High-Mass Star Formation

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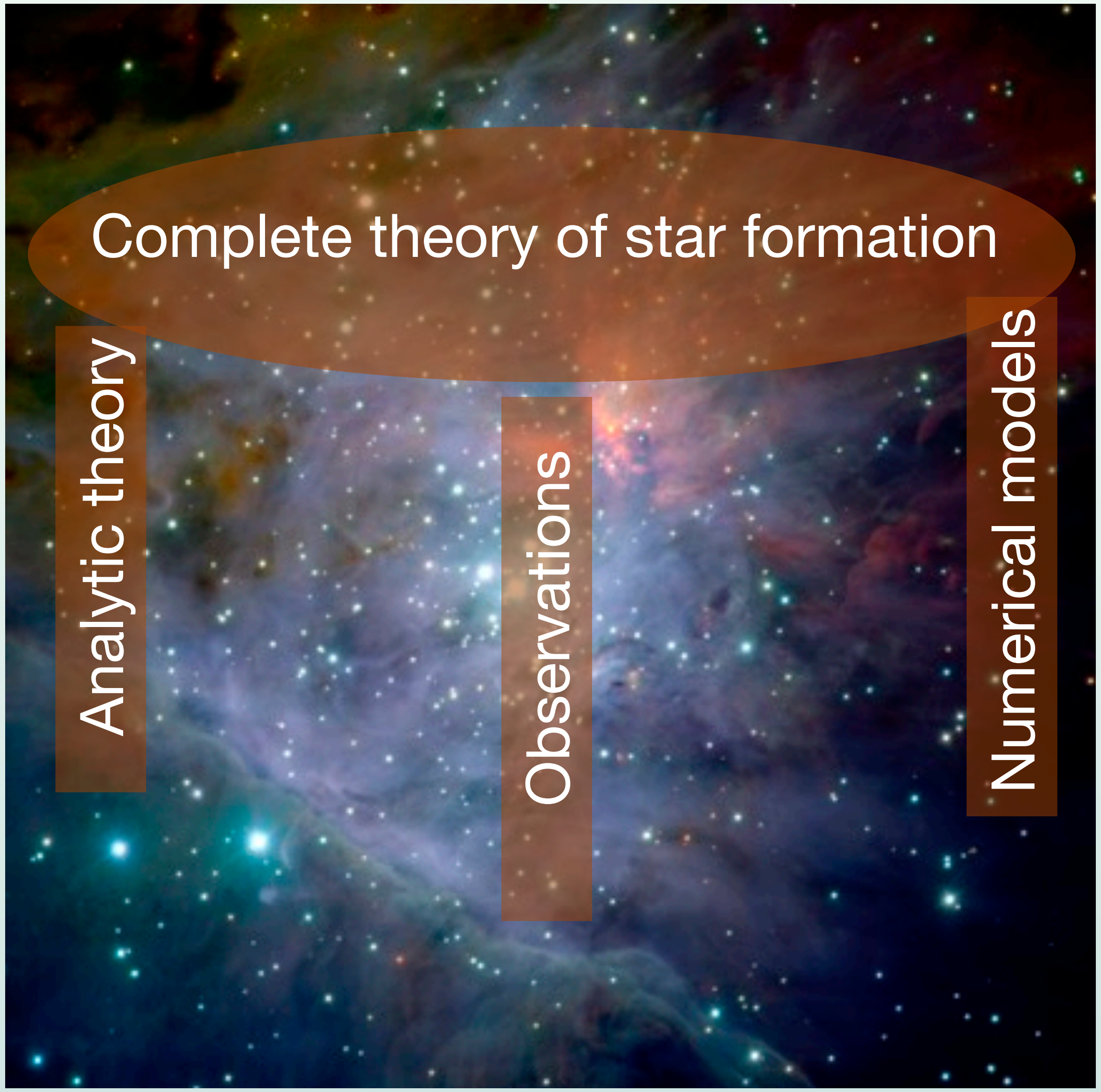
The Importance of Massive Stars

Zinnecker & Yorke (2007)
Tan et al. (2014)

The Physics of High-Mass Star Formation

A complicated, nonlinear process:

- 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.
- Chemical evolution of dust and gas.
- Fragmentation
- Stellar structure and evolution
- Feedback



Complete theory of star formation

Analytic theory

Observations

Numerical models

- Wide range of scales (~12 dex in space, time) and multidimensional.
- Uncertain/unconstrained initial conditions/boundary conditions.

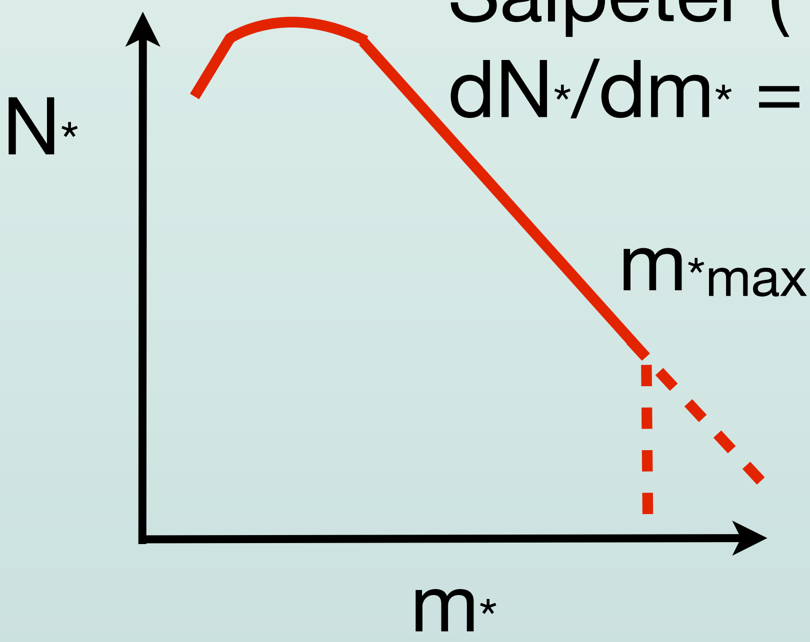
Notation for gas structures:
Core -> star or close binary
Clump -> star cluster

(Massive) Star Formation: Open Questions

- Causation: external triggering or spontaneous gravitational instability?
- Initial conditions: how close to equilibrium?
- Accretion mechanism: [turbulent/magnetic/thermal-pressure]-regulated fragmentation to form **cores** vs **competitive accretion / mergers**
- Timescale: fast or slow (# of dynamical times)?
- End result
  - Initial mass function (IMF)
  - Binary fraction and properties

Salpeter (1955)

$dN_*/dm_* = A\, m_*^{-2.35}$



How do these properties vary with environment?

Subgrid model of SF? Threshold n_{H*}? Efficiency ε_{ff}?

Outline

- Environments of Massive Star Formation
- Initial Conditions
- Timescales and Infall Rates
- Protostars - Accretion & Outflow
- Feedback
- Dynamical Interactions

The Environments of Massive Star Formation

Σ - M Diagram

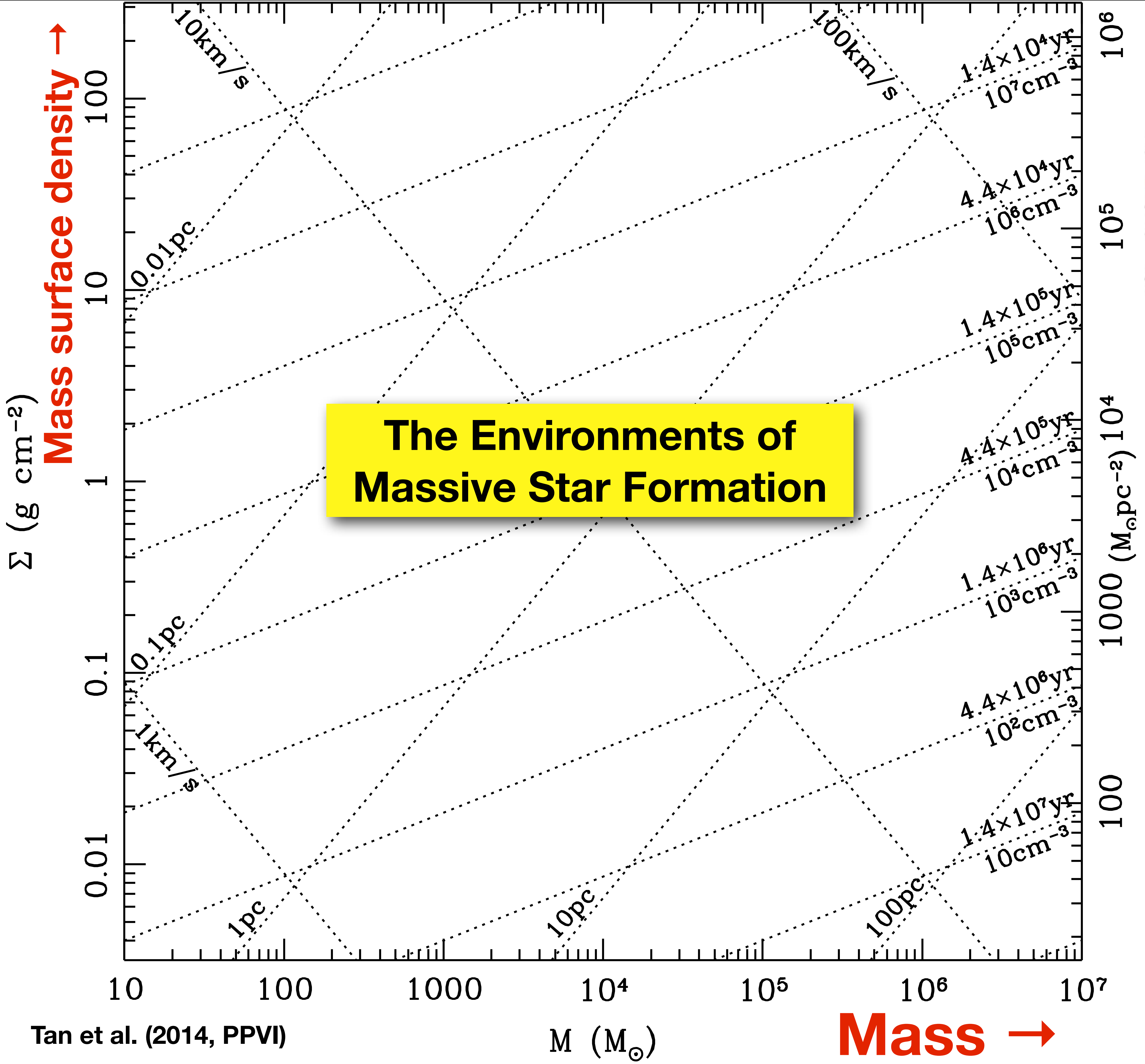
Physical Properties of Star-Forming Regions

$$\Sigma \equiv \frac{M}{\pi R^2}$$

$$\bar{P} \simeq G\Sigma^2$$

$$\bar{P}/k = 4.3 \times 10^8 \Sigma^2\, K\, cm^{-3}$$

$$t_{ff} = \left(\frac{3\pi}{32G\rho}\right)^{1/2}$$



Tan et al. (2014, PPVI)

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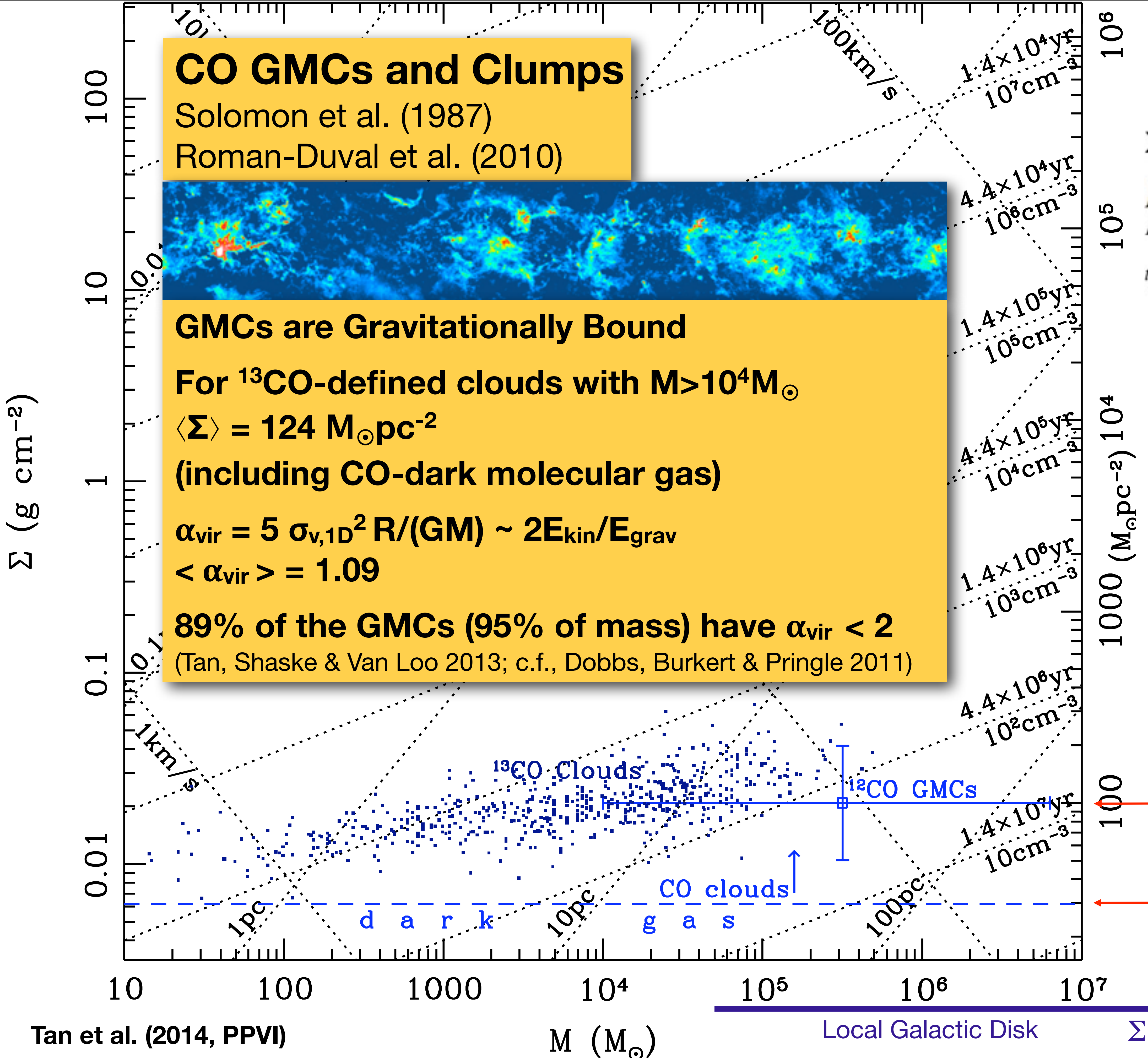


CO GMCs and Clumps

Solomon et al. (1987)

Roman-Duval et al. (2010)

GMCs are Gravitationally Bound

For ^{13}CO-defined clouds with M>10^4M$_\odot$

$\langle\Sigma\rangle$ = 124 M$_\odot$pc^{-2}

(including CO-dark molecular gas)

$\alpha_{vir} = 5\, \sigma_{v,1D}^2\, R/(GM) \sim 2E_{kin}/E_{grav}$

$< \alpha_{vir} > = 1.09$

89% of the GMCs (95% of mass) have $\alpha_{vir} < 2$

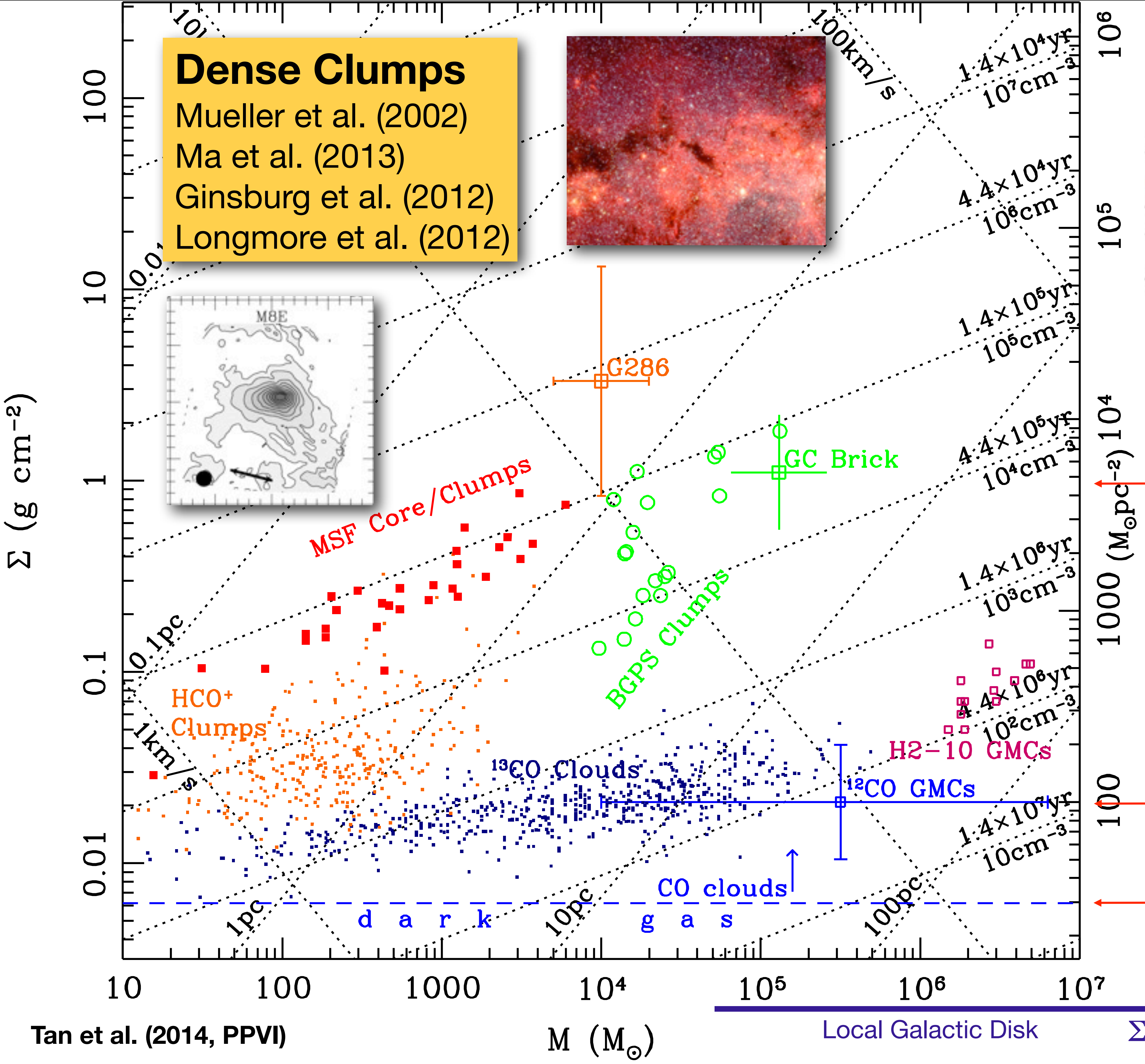
(Tan, Shaske & Van Loo 2013; c.f., Dobbs, Burkert & Pringle 2011)

A_V=7.5
$A_{8\mu m}$=0.30
N_H=1.6x10^{22}cm^{-2}
Σ=180 M$_\odot$ pc^{-2}

A_V=1.4
N_H=3.0x10^{21}cm^{-2}
Σ=34 M$_\odot$ pc^{-2}

Local Galactic Disk Σ~10 M$_\odot$ pc^{-2}

Tan et al. (2014, PPVI)



Dense Clumps

Mueller et al. (2002)
Ma et al. (2013)
Ginsburg et al. (2012)
Longmore et al. (2012)

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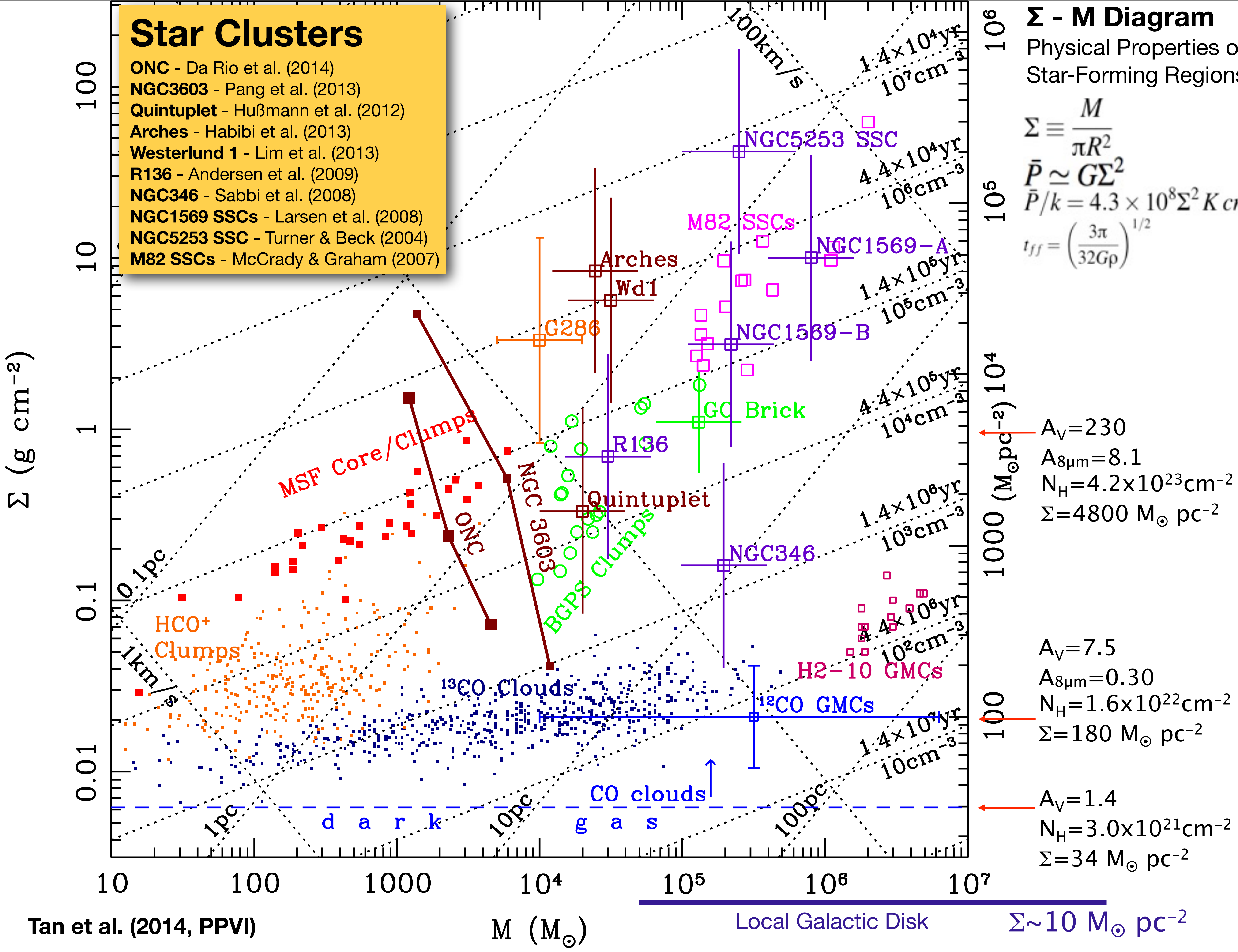

Star Clusters

ONC - Da Rio et al. (2014)
NGC3603 - Pang et al. (2013)
Quintuplet - Hußmann et al. (2012)
Arches - Habibi et al. (2013)
Westerlund 1 - Lim et al. (2013)
R136 - Andersen et al. (2009)
NGC346 - Sabbi et al. (2008)
NGC1569 SSCs - Larsen et al. (2008)
NGC5253 SSC - Turner & Beck (2004)
M82 SSCs - McCrady & Graham (2007)

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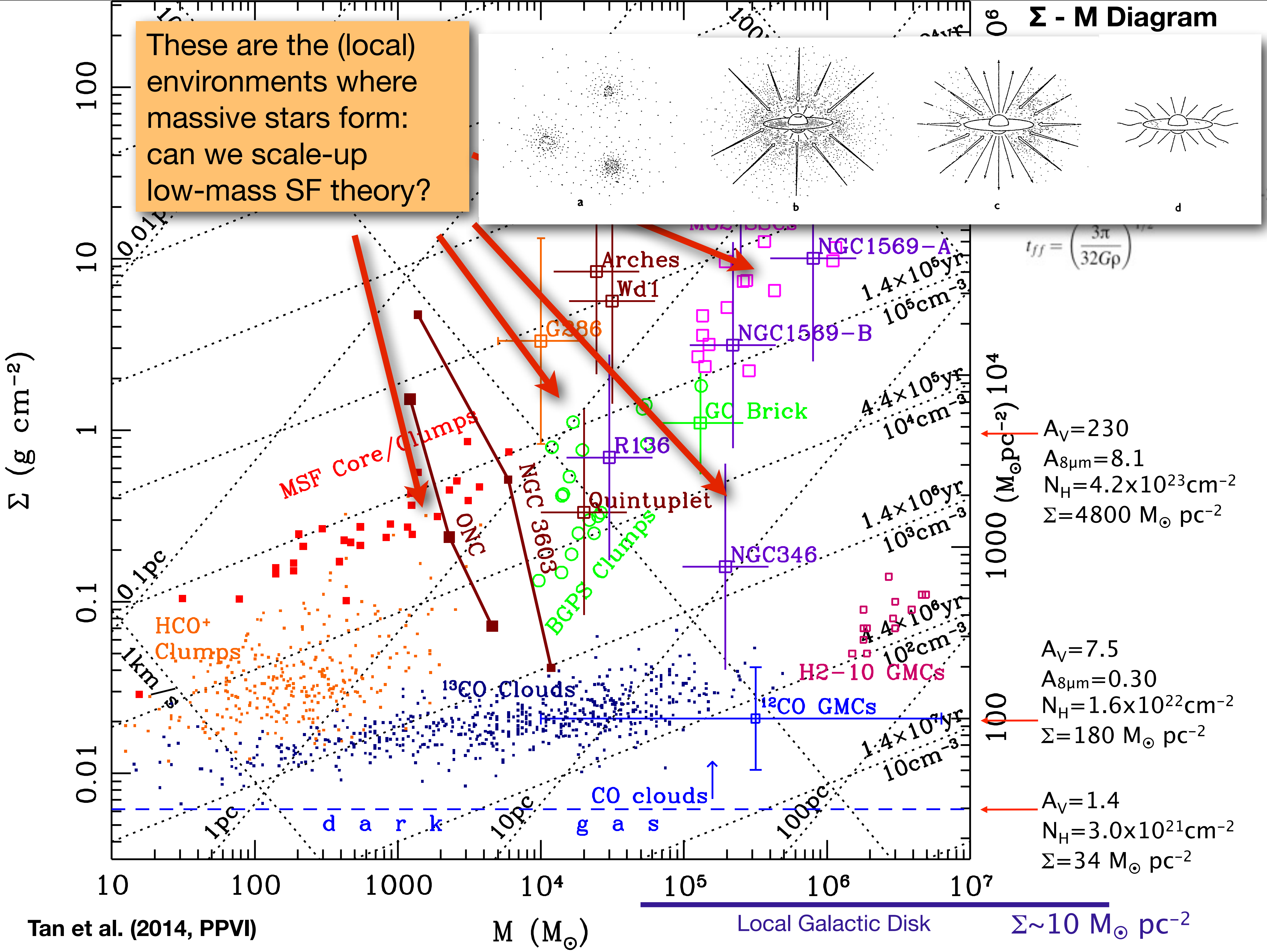
Tan et al. (2014, PPVI)

Local Galactic Disk

Σ~10 $M_\odot$ pc^{-2}

Σ - M Diagram

These are the (local) environments where massive stars form: can we scale-up low-mass SF theory?



