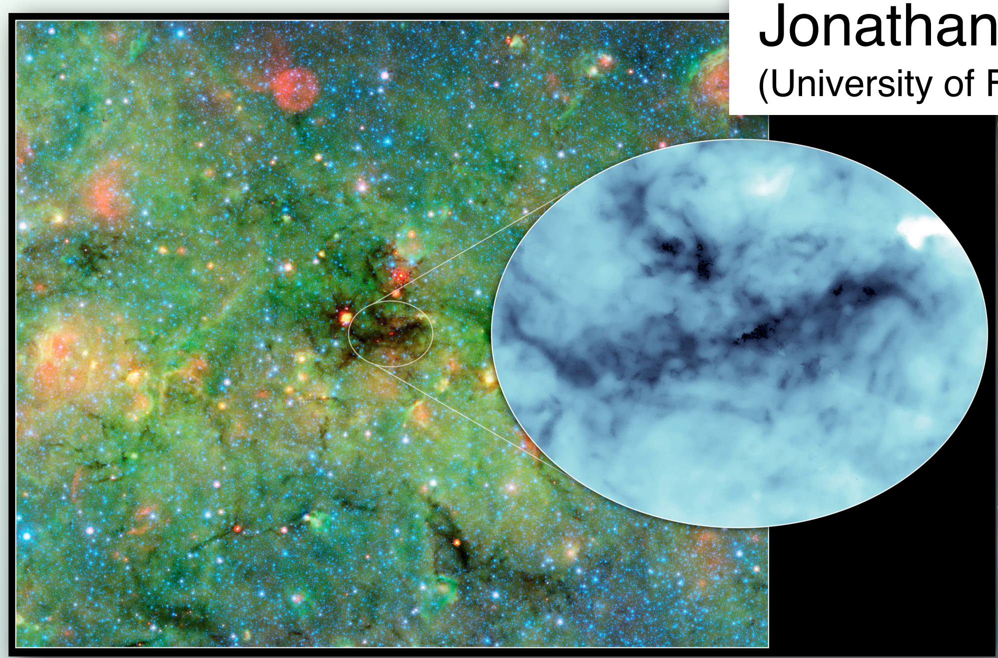
Filaments and High-Mass Star Formation

Jonathan Tan
(University of Florida)



Butler et al. (2014); NASA/Spitzer/IRAC+MIPS; IRDC G028.37+00.07

Orion Nebula Cluster (VLT; JHK) (McCaughrean)

Current & former students:
Michael Butler (U. Zurich)
Audra Hernandez (Wisconsin)
Shuo Kong
Wanggi Lim
Bo Ma
Ben Wu
Yichen Zhang (Yale/U.Chile)

Florida Theory Postdoc Fellows:
Sourav Chatterjee (Northwestern)
Nicola Da Rio
Kei Tanaka
Elizabeth Tasker (Hokkaido)
Sven Van Loo (Leeds)

Paola Caselli (MPE)
James De Buizer (SOFIA)
Francesco Fontani (Arcetri)
Jonathan Henshaw (LJM)
Izaskun Jimenez-Serra (ESO)
Jouni Kainulainen (MPIA)
Christopher McKee (UCB)
Thushara Pillai (MPIR)
...

Massive Star Formation Theories

Core Accretion:

wide range of $dm_*/dt \sim 10^{-5} - 10^{-2}\ M_\odot\ yr^{-1}$

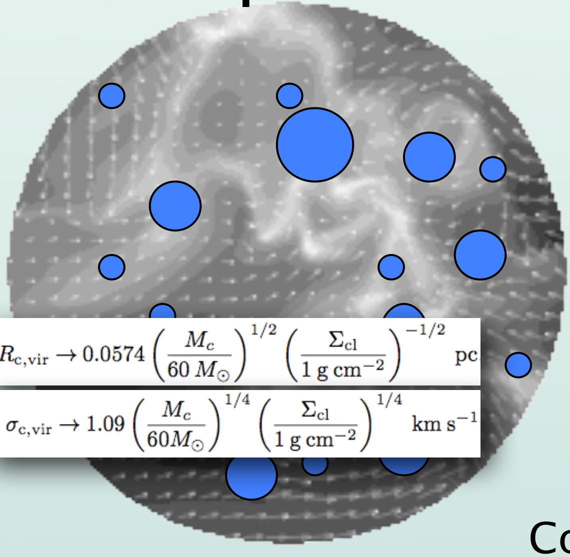
(e.g. Myers & Fuller 1992; Caselli & Myers 1995; McLaughlin & Pudritz 1997; Osorio+ 1999; Nakano+ 2000; Behrend & Maeder 2001)

Turbulent Core Model:

(McKee & Tan 2002, 2003)

Stars form from **"cores"** that fragment from the **"clump"**.

$$\bar{P} = \phi_P G \Sigma^2$$



$$R_{c,vir} \rightarrow 0.0574 \left(\frac{M_c}{60\ M_\odot}\right)^{1/2} \left(\frac{\Sigma_{cl}}{1\ \mathrm{g\ cm^{-2}}}\right)^{-1/2} \mathrm{pc}$$

$$\sigma_{c,vir} \rightarrow 1.09 \left(\frac{M_c}{60 M_\odot}\right)^{1/4} \left(\frac{\Sigma_{cl}}{1\ \mathrm{g\ cm^{-2}}}\right)^{1/4} \mathrm{km\ s^{-1}}$$

If in **equilibrium**, then **self-gravity** is balanced by **internal pressure**: B-field, turbulence, radiation pressure (thermal P is small)

Cores form from this turbulent/magnetized medium: at any instant there is a small mass fraction in cores. These cores collapse quickly to feed a central disk to form individual stars or binaries.

$$\dot{m}_* \sim M_{core}/t_{ff}$$

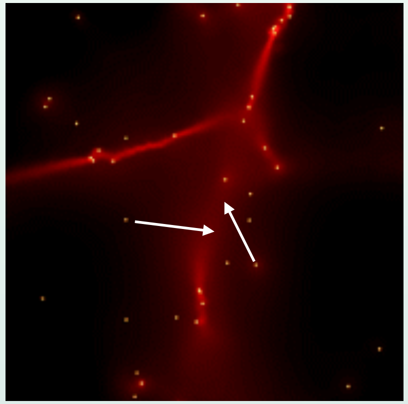
$$\rightarrow 4.6 \times 10^{-4} \left(\frac{m_{*f}}{30\ M_\odot}\right)^{3/4} \Sigma_{cl}^{3/4} \left(\frac{m_*}{m_{*f}}\right)^{0.5} M_\odot\ \mathrm{yr^{-1}}$$

Competitive (Clump-fed) Accretion:

(Bonnell et al. 2001; Wang et al. 2010)

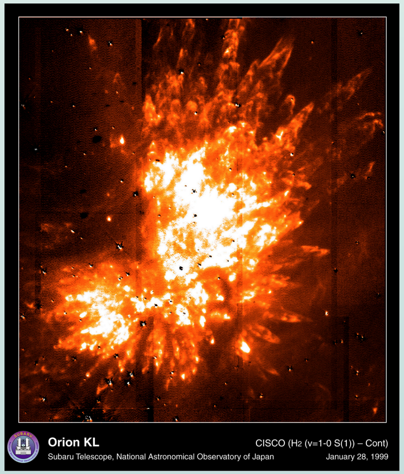
Massive stars gain most mass by Bondi-Hoyle accretion of ambient clump gas.

Massive stars form on the timescale of the star cluster.



Violent interactions? Mergers?

(Bonnell et al. 1998; Bally & Zinnecker 2005)



Effects of Filaments

Core Accretion:

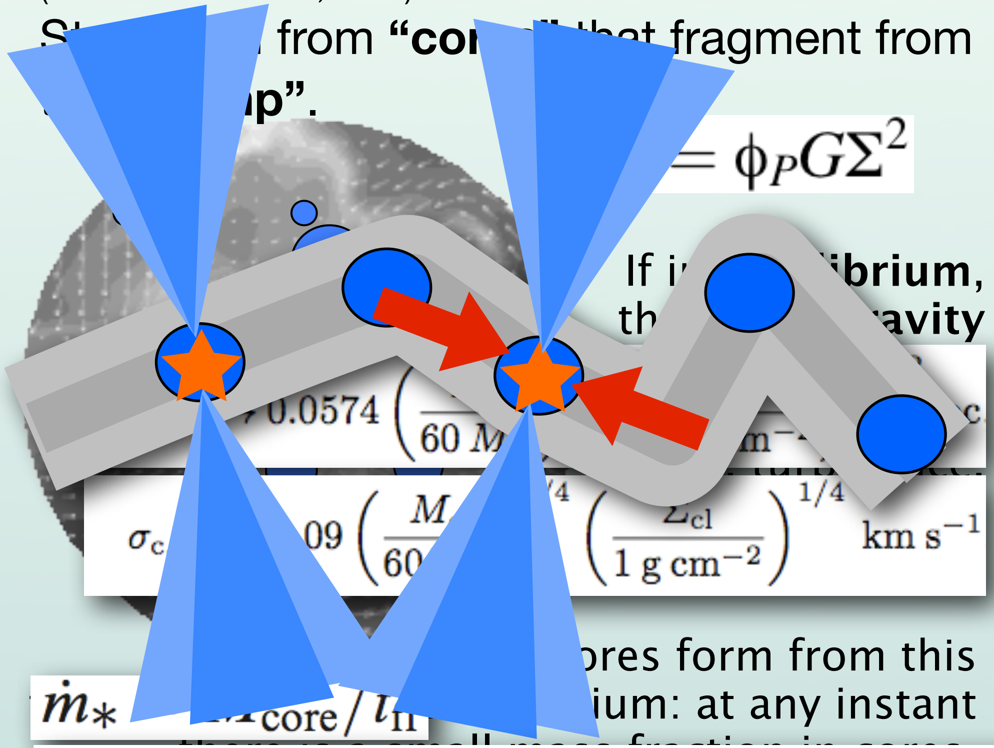
wide range of dm*/dt ~10^{-5} - 10^{-2} $M_\odot$ yr^{-1}

(e.g. Myers & Fuller 1992; Caselli & Myers 1995; McLaughlin & Pudritz 1997; Osorio+ 1999; Nakano+ 2000; Behrend & Maeder 2001)

Turbulent Core Model:

(McKee & Tan 2002, 2003)

S... from **"co**... that fragment from ... **p"**.



$= \phi_P G\Sigma^2$

If i... **ibrium,** th... **avity**

$0.0574 \left(\frac{\ \ }{60\ M}\right.$ ... m^{-2} ... c

σ_c ... $09 \left(\frac{M}{60}\right.$ ... $^{1/4} \left(\frac{\Sigma_{cl}}{1\ g\ cm^{-2}}\right)^{1/4}$ km s^{-1}

...ores form from this ...ium: at any instant

$\dot{m}_* \ \ \ M_{core}/t_{ff}$

$$\rightarrow 4.6 \times 10^{-4} \left(\frac{m_{*f}}{30\ M_\odot}\right)^{3/4} \Sigma_{cl}^{3/4} \left(\frac{m_*}{m_{*f}}\right)^{0.5} M_\odot\ yr^{-1}$$

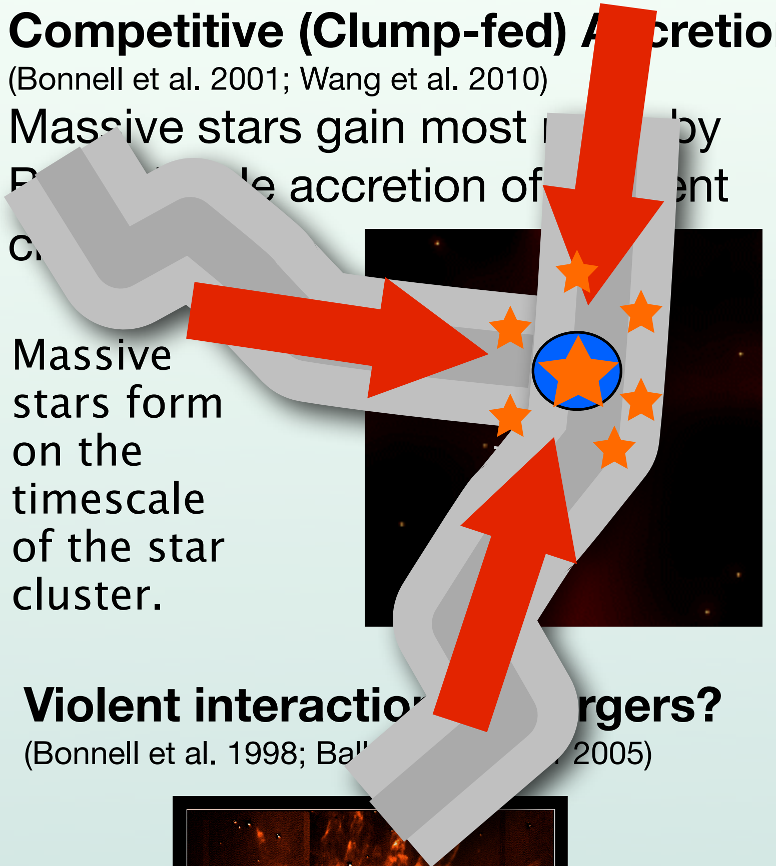
Competitive (Clump-fed) A... **cretion:**

(Bonnell et al. 2001; Wang et al. 2010)

Massive stars gain most ... by

B... e accretion of ... ent

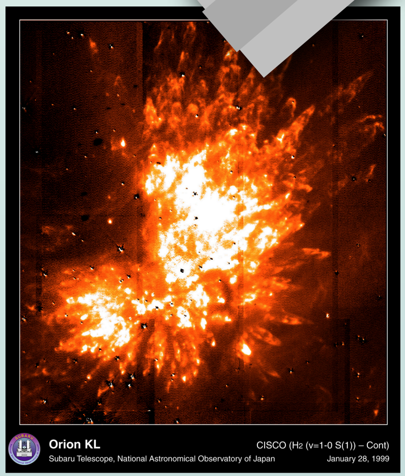
c...

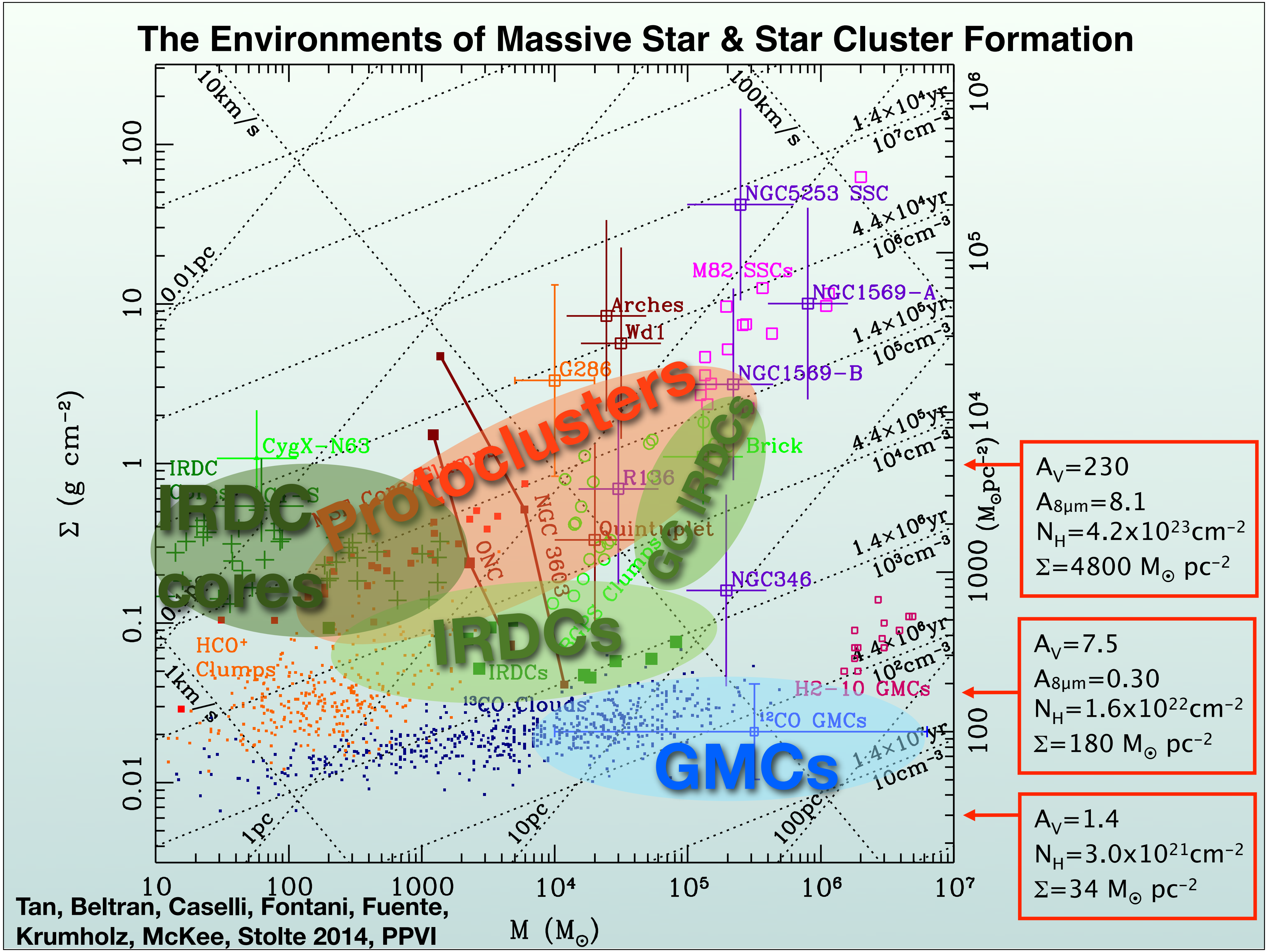


Massive stars form on the timescale of the star cluster.

