Open Questions in Massive Star Formation

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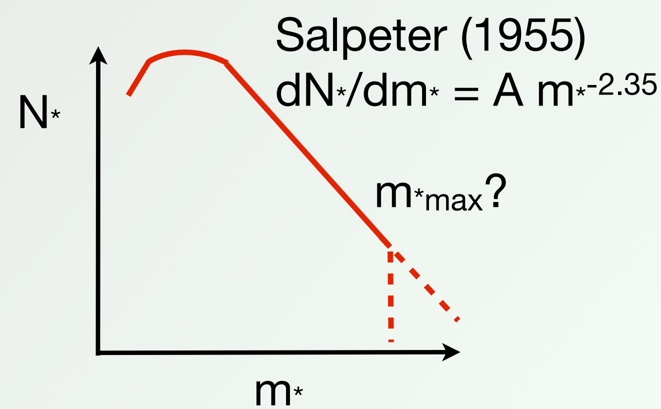
Background image: Bill Saxton & Alexandra Angelich (NRAO/AUI/NSF); ALMA (ESO/NAOJ/NRAO)

The Importance of Massive Stars and Clusters

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



How do these properties vary with environment?
Subgrid model of SF? Threshold n_{H*}? Efficiency ε_{ff}?

Massive Star Formation Theories

Core Accretion:

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

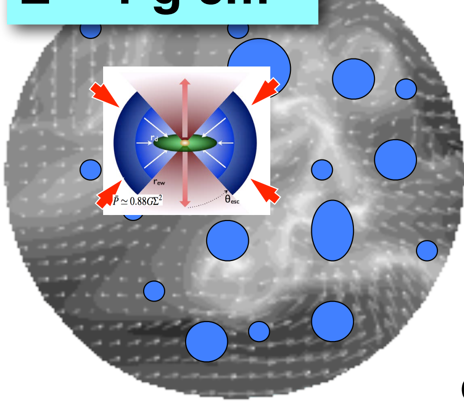
(e.g. Myers & Fuller 1992; Caselli & Myers 1995; McLaughlin & Pudritz 1997; Osorio+ 1999; Nakano+ 2000; Behrend & Maeder 2001)

Turbulent Core Model:

(McKee & Tan 2002, 2003)

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

$\Sigma \sim 1$ g cm^{-2}



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

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

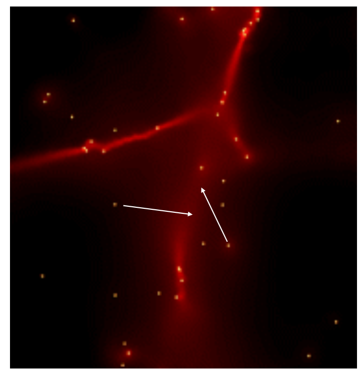
Cores form from this turbulent/magnetized medium: at any instant there is a small mass fraction in cores. These cores collapse quickly to feed a central disk to form individual stars or binaries.

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

Competitive (Clump-fed) Accretion:

(Bonnell, Clarke, Bate, Pringle 2001; Bonnell, Vine, & Bate 2004; Schmeja & Klessen 2004; Wang, Li, Abel, Nakamura 2010; Padoan et al. 2020 [Turbulence-fed]; Grudić et al. 2022)

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.

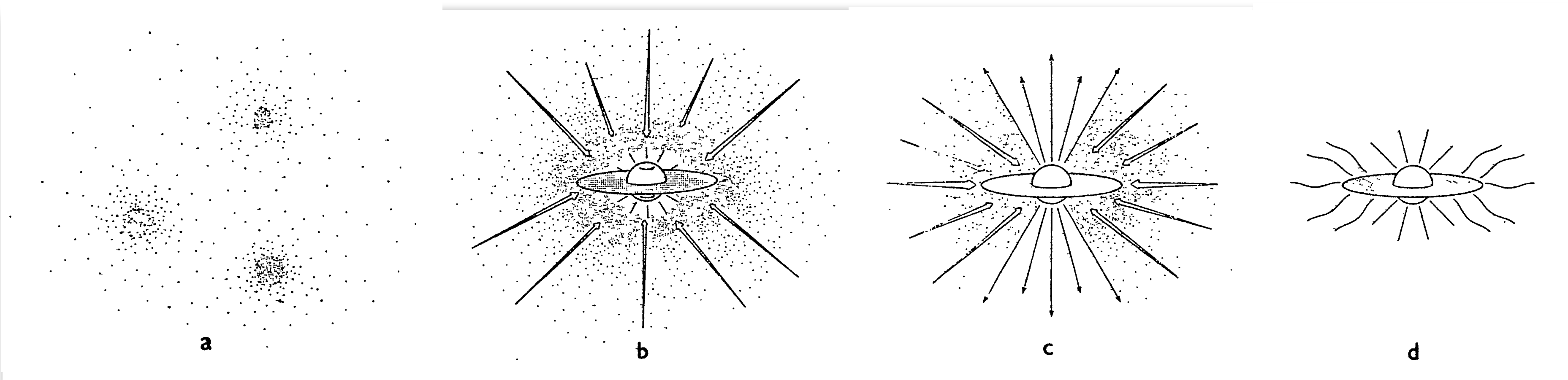
Violent interactions? Mergers?

(Bonnell, Bate & Zinnecker 1998; Bally & Zinnecker 2005 Bally et al. 2011; 2021)

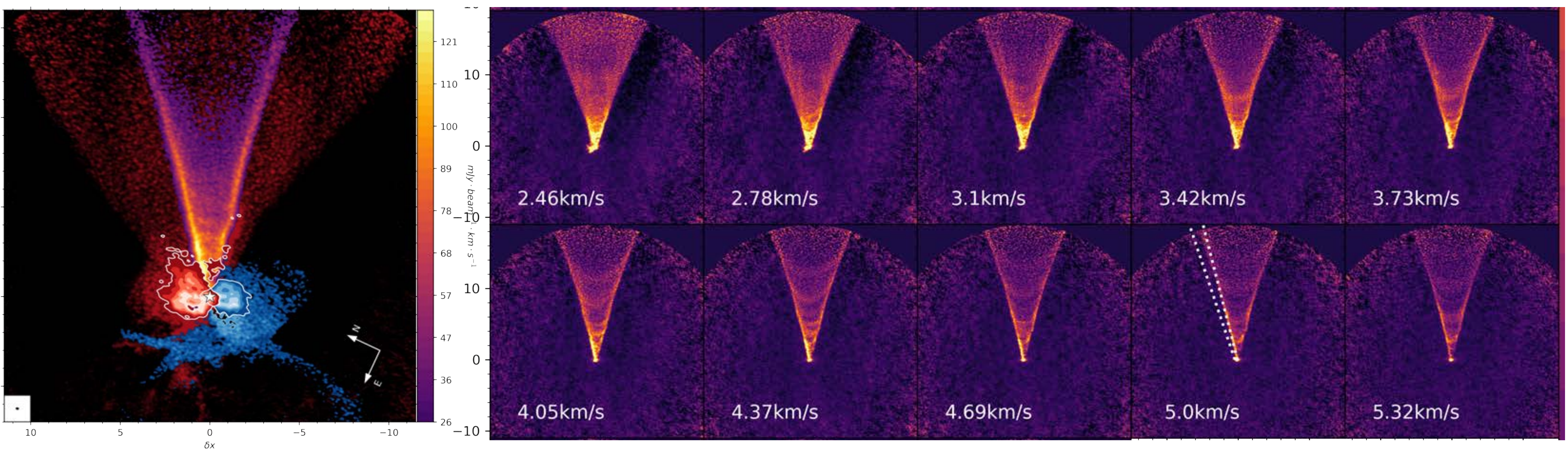
Core Accretion

Low-Mass Prestellar and Protostellar Gas Cores

Shu (1977), Shu, Adams & Lizano (1987)



Observed order in low-mass star formation



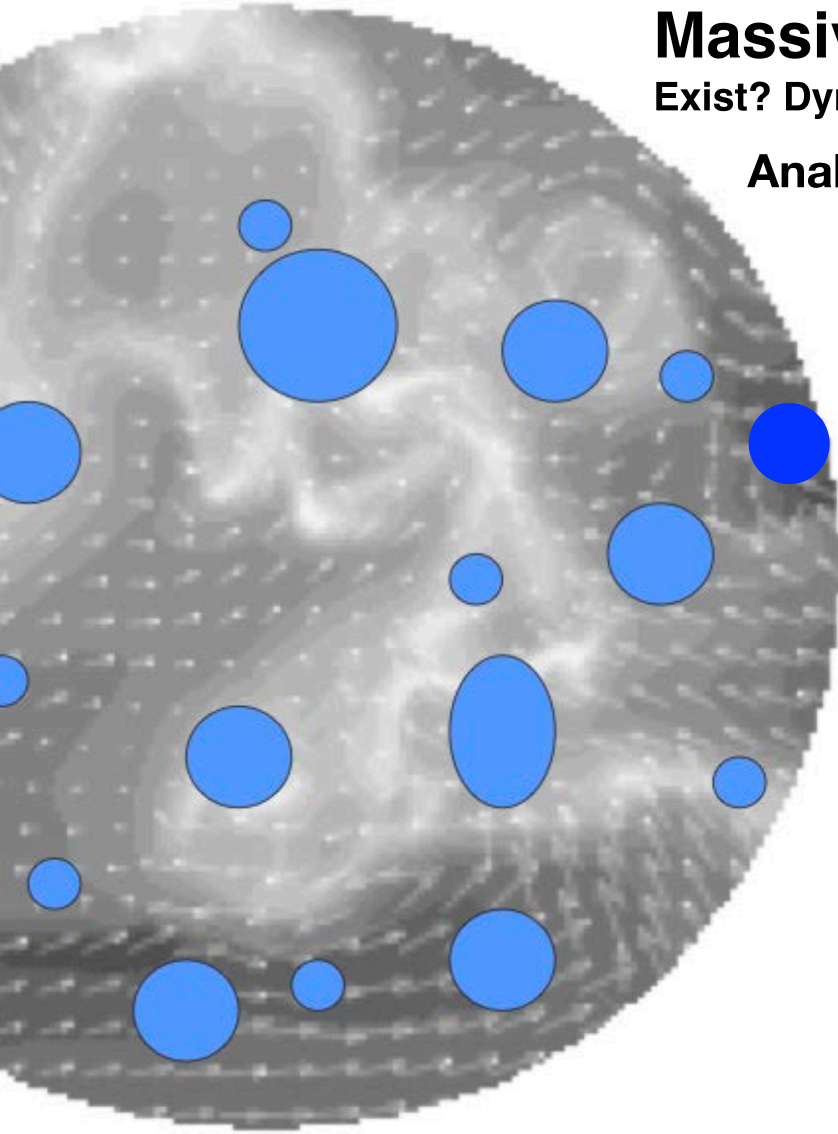
de Valon et al. (2020)

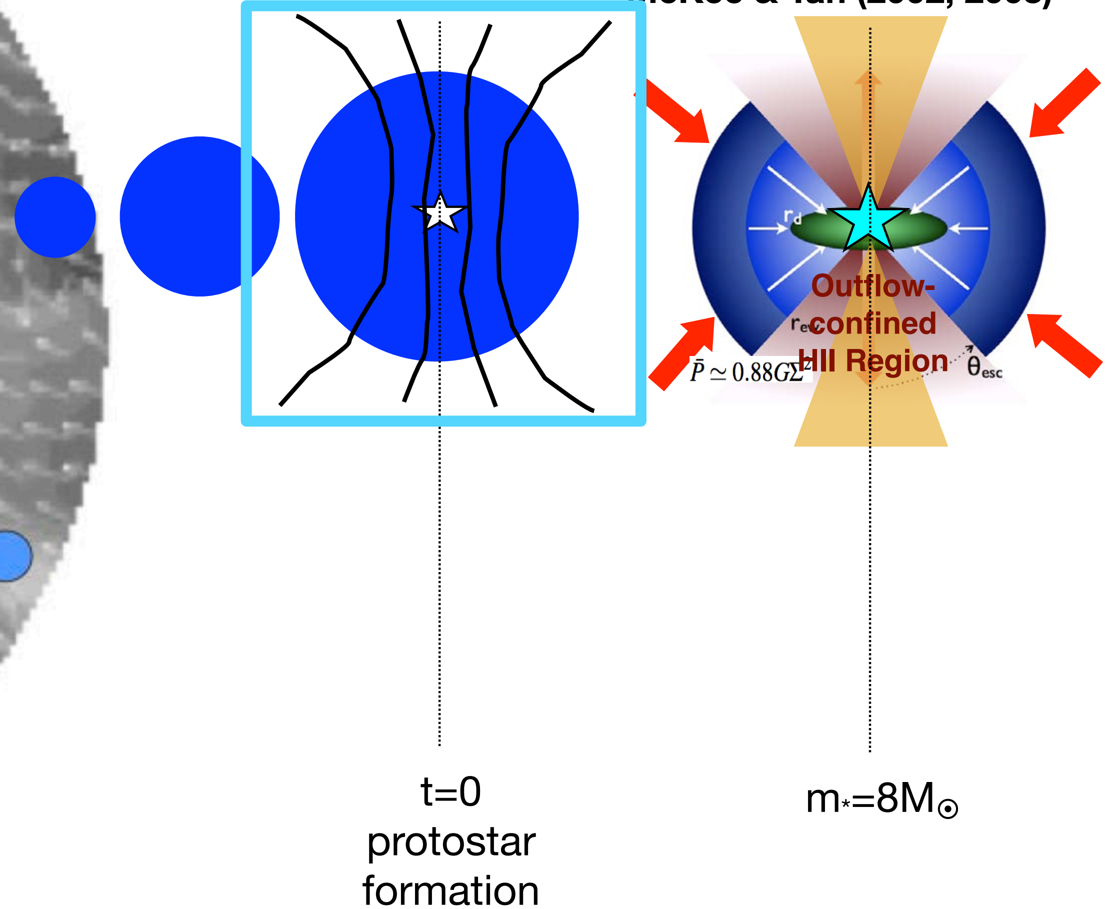
Massive Prestellar and Protostellar Cores

Exist? Dynamical state? SFE (CMF → IMF)? Multiplicity?