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Local Galactic Disk $\Sigma\sim10$ M$_\odot$ pc^{-2}

Tan et al. (2014, PPVI)

Massive Star Formation Theories

Core Accretion:

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

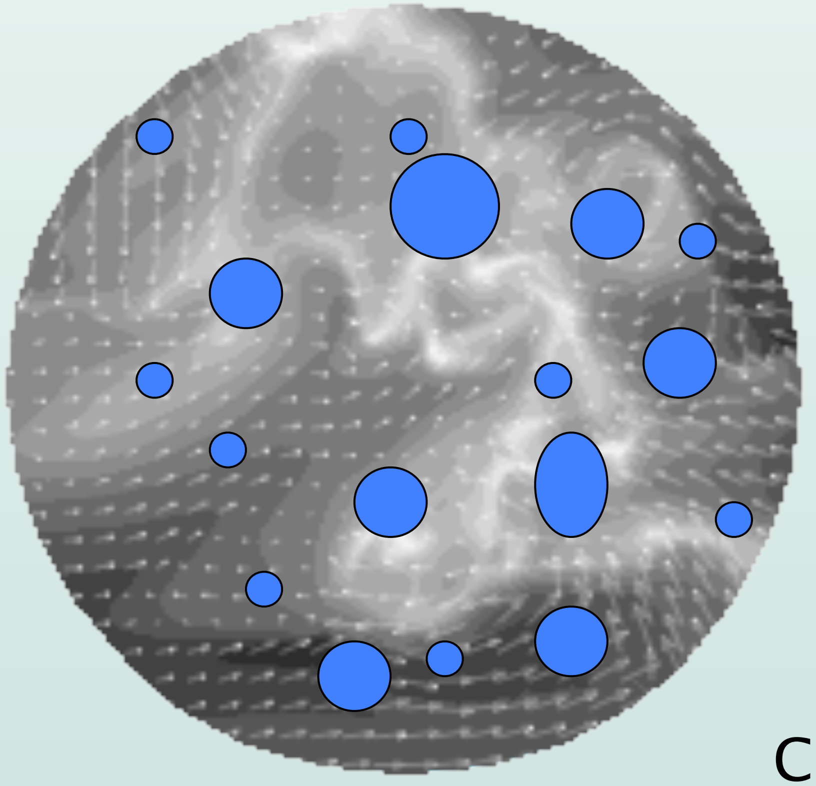
(e.g. Myers & Fuller 1992; Caselli & Myers 1995; McLaughlin & Pudritz 1997; Osorio+ 1999; Nakano+ 2000; Behrend & Maeder 2001)

Turbulent Core Model:

(McKee & Tan 2002, 2003)

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

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



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

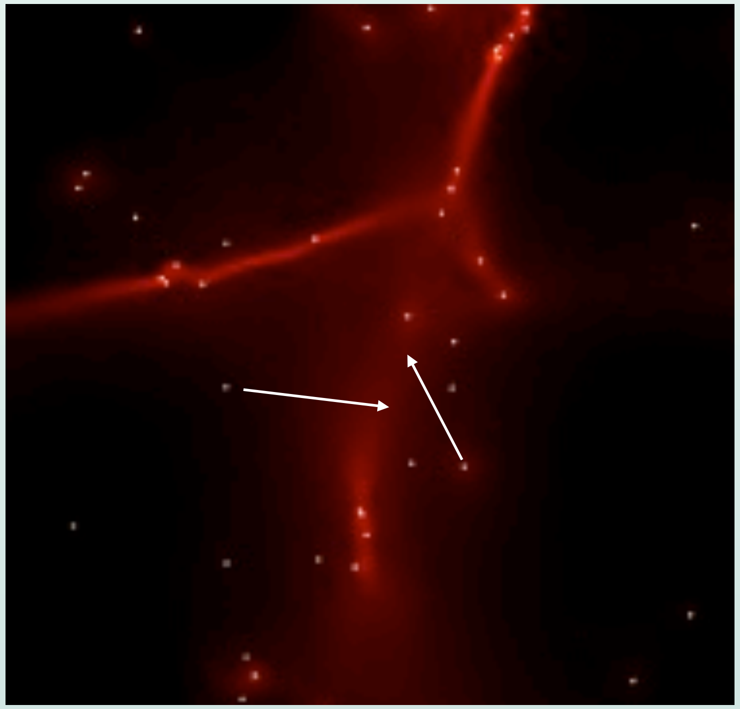
Cores form from this turbulent/magnetized medium: at any instant there is a small mass fraction in cores. These cores collapse quickly to feed a central disk to form individual stars or binaries.

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

Competitive (Clump-fed) Accretion:

(Bonnell, Clarke, Bate, Pringle 2001;
Bonnell, Vine, & Bate 2004;
Schmeja & Klessen 2004;
Wang, Li, Abel, Nakamura 2010; ...)

Stars, especially massive stars, gain most mass by Bondi-Hoyle accretion of ambient clump gas



Originally based on simulations including only thermal pressure.

Massive stars form on the timescale of the star cluster, with relatively low accretion rates.

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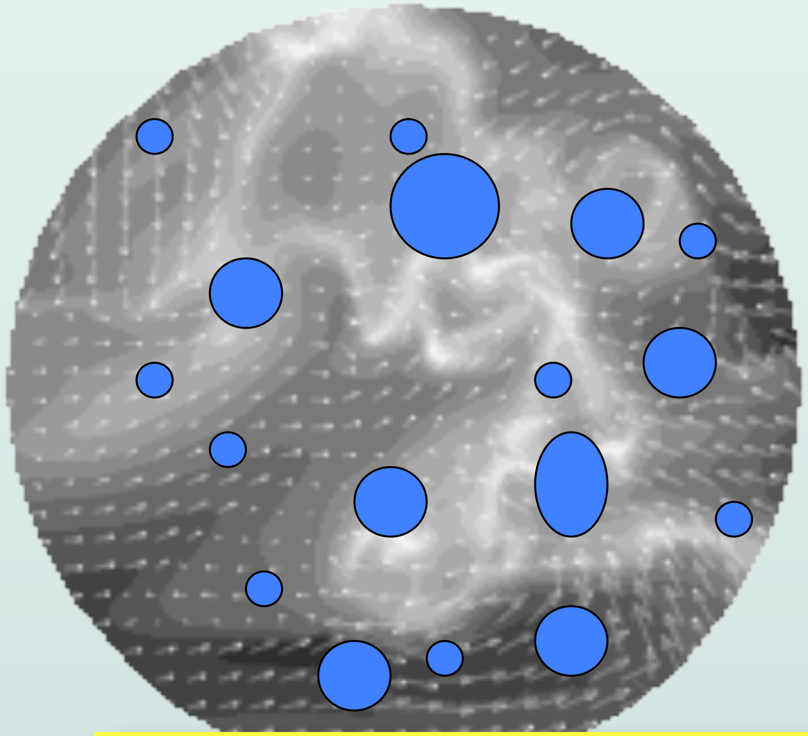

$$\bar{P} = \phi_P G \Sigma^2$$

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

SOFIA Result on Clump Infall

$v_{infall} \sim 0.1\ v_{ff}$

(Wyrowski et al. 2016)

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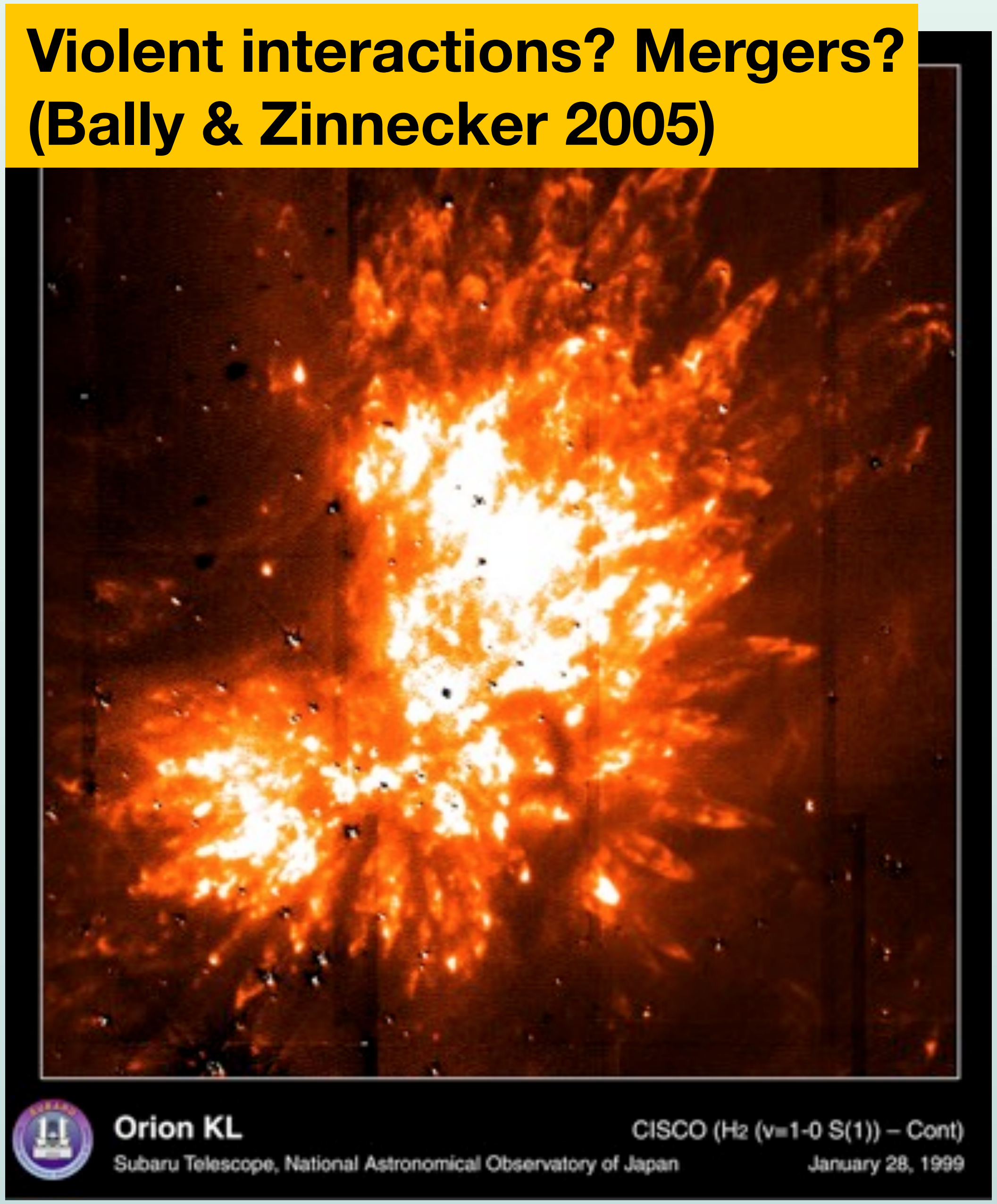
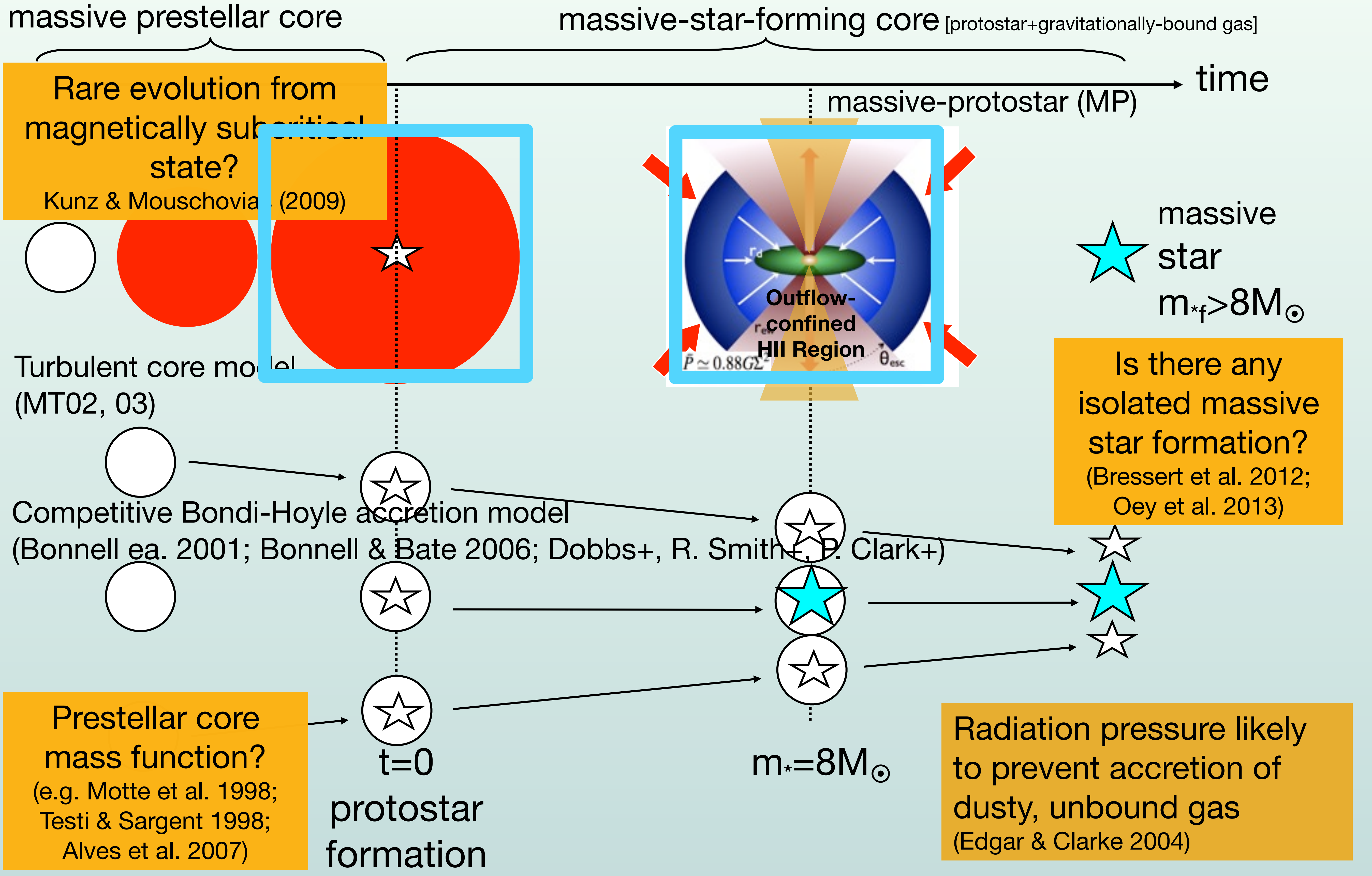
Violent interactions? Mergers? (Bally & Zinnecker 2005)



Schematic Differences Between Massive Star Formation Theories



Rare evolution from magnetically subcritical state?
Kunz & Mouschovia (2009)

Is there any isolated massive star formation?
(Bressert et al. 2012; Oey et al. 2013)

Prestellar core mass function?
(e.g. Motte et al. 1998; Testi & Sargent 1998; Alves et al. 2007)

Radiation pressure likely to prevent accretion of dusty, unbound gas
(Edgar & Clarke 2004)

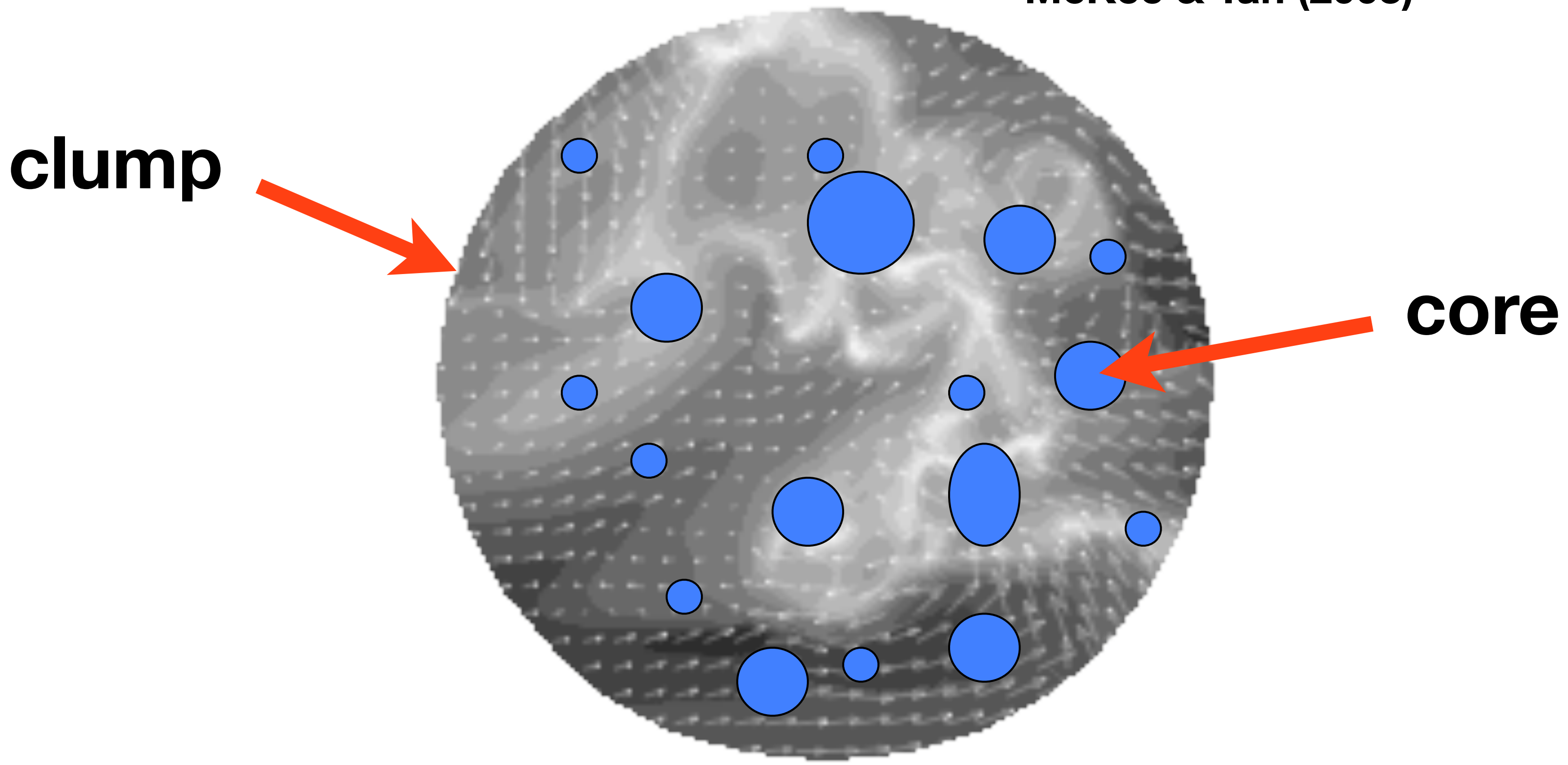
The Initial Conditions of Massive Star Formation

Do massive starless cores exist?
Are they close to virial equilibrium?

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

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

McKee & Tan (2003)



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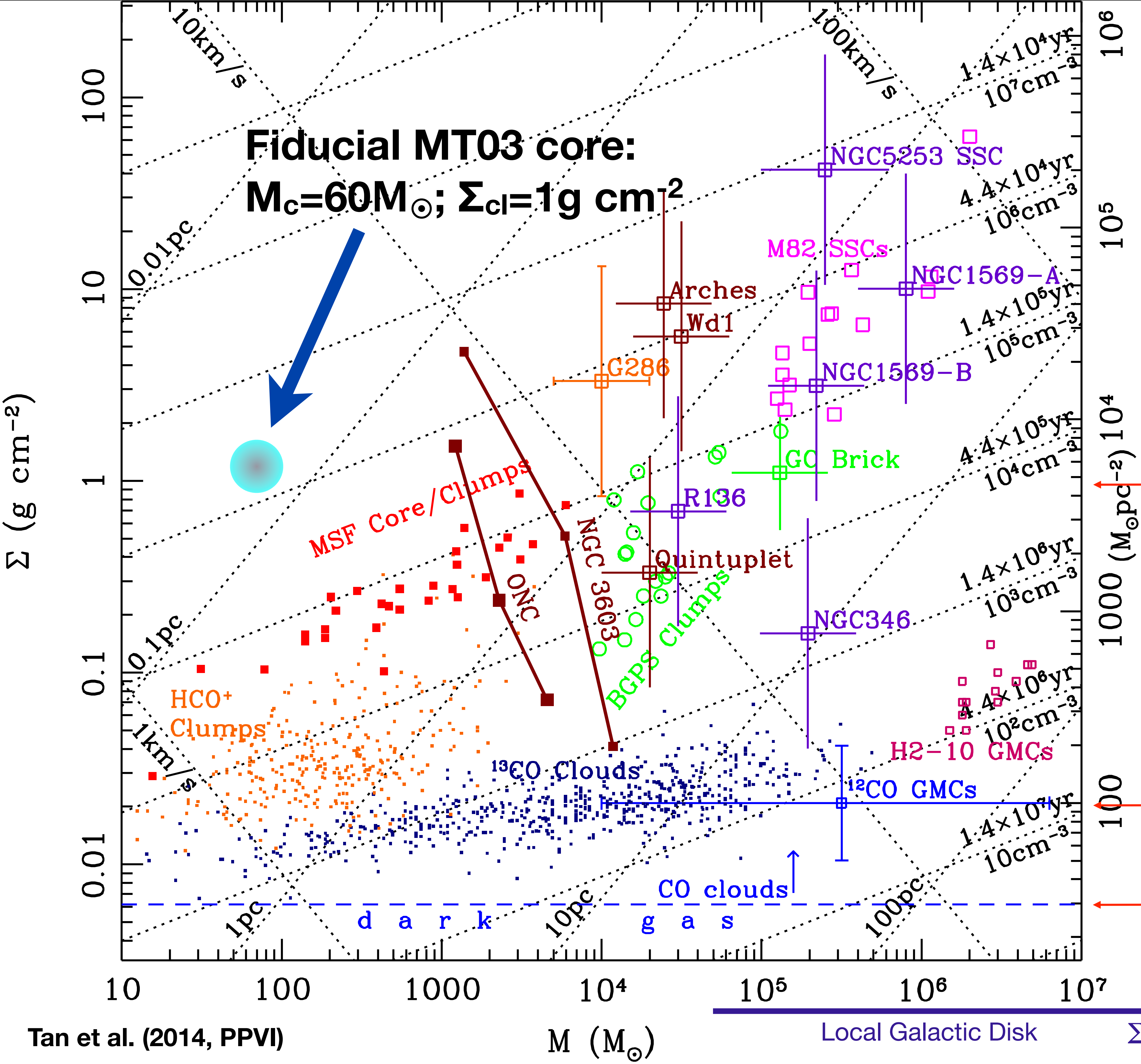

Fiducial MT03 core:
M_c=60$M_\odot$; Σ_{cl}=1g cm^{-2}

A_V=230
$A_{8\mu m}$=8.1
N_H=4.2x10^{23}cm^{-2}
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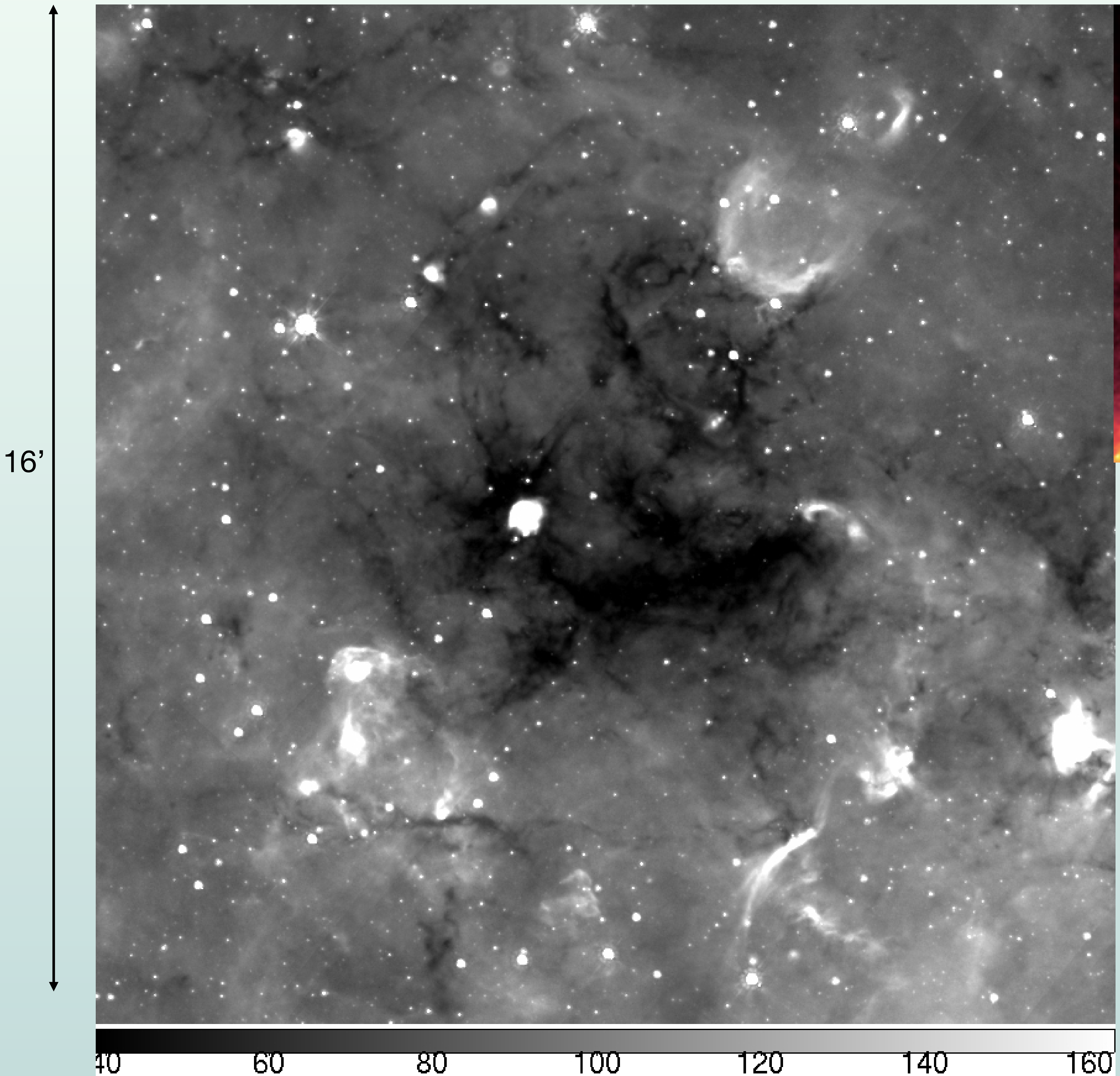
Local Galactic Disk Σ~10 $M_\odot$ pc^{-2}

Tan et al. (2014, PPVI)

Mid-IR Extinction Mapping of Infrared Dark Clouds

(Butler & Tan 2009, 2012; see also Peretto & Fuller 2009; Ragan et al. 2009; Battersby et al. 2010)

G28.37+00.07




Spitzer IRAC 8μm (GLIMPSE)

(Churchwell et al. 2009)