Violent interactio... **rgers?**

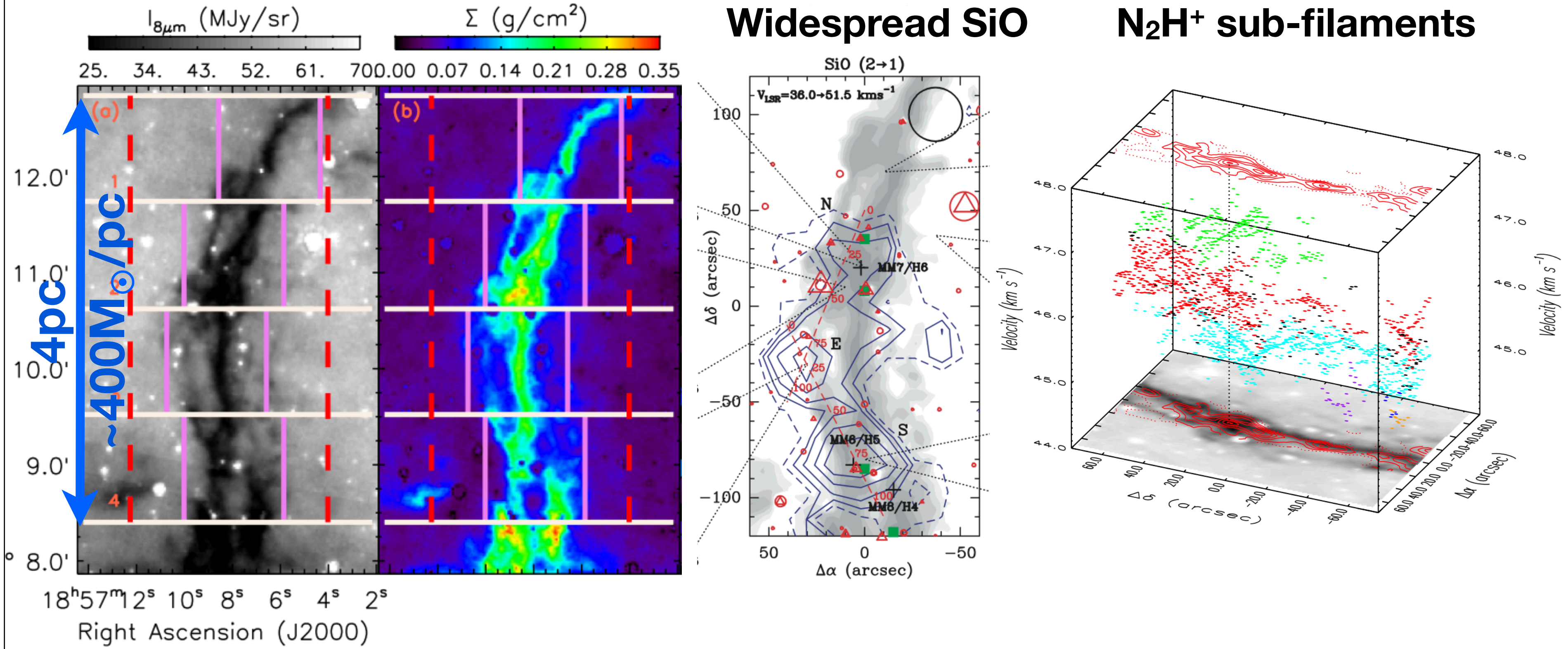
(Bonnell et al. 1998; Ba... 2005)




The Environments of Massive Star & Star Cluster Formation
Σ (g cm⁻²)
M (M☉)
(M☉pc⁻²)
10
100
1000
10⁴
10⁵
10⁶
10⁷
0.01
0.1
1
10
100
10⁶
10⁵
10⁴
1000
100
10km/s
100km/s
1km/s
0.01pc
1pc
10pc
100pc
1.4×10⁴yr
10⁷cm⁻³
4.4×10⁴yr
10⁶cm⁻³
1.4×10⁵yr
10⁵cm⁻³
4.4×10⁵yr
10⁴cm⁻³
1.4×10⁶yr
10³cm⁻³
4.4×10⁶yr
10²cm⁻³
1.4×10⁷yr
10cm⁻³
NGC5253 SSC
M82 SSCs
NGC1569−A
NGC1569−B
Arches
Wd1
G286
R136
Quintuplet
NGC346
Brick
CygX−N63
IRDC
ONC
NGC 3603
BGPS Clumps
HCO⁺ Clumps
IRDCs
¹³CO Clouds
¹²CO GMCs
H2−10 GMCs
IRDC cores
Protoclusters
GC IRDCs
IRDCs
GMCs
A_V=230
A_8μm=8.1
N_H=4.2x10²³cm⁻²
Σ=4800 M☉ pc⁻²
A_V=7.5
A_8μm=0.30
N_H=1.6x10²²cm⁻²
Σ=180 M☉ pc⁻²
A_V=1.4
N_H=3.0x10²¹cm⁻²
Σ=34 M☉ pc⁻²
Tan, Beltran, Caselli, Fontani, Fuente, Krumholz, McKee, Stolte 2014, PPVI

Dynamics of Filamentary IRDC G035.39–00.33

Hernandez & Tan 2011; Jimenez-Serra et al. 2010, 2014; Hernandez et al. 2011; 2012; Henshaw et al. 2013, 2014



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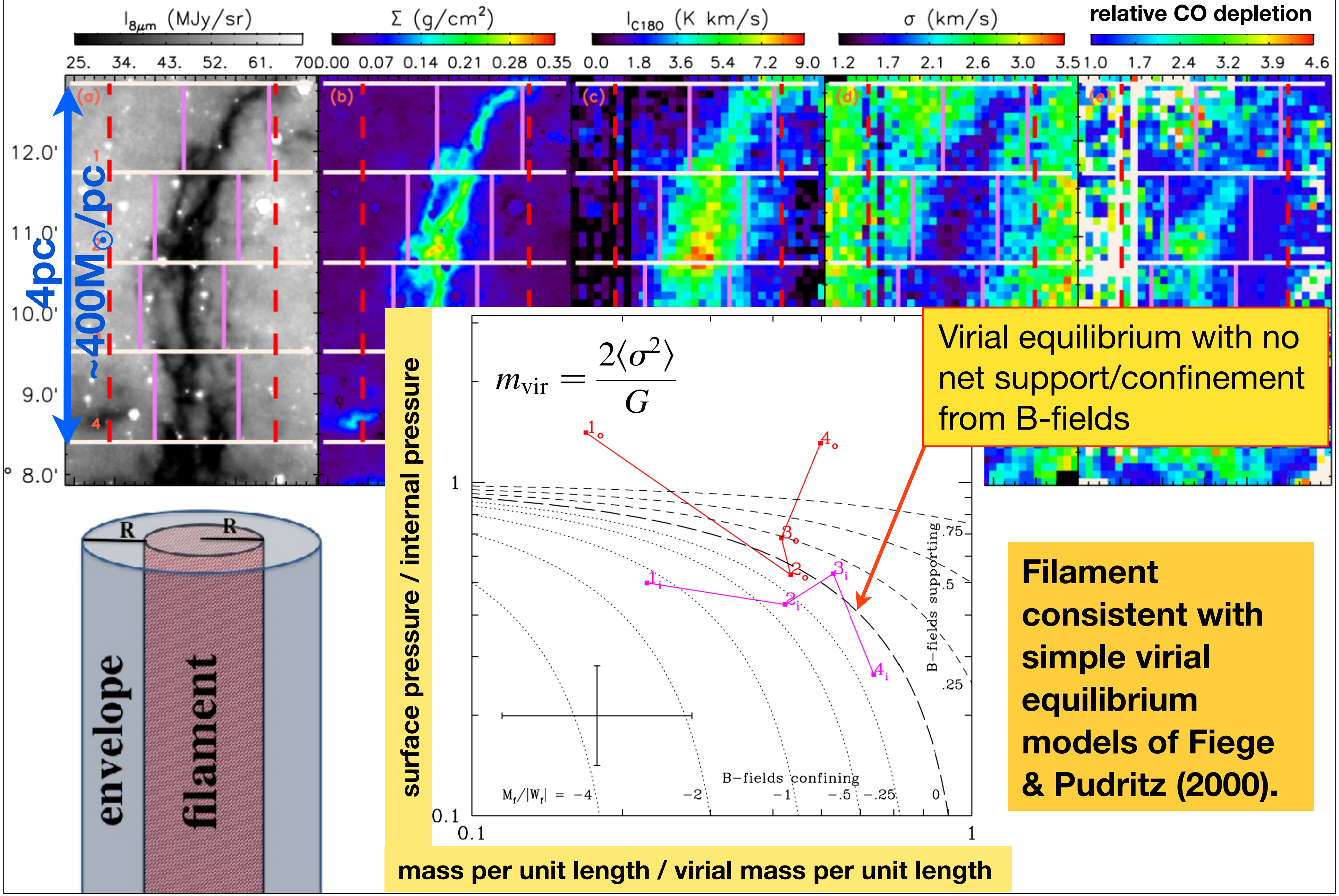
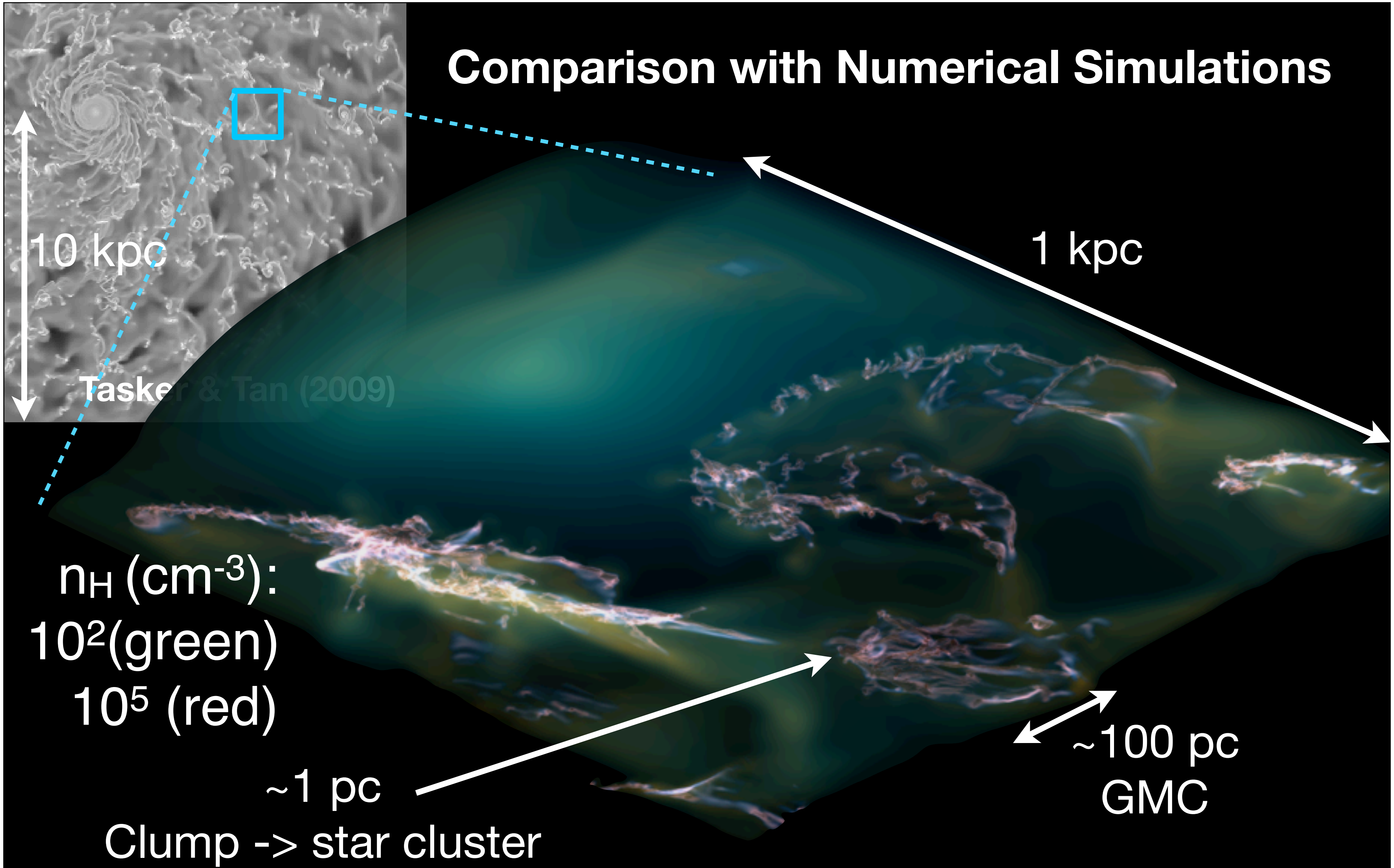


Virial equilibrium with no net support/confinement from B-fields

Filament consistent with simple virial equilibrium models of Fiege & Pudritz (2000).