Analytic Theory: e.g. Turbulent Core Model

McKee & Tan (2002, 2003)



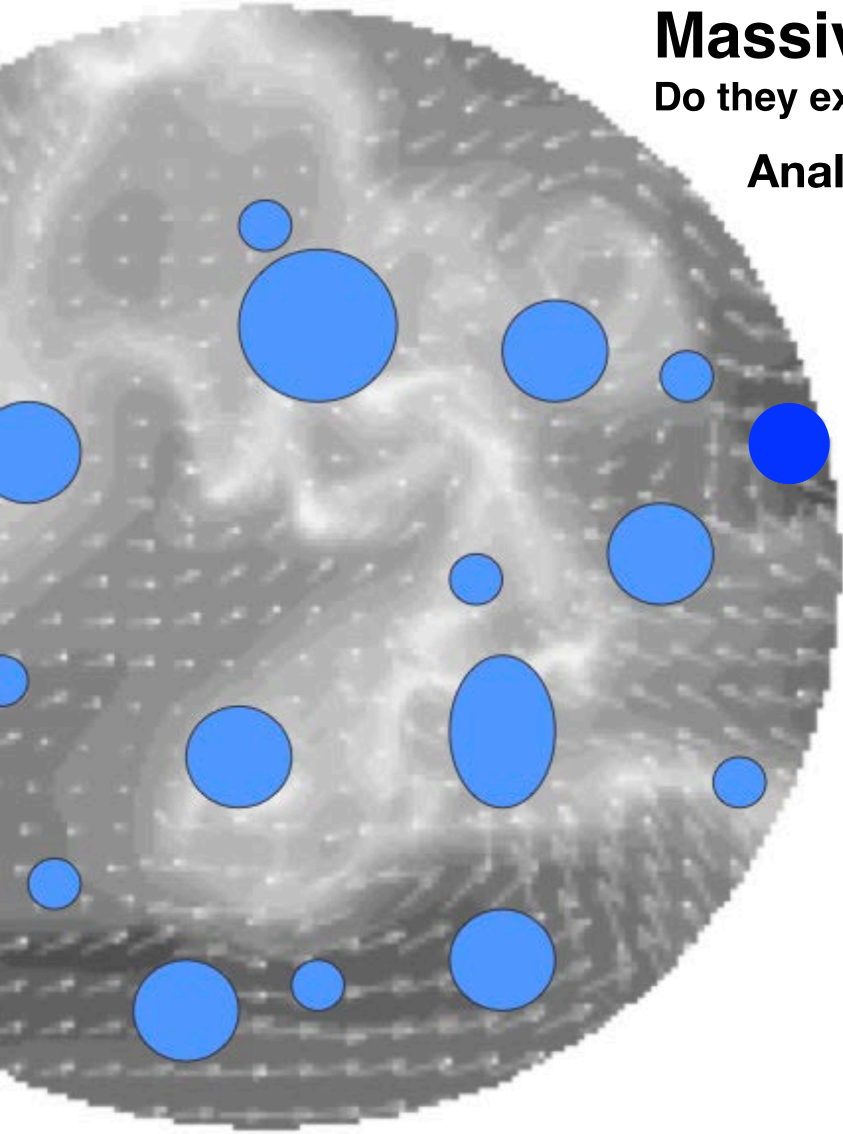


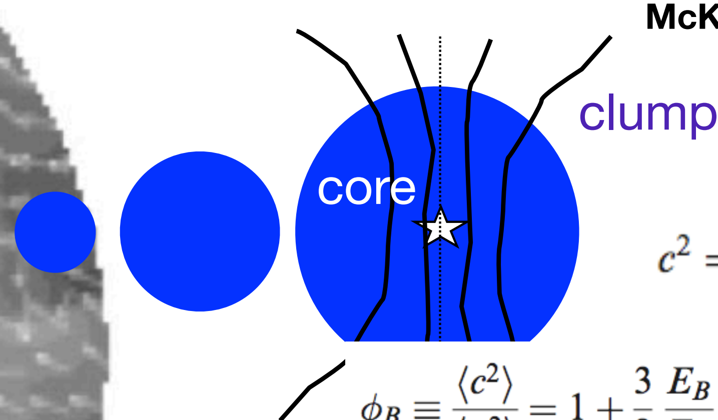
Massive Prestellar Cores

Do they exist? How to find them? Close to virial equilibrium?

Analytic Theory: e.g. Turbulent Core Model

McKee & Tan (2002, 2003)





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

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

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

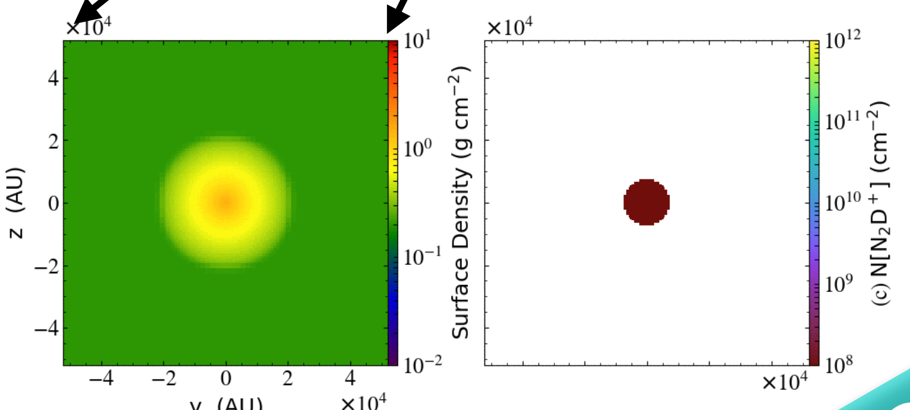
$$\sigma_{\rm c,vir} \rightarrow 1.09 \left(\frac{M_c}{60 M_\odot}\right)^{1/4} \left(\frac{\Sigma_{\rm cl}}{1\ {\rm g\ cm^{-2}}}\right)^{1/4} {\rm km\ s^{-1}}$$

$n_{\rm H,s} \rightarrow 1.1\times10^6\ {\rm cm^{-3}}$

t=0
protostar
formation

Numerical Simulations - MHD + Astrochemistry
Filaments, Clumps and Cores

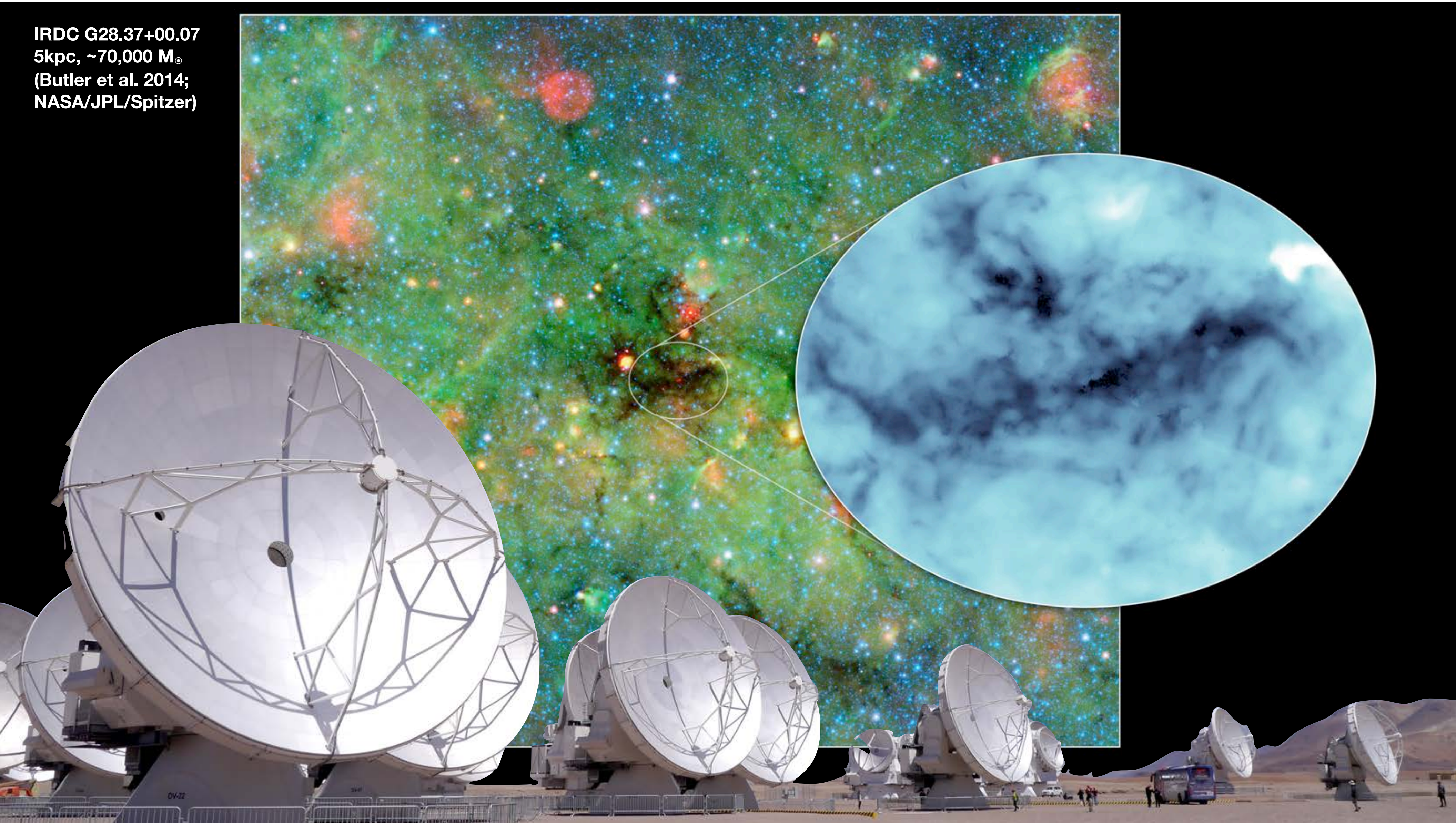
Chia-Jung Hsu
(Chalmers)



N_2H^+ and N_2D^+ as key tracers of prestellar cores
Goodson et al. 2016; Hsu et al. 2021

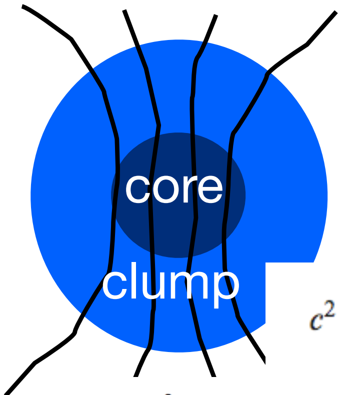
See Blake Drechsler's poster!

Wu et al. 2015, 2017
Hsu et al., in prep.
García-Alvarado et al., in prep.
Drechsler et al., in prep.


IRDC G28.37+00.07
5kpc, ~70,000 $M_\odot$
(Butler et al. 2014;
NASA/JPL/Spitzer)

Comparison to Turbulent Core Model

Tan et al. (2013)



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

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

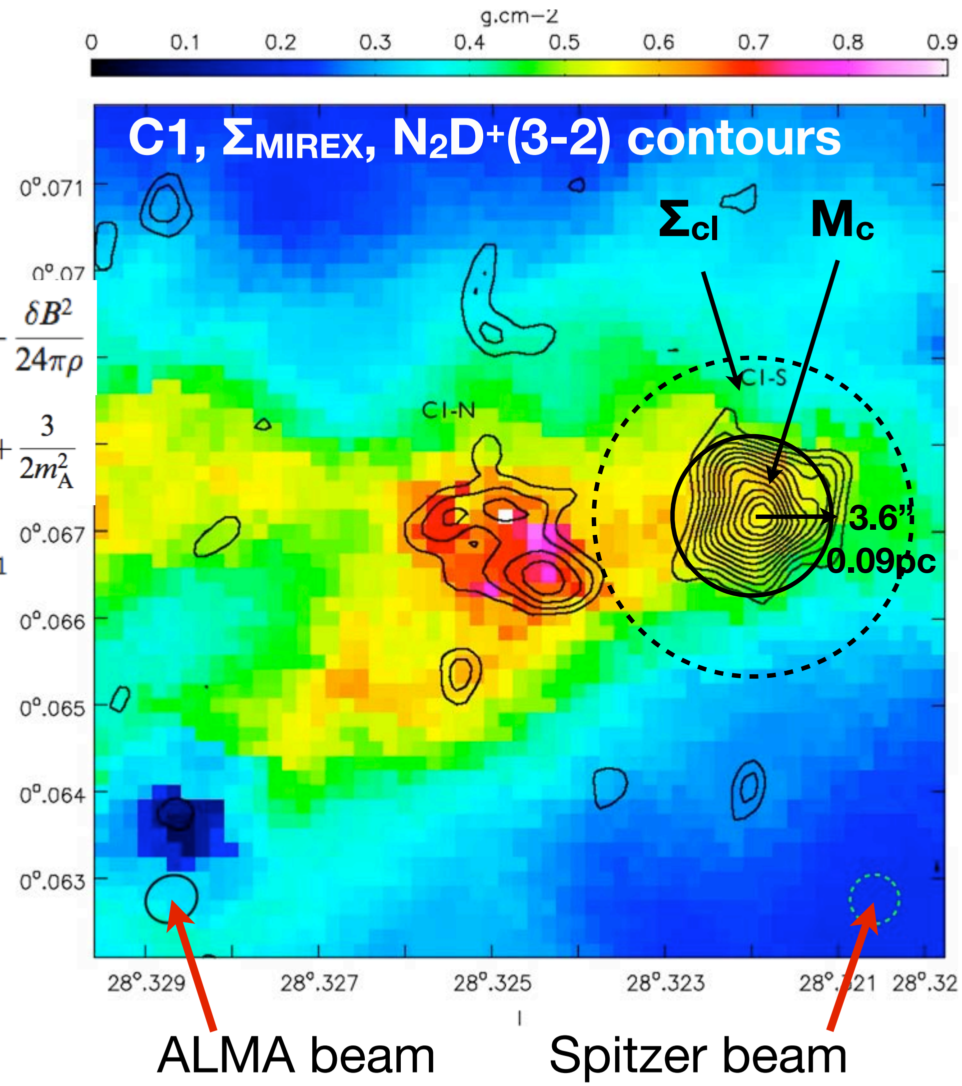
$$\sigma_{c,\mathrm{vir}} \rightarrow 1.09 \left(\frac{M_c}{60 M_\odot}\right)^{1/4} \left(\frac{\Sigma_{\mathrm{cl}}}{1\ \mathrm{g\ cm^{-2}}}\right)^{1/4} \mathrm{km\ s^{-1}}$$

