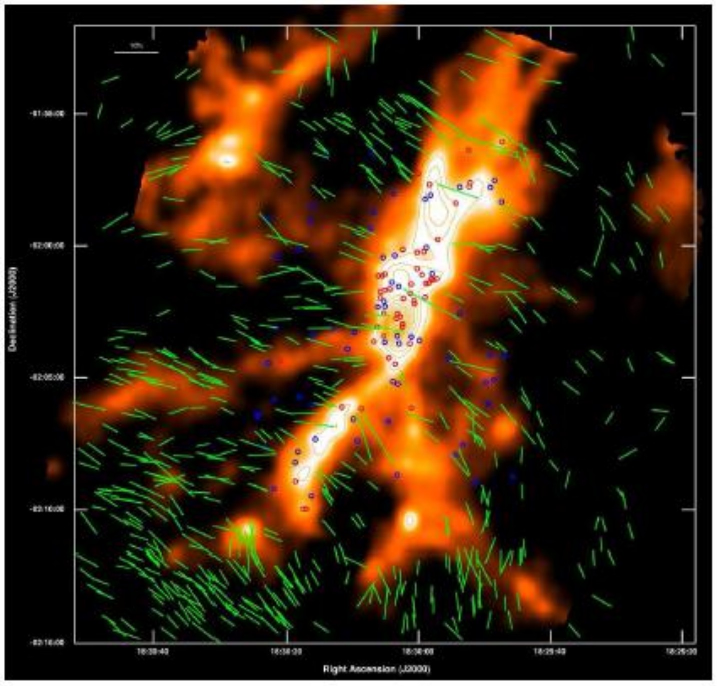


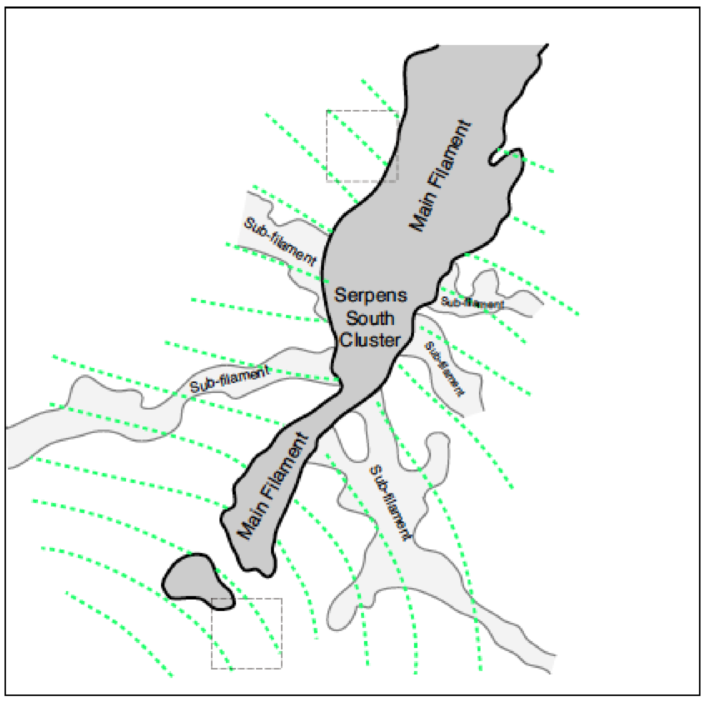
Similar distributions – shifted by factor of 3 in mass

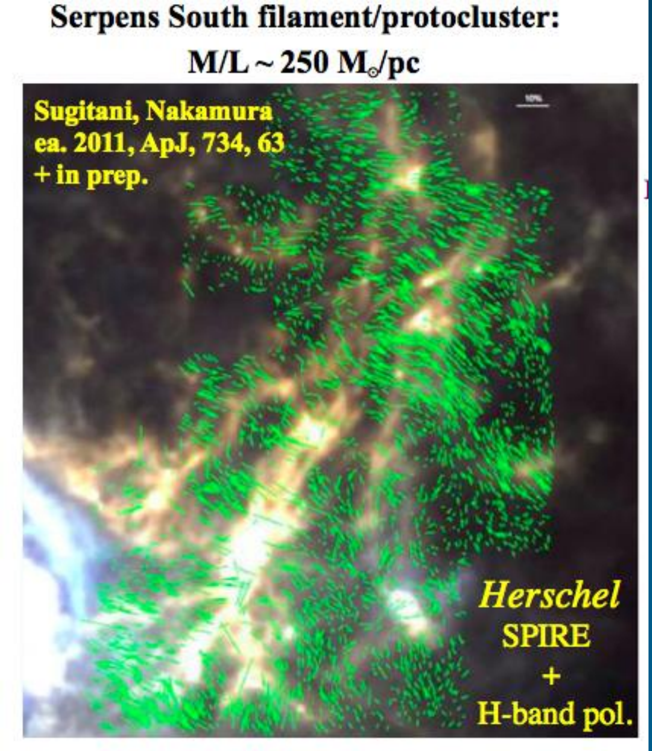
Filament, cluster and B field

Infrared (H band) polarization overlaid on column density map + young stellar cluster

- B often perp to filament
- Field strength ~ 100 µG







Serpens South filament/protocluster:

M/L ~ 250 $M_\odot$/pc

Sugitani, Nakamura ea. 2011, ApJ, 734, 63 + in prep.

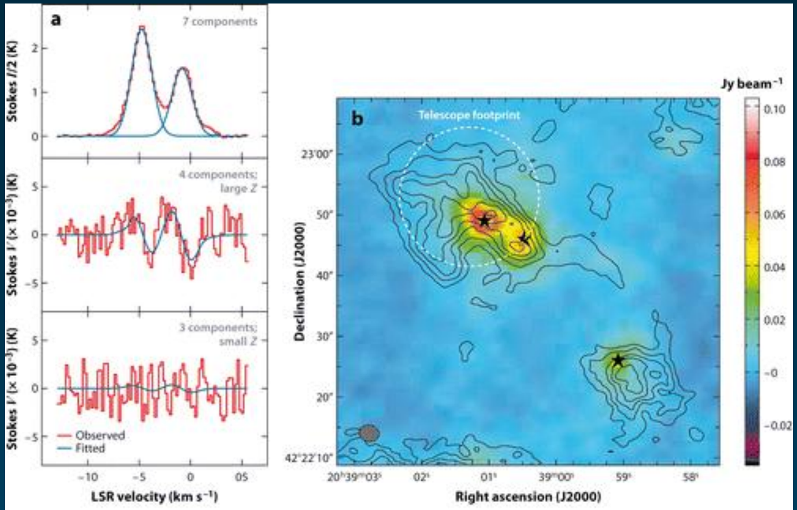
Herschel
SPIRE
+
H-band pol.

Zeeman measurements:

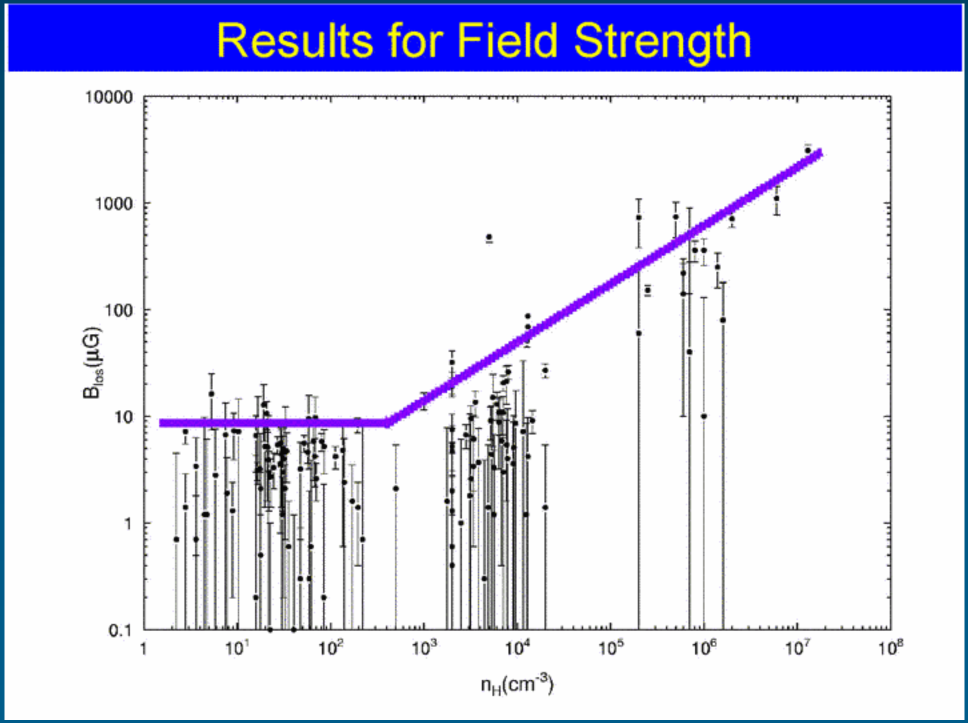
distribution of B field strengths measured in cores (Crutcher et al 2010; Crutcher 2012, ARAA)

- Low density medium: constant field – gas flow along field lines
- Molecular gas: self gravity important, compresses magnetized gas
- GMCs are supercritical (mass/flux = Γ ~ 2 -3)

$$\Gamma = 2\pi\sqrt{G}\Sigma / B = 1.4\beta^{1/2} n_J^{1/3}$$



Crutcher RM. 2012.
Annu. Rev. Astron. Astrophys. 50:29–63


Results for Field Strength

Making filaments and clusters:

Turbulence, filaments, and turbulent fragmentation

-Theory; eg. Larson 1981; Elmegreen & Scalo (2003)

-Reviews: eg. MacLow & Klessen 2004; McKee & Ostriker 2007; Bonnell et al 2007

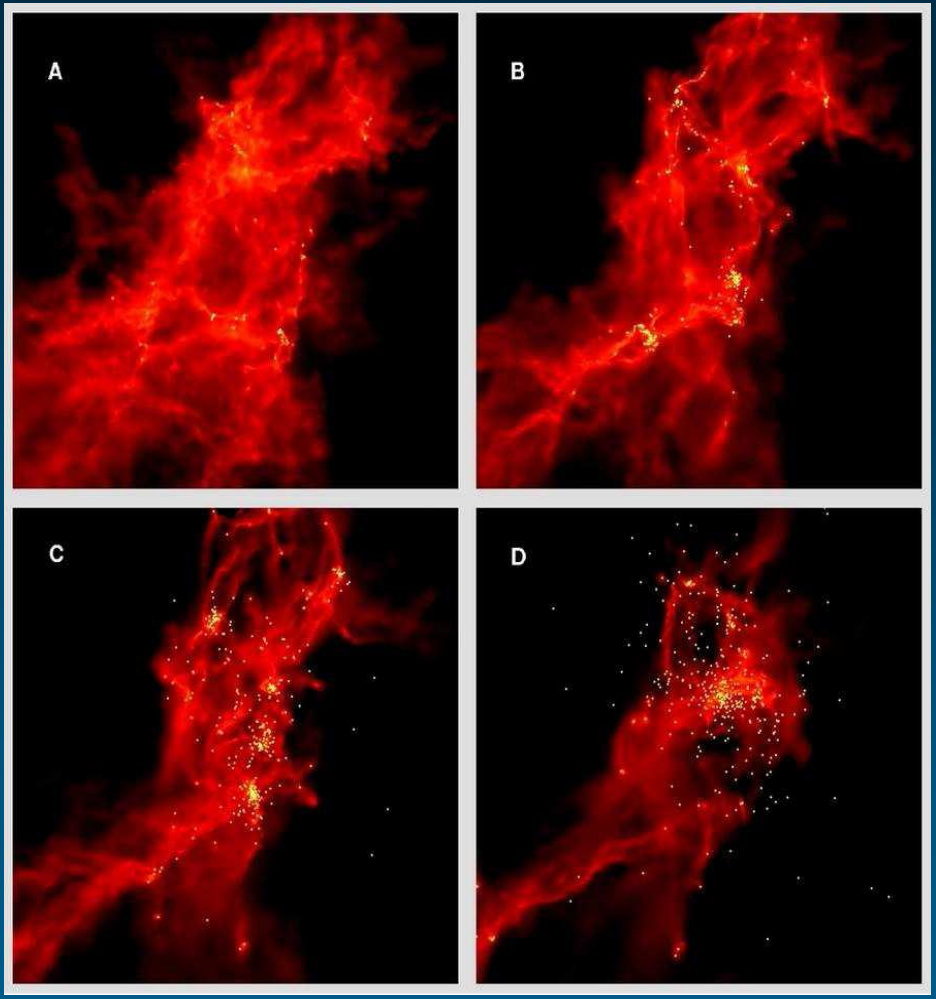
- Simulations; Porter et al 1994; Vazquez-Semadeni et al 1995, Bate et al 1995, Klessen & Burkert 2001; Ostriker et al 1999, Padoan et al 2001; Tilley & Pudritz, 2004,2007; Krumholz et al 2007, Federrath et al 2010,…

Shocks dissipate turbulent support as t^{-1}

(eg. Ostriker 2001)

Gas flows along filaments into local potential minima – cluster formation regions

(eg. Banerjee et al 2006, R. Smith et al 2012, Kirk et al 2012,..)