Comparison with Numerical Simulations

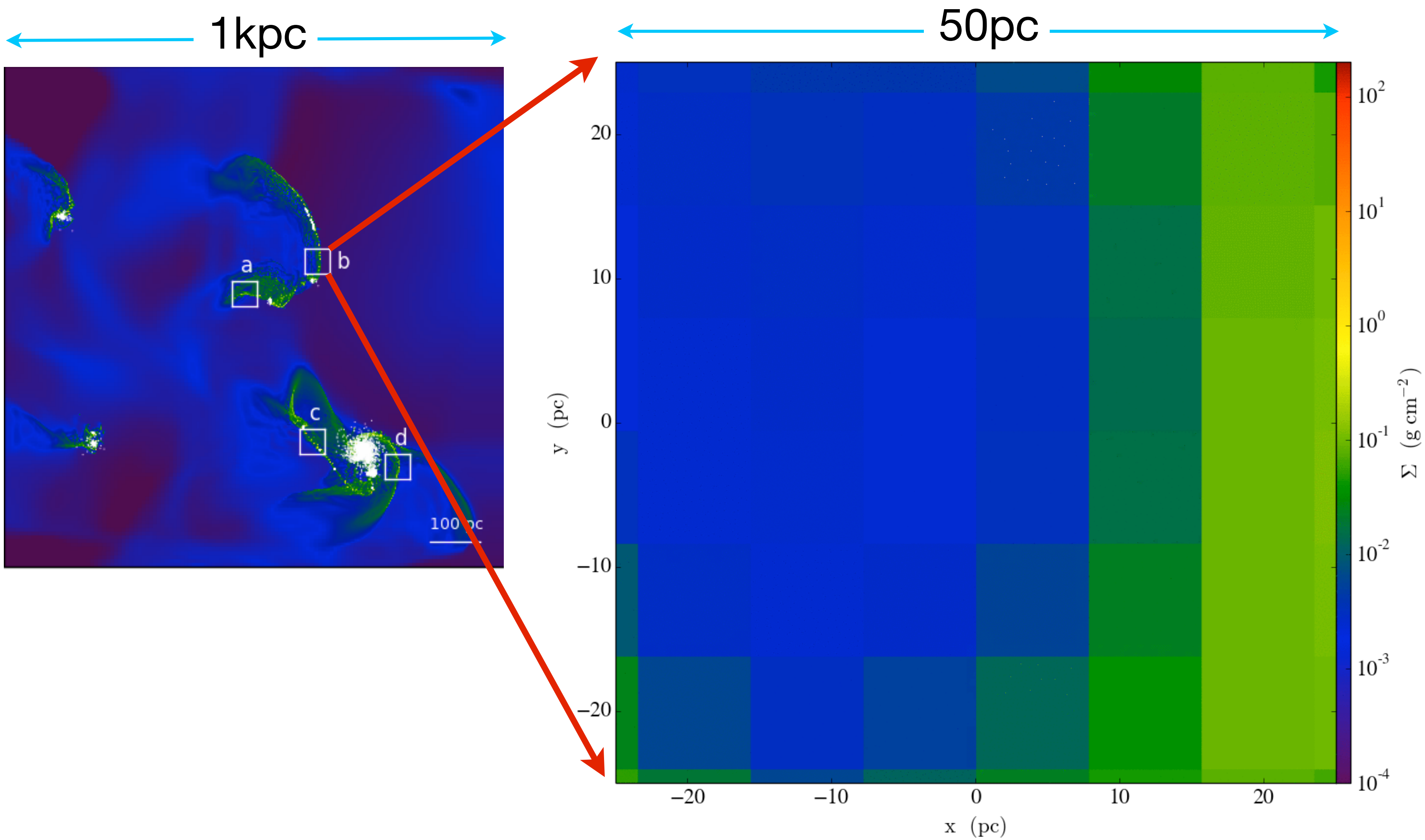


Series of Enzo/MG AMR simulations (M)HD;
PDR heating/cooling to <~10K; min. res. ~0.1pc
No feedback yet... maybe ok for IRDCs.

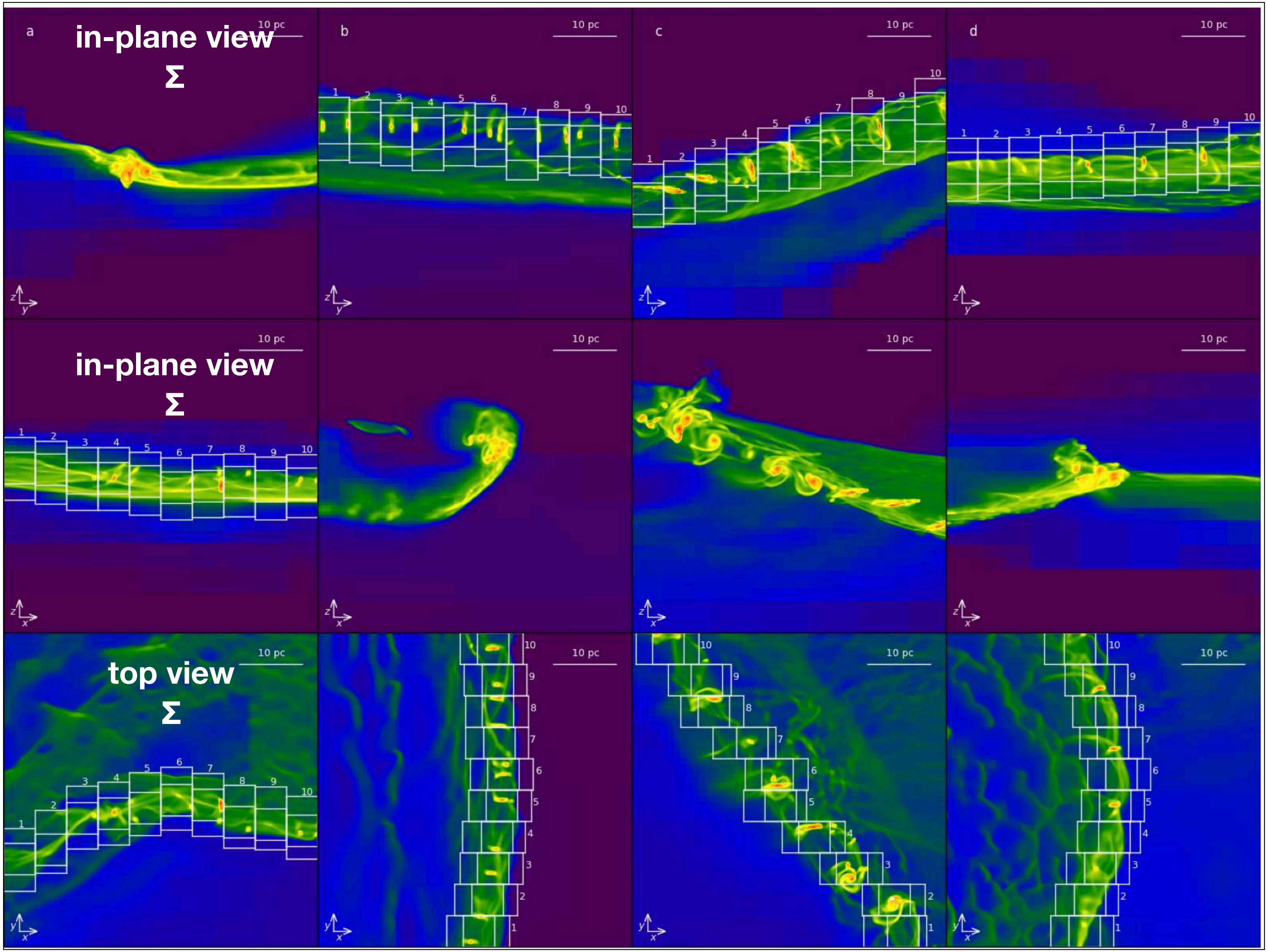
Van Loo, Butler, Tan (2013)
Butler et al. in prep.
Van Loo et al. in prep.

High Resolution (0.1pc) Hydro Results

Butler, Tan, Van Loo, in prep.

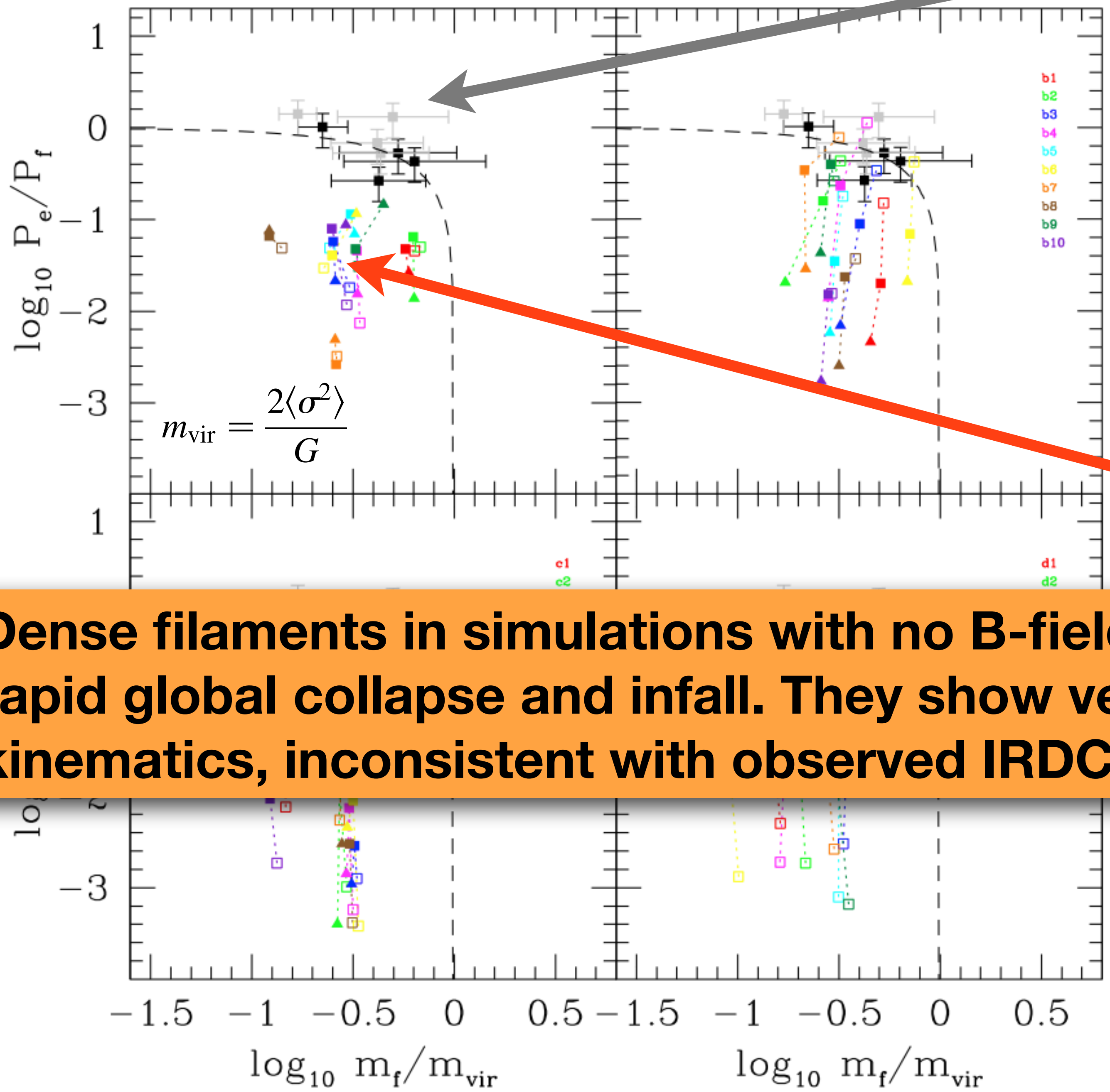


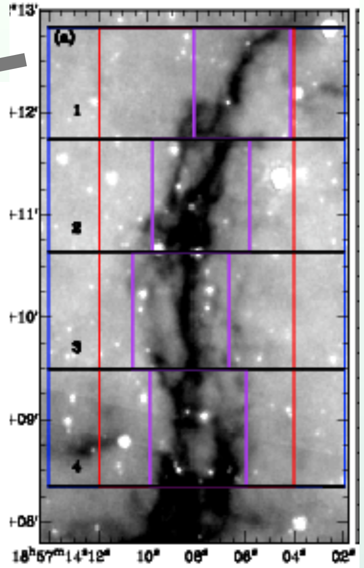
Filaments forming by global gravitational collapse from GMCs, mediated by a galactic shearing environment

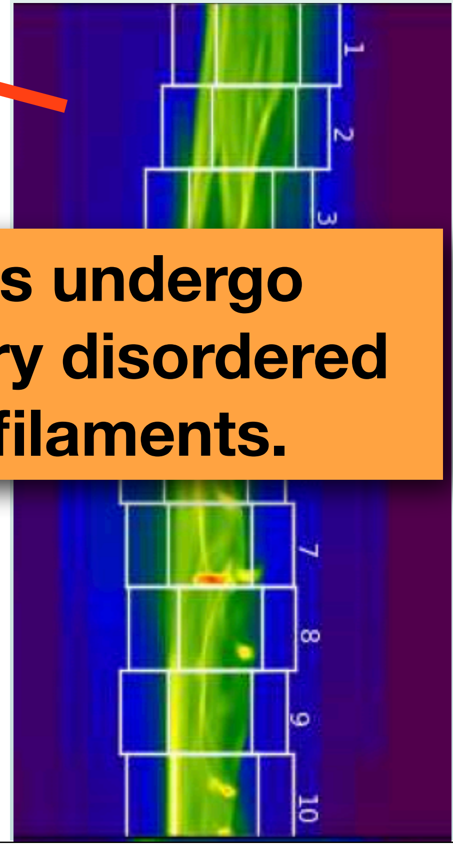


a
b
c
d
in-plane view
Σ
in-plane view
Σ
top view
Σ
10 pc

Filament Virial Analysis





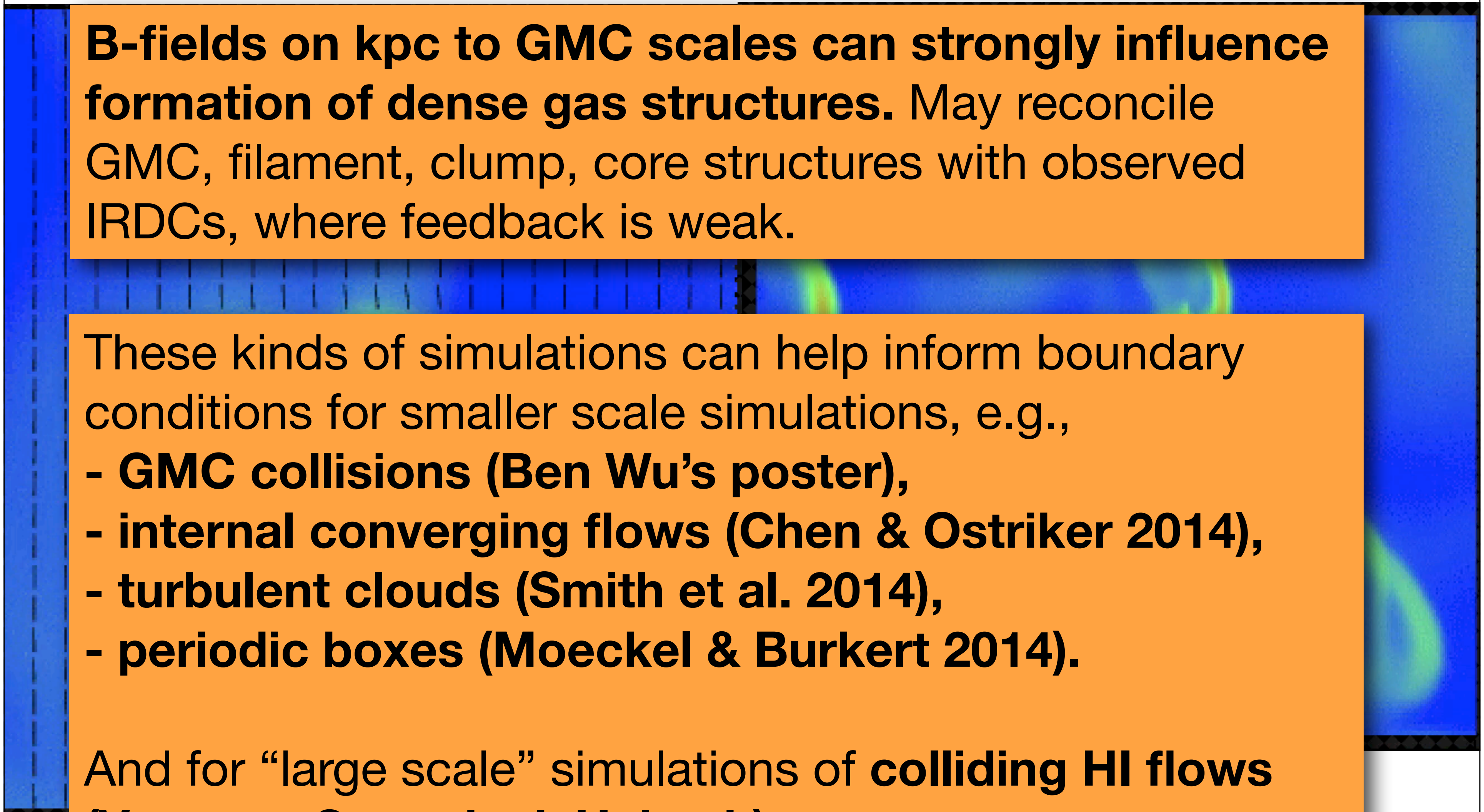


Dense filaments in simulations with no B-fields undergo rapid global collapse and infall. They show very disordered kinematics, inconsistent with observed IRDC filaments.