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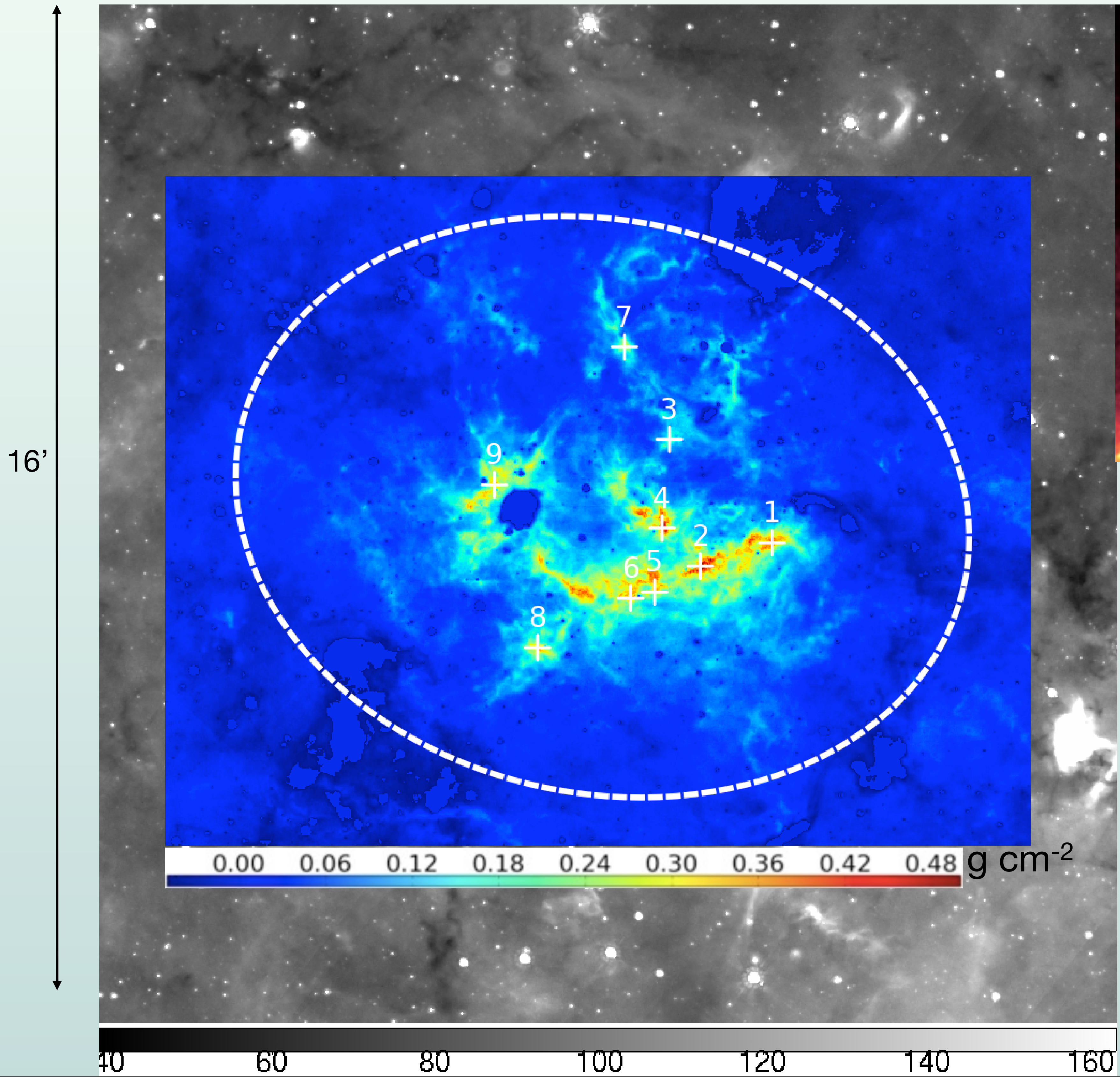


Median filter for background around IRDC; interpolate for region behind the IRDC

Correct for foreground

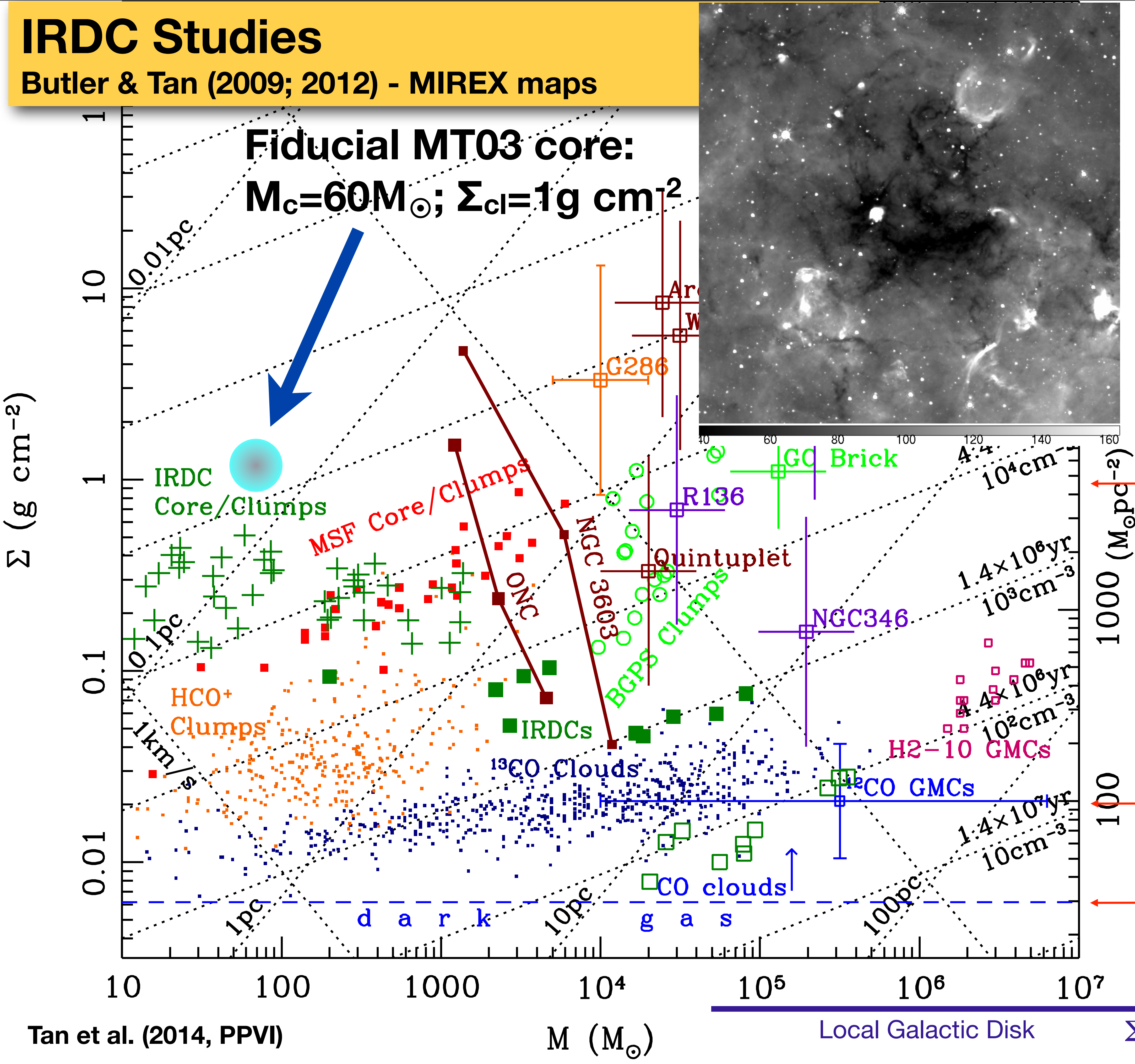
~Arcsecond scale maps of regions up to Σ ~0.5 g cm^{-2}; independent of dust temp.

Distance from molecular line velocities -> M(Σ)

IRDC Studies

Butler & Tan (2009; 2012) - MIREX maps

Fiducial MT03 core:
$M_c=60M_\odot$; $\Sigma_{cl}=1 g\ cm^{-2}$



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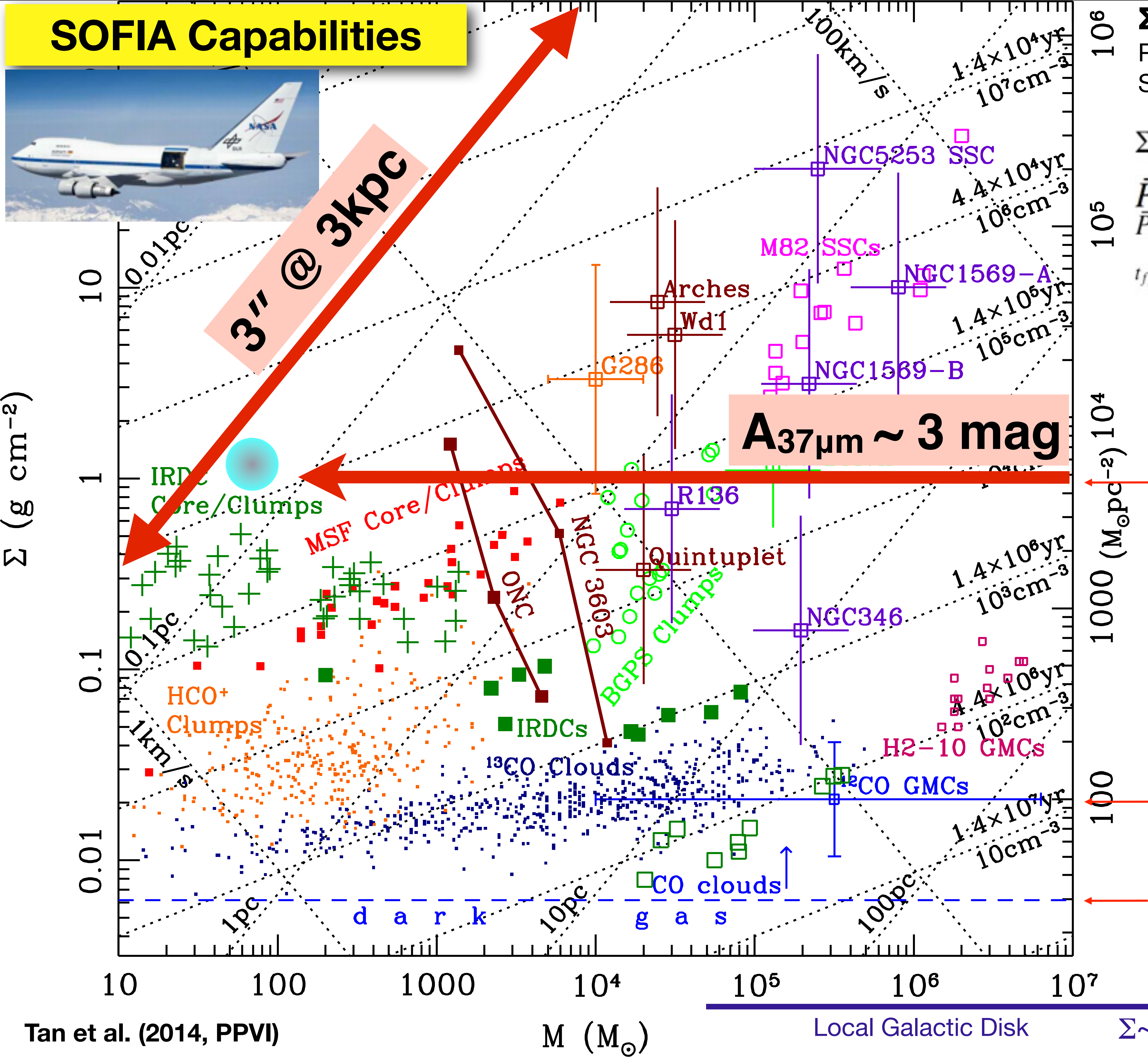
Local Galactic Disk Σ~$10\ M_\odot\ pc^{-2}$

Tan et al. (2014, PPVI)

SOFIA Capabilities



3″ @ 3kpc

$A_{37\mu m}$ ~ 3 mag

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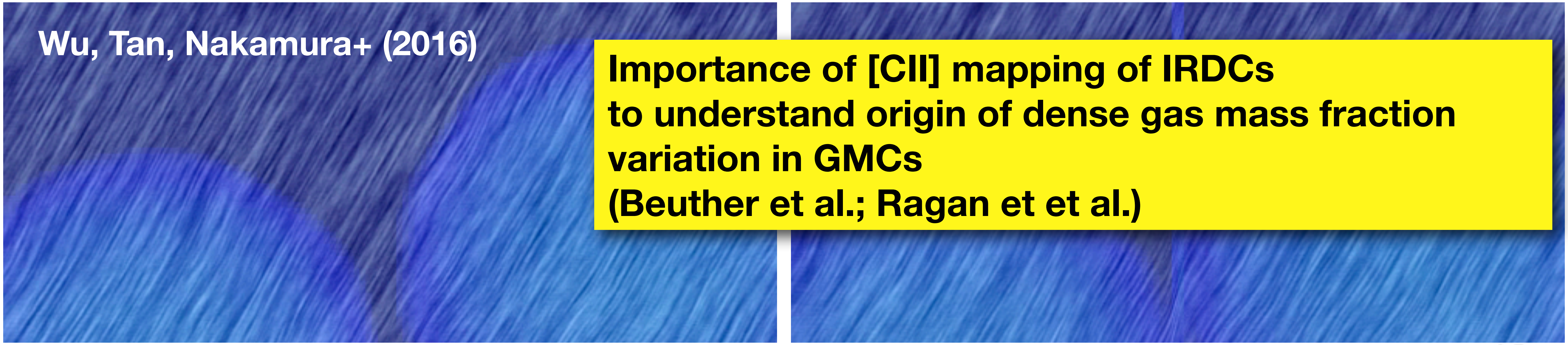
Local Galactic Disk Σ~10 $M_\odot$ pc^{-2}

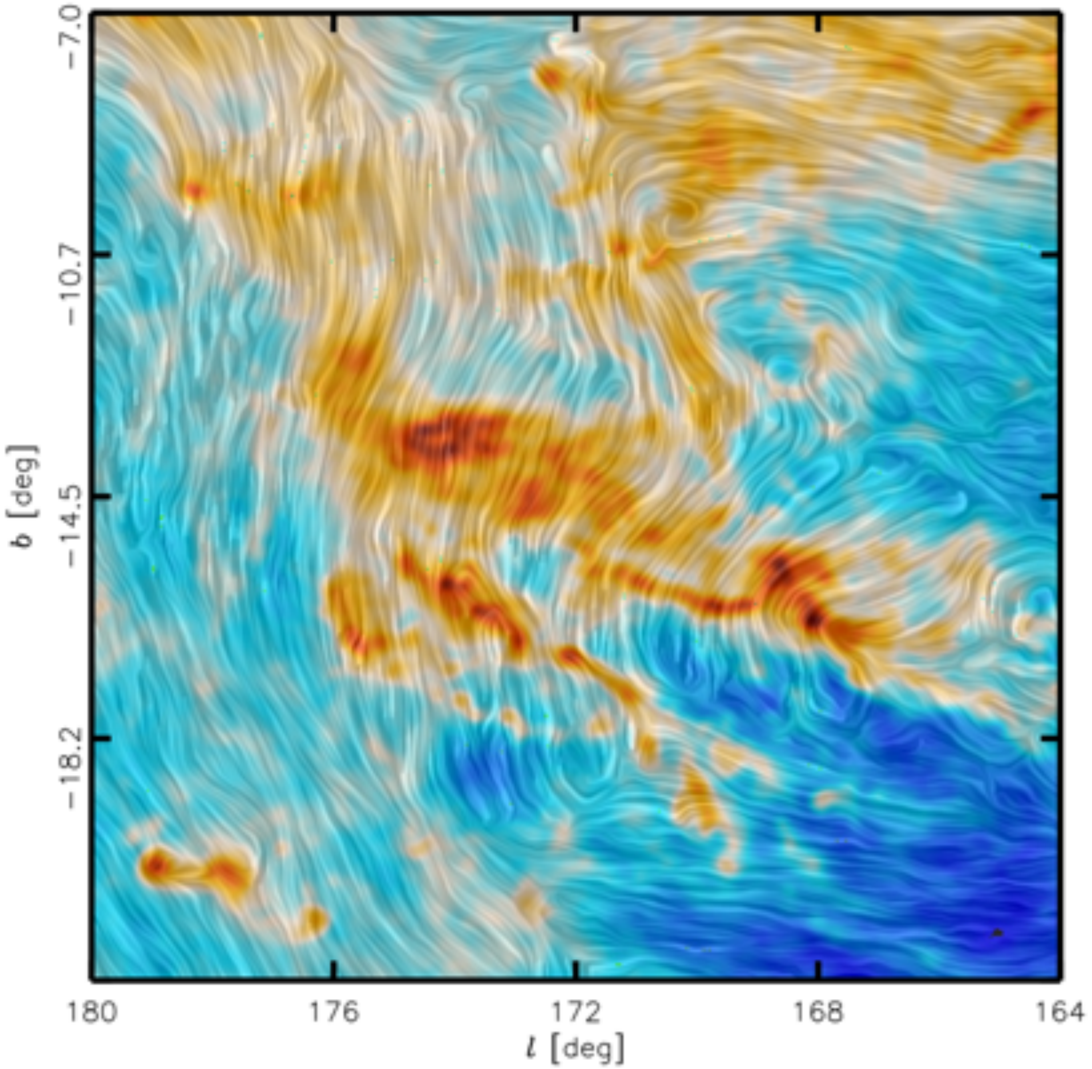
Formation of IRDCs, GMC Collisions, Dense Gas Mass Fractions & KS Relation

(Scoville et al. 1986; Tan 2000; Tasker & Tan 2009; Tan 2010; Suwannajak, Tan & Leroy 2014)

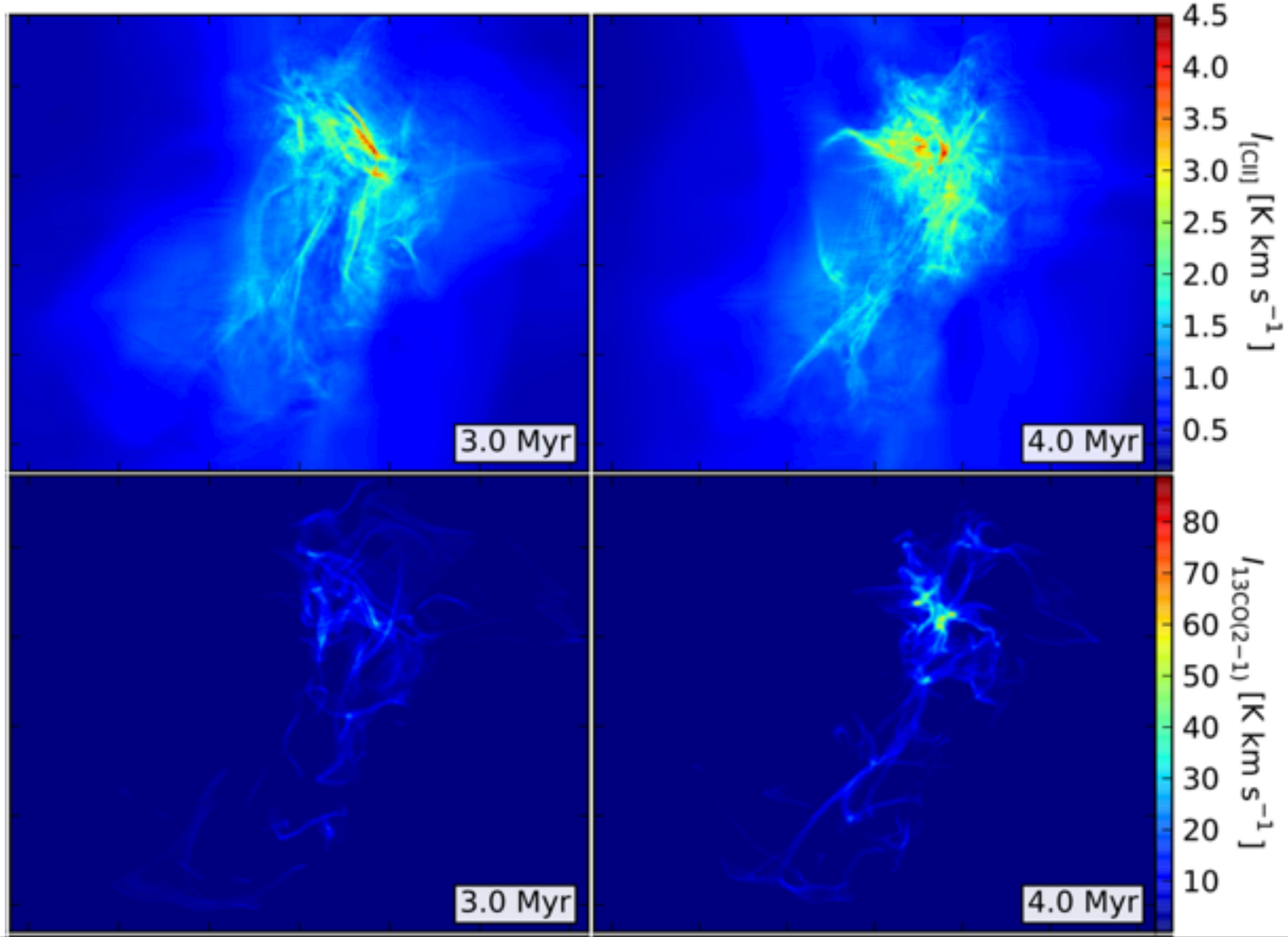


Wu, Tan, Nakamura+ (2016)

Importance of [CII] mapping of IRDCs to understand origin of dense gas mass fraction variation in GMCs (Beuther et al.; Ragan et et al.)



Taurus (Planck XXXV - Soler et al.)



Sample of ~50 massive “starless” core/clumps

(Butler & Tan 2012; Butler et al. 2014)

Mass surface densities ($M=60M_\odot$)

$$\bar{\Sigma} \simeq 0.1\text{–}0.4\,\mathrm{g\,cm^{-2}}$$

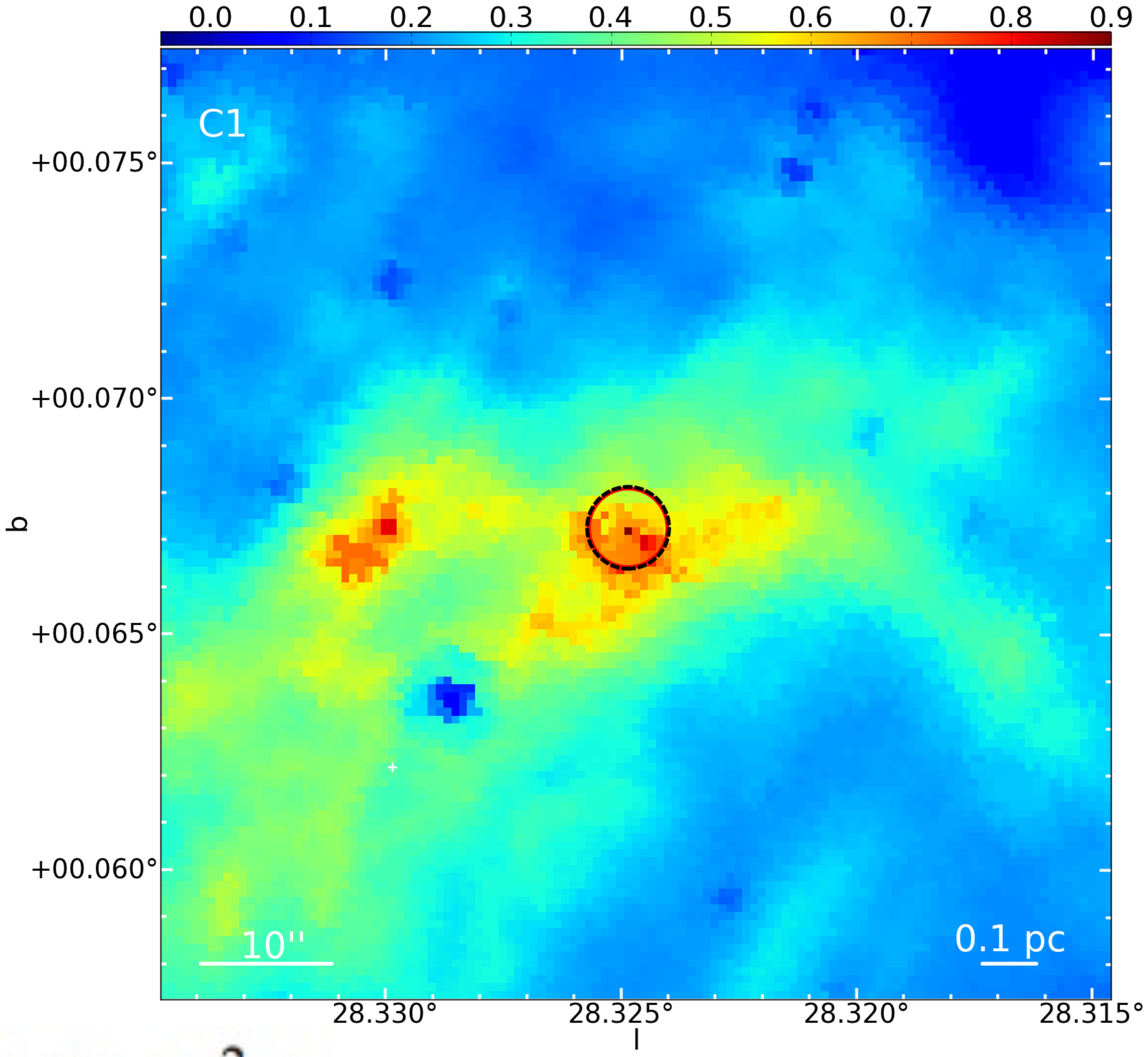
Cores show central concentration

$\rho \propto r^{-k_\rho}$ $\quad k_\rho =$ 1.5±0.3

Contain many Jeans masses.

B-fields suppress fragmentation?

Not radiative heating (c.f., Krumholz & McKee 2008).