Bonnell et al (2003)

Star cluster formation properties

Form in high density clumps, $n>10^4$ cm^{-3} (Lada & Lada 2003)

- More than 90% of stars form in embedded clusters with > 100 members
- Global star formation efficiencies in GMCs 2-8% (Kennicutt & Evans 2012)
- Embedded cluster SF efficiencies 20-30% (Lada & Lada 2003)

Star formation rates (SFR / M_{solar} yr^{-1}): $10^{-6} – 10^{-2}$

- Orion A: 7.2×10^{-4} (Lada et al 2010)
- Massive star formation cloud G29.960.02: $.1-.8 \times 10^{-2}$ (Beltran et al 2013)

Examples: small (Serpens South), intermediate (ONC cluster) ~ 4800 M_{solar} and 2200 stars and R~ 2pc ; massive (R136 – LMC) more than 120 stars with $M_v \sim 4$

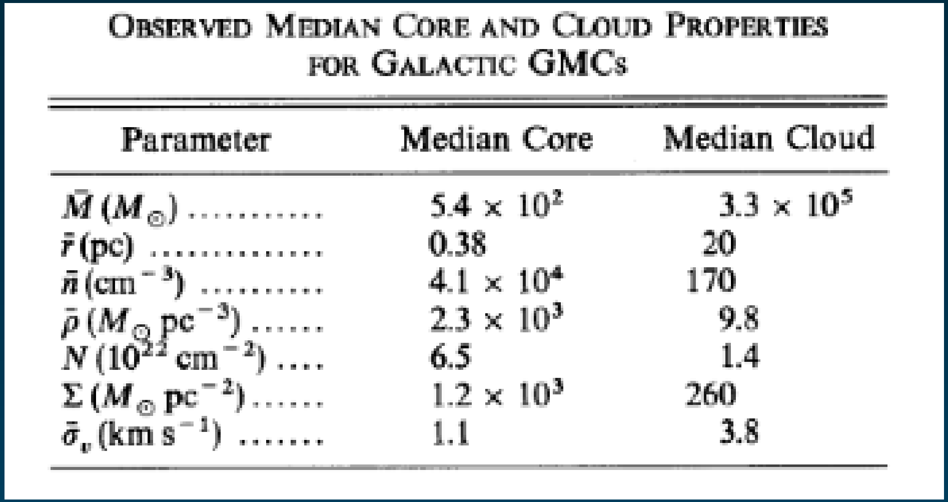
Link between GMCs clumps, & clusters

- Cluster properties form a smooth continuum from $10^2 – 10^6$ M_{solar} in terms of: mass function, stellar content (IMF),
- 3 similar mass functions: GMCs, Cluster forming clumps, and clusters (including globular clusters)

$$dN/dM \sim M^{-1.7}$$

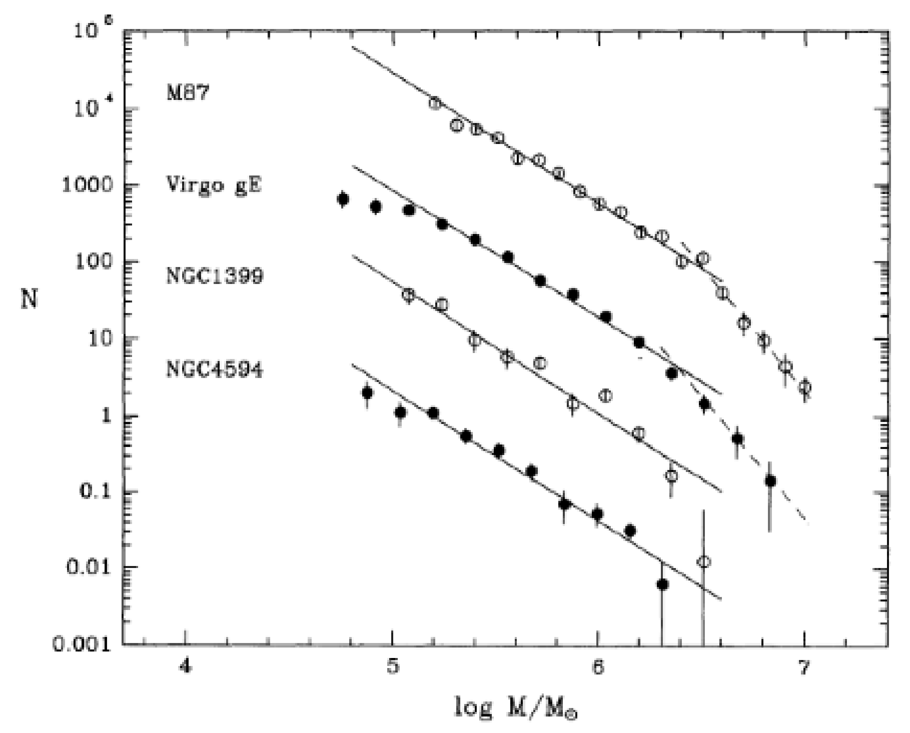
(Harris & Pudritz 1994, Mike Fall’s review talk,)

- Prediction: existence of supergiant GMCs (10^8 M_{solar}) for globular cluster formation



OBSERVED MEDIAN CORE AND CLOUD PROPERTIES FOR GALACTIC GMCs

Parameter	Median Core	Median Cloud
$\bar{M}$ ($M_\odot$)	5.4×10^2	3.3×10^5
$\bar{r}$ (pc)	0.38	20
$\bar{n}$ (cm^{-3})	4.1×10^4	170
$\bar{\rho}$ ($M_\odot$ pc^{-3})	2.3×10^3	9.8
N (10^{22} cm^{-2})	6.5	1.4
Σ ($M_\odot$ pc^{-2})	1.2×10^3	260
$\bar{\sigma}_v$ (km s^{-1})	1.1	3.8

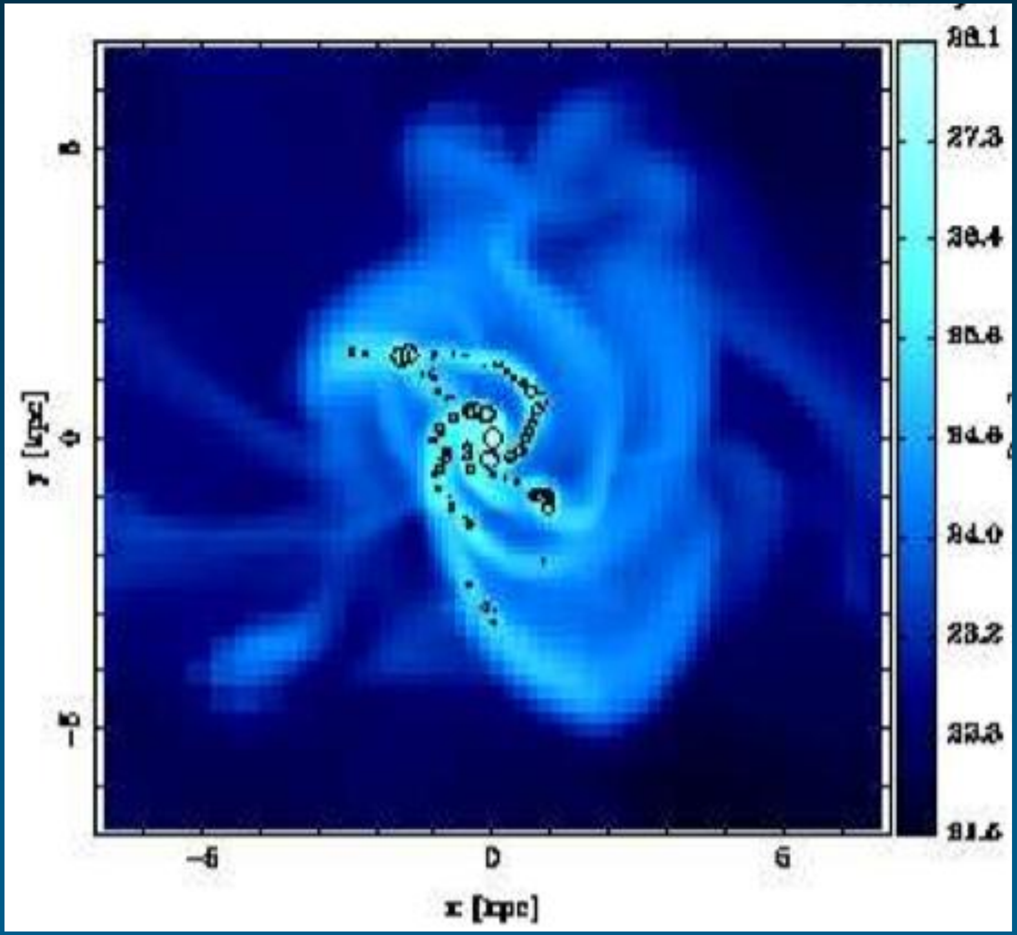


Harris & Pudritz 1994

… and in context of galaxy formation

Globular cluster formation in galaxy formation simulation: (Kravtsov & Gnedin 2005)

$dN/dM \sim M^{-2}$



General question: role of feedback for cluster formation?