MHD Results

Van Loo, Tan & Falle, in prep.

No magnetic field **[...5,10,20,40...]** **80 μG mean in-plane field**



B-fields on kpc to GMC scales can strongly influence formation of dense gas structures. May reconcile GMC, filament, clump, core structures with observed IRDCs, where feedback is weak.

These kinds of simulations can help inform boundary conditions for smaller scale simulations, e.g.,

- GMC collisions (Ben Wu's poster),

- internal converging flows (Chen & Ostriker 2014),

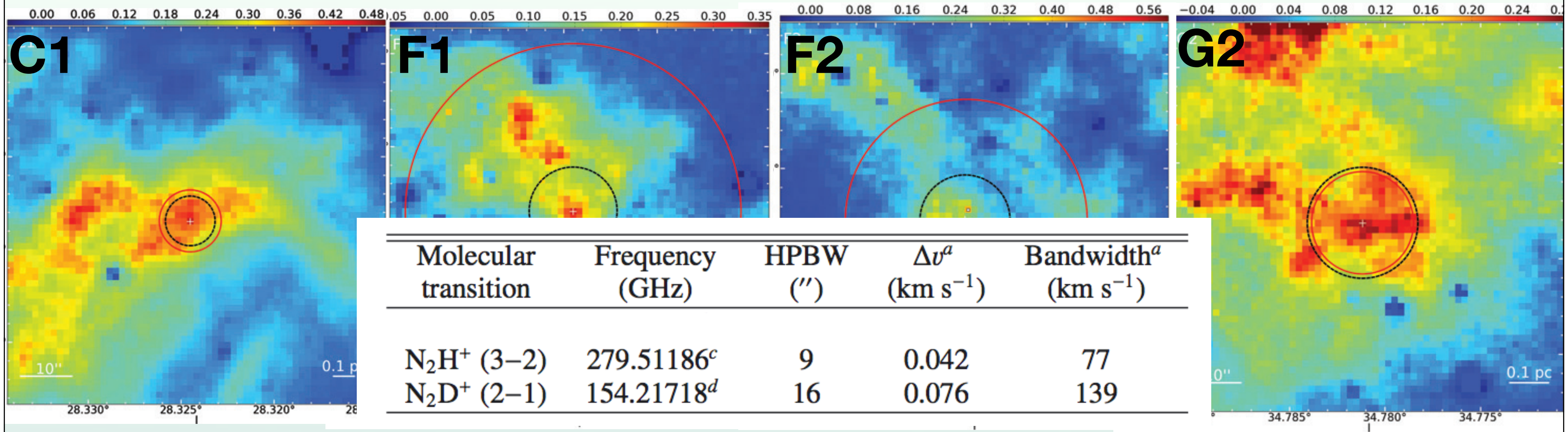
- turbulent clouds (Smith et al. 2014),

- periodic boxes (Moeckel & Burkert 2014).

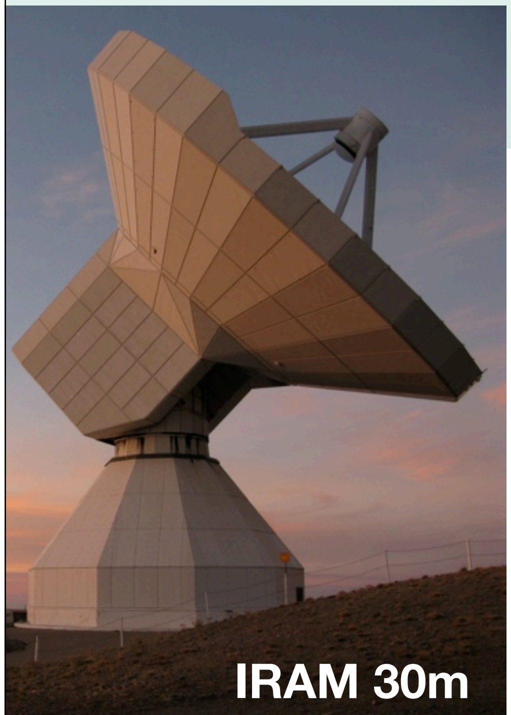
And for "large scale" simulations of **colliding HI flows (Vazquez-Semadeni, Heitsch).**

[Se
with Enzo & MG]

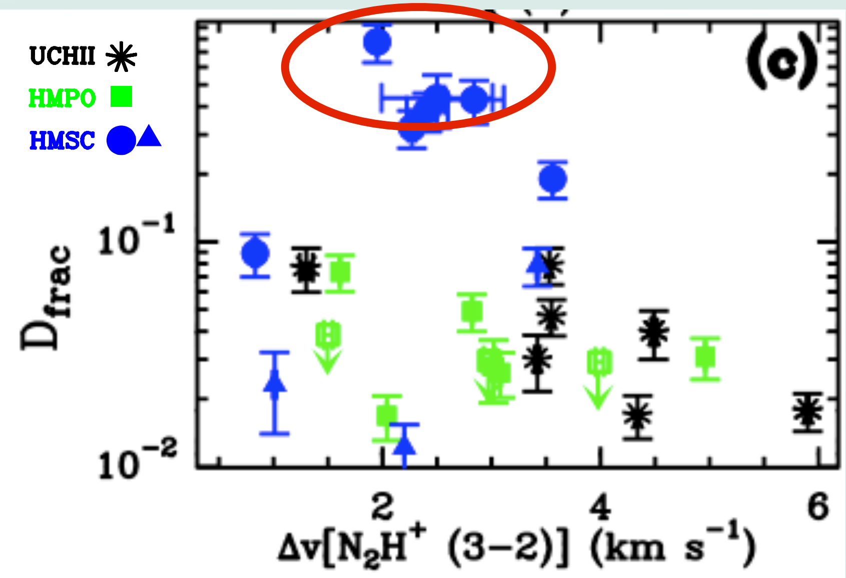
A Search for Massive Starless Cores: 4 IRDC core/clumps dark at 8, 24, 70μm



Molecular transition	Frequency (GHz)	HPBW ('')	Δv^a (km s^{-1})	Bandwidth[a] (km s^{-1})
N_2H^+ (3–2)	279.51186[c]	9	0.042	77
N_2D^+ (2–1)	154.21718[d]	16	0.076	139



High Deuterium Fraction [N_2D^+]/[N_2H^+]
(Fontani et al. 2011)



CO freeze-out
e.g. Hernandez et. al (2011)

$H_3^+ + CO \nrightarrow HCO^+ + H_2$

(T<20-30K)

$H_3^+ + HD \rightarrow H_2D^+ + H_2$

$H_2D^+ + N_2 \rightarrow H_2 + N_2D^+$

Astrochemical indicator that these are starless cores
(Caselli et al. 2002)

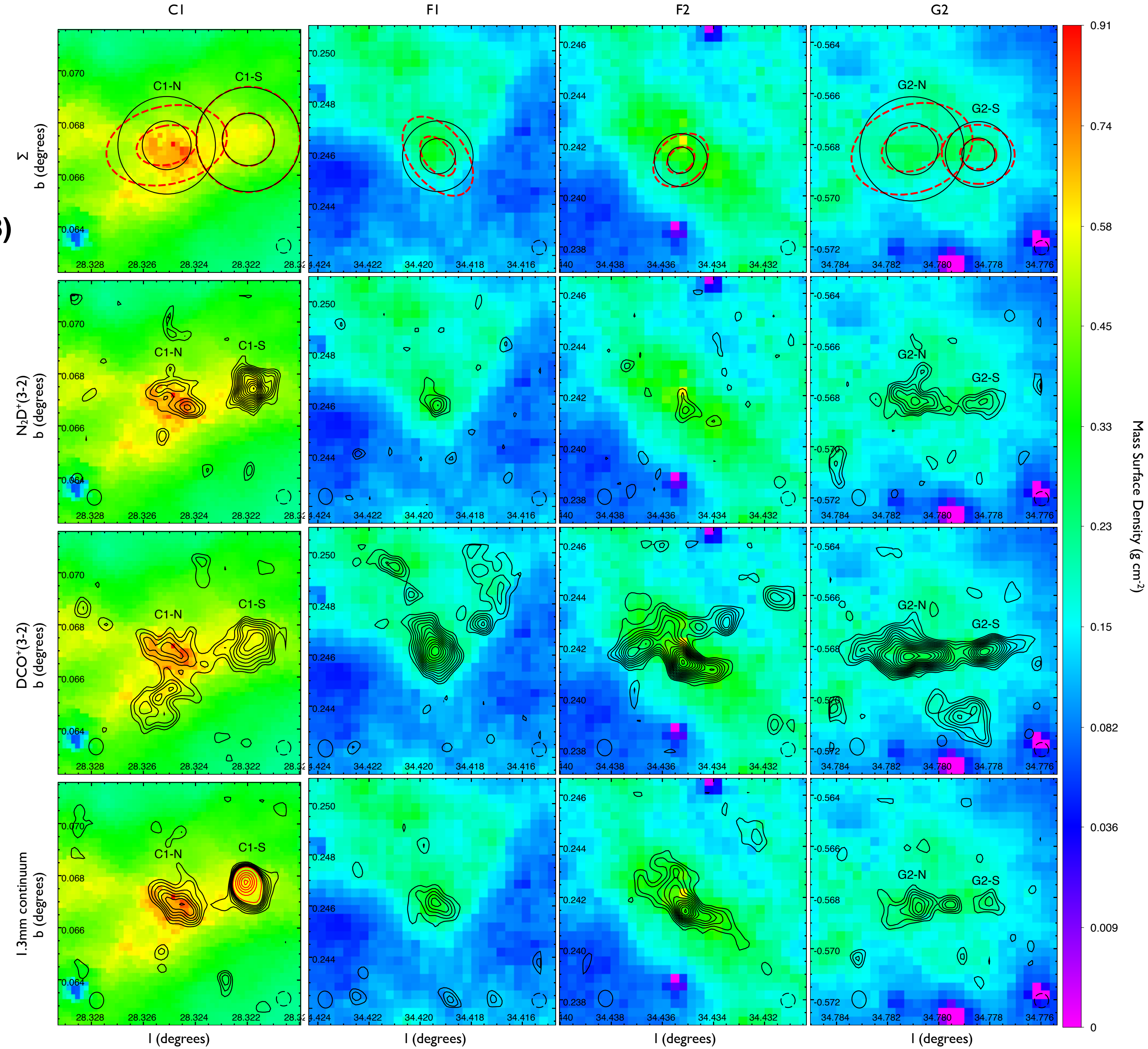
“Massive” “Starless” “Cores” with ALMA

(Tan, Kong et al. 13)