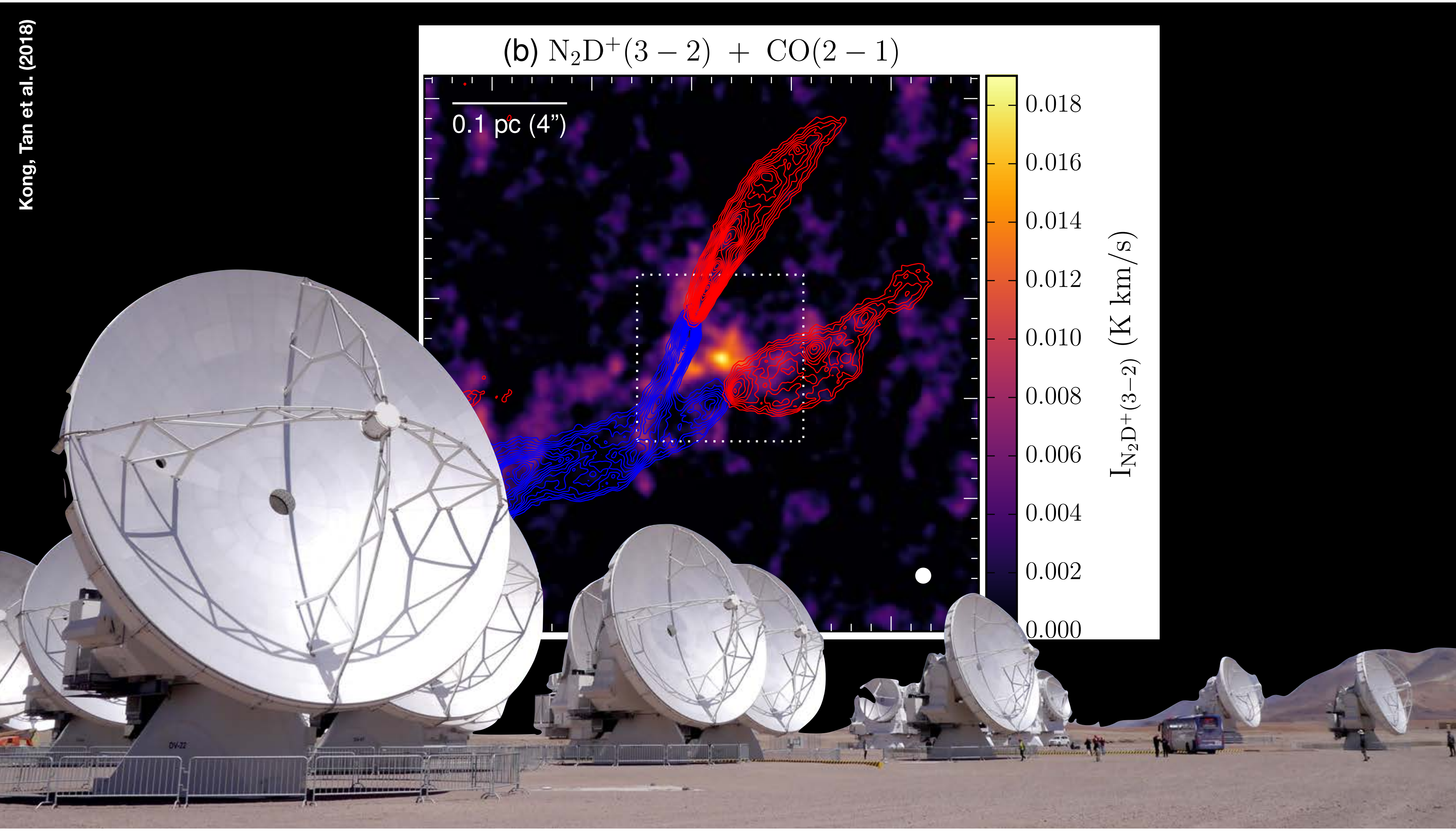
Core masses inside 3σ N_2D^+ contour:

Σ_{cl} = 0.36 g cm^{-2}

$M_{c,MIREX}$ = 55.2 ± 25 $M_\odot$

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

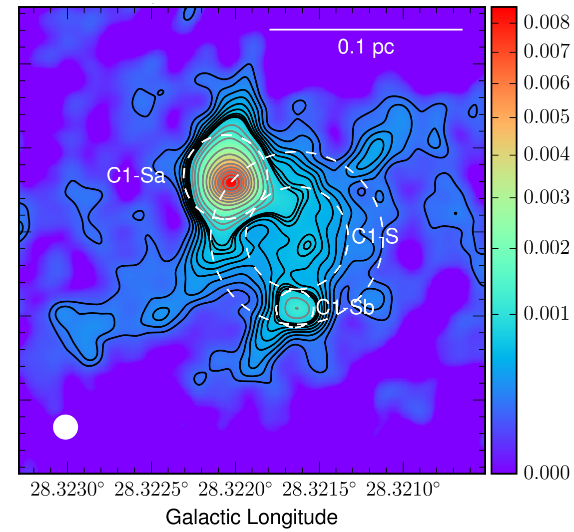


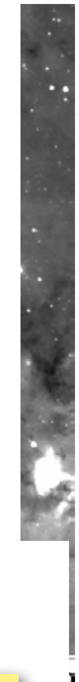


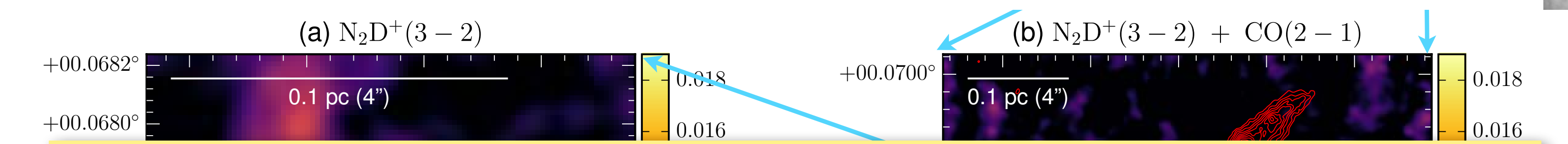
Kong, Tan et al. (2018)

Massive Pre-Stellar Cores?

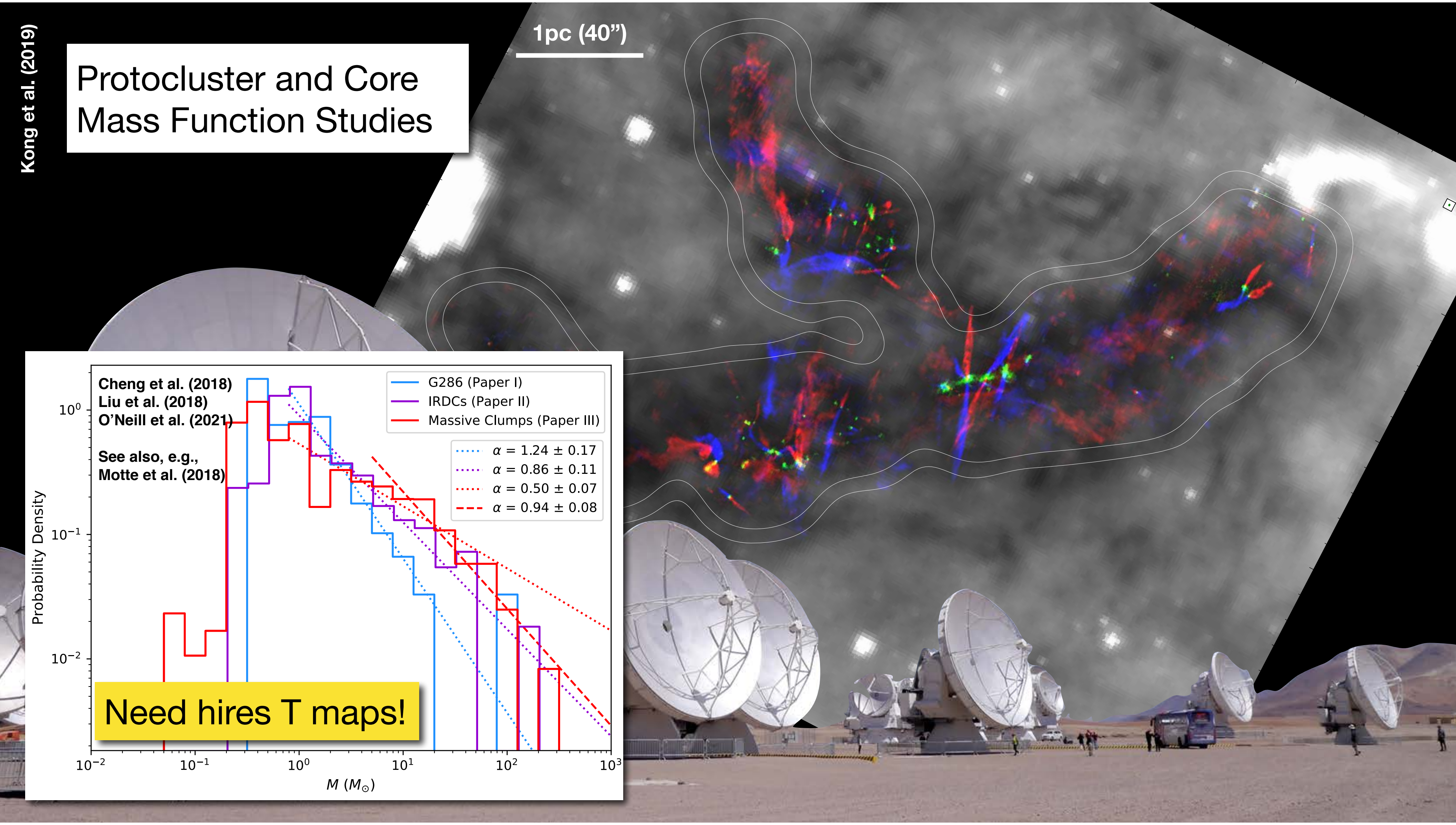
- ALMA survey of 30 IRDC clumps (Kong, Tan et al. 2017); automated N2D+(3-2) core finding; ~100 $N_2D^+(3\text{-}2)$ core candidates; dynamical analysis of 6 best cores: $< \sigma_{obs}/\sigma_{vir} > = 0.80 \pm 0.06$
- IRDC G28.37+0.07 at 0.2": C1-S, ~50 $M_\odot$. (Kong, Tan et al. 2018)
- G11.92-0.61-MM2: $\gtrsim$ 30 $M_\odot$ (Cyganowski, Brogan et al. 2014)
- However: G028.23-00.19: < 15 $M_\odot$ cores (Sanhueza et al. 2017)
- See also Nony+ (2018); Louvet+ (2018)







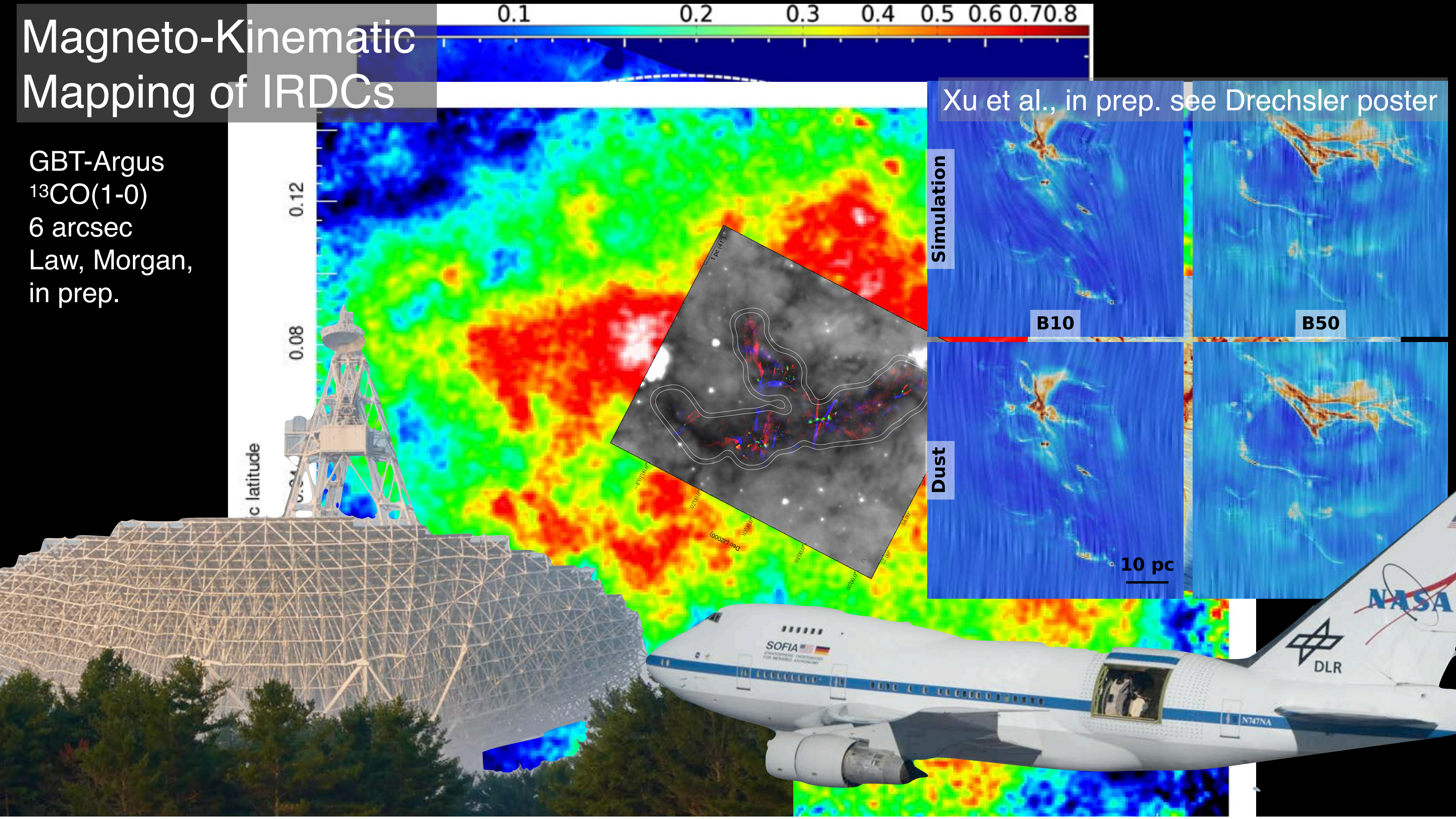
- Prestellar cores are weak in mm continuum (no surprise!); but highly deuterated (N_2D^+)
- Massive PSCs appear "sub-virial" with respect to fiducial turbulent core model. Virial if moderately stronger B-fields (~1-2 mG), i.e., sub-Alfvénic (see also Beuther et al. 2018).
- Appear chemically old (high deuteration; low OPR), compared to t_{ff}
- **Dedicated PSC mass function studies needed!**



Kong et al. (2019)
Protocluster and Core Mass Function Studies
1pc (40”)
Cheng et al. (2018)
Liu et al. (2018)
O’Neill et al. (2021)
See also, e.g., Motte et al. (2018)
G286 (Paper I)
IRDCs (Paper II)
Massive Clumps (Paper III)
α = 1.24 ± 0.17
α = 0.86 ± 0.11
α = 0.50 ± 0.07
α = 0.94 ± 0.08
Probability Density
10^0
10^{-1}
10^{-2}
10^{-2} 10^{-1} 10^0 10^1 10^2 10^3
M ($M_\odot$)
Need hires T maps!