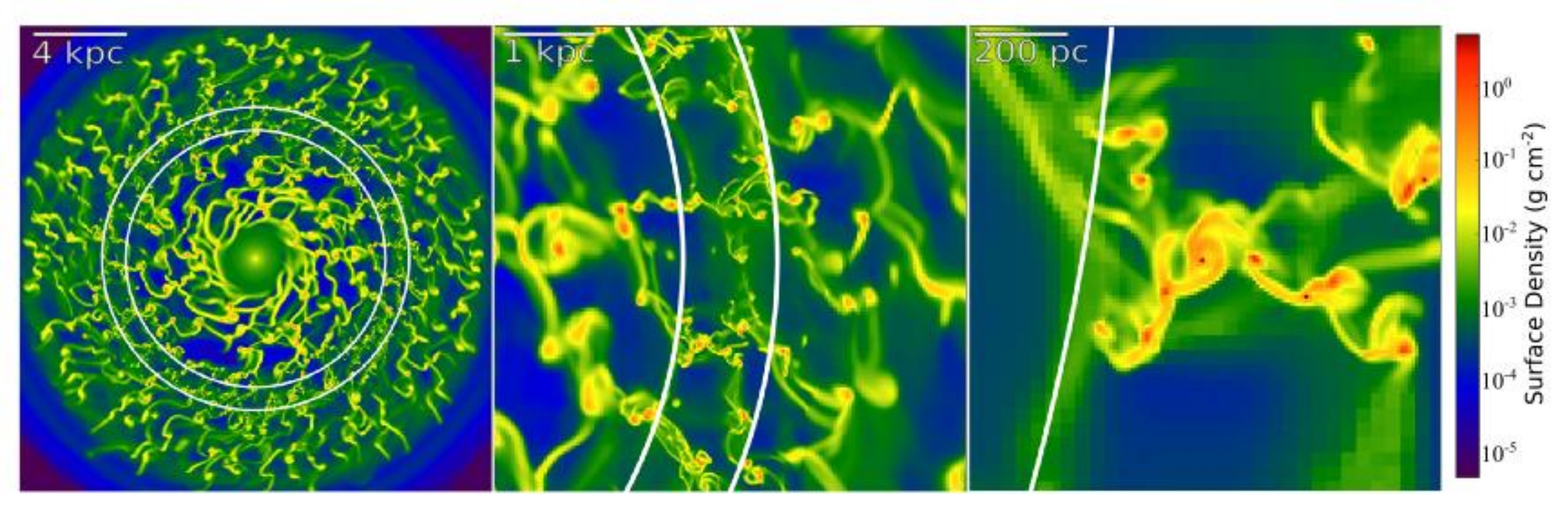
- Limiting cluster mass

II Simulating GMC formation and comparing with catalogues

Hydro simulations:

Local scale – colliding flows (Heitsch et al 2008, Banerjee et al 2009,..) produce highly turbulent clouds

Global scale - GI via Toomre instability and fragments to form GMCs (Tasker 2011, Dobbs et al 2011, Bournaud et al 2010, Agertz et al 2009, ..); Further growth by accretion and collisons…



Benincasa, Tasker, Pudritz, & Wadsley 2013, ApJ : **No Feedback

High res simulations: clouds in a co-rotating ring

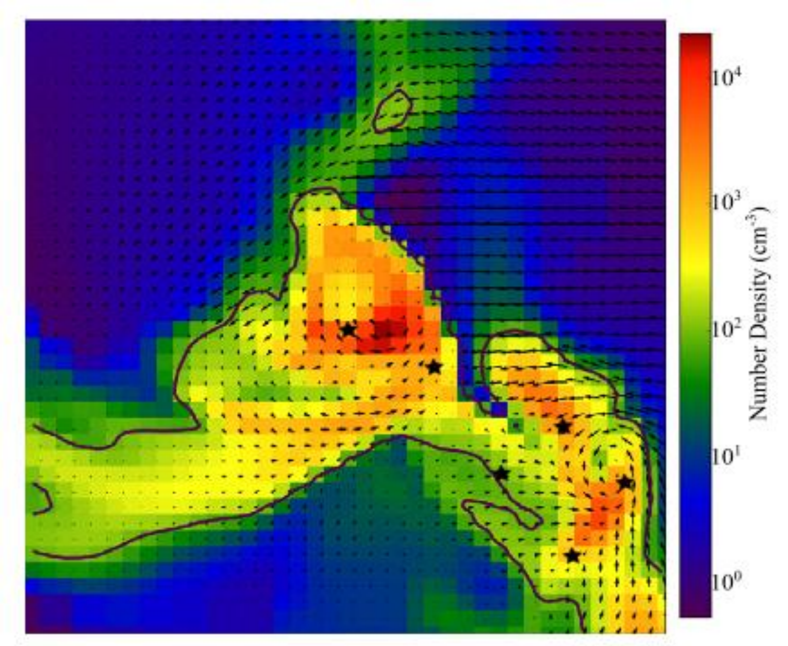
Method: 3D box of 32 kpc, root grid 128^3, 5 levels of refinment, reaching 7.8 pc. Enzo AMR code

- Radially dependent photoelectric heating (Tasker 2011)

- Cooling to 300K, equivalent to line width of 1.8 km/s. Cooling from Sarazin & White (1987) and Rosen & Bregman (1995)

- Fixed gravitational potential, disk mass $6.5\text{x}10^9$ M_{solar}

- Clouds sampled from co-rotating ring at 6kpc – minimizing artifical numerical support from circular motion in Cartesian mesh..



Slice through z=0 of tyical cloud – contour @ 100 $cm^{-3.}$ Box size 300 pc. Five clouds in neighbourhood, gas flows along filaments, gathering in several dense regions.

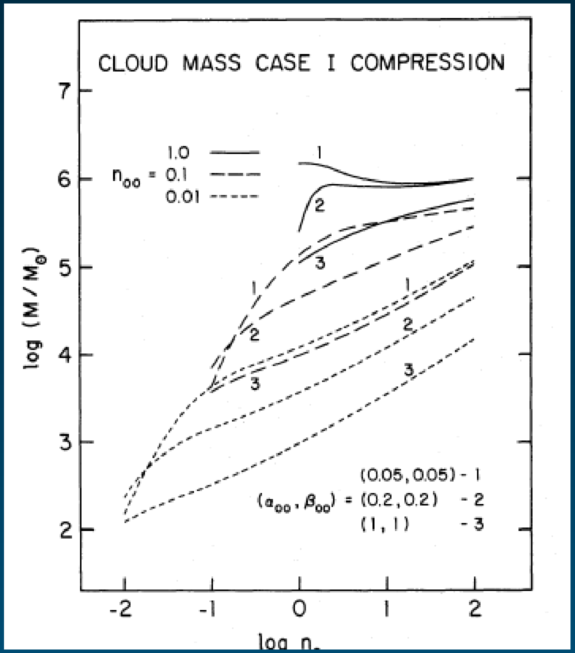
MHD Instabilities and GMC formation:

1. Parker / Jeans instability (Elmegreen 1982):

- gravity strongest in galactic plane,
- magnetic buoyancy peaks far from plane

- Growth rate: ~ Jeans time in higher density regions:

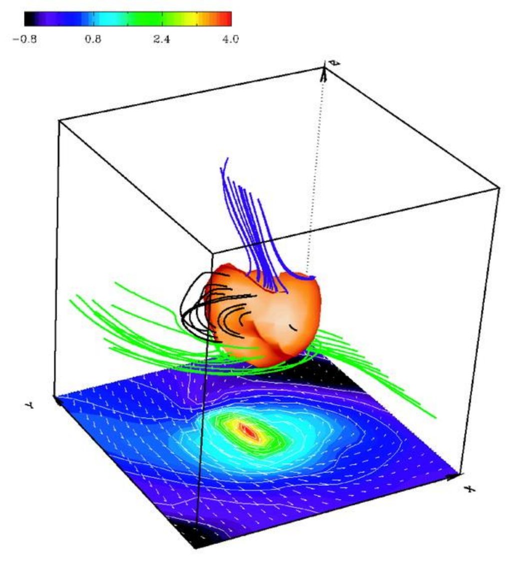
$$(4\pi G\rho_0)^{-1/2} = 23 / n_0{}^{1/2} \text{ million years}$$



- 10^6 solar mass GMCs in 10 Myr.

2. MRI / gravity (Sellwood & Balbus 1999; Kim, Ostriker, & Stone 2003), ..

- GI – Toomre swing amplifier– acts on larger scale MRI fluctuations - build self-gravitating objects 10^7 solar masses

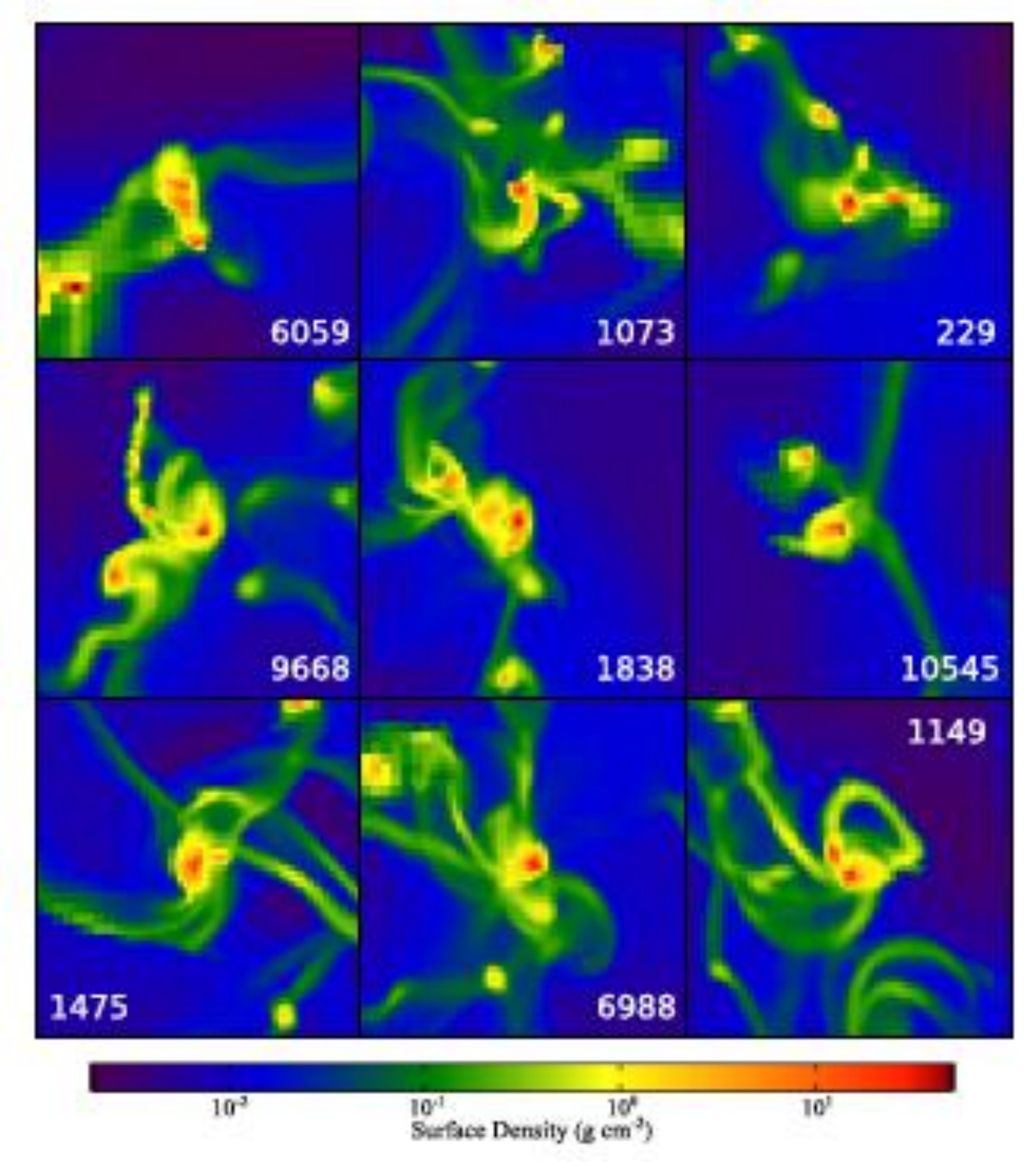


McClouds online catalogue of GMCs

Catalogue of over 50 GMCs, $M > 10^6 M_{solar}$; velocity dispersion, column density, effective radius, virial parameter