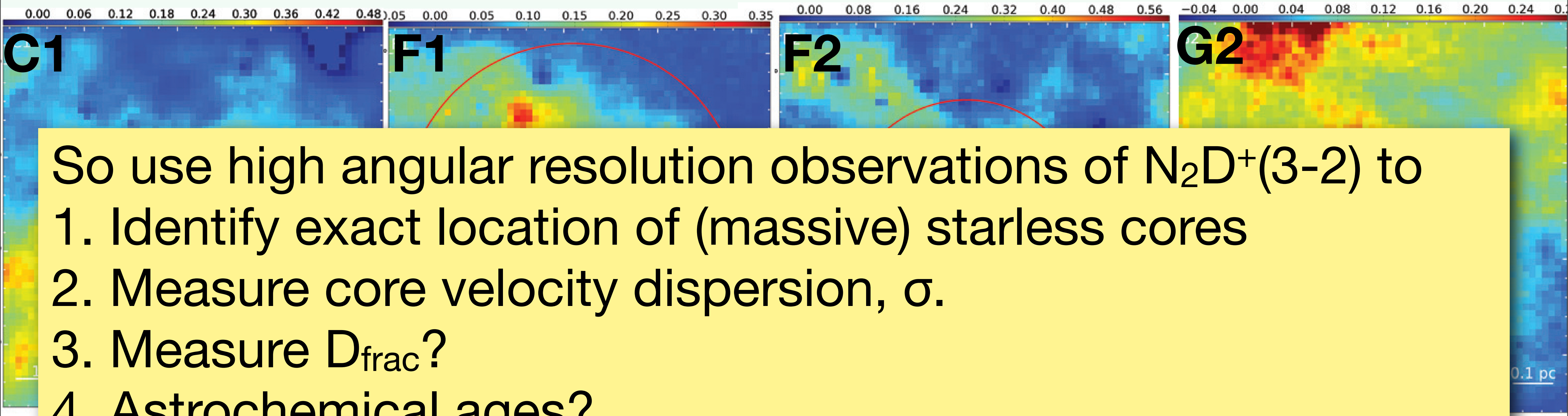
$$M_{\rm BE} = 1.182\frac{c_{\rm th}^4}{(G^3 P_{s,\rm core})^{1/2}} \rightarrow 0.0504\left(\frac{T}{20\ \rm K}\right)^2 \frac{1}{\Sigma_{\rm cl}}\ M_\odot$$

Magnetic Critical Mass (Bertoldi & McKee 1992)

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

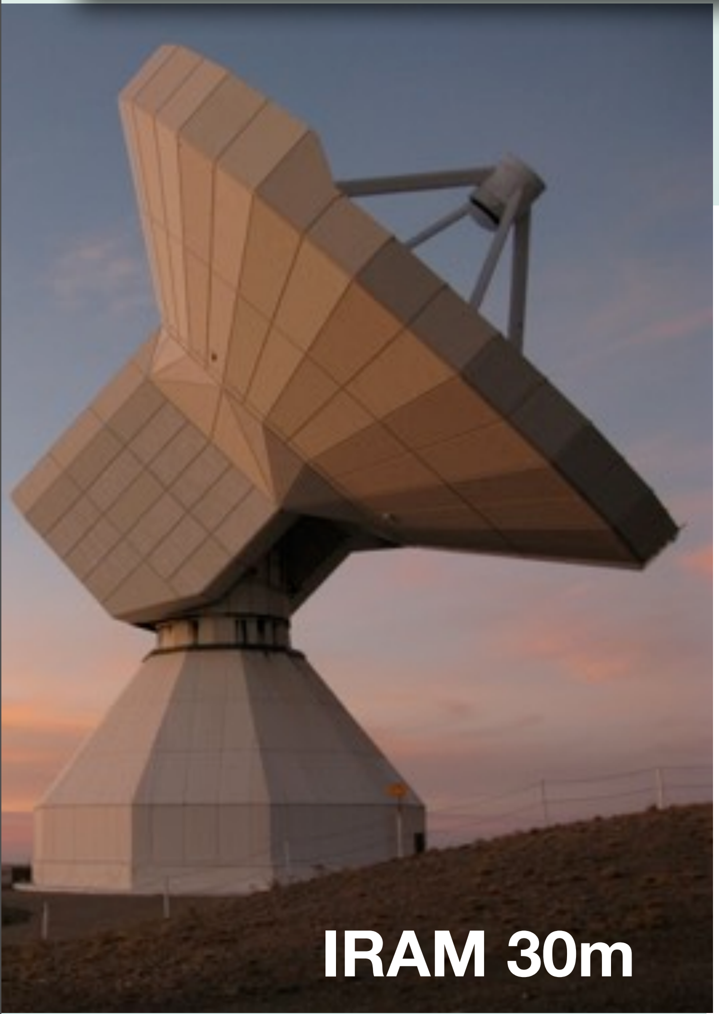
n_H~10^5cm^{-3}, B~200μG -> M_B~100 $M_\odot$

Four IRDC core/clumps selected to be dark at 8, 24, 70 μm

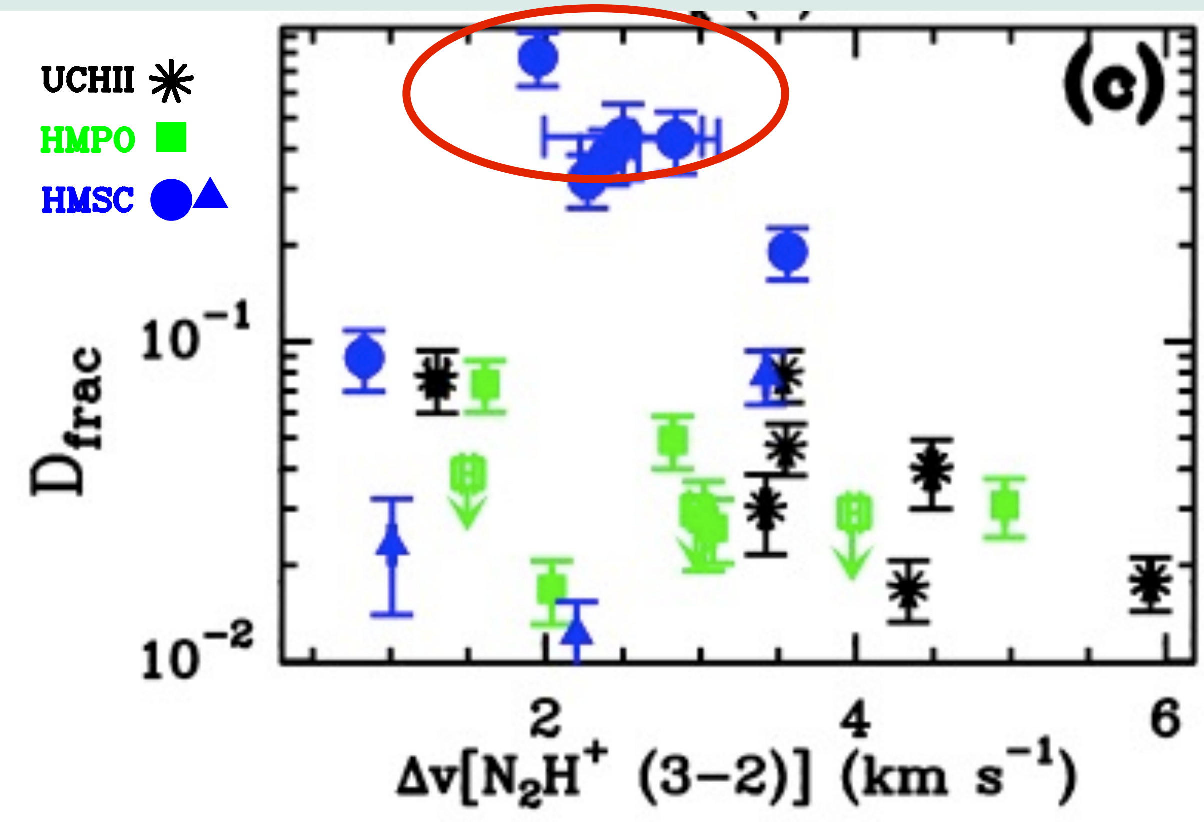


So use high angular resolution observations of N_2D^+(3-2) to

1. Identify exact location of (massive) starless cores
2. Measure core velocity dispersion, σ.
3. Measure D_{frac}?
4. Astrochemical ages?



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



CO freeze-out

e.g. Hernandez et. al (2011)

$$H_3^+ + CO \cancel{\rightarrow} HCO^+ + H_2$$

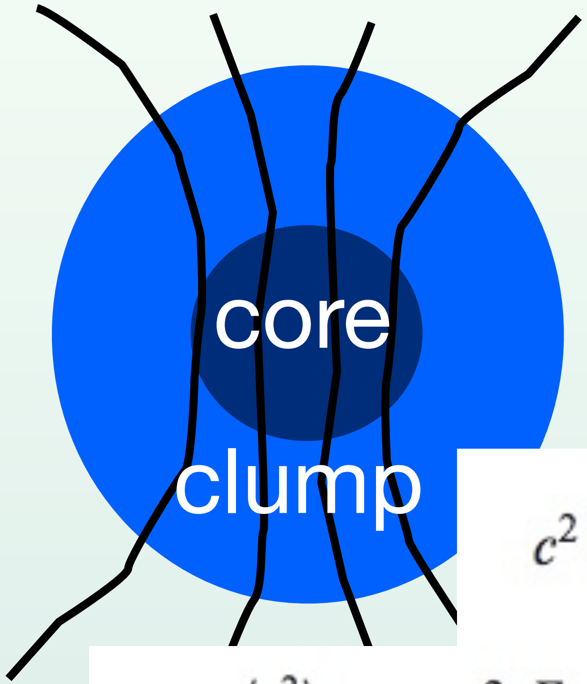
$$H_3^+ + HD \xrightarrow{(T<20K)} H_2D^+ + H_2$$

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

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

Comparison to Turbulent Core Model

Tan, Kong et al. (2013)



$$c^2 = \sigma^2 + \frac{B^2}{8\pi\rho} + \frac{\delta B^2}{24\pi\rho}$$

$$\phi_B \equiv \frac{\langle c^2\rangle}{\langle\sigma^2\rangle} = 1 + \frac{3}{2}\frac{E_B}{E_K} + \frac{E_{\delta B}}{2E_K} = 1.3 + \frac{3}{2m_{\rm A}^2}$$

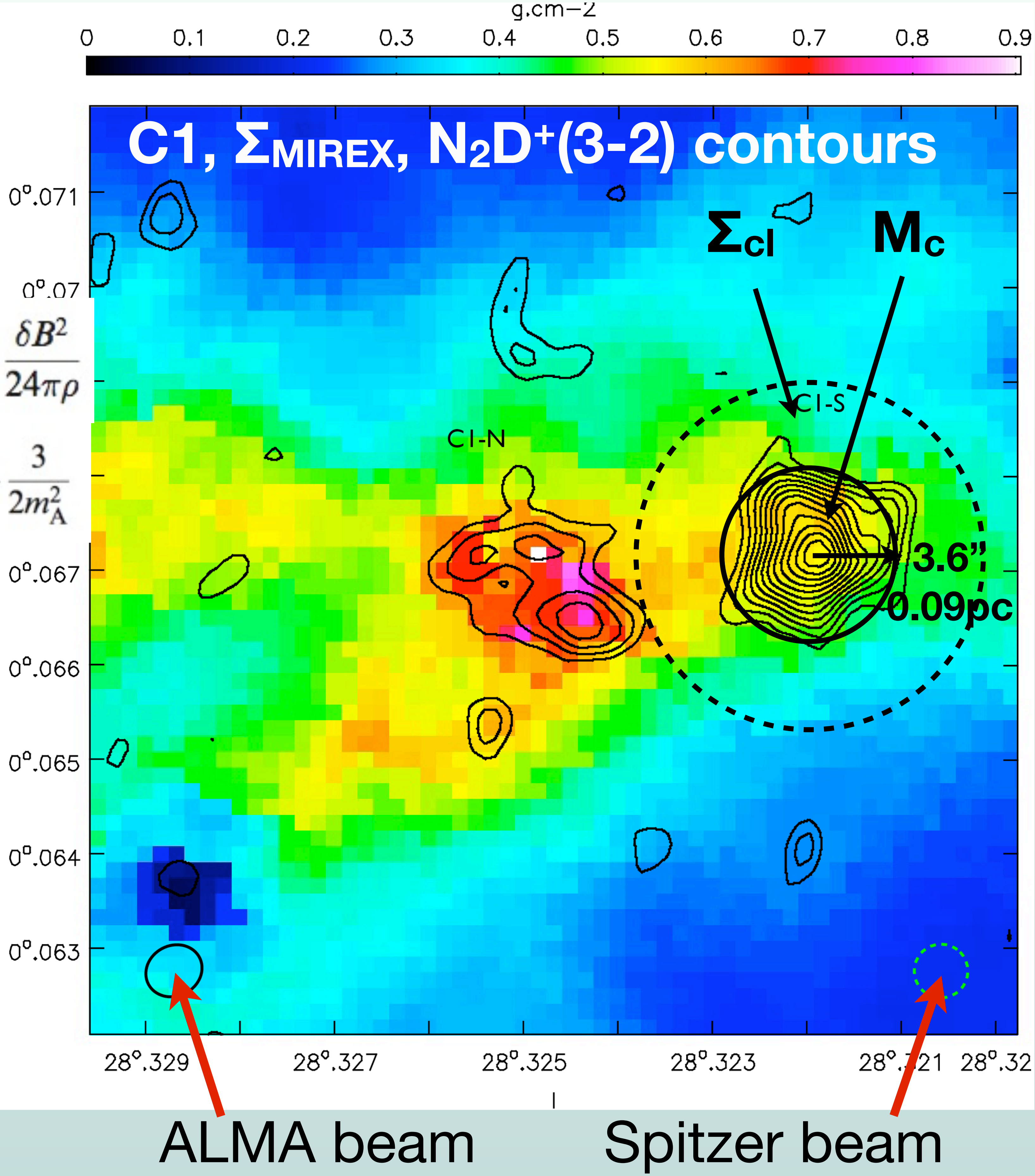
$$\sigma_{\rm c,vir} \to 1.09 \left(\frac{M_c}{60 M_\odot}\right)^{1/4} \left(\frac{\Sigma_{\rm cl}}{1\ {\rm g\ cm^{-2}}}\right)^{1/4} {\rm km\ s^{-1}}$$

Core masses inside 3σ N_2D^+ contour:

Σ_{cl} = 0.36 g cm^{-2}

$M_{c,MIREX}$ = 55.2 ± 25 $M_\odot$

$M_{c,mm}$ = 62.5 $^{129}_{26.9}$ $M_\odot$



Predictions from Virial Equilibrium

Tan, Kong et al. (2013)

- 1D velocity dispersion if virialized:

($m_A = \sqrt{3}\sigma_c/v_A$ = 1)

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

Core	C1-N	C1-S	F1	F2	G2-N	G2-S
Σ_{cl} (g cm^{-2})	0.48	0.40	0.22	0.32	0.21	0.19
M_c ($M_\odot$)	16	63	6.5	4.7	2.4	0.83
σ_{vir} (km/s)	0.66±0.22	0.88±0.30	0.43±0.15	0.44±0.15	0.33±0.11	0.25±0.09
σ_{obs} (km/s)	0.41±0.03	0.41±0.02	0.25±0.02	0.42±0.04	0.34±0.02	0.30±0.02

$< \sigma_{obs}/\sigma_{vir} > = 0.81 \pm 0.13$

$m_{A,vir} = 0.28$ -> B_{vir}=0.9mG

$B_{\rm med} \simeq 0.12 n_{\rm H}^{0.65}\ \mu{\rm G}$ (for $n_{\rm H} > 300\ {\rm cm}^{-3}$) (Crutcher et al. 2010)

$n_{H,c}$=6.4x10^{5}cm^{-3} -> B_{med} = 0.7mG

Tentative Conclusion: Cores appear to be near virial equilibrium, after accounting for clump envelope. Possibly slightly sub-virial; or have stronger B-fields (see also - Kauffmann, Pillai & Goldsmith 2013).

A Hunt for Massive Starless Cores

Kong, Tan et al. (2016b, arXiv:1609.06008)

- Snapshot ALMA survey of 32 IRDC clumps
- Automated N_2D^+(3-2) core finding
- ~100 N_2D^+(3-2) core candidates detected
- Dynamical analysis of 6 best cores: $\boldsymbol{<\sigma_{obs}/\sigma_{vir}>}$ = 0.80 ± 0.06

C9A

$M_{c,mm}$ =

$70.0^{146}_{32}\,M_\odot$

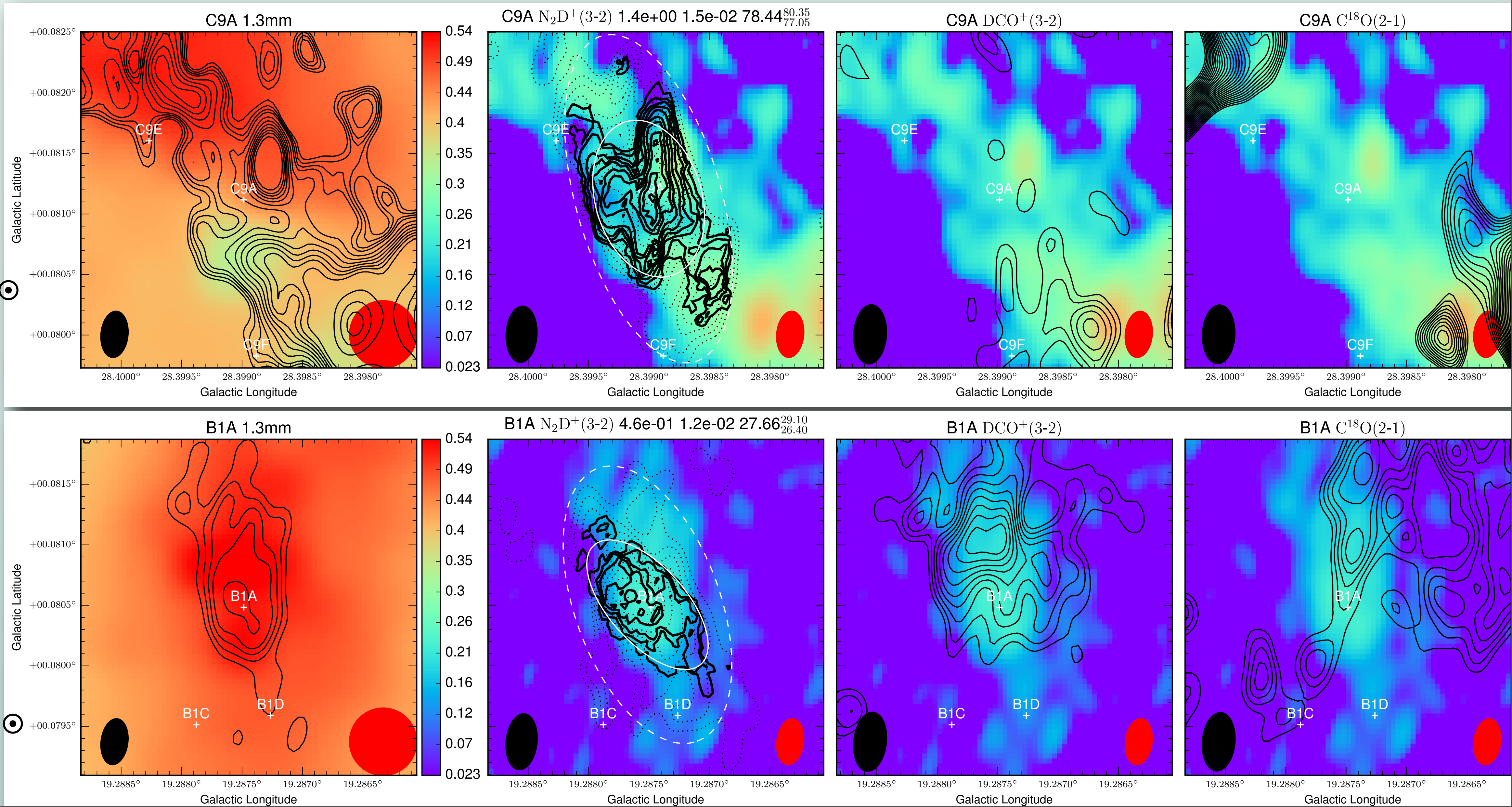
$170.0^{360}_{78}\,M_\odot$

B1A

$M_{c,mm}$ =

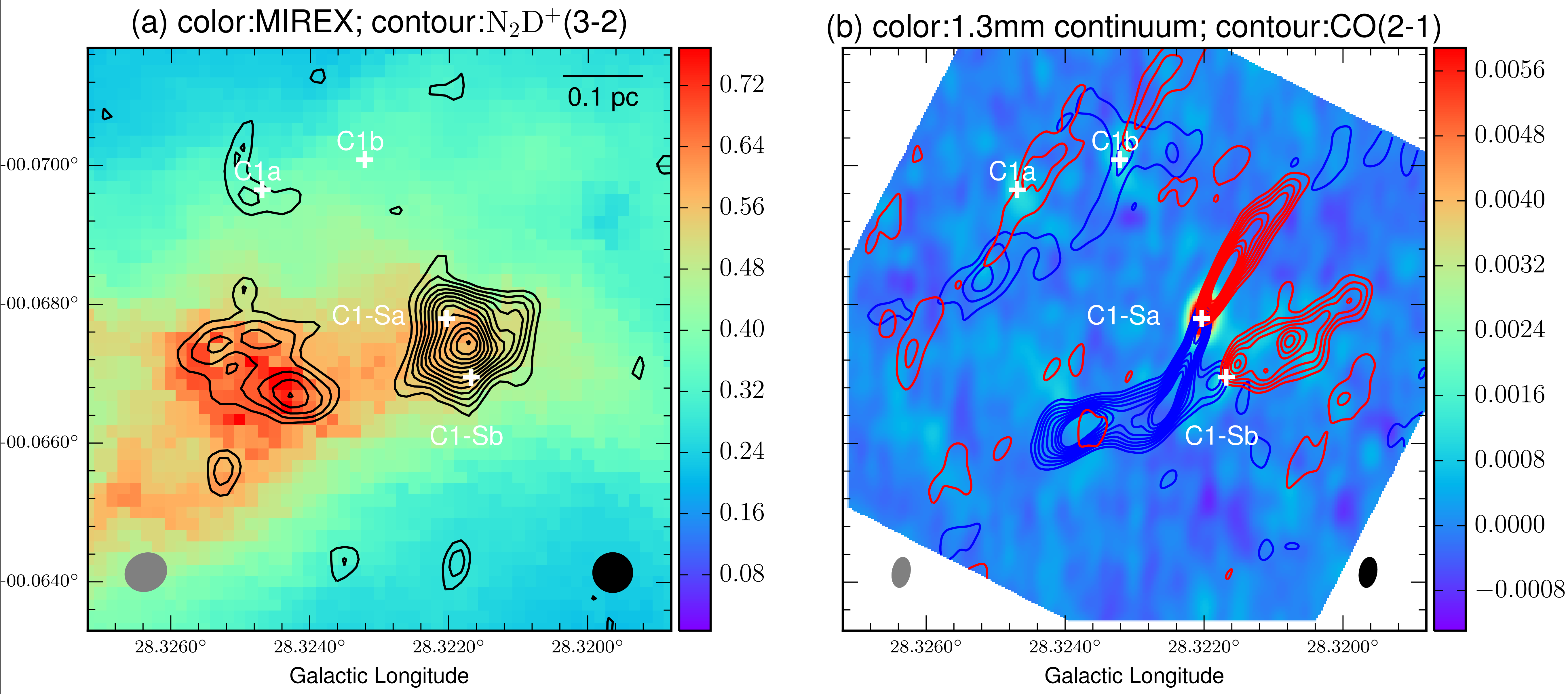
$4.9^{10.3}_{2.2}\,M_\odot$

$10.3^{21.6}_{4.7}\,M_\odot$



But are the “Cores” Starless? - sometimes not!

ALMA Cycle 2 follow-up of C1 region



(a) color:MIREX; contour:N_2D^+(3-2)

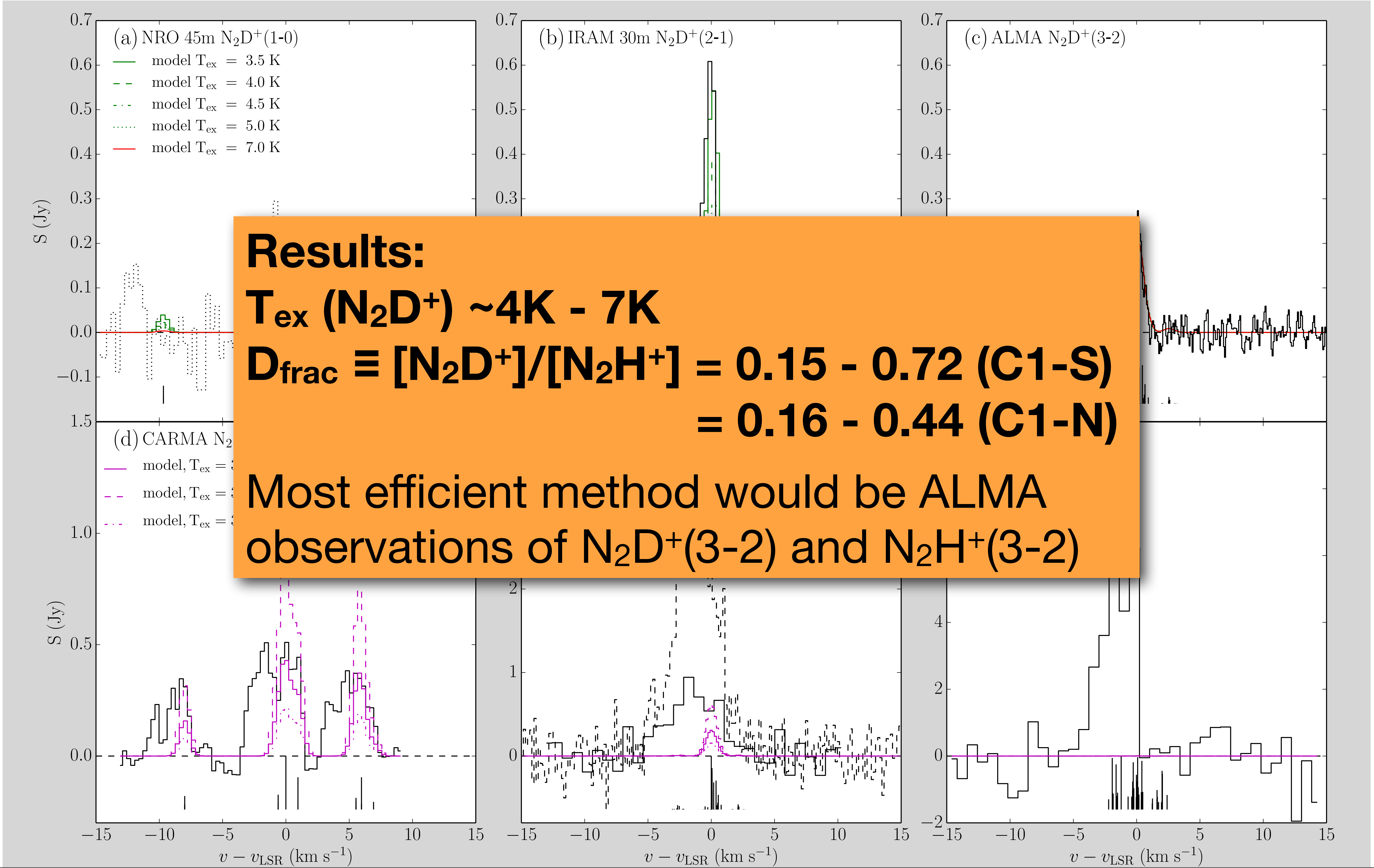
(b) color:1.3mm continuum; contour:CO(2-1)

Tan, Kong et al. (2016)

The Deuteration Fraction of C1-S & C1-N

Kong, Tan, Caselli, Fontani, Pillai, Butler, Shimajiri, Nakamura, Sakai (2016)

- Multi-transition study of N_2D^+ & N_2H^+



Results:

T_{ex} (N_2D^+) ~4K - 7K

$D_{frac} \equiv [N_2D^+]/[N_2H^+]$ = 0.15 - 0.72 (C1-S)

= 0.16 - 0.44 (C1-N)

Most efficient method would be ALMA observations of N_2D^+(3-2) and N_2H^+(3-2)

The Deuteration Clock

Kong, Caselli, Tan, Wakelam, Sipilä (2015) **(see also Pagani et al. 2009, 2013)**

- Modeling of N_2H^+ deuteration with gas-phase, spin-state network (132 species; 3232 reactions) to constrain age or collapse rate

Parameter	Description	Fiducial value
$n_{\rm H}$	number density of H nuclei	1.0×10^5 cm^{-3}
T	temperature	15 K
ζ	cosmic-ray ionization rate	2.5×10^{-17} s^{-1}
f_D	depletion factor	10
G_0	ratio to Habing field	1
A_V	visual extinction	30 mag
OPR^{H2}	ortho to para ratio of H_2	10^{-3} - 3