Magneto-Kinematic Mapping of IRDCs

GBT-Argus
$^{13}CO(1-0)$
6 arcsec
Law, Morgan, in prep.

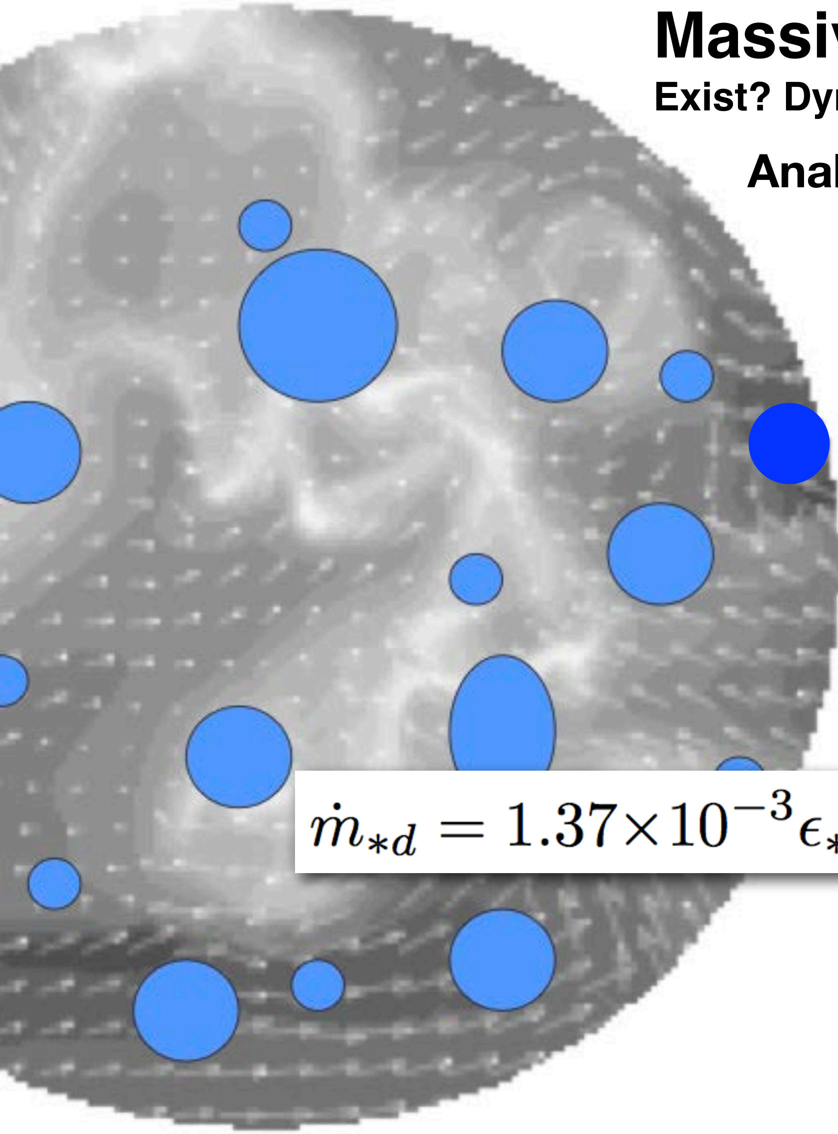


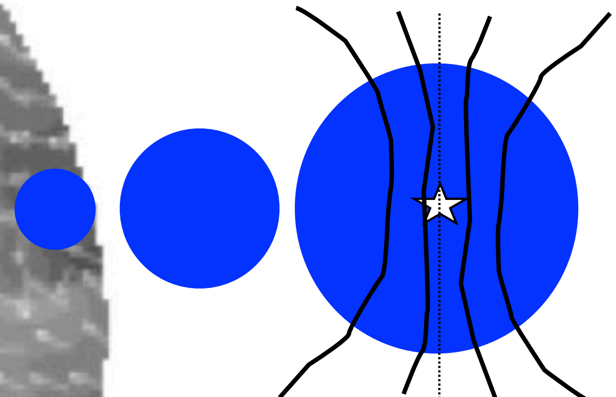
Massive Protostellar Cores

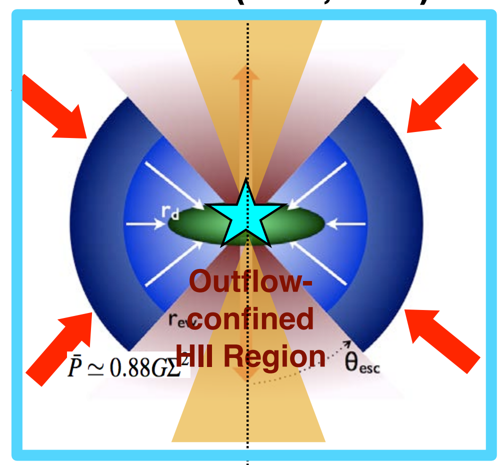
Exist? Dynamical state? SFE (CMF->IMF)? Multiplicity?

Analytic Theory: e.g. Turbulent Core Model

McKee & Tan (2002, 2003)







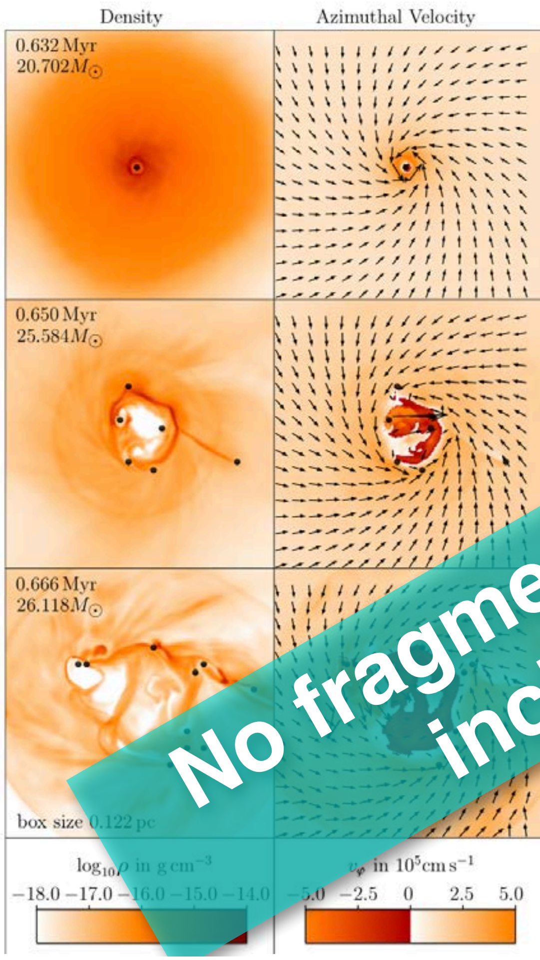
$$\dot{m}_{*d} = 1.37\times10^{-3}\epsilon_{*d}(M_{c,2}\Sigma_{\rm cl})^{3/4}(M_{*d}/M_c)^{1/2}M_\odot{\rm yr}^{-1}$$

t=0
protostar
formation

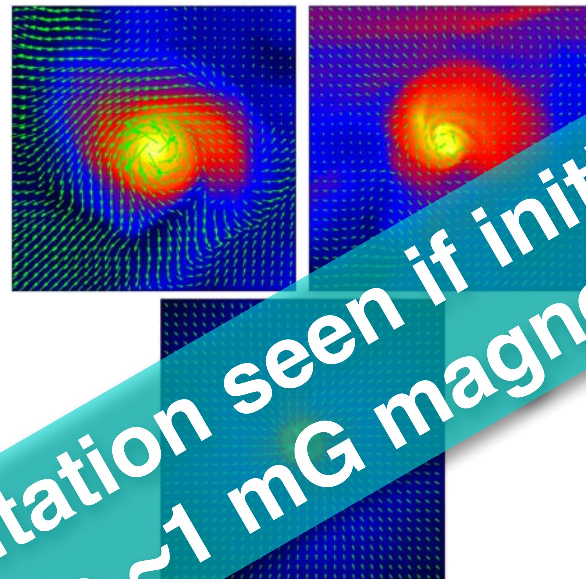
$m_* = 8M_\odot$

Massive Protostellar Cores: simulations

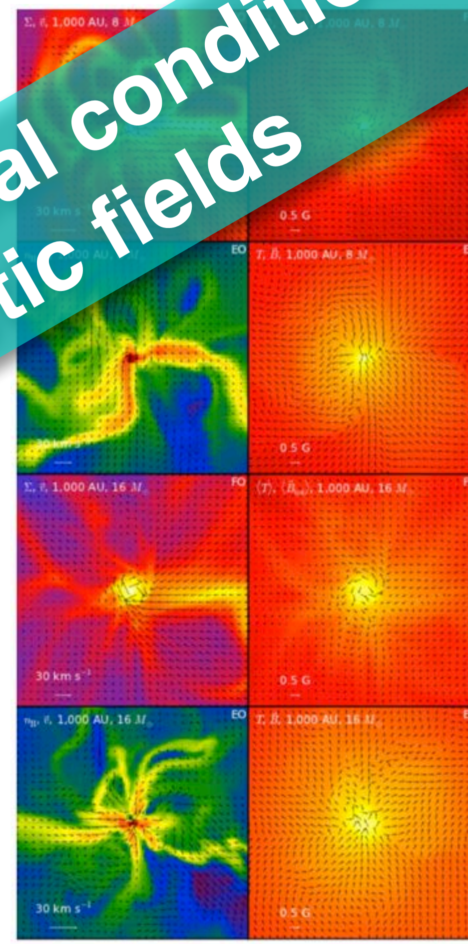
Peters et al. (2011)
M_c = 100$M_\odot$, R_c=0.5pc,
n_H = 5400cm^{-3}, B=10μG



Seifried et al. (2012)
M_c = 100$M_\odot$, R_c=0.25pc,
n_H = 4.4x$10^4 cm^{-3}$, B~1mG



Myers et al. (2013)
M_c = 300$M_\odot$, R_c=0.1pc,
n_H = 2.4x$10^6 cm^{-3}$, B~1mG

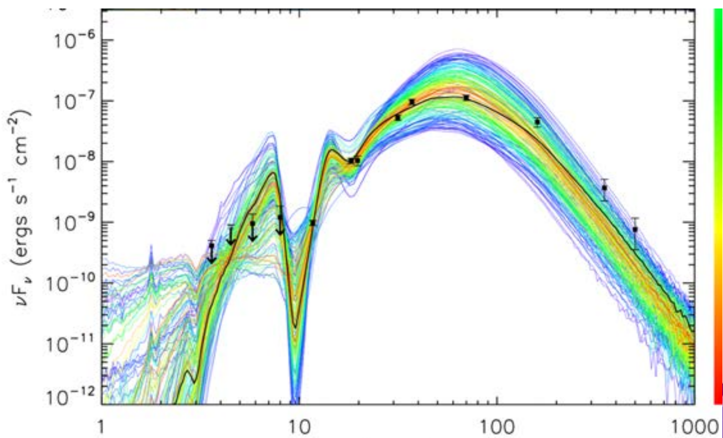


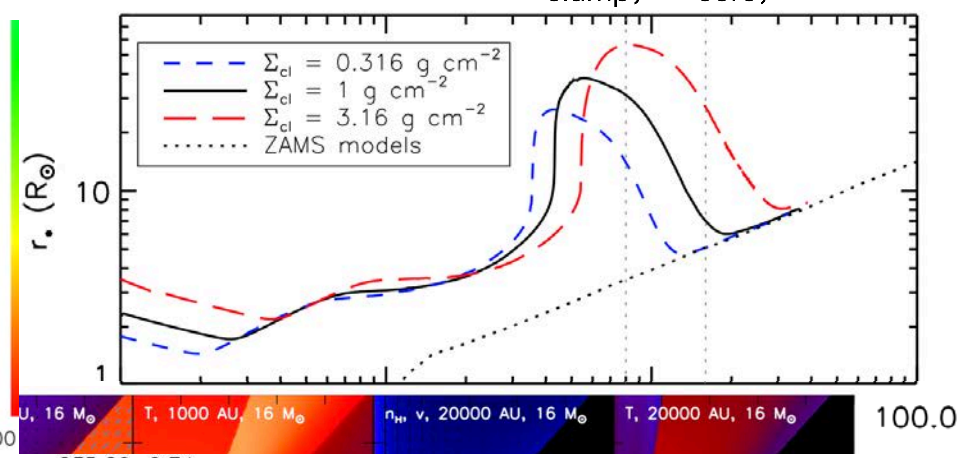
No fragmentation seen if initial conditions include ~1 mG magnetic fields

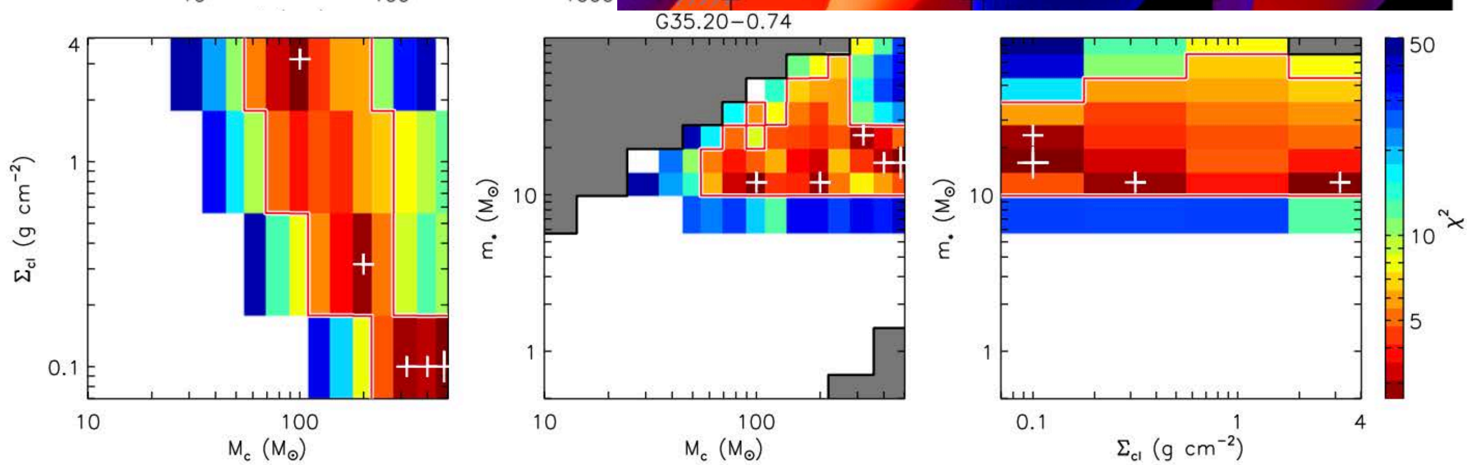
Massive Protostellar Cores: semi-analytic protostellar evolution & radiative transfer models