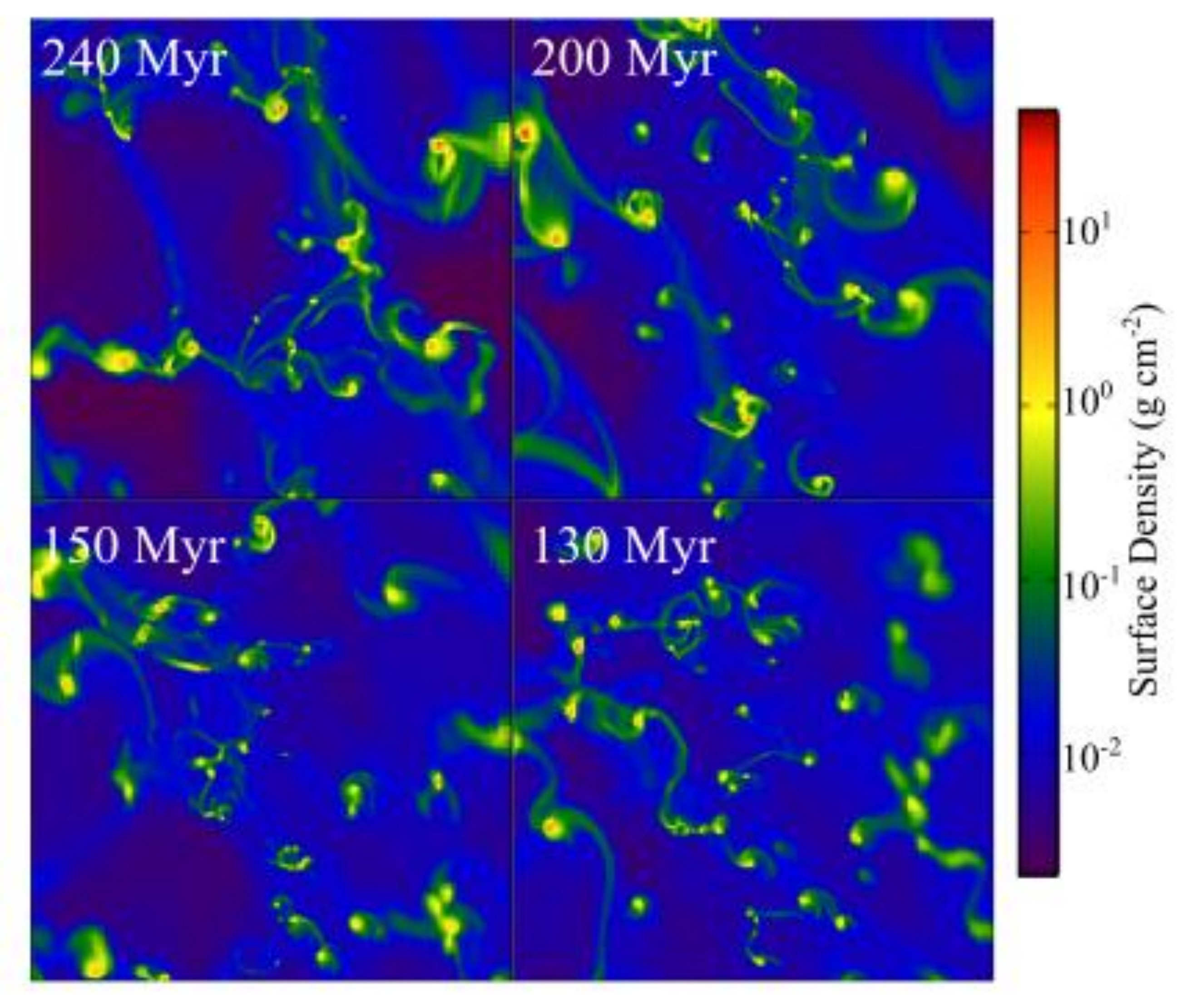
α: 0.65 – 2.5

http://www.physics.mcmaster.ca/mcclouds.



Time evolution of clouds:

- Initially smaller and more bead like
- cloud-cloud encounters; mass grows, tidal tails develop as gas stripped off outer layers.

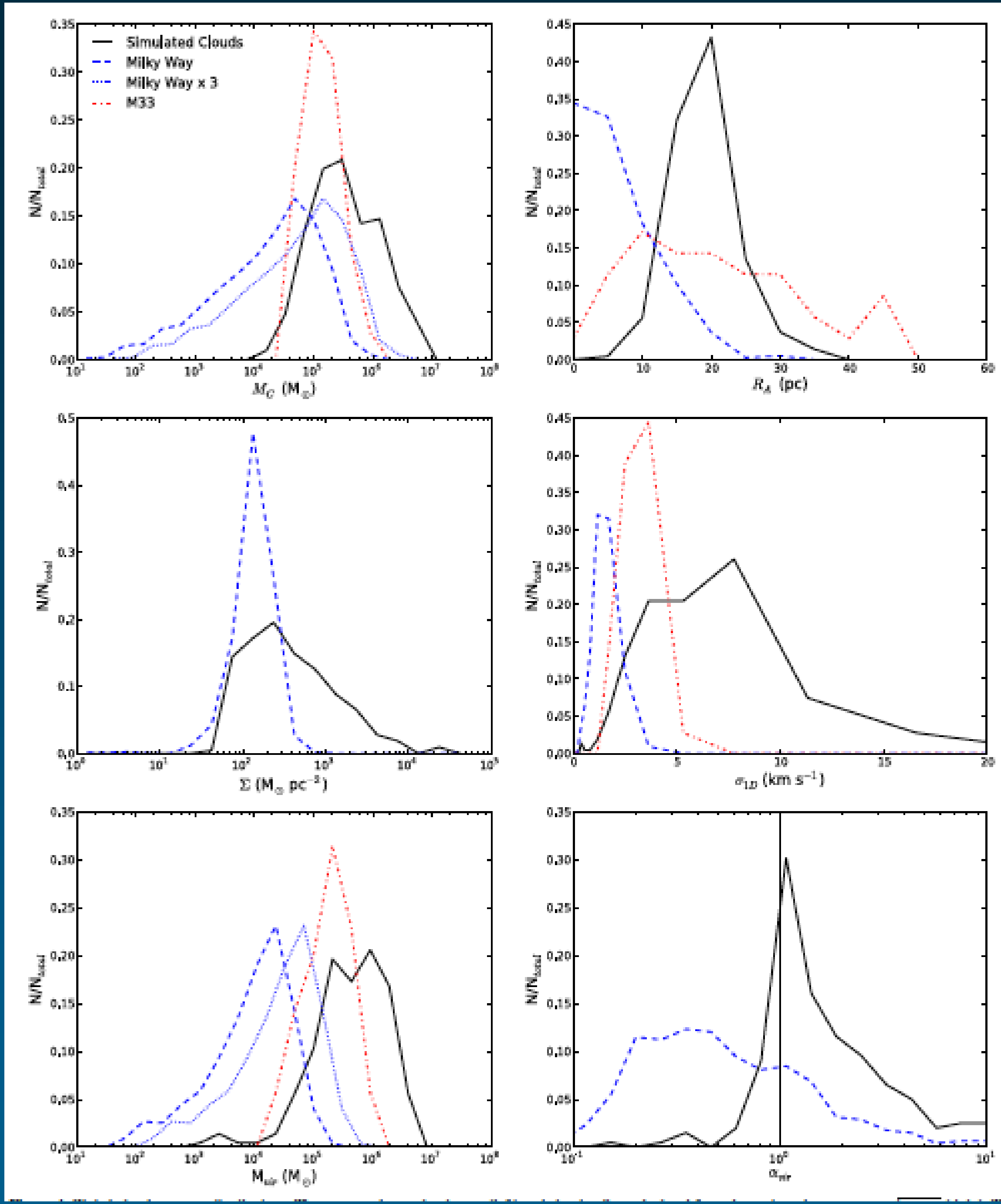


Comparing cloud catalogue properties with MW and M33 catalogues

Virial mass:

$$M_{vir} = 5(c_s^2 + s_{1d}^2)R_A / GM_c$$

Most common cloud radius R_A~20pc (for M33 it is 10pc)

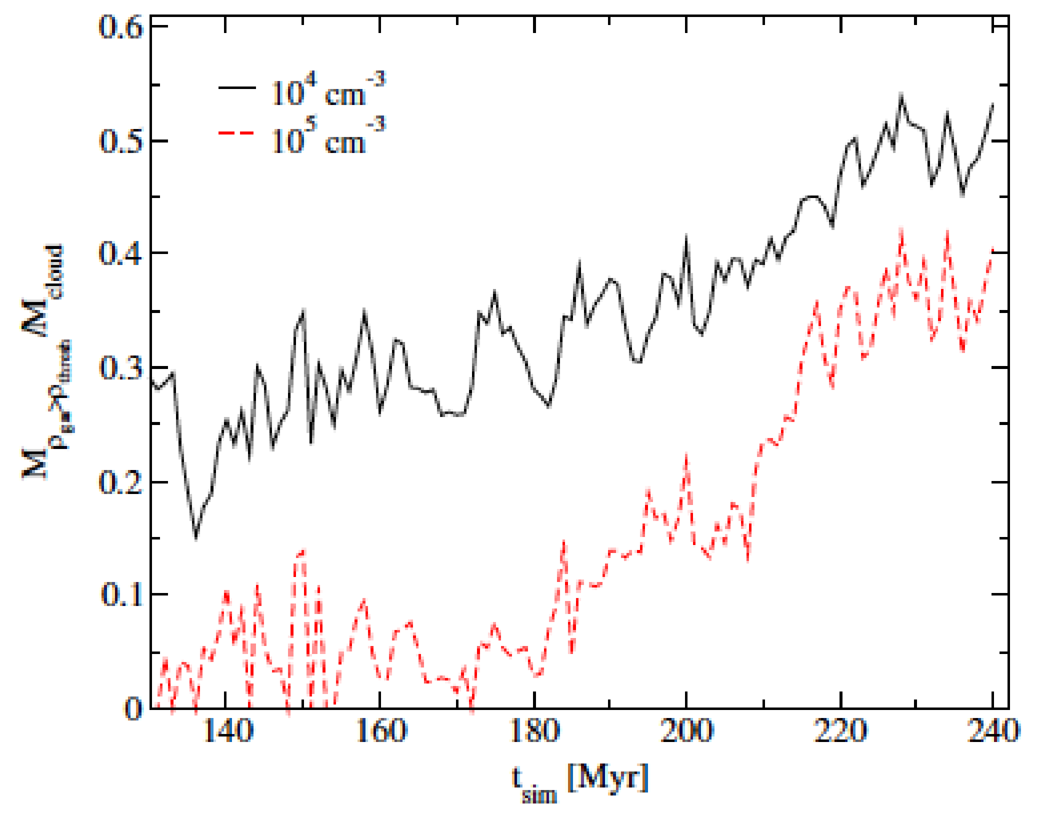


Mass fraction of star forming gas

Star forming gas has $n > 10^4$ cm^{-3} (Lada et al 2010)

Curve shows that the RATE at which star forming gas mass fraction increases is by 3% over 10 Myr… this is the SFR .

Point: Star formation proceeds at the rate at which dense mass fraction is growing in GMC



Solenoidal turbulence in GMCs

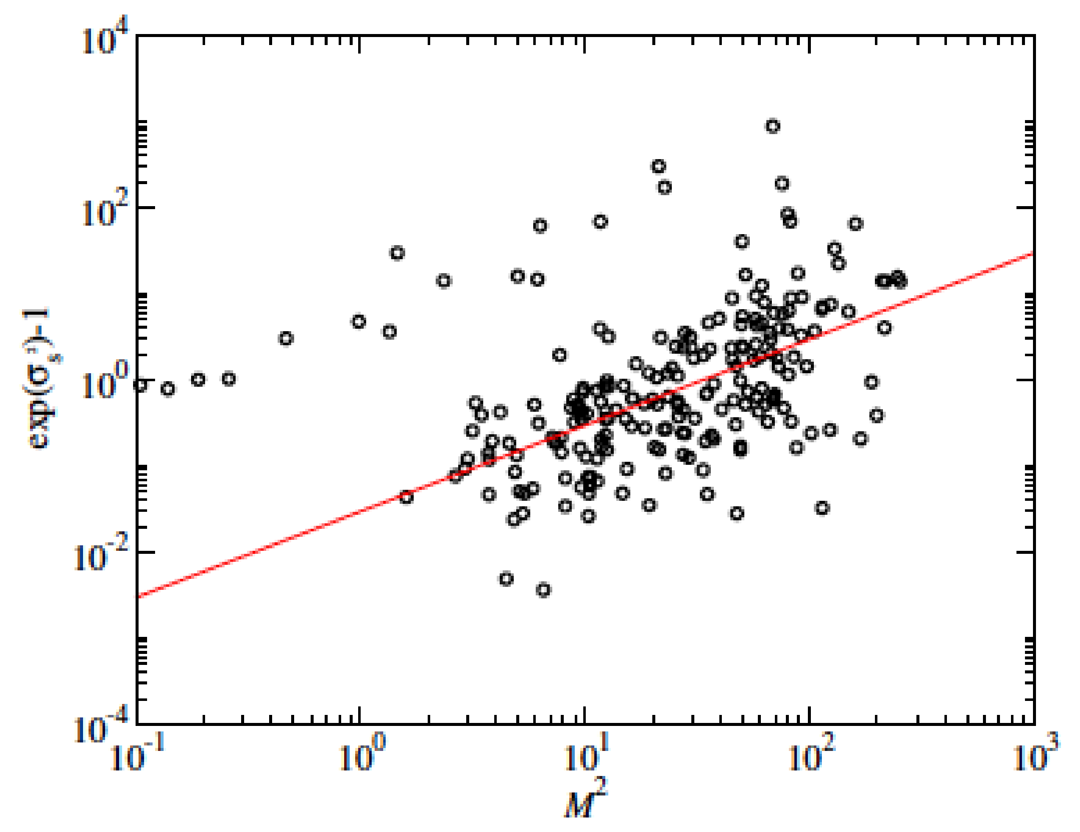
Solenoidal vs compressive turbulence: variance in log standard deviation in density with turbulent Mach number M is:

$$s_s^2 = \ln(1+b^2M^2)$$

b=1/3, fully solenoidal

B=1, fully compressive

(Federrath et al 2010, 2008)



Observations

(eg. Kainulainen & Tan 2013): b=0.2

Best fit (red line) to our simulated GMCs: b=0.17

Switching to high res mode – GMC substrucutre

- Higher resolution sim of GMC from catalogue – let cloud evolve at higher res before while turning on cooling
- Multiple dense clumps, lower in mass, finer filamentary structure.