CO freeze-out

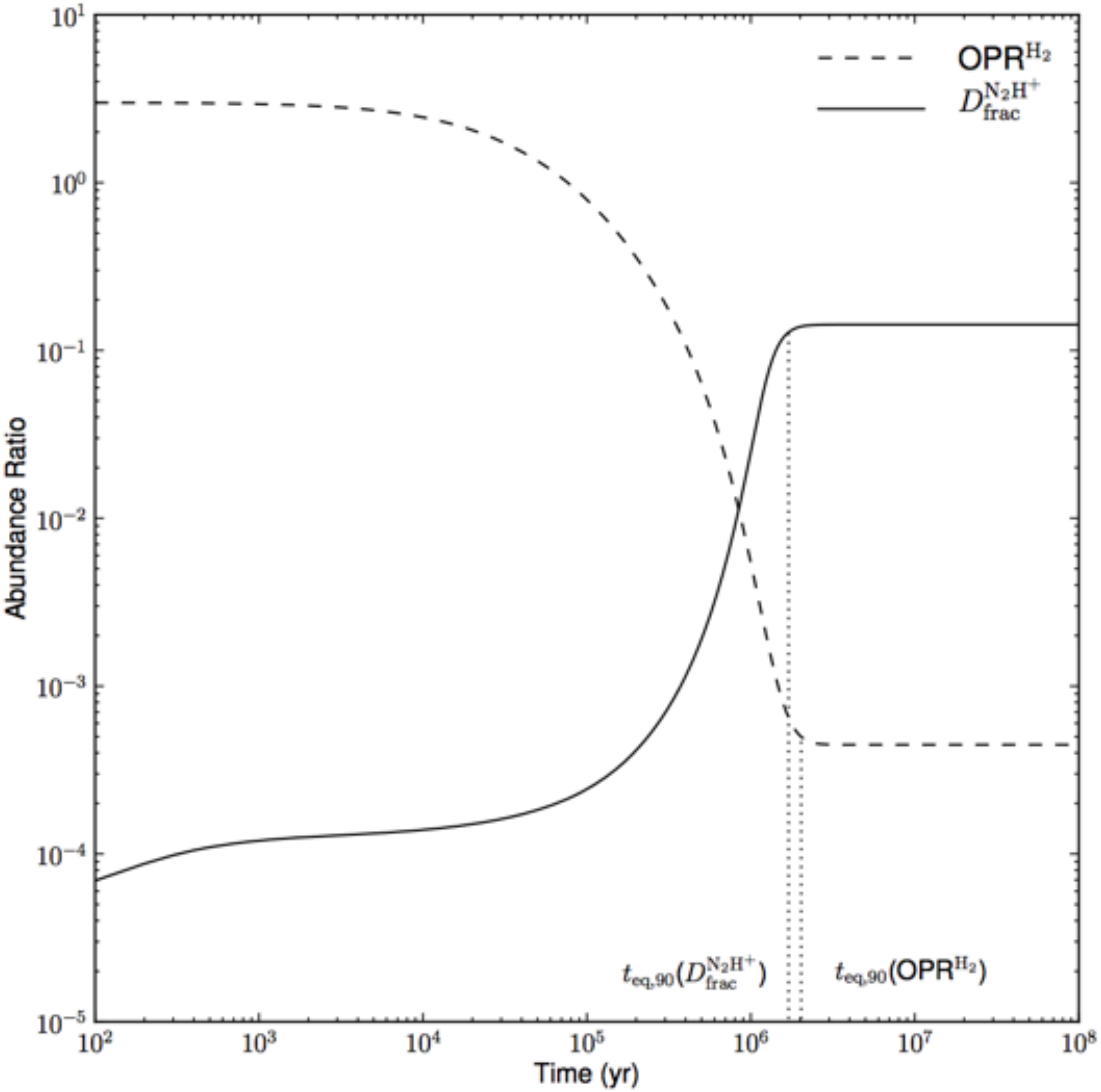
e.g. Hernandez et. al (2011)

$H_3^+ + CO \cancel{\rightarrow} HCO^+ + H_2$

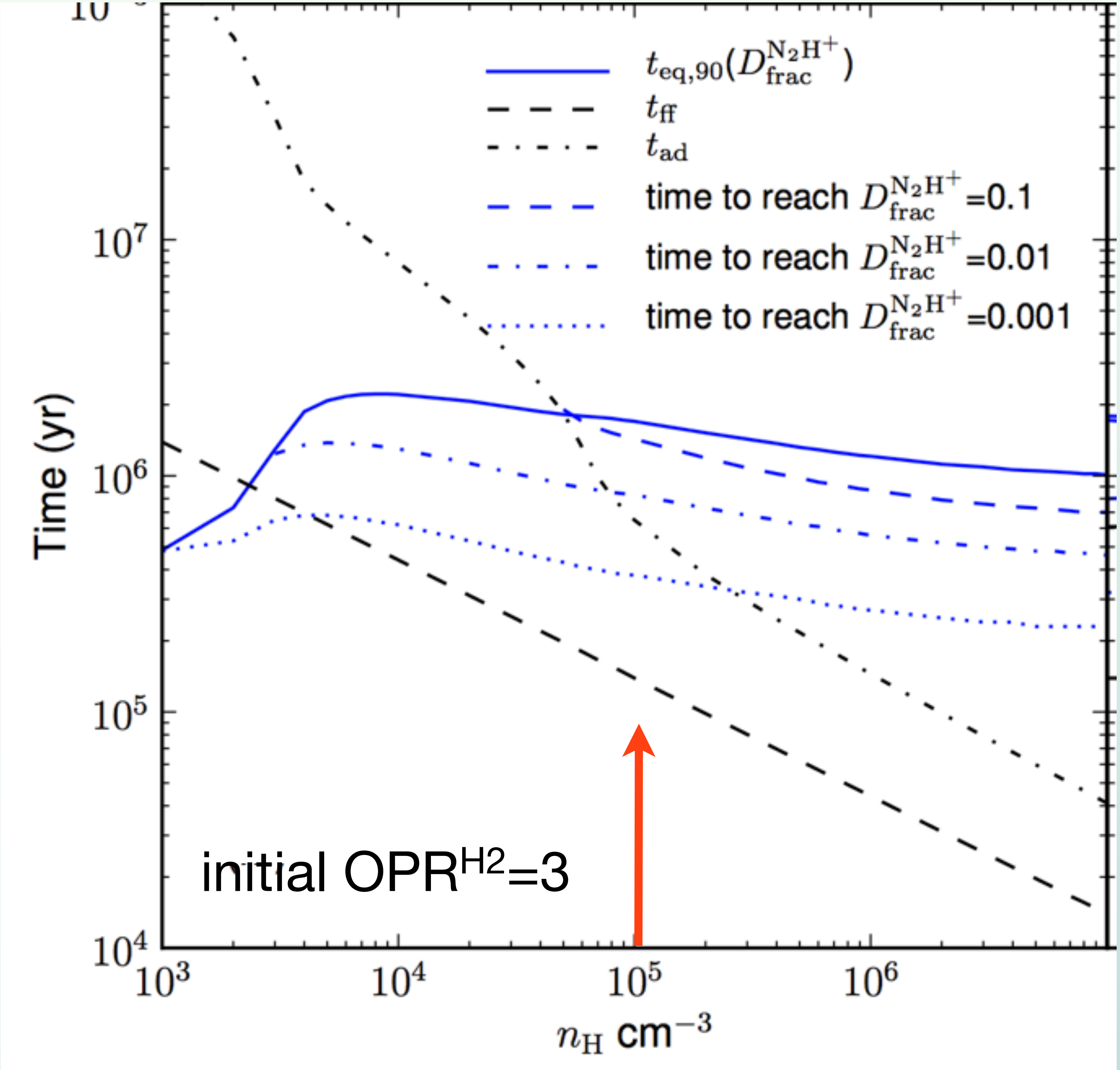
(T<20-30K for small OPR^{H2})

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

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



Parameter Space Exploration: n_H, T, ζ, f_D, OPR^{H2}
Deuteration time; comparison with t_{ff} & t_{ad}



initial OPR^{H2}=3

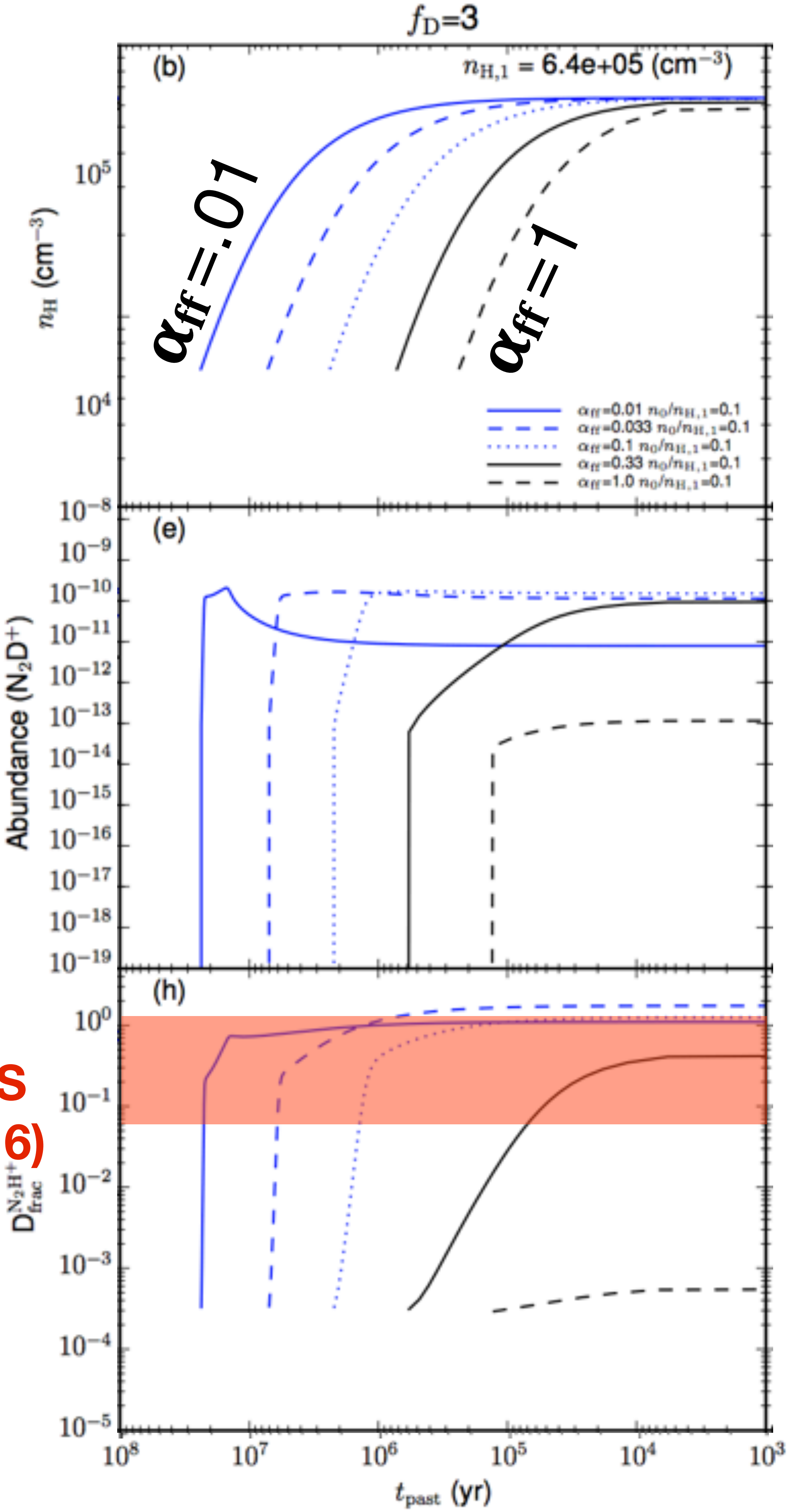
The Deuteration Clock

Kong, Caselli, Tan, Wakelam, Sipilä (2015)

- Evolving density model

$$\frac{dn_H}{dt} = \alpha_{ff}\frac{n_H(t)}{t_{ff}(t)}$$

If $n_0 \geq 0.1 n_1$
If initial $OPR^{H2} \geq 1$
initial $f_D = 1$
THEN $D_{frac} \geq 0.1 \Rightarrow \alpha_{ff} \leq 0.1$



Observed D_{frac} of C1-S (Kong+ 2016)

But, observed values of D_{frac} consistent with predicted equilibrium values

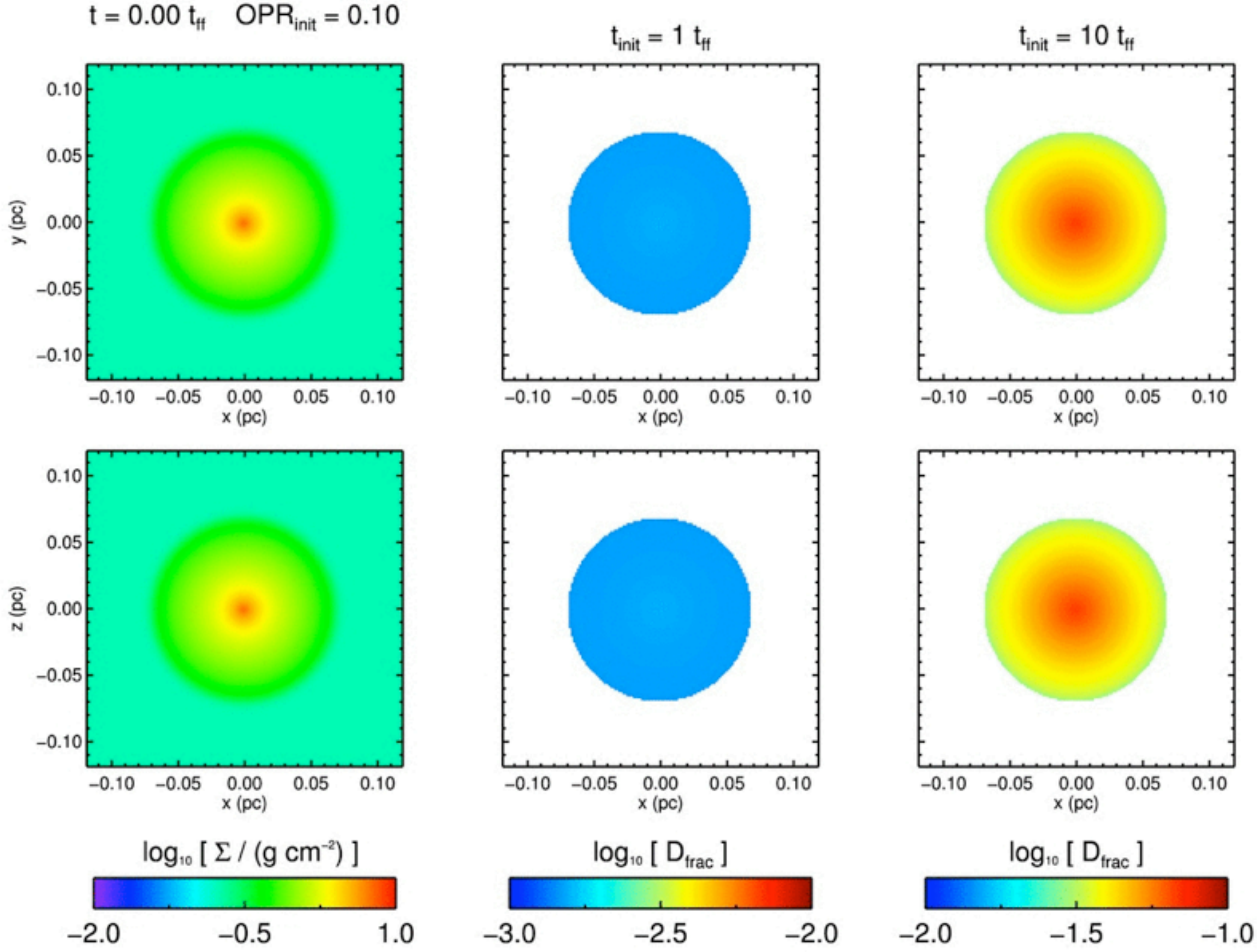
$D_{frac} \equiv [N_2D^+]/[N_2H^+]$ = 0.15 - 0.72 (C1-S)
= 0.16 - 0.44 (C1-N)

Magnetized, Turbulent, Massive Starless Core Simulations

Goodson, Kong, Tan et al. (2016, arXiv:1609.07107)

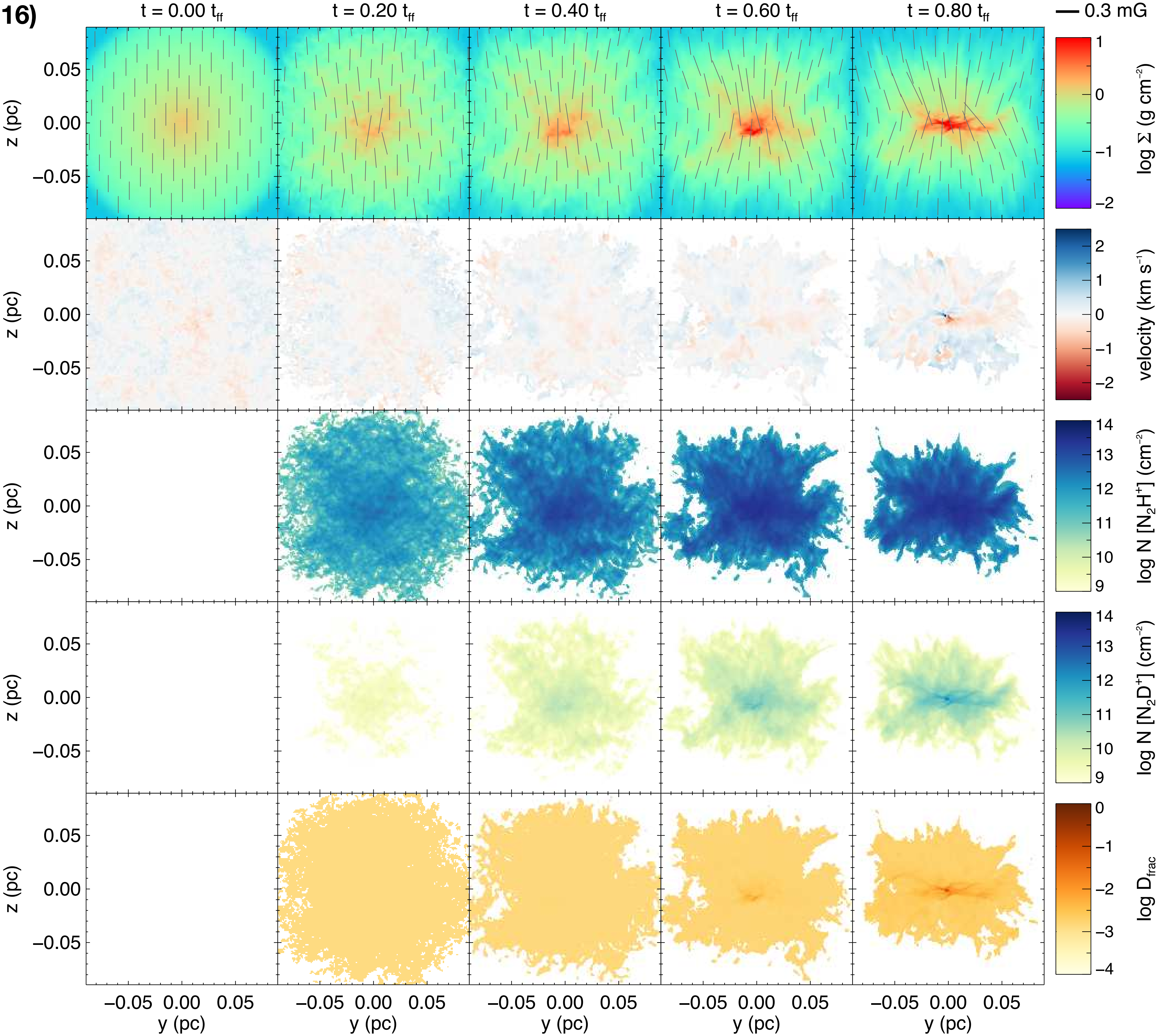
- ATHENA: ideal MHD; isothermal (15K; γ=1.01)
- Parameterized D chemistry (Kong et al. 2015): $d[N_2D^+]/dt$ (n_H); $d[N_2H^+]/dt$ (n_H)

C1-S: M_c=60$M_\odot$; r=0.07pc; Σ_{cl}=0.5 g cm^{-2}; n_H =6x10^5 cm^{-3}; t_{ff}=40kyr; B_0~2.5mG; B_s~0.5mG

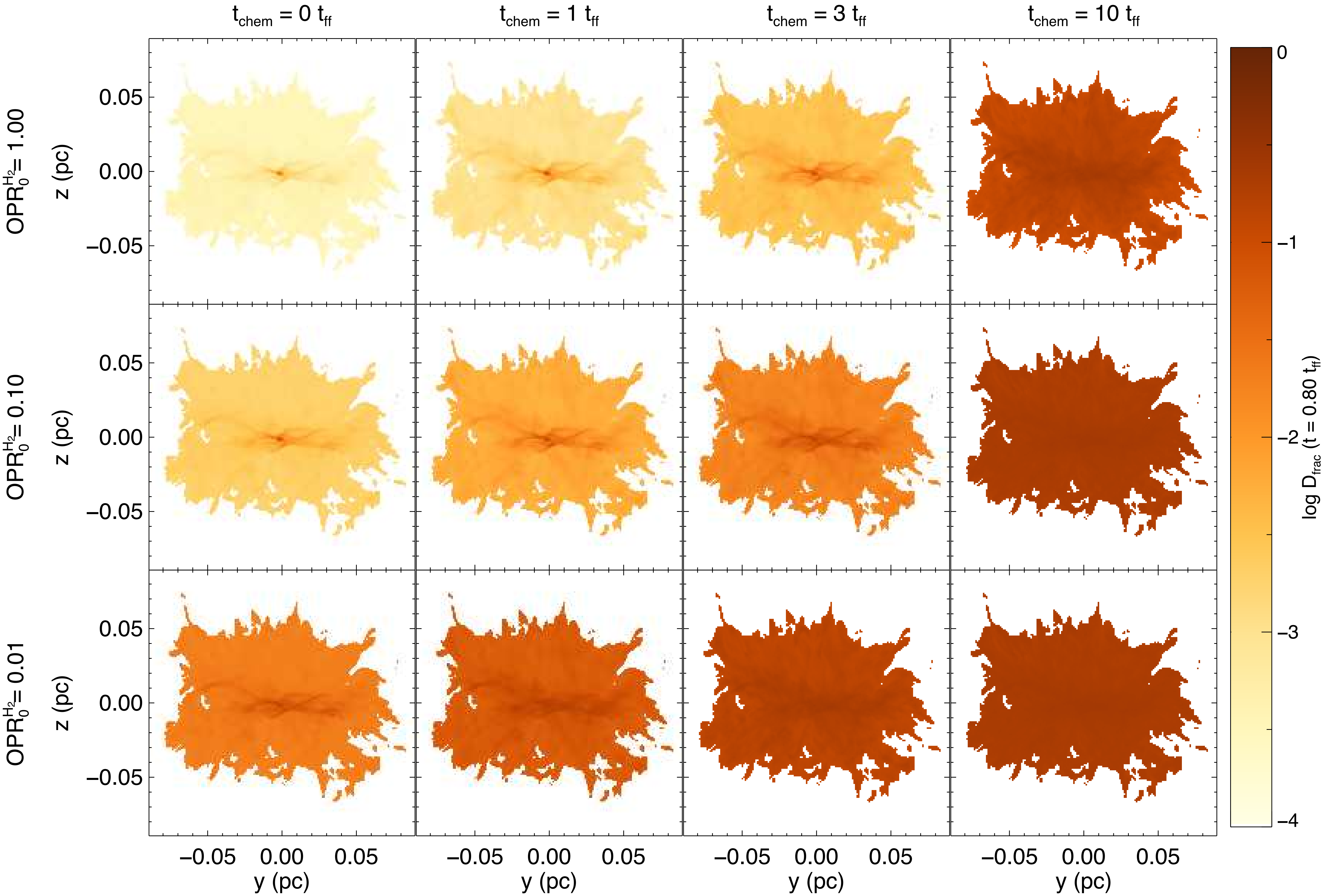


Magnetized, Turbulent, Massive Starless Core Simulations

Goodson et al. (2016)

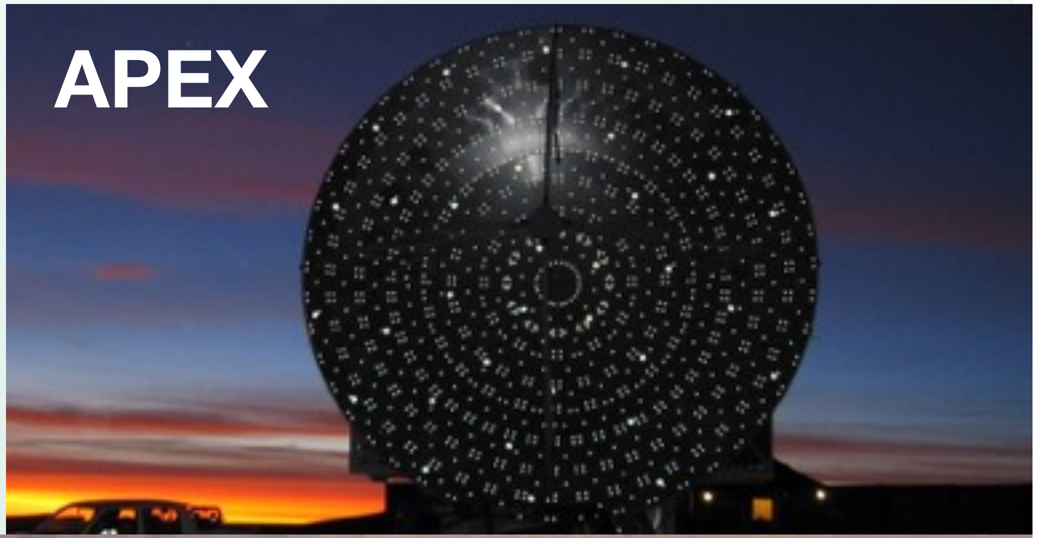


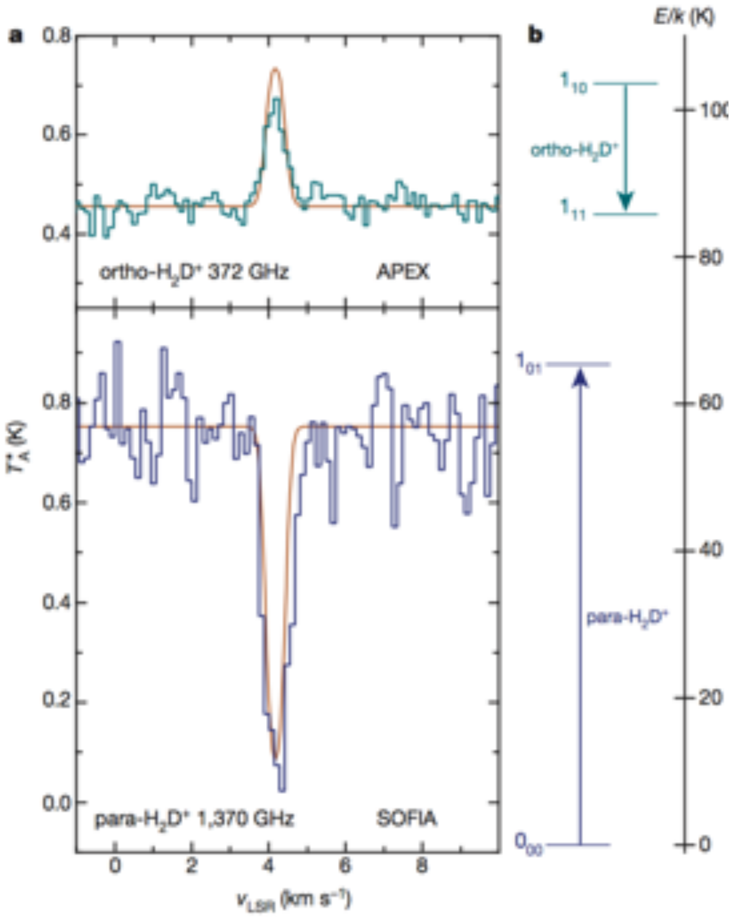
Goodson et al. 2016 - Simulated D_{frac} maps