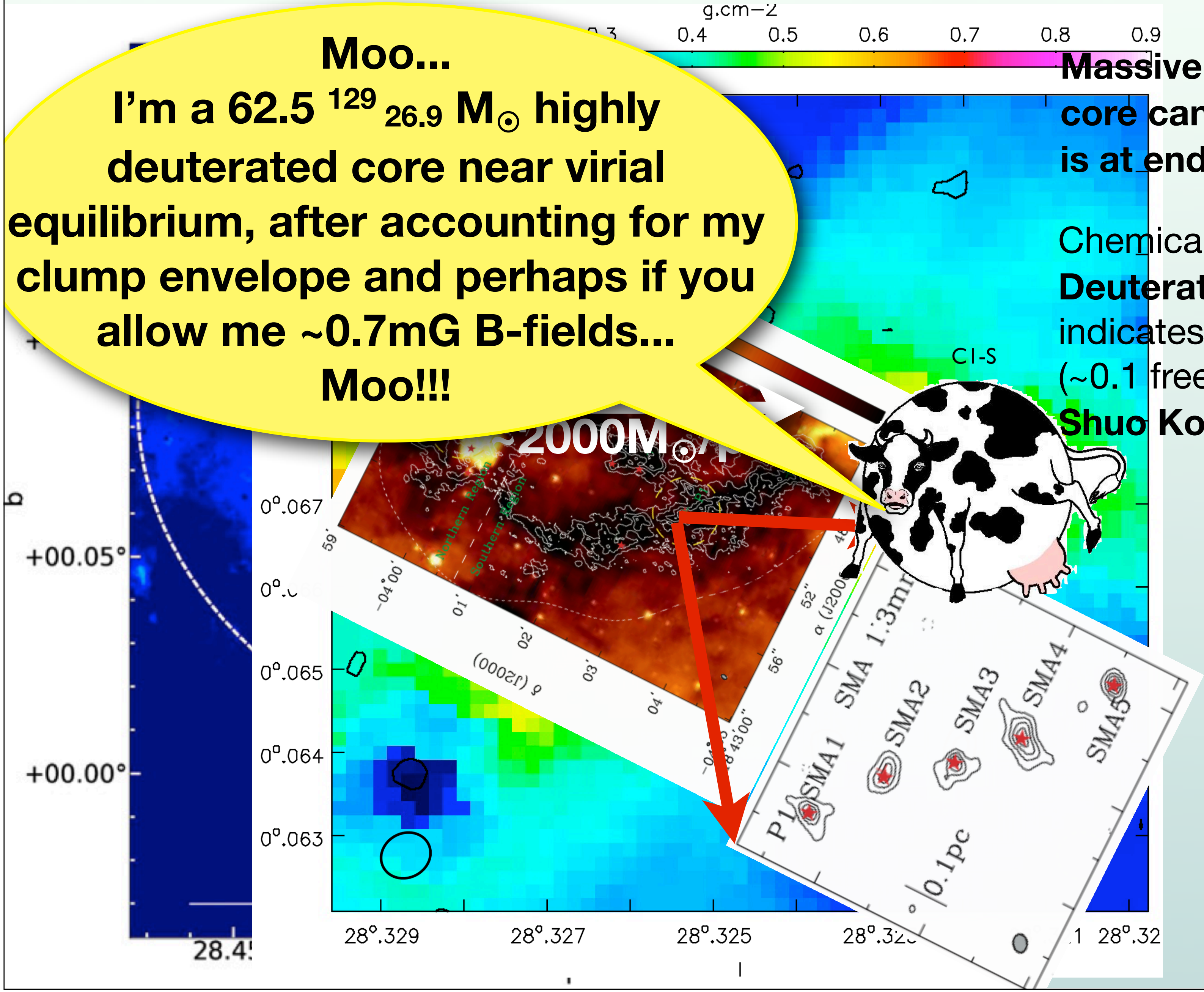
$N_2D^+(3\text{-}2)$

$DCO^+(3\text{-}2)$

1.3mm



N_2D^+ as a tracer of pre-stellar cores in IRDCs

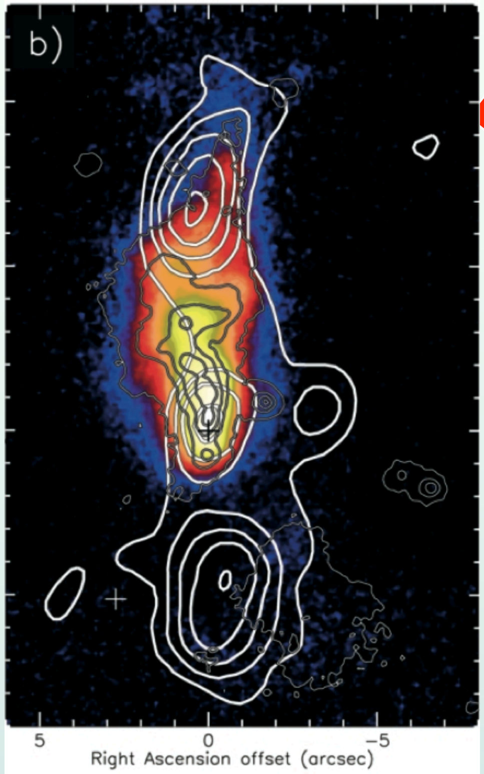


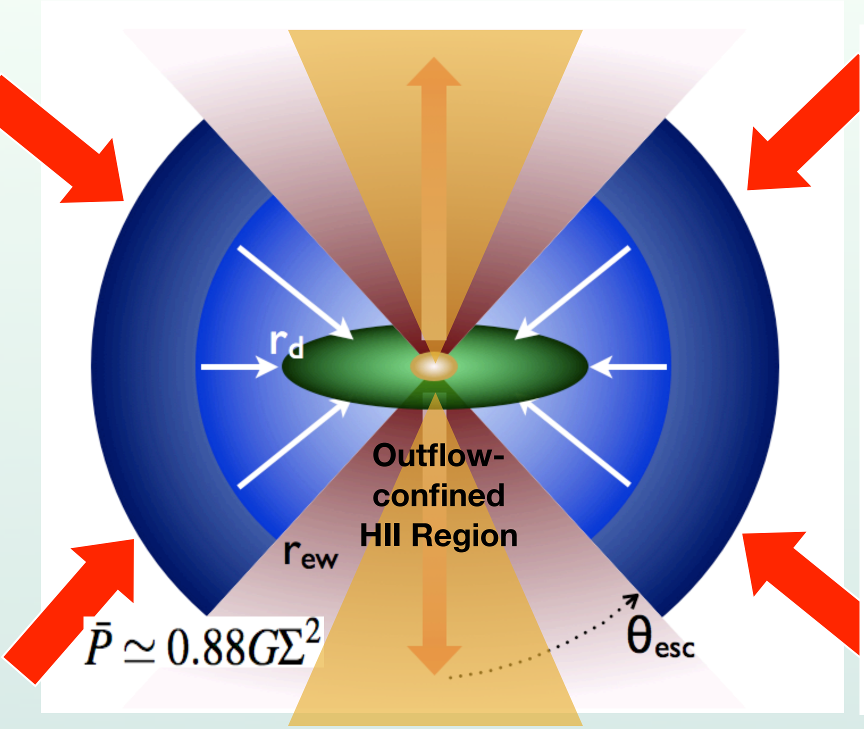
Massive starless core candidate C1-S is at end of filament.

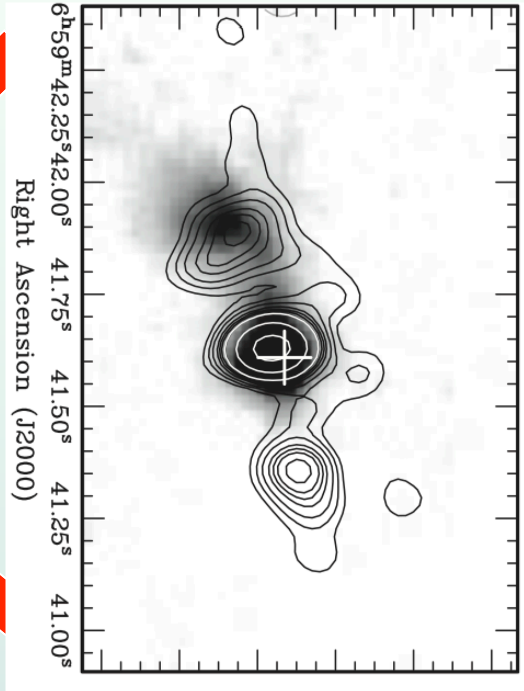
Chemical modeling of **Deuteration Clock** indicates slow collapse (~0.1 free-fall rate): **Shuo Kong’s poster.**

Regular spacing of massive protostellar cores, further along the filament (Zhang et al. 2009).

High-Mass Protostars



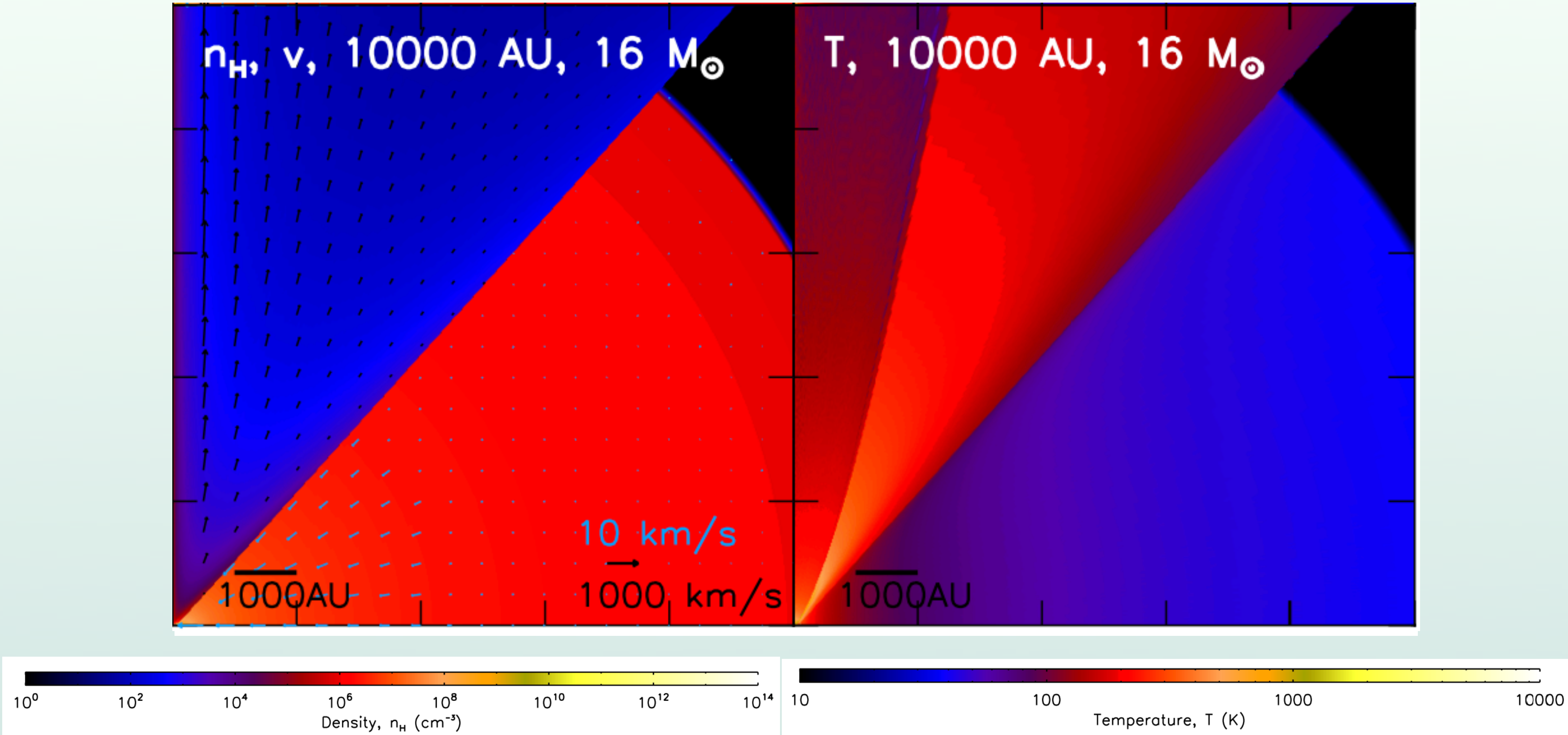




G35.2N:
De Buizer (2006)
Gibb et al. (2003)
Fuller et al. (2001)
Heaton & Little (1988)

IRAS 16562−3959:
Guzman et al. (2010)

High-Mass Protostars



Continuum RT modeling:

Robitaille, Whitney et al. (2006+);

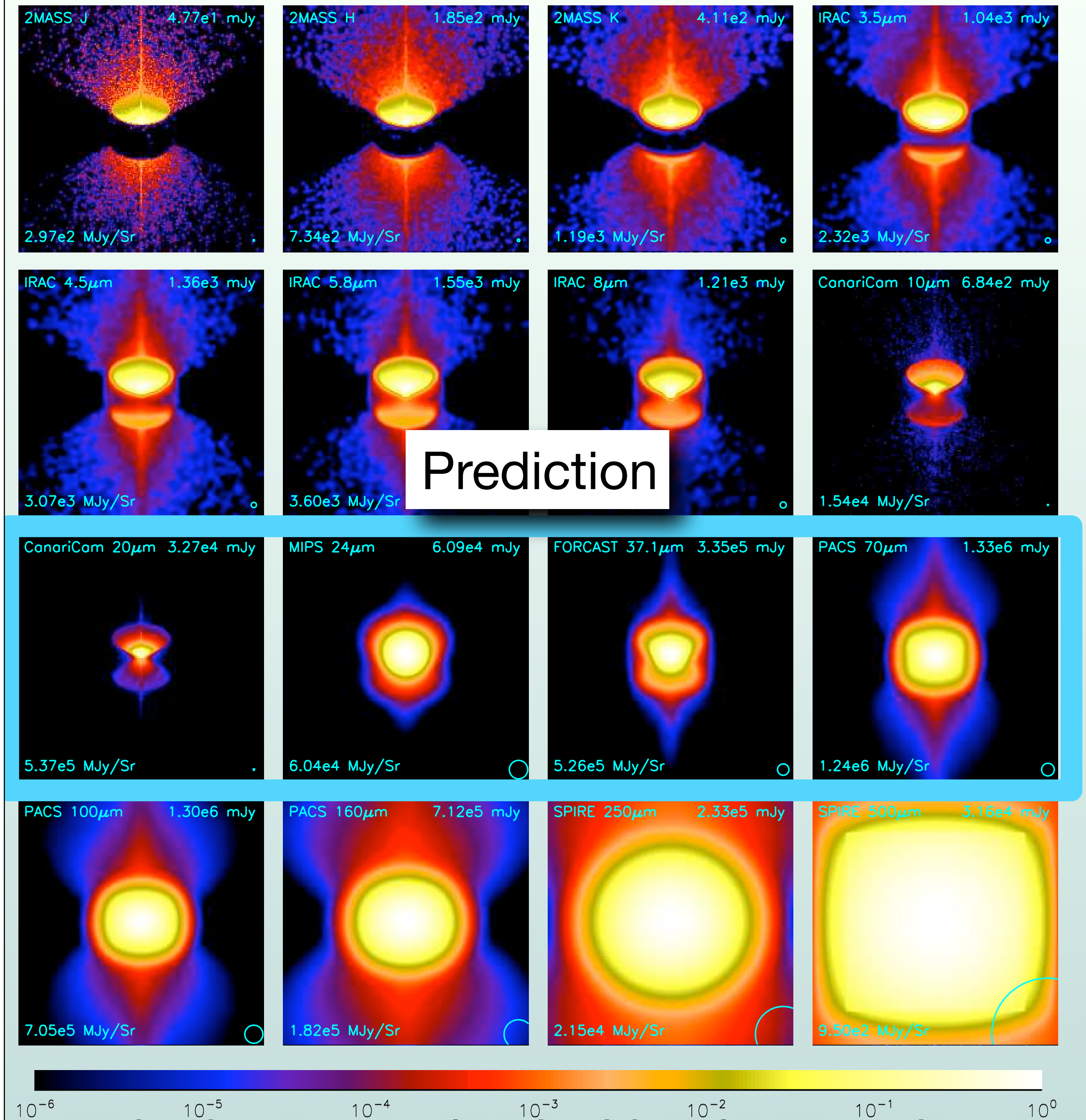
Indebetouw et al. (2006);

Molinari et al. (2008);

Zhang & Tan (2011); Zhang, Tan & McKee (2013); Zhang, Tan & Hosokawa (2014)

NIR to FIR morphologies

Zhang & Tan (2011); Zhang et al. (2013).



d=1kpc convolved with telescope beam

Rotation and outflow axis inclined at 60° to line of sight.

$\Sigma_{clump} = 1 \text{ g cm}^{-2}$

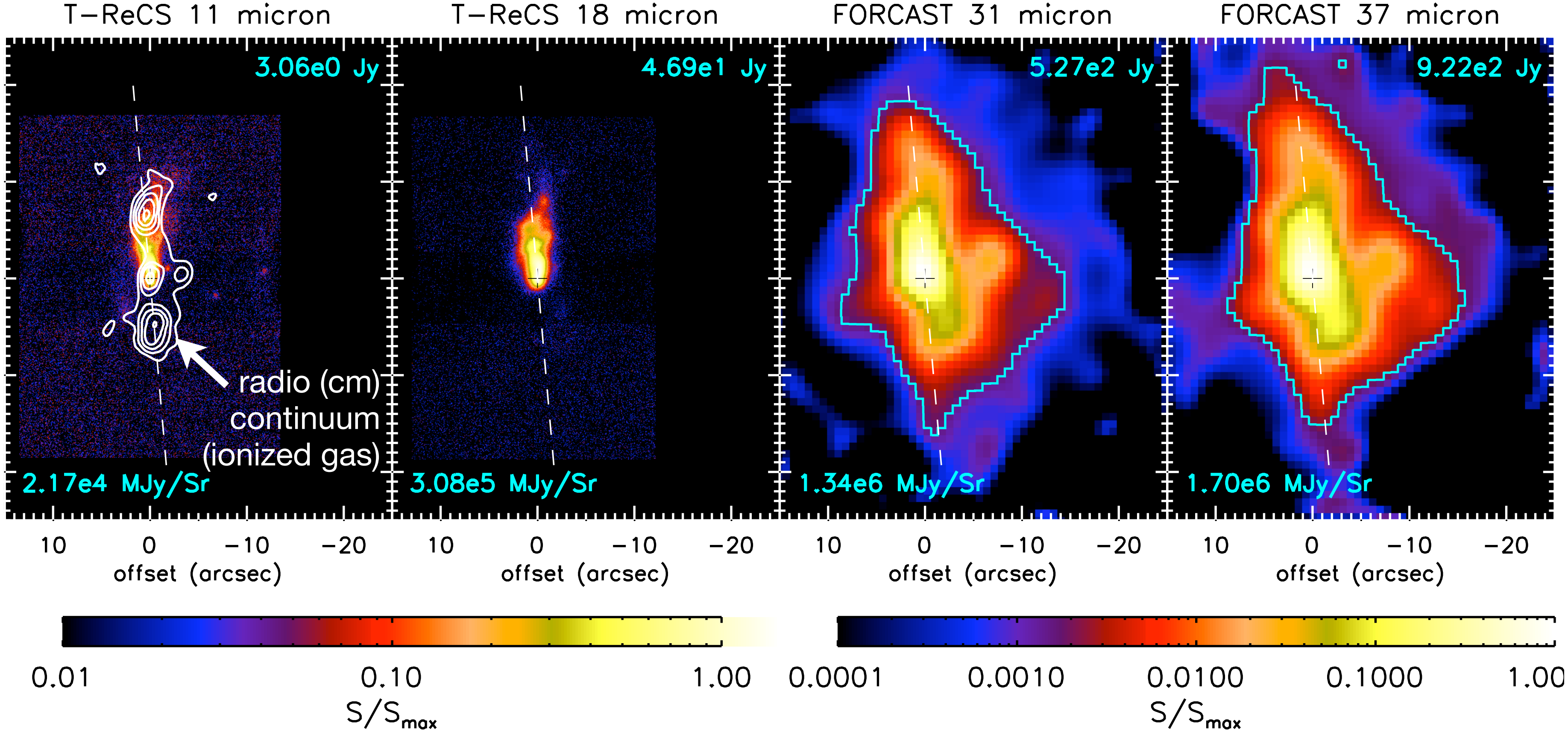
$M_{core} = 60 \, M_\odot$

$\beta = 0.02$

$m_* = 8 \, M_\odot$

$L_{bol} = 6\text{x}10^3 \, L_\odot$

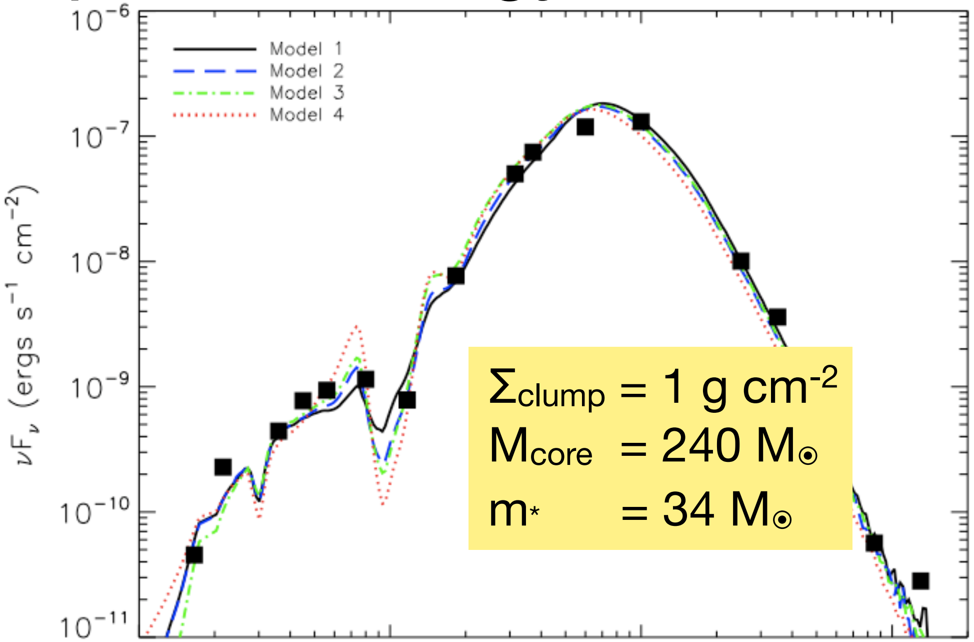
Massive Protostar G35.2N: d=2.3kpc; L~$10^5 L_\odot$