III Feedback on GMC scales: cluster SFR and rad feedback

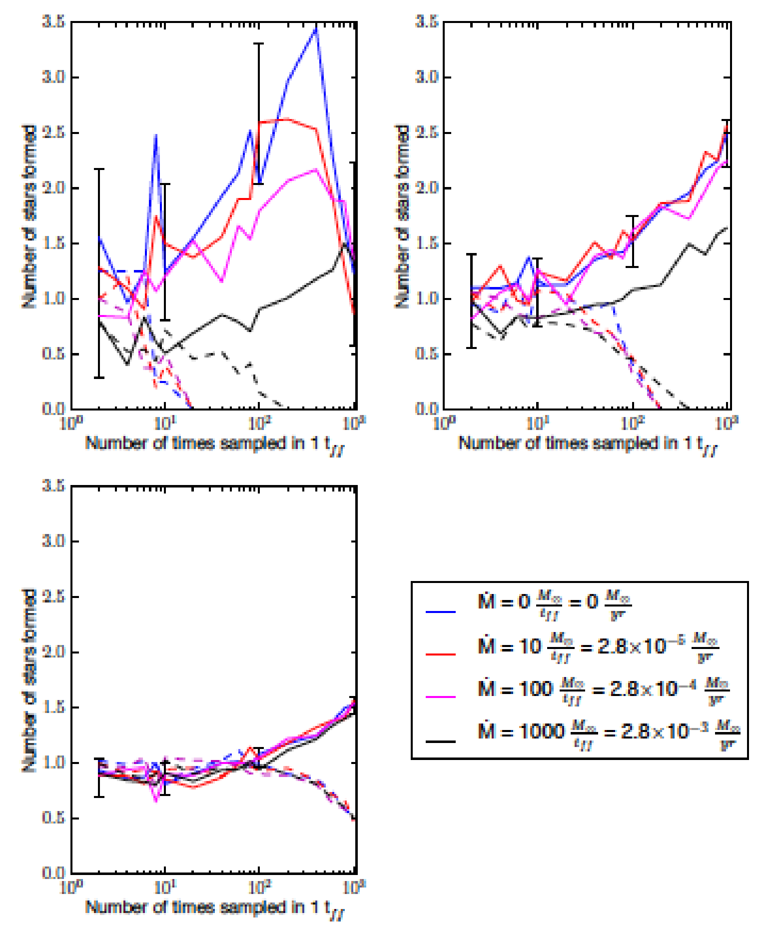
Modeling cluster formation: input for “cluster sink” particles

- GMC scales – can’t resolve individual stars:

Clusters as single objects with subgrid, IMF, typically output does not change (eg. L from mass with averaged IMF) (Tasker 2011, Hopkins et al 2012, Ceverino & Klypn 2009, Murray et al 2010,..)

Time dependent cluster growth:

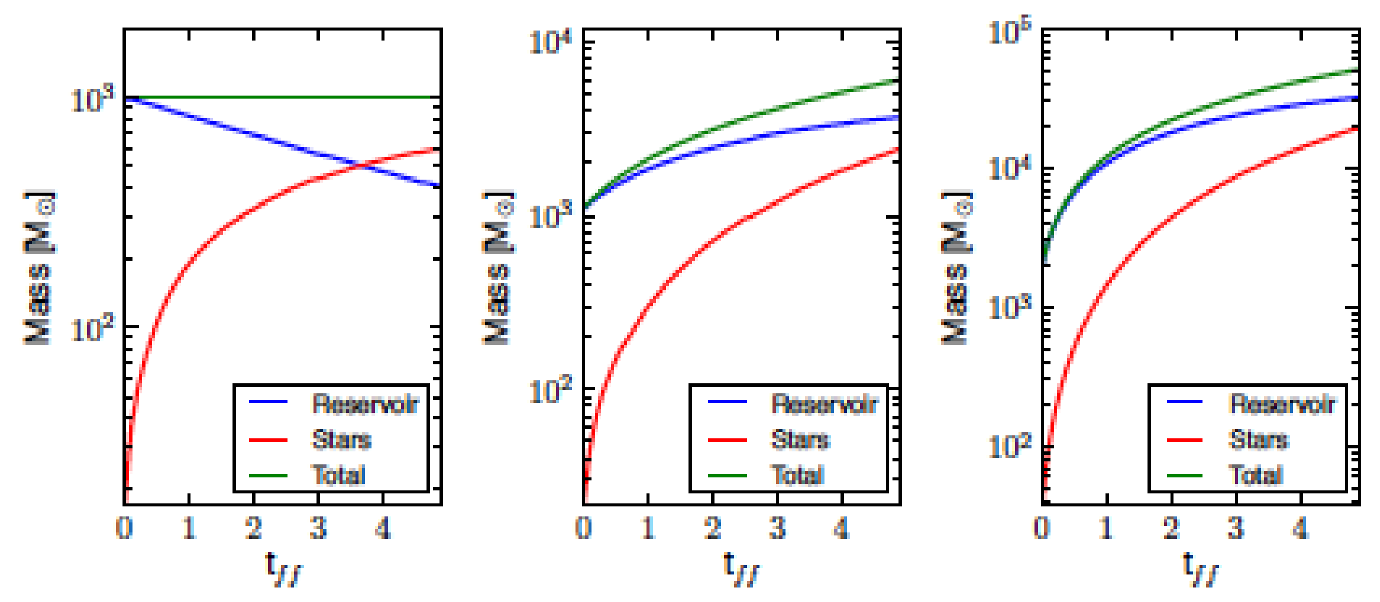
Gas reservoir: original clump + mass accretion. Stars: random sampling of IMF of 20% of available gas/ free fall time



Howard, Pudritz, & Harris 2013

Results: compute expected SFR, ionization rate, O stars, L produced by clusters with initial clump mass and accretion rates onto clumps

$$t_{ff} = 0.36 (n / 10^4 cm^{-3})^{1/2} Myr$$



Initial 10^3 solar mass clump for (0, 2.8x10^{-3}, 2.8x10^{-2}) M_{solar} yr^{-1}

Cluster L, ionizing flux, and SFR

Columns: initial clump masses

10^2, 10^3, 10^4 M_o

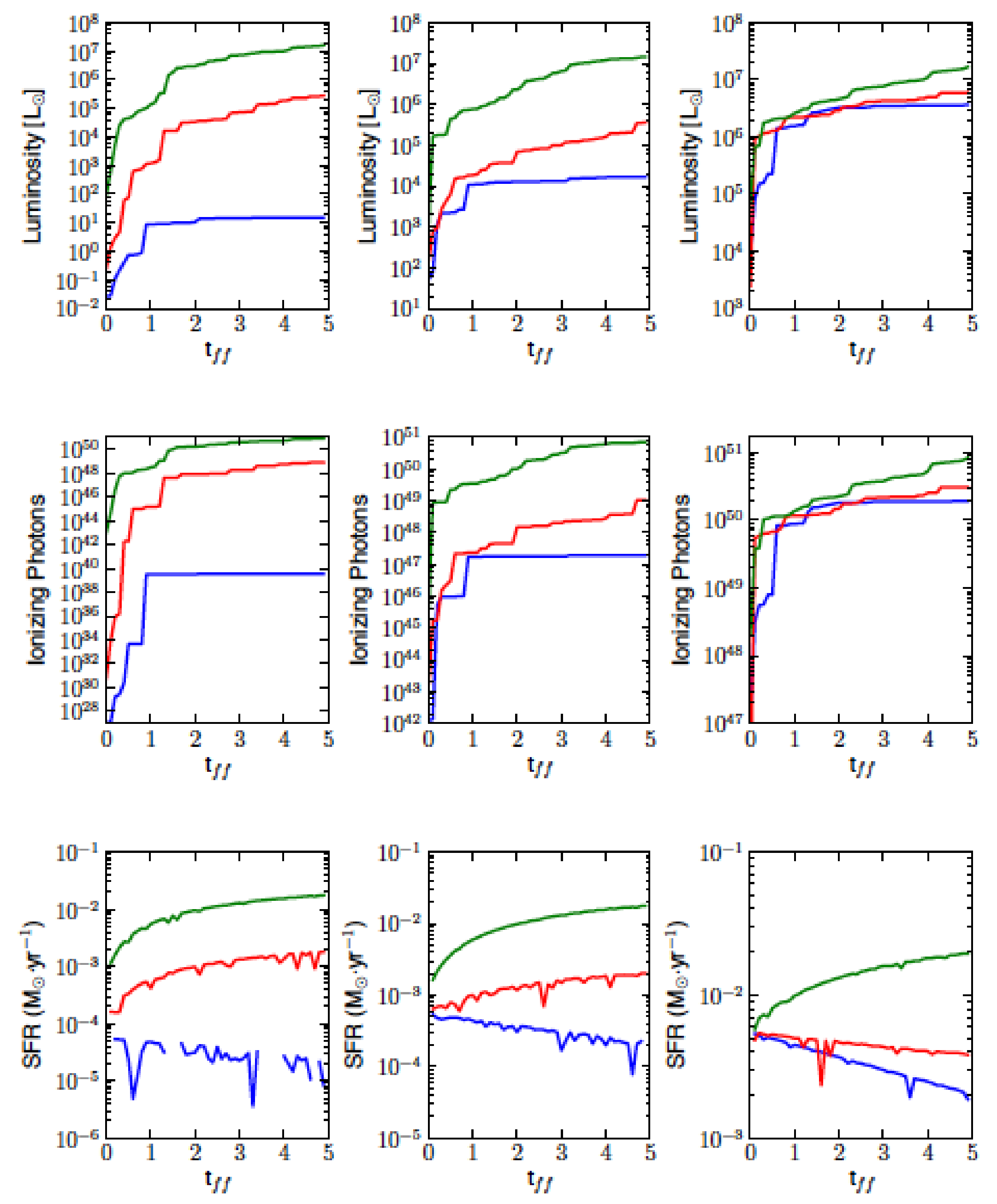
Accretion rates:

(M_o yr^{-1})