Zhang & Tan (2011), Zhang, Tan & McKee (2013), Zhang, Tan & Hosokawa (2014), Zhang & Tan (2018)

Three primary parameters of Turbulent Core Model: Σ_{clump}, M_{core}, m_*





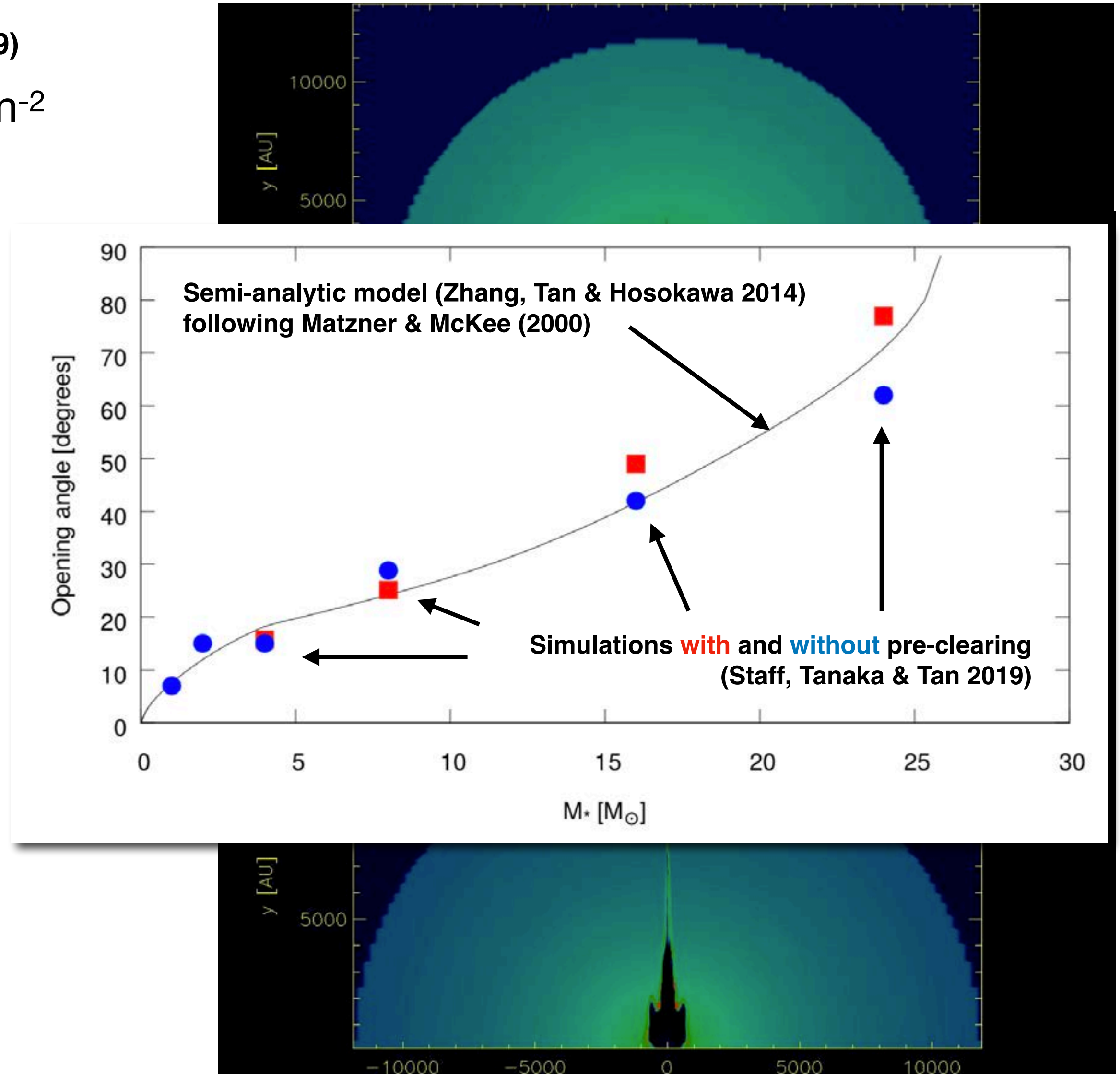


Massive Protostellar Cores: MHD outflow feedback

Staff, Tanaka, Tan (2019)

$\Sigma_{clump} = 1 \text{ g cm}^{-2}$
$M_{core} = 60\ M_{\odot}$

$m_* = 1 M_{\odot}$



$m_* = 8 M_{\odot}$

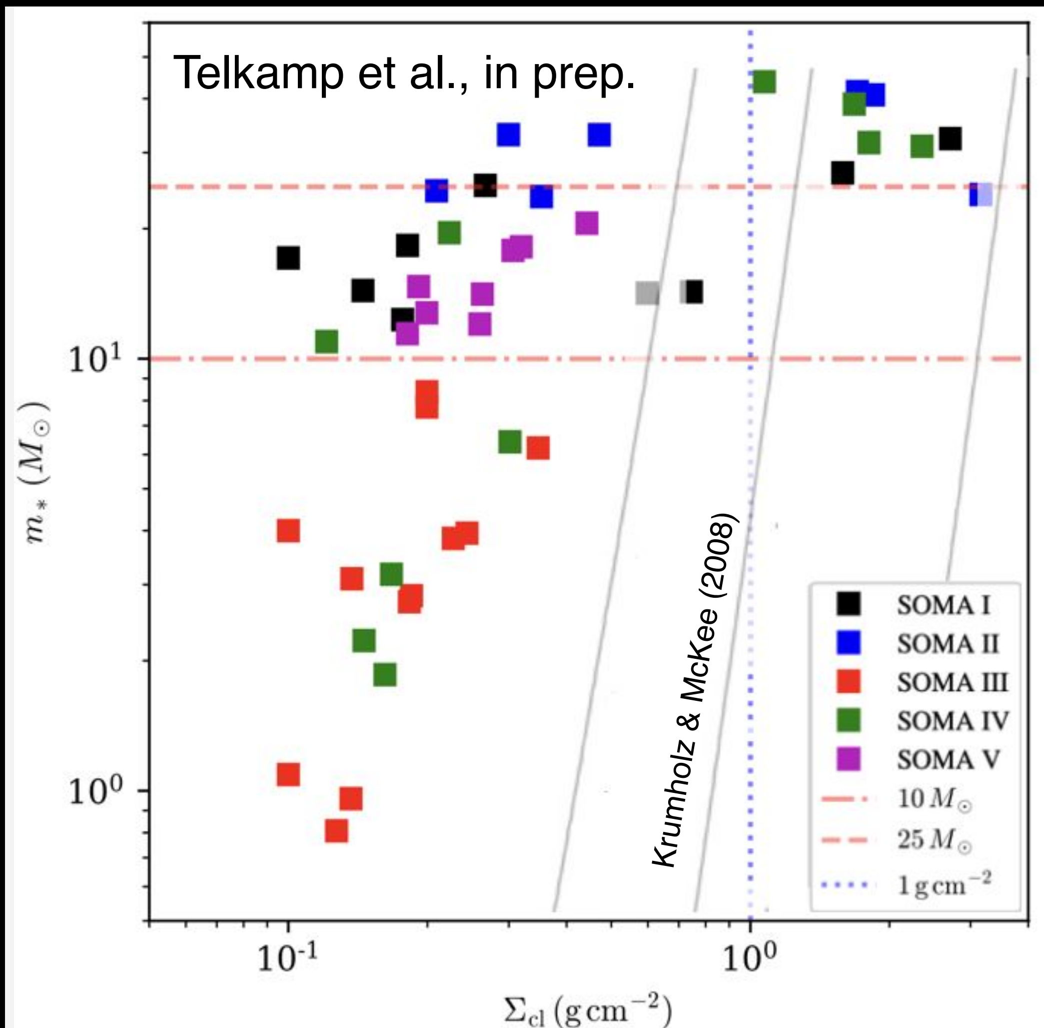
$m_* = 24 M_{\odot}$

Massive Protostar Observations

The SOFIA Massive (SOMA) Star Formation Survey

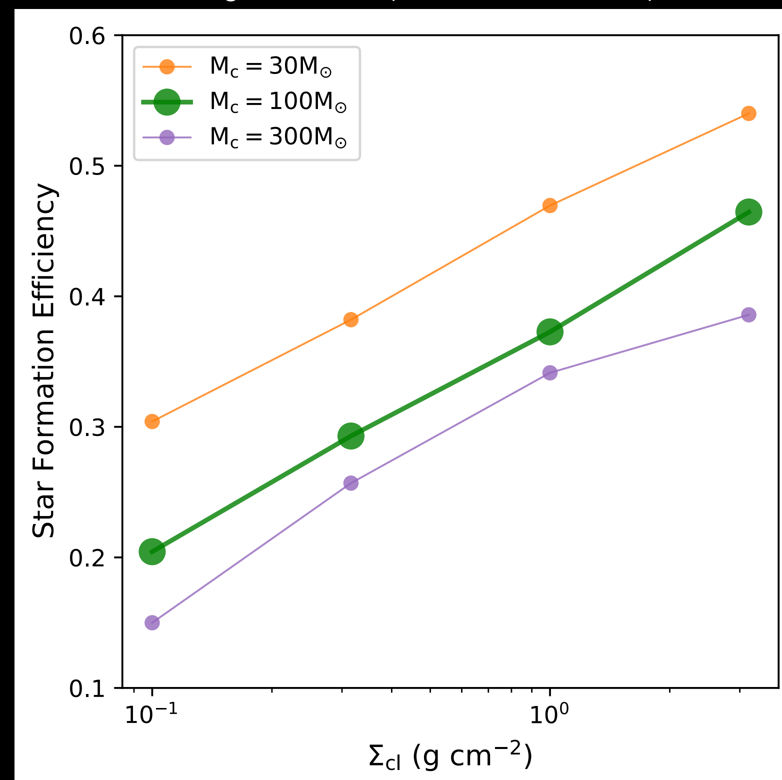
Conditions for Massive Star Formation?

Liu, Tan et al. (2020) (SOMA III) + Fedriani et al., in prep. (SOMA IV)



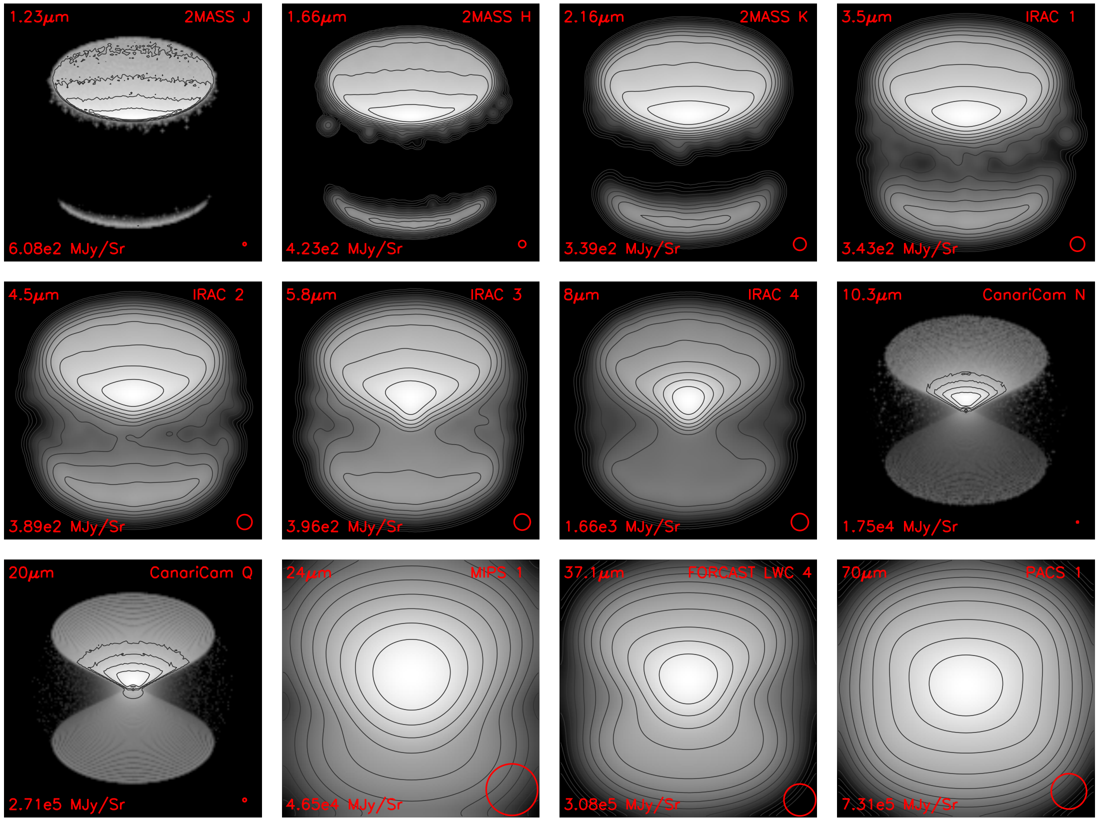
Massive protostars can form where $\Sigma_{cl} < 1$ g cm^{-2}
$m_* > 25 \, M_\odot$ generally favors high $\Sigma_{cl} > 1$ g cm^{-2}

Favoured physical interpretation: internal protostellar feedback limiting core SFE (Tanaka et al. 2017)