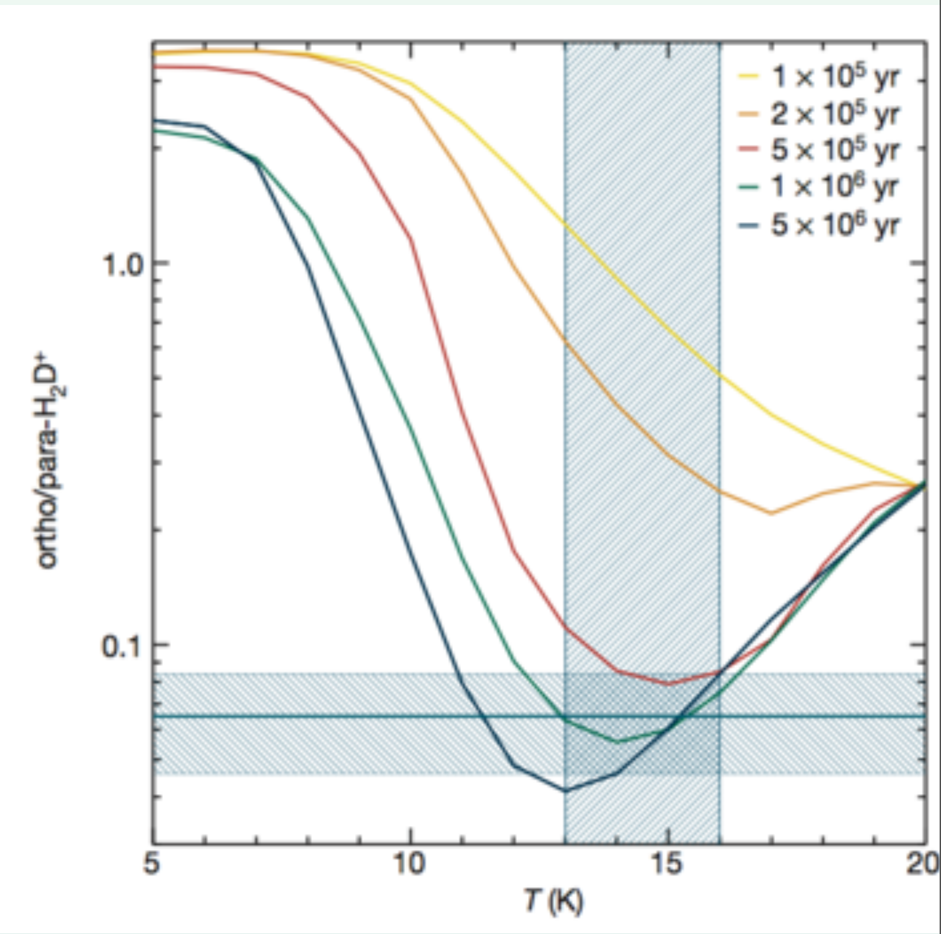


Chemical Clock with para-H_2D^+

ortho & para H_2D^+ to constrain ortho to para ratio of H_2 (Brünken et al. 2014)







Protostellar core IRAS 16293-2422 A/B (n_H~$2x10^5cm^{-3}$, t_{ff}=$1.0x10^5$yr)
OPR_{H2}~10^{-4}, which indicates chemical processing for >1Myr = $10t_{ff}$

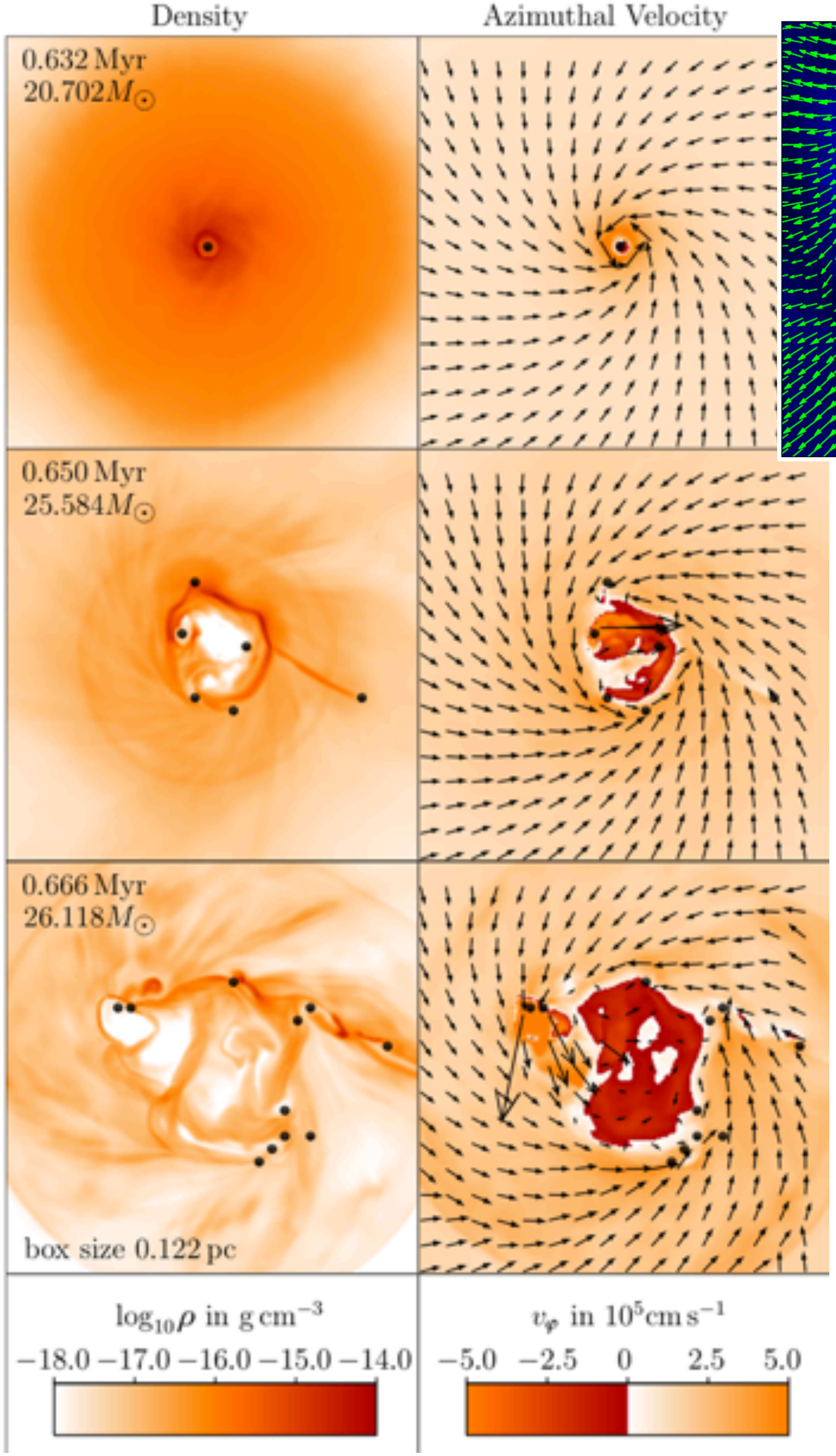
This information helps break degeneracies in Deuteration chemical clocks $[N_2D^+]/[N_2H^+]$
(Pagani et al. 2011, 2013; Kong et al. 2015)

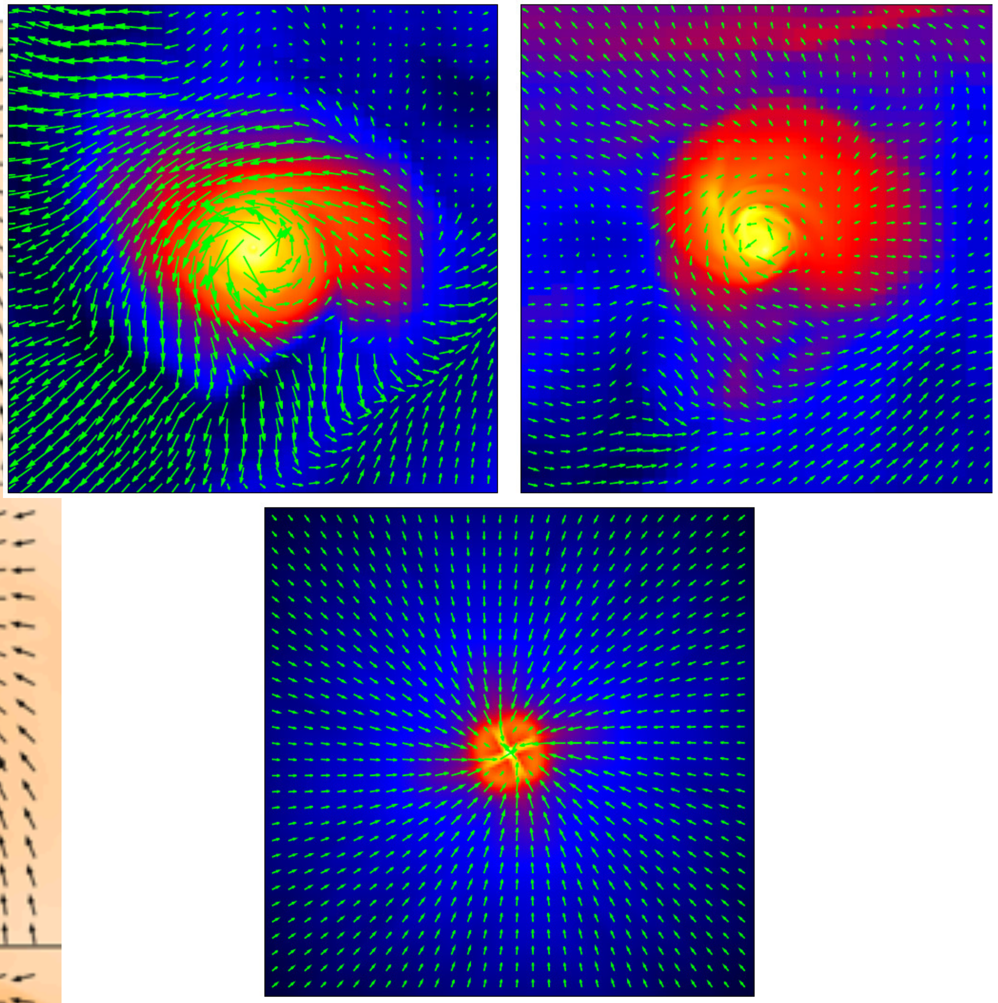
Constraints for Initial Conditions of Numerical Simulations

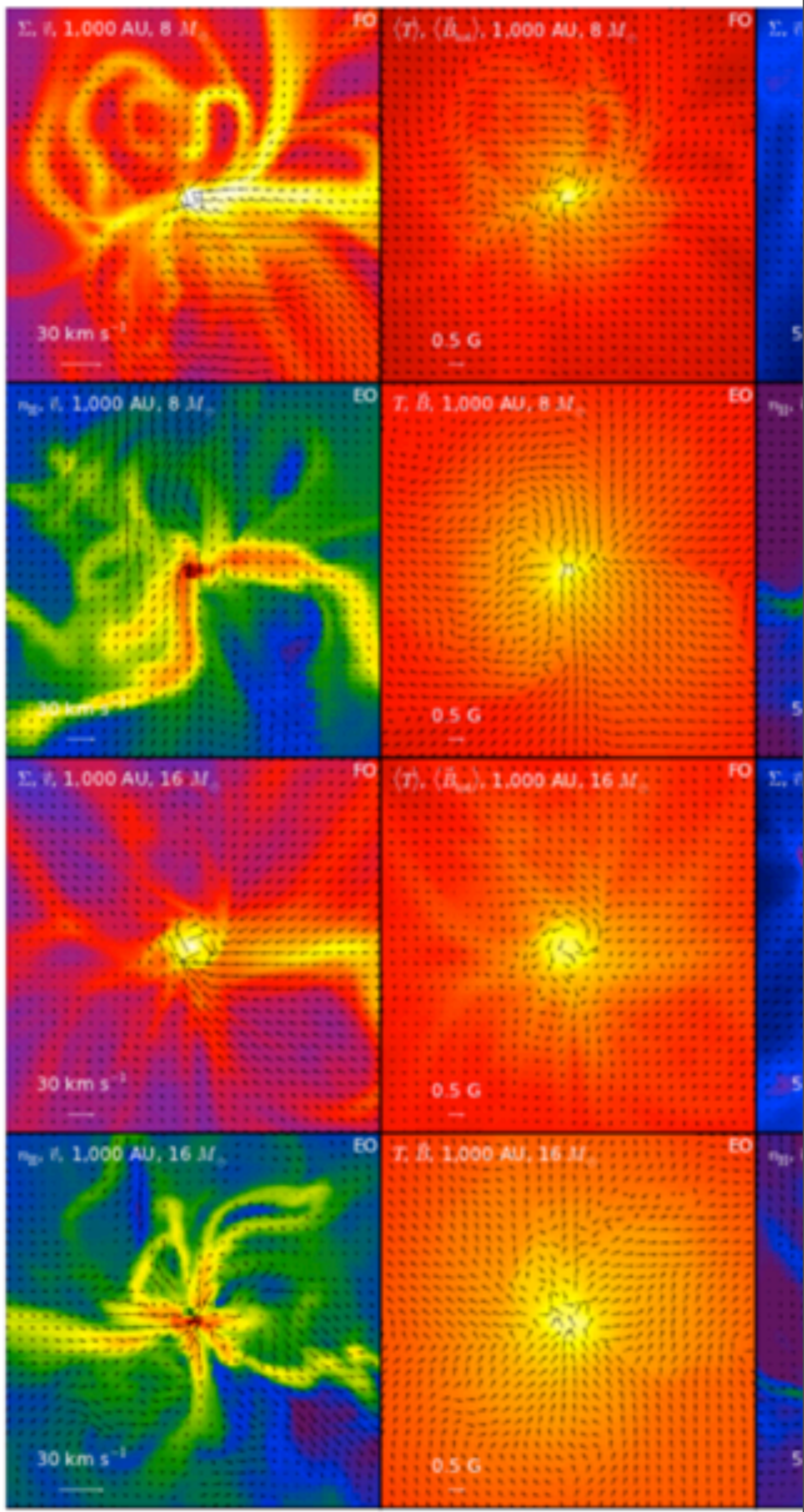
Peters et al. (2011)
M = 100M$_{\odot}$, R=0.5pc,
n$_{H}$ = 5400cm^{-3}, B=10μG

Seifried et al. (2012)
M = 100M$_{\odot}$, R=0.25pc,
n$_{H}$ = 4.4x10^{4}cm^{-3}, B~1mG

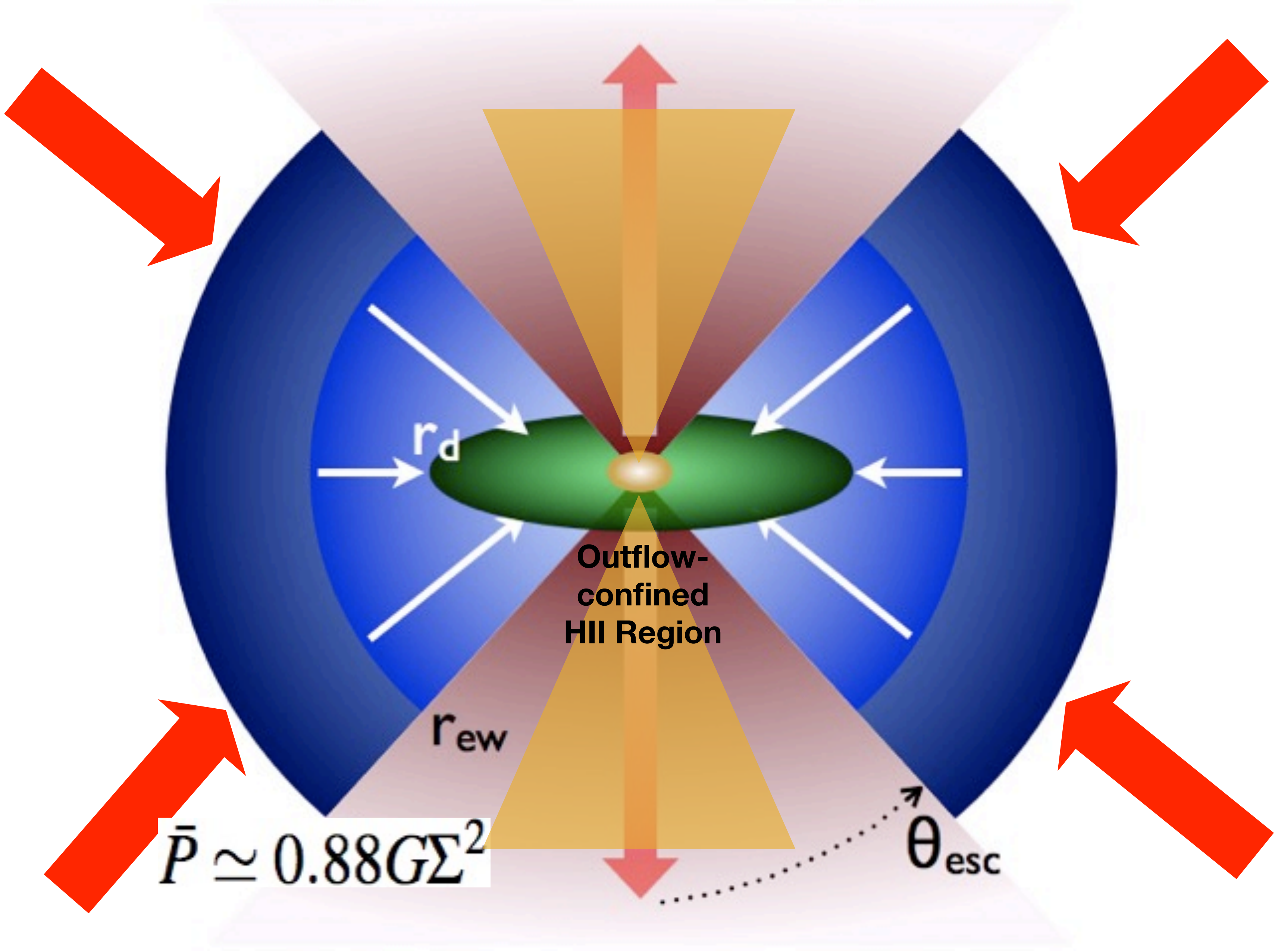
Myers et al. (2013)
M = 300M$_{\odot}$, R=0.1pc,
n$_{H}$ = 2.4x10^{6}cm^{-3}, B>~1mG







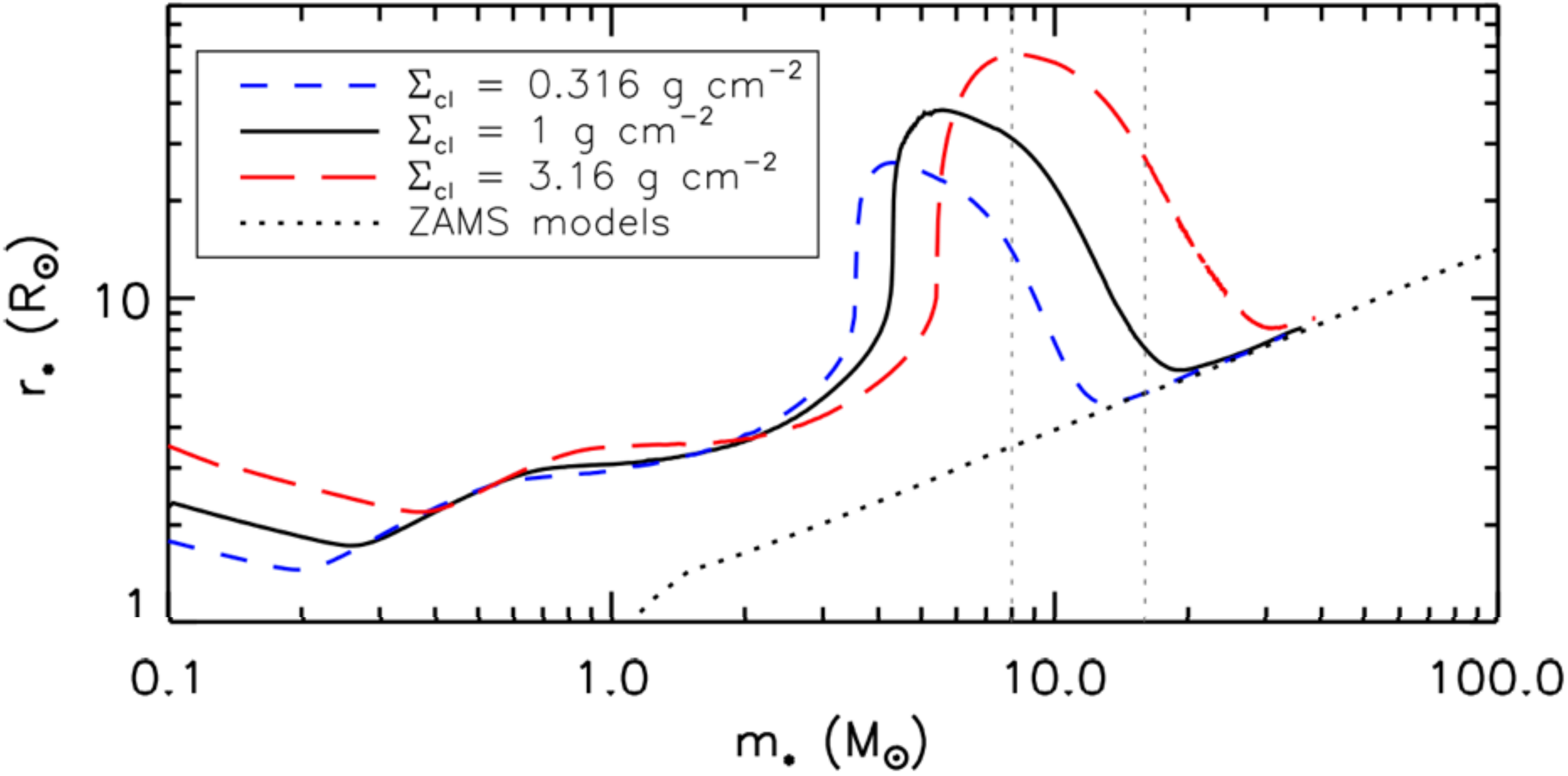
Do massive protostars have morphologies similar to low-mass protostars?
What sets the star formation efficiency from the core? CMF -> IMF?



$\bar{P} \simeq 0.88G\Sigma^2$

Protostellar Evolution

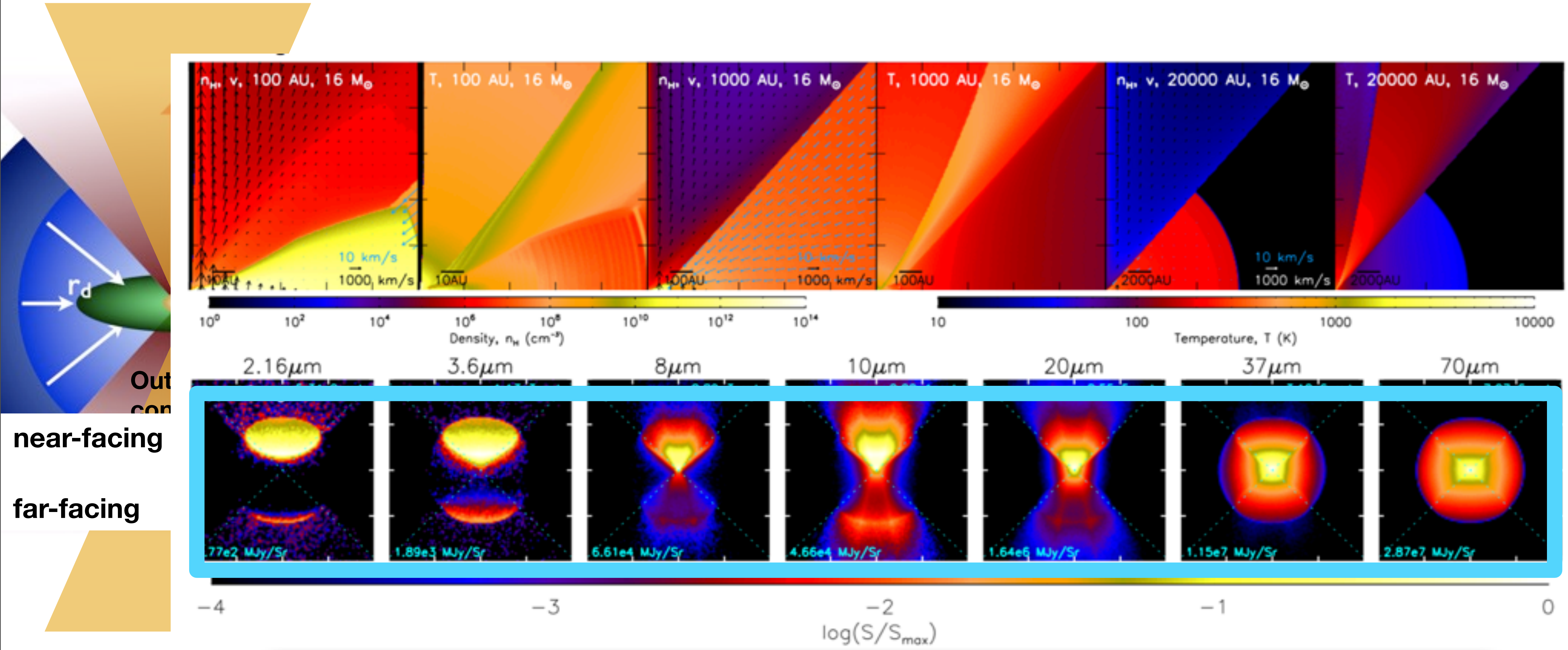
Zhang, Tan, Hosokawa (2014)



see also Palla & Stahler 1993; Hosokawa et al. (2010)

Diagnostics of the Turbulent Core Model

Zhang & Tan (2011), Zhang, Tan & McKee (2013), Zhang, Tan & Hosokawa (2014), Tanaka, Tan & Zhang (2016)