Blue - 0

Red - 2.8×10^{-3}

Green - 2.8×10^{-2}



Stellar mass functions

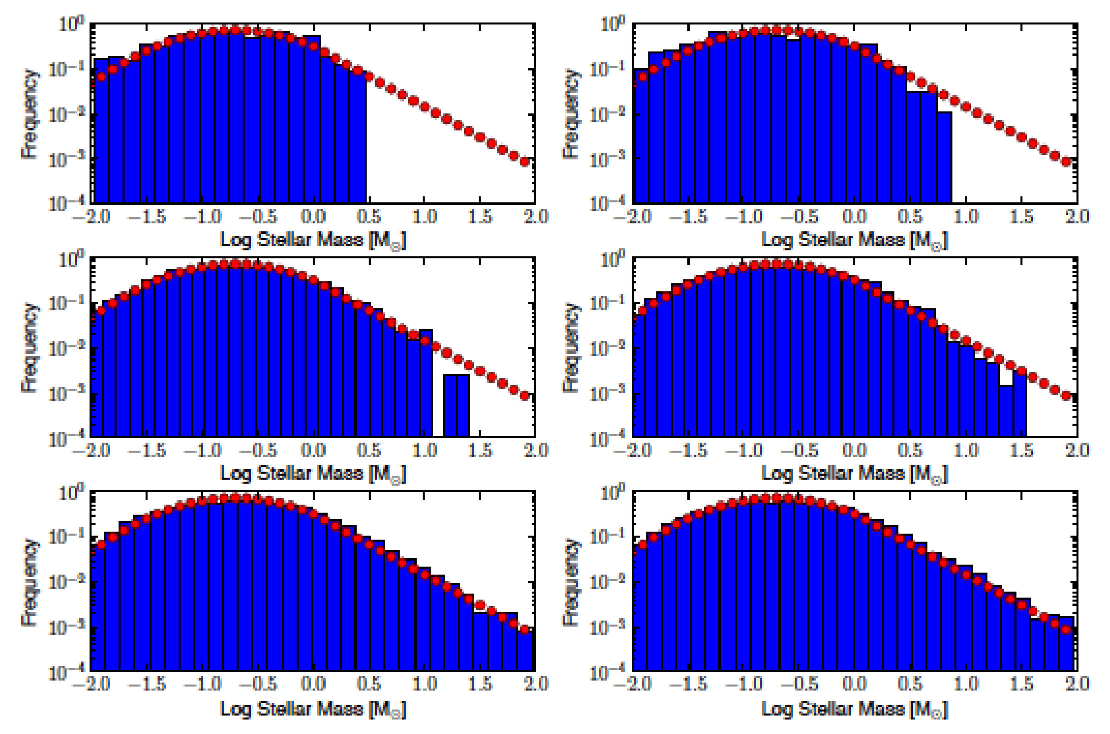
Same final mass clusters:

Rows: 3 different initial clump masses,

5x ($10^{2,}$ 10^3,10^4) M_{solar}

Columns: All mass accreted (left), All mass from initial reservoir (right)

At >10^4 M_{solar} distribution converges to full IMF



SFR at different times

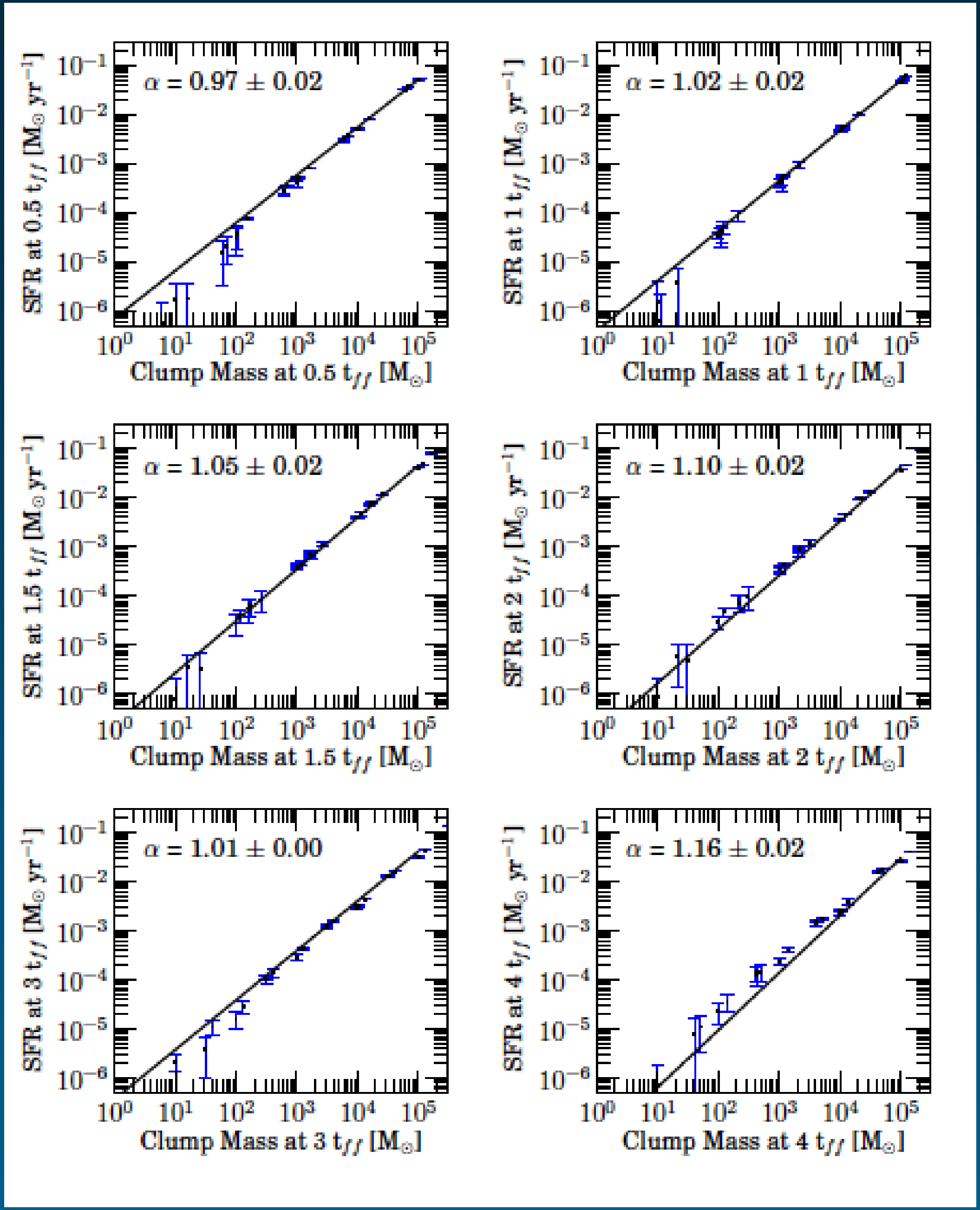
Find at different times

SFR ~ M$^{\alpha}$

α ~ 1

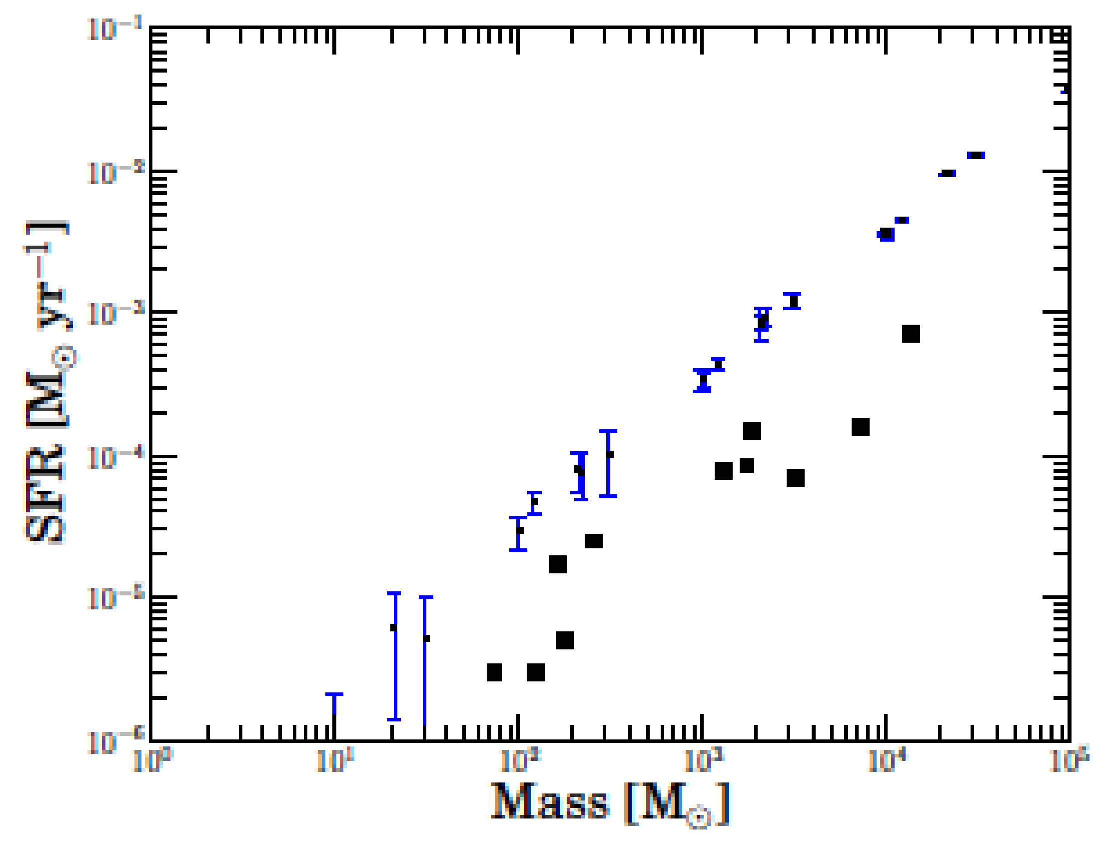
τ_{SFR} ~ M/SFR(M) ~ const

~ 3Myr (in clumps)



Star formation rates – compared to the data

- good agreement in linear behaviour
- upper slope – no feedback on gas



Data(black squares) from Lada et al 2010

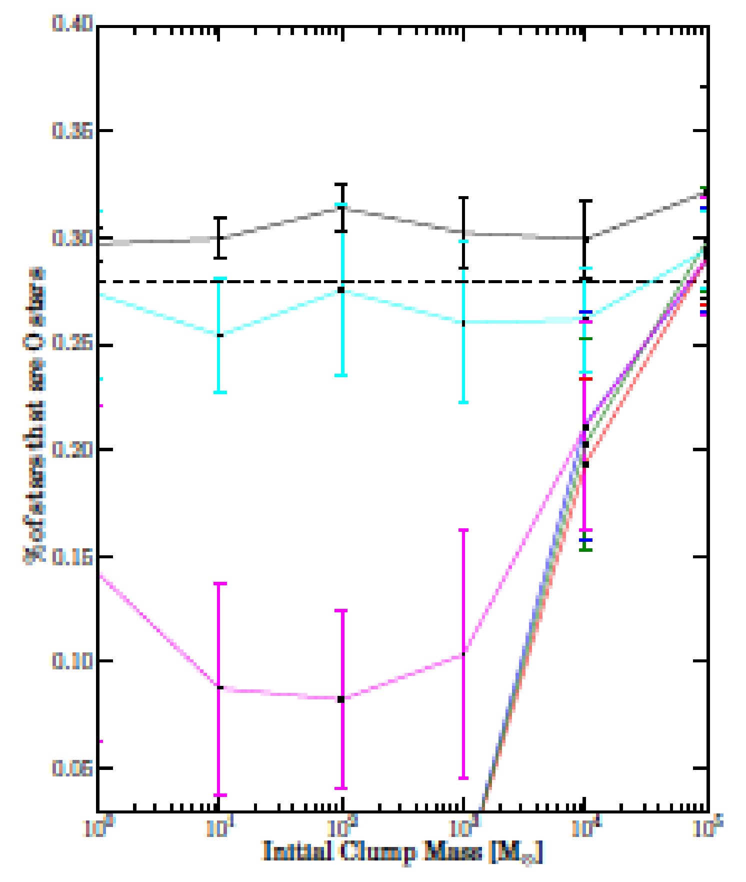
Expected numbers of O stars in clumps

Numbers vs initial clump masses, accreting at different rates.