De Buizer (2006)

Zhang, Tan, De Buizer et al. (2013)

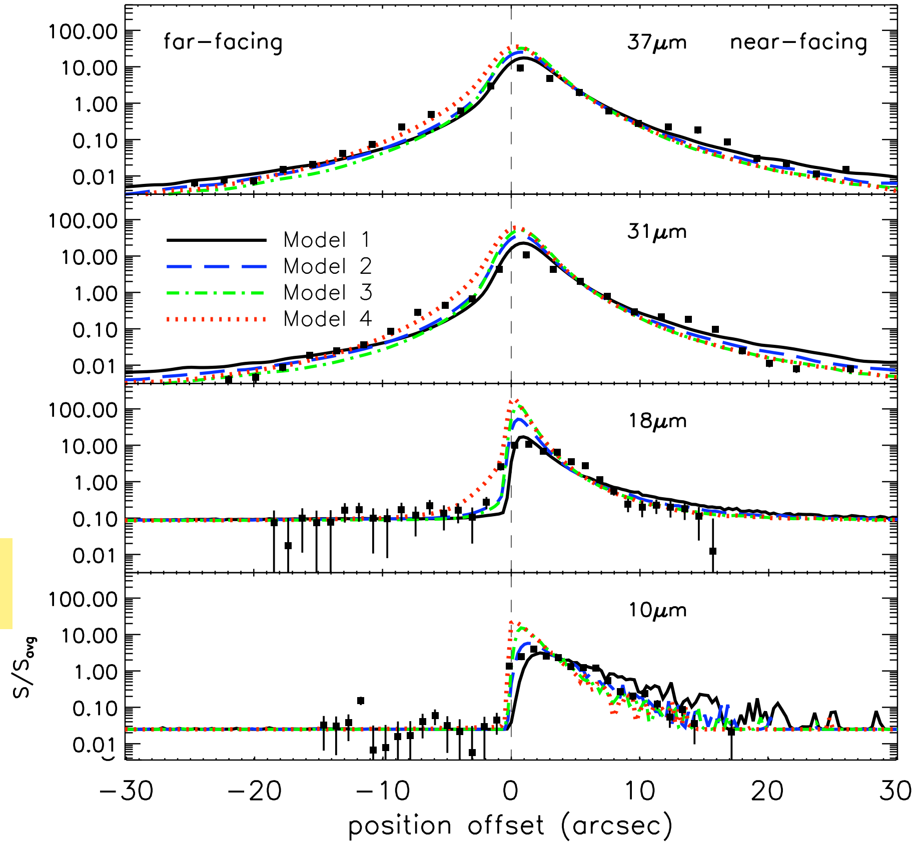
Spectral energy distribution

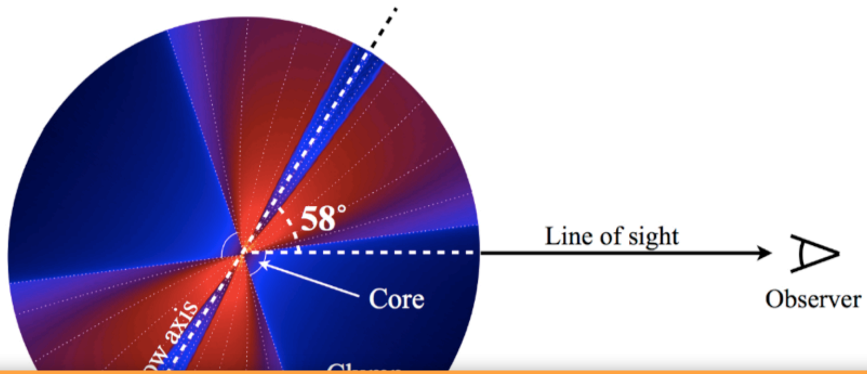


Σ_{clump} = 1 g cm^{-2}
M_{core} = 240 $M_\odot$
m_* = 34 $M_\odot$

MIR SED requires high Σ core/clump

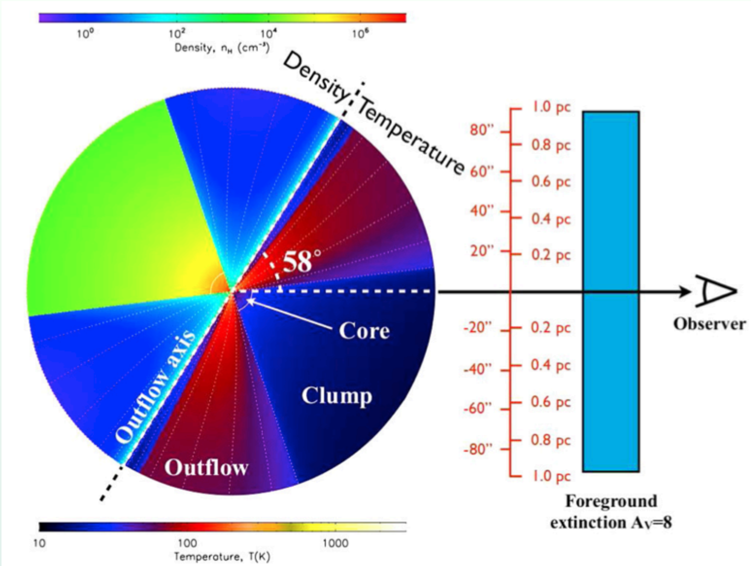
Flux profiles along outflow cavity axis

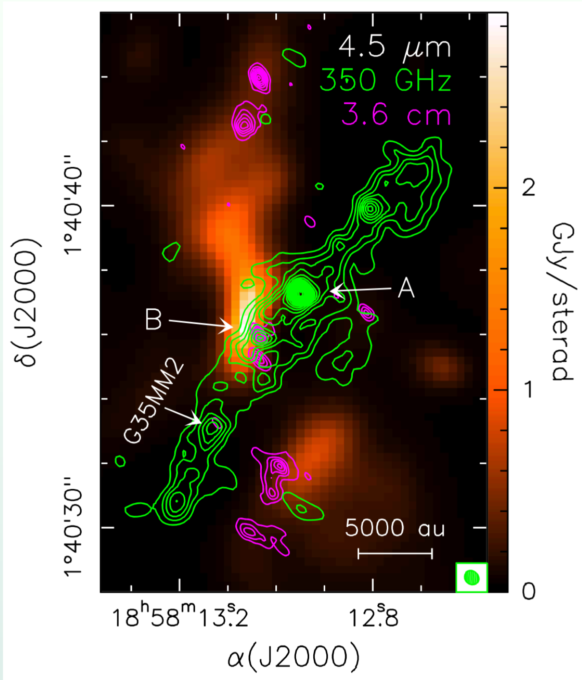




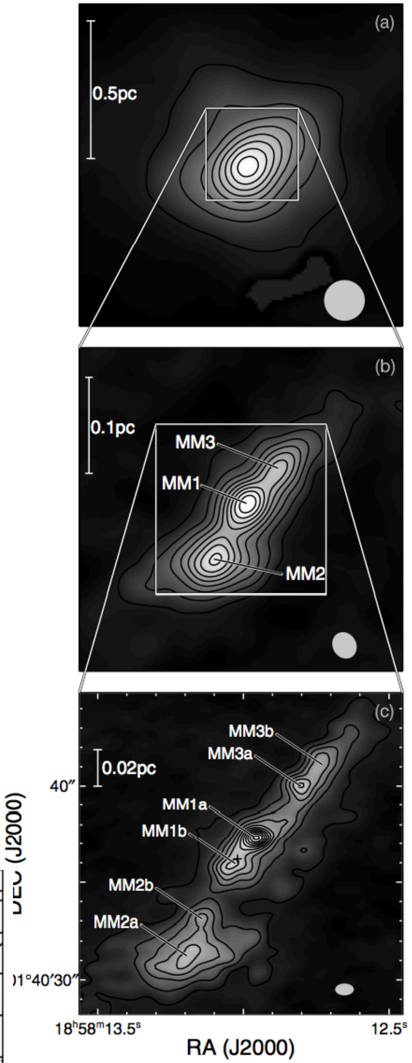
Simple, symmetric model provides good fit to SED & image intensity profiles: detailed constraints on how a massive star is forming.

L_{bol} ~ (0.66 - 2.2)×10^5 $L_\odot$
m_* ~ 20 - 34 $M_\odot$
M_{core} ~ 240 $M_\odot$
R_{core} ~ 0.1 - 0.2 pc
Σ_{cl} ~ 0.4 - 1 g/cm^2
θ_w ~ 35 - 51°; θ_{view} ~ 43 - 58°





Sanchez-Monge et al. (2013)



Qiu et al. (2013)

$L_{bol} \sim (0.66 - 2.2)\times10^5 L_\odot$

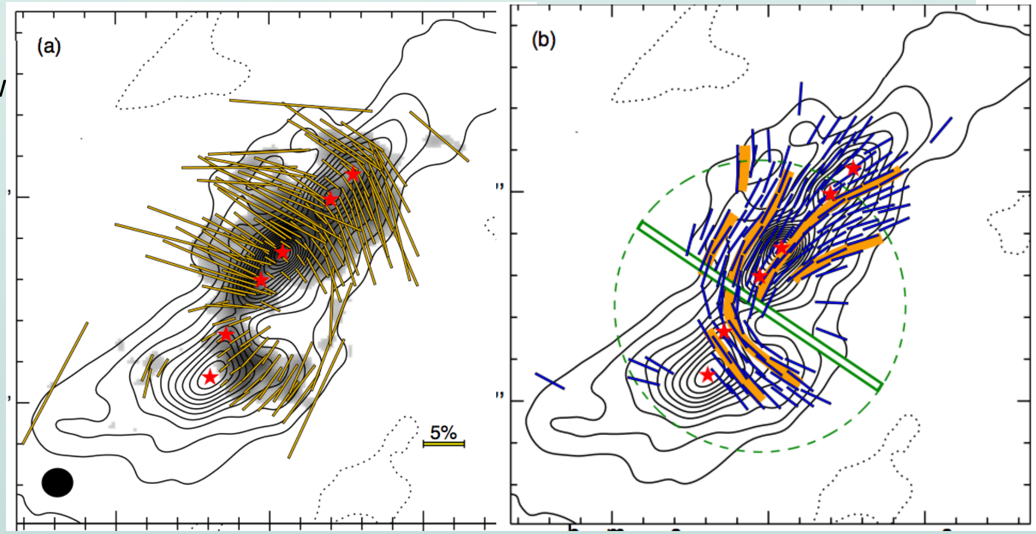
$m_* \sim 20 - 34\ M_\odot$

$M_{core} \sim 240\ M_\odot$

$R_{core} \sim 0.1 - 0.2$ pc

$\Sigma_{cl} \sim 0.4 - 1$ g/cm²

$\theta_w \sim 35 - 51^\circ$; θ_{view}



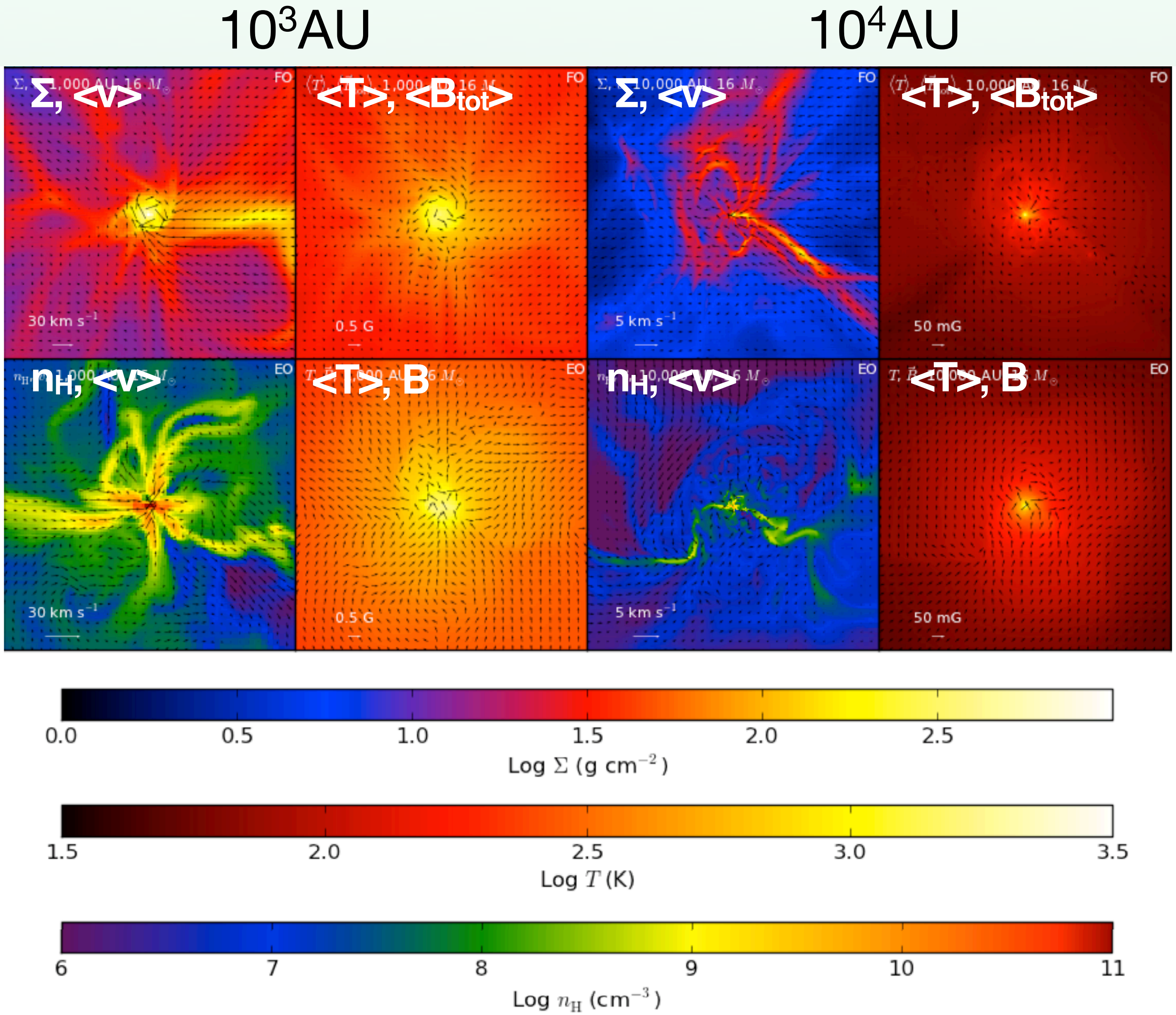
RMHD Simulation of Turbulent Core Accretion