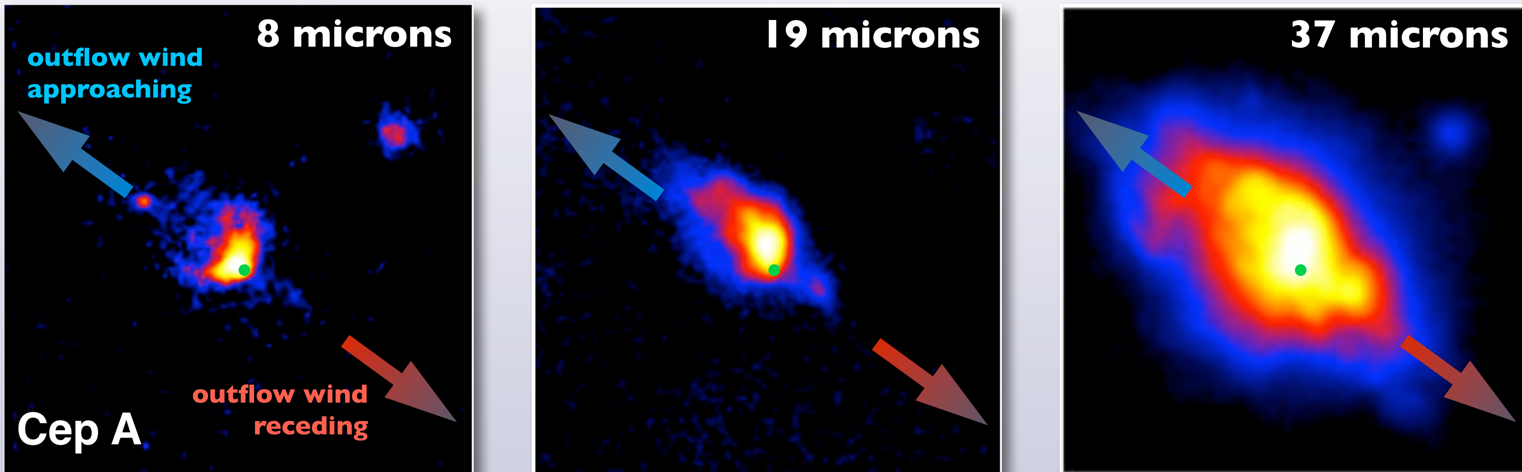
SOMA+
Beyond SED Fitting

THE ASTROPHYSICAL JOURNAL, 733:55 (20pp), 2011 May 20 ZHANG & TAN

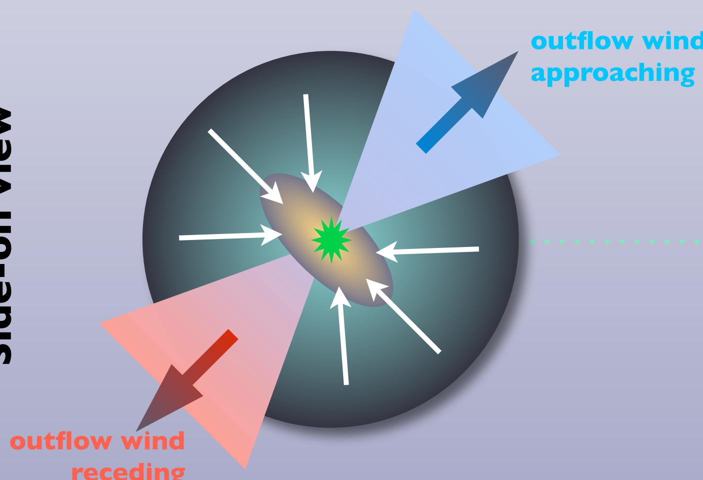


Peering to the Heart of Massive Star Birth

On-sky view



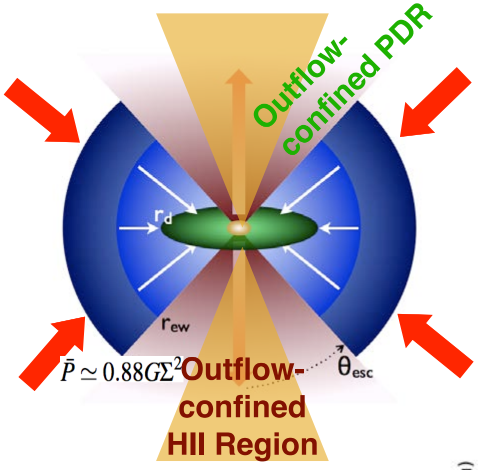
Side-on view

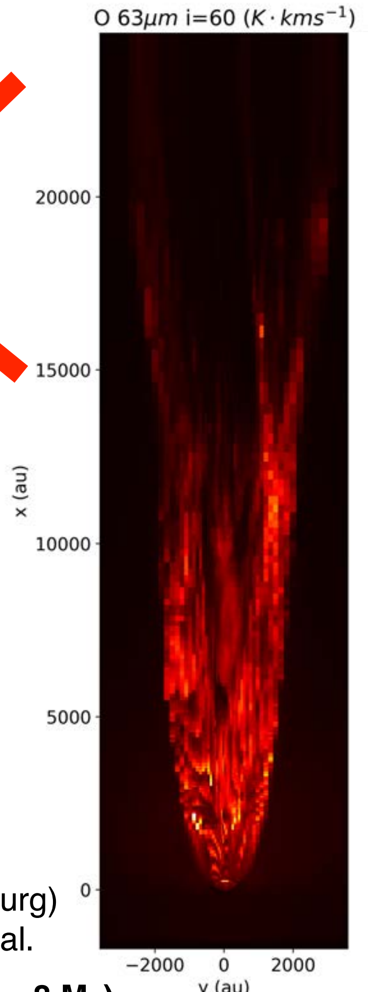


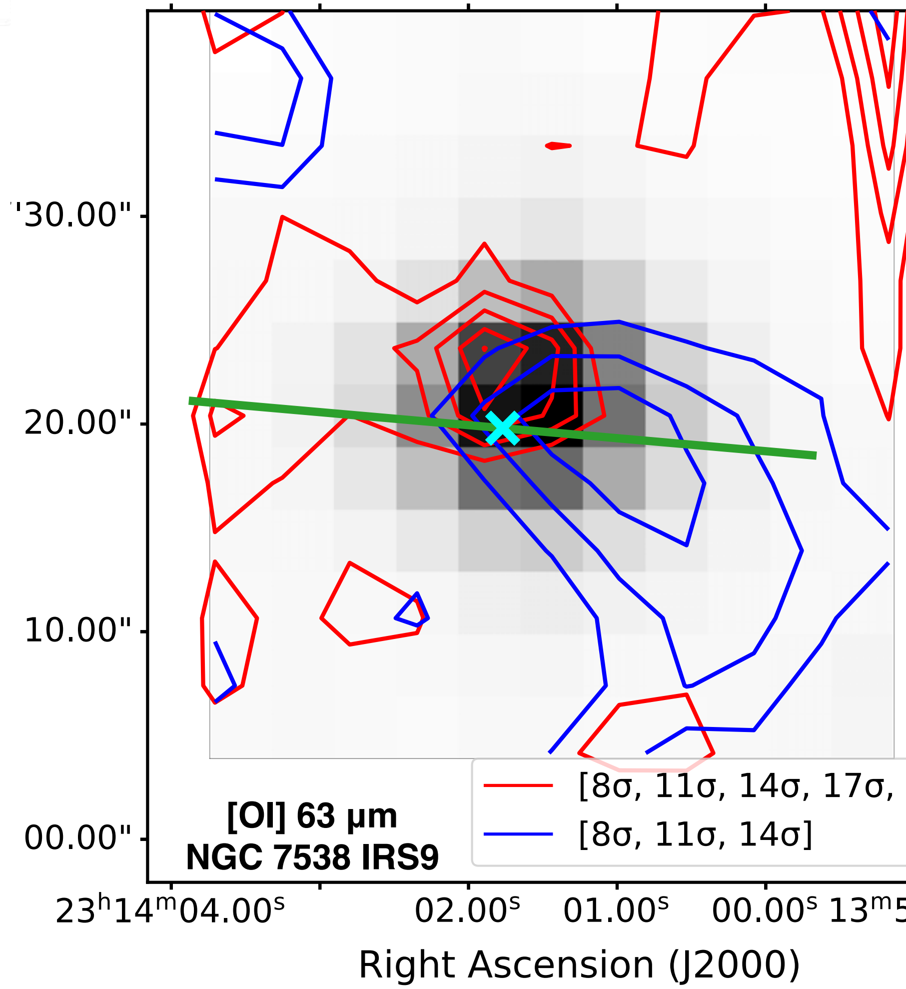
De Buizer, Liu, Tan et al. (2017)

SOMA FIFI-LS - Atomic Outflows

Lianis Reyes Rosa (U. Virginia)
Y-L. Yang, Tan et al.



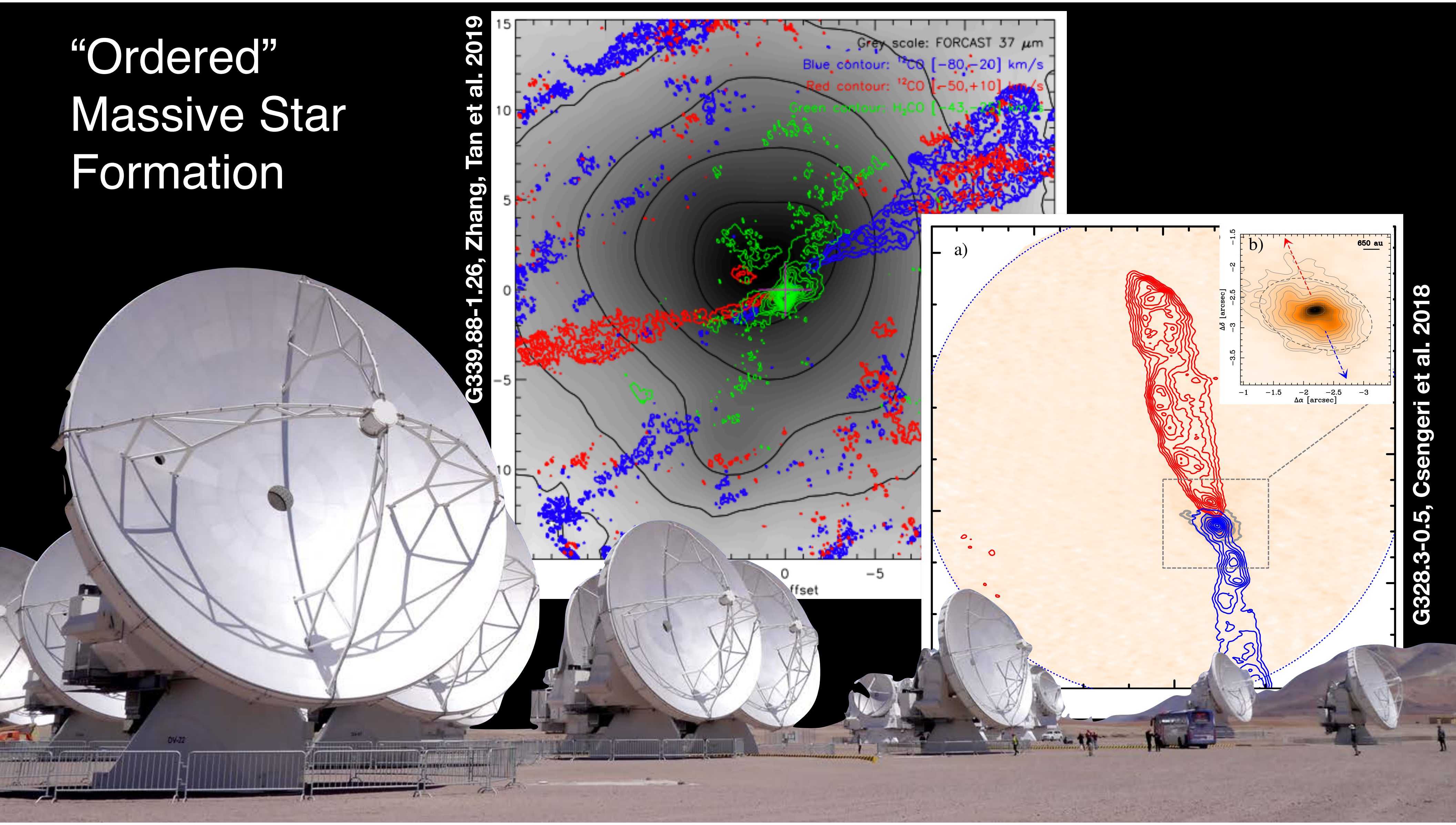




Marta Obolentseva (St. Petersburg)
Bisbas, Staff, Ramsey, Tan et al.

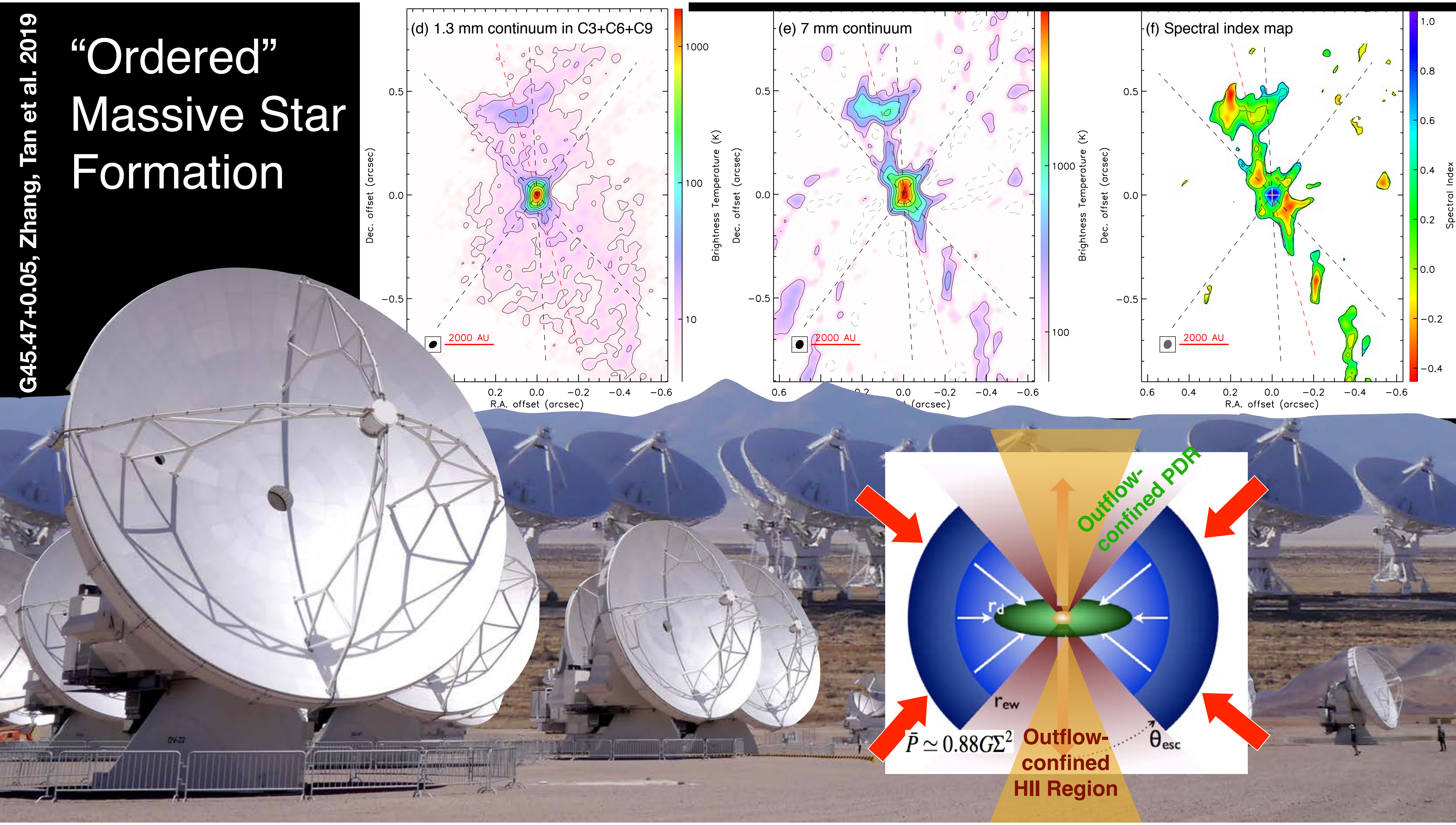
($M_c = 60\ M_\odot$; $\Sigma_{cl} = 1$ g cm^{-2}; $m_* = 8\ M_\odot$)