(blue is 2.8x10^{-2} M$_{solar}$yr^{-1})

Converges to nos. expected from IMF (M>16M$_{solar}$) ~ 0.28%

Lowest mass final clump producing O stars is 5000 M$_{solar}$ ~ Orion clump



IV. Feedback on Cluster Scale

Radiation

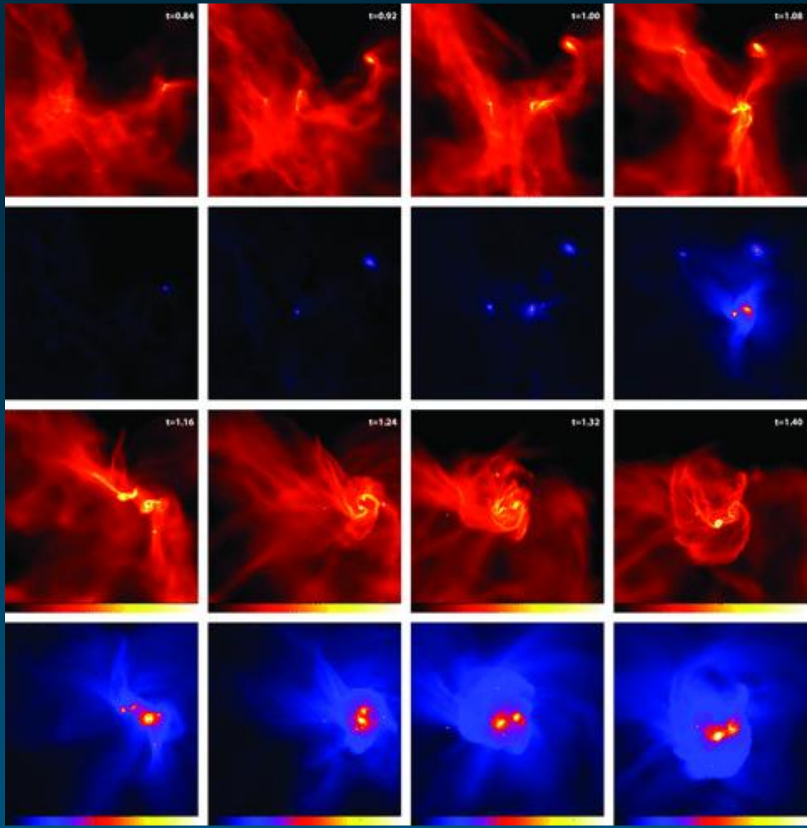
Radiative feedback f e stars:

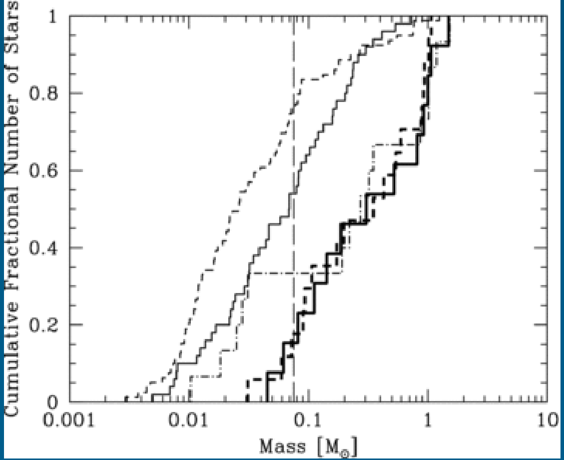
$$M_J \propto T^{3/2}$$

raises Jeans Mass

- filaments don’t fragment
- gas drains into primary and its disk (eg. Krumholz et al 2007)
- prevent fragmentation out to 1000 AU scales

Suppression of objects by factor 4 (Bate 2009): get robust low mass part of IMF…?





Bate (2009)

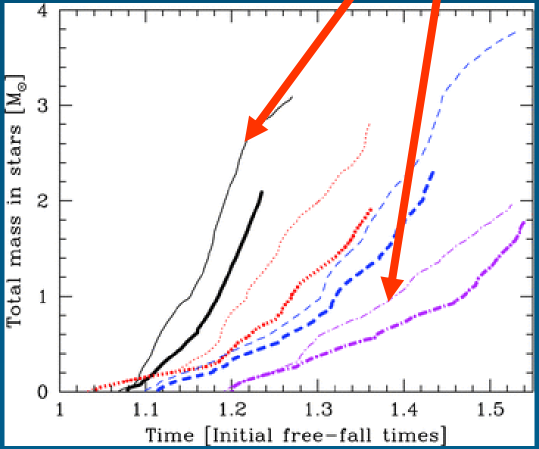
MHD and RT

MHD with SPH (eg. Price & 2012, Peters et al 2011,..)

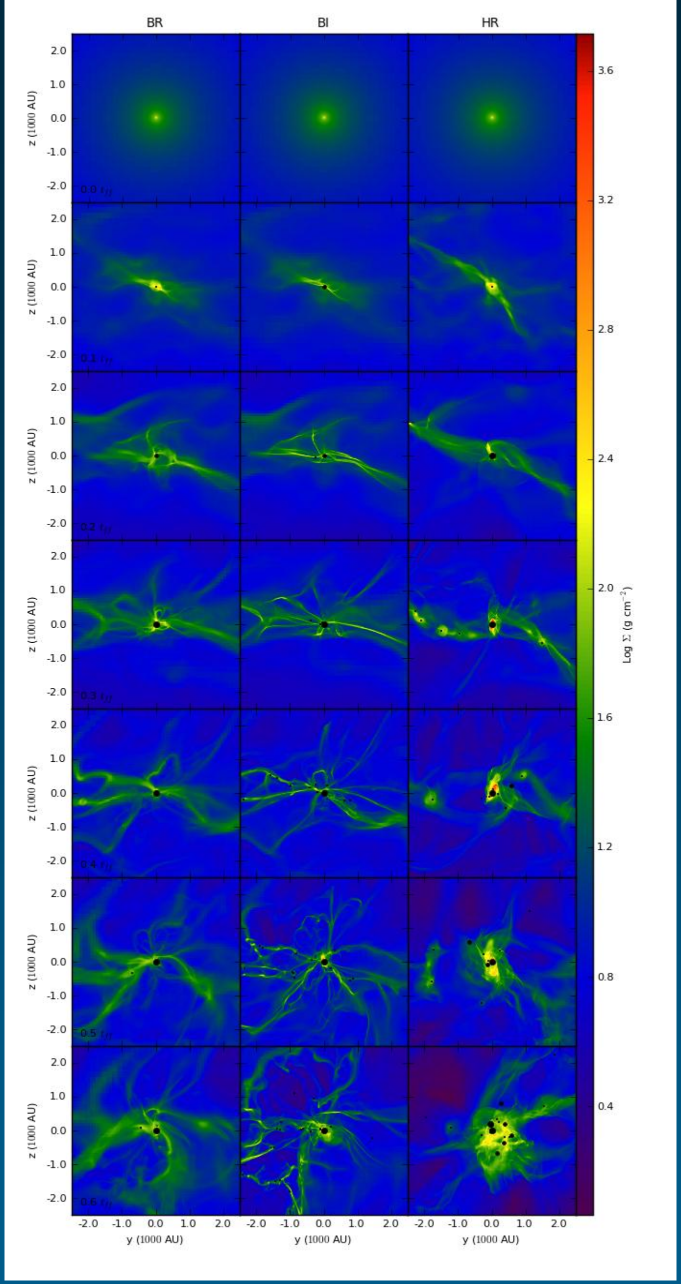
RT suppresses fragmentation – small scales

MHD suppresses larger scales

MHD has strong suppressive effect compared to hydro for supercritical cloud,Γ=3?



ALSO:
Commercons et al 2011, Peters et al 2011, Myers et al 2012



BR (left) , BI (middle), HR (right)

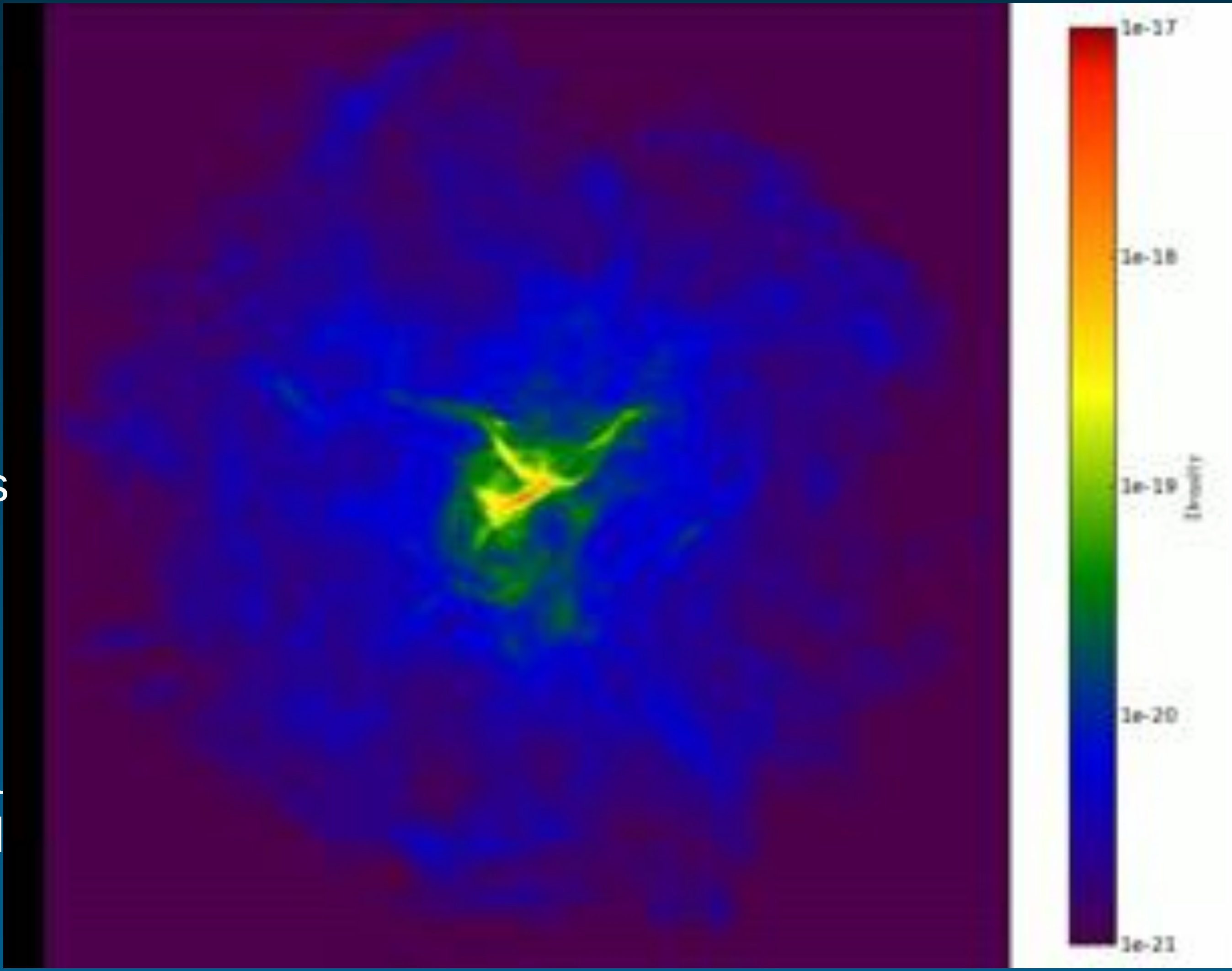
Myers et al 2013

Add in turb + B + ionizing rad:

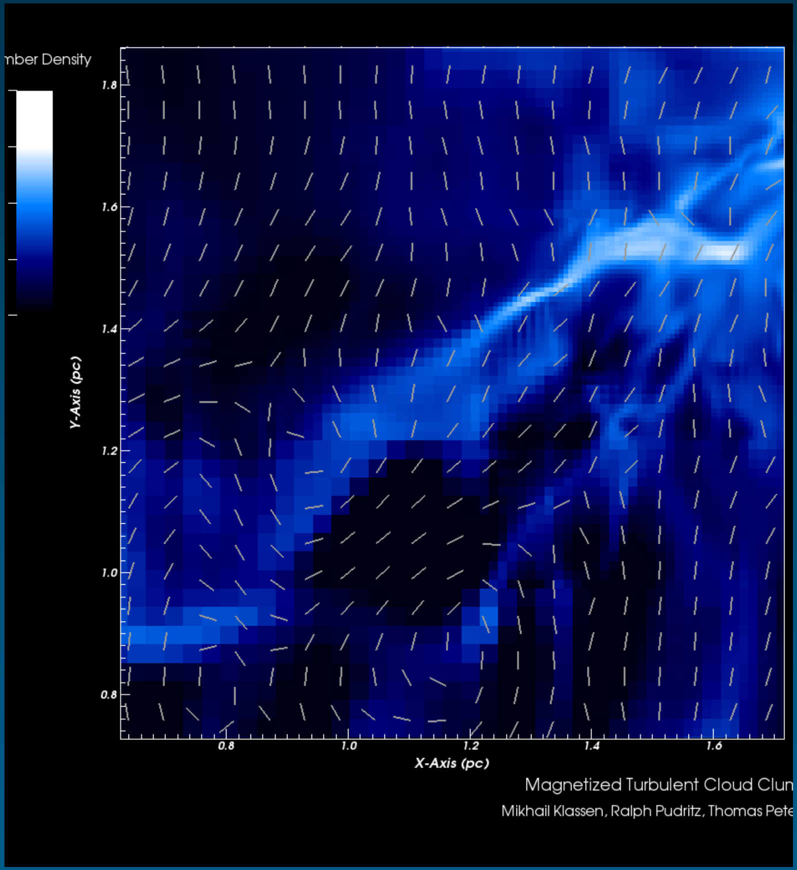
(Klassen, Pudritz, et al, in prep)

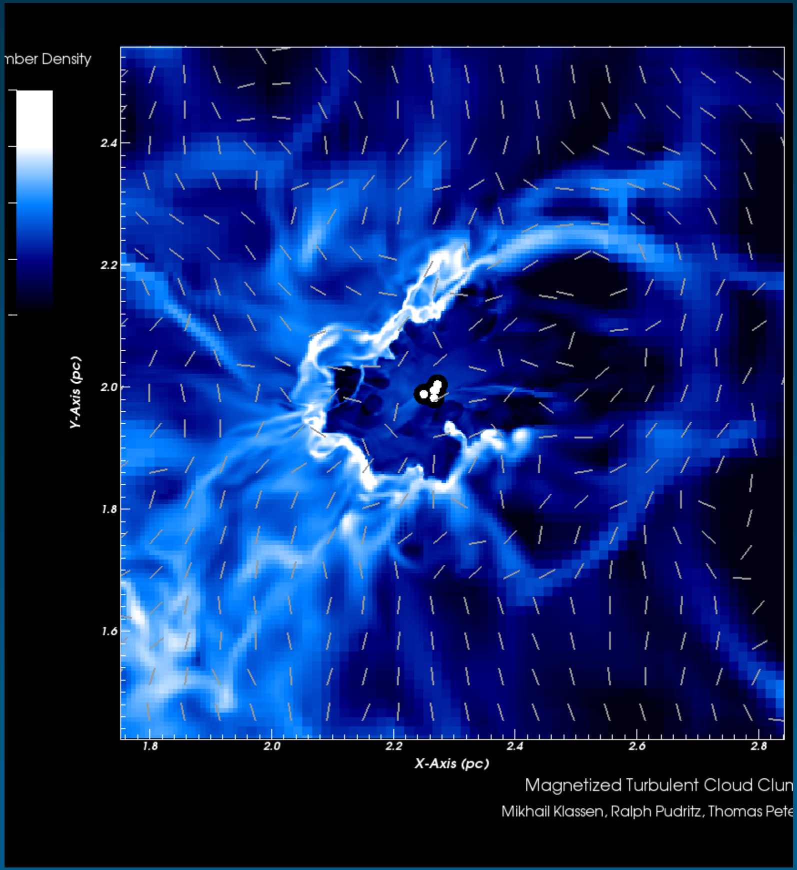
10^3 M_{sun} clump
rho ~ $r^{-1.5}$ power law profile
mass-to-flux ratio ~ 3.5
flux ~ 10 uG uniform in the z-direction
radiative feedback using protostellar tracks
turbulence RMS ~ Mach 5
turbulent power spectrum: P(k) ~ k^{-2}
rigid body rotation: beta ~5% of the gravitational potential

T (initial) = 30^o K



B fields associated with filaments and radiation driven bubble





Structure and evolution of filaments (Kirk, Klassen, Pudritz & Pillsworth 2014, in prep) (500 solar mass clump run)

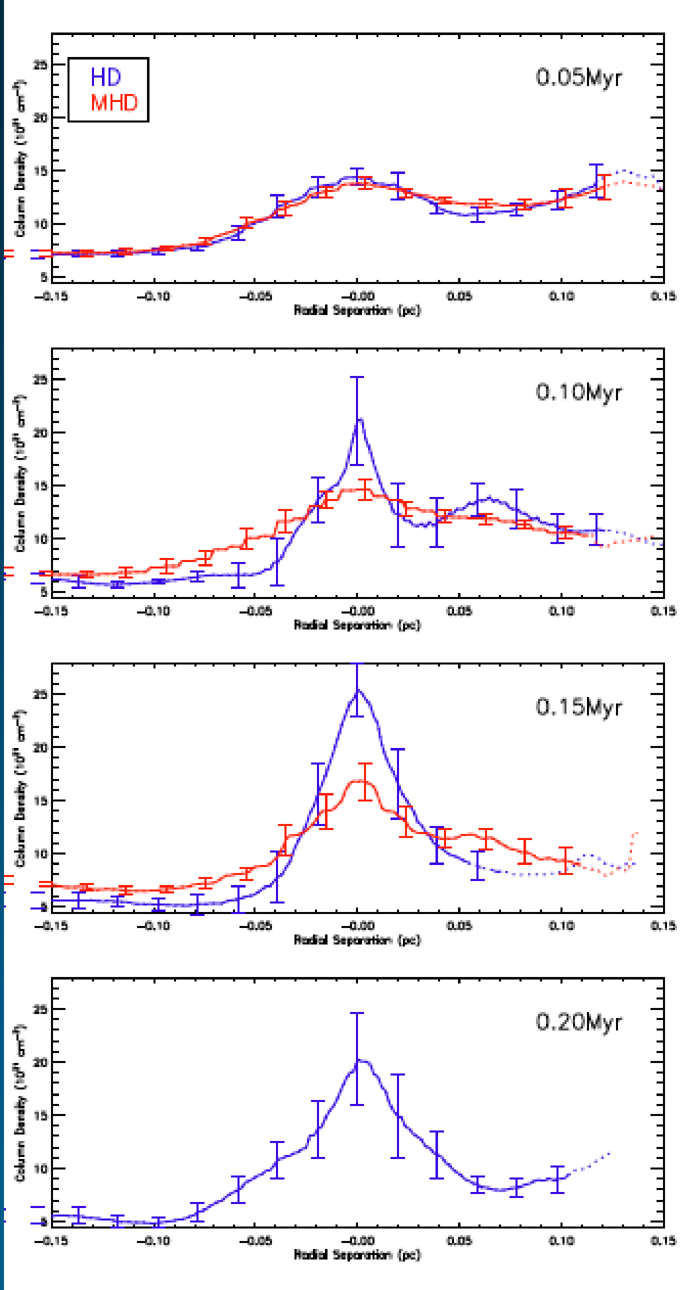
Accretion onto filaments,

Hydro profiles steepen more rapildy than MHD (magnetic pressure support in filaments)

Compare profiles with theory and observations

Filament cores around 0.1 pc with scatter

(see Andre et al PPVI for review

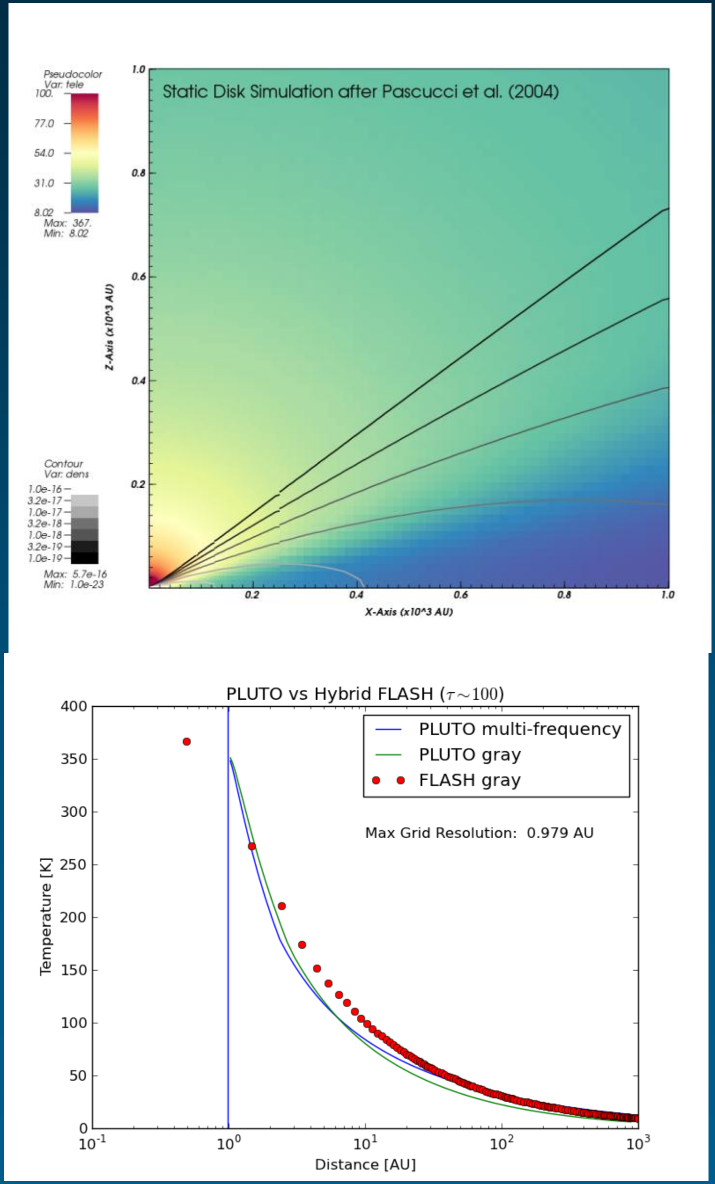


New AMR FLASH Hybrid RT Code for SF and Cluster feedback:

Klassen, Pudritz, Kuiper, Peters, Banerjee 2014

Principle: as Kuiper et al 2010, but;

- AMR FLASH 4
- Removes constraint of spherical symmetry, fixed source (for massive star formation studies), fixed grid
- Architecture: Port Peters et al ray trace code into FLASH 4, + FLD (FLASH 4 has implicit diffusion solver)
- Incorporate sinks (eg. for stars) with protostellar evolution (Klassen, Pudritz, & Peters 2011; Offner et al 2009)



Klassen et al 2014

Summary:

1. Radiative feedback occurs at several levels:

   Cluster to GMC and larger scales
   Individual star formation on stellar/cluster scales

2. Can build and test “subgrid” models for cluster and star formation that complement one another;

3. Filamentary formation of GMCs, clusters, stars have common properties - GI is different in filaments than spheres

4. Radiative feedback + MHD in filamentary environment essential - radiation escape into cavities and role of B in fragmentation