Myers, McKee et al. 2013

$M_{core} = 300\ M_\odot \sim 2\ M_\Phi$

$\Sigma_{cl} = 2$ g cm^{-2}

$m_* = 16\ M_\odot$



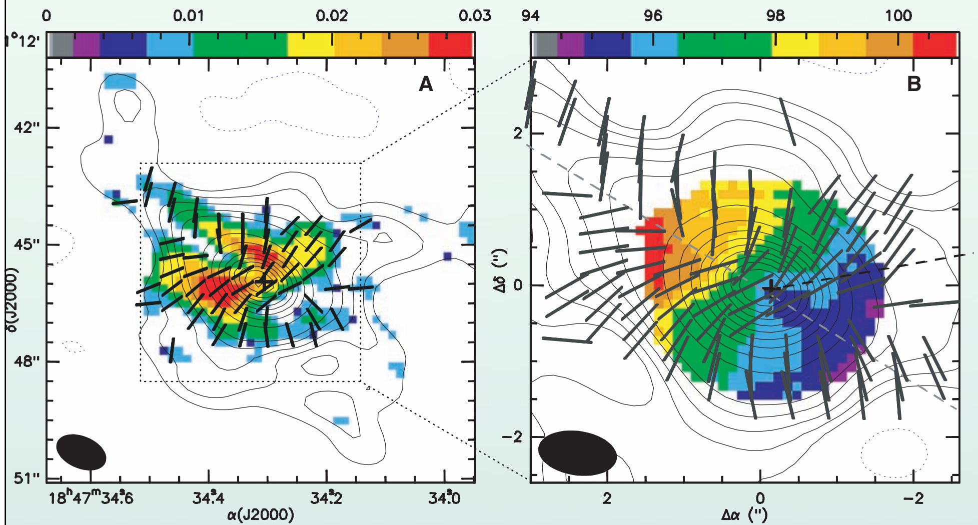
Face-on

Edge-on

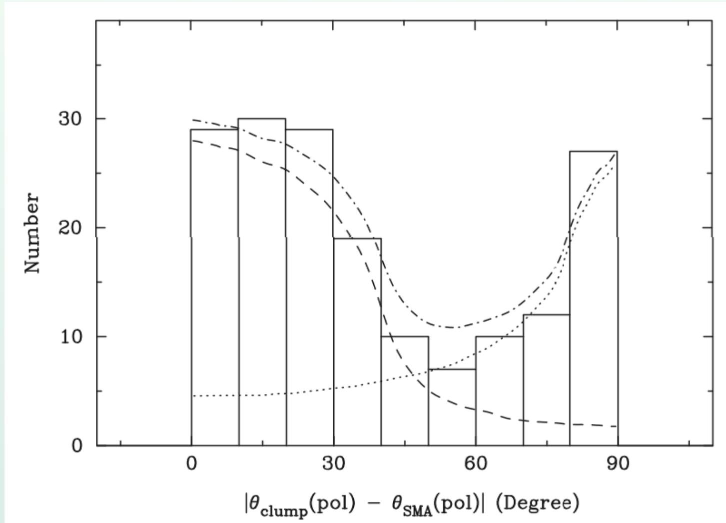
But no outflows

see also:
Seifried et al. (2014)

Strong B-fields in massive-star-forming cores



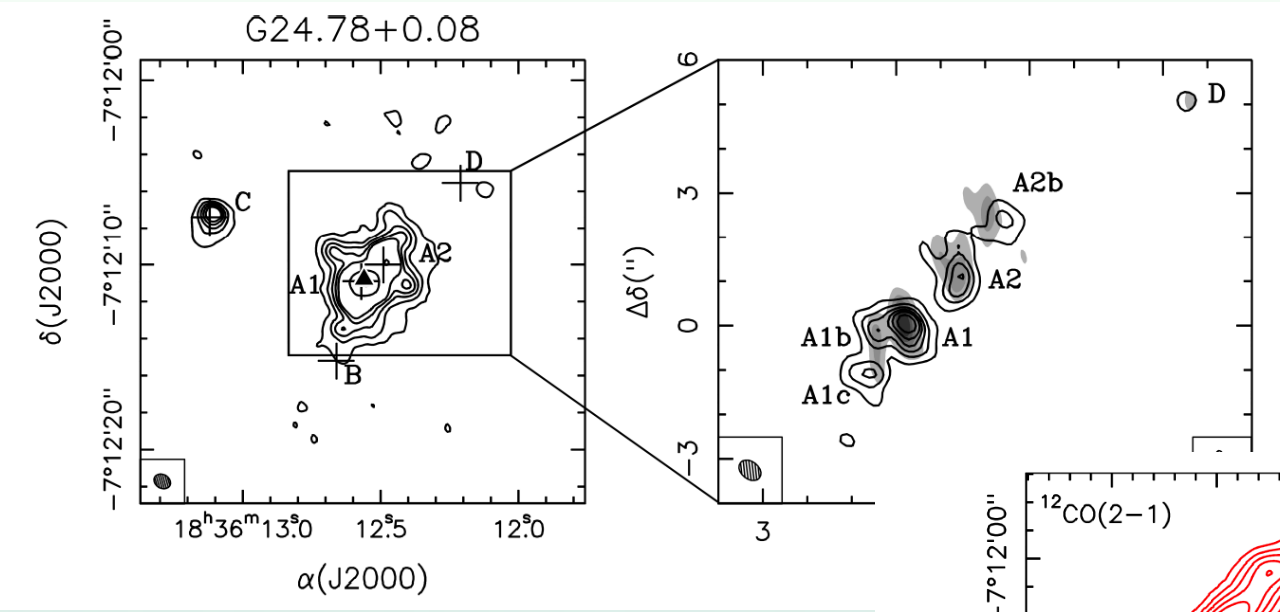
Girart et al. (2009)



Zhang, Q. et al. (2014)

May help regulate and order the collapse

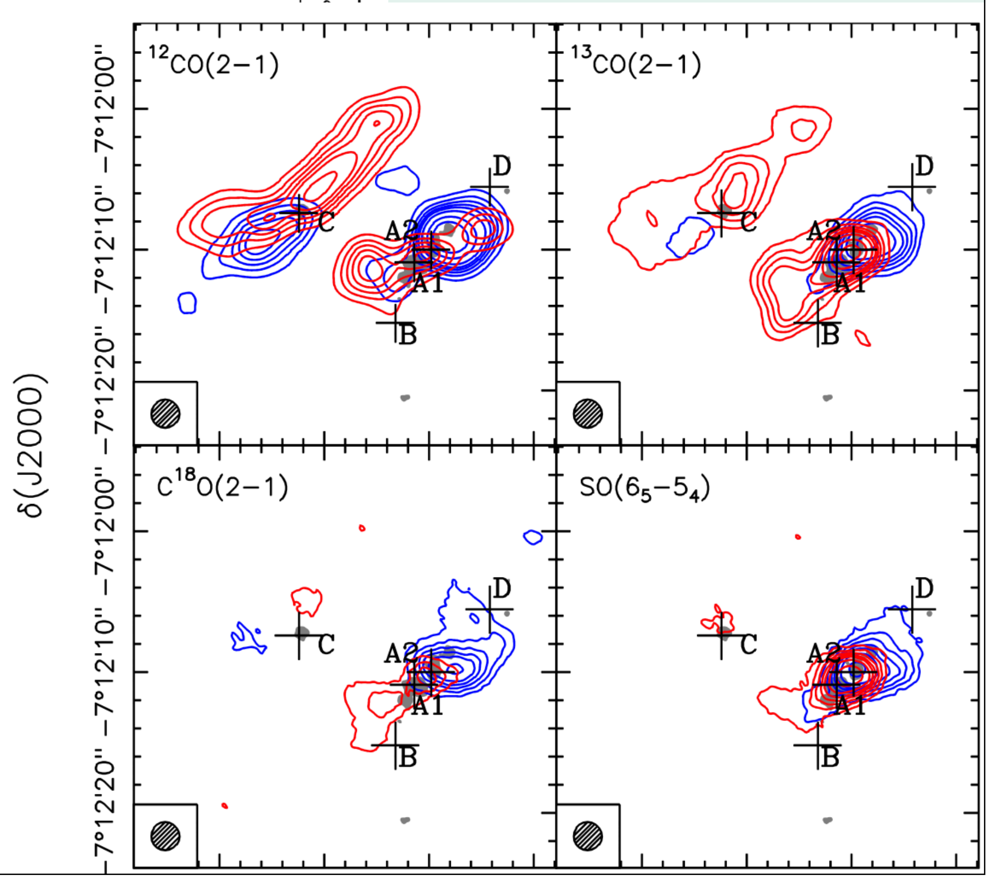
Aligned massive protostars?



G24.78+0.08
(Beltrán et al. 2004; 2011)

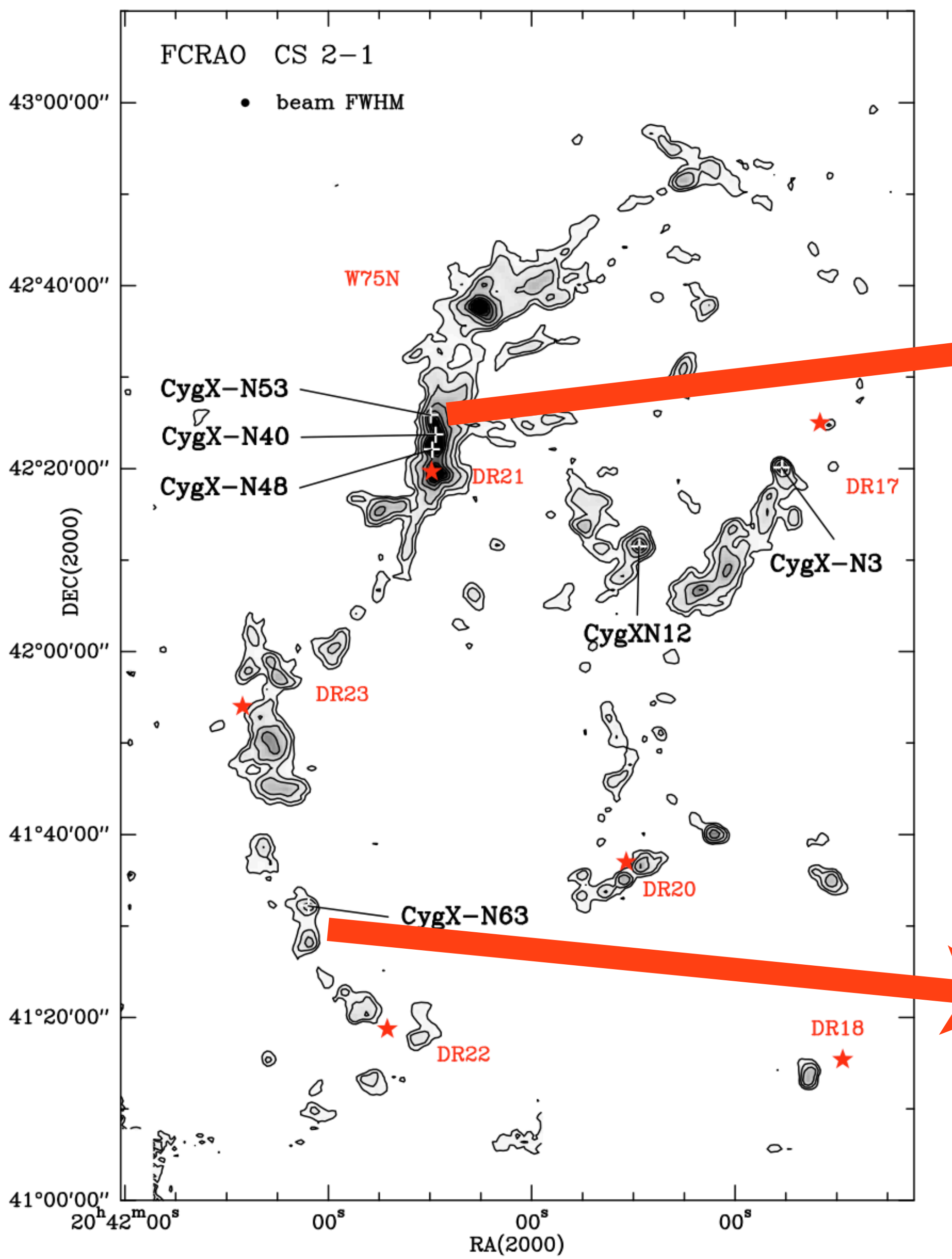
Formed from a filament/sheet, mediated by strong B-field?

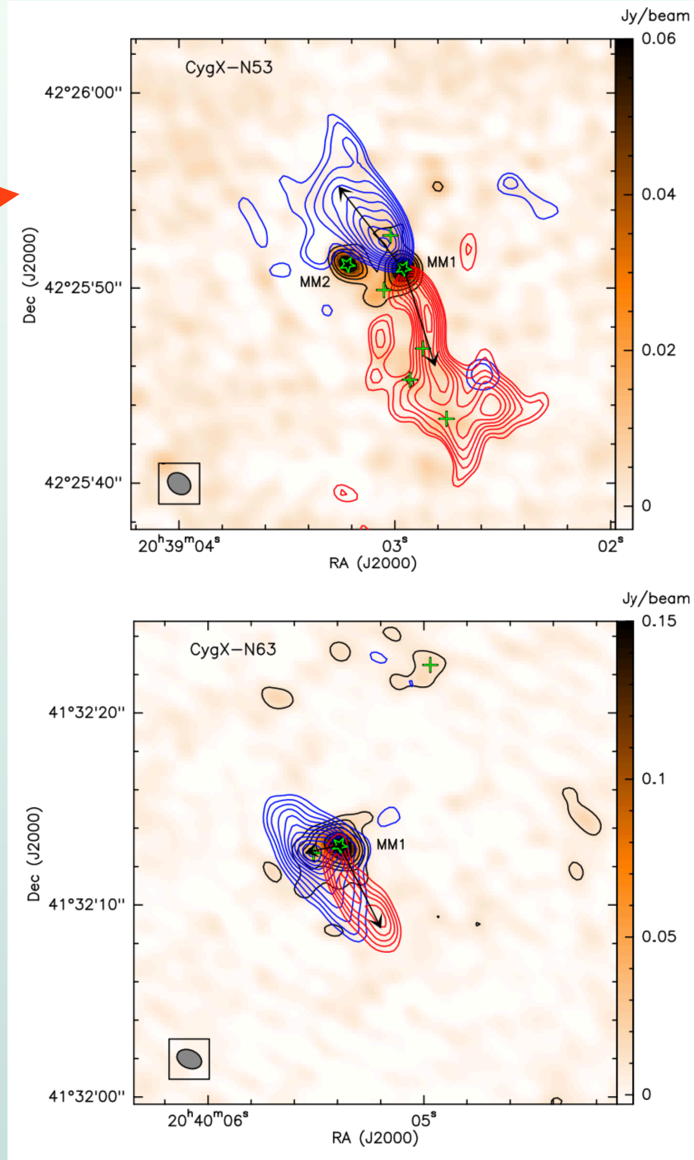
Can we find the filaments?