“Ordered” Massive Star Formation



“Ordered” Massive Star Formation

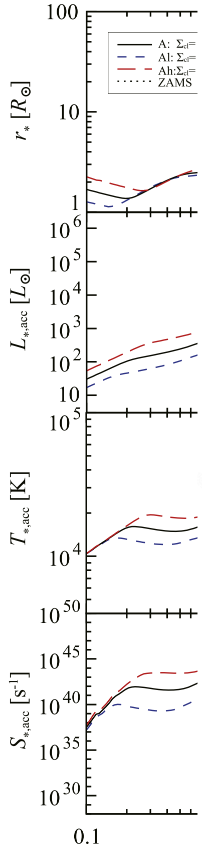
G45.47+0.05, Zhang, Tan et al. 2019

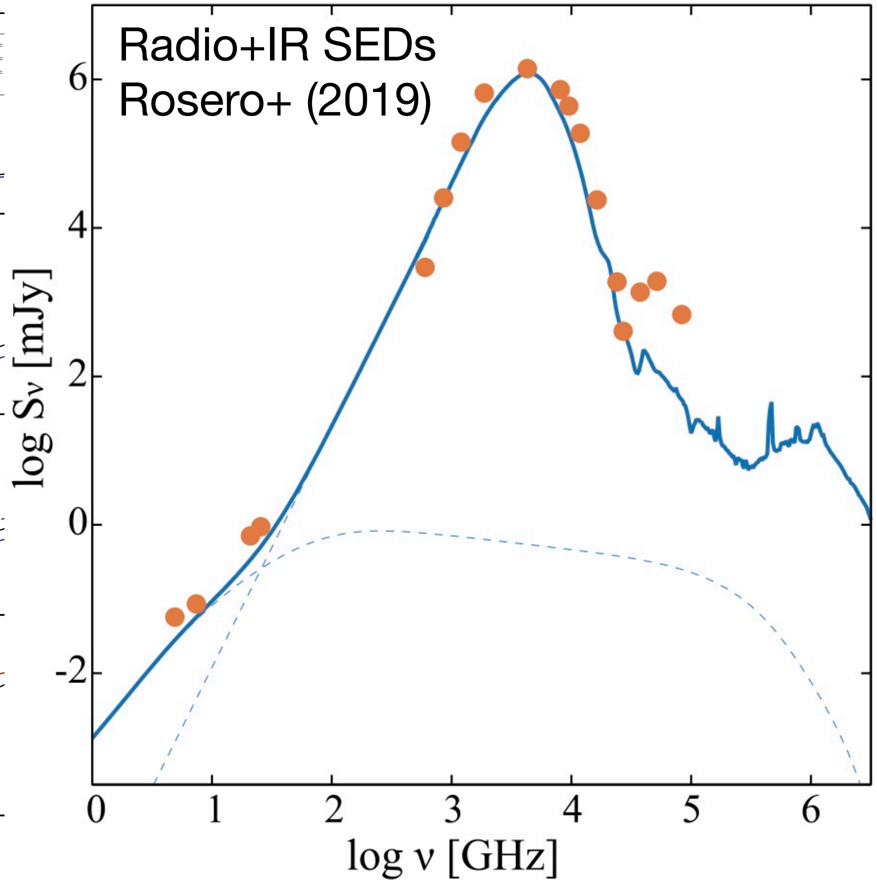


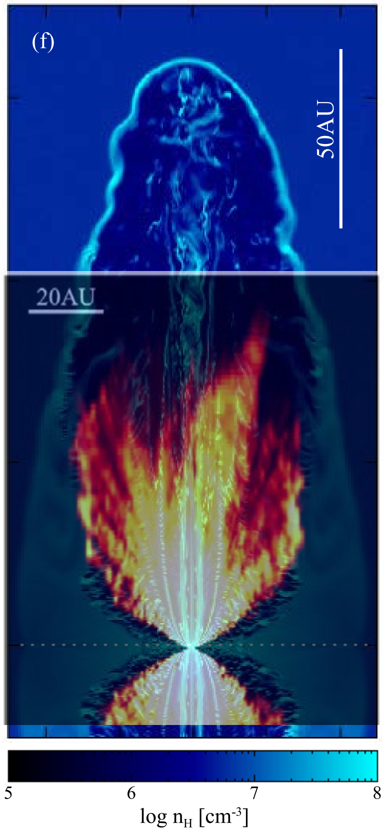
Massive Protostellar Cores: ionization
(feedback & diagnostics; outflow-confined HII regions)

Tan & McKee (2003); Tanaka, Tan & Zhang (2016); Tanaka, Tan, Staff & Zhang (2017); Rosero+ (2019).

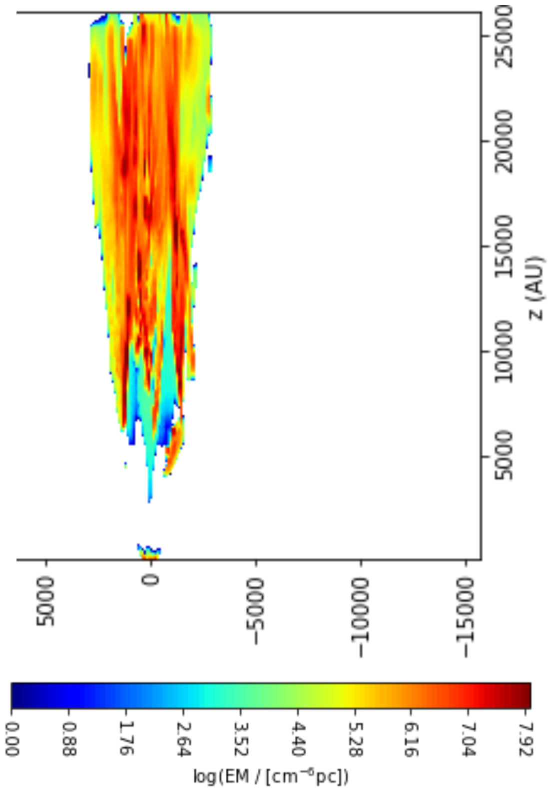
Photoionization models:

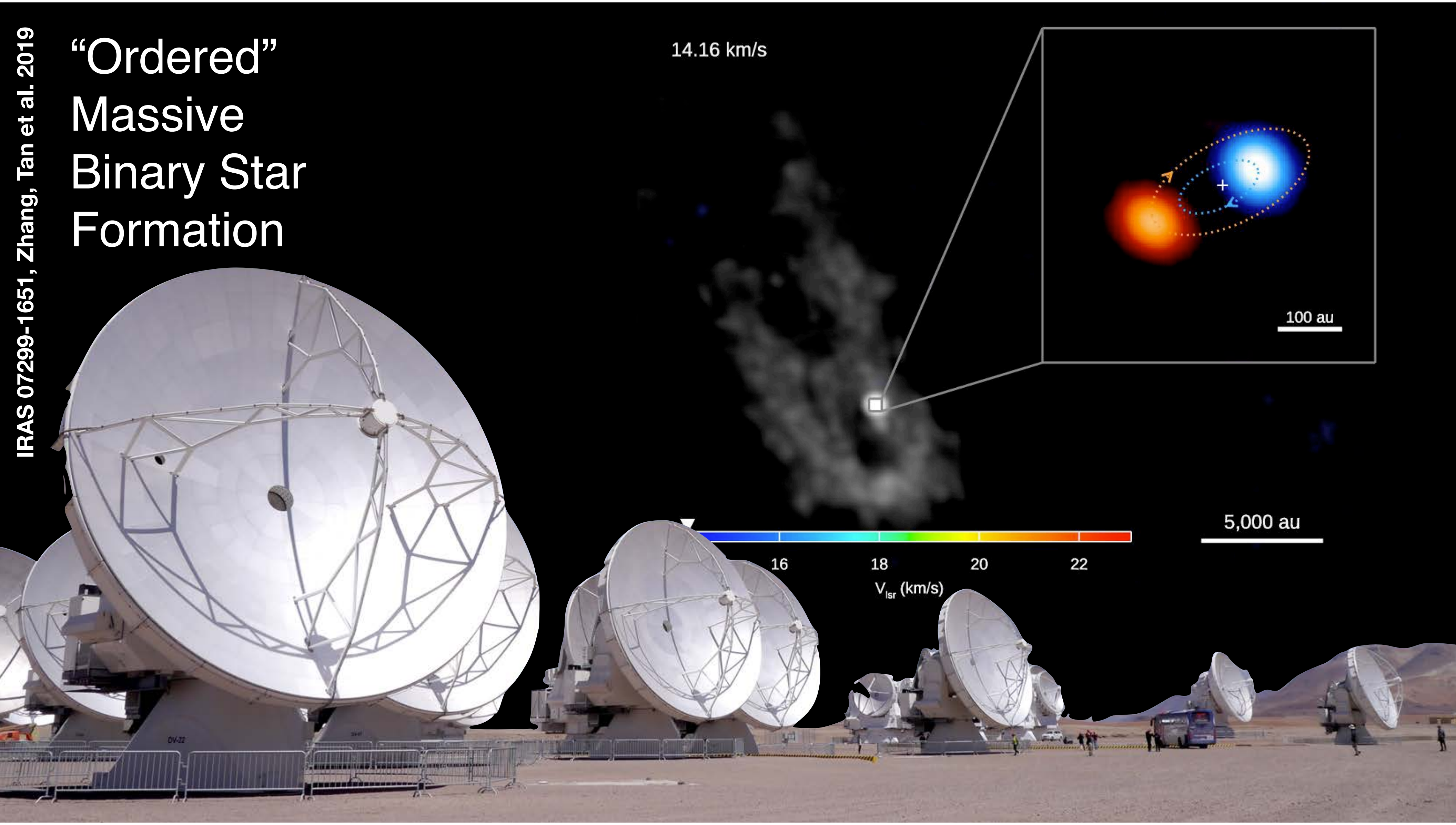






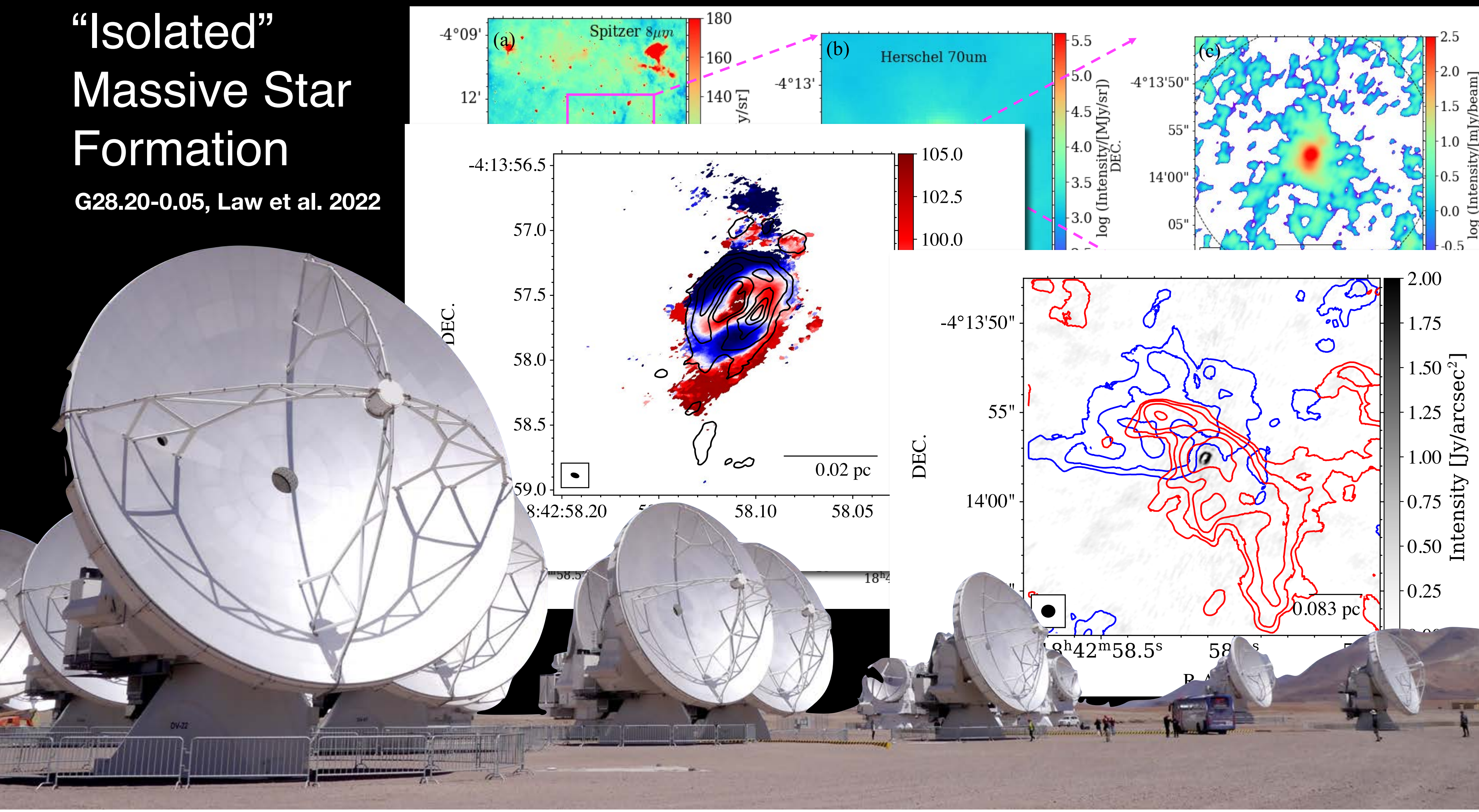
Shock Ionization Models:
Gardiner, Staff, Ramsey, Tan, in prep.