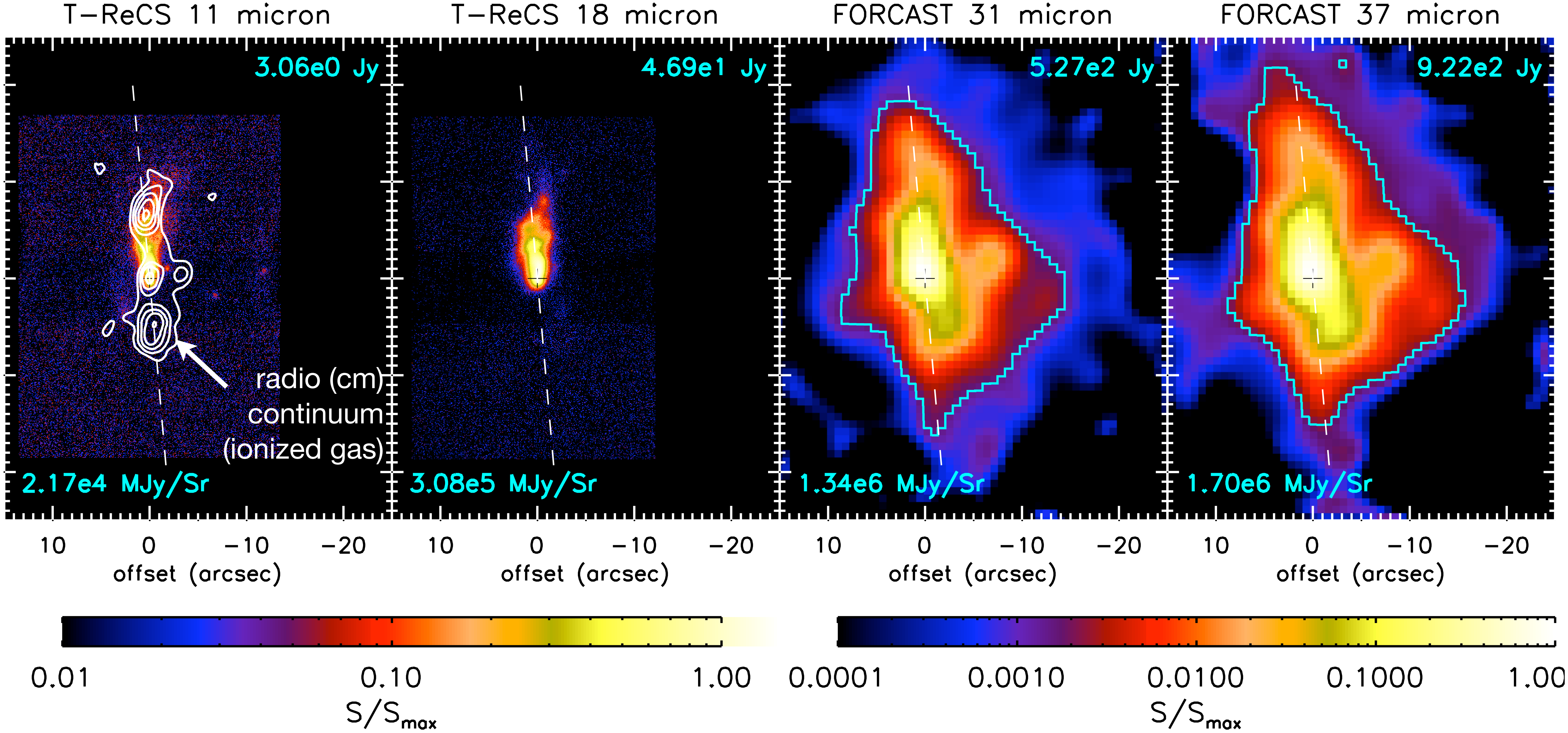


near-facing

far-facing

Prediction: increasing symmetry from MIR-FIR

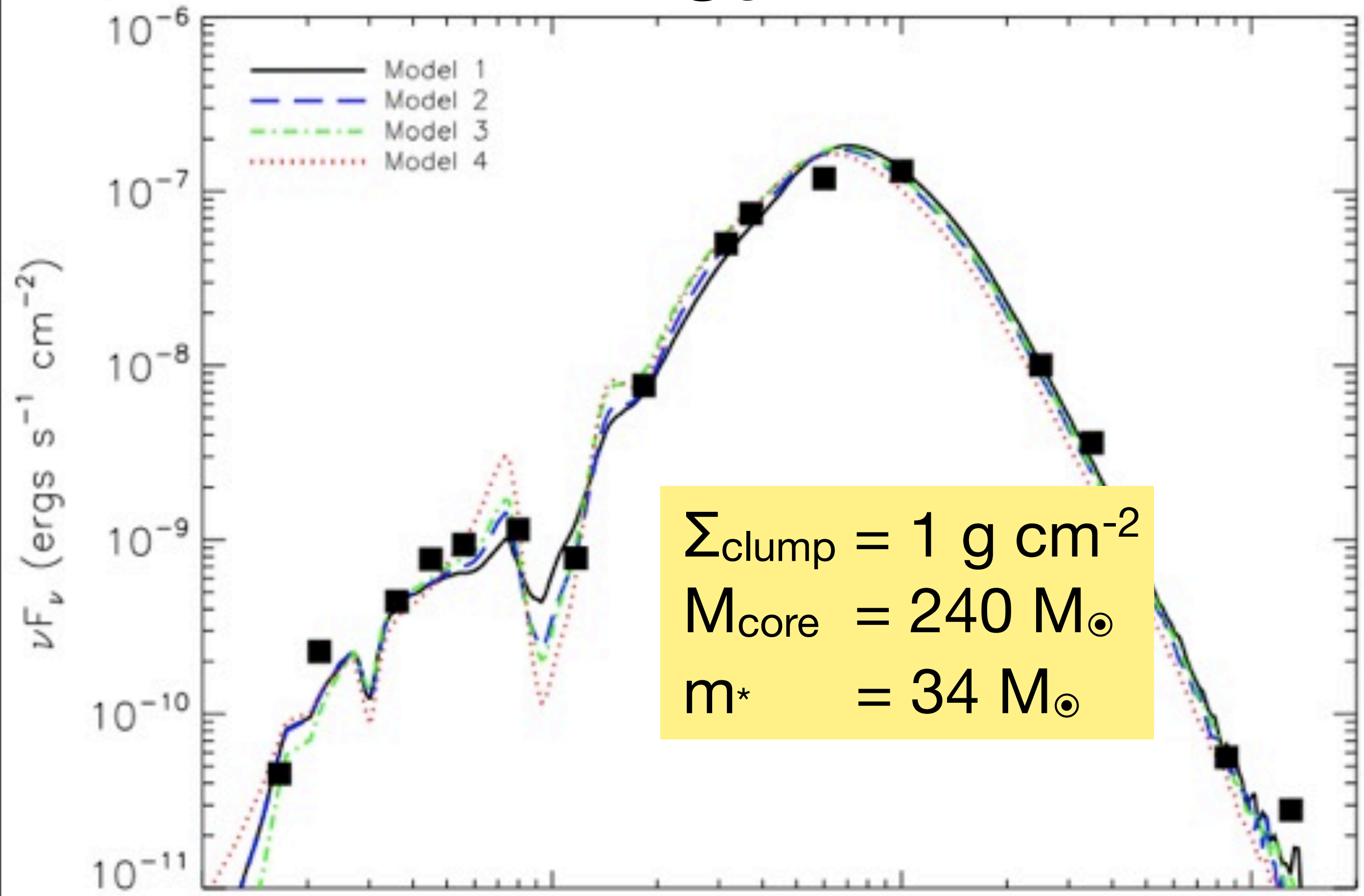
Massive Protostar G35.2N: d=2.2kpc; $L \sim 10^5 L_\odot$



De Buizer (2006)

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

Spectral energy distribution

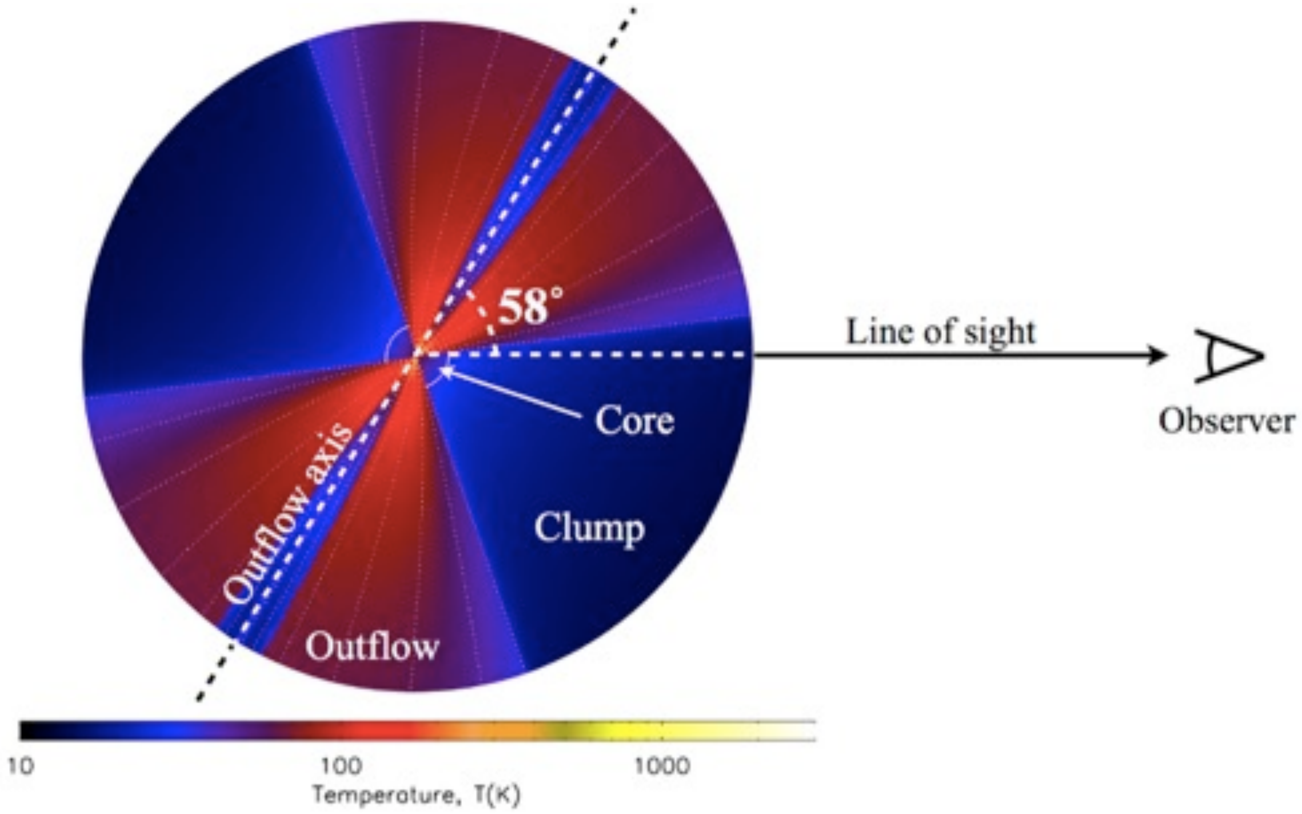


$\Sigma_{clump} = 1$ g cm^{-2}

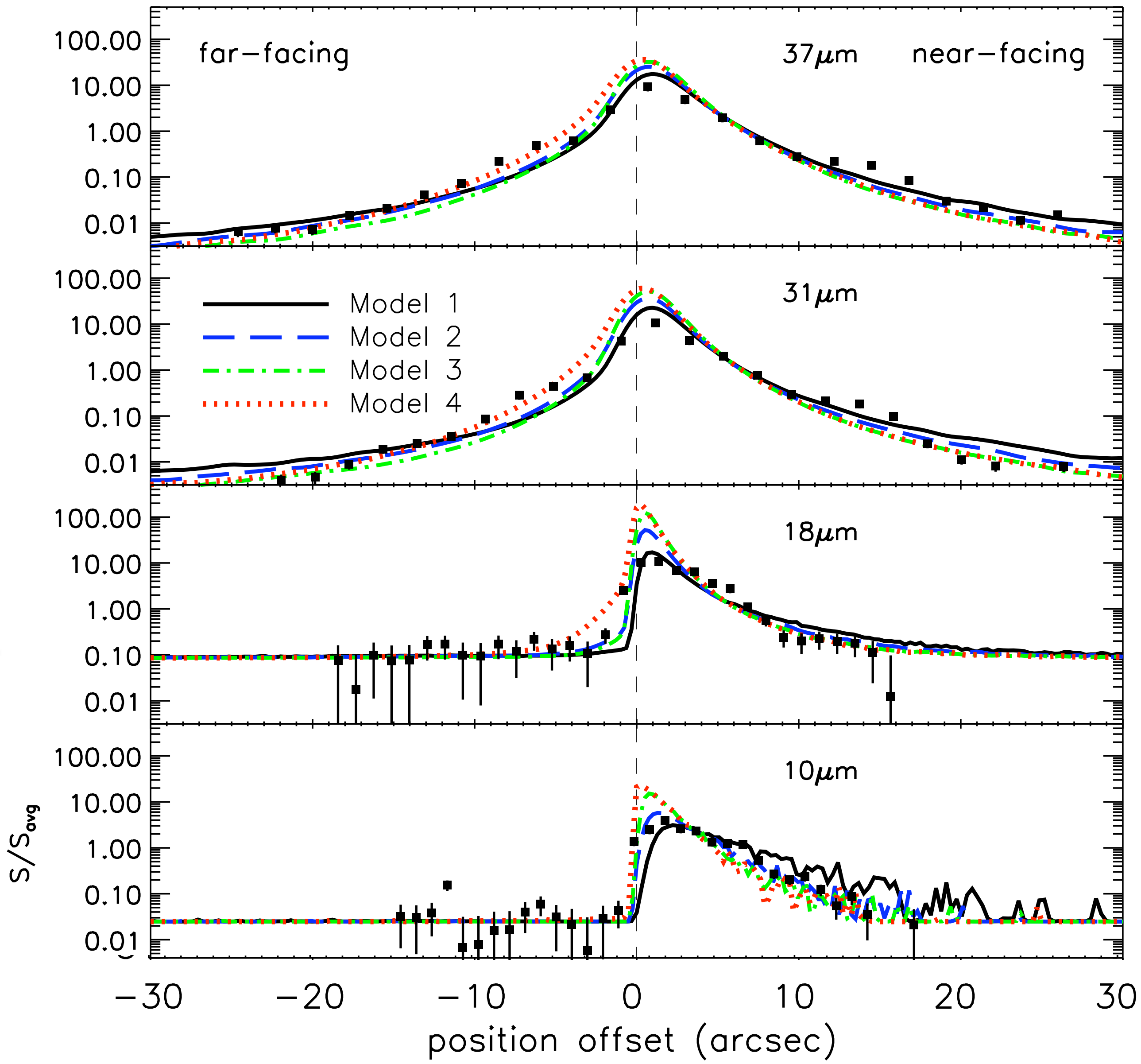
$M_{core} = 240\ M_\odot$

$m_* = 34\ M_\odot$

MIR SED requires high Σ core/clump



Flux profiles along outflow cavity axis



$L_{bol} \sim (0.66 - 2.2)\times 10^5 L_\odot$

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

$\Sigma_{cl} \sim 0.4 - 1$ g/cm^2

$\theta_w \sim 35 - 51^\circ$

$\theta_{view} \sim 43 - 58^\circ$

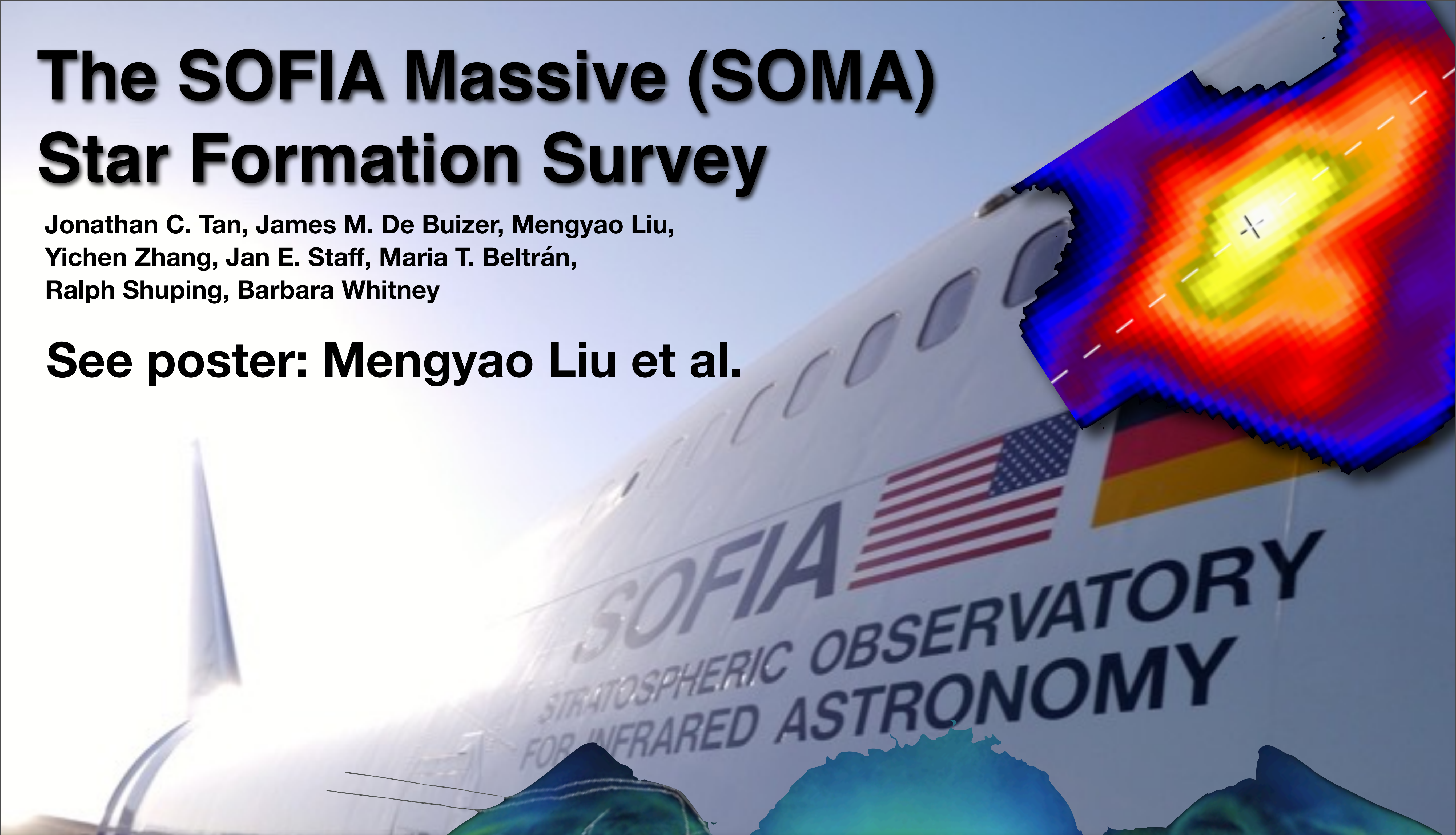
$m_* \sim 20 - 34\ M_\odot$

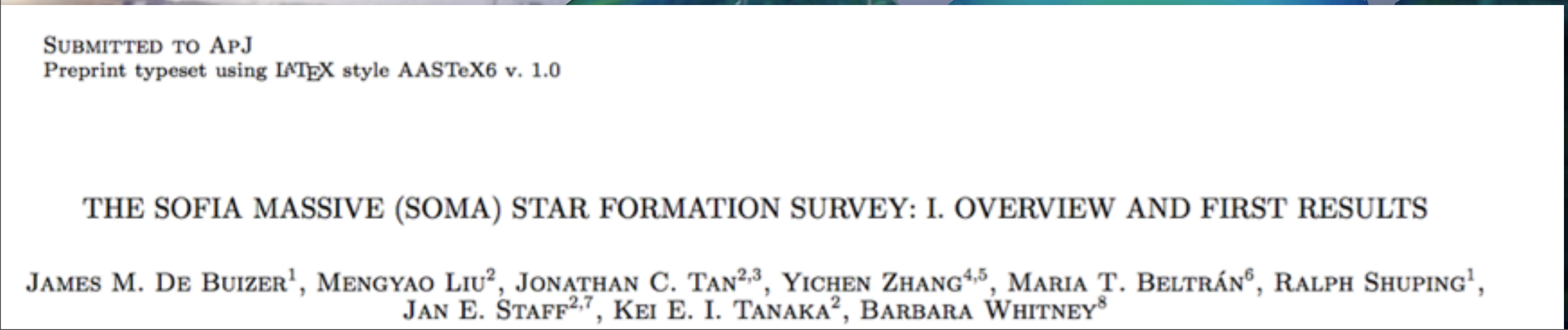
Simple, symmetric model provides good fit to SED & image intensity profiles: detailed constraints on how a massive star is forming.

The SOFIA Massive (SOMA) Star Formation Survey

Jonathan C. Tan, James M. De Buizer, Mengyao Liu,
Yichen Zhang, Jan E. Staff, Maria T. Beltrán,
Ralph Shuping, Barbara Whitney

See poster: Mengyao Liu et al.



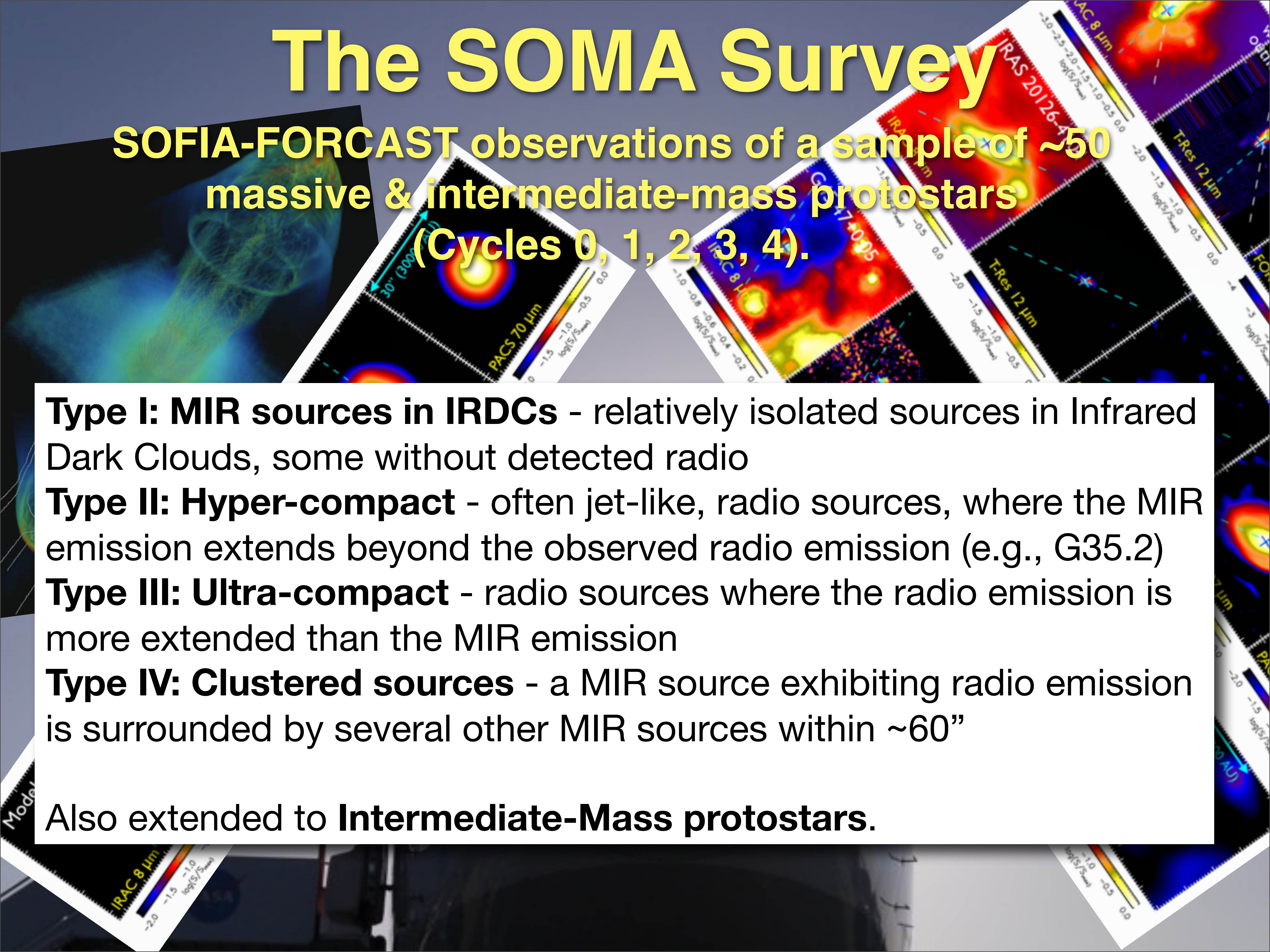

Submitted to ApJ
Preprint typeset using LaTeX style AASTeX6 v. 1.0

THE SOFIA MASSIVE (SOMA) STAR FORMATION SURVEY: I. OVERVIEW AND FIRST RESULTS

James M. De Buizer[1], Mengyao Liu[2], Jonathan C. Tan[2,3], Yichen Zhang[4,5], Maria T. Beltrán[6], Ralph Shuping[1],
Jan E. Staff[2,7], Kei E. I. Tanaka[2], Barbara Whitney[8]

The SOMA Survey

SOFIA-FORCAST observations of a sample of ~50 massive & intermediate-mass protostars (Cycles 0, 1, 2, 3, 4).



Type I: MIR sources in IRDCs - relatively isolated sources in Infrared Dark Clouds, some without detected radio

Type II: Hyper-compact - often jet-like, radio sources, where the MIR emission extends beyond the observed radio emission (e.g., G35.2)

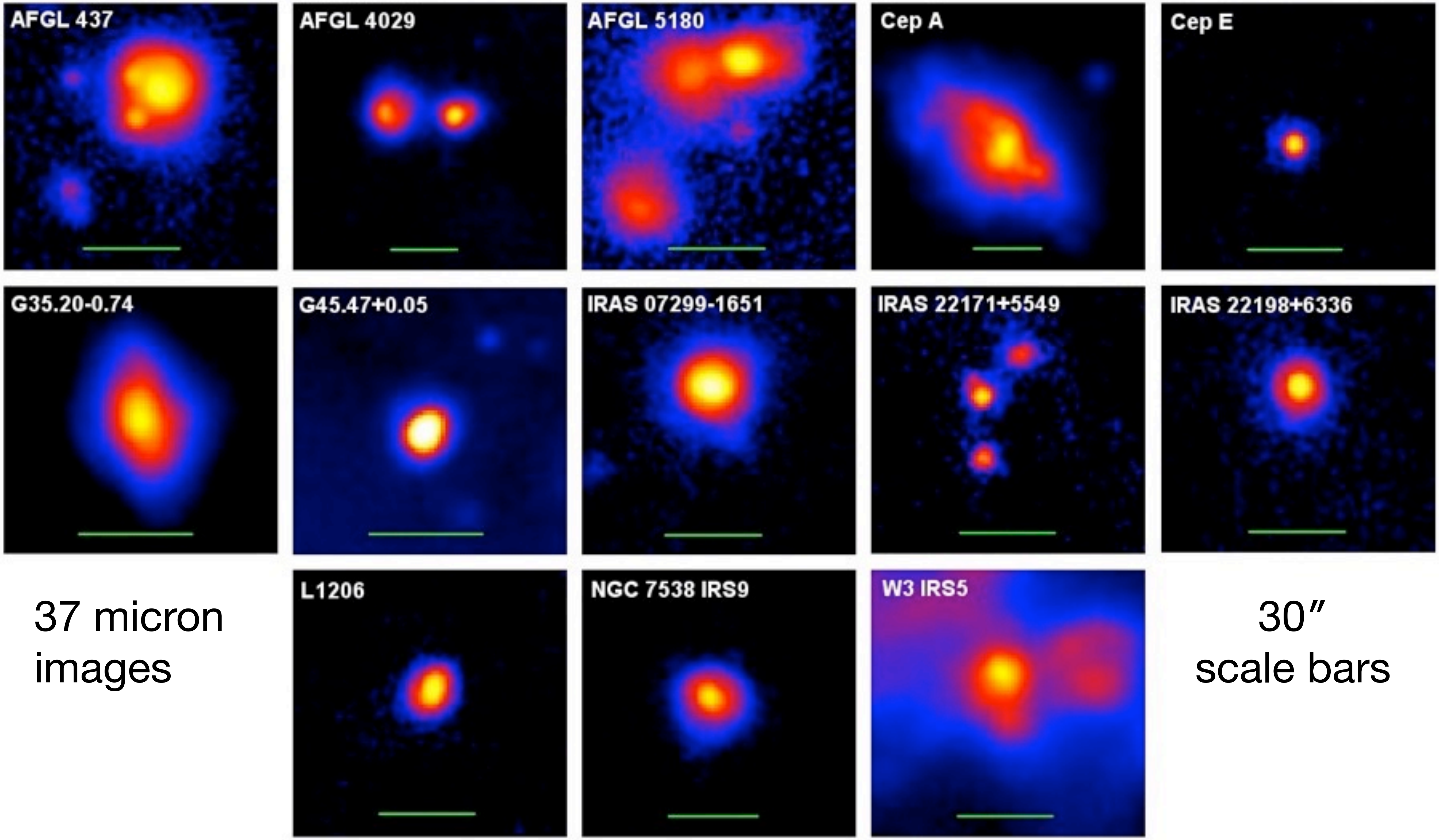
Type III: Ultra-compact - radio sources where the radio emission is more extended than the MIR emission

Type IV: Clustered sources - a MIR source exhibiting radio emission is surrounded by several other MIR sources within ~60”

Also extended to **Intermediate-Mass protostars**.