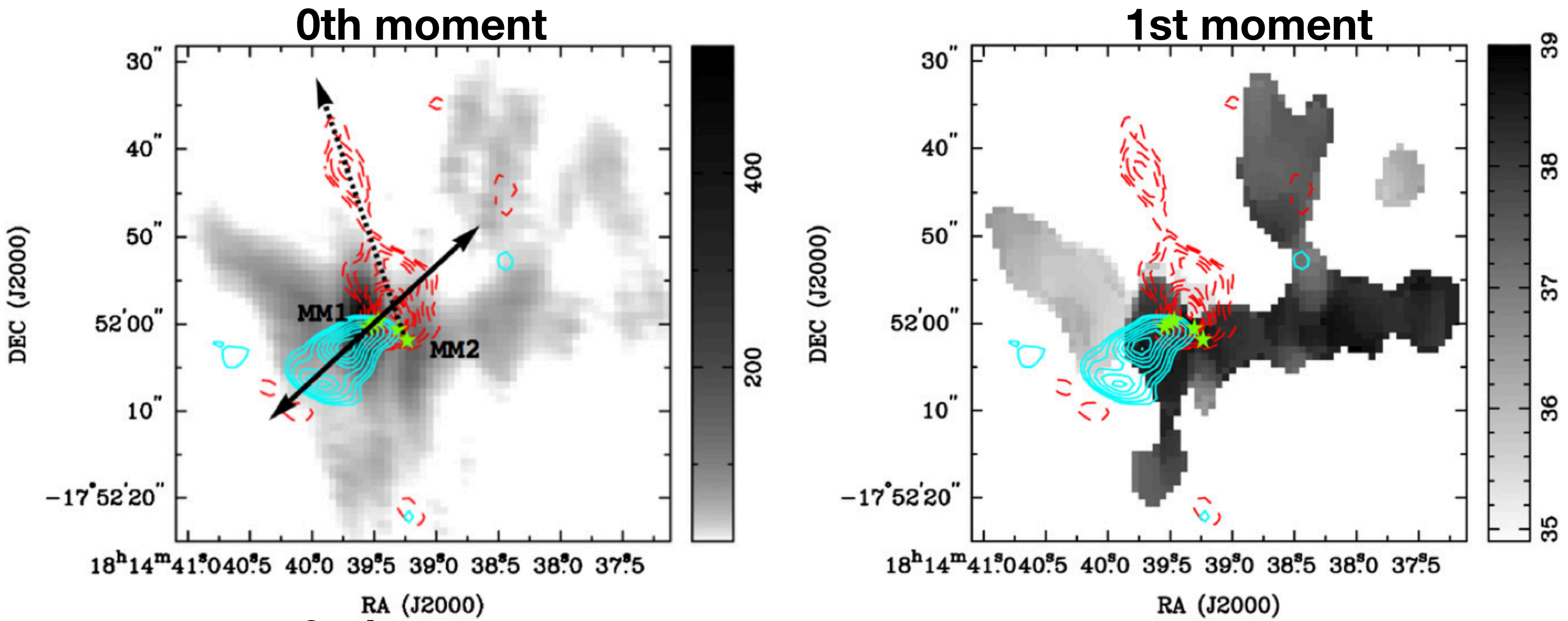


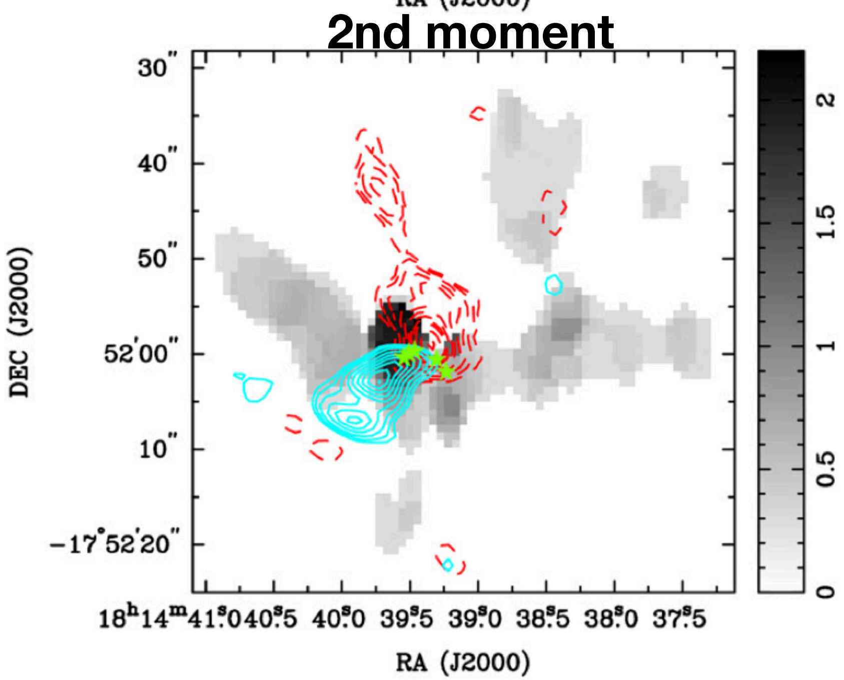
Cygnus X

Bontemps et al. (2010); Duarte-Cabral et al. (2013)









W33A

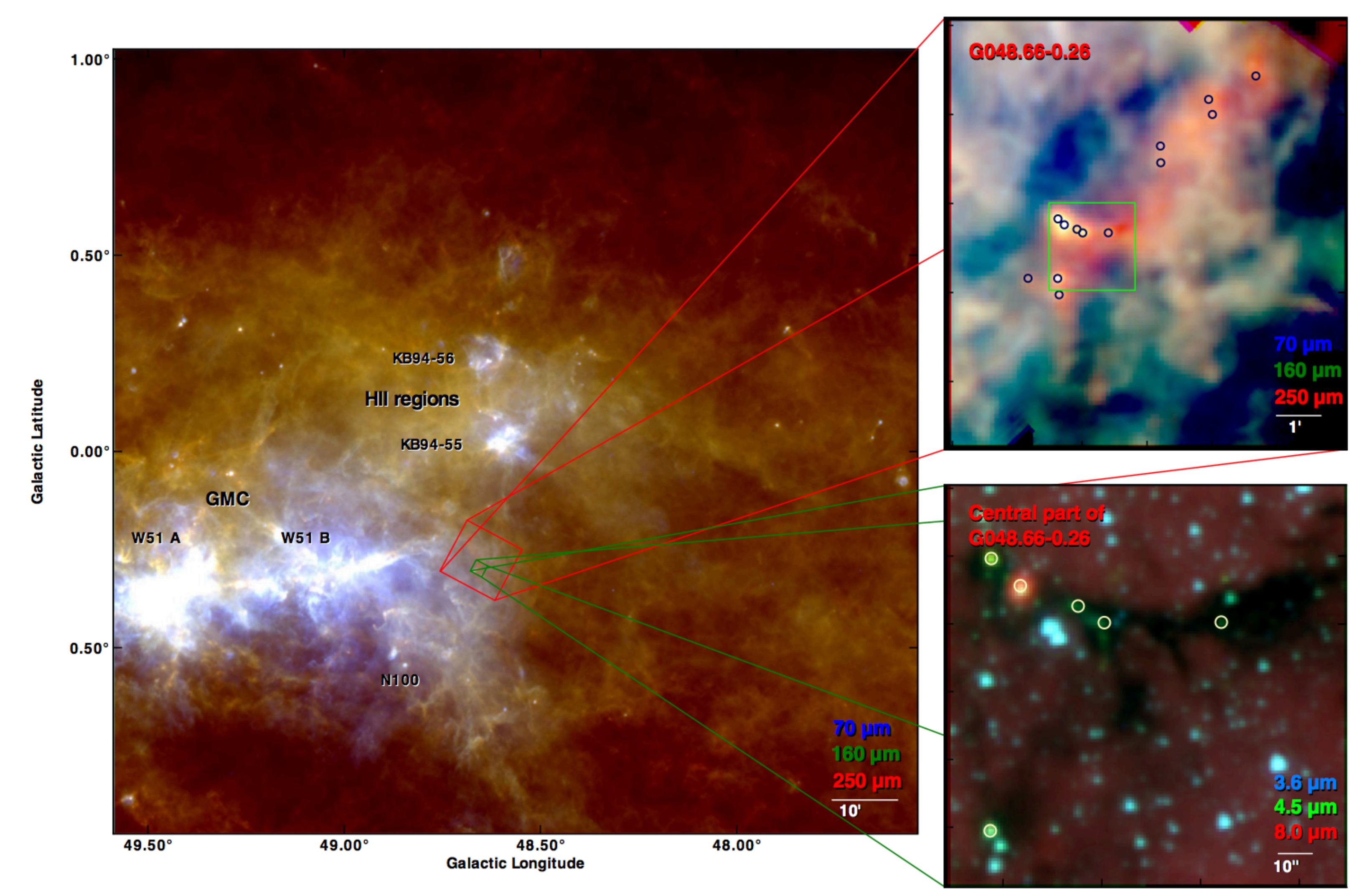
Galvan-Madrid et al. (2010)

NH_3(2,2)

CO(2-1) outflows

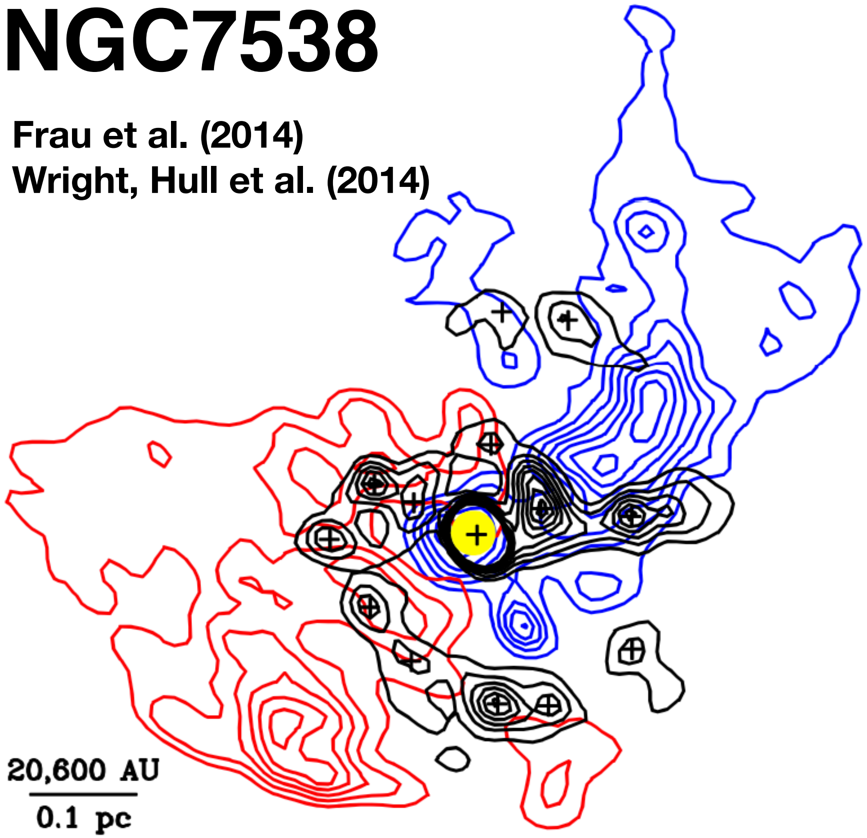
G48.66-0.26 **Relatively isolated site of massive star formation**

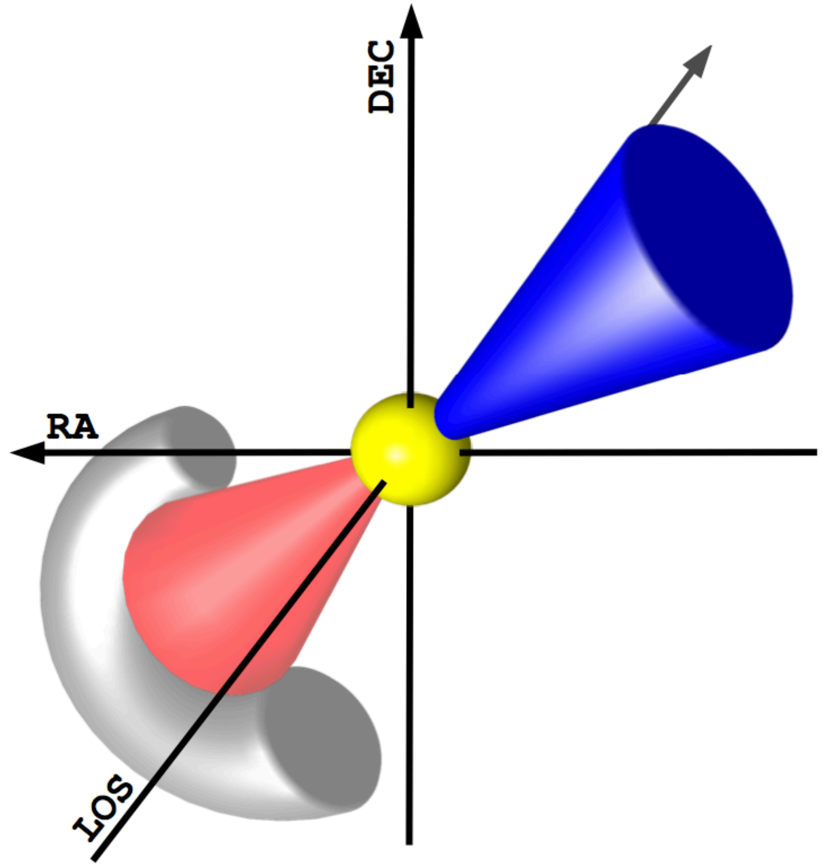
Pitann et al. (2013)



NGC7538

Frau et al. (2014)
Wright, Hull et al. (2014)



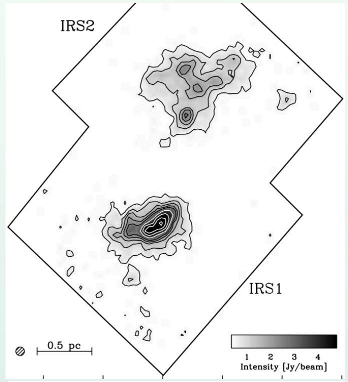


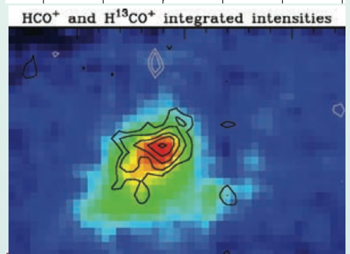
Filaments disturbed by outflow feedback?

Rate of Clump Collapse

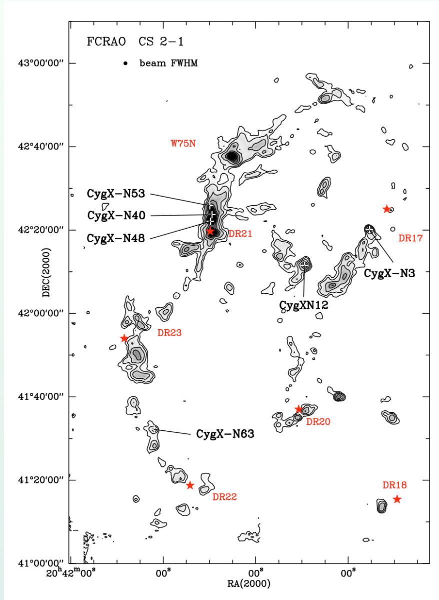
$$t_{infall} = M_{cl} / \dot{M}_{infall}$$

Clump	Reference	t_{infall} / t_{ff}
NGC 2264 IRS 1 NGC 2264 IRS 2	Williams & Garland (2002)	14 8.8
G286.21+0.17	Barnes et al. (2010)	6.7
SDC335	Peretto et al. (2013)	7.0 [25]





Conclusions



Clump scale:

Filaments help keep massive protostars isolated.

Infall appears to be slow compared to spherical free-fall collapse, perhaps due to filamentary geometry, B-fields, turbulence (including outflow feedback).

Core scale:

Depending on strength of turbulence vs. B-field, should lead to different degrees of internal structure (filaments).

Quasi-spherical massive starless core candidate found with ALMA in N_2D^+

Ordered, collimated, aligned outflows, rotating toroids, B-fields...