IRAS 07299-1651, Zhang, Tan et al. 2019
"Ordered"
Massive
Binary Star
Formation
14.16 km/s
100 au
5,000 au
16
18
20
22
V_lsr (km/s)

“Isolated” Massive Star Formation

G28.20-0.05, Law et al. 2022

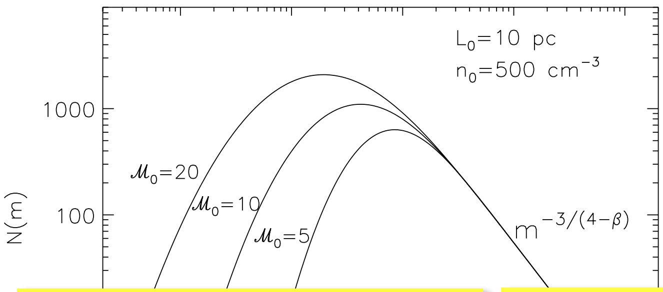


Magnetic Fields

What sets the rate and timescale of star formation?
What sets fragmentation and the stellar initial mass function?

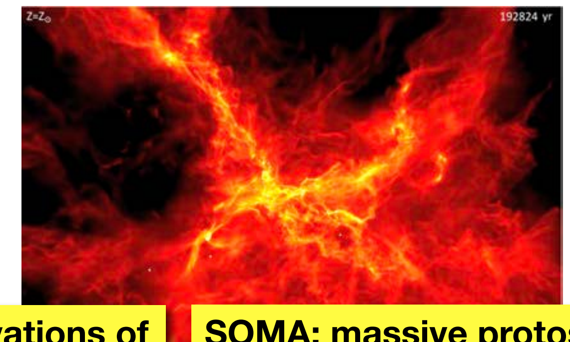
Turbulence-Regulated Fragmentation:

Padoan & Nordlund (2002); Tilley & Pudritz (2004); Hennebelle & Chabrier (2009)



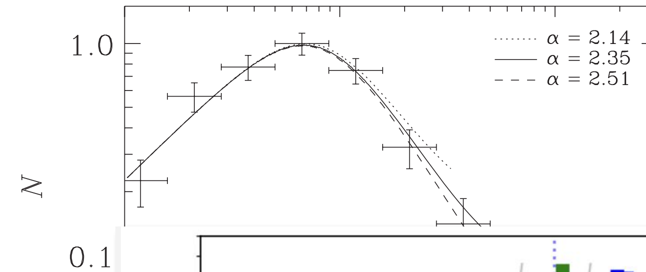
Competitive Accretion with feedback sets the IMF:

e.g., Bate (2012)



Magnetically-Regulated Fragmentation:

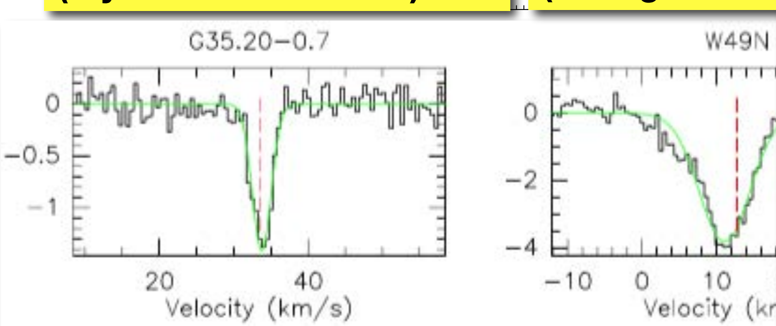
(Kunz & Mouschovias 2009)

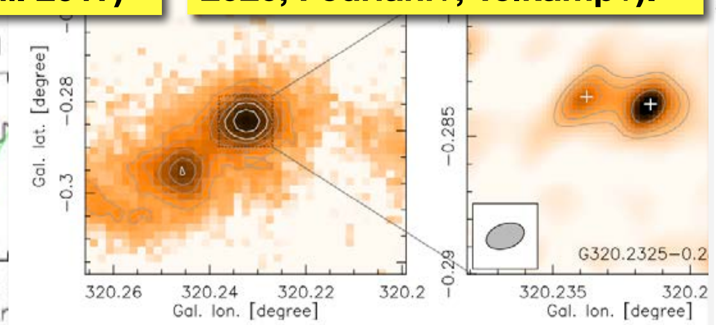


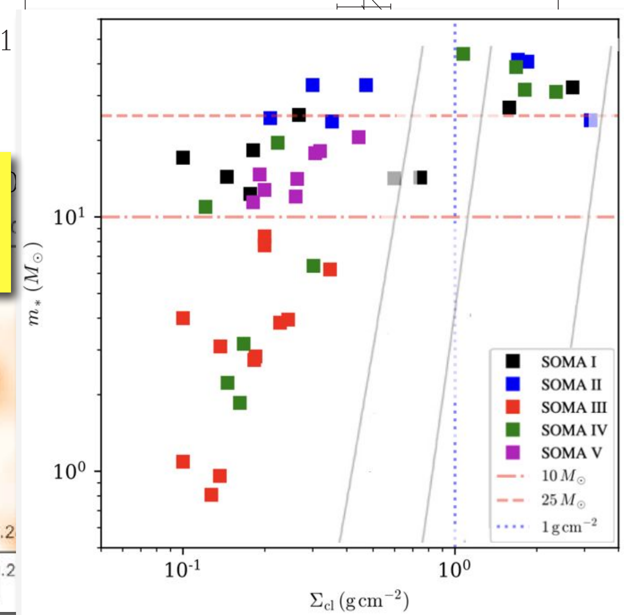
SOFIA observations of Clump Infall v_{infall} ~ 0.1 v_{ff} (Wyrowski et al. 2016)

ALMA observations of Limited Fragmentation (Csengeri et al. 2017)

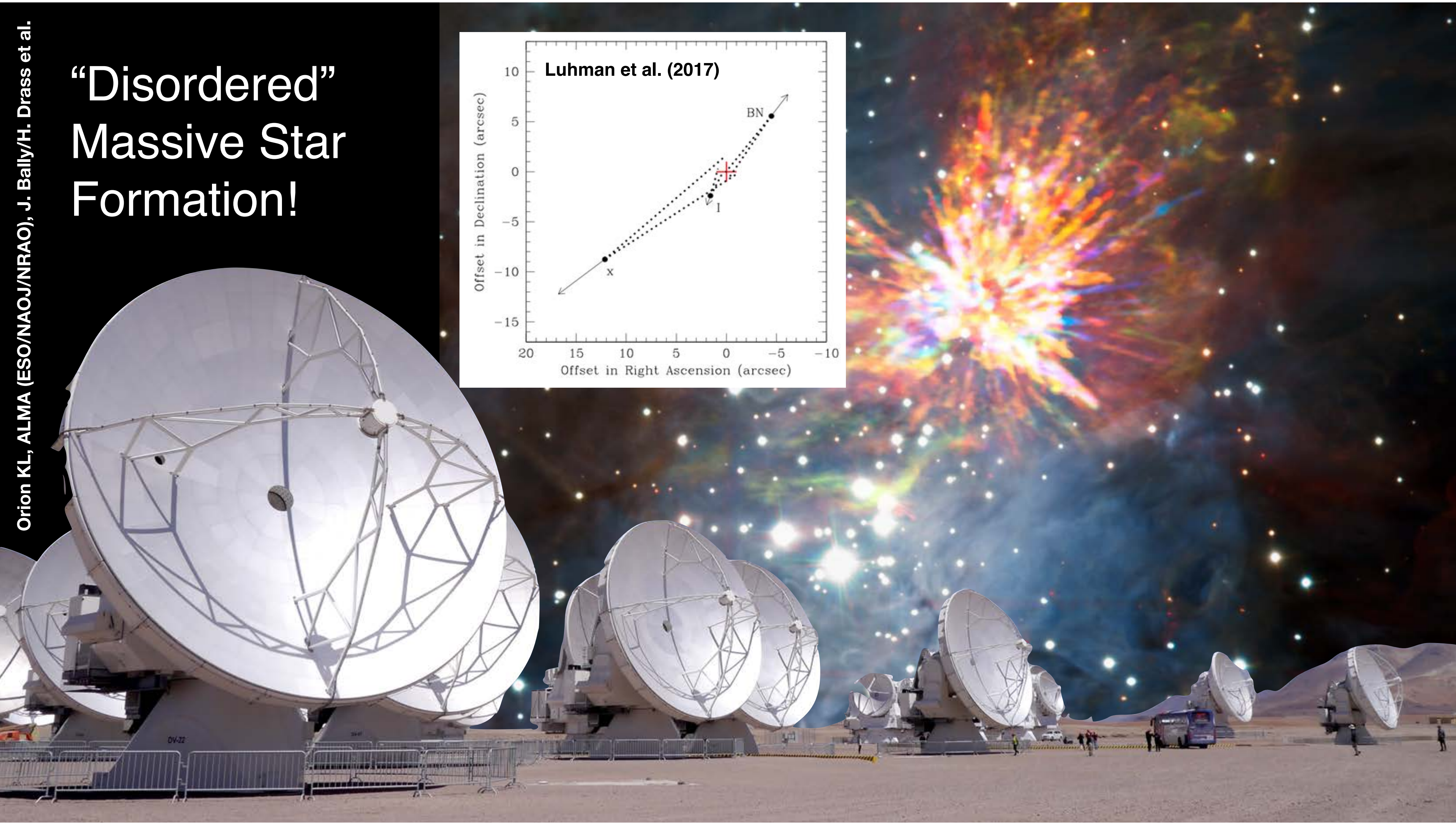
SOMA: massive protostars in low-Σ environs (Liu et al. 2020; Fedriani+; Telkamp+).







“Disordered” Massive Star Formation!



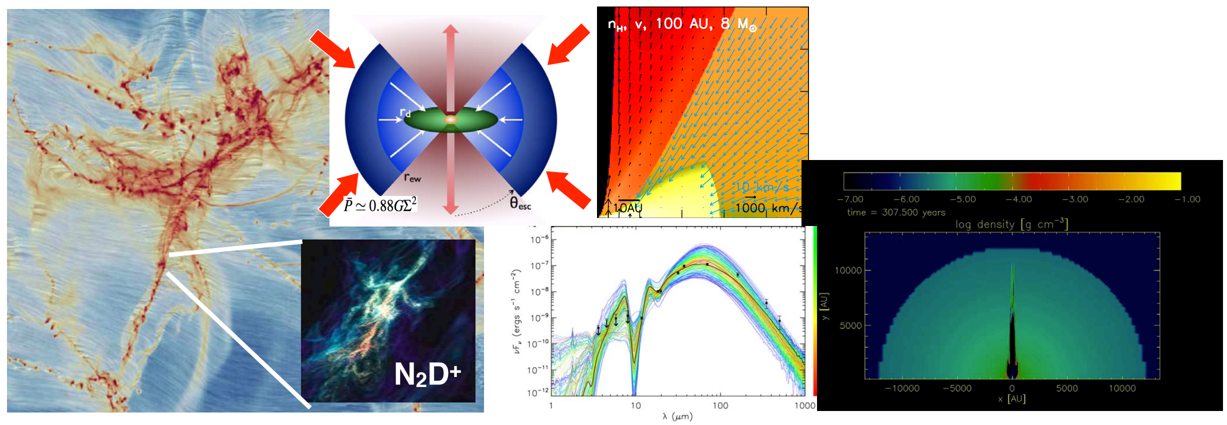
Orion KL, ALMA (ESO/NAOJ/NRAO), J. Bally/H. Drass et al.

Open Questions in Massive Star Formation

Some Quantitative Tests of Core Accretion Theory

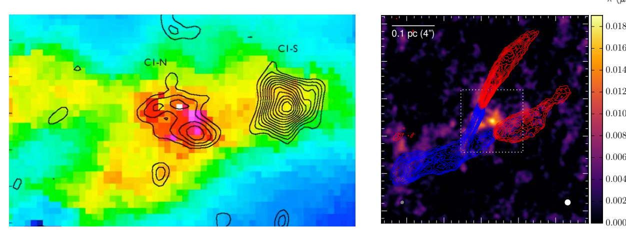
?

Theory: “Turbulent Core Model”:
- trans-Alfvénic turbulence in global clump
- core surface set by clump pressure, which then controls accretion rate
- core supported by B-fields & turbulence
- core interacts with a comparable mass from clump during collapse
- accretion streamers
- atomic & ionized outflows in later stages



?

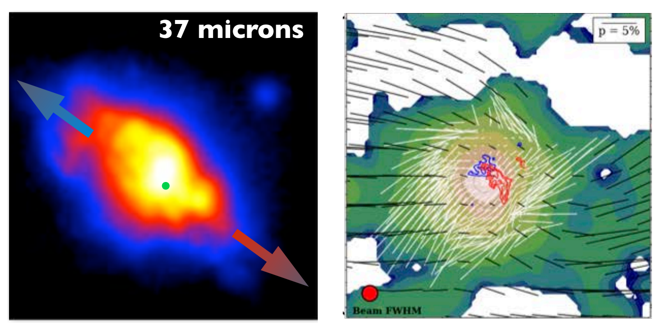
Massive prestellar clumps & cores
Near virial equil. (strong B-fields?)
Chemodynamical history of PSCs?
PSCMF can be measured across the Galaxy



Need for
- **Magneto-Kinematic Mapping of IRDCs**
- **Dfrac via N_2H^+, N_2D^+**

?

Massive Protostars: IR & Radio SEDs
→ physical model → chemical model
SOMA Survey (SOFIA; +ALMA; +HST; +VLA)
Massive protostar morphology;
Tests of core accretion: infall, disks, protostar, outflow, multiplicity, B-fields…



SOFIA:
- **MIR to FIR SEDs + Images**
- **Atomic Outflows**
- **Multiwavelength Polarization for B-field**