The SOMA Survey

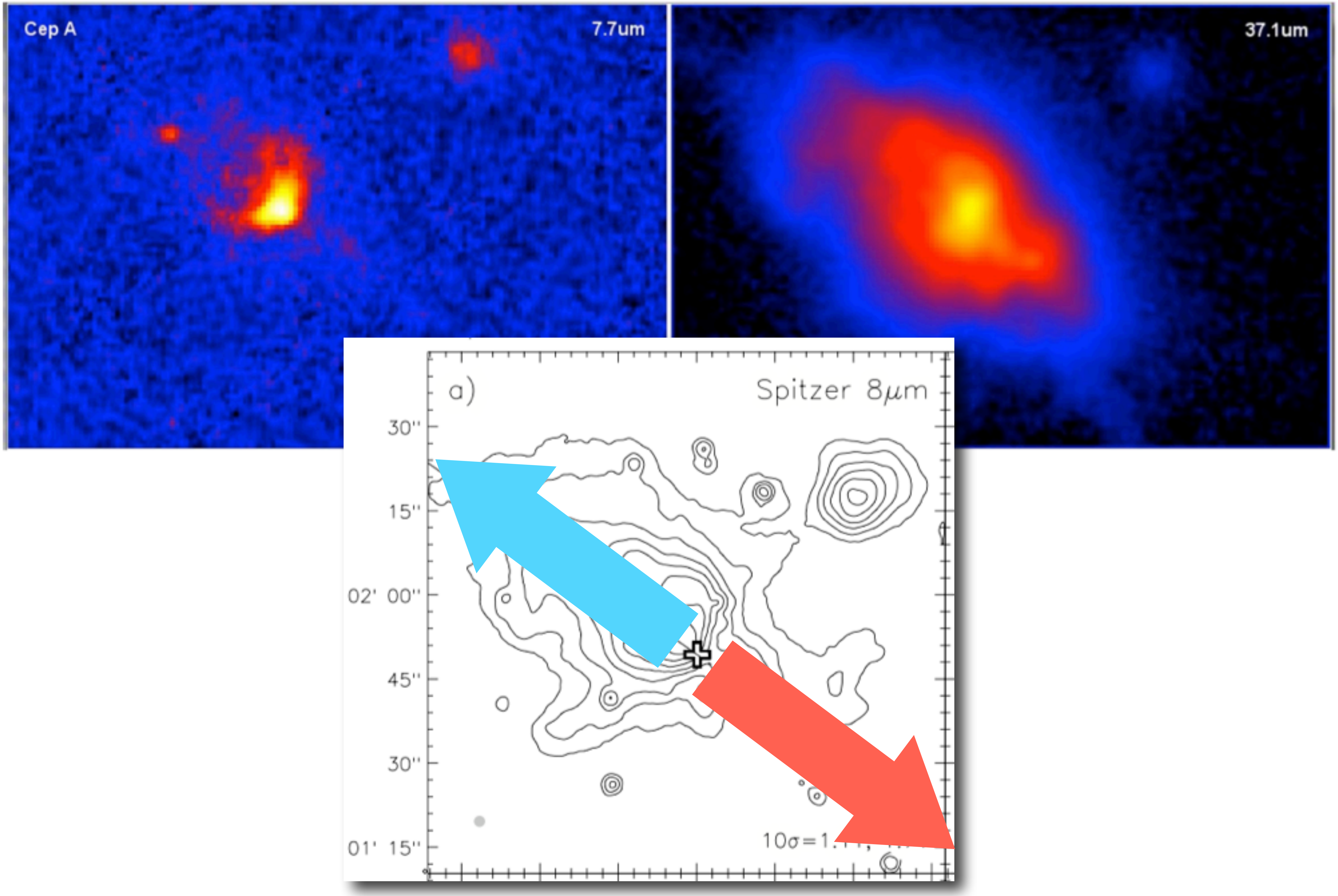
20 protostars observed as of Oct 2016 (end of Cycle 4).



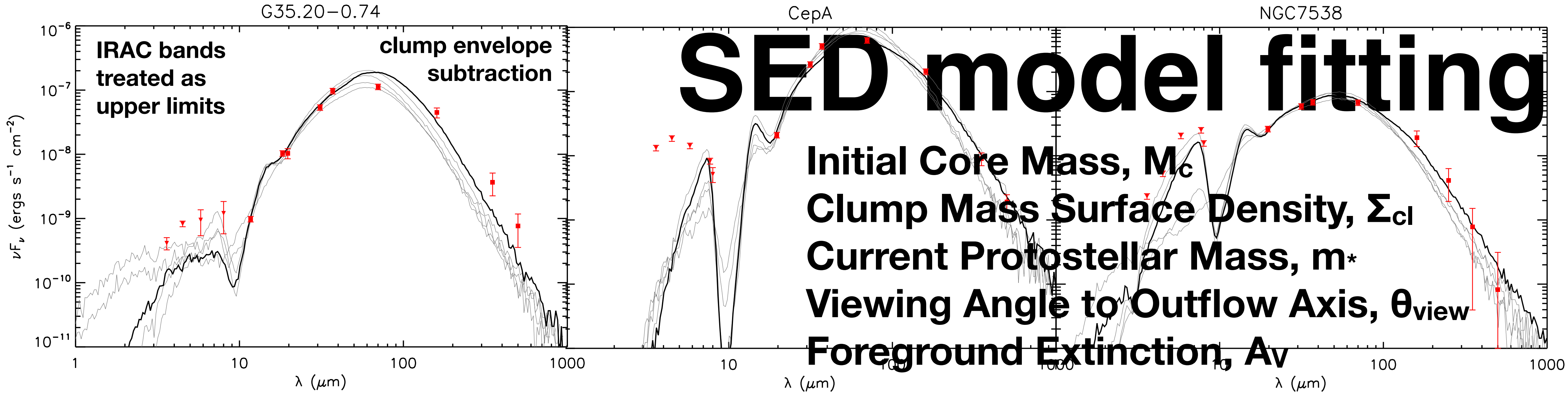
37 micron images

30″ scale bars

Cepheus A



SED model fitting



IRAC bands treated as upper limits

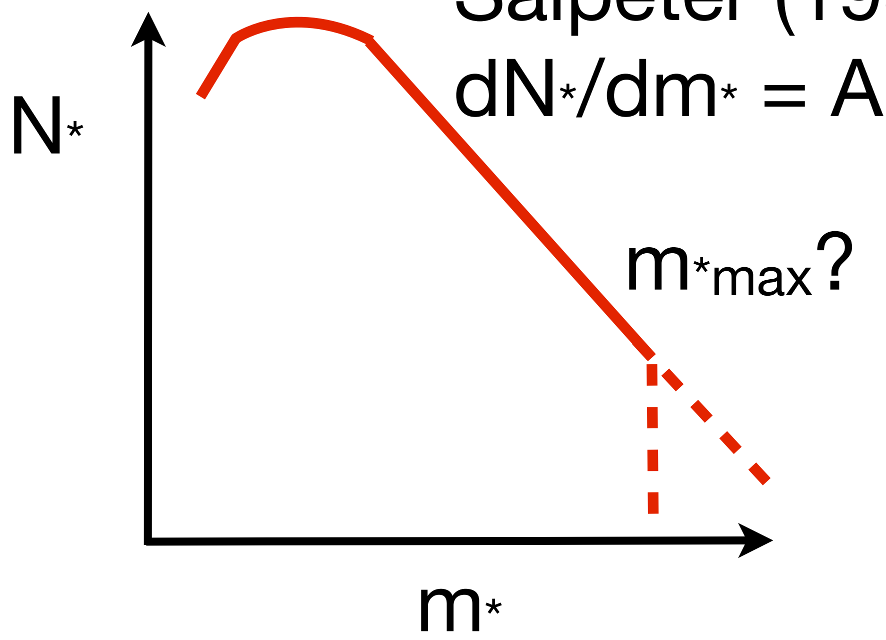
clump envelope subtraction

- **Initial Core Mass, M_c**
- **Clump Mass Surface Density, Σ_{cl}**
- **Current Protostellar Mass, m_***
- **Viewing Angle to Outflow Axis, θ_{view}**
- **Foreground Extinction, A_V**

	Zhang & Tan models									
Source	χ^2/N	M_c ($M_\odot$)	Σ_{cl} (g cm^{-2})	m_* ($M_\odot$)	θ_{view} (deg)	A_V (mag)	M_{env} ($M_\odot$)	$\theta_{w,esc}$ (deg)	$\dot{M}_{disk}$ ($M_\odot$/yr)	L_{bol} ($L_\odot$)
G35.20-0.74	4.3	120	3.2	12	29	37.6	99	18	9.6×10^{-4}	5.4×10^{4}
	8.0	120	1.0	24	48	57.2	68	37	4.9×10^{-4}	1.5×10^{5}
	8.0	120	1.0	12	29	3.5	96	20	4.0×10^{-4}	5.0×10^{4}
	9.8	60	3.2	16	48	81.1	31	32	8.4×10^{-4}	1.2×10^{5}
	10.8	60	3.2	12	48	7.1	38	27	7.6×10^{-4}	5.2×10^{4}
Cep A	4.9	480	0.1	12	83	81.1	458	12	1.0×10^{-4}	2.4×10^{4}
	5.0	480	0.1	16	89	100.0	441	15	1.2×10^{-4}	3.9×10^{4}
	6.9	120	0.3	12	62	61.4	93	24	1.6×10^{-4}	3.7×10^{4}
	7.0	60	3.2	16	68	87.0	31	32	8.4×10^{-4}	1.2×10^{5}
	7.4	120	1.0	24	55	100.0	68	37	4.9×10^{-4}	1.5×10^{5}
NGC 7538 IRS9	0.6	480	0.1	16	22	9.3	441	15	1.2×10^{-4}	3.9×10^{4}
	1.2	240	0.1	24	44	37.6	171	33	1.1×10^{-4}	8.3×10^{4}
	1.4	240	0.1	32	48	65.8	140	42	1.1×10^{-4}	1.5×10^{5}
	1.7	60	3.2	12	34	14.2	38	27	7.6×10^{-4}	5.2×10^{4}
	2.3	60	3.2	16	39	61.4	31	32	8.4×10^{-4}	1.2×10^{5}

Feedback During Massive Star Formation

Is there a maximum stellar mass set by by formation processes?



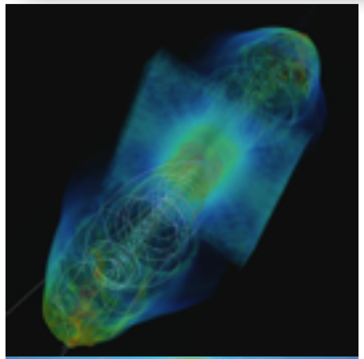
Salpeter (1955)
$dN_*/dm_* = A\, m_*^{-2.35}$

m_{*max}~150 $M_\odot$ (e.g. Figer 2005).

But Crowther et al. (2010) claim most massive star to form was initially ~300$M_\odot$, consistent with statistical sampling of Salpeter IMF with no maximum cutoff mass.

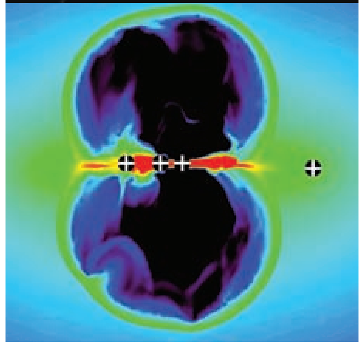
Feedback processes:

1. Protostellar outflows
2. Ionization
3. Stellar winds
4. Radiation pressure
5. Supernovae



Staff+ (2010); Kuiper+ (2015)

Peters et al. 2010, 2011



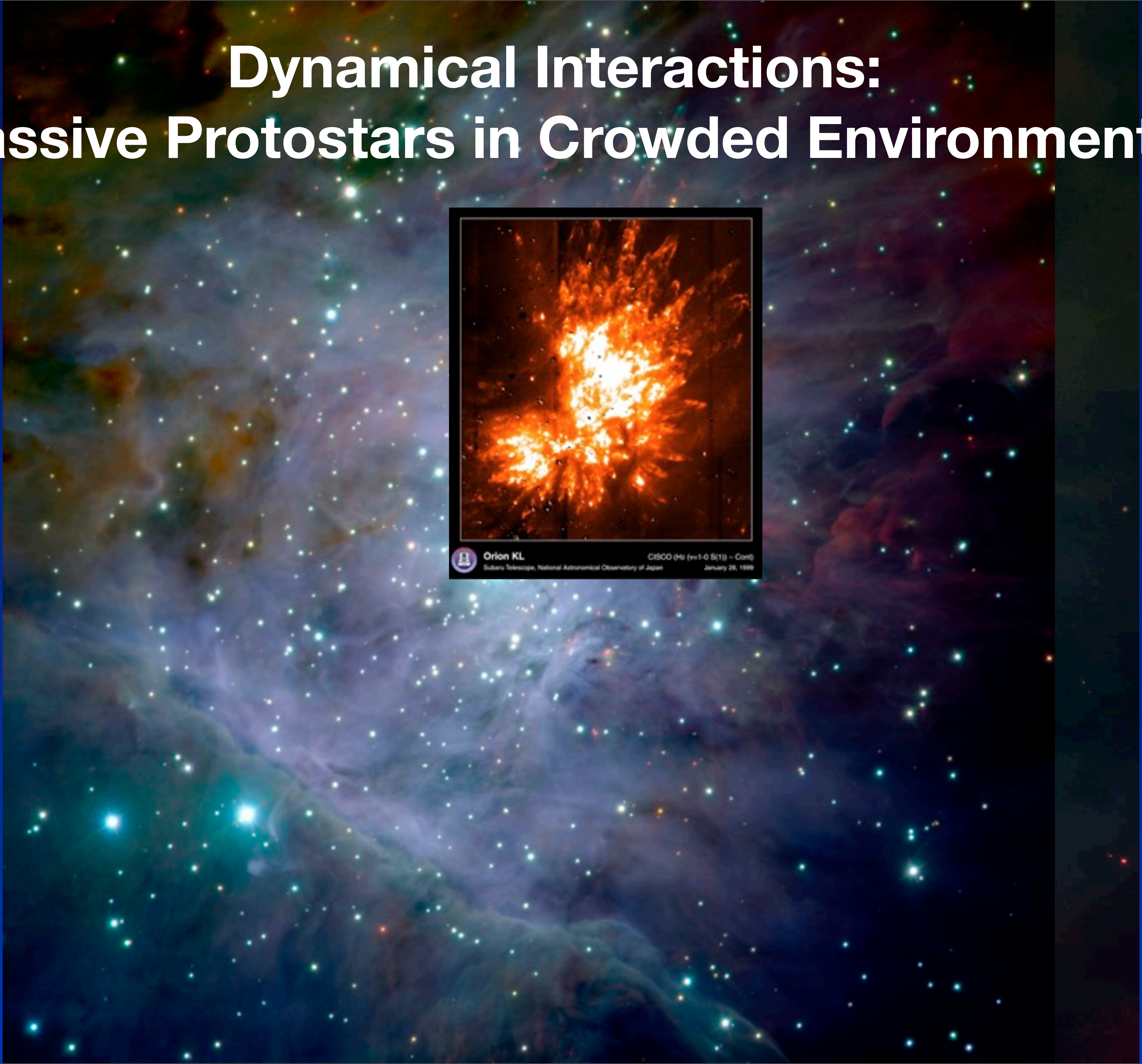
Krumholz+ (2009); Rosen+ (2016)
Kuiper et al. (2012); Klassen+ (2016)

Accretion processes: Core/disk fragmentation (Kratter & Matzner 06; Peters et al. 10)

Stellar processes: Nuclear burning instabilities/enhanced mass loss

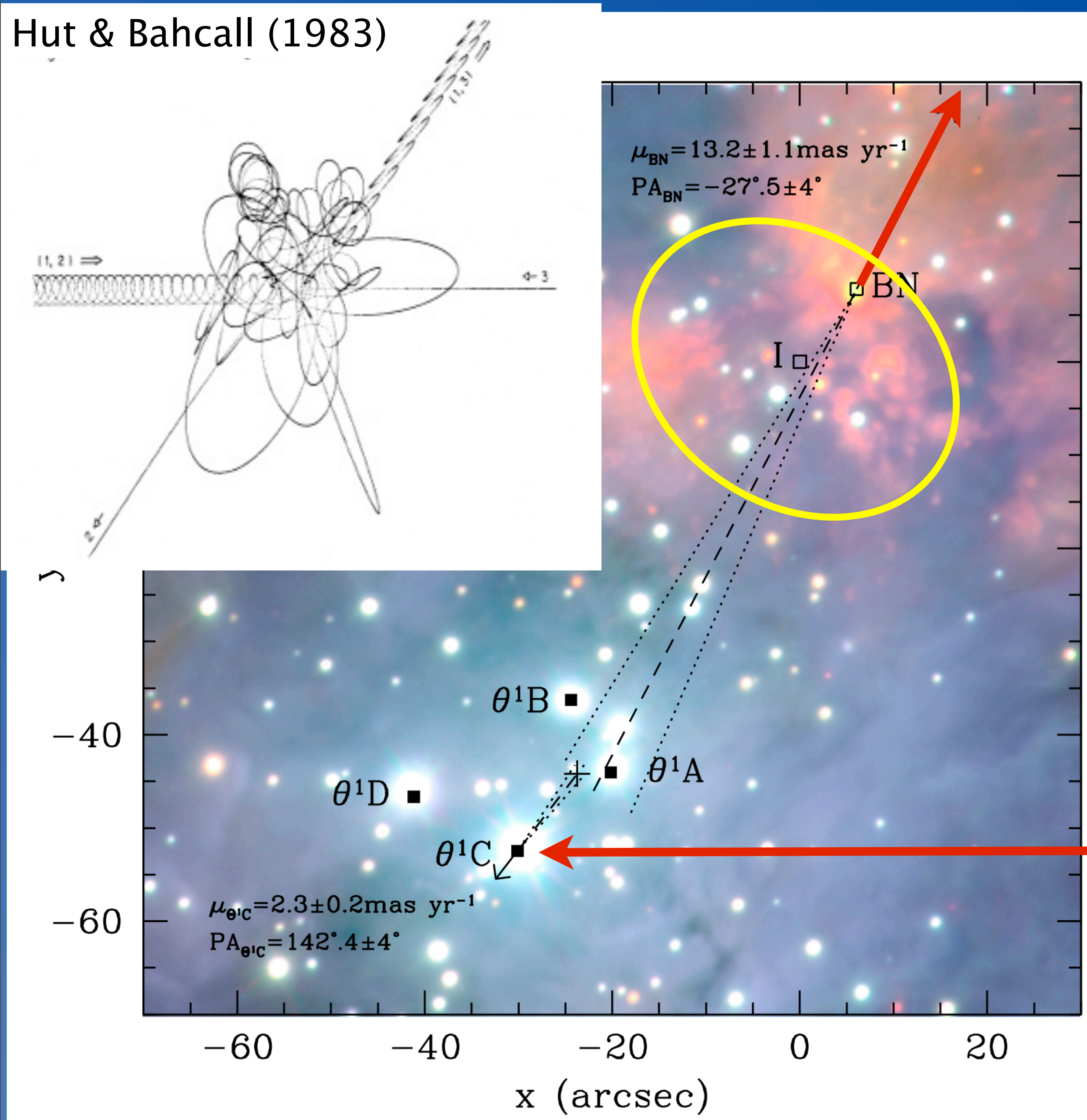
Currently unclear what sets the shape of the massive star IMF

Dynamical Interactions:
Massive Protostars in Crowded Environments



Orion KL protostar perturbed by a passing runaway star (BN) ejected from the Trapezium star θ^1C

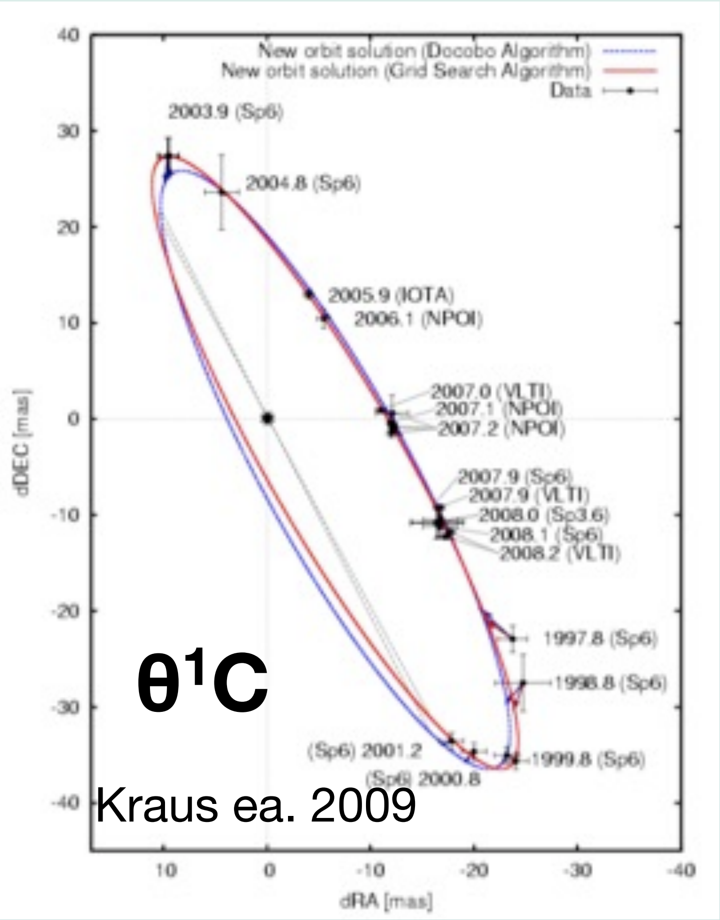
Tan (2004)
Chatterjee & Tan (2012)



BN is a runaway B star moving at ~30 km/s

(Plambeck et al. 1995)

Protostellar Core, centered on Source I



Kraus ea. 2009

Orion KL: a perturbed massive star-forming core

Tan (2004)
Chatterjee & Tan (2012)

Dynamical “harassment” of protostellar cores in star clusters.

Star cluster formation involves interplay of stellar and gas dynamics.

HOWEVER, SEE:
Bally & Zinnecker 2005;
Rodriguez et al. (2005)
Gomez et al. (2005)
Gomez et al. (2008)
Zapata et al. (2009)
Zapata et al. (2011a,b)
Bally et al. (2011)
Goddi et al. (2011)
Moeckel & Goddi (2011)
...

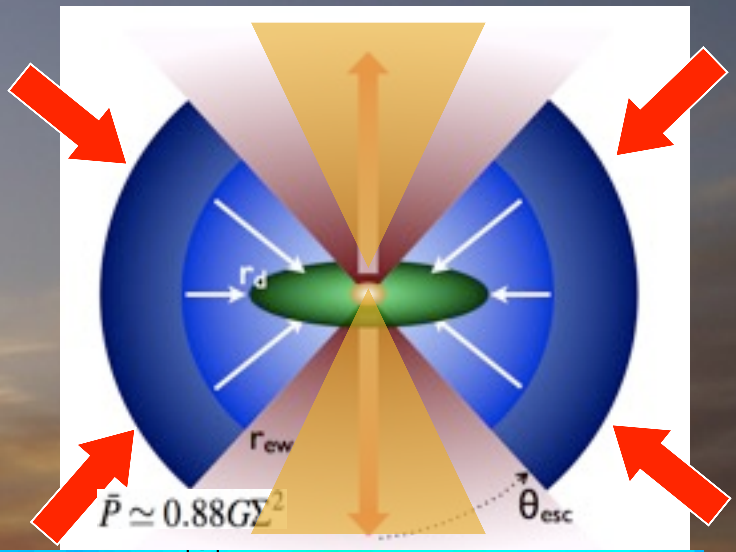
BUT, SEE
Plambeck et al. (2016)

Conclusions

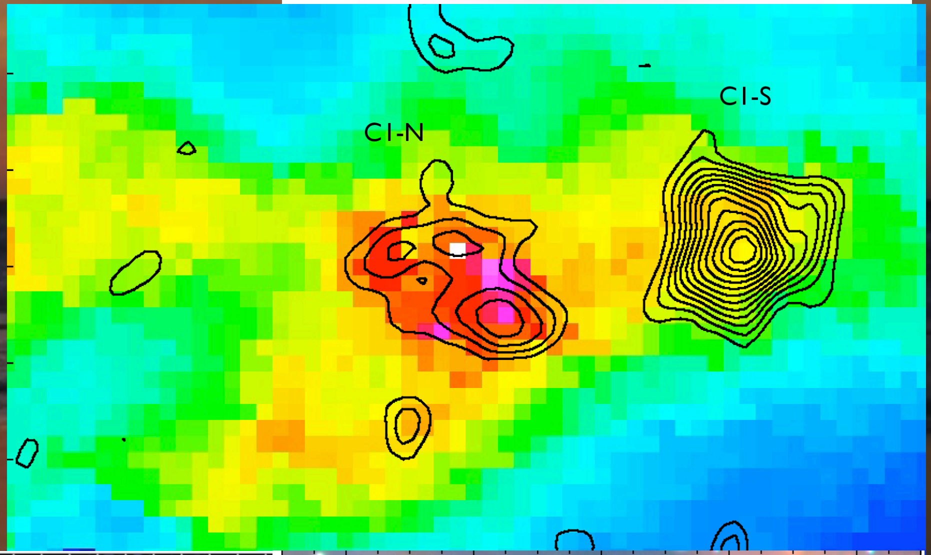
Massive Star Formation Theories:

Core Accretion; Competitive Accretion; Protostellar Collisions

Theory: “Turbulent Core Model”: normalize core surface pressure to surrounding clump pressure, i.e. self-gravitating weight. Core supported by non-thermal pressure (B-fields/turbulence).

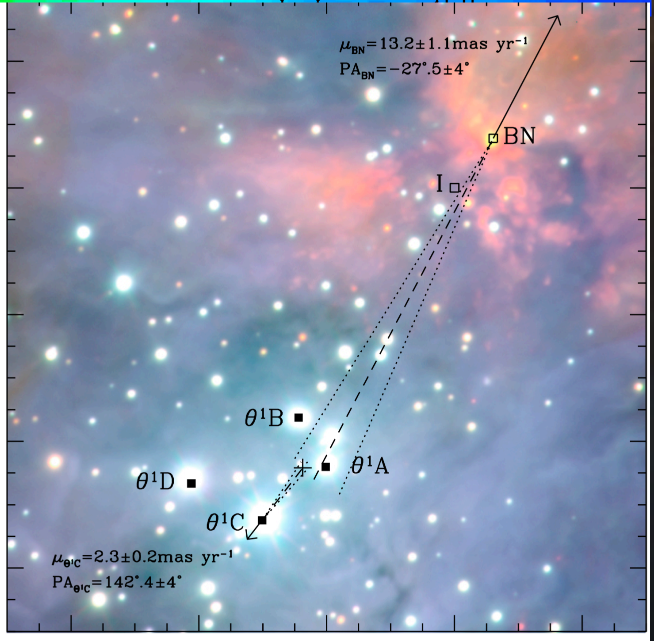


1: Massive starless/early-stage cores exist



2: They are near virial equilibrium

3: Massive protostars can have a similar morphology to low-mass protostars, but dynamical interactions can occur (BN/KL)



4. SOFIA is playing a crucial role: IRDC formation, clump infall, astrochemical ages, SEDs and images, and more!